LHC Physics: what next?

J. Alcaraz (CIEMAT – Madrid)

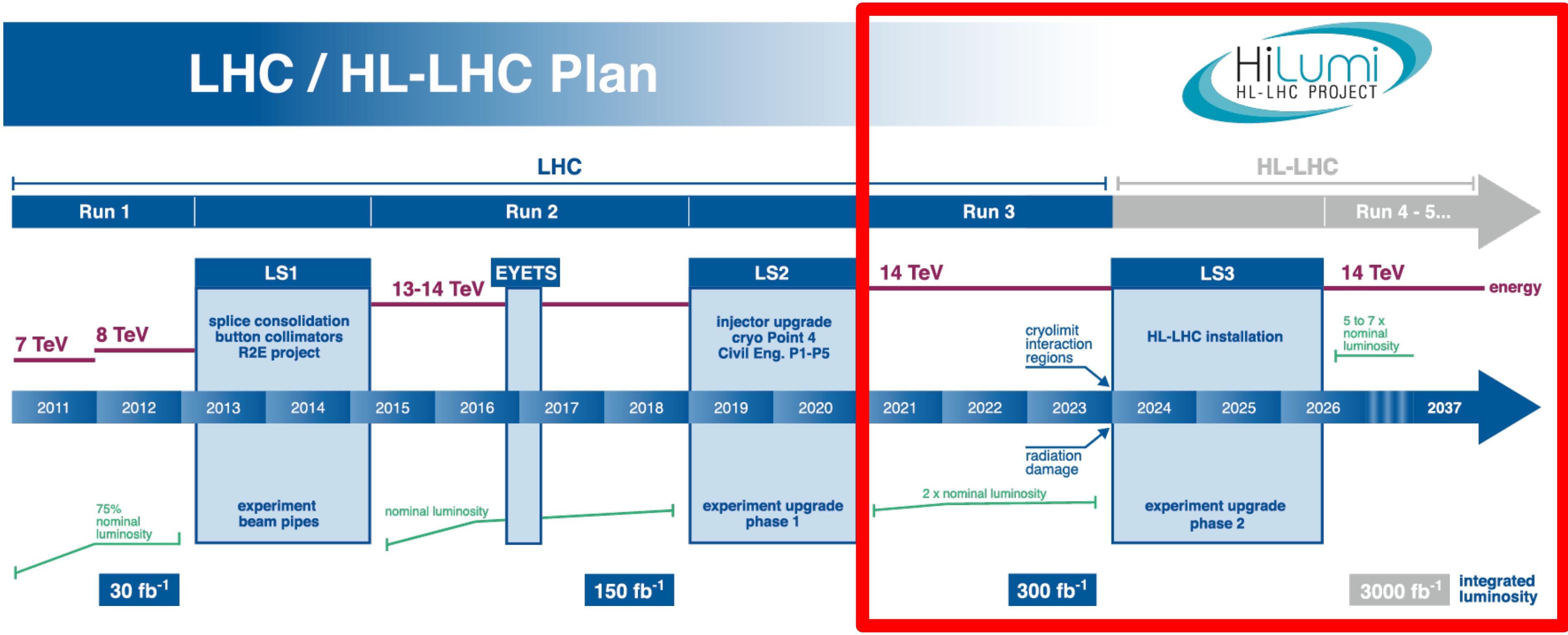
TAE 2019, Benasque

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
cfp CIEMAT física de partículas

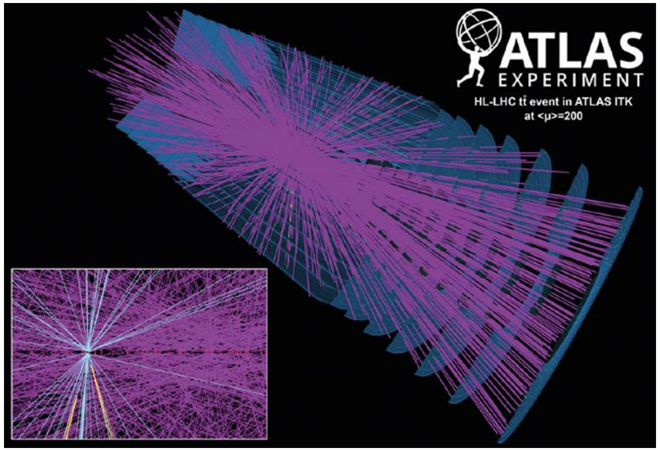
Outline

- HL-LHC and experimental conditions
- Main modifications to detectors
- Physics expectations

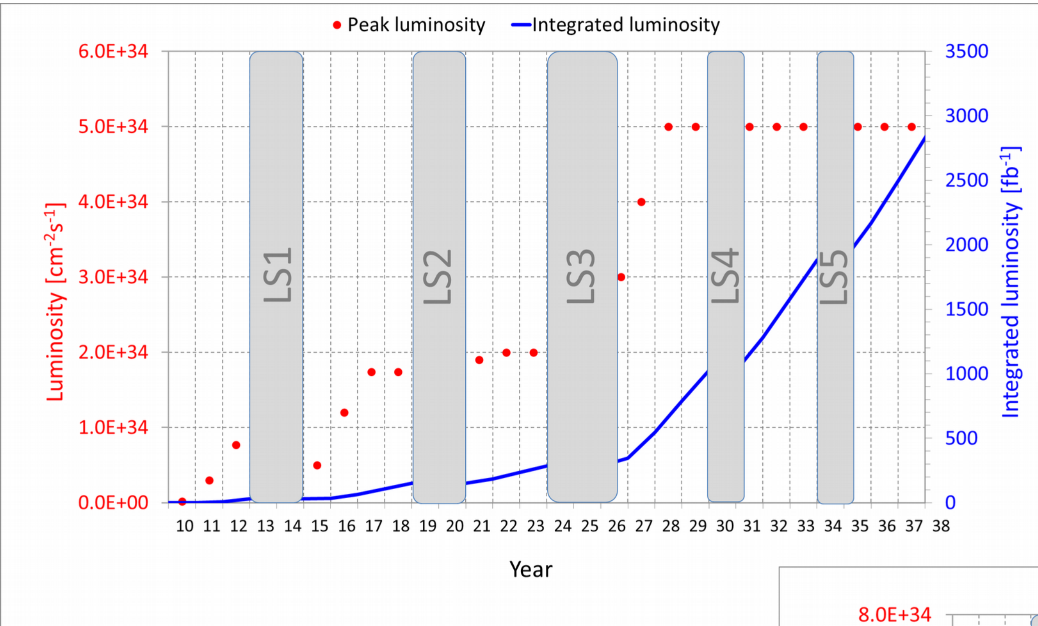
Evolution of LHC program



- Run3: moving to 14 TeV, add $\gtrsim$ 150 fb^{-1}
- HL-LHC: Up to 3000-4000 fb^{-1}
- Challenging conditions:
  - Instantaneous luminosities considered $\approx$ 5-7.5 10^{34} cm^{-2} s^{-1}
  - Pileup $\approx$ 200 events / crossing



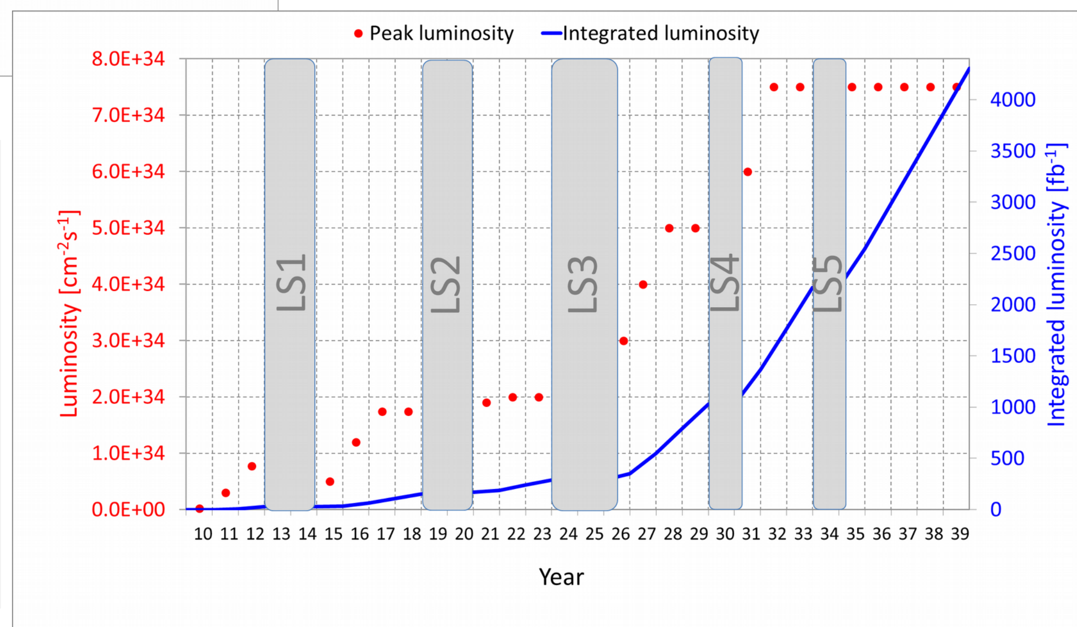
HL-LHC scenarios considered



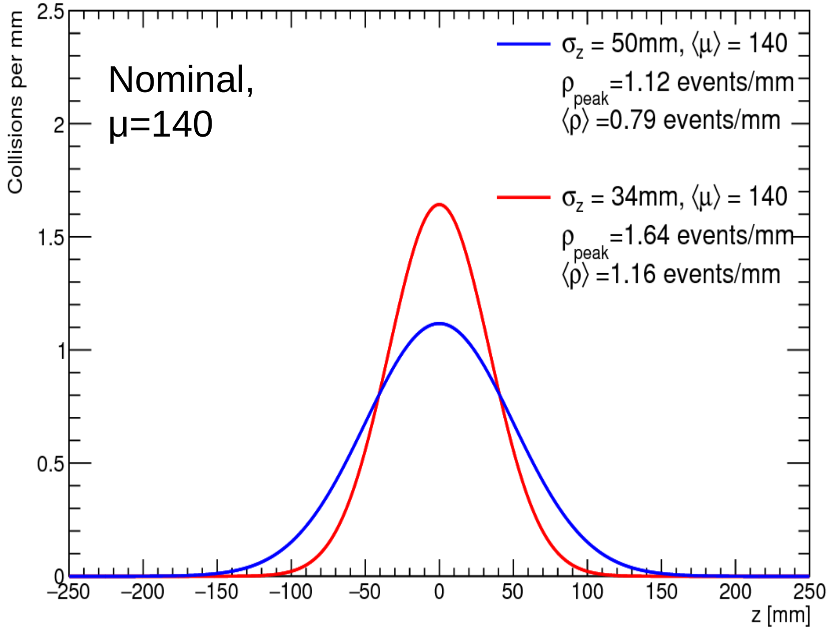
Nominal Scenario
Luminosity leveled at
5 x 10^{34} Hz/cm^2 ,
Pile-up $<\mu>$ = 140

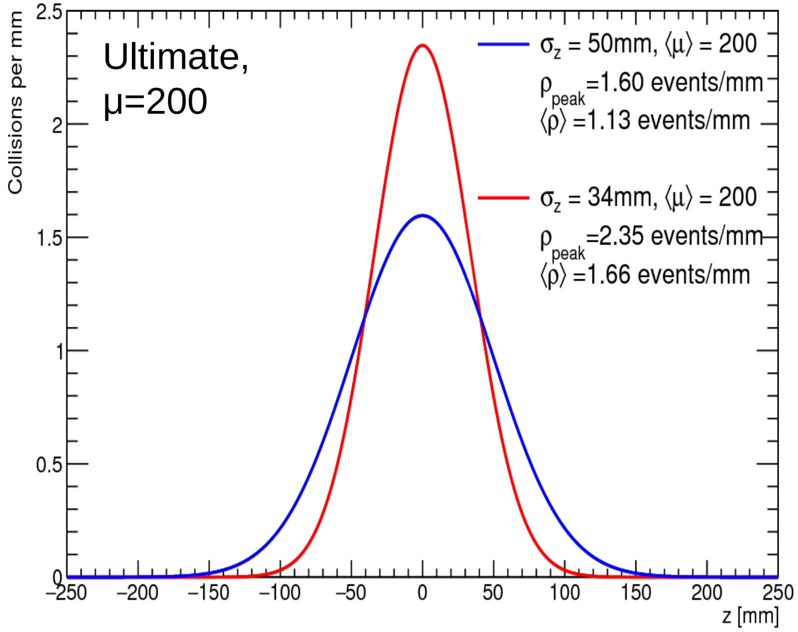
Ultimate Scenario
7. 5 x 10^{34} Hz/cm^2 ,
Pile-up $<\mu>$ = 200

→ ≃ 25% increase in integrated luminosity



HL-LHC pileup

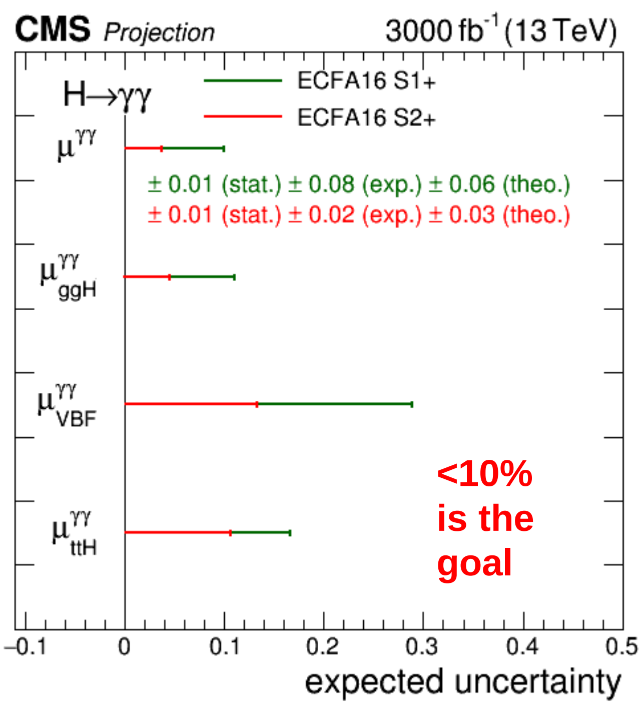


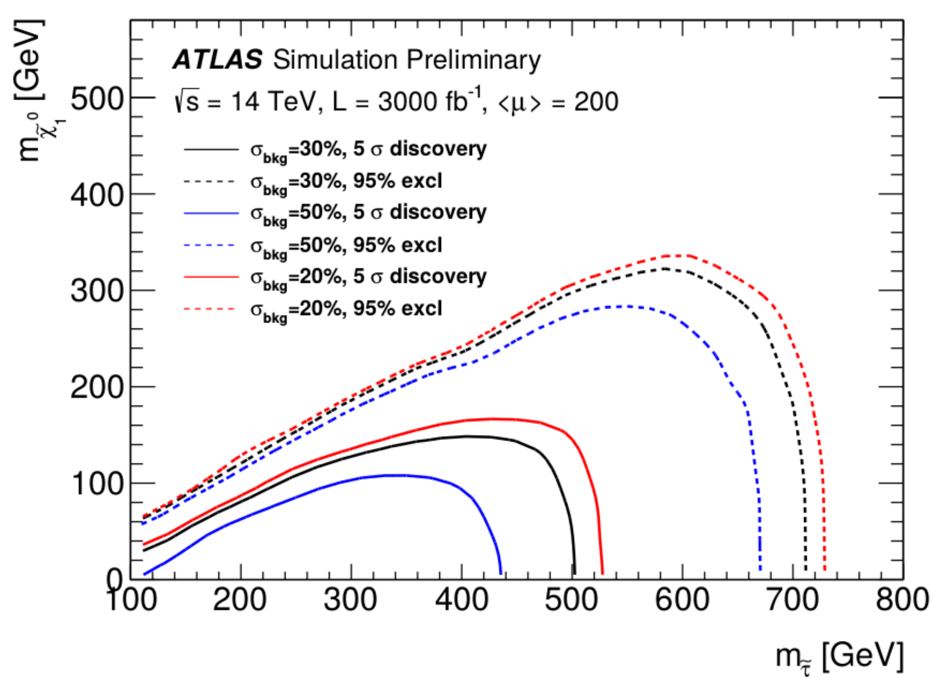


- **What is more relevant from the point of view of performance is the "event density" per crossing (typically expressed in events / mm)**

HL-LHC: Physics objectives

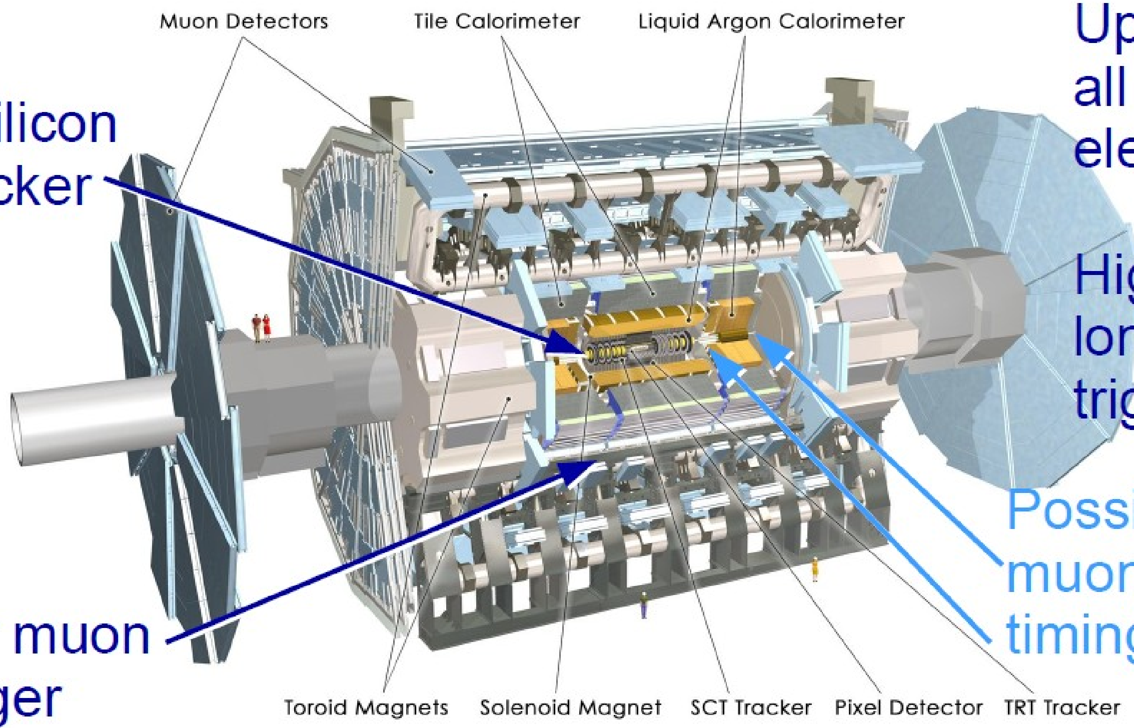
- **In a nutshell:**
  - **Next precision step for the understanding the Higgs / EWSB sector**
  - **Precision measurements of the SM in general, looking for deviations**
  - **Specific objective: measure/constrain the trilinear Higgs self-coupling**
  - **Search for New Physics signals, in particular with low predicted rates**





Big difference between exclusion and discovery reach

Summary of ATLAS Upgrades



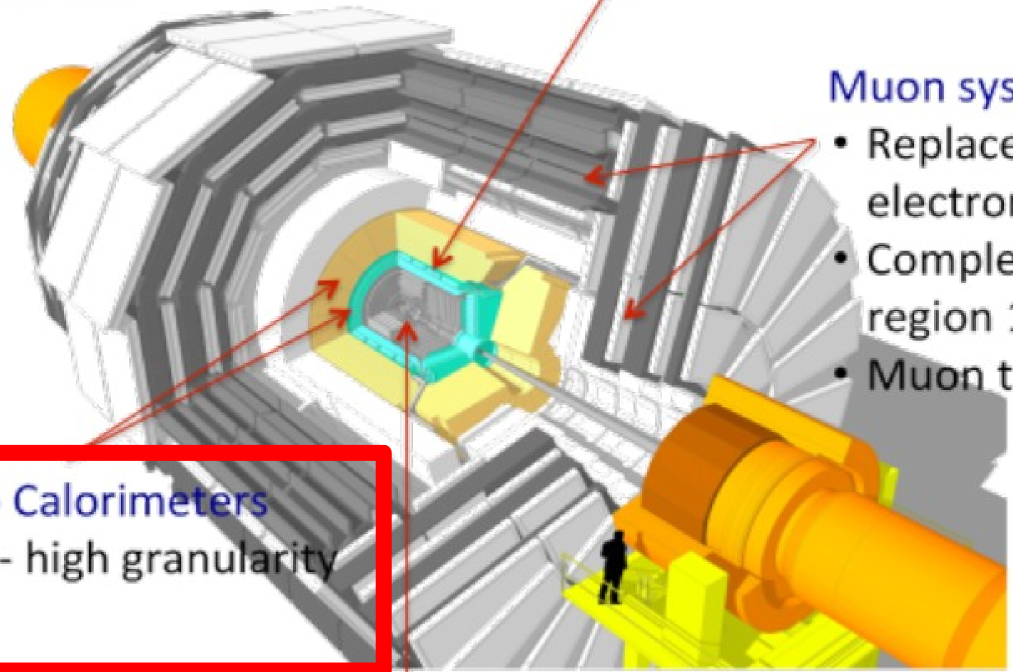
- **Commonalities between the two experiments:**
  - **New Inner Trackers**
  - **Upgraded electronics, able to cope with huge radiation dose/rates**
  - **New trigger systems (more latency, higher rate capabilities)**
  - **Plan to improve detection in forward regions, add timing capabilities**

Summary of CMS Upgrades

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 µs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8◦)

Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



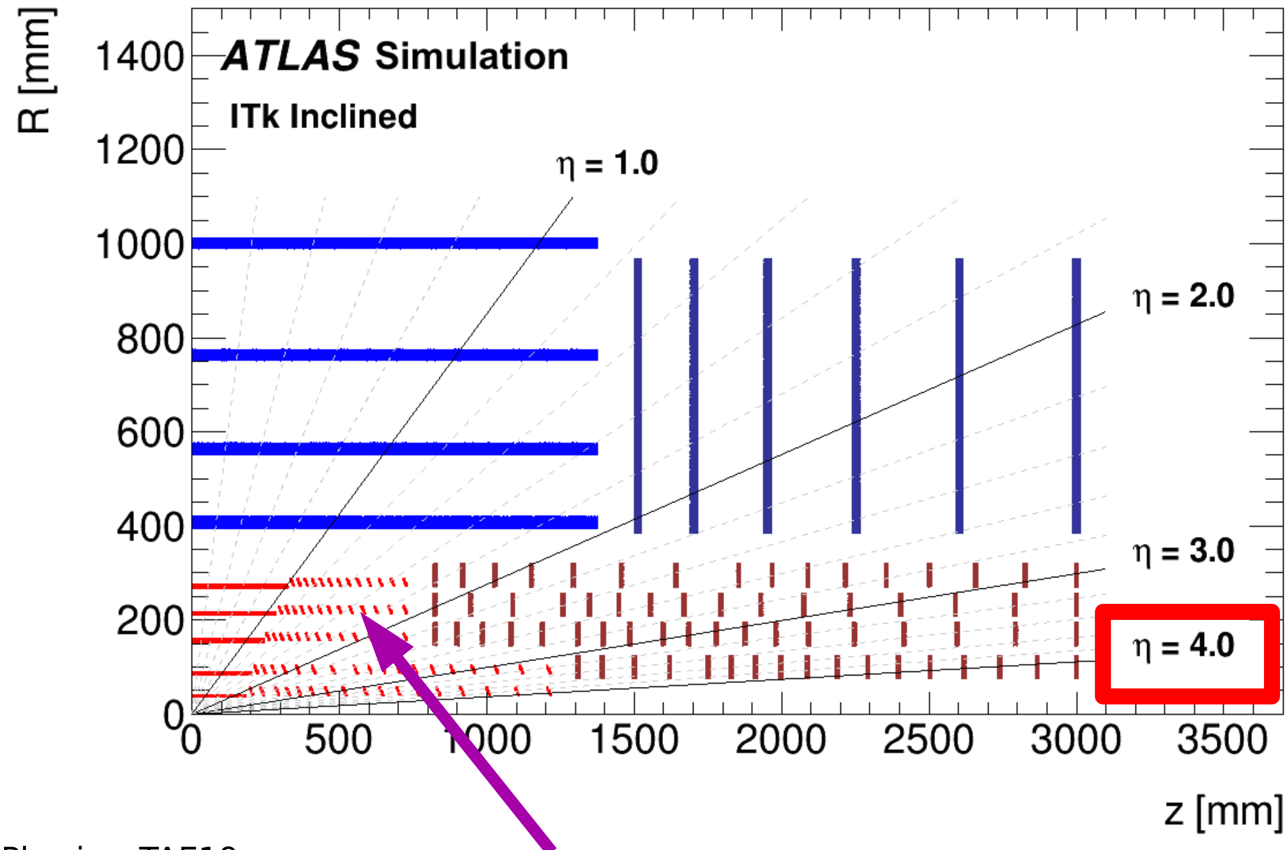
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

+ timing capabilities (barrel and endcap)

Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

ATLAS new inner tracker (ITk)

- Full silicon tracker (no TRT). Layout optimized since the first Letter of Intent:
  - Barrel: 5 pixel layers, 4 long outer strip layers
  - Endcap strips: 6 layers, covering up to $|\eta|<2.5$
  - Endcap pixel: multiple layers of sensors, including 'inclined' sensors in barrel (reducing material to be traversed); coverage up to $|\eta|<4$

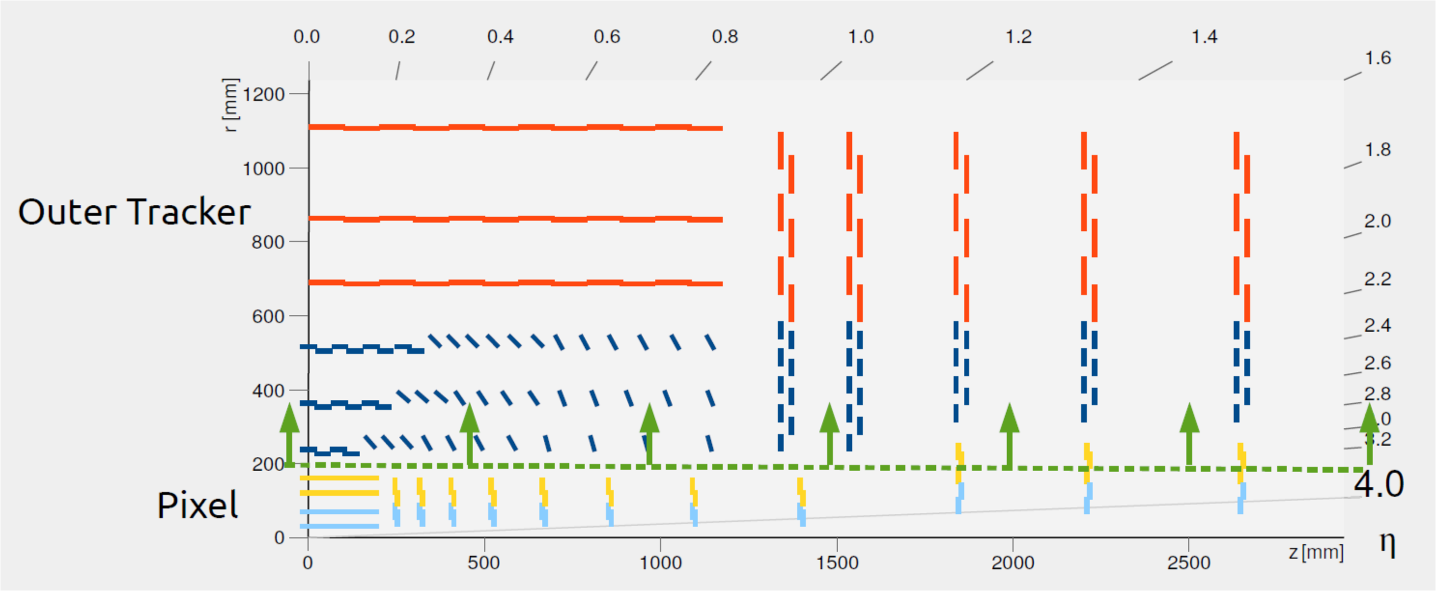


ATLAS-TDR-025

CMS new inner tracker

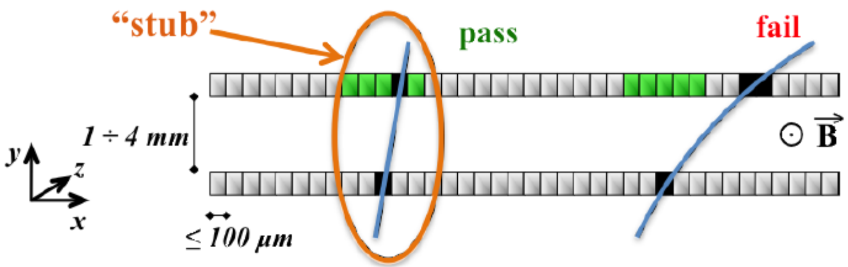
- **Specifically designed to provide inputs to L1 Trigger**
  - **Level 1 track-trigger finds tracks with pT≥2 GeV**
- **Outer tracker (6 layers, 5 disks)**
  - **Two-layer p_T-modules provide inputs to level 1 trigger**
  - **High granularity, efficient track reconstruction for >140 PU**
- **Pixel detector (4 layers, 11 disks)**
  - **Extended coverage with disks to |η|<4**
  - **Thin planar sensors 100μm or 3D sensors;**
  - **Small pixels (50x50 or 25x100 μm2)**
- **Improved material budget and radiation tolerance**

CMS-TDR-014

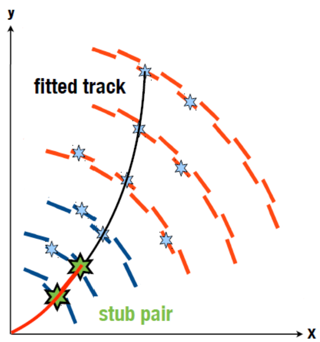


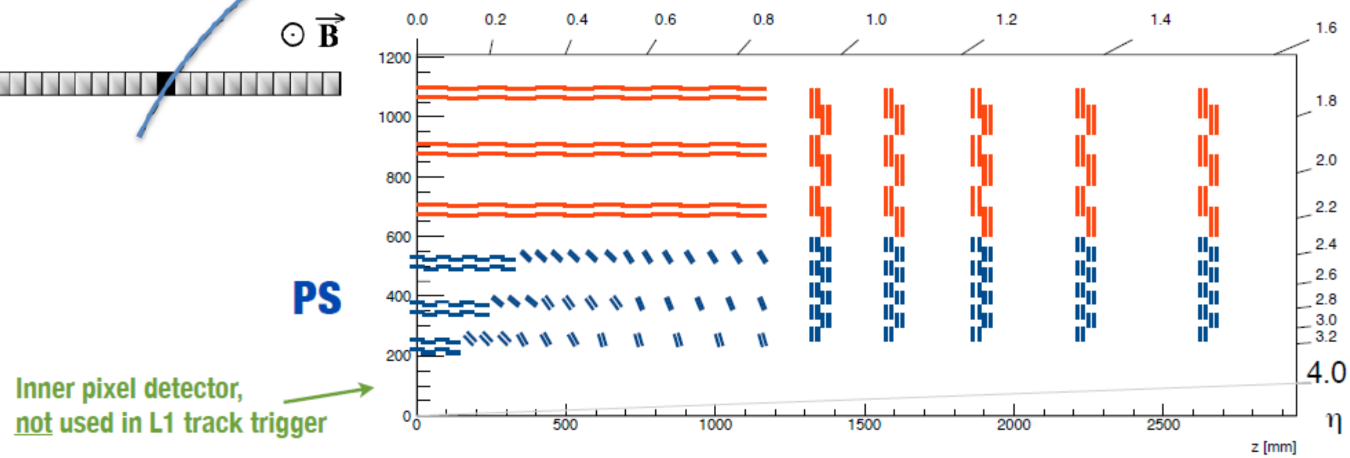
CMS L1 tracker trigger

- **Double layers in the outer part of the tracker are the inputs for L1 tracking**

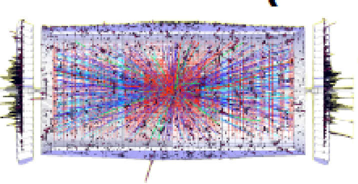


[CMS-TDR-014](CMS-TDR-014)





Data transfer (~50 Tbs)

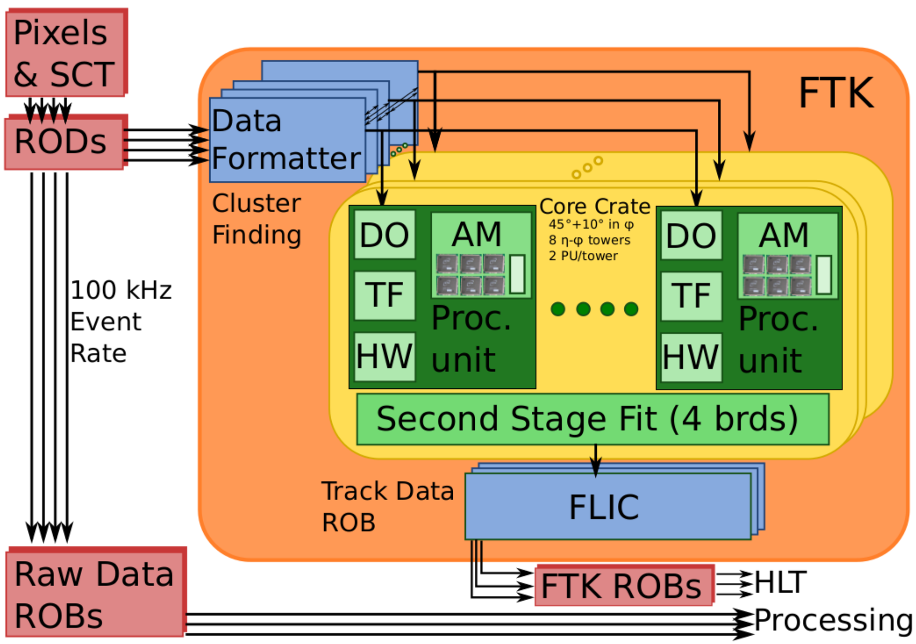


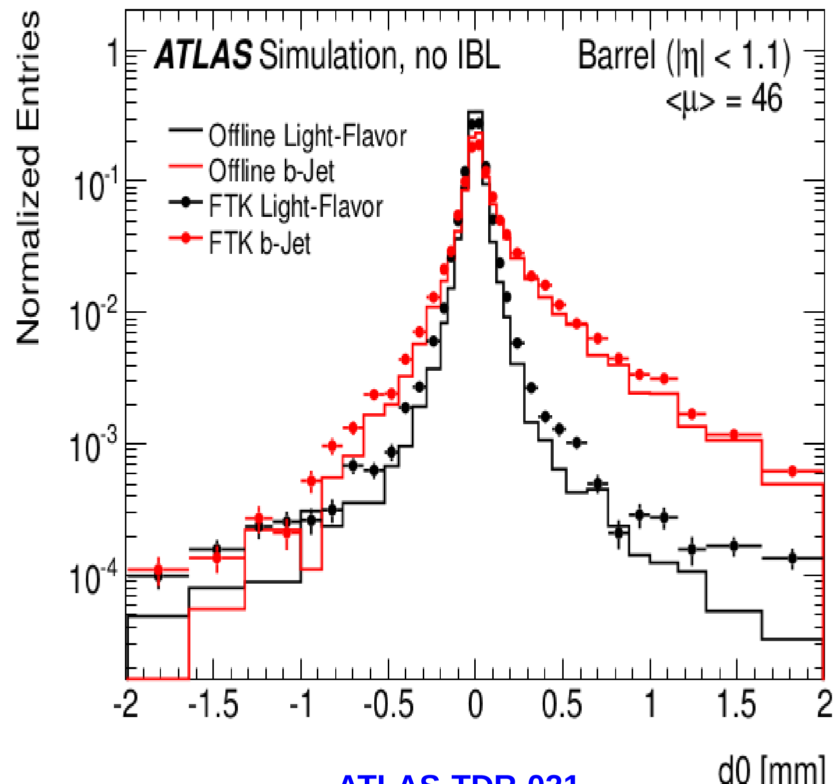
Δt = 0 → **Data formatting** → **Pattern recognition** → **Track fitting + duplicate removal** → **Δt = 4 μs**

Output tracks to L1 trigger

ATLAS L1 tracker triggers

- **L1Track: able to perform regional tracking at 1 MHz; latency: a few μs**
- **FTK++: able to perform full event tracking after L1 at ≈ 100 KHz using massive parallelism; latency ~ 100 μs**





ATLAS-TDR-021

- **FTK is part of the Phase1 ATLAS upgrade:**
  - **full system already deployed in Run2**

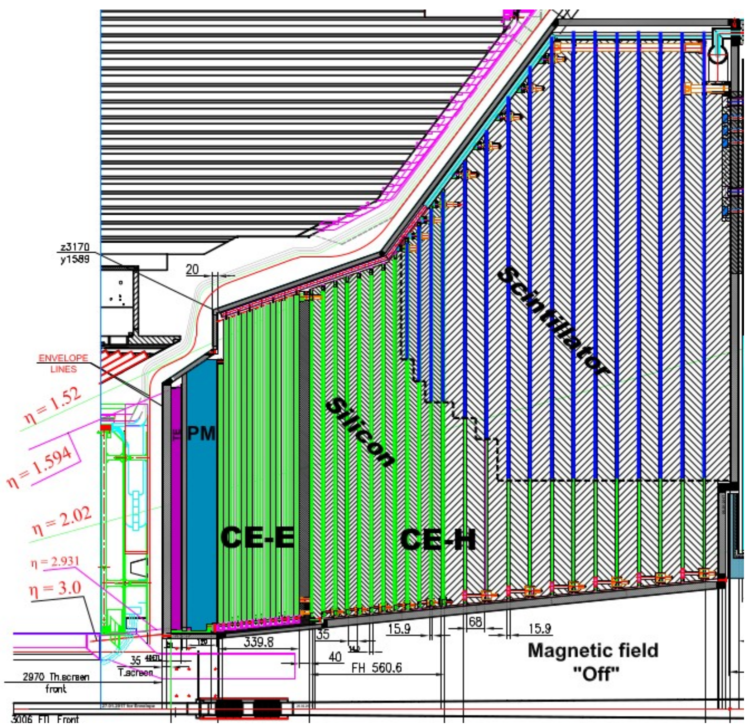
CMS endcap calorimeter (HGC)

HGC=High Granularity Calorimeter. Largely based on R&D studies for future detectors (CALICE). Use silicon sensors to allow detailed 4D (space-time) reconstruction of showers. Three parts:

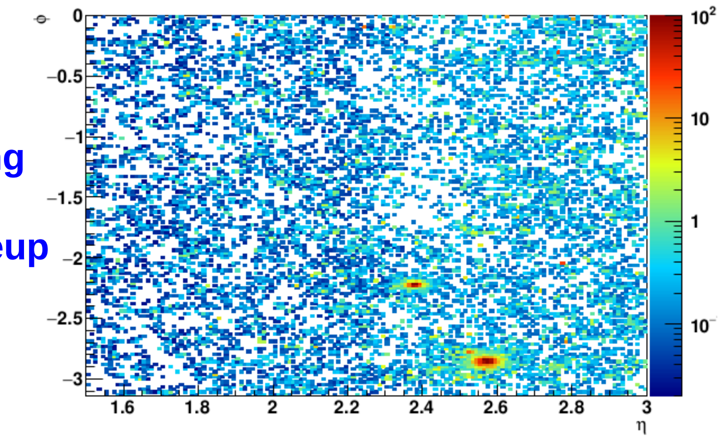
- **CE-E: 28 sampling layers with silicon sensors + W/Cu absorber, ≈ 26 X_0 (rad. lengths)**
- **CE-H: 12+12 layers of silicon/scintillators + stainless steel absorber**
- **Complicated structure due to expected radiation levels, ≈ 10.7 λ (absortion lengths) in total**

CMS-TDR-019

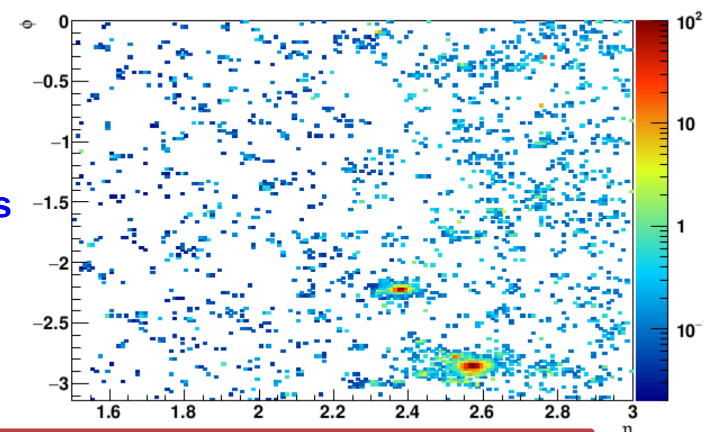
CMS-TDR-019



No timing cuts to reject pileup

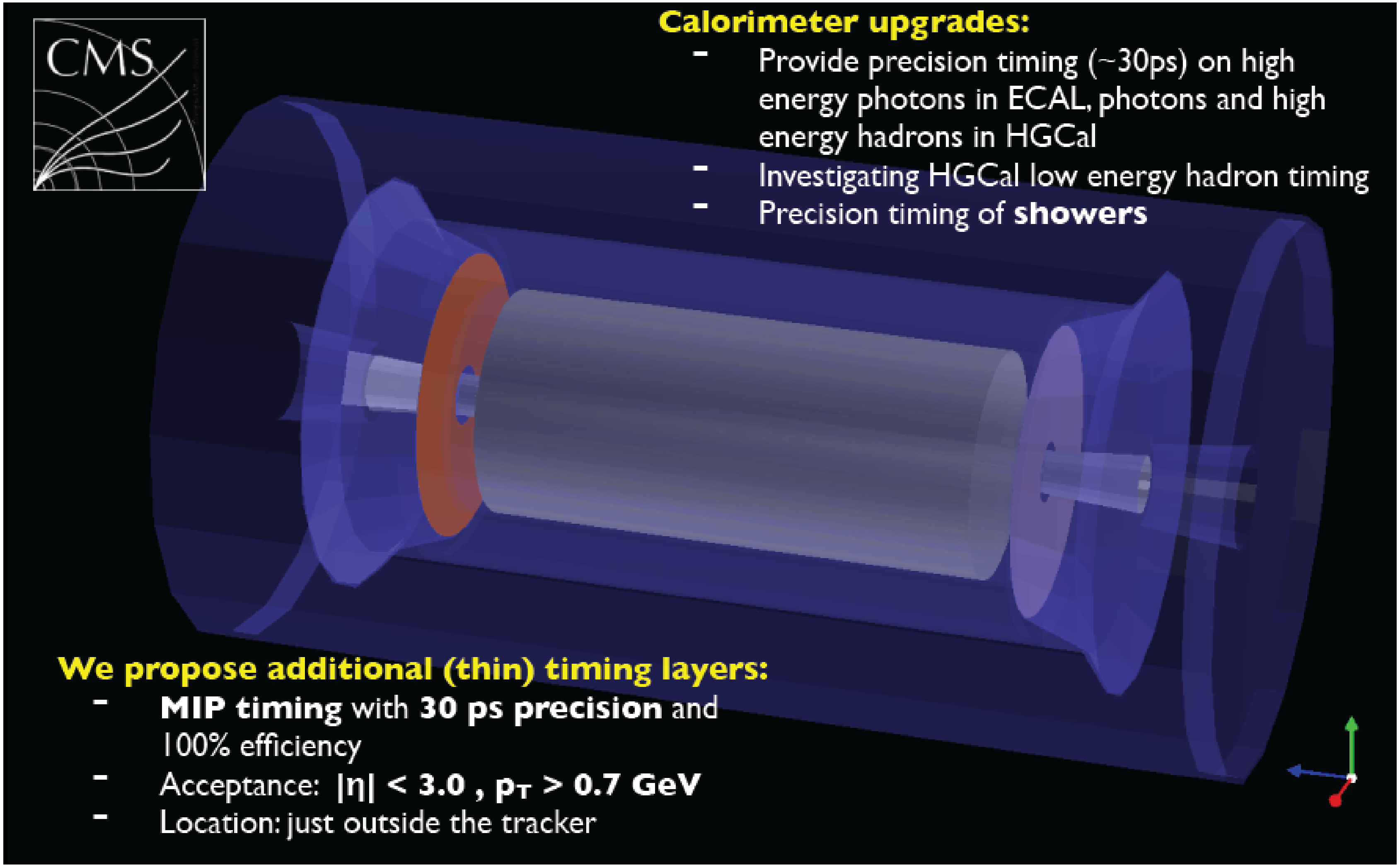


Reject Δt>90 ps hits



H→γγ simulated event, φ vs η map

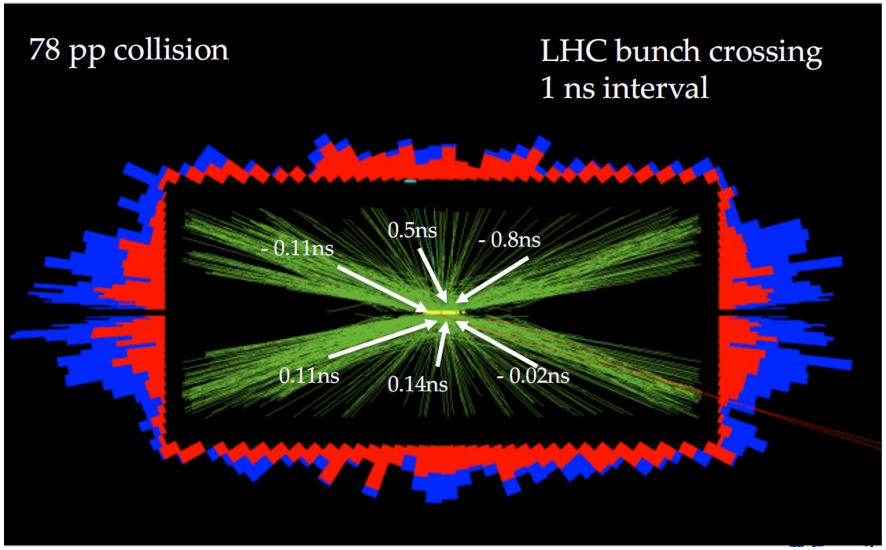
Specific timing detectors

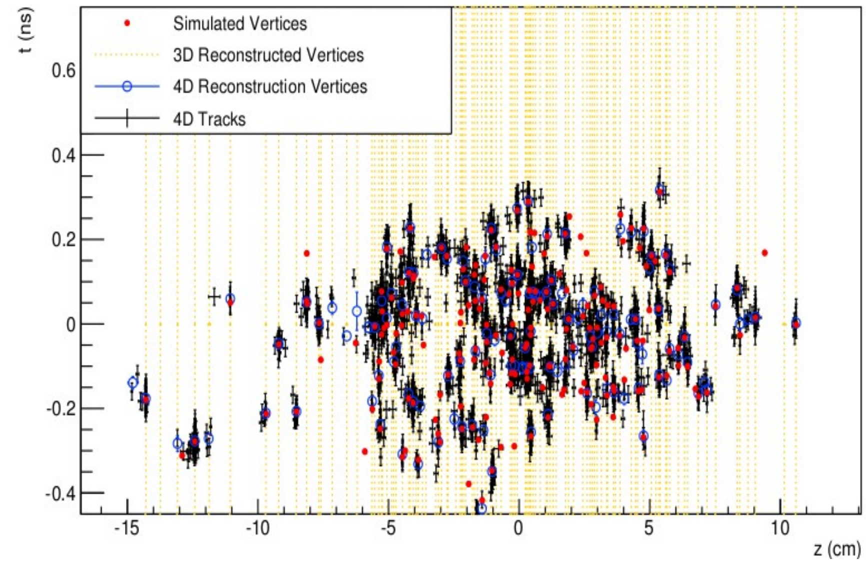


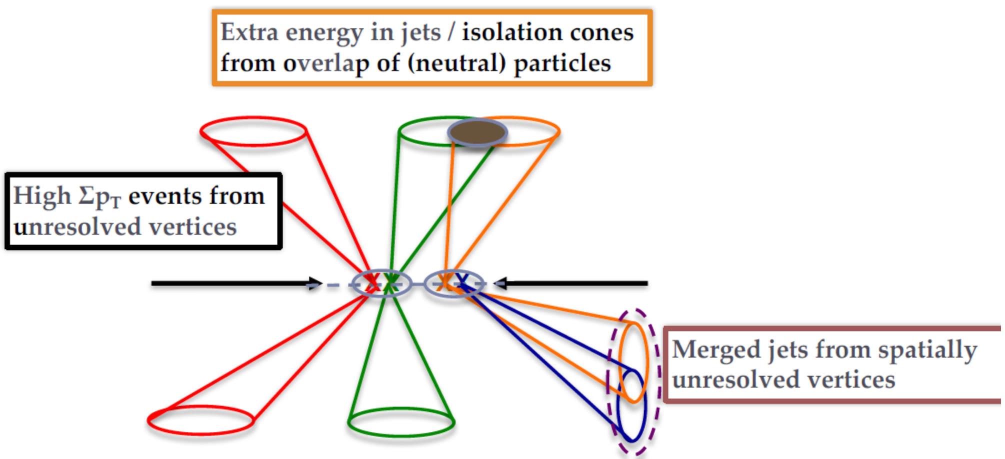
- **Significant potential to improve pileup identification (next slide)**

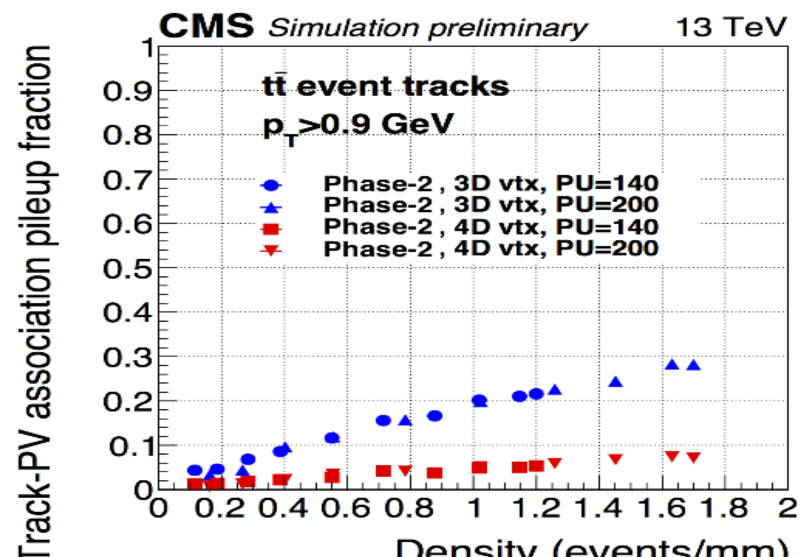
Timing detectors: CMS example

LHCC-P-009



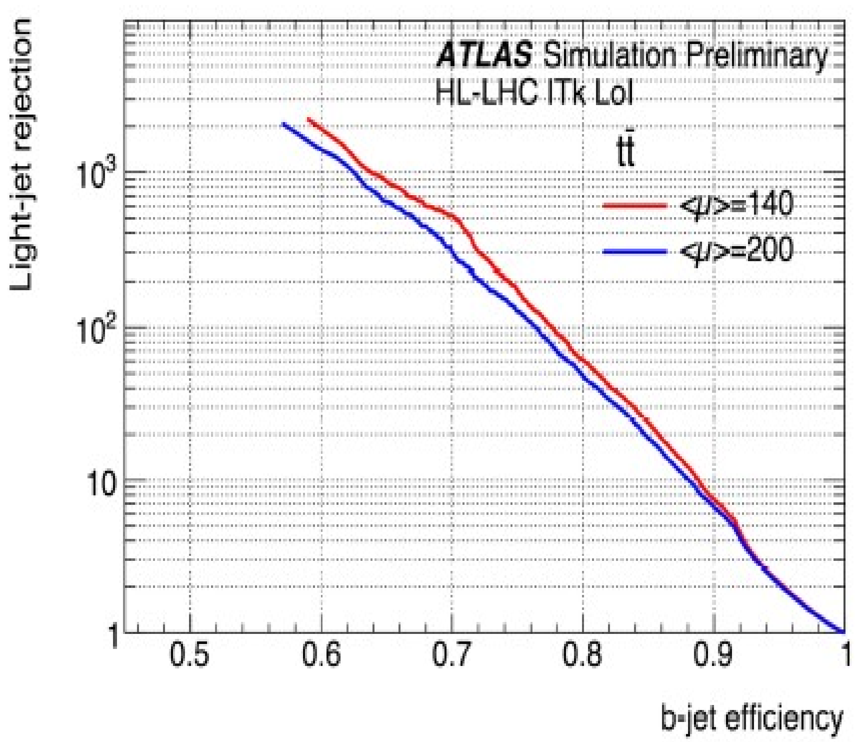


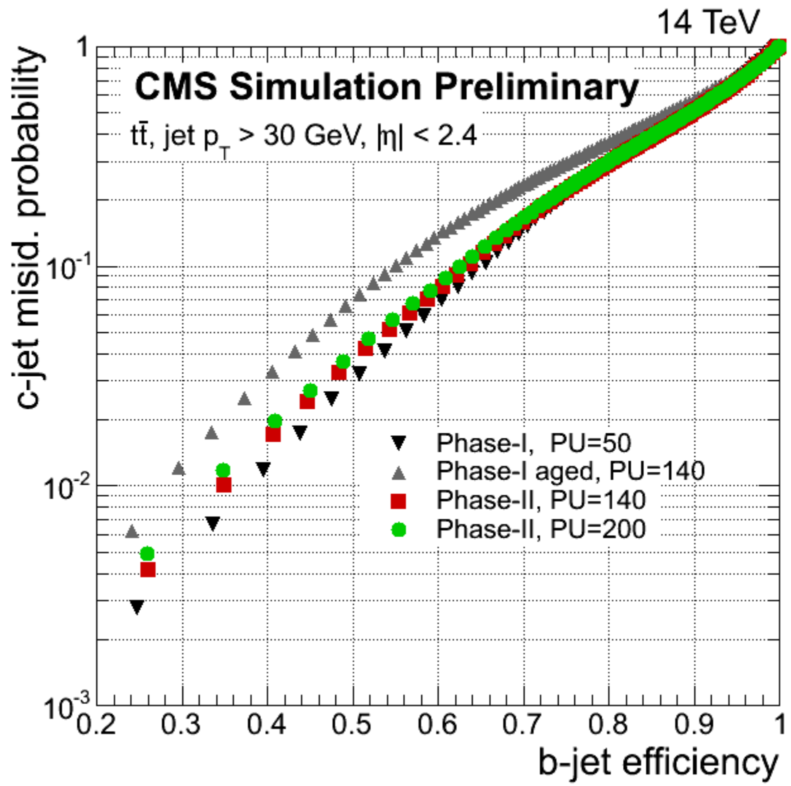




- **Significant potential to improve pileup identification performance**

Dealing with HL-LHC pileup



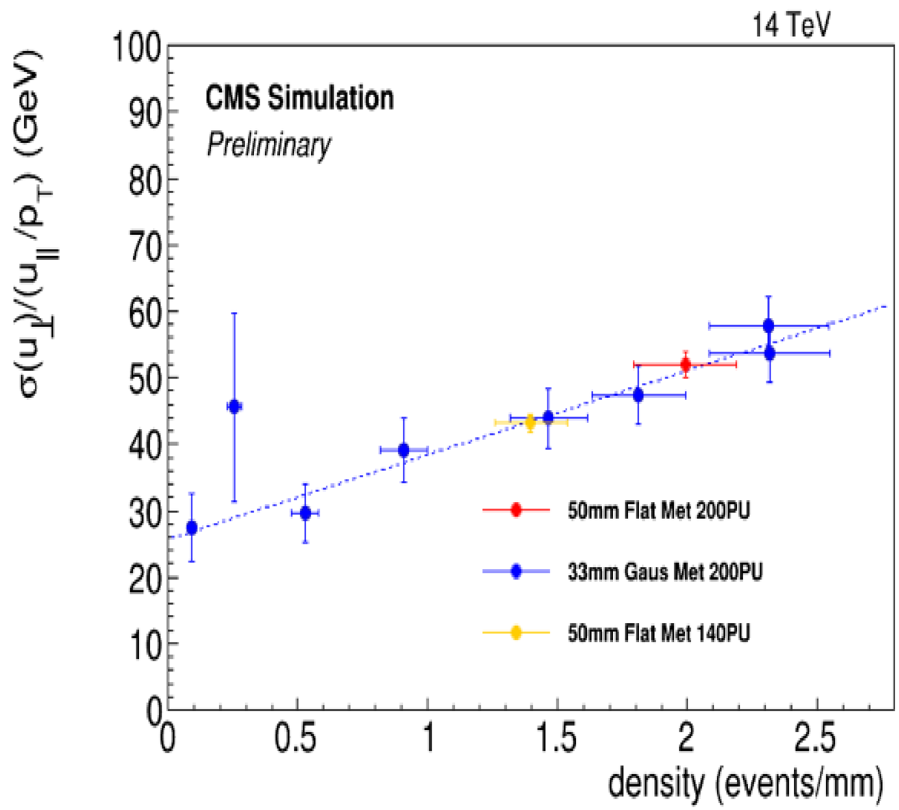


Small b-tagging degradation with pileup

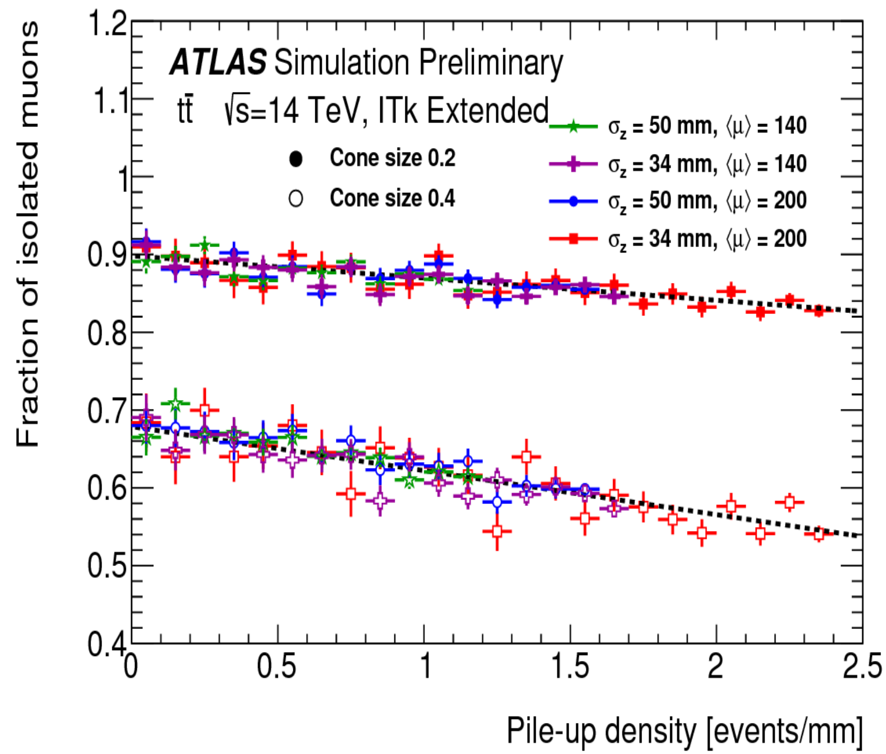
B-tagging capabilities similar to those available in Run2

- **Despite the harsh conditions, experiments are planning for upgraded detectors with optimal performance, at least similar to that of Run2**

Dealing with HL-LHC pileup



Missing transverse energy resolution (width of response shown; expected mean = 0 here)

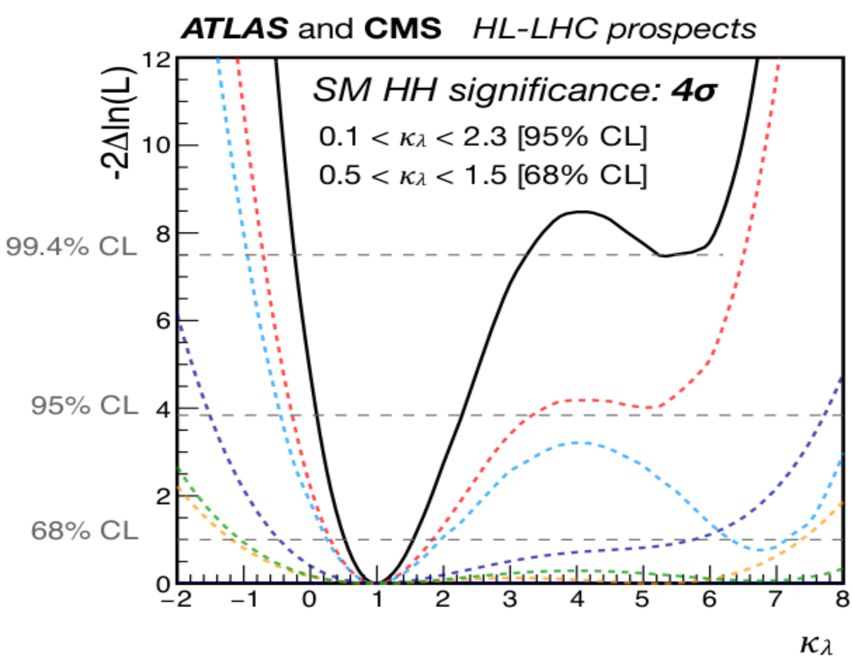


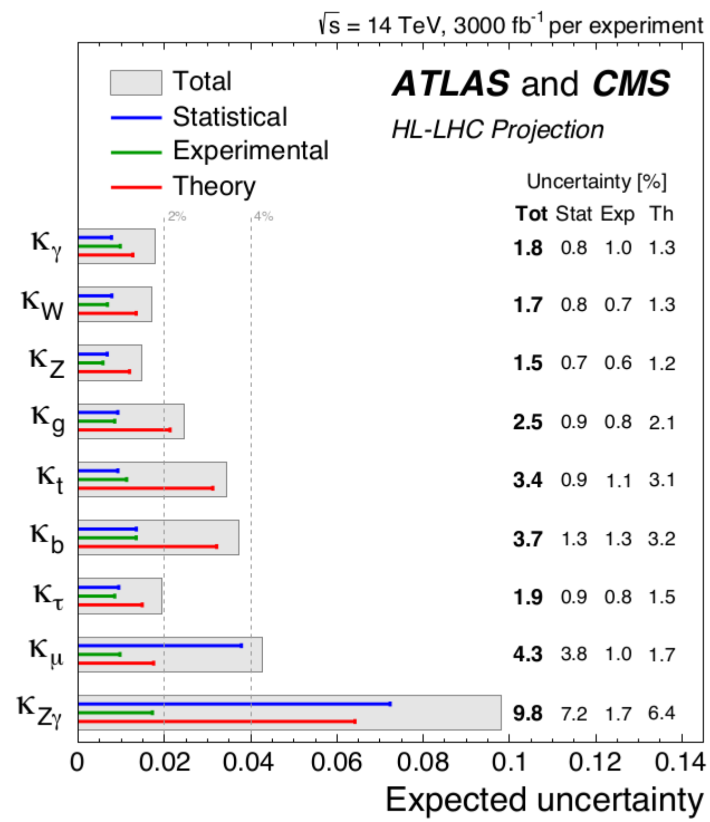
Isolation efficiency for muons

- **Performance dependent only on pileup density (not amount ot pileup or other beam bunch details)**
- **Despite the harsh conditions, experiments are planning for upgraded detectors with optimal performance, at least similar to that of Run2**

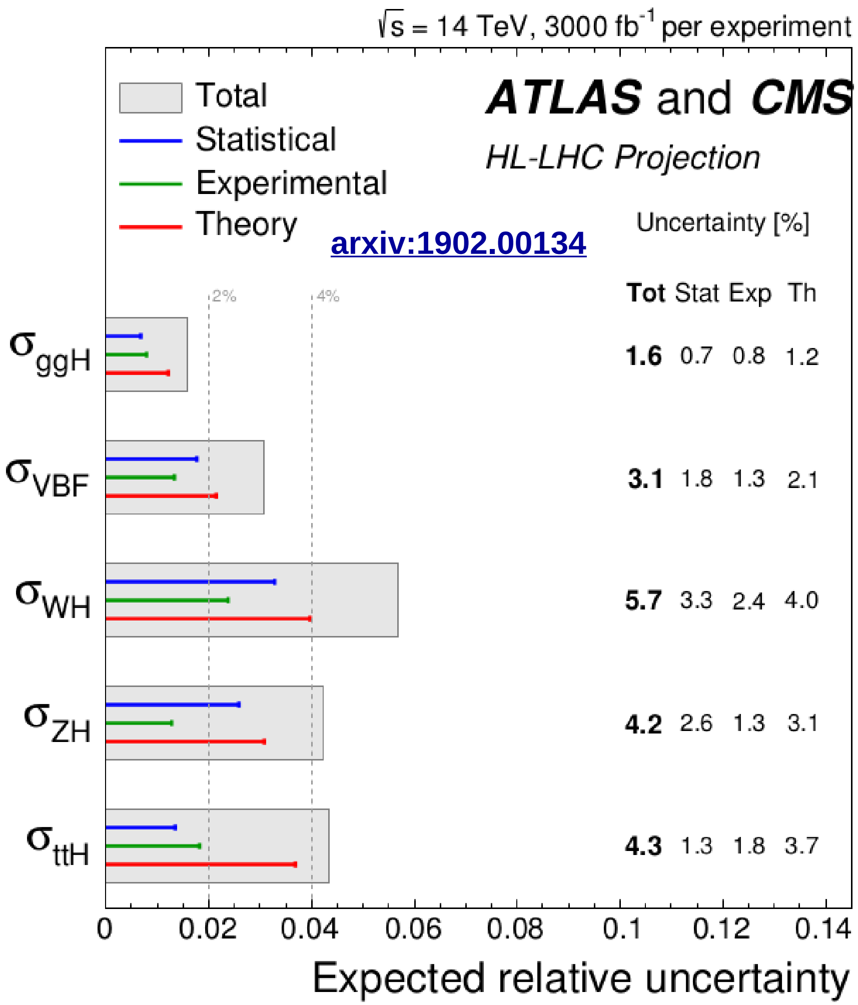
HL-LHC: physics studies

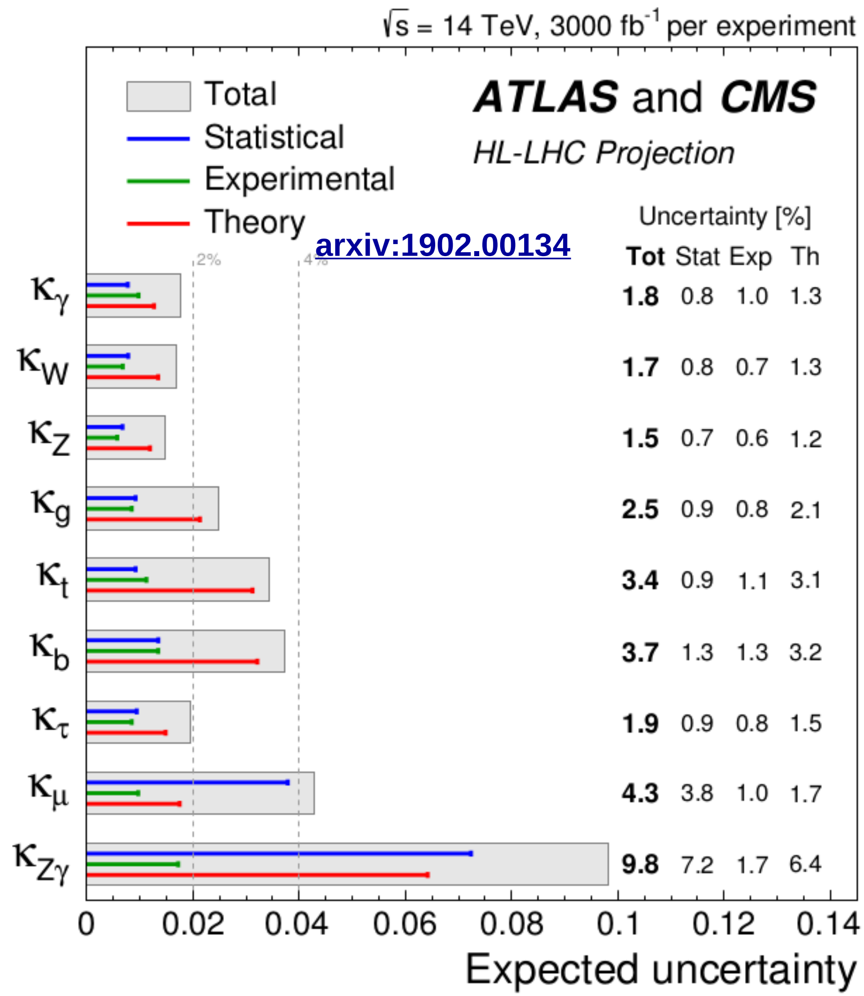
- **Physics objectives of HL-LHC (reminder):**
  - **Next precision step for the understanding the Higgs / EWSB sector**
  - **Precision measurements of the SM in general, looking for deviations**
  - **Specific objective: measure/constrain the trilinear Higgs self-coupling**
  - **Search for New Physics signals, in particular with low predicted rates**
- **Many studies were recently updated for the purpose of the ongoing European Strategy Group discussions. Steering references:**
  - **Higgs: https://arxiv.org/abs/1902.00134**
  - **SM: https://arxiv.org/abs/1902.04070**
  - **BSM: https://arxiv.org/abs/1812.07831**





Higgs production/couplings





- **Note that systematics and theory uncertainties are large and usually dominate**
- **$H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$ are the exceptions: low branching fractions ⇒ higher statistical uncertainty**
- **Precision on the individual production mechanism cross sections: $\lesssim$5%,**
- **On couplings → HWW,HZZ: <2%, H$\mu\mu$: <5%, other H$f\bar{f}$ couplings: <4%**

Uncertainties for HL-LHC

CMS PAS FTR-16-002

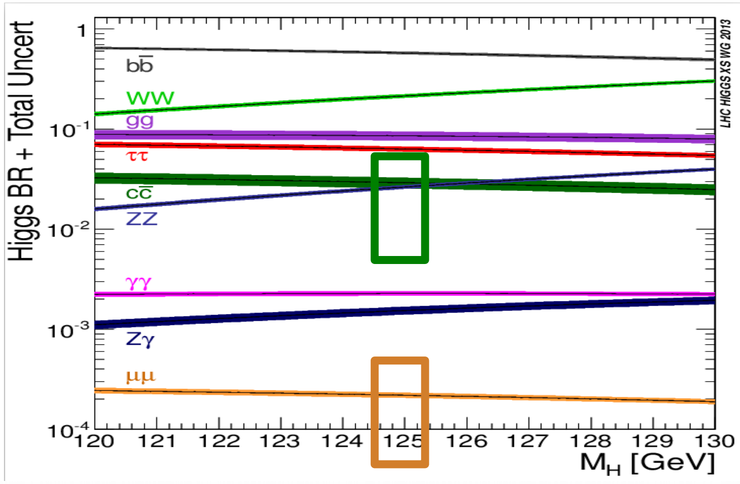
Implemented Strategy

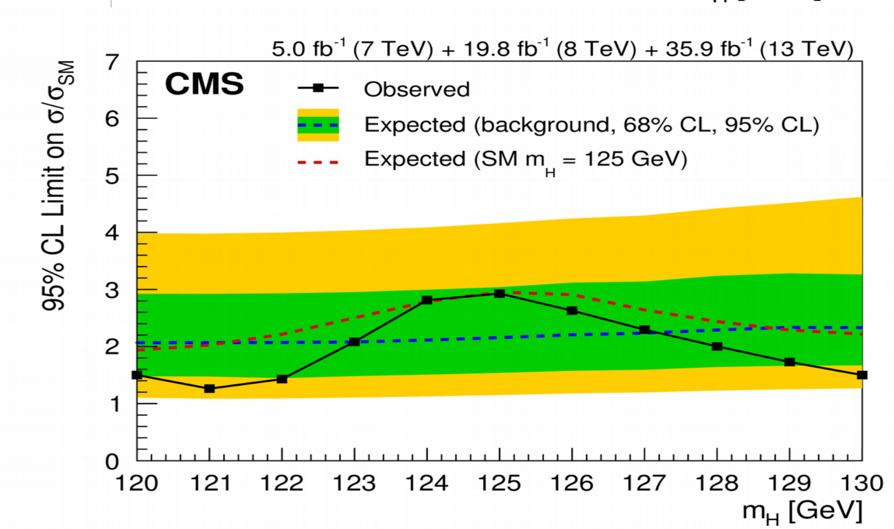
	S1	S1+	S2	S2+	
Data statistics	✓	✓	✓	✓	Scaling of statistical uncertainty √L
Detector improvements		✓		✓	Accounts for expected improvements of detector performance and degradation due to additional pile-up
Projection of systematics			✓	✓	Accounts for expected systematic uncertainties achievable at HL-LHC

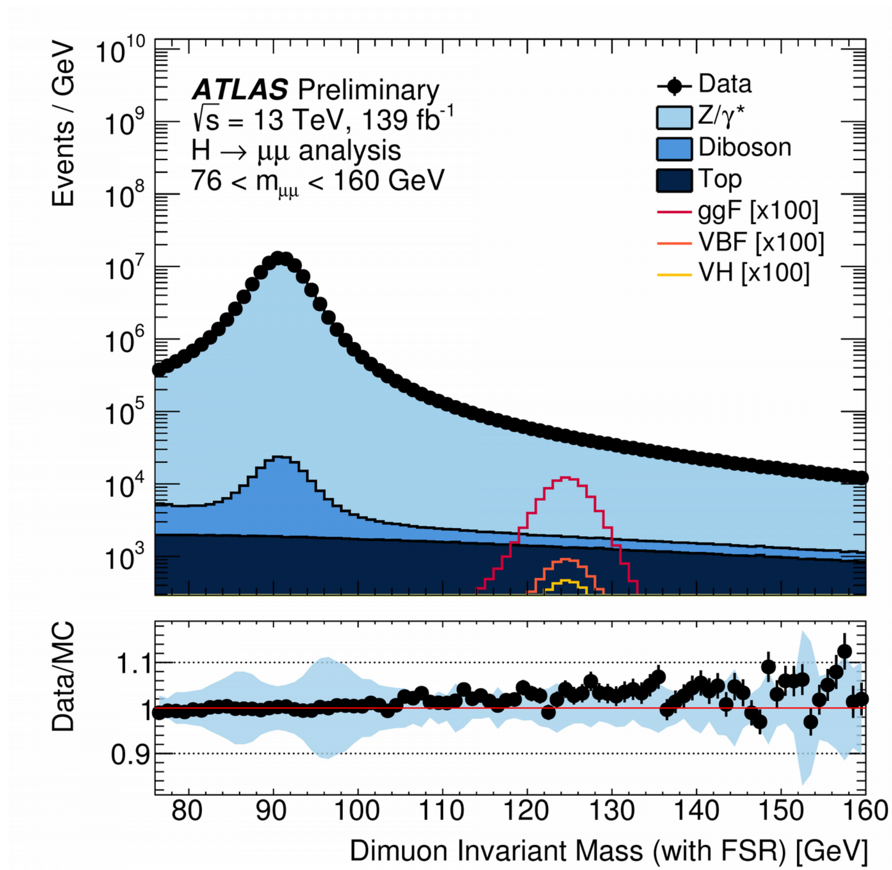
- **statistics-driven sources: data → √L, simulation → 0**
- **intrinsic detector limitations stay ~constant**
  - often new methods are expected to compensate pile-up effects
- **theory normalization/modeling → ½**

Reminder: H→μμ in Run2

- **Another critical test of EWSB within the SM: does the Higgs couple to second generation fermions?**
- **Next Higgs challenge at LHC: needs huge integrated luminosity to be observed. Currently only limits.**
- **$H \to c\bar{c}$ inaccessible even at high-luminosity LHC (backgrounds). SM H→μμ at reach in next LHC runs**
- **Search similar in spirit to H→γγ: narrow peak on top of a huge smooth background (≈SM Drell-Yan μμ)**



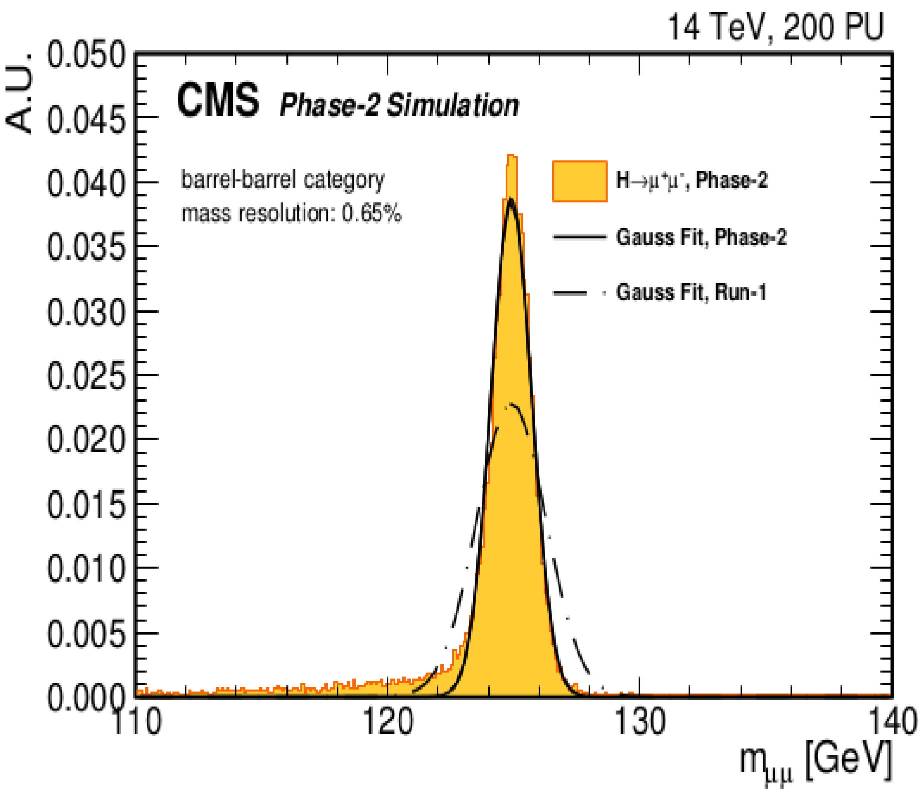




ATLAS-CONF-2019-028

H → μμ at HL-LHC

arxiv:1902.00134



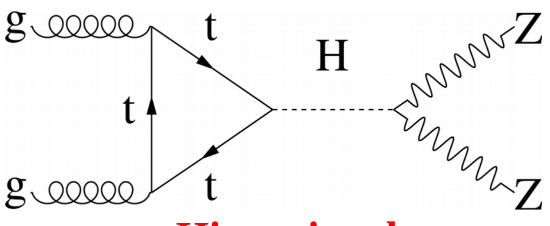
Experiment	ATLAS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	$^{+15\%}_{-14\%}$	$^{+13\%}_{-13\%}$
Statistical uncert.	$^{+12\%}_{-13\%}$	$^{+12\%}_{-13\%}$
Experimental uncert.	$^{+3\%}_{-3\%}$	$^{+2\%}_{-2\%}$
Theory uncer.	$^{+8\%}_{-5\%}$	$^{+5\%}_{-4\%}$

Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

- **The measurements profits from an improved tracker resolution at HL-LHC**
- **Note that uncertainties in these tables correspond to the signal strength | cross section, which is ≈twice the uncertainty on the Hμμ coupling**

Reminder: Higgs width measurement

- **Key feature: the Higgs off-shell contribution to "on-shell" ZZ final states is not negligible, even if the Higgs is narrow**
- **Exploit invariant mass of the 4l system plus additional kinematics information (matrix element)**



Higgs signal

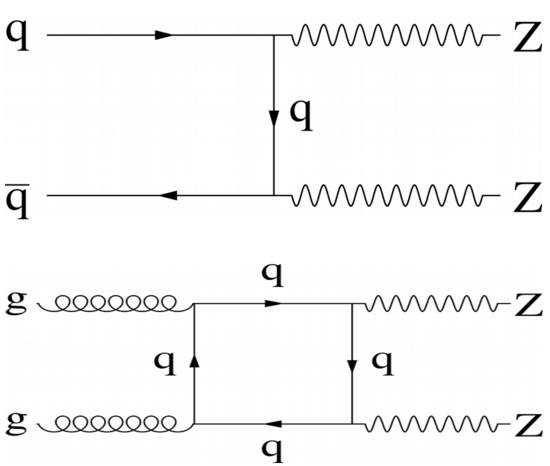
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H},$$

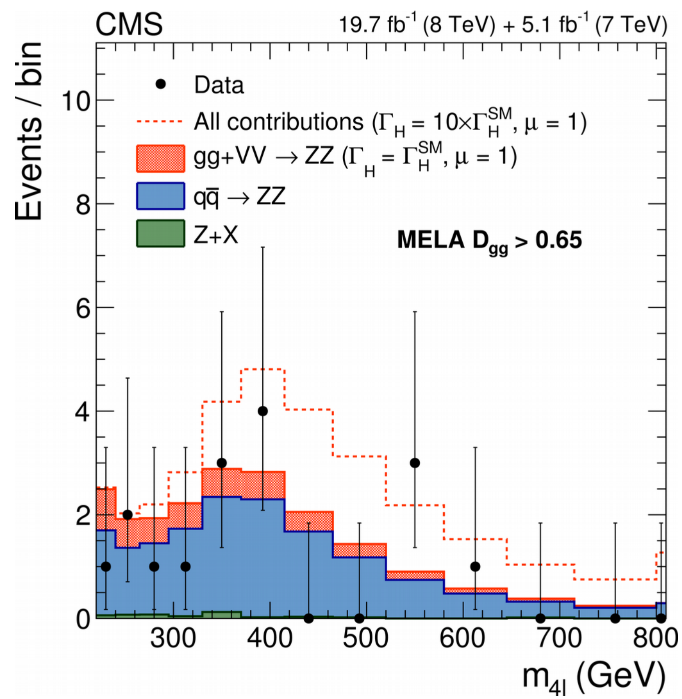
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}.$$

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

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

Background (interfering)



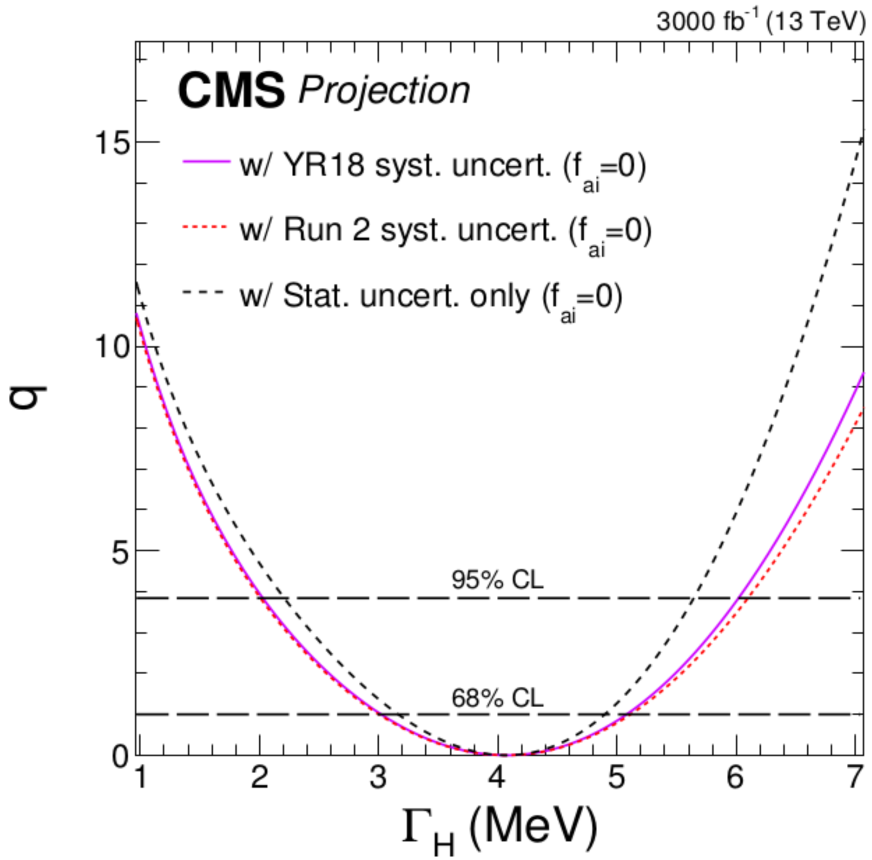


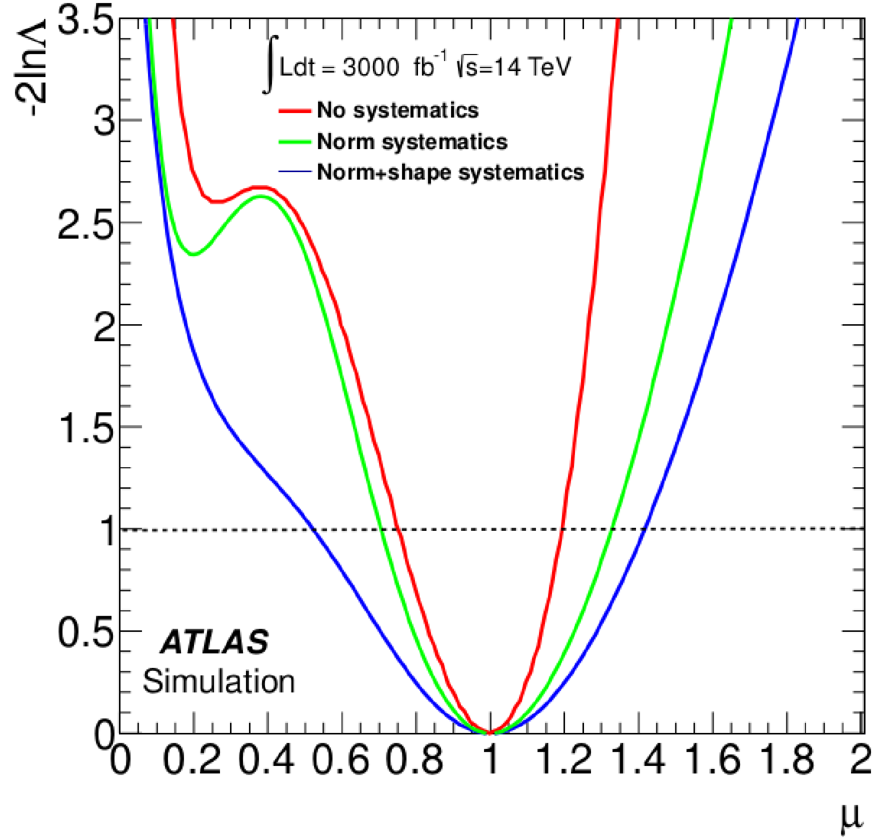
[arxiv:1405.3455](https://arxiv.org/abs/1405.3455)

Higgs width at HL-LHC

arxiv:1902.00134

- Precise measurement expected !!
- Similar techniques to those used in Run2: matrix element and m_{4l}
- Theoretical modeling of the invariant mass shape to be kept under control !!

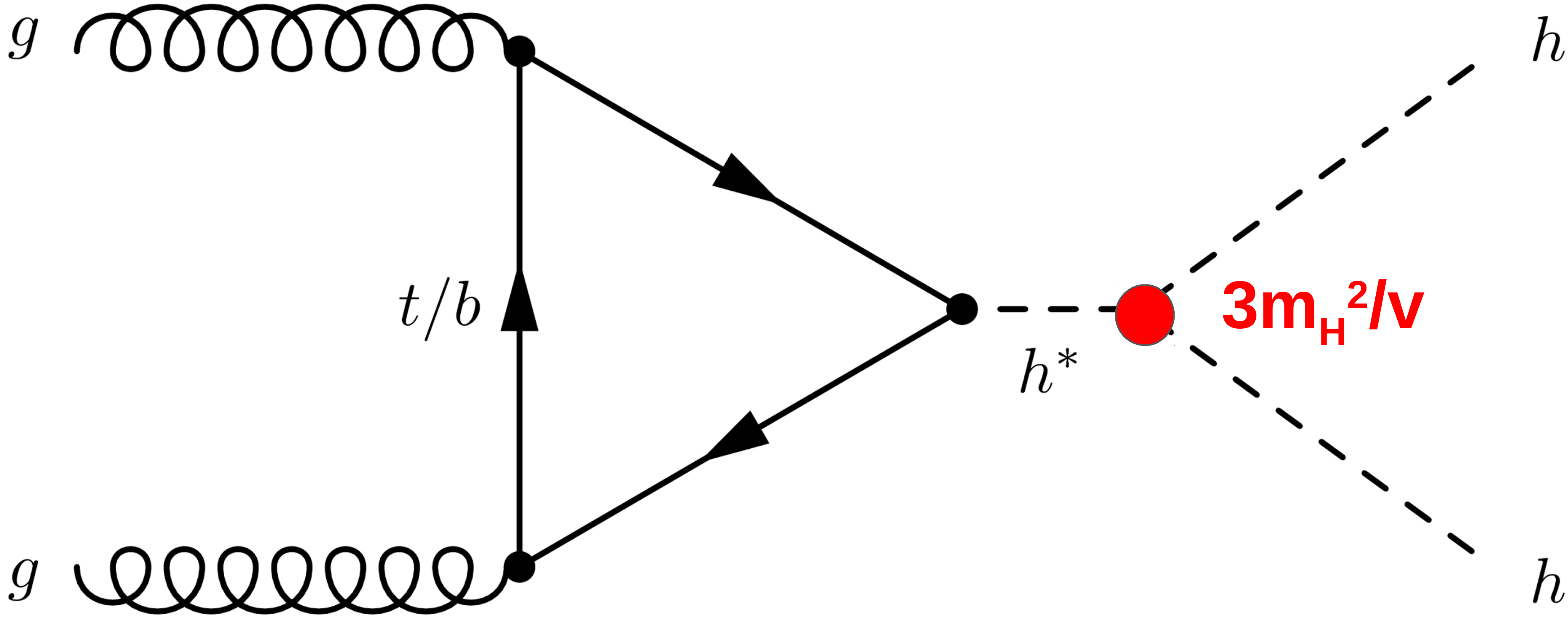




$$CMS\ study: \Gamma_H = 4.1^{+1.0}_{-1.1}\ \text{MeV} \qquad ATLAS\ study: \Gamma_H = 4.2^{+1.5}_{-2.1}\ \text{MeV}$$

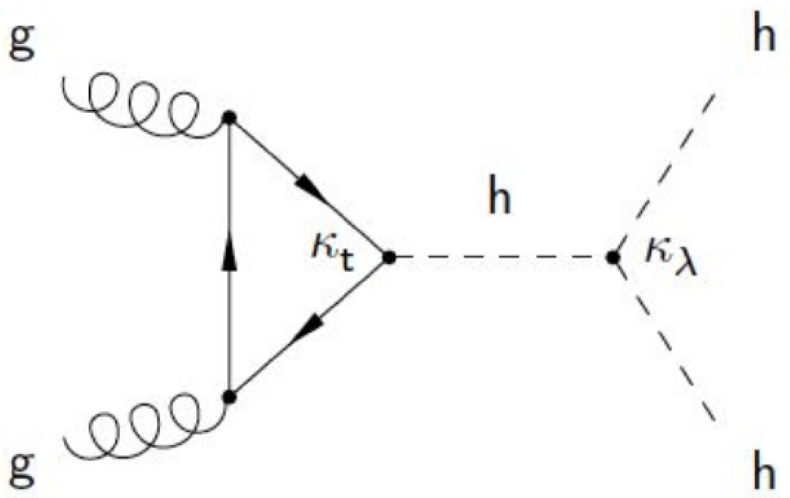
Higgs self-coupling

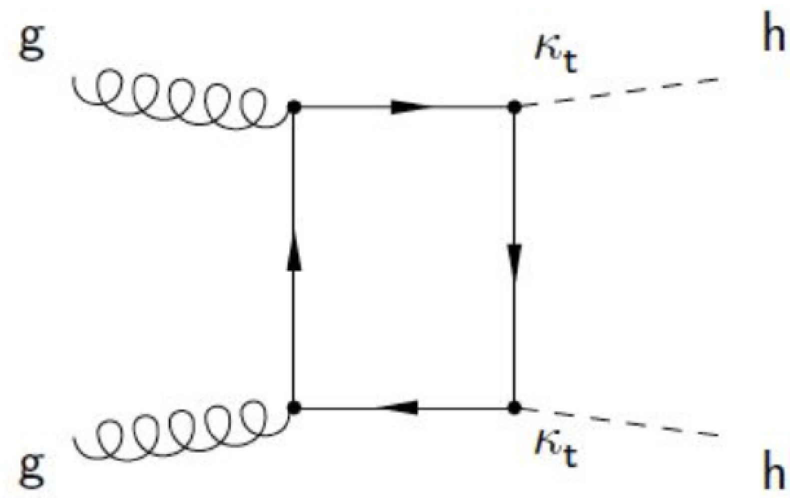
- **Main final state to try to explore the nature of the Higgs self-coupling, which is predicted to be non-zero in the SM**



Reminder: HH production

- **The di-Higgs production process receives contributions from two amplitudes that interfere destructively in the SM. Two main implications:**
  - **Small cross section in the SM (≈ 35 fb at $\sqrt{s}$=14 TeV) ⇒ measurable at HL-LHC ?**
  - **BSM may be un-affected by this negative interference: larger cross sections expected in case of new physics !!**



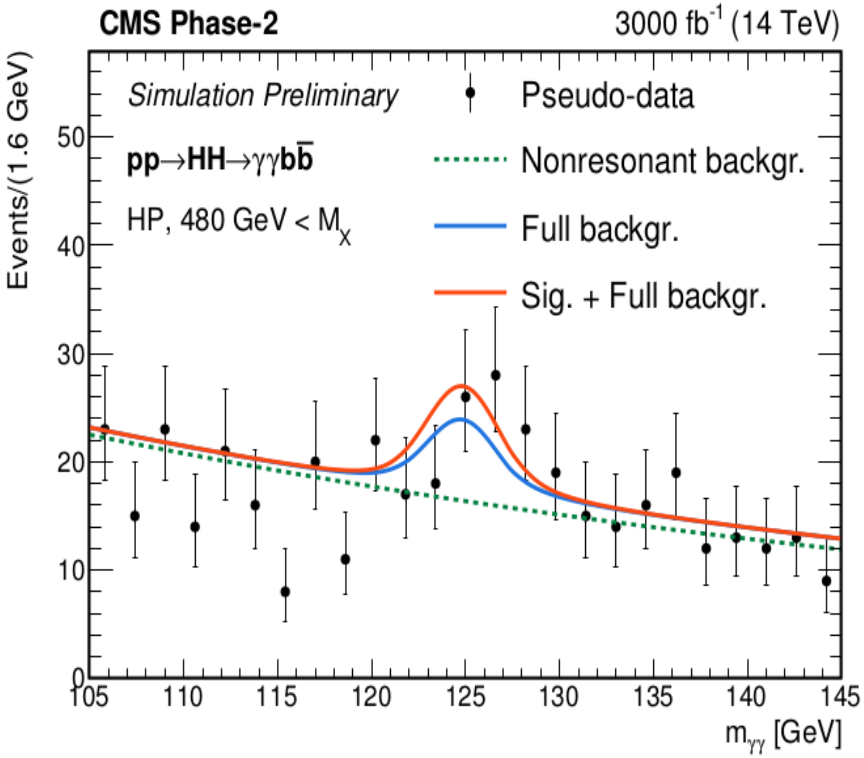


HH production at HL-LHC

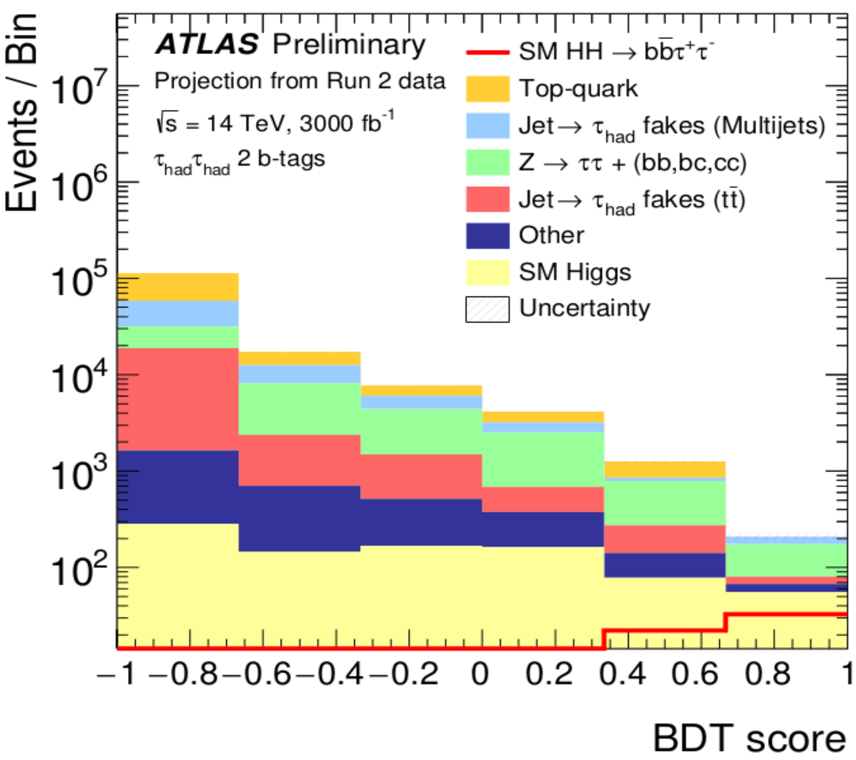
- All possible $b\bar{b}XX$ final states exploited in large detail to gain global sensitivity for the SM case:
  - $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, $b\bar{b}ZZ^*$, $b\bar{b}WW^*$
  - Mostly estimated by extrapolations of current Run2 analyses to L=3000 fb^{-1}
  - Largest sensitivity offered by $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ searches; use of multivariate methods mandatory

arxiv:1902.00134

$b\bar{b}\gamma\gamma$



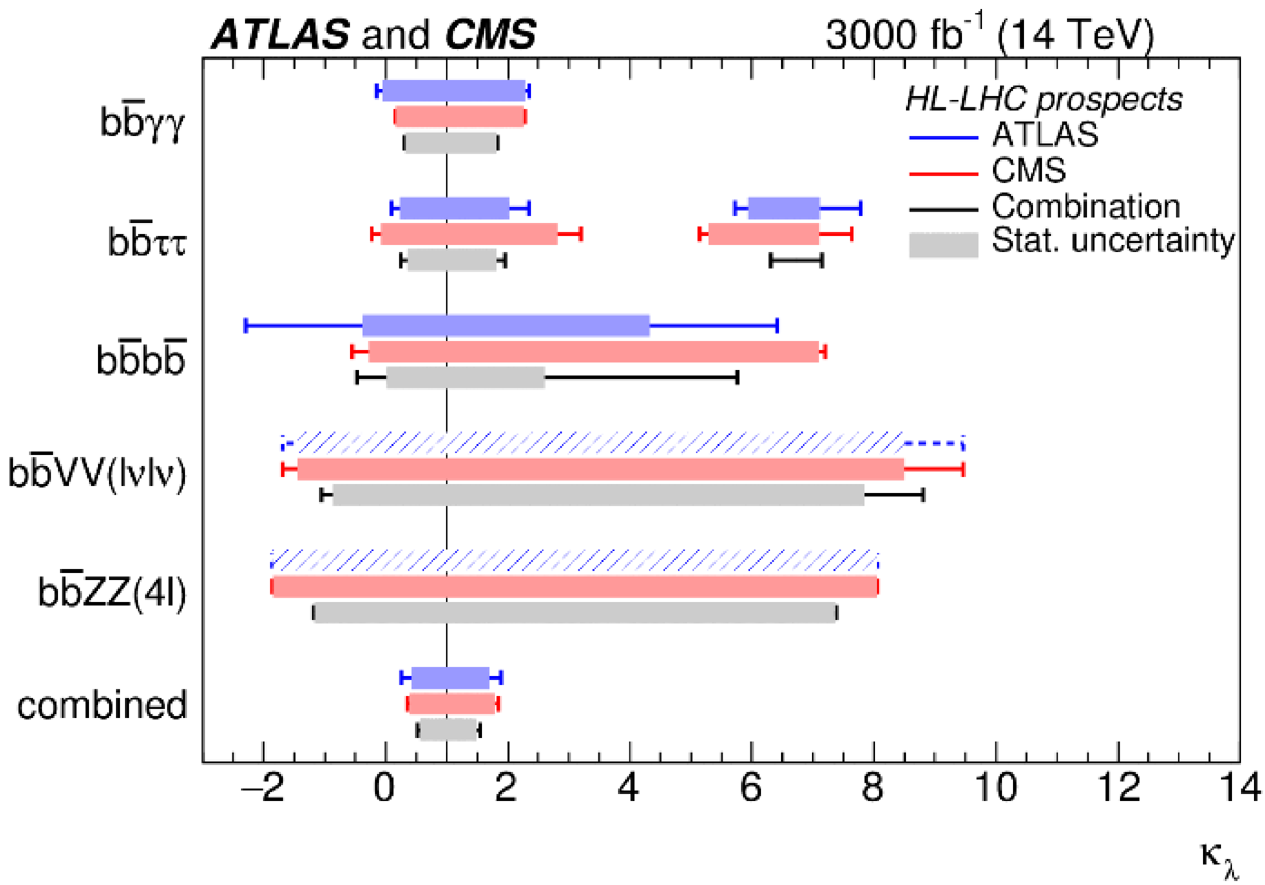
$b\bar{b}\tau\tau$



Higgs self-coupling: combination

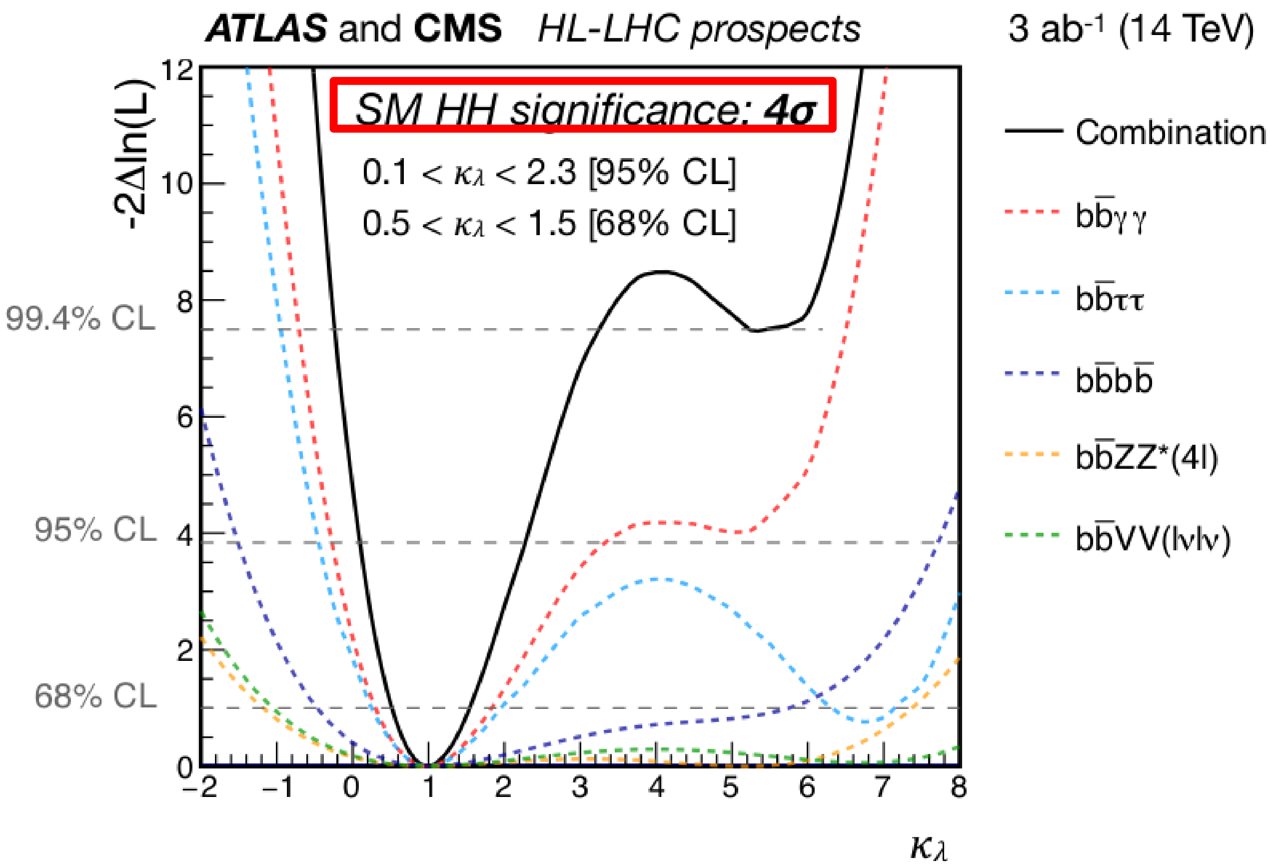
arxiv:1902.00134

Combined measurement of κ_γ (1σ)



Higgs self-coupling: combination

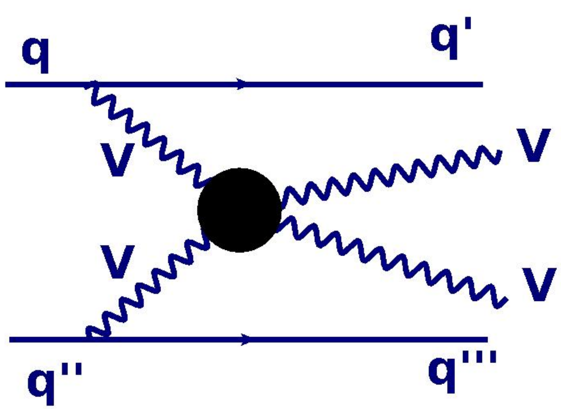
arxiv:1902.00134

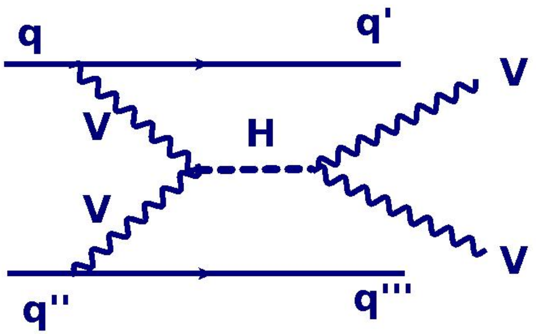


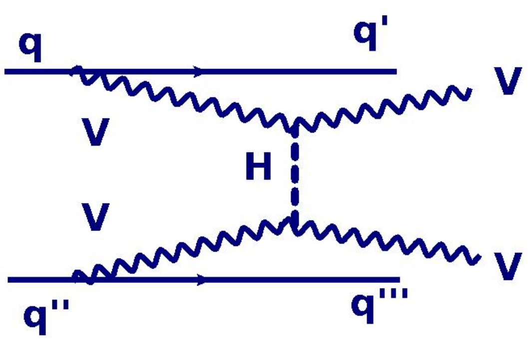
Vector Boson Scattering (VBS)

- **Vector boson scattering at high energies is a unique probe of the interaction of longitudinally polarized weak bosons**
  - **Cross section decreasing with √s due to the presence of the SM Higgs boson**
  - **Cross section diverges with √s in general in theories BSM: compositeness, …**
  - **Very important test of the EWSB mechanism**

$$\sigma_{V_L V_L \to V_L V_L} \propto \left[-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \right]$$

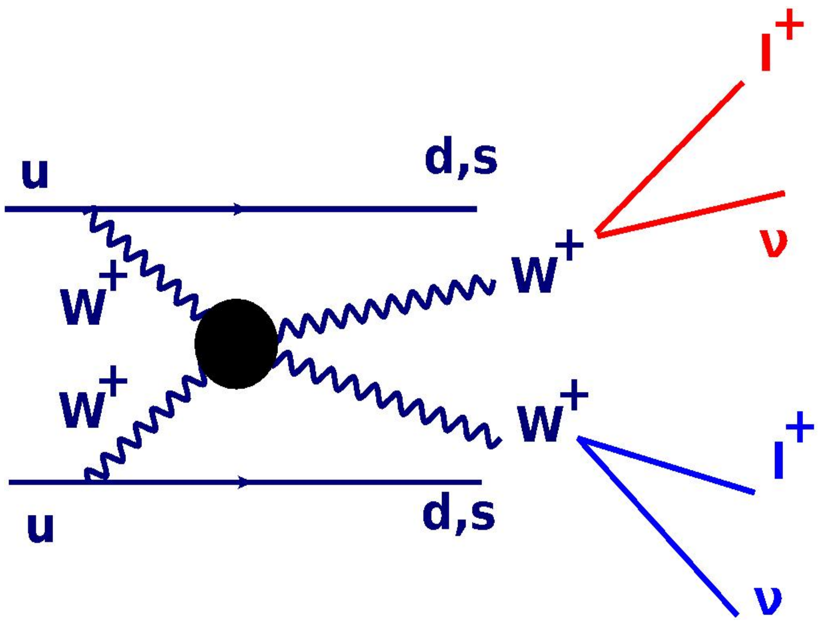


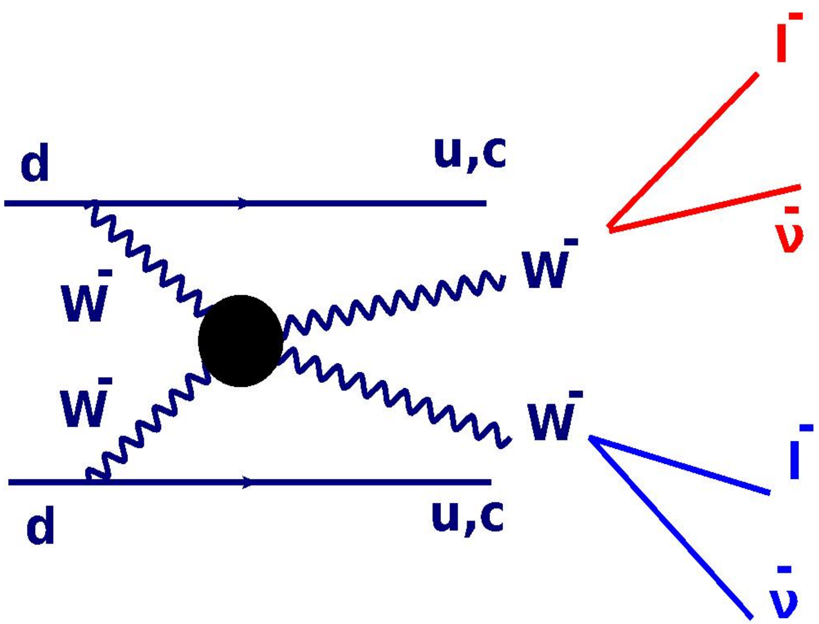




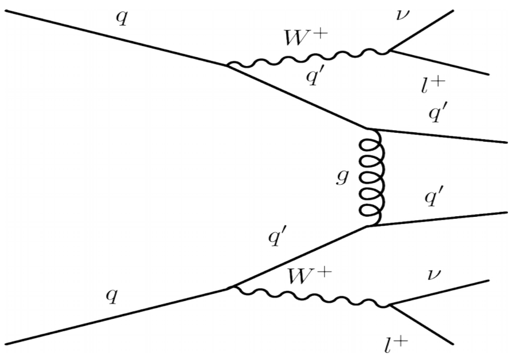
VBS at HL-LHC

- **Good channel from the experimental point of view: $W^{\pm}W^{\pm}$:**
  - **uu and dd in initial state are dominant at HLC (valence PDFs)**
  - **same-sign lepton pairs + missing energy: less SM background**





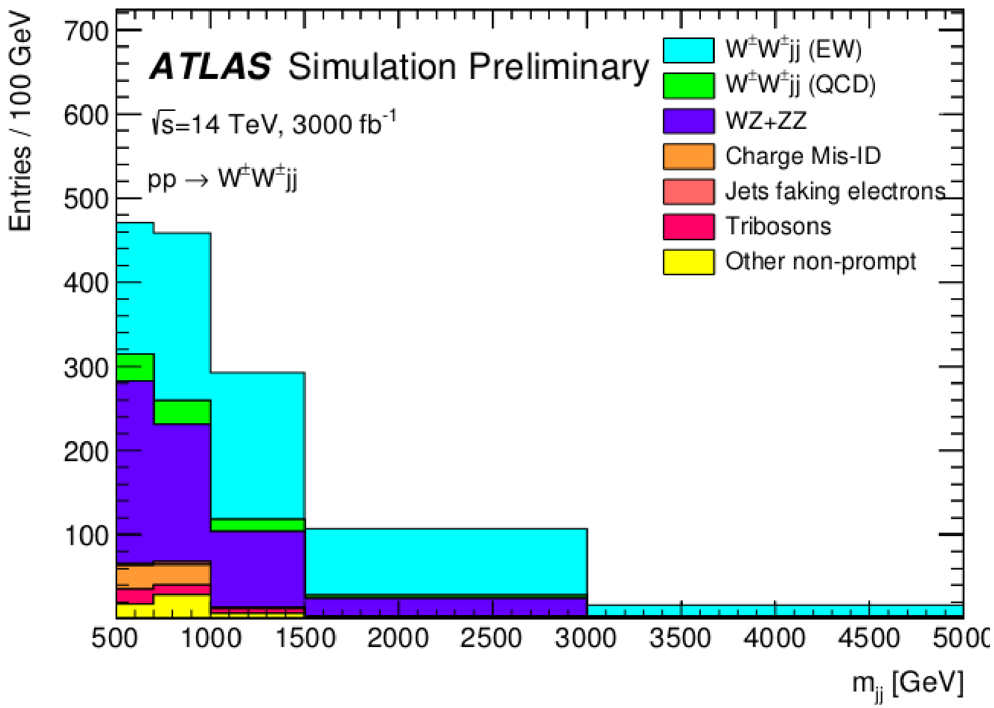
- **also: QCD-mediated diagrams do not have large contributions:**

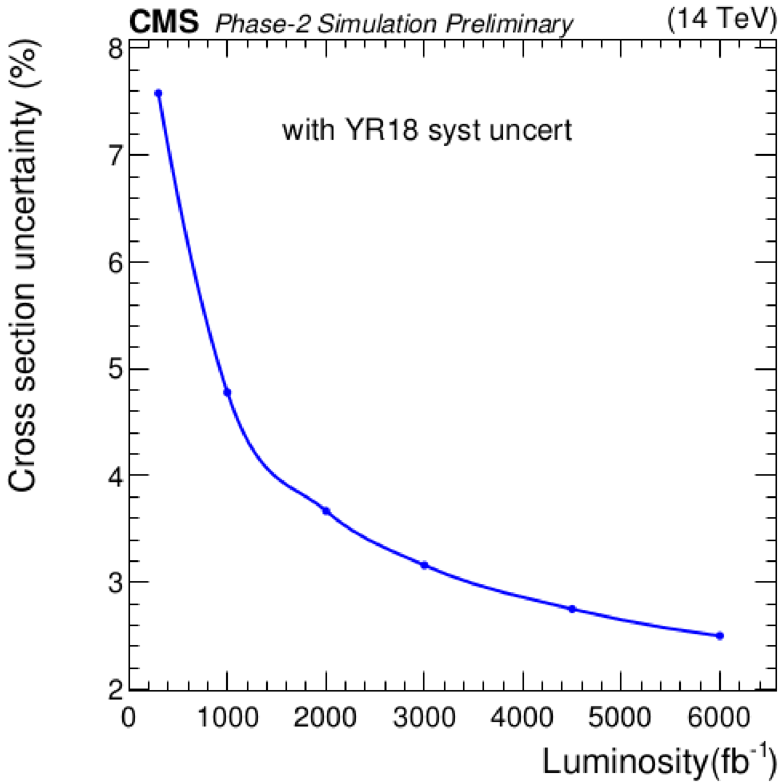


VBS at HL-LHC

arxiv:1902.04070

- **Main experimental handles to select $W^{\pm}W^{\pm}$ from VBS:**
  - **two same-sign leptons + missing transverse energy**
  - **two energetic forward jets on each side of the detector (⇒ high mass m_{JJ})**
  - **largest background is WZ+jets and ZZ+jets (1 or 2 leptons lost)**
  - **theoretical detail: assignment of QCD-mediated diagrams to "background"**



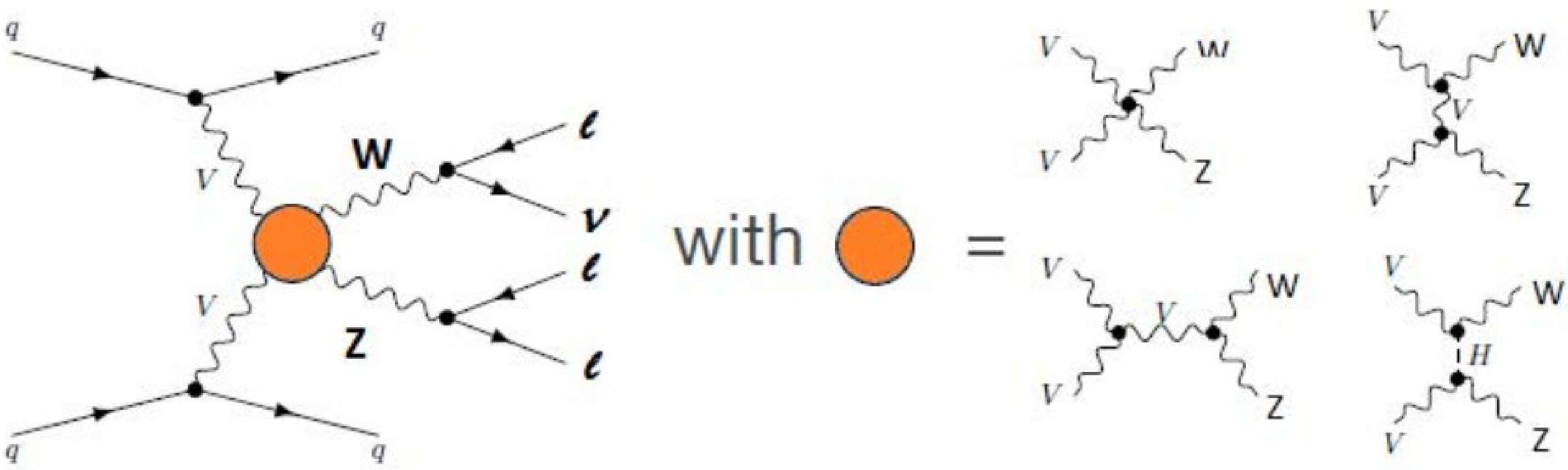


- **Expected uncertainties on the SM EWK cross section ≈ 3% at HL-LHC**

VBS at HL-LHC

arxiv:1902.04070

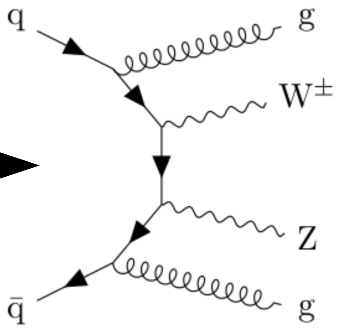
- **WZ channel:**
  - **particularly important because deviations from the SM at large √s are potentially larger (more interference with SM diagrams) → important channel for compositeness**
  - **clean channel from the experimental point of view, despite a smaller cross section compared with WW**

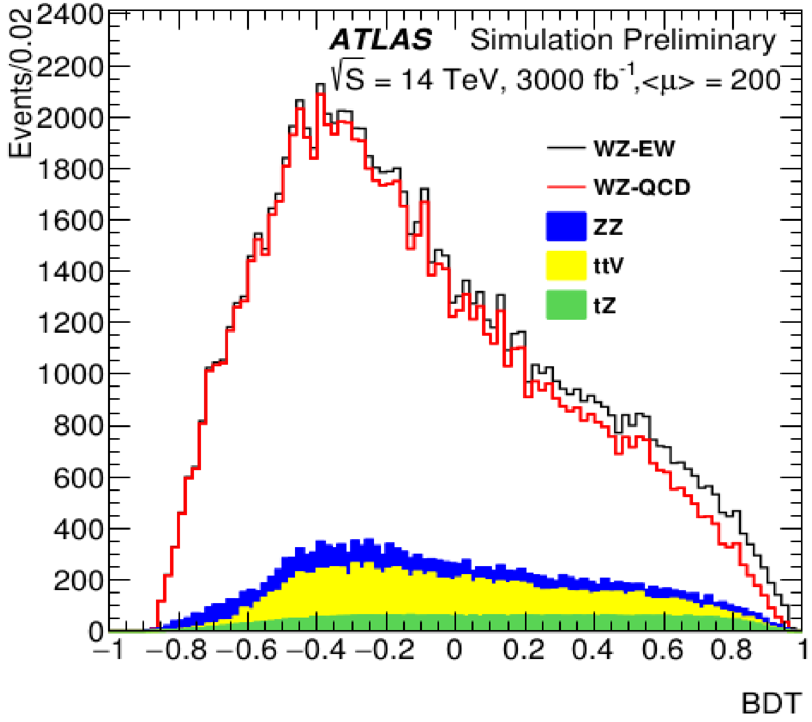


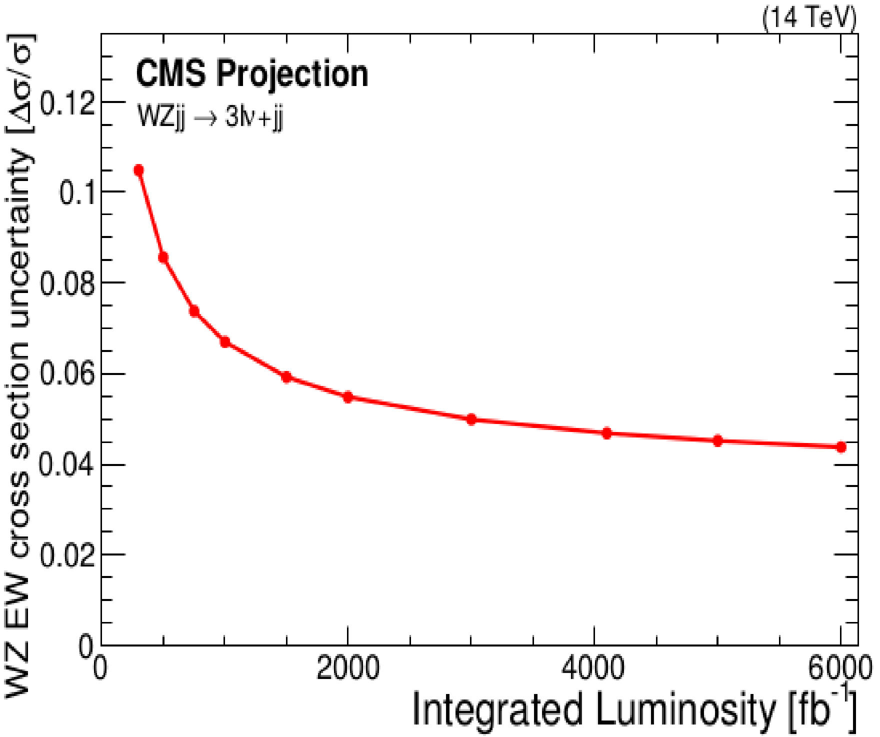
VBS at HL-LHC

arxiv:1902.04070

- **WZ channel:**
  - **dominant background is QCD-mediated production of WZ:**
    - **multivariate methods used to separate both contributions via kinematic differences**



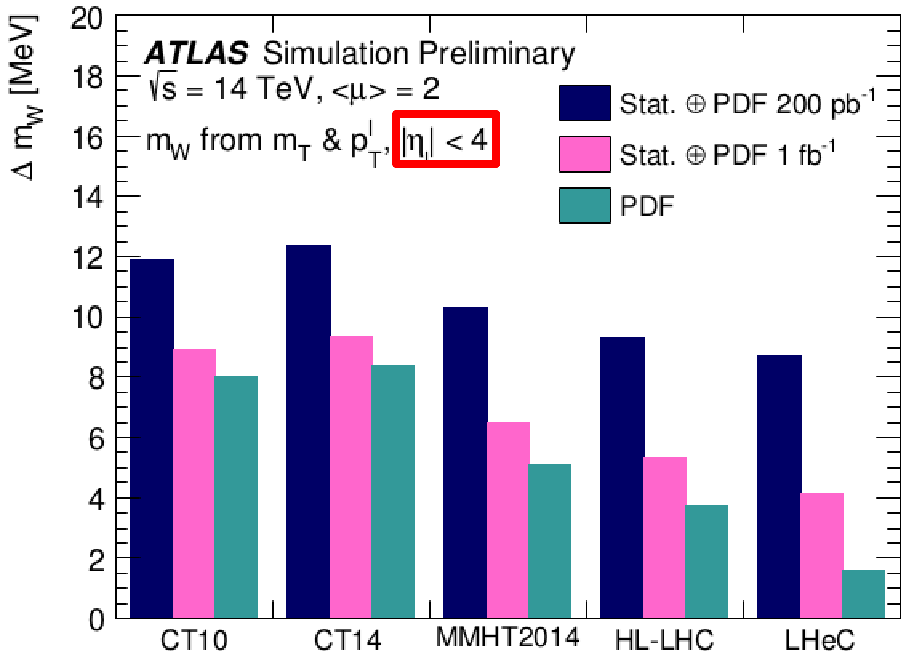




- **Expected uncertainties on the SM EWK cross section ≈ 5% at HL-LHC**

W mass at HL-HLC

arxiv:1902.04070



$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV]		
		CT10	CT14	MMHT2014
14	$\lvert\eta_\ell\rvert < 2.4$	16.0 (10.6 $\oplus$ 12.0)	17.3 (11.4 $\oplus$ 13.0)	15.4 (10.7 $\oplus$ 11.1)
14	$\lvert\eta_\ell\rvert < 4$	11.9 (8.8 $\oplus$ 8.0)	12.4 (9.2 $\oplus$ 8.4)	10.3 (9.0 $\oplus$ 5.1)

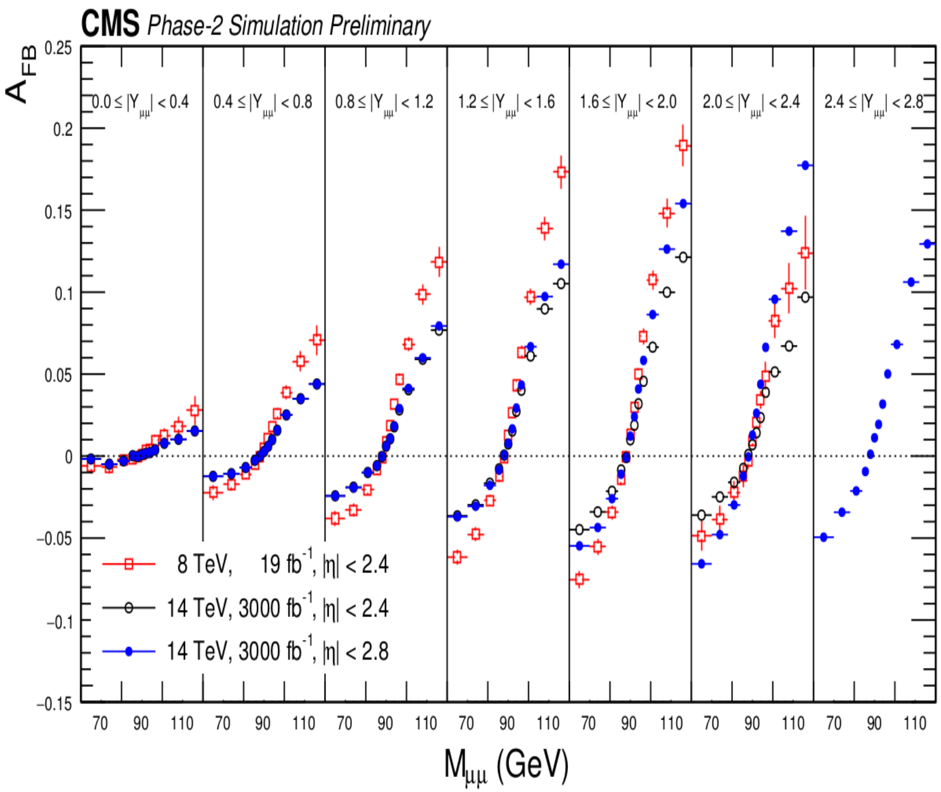
$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV]	
		HL-LHC	LHeC
14	$\lvert\eta_\ell\rvert < 2.4$	11.5 (10.0 $\oplus$ 5.8)	10.2 (9.9 $\oplus$ 2.2)
14	$\lvert\eta_\ell\rvert < 4$	9.3 (8.6 $\oplus$ 3.7)	8.7 (8.5 $\oplus$ 1.6)

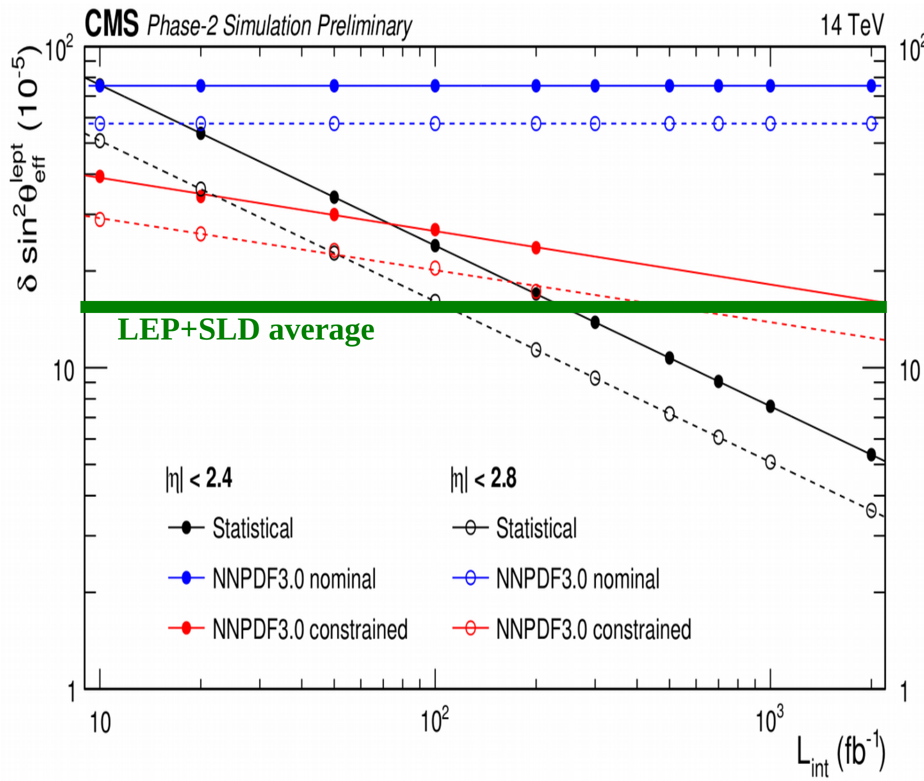
L=200 pb^{-1}

- **Improvements on the W mass are highly correlated with PDF improvements**
  - **It would benefit from ep running if available (LHeC)**

$\sin^2\theta_{eff}$ at HL-HLC

arxiv:1902.04070



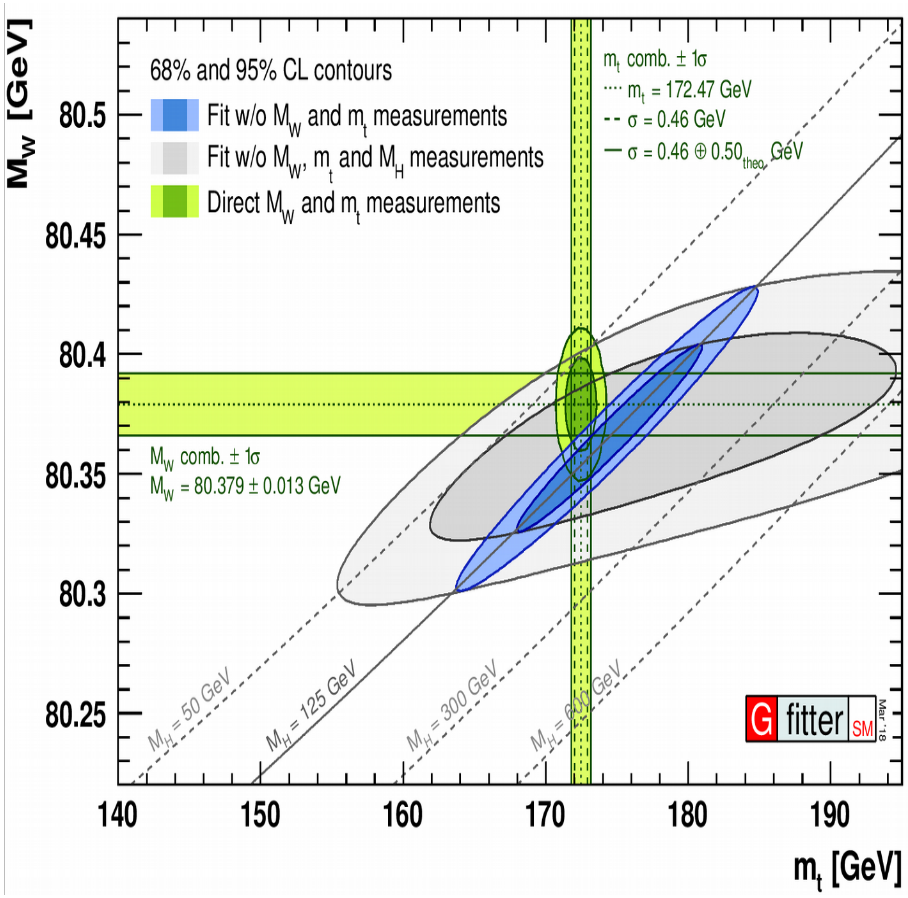


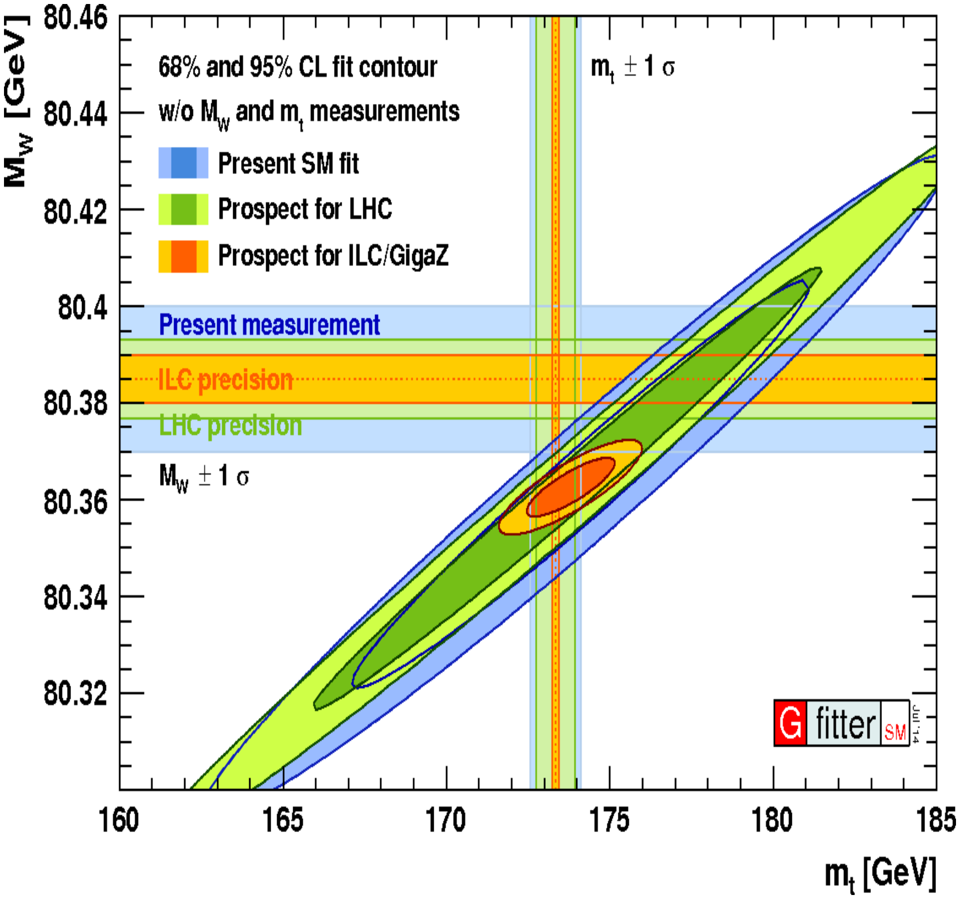
- **A precise measurement is obtained when the PDFs are simultaneously constrained in the analysis ("PDF constrained")**
  - **As a reference, the $\sqrt{s}$=8 TeV analysis from CMS (muons) gave $\delta \approx 32\times10^{-5}$**
  - **A_{FB} gets diluted at $\sqrt{s}$=14 TeV compared with $\sqrt{s}$=8 TeV: lower x ⇒ direction of larger rapidity is an "anti-quark" more frequently**
  - **This is compensated by an increased acceptance ($|\eta|$<2.8, CMS, larger η ⇒ less dilution)**

- **HL-LHC: better than LEP-SLD average ($\delta \approx 16\times10^{-5}$) with just 500 fb^{-1}**

Relevance of top mass measurements

Gfitter project



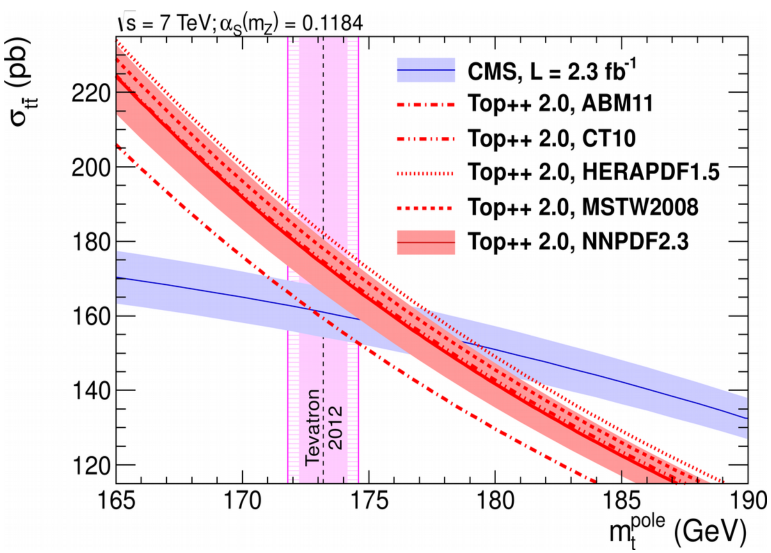


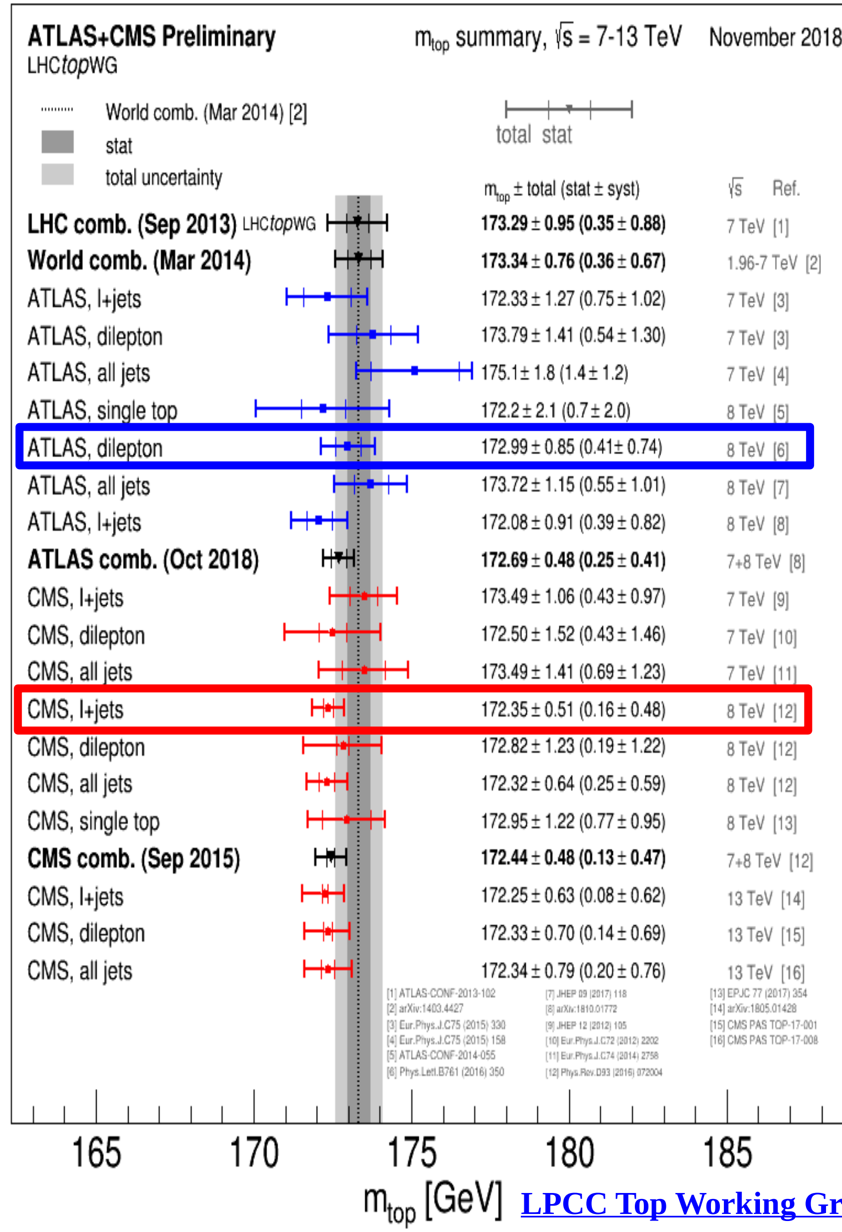
- Together with recent measurements of M_W and the Higgs mass, a precise measurement of m_t helps to severely constrain (or instead discover) deviations from the SM.

Top mass measurement at the LHC

- Statistics is very high, so measurements will be dominated by systematic uncertainties (theoretical and experimental)
- Many different methods employed, focusing on different systematic sources. Three main paths can be highlighted:
  - Most precise (today): lepton+jets channel
  - Experimentally cleanest: dilepton channel
  - Theoretically cleanest: $t\bar{t}$ or $t\bar{t}$+jet cross sections

arxiv:1307.1907



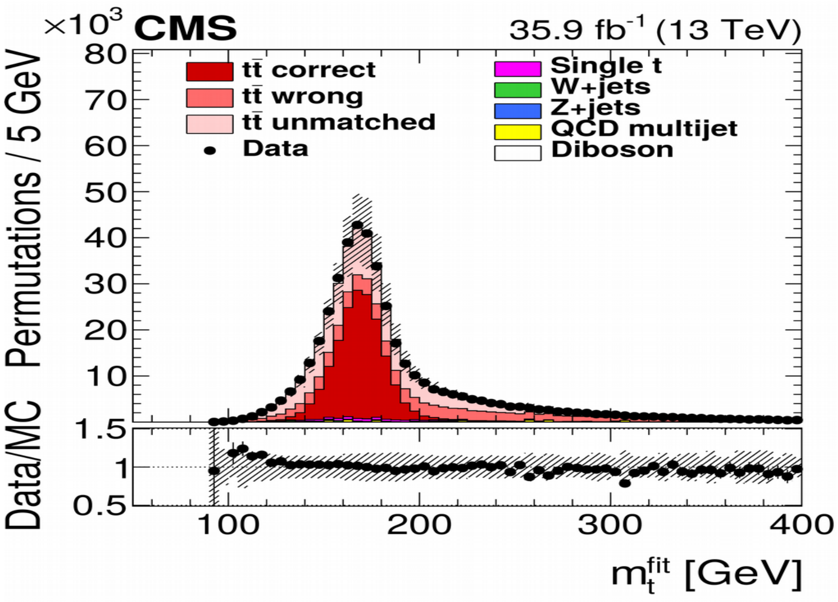


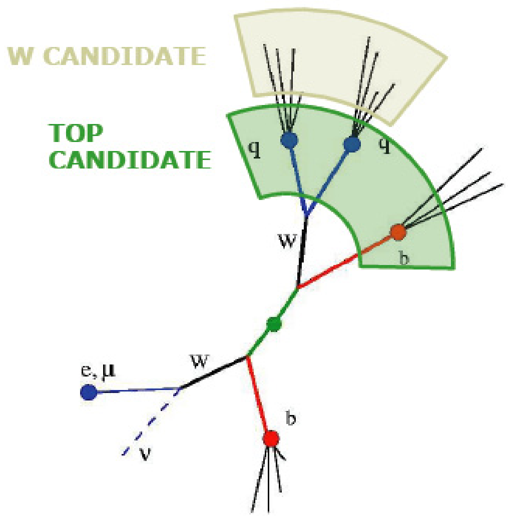
LPCC Top Working Group

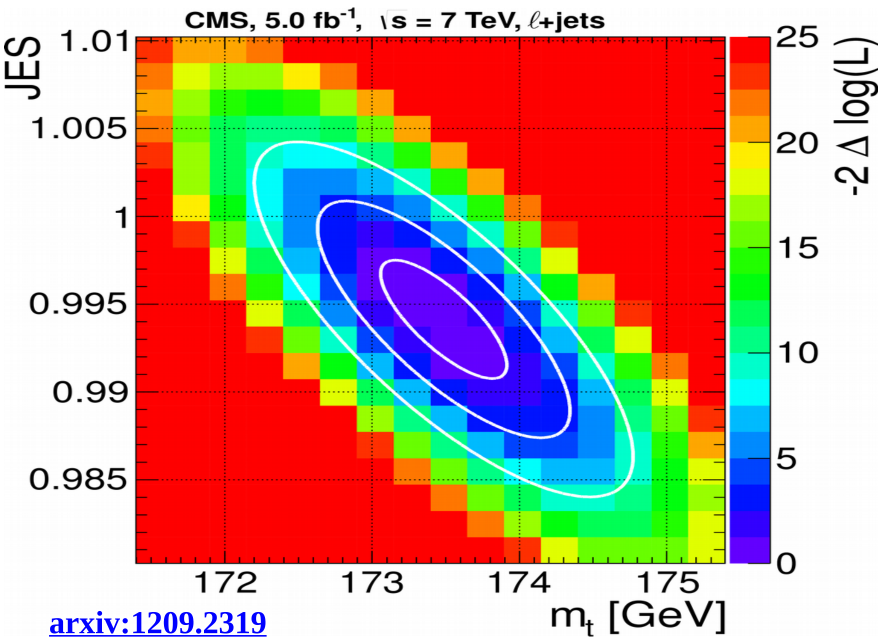
Top mass measurement at the LHC

- **Lepton+jet measurement:**
  - Basically, it implies a full kinematic reconstruction of the two tops in the event, where m_t is a free parameter in the game
  - An additional parameter is the energy scale factor for the jets in the event, which is partially constrained by the mass of the two light jets in the event (from the hadronic W)
  - Different versions for the final strategy: ideograms, templates, ...

arxiv:1805.01428







arxiv:1209.2319

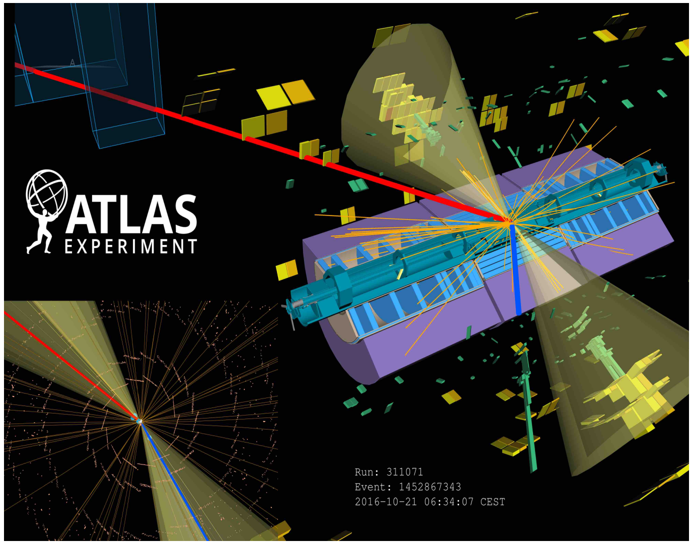
Top mass measurement at the LHC

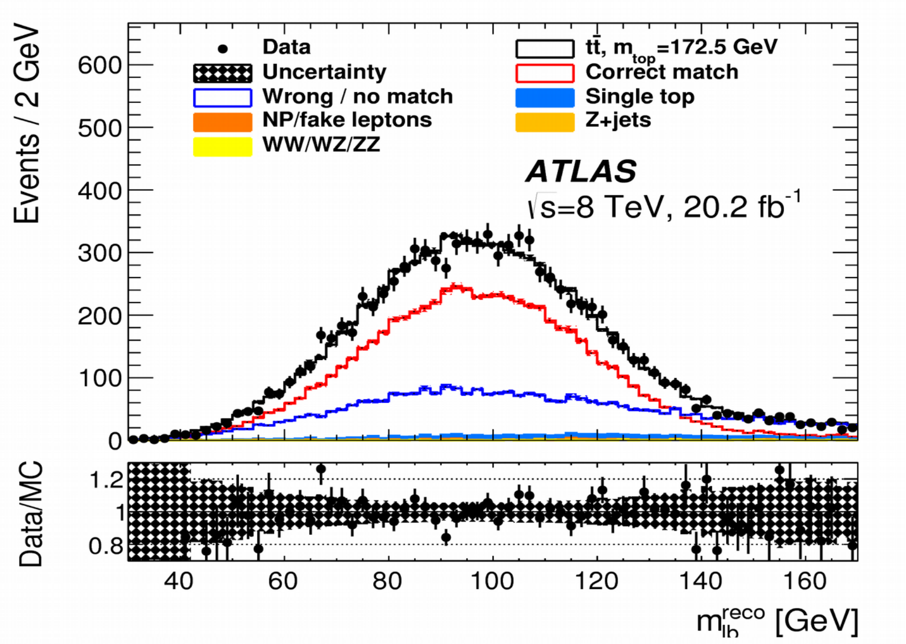
arxiv:1606.02179

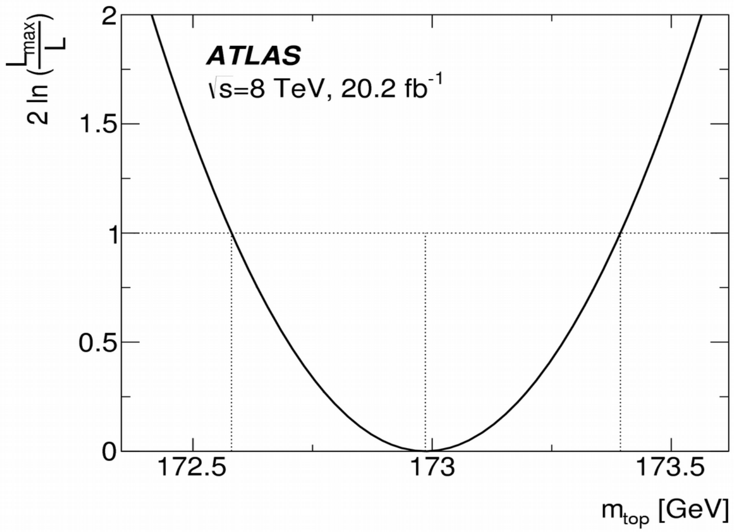
- **Dilepton measurement:**
  - Basically, it gets its sensitivity from the bl invariant mass distribution (no need to get the kinematics of the neutrinos)
  - It just assumes that there are no deviations in the Wtb vertex structure (i.e. no anomalous couplings):

$$M_{bl} = \sqrt{m_t^2 - m_W^2}\ \cos\left(\frac{\theta^*_{Wl}}{2}\right); \qquad (m_b \to 0)$$

  - Still directly dependent on b-jet energy scale uncertainties



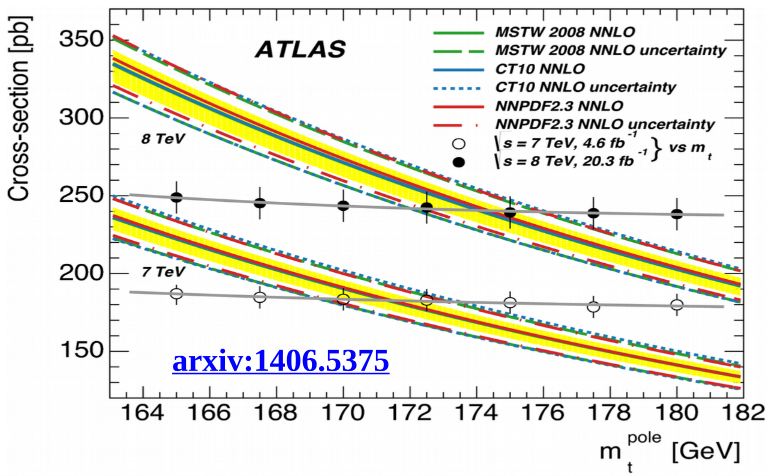


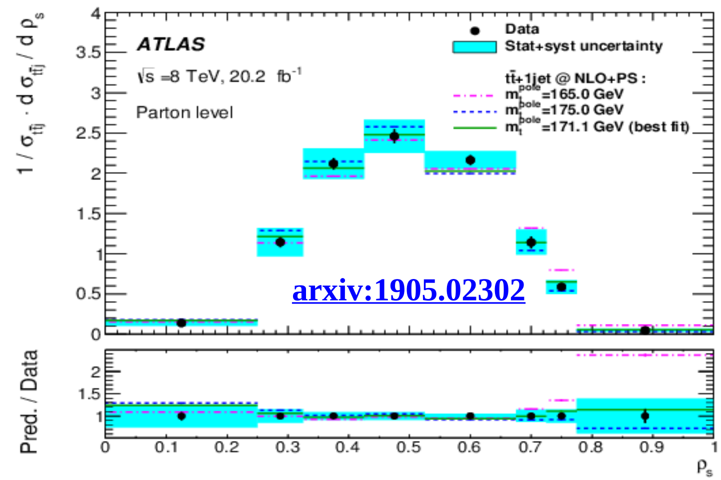


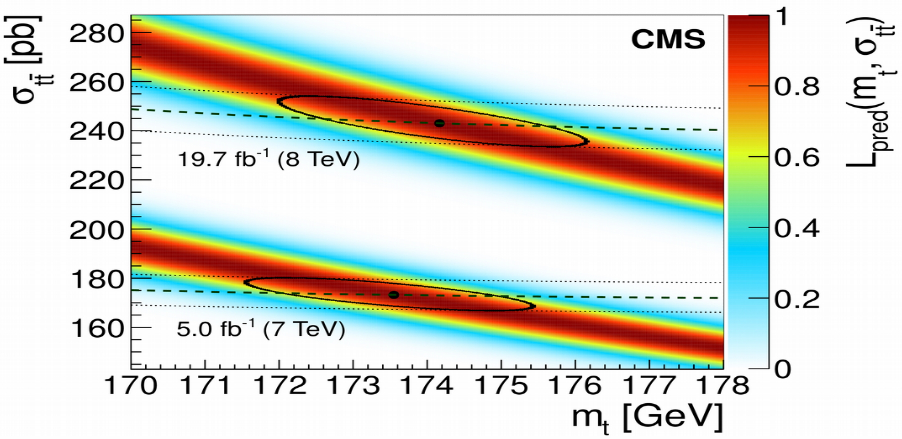
Top mass measurement at the LHC

- $t\bar{t}$ cross section measurements in general:
  - Reduce theoretical uncertainties: m_t (pole) is well defined in this context
  - Interesting interplay with theory uncertainties: PDFs, α_s, … → not so negligible !!

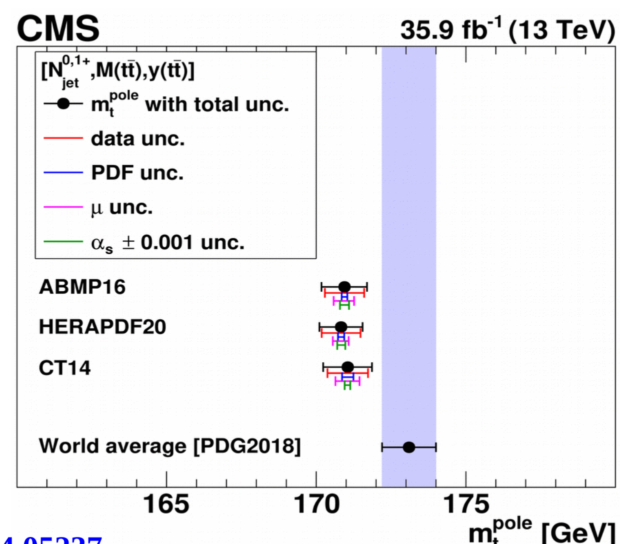
- New wave: differential cross sections as a function of different kinematic variables
  - ρ_s=340 GeV/mass($t\bar{t}$+1jet) (ATLAS)
  - N_{jet}, M($t\bar{t}$), y($t\bar{t}$) (CMS)





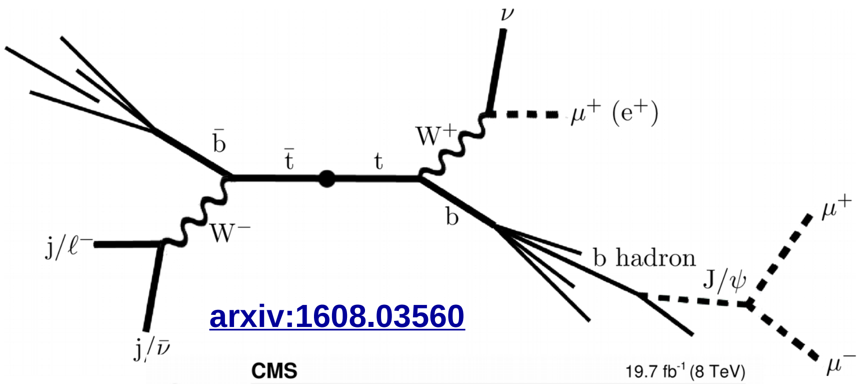


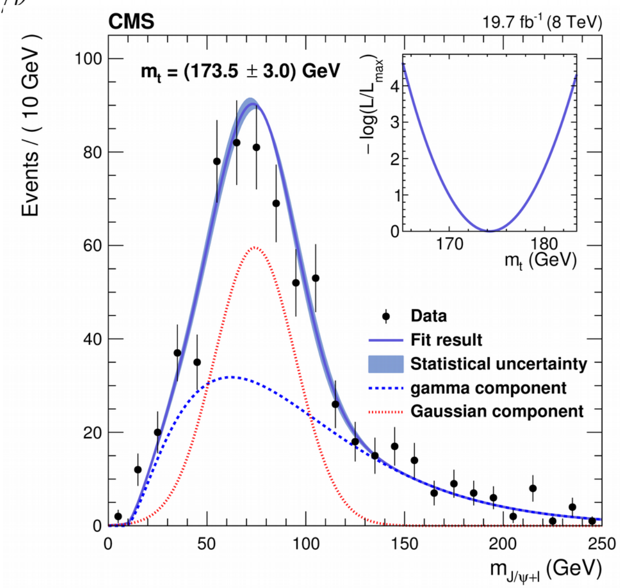
arxiv:1603.02303

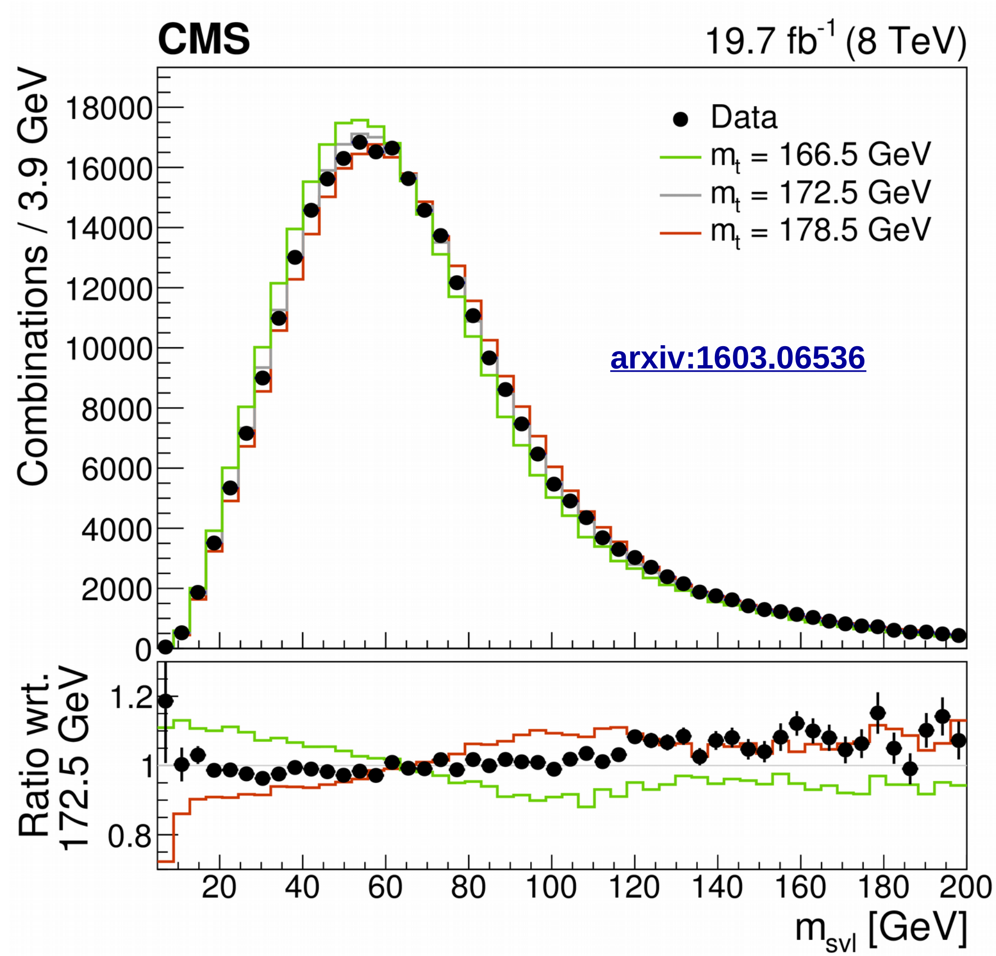


arxiv:1904.05237

More: J/Ψ+lepton an top mass



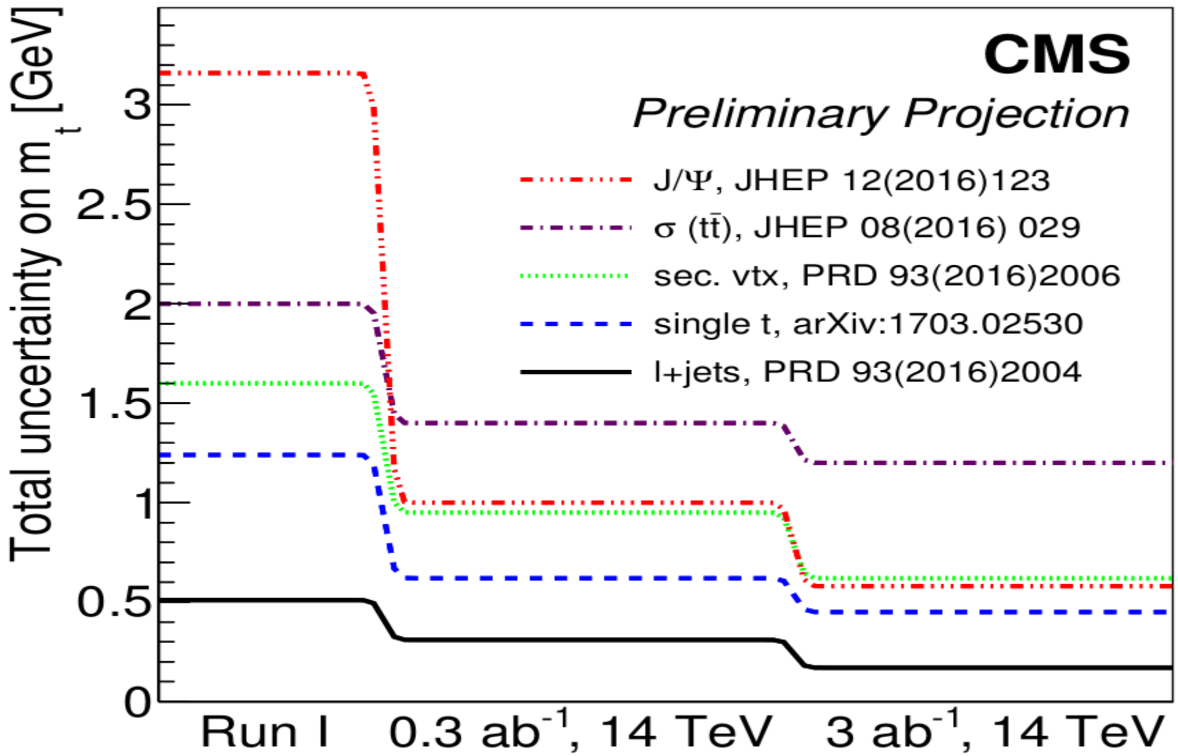




- **t→W+b→lν + J/Ψ(ll̄) + X, use mass of J/Ψ+l system:**
  - **no b-jet scale uncertainties anymore,**
  - **but fragmentation uncertainties are now an important ingredient**
- **Vertex method is similar in spirit → substitute J/Ψ by secondary vertex system**

Top mass at HL-HLC

arxiv:1902.04070



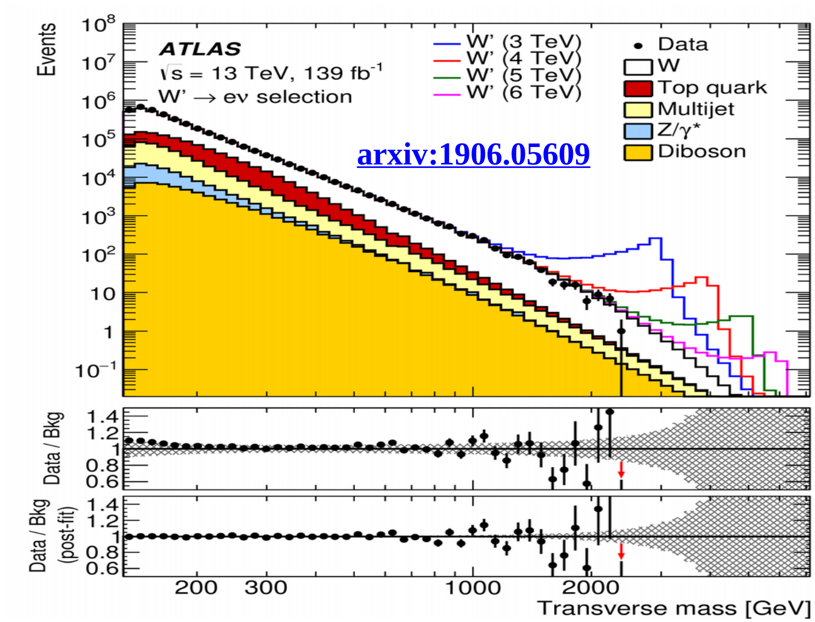
- **Some features:**
  - **Ultimate expected uncertainty $\lesssim$ 0.1%**
  - **$\sigma(t\bar{t})$: limited by theory and luminosity uncertainties**
  - **Some methods with large statistical uncertainties in Run1/Run2 become more relevant at HL-LHC**

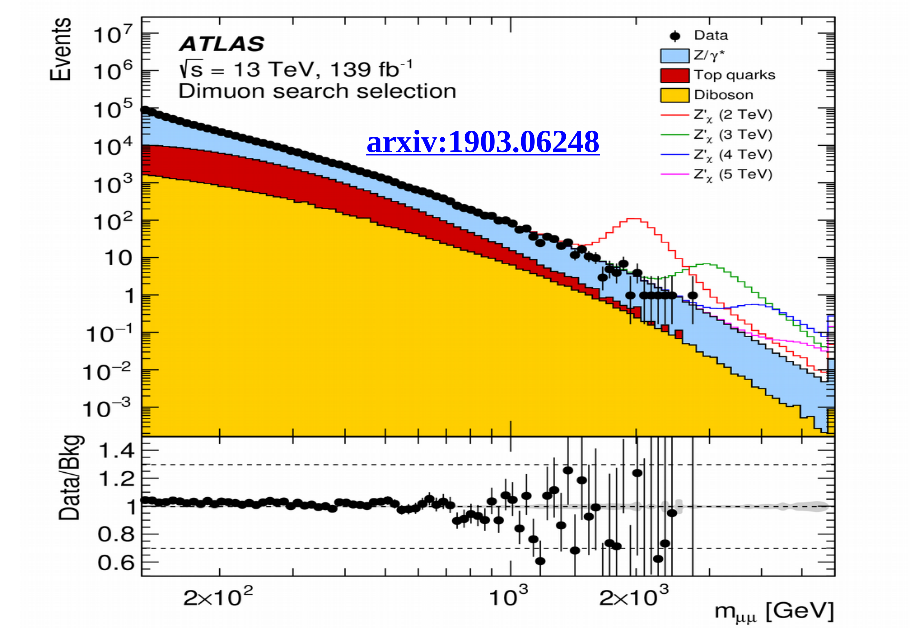
- **Also, more understanding of theoretical uncertainties needed**

Generic searches (Exotica)

New vector boson searches at LHC

- Leptonic decay channels, Z' → $l\bar{l}$, and W'→lν are typically the most sensitive ones to the presence of new gauge sectors extending the SM (minimal backgrounds):



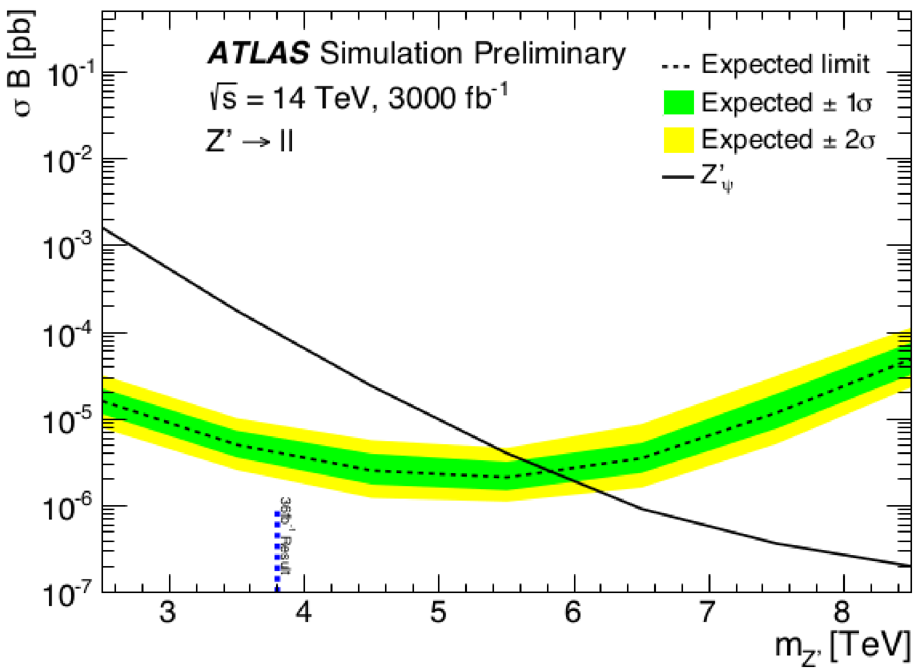


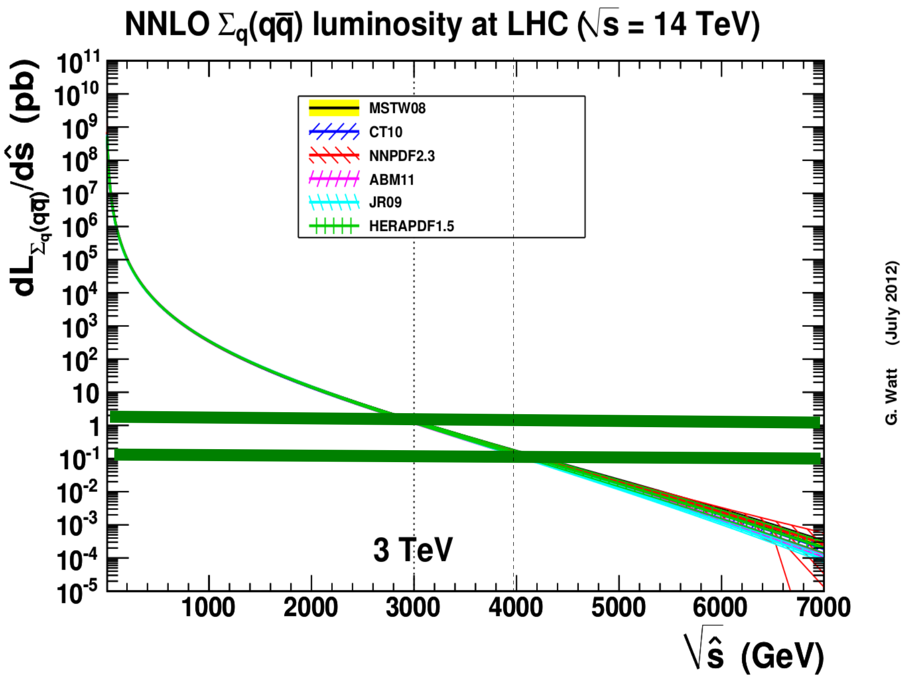
- Basic strategy:
  - Isolated leptons of extremely high momentum (TeV scale)
  - Look for 'peaks/bumps' in the di-lepton invariant mass or in the lepton+missing momentum transverse mass
- Key (critical) point: good lepton momentum resolution at ≈ TeV scale and very precise control of resolution, momentum biases, trigger, reconstruction efficiencies
- Main background: SM $l\bar{l}$ and lν with high mass (Z,W off-shell production)
- Limits typically given either on toy models (SM sequential) or theoretically more consistent ones (new gauge groups from unification theories)

Searches at HL-LHC

arxiv:1812.07831

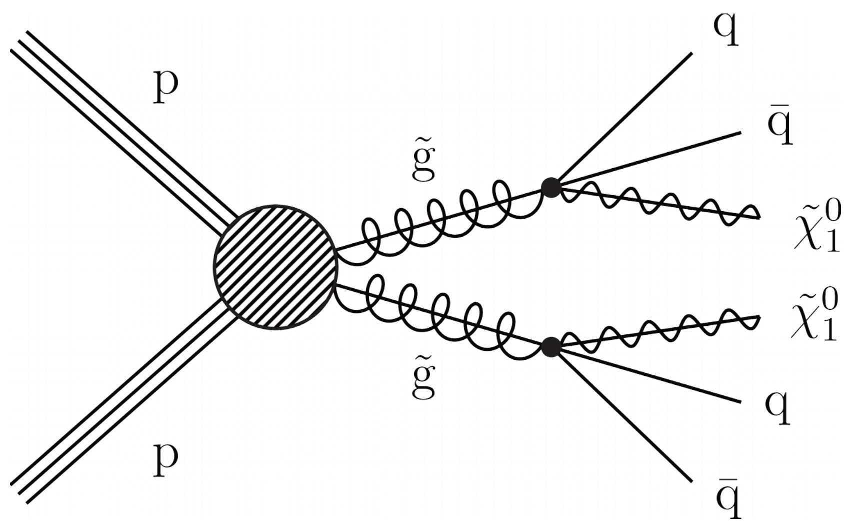
- **Regarding the reach at HL-LHC, one expects to improve current limits by 1-2 TeV:**
  - **√s is still the same as in Run3, and an increase of a factor 10 in integrated luminosity only leads to mild improvements of order 1 TeV**





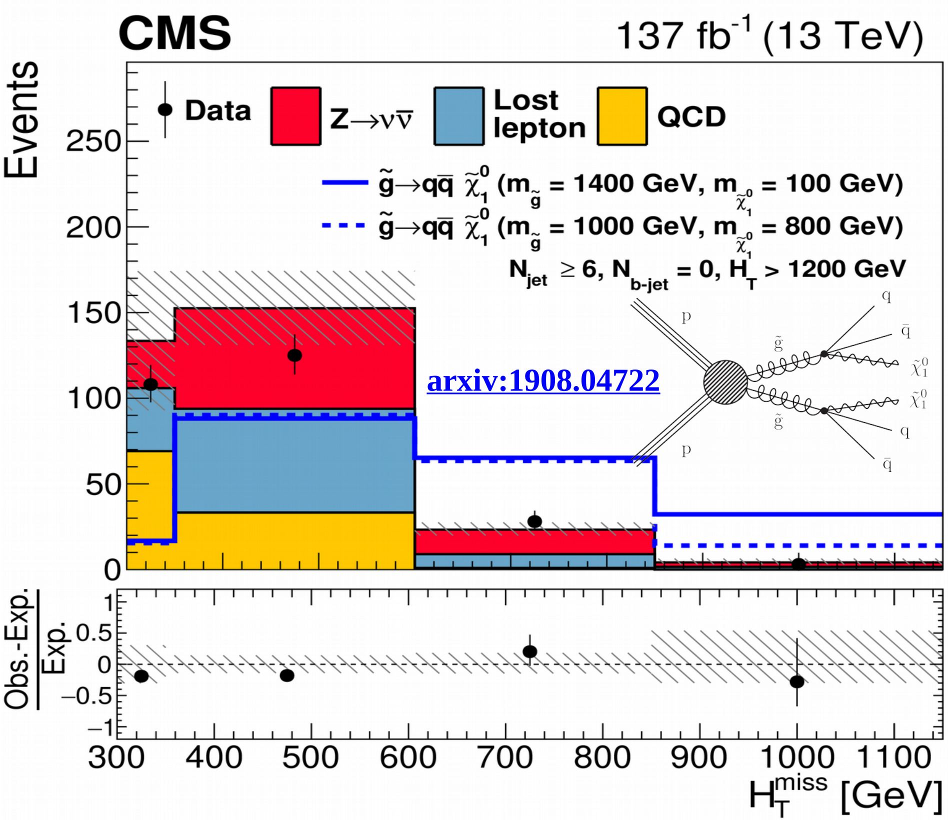
To be compared with the current ATLAS limit of m(Z'$_\psi$) > 4.5 TeV

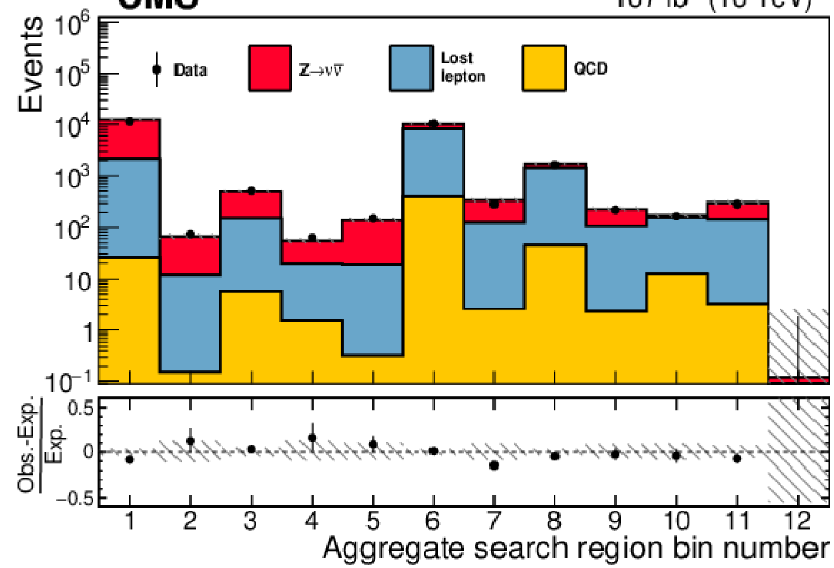
SUSY searches were mostly "hadronically driven" at Run1+Run2



SUSY@Run2: hadronic + missing E_T

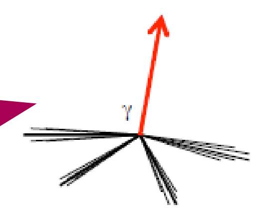
- Concentrate on final states with just jets and substantial missing H_T → same as missing E_T but calculated using only jets (unclusterized energy is ignored)





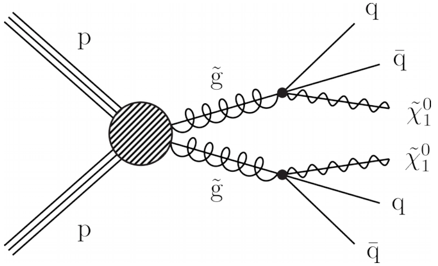
- Many variables used in practice:
  - #jets, #b-tagged jets, H_T, H_T^{miss}
- Many different subregions defined with them

- The detector resolution is so good that the key backgrounds are backgrounds that have intrinsic missing energy. In this example:
  - $\nu\bar{\nu}$+jets → control regions (CR) from photon+jets and $\mu^+\mu^-$+jets
  - W+jets/top (“lost lepton”) → CR with lepton and non-b/b tagging
  - QCD → normalization fixed with events with missing H_T close to jet directions

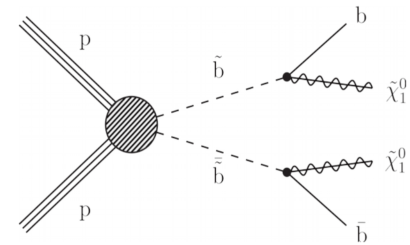


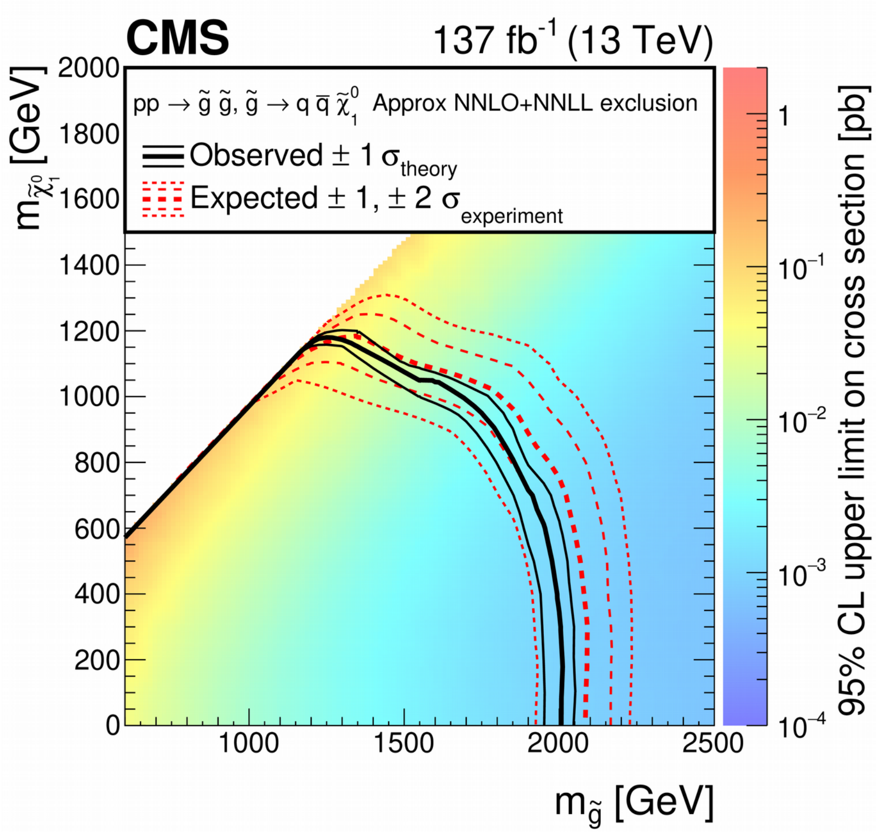
SUSY results: hadronic + missing E_T

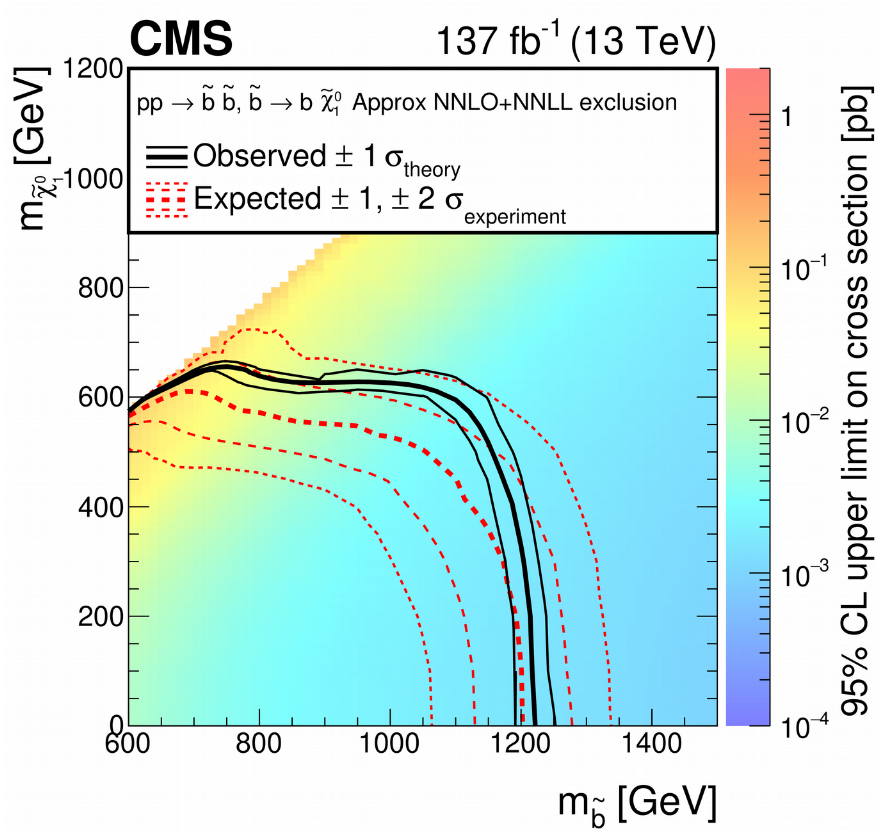
- We do not see any significant excess yet. We therefore set limits in some benchmark SUSY scenarios:



arxiv:1908.04722

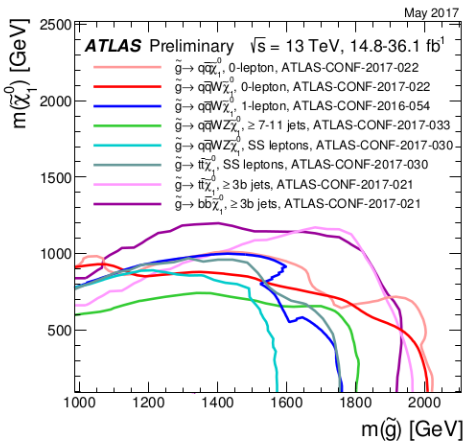




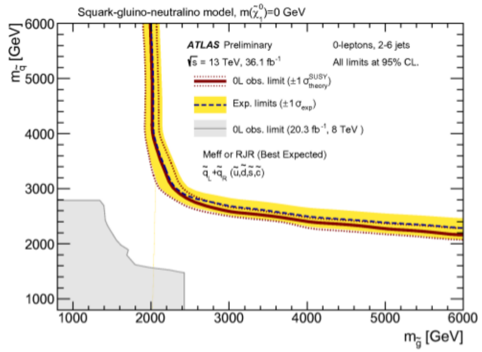


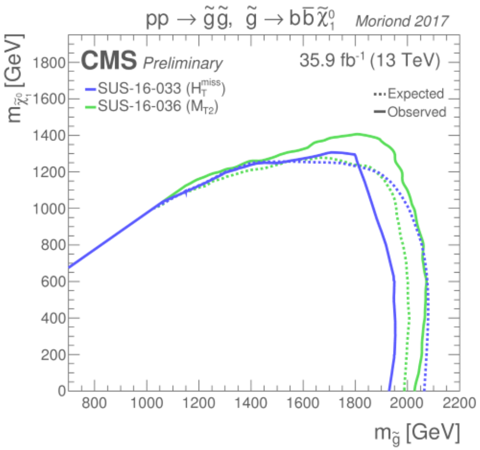
Large fraction of TeV-MSSM models excluded

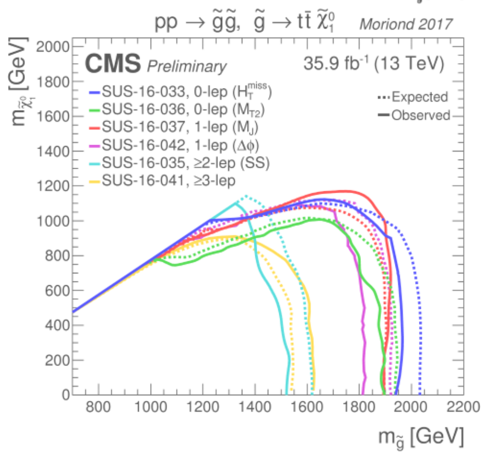
- Gluinos and light squarks produced directly at LHC excluded up to masses ≈ 2 TeV in Run2 (if neutralinos are not too massive)
- A large fraction of “phenomenological” MSSM possible models also excluded below 1 TeV or so since Run1



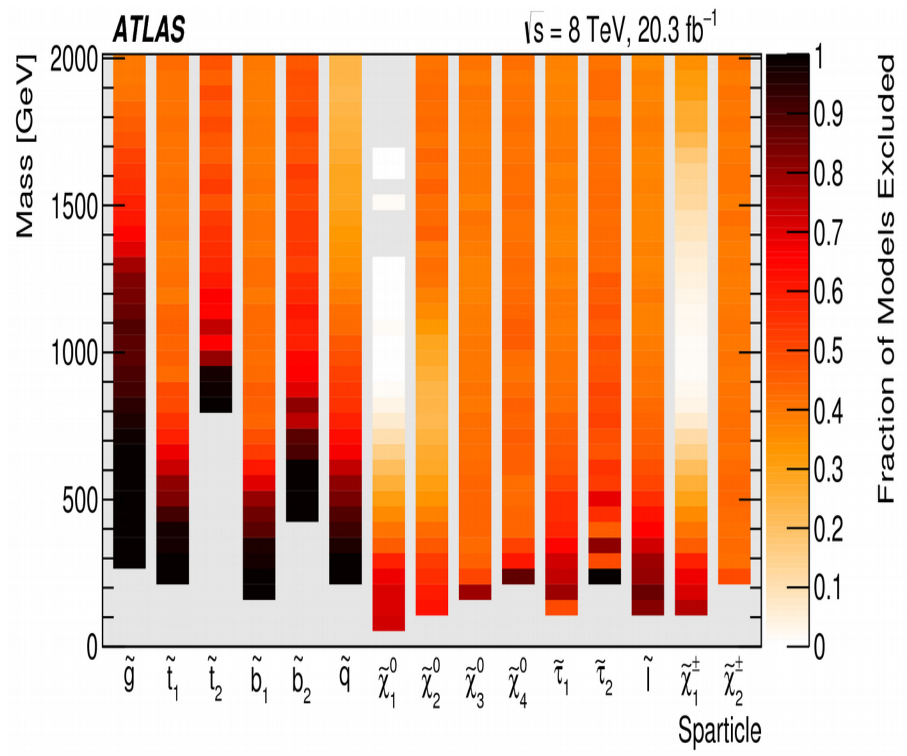
Taken from PDG 2018





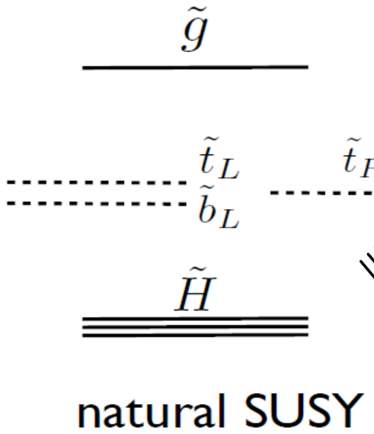


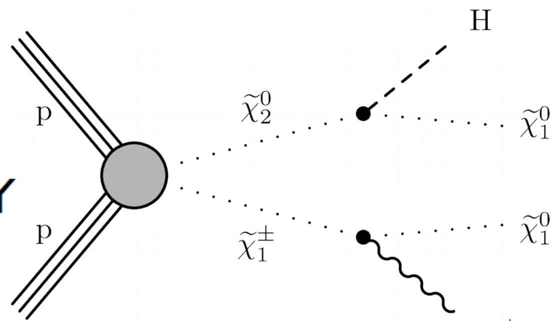
arxiv:1508.06608

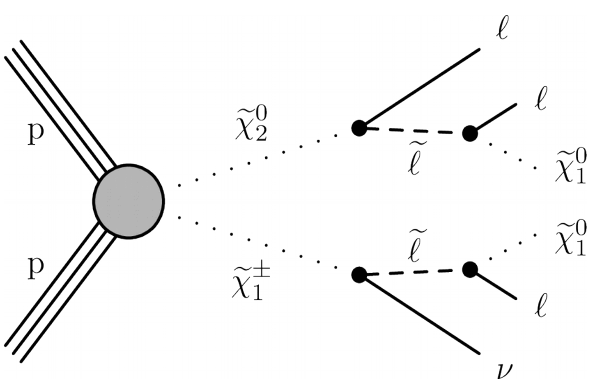


How can SUSY hide from observation at LHC

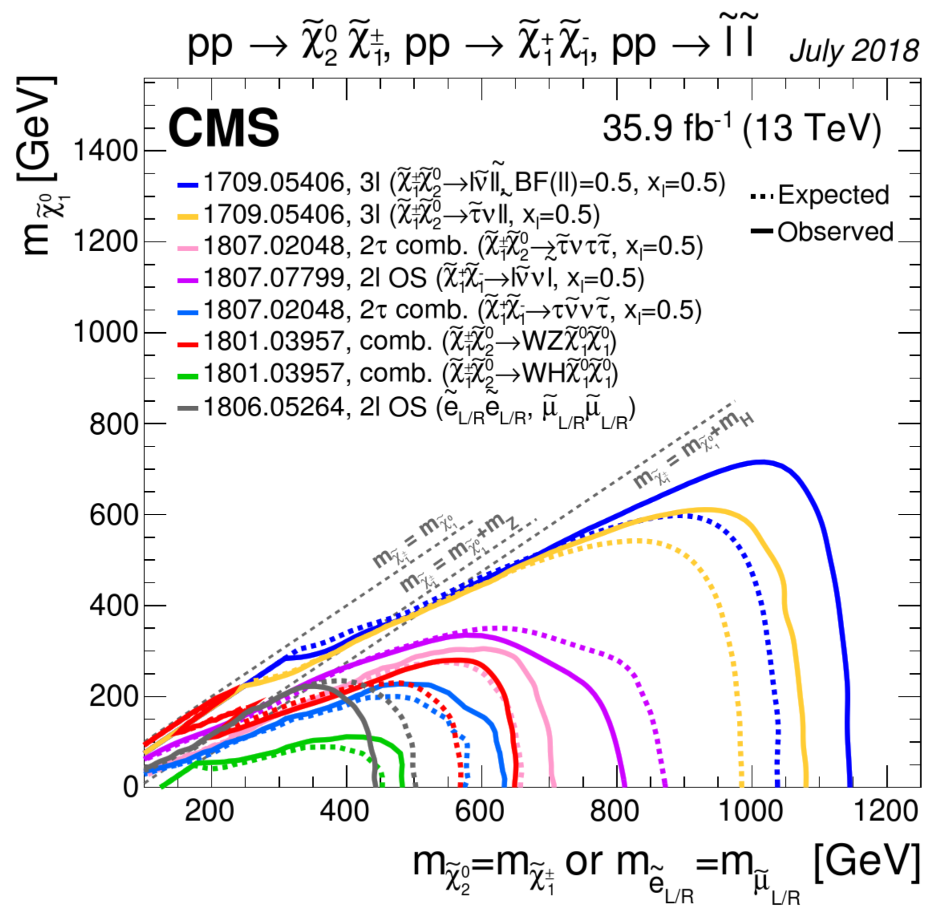
- By being more “complicated”: beyond MSSM, not SUGRA, R-parity violating (⇒ no missing energy), long-lived signatures, **only “electroweak” s-particles at low masses/scales**, ...





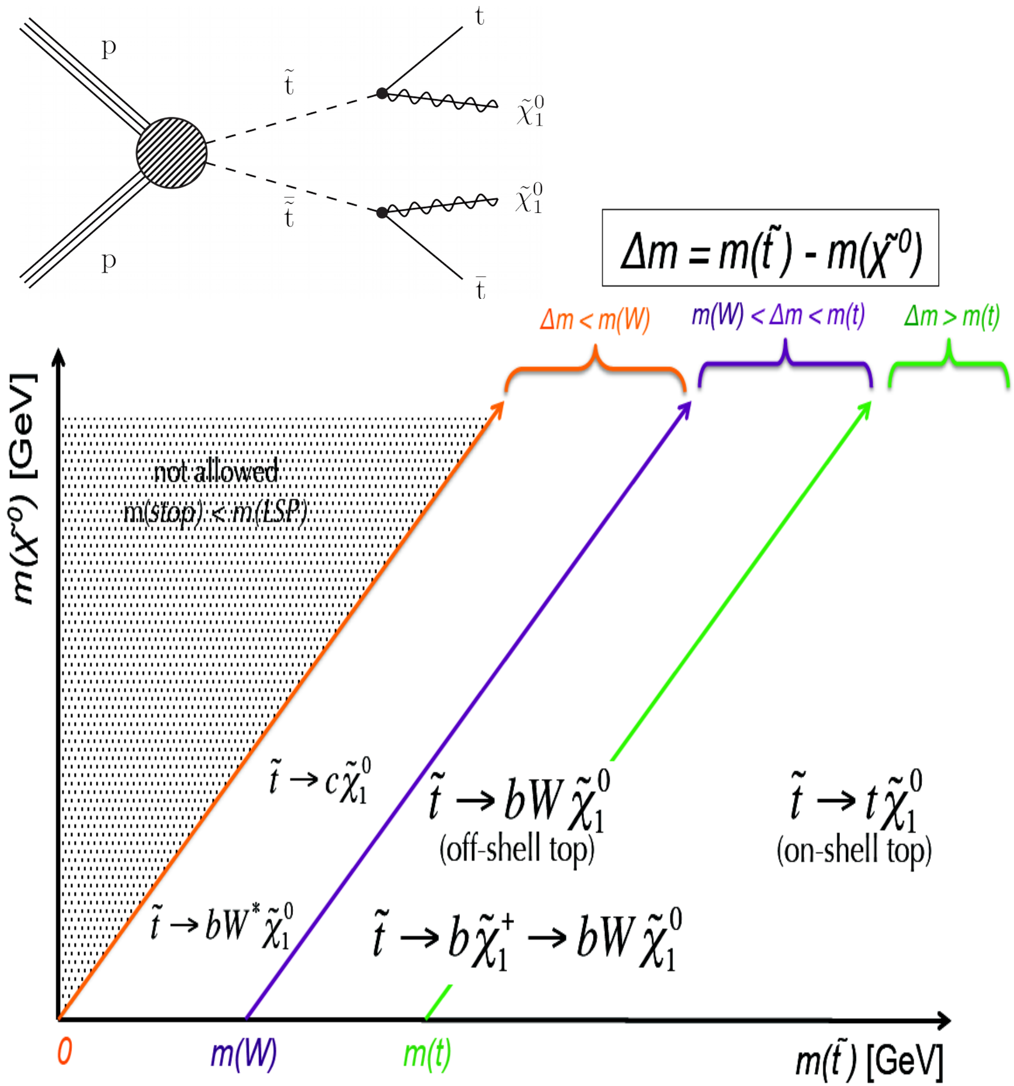


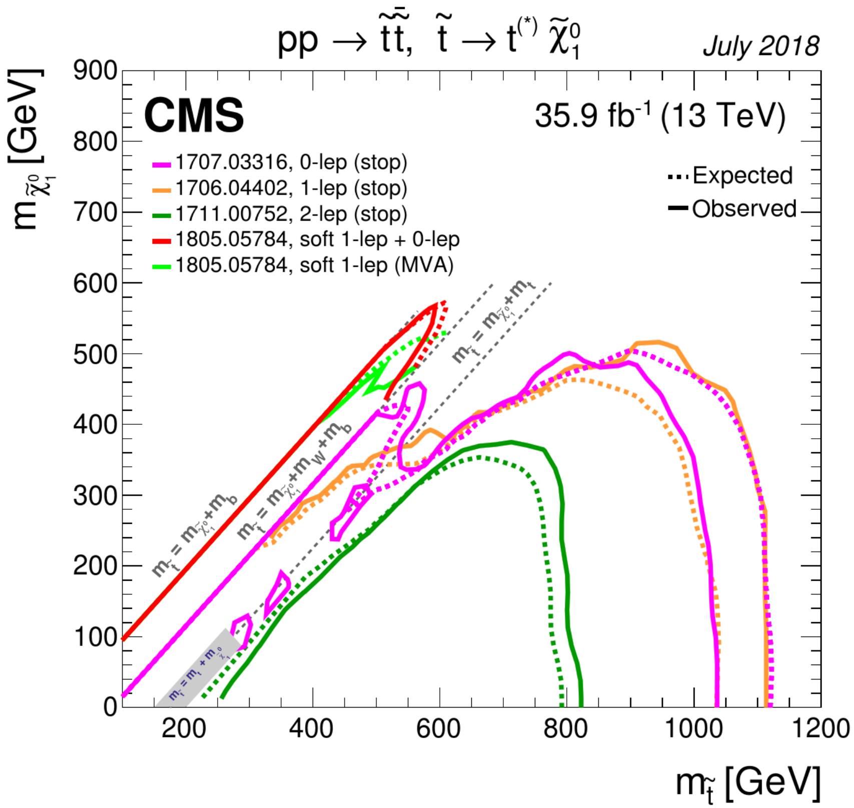
[Taken from CMS SUSY public results]



How can SUSY hide from observation at LHC

- "Compressed" spectra: masses too close to each other in the decay ⇒ low cross sections due to lack of phase space, orbidden decay channels, ...). **Example of the top squark:**



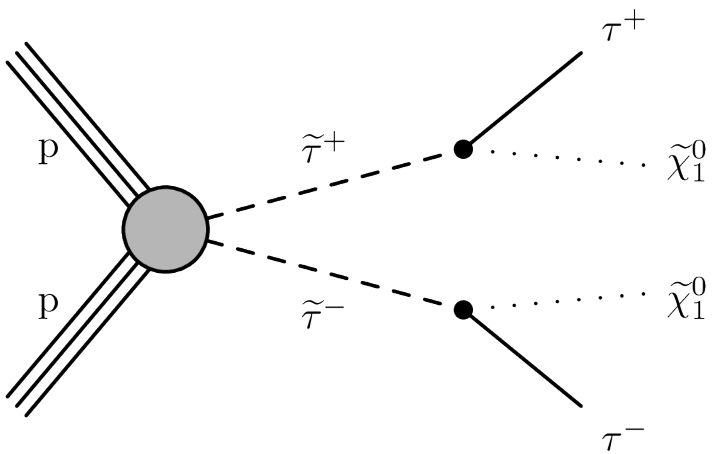


[Taken from CMS SUSY public results]

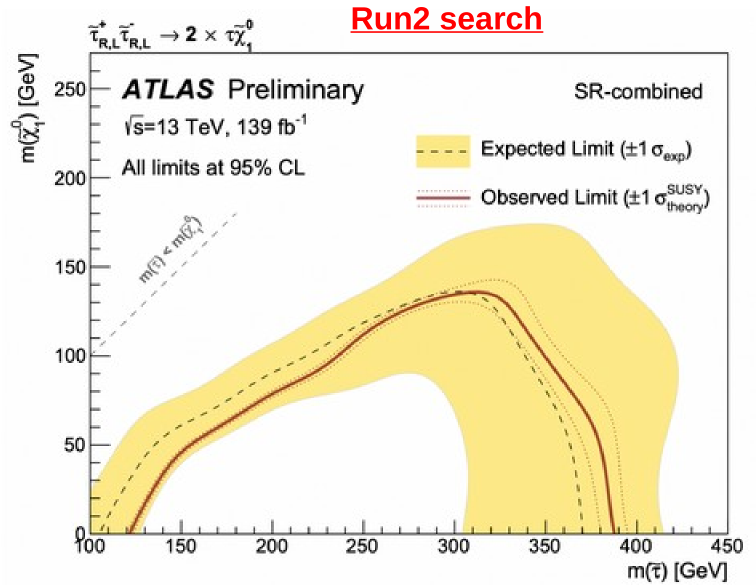
Searches at HL-LHC

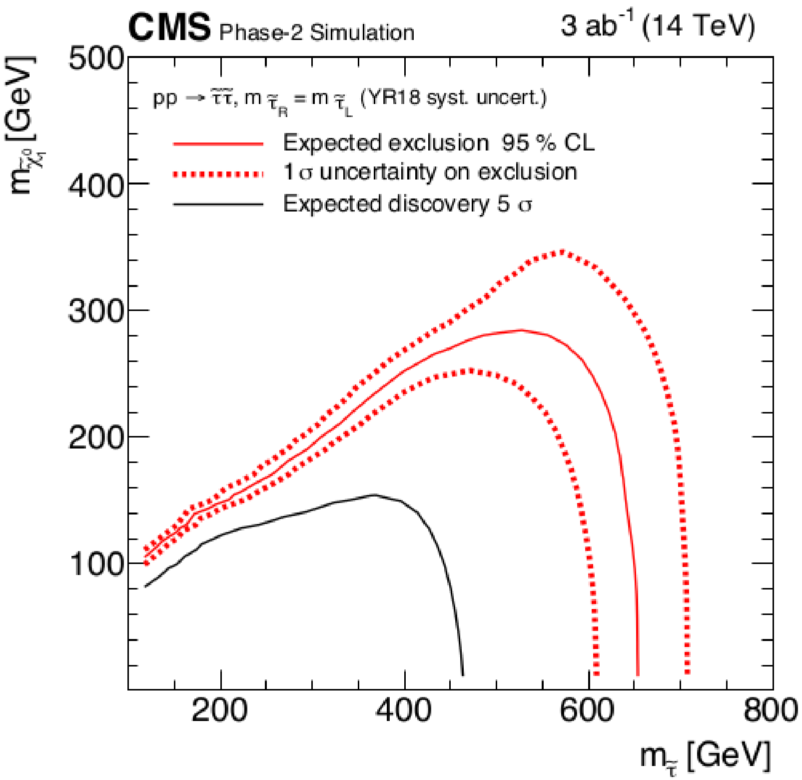
arxiv:1812.07831

- **The increase in luminosity may help in special important situations:**
  - **Confirmation of tiny excesses (≈ 1-3 σ) present in Run2-Run3 (exclusion vs discovery)**



Run2 search

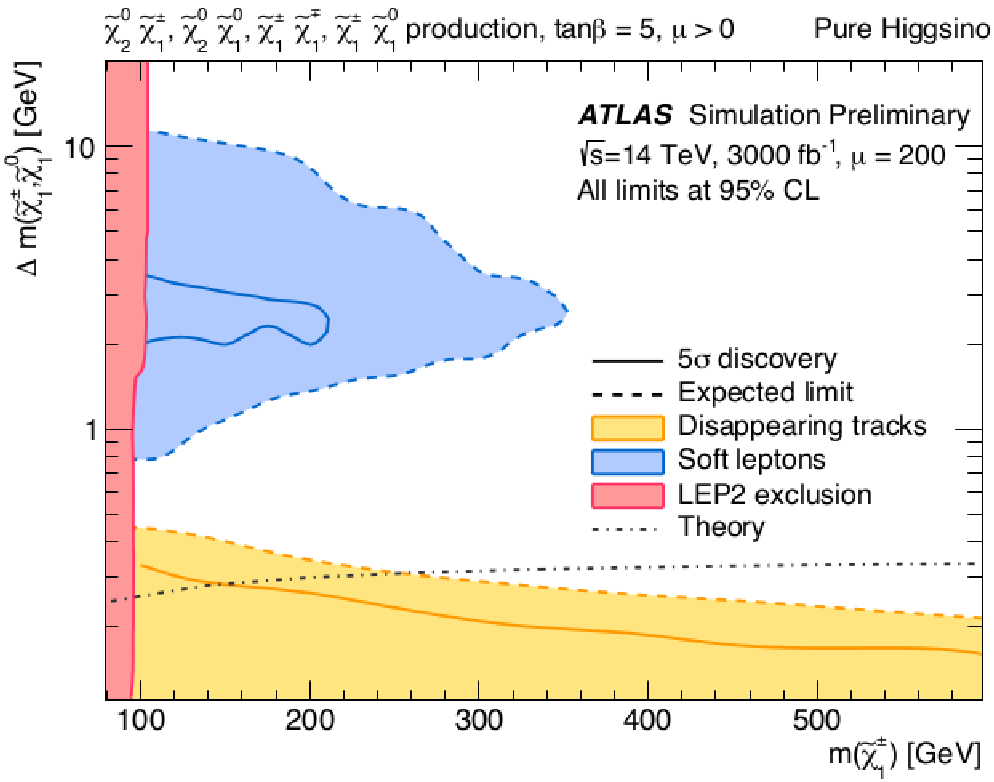


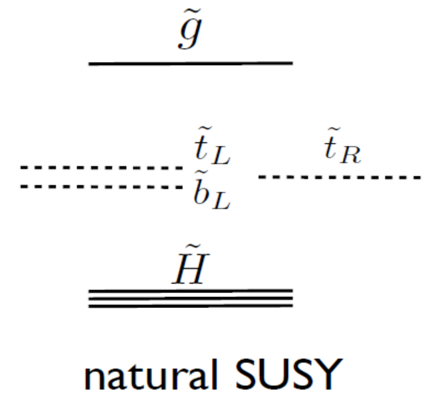


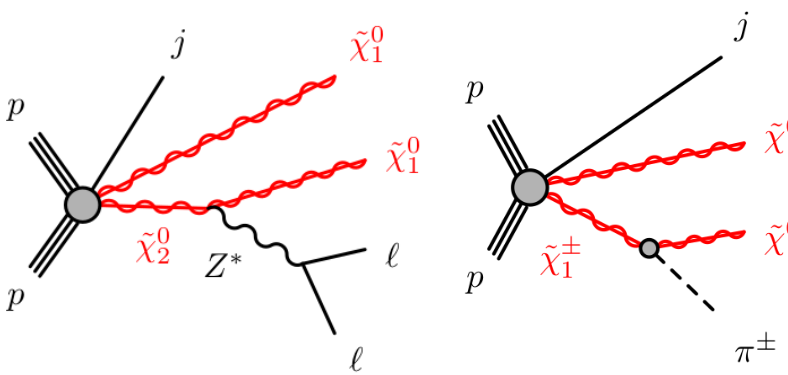
Searches at HL-LHC

arxiv:1812.07831

- **The increase in luminosity may help in some special situations:**
  - **New physics in regions with low rates (compressed and stealth SUSY, for instance)**



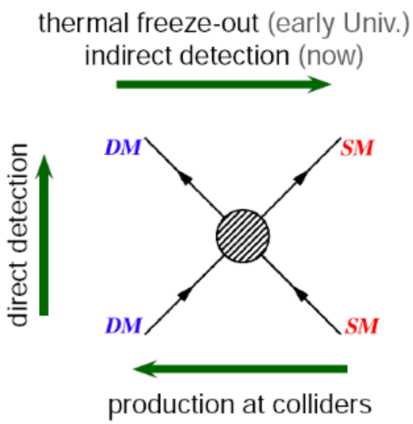


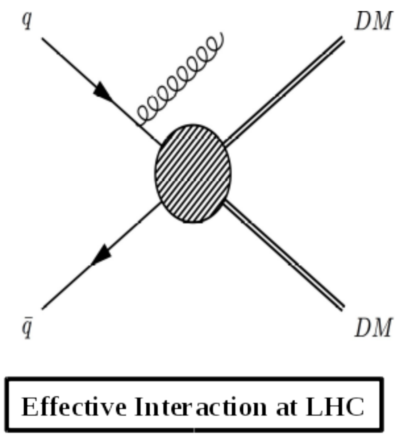


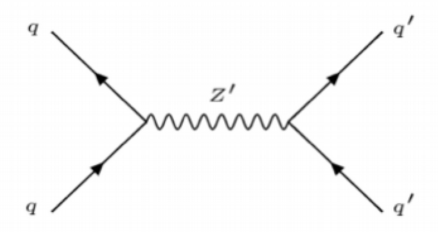
- **Example of search for ewkino pair production:**
  - **EWK-mediated SUSY has lower cross sections than QCD-driven SUSY → HL-LHC helps**
  - **Target "natural" scenarios: Higgsinos have the lowest masses and mass differences among them are small (few GeV, blue region) → small visible energy in the detector (leptons,...)**
  - **If mass differences are very close to zero (yellow region), particles are almost stable ⇒ long-lived charginos decaying into neutralinos (invisible) + very slow pion ⇒ "disappearing tracks"**

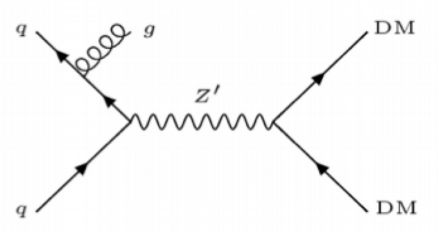
Dark matter (DM) searches at LHC

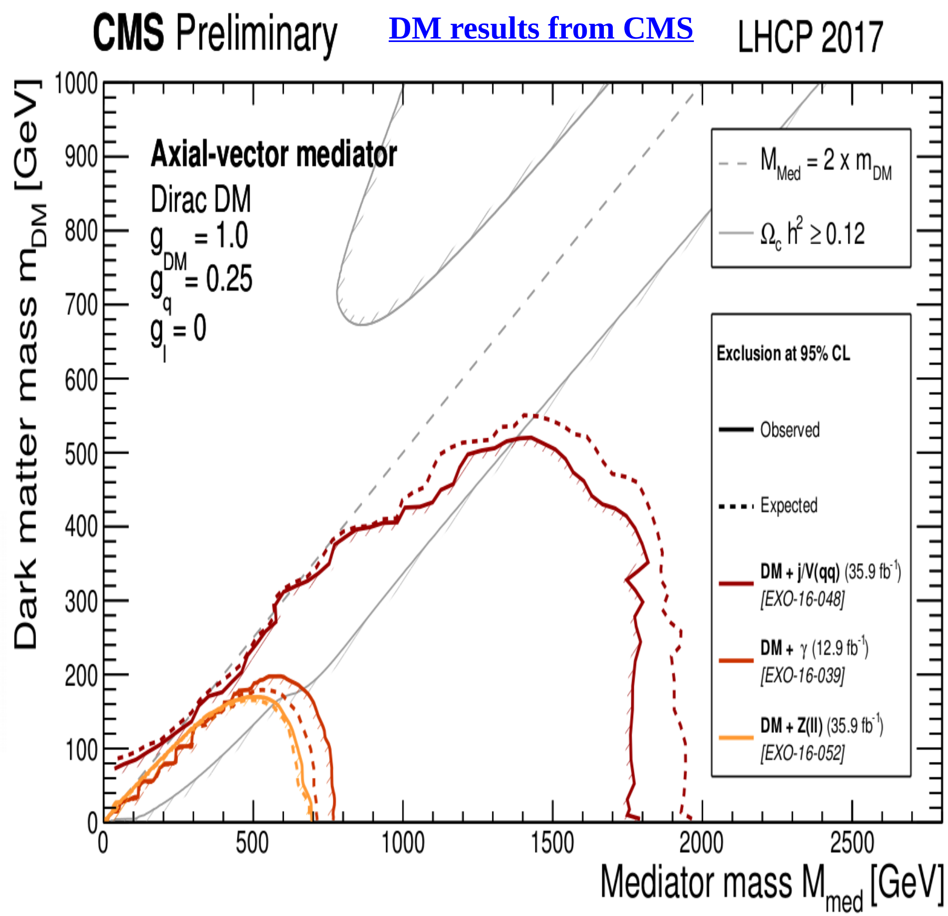
- **Most sensitive generic search is one initial-state radiation jet + missing energy from DM. Mediator may have vector/axial/scalar/pseudoscalar couplings to DM**











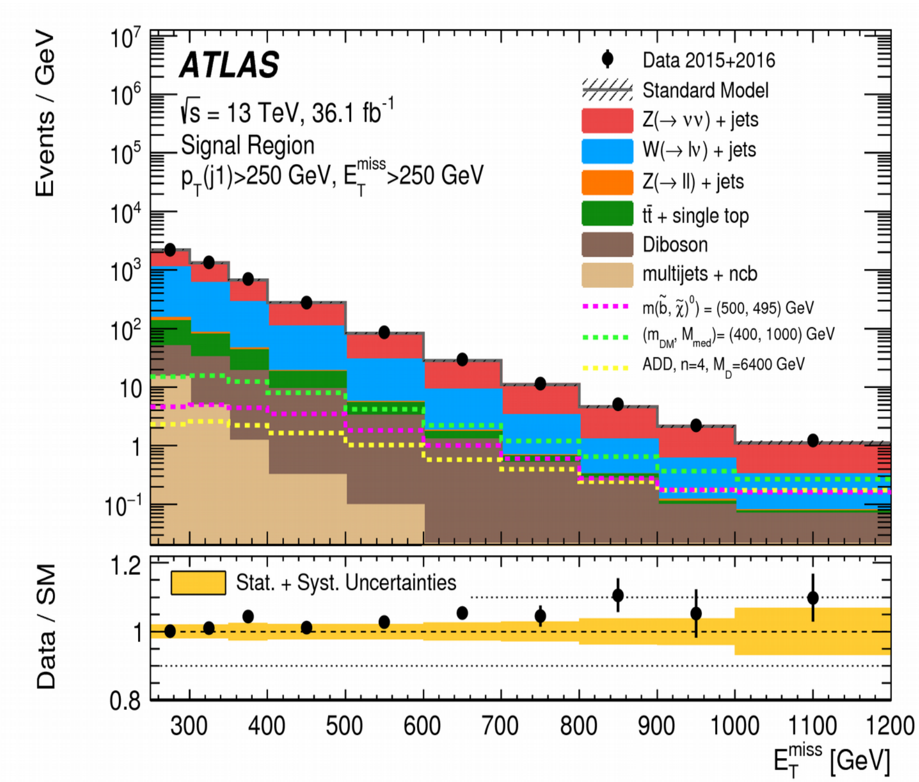
Direct coupling to quarks must exist

X+missing energy search; couplings to quarks and DM

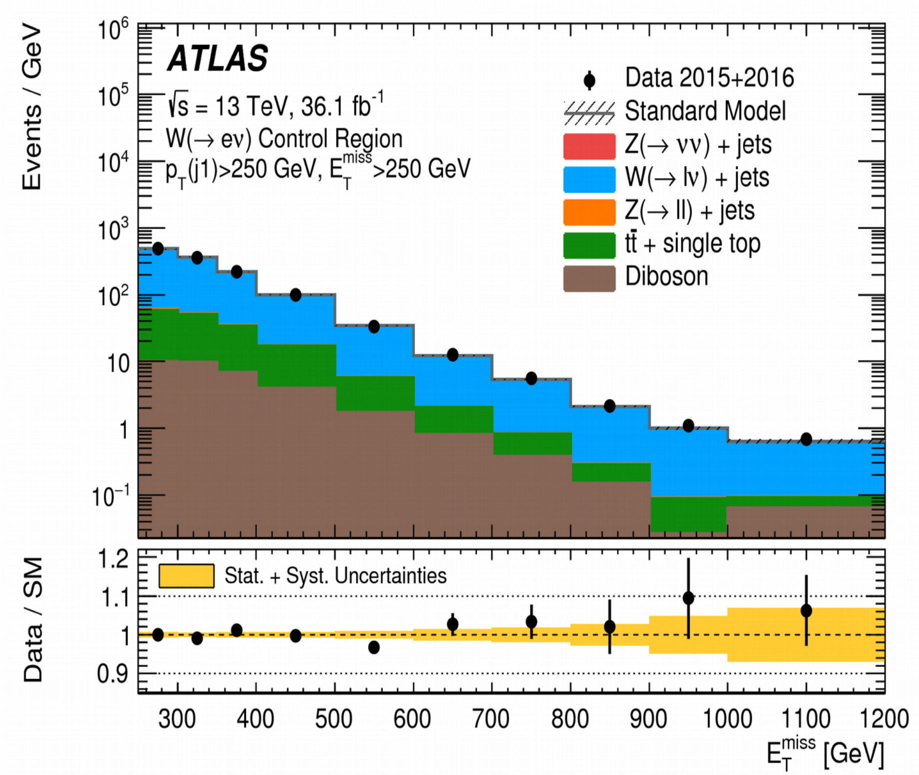
- **Results of the X+DM searches for a benchmark choice of couplings to quarks, DM and leptons**

Dark matter (DM) searches at LHC

- **Key points of the jet+missing energy analysis:**
  - **Trigger: missing transverse energy and jet momenta as low as possible**
  - **No resonance bump expected, but just an excess in the tail of the missing transverse energy ⇒ eprecise control of SM backgrounds (dominated by $\nu\bar{\nu}$ + jet) needed:**
    - **Estimated / monitored via specific control samples ($\mu^+\mu^-$ + jet, for instance)**



Missing transverse energy distribution

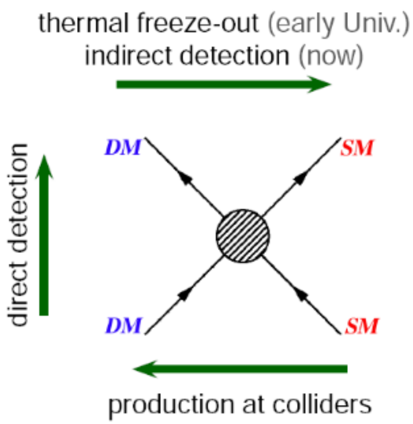


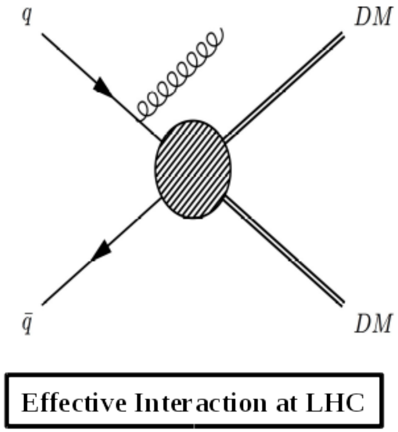
arxiv:1711.03301

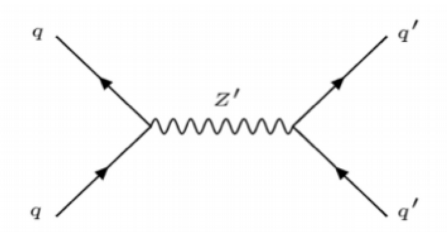
$\mu^+\mu^-$ + jet control sample

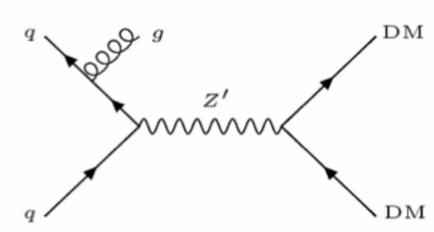
Dark matter (DM) searches at LHC

- **Most sensitive generic search is one initial-state radiation jet + missing energy from DM. Mediator may have vector/axial/scalar/pseudoscalar couplings to DM**





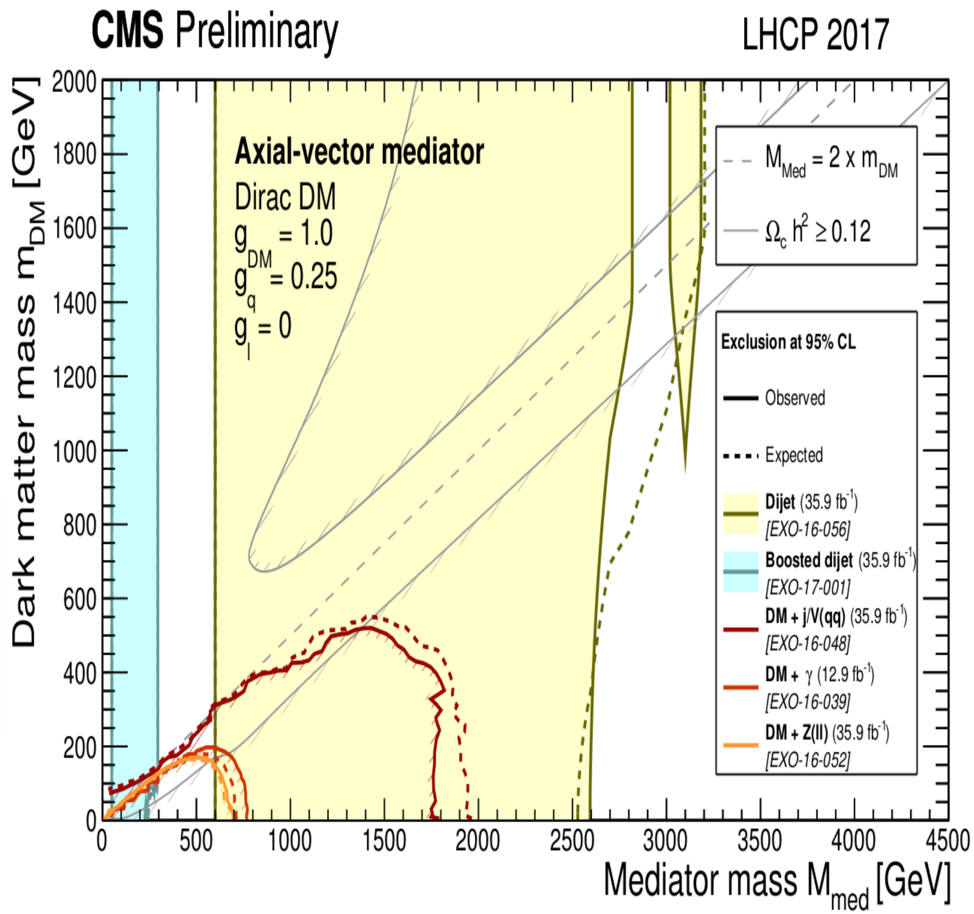




Direct coupling to quarks must exist

X+missing energy search; couplings to quarks and DM

[DM results from CMS](#)

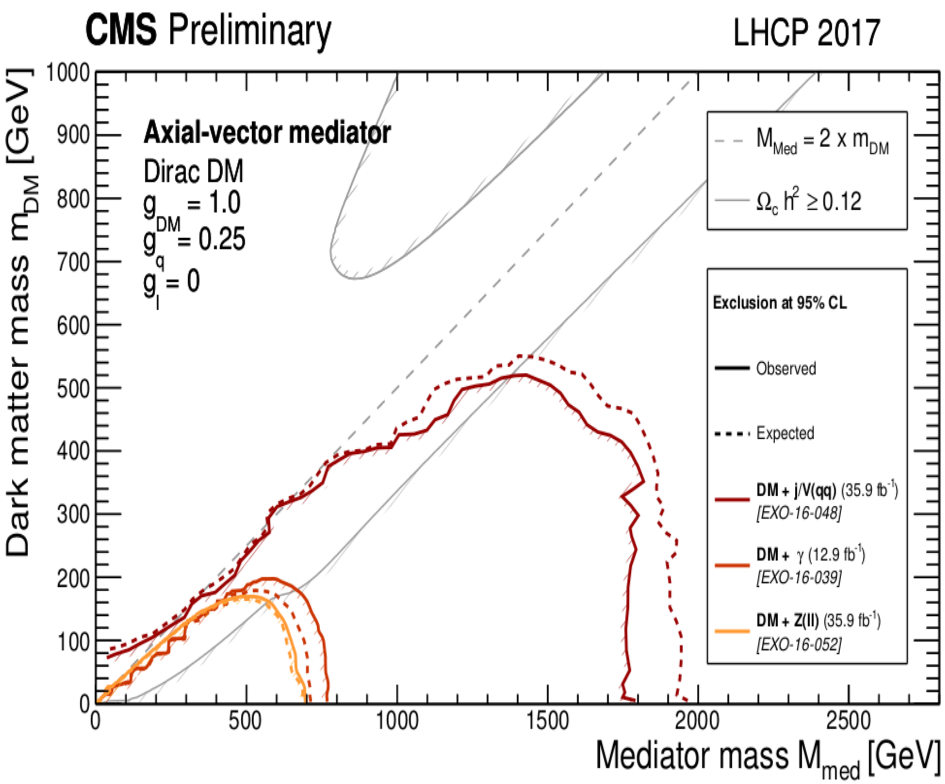


- **Pure dijet resonance searches are even more powerful when the mediator mass is high enough**

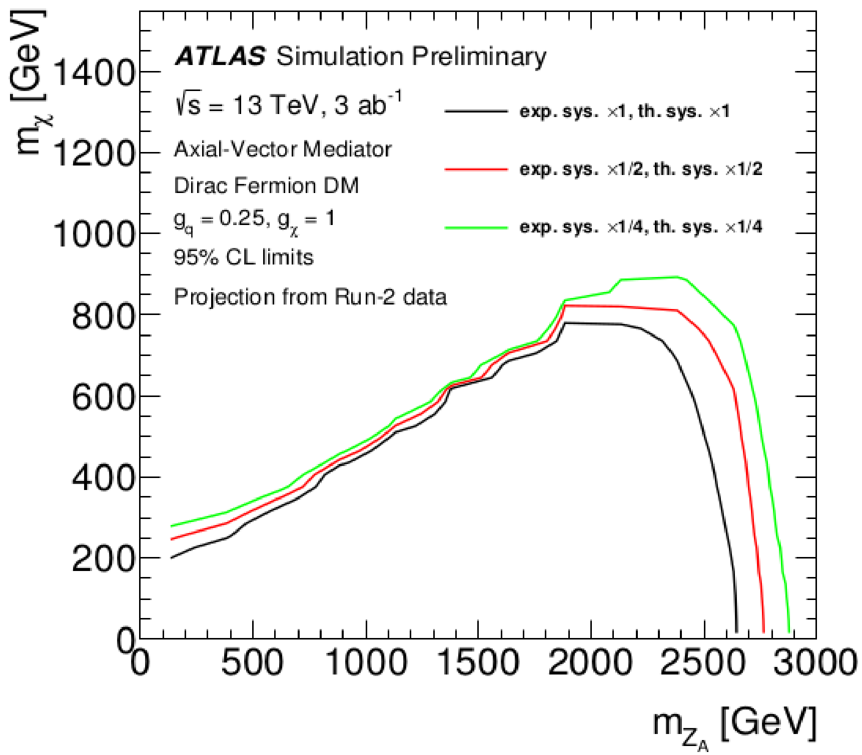
Dark matter searches at HL-LHC

- **Use as example the most sensitive jets+missing channel:**
  - **Main systematics will be the missing transverse energy uncertainties**
  - **Need to keep low thresholds at trigger level (p_T(jet), $E_T^{miss} \gtrsim 250$ GeV)**

DM results from CMS, Run 2



arxiv:1812.07831, HL-LHC



- **≈ 1 TeV larger reach for the dark matter "mediator" mass m_{Med}**
- **almost full coverage for all DM masses up to the kinematic limit $2*m_{DM}<m_{Med}$**

Outlook

- The HL-LHC program is on good track:
  - The experiments have basically finalized all their Technical Design Reports (TDRs) and are already preparing for the big upgrade during LS3 (after Run3: 2021-2023)
  - We expect a performance similar to the current one, despite the harsh pileup conditions
    - Much better trigger (tracker, throughput, …), new state-of-the-art electronics, better detectors

- First-class physics results expected thanks to the increased luminosity (3000 fb^{-1} or so):
  - Study of the EWSB of the SM at the few percent level
  - Good prospects for a sensitive measurement of the Higgs self-coupling ($\gtrsim 4\sigma$)
  - Very precise measurement of vector boson scattering at highes energies
  - More precise measurement of fundamental SM parameters: mH, mW, mt, sin2θeff
  - Improve the reach for the scale/masses of new particles/interaction predicted by a plethora of possible BSM models above the EWK scale by 1-2 TeV
  - And much, much more, uncovered in this talk due to lack of time → anomalous couplings, EFT constraints, search for axions, dark photons, ...

- Exciting times ahead

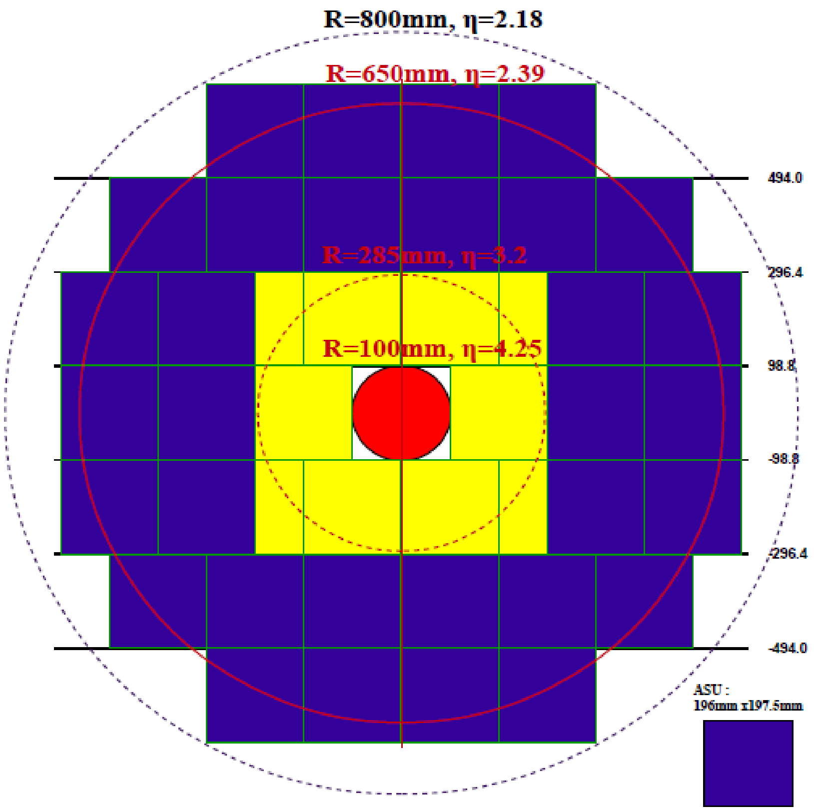
Outlook

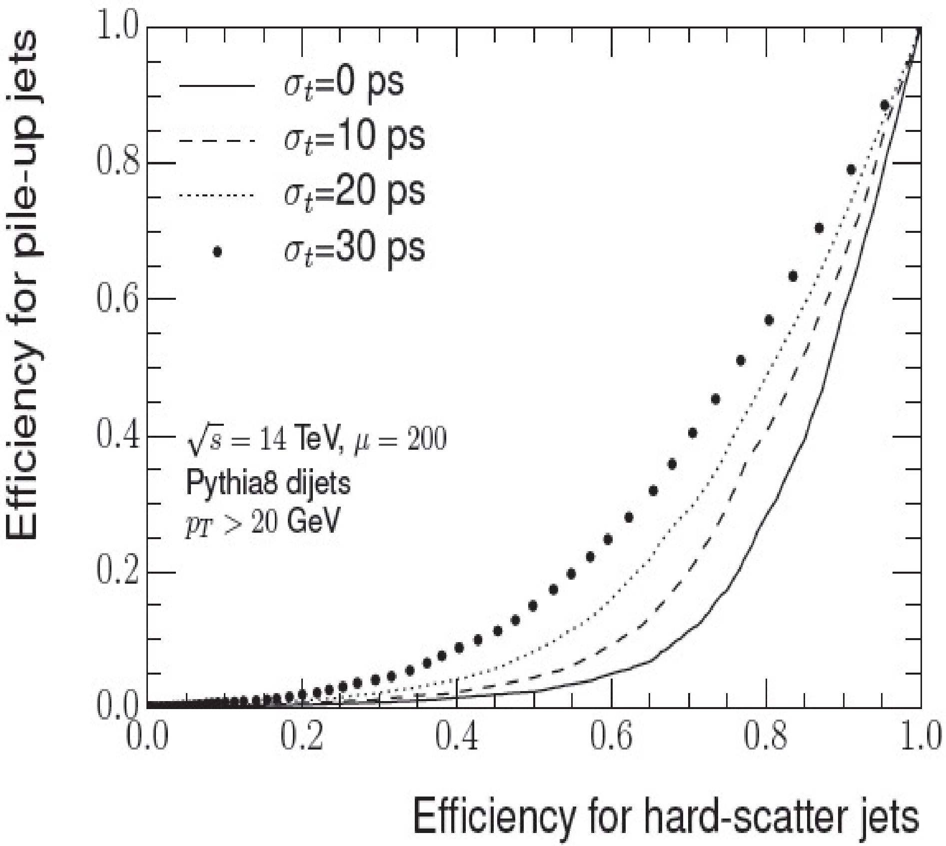
- **The HL-LHC is on good track**
  - **Experiments (ATLAS, CMS) have basically finalized all their Technical Design Reports (TDR) and performed a long list of physics studies and projections**
- **Tracking at early trigger levels is a new promising opportunity**
  - **First feedback from FTK (ATLAS) expected in 2017**
- **New efforts in timing and forward regions (both at hardware and software levels)**
  - **4D (space-time) tracking reconstruction**
  - **Forward jet tagging still remains a challenge**
- **Many studies in progress, in particular regarding:**
  - **Higgs properties**
  - **Di-Higgs production**
  - **FCNC in top**
  - **Searches**

- **Interesting times ahead at the LHC !!**

Backup

Timing detectors: ATLAS HGTD

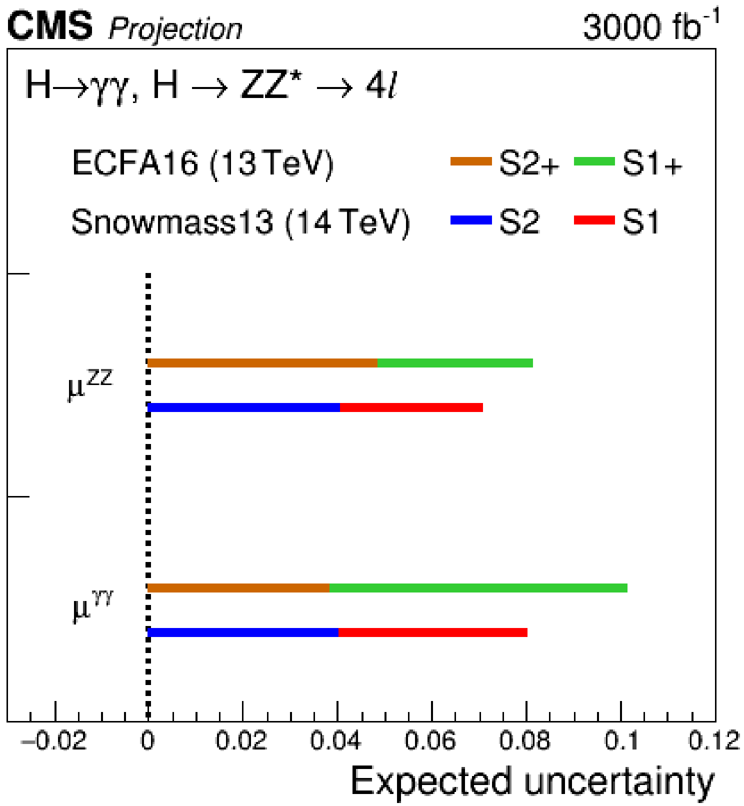


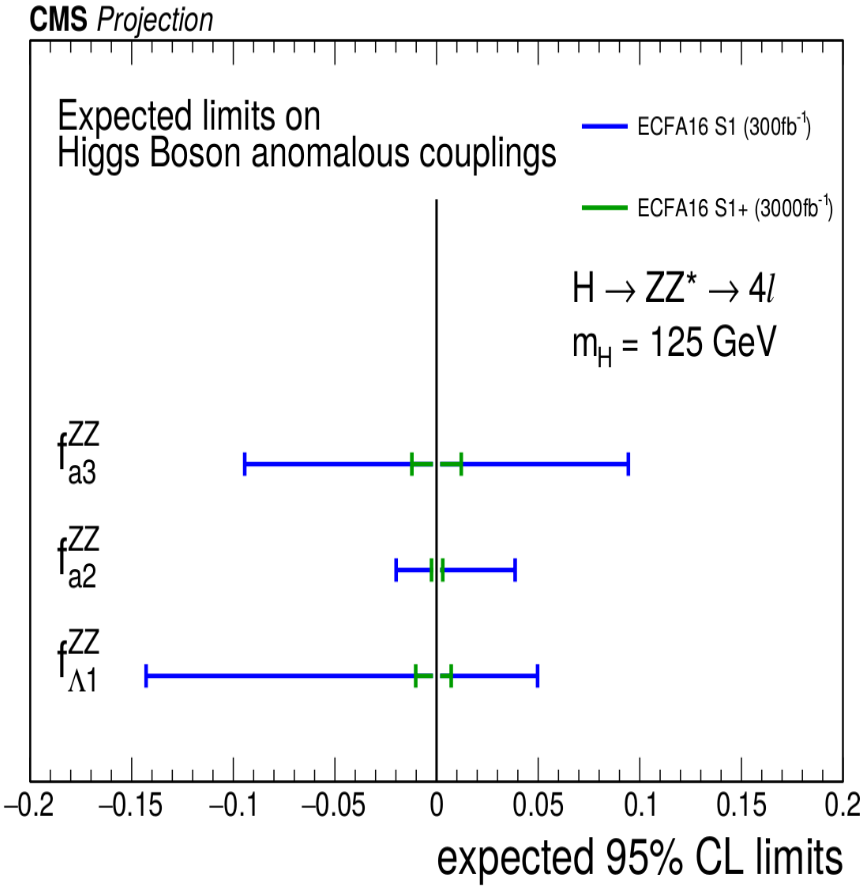


- **High Granularity Timing Detector (forward region): identification of the collision point for particles/jets using timing (the tracking z position uncertainties are large in the forward region)**
  - **4 layers of silicon plus optional layers with tungsten absorber**
  - **Expected resolution is 30-50 ps**
  - **Possibility to use it in trigger (L0)**

Higgs production/couplings

Updated CMS results for ECFA16 (CMS-DP-2016-064)





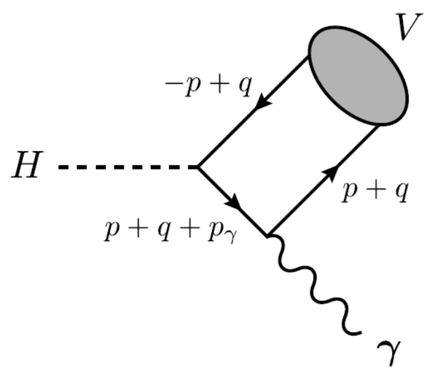
Inclusion of detector upgrade and pile-up effects for "+" scenarios

Statistically dominated: huge increase in sensitivity in anomalous coupling sensitivity going from 300 to 3000 fb^{-1}

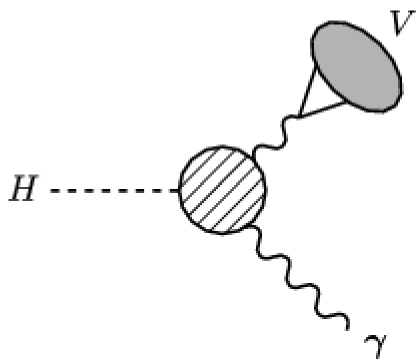
ATL-PHYS-PUB-2015-043

H->J/Psi gamma

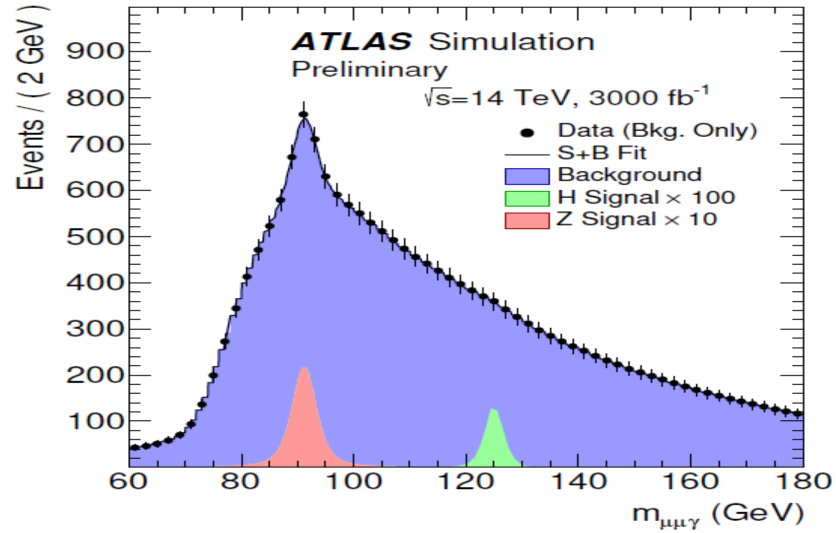
- **Higgs coupling to charm is challenging**
- **ATLAS study of the H→J/ψγ→μμγ channel at high LHC luminosities, sensitive to the Higgs-charm coupling via loops**



Direct



Indirect



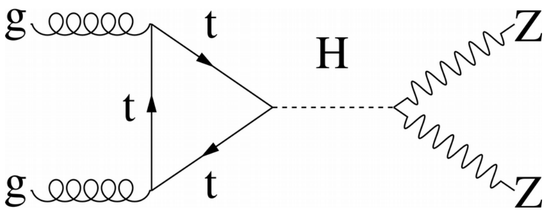
➡ SM expectation: $\mathrm{BR}(H \to J/\psi\,\gamma) = (2.9 \pm 0.2) \times 10^{-6}$

$J/\psi\,\gamma$ Final state						
	Expected Background				Signal	
	Inclusive QCD Mass Range [GeV]		Other Backgrounds $Z \to \mu^+\mu^-\gamma$	$H_{\gamma^*\gamma} \to \mu^+\mu^-\gamma$		
	80-100	115-135			Z	H
Cut Based Analysis	7800±500	3500±400	780 ±100	15.1 ±1.4	50±3	3.2±0.1
Multivariate Analysis		1700±200		13.7 ±1.3		2.9±0.1

- **Current expected limit with 3000 fb^{-1}: 15 times the expected SM Br**

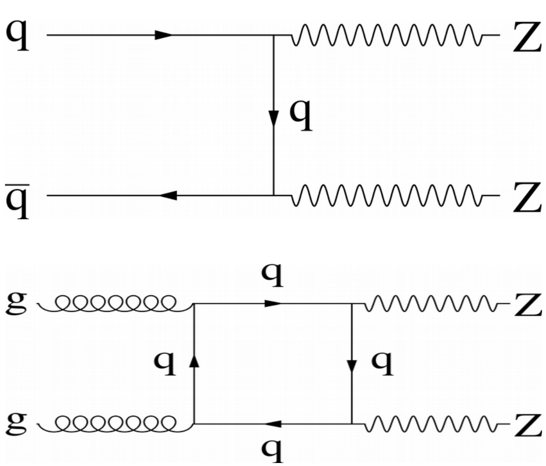
Higgs width in Run 2: bounds

- Strong prospects to really measure the Higgs width with much more statistics at HL-LHC
- Note that this is not fully BSM-independent (other particles present in the loop, for instance)

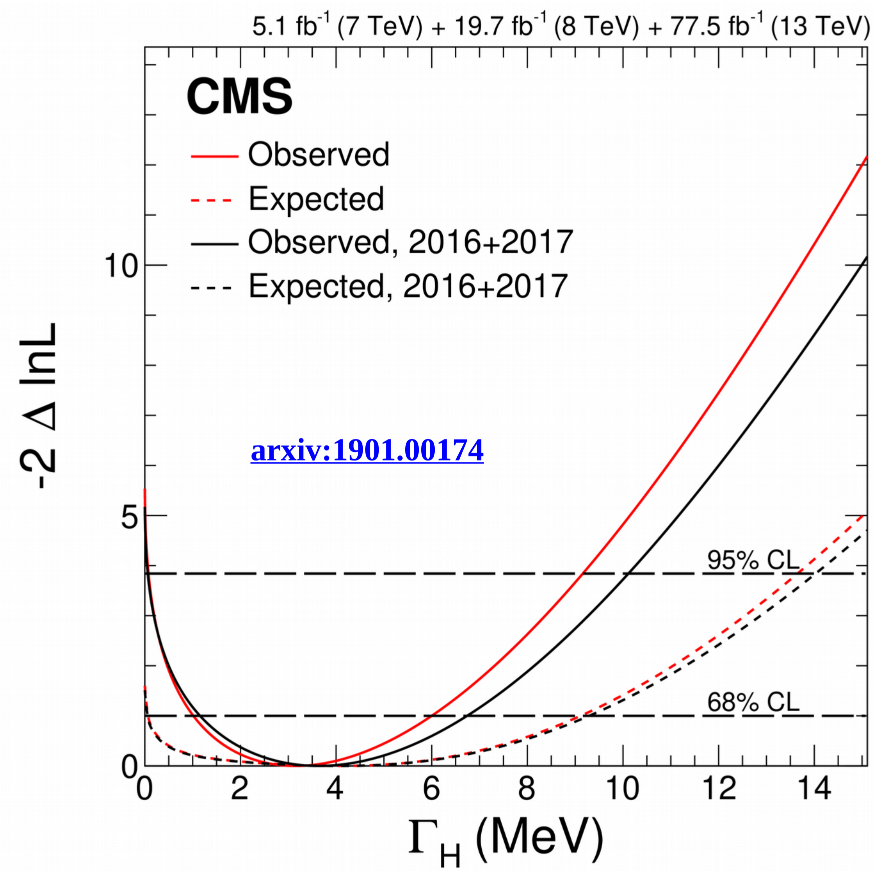


Higgs signal

Background (interfering)



Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

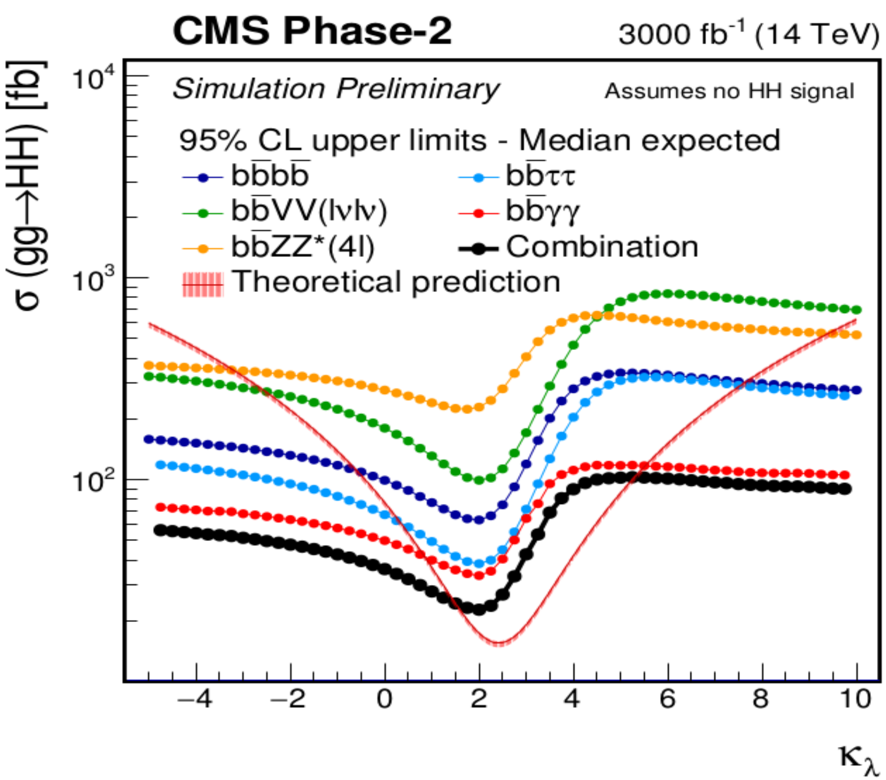


HH production at HL-LHC

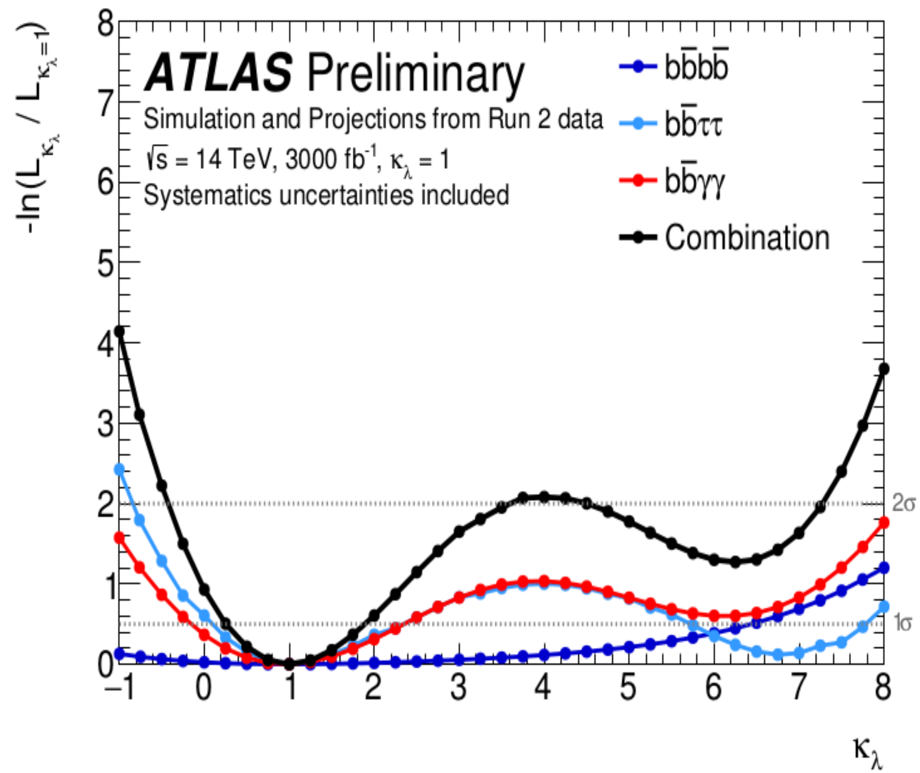
- All possible $b\bar{b}XX$ final states exploited in large detail to gain global sensitivity for the SM case:
  - $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, $b\bar{b}ZZ^*$, $b\bar{b}WW^*$
  - Mostly estimated by extrapolations of current Run2 analyses to L=3000 fb^{-1}
  - Largest sensitivity offered by $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ searches; usage of multivariate methods mandatory

arxiv:1902.00134

Cross section limits as a function of κ_λ

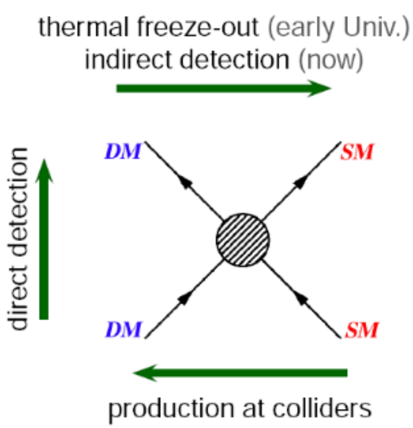


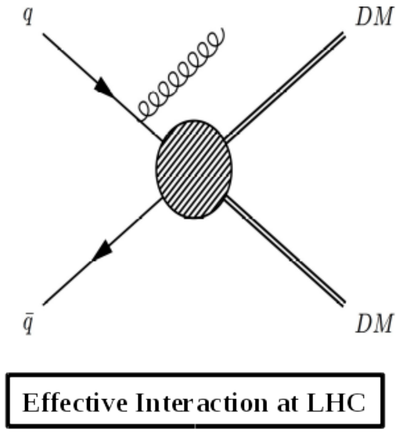
-log(L/L_{SM}) as a function of κ_λ



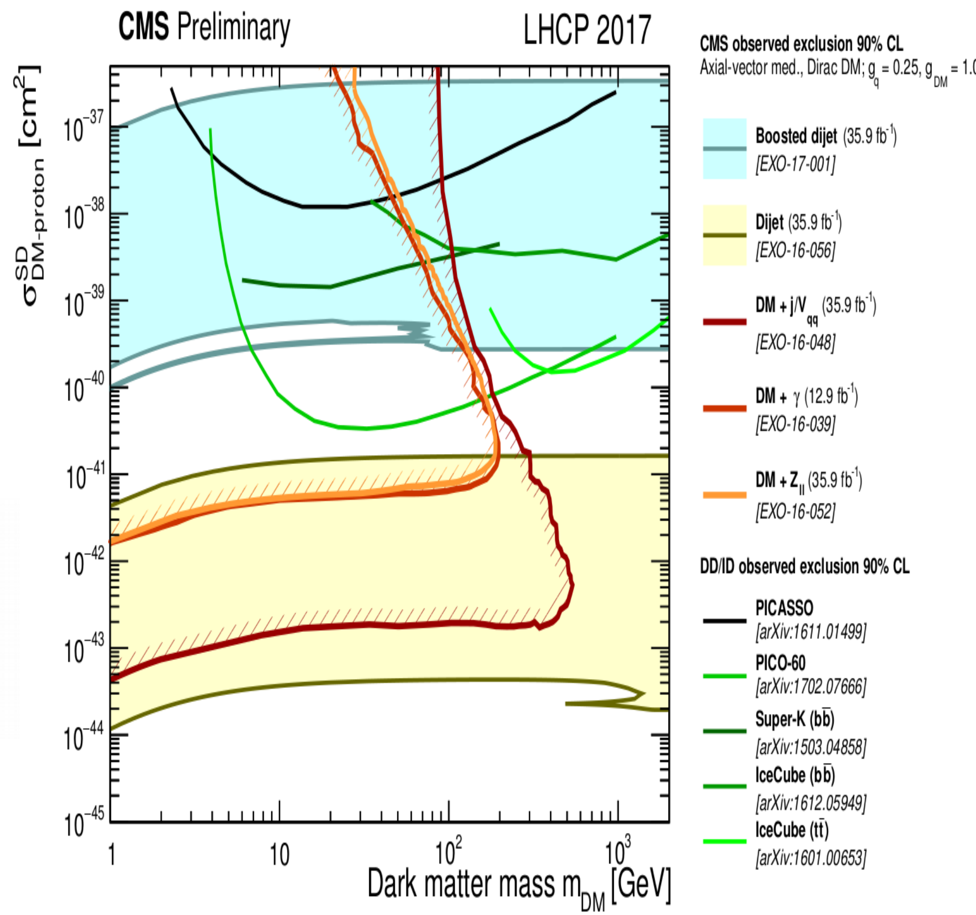
Dark matter (DM) searches at LHC

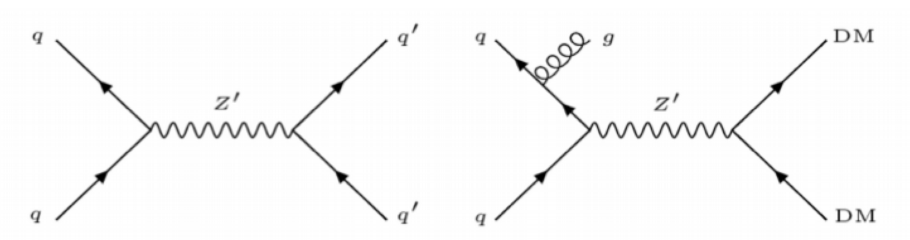
- Most sensitive generic search is one initial-state radiation jet + missing energy from DM. Mediator may have vector/axial/scalar/pseudoscalar couplings to DM





[DM results from CMS](#)





Direct coupling to quarks must exist

X+missing energy search; couplings to quarks and DM

- Comparison with Direct Detection (DD) searches

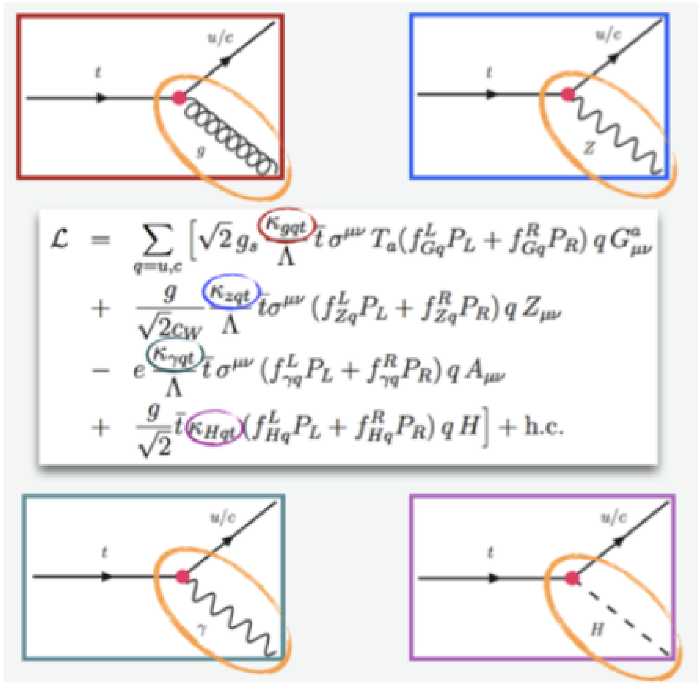
HL-LHC: top anomalous couplings

top quark + gluon

top quark + Z boson

top quark + photon

top quark + Higgs



$$\mathcal{L} = \sum_{q=u,c}\Big[\sqrt{2}g_s\frac{\kappa_{gqt}}{\Lambda}\bar{t}\sigma^{\mu\nu}T_a(f^L_{Gq}P_L + f^R_{Gq}P_R)qG^a_{\mu\nu} + \frac{g}{\sqrt{2}c_W}\frac{\kappa_{zqt}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^L_{Zq}P_L + f^R_{Zq}P_R)qZ_{\mu\nu} - e\frac{\kappa_{\gamma qt}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R)qA_{\mu\nu} + \frac{g}{\sqrt{2}}\bar{t}\kappa_{Hqt}(f^L_{Hq}P_L + f^R_{Hq}P_R)qH\Big] + \text{h.c.}$$

In Standard Model

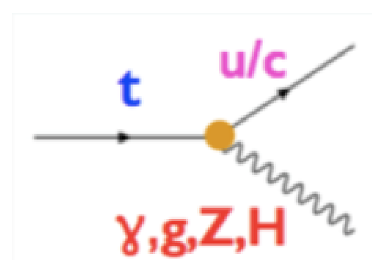
- forbidden at tree level
- only via loops, but highly suppressed

Search

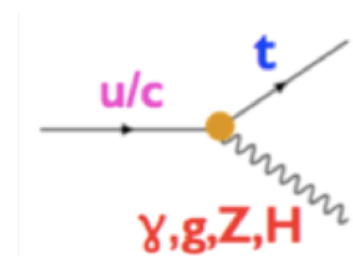
- single top (production)
- top-quark pair (decay)

	SM	2HDM	MSSM
BF($t\to cg$)	$5\cdot 10^{-12}$	$10^{-8}-10^{-4}$	$10^{-7}-10^{-6}$
BF($t\to cZ$)	$1\cdot 10^{-14}$	$10^{-10}-10^{-6}$	$10^{-7}-10^{-6}$
BF($t\to c\gamma$)	$5\cdot 10^{-14}$	$10^{-9}-10^{-7}$	$10^{-9}-10^{-8}$
BF($t\to cH$)	$3\cdot 10^{-15}$	$10^{-5}-10^{-3}$	$10^{-9}-10^{-5}$

$t\bar{t}$



single top

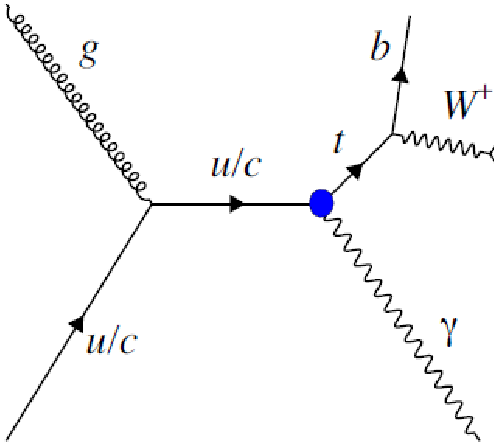


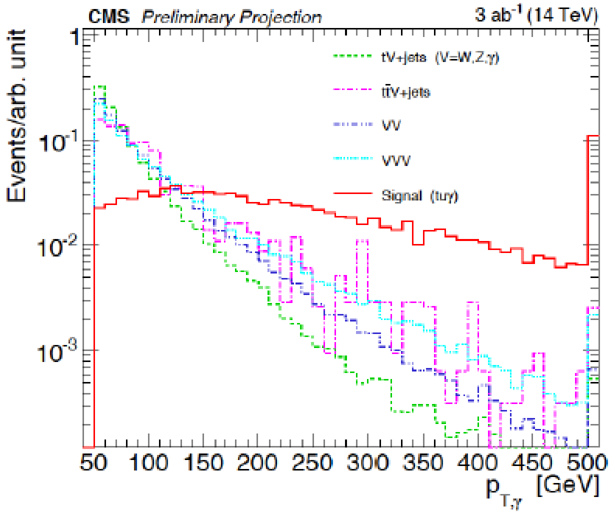
Taken from M. Cristinziani talk at ECFA16

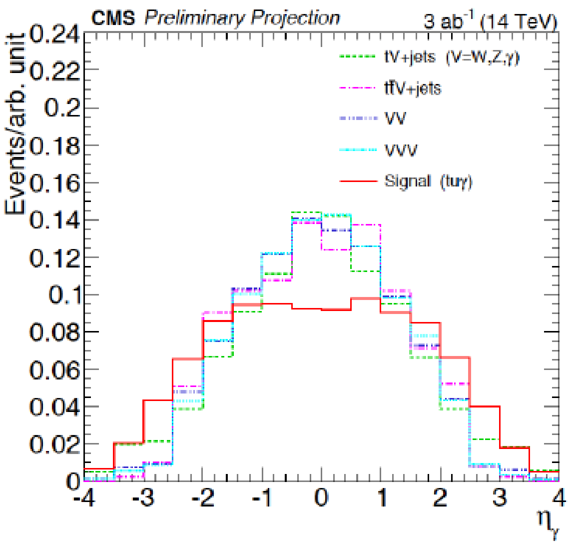
Top: anomalous couplings, FCNC

Selection (not reoptimised for 14TeV)

- exactly 1 tight, isolated μ
  - veto loose μ/e
- exactly 1 *b*-tagged jet
- exactly 1 isolated high E_T photon
  - well separated from jet and μ, $\Delta R = 0.7$
- reconstructed $130 < m_{top} < 220$ GeV





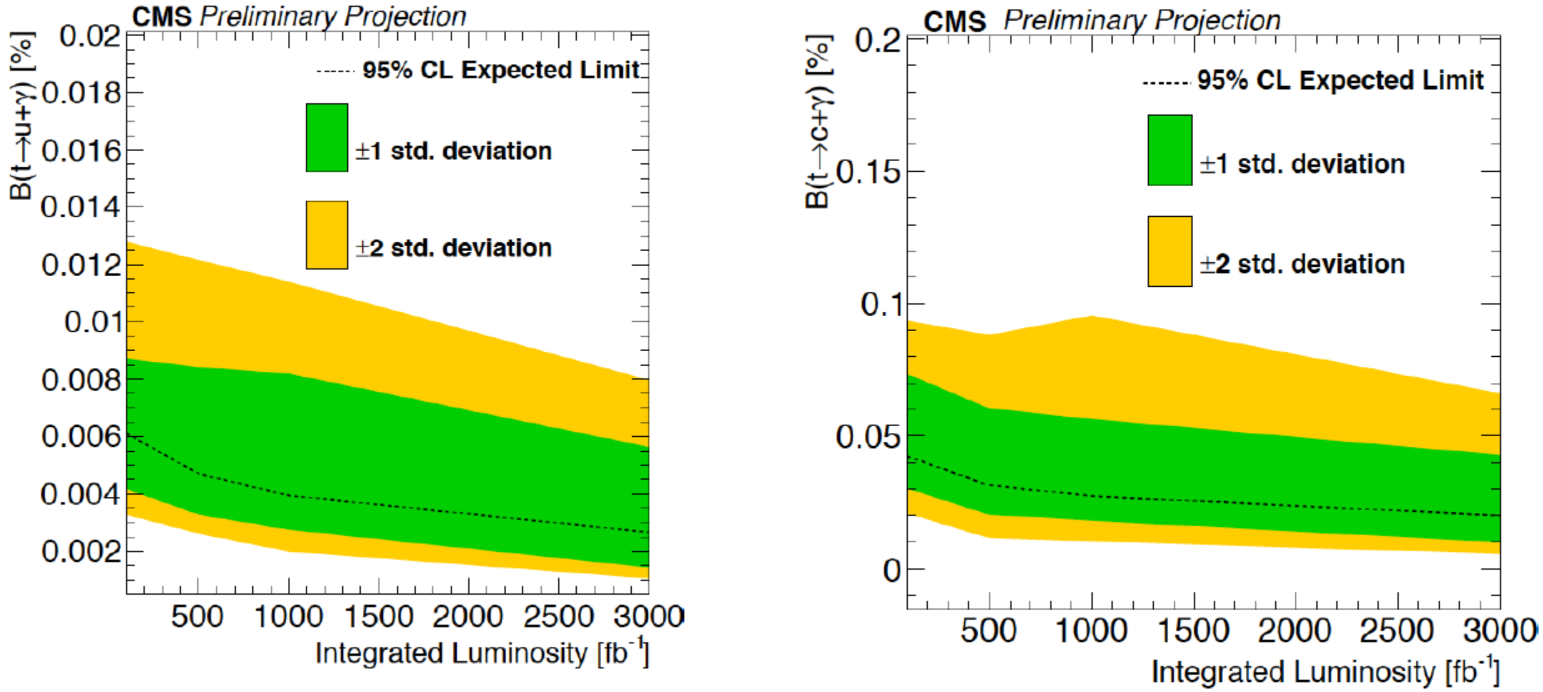


CMS-DP-2016-064

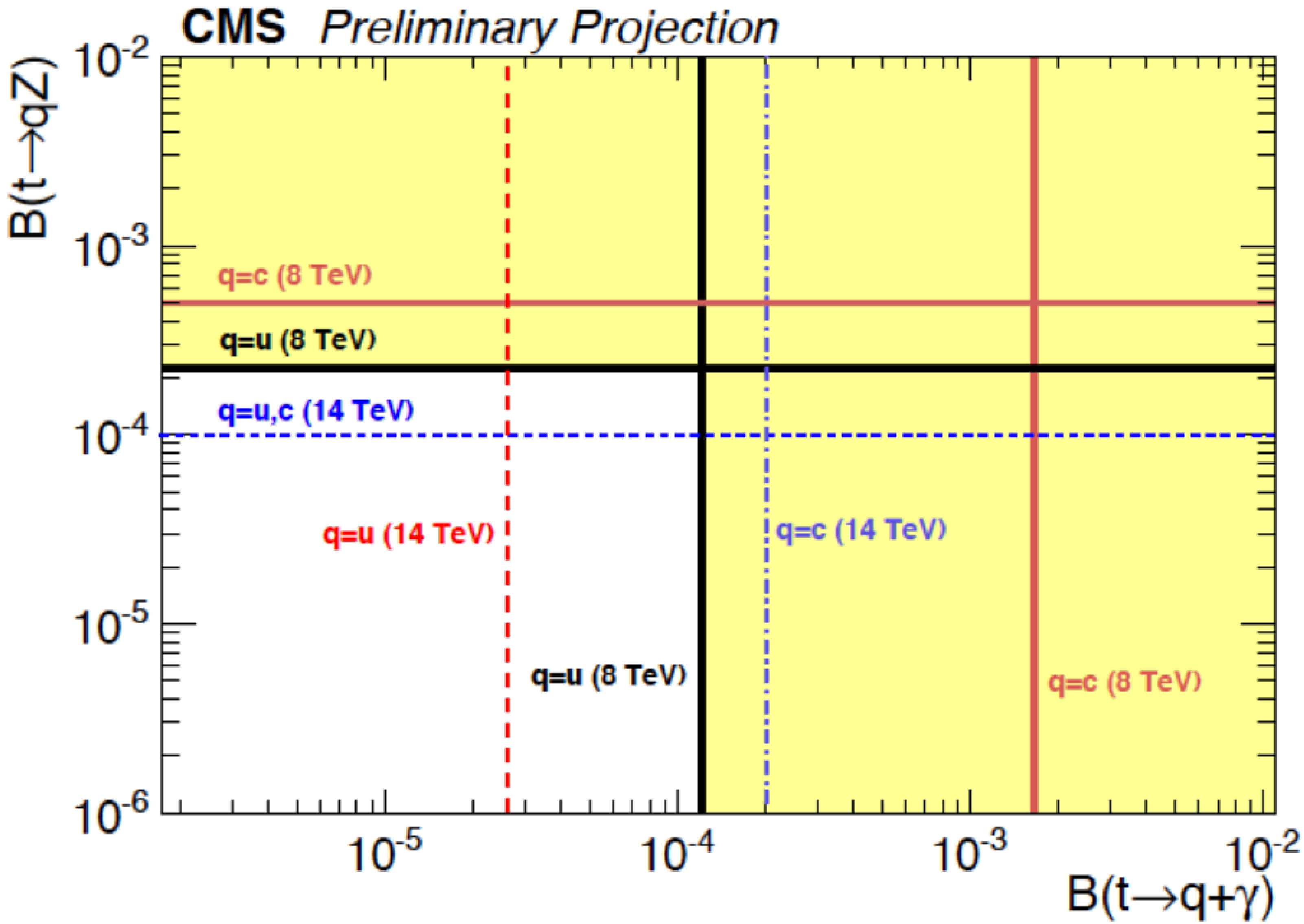
Top: anomalous couplings, FCNC

	19.7 fb^{-1} at 8 TeV	3 ab^{-1} at 14 TeV (Scenario 1)	3 ab^{-1} at 14 TeV (Scenario 2)
$B(t \to u + \gamma)$	1.3×10^{-4}	4.6×10^{-5}	2.7×10^{-5}
$B(t \to c + \gamma)$	1.7×10^{-3}	3.4×10^{-4}	2.0×10^{-4}

The 95% CL upper limit on the branching fractions of t → u + γ (left) and t → c + γ (right) are presented in terms of the integrated luminosity up to 3 ab^{-1}. The dashed curve is the expected upper limit at 95% CL and green and yellow bands show the ±1 and ±2 standard deviations from the expected limits. The results are obtained in a scenario of systematic uncertainties assuming better understanding of theoretical predictions and an improved detector performance.



Top: anomalous couplings, FCNC

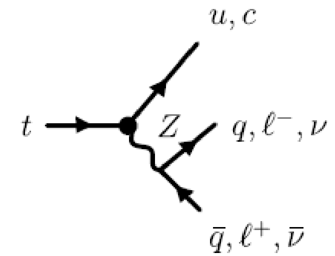


Top: anomalous couplings, FCNC

ATLAS-PUB-2016-019

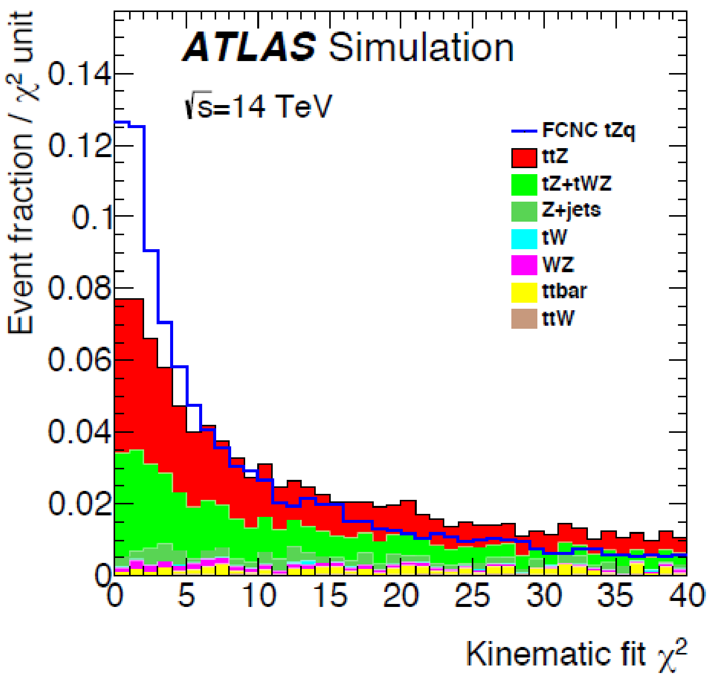
Selection

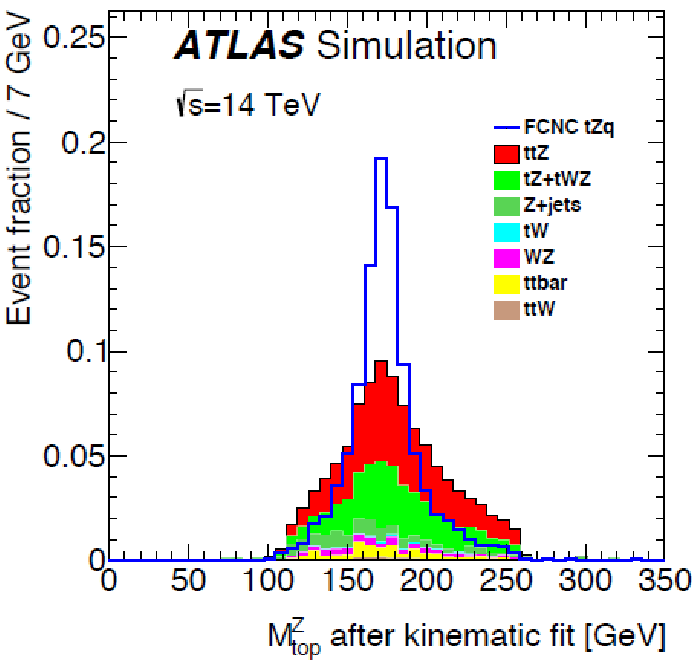
- three leptons, one OSSF in *Z*-mass window
- ≥1 *b*-jet, ≥ 1 non-*b*-jet



Kinematic reconstruction

$$\chi^2 = \frac{\left(m_Z - m^{\text{reco}}_{\ell_1\ell_2}\right)^2}{\sigma_Z^2} + \frac{\left(m_W - m^{\text{reco}}_{\ell_3\nu}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m^{\text{reco}}_{\ell_3\nu j_b}\right)^2}{\sigma_{t\to Wb}^2} + \frac{\left(m_t - m^{\text{reco}}_{\ell_1\ell_2 j_u}\right)^2}{\sigma_{t\to Zq}^2}$$





Top: anomalous couplings, FCNC

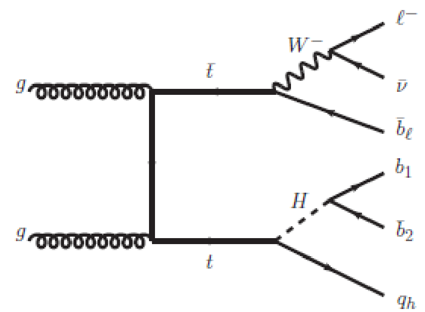
Consider several final states to cope with acceptance/inefficiency

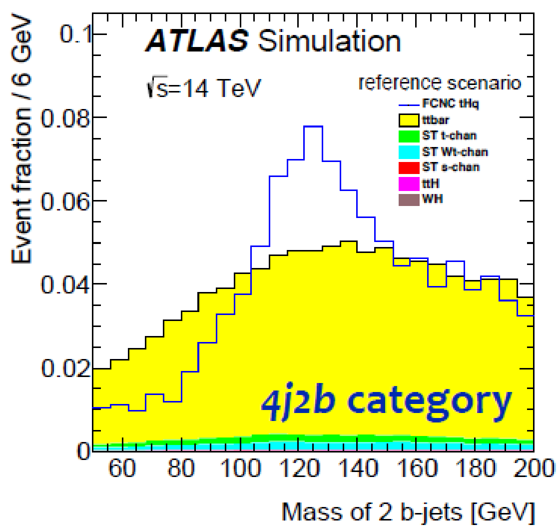
- 2 *b*-jets with 4 or ≥5 jets
- 3 *b*-jets with 3, 4, 5, or ≥6 jets

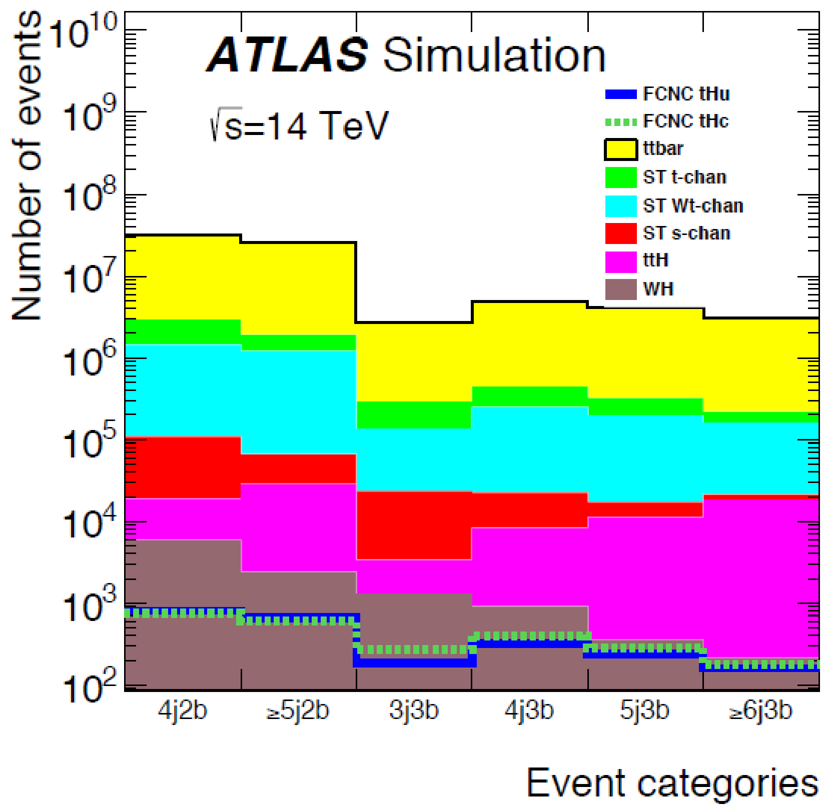
Discriminant variable

- constructed in each region
- try to identify Higgs, *W*, top peaks
- using every possible permutation

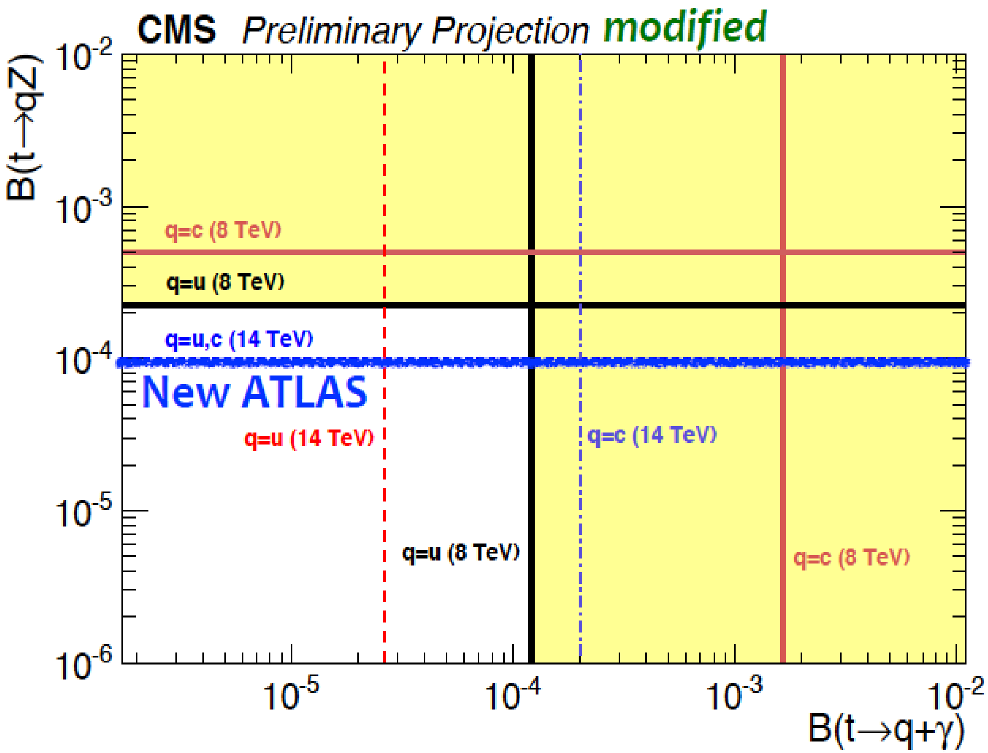
ATLAS-PUB-2016-019

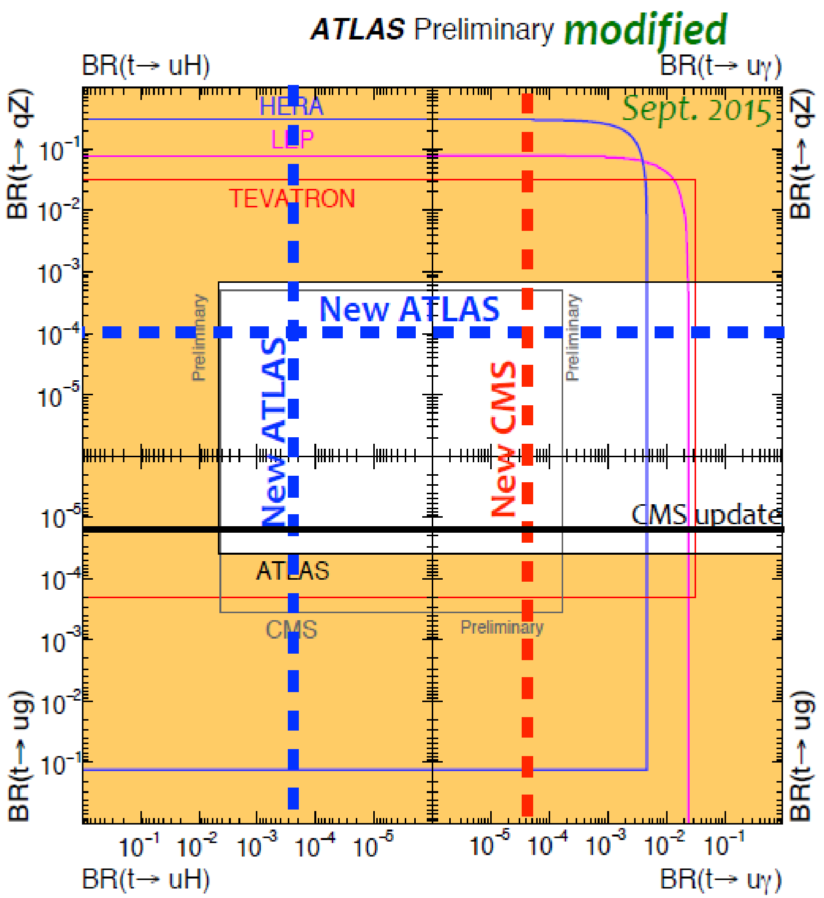






Top: anomalous couplings, FCNC





Taken from M. Cristinziani talk at ECFA16