LHC PHYSICS

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TAE 2024

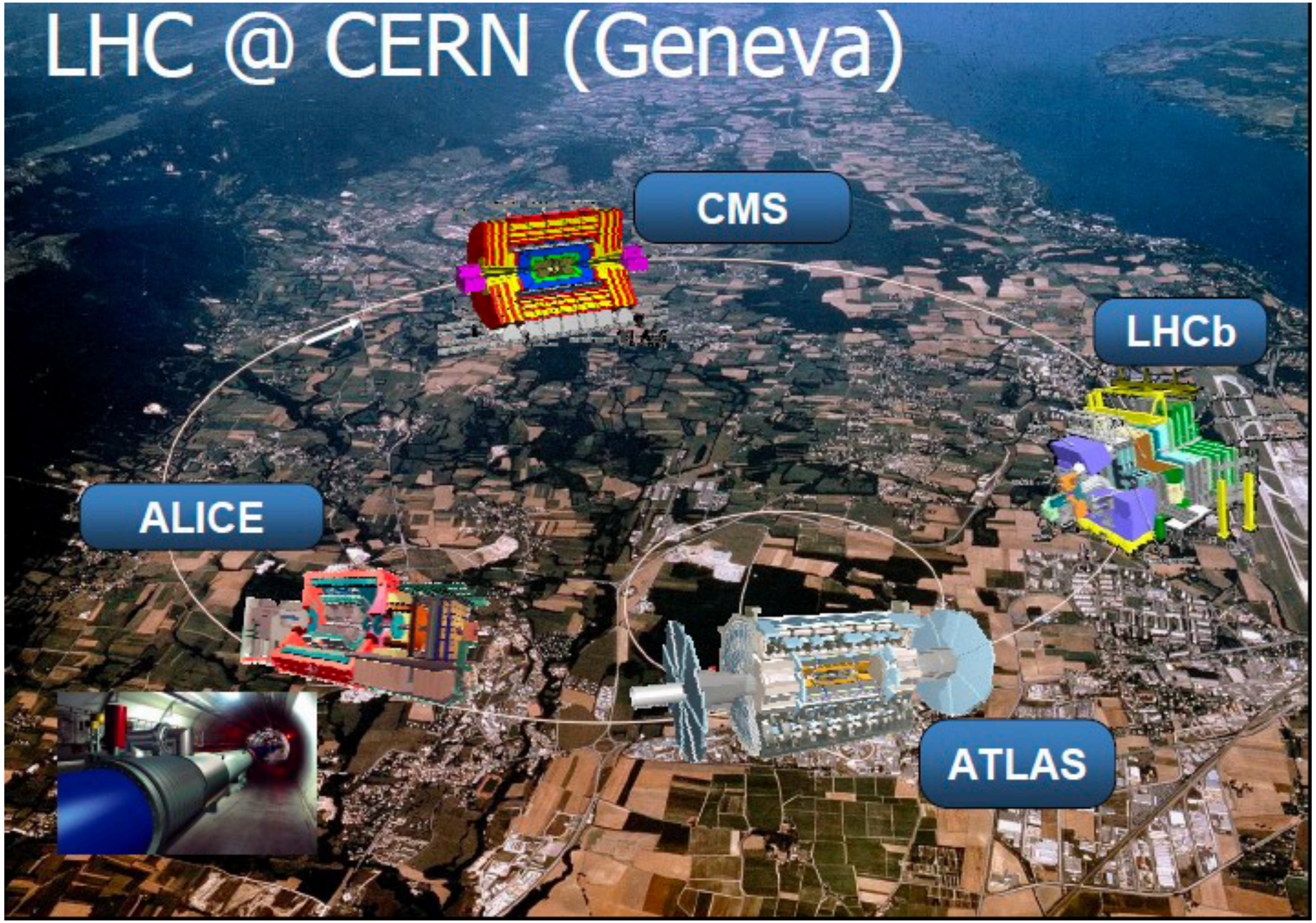
OUTLINE OF THE LECTURES

- Introduction: Experiments
- Setting the stage: Anatomy of a pp collision
- Precision SM Measurements: QCD; EW; TOP
- Higgs Physics
- Beyond the SM
- Conclusion

Not discussing detector issues - MaryCruz will discuss this on Monday!

No time to go in a lot of depth, nor to cover all the topics: general ideas, bias towards Higgs physics

THE LHC AND ITS EXPERIMENTS



High luminosity hadron collisions at the highest energies (pp→$\sqrt{s}$=7,8,13, 13.6 TeV):

- 2 multi-purpose experiments (ATLAS,CMS)
- 1 experiment dedicated to b/c quarks (CP violation; "multipurpose" in forward region)
- 1 experiment dedicated to heavy-ion collisions (QCD at high density/temperature)

Focus on ATLAS and CMS in this lecture: equivalent in reach.

I work for CMS, more examples from CMS as a result, no bias intended :)

UNPRECEDENTED POTENTIAL TO STUDY THE LIMITS OF THE SM

- **Precision measurements of the standard model**
  - How well do we know the standard model and its parameters? (W, top, Higgs, α_S, ..)
  - Electroweak Symmetry Breaking: do we understand the nature of the Higgs boson?
  - QCD: What is a proton like inside? Can we improve QCD predictions? Can we model collisions with Monte Carlo? What can we learn from Heavy Ion collisions?
  - Can we find BSM from deviations in global precision measurements? (EFT)

- **Exploring high-energy physics at the TeV scale**
  - No-Lose theorem: the LHC had to either discover the Higgs, or new physics at the TeV scale
  - Is there new physics beyond the standard model (BSM)? (SUSY at low energy, exotic models such as production of new resonances, more Higgs bosons…)
  - Can we connect dark matter with collider measurements?
  - Do we understand the physics of flavour? Anomalies

PHYSICS AT THE LHC... IN PLURAL

SM Measurements: W, Z, Jets…

Higgs Boson Physics

Top Quark Physics

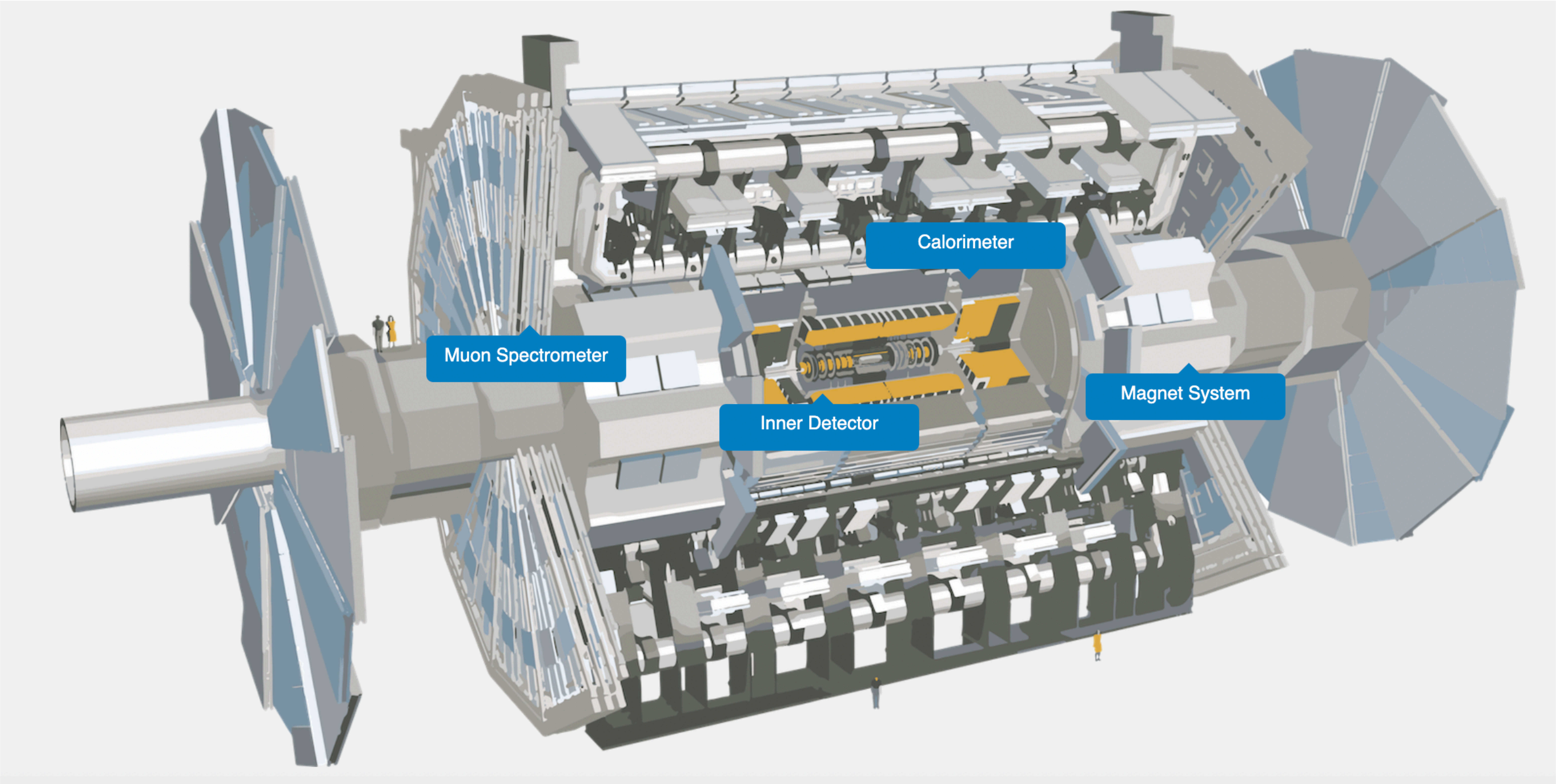
BSM Searches: Dark Matter, LLPs, New resonances, SUSY,….

B Physics

Heavy Ions

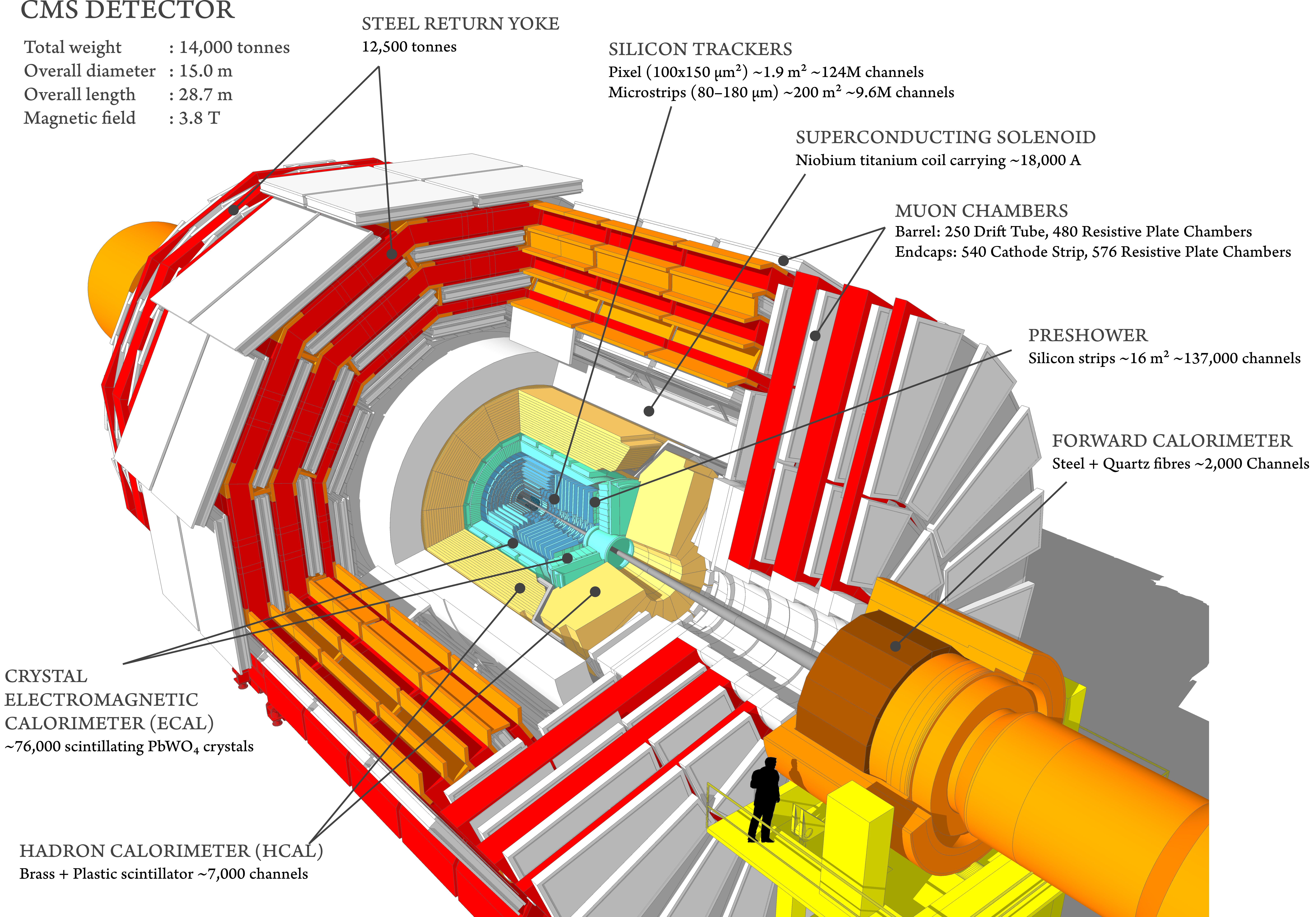
Many Experiments in one!

ATLAS


Calorimeter
Muon Spectrometer
Magnet System
Inner Detector

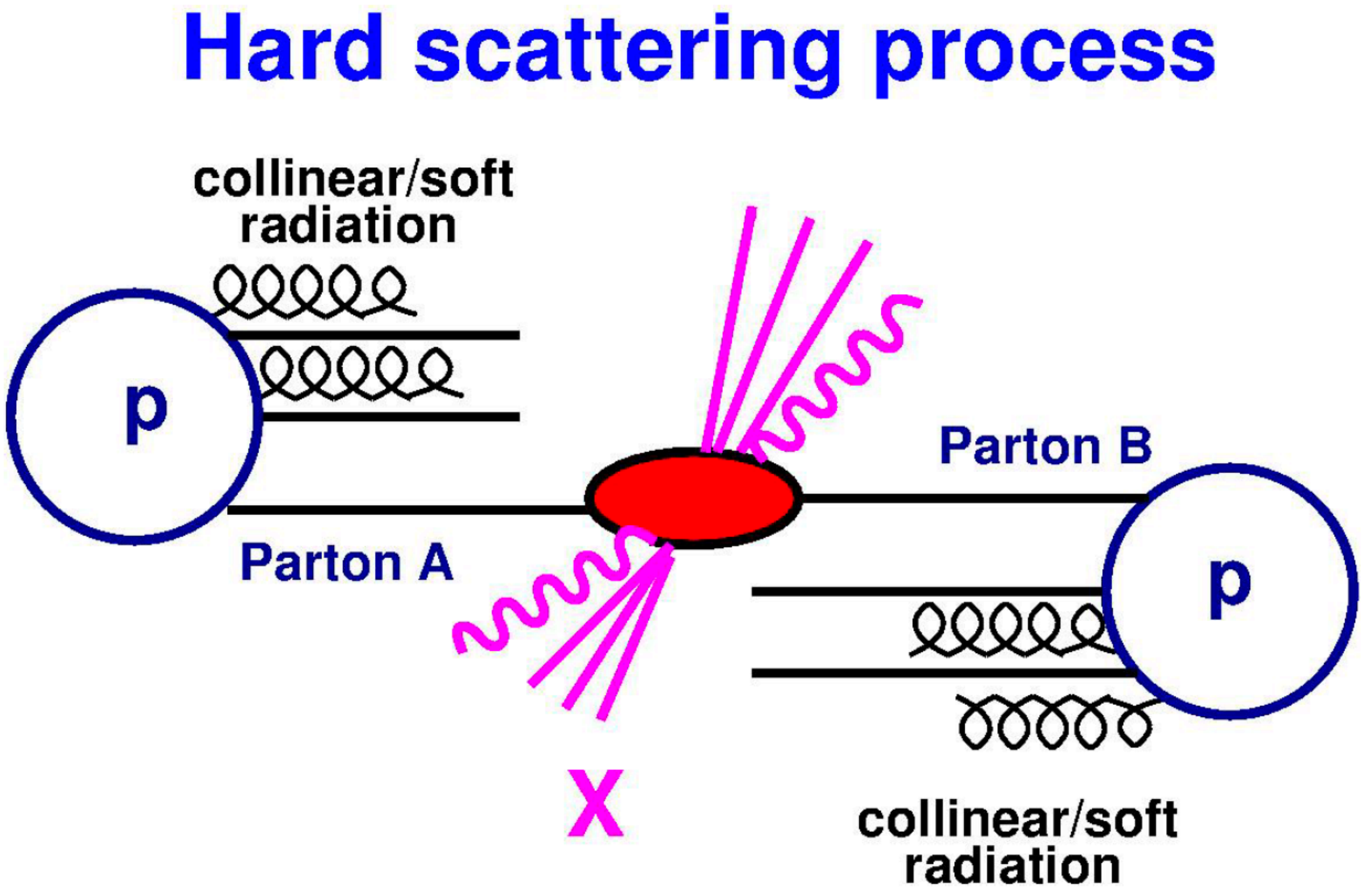

CMS


CMS
2T


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16 m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

SETTING THE STAGE: LHC COLLISIONS

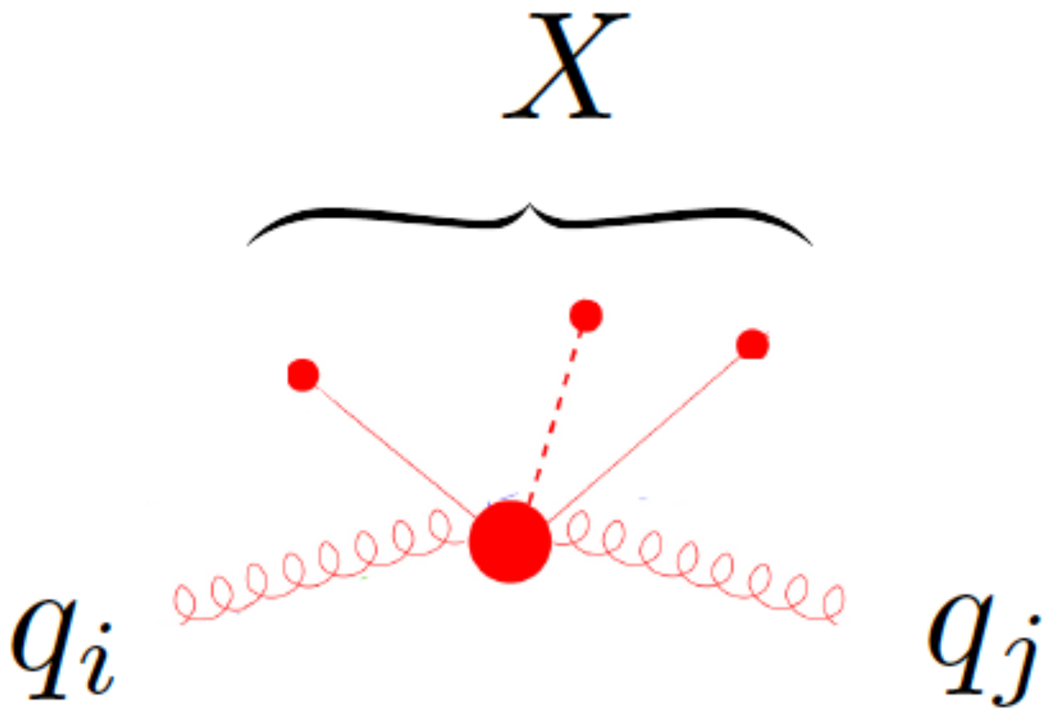
ANATOMY OF A LHC EVENT



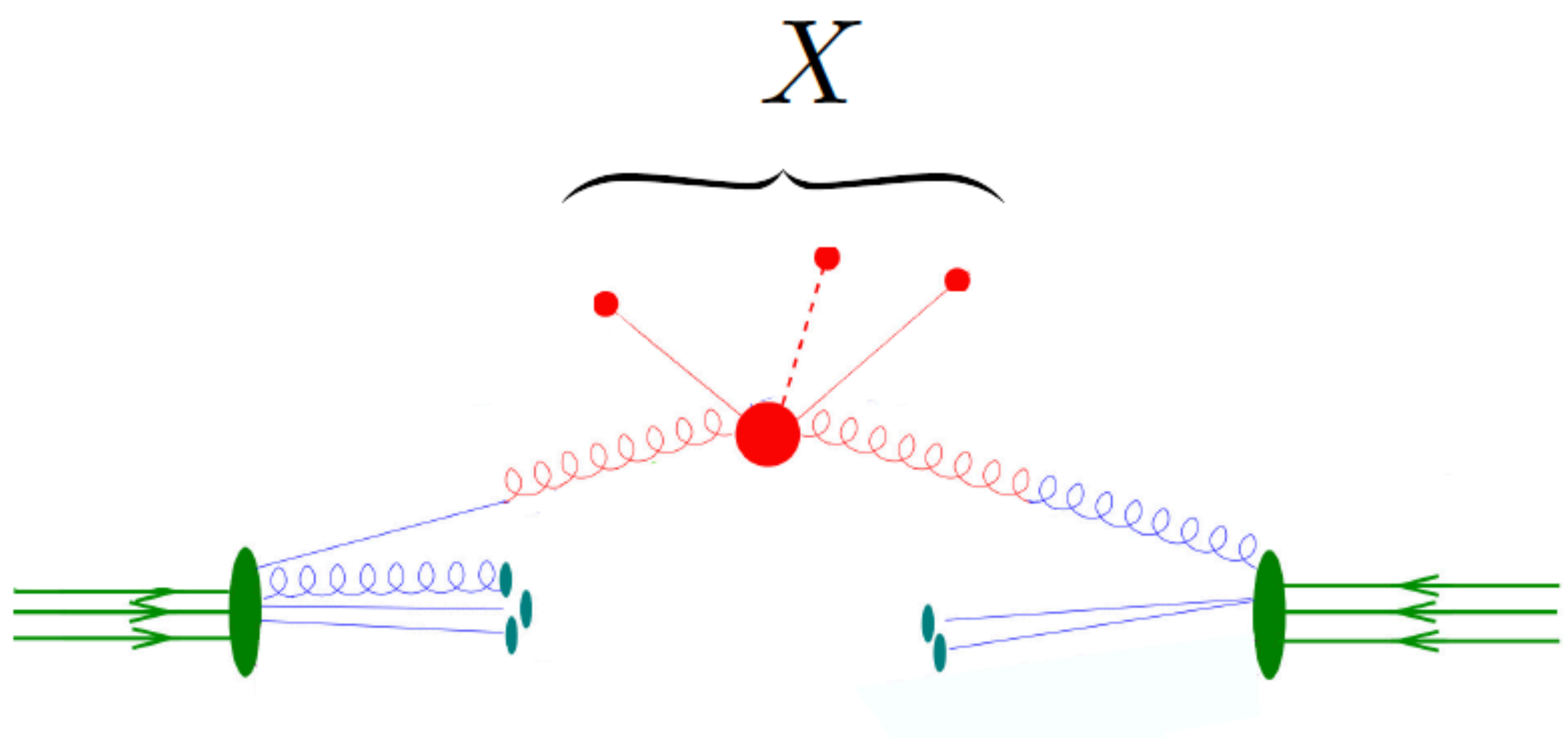
Factorization Theorem:

$$\sigma(\mathrm{pp} \to \mathrm{C} + \mathrm{X}; Q^2) = \sum_{\mathrm{A,B}} \int \mathrm{d}x_{\mathrm{A}} \int \mathrm{d}x_{\mathrm{B}}\, \mathrm{pdf}_{\mathrm{p}\to\mathrm{A}}(x_{\mathrm{A}}, Q^2)\, \mathrm{pdf}_{\mathrm{p}\to\mathrm{B}}(x_{\mathrm{B}}, Q^2)\, \sigma(\mathrm{AB} \to \mathrm{C})$$

Graph from F. Krauss



Graph from F. Krauss



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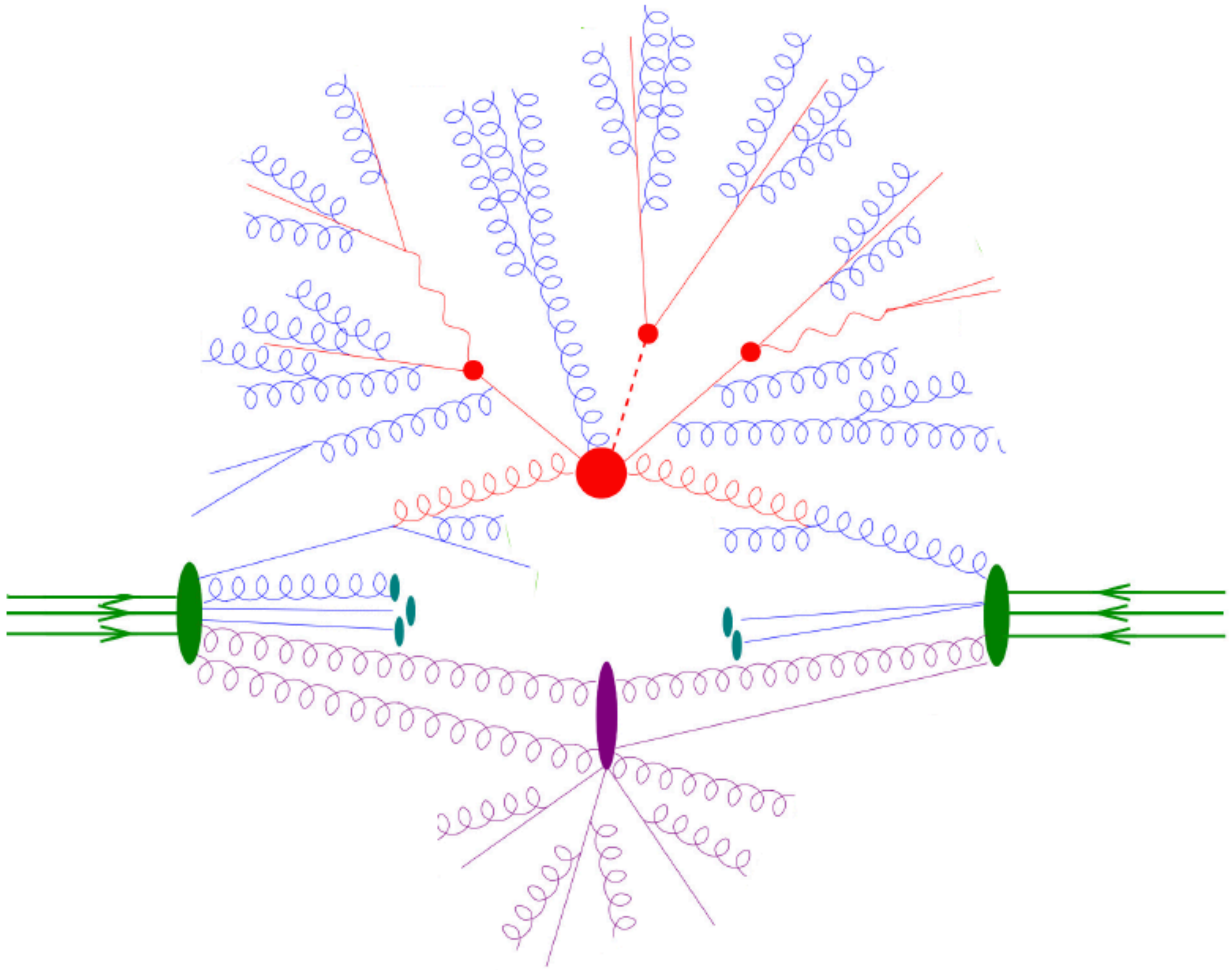

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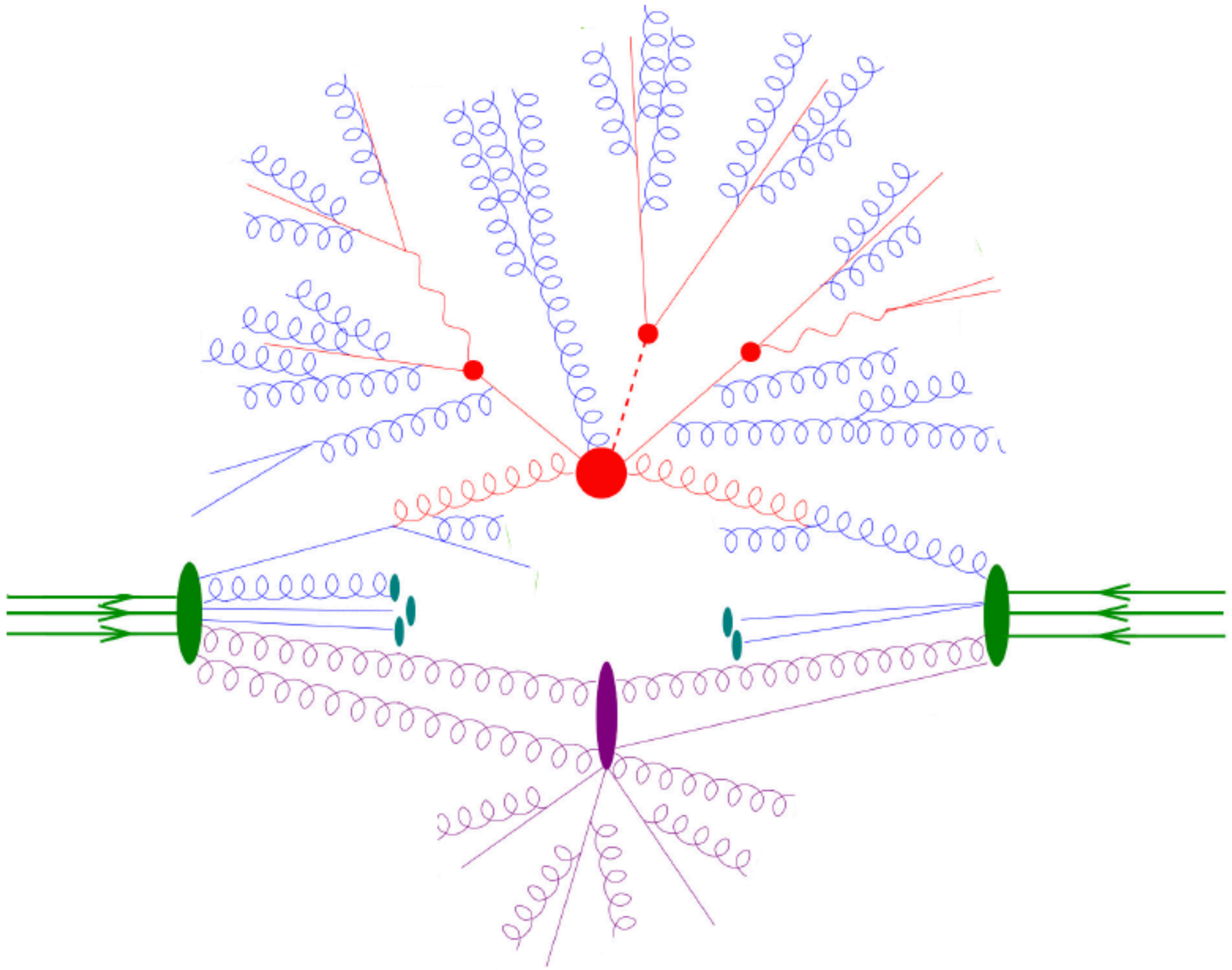

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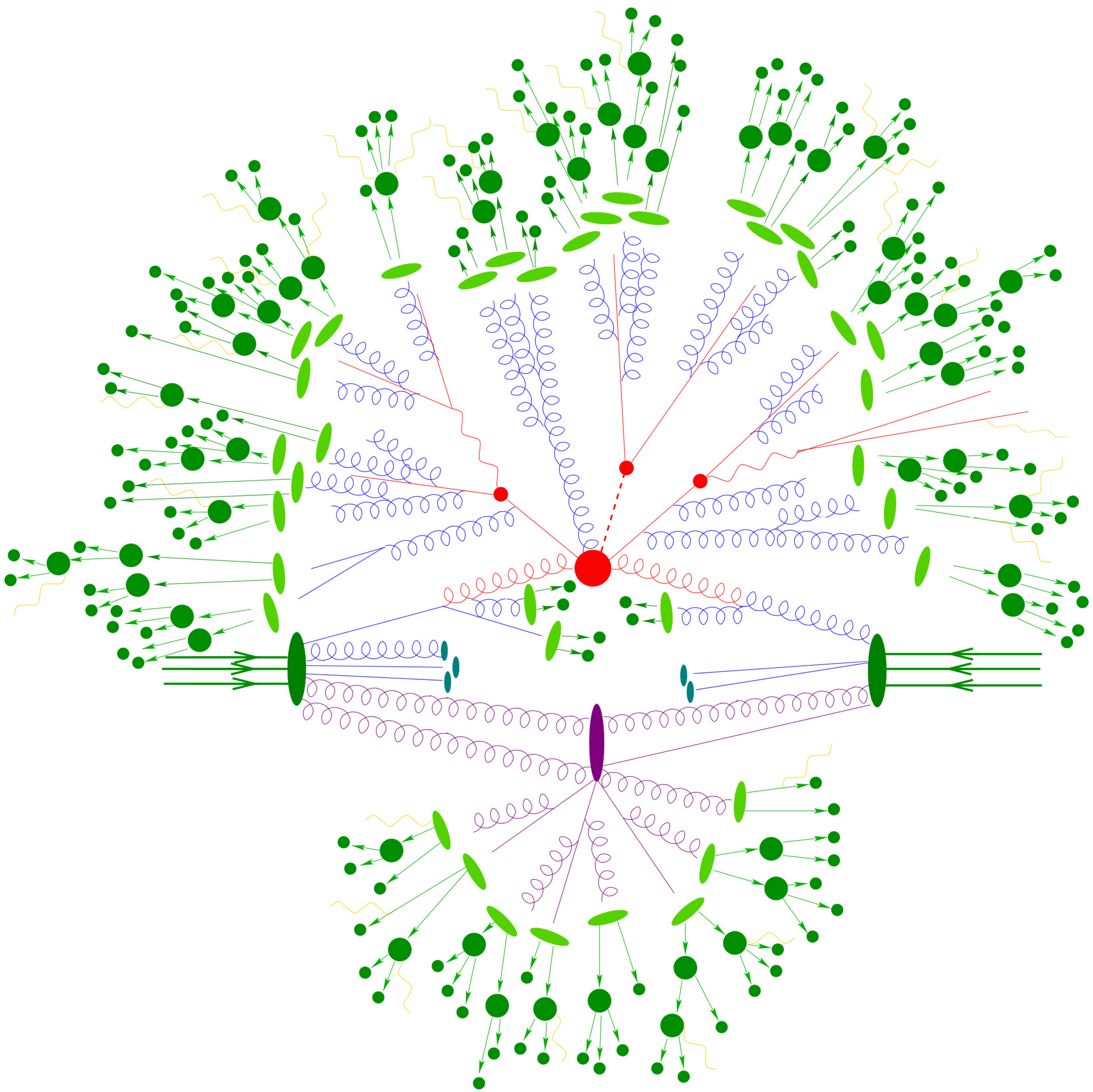

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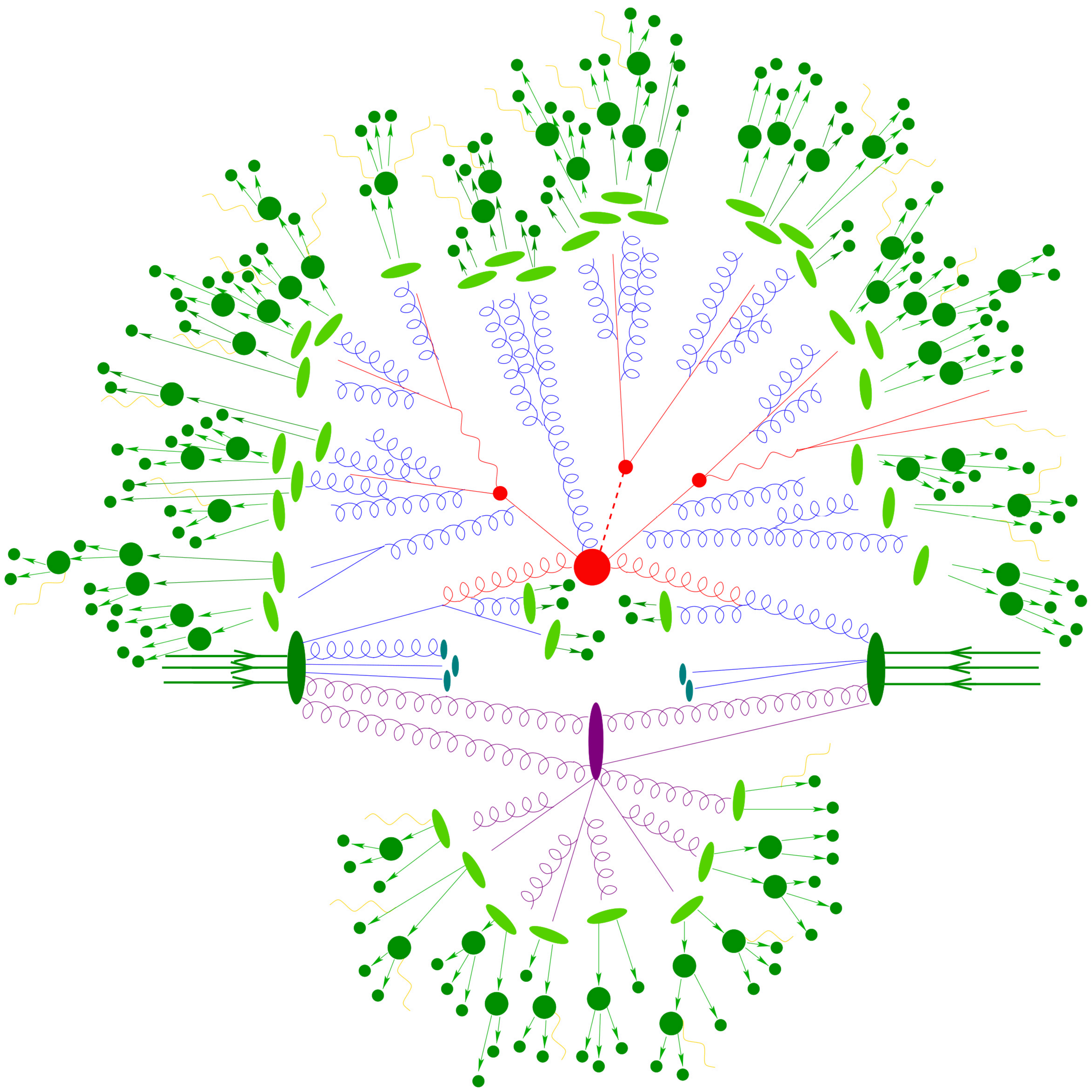
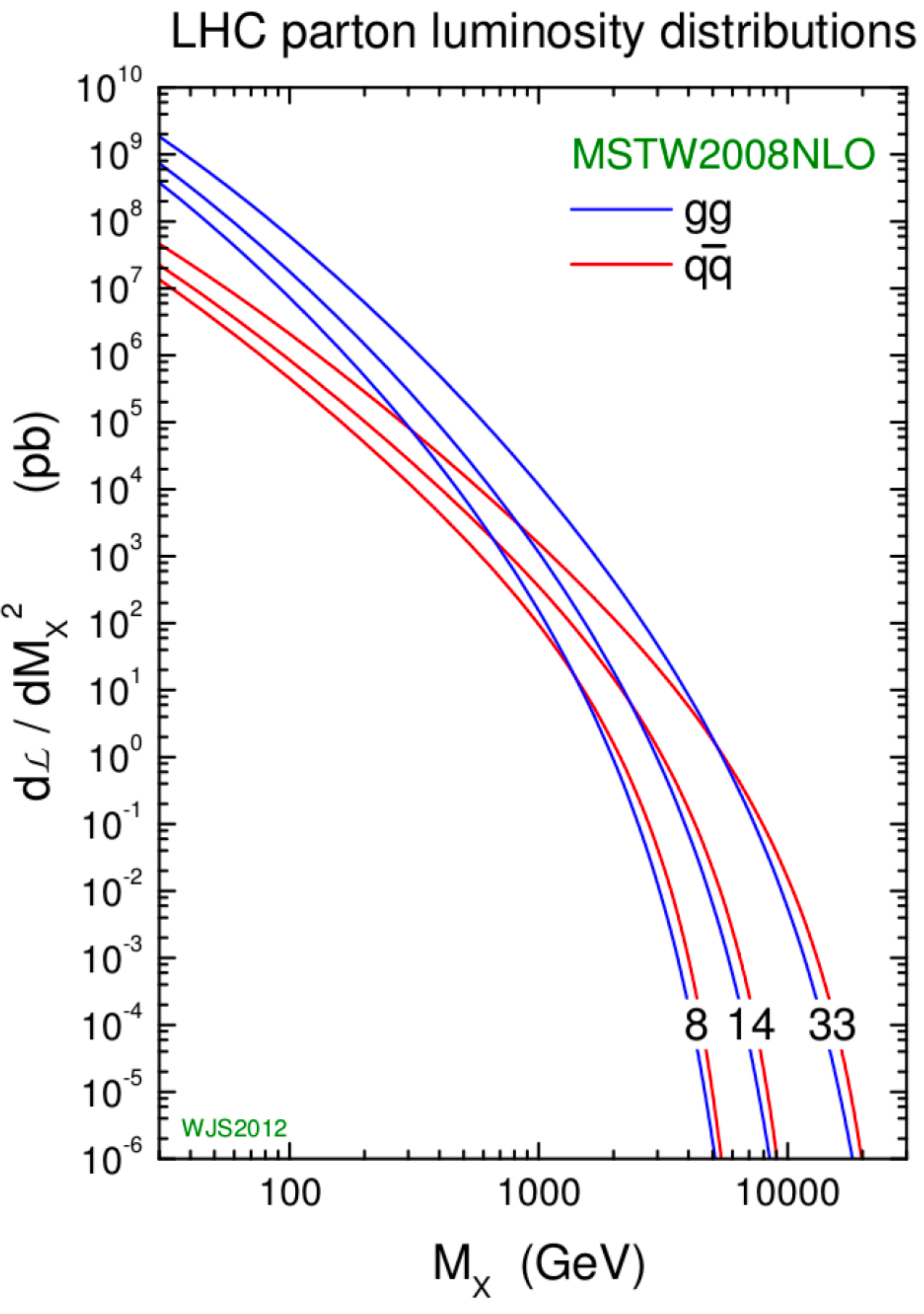


pp collisions: very complex environment

Underlying Event
Multiple Parton Interactions
Final and Initial State Radiation

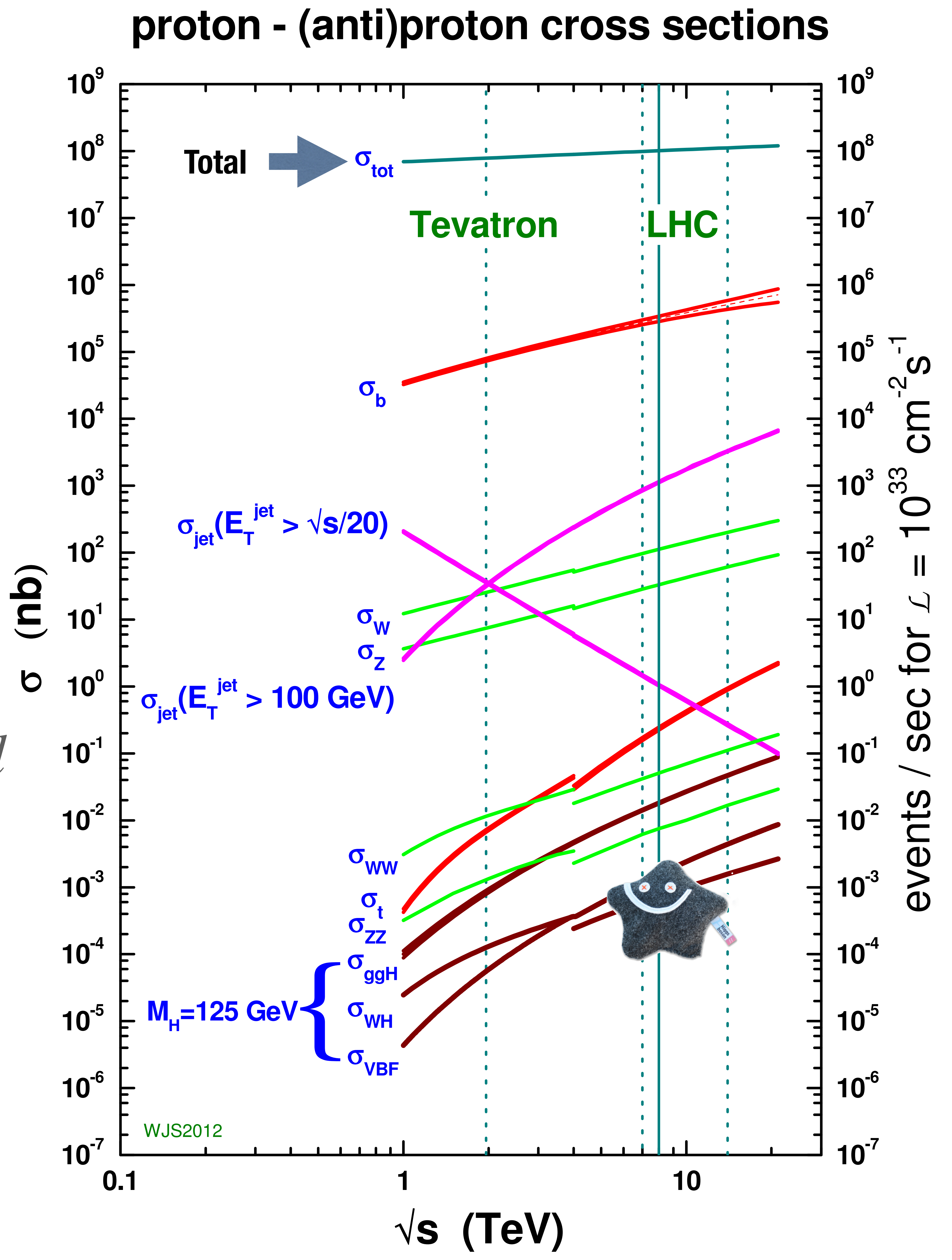
Graph from F. Krauss

CROSS SECTION...

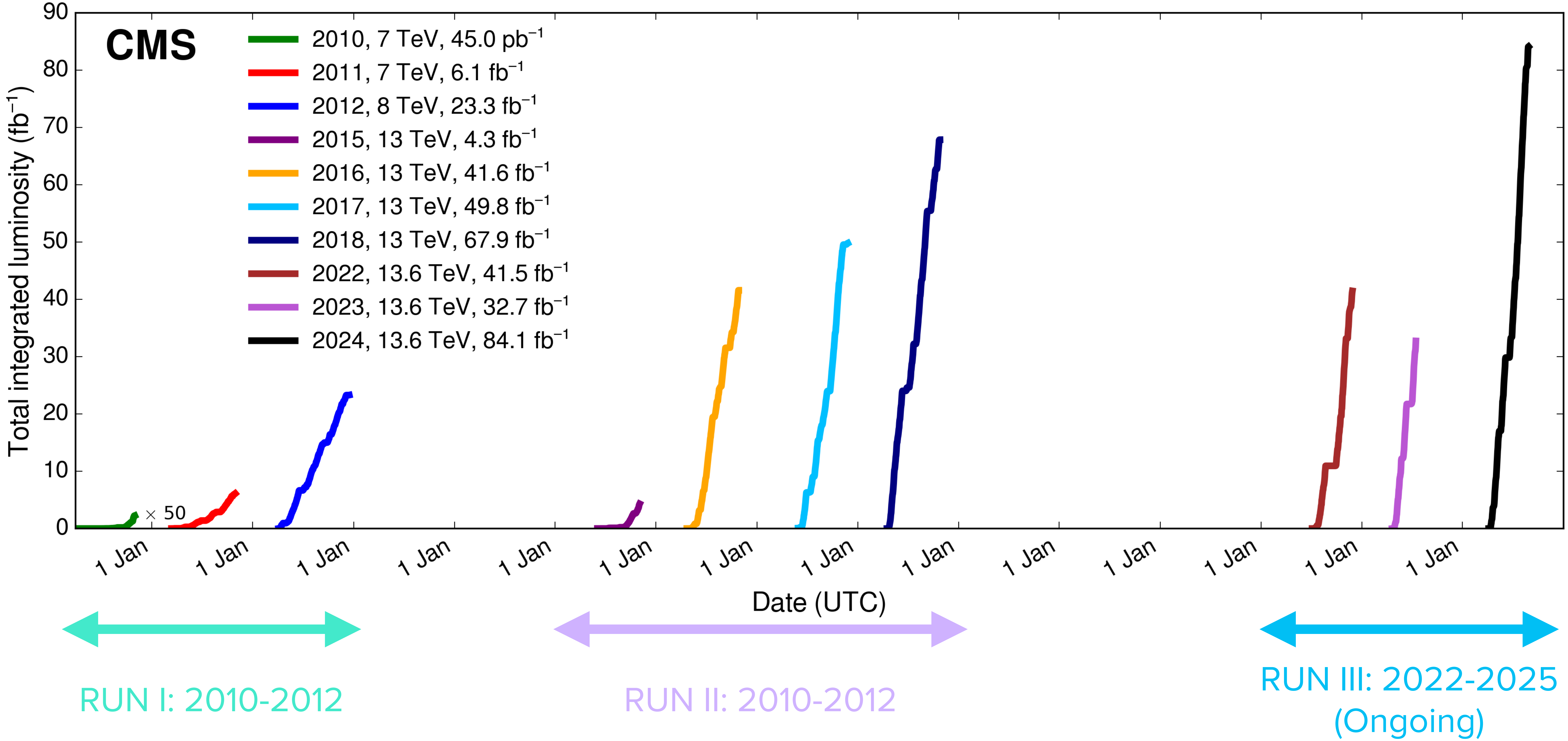


$$N_{Signal} = \sigma \times \mathscr{L}$$

$$N_{total} = N_{Signal} + N_{Background}$$

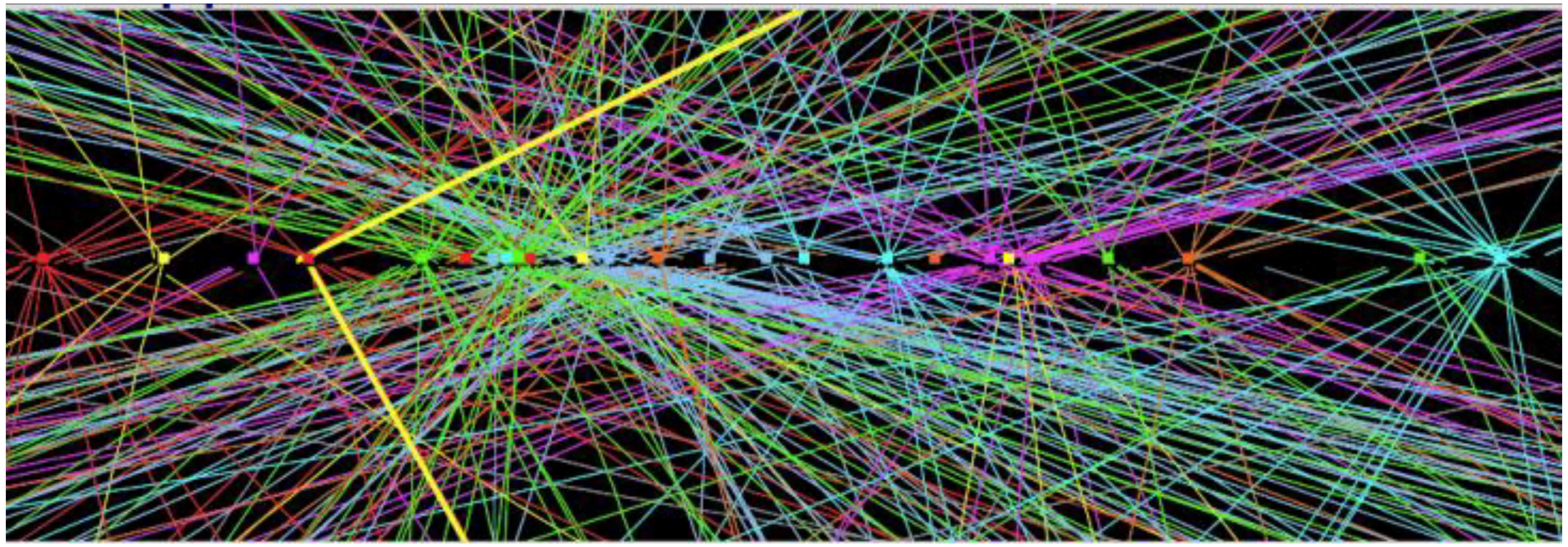


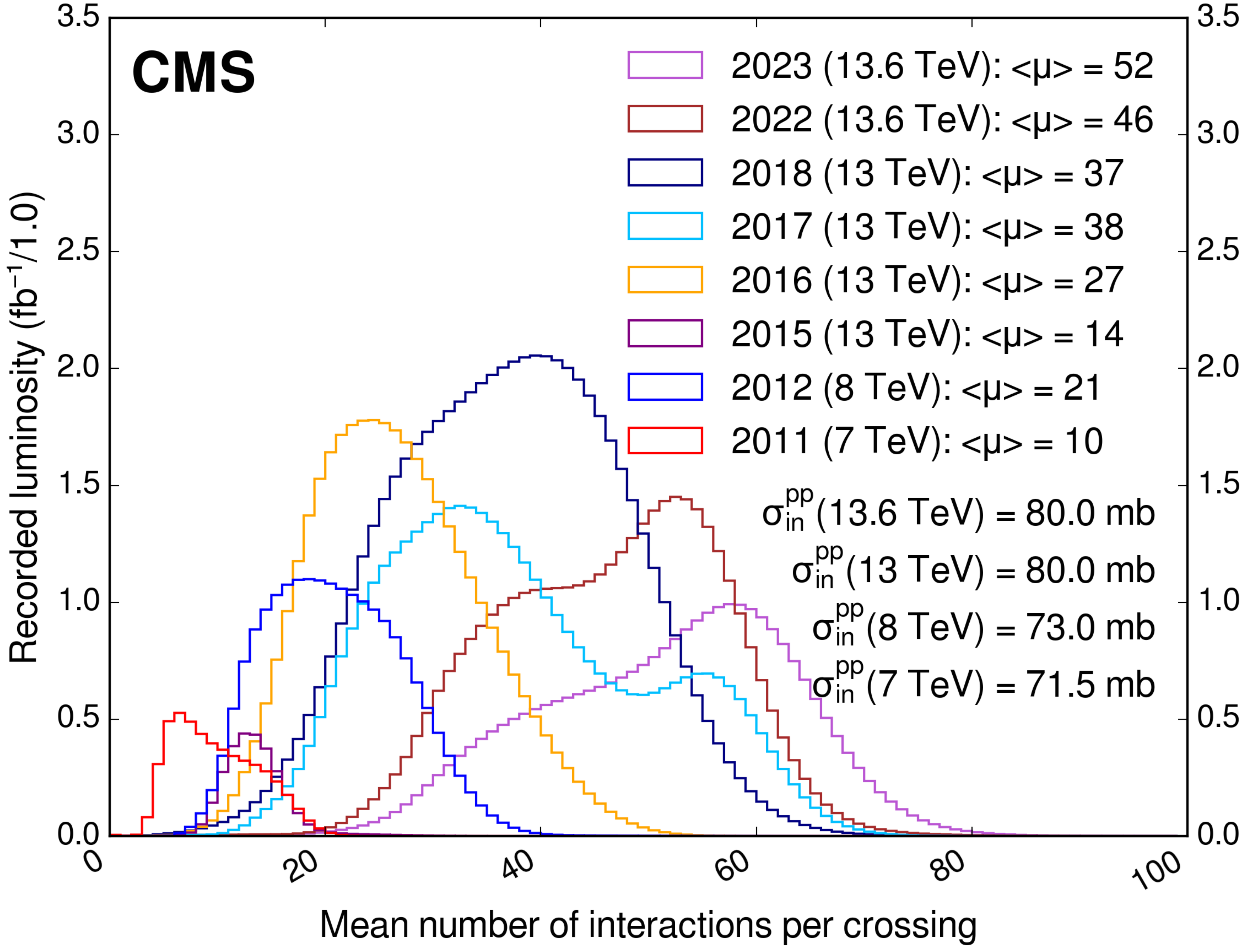
...LUMINOSITY...



CMS
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.3 fb⁻¹
2016, 13 TeV, 41.6 fb⁻¹
2017, 13 TeV, 49.8 fb⁻¹
2018, 13 TeV, 67.9 fb⁻¹
2022, 13.6 TeV, 41.5 fb⁻¹
2023, 13.6 TeV, 32.7 fb⁻¹
2024, 13.6 TeV, 84.1 fb⁻¹
× 50
Total integrated luminosity (fb⁻¹)
Date (UTC)
1 Jan
RUN I: 2010-2012
RUN II: 2010-2012
RUN III: 2022-2025
(Ongoing)

... AND PILEUP



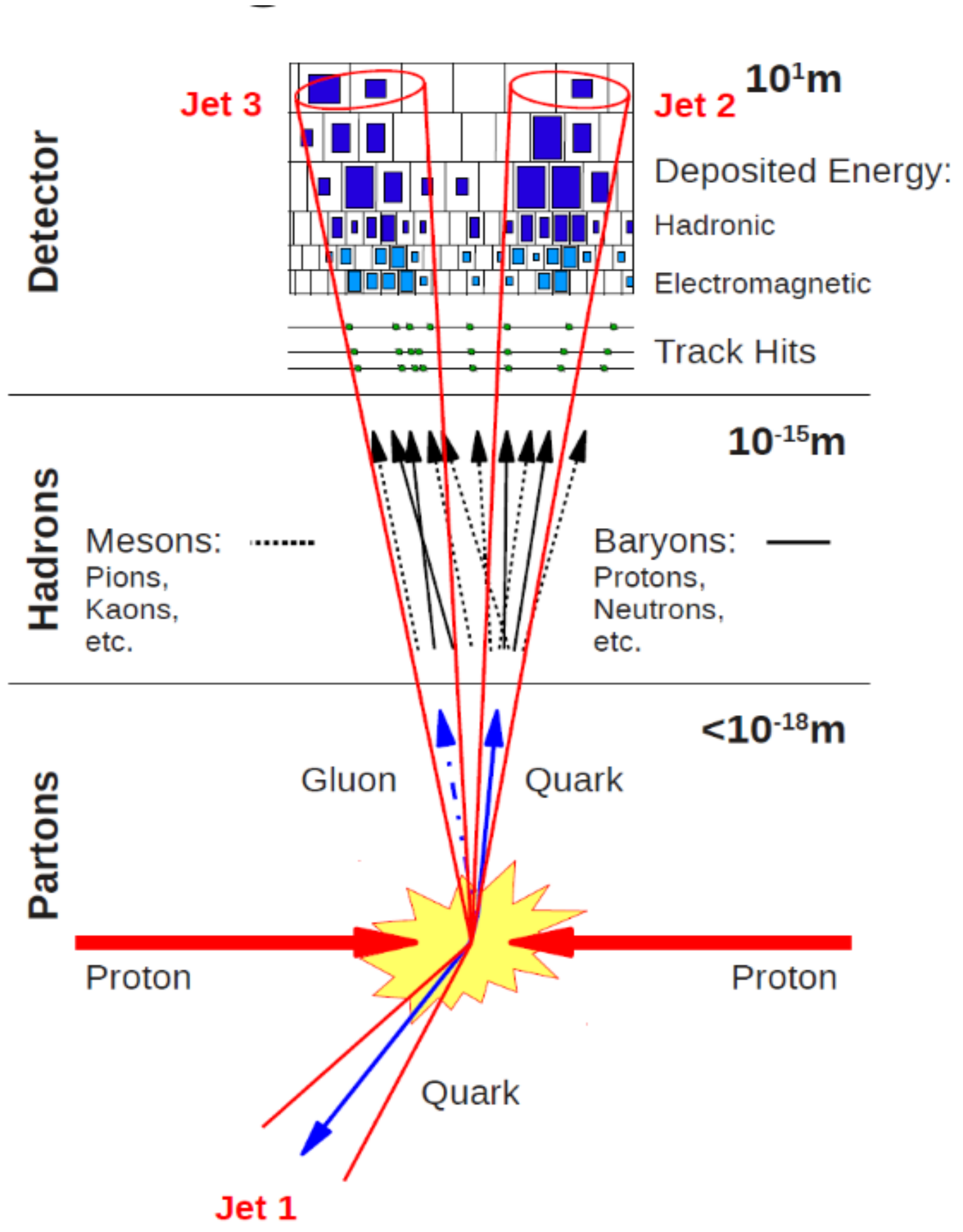


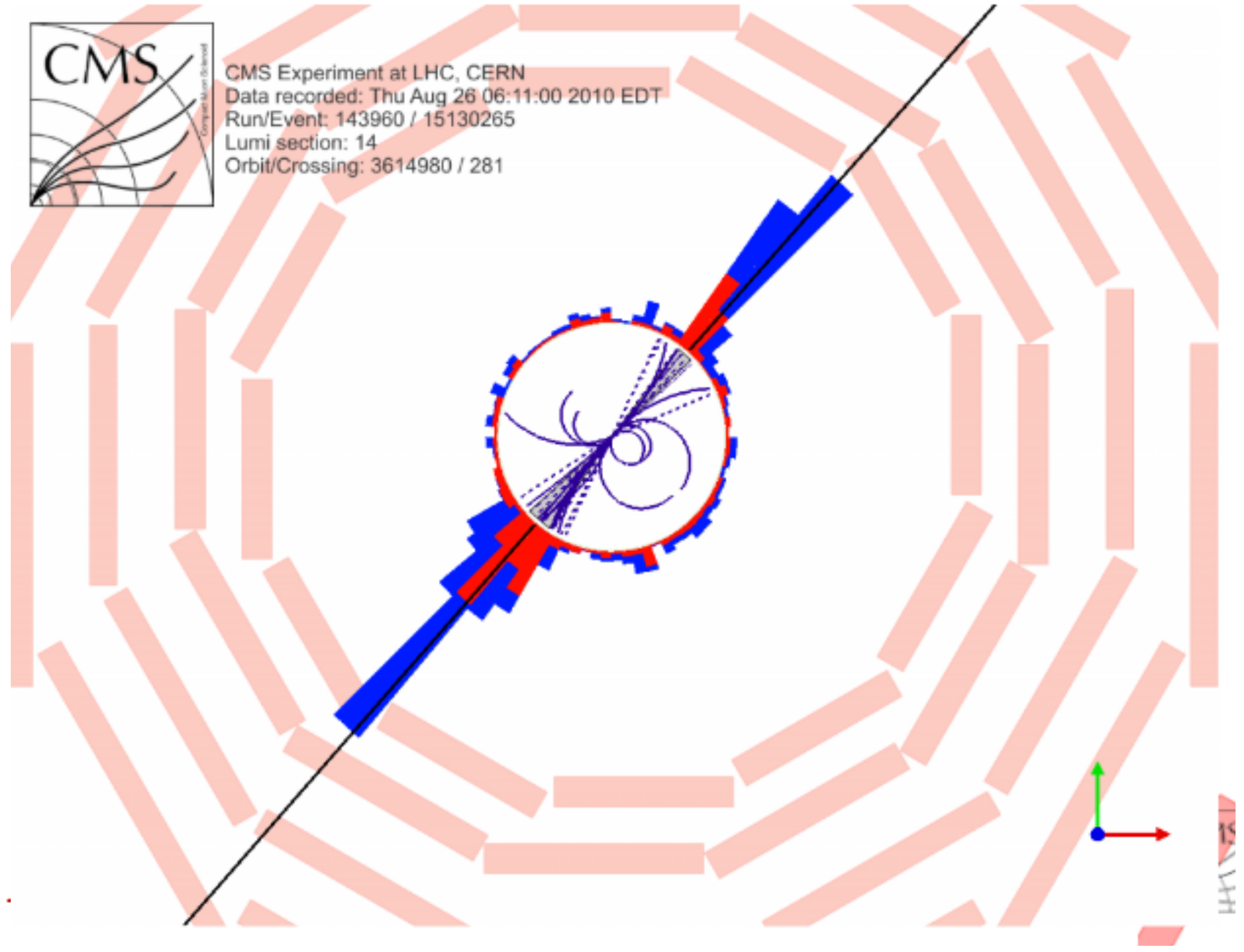
Impact on object identification

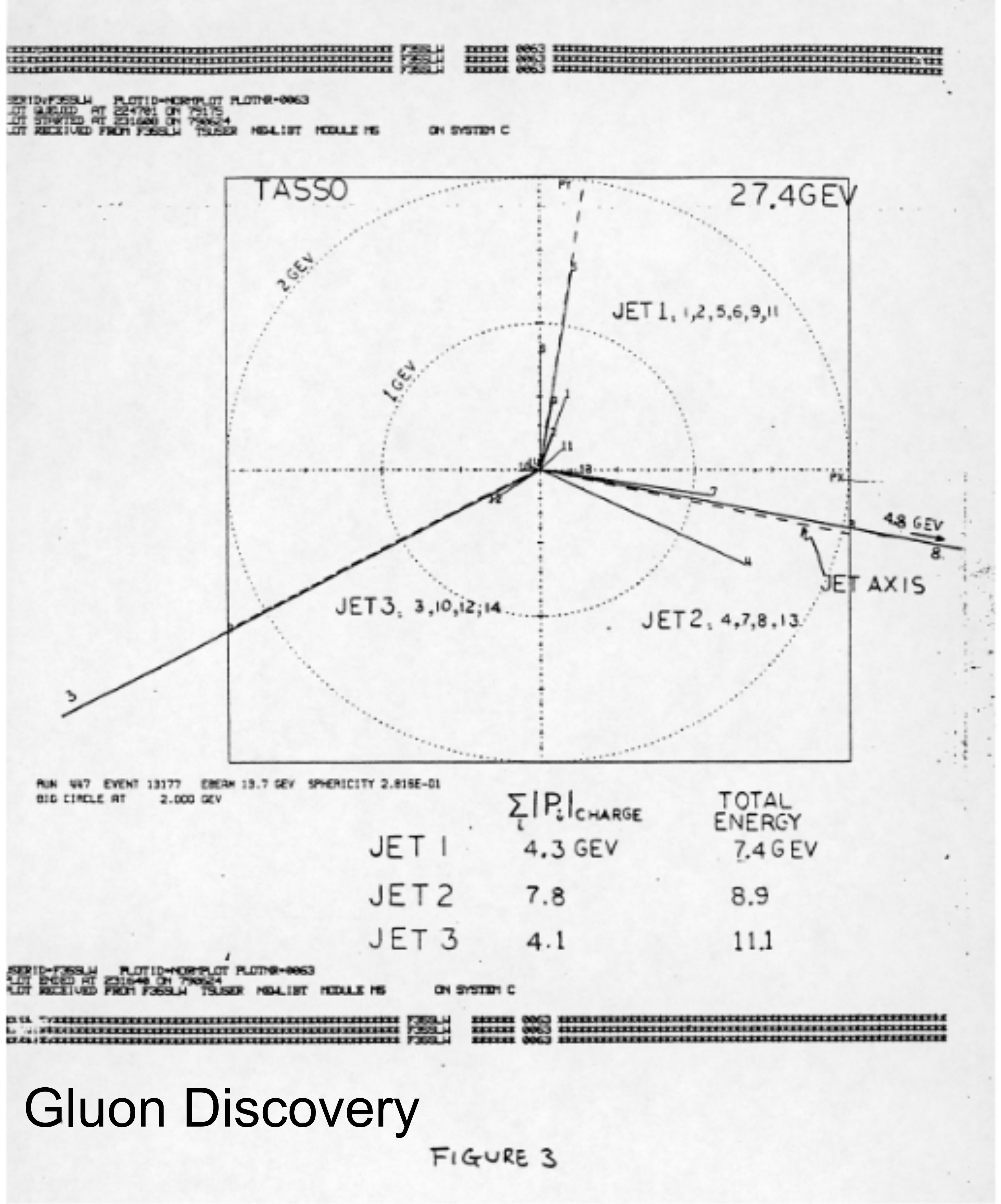
SM MEASUREMENTS

UNDERSTANDING QCD

- Almost all events produced in pp collisions are ‘QCD’
- They are characterized by having many “jets” (coming from the fragmentation and hadronization of quarks and gluons)
- Difficult to model theoretically: LHC data is key!





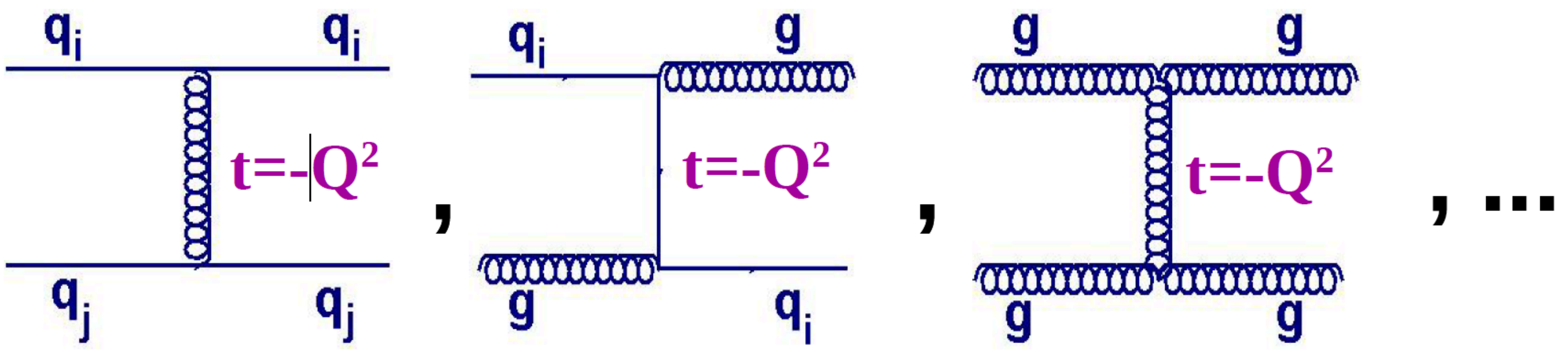


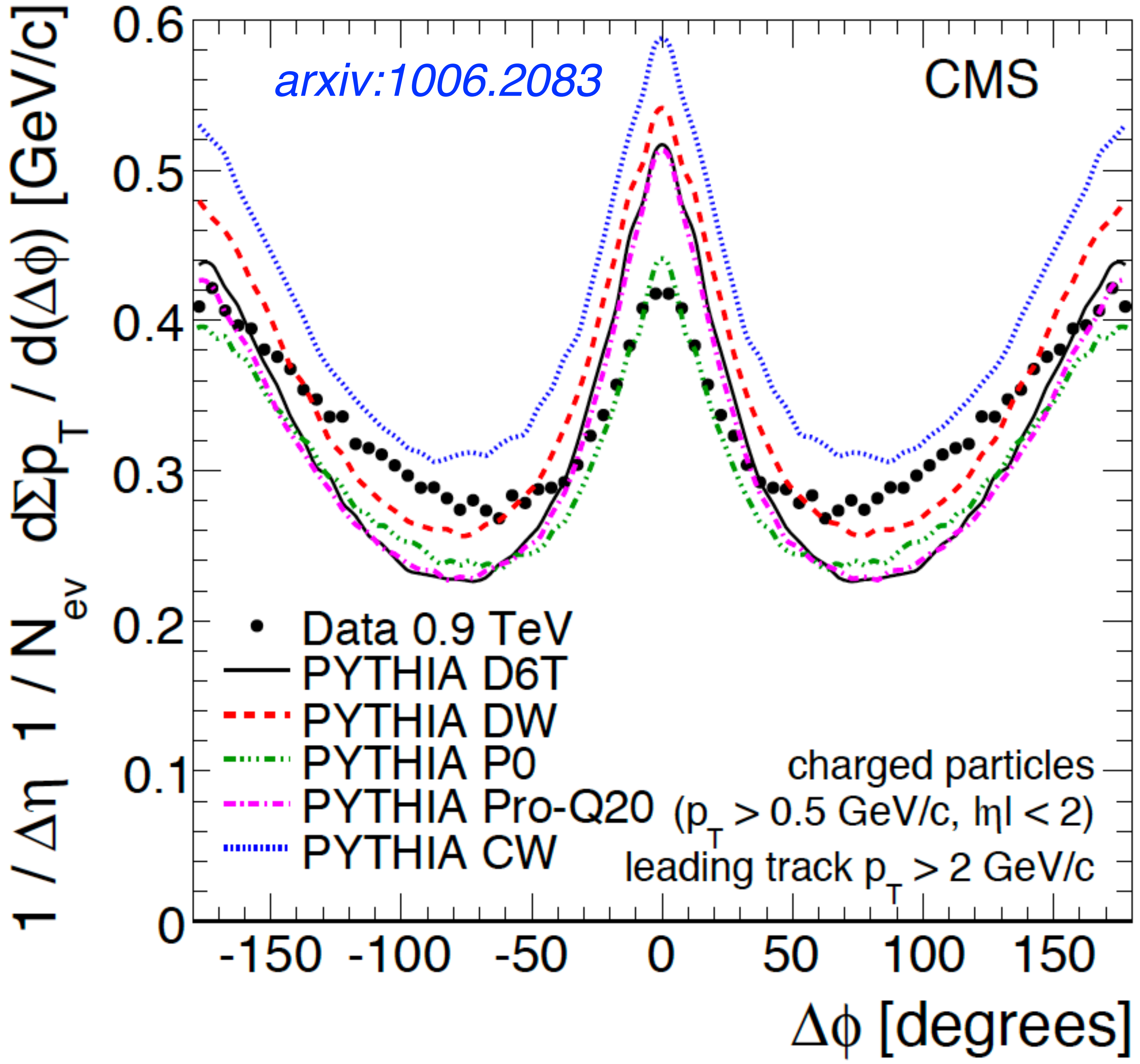
Gluon Discovery

- **Too many topics to cover: (multi-)jet production, dijet angular correlations, di-jet mass, mass distributions, distributions shape variables, measurement of α_s, jet substructure….**

LOW MOMENTUM

Most of the events that we record at hadron colliders correspond to pure QCD processes. Cross sections are huge, dominated by t-channel diagrams, with QCD couplings $\alpha_S(Q^2)$ that increase substantially at low Q^2





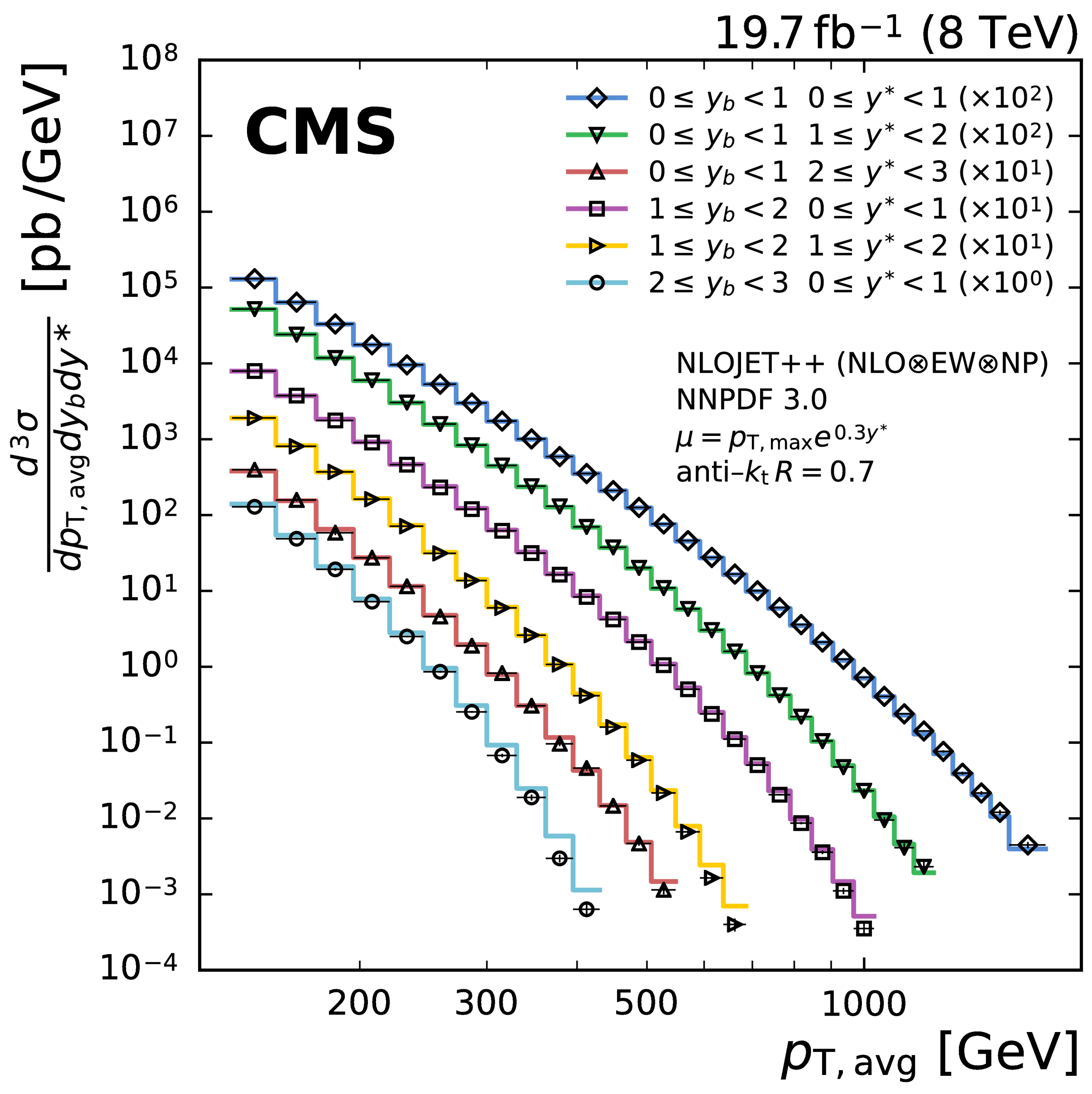
We expect many (inelastic) interactions with hadrons in the final state, most of them with low pT

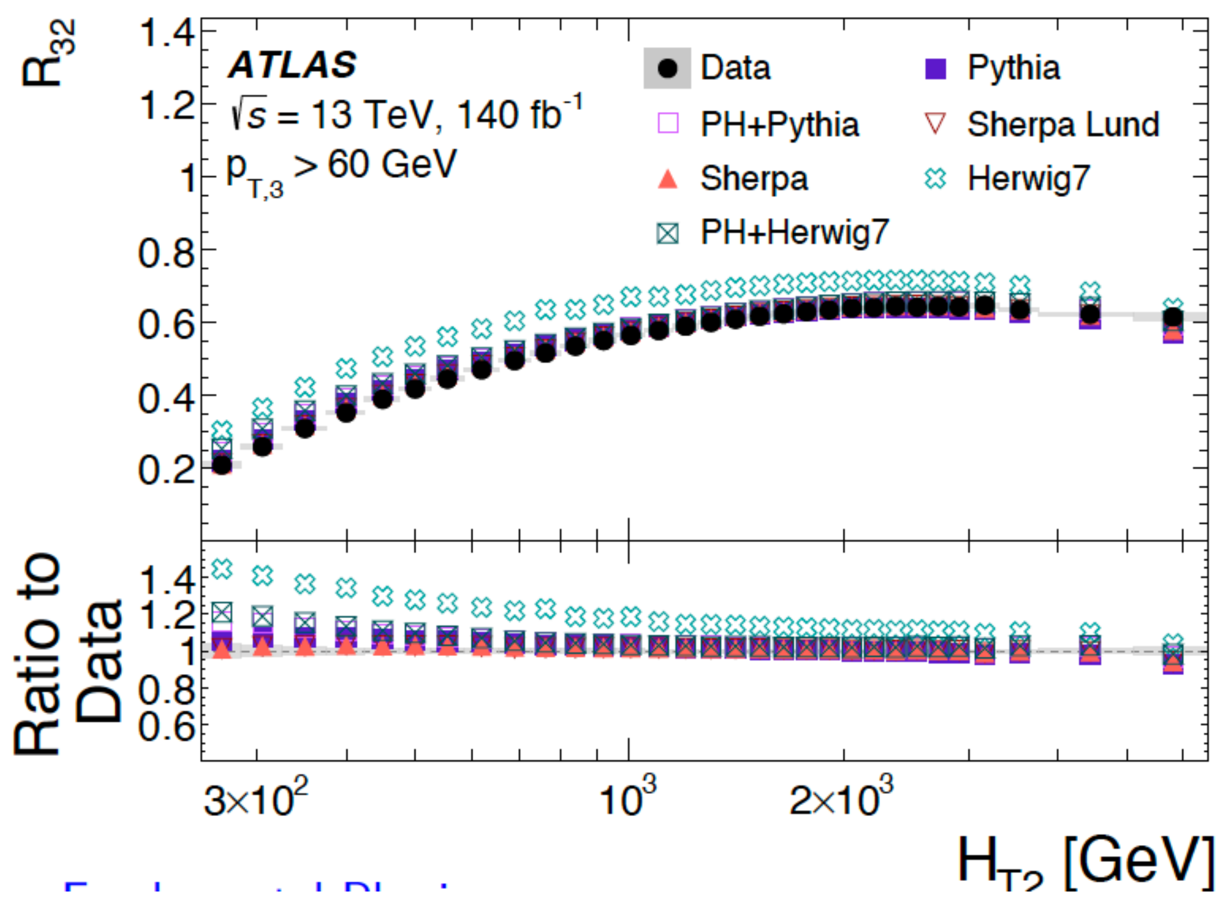
"MINIMUM BIAS": very loose activity (scintillators, calorimetry, tracks) in the detectors.

These led to some of the first LHC results! —> "non-perturbative" effects, Underlying Event

Not well described by initial models at the start of LHC ➔ importance of TUNING

HIGH PT: (MULTI-)JET PHYSICS





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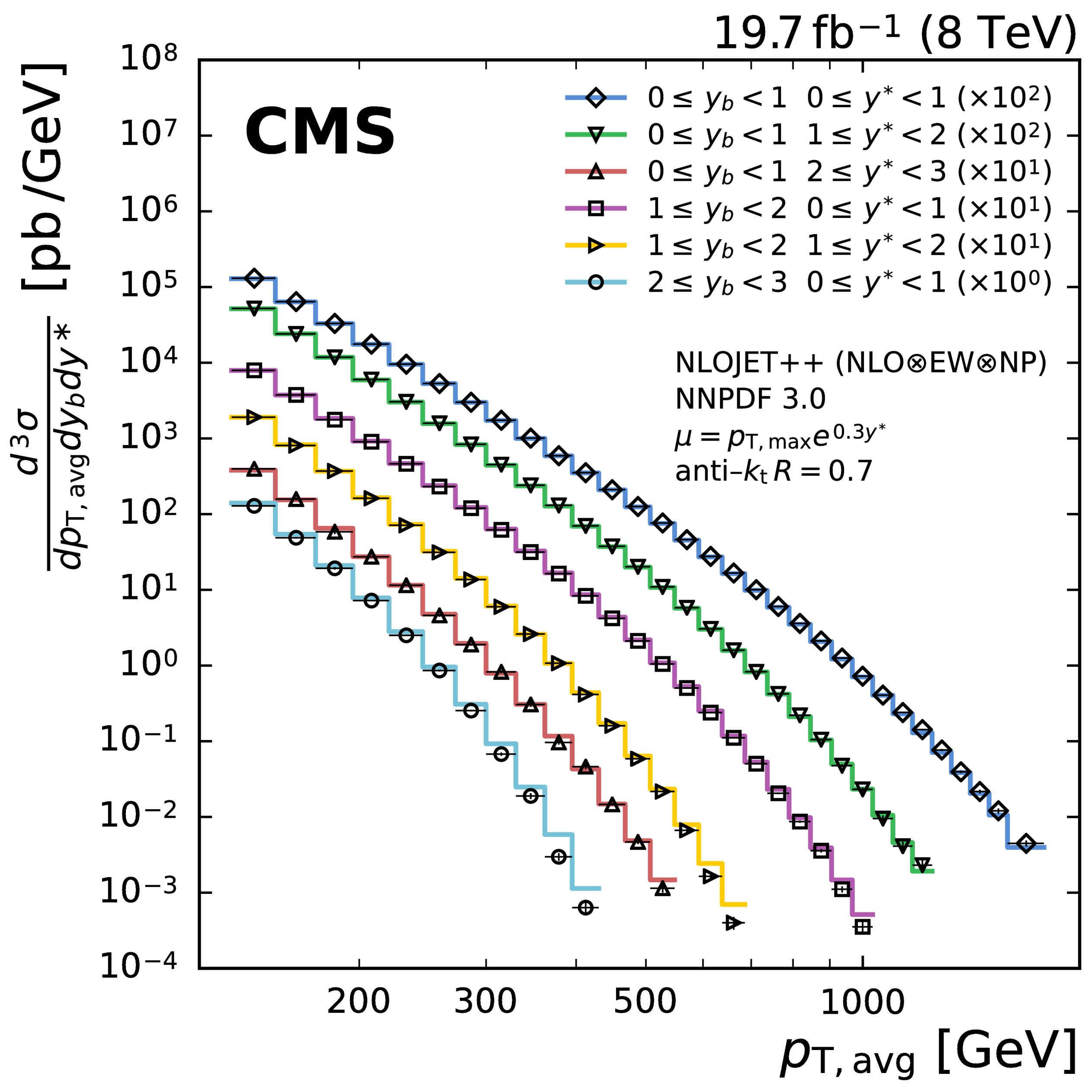
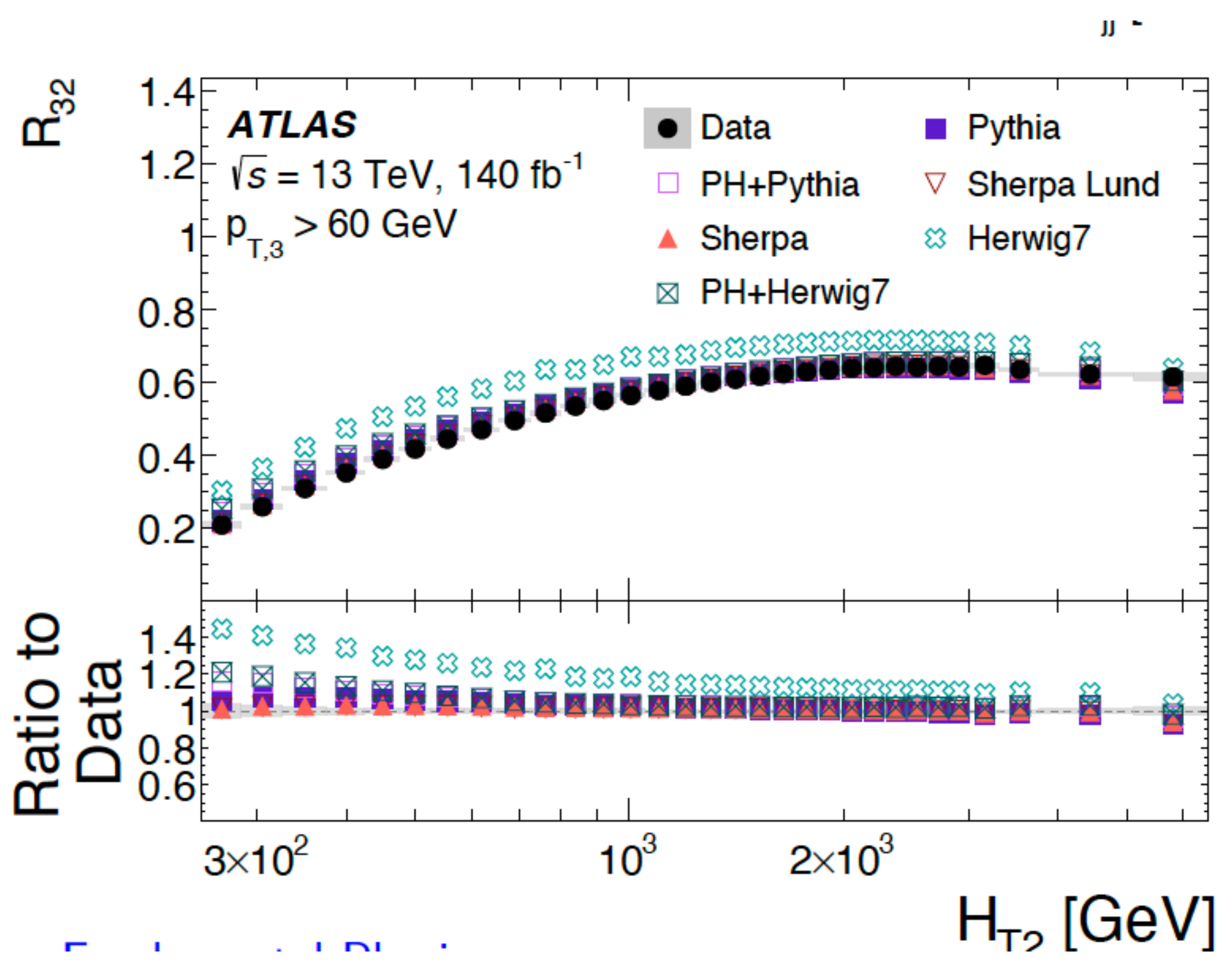


Test of QCD at high p_T: Cross sections, angular correlations, characterization of events, comparison with different simulations…



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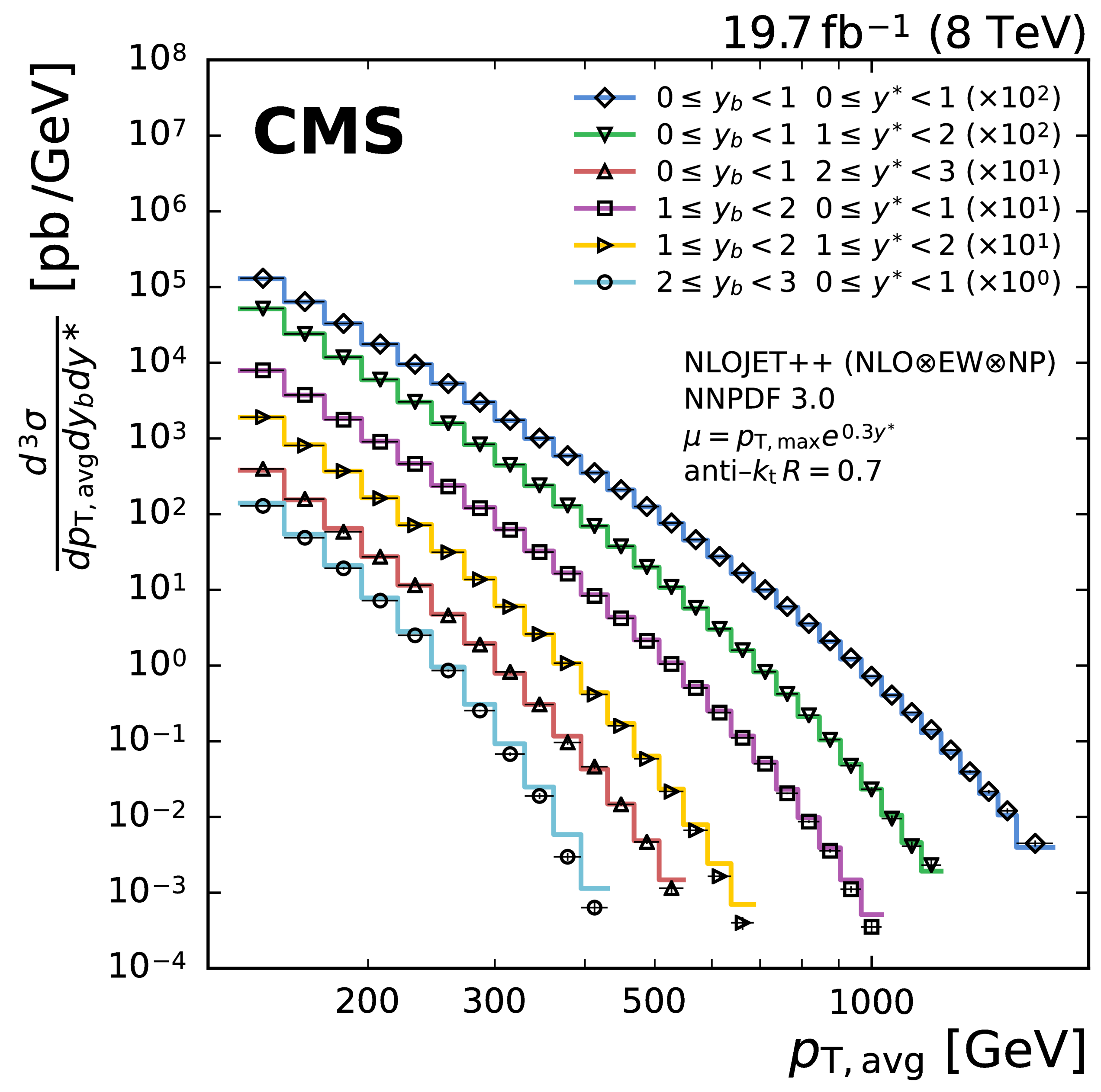

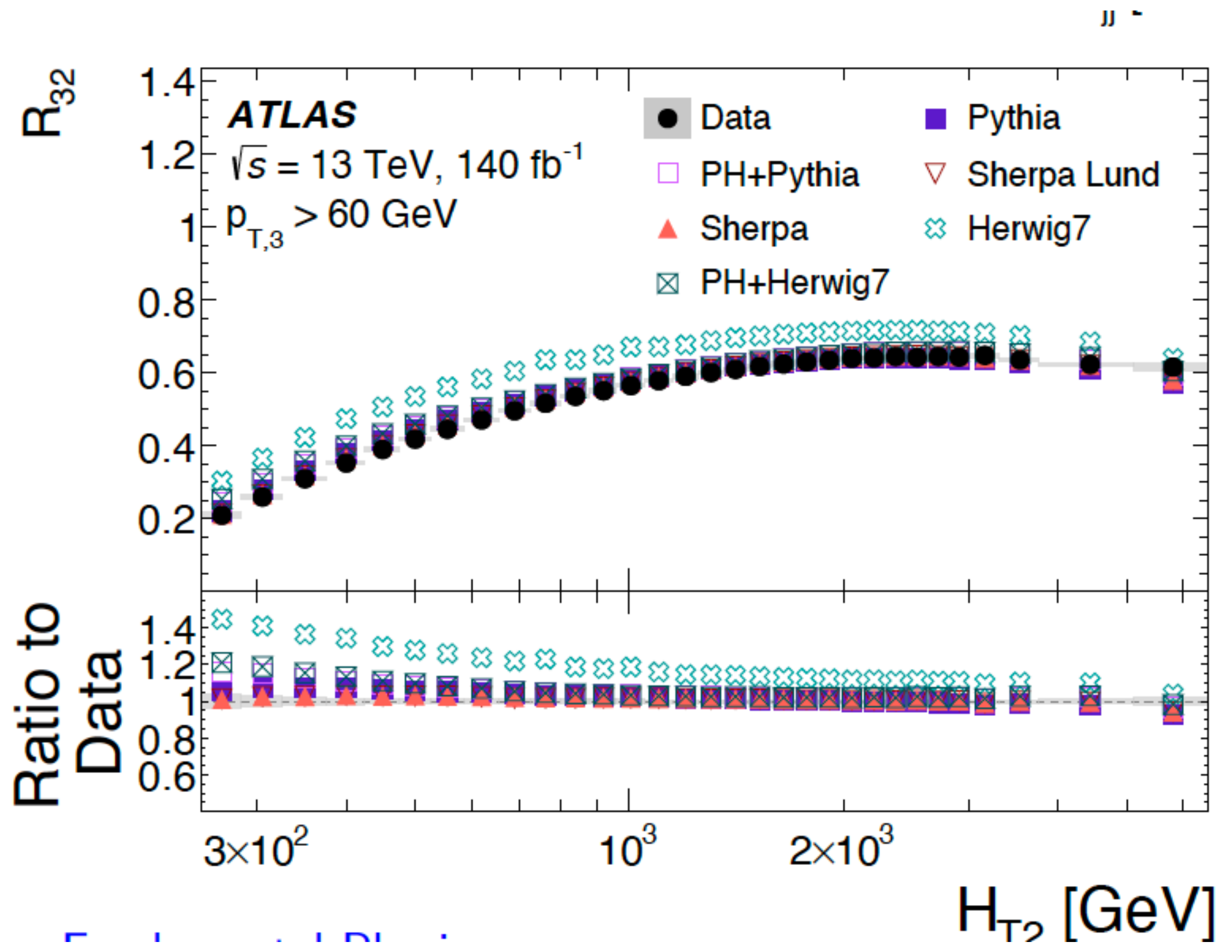

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From this characterization of the events we can measure other parameters of the standard model: many possible measurements

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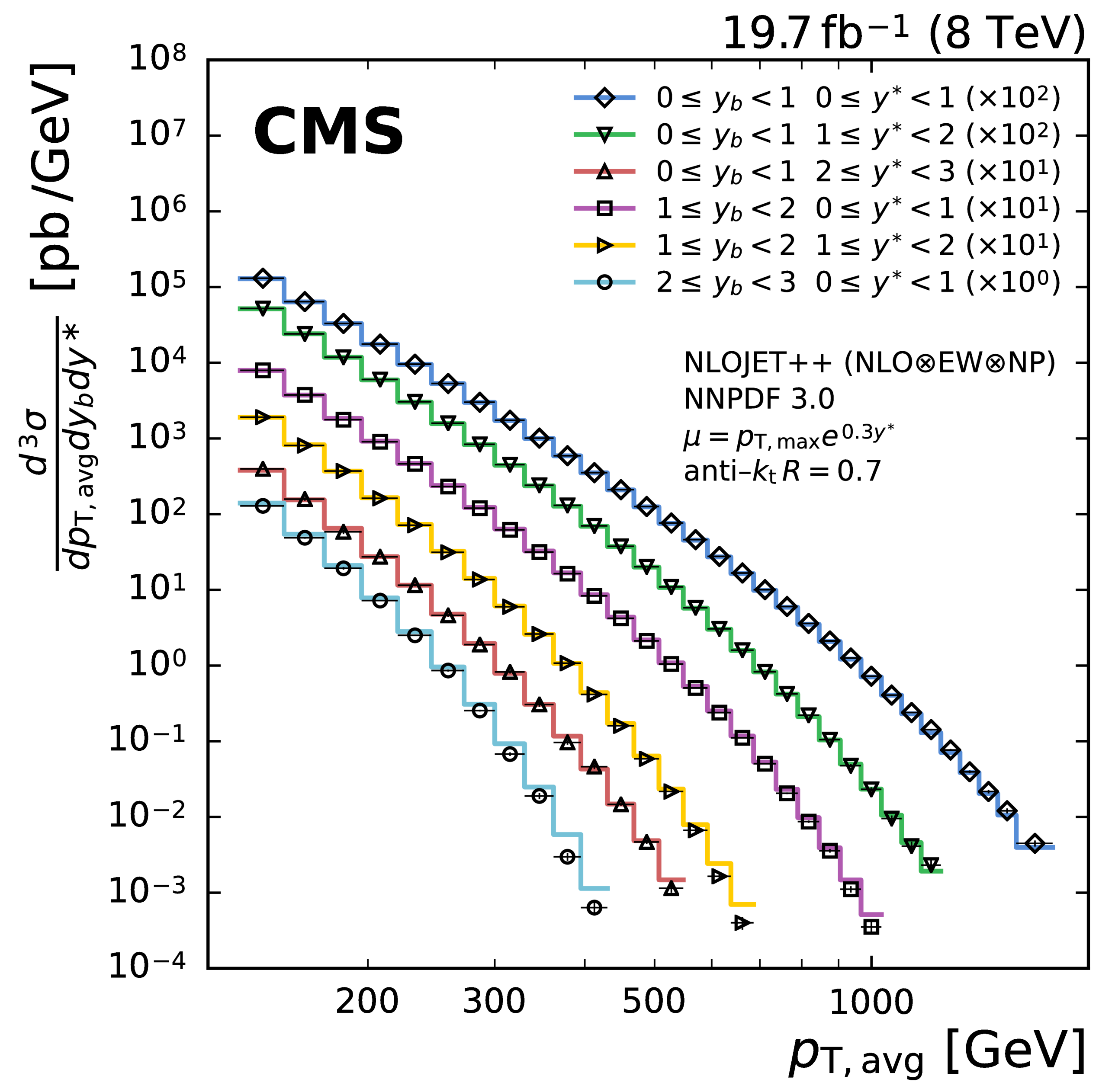

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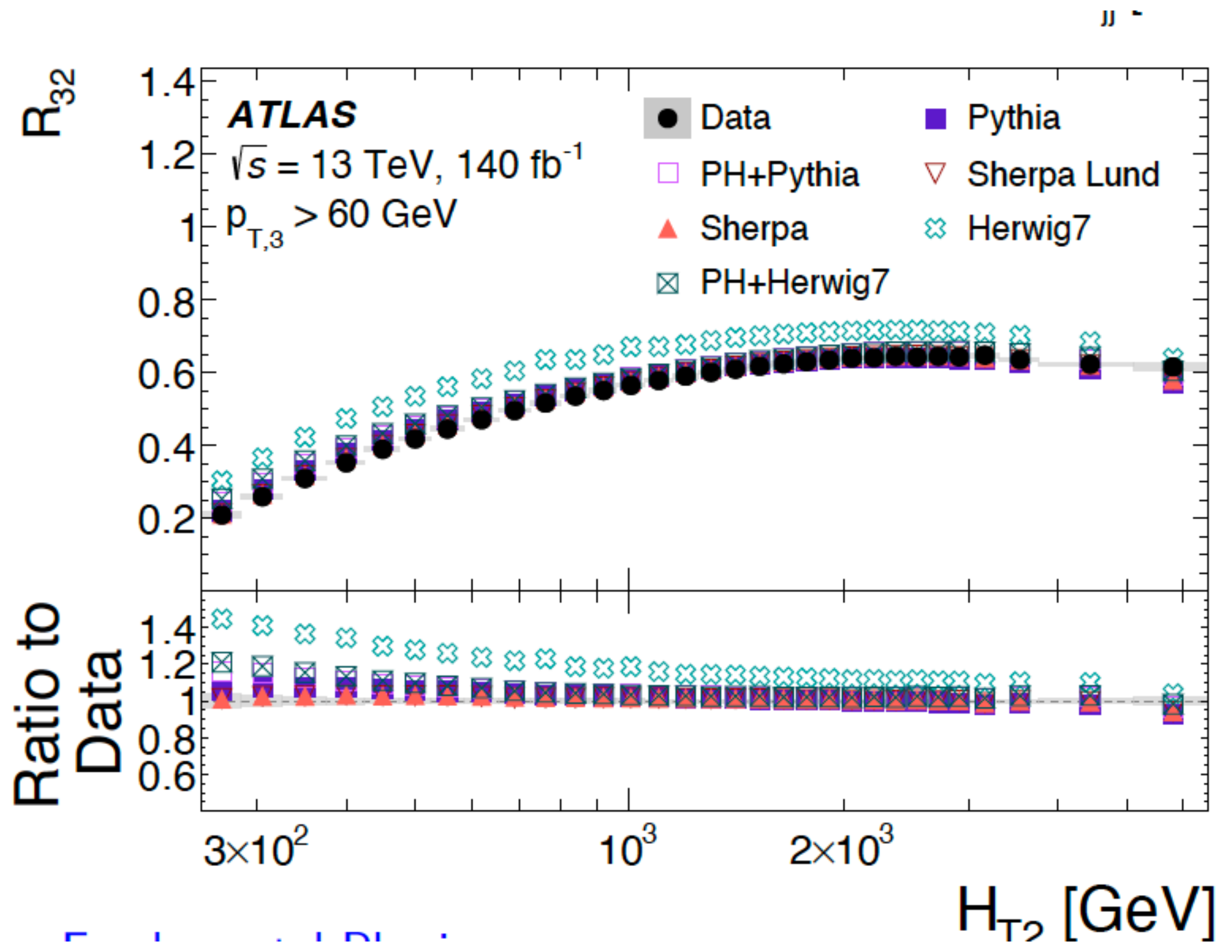
→ eg: running of the strong coupling constant, α_S



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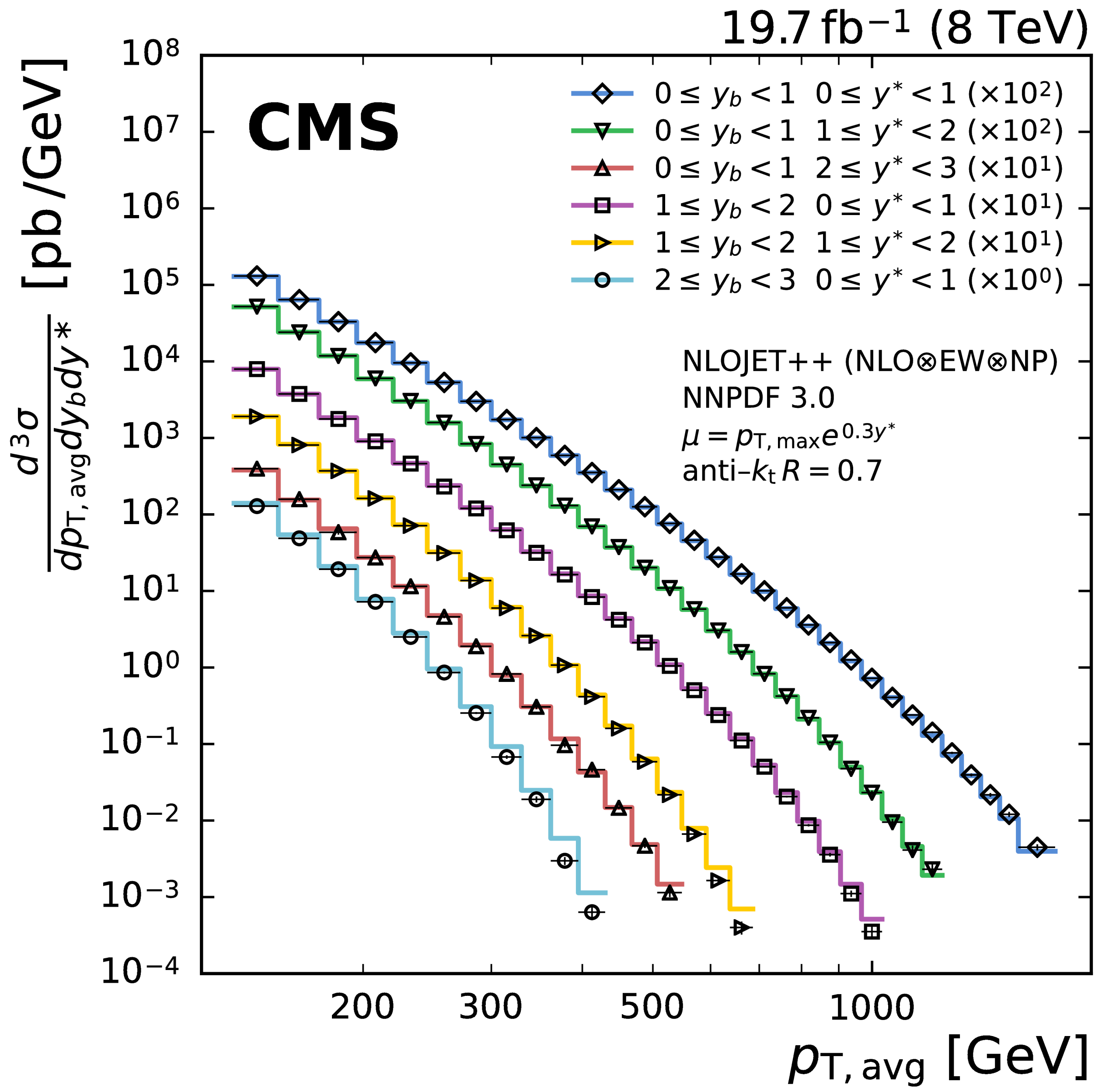

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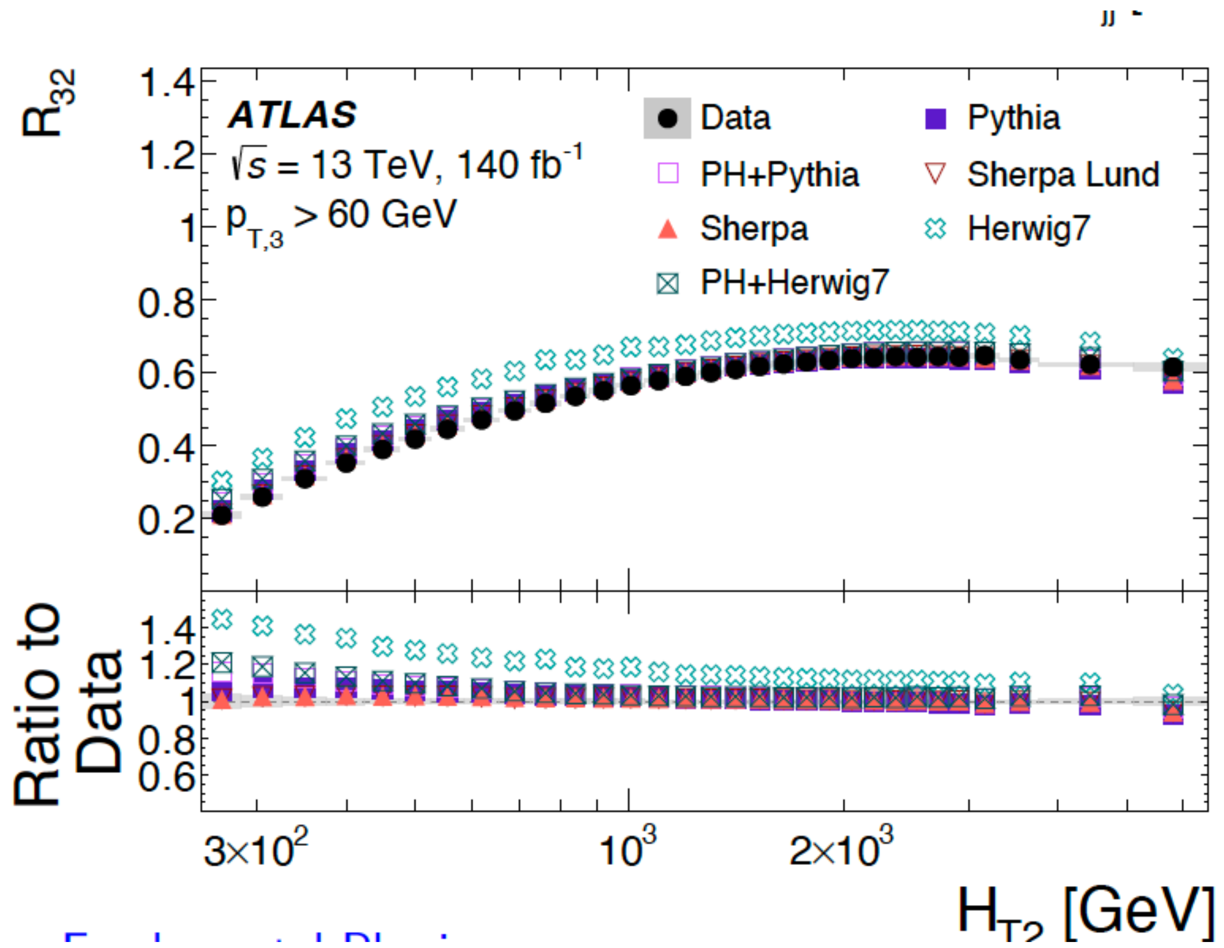
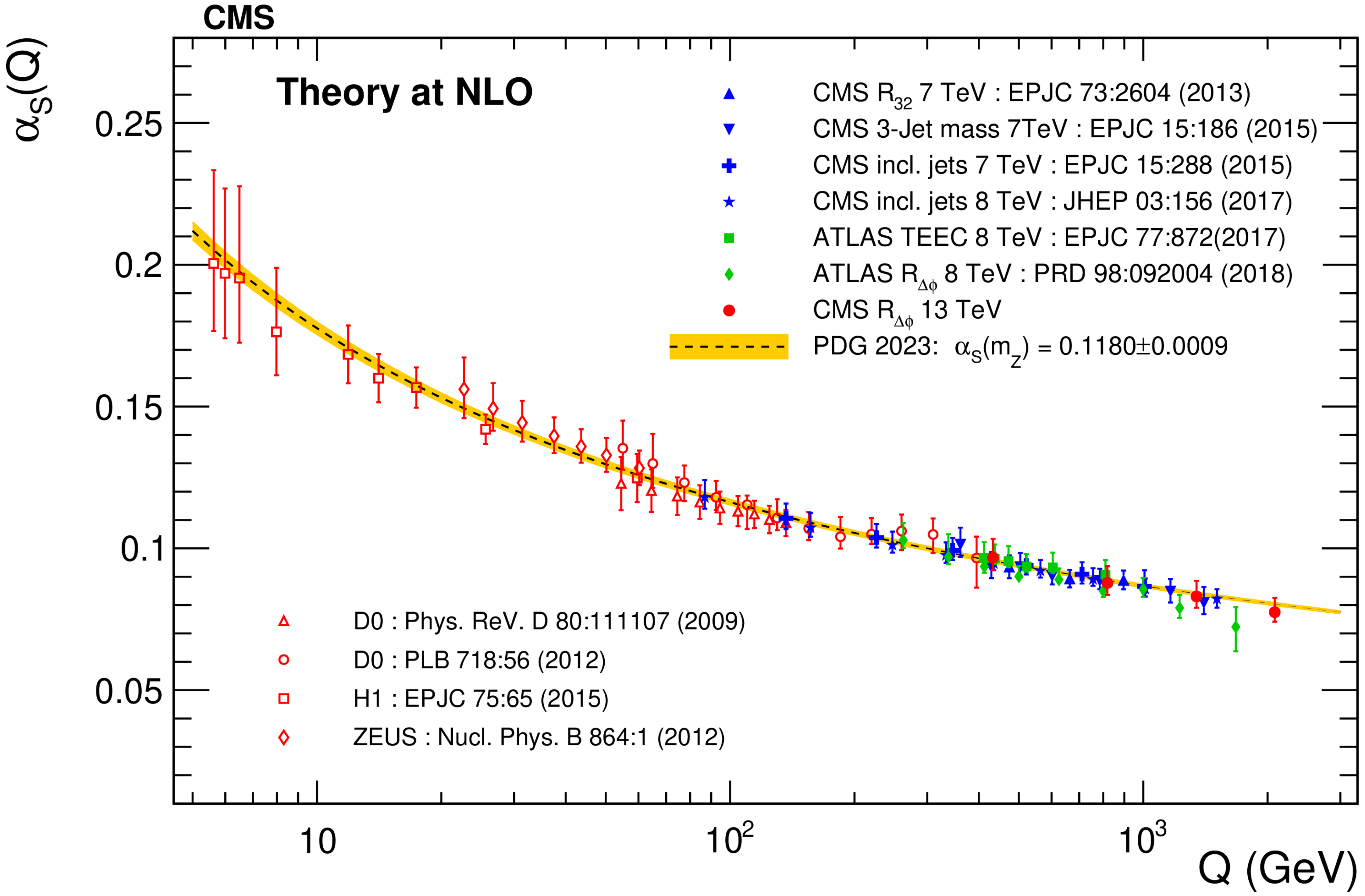
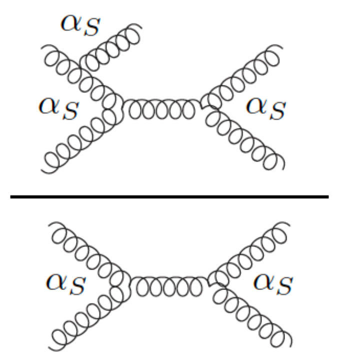




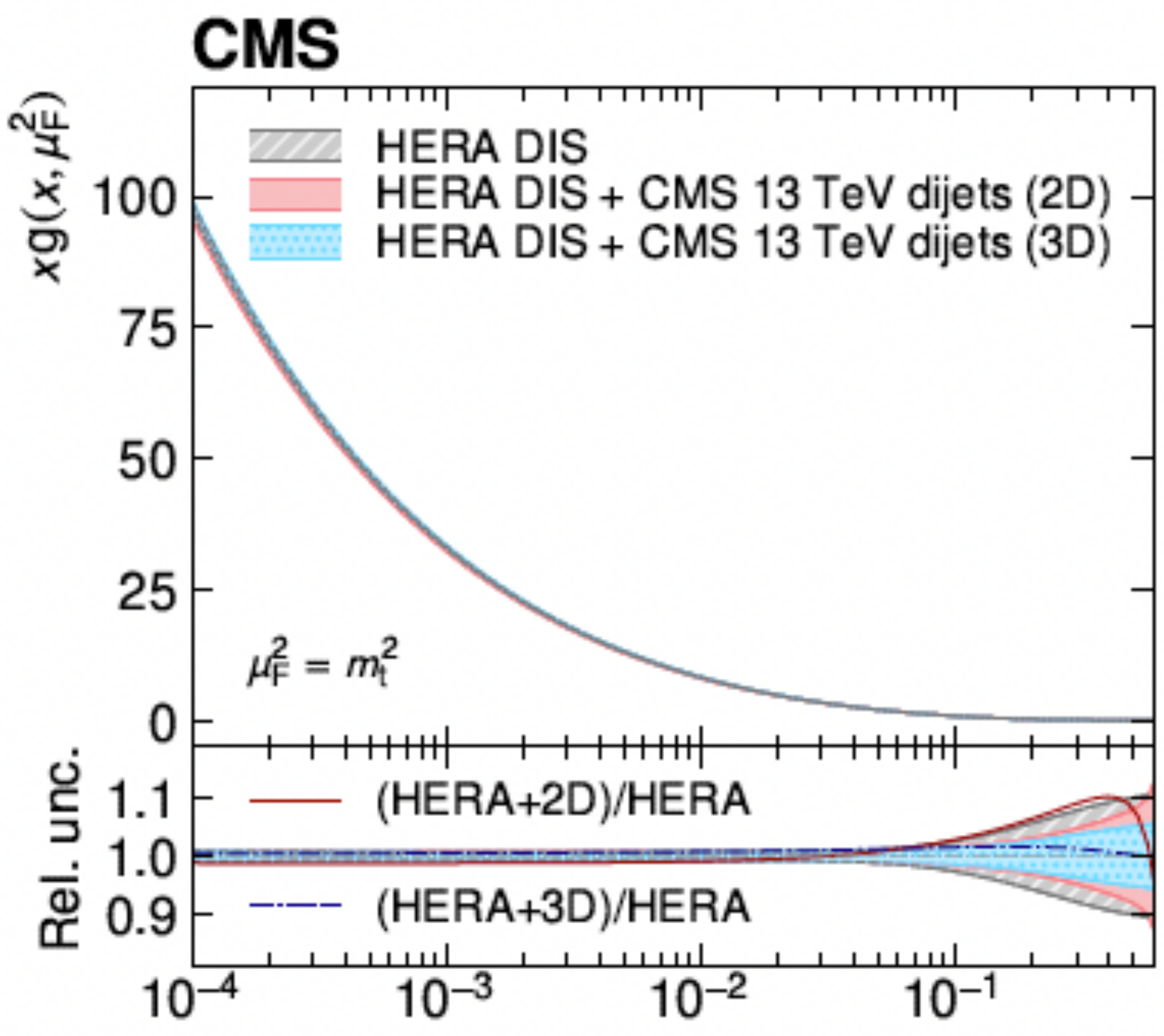
$$R_{3/2} = \frac{\sigma_{3-jets}}{\sigma_{2-jets}} =$$

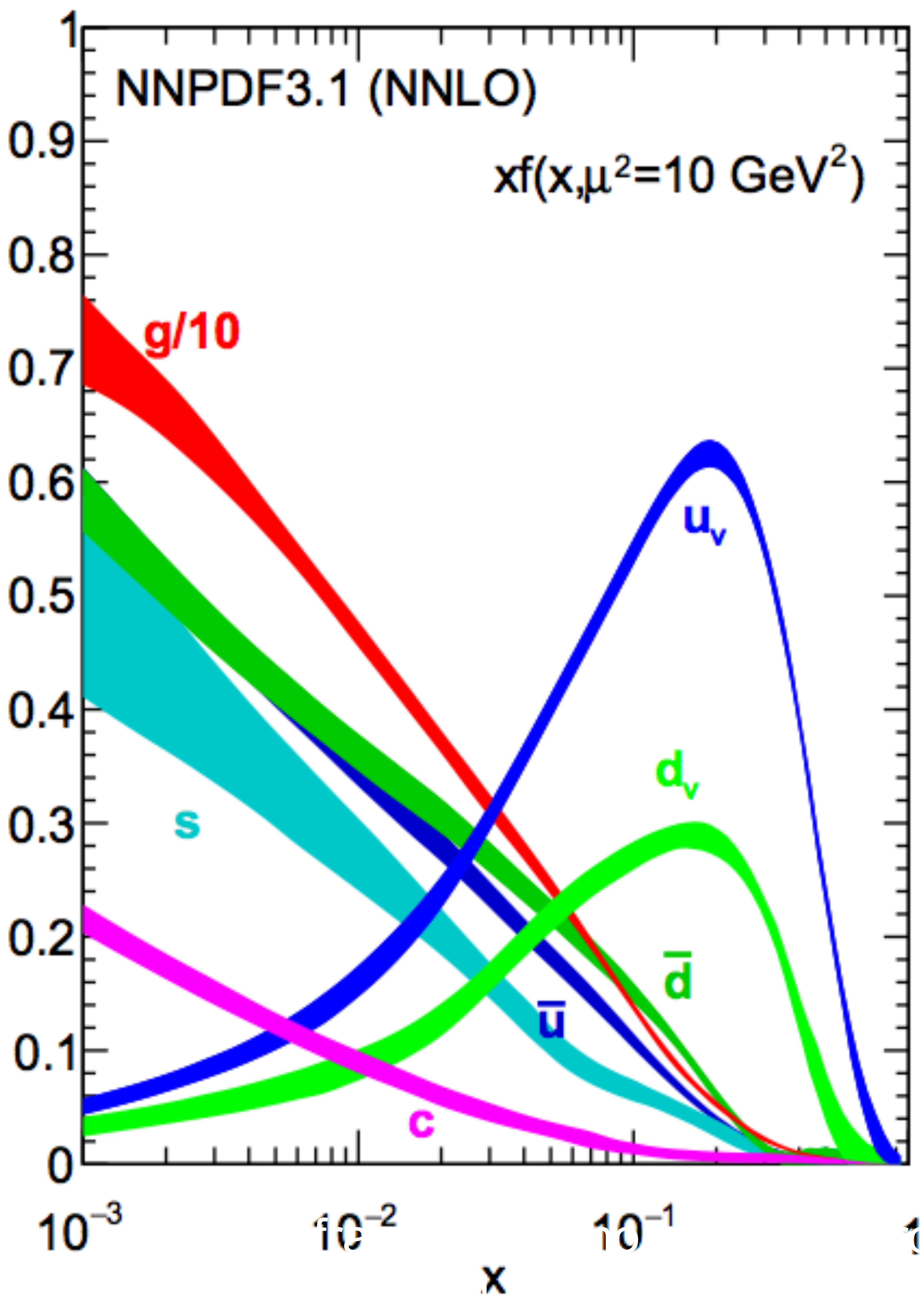


$$\propto \alpha_S$$

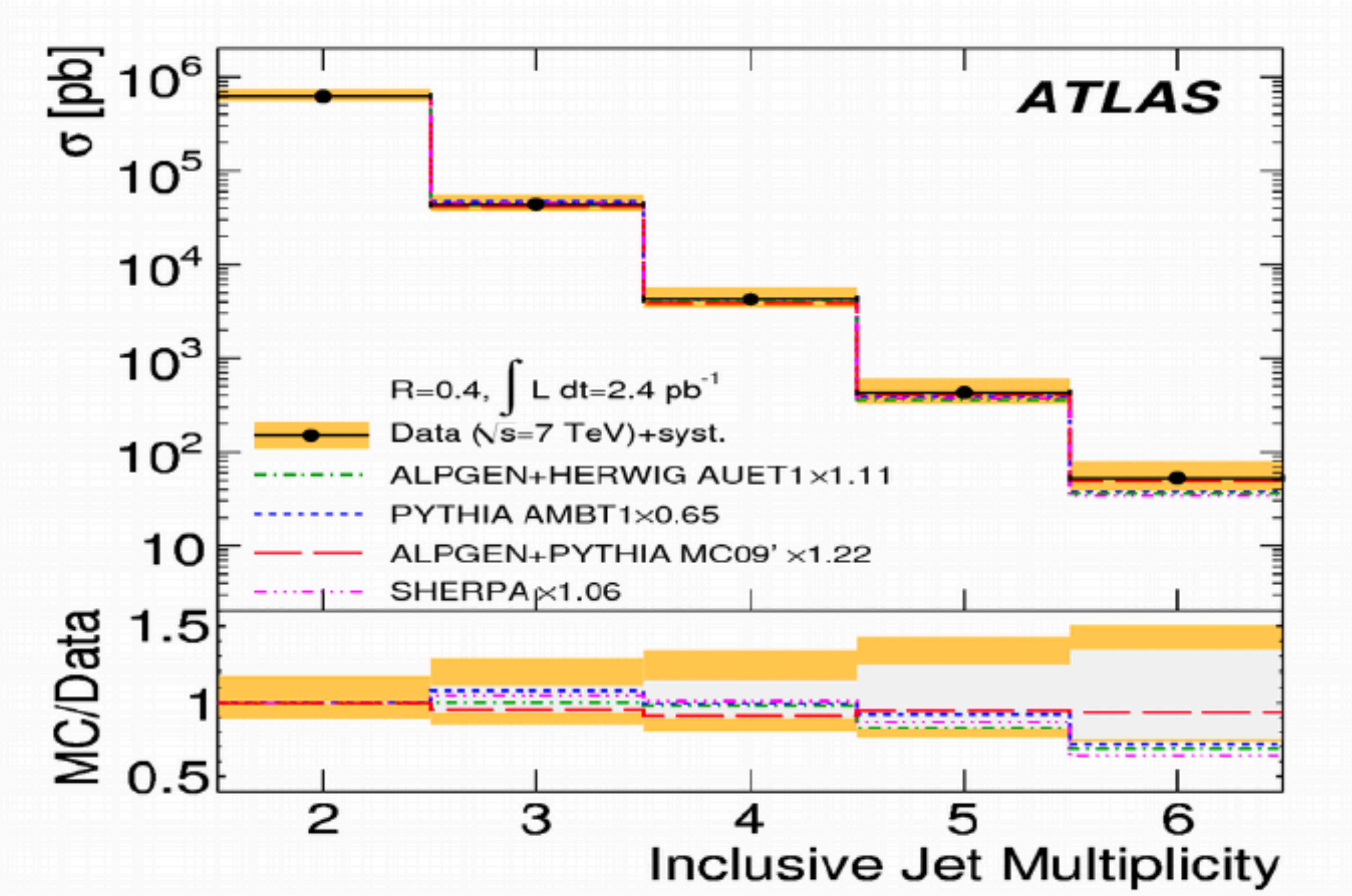
PROTON STRUCTURE

- Very important for accurately understanding proton-proton collisions (especially at high x)
- Source of uncertainty in measurements and searches.
- PDFs: Parton Density Functions
- DIS (HERA) + LHC data

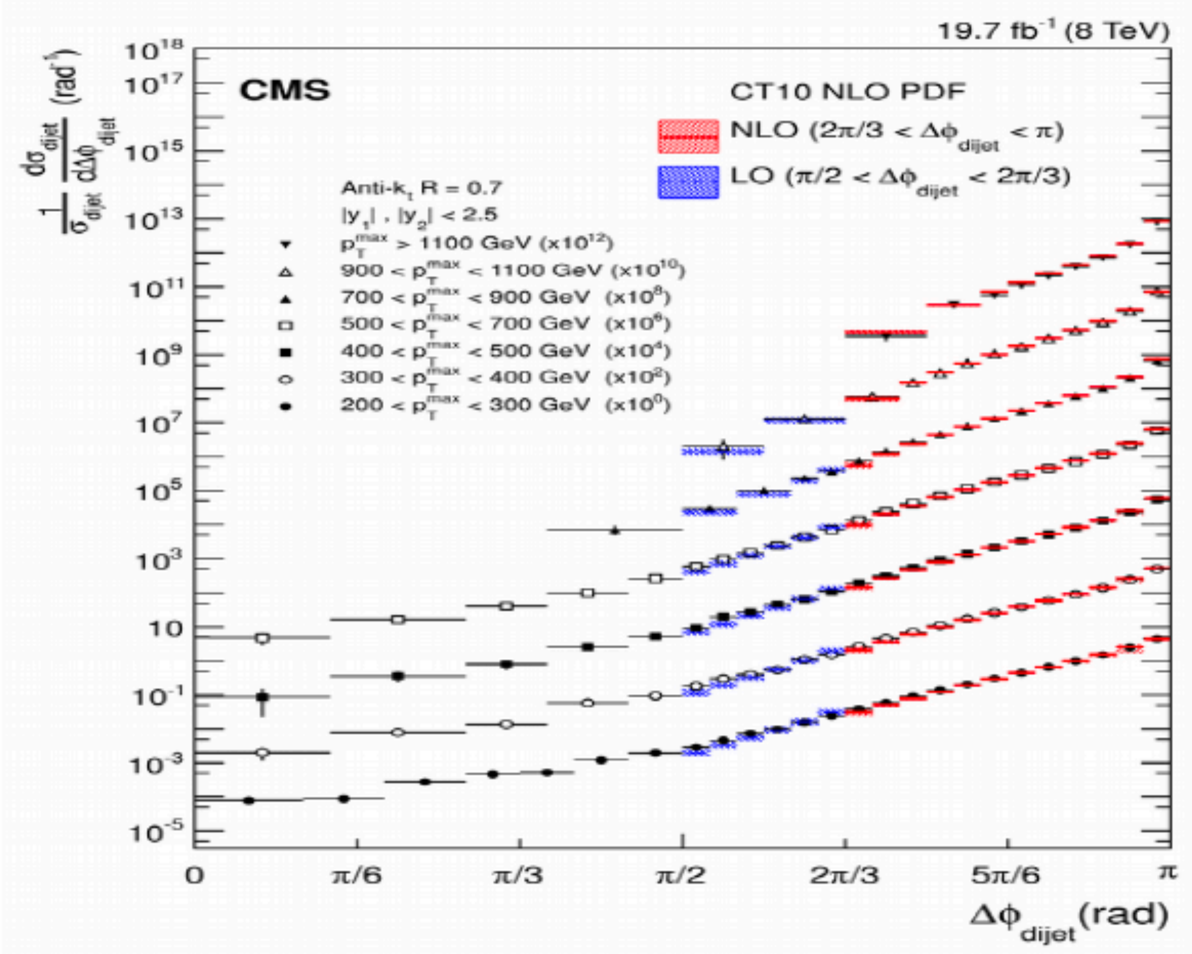




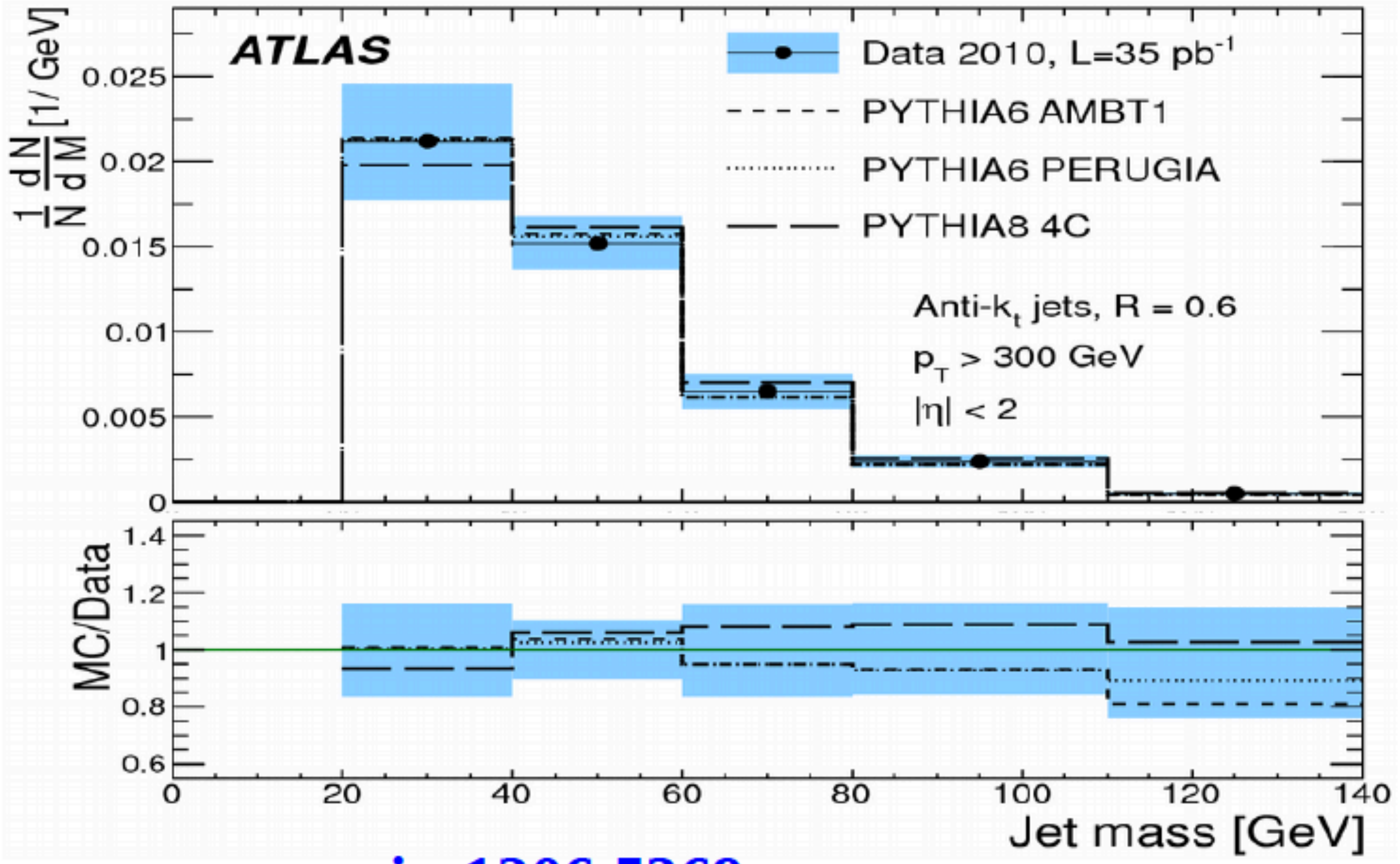
MANY MORE QCD @ LHC RESULTS…



[arxiv:1107.2092](https://arxiv.org/abs/1107.2092)



[arxiv:1602.04384](https://arxiv.org/abs/1602.04384)



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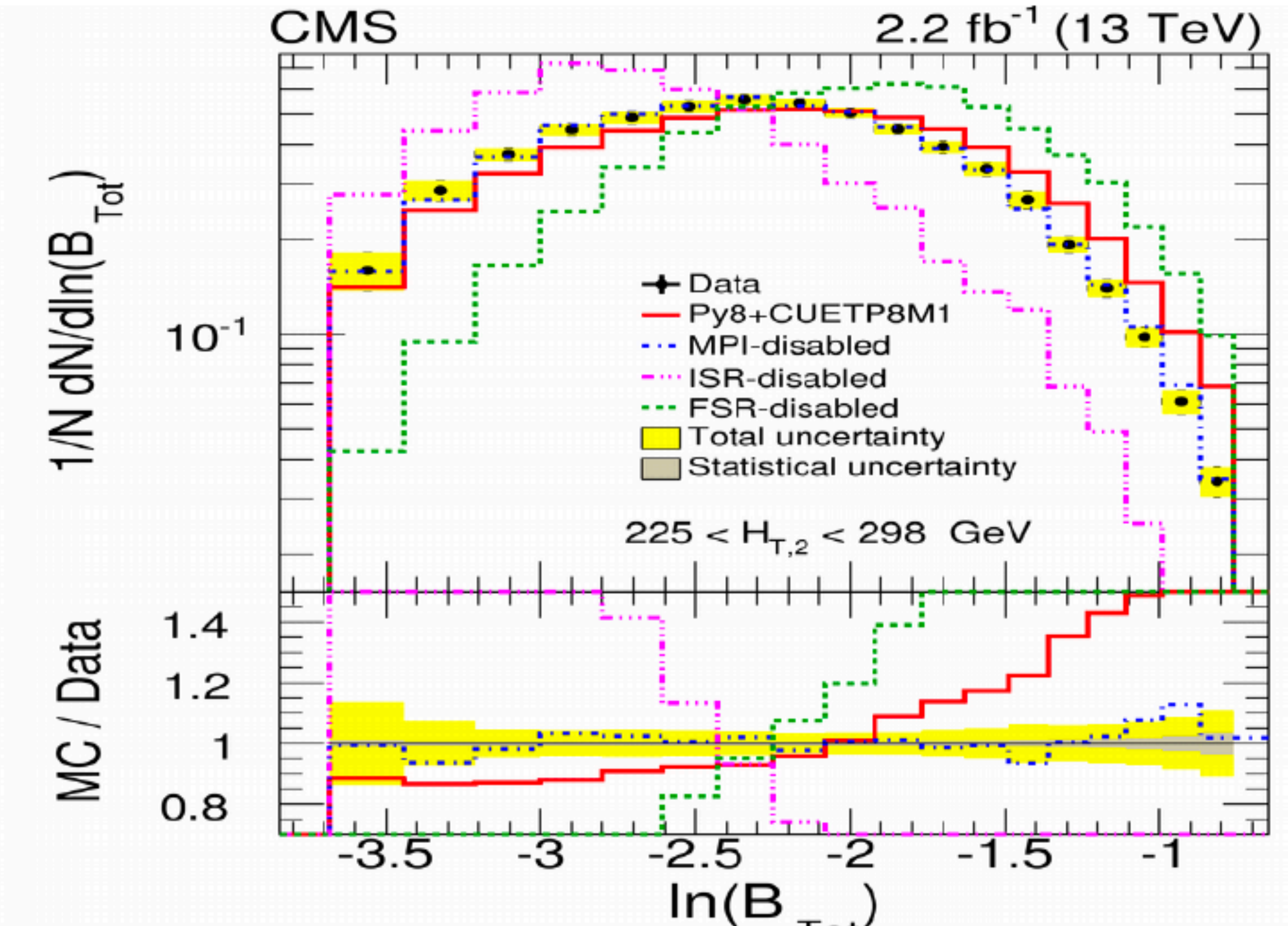
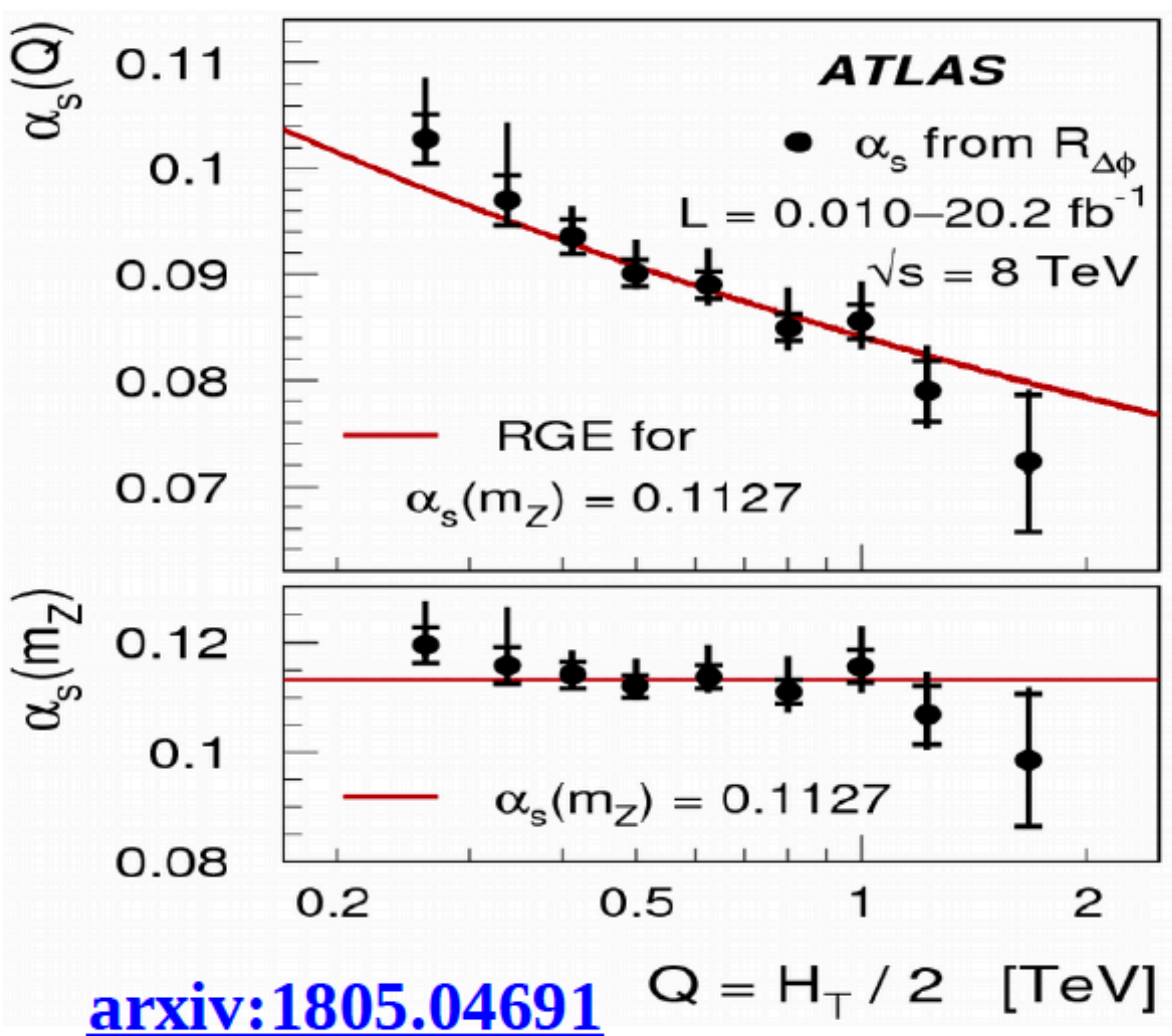
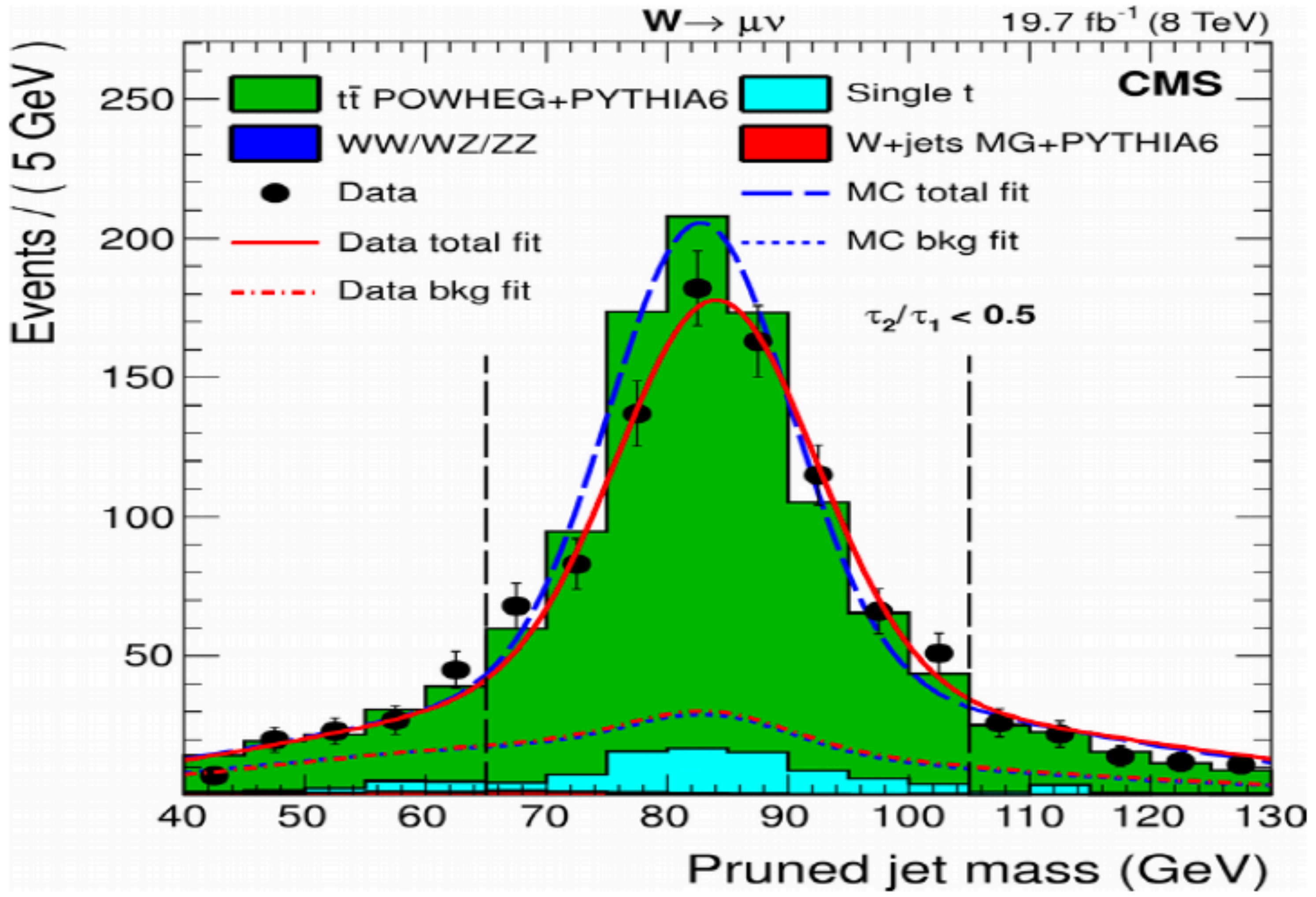


[arxiv:1811.00588](https://arxiv.org/abs/1811.00588)



[arxiv:1805.04691](https://arxiv.org/abs/1805.04691)



[arxiv:1410.4227](https://arxiv.org/abs/1410.4227)

VECTOR BOSONS: W AND Z PHYSICS

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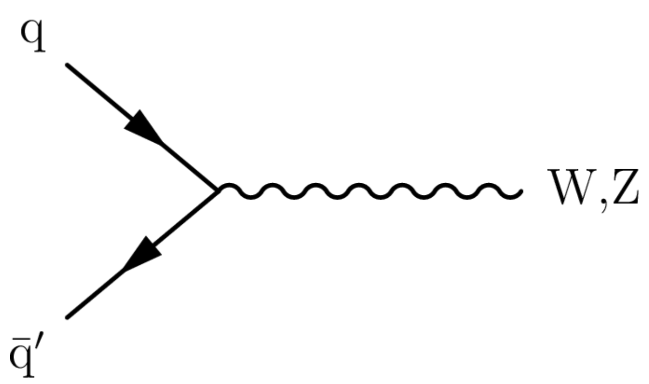
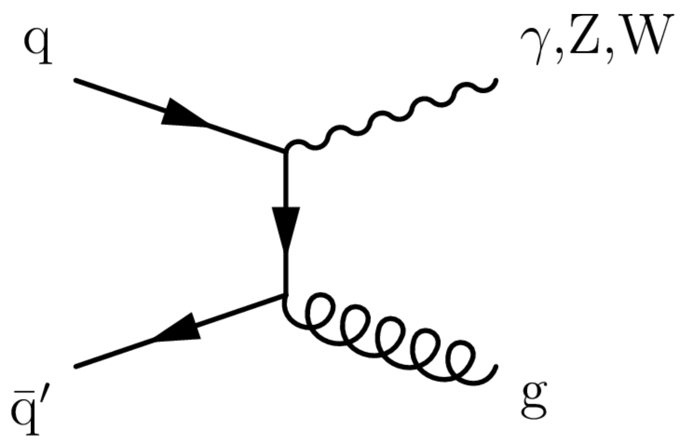
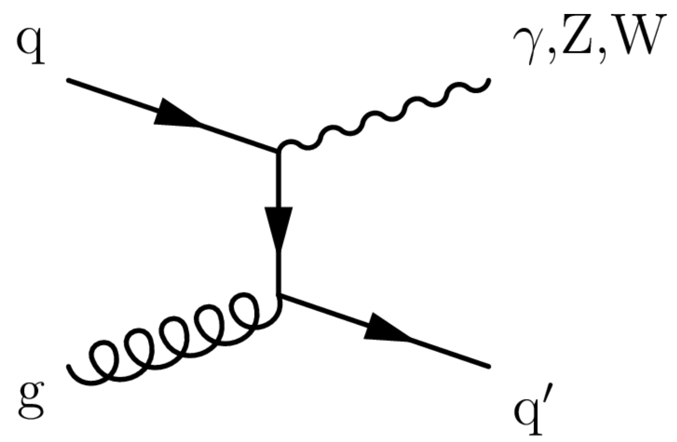
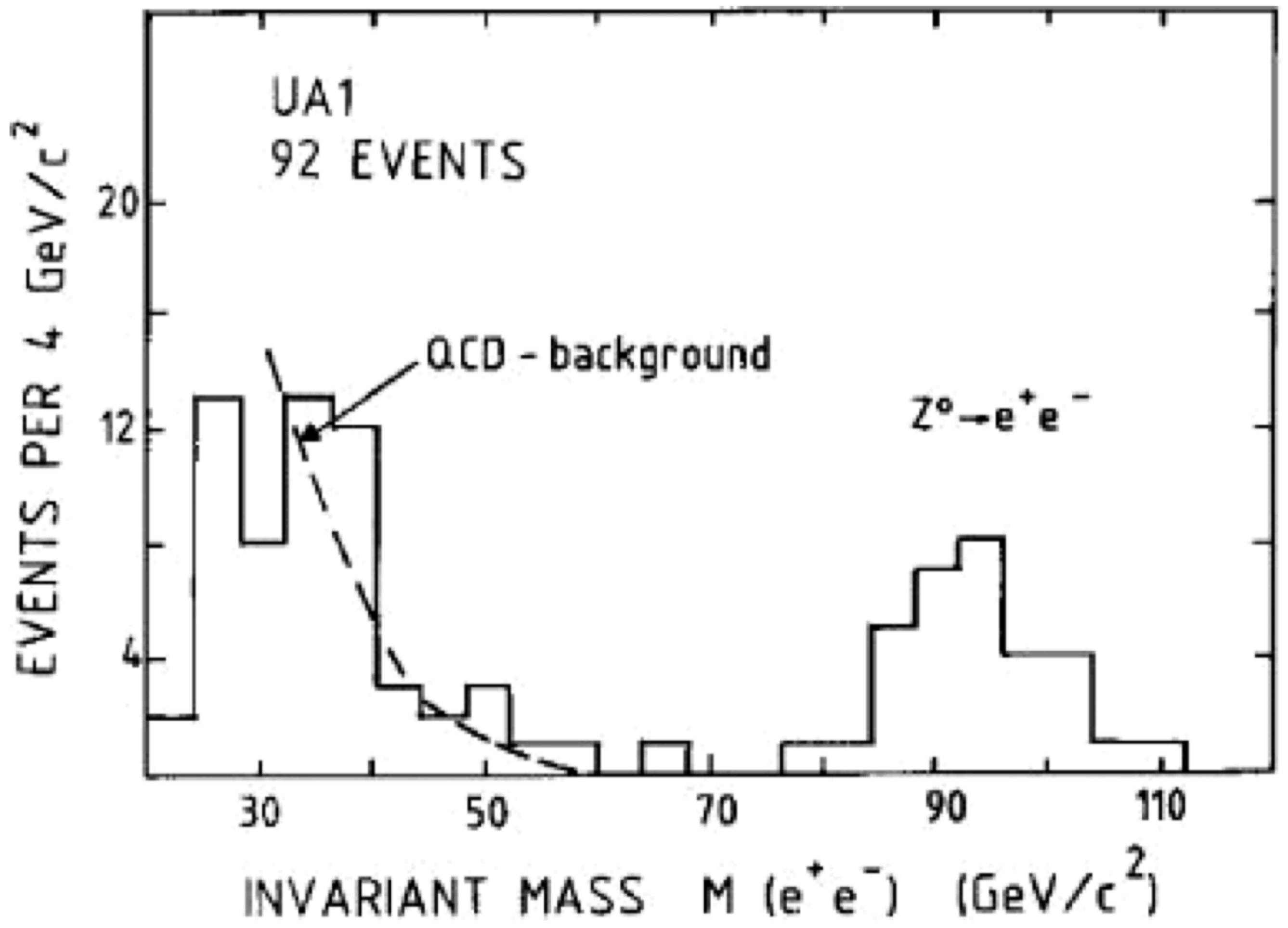
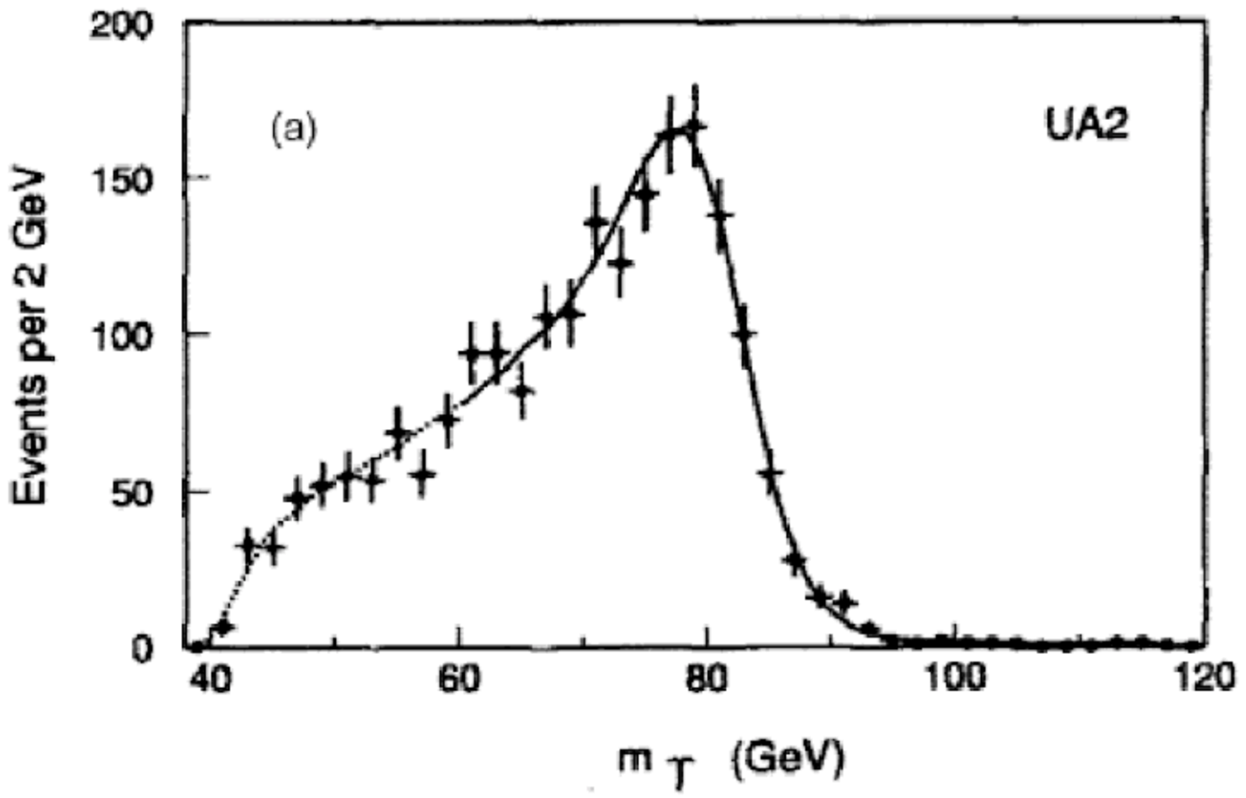




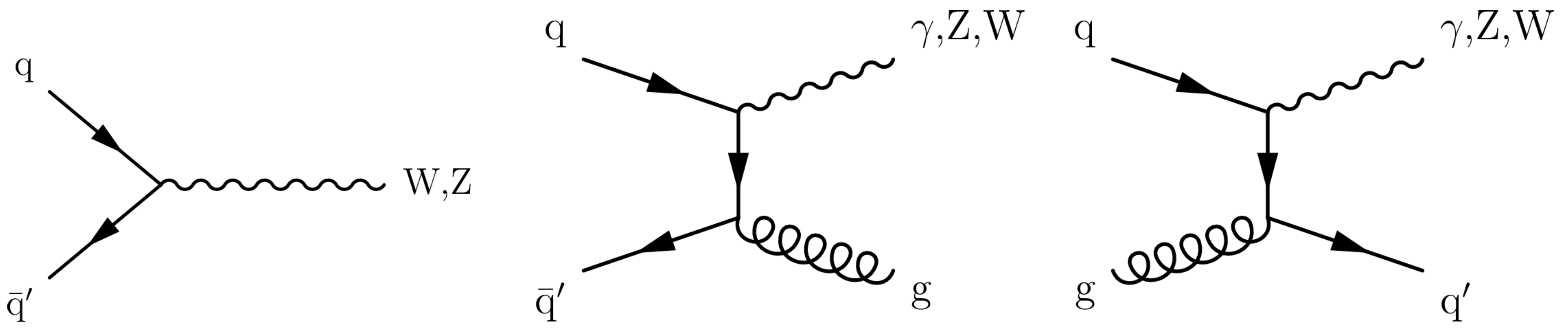


- Discovered in the SppS (Nobel in 1984)
- M_Z=91 GeV, M_W=80 GeV





VECTOR BOSONS: W AND Z PHYSICS



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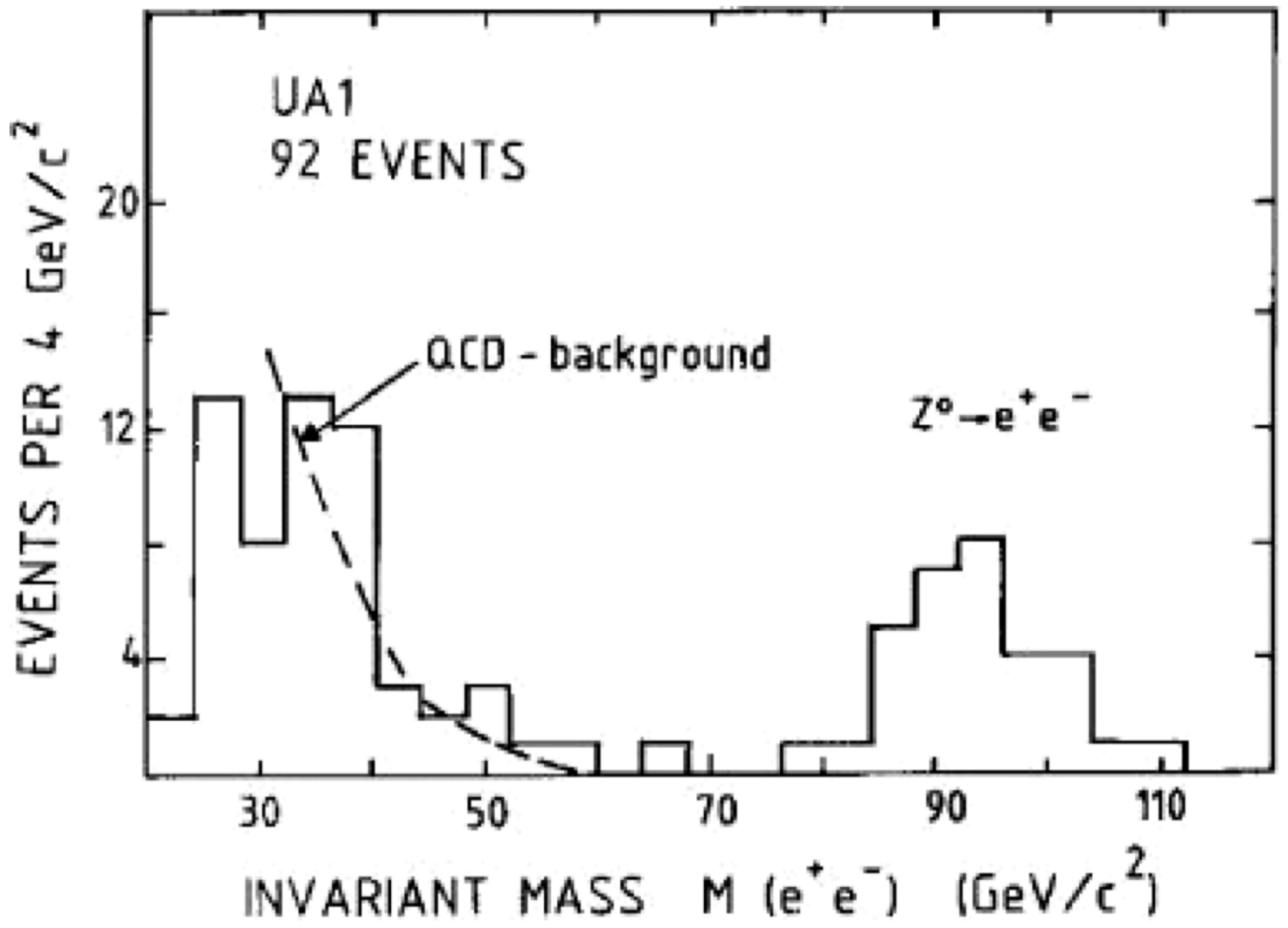

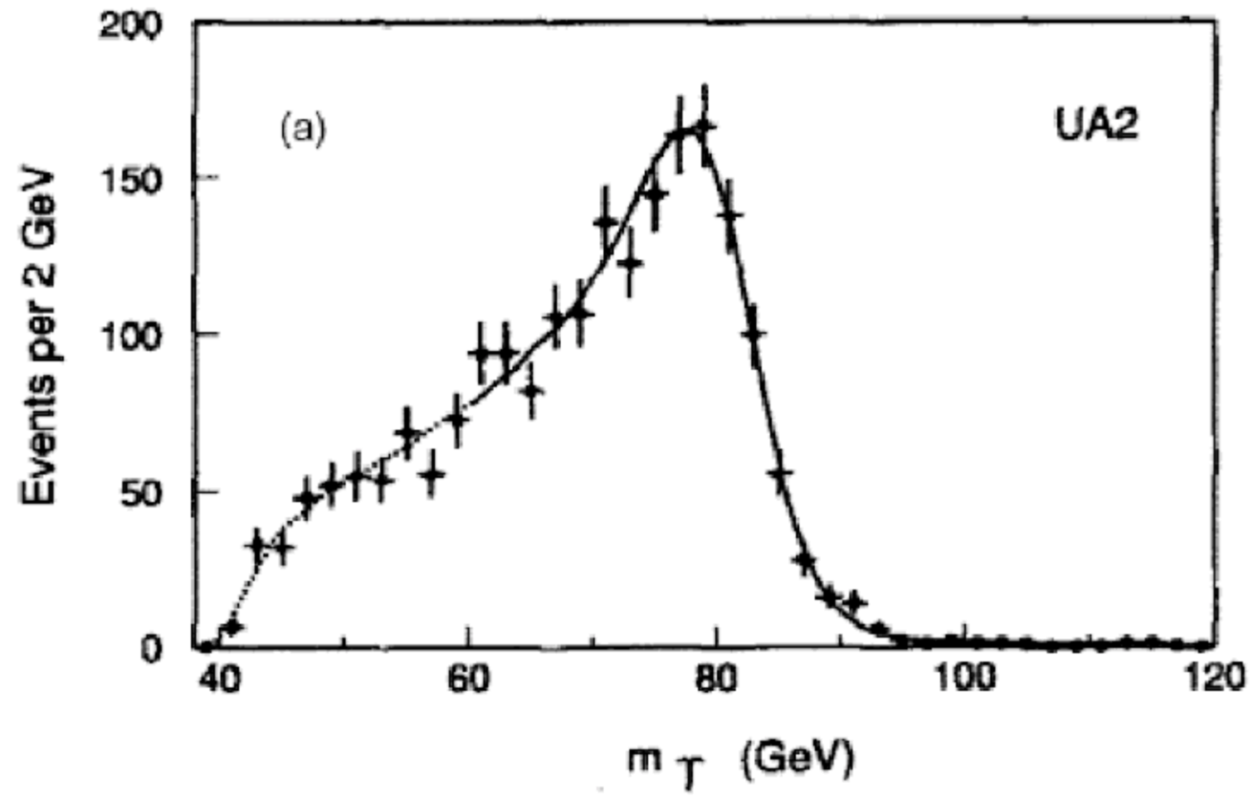

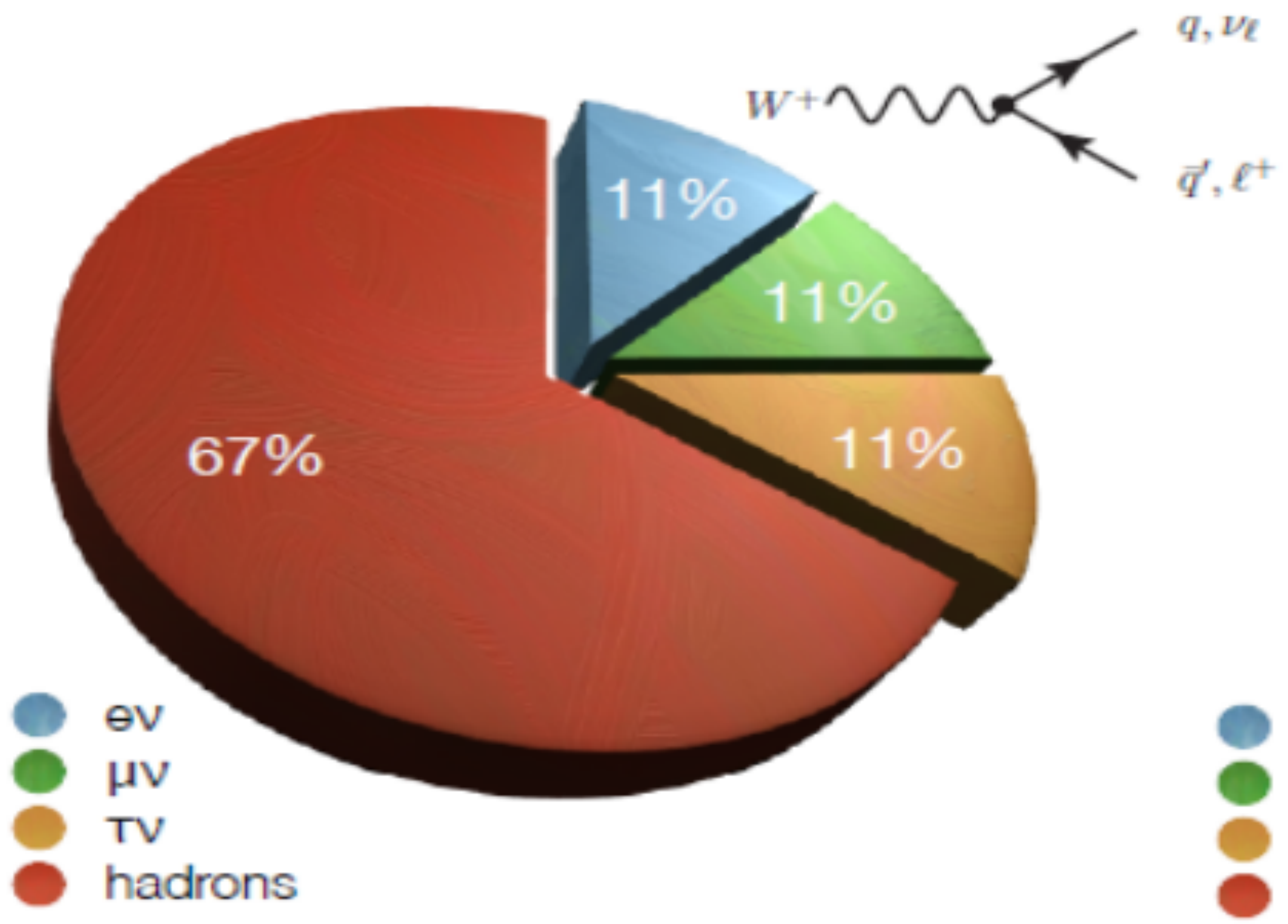

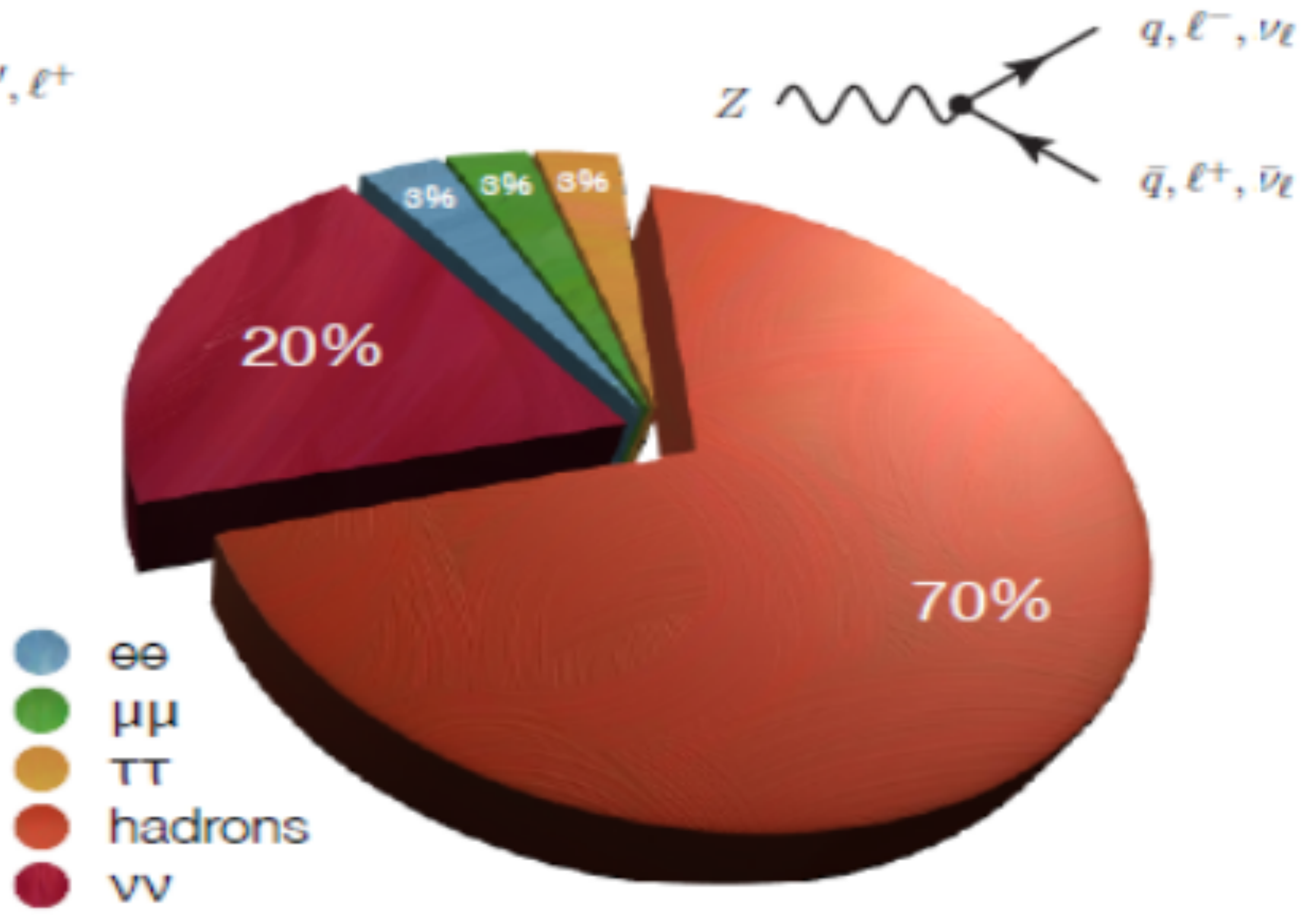

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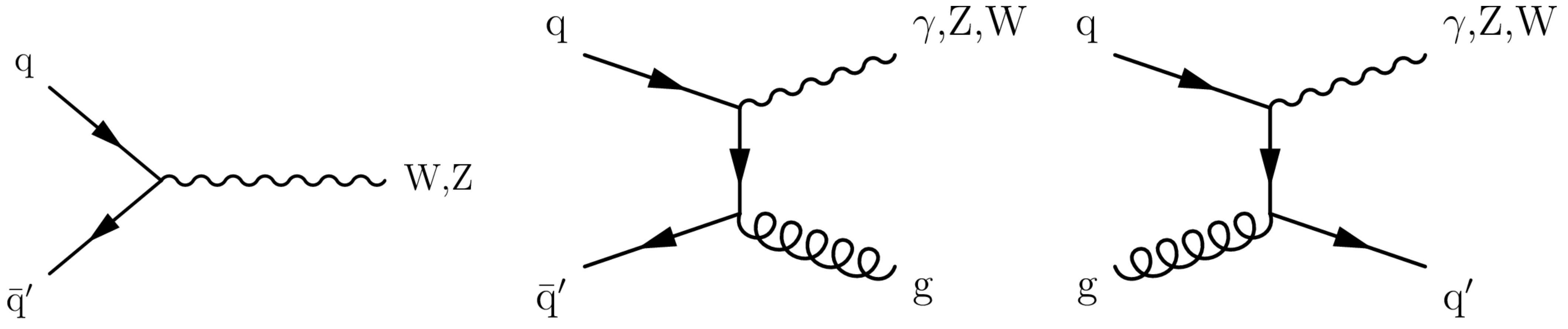
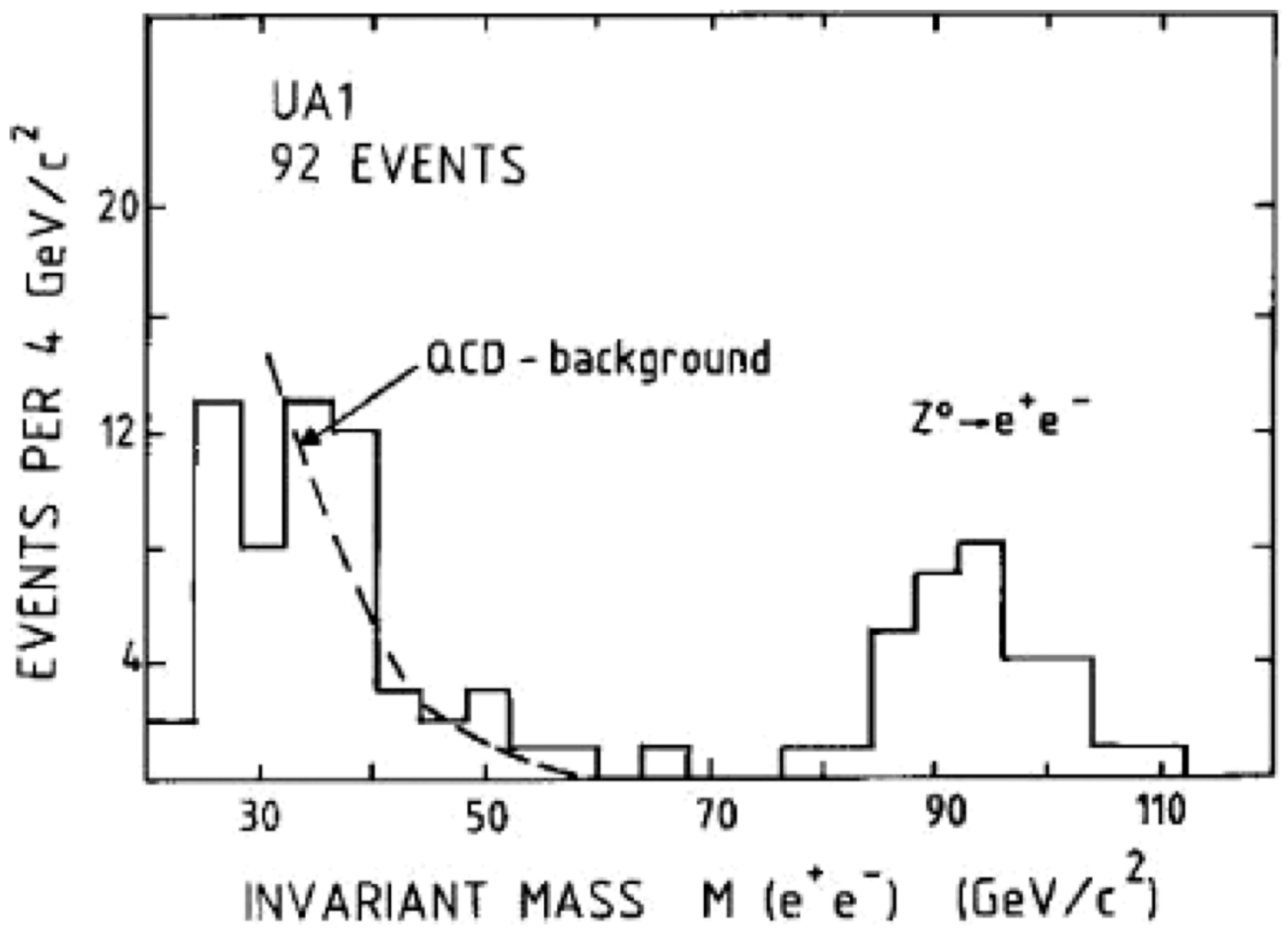
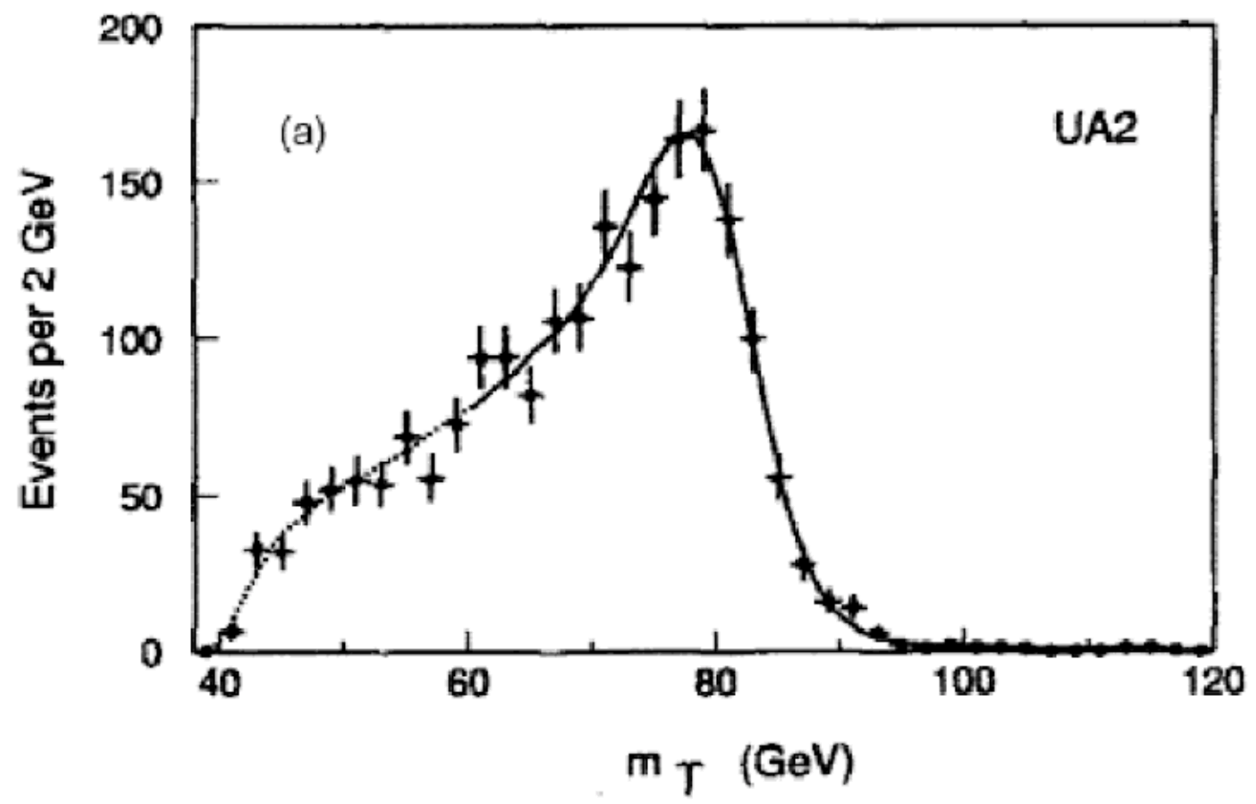
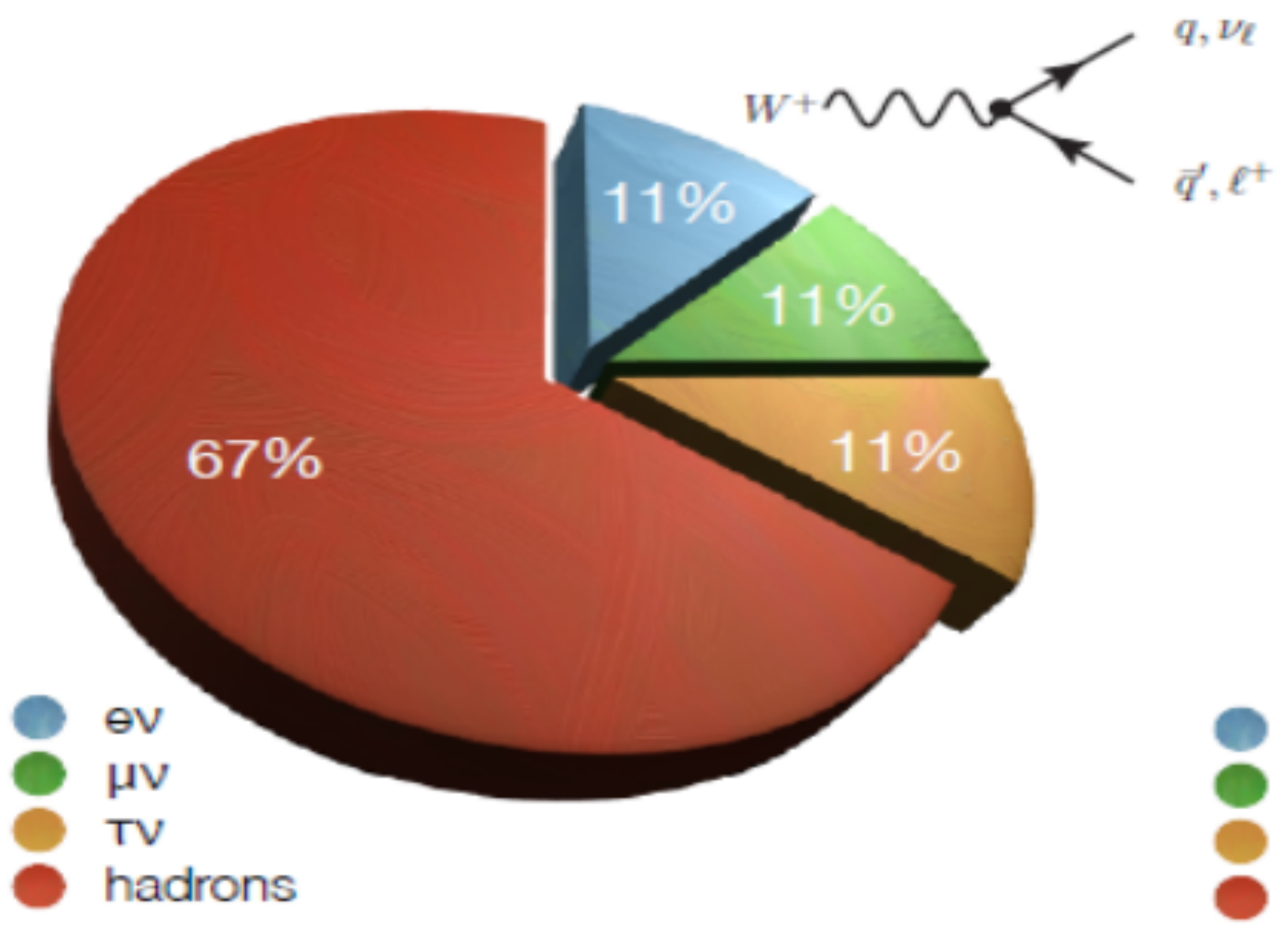
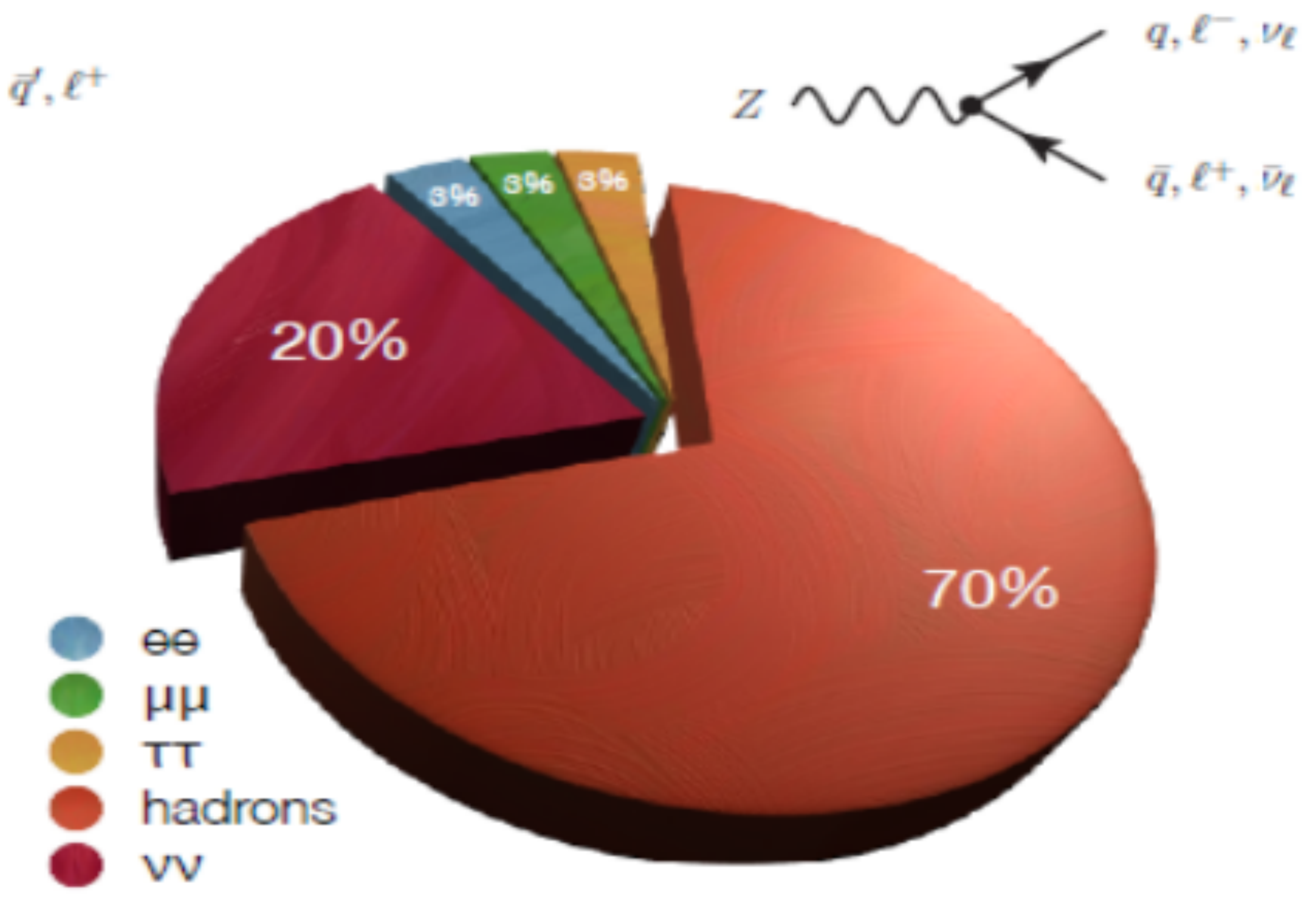


- Discovered in the SppS (Nobel in 1984)
- M_Z=91 GeV, M_W=80 GeV
- These are well-established processes, both theoretically and experimentally
  - 'Standard Candle' for many experimental measurements at the LHC, from efficiencies to comparing with Higgs/BSM production

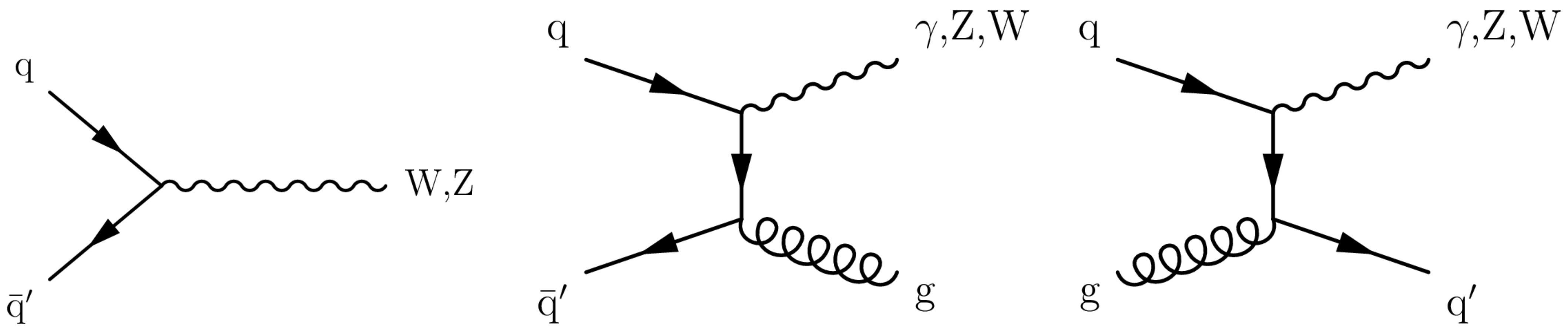




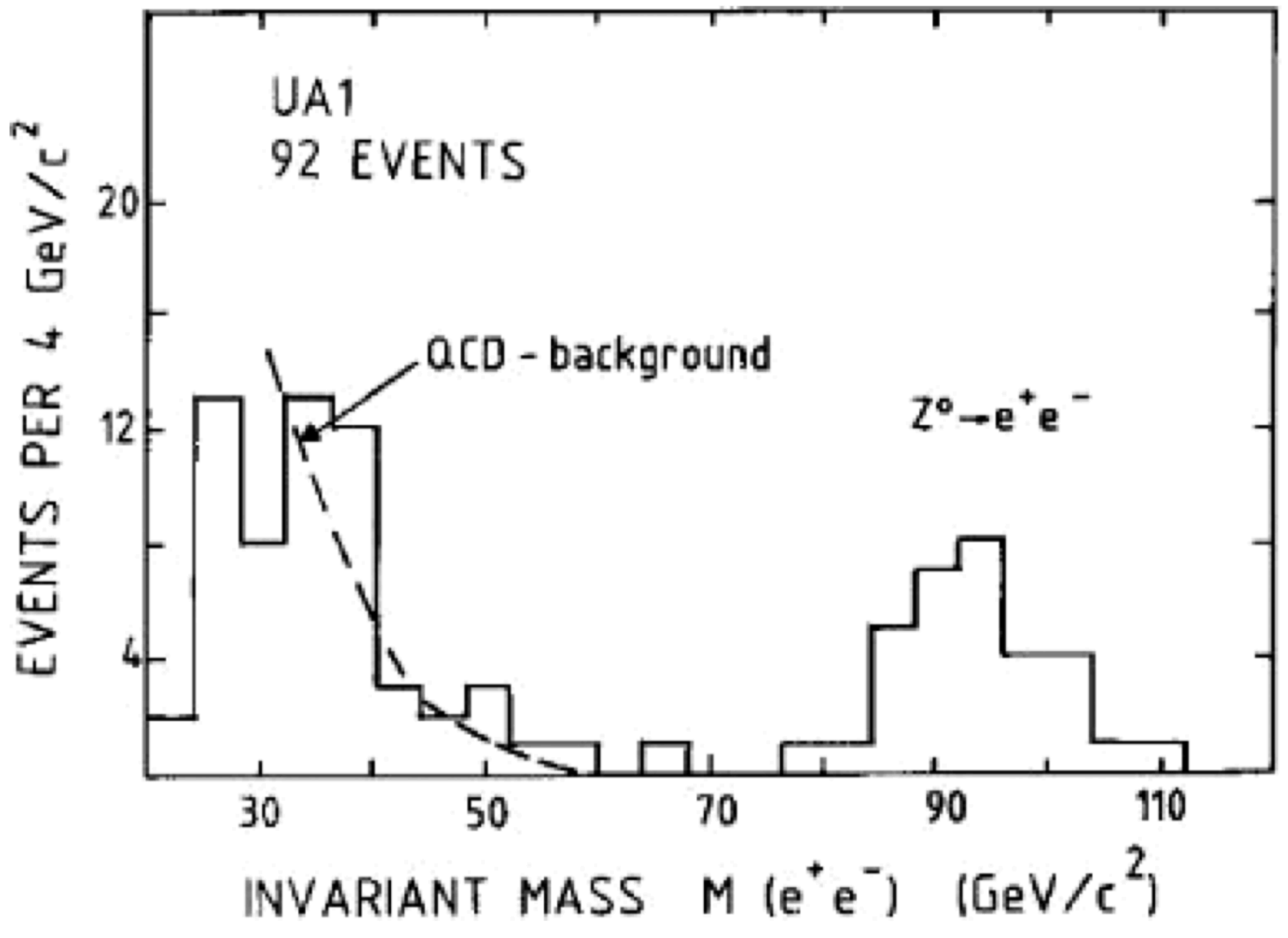


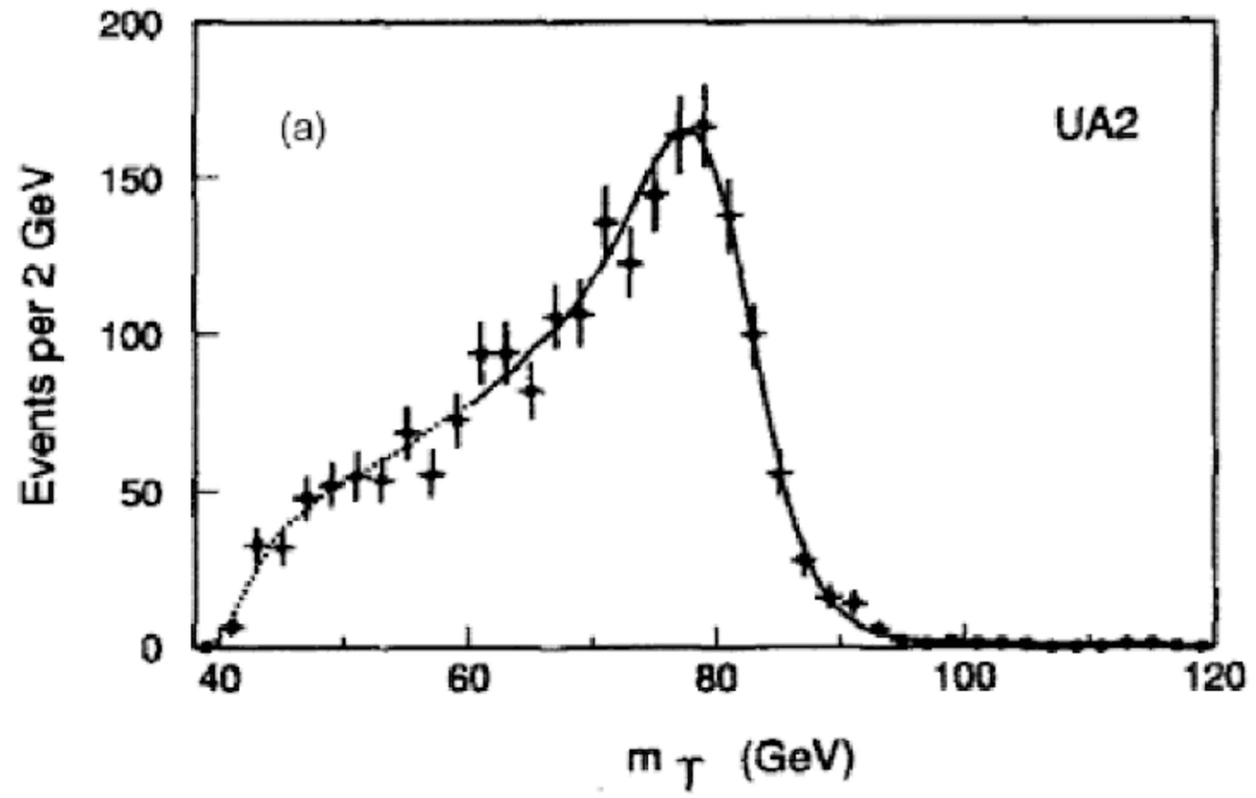


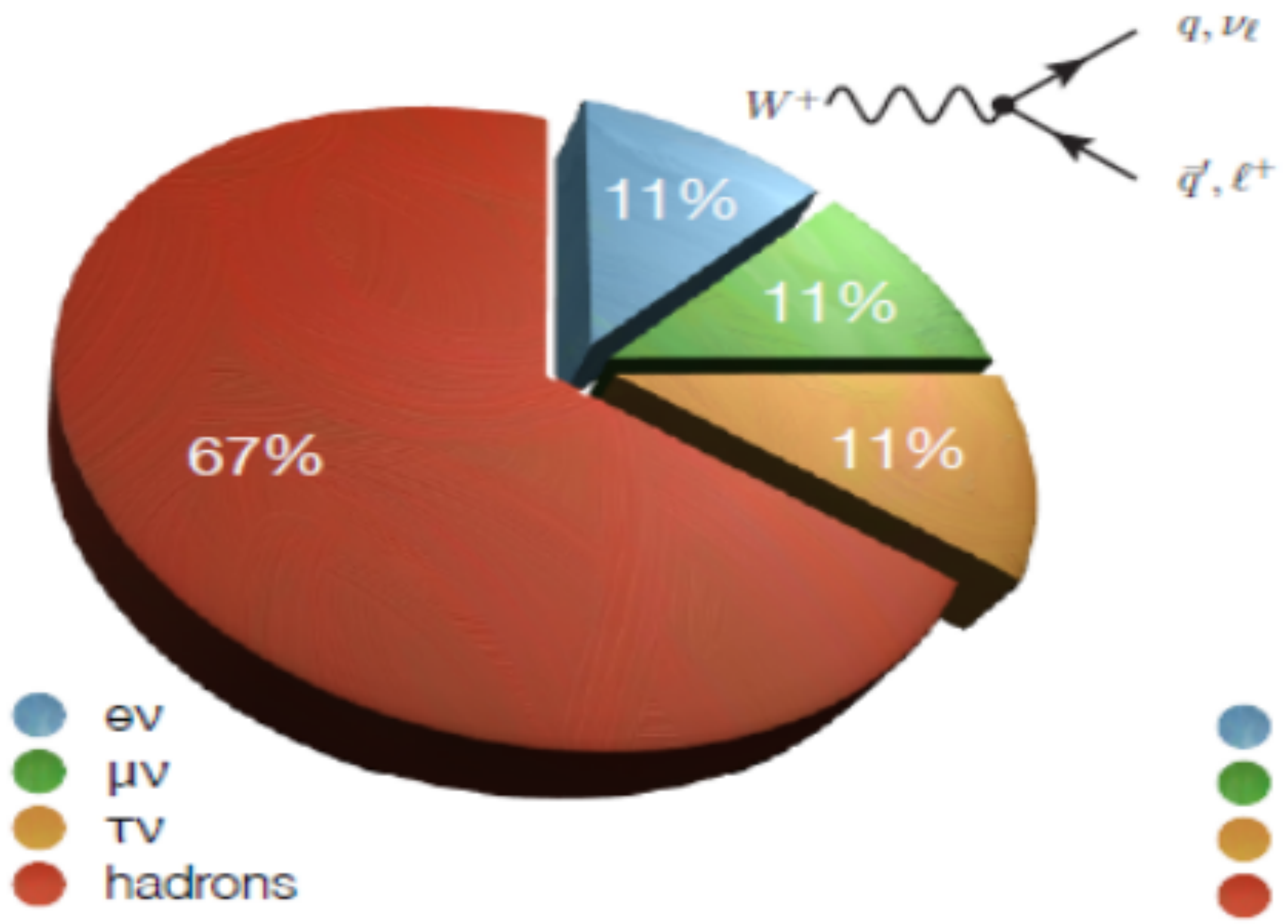
VECTOR BOSONS: W AND Z PHYSICS

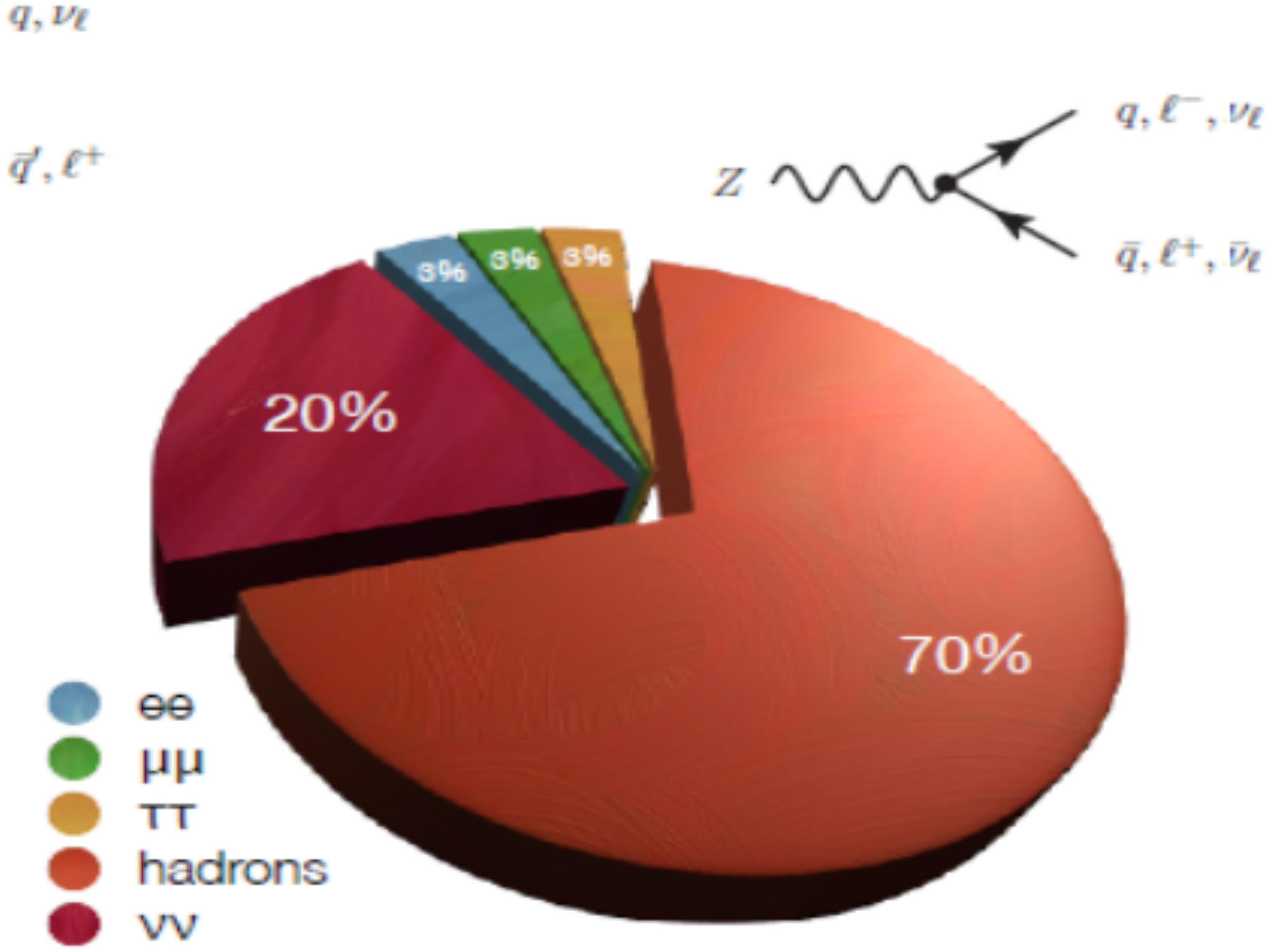


- Discovered in the SppS (Nobel in 1984)
- M_Z=91 GeV, M_W=80 GeV
- These are well-established processes, both theoretically and experimentally
  - ‘Standard Candle’ for many experimental measurements at the LHC, from efficiencies to comparing with Higgs/BSM production
- Nevertheless, a lot to learn about them: very rich program of studies associated to its production: V, V+Jets, VV…
- Measuring their properties accurately ➜ limits of our knowledge of the SM



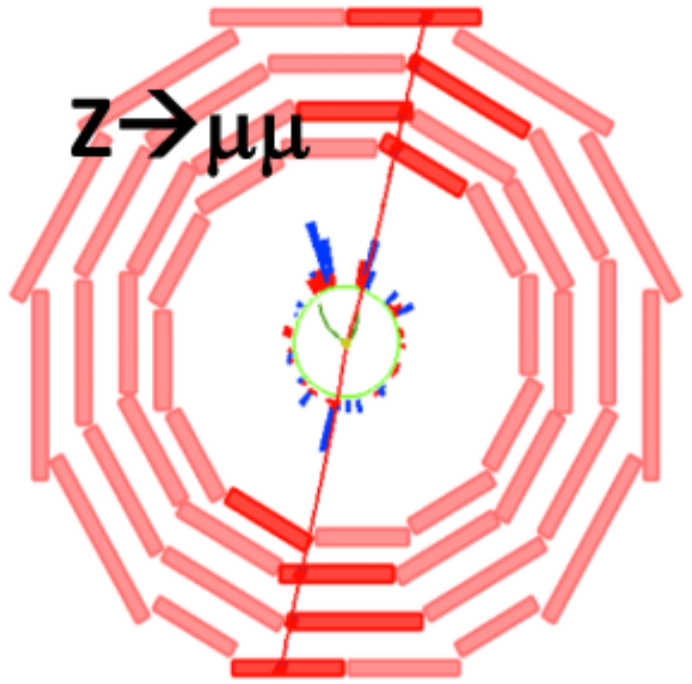


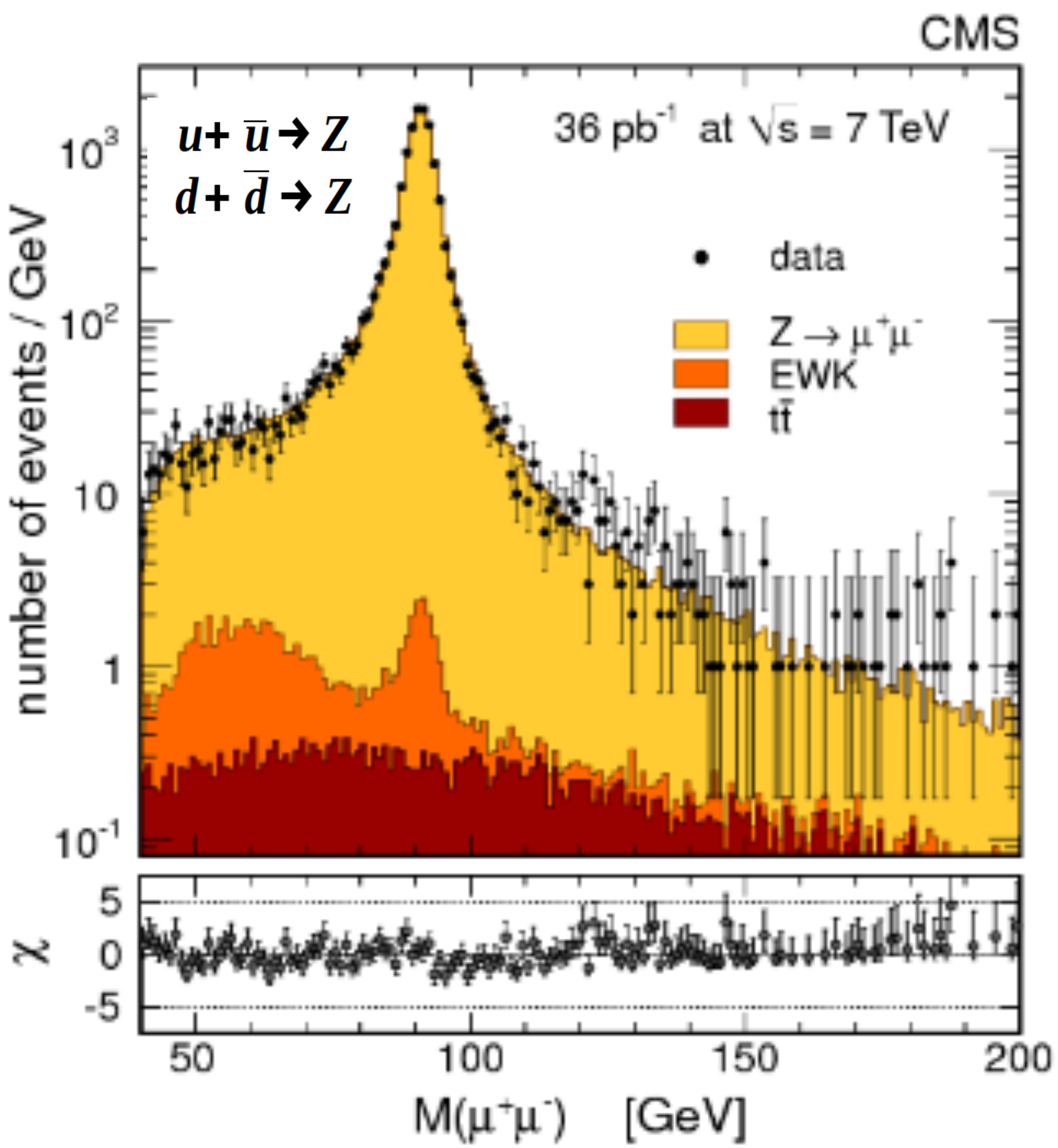


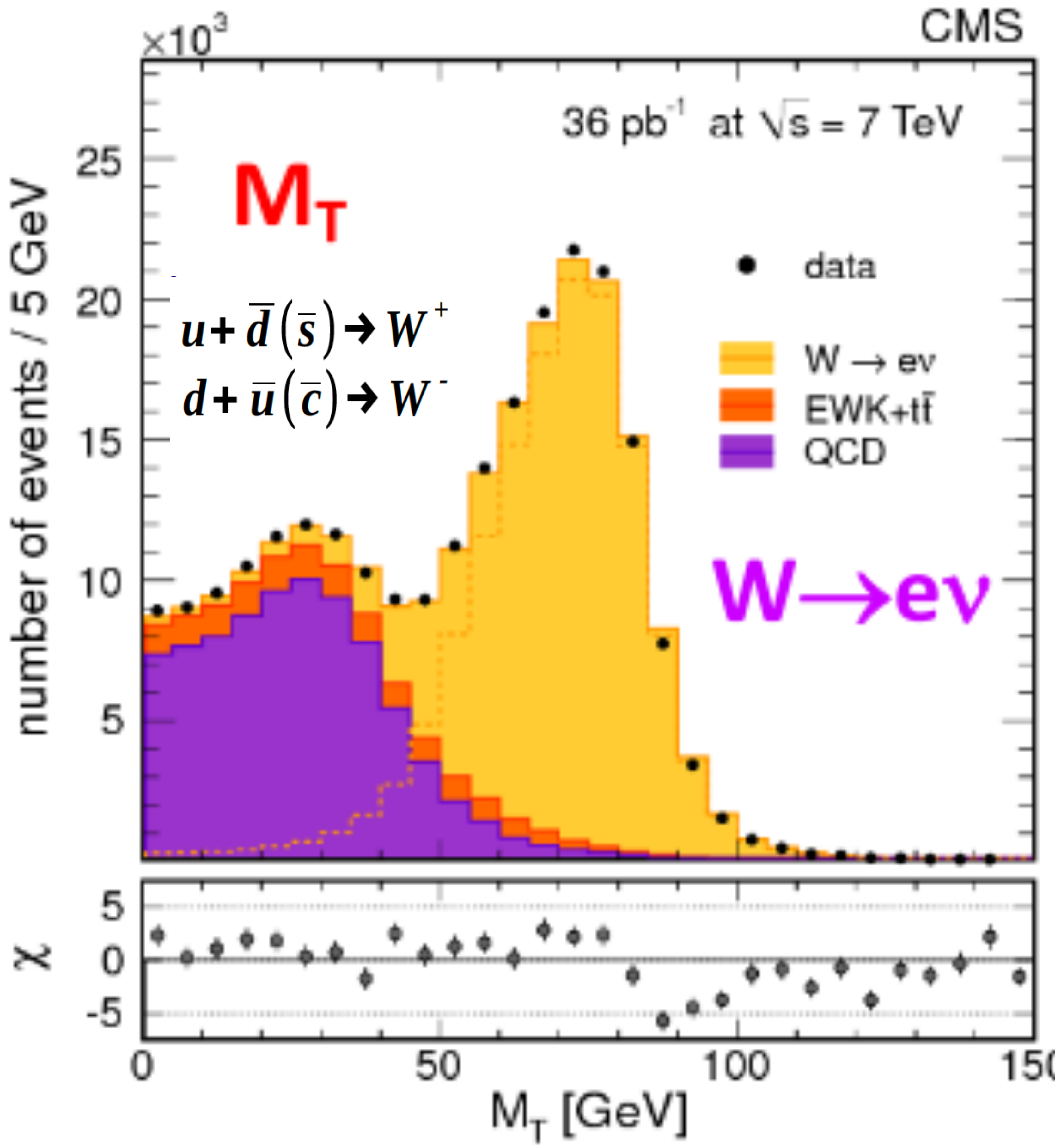


VECTOR BOSONS: W AND Z PHYSICS

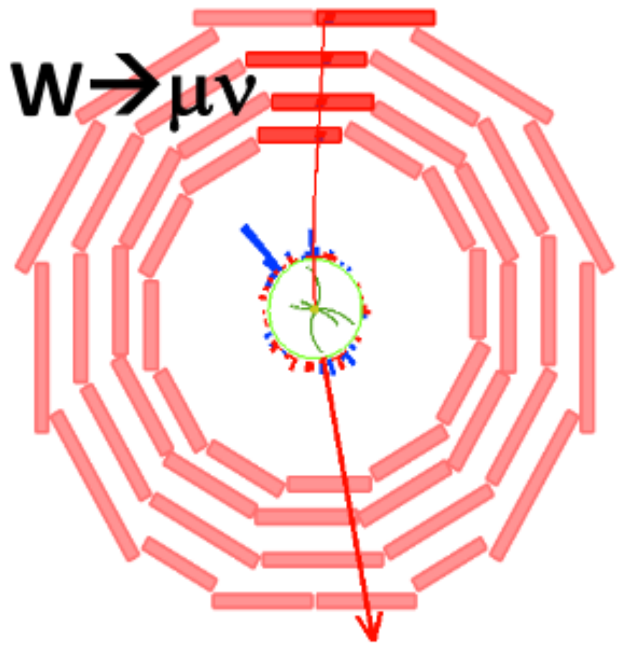
Z:
All the information is there in Mu/Ele channels







W:
Missing Neutrino Information!

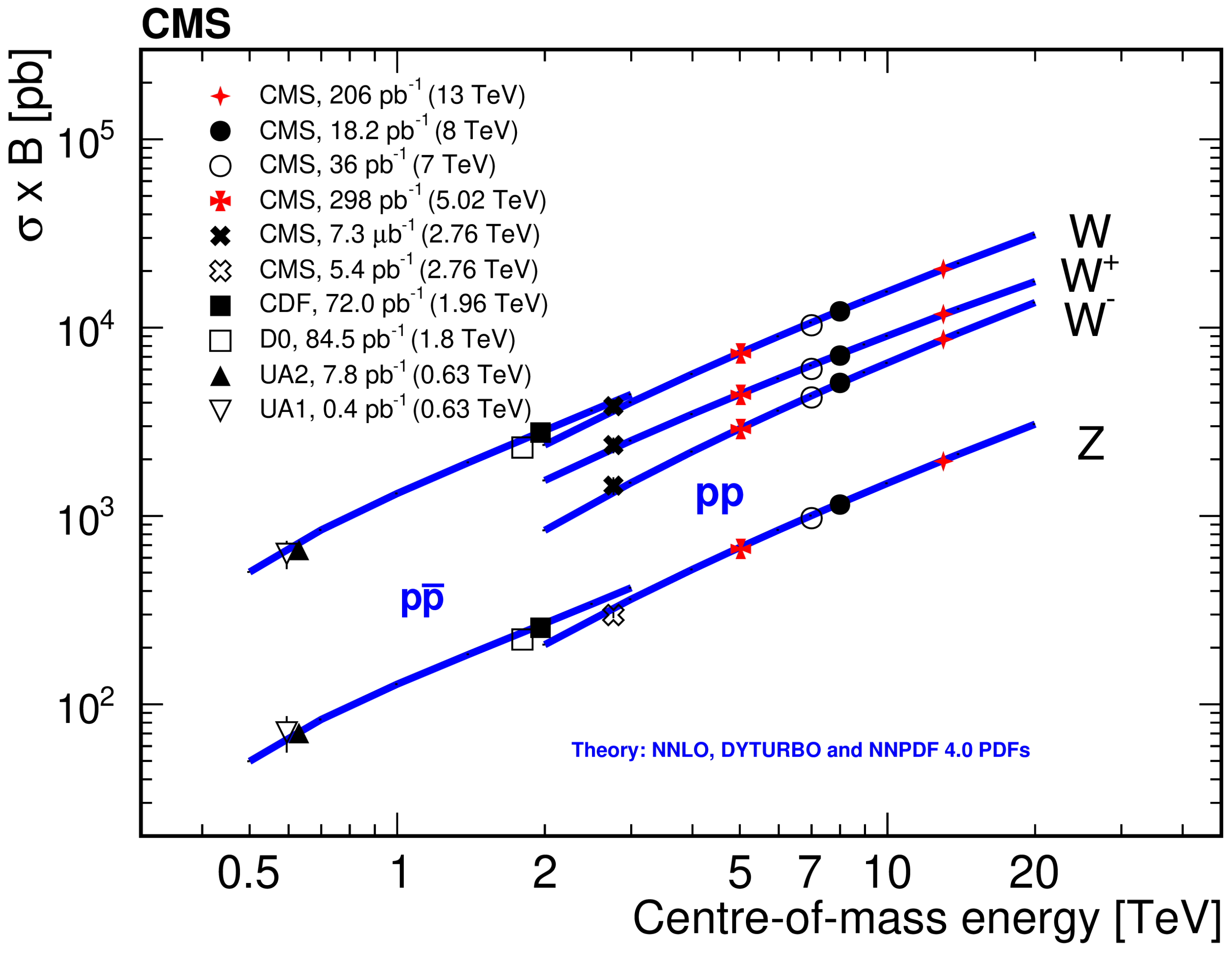


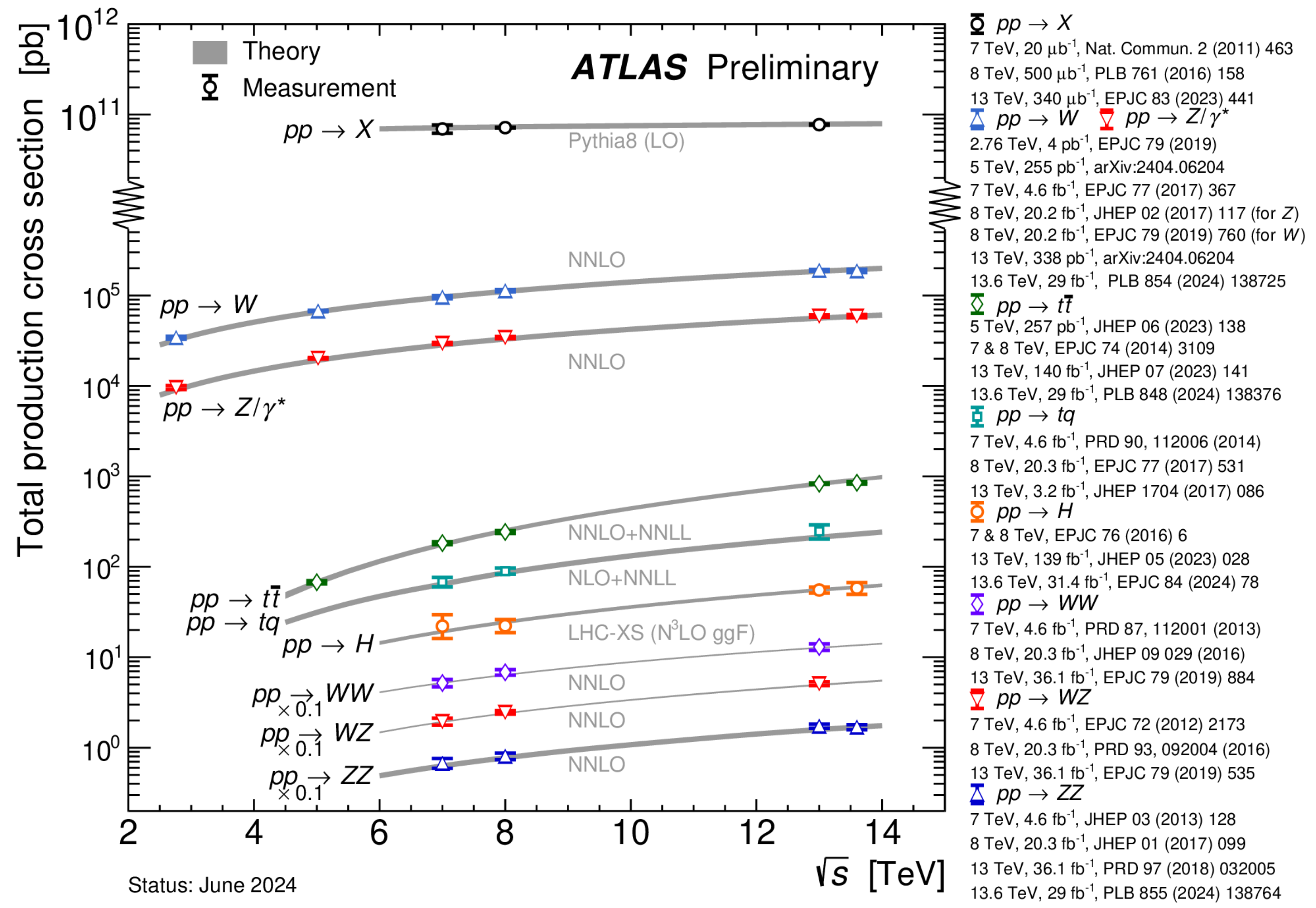
$$M^2 = 2p_T(\ell_1)p_T(\ell_2)(\cosh\Delta\eta_{12} - \cos\Delta\phi_{12})$$

$$M^2 = 2p_T(\ell)p_T(\nu)(1 - \cos\Delta\phi(\ell,\nu))$$

PRECISION PHYSICS WITH W AND Z

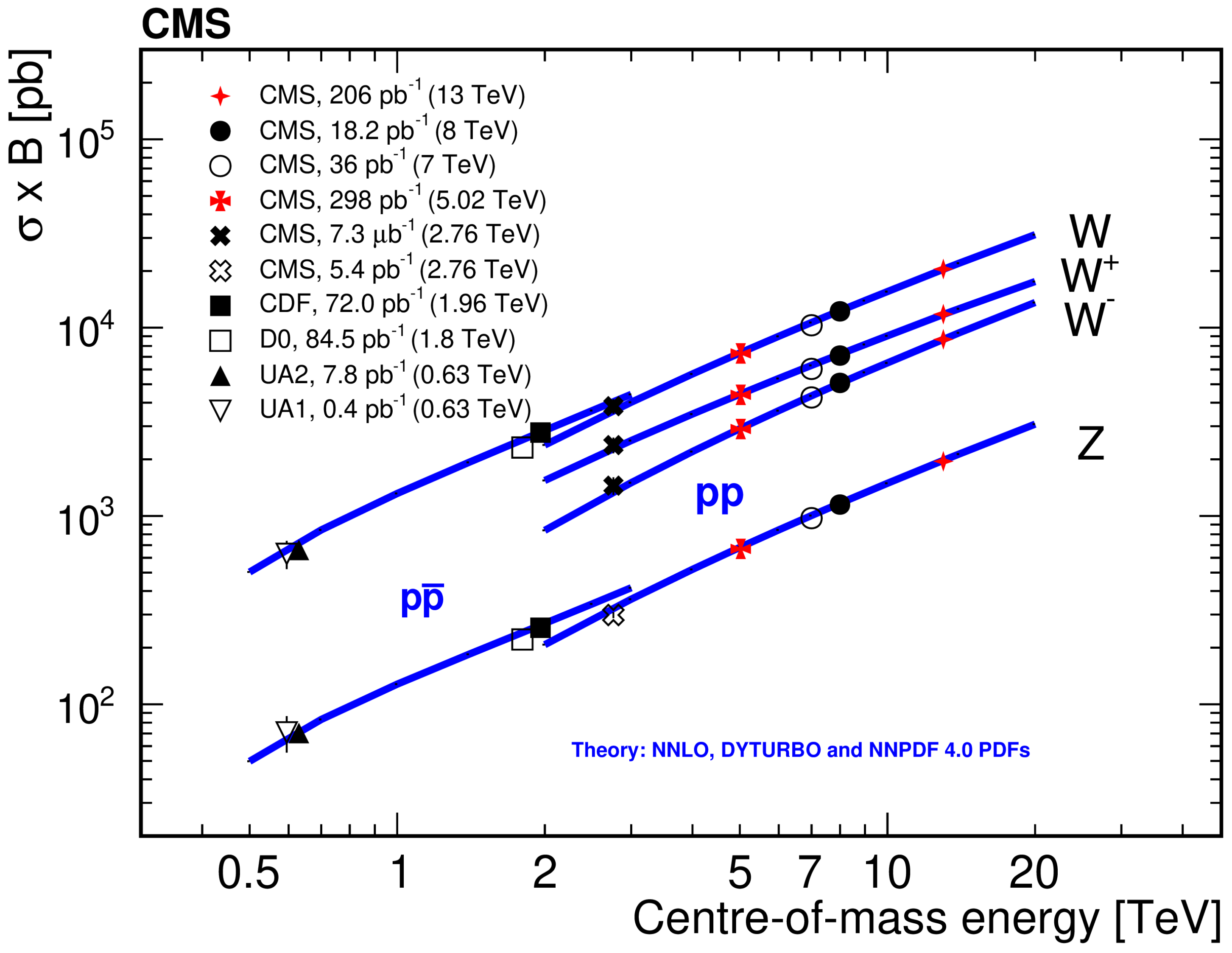
Cross Sections

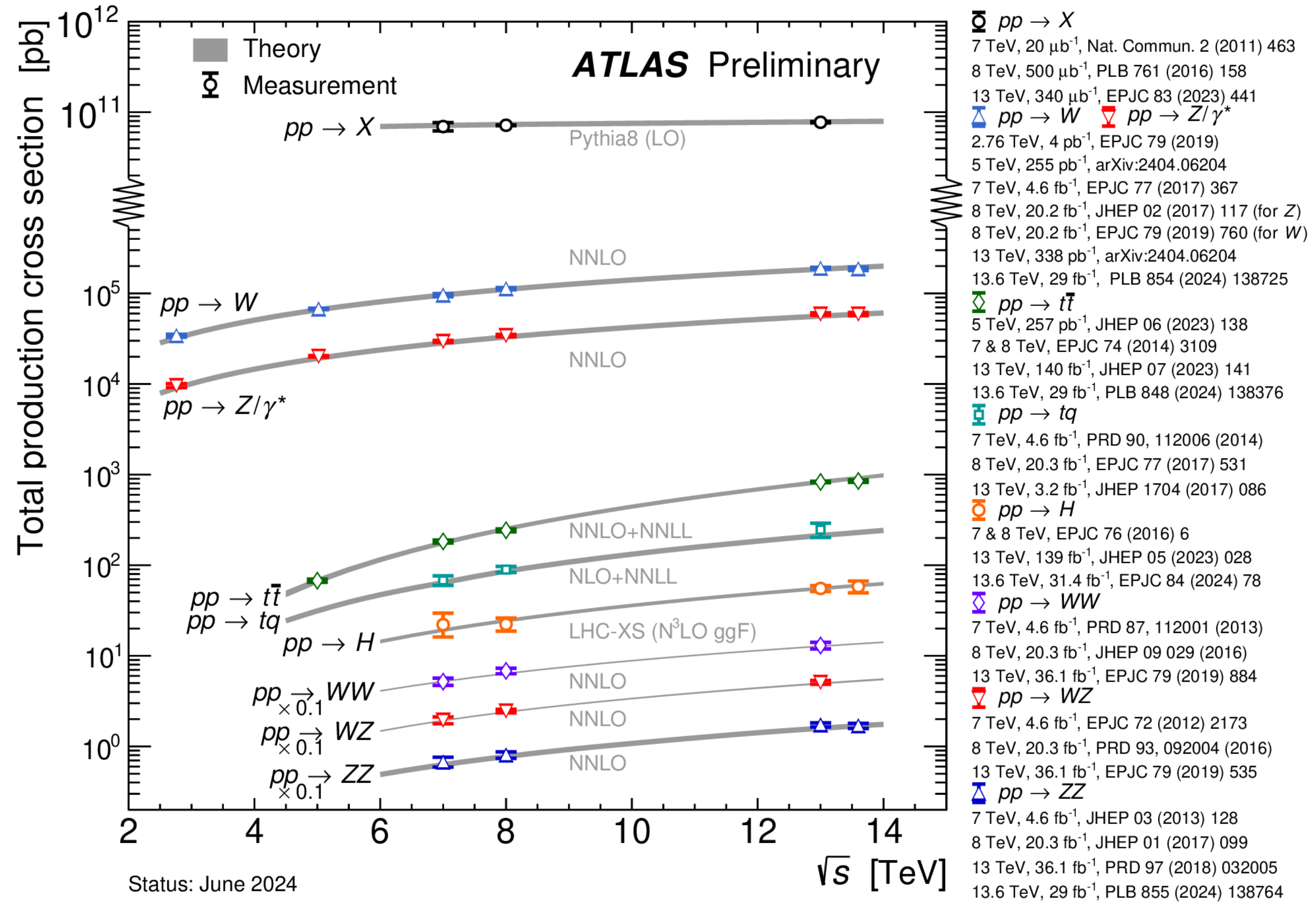




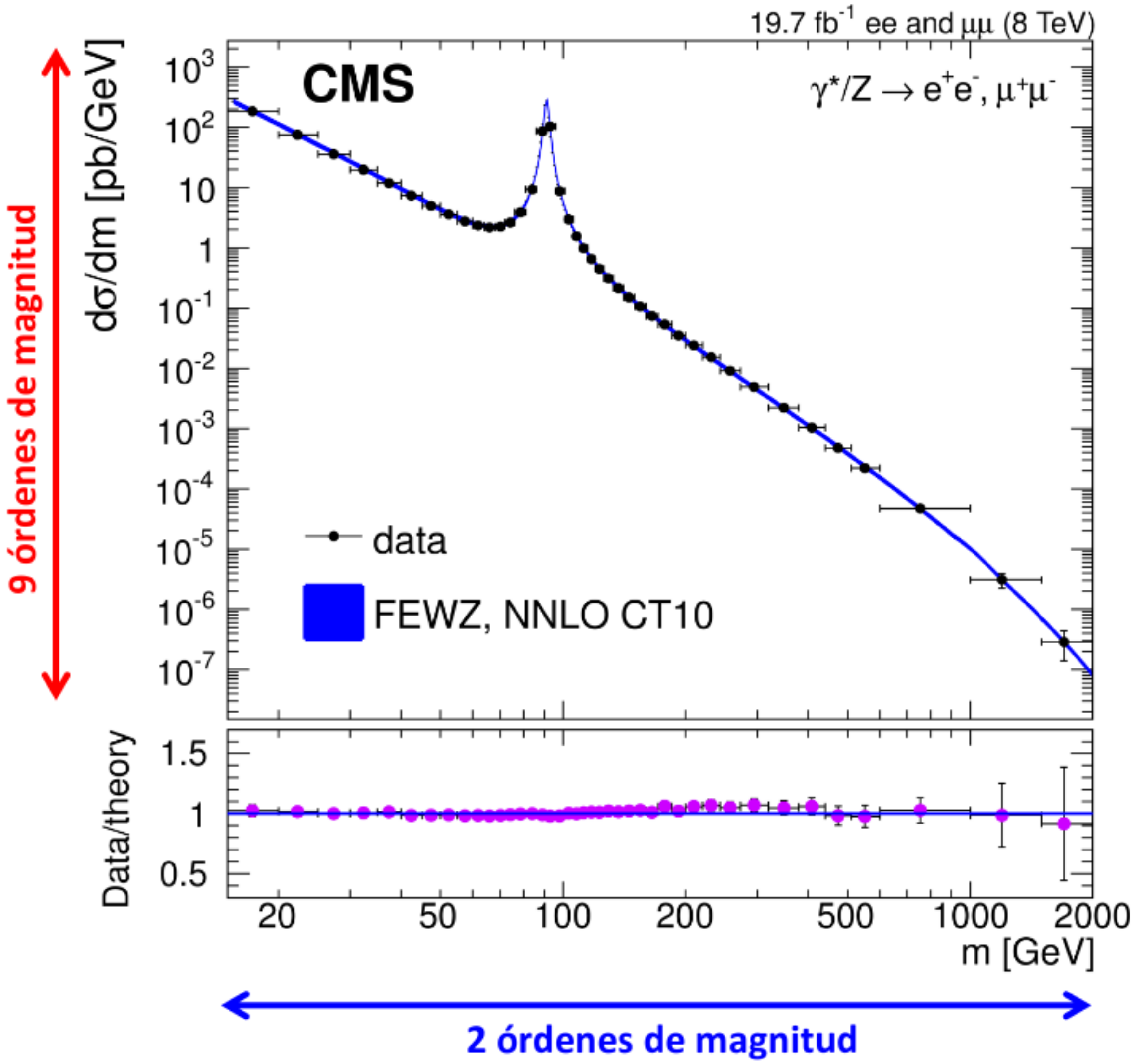
PRECISION PHYSICS WITH W AND Z

Cross Sections



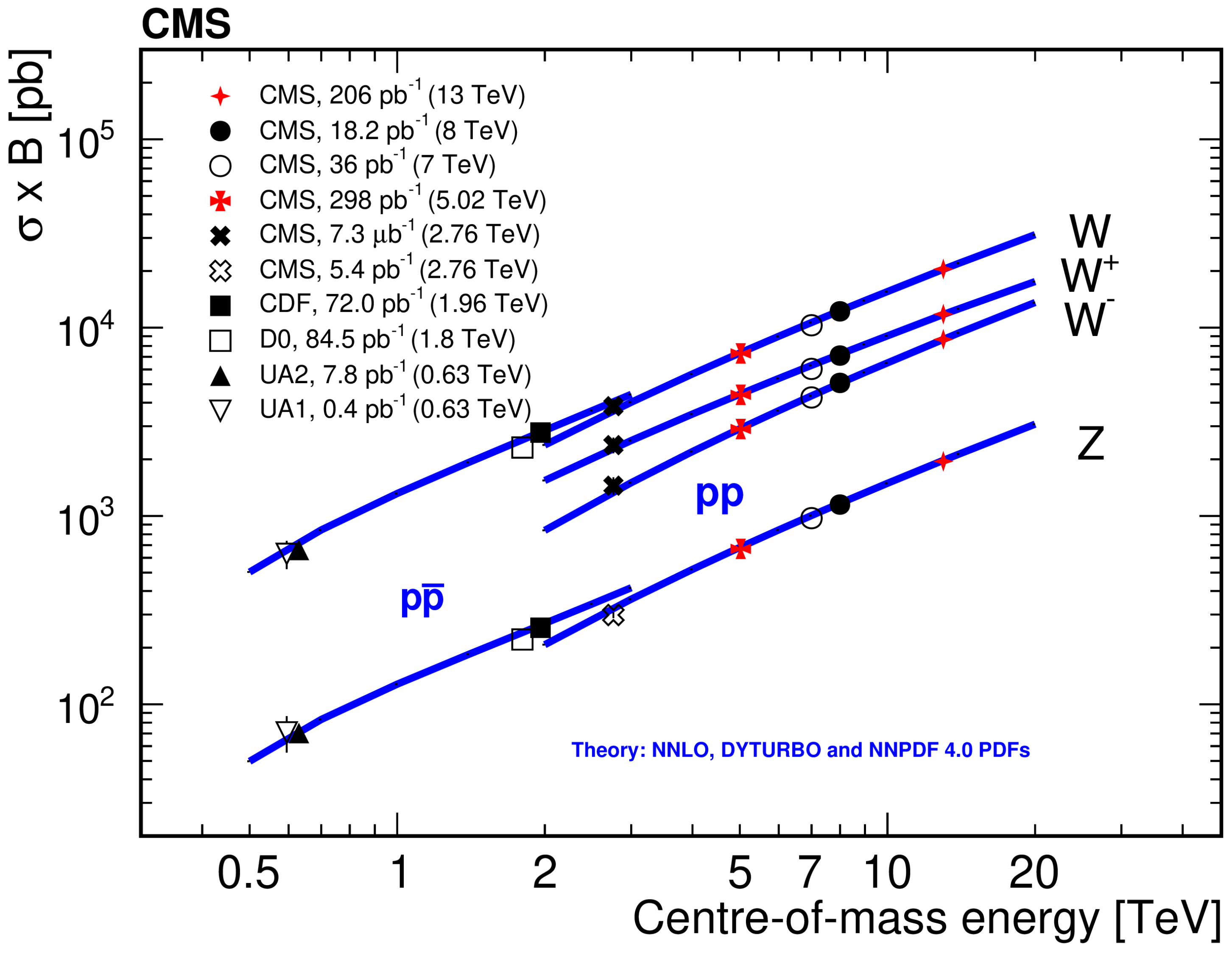


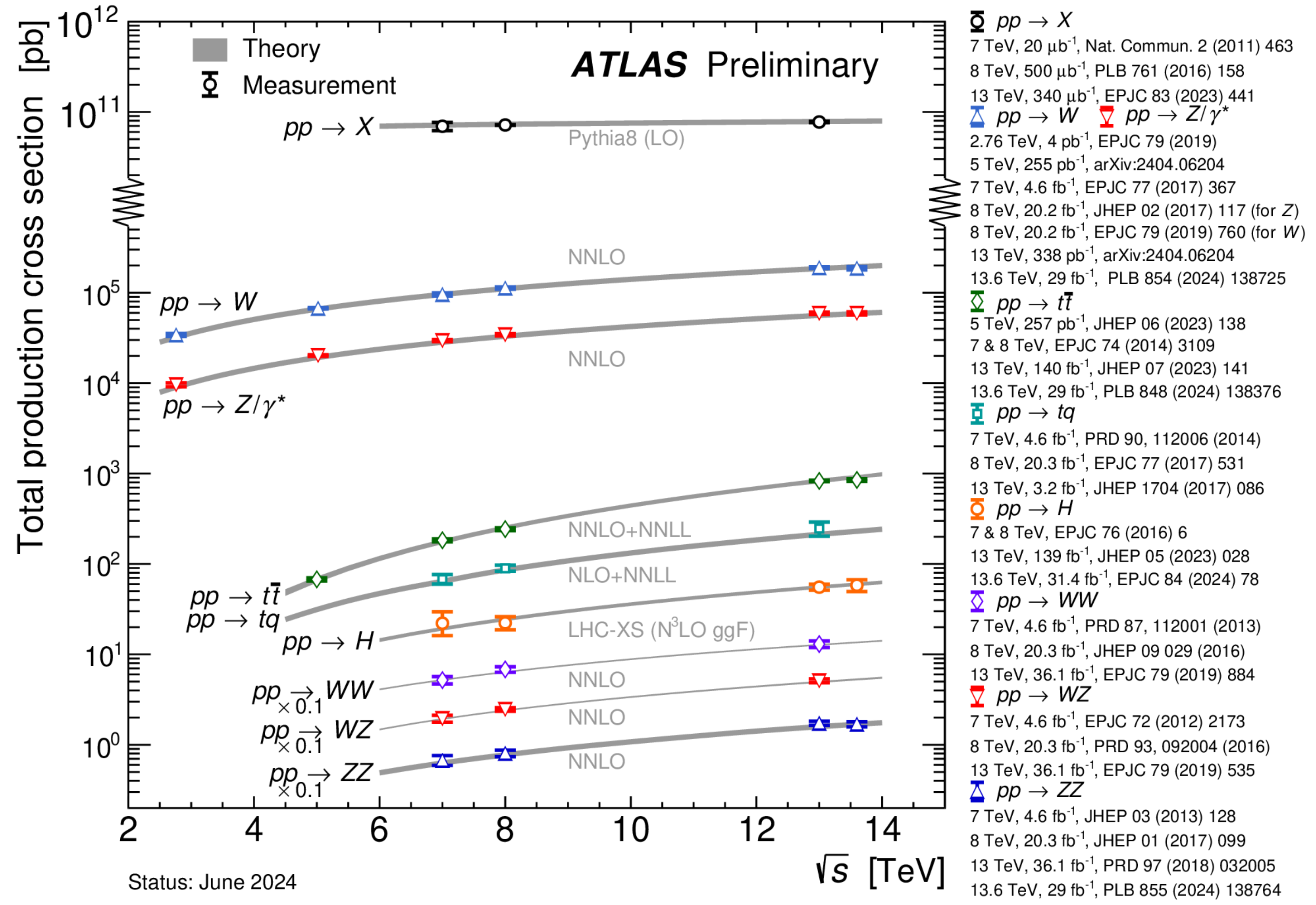
Differential Distributions



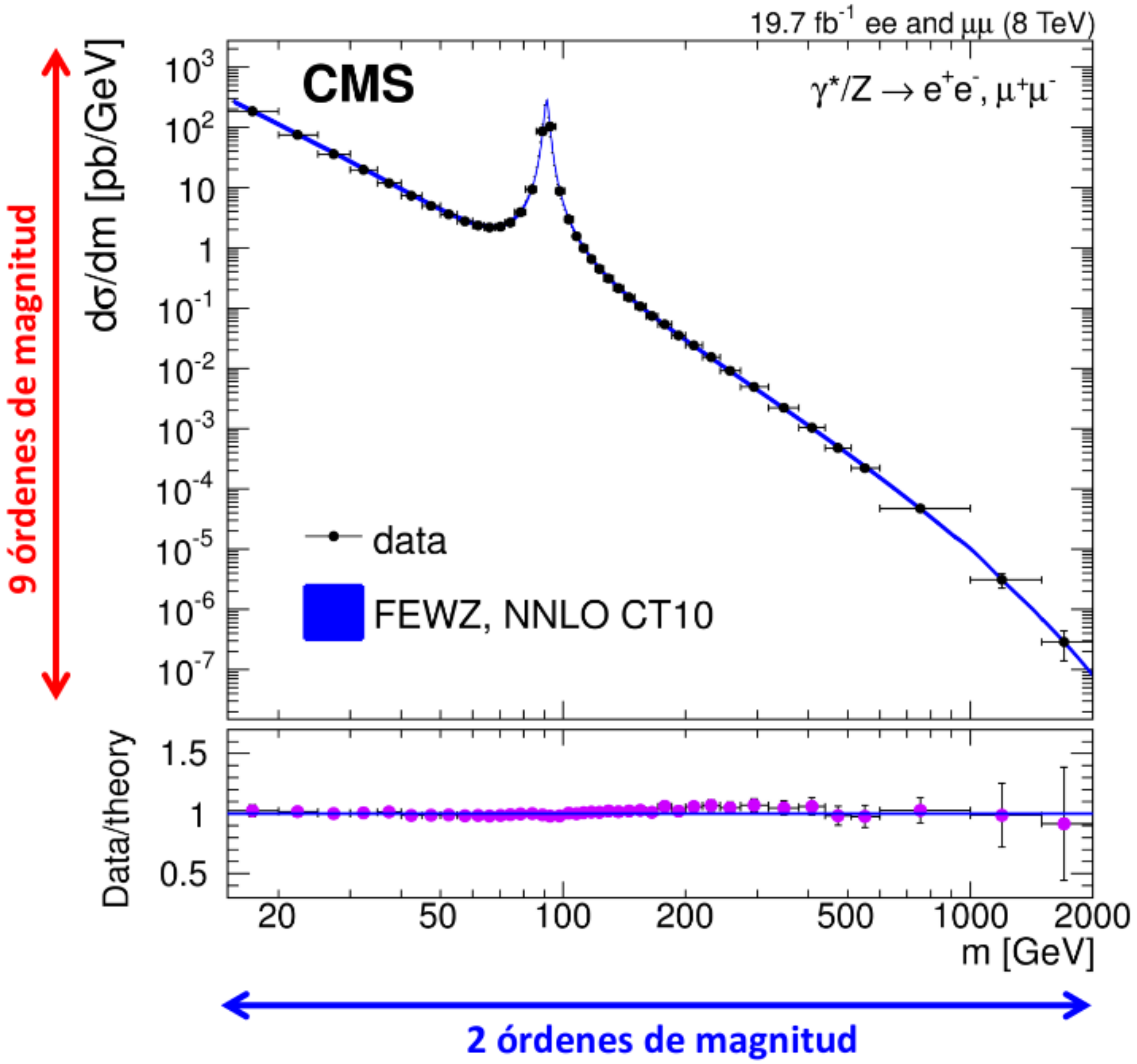
PRECISION PHYSICS WITH W AND Z

Cross Sections

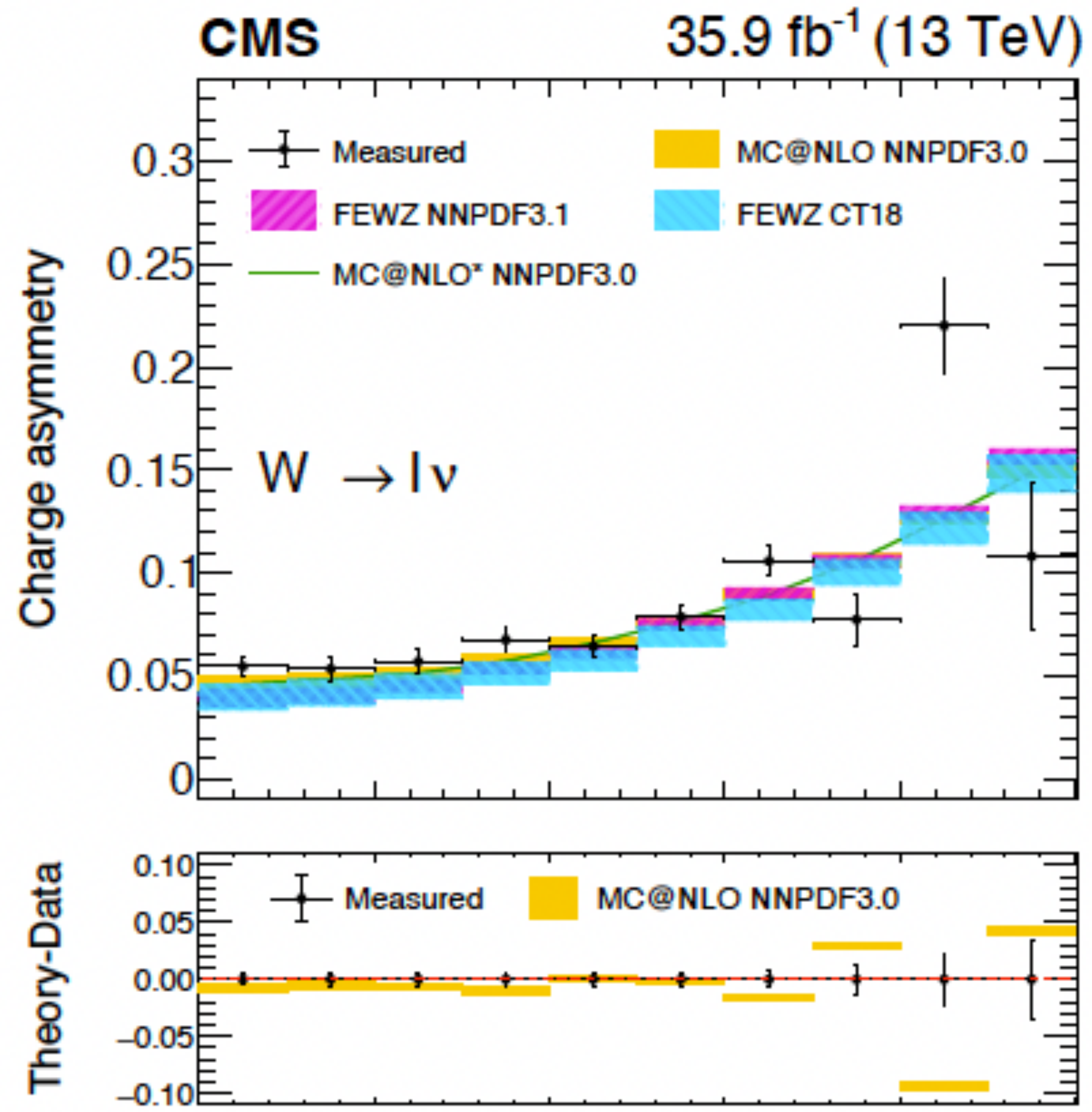




Differential Distributions

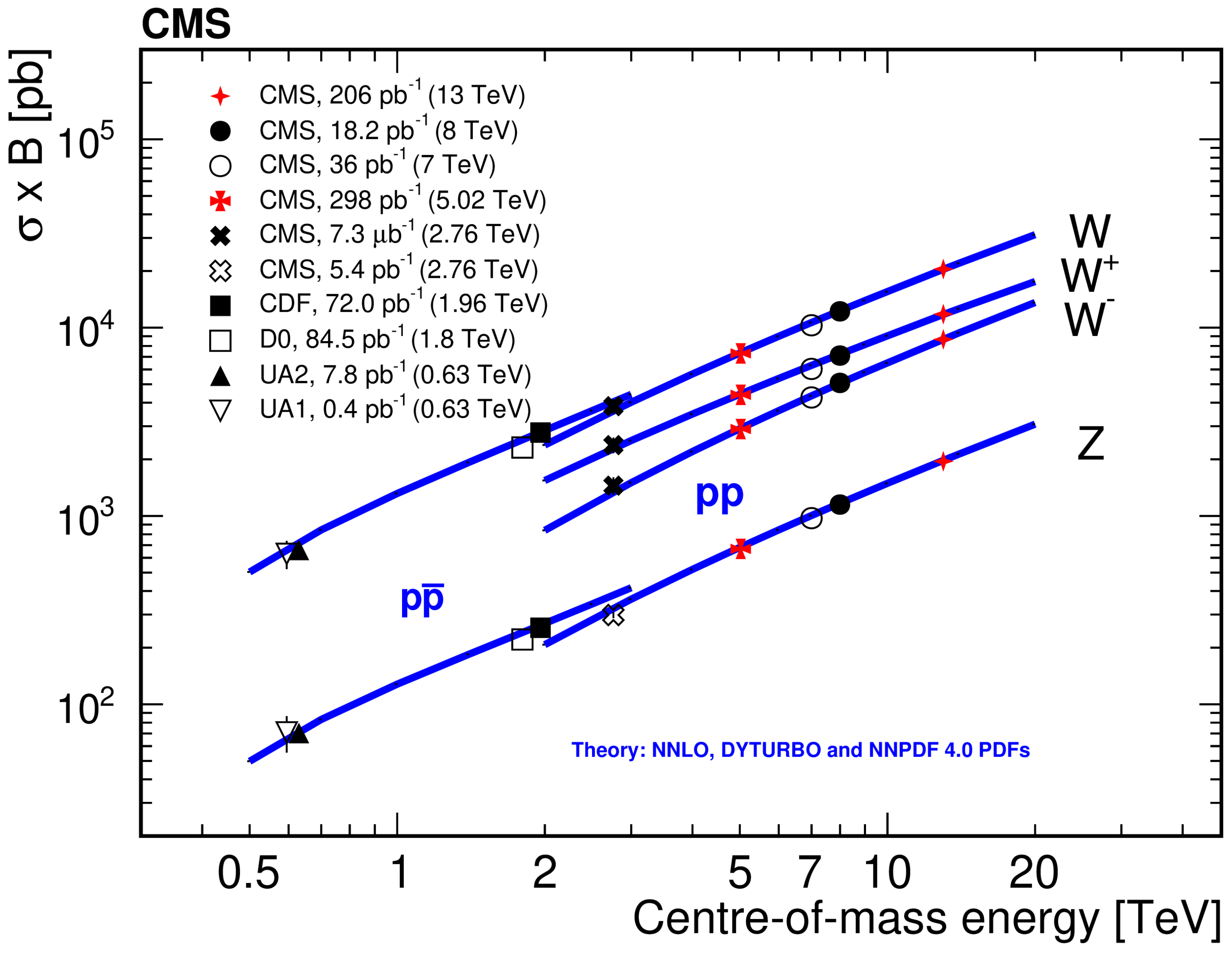


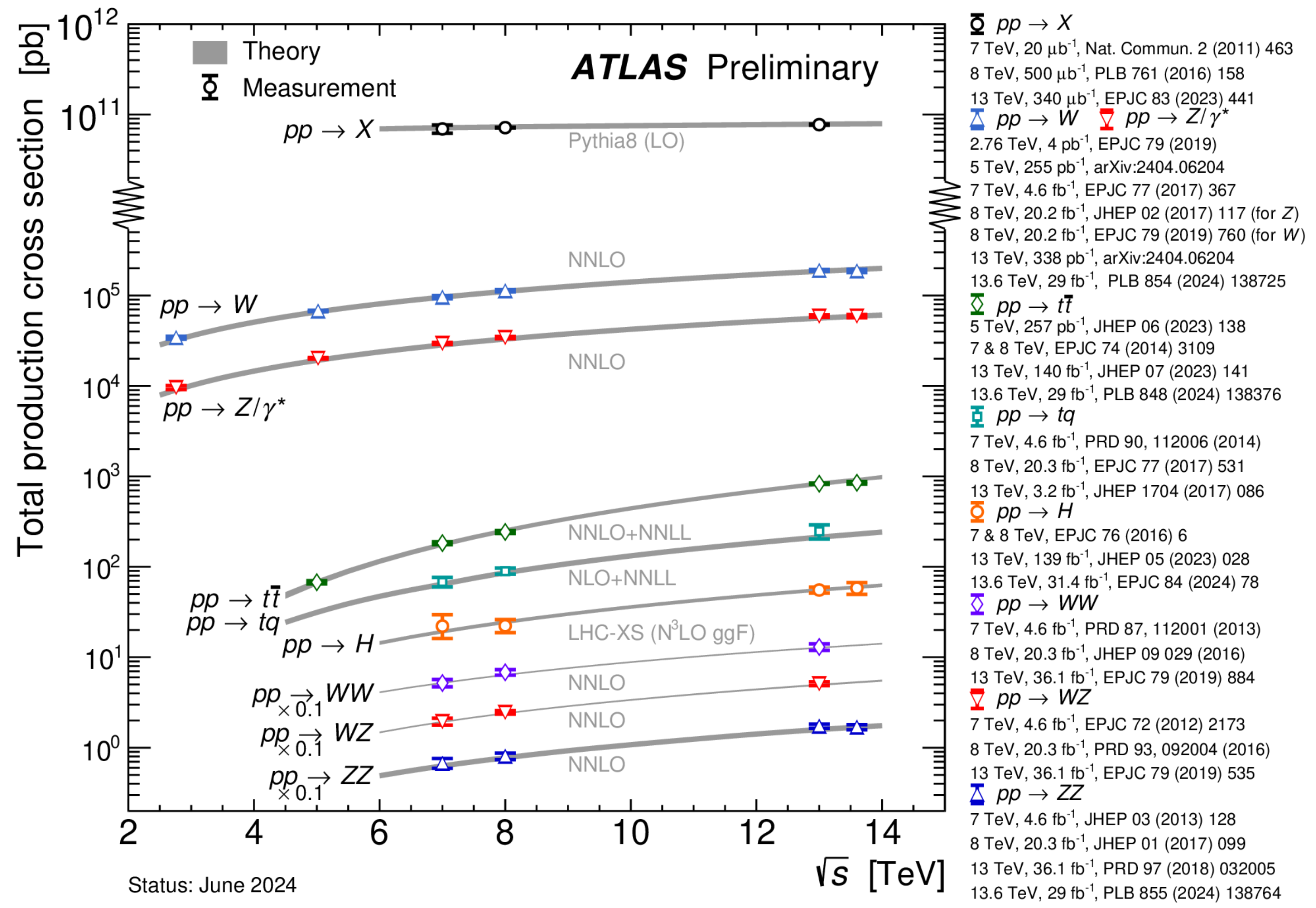
Assymetries:
Insight on PDFs from W+/W-



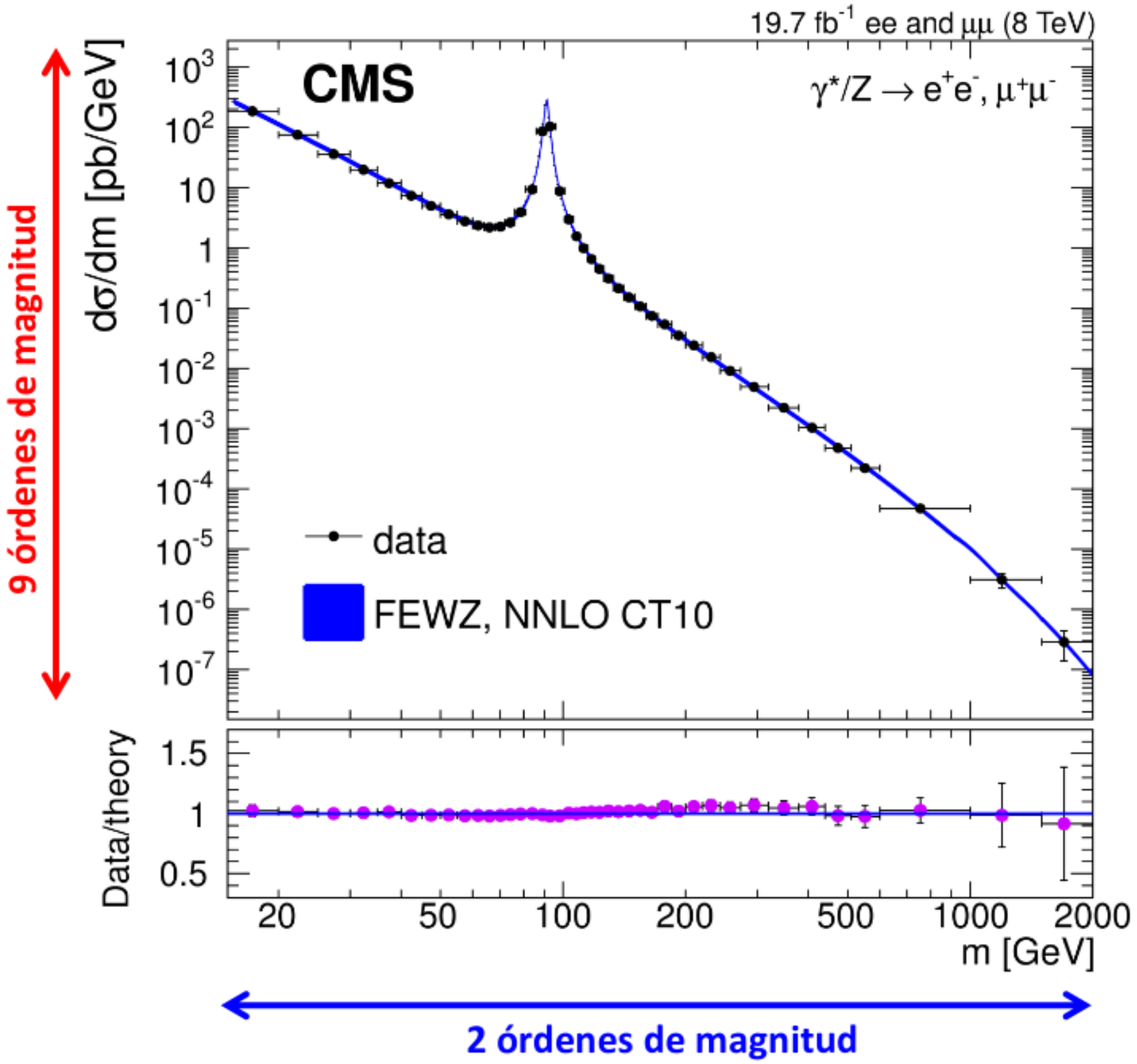
PRECISION PHYSICS WITH W AND Z

Cross Sections

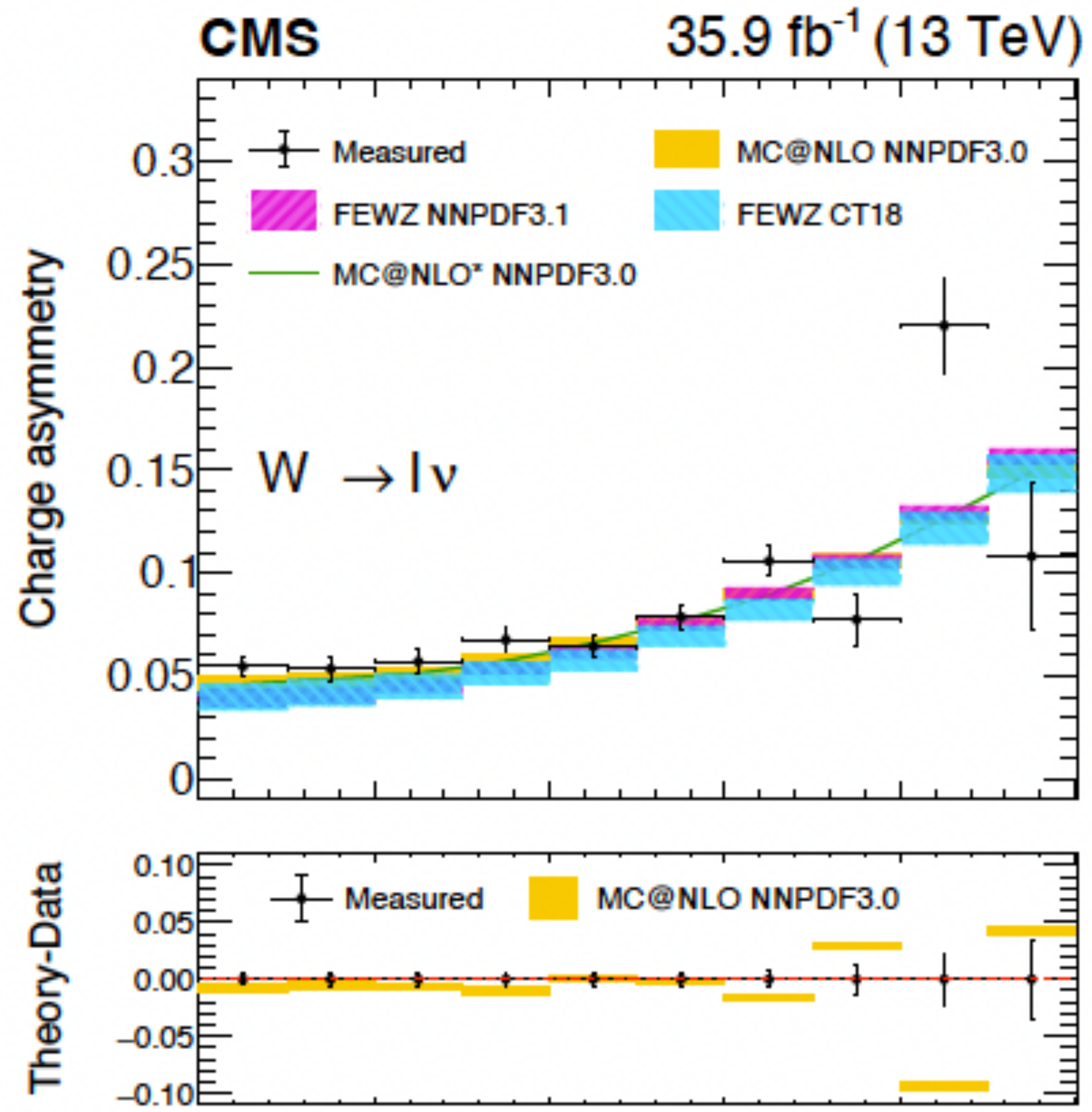




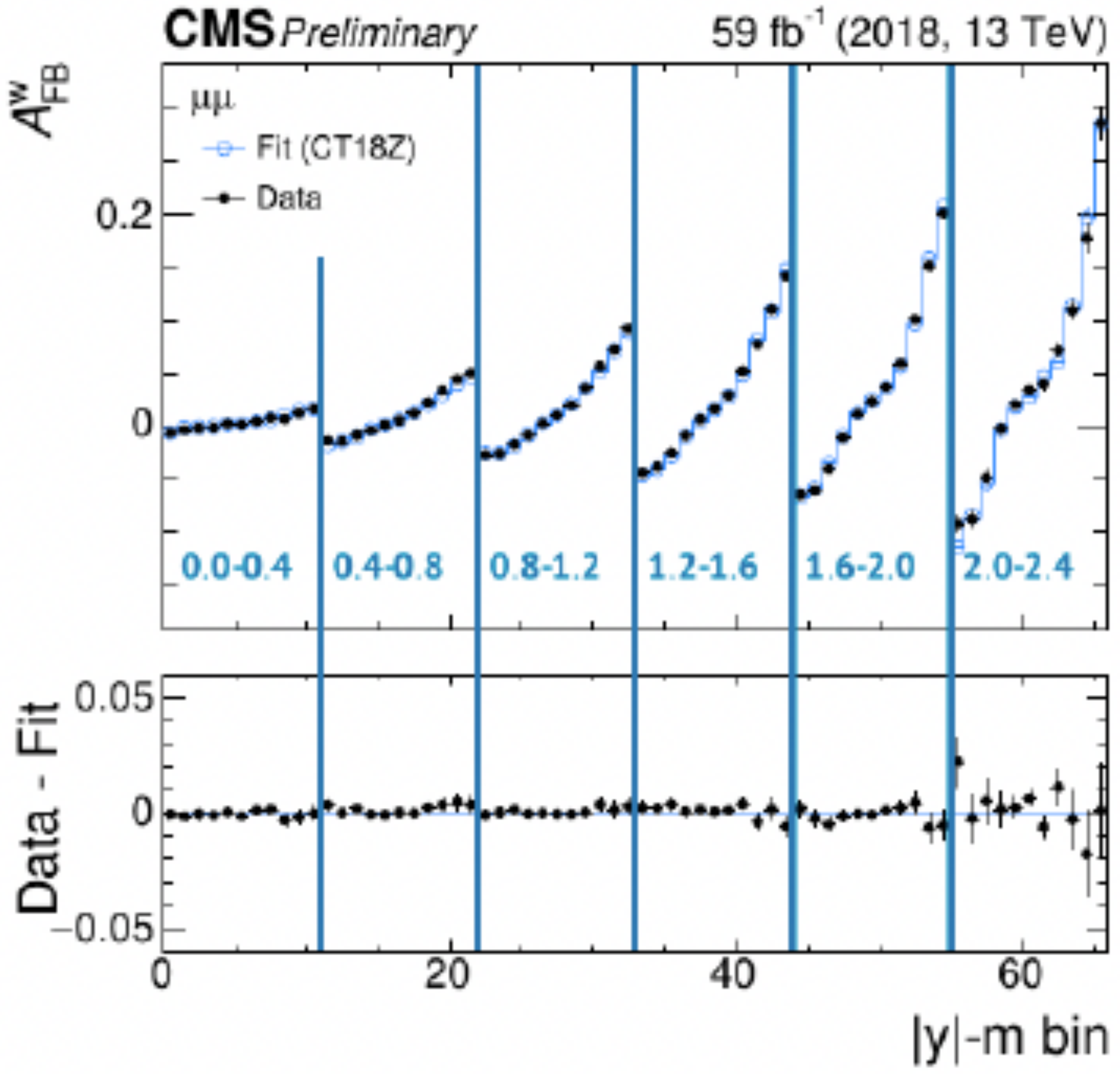
Differential Distributions



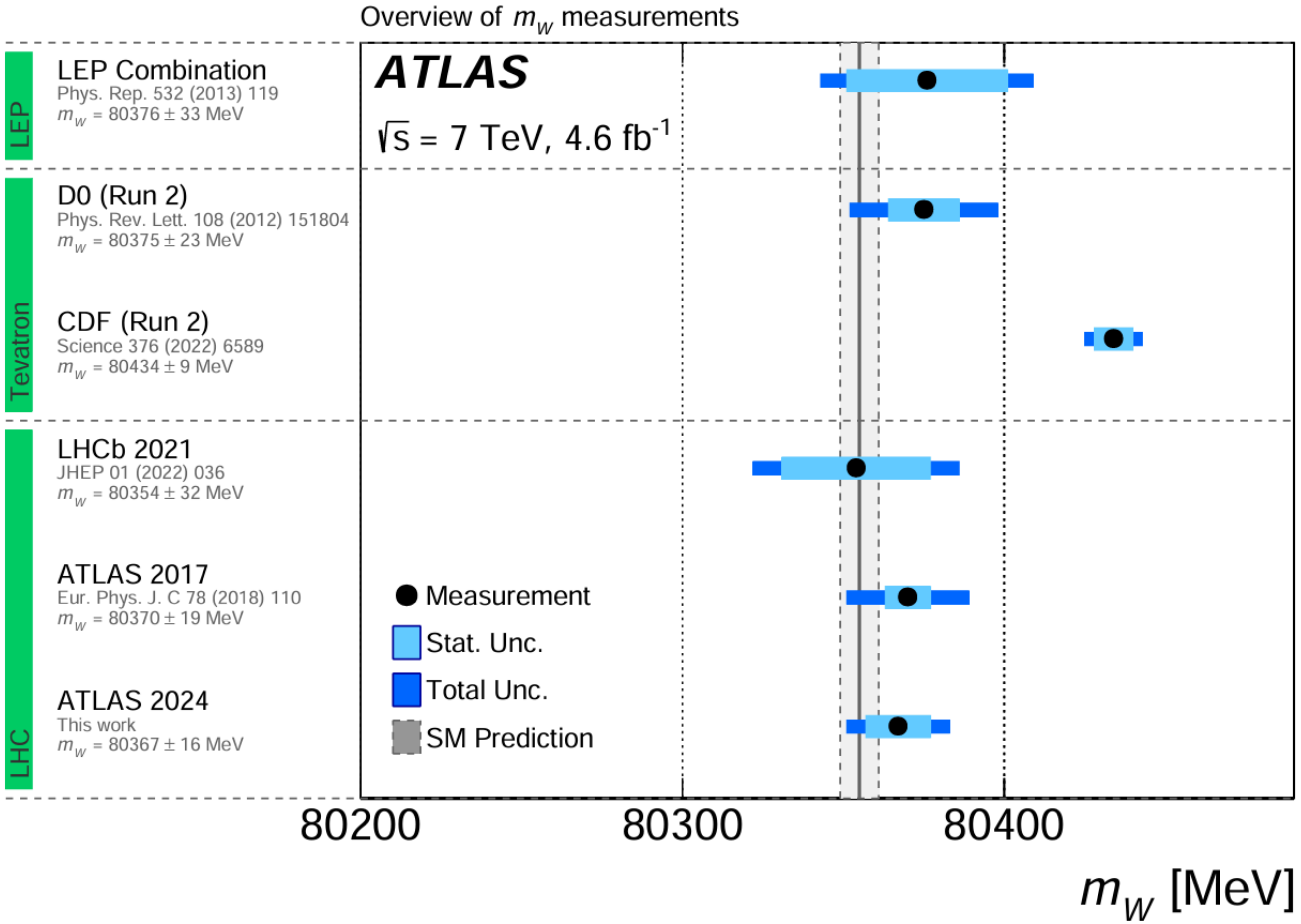
Assymetries: Insight on PDFs from W+/W-

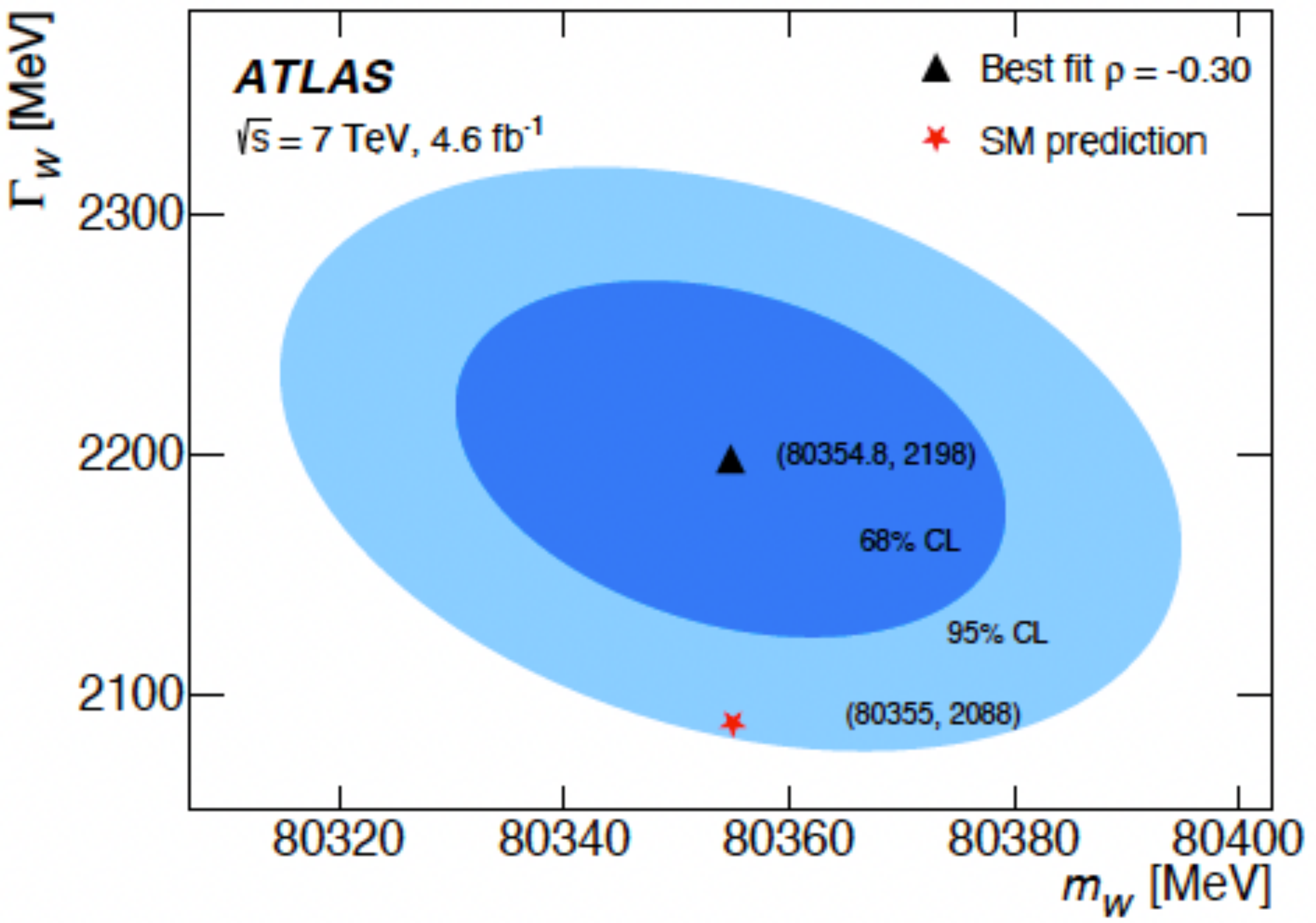


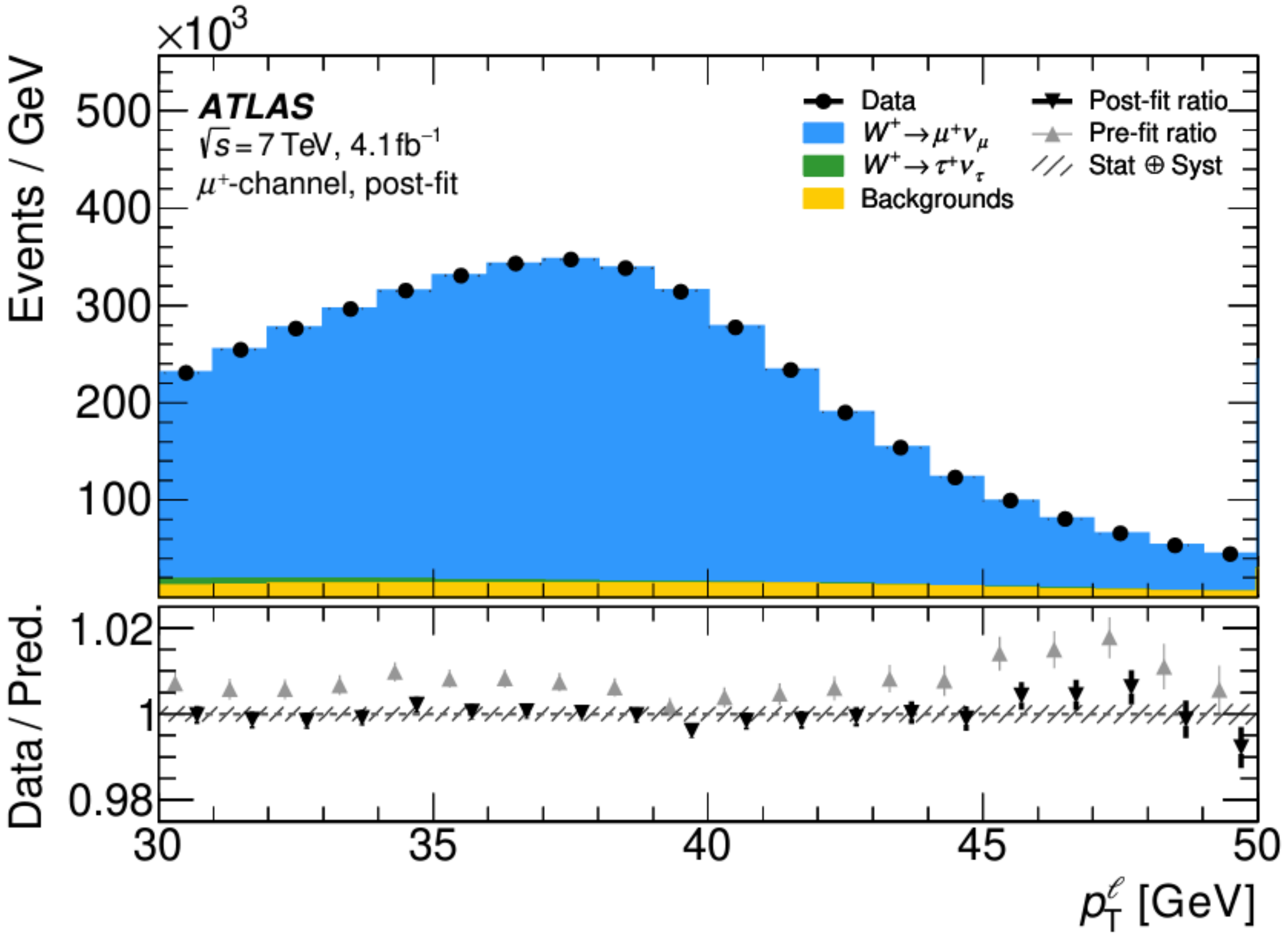
sin θeff from Forward-Backward in Z



W MASS AND WIDTH?



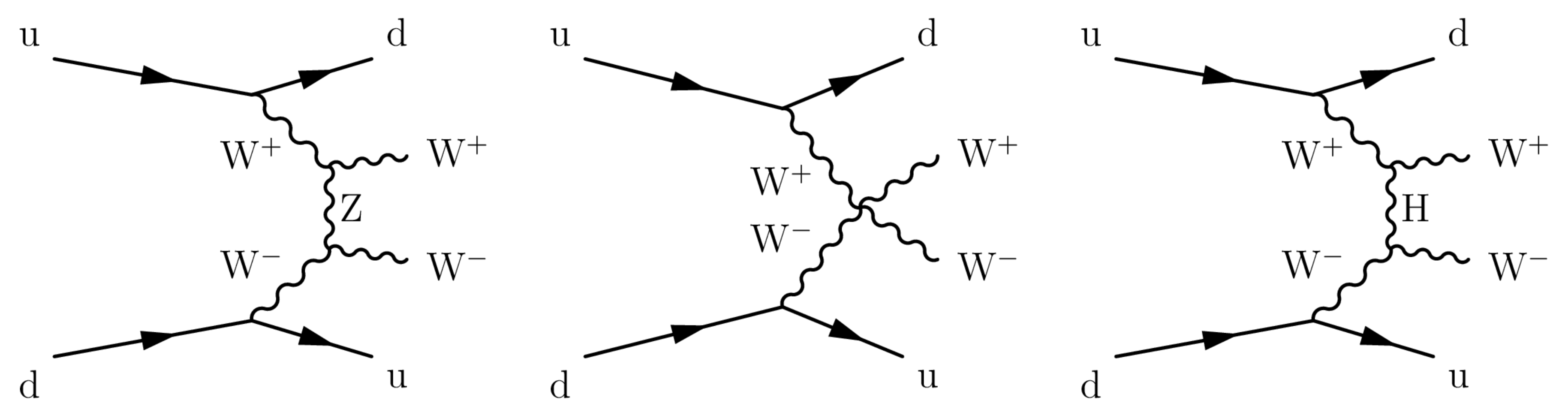


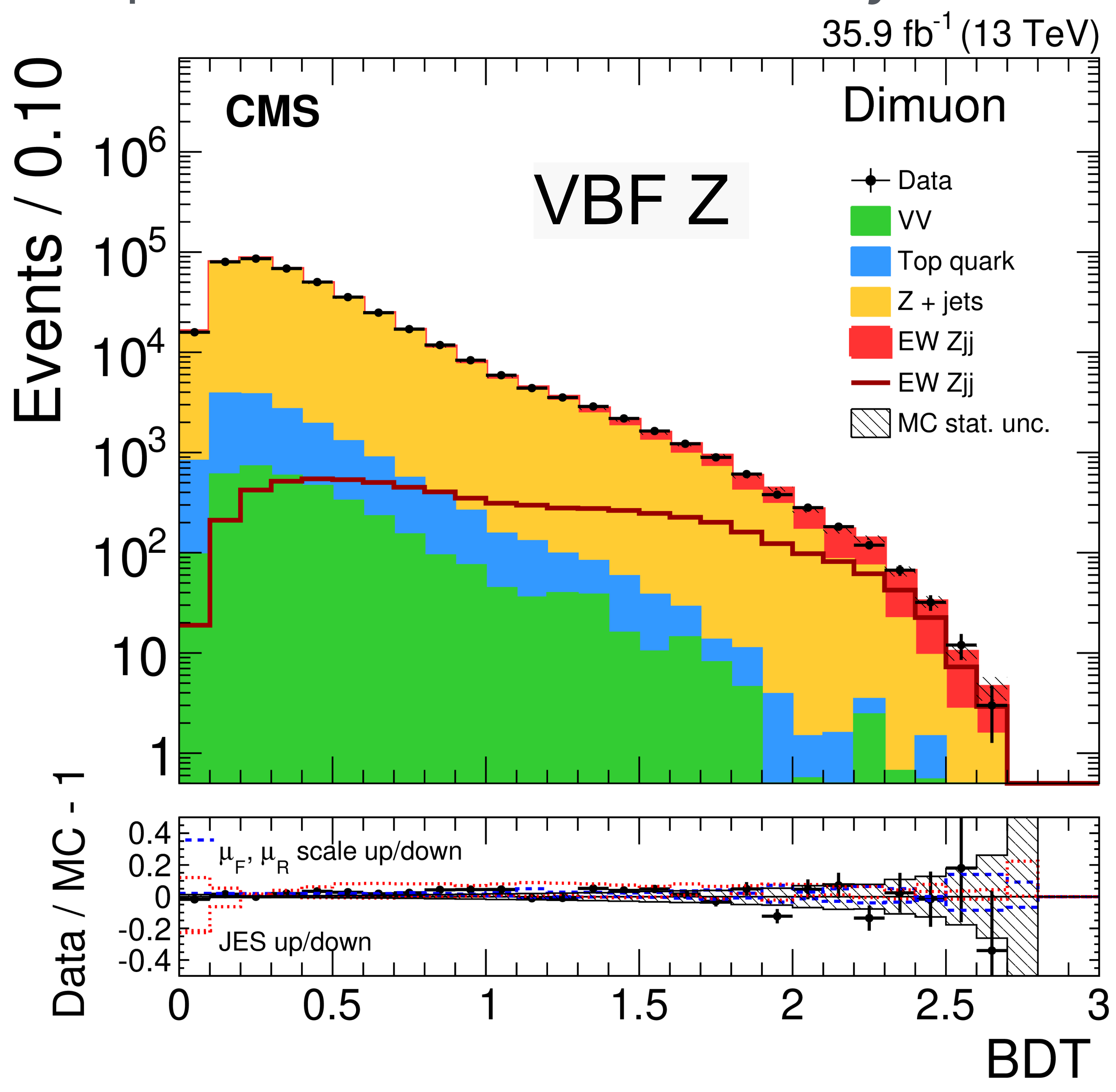


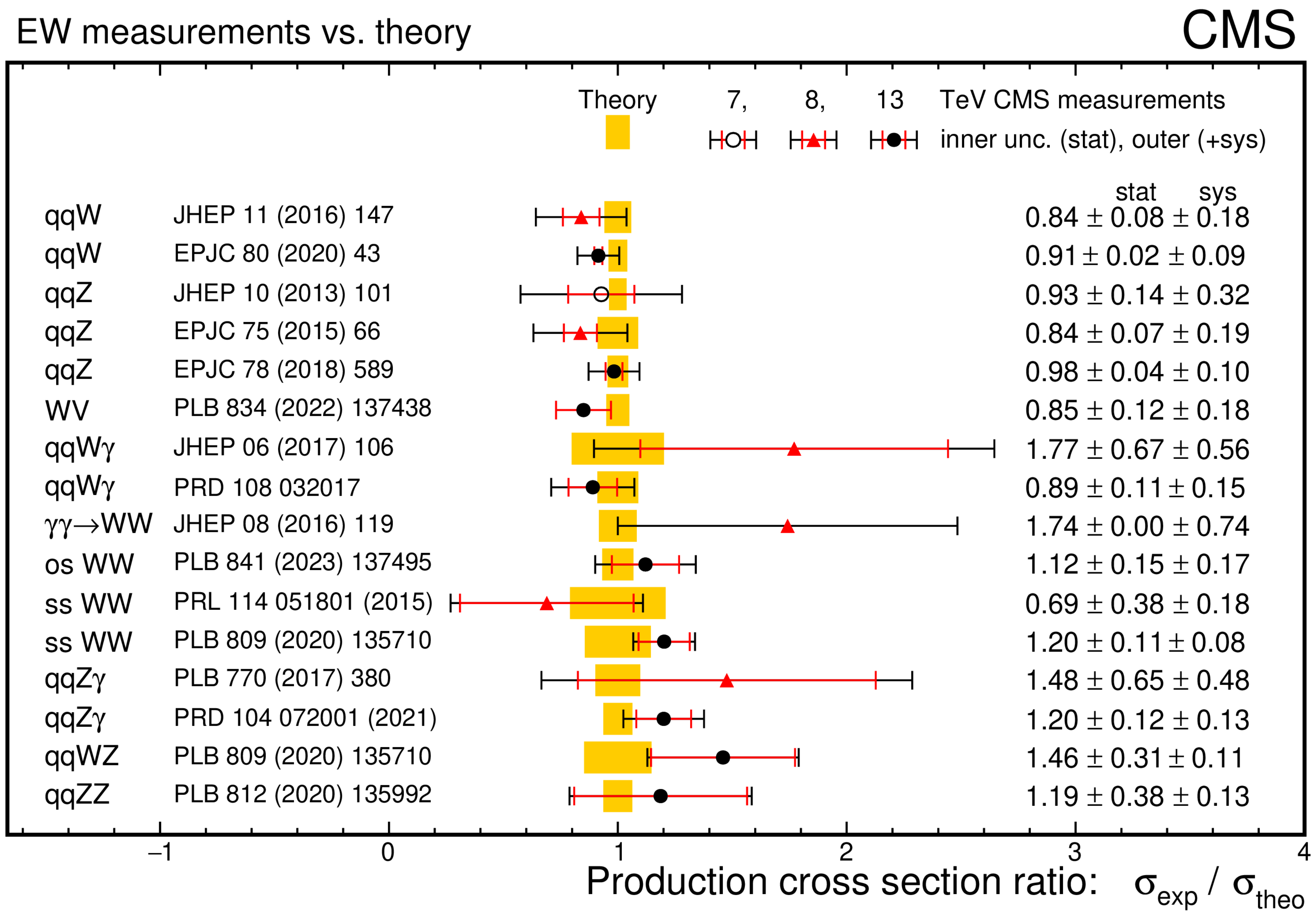
Even years after discovery, properly understanding the properties of Ws and Zs is an ongoing effort: fundamental for the SM
Note how the small the uncertainties need to be! High precision required: very thorough understanding of uncertainties (eg: momentum scale and PDFs) a must

RARE PROCESSES: VECTOR BOSON SCATTERING

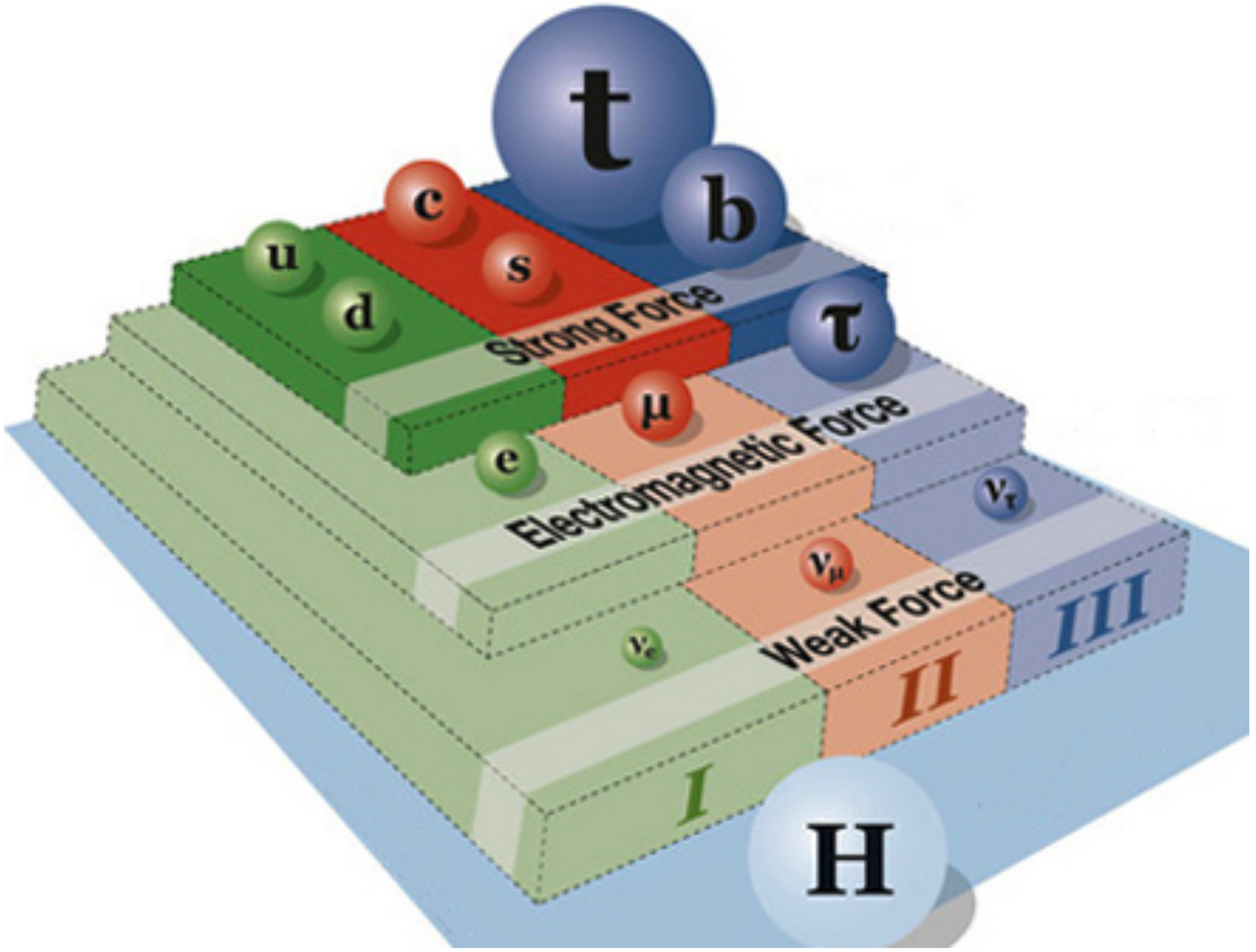
- The LHC experiments explore production beyond the basics: V+Jets, V+HF, Di and Triboson production…
- And ElectroWeak Production:
  - Bosons are radiated off incoming quarks and either fuse to a single boson (VBF) or scatter to pairs of bosons (VBS) : essential test of the EW sector of the SM. Probe of TGCs
  - Rare processes: statistics is key





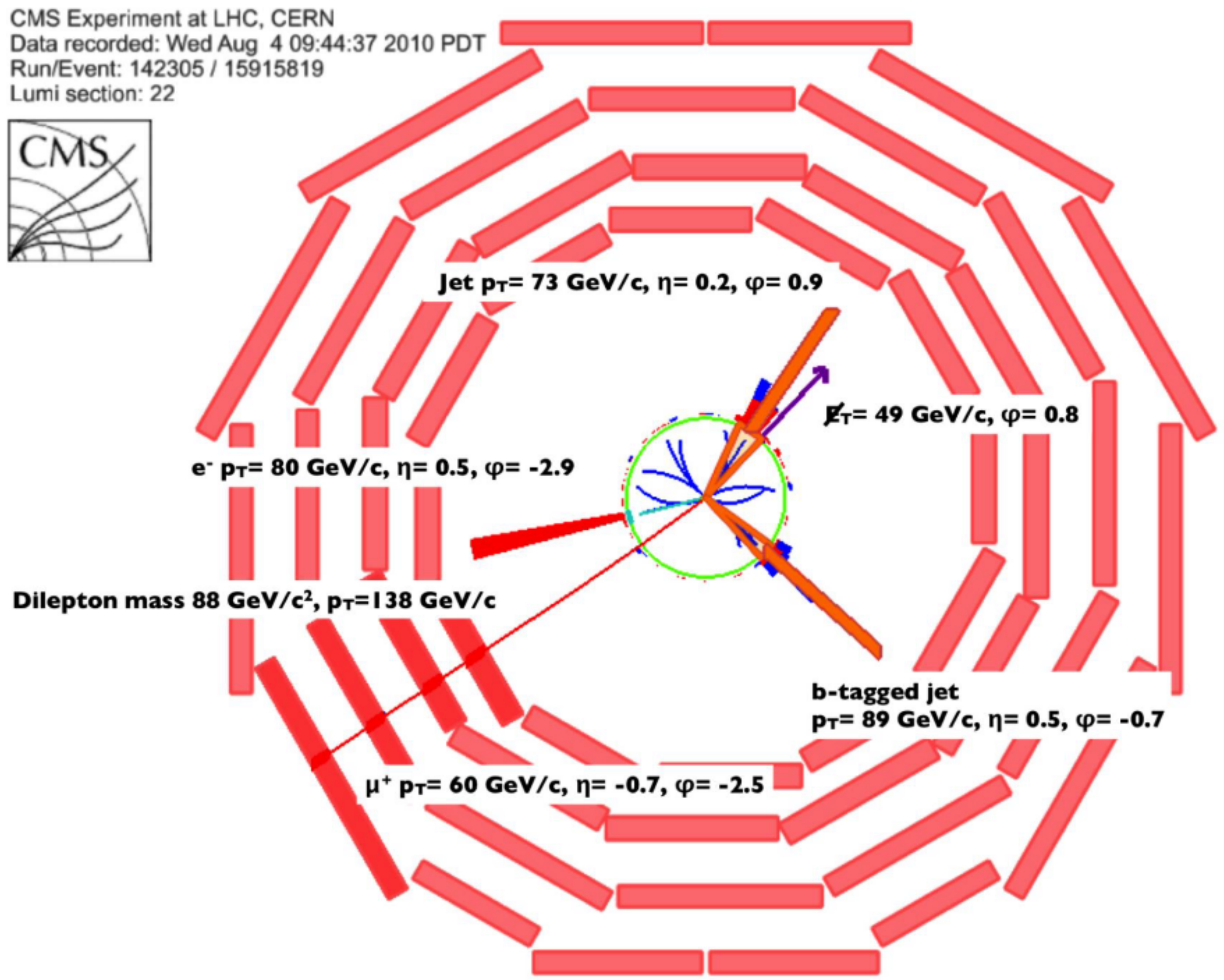


TOP QUARK PHYSICS



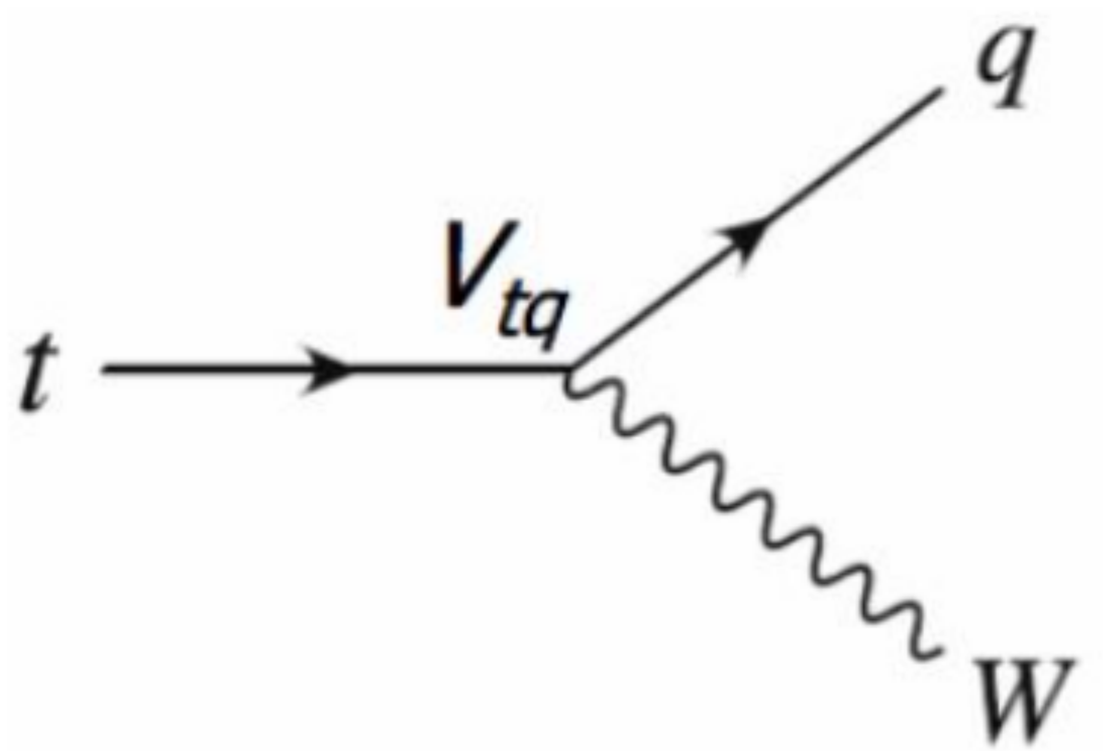
The most massive elementary particle ever discovered: this makes it a very special quark with an extensive study programme dedicated to understanding its characteristics

It is the only quark that we can observe directly (it decays before having hadronisation, fully dominated by t→Wb)



Test of QCD

Gateway to new physics?

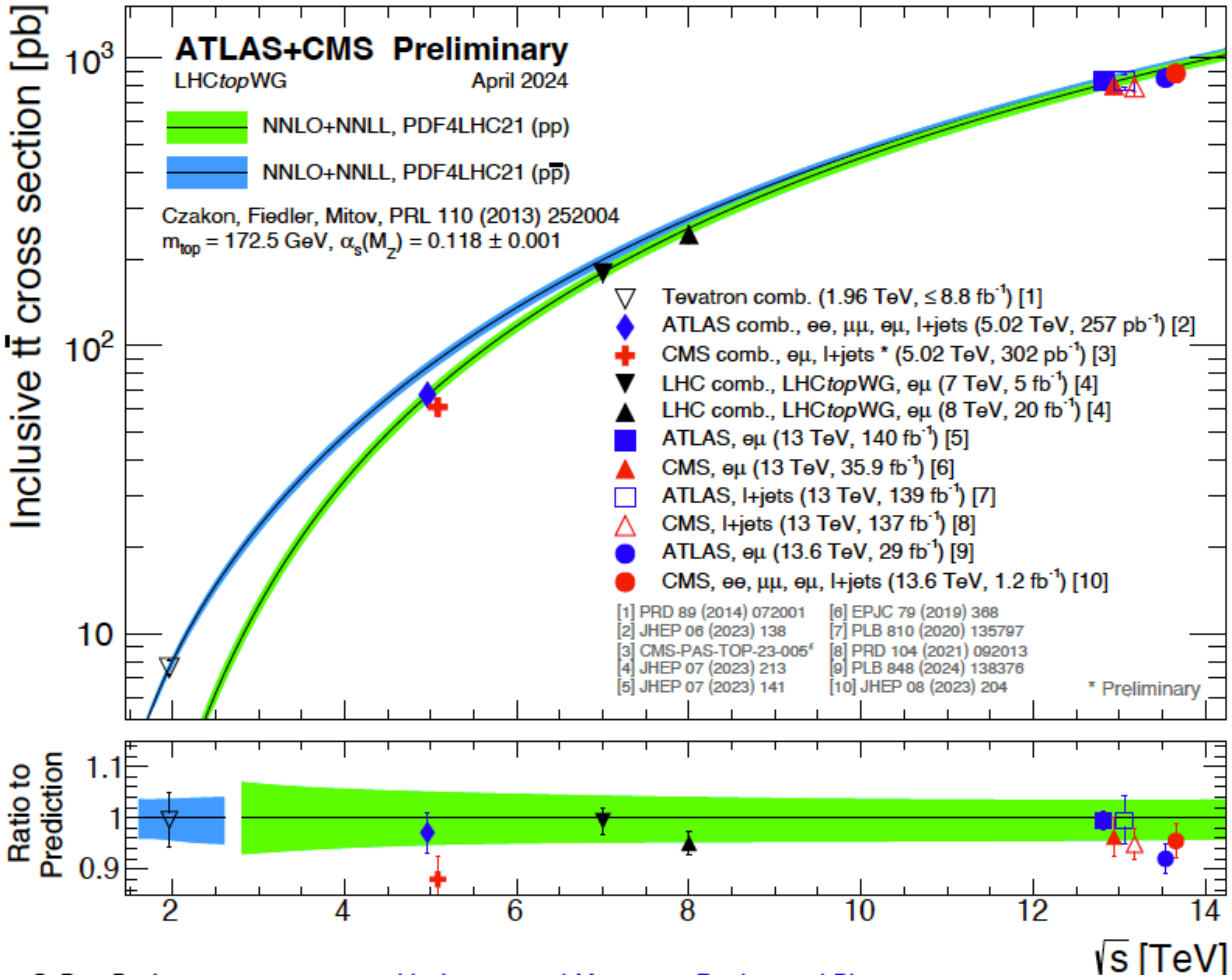


The LHC is a 'Top Factory'

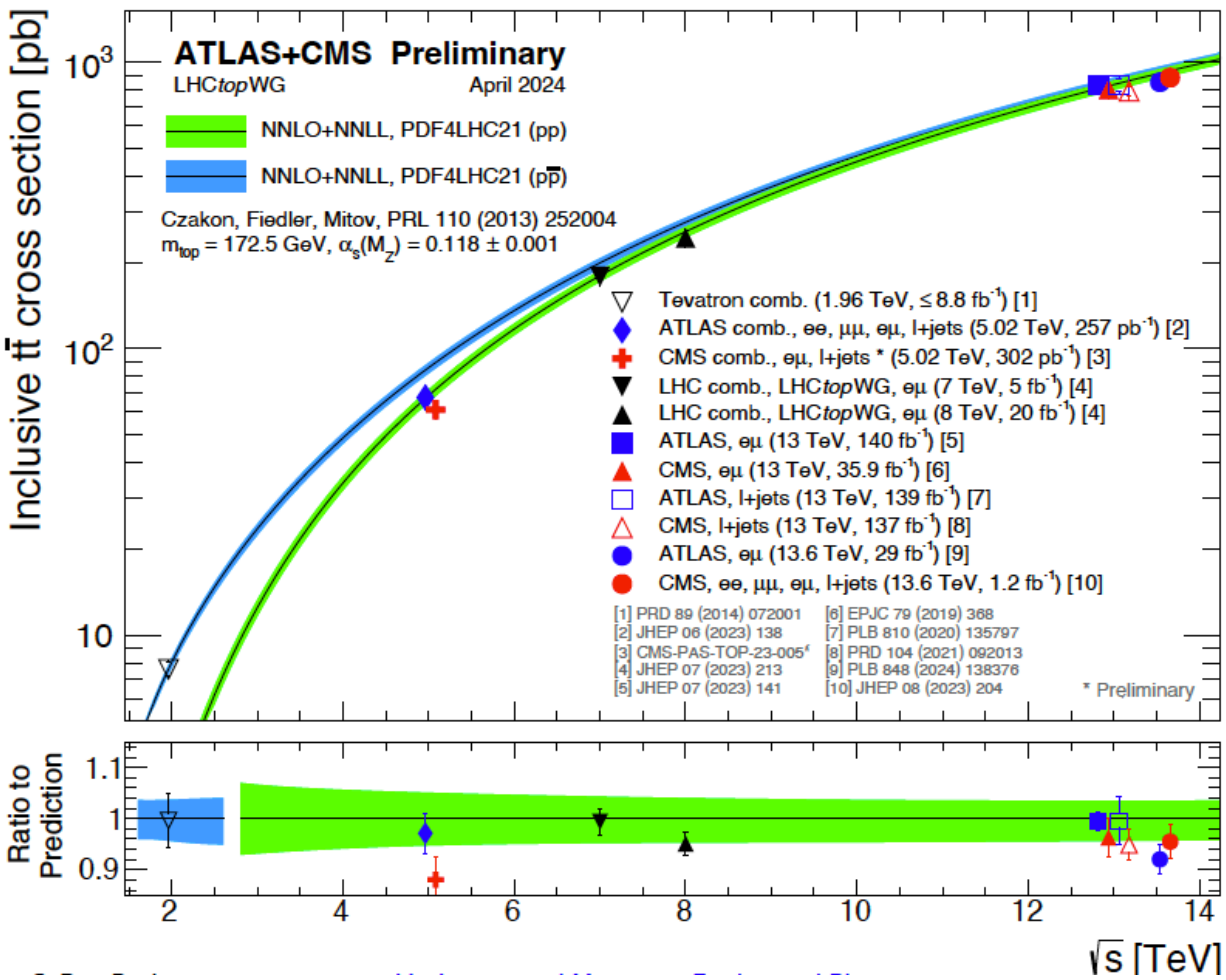
WHAT CAN WE LEARN FROM THE TOP?

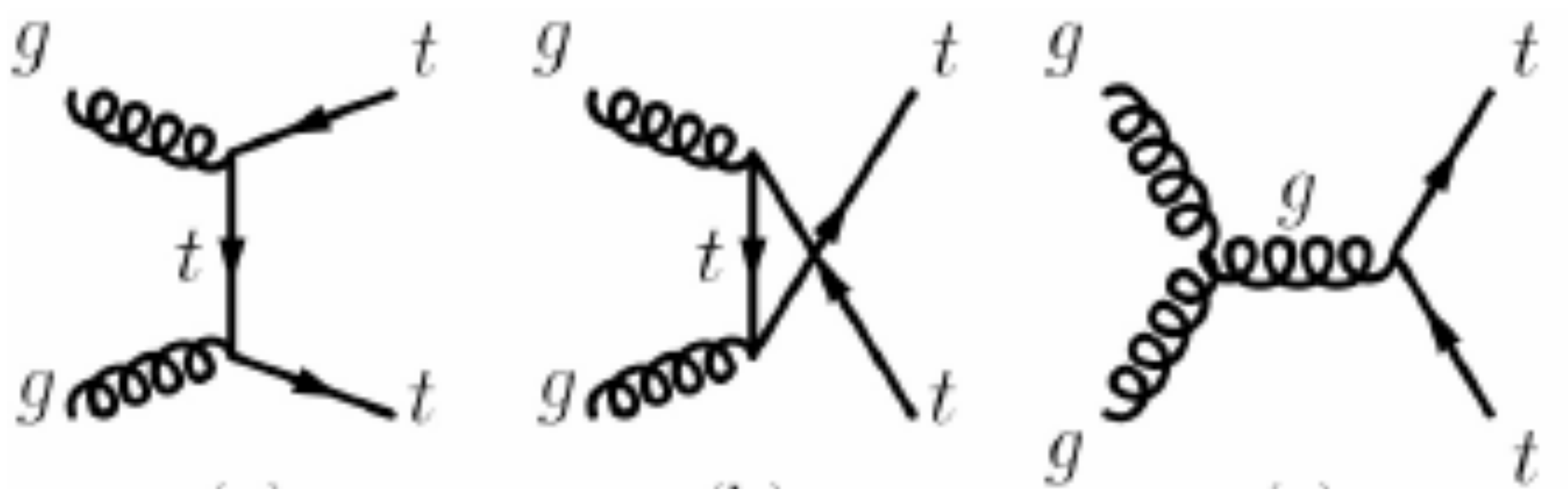
- Probe structure the standard model through the measurement of intrinsic properties of the top: any deviation would be a hint of new physics Top mass, top width
  - Differential analysis
  - $qq \rightarrow tt$ forward-backward asymmetries (very small in the SM)
  - Top polarization (SM expectations: 0 in tt, very large in single-top production)
  - Spin correlations between top and antitop in top-pair events: sign of any additional contributions beyond the SM ?
  - Wtb vertex structure: any anomalies ?
  - Associated production: $tt+\gamma$, $tt+Z$, tttt, ttbb, … → background to many new physics searches, sensitive to new physics by themselves
  - Rare decays: Flavor Changing Neutral Currents (FCNC), which are extremely suppressed in the SM ($t \rightarrow Z+c$, $t \rightarrow Z+u$, $t \rightarrow \gamma+c$, $t \rightarrow \gamma+u$, …), …

TOP PAIR PRODUCTION (TTBAR)

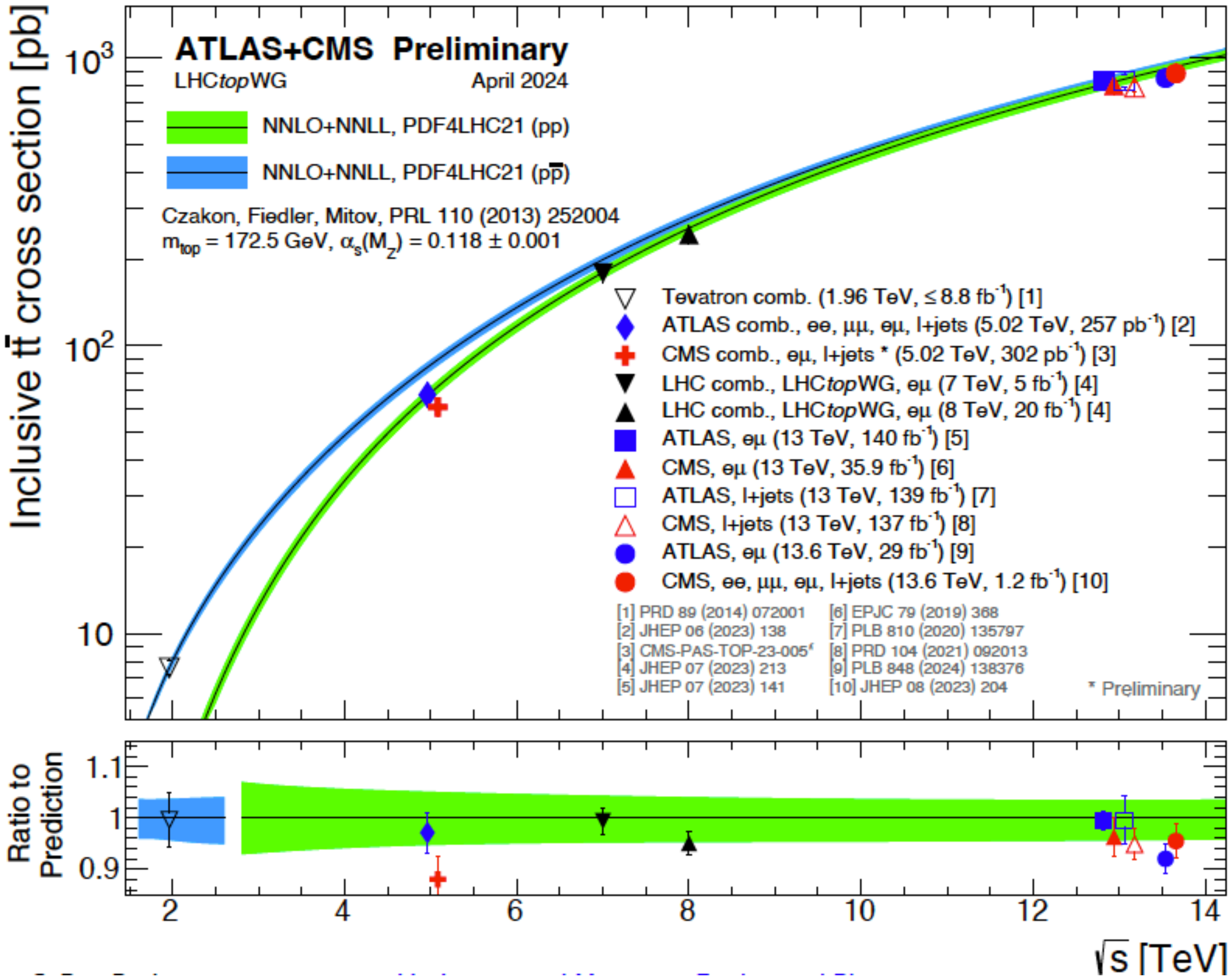


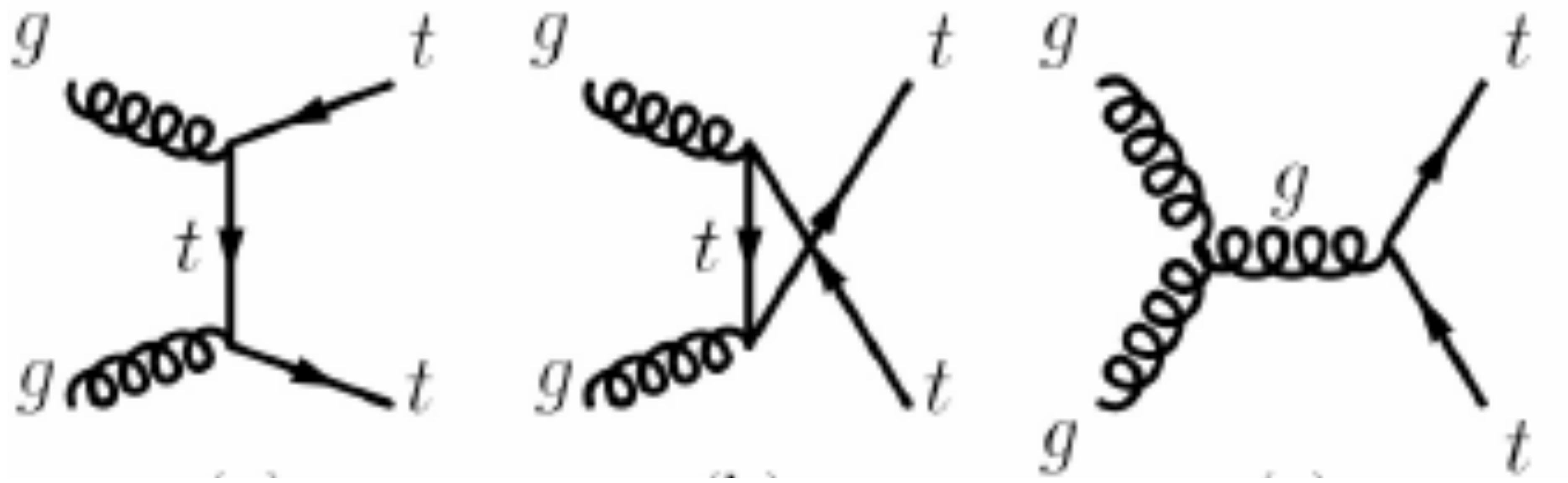
TOP PAIR PRODUCTION (TTBAR)

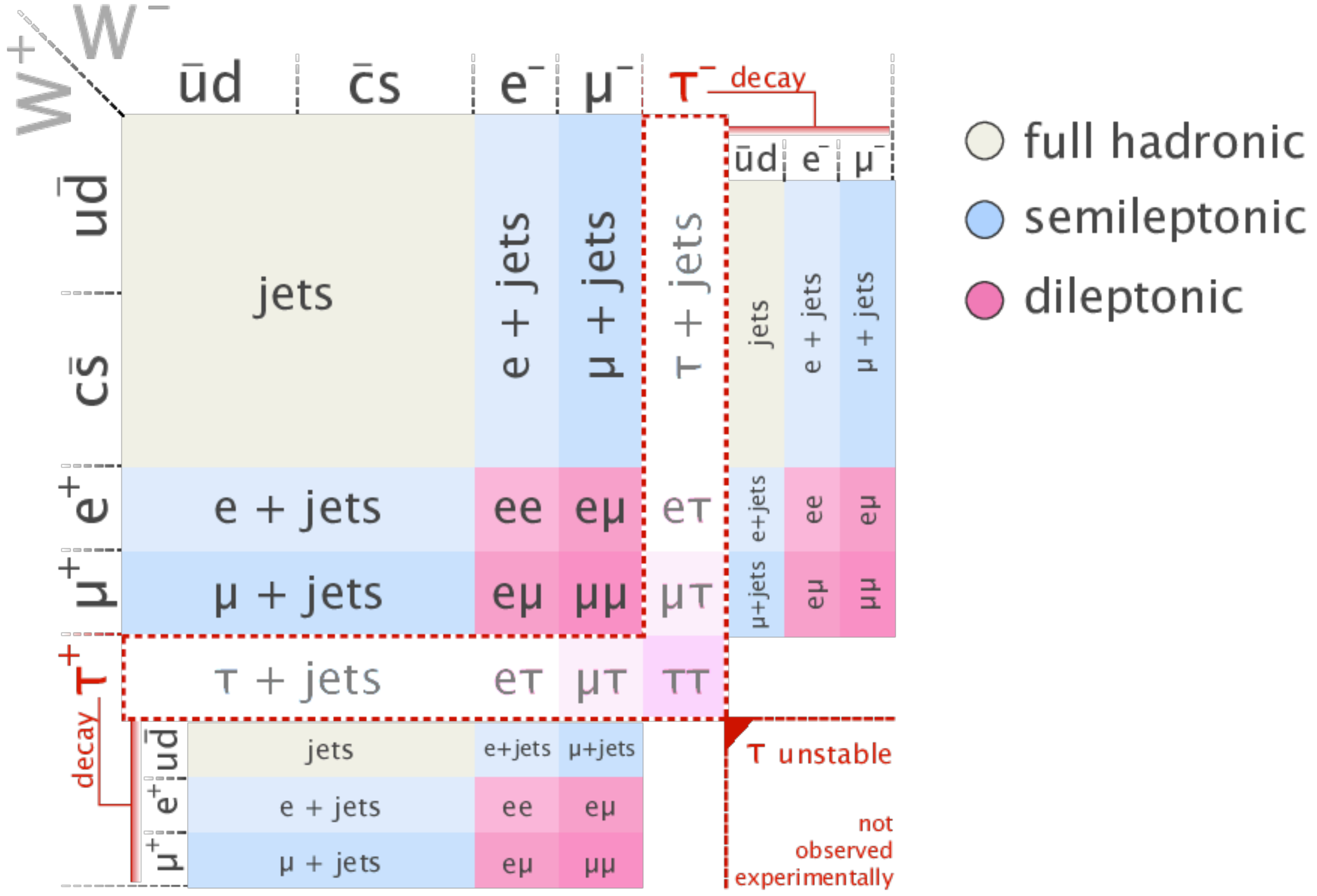




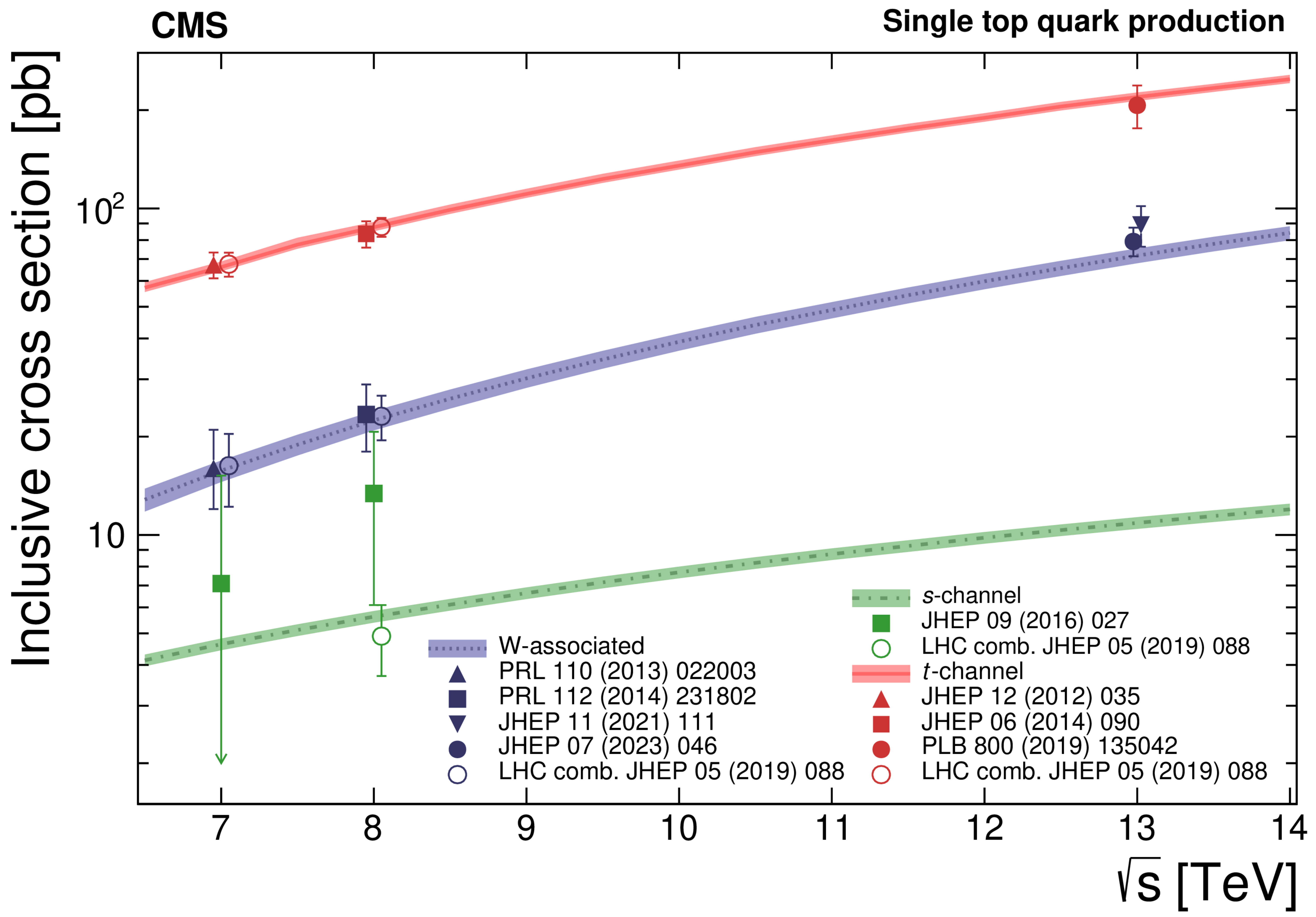
TOP PAIR PRODUCTION (TTBAR)

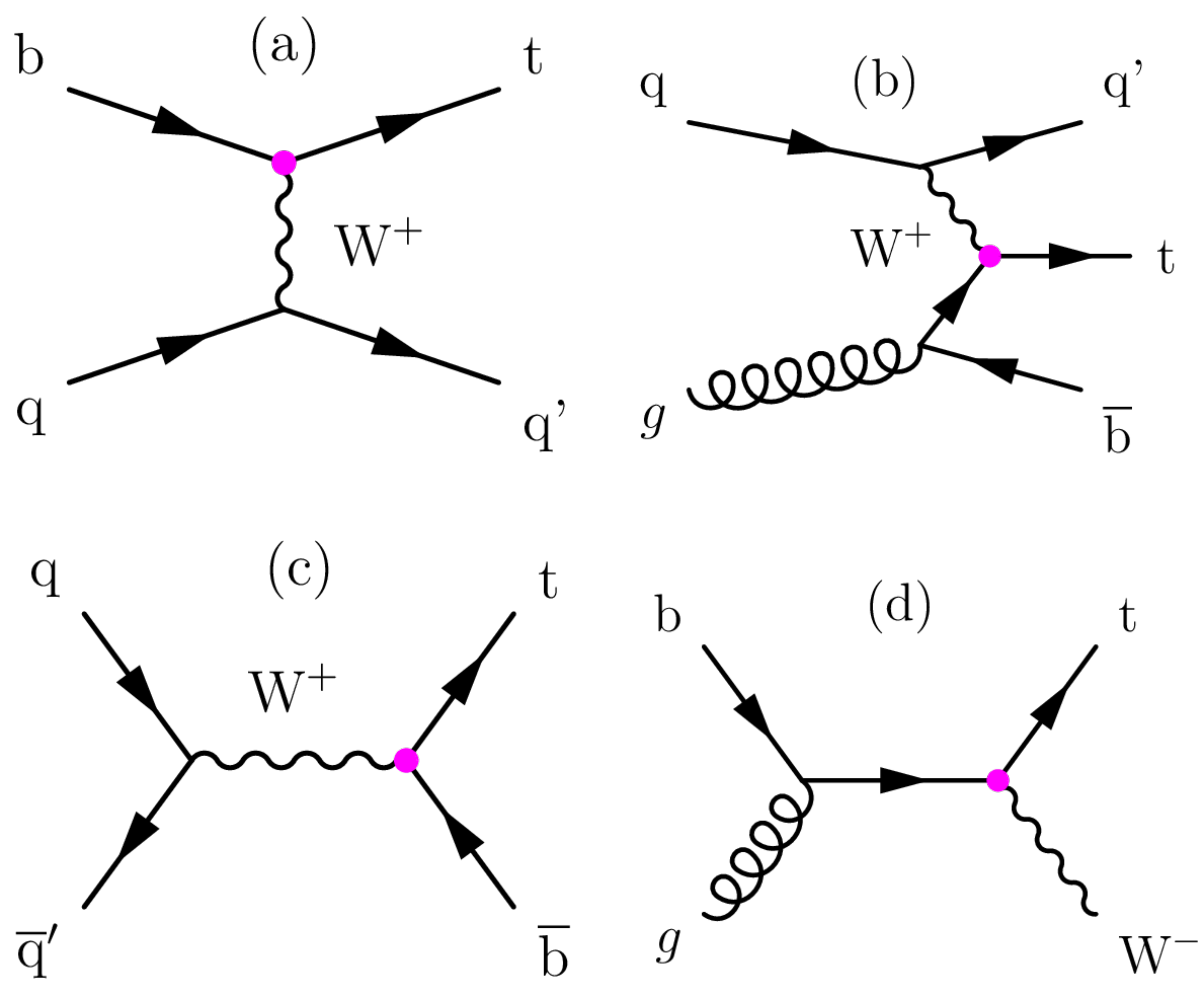




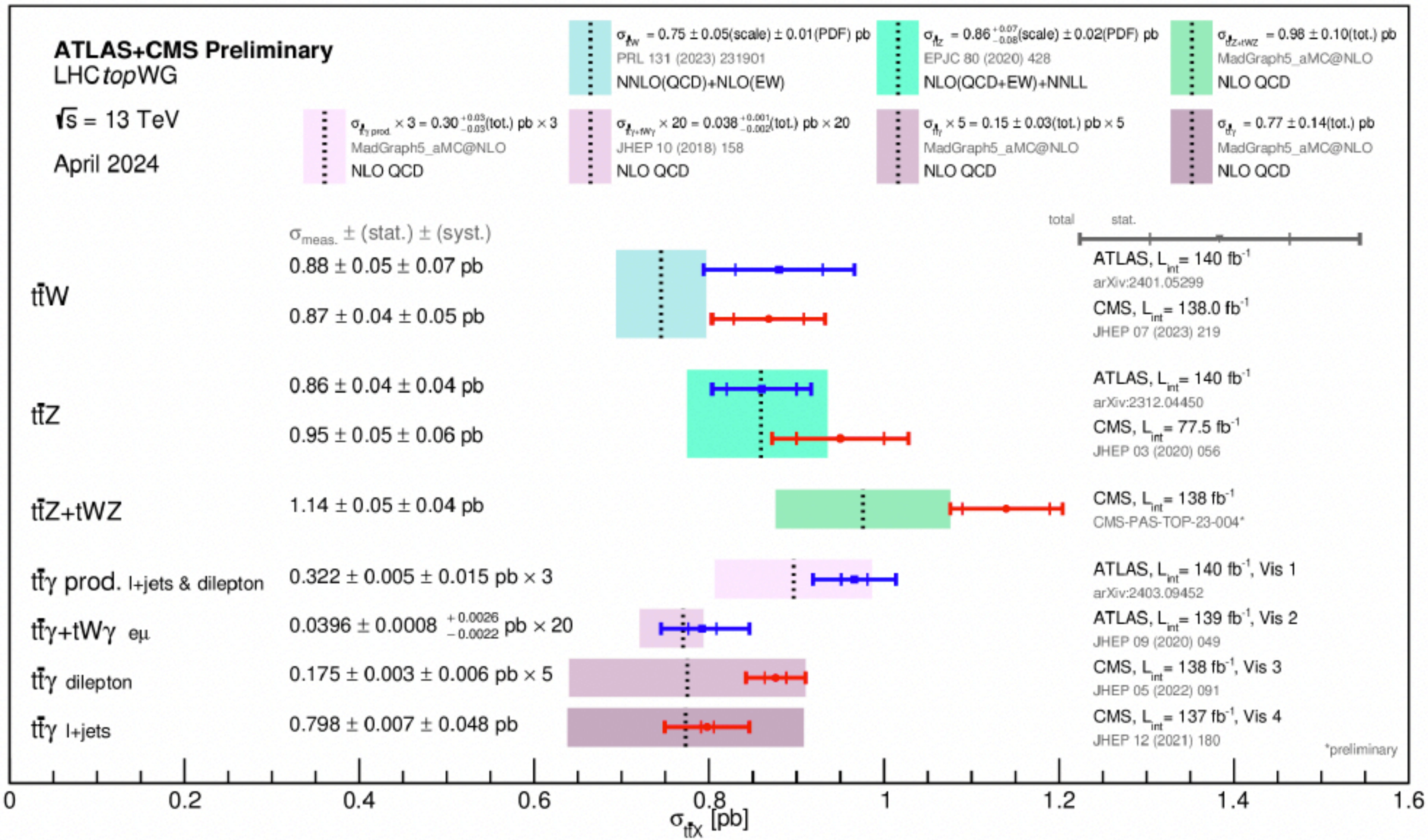


SINGLE TOP PRODUCTION



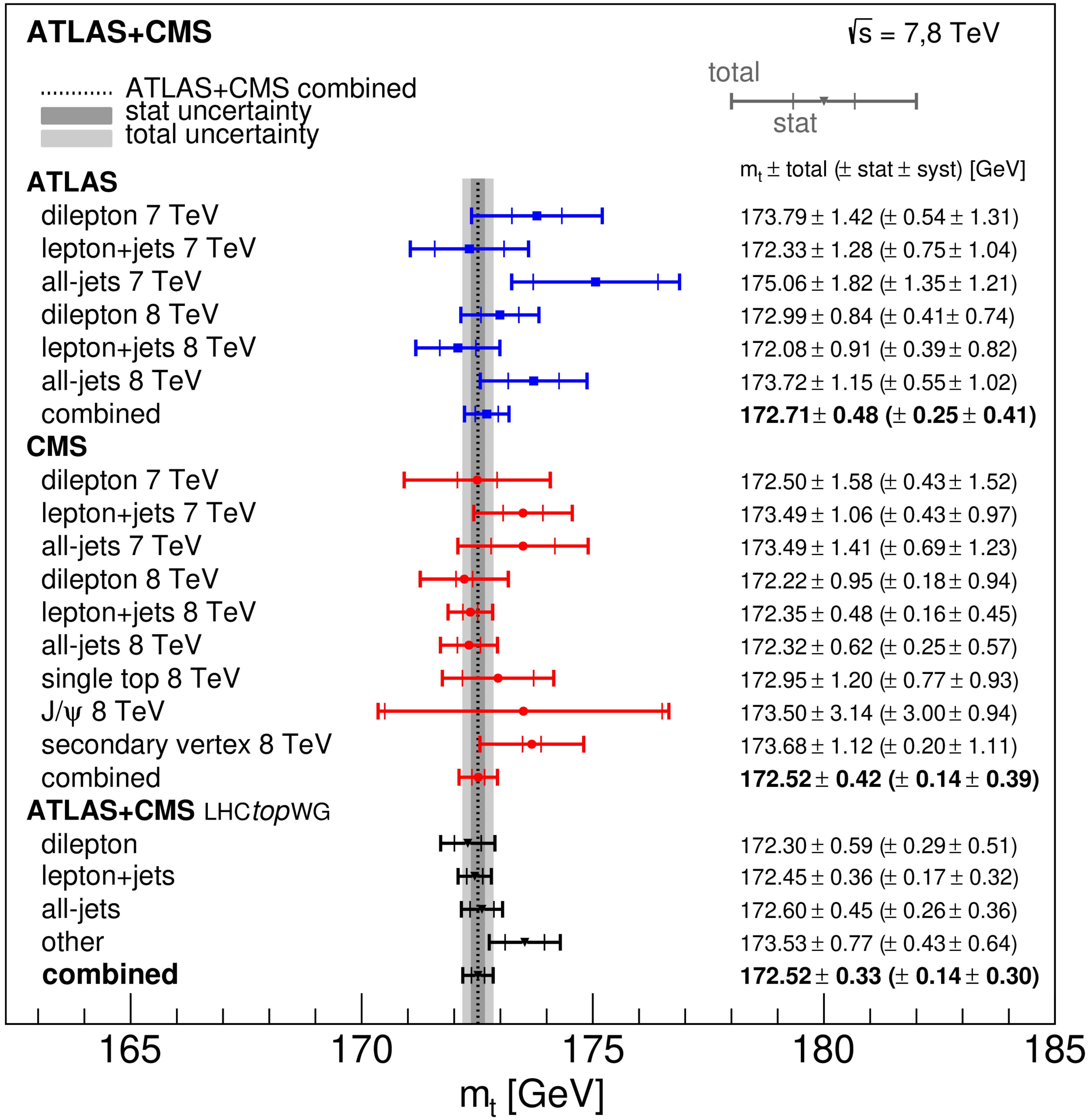


TOP+X

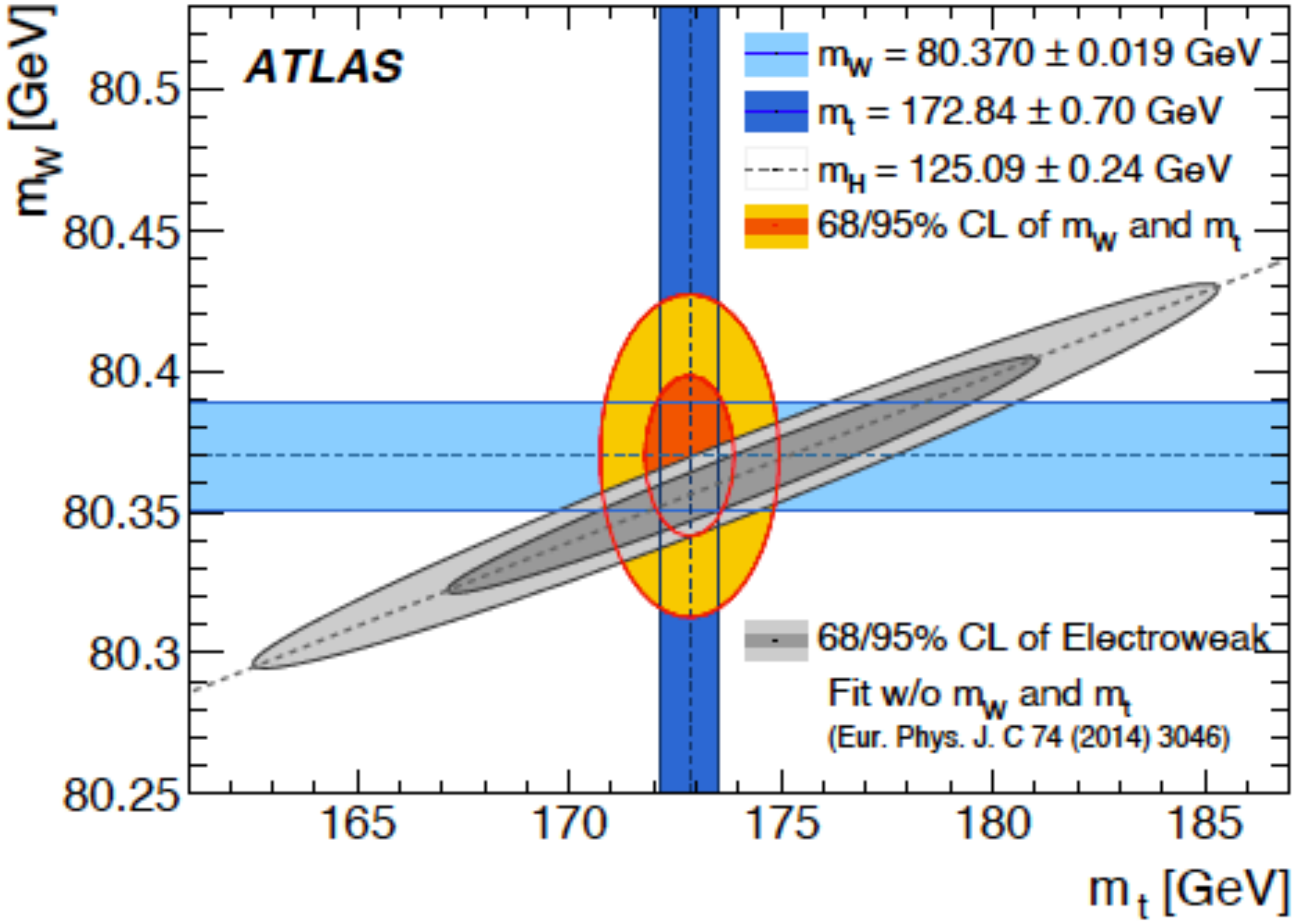


ATLAS+CMS Preliminary
LHC topWG
√s = 13 TeV
April 2024
σ_meas. ± (stat.) ± (syst.)
tt̄W
0.88 ± 0.05 ± 0.07 pb
0.87 ± 0.04 ± 0.05 pb
tt̄Z
0.86 ± 0.04 ± 0.04 pb
0.95 ± 0.05 ± 0.06 pb
tt̄Z+tWZ
1.14 ± 0.05 ± 0.04 pb
tt̄γ prod. l+jets & dilepton
0.322 ± 0.005 ± 0.015 pb × 3
tt̄γ+tWγ eμ
0.0396 ± 0.0008 +0.0026 −0.0022 pb × 20
tt̄γ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
tt̄γ l+jets
0.798 ± 0.007 ± 0.048 pb
total stat.
ATLAS, L_int = 140 fb^-1
arXiv:2401.05299
CMS, L_int = 138.0 fb^-1
JHEP 07 (2023) 219
ATLAS, L_int = 140 fb^-1
arXiv:2312.04450
CMS, L_int = 77.5 fb^-1
JHEP 03 (2020) 056
CMS, L_int = 138 fb^-1
CMS-PAS-TOP-23-004*
ATLAS, L_int = 140 fb^-1, Vis 1
arXiv:2403.09452
ATLAS, L_int = 139 fb^-1, Vis 2
JHEP 09 (2020) 049
CMS, L_int = 138 fb^-1, Vis 3
JHEP 05 (2022) 091
CMS, L_int = 137 fb^-1, Vis 4
JHEP 12 (2021) 180
*preliminary
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
σ_tt̄X [pb]

TOP QUARK MASS



Together with recent measurements of the W mass and the Higgs mass, a precise measurement of m_t helps to severely constrain (or potentially discover) deviations from the SM.

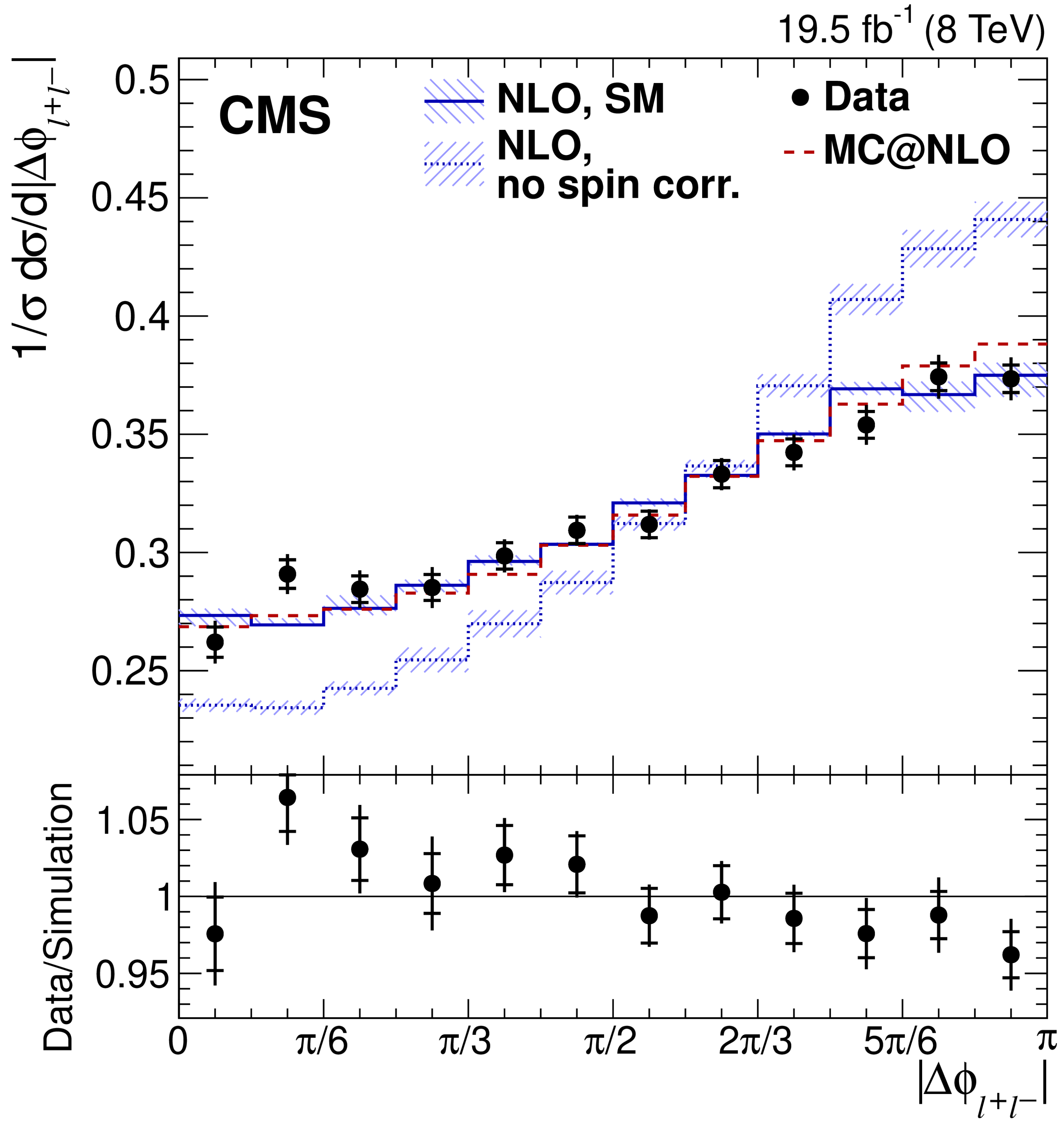


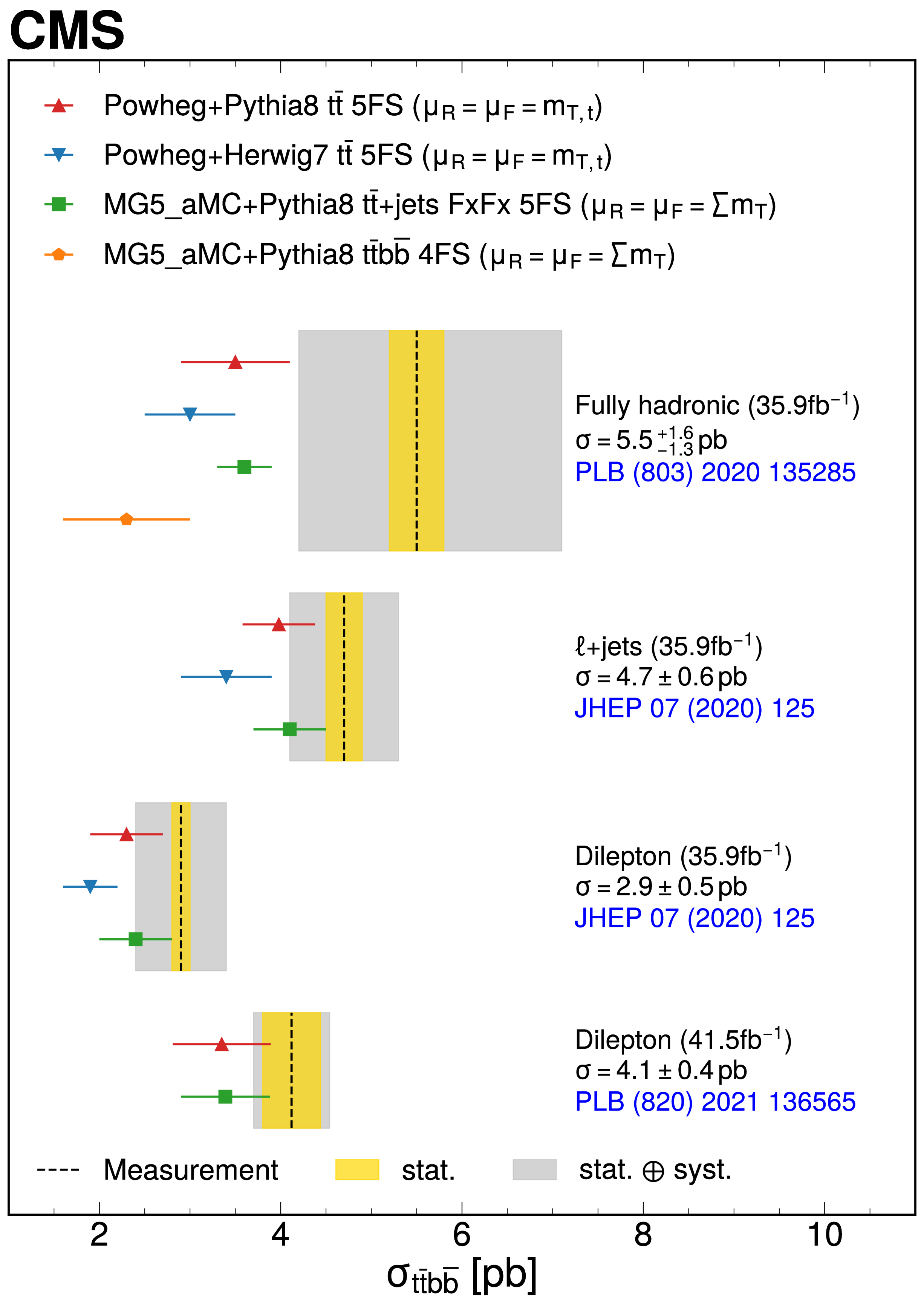
Measurements dominated by systematic uncertainties (theoretical and experimental). Different methods employed, focusing on different systematic sources. Highlights:

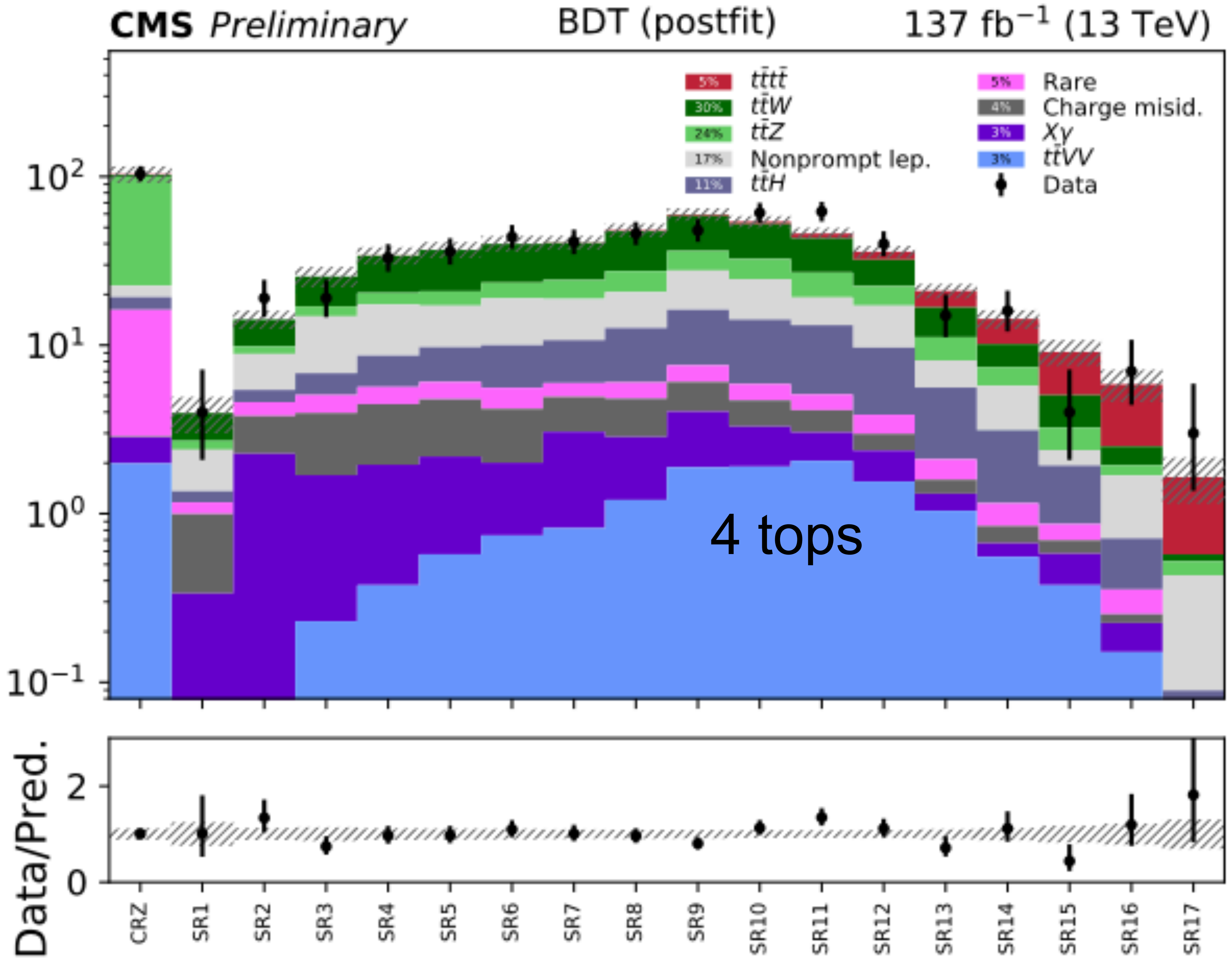
- Most precise today: lepton+jets channel
- Experimentally cleanest: dilepton channel
- Theoretically cleanest: tt or tt+jet cross sections

TOP AS A LABORATORY

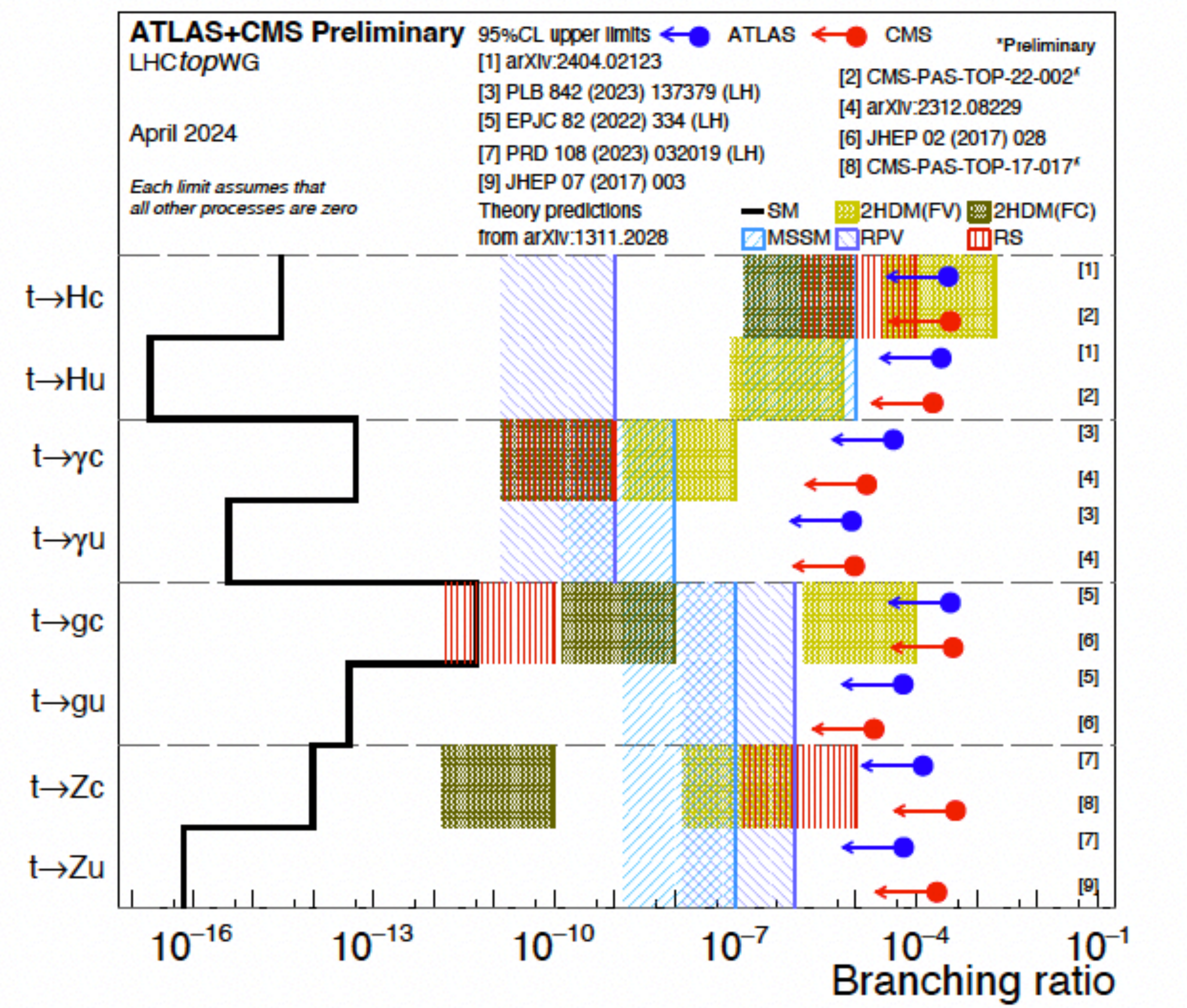
- Spin, Couplings, asymmetries, rare and multiple production modes…
- Studying the properties of top and more complex modes of production involving top quarks (tt+X) is a strong test theoretical predictions: new physics







EXAMPLE: SURPRISES WITH FLAVOUR?

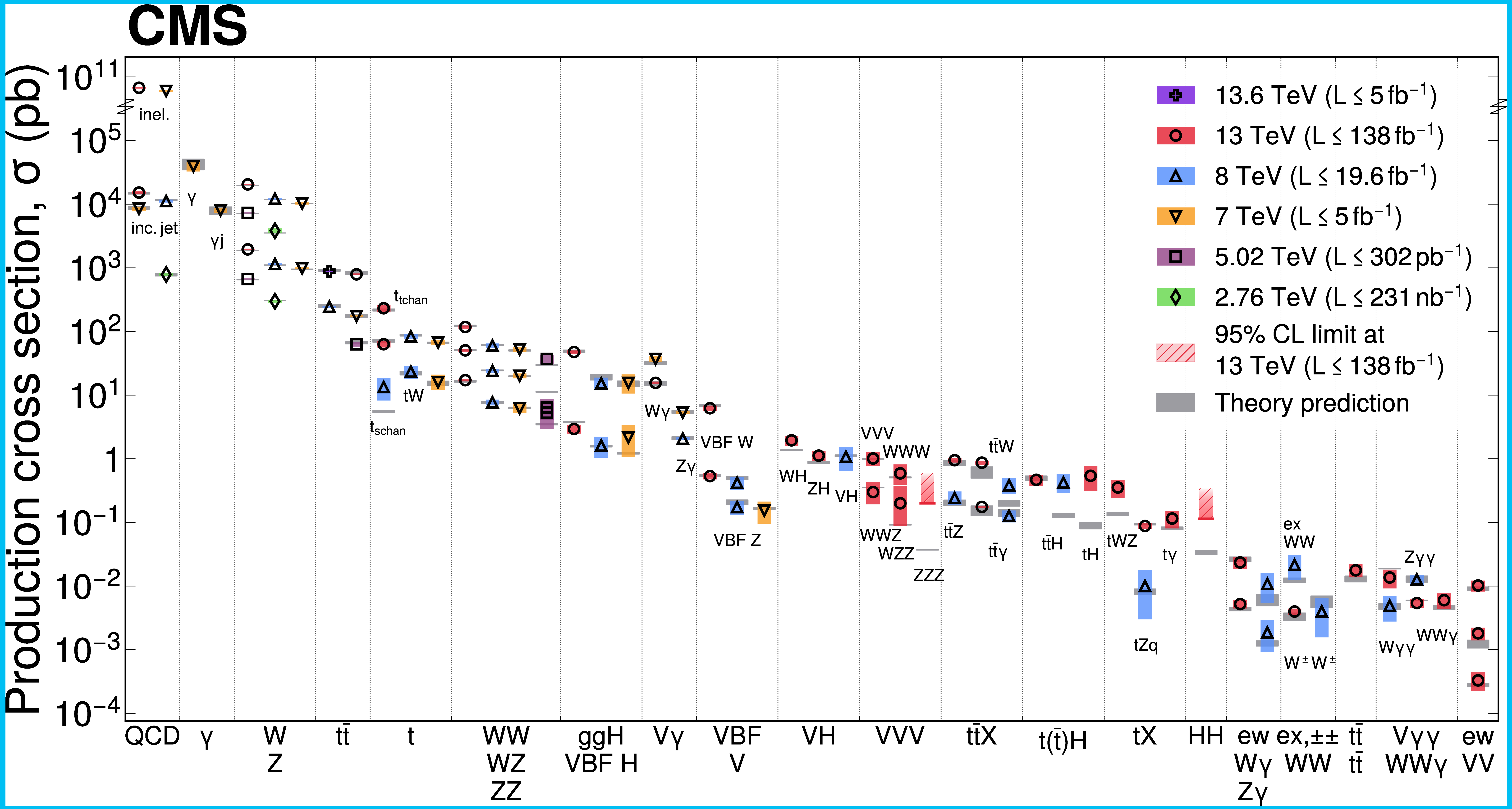


Flavour Changing Neutral Currents:
Forbidden in the SM at Tree level

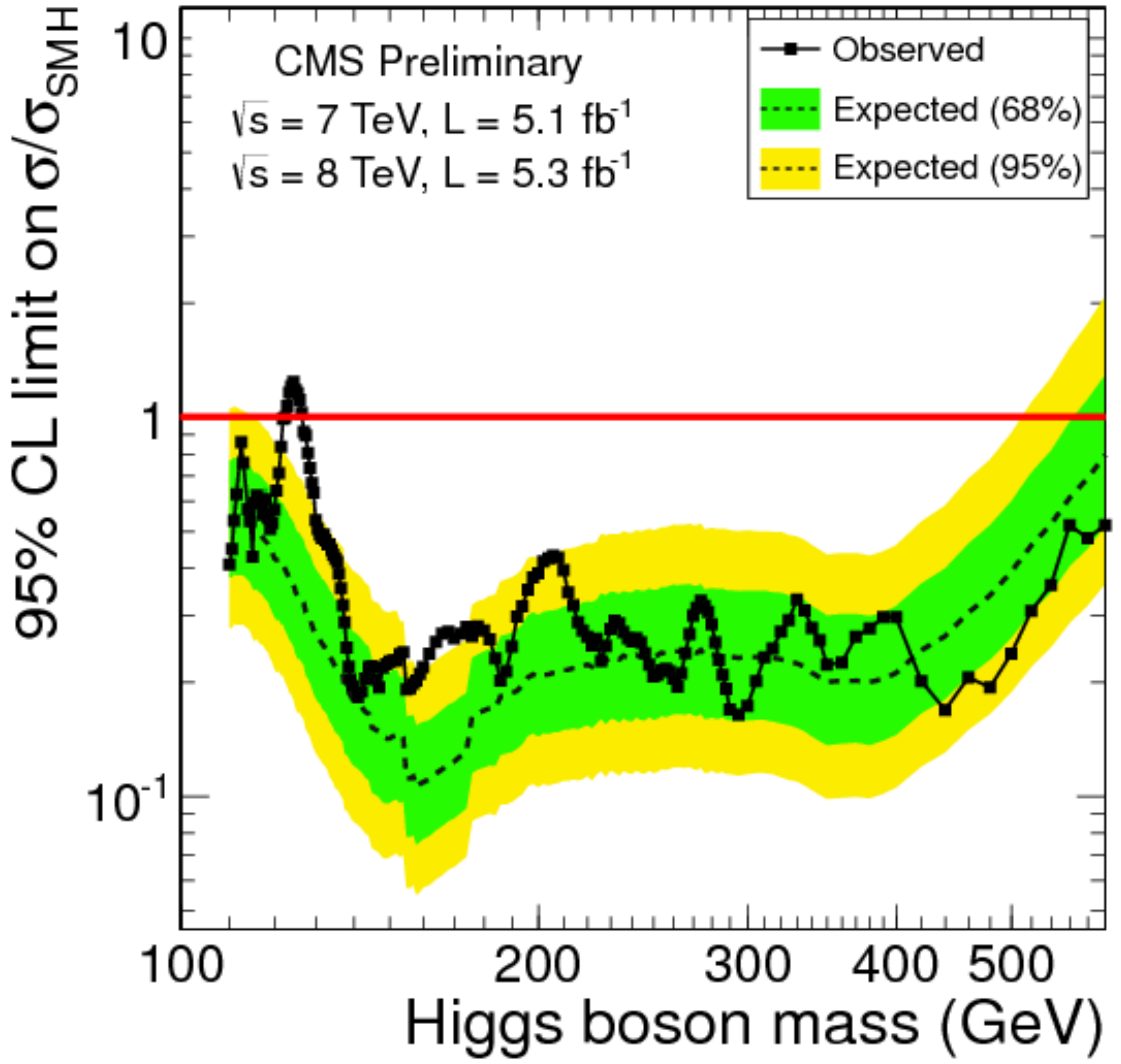
Possible in many BSM scenarios (eg 2HDM)

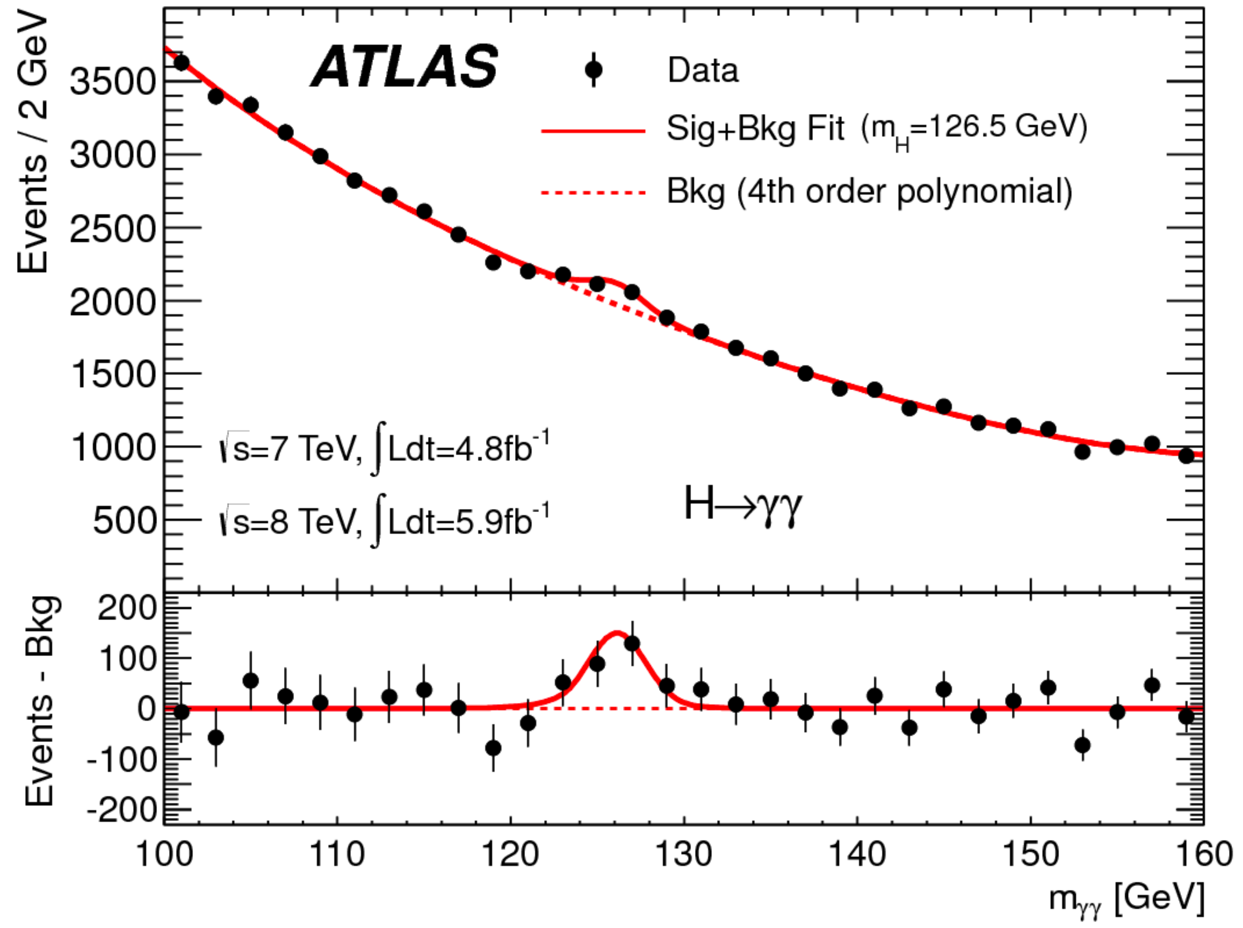
So far no signs , now approaching sensitivity to interesting BSM models (10^{-4})

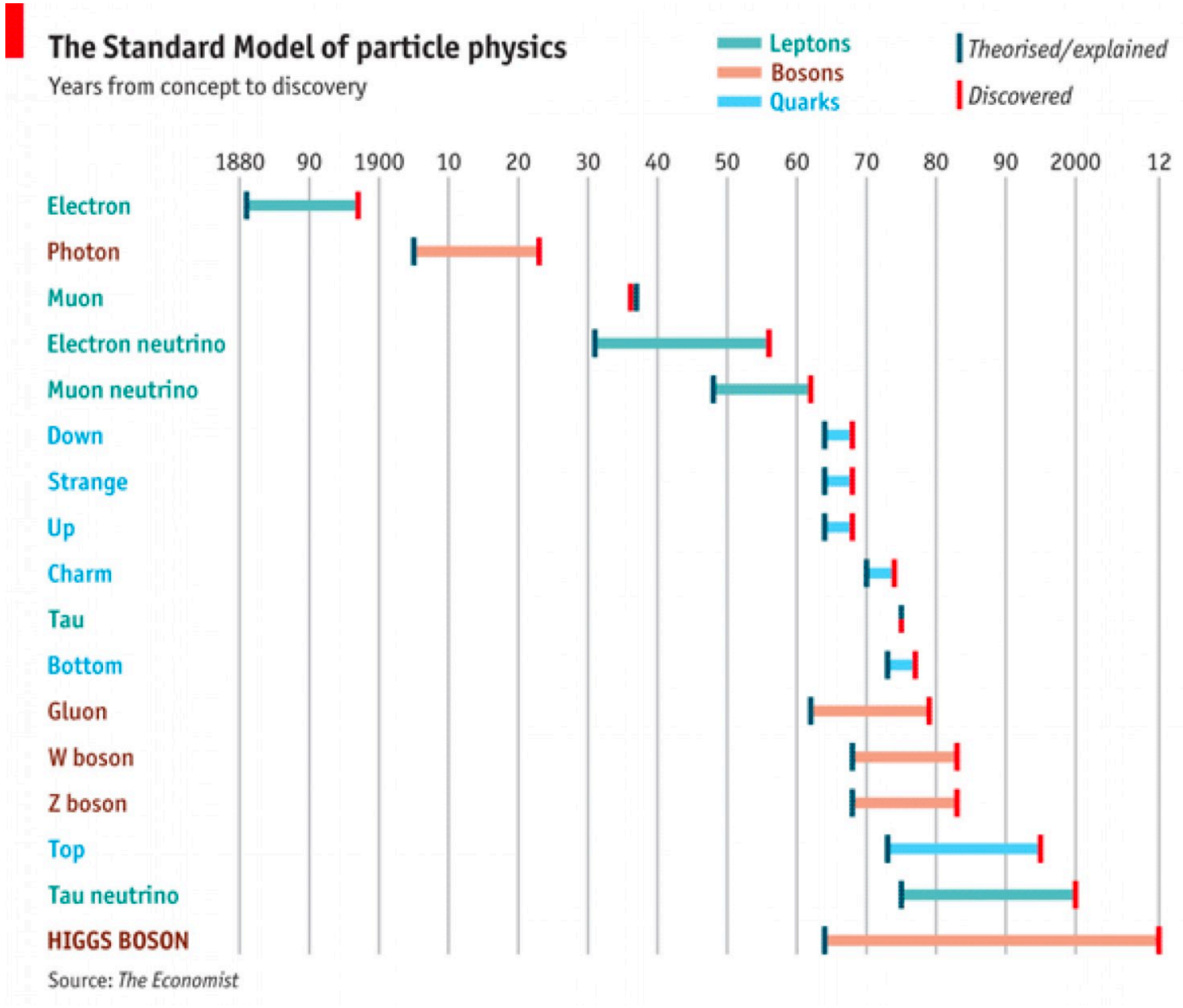
PRECISION ACROSS MANY ORDERS OF MAGNITUDE



HIGGS@LHC

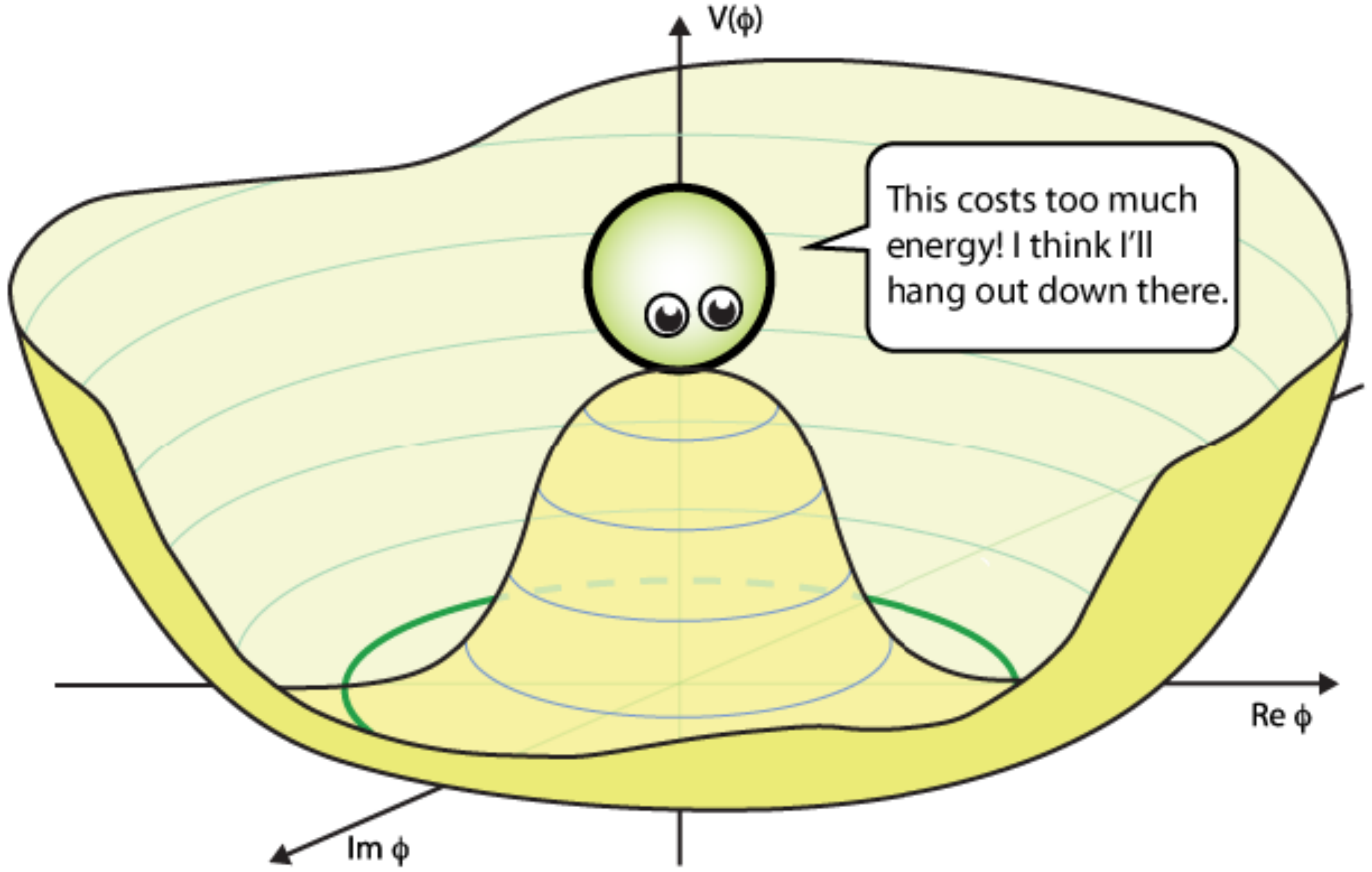






At the time the LHC started, finding the Higgs critical for particle physics: without it, no SM!
Twelve years after discovery, understanding its properties remains at the head of the priority list of the European&American strategies! A lot to do understand still

THE BROUT-ENGLERT-HIGGS MECHANISM



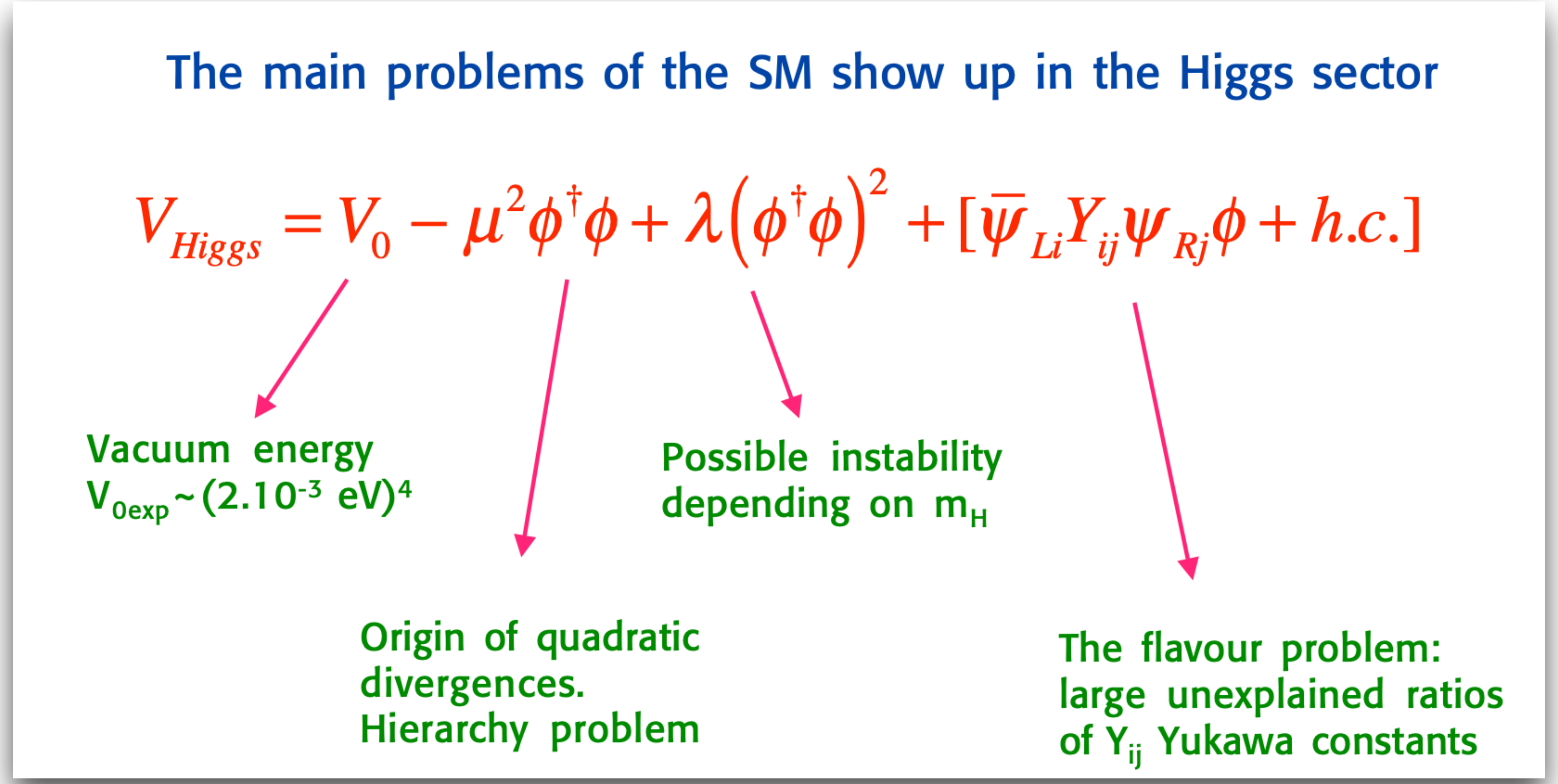
$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

- Electro-Weak Symmetry Breaking: mass of W, Z (photons massless)
  - Prediction of the relation between the gauge boson masses and their couplings
  - Prediction of a new boson, the Higgs
- What about fermion masses? Yukawa couplings

$$\mathcal{L}_{Y_i} = y_i h f_L^i f_R^i + h.c. \text{ with } y_i = \frac{m_i}{v}$$

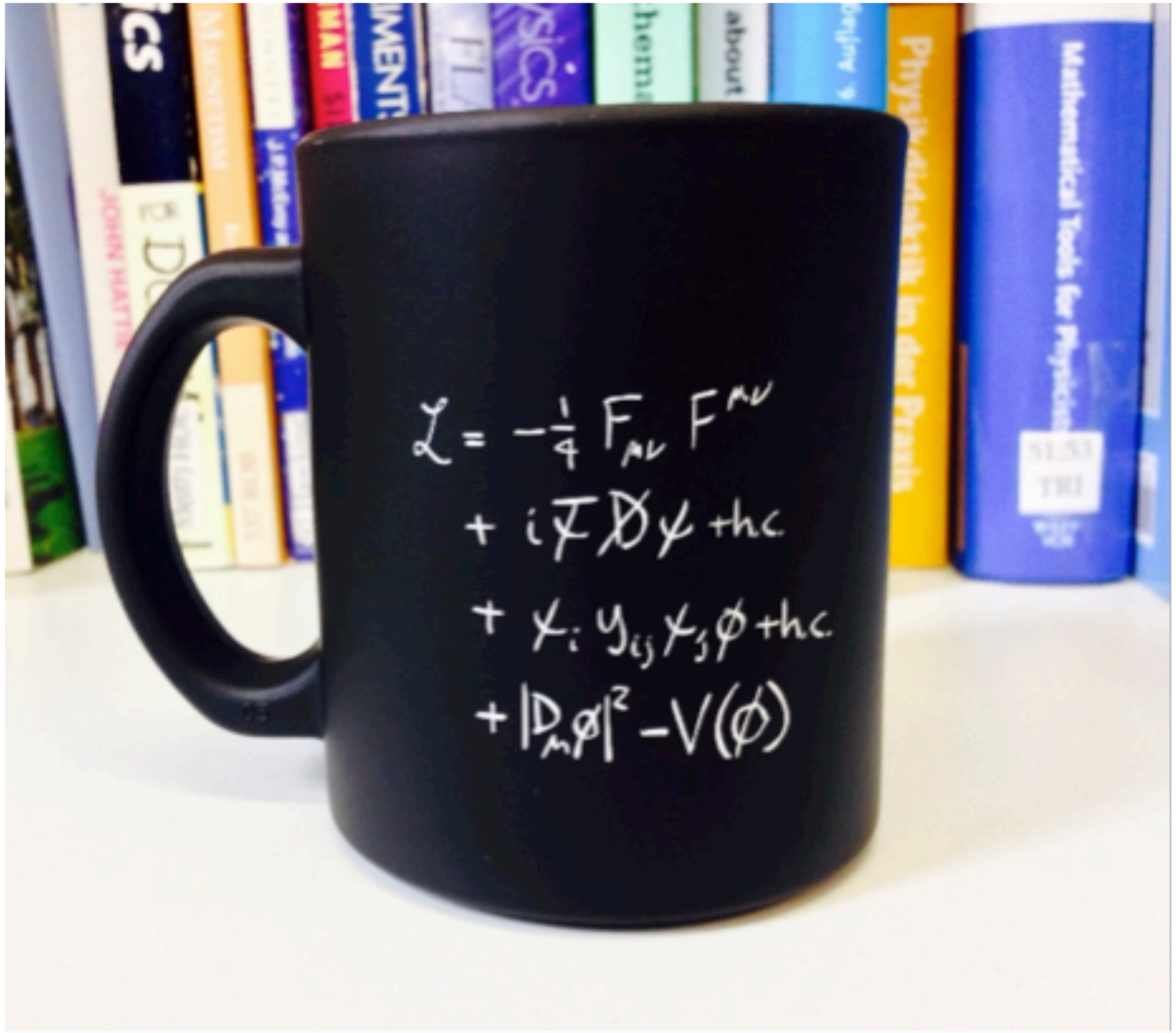
WHY SO IMPORTANT?



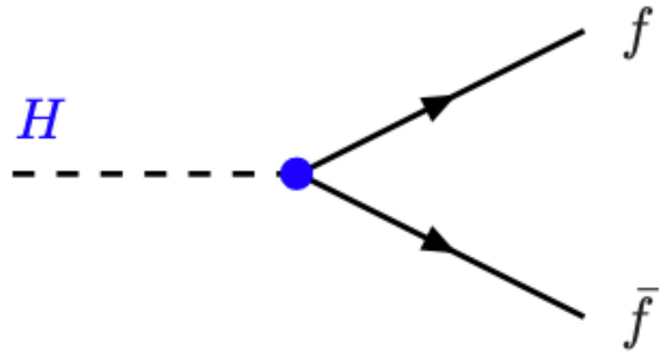
Guido Altarelli
Lepton Photon 2009

- Only known fundamental particle with spin 0
- Gives mass to other particles, including itself: this has deep implications
- Door to the unknown: what can we learn about BSM through the study of the Higgs boson?

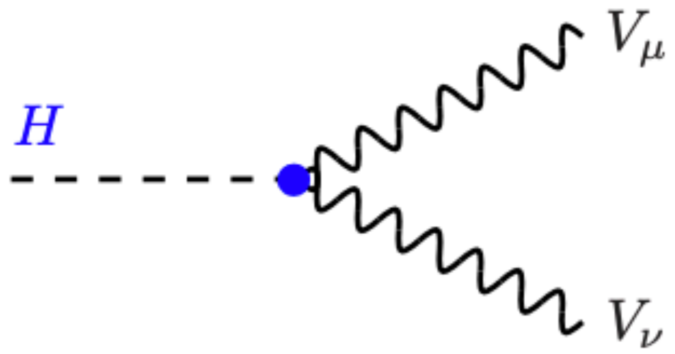
The central role of the Higgs in the SM makes it particularly sensitive to deviations coming from new physics. BSM can alter couplings, kinematics: we need to measure its properties precisely



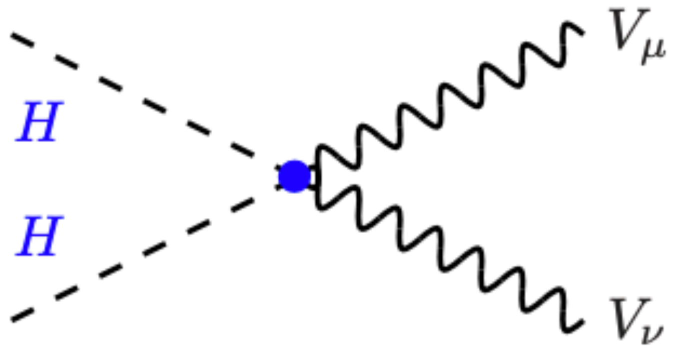
Couplings are proportional to mass!



$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \quad \times (i)$$



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \times (-i g_{\mu\nu})$$



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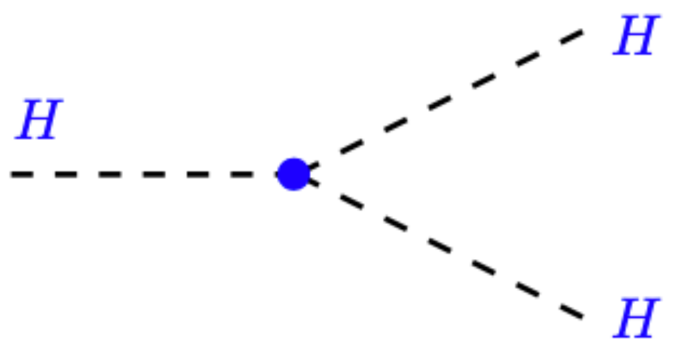
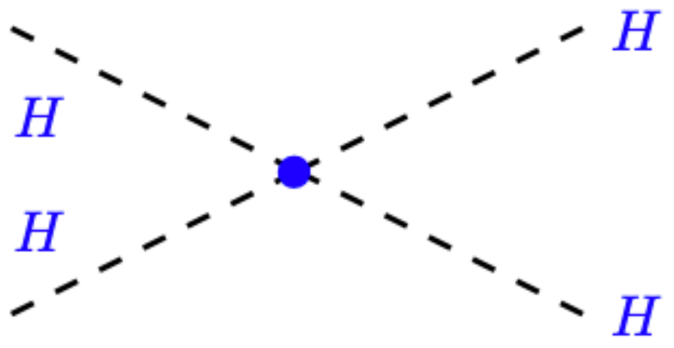


$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \times (i)$$



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UNDERSTANDING THE HIGGS BOSON AT A COLLIDER

Finding a particle is the beginning of a long way to understand it: what is really the Higgs boson? Does it follow the SM rules?

H^0 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

- How is the Higgs boson produced? How does it decay?
- What kind of particle is the Higgs? (Properties: Mass, Width, Spin)
- How does it couple to Standard Model particles?
  - Does it couple to all matter generations?
  - Does it couple to itself?
  - Does it couple unusually? (eg: Dark Matter?)
- Is the Higgs alone?
- Is it really an elementary particle?
- Where does the Higgs mechanism come from?

HOW IS THE HIGGS PRODUCED*?

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

(* in pp collisions)

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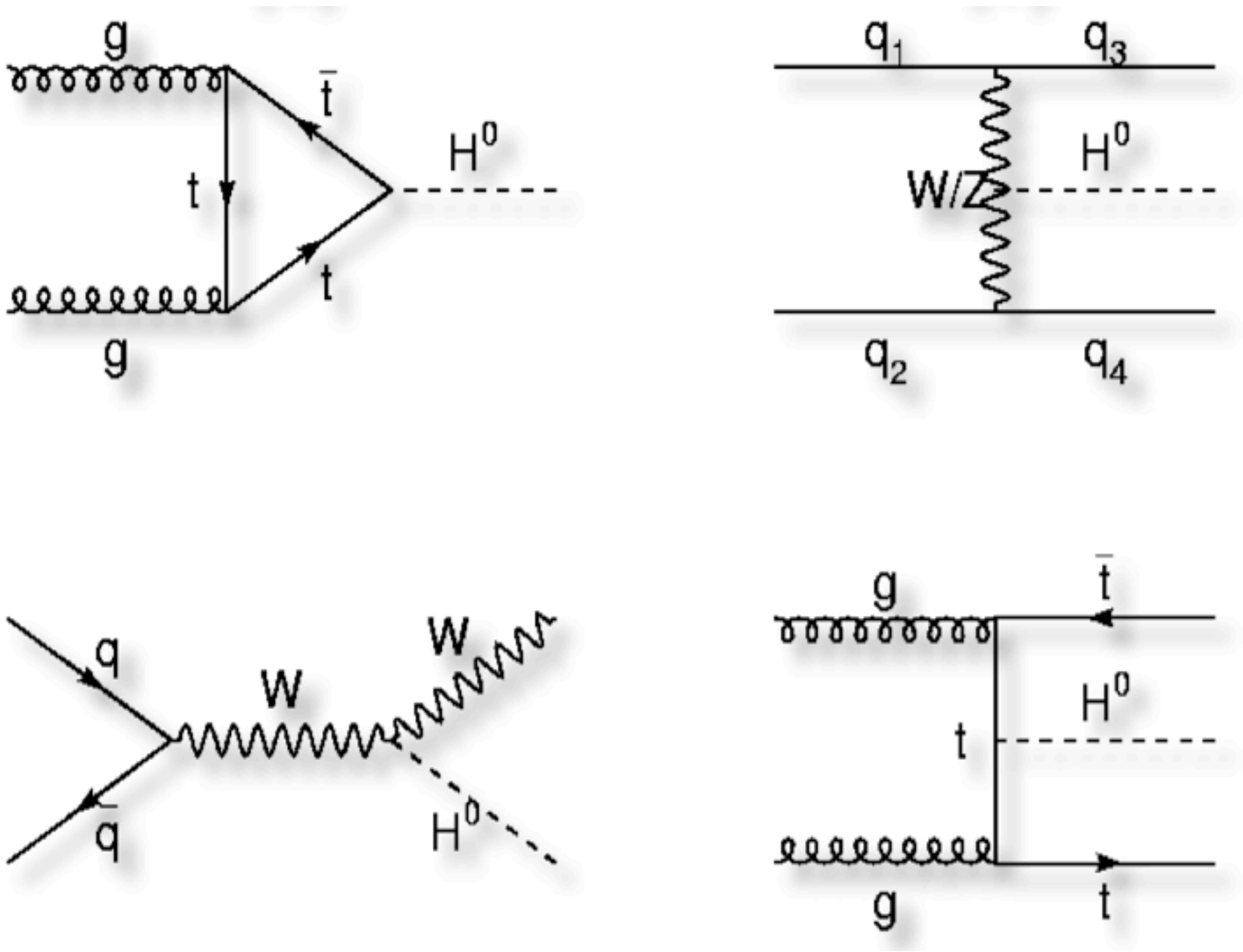

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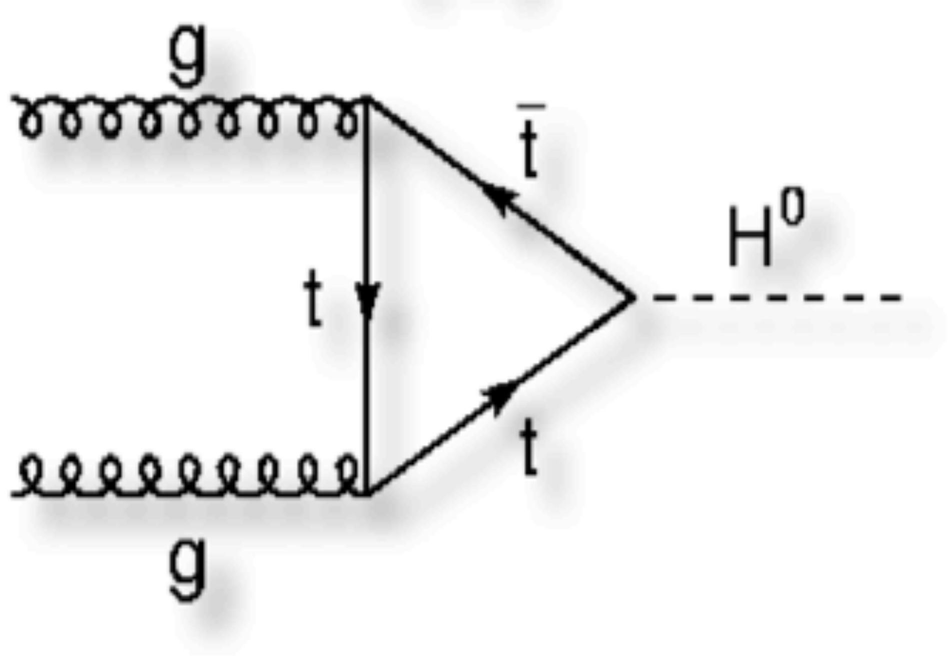
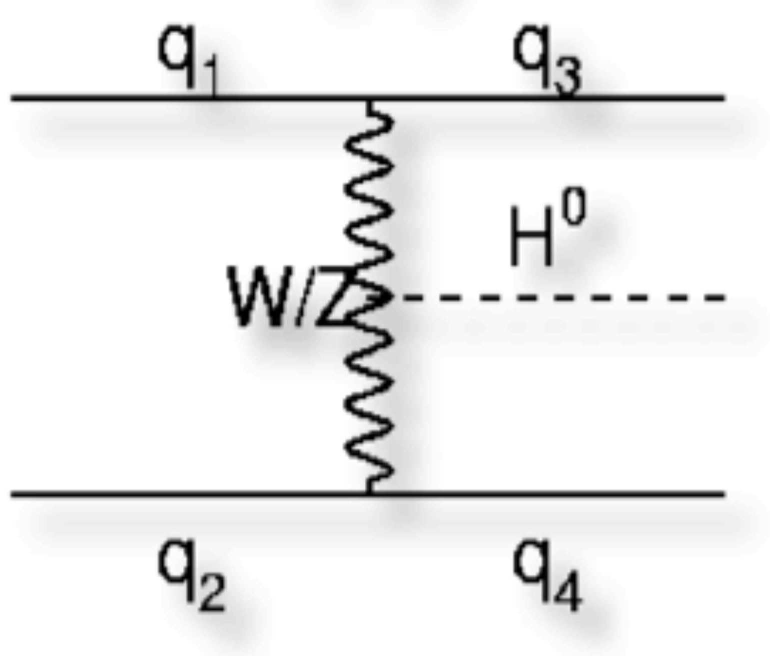
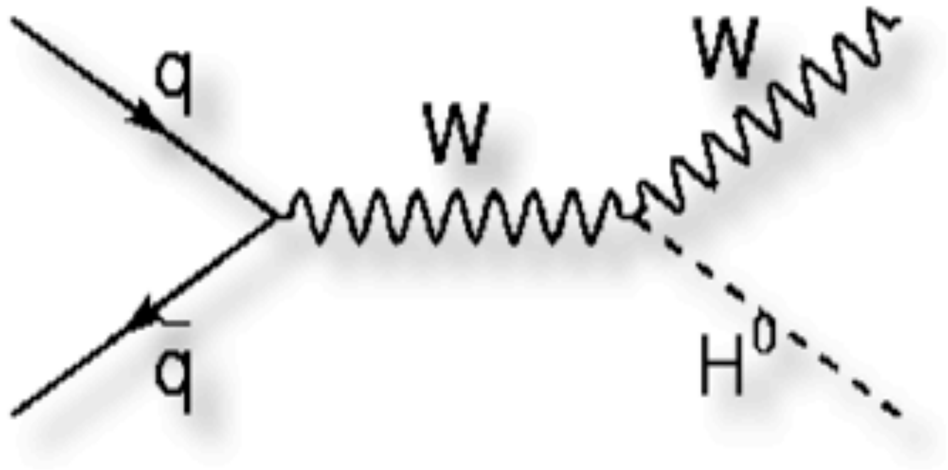
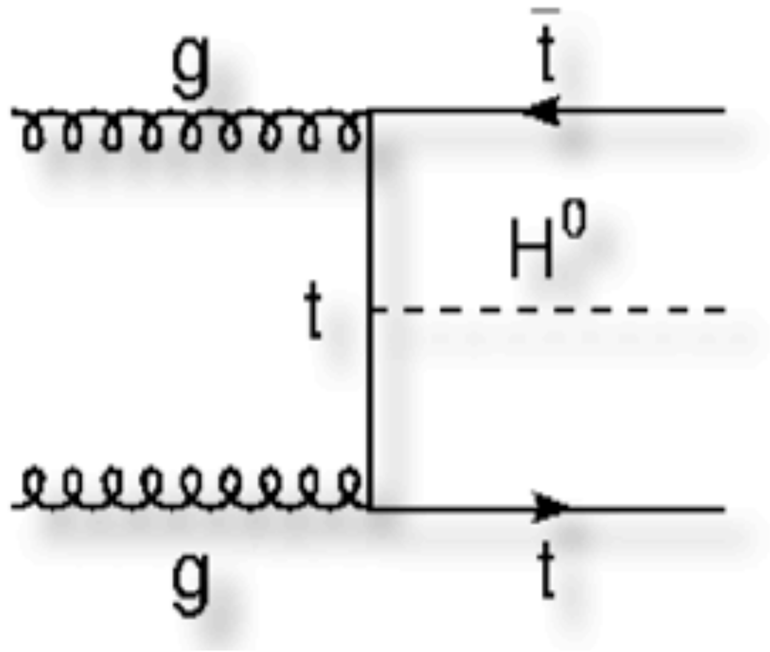


gluon fusion, ggH







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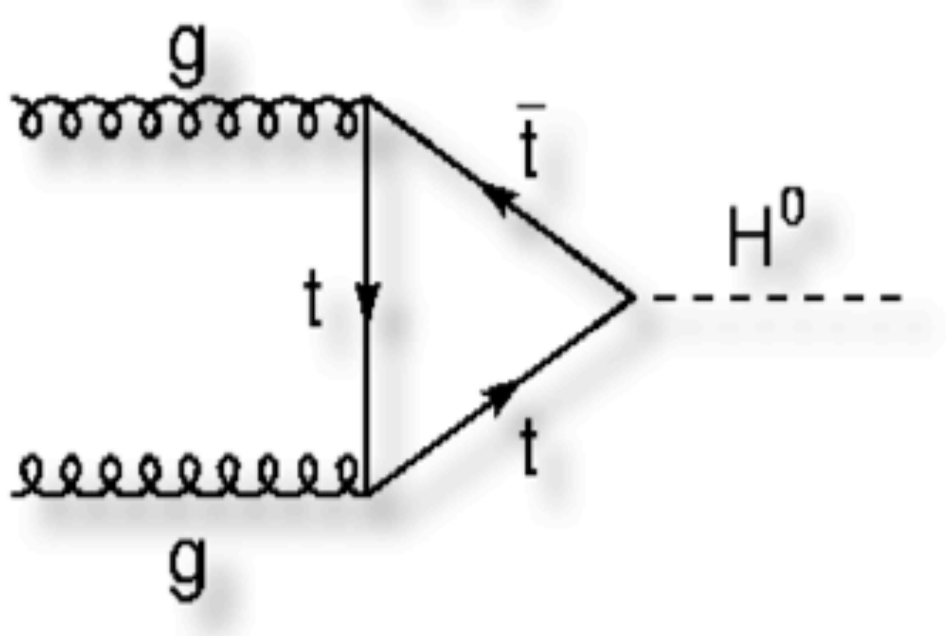

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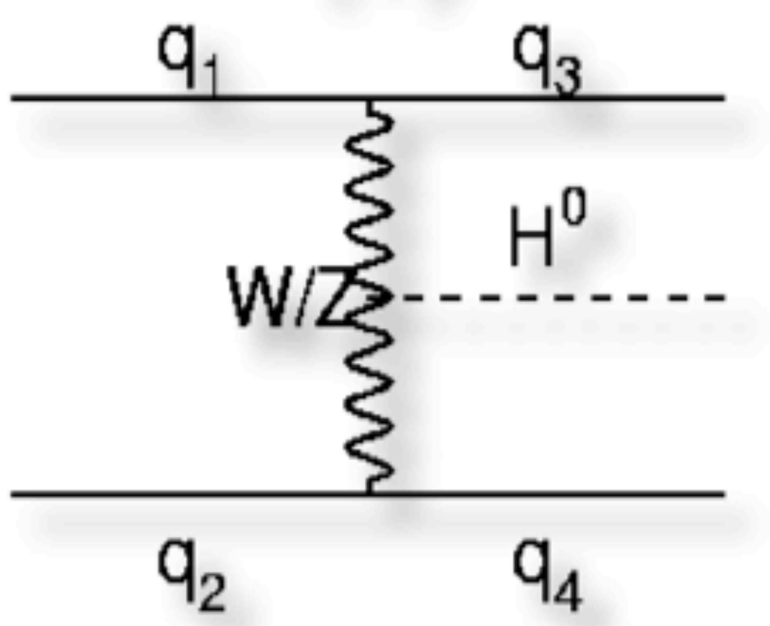

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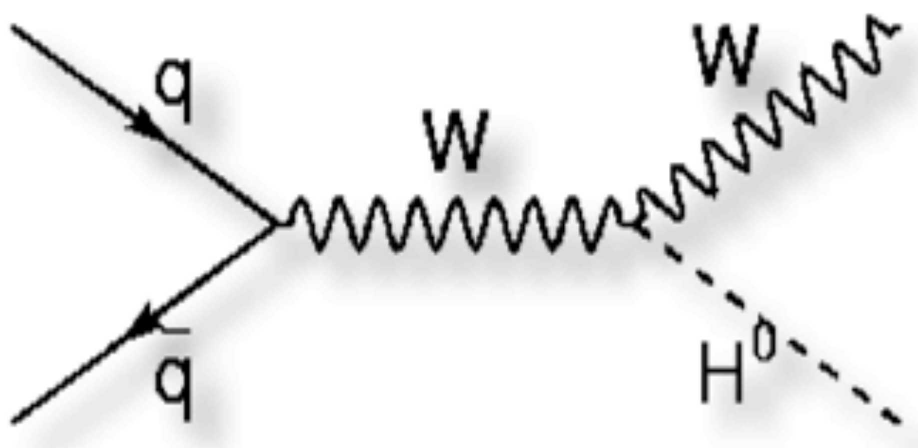

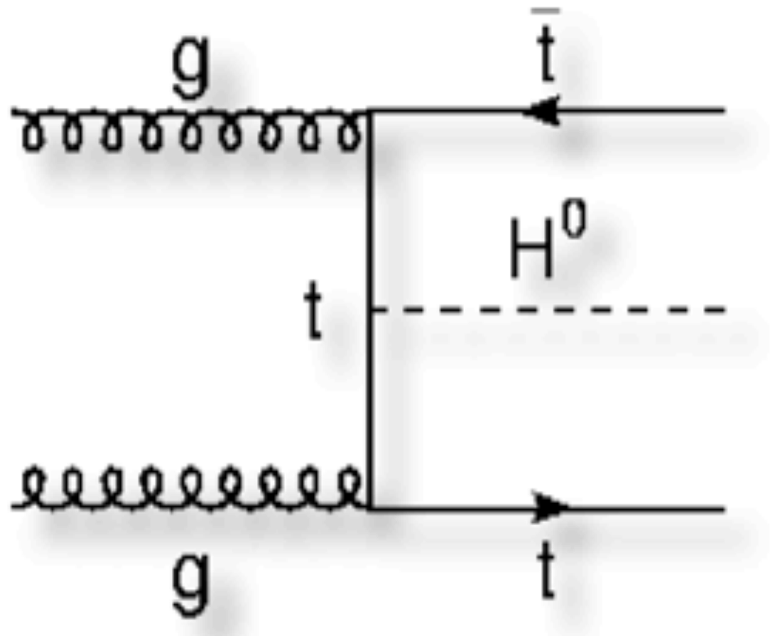

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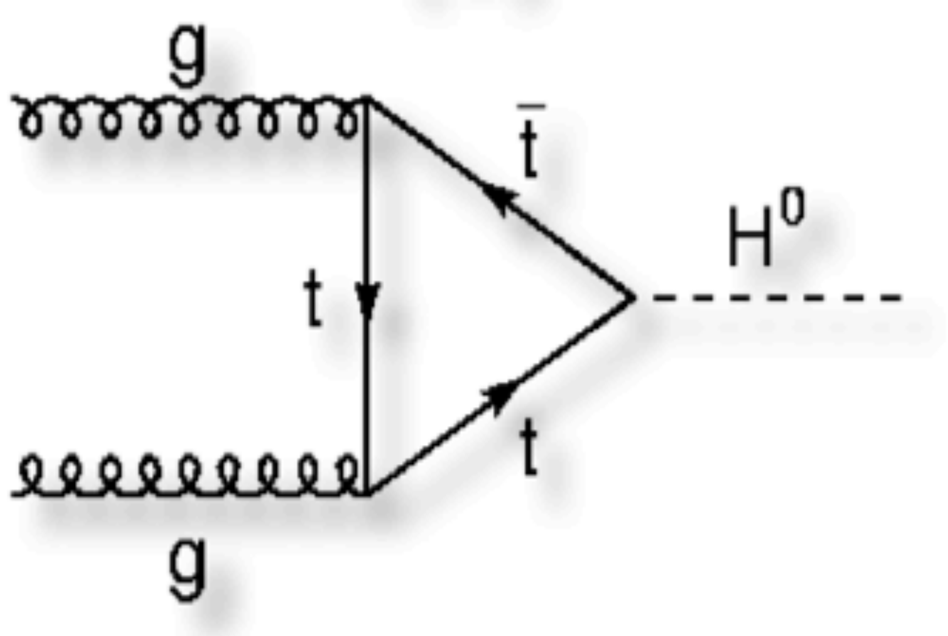

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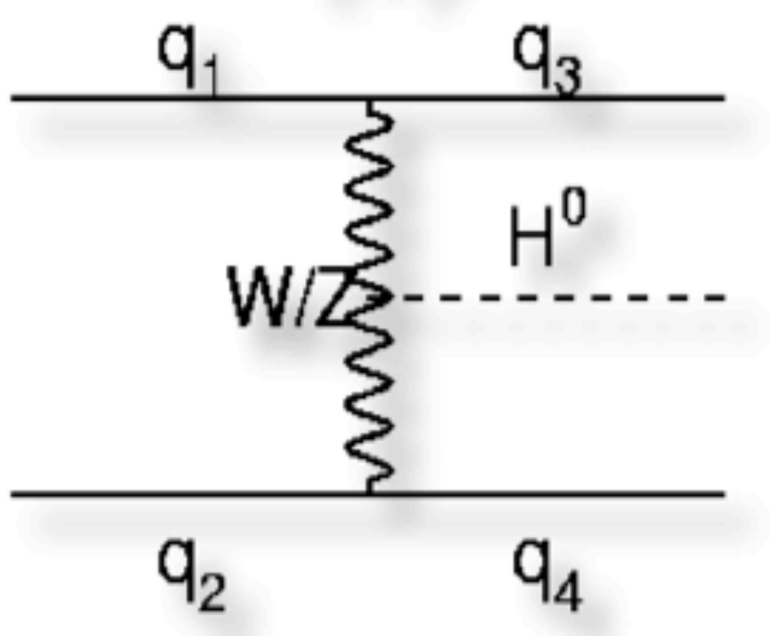

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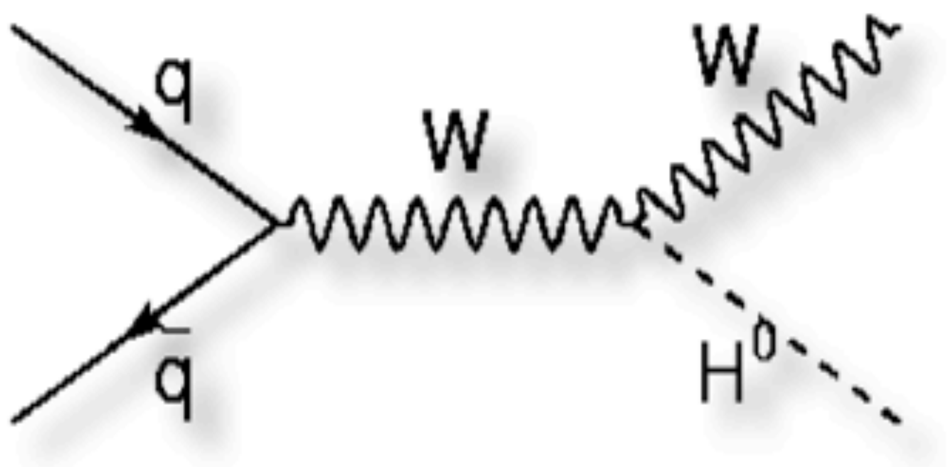
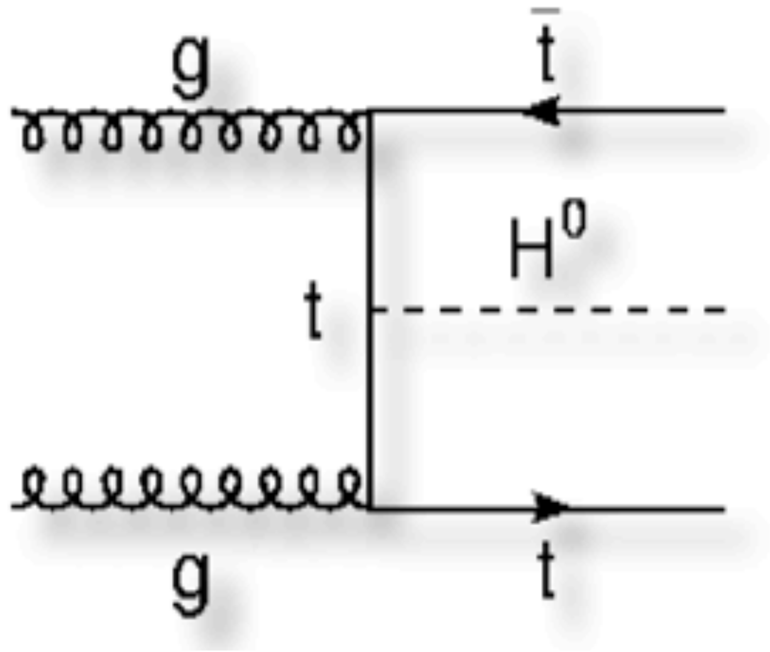


Higgs-strahlung, VH



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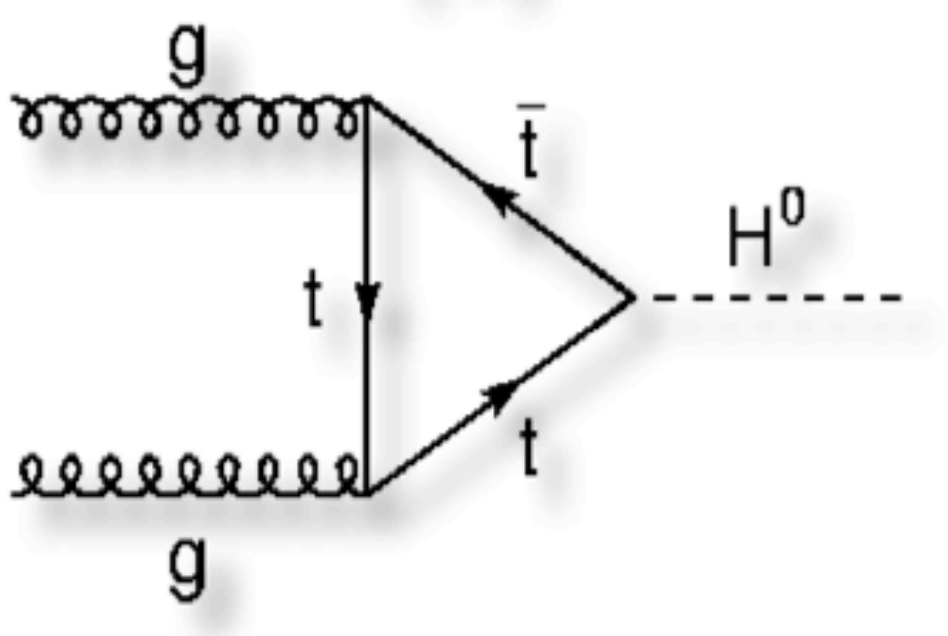

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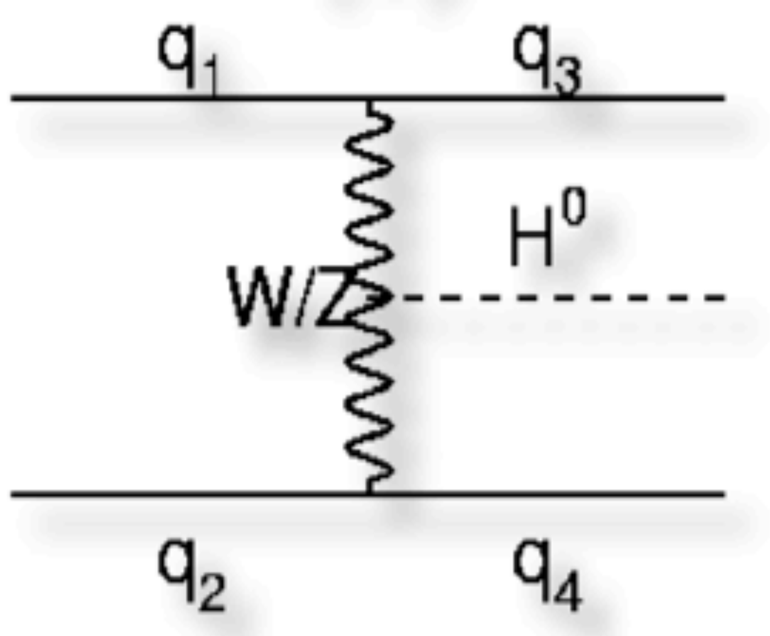

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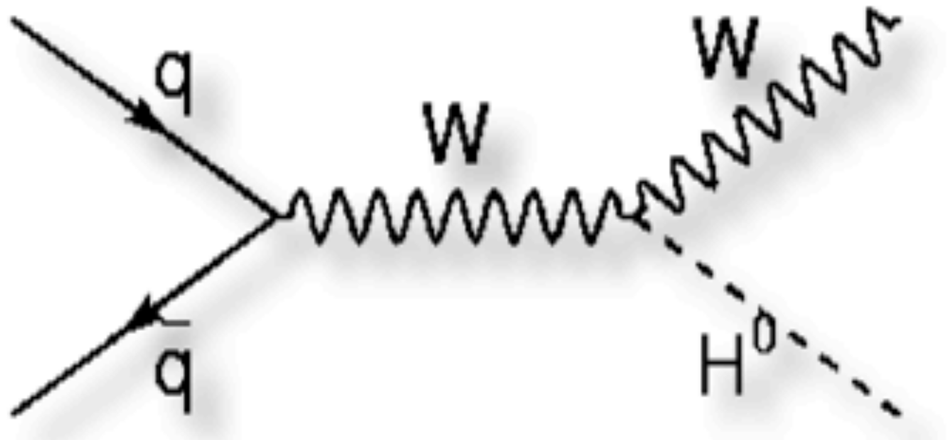

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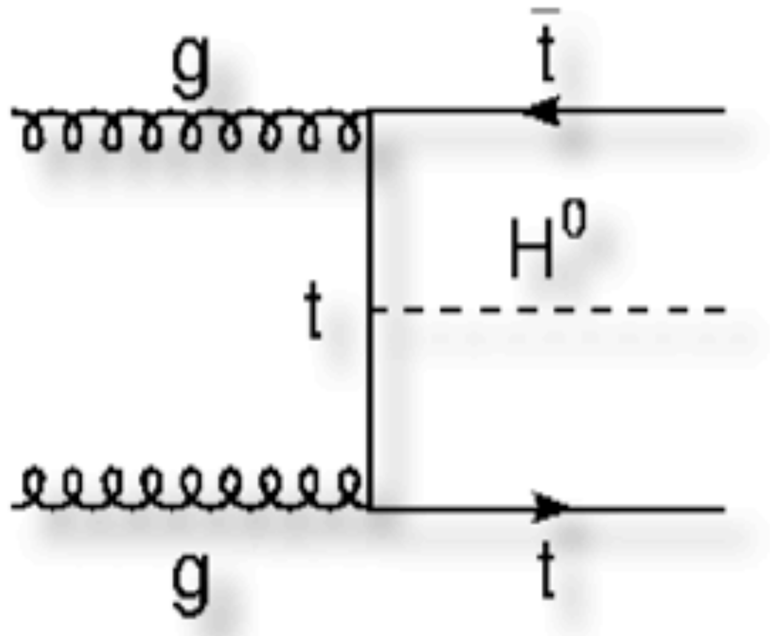

associated production, ttH

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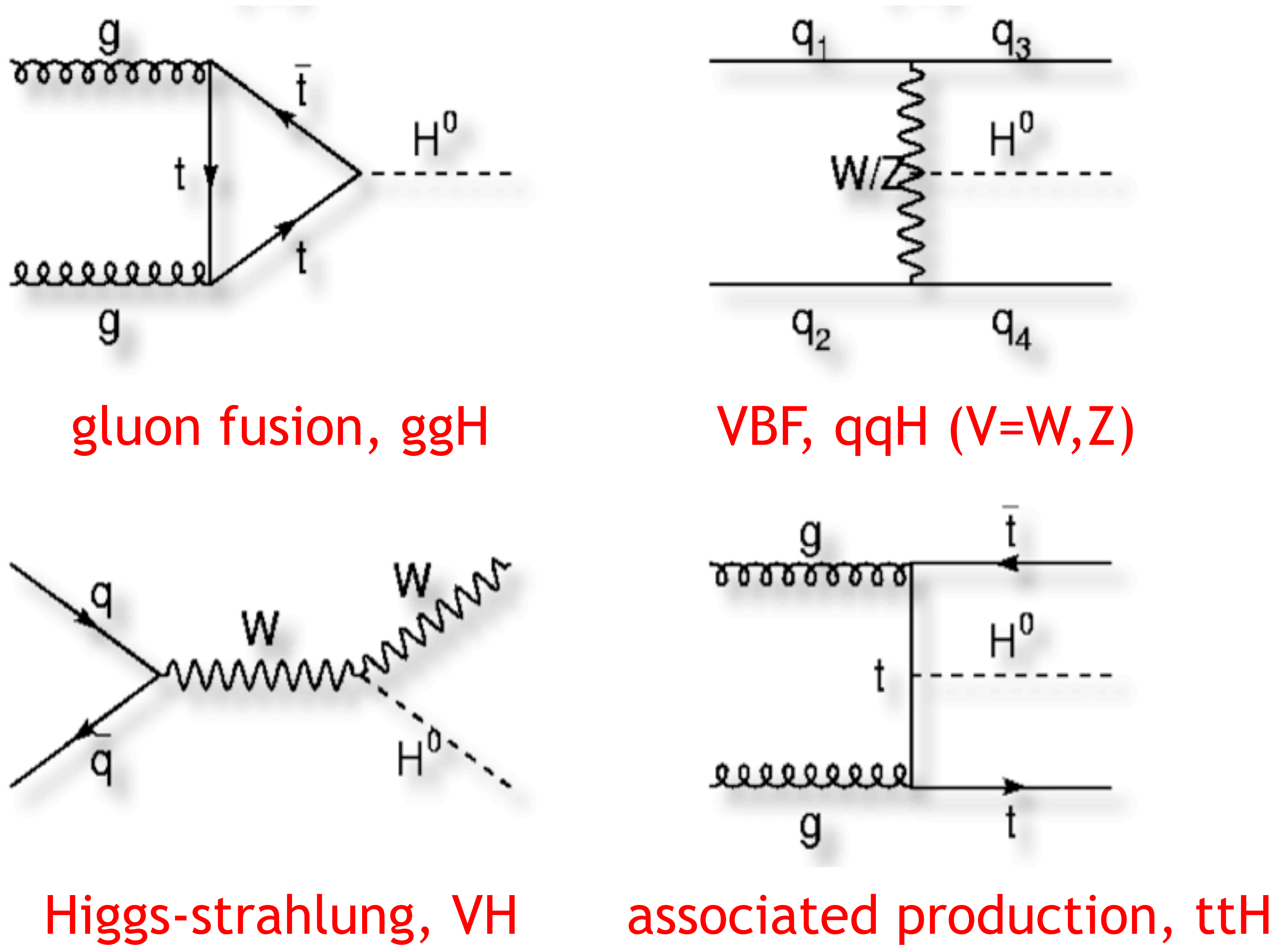

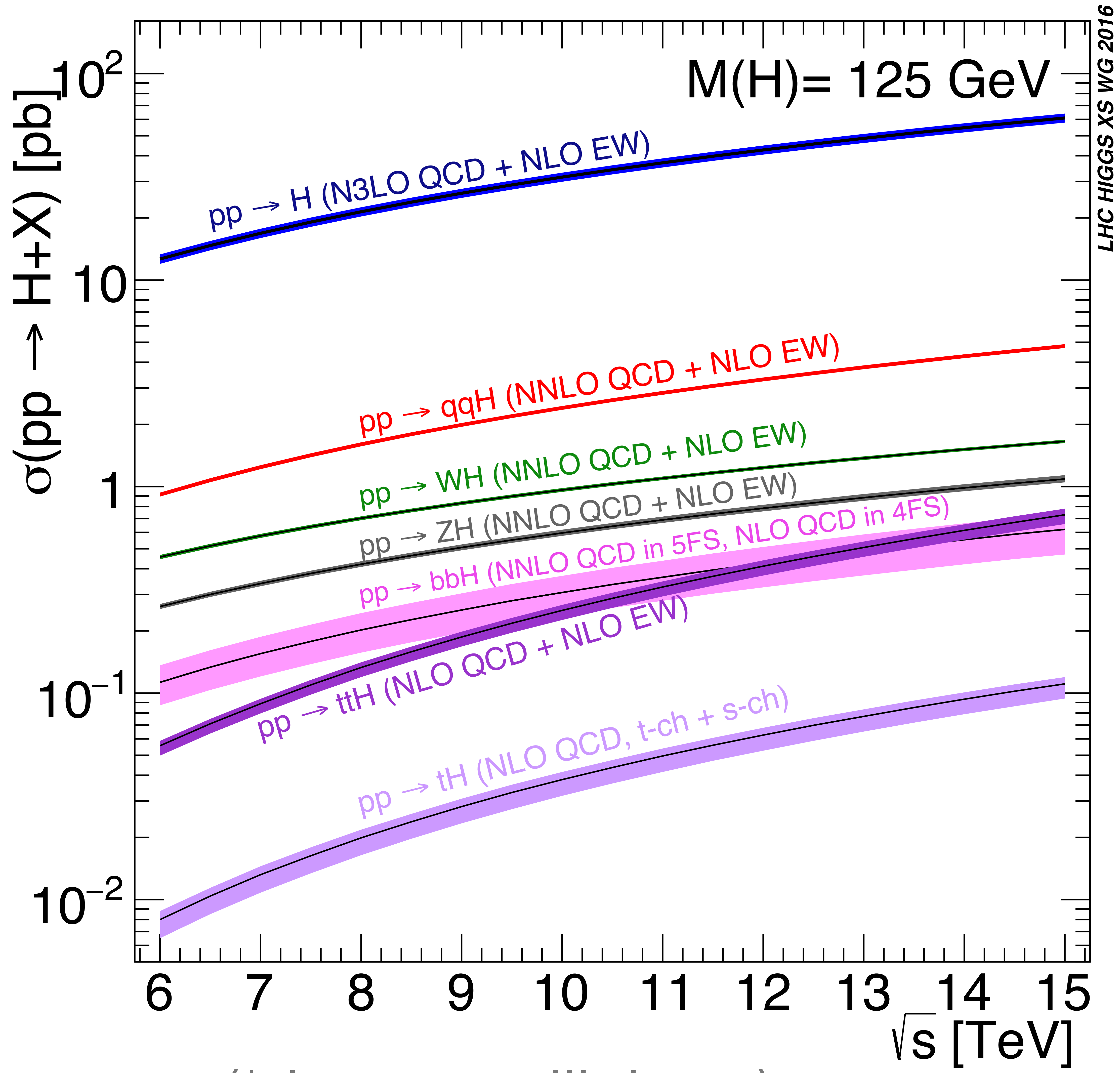

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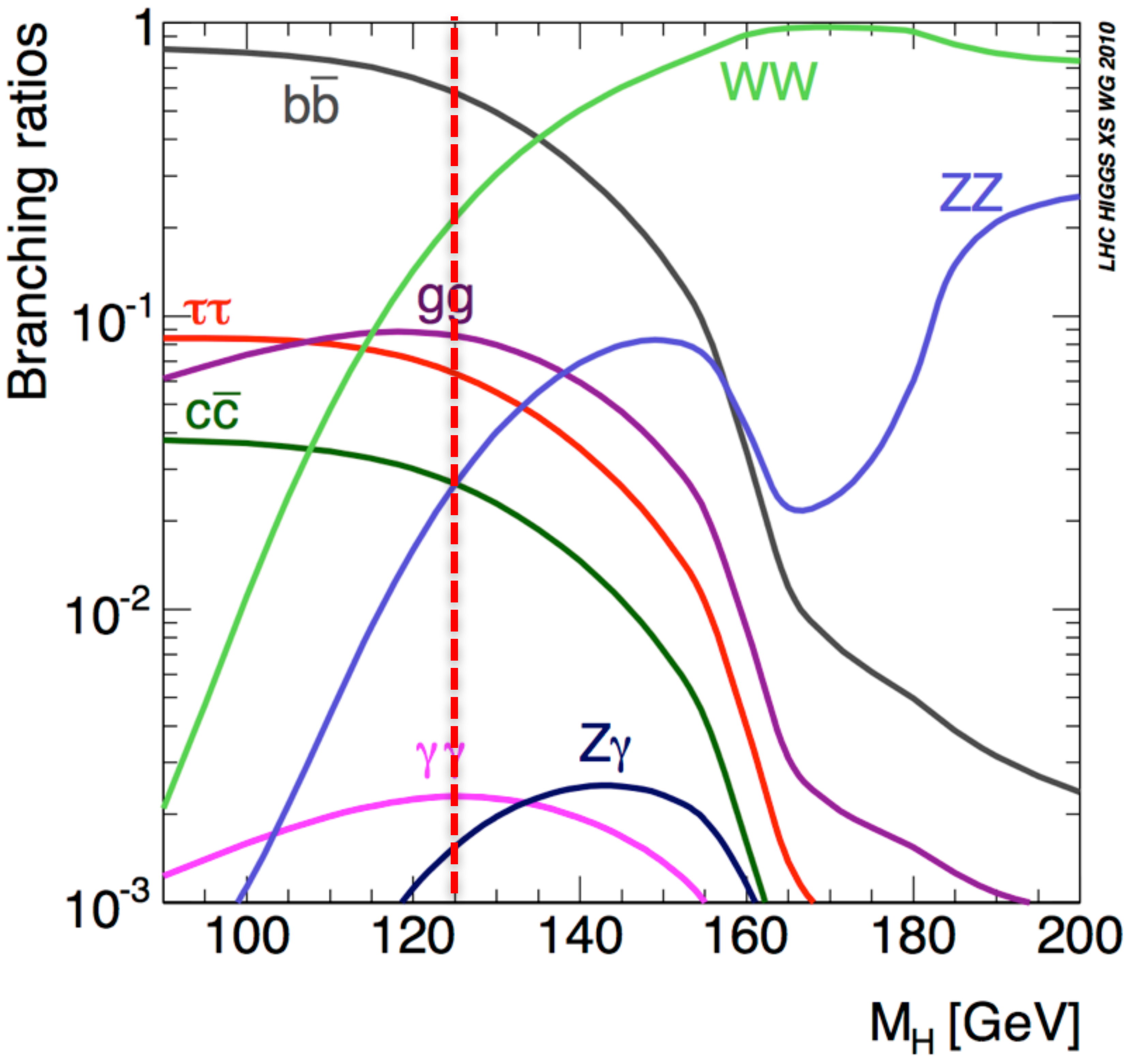

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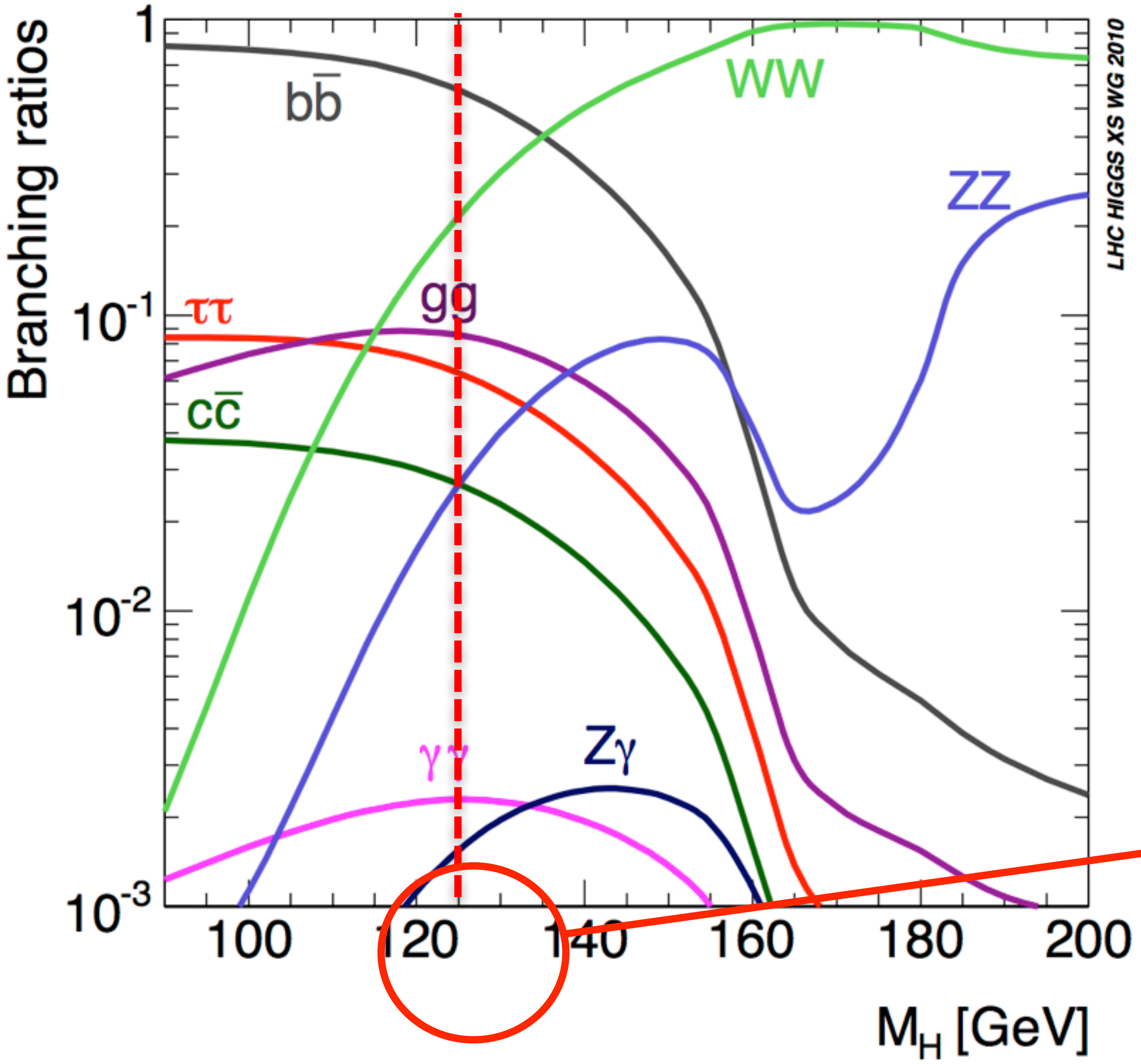

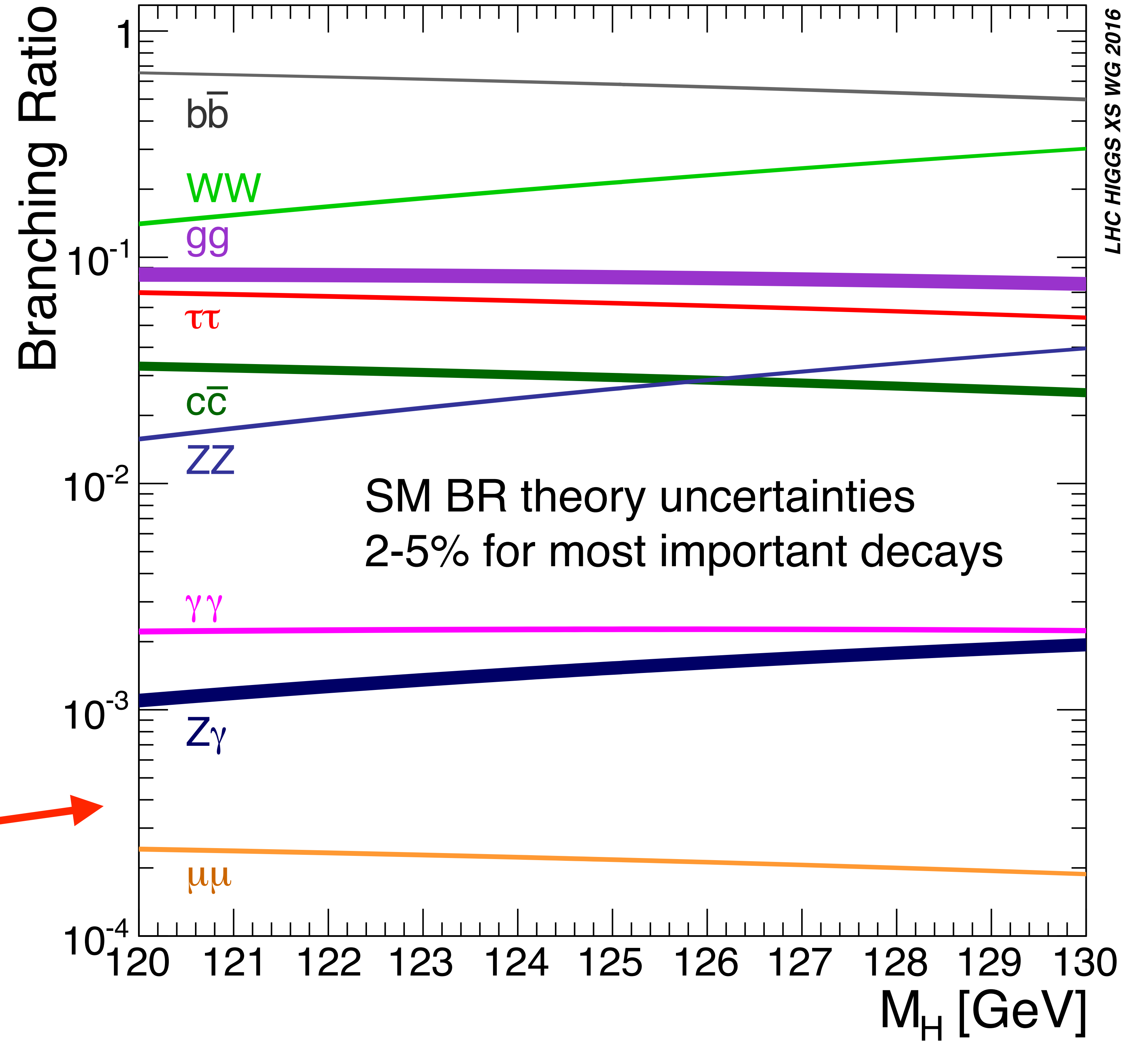

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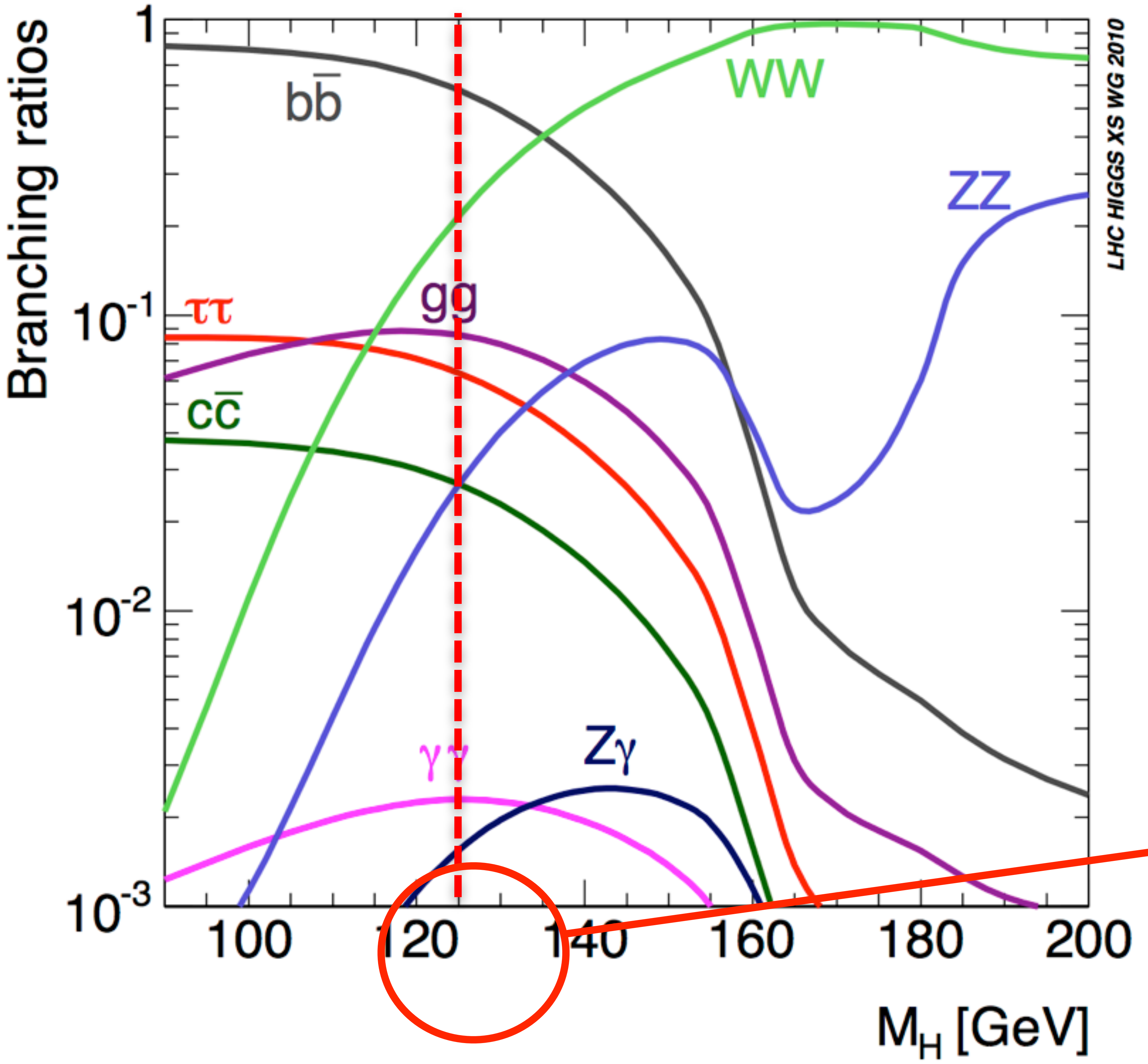
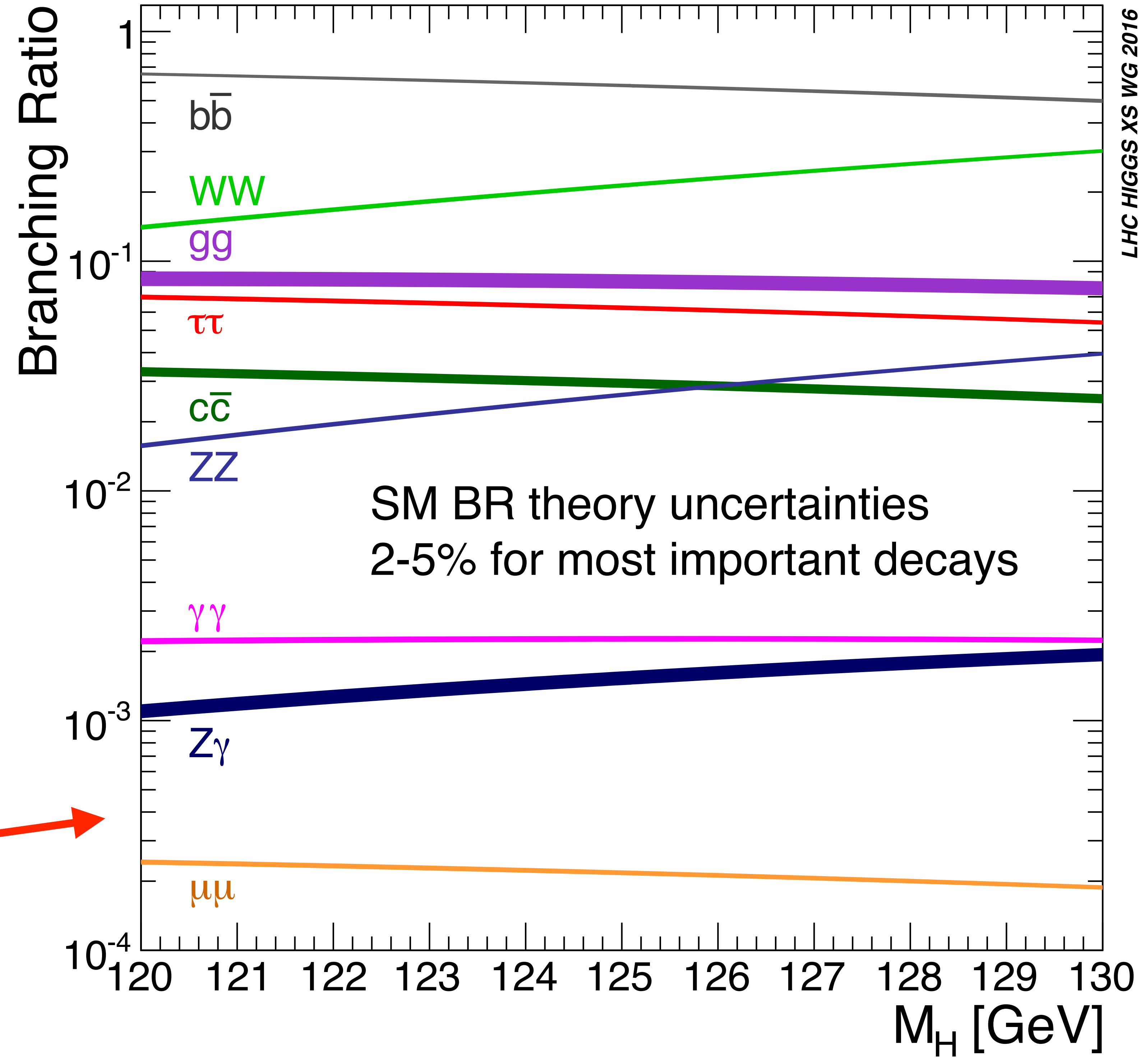
- Subsequent decay of vector bosons, and hadronization of qq events, yield a large variety of decay processes with very different relative abundances: These processes are identified through the particle content of the events.





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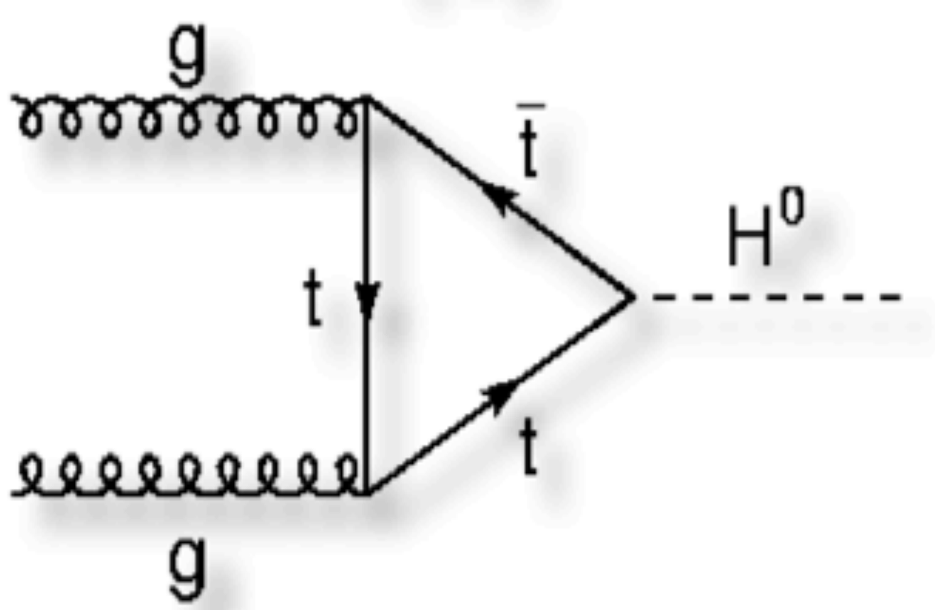
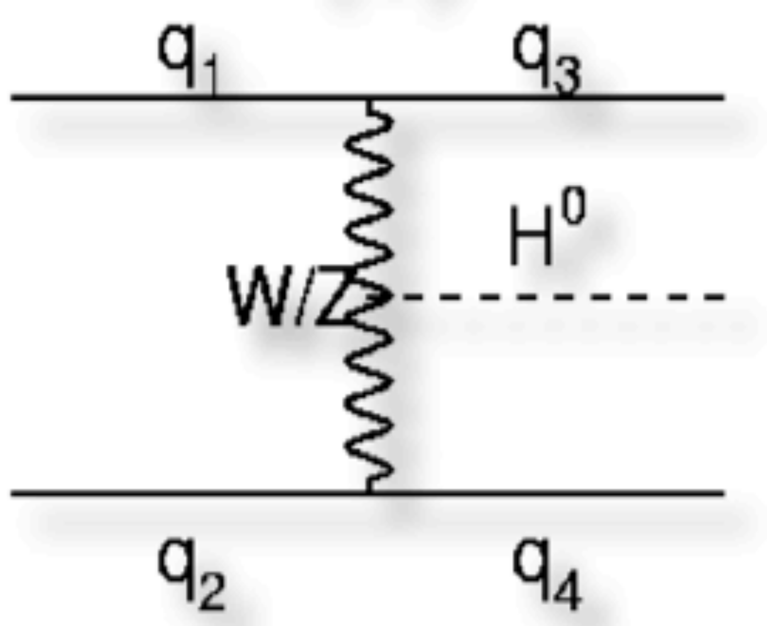
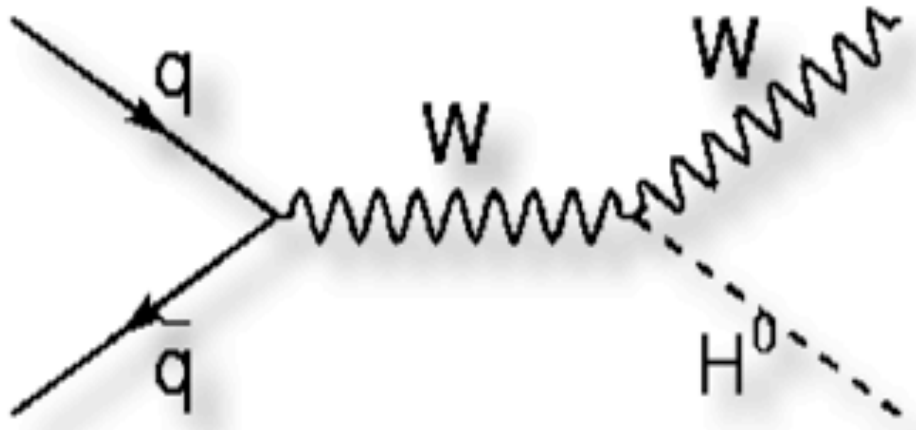
PRODUCING HIGGSES AT THE LHC



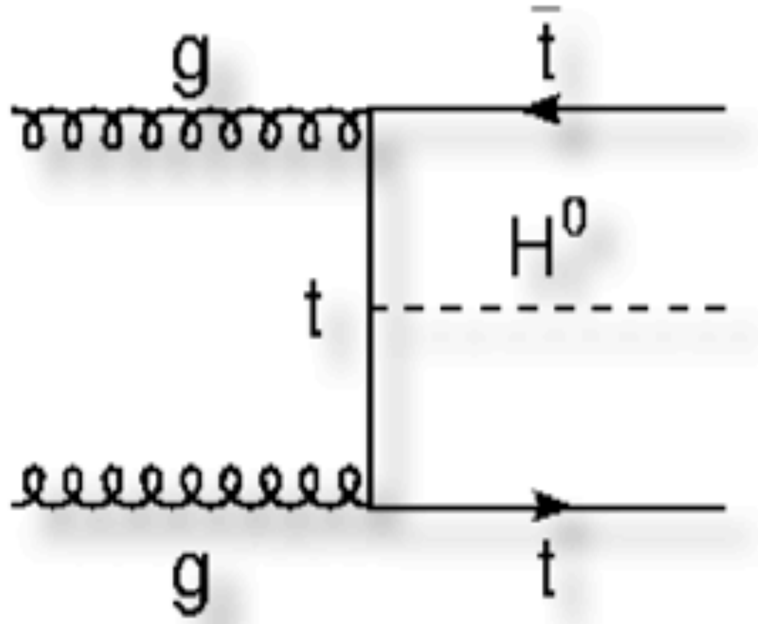
gluon fusion, ggH
48.52 pb



VBF, qqH (V=W,Z)
3.78 pb



Higgs-strahlung, VH
1.373
+ 0.8839 pb



Top associated production
0.5071 pb

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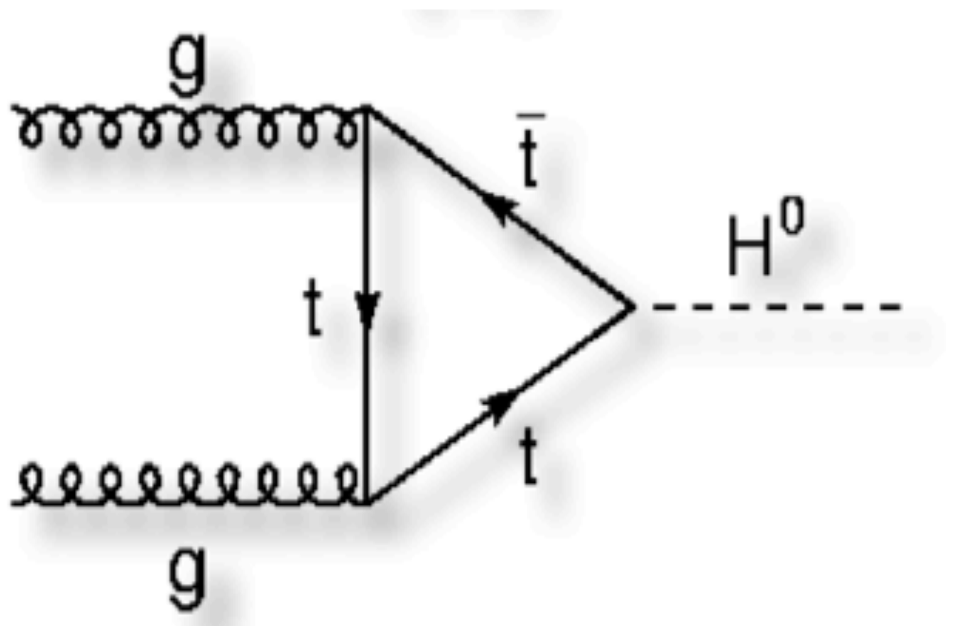

gluon fusion, ggH
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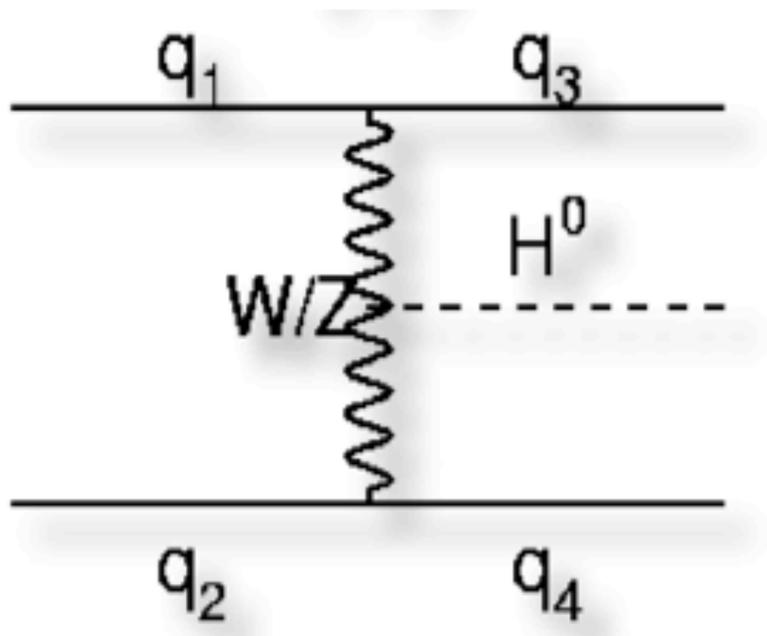

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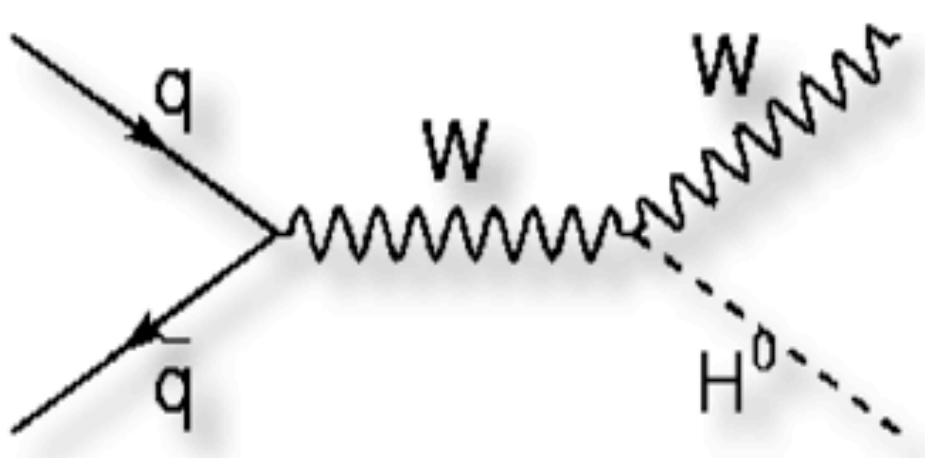

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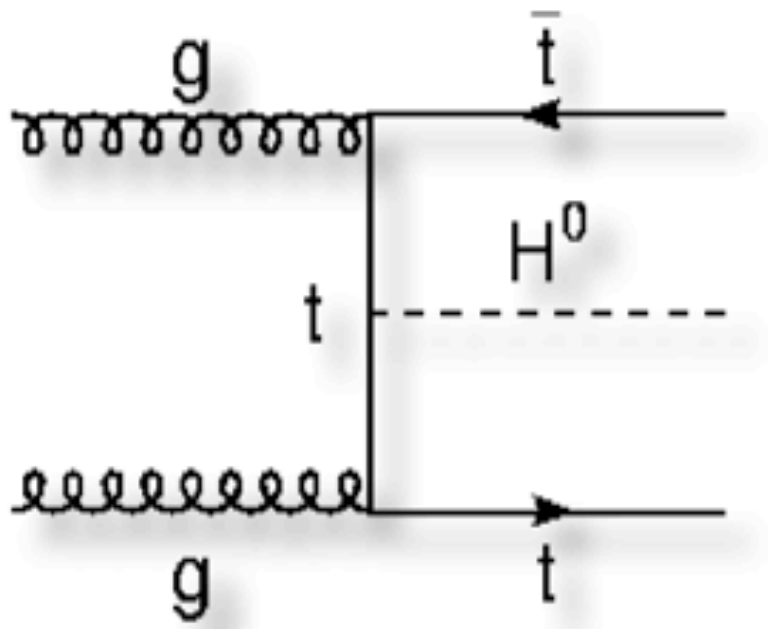

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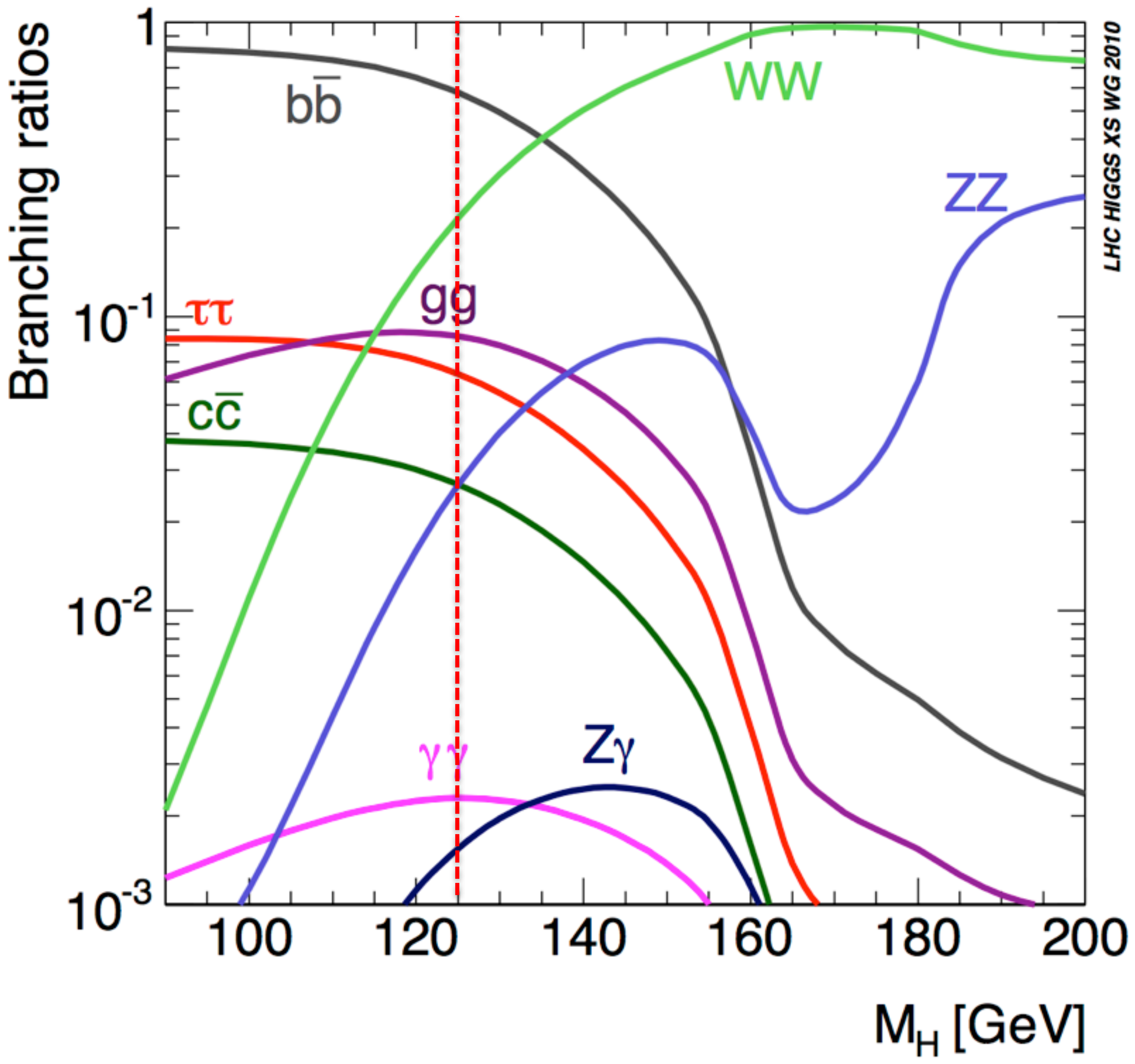

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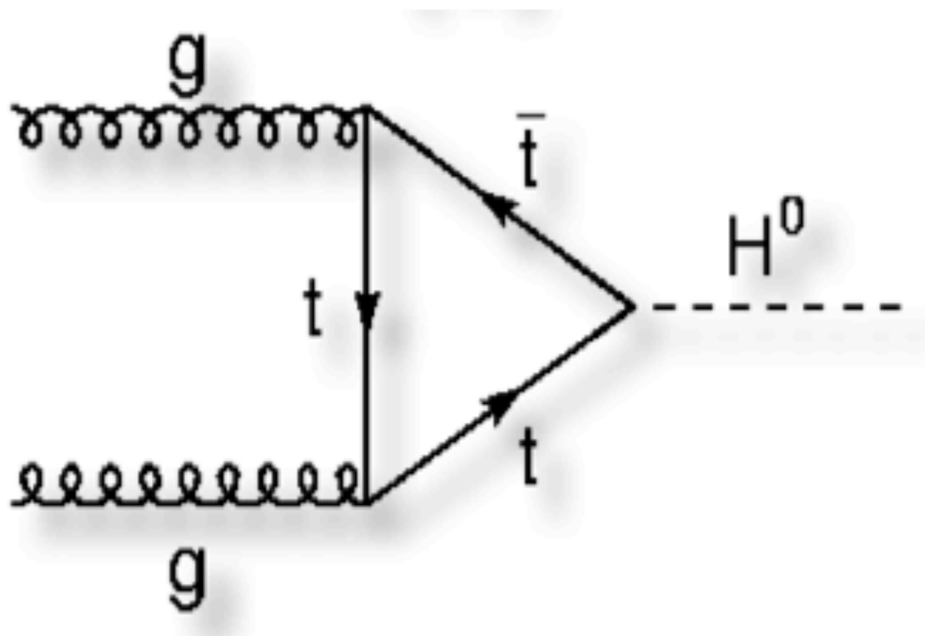

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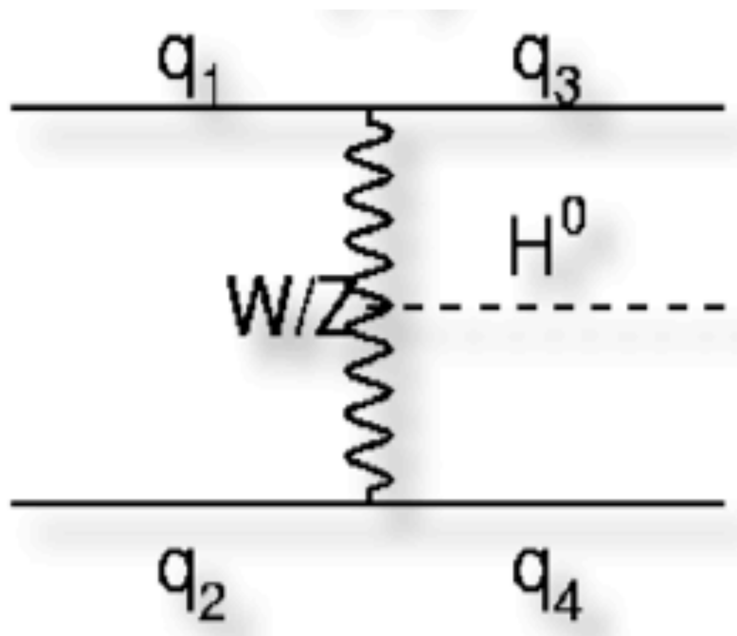

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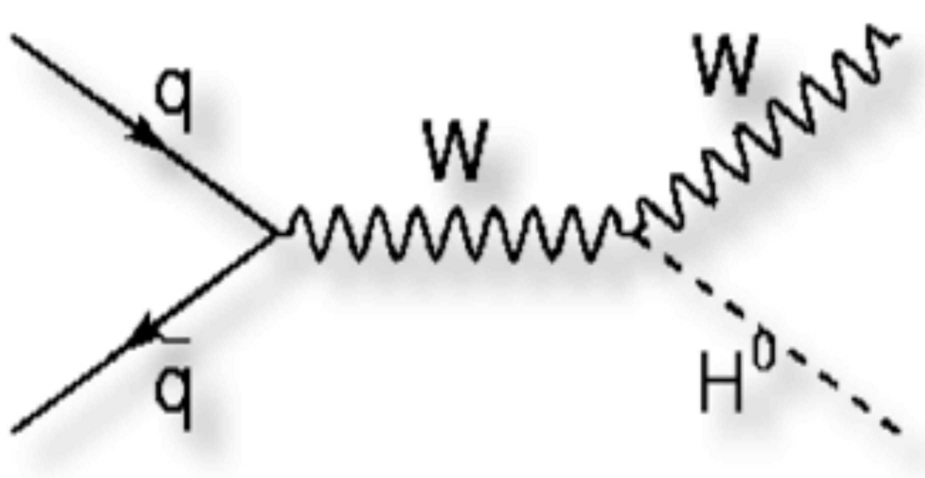

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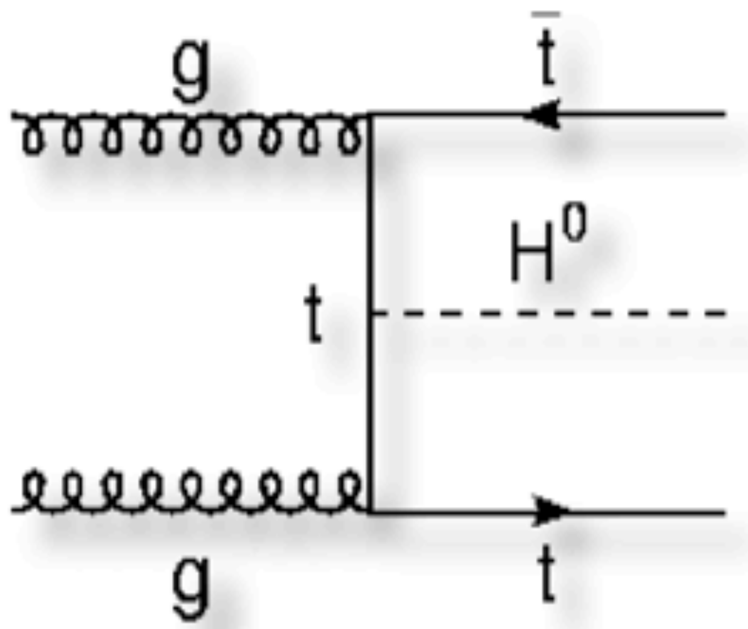

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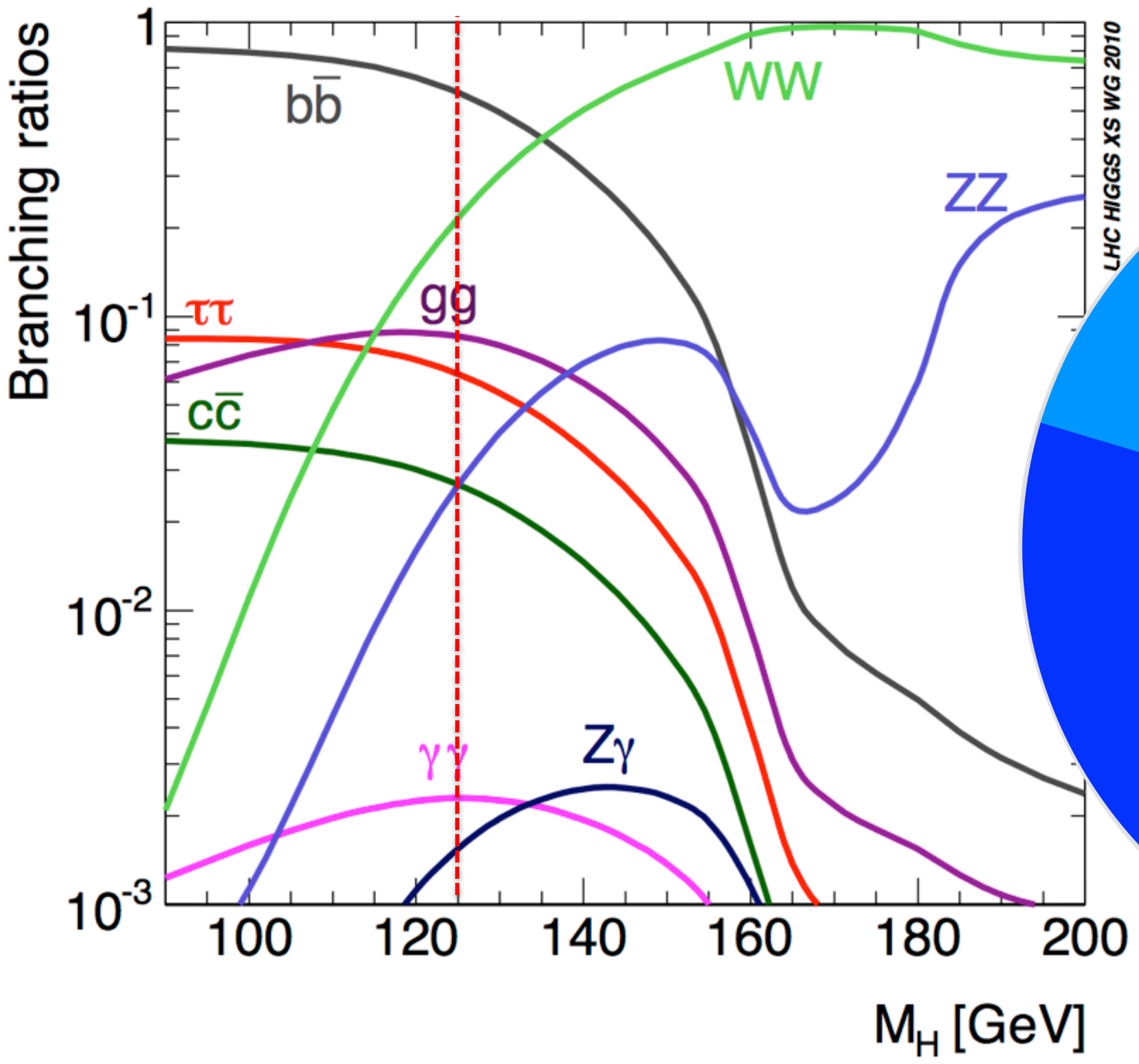
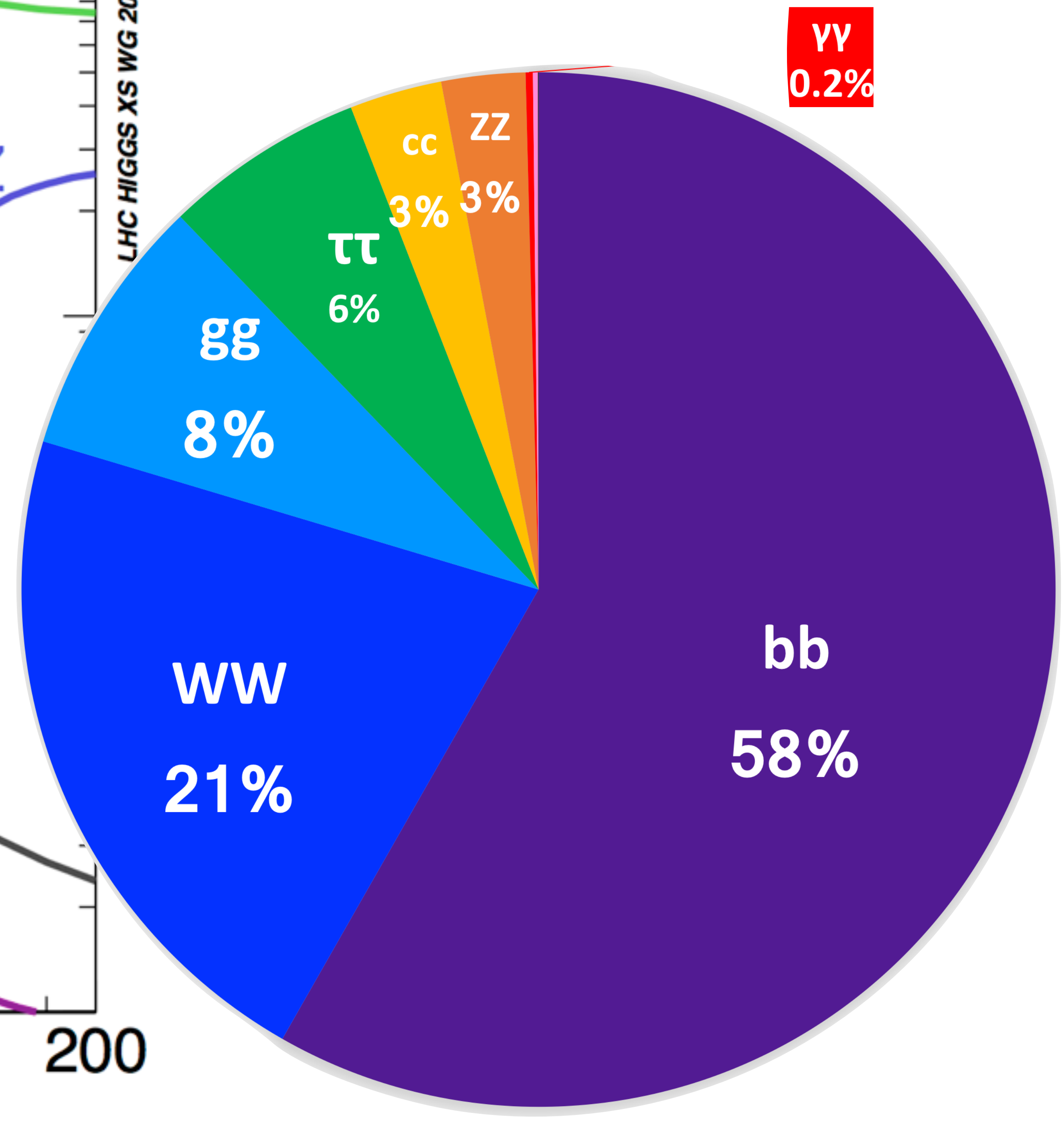
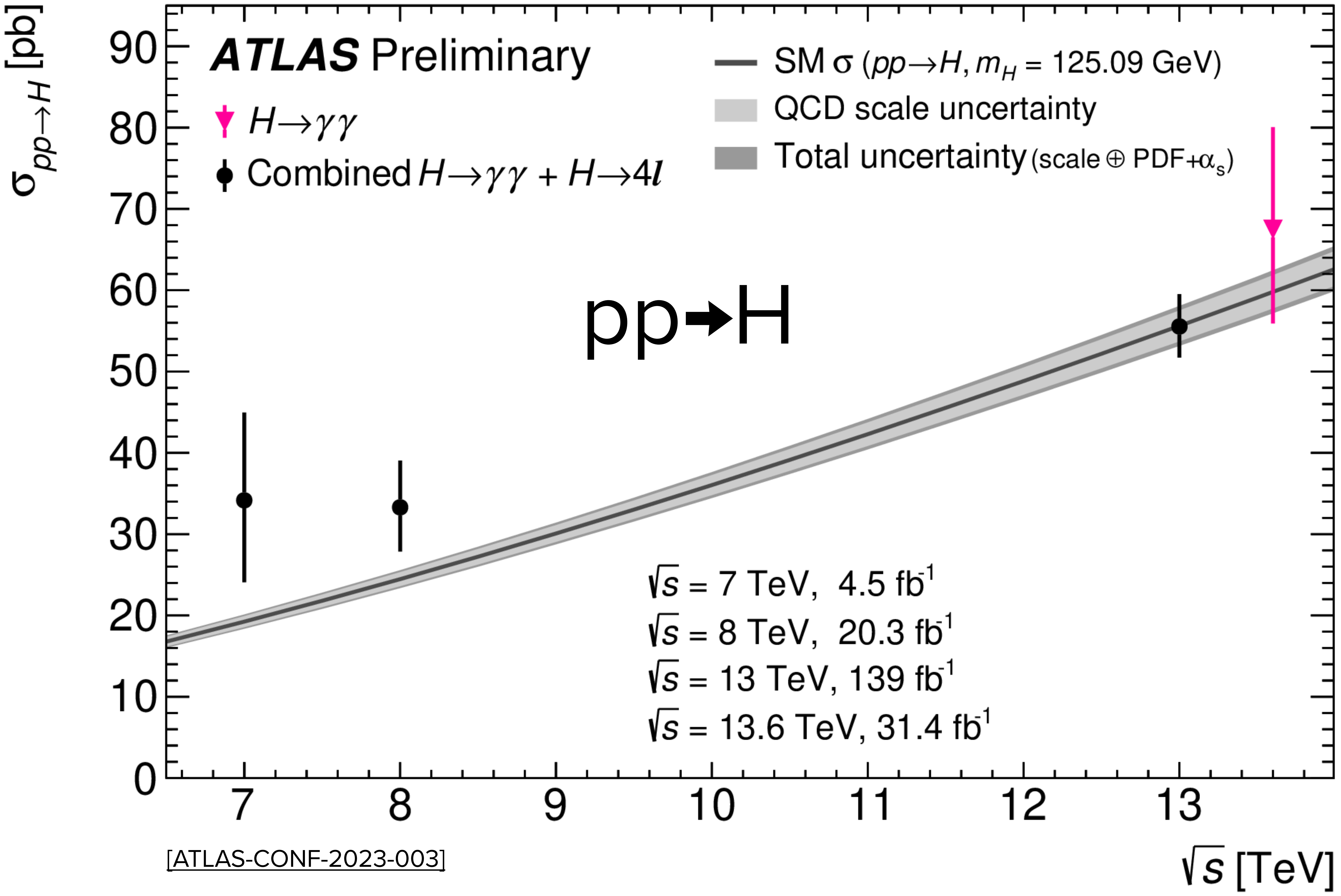
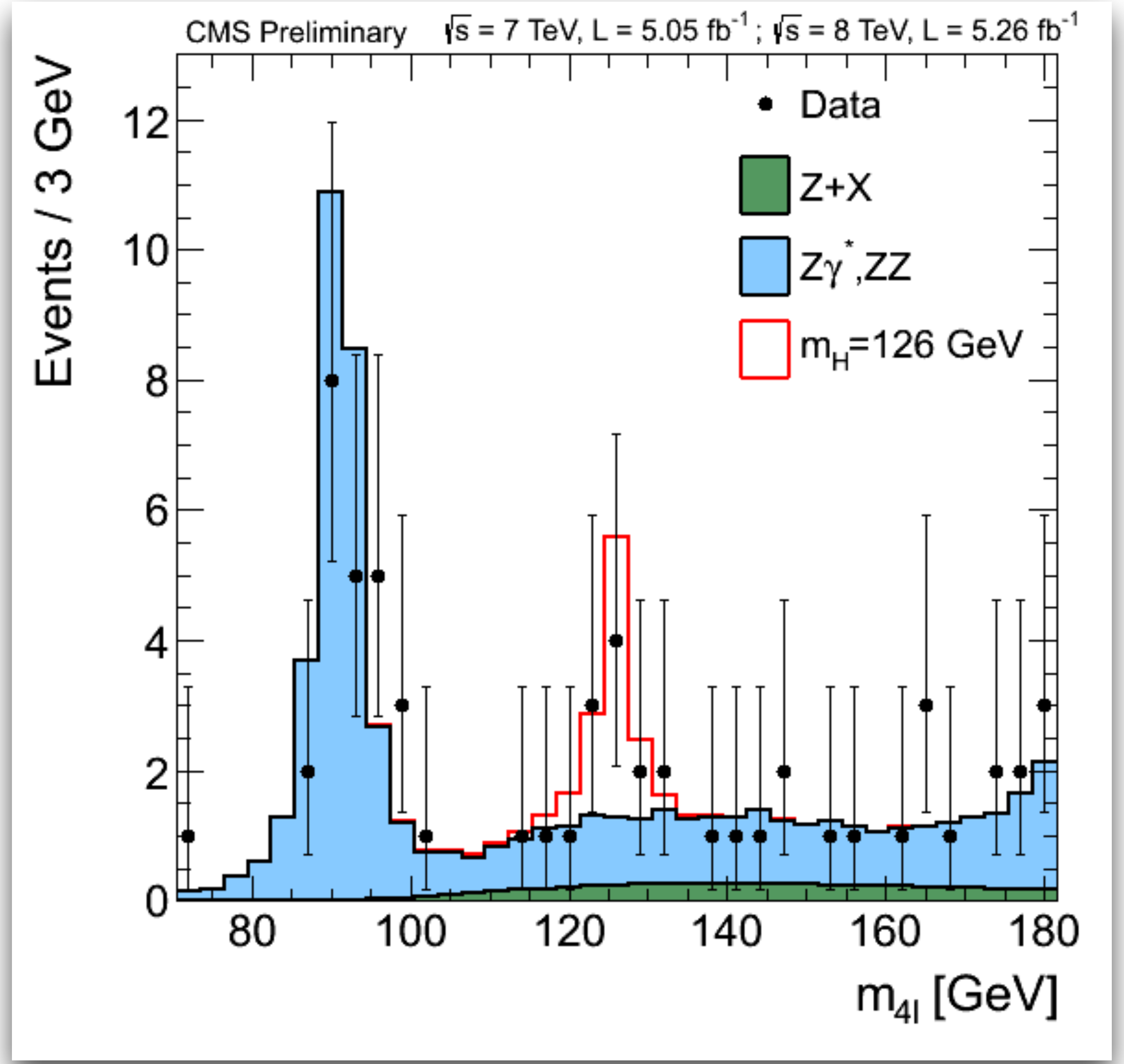


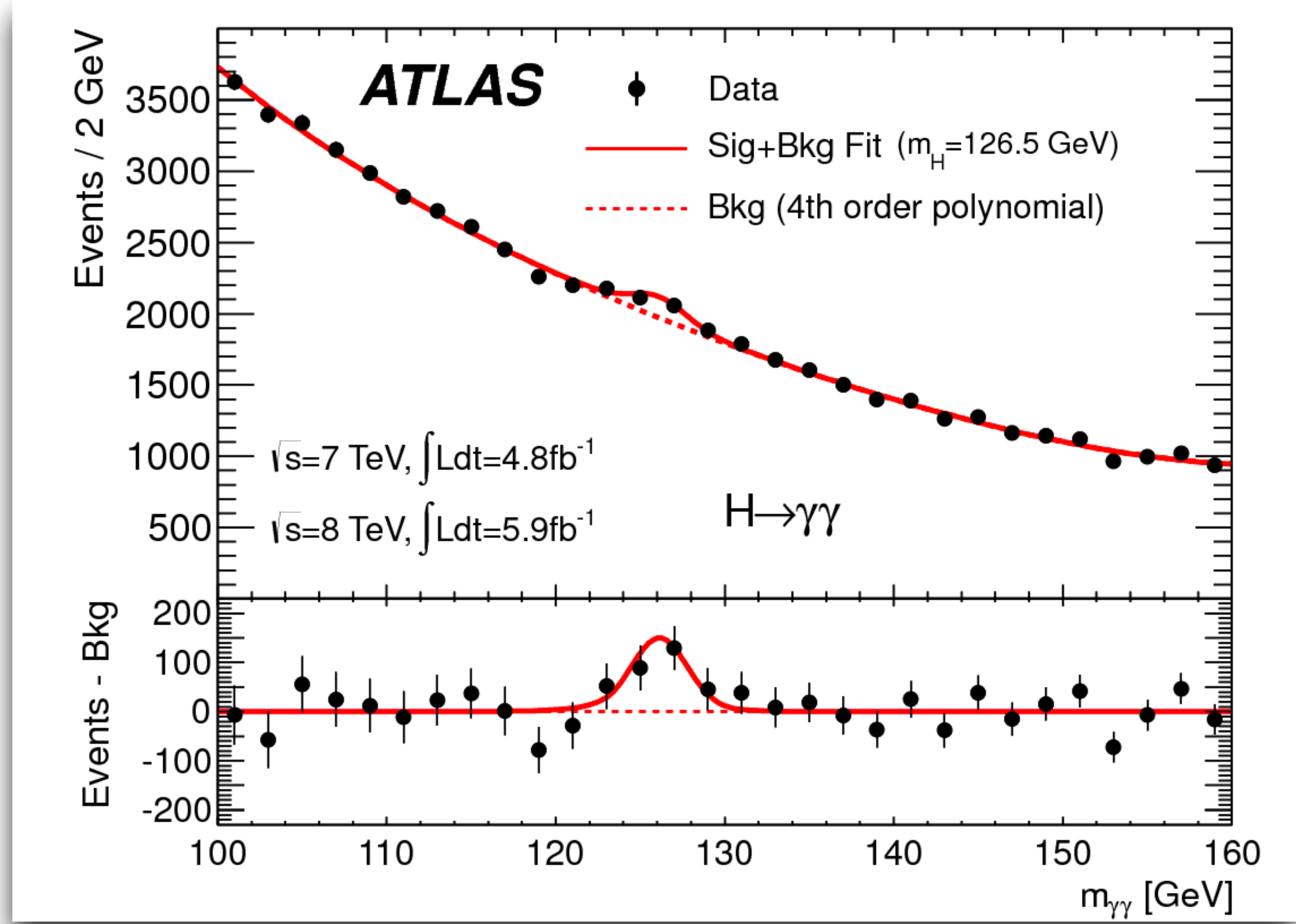


HIGGSES AT 7, 8, 13... AND 13.6 TEV!



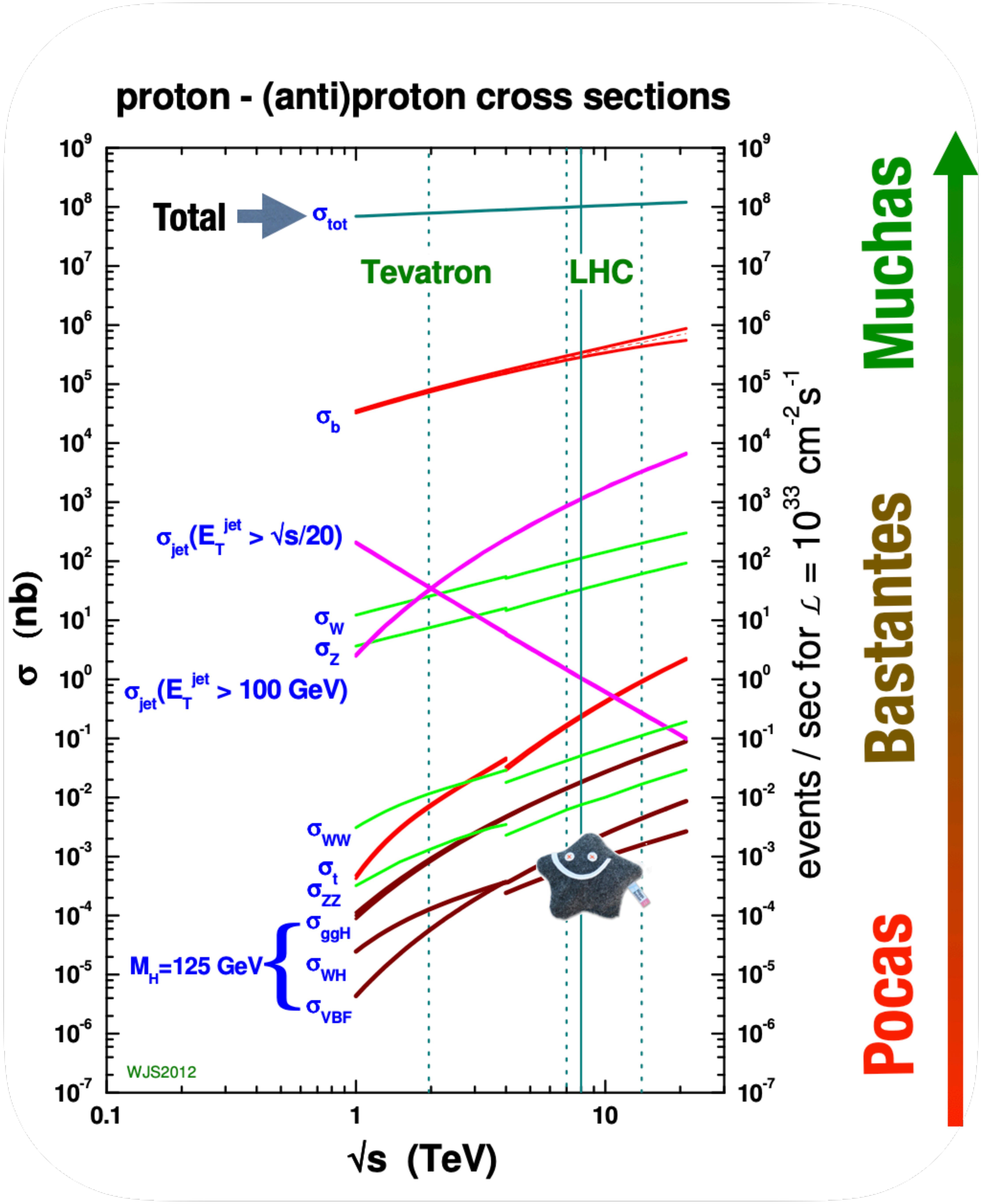
[ATLAS-CONF-2023-003]


CMS Preliminary √s = 7 TeV, L = 5.05 fb-1 ; √s = 8 TeV, L = 5.26 fb-1
Events / 3 GeV
Data
Z+X
Zγ*,ZZ
mH=126 GeV
m4l [GeV]


ATLAS
Data
Sig+Bkg Fit (mH=126.5 GeV)
Bkg (4th order polynomial)
Events / 2 GeV
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
Events - Bkg
mγγ [GeV]

HIGGSES?

OR OTHER SM PROCESSES?



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  - Reconstruct Higgs mass and kinematics (pt, eta) by vectorial sum of the 4 momenta of the decay products

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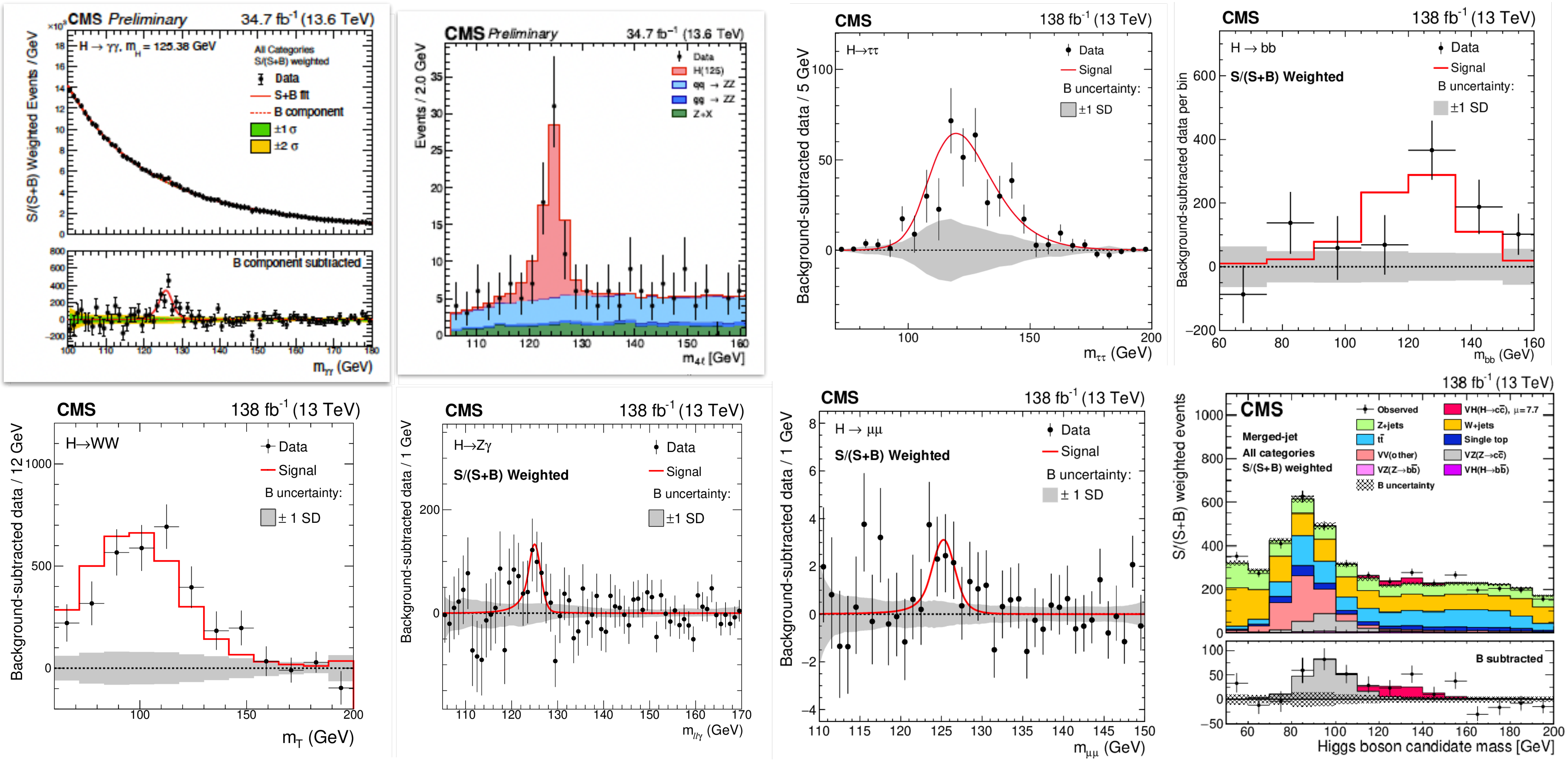
- Complex analyses with many different categories enhanced in signal (targeting different production modes and decays) and backgrounds (to control them or even measure them directly in a common fit, if possible)

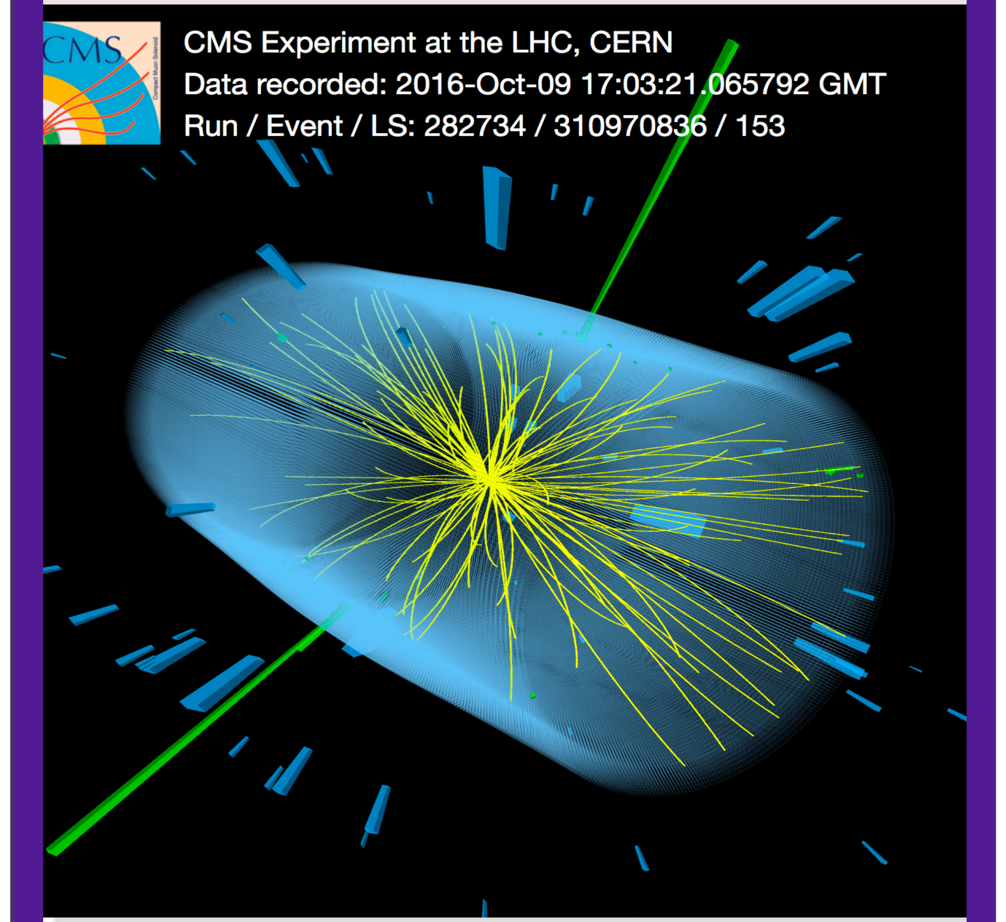
TODAY...

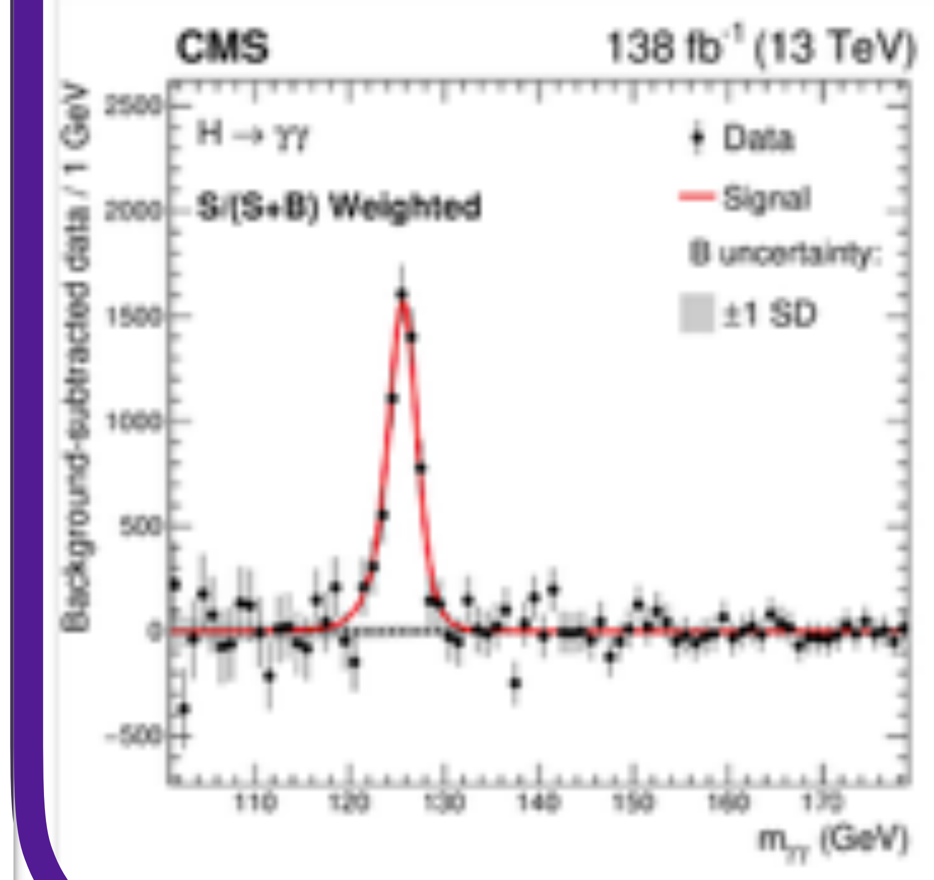


NOTE: I tend to use CMS for the examples I show: ATLAS&CMS have very similar performance, in general whatever I show for one experiment will be available for the other one

$H \rightarrow \gamma\gamma$

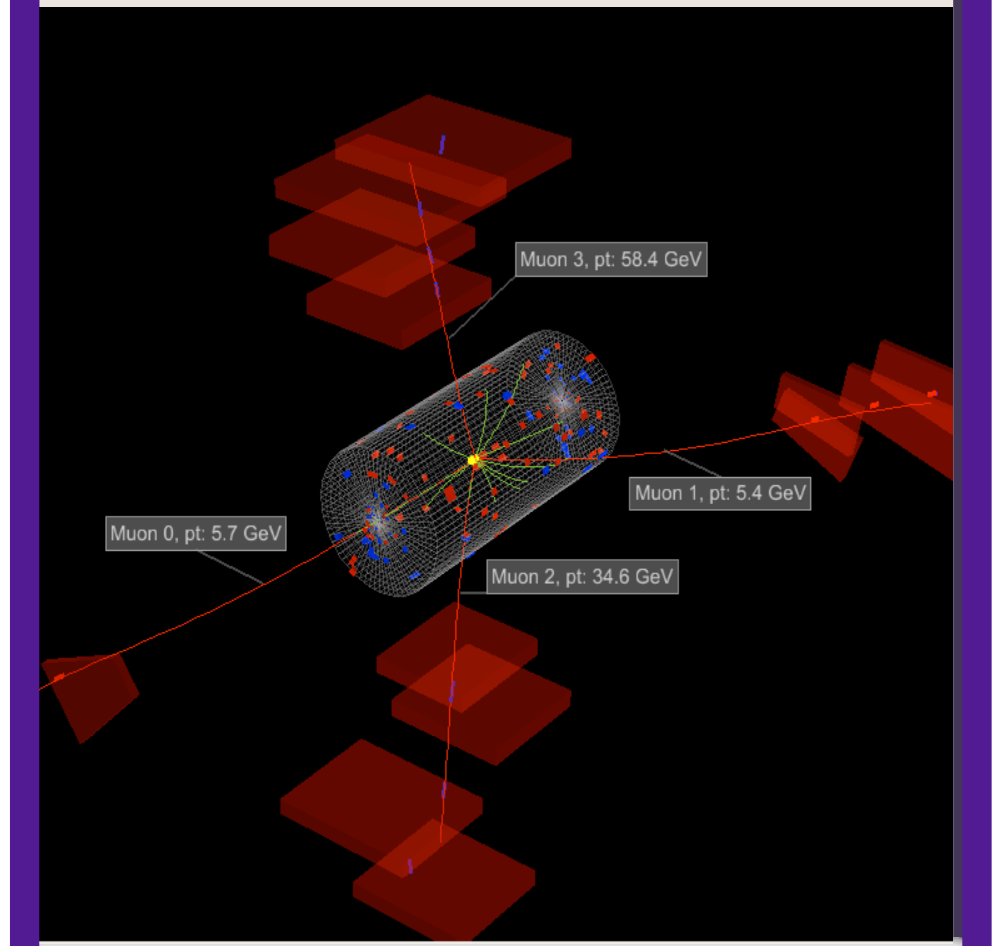
Br~0.2%

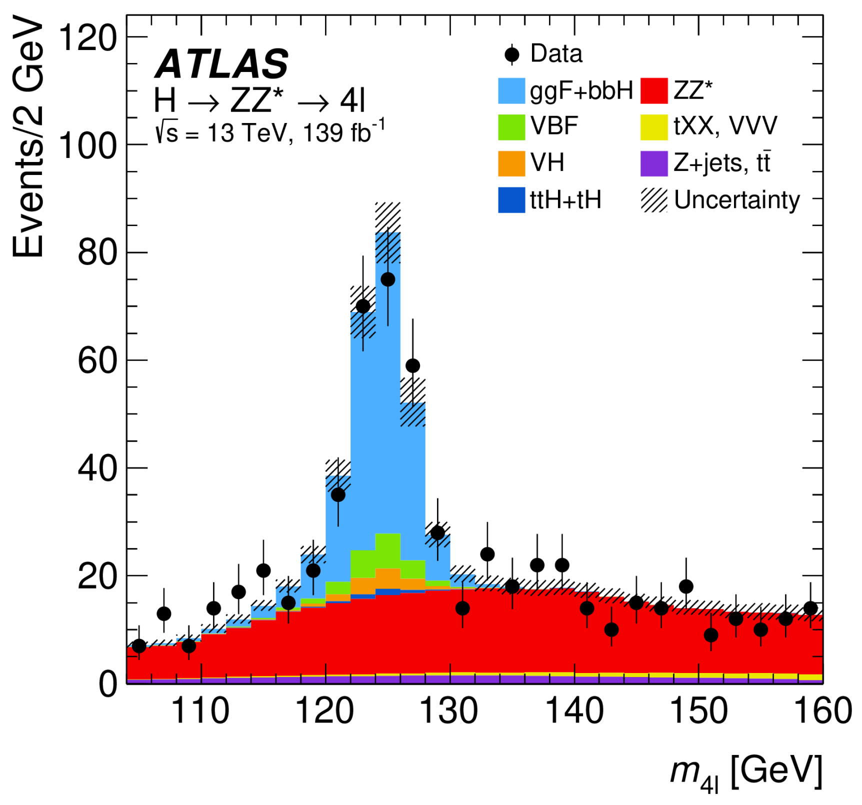




$H \rightarrow ZZ$

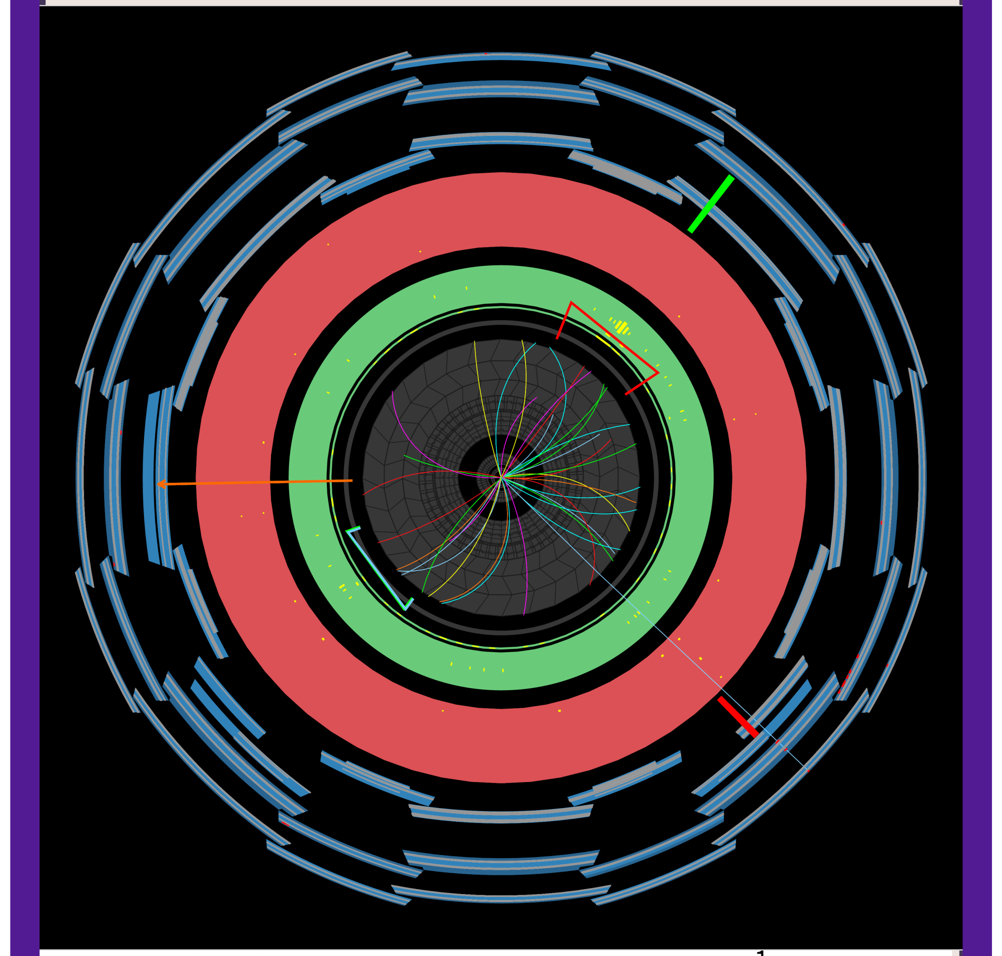
Br~3%

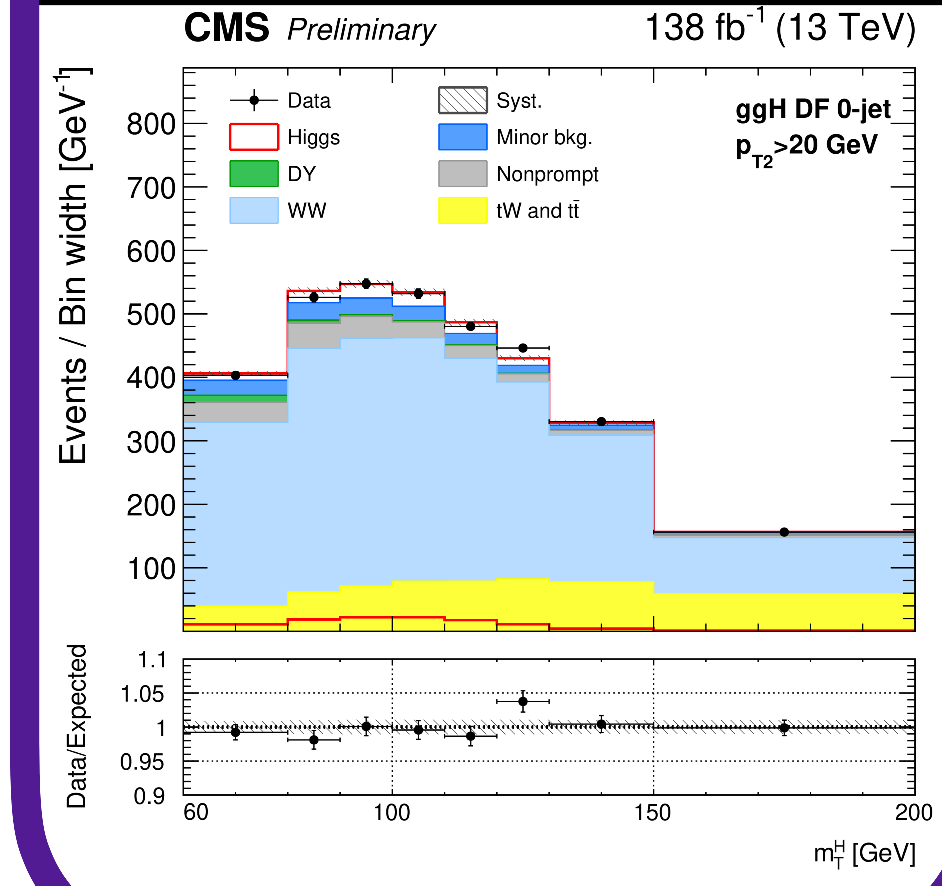




$H \rightarrow WW$

Br~21%

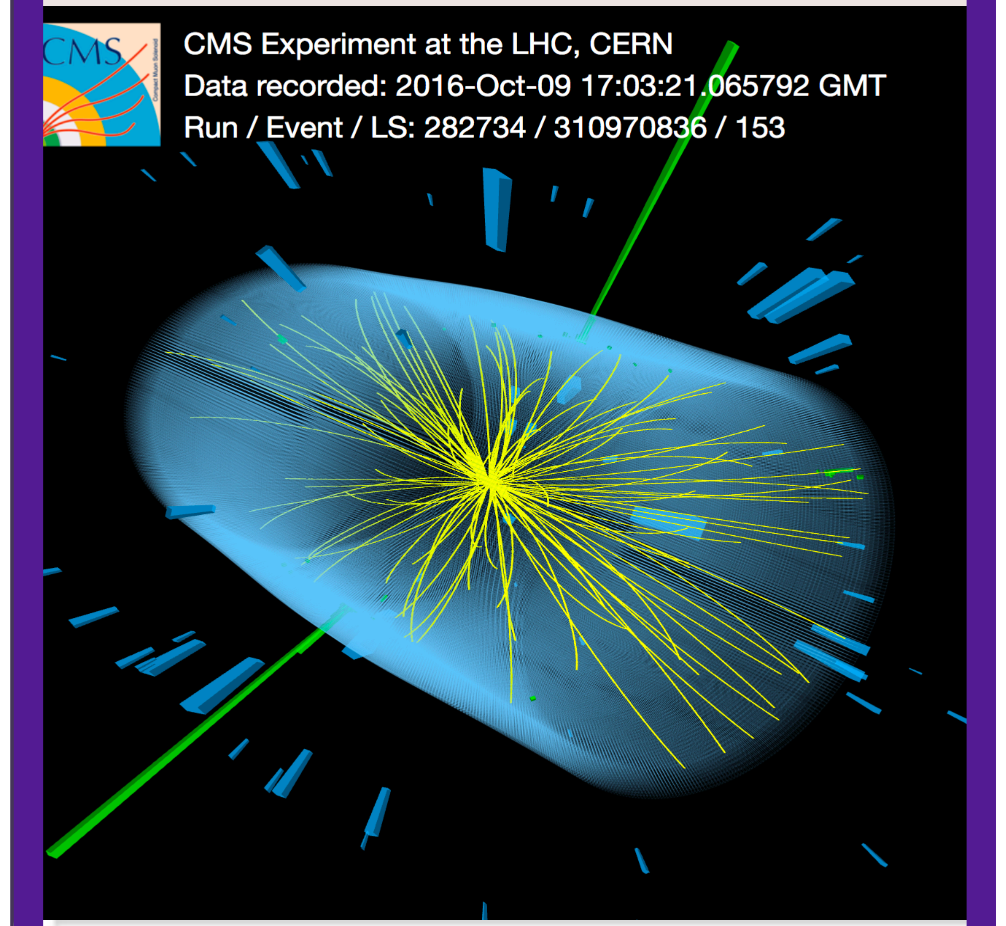


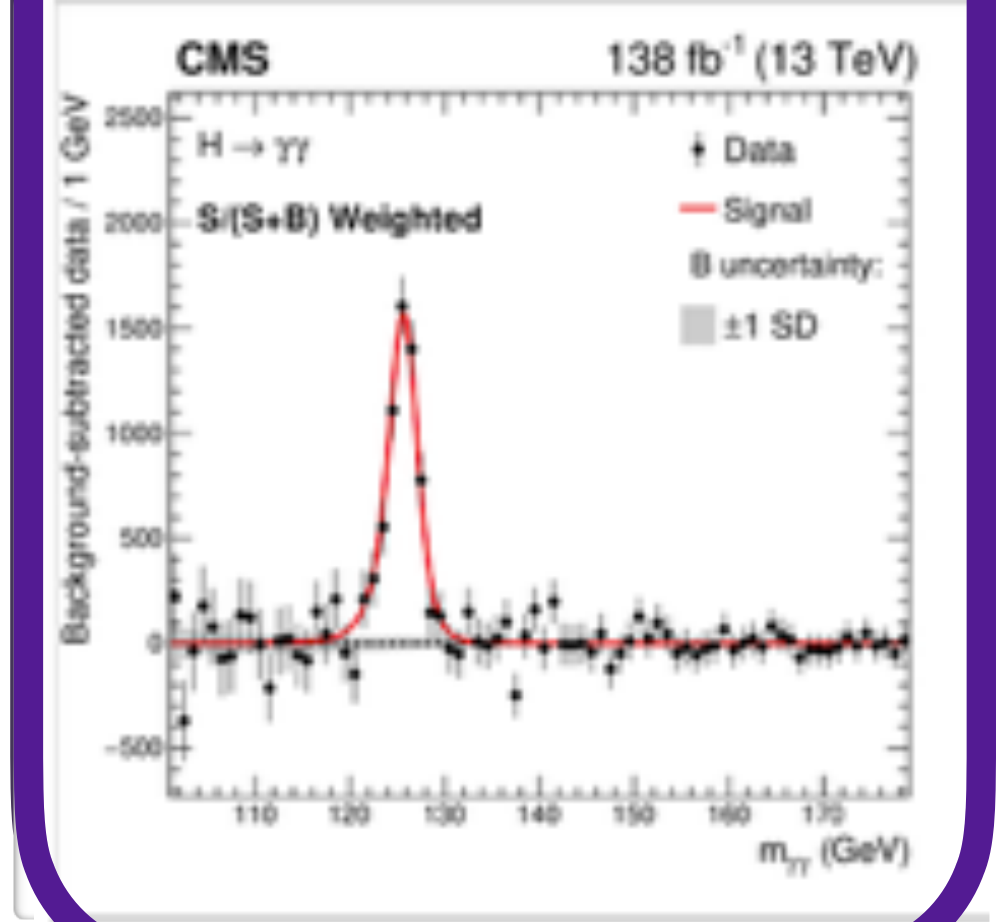


Coupling to Vector Bosons

$H \to \gamma\gamma$

Br~0.2%





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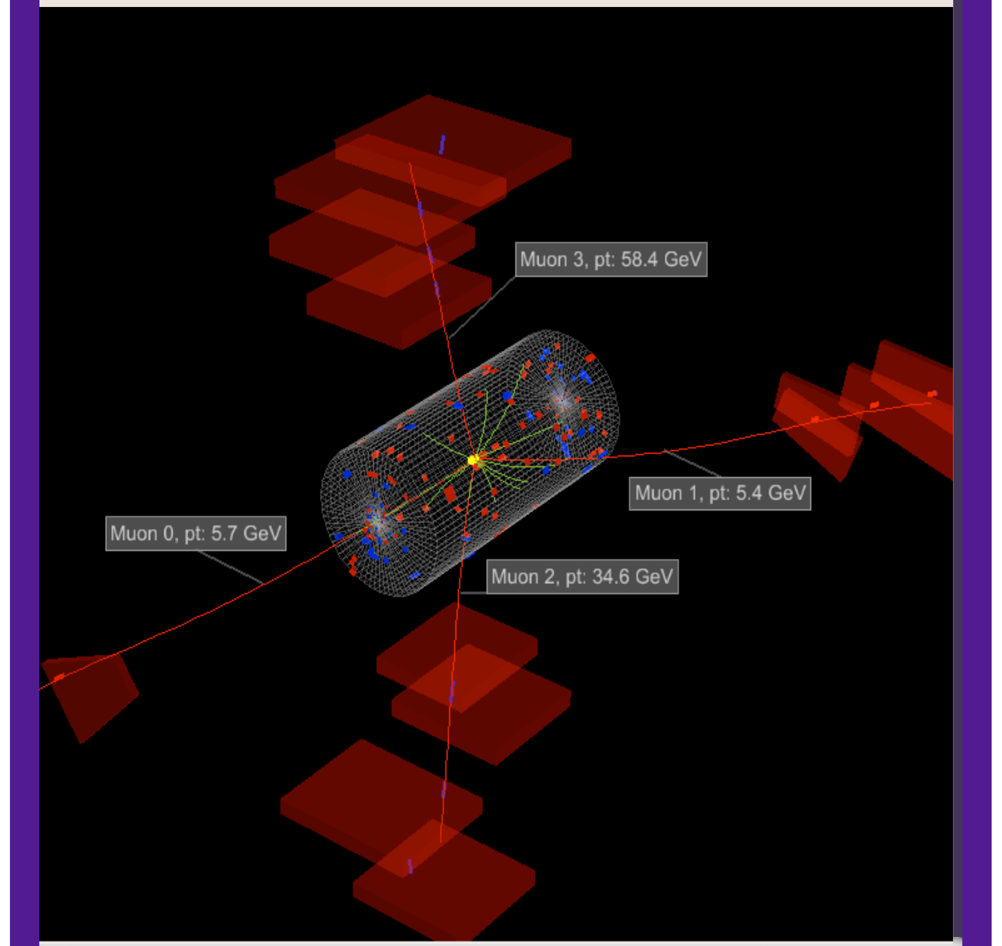

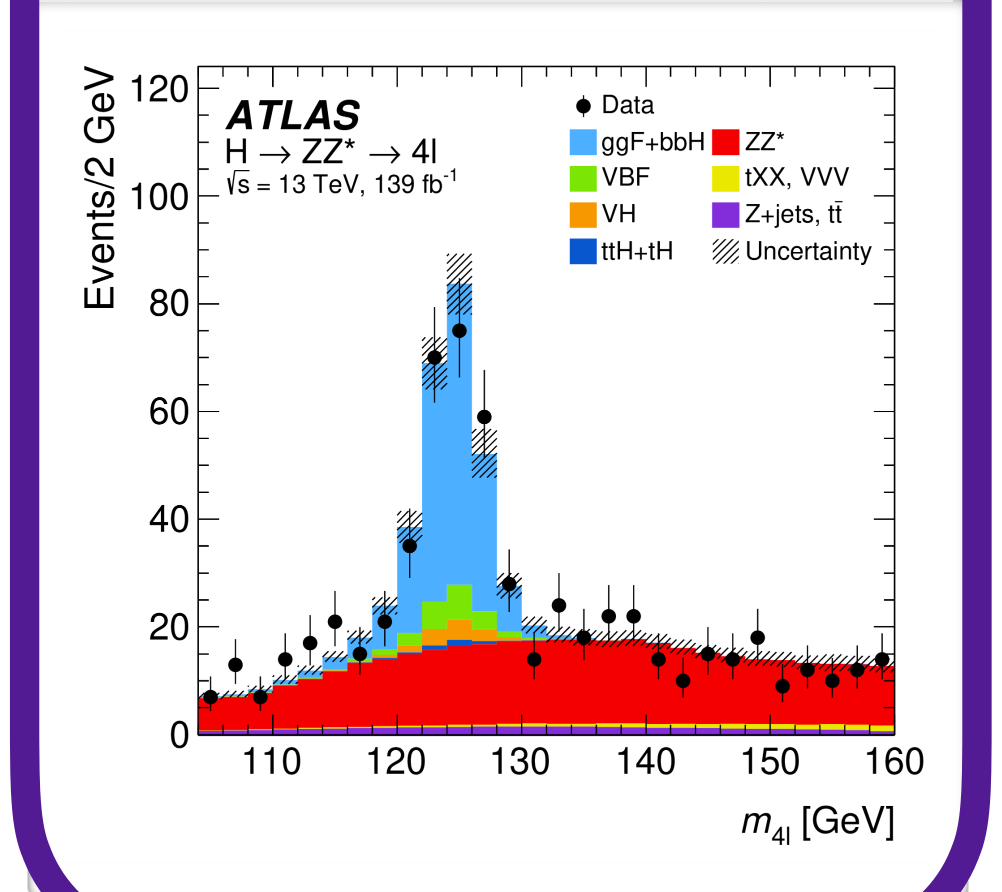

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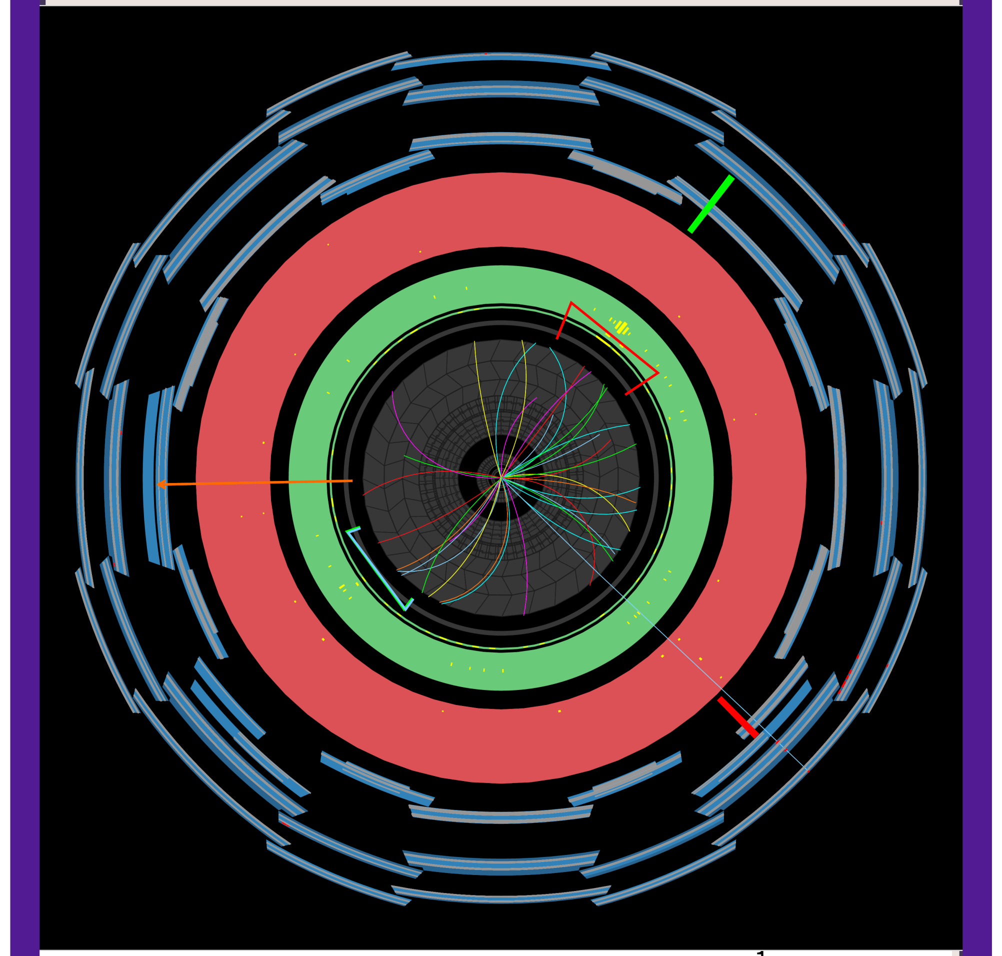

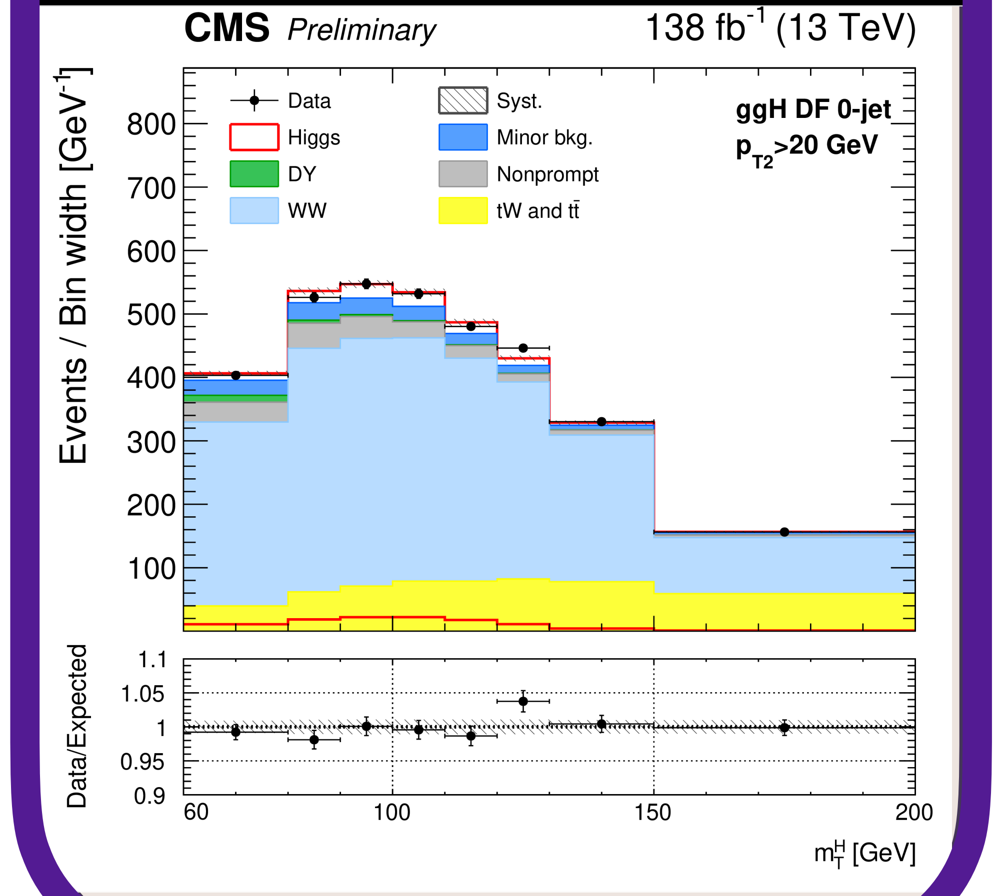

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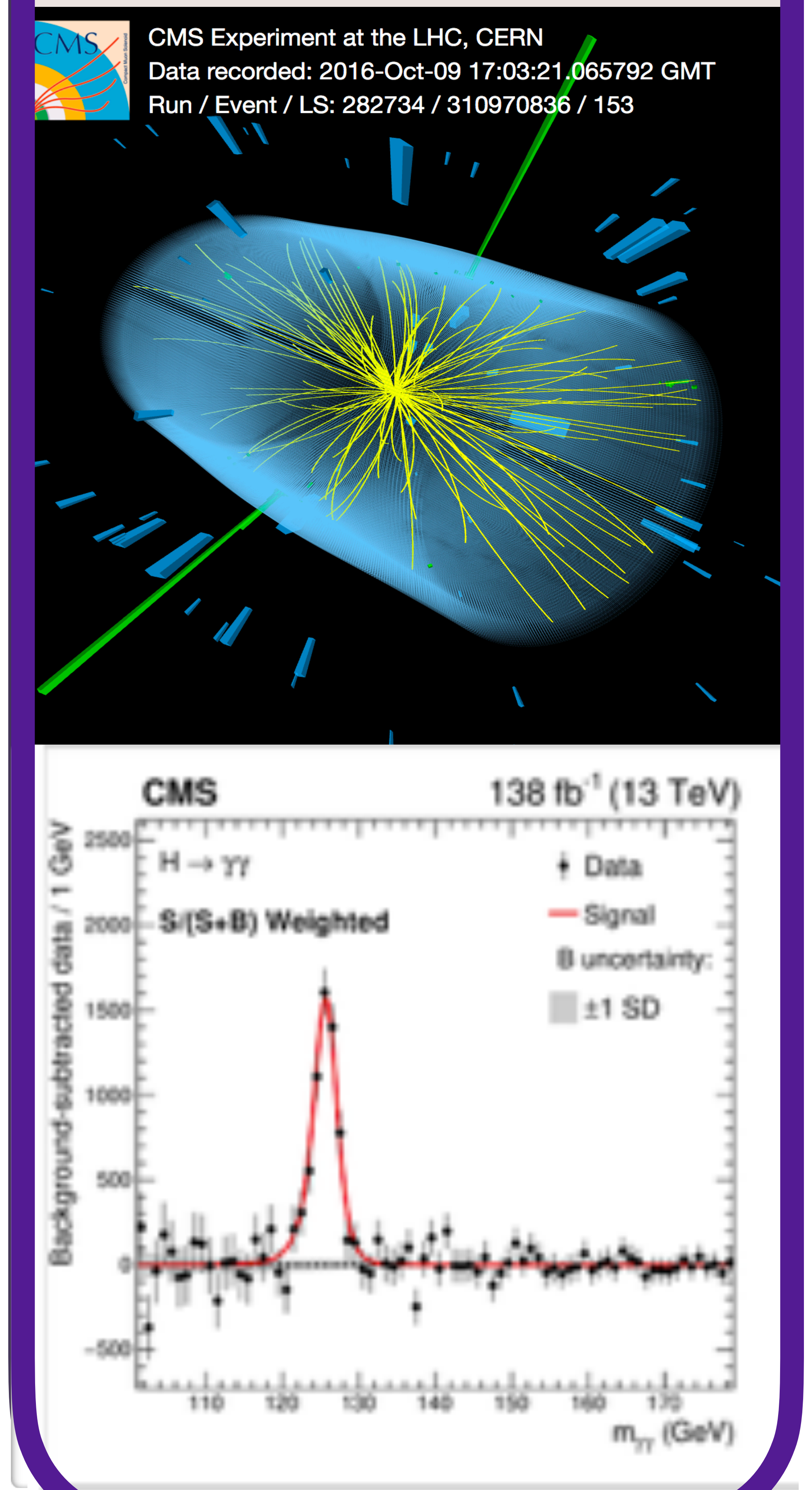

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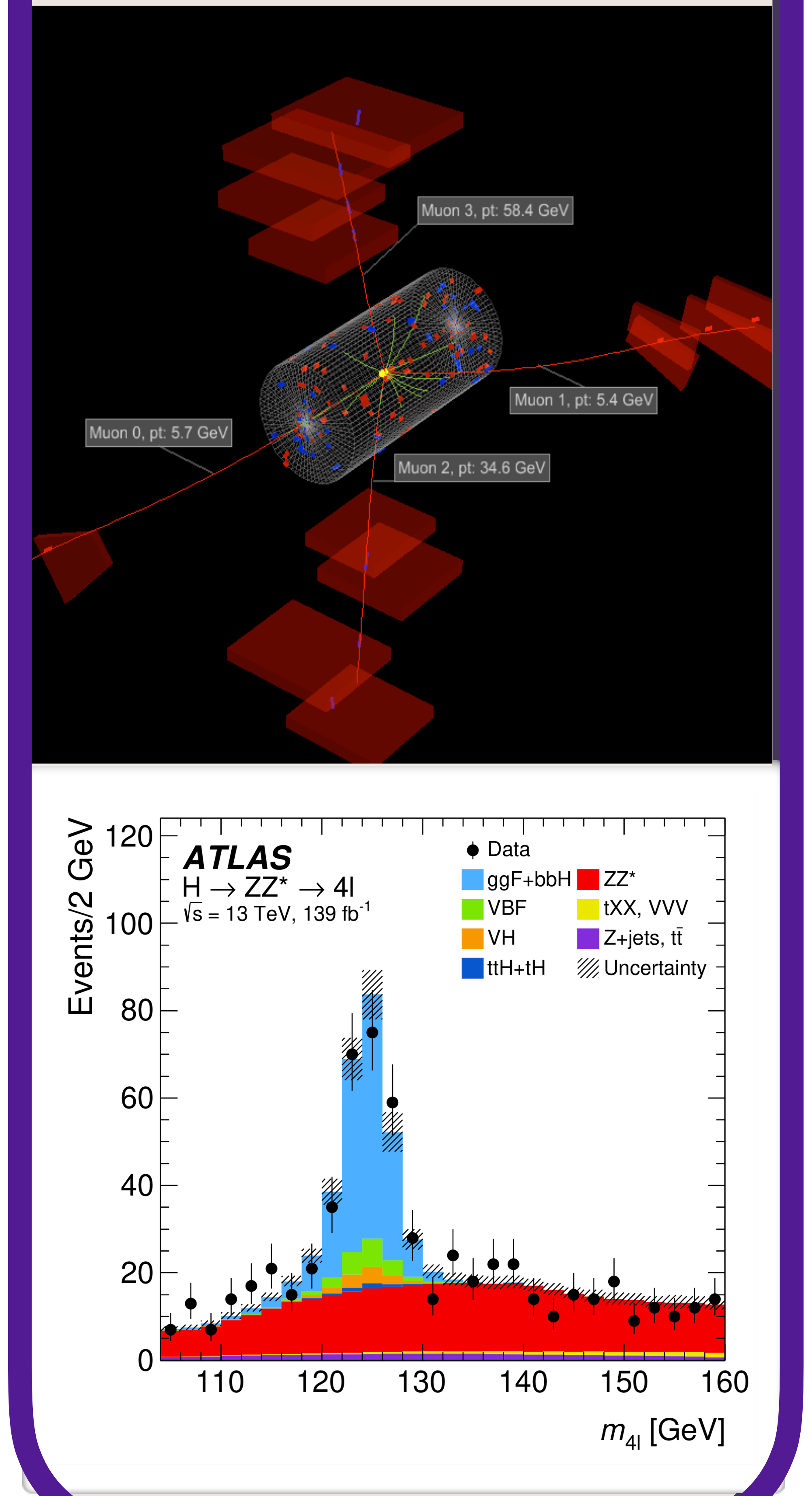

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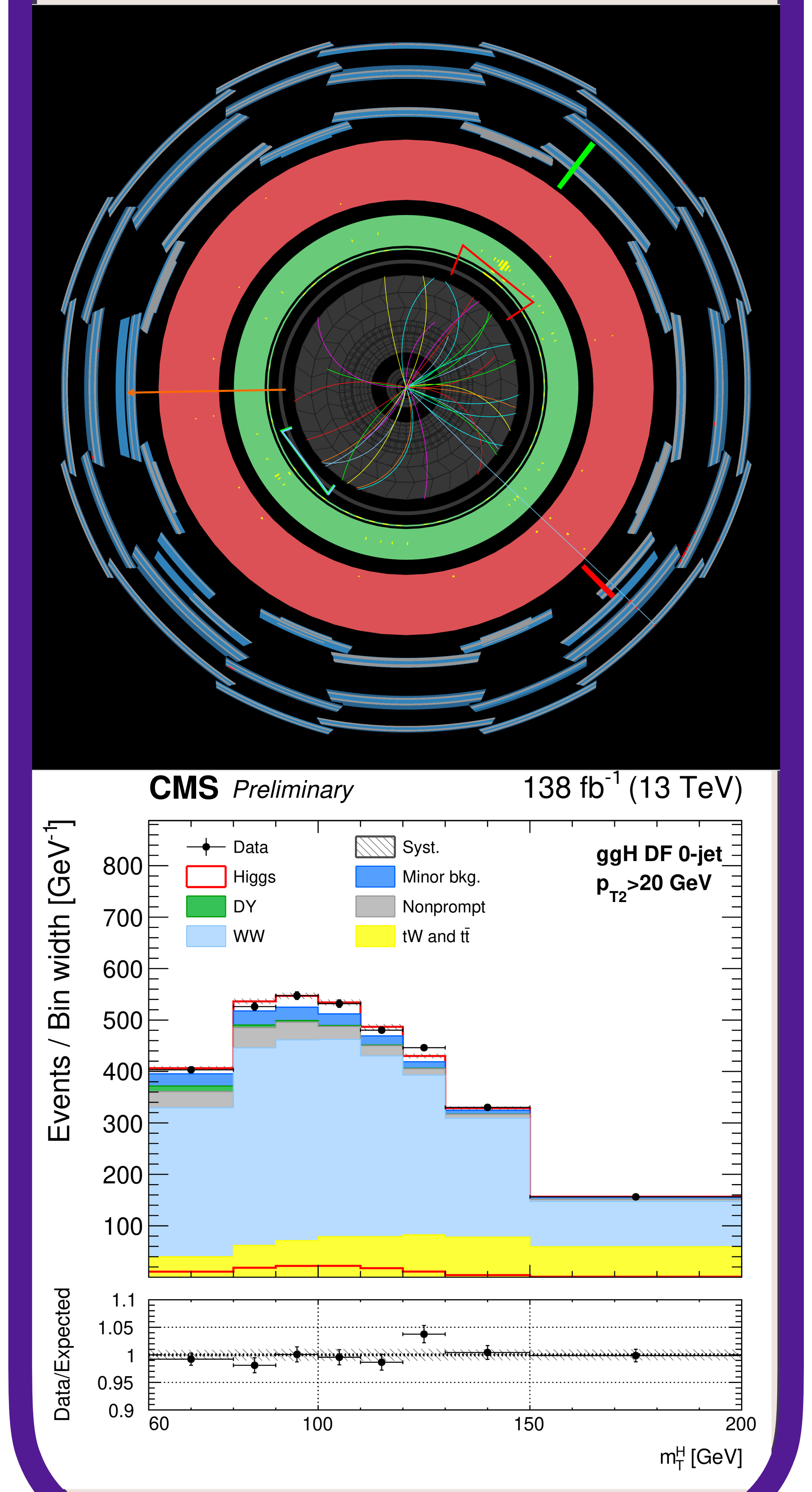

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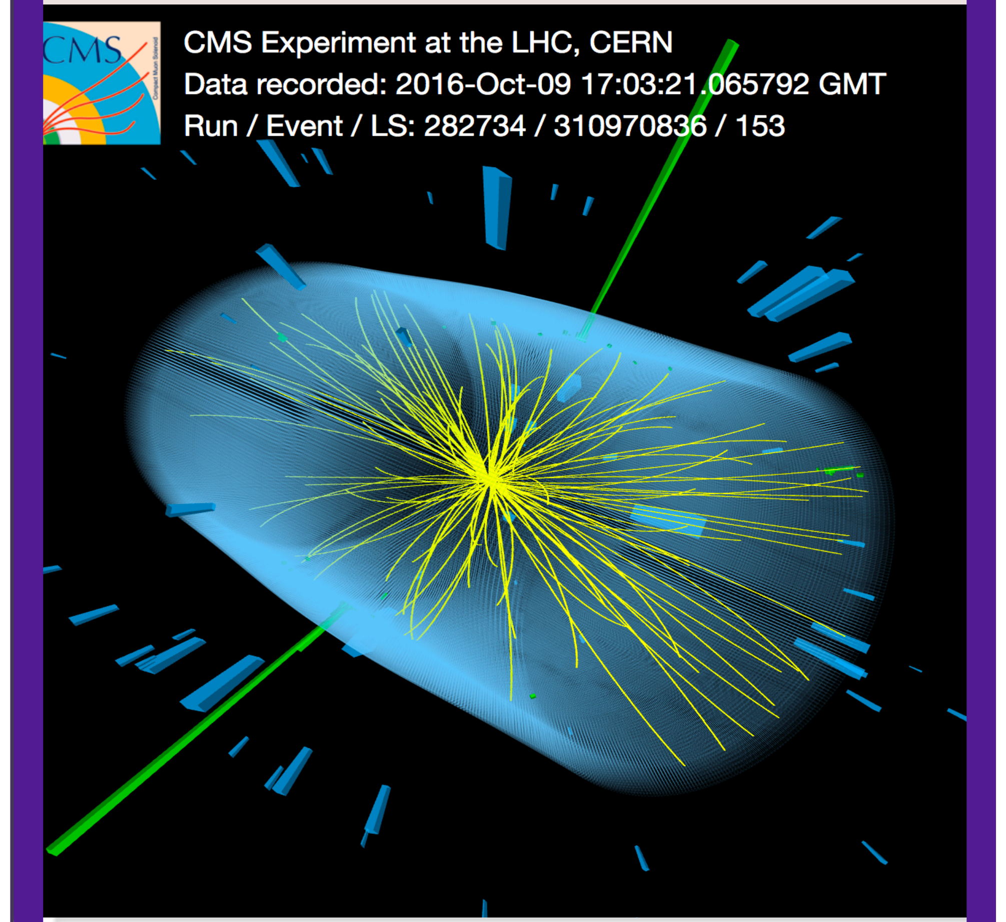

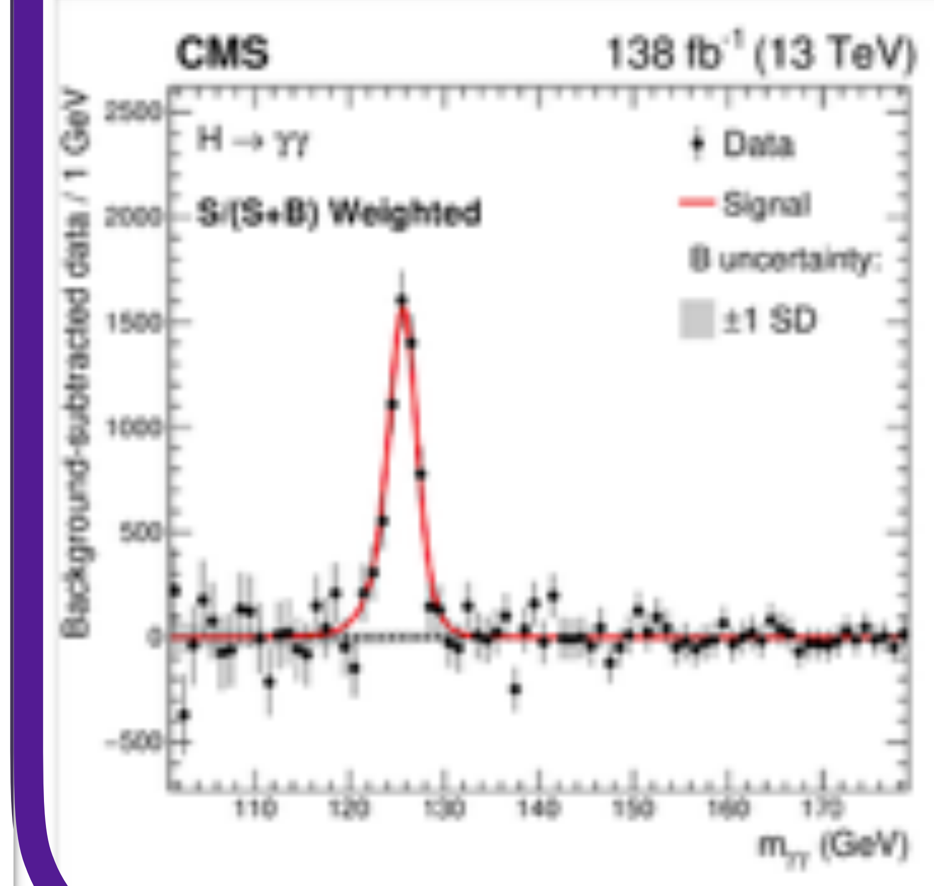

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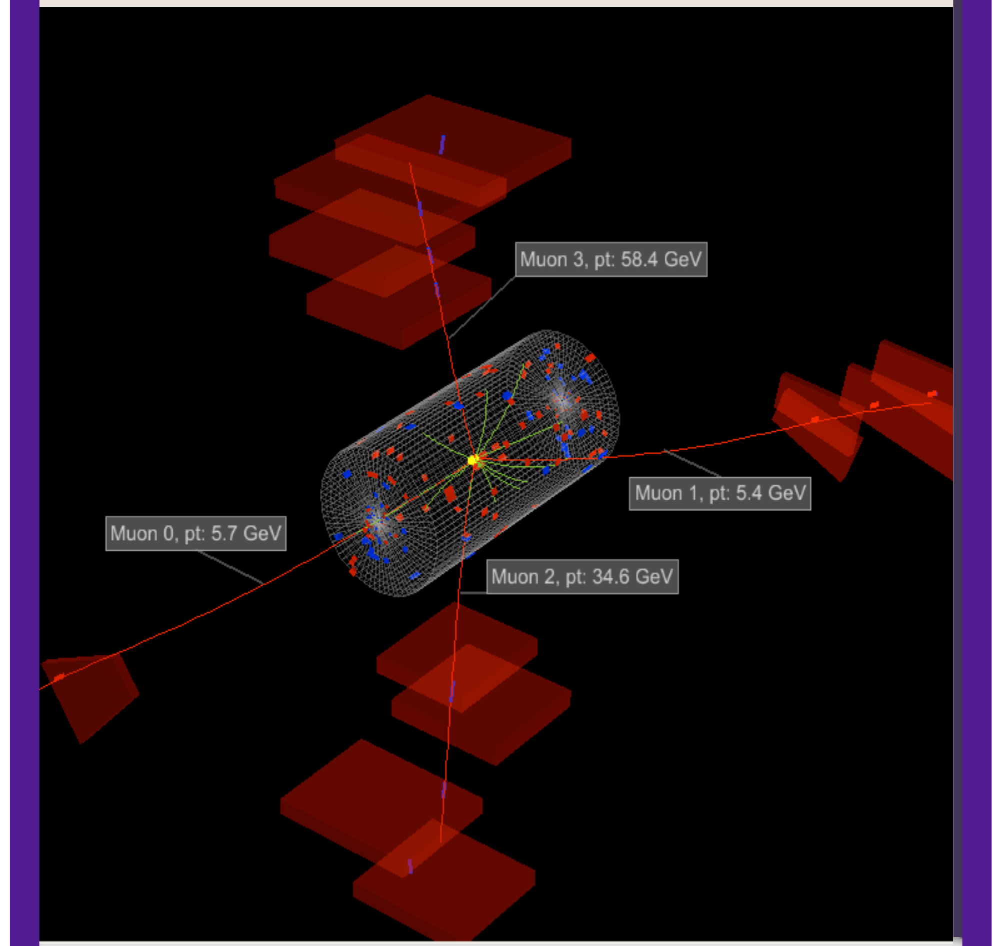

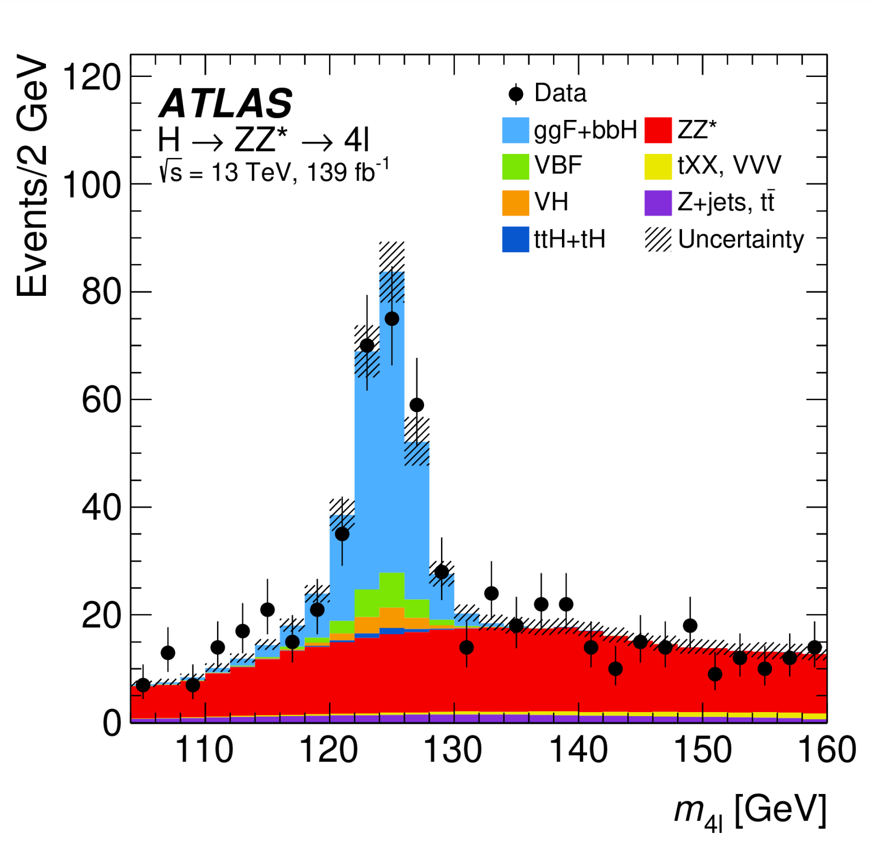

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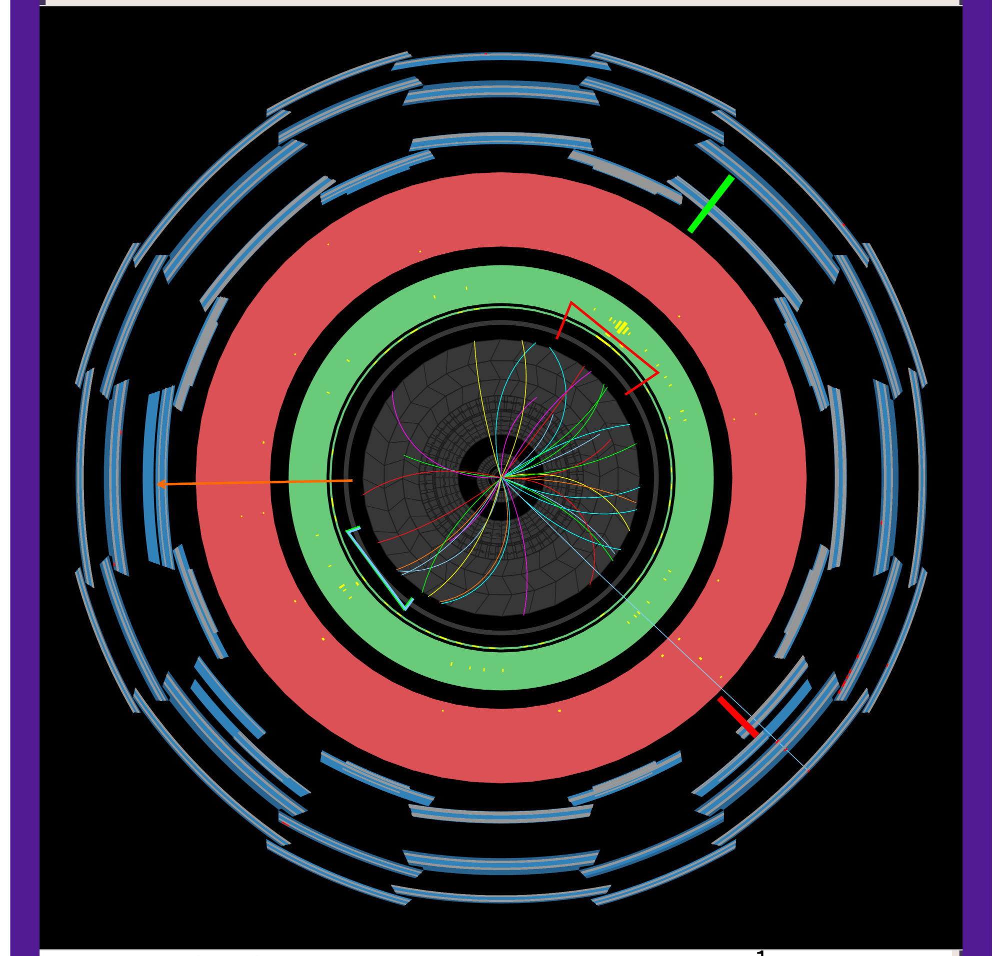

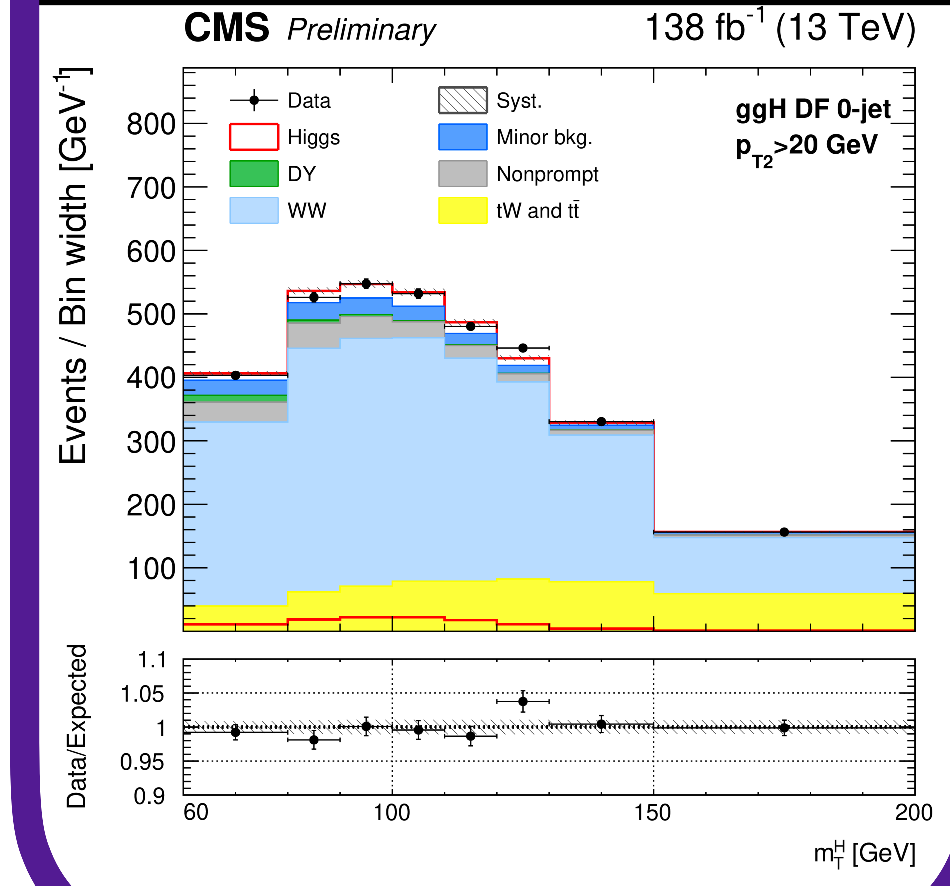

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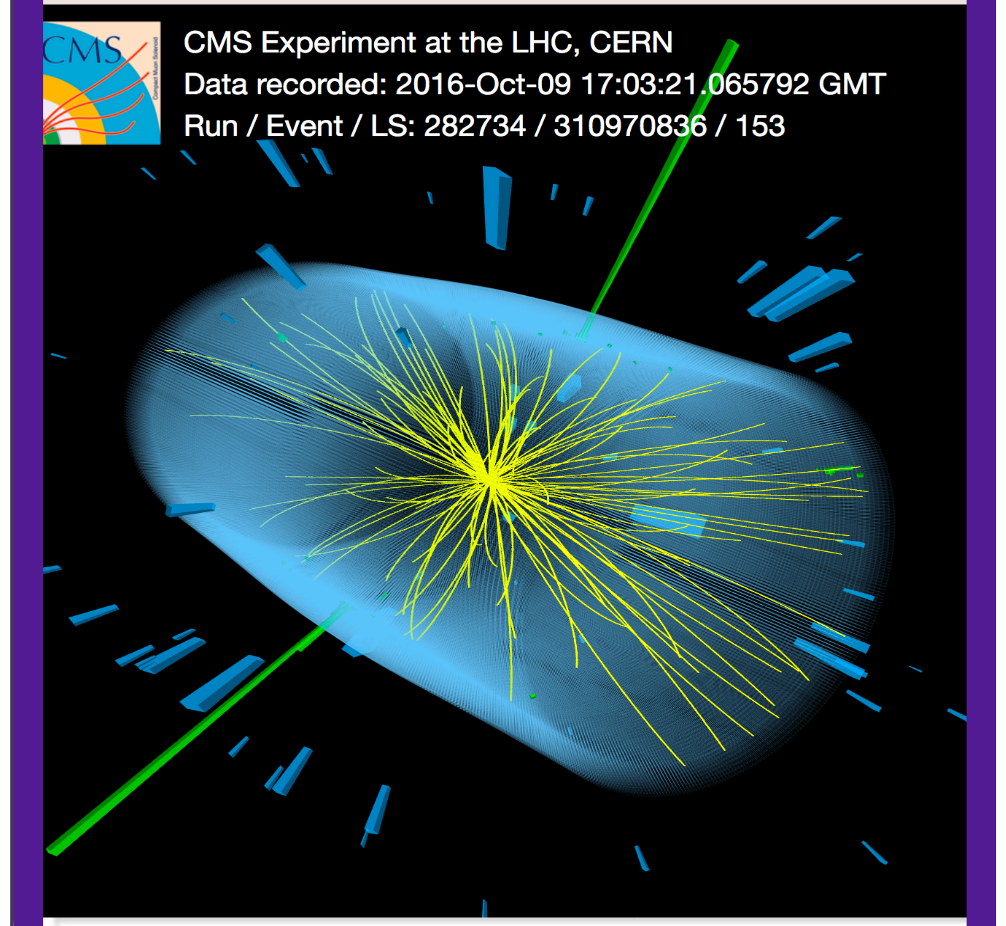

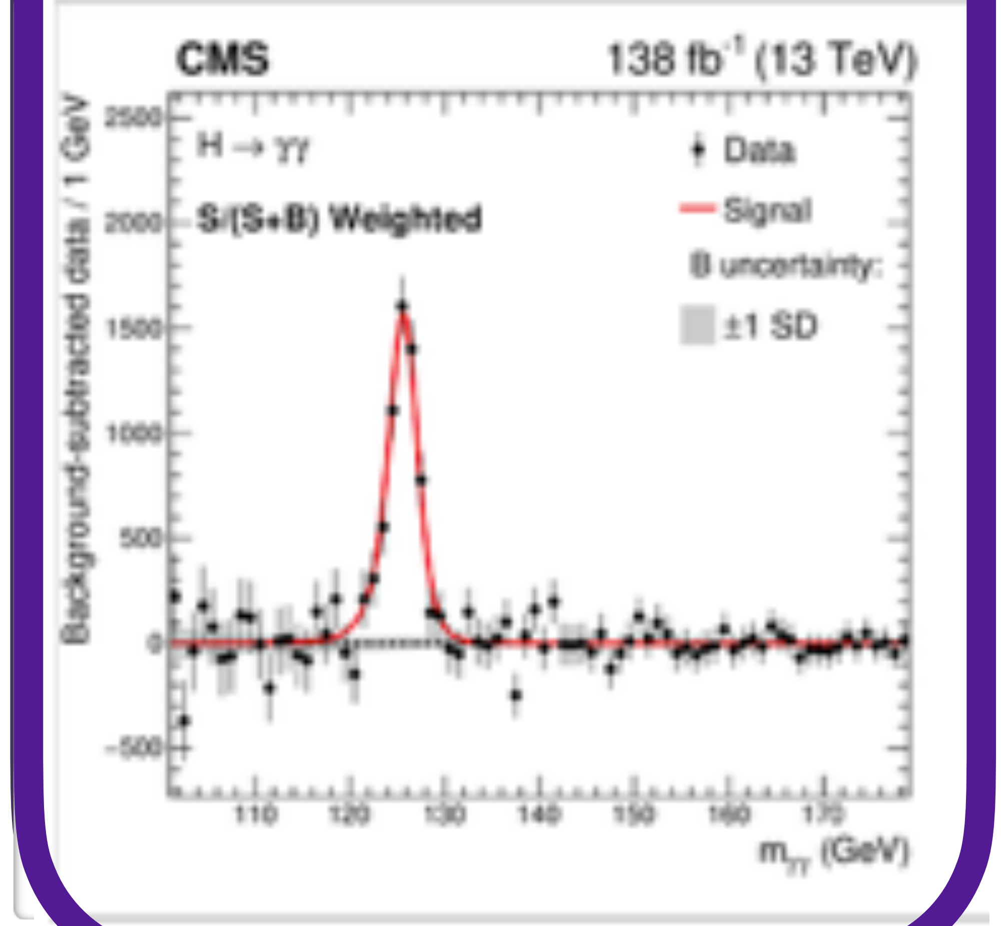

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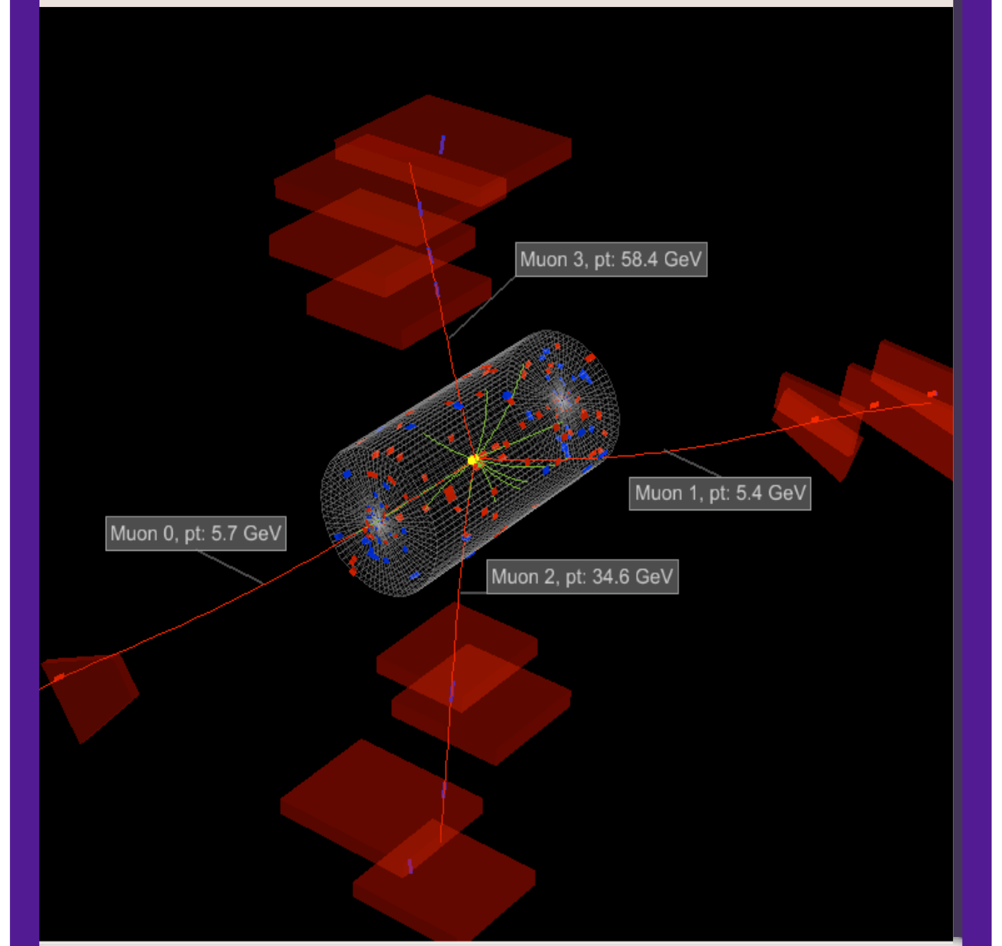

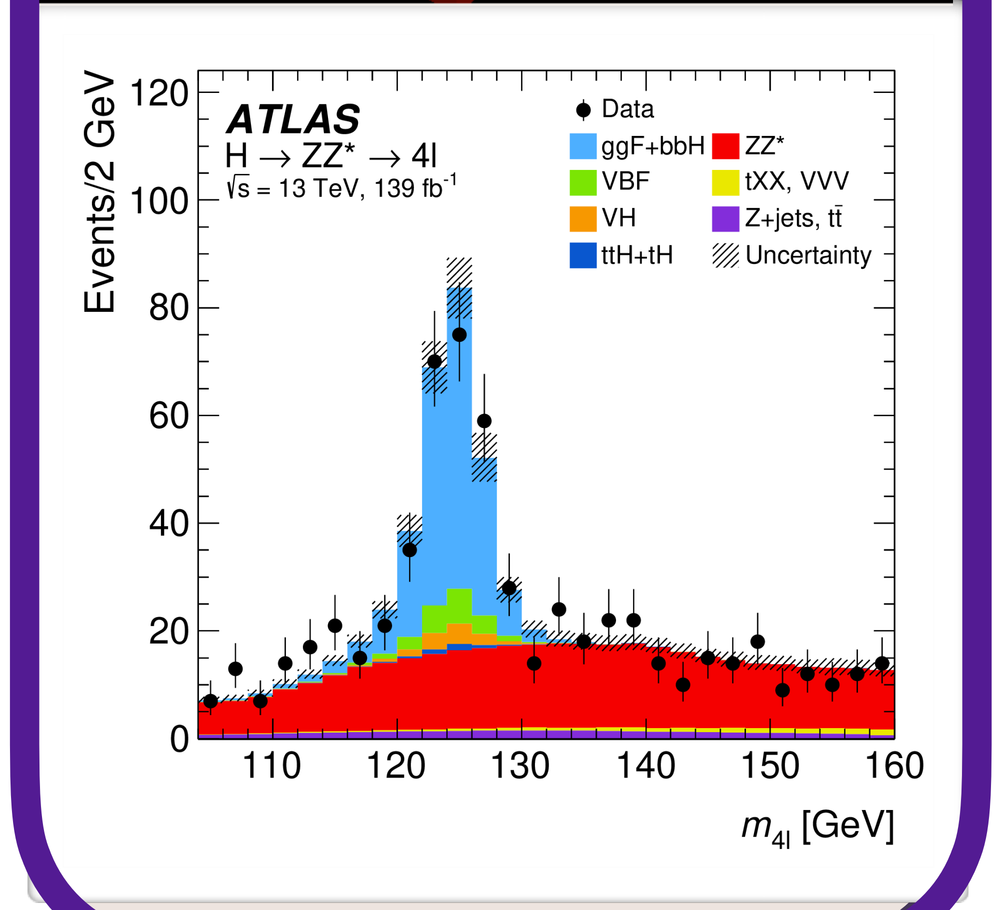

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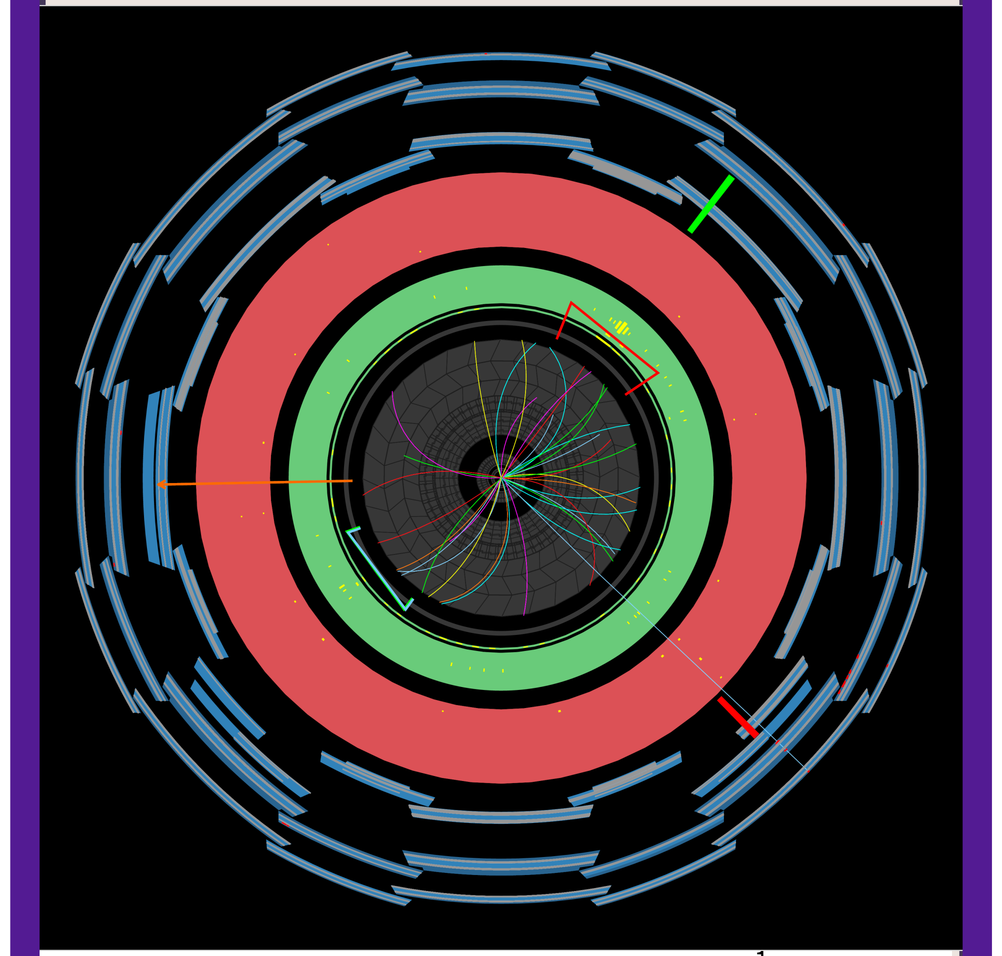

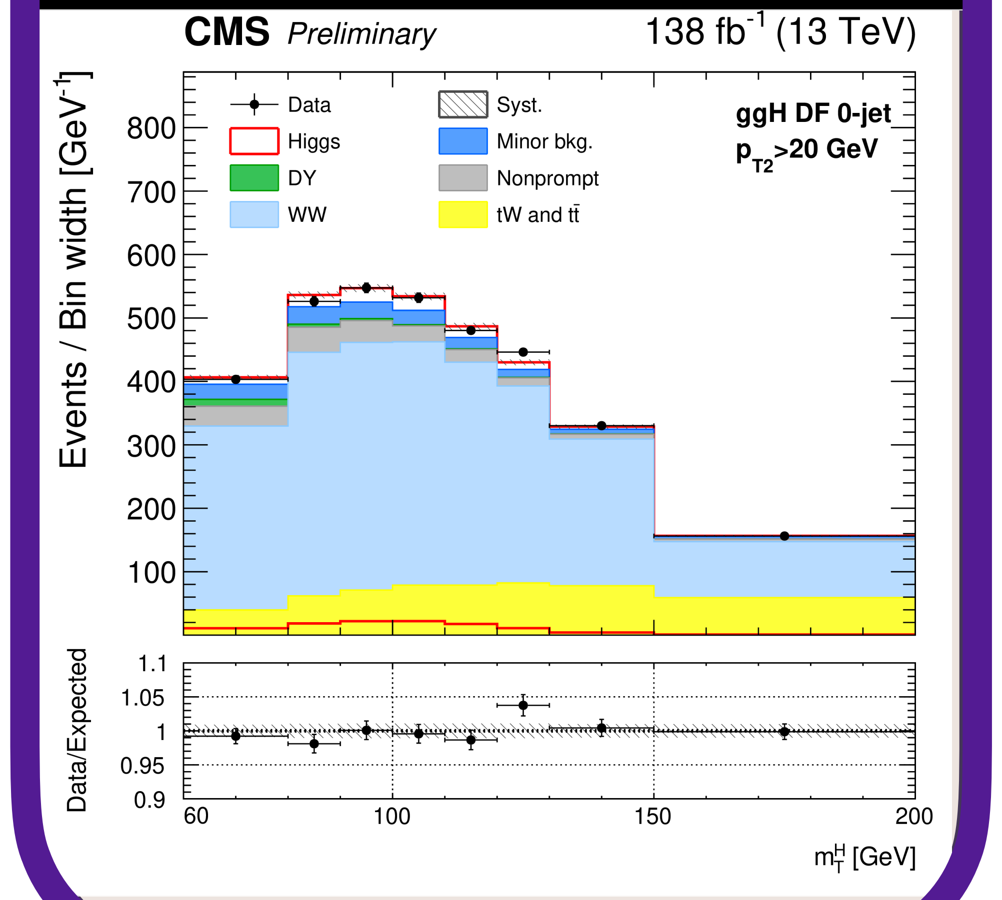

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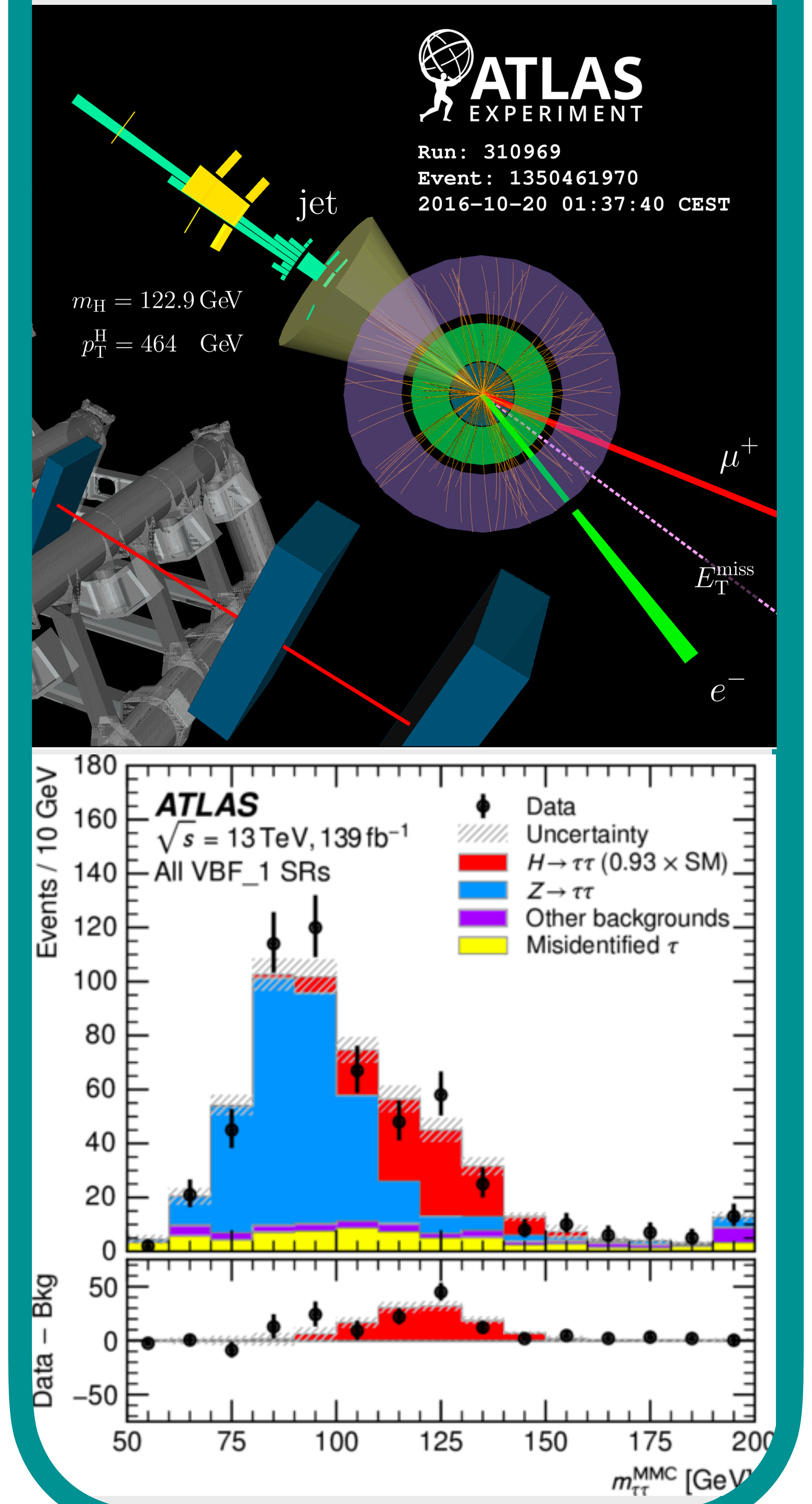
- WW: large branching ratio, but missing final state information (neutrinos) ➔more complicated experimentally, even in the W➔lν case. Also well into the precision regime now.

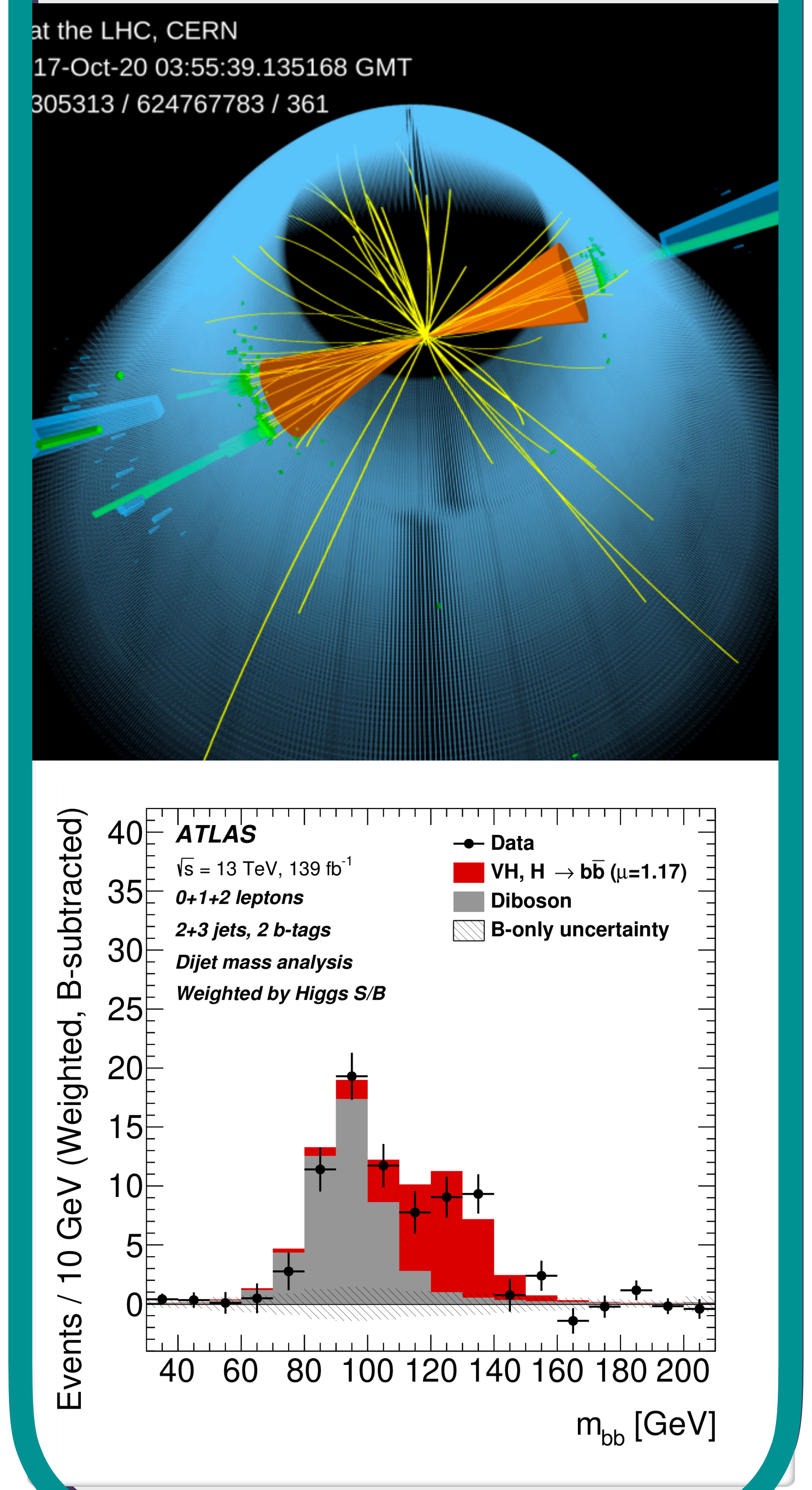
$H \rightarrow \tau\tau$

Br~6%



$H \rightarrow bb$

Br~58%



Does the Higgs boson couple to Fermions?

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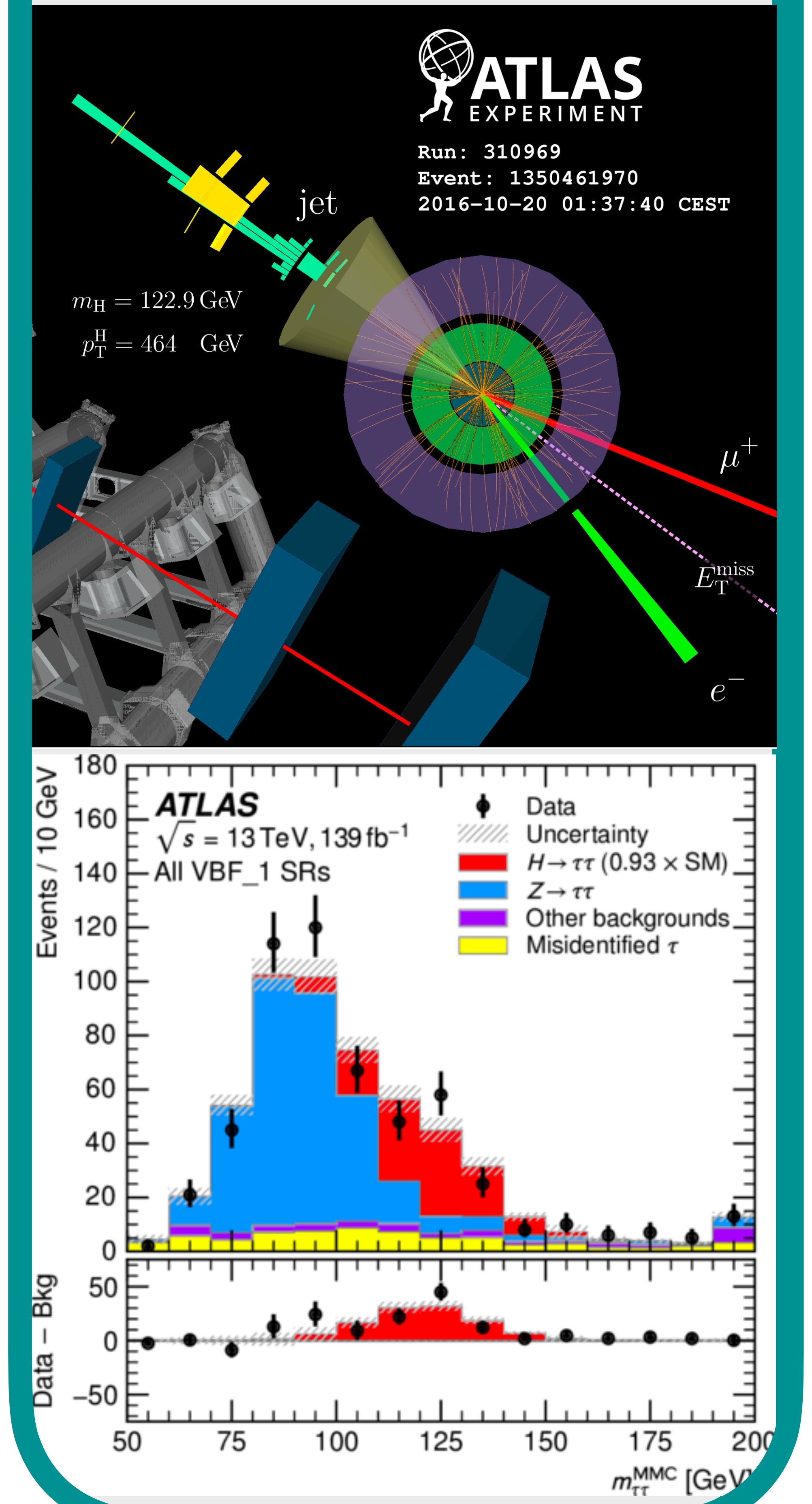

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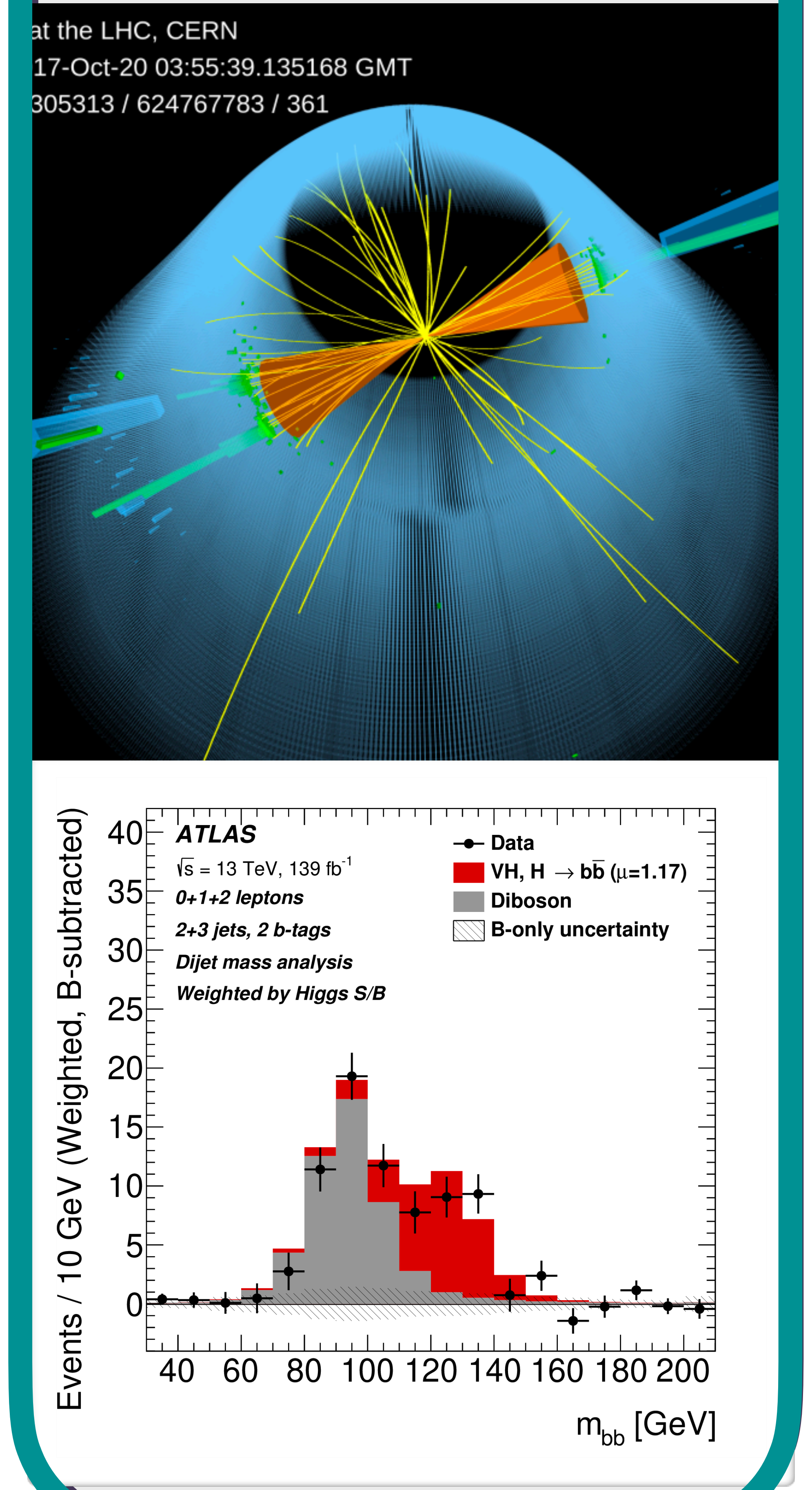

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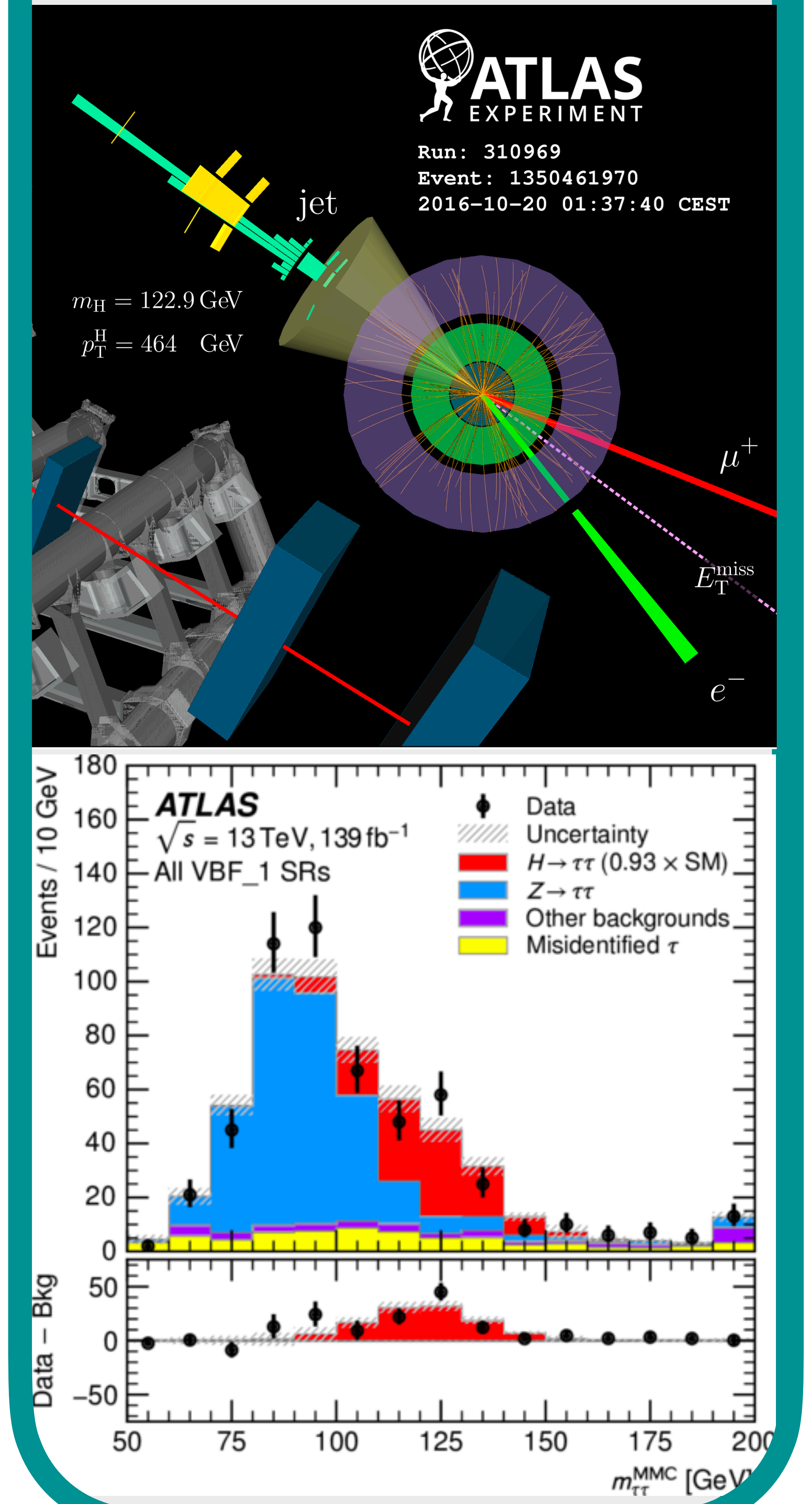

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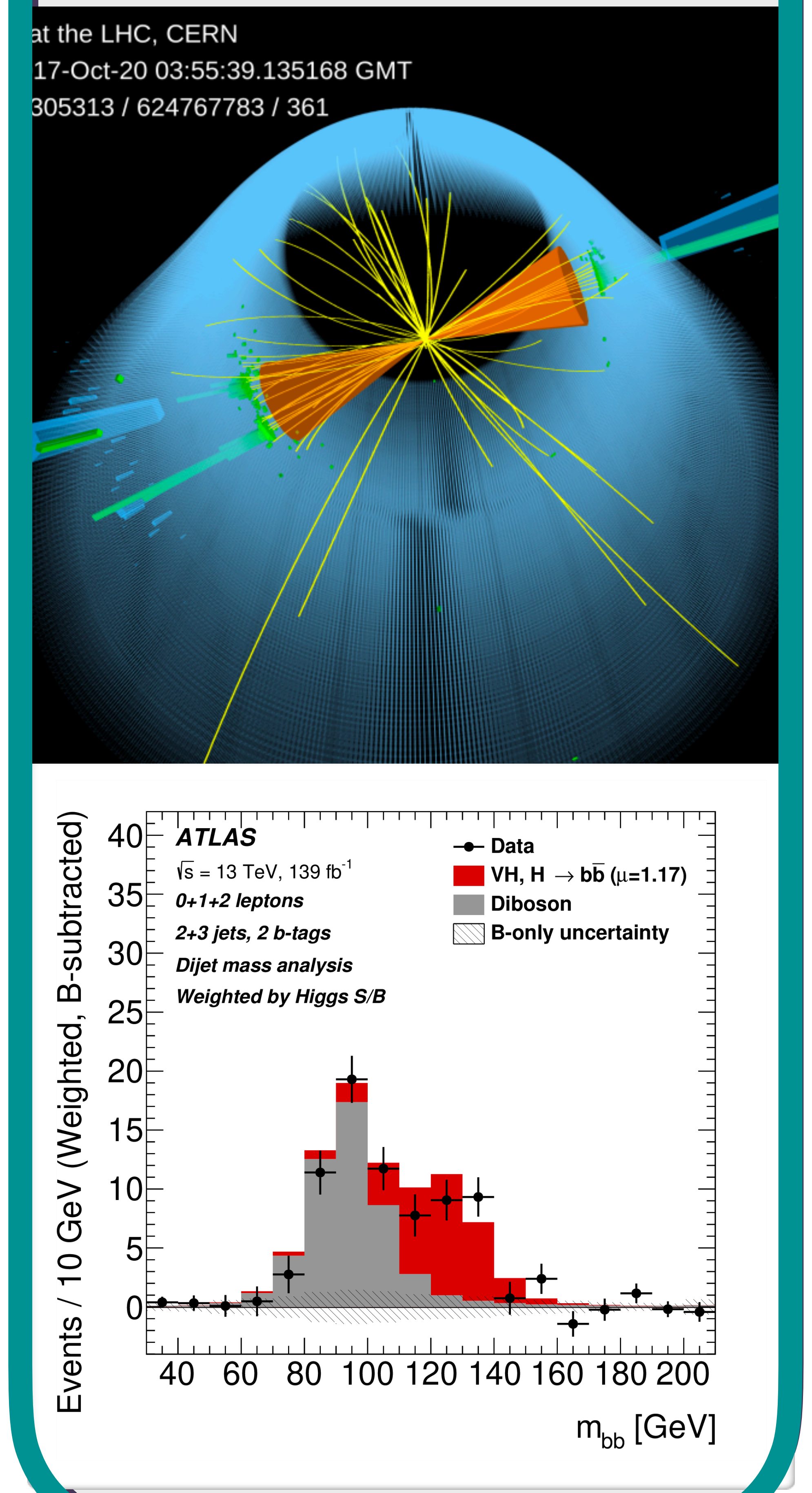

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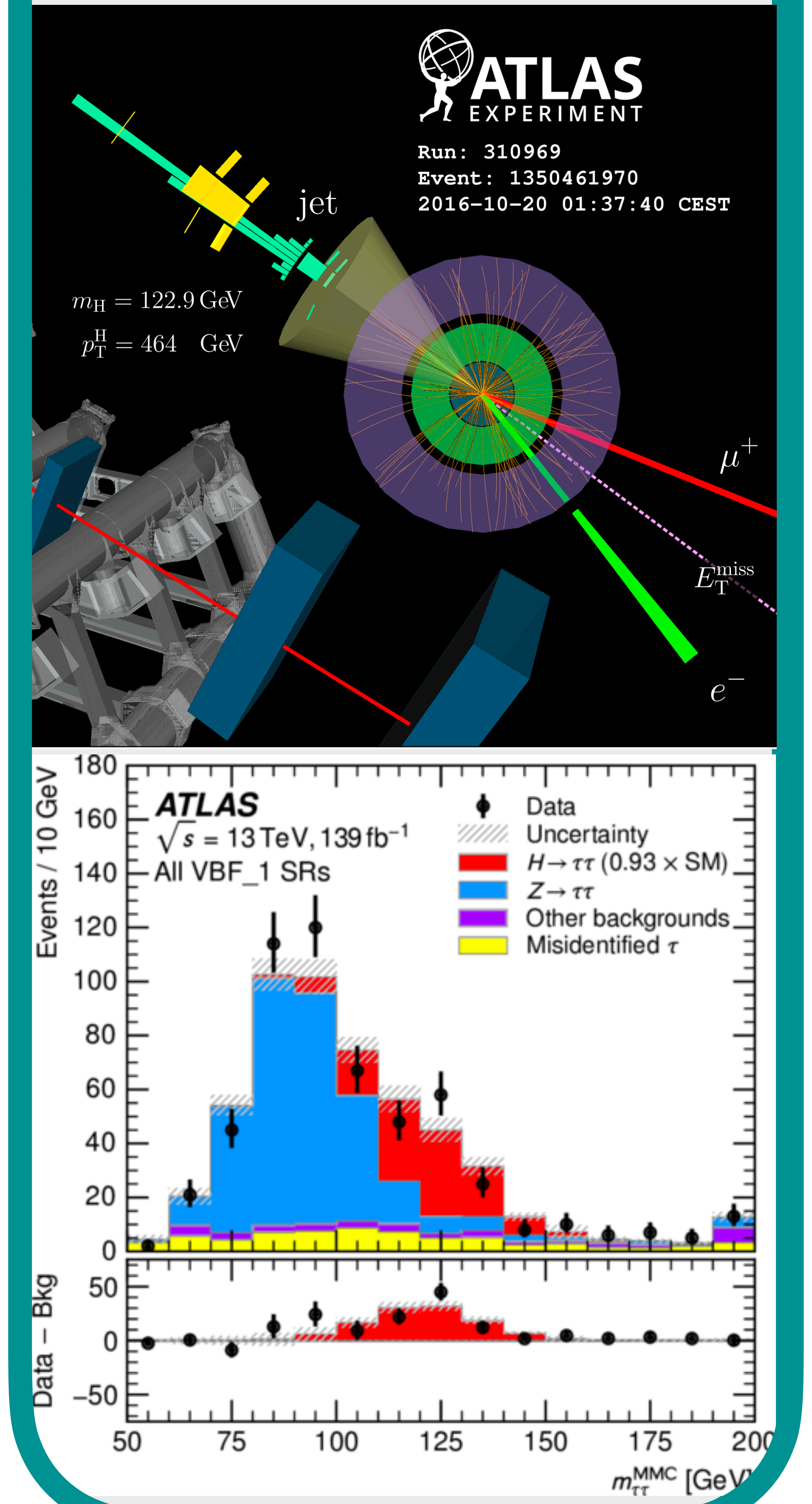

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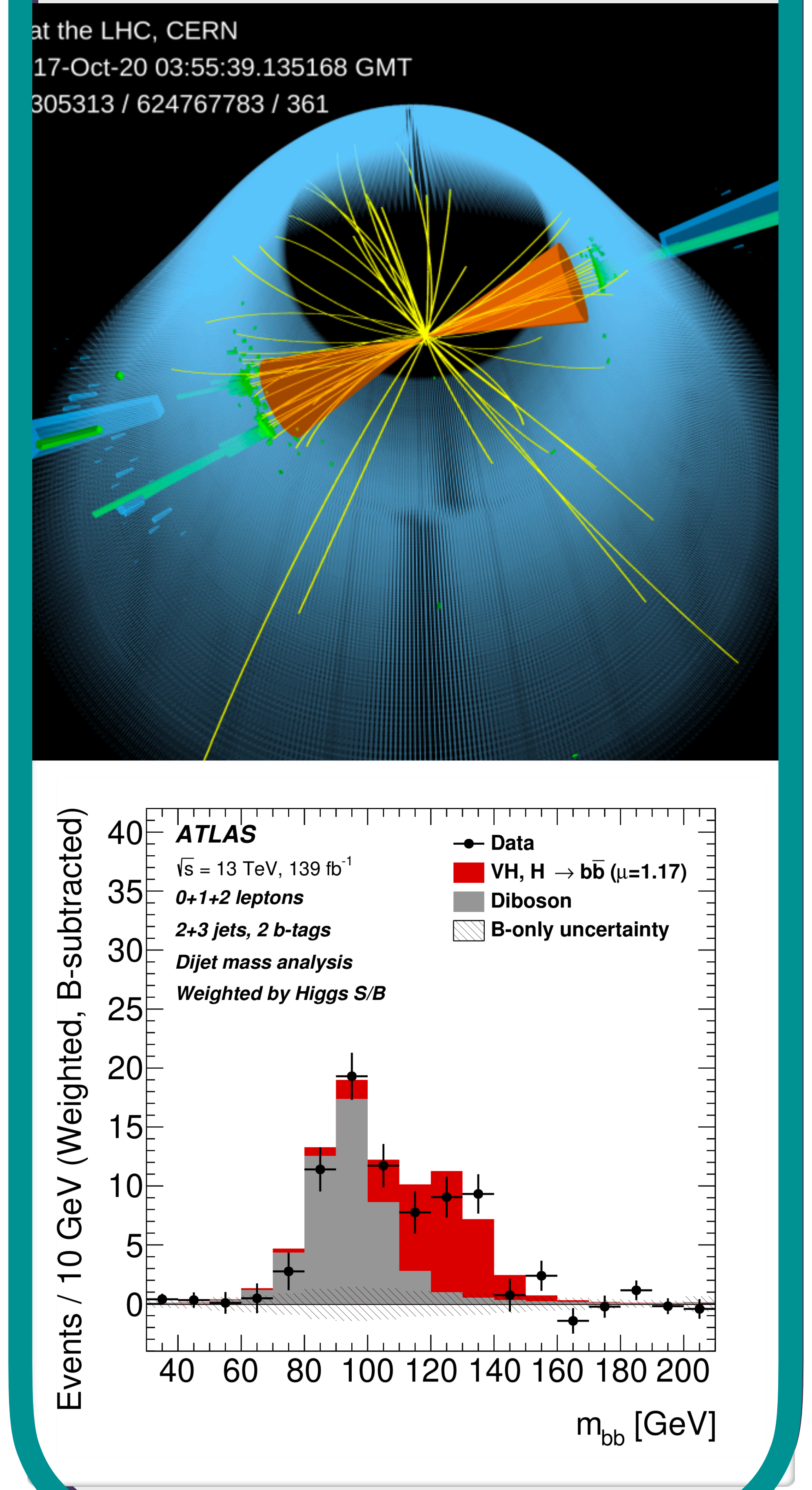

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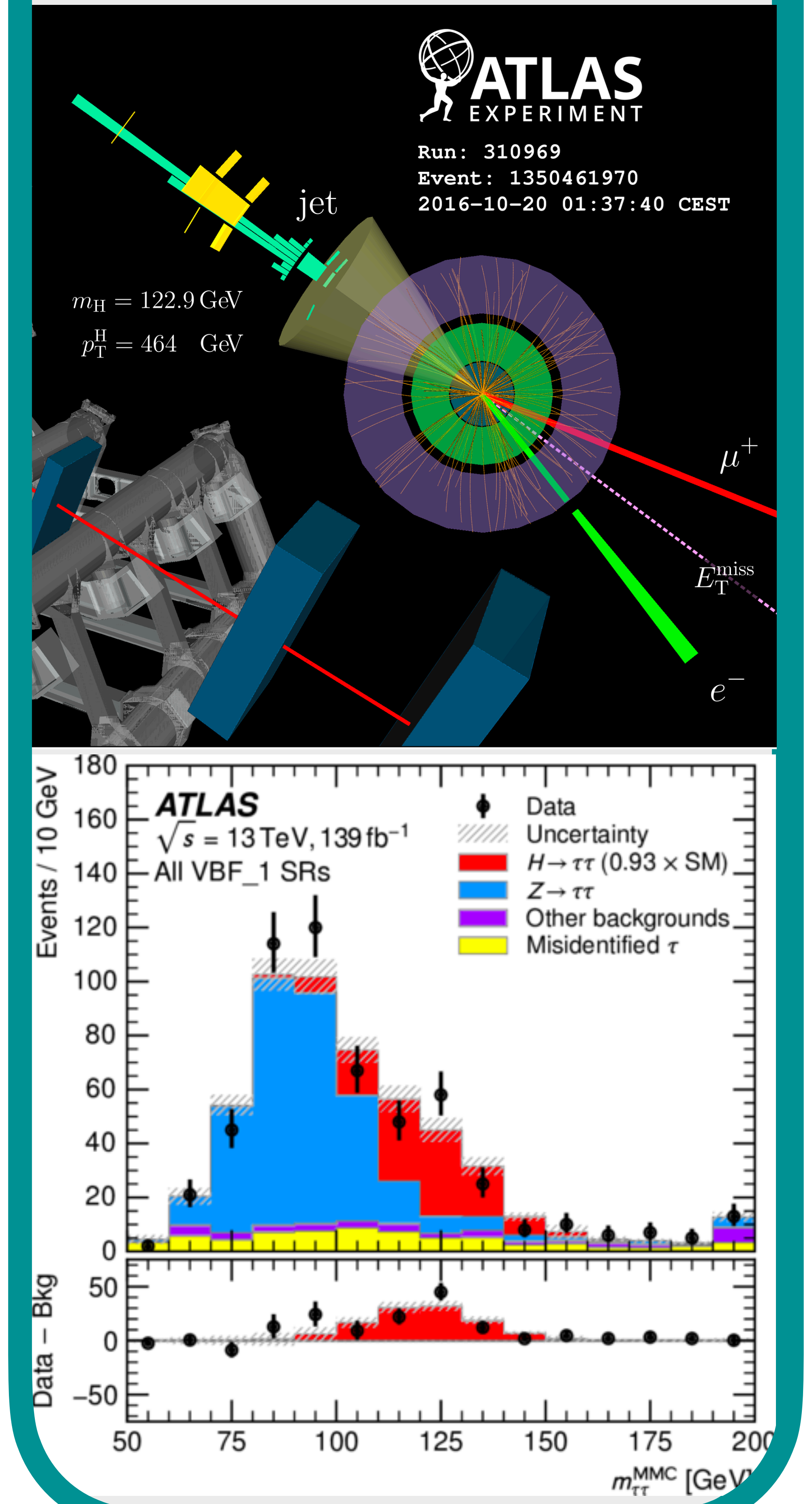
- Now moved to precision measurements! Cross Sections (including fiducial, differentials and STXS) and CP studies
- What about the second generation of fermions? (muons, charm quark)

$$H \to \tau\tau$$

Br~6%



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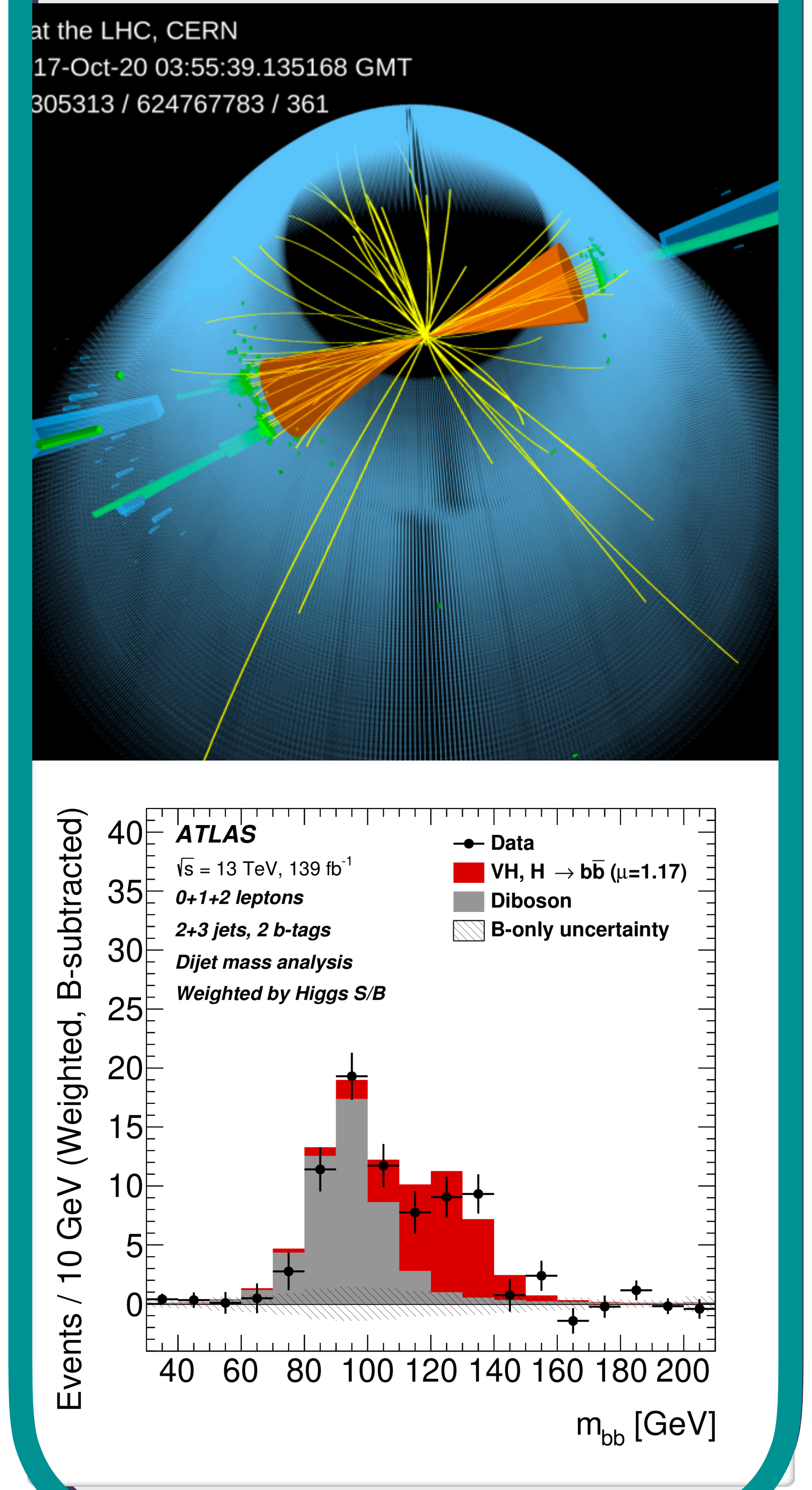
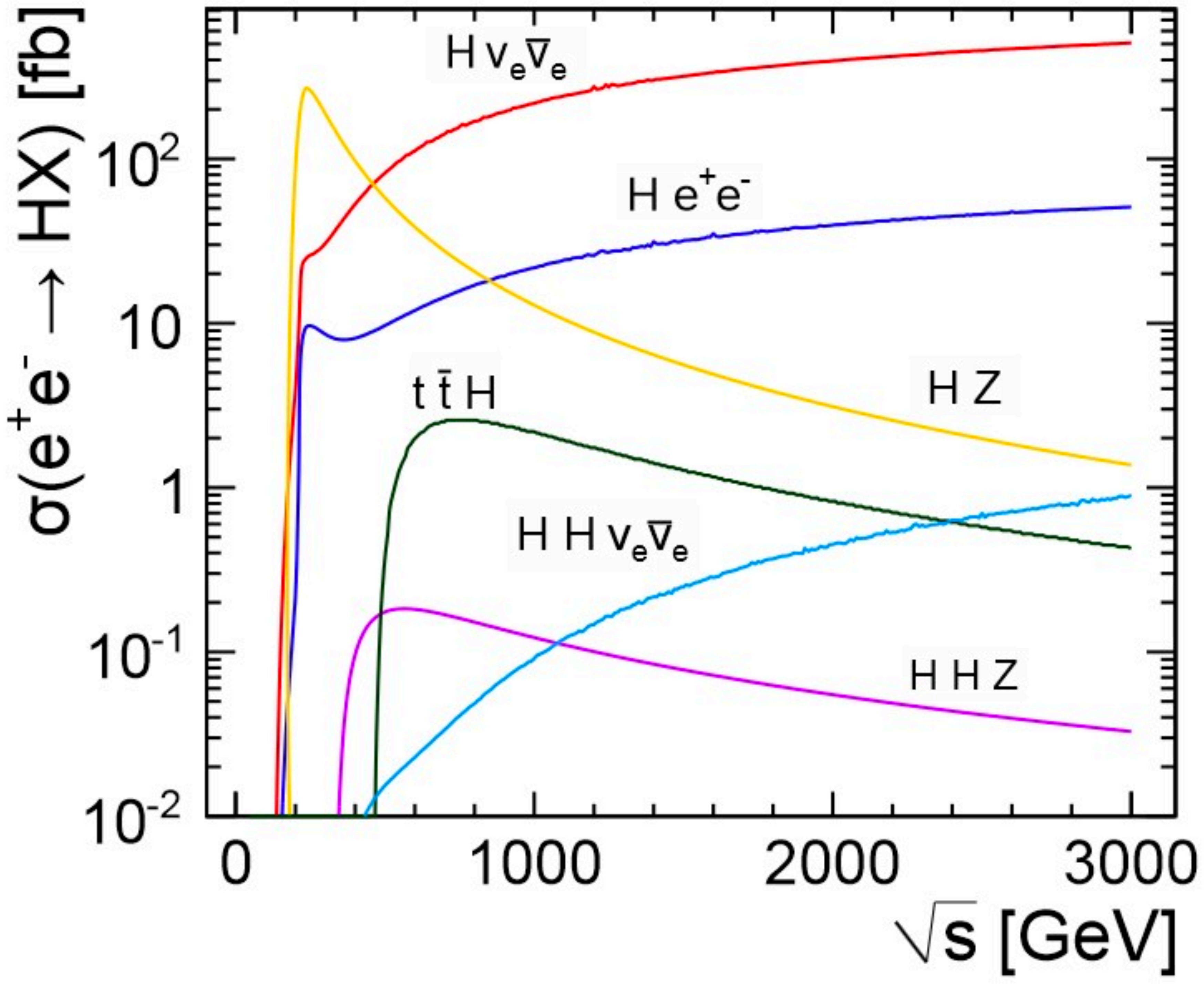
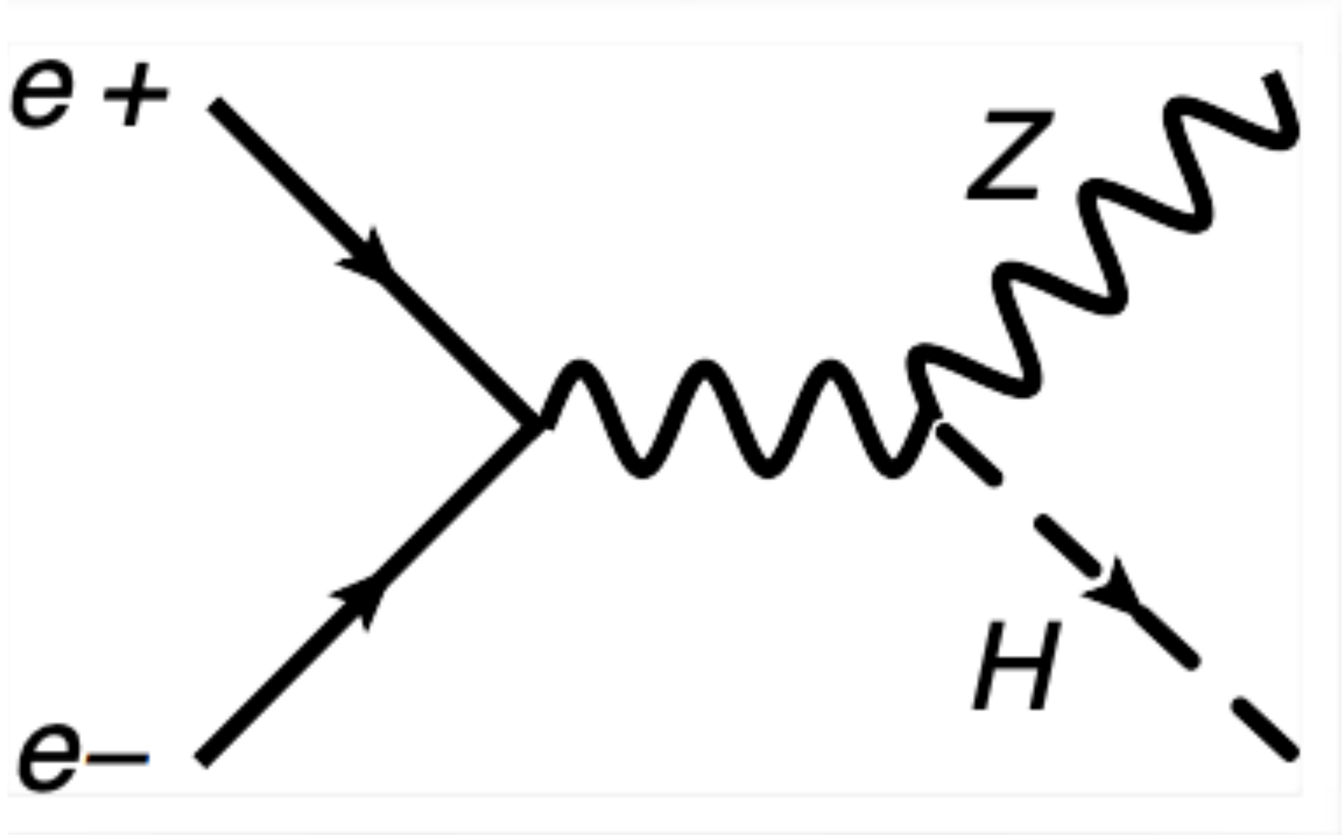


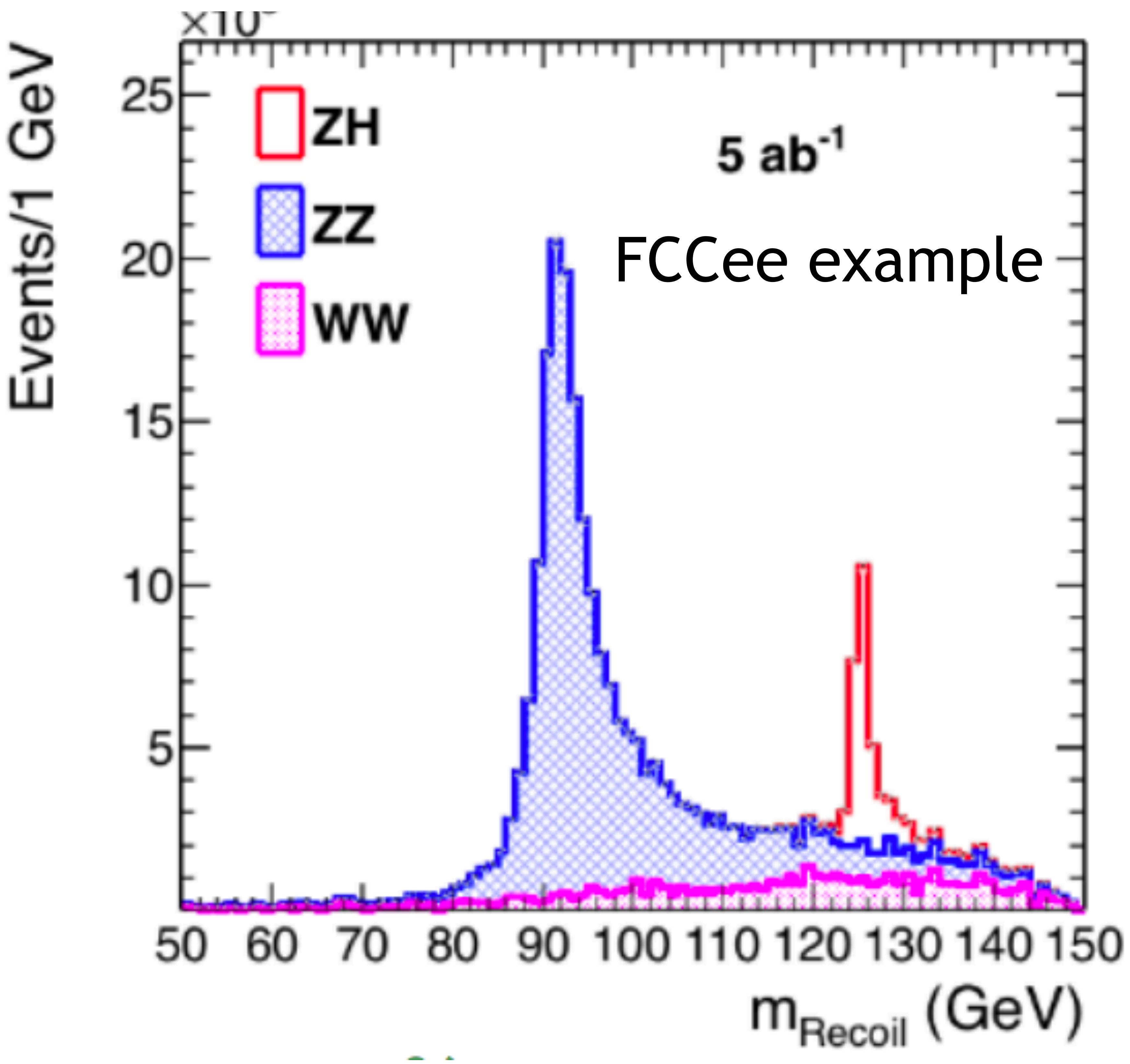
WHAT ABOUT e+e-?

This class focuses on current results on pp
For the **Future "Higgs Factories" (e+e- machines, different proposals being discussed)** : different diagrams and very different experimental scenario (very clean)

Exploit the recoil against a Z for a precise, model independent measurement of ZH

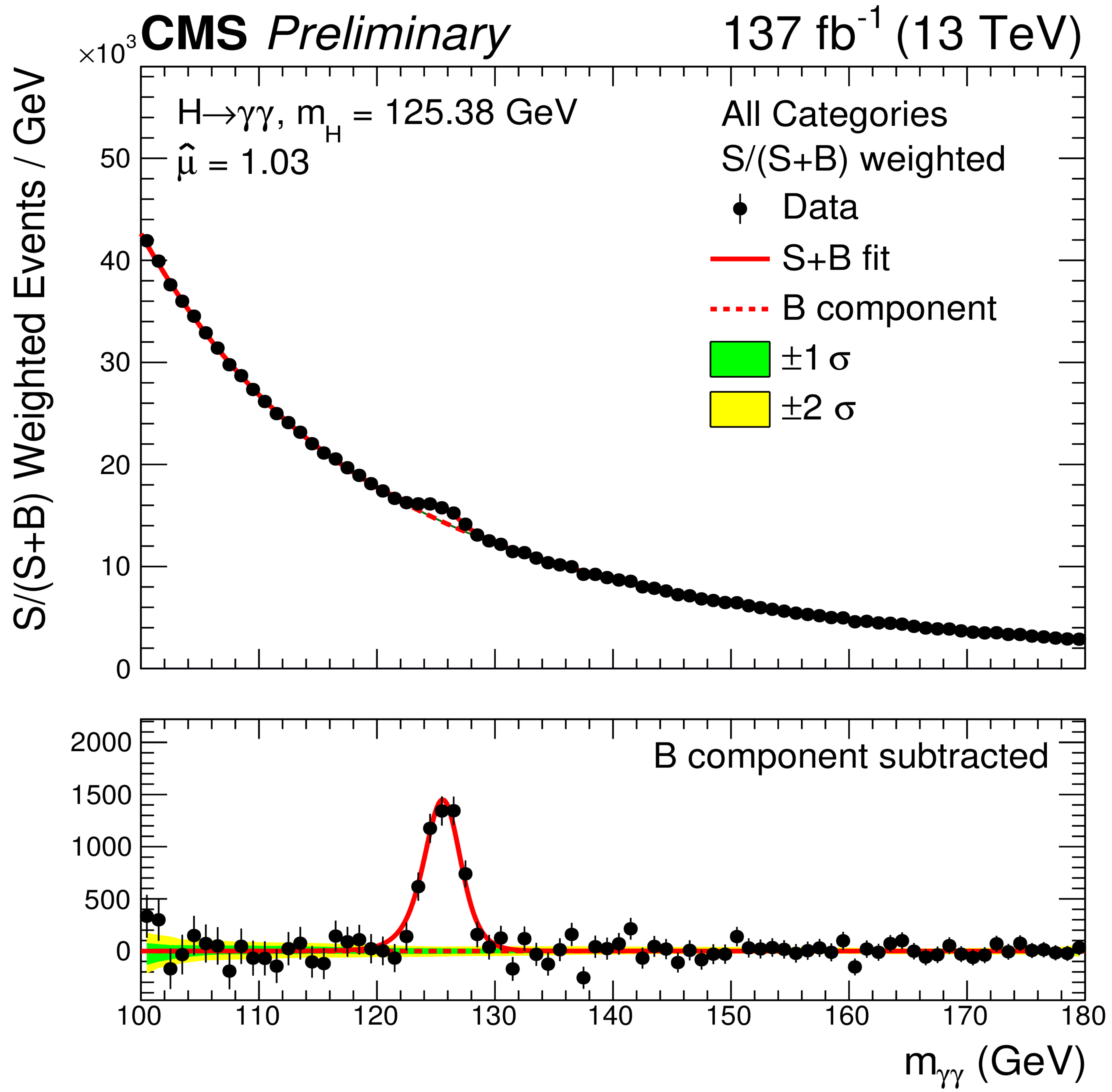


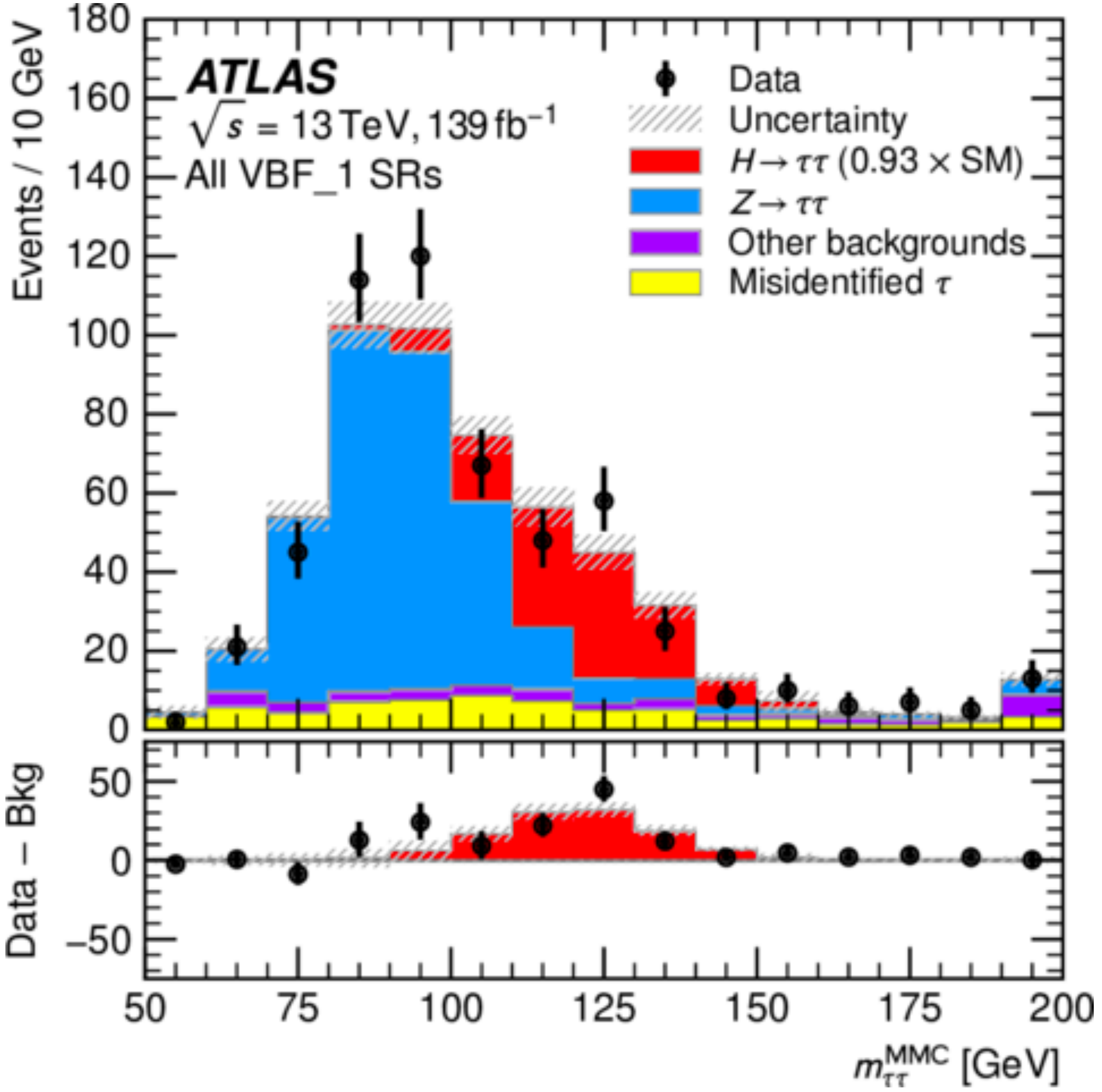




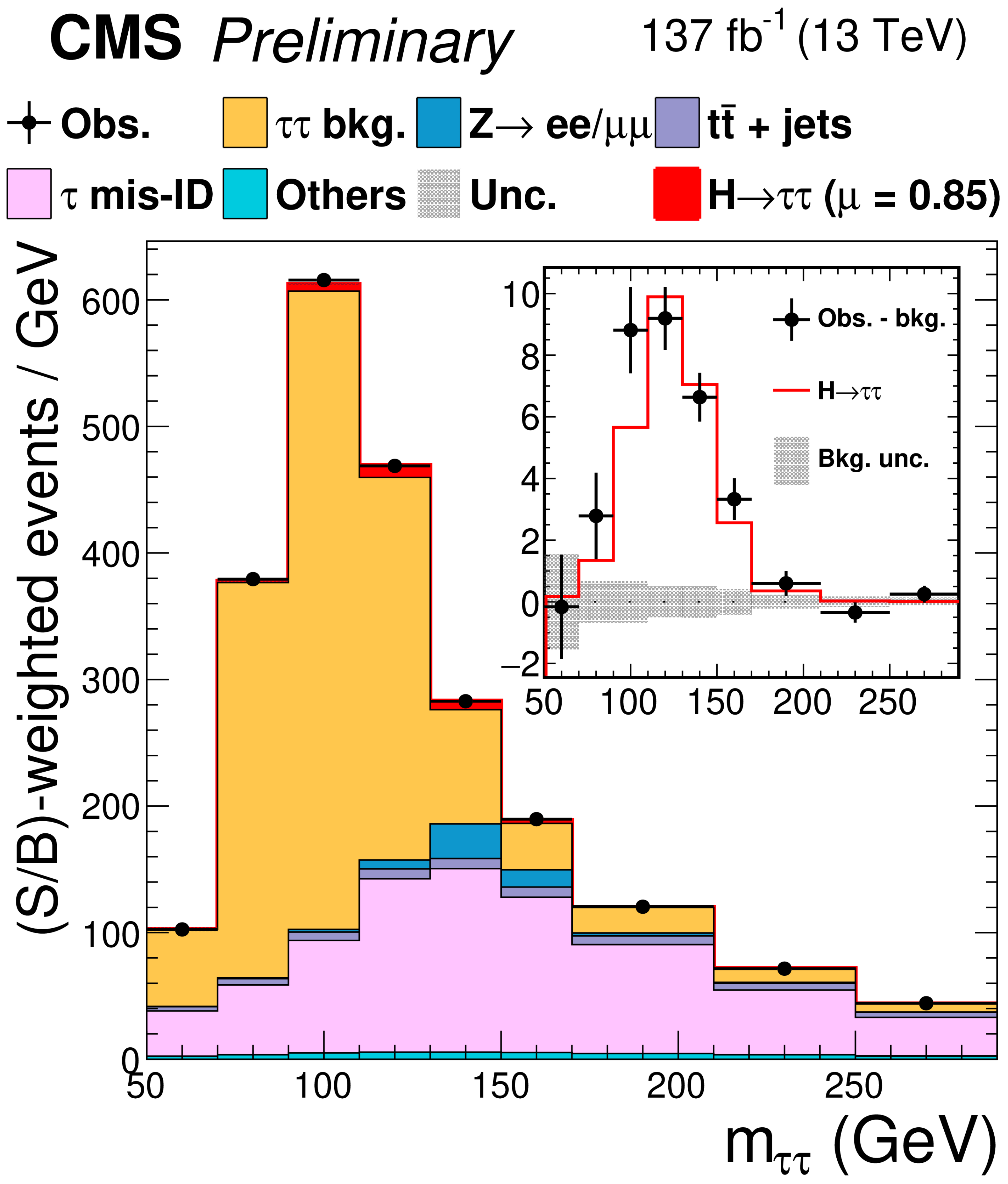
WHAT DO WE ALREADY KNOW?

FIRST STEP: STUDY SIGNAL AND BACKGROUND IN DETAIL





SECOND STEP: CROSS-SECTIONS? IS THE RATE AS YOU EXPECT?



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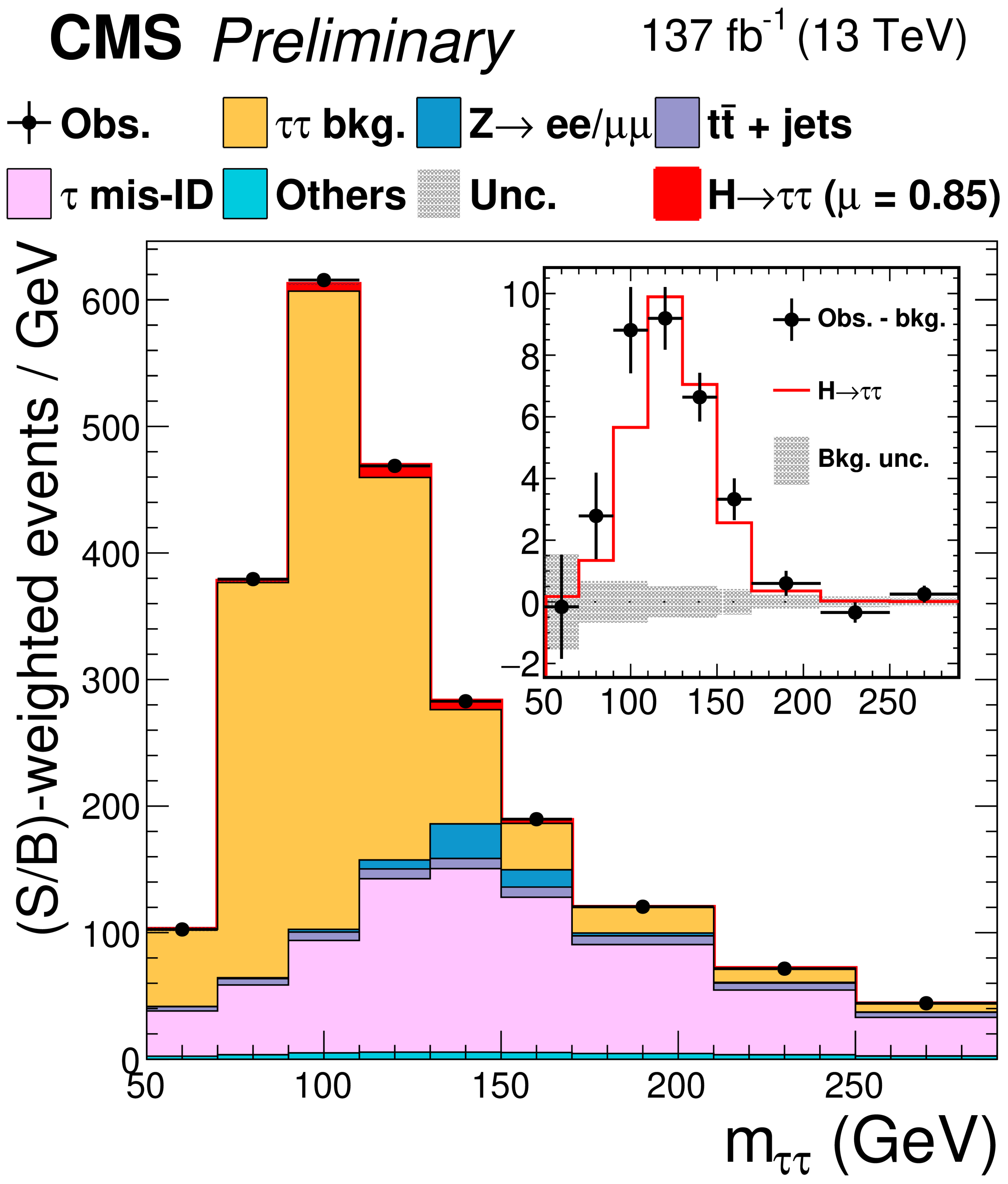

$$N_{total,SM} = \sigma \times \mathcal{B} \times \mathcal{L}$$

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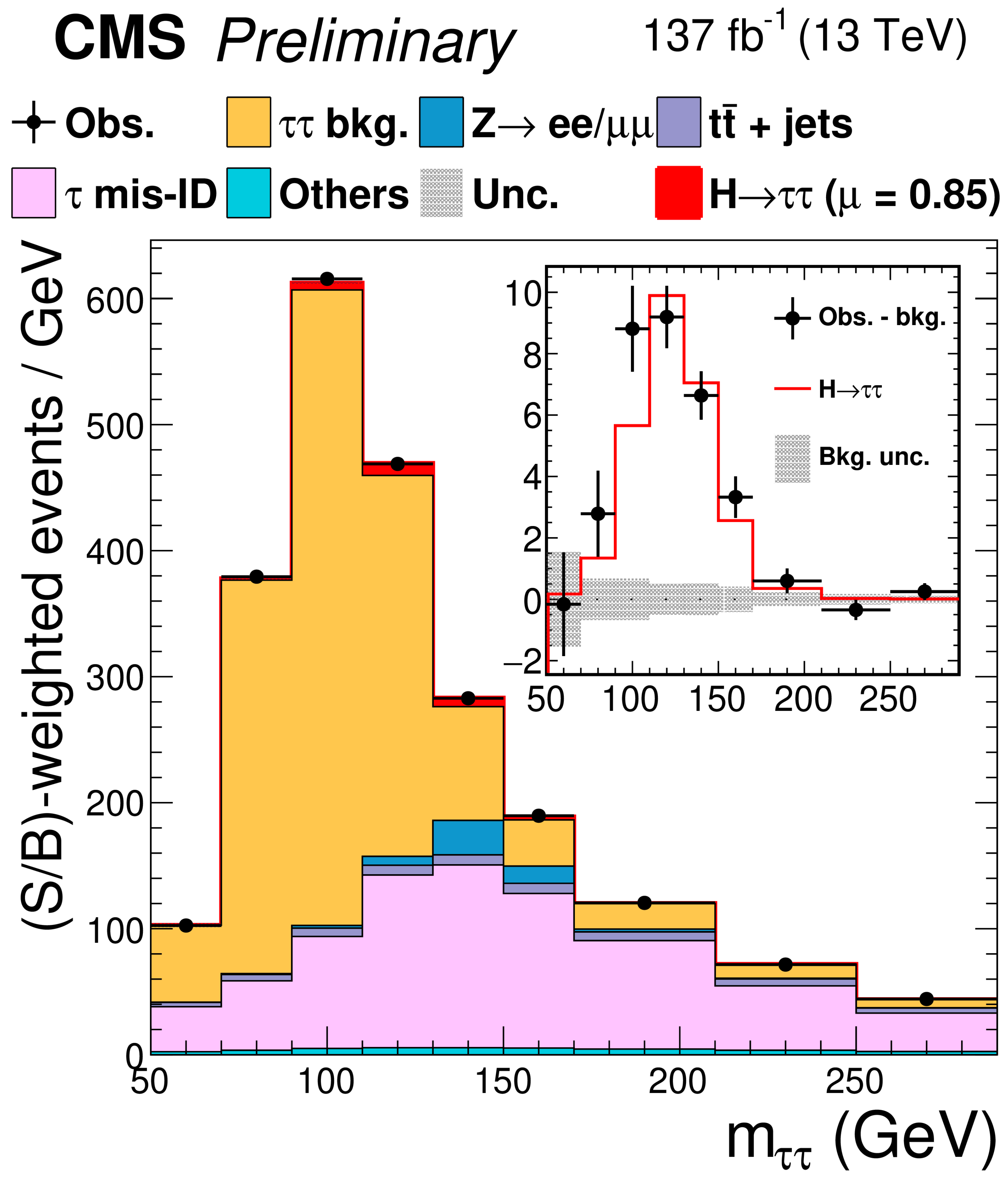

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selection!

$$N_{SM} = \sigma \times \mathscr{B} \times \mathscr{L} \times A \times \epsilon$$

Acceptance: pt, eta cuts -> fiducial volume

Efficiency: object selection, detector effects

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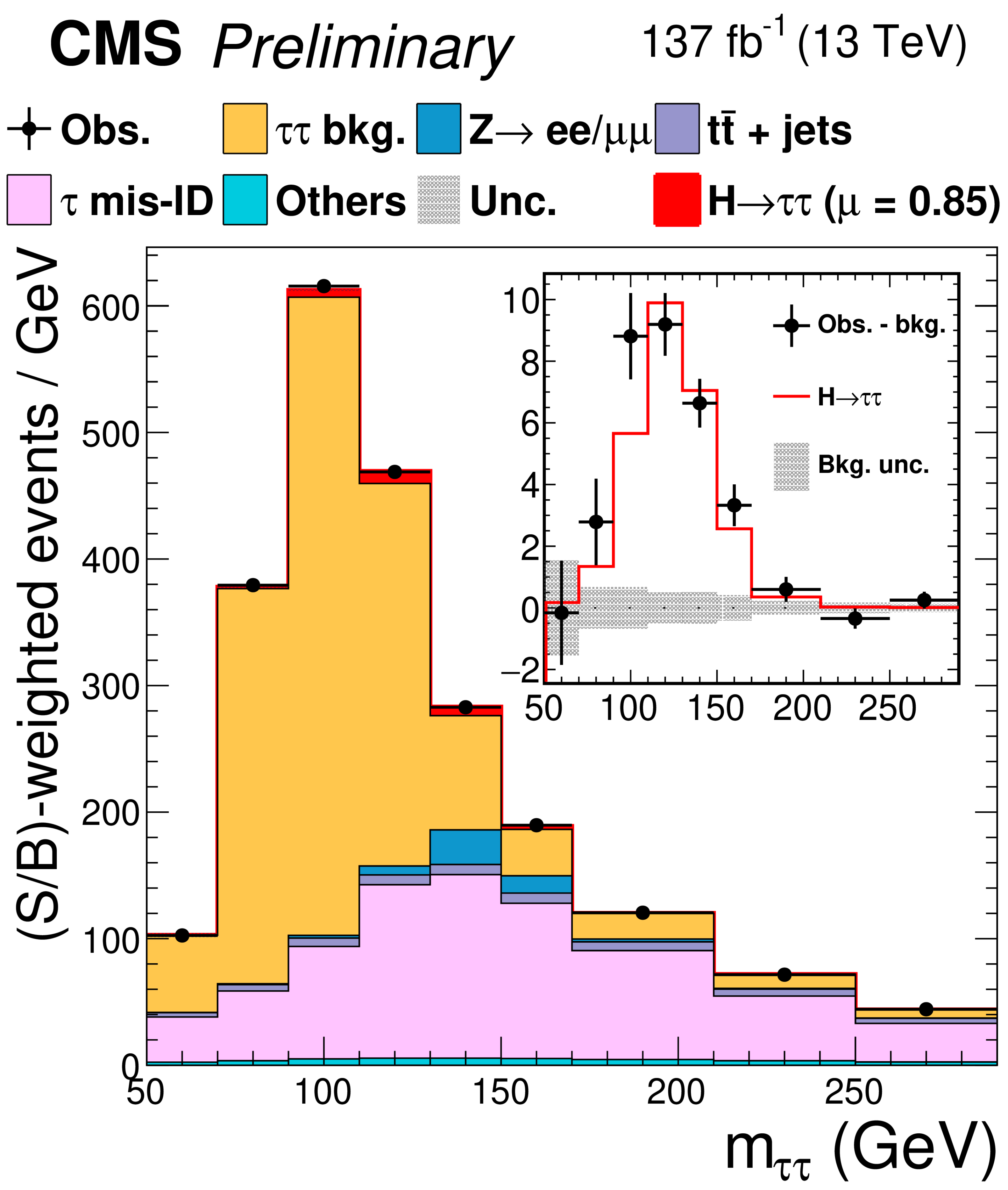

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When comparing to the data: not only signal!!

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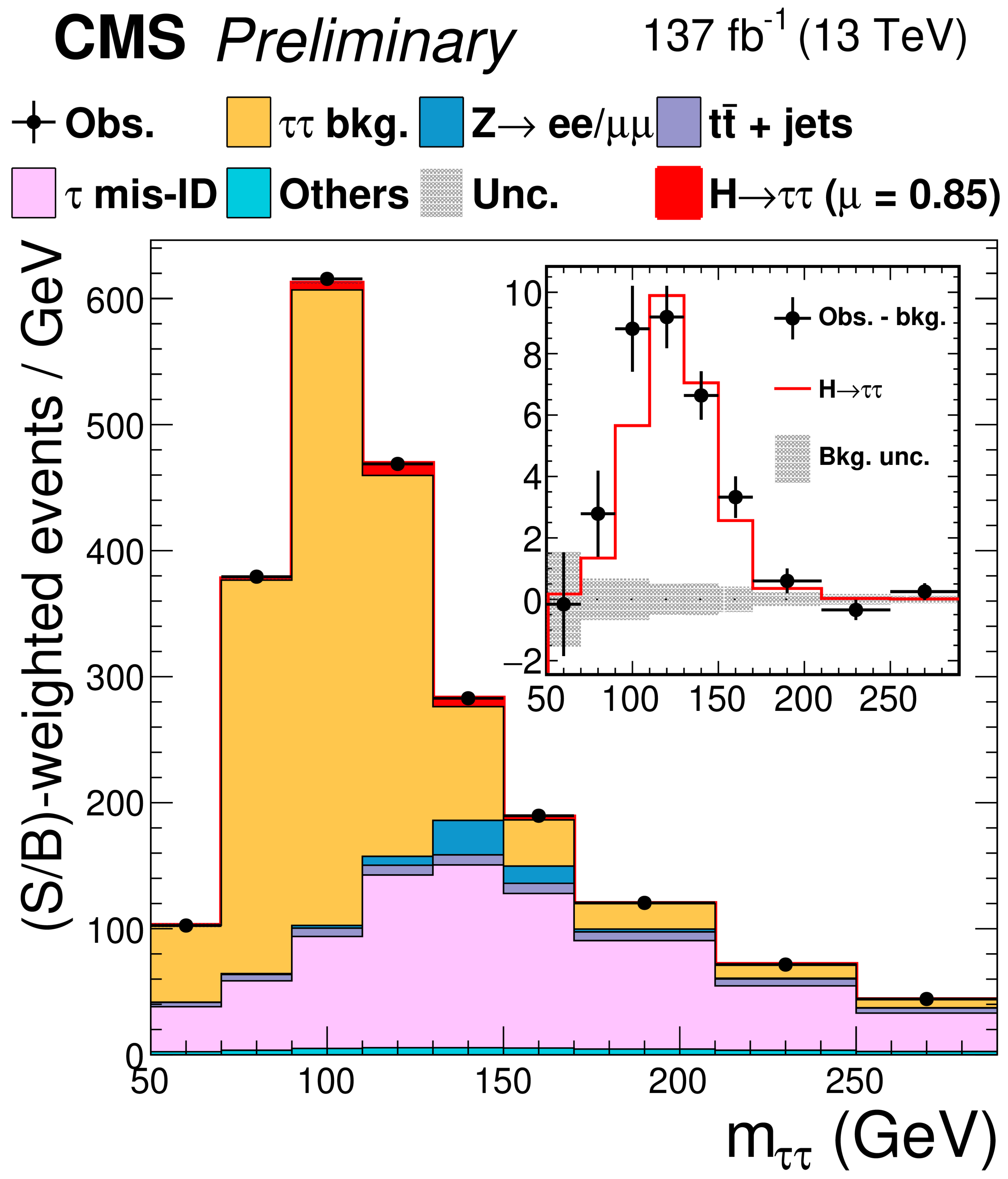

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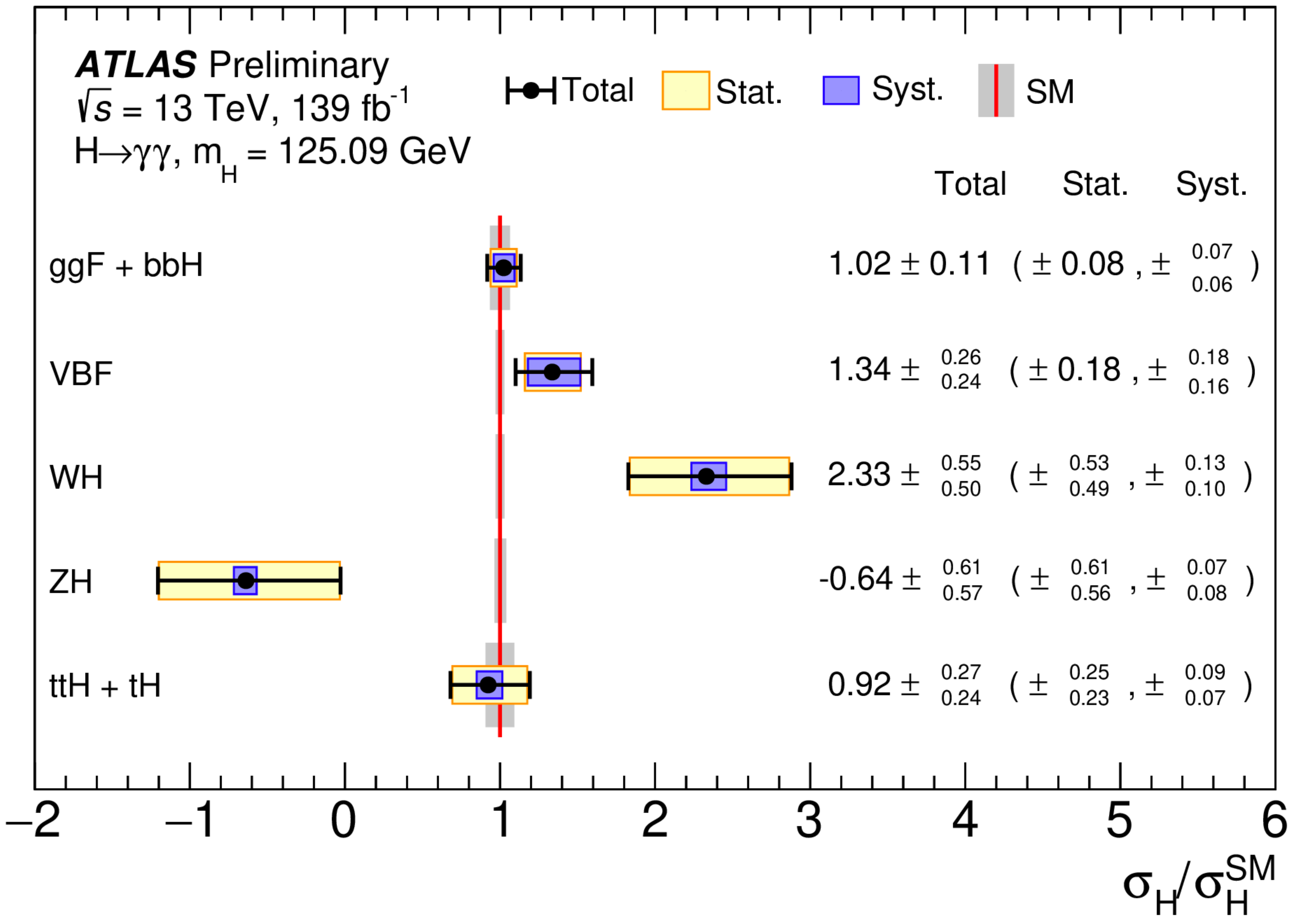
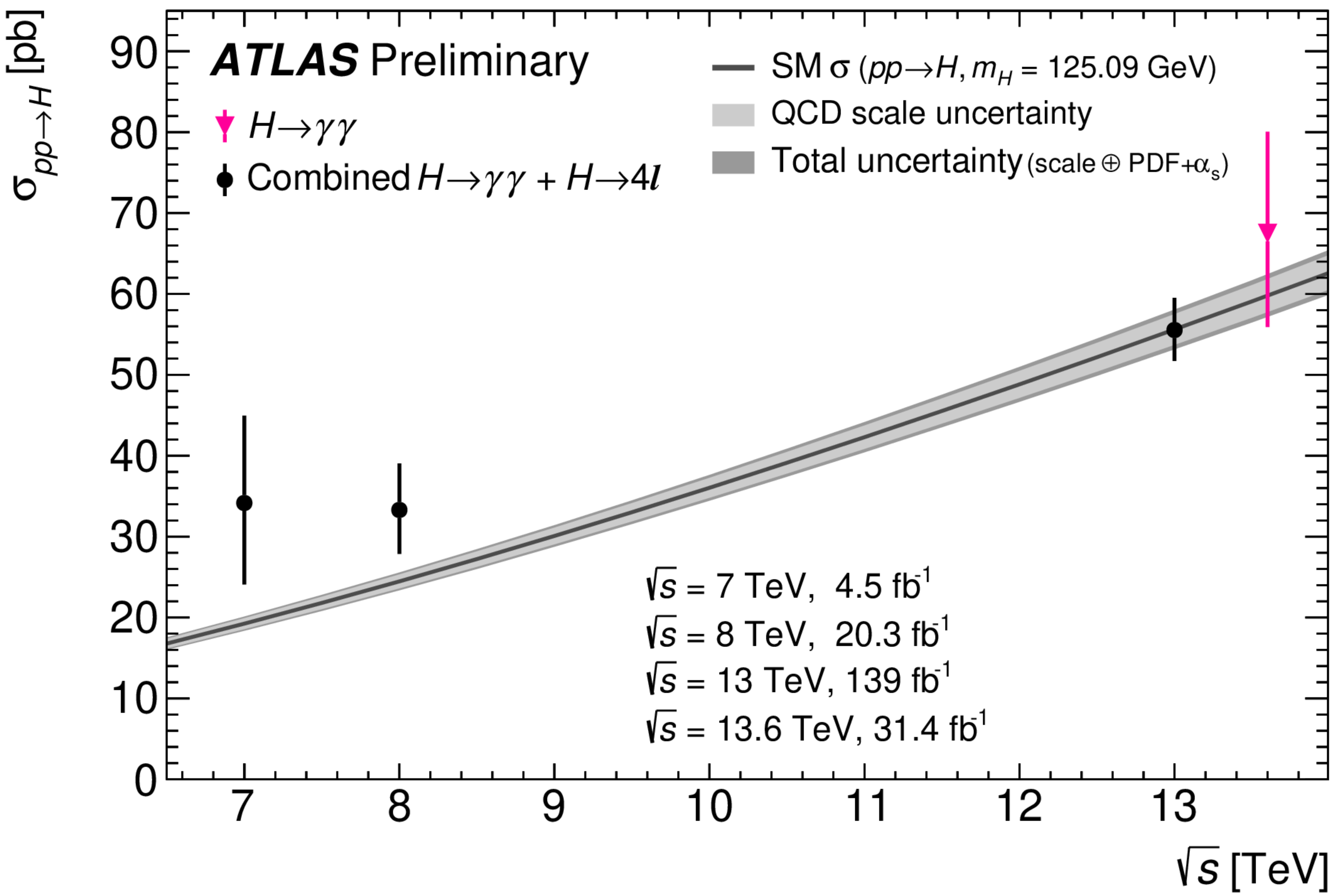
we have to estimate this well!

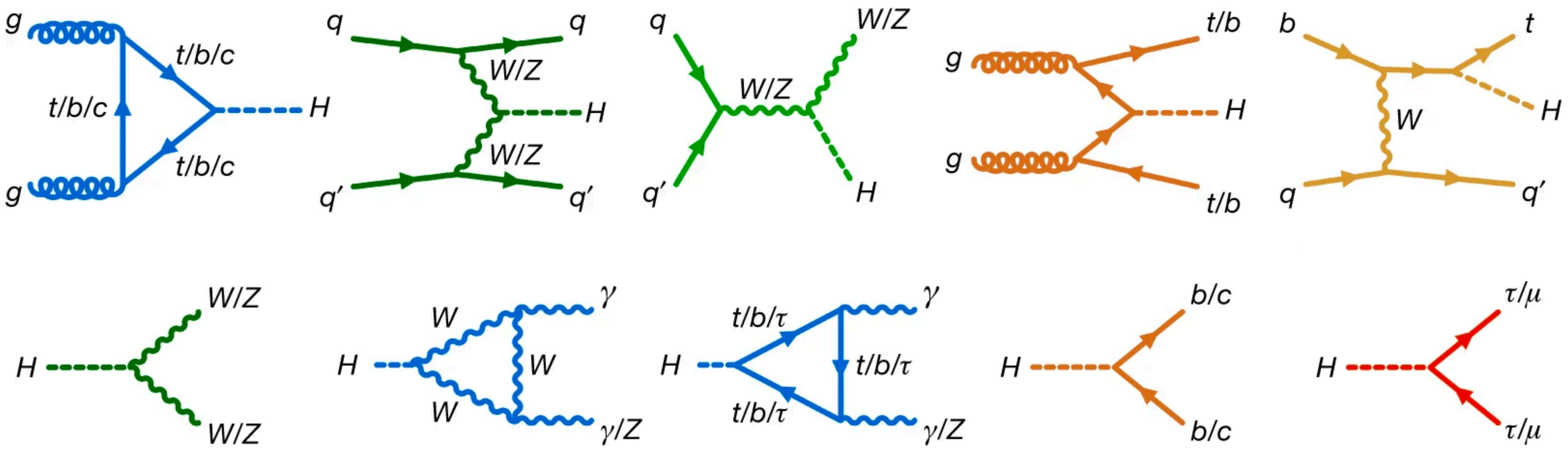
$$N_{Signal}/N_{SM} \propto (\sigma \times \mathscr{B})/(\sigma_{SM} \times \mathscr{B}_{SM})$$

SECOND STEP: COUNT HIGGSES! IS THE RATE AS YOU EXPECT?





rates, signal strengths ($\mu=\sigma_H/\sigma_H^{SM}$), production cross sections



LOOKING AT ALL THE CHANNELS TOGETHER

GLOBAL VIEW OF HIGGS PRODUCTION

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- μ "signal strength" per production and decay mode (what we measure in each analysis). In a "i -> H -> f" mode:

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

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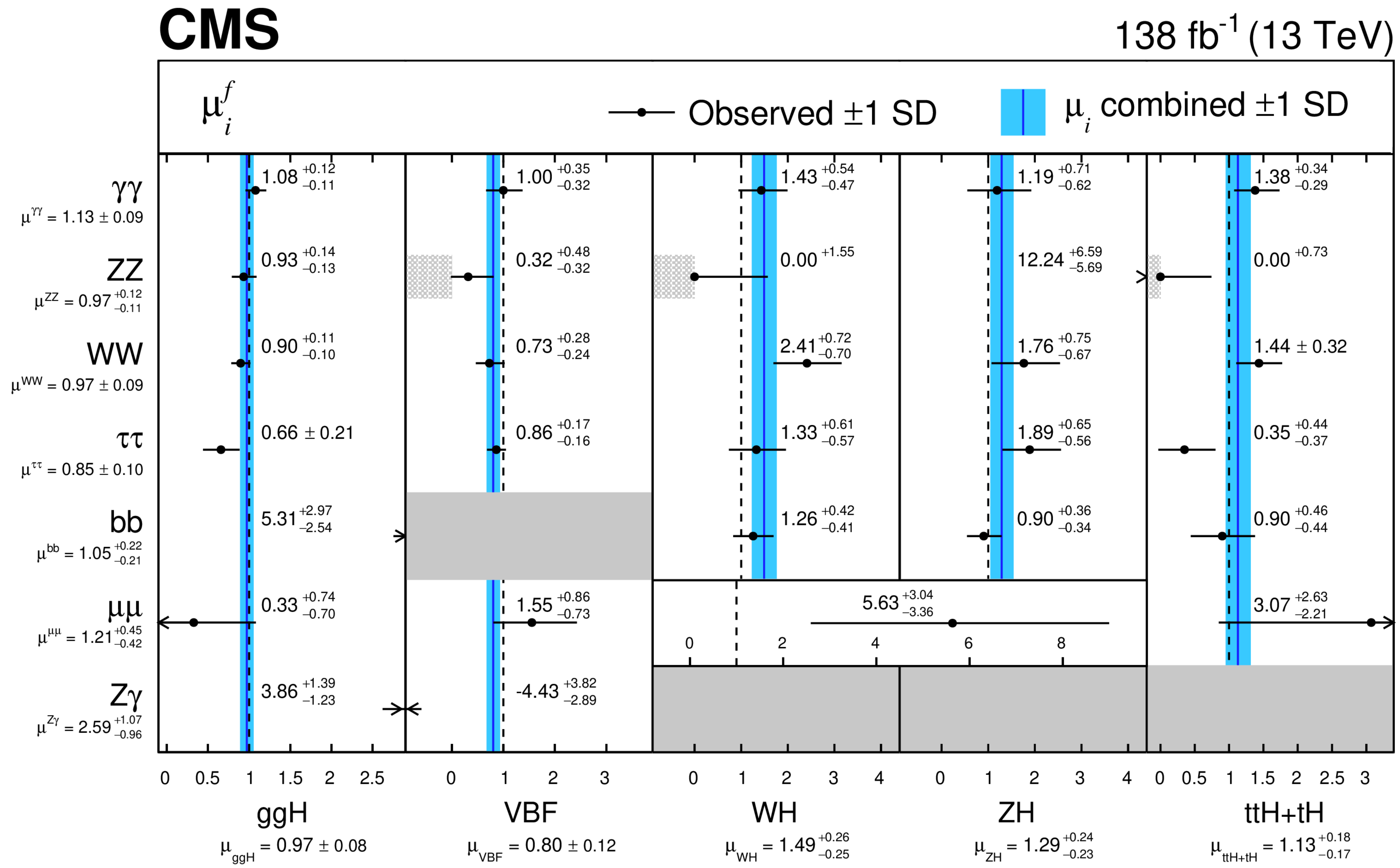
- To combine the channels, we start to make assumptions. Eg:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

GLOBAL VIEW OF HIGGS PRODUCTION

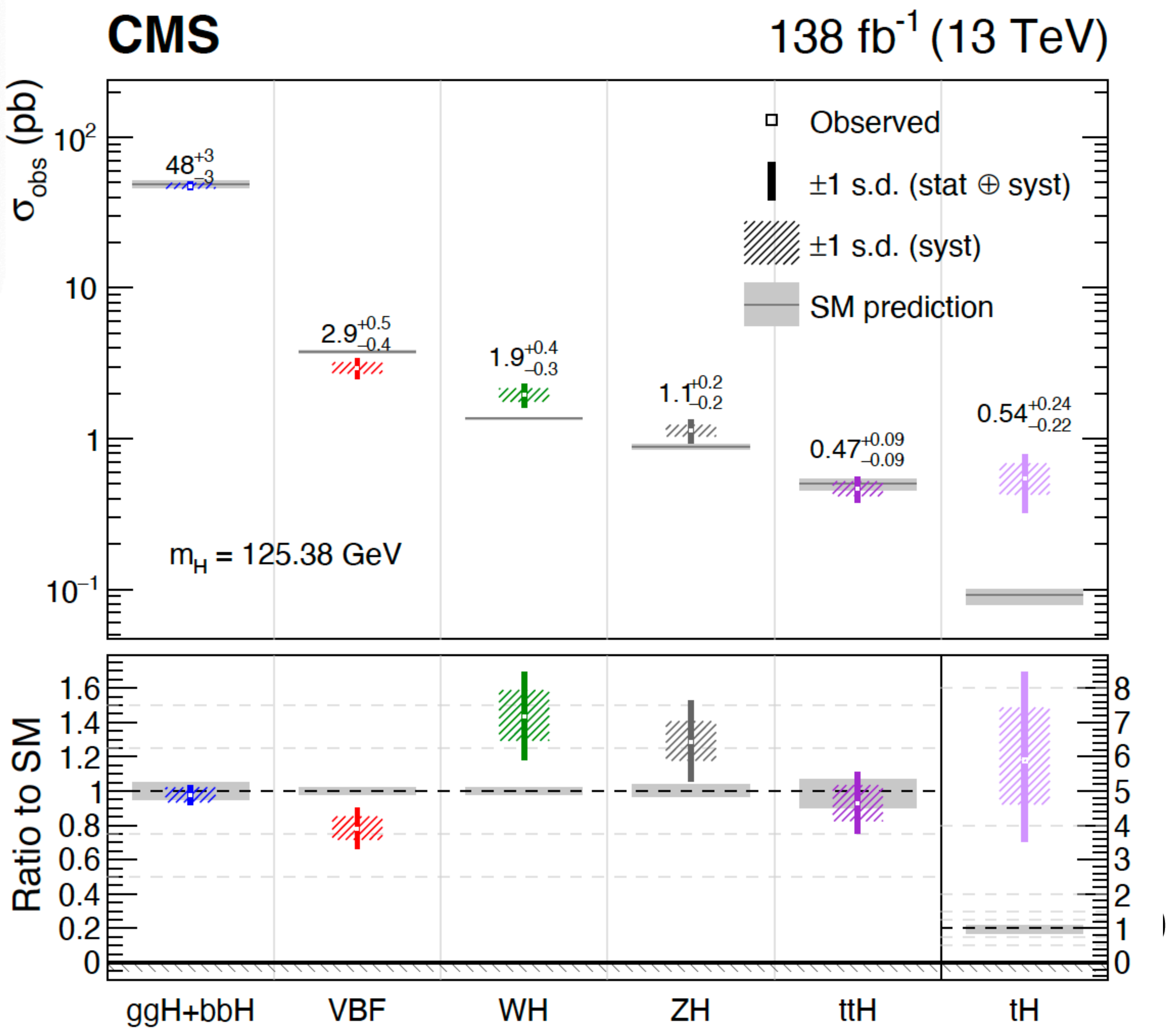


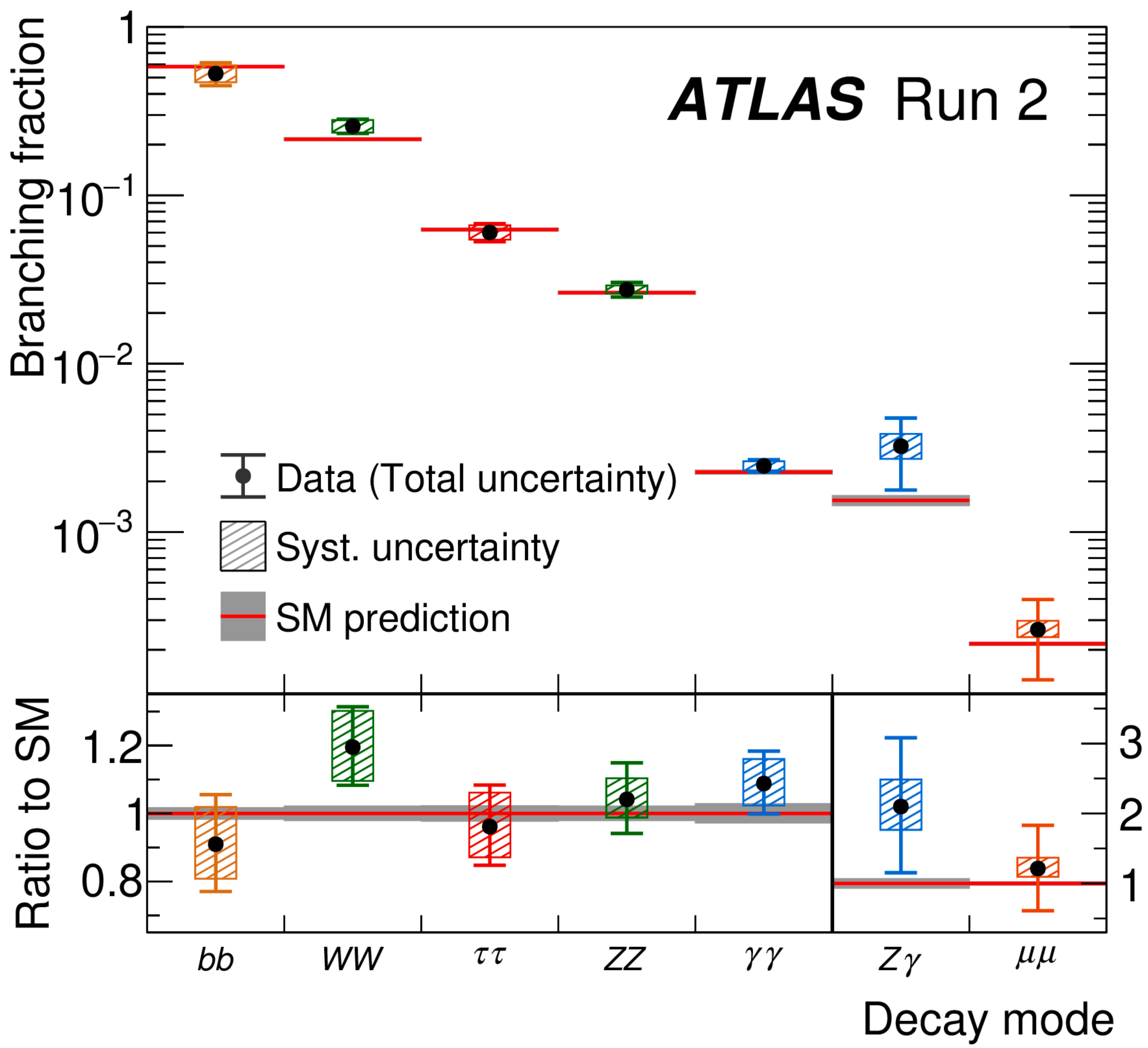
$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

$$\mu_{CMS} = 1.002 \pm 0.057$$

$$\mu_{ATLAS} = 1.05 \pm 0.06$$

PRODUCTION X DECAY





Today, CMS&ATLAS have independently measured the main production and decay modes. Rarer modes (tH, Muons, ZGamma, Charm) not yet observed: being targeted for future runs. Overall, uncertainties are still larger than we need.

WHAT KIND OF PARTICLE IS THE HIGGS?

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Mass?

Total Width?

$$\Gamma \propto lifetime^{-1}$$

Spin?

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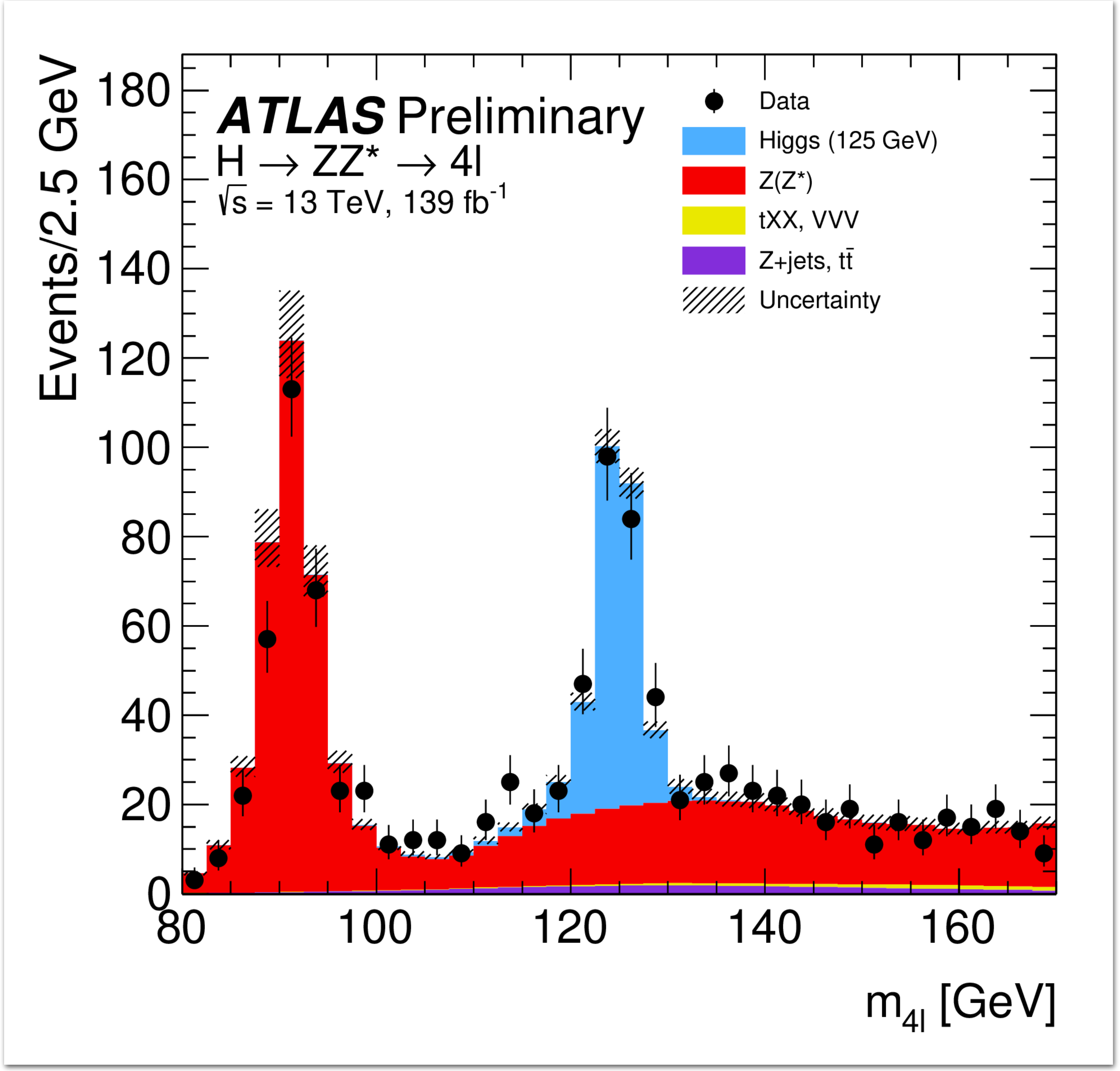

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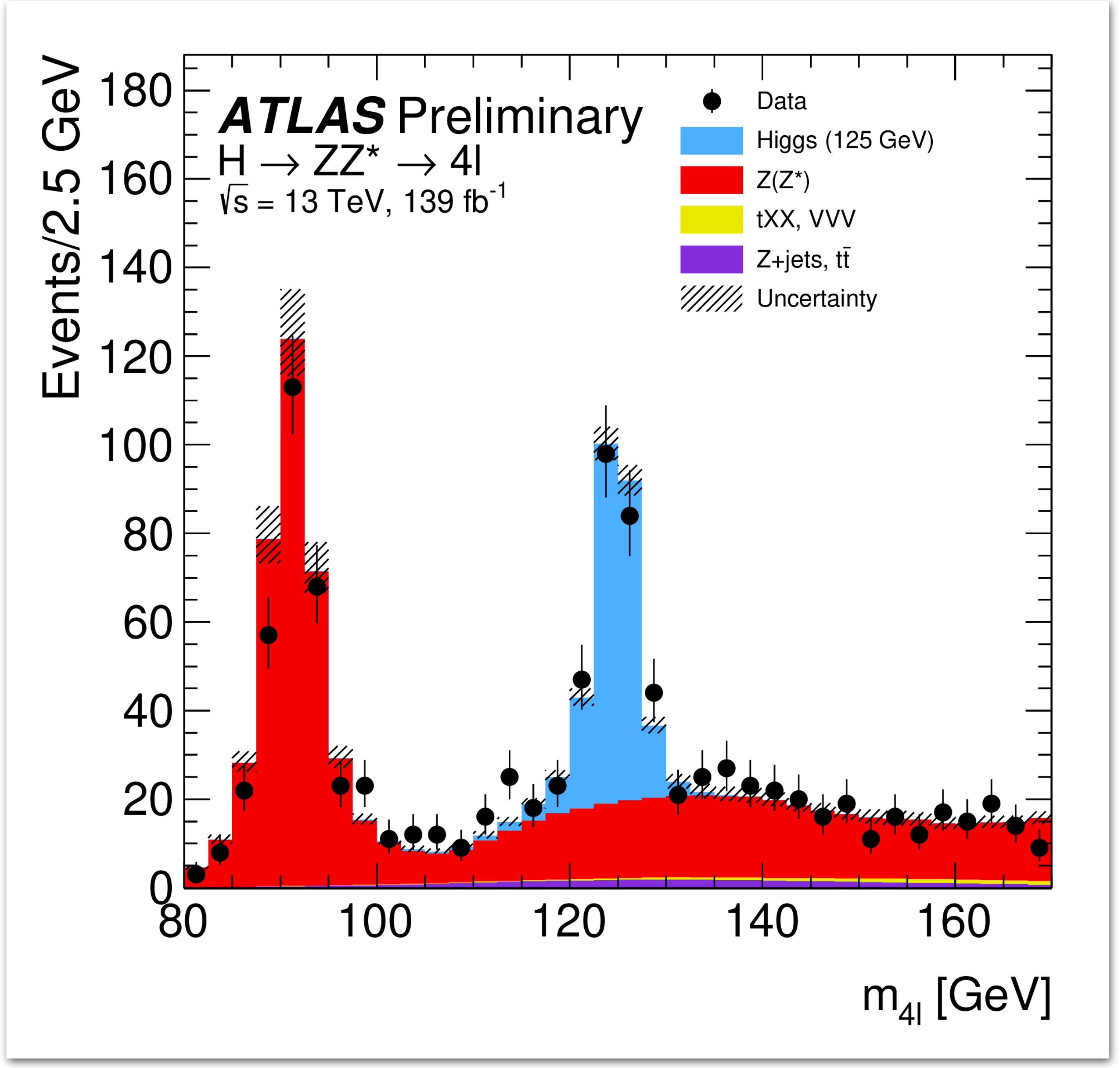
Mass

Free in the SM, now known better than 0.1%! ($H \to ZZ \to 4l$ and $H \to \gamma\gamma$)



$$CMS: 125.08 \pm 0.12\ GeV$$
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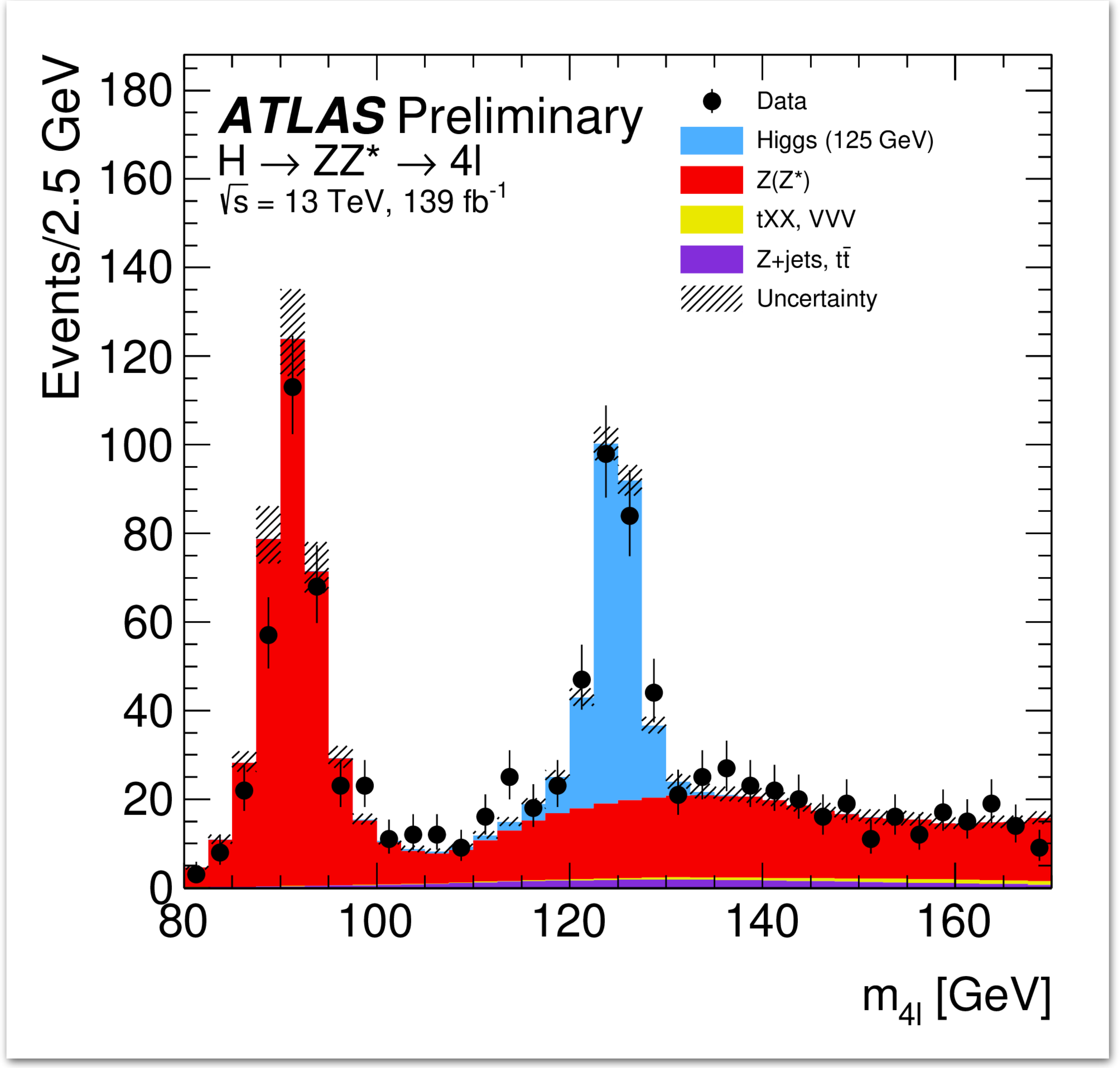
WHAT KIND OF PARTICLE IS THE HIGGS?

Mass

Free in the SM, now known better than 0.1%! ($H \to ZZ \to 4l$ and $H \to \gamma\gamma$)



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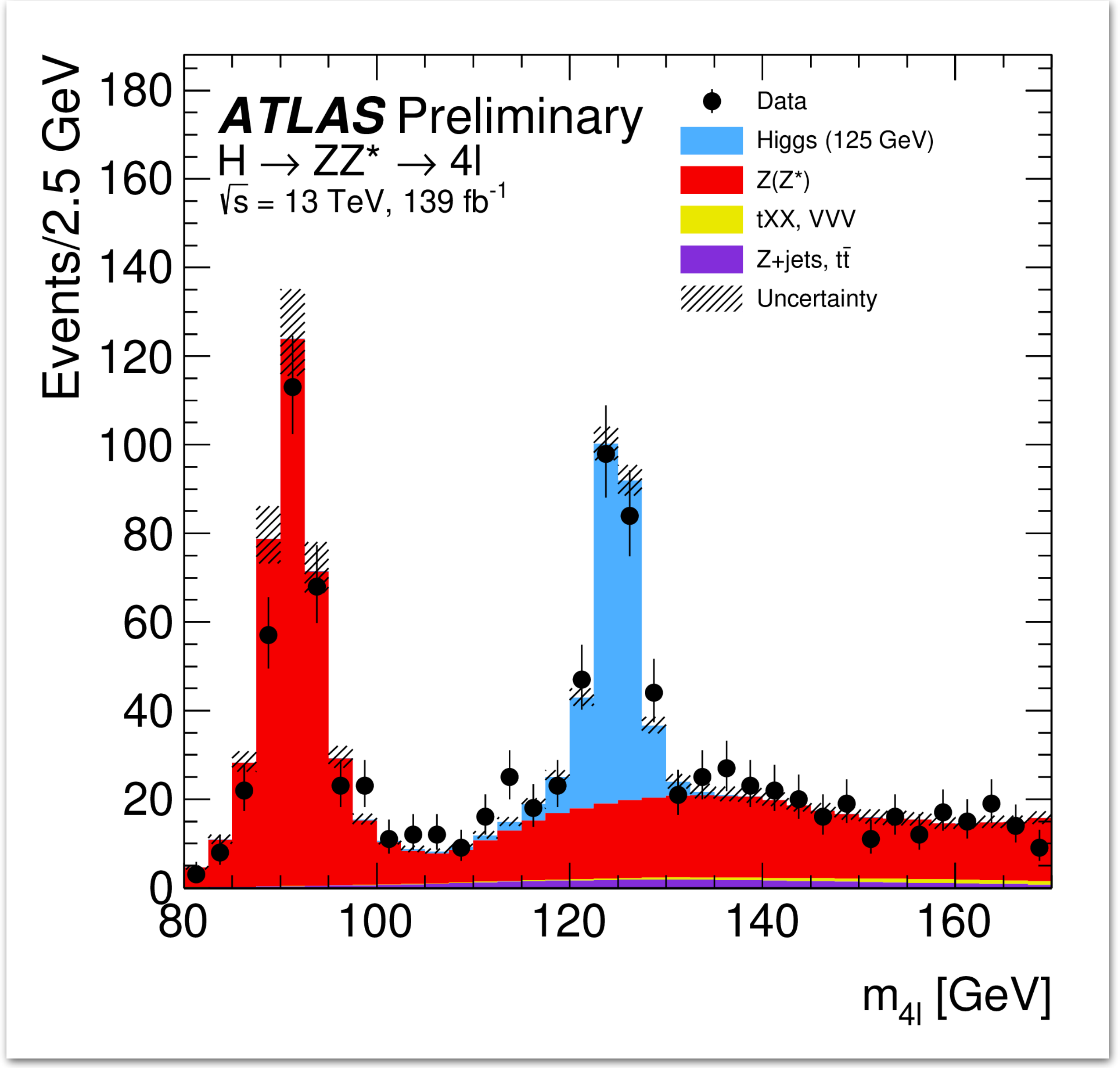

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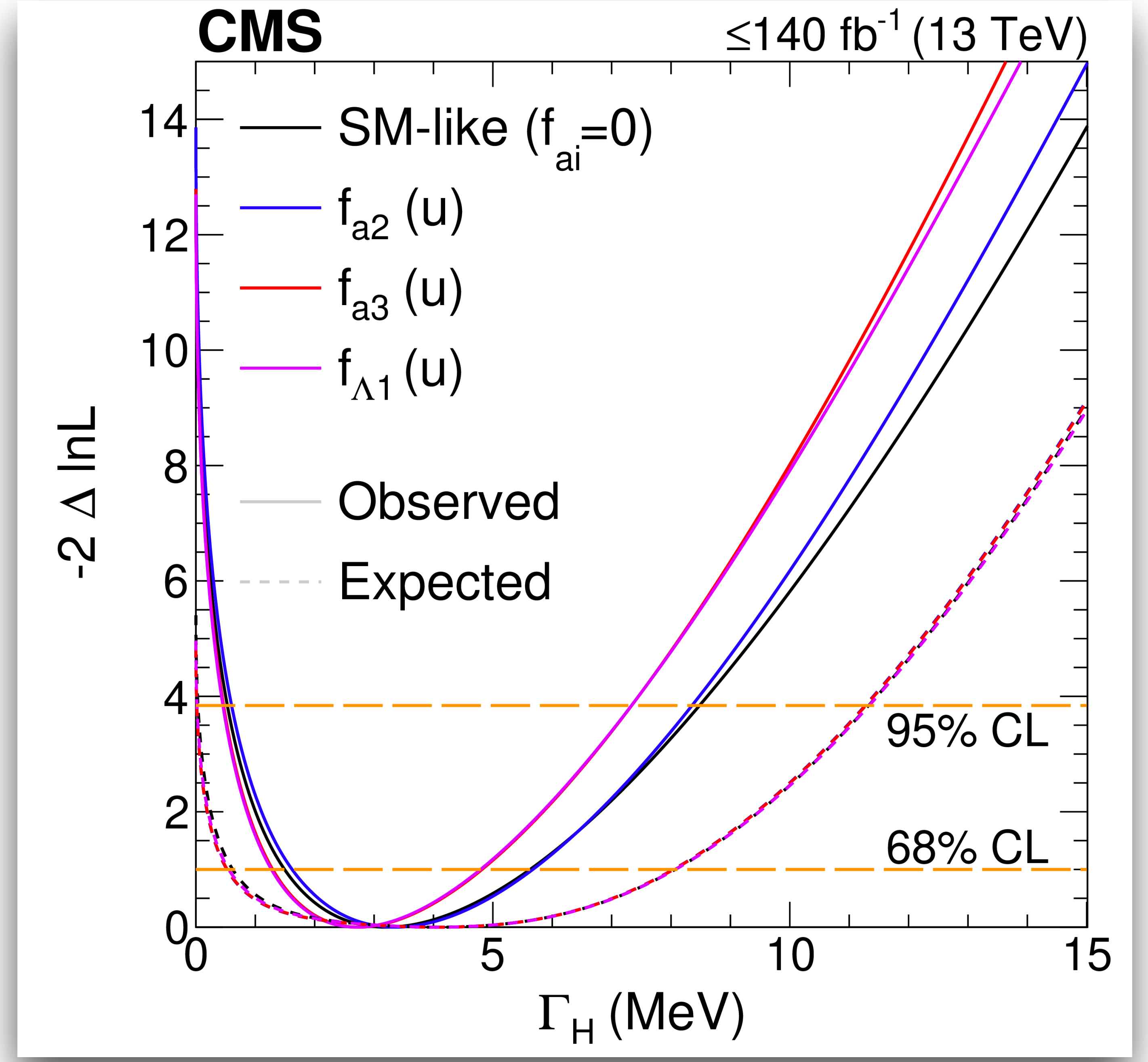

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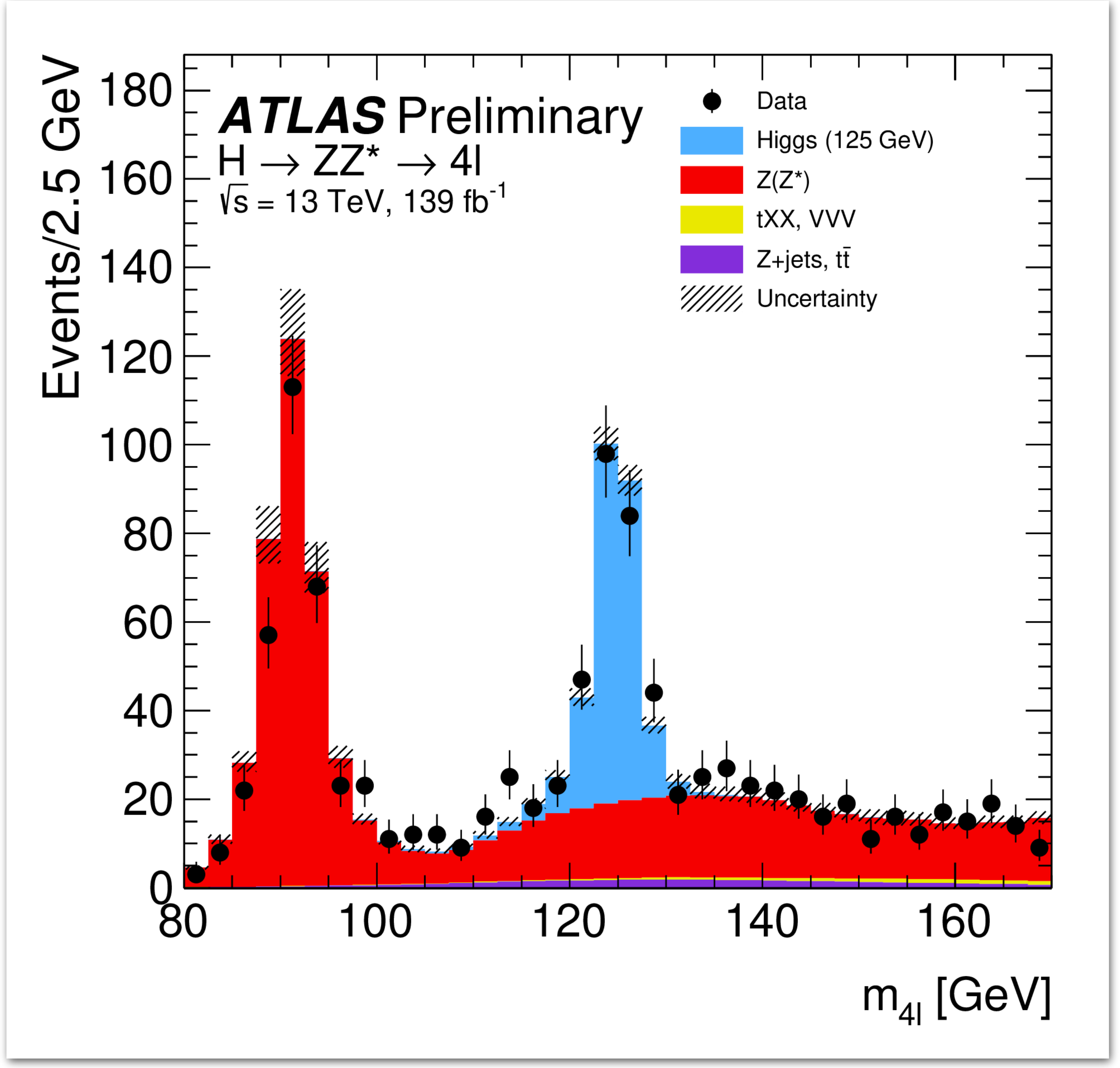

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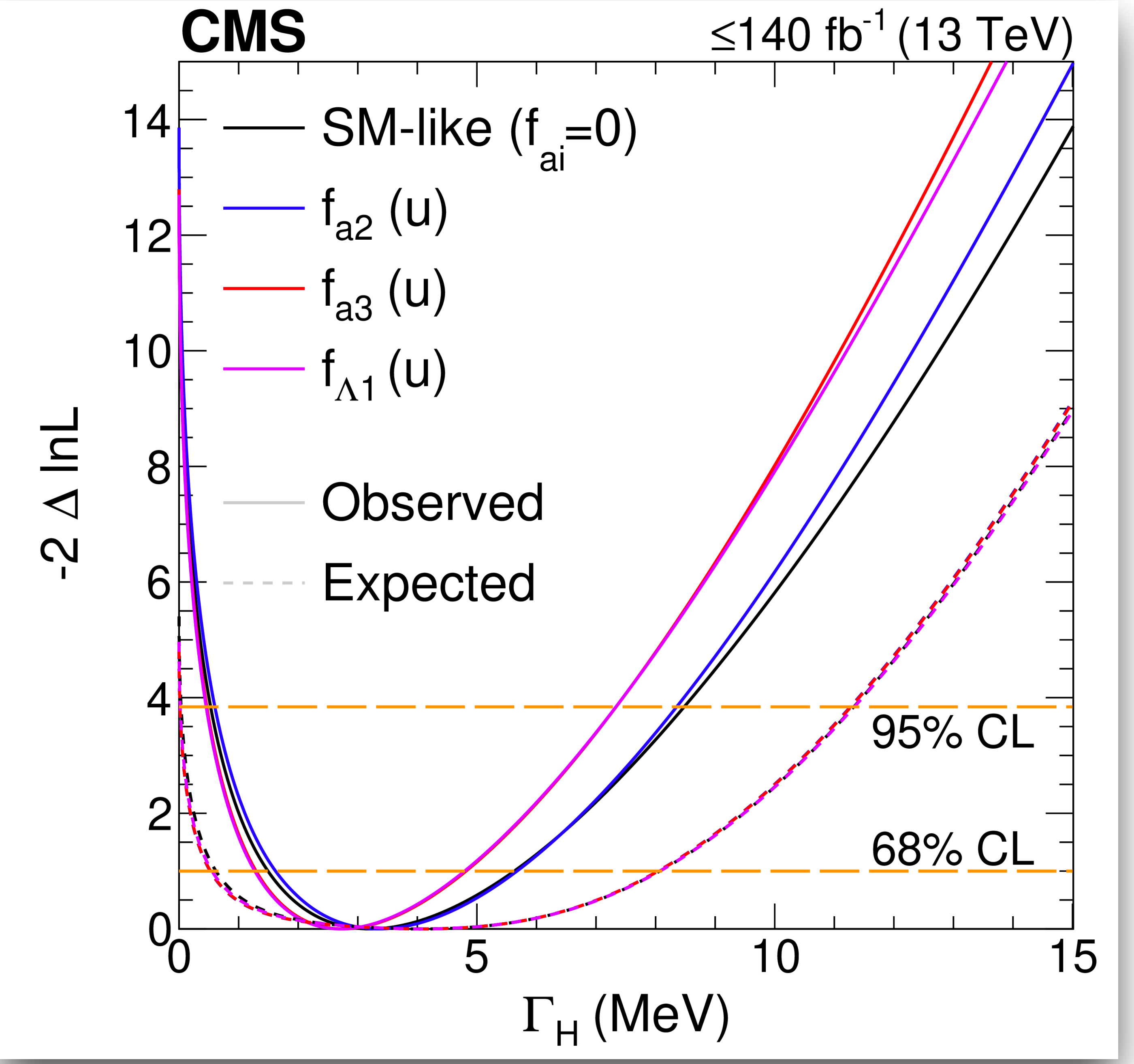

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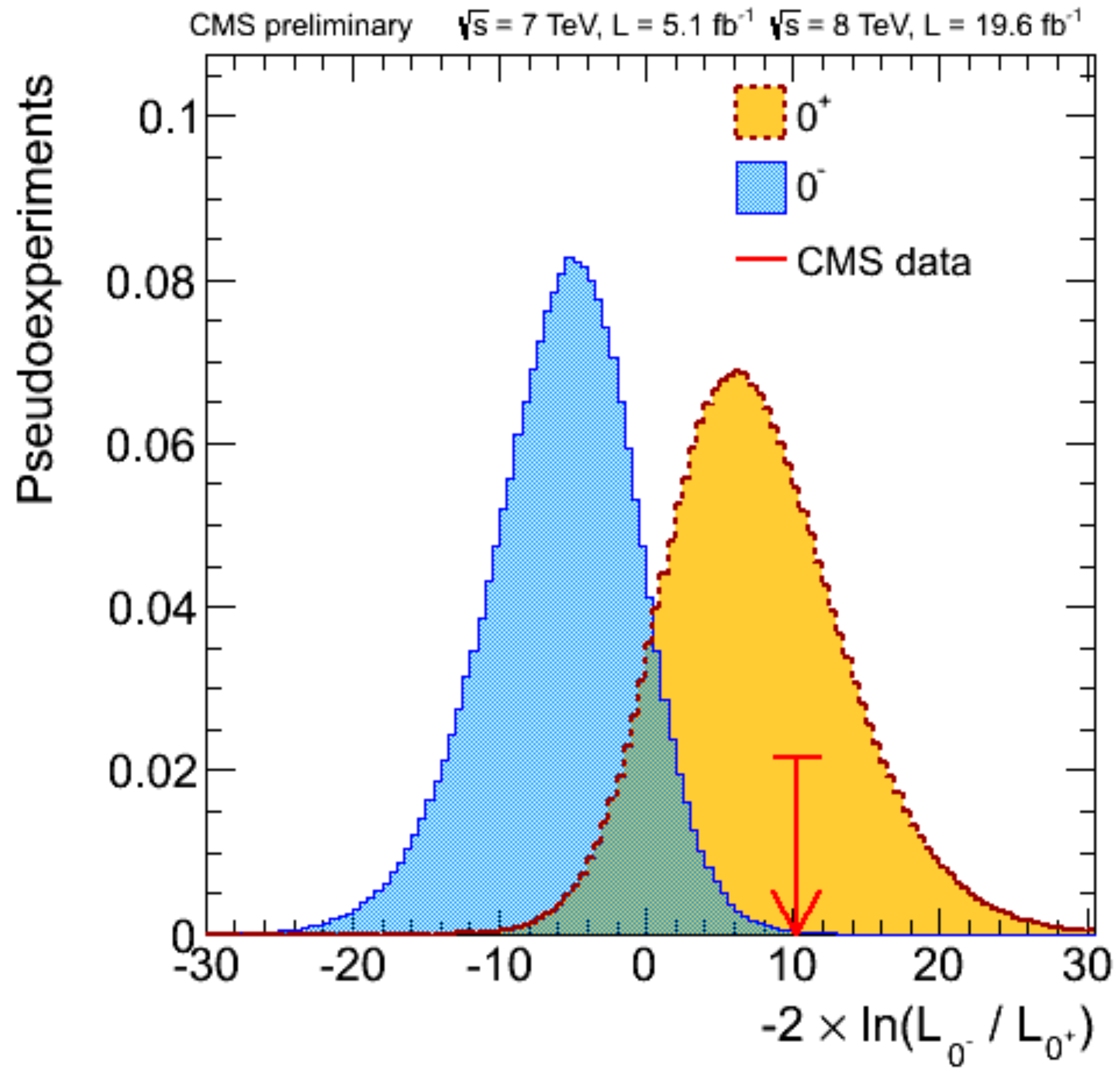
Spin: 0+ (SM-like)



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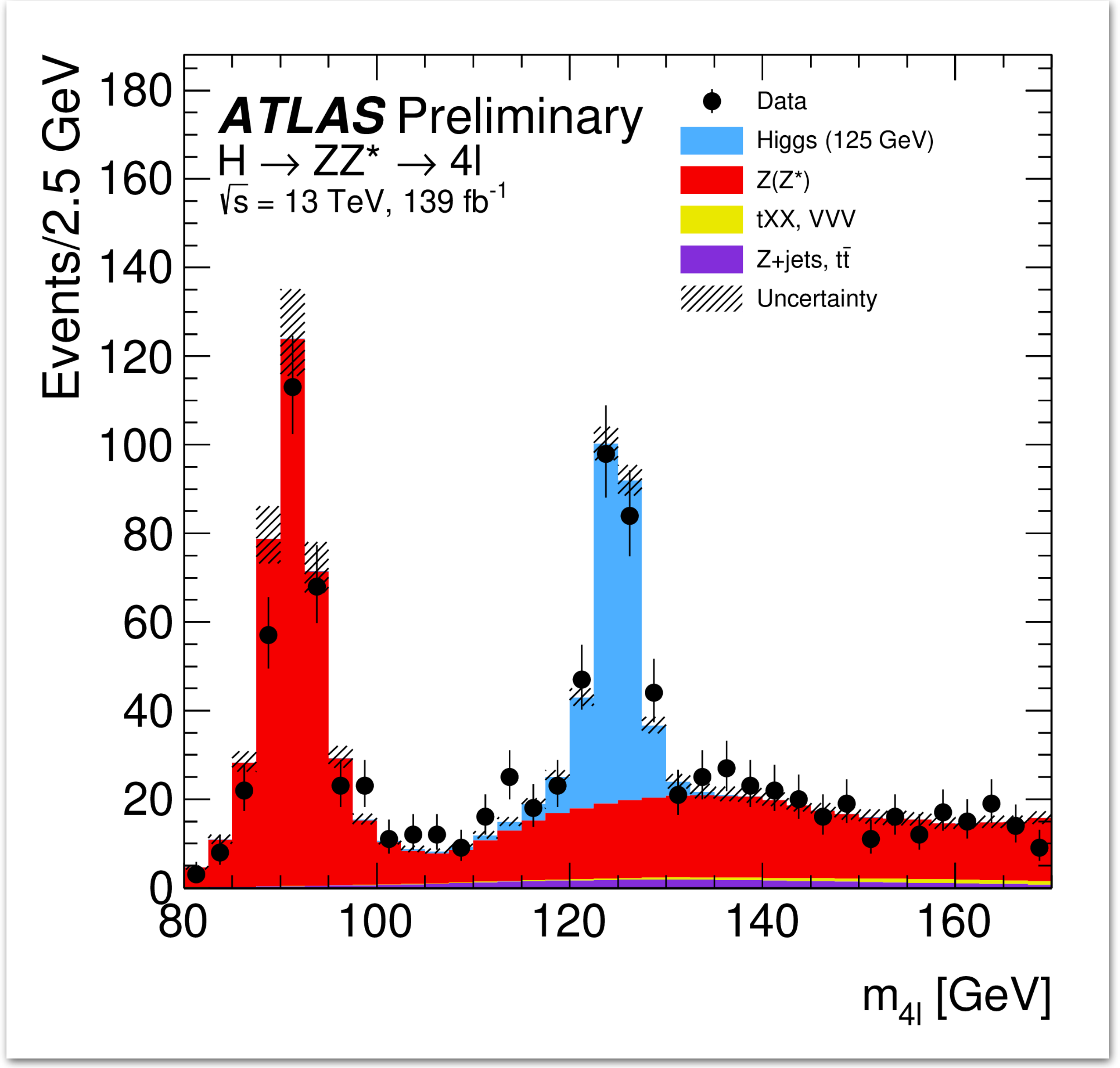

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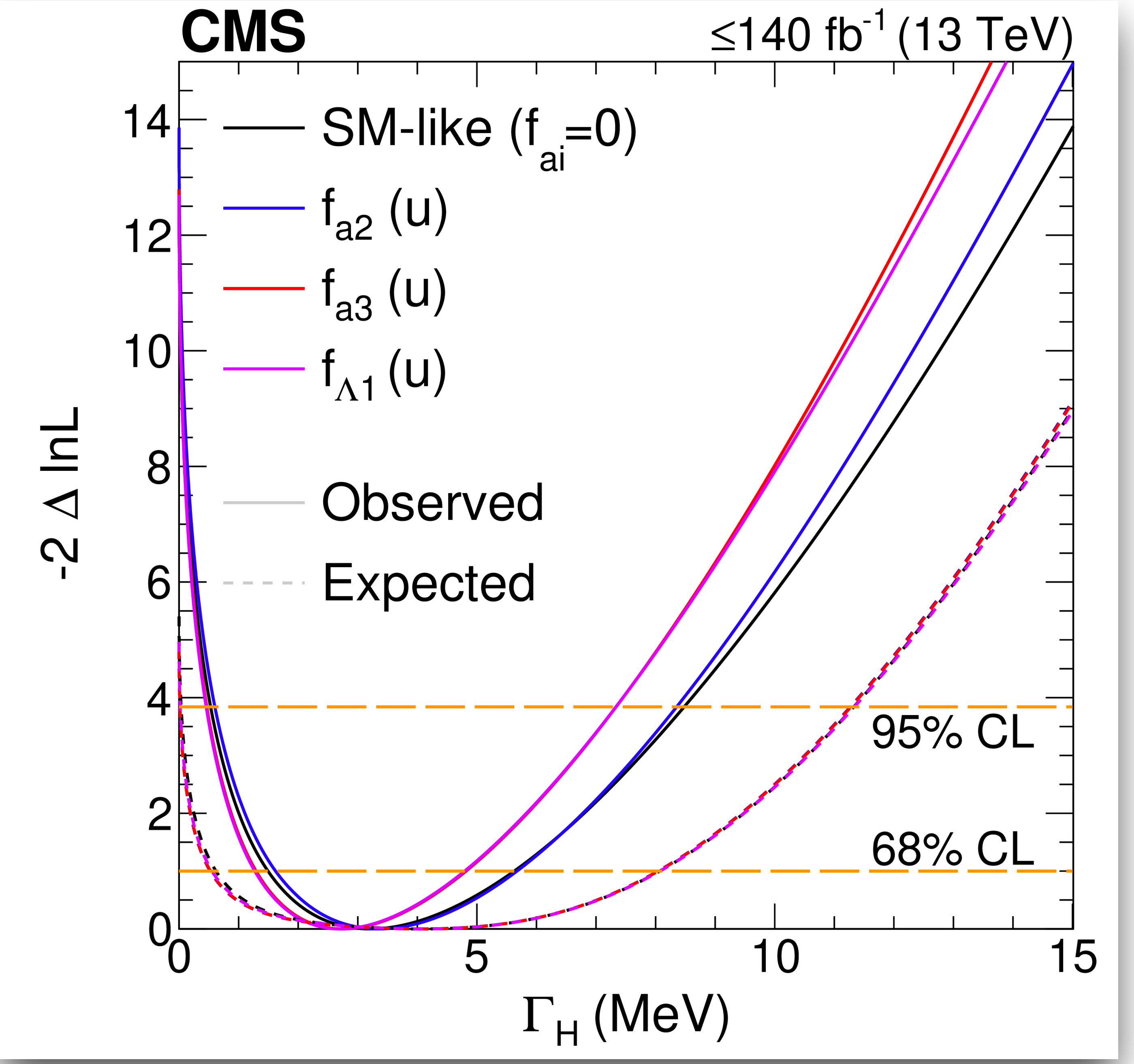

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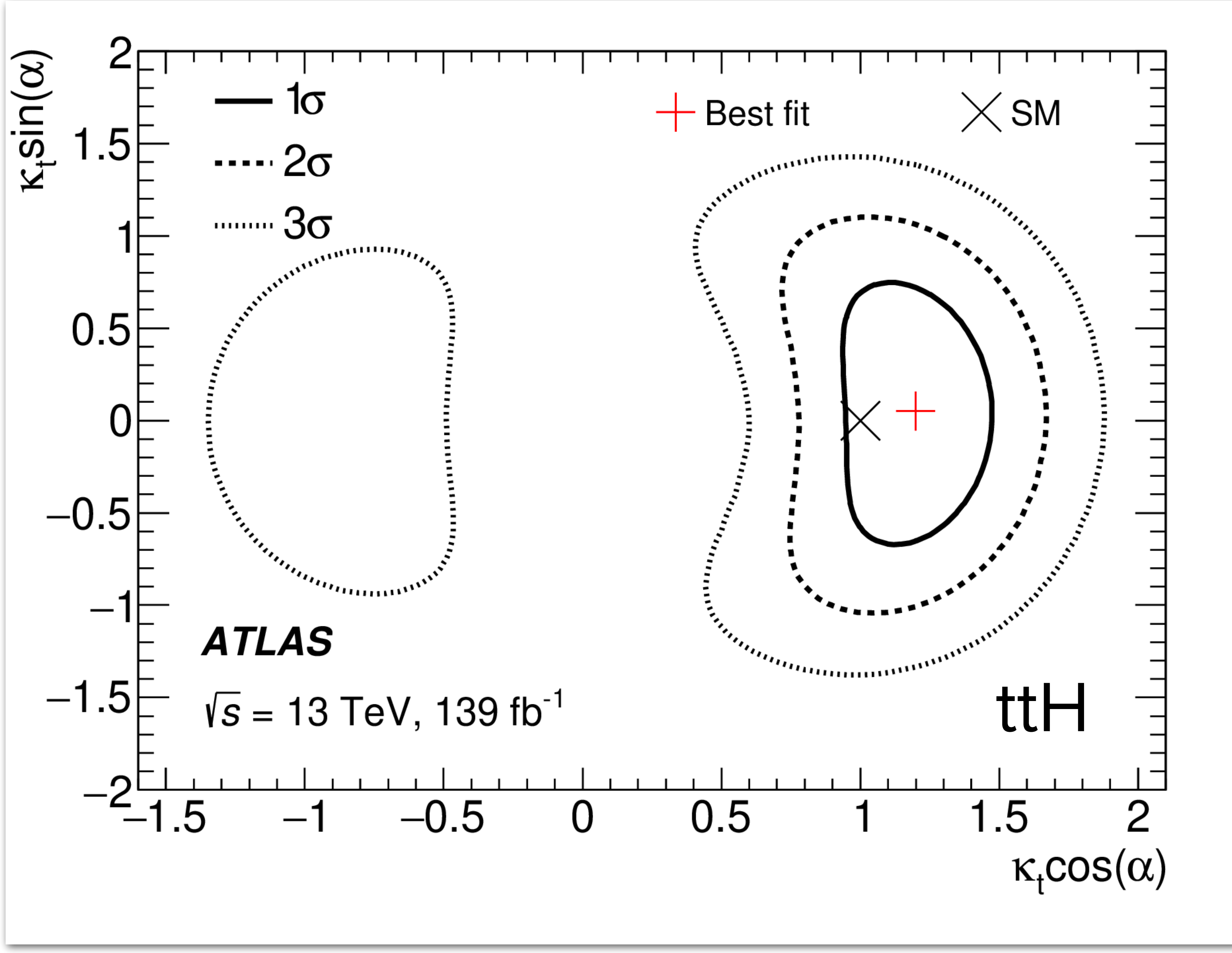
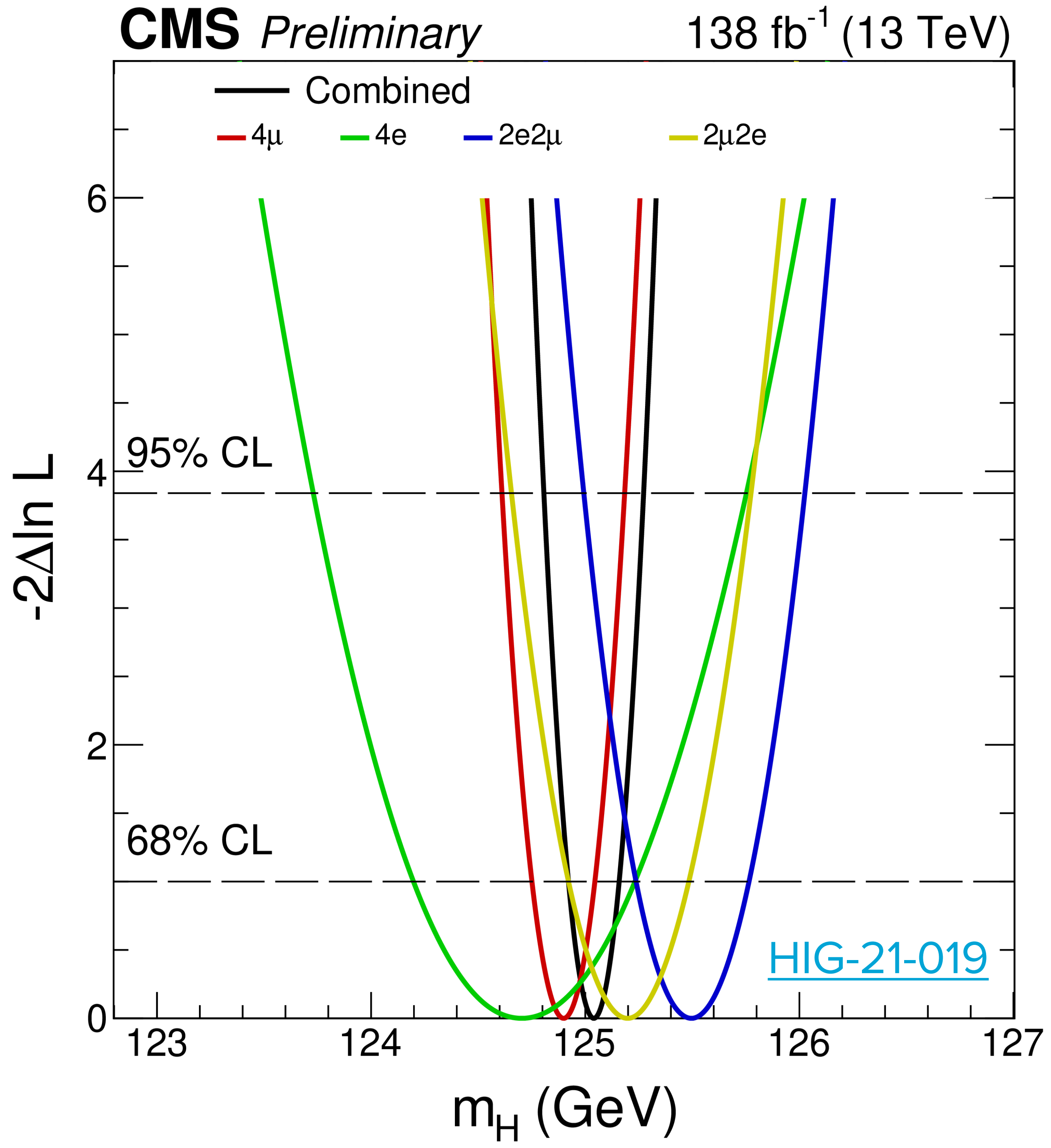
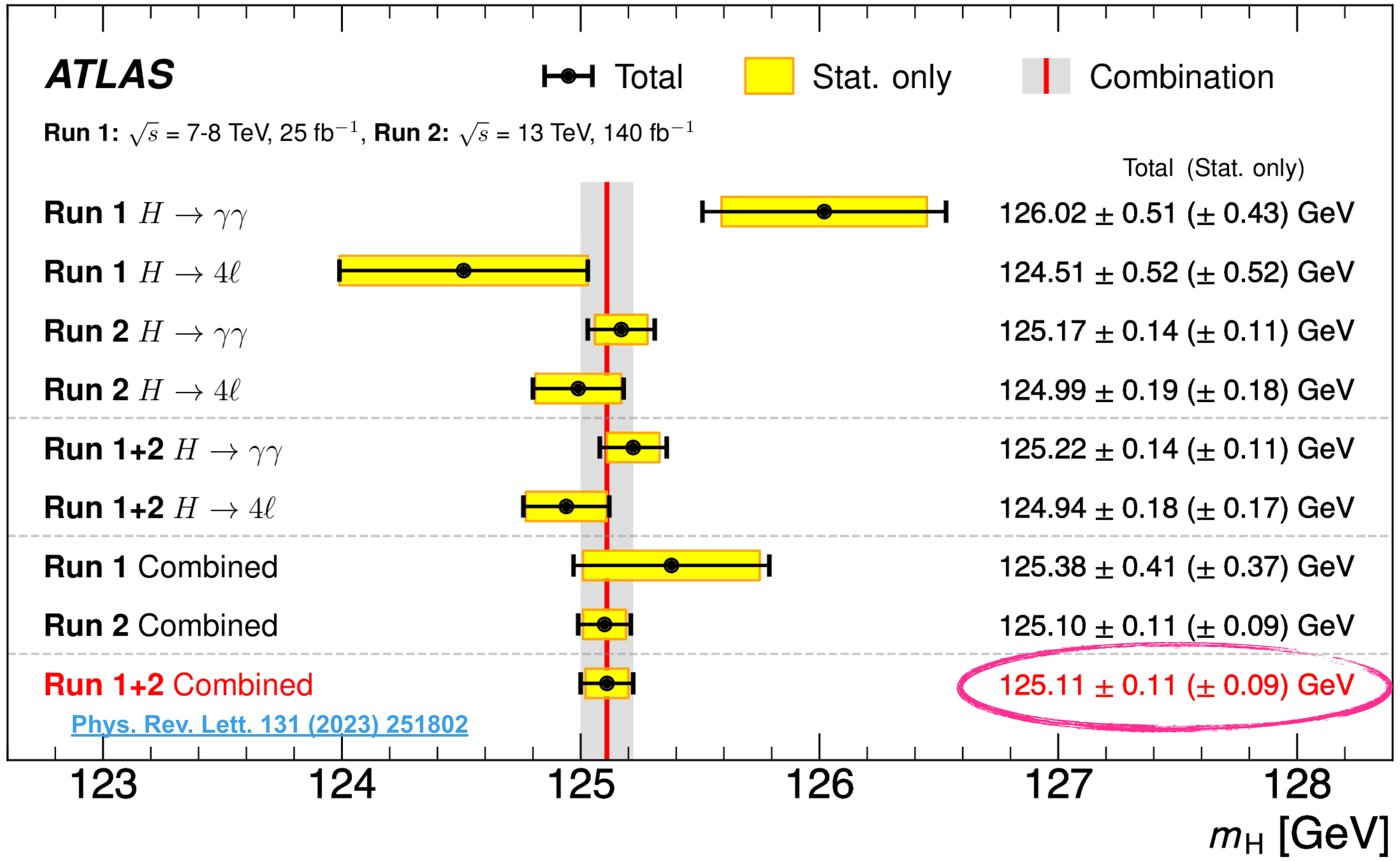


Does the Higgs sector have a new source of Charge-Parity violation?

HOW WELL DO WE KNOW THE HIGGS MASS?

- **Free parameter in the SM, and already very precisely measured by CMS and ATLAS (in $H \rightarrow ZZ -> 4l$ and $H \rightarrow \gamma\gamma$)**
- The precision with which we can measure m_H is directly linked to the reconstruction (energy scale and resolution) of photons and leptons —> **Known to the per mil level already**





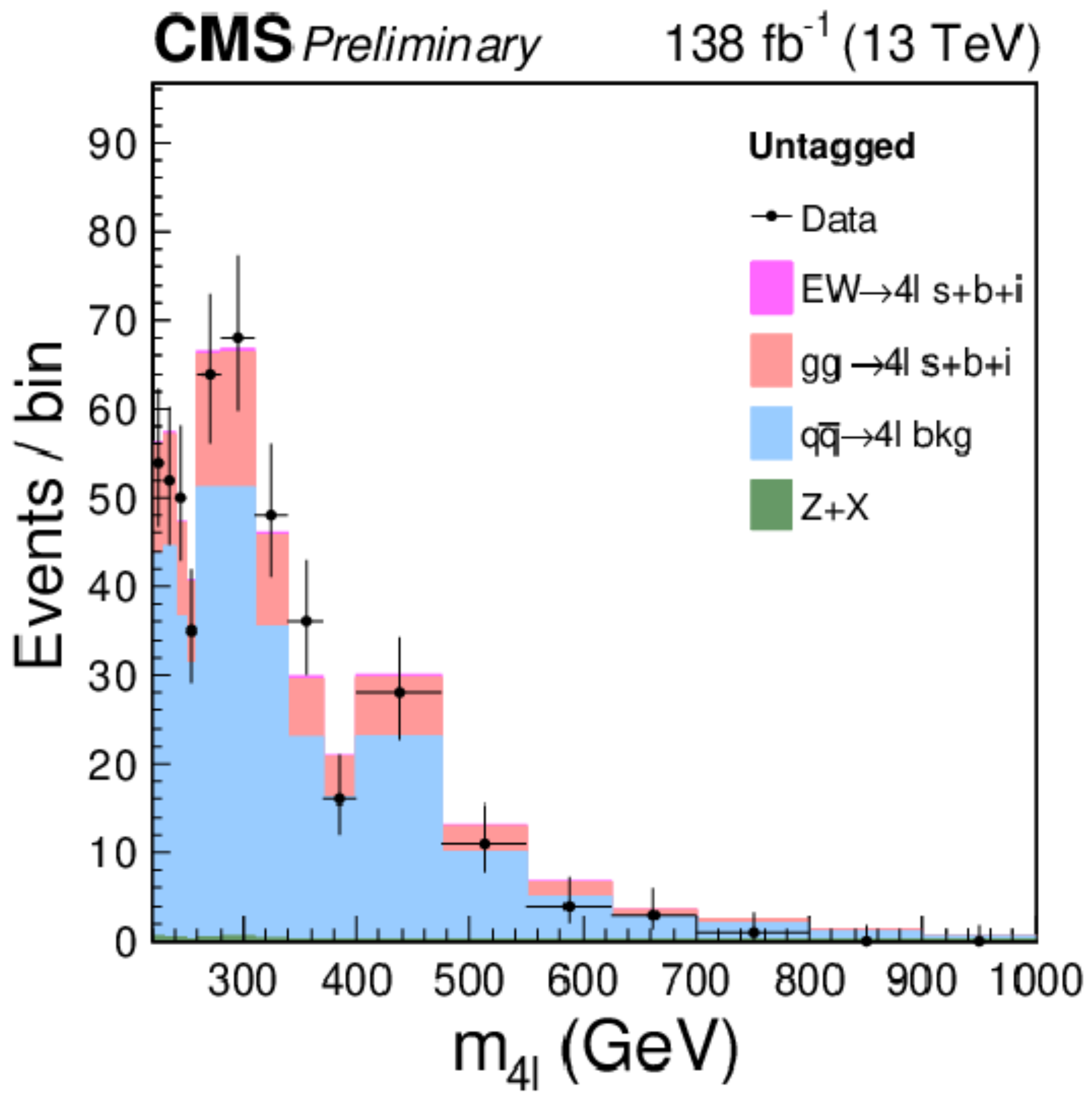
$$CMS(36\ fb^{-1} ZZ + \gamma\gamma) : 125.38 \pm 0.14\ GeV$$

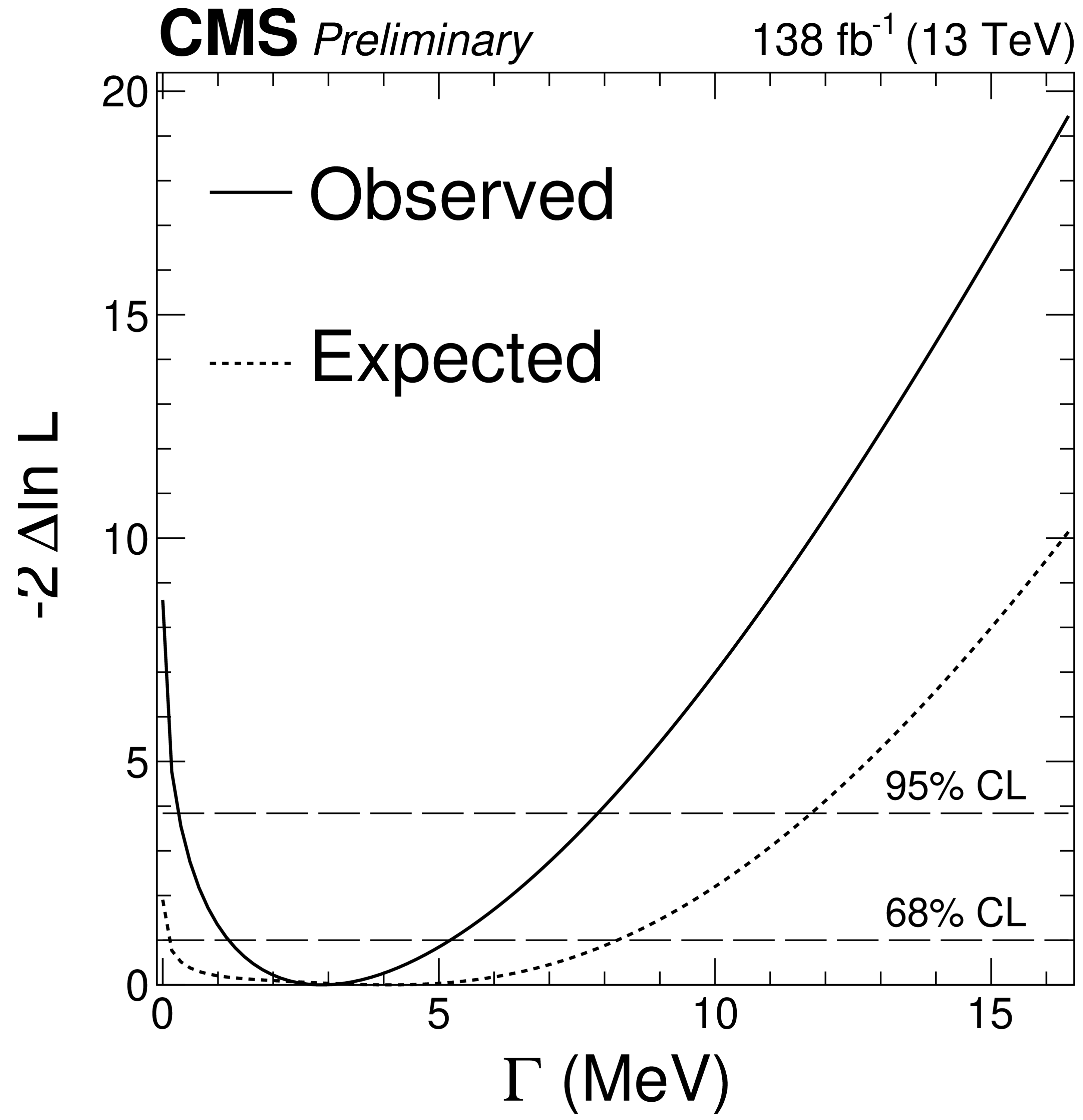
$$CMS(138\ fb^{-1},\ ZZ \rightarrow 4l) : 125.08 \pm 0.12\ GeV$$

$$ATLAS(140\ fb^{-1},\ ZZ + \gamma\gamma) : 125.11 \pm 0.11\ GeV$$

HOW WELL DO WE KNOW THE HIGGS WIDTH?

- Γ_H (SM)= 4.1 MeV (very small!)
- Direct measurement: < 330 (750) MeV (at 95% CL) (CMS, HIG-21-019)
- H→ZZ→4l: measure through the relative on-shell and off-shell production rates (model dependent): **First measurements reaching SM sensitivity, though still with uncertainty close to 100%**





$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}.$$

$m_{ZZ} \sim m_H$
(On-shell production)

$m_{ZZ} > m_{2Z}$
(Off-shell production)

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\ \text{MeV}$$

(CMS, HIG-21-019)

WIDTH IN e+e-

JHEP01(2020)139

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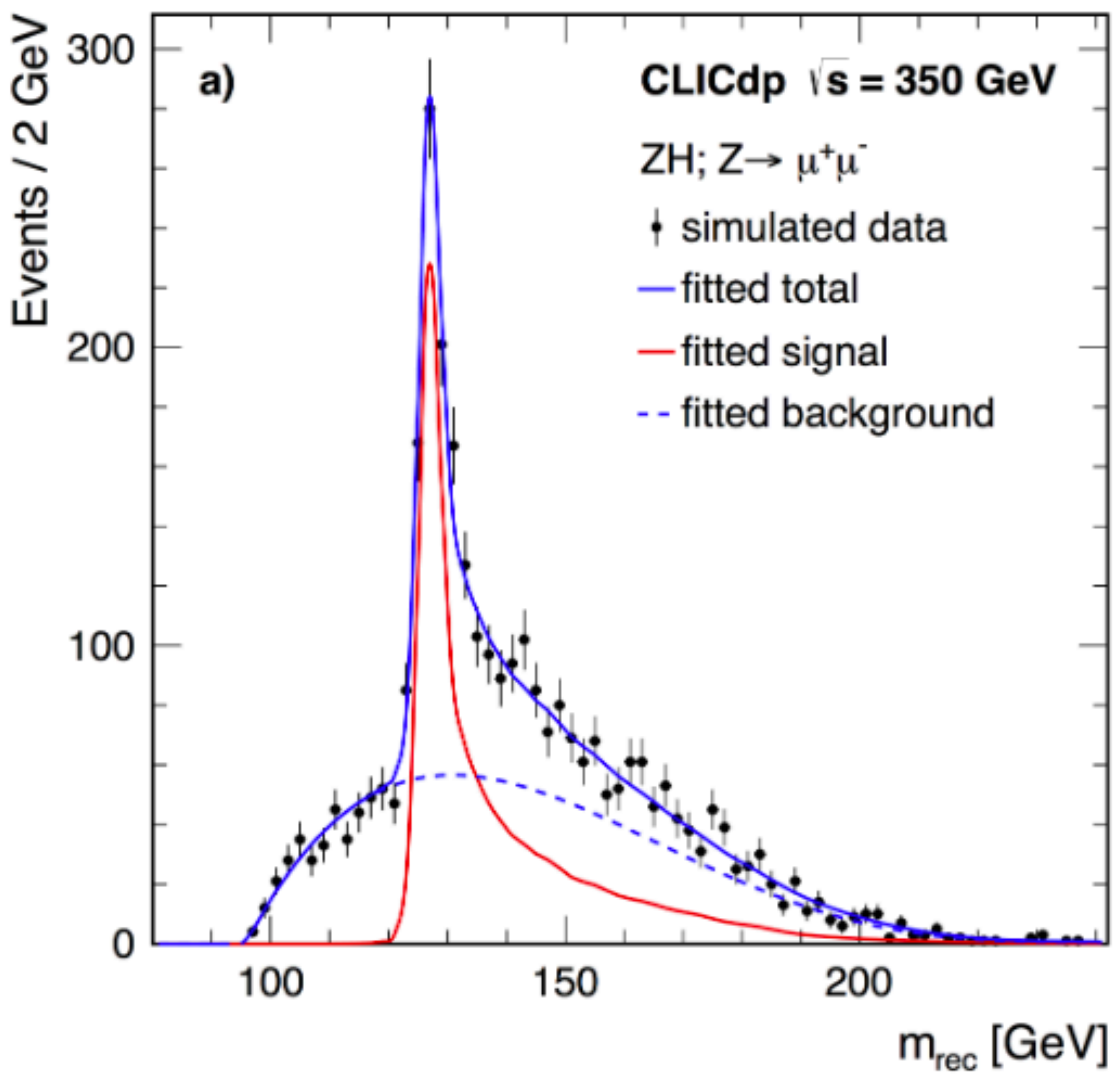

$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

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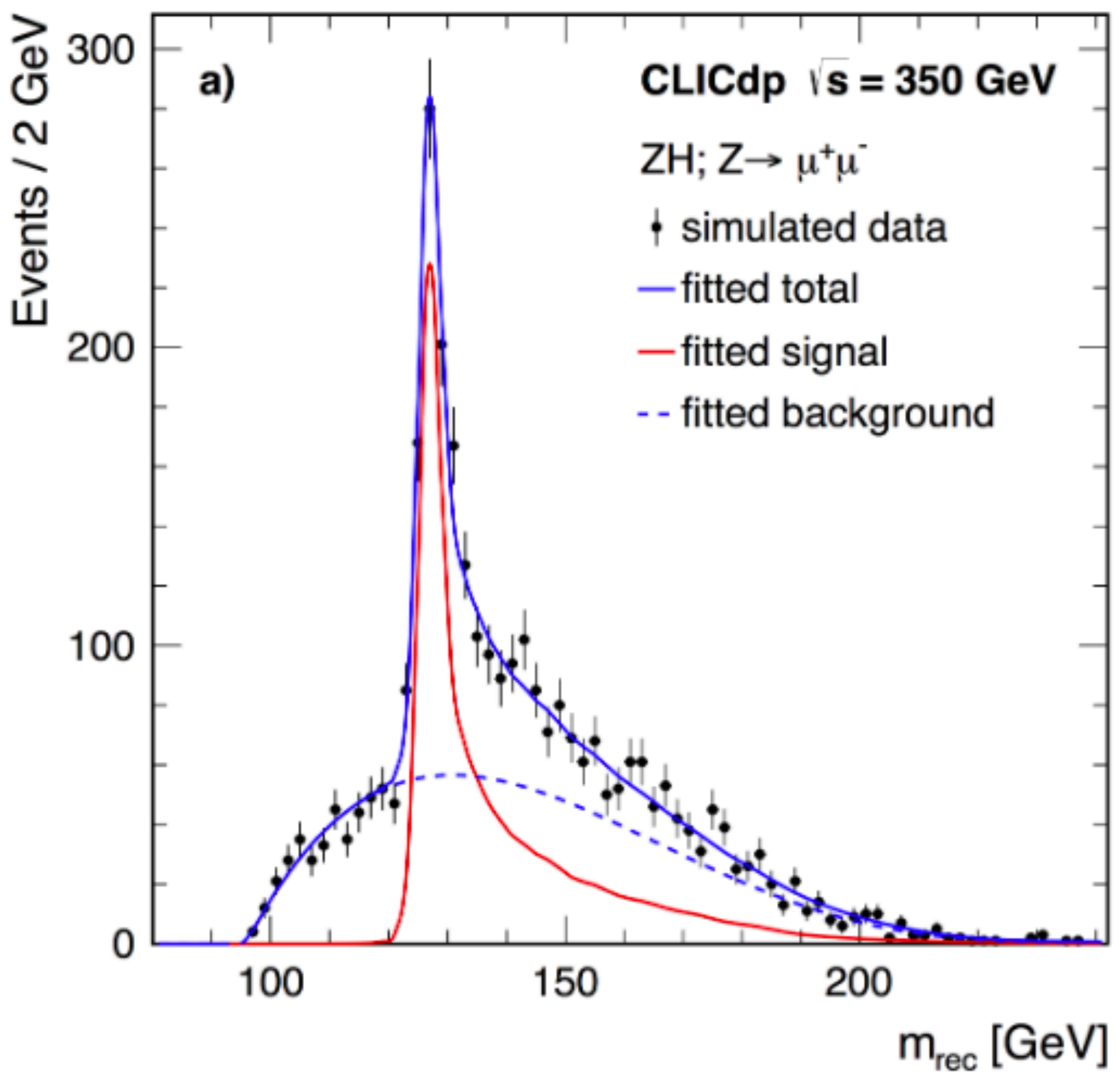

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Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [80]	2.6
CLIC_{1500}	2.6	κ-framework [80]	1.7
CLIC_{3000}	2.5	κ-framework [80]	1.6
CEPC	3.1	$\sigma(ZH,\nu\bar{\nu}H)$, BR$(H \to Z, b\bar{b}, WW)$ [85]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

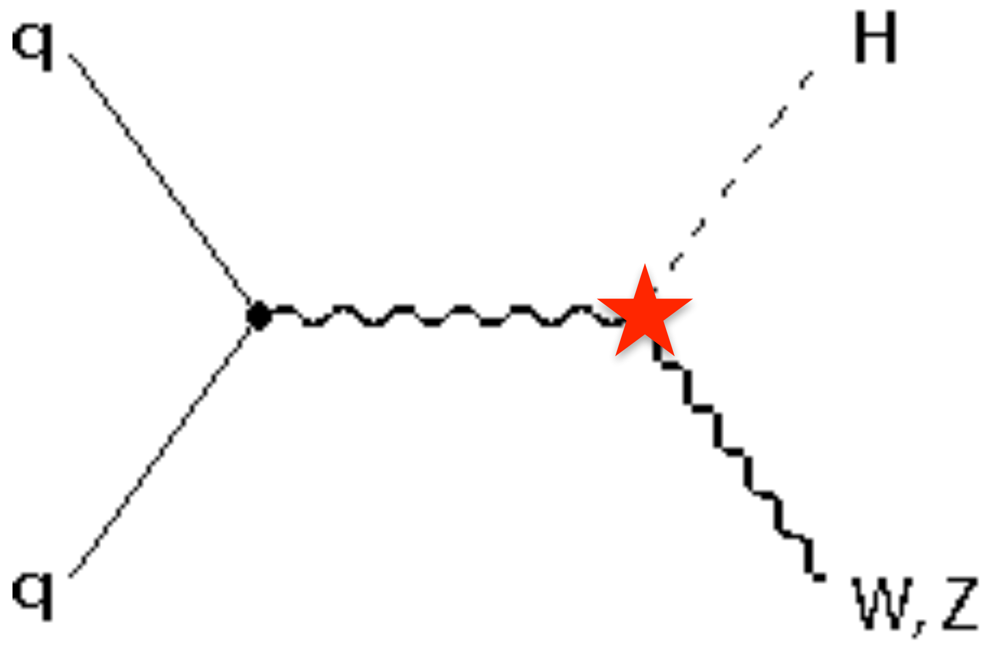
JHEP01(2020)139

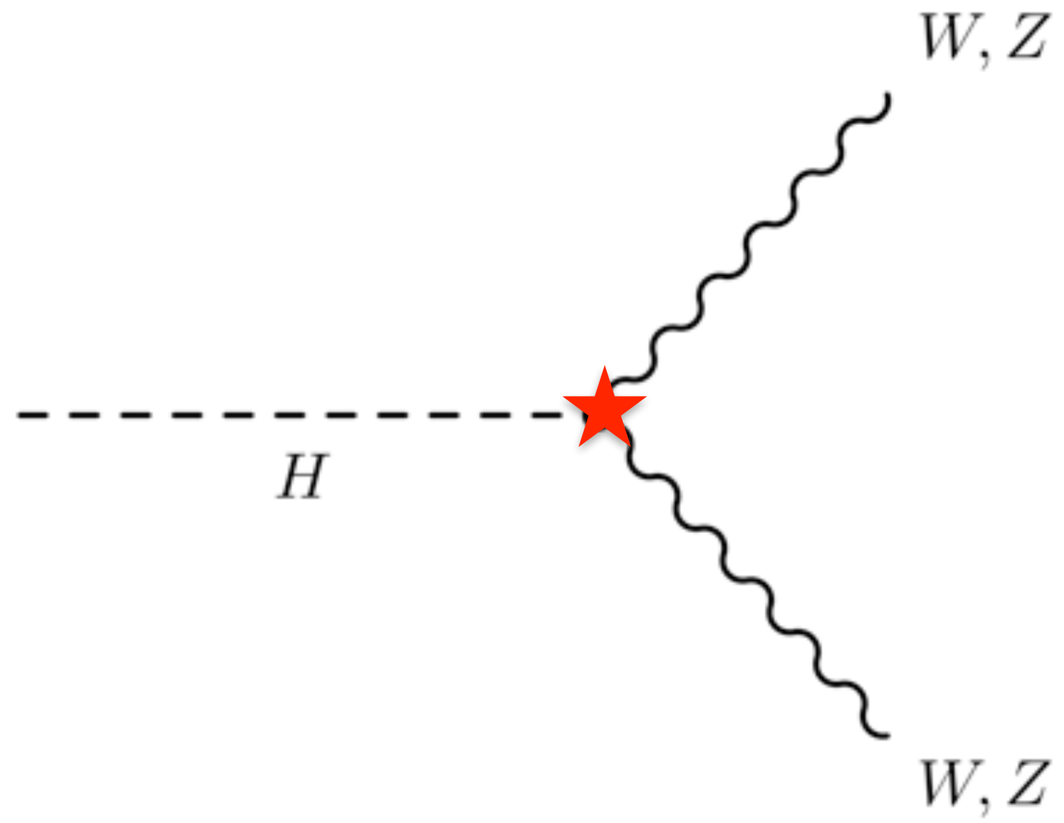
HIGGS COUPLINGS

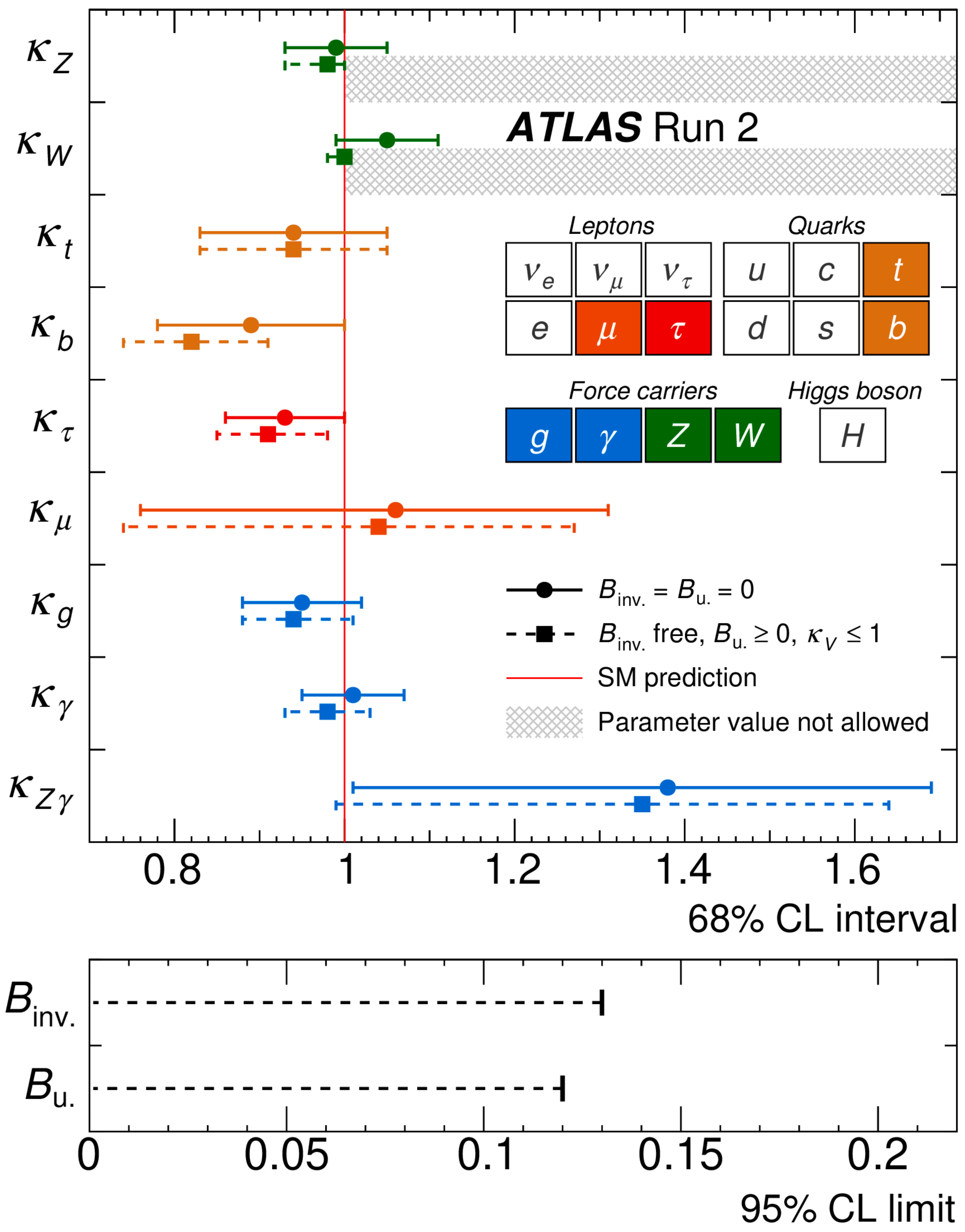
- **What is the strength of the interaction of the Higgs to the different SM particles?**
- Kappa Framework: simple parametrisation widely used by LHC experiments (not perfect, but useful) already known to 6-15%

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$







KAPPA FRAMEWORK

- Different fits are performed depending on the assumptions (more or less constrained to the SM predictions)

(arXiv:1307.1347 for details)

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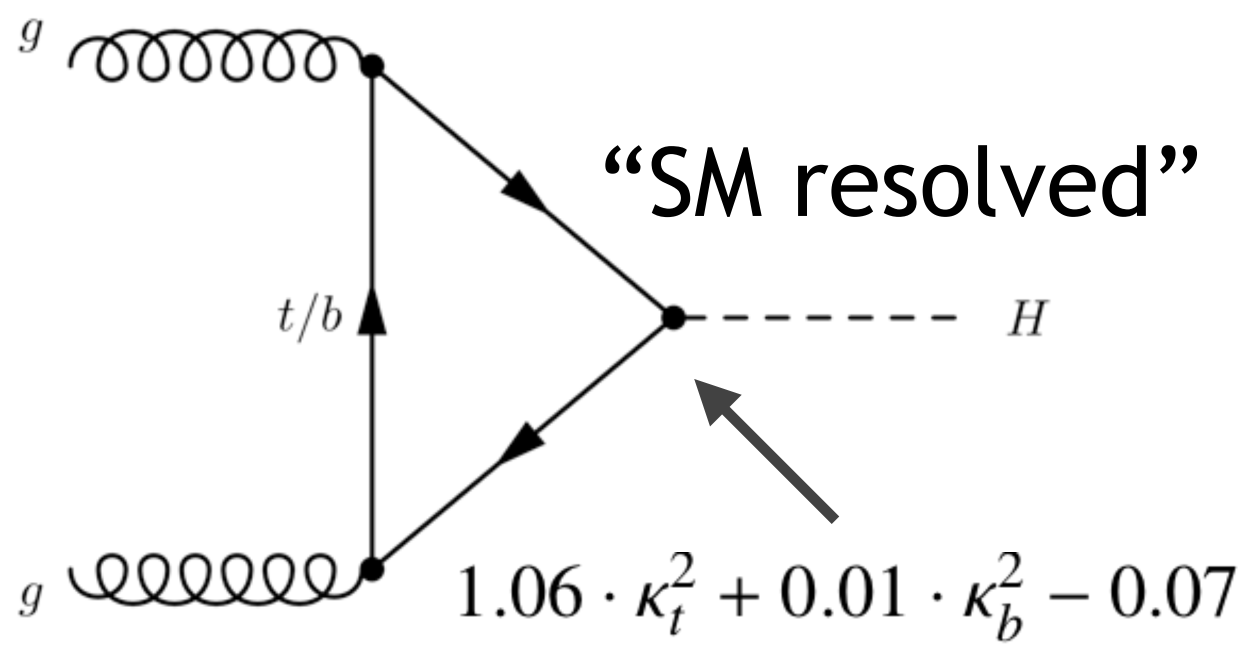
Assuming no new physics:

$$\Gamma_H(\kappa_j) = \kappa_H^2(\kappa_j) \cdot \Gamma_H^{SM}$$

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$



$$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$$

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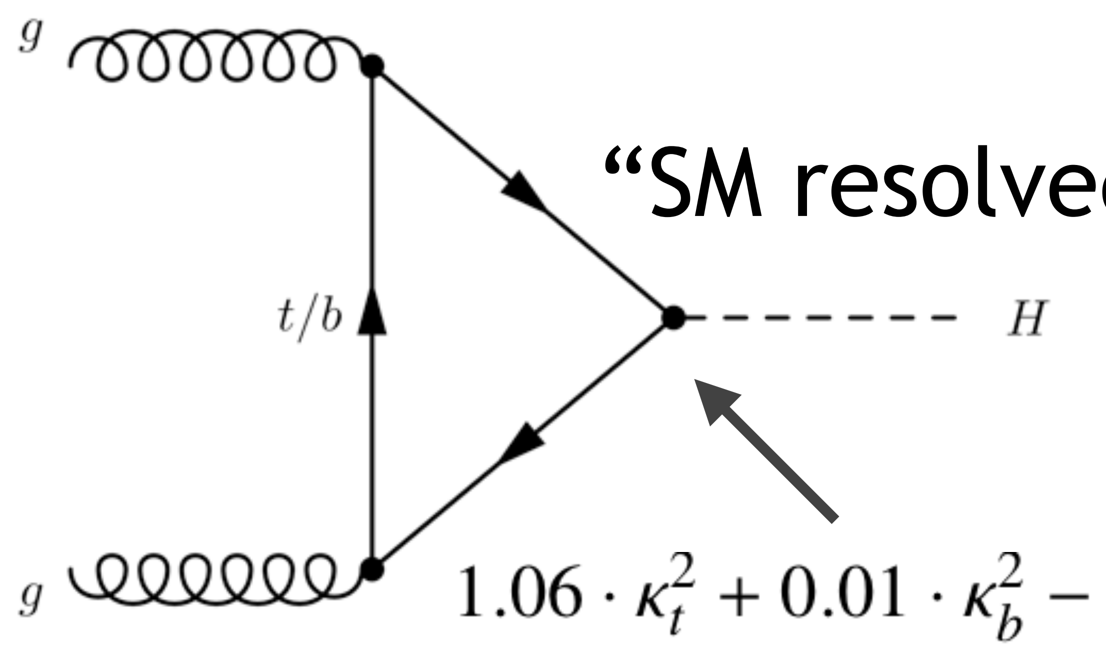
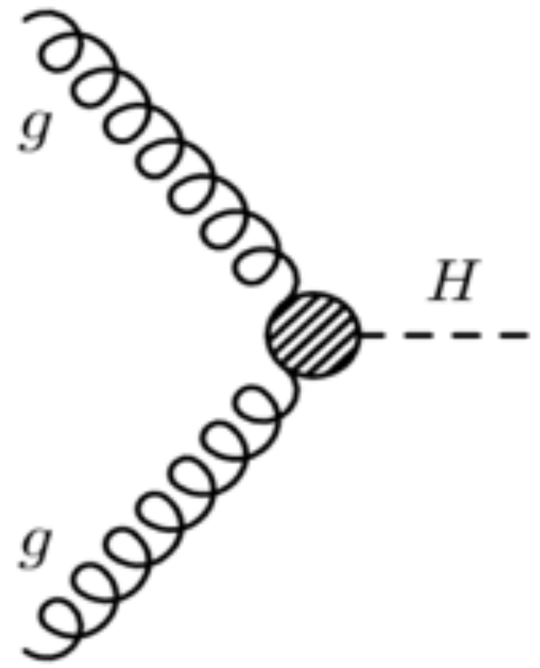


"SM resolved"

$$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$$

Allowing for BSM effects:

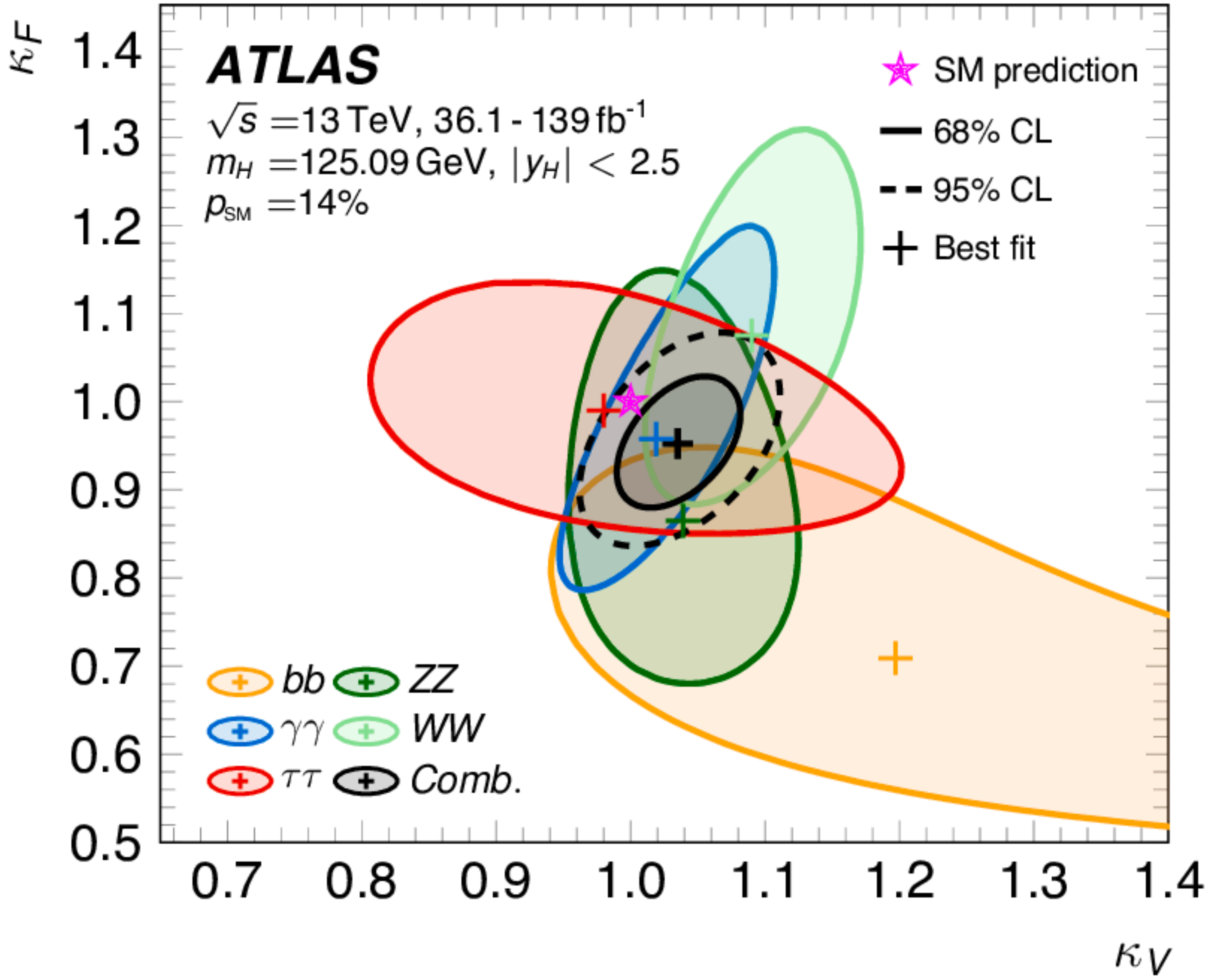
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

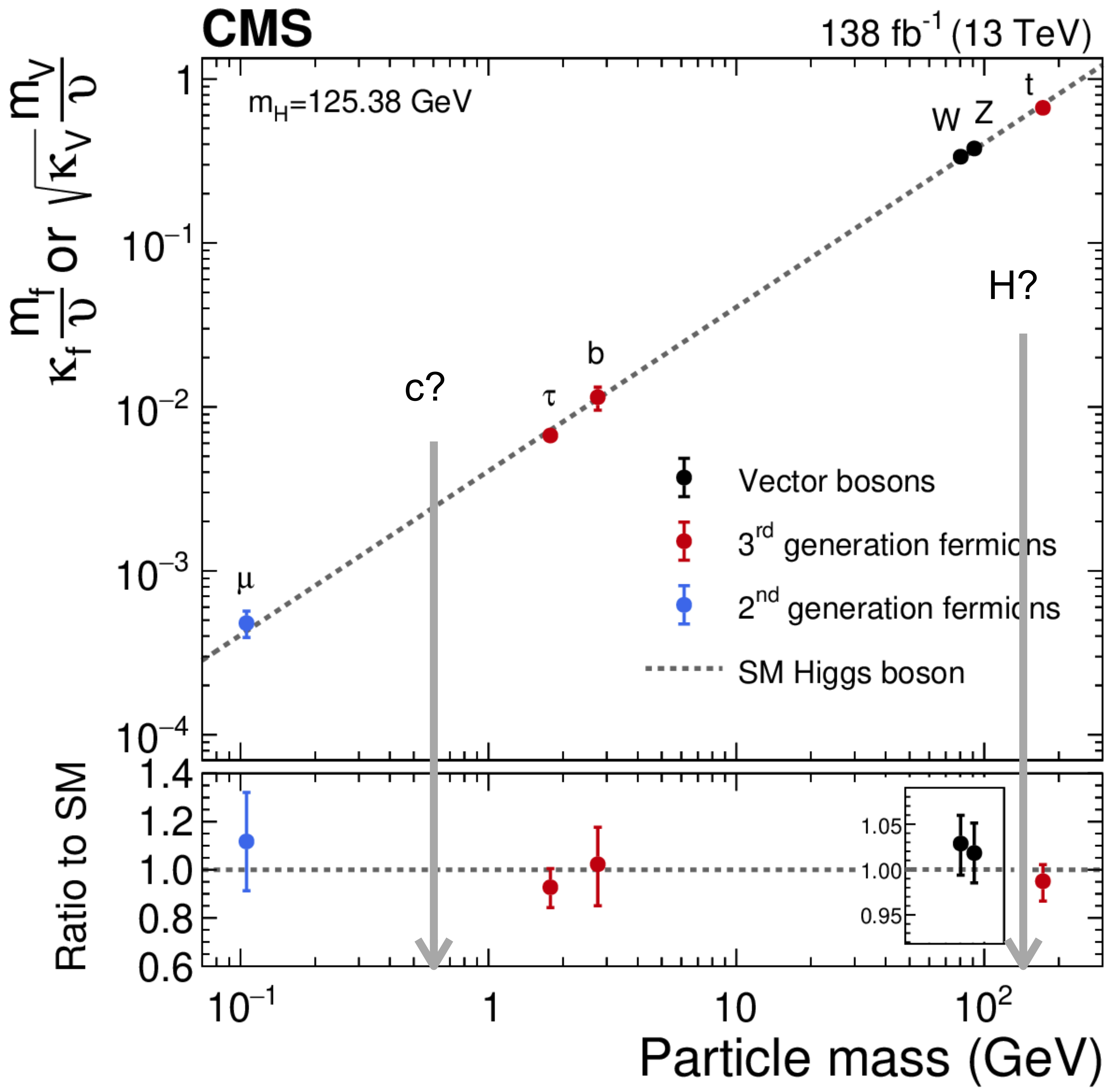


Effective coupling κ_g

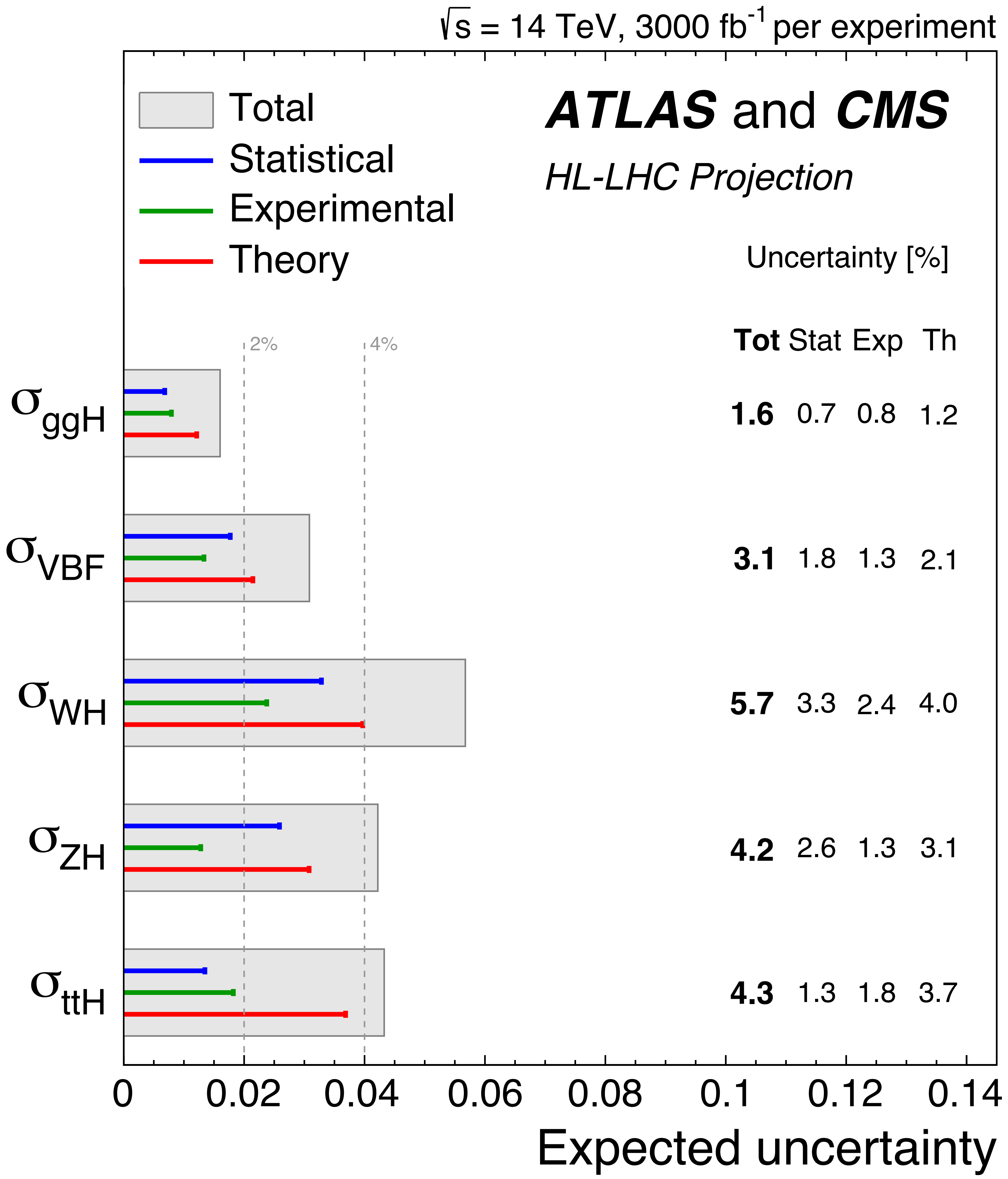
(arXiv:1307.1347 for details)

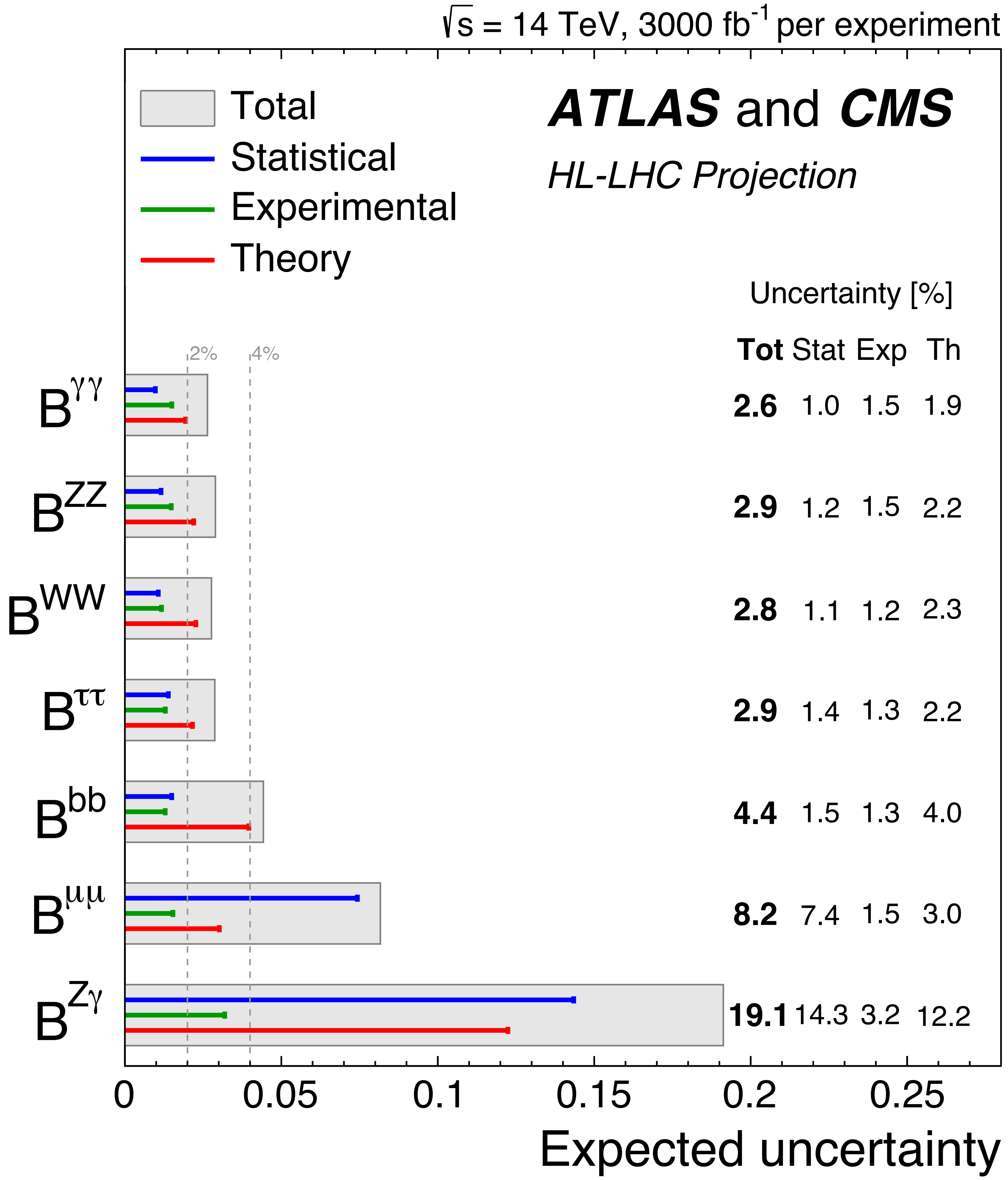
HIGGS COUPLINGS





WHAT HAPPENS WITH MORE LUMINOSITY?

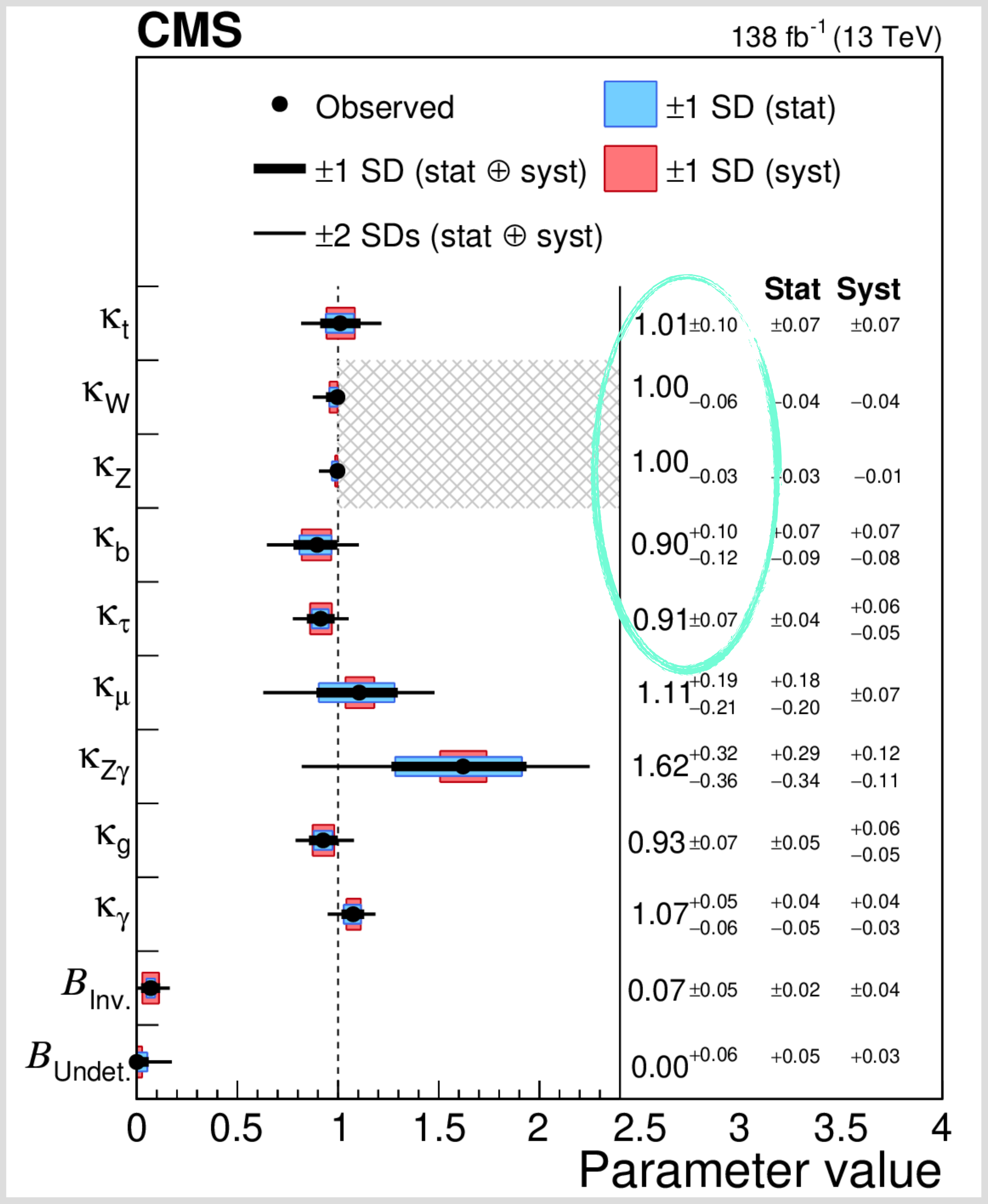




- Importance of Theory / MC understanding: important for signal and for background modelling!

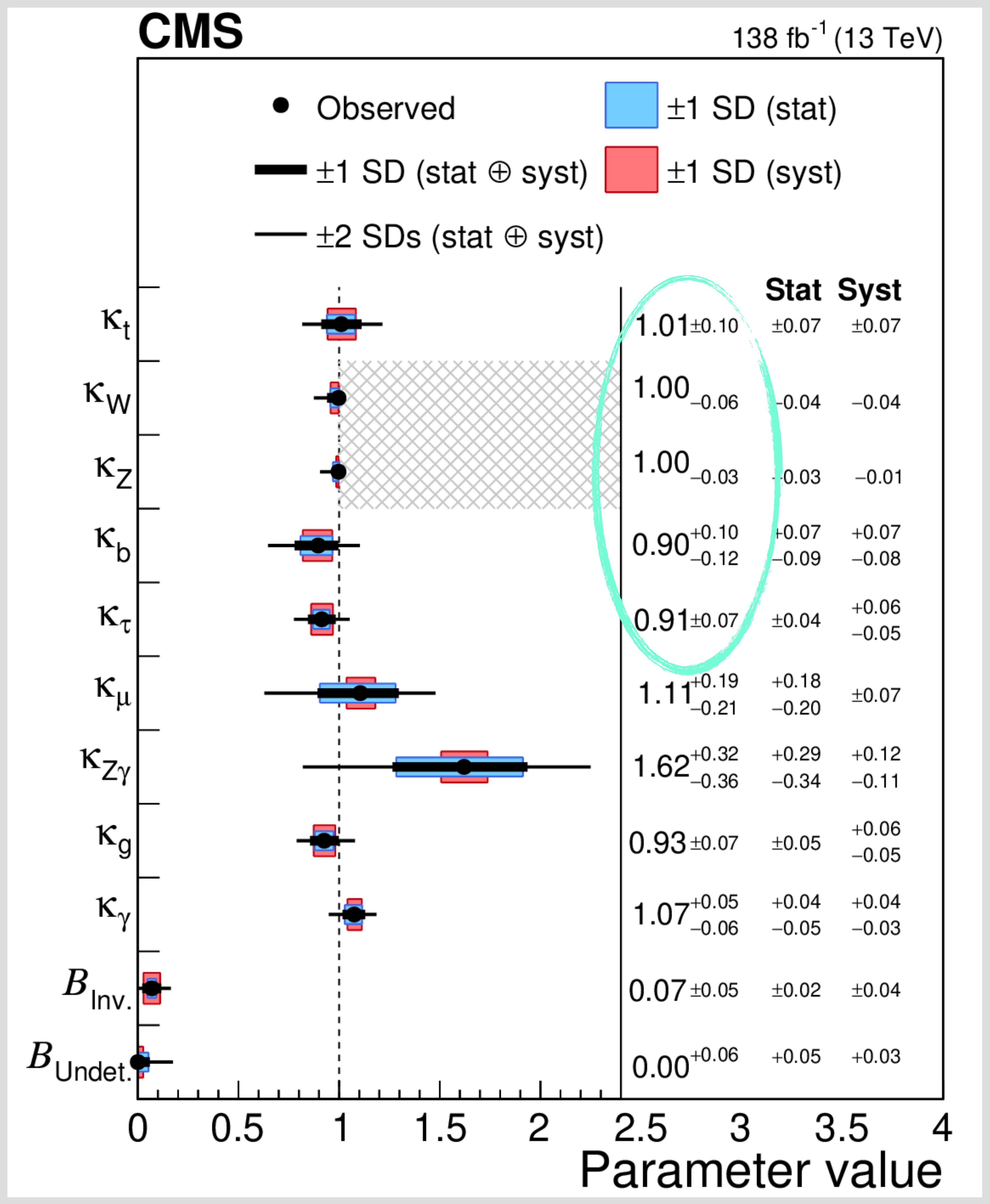
arXiv:1902.00134

THE FUTURE?



CMS
138 fb^{-1} (13 TeV)
Observed
±1 SD (stat)
±1 SD (stat ⊕ syst)
±1 SD (syst)
±2 SDs (stat ⊕ syst)
Stat Syst
κ_t 1.01 ±0.10 ±0.07 ±0.07
κ_W 1.00 −0.06 −0.04 −0.04
κ_Z 1.00 −0.03 −0.03 −0.01
κ_b 0.90 +0.10 −0.12 +0.07 −0.09 +0.07 −0.08
κ_τ 0.91 ±0.07 ±0.04 +0.06 −0.05
κ_μ 1.11 +0.19 −0.21 +0.18 −0.20 ±0.07
$\kappa_{Z\gamma}$ 1.62 +0.32 −0.36 +0.29 −0.34 +0.12 −0.11
κ_g 0.93 ±0.07 ±0.05 +0.06 −0.05
κ_γ 1.07 +0.05 −0.06 +0.04 −0.05 +0.04 −0.03
$B_{Inv.}$ 0.07 ±0.05 ±0.02 ±0.04
$B_{Undet.}$ 0.00 +0.06 +0.05 +0.03
0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

THE FUTURE?



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κt 1.01±0.10 ±0.07 ±0.07
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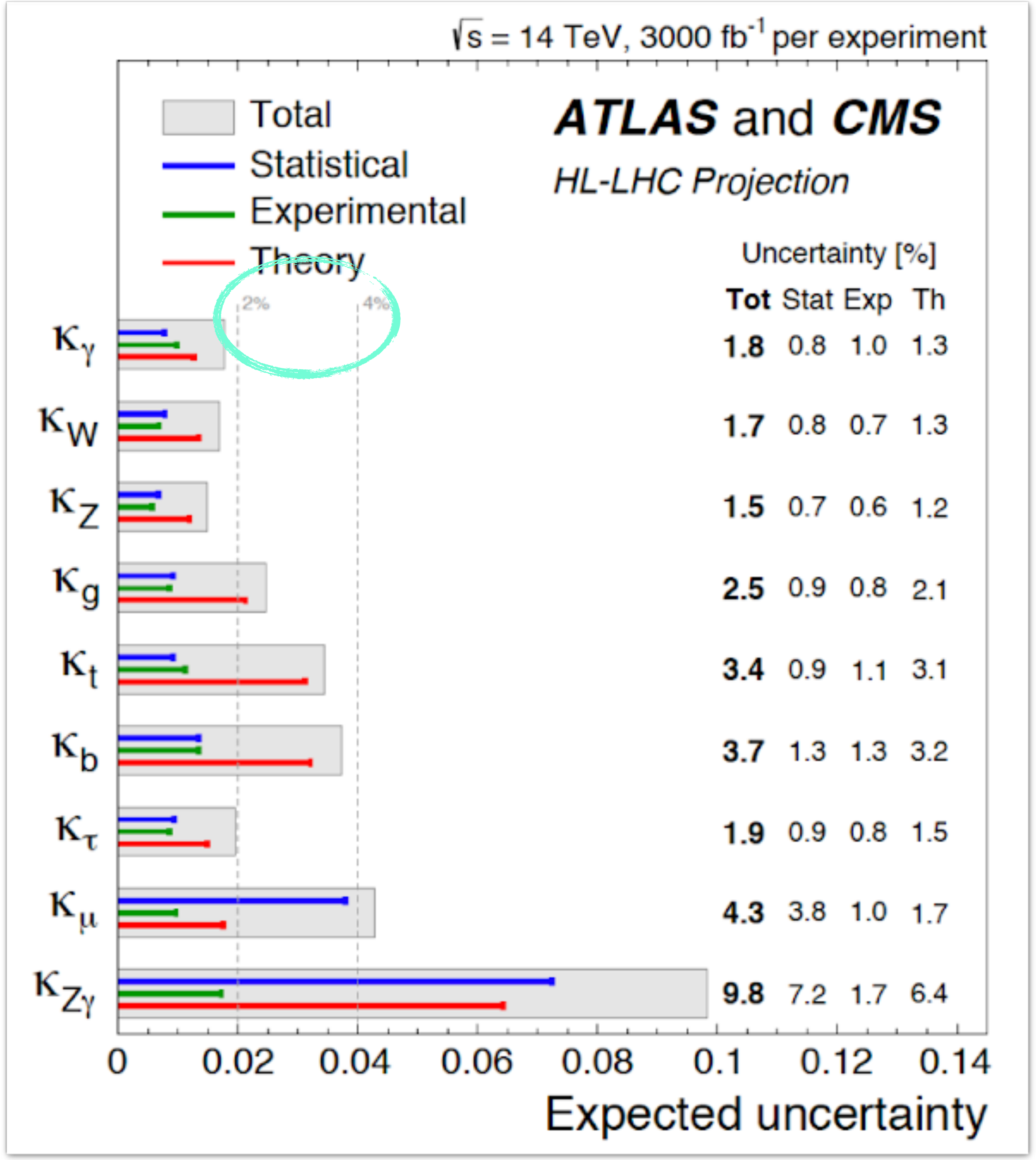
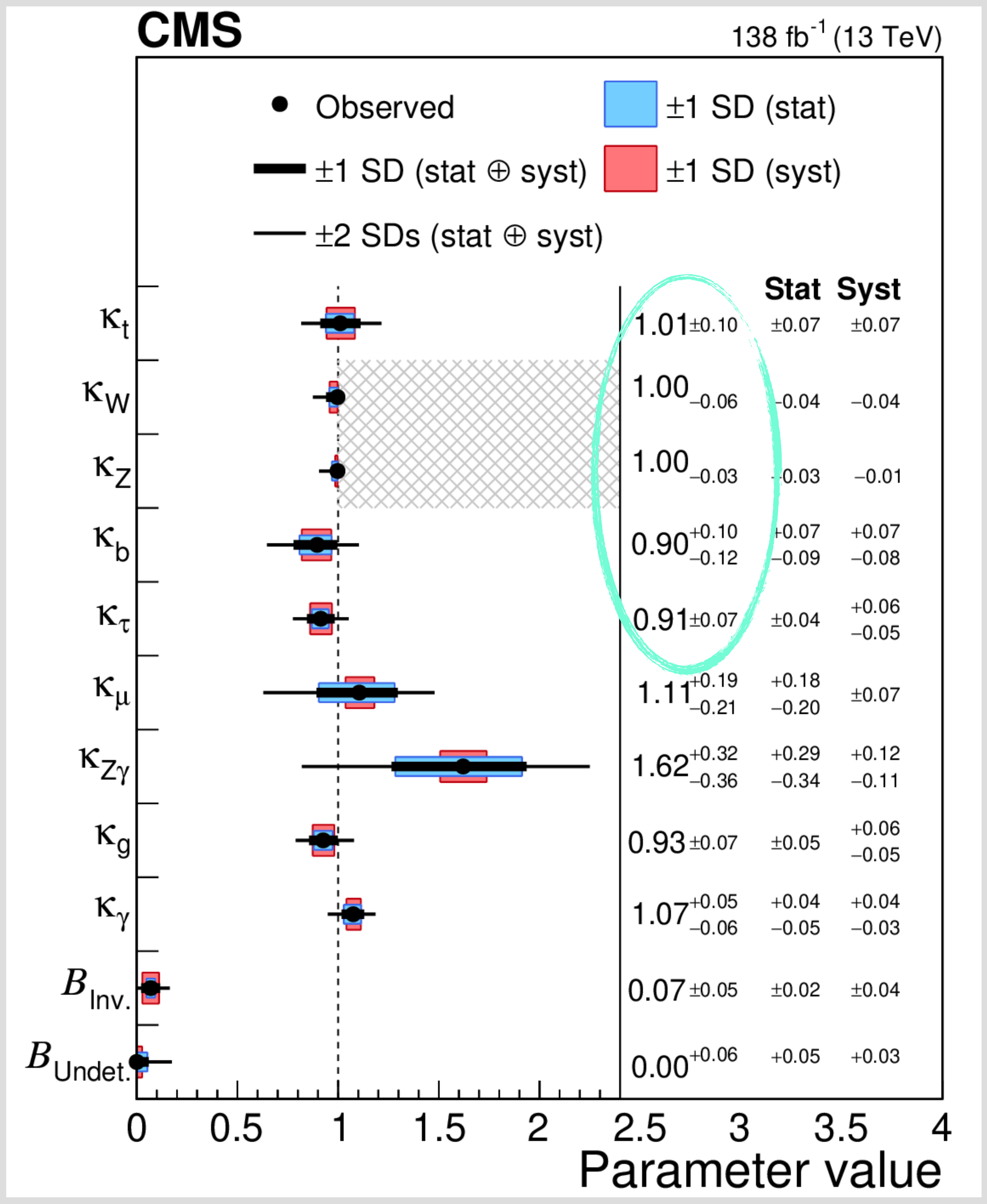
0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value



√s = 14 TeV, 3000 fb-1 per experiment
Total
Statistical
Experimental
Theory
ATLAS and CMS
HL-LHC Projection
Uncertainty [%]
Tot Stat Exp Th
κγ 1.8 0.8 1.0 1.3
κW 1.7 0.8 0.7 1.3
κZ 1.5 0.7 0.6 1.2
κg 2.5 0.9 0.8 2.1
κt 3.4 0.9 1.1 3.1
κb 3.7 1.3 1.3 3.2
κτ 1.9 0.9 0.8 1.5
κμ 4.3 3.8 1.0 1.7
κZγ 9.8 7.2 1.7 6.4
2%
4%
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14
Expected uncertainty

THE FUTURE?



		Stat	Syst
κ_t	1.01 ± 0.10	± 0.07	± 0.07
κ_W	$1.00_{-0.06}$	-0.04	-0.04
κ_Z	$1.00_{-0.03}$	-0.03	-0.01
κ_b	$0.90^{+0.10}_{-0.12}$	$^{+0.07}_{-0.09}$	$^{+0.07}_{-0.08}$
κ_τ	0.91 ± 0.07	± 0.04	$^{+0.06}_{-0.05}$
κ_μ	$1.11^{+0.19}_{-0.21}$	$^{+0.18}_{-0.20}$	± 0.07
$\kappa_{Z\gamma}$	$1.62^{+0.32}_{-0.36}$	$^{+0.29}_{-0.34}$	$^{+0.12}_{-0.11}$
κ_g	0.93 ± 0.07	± 0.05	$^{+0.06}_{-0.05}$
κ_γ	$1.07^{+0.05}_{-0.06}$	$^{+0.04}_{-0.05}$	$^{+0.04}_{-0.03}$
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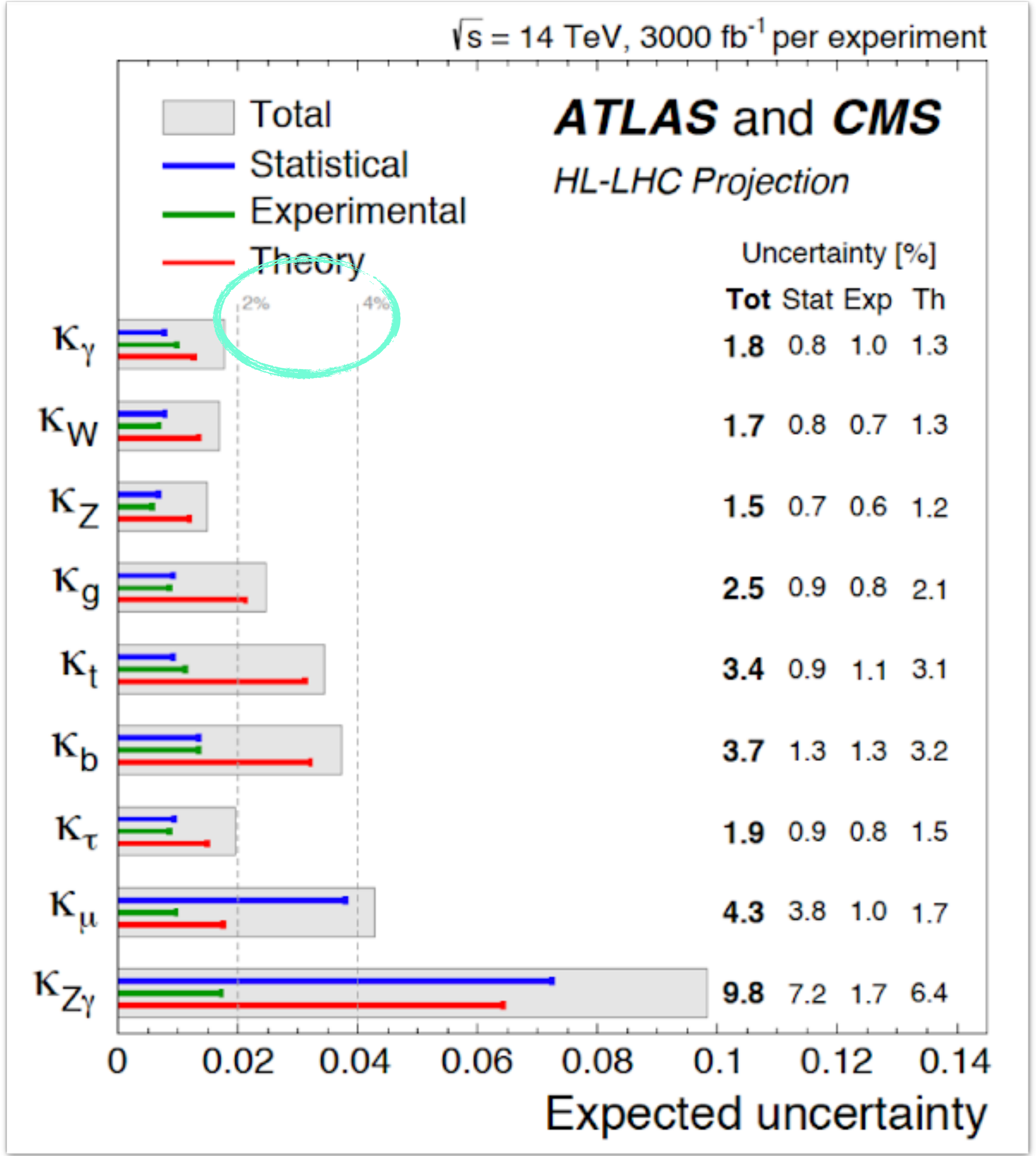
$B_{Undet.}$	$0.00^{+0.06}$	$+0.05$	$+0.03$

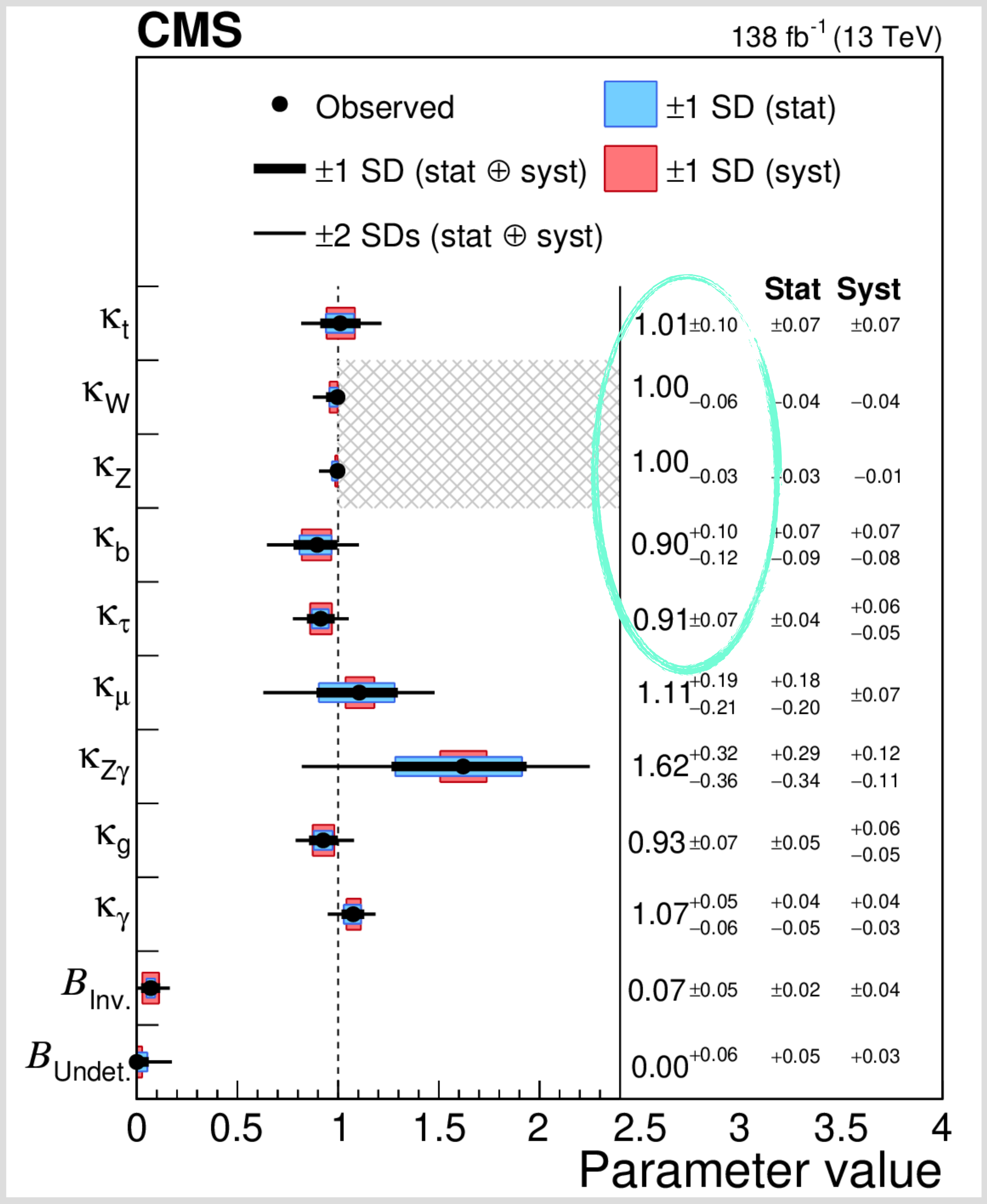


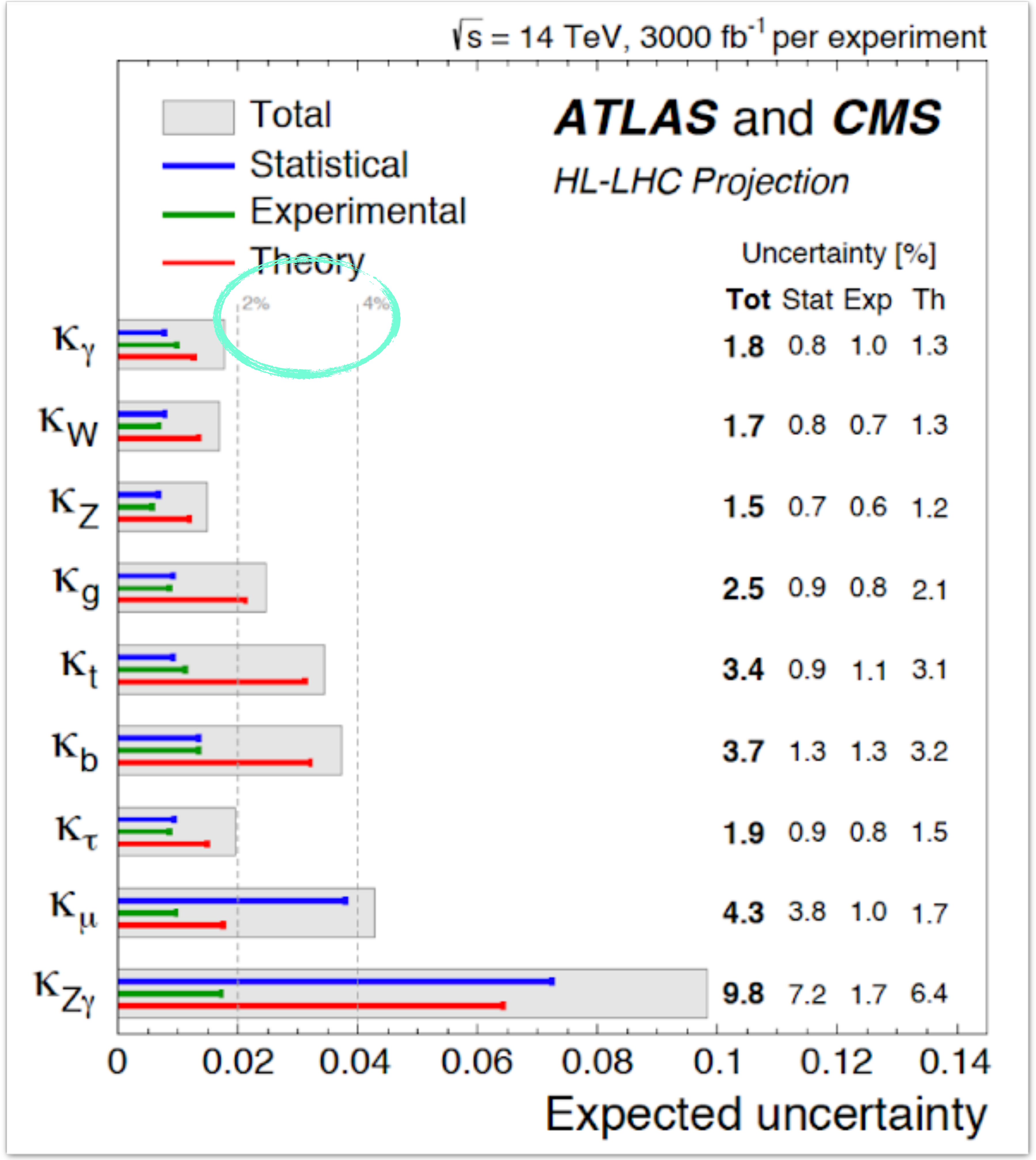
Uncertainty [%]

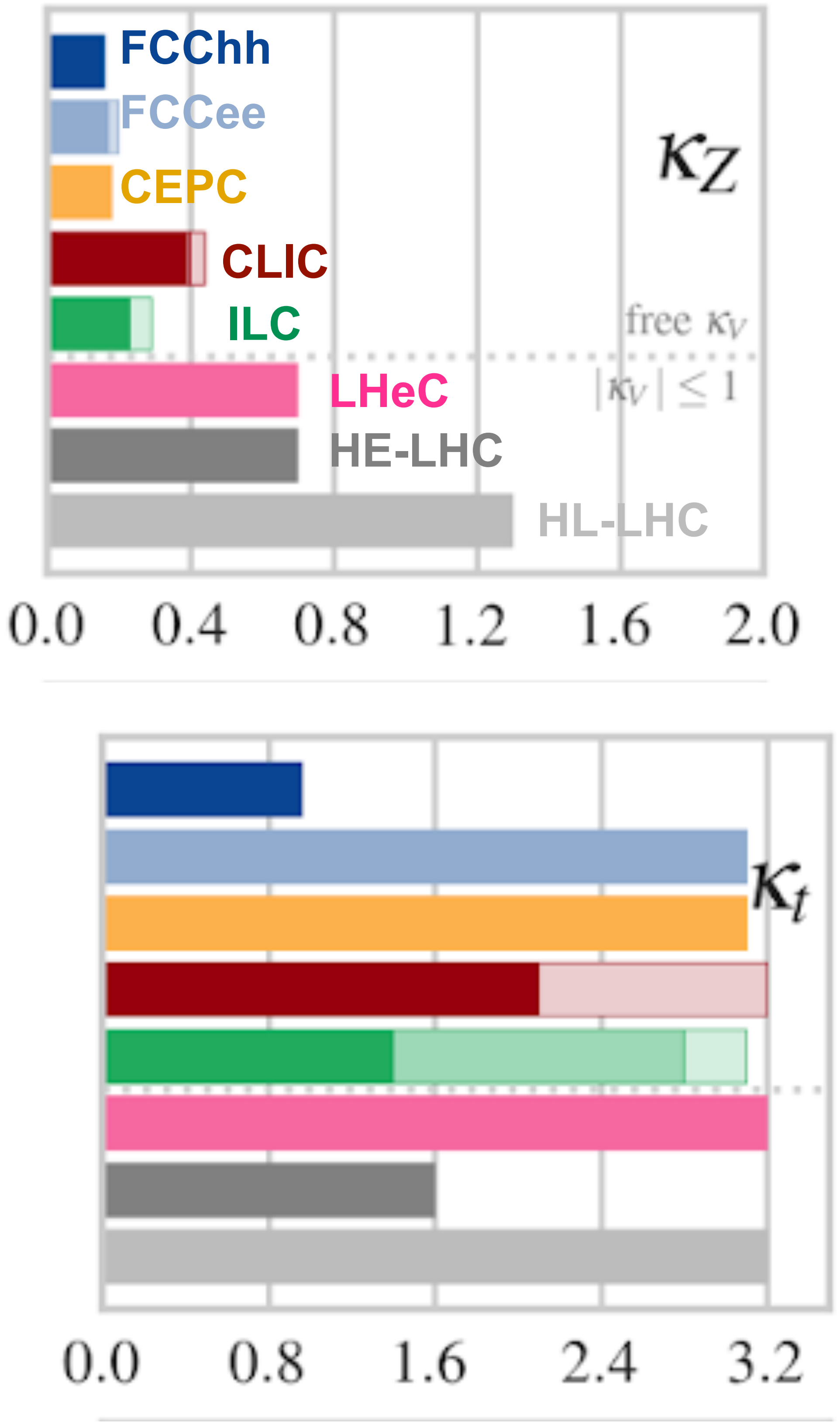
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

Experimental challenge: improve our measurements.
Theoretical challenge: improve the predictions!

THE FUTURE?







Experimental challenge: improve our measurements.
Theoretical challenge: improve the predictions!

HOW WELL *SHOULD* WE KNOW THE HIGGS COUPLINGS?

SMALL CORRECTIONS EXPECTED IN MANY BSM MODELS

If new physics is at 1 TeV:

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

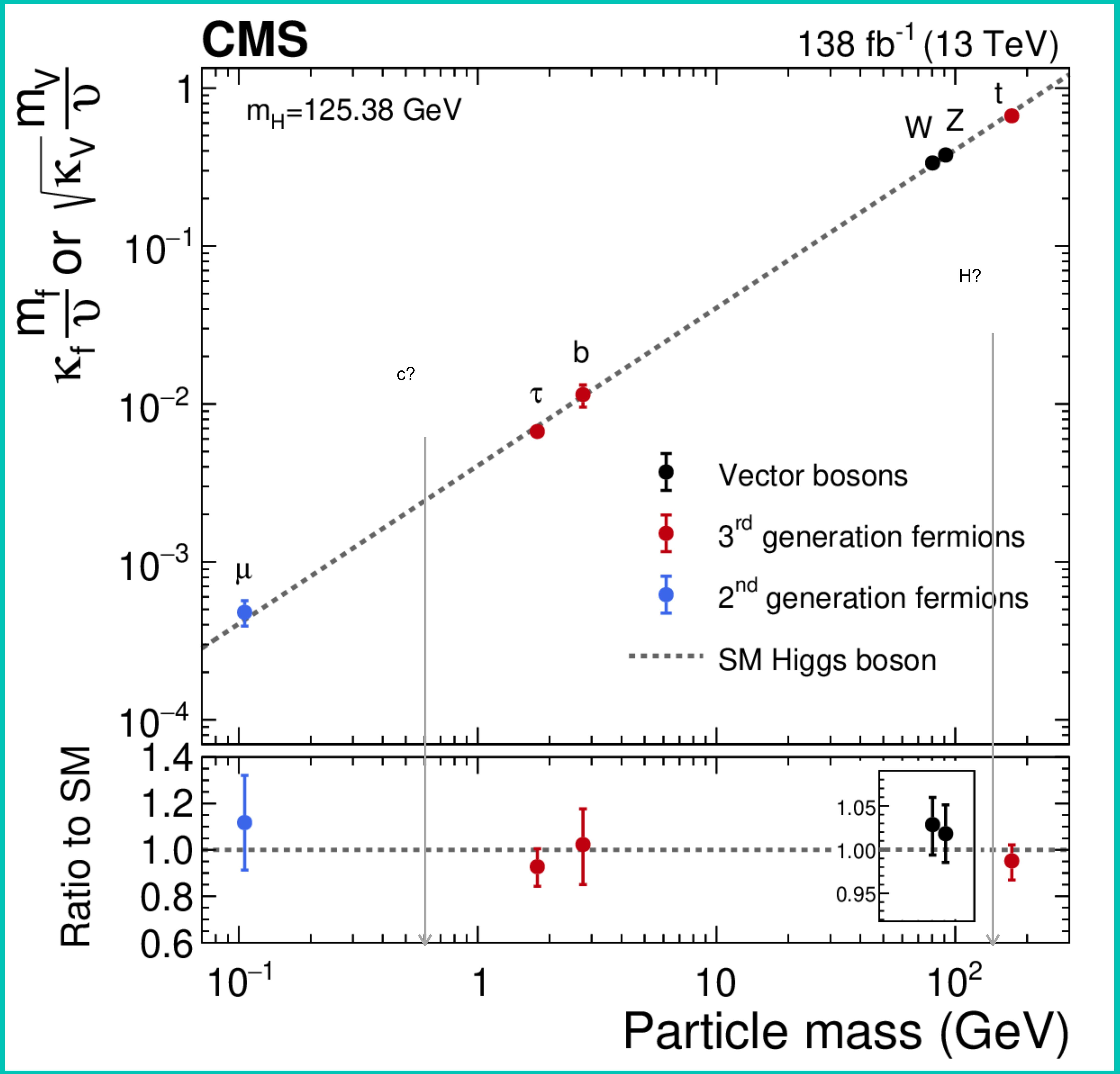
Patterns of deviations can pinpoint specific BSM physics

- Generically new physics effects on couplings $\sim \frac{v^2}{M^2} \sim \mathcal{O}(6\%)$ for M=1 TeV
- Only now are we approaching sensitivity where we expect deviations

Sally Dawson

WHAT WE KNOW TODAY

- Measurements of Mass (to 0.11%!), Width, CP
- Main production modes explored in depth by now, with precise measurements of the signal strength/cross section (down to 10% precision)
- Measurements going differential, and towards precision in properties
- Coupling to the SM particles well established for the main decay modes, and already at evidence level for several of the statistically dominated ones
- The decays to SM particles we have seen so far are only part of the full spectrum of possible decays. Rare processes starting to become accessible.



BRIEF REMINDER OF THE UNKNOWNS....

- How is the Higgs boson produced? How does it decay?
- What kind of particle is the Higgs? (Properties: Mass, Width, Spin)
- How does it couple to Standard Model particles?
  - Does it couple to itself?
  - Does it couple unusually? (eg: Dark Matter?)
- Is the Higgs alone?
- Is it really an elementary particle?
- Where does the Higgs mechanism come from?

H^0 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.10 \pm 0.11$
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$

→We have just scratched the surface until now....

RARE DECAYS? HOW CHARMING IS THE HIGGS?

- We have only probed the 'easiest' Higgs decays for now. And the rest?
- **Coupling to second generation leptons through muons (evidence) What about the coupling to second gen quarks? Can we see it at LHC?**
- Charm quark: only up quark for which we could possibly measure the branching ratio Br(H->cc)~3%
  - Do up-type quarks get their mass from the same Higgs fields as down-type quarks and charged leptons?
- Difficult measurement (not only statistics, we need to be able to identify charm jets!)

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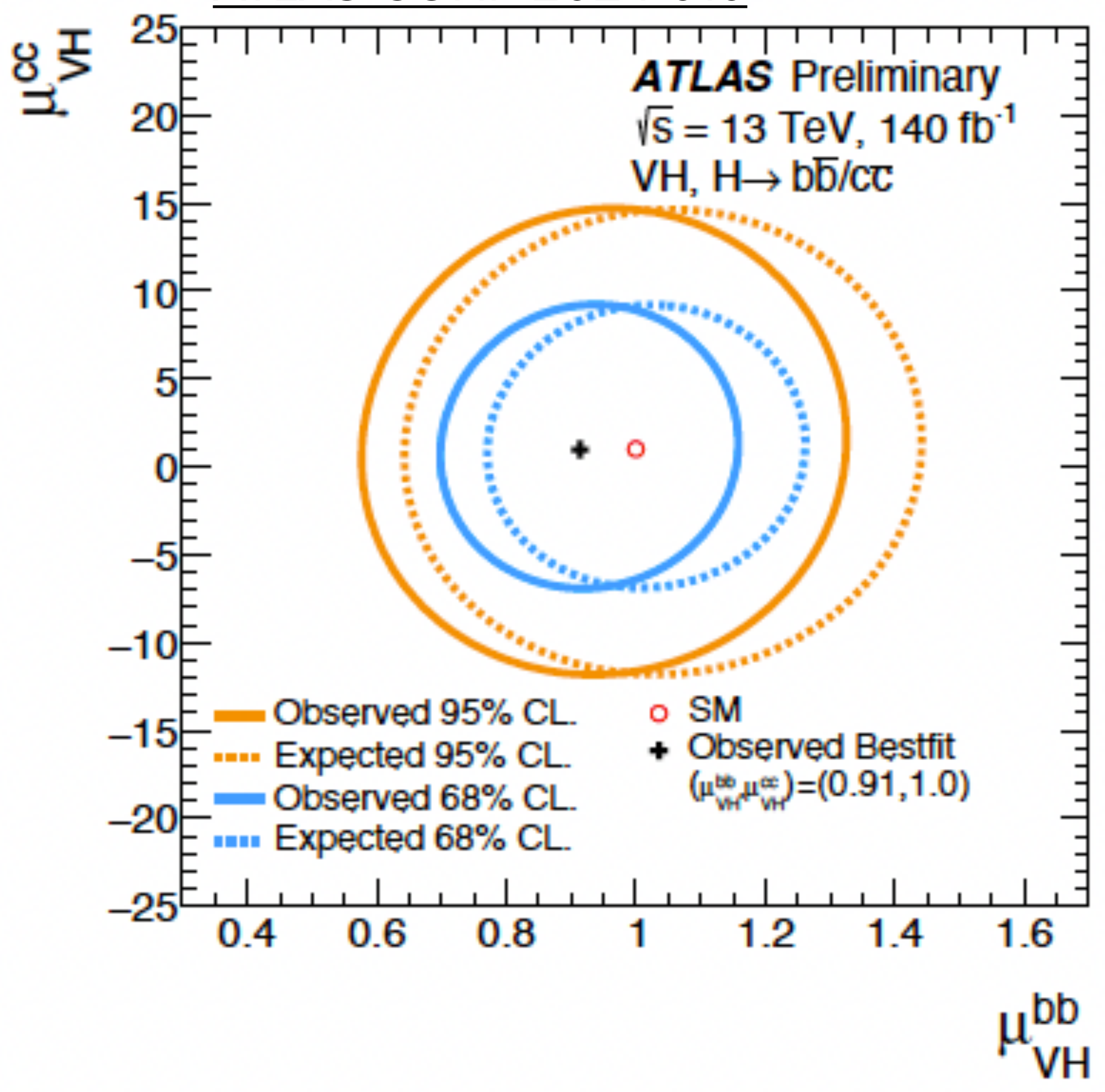

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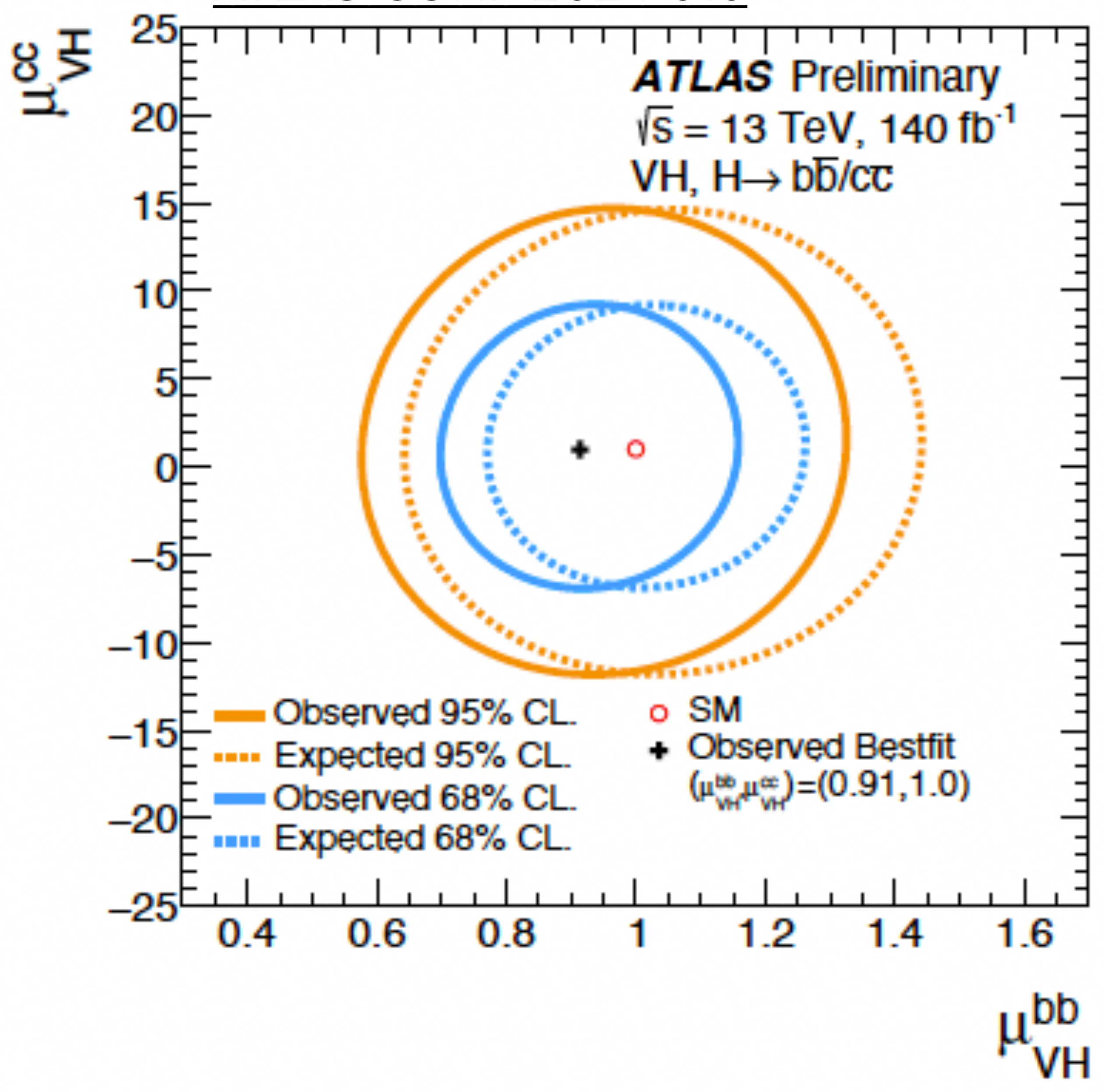
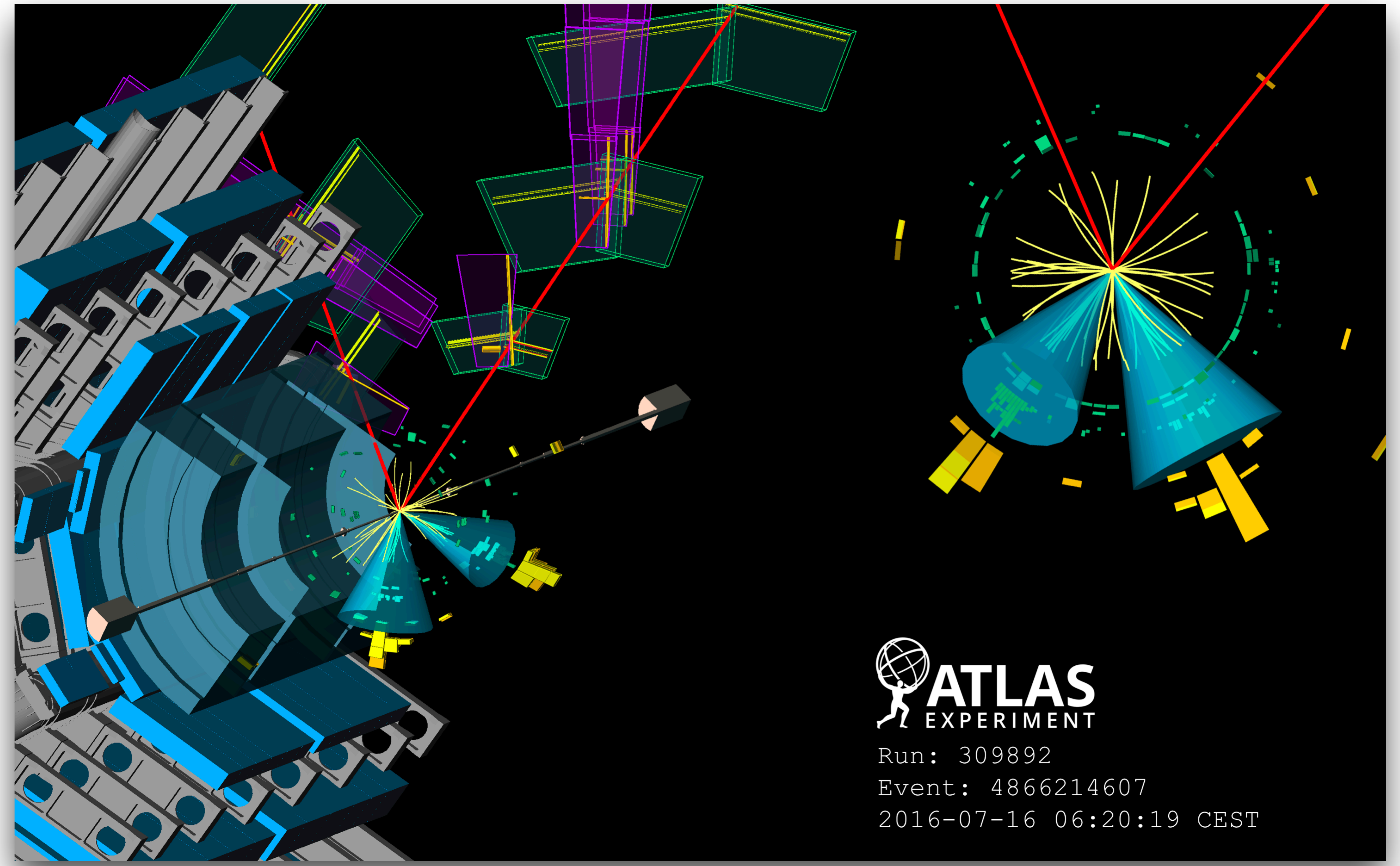
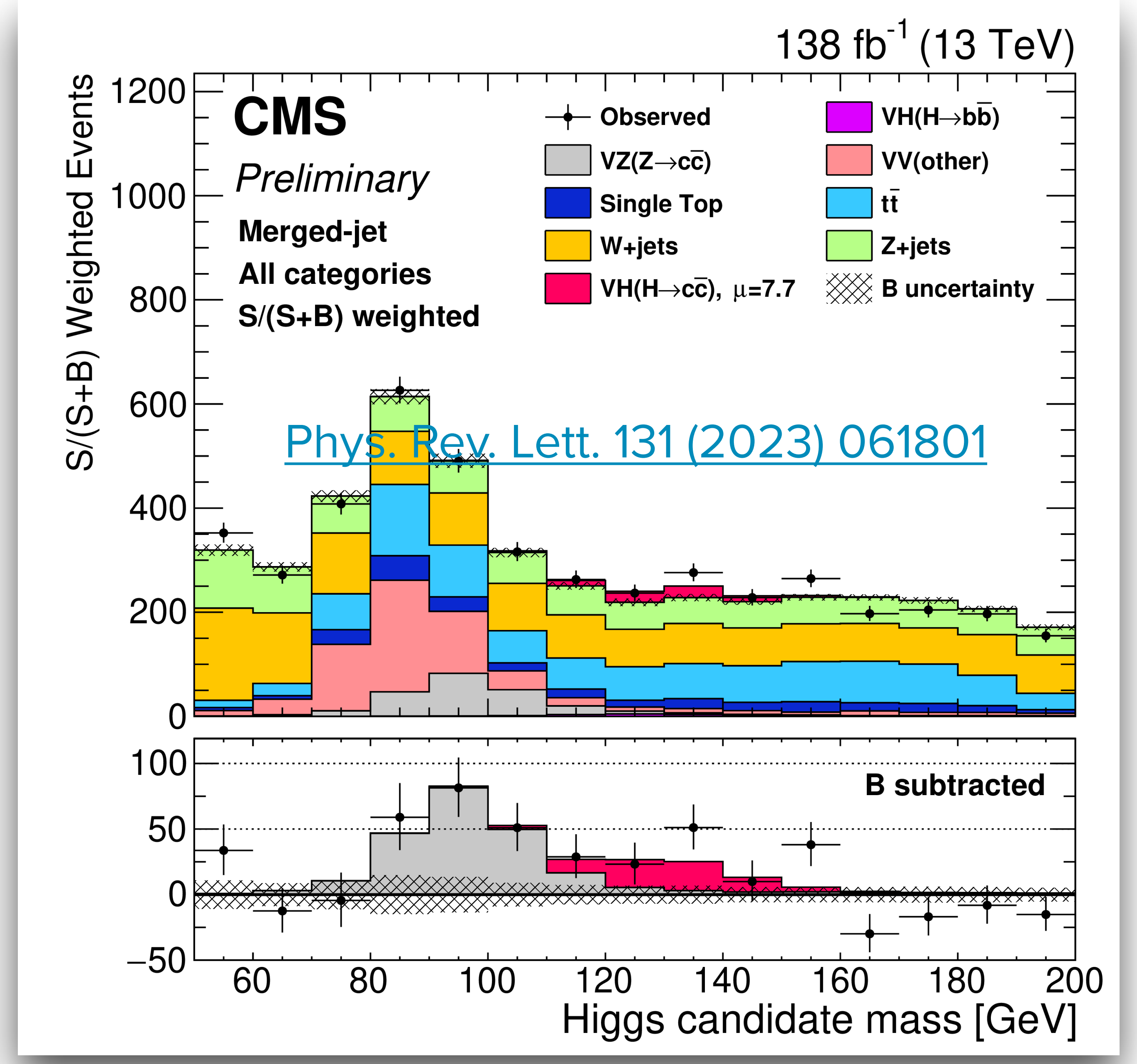




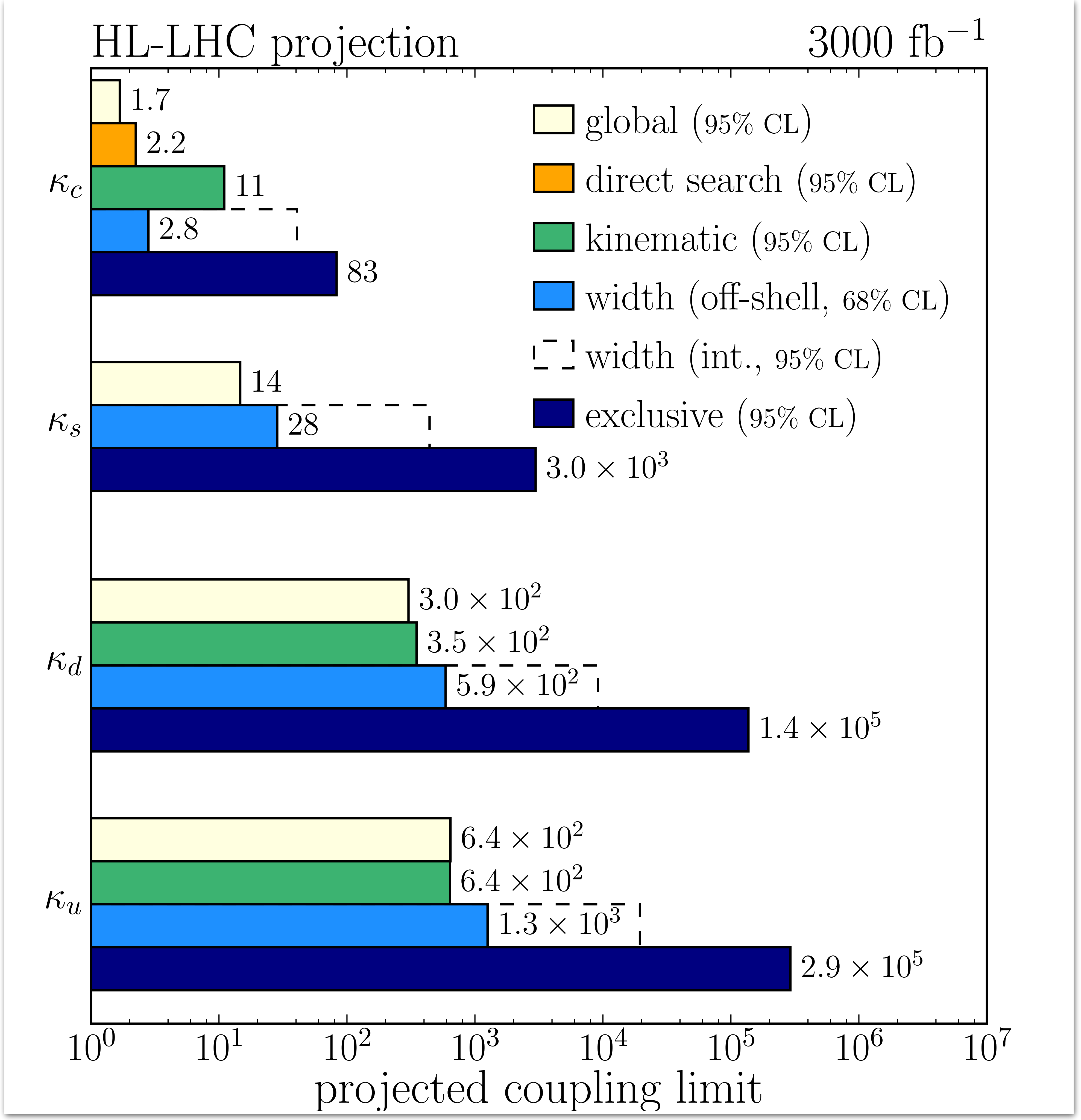


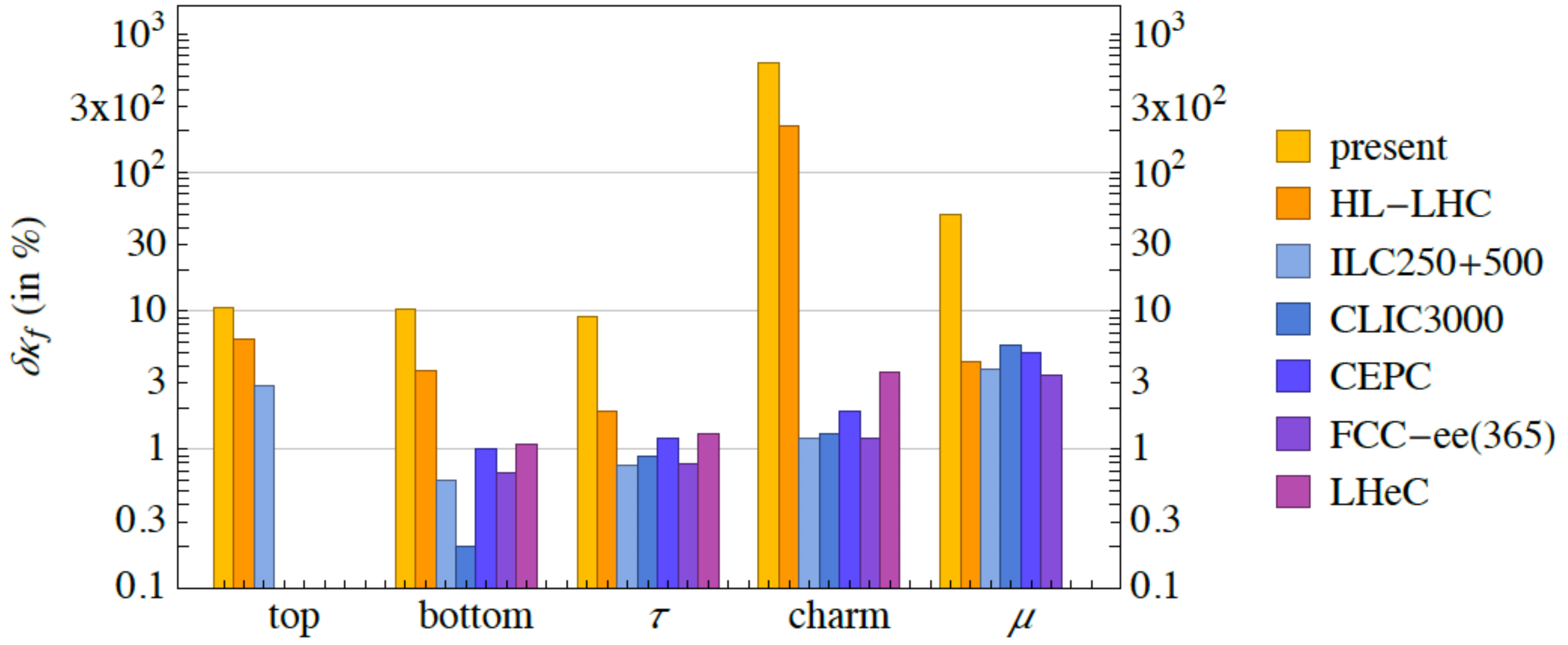
Phys. Rev. Lett. 131 (2023) 061801

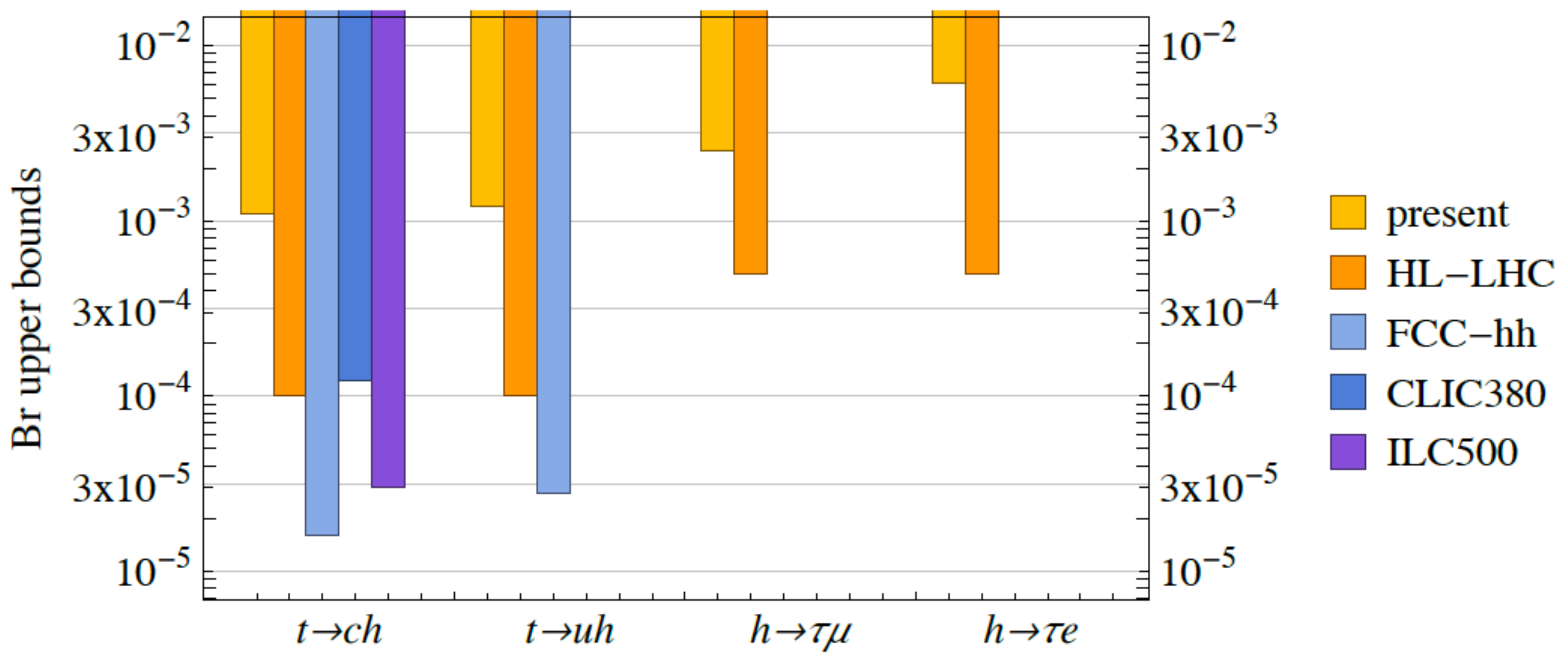
CMS:
μ(VH, Hcc) < 14(7.60)xSM (95%CL)

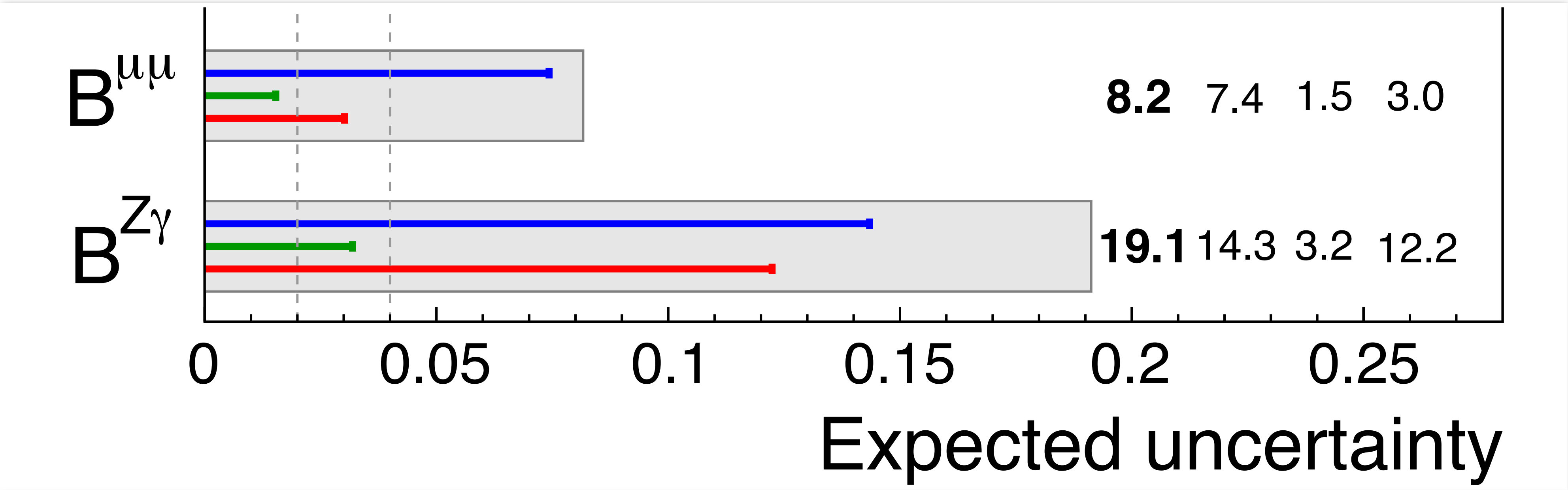
ATLAS:
μ(VH, Hcc) < 11.3 (10.4)xSM (95%CL)

MORE ON RARE DECAYS...

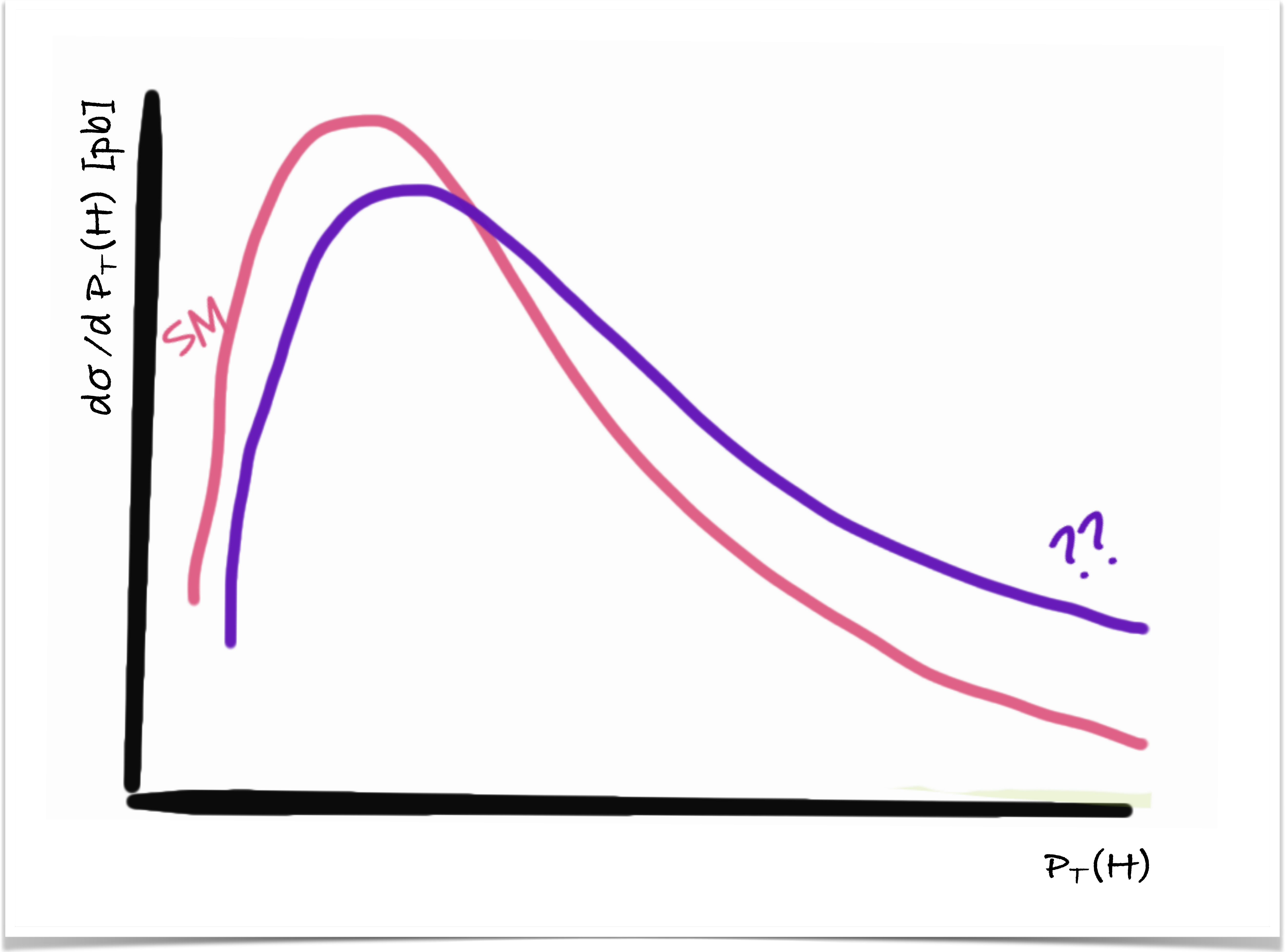




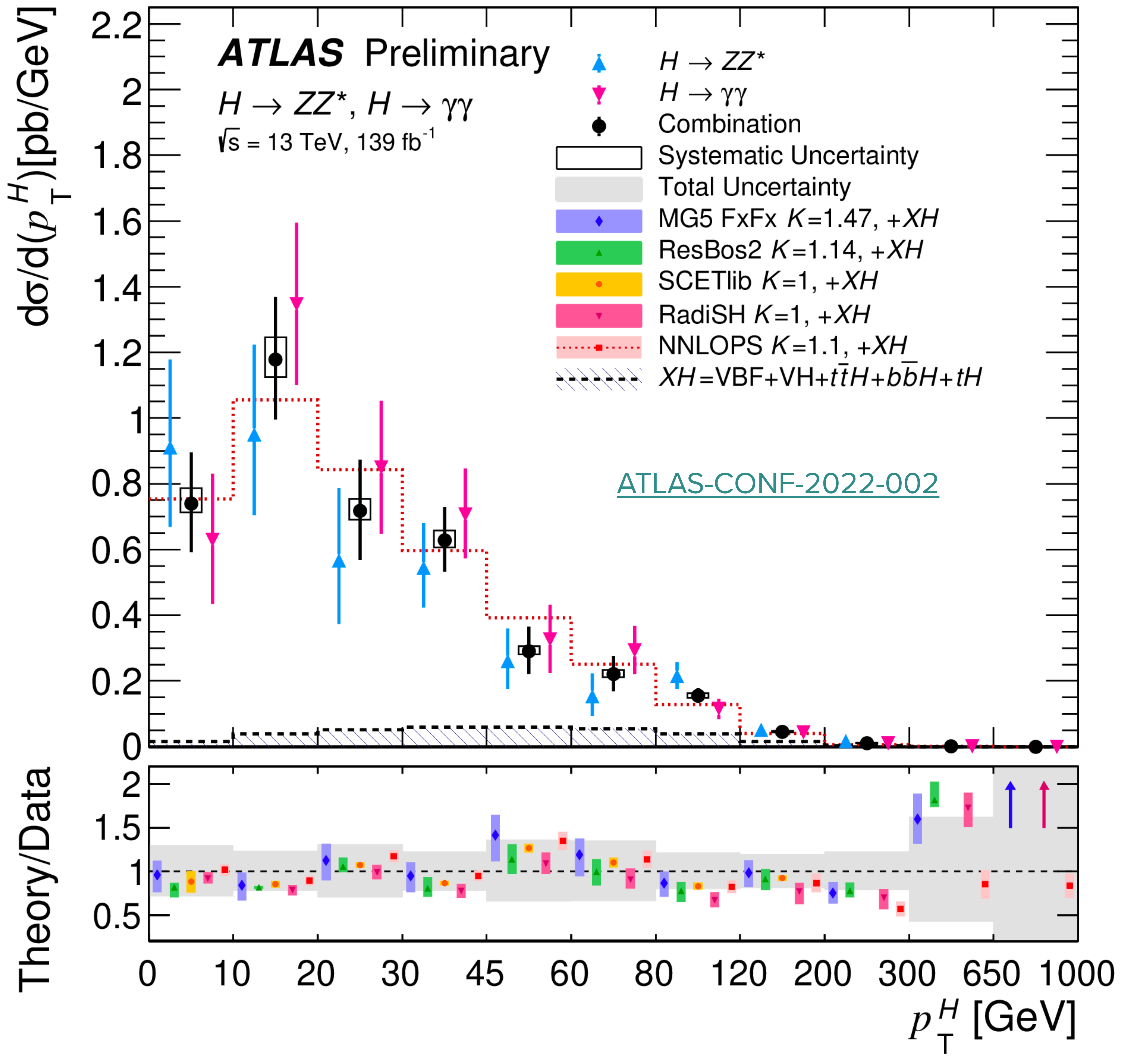




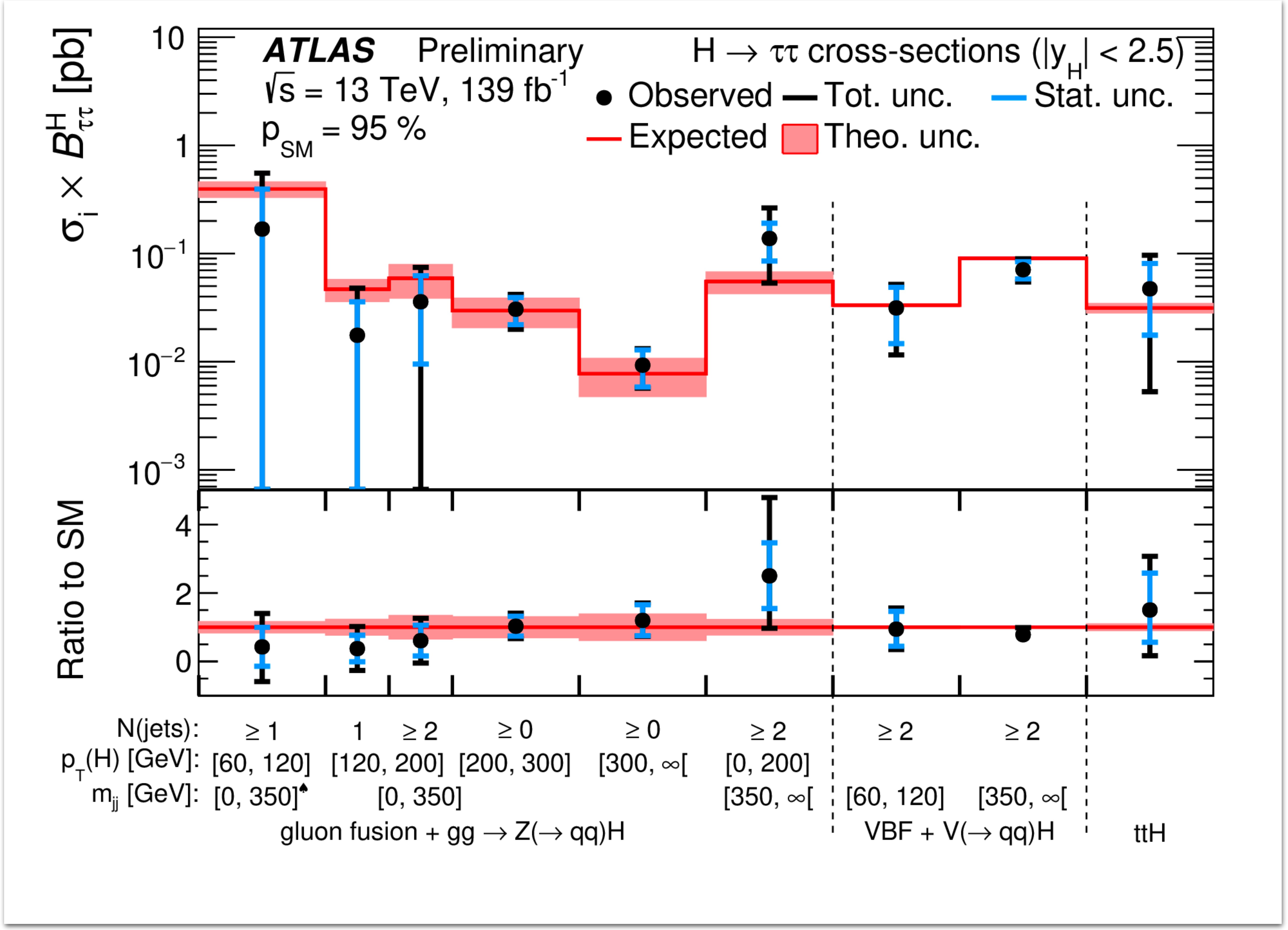
COUNTING IS ONLY THE BEGINNING...

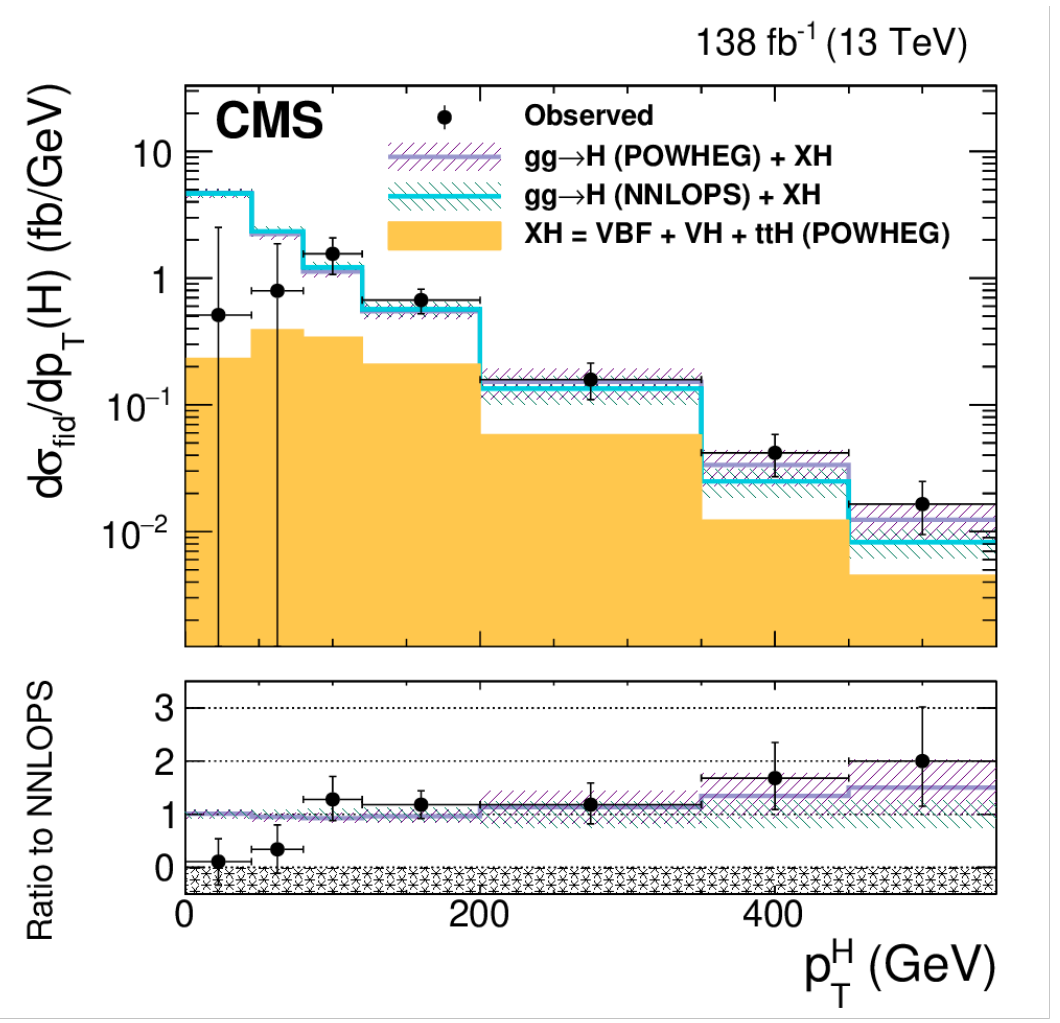


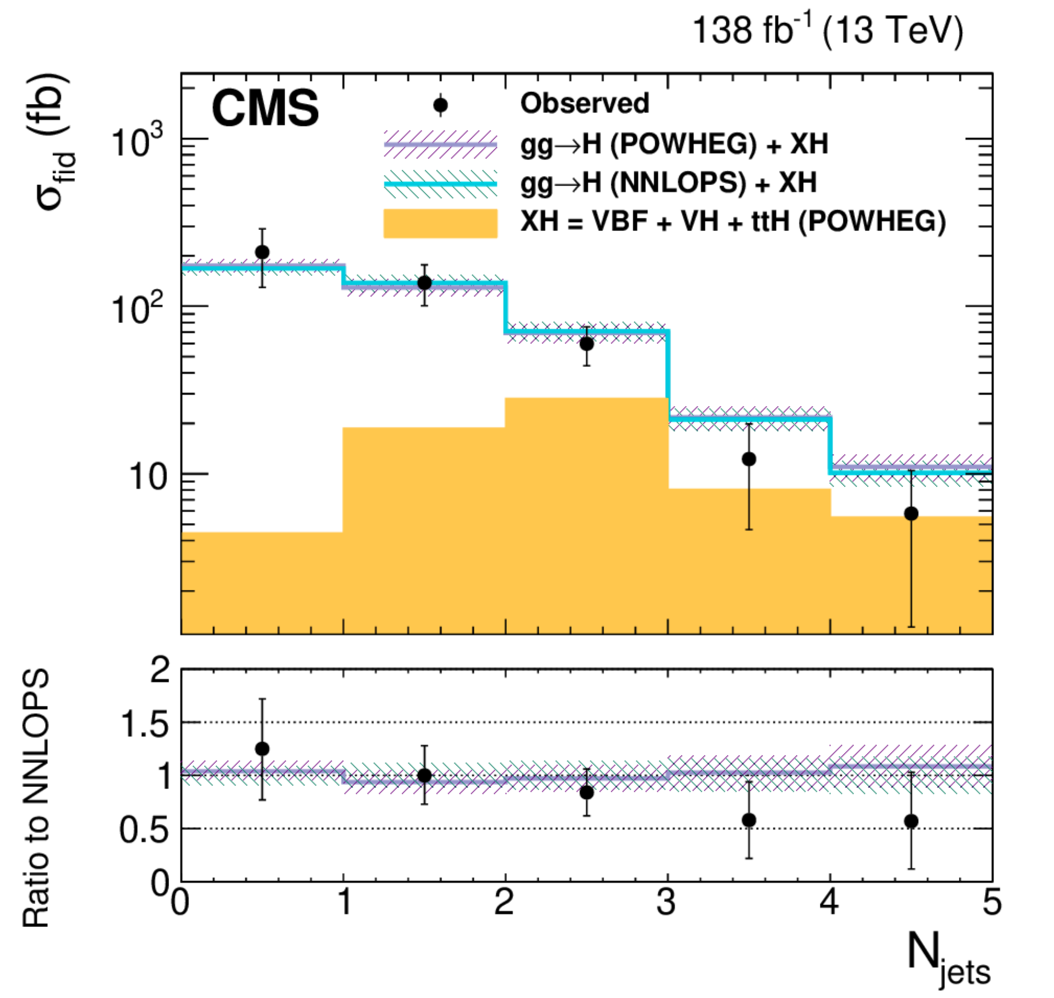
COUNTING IS ONLY THE BEGINNING... DISTRIBUTIONS!

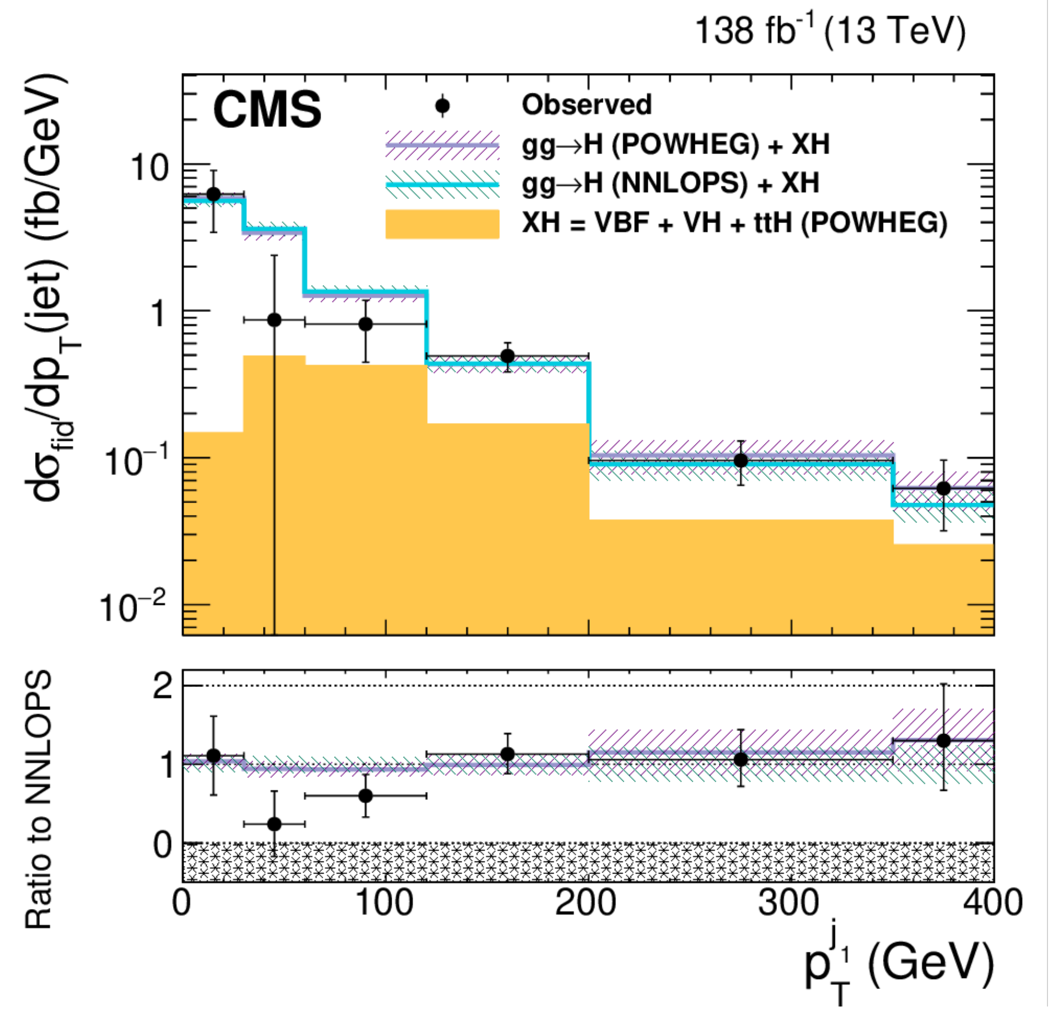


KINEMATIC REGIMES



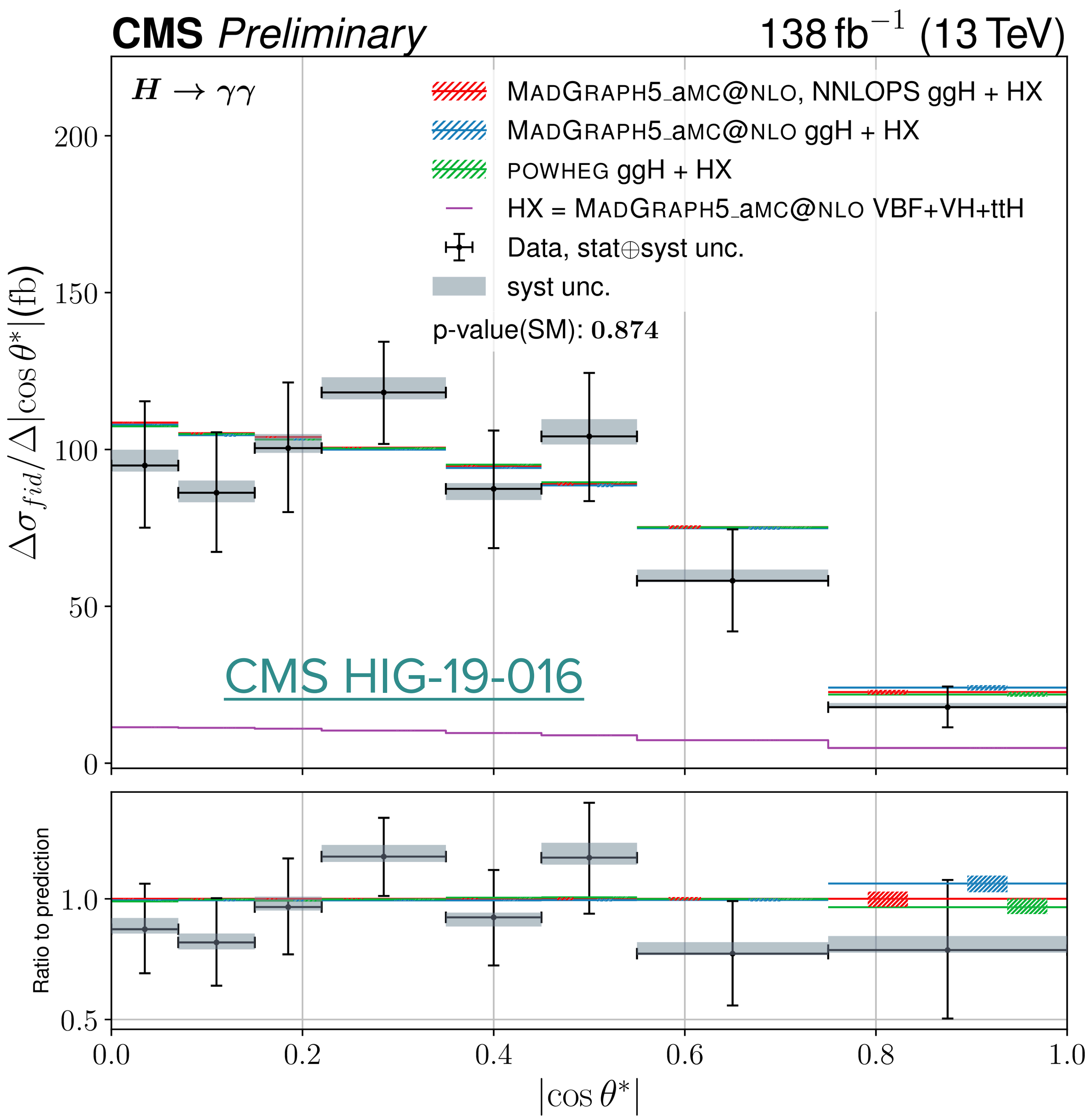


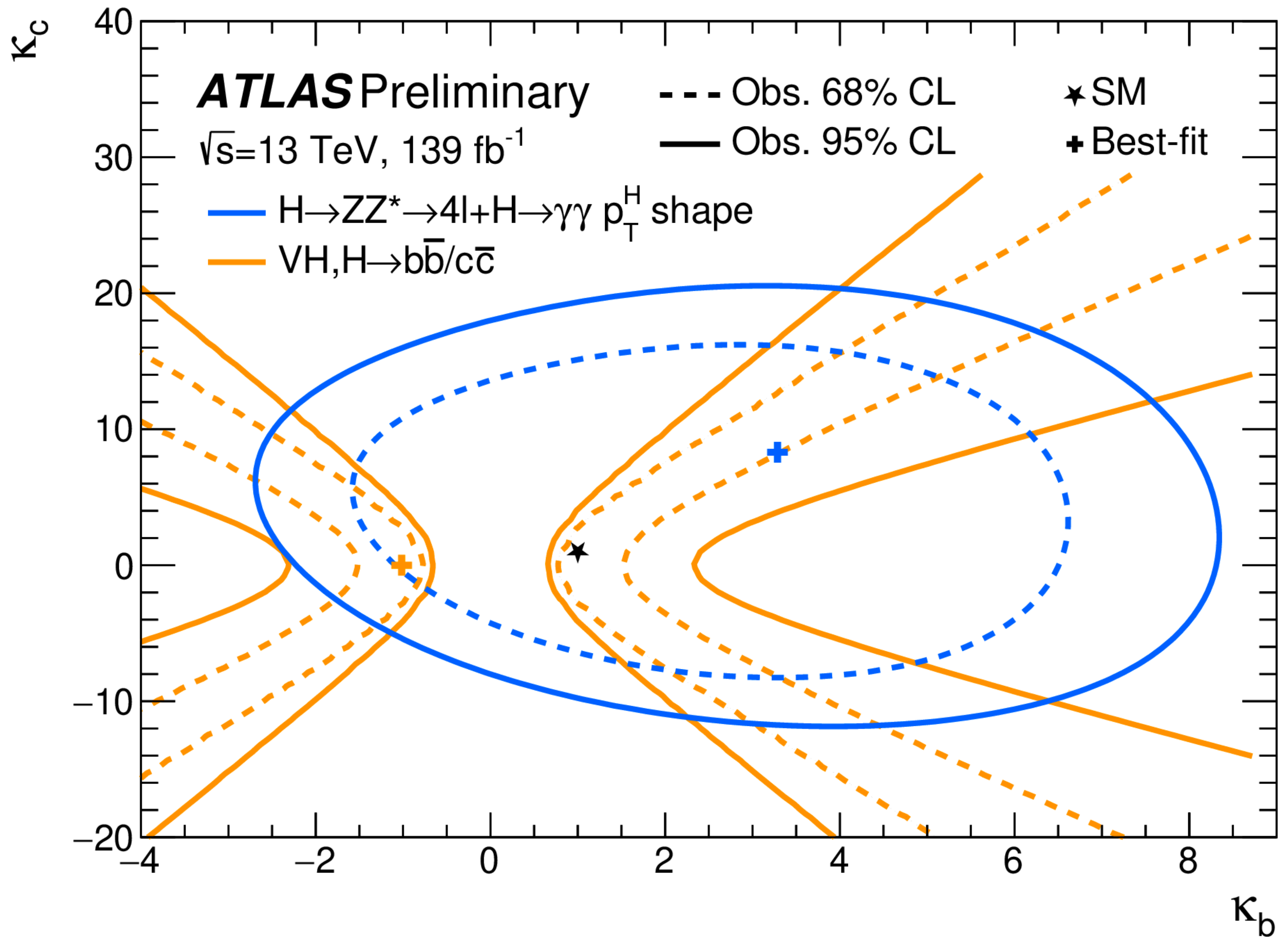




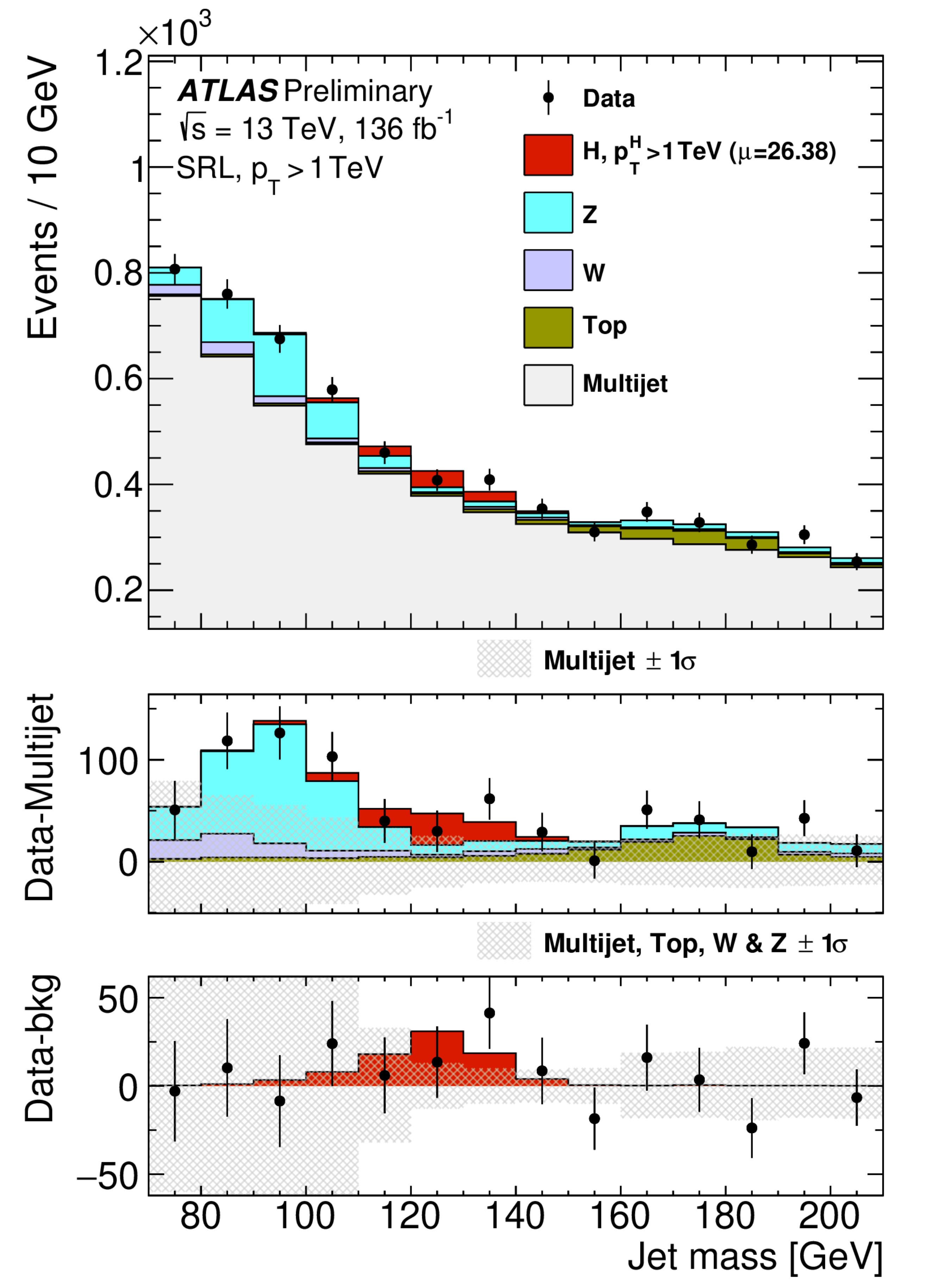
FROM SIGNAL STRENGTHS TO DIFFERENTIAL CROSS SECTIONS

- Measure the cross section as a function of Higgs kinematic variables (pt, eta of the products or of the Higgs, number of jets in the event,…)
- Do the current MC tools model the Higgs behaviour correctly?
- Indirect Constraints





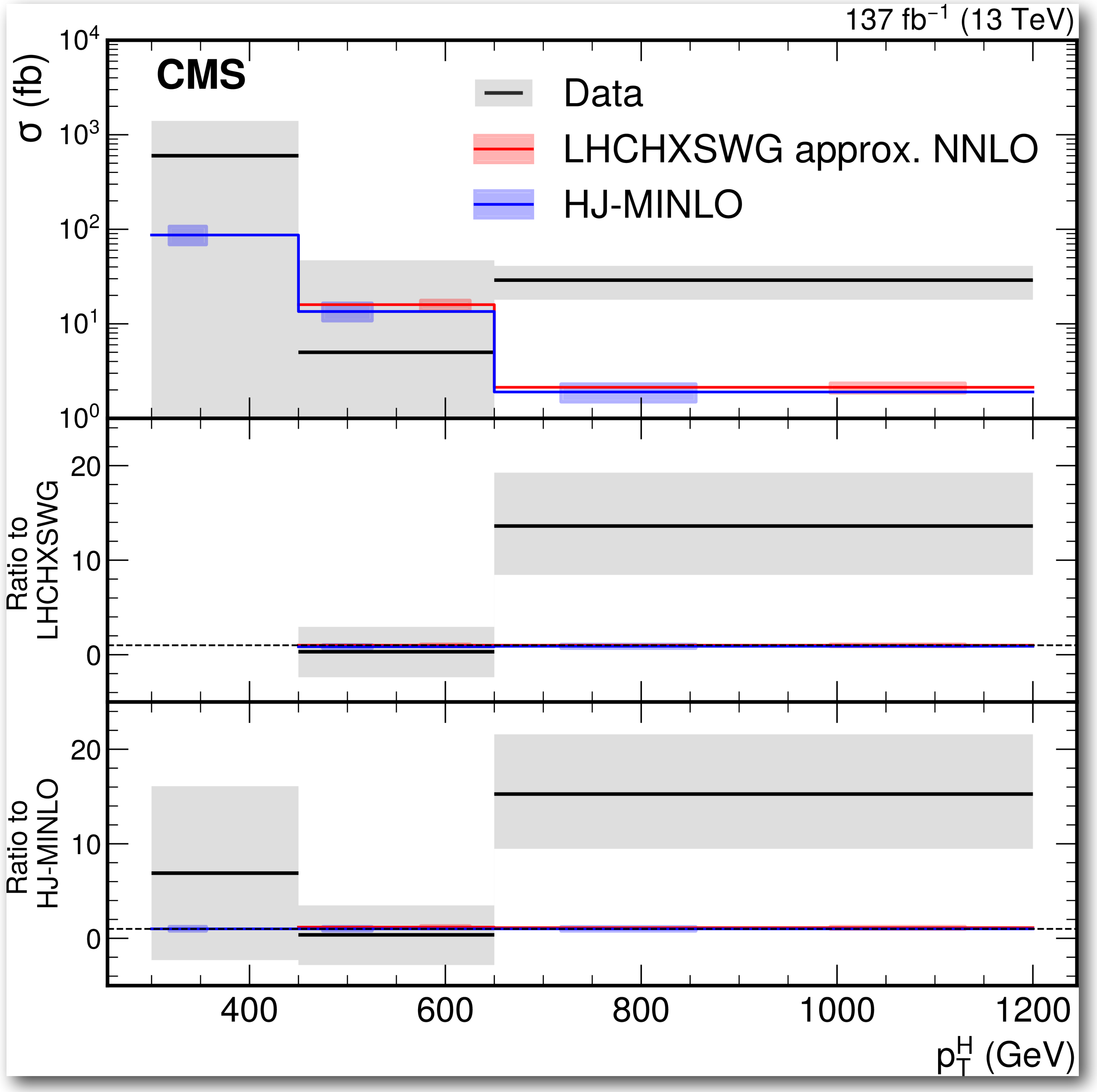
HOW HIGH WE CAN REACH IN HIGGS PT?



ATLAS-CONF-2021-010

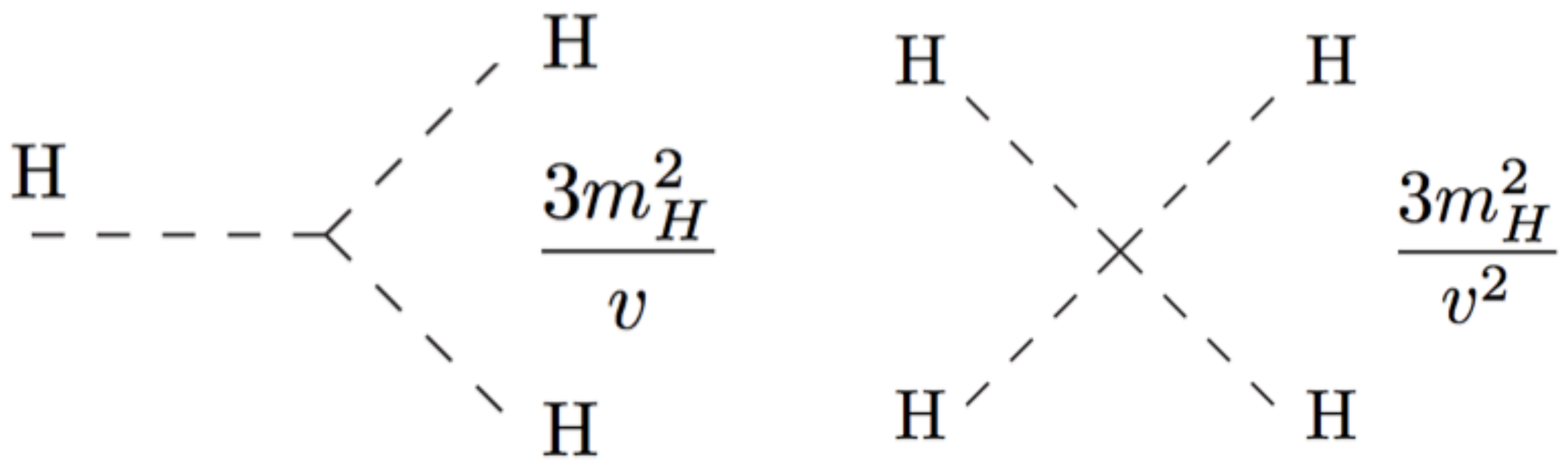
- **High p_T:**
  - Dominated by statistical uncertainty
  - Worse theoretical understanding (larger modeling uncertainties)
  - Enhanced sensitivity to BSM at high P_T
- ➡ Very interesting phase space and topologies to cover as we collect data

- Need statistics: **boosted ggF Hbb** analysis dominates
  - AK8 jets & jet substructure techniques: soft-drop SD mass algorithm
  - Measurements of the cross section in bins of pt from 450-500 GeV up to 800-1200 GeV
  - Parallel Z→bb measurements as control analyses



JHEP 12 (2020) 085

DOES THE HIGGS BOSON COUPLE TO ITSELF?



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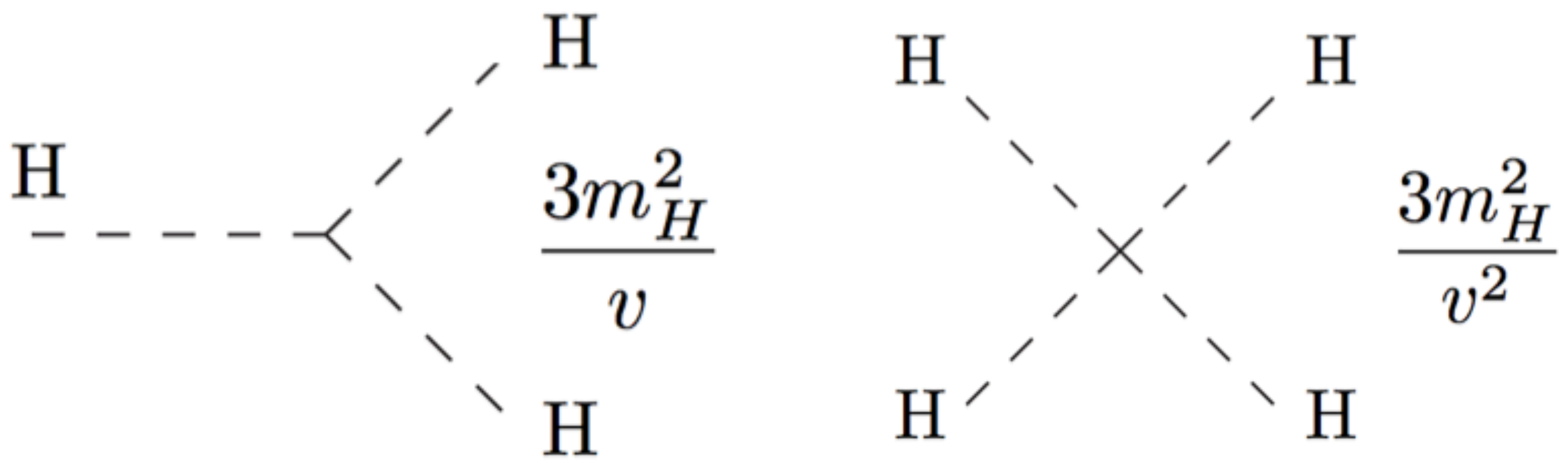

$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

→Access the shape of the Higgs potential

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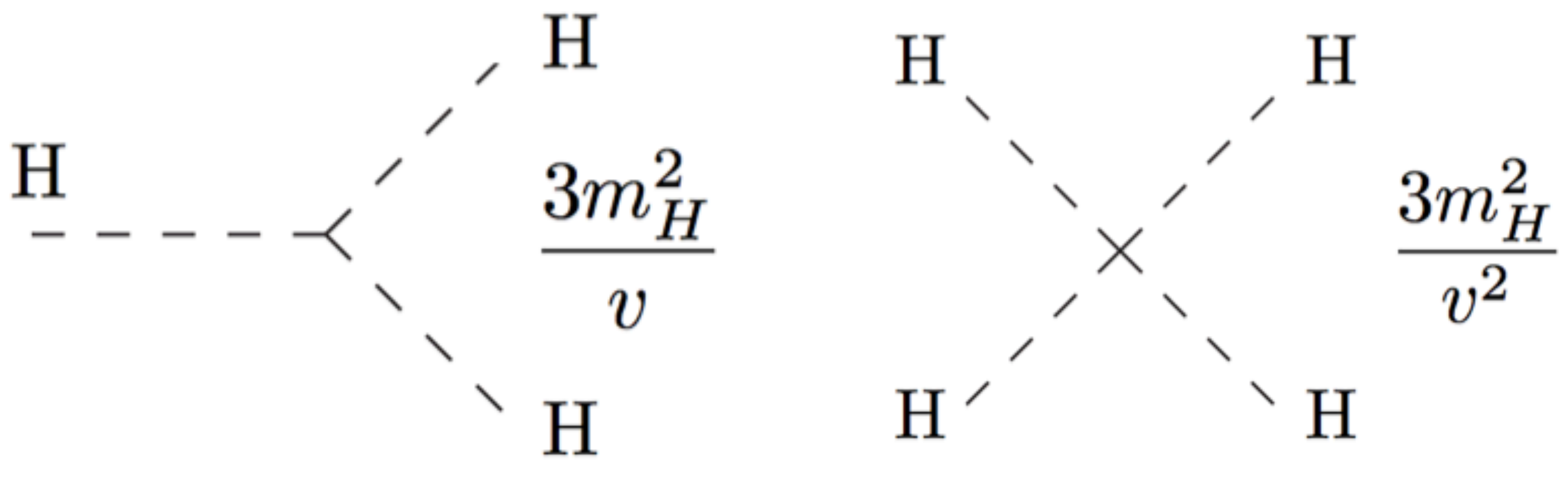

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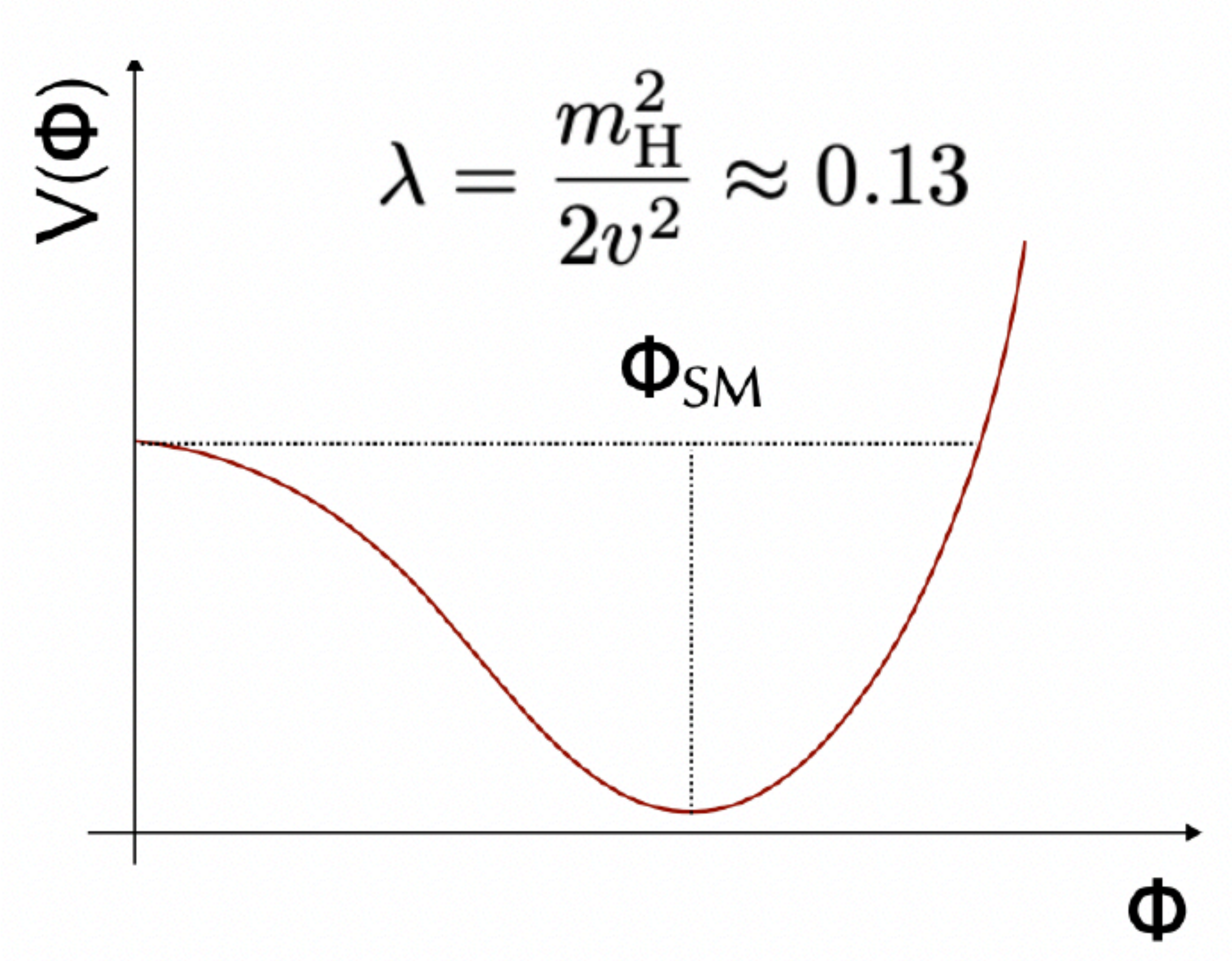

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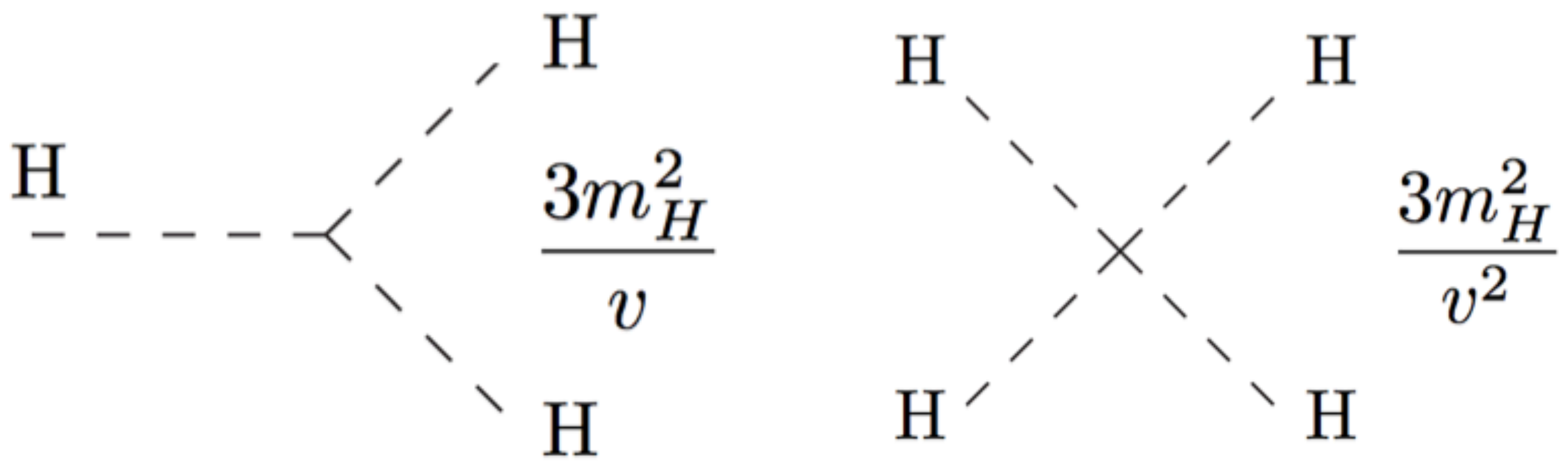

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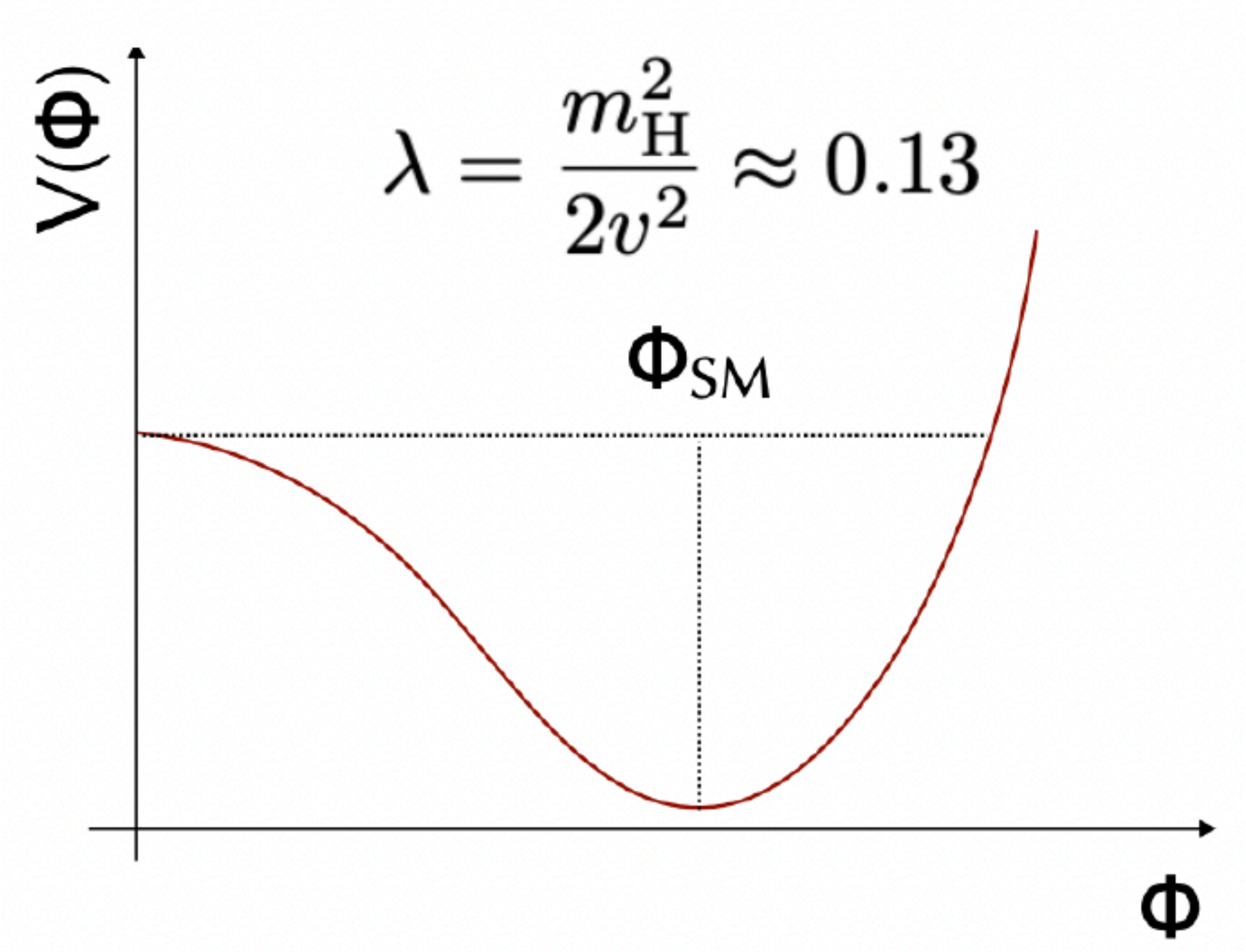


$$V(H) = \frac{M_H^2}{2}H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

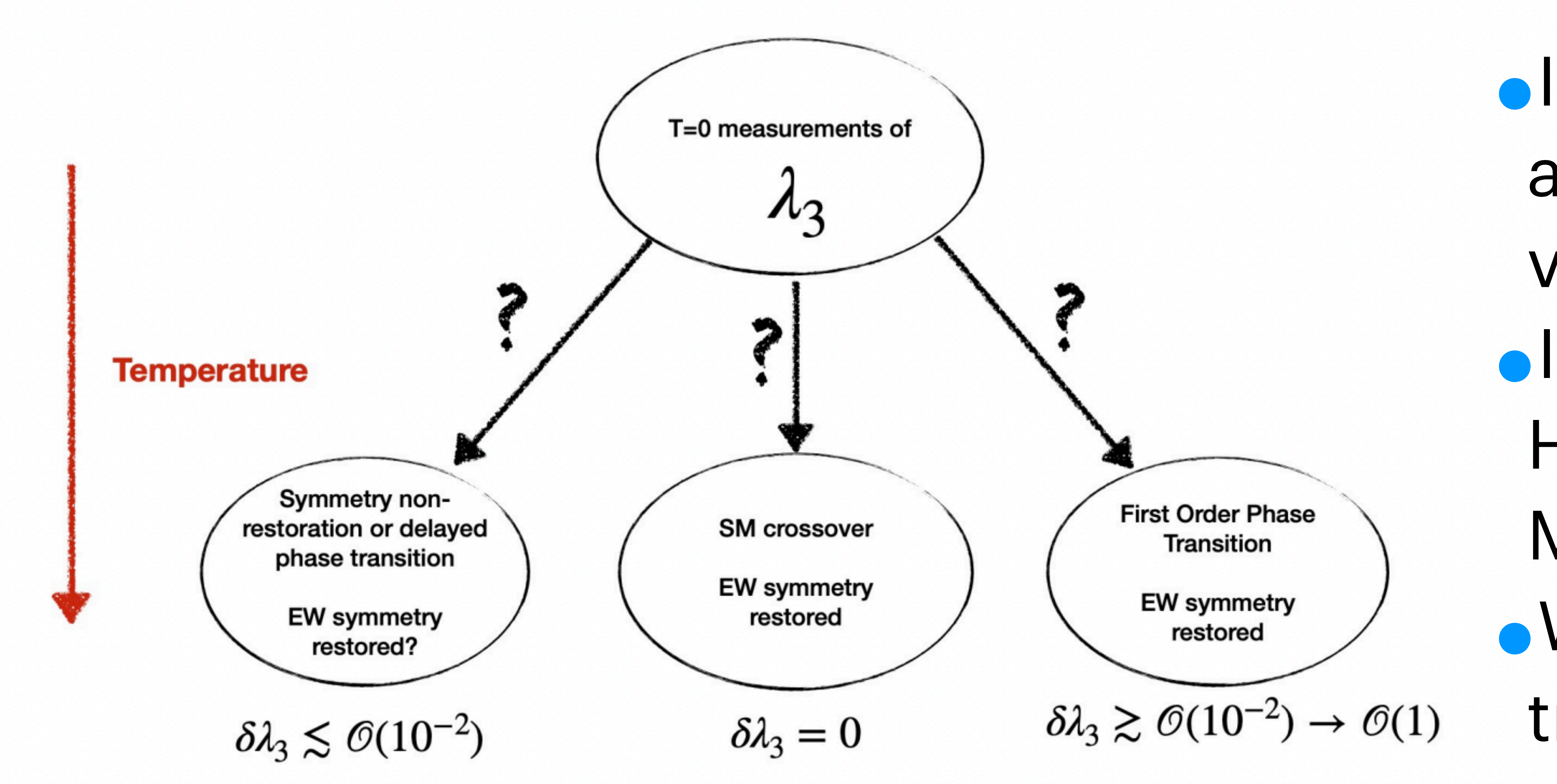
mass

λ_{HHH} λ_{HHHH}

Self-couplings

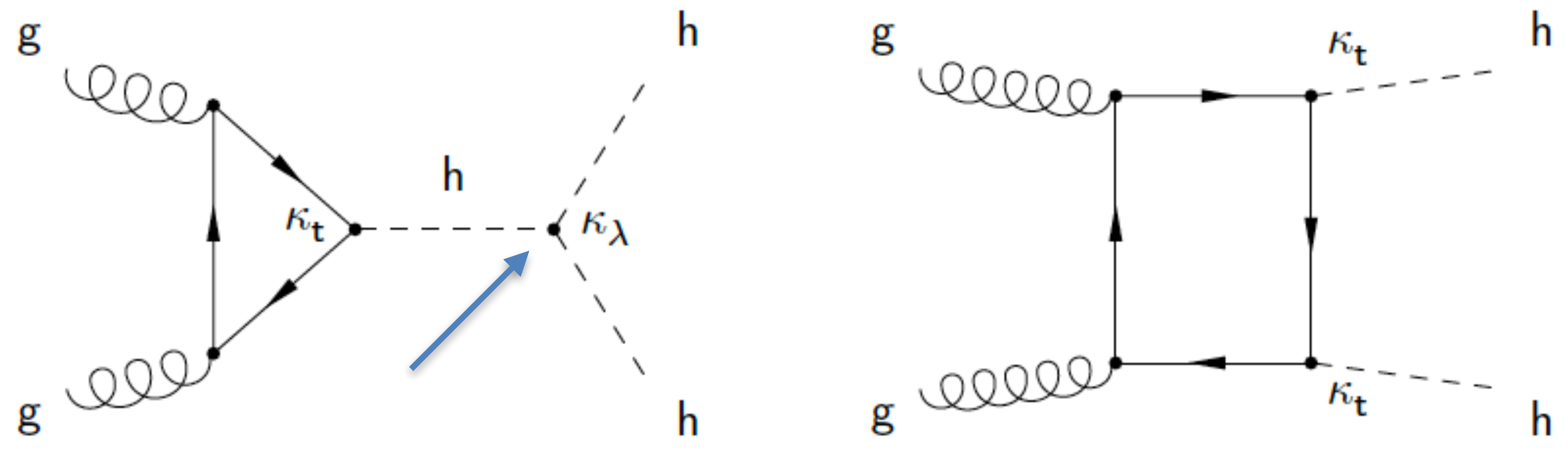
CONNECTION TO COSMOLOGY

Studying the Higgs Self-Coupling transcends particle physics: understanding the Higgs Potential and the vacuum connects with the structure of the Universe



- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a connection between the Higgs/EWSB and baryogenesis, Dark Matter, or inflation?
- What happens at the EW phase transition during the Big Bang?

LOOKING FOR HIGGS BOSON PAIRS



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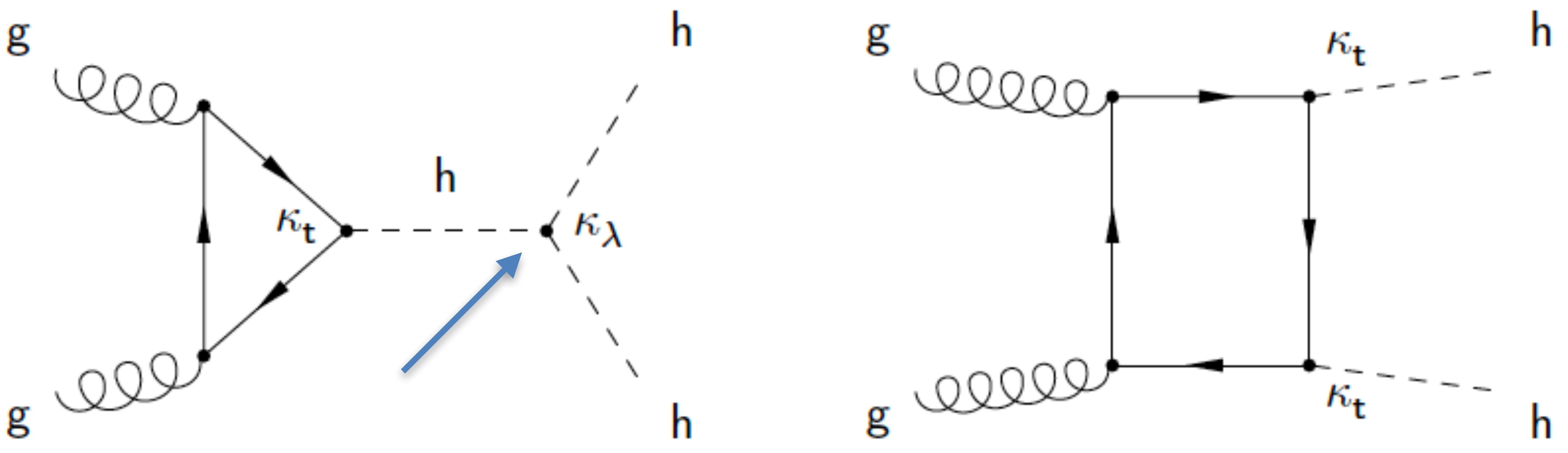

- **Simplest way to access the self coupling at LHC—> Look for two Higgses**
- Easiest does not mean easy! Very low cross section (σ~ 31 fb@13TeV): destructive interference between triangle and box diagrams
- Sensitive to BSM physics : *Small* changes of the couplings can lead to *large* changes in production

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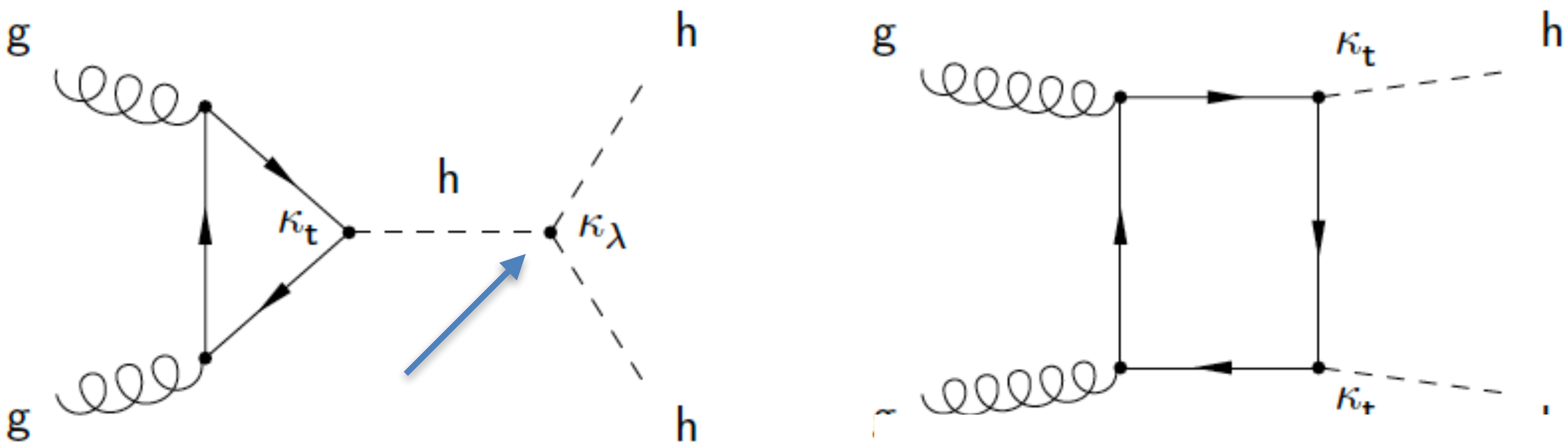

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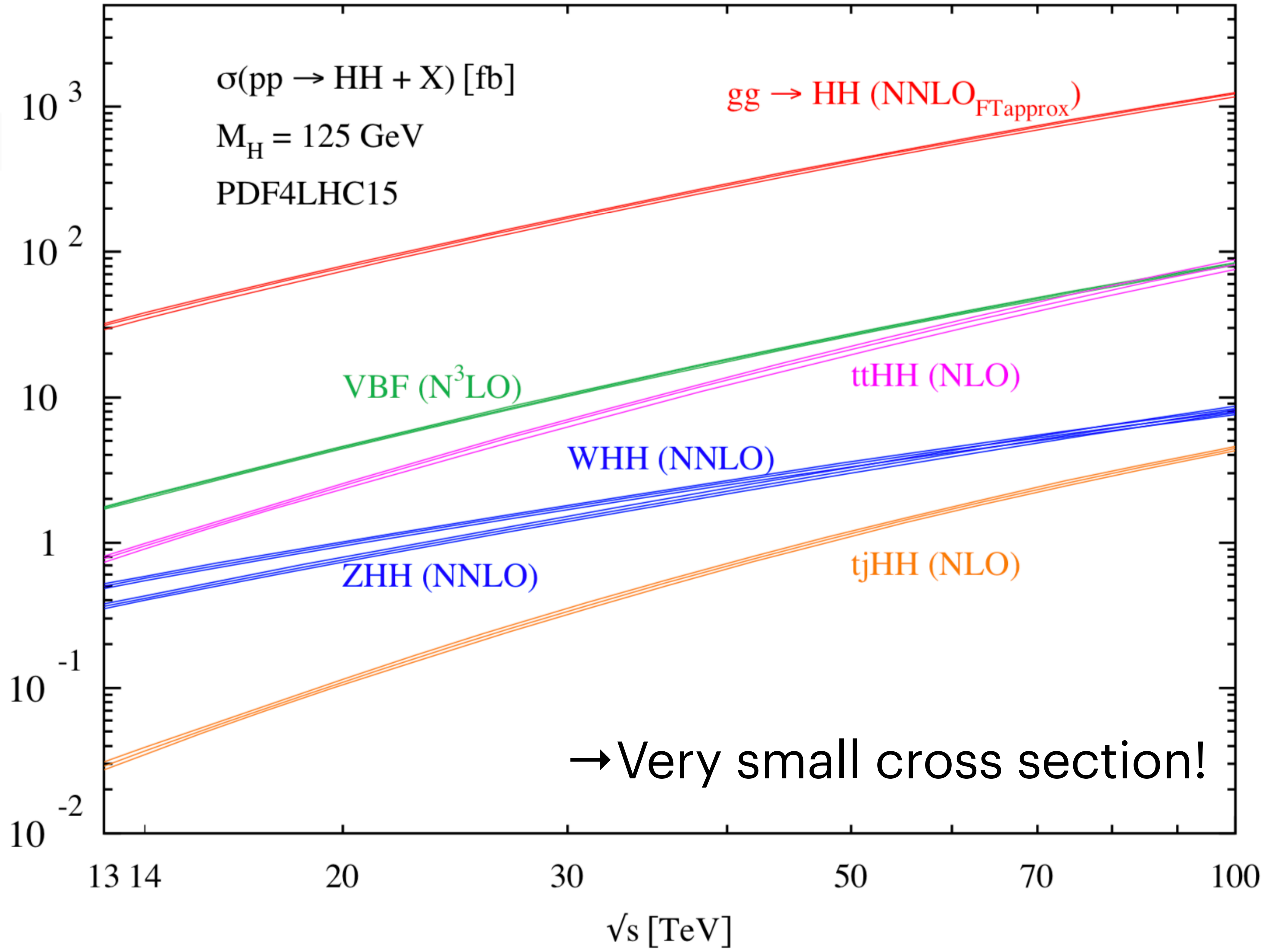

WHICH CHANNEL TO STUDY?

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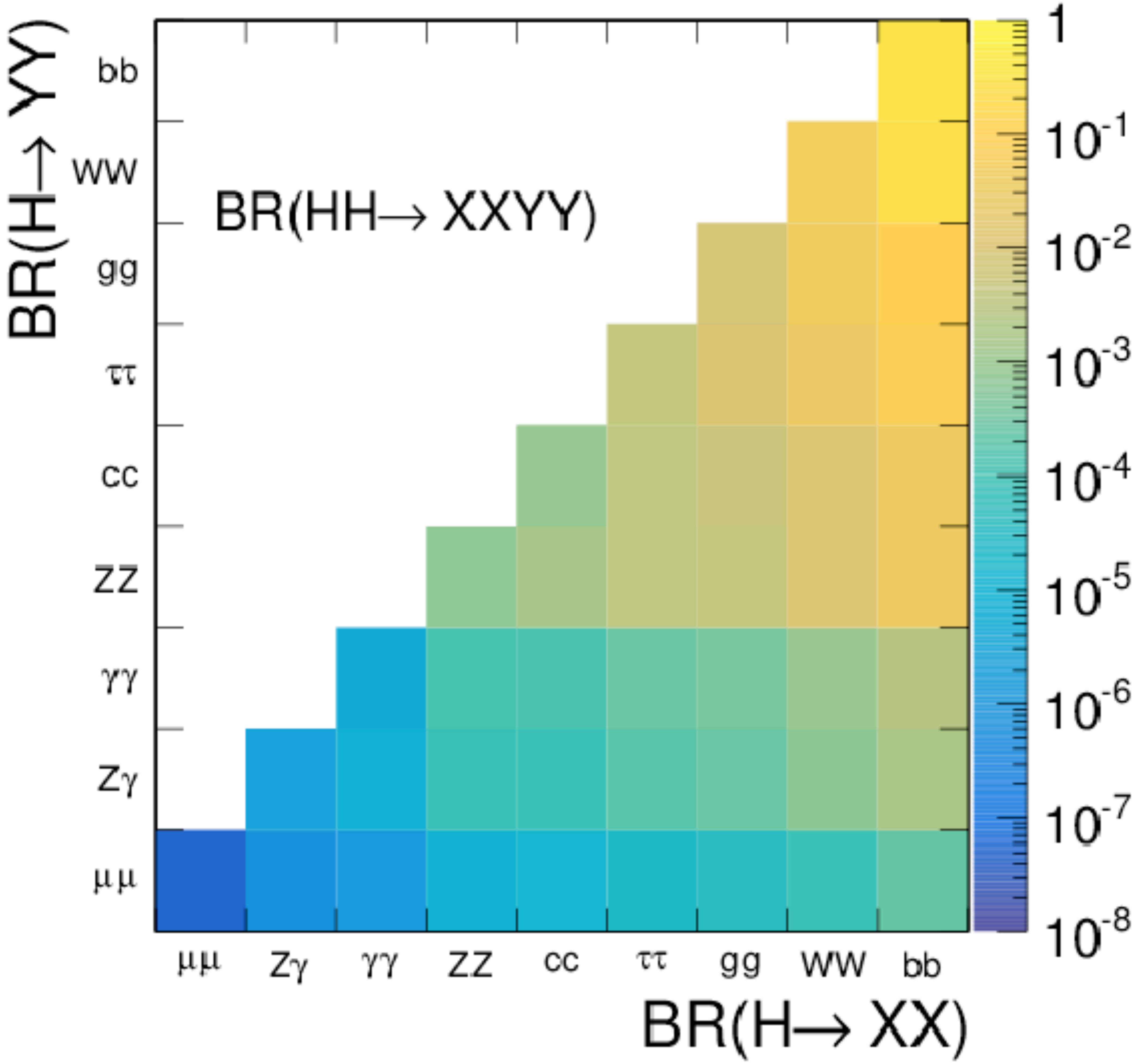
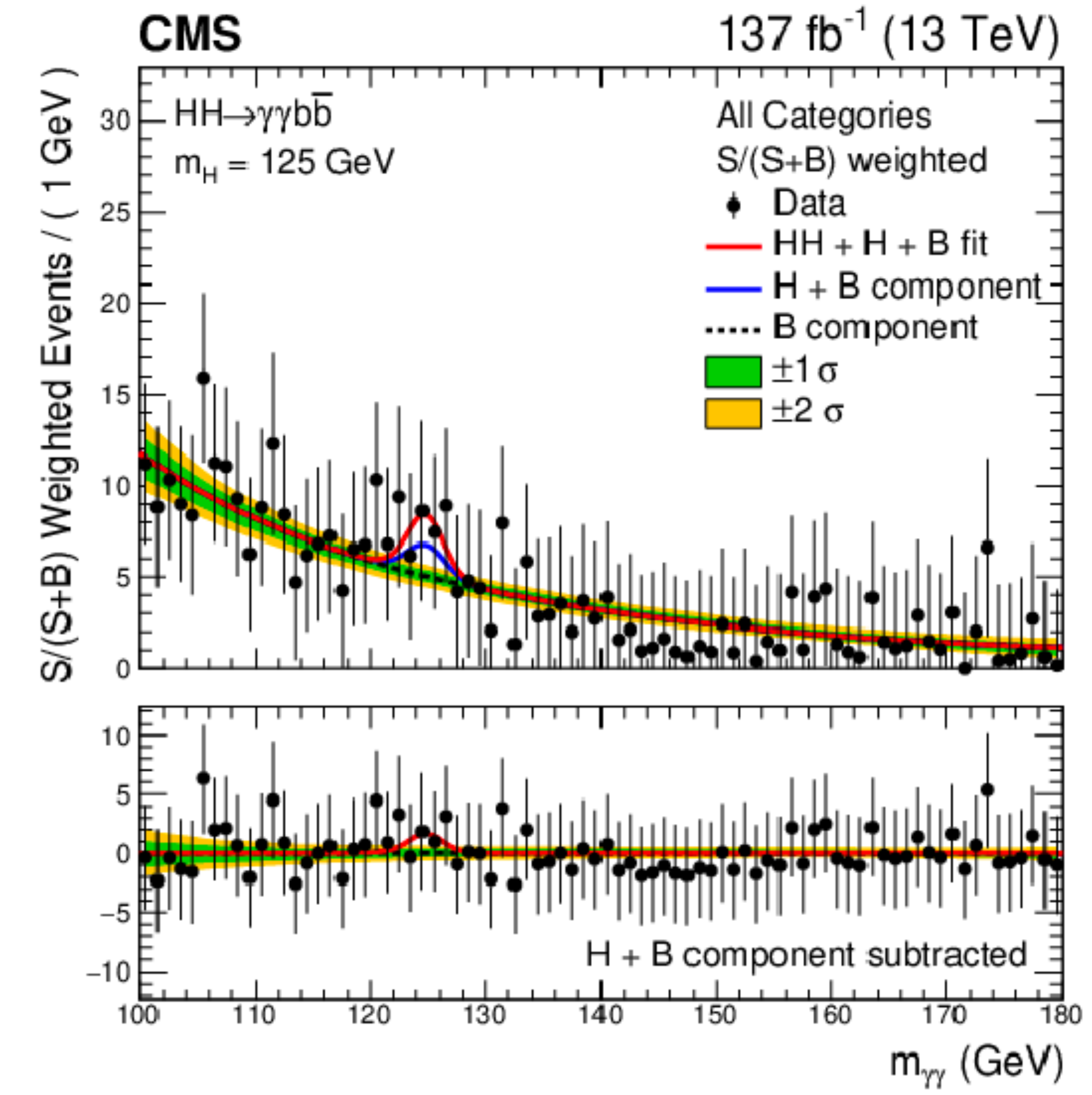
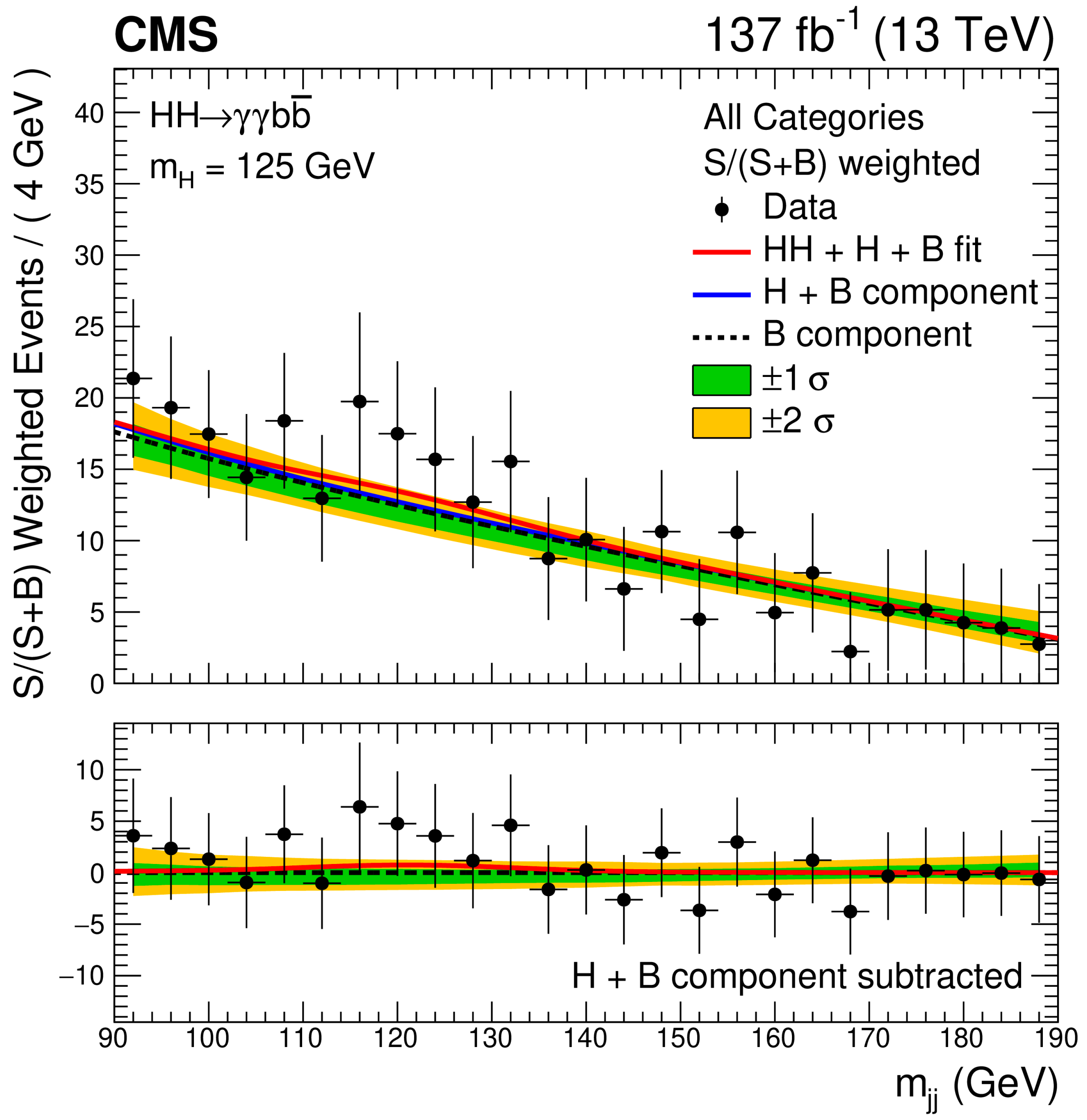
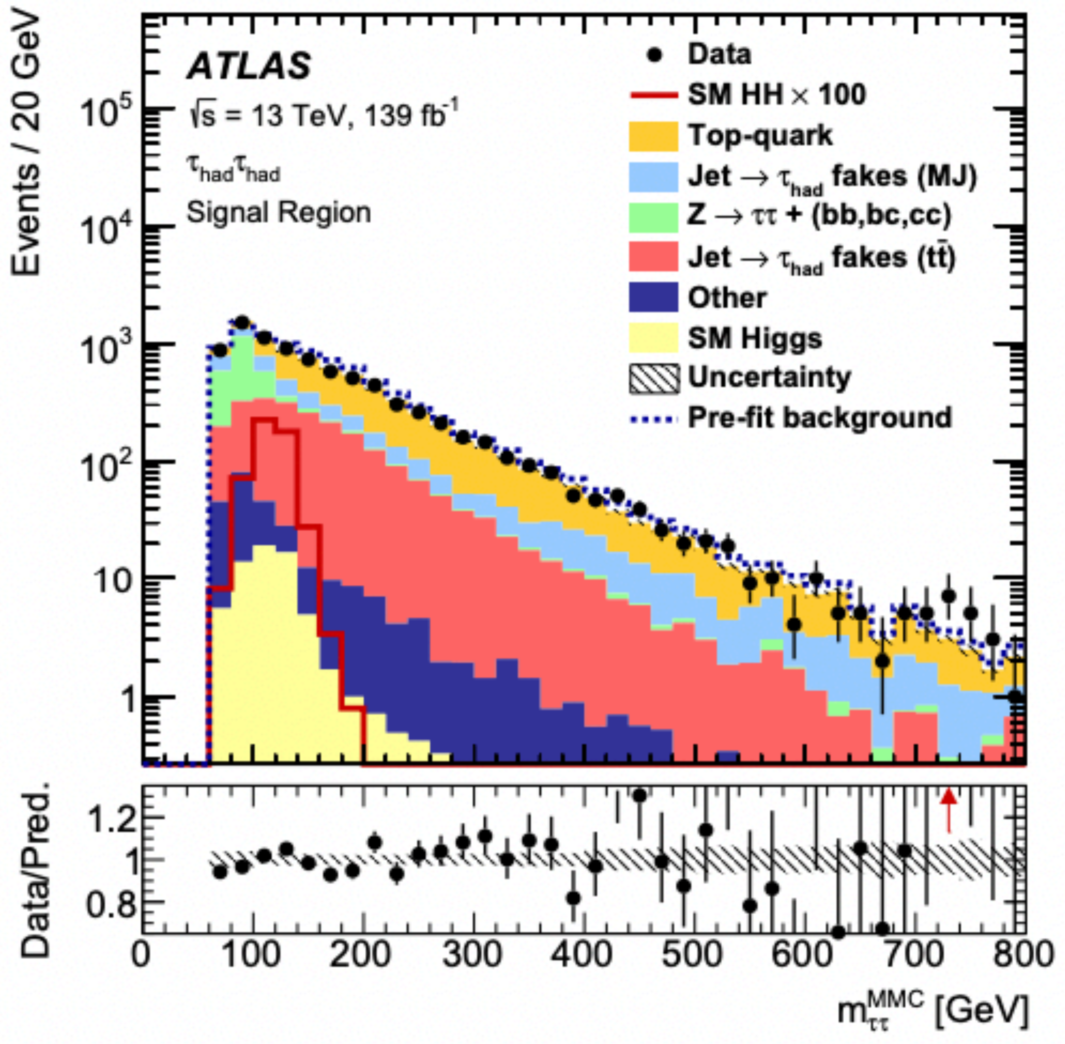


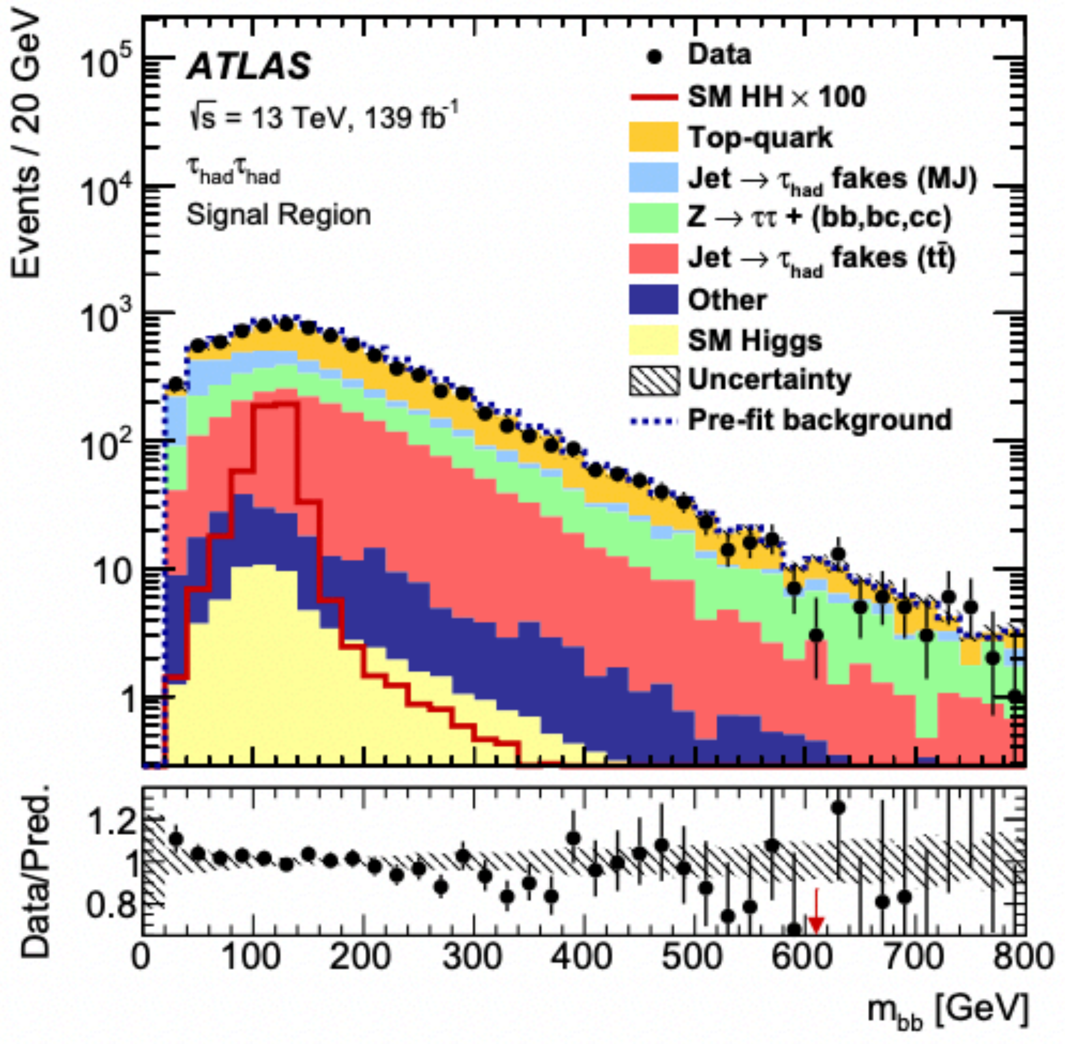
"GOLDEN" CHANNELS: $bb\gamma\gamma, bb\tau\tau, bbbb$

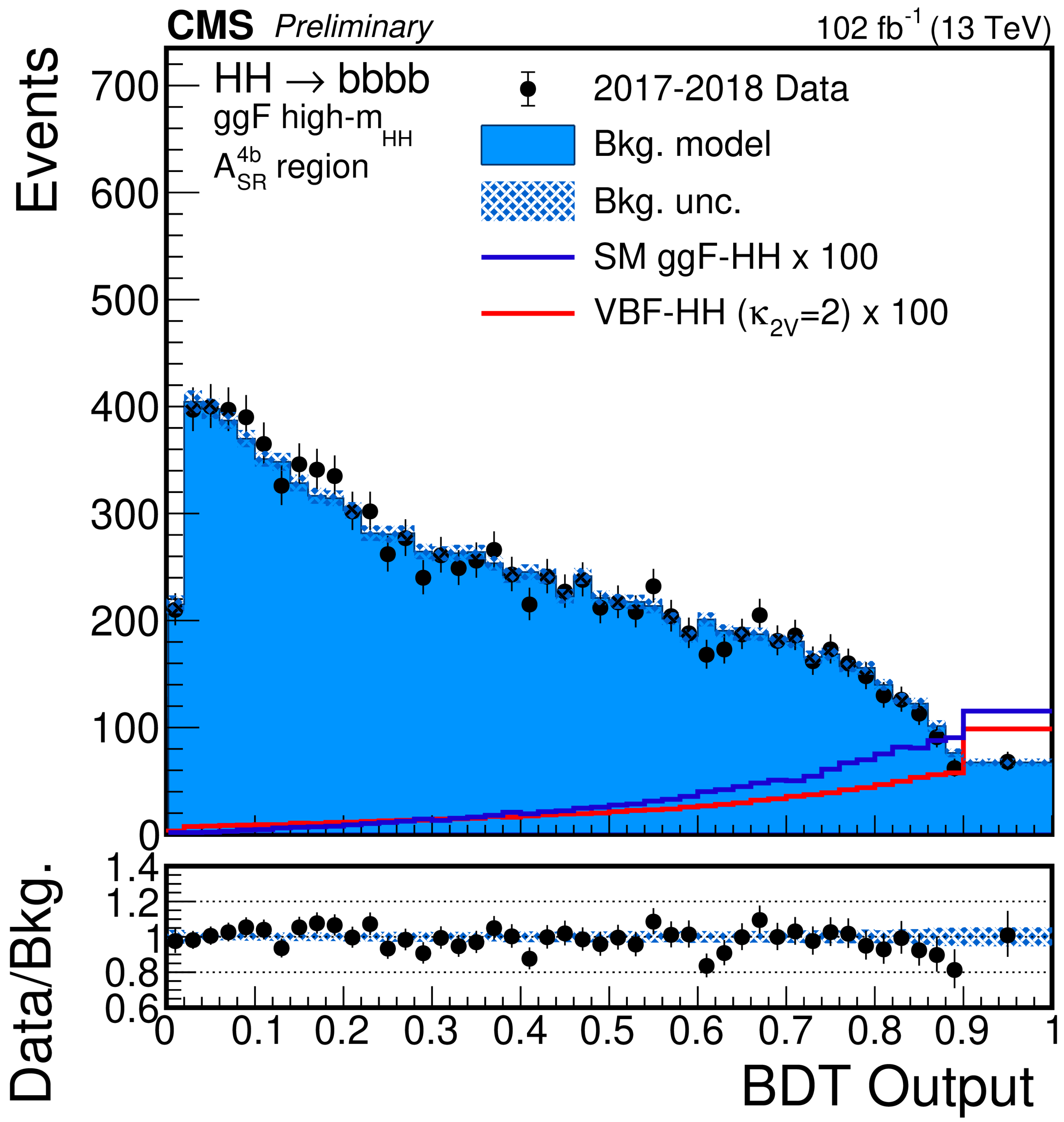




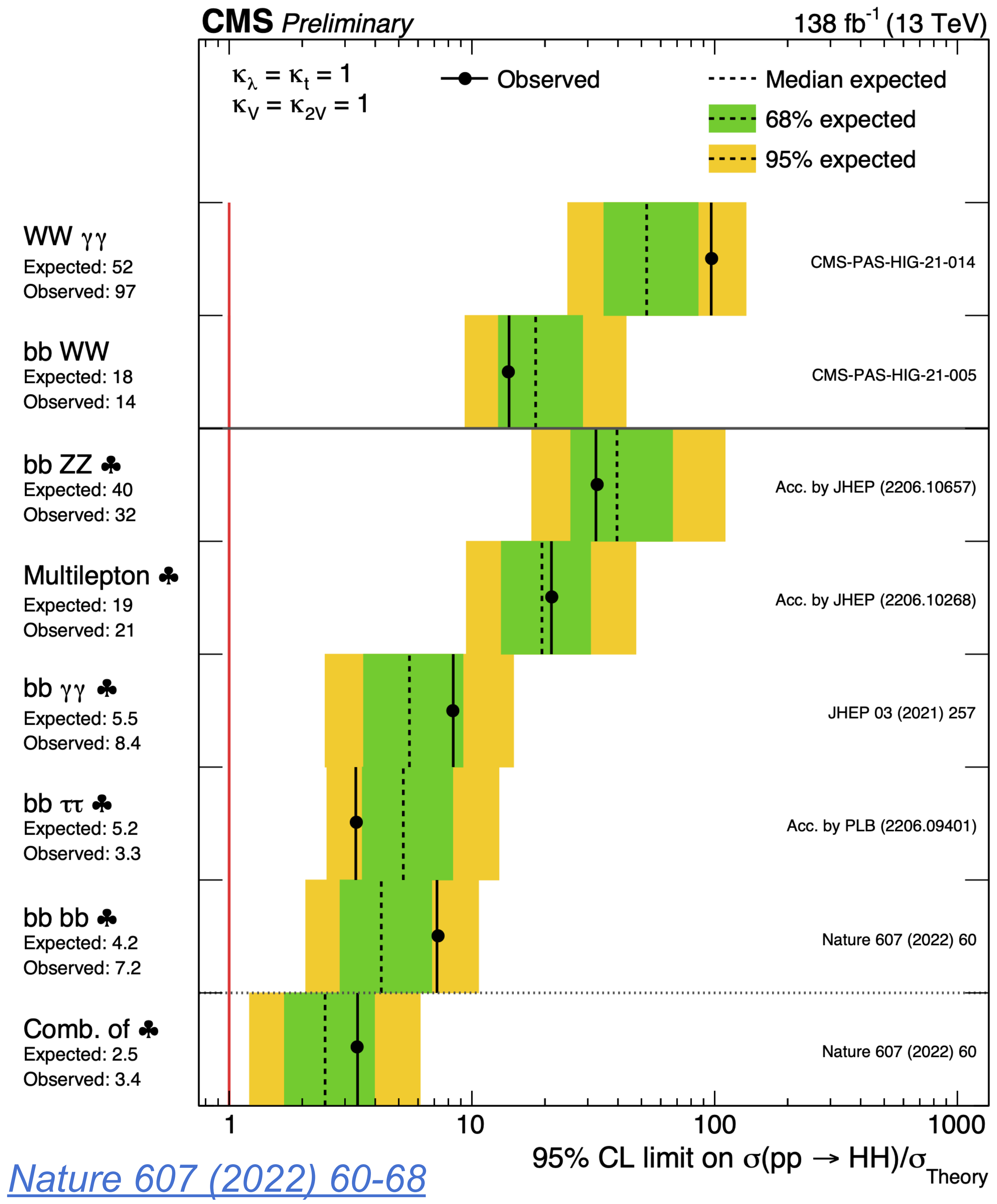


(d)

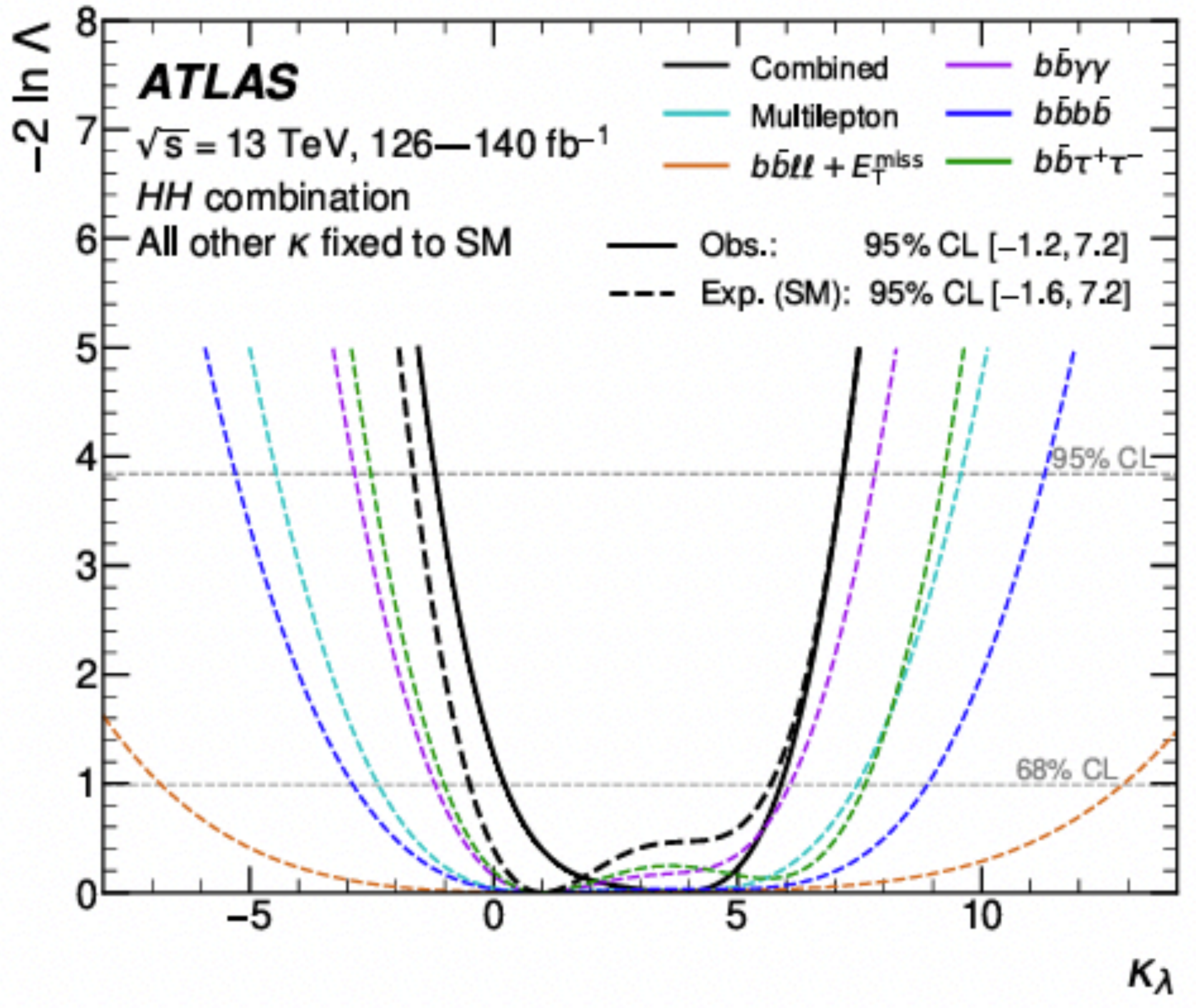


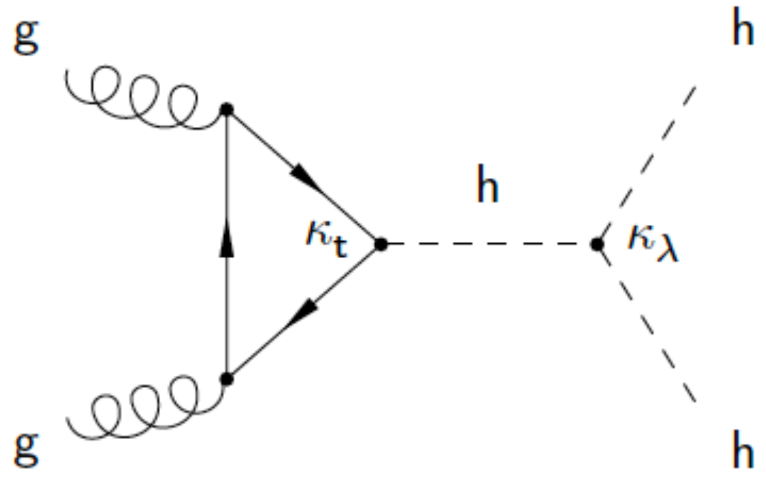


CROSS SECTION VS COUPLING



Nature 607 (2022) 60-68





$$\kappa_\lambda \equiv \lambda_{HHH} / \lambda_{HHH}^{SM}.$$

CROSS SECTION VS COUPLING

Partial Run2	ggF+VBF: upper limit at 95% CL on σ/σ_{SM}	95% CL limits on κ_λ observed
ATLAS	**2.9 (2.4)**	**[-1.2 , 7.2]**
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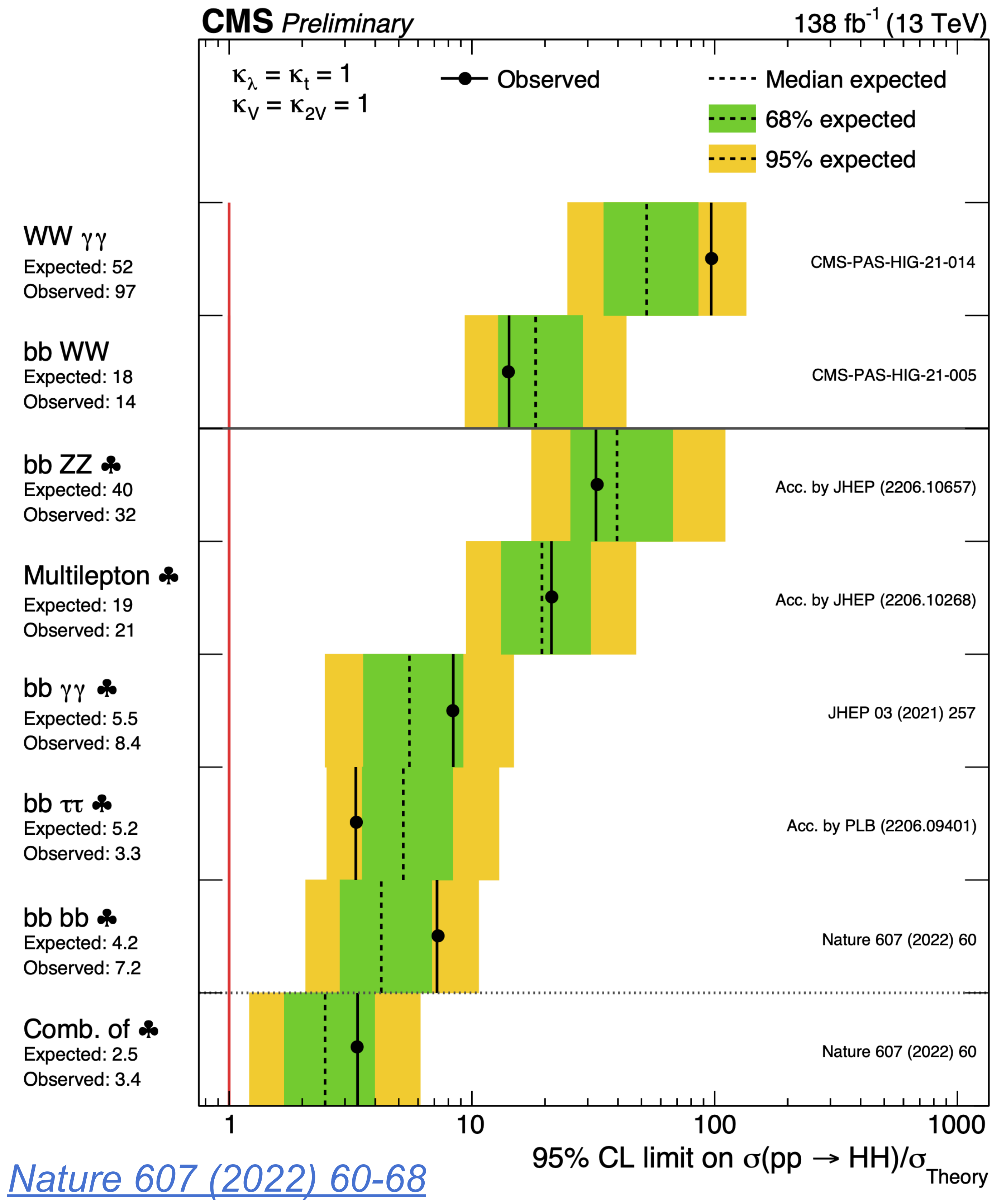

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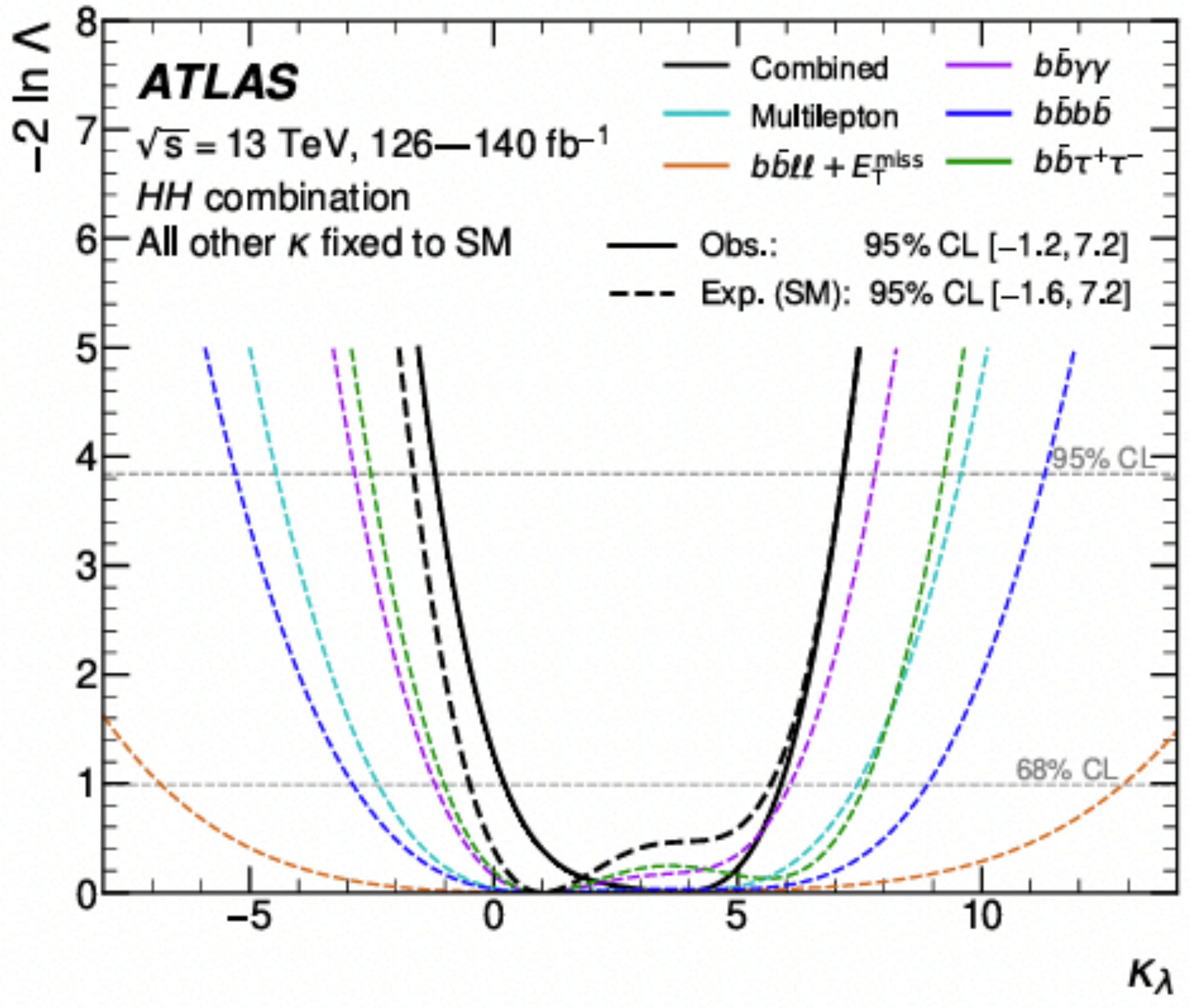

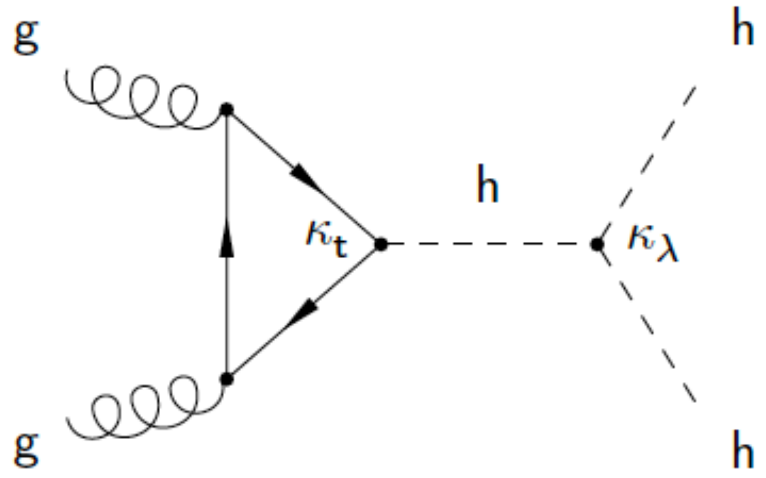

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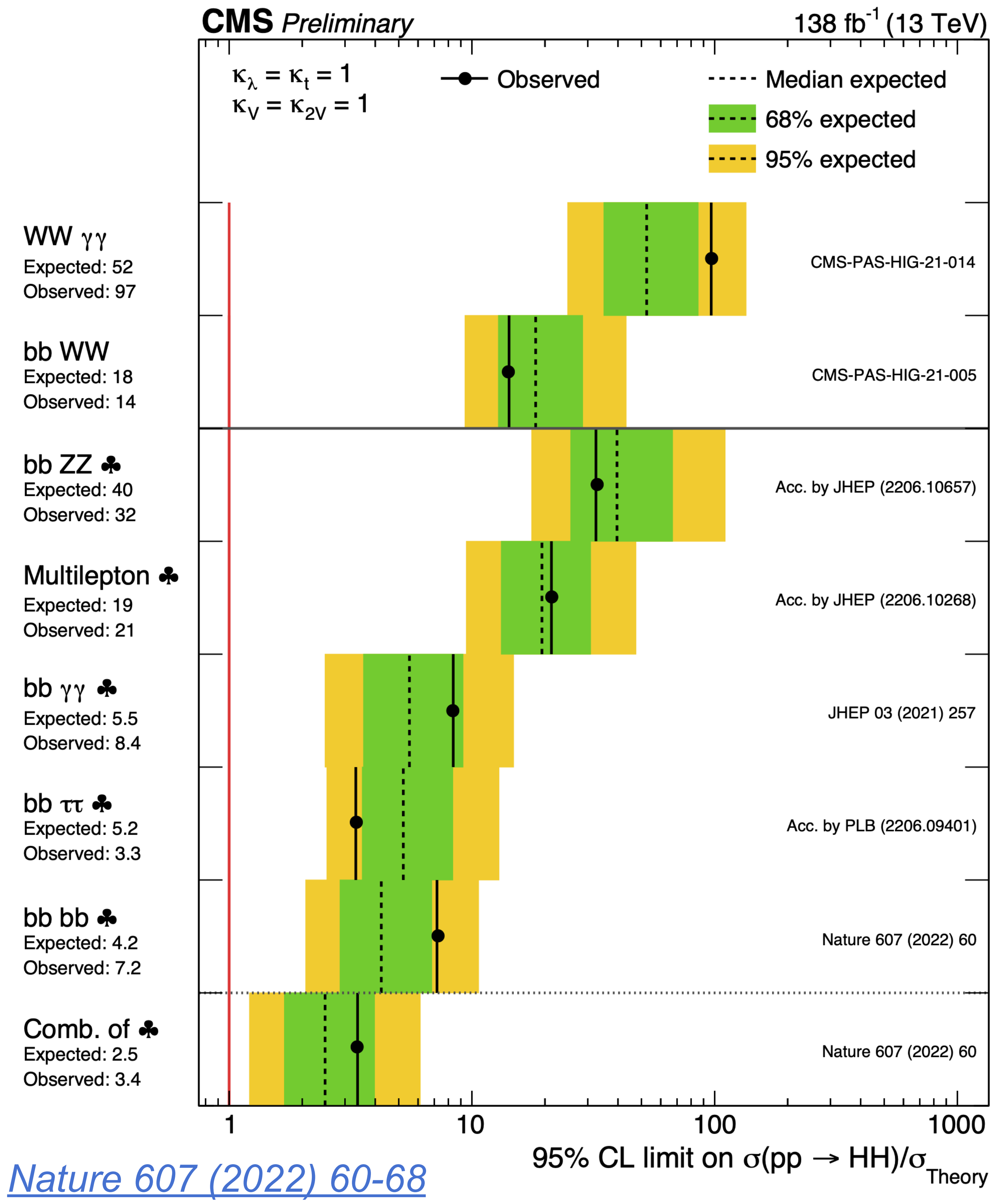

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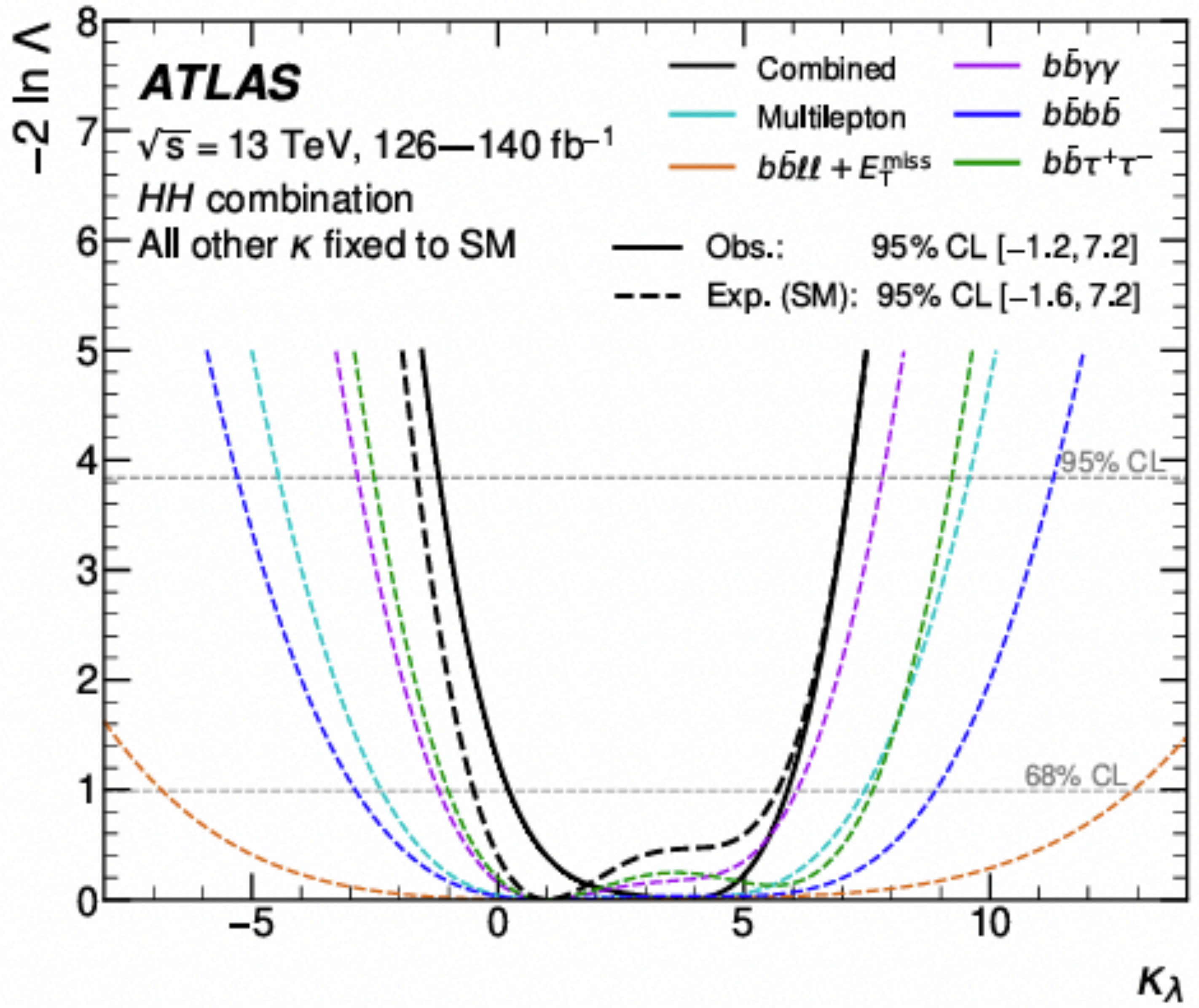
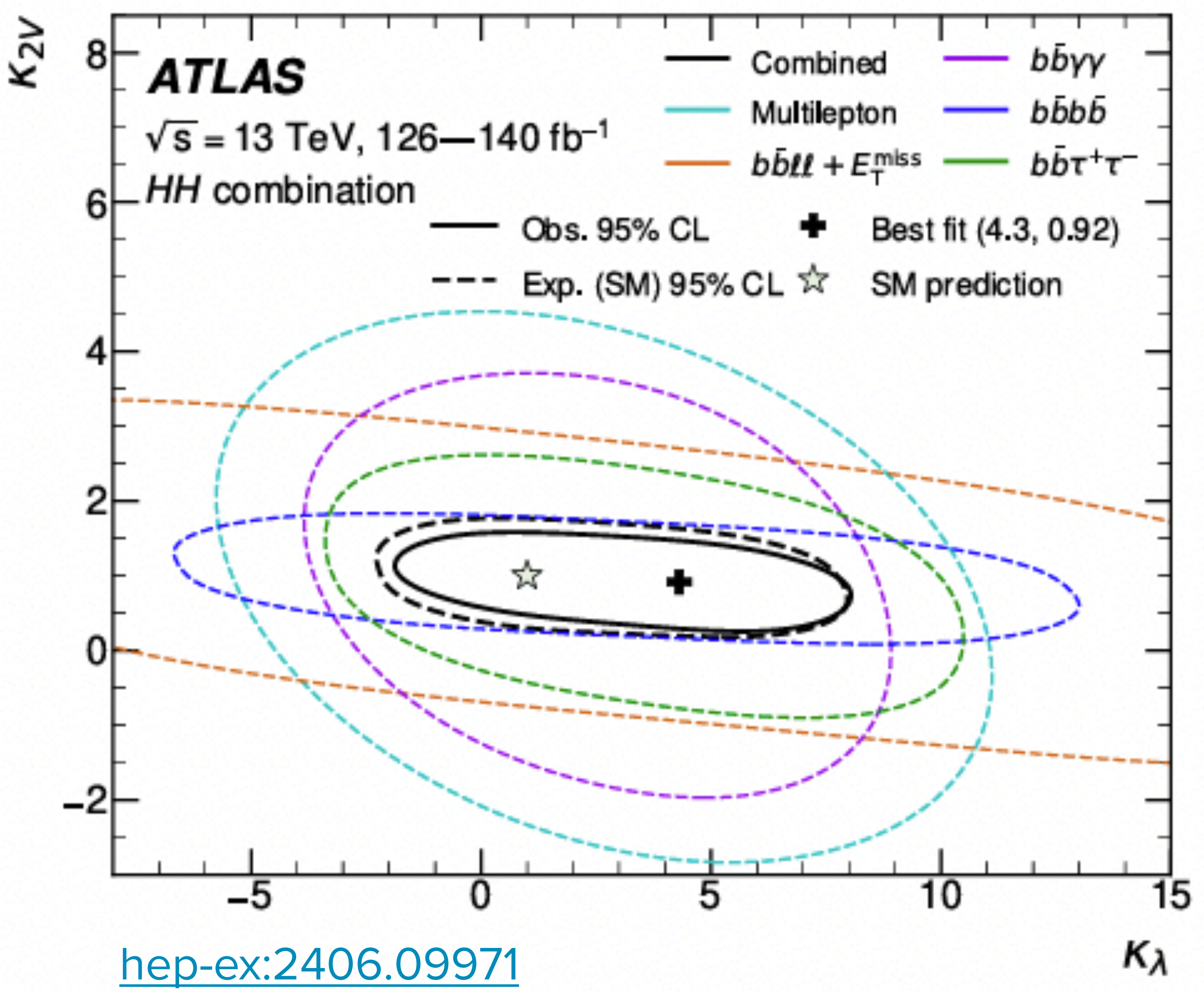
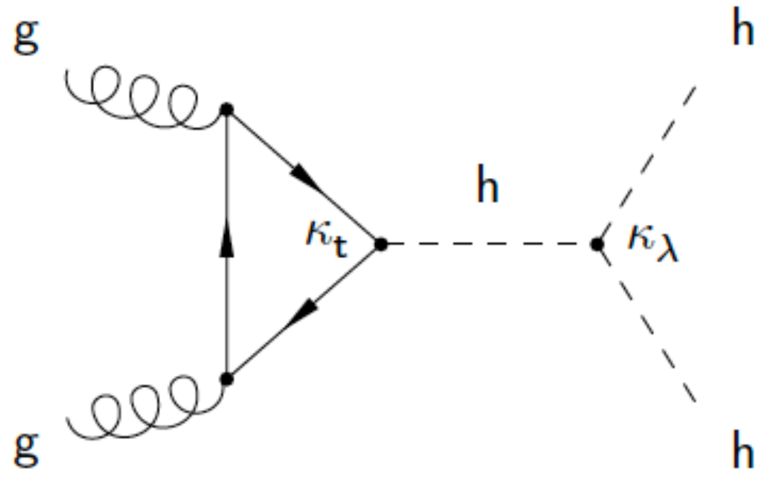




hep-ex:2406.09971



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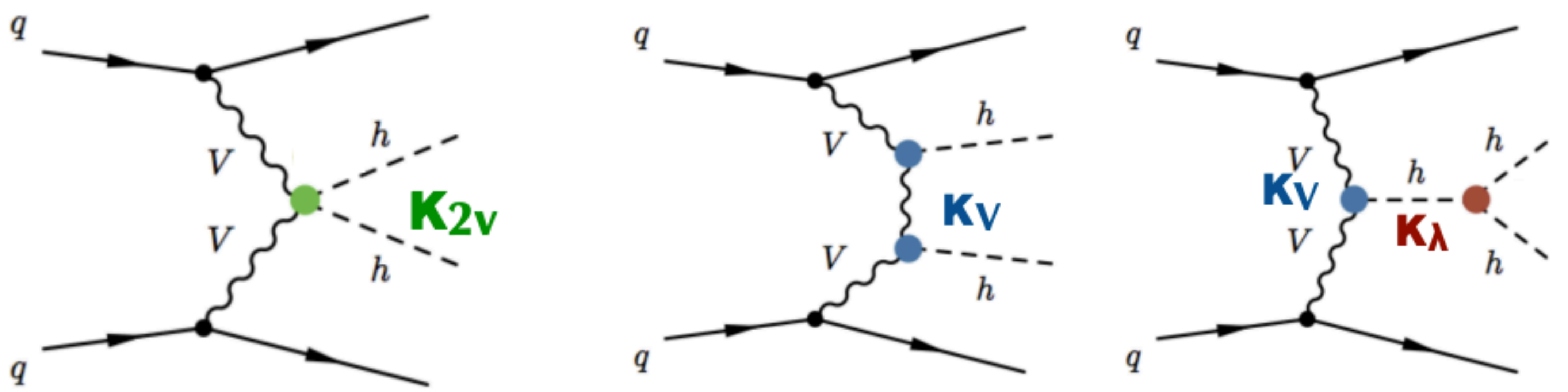
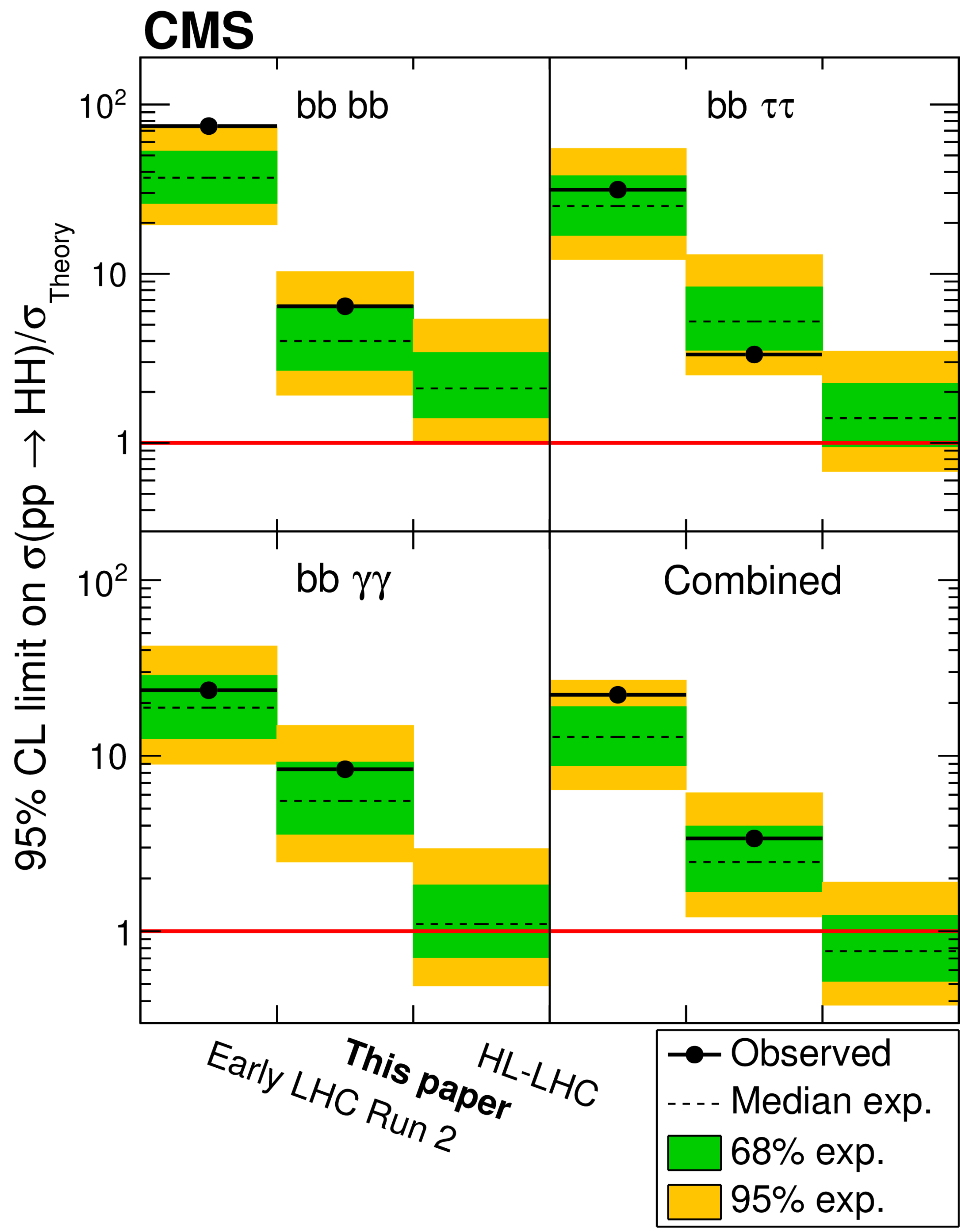
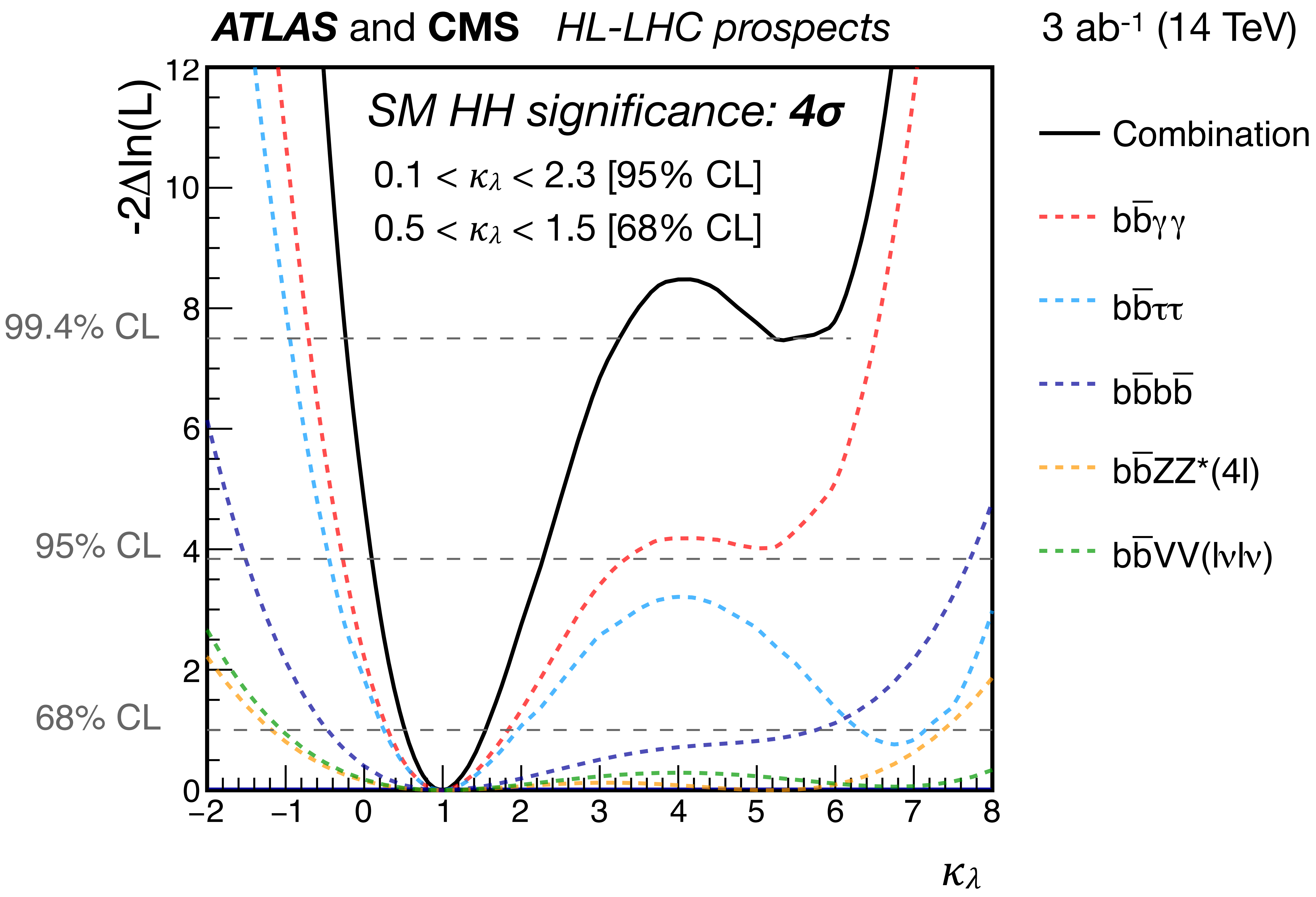


DIHIGGS: HL-LHC!





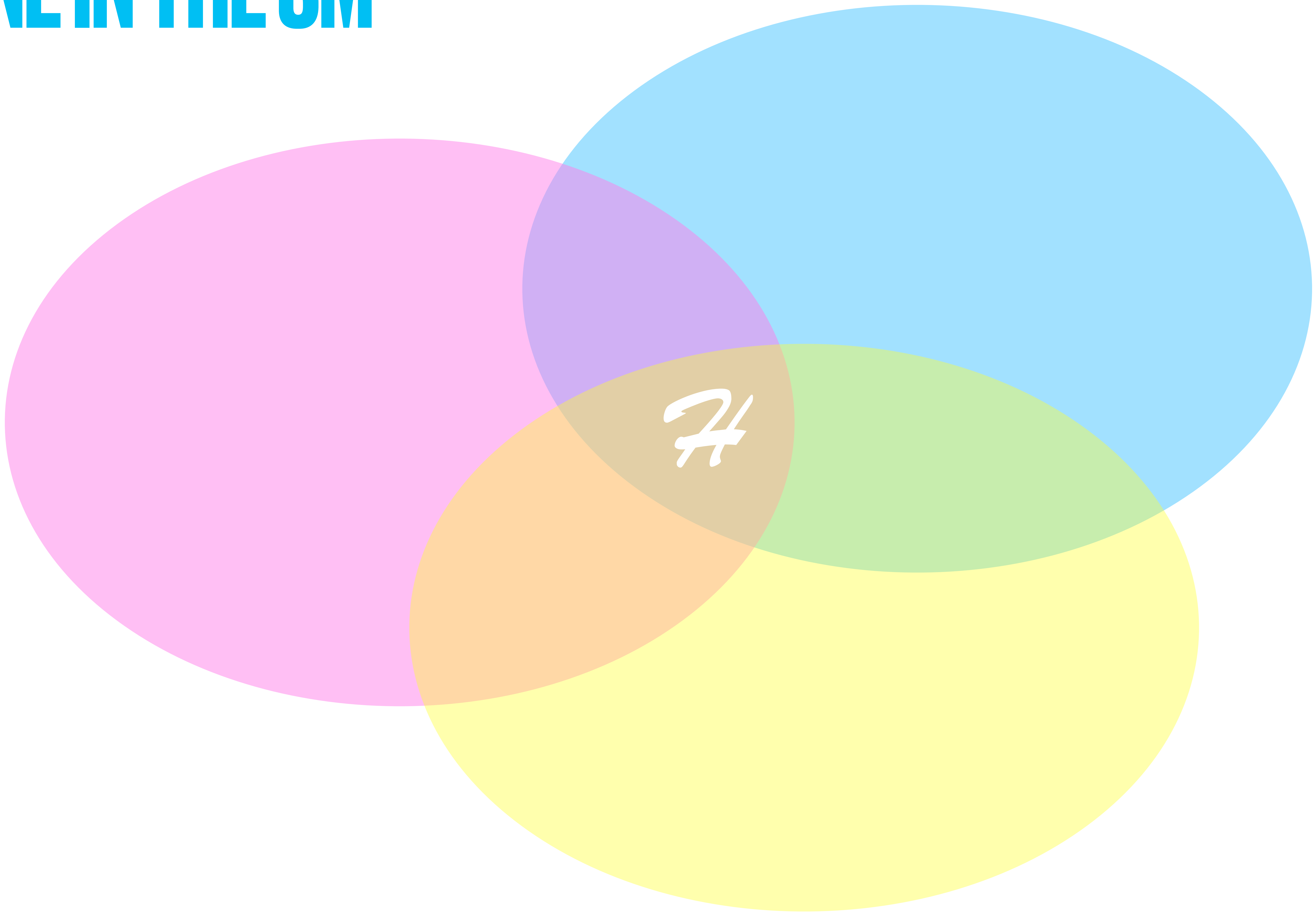
Combining the ATLAS and CMS results a significance of 4 standard deviation can be achieved at the end of the HL-LHC

arXiv:1902.00134

KEYSTONE IN THE SM

(* This is just an illustration, note that the different questions are more multifaceted than this shows)

KEYSTONE IN THE SM



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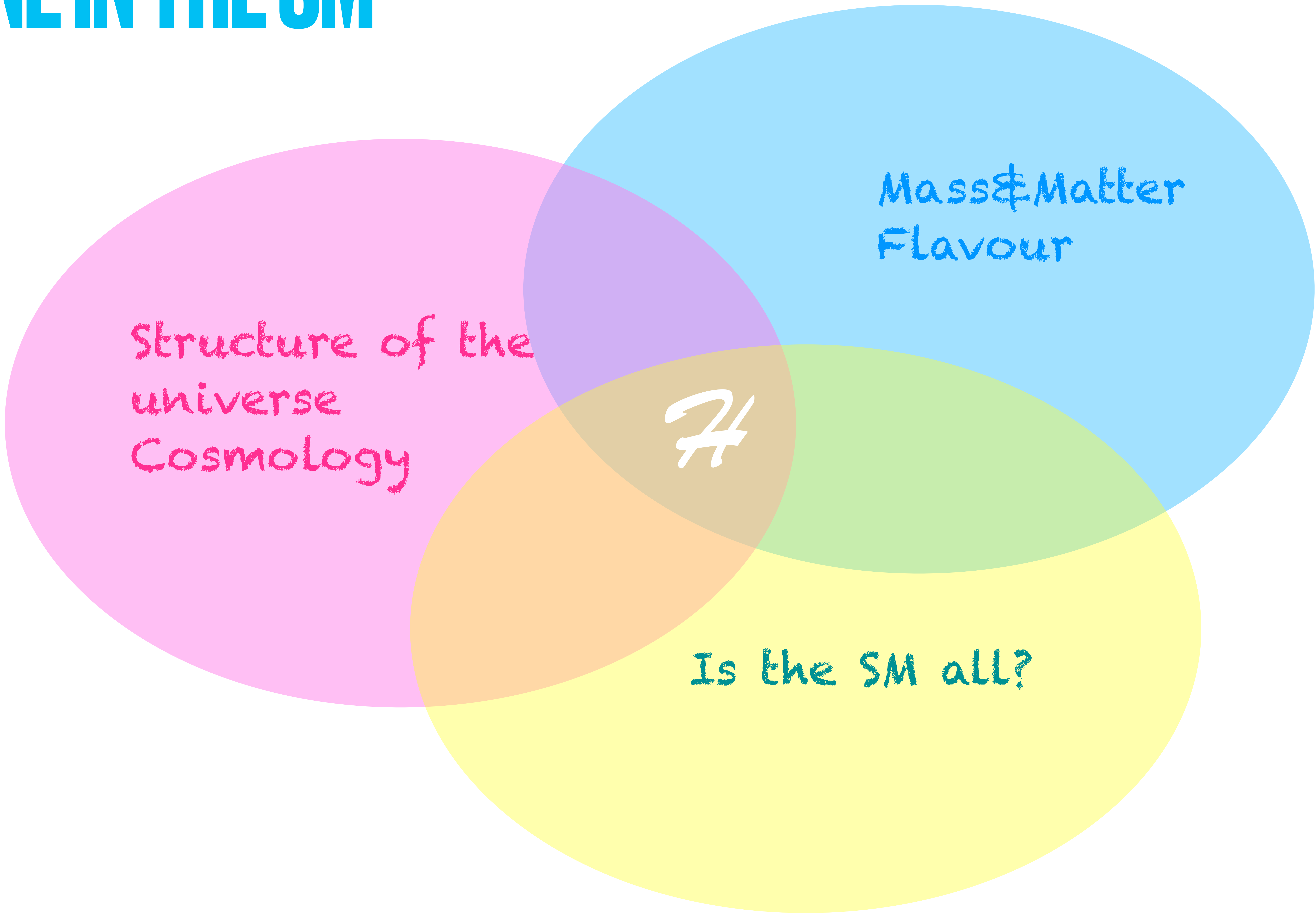

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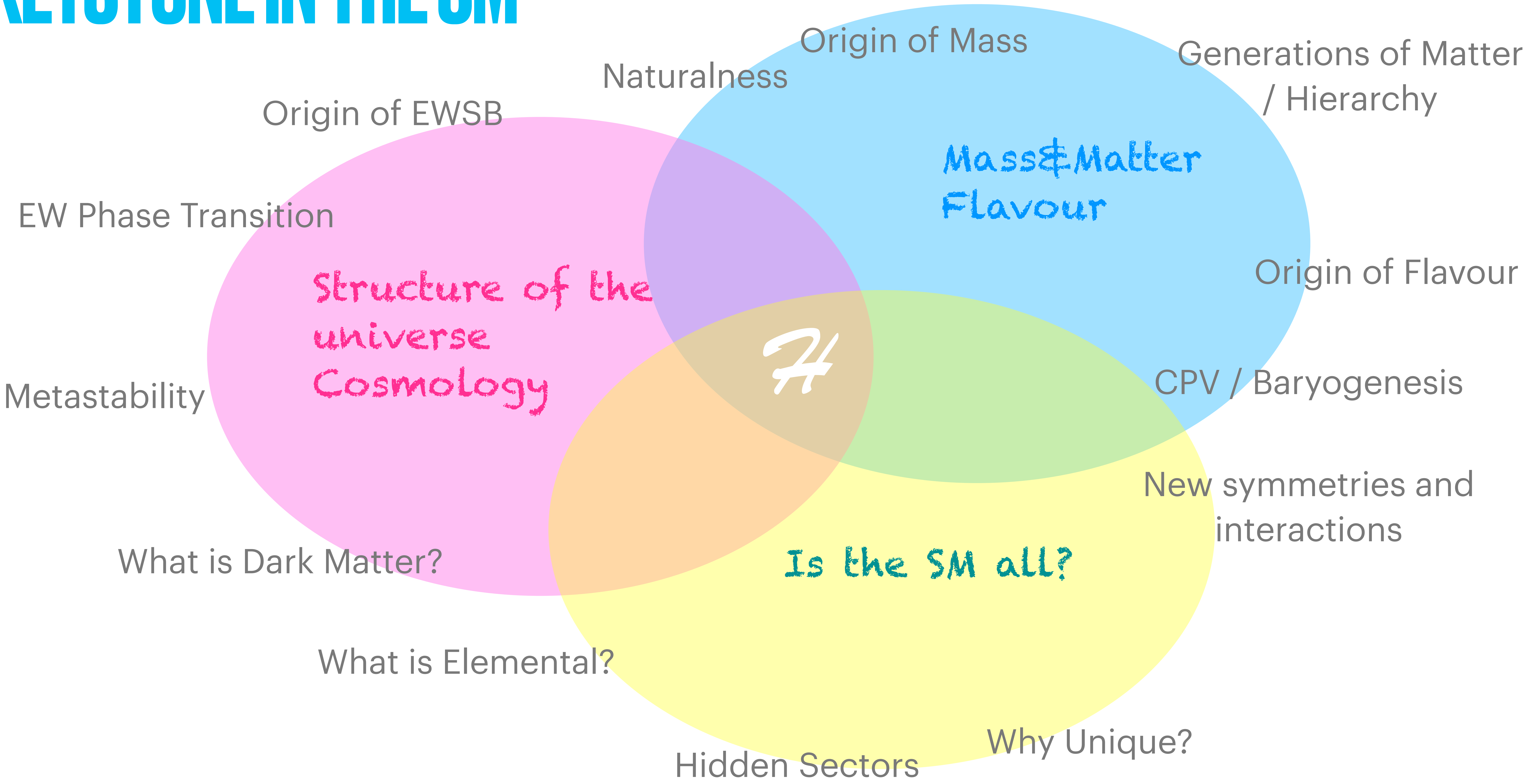


(* This is just an illustration, note that the different questions are more multifaceted than this shows)

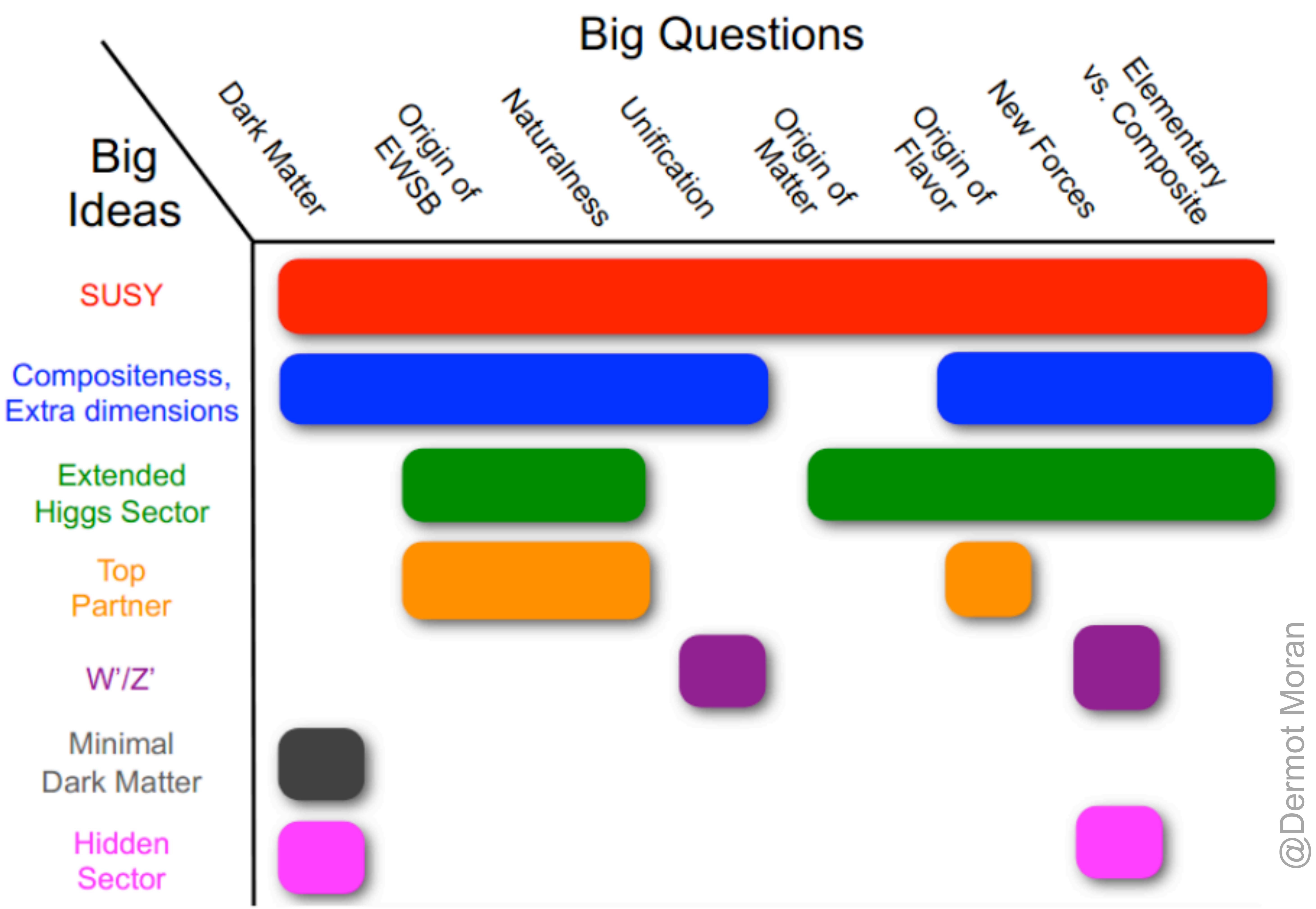
REACHING BEYOND THE SM?

HOW LONG CAN WE CONTINUE PATCHING THE SM?

- As you know, the SM is paradoxical: it is extraordinarily successful in describing and quantifying the universe… and at the same time we know it is not the 'final theory': structural problems (experimental observations, theoretical inconsistencies):
  - Origin of Mass: 3 Generations of Matter, Mass hierarchy
  - (Meta)stability of the universe
  - Matter/Antimatter Asymmetry, Baryogenesis
  - Neutrino masses and the flavor puzzle
  - Dark Matter
  - Dark Energy
  - Gravity, unification of forces

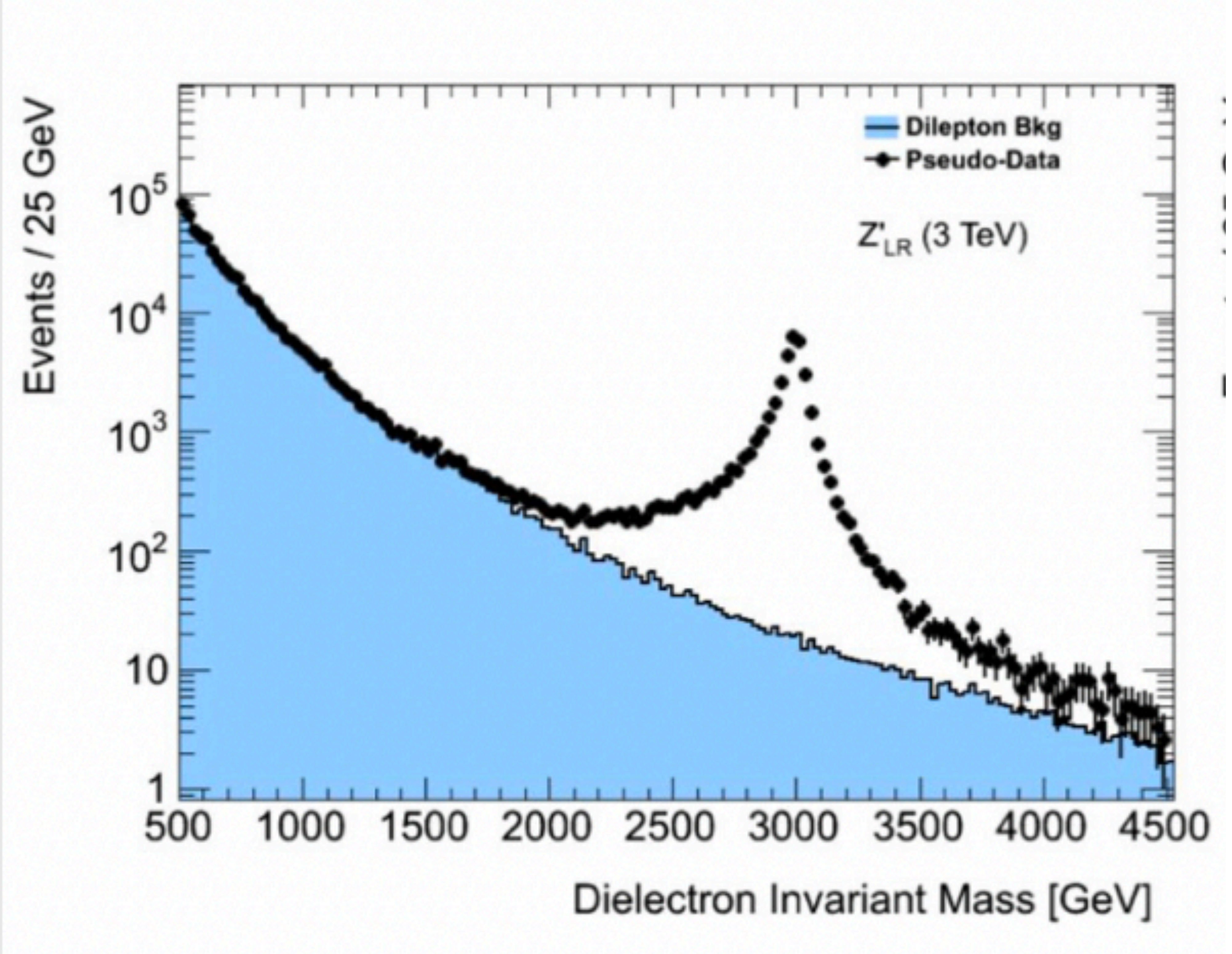
- **Synergy and complementarity are keys to understand the problems of the SM**
- The LHC is capable of attacking many of these problems

PICK YOUR FAVORITE...

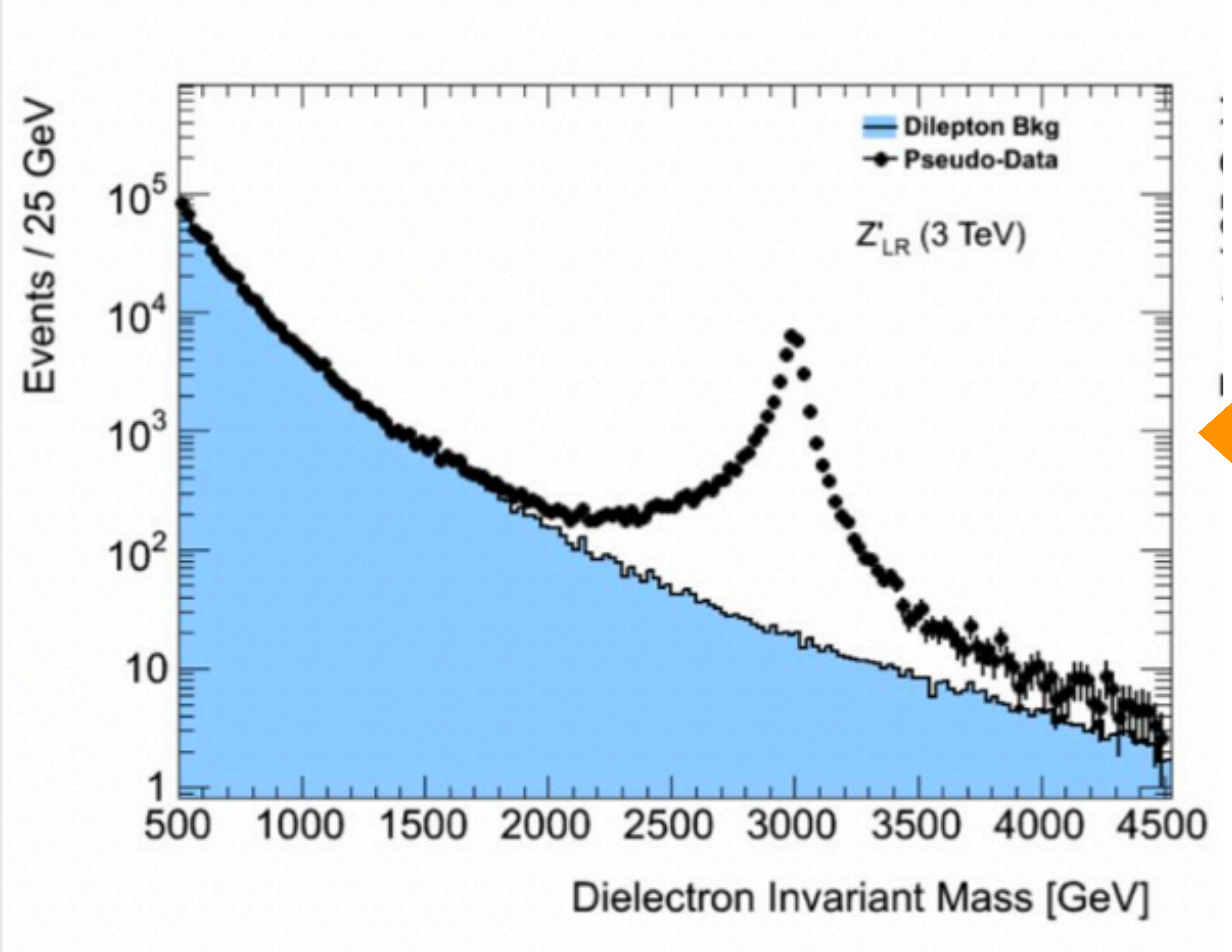


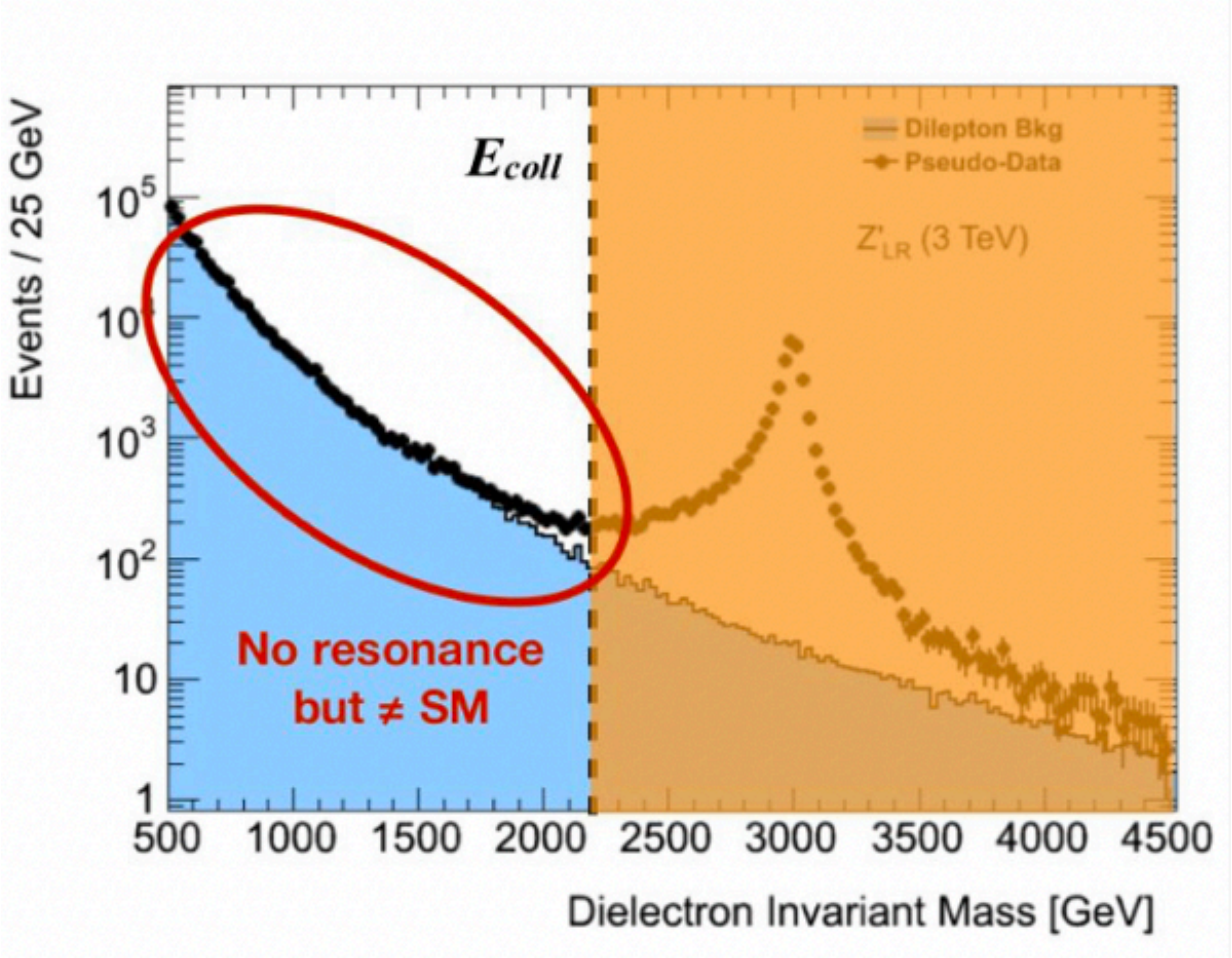
- Out of the many extensions of the SM out there, almost all of them predict either new particles at the TeV scale ('visible' at the LHC) or deformations of SM that we would see in our precision measurements

DIRECT VS INDIRECT

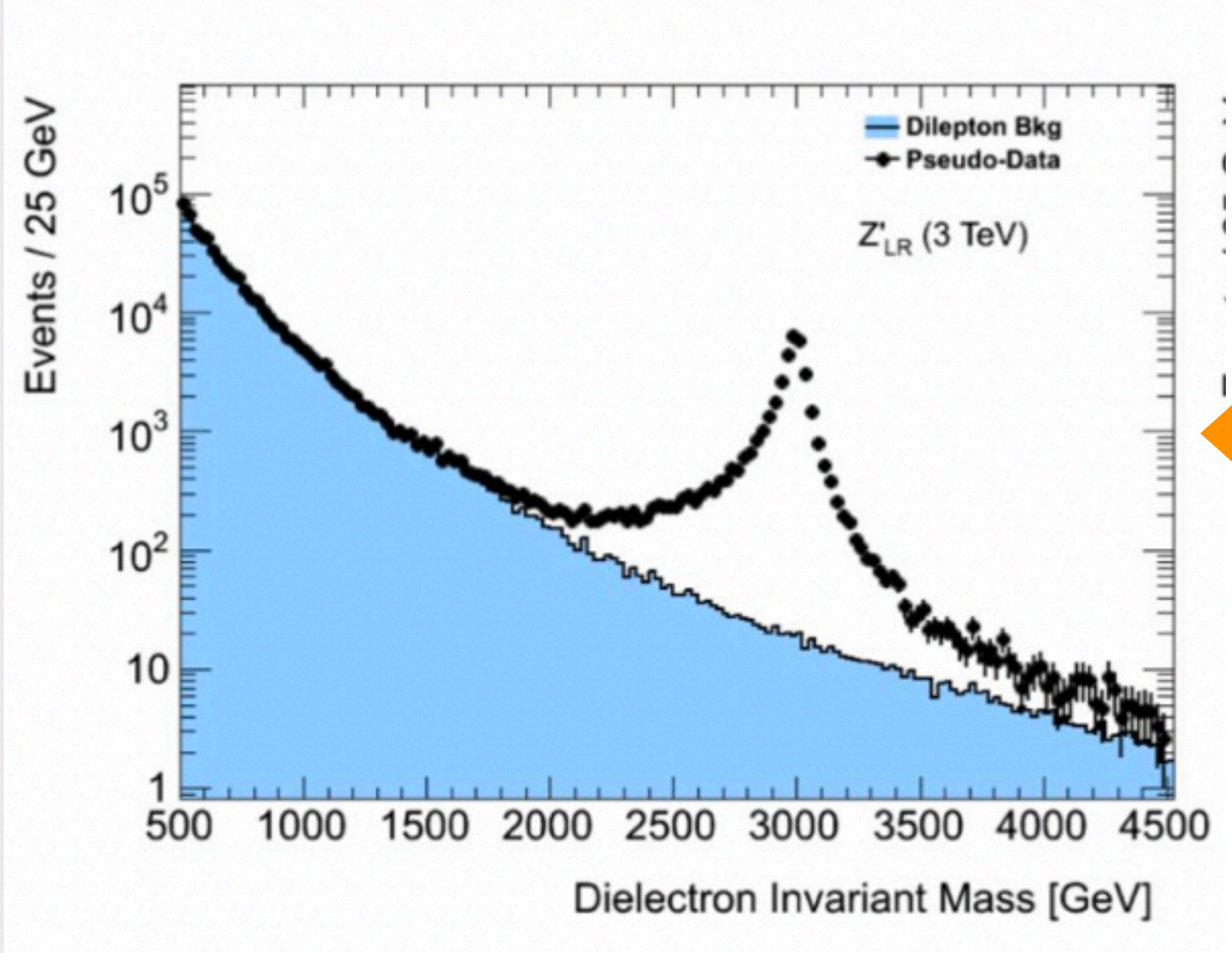


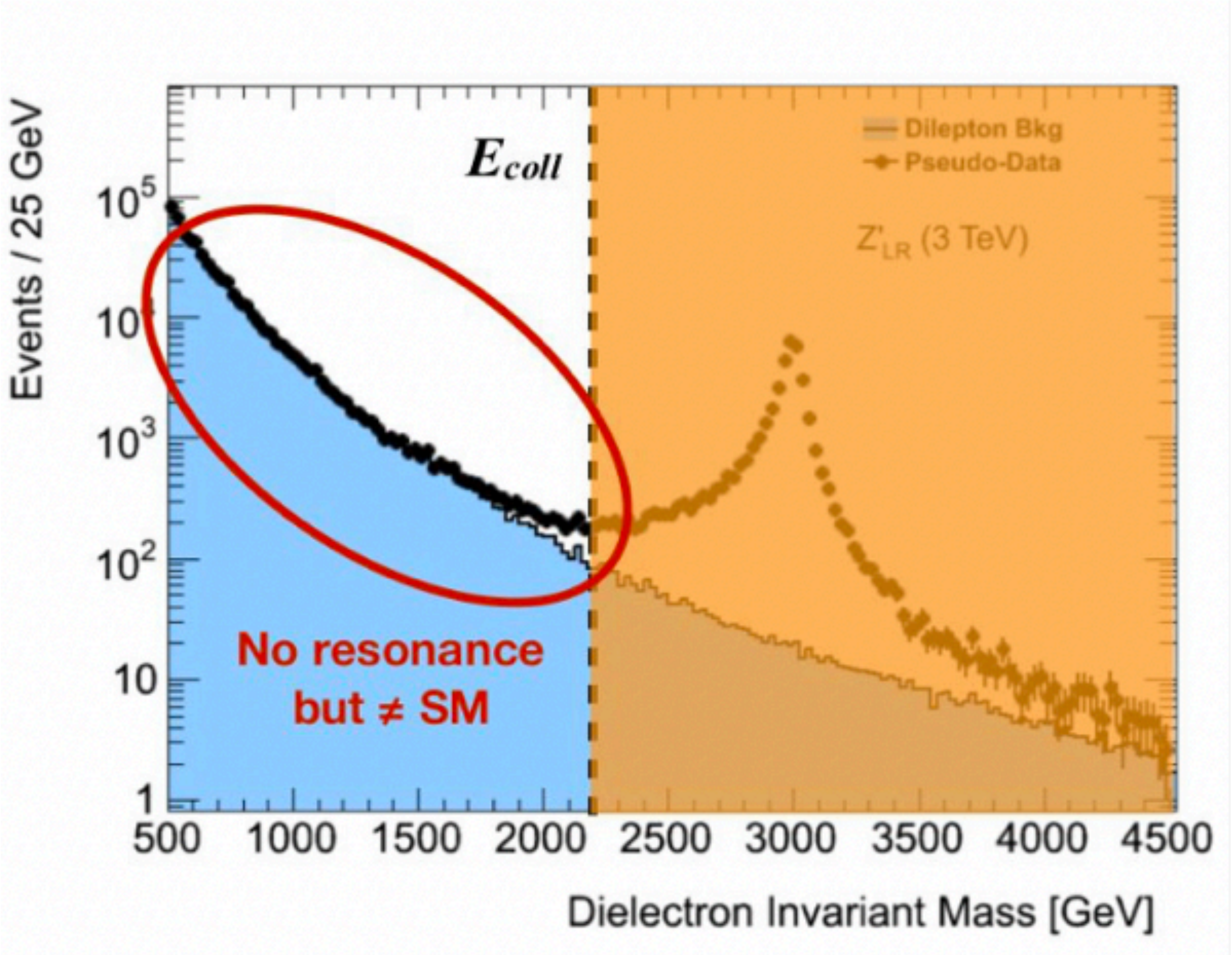
DIRECT VS INDIRECT





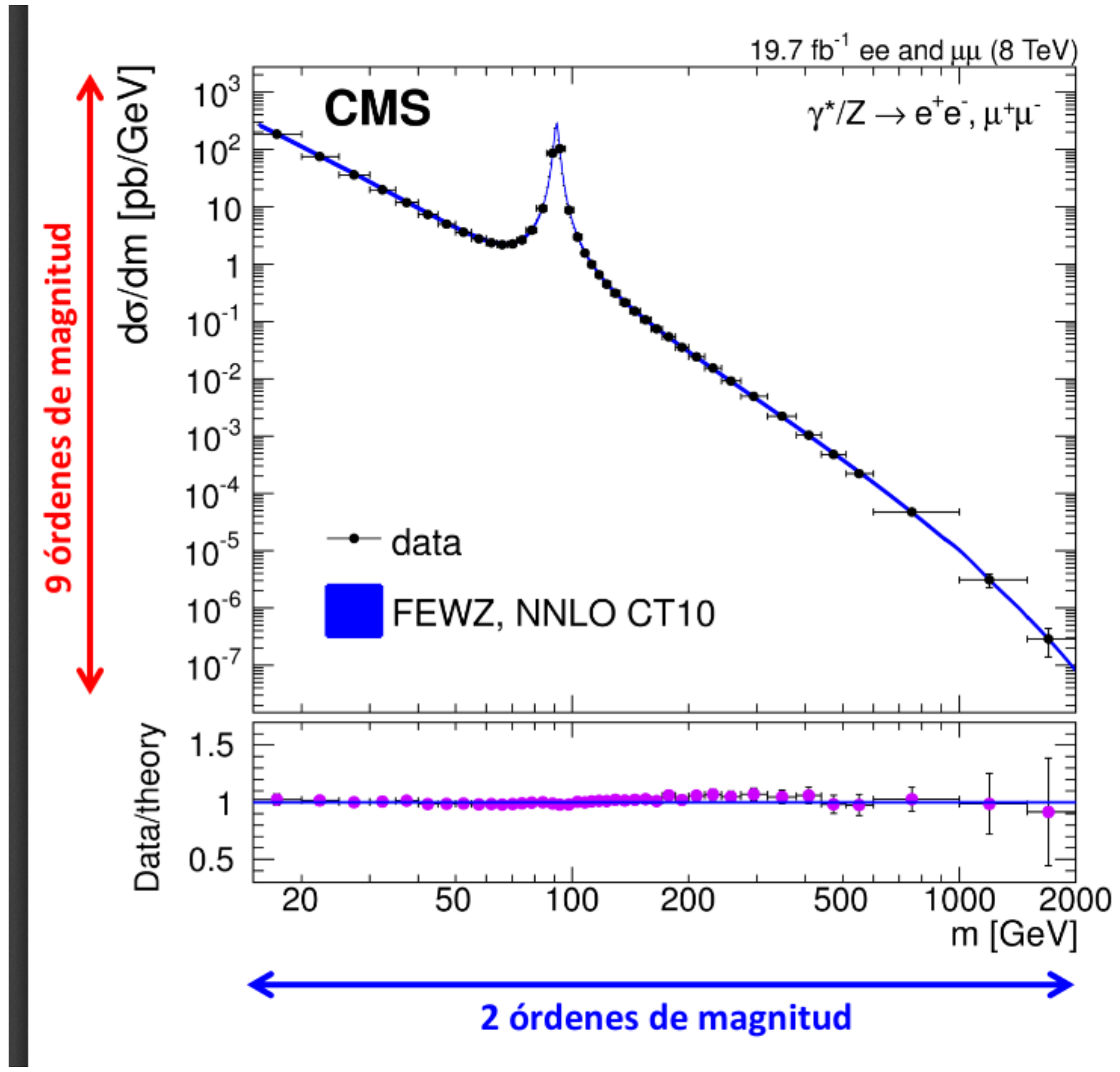
DIRECT VS INDIRECT



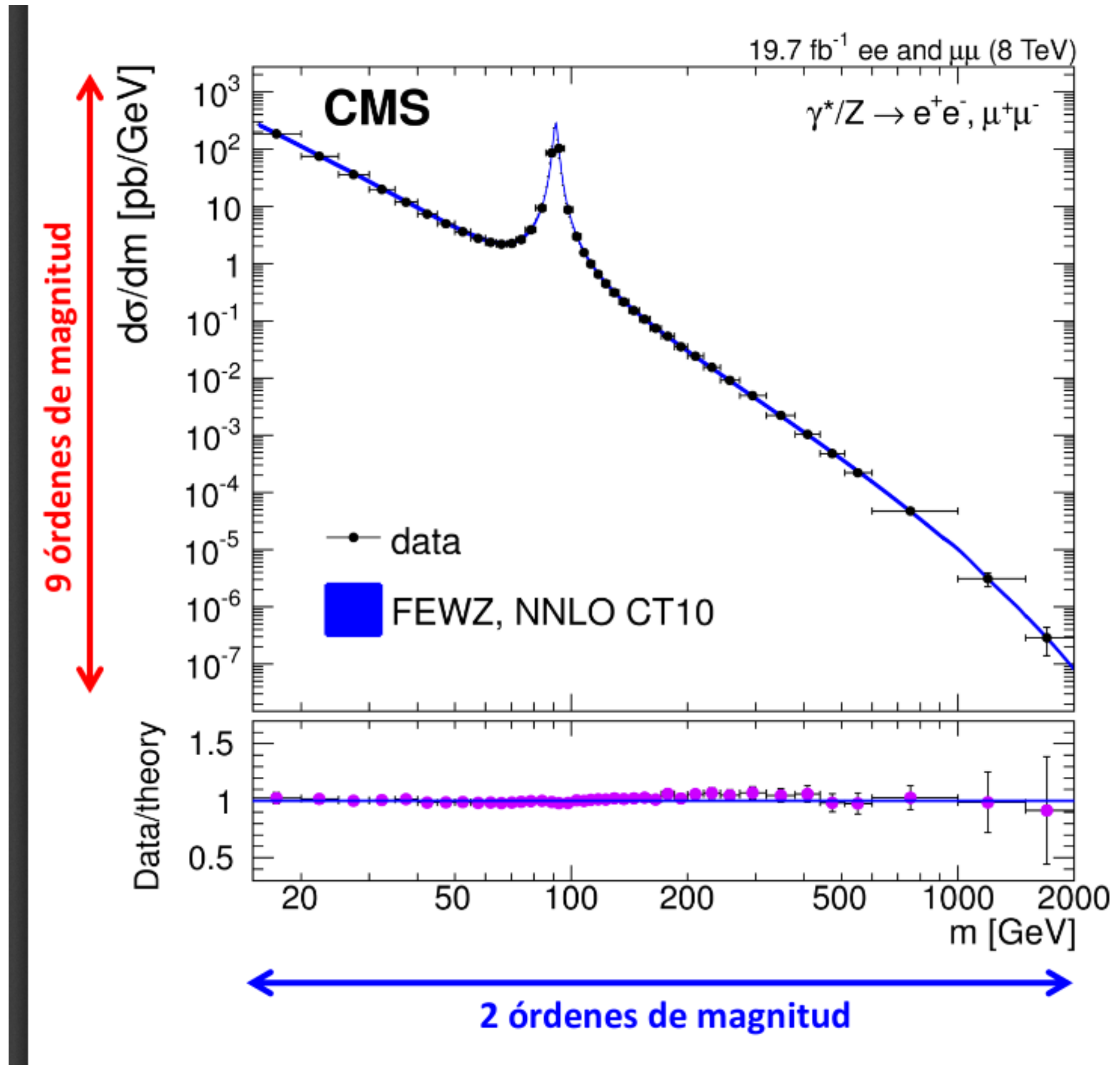


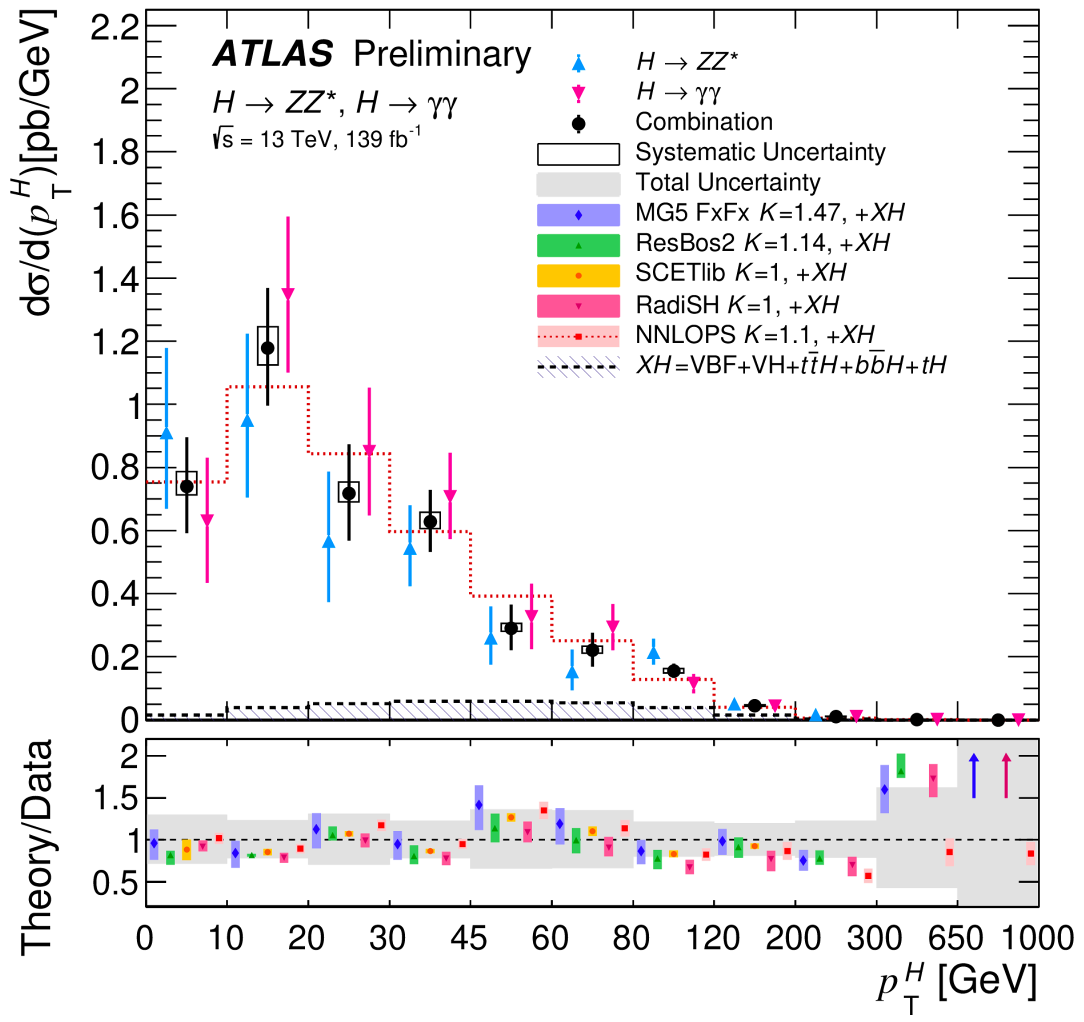
- Direct: look for a peak / resonance
- Indirect: deviation vs prediction on a well understood observable

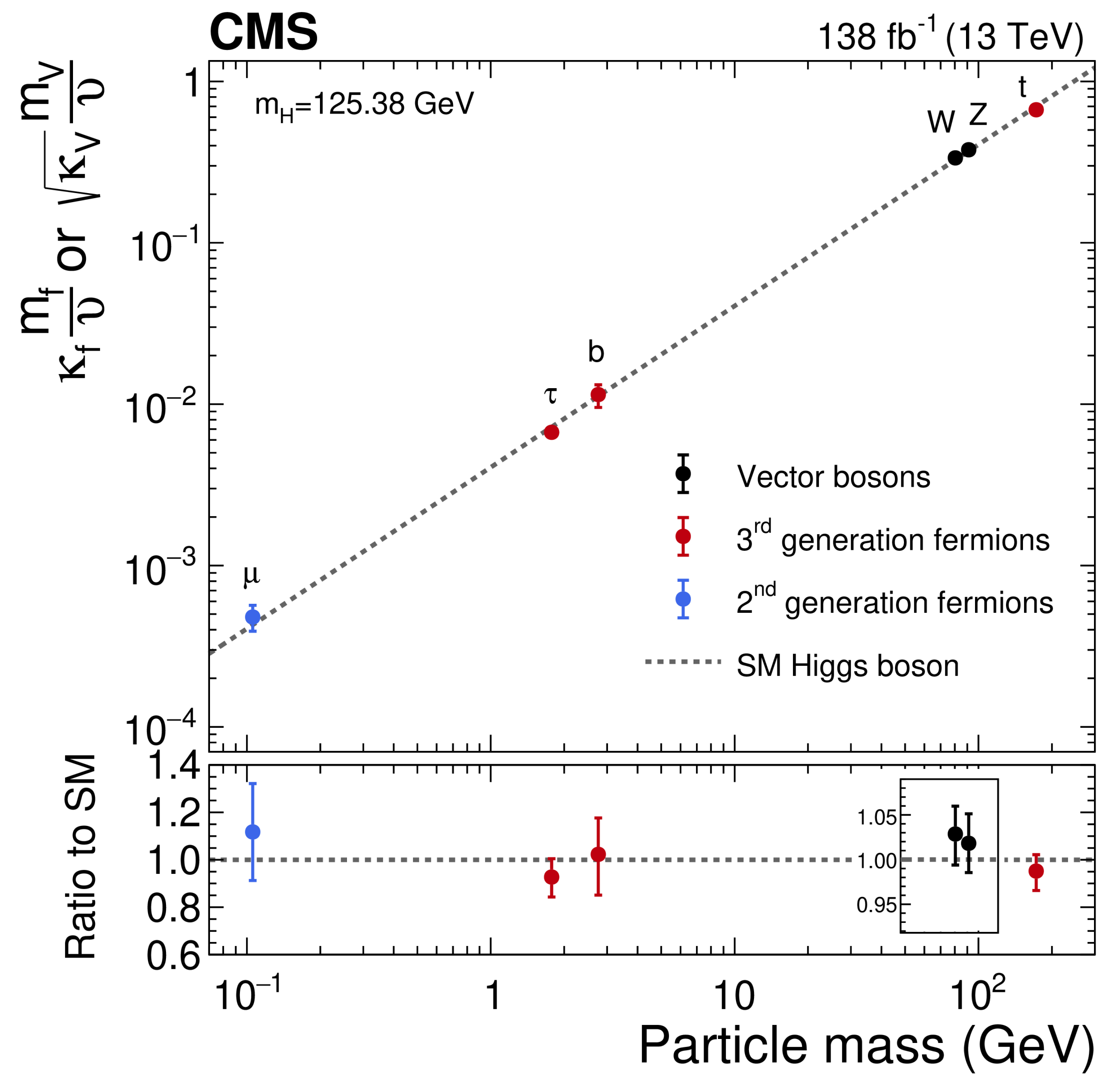
WE HAVE ALREADY DISCUSSED THE INDIRECT…



WE HAVE ALREADY DISCUSSED THE INDIRECT...







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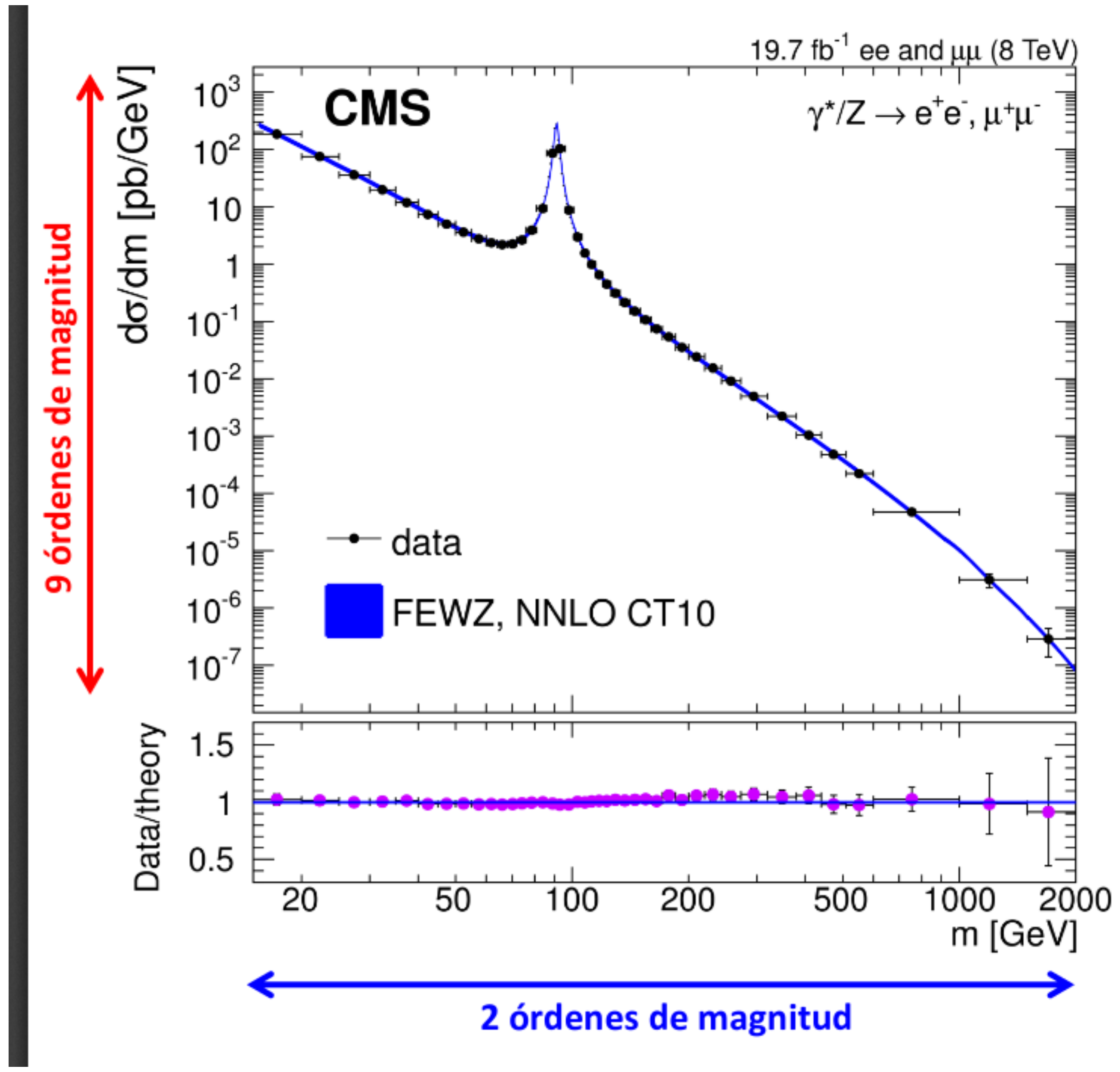

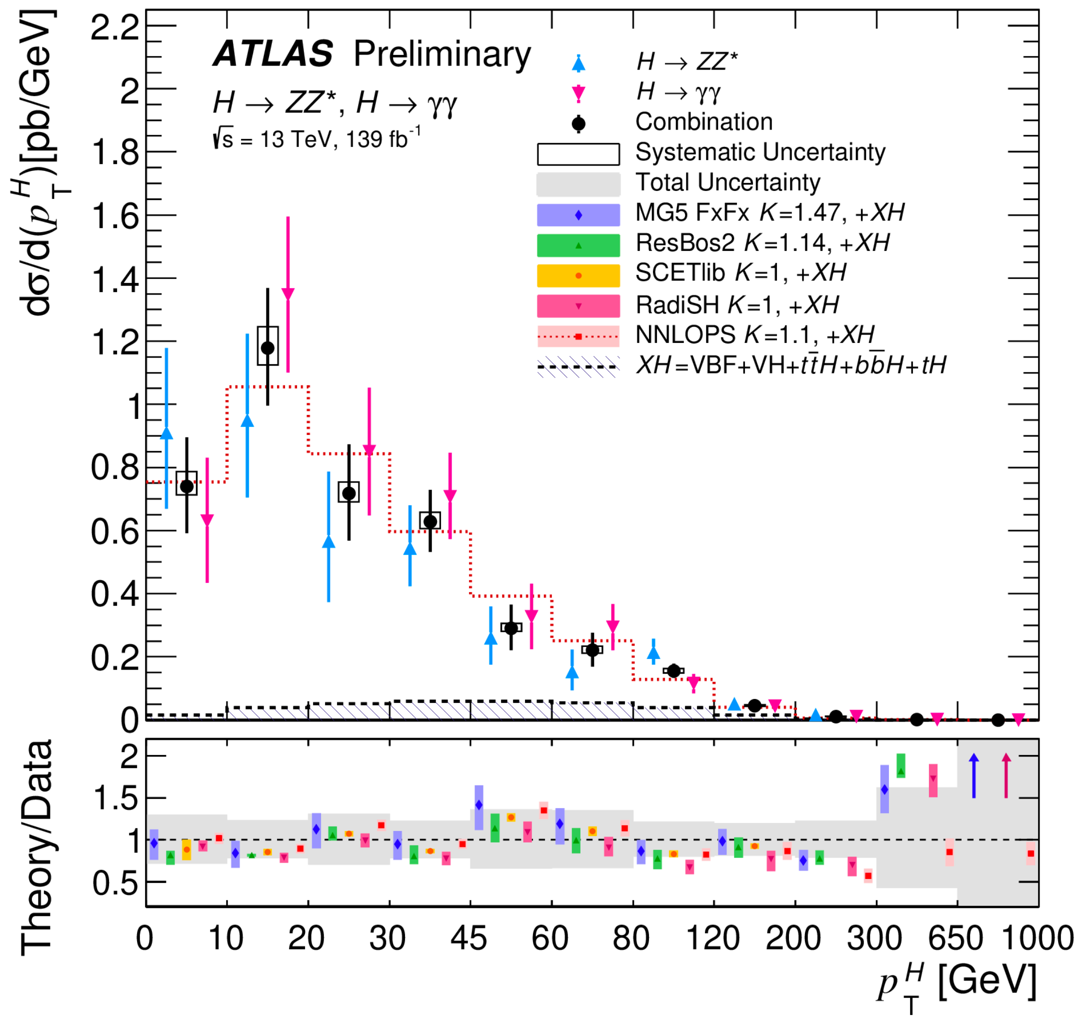

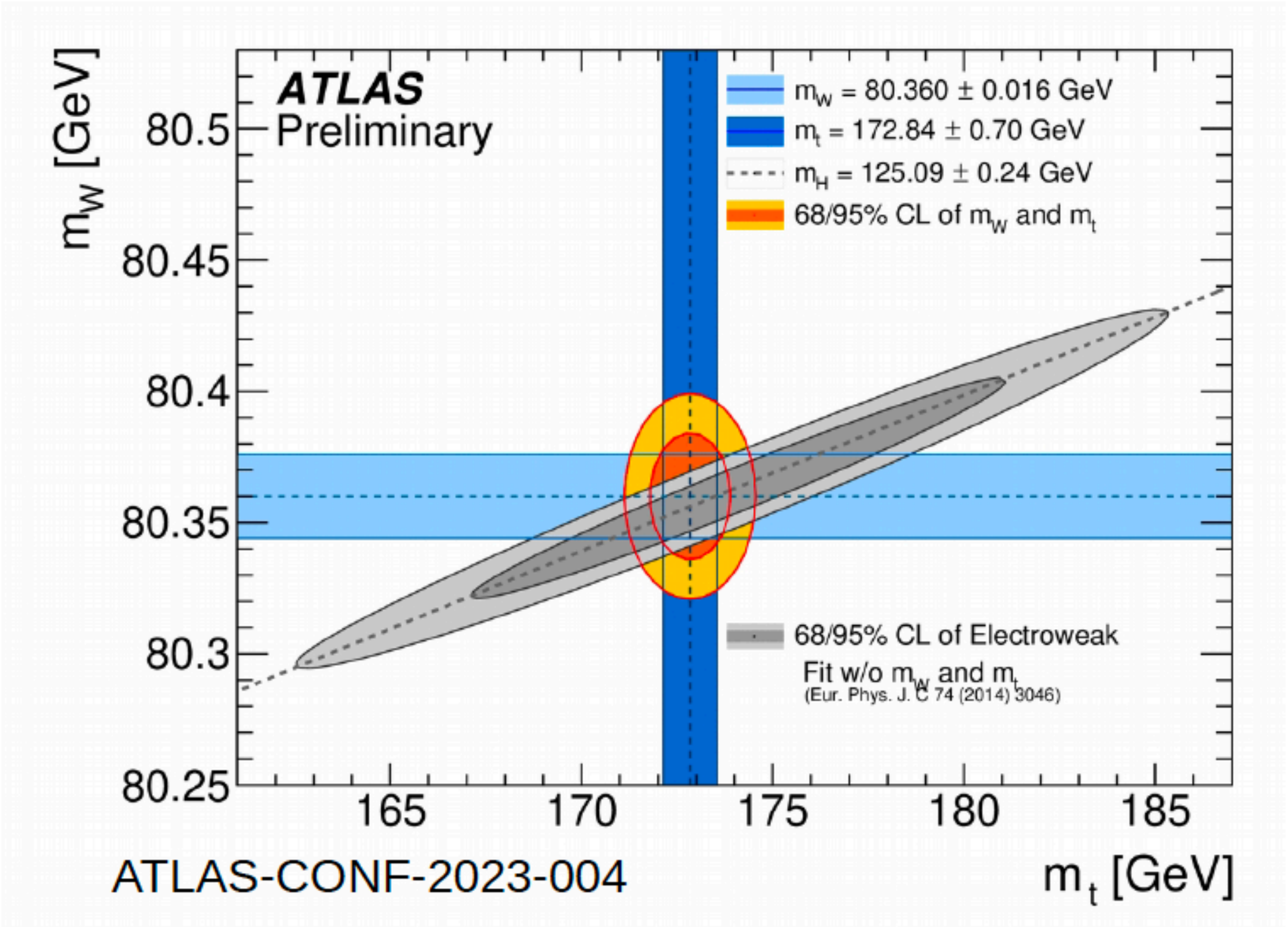

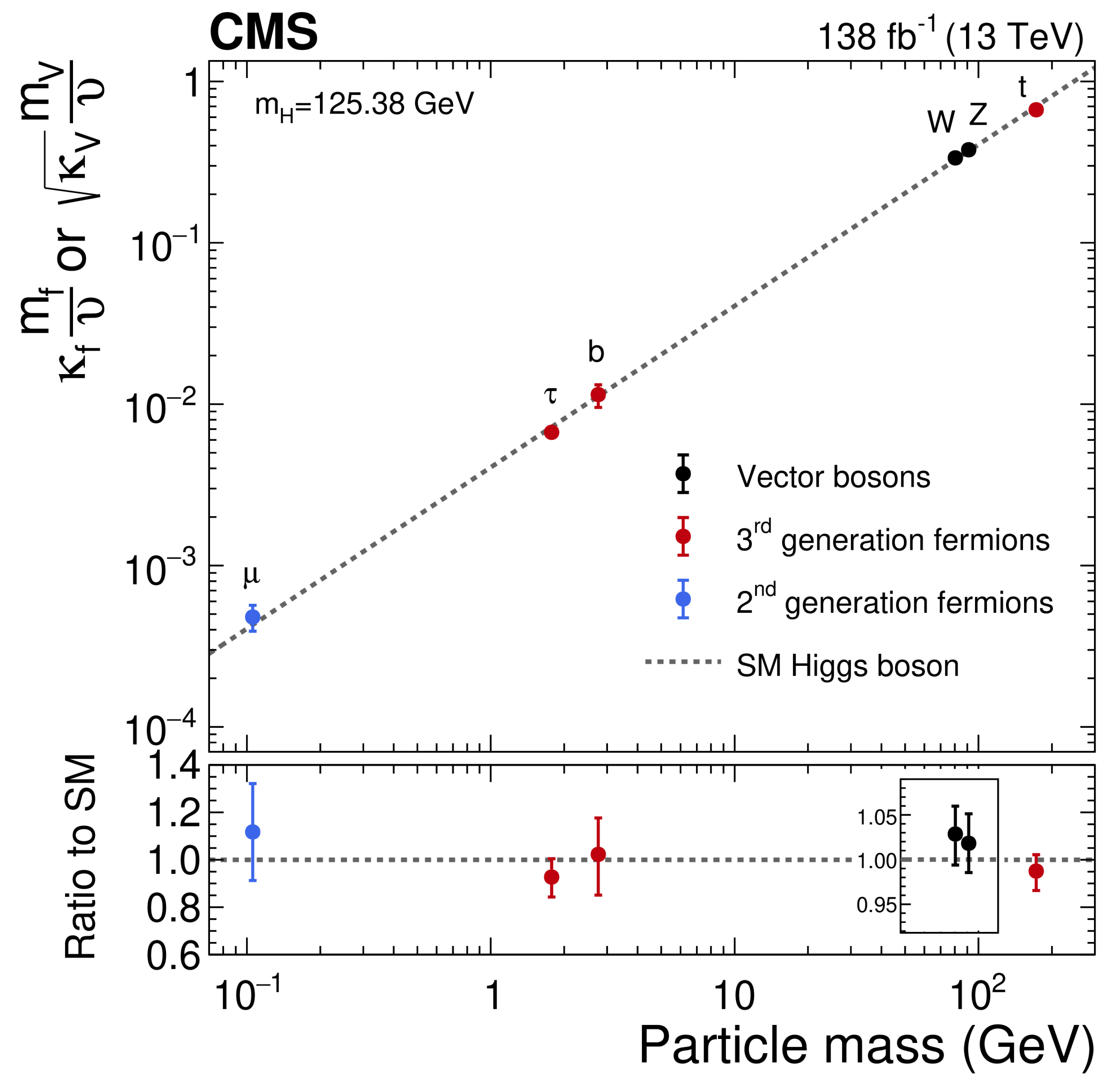

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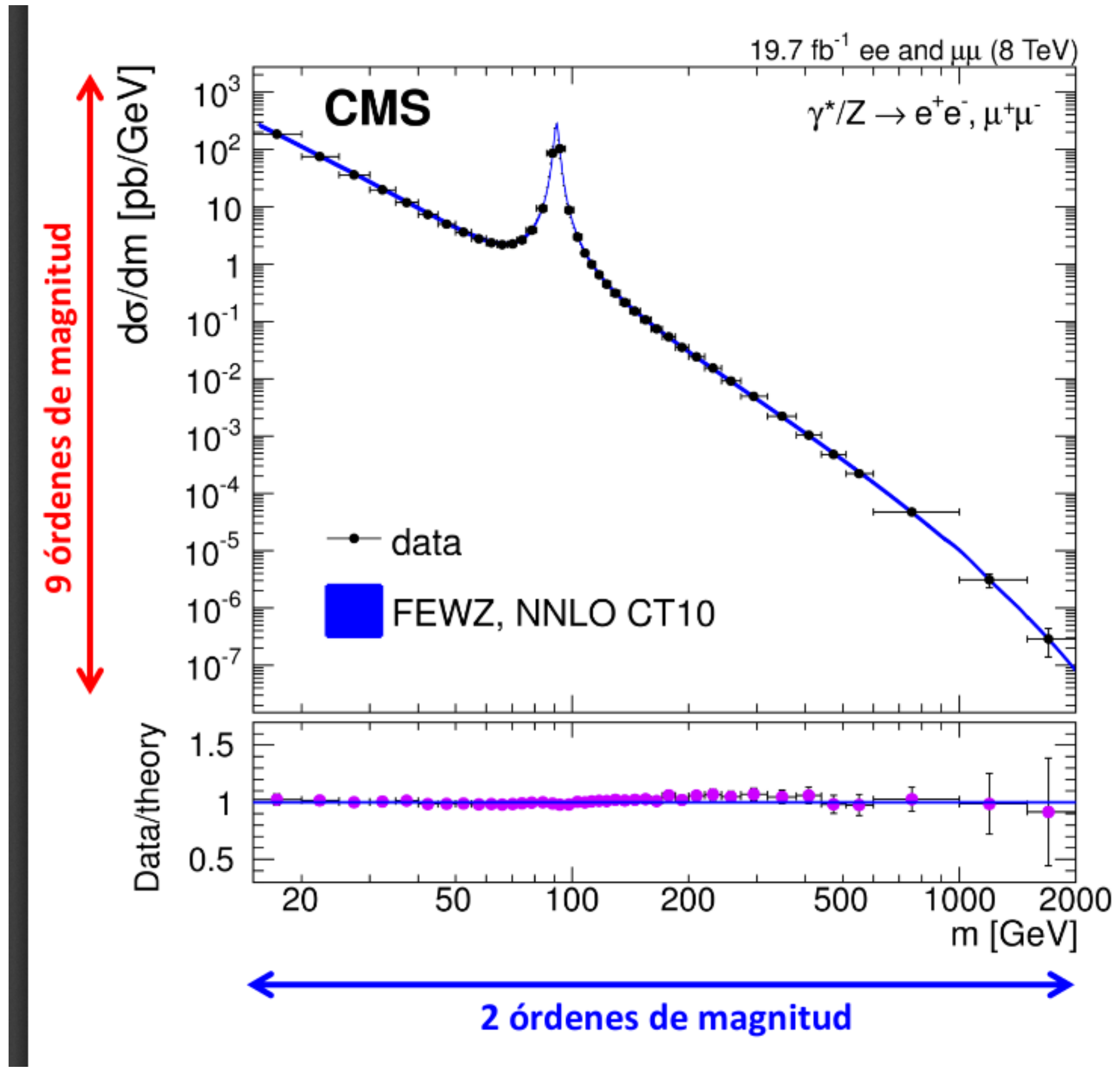
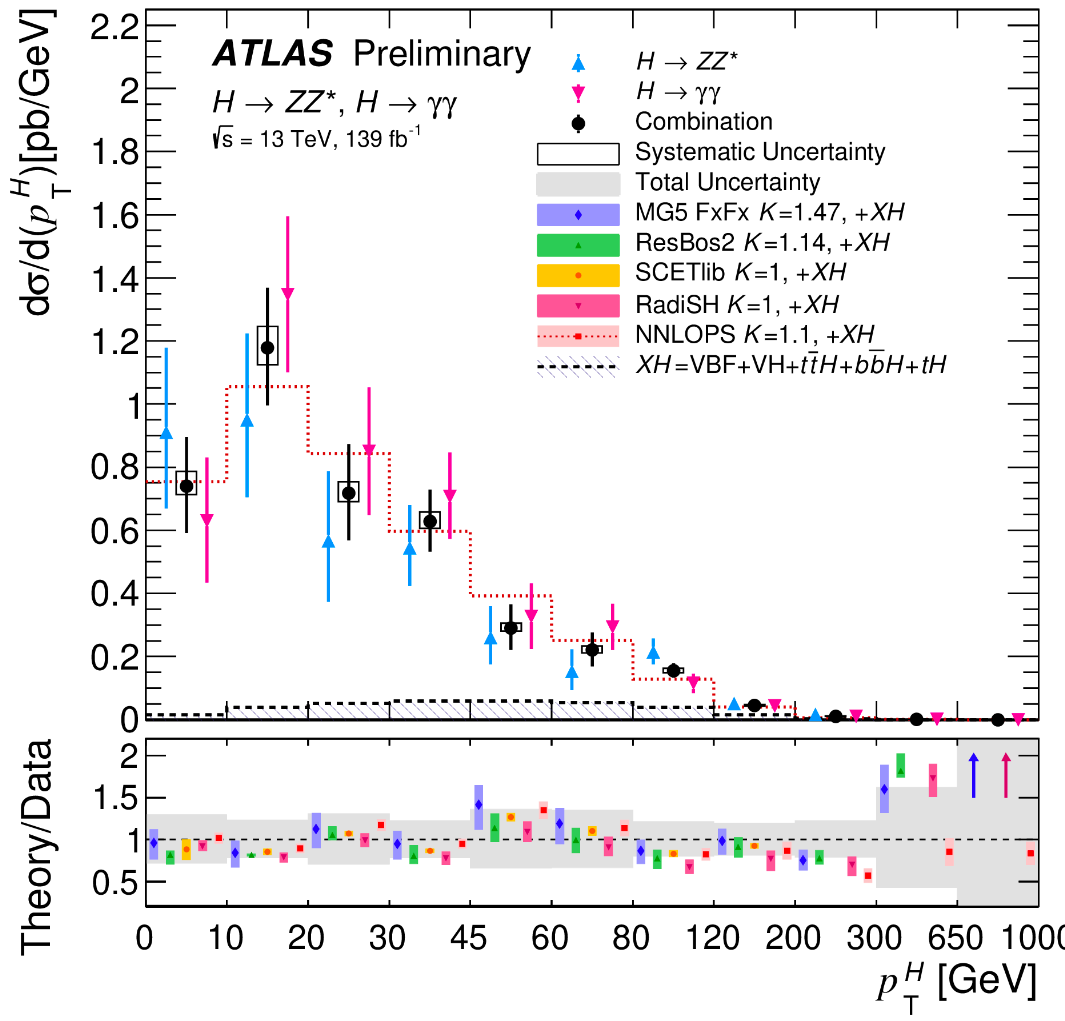
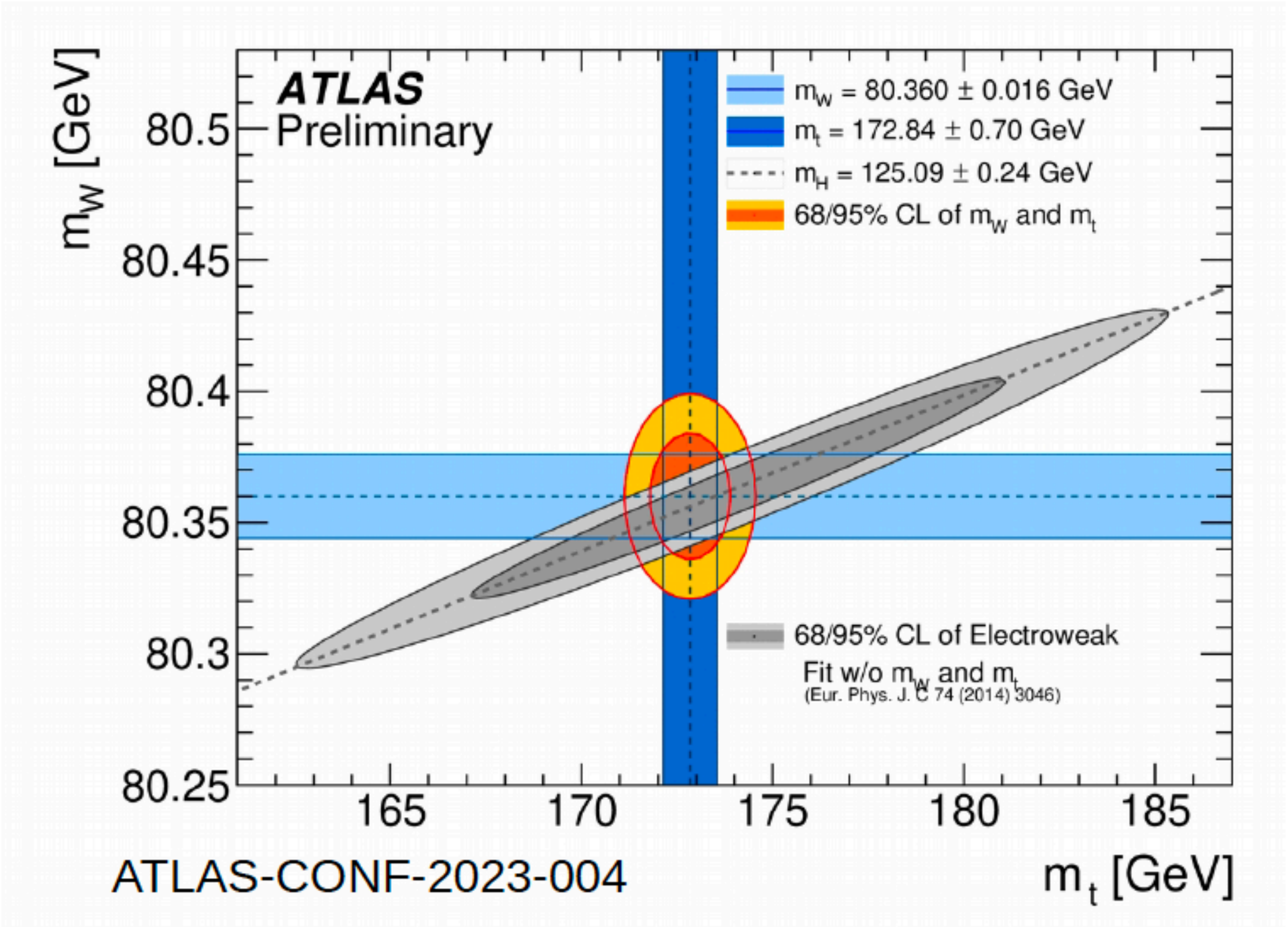
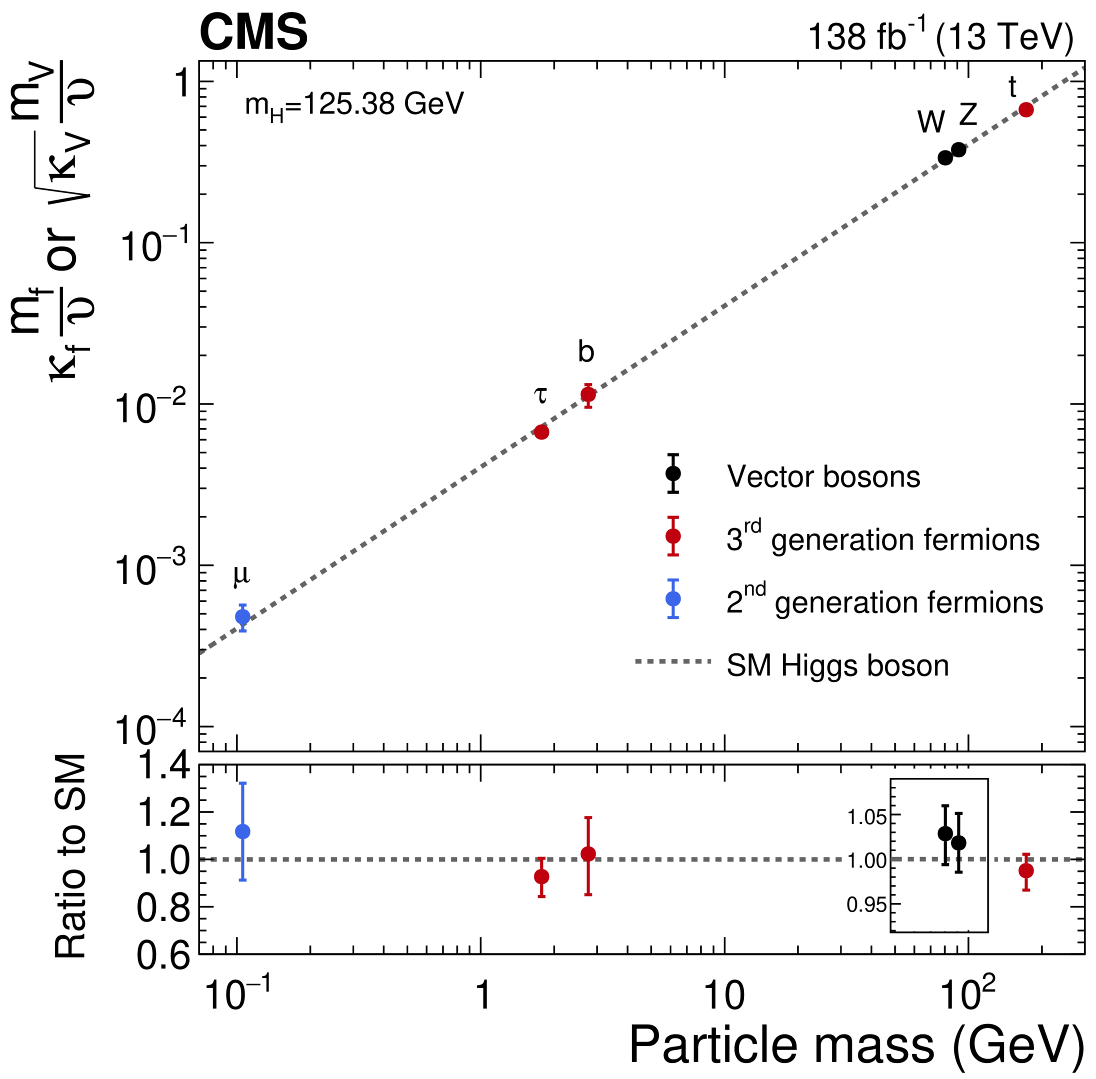
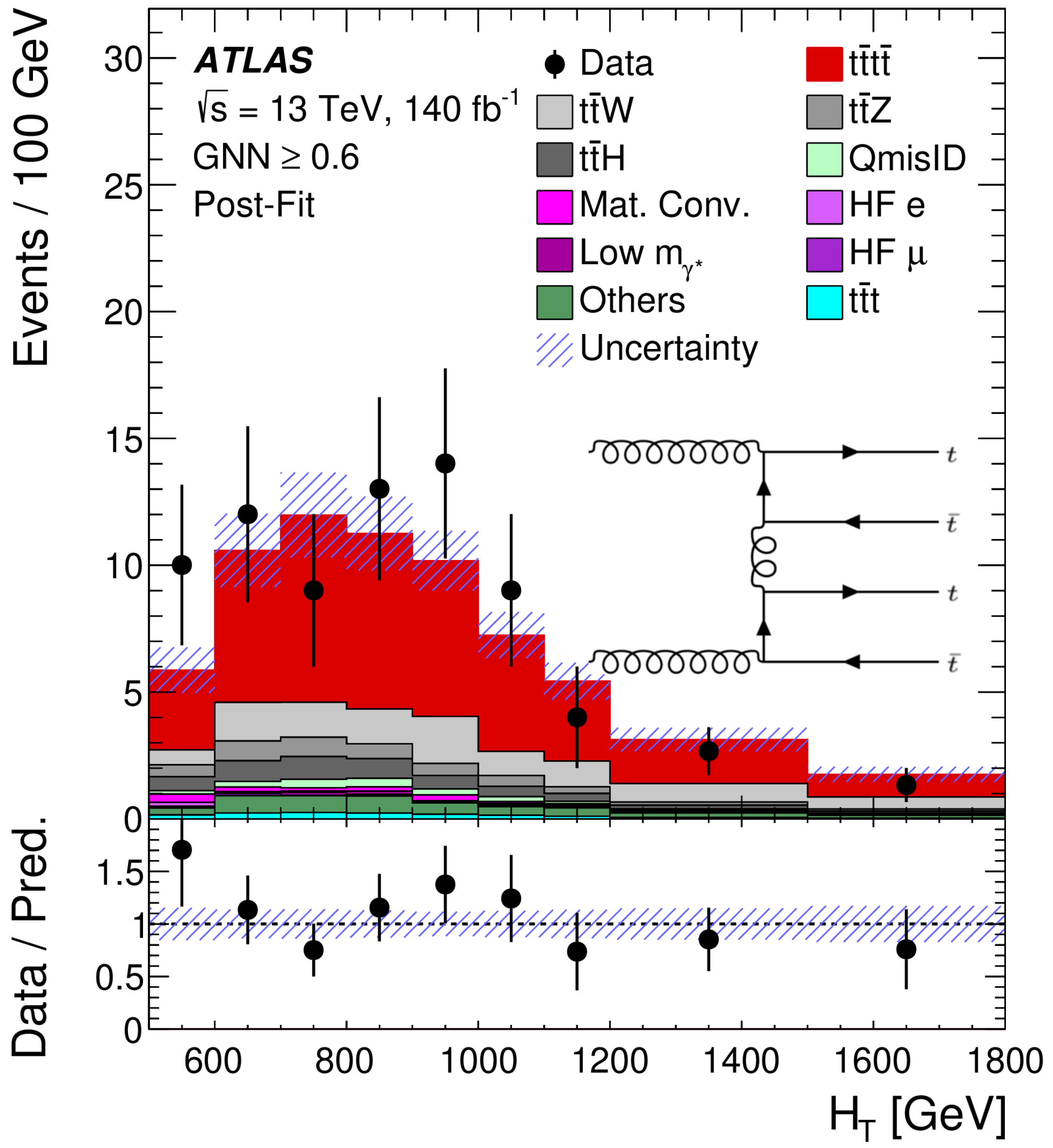


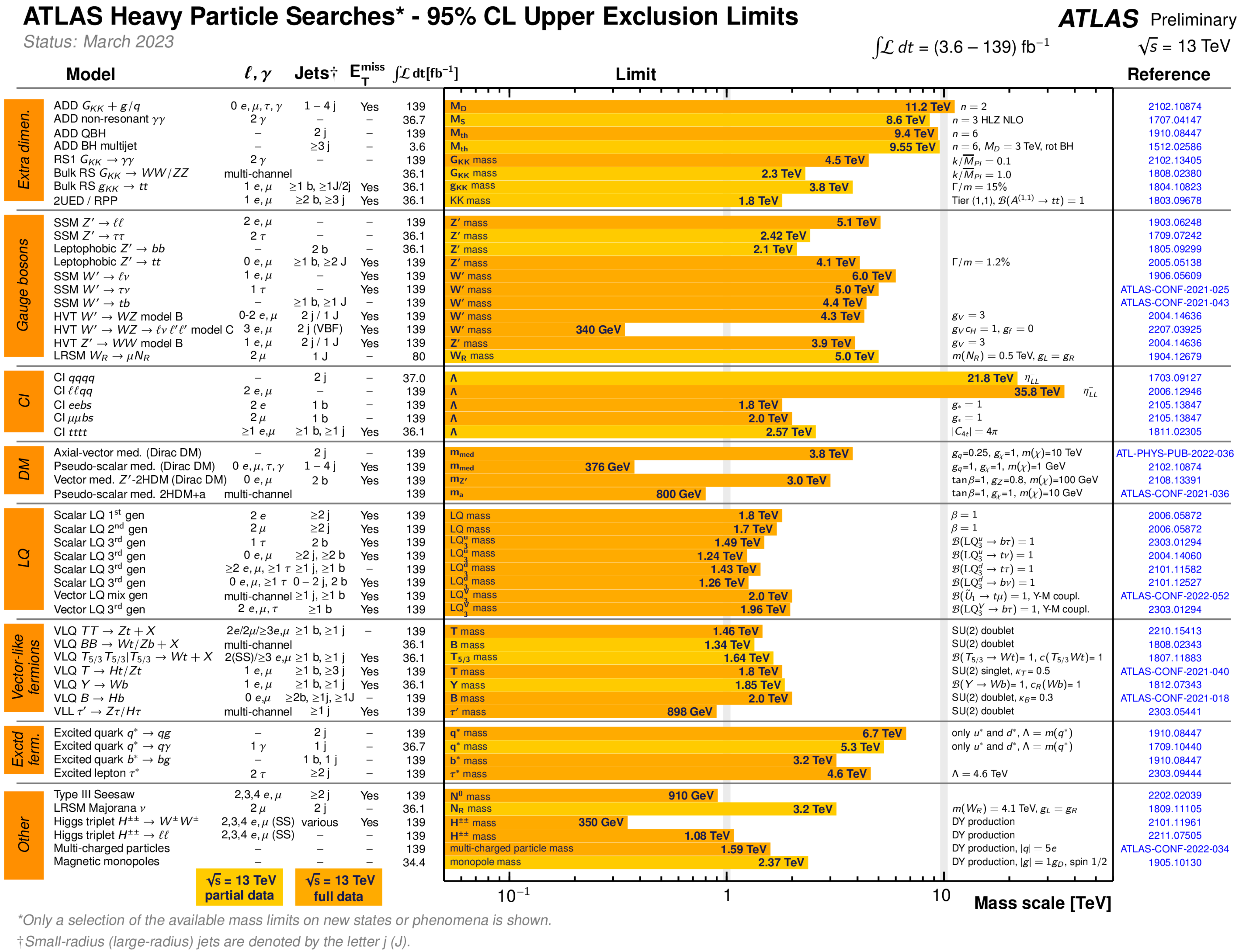








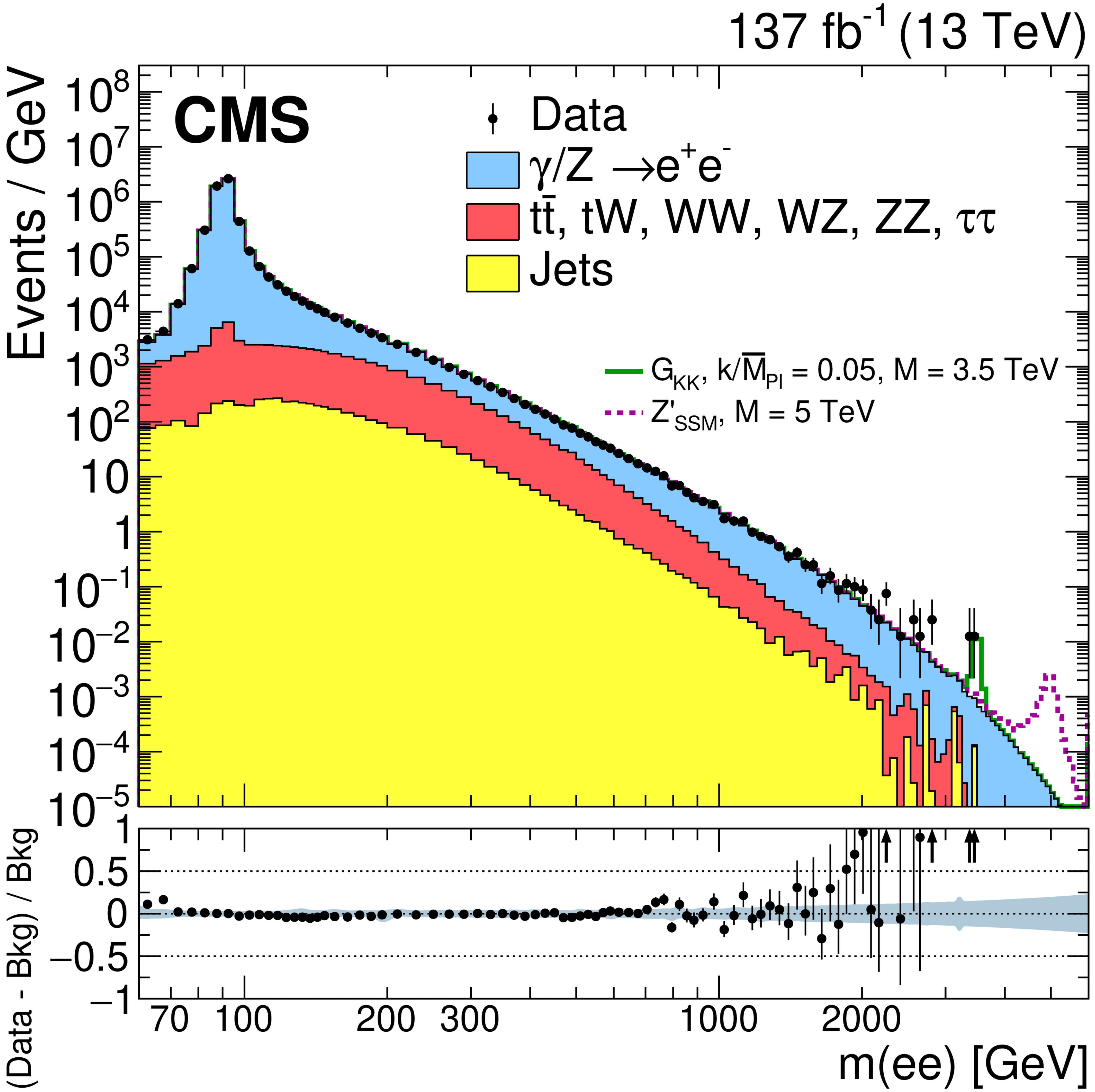
DIRECT BSM SEARCHES: EVERYTHING EVERYWHERE ALL AT ONCE



- SUSY
- Dark Matter
- New Gauge Bosons (W', Z')
- New Interactions
- Extra Dimensions
- Additional Higgses
- Axions
- Compositeness
- GUT
- Leptoquarks
- Excited Fermions
- Magnetic Monopoles
- Quantum Black Holes
- ....

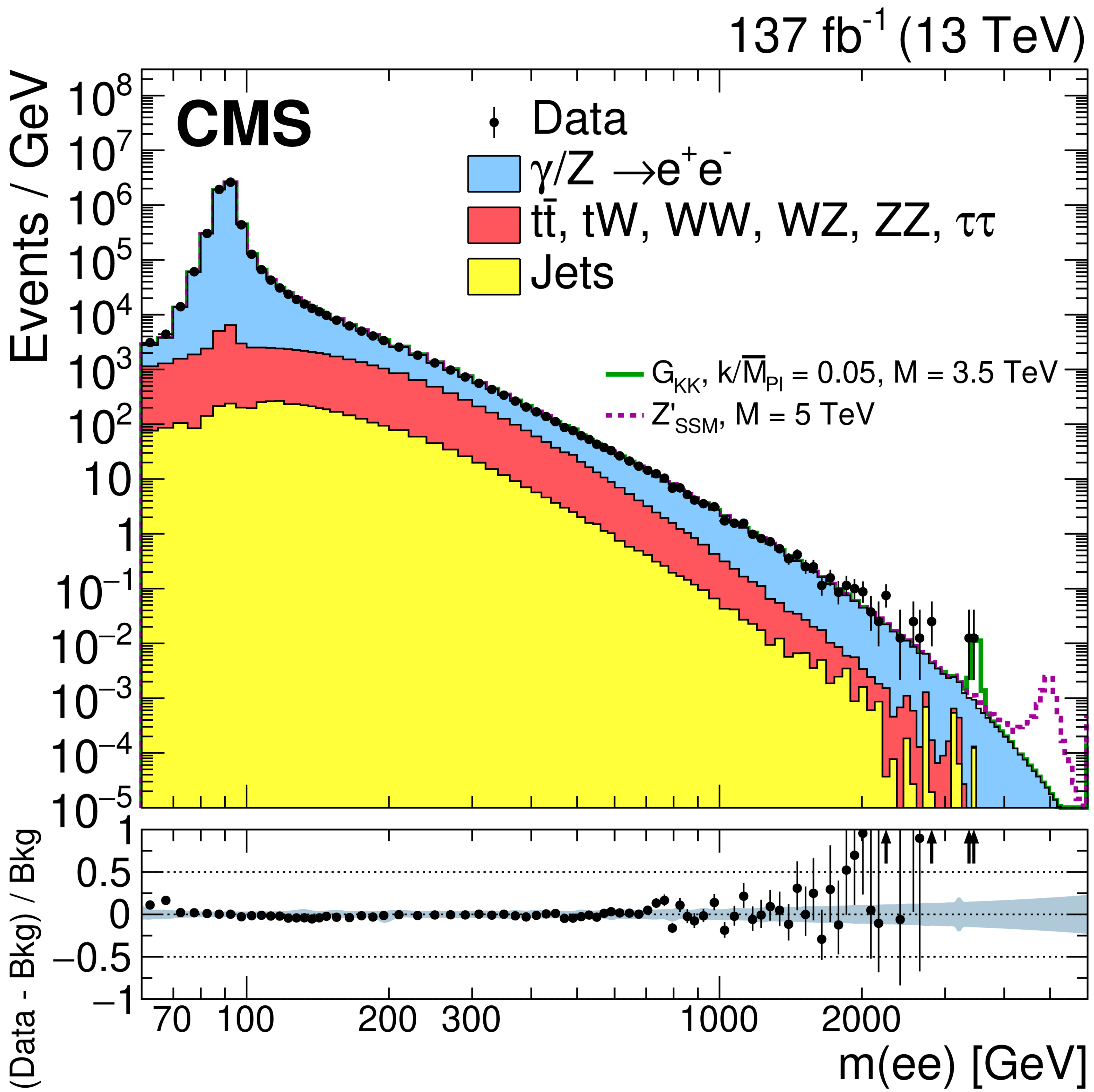
Not possible to cover all of them!

NEW RESONANCES?

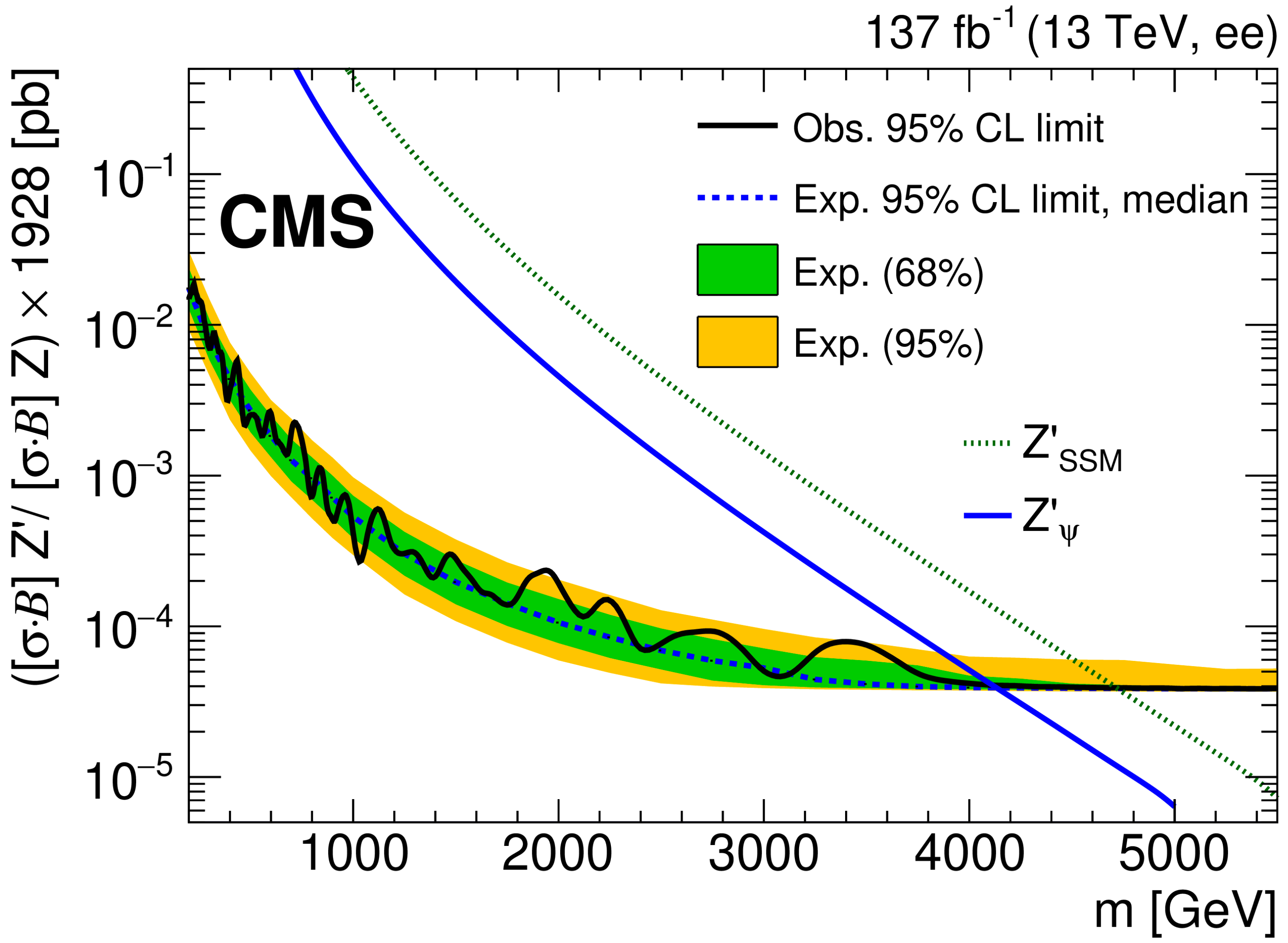


ej: X→e+e- ?

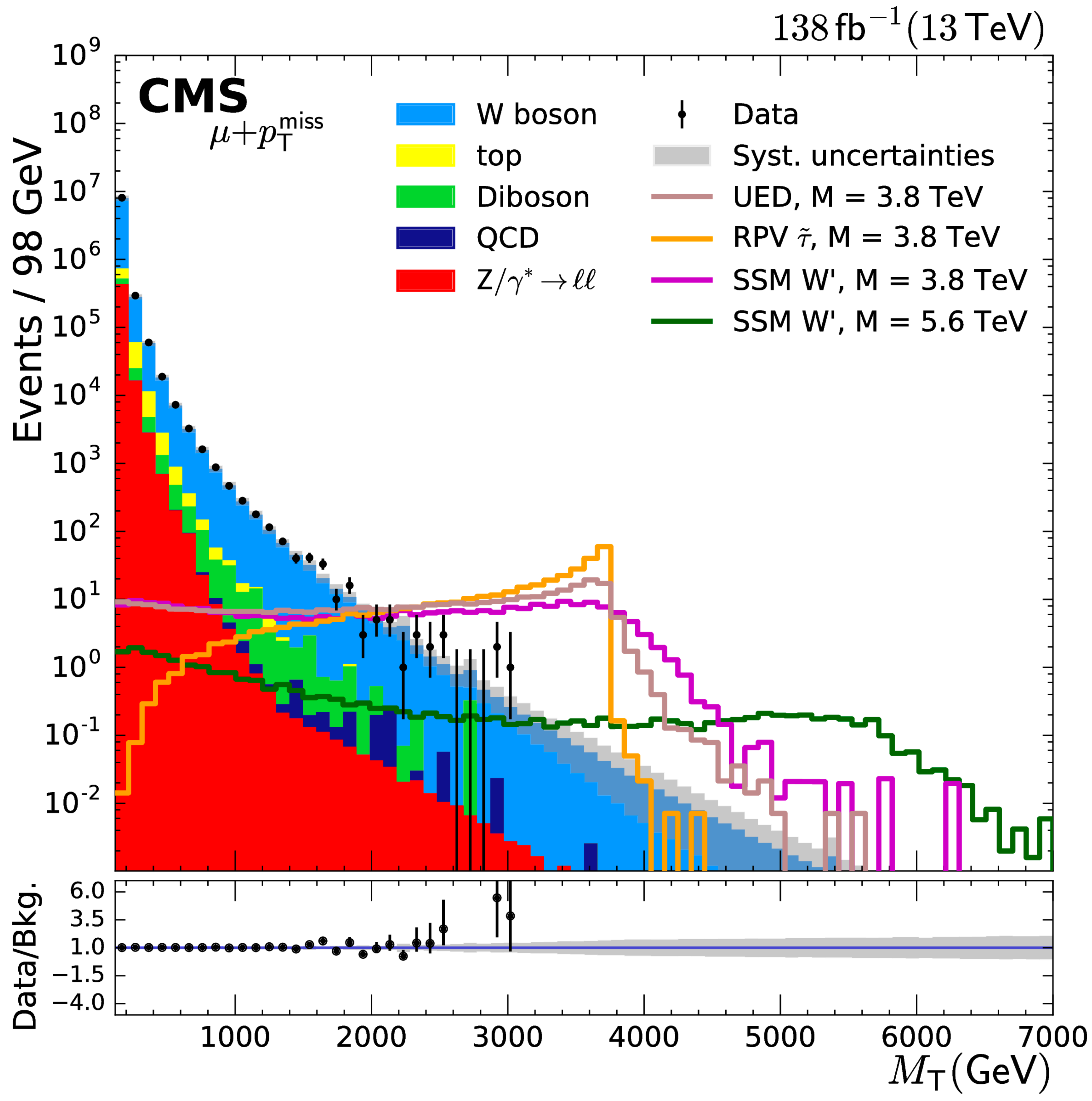
NEW RESONANCES?



ej: X→e+e- ?



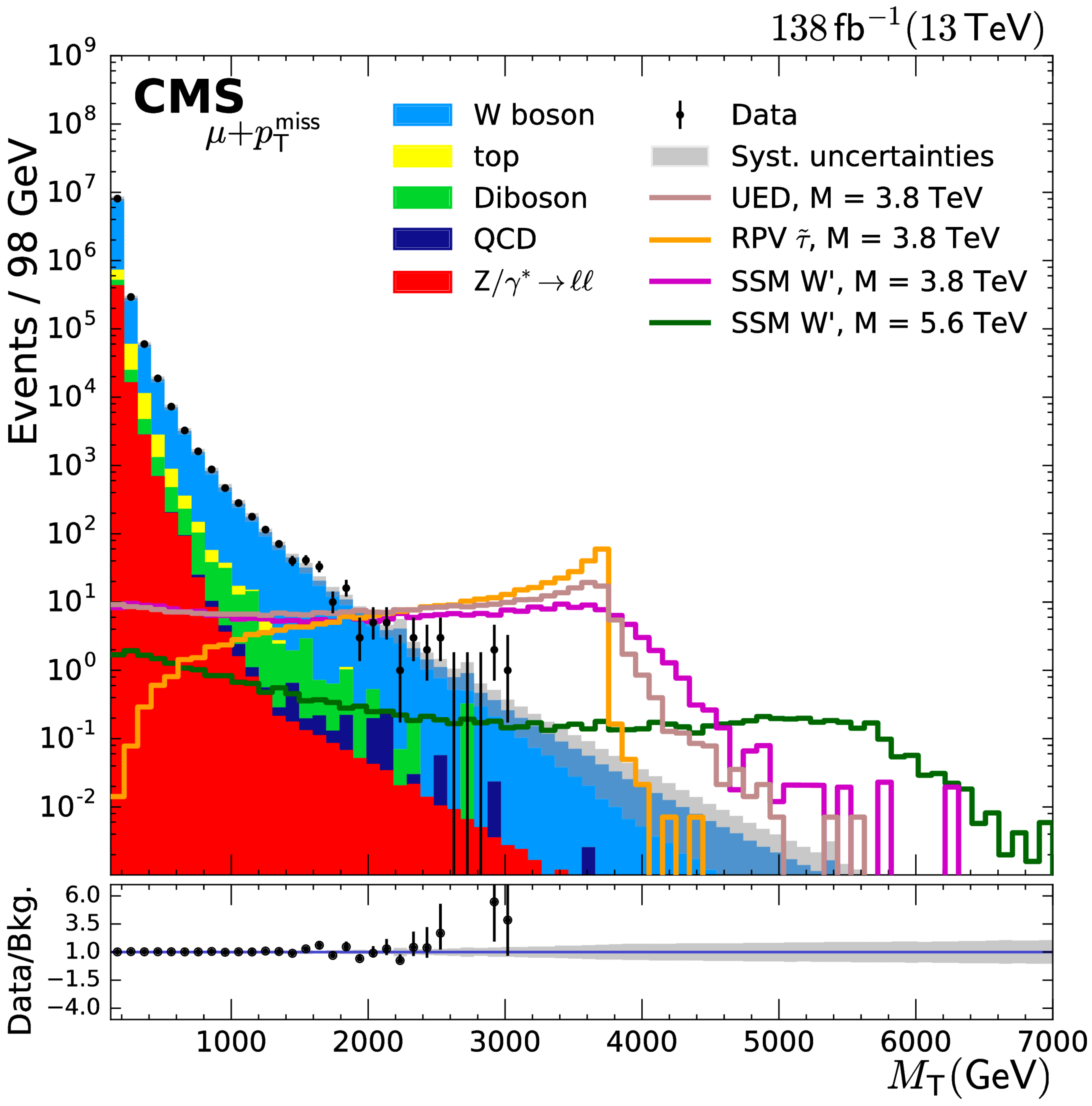
(Also di-jets, difotons, dimuons, ditaus… di-bosons… :))



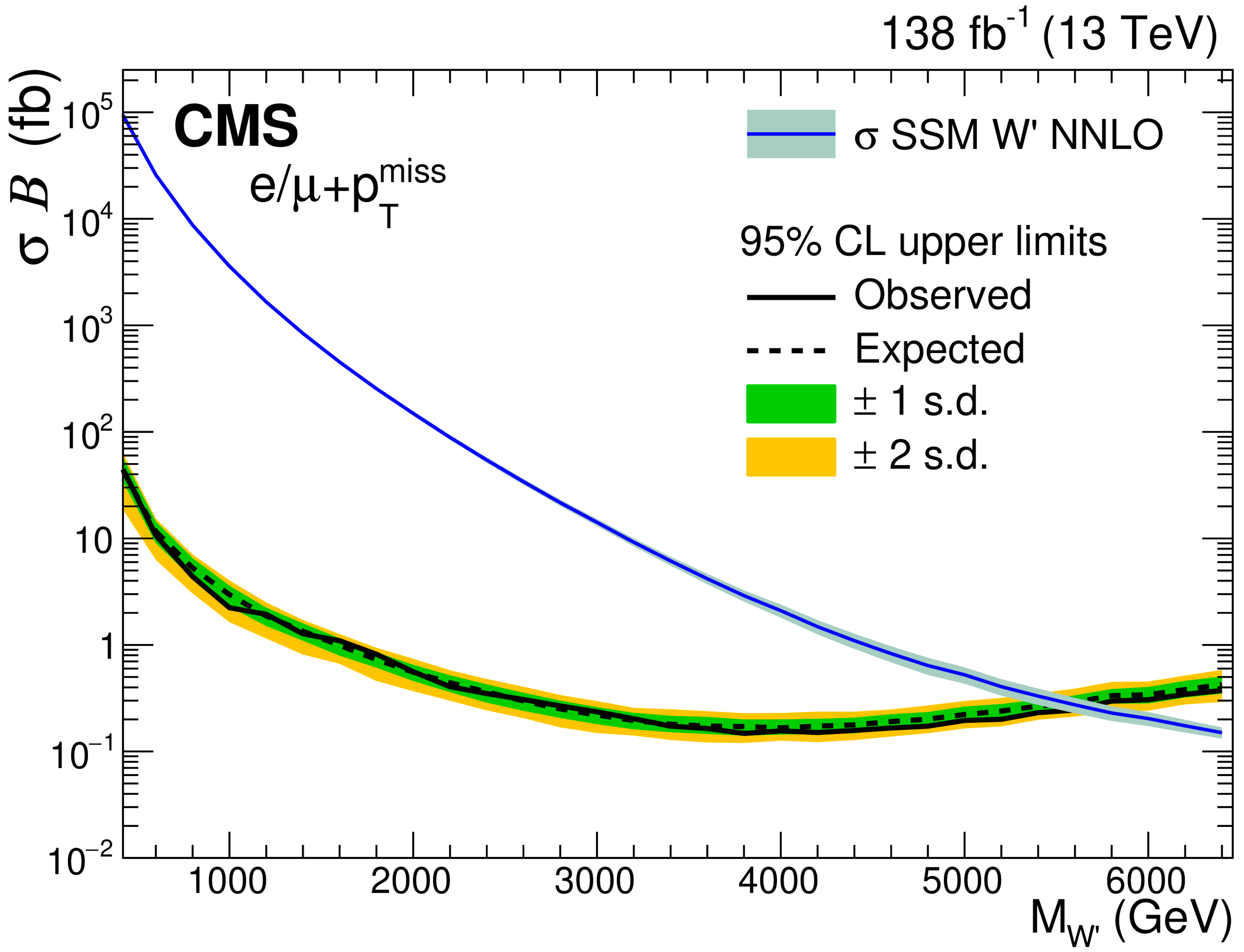
NEUTRINOS?

ej: $X \rightarrow \mu\nu$?

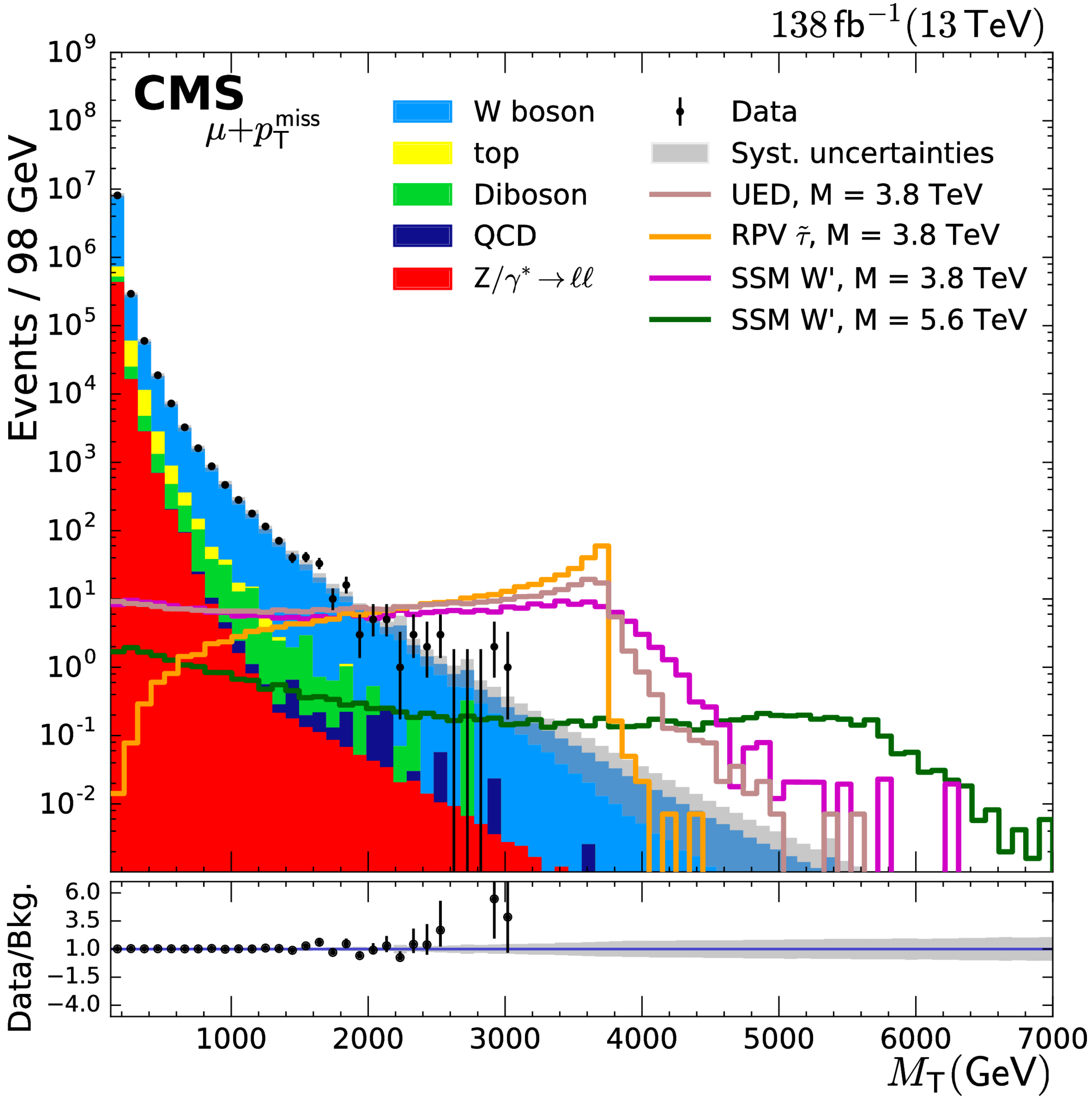
NEUTRINOS?



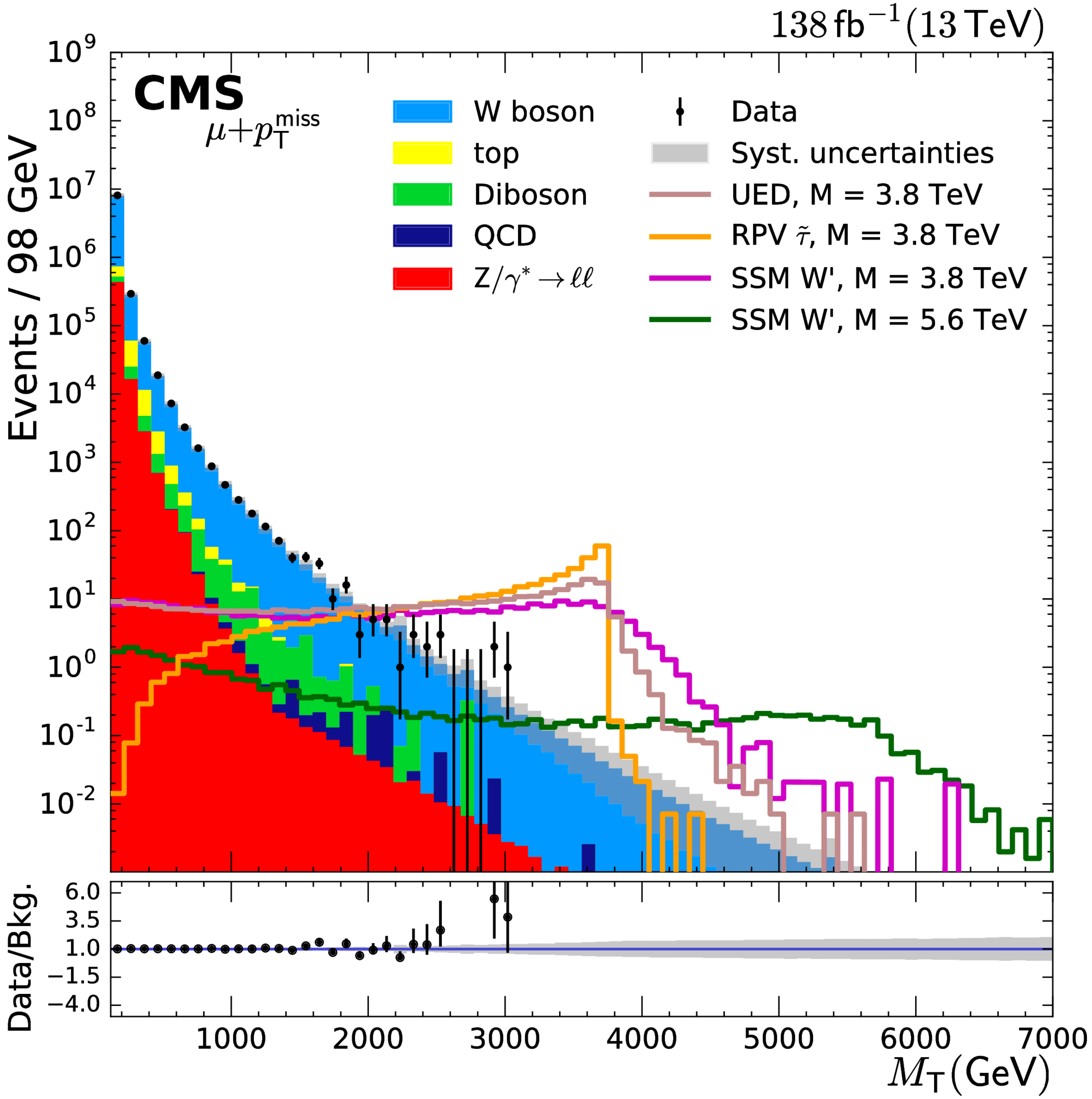
ej: $X \to \mu\nu$?

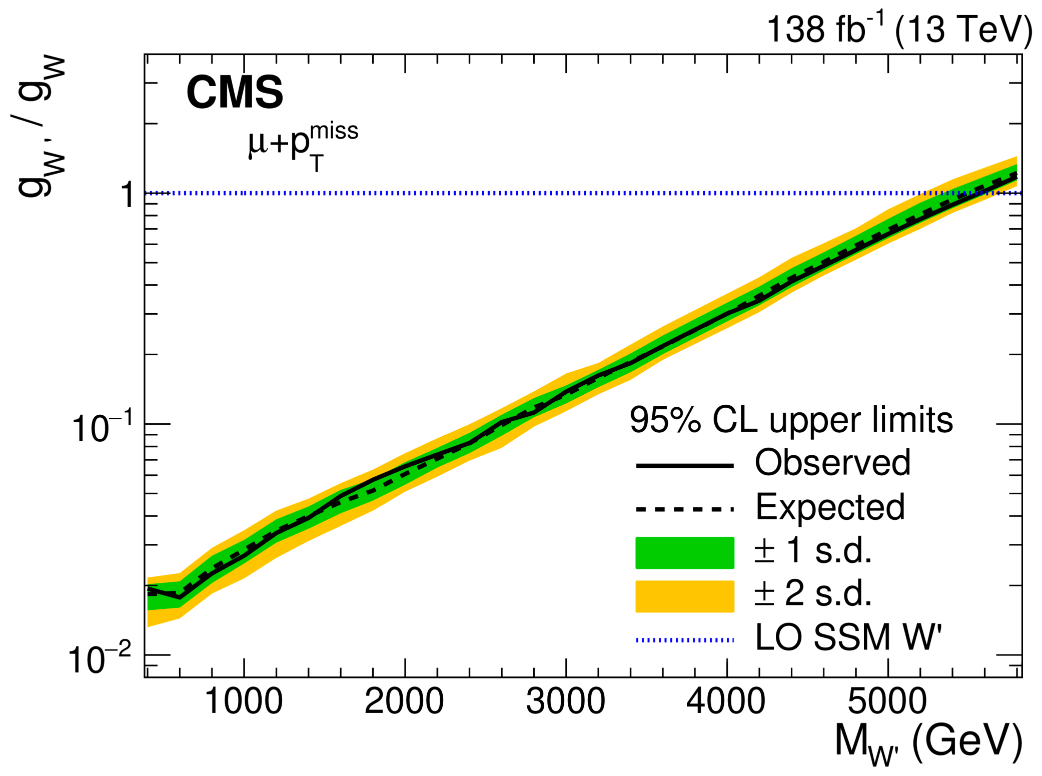


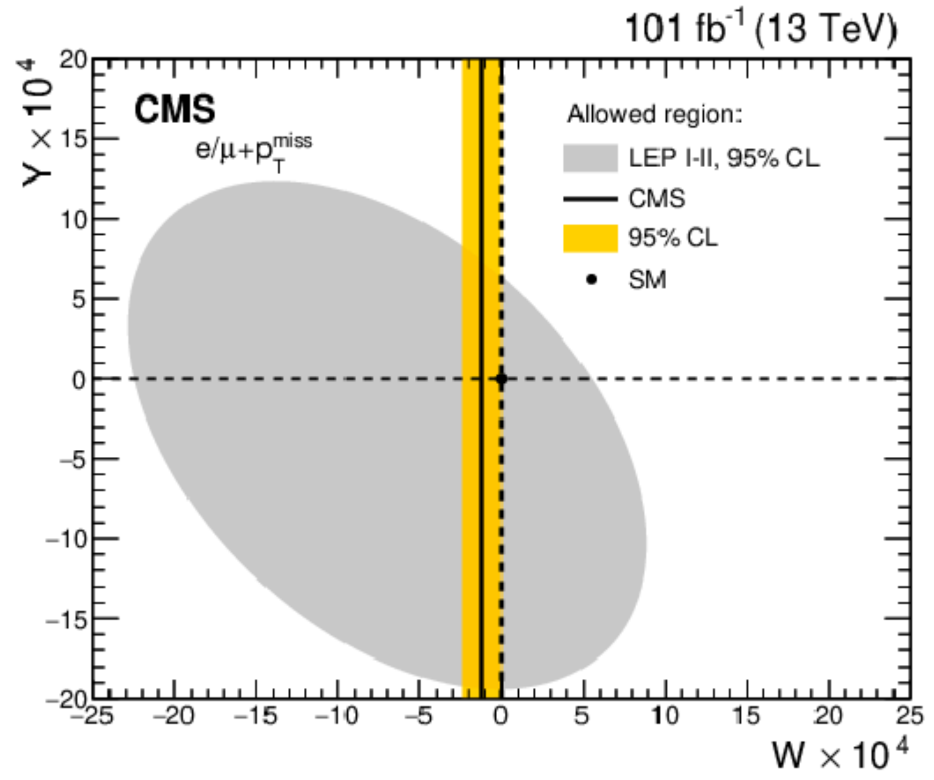
ONE FINAL STATE: MANY INTERPRETATIONS

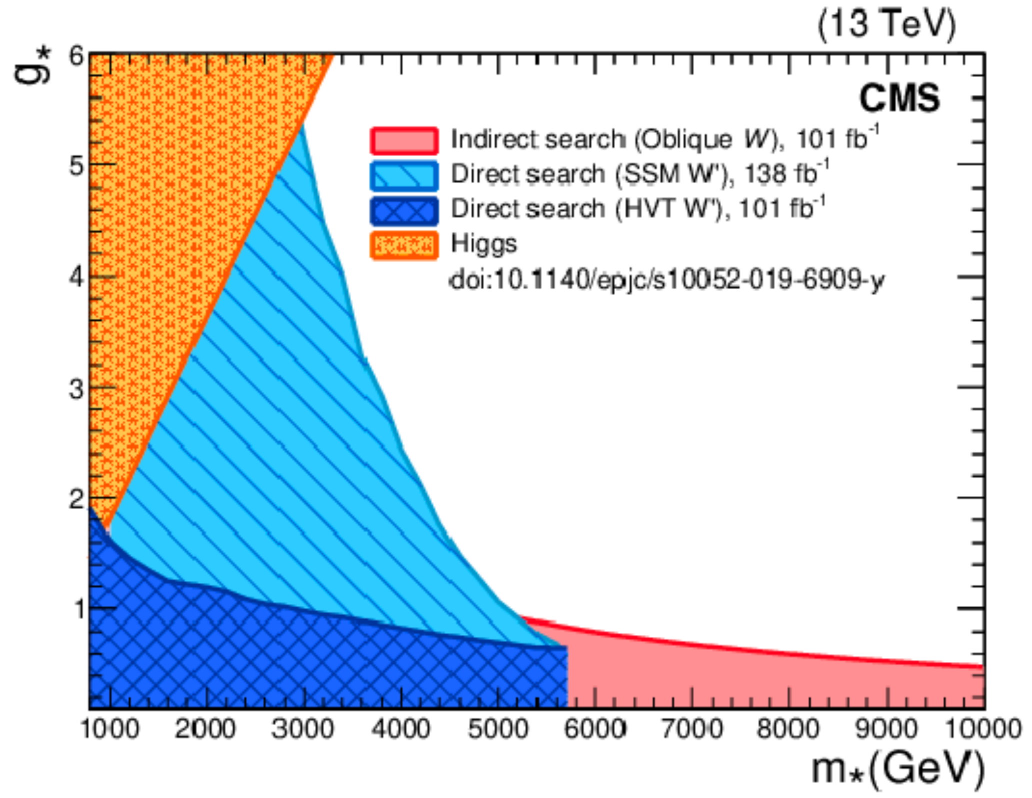


ONE FINAL STATE: MANY INTERPRETATIONS



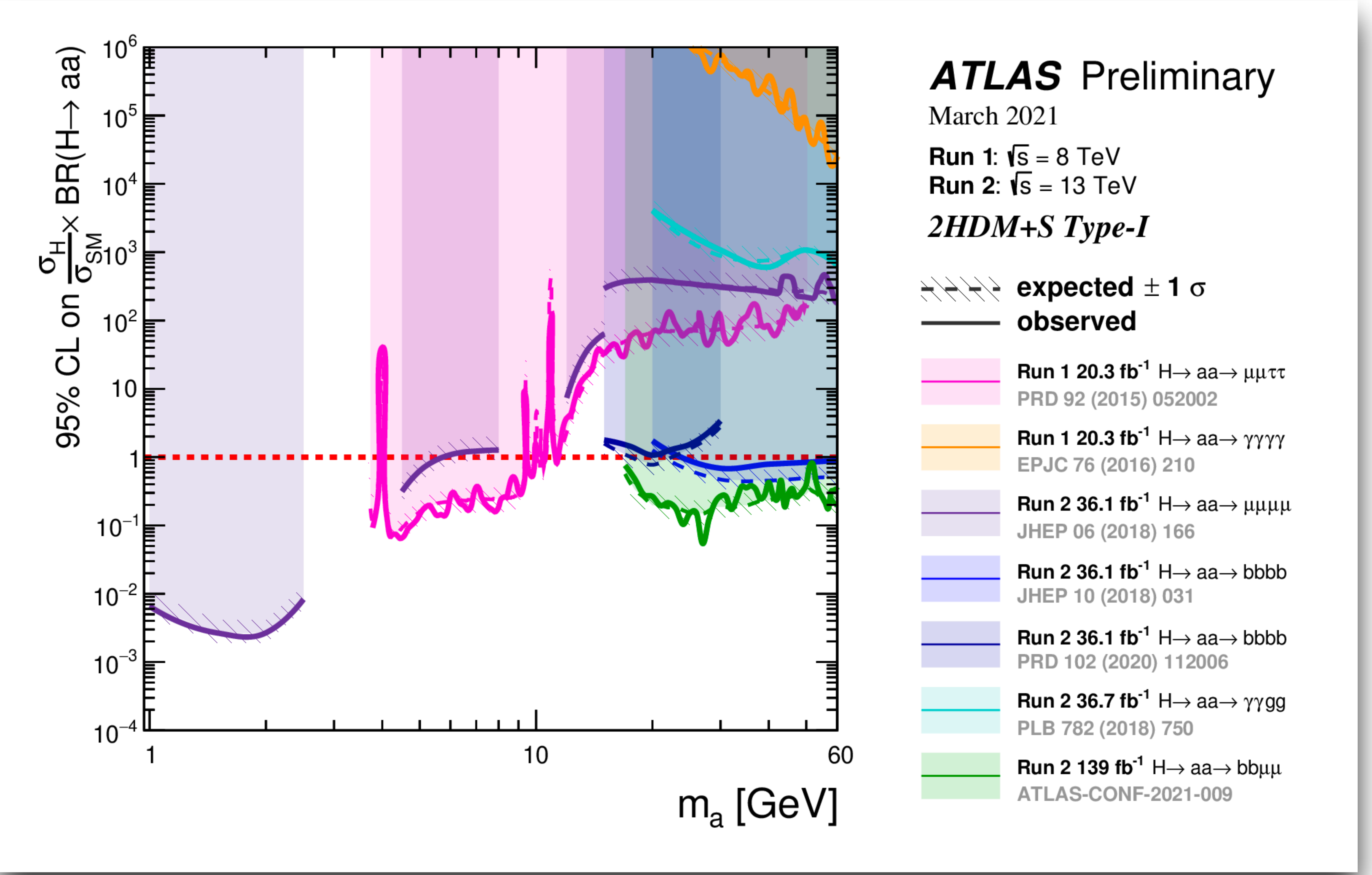


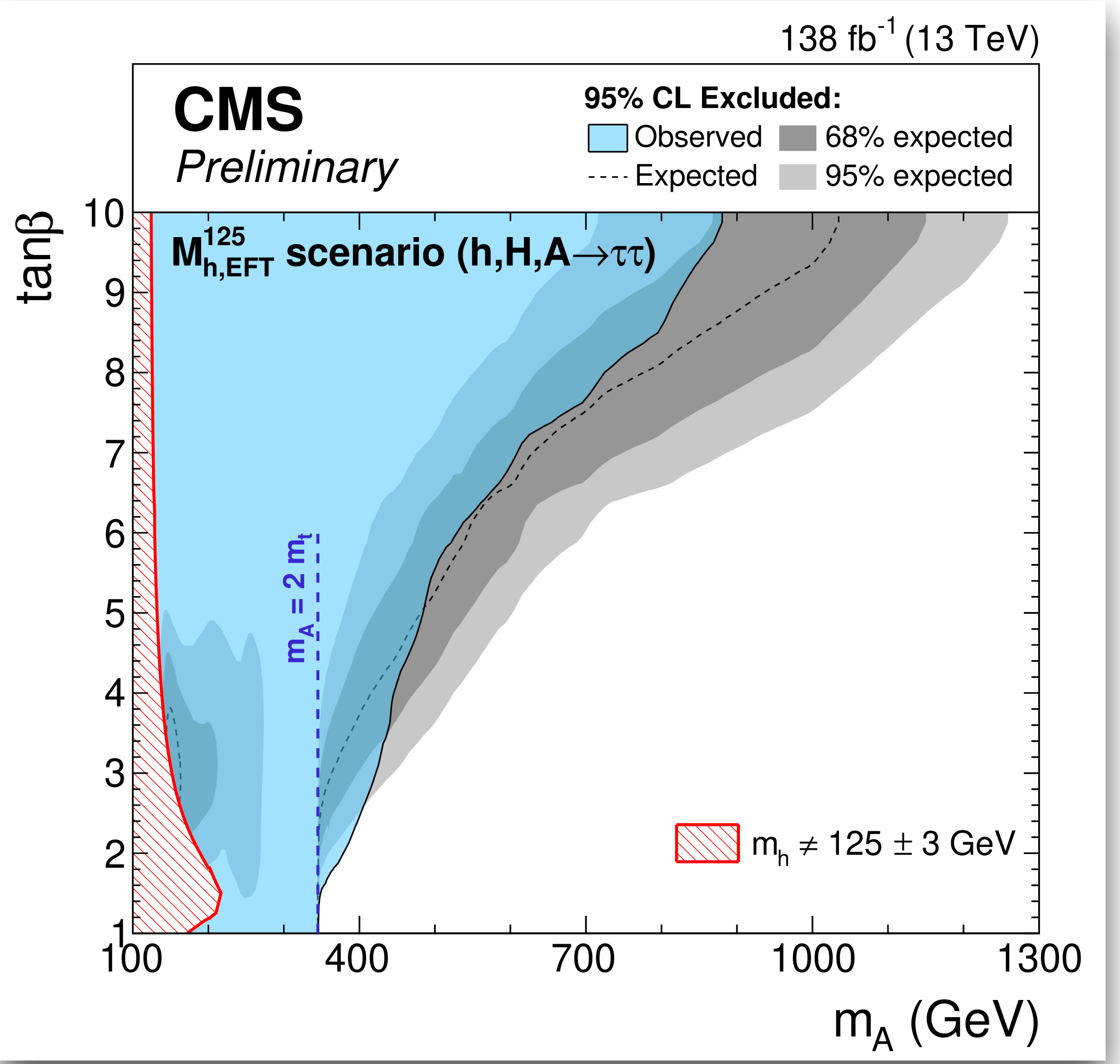




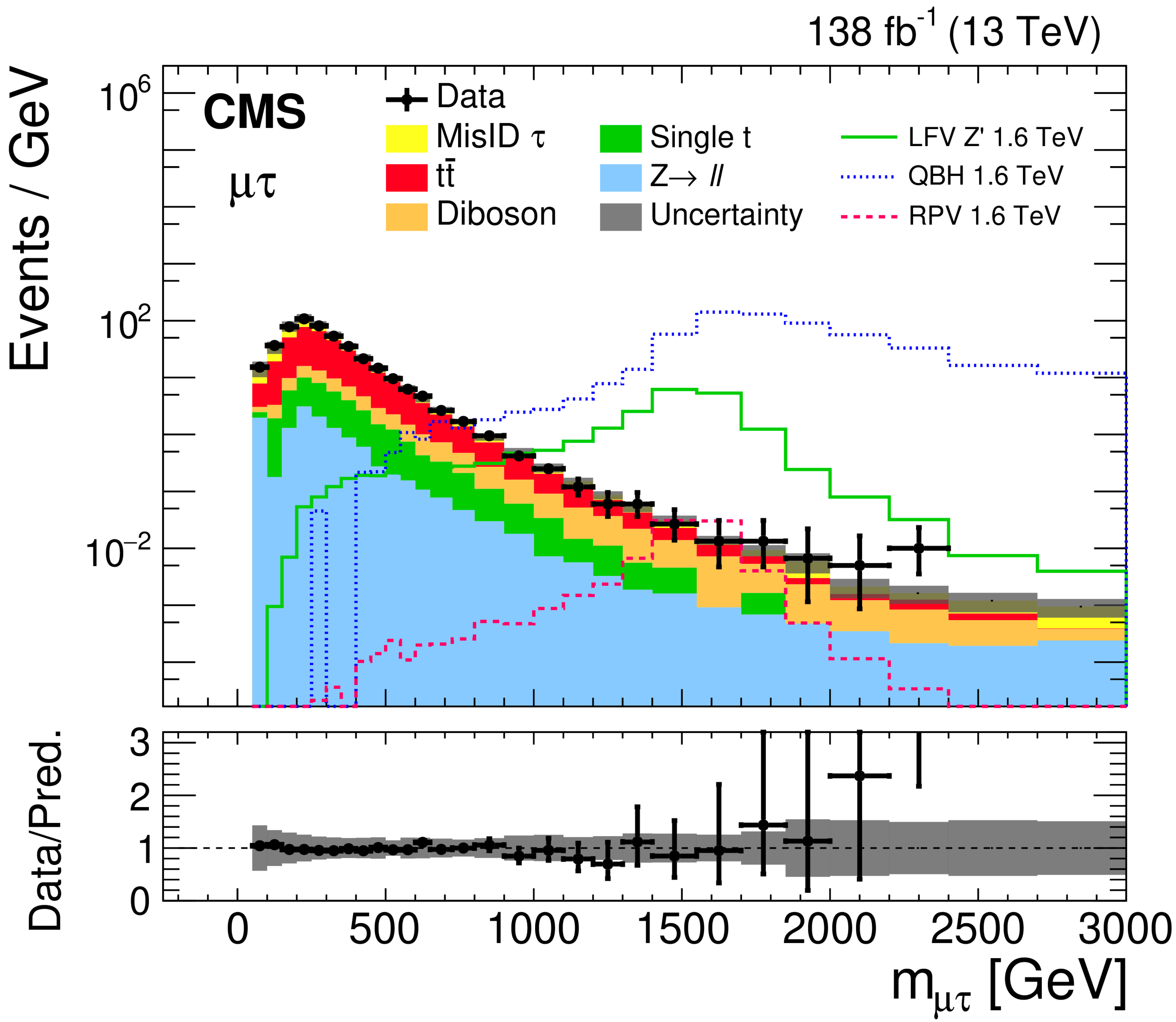
IS THE HIGGS ALONE?

- BSM models tell us that the Higgs does not like being lonely: looking for additional Higgses (at high or low masses, scalar pseudo scalar or charged) is a key part of the Higgs program of the LHC: large phase space to probe!

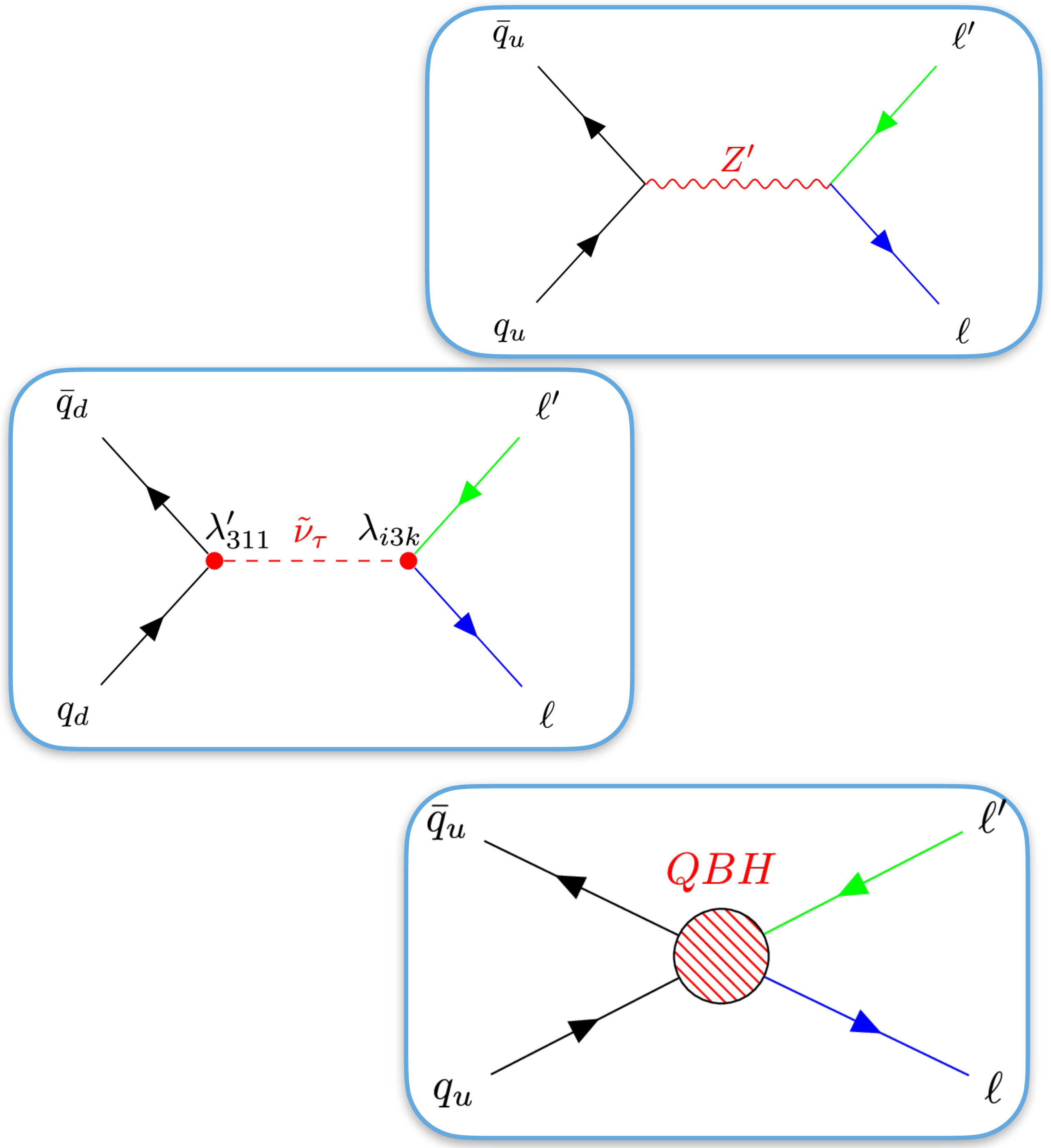




BSM: BREAK THE RULES



ej: lepton number conservation?



PS: Not only at high mass! Think also about FCNC in TOP, Flavour Violating Decays / Yukawas in Higgs. Any news in Flavour?

DARK MATTER AT A COLLIDER?
LOOK FOR WHAT IS MISSING

DARK MATTER AT A COLLIDER?
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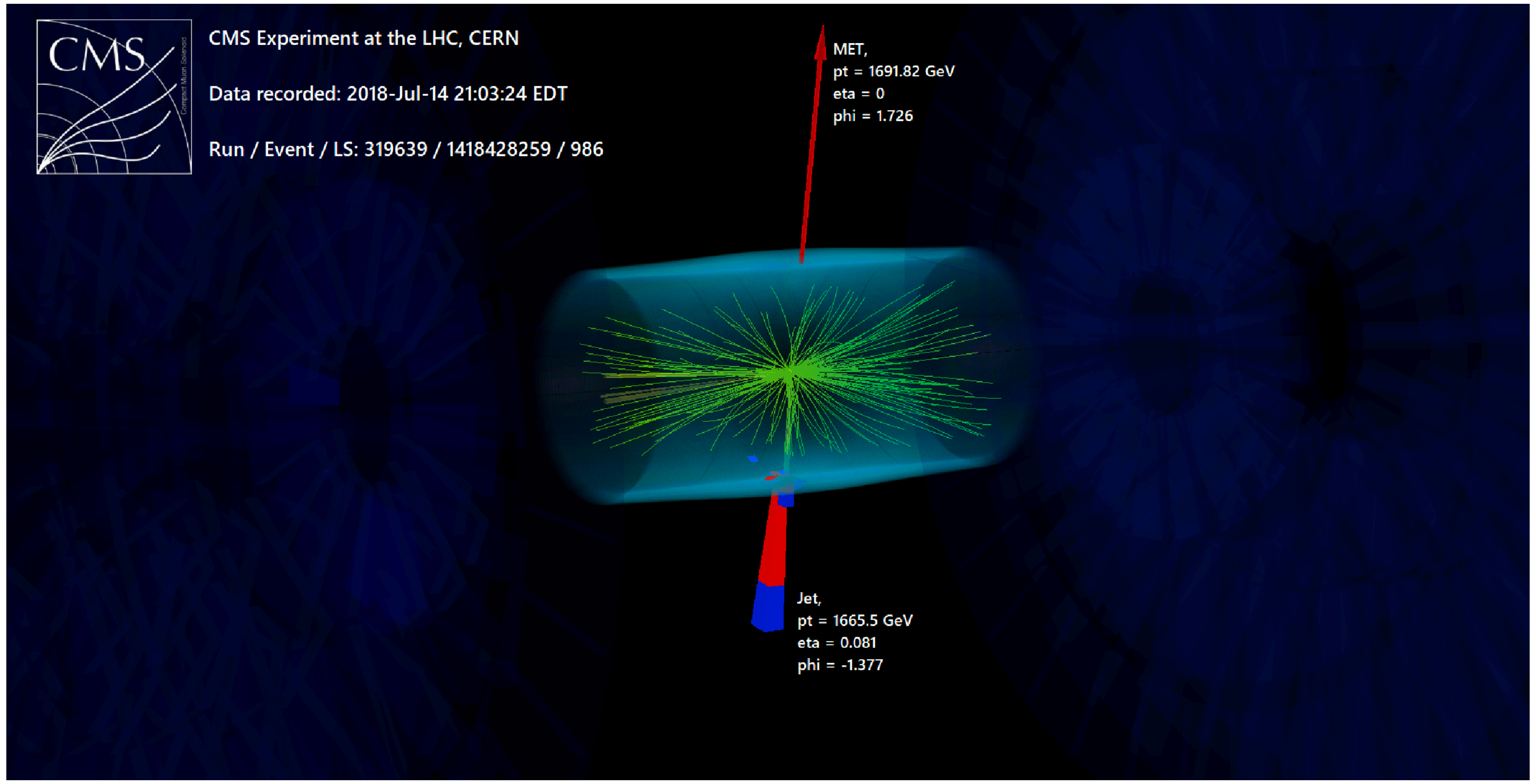

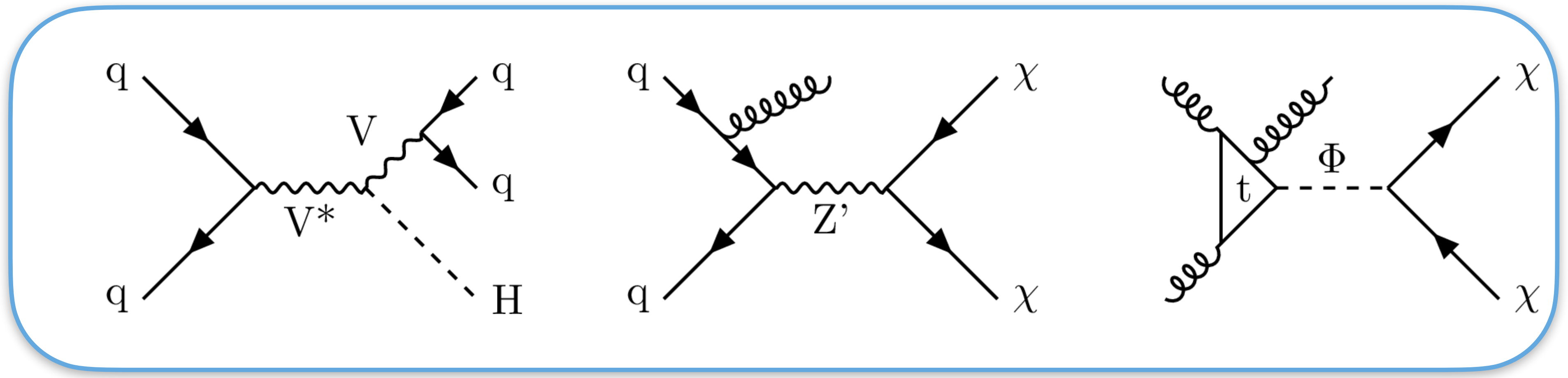

DARK MATTER AT A COLLIDER?
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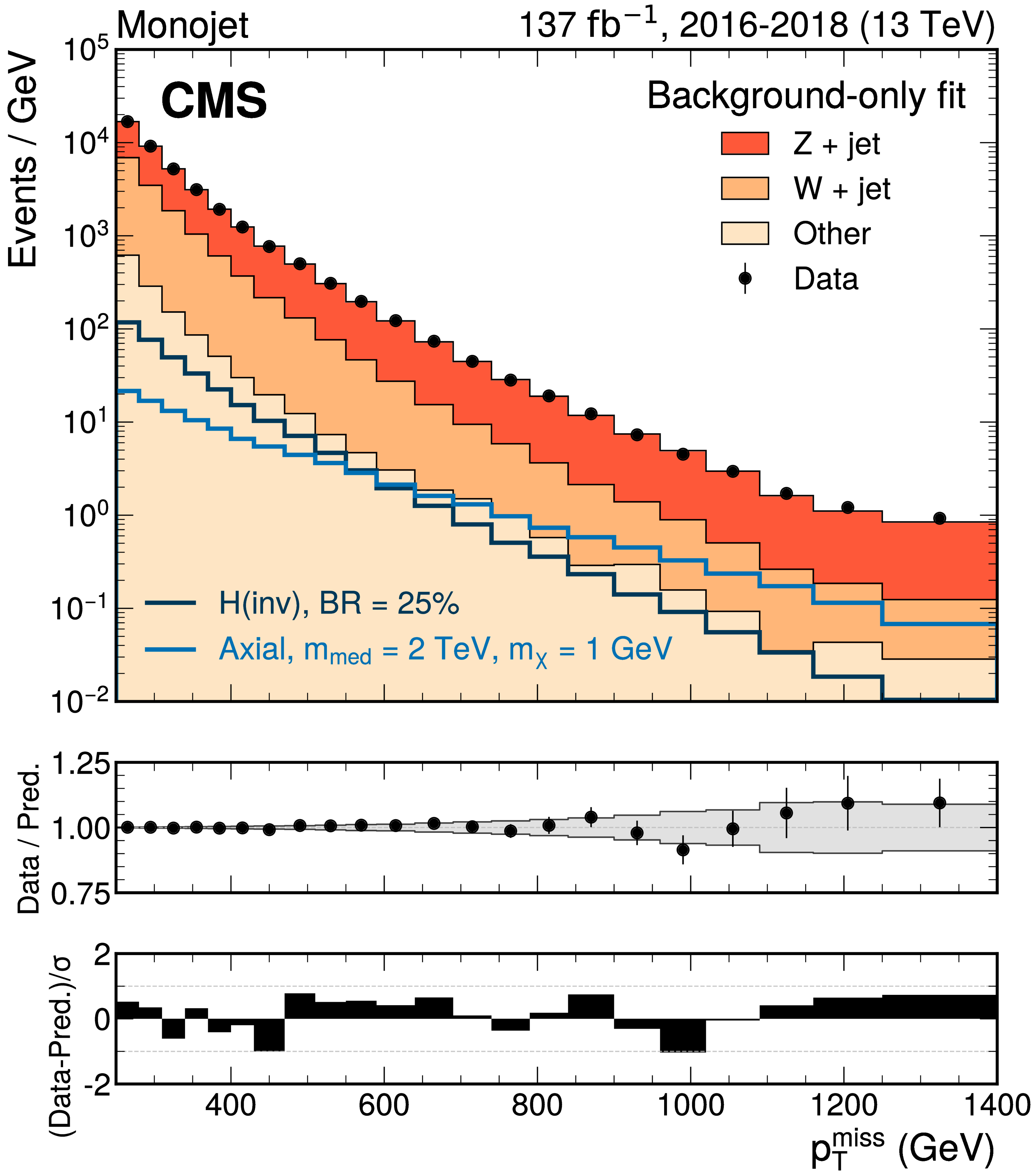
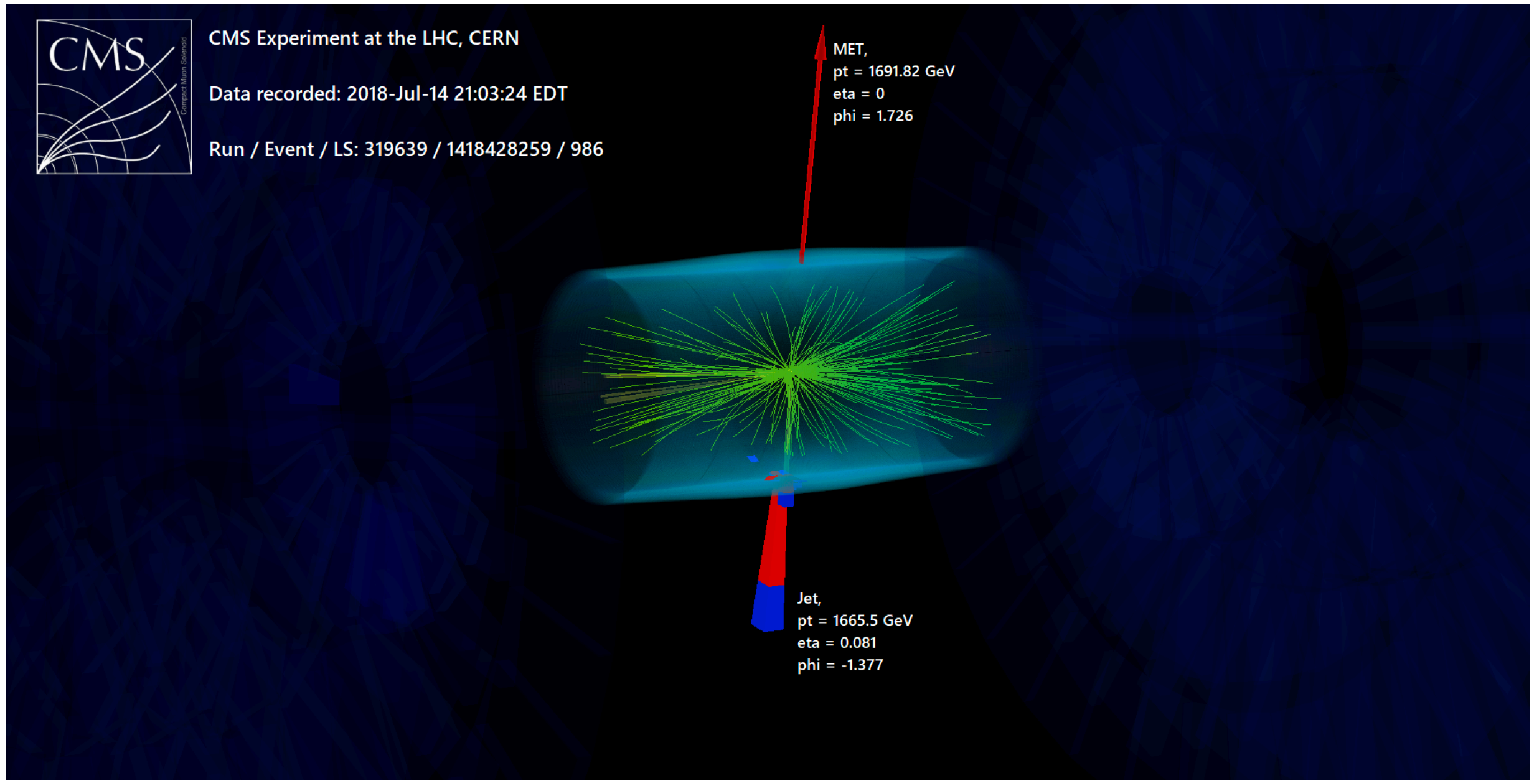
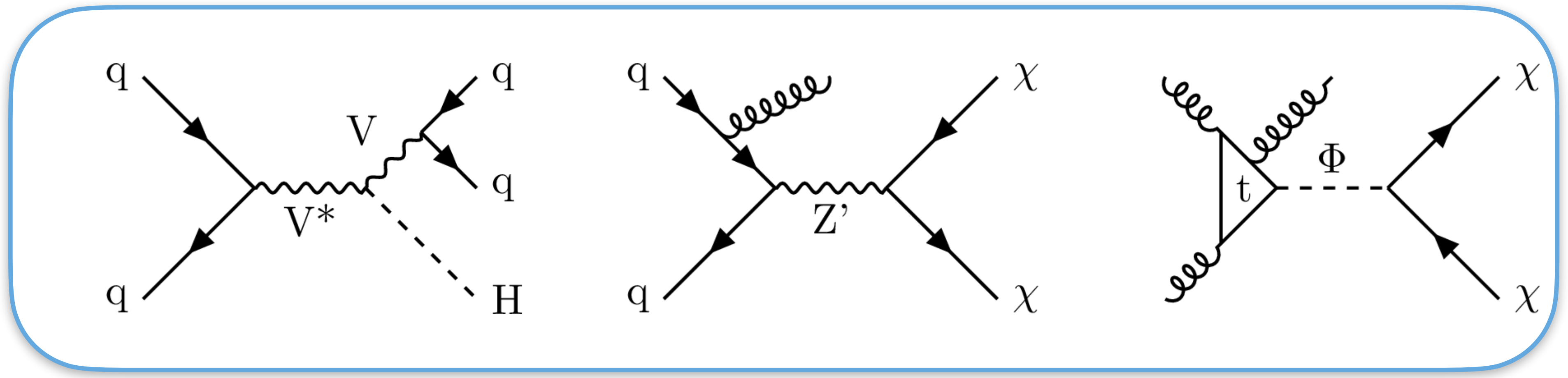
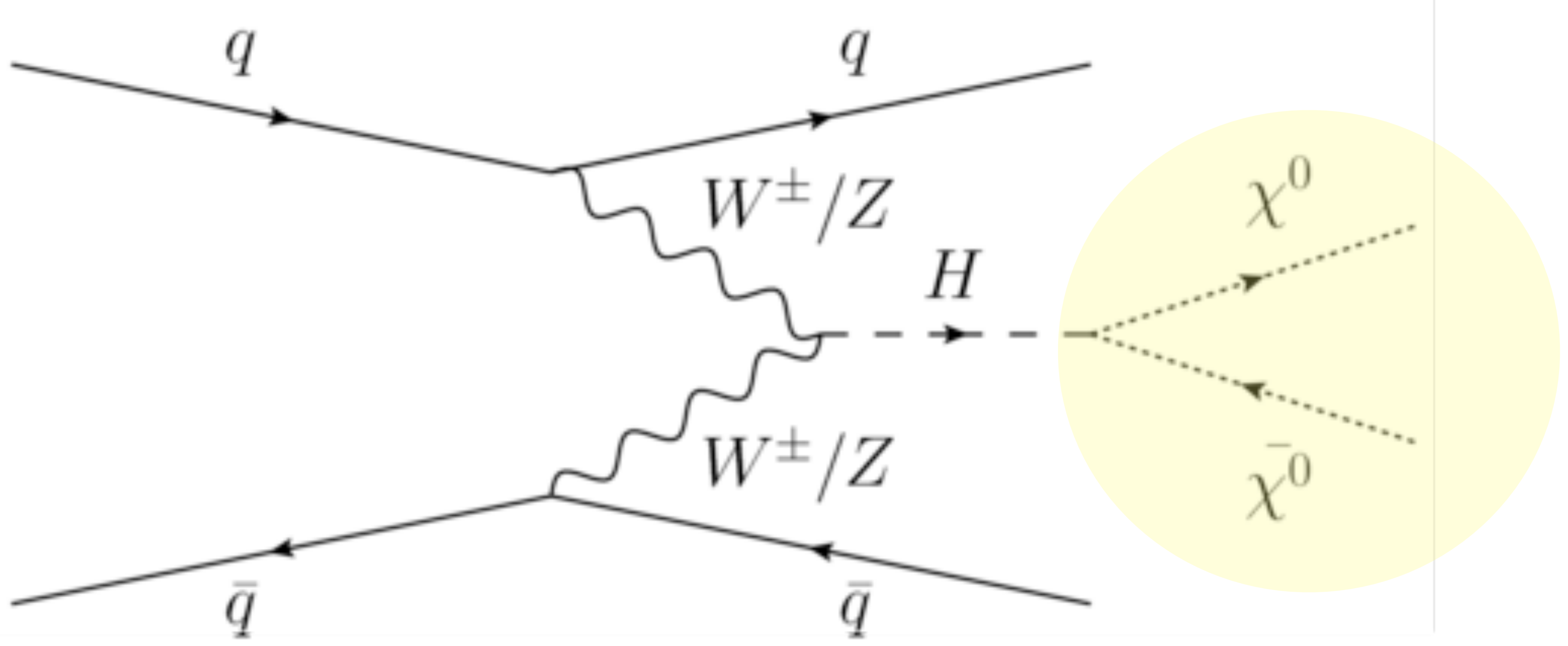






EG: CAN THE HIGGS BOSON DECAY TO DARK MATTER?

- Why should we assume the Higgs boson follow the SM rules strictly? Can it decay to the unexpected, to BSM particles?
- Does DM couple to the Higgs???



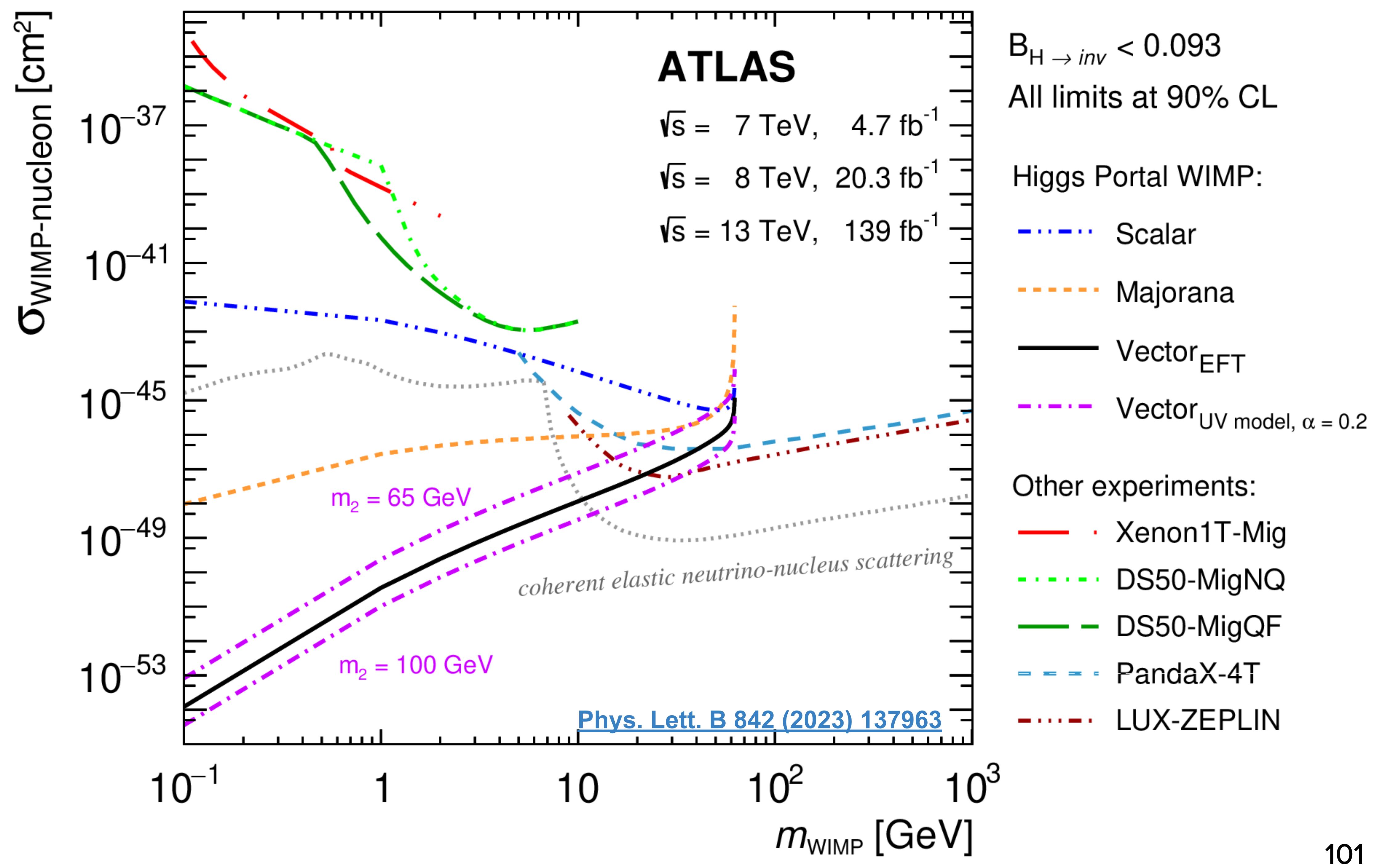
Direct searches for Higgs decays to **undetectable** particles = 'invisible decay'

How do we see this experimentally? Look for missing energy!

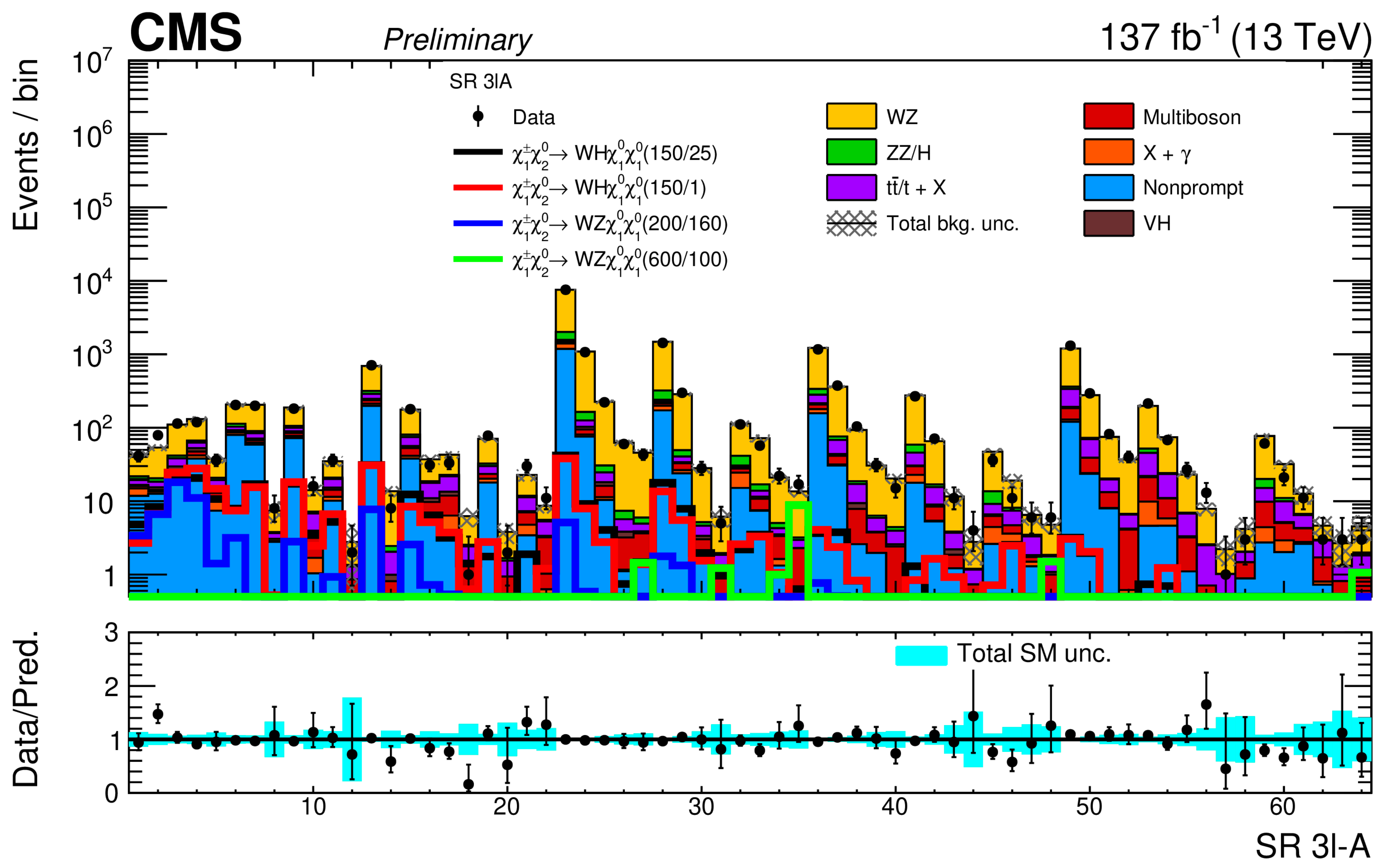
Limits at 95%CL:

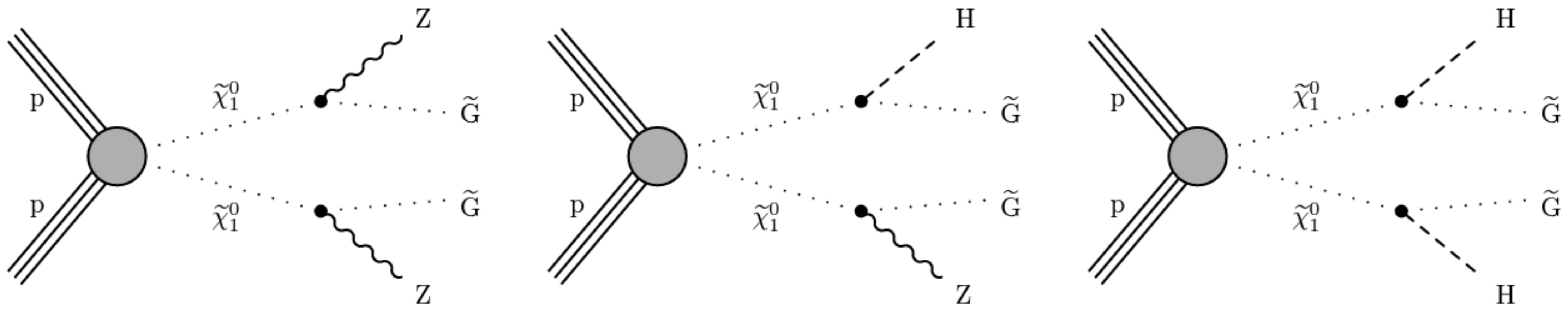
CMS: Br(H_{inv}) < 15% (8%) (Eur. Phys. J. C 83 (2023) 933)

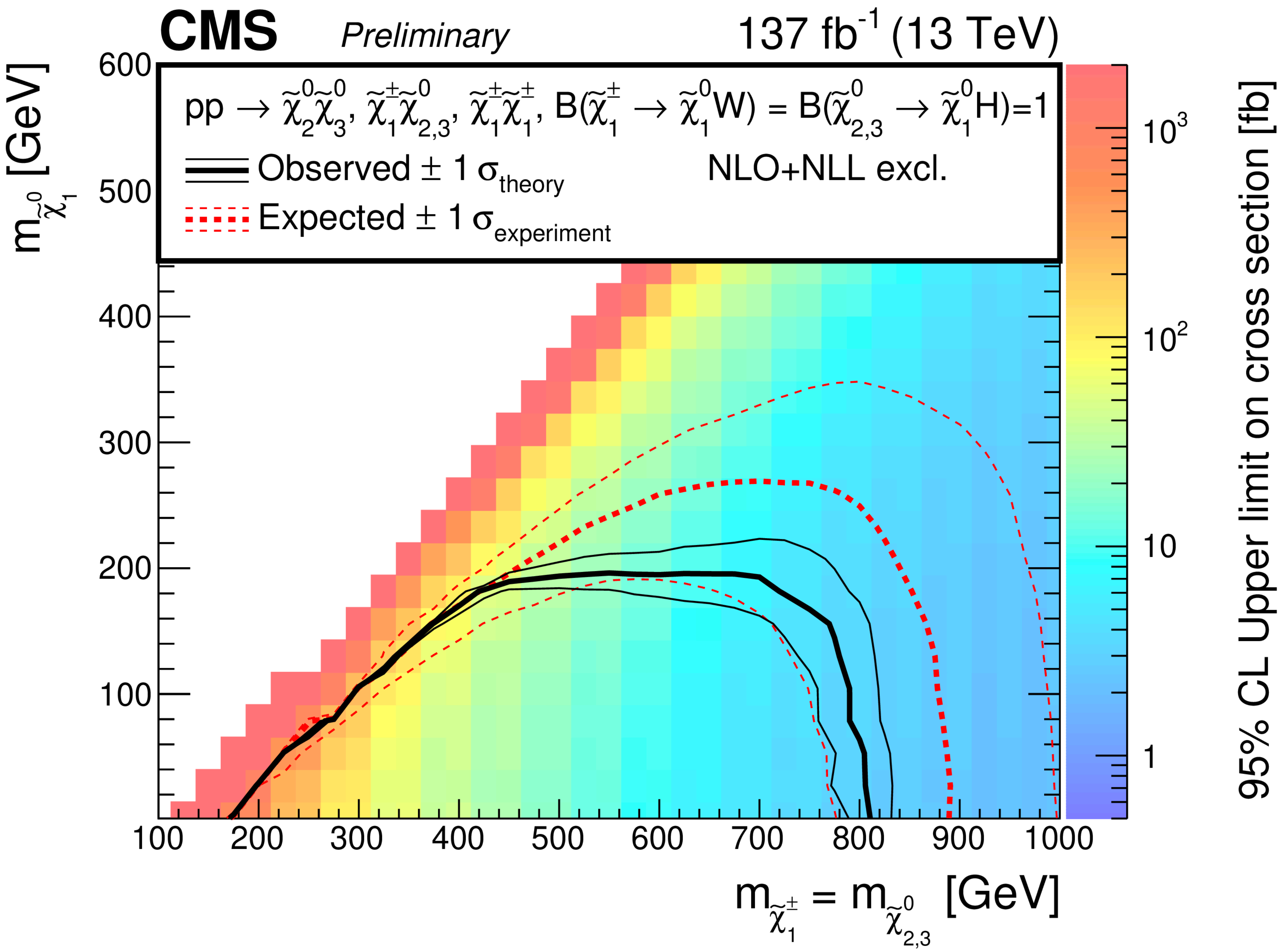
ATLAS: Br(H_{inv}) < 14.5% (10.3%)



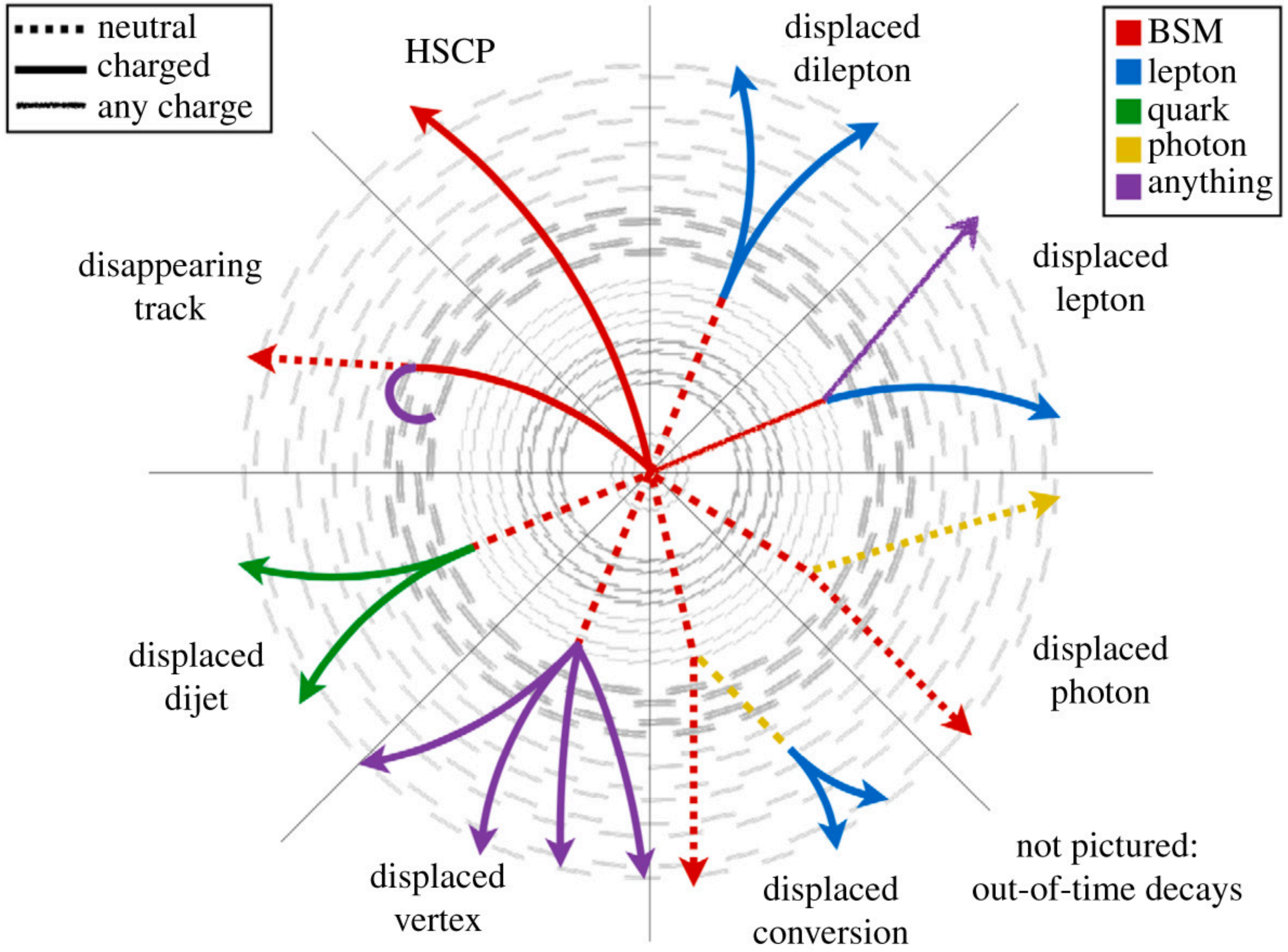
COMPLEX PHASESPACES, SMALL SIGNALS —> COMPLEX ML ANALYSIS







WHAT IF THE SIGNAL IS LONG LIVED?



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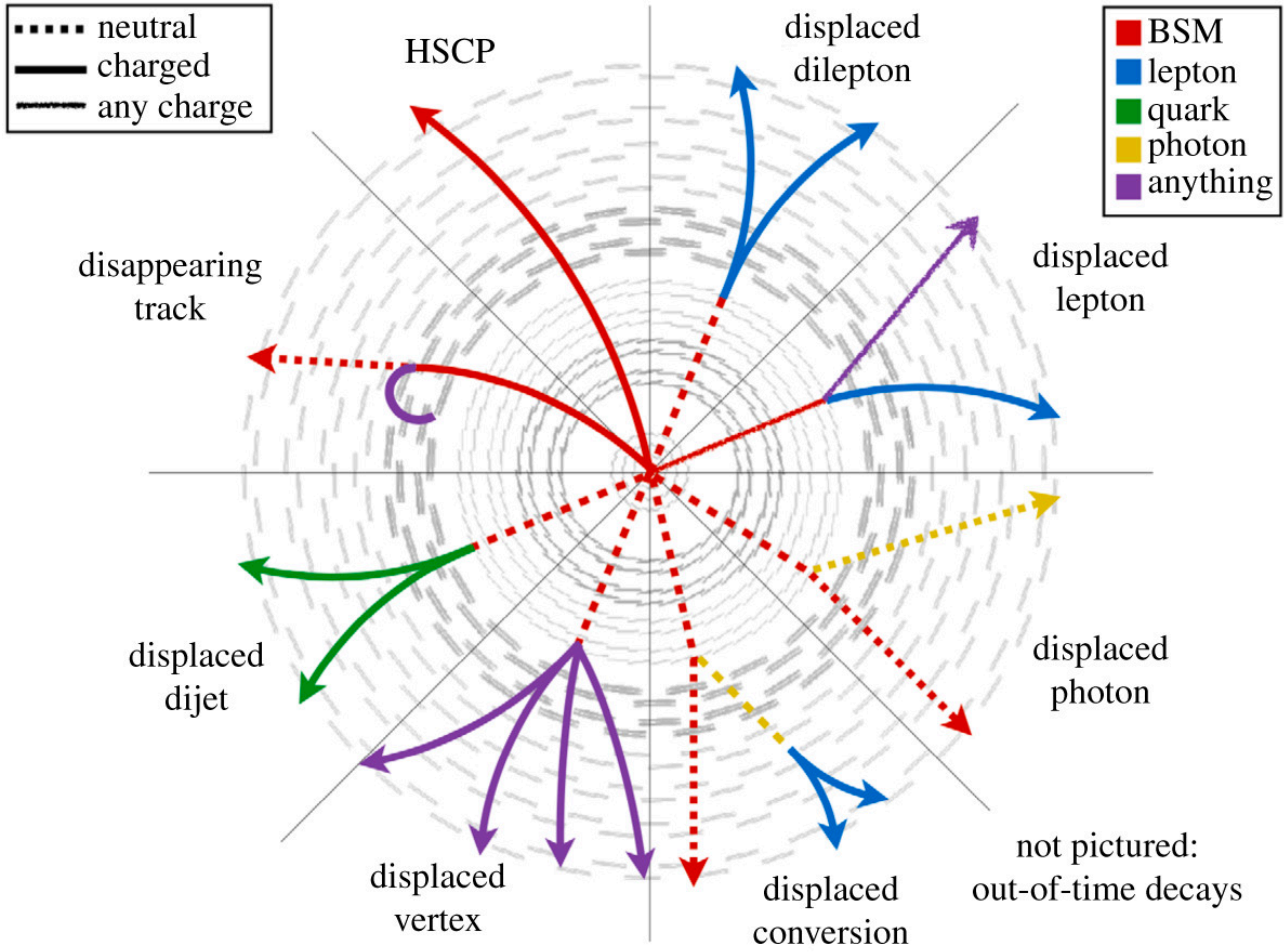

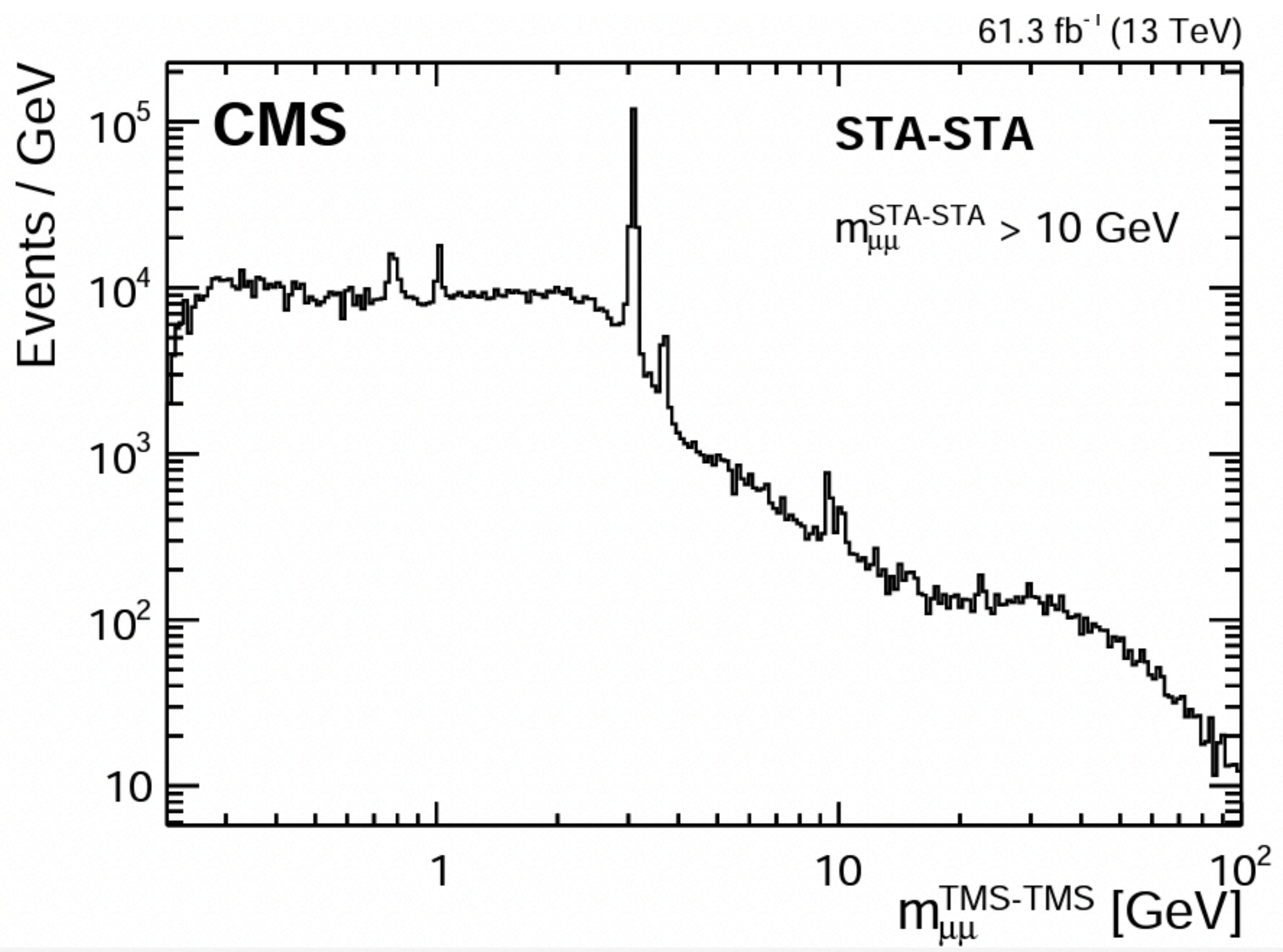

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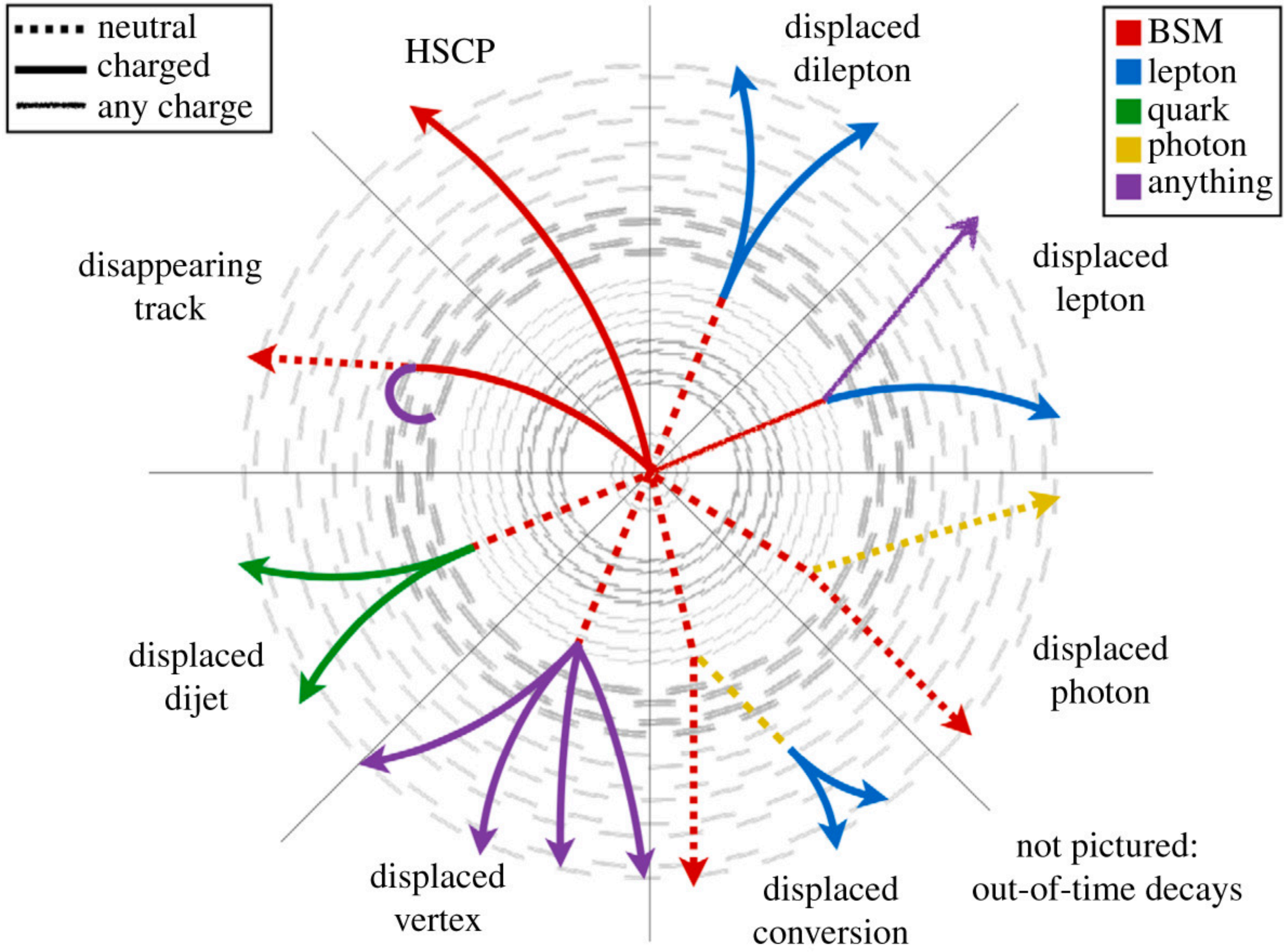
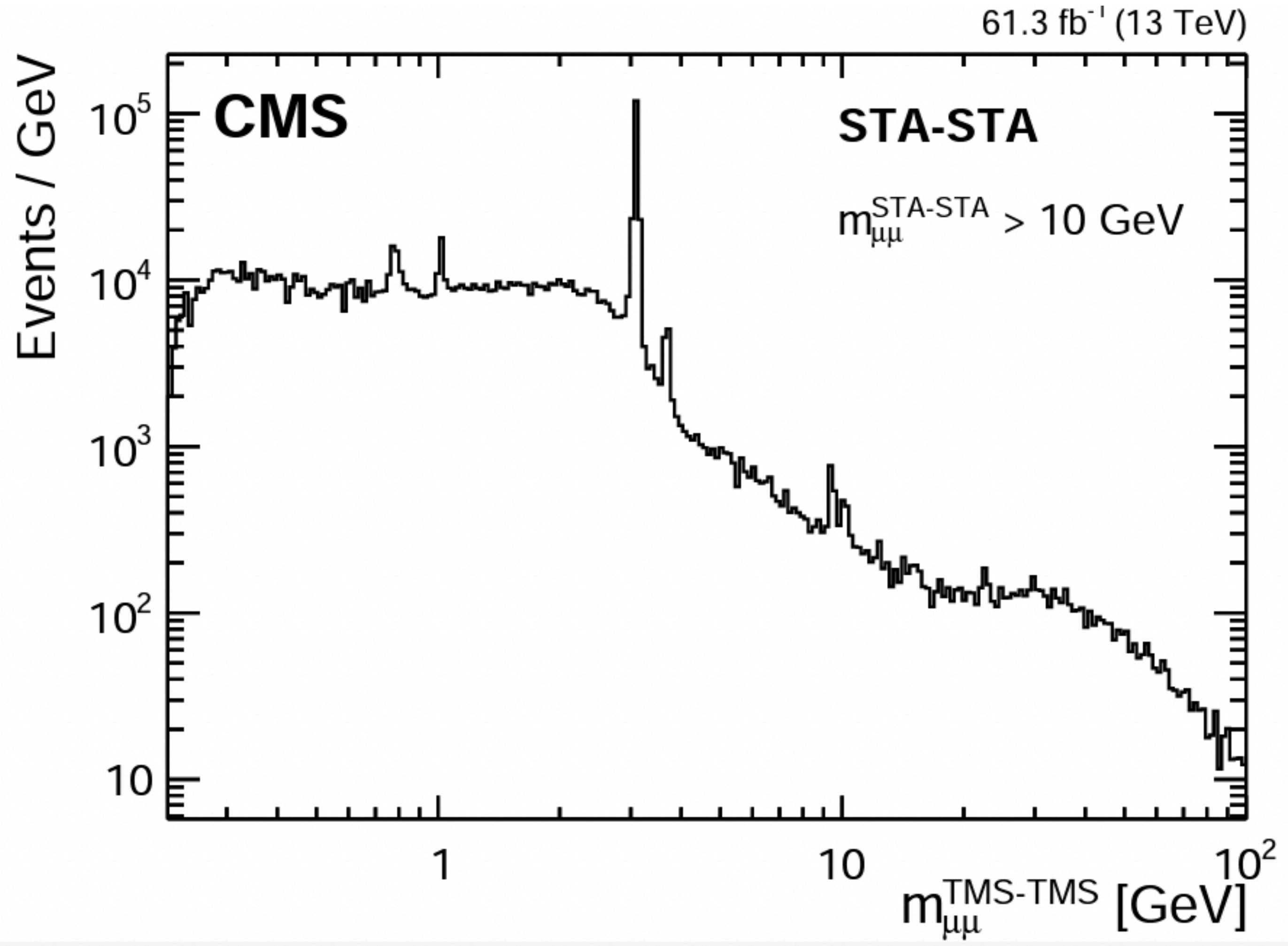
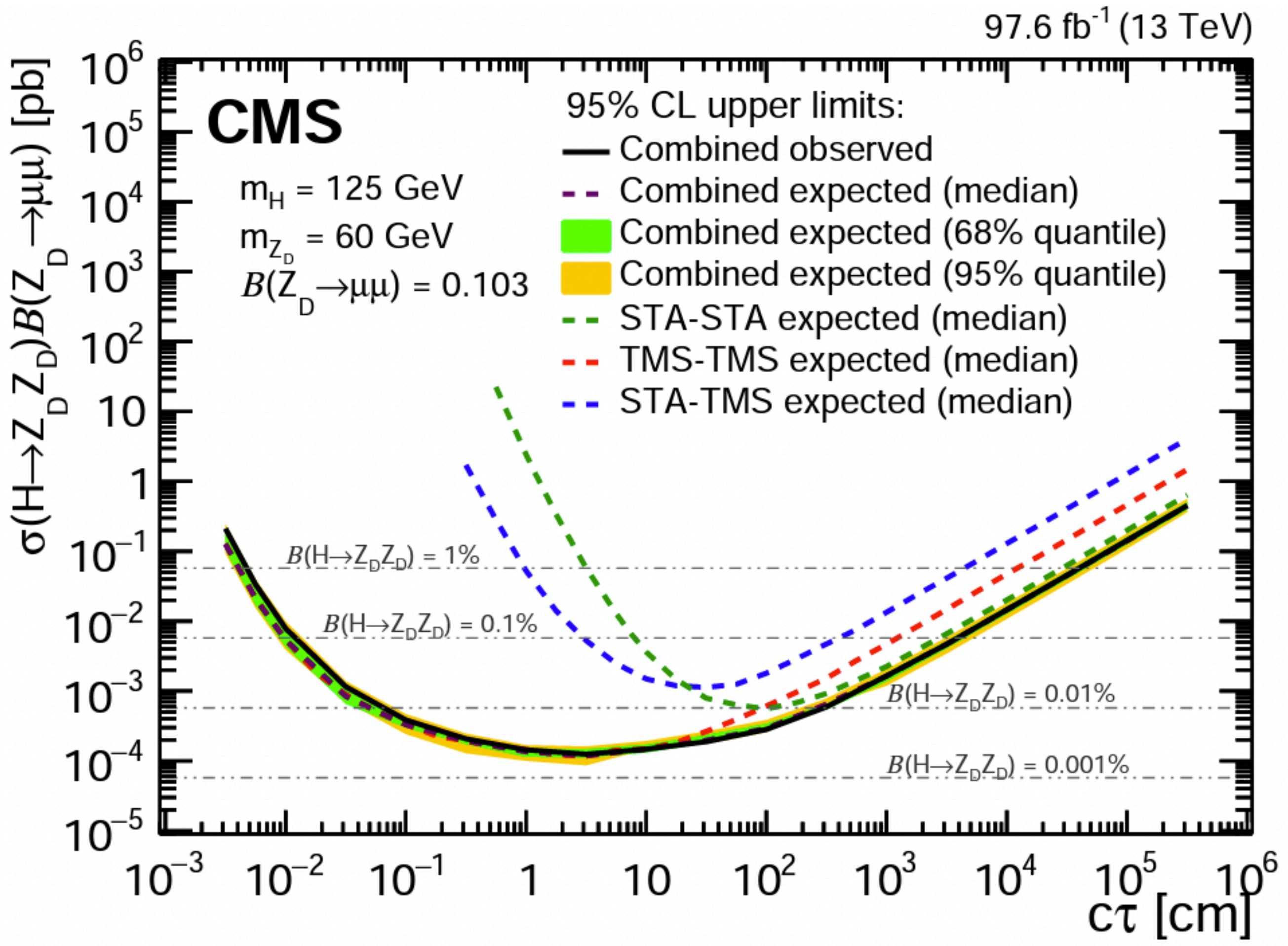
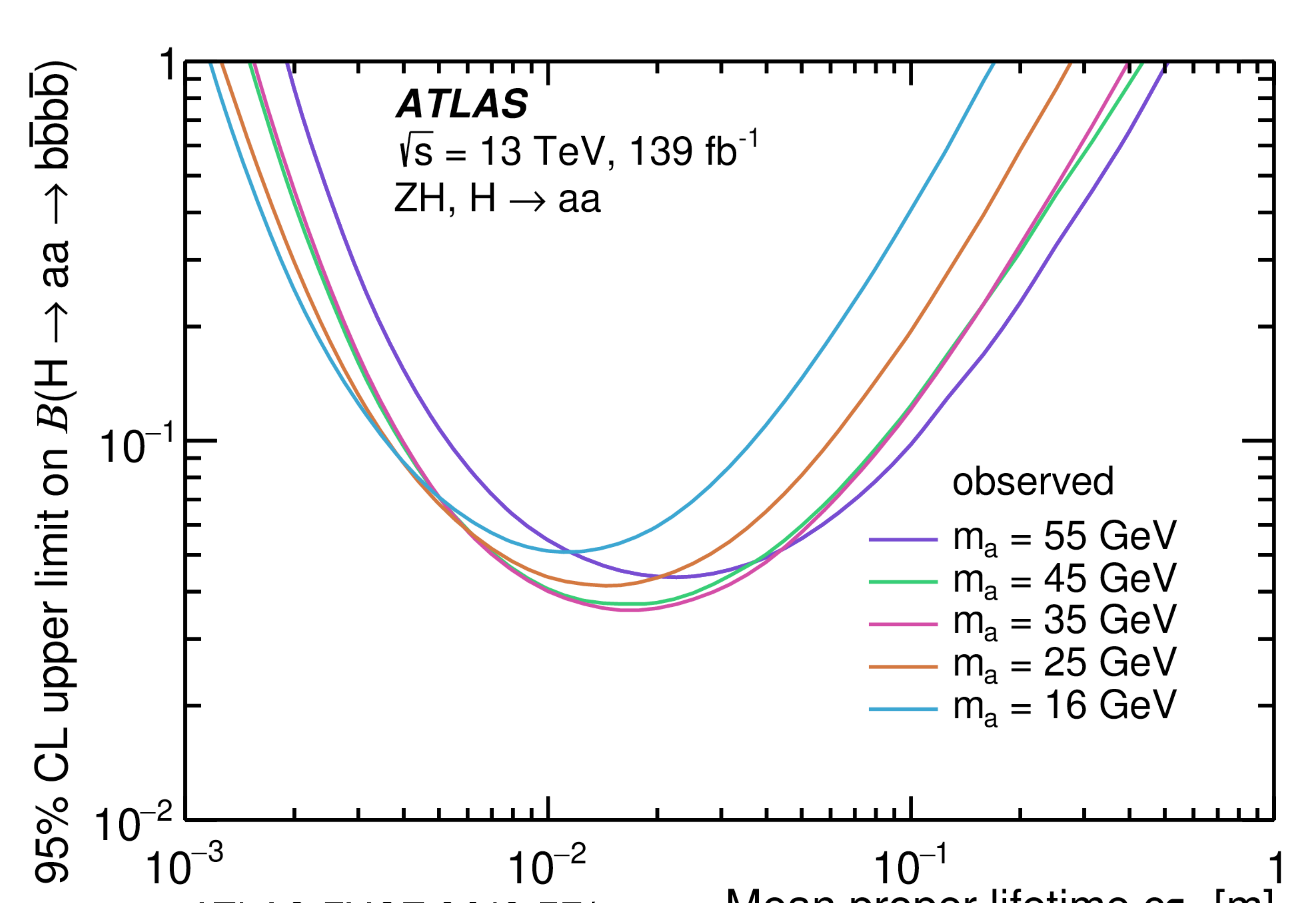




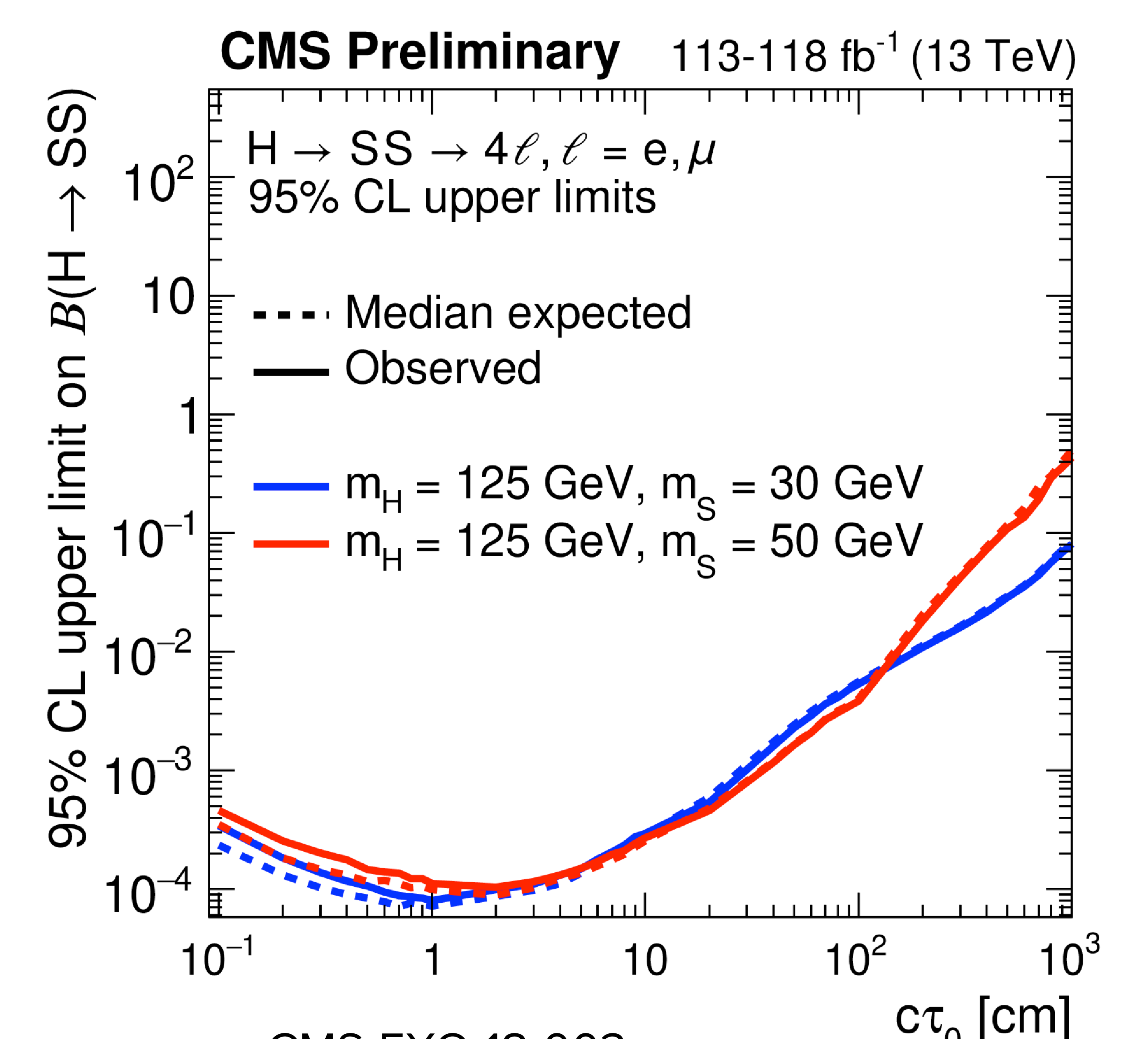


EG: LONG LIVED HIGGS DECAYS?

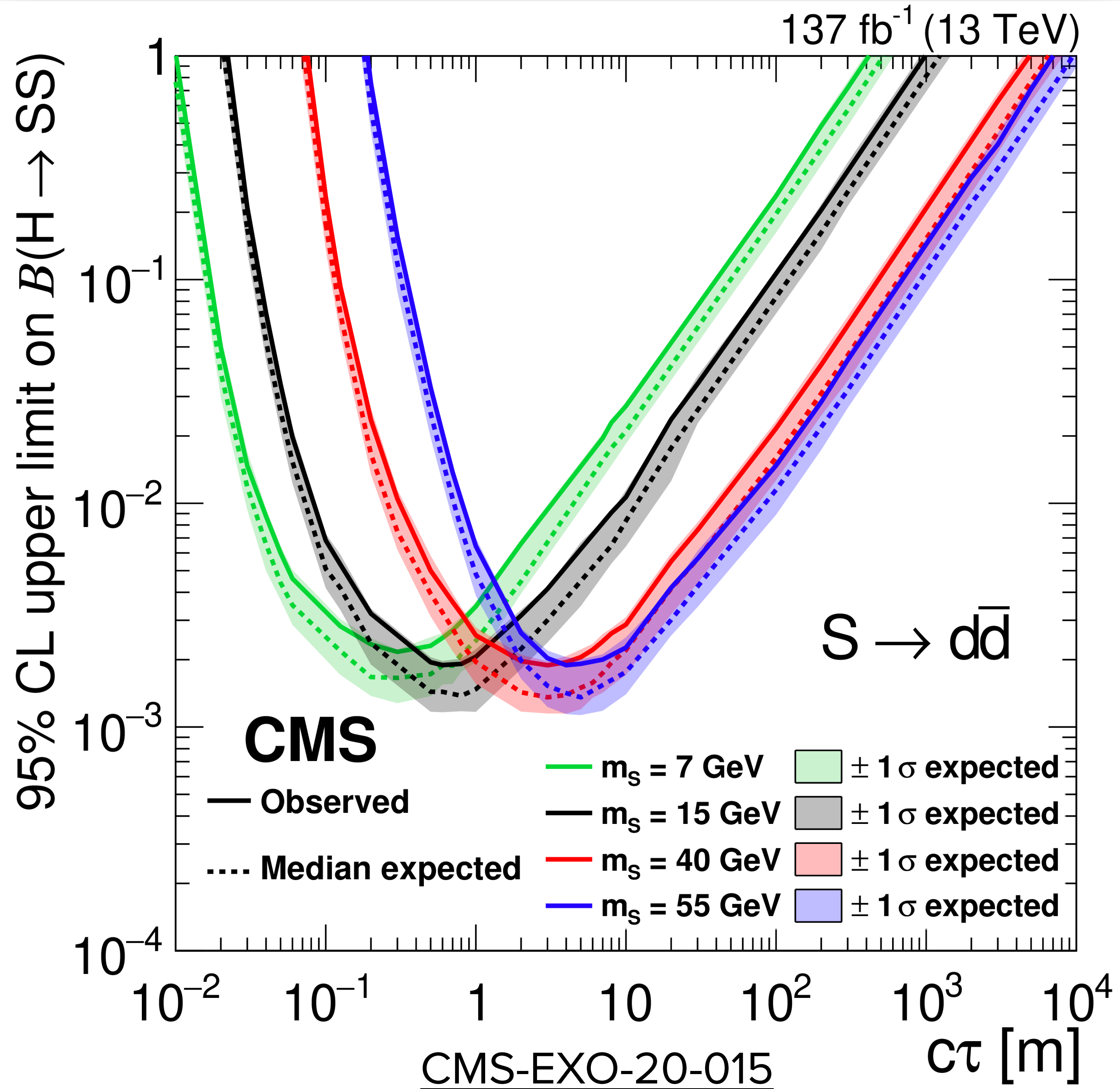
- Looking for exotic Higgs decays goes beyond the traditional h➔aa/ss searches
- Effort ongoing to probe for decays to Dark Bosons, ALPs, Long Lived particles: one of the next frontiers



ATLAS-EXOT-2018-57/



CMS-EXO-18-003

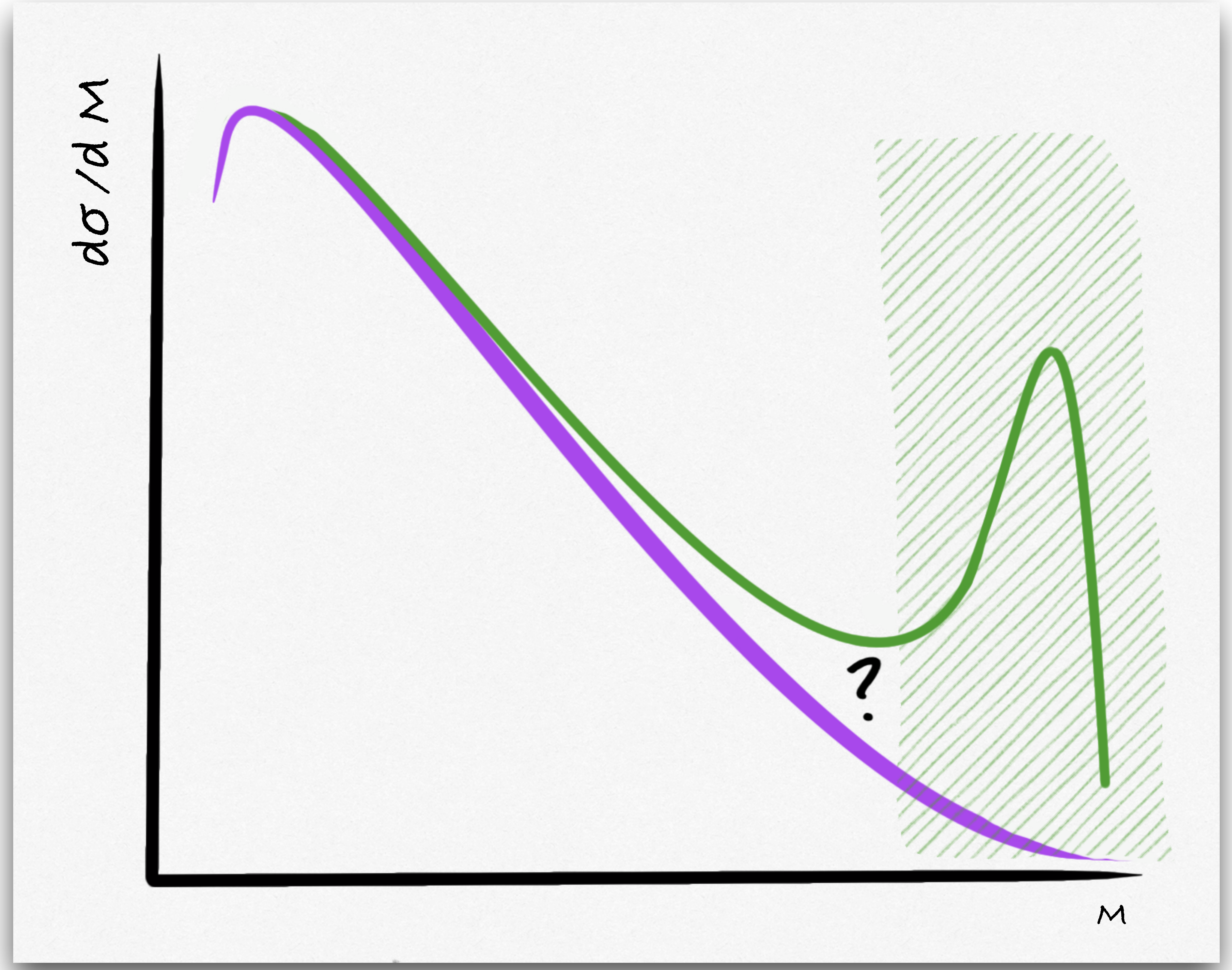


CMS-EXO-20-015

EFFECTIVE FIELD THEORIES

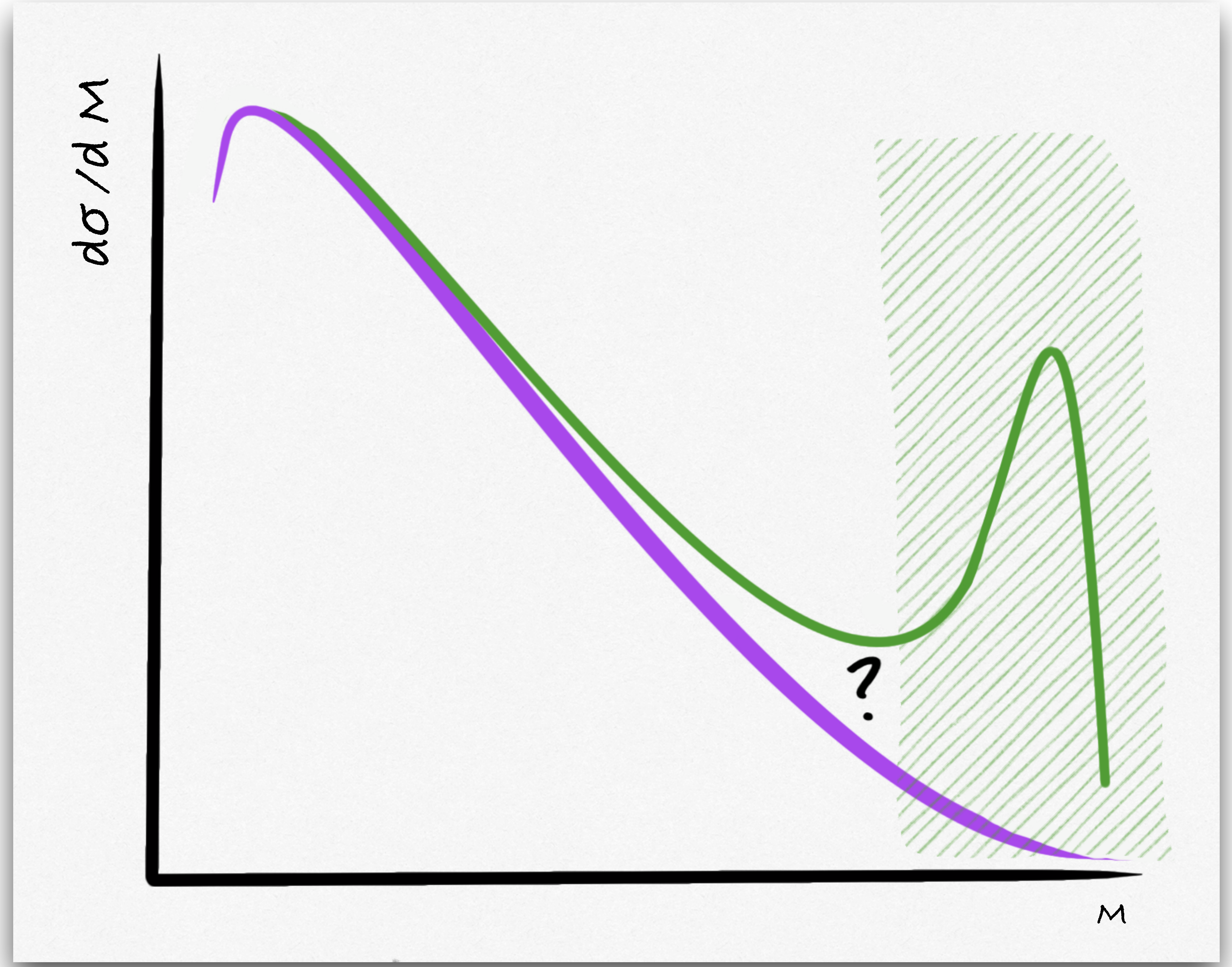
LHC Physics group: LHCEFT

EFFECTIVE FIELD THEORIES



LHC Physics group: LHCEFT

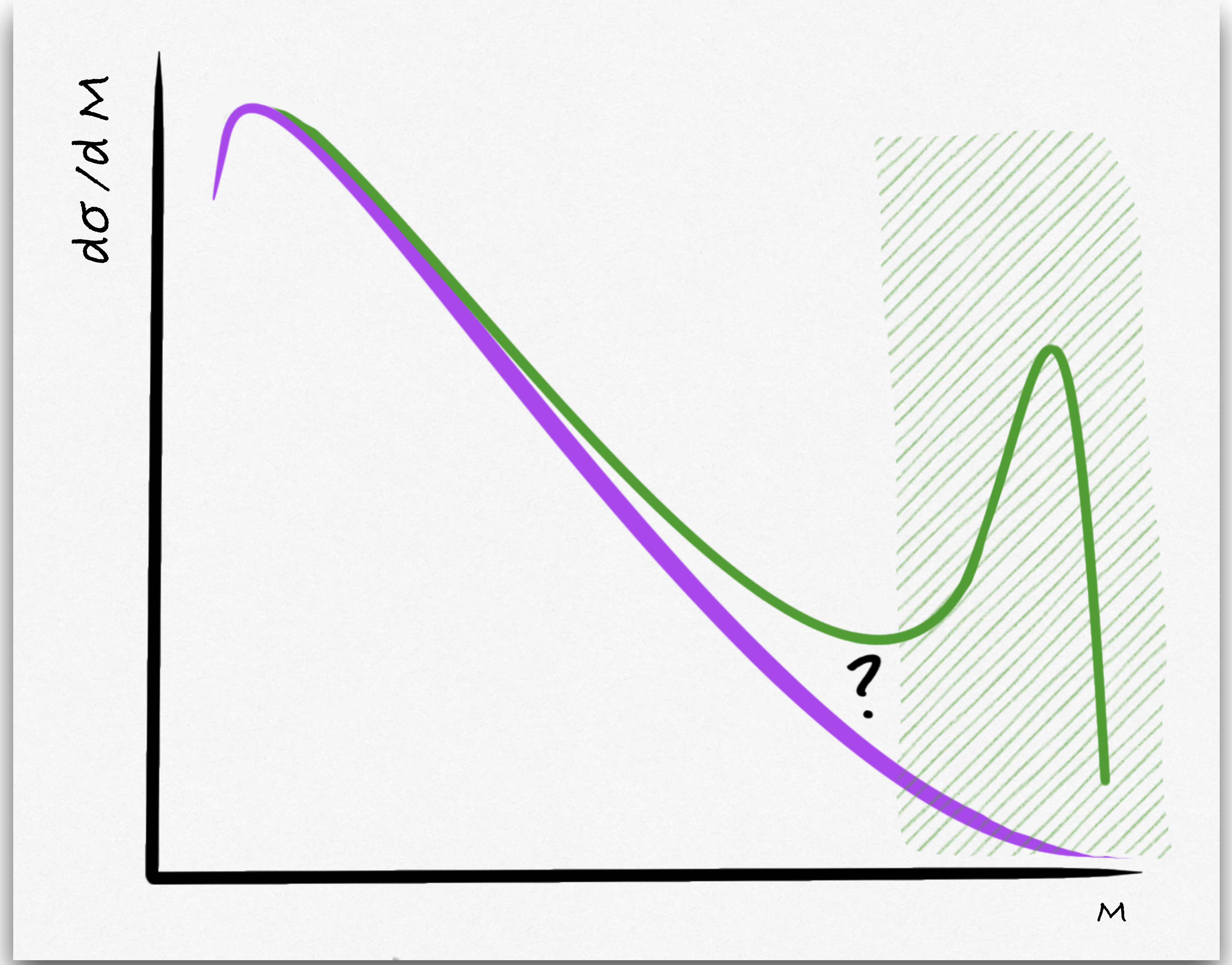
EFFECTIVE FIELD THEORIES



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

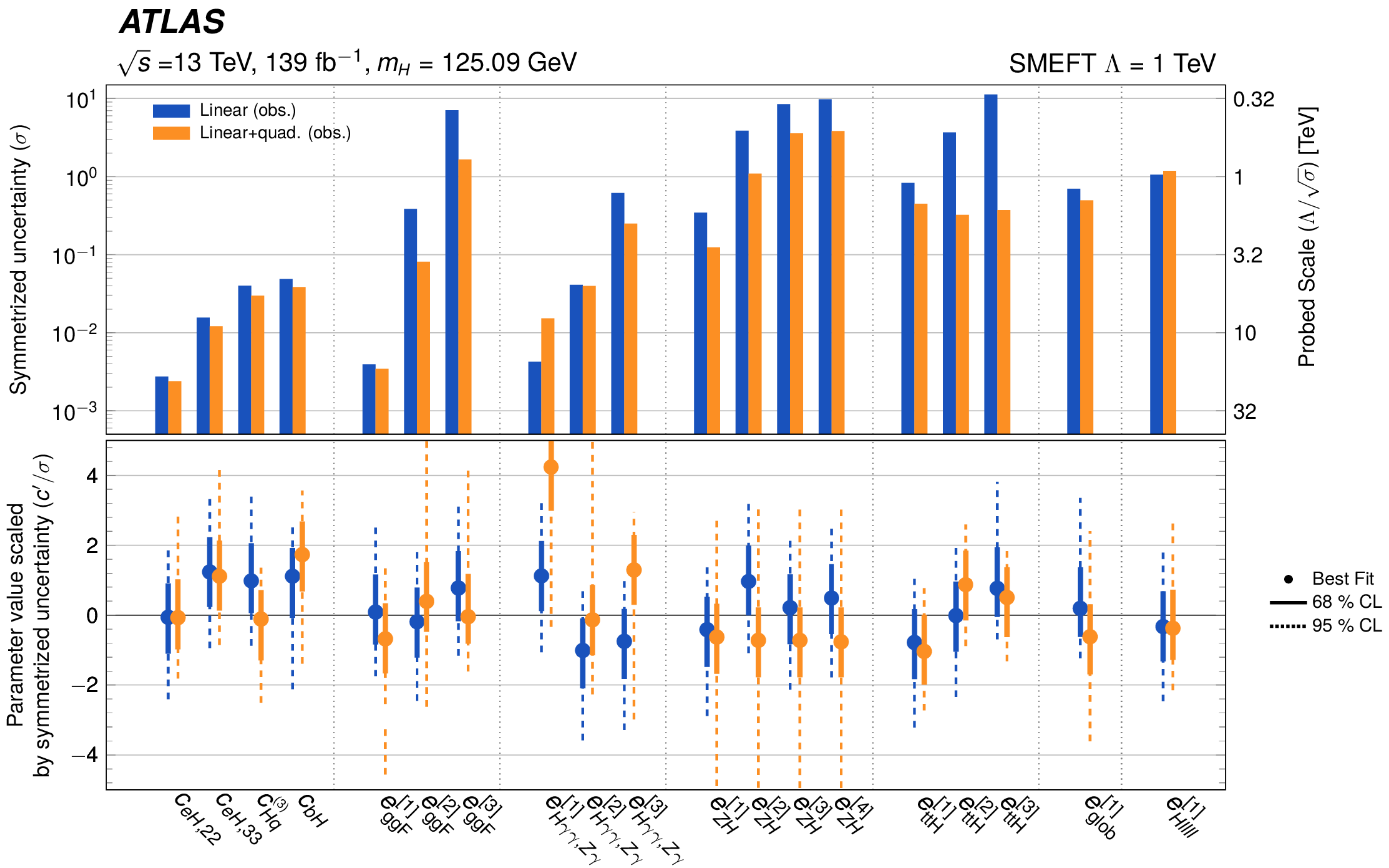
LHC Physics group: LHCEFT

EFFECTIVE FIELD THEORIES



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

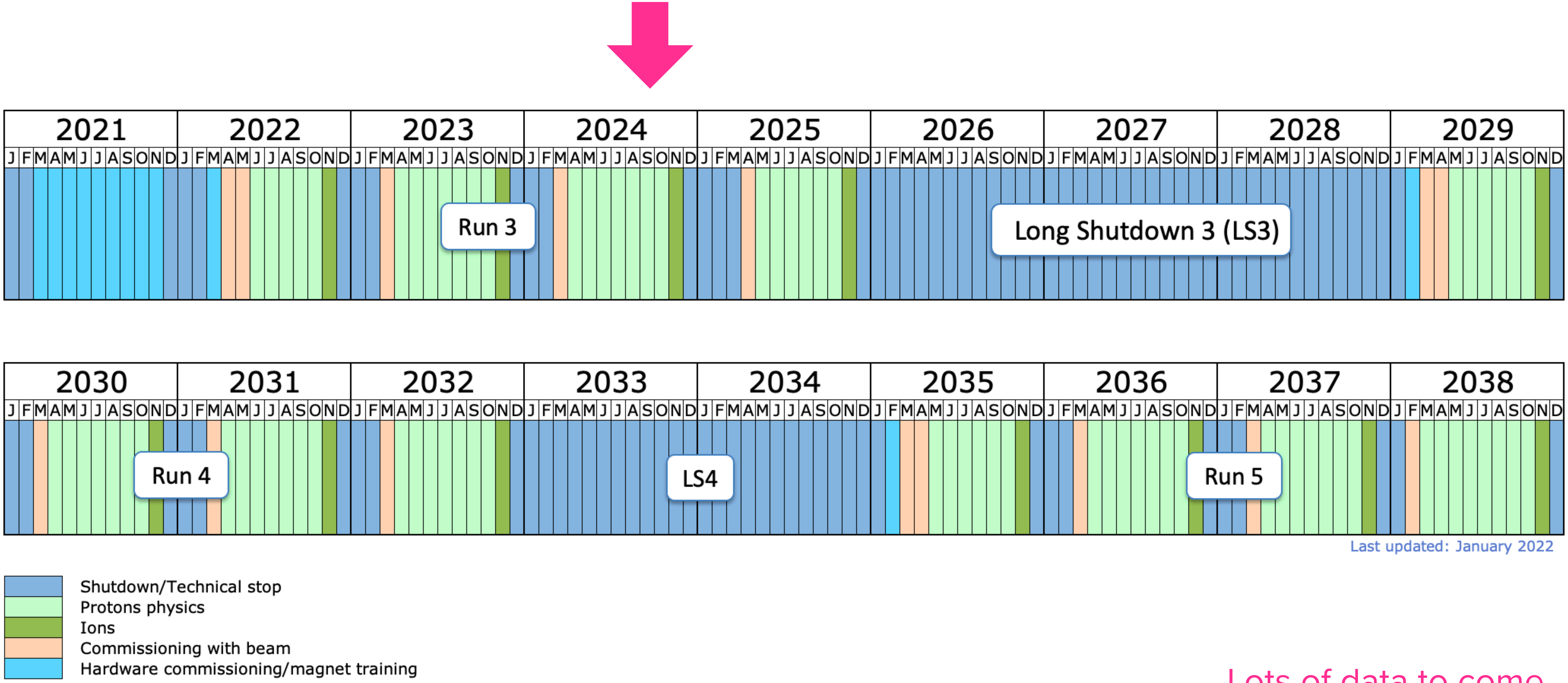
LHC Physics group: LHCEFT



arXiv:2402.05742

- We have analyzed only ~5% of the data that the LHC will ultimately collect (~140 fb^{-1} out of 3000 fb^{-1}, + partial analysis of Run3)
- We have not yet seen clear signs of new physics, but we have only excluded the simplest options
  - Nobody said nature was simple…
- We continue to explore, pushing for new and more complex signatures
- In parallel, measuring accurately takes us to the frontier of knowledge: measuring and searching are two sides of the same coin

WHAT NEXT?



Lots of data to come...

EVERYTHING?

SM Measurements: W, Z, Jets…

Higgs Boson Physics

Top Quark Physics

BSM Searches: Dark Matter, LLPs, New resonances, SUSY,….

B Physics

Heavy Ions

?

This is not all…
I leave Bphysics and Heavy Ions to other lecturers

SUMMARY

- The LHC is an unprecedentedly successful machine, **many experiments in one.**
  - In its first decade we have explored the word of particle physics in depth and delivered thousands of important precision measurements that cement our understanding of the SM _AND_ explored multiple different scenarios of new physics to go beyond its limits…
  - …. plus we discovered a new particle :), central to the SM, and fundamental to bring particle physics forward
- We are exploring the SM in depth though **precision studies in the QCD and EW realm:**
  - Foundation on which any LHC physics to do any other analyses
  - Measurement of fundamental SM parameters like mW, mt, sin2θeff, …
  - Much more to come: precision takes time
- **The LHC is a 'Top Factory'**, and the top a great laboratory to really explore the limits of our understanding of QCD

SUMMARY

- Understanding the nature of the **Higgs** is a priority for the field (European and American strategies dixit), and right now the LHC is the only machine able to study it:
  - In 2012 we knew we had found a new particle that looked like the Higgs boson, but we did not yet know what it was
  - 10 years later, we have measured its properties, observed it couple to bosons and fermions, and studied of its kinematics with increasing precision. It is now one of our best tools to understand the standard model and go beyond. We clearly surpassed many of the initial expectations, but there are many measurements to come, eg the self-coupling
  - Do we understand what it is, what it implies for the universe? Measuring precisely its properties is one of the keys to the unknown BSM realm, and one of the main goals of experimental particle physics today.
- **New physics searches at high masses/scales**:
  - One of the main objectives of the LHC program. Nothing new/exciting found until now, but still not the last word: Scope being extended to more exotic signatures and complicated phase spaces
  - More luminosity & detector enhancements in the next years should enlarge the scale reach and uncover possible signals at lower masses hiding under the background
- **We have only explored a very small fraction of the full LHC dataset, a lot of work and data is yet to come to better measure (or break?) the SM**