Measurements of third generation Higgs boson Yukawa couplings

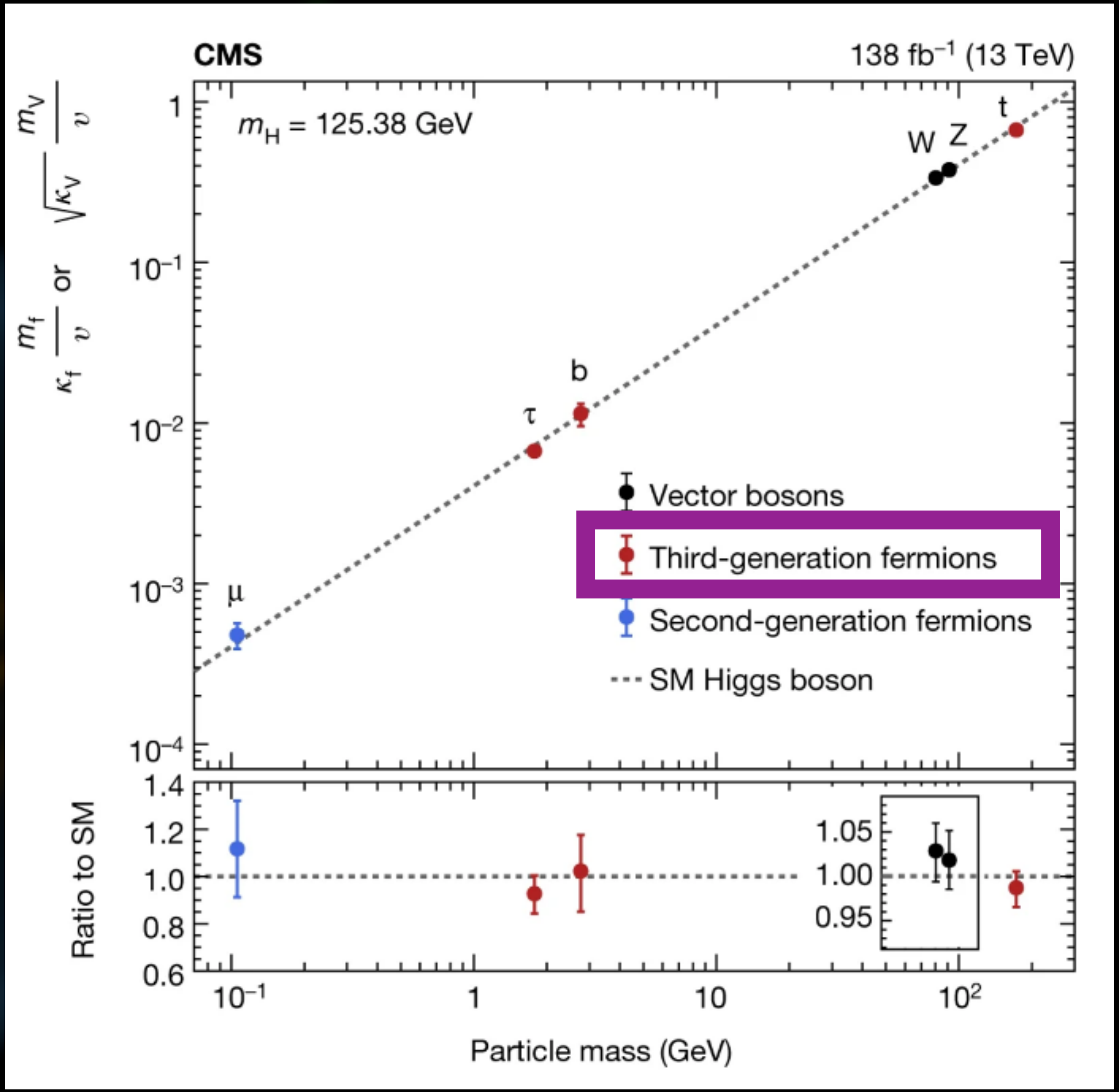
For

Chris Palmer (UMD/CMS)

November 27th, 2023

Overview

- The Higgs boson has been decisively shown to facilitate electroweak symmetry breaking from its coupling strength being proportional to mass.
- This talk will cover 3rd generation Higgs-fermion Yukawa couplings established by ATLAS and CMS Collaborations.
    - $\mathrm{t\bar{t}H}$ production
    - $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ decays
    - $\mathrm{H} \rightarrow \tau\bar{\tau}$ decays



https://www.nature.com/articles/s41586-022-04892-x

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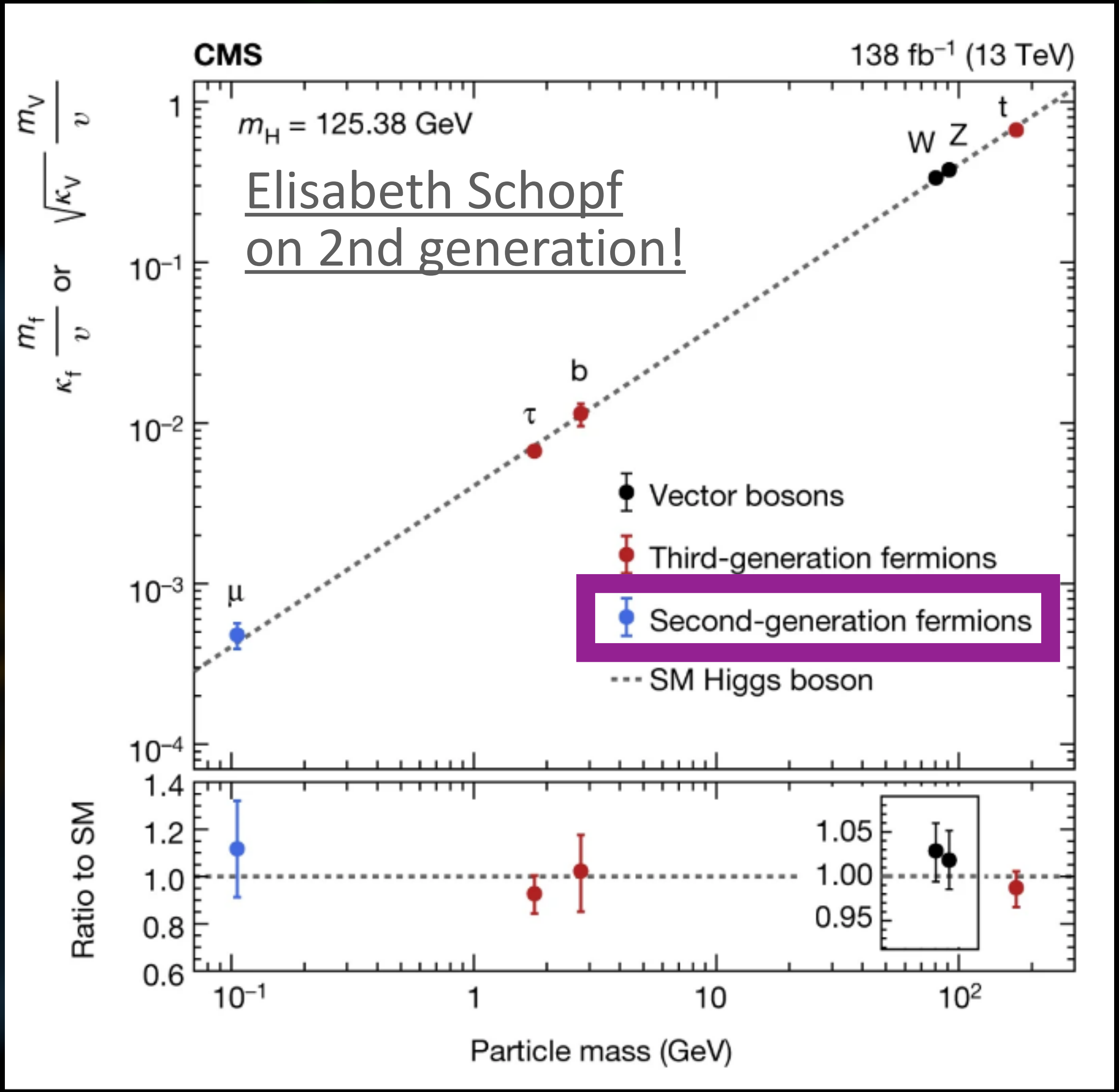

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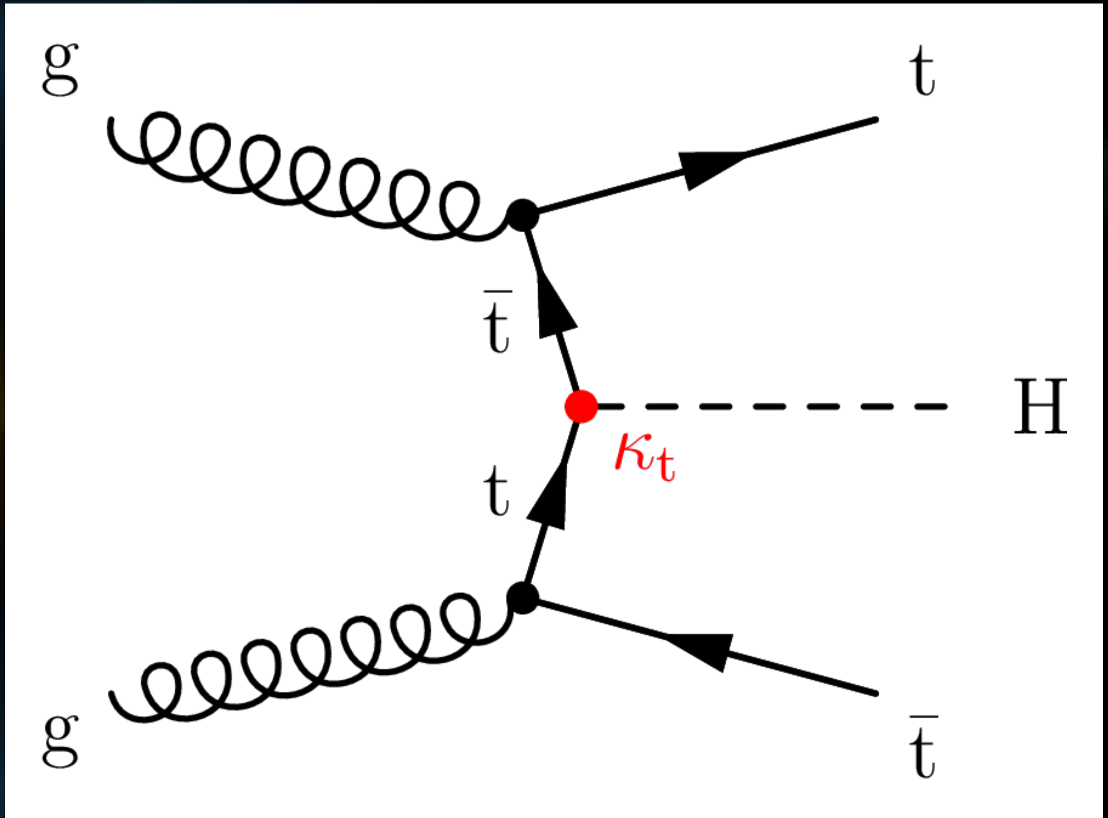
$t\bar{t}H$ Production Overview

- With top Yukawa coupling and two top quarks in the final state give a variety of experimental opportunities.
    - Direct confirmation of the coupling with the observation
    - Searches for CP violation with enough signal and S/B in reconstructable channels.
    - Searches for invisible Higgs boson decays with double top tagging and lots of missing transverse momentum.



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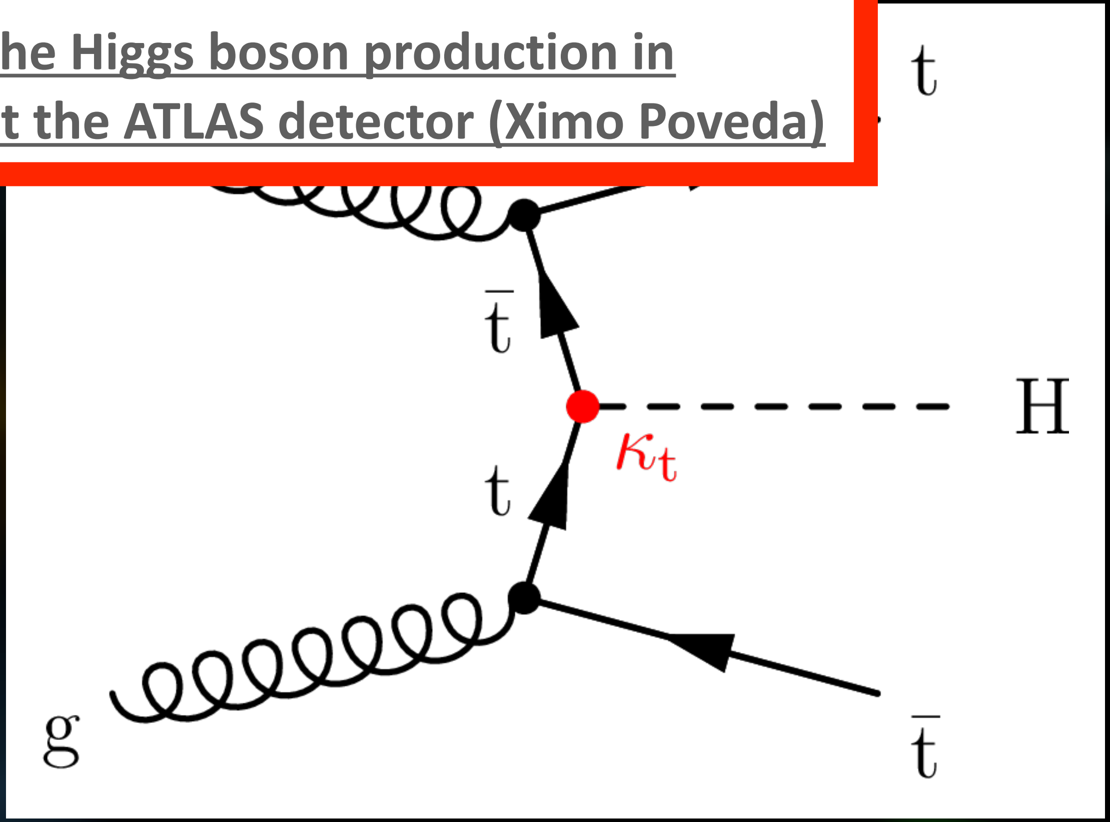
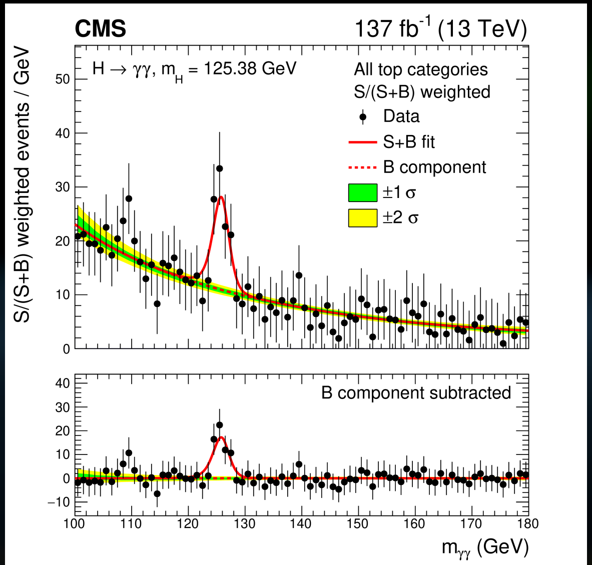
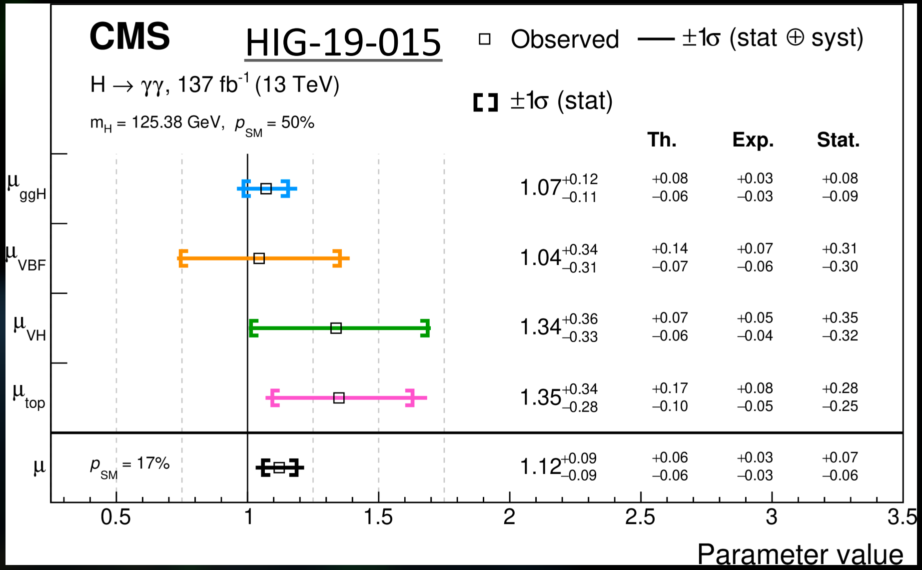
More details Thursday:
Property measurements of the Higgs boson production in association with top quark at the ATLAS detector (Ximo Poveda)

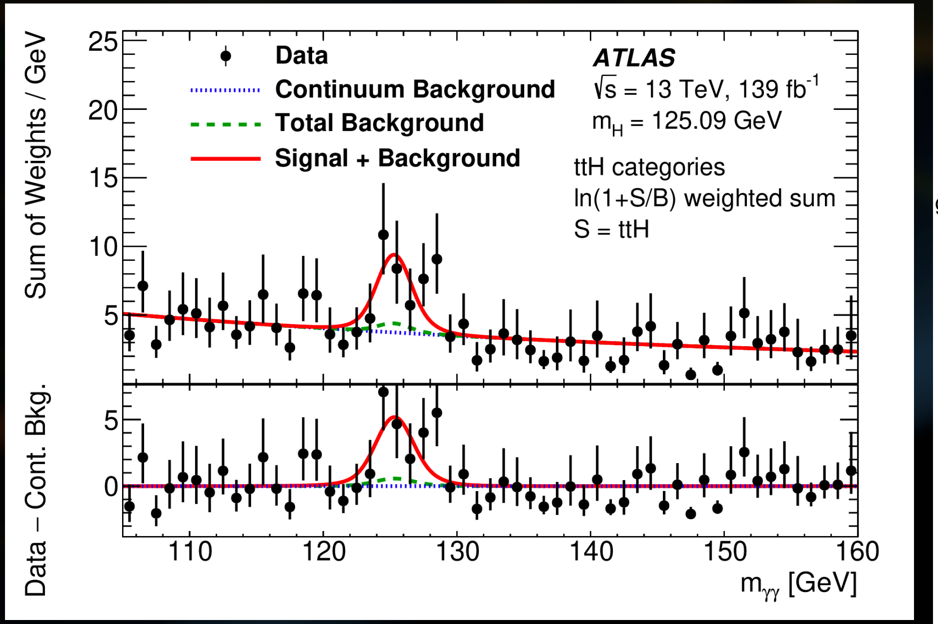


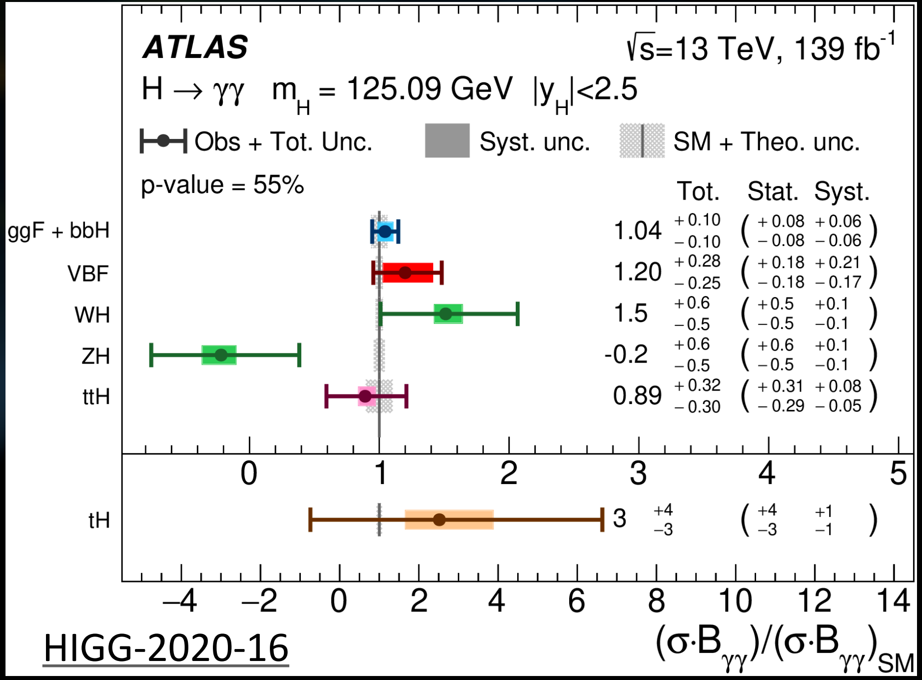
$t\bar{t}H$, $H \to \gamma\gamma$

- Anchoring on the diphoton decay gives experimental access to production mode tagging.
- ATLAS and CMS have made great use of this in their Run 2 $H \to \gamma\gamma$ measurements.
- Both also made dedicated channels for tH production.





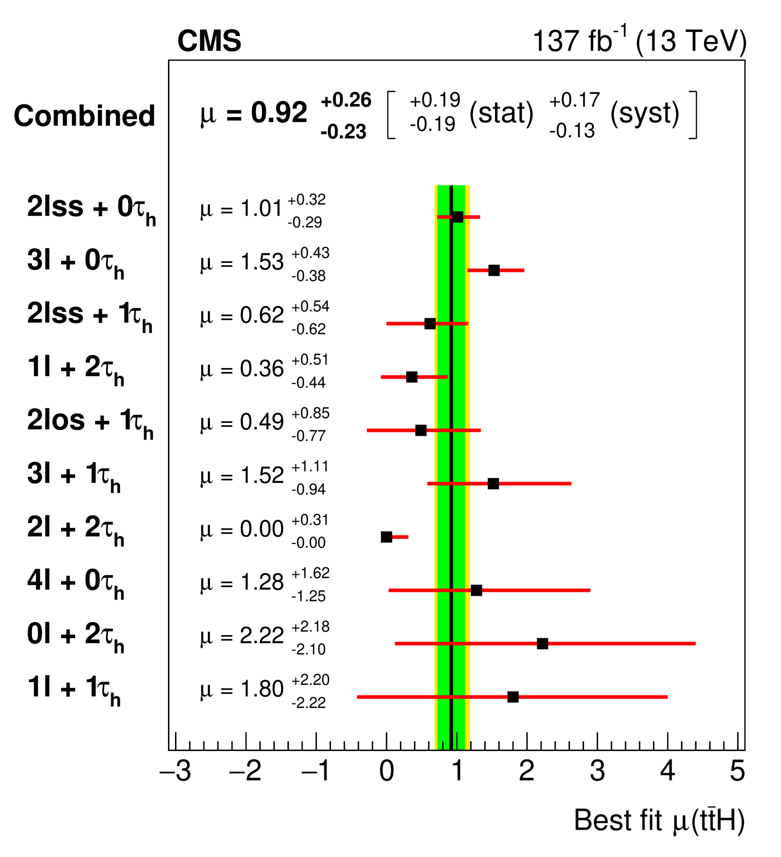




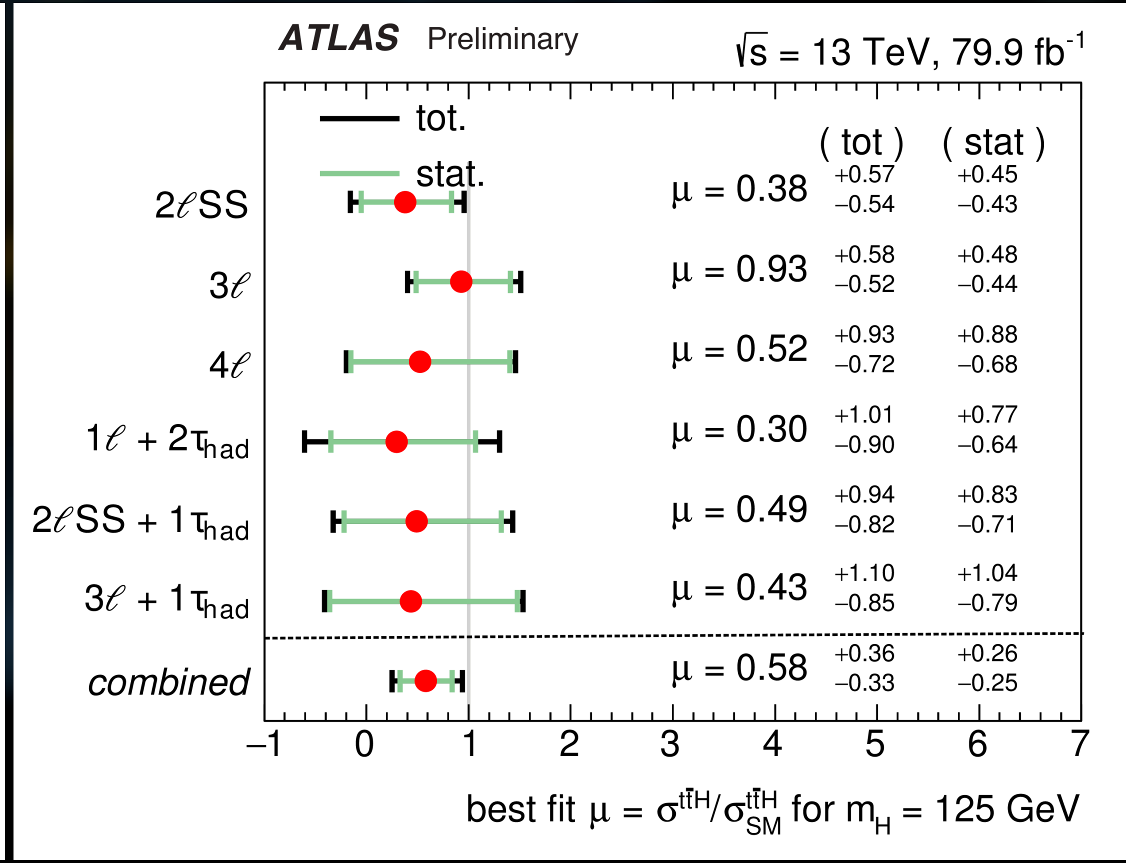
$t\bar{t}H$, H → multi-leptons

- Many sources of leptons when there are 2-4 vector bosons in the final state.
- Optimization entails specific kinematic variables and b-tagging multiplicity as inputs for BDTs for each channel.

Full Run 2

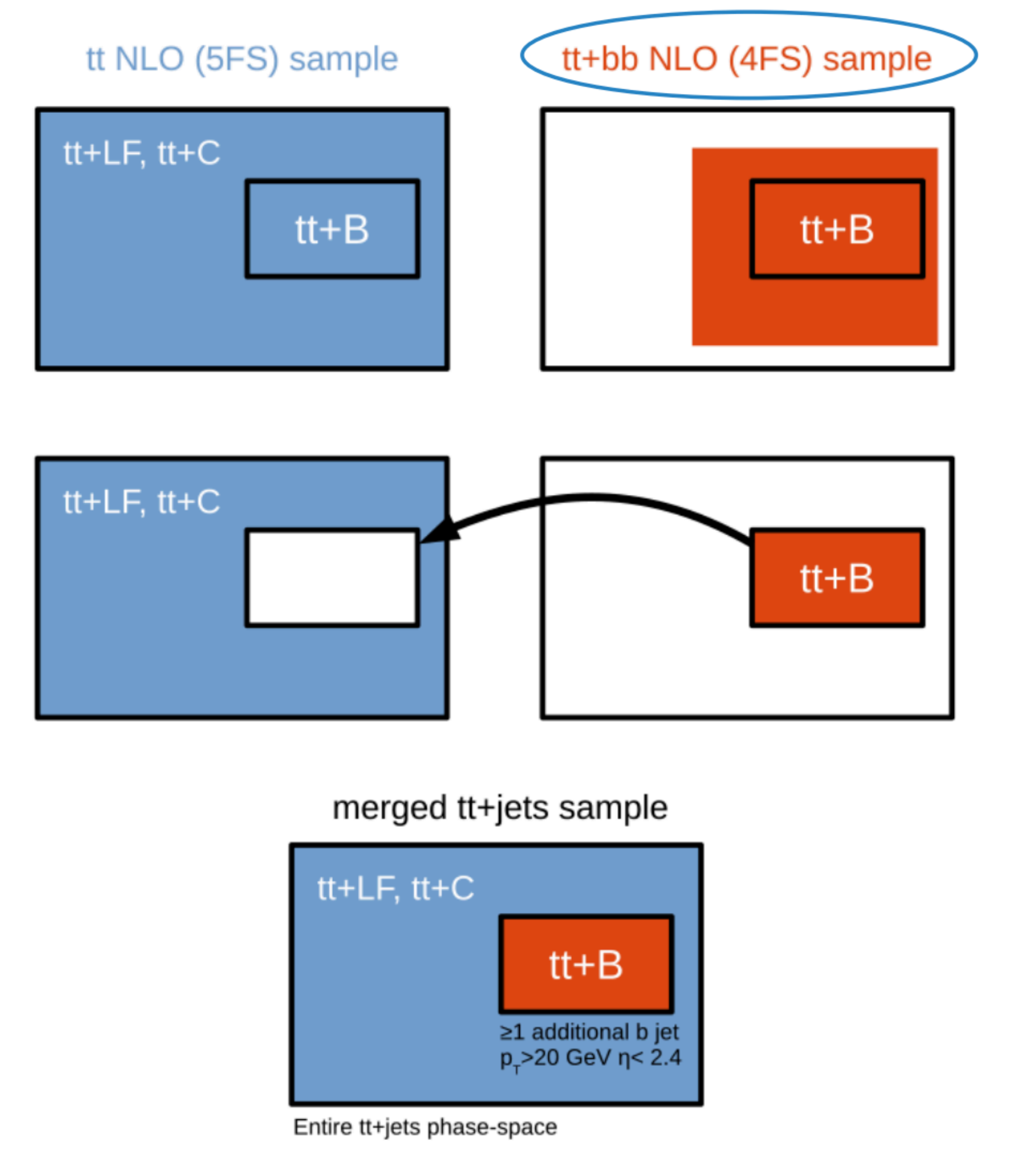


2015-2017

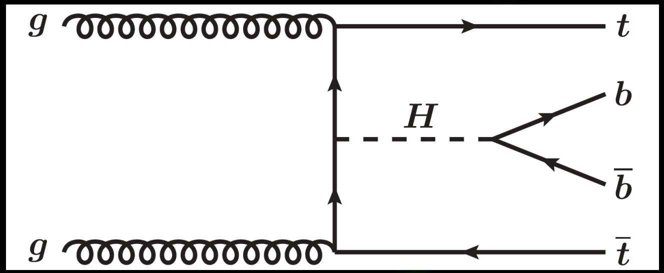


$t\bar{t} + b\bar{b}/X$ Backgrounds

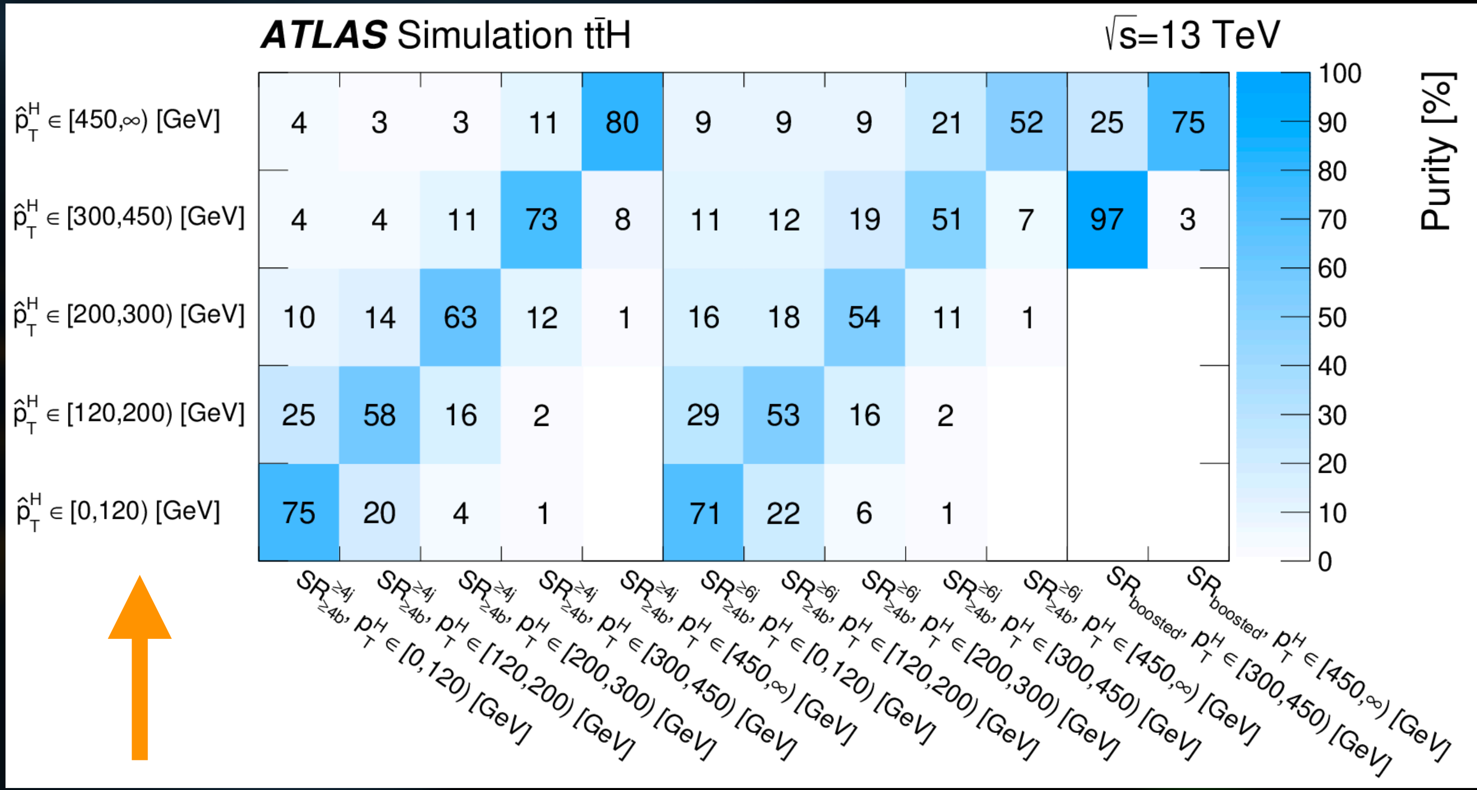
- Common
  - Four flavor scheme (4SF)
    - More directly from the ME
  - Five FS still needed for the the charm and light flavor components.
- Differences
  - PS: Pythia vs Herwig (ATLAS), Pythia uncertainties (CMS)
  - CMS floats $t\bar{t} + \mathrm{B/C/LF}$ freely
  - ATLAS floats $t\bar{t} + b\bar{b}$; $t\bar{t} + b$ extrapolation; $t\bar{t} + \mathrm{C}$ 100% prior; $t\bar{t} + \mathrm{LF}$ tighter prior



$t\bar{t}H$, $H \to b\bar{b}$



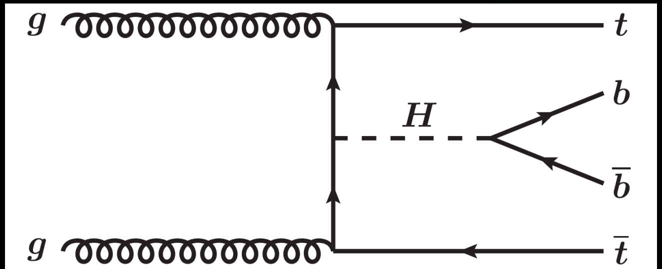
- Primary analysis goals: STXS bin and inclusive signal measurements
- Search anchored in 1-2 muons or electrons.
- Differential in number of b-tagged jets and p_T of the Higgs boson candidate.
- In each event a "Reconstruction BDT" is evaluated under each b-jet association assumption (i.e., from the Higgs or from a top).
    - The assumption yielding the highest score is used to assign the dijet for Higgs candidate.
- In the 1-lepton channel, a topology of large-R (anti-k_T 1.0) jets containing two small-R jets is analyzed for events with $p_T^H > 300$ GeV.
    - A DNN is used to select events to put into this topology.



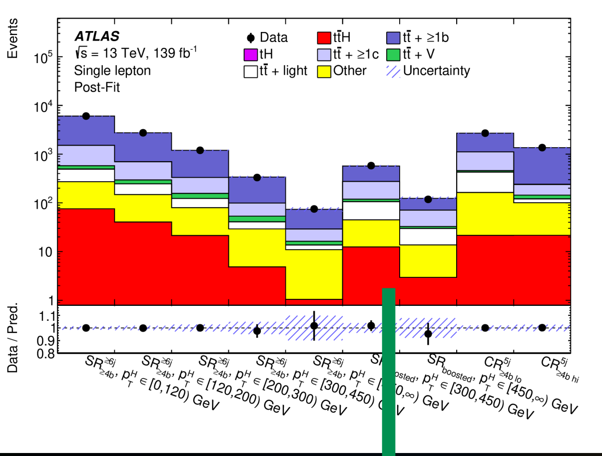
Particle-level STXS bin

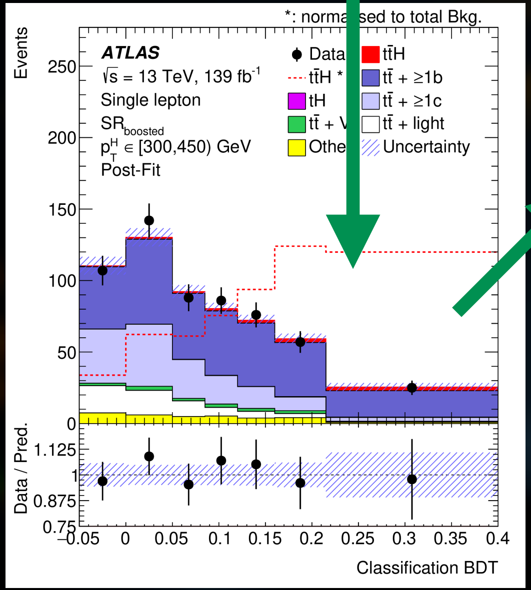
Reconstruction bin

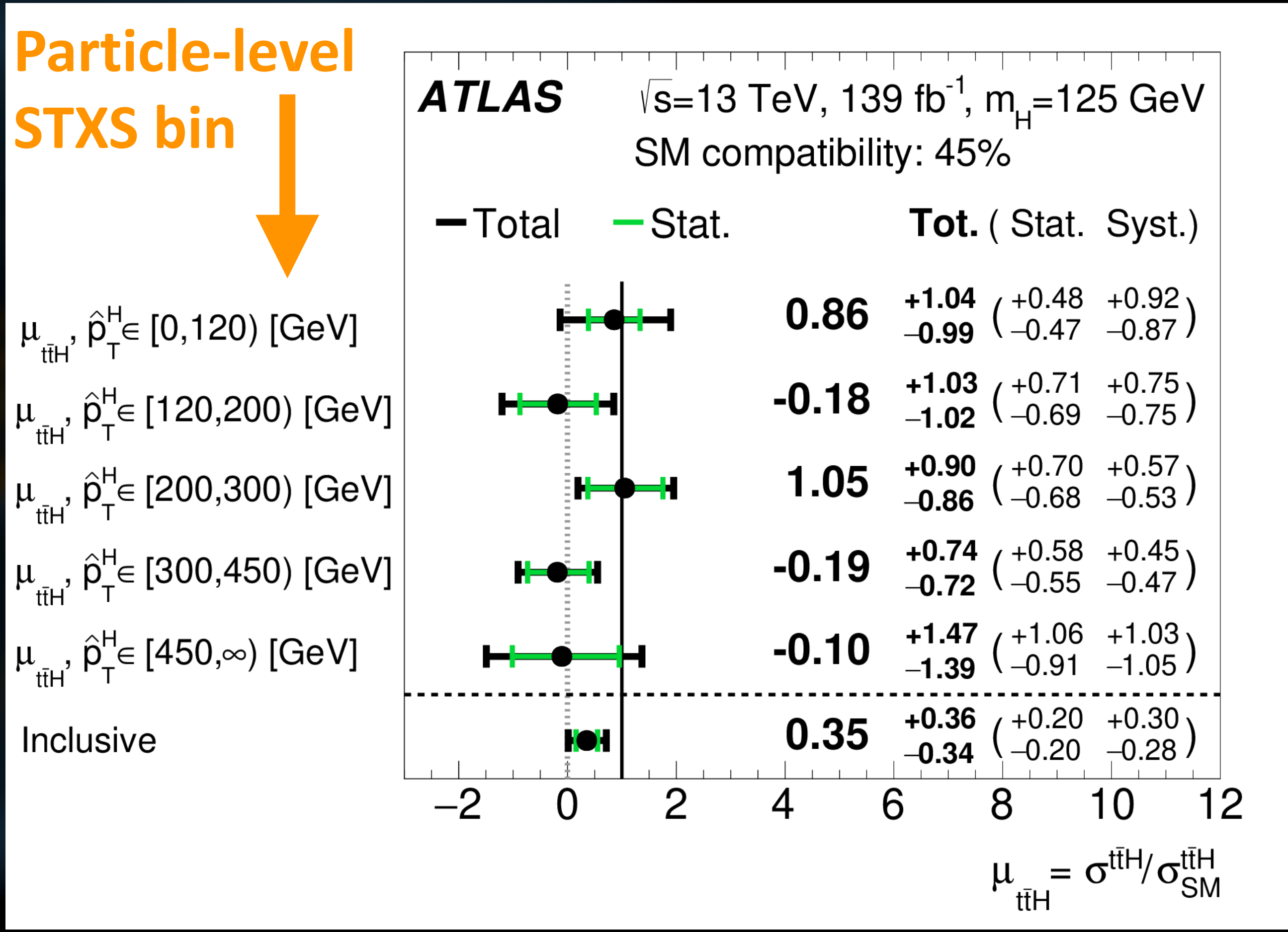
$t\bar{t}H$, $H \rightarrow b\bar{b}$



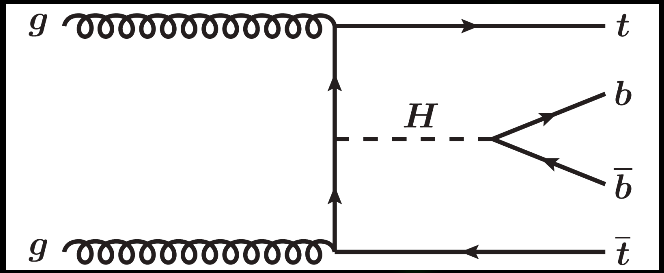
- Classification BDTs are used in all signal regions to separate signal from background.



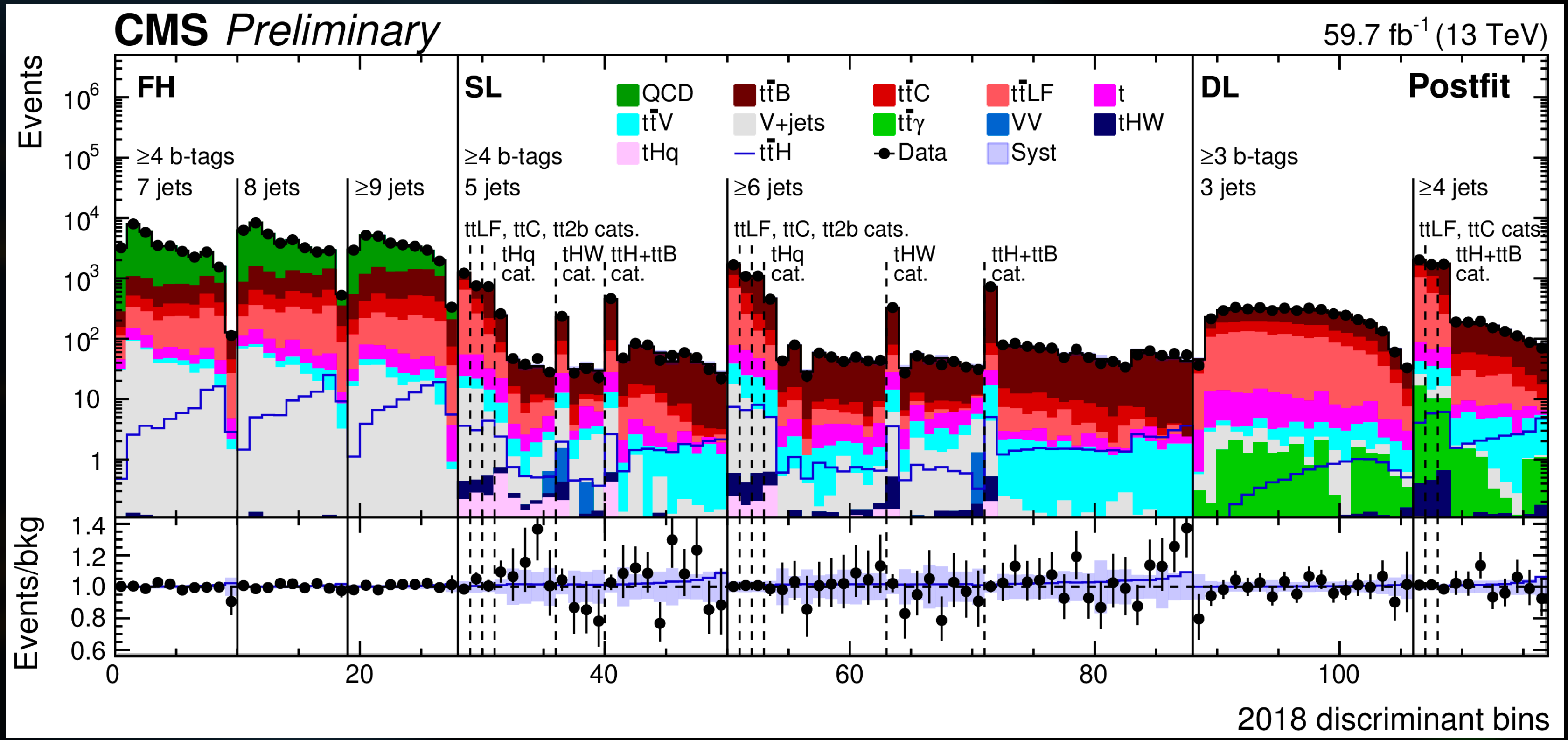




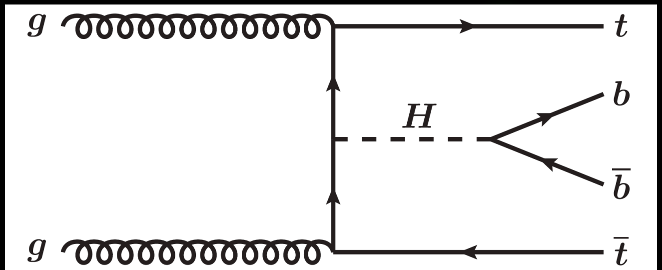
$t\bar{t}H$, $H \rightarrow b\bar{b}$



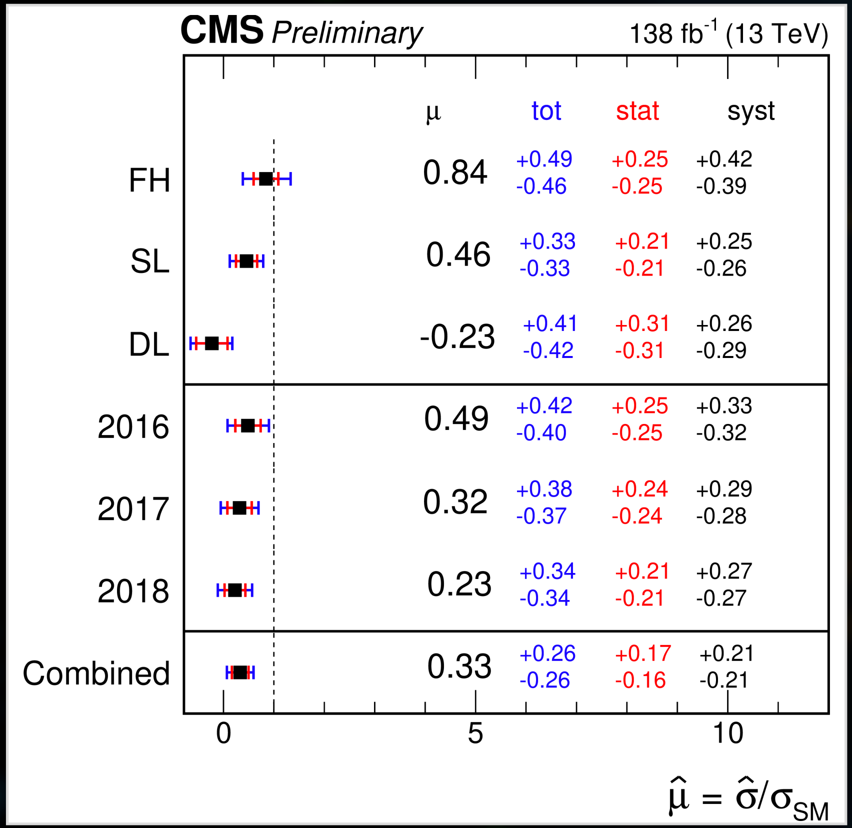
- Primary analysis goals: STXS bin and inclusive signal measurements
- Anchored in 1-2 leptons (electrons or muons) as well as a full hadronic analysis.
- Relies on jet and b-jet multiplicity for categorization.



$t\bar{t}H$, $H \rightarrow b\bar{b}$

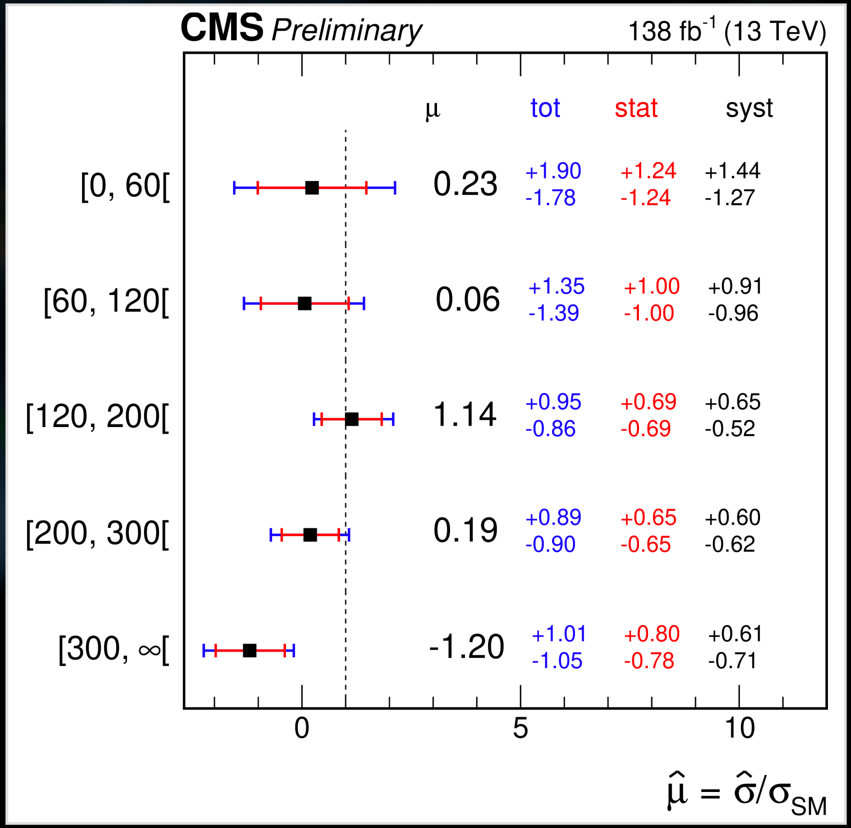


Inclusive

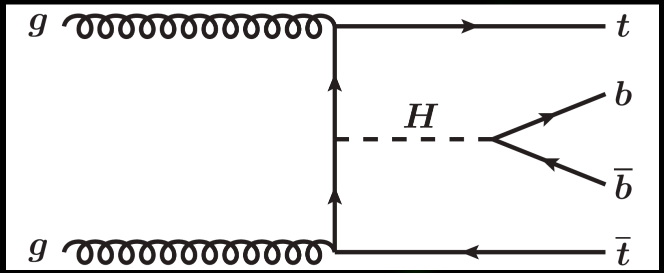


- Inclusive signal extraction is performed without STXS categorization.
- STXS categorization is made with an additional neural network that gives the most probable Higgs p_T.
- Based on the most likely Higgs p_T a category is assigned.

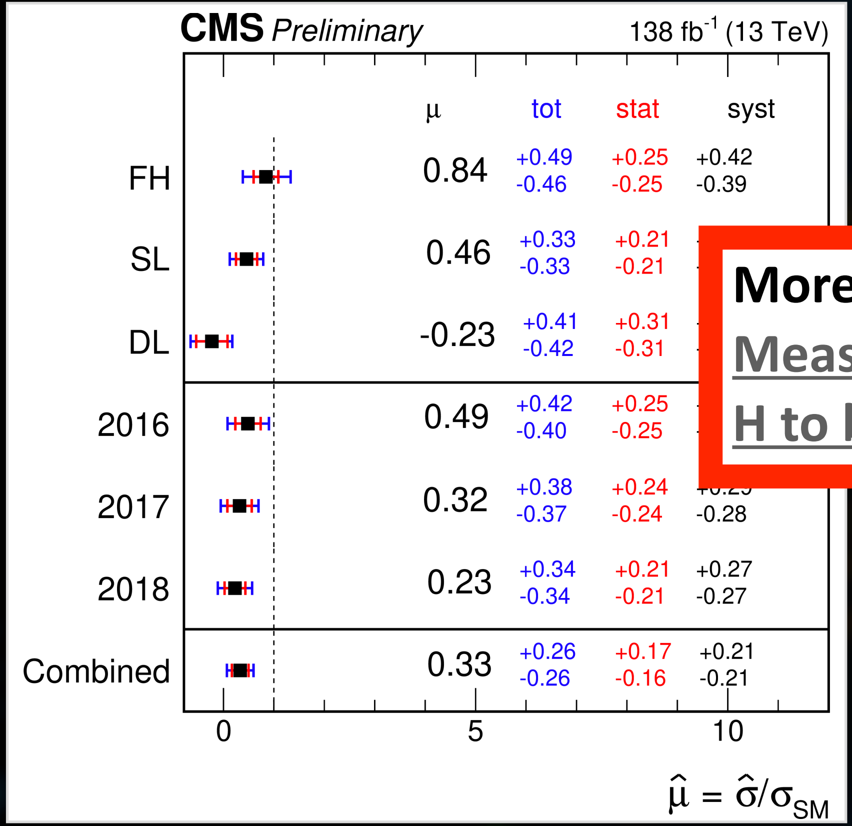
STXS



$t\bar{t}H, H \to b\bar{b}$



Inclusive

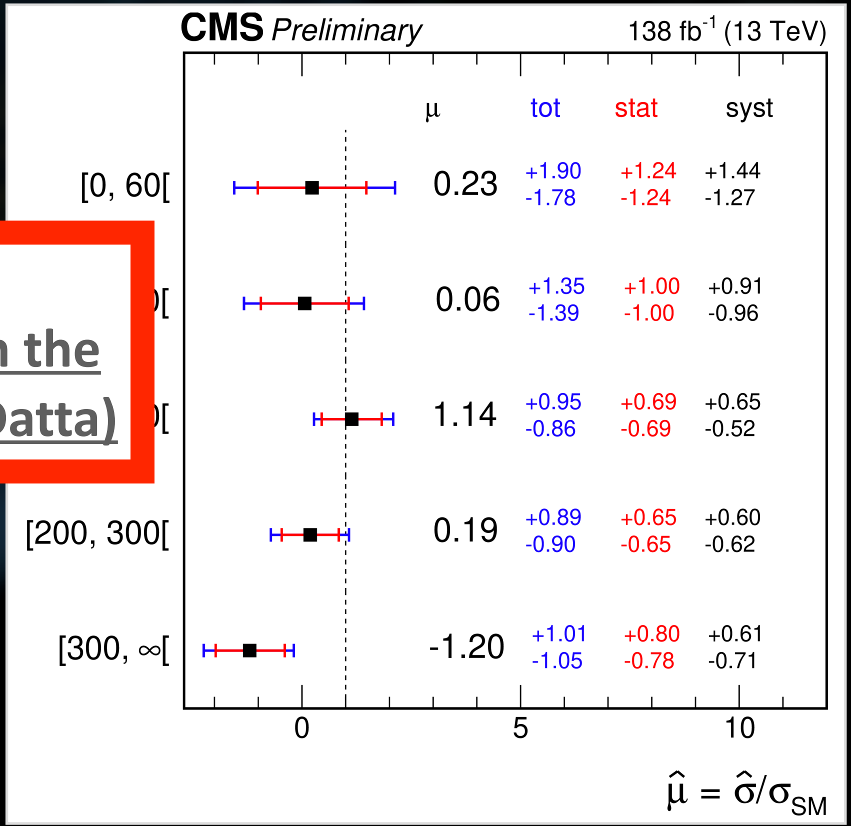


STXS

- Inclusive signal extraction is performed without STXS categorization.

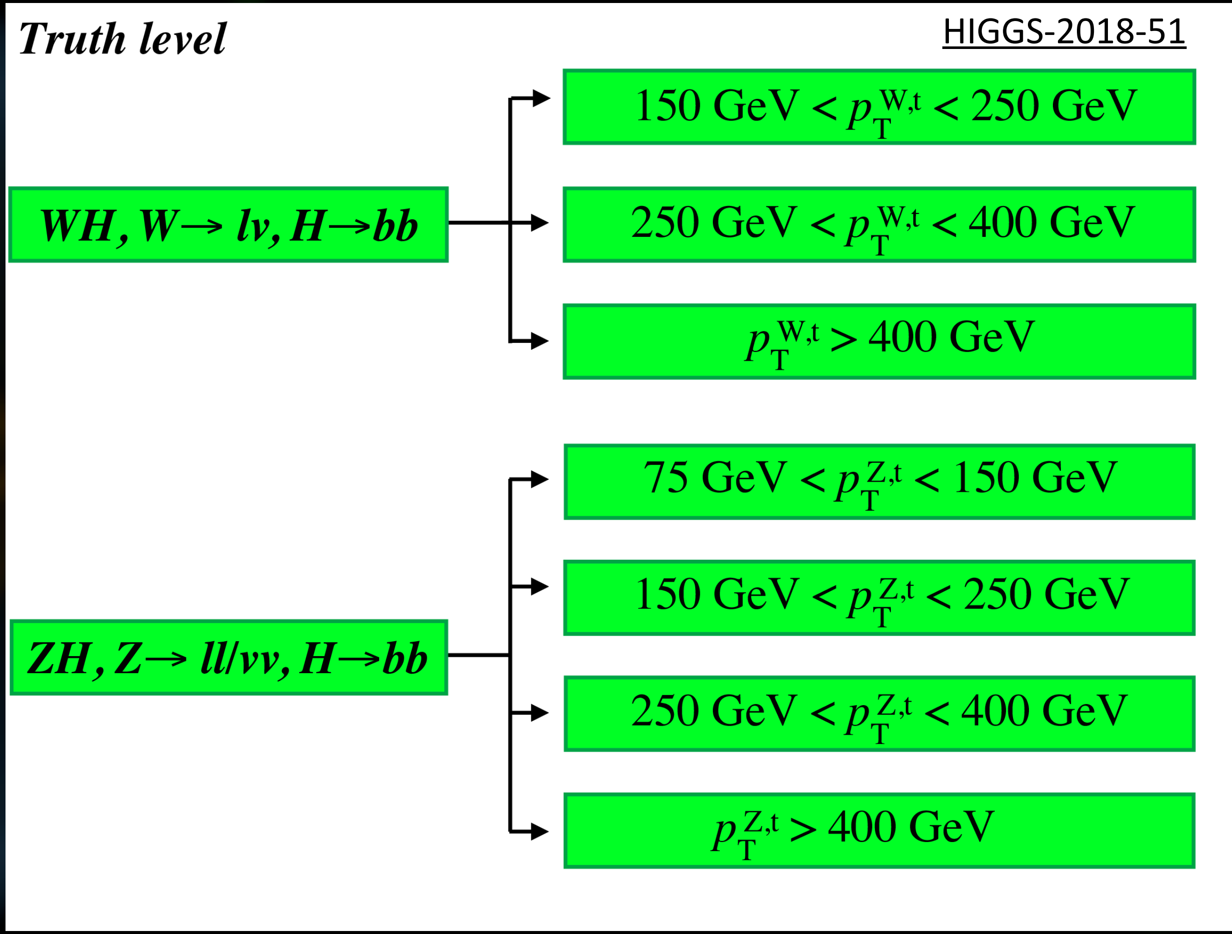
More details Thursday:
Measurement of ttH and tH Production in the H to bb Decay Channel at CMS (Abhisek Datta)

- Based on the most likely Higgs p_T a category is assigned.



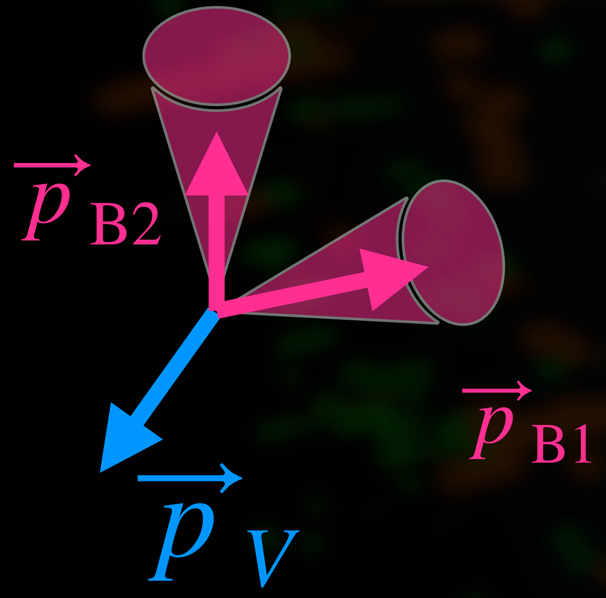
V(leptonic)H, H $\rightarrow b\bar{b}$

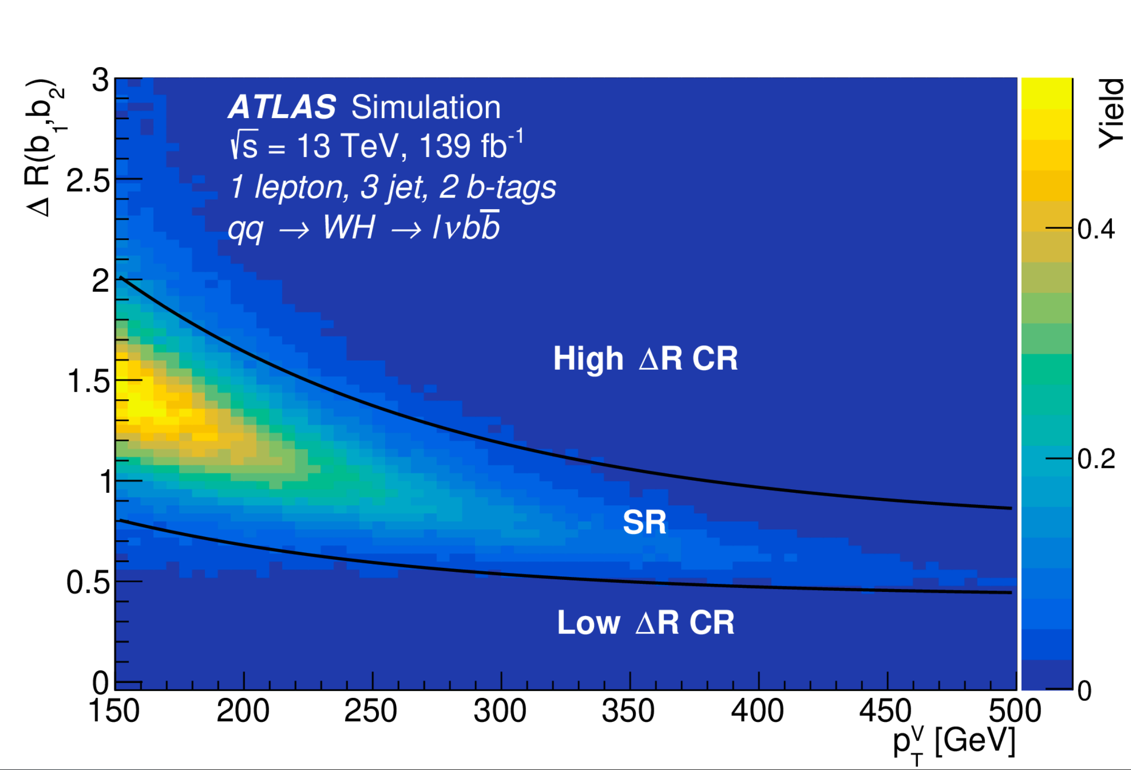
- Both ATLAS and CMS analyses rely on W/Z boson leptonic decays from trigger to high-level selection.
  - $Z \rightarrow \nu\nu$, $W \rightarrow \ell\nu$, and $Z \rightarrow \ell\ell$
- The primary goals of the Run 2 analyses are inclusive signal strength and STXS bin measurements.
  - Binning primarily in $p_{T,V}$ but also in jet multiplicity for ZH 150-250 GeV bin.

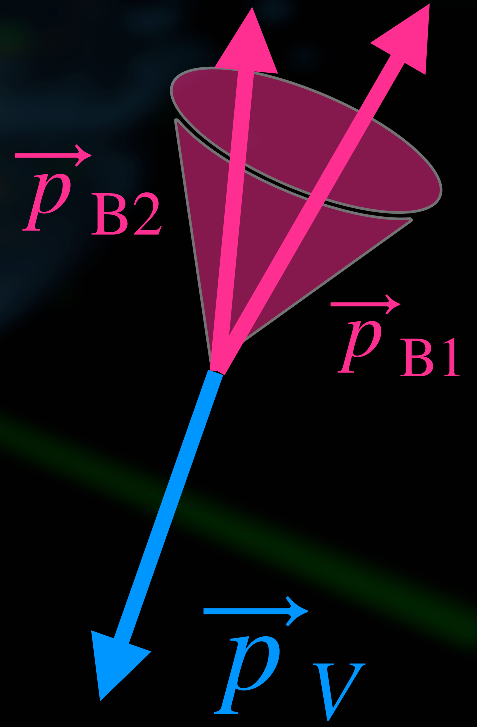


V(leptonic)H, H → $b\bar{b}$

- Small-radius (anti-k_t $R = 0.4$) and large-radius (anti-k_t $R = 0.8$ for CMS and $R = 1.0$) topologies are both explored, and a combination of the two has been made.
- Overlap: CMS chooses event by event with priority given to the small-radius signal region, while ATLAS uses the large-radius topology when $p_{T,V} > 400$ GeV in the combination.







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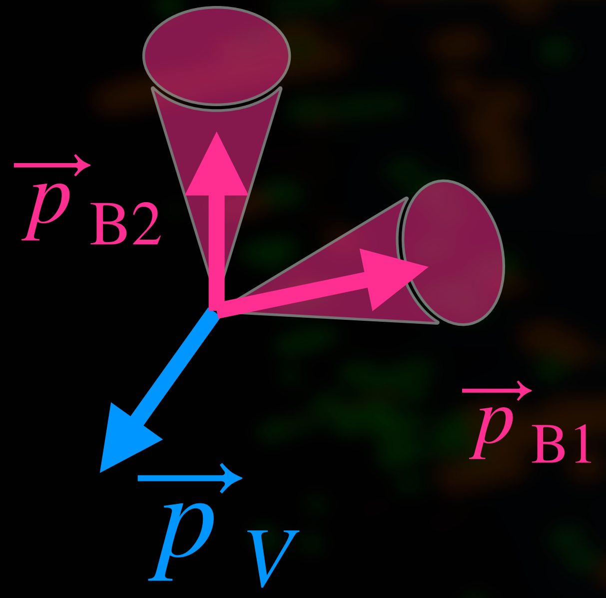
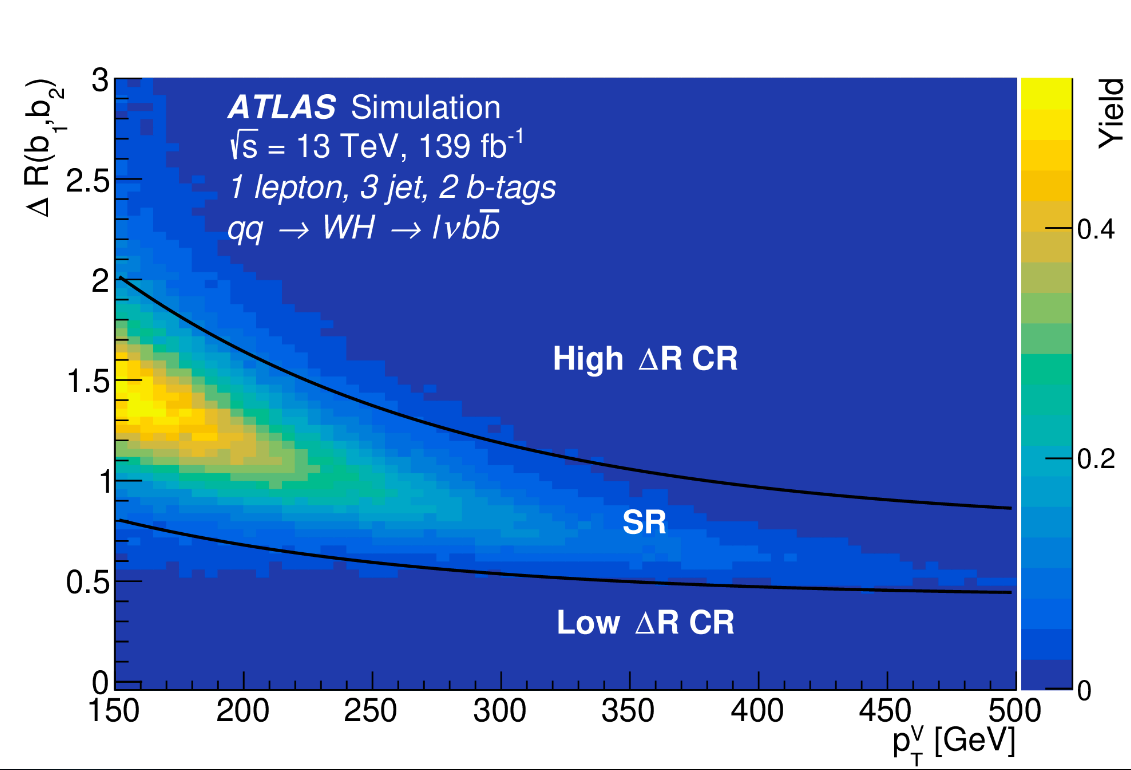
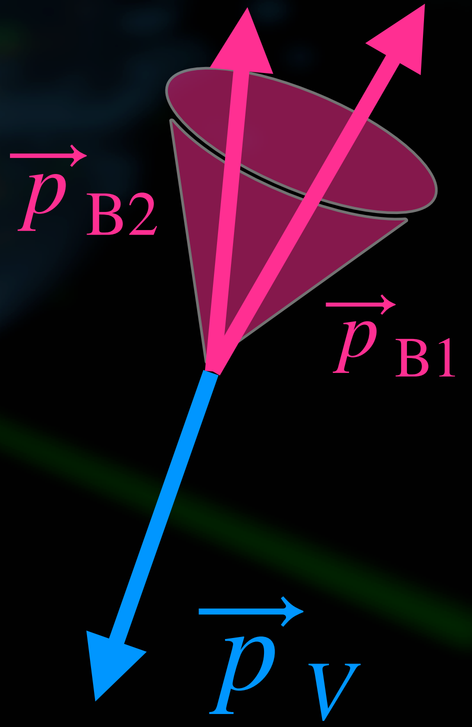
Thursday:
Study of the boosted Higgs boson production (Jie Xiao)

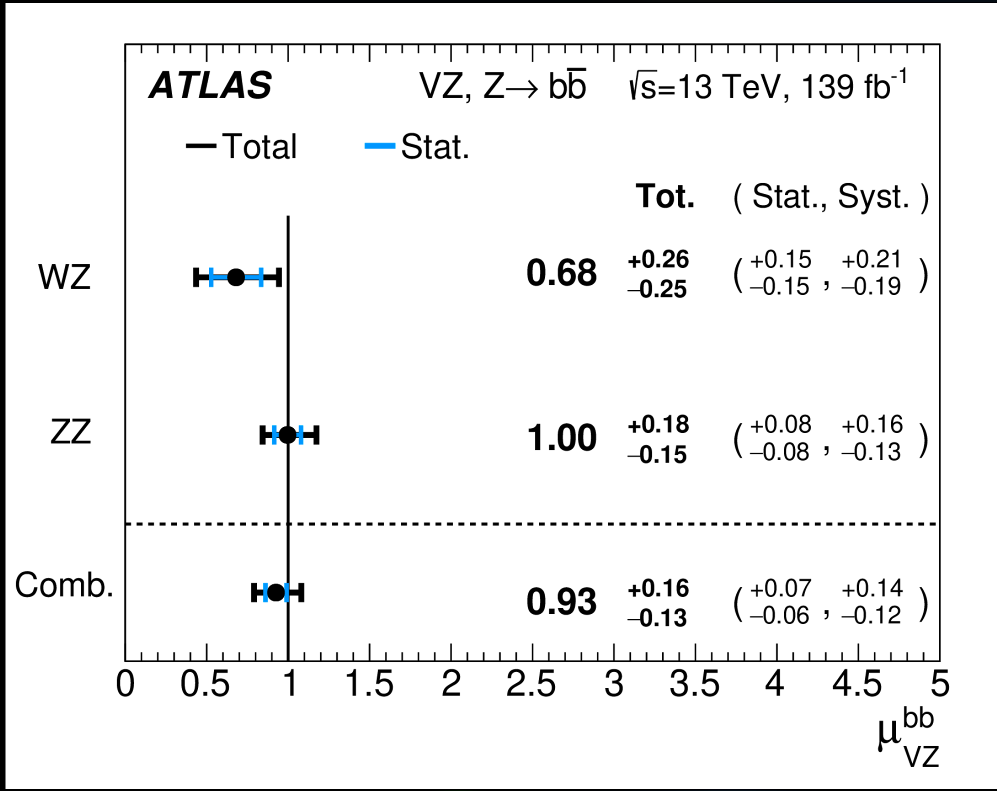


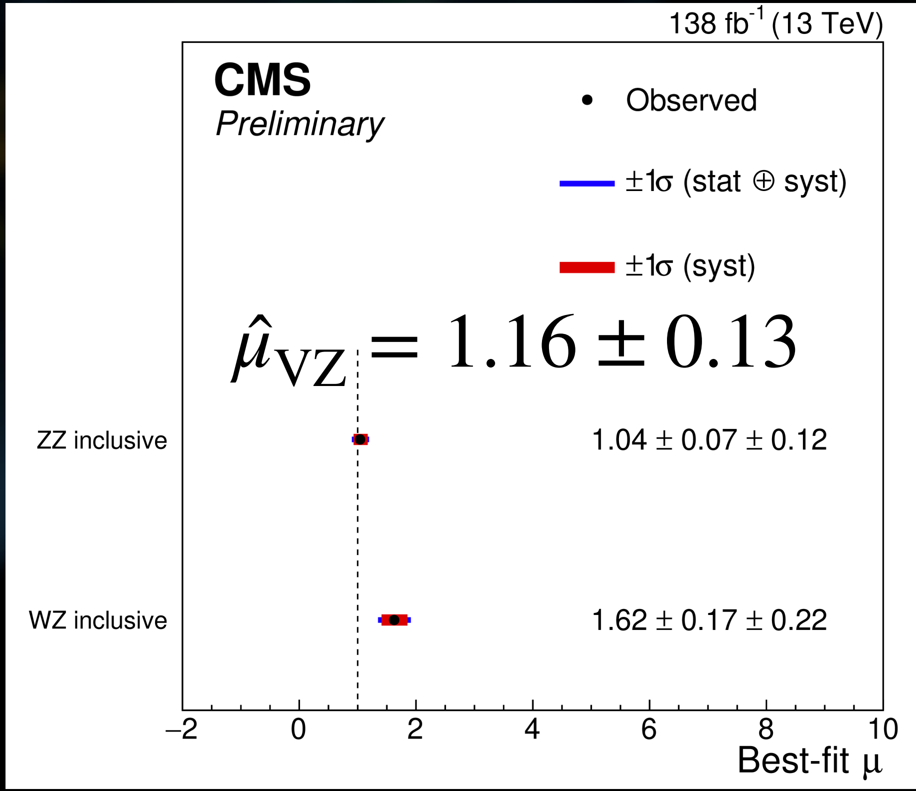




$\mathrm{V(leptonic)Z, Z \to b\bar{b}}$, Resolved Validation

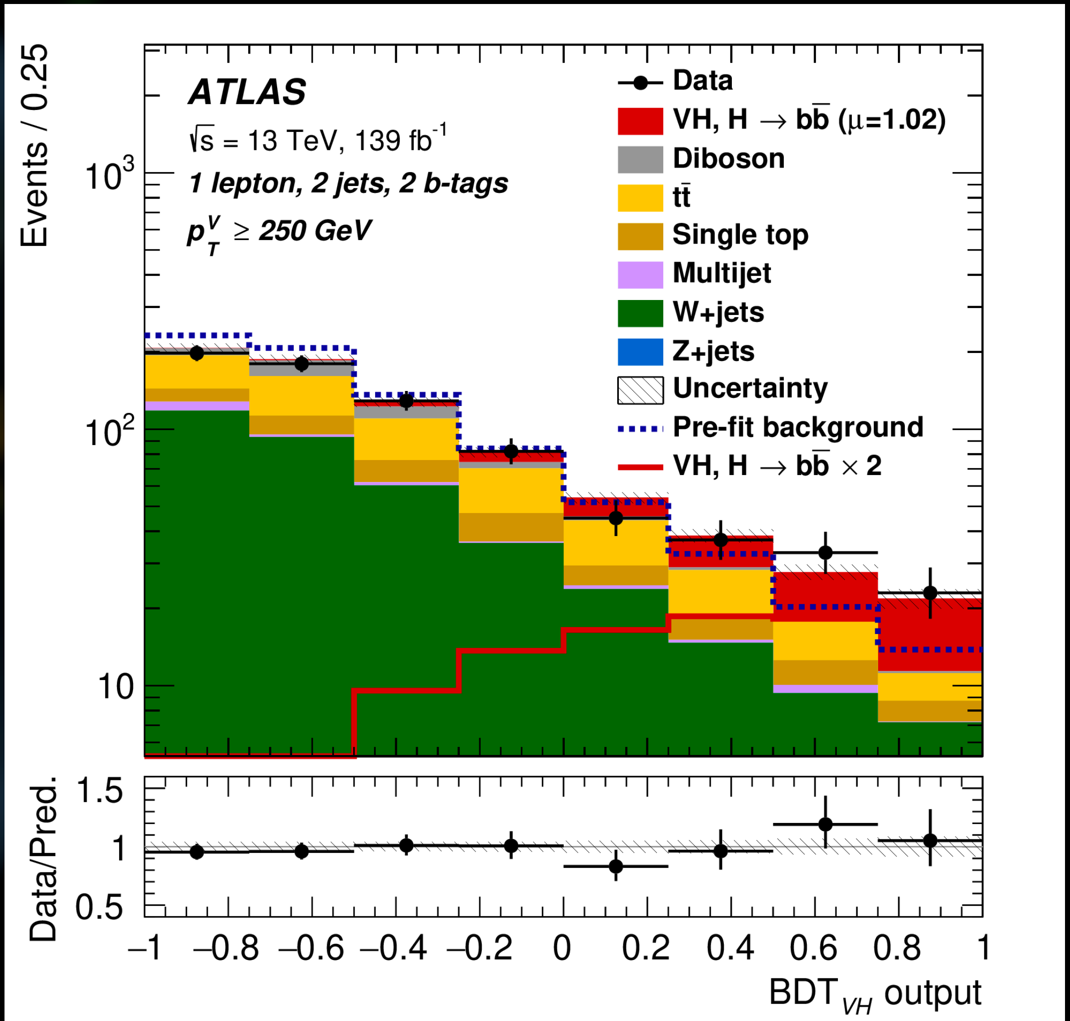
- Both analyses use the VZbb signature as a standard candle for validation of the primary analysis.





V(leptonic)H, H → $b\bar{b}$

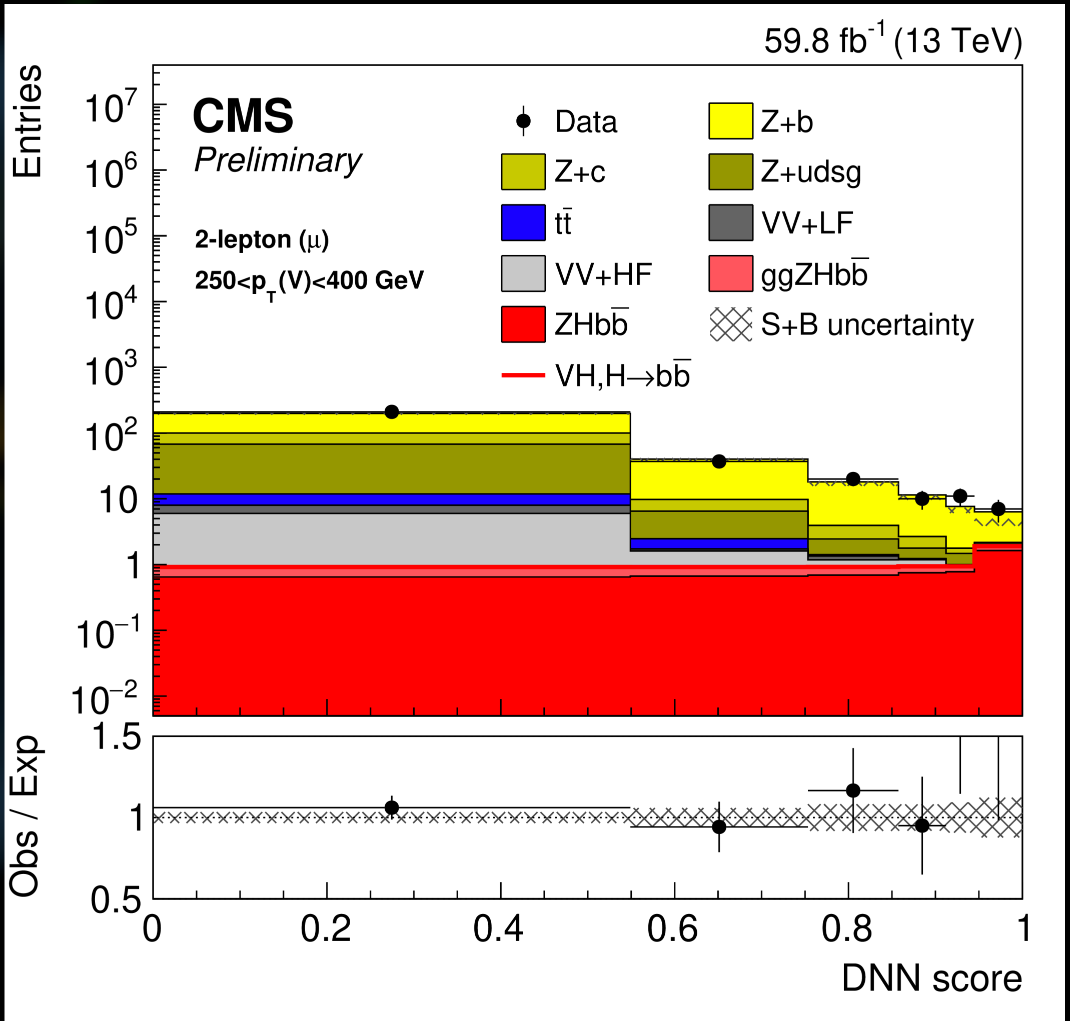
- Shape and uncertainties for V+jets MC is critical for VHbb.
  - ATLAS default is Sherpa NLO MC
- V+HF is decomposed into bb, bc, bl, and cc.
  - V+HF normalization floats and bc, bl, cc have uncertainties relative to bb.
- W+HF shape uncertainties are assessed by comparing to MadGraph5_aMC@NLO.
- Z+HF shape uncertainties are assessed in dijet sidebands with comparisons to data.
- Signal regions are BDT outputs.



Resolved (HIGGS-2018-51), boosted (HIGGS-2018-52) and combo (ATLAS-CONF-2021-051)

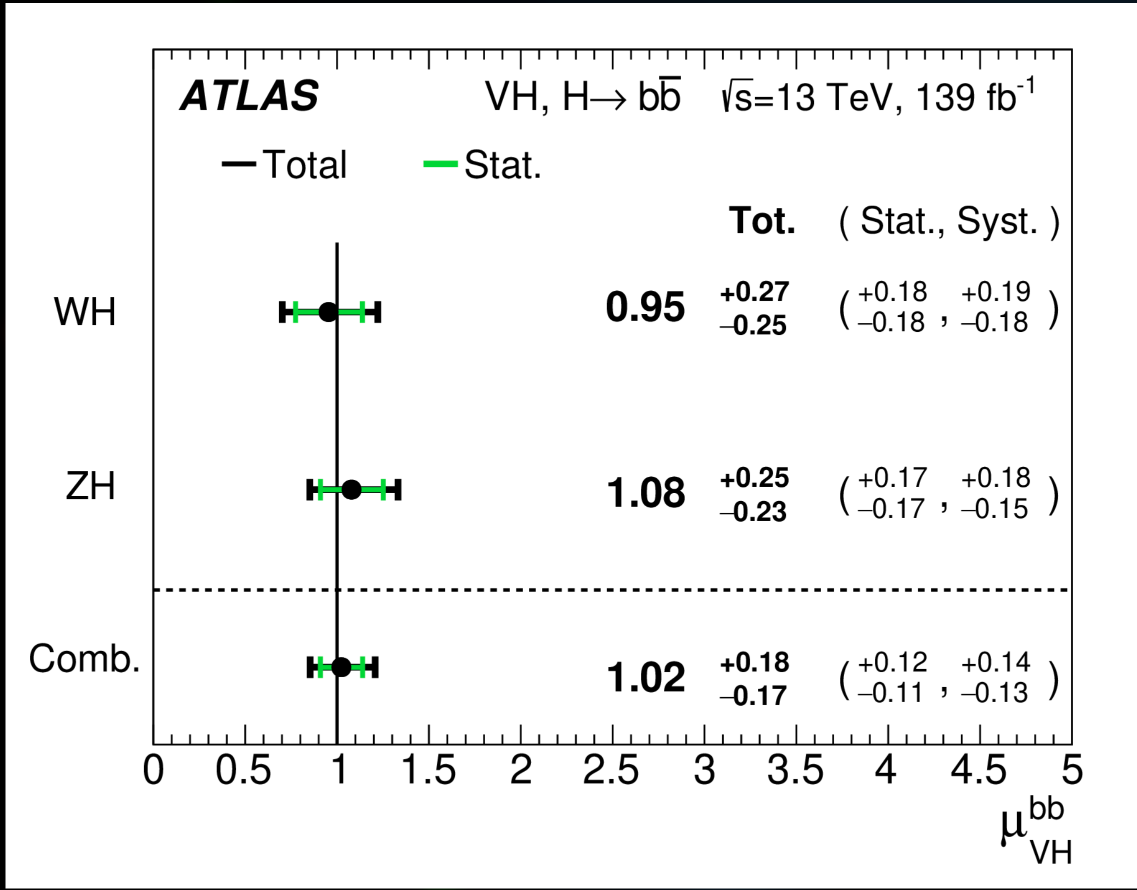
V(leptonic)H, $H \rightarrow b\bar{b}$

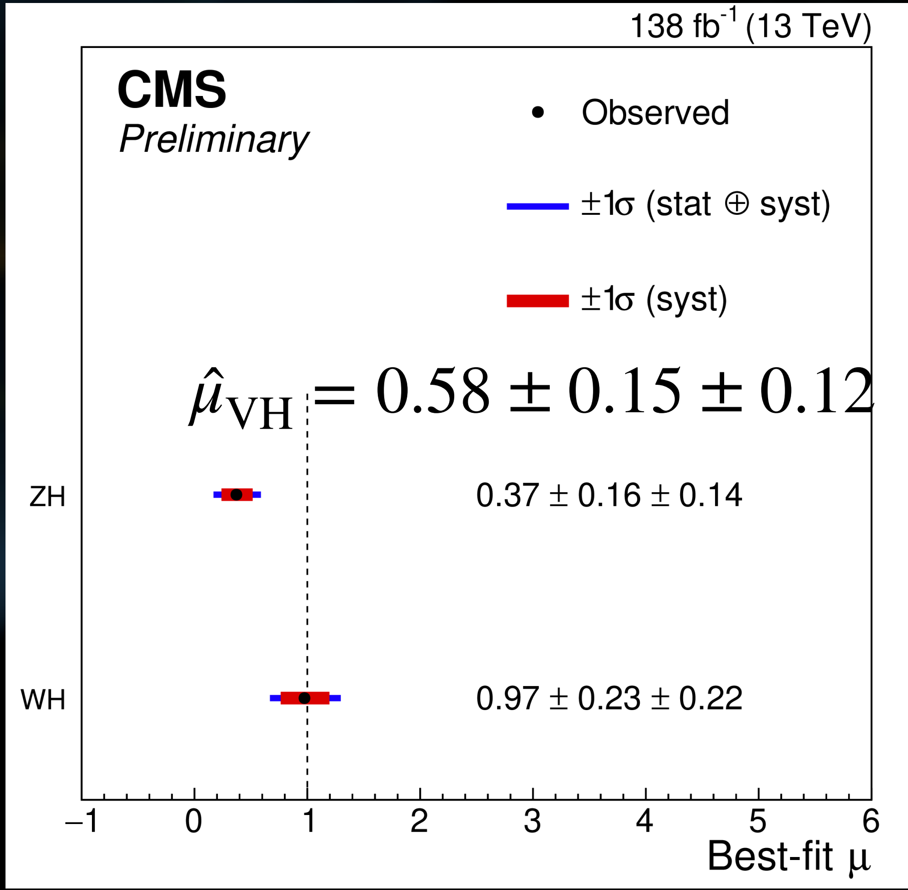
- Shape and uncertainties for V+jets MC is critical for VHbb.
  - CMS default is MadGraph5_aMC@NLO MC
- V+jets is decomposed into V+b(b), V+c, and V+LF.
  - All components have floating normalizations and linear $p_{T,V}$ shape uncertainties.
- DNN (BDT) outputs for resolved (boosted) are used for signal region observables.



V(leptonic)H, H → $b\bar{b}$

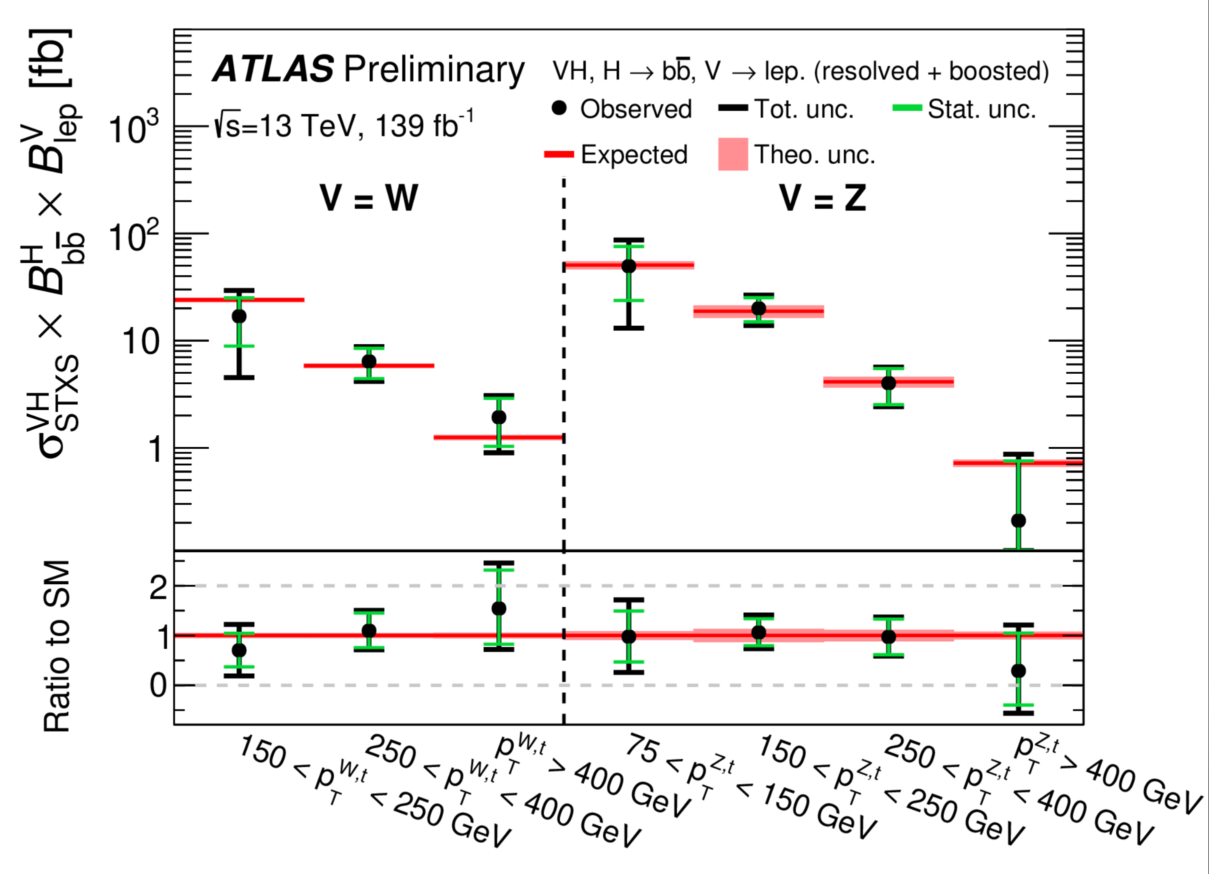
- Both analyses see WH near the SM while there are divergent results in the ZH channels.

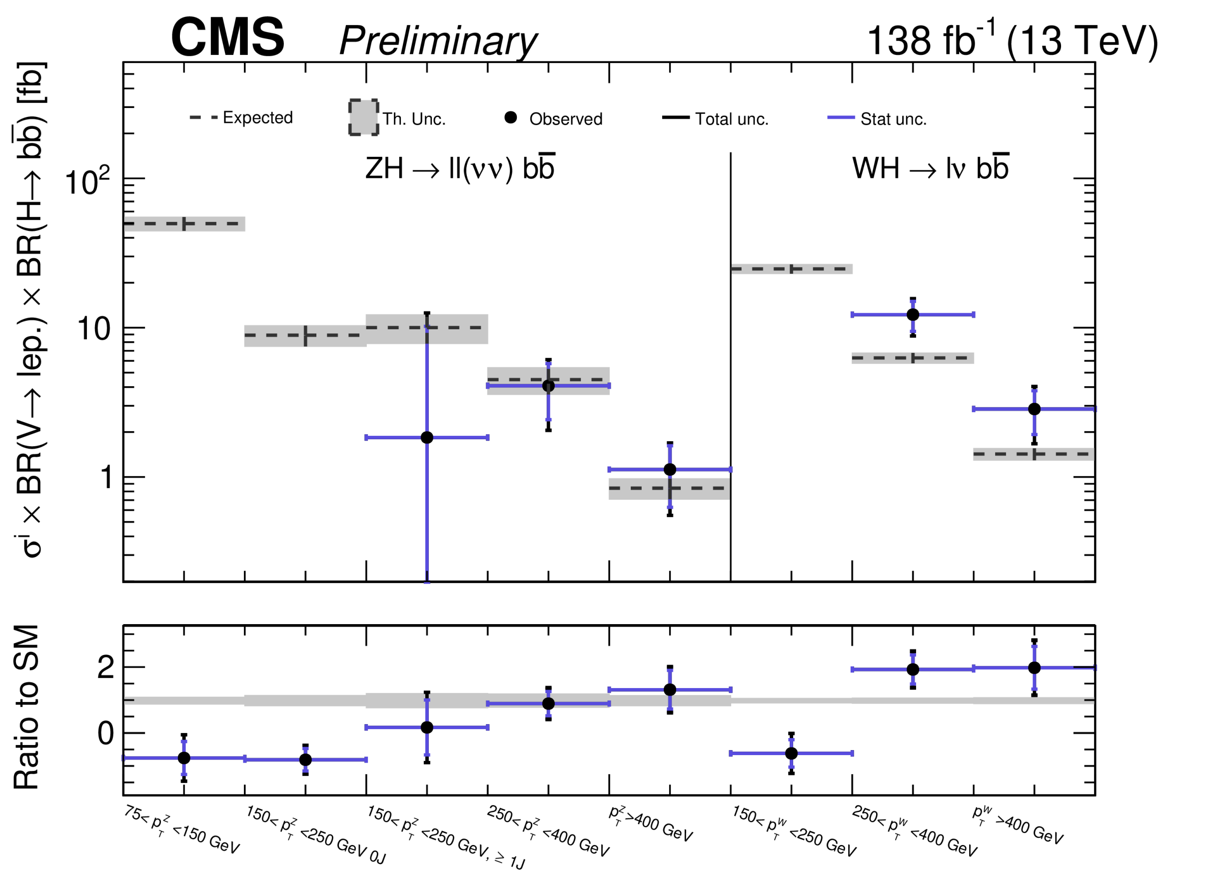




V(leptonic)H, H → $b\bar{b}$, STXS

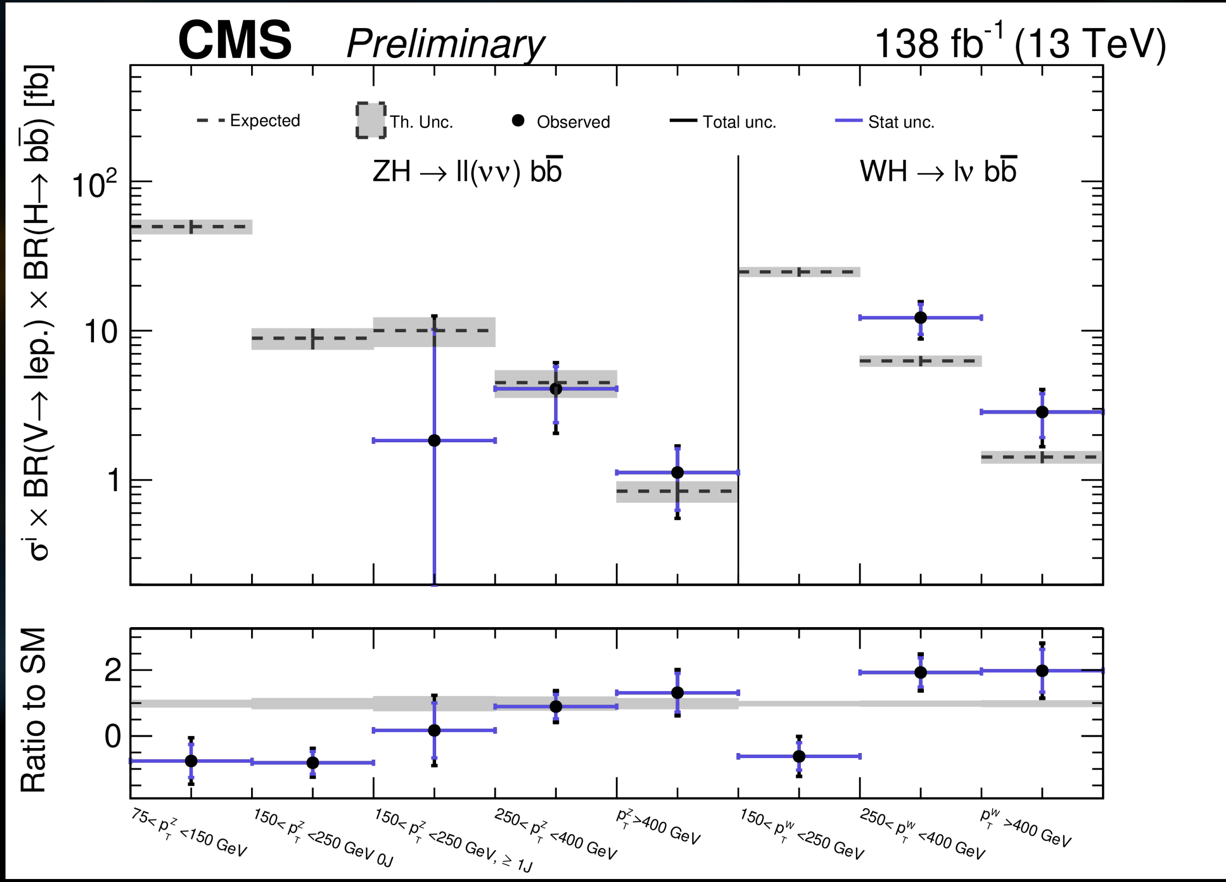
- ATLAS STXS measurements are highly compatible with the SM while there is some discrepancy with the SM in the CMS results.





V(leptonic)H, H → $b\bar{b}$, STXS

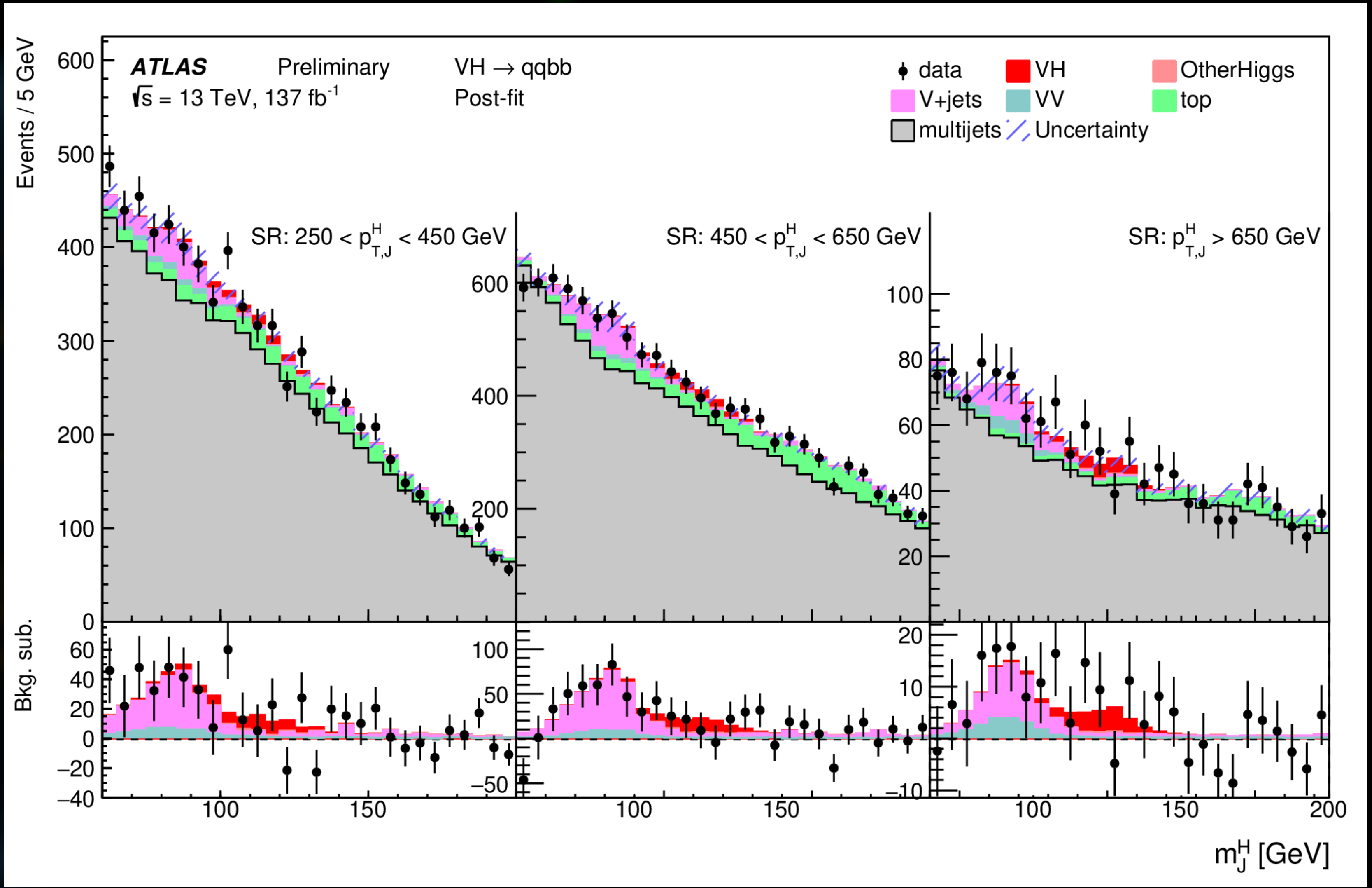
- ATLAS STXS measurements are highly compatible with the SM while there is some discrepancy with the SM in the CMS results.
- CMS has been studying these results and underlying analysis features during the past year.
- CMS is nearly ready to share the final results, so keep checking arxiv in the coming weeks.



V(hadronic)H, H → $b\bar{b}$

- Both the bosons need to be reconstructed in large-radius ($R = 1.0$) jets.
- The multijet component of the background is estimated using a data-driven template from control regions with in situ transfer factor.

$$\hat{\mu} = 1.4^{+1.0}_{-0.9}$$

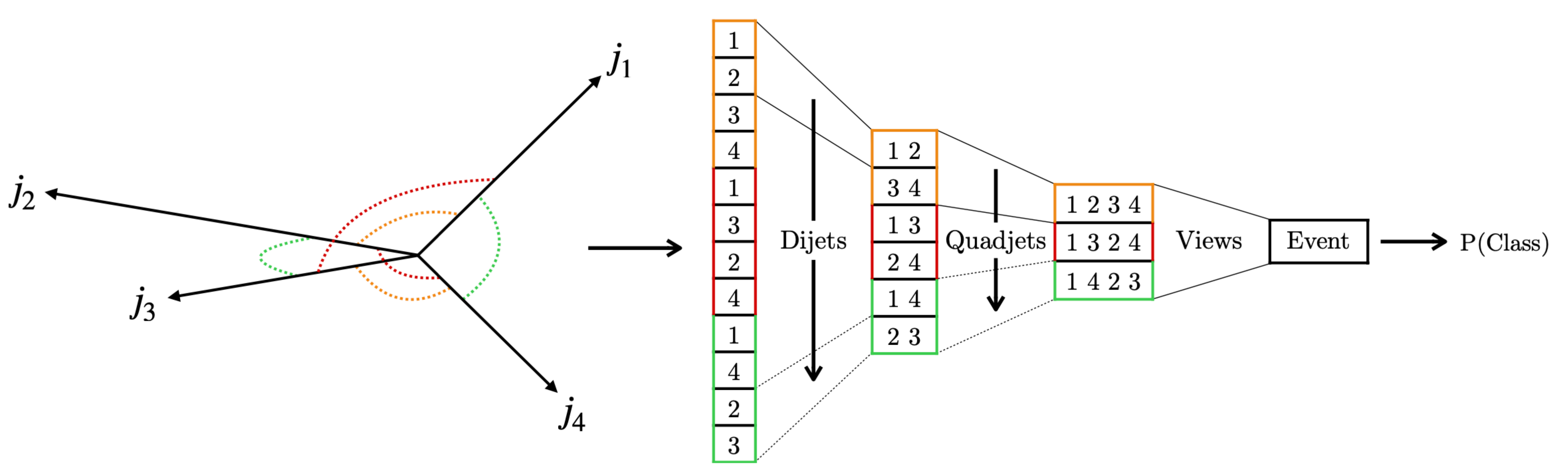


$ZH(ZZ) \rightarrow b\bar{b}b\bar{b}$

NEW

CMS

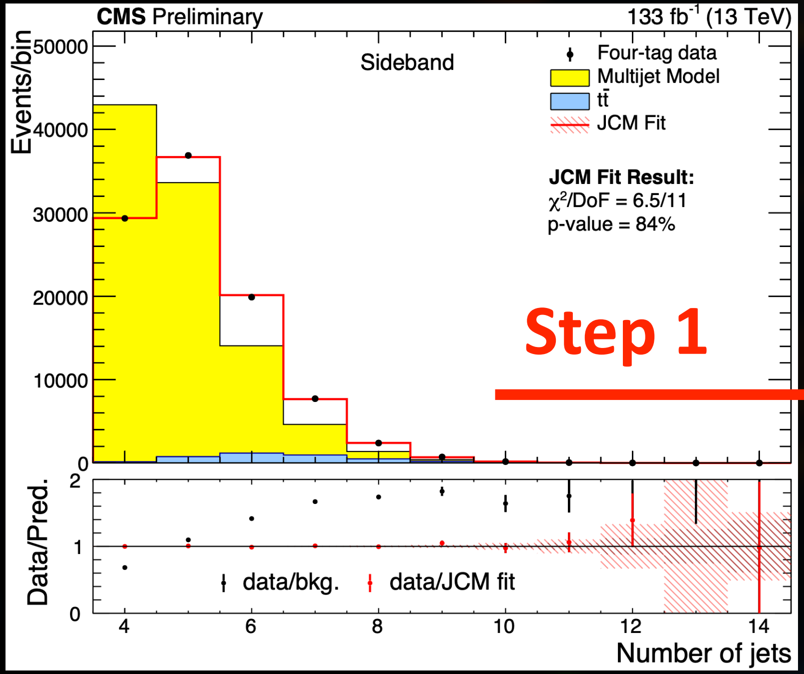
- This analysis studies new methodologies on larger cross section 4b final states.
- The selection requires 4 b-tagged jets with kinematic requirements slightly tighter than 4 jet triggers.
- A neural network considers all potential combinations, but at least one of the combinations must be compatible with the masses of the signal (ZH or ZZ).

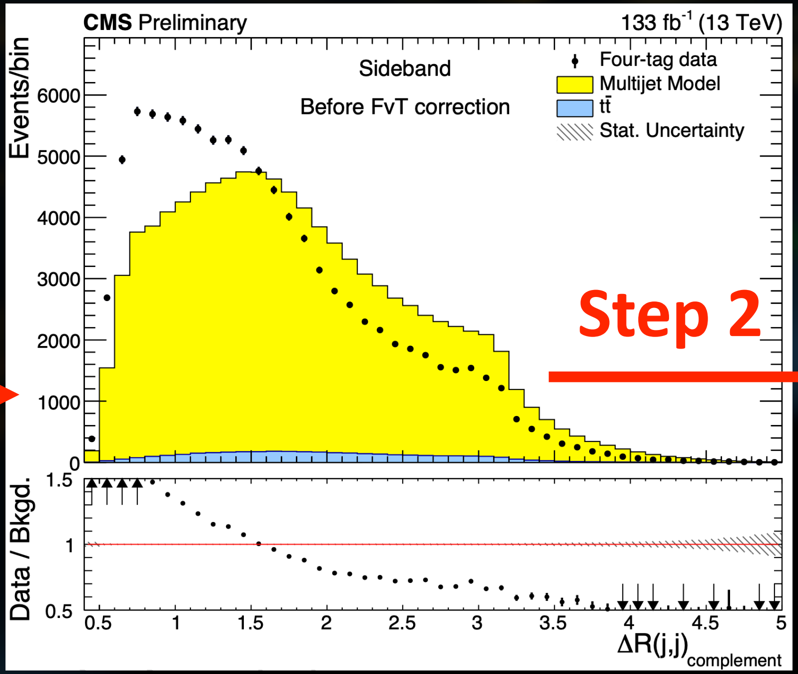


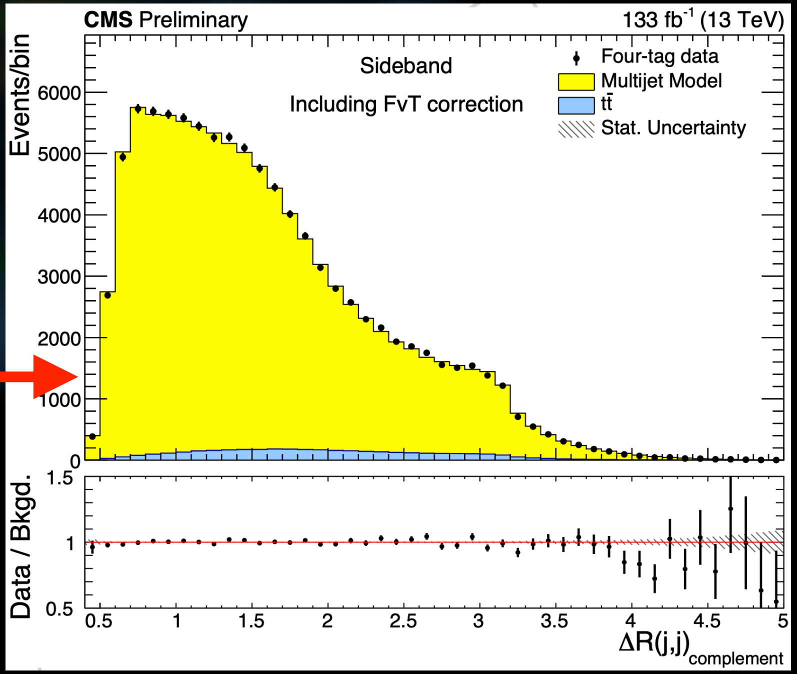
ZH(ZZ) → $b\bar{b}b\bar{b}$

NEW

- Mulitjet background is estimated from data using 4j3b.
  - The 4j3b data requires reweighting to match the kinematics of the signal region.
  - Trained and validated in a sideband region.

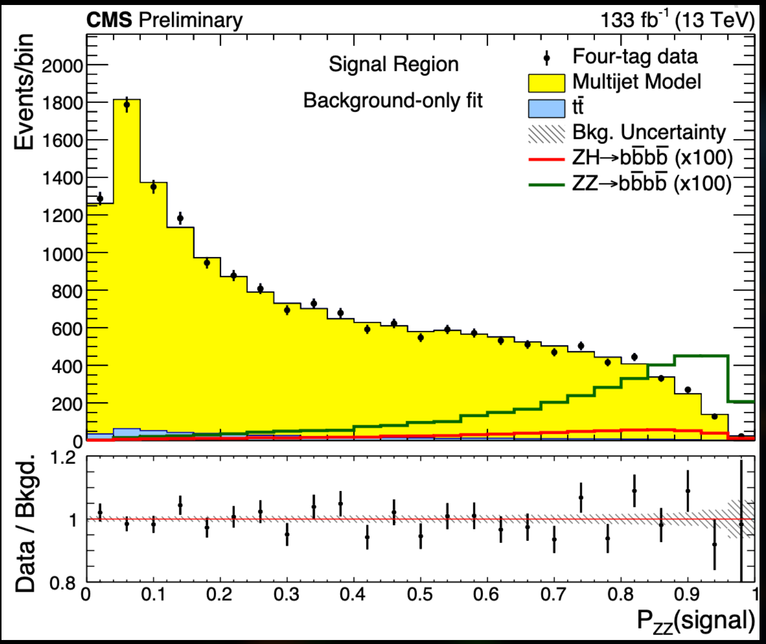


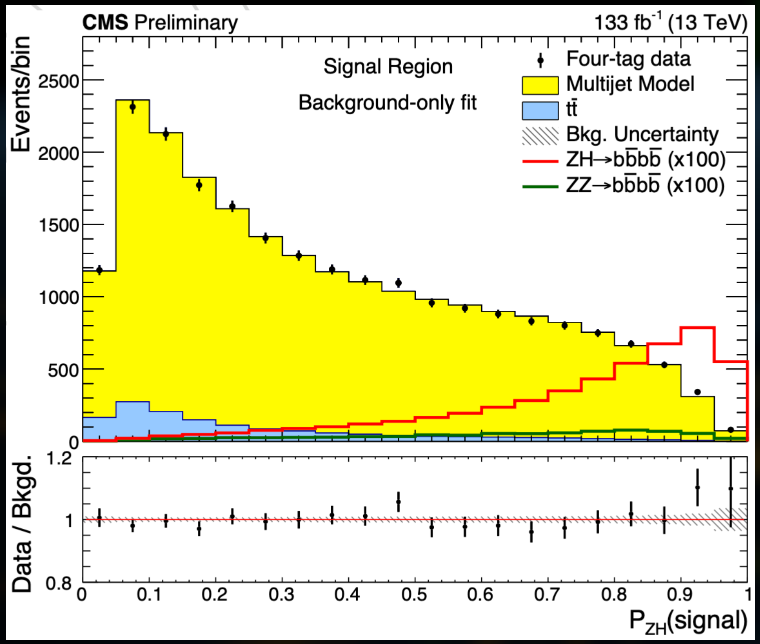




ZH(ZZ) → $b\bar{b}b\bar{b}$

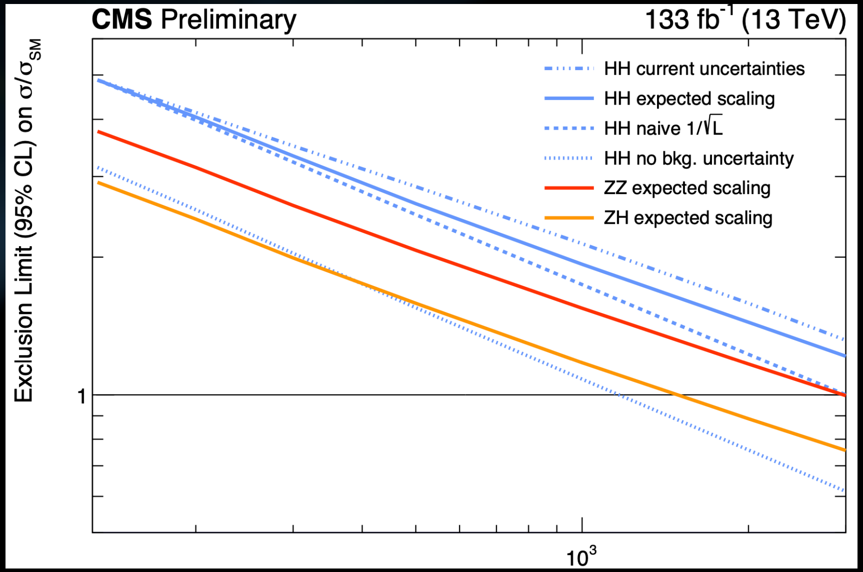
NEW





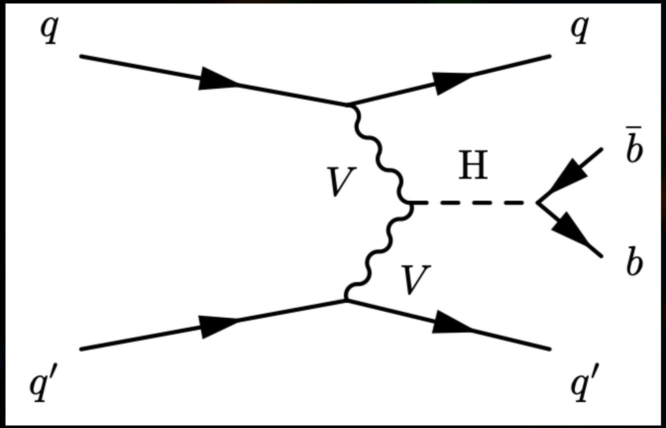
- The primary systematic uncertainty is from an updated version of hemisphere mixing of 4j3b samples to generate synthetic data.
- Future plans include reducing this systematic uncertainty so these measurements can be made by HL-LHC.

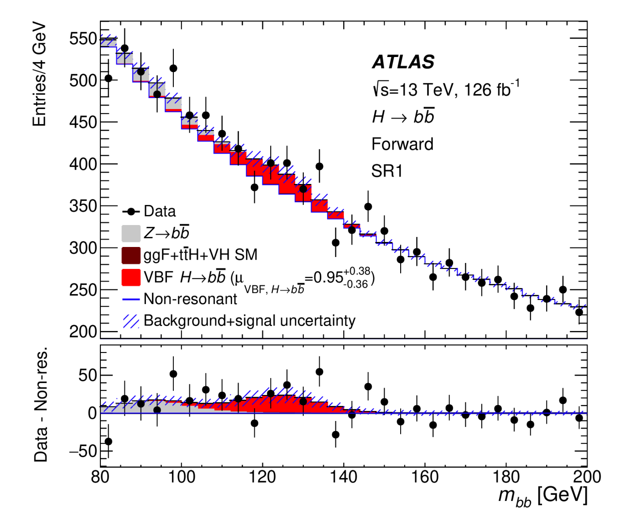
	ZZ	ZH
Signal strength expected (stat-only)	$1^{+1.9}_{-1.7}$ $(1^{+1.4}_{-1.3})$	$1^{+1.5}_{-1.4}$ $(1^{+1.1}_{-1.1})$
Signal strength observed	$0.0^{+2.0}_{-1.7}$	$2.2^{+0.9}_{-0.8}$
Expected Limit at 95% CL (stat-only)	3.8 (2.8)	2.9 (2.3)
Observed Limit at 95% CL	3.8	5.0

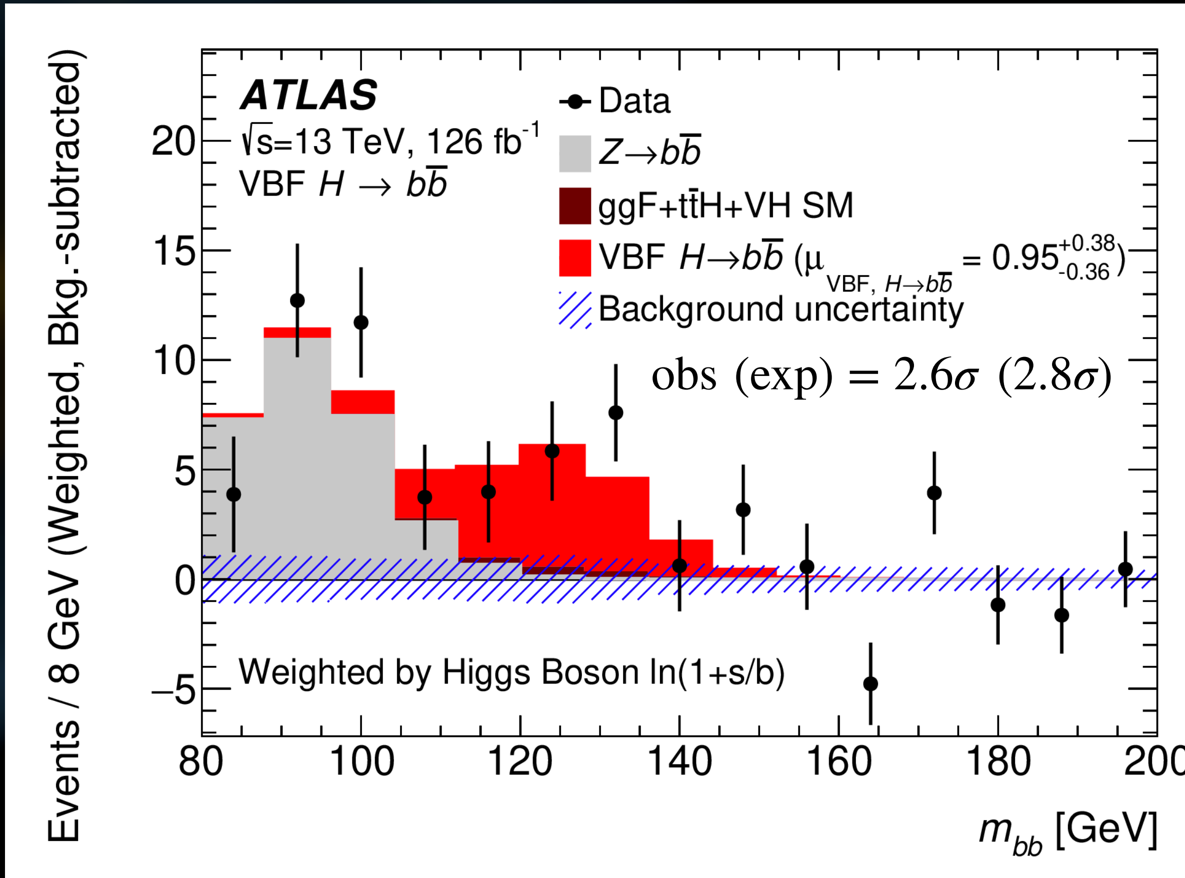


VBF H, H → $b\bar{b}$

- Adversarial neural network used for classification on two small-radius b-jets and two other jets.
- m_{bb} dependence removed so it can be fit.
- QCD fit from template and Zbb template comes from Zμμ with data imbedding.

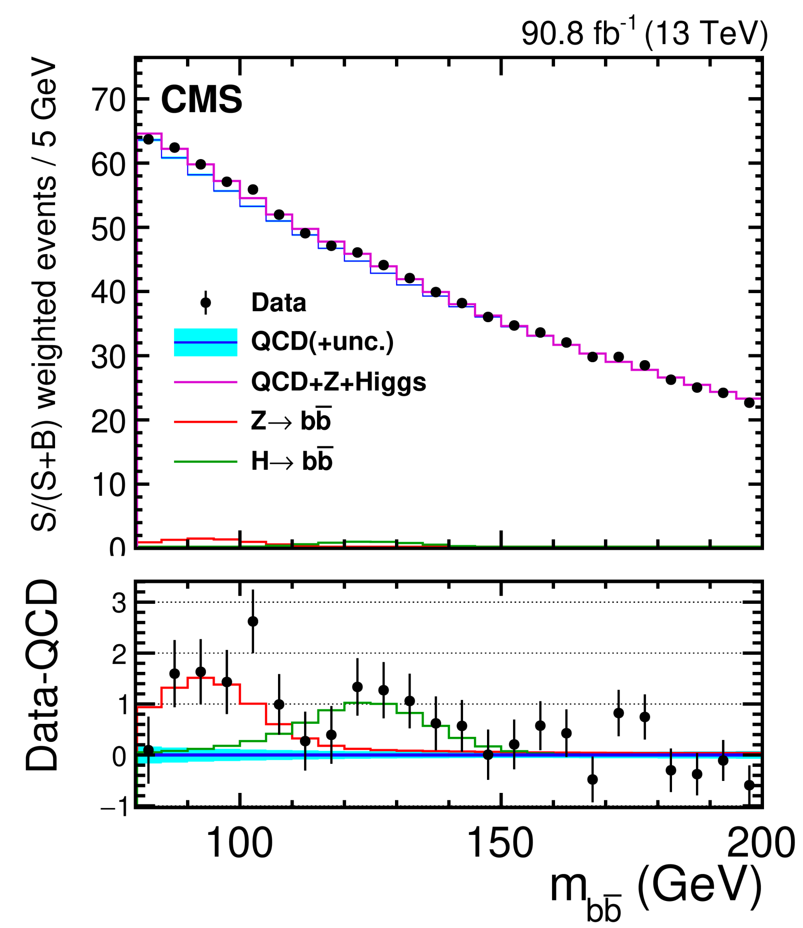


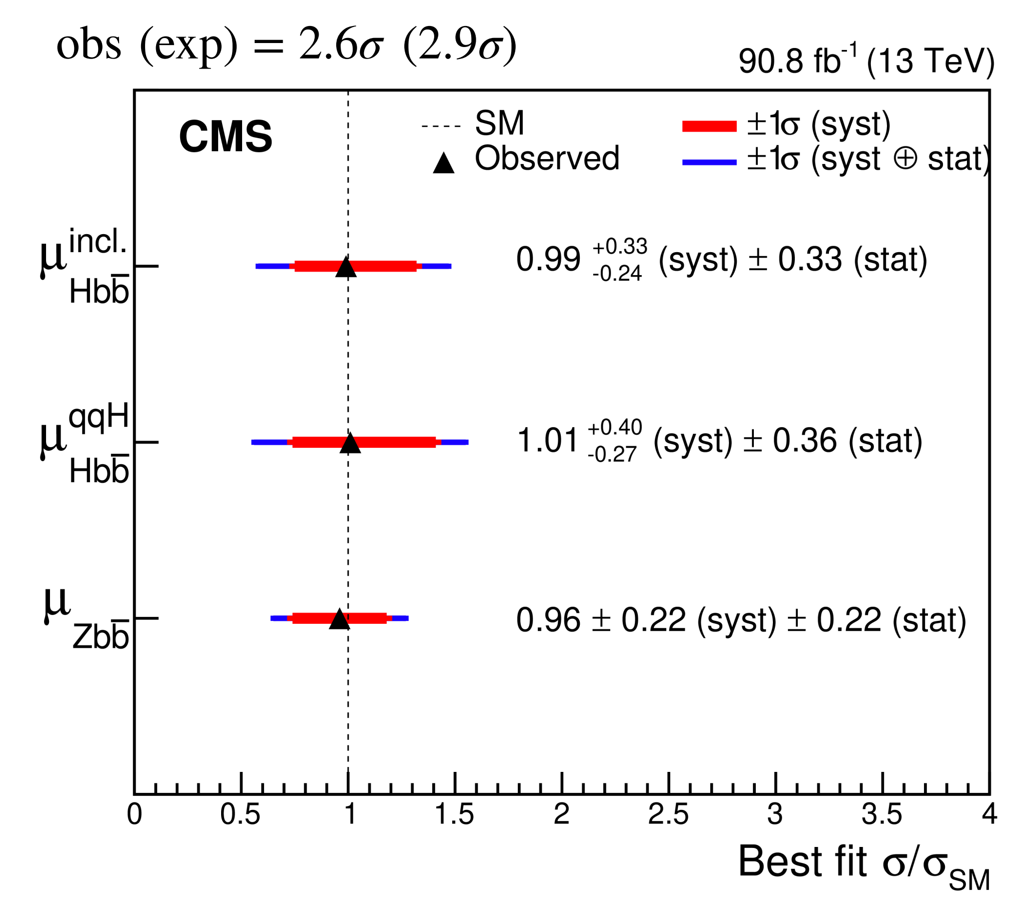




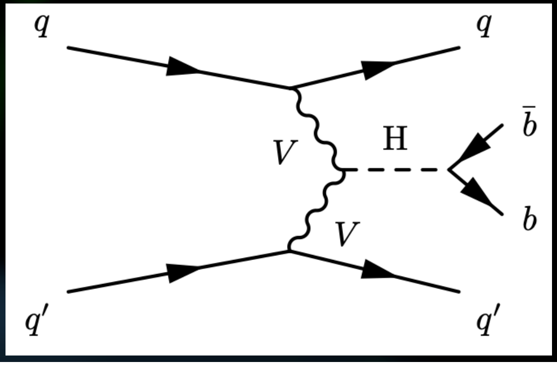
VBF H, H → $b\bar{b}$

- Two small-radius b-jets
  - DeepJet b-tagger
- Two additional jets
- Categorize with a BDT with kinematic and b-tagging inputs.
  - m_{bb} independent
- m_{bb} is fit observable
- QCD is fit directly in SR.
- Minimal (<10%) bias
  - No additional uncertainties

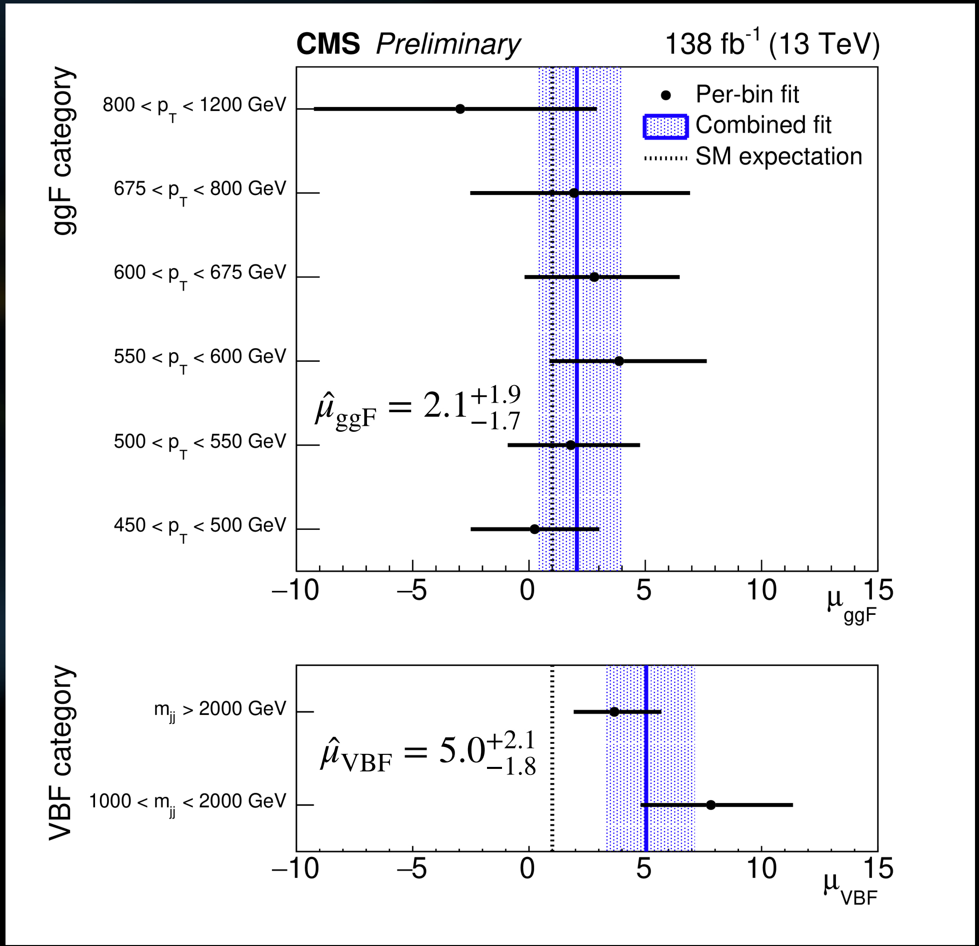


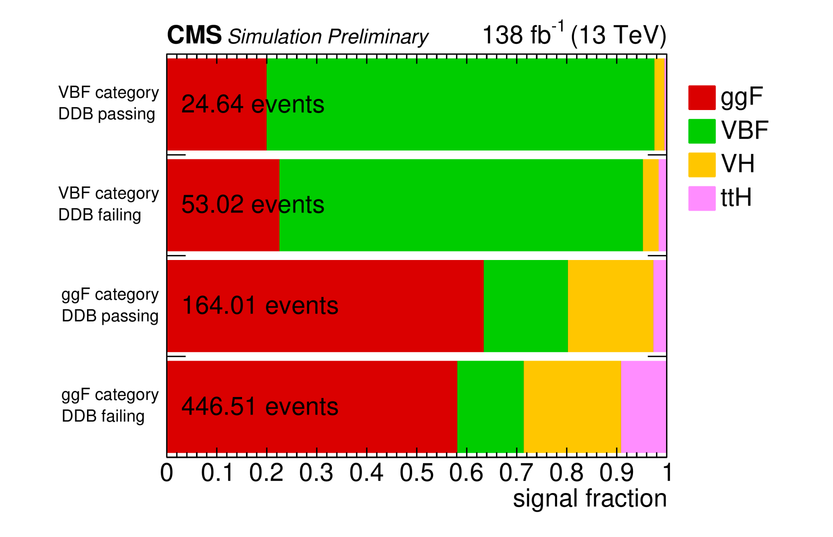


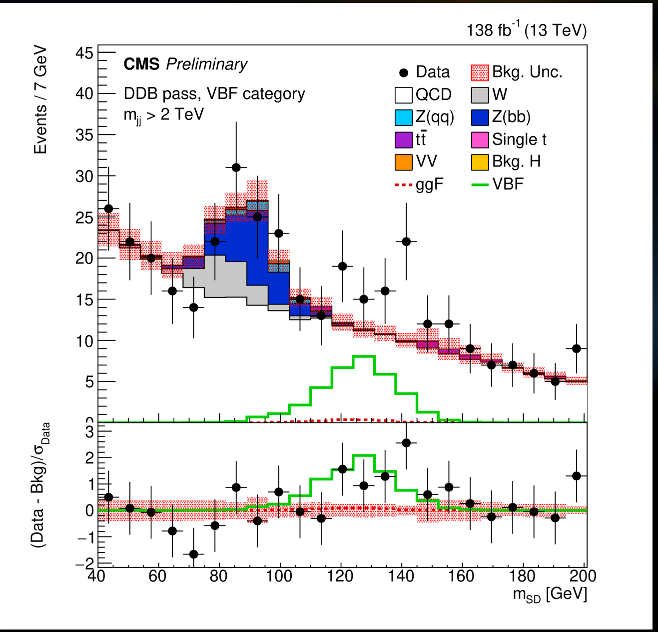
VBF H, H → $b\bar{b}$



- One large-radius bb jet and two small-radius jets are selected.
- The large-radius jet mass is the observable, and the DeepDoubleBvL-v2 is used to define a signal and control region.
- QCD template is a fit of the control region multiple by a transfer function.

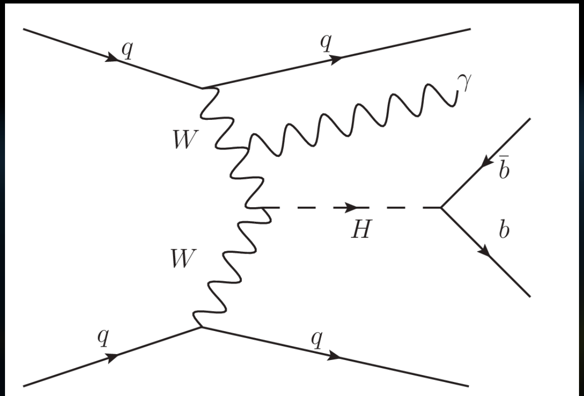


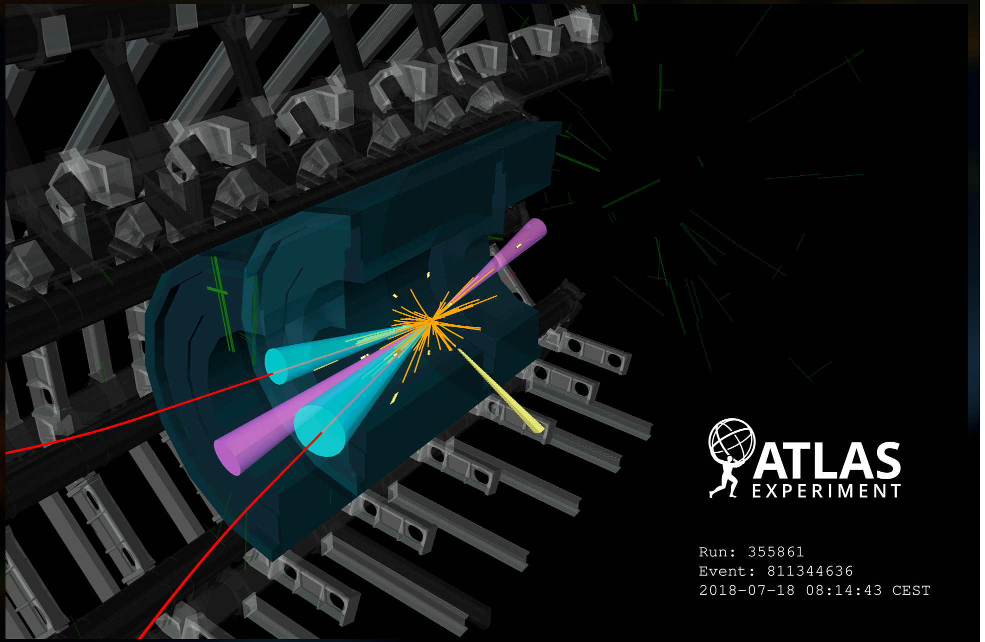


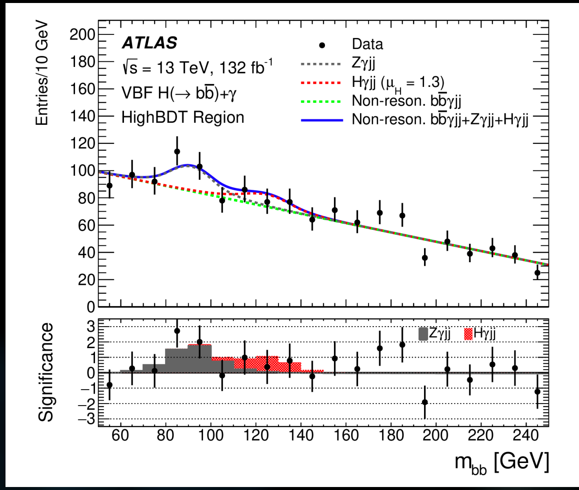


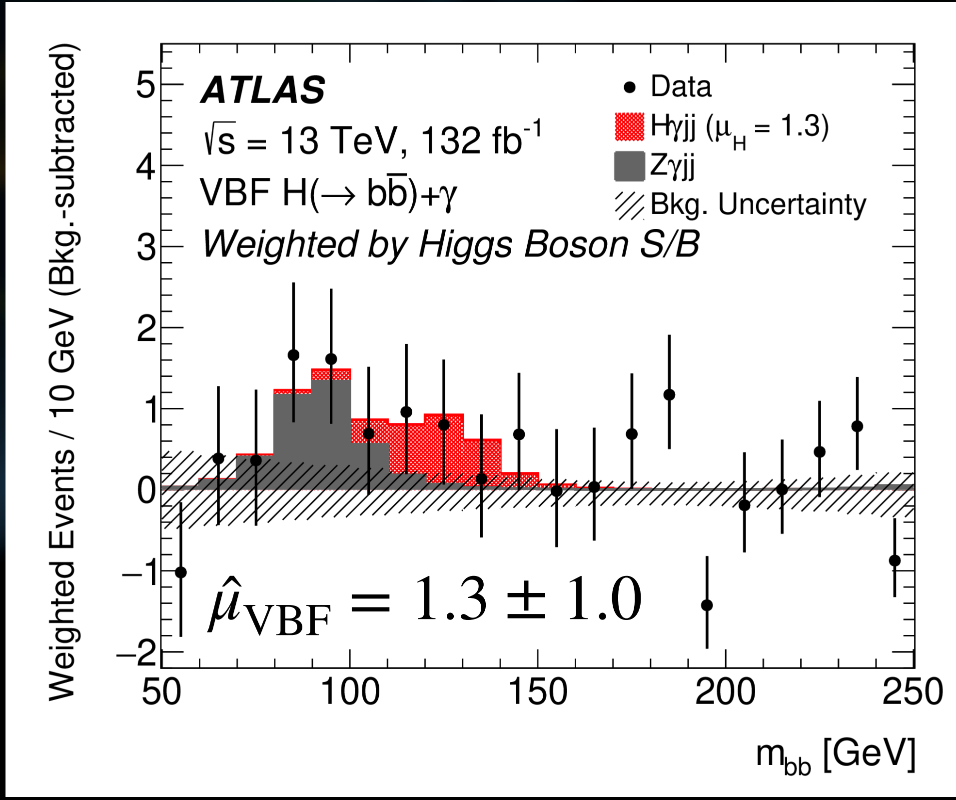
VBF H, H → $b\bar{b} + \gamma$

- Unique assess to WBF.
- Triggering on the photon at L1 leaves the rest of the system unbiased.
- HLT requires 1 photon and 3-4 jets.



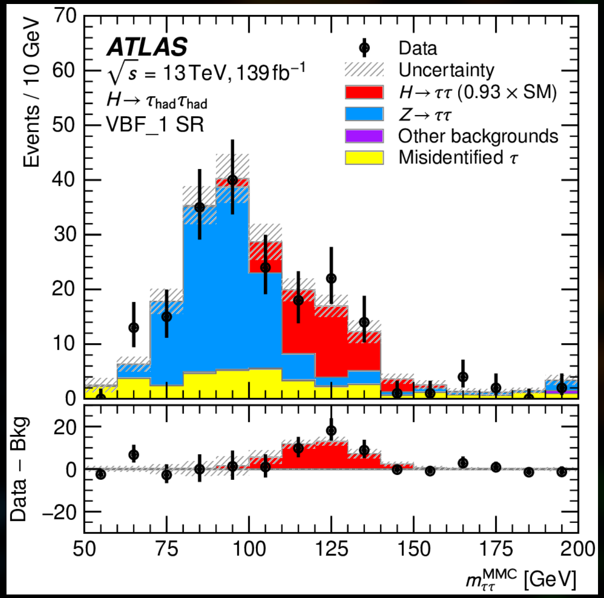


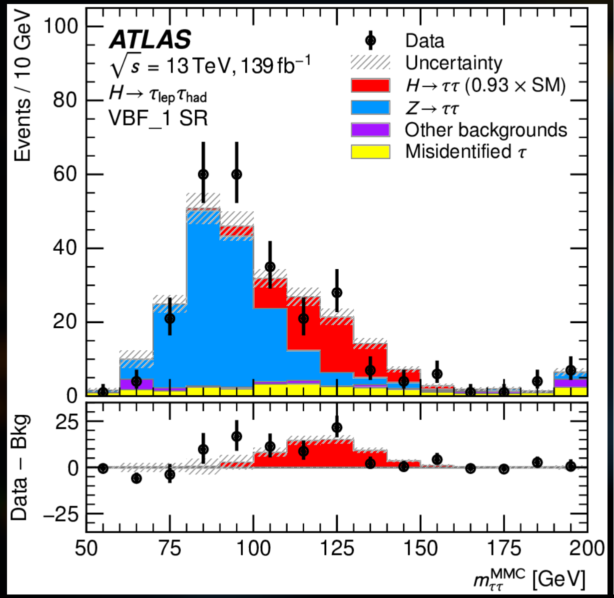


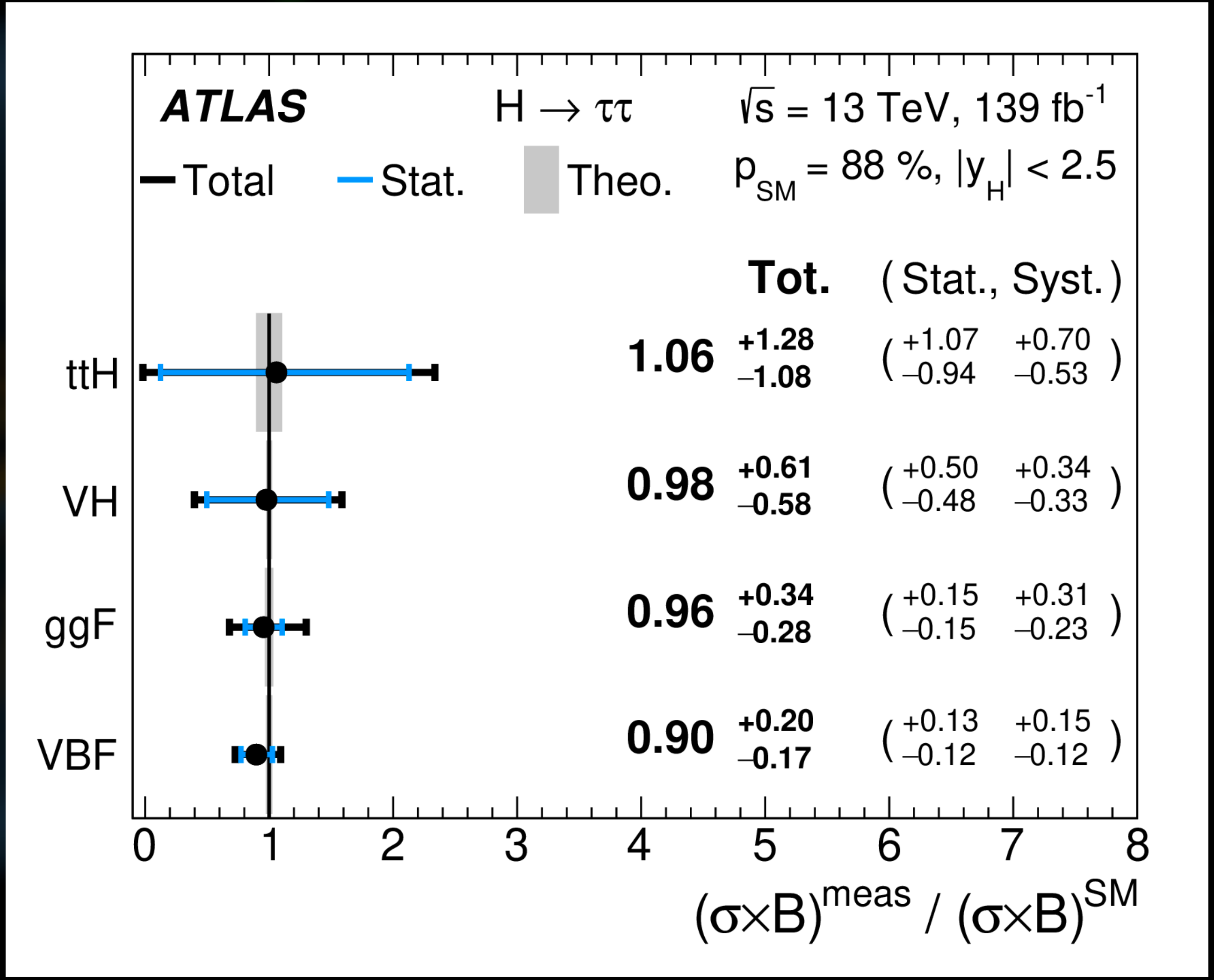


$\mathrm{H} \rightarrow \tau\bar{\tau}$

- Triggers rely on τ decay products.
  - Like $\mathrm{H} \rightarrow \gamma\gamma$ all production channels accessible to the analysis.
- VBF is one of the most sensitive.

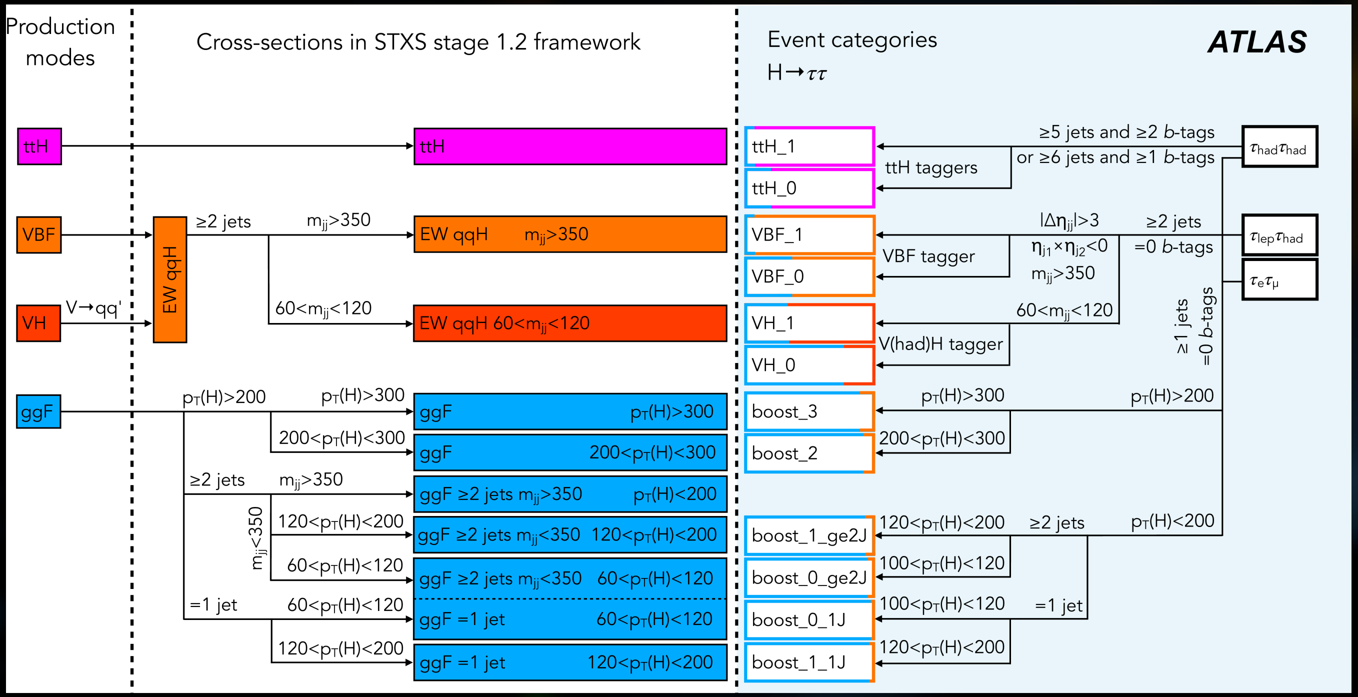


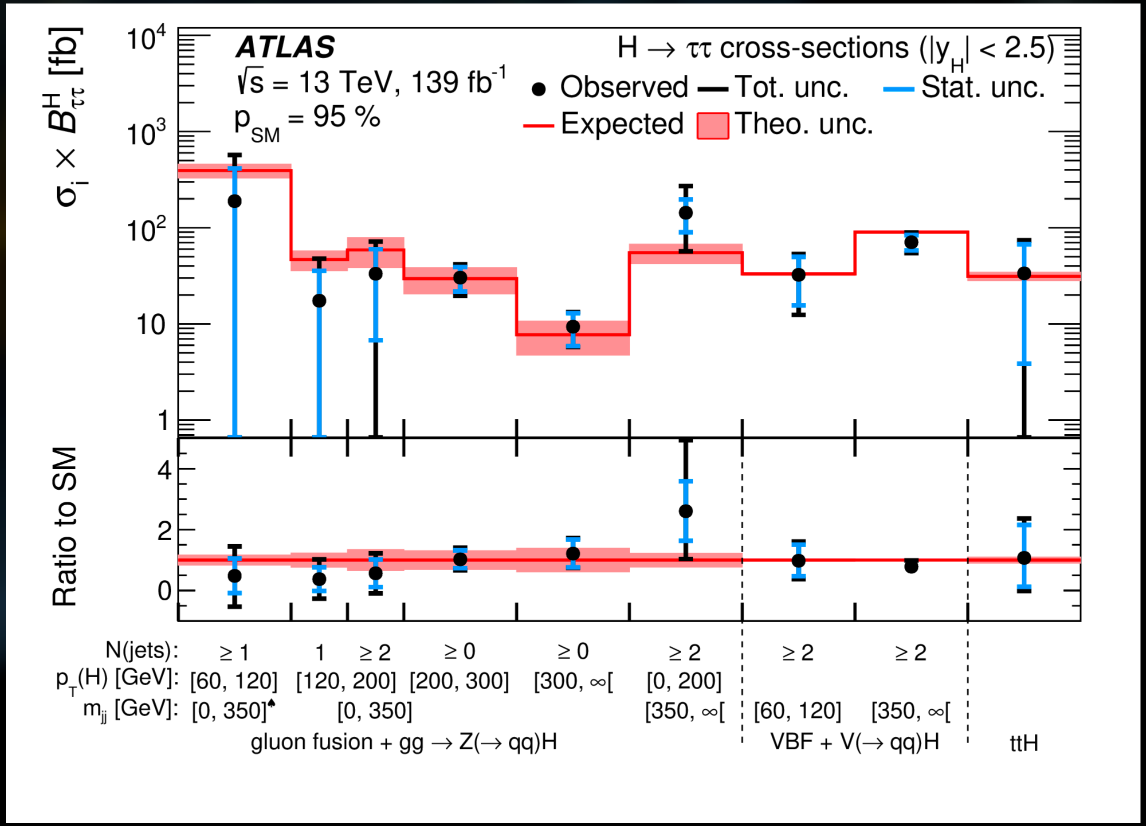




$H \to \tau\bar{\tau}$

- STXS categorization is rich and follows the reconstructed Higgs boson and production mode topologies.

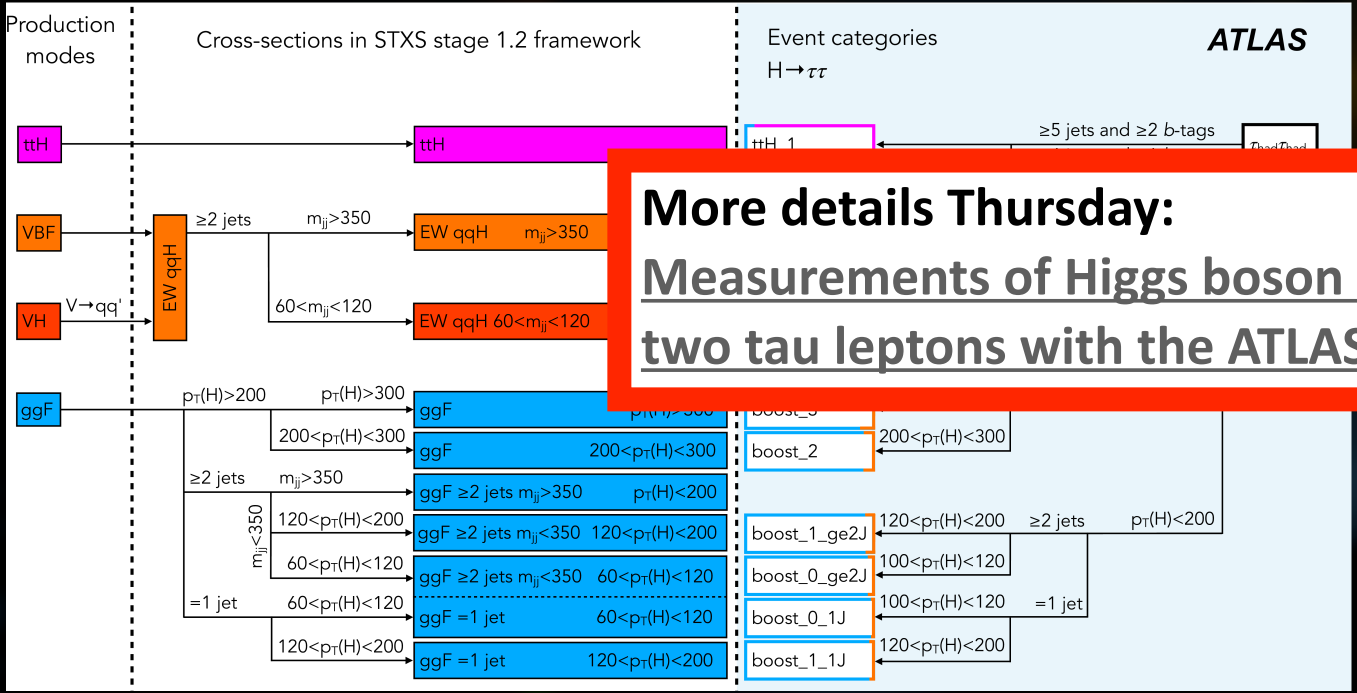


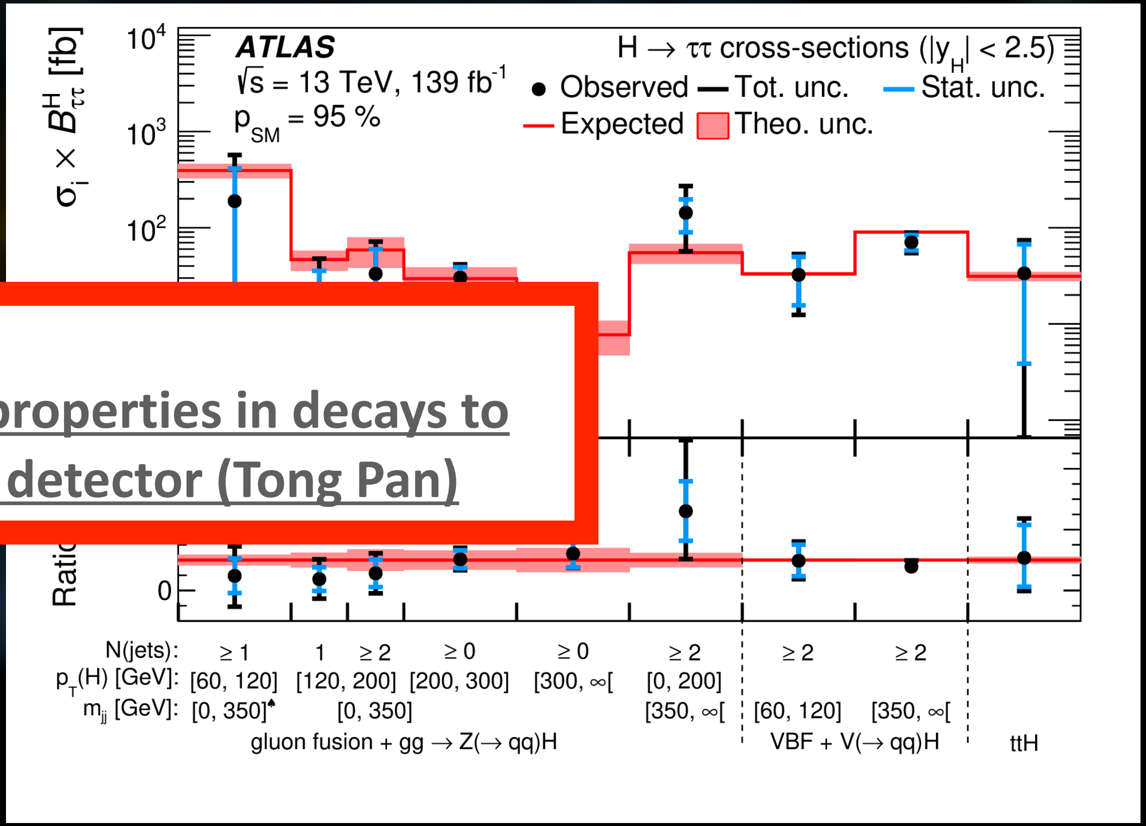


$H \rightarrow \tau\bar{\tau}$

ATLAS EXPERIMENT

- STXS categorization is rich and follows the reconstructed Higgs boson and production mode topologies.



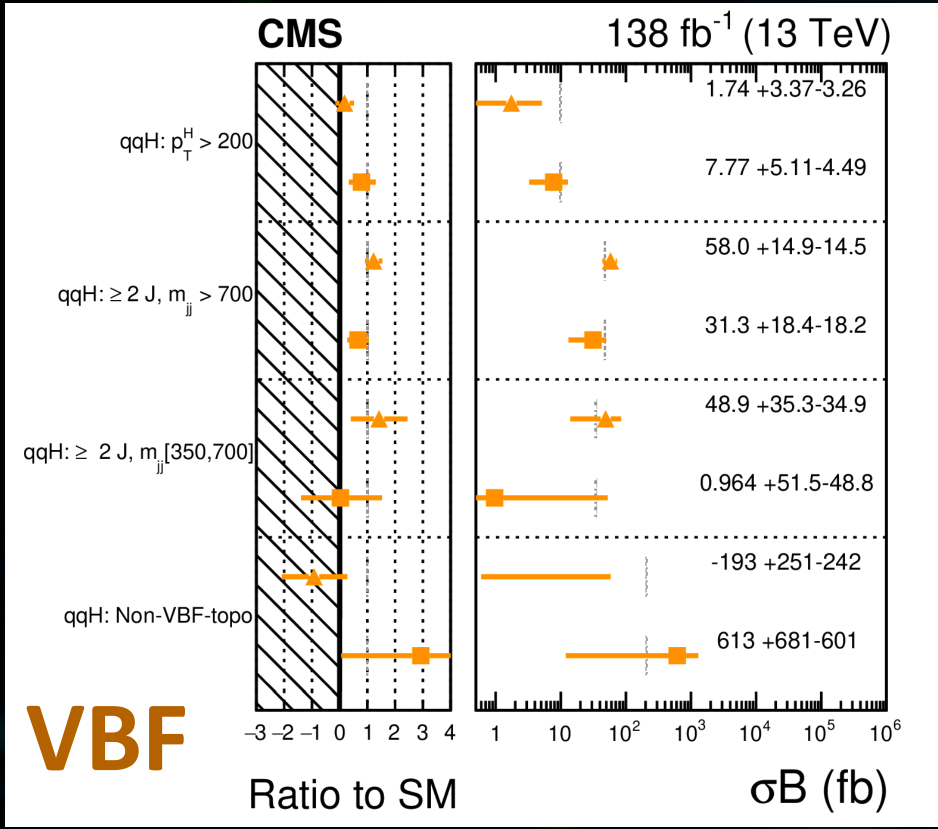


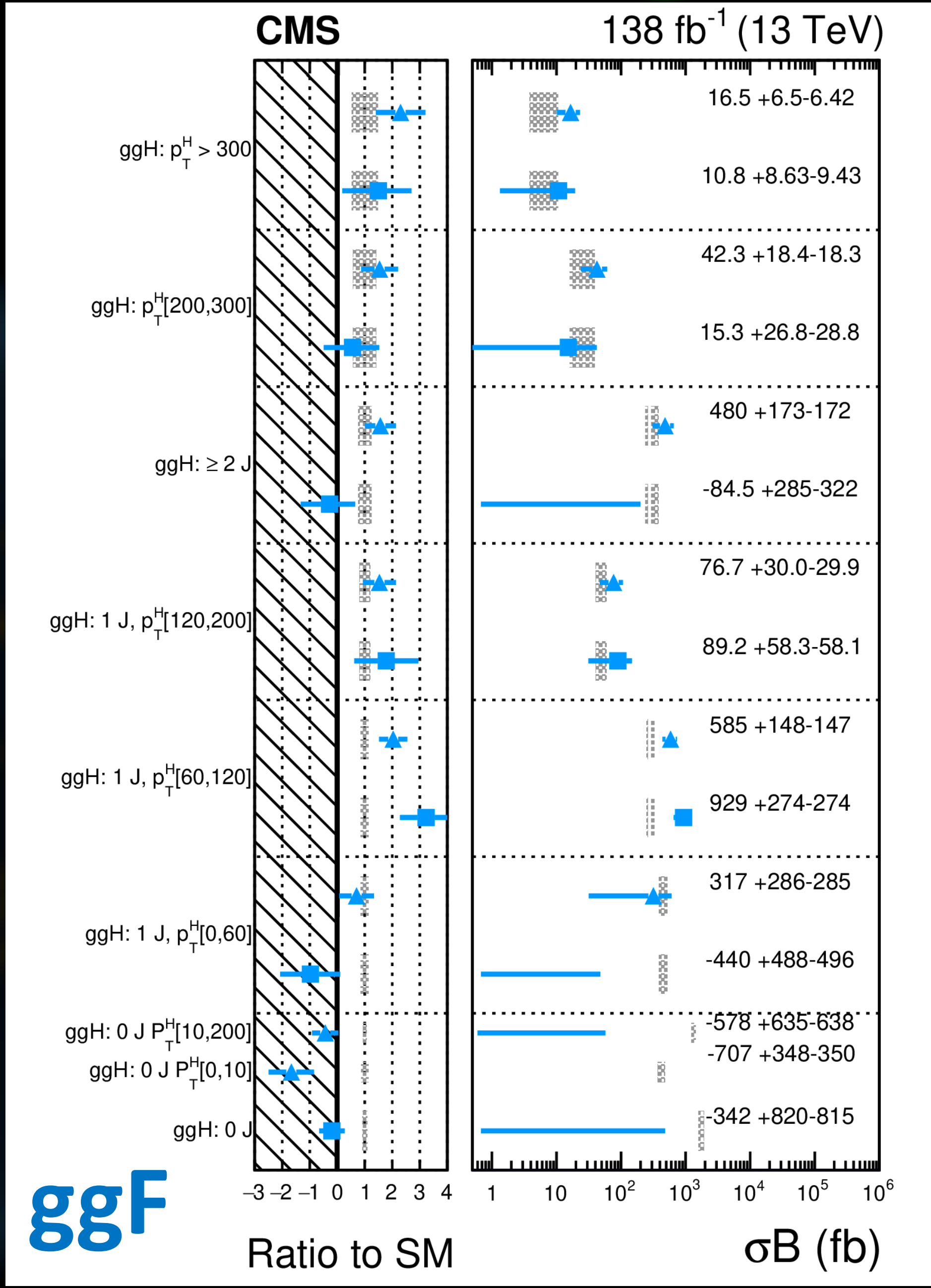
More details Thursday:

Measurements of Higgs boson properties in decays to two tau leptons with the ATLAS detector (Tong Pan)

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

- Cut-based cross check
  - $m_{\tau\tau}$ observable + categorization
- Neural network (main results)



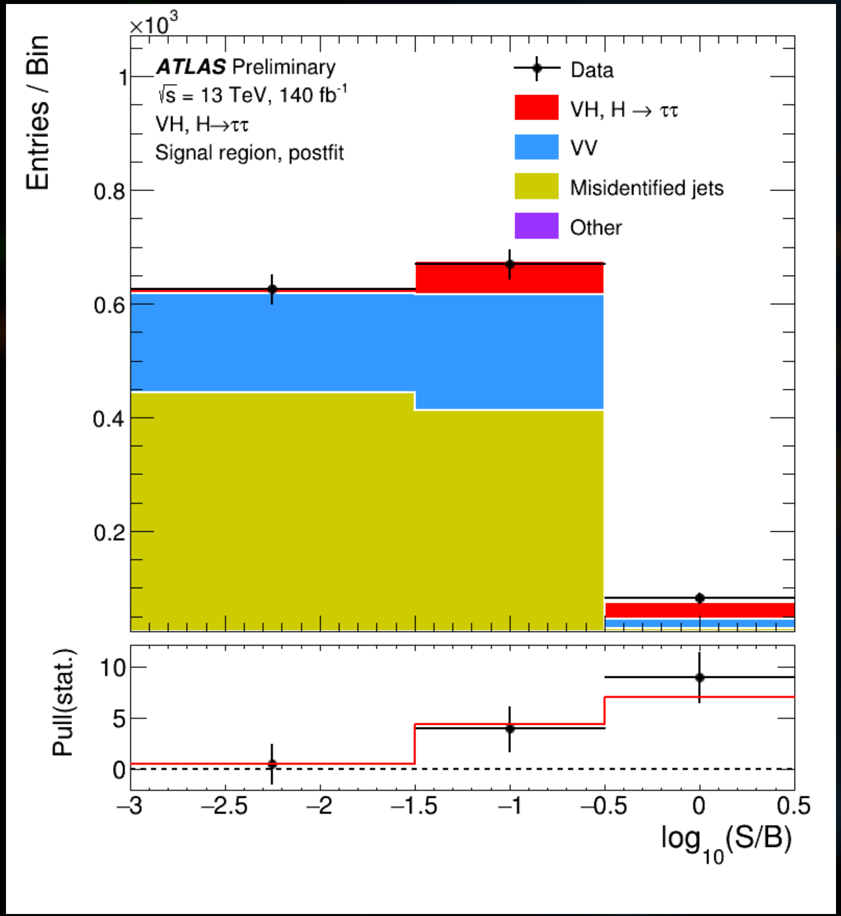


- STXS results in bins of Higgs p_T, 0 or 1 jets, and m_{jj} for VBF.
- CMS also has a dedicated $t\bar{t}H$, $H \to \tau\tau$ analysis.

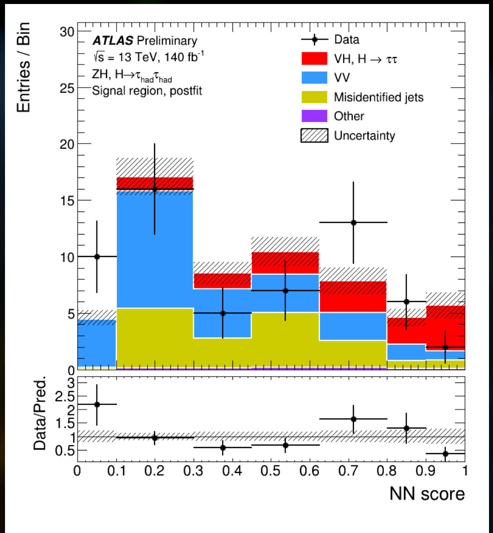
HIG-19-010 (ggH, VBF, VH)
HIG-19-008 (ttH)

VH, H → $\tau\bar{\tau}$, NN

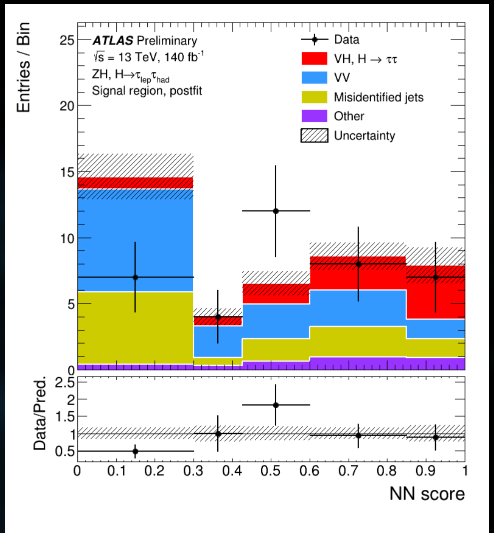
- Z/W leptonic decays + $\tau_{Lep}\tau_{Had}$ OR $\tau_{Had}\tau_{Had}$
- NN and mass-fit analyses



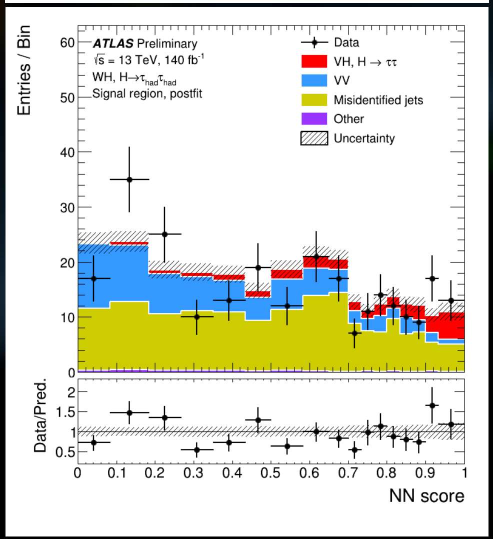
ZH $\tau_{Had}\tau_{Had}$



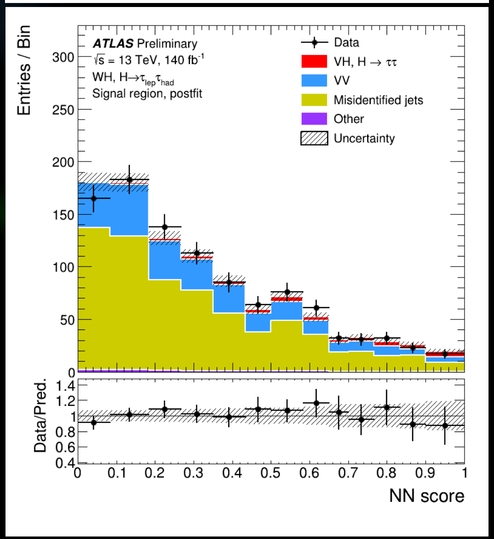
ZH $\tau_{Had}\tau_{Lep}$



WH $\tau_{Had}\tau_{Had}$



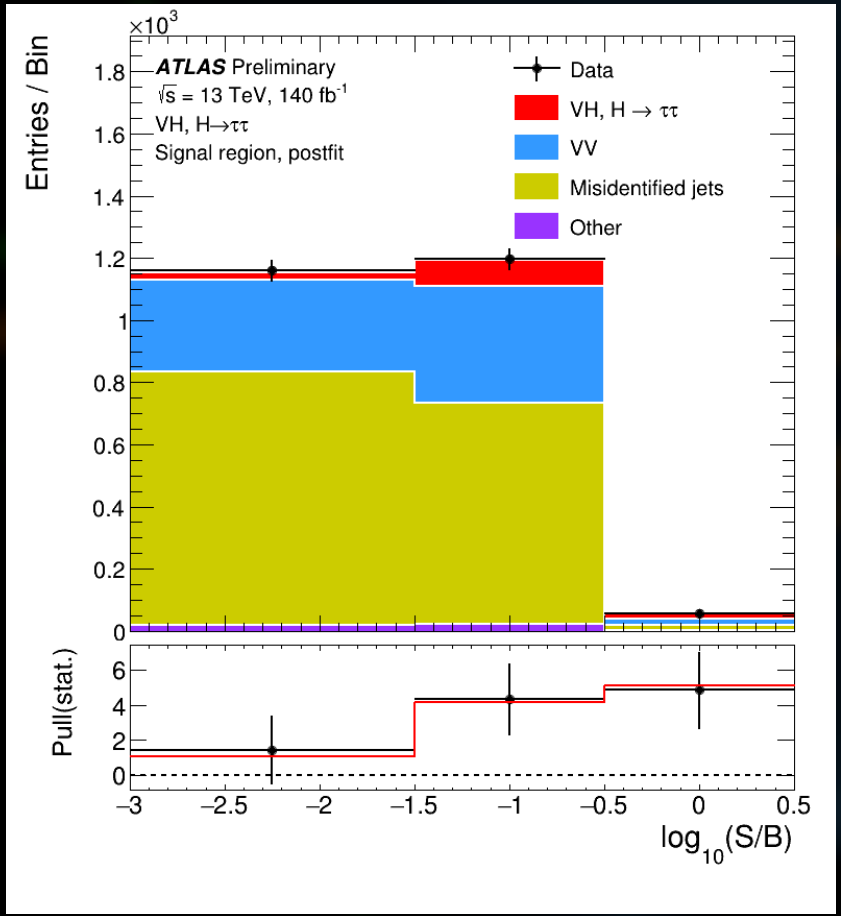
WH $\tau_{Had}\tau_{Lep}$



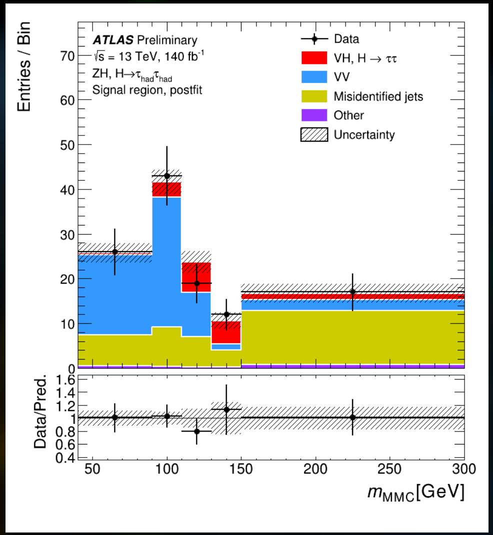
VH, H $\rightarrow \tau\bar{\tau}$, Mass NEW

ATLAS EXPERIMENT

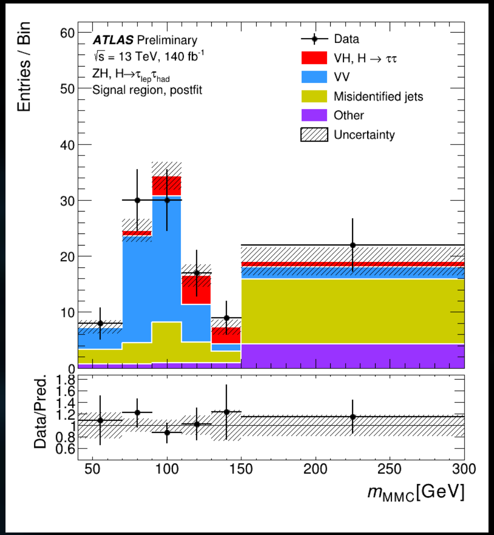
- Z/W leptonic decays + $\tau_{\mathrm{Lep}}\tau_{\mathrm{Had}}$ OR $\tau_{\mathrm{Had}}\tau_{\mathrm{Had}}$
- NN and mass-fit analyses



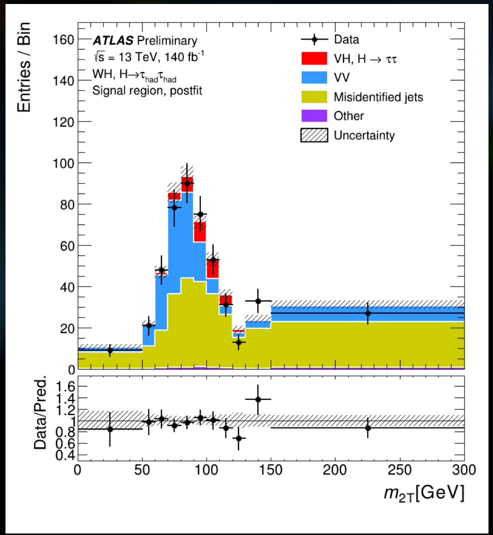
$\mathrm{ZH}\tau_{\mathrm{Had}}\tau_{\mathrm{Had}}$



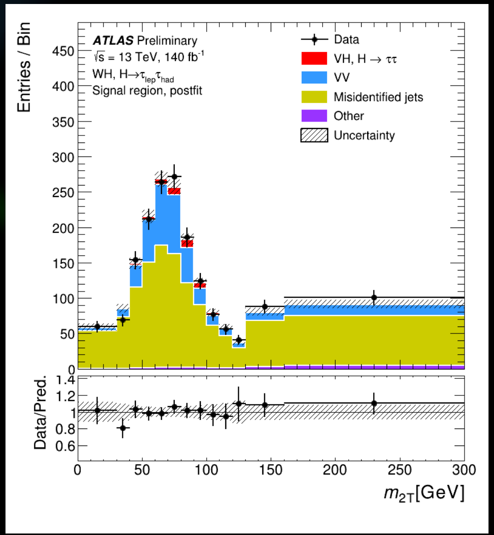
$\mathrm{ZH}\tau_{\mathrm{Had}}\tau_{\mathrm{Lep}}$



$\mathrm{WH}\tau_{\mathrm{Had}}\tau_{\mathrm{Had}}$



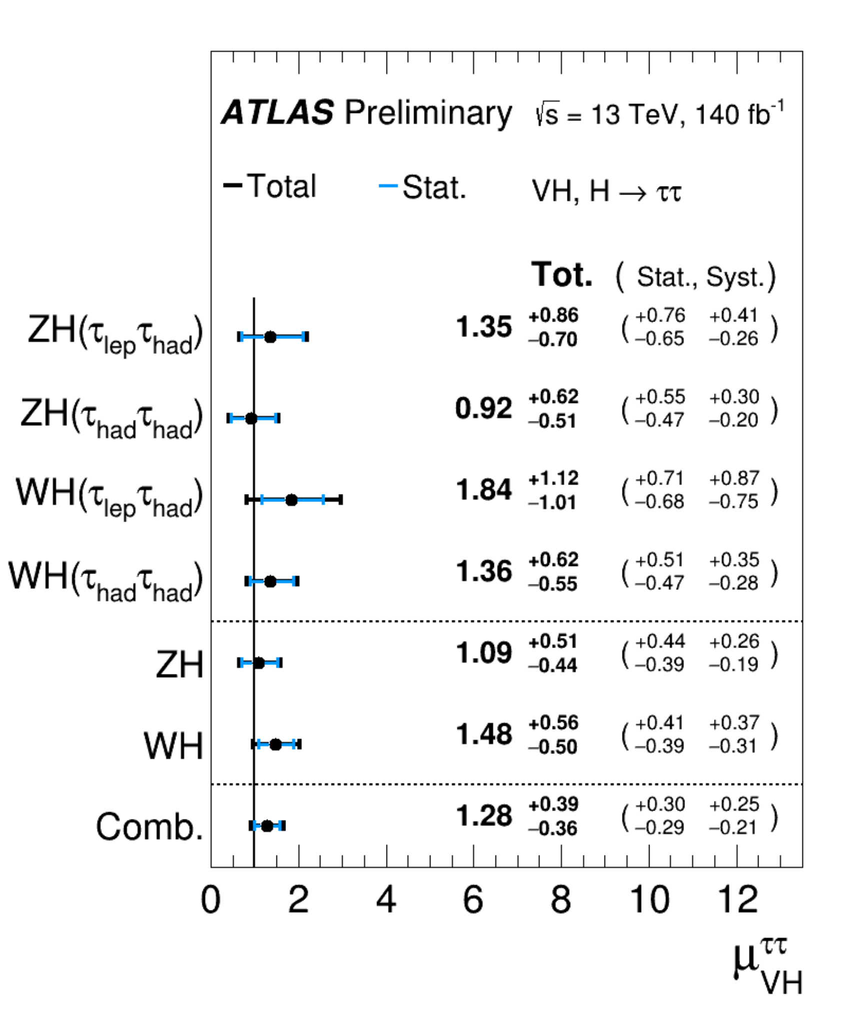
$\mathrm{WH}\tau_{\mathrm{Had}}\tau_{\mathrm{Lep}}$



VH, H → $\tau\bar{\tau}$

- NN and mass-fit analyses
- Evidence-level signal!

Significance (σ)	exp	obs
WH	2.2	3.3
ZH	2.9	2.8
Combined	3.6	4.2

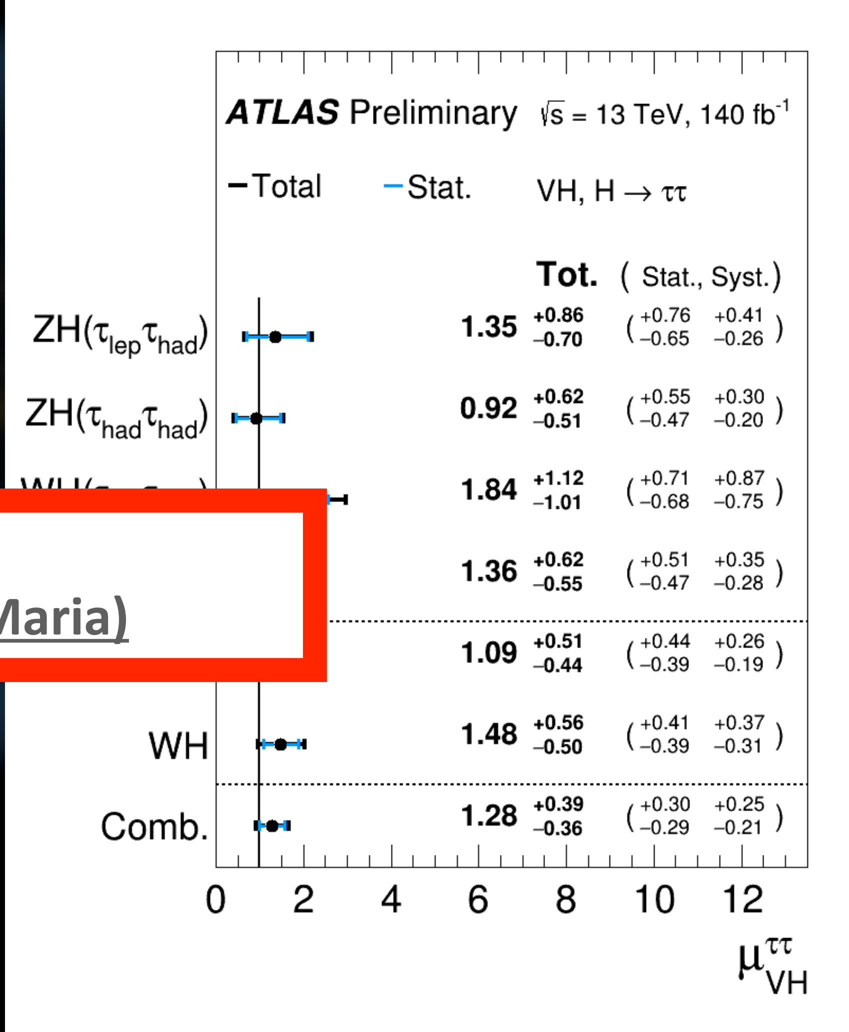


VH, H → $\tau\bar{\tau}$

- NN and mass-fit analyses
- Evidence-level signal!

Significance (σ)	exp	obs
WH		
ZH	2.9	2.8
Combined	3.6	4.2

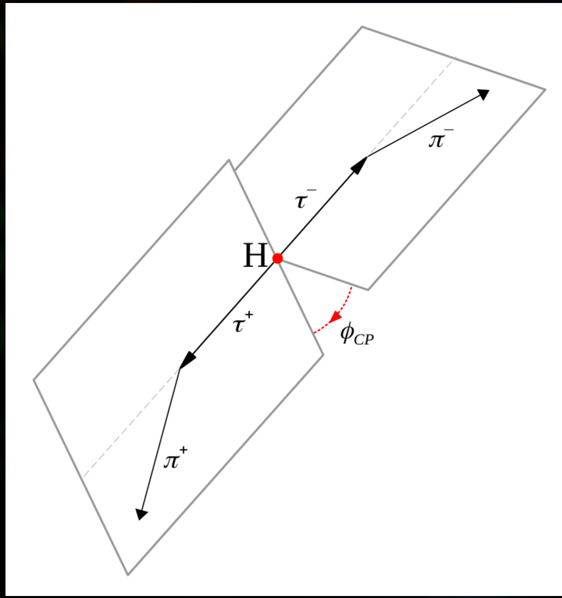
More details early today:
[Searches with H->ττ at ATLAS (Antonio De Maria)]



CP Violation and Anomalous Coupling Searches

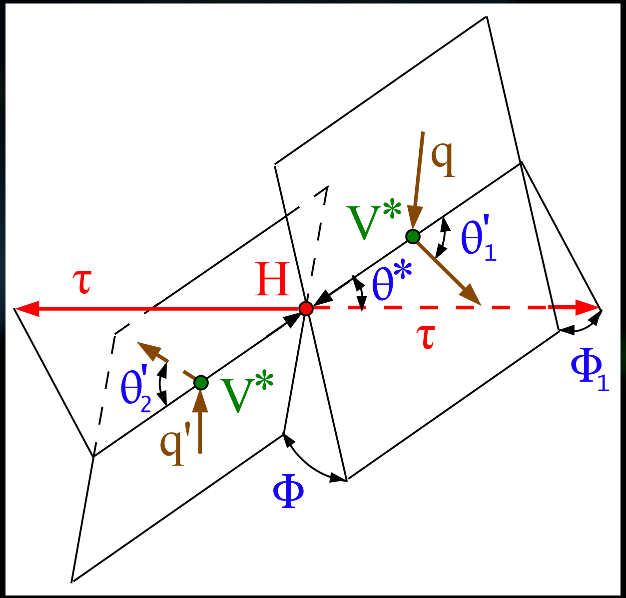
ATLAS EXPERIMENT

- $t\bar{t}H, H \rightarrow b\bar{b}$, HIGG-2020-03
- $t\bar{t}H, H \rightarrow \gamma\gamma$, HIGG-2019-01
- $H \rightarrow \tau\tau$, HIGG-2019-10



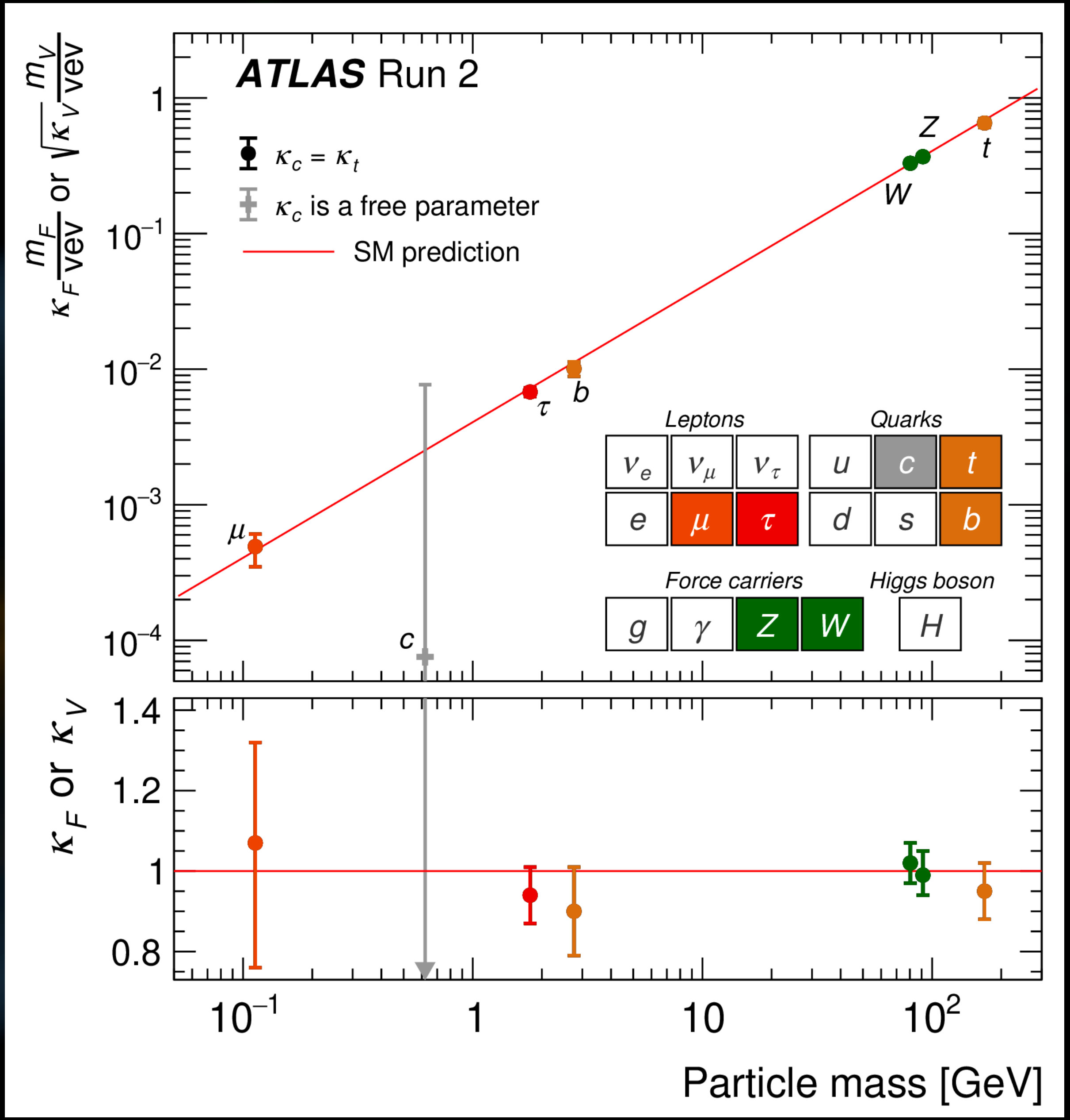
CMS

- $t\bar{t}H/tH, H \rightarrow$ multilepton, HIG-21-006
- $t\bar{t}H, H \rightarrow \gamma\gamma$, HIG-19-013
- $H \rightarrow \tau\tau$, HIG-20-006 HIG-20-007



Summary

- Higgs boson couplings to third generation fermions are firmly established by both ATLAS and CMS.
- Now efforts focus on differential measurements, more niche signals, and refining techniques as we head toward HL-LHC.
- Full Yukawa agenda this week including two session on the frontiers of couplings.
  - [Yukawa 1 - Tuesday Morning]
  - [Yukawa 2 - Tuesday Mid-day]



https://www.nature.com/articles/s41586-022-04893-w

Thank you! Questions?

VH, H → $\tau\bar{\tau}$

NEW

- Mass-fit

	$\mu_{VH}^{\tau\tau}$ obs	Significance exp	Significance obs
WH	$1.27^{+0.80}_{-0.75}$	1.4	1.7
ZH	$1.46^{+0.61}_{-0.53}$	2.2	3.1
Combined	$1.40^{+0.49}_{-0.45}$	2.5	3.5

- NN

Significance (σ)	exp	obs
WH	2.2	3.3
ZH	2.9	2.8
Combined	3.6	4.2