

“Standard Model Higgs” Results from CMS and ATLAS at 13 TeV

12th LHC-HXSWG Workshop
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David Sperka
University of Florida

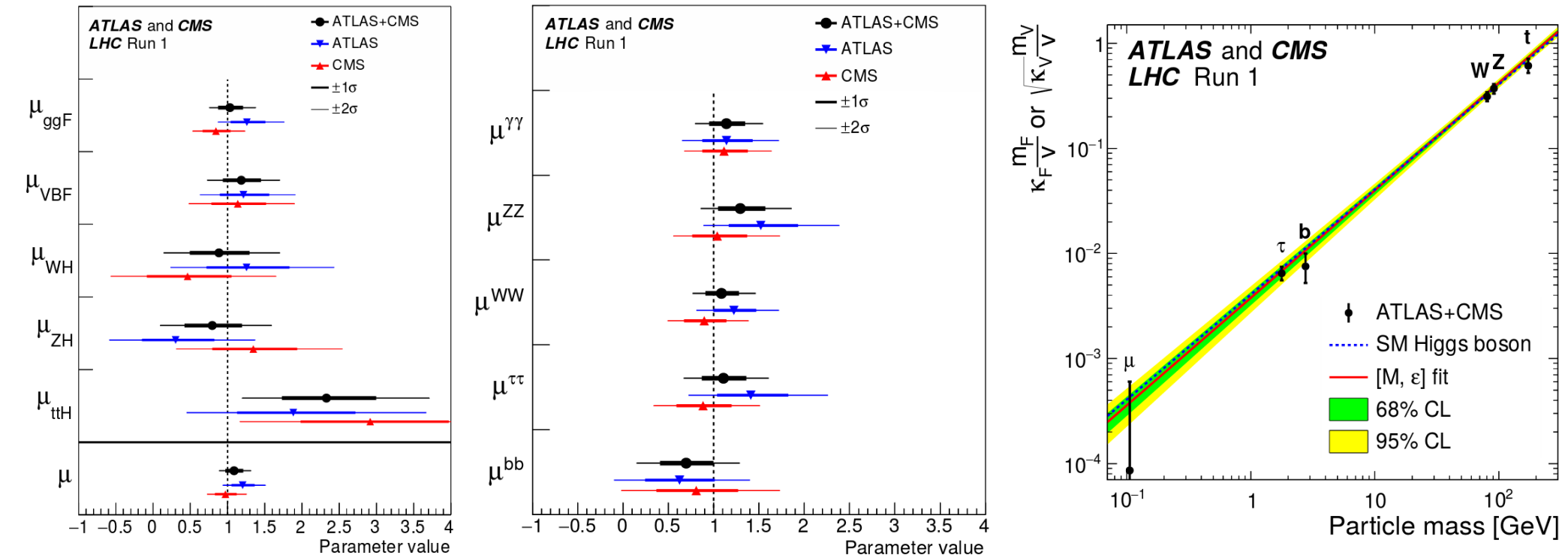
On Behalf of the ATLAS and CMS Collaborations



Introduction:

Where We Stood Before Run 2

- The **discovery of the 125 GeV Higgs boson** was the triumph of LHC Run 1
- Mostly SM like, but there were some deviations, which should be followed

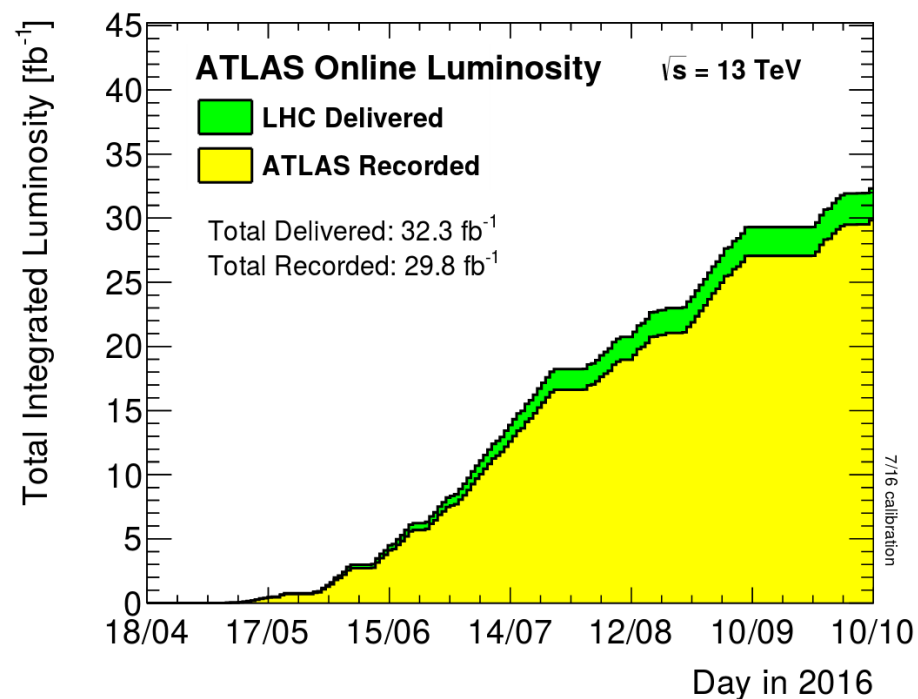
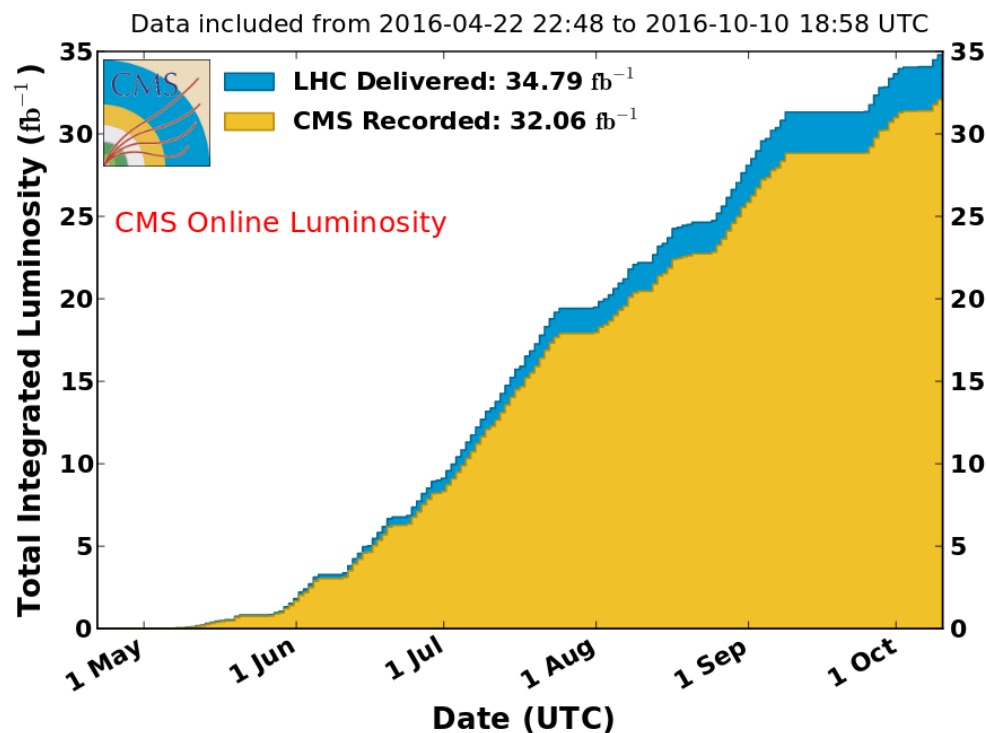


- The experiments continue to test the SM predictions for the Higgs sector
 - **Rediscover** the 125 GeV Higgs boson at 13 TeV
 - **Increase the precision**, improve measurement strategies
 - Measurements of the 125 GeV Higgs may reveal **deviations from the SM**

LHC Experiments at 13 TeV

- The LHC, ATLAS and CMS are all performing extremely well at 13 TeV
- $\sim 30 \text{ fb}^{-1}$ per experiment recorded so far, ~ 2 weeks of data taking left

CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = 13 \text{ TeV}$

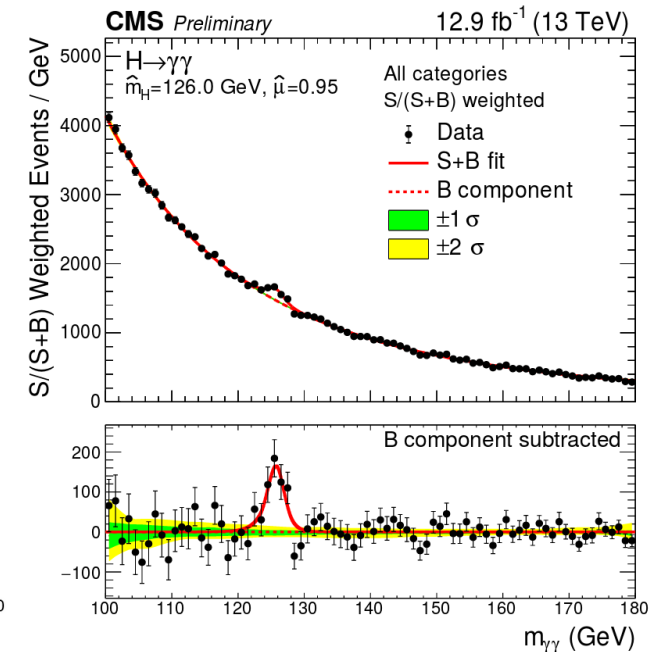
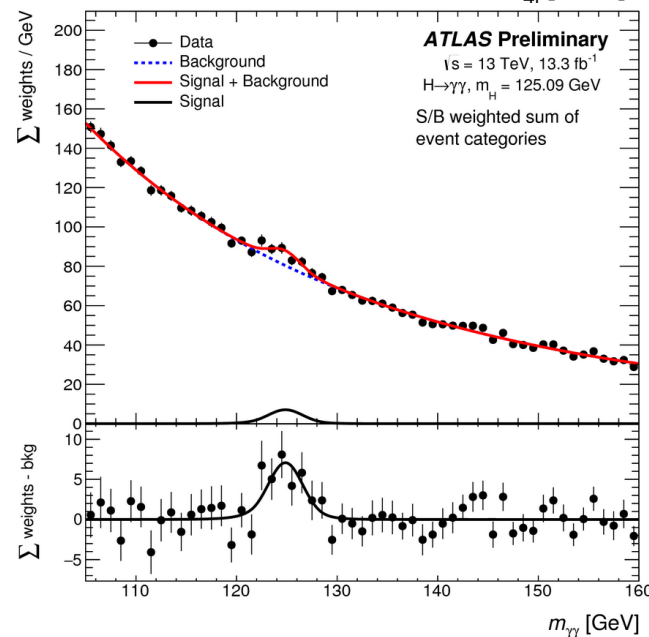
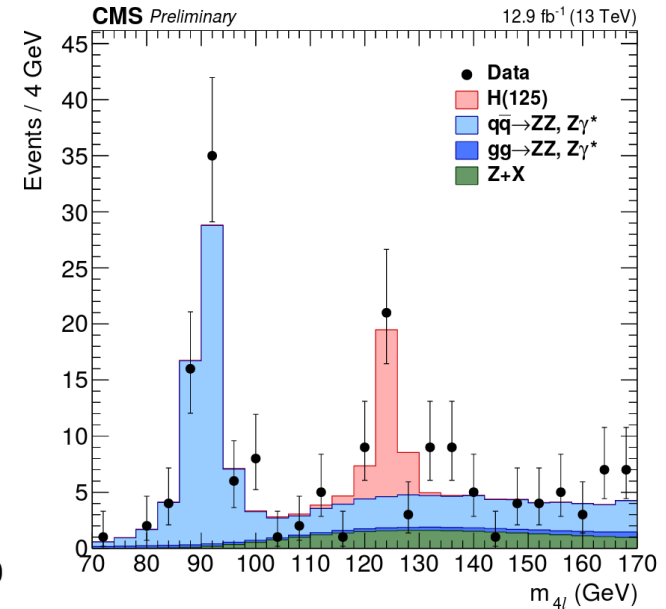
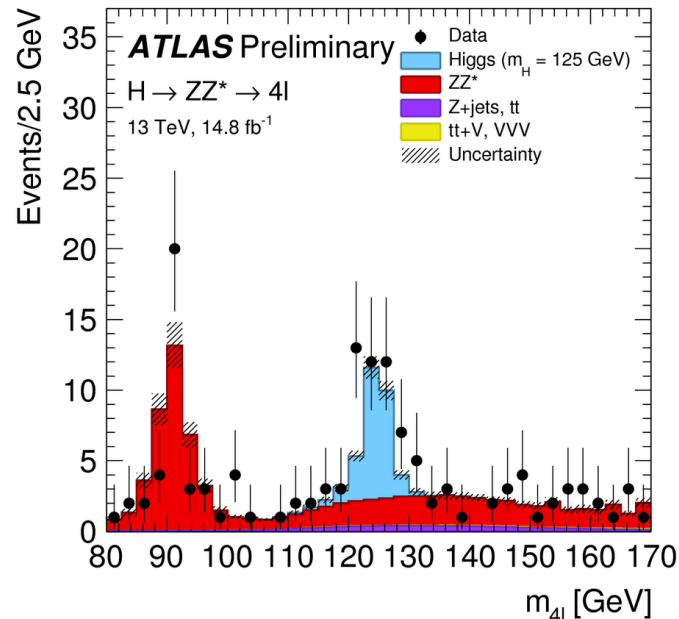


- Results shown today obtained with Moriond (2015, $\sim 3 \text{ fb}^{-1}$) or ICHEP (2016, $\sim 13 \text{ fb}^{-1}$) datasets, similar precision as Run 1

Rediscovery:

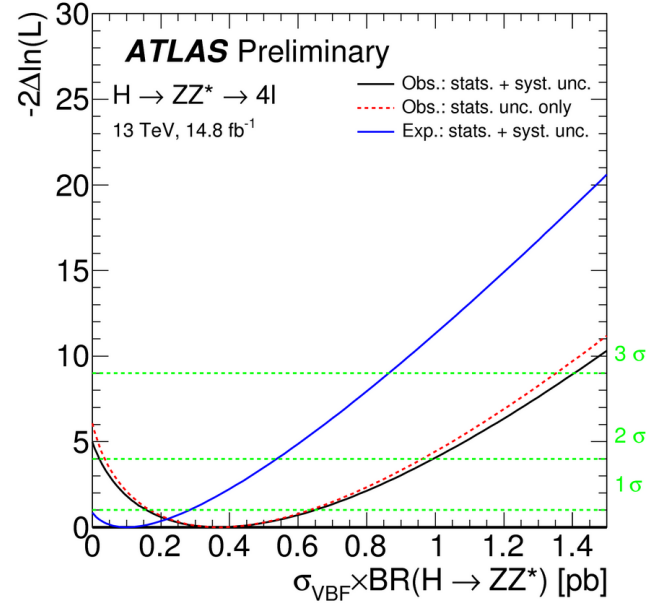
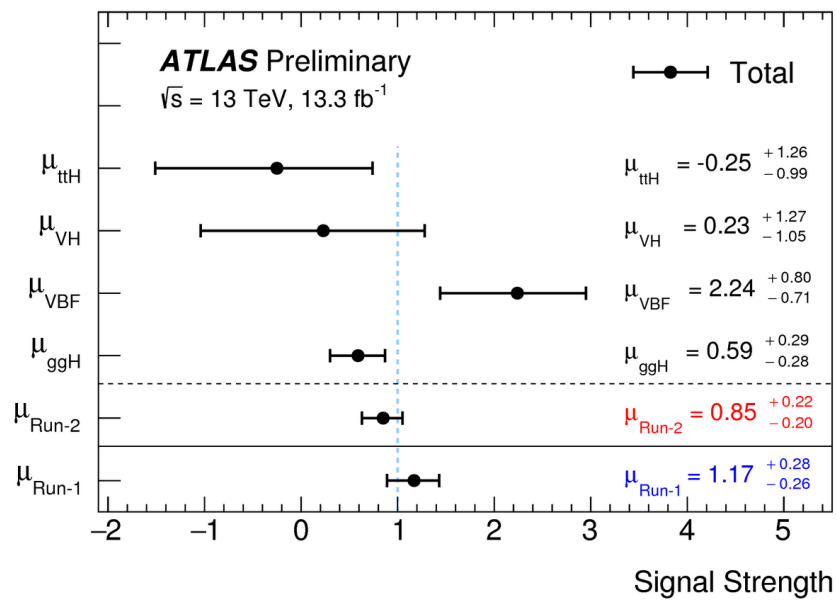
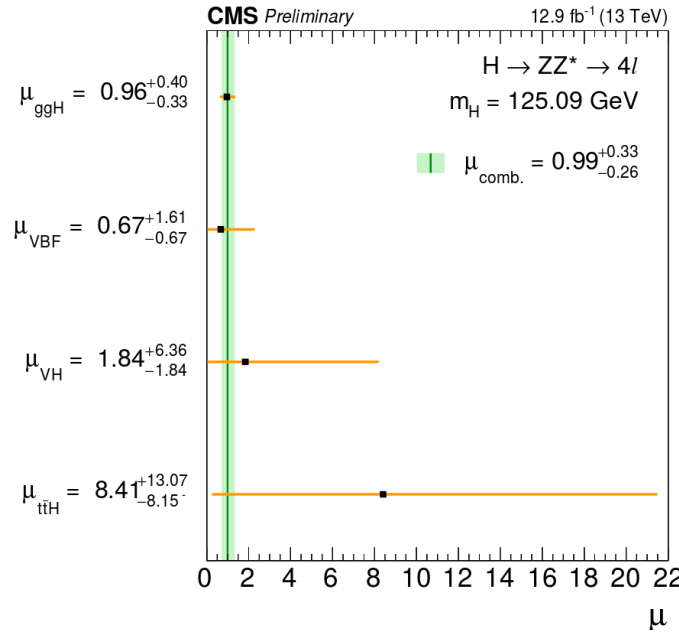
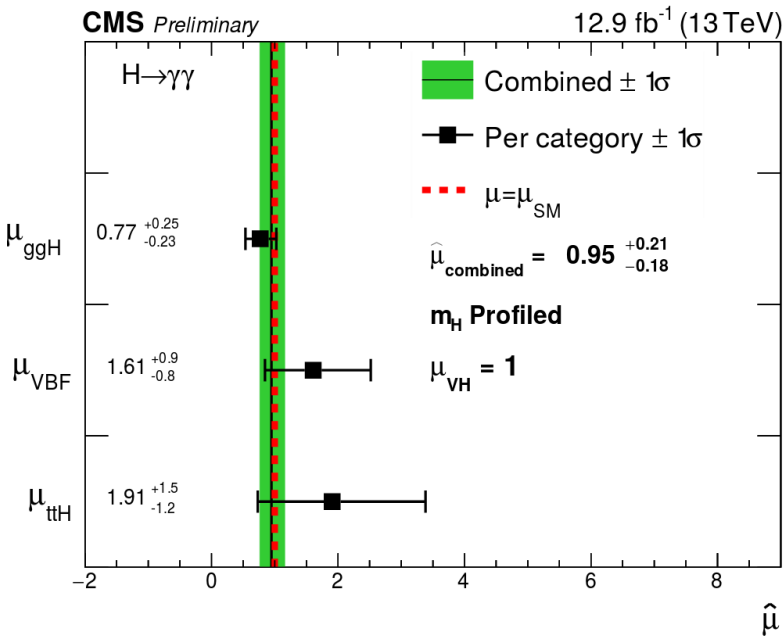
Observation of H(125) at 13 TeV

- The first major milestone of the Higgs physics program at Run2 was to re-establish the presence of the 125 GeV Higgs boson
- Accomplished with the $ZZ \rightarrow 4\ell$ and $\gamma\gamma$ channels
 - $\rightarrow \sim 6\sigma$ significance per channel
- Ability to trigger on and reconstruct physics objects no small feat (LHC operating above design luminosity)



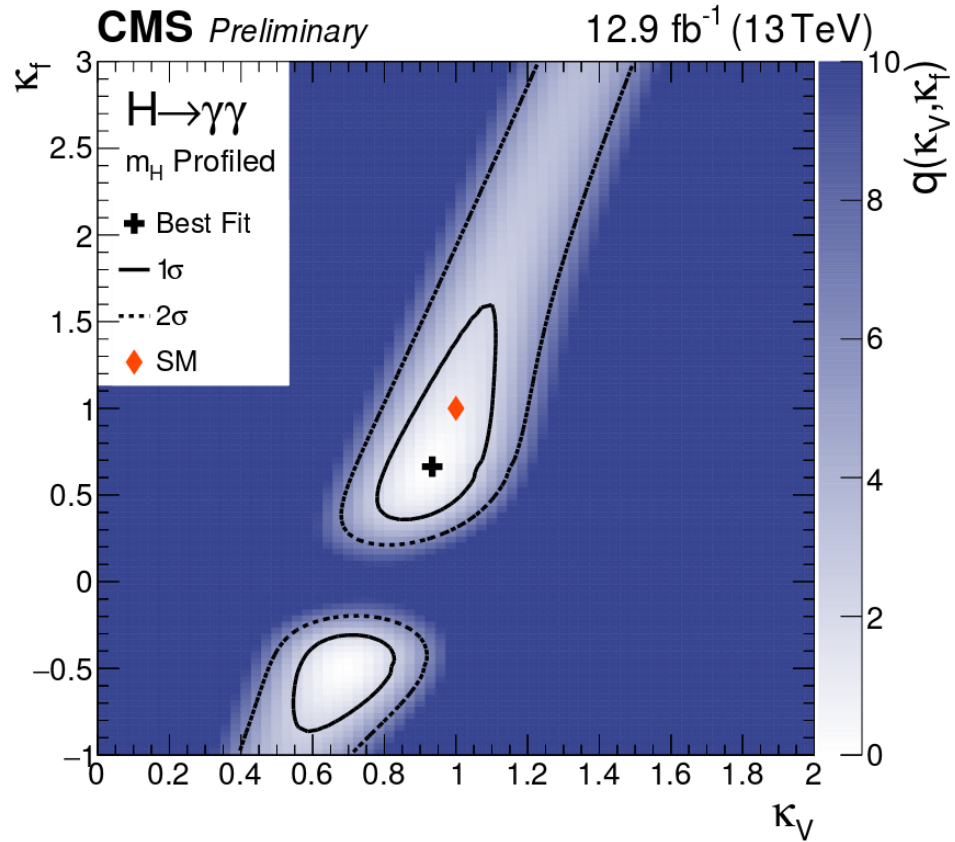
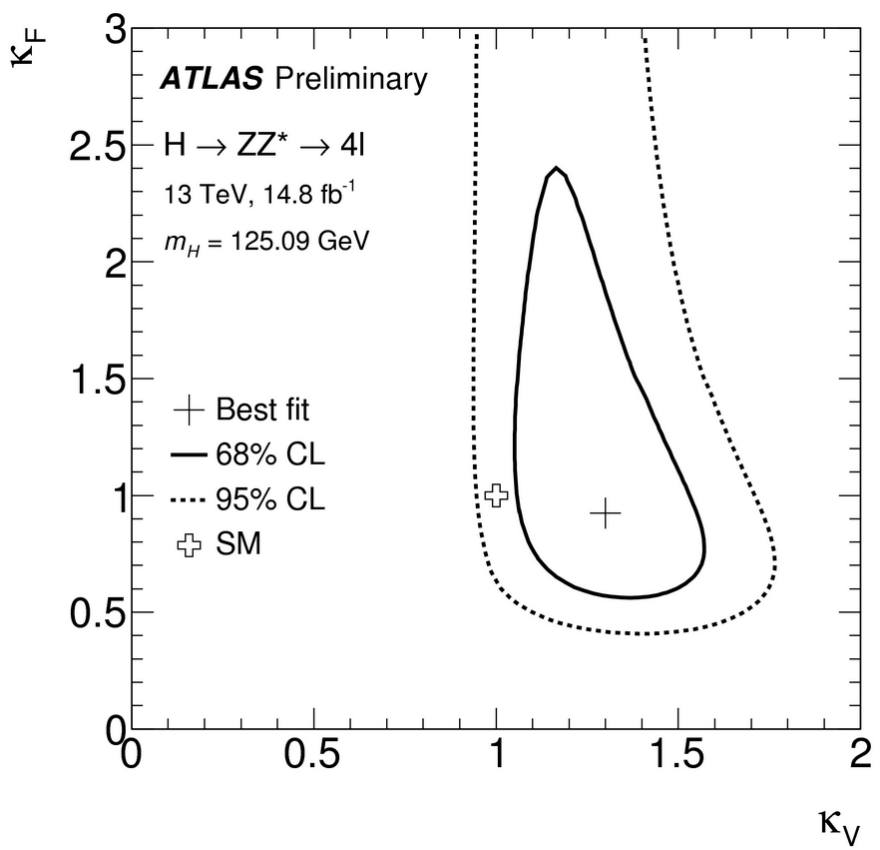
Signal Strengths: Diboson Signal Strengths at 13 TeV

- Signal strength per production mode measured using **dedicated event categories**
- **Improvements in modeling** compared to Run 1, e.g.:
 - ZZ background at NNLO
 - In CMS, NLO MC for all signal processes
- **Latest cross sections and uncertainties from YR4**



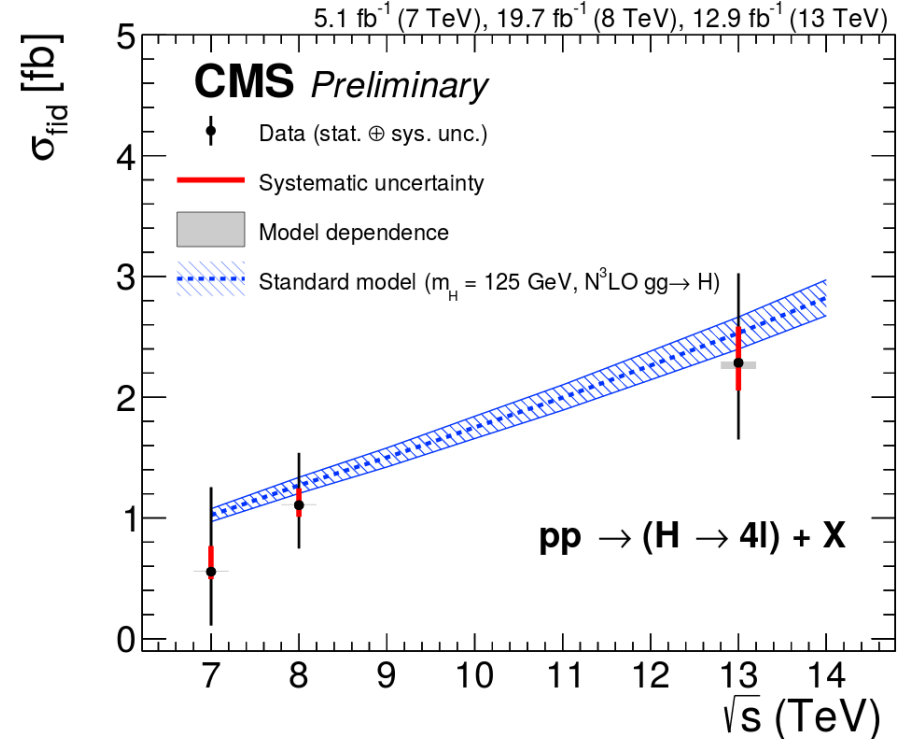
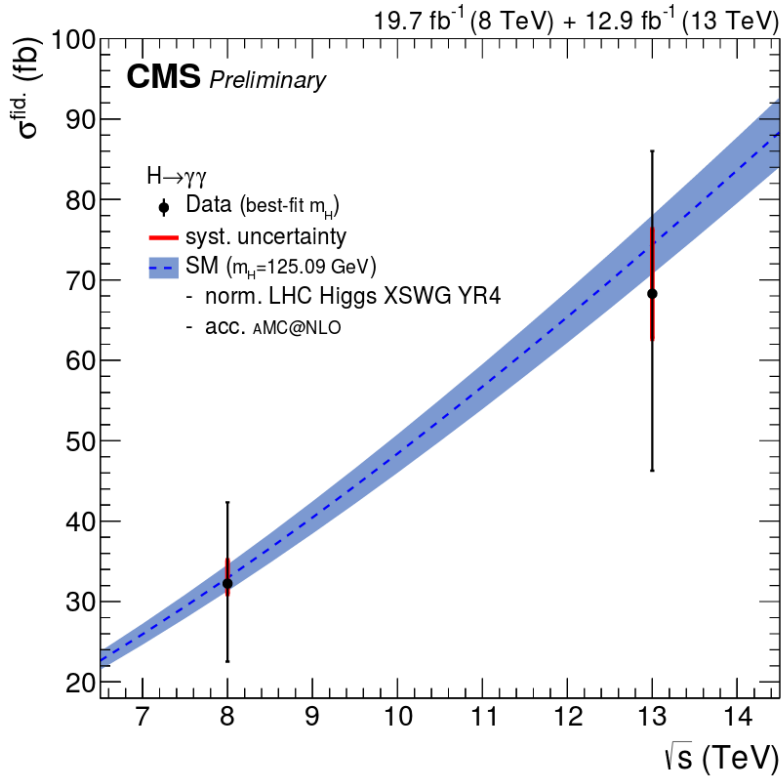
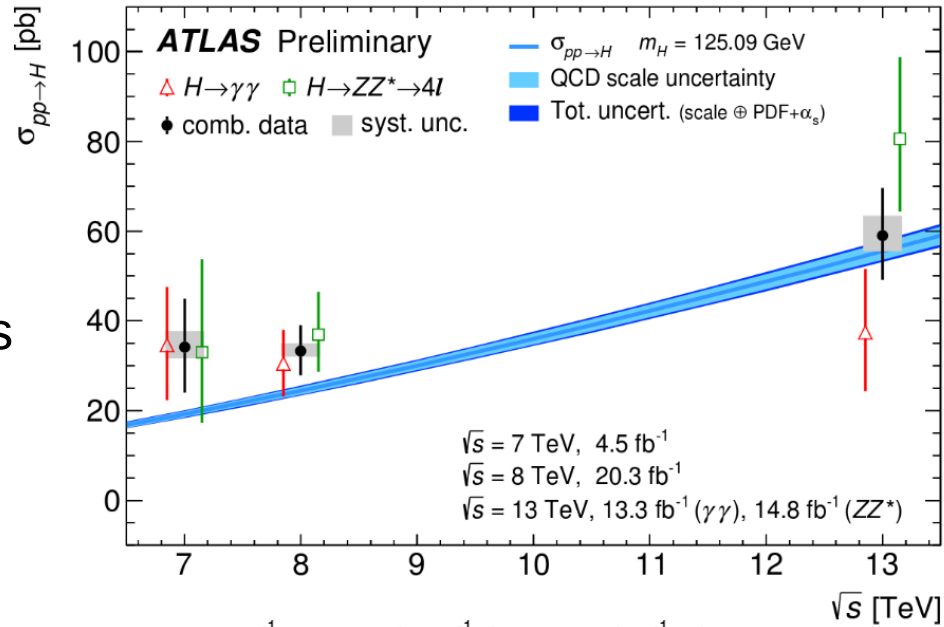
Kappa Framework Interpretations

- A starting point for interpretations, developed in context of YR3
 - Designed to help establish whether the 125 GeV Higgs is SM-like
 - Use best available SM predictions, while also allowing for deviations
- Updated 2D constraints on $\kappa_V - \kappa_F$ using $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ decay channels



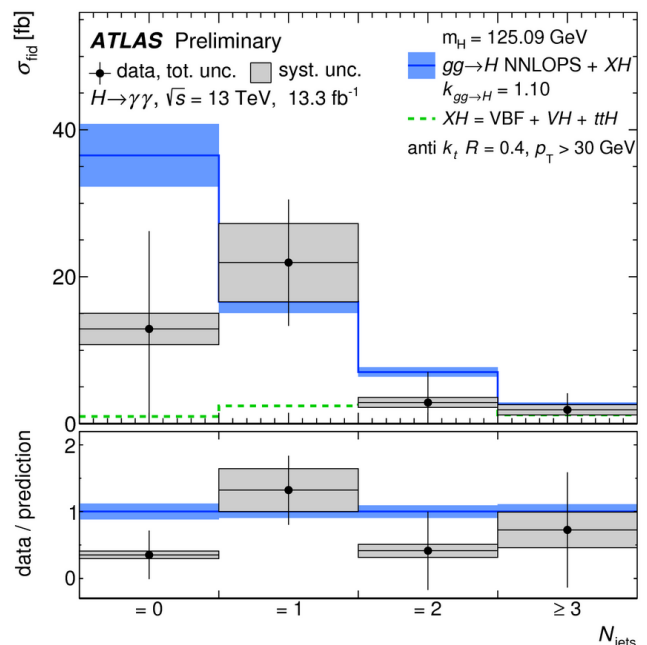
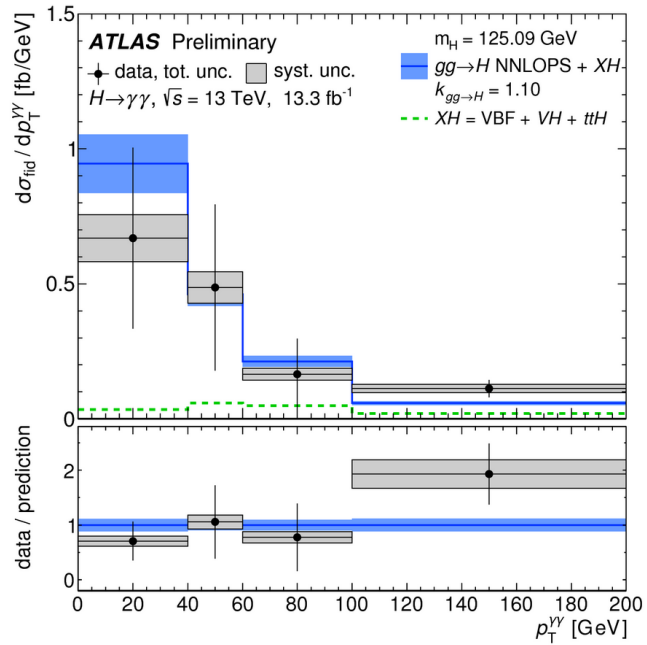
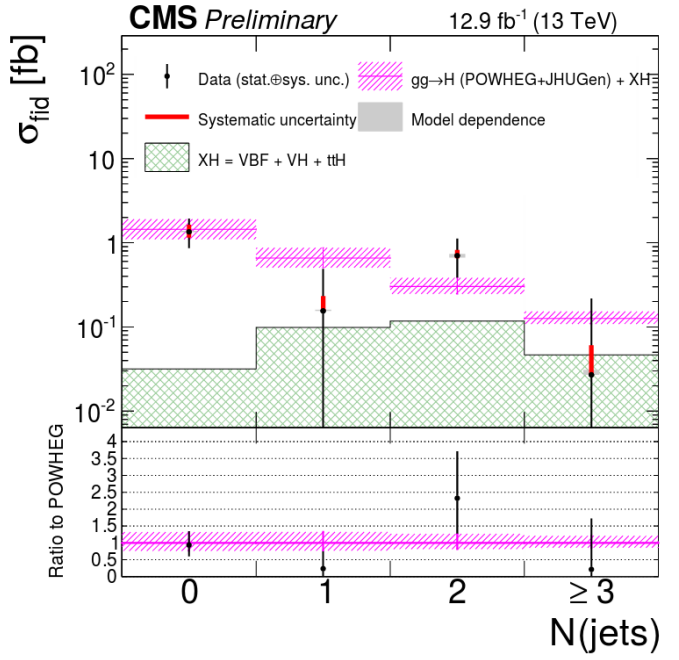
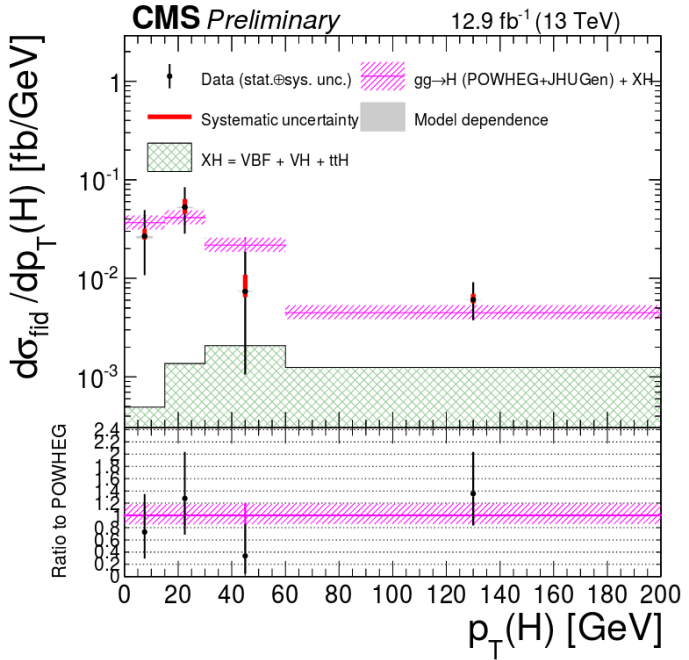
Measurements with Dibosons: Fiducial Cross Sections

- New measurements of **model independent** fiducial cross sections, fiducial volume closely matching experimental acceptance
 - Not sensitive to production mechanism
 - **Decouple uncertainties** on the signal cross section from the measurement uncs.
 - Compared to latest YR4 cross sections, i.e. gluon fusion prediction at **N³LO**



Measurements with Dibosons: Differential Fiducial Cross Sections

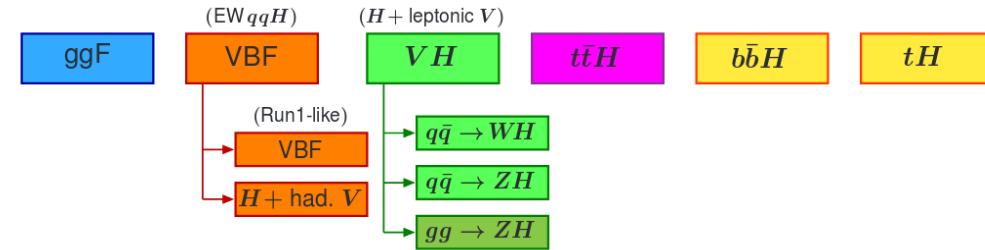
- Already we have seen updated differential fiducial cross section measurements at 13 TeV in ZZ (CMS) and $\gamma\gamma$ (ATLAS)
- Important test of SM calculations
- Can also be used to probe BSM physics, e.g. tails of $p_T(H)$ spectrum
- Provide indirect constraints on light quark yukawa couplings ([Bishara et. al.](#), [Soreq et. al.](#))
- What more can we learn from distributions?



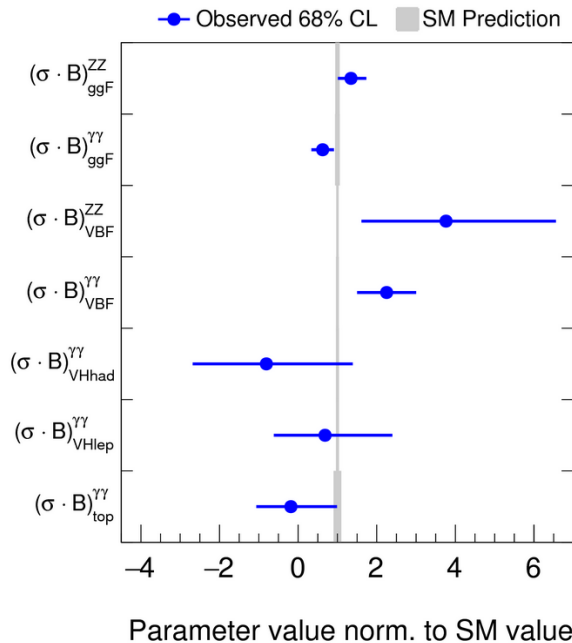
Measurements with Dibosons:

Simplified Template Cross Sections

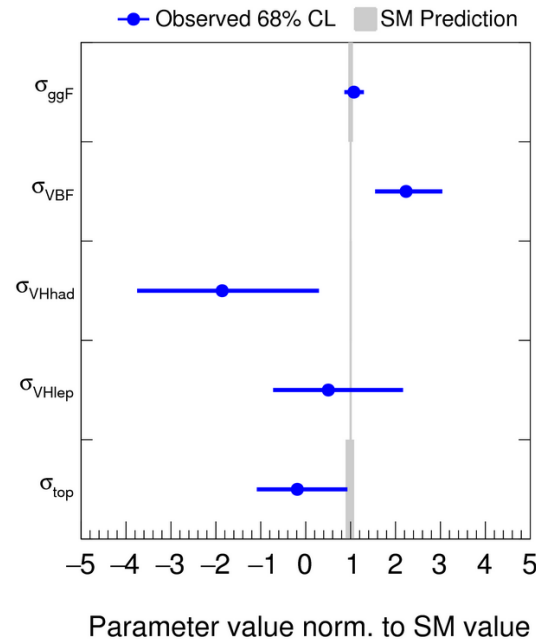
- ATLAS has taken the **first step towards template cross section measurements**
 - Stage-0 Categorization
 - **Combination of ZZ and $\gamma\gamma$ final states**
 - Including interesting ratio measurements
- **Some tension** between the two final states
 - Only at 13 TeV, and combined result compatible with SM prediction



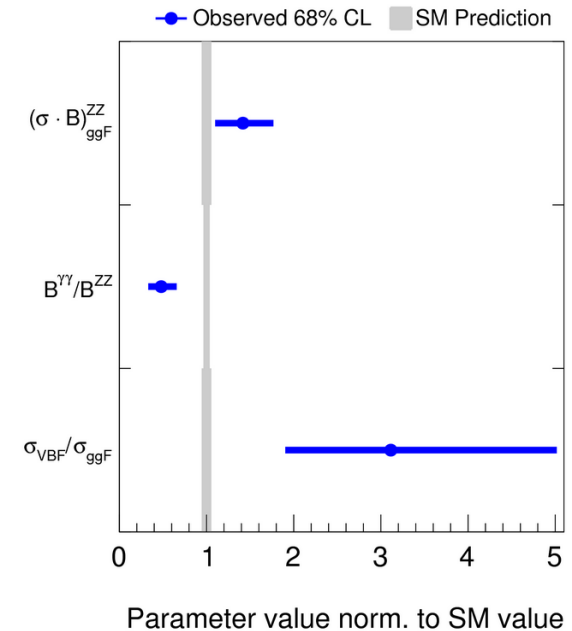
ATLAS Preliminary $m_H=125.09$ GeV
 $\sqrt{s}=13$ TeV, 13.3 fb^{-1} ($\gamma\gamma$), 14.8 fb^{-1} (ZZ)



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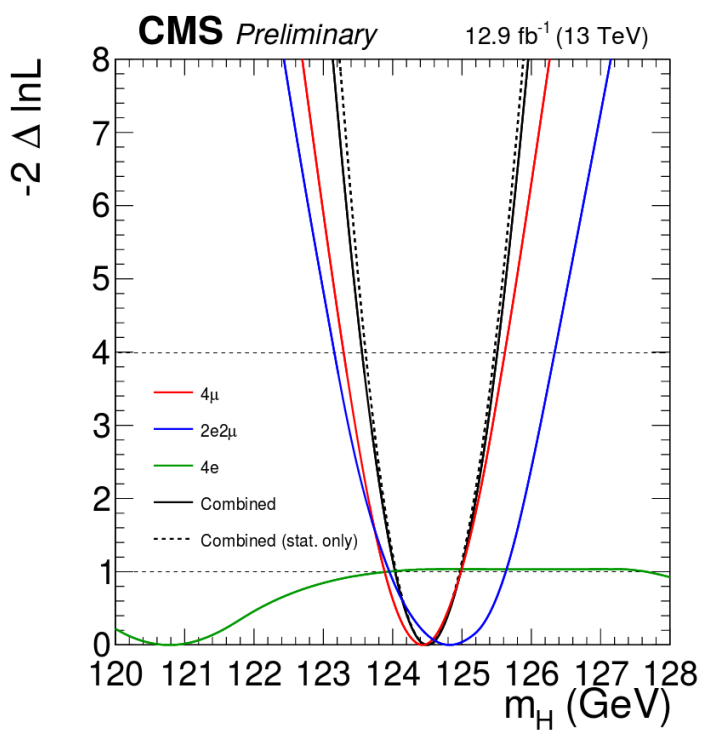


ATLAS Preliminary $m_H=125.09$ GeV
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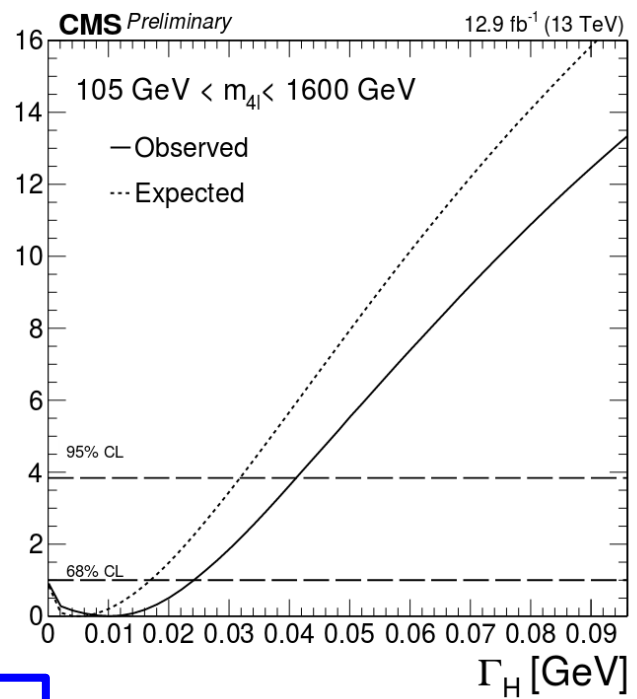


Measurements with Dibosons: Mass and Width

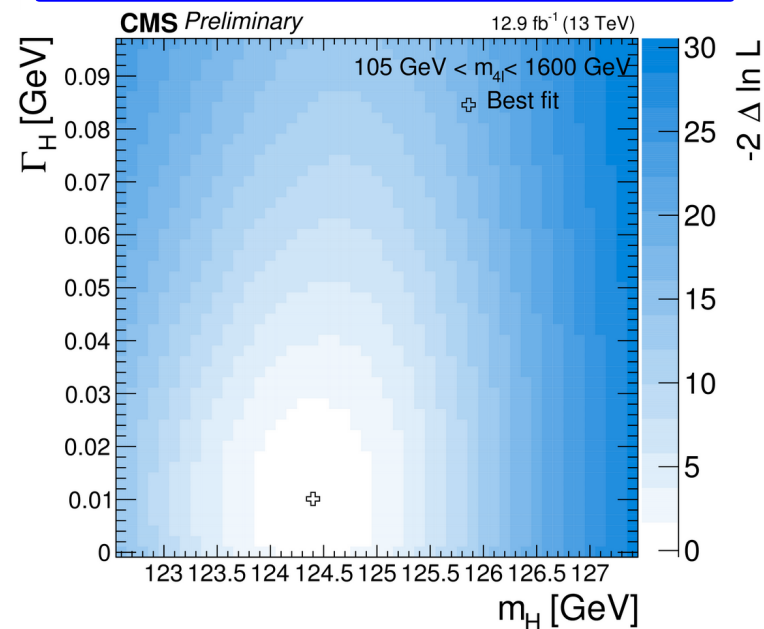
- The mass and width of the boson have been remeasured by CMS using the $ZZ \rightarrow 4\ell$ decay channel, using combination of on-shell and the off-shell tail
 - Also 2D constraint in $m_H - \Gamma_H$ plane
- Mass measurement compatible with ATLAS+CMS Run 1 combination
- Best fit of width slightly broader than expected, opposite to Run 1



$m_H = 124.5 \pm 0.48 \text{ GeV}$



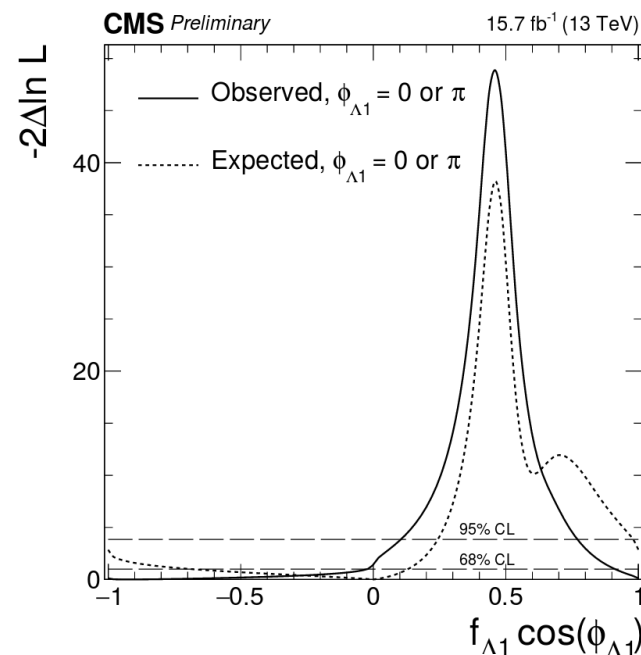
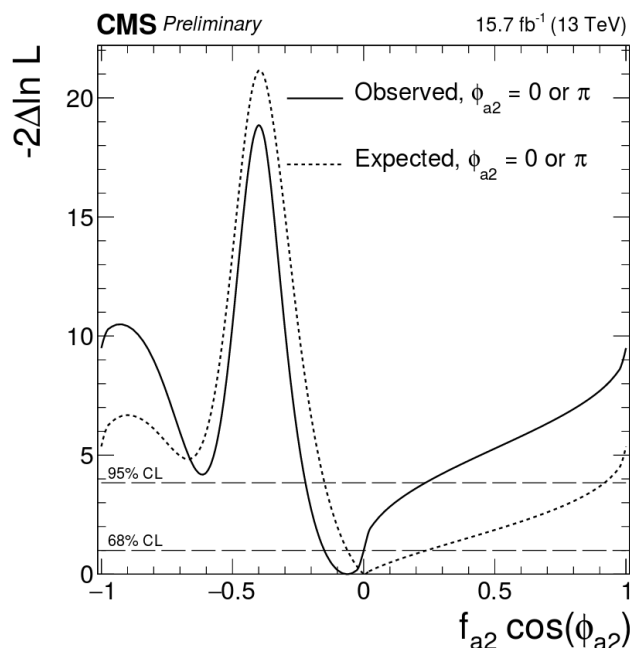
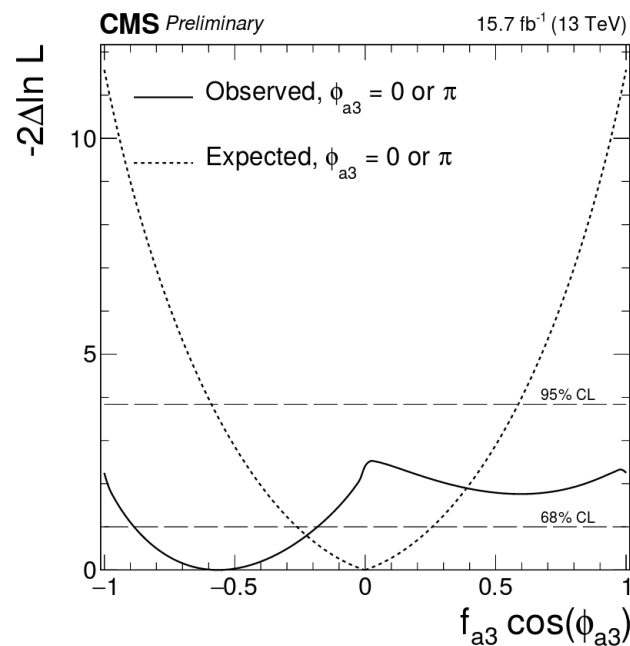
$\Gamma_H < 41 \text{ MeV (95% CL)}$



Anomalous Coupling Constraints

- **Tensor structure constrained** using the the $ZZ \rightarrow 4\ell$ decay channel
 - Test for anomalous spin-0 HVV interactions using decay kinematics
 - Still **no sign of any BSM** contributions with current statistics

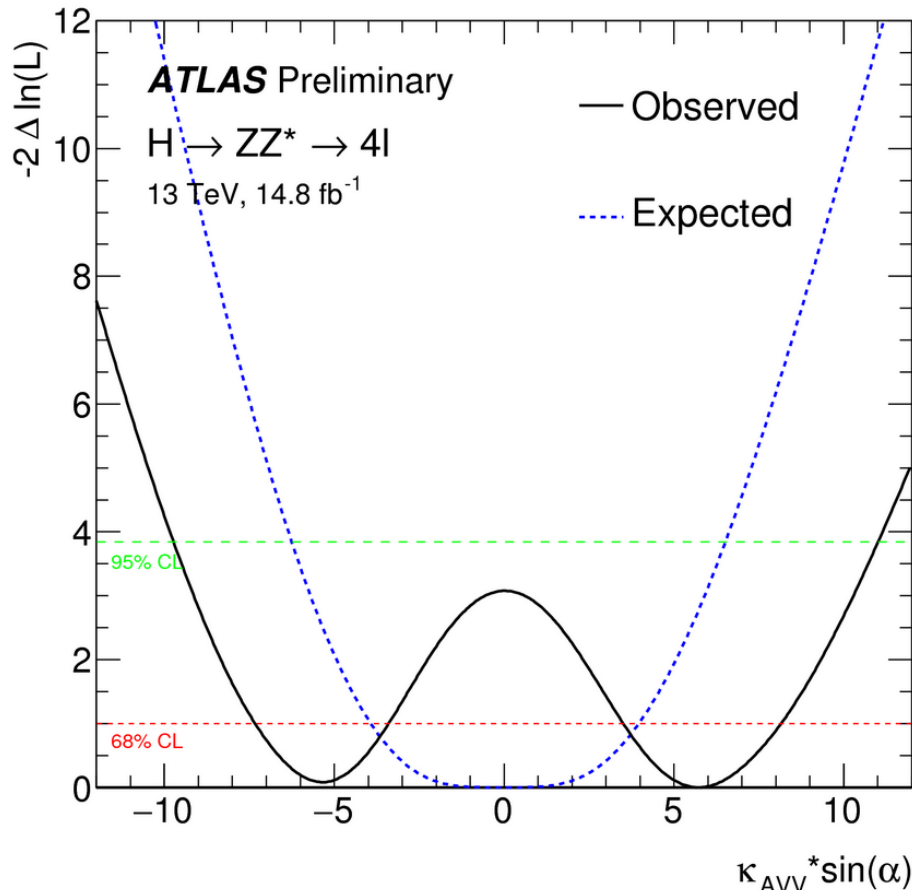
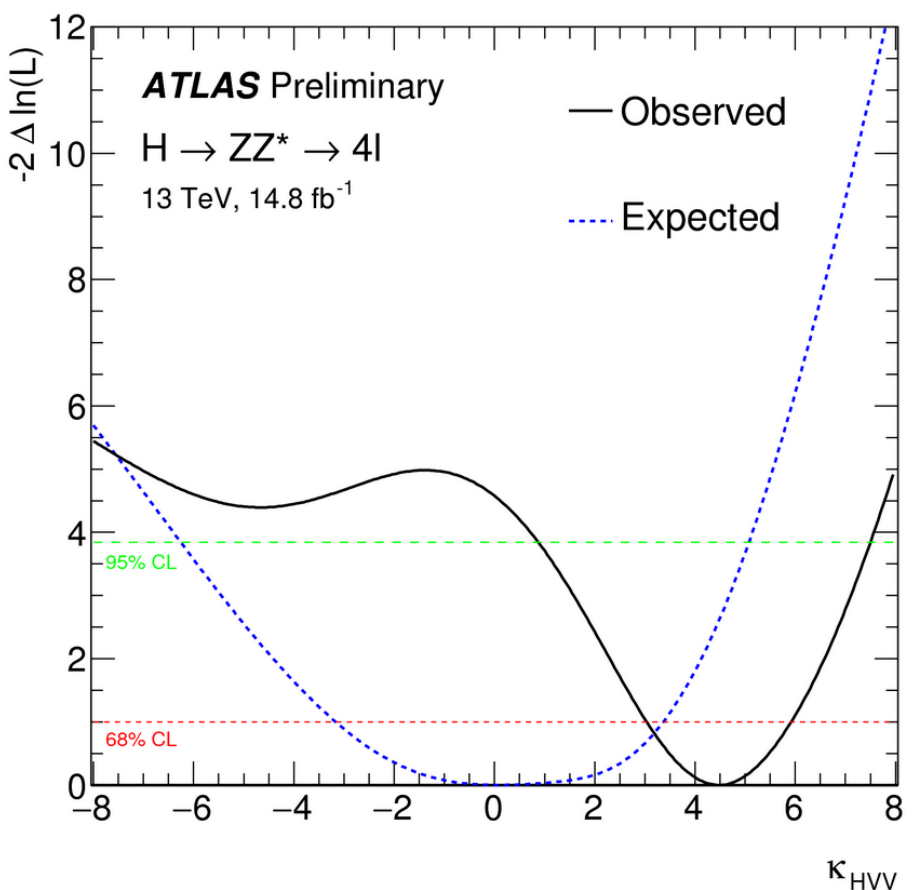
$$A(HVV) \sim \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1} + q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$



Parameter	Observed	Expected
$f_{a3} \cos(\phi_{a3})$	$-0.56^{+0.38}_{-0.32} [-1.00, 1.00]$	$0.00^{+0.26}_{-0.26} [-0.59, 0.59]$
$f_{a2} \cos(\phi_{a2})$	$-0.06^{+0.06}_{-0.09} [-0.22, 0.24]$	$0.00^{+0.24}_{-0.06} [-0.15, 0.92]$
$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$	$-0.93^{+0.90}_{-0.16} [-1.00, 0.10] \cup [0.77, 1.00]$	$0.00^{+0.13}_{-0.69} [-1.00, 0.24] \cup [0.98, 1.00]$

Effective Lagrangian Interpretations

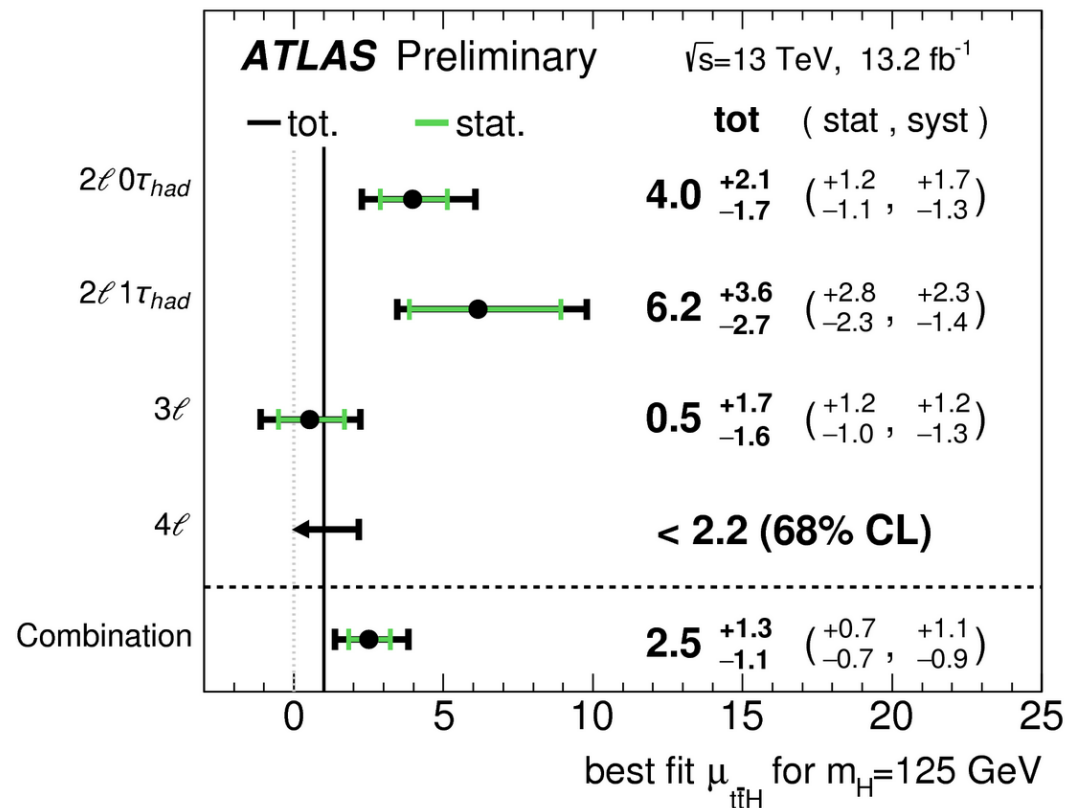
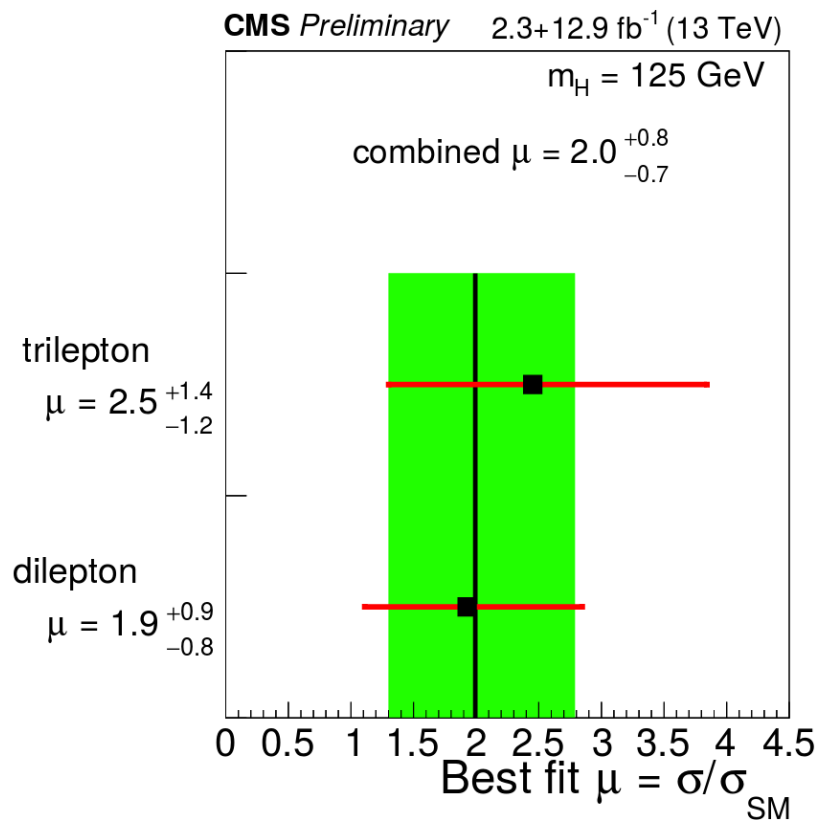
- Effective Lagrangian interpretation from in the context of the [Higgs Characterization Model](#) from ATLAS using the the $ZZ \rightarrow 4\ell$ decay channel
 - BSM interactions affect the signal yields in different event categories
 - Test for [anomalous BSM scalar and pseudo-scalar interactions](#)



$H \rightarrow \text{fermions}$:

Search for $t\bar{t}H \rightarrow \text{multileptons}$

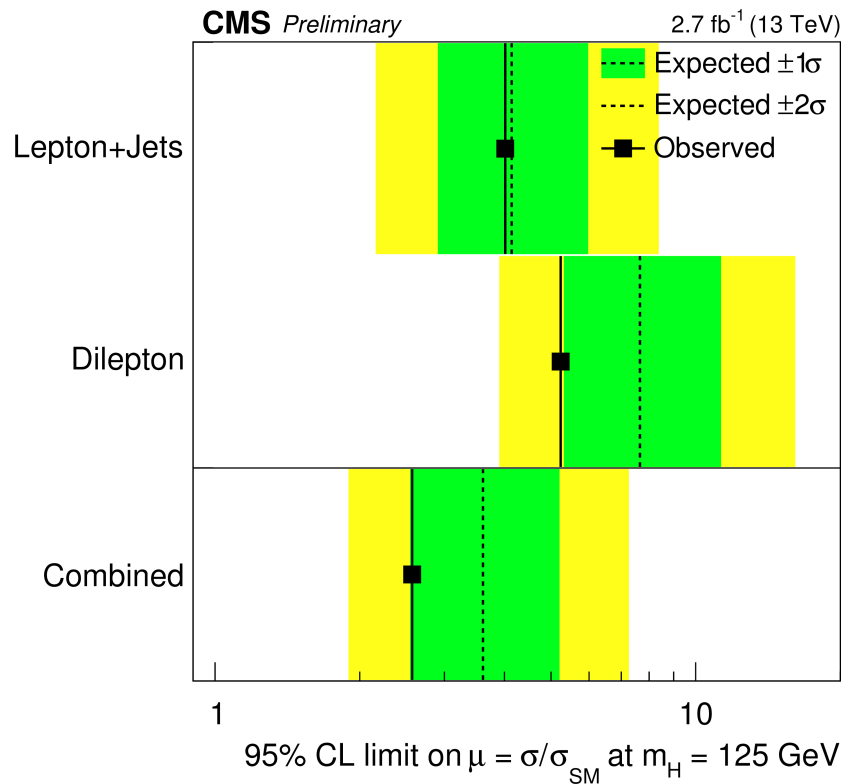
- One of the more interesting anomalies in Run 1 was $t\bar{t}H$
 - Run 1 combination gives $\mu_{t\bar{t}H} = 2.3 \pm 0.7$
 - Biggest excess in the multilepton categories
 - Cross section at 13 TeV nearly 4x that of 8 TeV → better sensitivity
- So far in Run 2, the multilepton excess appears again



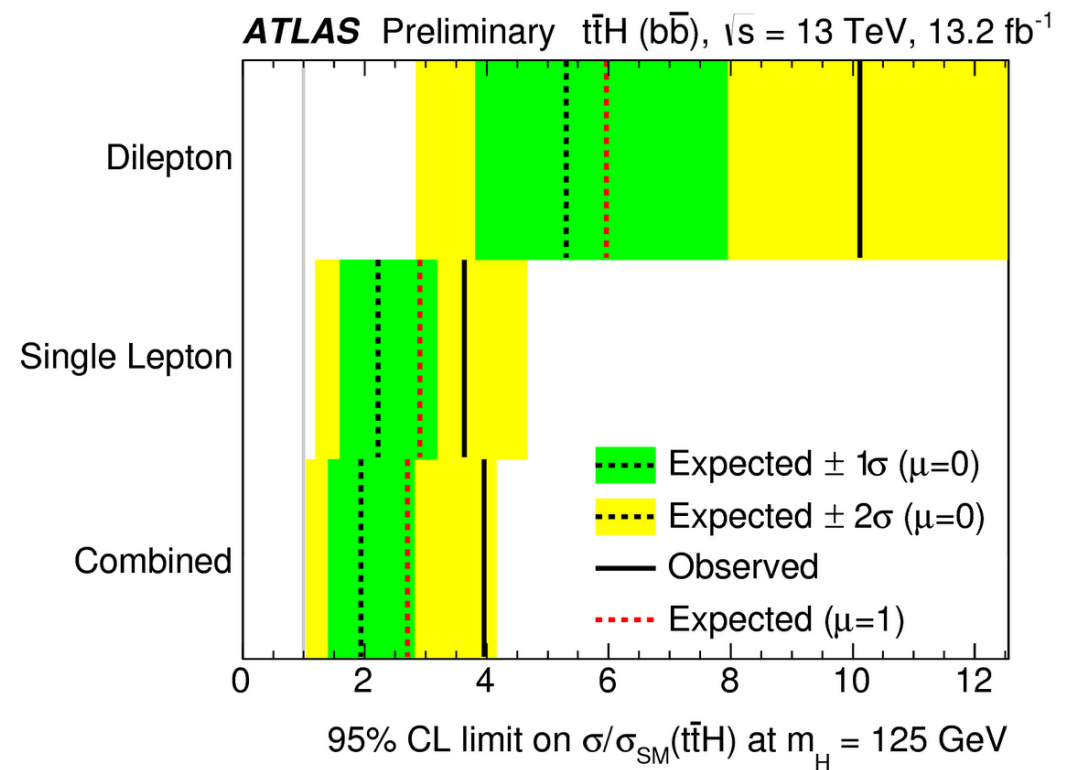
$H \rightarrow \text{fermions}$:

Search for $t\bar{t}H(\rightarrow bb)$

- **New results at 13 TeV** from CMS (2.7 fb^{-1}) and ATLAS (13.2 fb^{-1})
- ATLAS sees a mild excess, while CMS sees a slight deficit
- CMS $t\bar{t}H(bb)$ almost excludes ATLAS multilepton... **what's going on?**



$\mu(t\bar{t}H) < 2.6$ (95% CL)

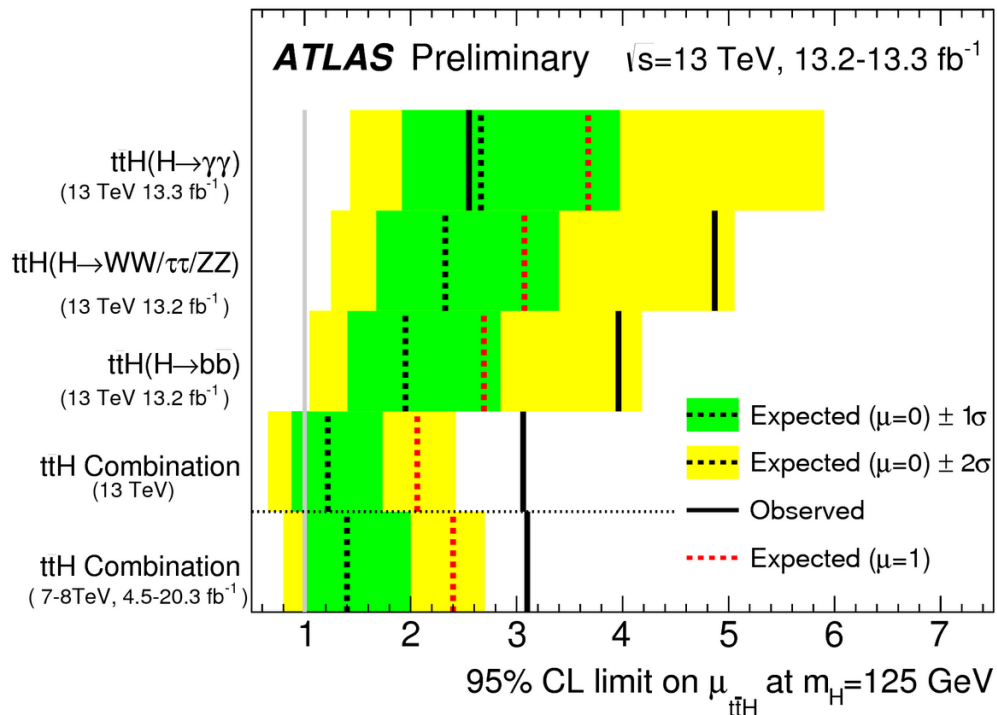


$\mu(t\bar{t}H) < 4.0$ (95% CL)

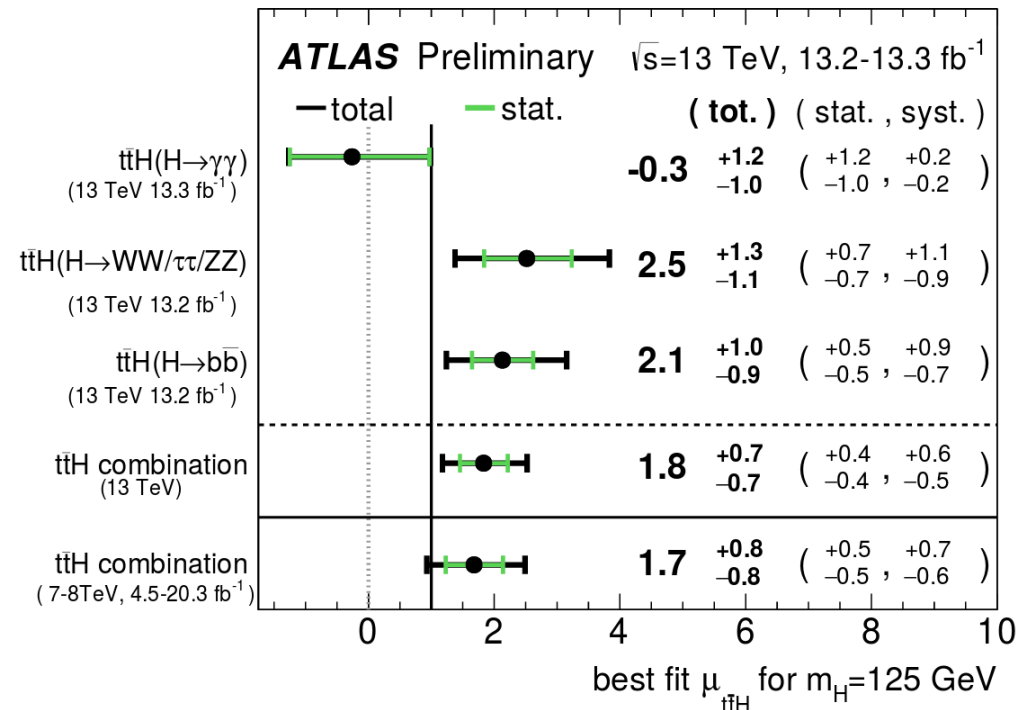
$H \rightarrow \text{fermions}$:

Combination of ttH searches

- Is this the first sign of BSM? A fluke? Unknown Systematics?
- ATLAS has made a combination of $\gamma\gamma$, bb , and multilepton channels
 - Mild excess in all channels except for $\gamma\gamma$, which has a slight deficit
- Combination lessens the significance, but **very compatible with Run 1**



$$\mu(\text{ttH}) < 3.0 \text{ (95\% CL) (13 TeV)}$$

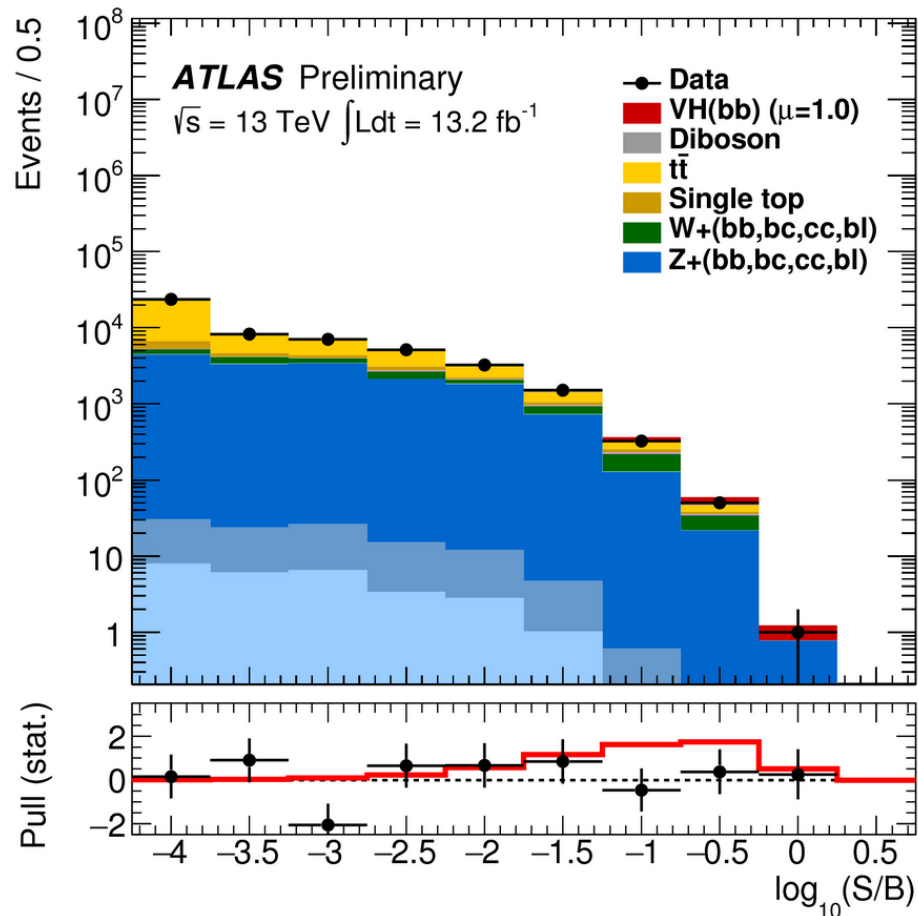


$$\mu(\text{ttH}) = 1.8 \pm 0.7 \text{ (13 TeV)}$$

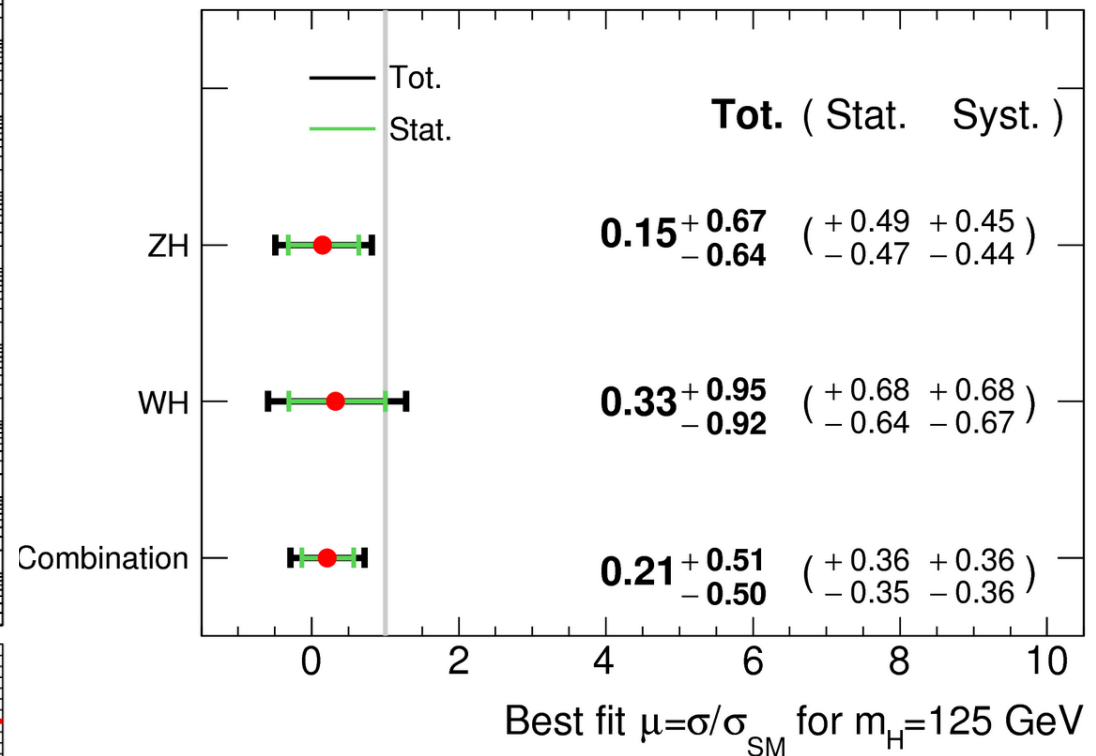
$H \rightarrow \text{fermions}$:

Search for $VH(\rightarrow bb)$ at 13 TeV

- Another potential “anomaly” from Run 1 was the low value of $\mu(H \rightarrow bb)$
- ATLAS has updated results for $VH(\rightarrow bb)$ with 13.2 fb^{-1}
 - Again, slight deficit in the measured signal strength...
- Also fit for $VZ(\rightarrow bb)$ signal strength as validation: $\mu = 0.91 +0.36/-0.32$



ATLAS Preliminary $\sqrt{s}=13 \text{ TeV}$, $\int \mathcal{L} dt = 13.2 \text{ fb}^{-1}$

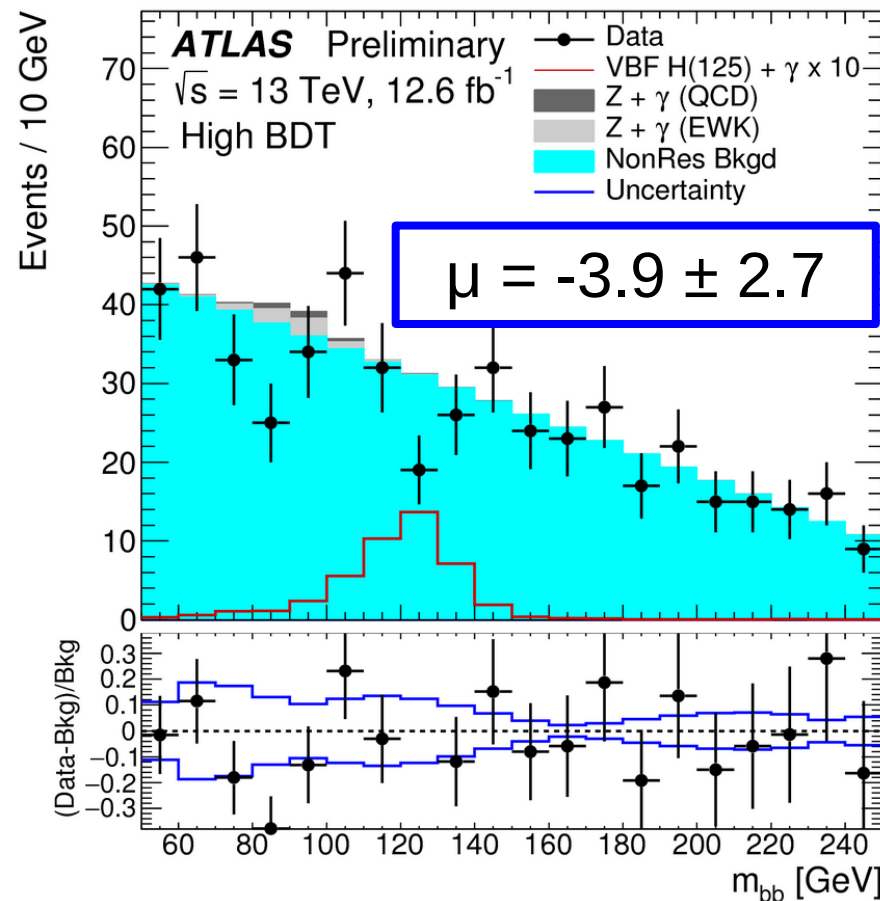
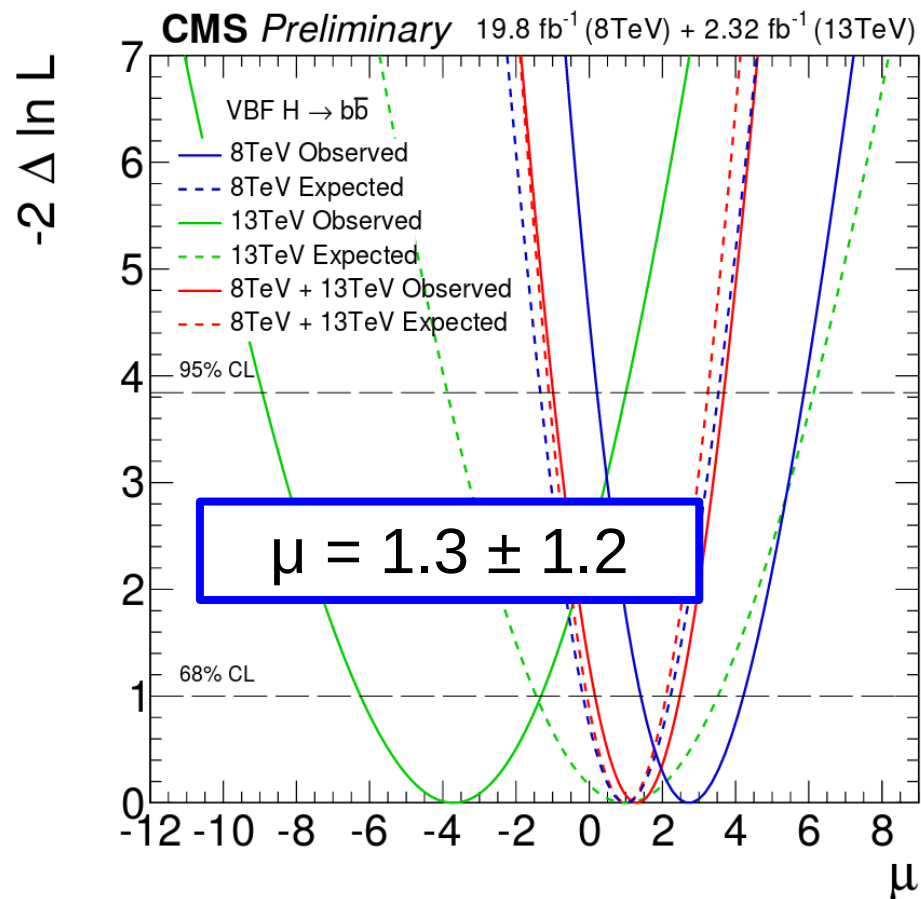


$$\mu_{VH}^{bb} = 0.2 \pm 0.5$$

$H \rightarrow \text{fermions}$:

Search for VBF $H(\rightarrow b\bar{b})$ at 13 TeV

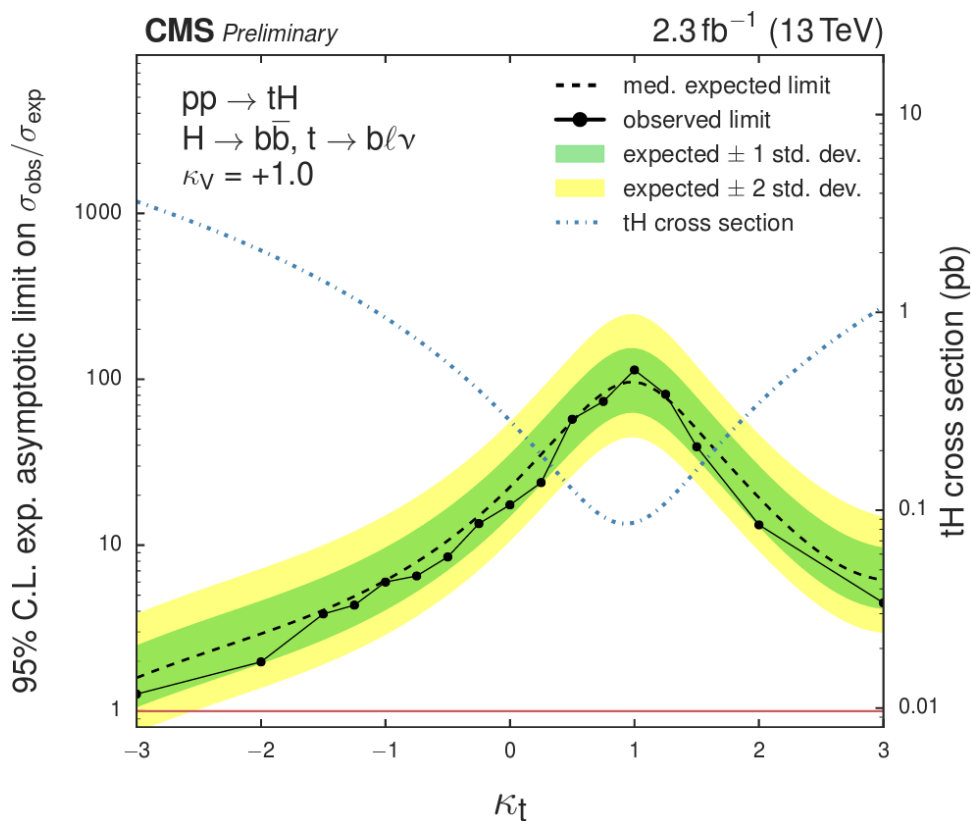
- Updated results on the search VBF $H(\rightarrow b\bar{b})$ from both experiments
 - CMS 2.3 fb⁻¹ at 13 TeV, combined with 19.8 fb⁻¹ at 8 TeV
 - ATLAS 12.6 fb⁻¹ at 13 TeV, requiring presence of additional photon
- Both measurements are compatible with SM hypothesis



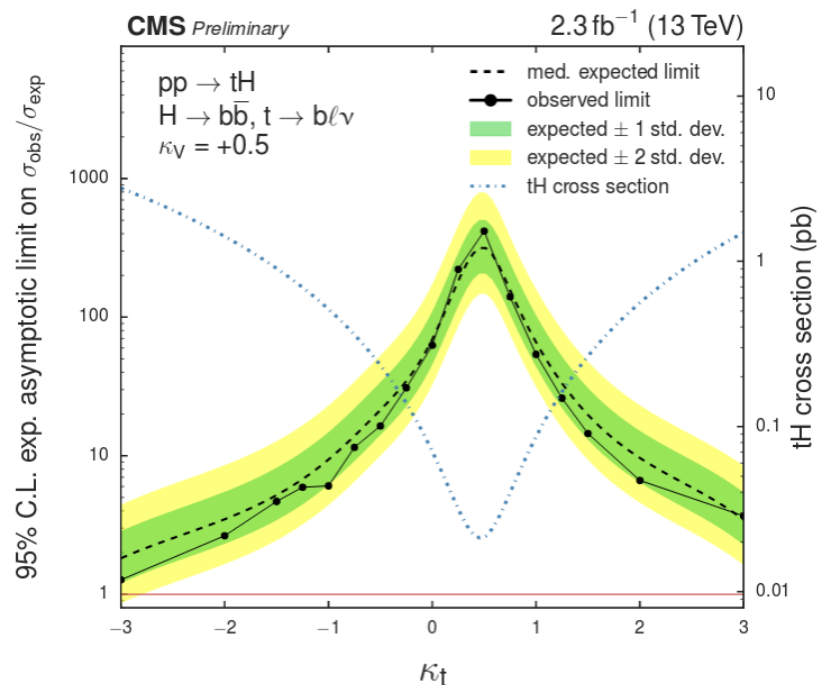
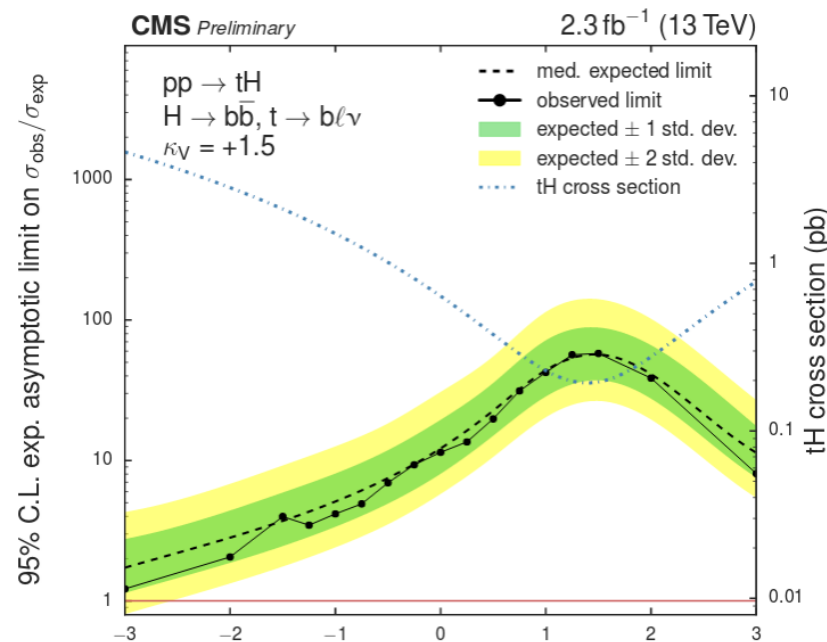
$H \rightarrow \text{fermions}$:

Search for $tH(\rightarrow bb)$

- First results on single top $tH(\rightarrow bb)$ at 13 TeV from CMS with 2.3 fb^{-1}
 - Including for the first time tW channel
- Upper limits on κ_t for several κ_V



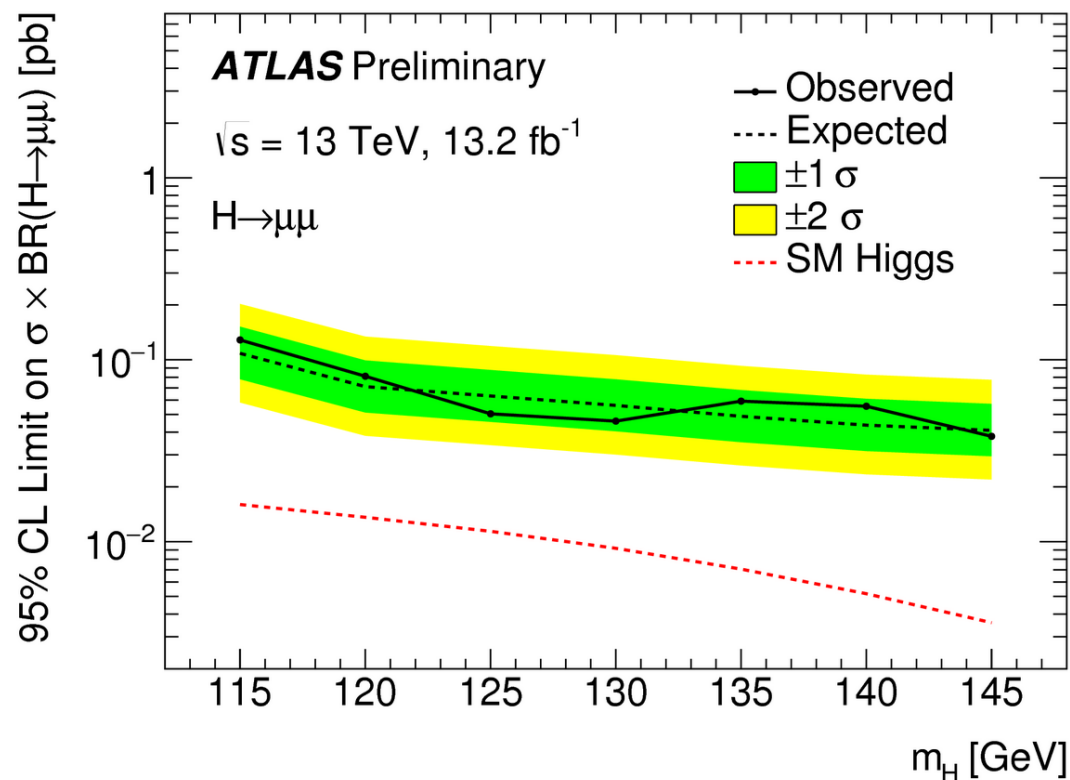
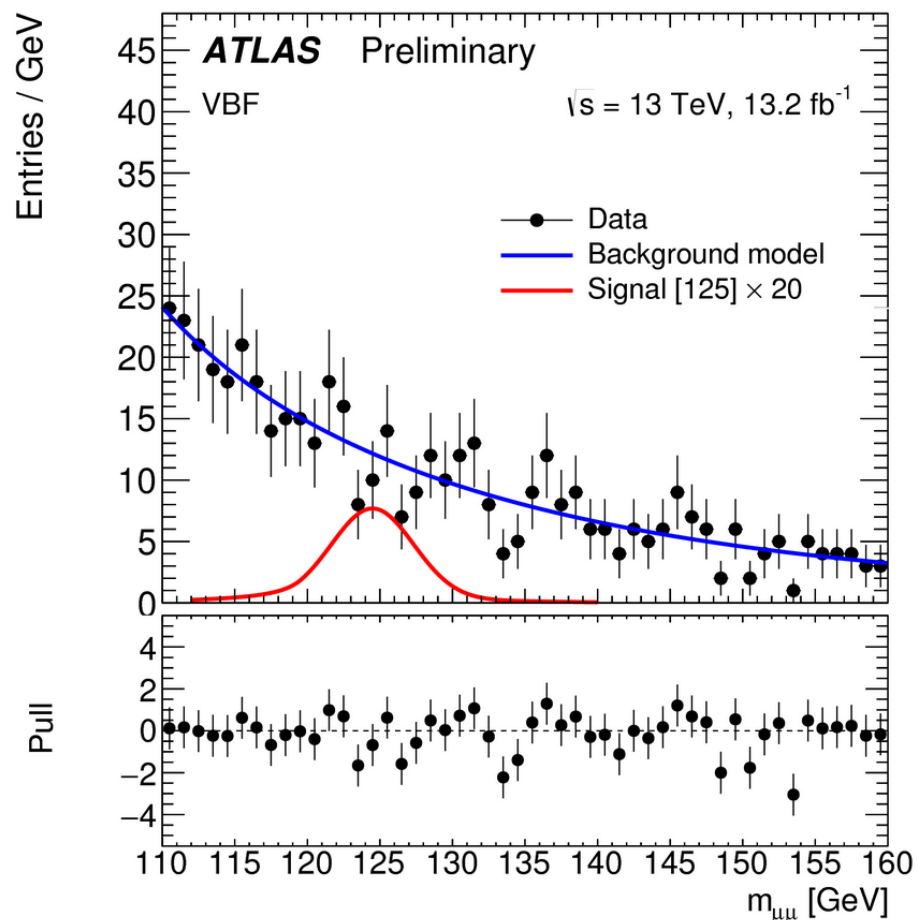
$\mu(\kappa_t = -1, \kappa_V = +1) < 6.0$ (95% CL)



$H \rightarrow \text{fermions}$:

Search for $H \rightarrow \mu\mu$

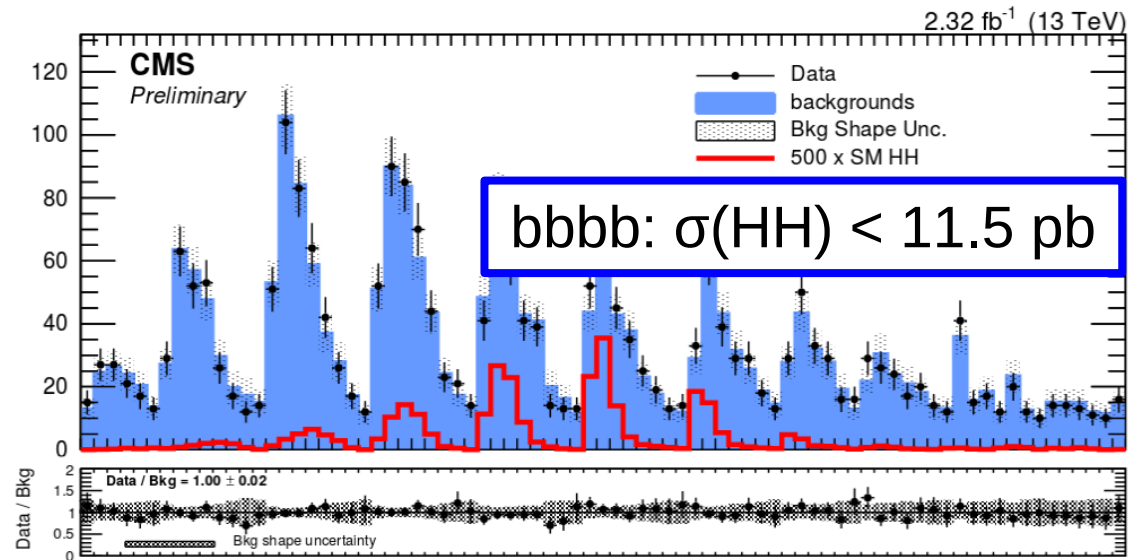
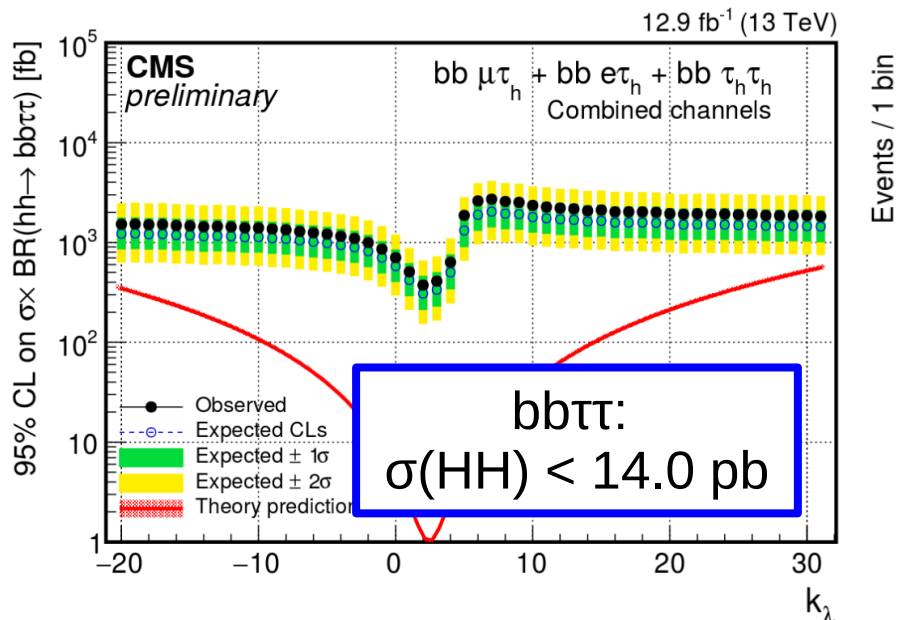
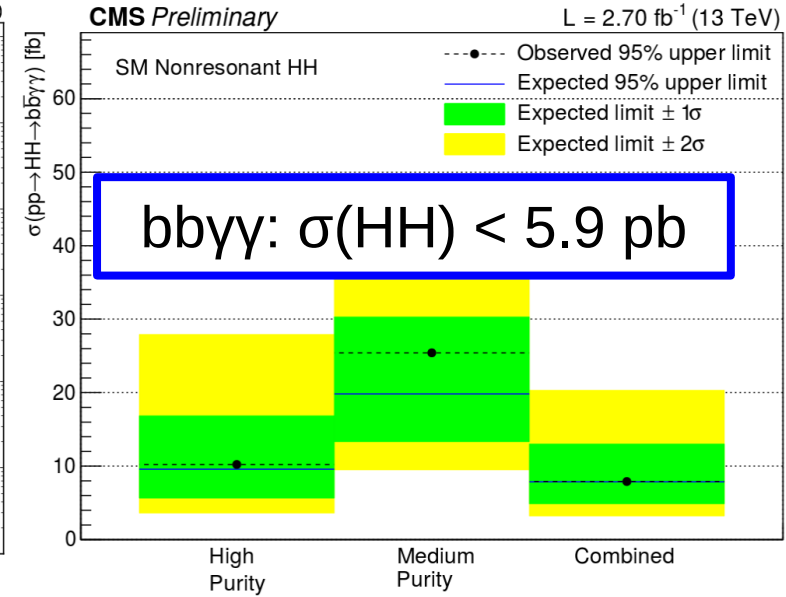
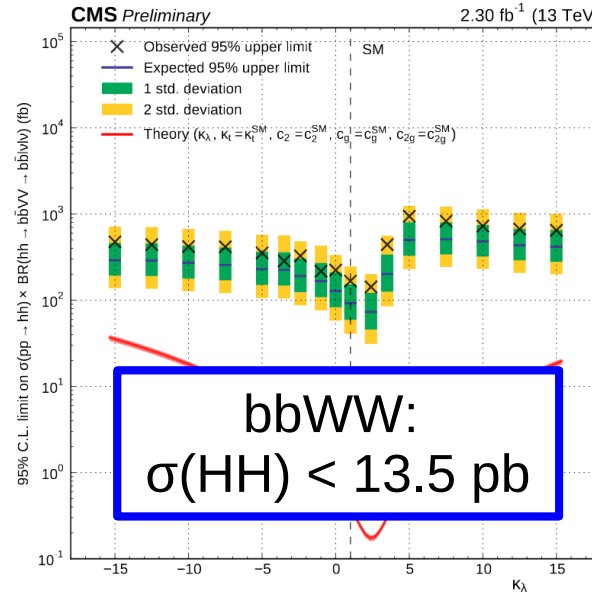
- New results on search for $H \rightarrow \mu\mu$ from ATLAS with 13.2 fb^{-1} at 13 TeV
- **Most sensitive result to date** when combined with Run 1 measurement



$\mu(H \rightarrow \mu\mu) < 4.4$ (Run 2)
 $\mu(H \rightarrow \mu\mu) < 3.5$ (Run 1 + Run 2)

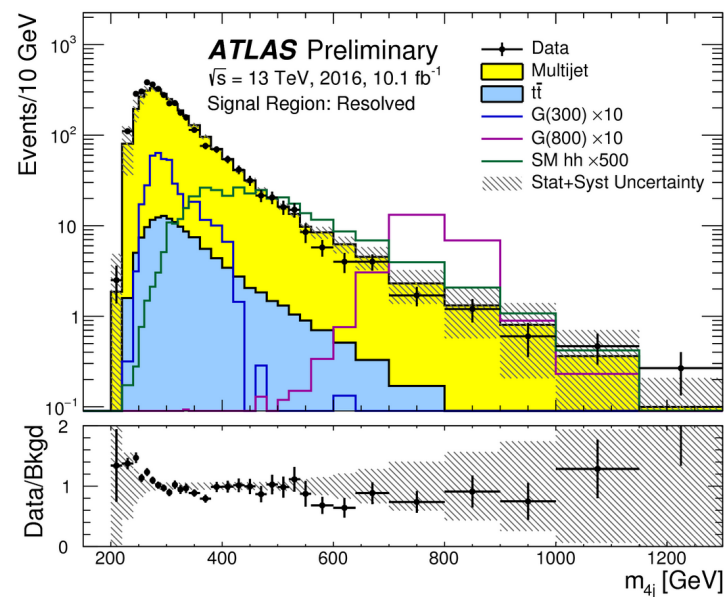
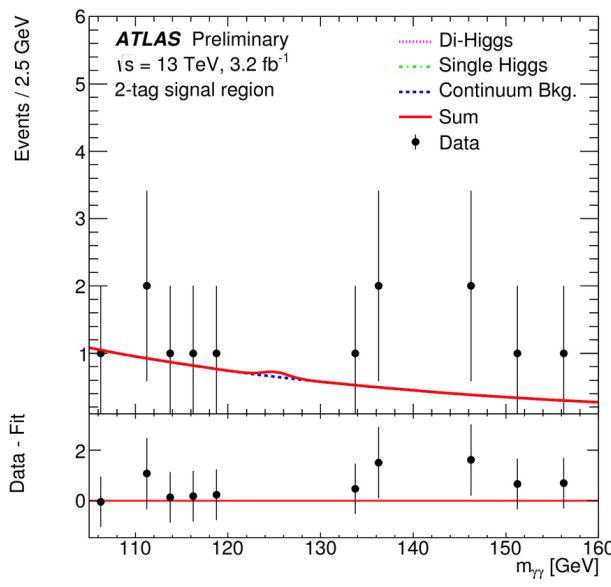
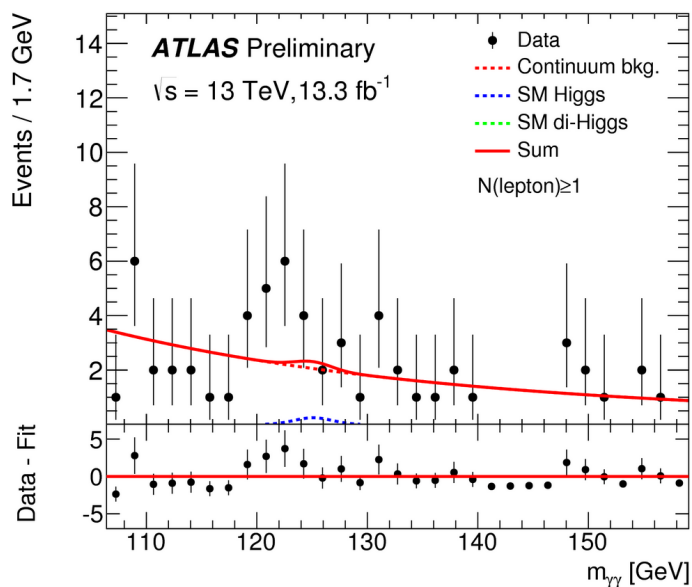
Double Higgs Production: Search for HH at 13 TeV: CMS

- Very low cross section, **a challenging task for the experiments** as we collect more data
- Updated results from CMS at 13 TeV with 2.3–12.9 fb⁻¹
- bbyγ, bbττ, bbWW, bbbb final states have been considered



Double Higgs Production: Search for HH at 13 TeV: ATLAS

- Updated results from ATLAS at 13 TeV with 3.2–13.3 fb⁻¹
- bbyy, WWyy, bbbb final states considered
→ Good sensitivity from bbbb, a channel previously unstudied

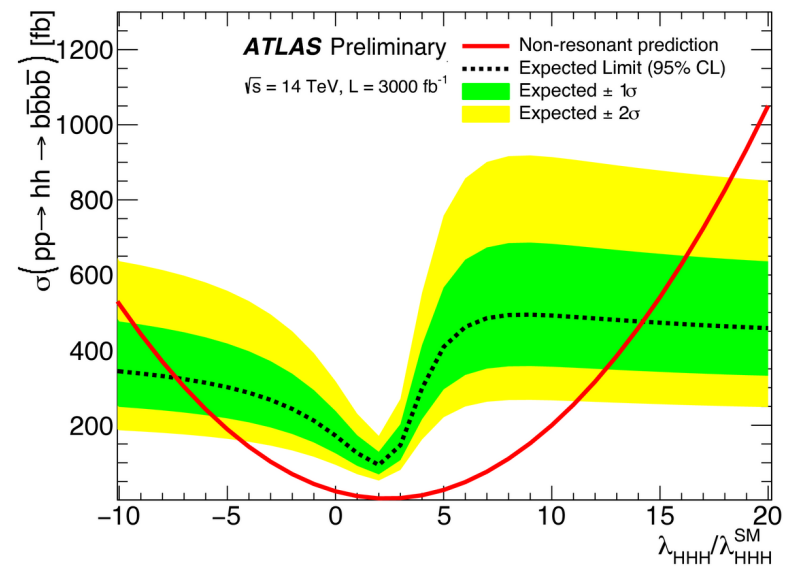
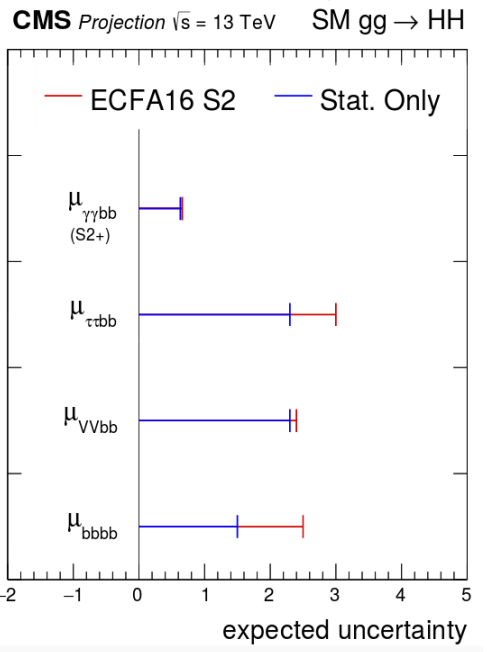
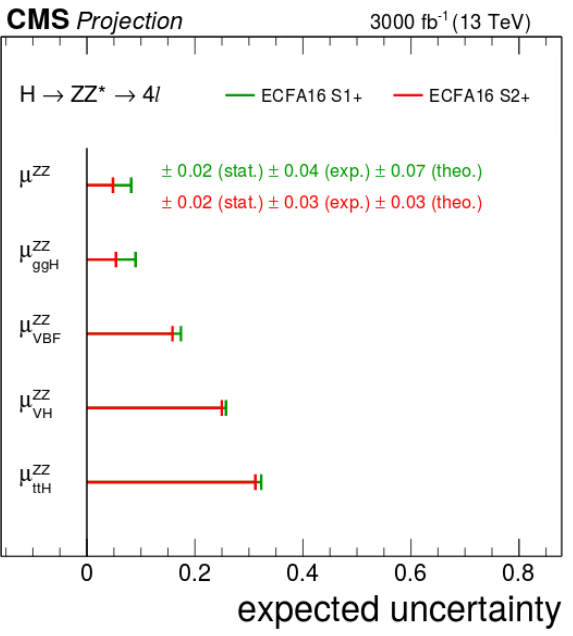
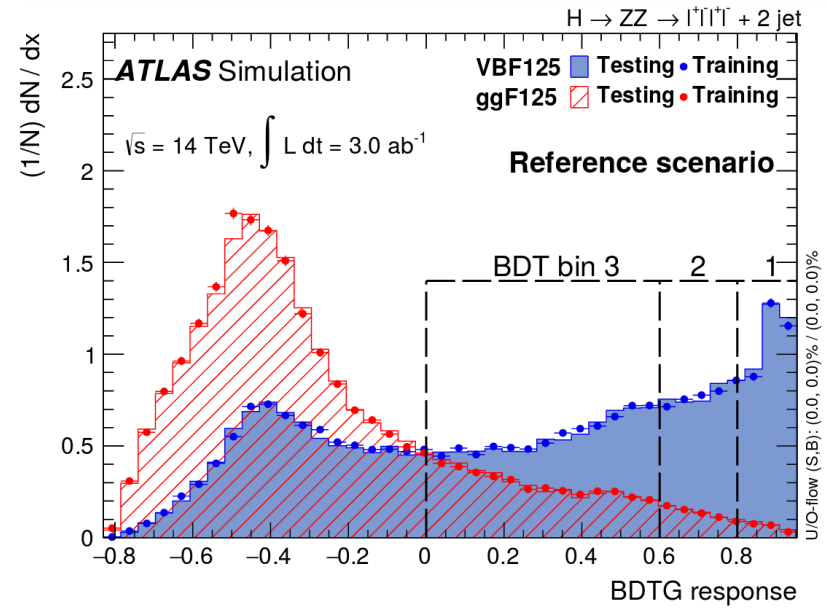
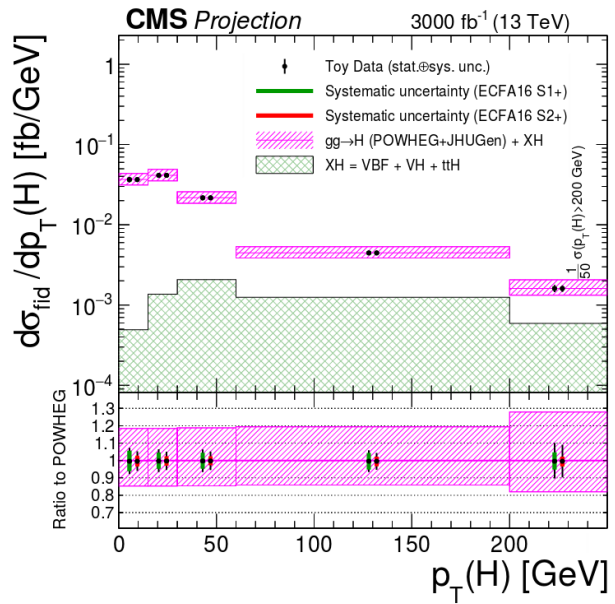
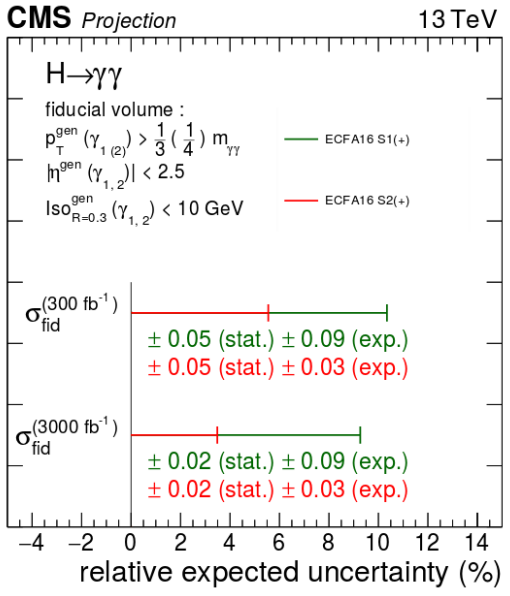


WWyy:
 $\sigma(\text{HH}) < 25.0 \text{ pb}$

bbyy:
 $\sigma(\text{HH}) < 3.9 \text{ pb}$

bbbb:
 $\sigma(\text{HH}) < 0.98 \text{ pb}$

Recent Studies from the ECFA Workshop



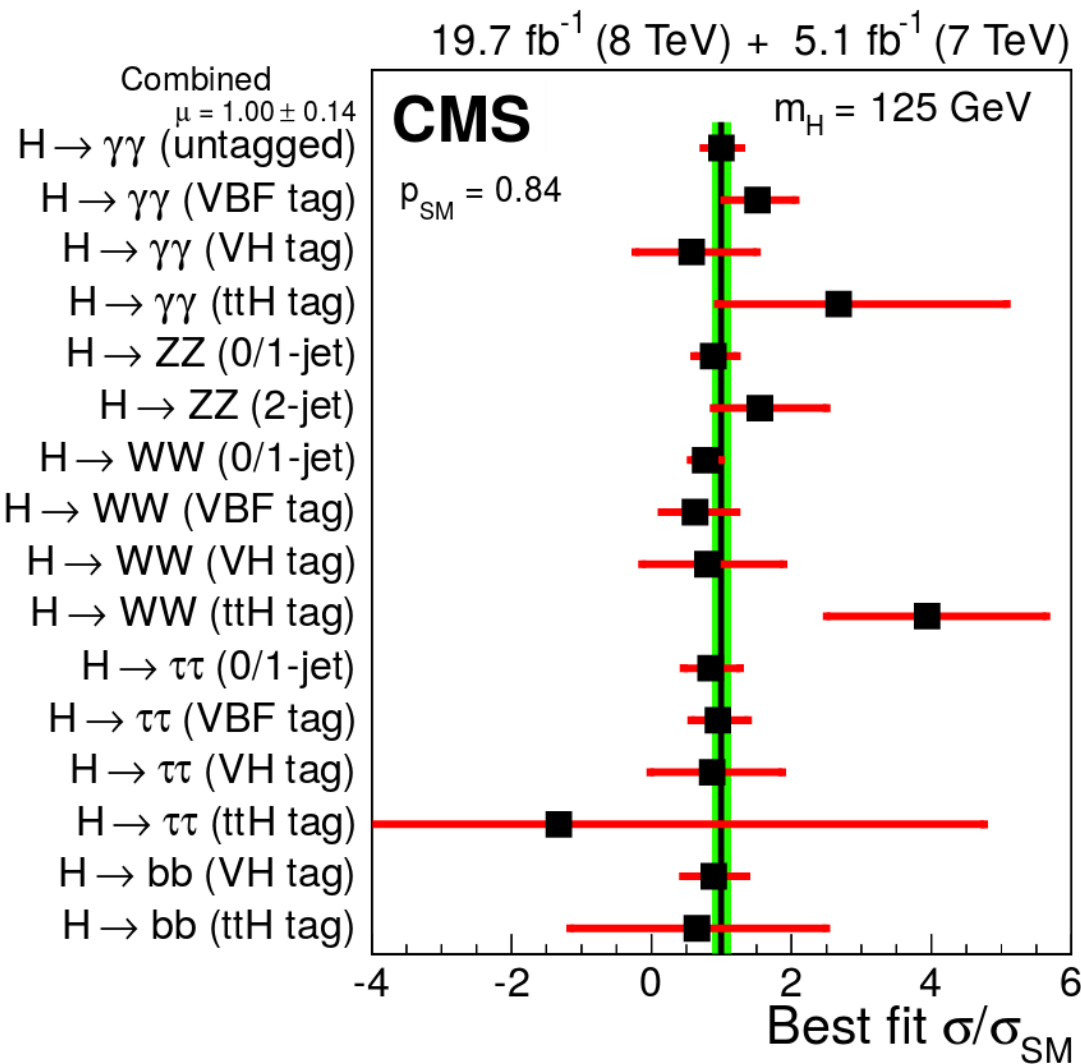
Conclusions

- **CMS Higgs Physics program for Run 2 is well under way, and outlook is good for the future**
- **Some old anomalies are gone, some remain, and some new ones appeared**
- **Experiments are well prepared to release new results on the full 2016 dataset, which will far surpass Run 1 sensitivity**
- **Higgs physics program will remain an important aspect of the LHC experiments**
 - It's a great time to be a Higgs Boson Physicist!!!

Backup

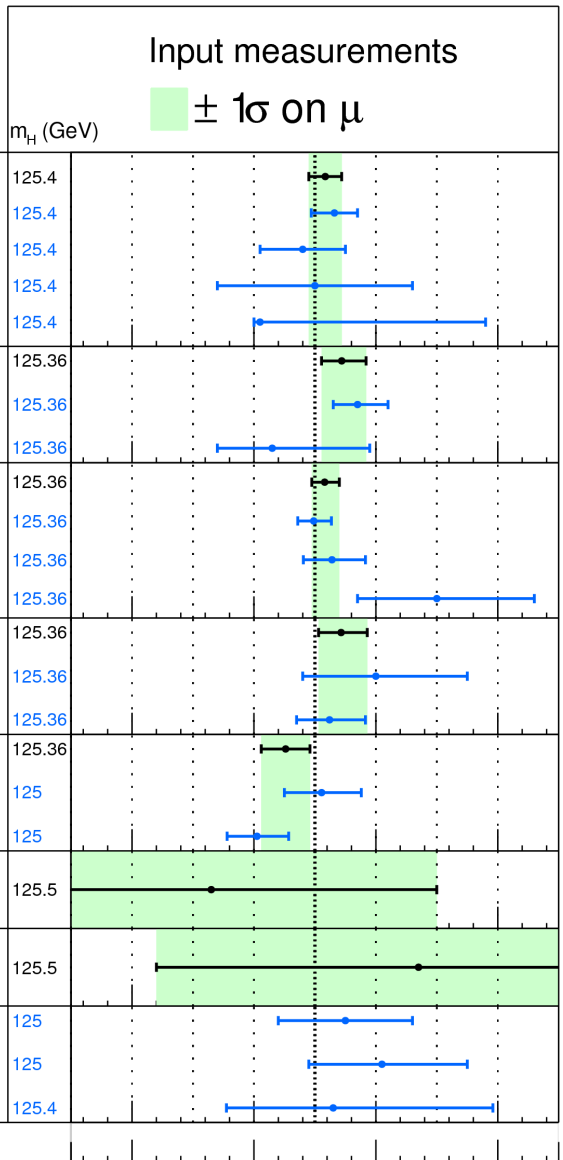
Run 1 Results:

Signal Strength in Individual Categories



ATLAS

Individual analysis

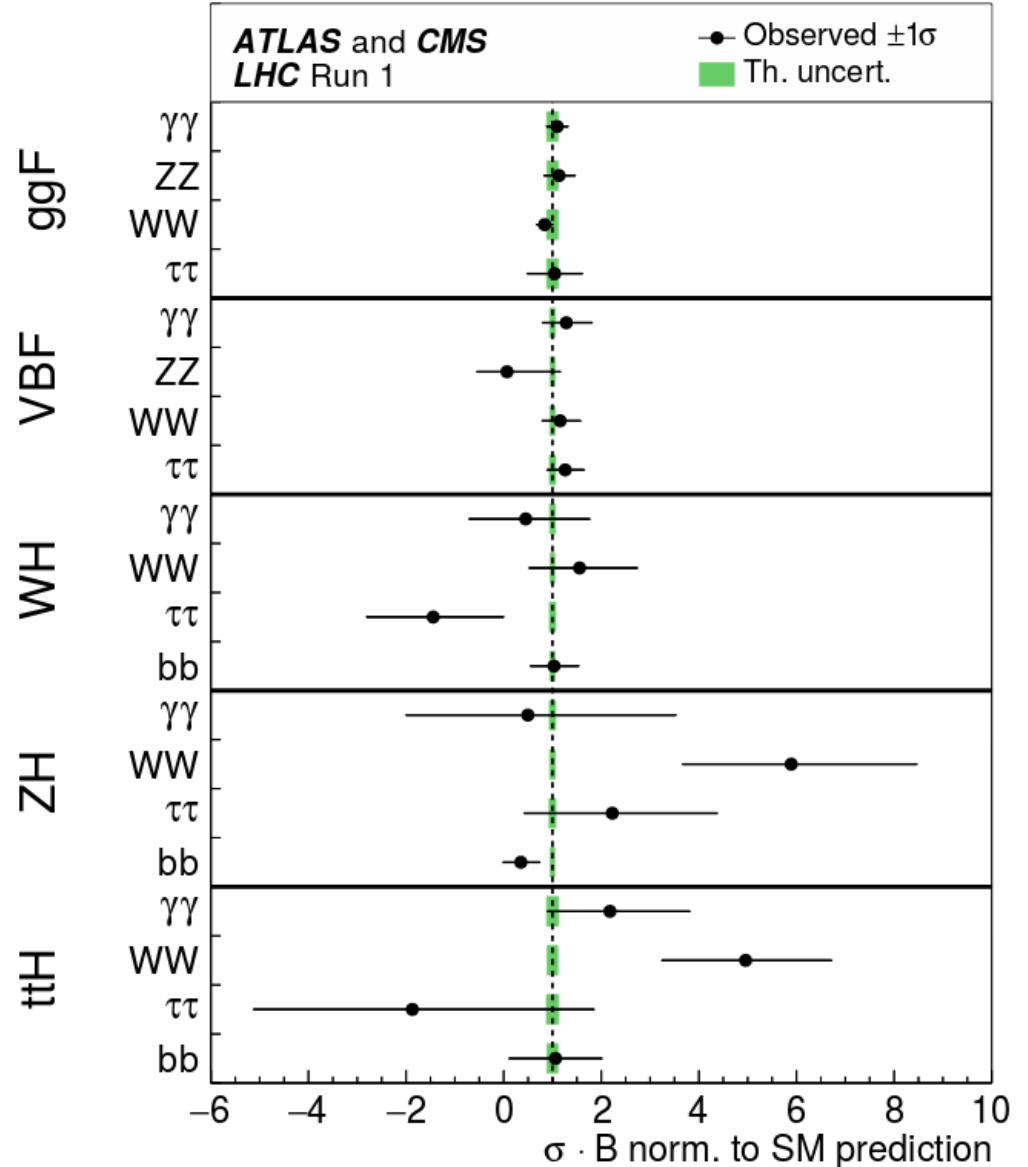
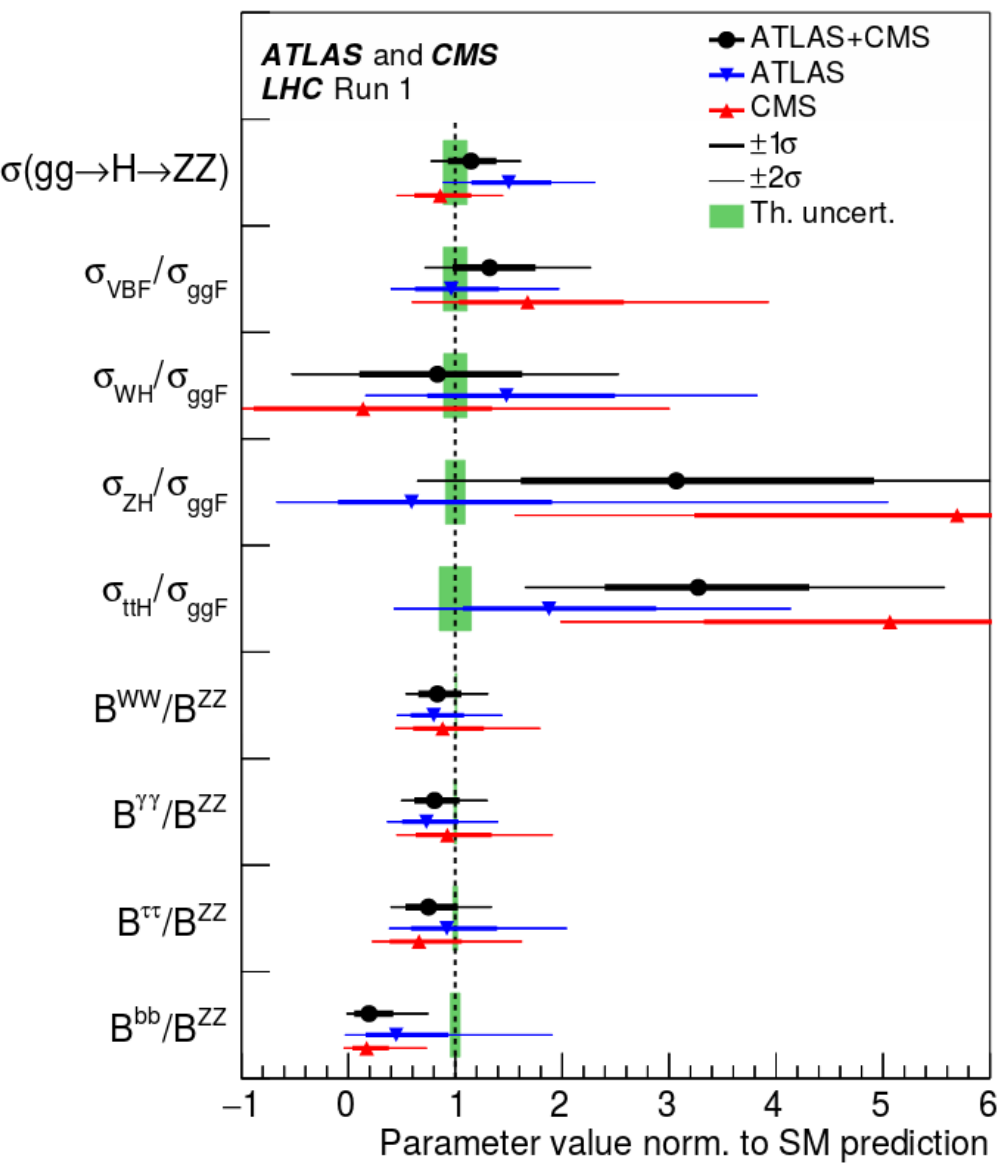


$\sqrt{s} = 7$ TeV, 4.5-4.7 fb⁻¹

$\sqrt{s} = 8$ TeV, 20.3 fb⁻¹

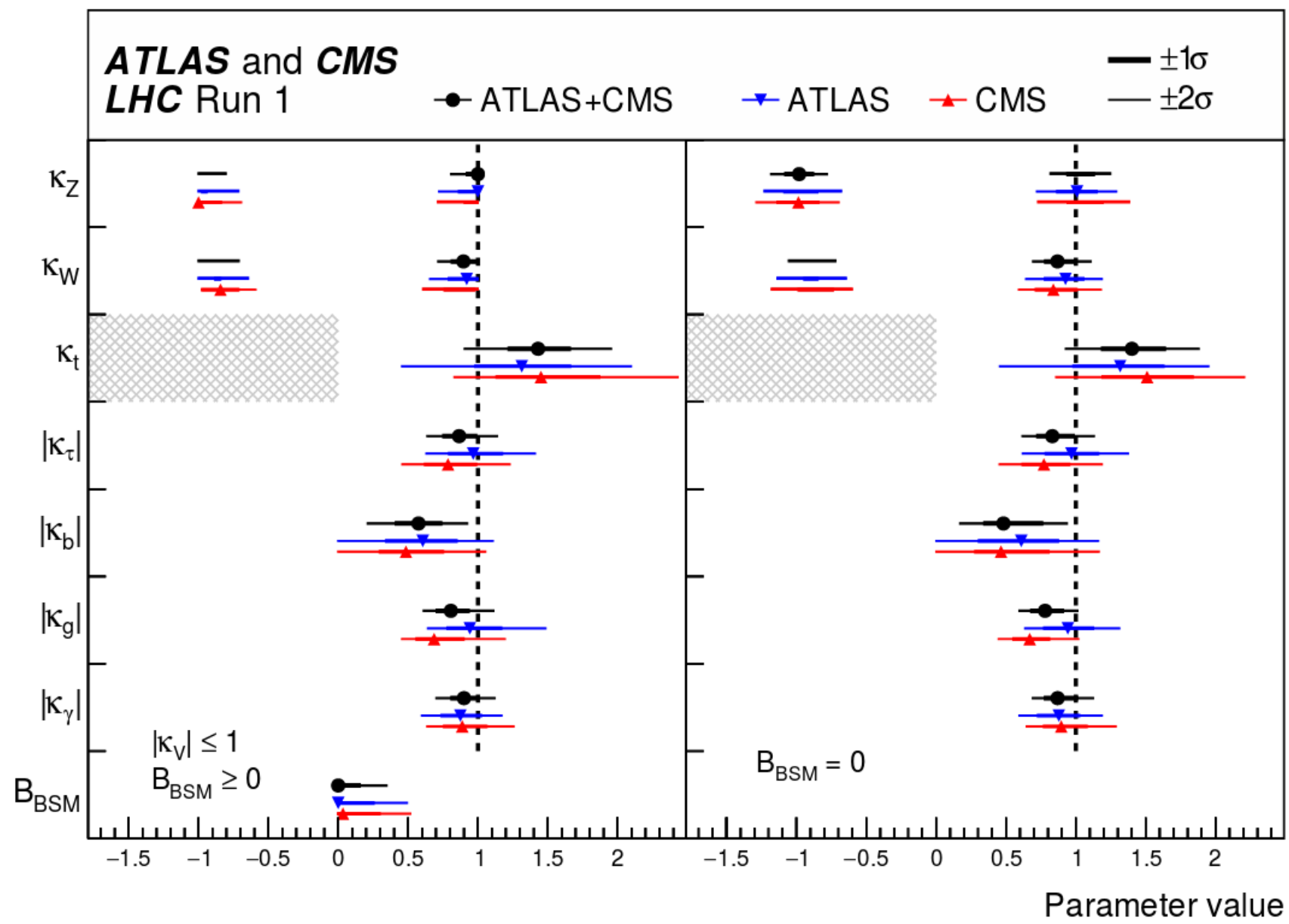
Signal strength (μ)

Run 1 Results: ATLAS+CMS Combination



Run 1 Results:

ATLAS+CMS Combination



Run 1 Results:

Combined Mass Measurement

