Highlights from the ATLAS Experiment

Tsukuba Global Science Week 2017, September 26, 2017

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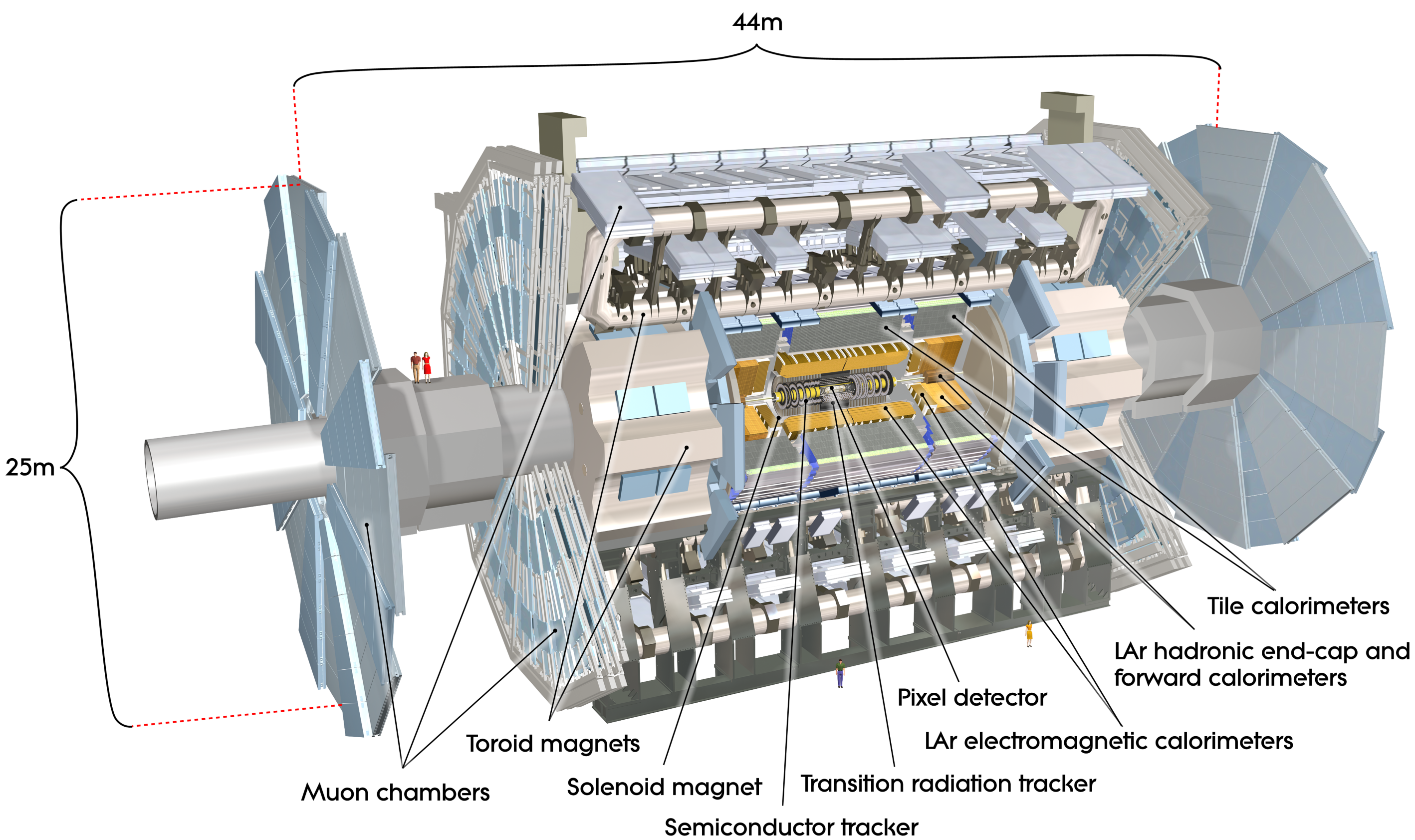
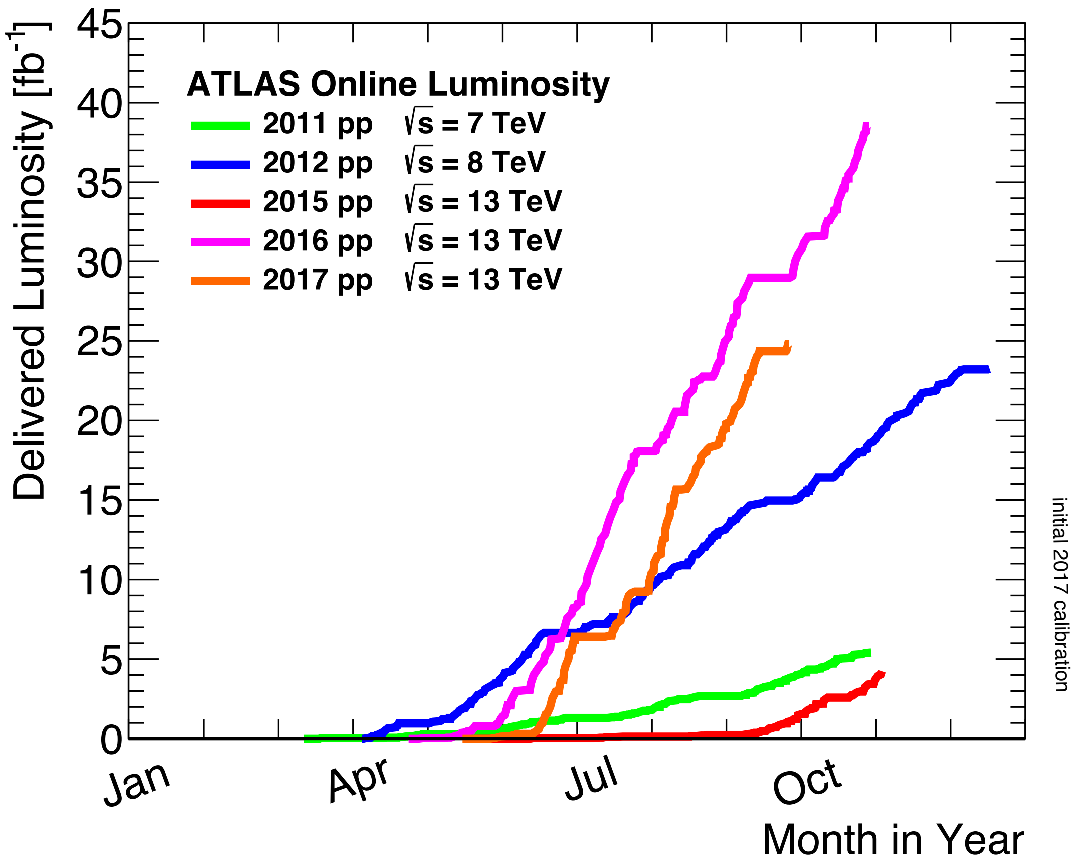
CERN & LHC

- CERN (European Organization for Nuclear Research) is located at Geneva, Switzerland.
- Large Hadron Collider (LHC) is one of its “flagship” projects with the circumference of 27 km, providing **p-p, p-Pb & Pb-Pb collisions** at the energy frontier ($\sqrt{s}$=13 TeV for p-p, $\sqrt{s_{NN}}$=2.76, 5.02 TeV for Pb-Pb, p-Pb) & have 4 major experiments.
- Reached a new record of 1.75 times the design luminosity in 2017.

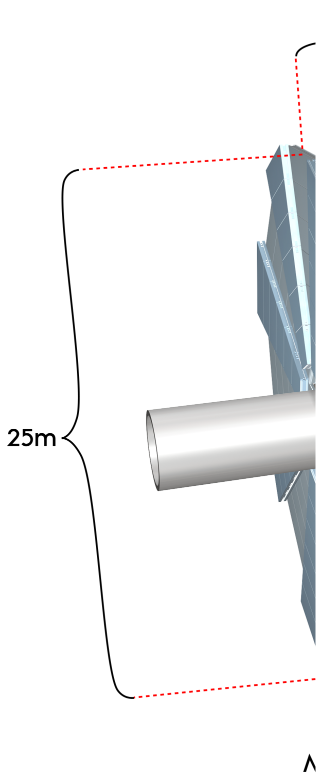
ATLAS Experiment

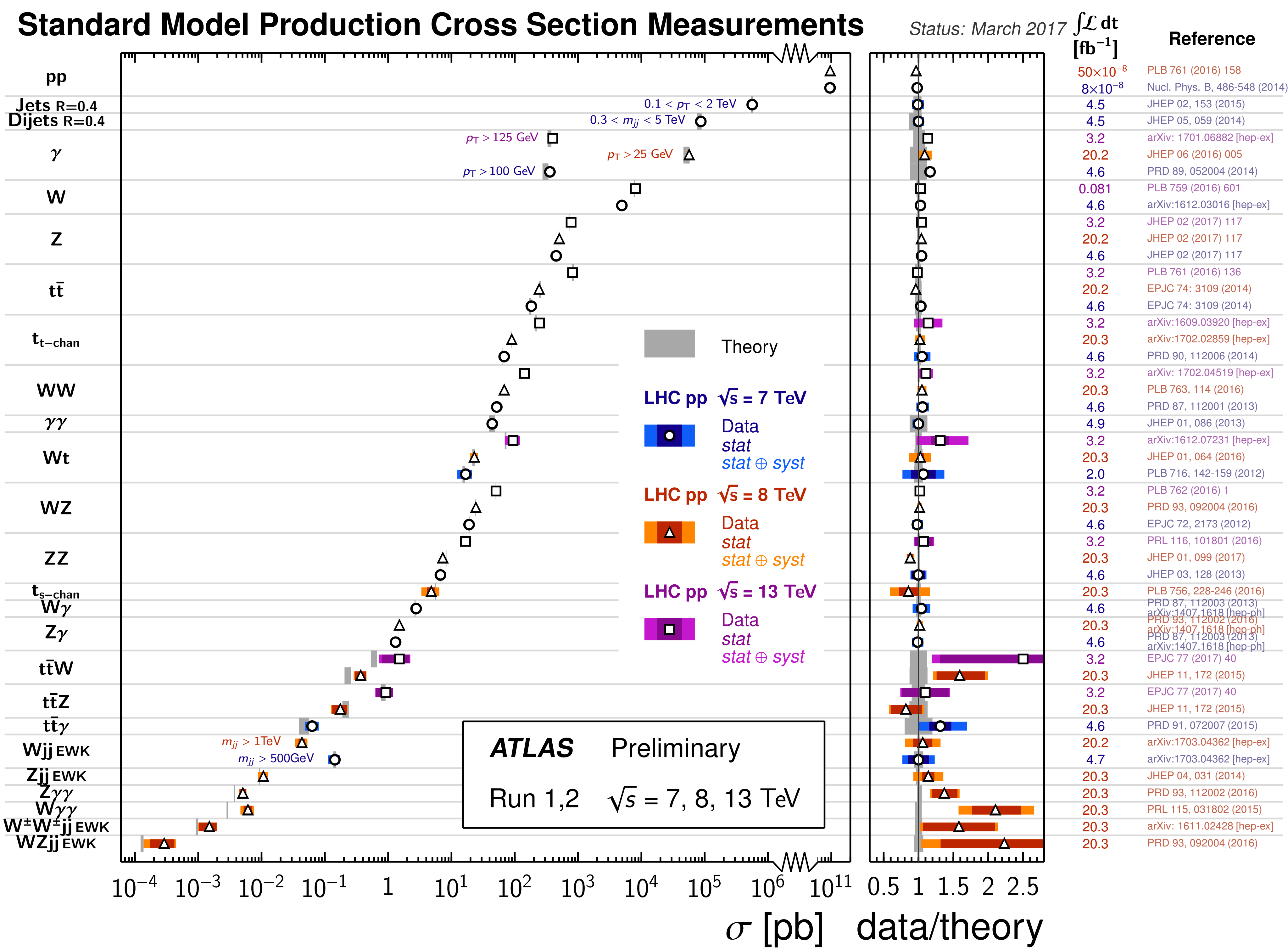


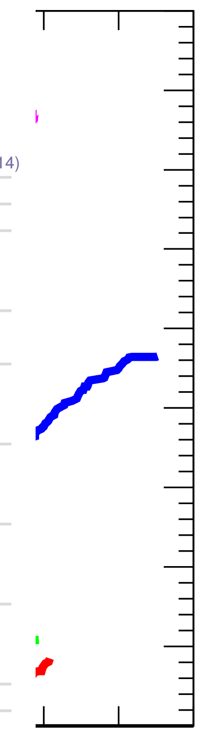


- ATLAS is one of the two generic purpose detectors at the LHC, being able to measure variety of phenomena (QCD, electroweak, b-physics, top-quark, new physics searches, heavy ion) with a wide dynamic range (MeV→TeV).
- ATLAS has already recorded ~23 fb^{-1} of data this year. Likely to collect another ~25 fb^{-1} by the end of this year, but it will depend on the LHC status.

ATLAS Experiment







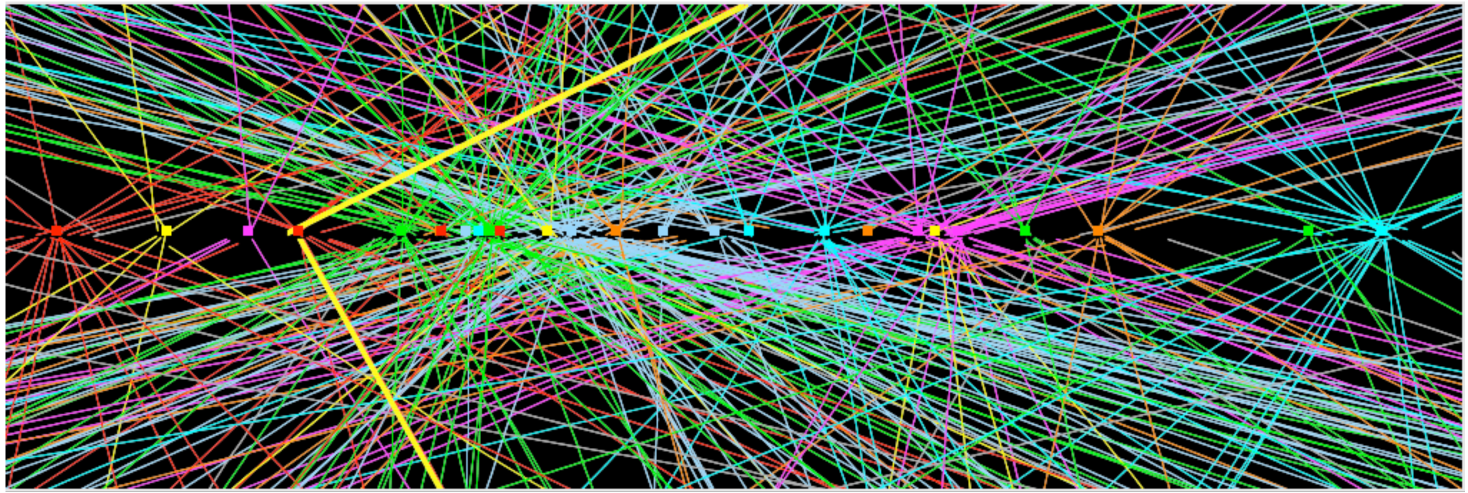
- ATL… mea… phys…
- ATL… fb-1 b…

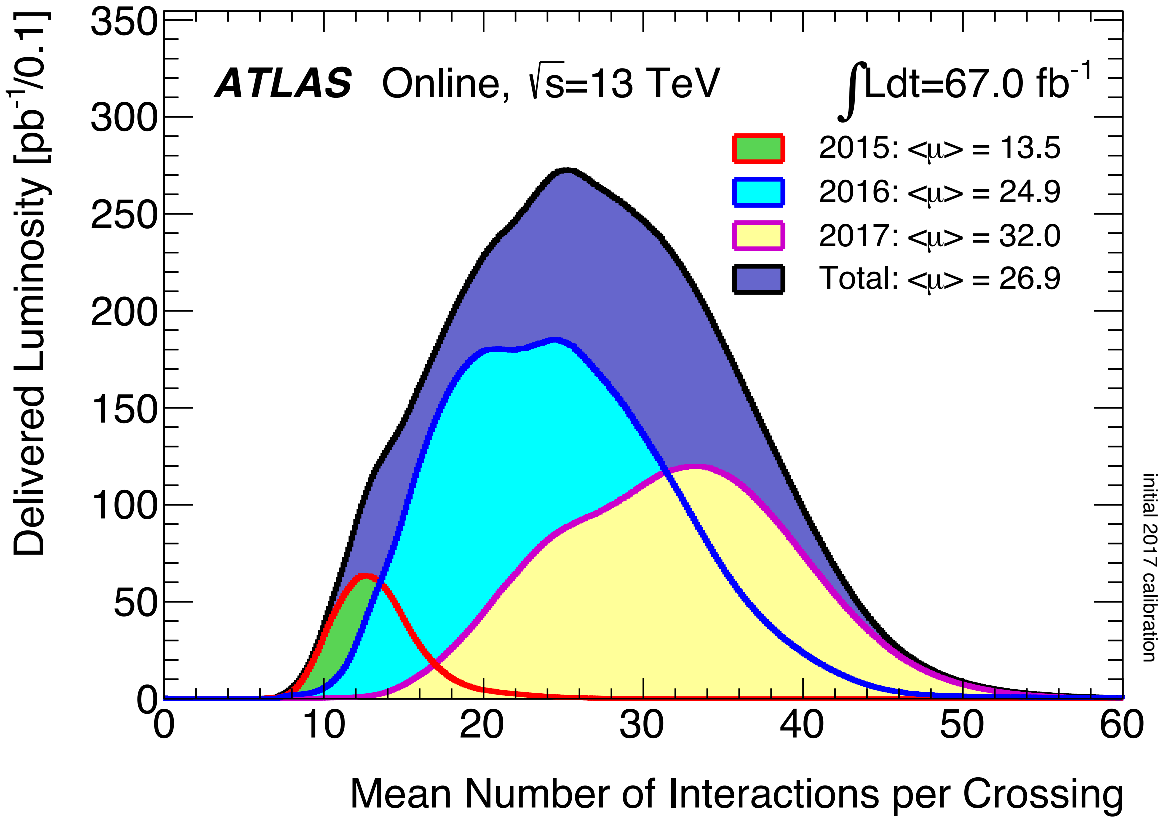
…n in Year

r ~25

ATLAS Experiment

Pileup
(multiple proton-proton interactions)





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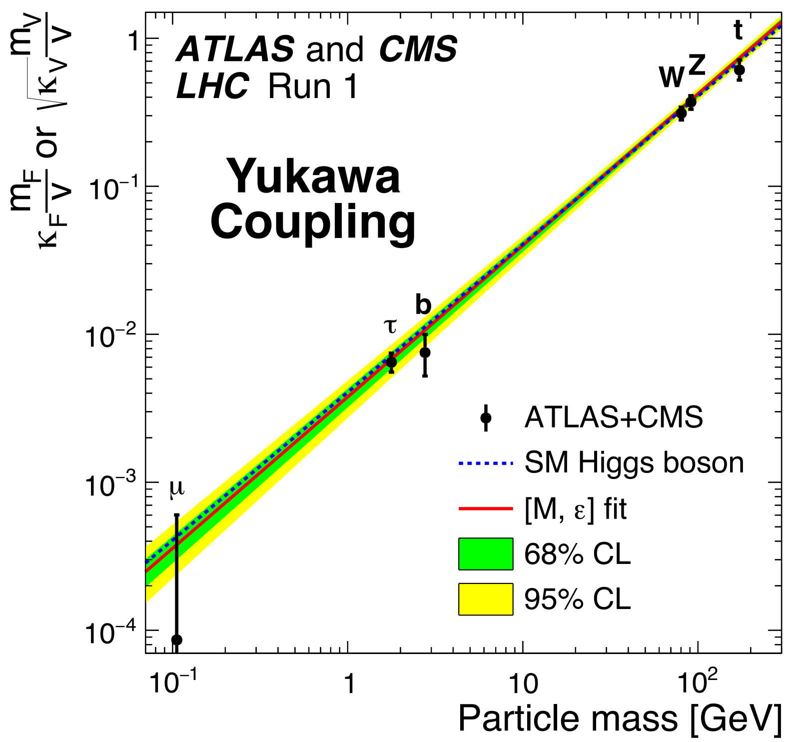
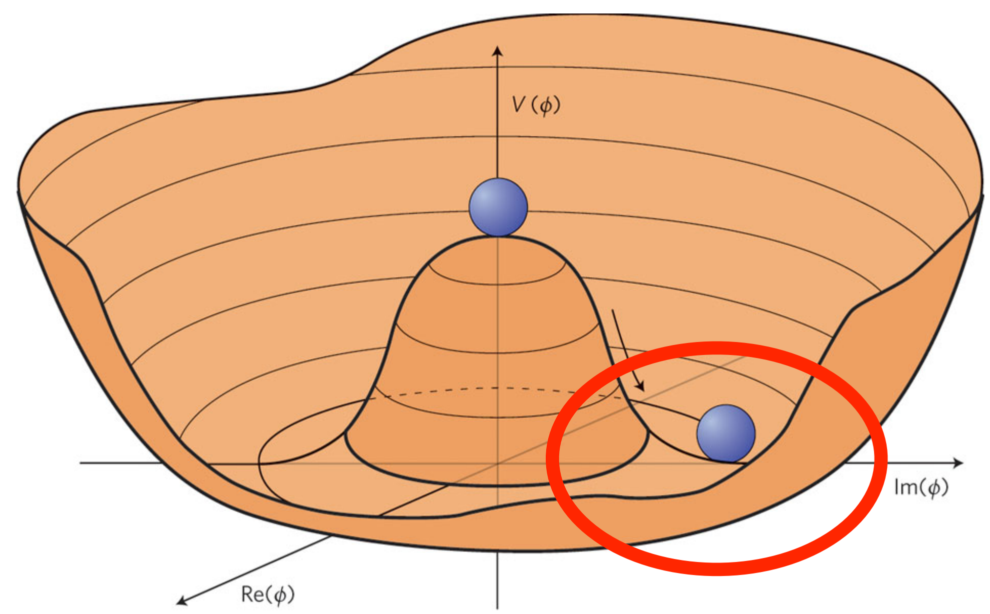
- ATLAS has already recorded ~23 fb^{-1} of data this year. Likely to collect another ~25 fb^{-1} by the end of this year, but it will depend on the LHC status.
- Due to the increase in luminosity, the pileup is continuously going up from 2015-2017 (one of the major challenges at the LHC).

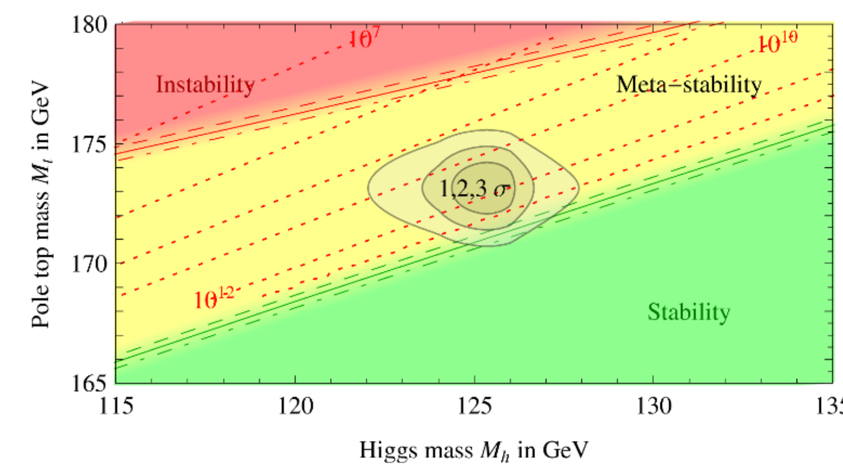
Beyond Higgs Discovery





What we have observed

Stability of the vacuum & top/Higgs masses

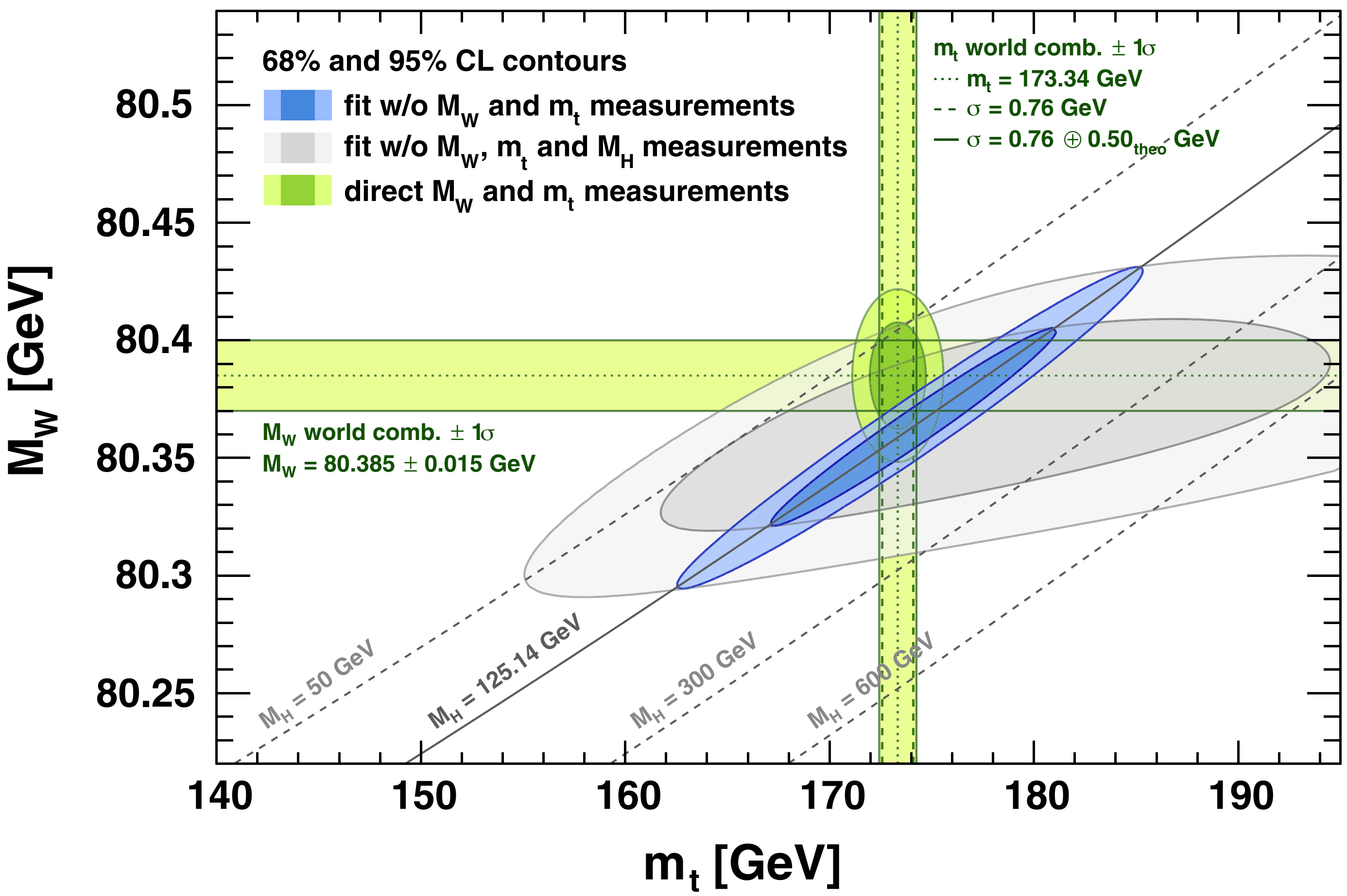


- **In 2012, ATLAS & CMS experiments have discovered a Higgs boson.**
    - Consistent with the Standard Model so far.
    - However, we have only observed a small fraction of the overall Higgs potential.
- **Is the discovered Higgs boson really consistent with the Standard Model? (Any anomalous coupling or decay? Heavy Higgs bosons? Is it elementary of composite?)**
- **Is there anything between the electroweak (EW) & Planck scales?**

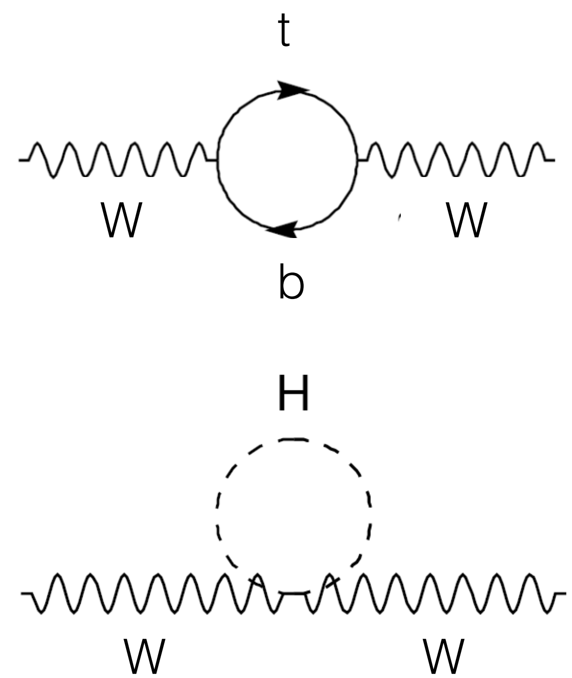
Measurements in the Electroweak & Higgs Sectors

Masses in EW Sector

The GFitter Group, EPJC (2014) 74:3046



A.Hoecker, arXiv:1611.07864



$\sim m^2_{top}$

$\sim \ln(m^2_H)$

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r),$$

- W boson mass depends on the 3 SM parameters (α,G_μ,m_Z) as well as the higher order corrections, mainly from the top quark & Higgs masses (Δr)。

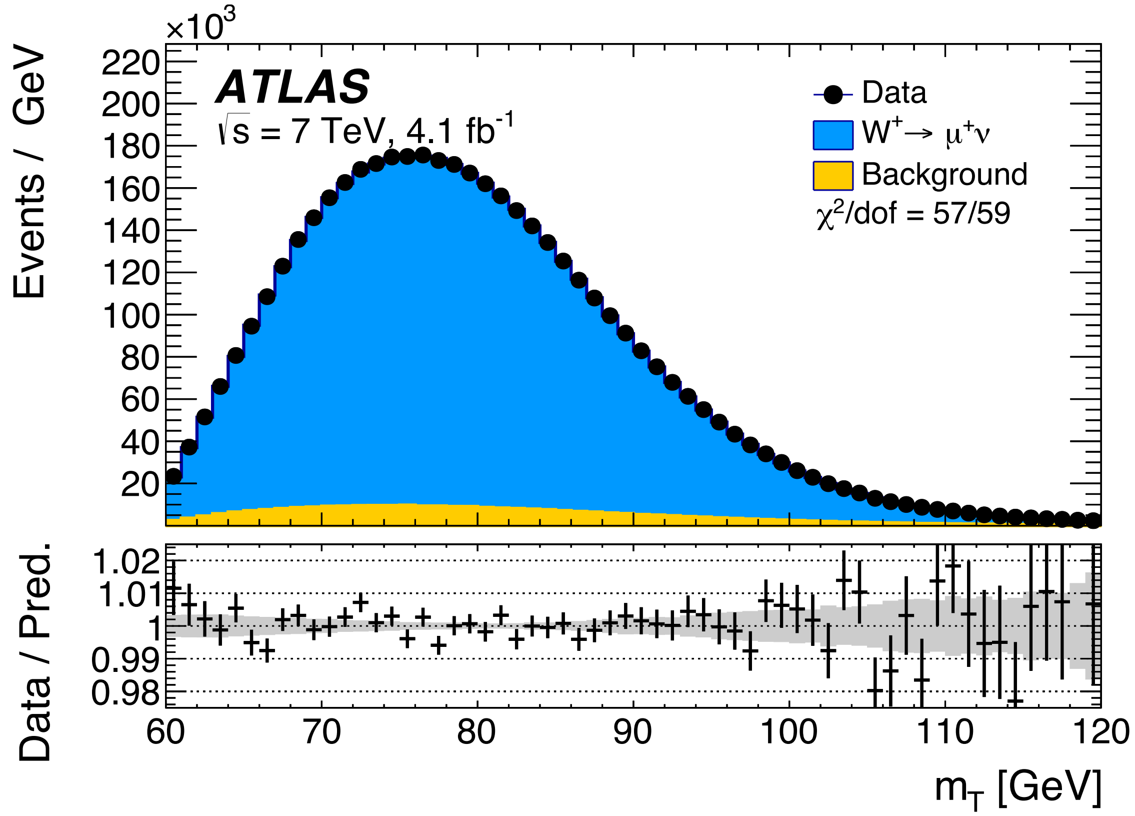
α: fine structure constant,
G_μ: Fermi constant,
m_Z: Z boson mass,
Δr: higher order corrections

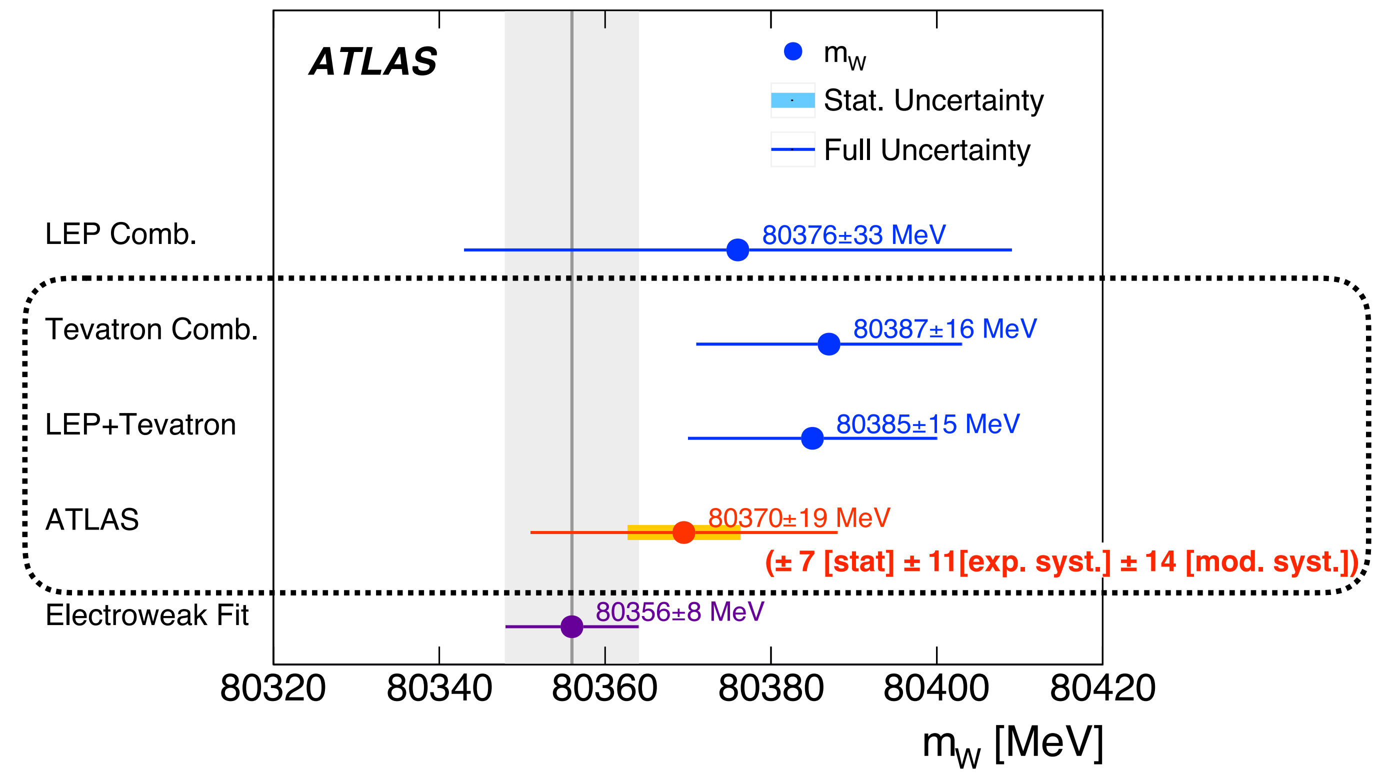
- *Δr* could contain contributions from new heavy particles.

- Currently, uncertainties on the W mass are dominantly limiting the SM validity checks.

W Mass Measurement

First LHC measurement of the W mass!

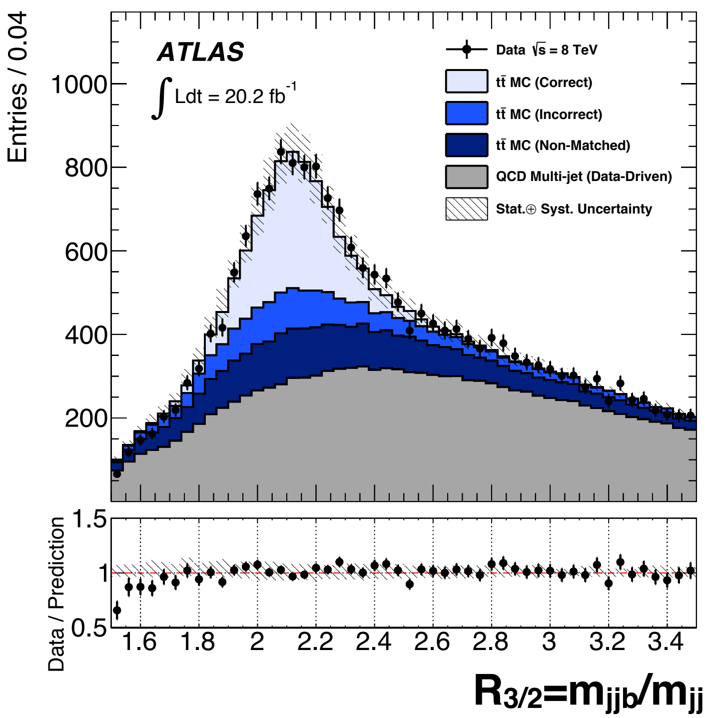




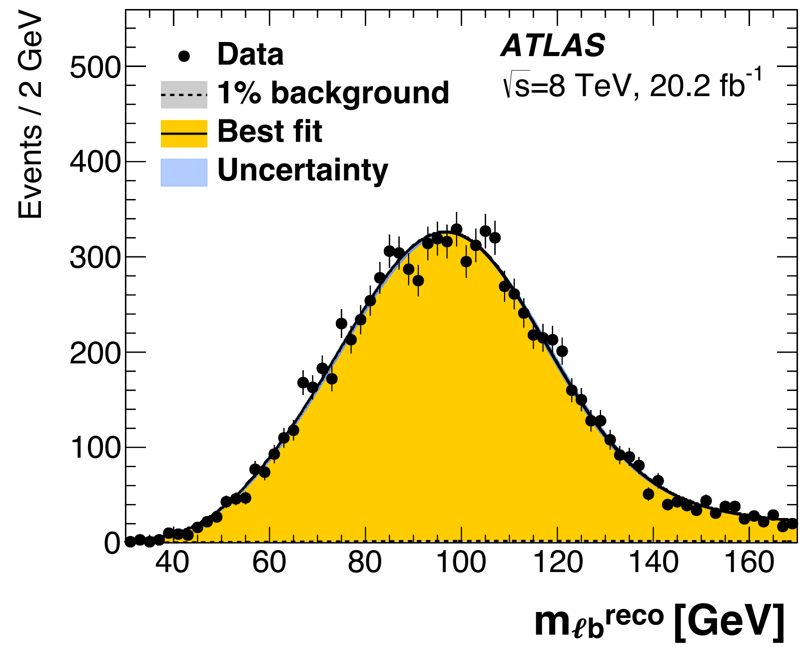
- Simultaneous fit on the lepton p_T & transverse mass m_T templates. **Reaching the Tevatron sensitivity.**
- **Dominant sources of systematic uncertainties are from the lepton reconstruction, W recoil, parton distribution function (PDF) & parton shower.**
- **There is space for improvement in both the experimental & theoretical uncertainties.**
- Adding the √s=8 & 13 TeV data would help, but the pileup is challenging.

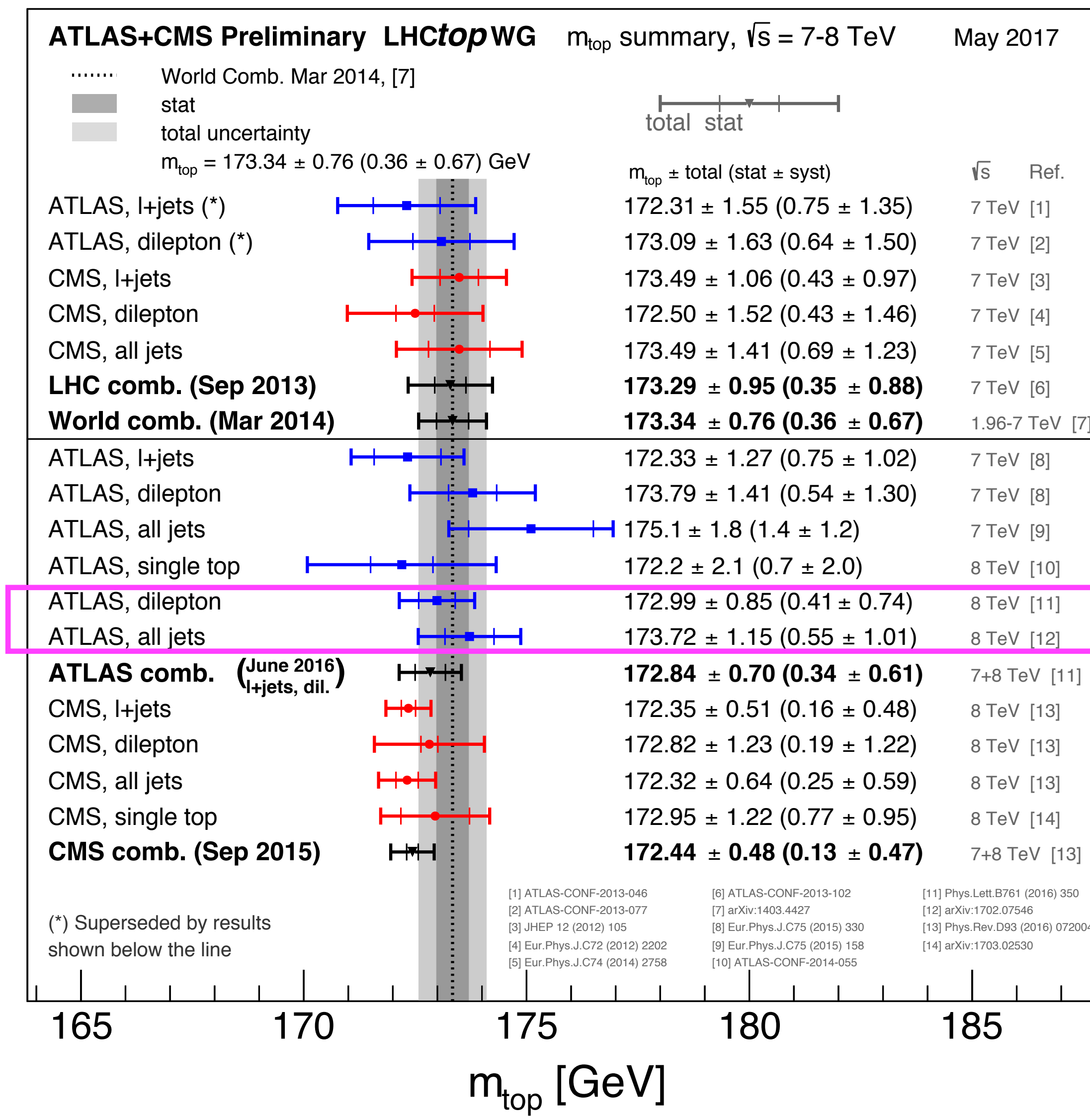
Top Mass Measurement

Hadronic decay ("all jets") channel



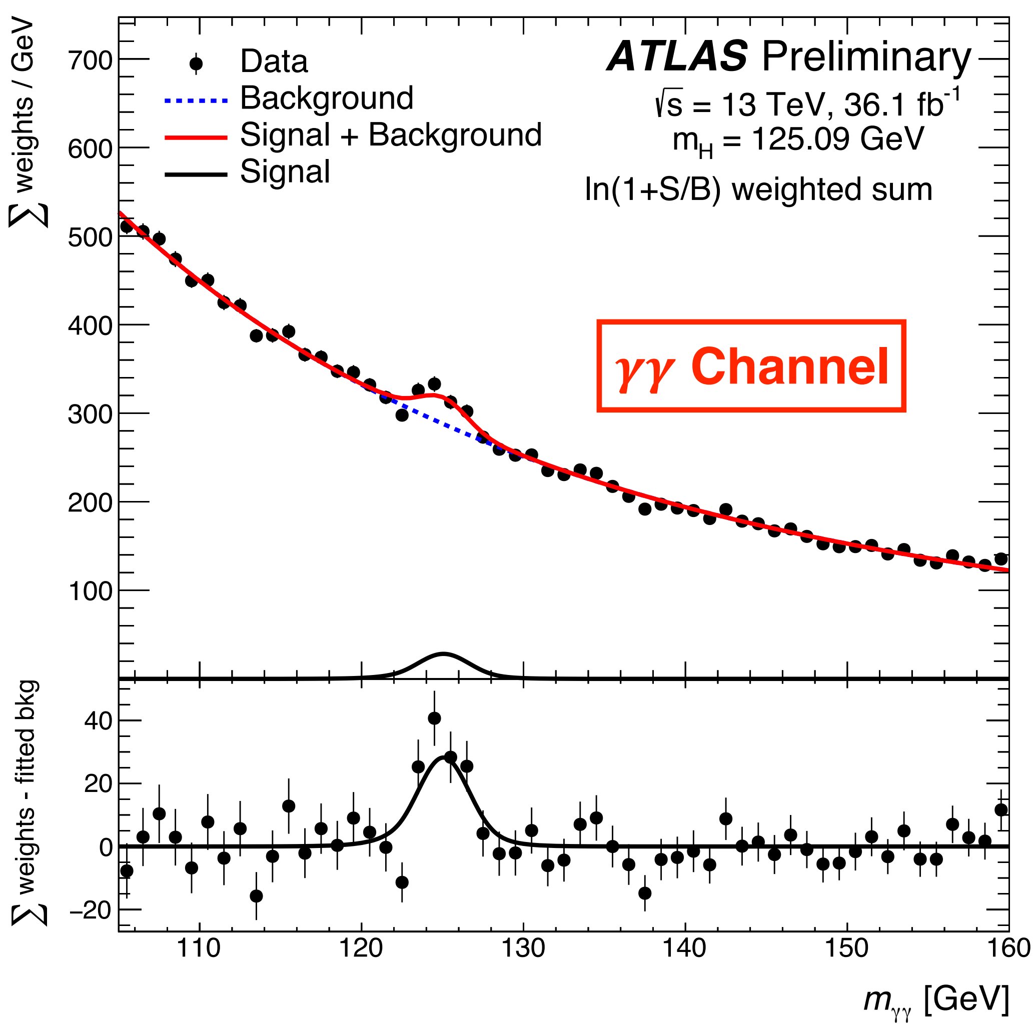
Dilepton channel

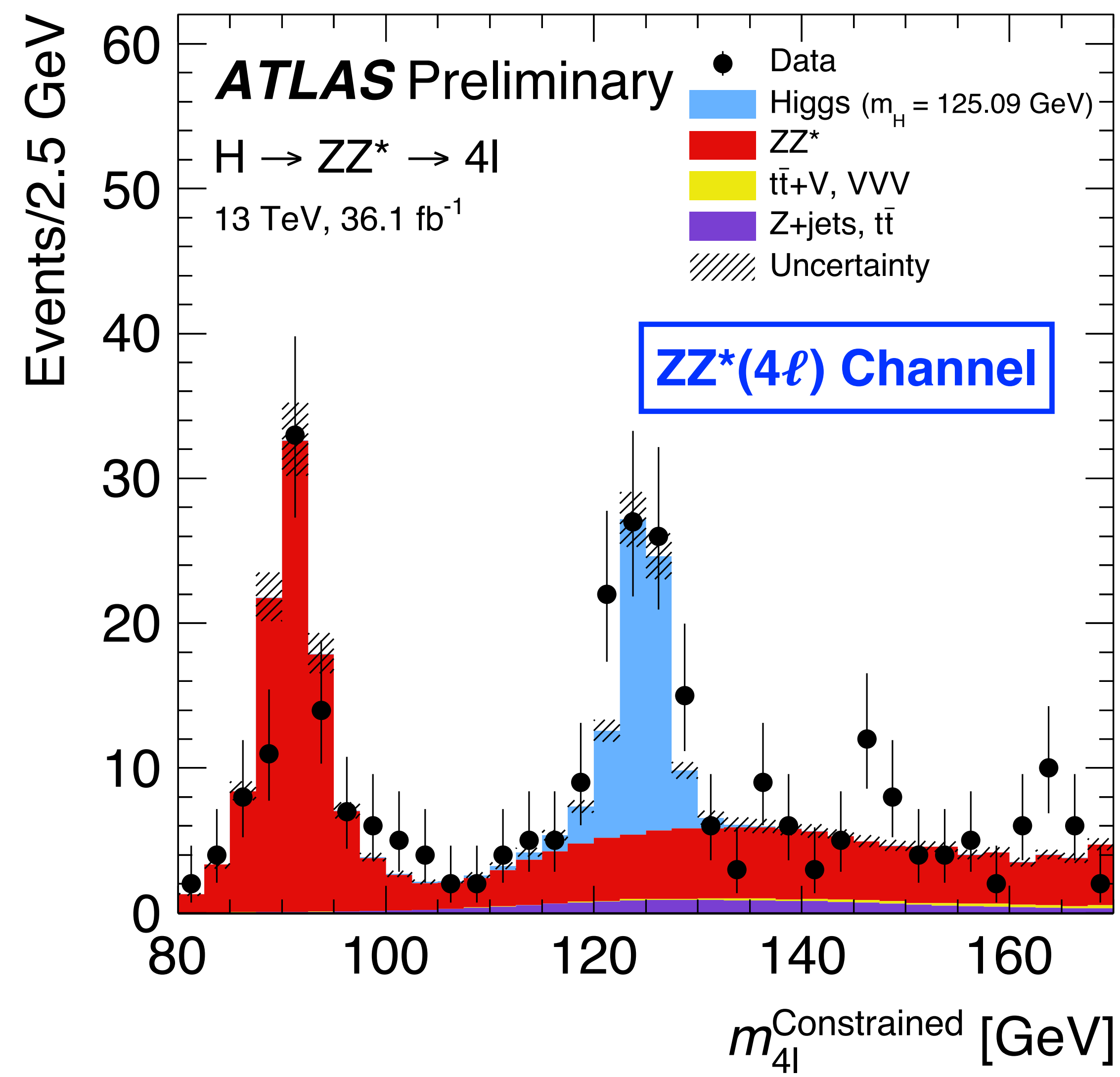




- Results from ATLAS & CMS are consistent, but systematically lower than the Tevatron(?)
  - **ATLAS: 172.84 ± 0.70 GeV**
  - **CMS: 172.44 ± 0.48 GeV**
  - **Tevatron: 174.34 ± 0.64 GeV**
- The precision will reach 0.3-0.4 GeV at the future LHC. Sufficient for the Standard Model test. Higher precision would not hurt for the vacuum stability checks.

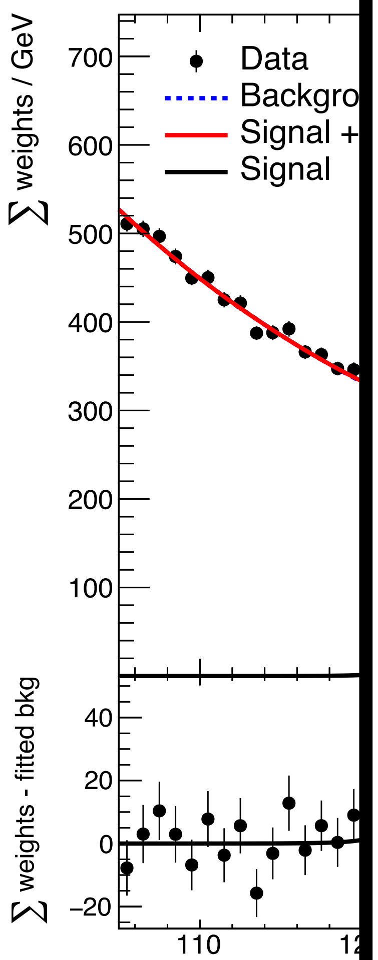
Beyond Higgs Discovery

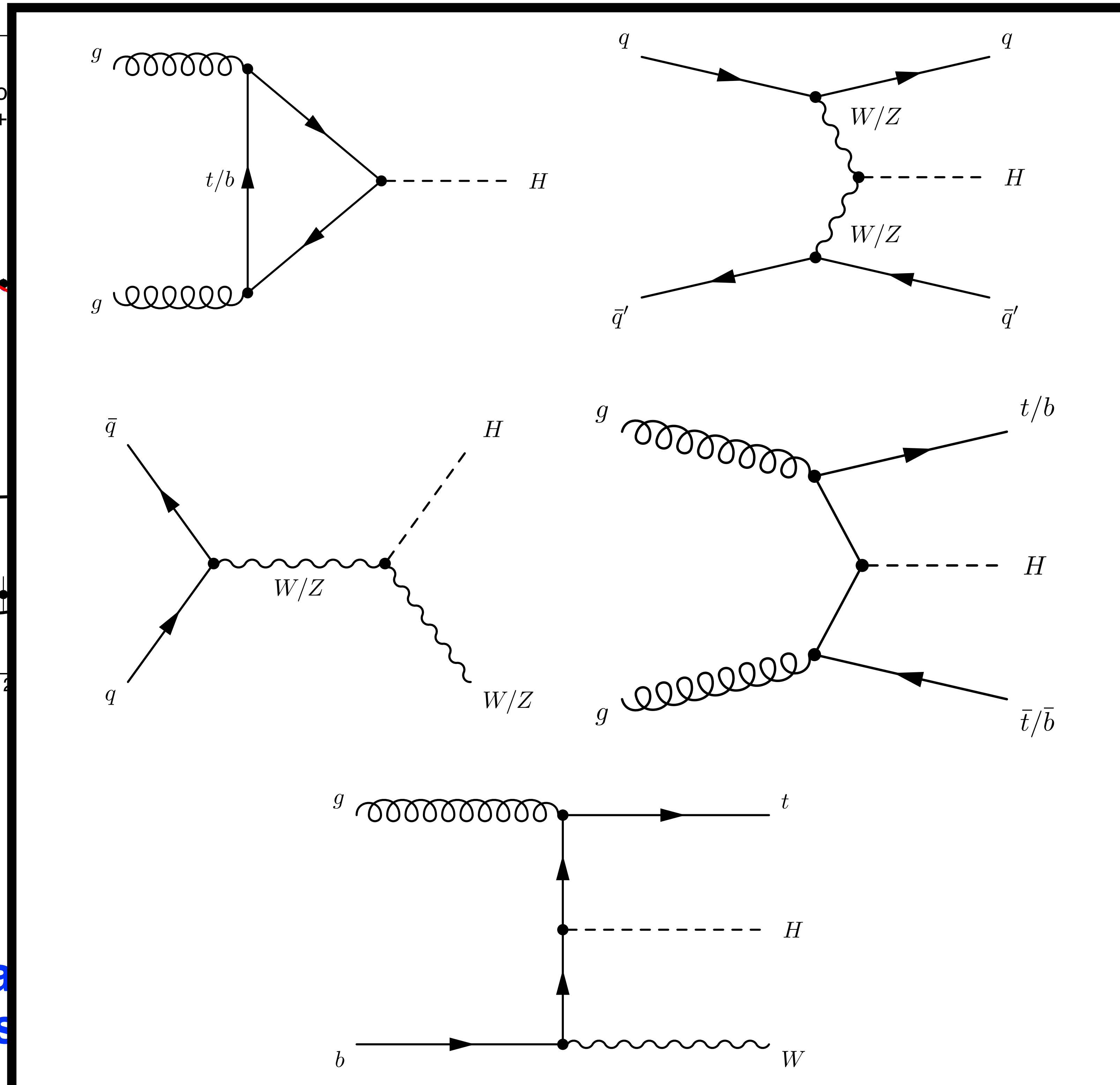


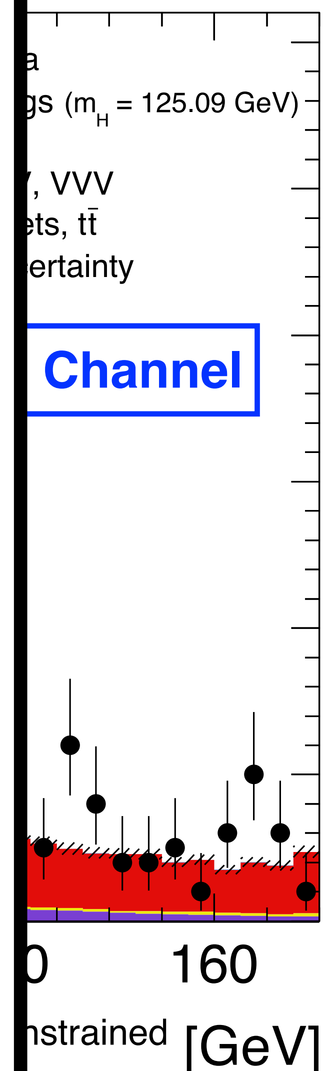


- Higgs boson was discovered by the "Golden" channels: $\gamma\gamma$, ZZ*(→4ℓ) at LHC Run-1. **LHC Run-2 is the dawn of the Higgs precision measurements.**
- **The two channels were combined to measure the cross section & mass, as well as the signal strengths of various production modes.**

Beyond Higgs Discovery

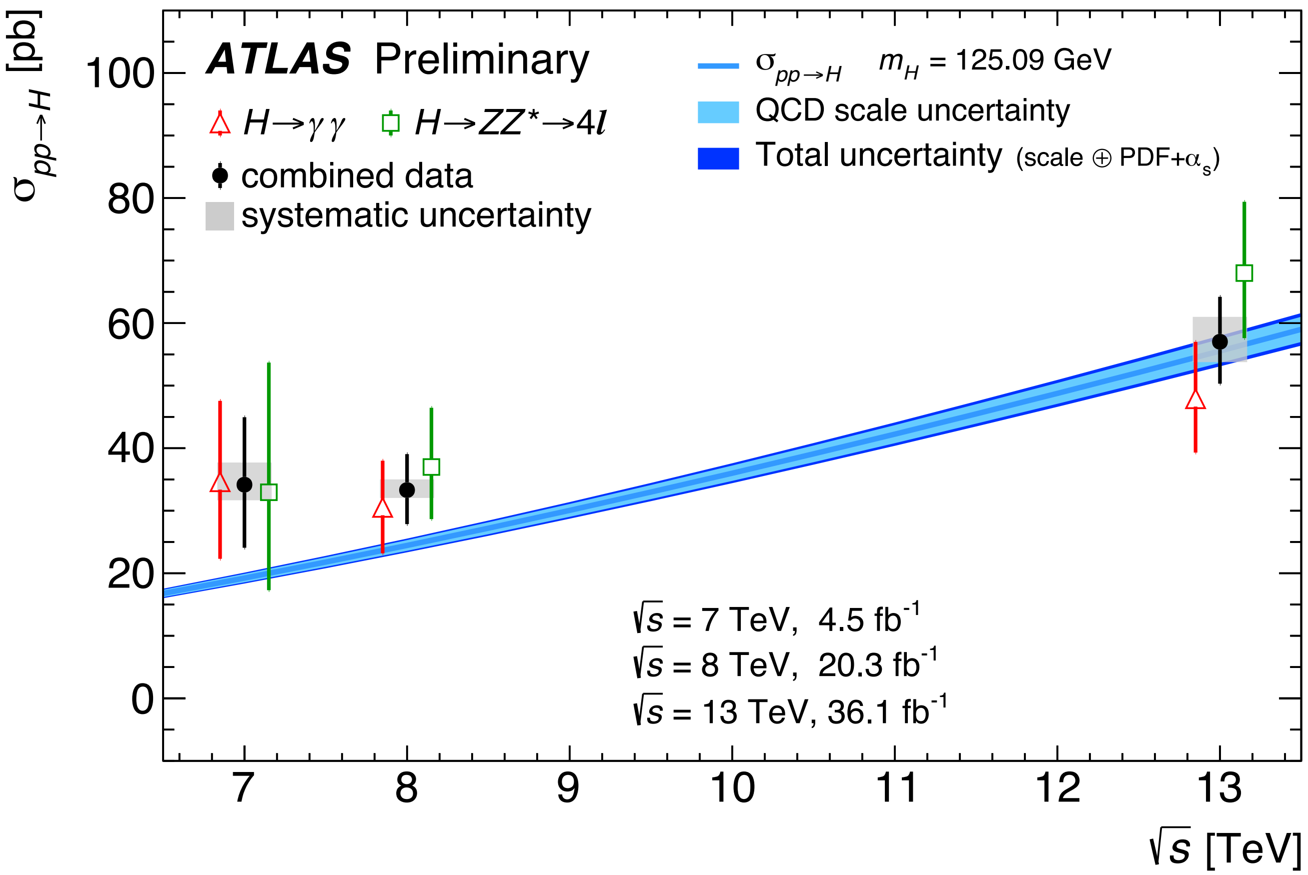


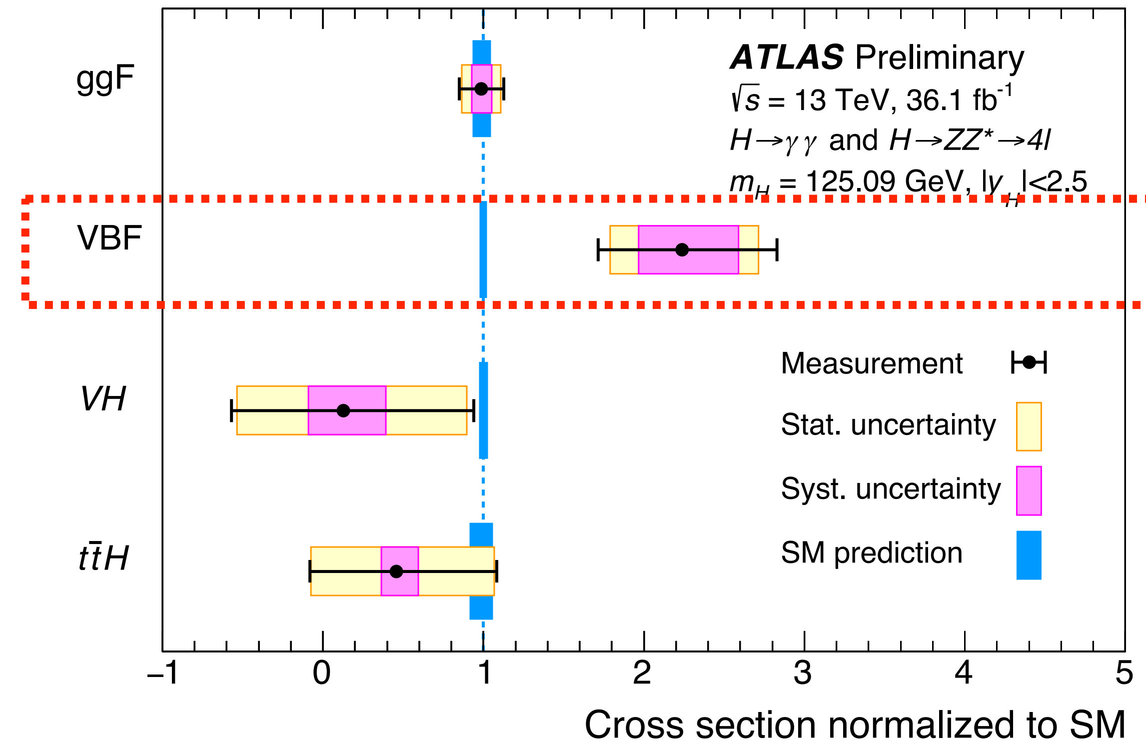


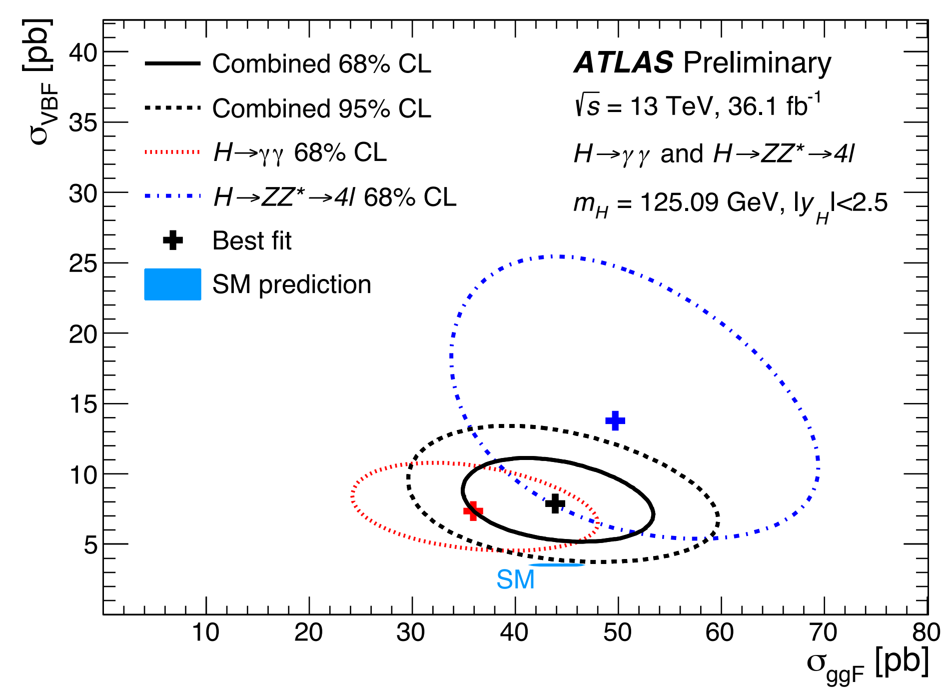


- Higgs boson ... →4ℓ) at LHC Run-1. **LHC ... ements.**
- **The two cha ... on & mass, as well as the s ...**

Higgs Cross Sections

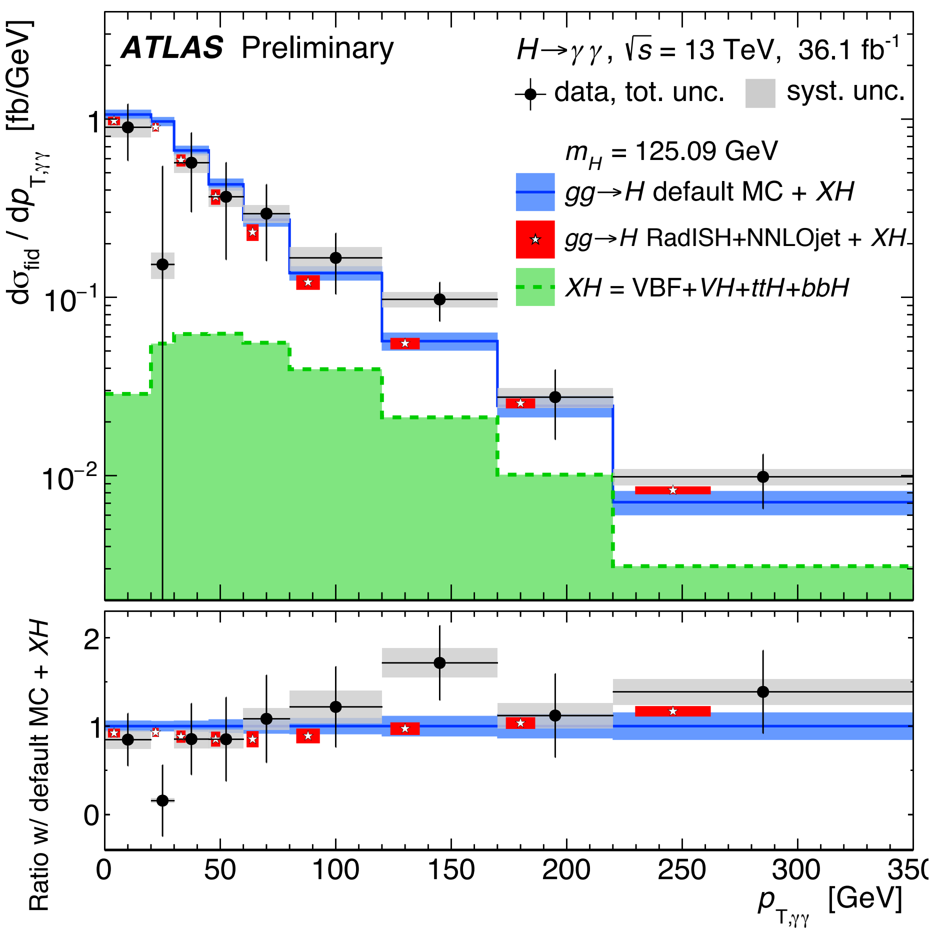


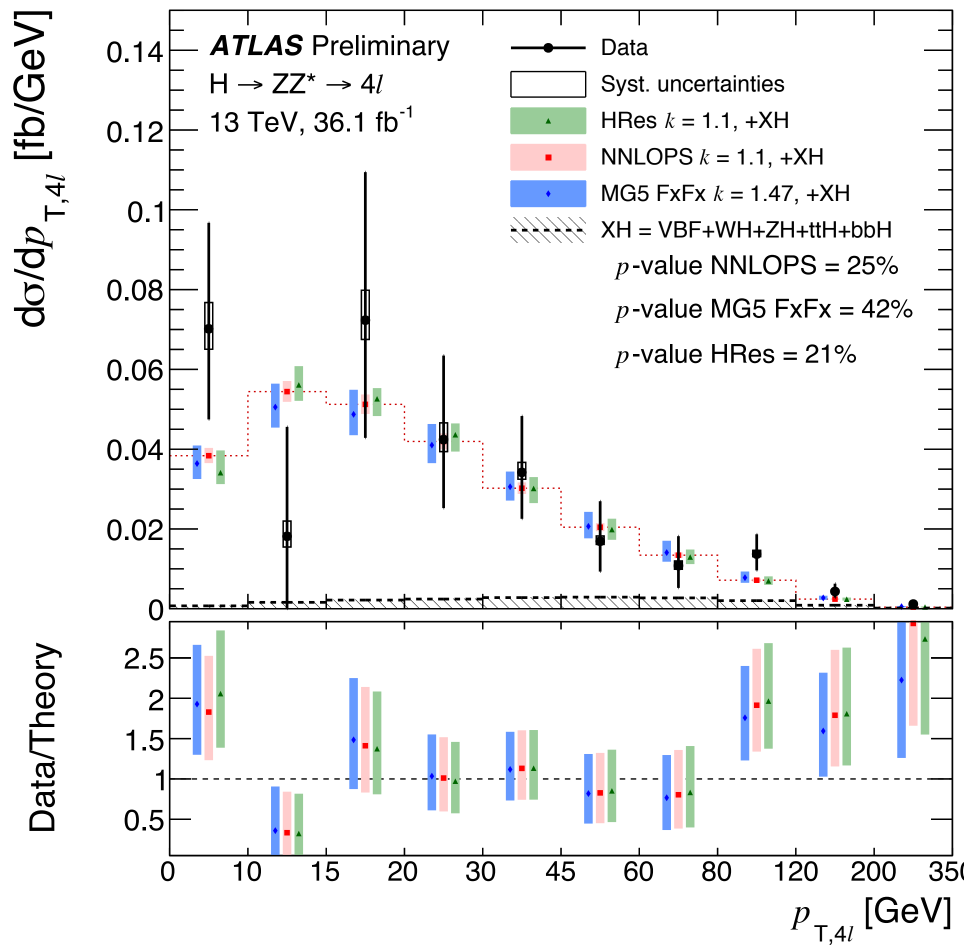




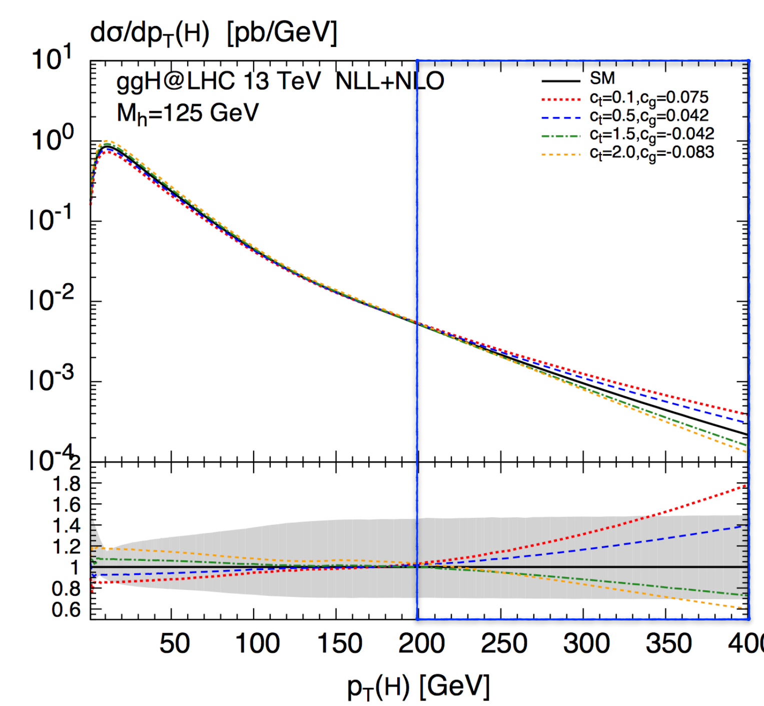
- **Higgs production cross section matches very well (within 2.5%) with the N³LO prediction.**
- There is ~2σ excess in the VBF mode, but CMS observes the opposite.

Higgs Diff. Cross Sections





Impact of new physics on Higgs p_T

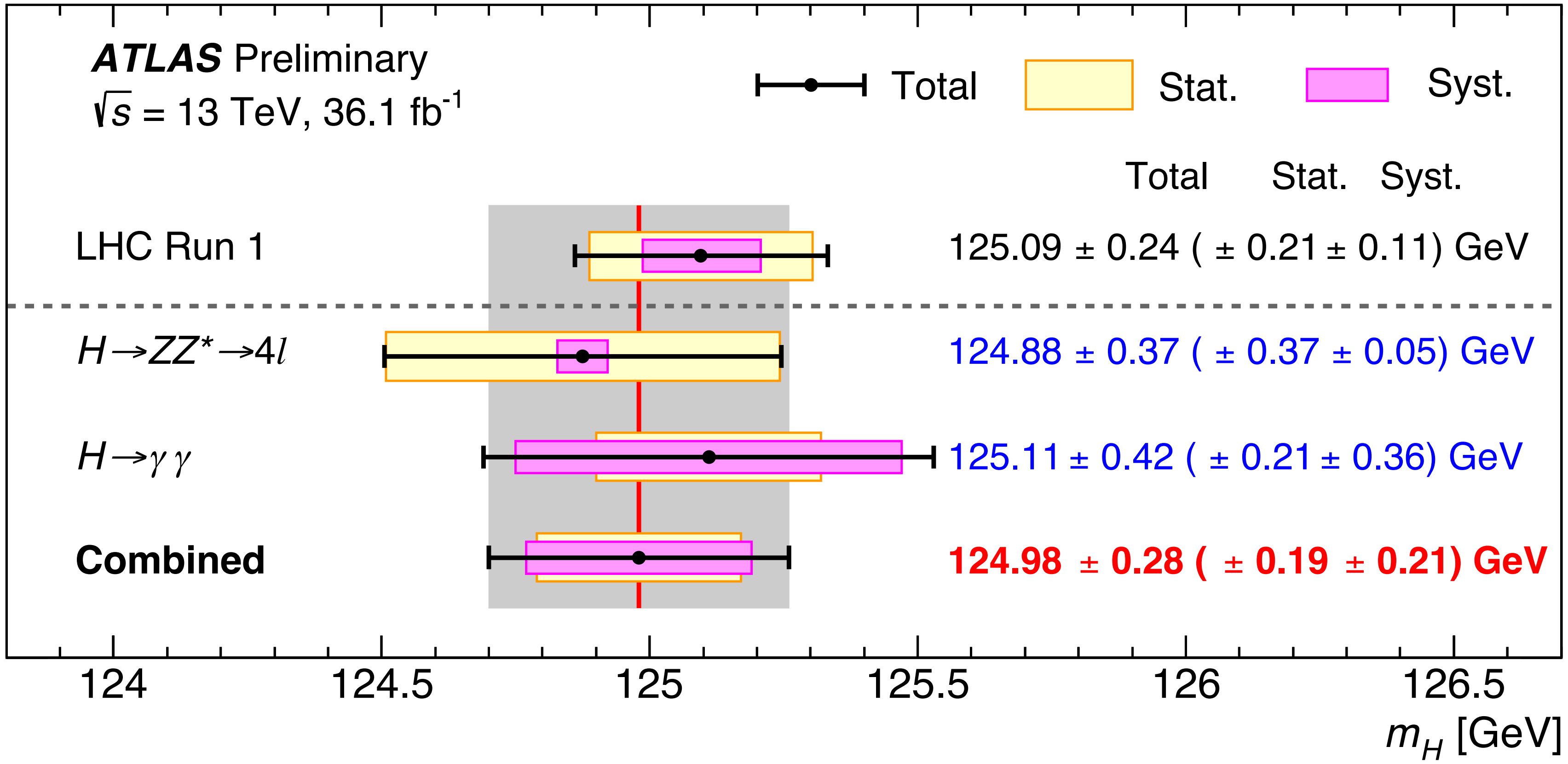


JHEP(2017) 2017:115

- Kinematic distributions (Higgs p_T, y, number of jets & jet p_T) are important probes **to check the validity of the perturbative QCD** and **to understand/ improve the Monte Carlo generators**.

- **Higgs p_T is also sensitive to physics beyond the Standard Model** & is important to measure it precisely.

Higgs Mass



CMS Run-2 Measurement

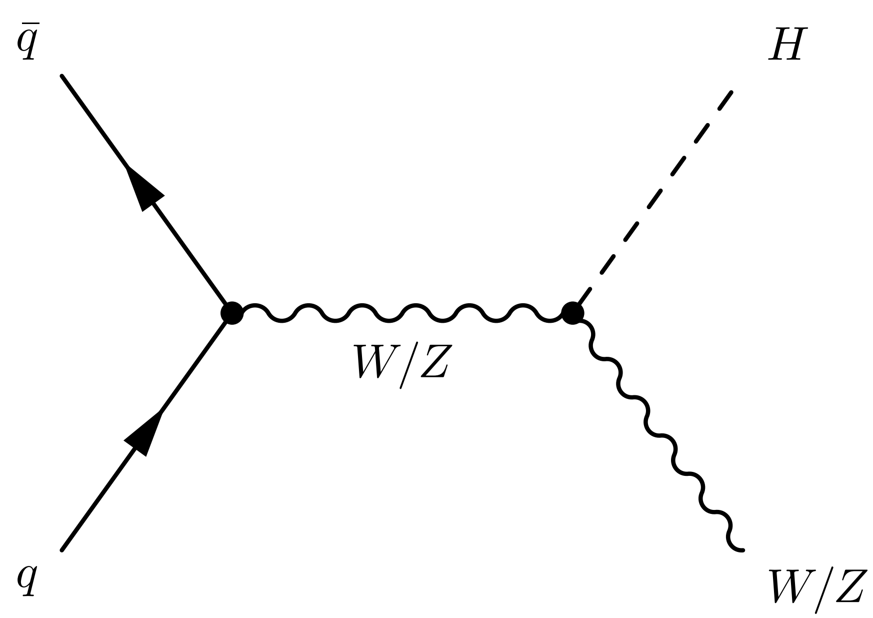
$ZZ^* \to 4\ell$: 125.26 ± 0.20 [Stat.] ± 0.08 [Syst.]

$\gamma\gamma$: 125.4 ± ~0.15 [Stat.] ± ~0.2-0.3 [Syst.]
(very preliminary)

- **Similar precision (~0.2%) with the ATLAS-only Run-2 data as the Run-1 (ATLAS+CMS) measurement.**
- $\gamma\gamma$ & $ZZ^*(\to 4\ell)$ channels are compatible in precision.
- **$ZZ^*(\to 4\ell)$ channel is dominated by the statistical uncertainties.**
- **$\gamma\gamma$ channel needs to cope with the systematic uncertainties** (electromagnetic calorimeter response & materials from the inner detectors) to further reduce the uncertainties.

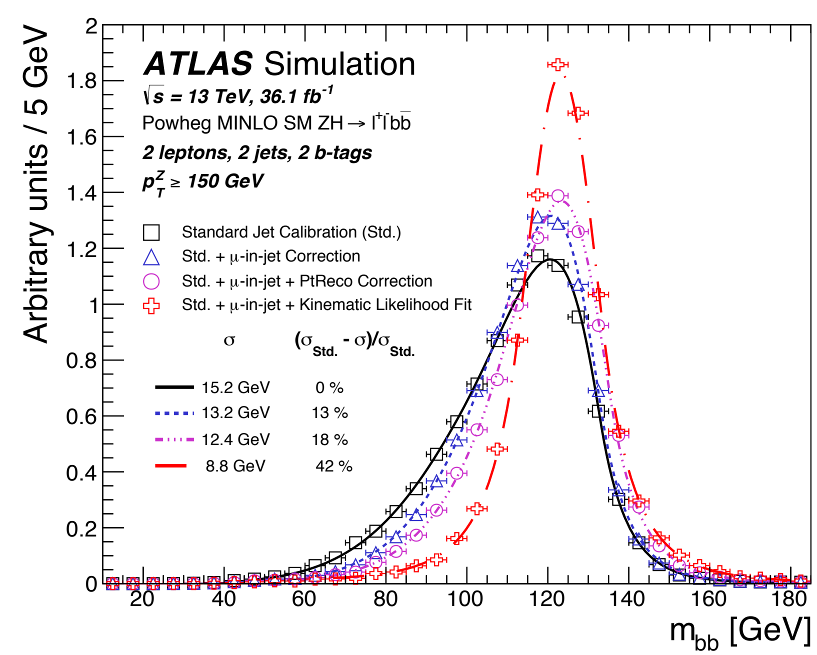
H($b\bar{b}$) Observation

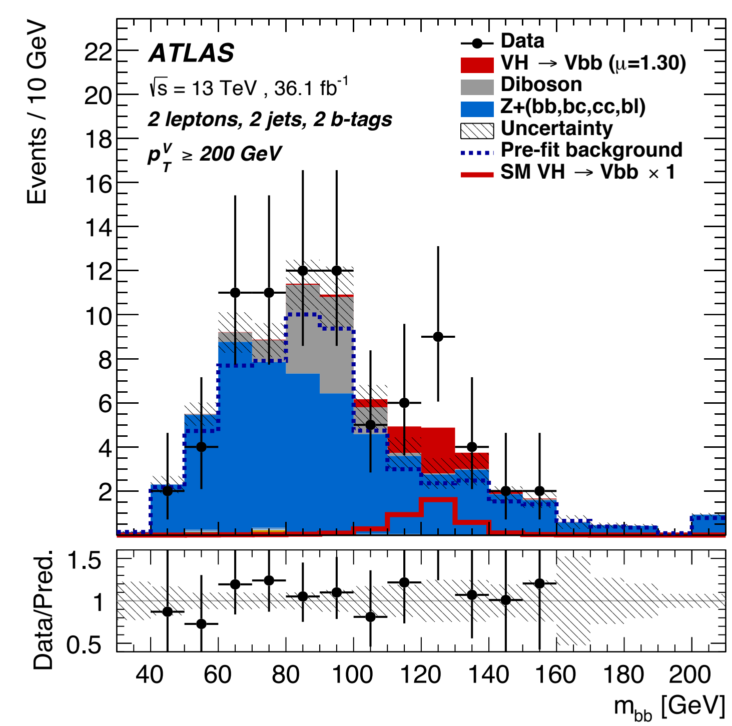
- **H($\rightarrow b\bar{b}$) has the largest branching fraction (58%), but was difficult to observe due to the large BG.**
- **WH, ZH production mode has the highest sensitivity.**
- Considered m_{bb} & various kinematic distributions as inputs to multivariate analyses (boosted decision tree; BDT).



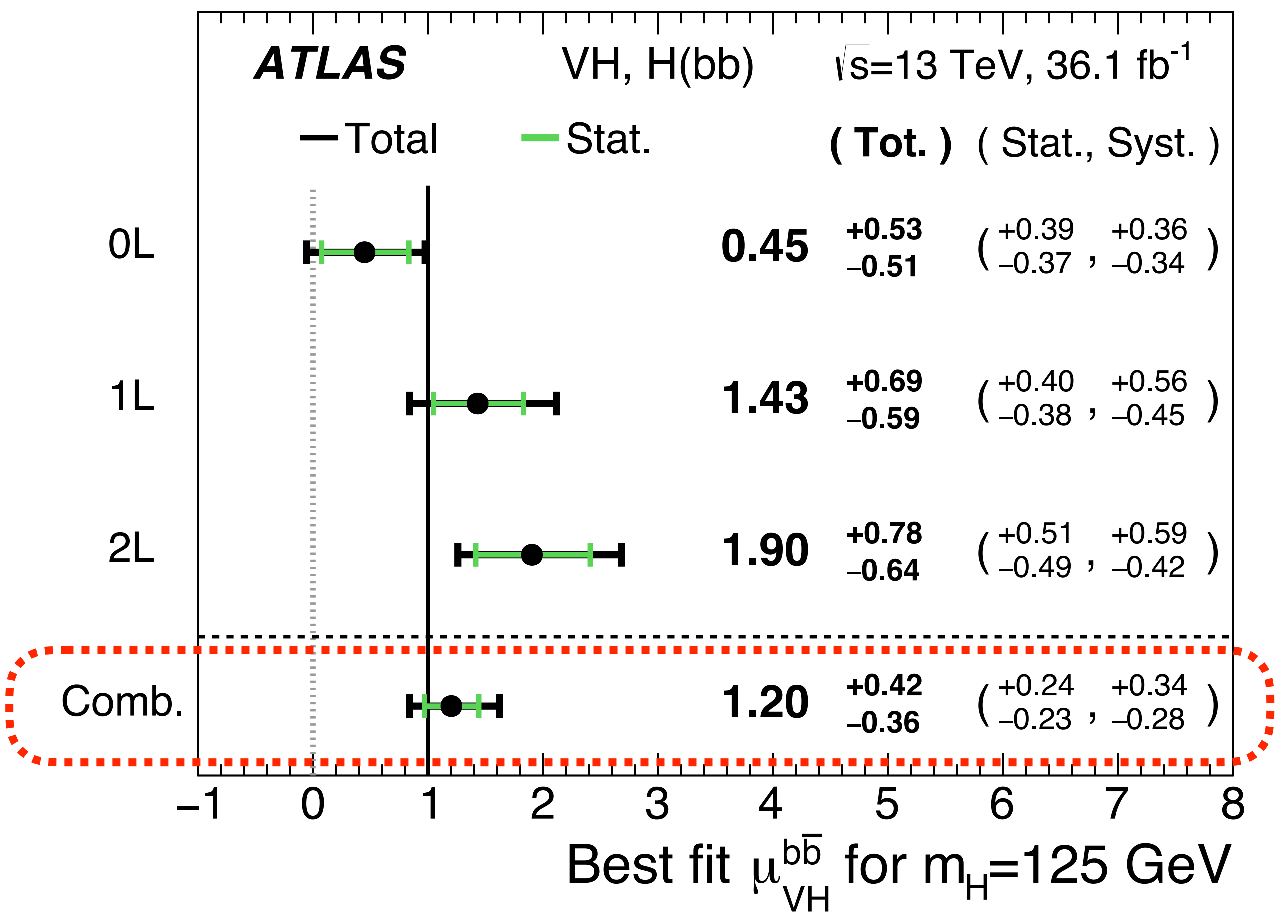
- 0 lepton: $Z(\rightarrow \nu\nu)H(\rightarrow b\bar{b})$
- 1 lepton: $W(\rightarrow \ell\nu)H(\rightarrow b\bar{b})$
- 2 leptons: $Z(\rightarrow \ell\ell)H(\rightarrow b\bar{b})$

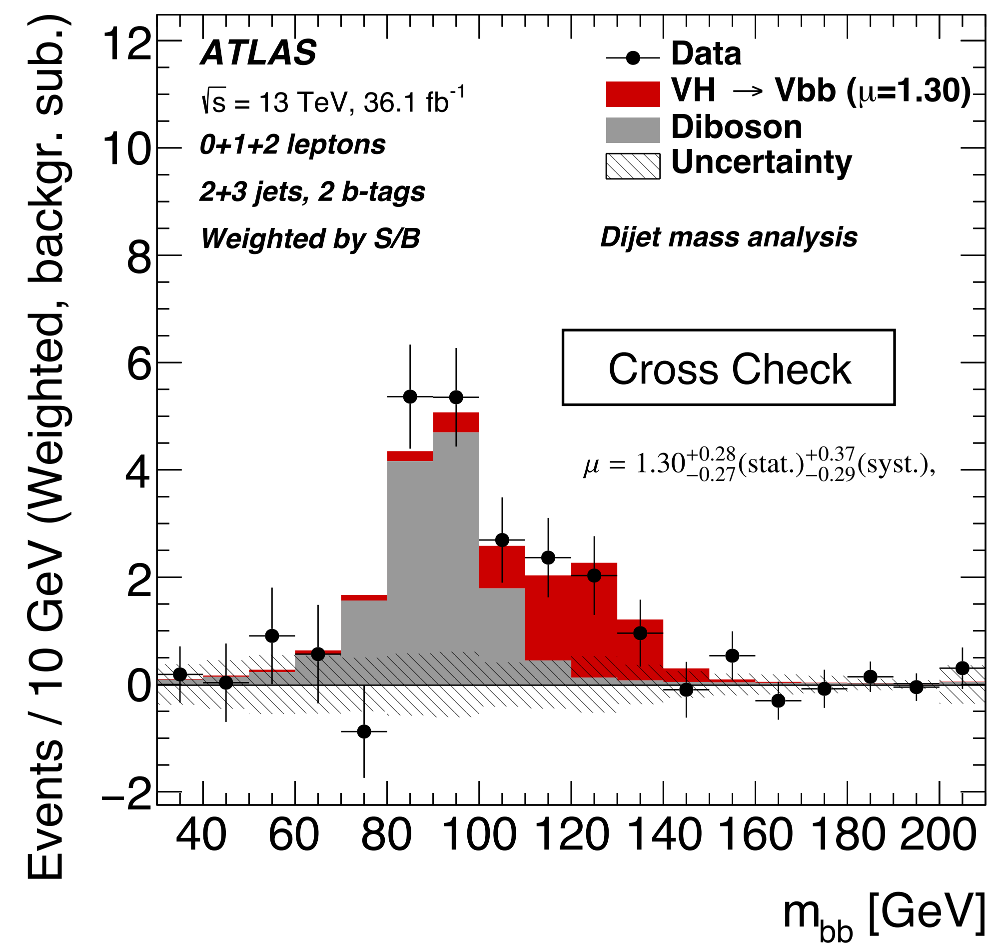
- Grouped into 8 categories by the numbers of leptons/ jets & W/Z p_T.





H($b\bar{b}$) Observation

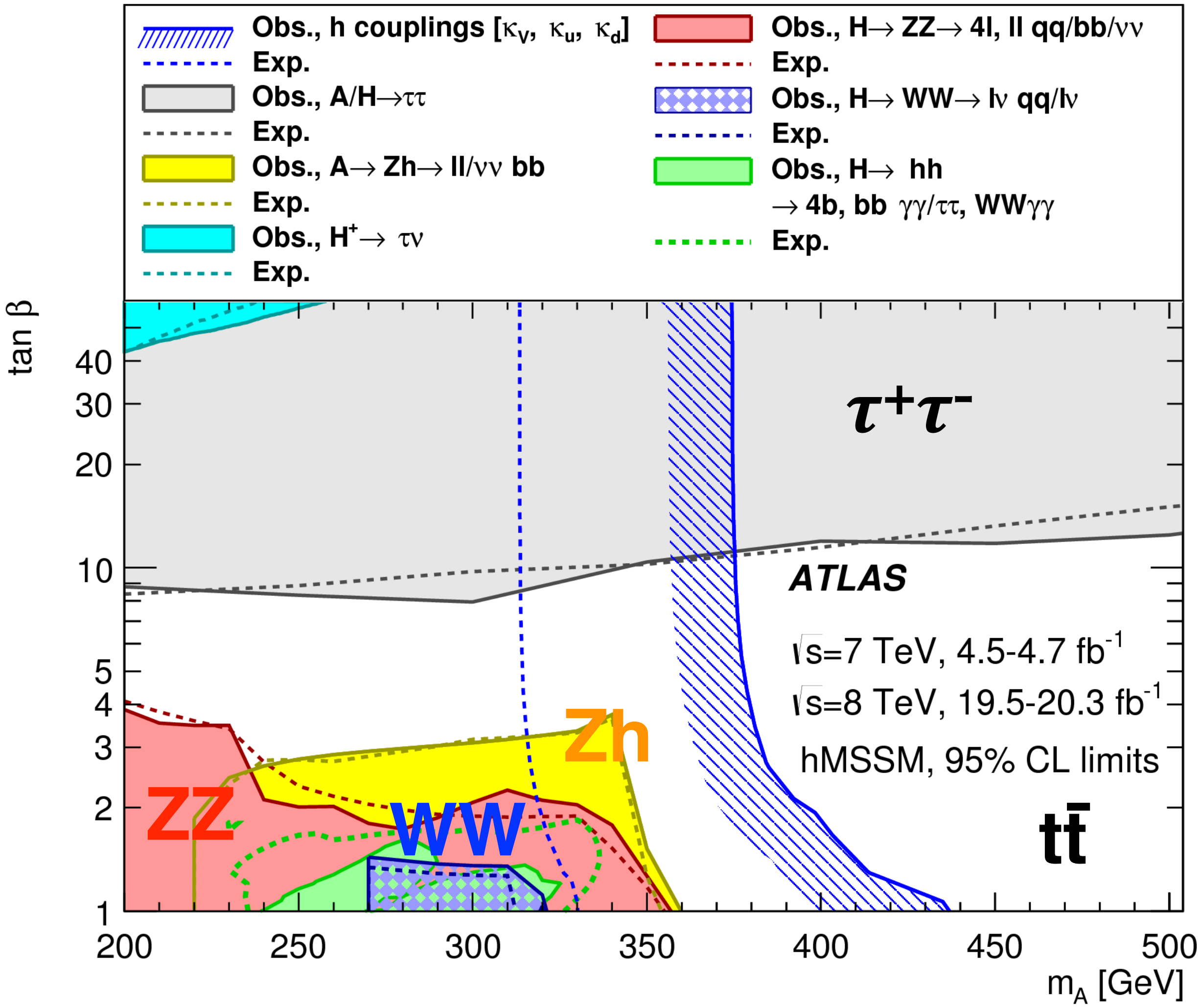




- **First observation of H($b\bar{b}$)!** **(3.5σ [obs], 3.0σ [exp])** Later confirmed by CMS (3.3σ [obs], 2.8σ [exp]).
- Consistent results with the cut-based analysis (performed as a cross-check).
- Currently looking into $t\bar{t}$H & other production modes. Gluon fusion mode was initially considered to be challenging/impossible, but may be doable with a new technique: boosted Higgs tagging using large-R jets.

Heavy Higgs & Other Resonance Searches

Heavy Higgs Searches

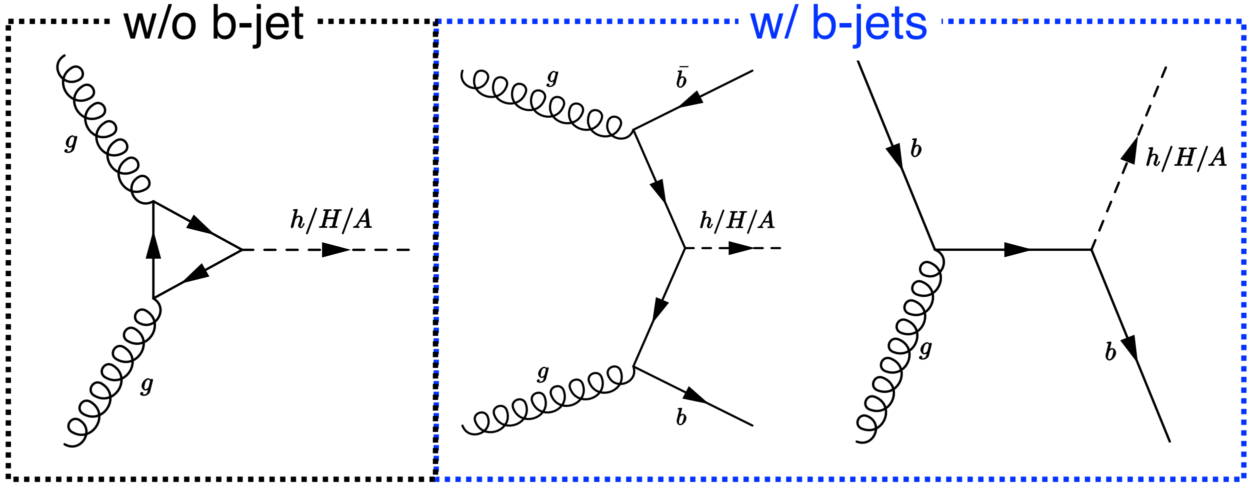


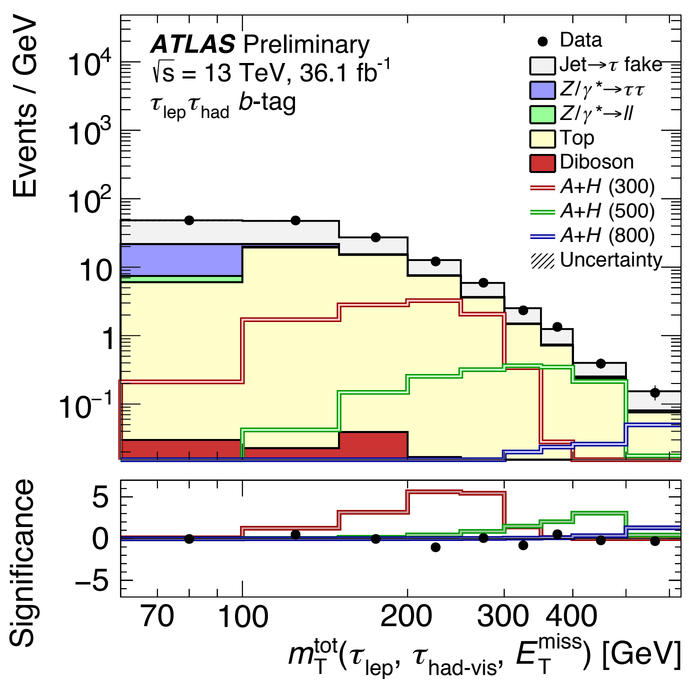
- **If the Higgs sector is extended by another doublet (Two Higgs Doublet Model; 2HDM), the decay modes depend on the heavy Higgs mass & tan β.**
- Neutral Heavy Higgs (H/A) searches:
  - High tan β: $\tau^+\tau^-$
  - Low tan β: ZZ,Zh,WW ($m_{H/A} < \sim 2m_t$)
    $t\bar{t}$ ($m_{H/A} > \sim 2m_t$)
- Charged Higgs ($H^\pm$) searches (dominated by tb, $\tau^\pm\nu$)

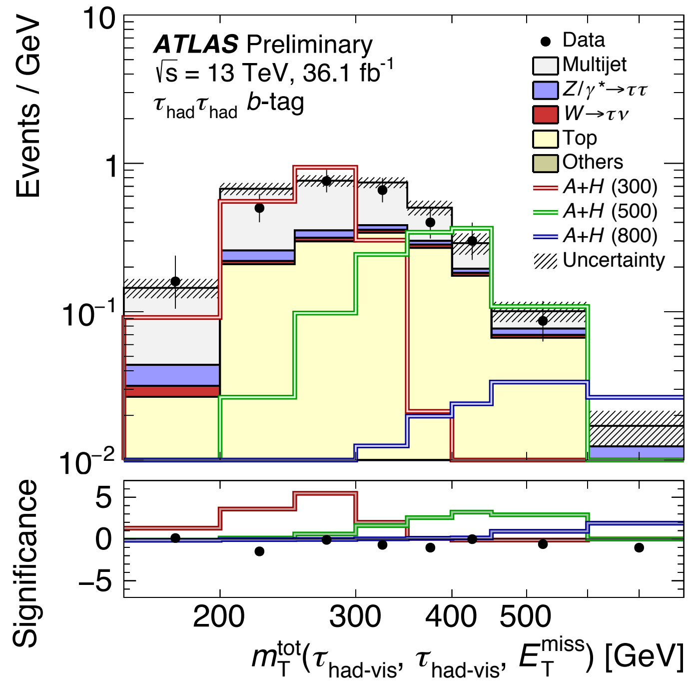
- If the Higgs sector is extended by a triplet, there could also be doubly-charged Higgs ($H^{\pm\pm}$).
- If the Higgs is composite, there could be diboson resonances in the TeV region?
- **It is crucial to perform diverse searches assuming various scenarios.**

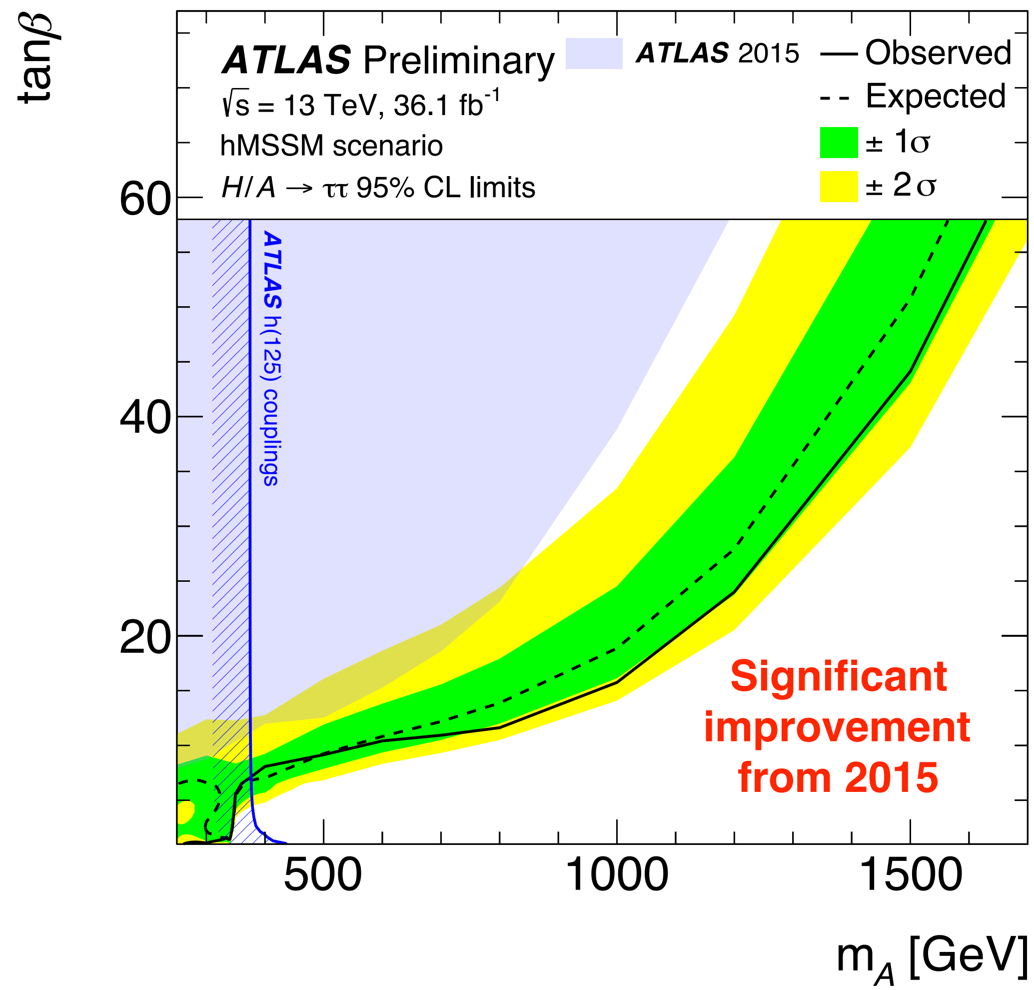
h/H/A → $\tau^+\tau^-$

- Particularly important for high tan β scenarios.
- Search for $\tau\tau$ resonances, at least with one hadronic τ ($\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$) b-tagged, b-veto categories.
  - $\tau_{had}\tau_{had}$ is more sensitive in the high mass region.
- Categorized into b-veto & b-tag regions to search for gluon fusion & bb-associated processes respectively.





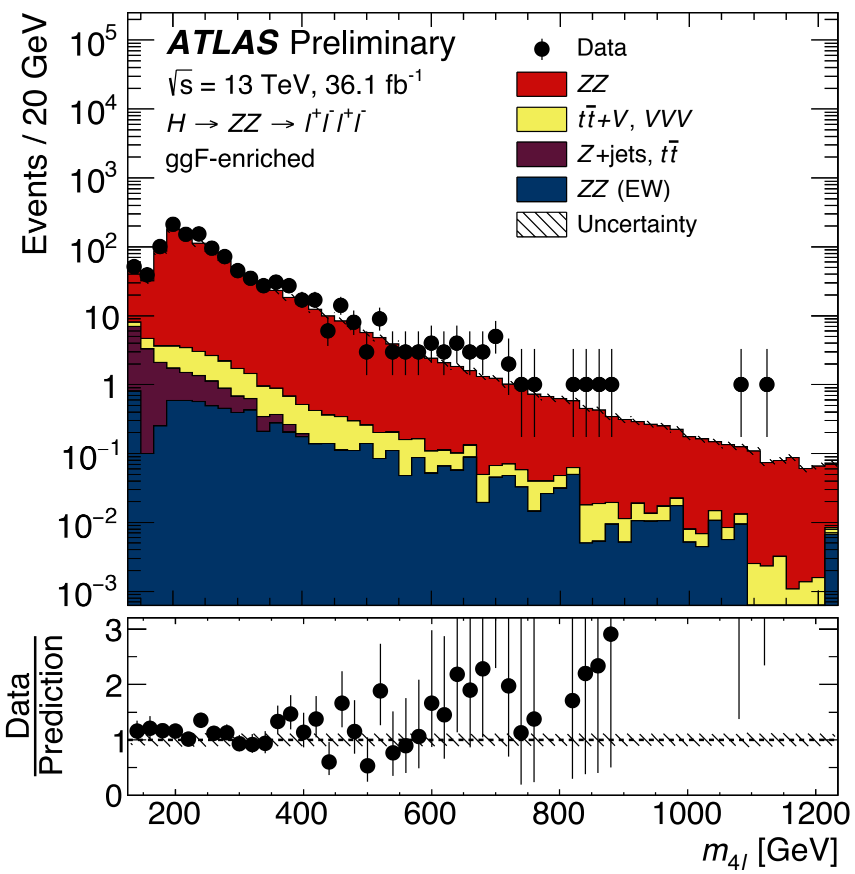




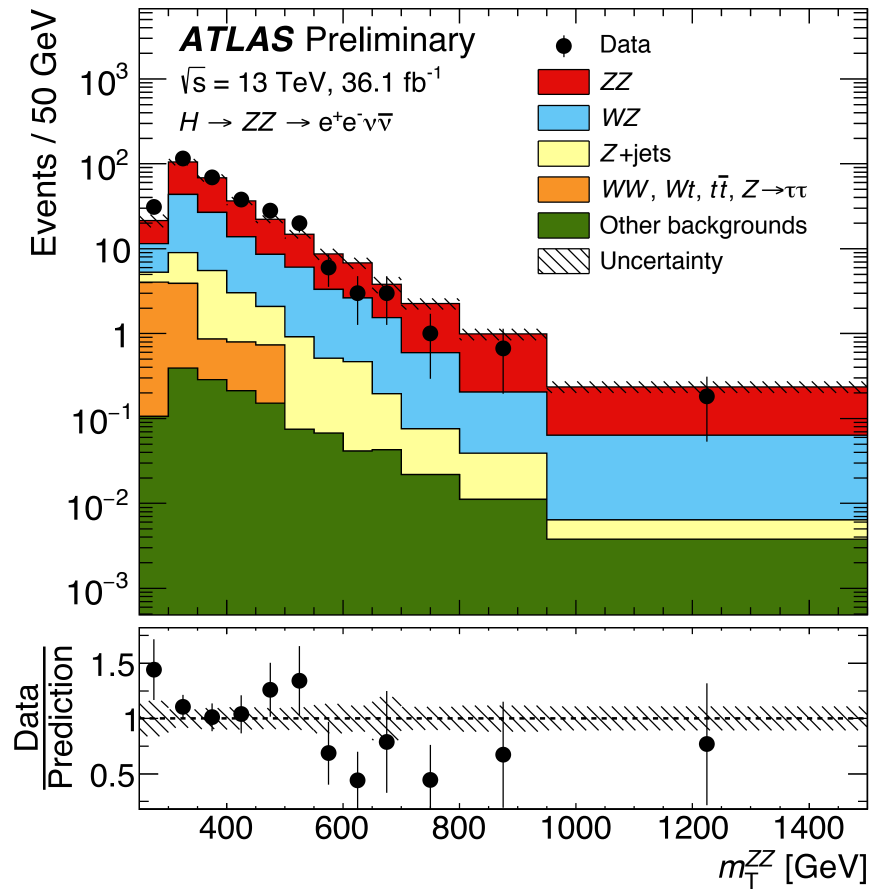
$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}.$$

X(→ZZ)

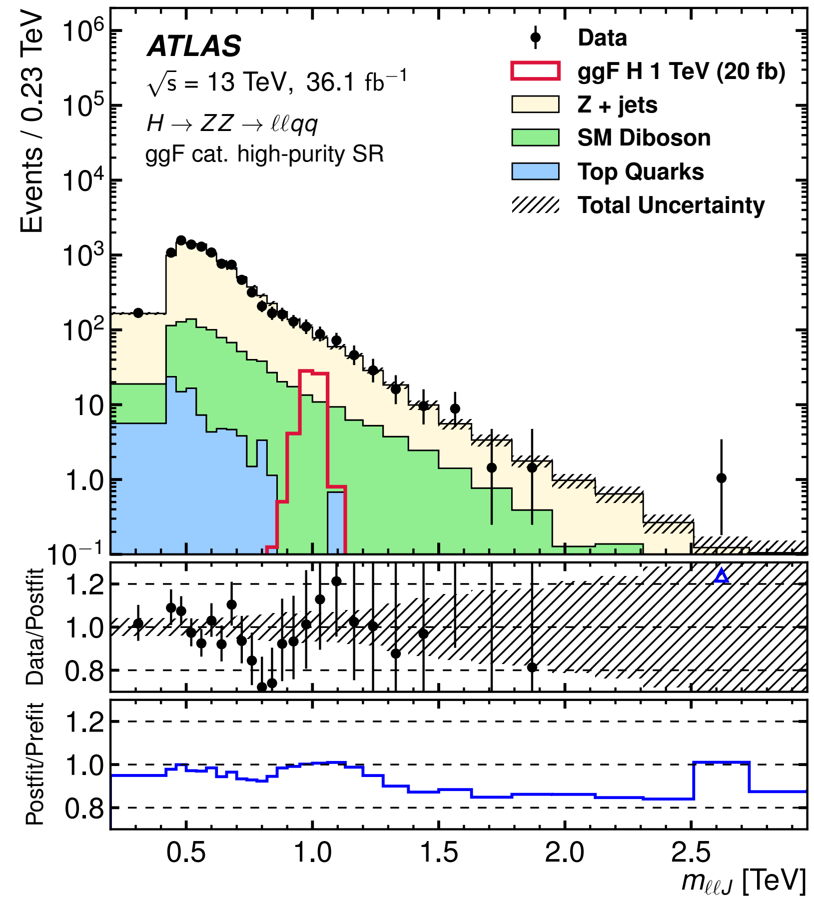
X→ZZ→4ℓ



X→ZZ→ℓℓνν



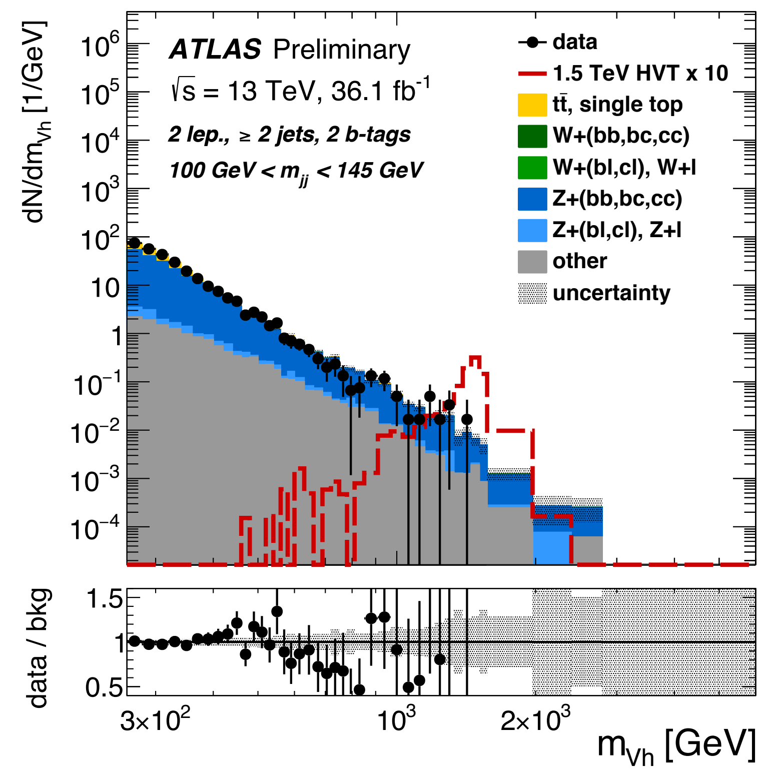
X→ZZ→ℓℓqq

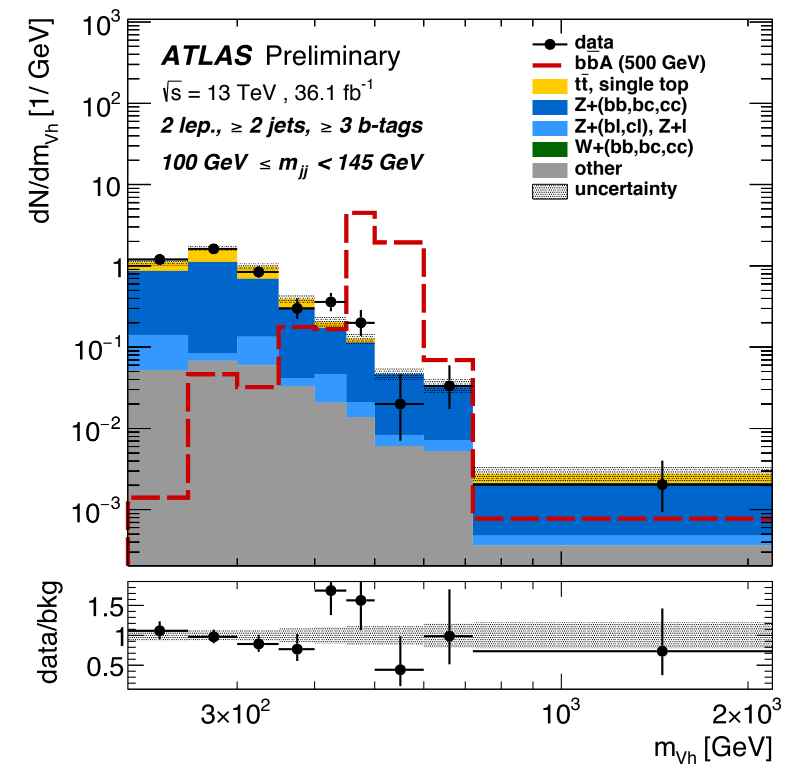


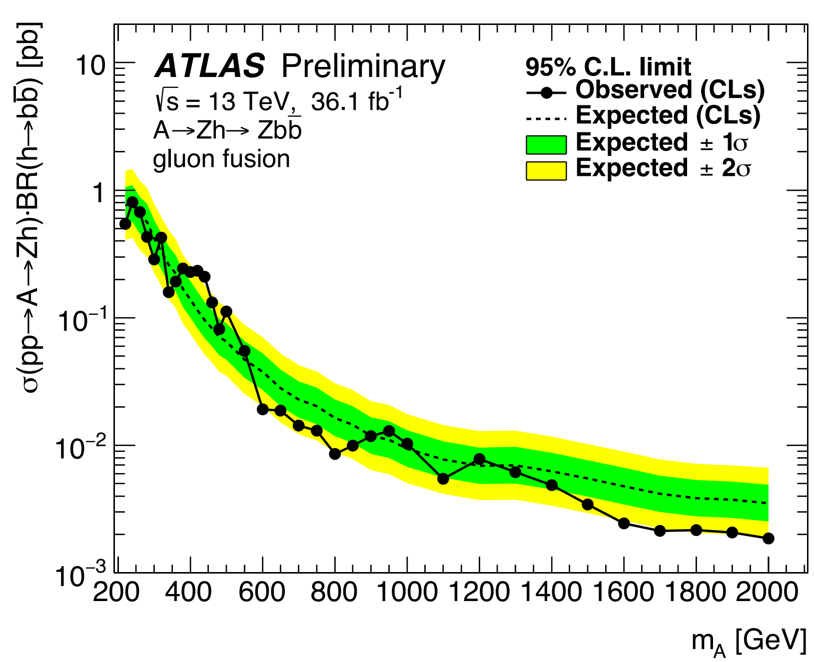
- **Visible excess of 3.6σ** (global 2.2σ) at 240 & 700 GeV. Mainly 4e for 240 GeV.
  - **700 GeV is not expected from the 2HDM.**
- 700 GeV excess not observed in $\ell\ell\nu\nu$, $\ell\ell$qq (deficit in the latter..)
- Need improvement on the ZZ BG estimation for 4ℓと$\ell\ell\nu\nu$ (currently fully relying on MC w/ NNLO QCD & NLO EW precision).

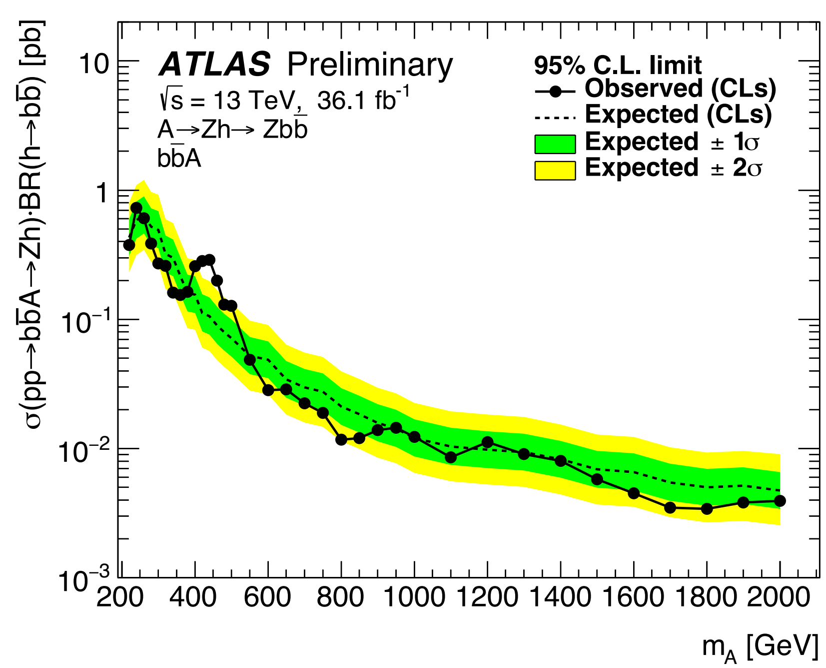
A(→Zh)

- **Important for low tanβ & m_A<2m_t cases.**
- Similar strategies as the Vh(→bb) measurement.
- **Visible excess ~440 GeV (3.6σ local, 2.4σ global).**
  - **In both gluon fusion & bbA production modes.**
- If it is form 2HDM, there might also be $t\bar{t}$ resonances.
  - Though, challenging due to the negative interference.

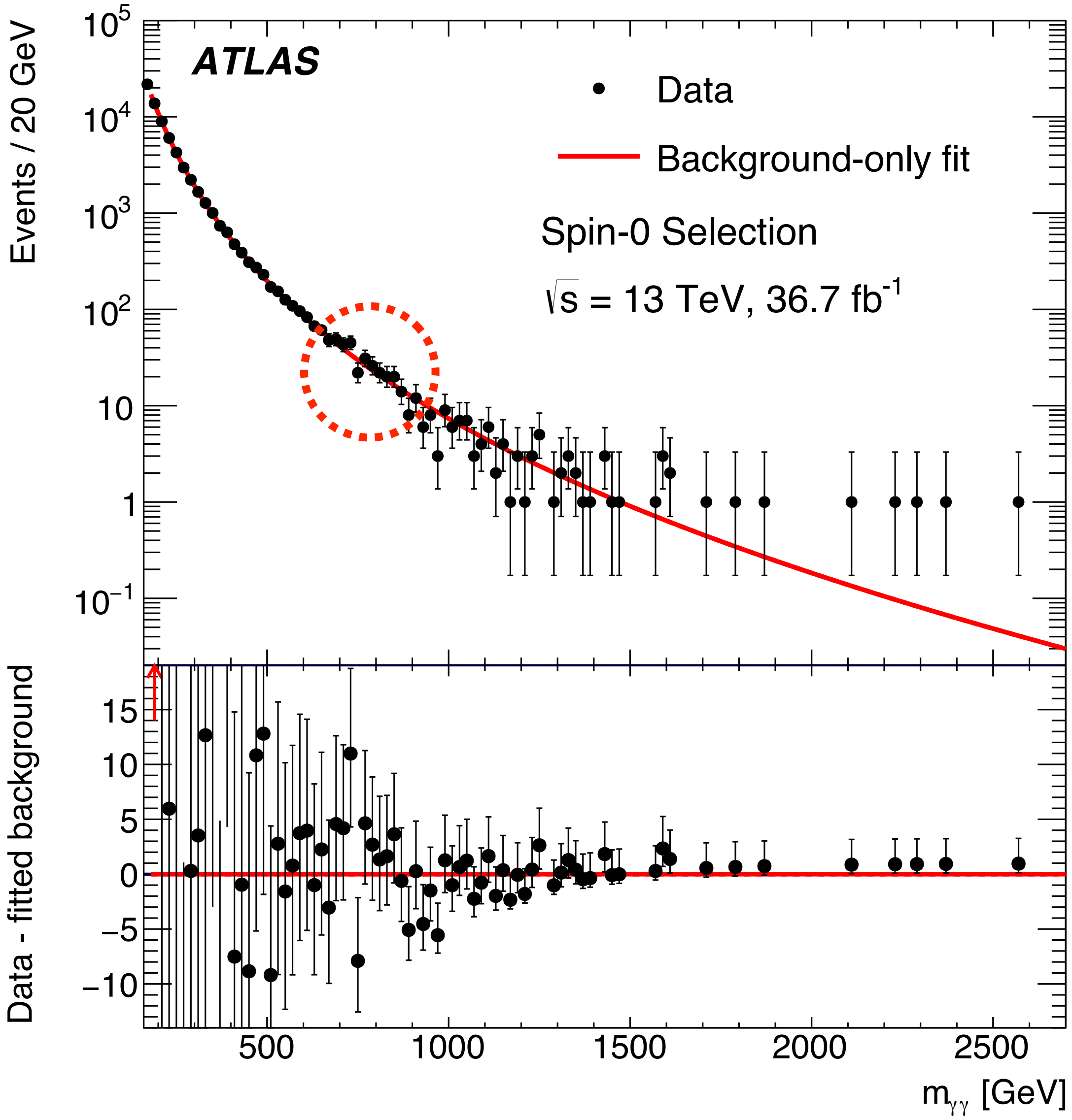


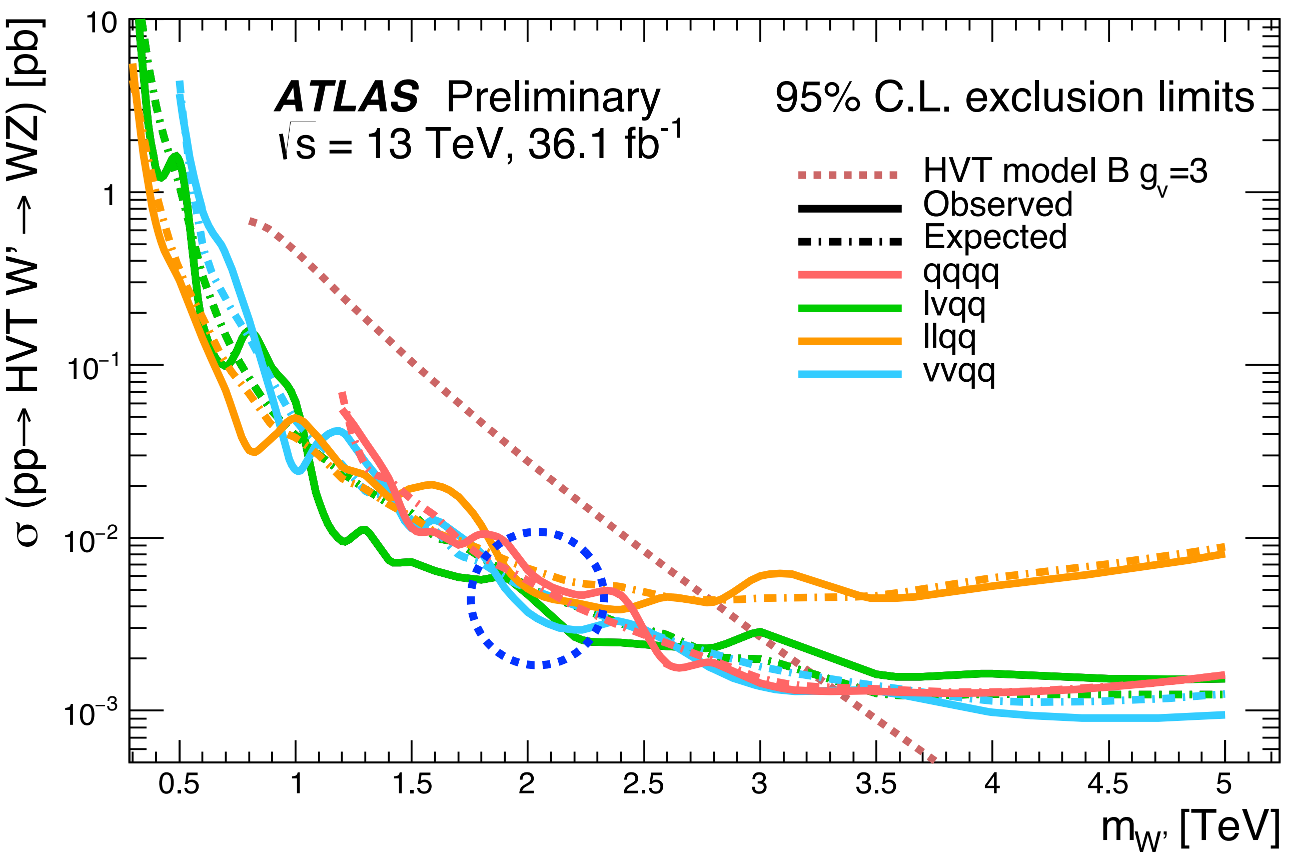






Excesses Gone?



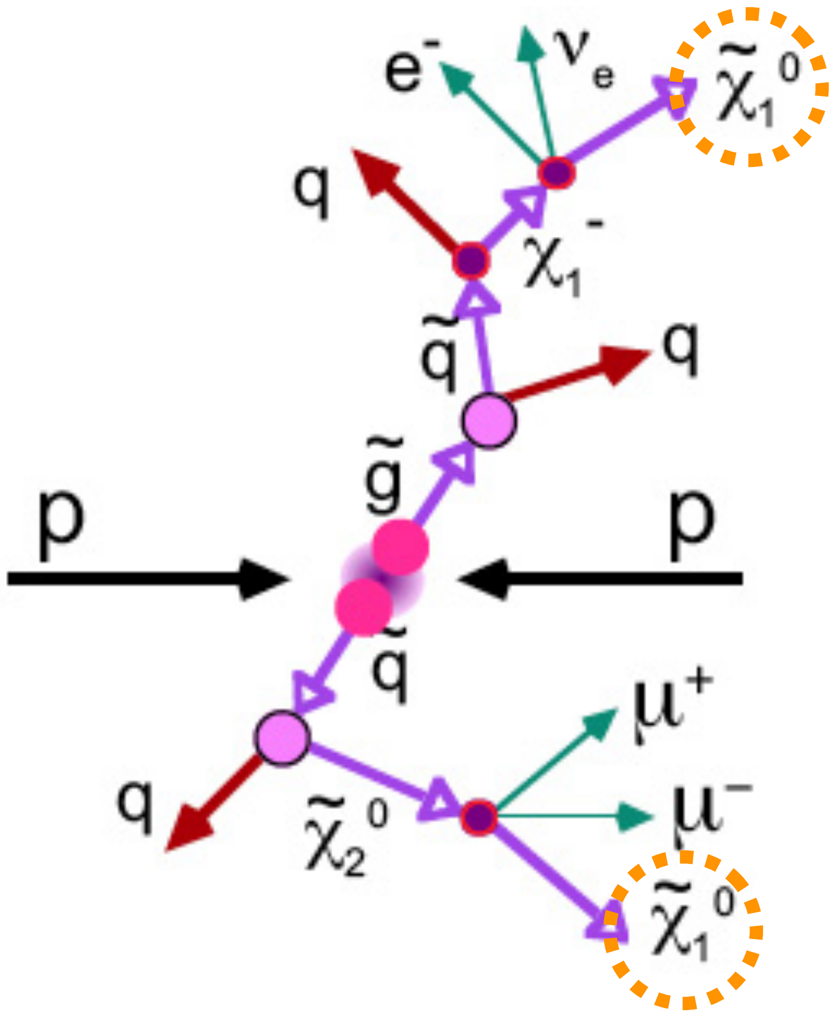


- Two famous excesses in $\gamma\gamma$ (750 GeV) & diboson resonance (~2 TeV) searches seem to have been from statistical fluctuations.
- There is still a 3σ excess in spin-2 $\gamma\gamma$ searches, but the local significance is rather small.

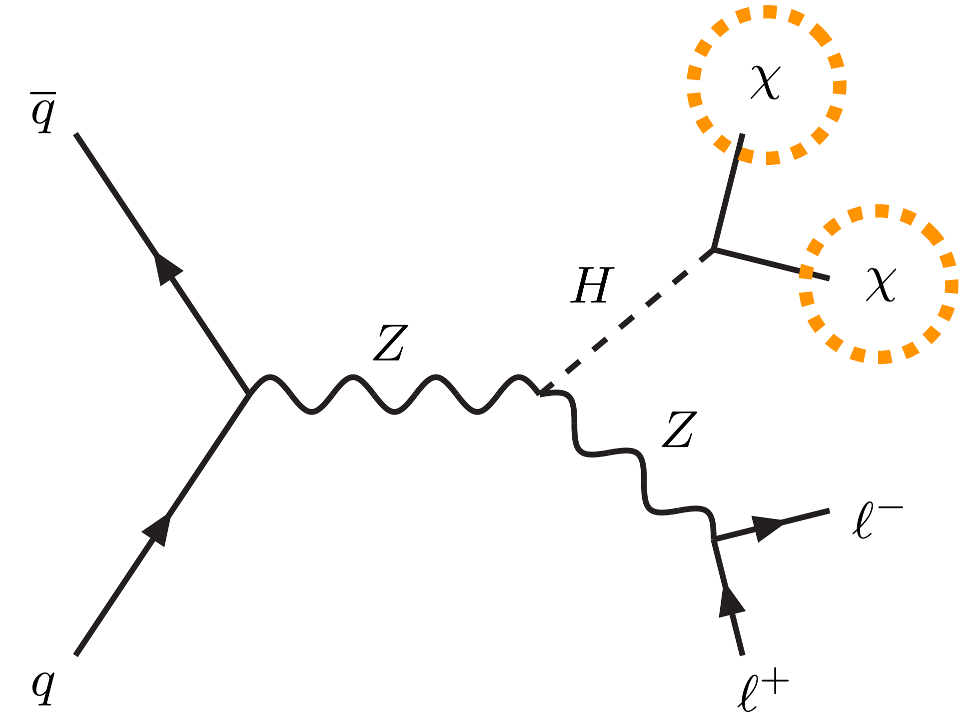
Dark Matter & Supersymmetry

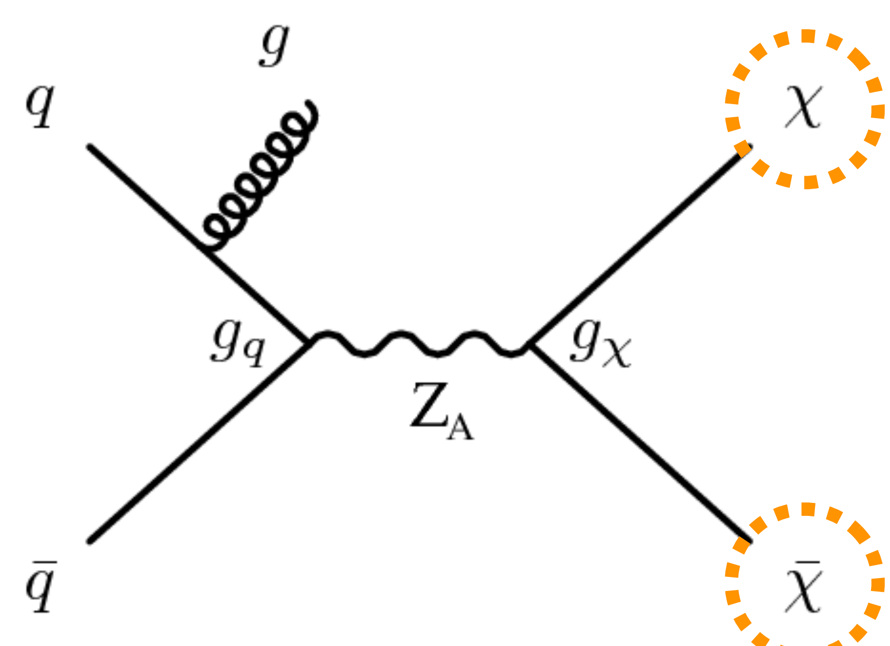
Dark Matter@LHC

Dark matter from cascade decays from Supersymmetric particles



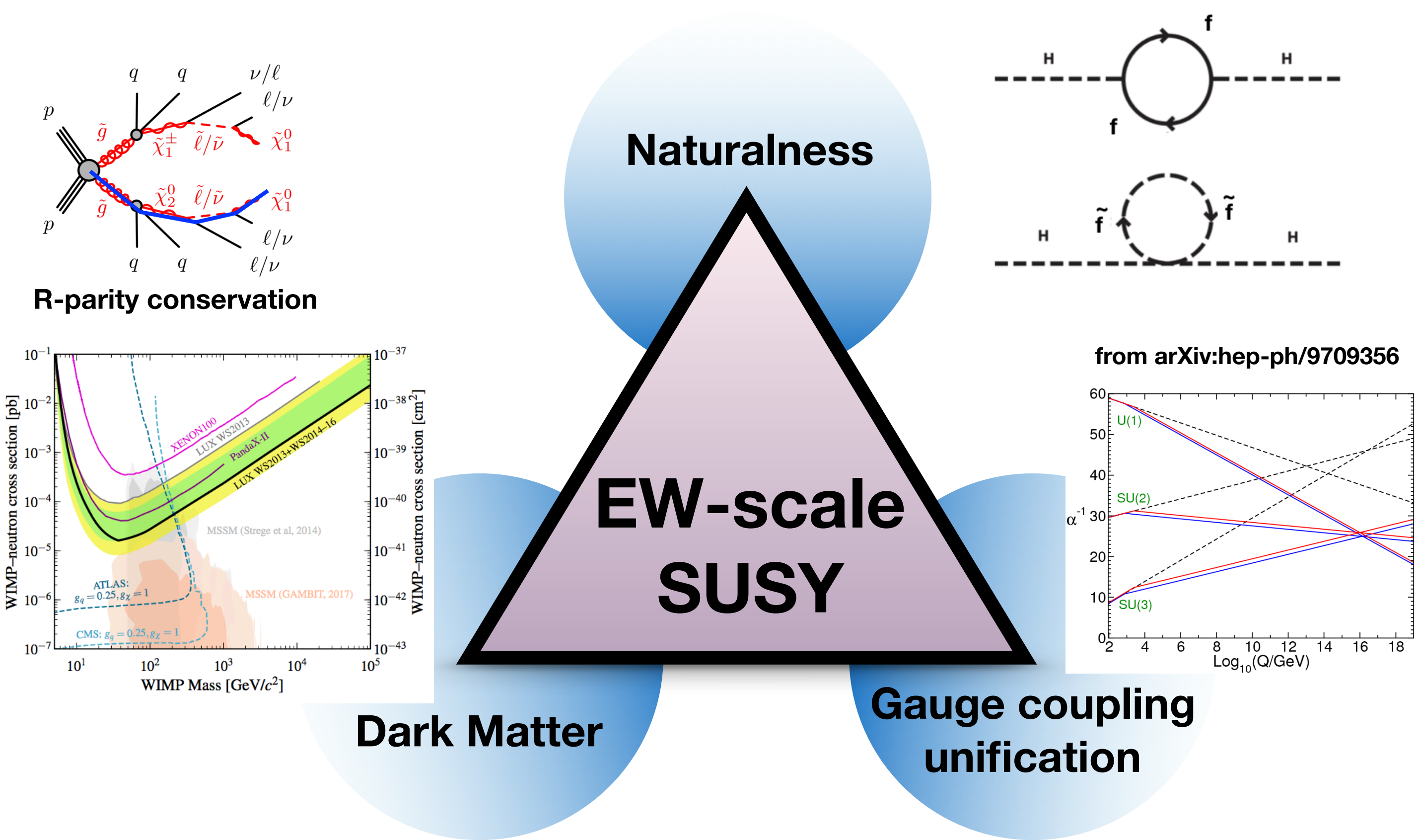
Dark matter directly produced via mediators



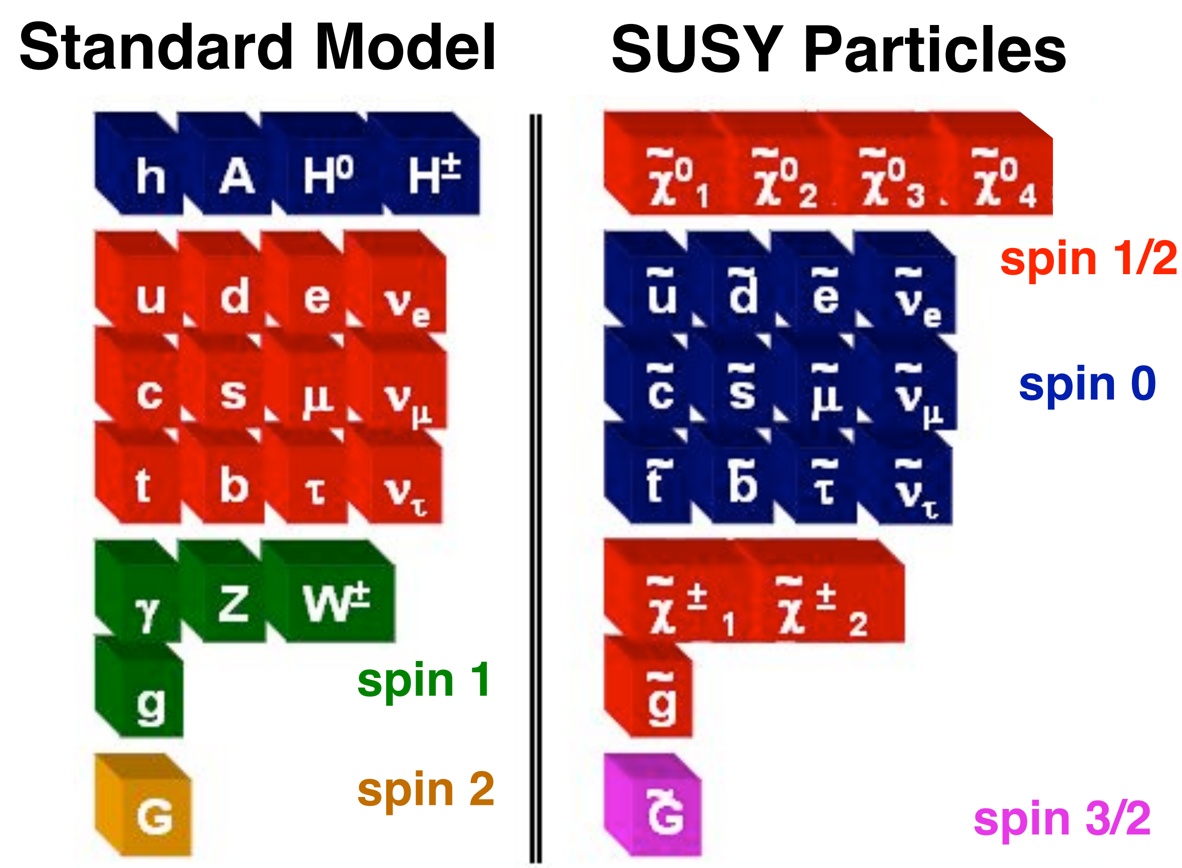


Dark matter could be produced through cascade decays from new particles (e.g. supersymmetric partners) or directly via mediator.

Supersymmetry



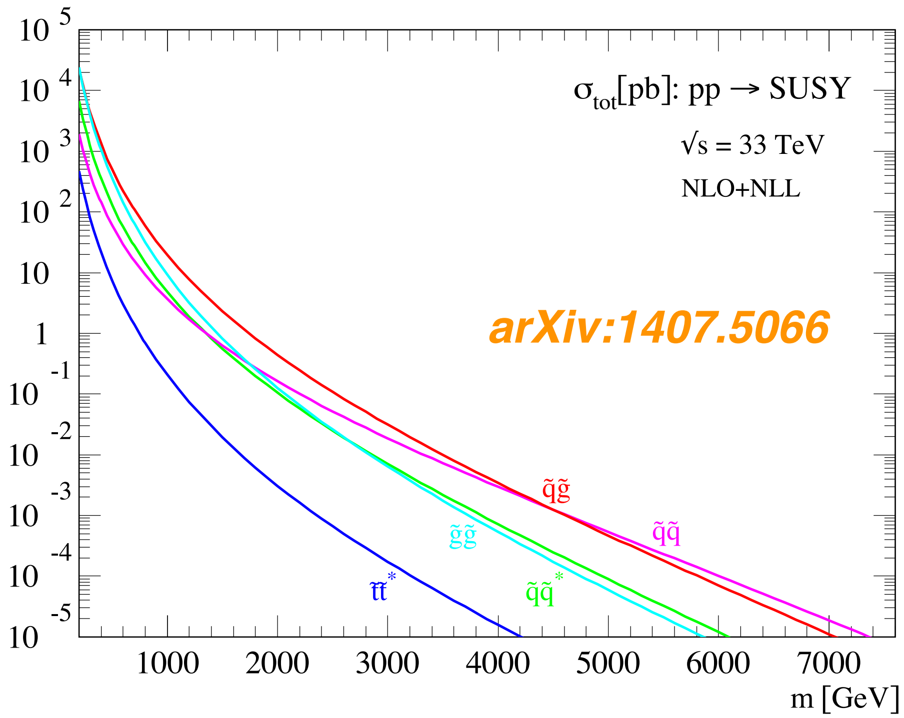
Thanks to N. Craig for the idea

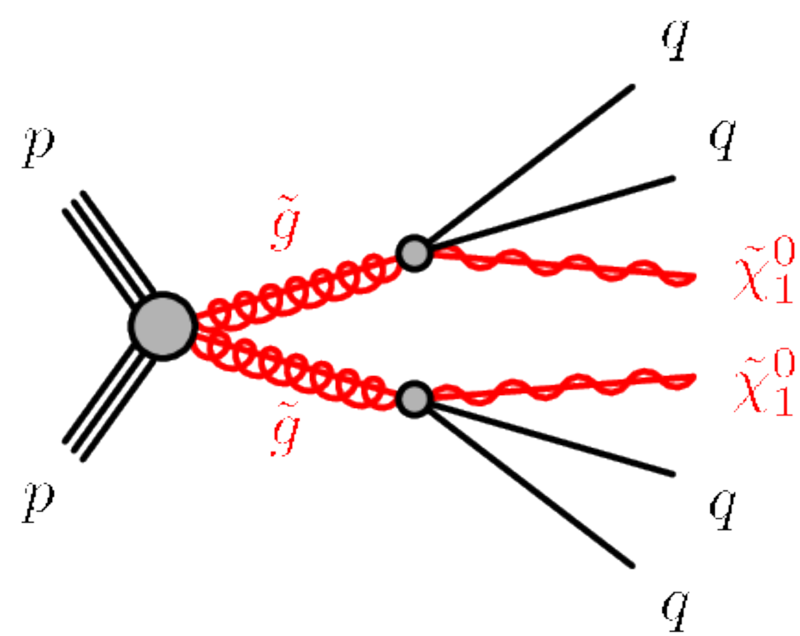


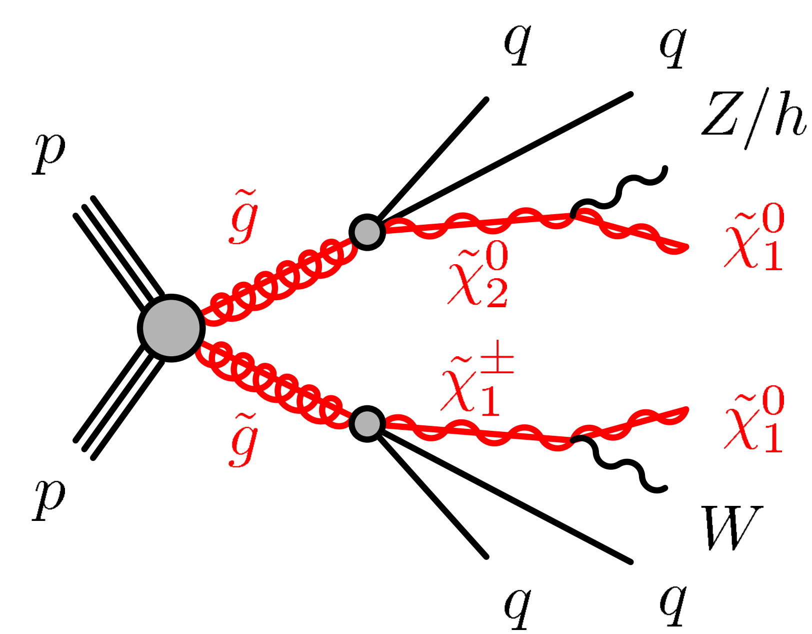
I. Vivarelli

- EW-scale Supersymmetry (SUSY) is motivated by three outstanding points (though naturalness is becoming less compelling now due to the lack of low mass SUSY particles).
- Supersymmetry predicts existence of a new set of partner particles (“sparticles”) to the Standard Model ones.

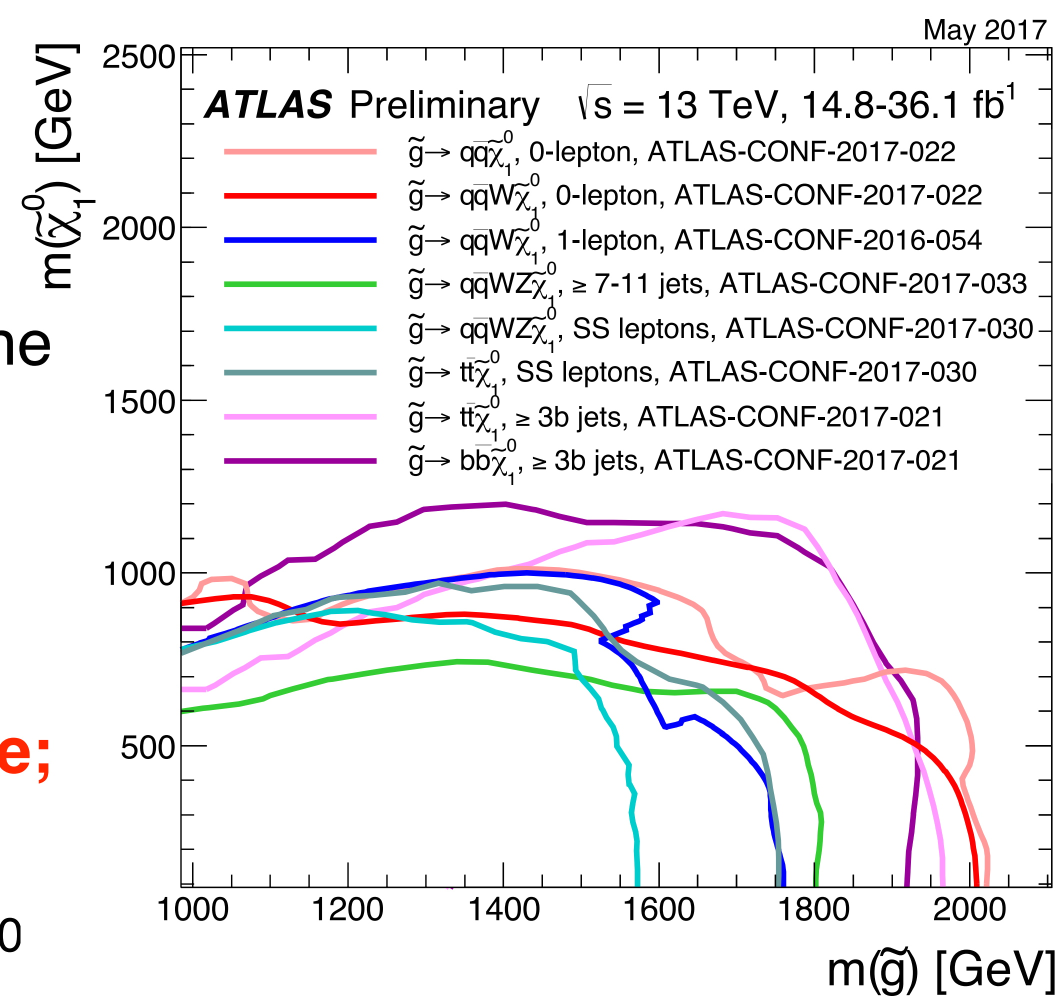
Gluino Searches



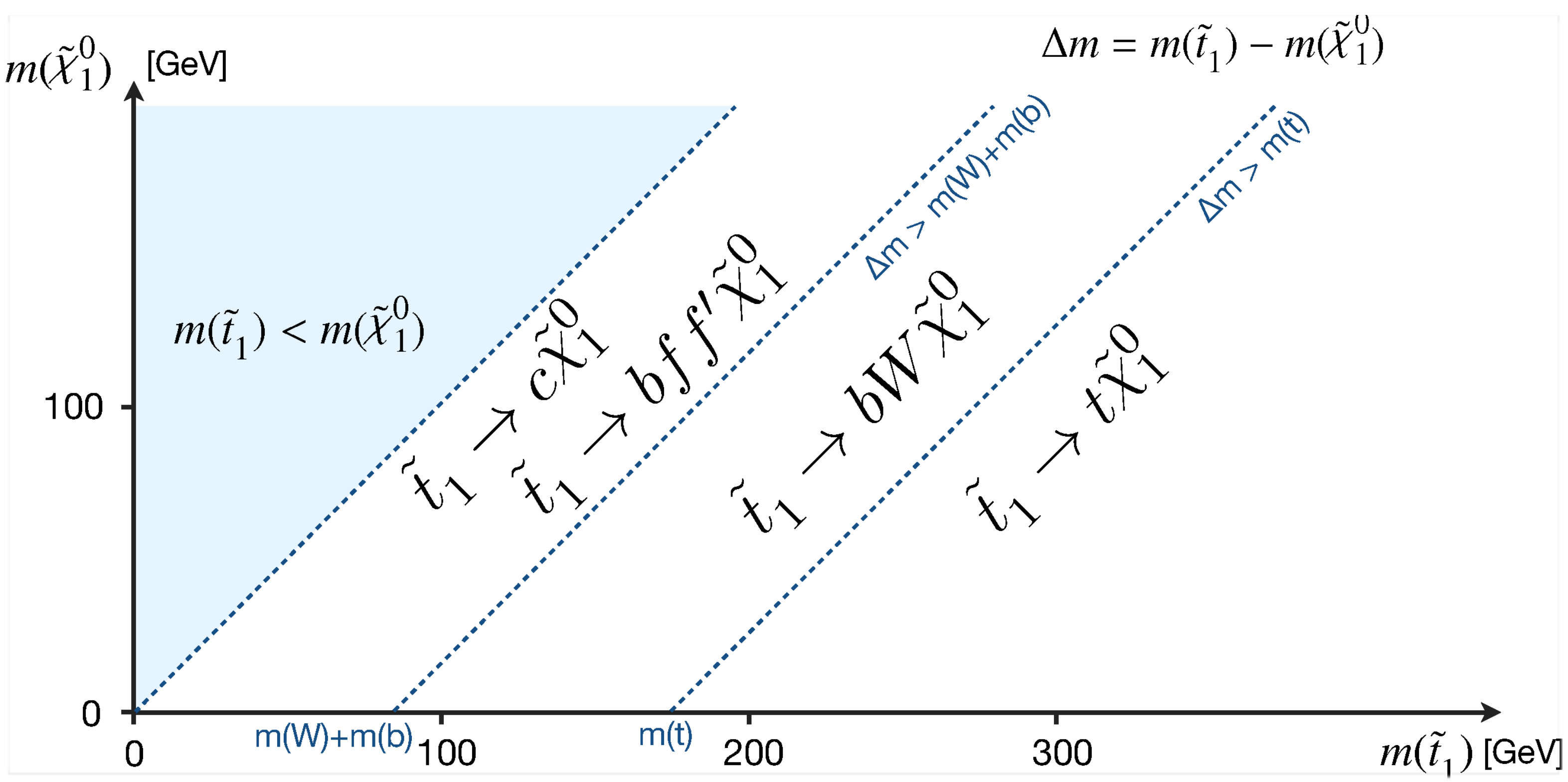


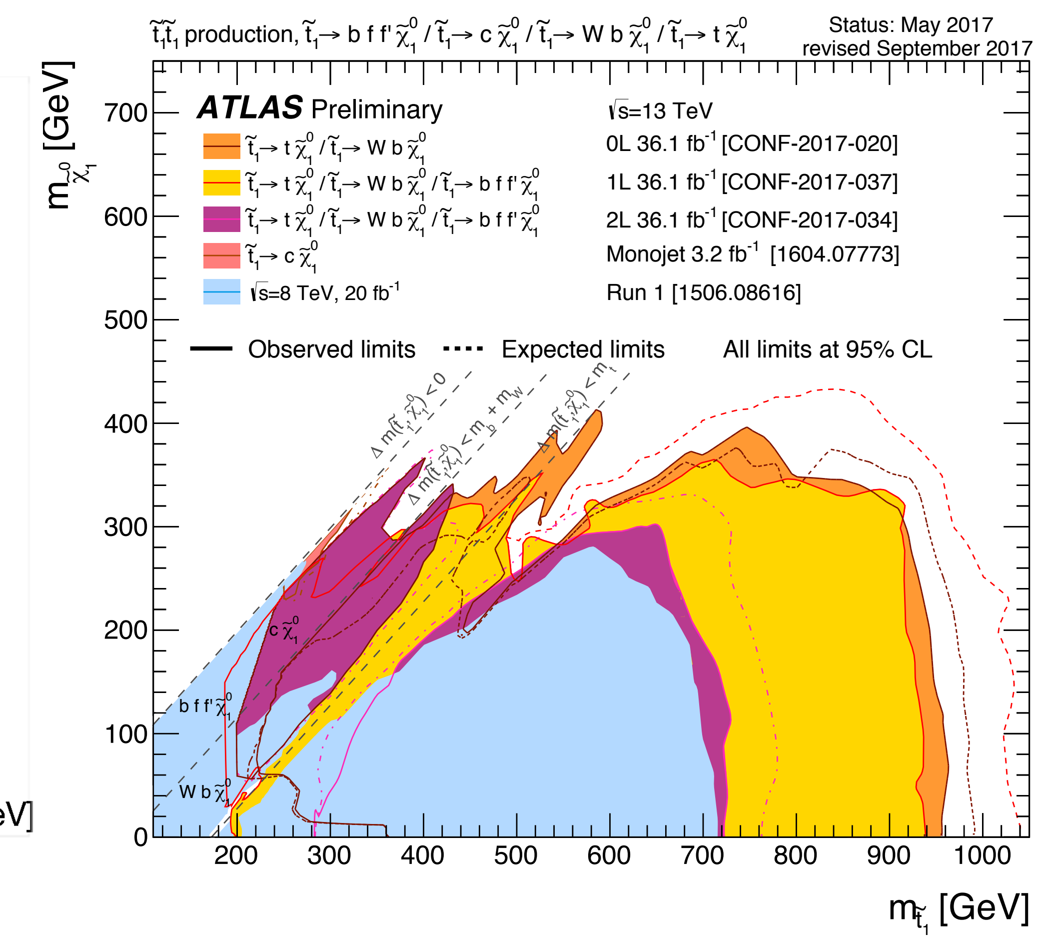


- **Gluino pairs could be one of the most-largely produced sparticles for a specific mass.**
- 0-lepton channel has the best reach & coverage in the sparticle mass plane.
- Jet multiplicity depends on the number of cascade decays & boson decays. b-jets exist in many cases.
- **m_{gluino} ~ 2 TeV is excluded in generic phase space; but much reduced in compressed scenarios.**



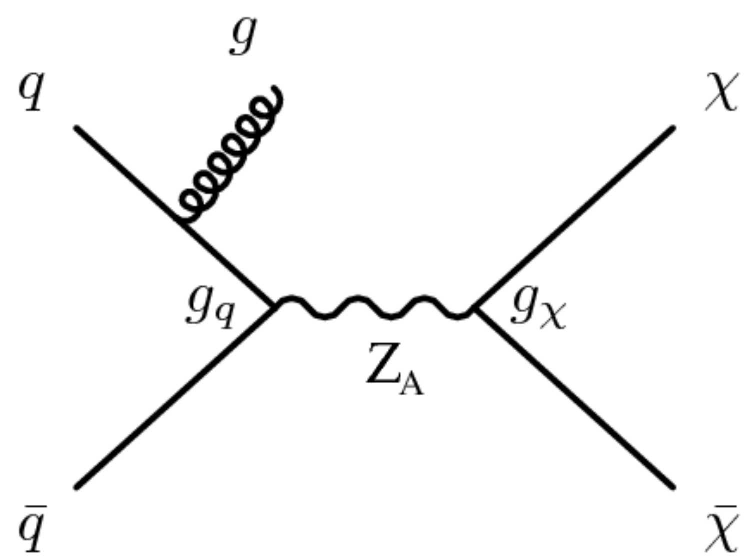
Stop Searches

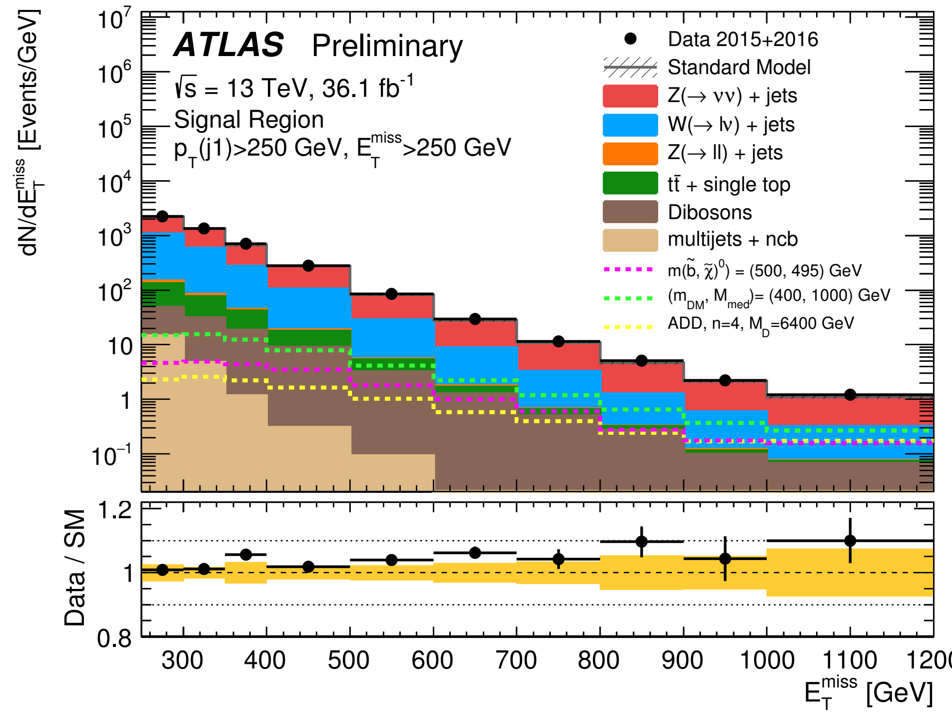


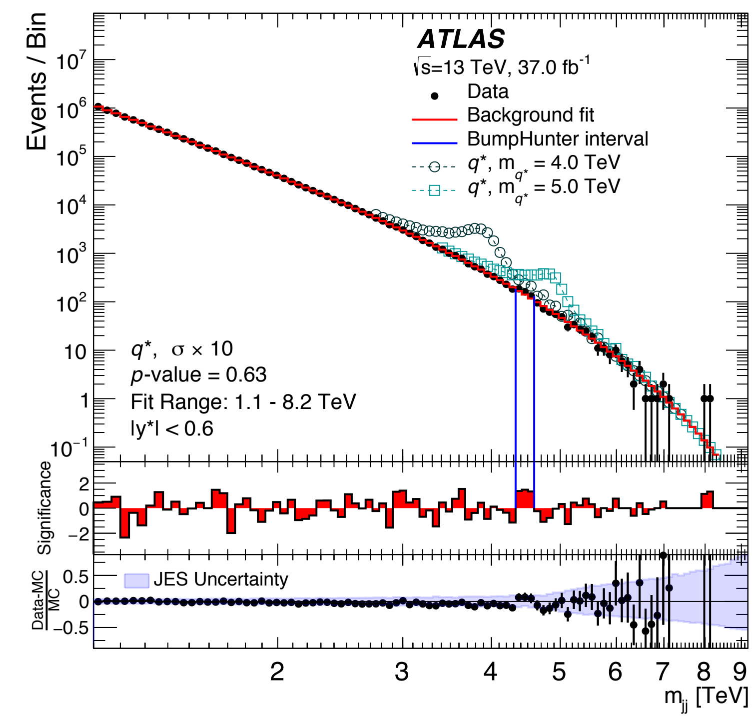


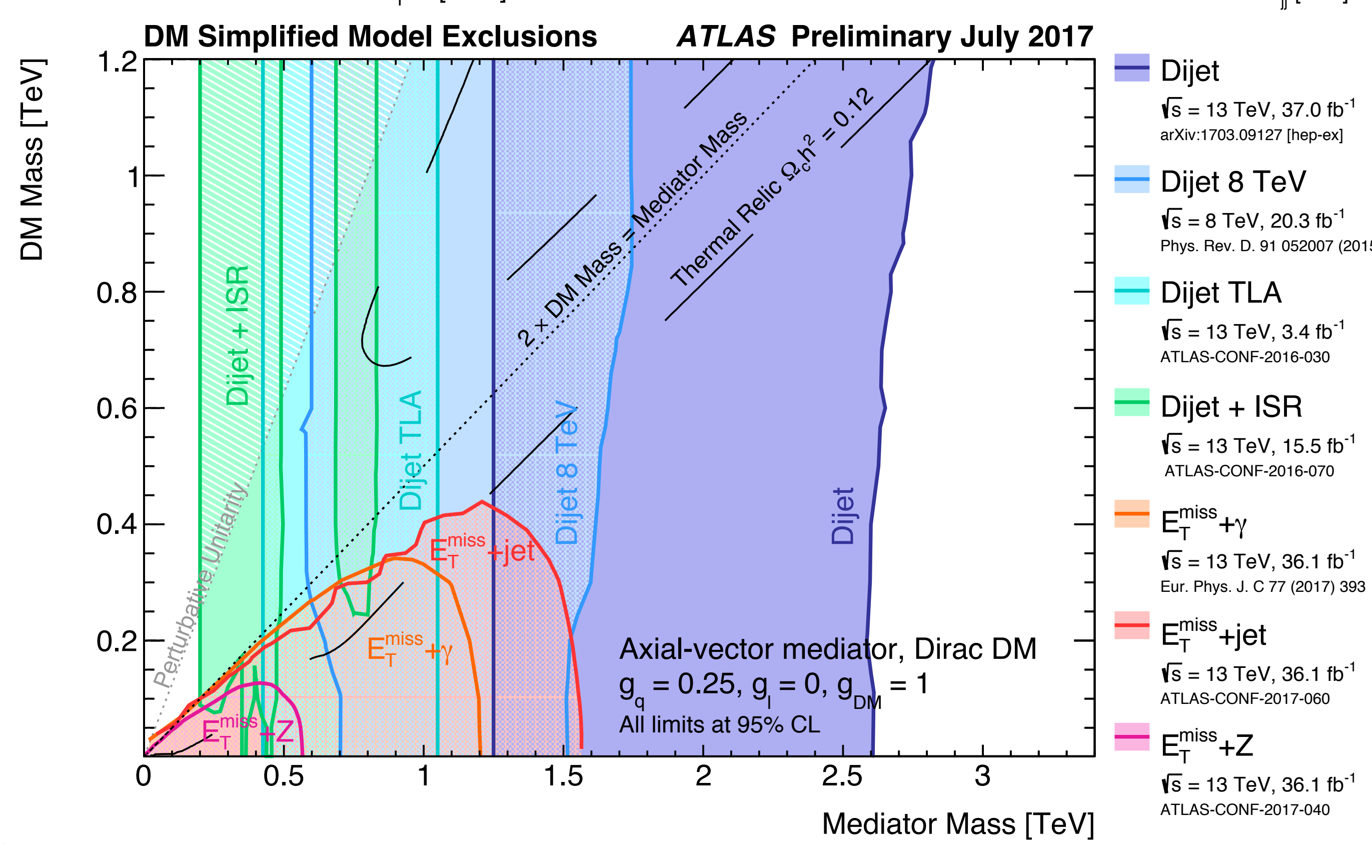
- **Top squarks (or “stop’s”)** could have relatively low masses (& possibly reachable by the LHC) due to naturalness.
- Its decay pattern depends on the mass difference between the lightest supersymmetric particles (LSP’s) and stop’s.
- **m_{stop} ~ 950 GeV is excluded for large phase space. Nature seems to be “fine-tuned” at some level.**

More Generic DM Searches





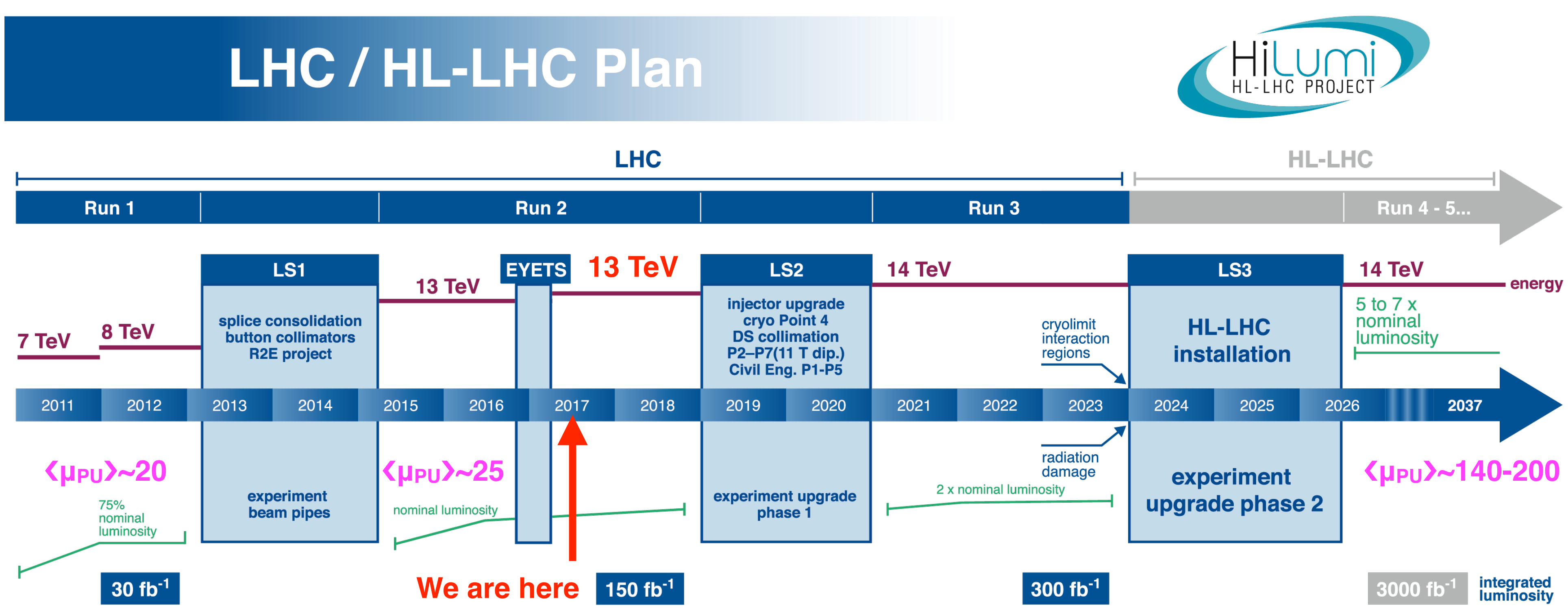




- Direct productions of DM are searched in "E_T^{miss} + ISR (jet,γ, W/Z, etc.)" final states.
- "Monojet" channel (ISR=jet) has the highest sensitivity for generic cases.
- Assuming the simplified model above, the dijet resonance searches can also be interpreted for DM models.

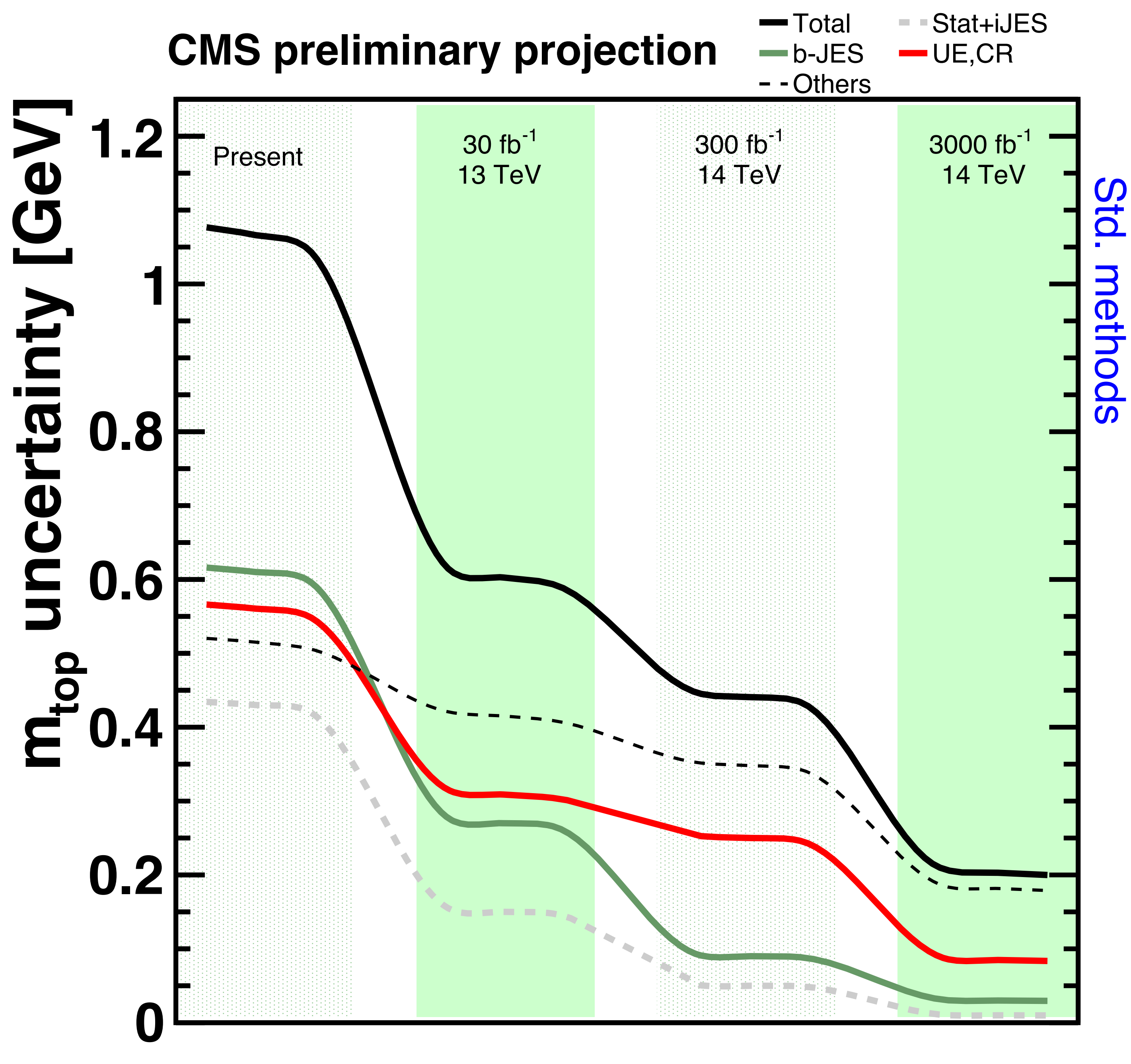
Summary

- **Properties of the discovered Higgs boson is consistent with the Standard Model so far.**
- However, for new particle searches, there are a few excesses here and there, and they should be investigated further with more data.
- We will continue the precision measurements & searches with more data, and will also introduce various improvements and new methodologies to improve sensitivities to new phenomena.

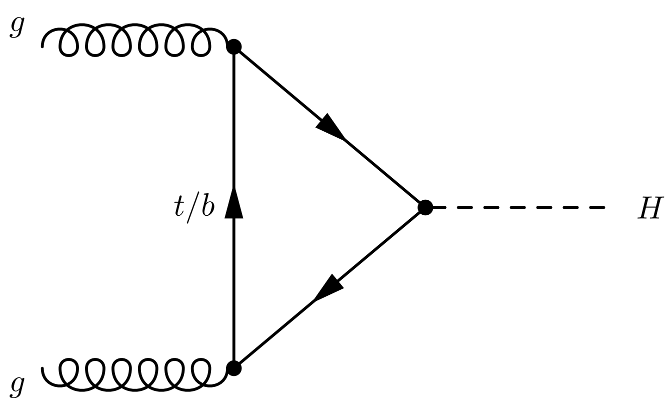


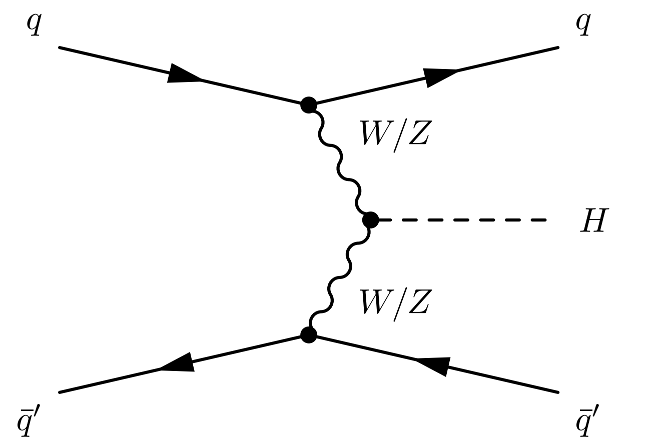
Backup

Top Mass Prospects

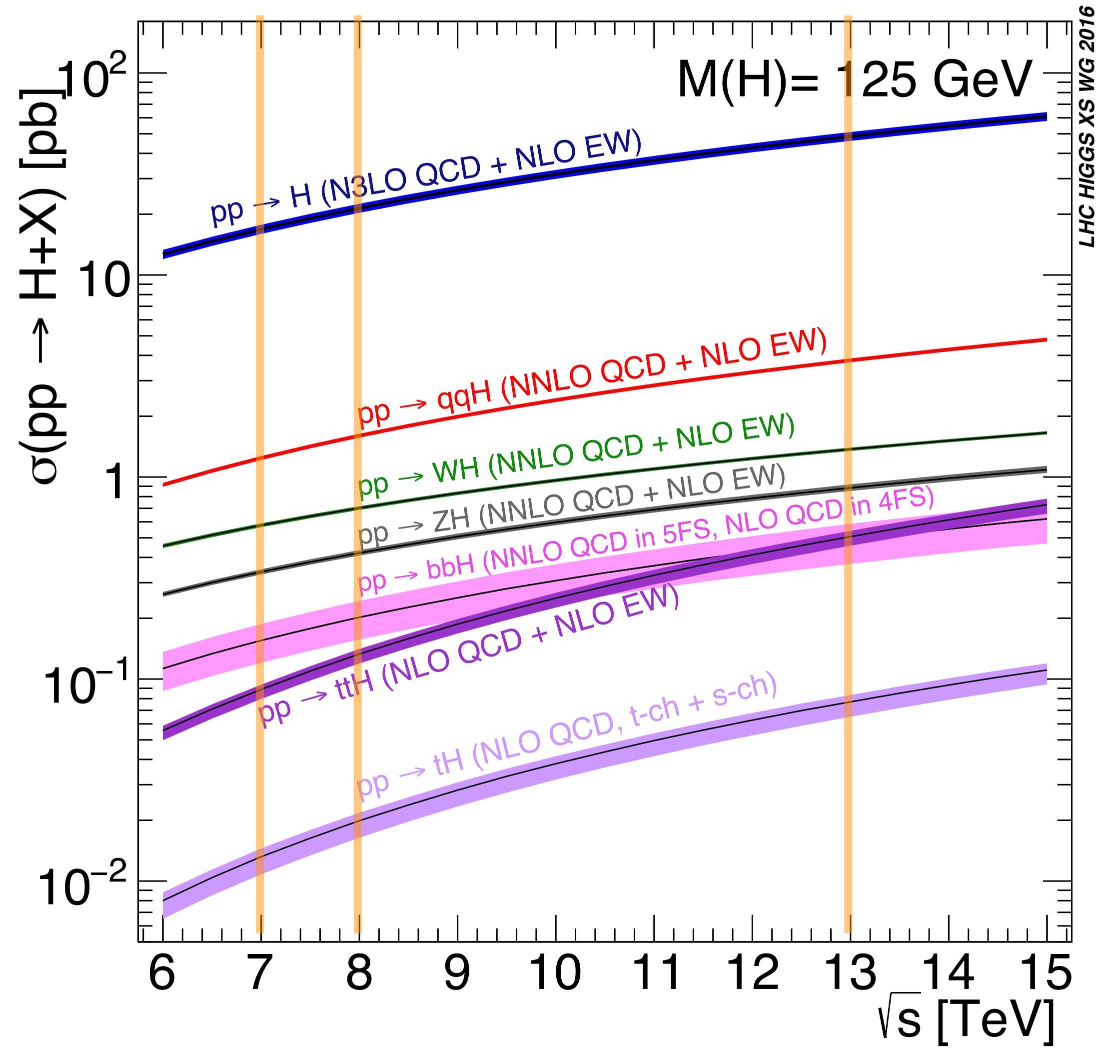


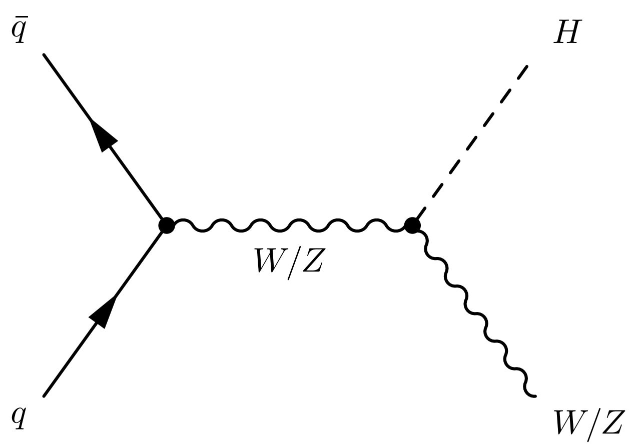
Higgs Production

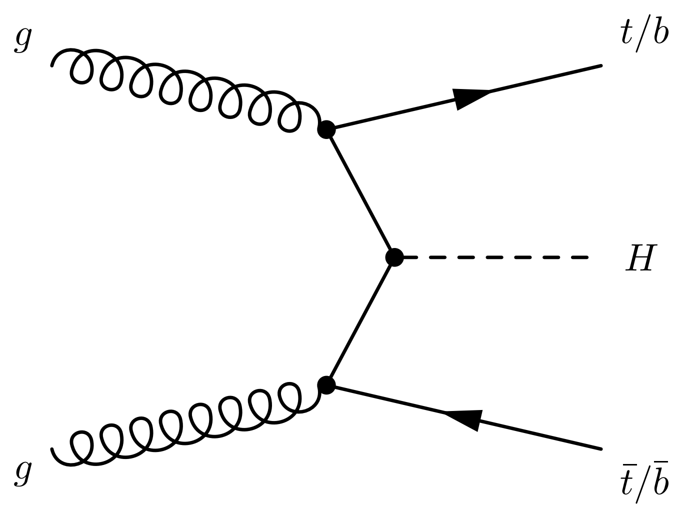


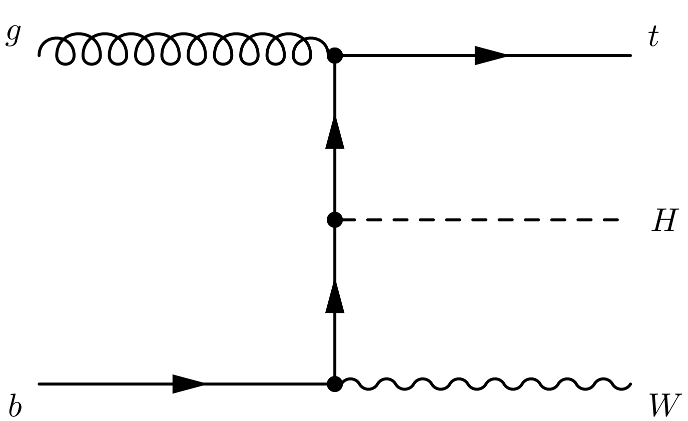


LHC Higgs Cross Section Working Group





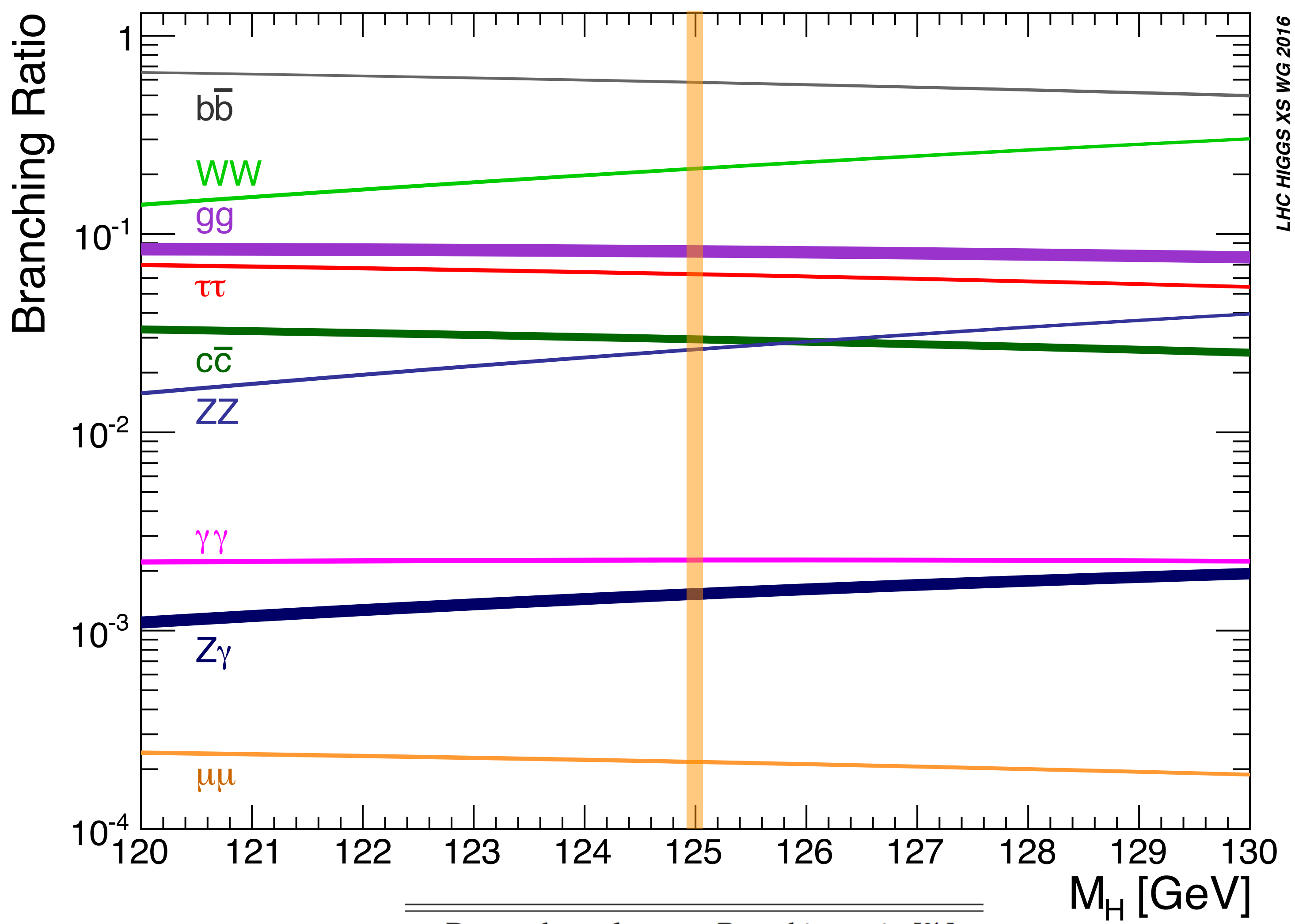




- **Notable increase in the cross section (×2.3 for ggH, ×3.9 for $t\bar{t}$H, ×3.3 for HH) from √s=8→13 TeV.**
- **Run-2 is the dawn of precision measurements for the Higgs boson & discovery phase of the $t\bar{t}$H.**

Higgs Decays

LHC Higgs Cross Section Working Group

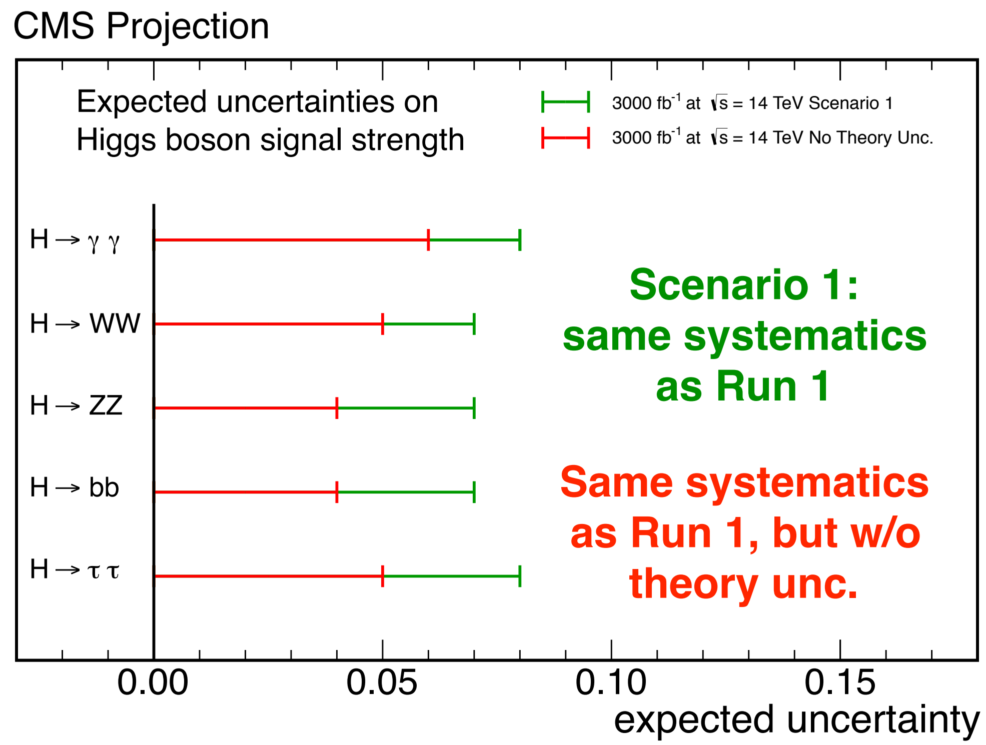


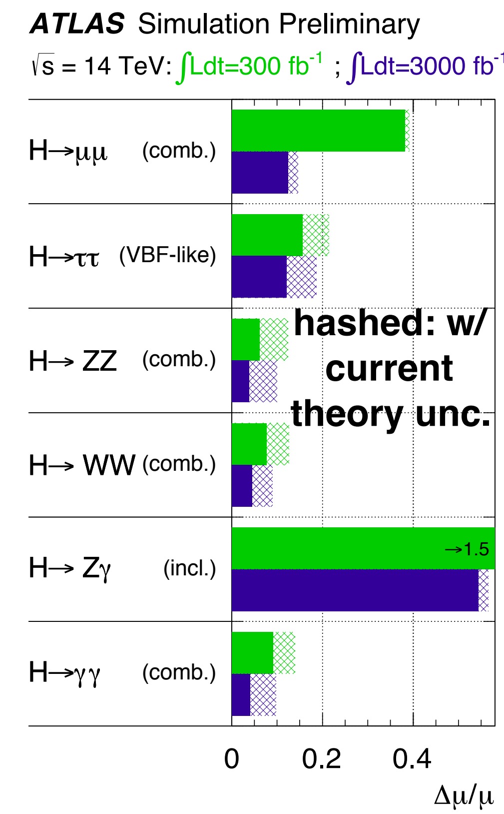
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

- **$\gamma\gamma$, ZZ(→4l): Discovery channels.** Small branching ratios (BRs), but good mass resolution & clean signatures.
- **WW(→lνlν): Large BR, good sensitivity**, but poor mass resolution due to two neutrinos.
- **$b\bar{b}$: Has the largest BR, but suffers from large BG.** The last major channel to be observed.
- **$\tau\tau$:** Good sensitivity with the VBF prod. **Observation of Higgs-fermion coupling.**
- $Z\gamma$, μμ: Very low BRs. Need to wait until the HL-LHC for μμ. $Z\gamma$ is challenging even for the HL-LHC.

Higgs Coupling

- Signal strength of main channels (H→γγ, H→ZZ, H→WW, H→ττ, H→bb) could be measured within **~5% (~10%) without (with) theory uncertainties**.
- Similar precision between ATLAS/CMS





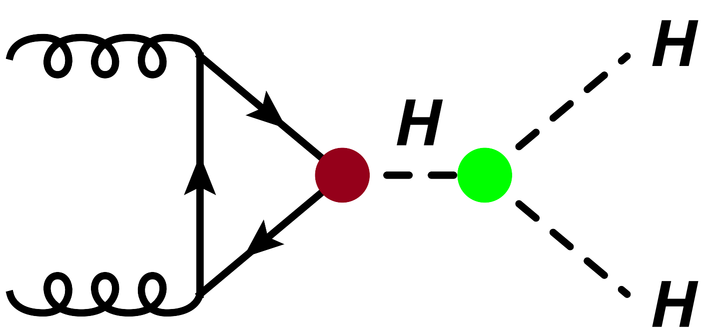
- **H→μμ:** 7.0σ significance w/ 3000 fb^{-1} w/ ATLAS. Probe coupling dependence on lepton-flavor.
- **H→inv.:** BR < 10% w/ 3000 fb^{-1} using the Z(ll)H channel only. With a reduced systematics, the VBF will provide a tighter constraint (*CMS-DP -2016-064*).

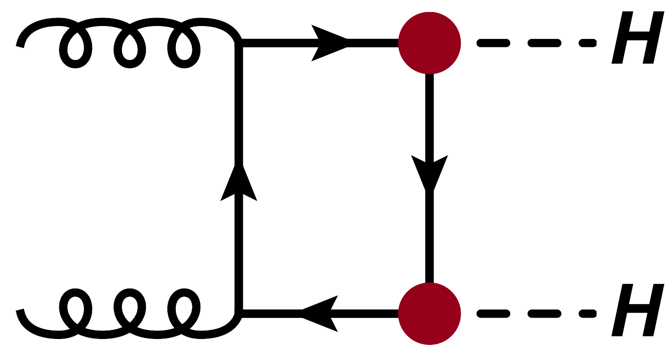
Snowmass, Energy Frontier Report, 2013

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

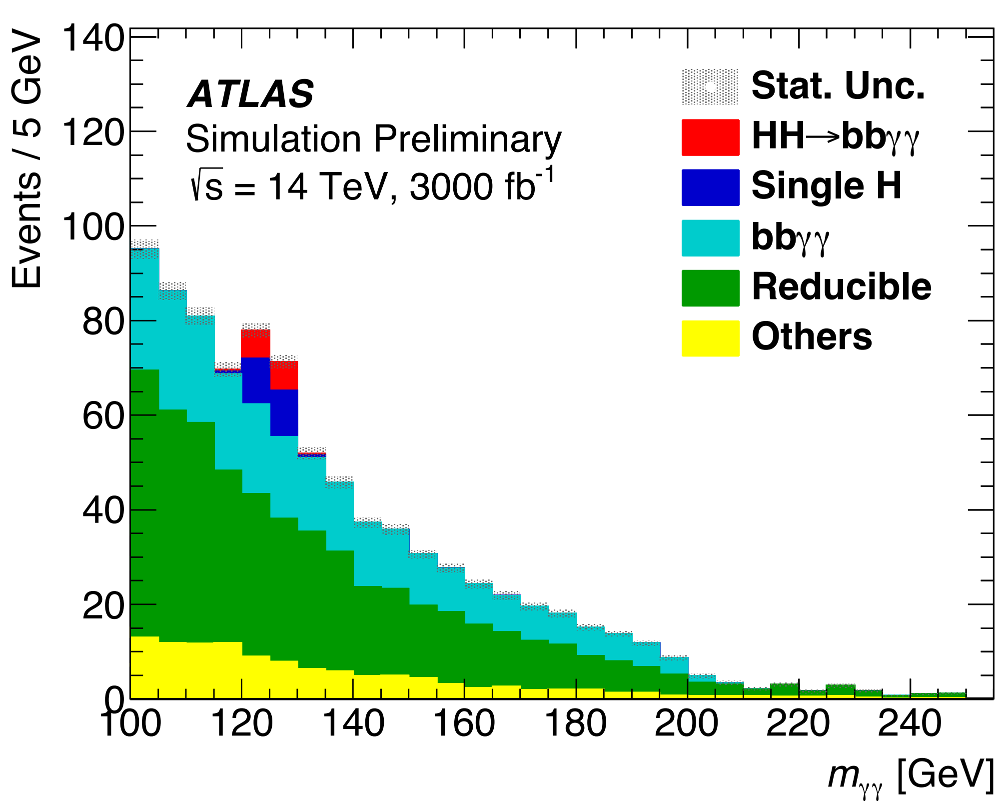
Higgs Self-Coupling

ATL-PHYS-PUB-2014-019, ATL-PHYS-PUB-2015-046, ATL-PHYS-PUB-2016-023, ATL-PHYS-PUB-2016-024, ATL-PHYS-PUB-2017-001





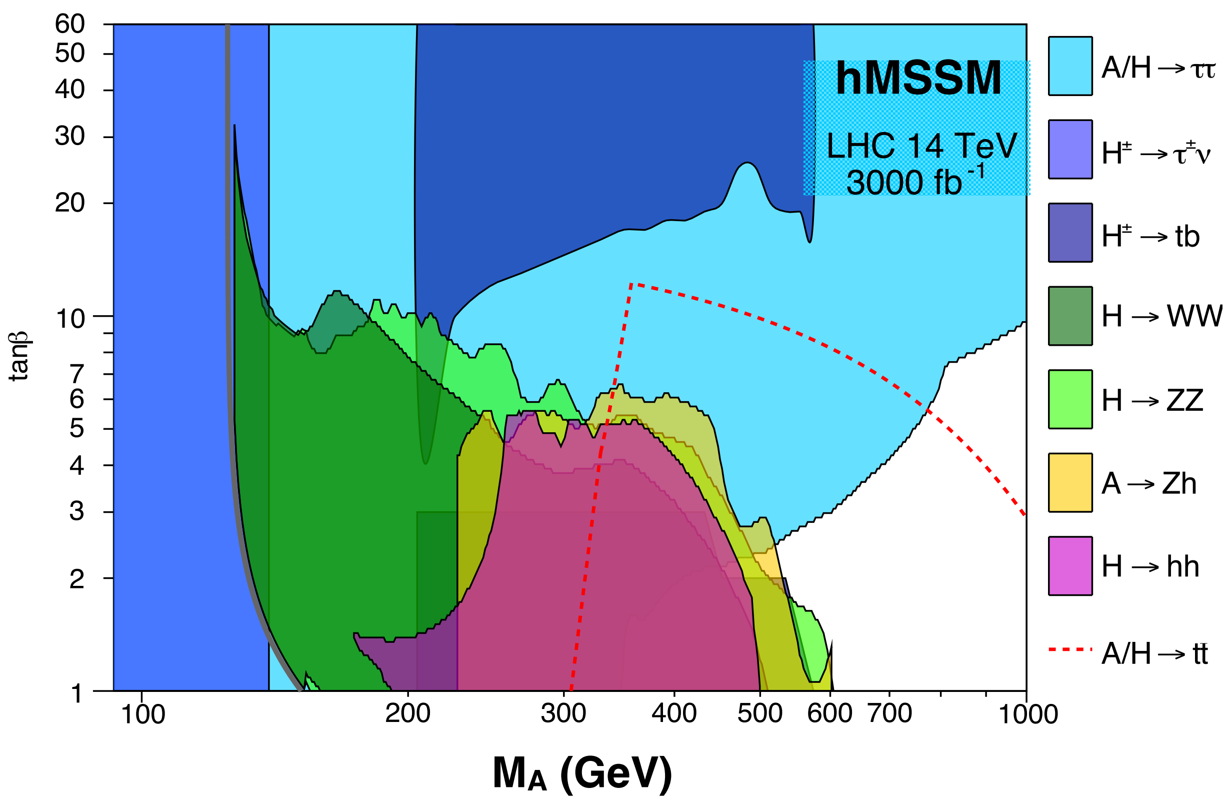
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b}+b\bar{b}$	33%	4.1×10^4
$b\bar{b}+W^+W^-$	25%	3.1×10^4
$b\bar{b}+\tau^+\tau^-$	7.4%	9.0×10^3
$W^+W^-+\tau^+\tau^-$	5.4%	6.6×10^3
$ZZ+b\bar{b}$	3.1%	3.8×10^3
$ZZ+W^+W^-$	1.2%	1.4×10^3
$\gamma\gamma+b\bar{b}$	0.3%	3.3×10^2
$\gamma\gamma+\gamma\gamma$	0.0010%	1



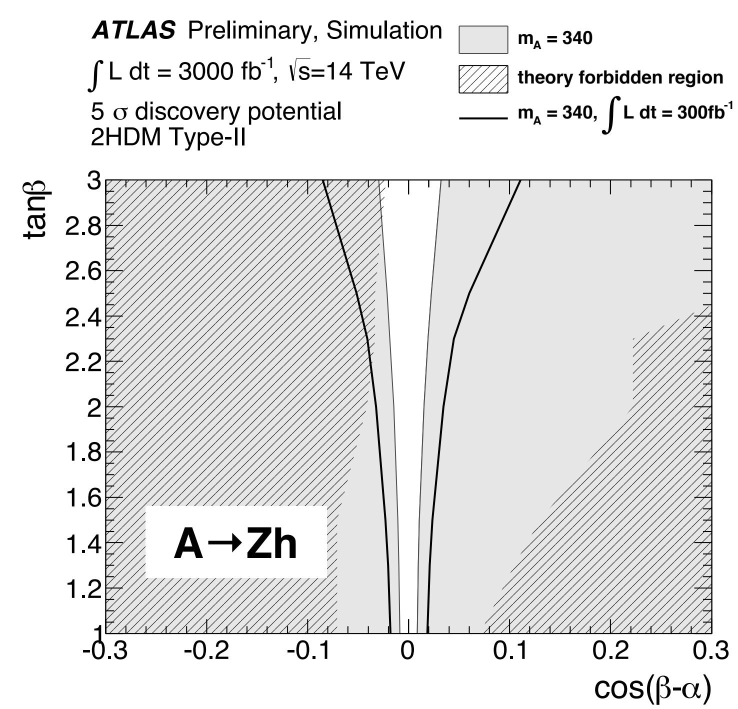
- HL-LHC provides sizable statistics of pair-produced Higgs boson events.
- Constraints on the Higgs self-coupling can be extracted from non-resonant HH production.
- bb$\gamma\gamma$: **$-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$** (95%CL, no syst.)
  bbbb: **$0.2 < \lambda_{HHH}/\lambda_{SM} < 7.0$** (95%CL, no syst.),
  $-3.5 < \lambda_{HHH}/\lambda_{SM} < 11$ (95%CL, Run-2 syst.)
  bb$\tau\tau$: **$-4 < \lambda_{HHH}/\lambda_{SM} < 12$** (95%CL, no syst.)
- **These are all cut-and-count studies.** Sensitivities should improve with shape information.

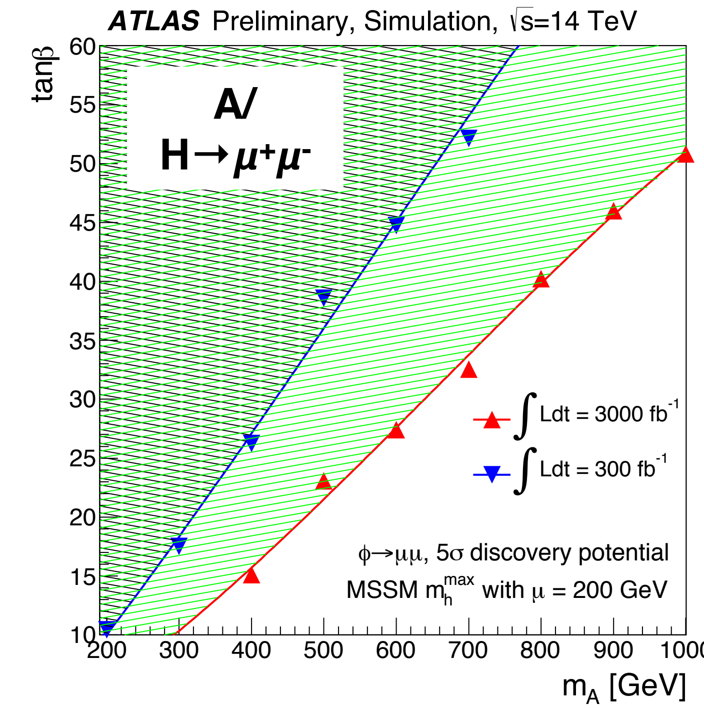
Heavy Higgs

J.Baglio, A.Djouadi,J.Quevillon, Rep. Prog. Phys. 79 (2016) 116201



ATL-PHYS-PUB-2013-016





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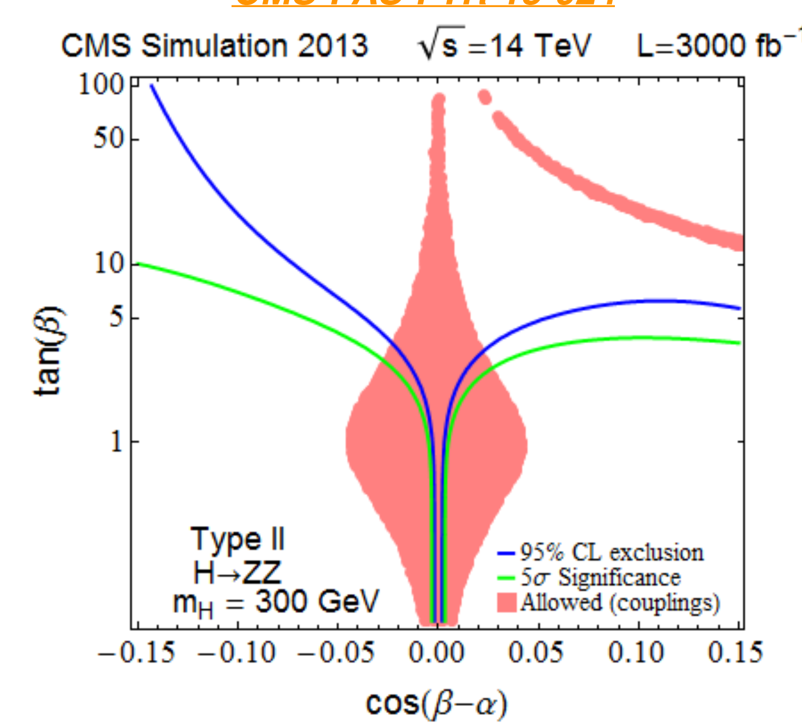

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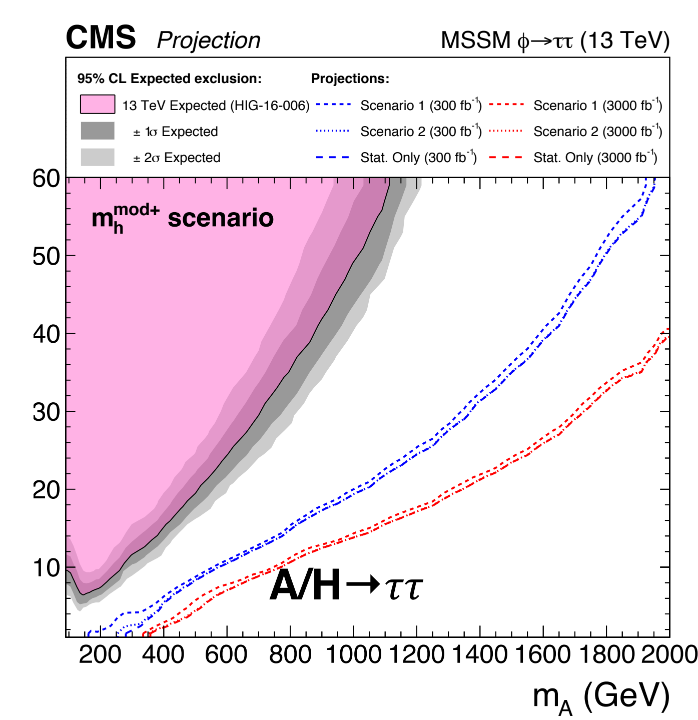

- **Large phase space of the M_A-tanβ plane up to M_A~1 TeV** will be covered by the various channels under consideration
- **A/H→$\tau\tau$, tt are dominant in the high mass region.**