Higgs and Electro-weak Physics at the LHC

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on behalf of ATLAS and CMS

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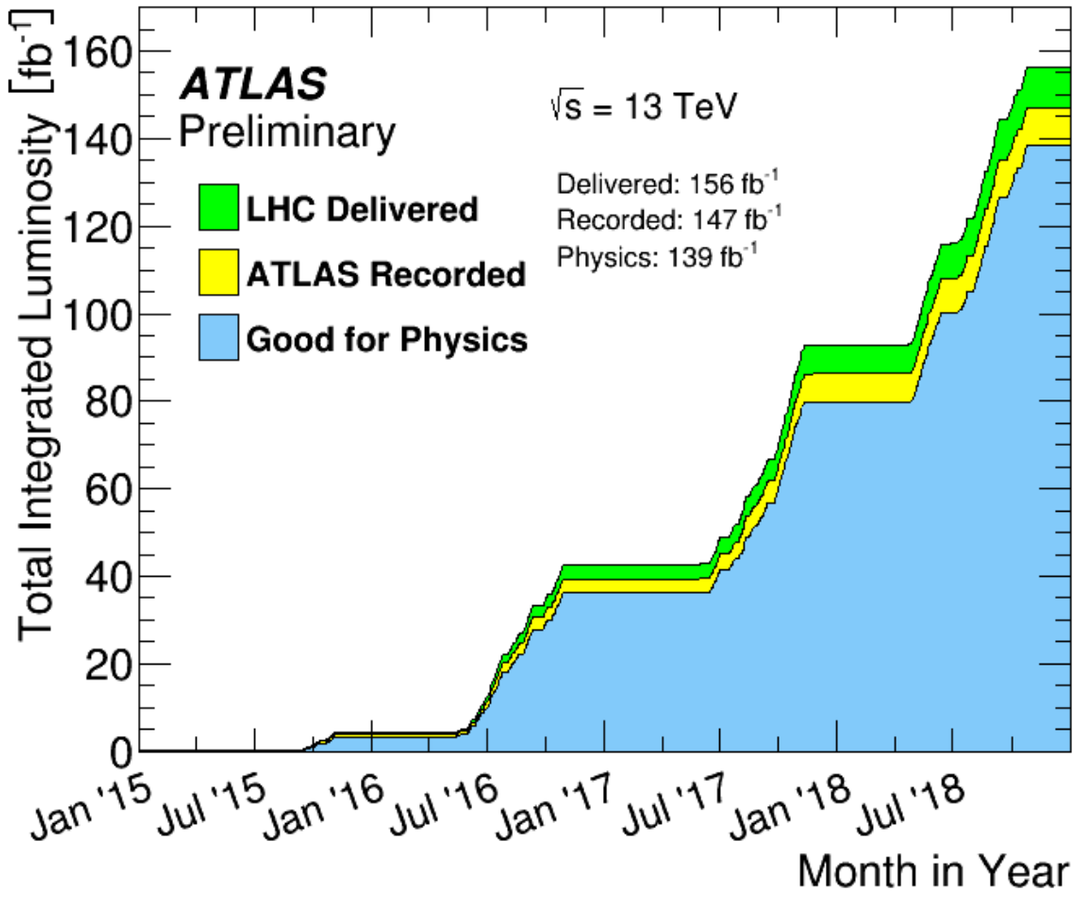
Introduction

- Electroweak physics is at the heart of the physics program at the LHC.
  - The first chance to directly study the electroweak symmetry breaking and the quantum of the Higgs field, the Higgs boson.
  - Many predictions of the SM have been tested, but several still remain to be probed.
- New physics could hide in the details.
  - History tells us that percent level precision could be necessary to probe effects from new and heavy virtual particles.



- Precision measurements take time to complete.
  - The Run 2 of the LHC (2015-2018) saw about 150 fb^{-1} of data being delivered to the experiments.
  - Most results shown today use the 2015-2016 dataset (~36 fb^{-1}) or the 2015-2017 dataset (~80 fb^{-1}), a few use the full Run 2 dataset, corresponding to ~140 fb^{-1} of data useable for physics.
- Will quickly summarise the current status, and highlight some of the new results being produced this summer.

SM Electroweak Measurements

- High-precision measurements of key EW parameters such as m_W and $\sin^2\theta_W$.
  - New results involving single W and Z boson production will be covered in the "QCD at the LHC" talk by Lauren on Thursday afternoon.
- Precision measurements of di-boson production, including differential cross sections.
- Starting to probe very rare processes such as Vector Boson Fusion (VBF) and Vector Boson Scattering (VBS) production of di-boson pairs.
  - Will go through some recent di-boson results in the following slides.

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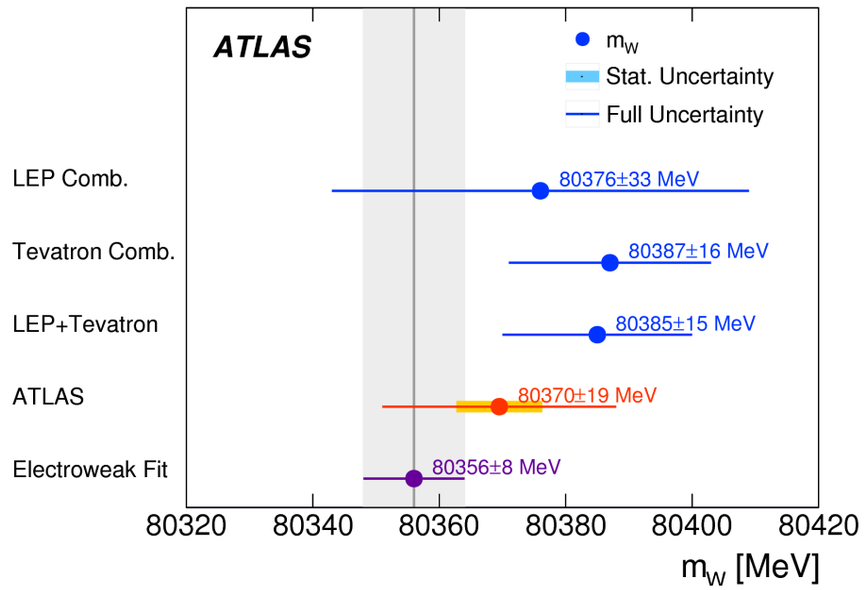

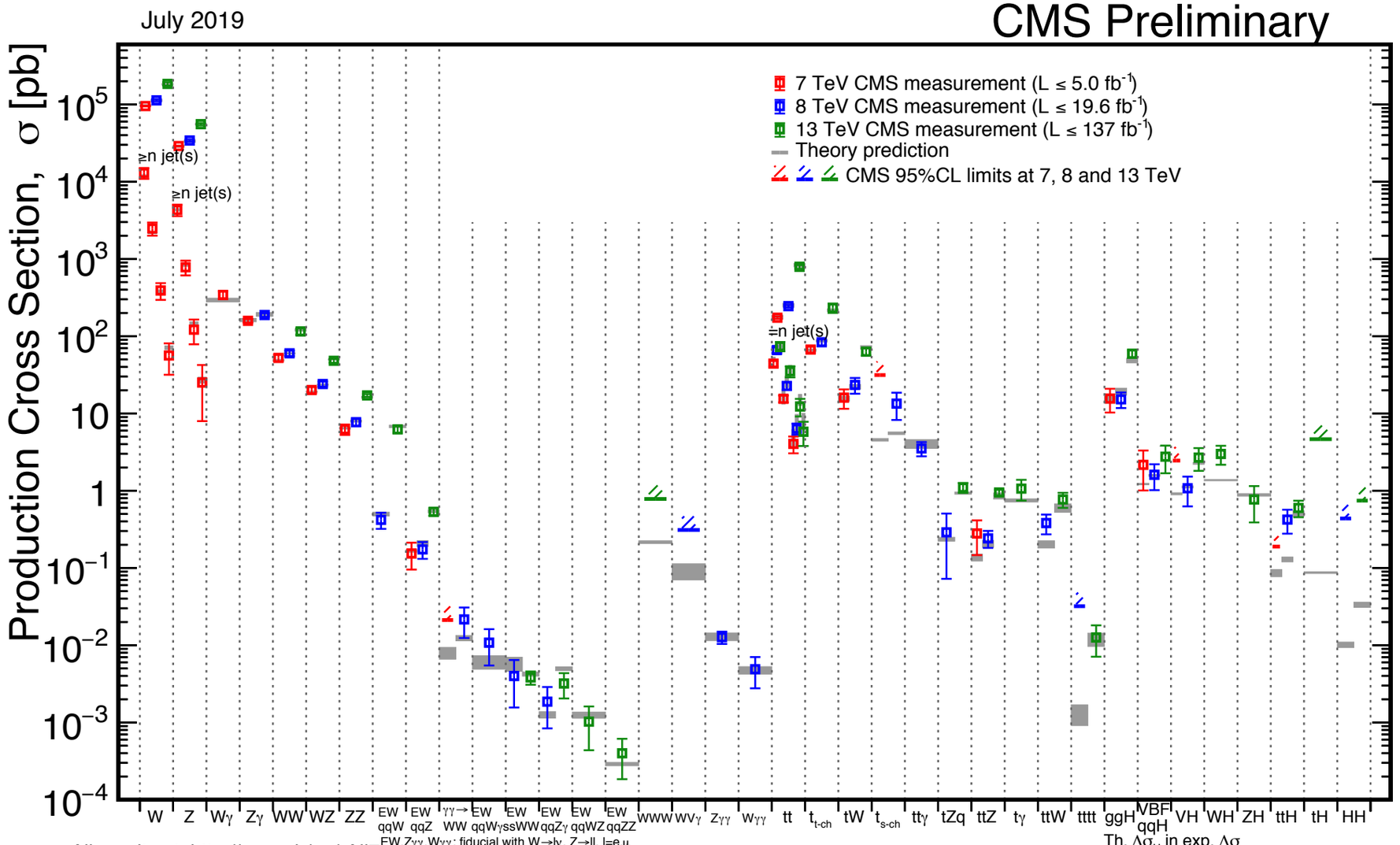

WW and WZ Production

- Precision measurement of WW and WZ cross sections using 36 fb^{-1} of data.
  - Including differential distributions and WZ charge asymmetries.
- First measurement of the W and Z boson polarisation in WZ production.
  - The Higgs field provides the longitudinal polarisation degree of freedom.

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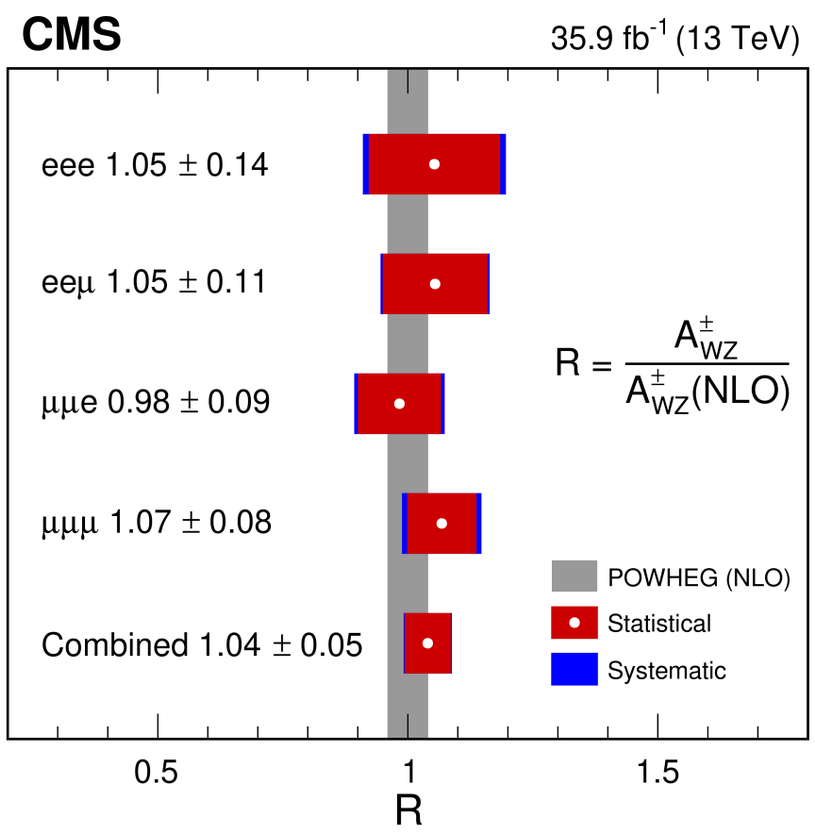
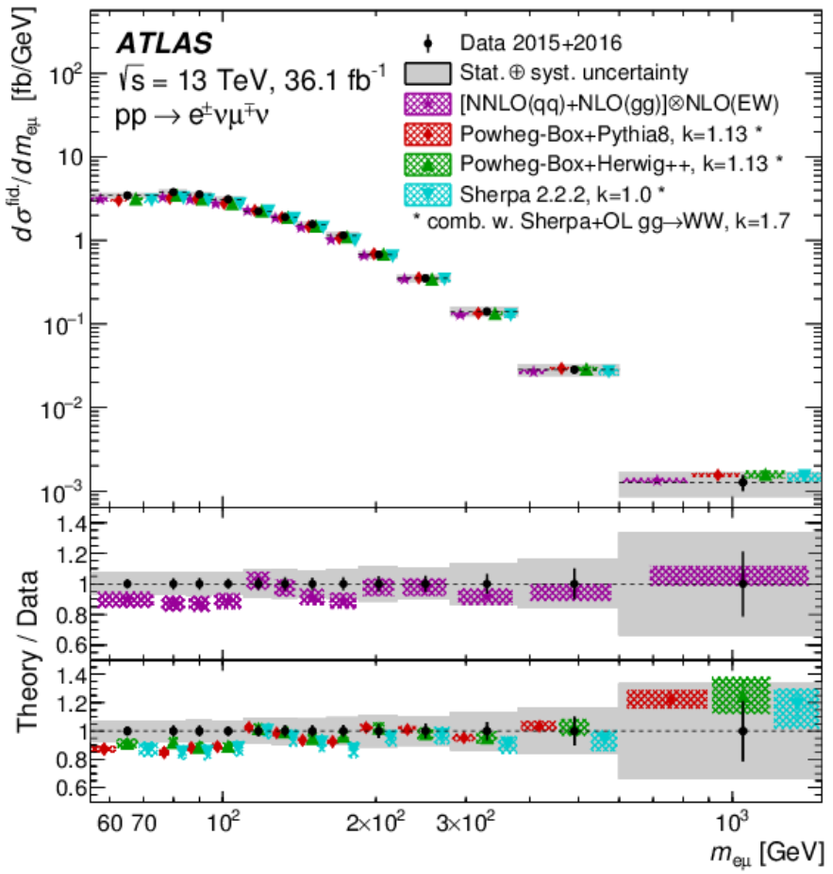
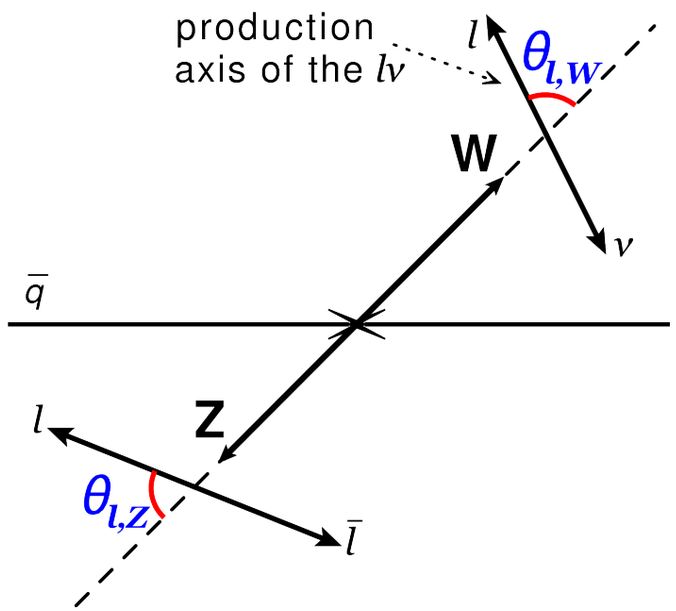
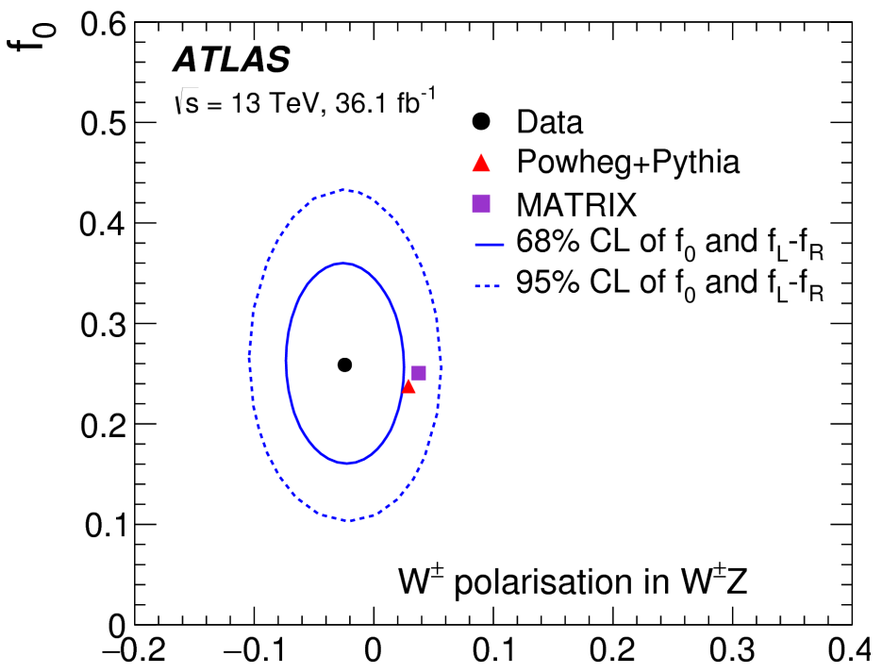
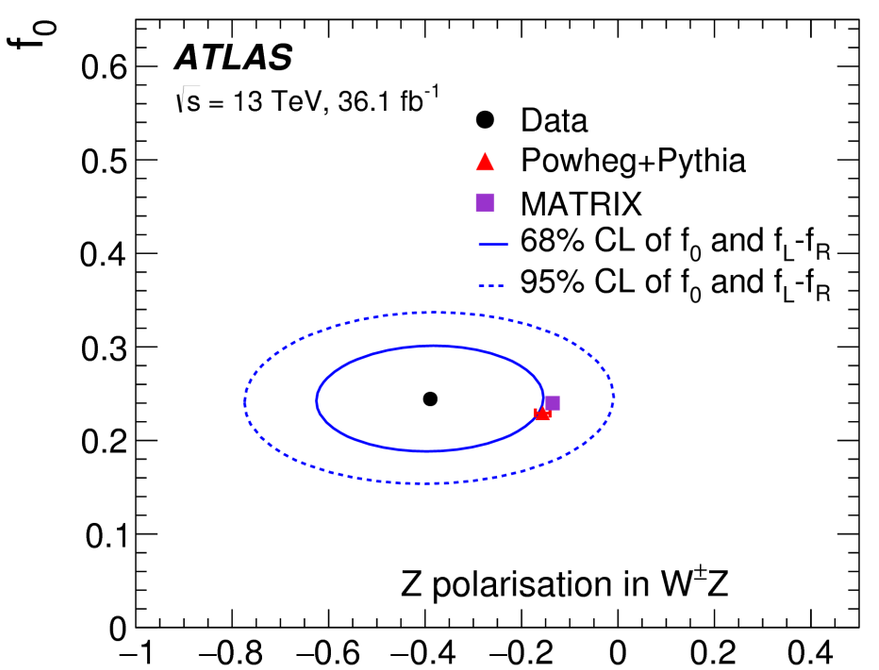


arXiv:1905.04242









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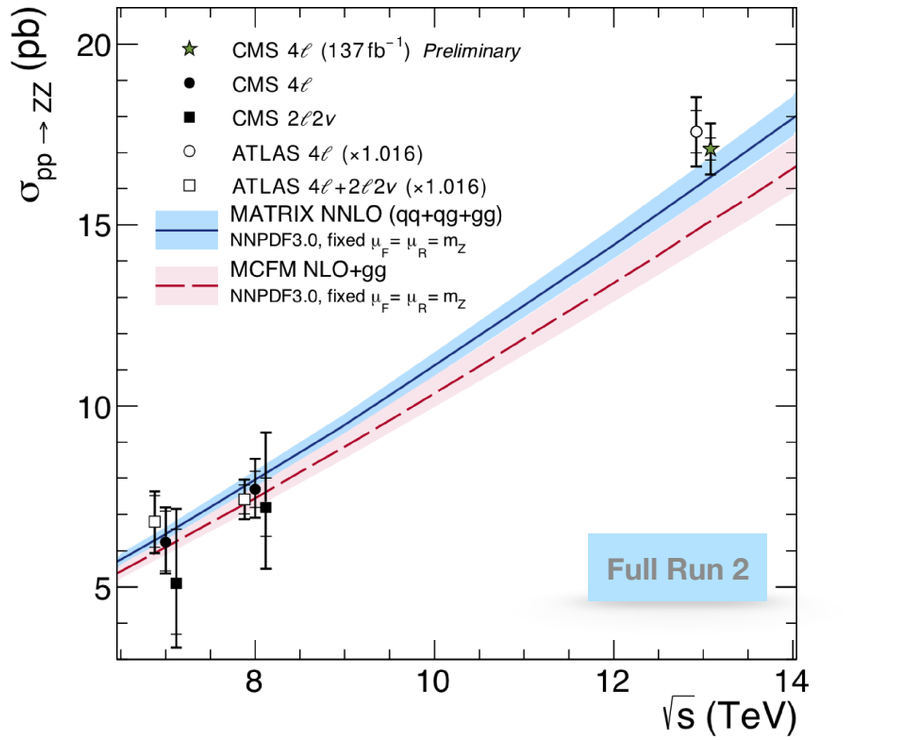
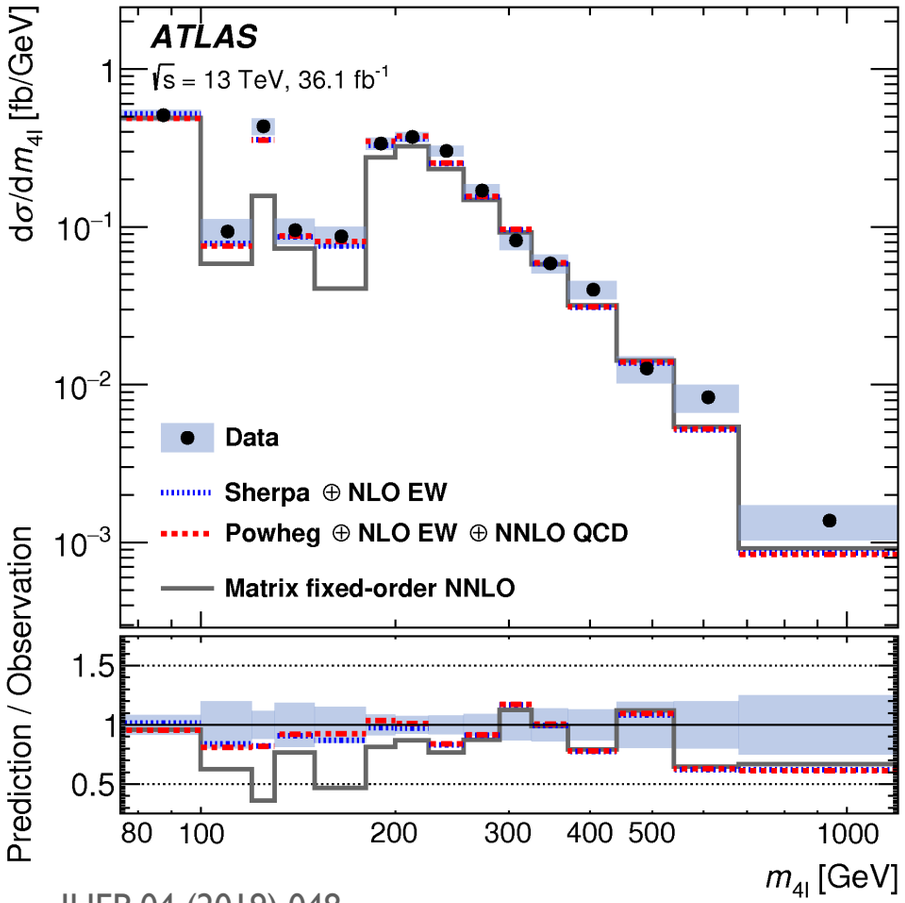
ZZ and Zγ Production

- Cross section measurement for ZZ production using the full Run 2 dataset.
  - NNLO calculation necessary to agree with the ZZ cross section measured in data.
  - Measurement of the full 4ℓ invariant mass spectra using 36 fb^{-1} of data.
- Total and differential Zγ cross section measured with the full Run 2 dataset.

CMS-PAS-SMP-19-001





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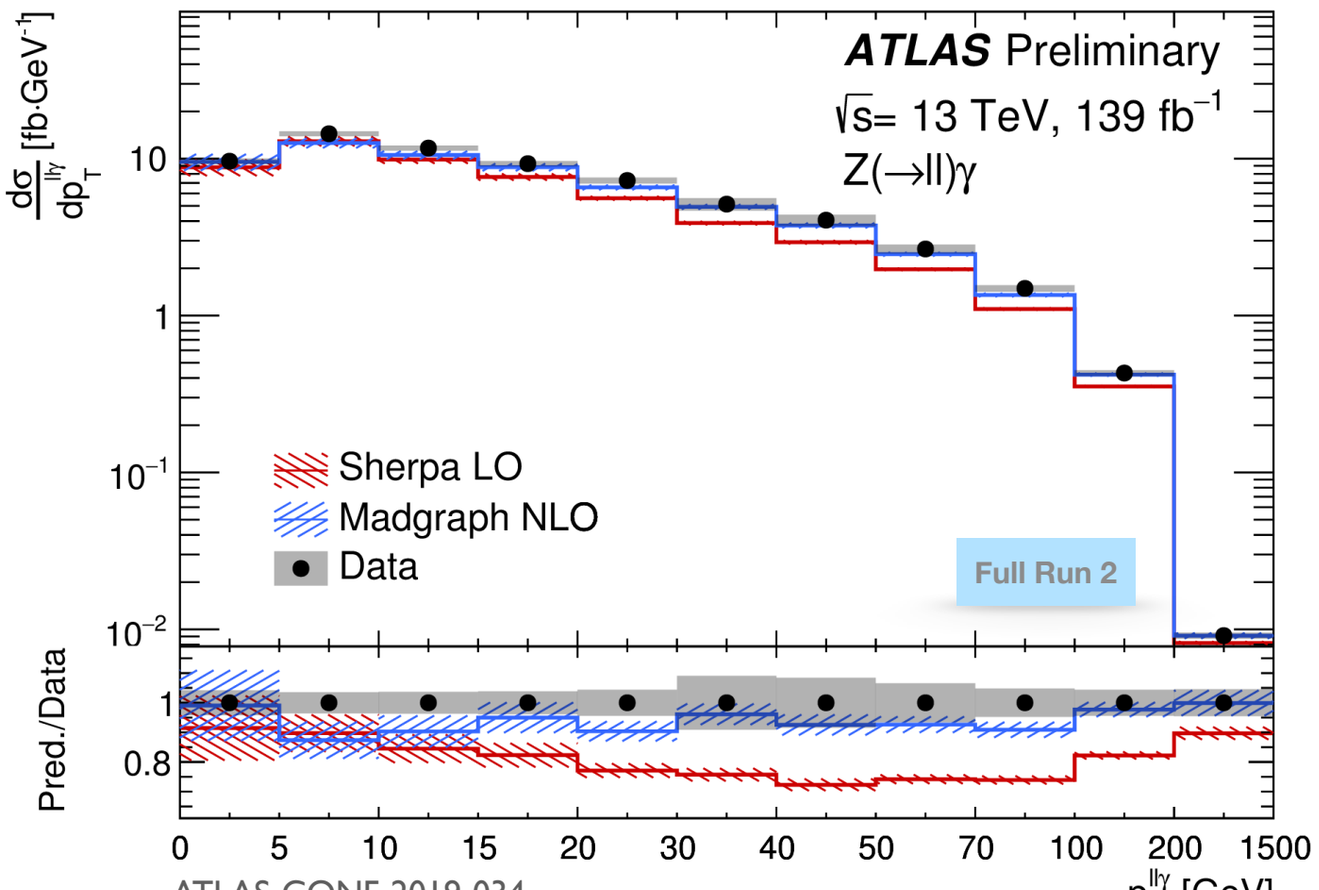
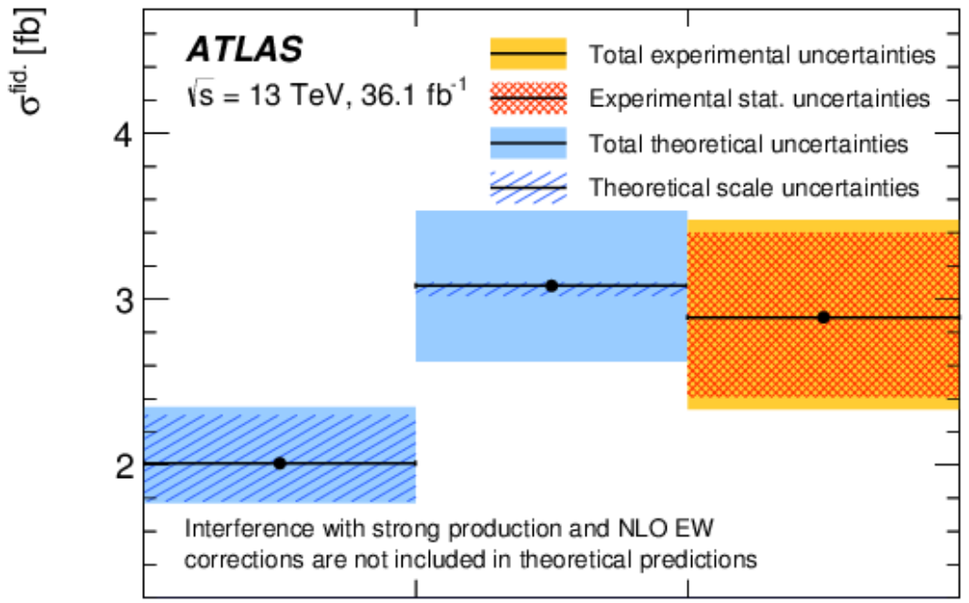
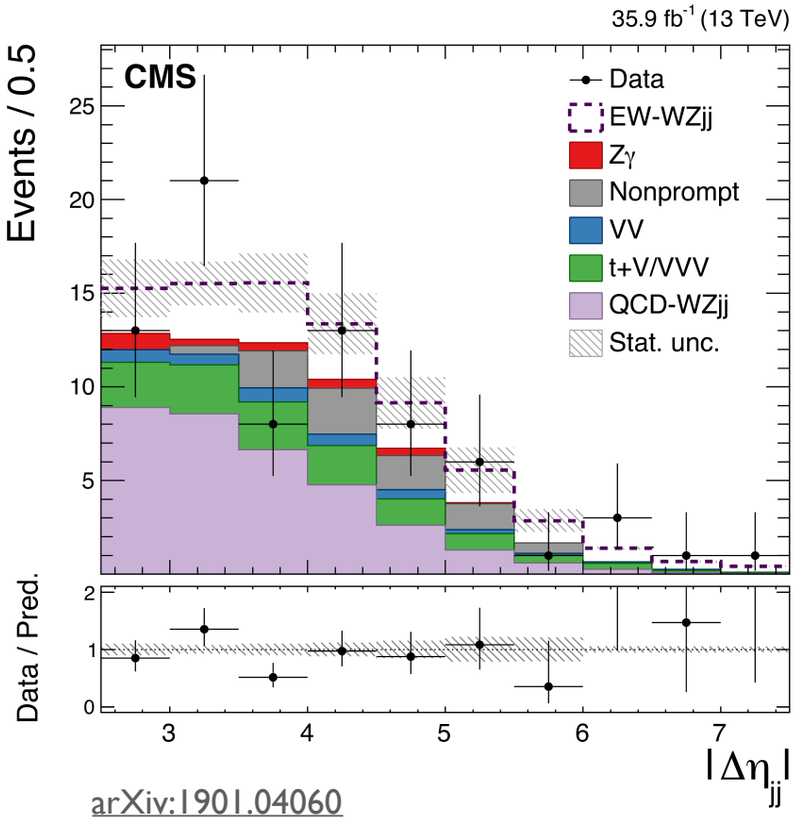


ATLAS-CONF-2019-034

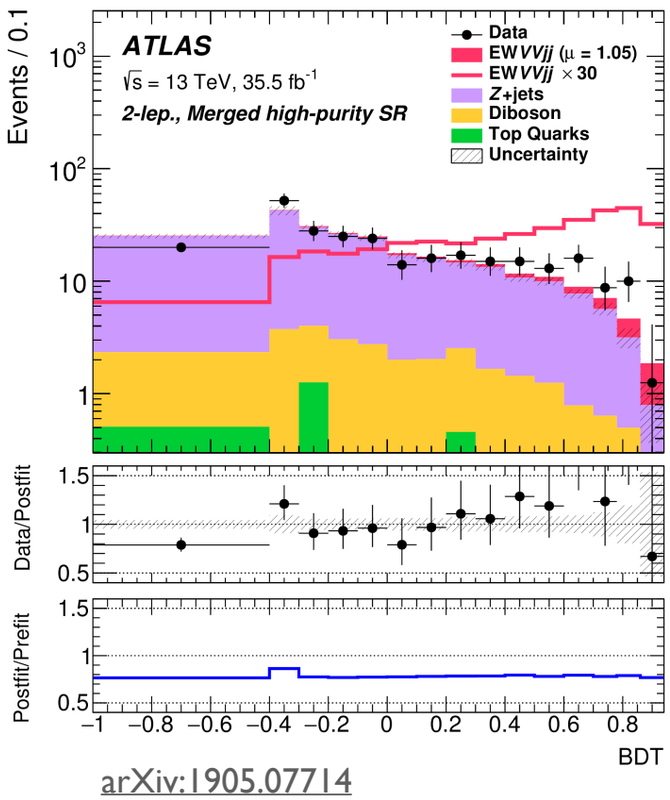
Electroweak Production of WW and WZ

- Electroweak production of same-charge WW pairs measured with 36 fb^{-1} of data.
  - Signal observed with 6.5σ significance.
- CMS measures electroweak production of WZ pairs with a significance of 2.2σ.
  - For details on the corresponding ATLAS measurement, please see the talk by Despina Sampsonidou this afternoon.
- ATLAS measures electroweak VV (WW, WZ, and ZZ) production in the semi-leptonic decay mode with a significance of 2.7σ.





arXiv:1901.04060



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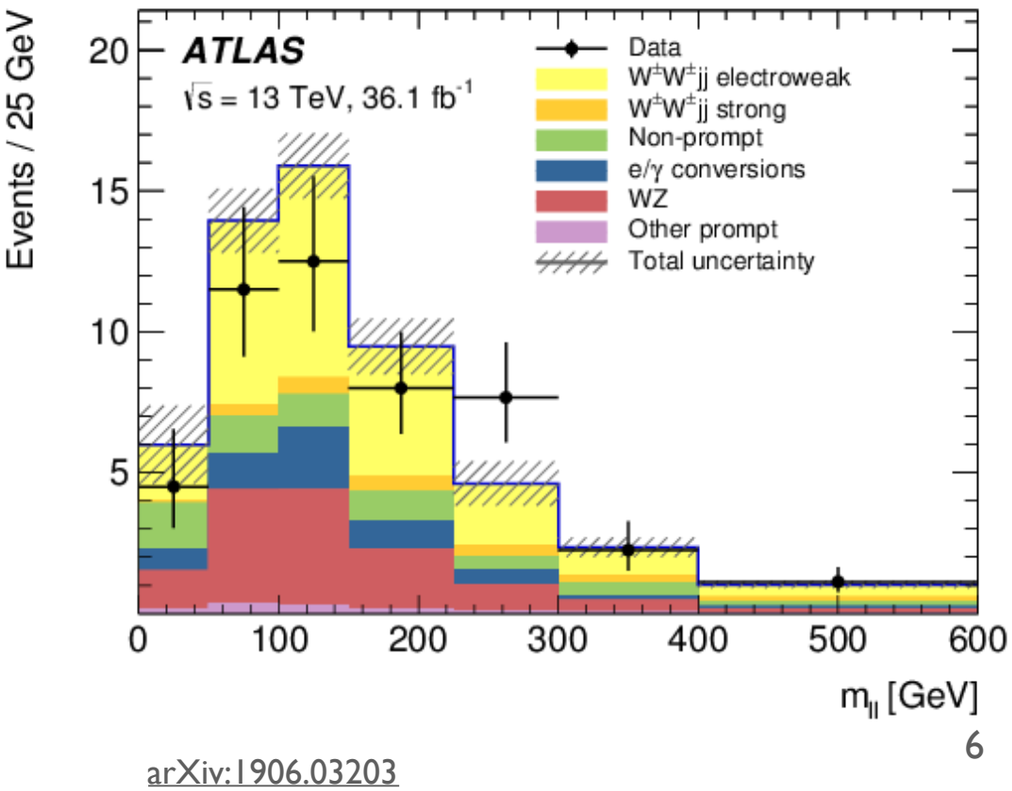
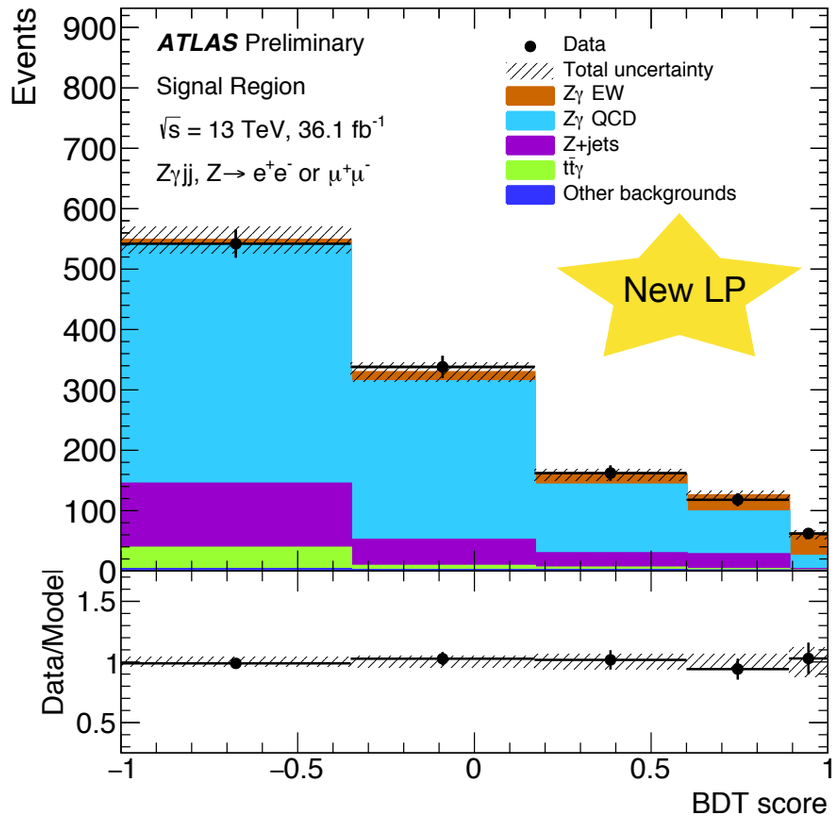


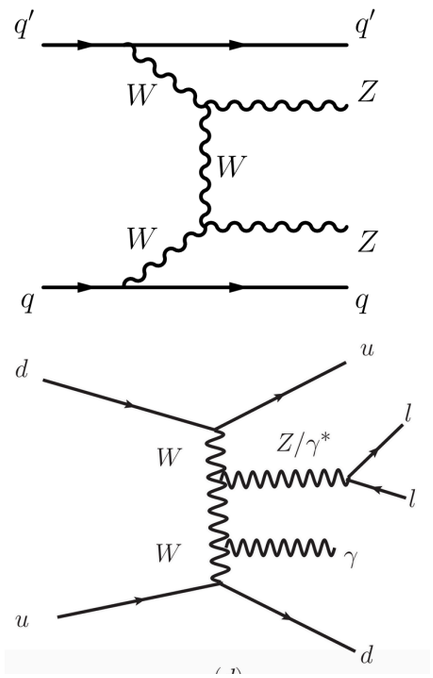
arXiv:1906.03203

Electroweak Production of ZZ and Zγ

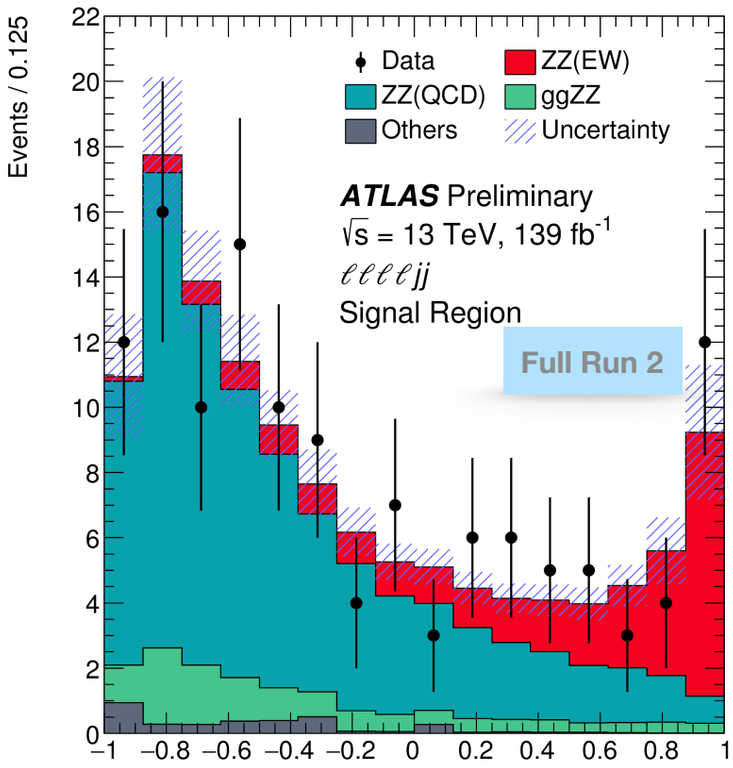
- EW production of ZZ pairs using the $\ell\ell\ell\ell jj$ and $\ell\ell\nu\nu jj$ final states observed with 5.5σ significance using the full Run 2 dataset.
- CMS and ATLAS recently measured electroweak Zγ production using ~36 fb^{-1} of 13 TeV data.
  - Combined with 8 TeV result yields an observed significance of 4.7σ for CMS and the 13 TeV data alone give 4.1σ for the ATLAS result.
- Signal strength in fiducial region for EW Zγ production:
  - $\mu_{EW} = 0.64^{+0.23}_{-0.21}$ (CMS).
  - $\mu_{EW} = 1.0 \pm 0.26$ (ATLAS).

ATLAS-CONF-2019-039





Example EW ZZ/Zγ production diagrams



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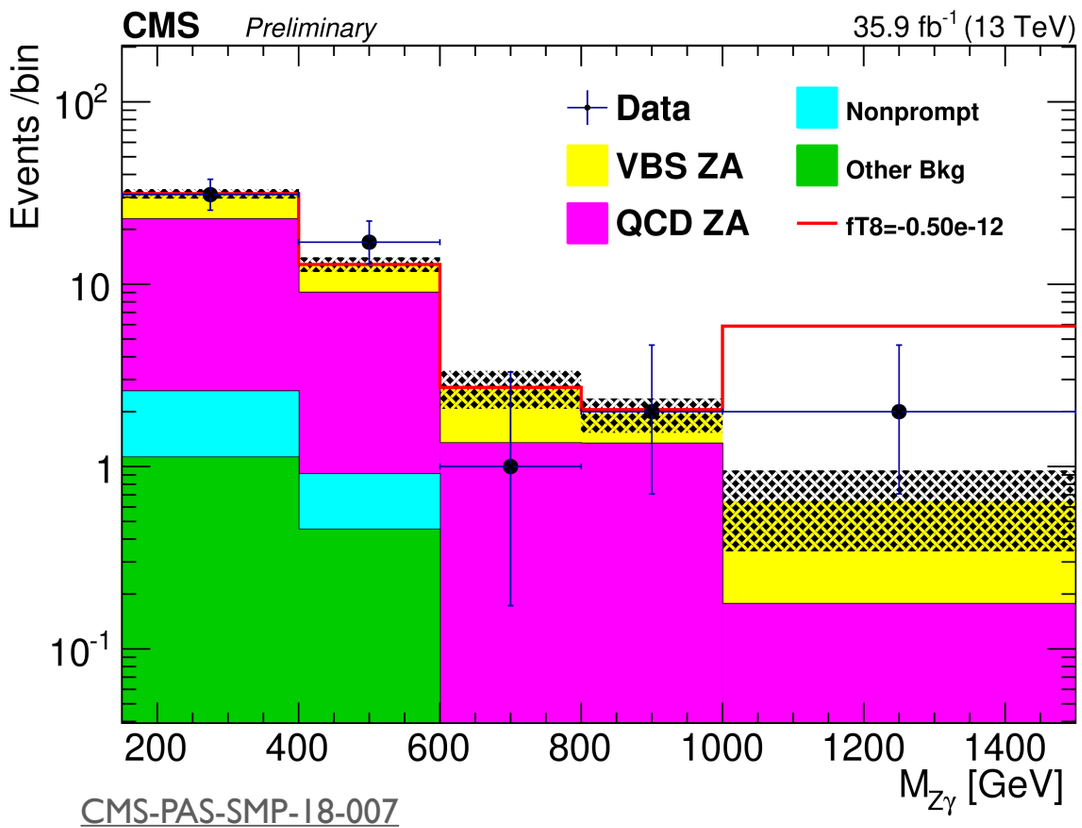
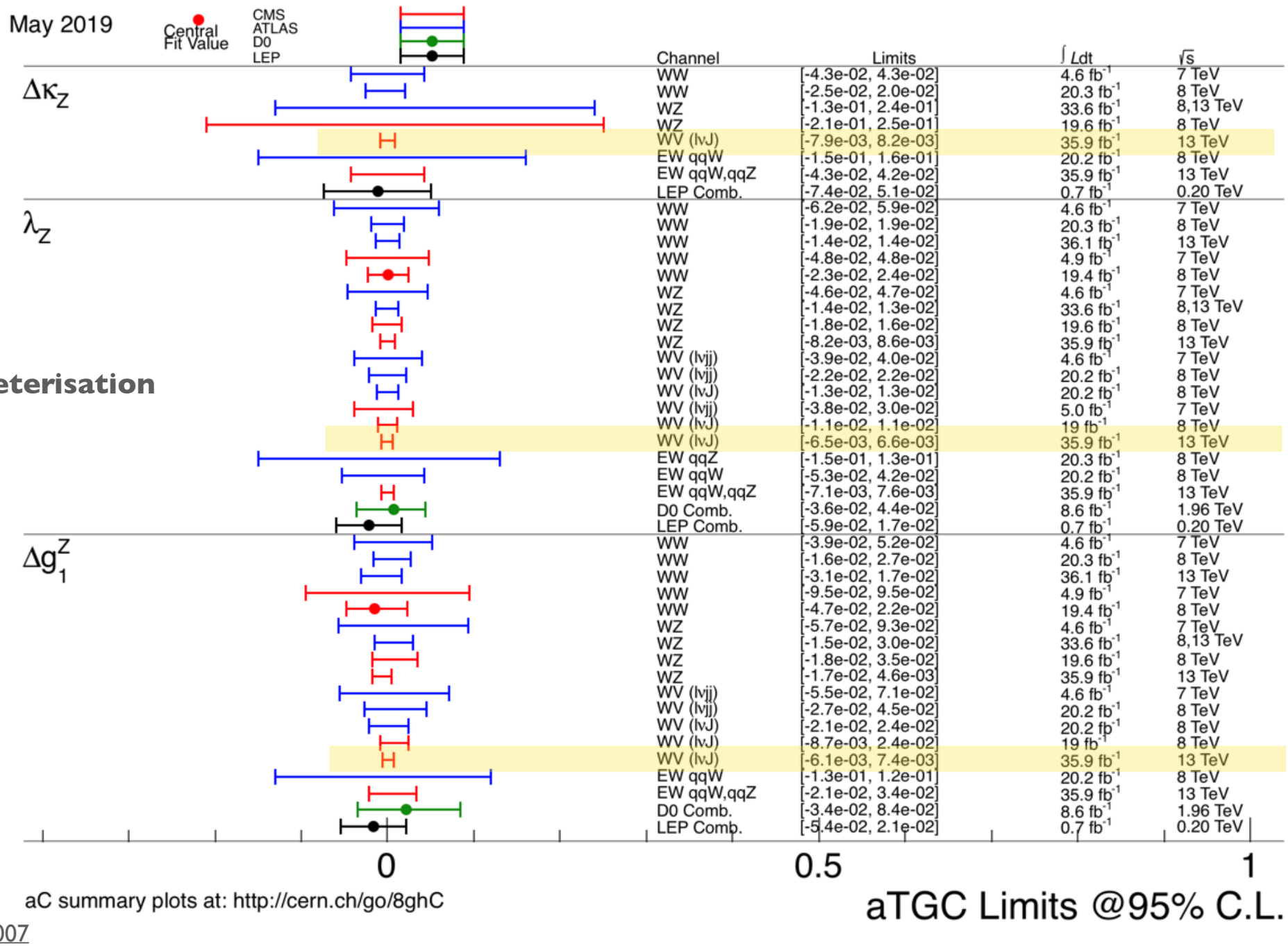


CMS-PAS-SMP-18-007

Di-bosons: Anomalous Couplings

- CMS place limits on anomalous triple gauge boson couplings (aTGC) using the measurements of WW, WZ and ZZ semi-leptonic decays.
  - Most stringent constraints to date on new non-SM couplings for WWγ and WWZ interactions. Put limits on the $\Delta\kappa_Z$, λ_Z, and Δg_1^Z parameters in the LEP parameterisation.

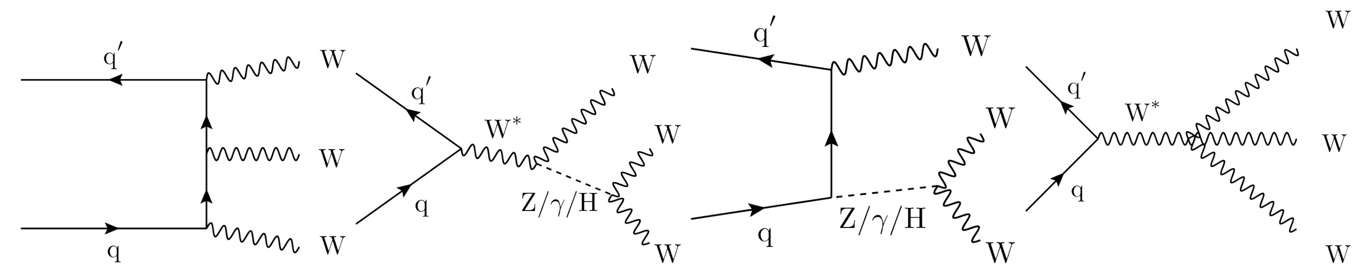
LEP Parameterisation



CMS-PAS-SMP-18-007

Tri-boson VVV Production

- Observed WVV production with 4σ significance (3.1σ expected) using 79.8 fb^{-1} of ATLAS data.
  - CMS searched for $W^{\pm}W^{\pm}W^{\mp}$ production, signal significance 0.6σ (1.8σ expected), using 35.9 fb^{-1} of data.
- Limits are placed on three anomalous quartic gauge couplings and on the production of massive axion-like particles.
  - Masses in the range $200 < m_a < 480$ GeV are excluded for the parameter value $1/f_a = 5\ TeV^{-1}$.



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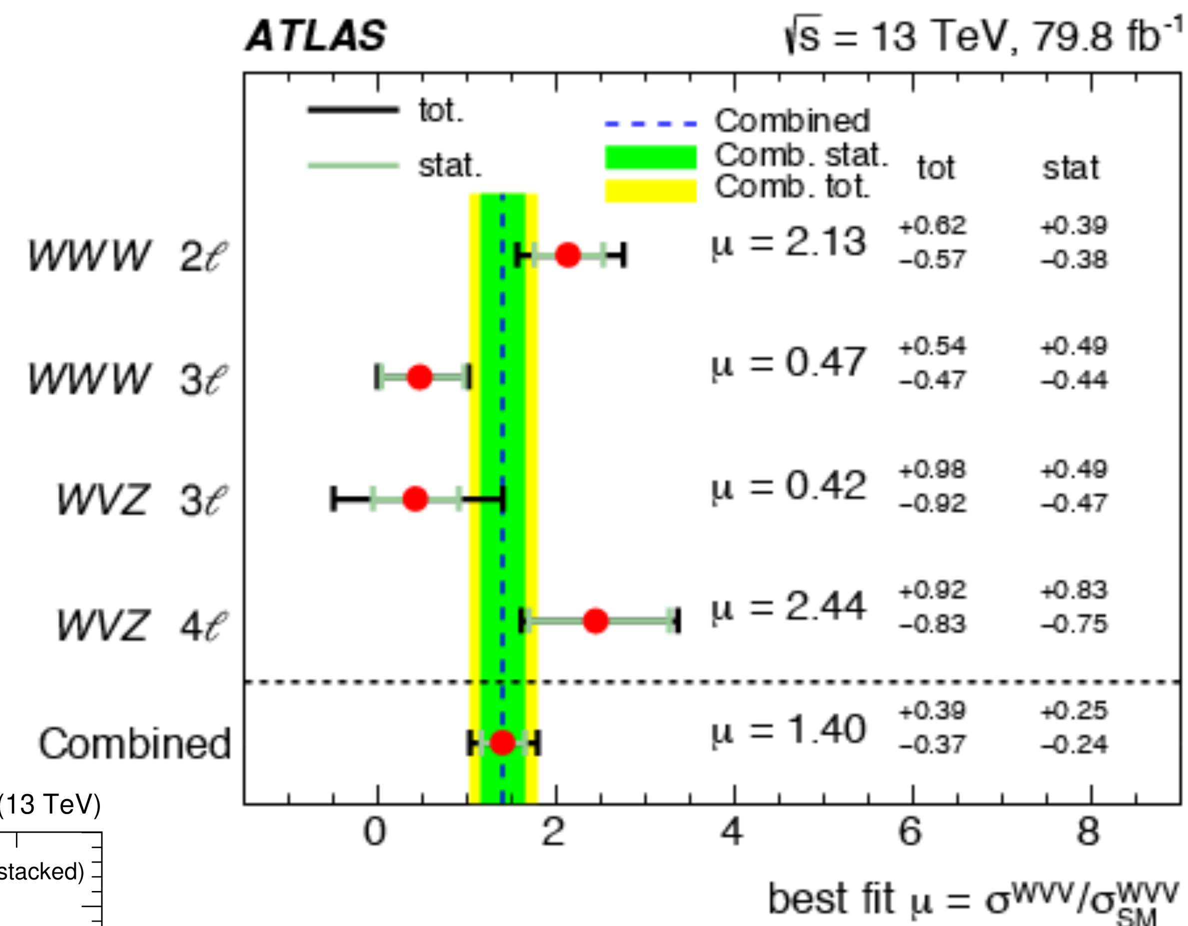

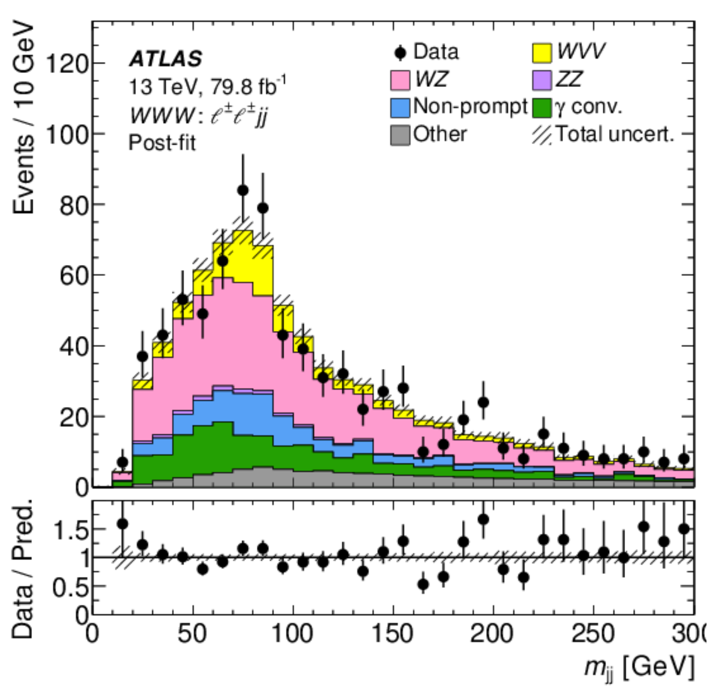

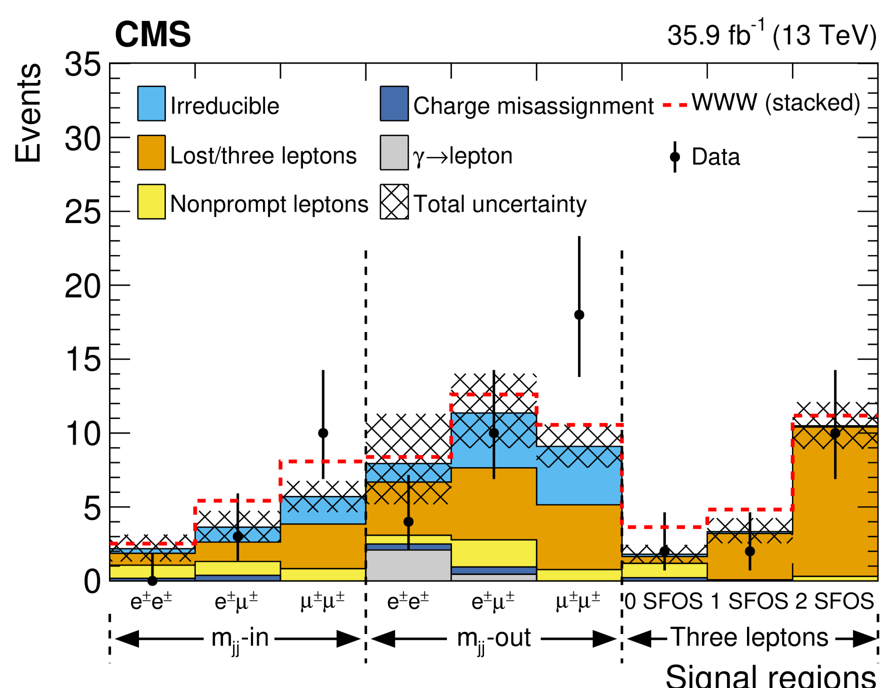

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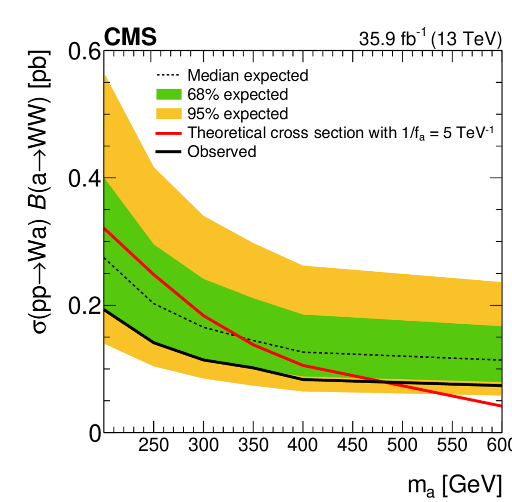
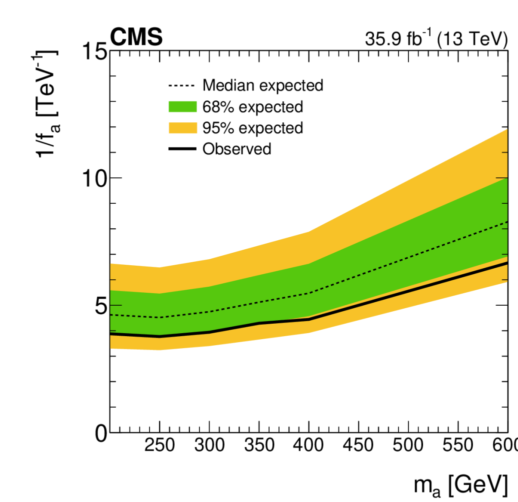
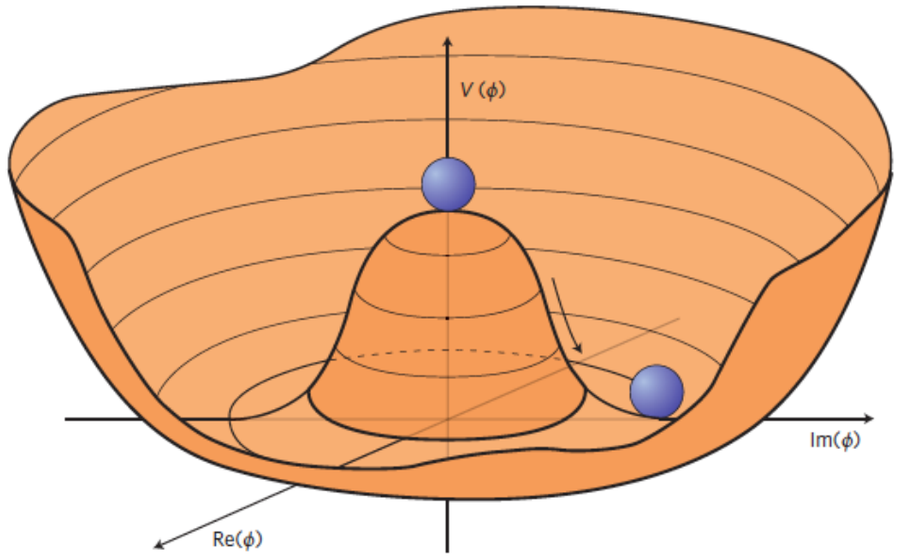
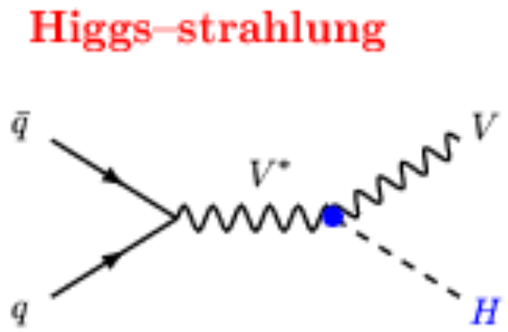


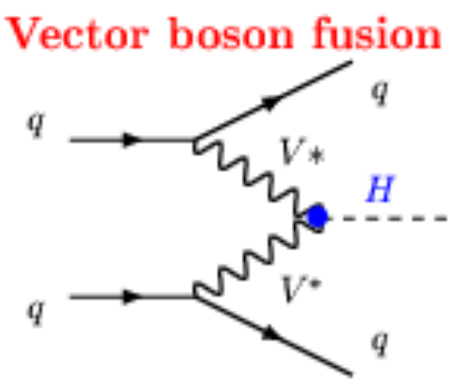


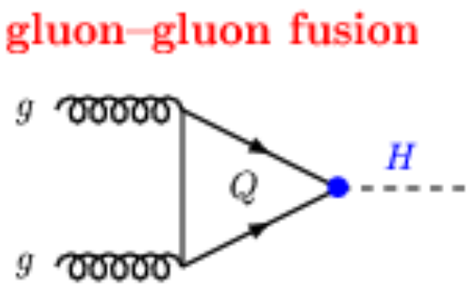
The Higgs Boson

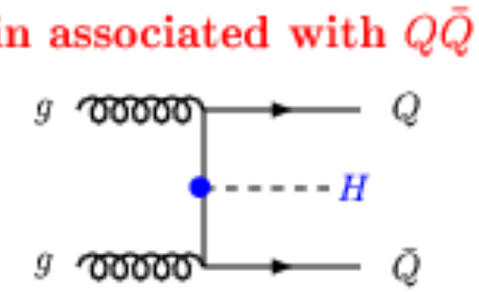
- The spontaneous symmetry breaking of the Higgs field responsible for generating particle masses.
  - The quantum of the Higgs field is the Higgs boson, discovered in 2012 by ATLAS and CMS.
- Higgs boson couples to the other SM particles:
  - To bosons (W, Z) with strength ~M_V^2/v, where v is the vacuum expectation value $v \approx 246$ GeV.
  - To fermions (f) with strength ~M_f/v.
  - These couplings completely determine the production and decay probabilities.
  - Would like to experimentally test all these different couplings of the Higgs boson.

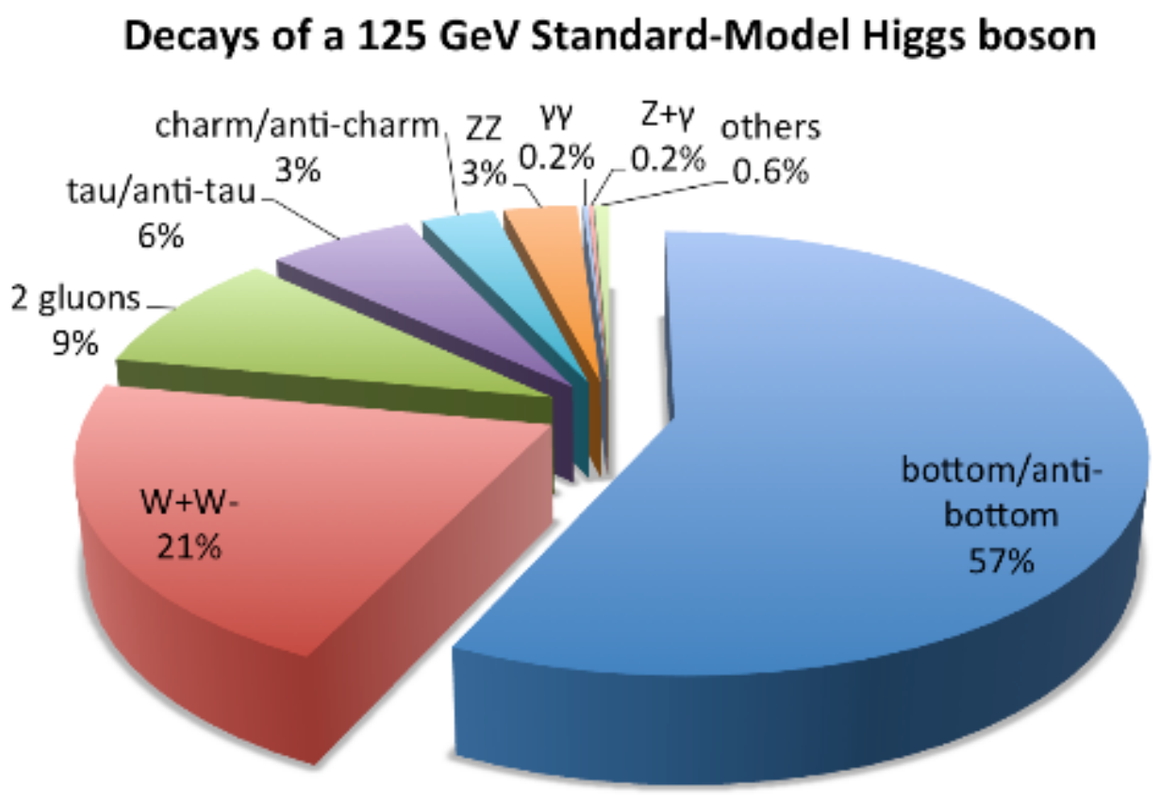






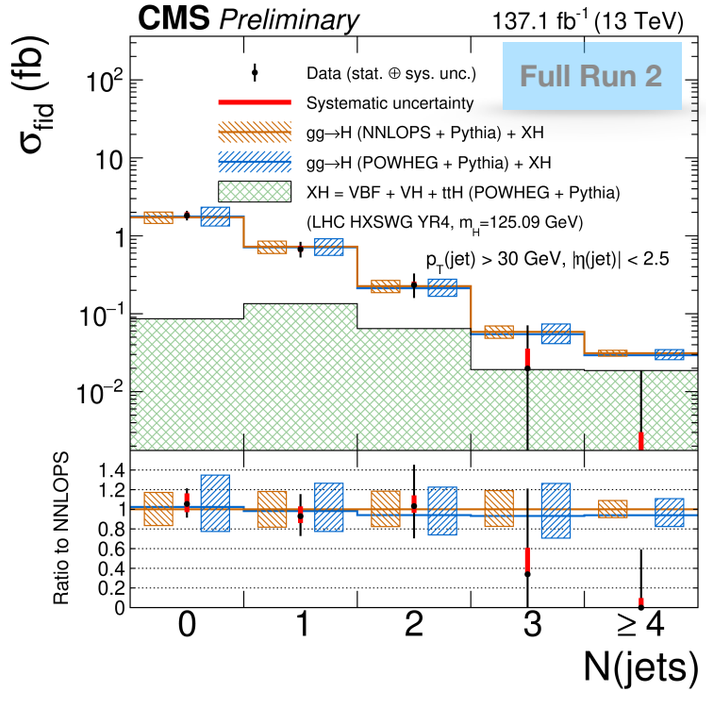






Differential Measurements and STXS

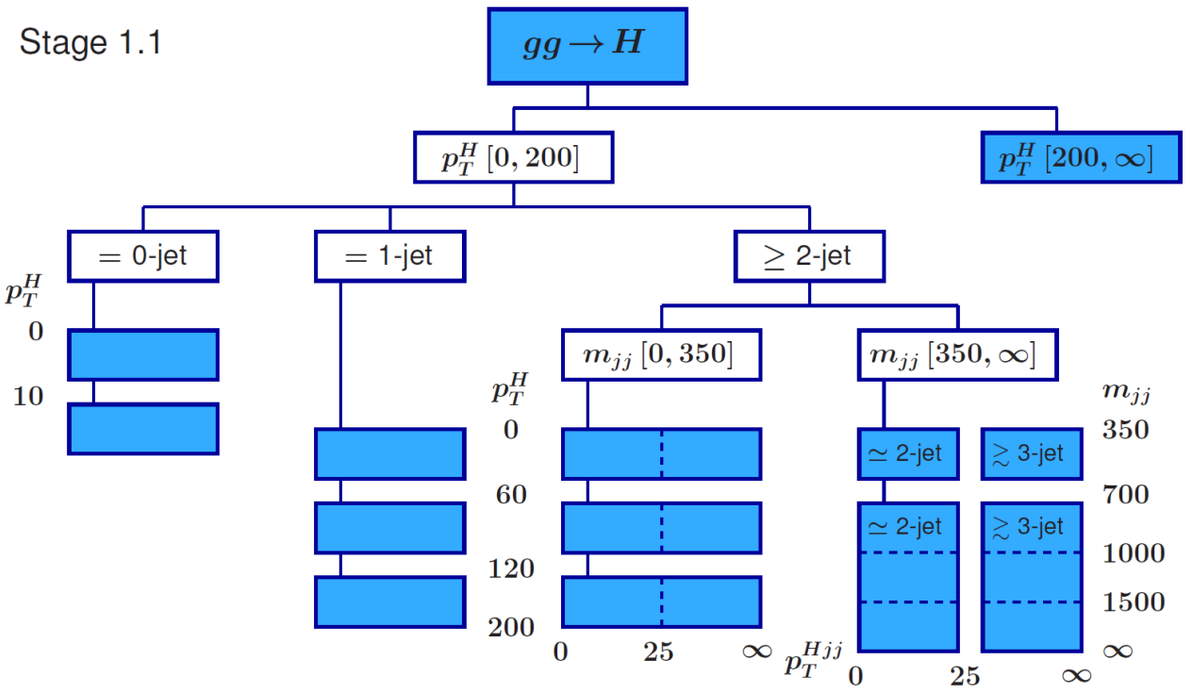
- Fiducial and differential cross sections:
  - Measure the rate of Higgs boson production in a certain region(s) of phase space, e.g. in different regions of Higgs boson p_T.
  - *Inclusive* in Higgs boson *production mode*.



CMS-PAS-HIG-19-001

Example: Fiducial cross section as a function of number of jets in the H→ZZ→4ℓ final state.

Example: STXS stage 1.1 for ggF production

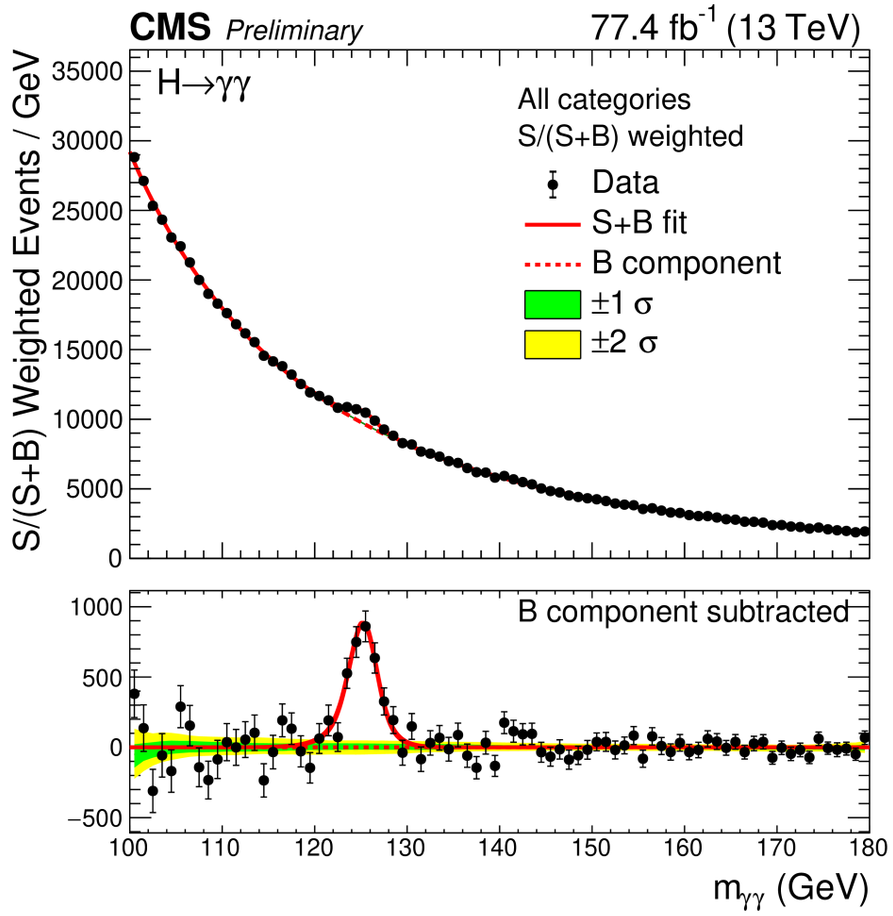


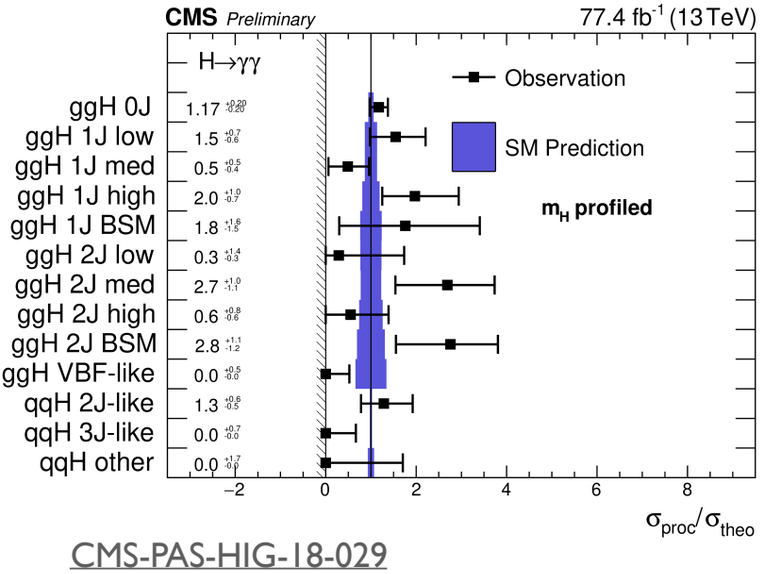
LHCHXSWG

- Simplified Template Cross Sections (STXS). Dividing phase space into bins:
  - According to *production mode*, and kinematic distributions like number of jets, $p_T(H)$, and m_{jj} (where applicable).
  - Designed to reduce impact of theoretical uncertainties on the results.
  - Bins are merged if lack of statistics, called different "stages" of STXS.
- Defined set of regions allows for combination of different Higgs channels and across ATLAS and CMS.

Higgs to bosons: H→γγ

- Events divided the into different categories depending on γγ quality and associated objects.
  - Fit peak in the invariant mass spectrum, $m_{\gamma\gamma}$, on top of a continuous background from non-resonant γγ production.
- Total Higgs cross section measured, $\sigma_H = 56.7^{+6.4}_{-6.2}$ pb, in good agreement with theoretical prediction.
- Differential cross sections measured using the full Run 2 dataset.
  - N_{jets}, $p_T^{\gamma\gamma}$, $|y_{\gamma\gamma}|$, p_T^{j1}, m_{jj}, and $\Delta\phi_{jj}$.
- Results in STXS bins (some merged).





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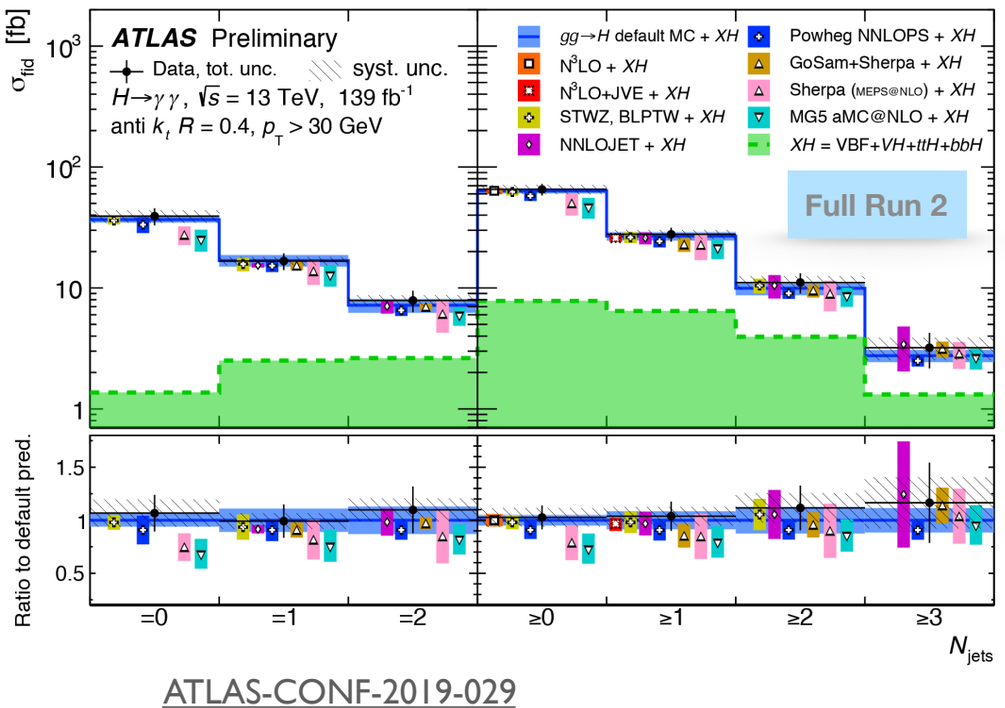

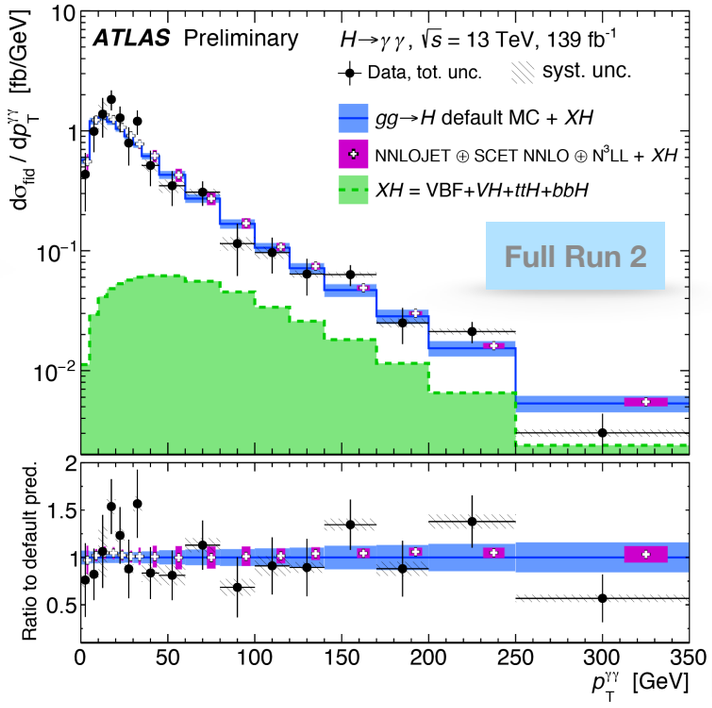

ATLAS-CONF-2019-029

H→γγ EFT Interpretation and H-c coupling constraint

- The H→γγ analysis used here as an example of how measurements can be interpreted.
  - Put constraints on the Wilson coefficients of the chosen base for the Effective Field Theory, assuming all but one are fixed at SM-value.
  - Also constrain the H-charm coupling, from effect of κ_c on the Higgs p_T distribution.

Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$

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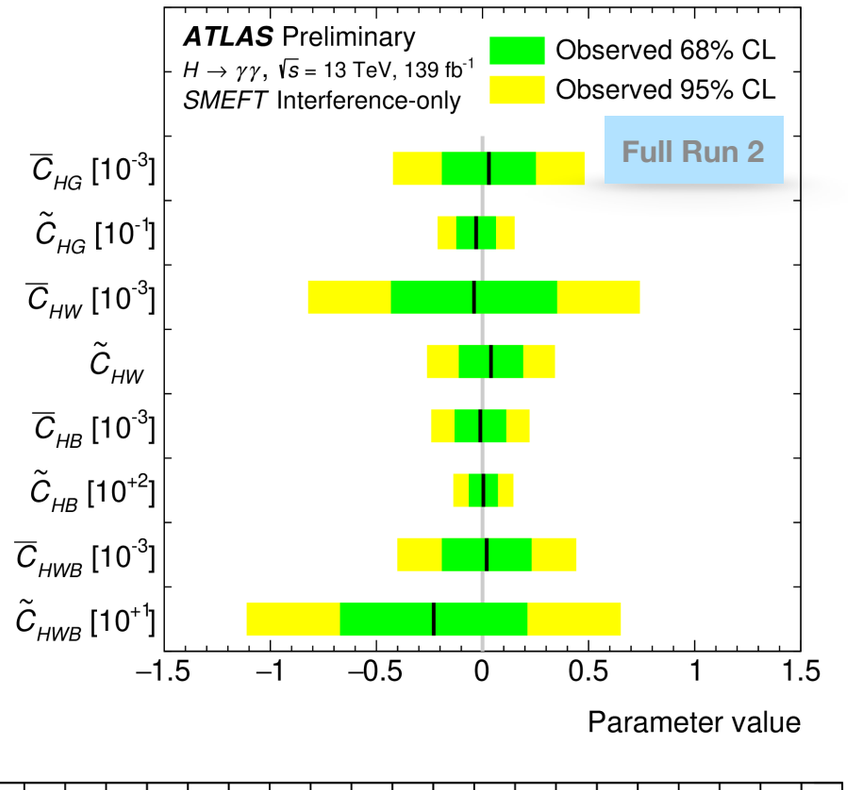

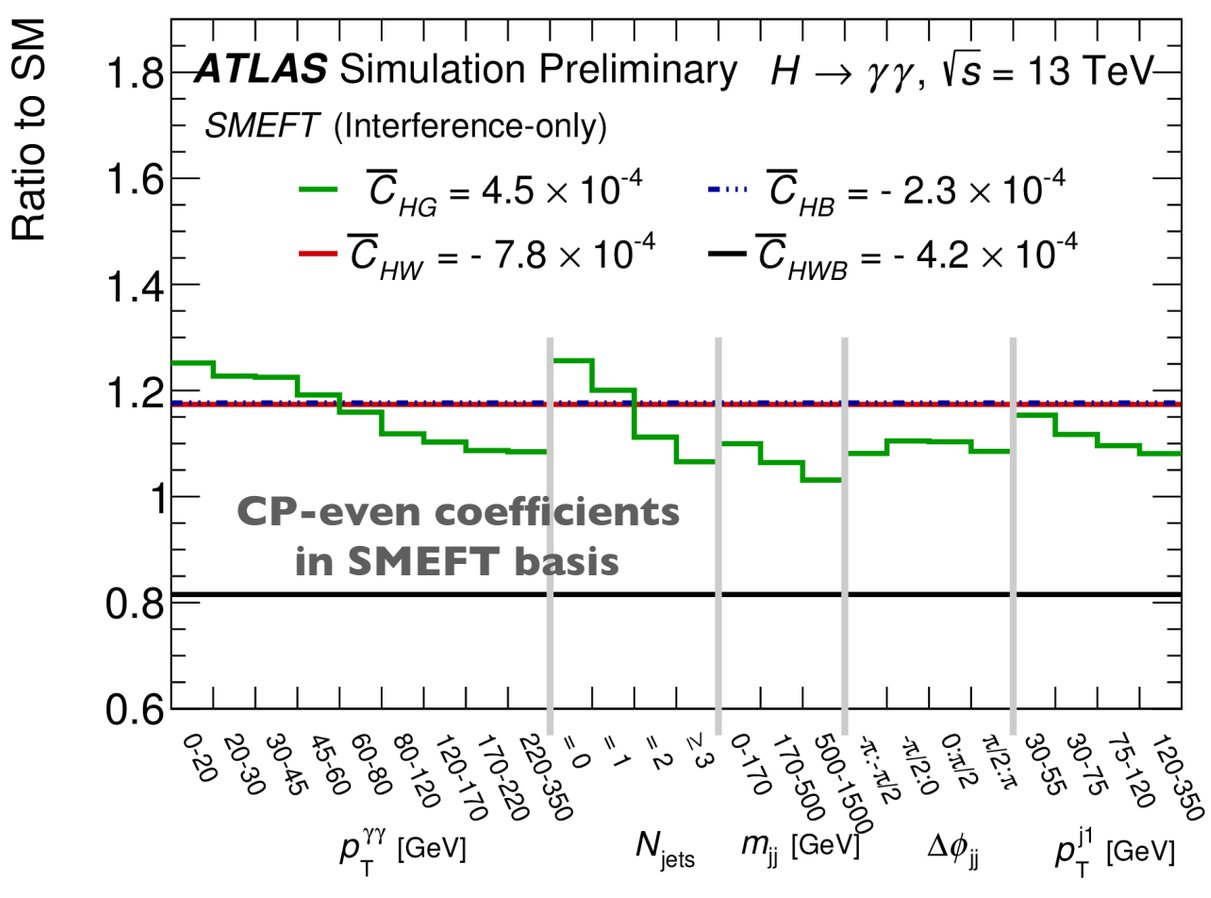

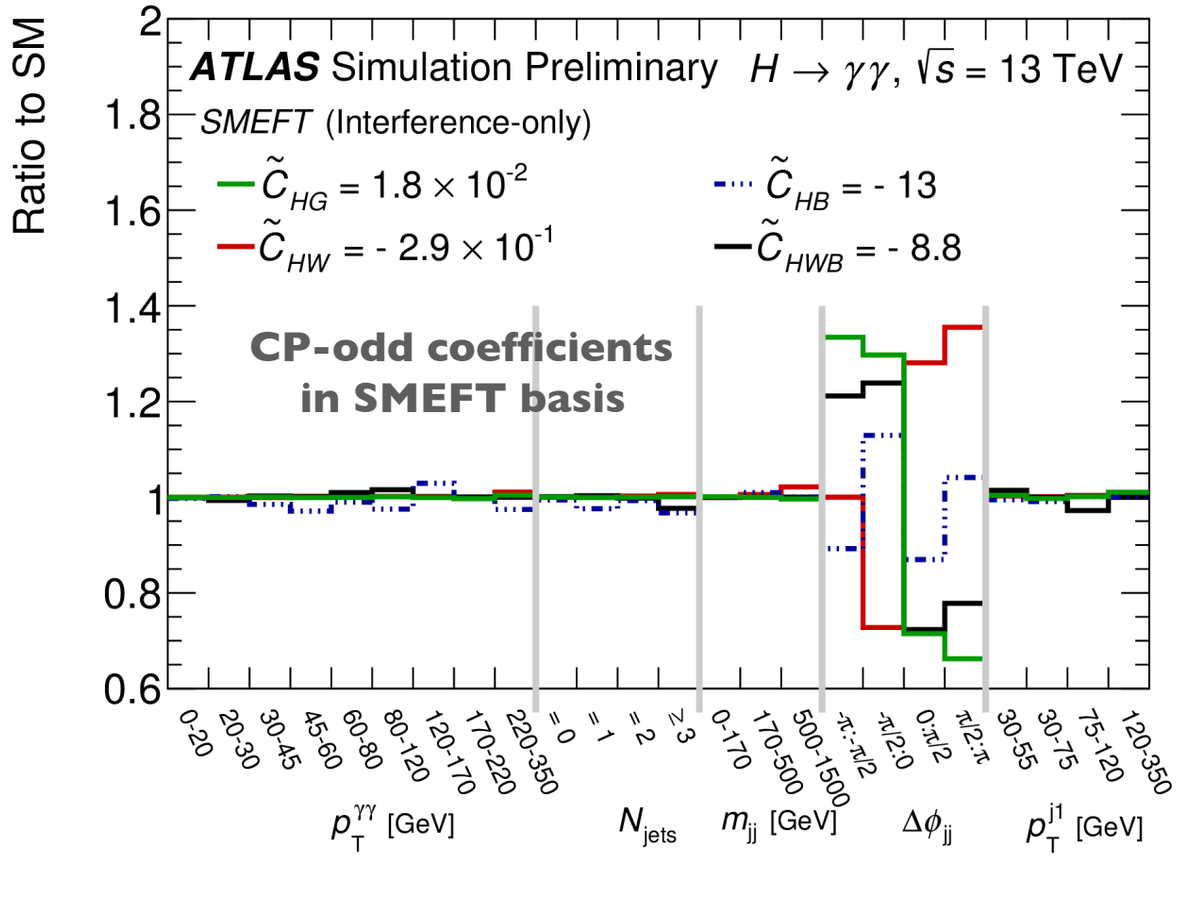

Higgs to bosons: H→ZZ→4ℓ

- Full Run 2 dataset analysed by both experiments.
  - Measurements of total and differential cross sections, and STXS.
- Global signal strength ($\mu = \sigma / \sigma_{SM}$):
  - ATLAS: $\mu = 1.04^{+0.12}_{-0.10}$
  - CMS: $\mu = 0.94^{+0.11}_{-0.10}$

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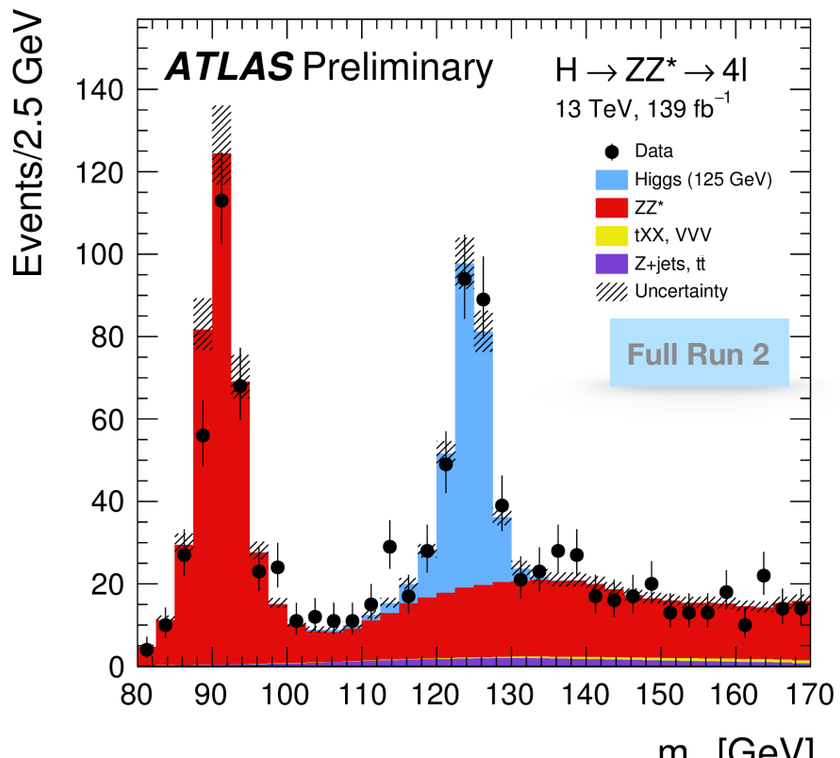

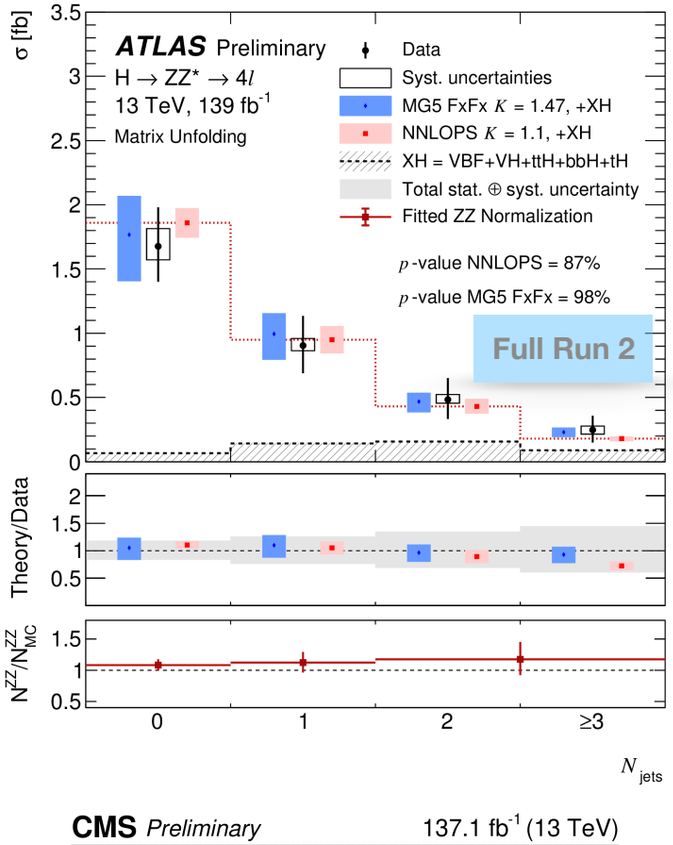

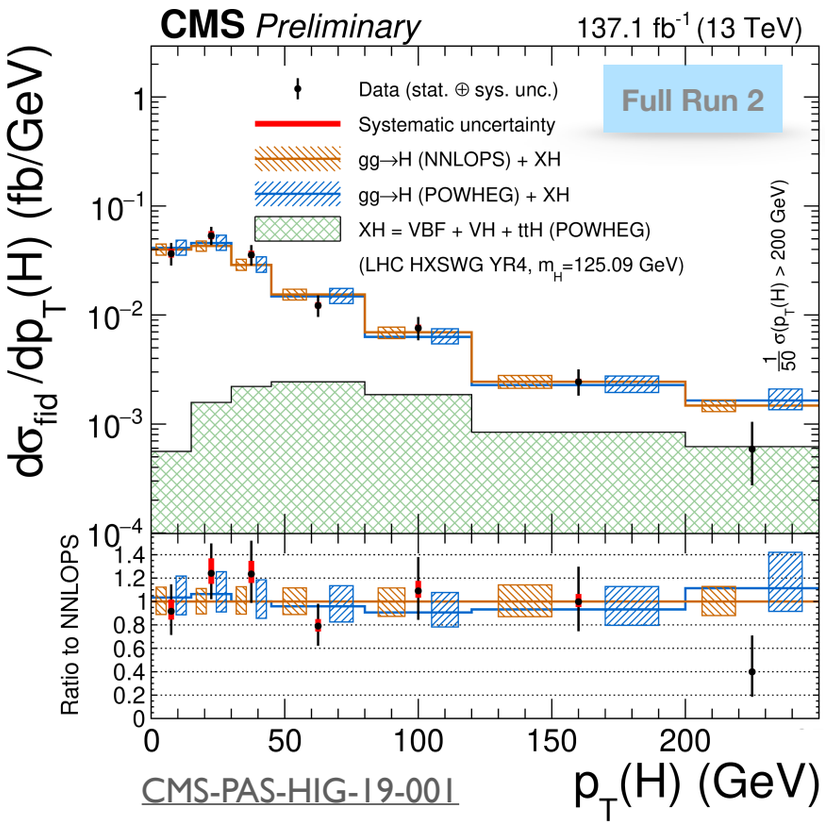

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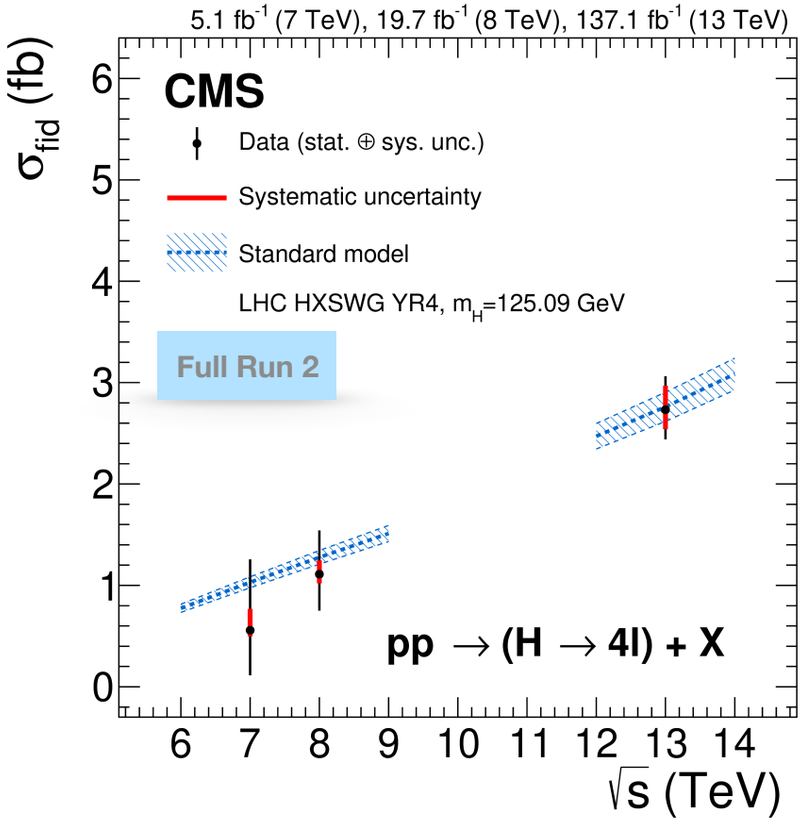
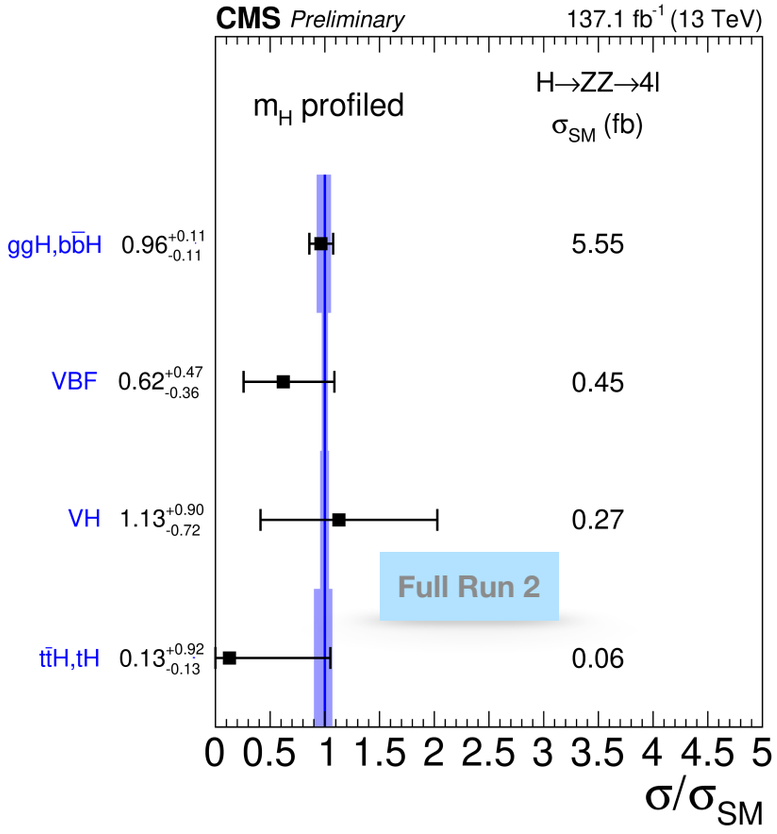
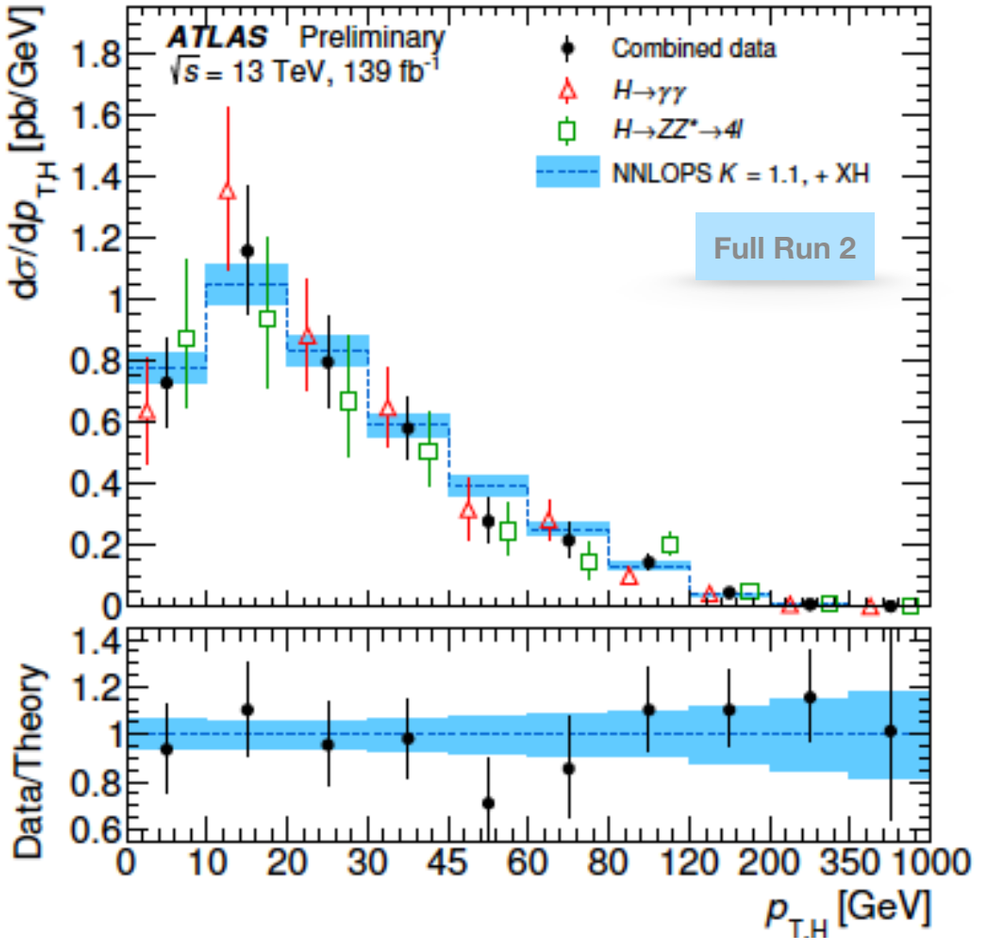
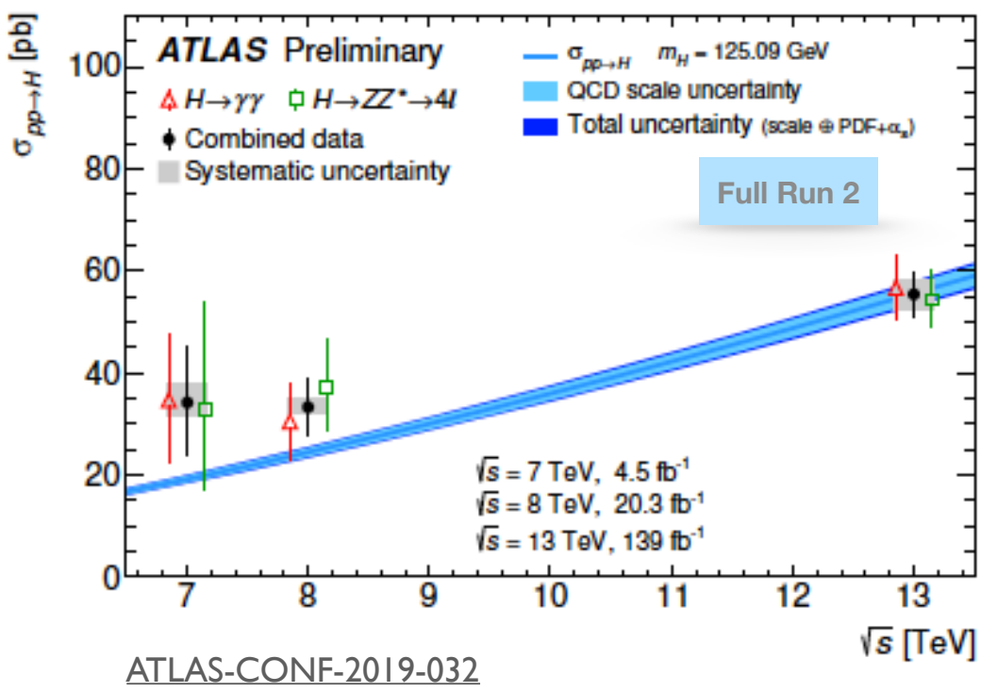




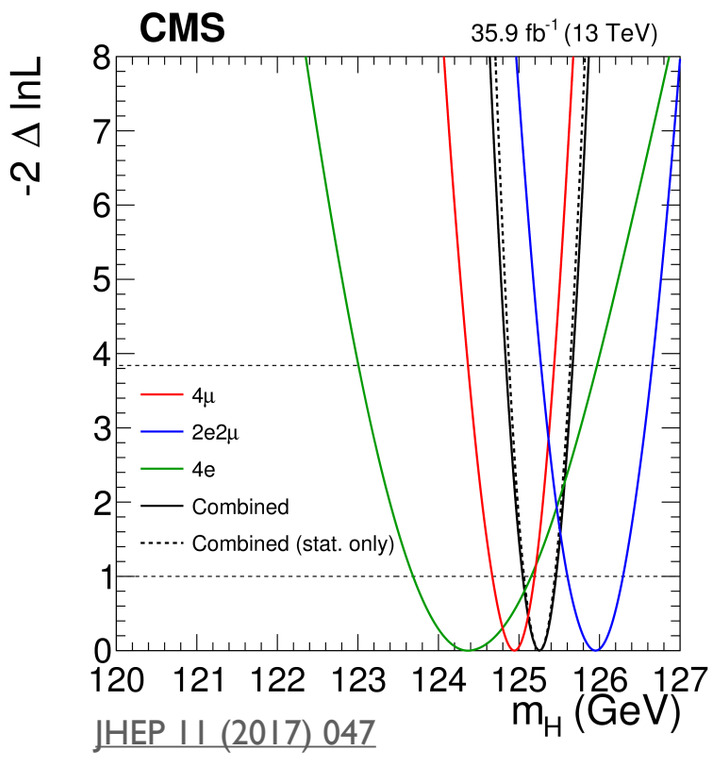
H→γγ and H→ZZ→4ℓ

- Combination of the γγ and 4ℓ channels yield the best values for the mass. Higgs boson width probed in the H→ZZ channel (through measurement of off-shell production):
  - m_H: 125.26±0.21 GeV, (CMS)
    124.97±0.24 GeV (ATLAS).
  - Γ_H: 0.08 < Γ_H < 9.16 MeV (CMS),
    Γ_H < 14.4 MeV (ATLAS).
- Measurements of total and differential σ_H.
  - Good agreement in e.g. $p_T(H)$ distribution with NNLOPS prediction (normalised to total σ_H).

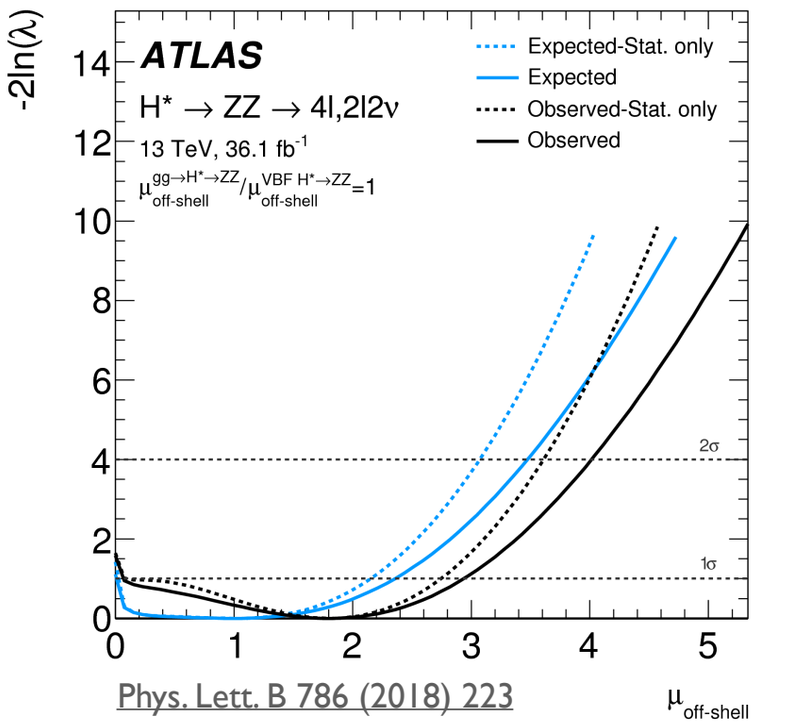




ATLAS-CONF-2019-032



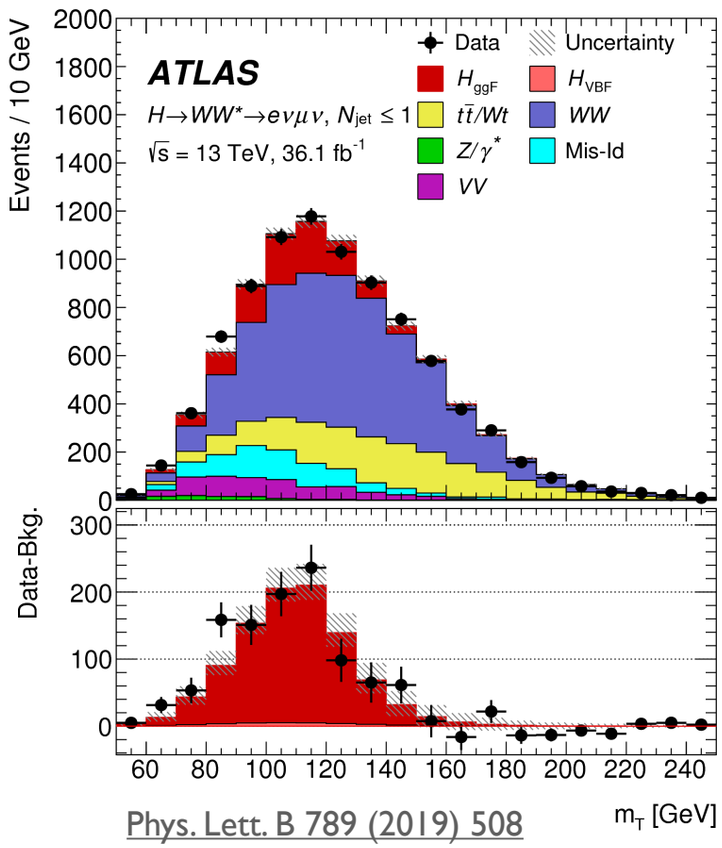
JHEP 11 (2017) 047



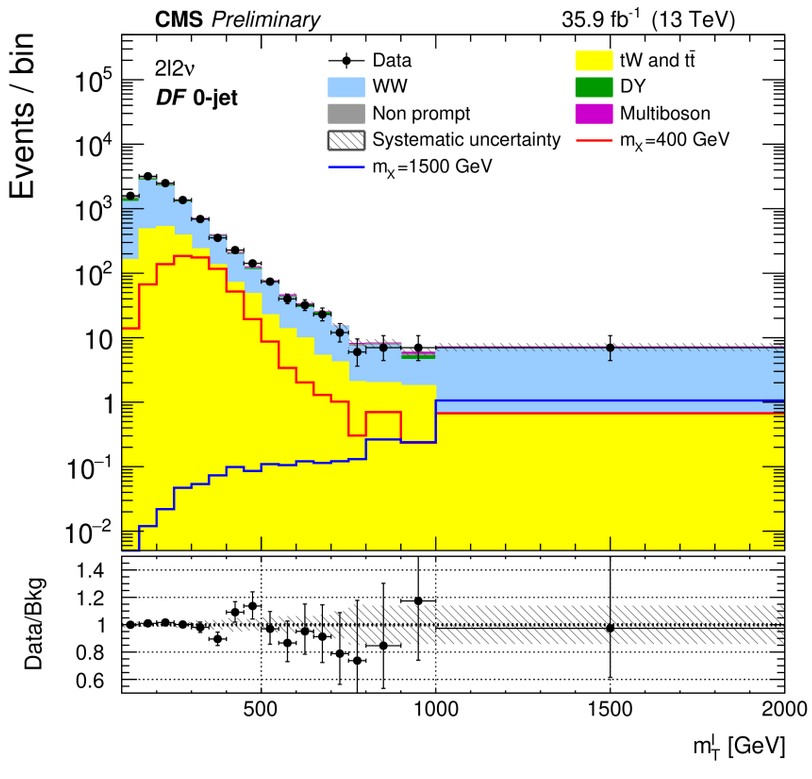
Phys. Lett. B 786 (2018) 223

Higgs to bosons: H→WW

- Cross sections measured with 36 fb^{-1} in the H→WW→$\ell\nu\ell'\nu'$ channel.
  - Gluon-fusion production: $\mu = 1.10^{+0.21}_{-0.20}$
  - Vector boson fusion production: $\mu = 0.62^{+0.36}_{-0.35}$
  - WH: $\mu = 2.3^{+1.2}_{-1.0}$ and ZH production: $\mu = 2.9^{+1.9}_{-1.3}$
- Transverse mass spectra probed for signs of heavy Higgs boson decays to $\ell\nu\ell'\nu'$ and $\ell\nu$qq.
  - SM-like production of heavy Higgs boson excluded.
  - Similar heavy Higgs boson searches performed in other Higgs decay channels, but not reported in this talk.



Phys. Lett. B 789 (2019) 508



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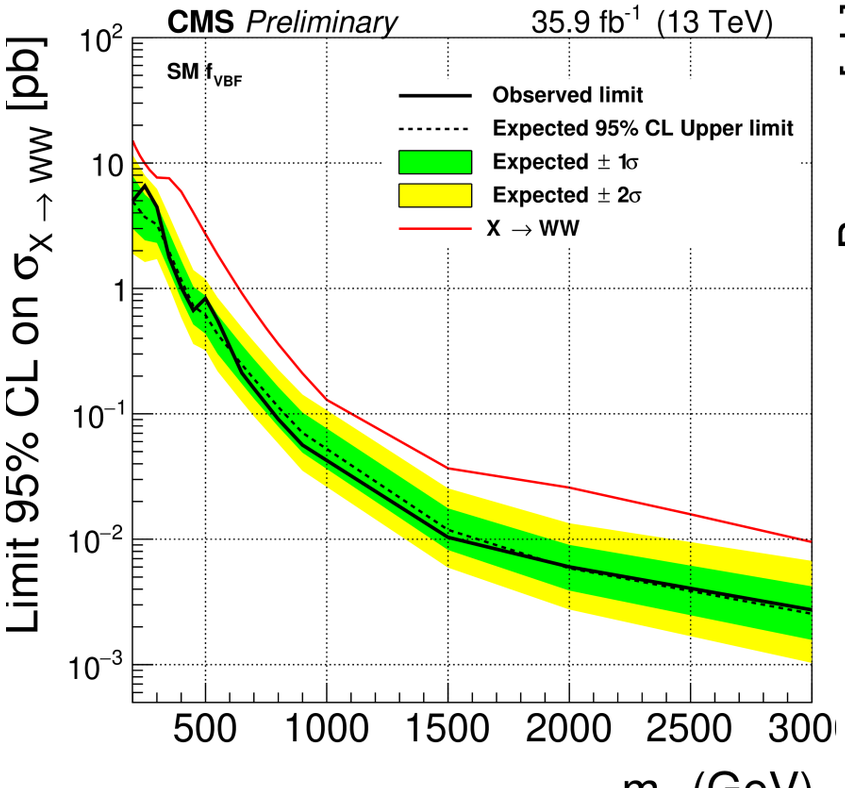
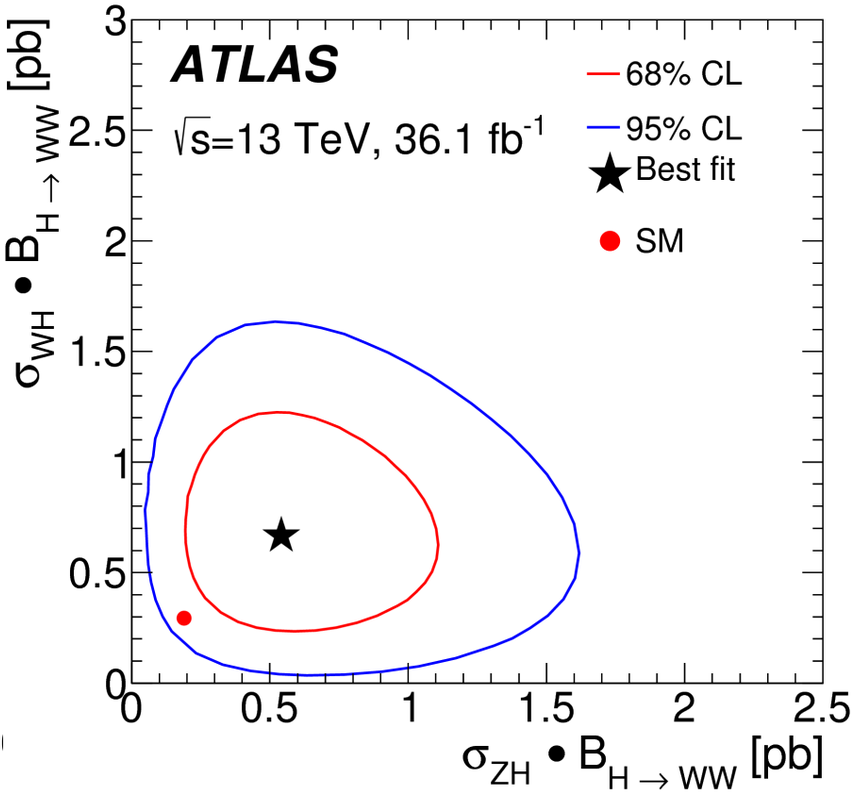
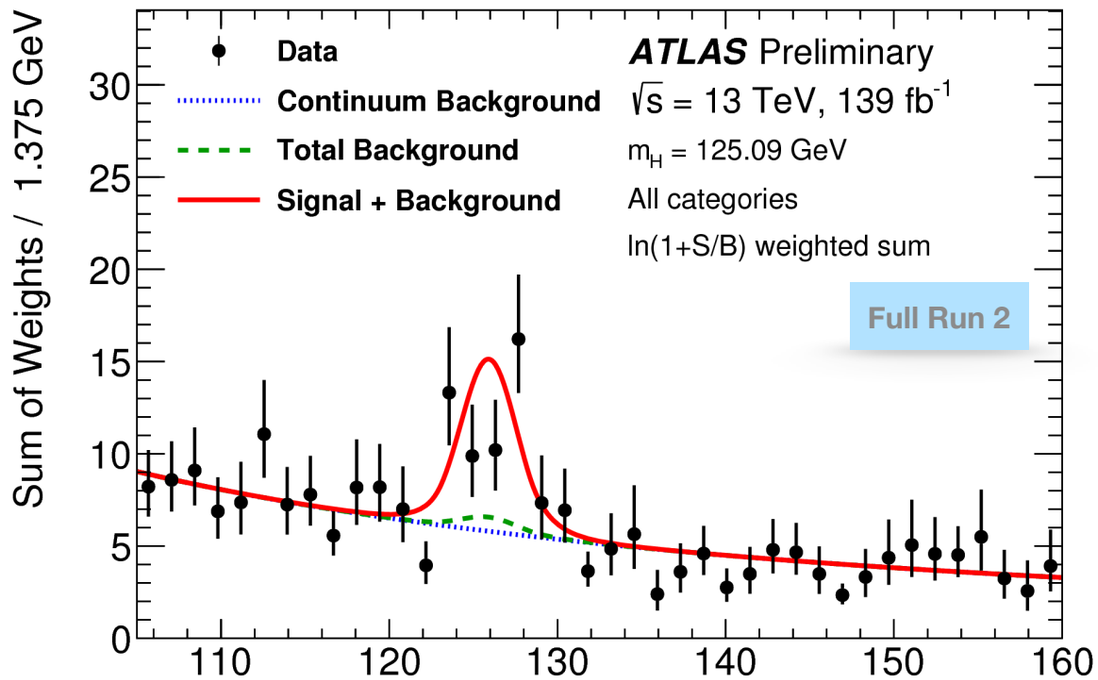


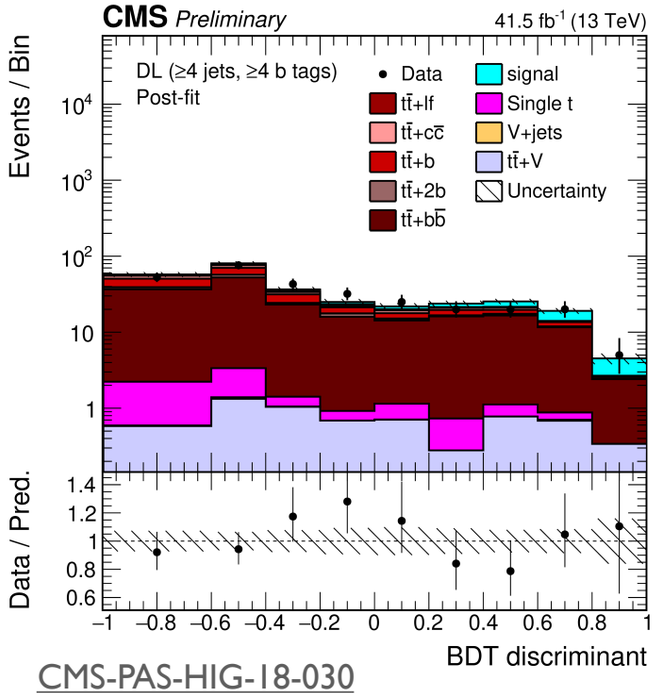


arXiv:1903.10052

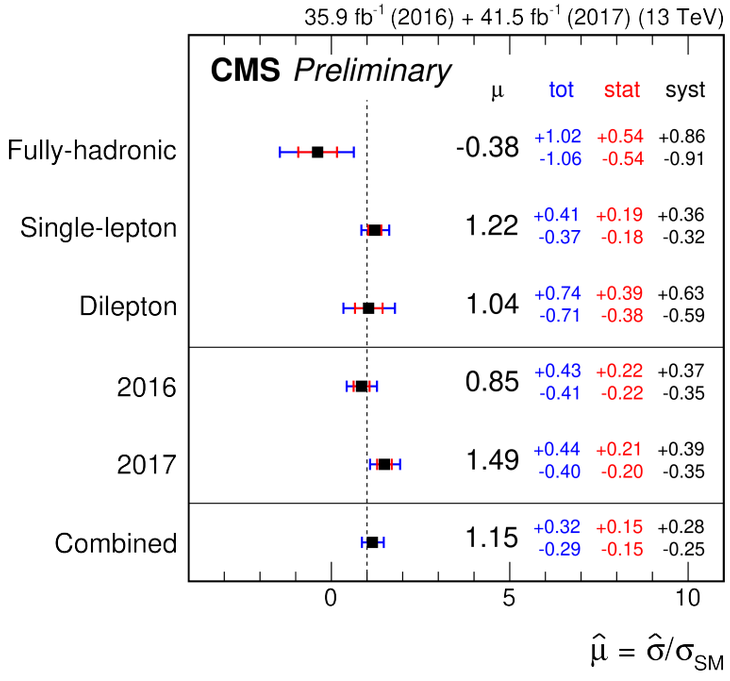
Higgs and 3rd generation fermions: ttH

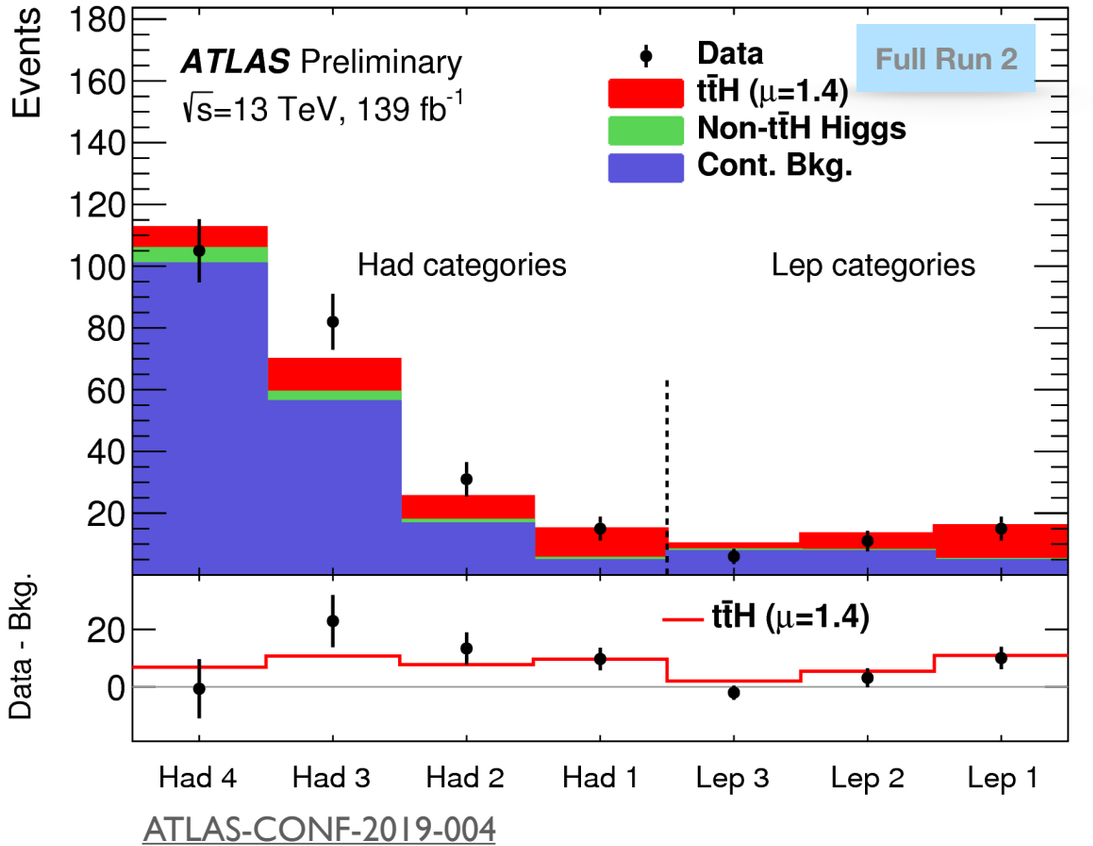
- The H-top coupling can only be directly probed in the Higgs boson production.
  - Top quark too heavy for the H→tt decay.
- Using the H→bb,WW,$\tau\tau$,$\gamma\gamma$,ZZ decays.
  - First results on full Run 2 in the ttH(→$\gamma\gamma$) and ttH(→ZZ) channels.
- Signal strength from combination of channels (Run 1 plus part of Run 2):
  - $\mu = 1.32^{+0.28}_{-0.26}$ (ATLAS)
  - $\mu = 1.26^{+0.31}_{-0.26}$ (CMS)





CMS-PAS-HIG-18-030



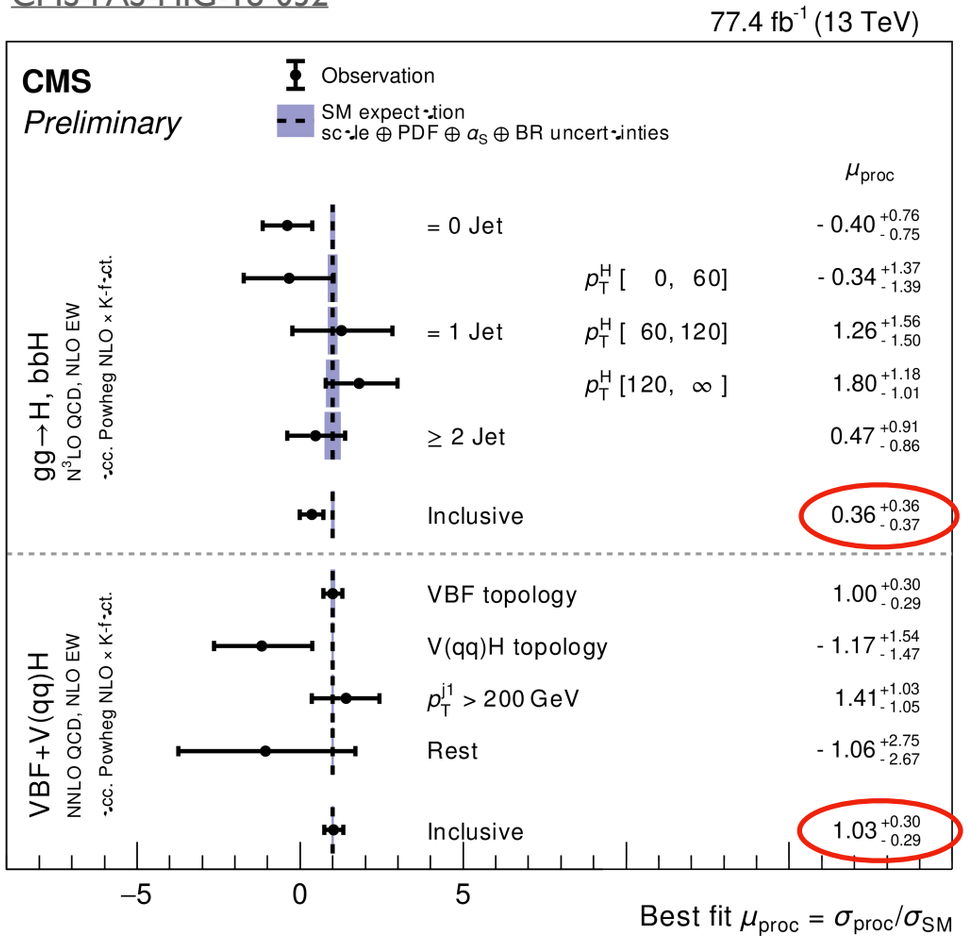


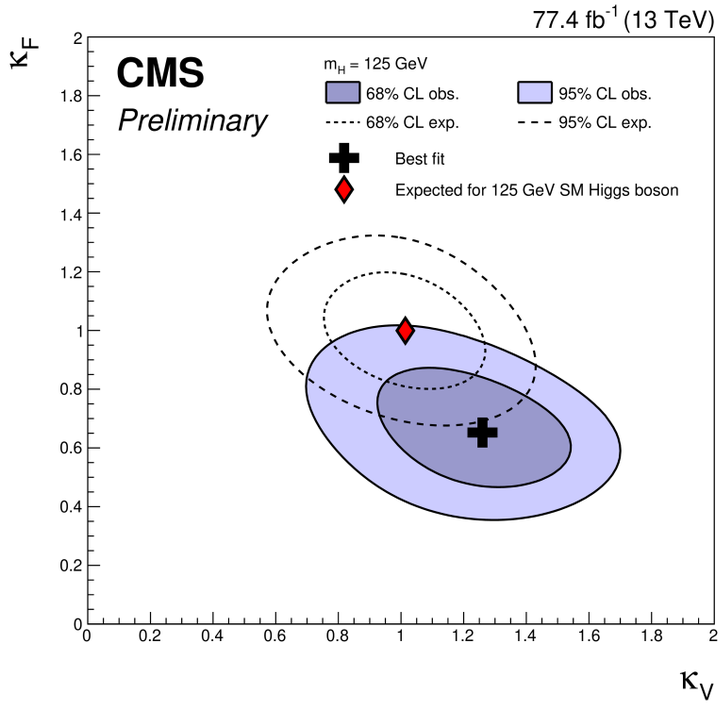
ATLAS-CONF-2019-004

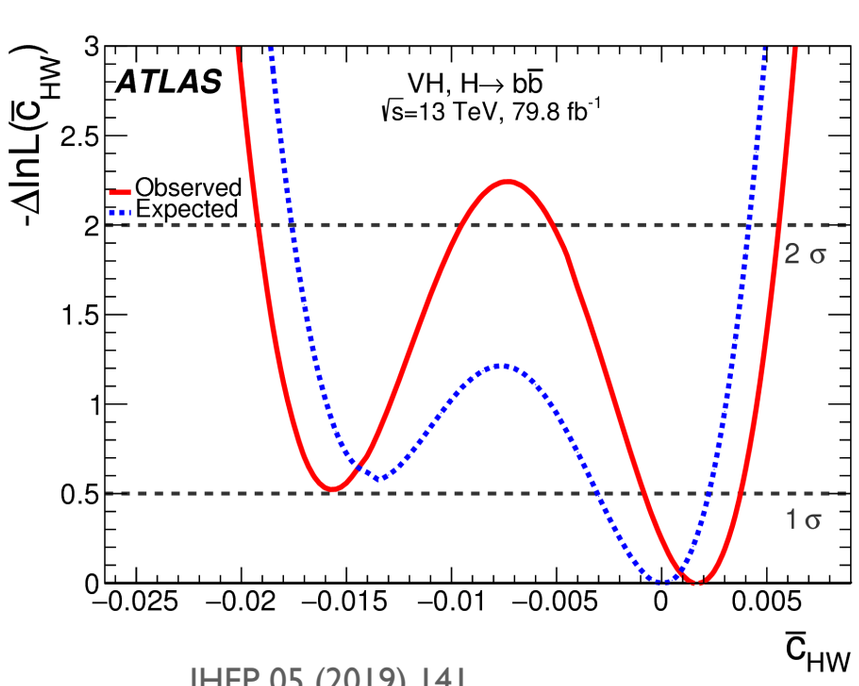
Higgs and 3rd generation fermions: H→bb and H→$\tau\tau$

- H→bb and H→$\tau\tau$ observed with more than 5σ significance by both experiments.
- H→$\tau\tau$ result on 77.4 fb^{-1} by CMS.
  - Measurements in STXS bins, results split by production mode and limits are placed on the κ_V and κ_F coupling modifiers.
- H→bb can mostly be accessed in associated production, VH most sensitive.
  - Differential cross section measurement for VH production has sensitivity to p_T^V.
  - Results interpreted in EFT, limits placed on new H-W interaction coefficient $\bar{c}_{HW}$.
  - More details in talk by Luca Ambroz this afternoon.

CMS-PAS-HIG-18-032







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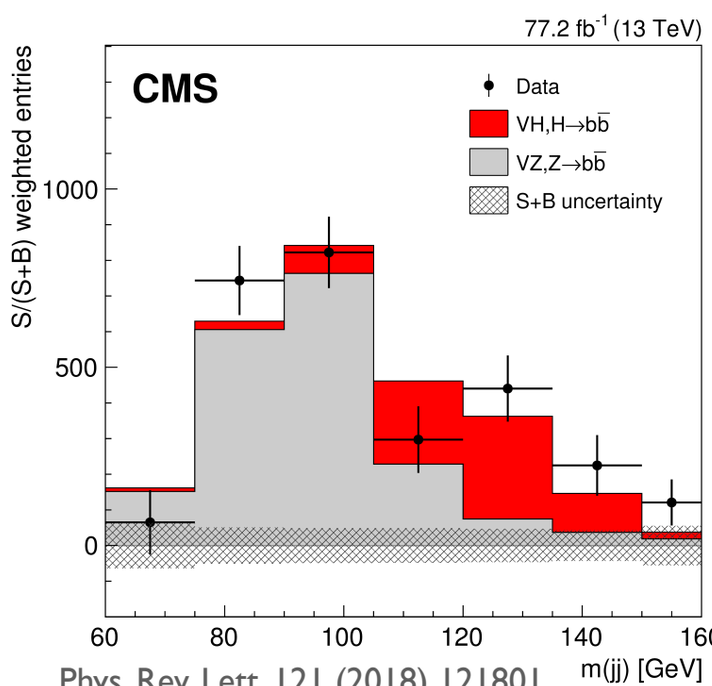
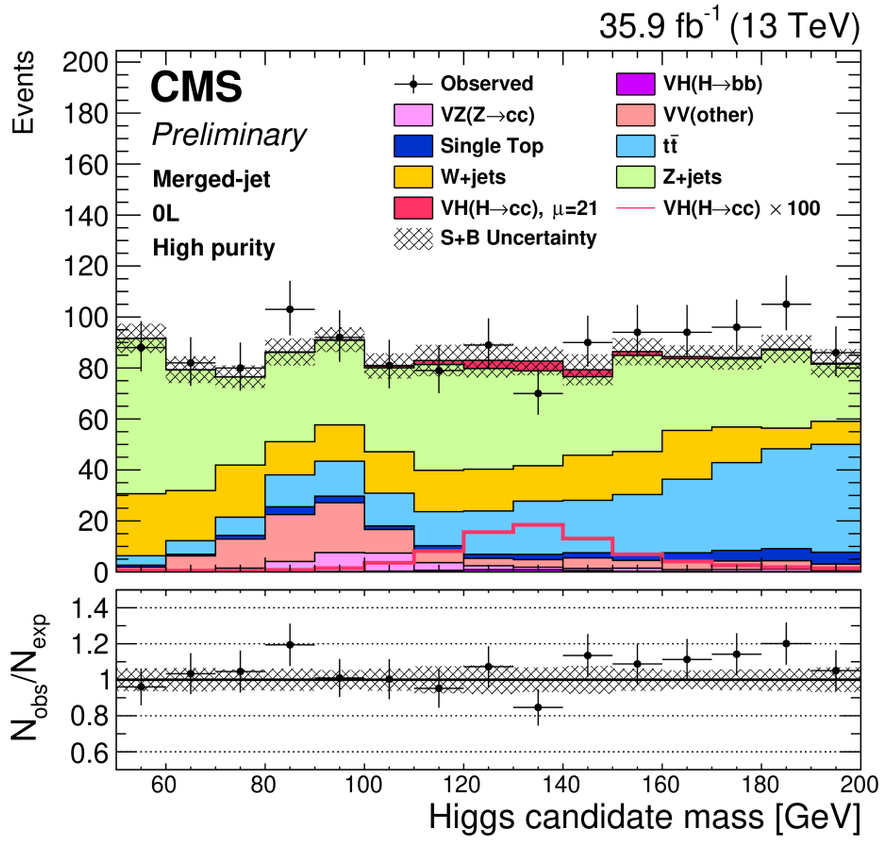


Phys. Rev. Lett. 121 (2018) 121801

Higgs and 2nd generation fermions: H→cc

- The BR(H→cc) is 2.9%, not insignificant.
  - Very hard to separate the signal from the overwhelming background at a hadron collider.
- CMS has searched for H→cc in VH production.
  - Analysis separated according to number of leptons, and depending on whether the c-quarks are reconstructed as one or two jets.
  - Apply novel c-tagging techniques.
- Limit placed on $\mu < 70$ ($\mu < 36^{+16}_{-11}$ expected).



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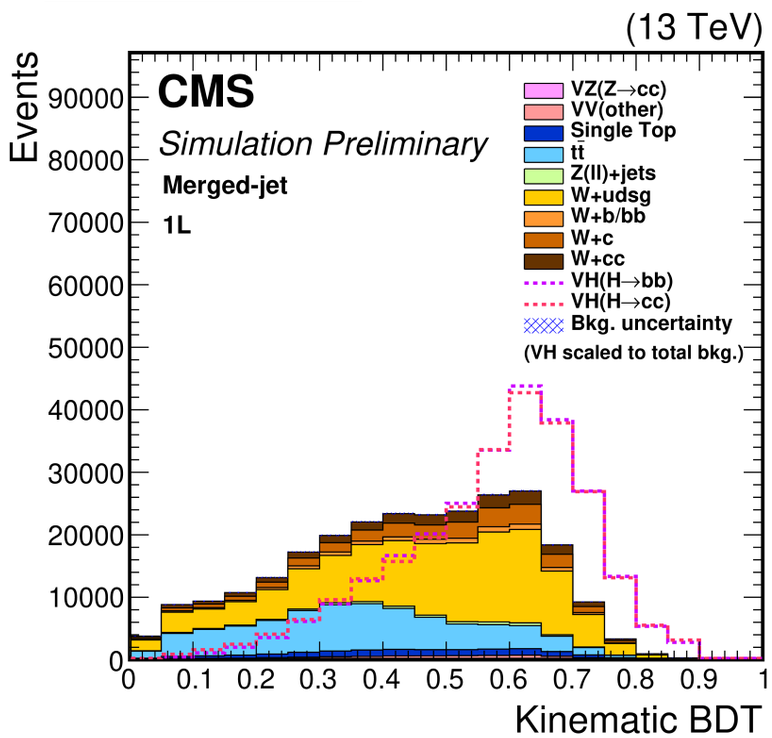
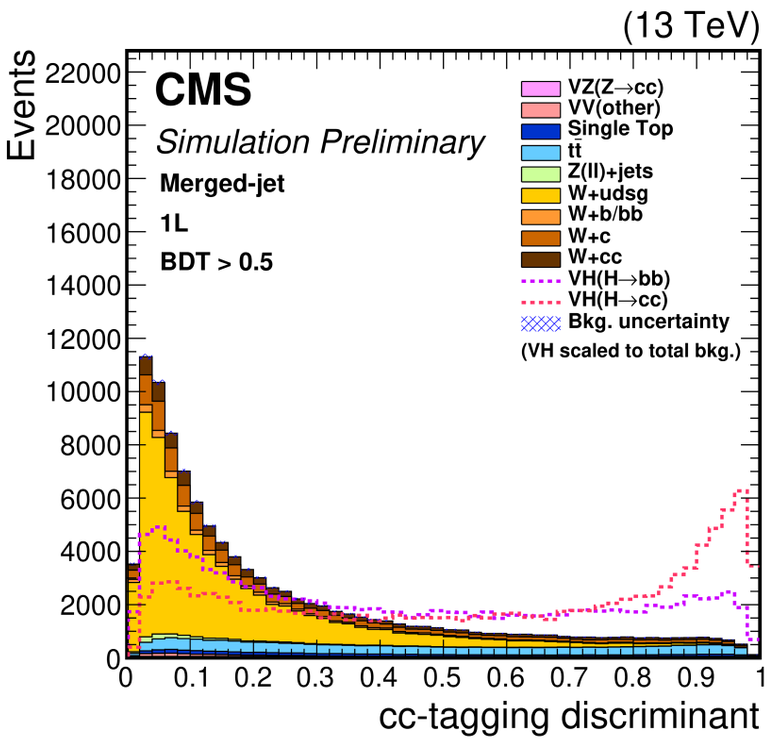
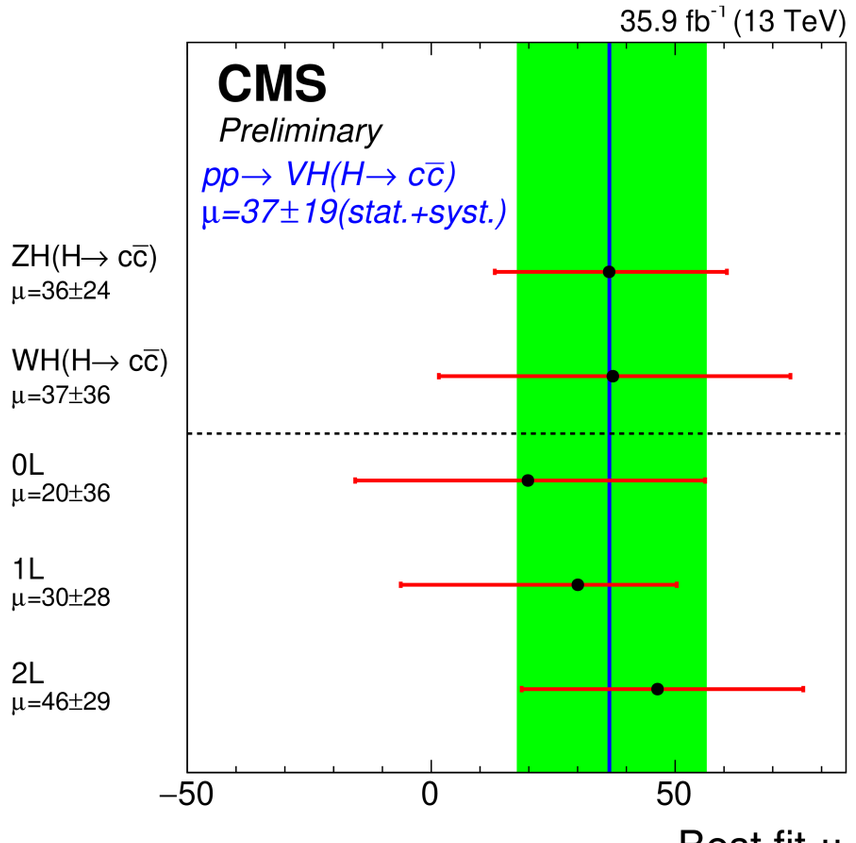


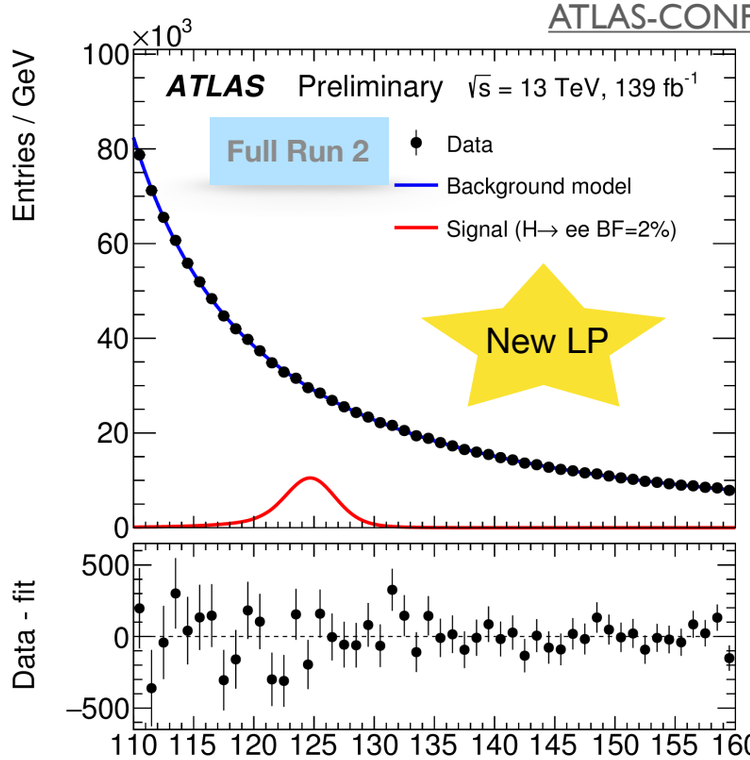


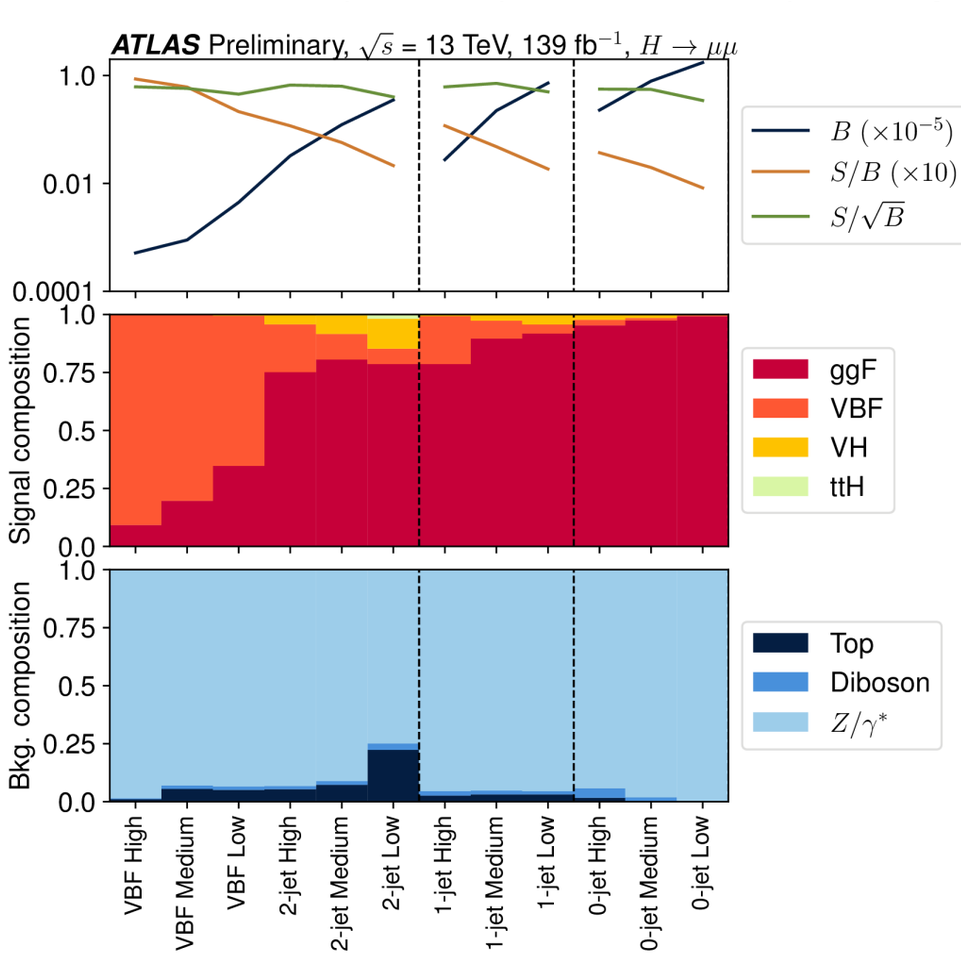


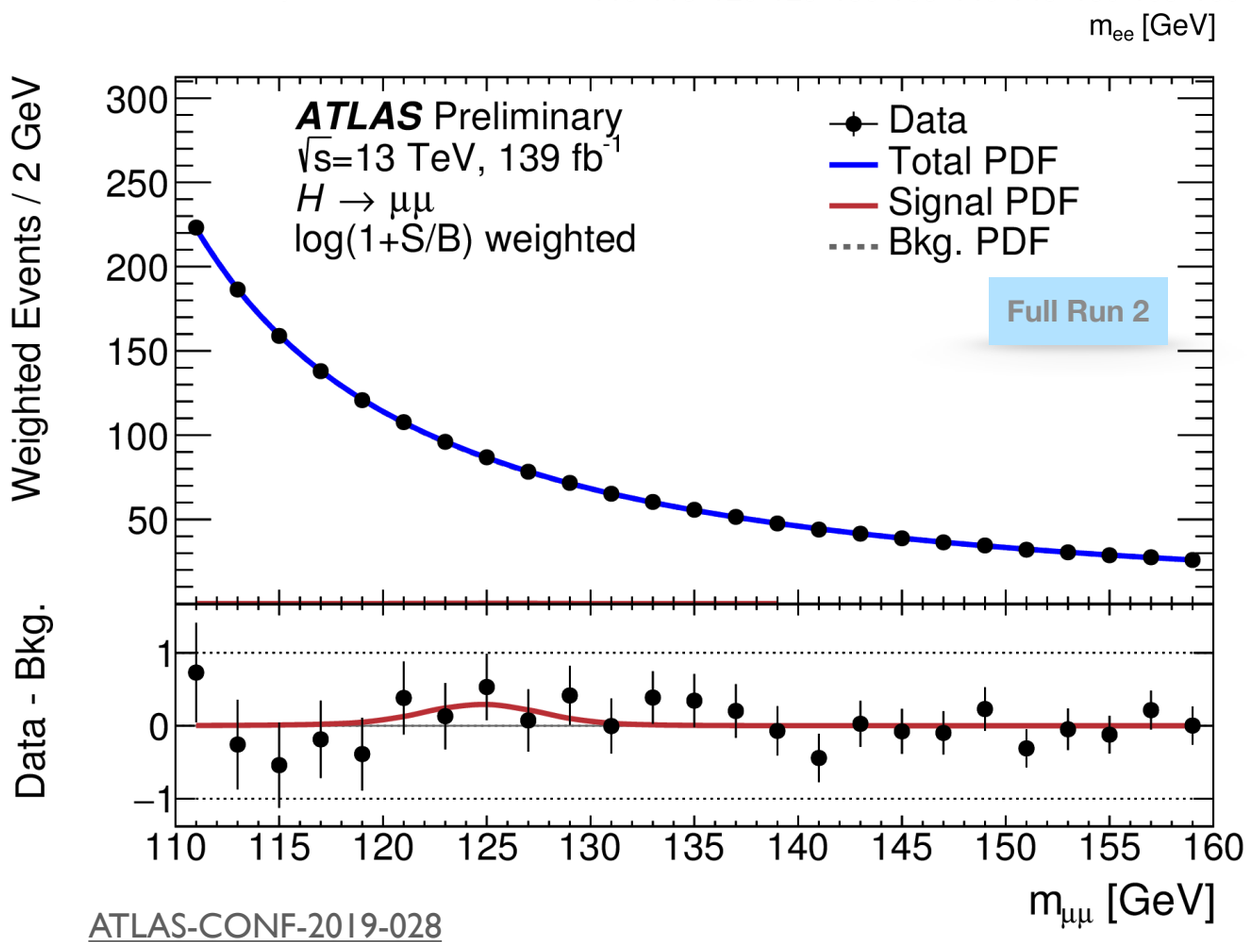
Higgs to 2nd and 1st generation: H→$\mu\mu$ and H→ee

- Recently released results for a search for H→$\mu\mu$ using the full Run 2 dataset.
  - Small BR(H→$\mu\mu$) ≈ $2 \cdot 10^{-4}$.
  - Dividing events in categories, and then look for peak in the $m_{\mu\mu}$ spectrum.
- Upper limit set on μ < 1.7.
  - Observed μ = 0.5 ± 0.7.
  - Significance of the signal 0.8σ (expected 1.5σ).
- Search for H→ee using full Run 2 dataset.
  - Limit BR(H→ee) < $3.6 \cdot 10^{-4}$ (SM expectation ~$5 \cdot 10^{-9}$).

ATLAS-CONF-2019-037



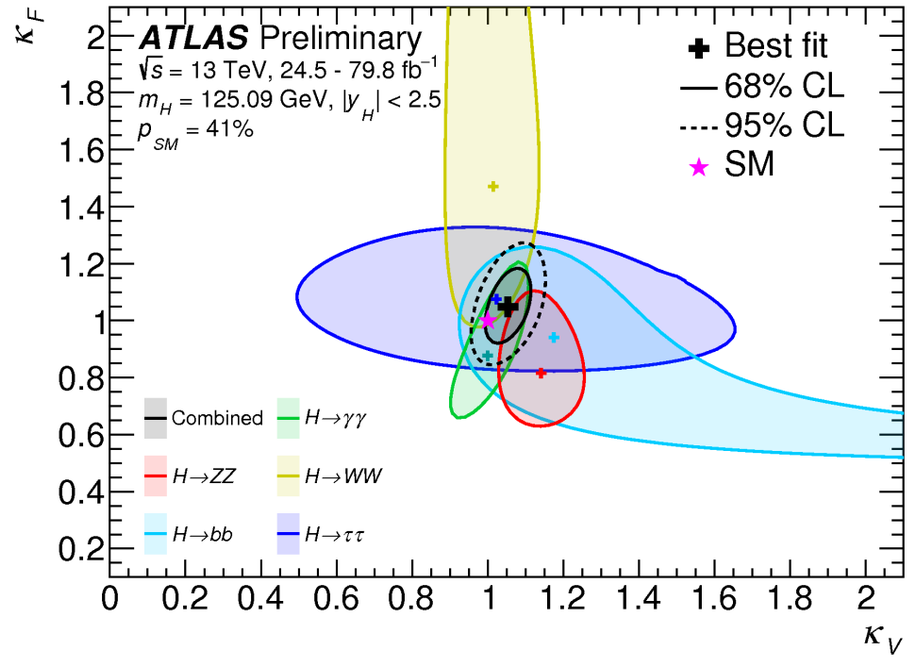


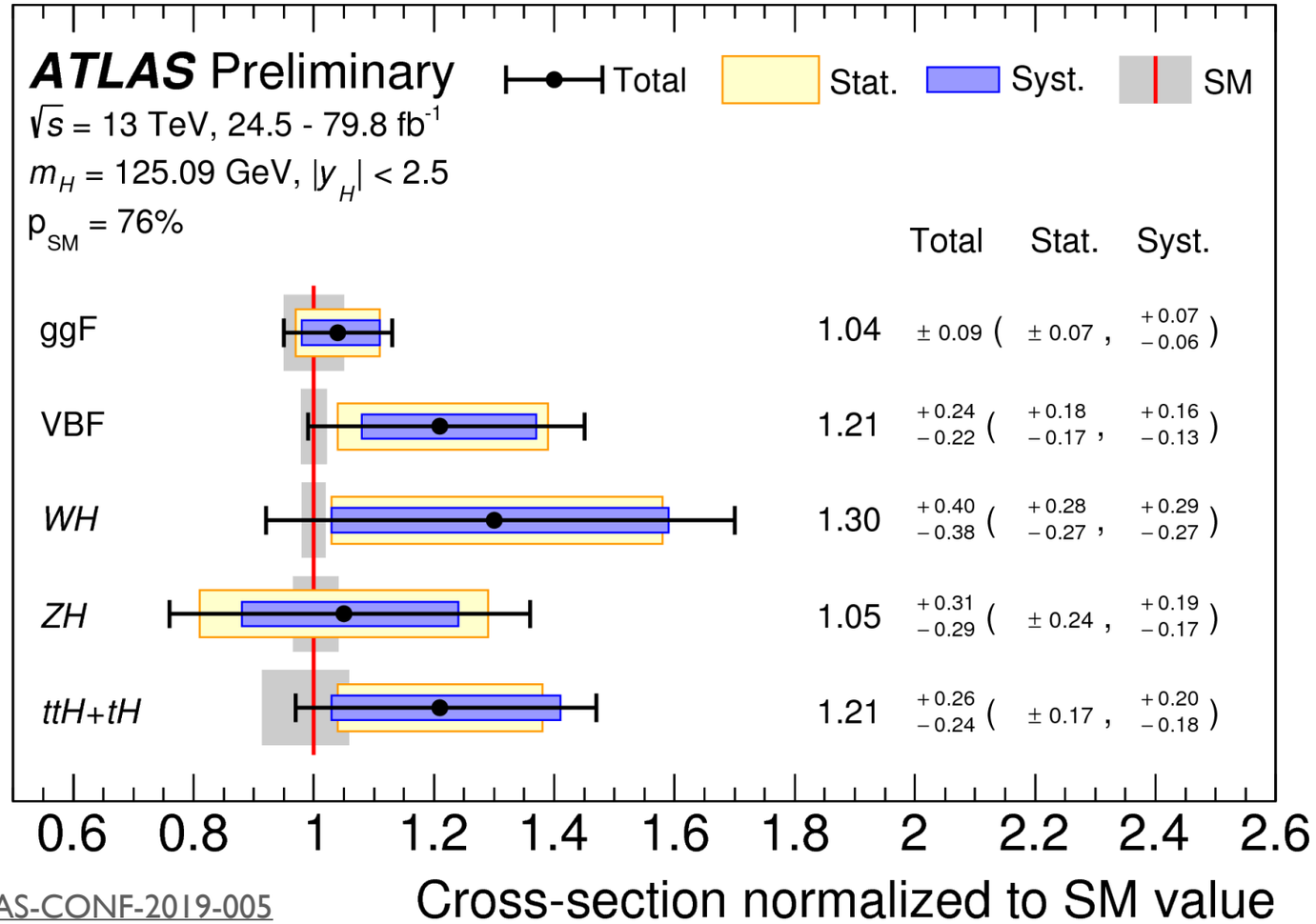


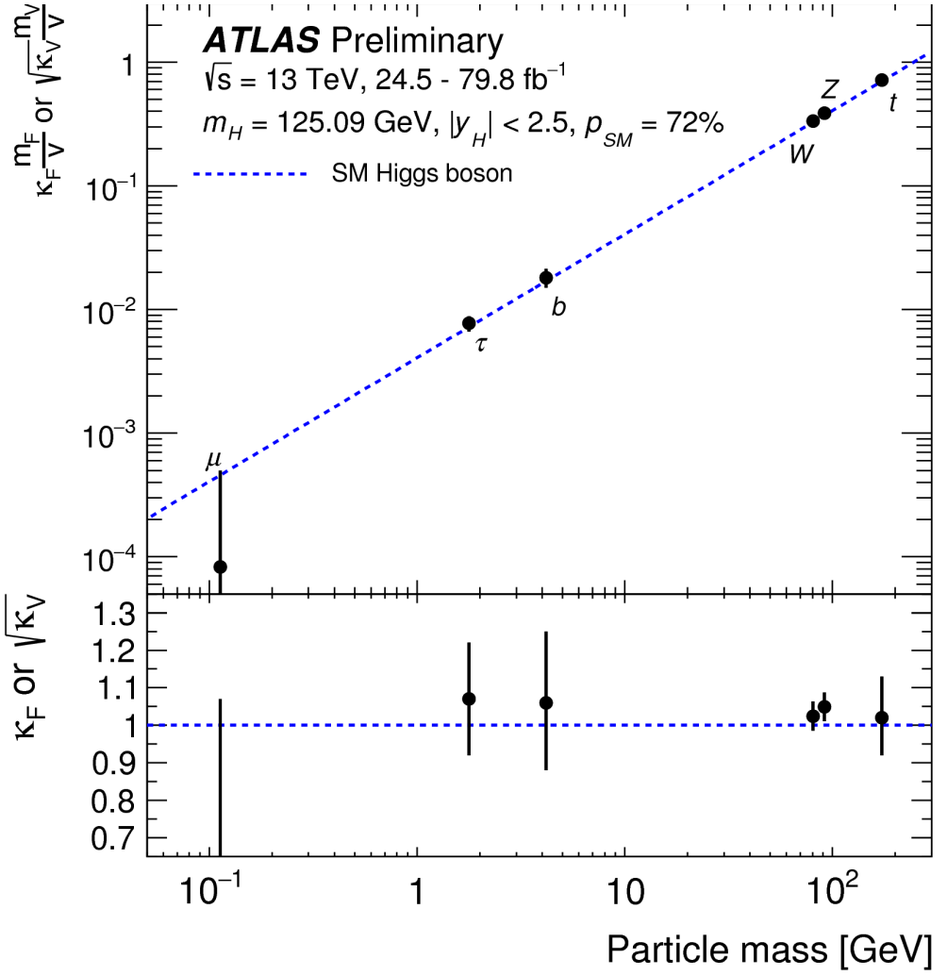
ATLAS-CONF-2019-028

Higgs Couplings from Combination

- Combination of the H→γγ, ZZ, WW, $\tau\tau$, bb and $\mu\mu$ channels using up to 79.8 fb^{-1} has been used to:
  - Measure production mode cross sections.
  - Measure Higgs boson couplings.
  - Place limits on coupling scaling factors, for example on overall scaling factors for couplings to vector bosons, κ_V, and to fermions, κ_F.





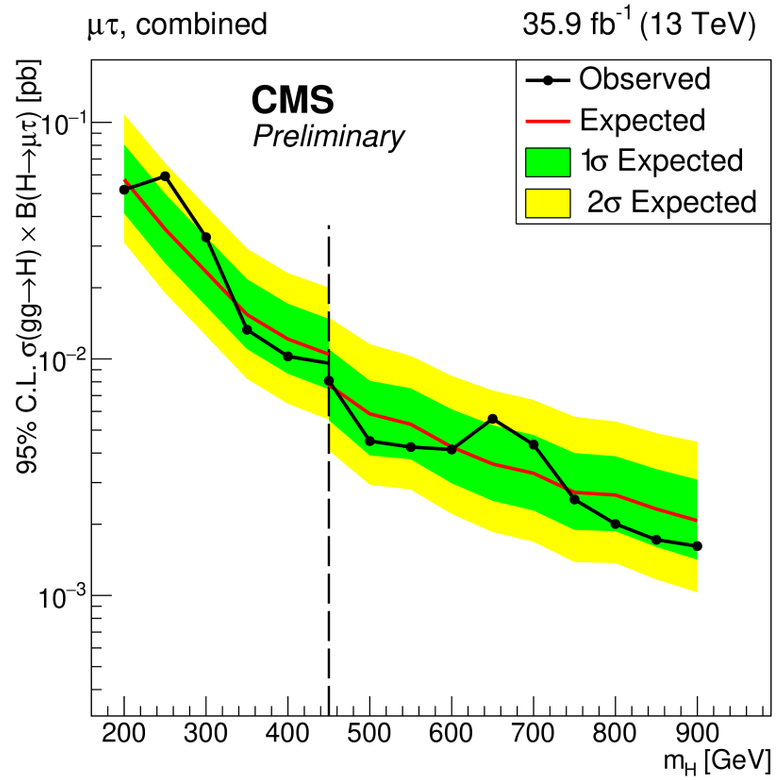


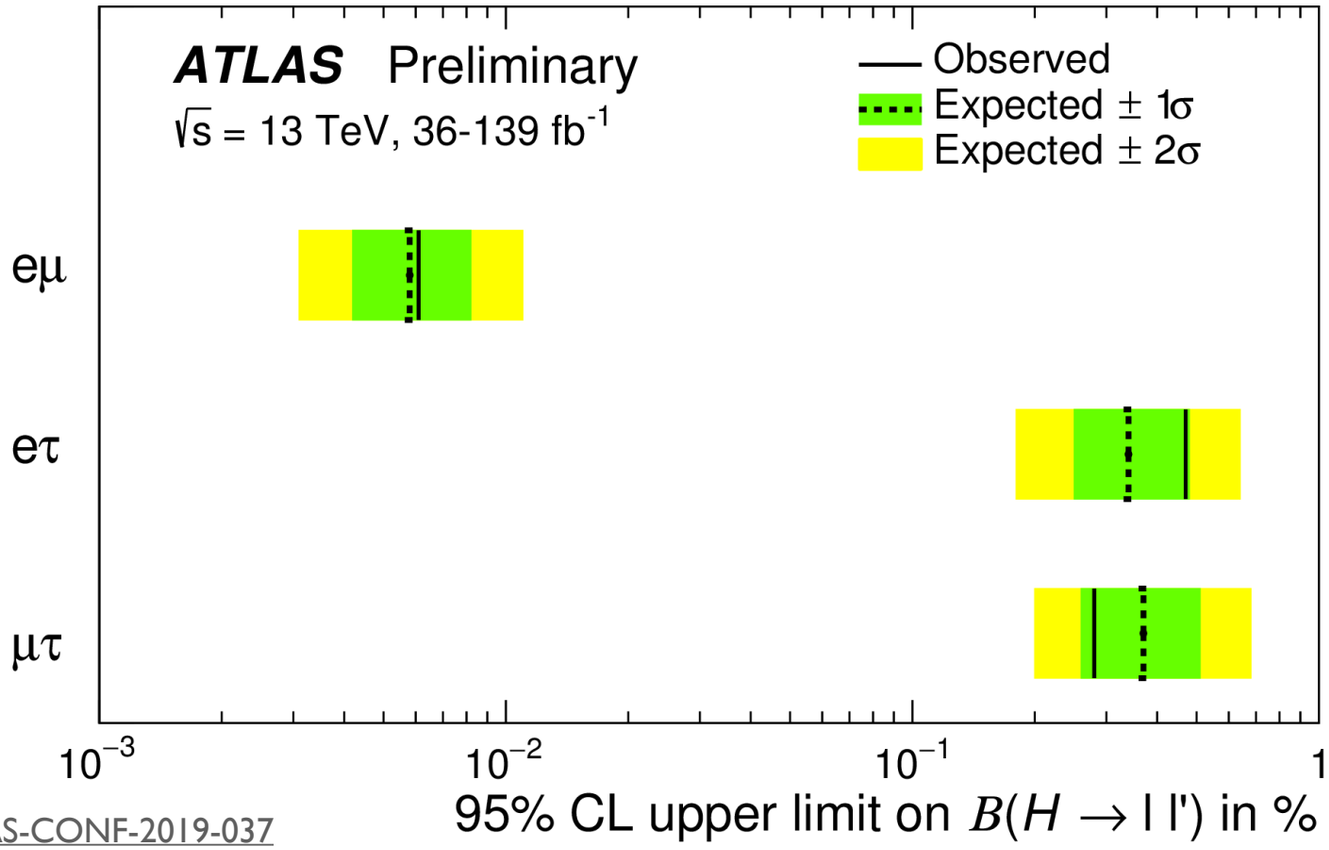
ATLAS-CONF-2019-005

Search for Lepton Flavour Violating Decays

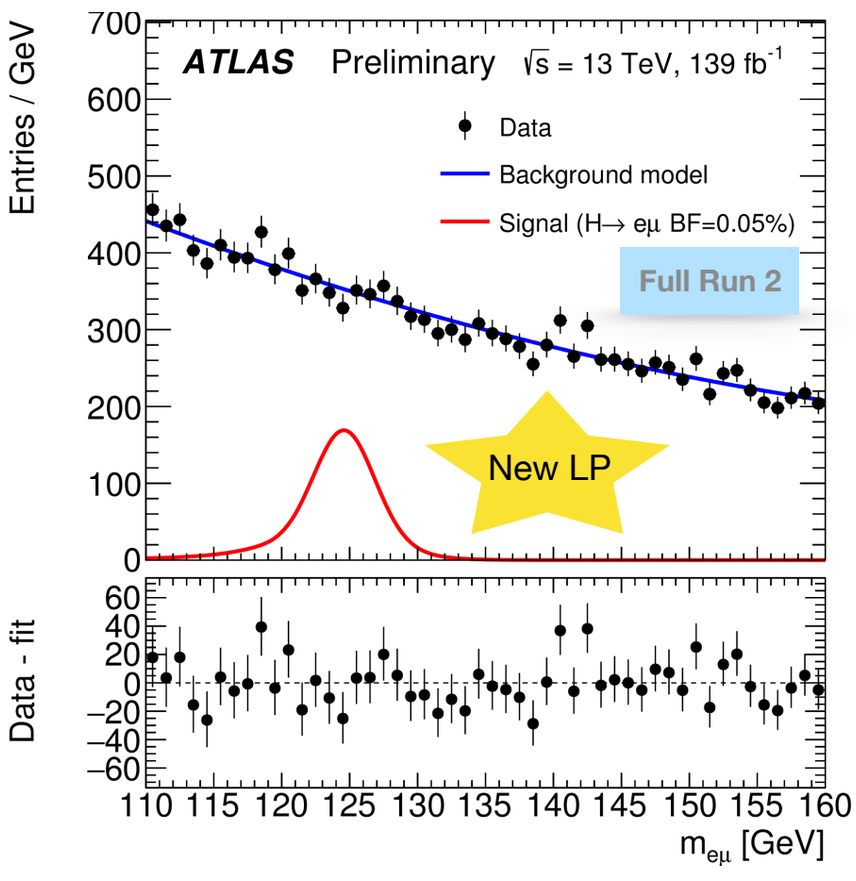
- Lepton flavour violating decays H→eτ and H→$\mu\tau$ have been searched for by CMS (high mass Higgs boson) and ATLAS (for the observed Higgs boson).
  - Using 36 fb^{-1} of data, limits represent a significant improvement on Run 1 results.
- No signal is observed, limits are placed on the branching ratio (ATLAS) or the cross section times branching ratio (CMS).
  - BR(H→eτ) and BR(H→$\mu\tau$) both constrained to be less than 0.5% for the observed Higgs boson.
- Search for H→eμ with the full Run 2 dataset.
  - Limit BR(H→eμ) < 6.1 · 10^{-5}.

CMS-PAS-HIG-18-017



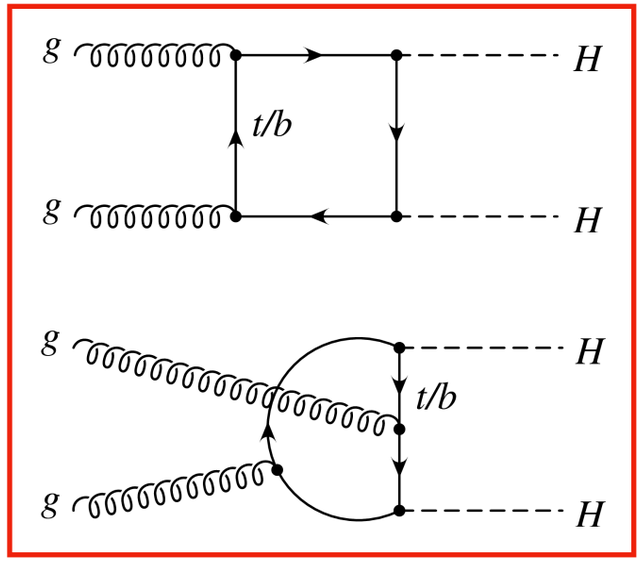


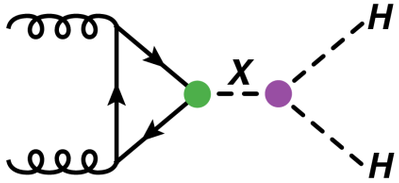
ATLAS-CONF-2019-037

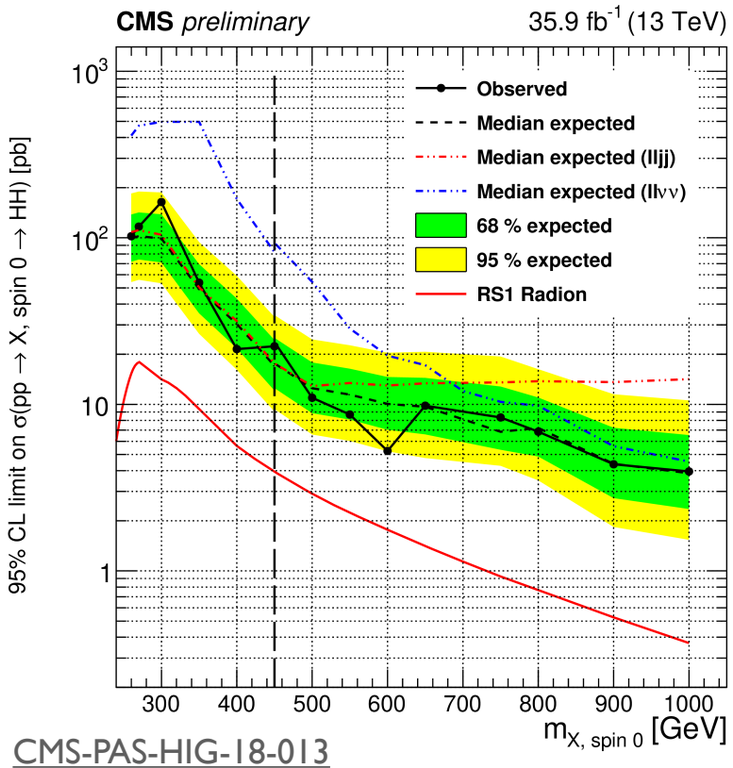


Di-Higgs Boson Production

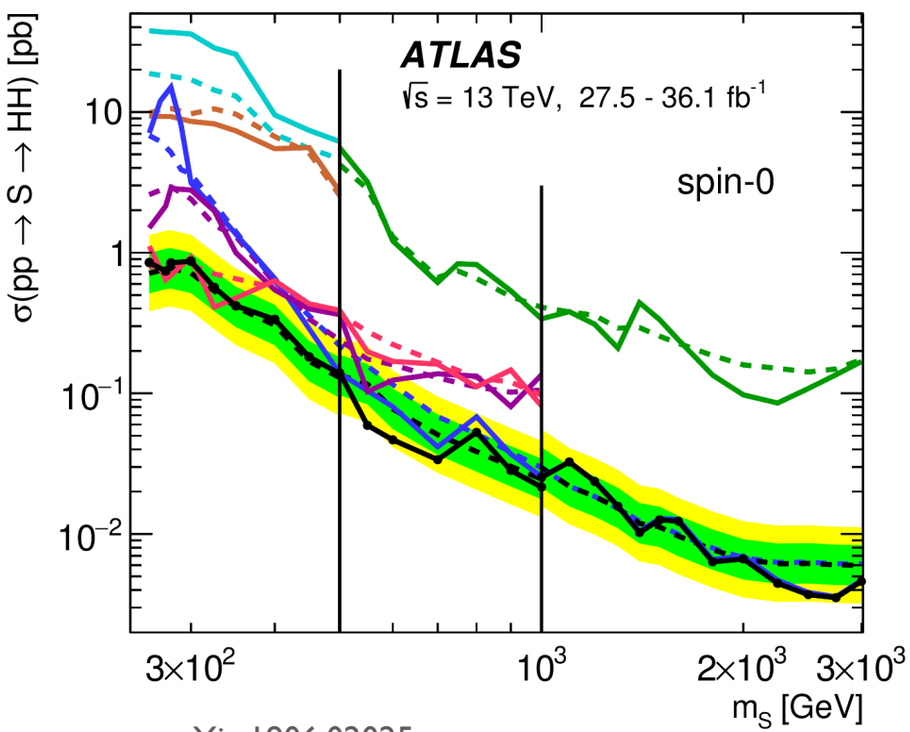
- Accessing the Higgs boson self-coupling, λ, is essential to exploring the electroweak symmetry breaking.
  - Determines the characteristic Mexican-hat shape of the Higgs field potential, $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$.
- Self-coupling can only be directly accessed in di-Higgs production. Small cross section.
  - Destructive interference between diagrams proportional to Higgs-heavy-quark coupling squared, and the self-coupling diagram.
- Potential enhancement of cross section from decays of a new spin-0 or spin-2 particle.



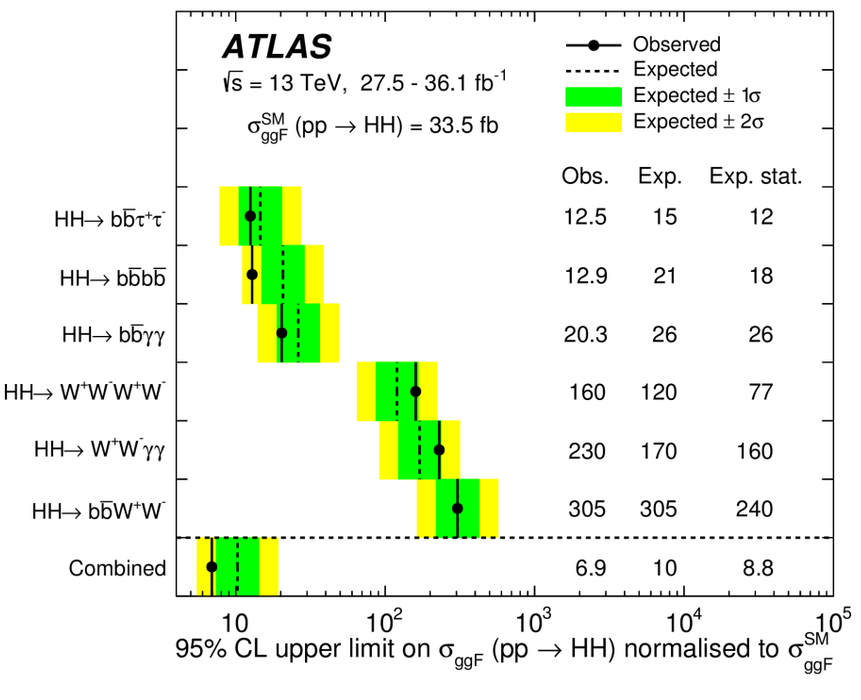




CMS-PAS-HIG-18-013

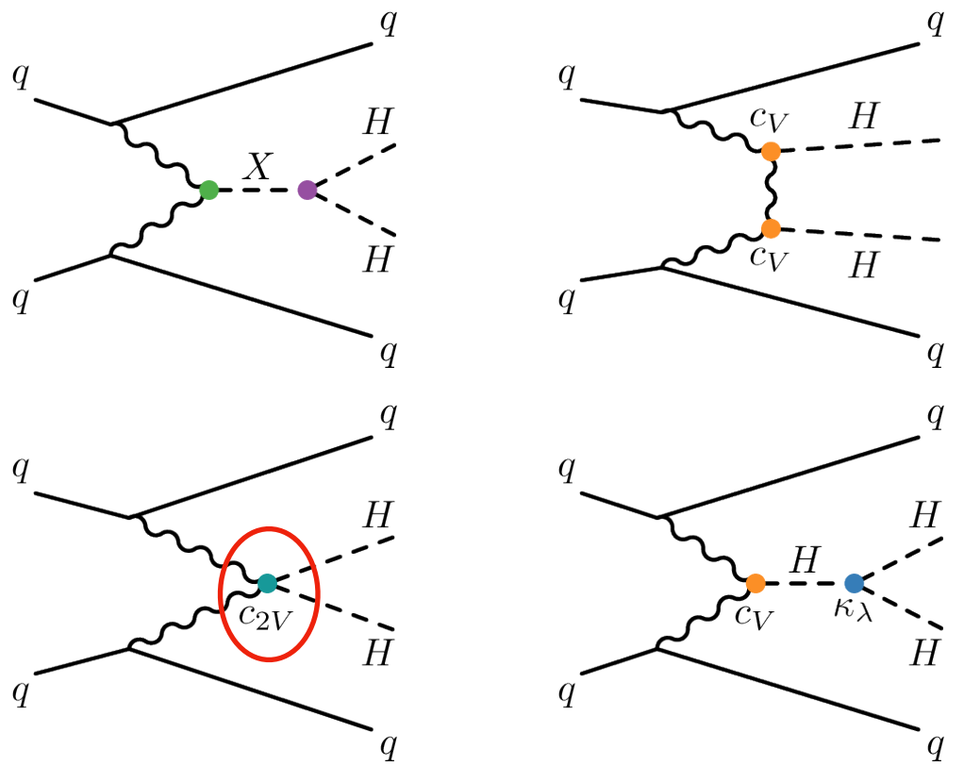


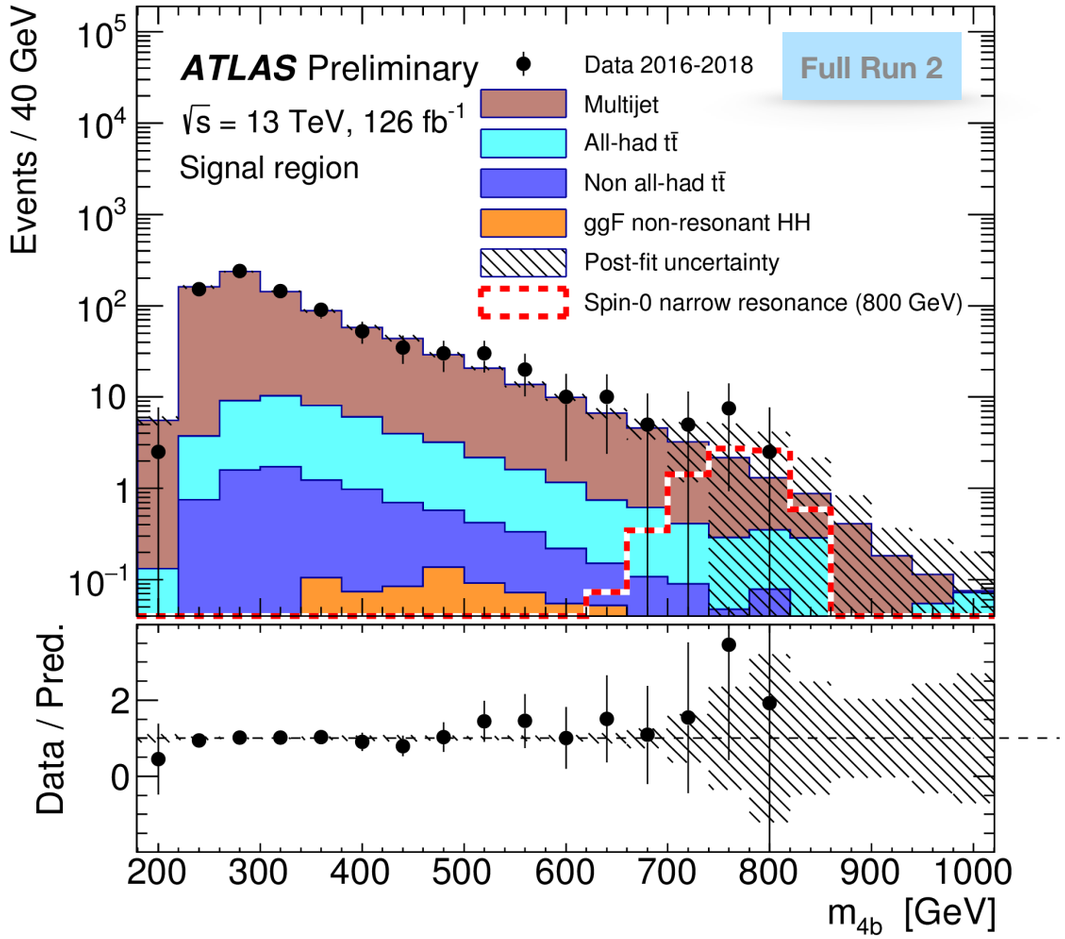
arXiv:1906.02025

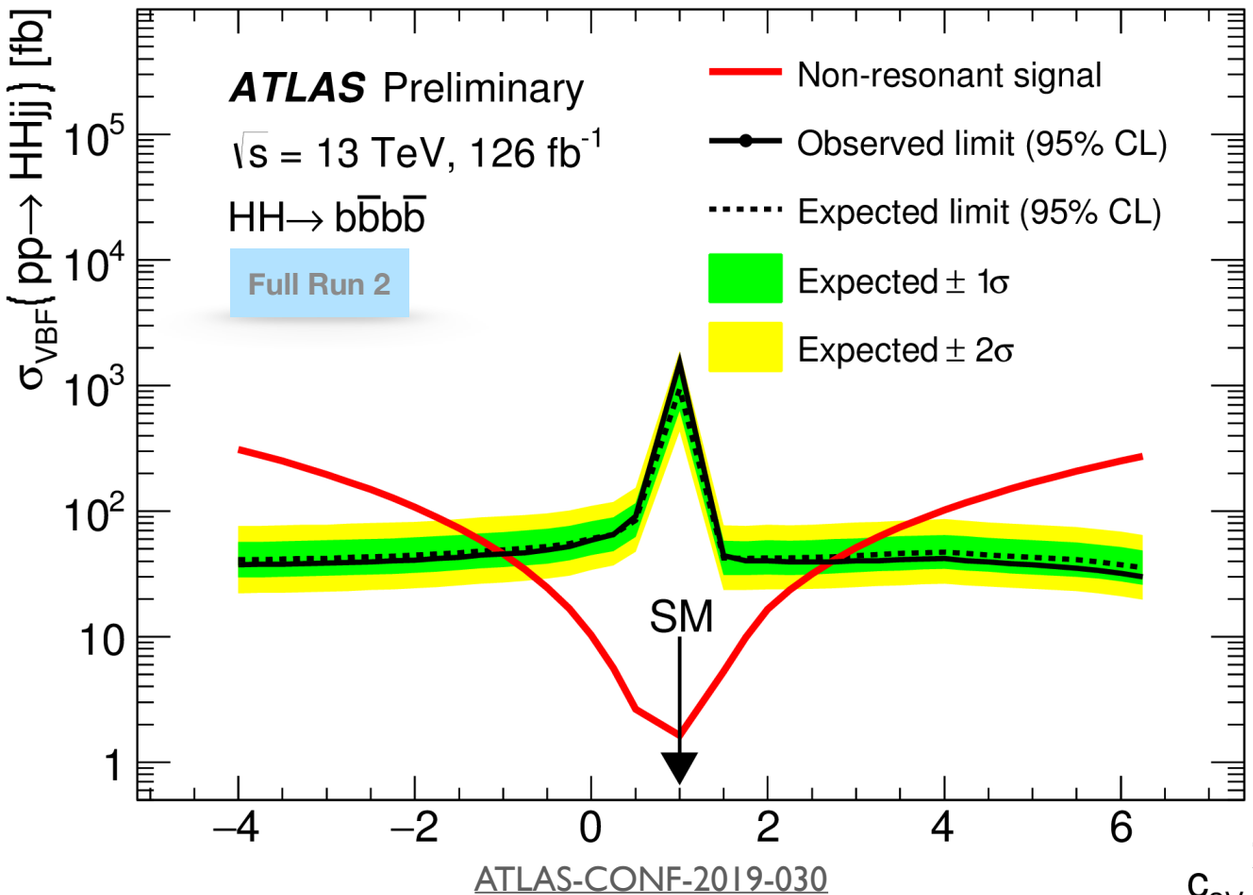


Di-Higgs Boson Production

- Recent result on search for VBF production of HH using full Run 2 dataset, 126 fb^{-1}.
  - Using the decay H→bb for both Higgs bosons.
- Use results to set limits on the VVHH quartic coupling, c_{2V}.
  - $c_{2v} < -1.02$ and $c_{2v} > 2.71$ are excluded.
- Results also used to set limits on new particles, looking for a peak in the m_{4b} spectrum.



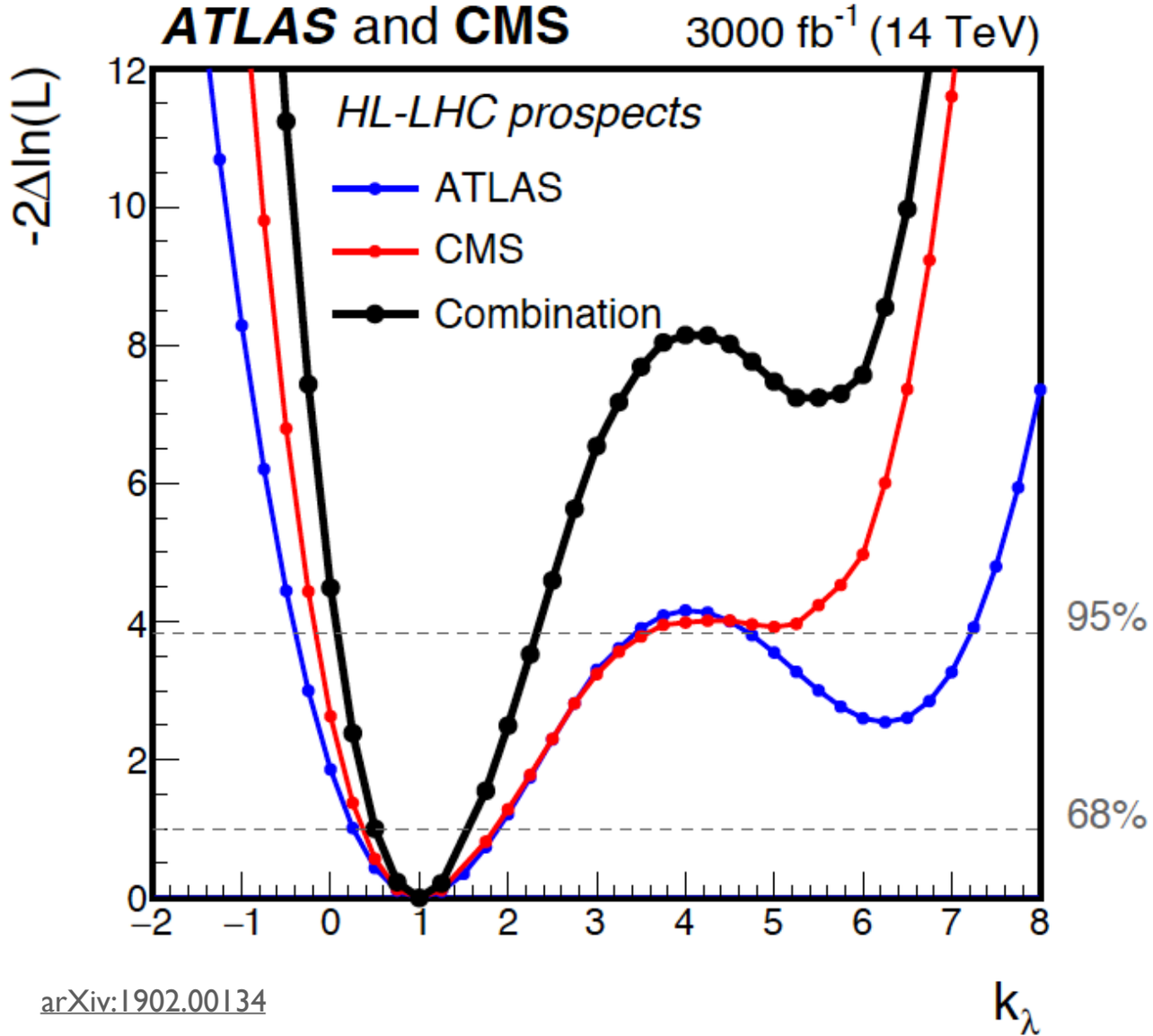


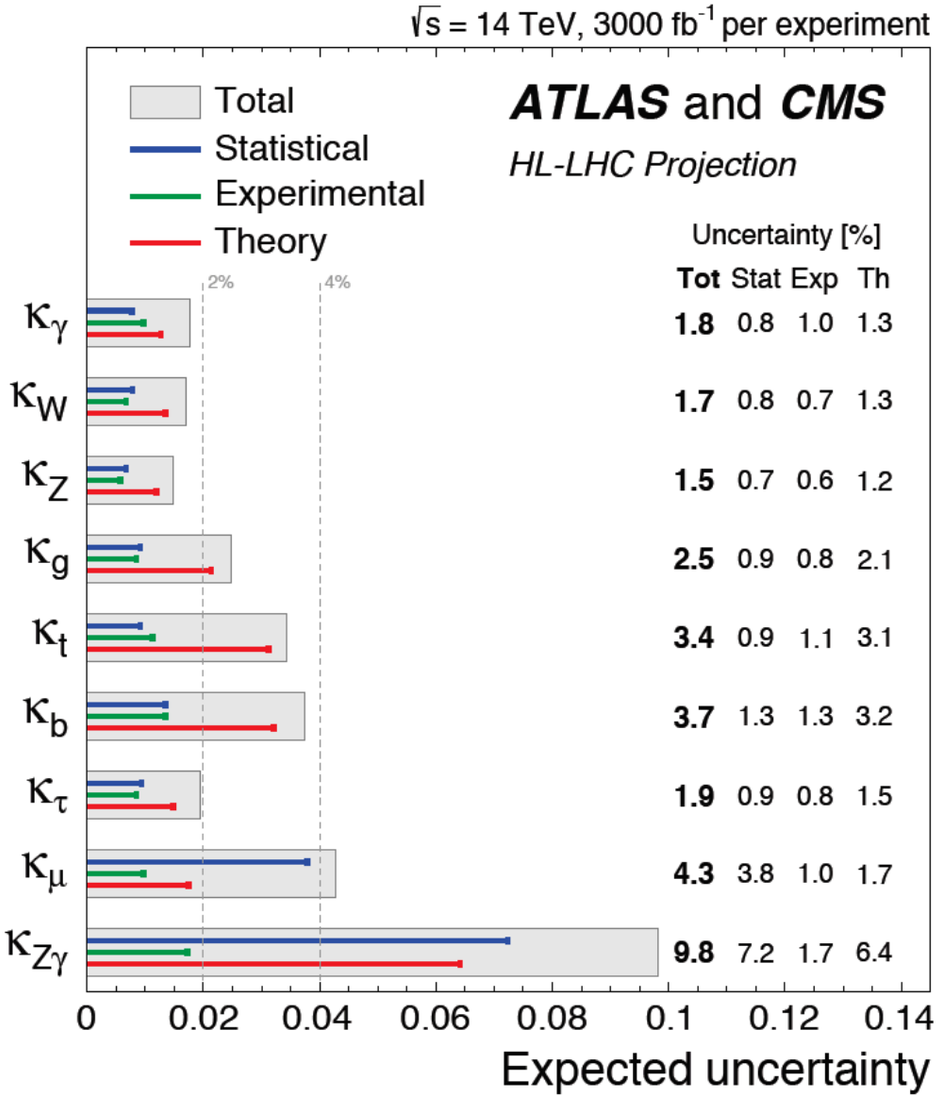


ATLAS-CONF-2019-030

Towards HL-LHC

- One of the key deliverables for the upgraded High Luminosity LHC (HL-LHC) will be able to measure di-Higgs production, ~4σ significance expected with 3000 fb^{-1}.
- Expected sensitivity to the self-coupling modifier κ_λ using 3000 fb^{-1}:
  - In the range $0.1 < \kappa_\lambda < 2.3$ at 95% C.L. ($0.5 < \kappa_\lambda < 1.5$ at 68% C.L.).
- Expect $\mathcal{O}$(%) precision on the most accessible Higgs boson couplings.
  - Many limited by uncertainties from theoretical considerations.

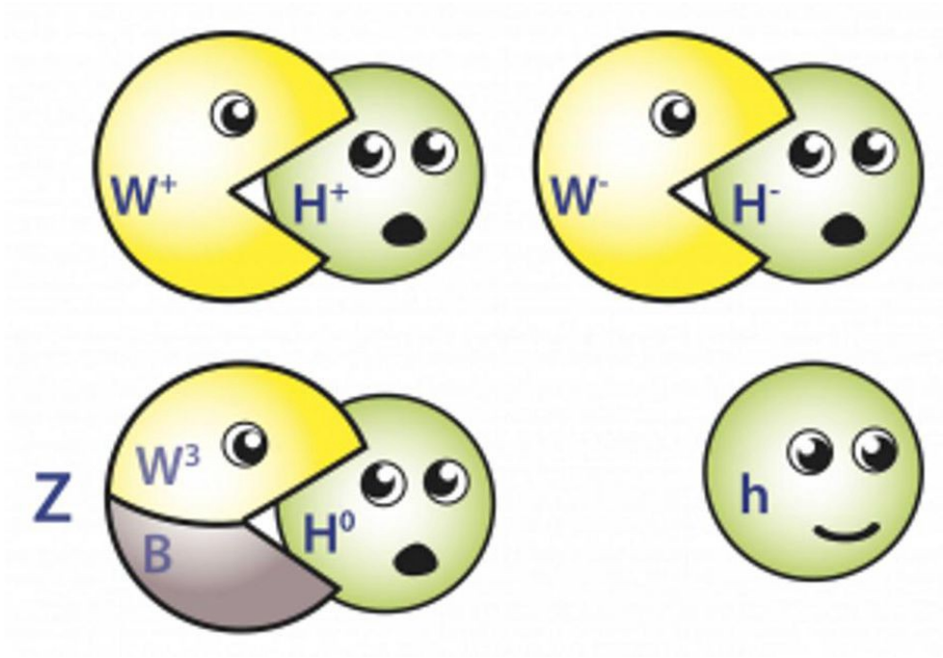




arXiv:1902.00134

Conclusions

- Hard to summarise the rich field of EW and Higgs physics in a short time.
  - Apologies to all the people whose results were omitted in this presentation!
- Standard model EW measurements are starting to probe very rare processes.
  - Observed electroweak production of di-boson pairs, will soon have sensitivity to probe Vector Boson Scattering processes.



(FLIP TANEDO / QUANTUM DIARIES)

- A few results have started appearing on the full Run 2 dataset, for Higgs analyses most notably $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ results.
  - For the more intricate Higgs boson channels and Higgs boson combinations we can expect to see results appearing in the upcoming year.
  - Results in STXS bins, and interpreted in Effective Field Theories. Ideally a combination of Higgs boson and SM electroweak measurements are used as inputs.
- New physics can hide in the details, increased precision can be as important as direct searches for new particles to find deviations from the standard model.

Still to see the full impact of the Run 2 dataset!

Backup