LHC Physics: Higgs and searches for new physics

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Outline

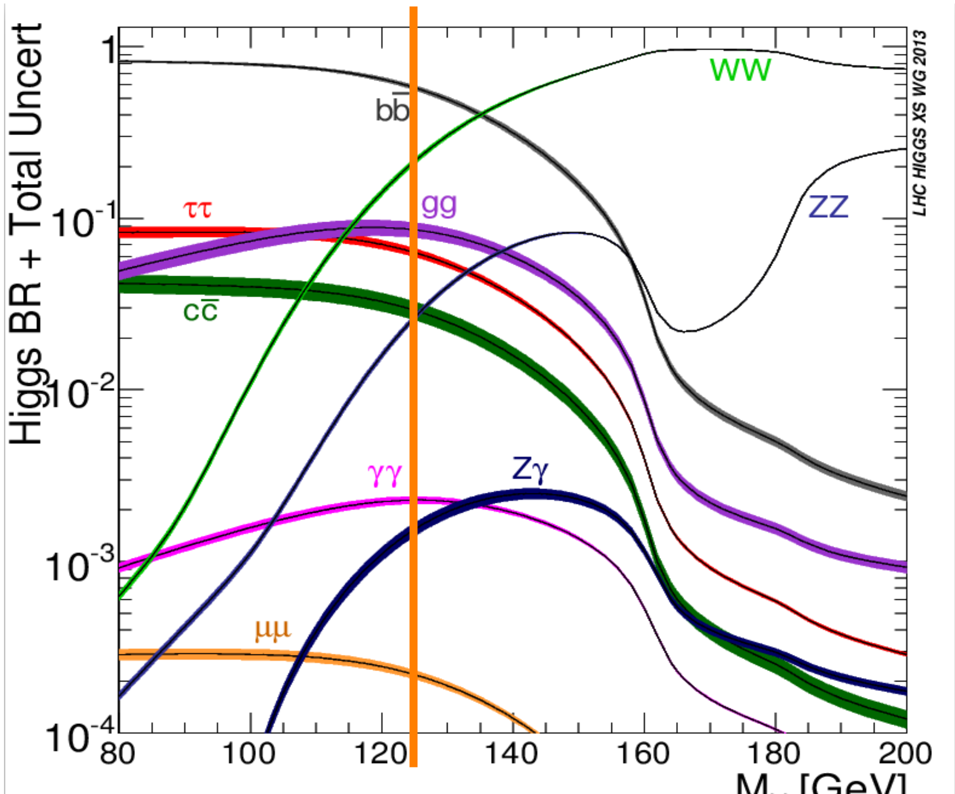
- Studies and results within the Standard Model
  - Higgs physics
  - Generic searches: some examples and current trends
  - SUSY: some generalities and current trends

Higgs

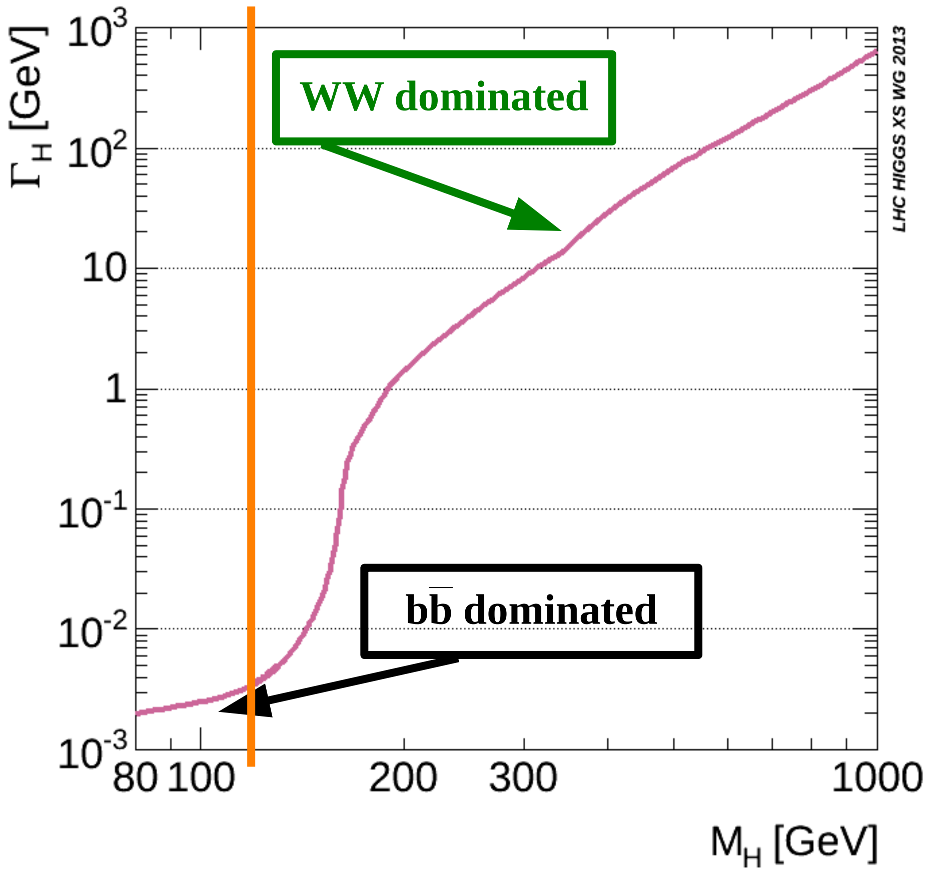
SM Higgs properties

1) It couples to particles proportionally to their mass. This determines most of the Higgs production properties

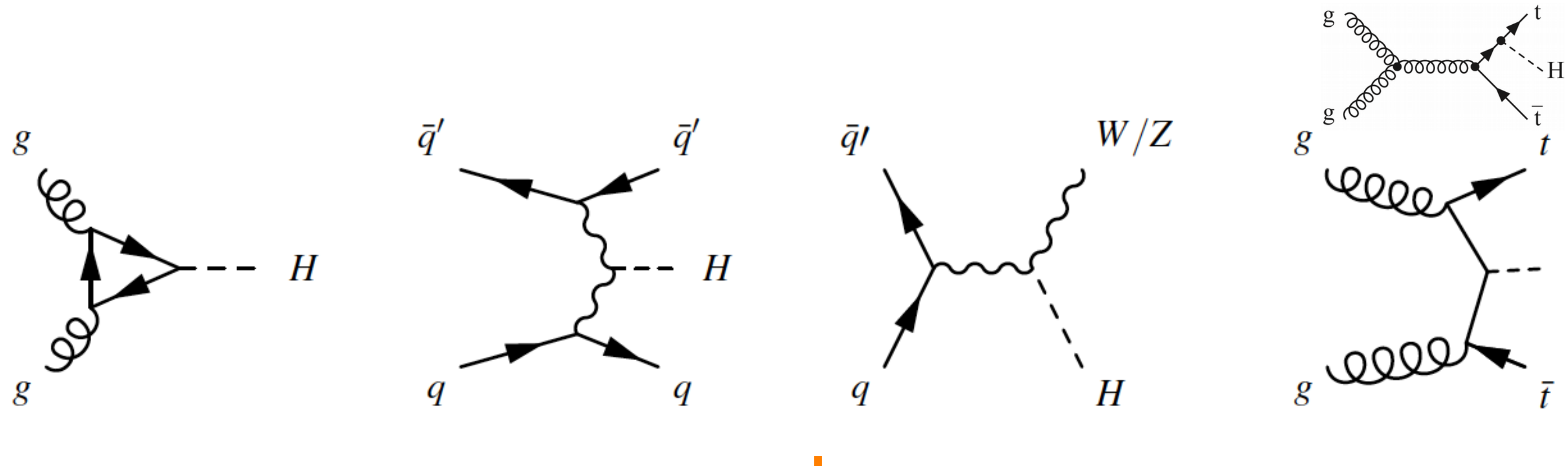
2) The value of the Higgs mass determines which decays are accessible (→ width and BRs)



[Taken from LHC Higgs XSection WG](#)

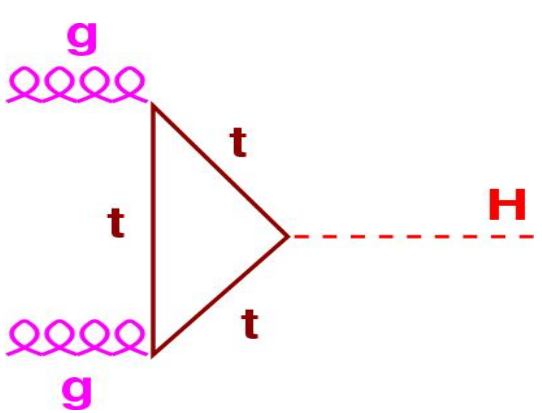


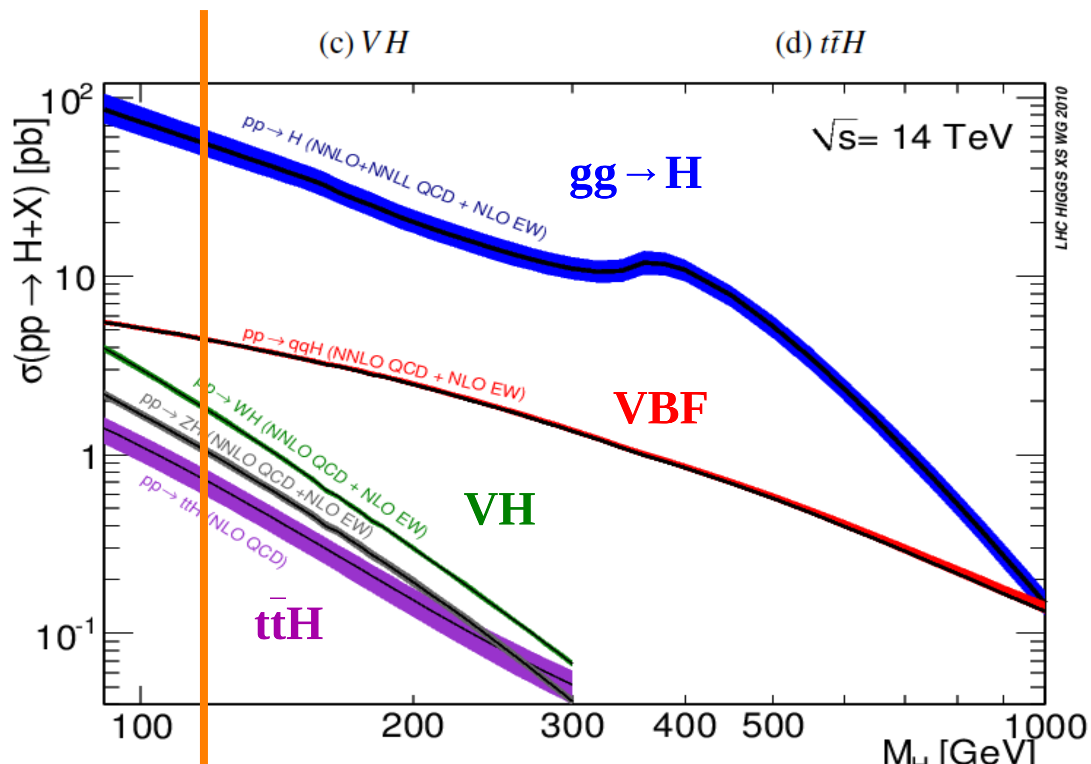
SM Higgs production in hadron colliders



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

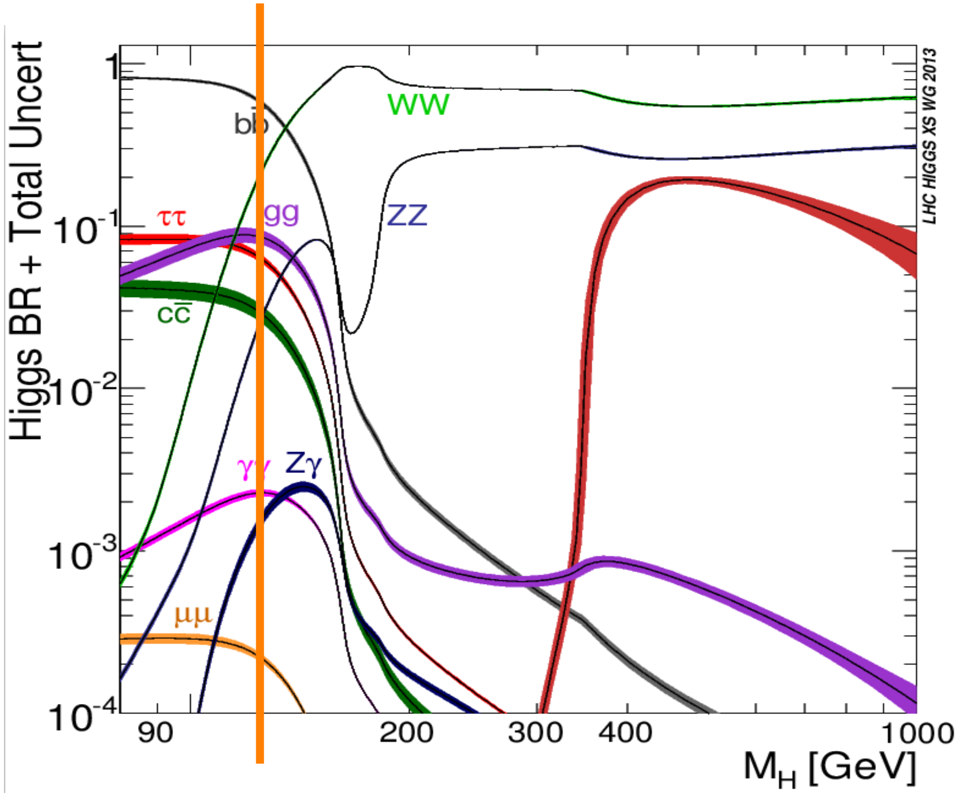
- **Key: look for top-Higgs and V-Higgs couplings at initial and final states**
- **gg→H is the dominant production mechanism at the LHC**





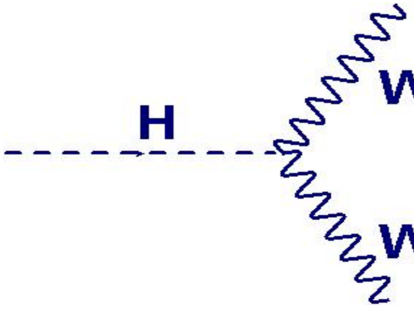
Taken from LHC Higgs XSection WG

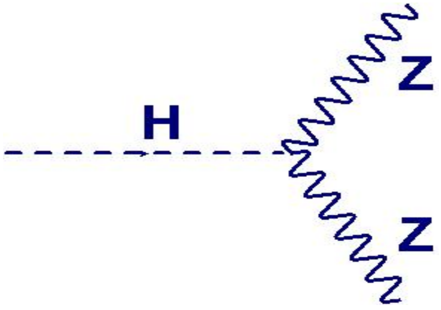
$\underline{SM}$ Higgs decay in hadron colliders



Taken from LHC Higgs XSection WG

- **The WW* and ZZ* decay channels open up above M_W/M_Z, and are dominant above 140 GeV**

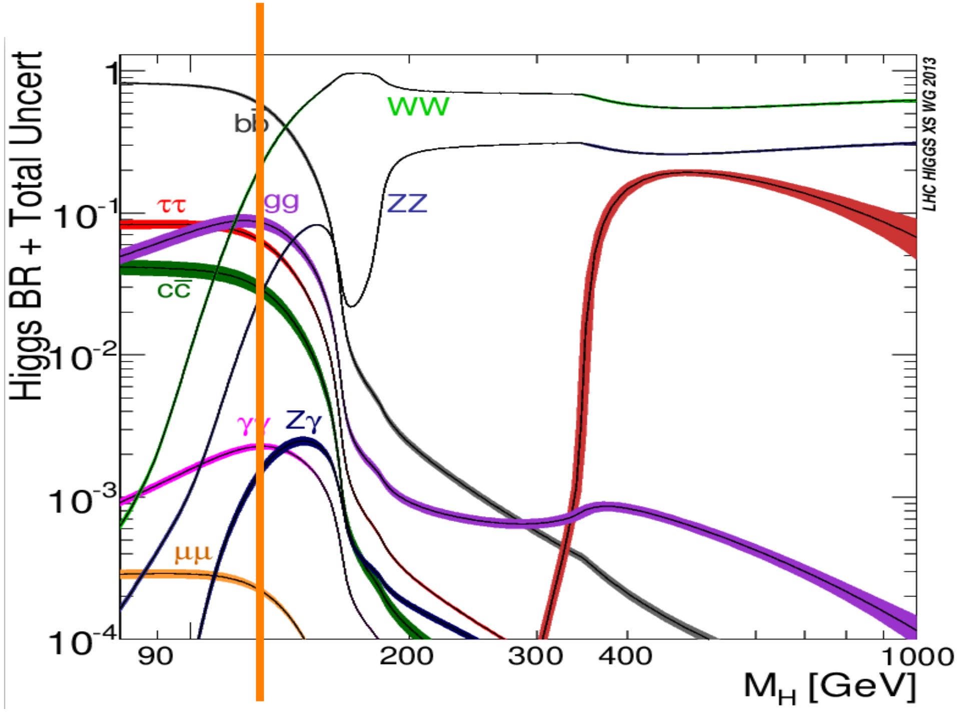




- **In clean final states (electrons, muons), the dominant backgrounds are SM WW* and ZZ* events**

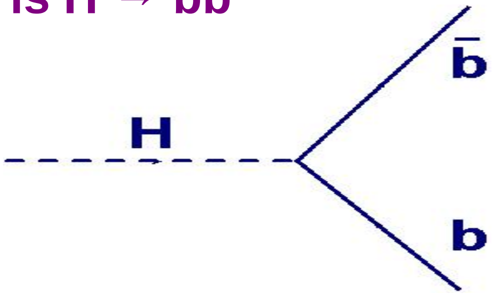
- **We preferentially exploit electron and muon decays of W and Z, but not exclusively:**
  - **$gg \rightarrow H \rightarrow ZZ \rightarrow l\bar{l}\ q\bar{q},\ l\bar{l}\nu\bar{\nu}$ are also convenient at very high Higgs masses (important when looking for additional Higgs bosons)**

SM Higgs decay in hadron colliders



[Taken from LHC Higgs XSection WG]

- **For Higgs masses below 140 GeV or so, the most probable decay is H → $b\bar{b}$**



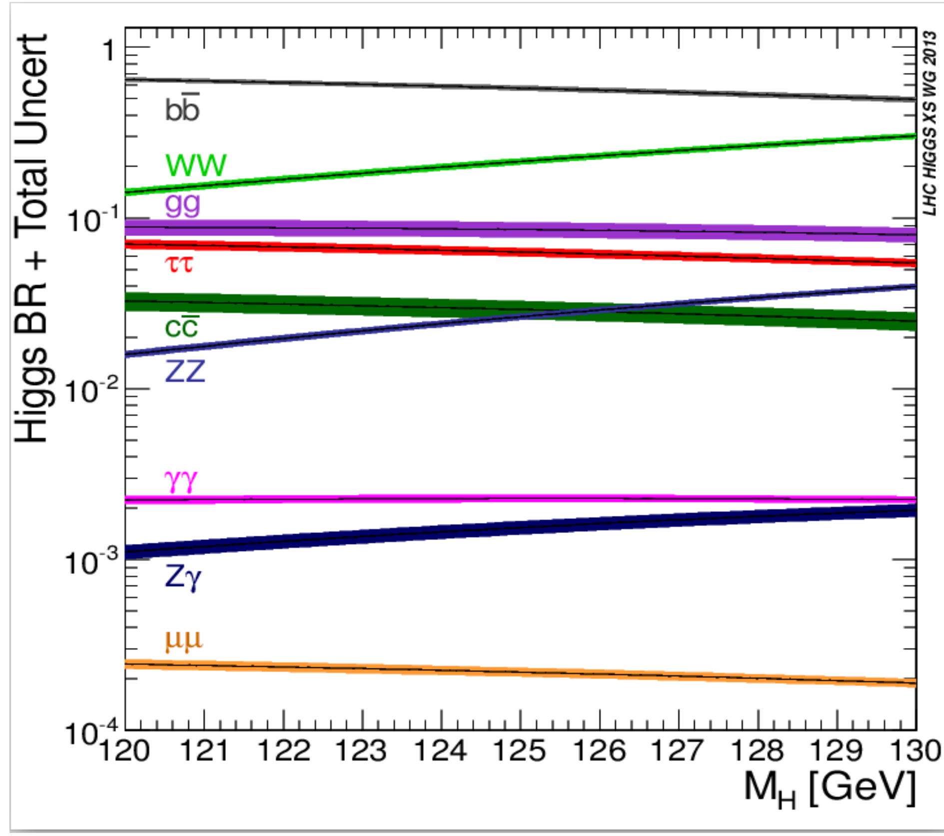
- **Unfortunately, $b\bar{b}$ backgrounds from pure QCD processes are huge, and gg → H → $b\bar{b}$ is not a good channel for Higgs search**

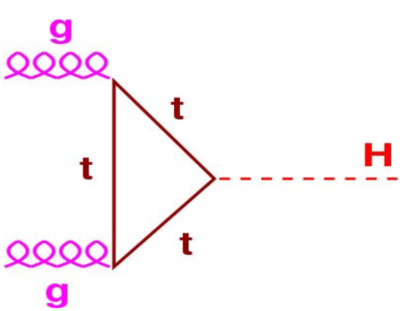
- **We exploit other decay channels and production mechanims:**
  - **gg→H→γγ (very low BR, but clean peak in γγ mass)**
  - **$q\bar{q}$ → VH→V$b\bar{b}$ (but still difficult, due to V+$b\bar{b}$ and top backgrounds)**
  - **$q\bar{q}$ → q'$\bar{q}$' H→q'$\bar{q}$' $\tau\bar{\tau}$ (VBF, good tau identification needed)**
  - **Also gg → H →$\tau\bar{\tau}$, because the tau mass is not so small (≈1.8 GeV)**

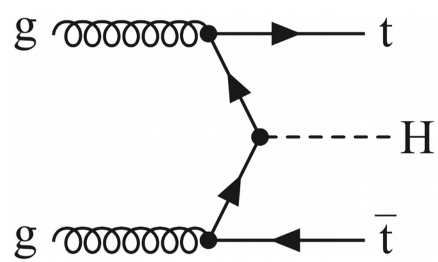
We were lucky...

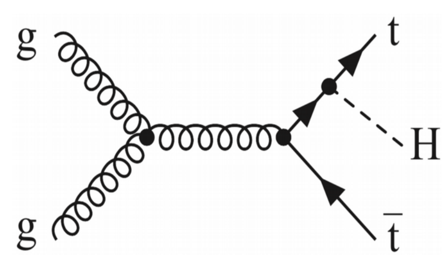
- A mass value of m_H≈125 GeV is a good thing:
  - Despite the low cross sections (⇒ more luminosity needed), one can access the γγ and ZZ*→4 lepton decay channels ⇒ clean measurements of mass and properties
  - Many more channels are hard but eventually accessible (ττ,bb,μμ/Zγ with huge statistics) ⇒ rich and comprehensive coverage of Higgs couplings, search for deviations from the SM
  - Completed with study of ttH couplings at production/decay

Taken from LHC Higgs XSection WG





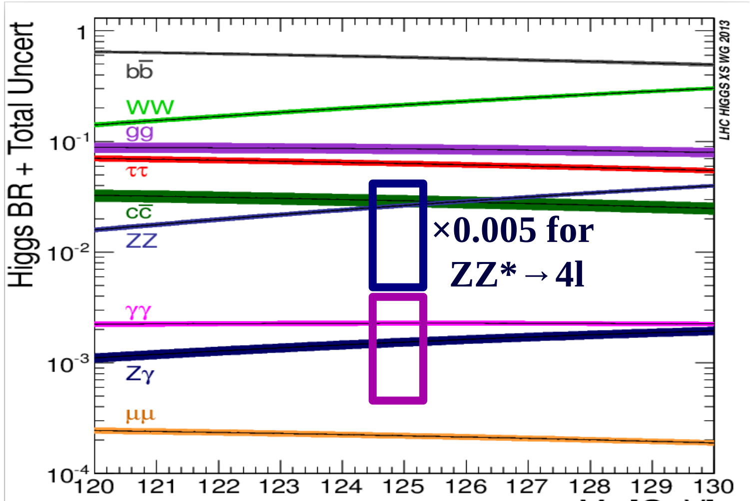




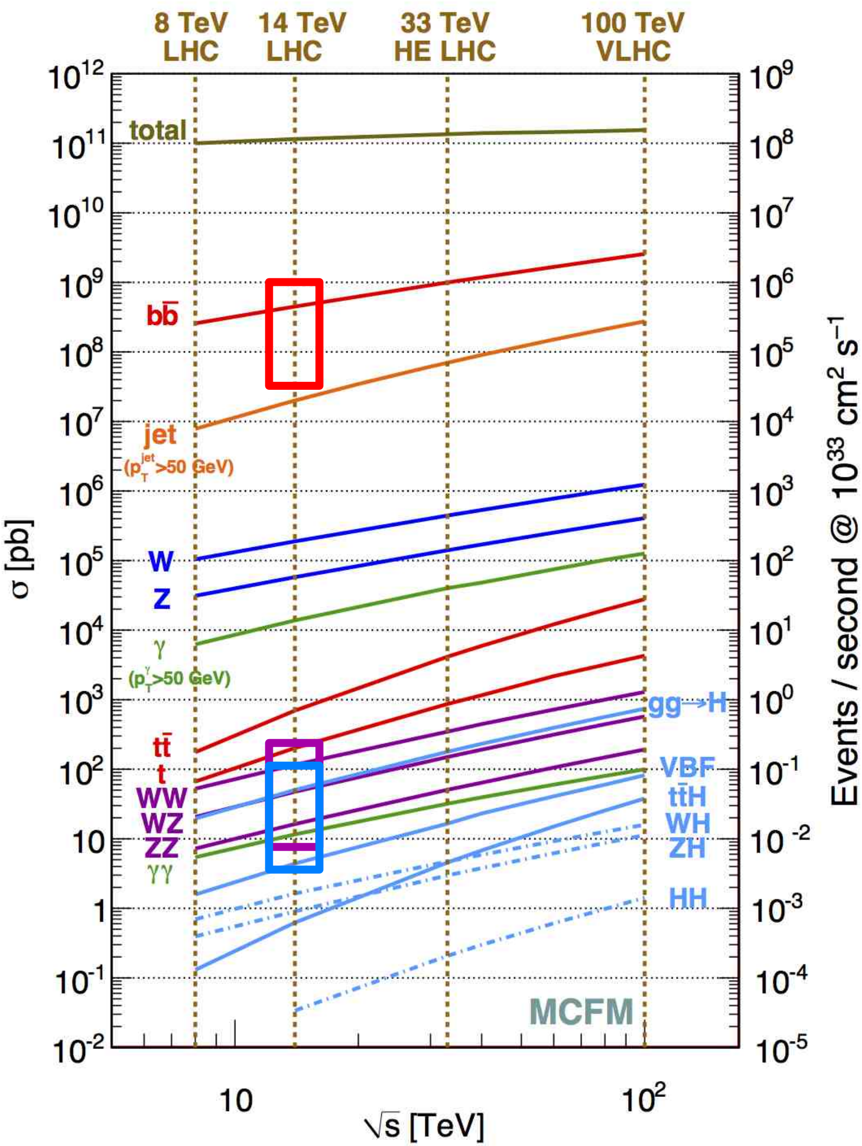
The Higgs search at the LHC

- **Problem 1: cross section is relatively low compared to other processes**
- **Problem 2: for the dominant decay channels ($b\bar{b}$ and WW*) backgrounds are huge**
- **Problem 3: we need to be able to measure all Higgs decay products in order to establish its mass (i.e. see a bump)**

- **Solution: choose very clean channels with leptonic/photonic decays, even if their branching fractions are very low**



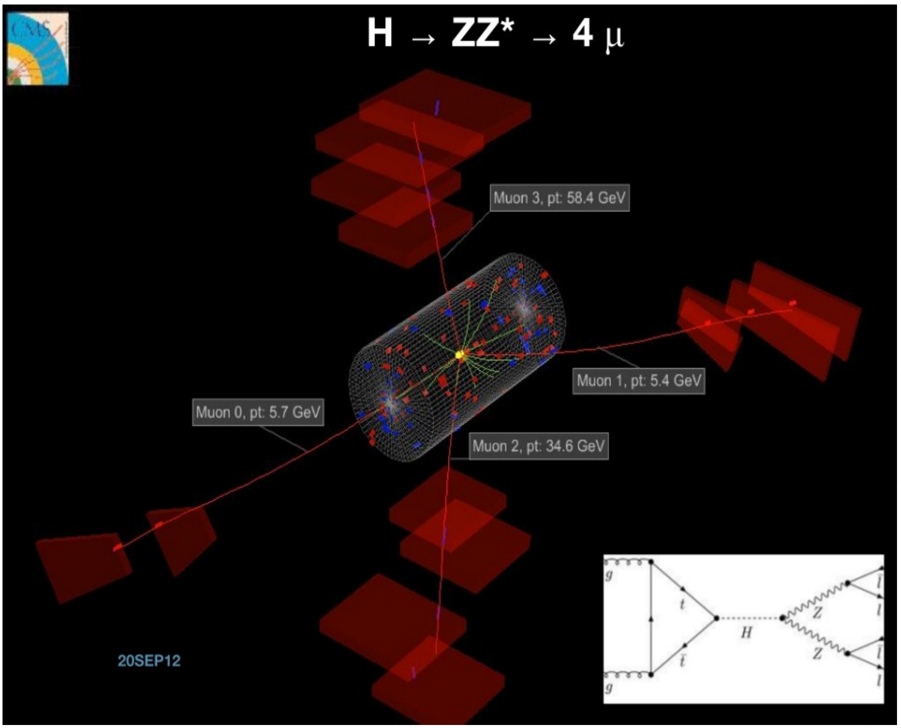
[Taken from LHC Higgs XSection WG]

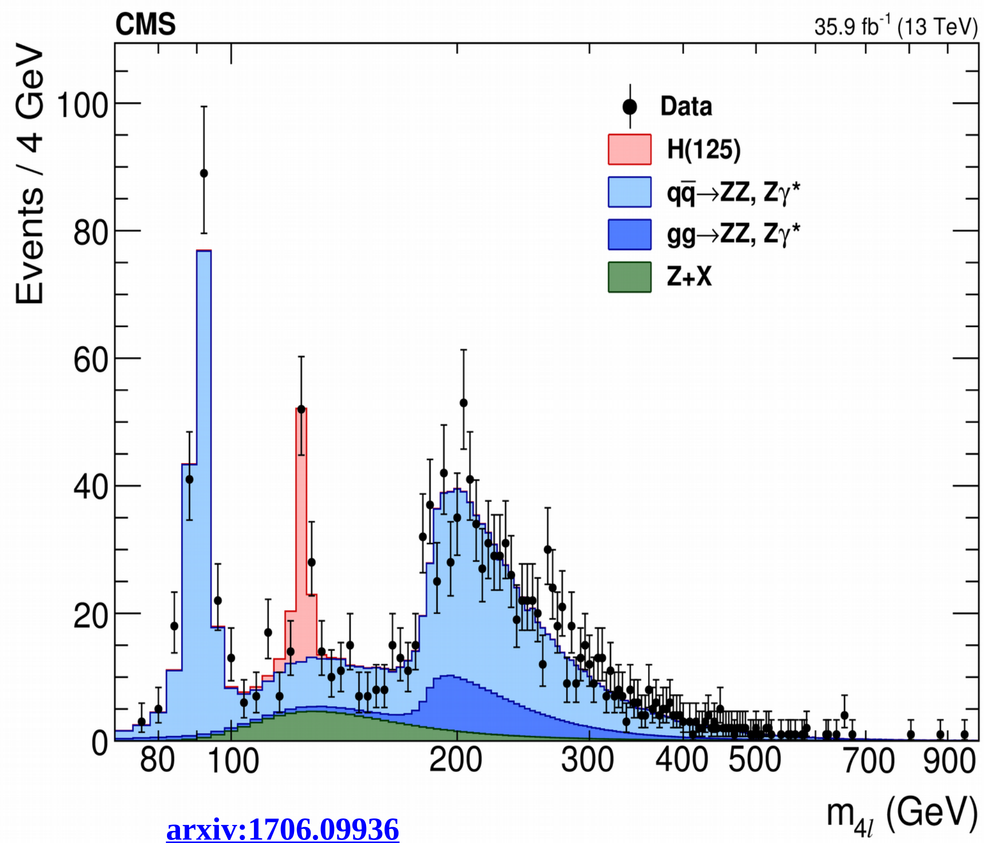


[Taken from MCFM Web page]

H→ZZ*→4l: the cleanest

- Small cross section but rather low backgrounds (under the H peak)
- Extremely good resolution with leptons
- The best channel to believe it exists if you are difficult to convince !





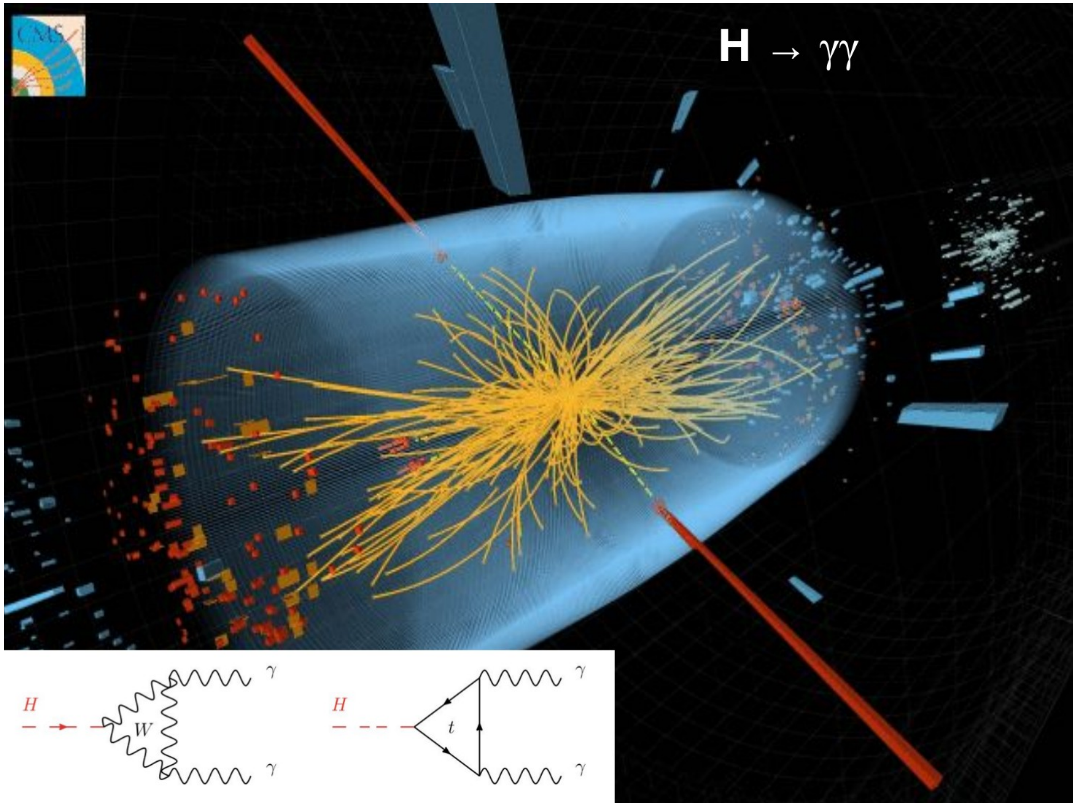
arxiv:1706.09936

Animated GIF (Run 1)

$H \to \gamma\gamma$

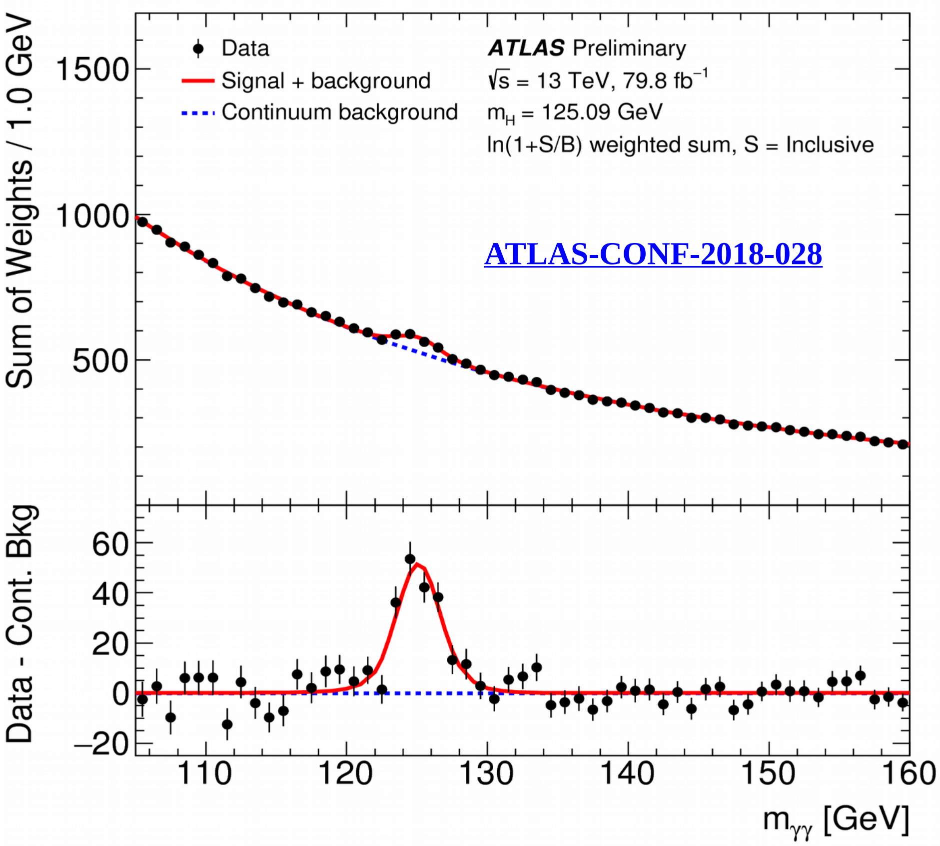
- **Also clean – it provides a narrow and precise resonance peak**
- **Backgrounds are large. Mostly true photon pairs in hadronic environment, but also fake photons (instead of π^0's, for instance). Difficult to reproduce in simulations (⇒fit it in data)**
- **Electromagnetic resoltion pushed to the limit ⇒ control of independent term below 1%, which is sensitivite to non-uniformities, calibrations ($Z \to ee$), ...**

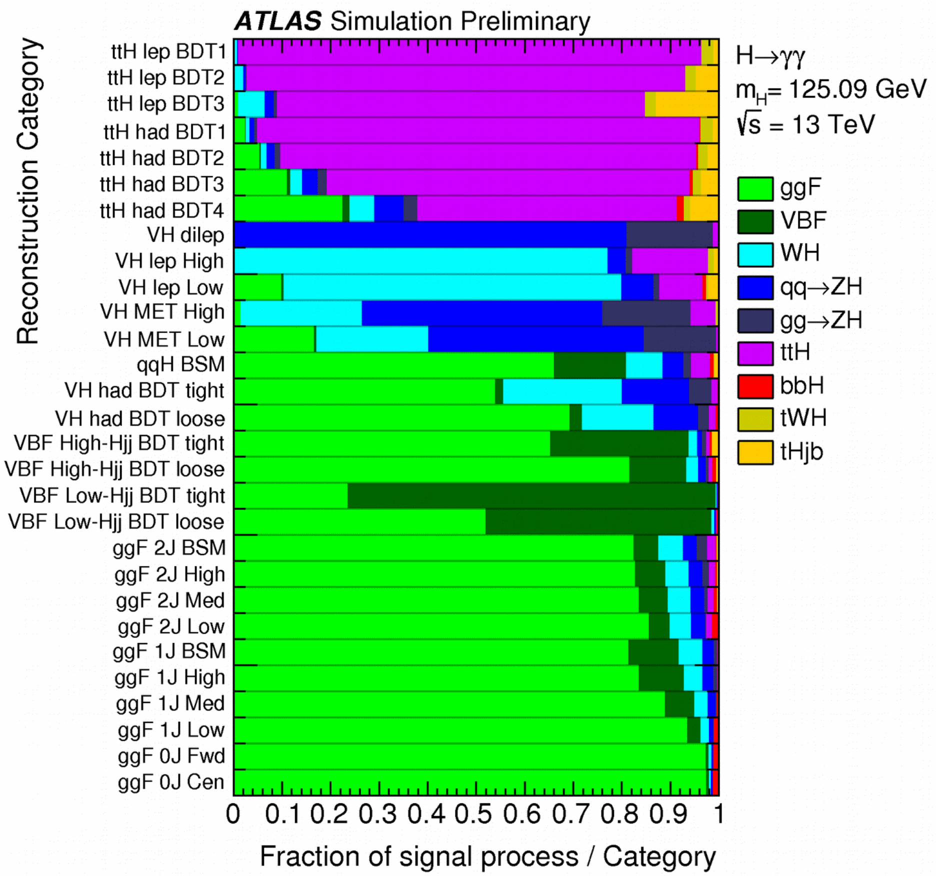
$$\lim_{E \to \infty} \frac{\sigma}{E} = C; \quad C < 1\%$$



H → γγ

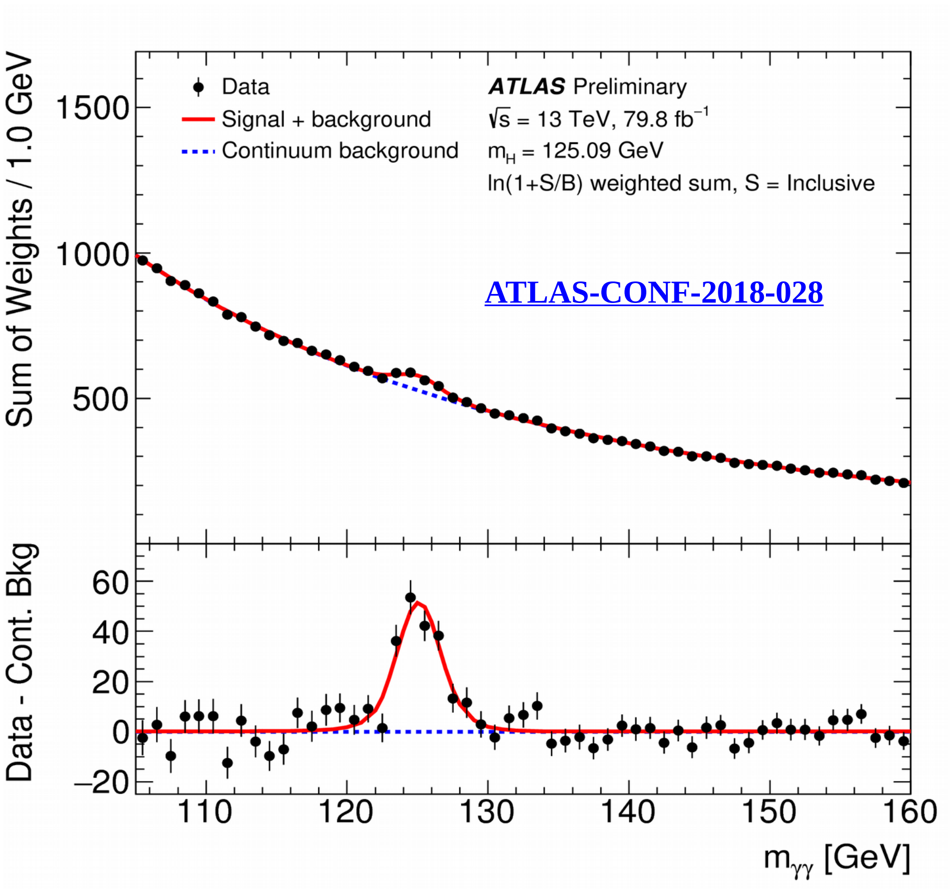
- **Almost all production mechanism contribute: selections focused on different signatures**
- **Categorization of photons depending on the quality of identification, multivariate methods**
- **Key sources of systematics: photon identification, resolution, theory uncertainties, ...**





H → γγ

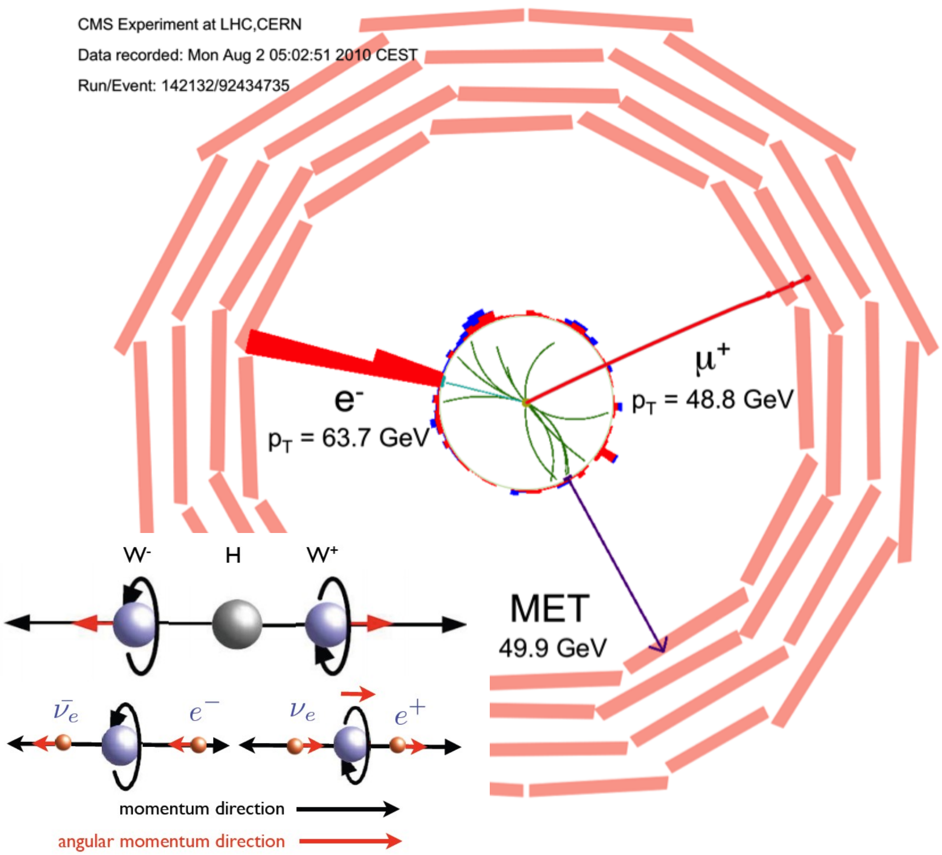
- **Almost all production mechanism contribute: selections focused on different signatures**
- **Categorization of photons depending on the quality of identification, multivariate methods**
- **Key sources of systematics: photon identification/fakes, resolution, theory uncertainties, ...**

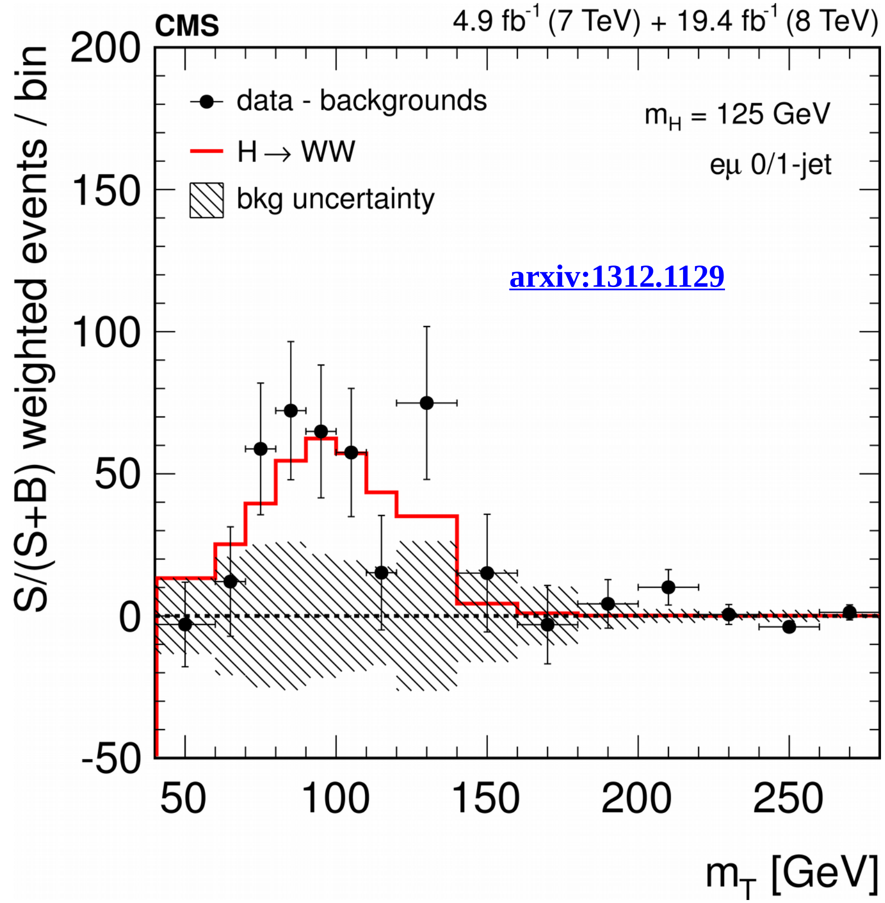


Source	Uncertainty (%)
Fit (stat.)	10
Fit (syst.)	8.3
Photon energy scale & resolution	4.0
Background modeling (spurious signal)	7.3
Correction factor	5.2
Photon isolation efficiency	4.6
Pileup	1.9
Photon ID efficiency	1.3
Trigger efficiency	0.7
Dalitz Decays	0.4
Theoretical modeling	$^{+0.3}_{-0.4}$
Diphoton vertex selection	0.1
Photon energy scale & resolution	0.1
Luminosity	2.0
Total	14

$H \to WW^* \to$ leptonic

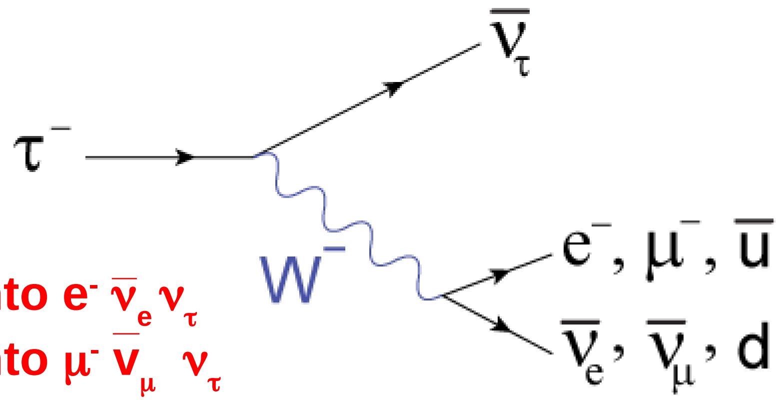
- No peak, use other discriminating variables: transverse mass, dilepton kinematics, ...
- W decays into b-quarks CKM-suppressed: anti b-tag of any jet in the event
- Keys of the analysis: control the almost irreducible SM WW* background, precise understanding of lepton identification/fakes at low p_T
- Again, multiple categorization and multivariate methods are typically used



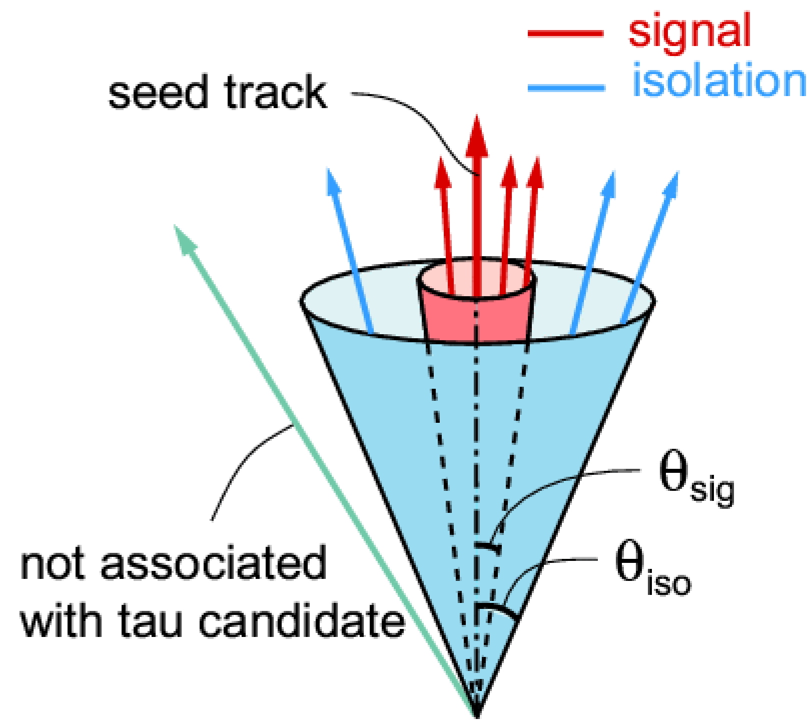


$H \to \tau\bar{\tau}$; but general slide on taus first

- Reminder on tau decays:



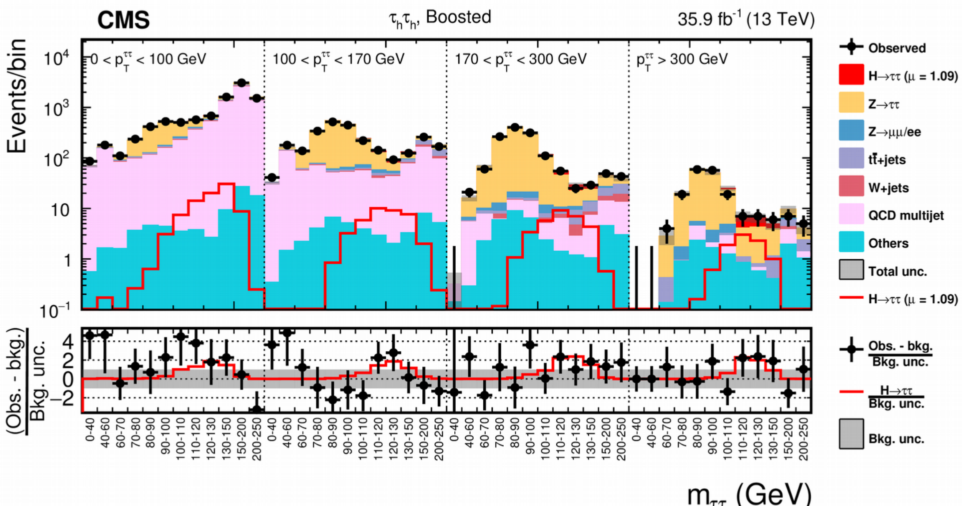
~17% into $e^- \bar{\nu}_e \nu_\tau$
~17% into $\mu^- \bar{\nu}_\mu \ \nu_\tau$
~25% into $\rho^- \nu_\tau$
~11% into $\pi^- \nu_\tau$
~85% into 1 charged particle + X
(``one prong")
~15% into 3 charged particles + X
(``three prong")

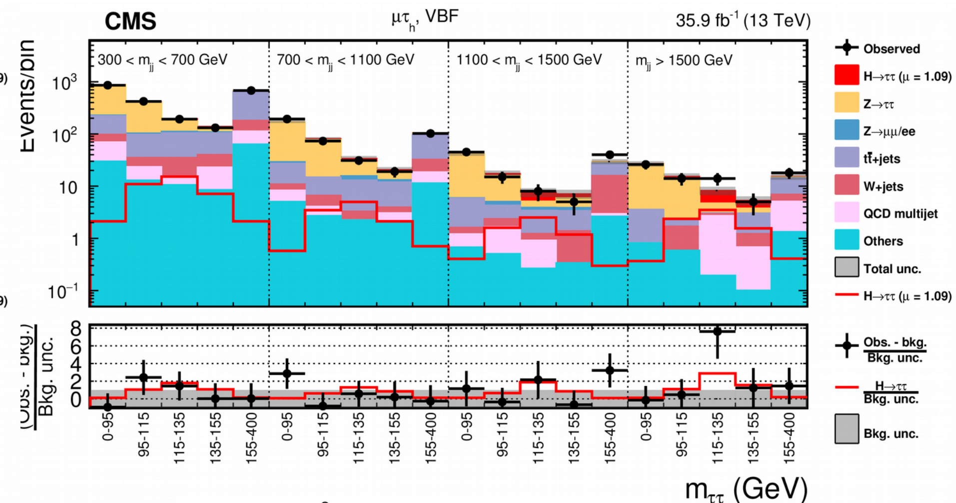


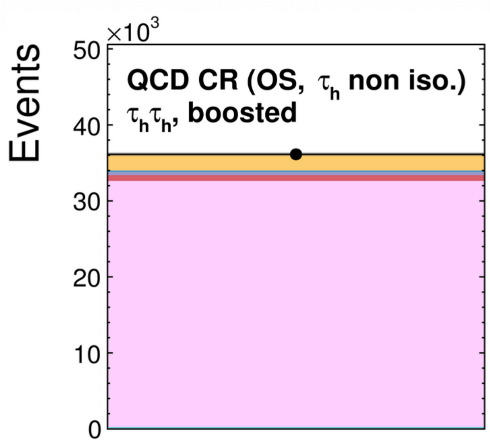
- **The signature of a ``hadronic tau" decay, τ_{had}, is the presence of a high-p_T and collimated jet with very low multiplicity (typically just one charged track, and at most three charged tracks), well isolated from other particles in the event**

$H \to \tau\bar{\tau}$

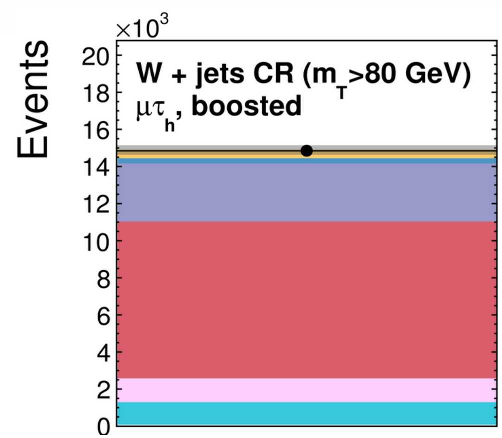
- Due to the presence of neutrinos, signal is wider than for $H \to ZZ^*$ or $H \to \gamma\gamma$
- Use visible mass or even a reconstructed full Higgs mass (likelihood from tau decays)
- Distinct signal regions: $gg \to H$ (0 jet, less sensitive), VBF, boosted (mostly $VH \to V+\tau\tau$)
- Final visible states studied channels: $e+\mu$, $\mu+\tau_{had}$, $\tau_{had}+\tau_{had}$, $e+\tau_{had}$
- Backgrounds: $Z \to \tau\bar{\tau}$, W+jets, $t\bar{t}$, QCD ⇒ control regions for all of them





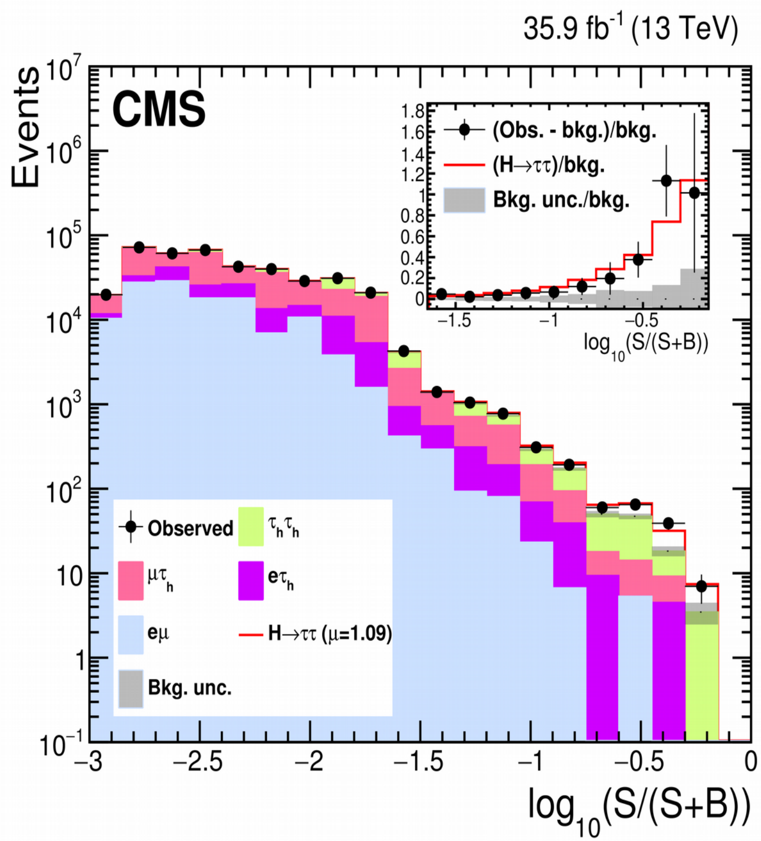


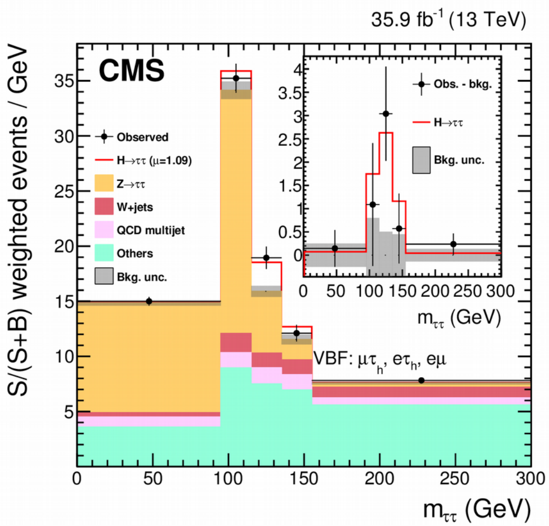
[arxiv:1708.00373](https://arxiv.org/abs/1708.00373)

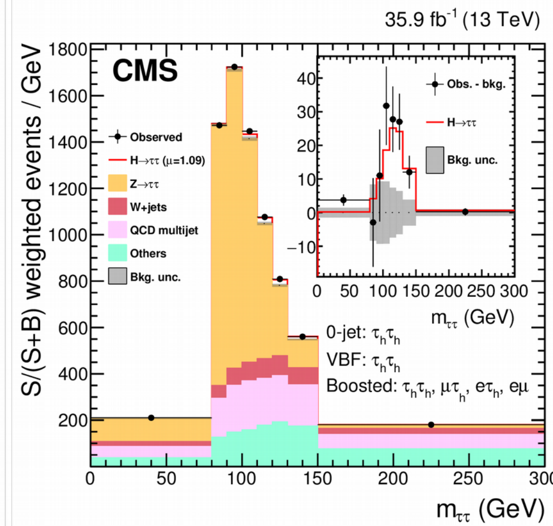


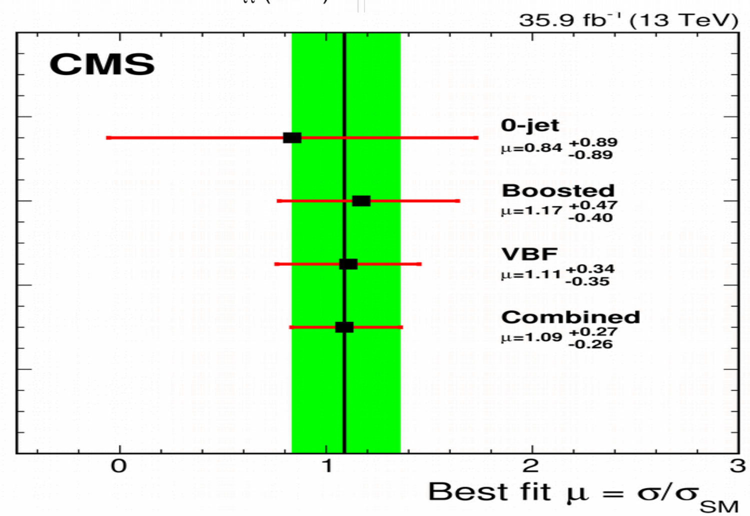
$H \rightarrow \tau\bar{\tau}$

- **Critical observation for EWSB in SM: first observation of Higgs coupling to leptons!**
- **Most sensitivity in VBF production (2 forward jets) and boosted Higgs (mostly VH→V+ττ)**
- **Most sensitive channels: μ+τhad, τhad+τhad**
- **Combination of all channels via a likelihood method**





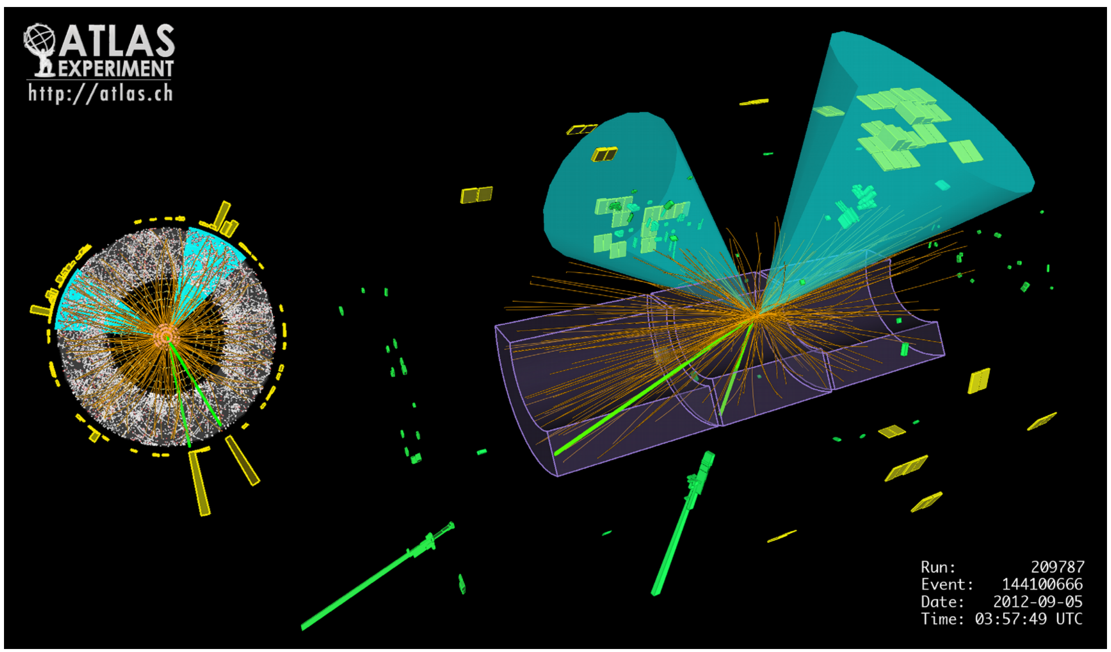


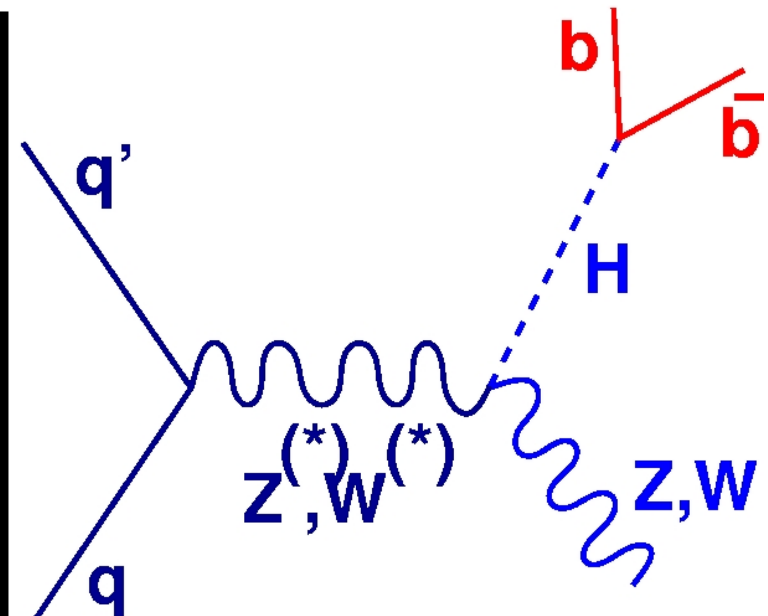


[arxiv:1708.00373](https://arxiv.org/abs/1708.00373)

$H \rightarrow b\bar{b}$

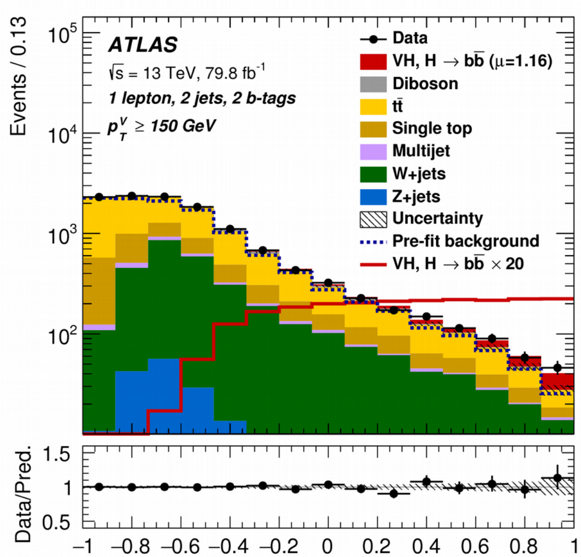
- Central for testing EWSB: Higgs coupling to down-type quarks
- Huge background from $b\bar{b}$+X in the SM, particularly in the $gg \rightarrow H \rightarrow b\bar{b}$ production mode. Central role of b-tagging,
- Focus on VH associated production, even if still large (almost irreducible backgrounds from V+b jets)
- Categorization depending on the targeted associated boson: 0 charged leptons ($Z \rightarrow \nu\bar{\nu}$), 1 charged lepton ($W \rightarrow l\bar{\nu}$), 2 charged leptons ($Z \rightarrow l\bar{l}$)



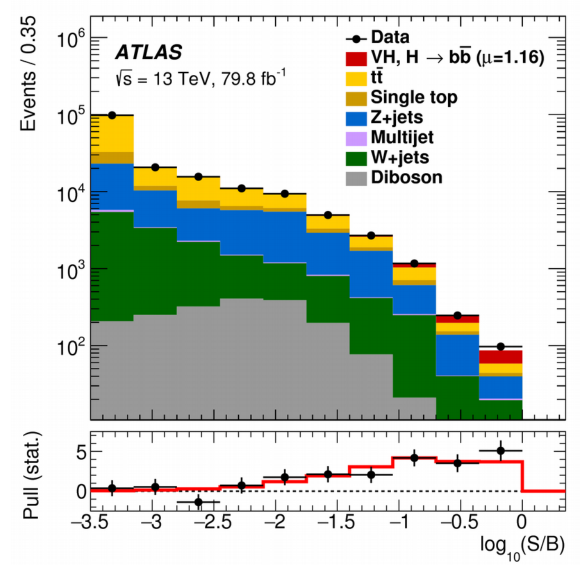


$H \to b\bar{b}$

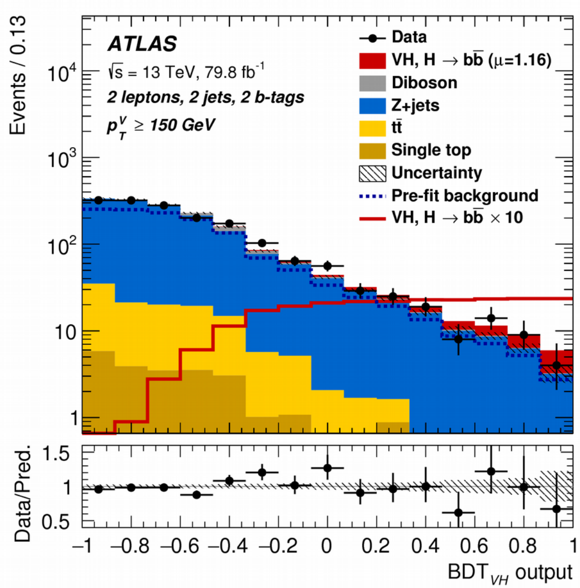
- **Focus on VH associated production. Categorization depending on the targeted associated boson: 0 charged leptons ($Z \to \nu\bar{\nu}$), 1 charged leptons ($W \to l\bar{\nu}$), 2 charged leptons ($Z \to l\bar{l}$)**



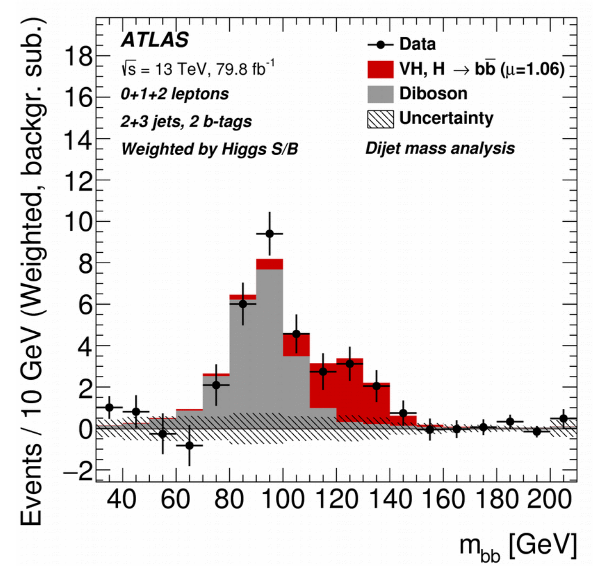
WH→ $l\bar{\nu}\, b\bar{b}$



Combined likelihood



ZH→ $l\bar{l}\, b\bar{b}$

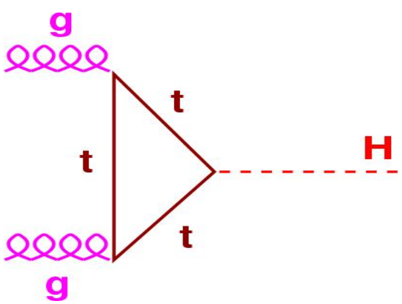


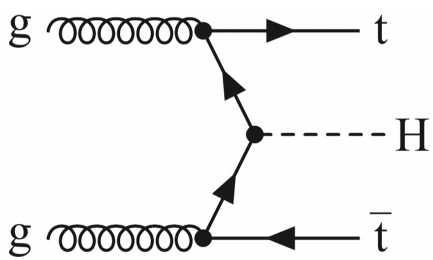
Excess consistent with a 125 GeV mass Higgs

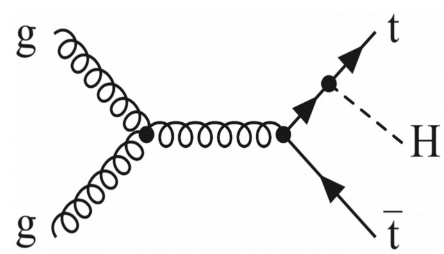
[arxiv:1808.08238](https://arxiv.org/abs/1808.08238)

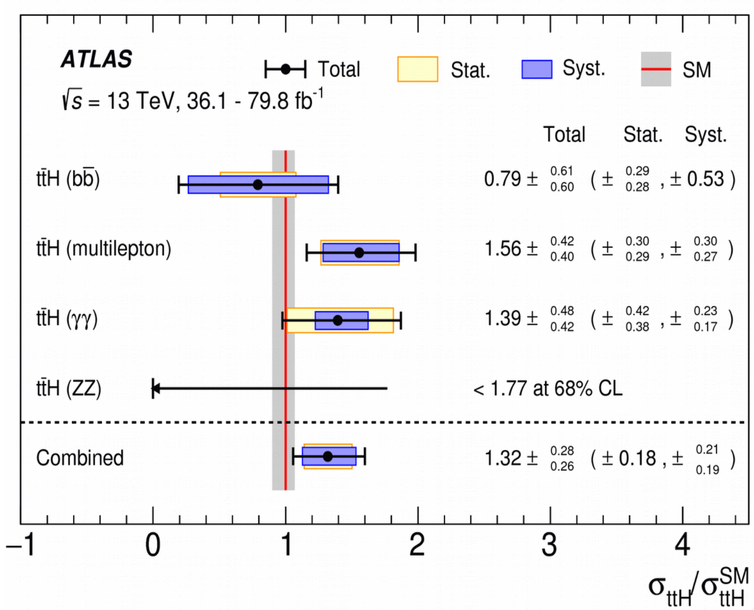
$H \rightarrow t\bar{t}$

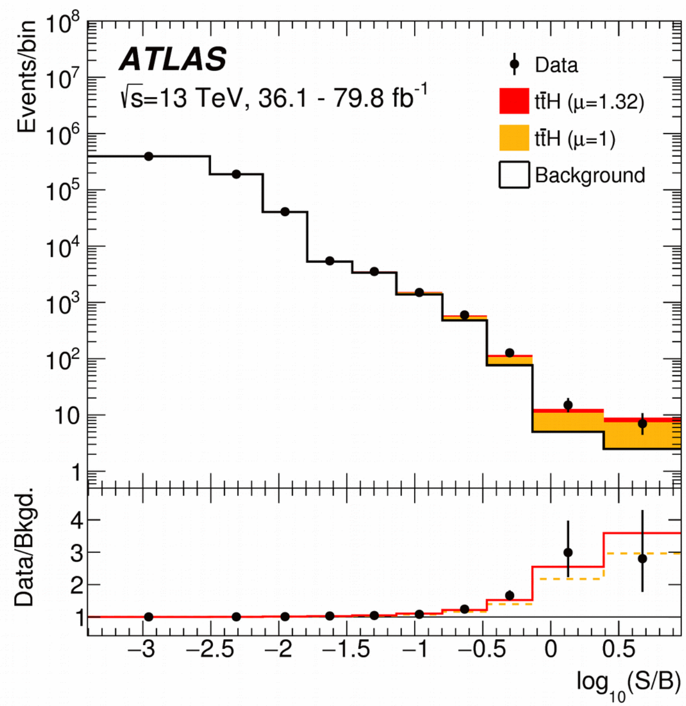
- Indirect evidence of its existence through the presence of significant $gg \rightarrow H$ production
- But this is just under SM assumptions: more/different particles could operate in the ggH loop
- Difficult channel: low cross section, almost irreducible backgrounds ($t\bar{t}b\bar{b}$). Multivariate methods mandatory
- Nevertheless, recently “observed” by both ATLAS and CMS (ATLAS shown in this slide)







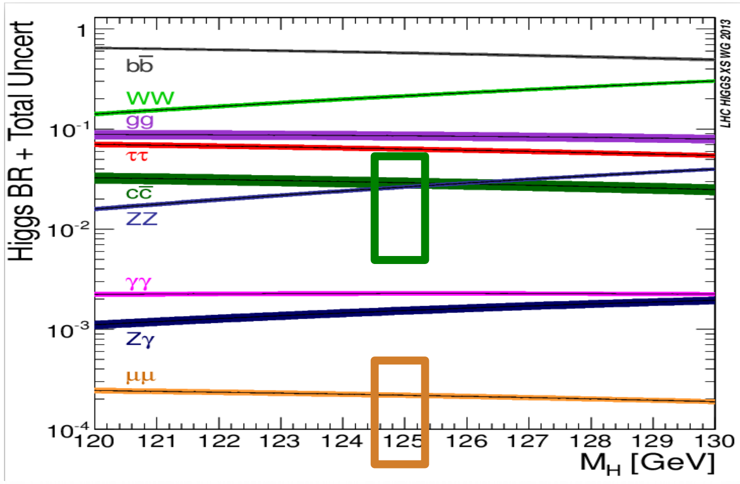


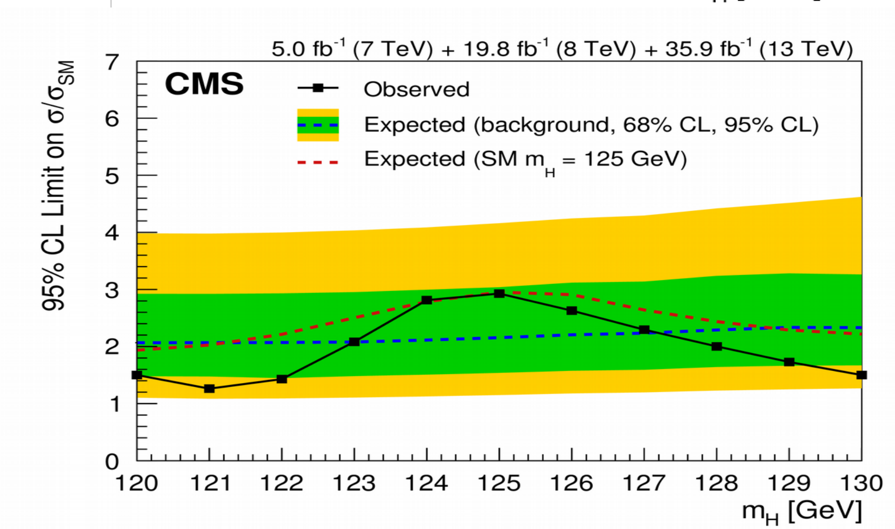


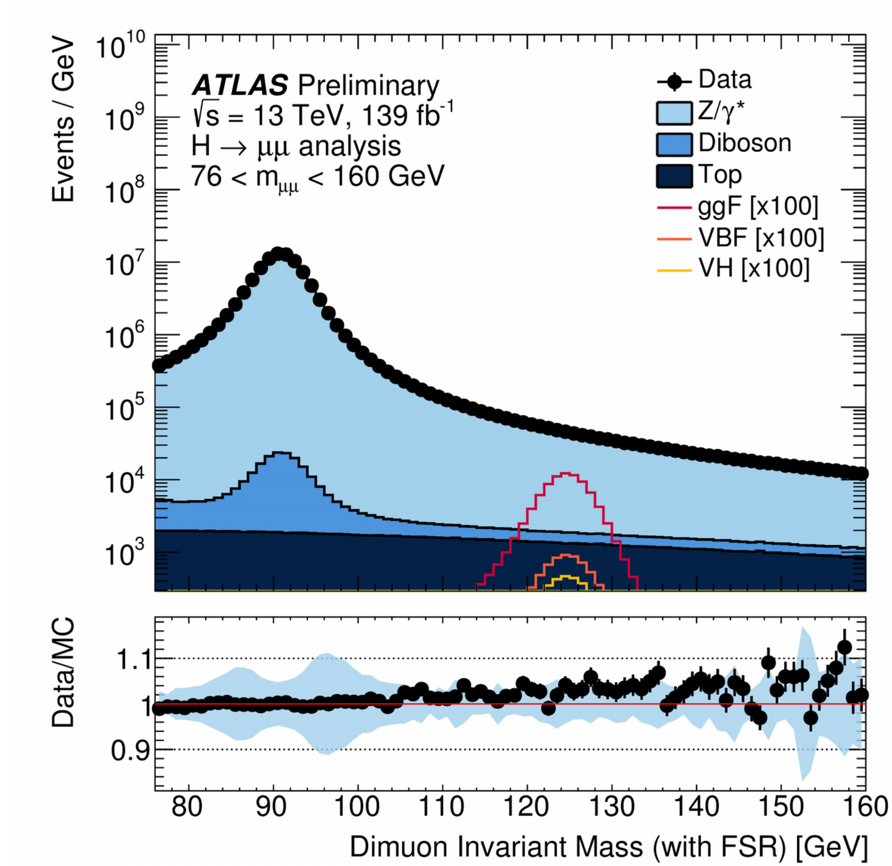
arxiv:1806.00425

H → μμ

- 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.
- $H\rightarrow c\bar{c}$ 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)



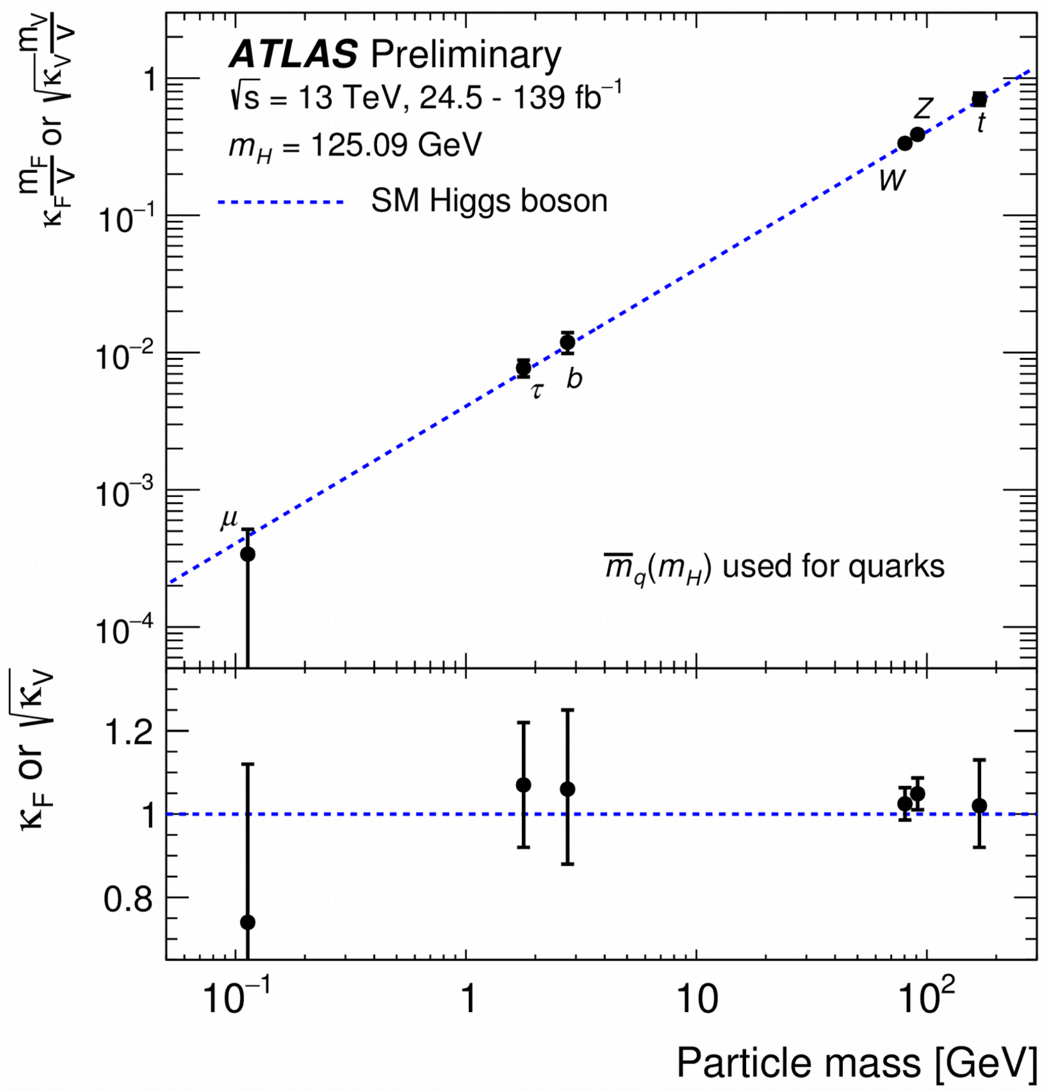




ATLAS-CONF-2019-028

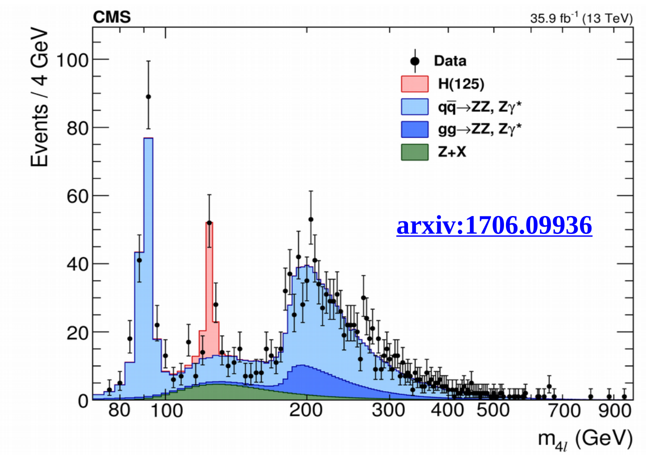
arxiv:1807.06325

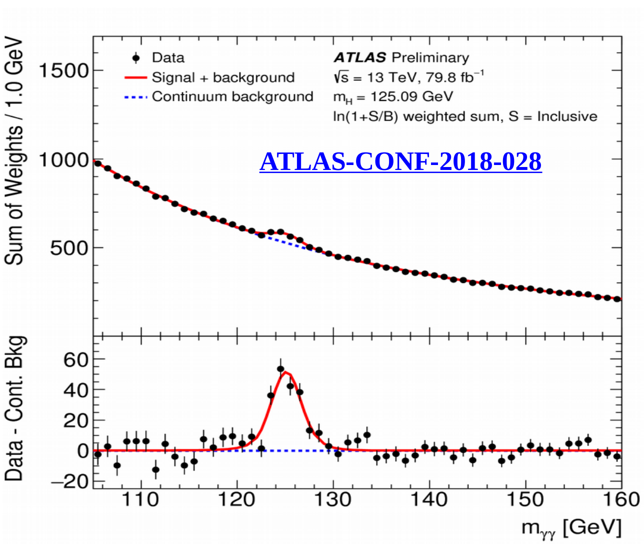
The textbook plot

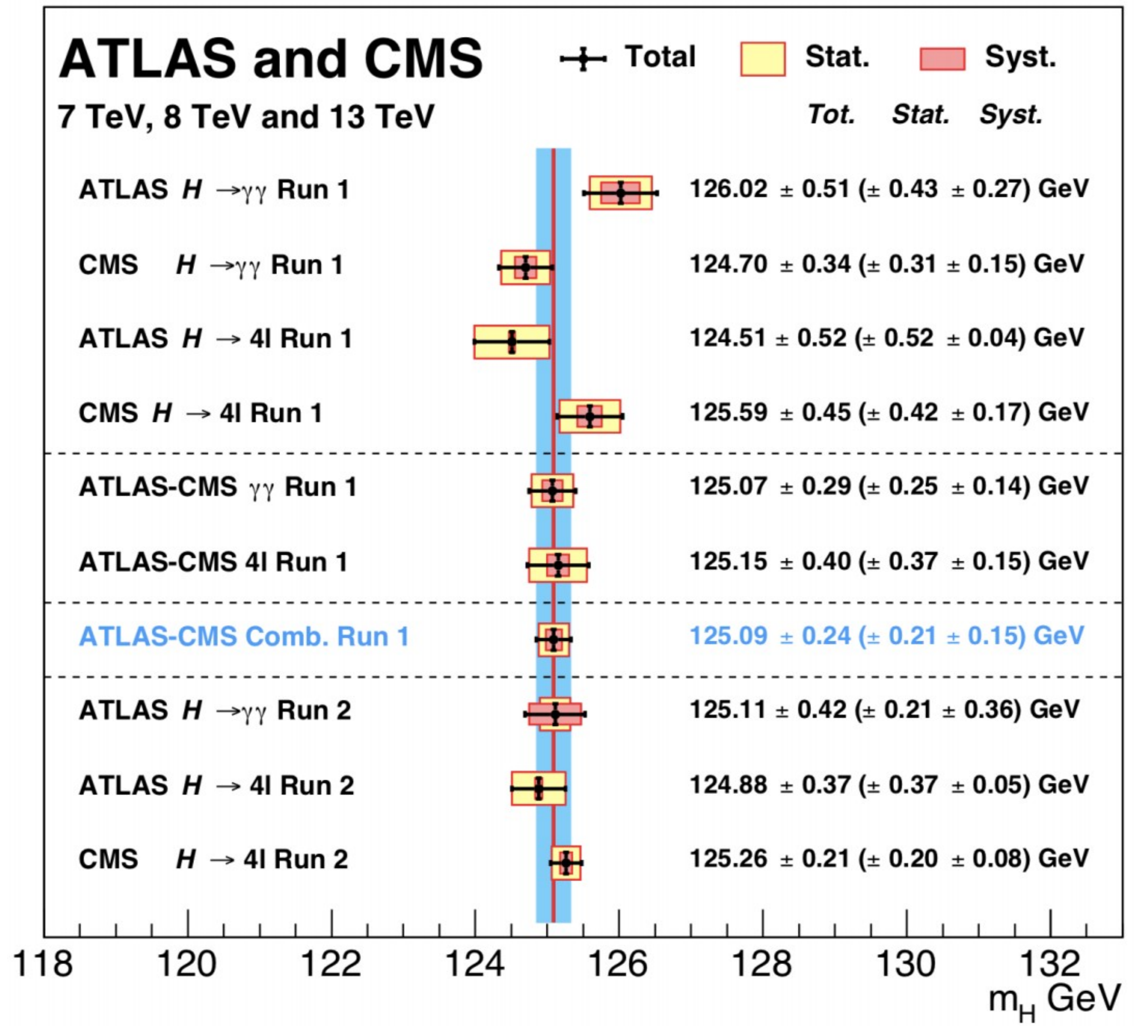


Higgs properties: mass, J^P, width

- The $ZZ \to 4l$ and $\gamma\gamma$ decay channels provide a high precision measurement of the Higgs mass
- m_H is a fundamental input parameter of the SM: deviations from new physics ⇒ accurate measurement
- Currently known at the 2 ‰ level !

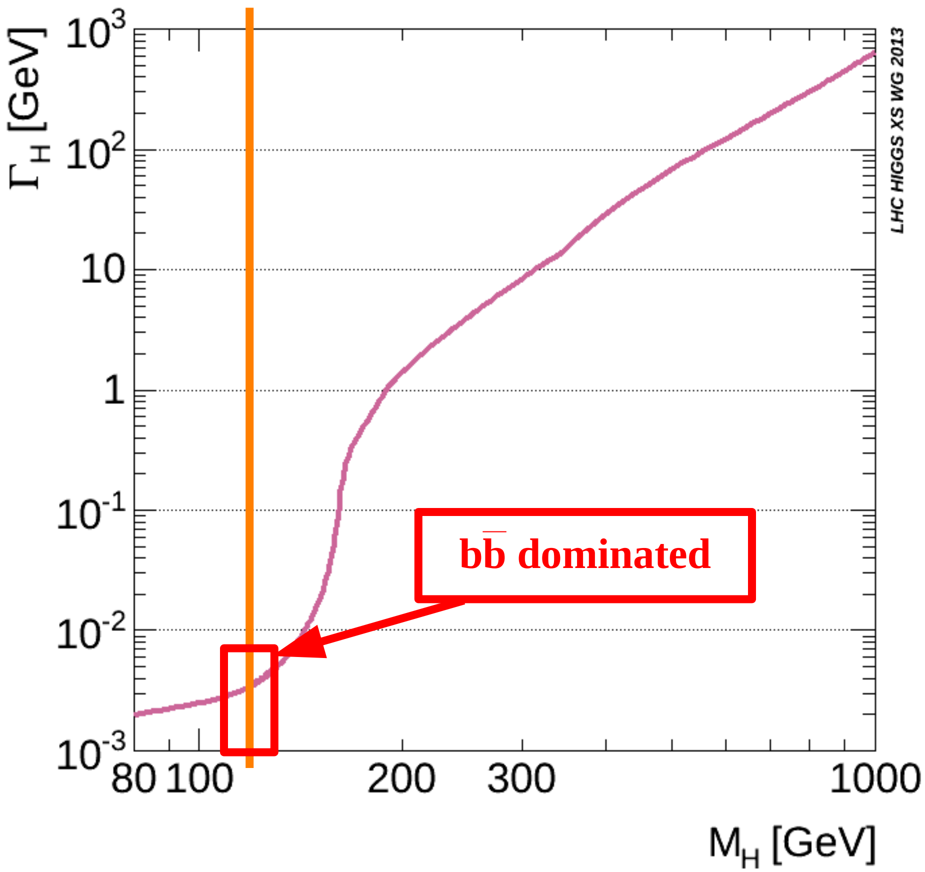


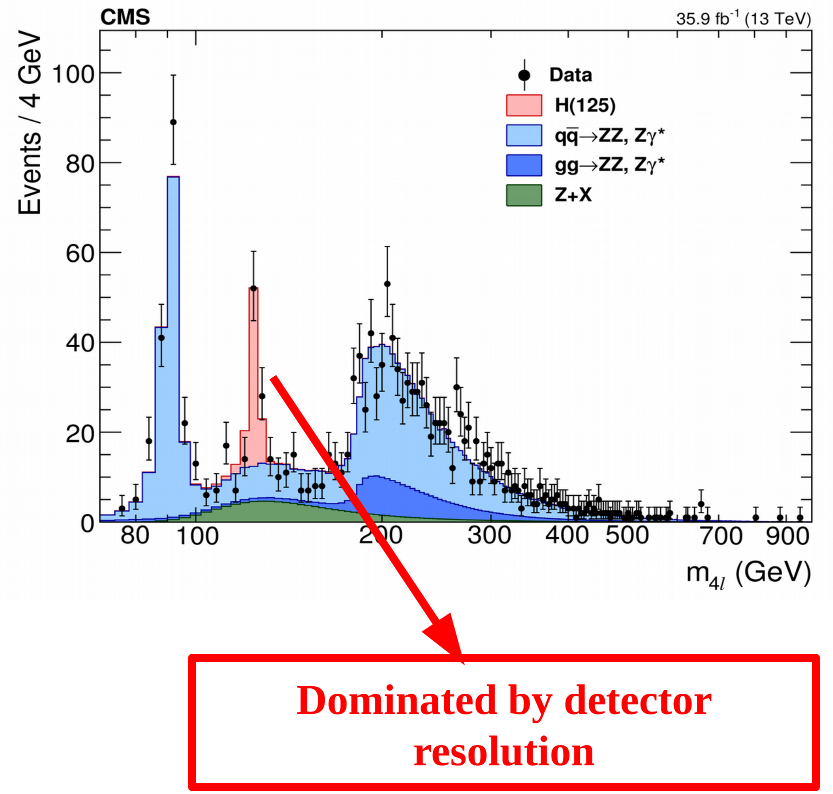




Higgs width

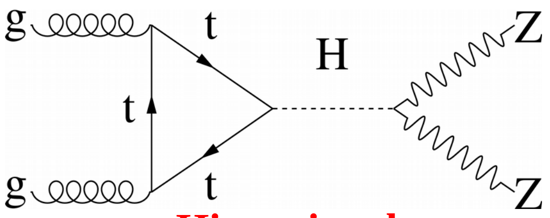
- **Not accessible via lifetime: $\tau_H \approx \hbar c/(4\ \text{MeV}) \approx (200\ \text{MeV*fm})/(4\ \text{MeV}) = 50$ fm; $vt =: p_H/m_H * \tau_H$ not measurable**
- **Direct measurement of the resonance width not possible: (4 MeV)/(125 GeV) << detector resolution (≈%)**





Higgs width

- **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

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

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

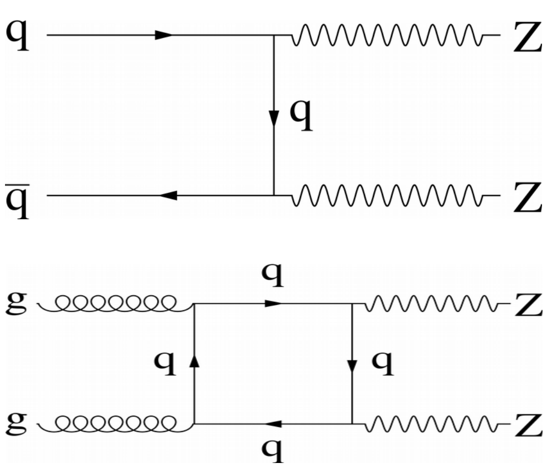
$m_{ZZ} \sim m_H$

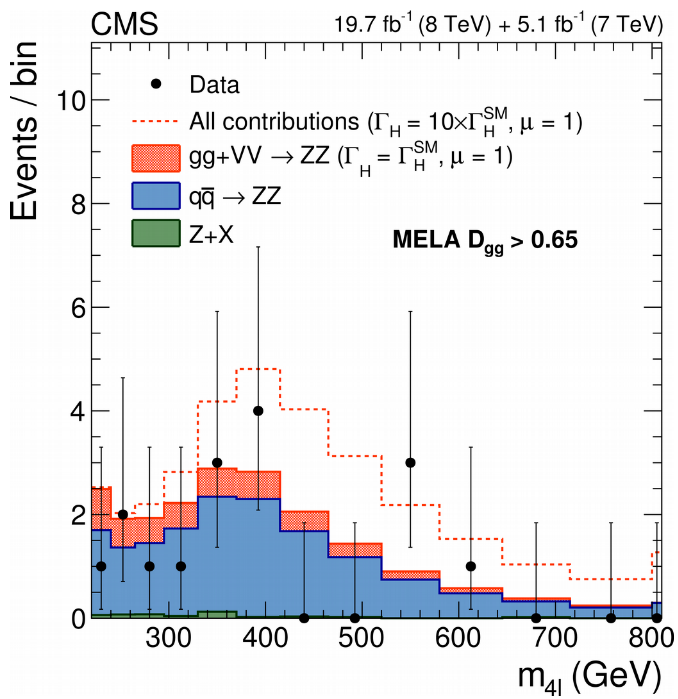
(On-shell production)

$m_{ZZ} > m_{ZZ}$

(Off-shell production)

Background (interfering)

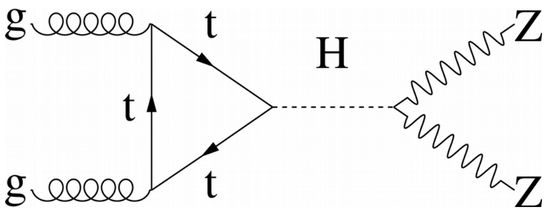




arxiv:1405.3455

Higgs width

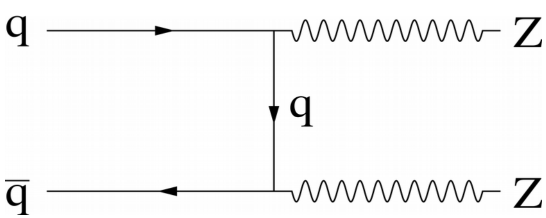
- **Strong prospects to really measure the Higgs width with much more statistics at HL-LHC**
- **Note that this is not fully BSM-independent (other particles present in the loop, for instance)**

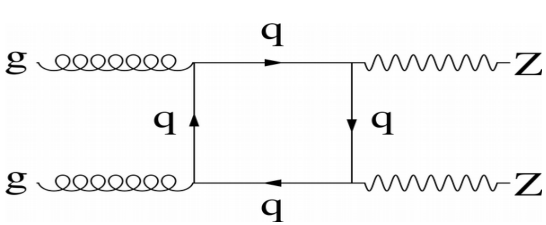


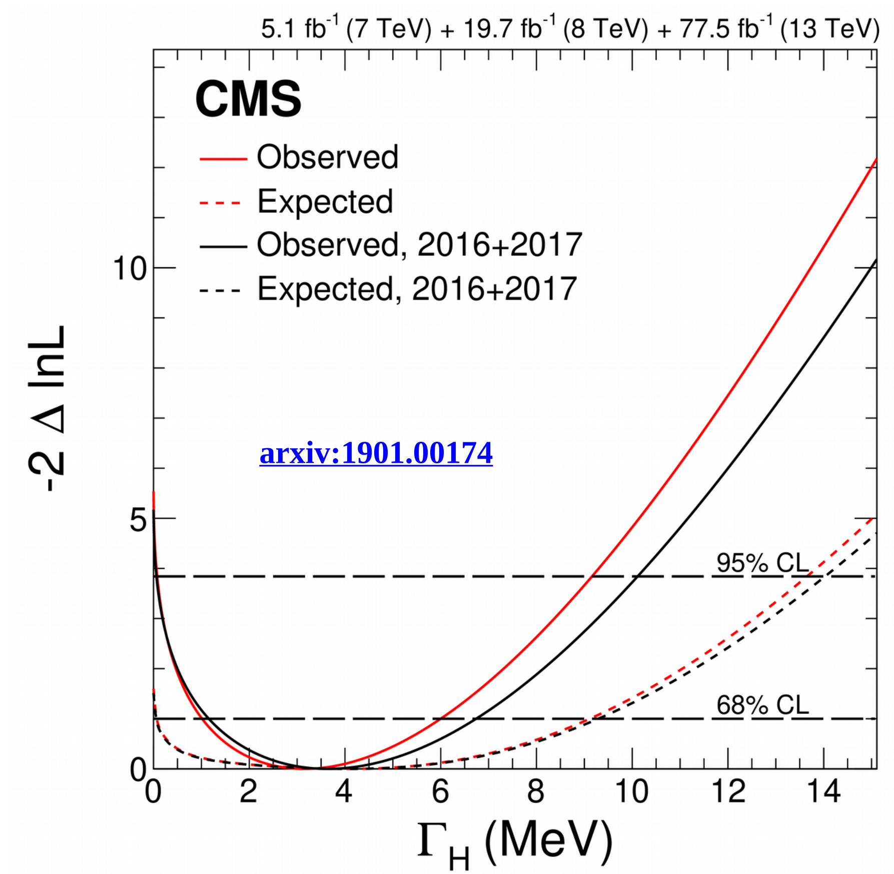
Higgs signal

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

Background (interfering)

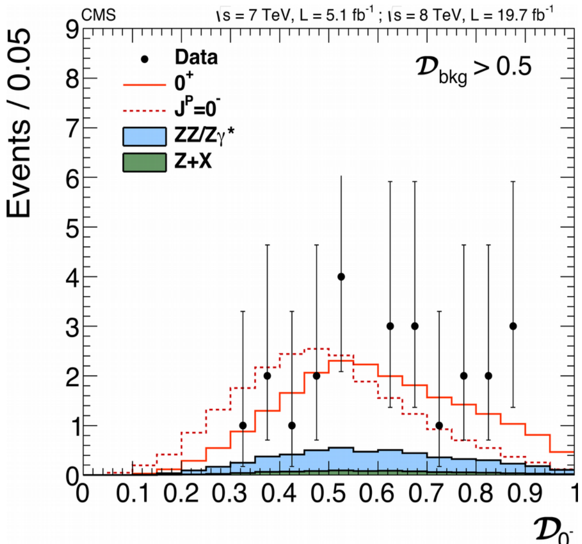


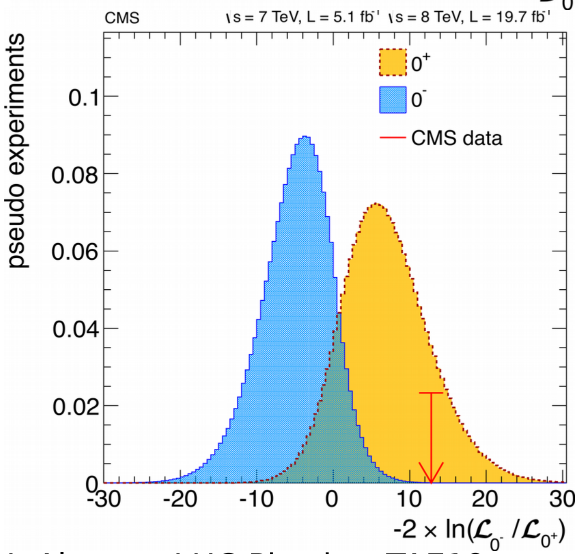


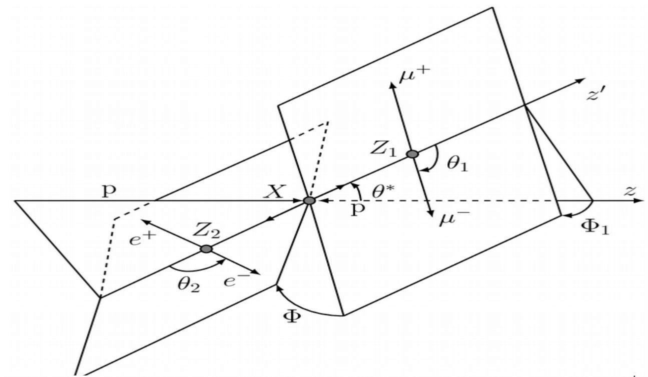


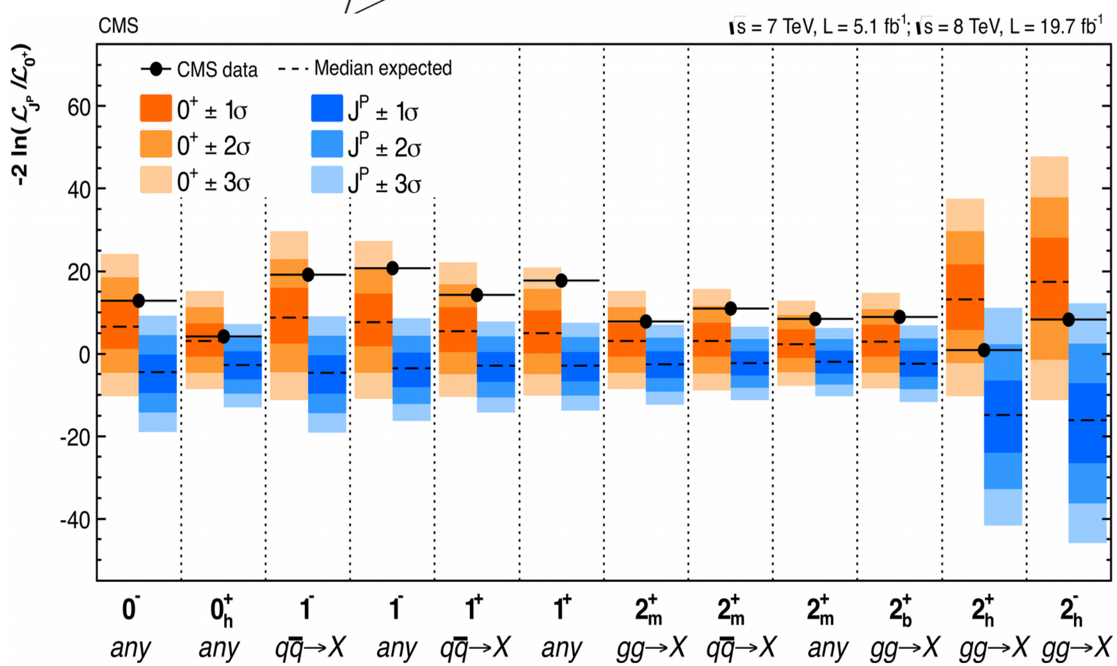
Higgs properties: spin-parity

- The existence of the H→γγ decay implies that the Higgs can not have spin 1 (Landau-Yang theorem)
- The ZZ*→4l decay channel it is an ideal spin analyzer, in particular to separate 0^+ and 0^- hypotheses
- Use discriminators based on matrix-element probability ratios for each 4l kinematic configuration









arxiv:1312.5353

Higgs: LHC combinations

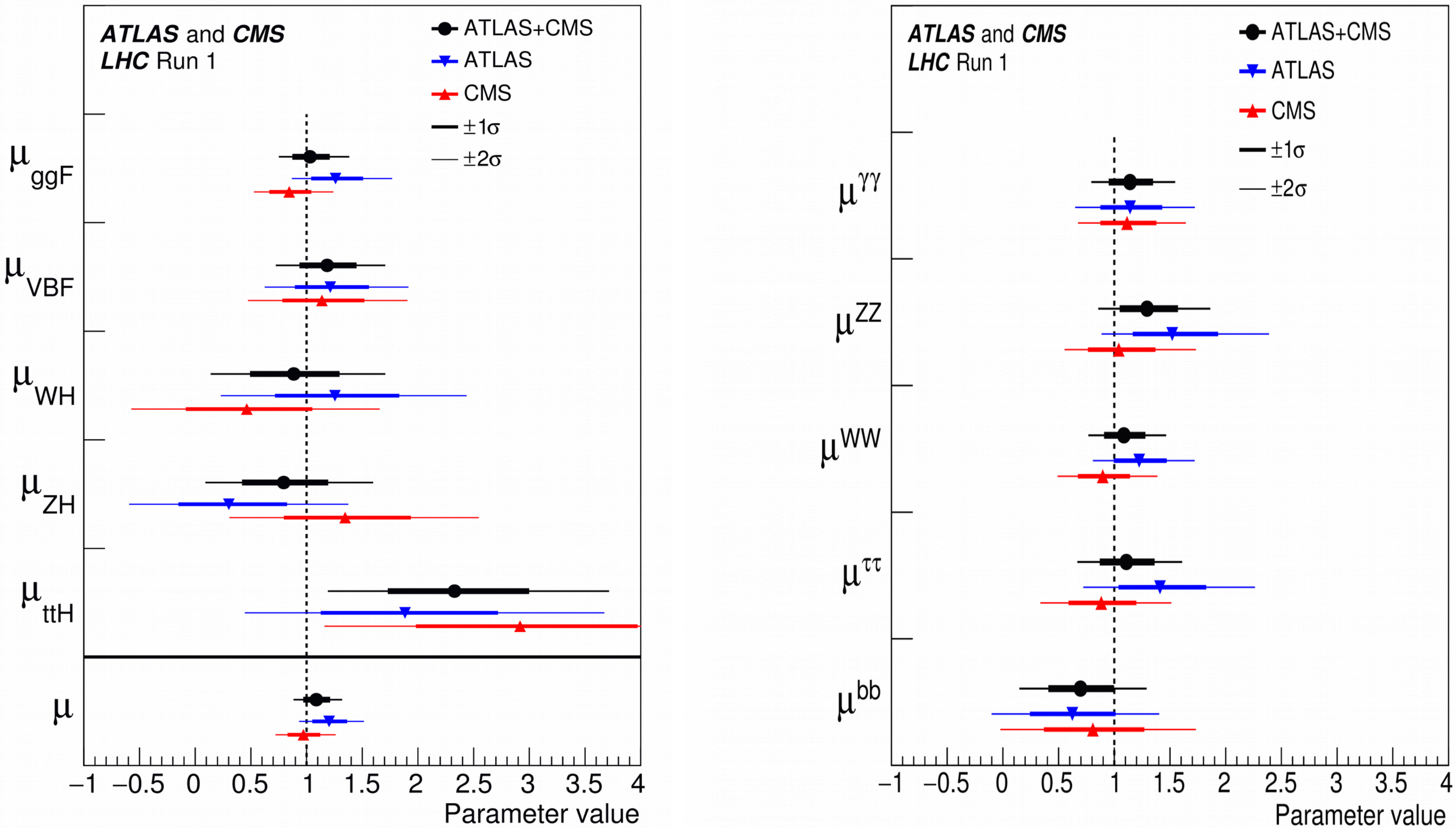
- **Given the present level of precision of cross section*branching fraction measurements (≈10%), results from different channels and experiments are combined in a "simplified way":**
  - **The SM coupling structure is assumed ⇒ only couplings are scaled when looking for deviations:**
    - **Several important BSM scenarios predict partial/global scaling: composite Higgs, mixing of the Higgs with another scalar singlet, …,**
    - **One can always complicate the picture a posteriori if we see significant deviations from the SM**
  - **Still, several ways to "scale" couplings before performing a fit:**

  a) Scale production cross sections and branching fractions independently: "μ" framework

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

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

Higgs: μ-framework combinations



arxiv:1606.02266

- **Good agreement with SM predictions**

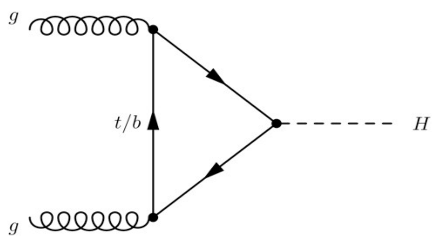
Higgs: LHC combinations

- **Given the present level of precision of cross section*branching fraction measurements (≈10%), results from different channels and experiments are combined in a “simplified way”:**
  - **The SM coupling structure is assumed ⇒ only couplings are scaled when looking for deviations:**
    - **Several important BSM scenarios predict partial/global scaling: composite Higgs, mixing of the Higgs with another scalar singlet, …,**
    - **One can always complicate the picture a posteriori if we see significant deviations from the SM**
  - **Still, several ways to “scale” couplings before performing a fit**

b) Direct scale of couplings: “kappa scheme”, taking special care of “loops” and “invisible” width

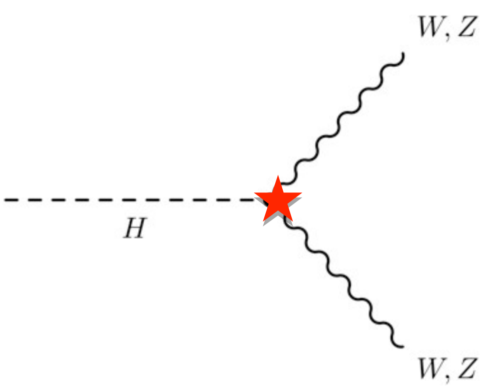
$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

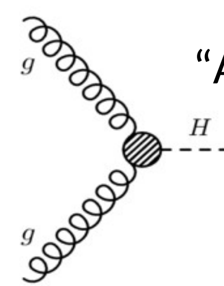
$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$



“SM resolved”

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

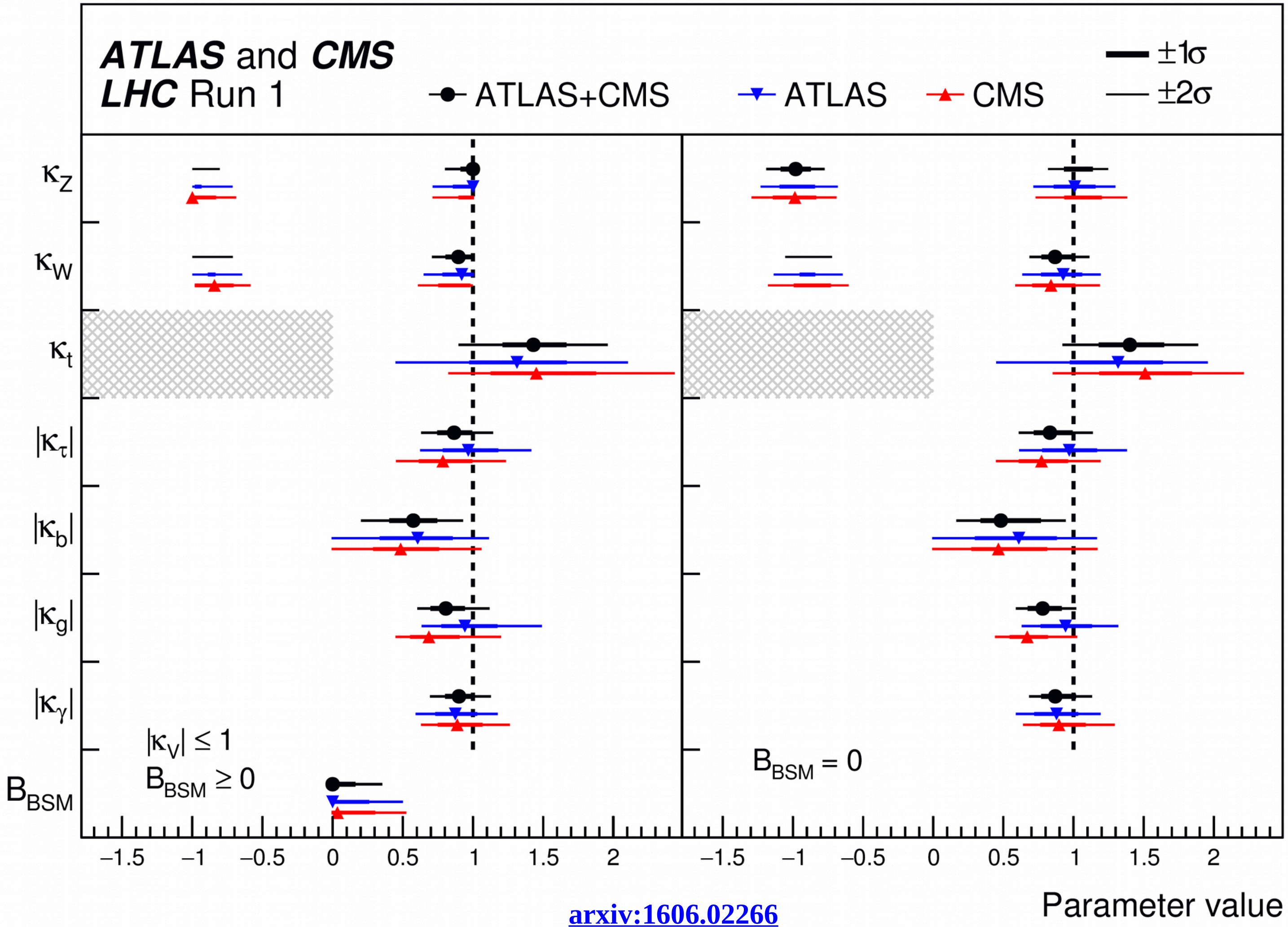




“Allow for BSM”

Effective coupling κ_g

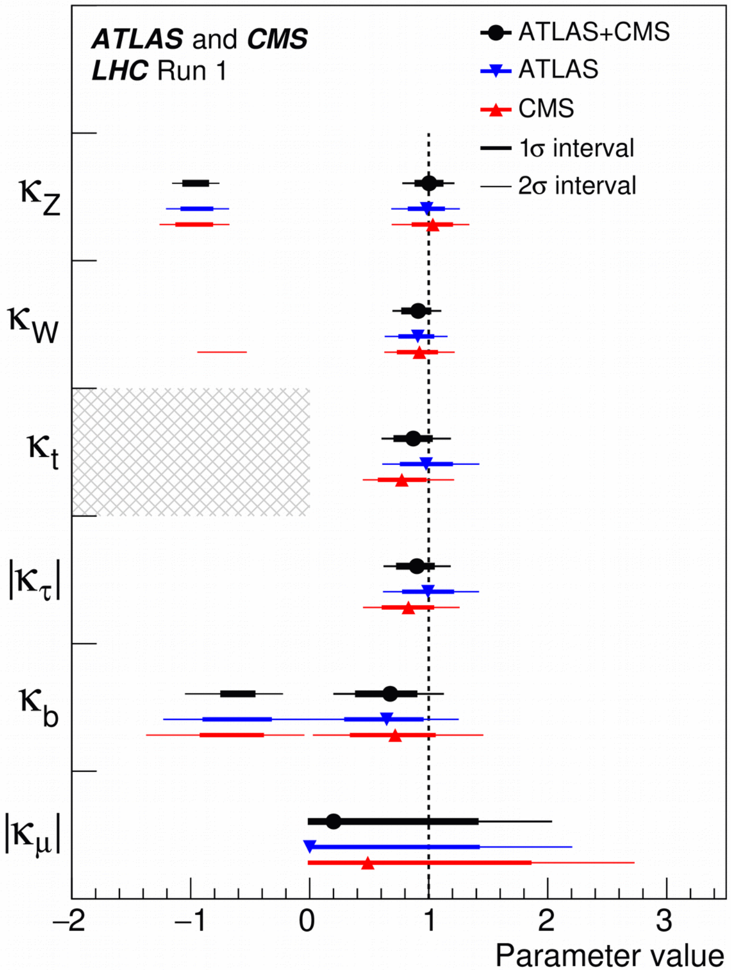
Higgs: kappa framework combinations

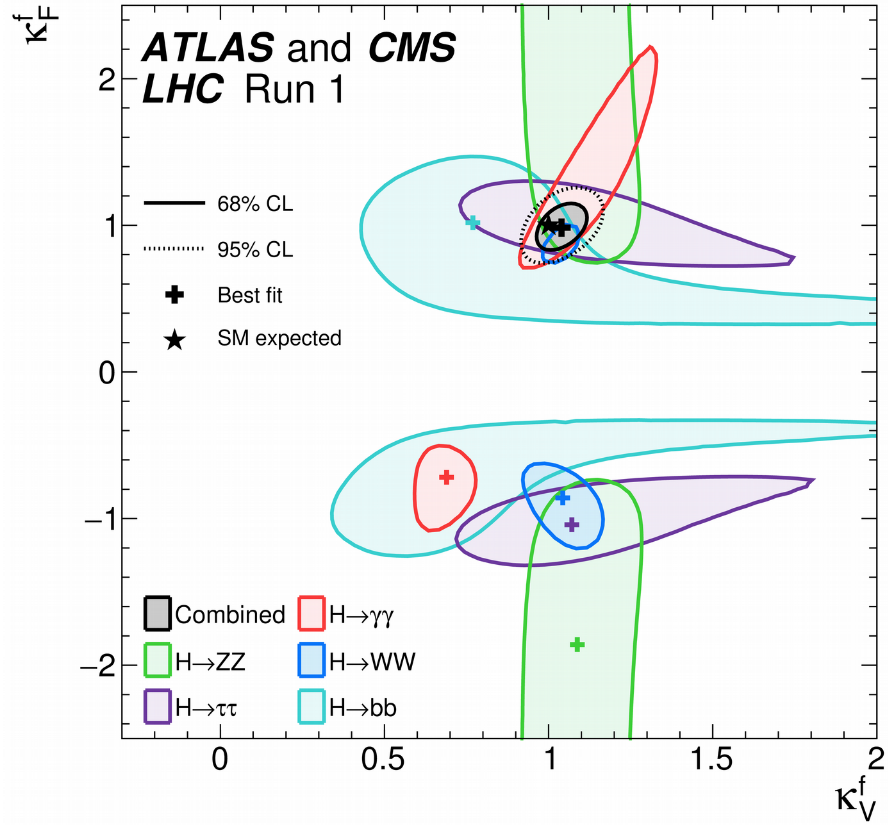


arxiv:1606.02266

- **Good agreement with SM predictions**

Higgs: kappa framework combinations



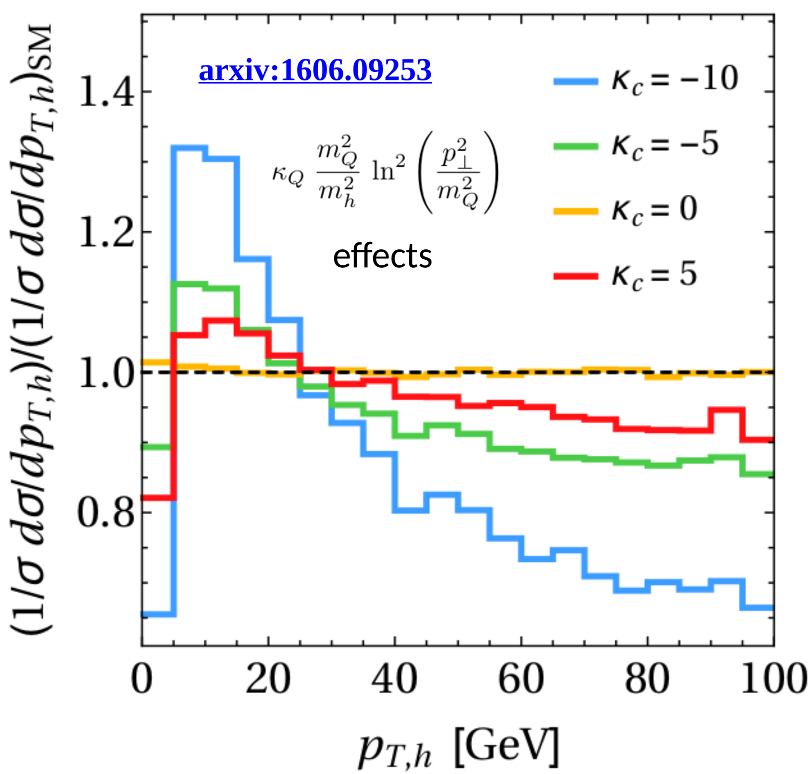


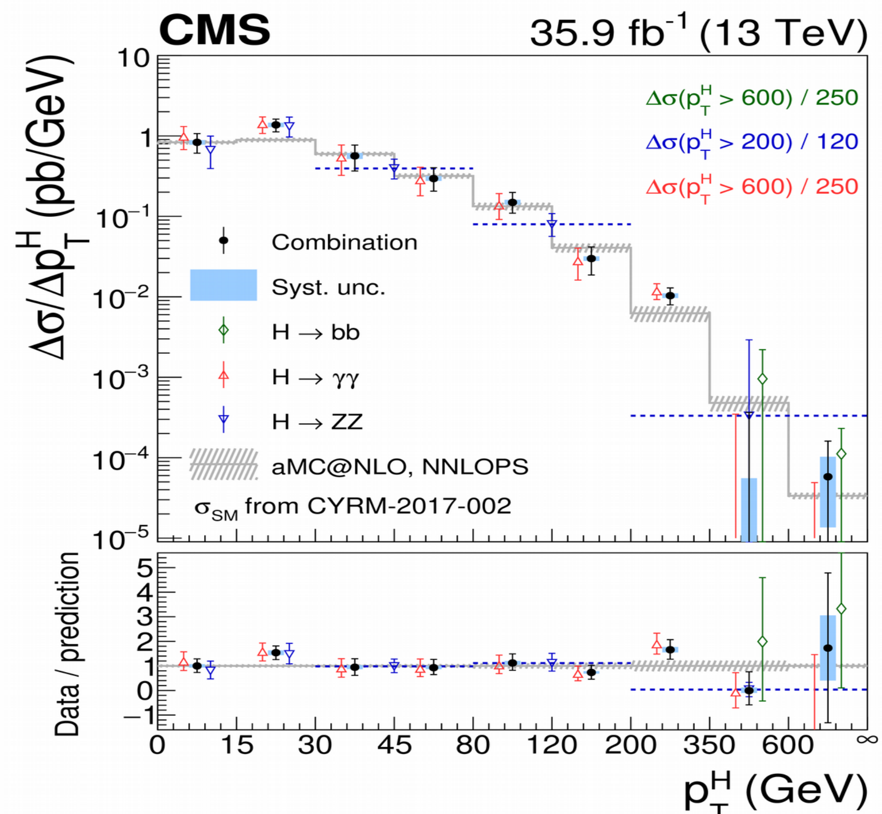
arxiv:1606.02266

- **Good agreement with SM predictions**

BSM Higgs and current trends

- Another intensive field of activity is dedicated searches for deviations from the SM, either direct or indirect. This is closely related with current and future trends for Higgs physics at LHC:
  - Searches for more Higgses: at low mass, at high mass, scalar, pseudoscalar, charged, ...
  - Invisible decays of the Higgs → connection with dark matter searches
  - Search for lepton / flavor violating decays
  - Study of differential cross sections, in particular as a function of the Higgs p_T, boosted decays, ...
  - Search for Higgs pair production → extremely important for HL-LHC and future accelerator programs

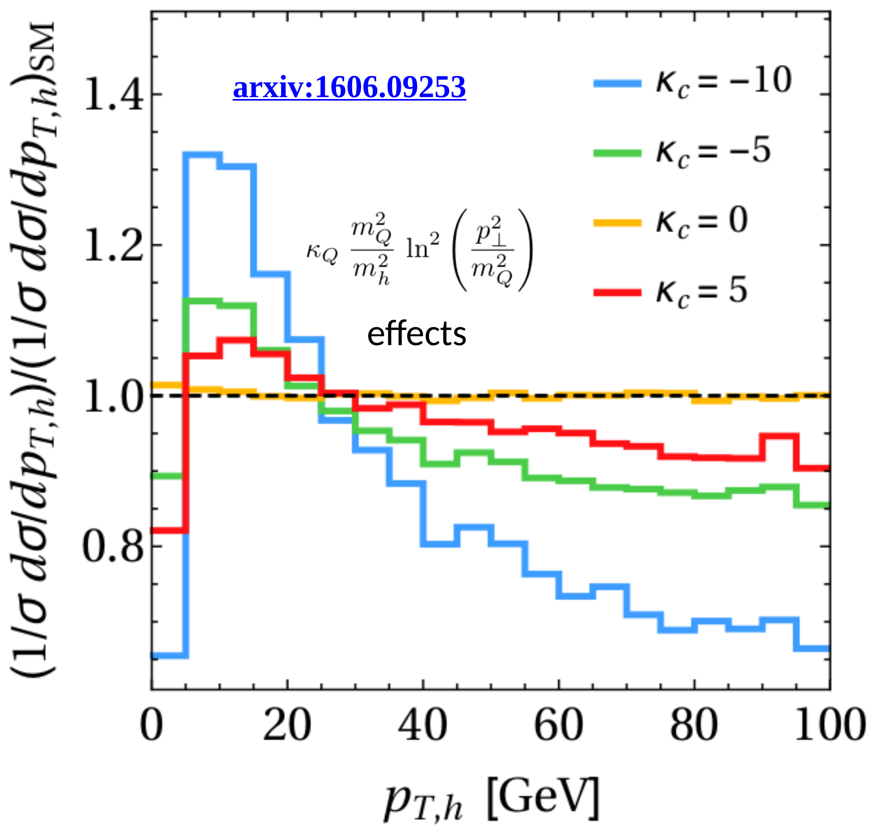


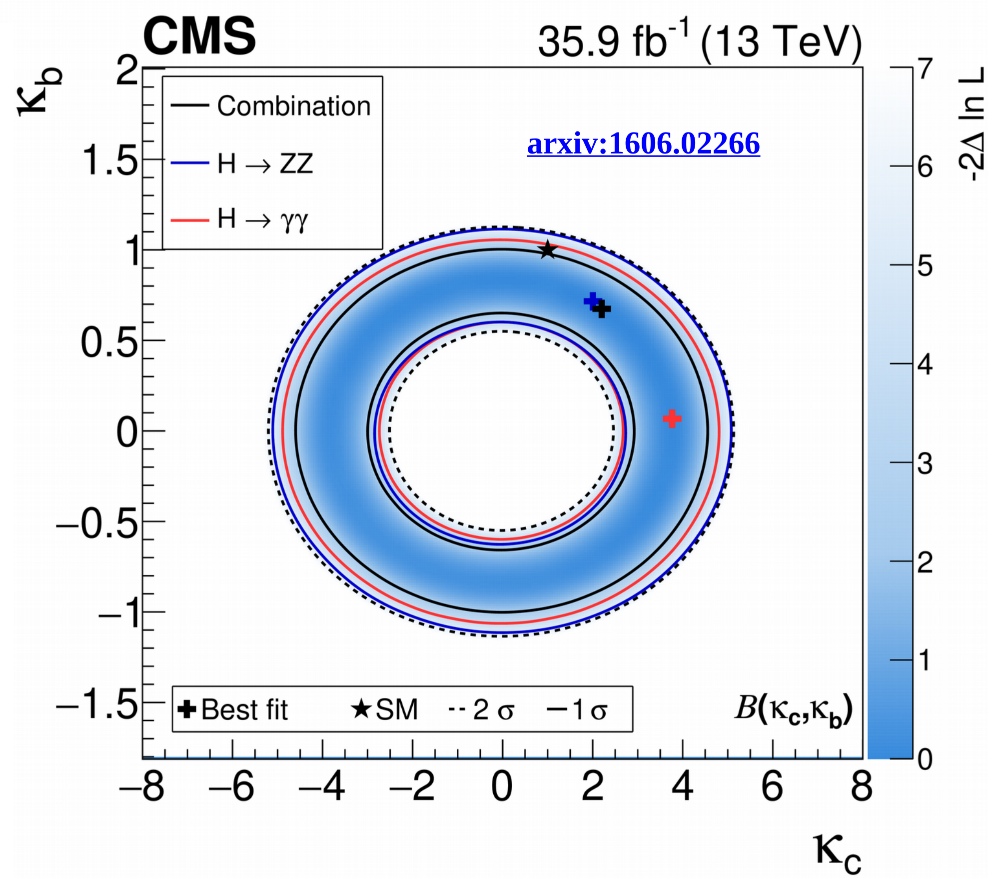


arxiv:1606.02266

BSM Higgs and current trends

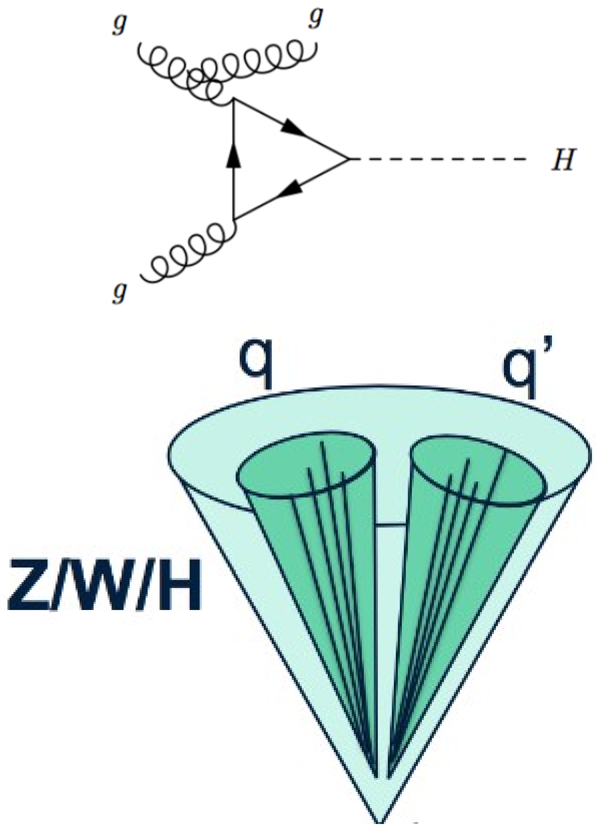
- **Another intensive field of activity is dedicated searches for deviations from the SM, either direct or indirect. This is closely related with current and future trends for Higgs physics at LHC:**
  - **Study of differential cross sections, in particular as a function of the Higgs p_T**
    - **Example: indirect constrains on quark couplings: charm, top, ...**

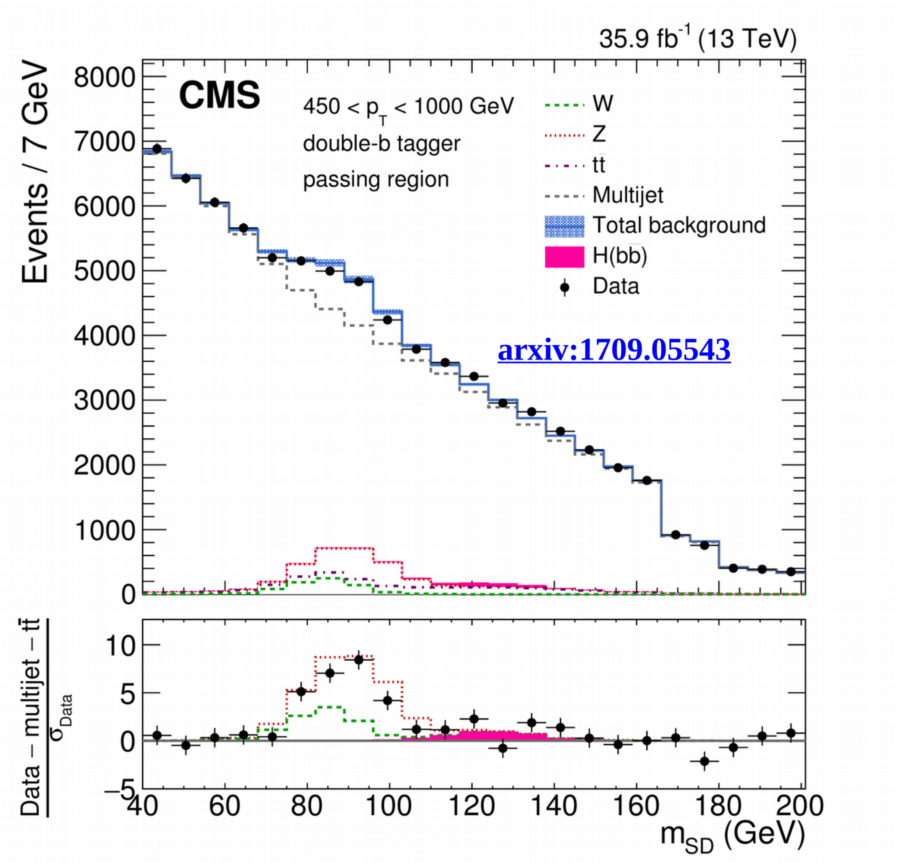




- **Sensitive to $Hc\bar{c}$ coupling !**

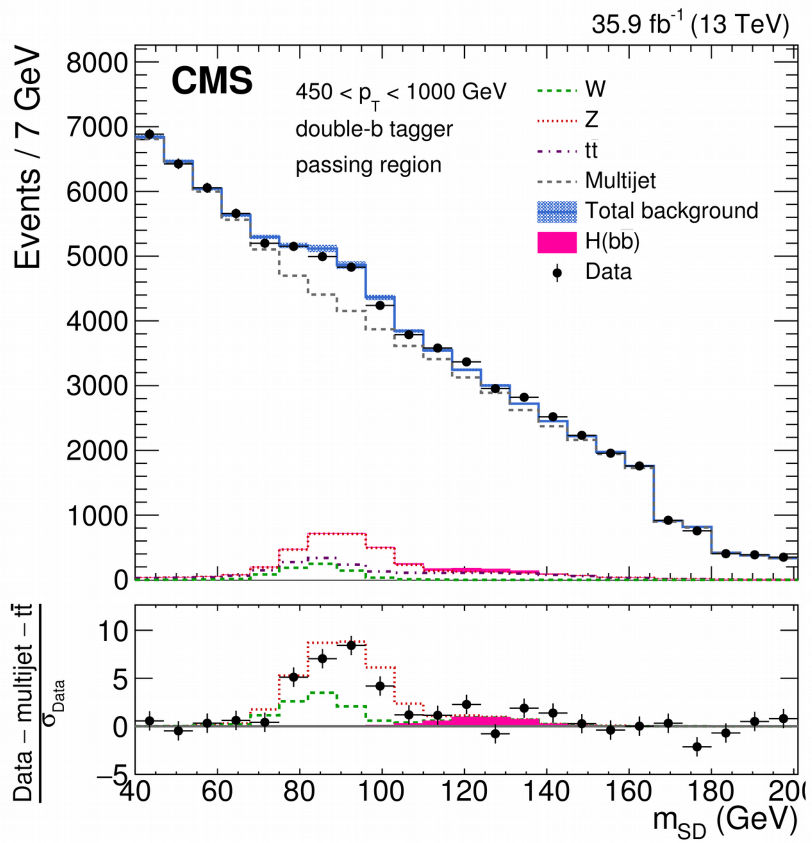
Recent trends: boosted H→bb



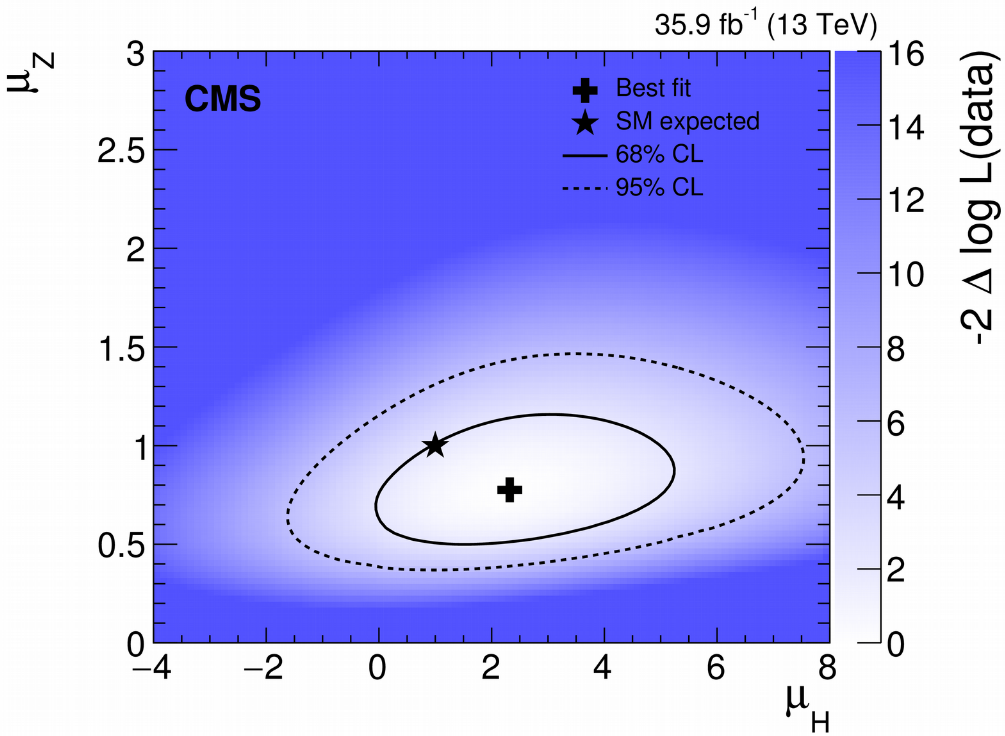


- **Targeting the very difficult gg→H→b$\bar{b}$ process, using latest developments in boosted topologies**
- **The Higgs is identified as one wide jet containing the two b quarks, highly boosted and recoiling against a high-p_T jet.**
- **The relative multijet QCD background gets significantly reduced in this configuration**

Recent trends: boosted H→bb



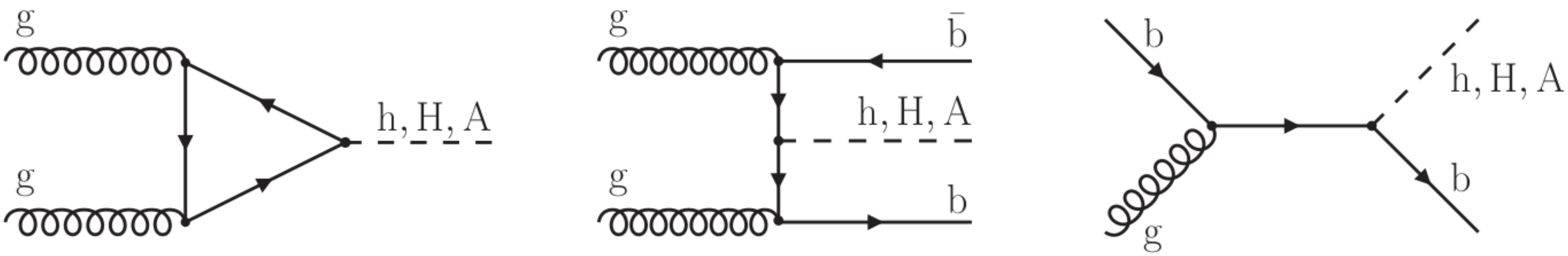
[arxiv:1709.05543](https://arxiv.org/abs/1709.05543)



- **Targeting the very difficult gg → H → $b\bar{b}$ process, using latest developments in boosted topologies**
- **The relative multijet QCD background gets significantly reduced in this configuration**
- **Current local significance of H → $b\bar{b}$ is ≈1σ; as well as an observation of the Z → $b\bar{b}$ decay (>5σ)**
- **Promising result in view of a future observation of H → bb in gluon-fusion production !!**

BSM Higgs and current trends

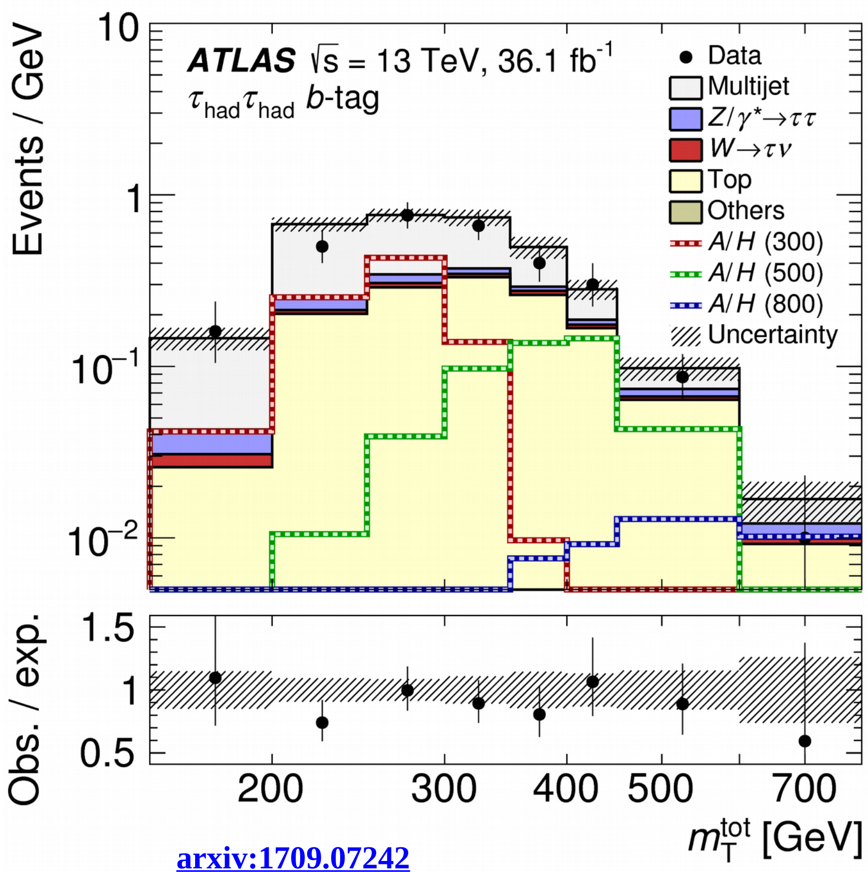
- Another intensive field of activity is dedicated searches for deviations from the SM, either direct or indirect. This is closely related with current and future trends for Higgs physics at LHC:
  - Searches for more Higgses: at low mass, at high mass, scalar, pseudoscalar, charged, ...
    - Example of searches for additional neutral Higgses from a new doublet scalar field



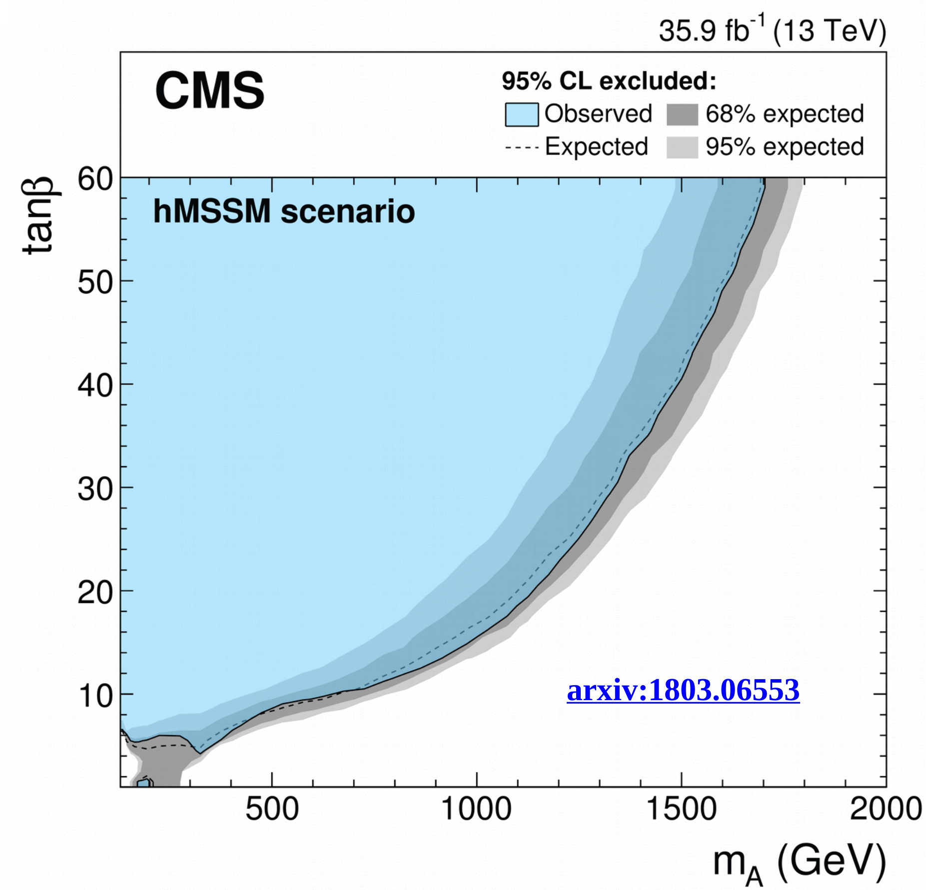
- Possible enhancement of the $b\bar{b}$ and ττ couplings in Two-Higgs doublet models of Type II (SUSY is an example)
- Enhancement factor is: $\tan\beta = v_u/v_d$, the ratio of vacuum expectation values of the two Higgs doublets, associated to up-type and down-type fermions, respectively
- Particularly interesting decay channel is $h/H/A \rightarrow \tau\tau$ (cleaner than $b\bar{b}$)

Search for Φ → ττ

- **Categorization: different tau decay channels (leptonic+τ_{had}, τ_{had}+τ_{had}), with/without b-tagging**
- **Exploit the total transverse mass of the system (visible tau decays + missing transverse momentum)**



arxiv:1709.07242

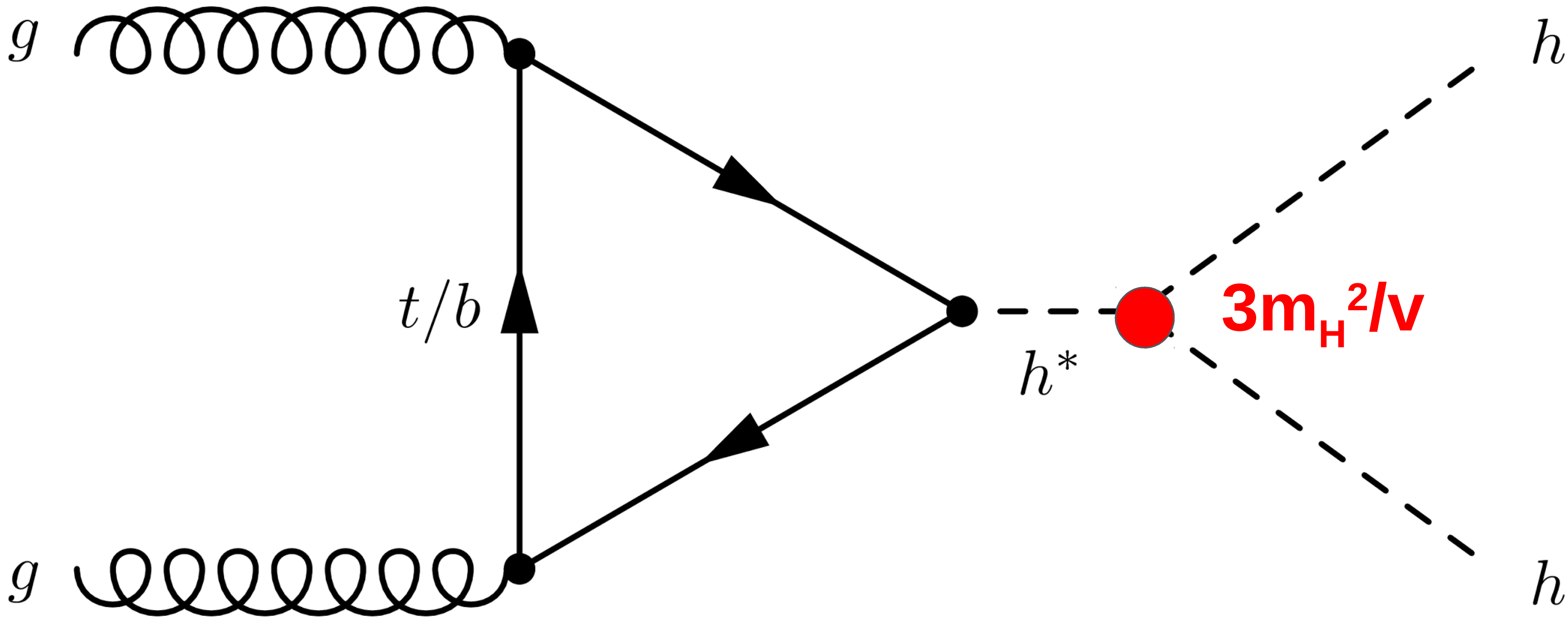


arxiv:1803.06553

- **hMSSM ≡ MSSM scenario assuming m_h=125 GeV**

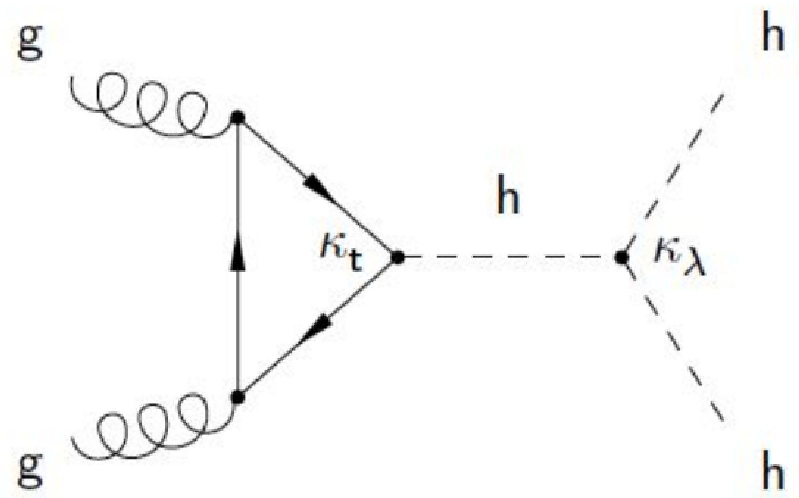
Higgs self-coupling and HH production

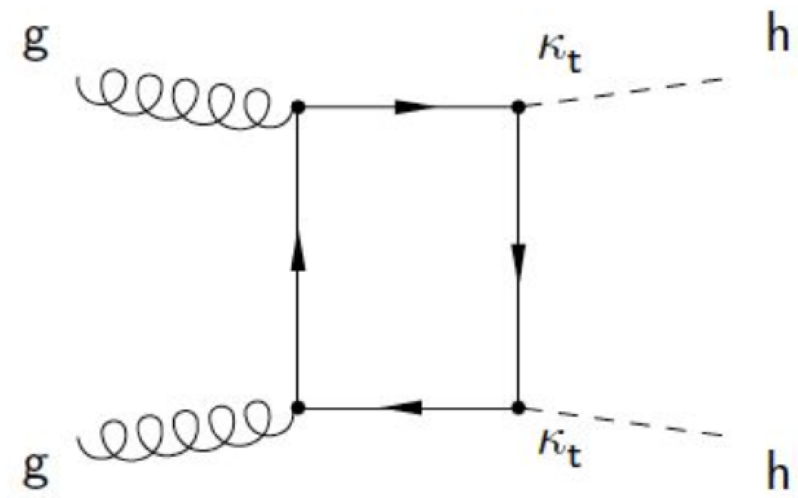
- **Main final state to explore the nature of the Higgs potential and its self-coupling, predicted to have a well defined, non-zero value in the SM**



Higgs self-coupling and 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 (≈ 30 fb at $\sqrt{s}$=13 TeV) ⇒ only measurable with huge luminosities (hopefully at HL-LHC)**
  - **BSM may be un-affected by this negative interference: larger cross sections expected!**

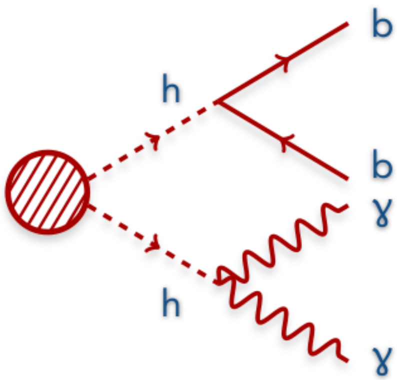


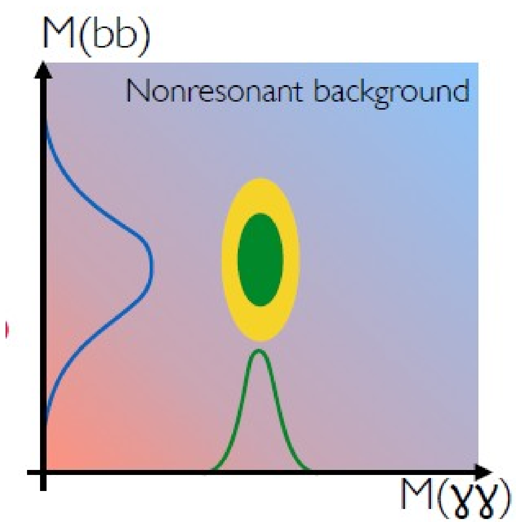


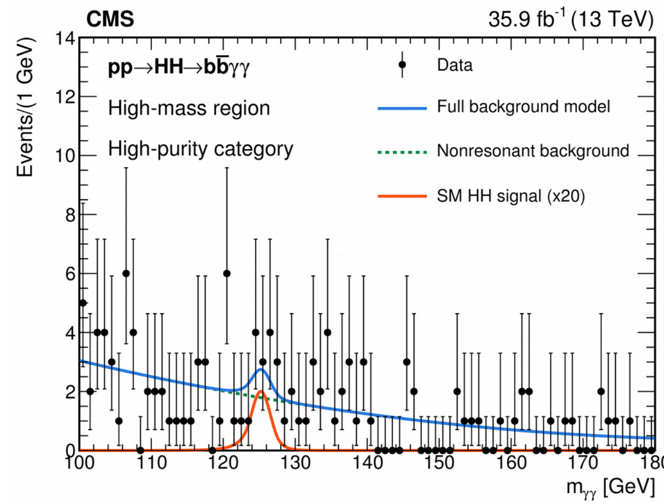
HH search example: HH→b$\bar{b}$γγ

- HH→b$\bar{b}$ γγ is currently one of the best channels to look for HH production:
  - Two Higgs masses are available
  - The large H→b$\bar{b}$ branching fraction compensates the low H→γγ branching fraction
  - SM backgrounds are non-resonant and also reducible (b-tagging, kinematics, ...)

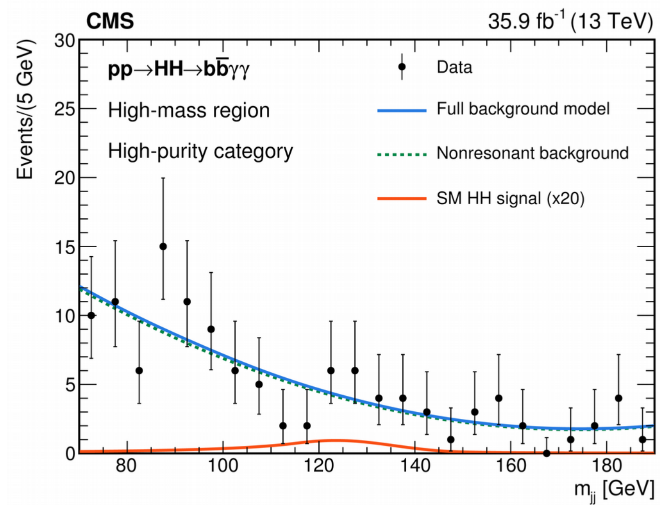
[arxiv:1806.00408](https://arxiv.org/abs/1806.00408)







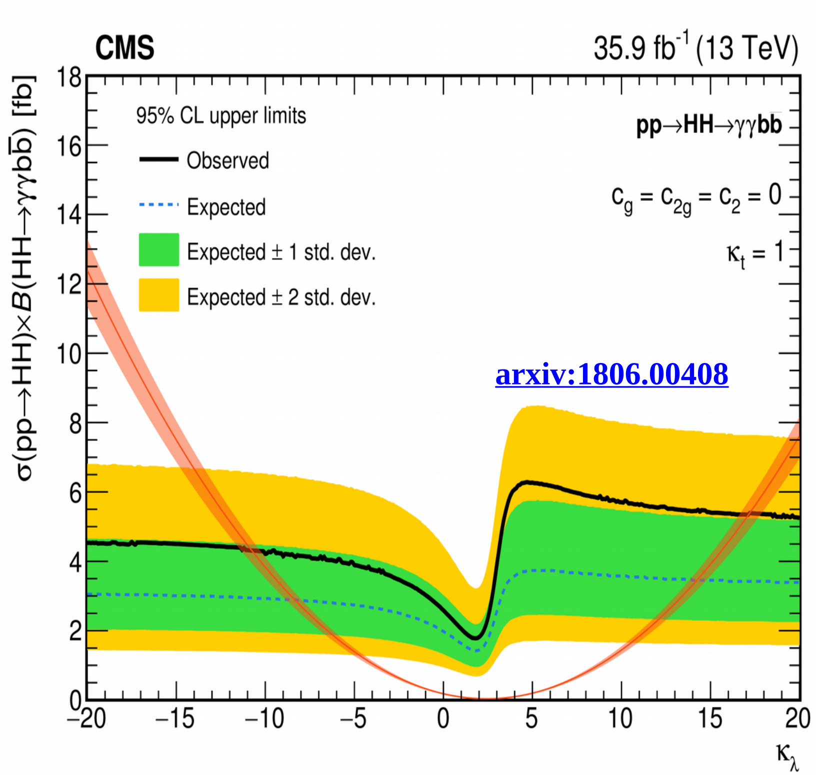
γγ mass



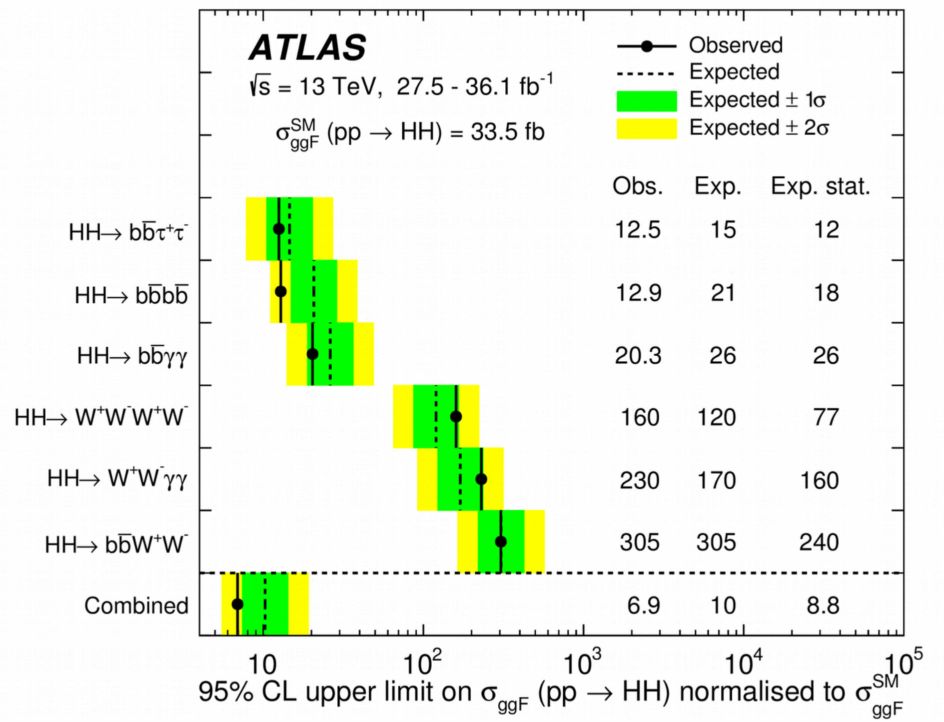
b$\bar{b}$ mass

HH search example: HH→ $b\bar{b}\gamma\gamma$

- LHC is already sensitive to large values of the κ_λ parameter (⇒ cross sections much larger than in the SM)
- $b\bar{b}\gamma\gamma$ is not the only channel under study



arxiv:1906.02025

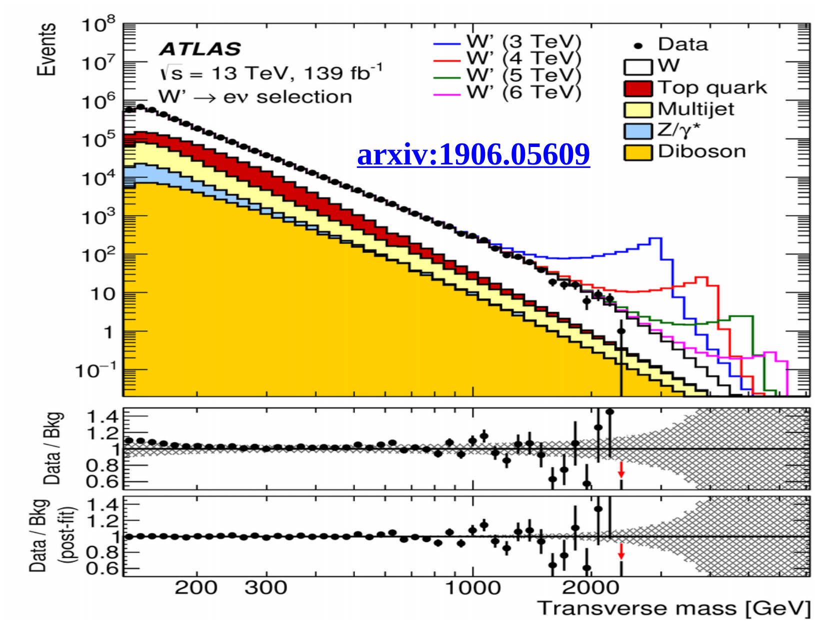


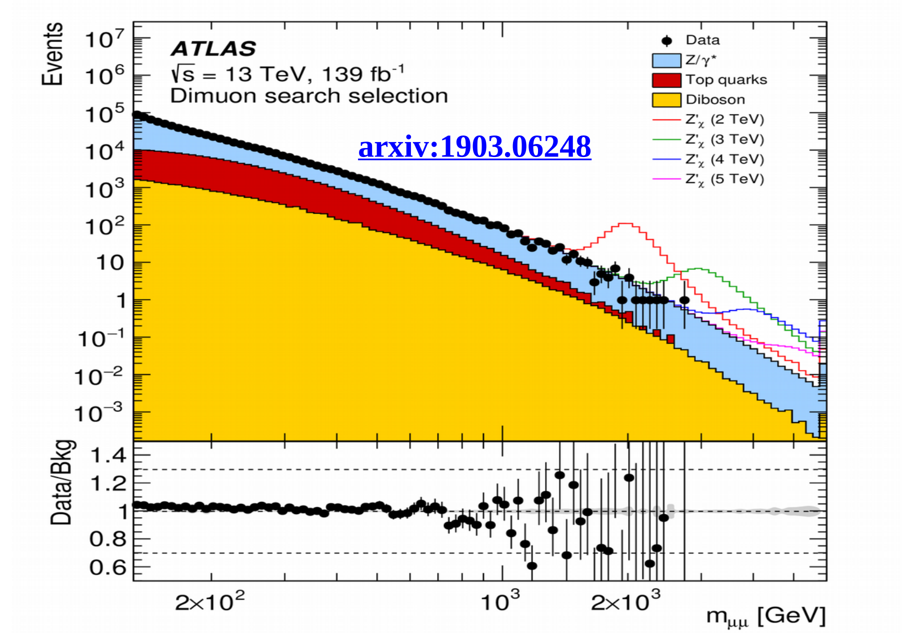
- Other channels also contribute significantly to the search ⇒ combine them !
- Large values of κ_λ ($|\kappa_\lambda| \lesssim 10$ or excluded in LHC Run2 !

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):

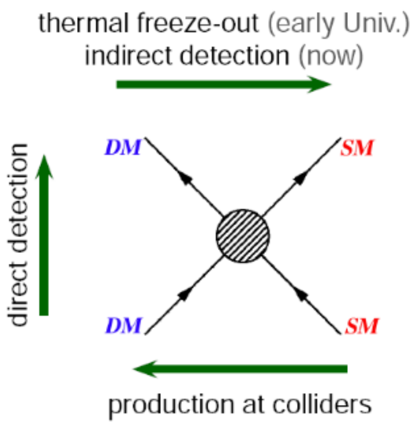


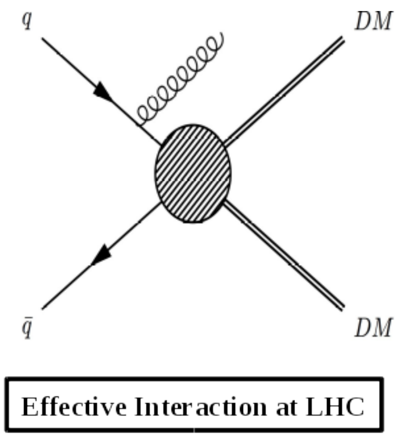


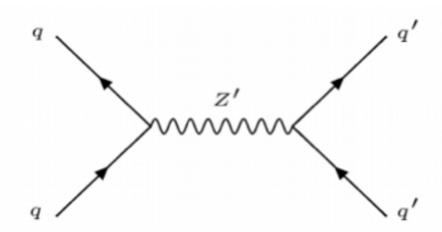
- Basic strategy:
  - Isolated leptons of extremely high momentum (TeV scale)
  - Look for 'peaks/bumps' in the di-lepton invariant mass or in the lepton+missing momentum transverse mass
- Key (critical) point: good lepton momentum resolution at ≈ TeV scale and very precise control of resolution, momentum 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)

Dark matter (DM) searches at LHC

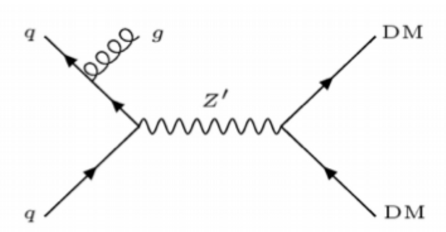
- **Most sensitive generic search is one initial-state radiation jet + missing energy from DM. Mediator may have vector/axial/scalar/pseudoscalar couplings to DM**



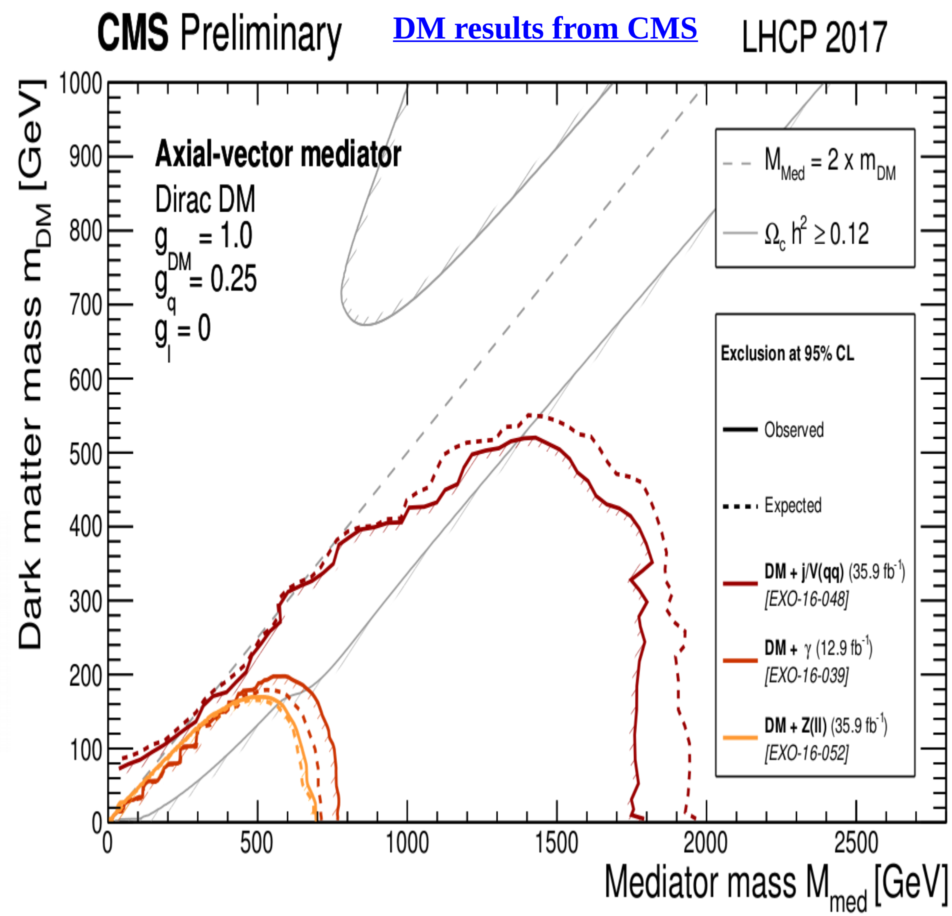




Direct coupling to quarks must exist



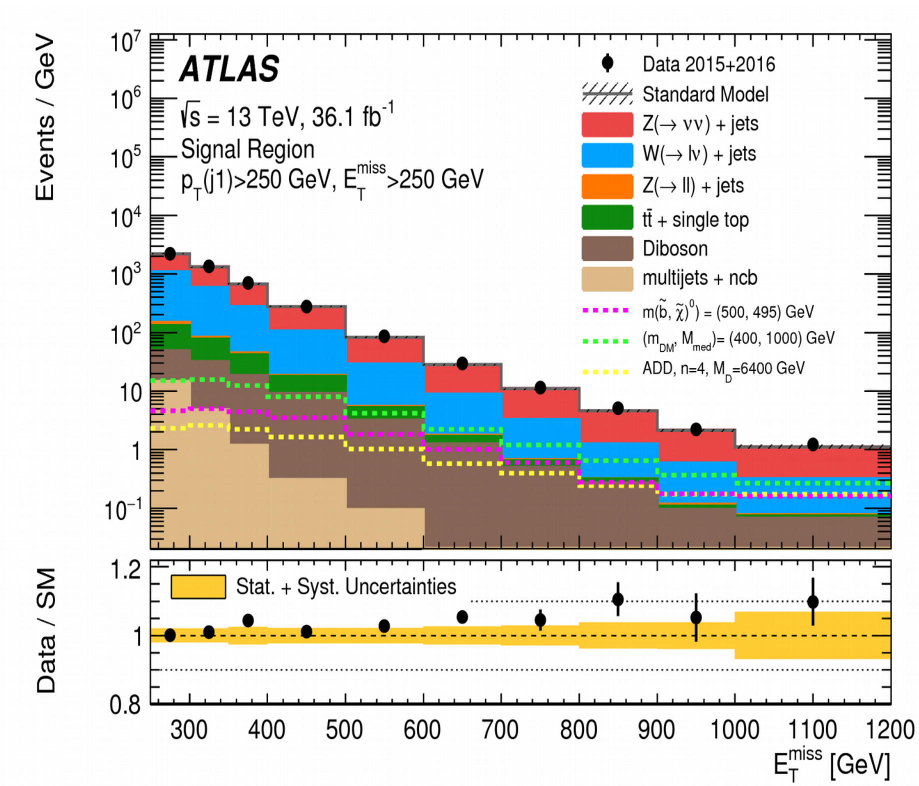
X+missing energy search; couplings to quarks and DM



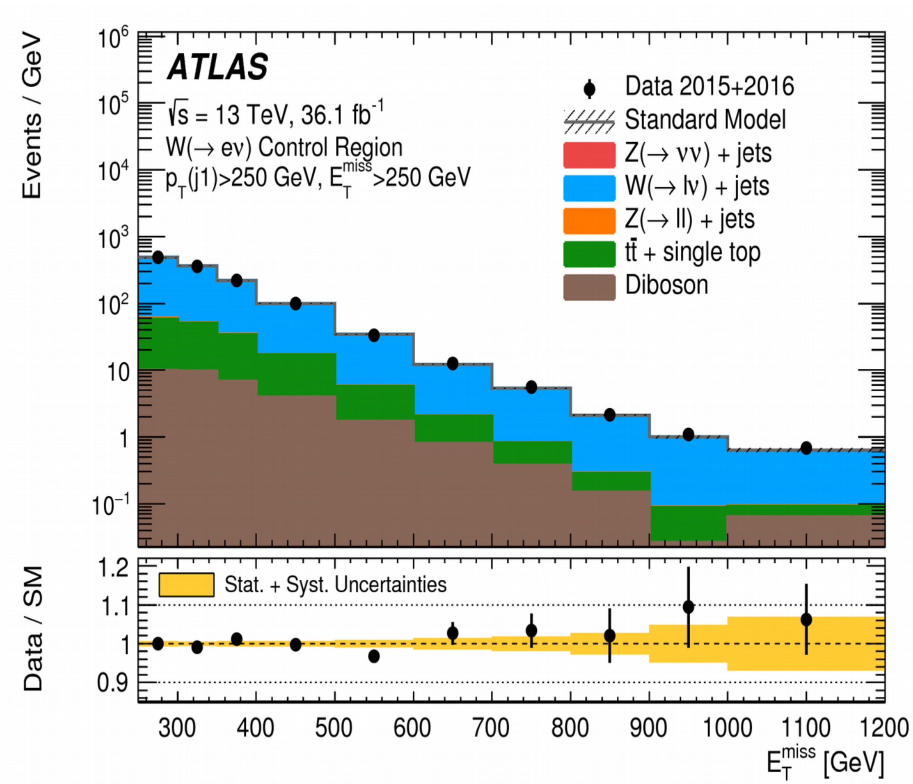
- **Results of the X+DM searches for a benchmark choice of couplings to quarks, DM and leptons**

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

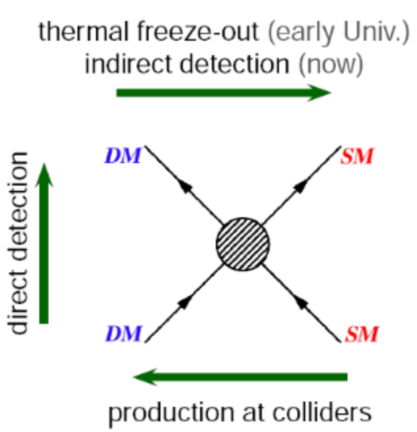


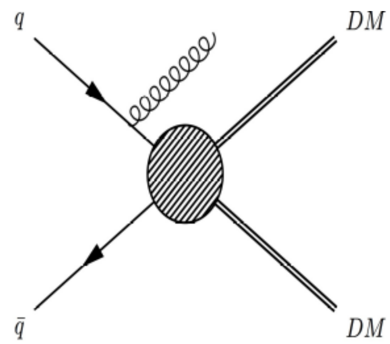
arxiv:1711.03301

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

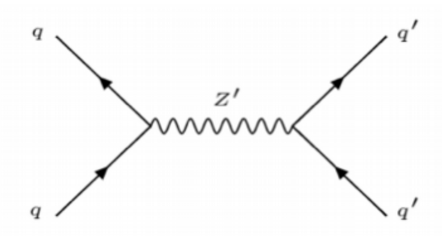
Dark matter (DM) searches at LHC

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

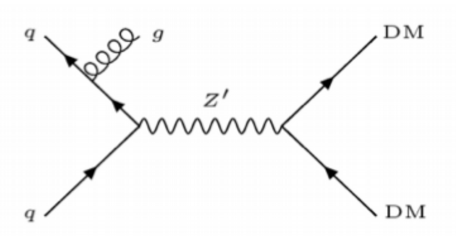




Effective Interaction at LHC

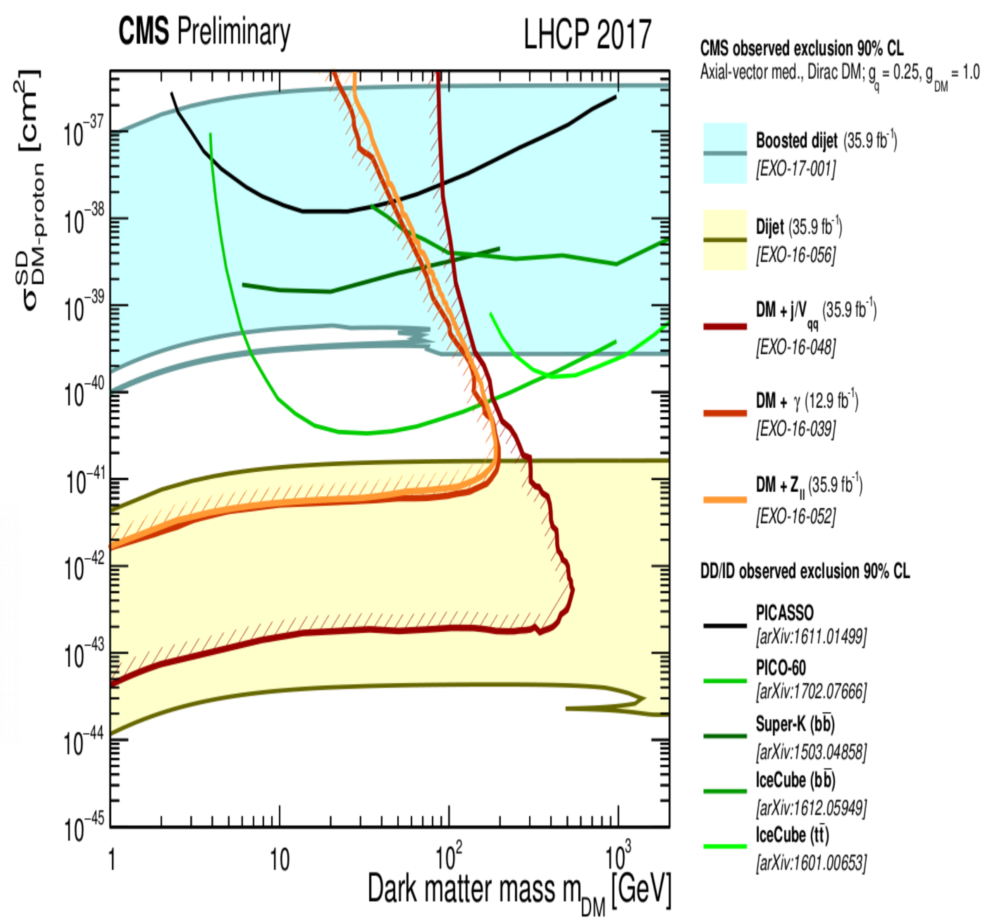


Direct coupling to quarks must exist



X+missing energy search; couplings to quarks and DM

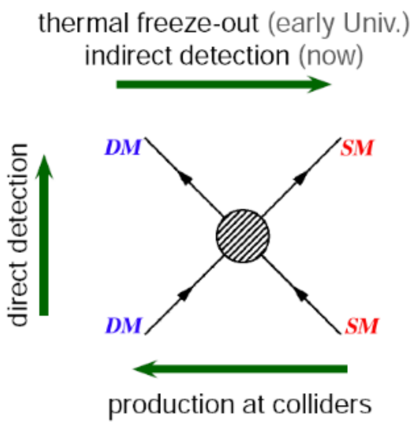
[DM results from CMS](#)

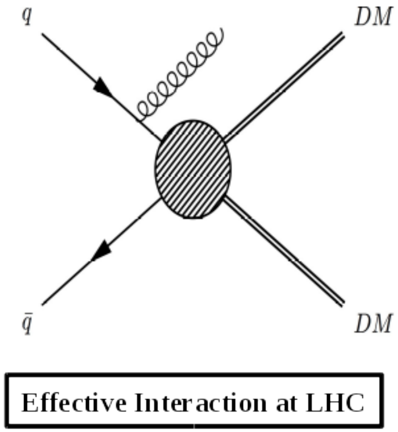


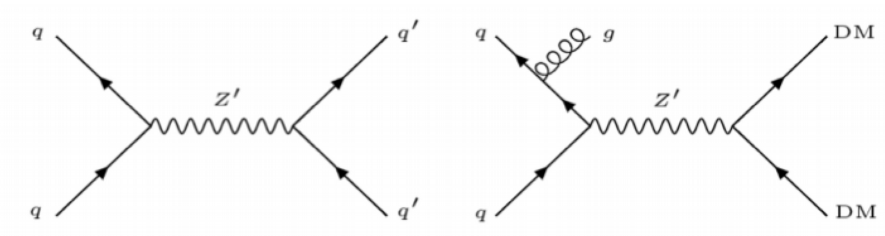
- Comparison with Direct Detection (DD) searches

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

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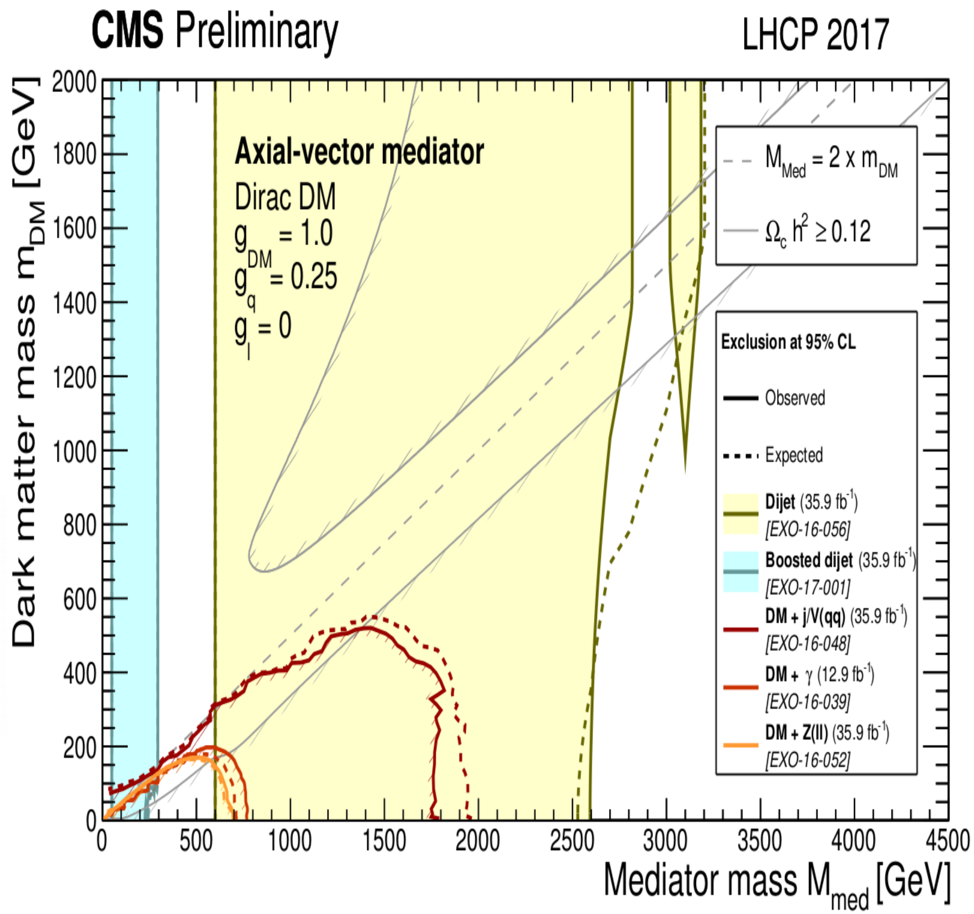
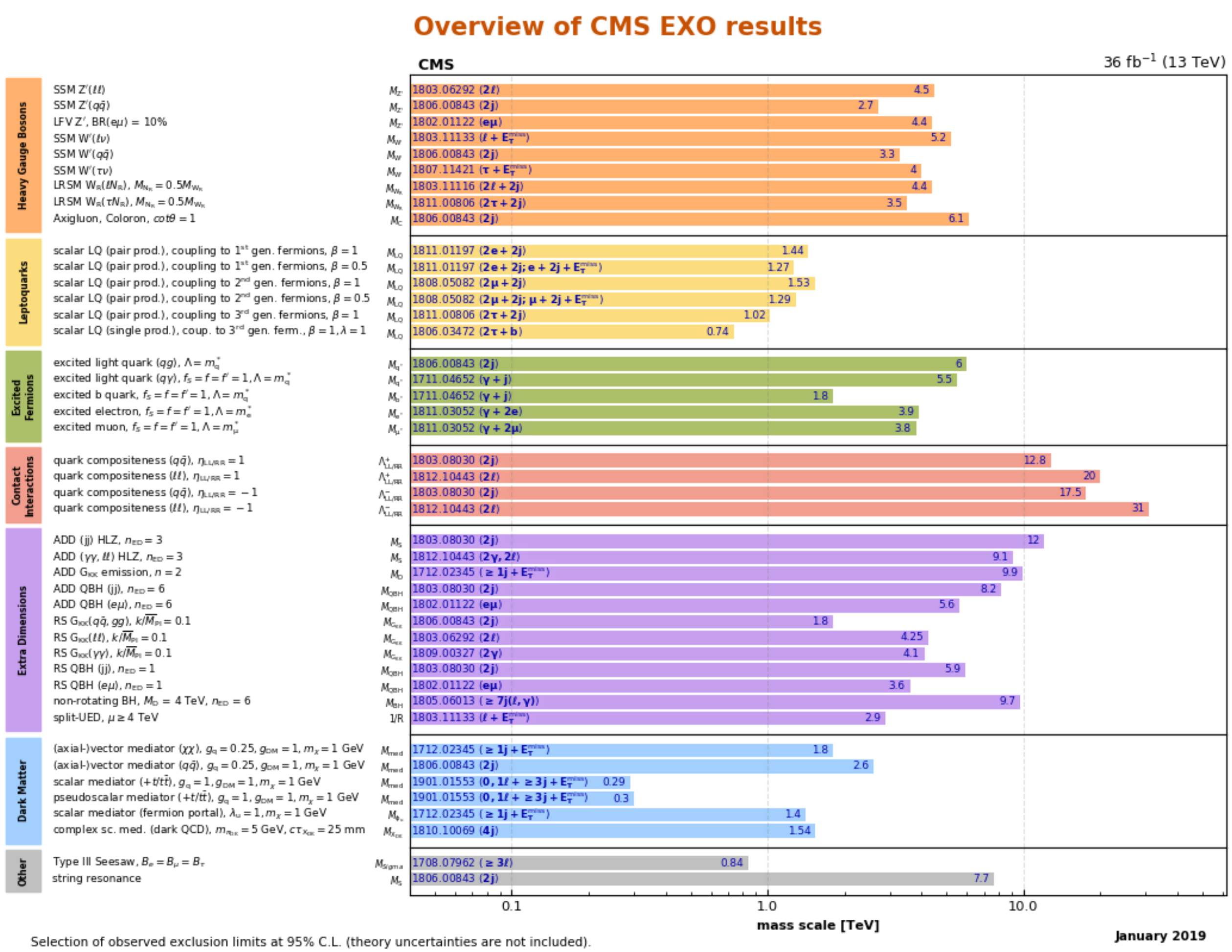


- Pure dijet resonance searches are even more powerful when the mediator mass is high enough

More generic searches at LHC

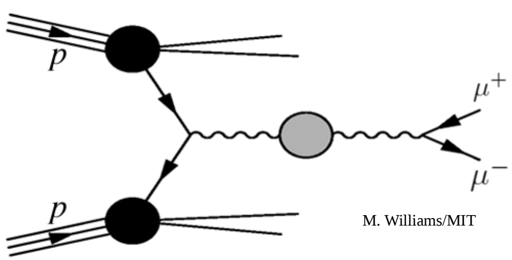
- The list of possible searches beyond the SM is almost infinite ...



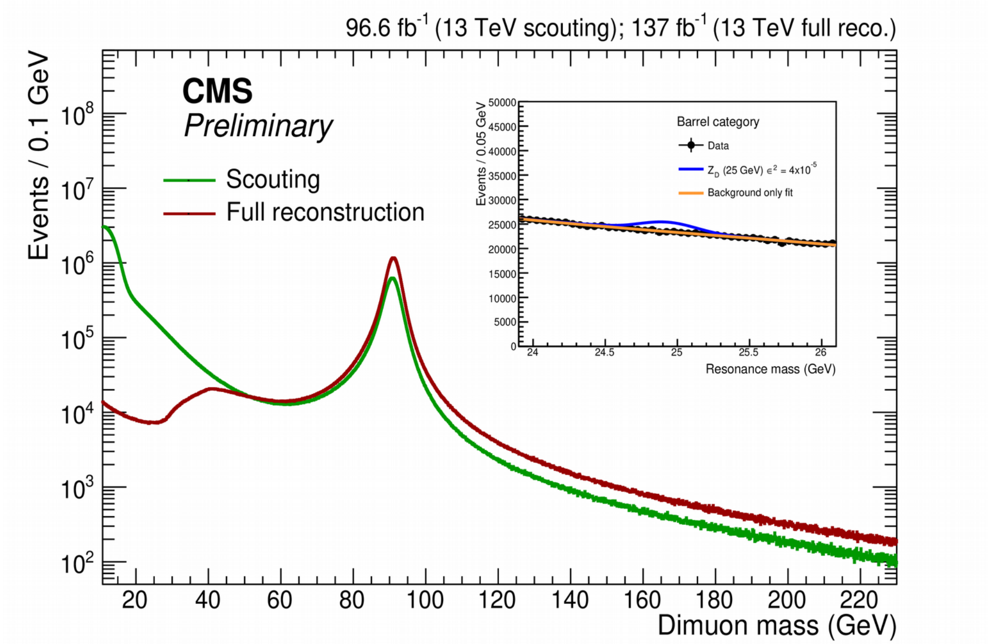
The main message is that we have not found new exotic signals … YET!

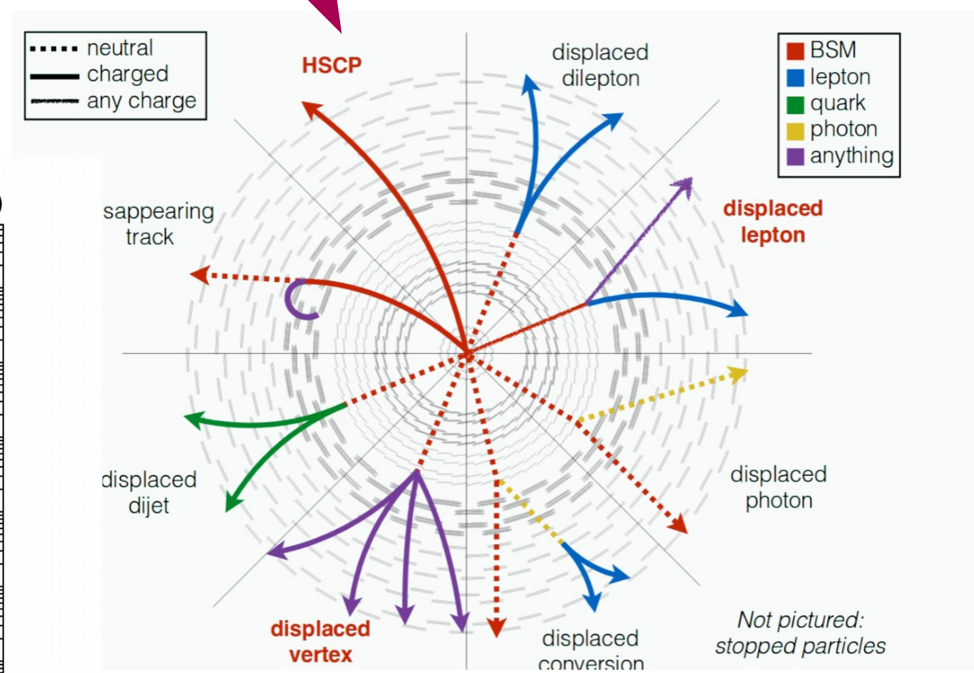
Current trends in searches at LHC

- Search for low-mass and/or “long-lived” resonances (axions, particles with very weak couplings in decay, ...)
- Challenging from many points of view (trigger, object reconstruction, ….)



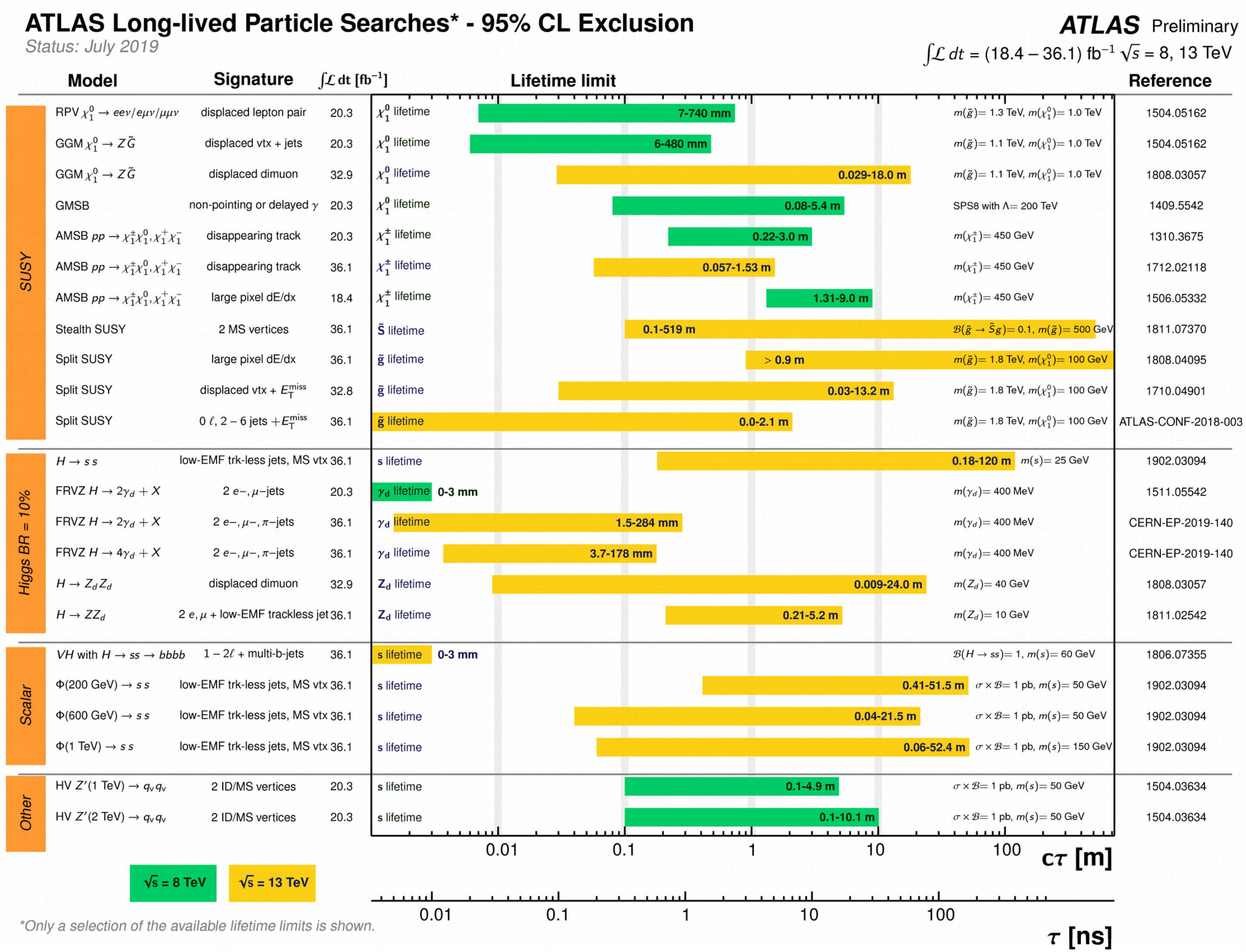
CMS-PAS-EXO-19-018





Current trends in searches at LHC

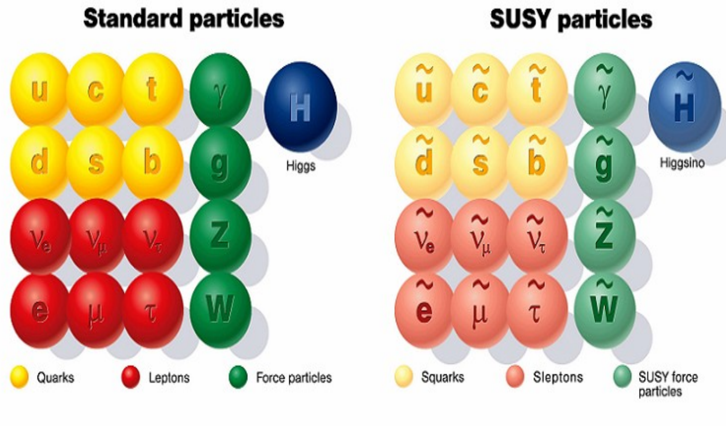
Long-lived exclusion in lifetime phase space



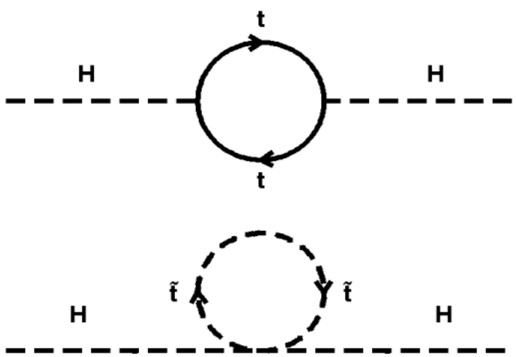
SUSY

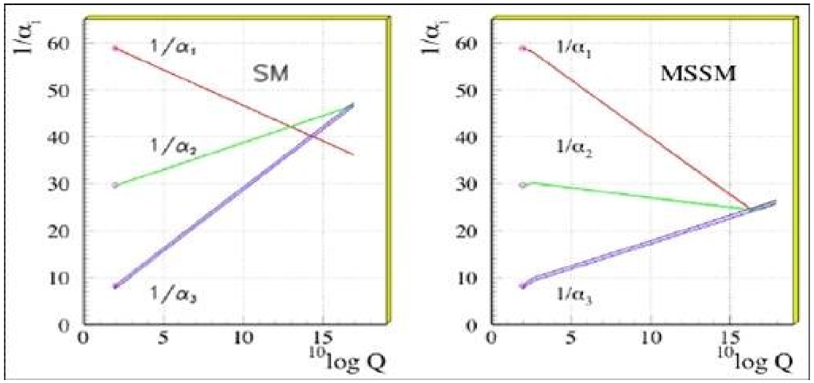
SUperSYmmetry

- Super-symmetry is a new symmetry relating bosons and fermions. For each known particle, we expect a super-symmetric partner, of spin differing by 1/2



- Why SUSY at the TeV scale? According to theorists:





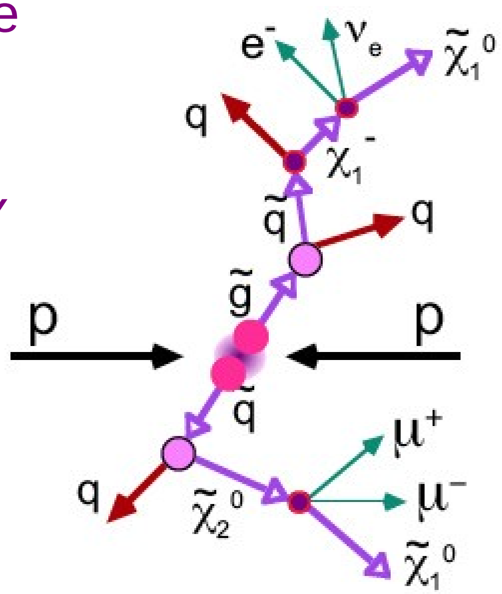
Hierarchy problem solved **Natural unification of forces** **Dark matter candidate**

- If found at the LHC: many new particles, couplings and properties to be studied at the TeV scale...

SUperSYmmetry

- How does it manifest at the LHC? We have not seen SUSY particles yet, so this new symmetry must be broken and SUSY particles must have masses above the current scale (but not much, to solve the hierarchy problem)

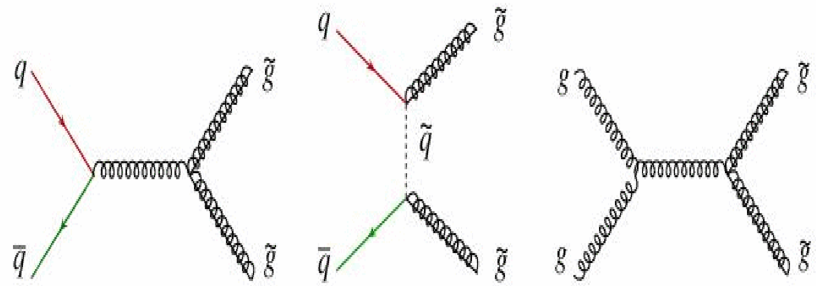
- In most cases (but not all) it will be assumed that at the LHC:
  - We will produce heavy squarks and gluinos via strong couplings. They will decay into lighter SUSY particles (+other SM particles)
  - The lightest SUSY particle is stable (R-parity conservation) and interacts very weakly with matter (dark matter candidate, undetectable)



- From the detector point of view:
  - Long cascade decays with jets and eventually Z, W, leptons, γ
  - Substantial missing E_T

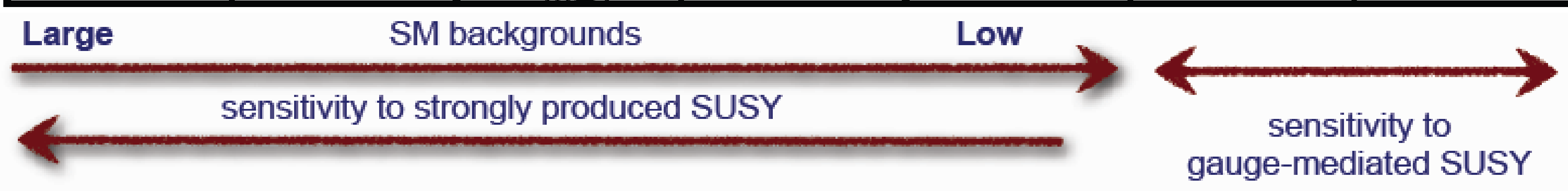
Strategy to search for SUSY at LHC

- SUSY has many parameters (>100):
  - We know the gluino and squark cross sections, given their mass
  - But the subsequent cascade depends too heavily on those parameters and mass differences



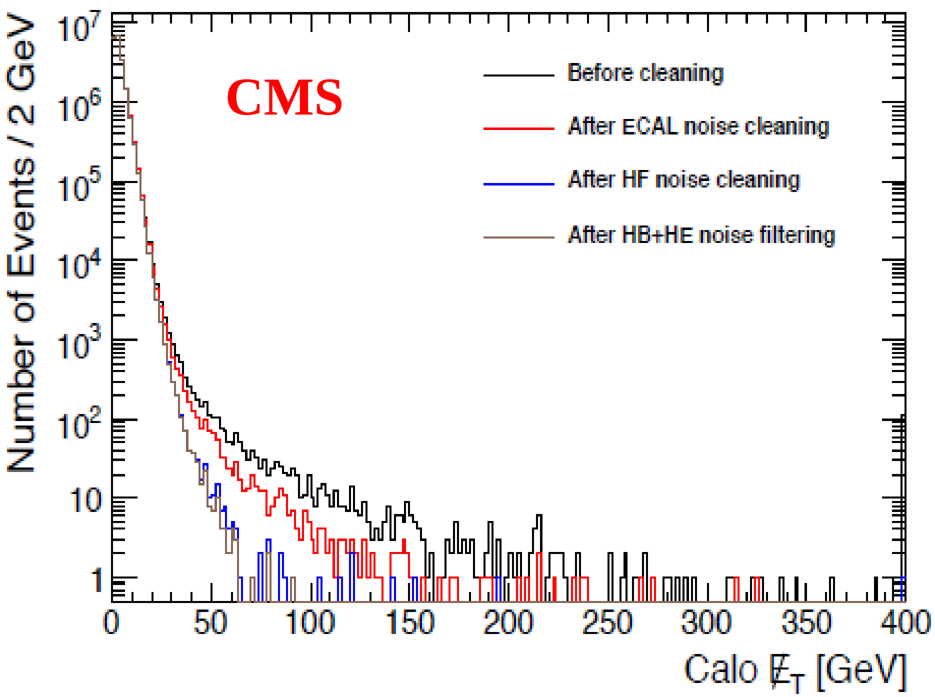
- We want to find SUSY if existing. So, to be more independent on parameter choices, we focus on generic signatures:

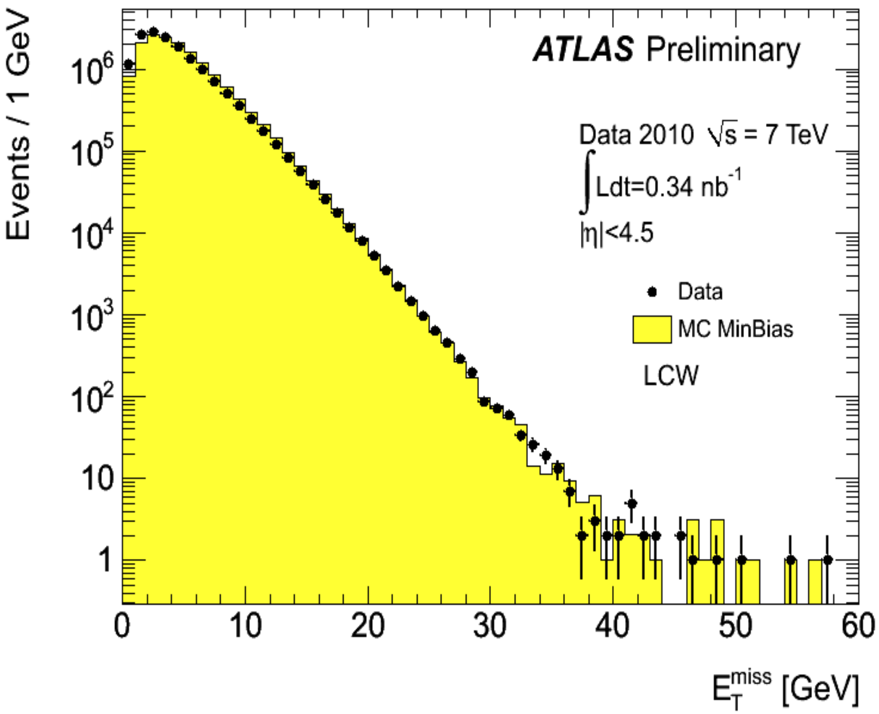
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET



SUSY at LHC: jets and missing E_T

- An excellent jet resolution and an excellent missing E_T resolution are a MUST for SUSY searches. Both ATLAS and CMS have them, but this required some extra effort:

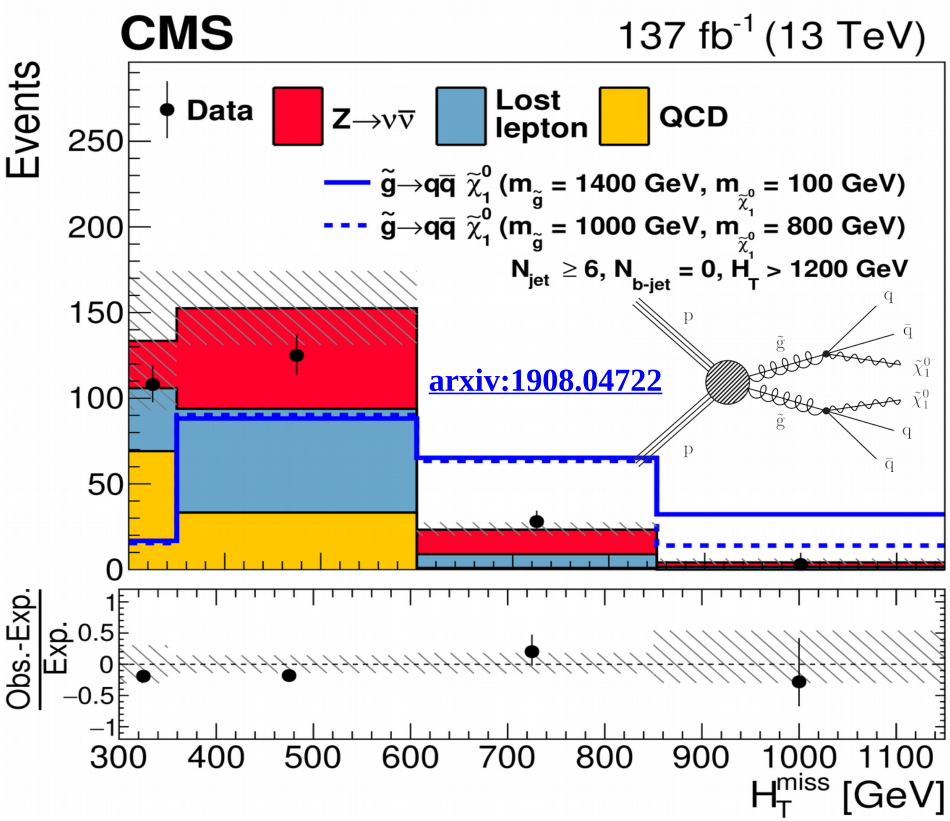


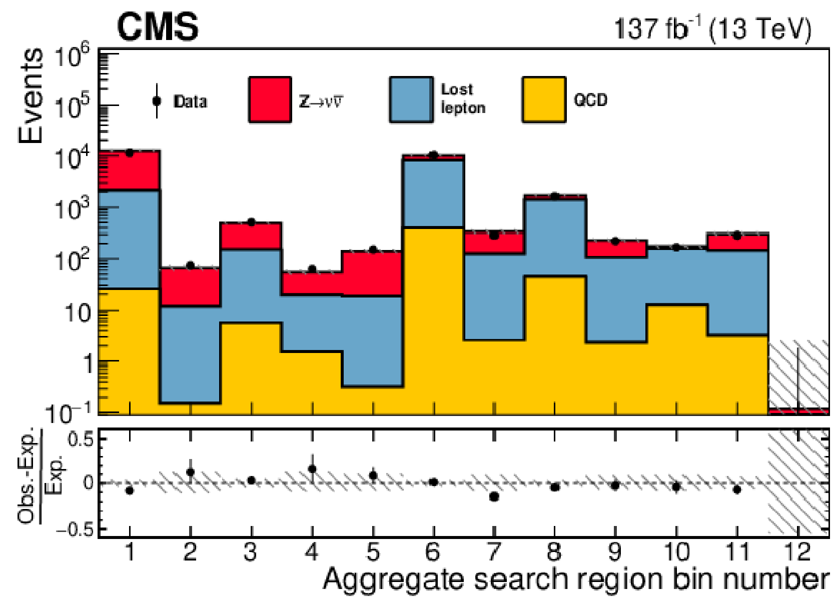


- This is more challenging that what it seems. Having a well calibrated missing ET from (almost) the start was a very optimistic scenario !!

SUSY results: hadronic + missing E_T

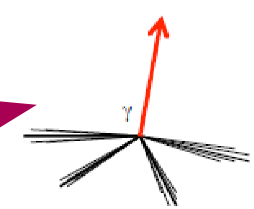
- Concentrate on final states with just jets and substantial missing H_T → same as missing E_T but calculated using only jets (unclusterized energy is ignored)





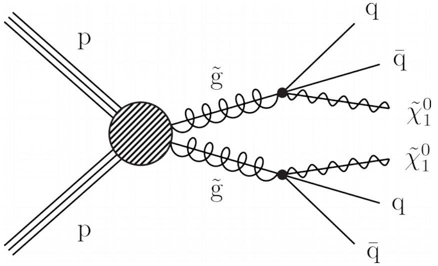
- Many variables used in practice:
  - #jets, #b-tagged jets, H_T, H_T^{miss}
- Many different subregions defined with them

- 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

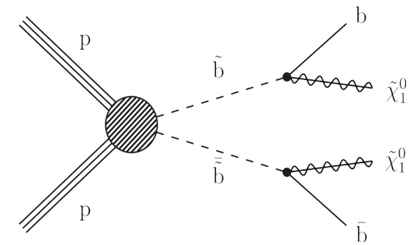


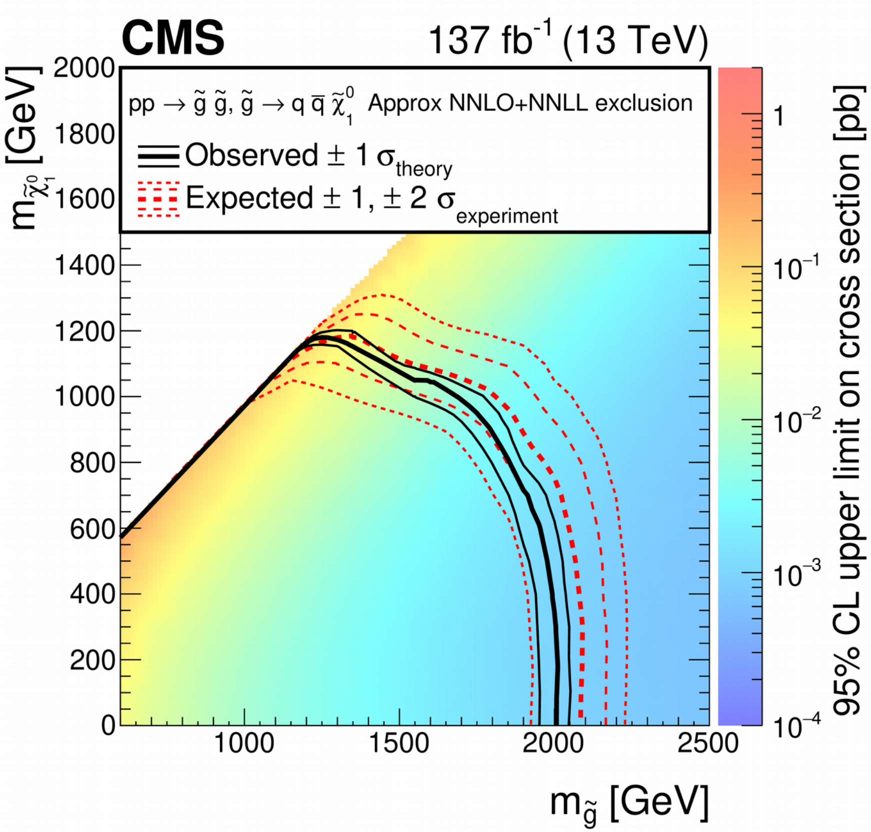
SUSY results: hadronic + missing E_T

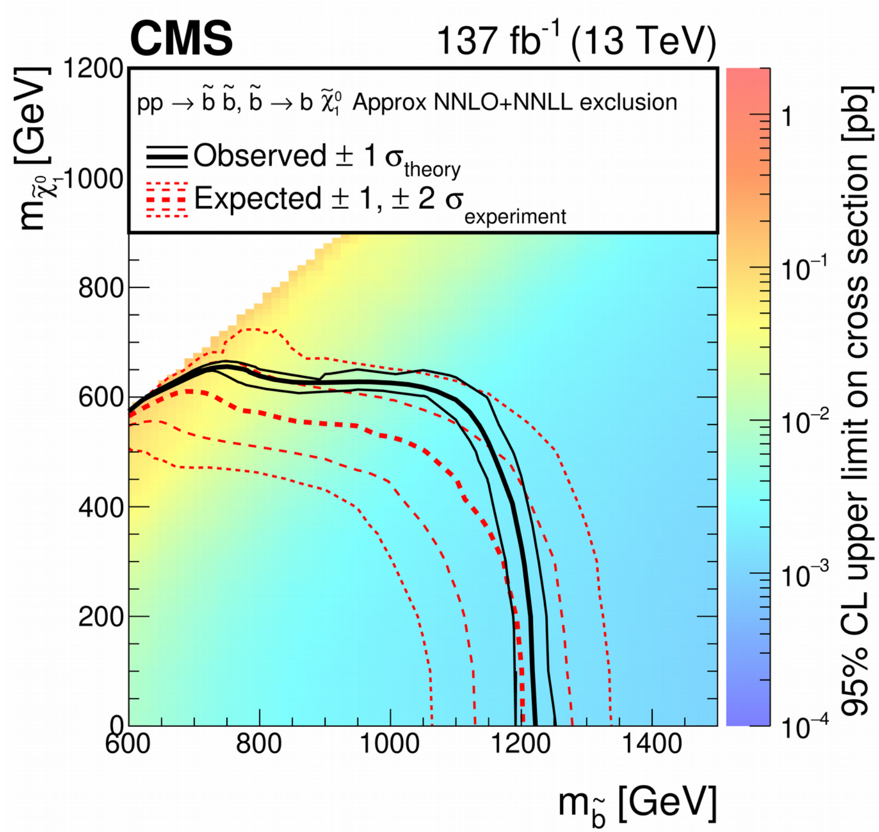
- We do not see any significant excess yet. We therefore set limits in some benchmark SUSY scenarios:



arxiv:1908.04722

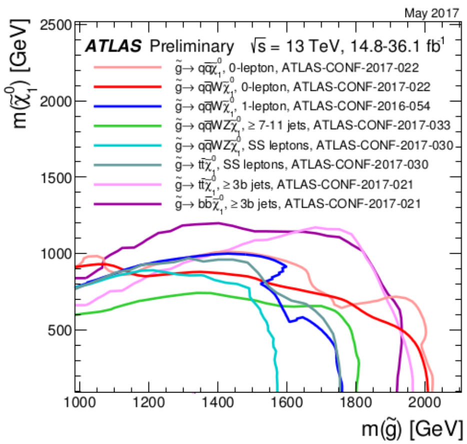




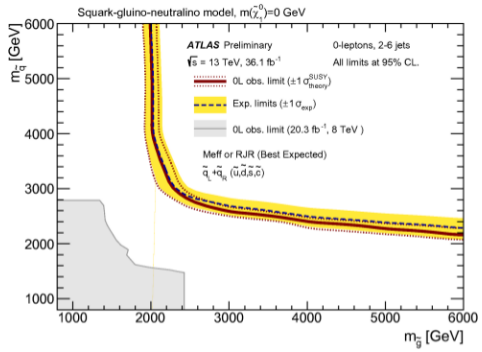


Large fraction of TeV-MSSM models excluded

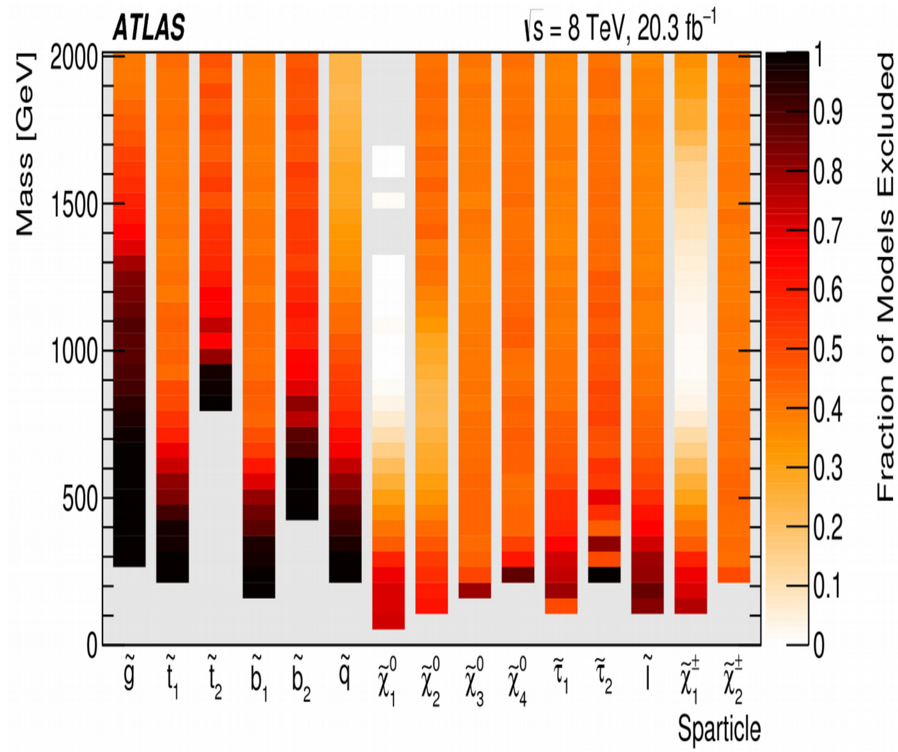
- Gluinos and light squarks produced directly at LHC excluded up to masses ≈ 2 TeV in Run2 (if neutralinos are not too massive)
- A large fraction of “phenomenological” MSSM possible models also excluded below 1 TeV or so since Run1

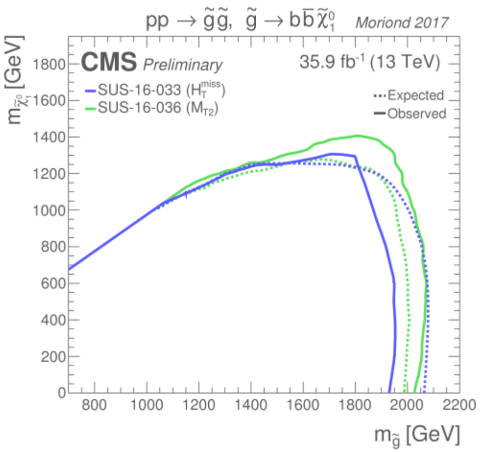


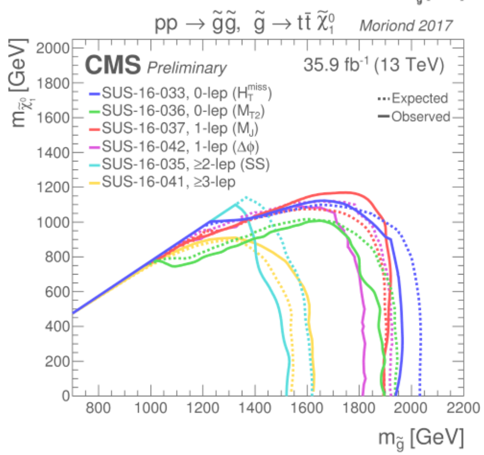
Taken from PDG 2018



arxiv:1508.06608

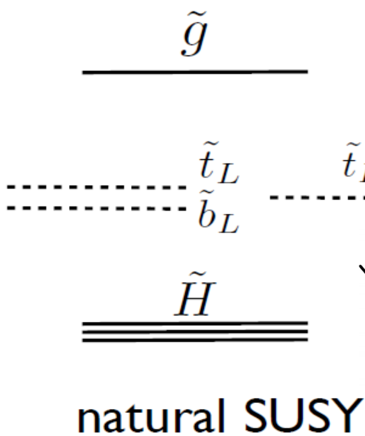


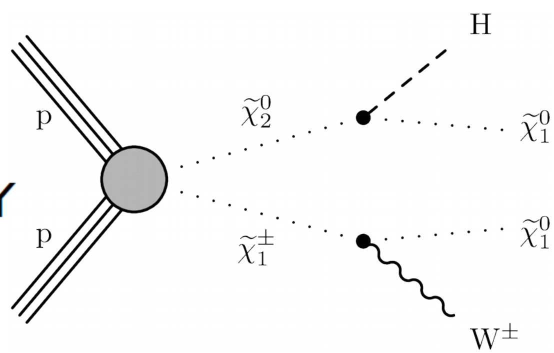


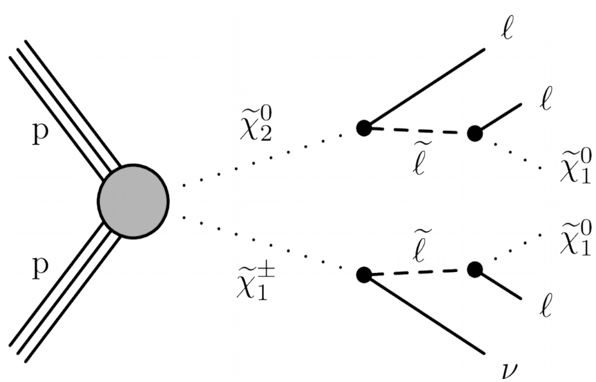


How can SUSY hide from observation at LHC

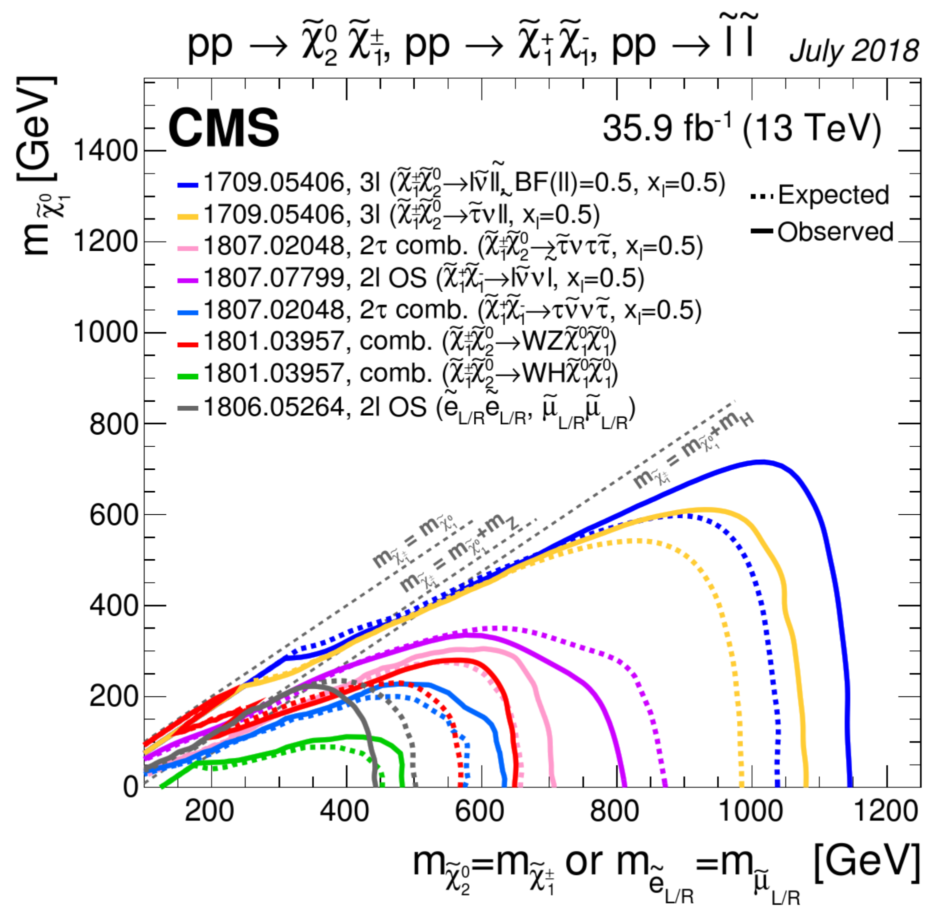
- By being more “complicated”: beyond MSSM, not SUGRA, R-parity violating (⇒ no missing energy), long-lived signatures, **only “electroweak” s-particles at low masses/scales**, ...





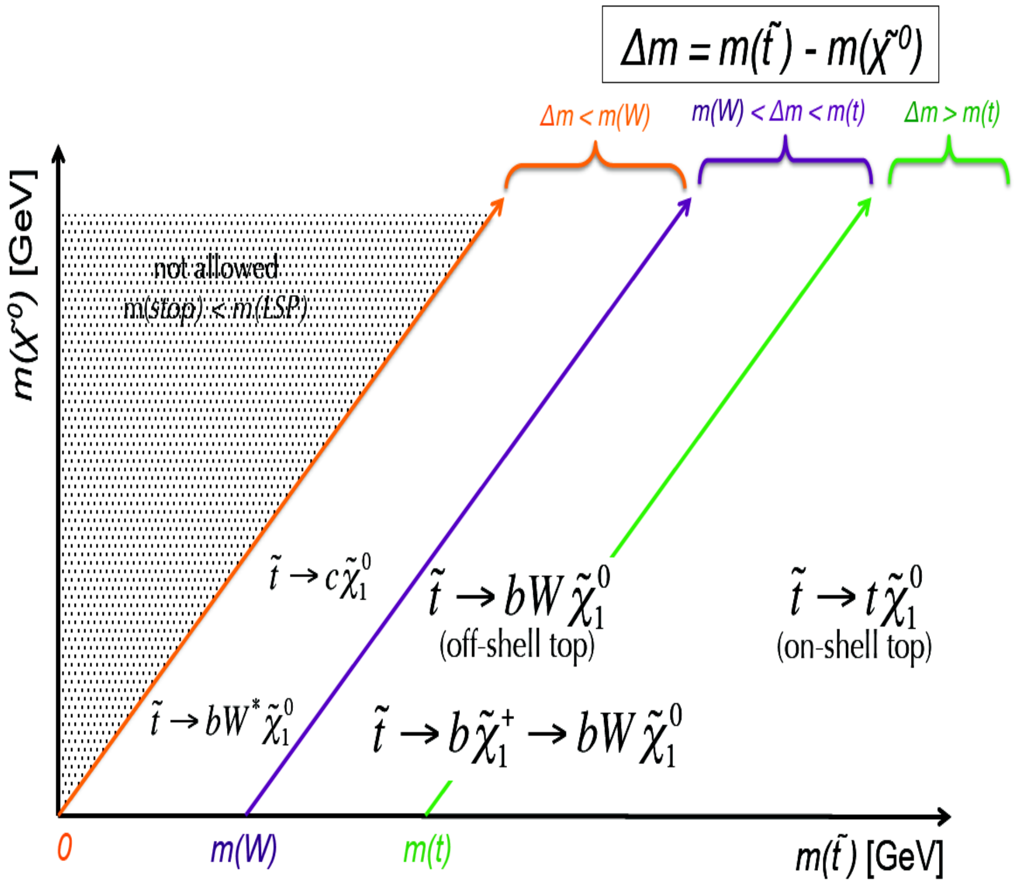


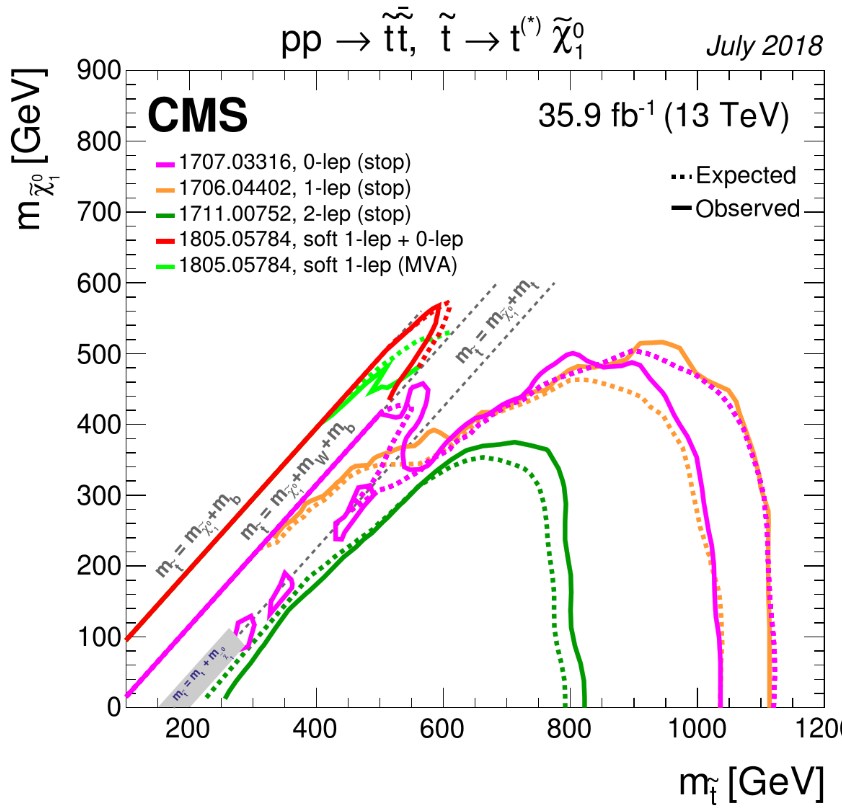
Taken from CMS SUSY public results



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]()

Outlook

- Higgs studies and searches are one of the most exciting fields of research at the LHC:
  - We clearly surpassed many of the initial expectations: observation of many processes with low cross section, sensitivity to the Higgs width, differential studies, ...
  - Bright future for the next HL-LHC phase: almost 1 order of magnitude improvement in the measurement of couplings, Higgs self-coupling, … (next talk)

- New physics searches at high masses/scales:
  - One of the main objectives of the LHC program. Nothing new/exciting found until now. Scope being extended to more exotic signatures and complicated phase space regions
  - More luminosity in the next years should enlarge the scale reach and uncover possible signals at lower masses hiding under the background (next talk)

Backup