QCD@LHC-X 2020, online
2 September 2020

Status of SM Higgs measurements and searches for BSM Higgs

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on behalf of the ATLAS and CMS Collaborations

Disclaimers & outline

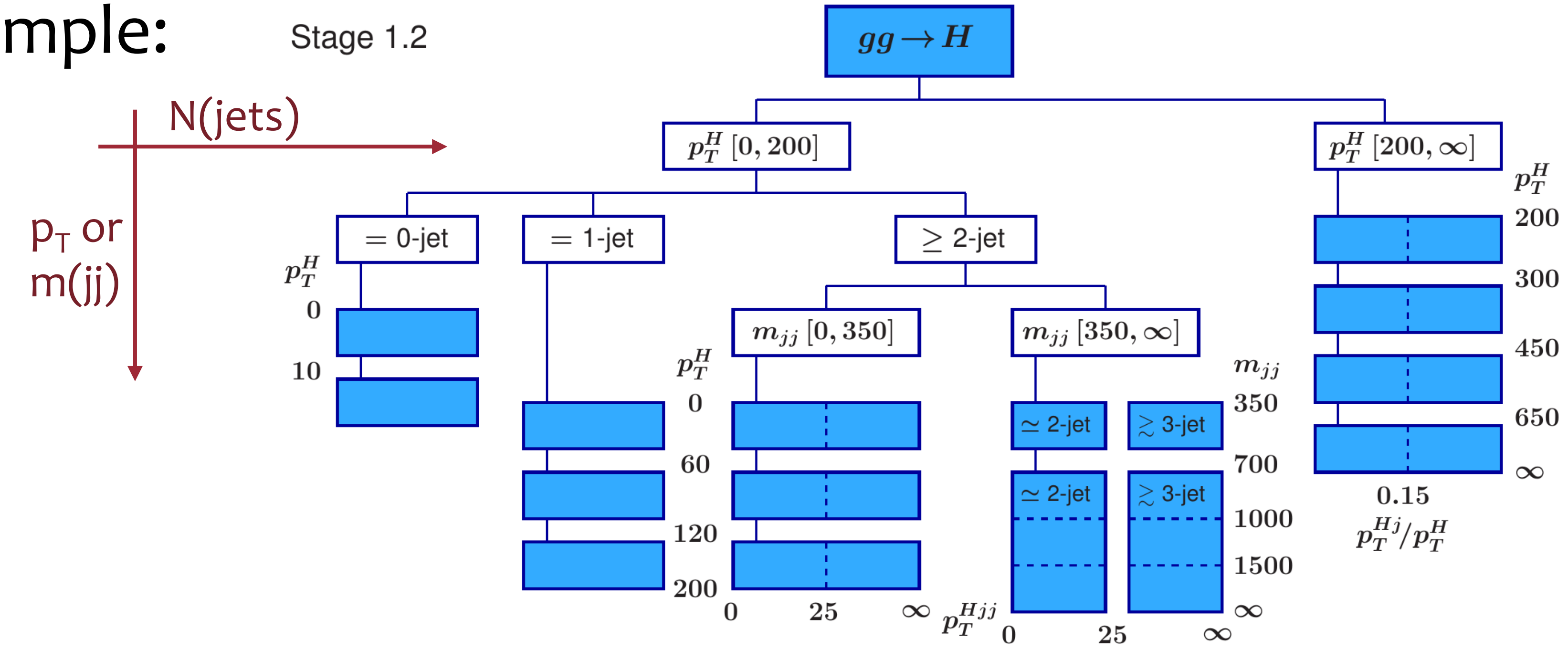
- There's by far too many recent SM measurements and BSM searches to be able to review all of them in a single talk
  - Some I will review very briefly or just advertise, and some I will skip (more information in the slides, backup, and linked documentation)
  - I will focus mostly on measurements, privileging importance over novelty
  - Only results with full LHC run 2 dataset

New (Summer '20)

Cross sections (STXS, Differential)	Other topical measurements	Couplings, EFT, CP	BSM
γγ STXS & Diff.	**H → μμ**	**Comb. κ,**	VBF H → inv.
ZZ STXS & Diff.	H → Zγ	**EFT STXS bb**, ZZ	**H_{BSM} → ZZ**
WW Diff.	**VBF H → WW**	**EFT & AC ZZ**	**H_{BSM} → γγ**
ττ STXS	**ttH multilep.**	CP ttH, H → gg	
bb STXS		**CP H → ττ decay**	
Comb STXS			

Simplified Template Cross Sections (STXS)

- Split Higgs production modes in gen-level bins in p_T, N(jets), m_{jj}
  - Assume within each bin SM kinematics is a good proxy for the true physics
  - Allow re-interpretation of results in different models (e.g. EFT) or with different assumptions (e.g. on theory uncertainties)
- Example:



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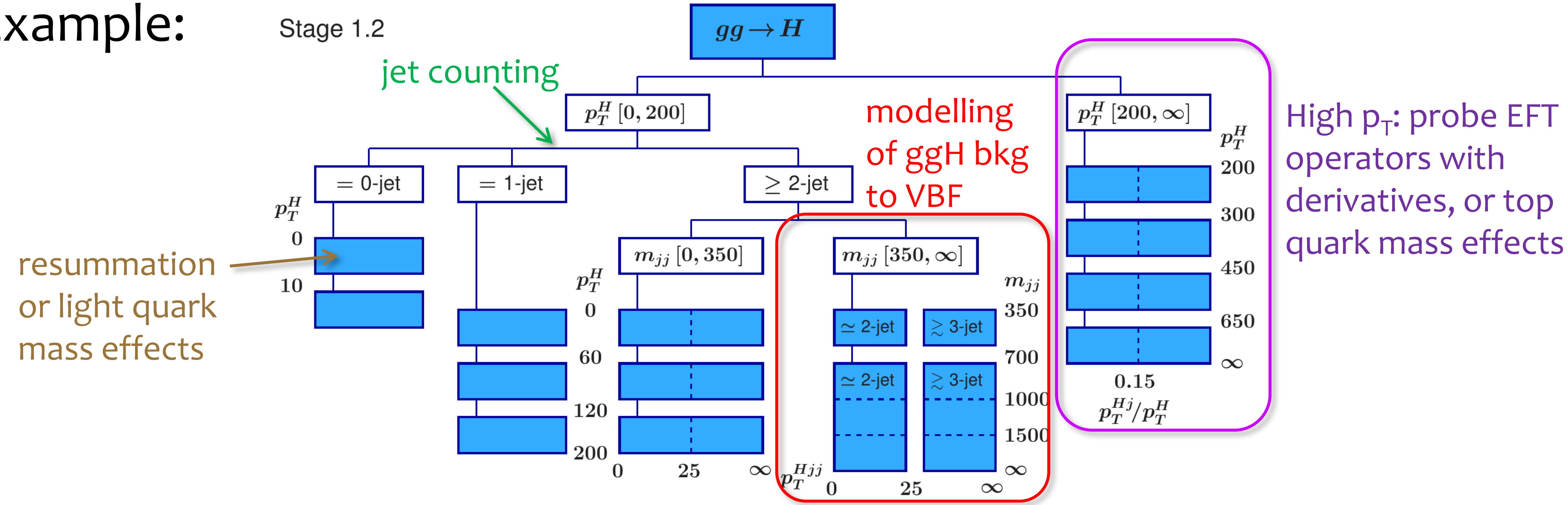
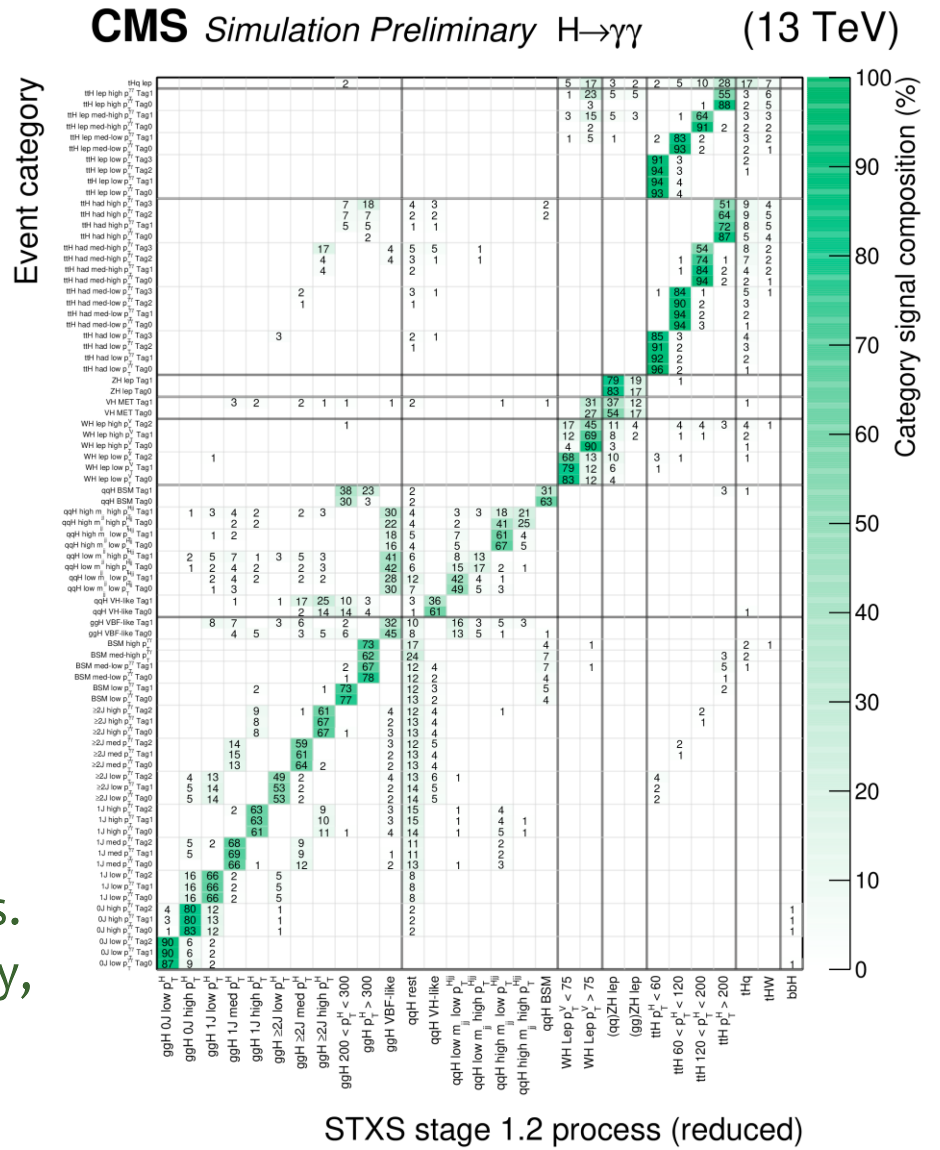


$H \to \gamma\gamma$: STXS

- $H \to \gamma\gamma$ very well suited to STXS measurements:
  - yields, efficiency and S/B across whole phase space
  - robust background estimation from $m(\gamma\gamma)$
- Full LHC Run 2 dataset, targeting all productions: ggH, VBF, WH, ZH, ttH, tH
  - including first ttH measurements differential in $p_T(H)$
- Similar overall strategy deployed:
  1. First level categorization associated to STXS bins, often employing MVAs to improve classification accuracy.
  2. MVAs to splitting in subcategories to improve S/B,
  3. Signal extraction by fitting $m(\gamma\gamma)$ shape in all categories.
  4. Fit together STXS bins that can't be resolved individually, at times merging also the associated categories.



$H \rightarrow \gamma\gamma$ STXS categorization

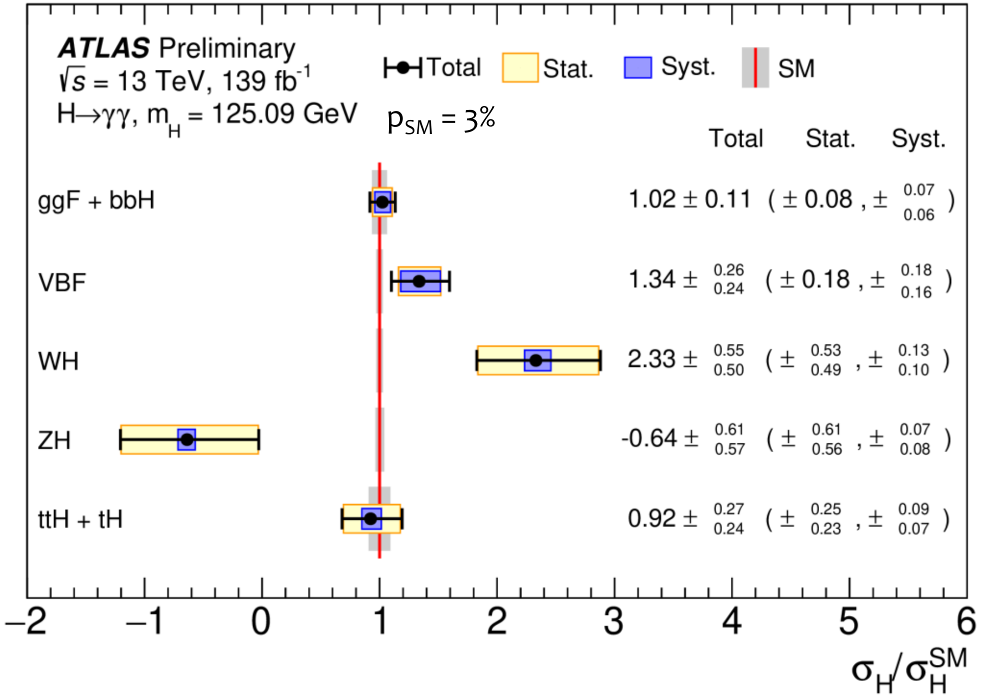
ATLAS EXPERIMENT

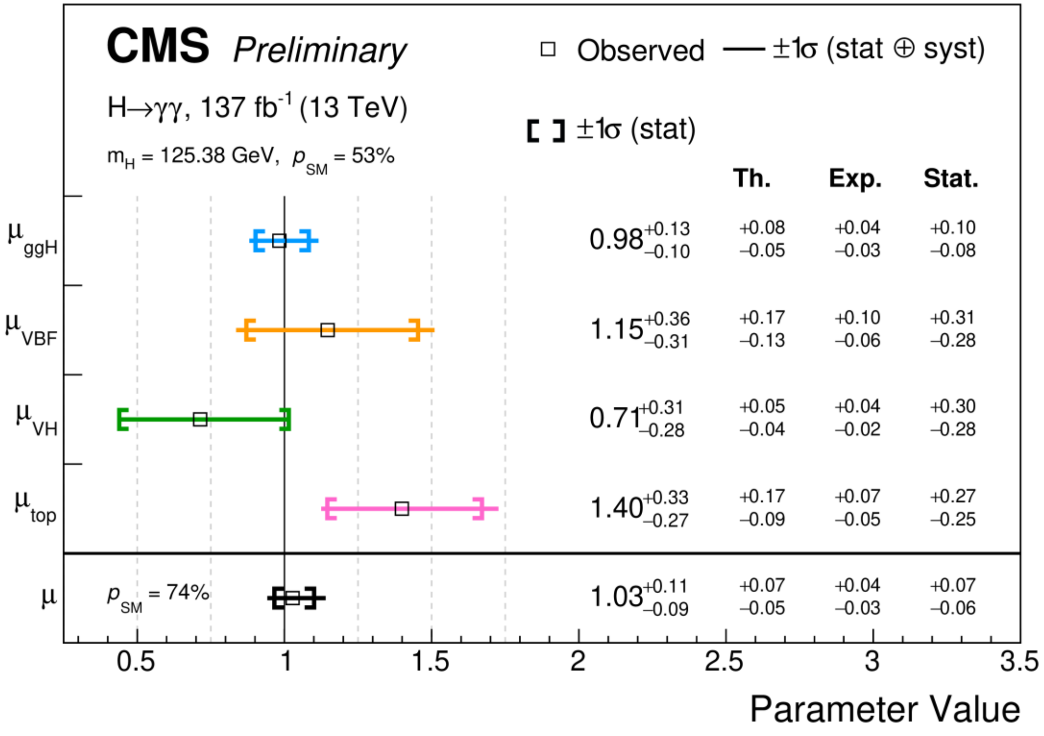
- Multiclass BDT trained on all STXS bins (44 classes), using full event information (photons, jets, b-tags, leptons, tagged top quarks, …)
  - Compute per event probabilities z_i for each class ($\Sigma z_i = 1$)
  - Assign events to category with max weighted probability $w_i \cdot z_i$
  - Weights w_i optimized to minimize the determinant of the covariance matrix of the fit

CMS

- Groups of categories designed for each production mode
  - Multiclass BDT for VBF-like events (qqH vs ggH vs background)
  - Multiclass BDT for ggH SXTS bins except p_T>200 GeV & VBF-like ones
  - Dedicated MVAs also in other categories, e.g. tHq vs ttH
- Event assigned to the highest priority category that accepts it
  - tHq(lep), ttH(lep), ZH(2ℓ), WH(1ℓ), VH(0ℓ), ttH(had), VBF, VH(had), ggH

H → γγ STXS stage 0 results

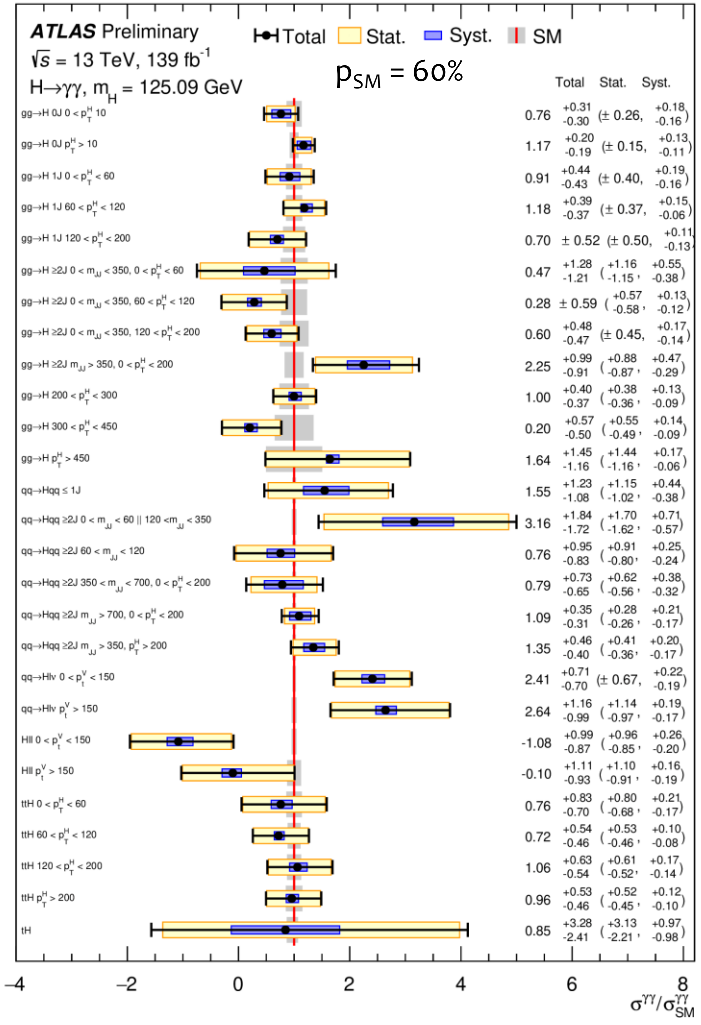


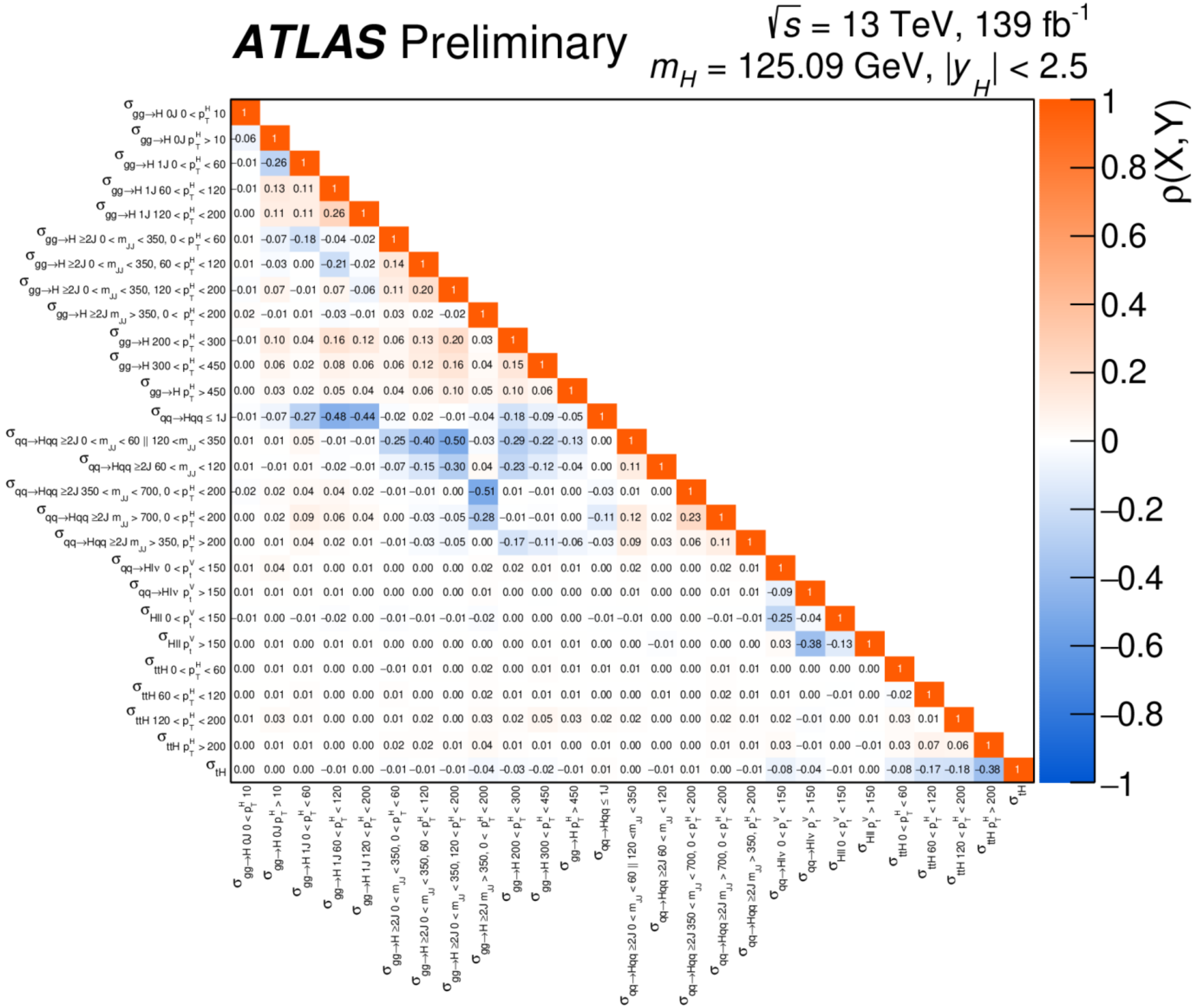


μ(WH) & μ(ZH) anti-correlated, ρ = −0.41

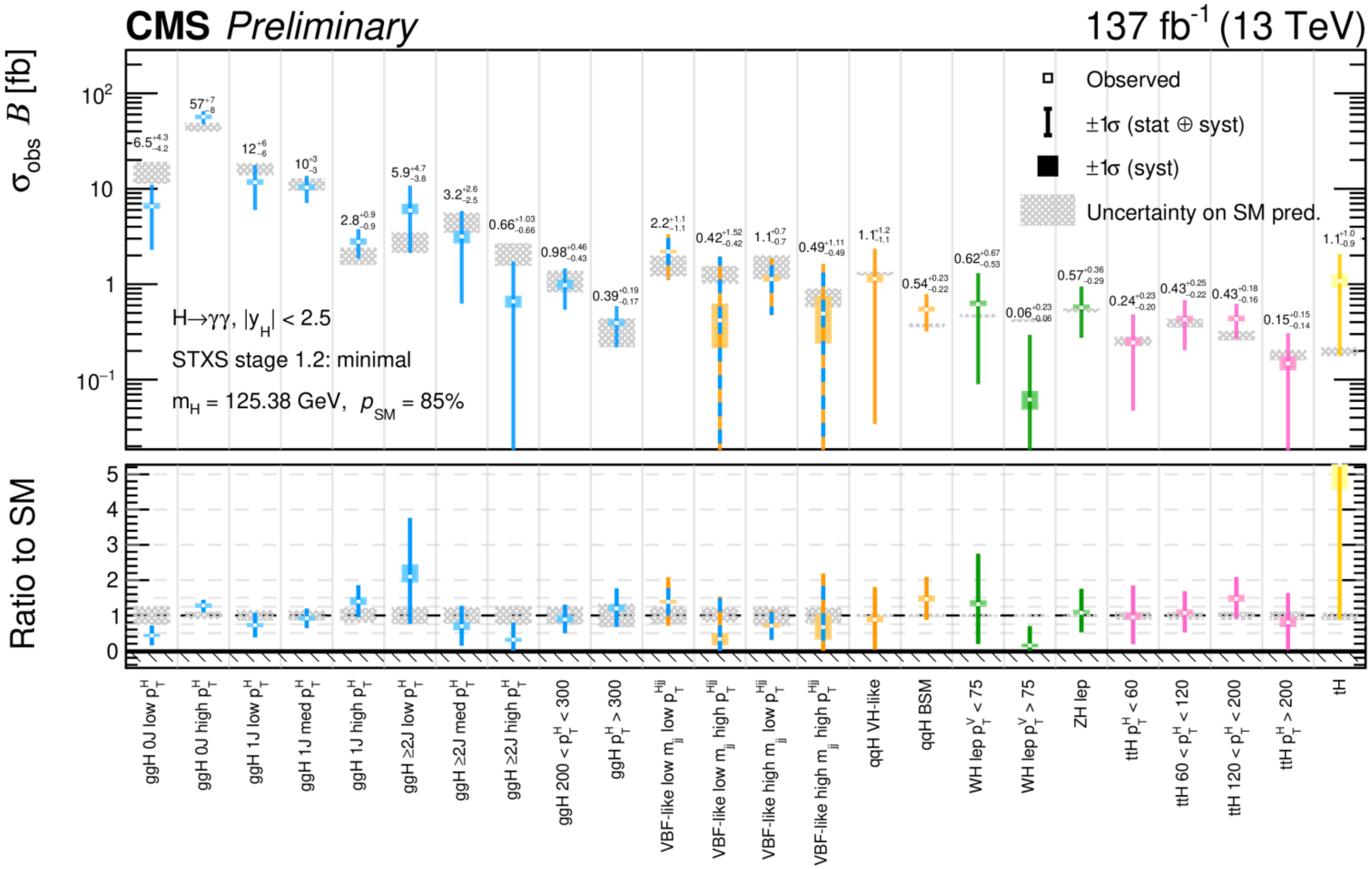
When using the same parameter for both, the fit gives μ(VH) = 1.3 ± 0.3 and overall p_{SM} = 50%

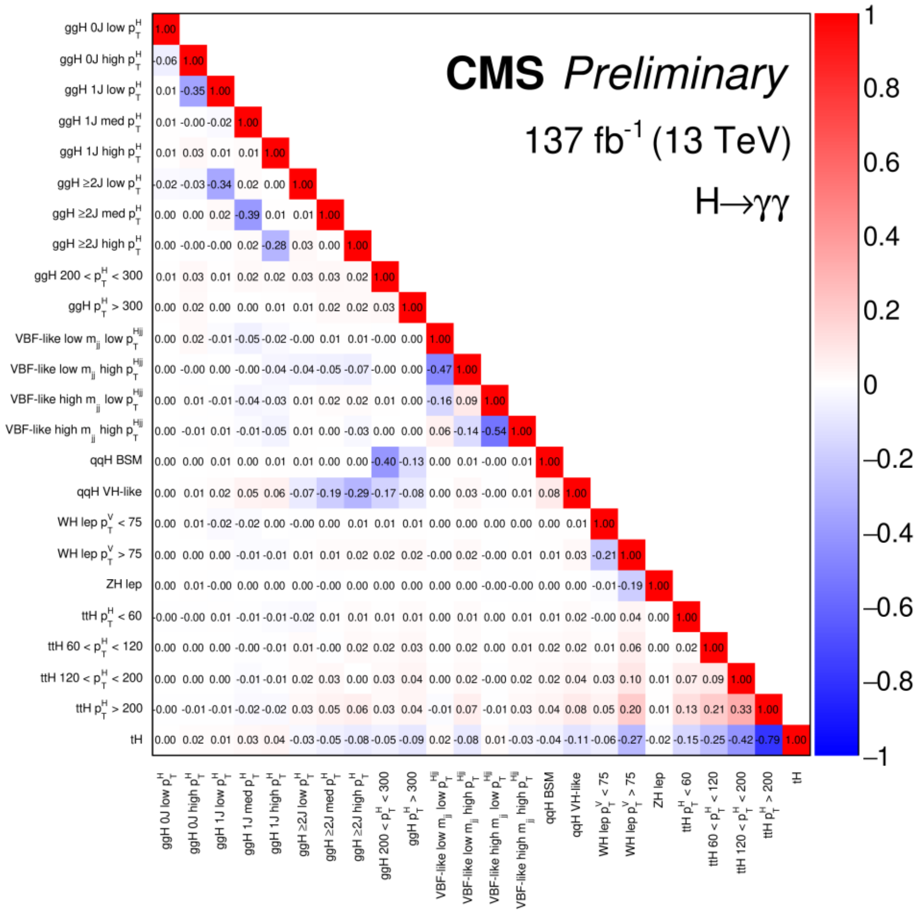
$H \rightarrow \gamma\gamma$ STXS results, ATLAS (27 params)





H → γγ STXS results, CMS (24 params)



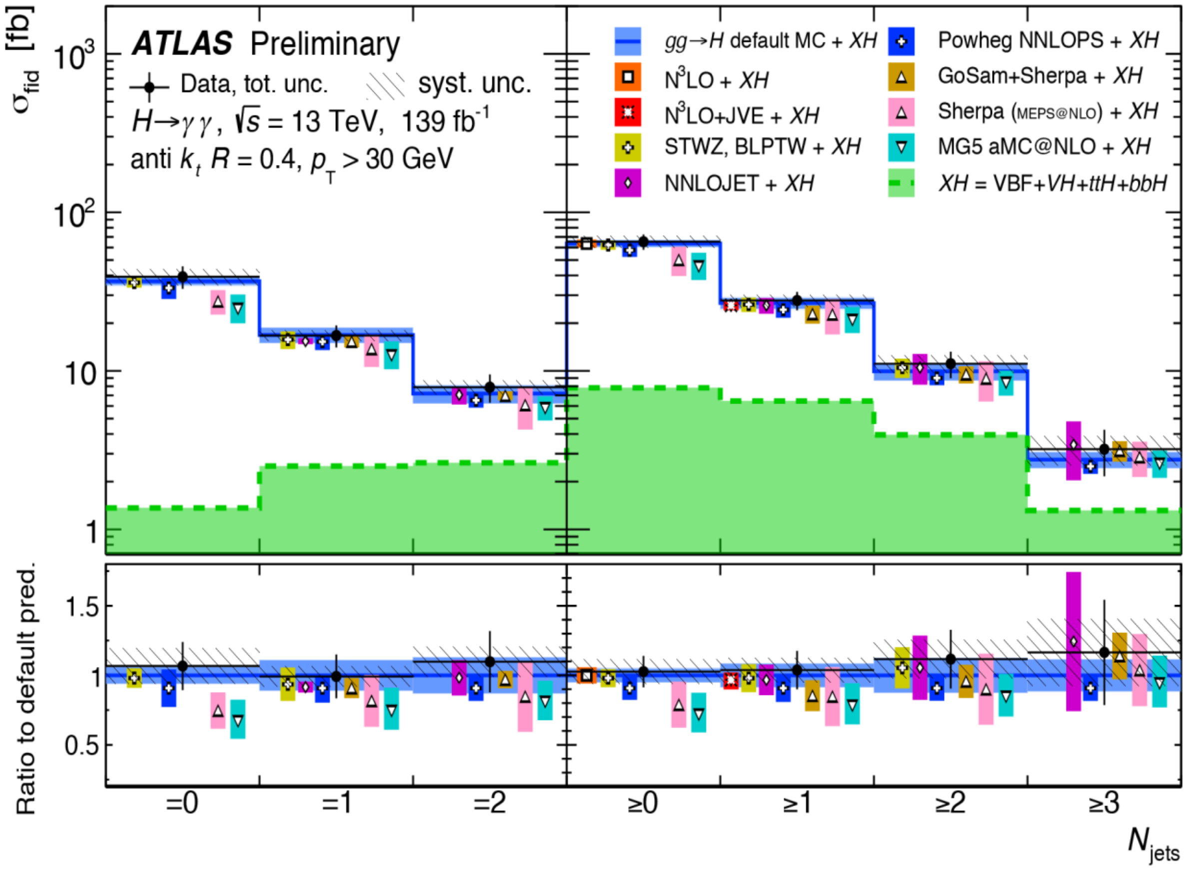


$H \to \gamma\gamma$ differential & fiducial

- First $H \to \gamma\gamma$ differential result on full run 2 data from ATLAS
  - Focus on few key distributions: $p_T(H)$, $y(H)$, N(jets), $p_T(j1)$, m(jj), $\Delta\varphi(jj)$
  - Unfolding via bin-by-bin corrections. Matrix unfolding used as cross-check
  - For reinterpretation, covariance matrix across bins of different distributions is provided (extracted from bootstrap)
- Fiducial cross section:

$\sigma_{fid} = 65.2 \pm 4.5^{(stat.)} \pm 5.6^{(syst.)} \pm 0.3^{(th.)}$ fb (11%)

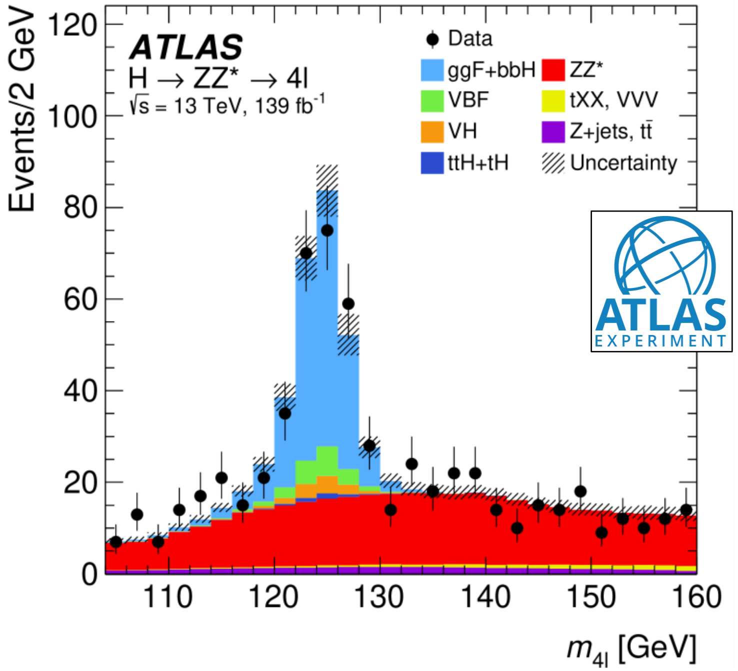
SM prediction 63.6 ± 3.3 fb

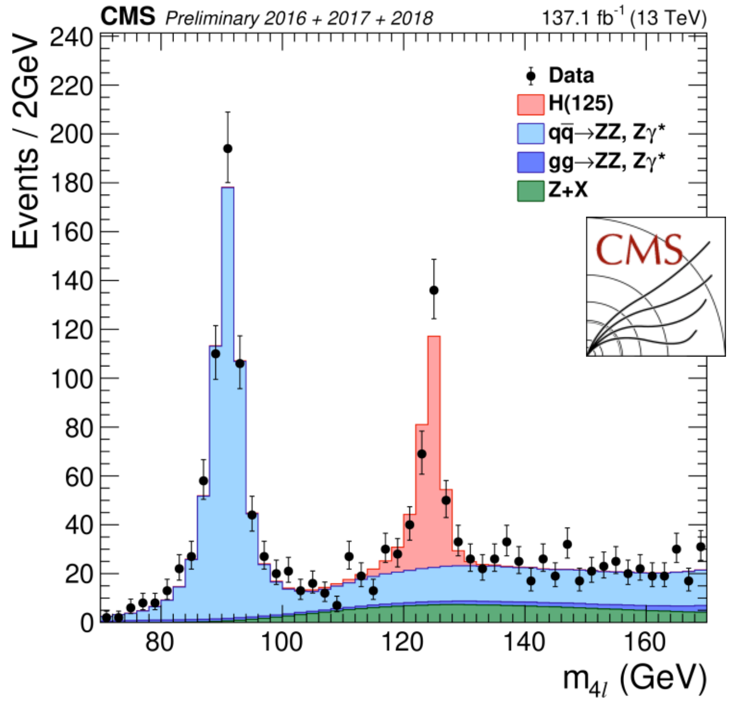


arXiv:2004.03447 (EPJC)
CMS PAS HIG-19-001

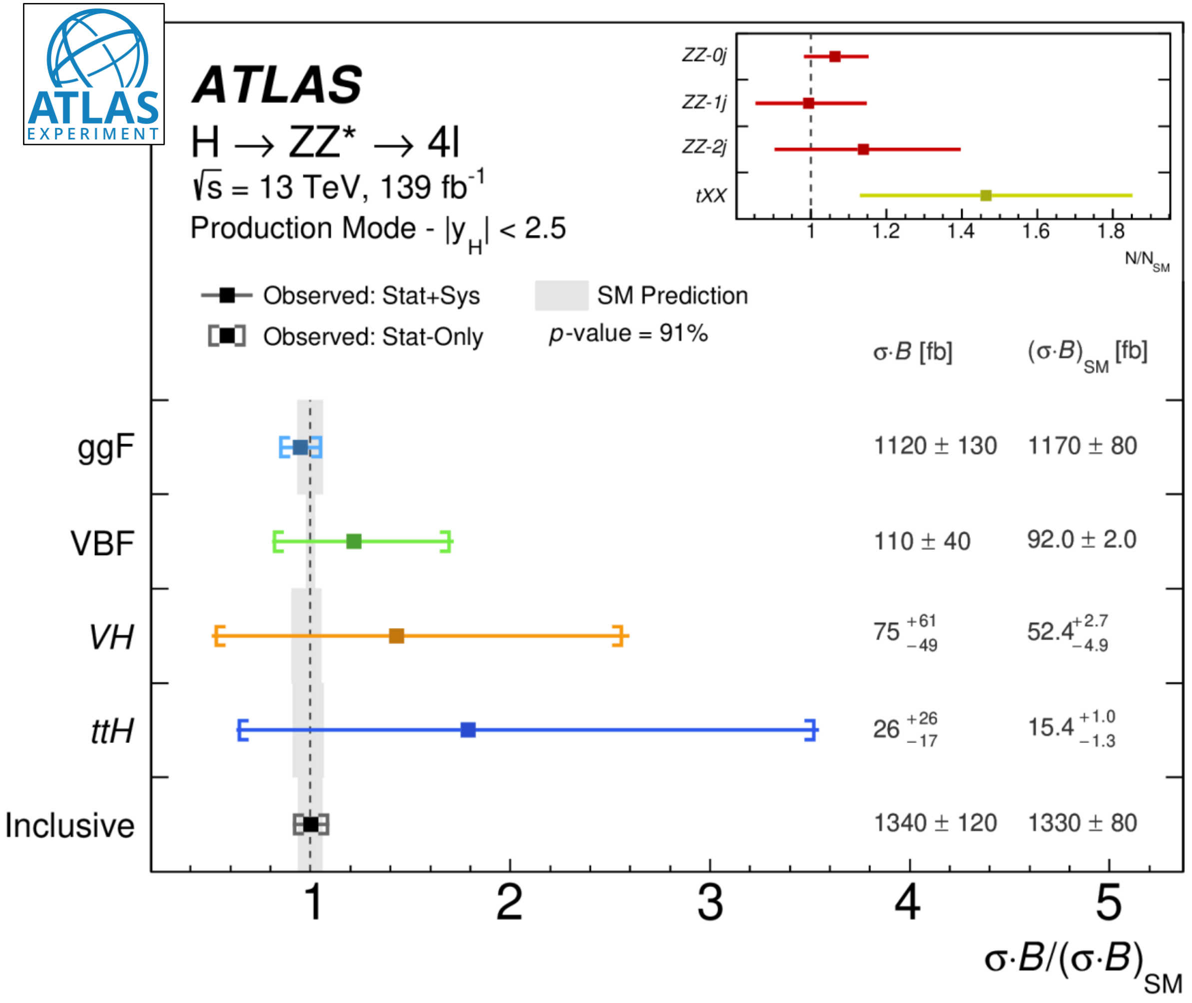
H → ZZ: STXS

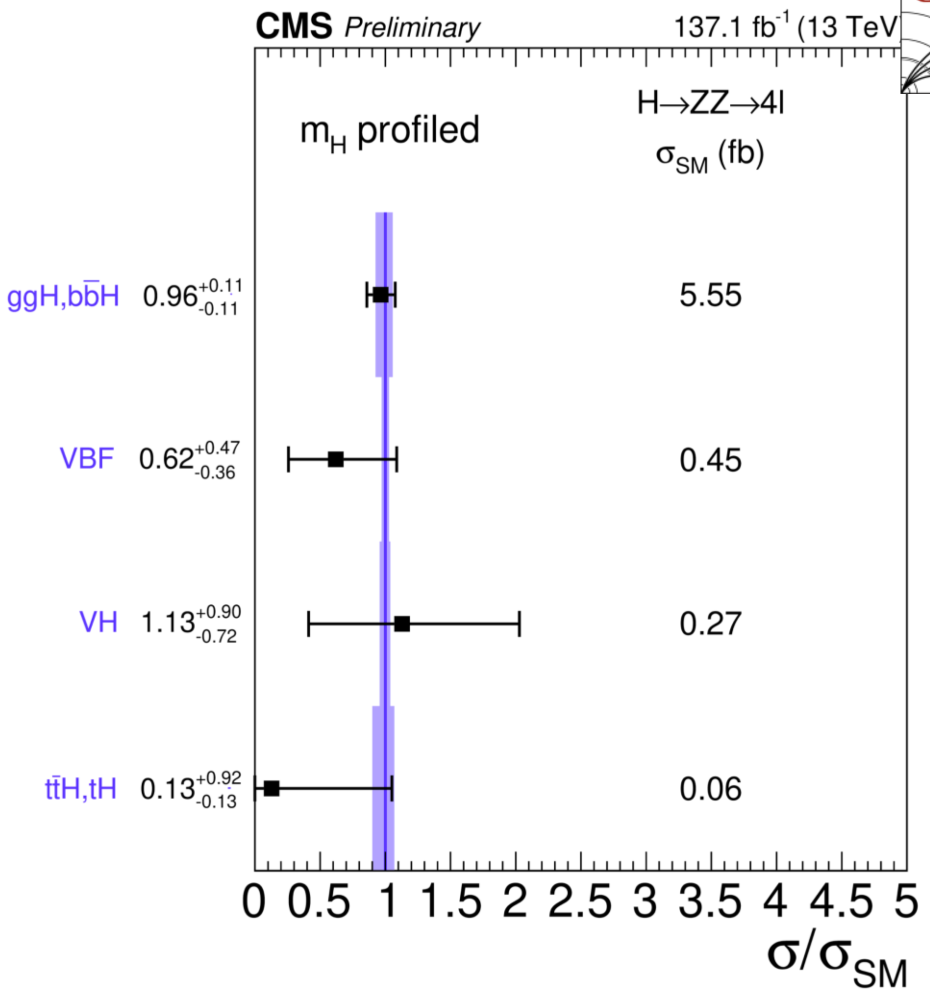
- Very clean final state but small event yields:
  - Must group STXS bins to improve sensitivity, especially for VH & ttH processes
- Different analysis strategies used:
  - ATLAS: cut-based categories, fit to DNN discriminants
  - CMS: cuts & Matrix Element for categories, 2D fit to m(4ℓ) and ME discrim.
- Other highlights
  - CMS: Matrix element to tag VBF 1-jet events
  - ATLAS: ZZ + 0/1/2 jets & tXX bkgs freely floating



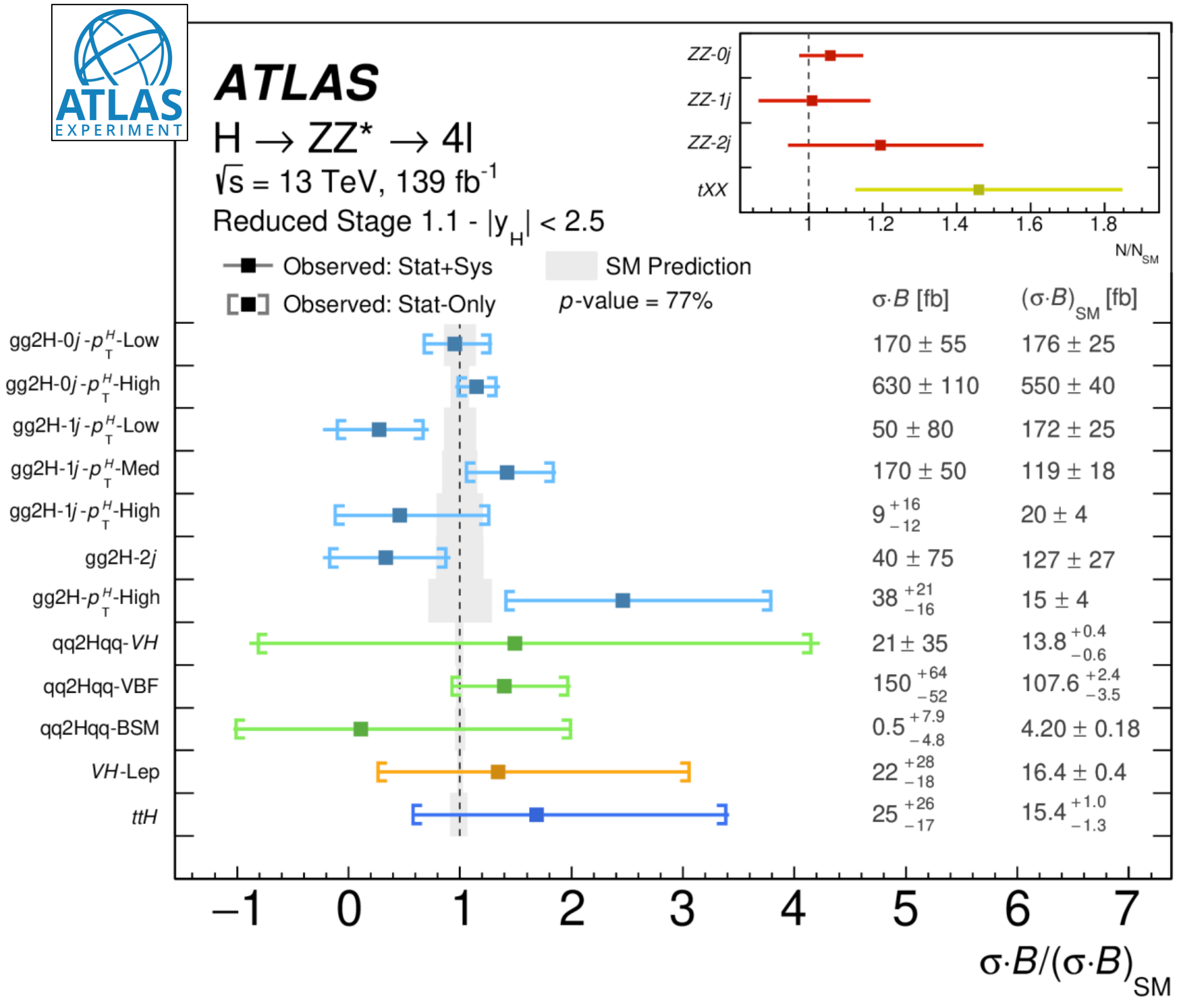


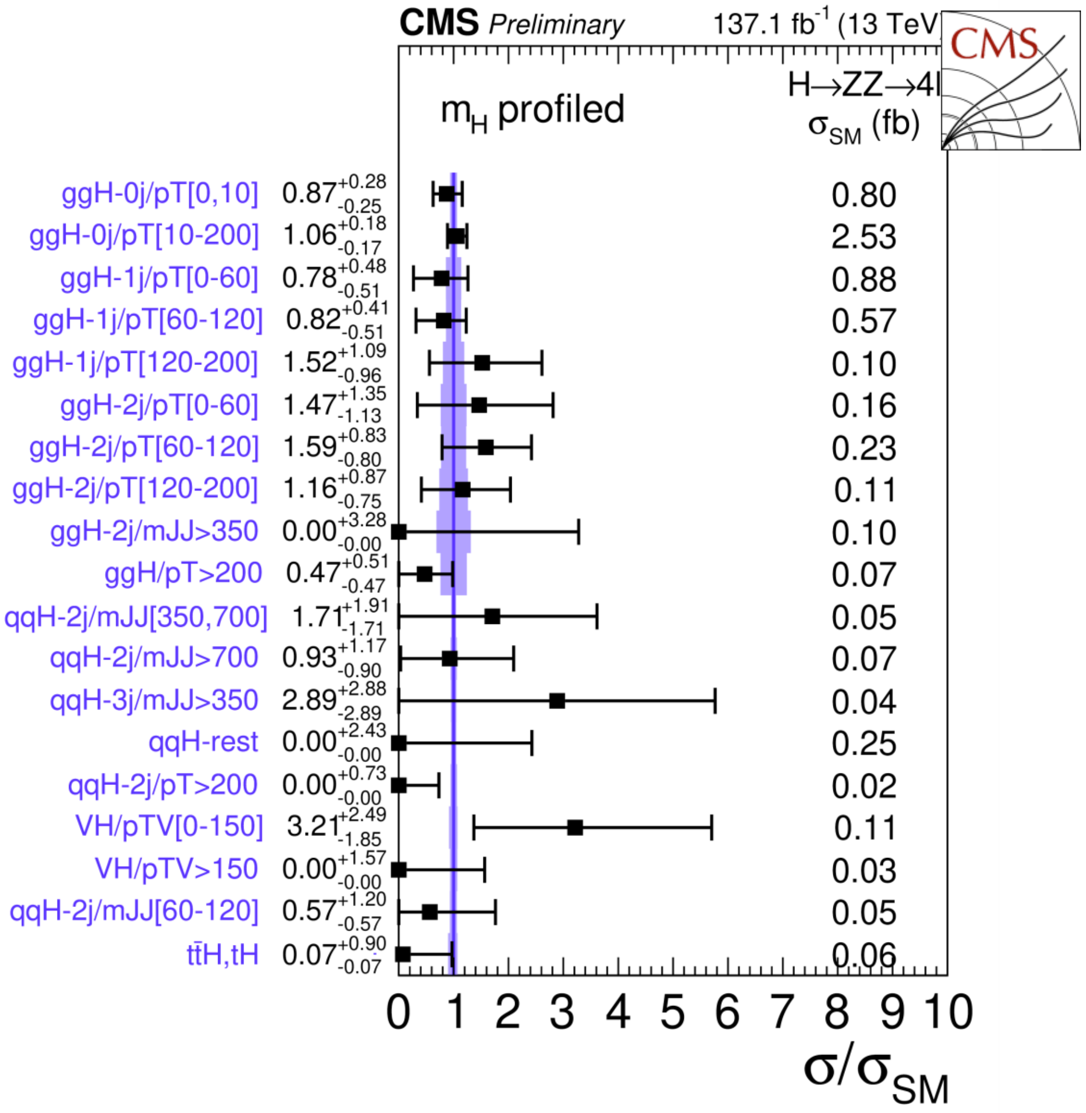
H → ZZ STXS stage 0 results





H → ZZ STXS stage 1.x results

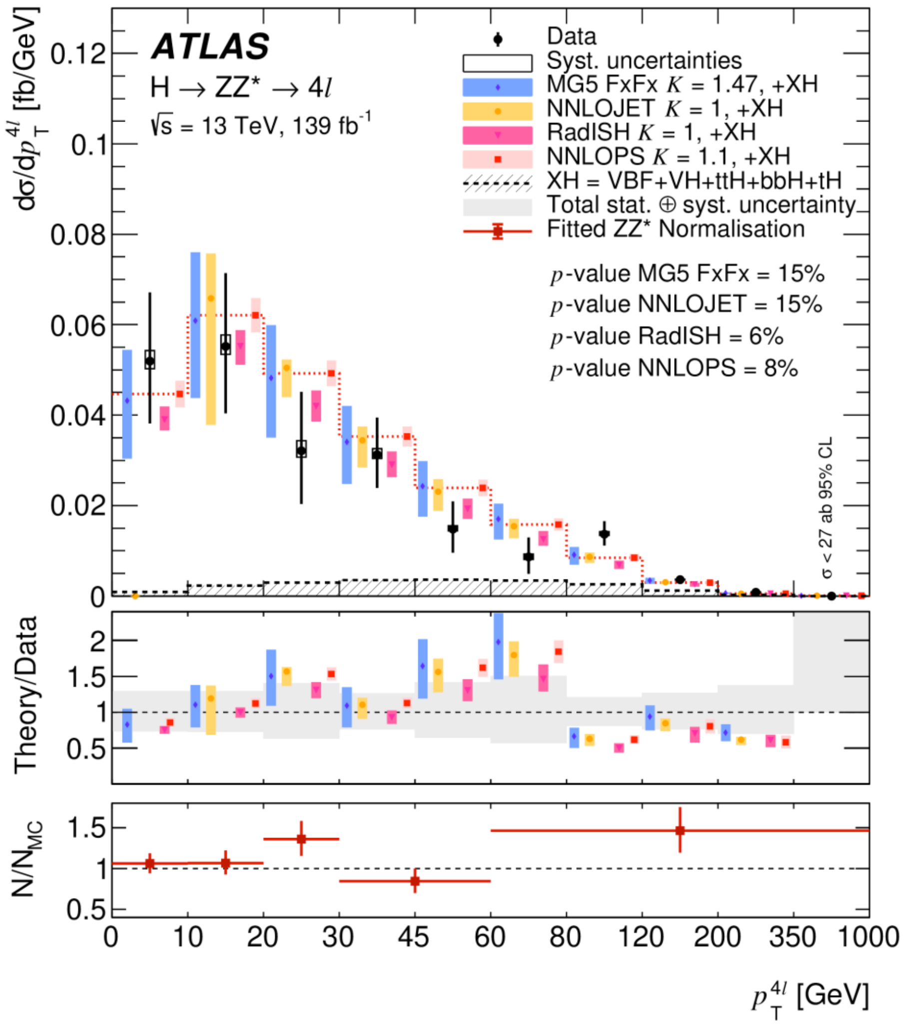




H → ZZ: differential & fiducial

- Most recent result from ATLAS:
  - extensive set of 1D and 2D distributions
  - ZZ background fitted in situ bin by bin
  - comparisons to many different MC codes (e.g. RadISH, NNLOJET, Prophecy4f, HTo4l)
- Also older result from CMS with more limited set of variables & MC codes
- Fiducial cross sections:

	Measured ± stat ± syst [fb]		SM prediction [fb]
ATLAS	3.18 ±0.31 ± 0.11	(10%)	3.41 ± 0.18
CMS	$2.73^{+0.23}_{-0.22}$ $^{+0.24}_{-0.29}$	(11%)	2.76 ± 0.14

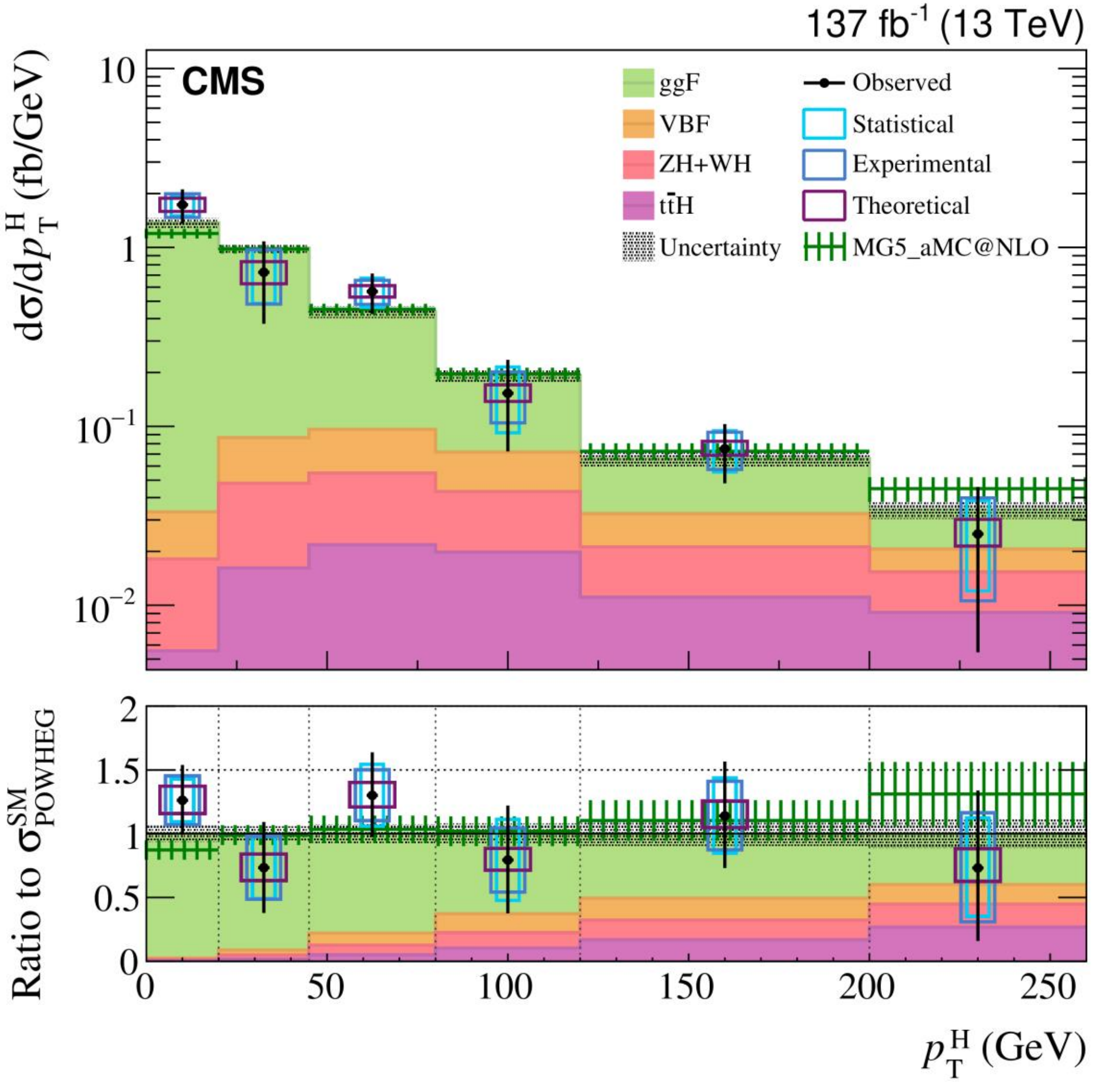


H → WW: differential & fiducial

- Differential distribution in p_T(H) and number of jets
  - Regularization used for p_T(H), strength derived minimizing global correlation on Asimov
  - Likelihood-based unfolding (no Gaussian approximations)
  - STXS definitions used for p_T(H) and N(jets)
- Fiducial cross section:

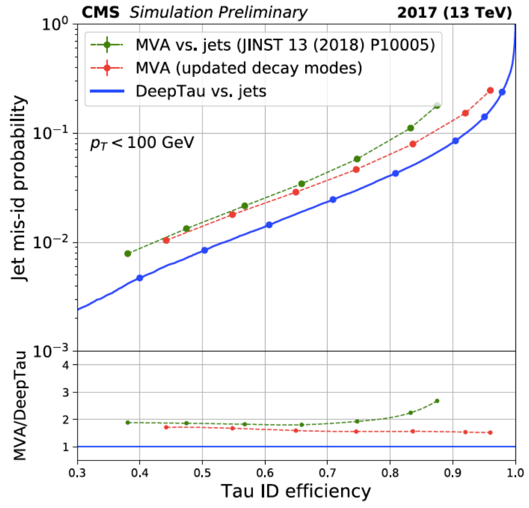
  $\sigma_{fid} = 86.5 \pm 4.1^{(stat)} \pm 6.3^{(exp)} \pm 5.8^{(th)}$ fb *(11%)*

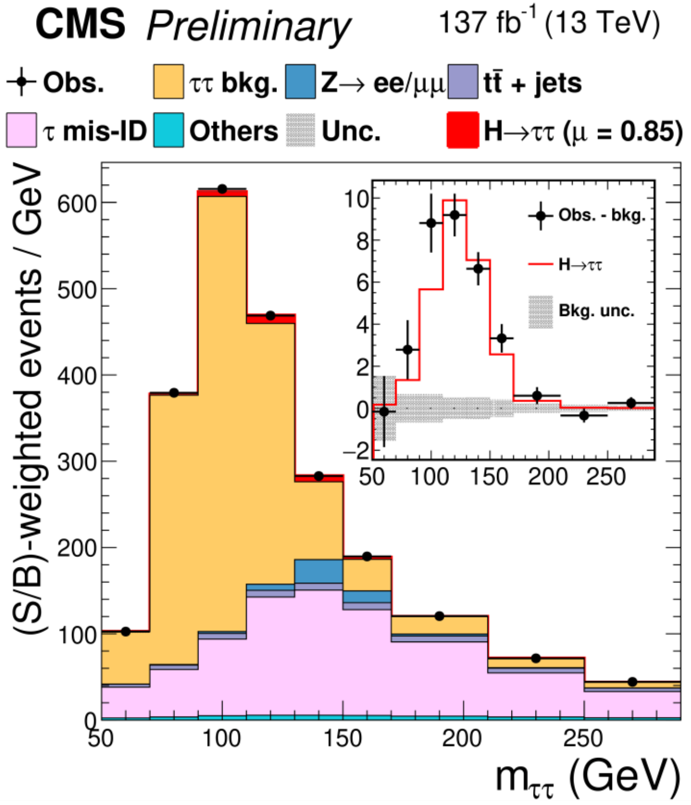
  SM prediction: 82.5 ± 4.2 fb



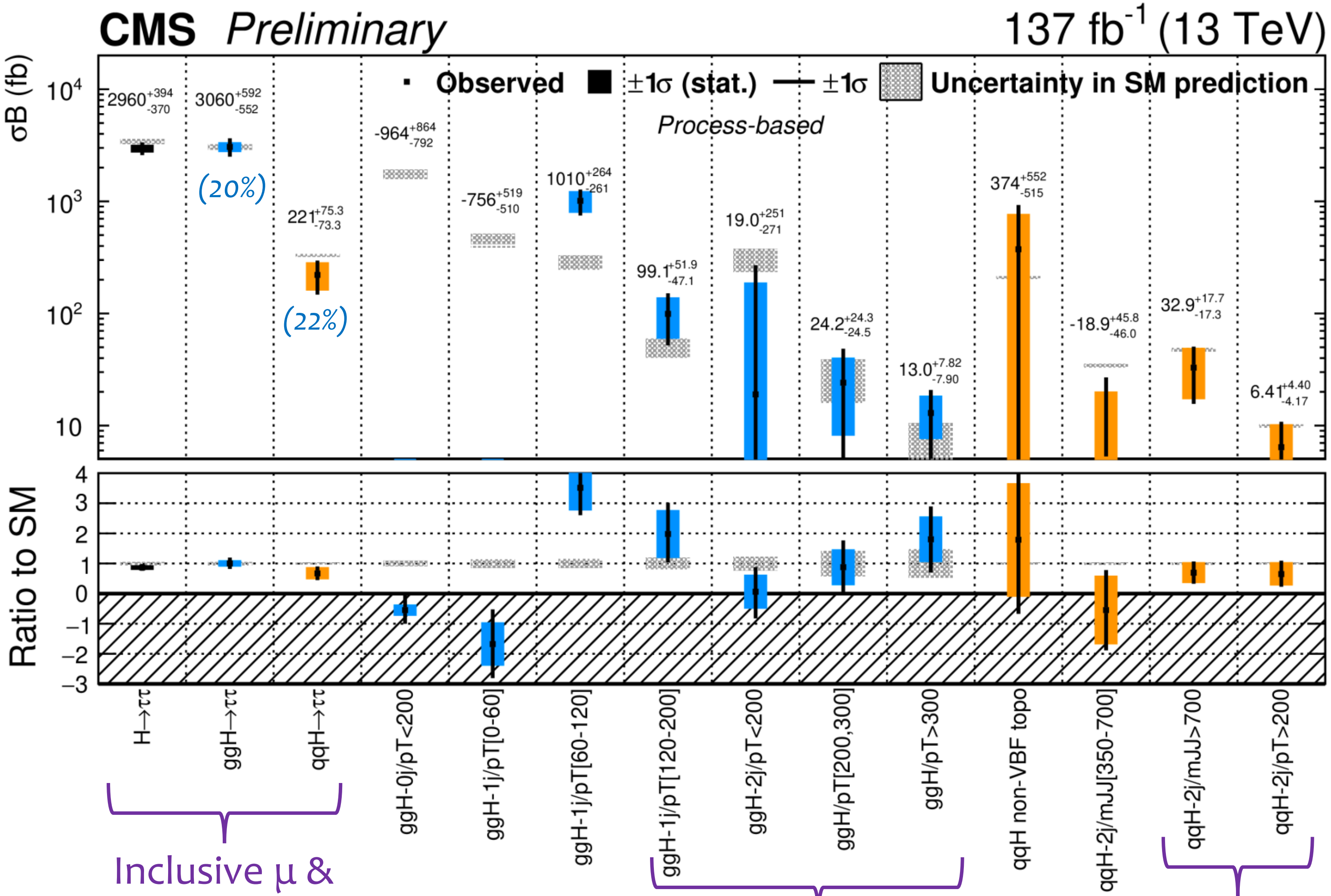
H → ττ: STXS

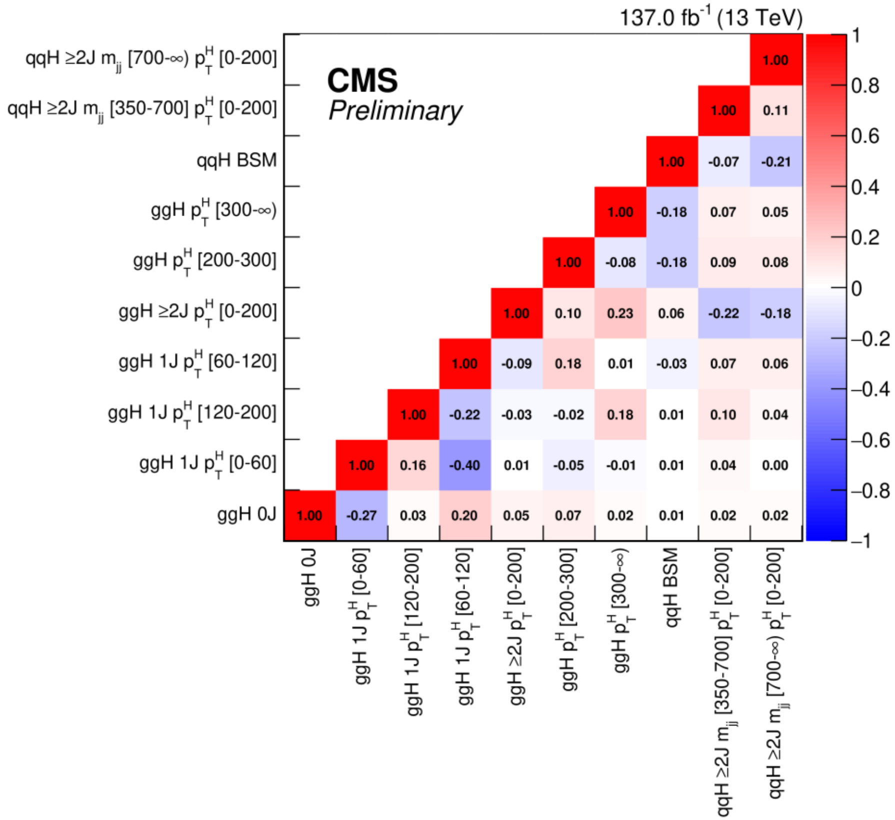
- Complement H → γγ and 4ℓ in regions where the σ_{SM} is small and S/B good:
  - High p_T gluon-fusion, high m(jj) VBF
- Analysis highlights:
  - State of the art τ ID: DNN using PF candidates
  - Dominant backgrounds estimated from data: **genuine ττ bkg** via embedding, **reducible bkg** via fake rate method
- Traditional cut-based strategy:
  - Split in $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, eμ and 0j / VBF / ≥1 j
  - Fit $m_{\tau\tau}$ distribution in bins of p_T(H) or m(jj)





$H \to \tau\tau$ STXS results





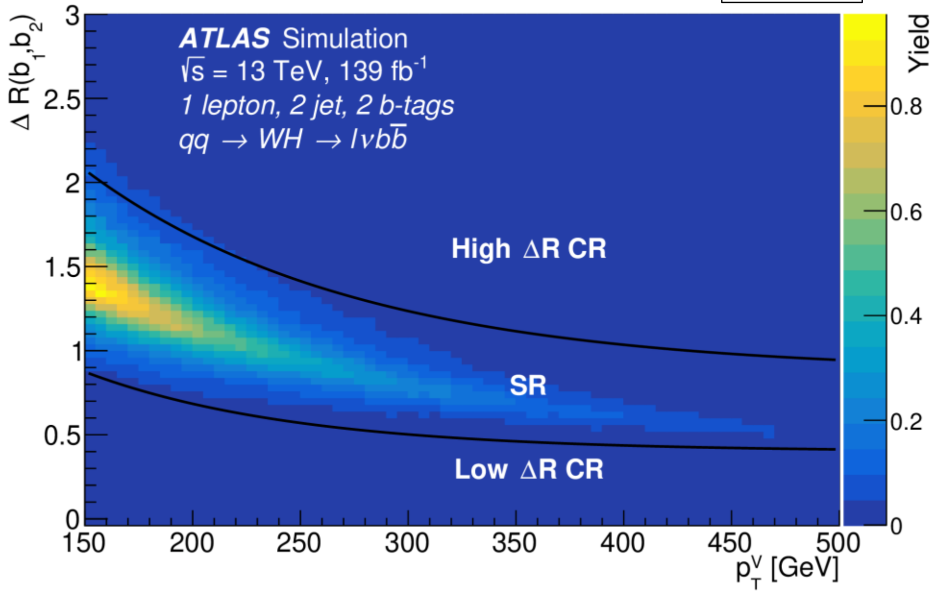
Inclusive μ & stage 0 STXS

ggH high p_T

VBF high p_T or m(jj)

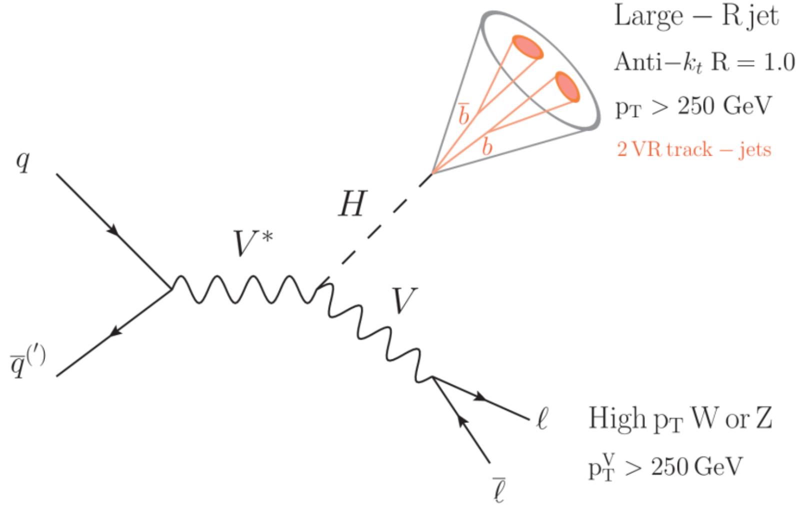
arXiv:2007.02873 (sub. to EPJC)
arXiv:2008.02508 (sub. to PLB)

VH, H → bb



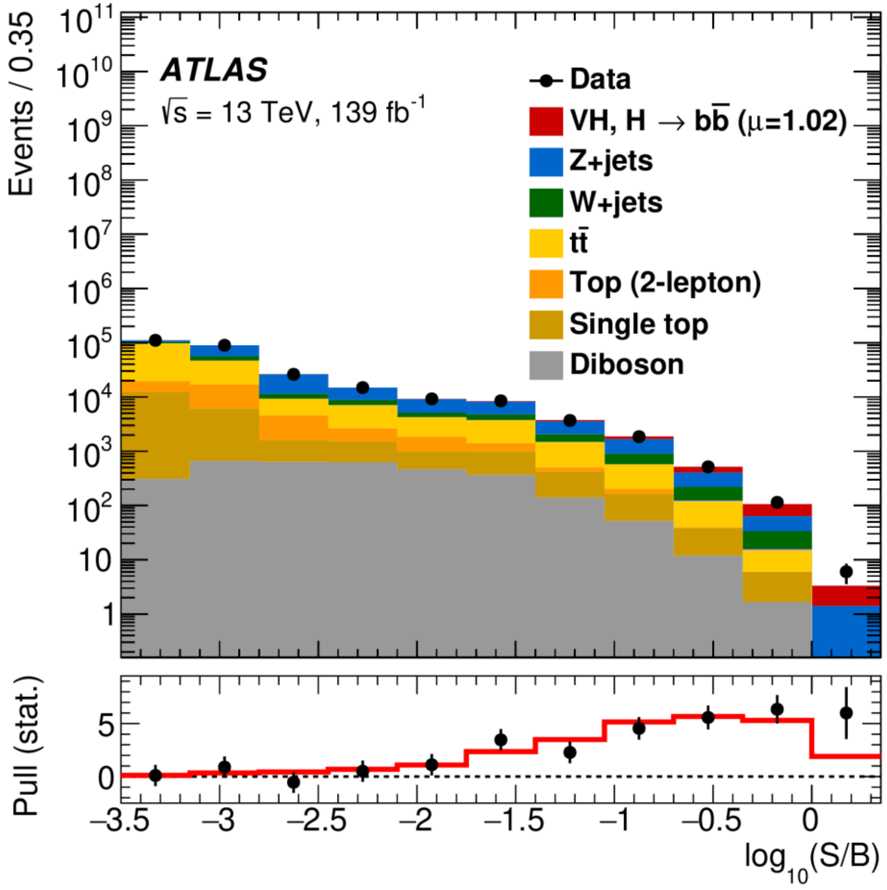
Two analyses on full run 2 dataset

- Traditional analysis with anti-k_T(R=0.4) jets, using MVA methods.
  - Similar strategy as H → bb observation paper but with improvements in objects, MVA, control regions, background modelling …
- Boosted analysis targeting $p_T(V) > 250$ GeV
  - use large radius jets (anti-k_T, R=1.0) with substructure info, and track jets for b-tag
  - cut-based categorization, with groomed jet mass as final discriminant



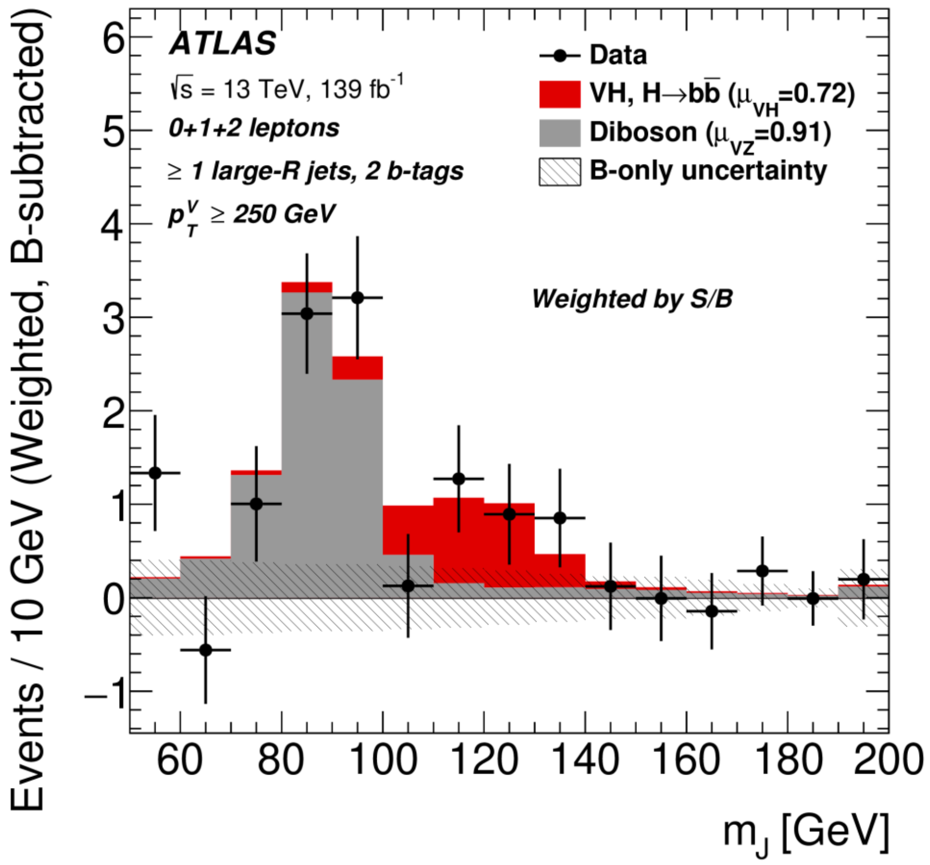
VH, H → bb

Resolved analysis



$\mu(VH) = 1.02 ^{+0.12}_{-0.11}$ (stat.) $^{+0.14}_{-0.13}$ (syst.)

Boosted analysis

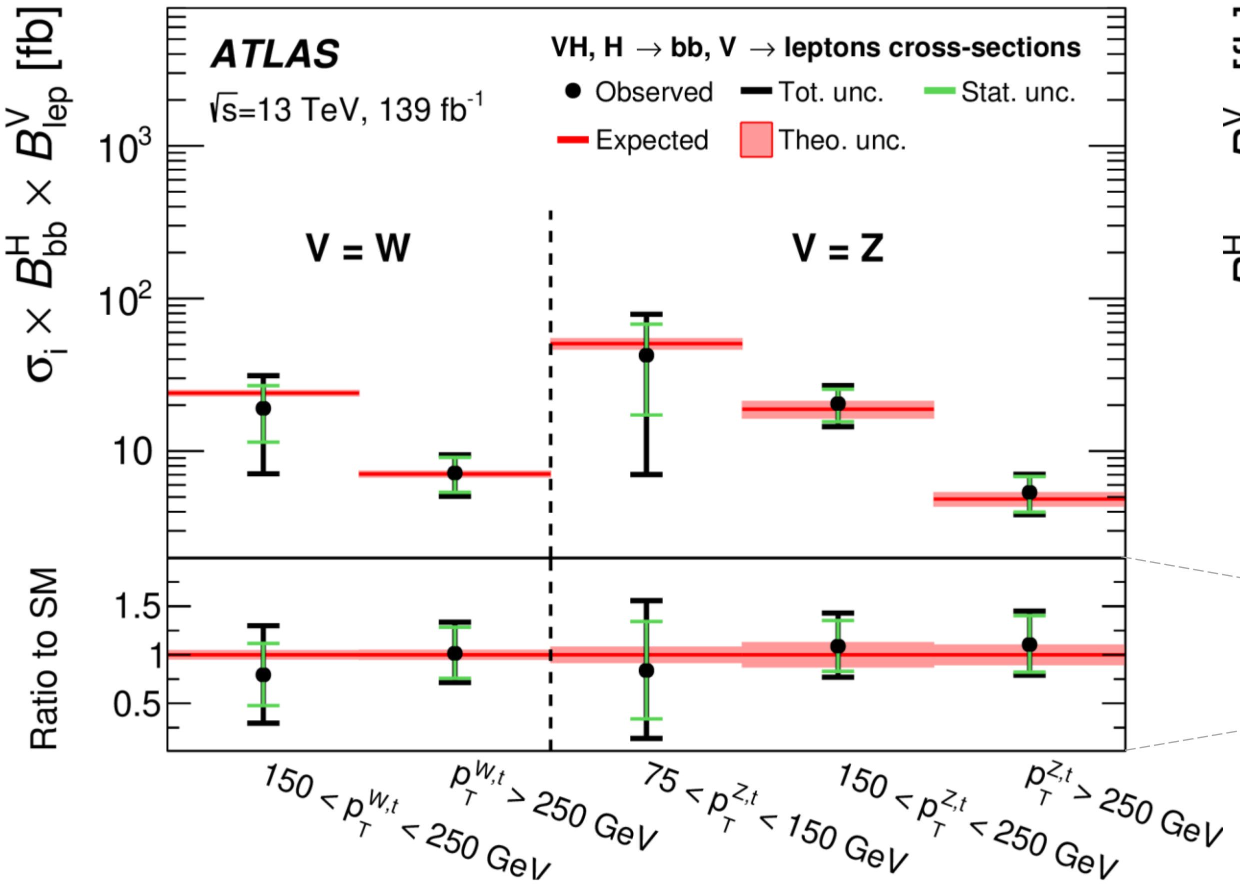


$\mu(VH) = 0.72 ^{+0.29}_{-0.28}$ (stat.) $^{+0.26}_{-0.22}$ (syst.)

VH, H → bb: STXS results

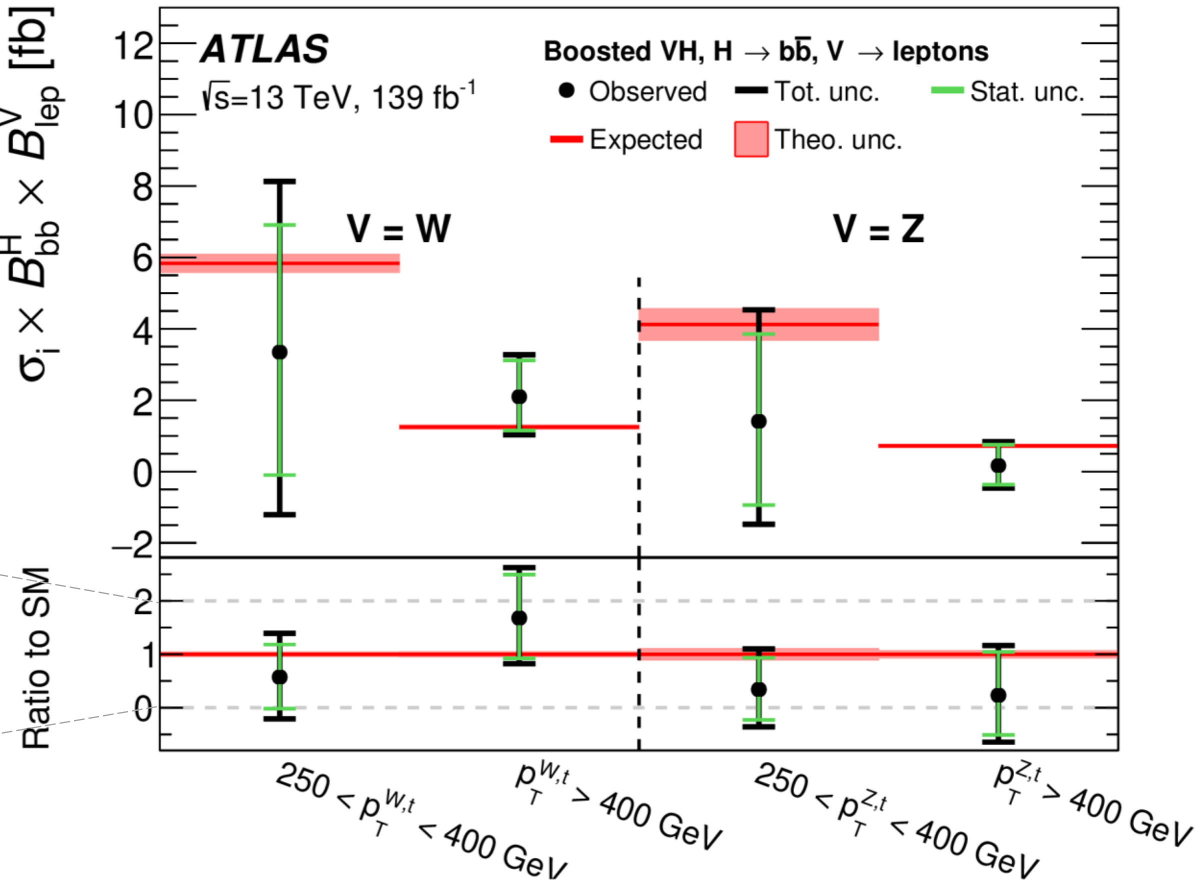
Resolved analysis

stage 1.2 STXS for qq→ VH



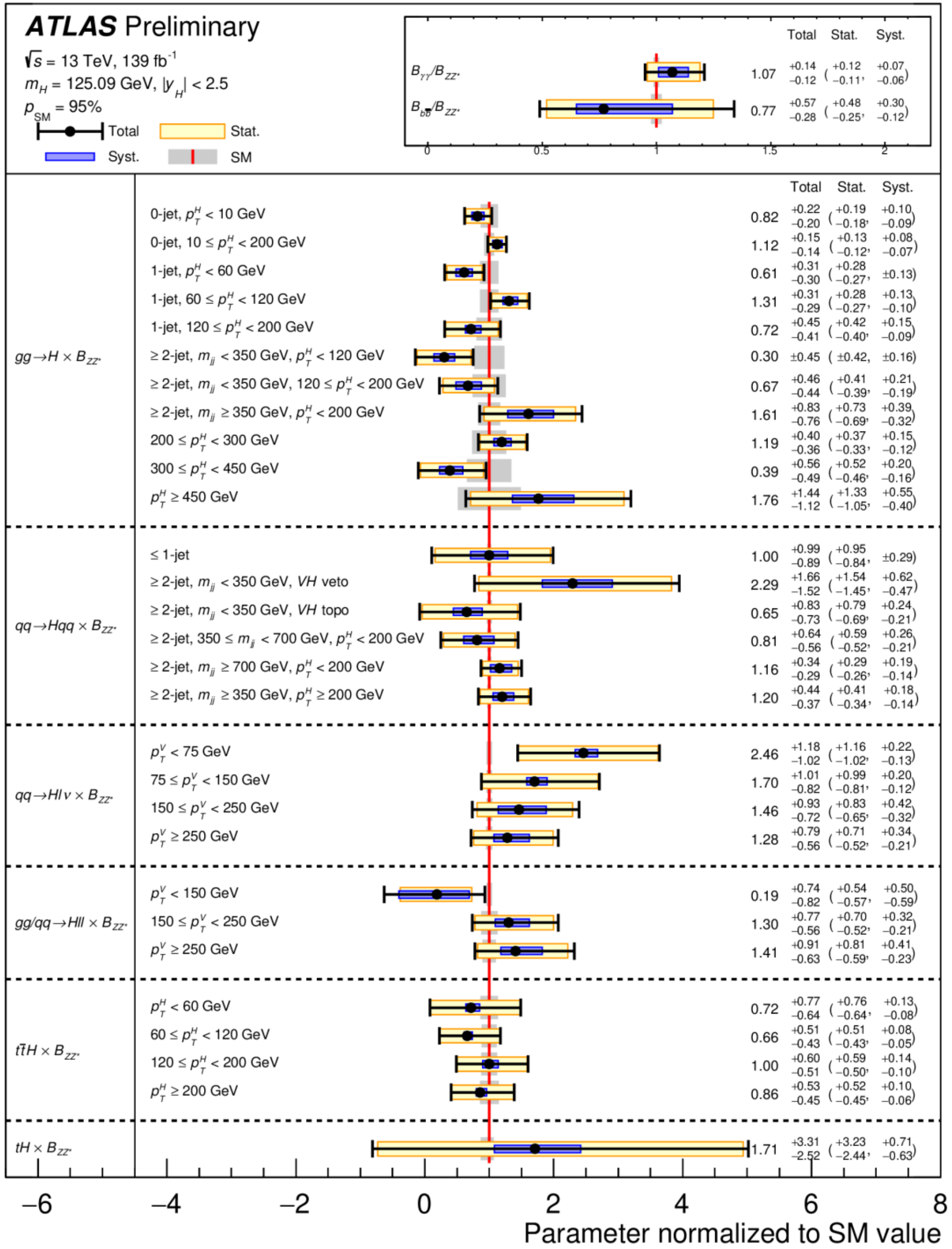
Boosted analysis

extra $p_T(V)$ bin at 400 GeV added



Combined STXS

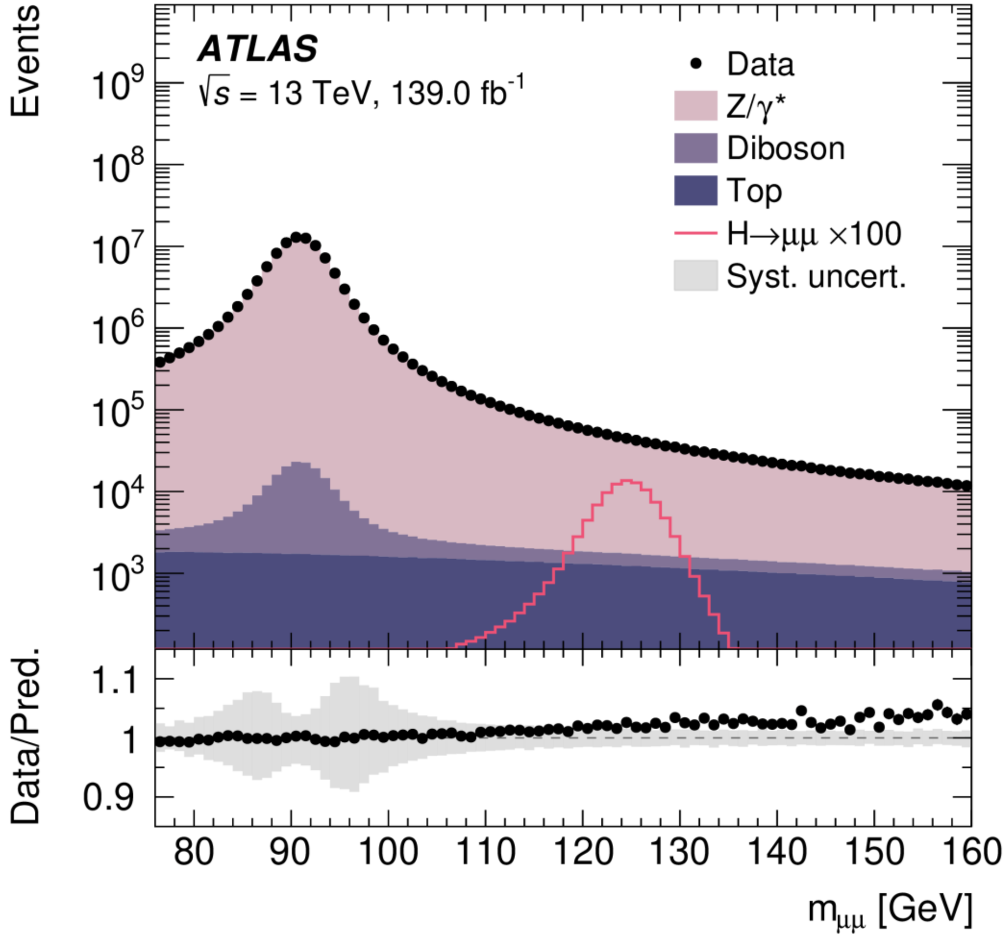
- Including full Run 2 γγ, ZZ, VH_{bb}
- H→ZZ* taken as reference for defining the cross sections
  - Fit also $B_{\gamma\gamma}/B_{ZZ*}$ and B_{bb}/B_{ZZ*}
- Measure 29 STXS bins:
  - Merging mainly 2-jet vs 3-jet VBF, 0-jet vs 1-jet VH, and few other bins in $p_T(H)$ or $p_T(Z)$
- Uncertainties in 15-100% range
  - except tH (300%), ggH p_T > 450 (150%), and one qqH m_{jj} bin (150%)



Topical measurements

$H \to \mu\mu$

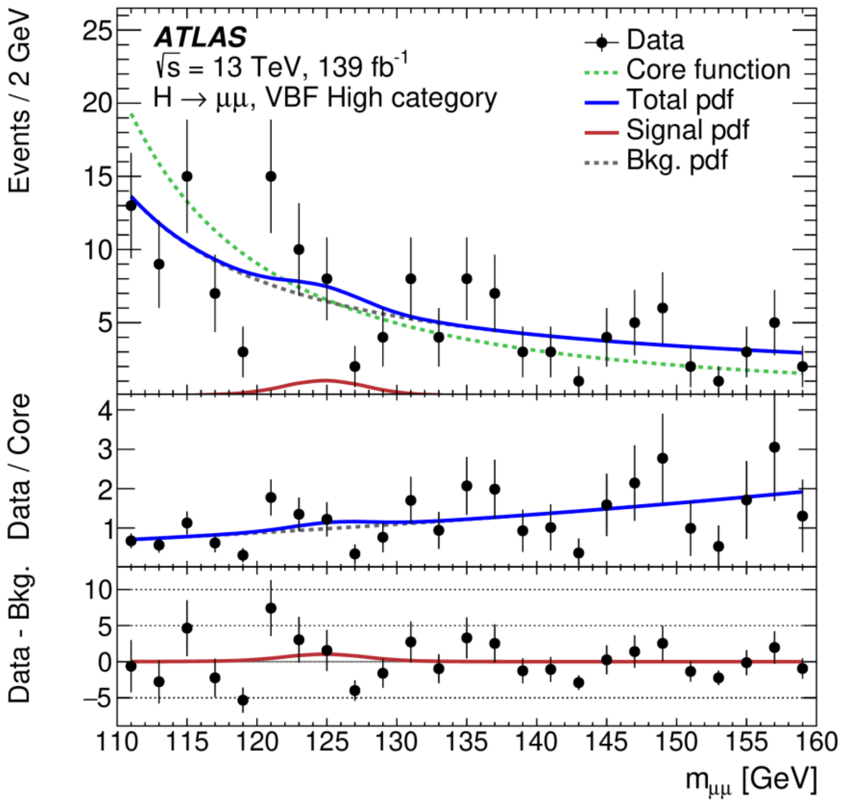
- Most promising channel to test couplings to 2nd generation fermions
- $BR_{SM}(H \to \mu\mu) \sim 2.2 \times 10^{-4}$, and large irreducible DY $\to \mu\mu$ background
  - S/B ~ 0.1% for inclusive events at 125 GeV
- Strategies to increase sensitivity:
  - Improve $\sigma(m_{\mu\mu})$ with FSR recovery, and constraining tracks to beam line (CMS only)
  - Categorization & MVAs to select events at high S/B, e.g. from VBF, VH, ttH
  - More advanced signal extraction method



$H \rightarrow \mu\mu$ signal extraction

- The background is dominated by very well known DY $\rightarrow \mu\mu$. Can rely on that to improve the sensitivity of the analysis.

1. Estimate bkg in each category as product of a common fixed *core pdf* and an *empirical pdf*
   - Can achieve good fit quality and acceptable bias with a reduced number of degrees of freedom
   - Used by ATLAS in all categories. (very similar approach used also by CMS in the ggH categories)

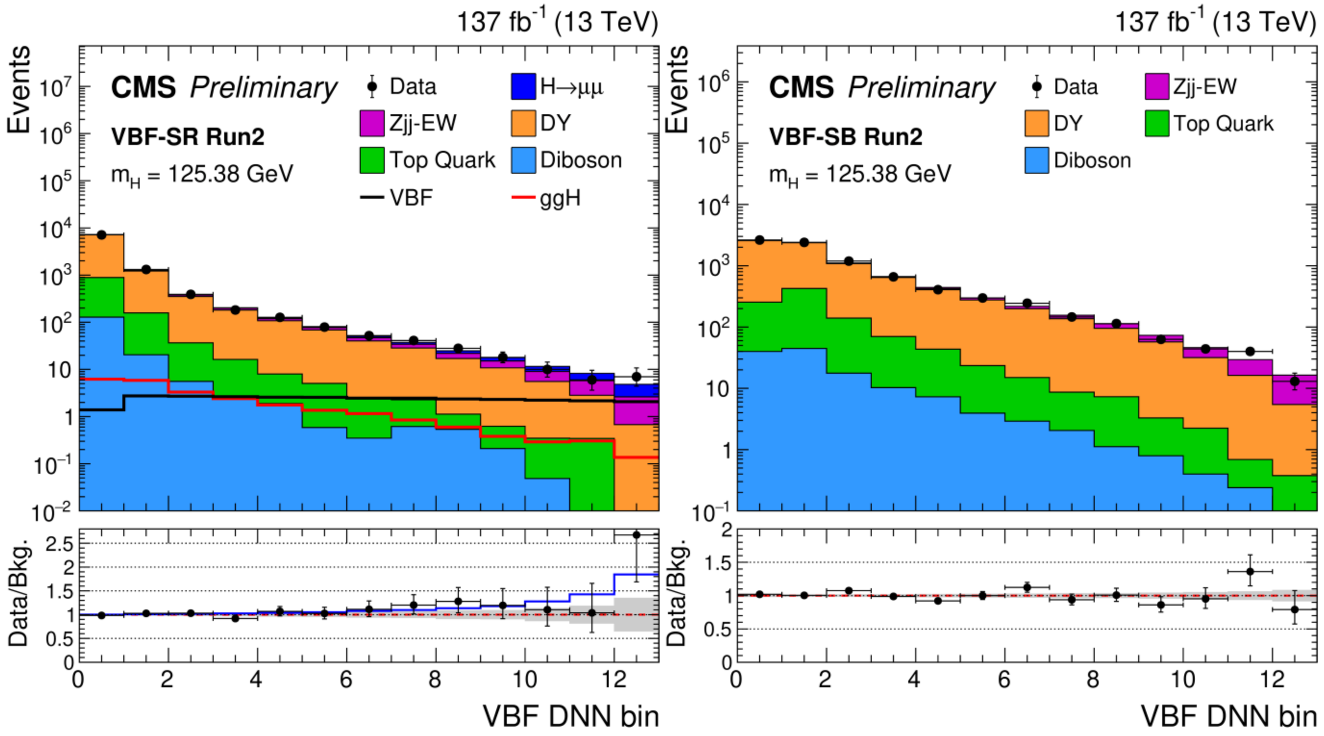


$H \to \mu\mu$ signal extraction

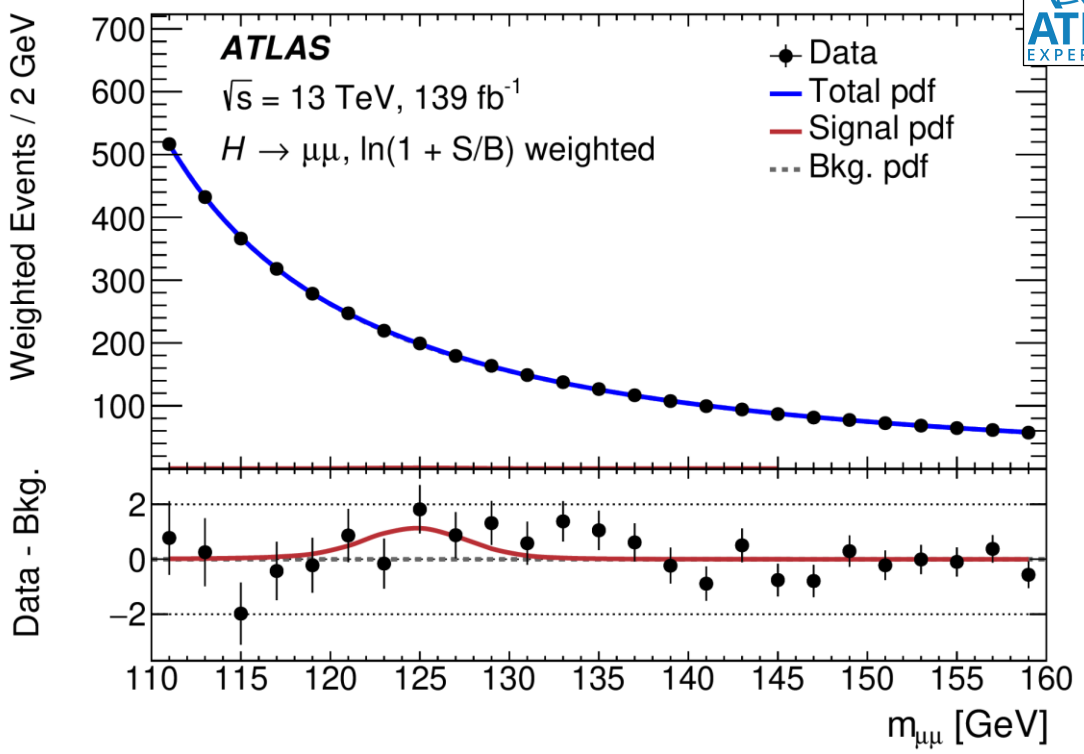
2. MC template-based analysis, including $m(\mu\mu)$ in the MVA.
   - Bkg at high S/B constrained by data at lower S/B bins and $m_{\mu\mu}$ sideband (fixing $m_{\mu\mu} = m_H$ when evaluating the MVA there)
   - Requires good MC modelling: theory (e.g. parton shower) and experiment (JEC, pileup). Rely on past VBF Z experience.
   - Used by CMS for VBF channel, gain in sensitivity ~20%

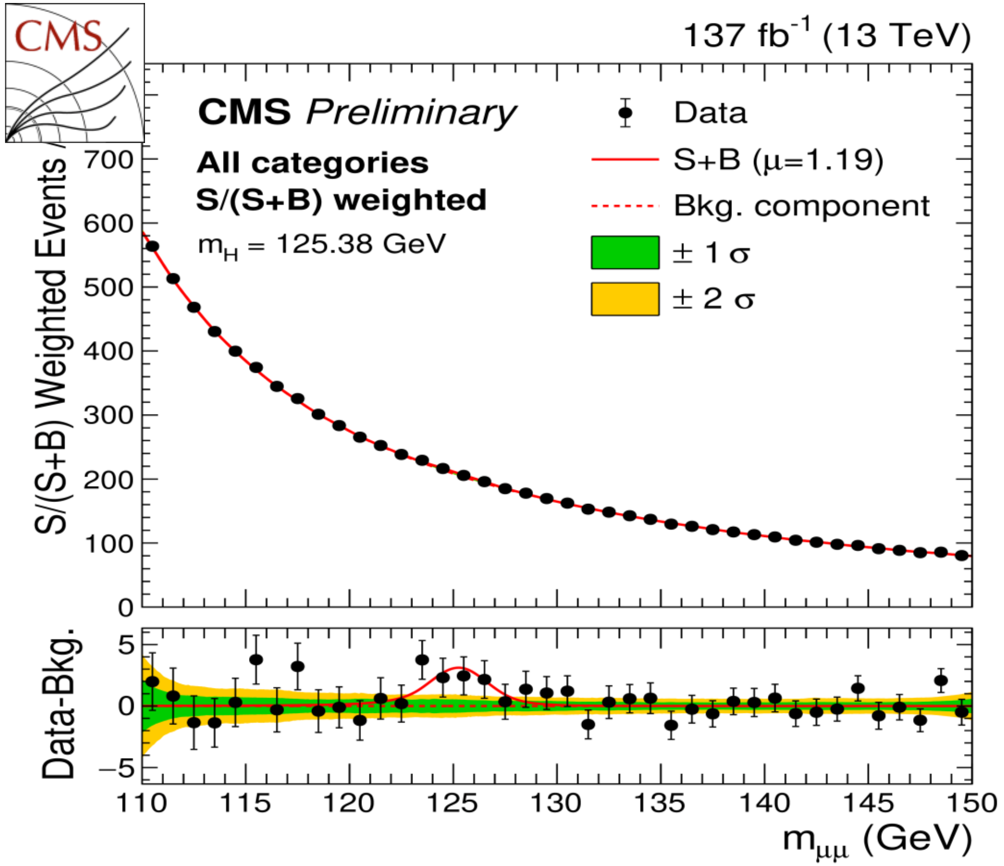
Signal region, post-fit ($115 < m_{\mu\mu} < 135$)

Sideband, post-fit ($m_{\mu\mu} \in 110–115 + 135–150$)



$H \to \mu\mu$ results





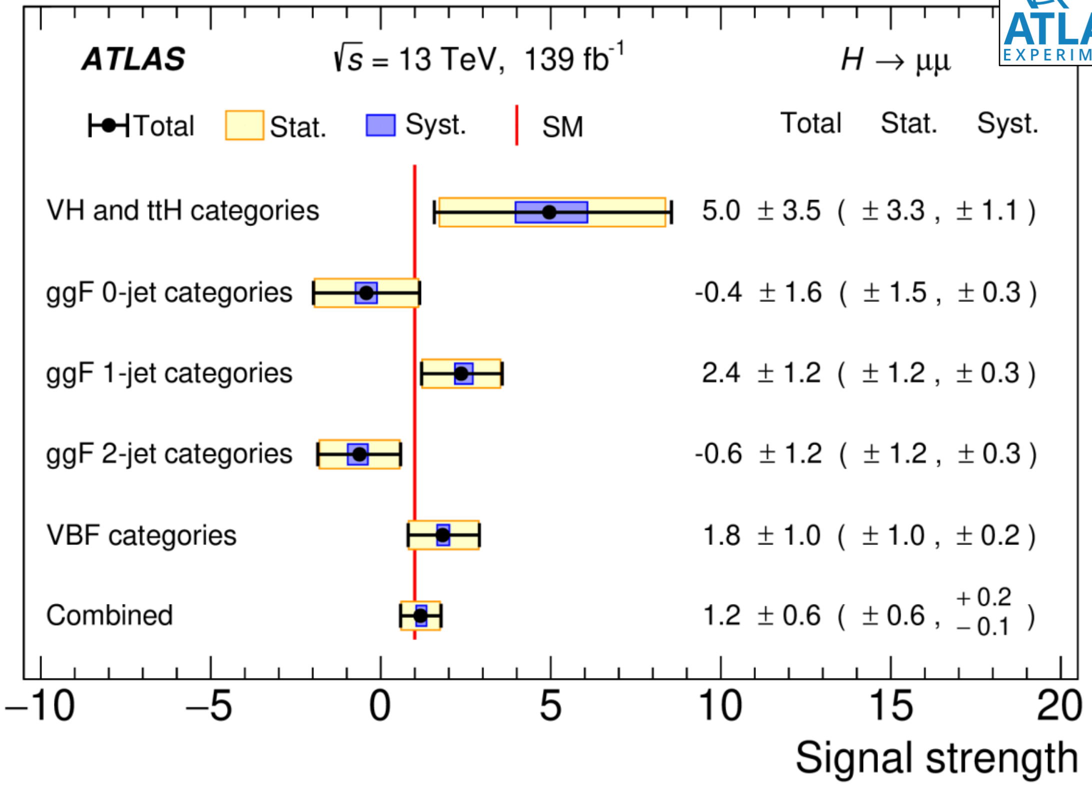
Signal strength: $\mu = 1.2 \pm 0.6$

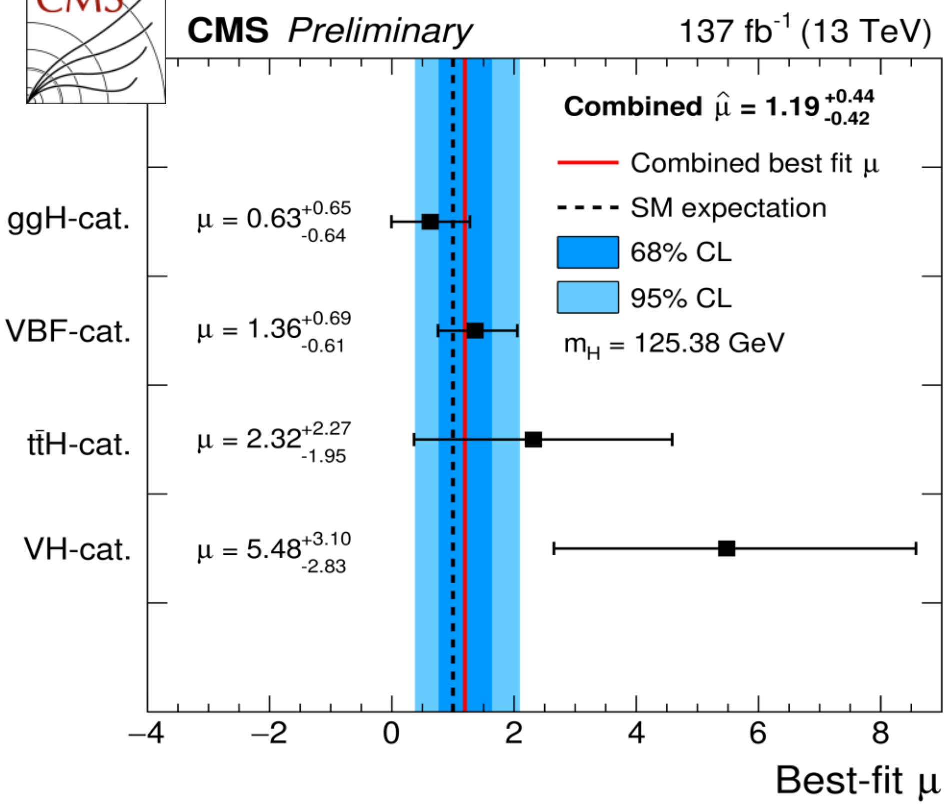
Significance: 2.0σ (1.7σ expected)

Signal strength: $\mu = 1.2 \pm 0.4$

Significance: 3.0σ (2.5σ expected)

$H \rightarrow \mu\mu$ results





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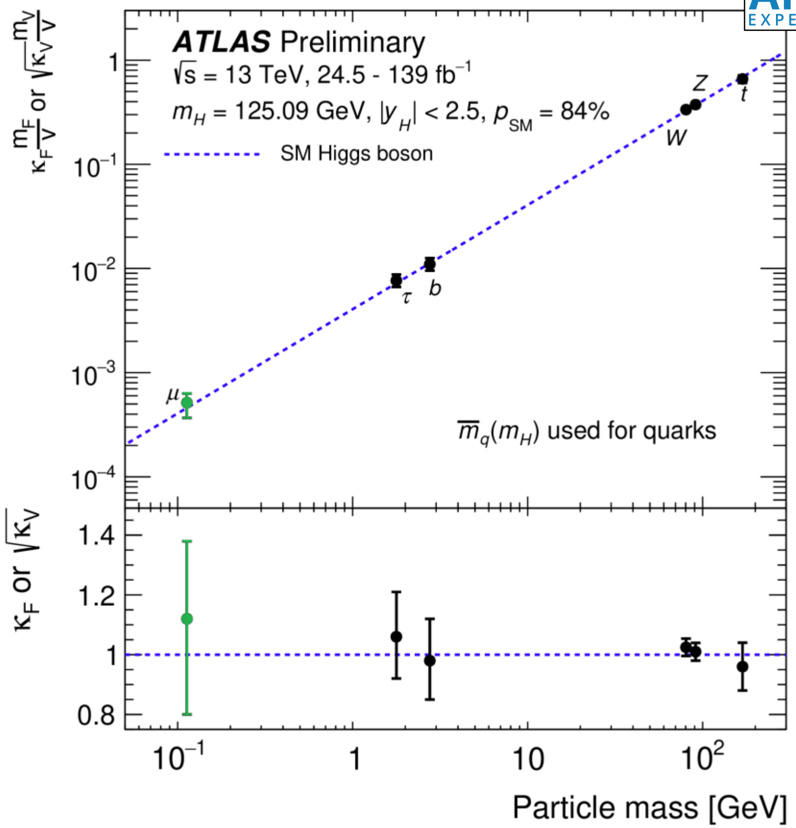
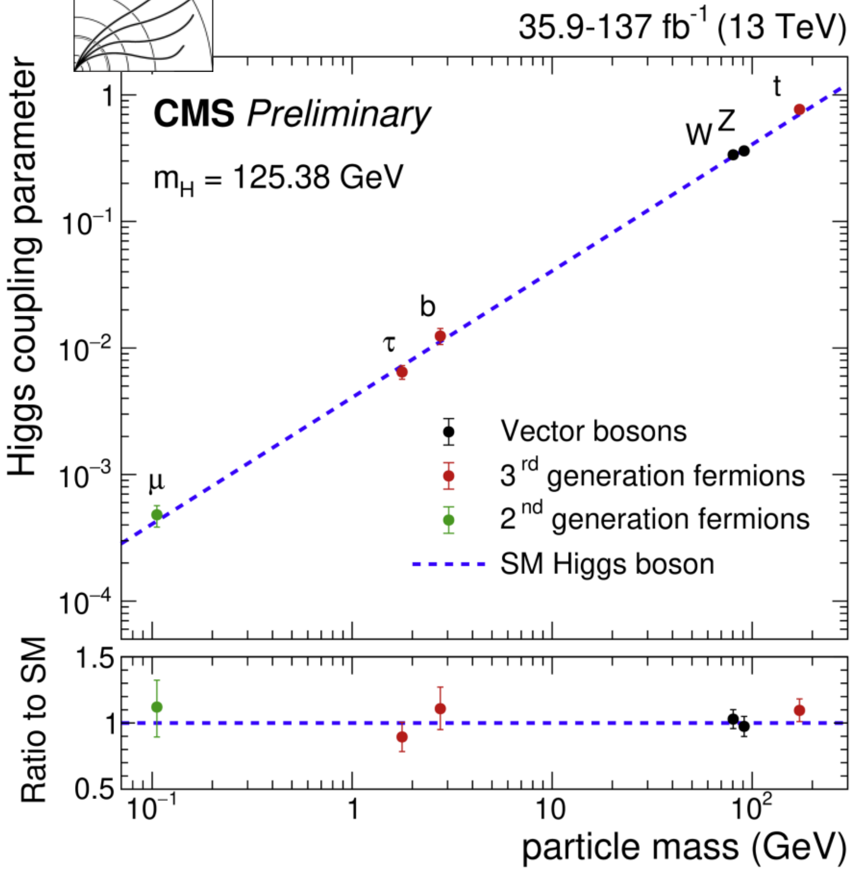
Signal strength: $\mu = 1.2 \pm 0.4$
Significance: 3.0σ (2.5σ expected)

H → μμ results



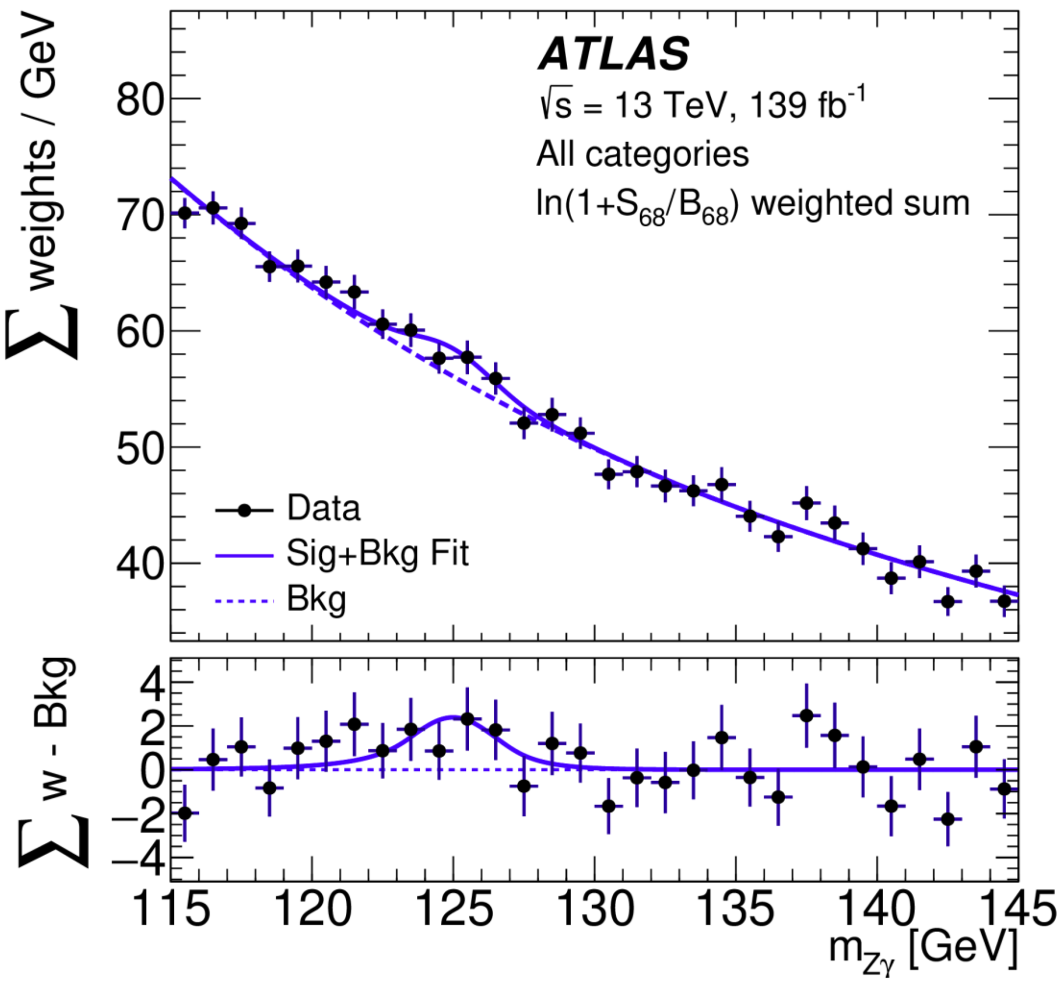


Signal strength: μ = 1.2 ± 0.6
Significance: 2.0σ (1.7σ expected)
Coupling mod.: **$\kappa_\mu = 1.12^{+0.26}/_{-0.32}$**

Signal strength: μ = 1.2 ± 0.4
Significance: 3.0σ (2.5σ expected)
Coupling mod.: **$\kappa_\mu = 1.13^{+0.21}/_{-0.22}$**

$H \to Z\gamma$

- $SU(2)_L$ symmetry ties together the HWW, HZZ, Hγγ, HZγ interactions
  - If heavy new physics respects $SU(2)_L$, correlated effects across the four
- $BR(H \to Z\gamma \to \ell\ell\gamma) = 0.5 \cdot 10^{-4}$
  - Similar BR to $H \to 4\ell$, but larger background from Zγ production
- As in $H \to \mu\mu$, key ingredients are:
  - **Improve signal mass resolution:** FSR recovery, kinematic refit of $Z \to \ell\ell$
  - **Improve S/B via categorization:** BDT targeting VBF production; p_T and p_{Tt}



Signal strength: **$\mu = 2.0 \pm 1.0$**

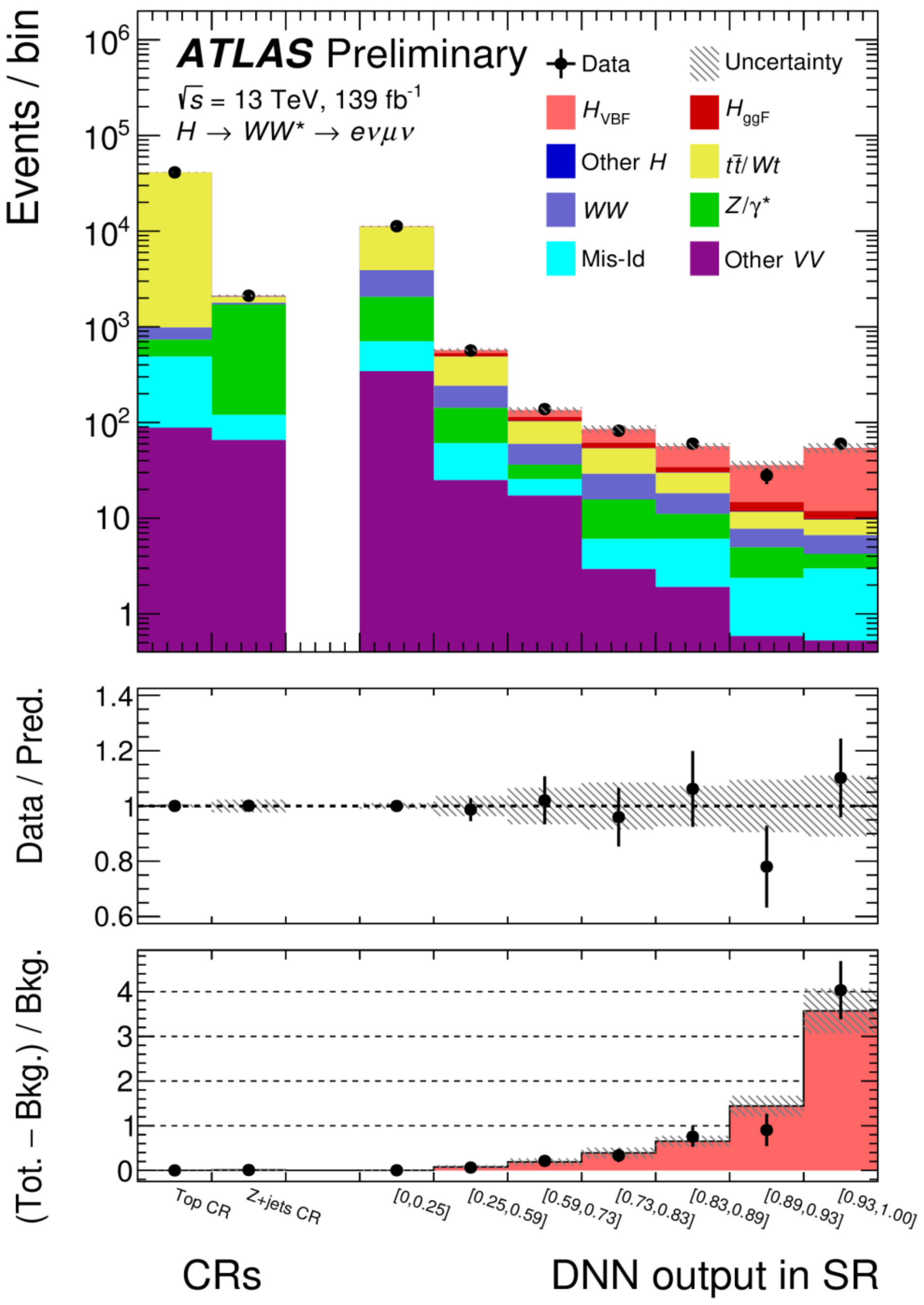
Significance: **2.2σ** (1.2σ expected)

VBF H ⟶ WW

- Dedicated analysis to probe for VBF
  - Using only the cleanest eμ final state
- Use DNN to discriminate the VBF signal from the backgrounds
  - Inputs are 15 kinematic variables built from leptons, jets, E_t^{mis}
  - **Best S/B ever achieved in H⟶WW ?**
- Measure σ×BR for VBF H ⟶ WW:

Obs. ± stat. ± syst.	SM prediction
0.85 ±0.10 $^{+0.17}_{-0.13}$ pb	**0.81 ± 0.02 pb**

Significance: **7.0σ** (6.2σ expected)



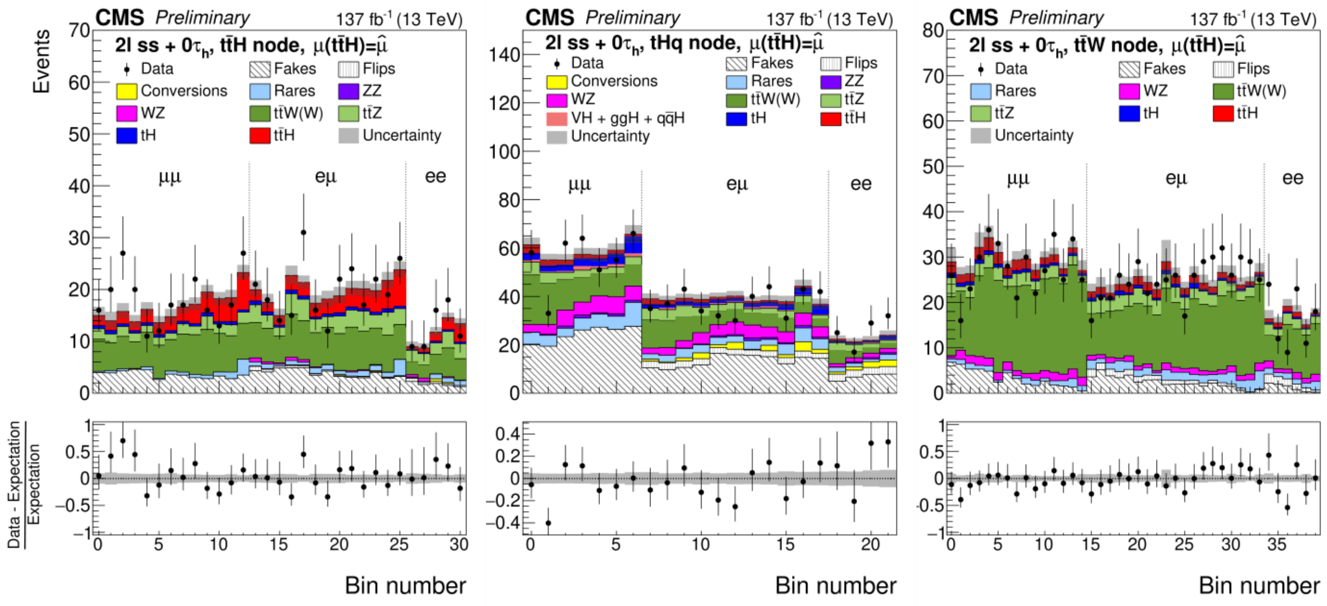
ttH & tH multilepton

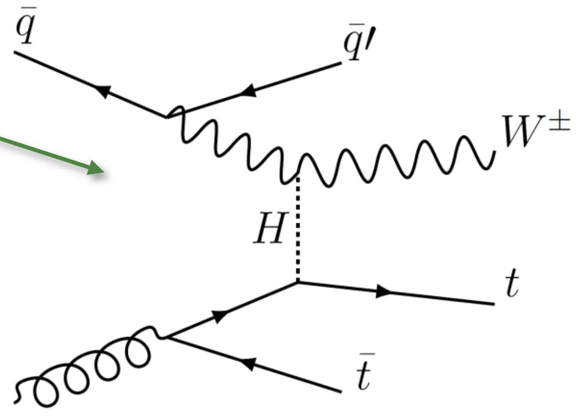
- Extended 80fb^{-1} multilepton analysis to also target tH
  - use multiclass DNN to separate ttH, tH and backgrounds in 2ℓss, 2ℓss + 1τ_h, 3ℓ categories.
- ttW and ttZ fitted from data
  - Improved MC for ttW adding α_{EW}^3 and $\alpha_S \cdot \alpha_{EW}^3$ contributions

Signal strengths		Bkg norm factors	
ttH	$0.92^{+0.26}_{-0.23}$	ttW	1.42 ± 0.21
tH	$5.7^{+4.1}_{-4.0}$	ttZ	1.03 ± 0.14

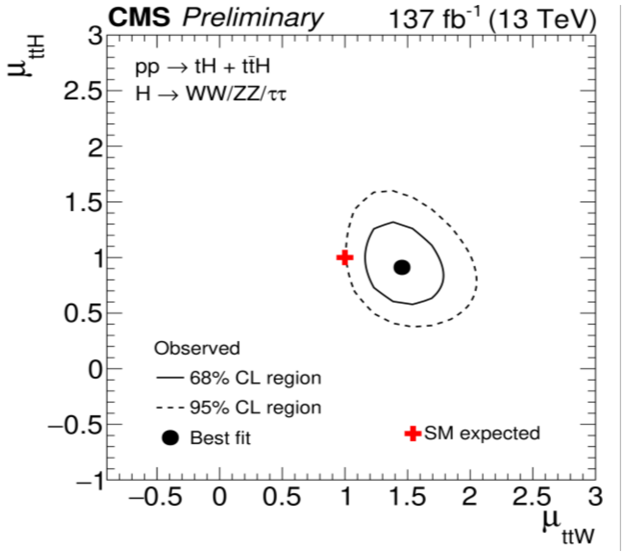
Significance for ttH: 4.7σ (5.2σ expected)

ttH tH ttW





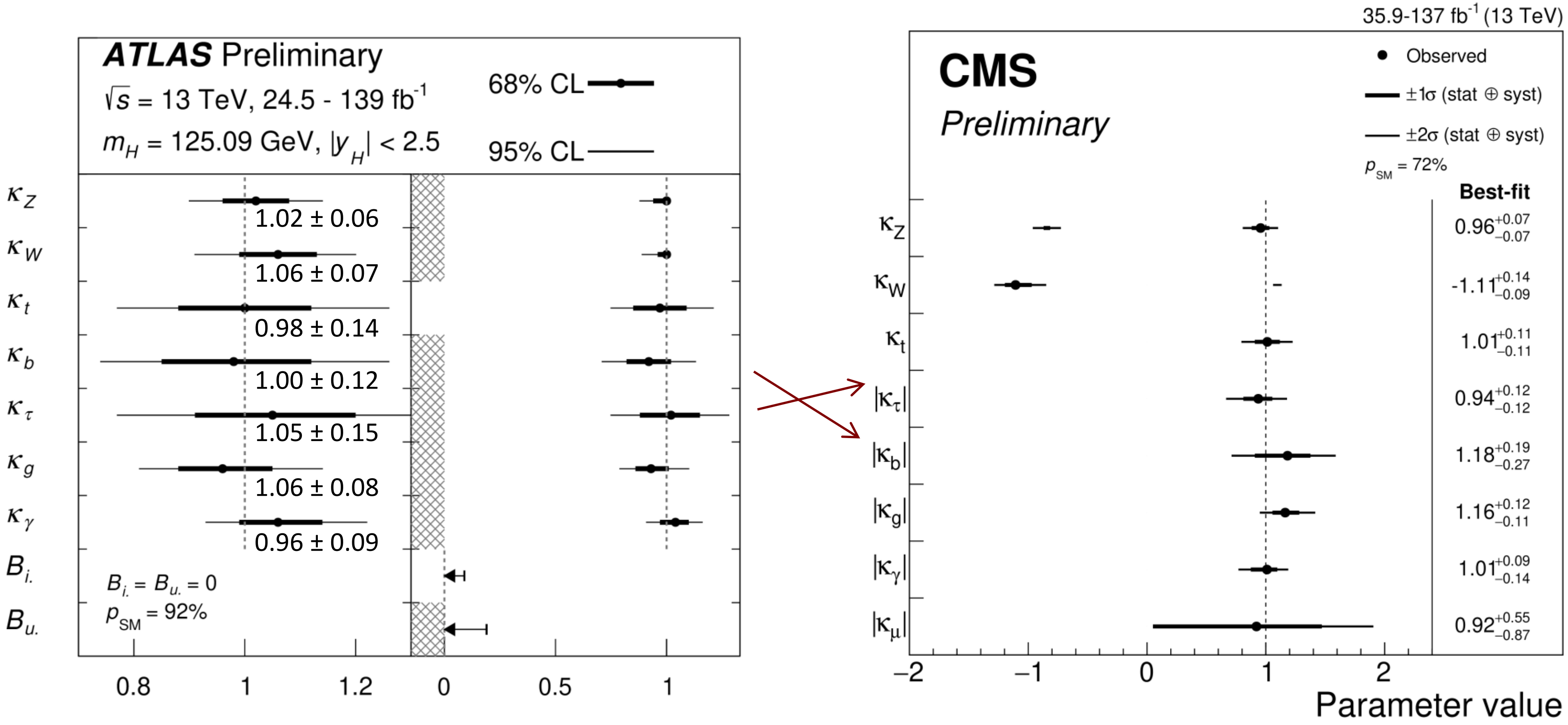
[JHEP 02 (2018) 031]



Couplings, EFT interpretations & CP studies

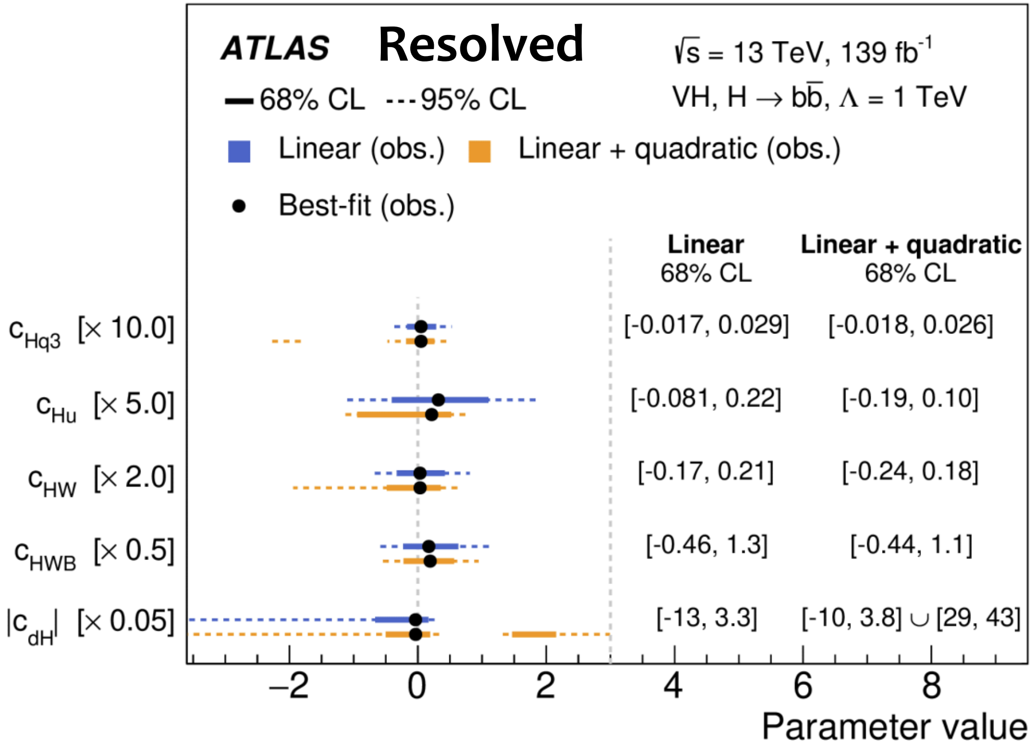
Couplings in κ framework

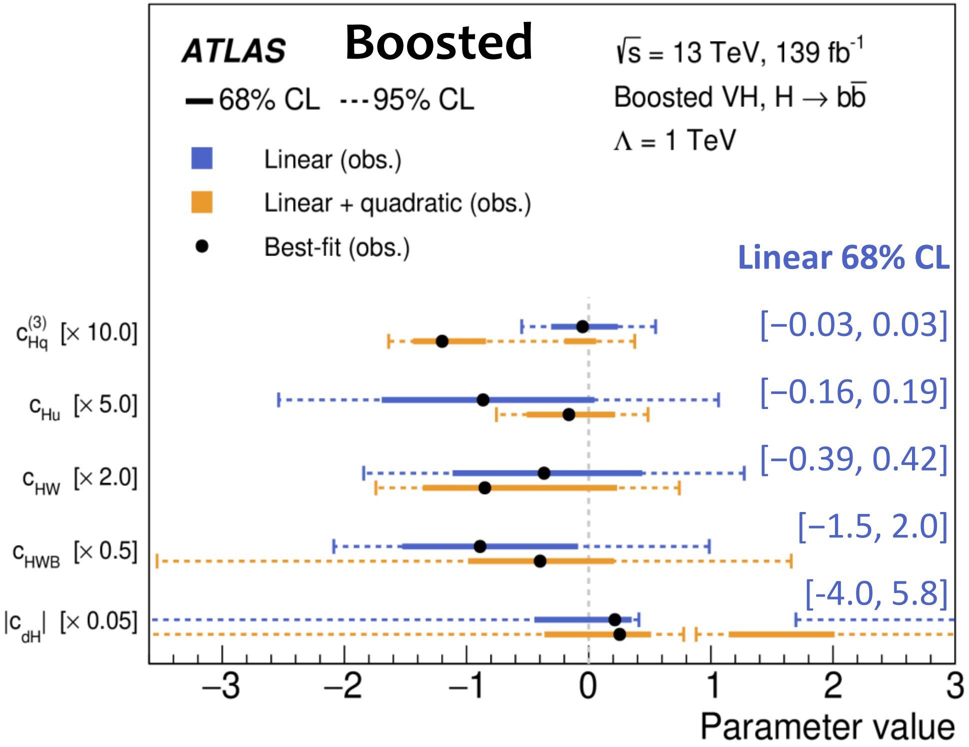
- Combinations are a moving target. Current state of the art:
  - ATLAS: full run 2 γγ, ZZ, VHbb, μμ, invis. (+ all other channels at 36 fb⁻¹)
  - CMS: full run 2 ZZ, and 80 fb⁻¹ γγ, ττ, VHbb, ttH (+ WW, μμ, … at 36 fb⁻¹)



VH, H → bb: SMEFT interpretation

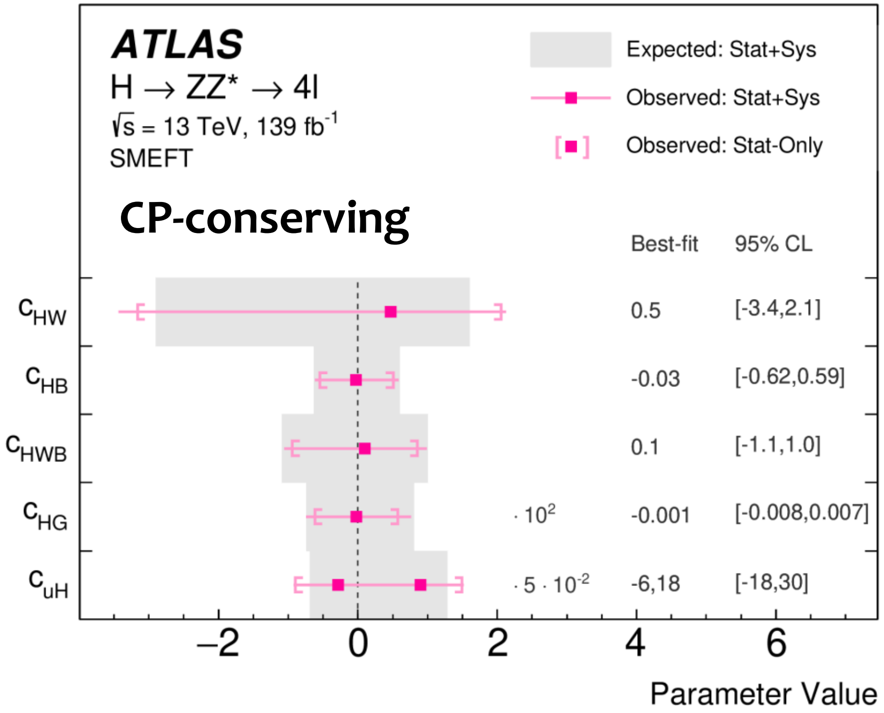
- STXS yields parameterized at LO in Warsaw basis using SMEFTsim
  - Acceptance effects small (10-20%), neglected in interpretation
- Set limits on individual parameters, and 4-5 eigenvectors from perform principal component decomposition of the full covariance





$H \to 4\ell$: SMEFT interpretation

- STXS yields parameterized at LO in Warsaw basis using SMEFTsim
  - Acceptance effects are important, e.g. from $m_{\ell\ell}$ cuts: estimated at particle-level and parameterized as function of c_{HW}, c_{HB}, c_{HWB} or $\tilde{c}_{HW}$, $\tilde{c}_{HB}$, $\tilde{c}_{HWB}$
- Set limits on 1-2 parameters at a time



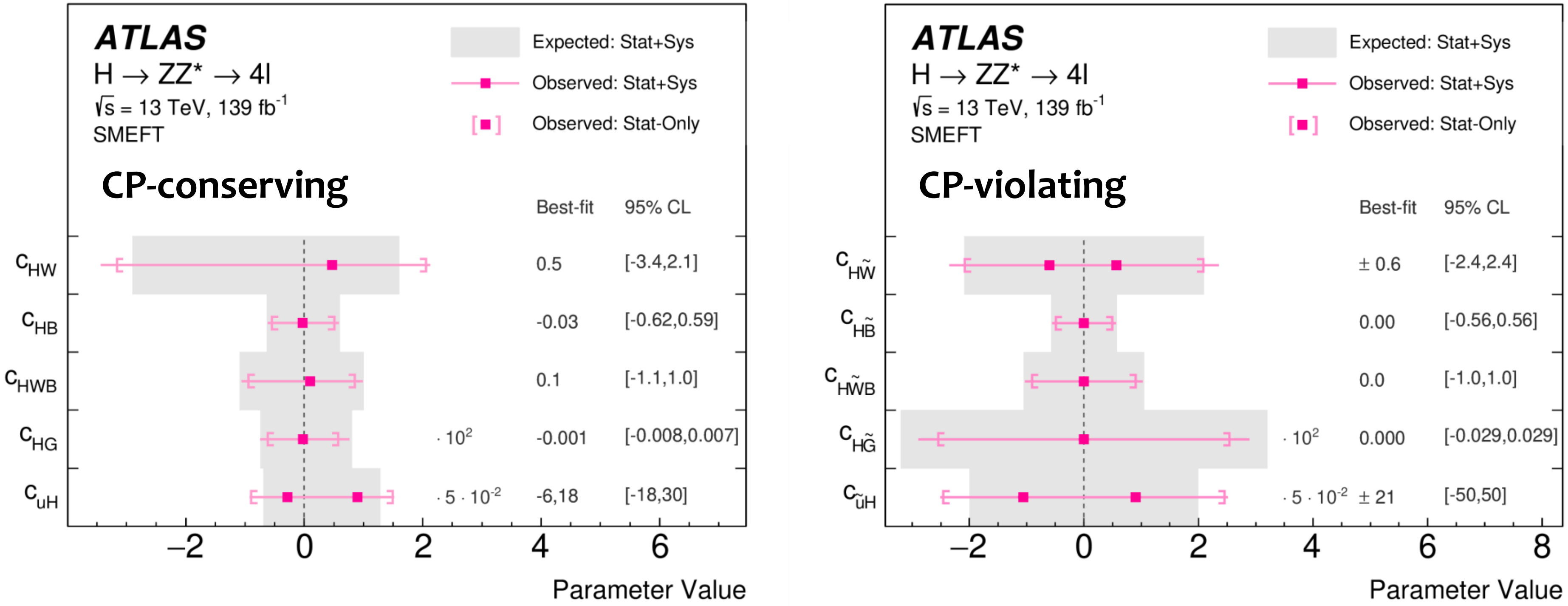
Modify HVV coupling (C_{HWB} also Vff ones)
Constrained by BR $H\to 4\ell$ and σ(VBF, VH)

Generate Hgg coupling → constrained by σ(ggH)

Modify Htt coupling → constrained by σ(ttH)
as in SMEFTsim LO c_{uH} doesn't modify σ(ggH)

$H \to 4\ell$: SMEFT interpretation

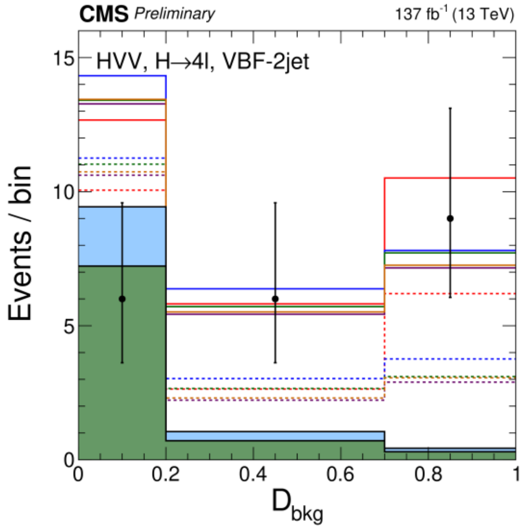
- STXS yields parameterized at LO in Warsaw basis using SMEFTsim
  - Acceptance effects are important, e.g. from $m_{\ell\ell}$ cuts: estimated at particle-level and parameterized as function of c_{HW}, c_{HB}, c_{HWB} or $\tilde{c}_{HW}$, $\tilde{c}_{HB}$, $\tilde{c}_{HWB}$
- Set limits on 1-2 parameters at a time



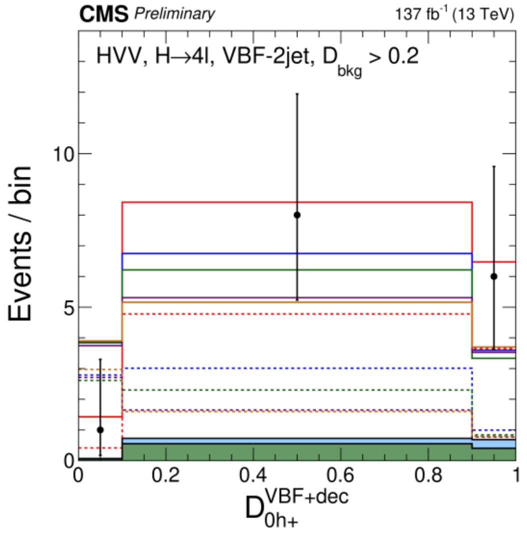
$H \to 4\ell$: AC & EFT analysis

- Dedicated analyses for anomalous couplings, separately to probe HVV and Hff+Hgg couplings
  - Including SMEFT interpretation in the Higgs basis
- Higgs production modes categories (~ STXS stage 0), and them multi-dimensional binning in discriminators:
  - D_{bkg} against qqZZ, using $m_{4\ell}$ & Matrix Element
  - Discr. for different AC hypotheses from ME / MVA (for ttH)
  - Up to 7 dimensions in VH & VBF categories
- Signal modelled as combination of templates
  - Generated full-simulation of SM and some AC benchmarks
  - Use per-event matrix element reweighting to create more

VBF $H(4\ell)$ vs qqZZ+2j



SM vs a_2 amplitude
($h\, Z^{\mu\nu}Z_{\mu\nu}$ op., c_{ZZ})



$H \to 4\ell$: AC & EFT analysis

- SMEFT result for HVV analysis, fitting 4 coefficients simultaneously
  - c_{gg} & $\tilde{c}_{gg}$ included and profiled away; no ttH category → insensitive to κ_t, $\tilde{\kappa}_t$
  - $c_{\gamma\gamma}$ & $c_{Z\gamma}$ set to zero, assuming tightly constrained by BR(γγ), BR(Zγ)

Coupling	Observed	Expected	Observed correlation			
δc_z	$-0.25^{+0.27}_{-0.07}$	$0.00^{+0.10}_{-0.28}$	1			
c_{zz}	$0.03^{+0.10}_{-0.10}$	$0.00^{+0.22}_{-0.16}$	+0.144	1		
$c_{z\Box}$	$-0.03^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$	−0.186	−0.847	1	
$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$	+0.077	−0.016	+0.009	1

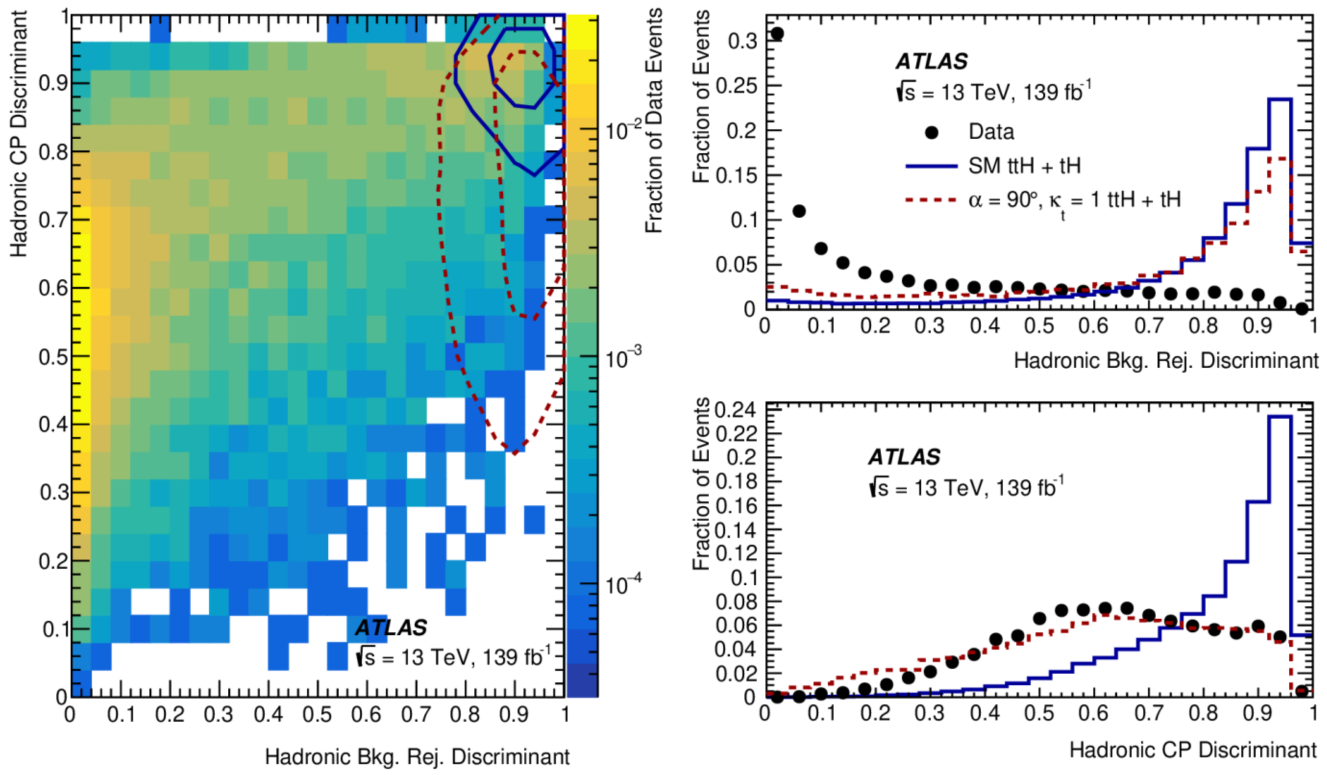
Approx translation to Warsaw basis for comparison:

$\delta c_Z = 0.2 \to c_{H\Box} = 3.3$; $c_{ZZ} = 0.2 \to c_{HW} = c_{HB} = 0.45$ (and same for CP-odd)

CP: ttH & tH with H → γγ

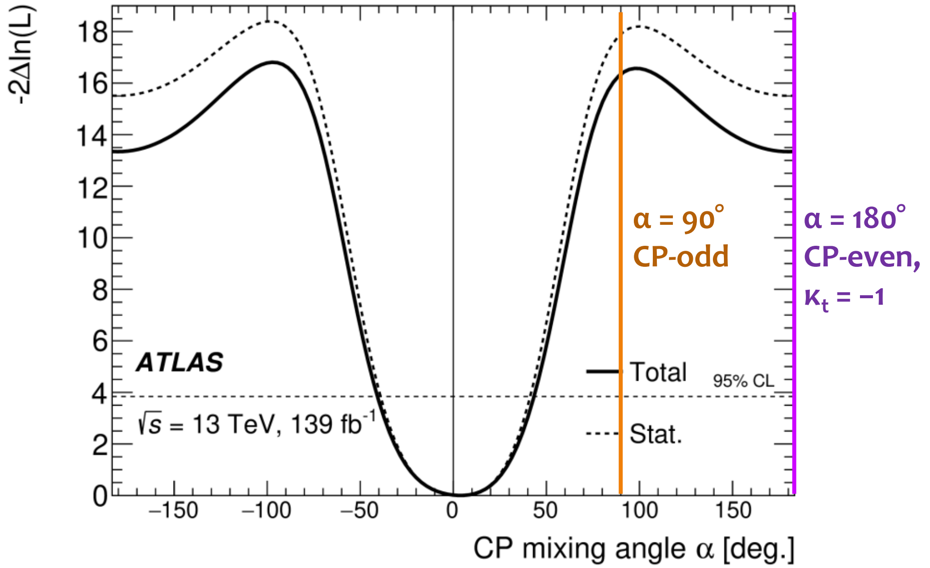
Analysis strategy:

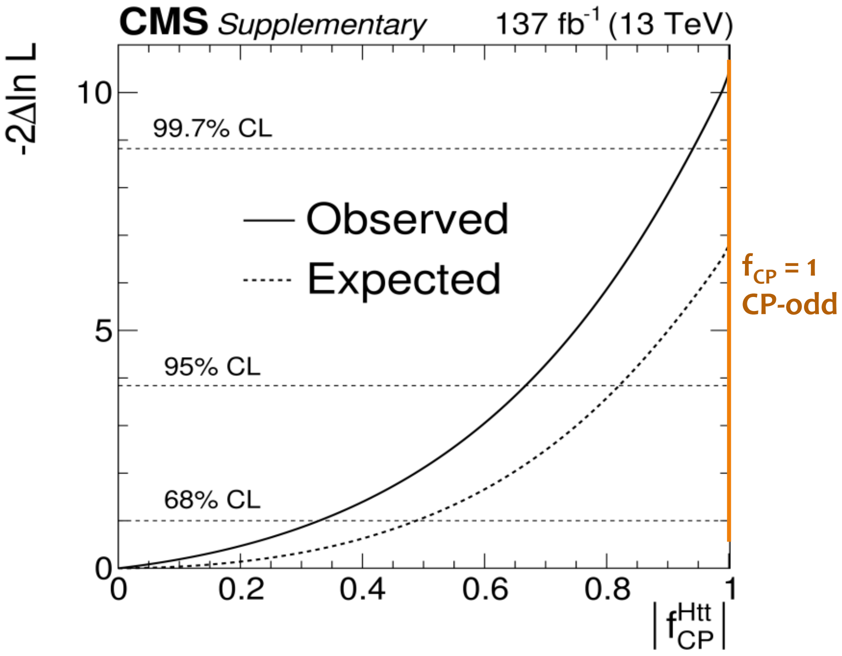
- Build MVA discriminator for CP-even vs CP-odd top quark couplings, for ttH (CMS) or ttH+tH (ATLAS)
- Categorize events in CP MVA bins and Sig vs Bkg MVA bins
- Fit $m_{\gamma\gamma}$ in all categories



CP: ttH & tH with H → γγ

- Constrain CP mixing angle or CP-odd fraction of coupling
  - $|f_{CP}| = |\tilde{\kappa}|^2 / (|\kappa|^2 + |\tilde{\kappa}|^2) = \sin(\alpha_{CP})^2$





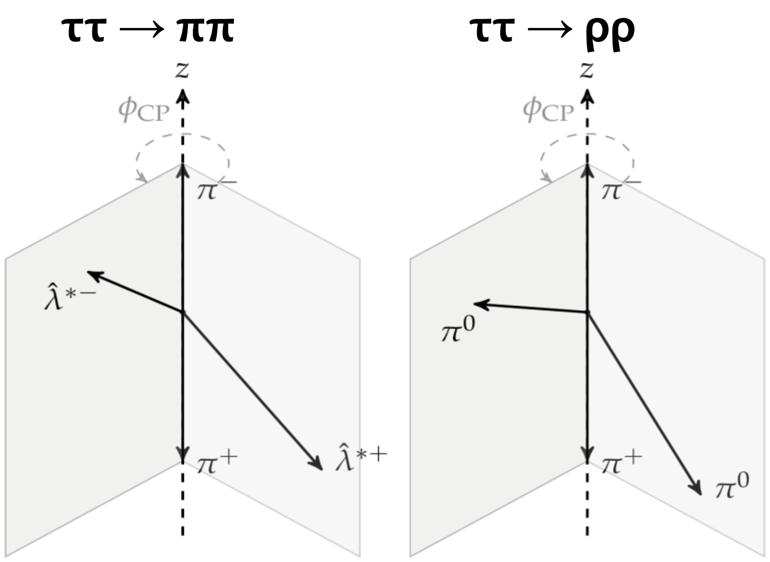
95%CL limit: $|\alpha| < 43°$ ($|f_{CP}| < 0.47$)
Pure CP-odd excluded at 3.9σ

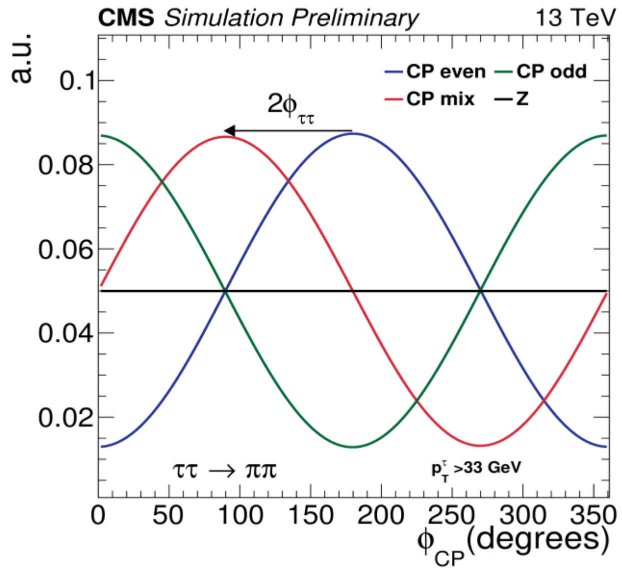
95%CL limit: $|f_{CP}| < 0.67$ ($|\alpha| < 55°$)
Pure CP-odd excluded at 3.2σ

CP: τ decays

Physics textbook analysis strategy:

- Select $H \to \tau_h \tau_h$ or $\mu\,\tau_h$, with τ_h decays to $\pi^\pm$, $\rho^\pm(\pi^\pm\pi^0)$, $a_1^\pm(\pi^\pm\pi^0\pi^0)$, $a_1^\pm(\pi^\pm\pi^+\pi^-)$
- For each τ reconstruct a decay plane
  - For 1-prong decays ($\mu^\pm$, $\pi^\pm$), use the track impact parameter vector and momentum to build the plane
- Use the distribution of the angle φ_{CP} between the two τ decay planes

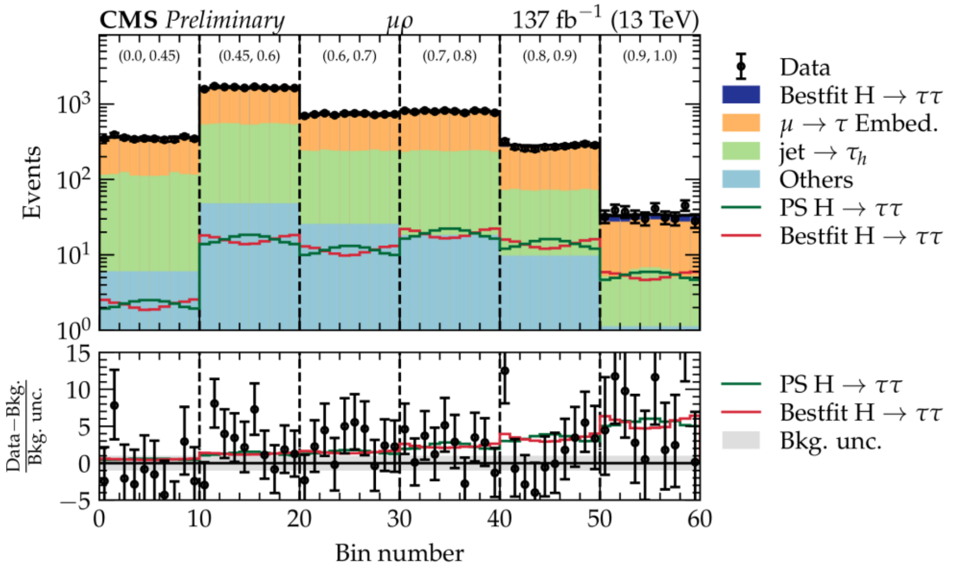


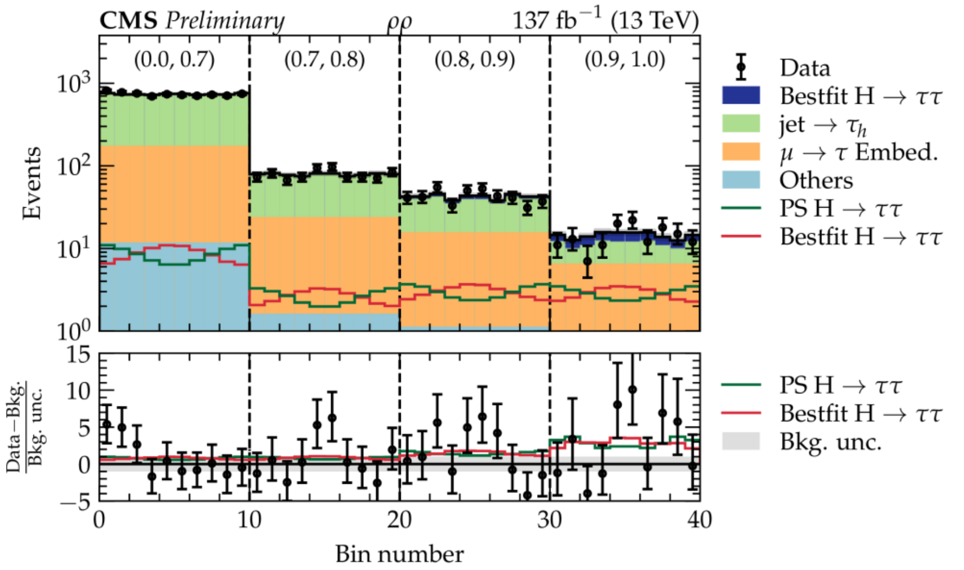


CP: τ decays

Experimental aspects:

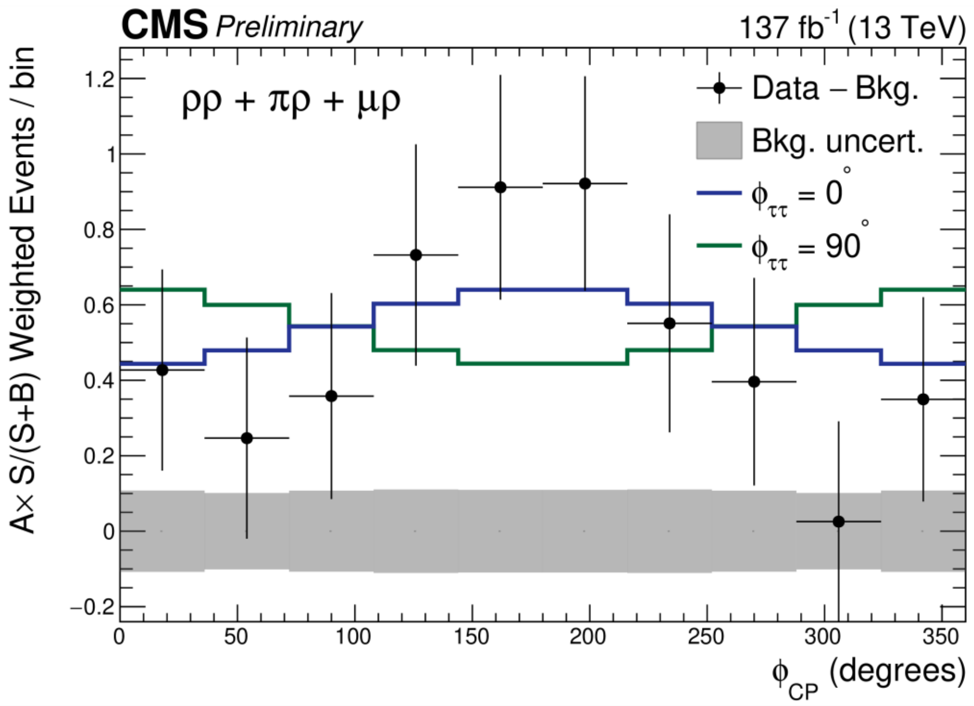
- Dedicated τ ID to tag decay modes
- Multiclass MVA to separate $H \to \tau\tau$ sig. vs two main bkgs: **genuine [Z→]ττ** events & **reducible (jet → τ_h)**
- φ_{CP} binned in slices of MVA signal score
  - separately for each decay mode
- Background estimation as STXS $H \to \tau\tau$: τ embedding and fake rate



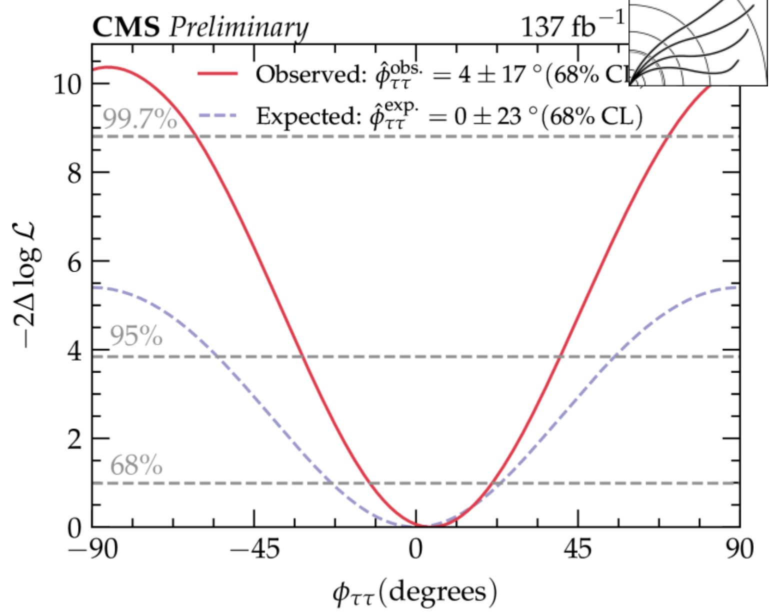


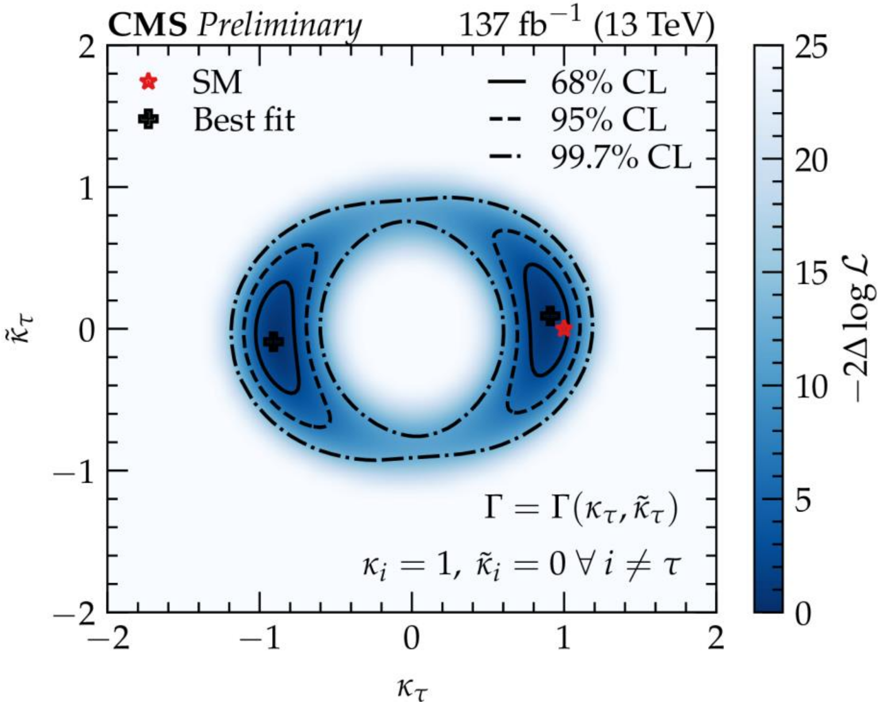
CP: τ decays

- Most sensitive final states: μρ, ρρ, πρ



- Data prefers the CP-even hypothesis:
  - 95% CL limit $|\varphi_{\tau\tau}| < 36°$ ($|f_{CP}| < 0.34$)
  - CP-odd excluded at 3.2 σ

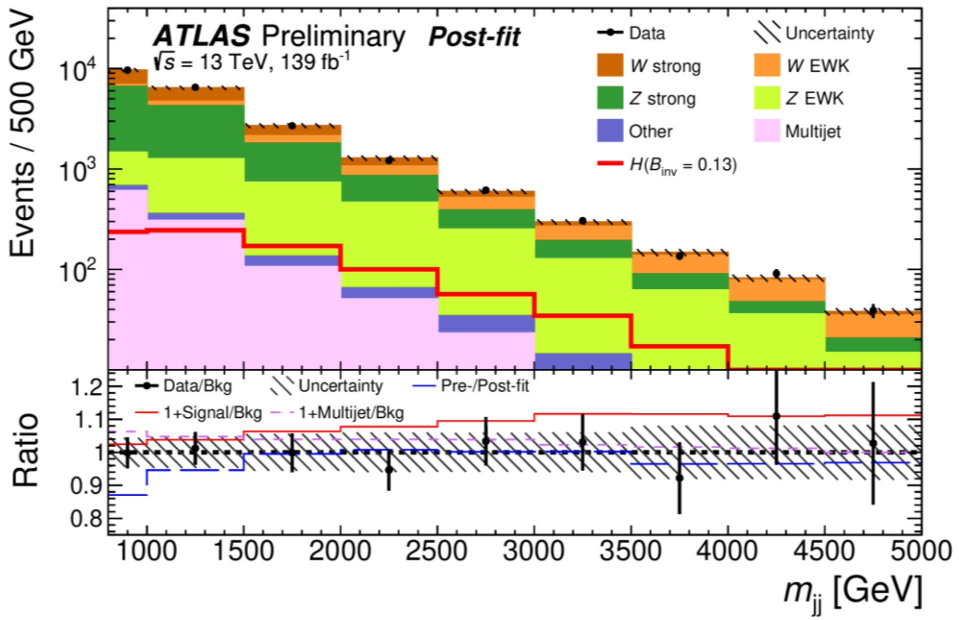


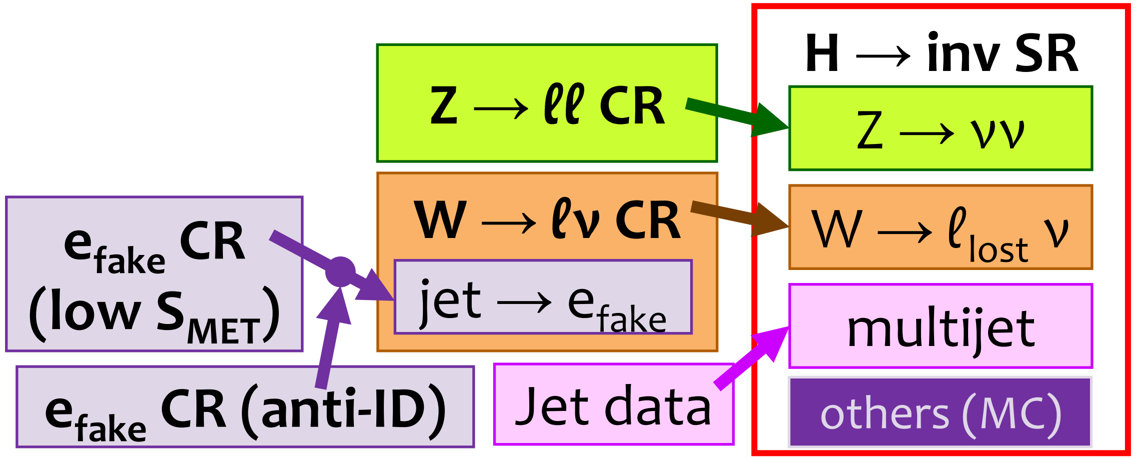


BSM

VBF H ⟶ invisible

- Search for Higgs boson decays to Dark Matter ($m_{DM} < m_H / 2$)
- VBF offers the best balance of cross section & purity
- Dominant backgrounds from Z ⟶ νν and W ⟶ ℓν (with lost ℓ)
  - Estimated from simultaneous fit using CRs of Z ⟶ ℓℓ and W ⟶ ℓν
- Sets world's best upper limit:
  - **BR(H⟶inv) < 0.13 (exp. 0.13)**

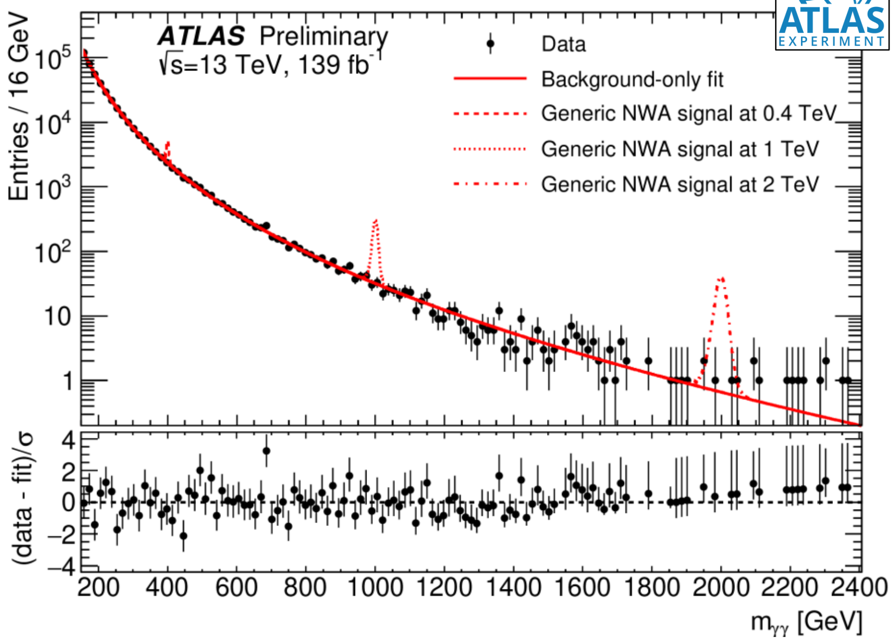


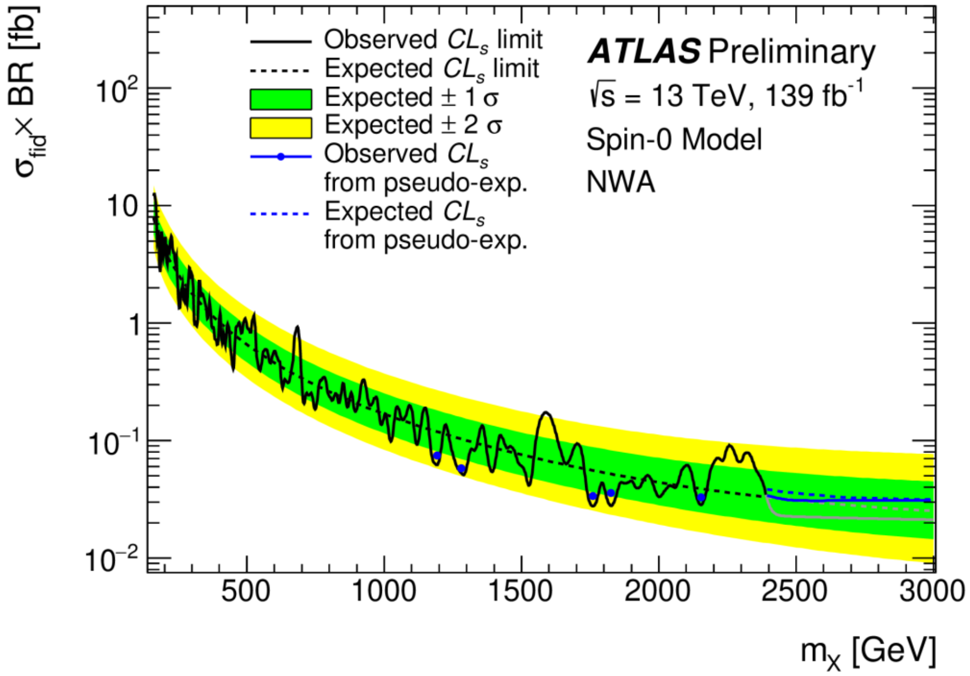


Also older 36 fb⁻¹ + Run 1 combinations from CMS [PLB 793 (2019) 520] and ATLAS [PRL 122 (2019) 231801]
BR(H ⟶ invis) upper limits: CMS 0.19 (expected 0.15), ATLAS 0.26 (expected 0.17)

$H_{BSM} \to \gamma\gamma$

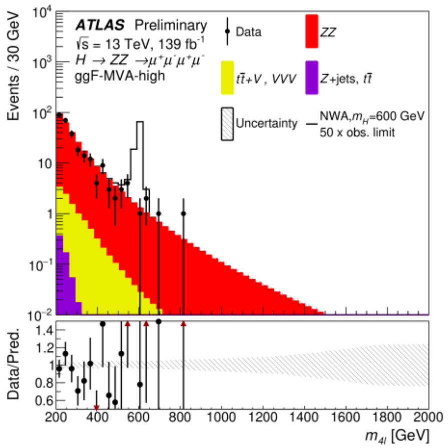
- Search for a generic spin-0 or spin-2 resonance decaying into a photon pair
- Inclusive analysis, no categorization
  - Background modelled with analytic functions as in $H \to \gamma\gamma$
  - Probe both NWA and Γ/m up to 10%
- Upper limits on σ×BR in 10 – 0.02 fb
  - Largest local excess 3.3σ at 684 GeV, Global significance 1.3σ

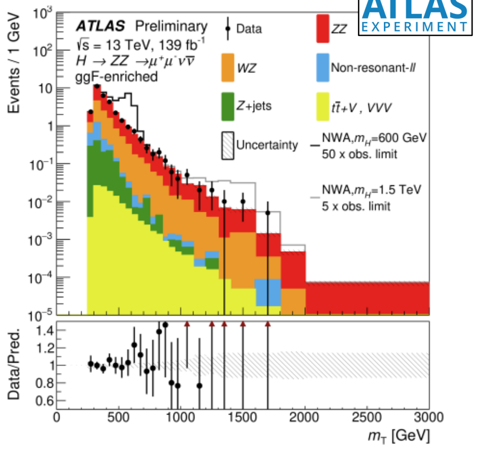


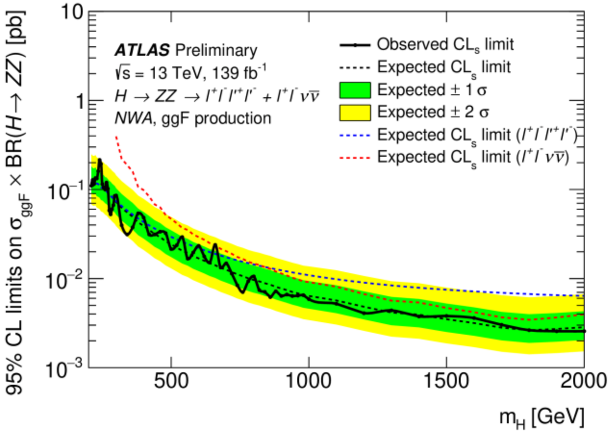


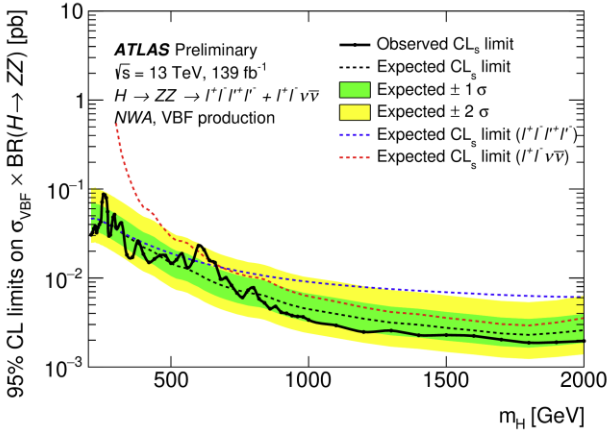
$H_{BSM} \rightarrow ZZ$

- Exploit both 4ℓ and $2\ell2\nu$ final states to increase reach at high mass
- Consider both Narrow Width Approx. and Γ/m = 1%, 5%, 10%, 15% benchmarks
  - Including interference H_{125} – H_{BSM} – ggZZ bkg
- $H \rightarrow 4\ell$ strategy
  - Use NN classifier trained against ZZ bkg to define high purity VBF and ggH categories
  - m(4l) used as final discrim. variable in fit
- $H \rightarrow 2\ell\ 2\nu$ strategy
  - Cut-based categorization for ggH & VBF
  - Transverse mass m_T used for fitting$
- Set limits on σ×BR in 200–2 fb range
  - And interpret them in 2HDM benchmarks









A lot more that I didn't describe

all using full LHC run 2 data!

ATLAS

- VBF + γ H → bb [new!]
- H^{+}_{BSM} → tb [new!]
- HH → bb WW
- VBF HH → 4b
- H → Za → $\ell\ell$ jet
- H → ZZ mass
- MSSM H → $\tau\tau$
- H → eμ (LFV), ee

CMS

- HH → bb 4ℓ [new!]
- ZH, H → invis [new!]
- H → γ + invis
- H → $Z_{(D)}Z_D$ → 4ℓ
- H → Z ρ, Z φ
- ggH, H → bb

(1-2 slides in backup for most of them)

All ATLAS results: **Higgs**, **HDBS** **"Higgs and Diboson searches"**

All CMS Higgs results: **papers**, **preliminary results**

Conclusions

Wealth of Higgs boson results from full LHC run 2 dataset:

- STXS and differential measurements with many bins.
  ttH differential measurements, and improved tH constraints.
- Fiducial cross sections at 10% precision, and κ's at 10% or better,
  EFT interpretations and dedicated EFT analyses
- First evidence for 2nd generation fermion couplings,
  and first bounds on CP violation in 3rd gen. fermion couplings

And a lot is still to come…

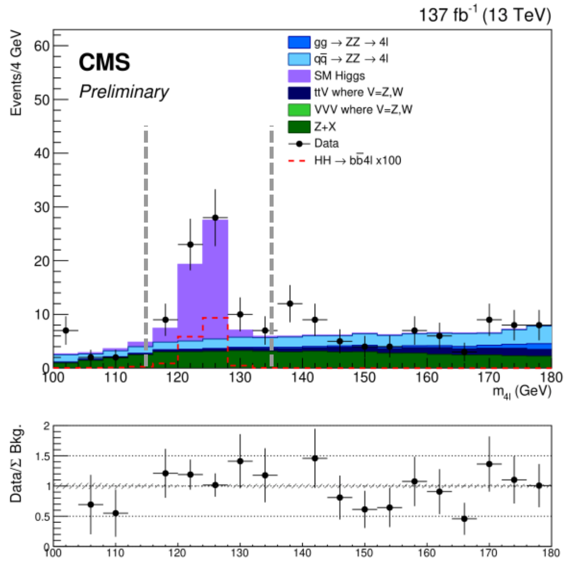
END

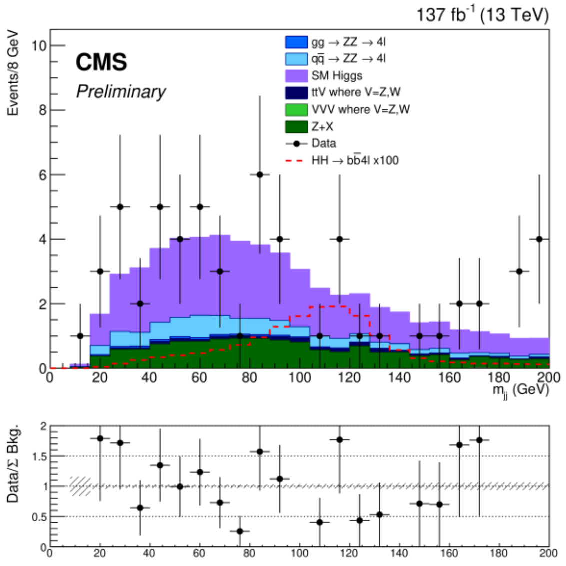
Bonus (things I didn't cover)

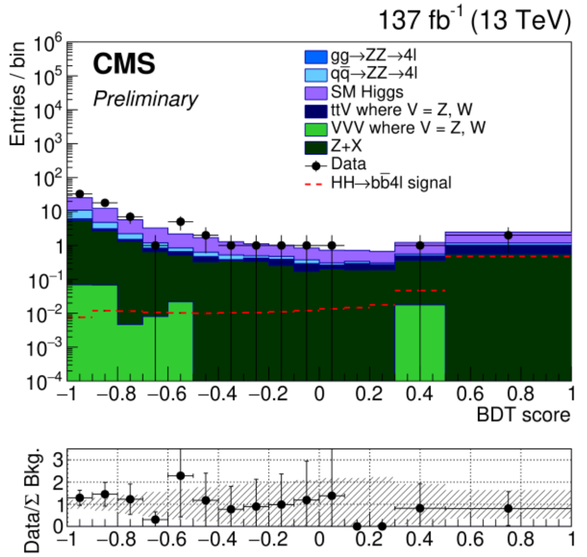
Including older slides from "HH, Rare & BSM" talk at LHCP 2020

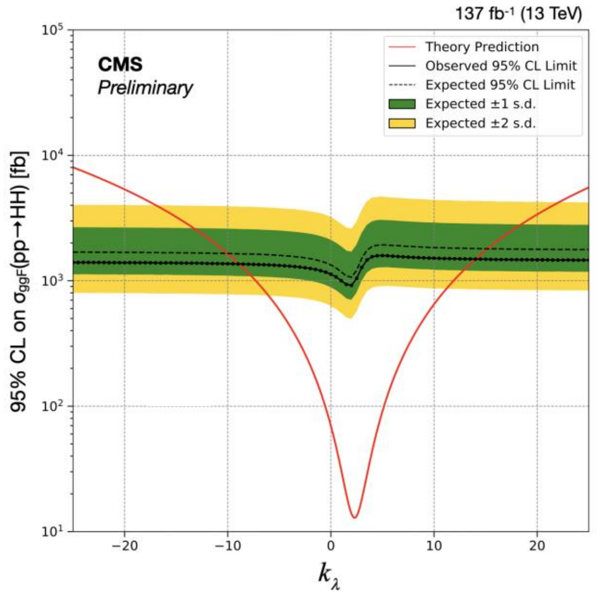
$HH \to bb\, 4\ell$

- Based on $H \to 4\ell$ analysis, requiring $115 < m(4\ell) < 135$
- Make $H \to bb$ candidate
  - $p_T(\text{jet}) > 20$ GeV, $|\eta| < 2.4$
  - If > 2 jets, pick the two with highest b-tag discriminator
- Use BDT to separate HH from backgrounds (H, ZZ, ttV)
  - Most discriminant variables: jet b-tag values, m(jj), ΔR(HH)
- Set limits $\sigma_{HH} < 30\times$SM and $-9 < \kappa_\lambda < 14$ at 95% CL



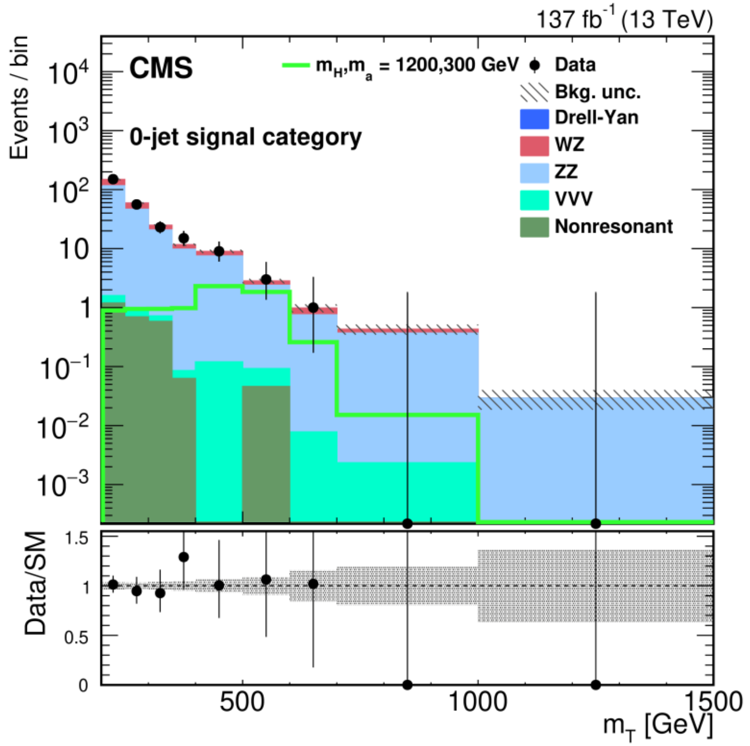


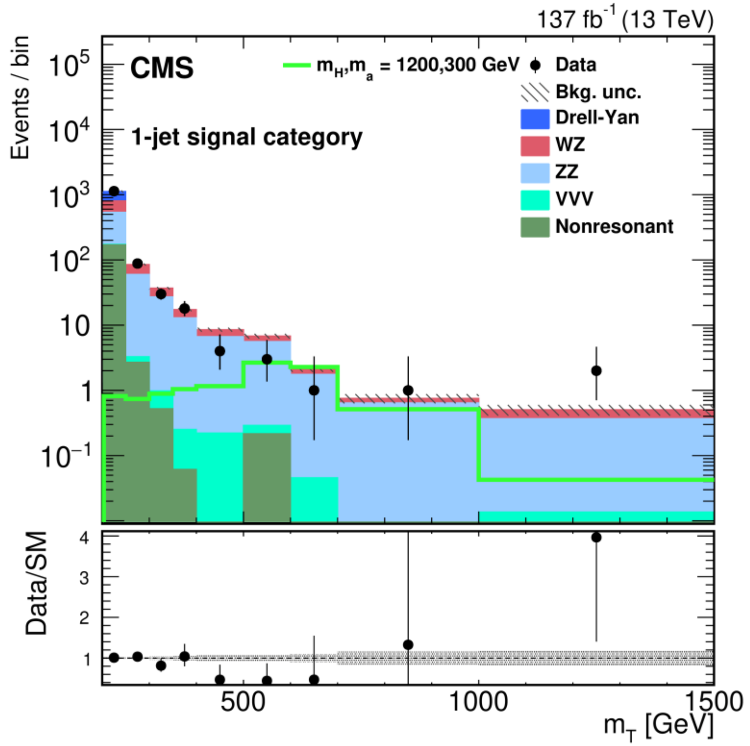


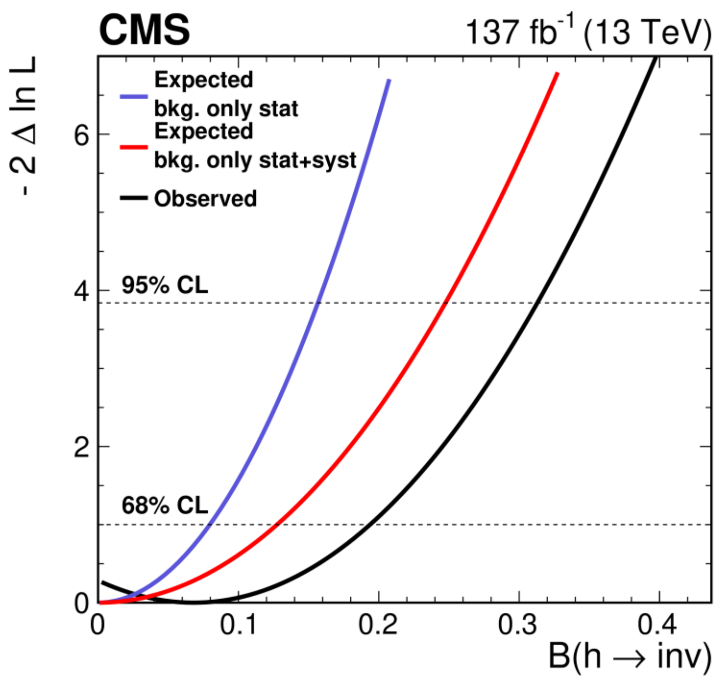


ZH, H → invisible

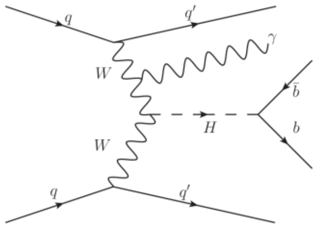
- Interpretation of $Z_{\ell\ell}$ + MET Dark matter search
- Dominant bkg are WZ and ZZ, from data in 3ℓ and 4ℓ CRs
- Set 95% CL upper limit BR(H→ inv) < 29% (expected: 25%)

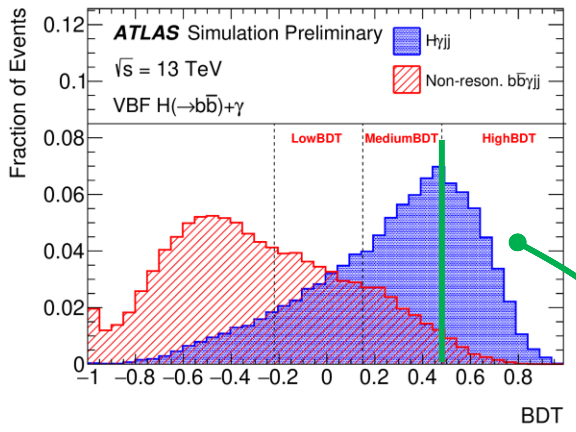


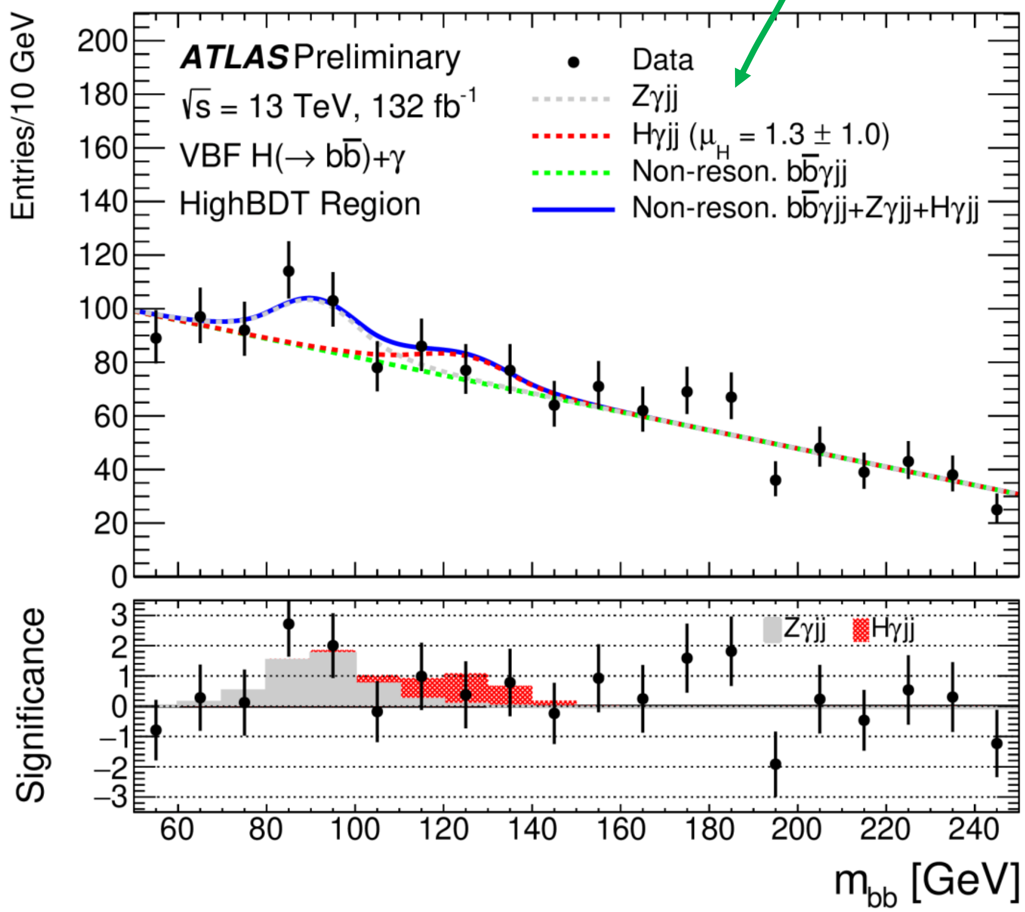




VBF + γ, H → bb

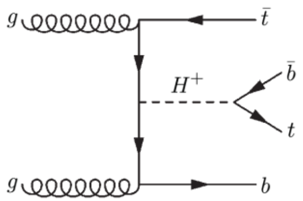






- Look for VBF H → bb with a hard photon radiation:
  - Suppress QCD background
  - Provide handle to trigger events
  - Select only WW fusion (ZZ fusion suppressed by ISR-FSR interference)
- BDT against non-resonant bbγjj
  - Trained on LO MC reweighted to match data in mass sidebands
- Fit m(bb) in BDT categories
  - **μ = 1.3 ± 1.0 (significance 1.3σ)**

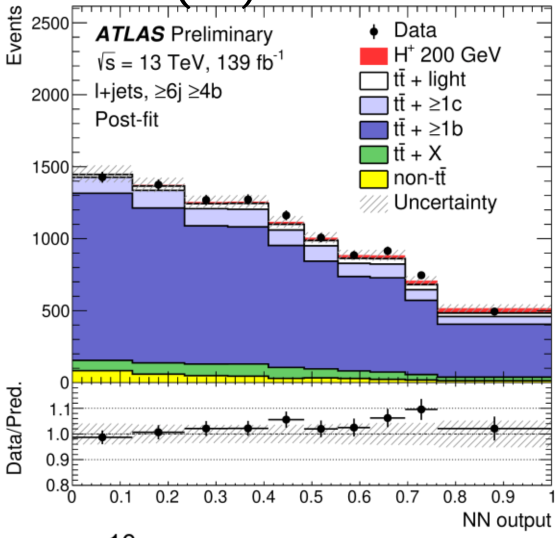
$H^+_{BSM} \rightarrow$ tb search



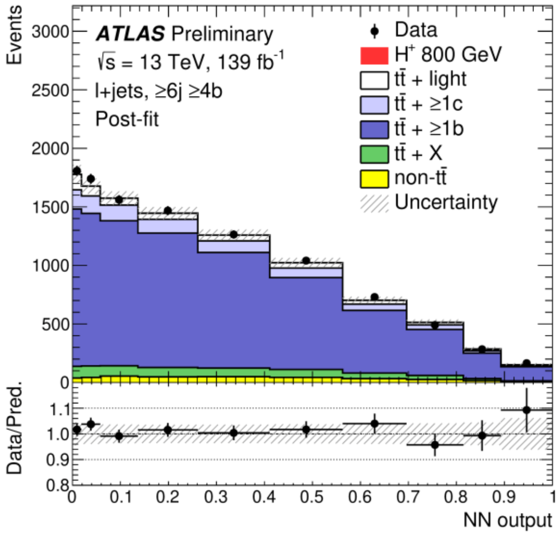
- Look for $tbH^+ \rightarrow$ ttbb production
  - Dominant production and decay mode in MSSM at low tan(β)
- Select the ℓ + jets final state, main background tt + (b-)jets
  - data/MC corrections derived for tt vs N_{jets} and H_T in events with = 2 b-jets
  - tt + ≥1 b & tt ≥ 1 c normalizations kept freely floating in the fit
- DNN parameterized on H^+ mass
  - Single DNN training with all masses
  - Signal extraction for each mass point separately from DNN output shape

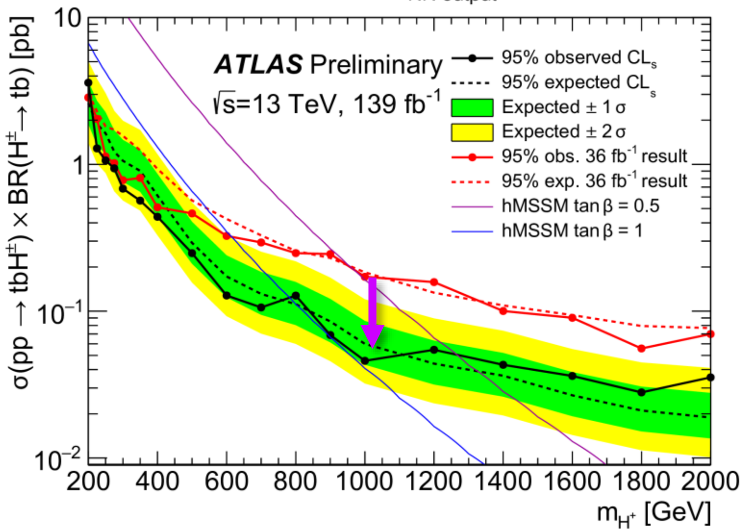
Same data & DNN training, but different $m(H^+)$ hypothesis tested

$m(H^+)$ = 200 GeV



$m(H^+)$ = 800 GeV

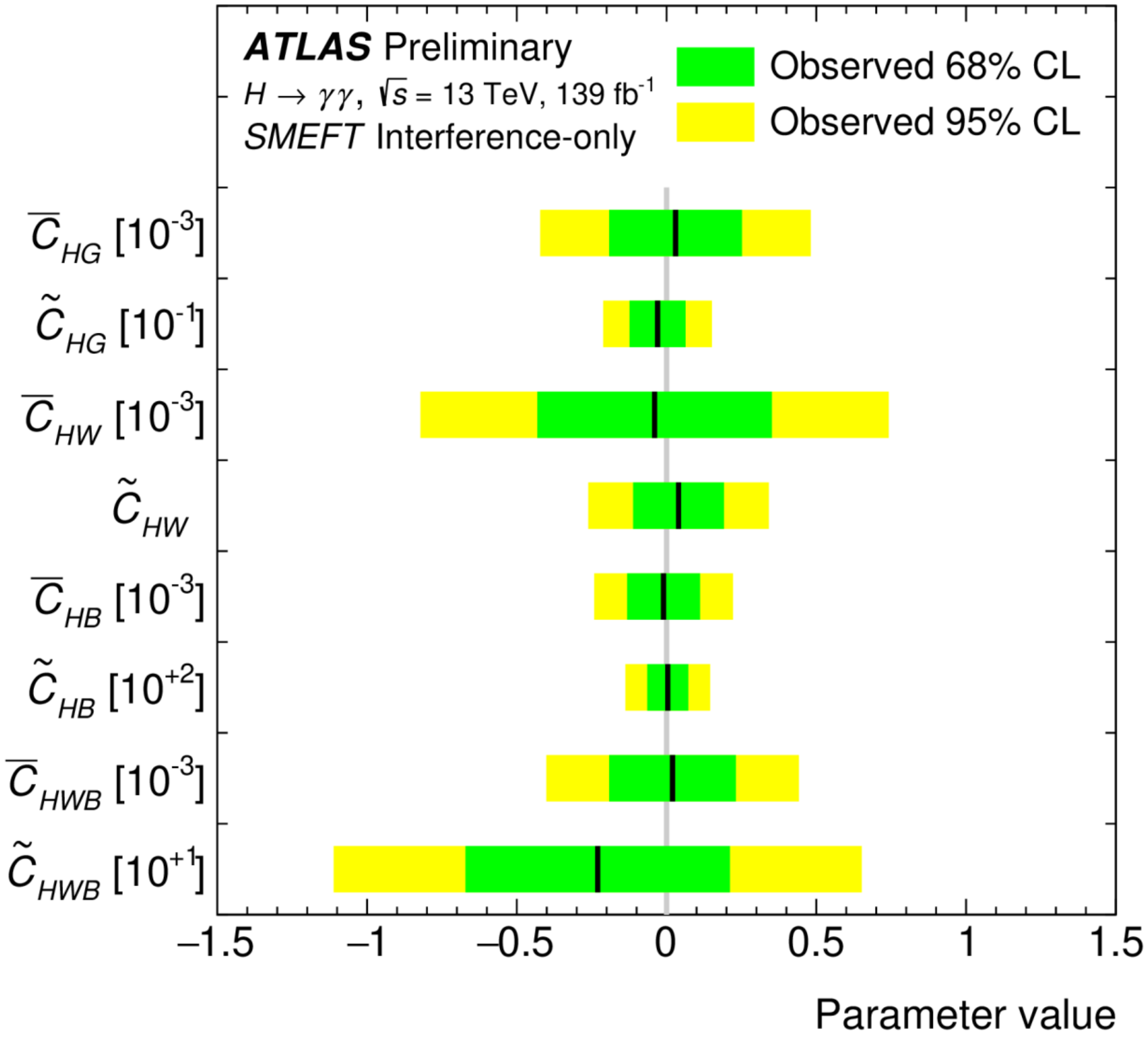




Sensitivity better by a factor 2–4 wrt 36 fb⁻¹ result

$H \to \gamma\gamma$ differential: SMEFT interpretation

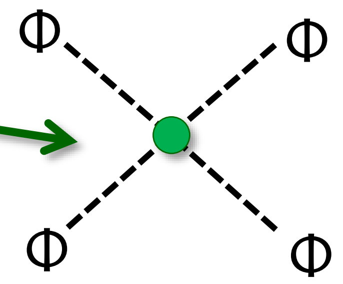
- Likelihood built from product five 1D distributions p_T^H, N_{jets}, p_T^{j1}, m_{jj}, $\Delta\varphi_{jj}$ and their covariance matrix
- Signal yields per fiducial bin derived from SMEFTsim
  - LO ratio of SMEFT/SM yields applied on top of SM prediction
  - Keeping only terms linear in $1/\Lambda^2$
- Warsaw basis, fitting one operators at a time
- BR($\gamma\gamma$) SMEFT parametrization from arXiv:1906.06949

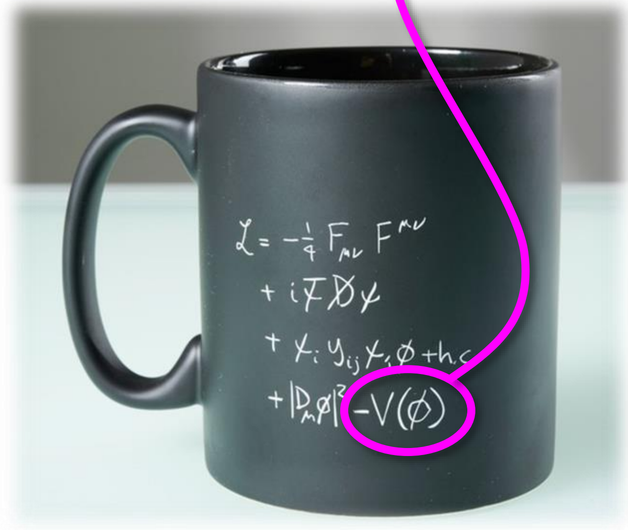


Higgs boson self-coupling

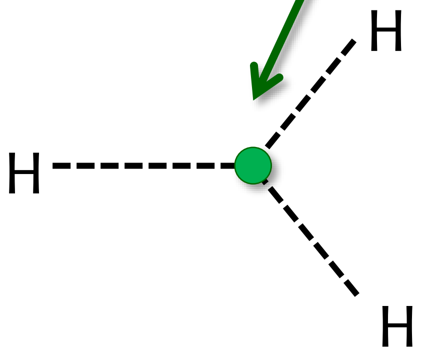
- An essential component of electroweak symmetry breaking

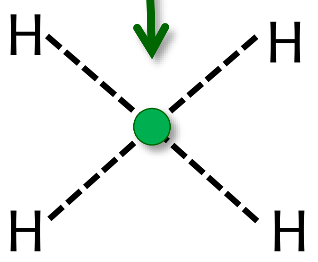
$$V(\Phi) = -\mu^2 |\Phi^\dagger \Phi| + \lambda |\Phi^\dagger \Phi|^2$$





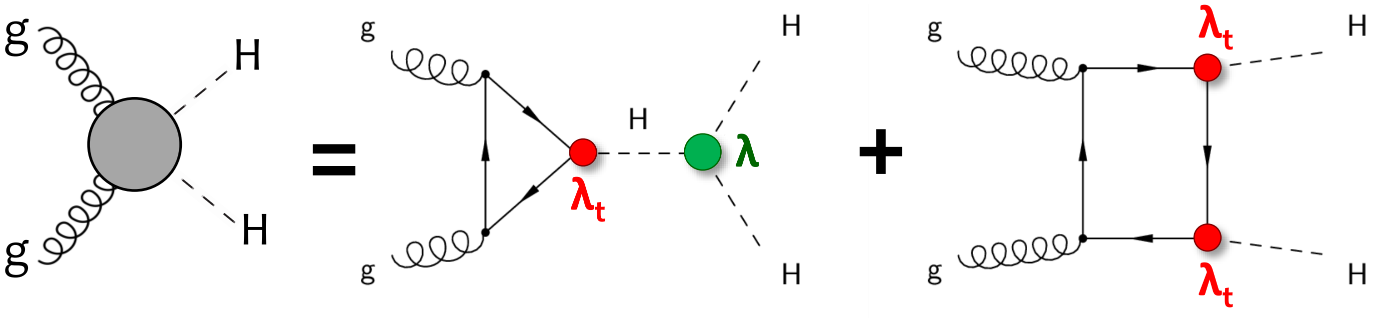
$$= V_0 + \tfrac{1}{2} m_H^2 H^2 + \lambda v H^3 + \tfrac{1}{4} \lambda H^4$$



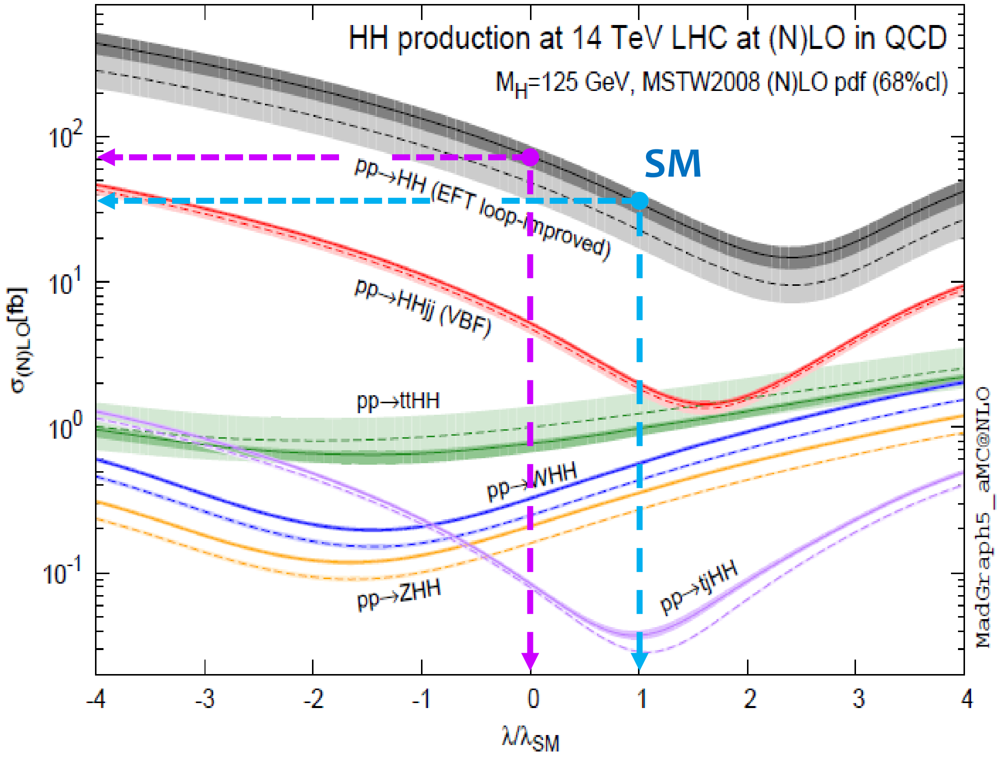


HH production in the SM: gluon fusion

- Dominant HH production mode in the SM is **gluon fusion,** driven by on **self-coupling λ** and **Higgs-top couplings λ_t**
  - $\sigma_{SM}(ggHH) = 31$ fb [~ 1/1500 of $\sigma(ggH)$!]



[PLB 732 (2014) 142-149]



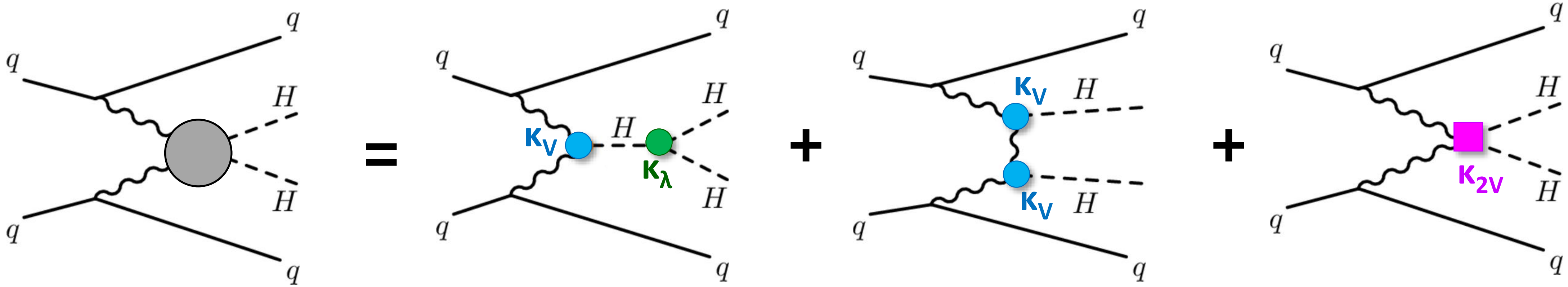
- **Destructive interference** between the two contributions: σ larger at λ = 0!

$$\sigma/\sigma_{SM} \sim 2.09\,\kappa_t^4 - 1.36\,\kappa_\lambda\kappa_t^3 + 0.28\,\kappa_\lambda^2\kappa_t^2$$

[$\kappa_t := \lambda_t / \lambda_t^{SM}$; $\kappa_\lambda := \lambda / \lambda_{SM}$]

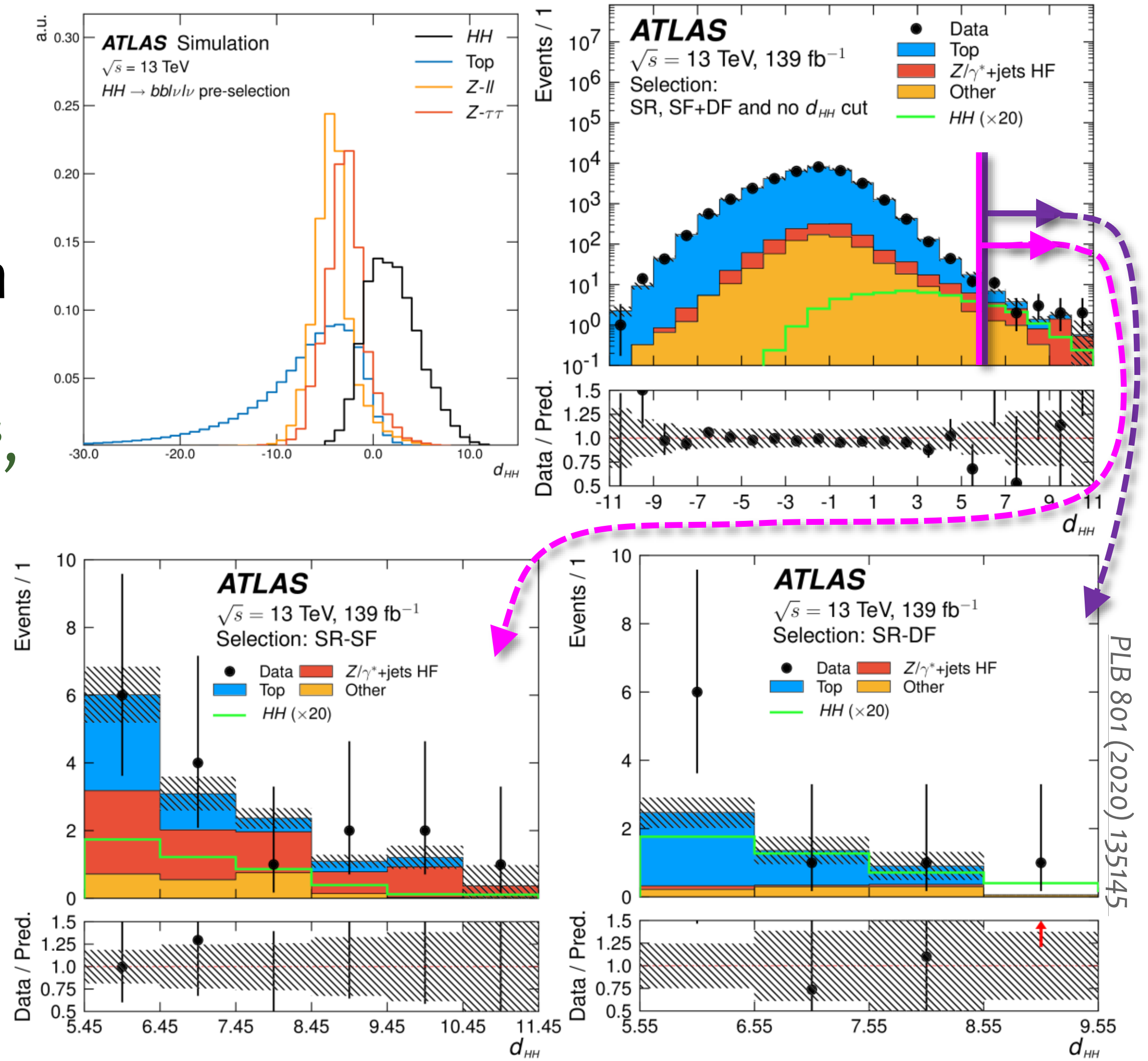
HH production: vector boson fusion

- VBF is the second production mode, with **σ_{SM} = 1.72 fb**
  - ~1/20 of ggHH, ~1/2000 of VBF H
- Receives contributions from **self-coupling** HHH, **HVV** coupling (κ_V, well measured in single Higgs), and **HHVV** quartic vertex (κ_{2V}).
  - $\kappa_{2V} = \kappa_V^2$ if H is part of a $SU(2)_L$ doublet, as in the SM or the SMEFT.
  - Otherwise, large increase in σ_{VBF} possible: $V_L V_L \rightarrow H H$ would violate unitary



HH → bb $W_{\ell\nu}W_{\ell\nu}$

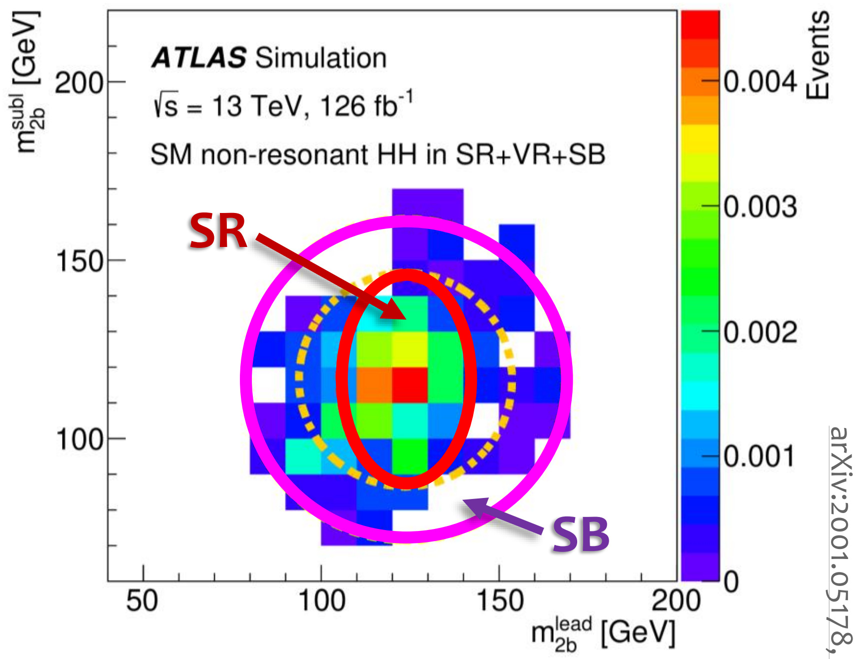
- First HH → $bb\ell\nu\ell\nu$ analysis at ATLAS
- Multiclass DNN to separate **HH** from 3 main backgrounds: $t\bar{t}$, $Z(\ell\ell)$, $Z(\tau\tau)$
  - Inputs are individual leptons, jets, E_T^{miss}, high-level variables (e.g. $\Delta R_{\ell\ell}$, m_{T2}^{bb})
  - Output $\mathbf{d_{HH} := \ln(p_{HH} / \Sigma\, p_{bkg})}$
- Signal regions defined by d_{HH} cuts
- ×8/×3 better sensitivity than old 36 fb⁻¹ analyses from ATLAS[*]/CMS:
  - Set limit at **σ_{HH} < 40×SM (exp.: 29×SM)**

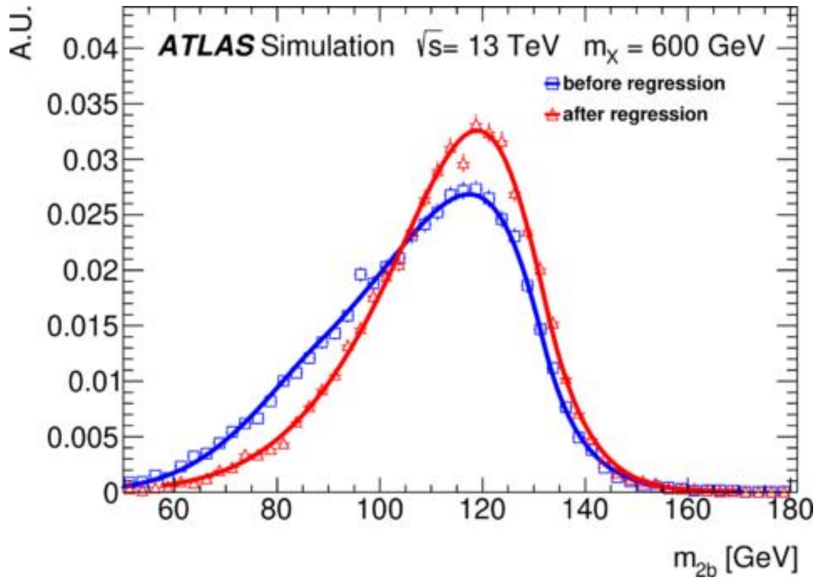


[*] older analysis was for the H→ WW→ ℓνqq, qqqq decays

VBF HH → 4b

- Target the more extreme kinematic of $\kappa_{2V} \neq 1$
  - **Tight cut-based VBF cuts: m_{jj} > 1 TeV, $|\Delta\eta_{jj}|$ > 5**
- Largely based on earlier HH → 4b search on 36 fb^{-1} dataset *[JHEP 01 (2019) 030]*
  - Same strategy used for HH → 4b selection: ΔR_{bb} cuts dependent on m_{4b}, elliptic **signal region** in the plane of the two m_{2b} masses
  - Same estimation of main QCD multi-jet and $t\bar{t}$ background: from events with 2 b-tags, with weights derived in **mass sideband**
- New b-jet energy regression using a BDT
  - ~10% better b-jet energy resolution

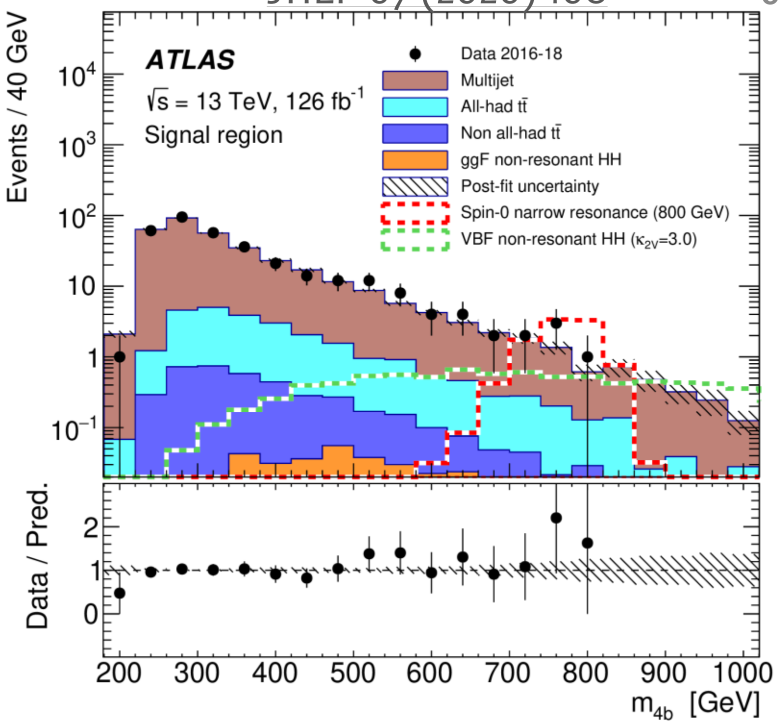


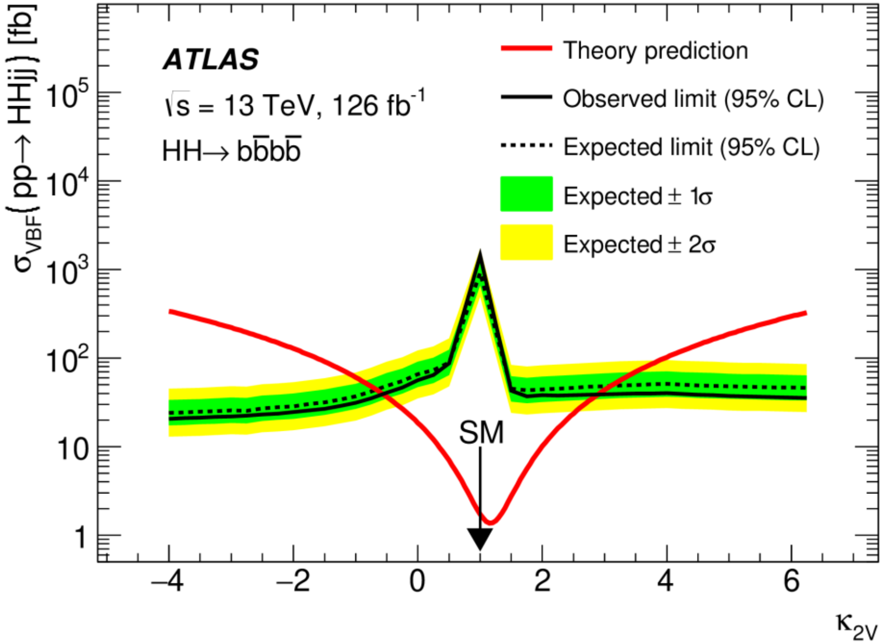


arXiv:2001.05178, sub. to JHEP

VBF HH → 4b

- Use m(4b) as final discriminating variable
  - Searching also for resonant VBF X → HH
- Focus on probing **anomalous κ_{2V}**
  - Set $\kappa_V = 1$, $\kappa_\lambda = 1$
  - SM ggHH negligible with present sensitivity
- Set limit **$-0.56 < \kappa_{2V} < 2.89$** @ 95% CL (expected limit $-0.67 < \kappa_{2V} < 3.10$)
  - **First constraints on κ_{2V} at LHC !**
  - But still far from sensitivity to SM VBF HH. Set upper limit $\sigma/\sigma_{SM} < 840$ (exp. 540)

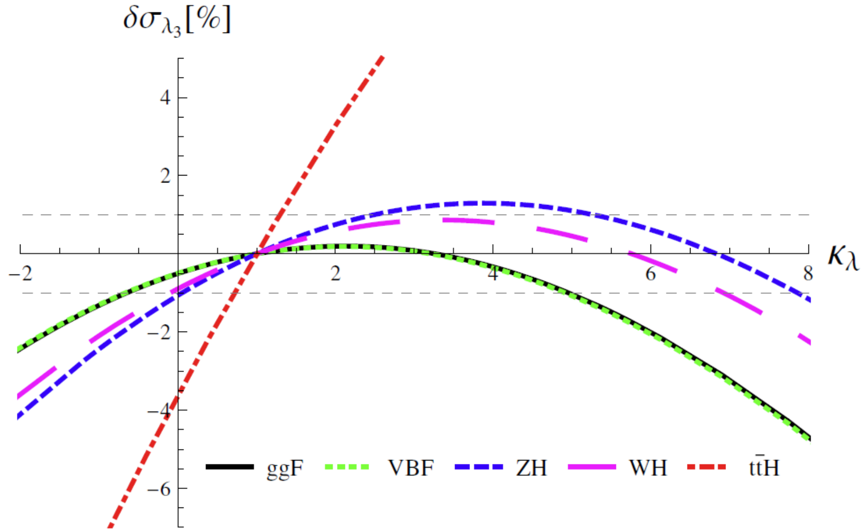




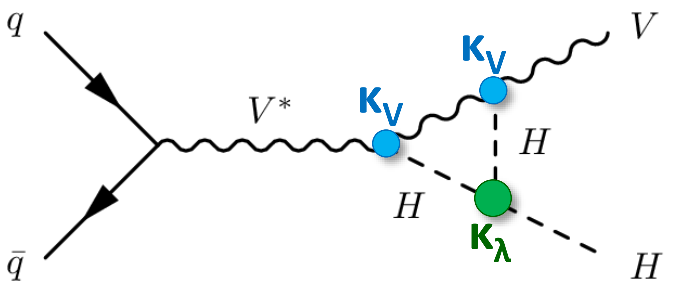
arXiv:2001.05178, sub. to JHEP

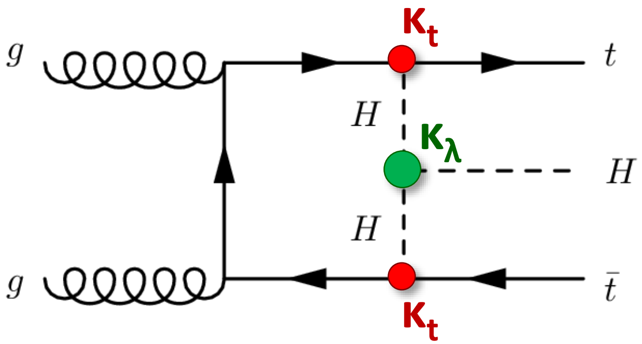
Constraining self-coupling from single H

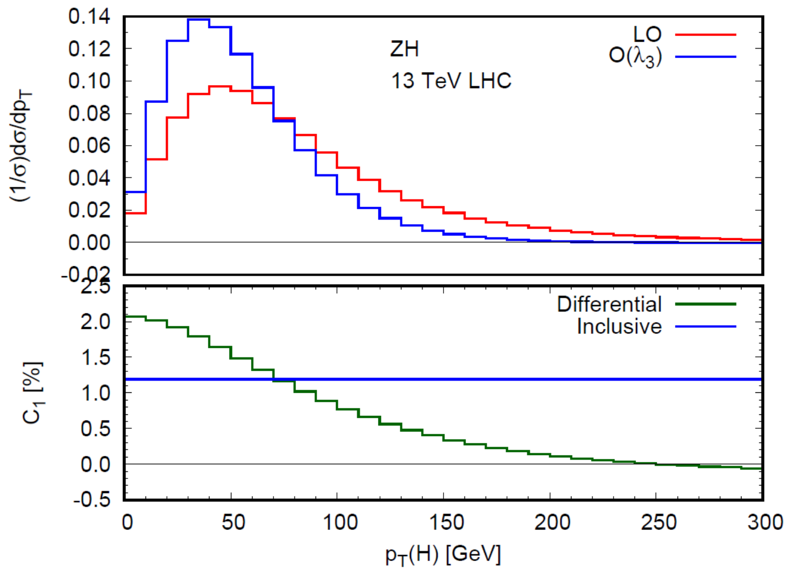
- At NLO, single Higgs observables are sensitive to Higgs boson self-coupling
  - O(1%) corrections to σ_H and BRs for $\Delta\kappa_\lambda = 1$ Largest effect inclusively is ~3.5% on σ_{ttH}
  - Use of kinematic information, e.g. $p_T(H)$, can enhance the effect further (~×2–3)



JHEP 12 (2016) 080





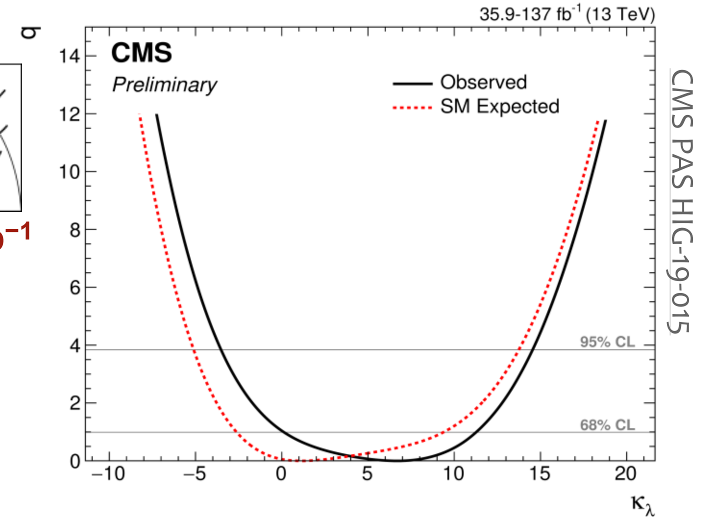


EPJC 77 (2017) 12, 887

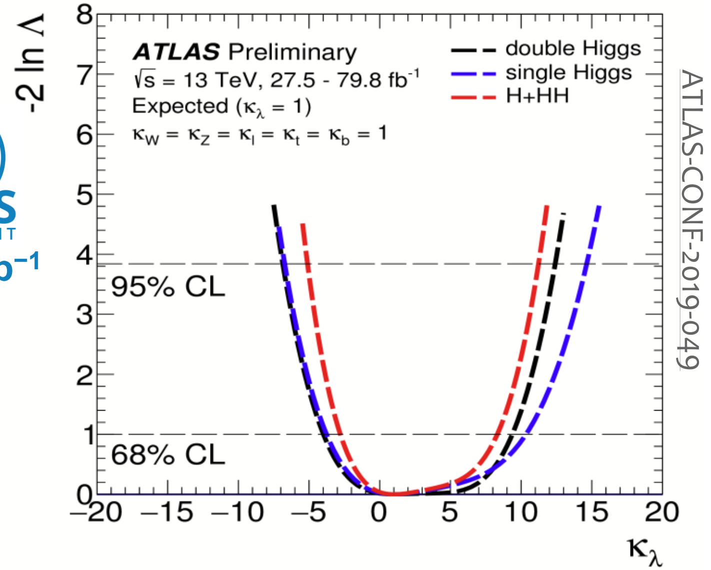
Constraining self-coupling from single H

- Explored by both ATLAS & CMS in the latest single-H combinations
  - ATLAS also including some kinematic information via STXS in VH & VBF prod.
- Constraints comparable to HH searches but only under tight mode assumptions
  - All other couplings fixed to SM, or only floating κ_V or only κ_f
- ATLAS: also combined H + HH fit*
  - Tighter constraint in κ_λ-only fit
  - Allow more general model with floating individual κ's and also κ_λ

L ≤ 137 fb^{-1}



L ≤ 80 fb^{-1}



*: *ttH(γγ) dropped from H inputs due to large overlap with HH(bbγγ)*

Overall summary of 95% CL limits on κ_λ

inputs	model.	ATLAS	*(expected)*	CMS	*(expected)*
Single H	only κ_λ	−3.2, 11.9	*−6.2, 14.4*	−3.5, 14.5	*−5.1, 13.7*
HH	only κ_λ	−5.0, 12.0	*−5.8, 12.0*	−11.8, 18.8	*−7.1, 13.6*
H + HH	only κ_λ	−2.3, 10.3	*−5.1, 11.2*		
H + HH	κ's & κ_λ	−3.7, 11.5	*−6.2, 11.6*		

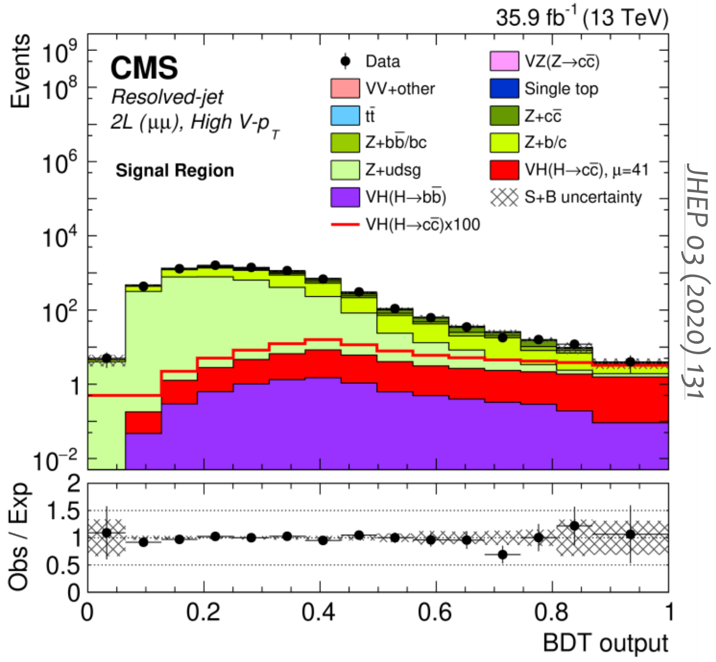
Disclaimer: these are still rather ad-hoc models; still a lot of work ahead for both theorists and experimentalists before we can have a more sounded global fit with full NLO SMEFT or HEFT

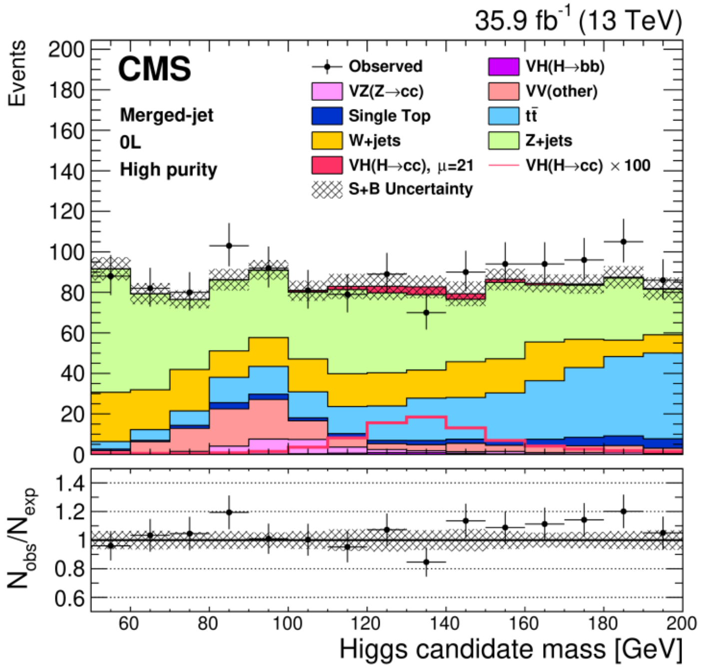
$H \to c\bar{c}$

L = 36 fb^{-1}

- $BR_{SM}(H \to c\bar{c})$ = 2.9% ~ 1/20 of $BR(H \to b\bar{b})$
- Target VH with V = $Z \to \ell\ell$, $W \to \ell\nu$, $Z \to \nu\nu$, with the combination of two strategies:
  - **Resolved analysis**: based on VH($b\bar{b}$) analysis, but with charm tagging. Signal extraction from fit to BDT
  - **Boosted analysis:** use anti-k_T(R=1.2) jets with advanced H→cc DNN tag (flavour + substructure), Signal extraction from groomed jet mass
- Multiple control regions to normalize in data the main backgrounds, i.e. V + jets and $t\bar{t}$
- **Set limits $\sigma \times BR(H \to c\bar{c})$ < 70×SM (exp. 37×SM)**

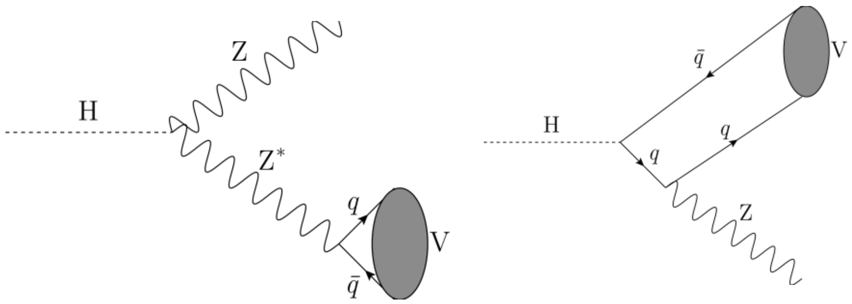
Also older ATLAS VH($c\bar{c}$), 36 fb^{-1}, only $Z \to \ell\ell$ channel and simpler analysis, Observed upper limit 110 × SM (expected 150 × SM) [PRL 120 (2018) 211802]



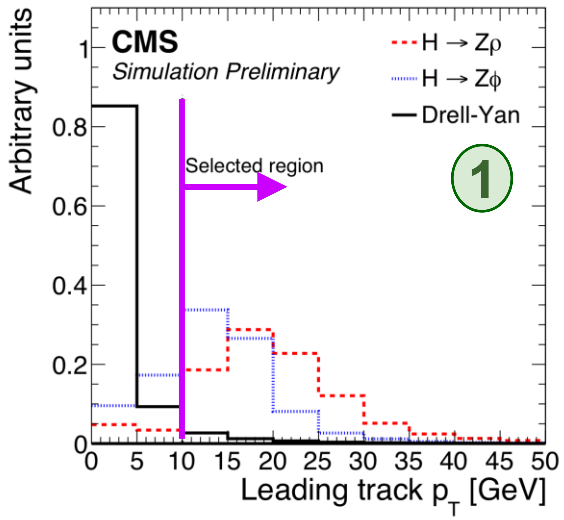


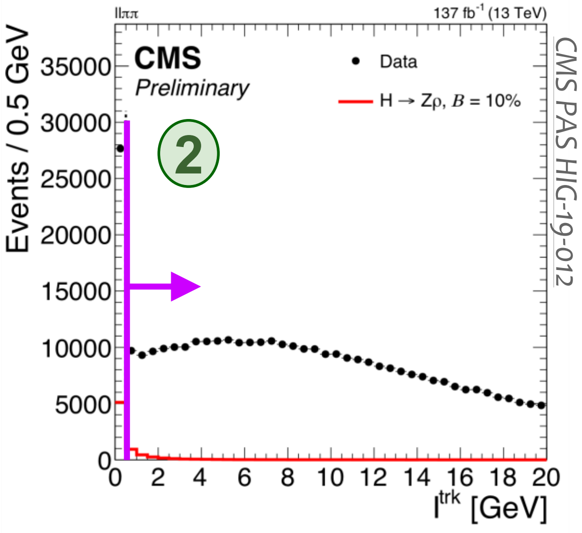
L = 137 fb^{-1}

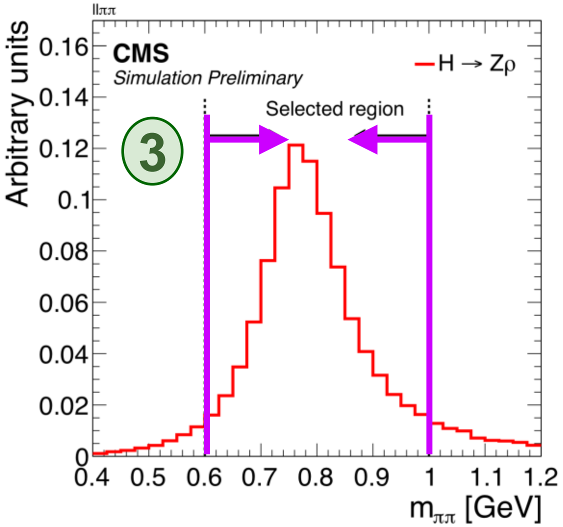
H → Z + ρ/φ

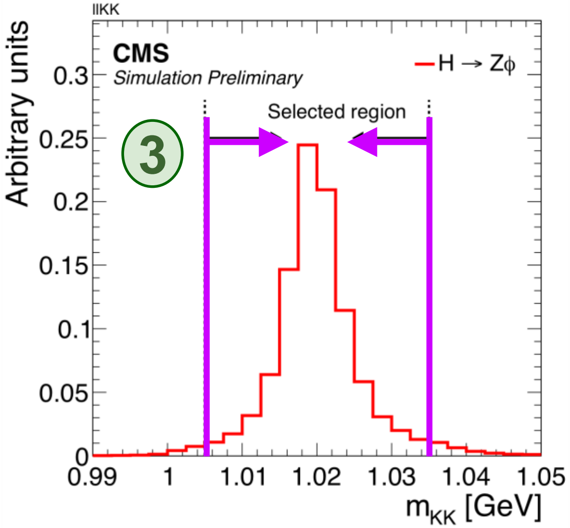


- SM BR mainly via H → Z Z/γ* → Z V, but H → qq channel may have large enhancement in some BSM models
- Target **ρ** → **π**$^+$ **π**$^-$ and **φ** → **K**$^+$ **K**$^-$
  1. Select pairs of opposite-charge tracks, ΔR < 0.1 and p_T^{lead} > 10 GeV
  2. Require di-track pair to be isolated
  3. Select window in di-track mass



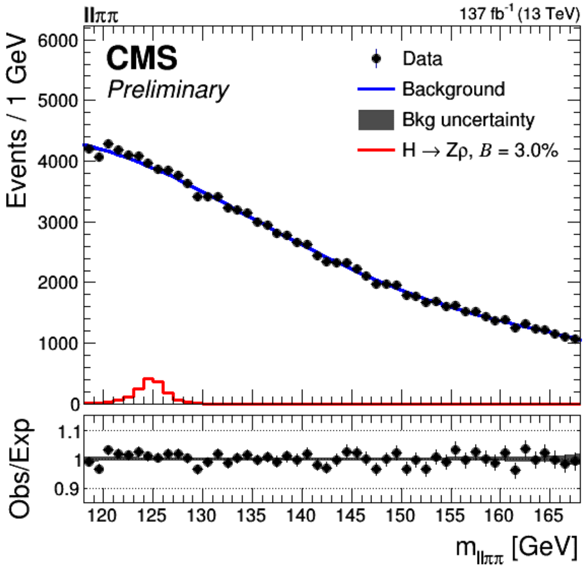


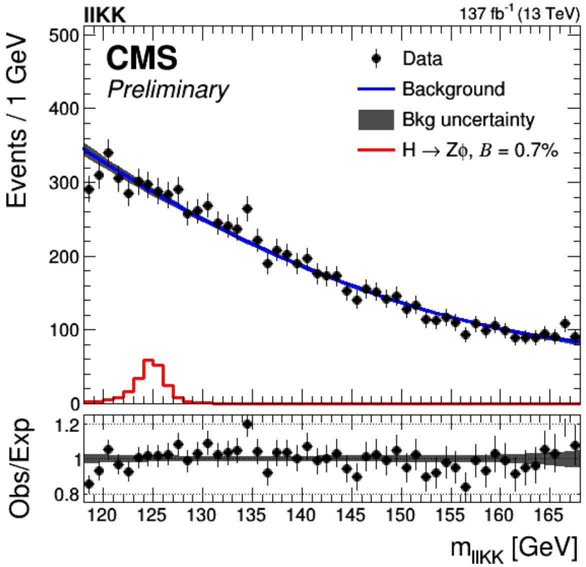


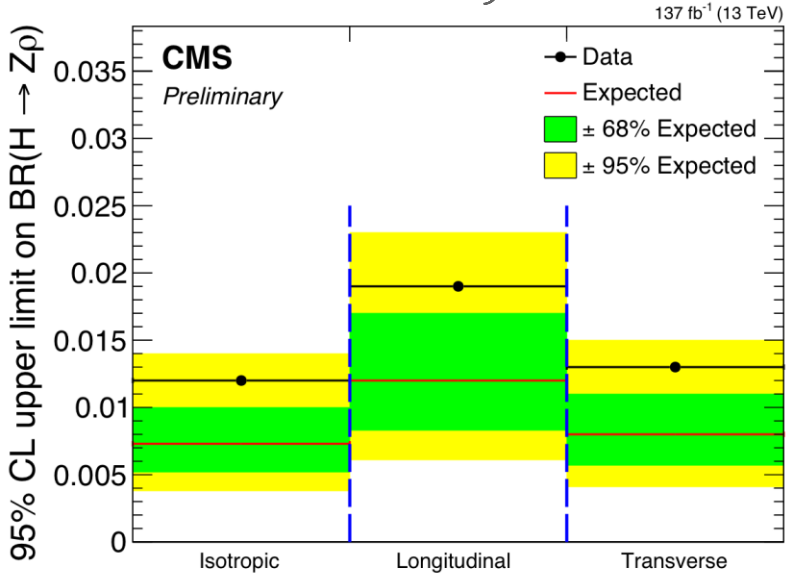


H → Z + ρ/φ

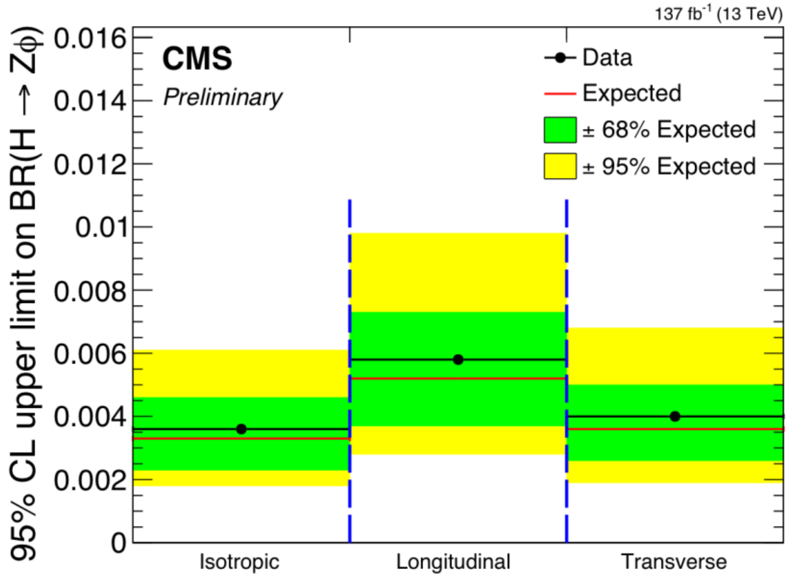
- **Fit m(ℓℓππ) or m(ℓℓKK)** to extract signal
  - Agnostic background model, *a la* H → γγ
- Set upper limits in the 0.3 – 2 % range
  - Acceptance depends on polarization, limits provided for different scenarios
  - Corresponding to ~ 860 – 1350 × SM BR







CMS PAS HIG-19-012



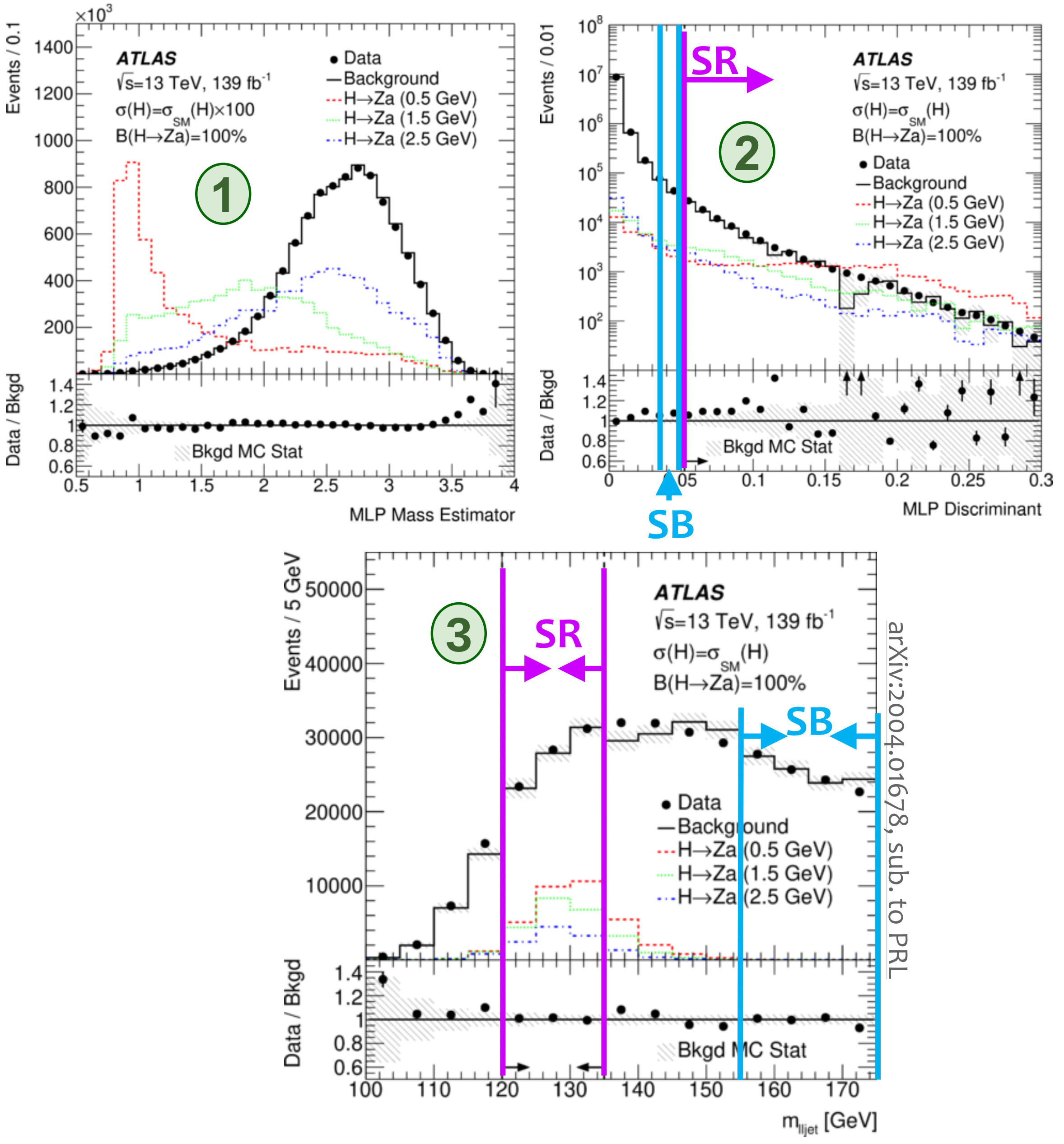
ATLAS EXPERIMENT

Also older ATLAS H → γ ρ/φ with 36 fb⁻¹
Set BR limits at 52 / 208 × SM for ρ / φ
[JHEP 07 (2018) 127]

$H \to Z\,a \to \ell\ell\,j$

ATLAS EXPERIMENT
$L = 139\ \mathrm{fb}^{-1}$

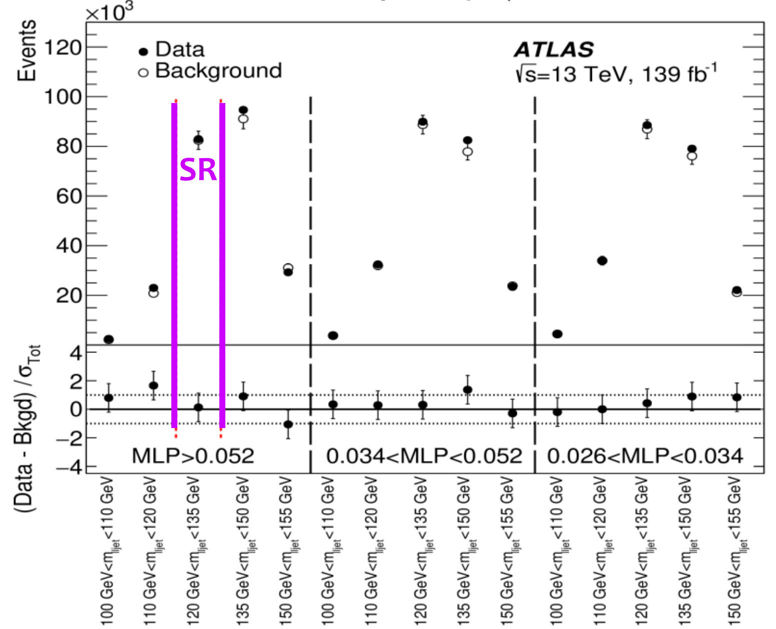
- Search for pseudoscalar "**a**"
  - e.g. in NMSSM or 2HDM+S models
- Target **inclusive hadronic decays $a \to$ jet**, for **m_a < 4 GeV**
  1. **MLP regression** to estimate a mass from jet substructure information
  2. **MLP discriminator** vs Z + jets bkg (using MLP regression as input)
  3. Define **signal region** by cutting on m(ℓℓj) and discriminator output
- Estimate backgrounds from data:
  - "ABCD" method with **sidebands** in m(ℓℓj) & MLP discriminant (+ corrections)

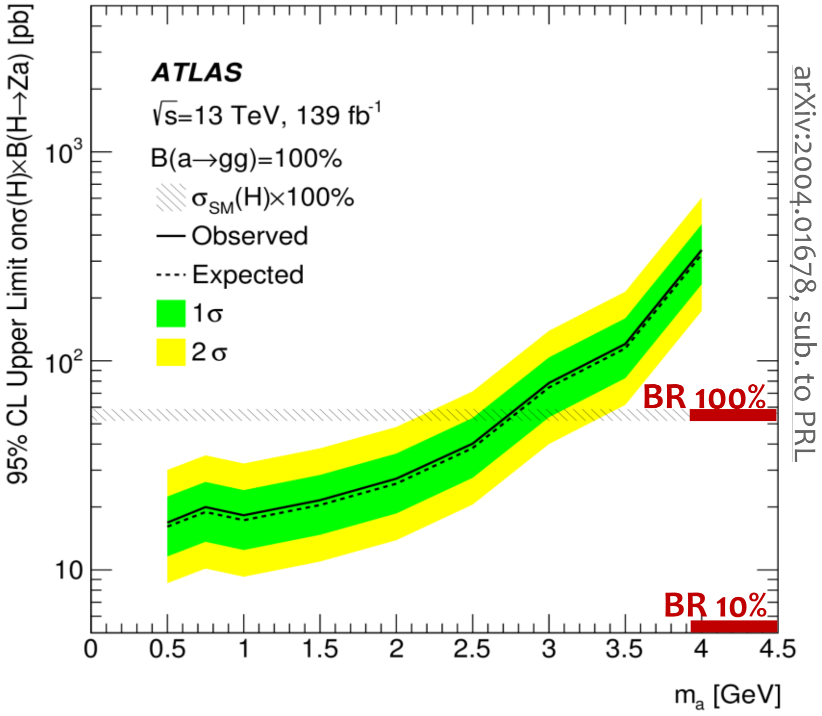


$H \to Z\, a \to \ell\ell\, j$

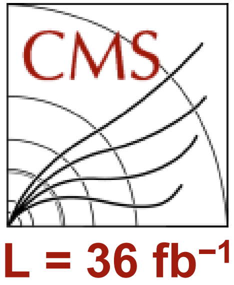
ATLAS EXPERIMENT
L = 139 fb^{-1}

- Search for pseudoscalar **"a"**
- Target **inclusive hadronic decays** **a → jet**, for $\mathbf{m_a}$ **< 4 GeV**
- Good agreement found between data and background predictions in signal region and validation regions
- Set upper limits on σ · BR(H → Za)
  - Interpreted separately for a → gg / $s\bar{s}$ (different efficiency of MLP discr. cut)
  - Also set upper limits on BR(H → Z η_c) and BR(H → Z J/ψ), but at BR ~ 200%

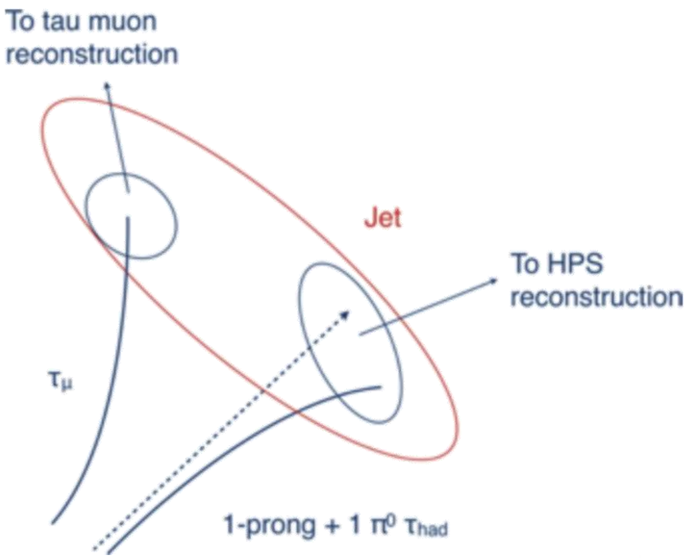


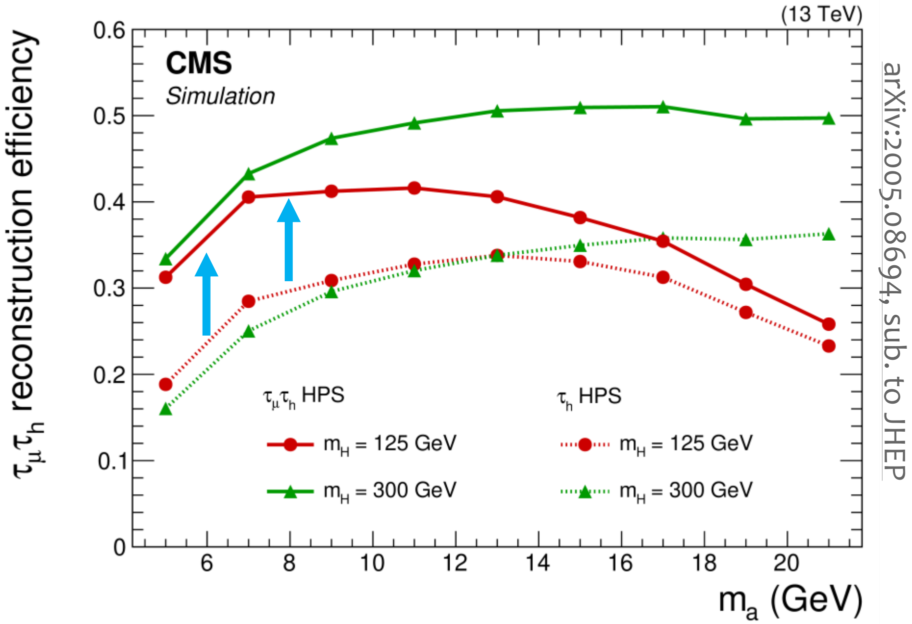


$H \rightarrow a_{\mu\mu}\ a_{\tau\tau}$ at low m_a



- Dedicated τ reco. for overlapping decay products of $a \rightarrow \tau_\mu\ \tau_h$
  - **Gain +50% efficiency at low m_a**



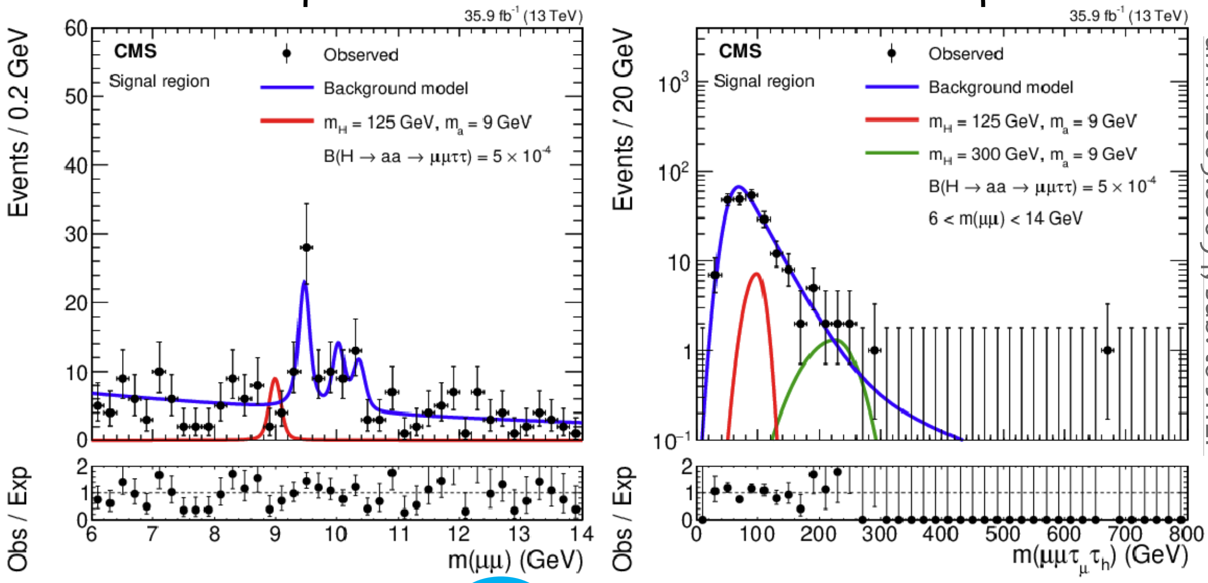


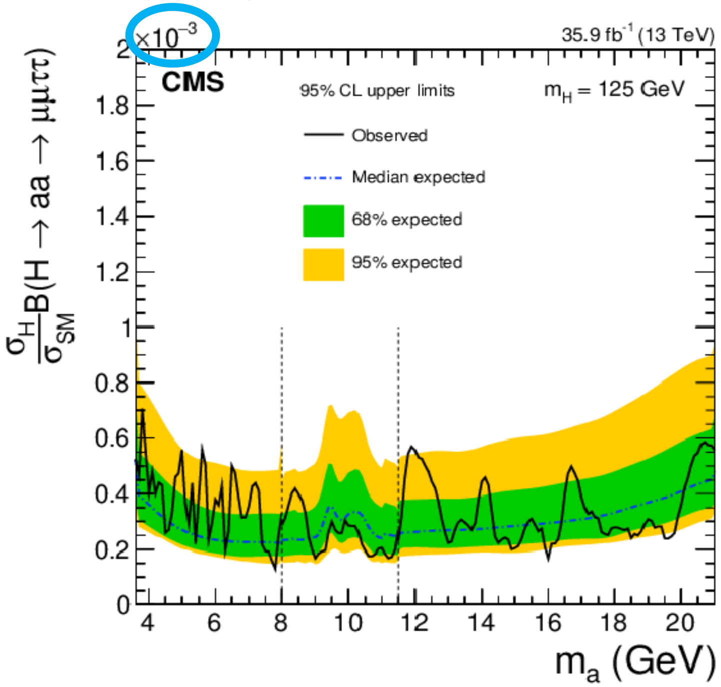
HPS (Hadrons Plus Strips) is the CMS algorithm for hadronic τ reconstruction using Particle Flow

$H \to a_{\mu\mu}\ a_{\tau\tau}$ at low m_a

- Dedicated τ reco. for overlapping decay products of $a \to \tau_\mu\, \tau_h$
- 2D fit in $m(\mu\mu) \times m(\mu\mu\tau_\mu\tau_h)$ plane
  - Fit separately in 3 $m(\mu\mu)$ ranges, to reduce correlations with $m(\mu\mu\tau_\mu\tau_h)$
  - Control regions included to constrain the continuum and $\psi_{(2S)}$ and Y peaks
- Set model-independent limits on BR($H \to aa \to \mu\mu\tau\tau$) ~ 0.02–0.08%
  - And in 2HDM+S benchmark models
  - Also demonstrate potential for $H_{Heavy} \to aa$ using m_H = 300 GeV

1D projections from 2D fit

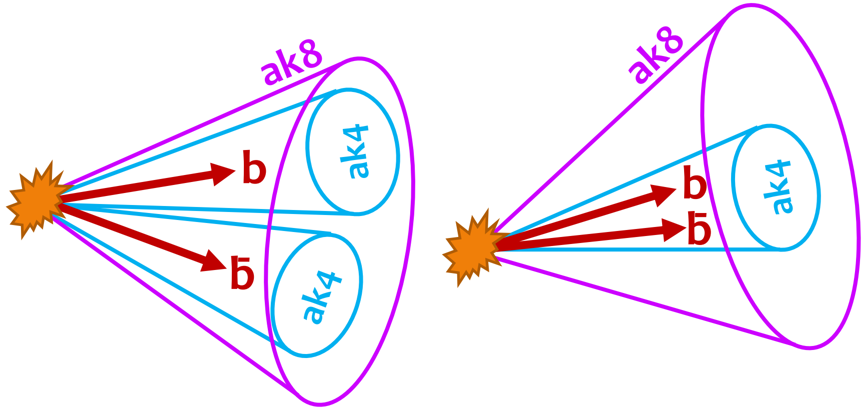




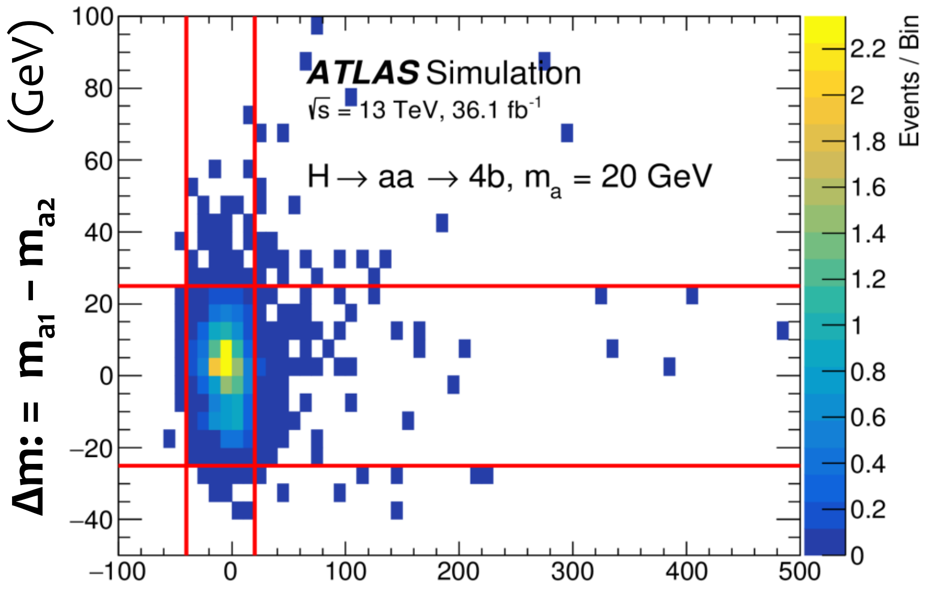
arXiv:2005.08694, sub. to JHEP

$H \to a_{b\bar{b}}\, a_{b\bar{b}}$ at low m_a

ATLAS EXPERIMENT $L = 36\ fb^{-1}$



- Rely on $Z_{\ell\ell}H$ associated production
- Recluster jets with anti-k_T(R=0.8)
  - One ak8 jet for each $a \to b\bar{b}$ candidate
- Tag ak8 jets relying on substructure and b-tagging information from associated tracks and sec. vertices
  - Trained vs jets that contain a single b quark
  - ×100/×30 rejection of b-jets from $t\bar{t}$ & Z+jets at $a \to b\bar{b}$ signal efficiency of ~ 25% / 30%
- Select events with kinematic compatible with $H \to aa$ decay
  - Separately each m_a mass hypothesis



$m_{red} := [\, m_{aa} - (m_{a1} + m_{a2} - 2\, m_a)] - m_H$ (GeV)

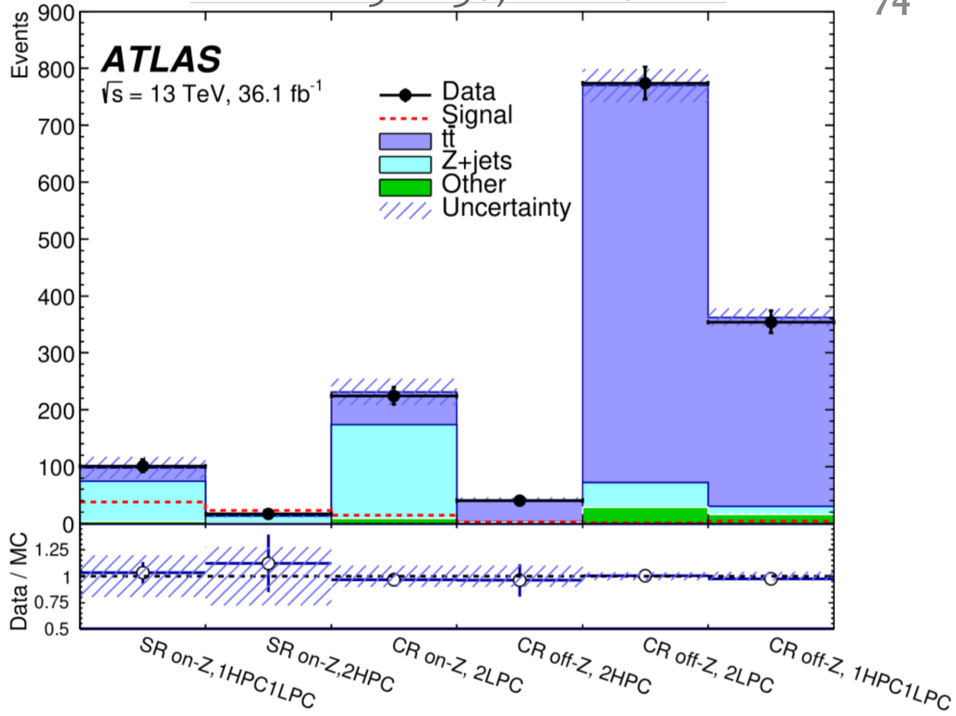
correct reco m_{aa} for m_{ai} jet mismeasurement

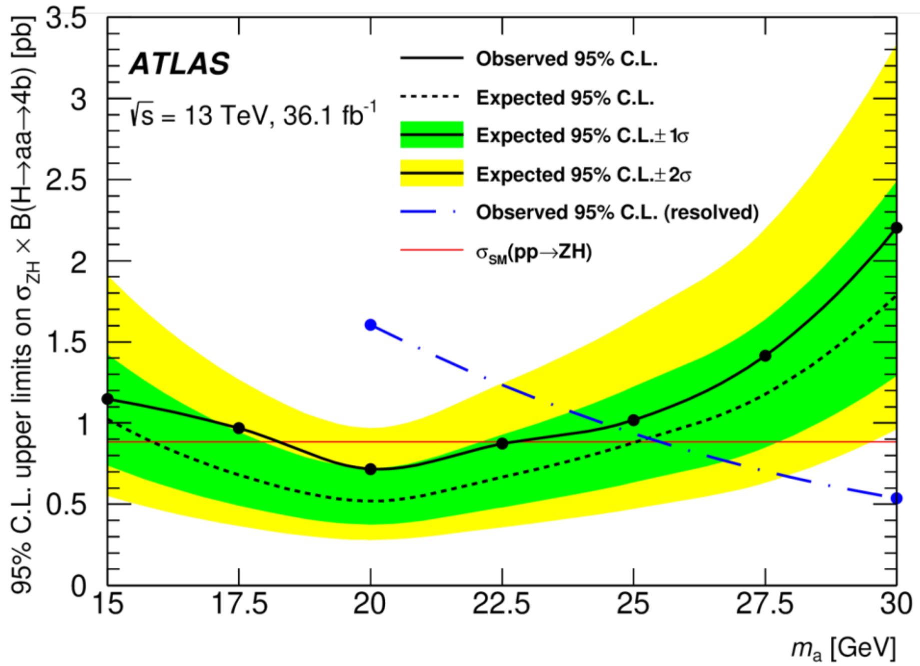
fixed inputs from signal hypothesis

$H \rightarrow a_{bb}\ a_{bb}$ at low m_a

ATLAS EXPERIMENT
$L = 36\ fb^{-1}$

- Define signal and control regions depending on $m_{\ell\ell}$ and number of loose (LP) & tight (HP) ak8 tags
  - Constrain dominant backgrounds from Z+jets and ttbar
- Set limits on $\sigma_{ZH} \times BR(H \rightarrow aa \rightarrow 4b)$ for m_a in 15–30 GeV range
  - Best sensitivity at m_a = 20 GeV Set limit at 80%×σ_{ZH}^{SM} (exp. 60%×σ_{ZH}^{SM})
  - at large m_a, sensitivity taken over by older H→ aa → 4b "resolved" analysis [JHEP 10 (2018) 031]





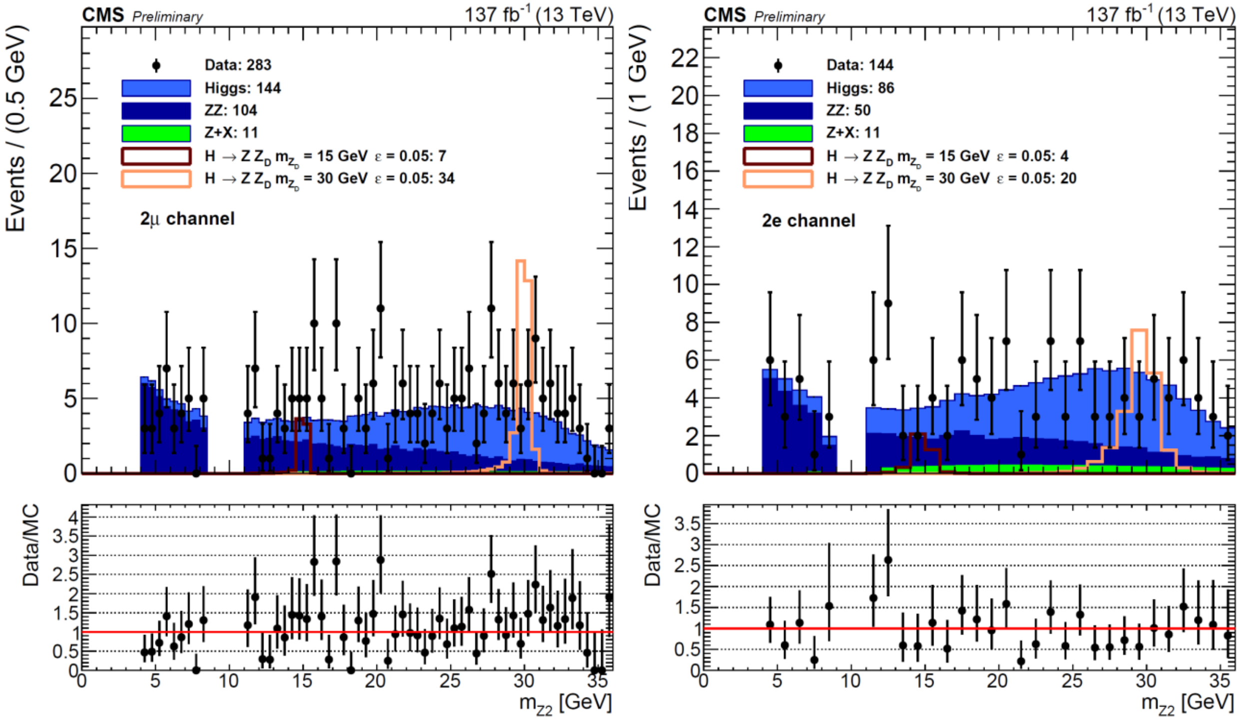
NEW FOR LHCP2020

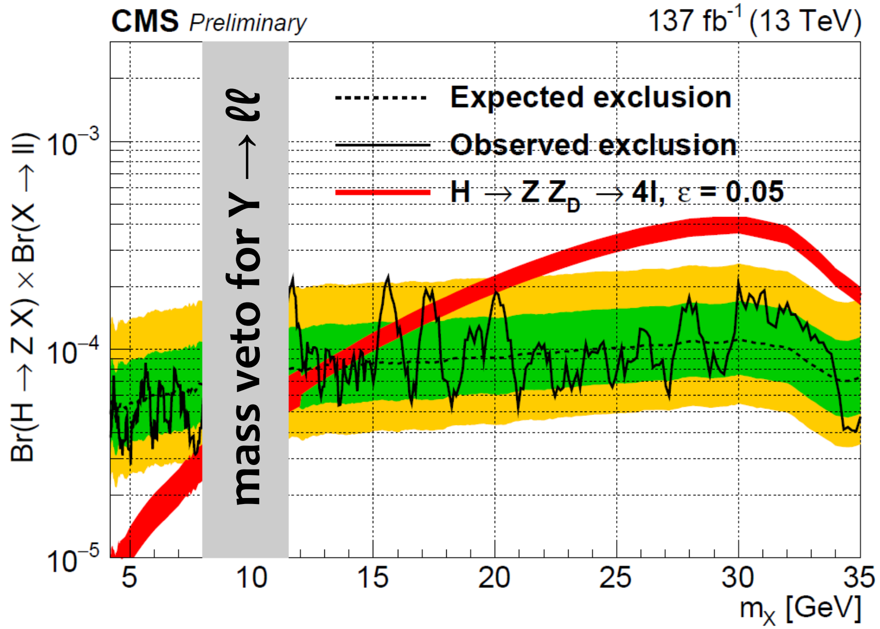
$H \rightarrow Z_{(D)}\, Z_D \rightarrow 4\ell$

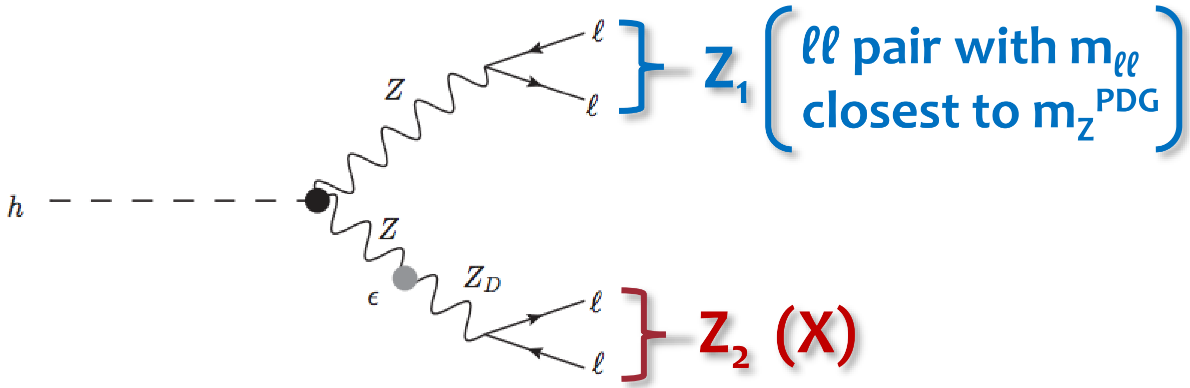
L = 137 fb^{-1}

- Search for dark photons or ALPs
- Based on $H \rightarrow Z\,Z^* \rightarrow 4\ell$ analysis
  - objects, background estimation, …

1. $H \rightarrow Z\,X \rightarrow 4\ell$ search:
   - m_{Z1} > 40 GeV, **118 < m_{4l} < 130 GeV**
   - Scan $\mathbf{m_{Z2}}$ distribution with window of size 4% / 10% for X → μμ / ee
   - Set limits for X → ℓℓ, μμ, ee







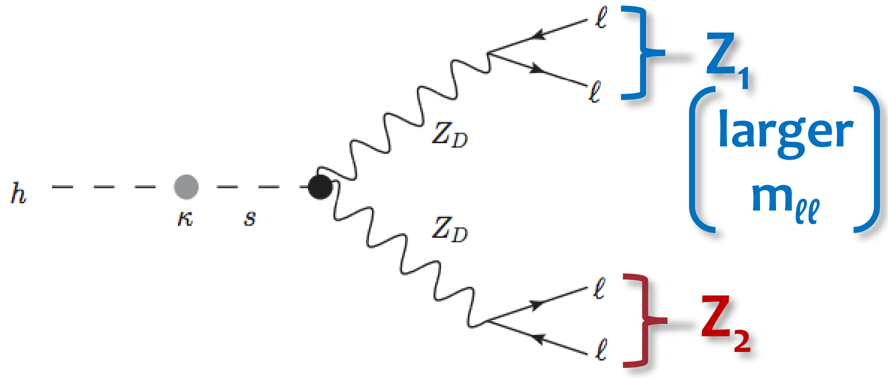
NEW FOR LHCP2020

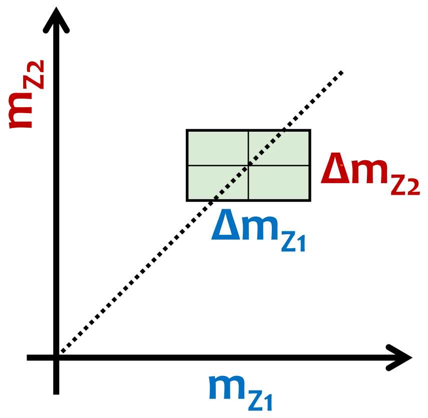
CMS PAS HIG-19-007

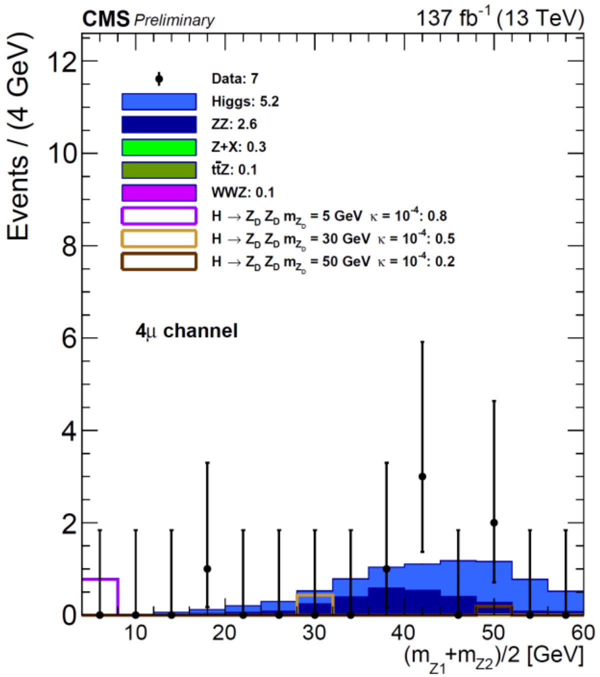
$H \to Z_{(D)} Z_D \to 4\ell$

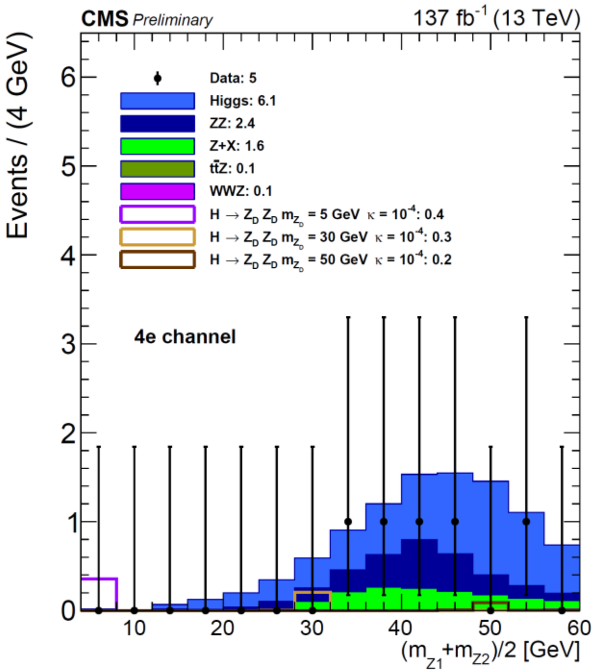
$L = 137\ \text{fb}^{-1}$

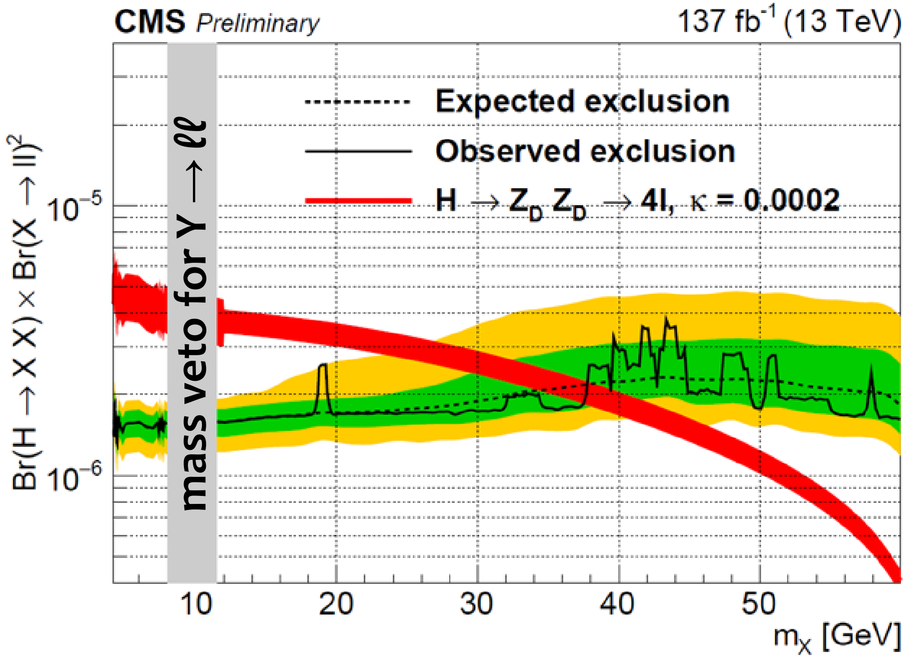
2. $H \to X\,X \to 4\ell$ search:
   - Select lepton pairings minimizing $|m_{Z1} - m_{Z2}| / (m_{Z1} + m_{Z2})$
   - $m_{Zi} \in 4$–62.5 GeV, $m_{4l} \in 118$–130 GeV
   - Scan m_{Z1}, m_{Z2} plane with 2D box centered on $m_{Z1} = m_{Z2} = m_X$ of size $\Delta m_{Zi} = 4\% / 10\%$ for $Z_i \to \mu\mu$ / ee
   - Set limits for $X \to \ell\ell$, $\mu\mu$, ee











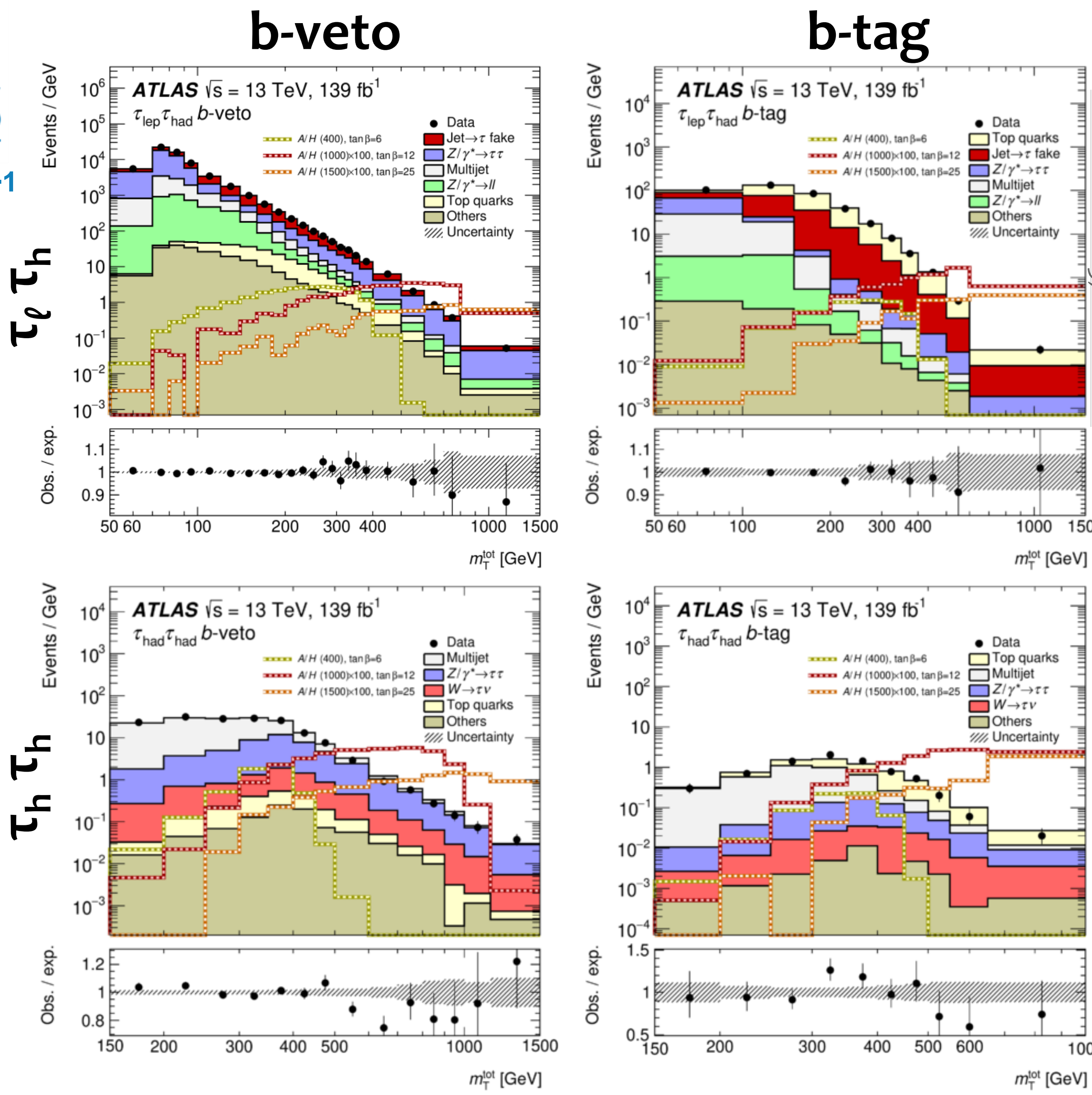
MSSM $A/H \rightarrow \tau\tau$

ATLAS EXPERIMENT

$L = 139\ fb^{-1}$

- Flagship mode at high tan(β)
  - Enhanced BR($A/H \rightarrow \tau\tau$) and bbH production
- Main backgrounds:
  - Reducible jet $\rightarrow \tau_h$: from data using fake rate methods
  - Irreducible $Z \rightarrow \tau\tau$, $t\bar{t}$: estimated from MC, plus CR at high $m_T^{\ell\nu}$ for $t\bar{t}$
- Final discriminating variable

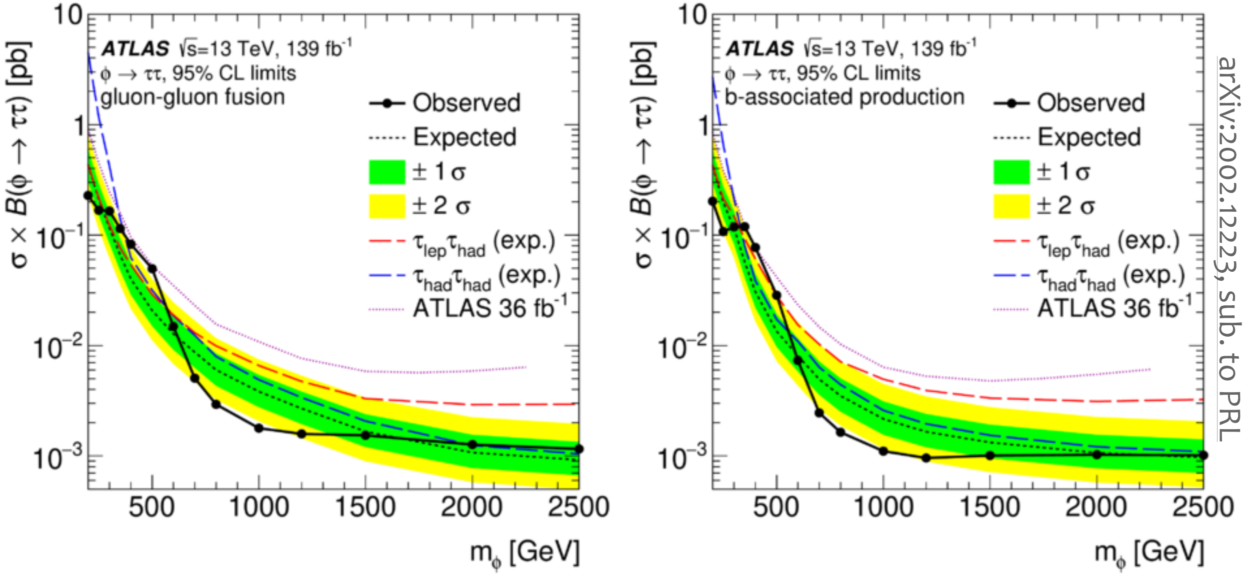
$$m_T^{tot} = \sqrt{\left(p_T^{\tau 1} + p_T^{\tau 2} + E_T^{miss}\right)^2 - \left(\overrightarrow{p_T^{\tau 1}} + \overrightarrow{p_T^{\tau 2}} + \overrightarrow{E_T^{miss}}\right)^2}$$

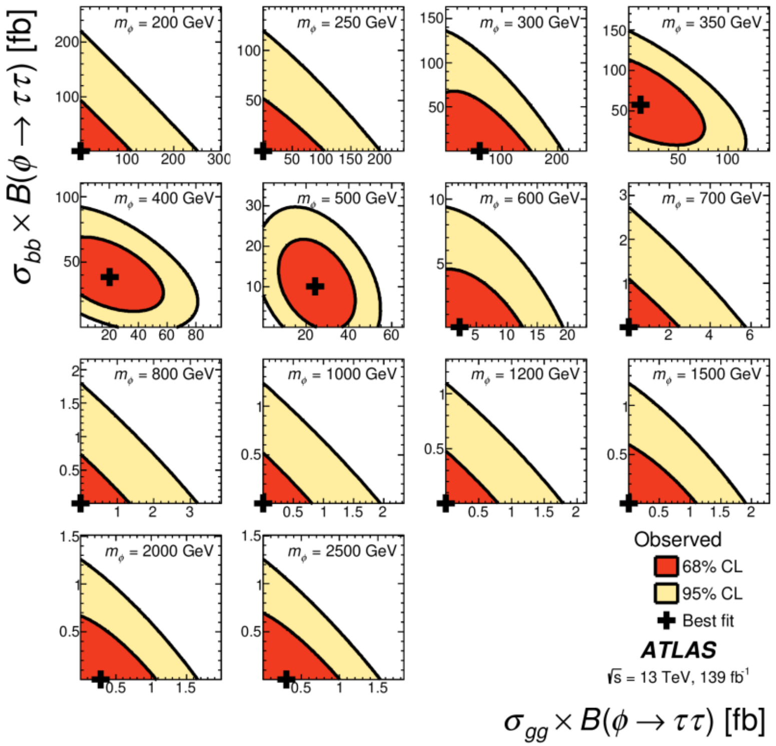


arXiv:2002.12223, sub. to PRL

MSSM A/H → ττ

- Interpretation as limits on σ×BR for generic scalar φ
  - Provide 1D and 2D limits and likelihoods vs m_φ, σ_{ggF}, σ_{bbH}
  - Largest excess at m_φ ~ 400 GeV, local significance ~ 2 σ

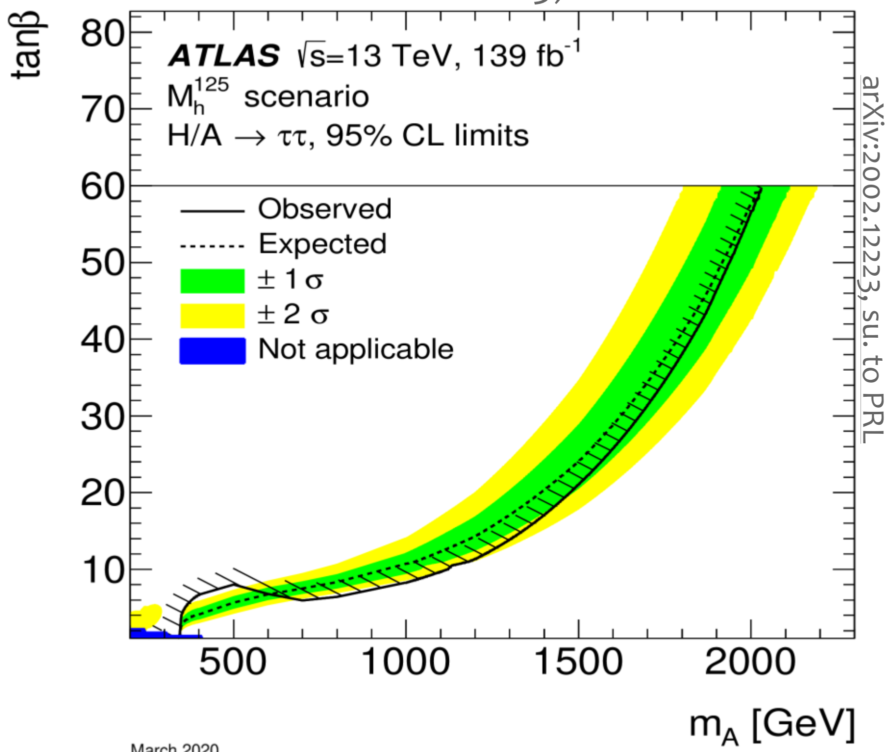


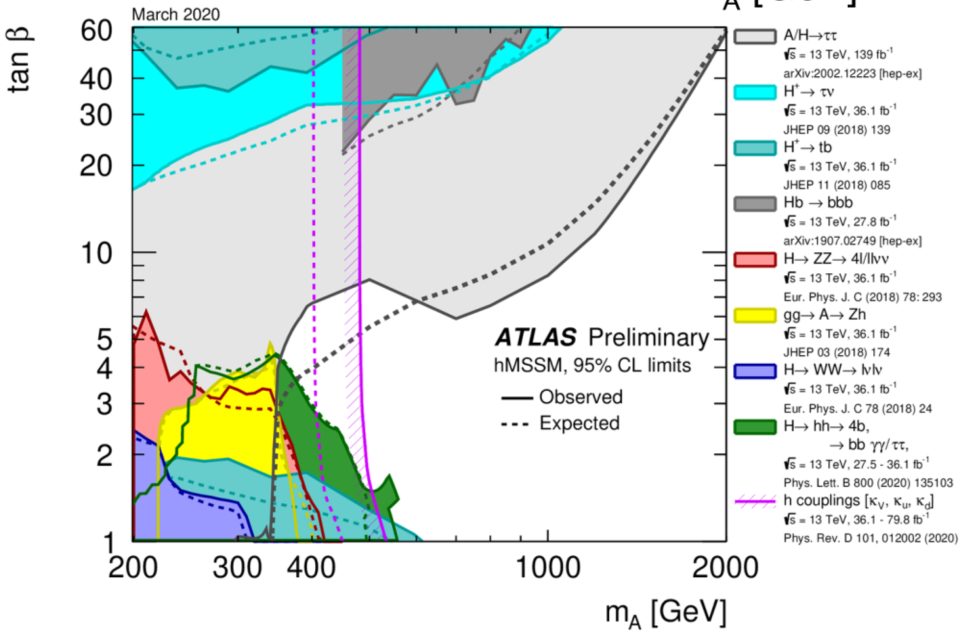


MSSM A/H → ττ

- Interpretation as limits on σ×BR for generic scalar φ
  - Provide 1D and 2D limits and likelihoods vs m_φ, σ_{ggF}, σ_{bbH}
  - Largest excess at m_φ ~ 400 GeV, local significance ~ 2 σ
- MSSM interpretations
  - New M_h^{125} benchmark scenarios e.g. tan(β) < 8 at 1 TeV (expected: < 10)
  - hMSSM, to compare with old result

arXiv:2002.12223, sub. to PRL





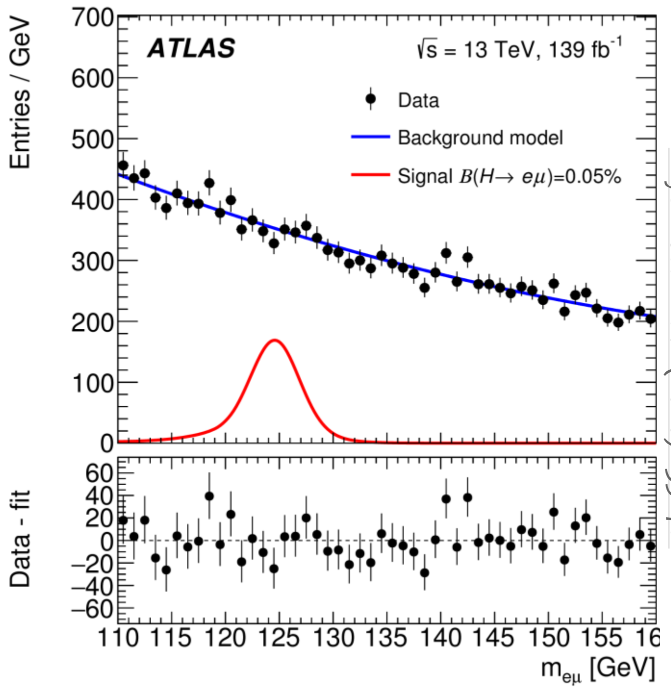
ATL-PHYS-PUB-2020-006

CMS: Also older CMS result on 36 fb⁻¹ [*JHEP 09 (2018) 007*]
M_h^{125} limits, e.g. tan(β) < 15 at 1 TeV (expected: < 16)

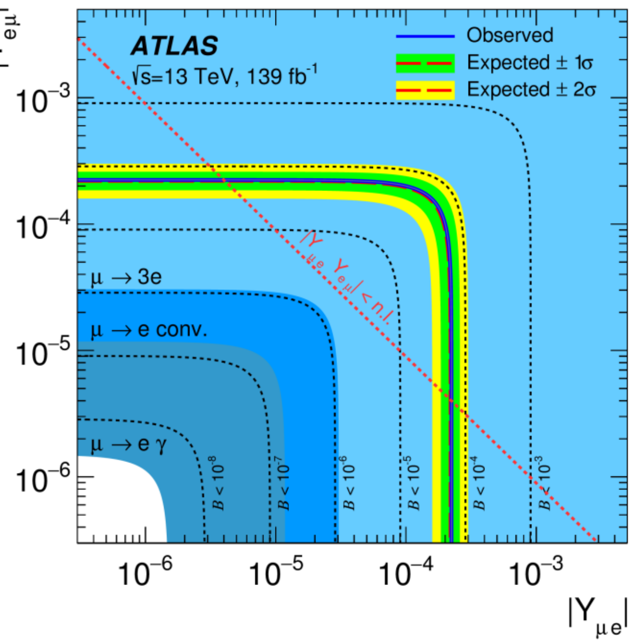
Lepton flavour violating decays

ATLAS EXPERIMENT
L = 139 fb^{-1}

- Probe for H → eμ: direct test for LFV $y_{e\mu}$ Yukawa coupling
  - Very stringent limits from μ → eγ and electron EDM, but depend on yet unobserved y_{ee} and $y_{\mu\mu}$
- Categorize by p_T^{ℓ}, $|\eta_\ell|$, $p_T^{\ell\ell}$
  - Select events with higher S/B or better dilepton mass resolution
- Set upper limit $BR_{e\mu} < 6.2 \times 10^{-5}$
  - Factor ~6 better than Run 1 limit
- Also set BR(H → ee) < 3.6×10^{-4}
  - $BR_{SM} \sim 5 \times 10^{-9}$ well out of reach

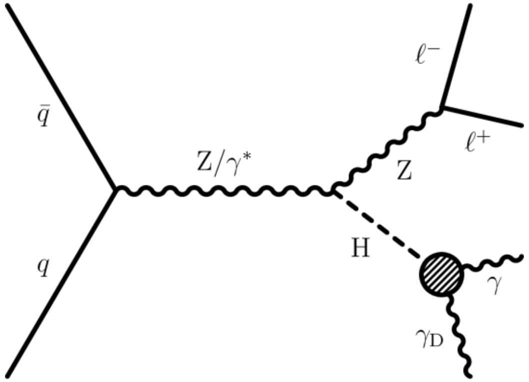


Phys. Lett. B 801 (2020) 135148



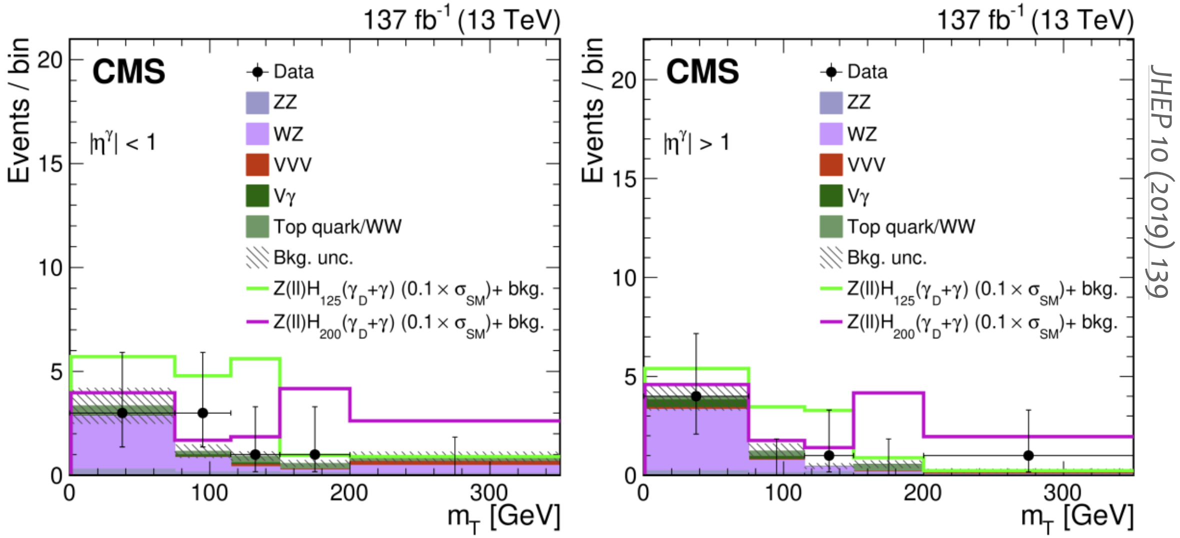
Also older 36 fb^{-1} from CMS [JHEP 06 (2018) 001] and ATLAS [PLB 800 (2020) 135069] setting limits on BR(H → eτ) and BR(H → μτ) in the 0.25% – 0.6% range

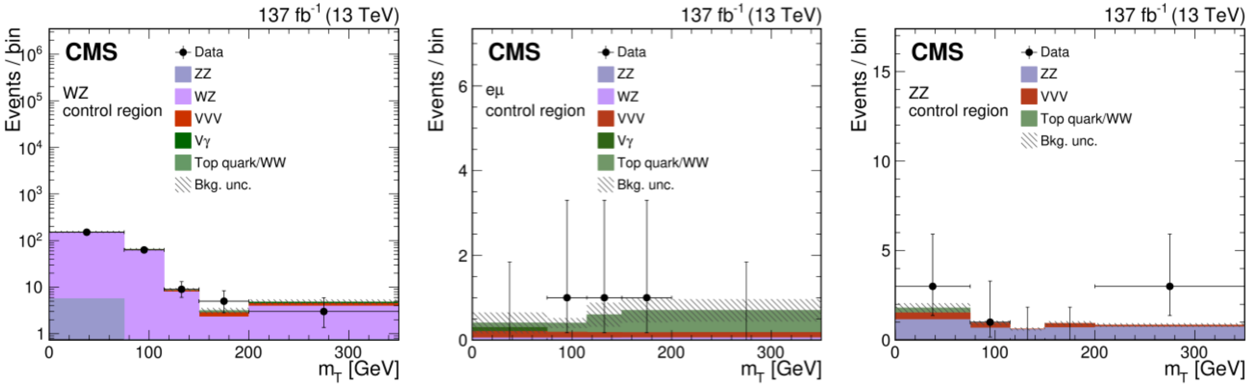
$H \to \gamma$ + invisible



L = 137 fb^{-1}

- Probe e.g. for $H \to \gamma\, \gamma_D$ (dark photon)
- Rely on $Z(\ell\ell)$ H associated production
  - Require high-p_T $Z_{\ell\ell}$, back-to-back and balanced with $\gamma + E_T^{miss}$ vector
- Dominant background: $WZ \to 3\ell\nu$
  - With electron mis-id as photon, or genuine γ from ISR/FSR and a lost ℓ
- Transverse mass m_T of $\gamma + E_T^{miss}$ system used to look for a signal
  - Control regions for **WZ**, **$t\bar{t}$/WW**, **ZZ**
- Set limits **BR(H → γ + inv.) < 4.6%**
  - Tiny $BR_{SM}(H \to Z\gamma \to \nu\nu\gamma) \sim 3\times10^{-4}$



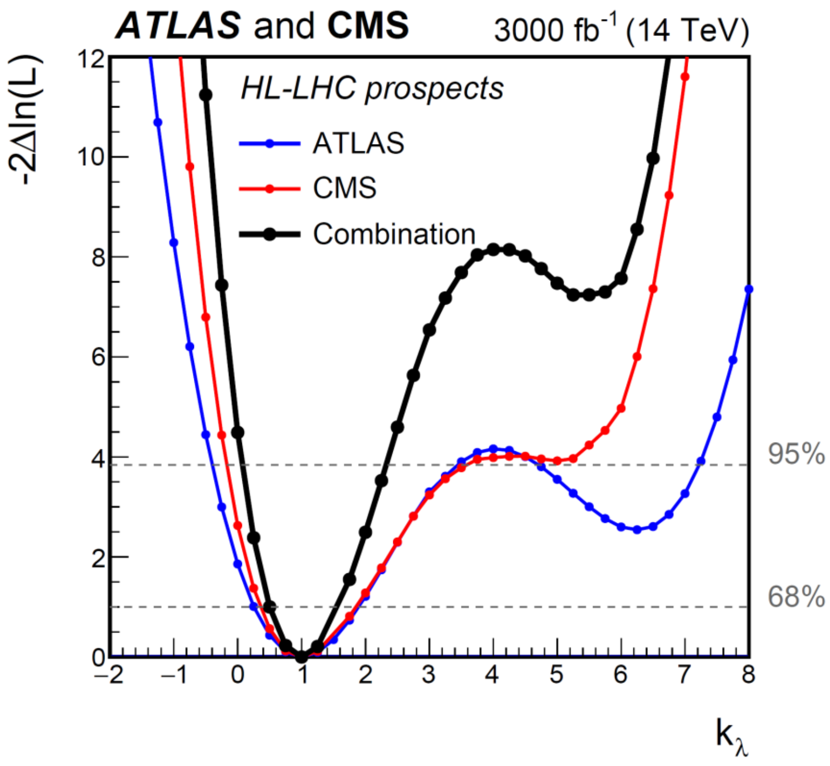


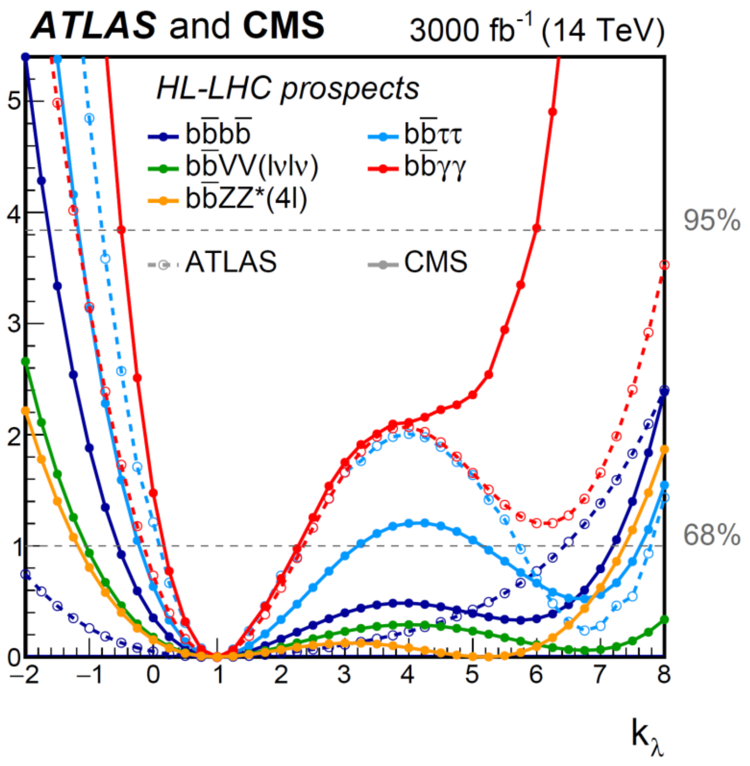
Part II: brief outlook at HL-LHC

- HH production: ~4σ evidence, measure κ_λ with ~ ±50% uncertainty
  - Projections based on a combination of extrapolations from Run 2 analyses and new analyses designed for HL-LHC

Expected significance for HH

	ATLAS	CMS
$\bar{b}b\,\bar{b}b$	0.61	0.95
$\bar{b}b\,\tau\tau$	2.1	1.4
$\bar{b}b\,\gamma\gamma$	2.0	1.8
$\bar{b}b\,VV(\ell\ell\nu\nu)$		0.56
$\bar{b}b\,ZZ(4\ell)$		0.37
combined	**3.0**	**2.6**
LHC comb.	**4.0**	

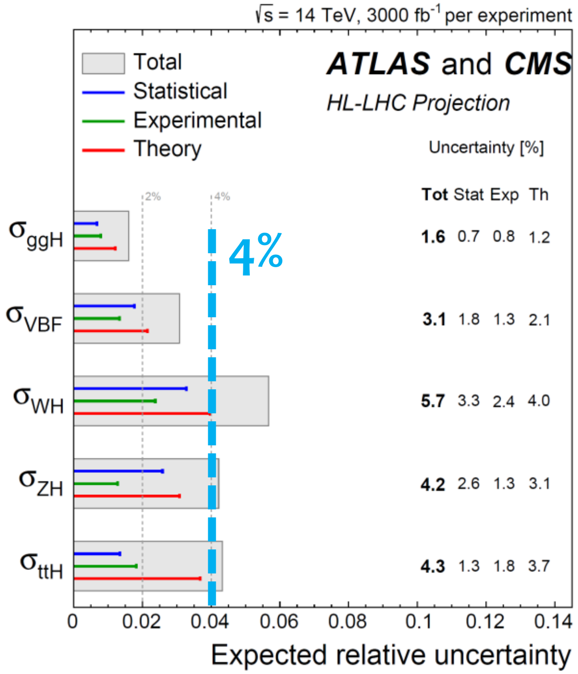


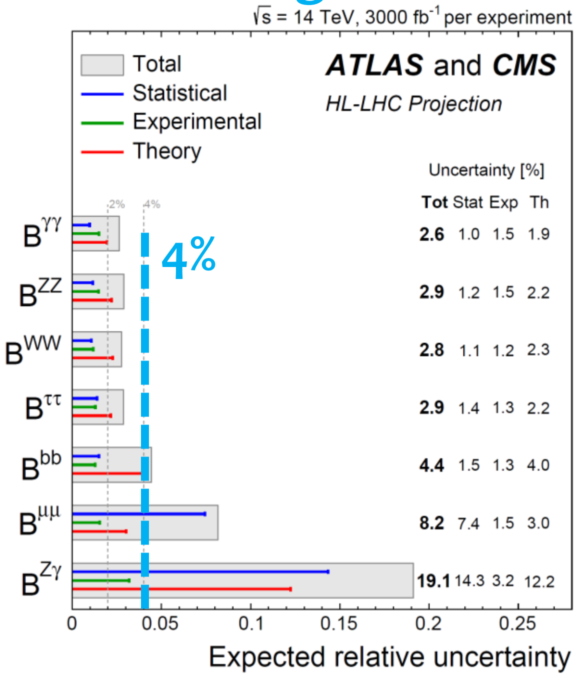


Part III: brief outlook at HL-LHC

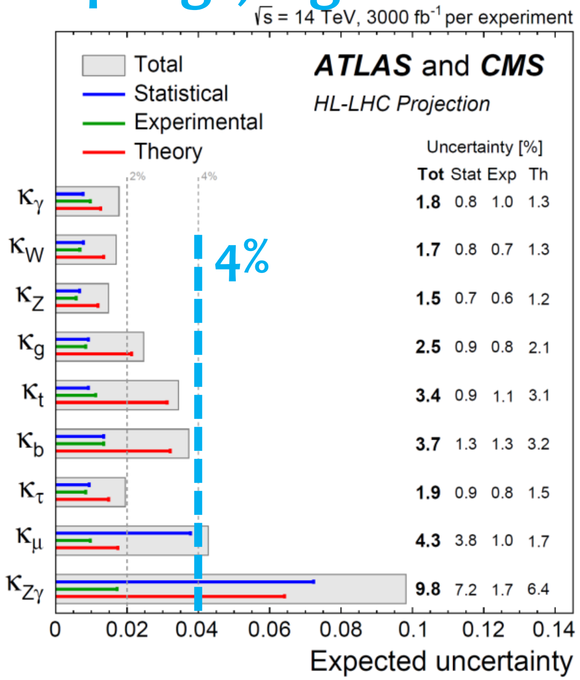
- Sensitivity for Higgs boson physics at HL-LHC evaluated back in 2018 in the context of the European Strategy update
  - Mostly based on knowledge from early LHC run 2 analyses (2016 data)
- Single Higgs boson observables: can reach few-percent precision

Cross sections and branching ratios

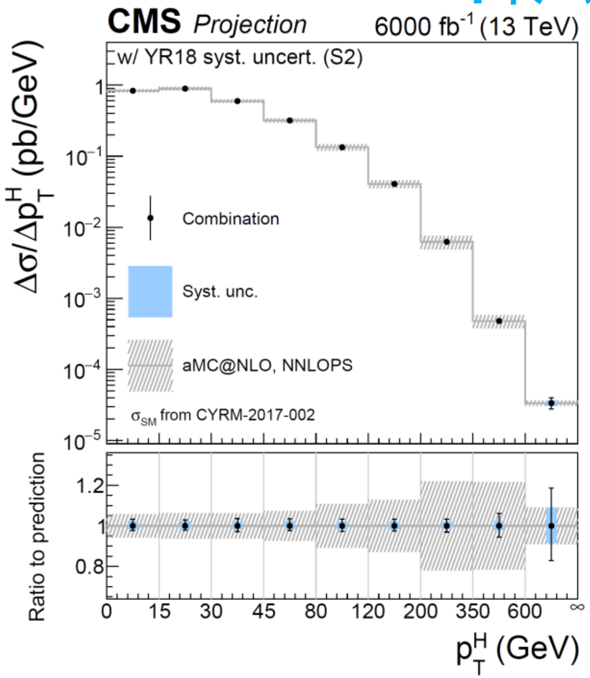




Couplings, e.g. κ fit

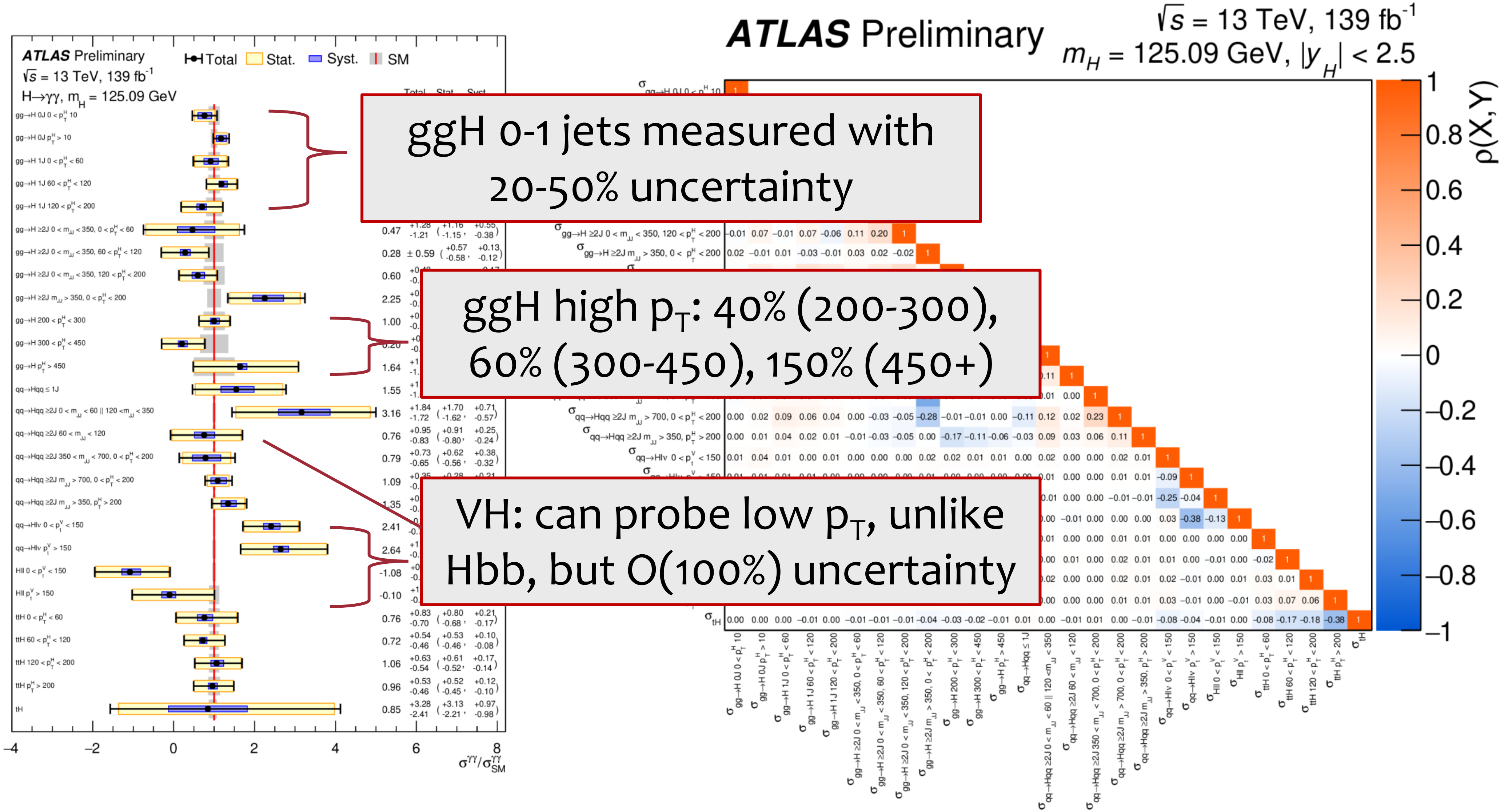


Differential $d\sigma/dp_T(H)$



Attic

STXS H → γγ: results, ATLAS (27 params)



ggH 0-1 jets measured with 20-50% uncertainty

ggH high p_T: 40% (200-300), 60% (300-450), 150% (450+)

VH: can probe low p_T, unlike Hbb, but O(100%) uncertainty

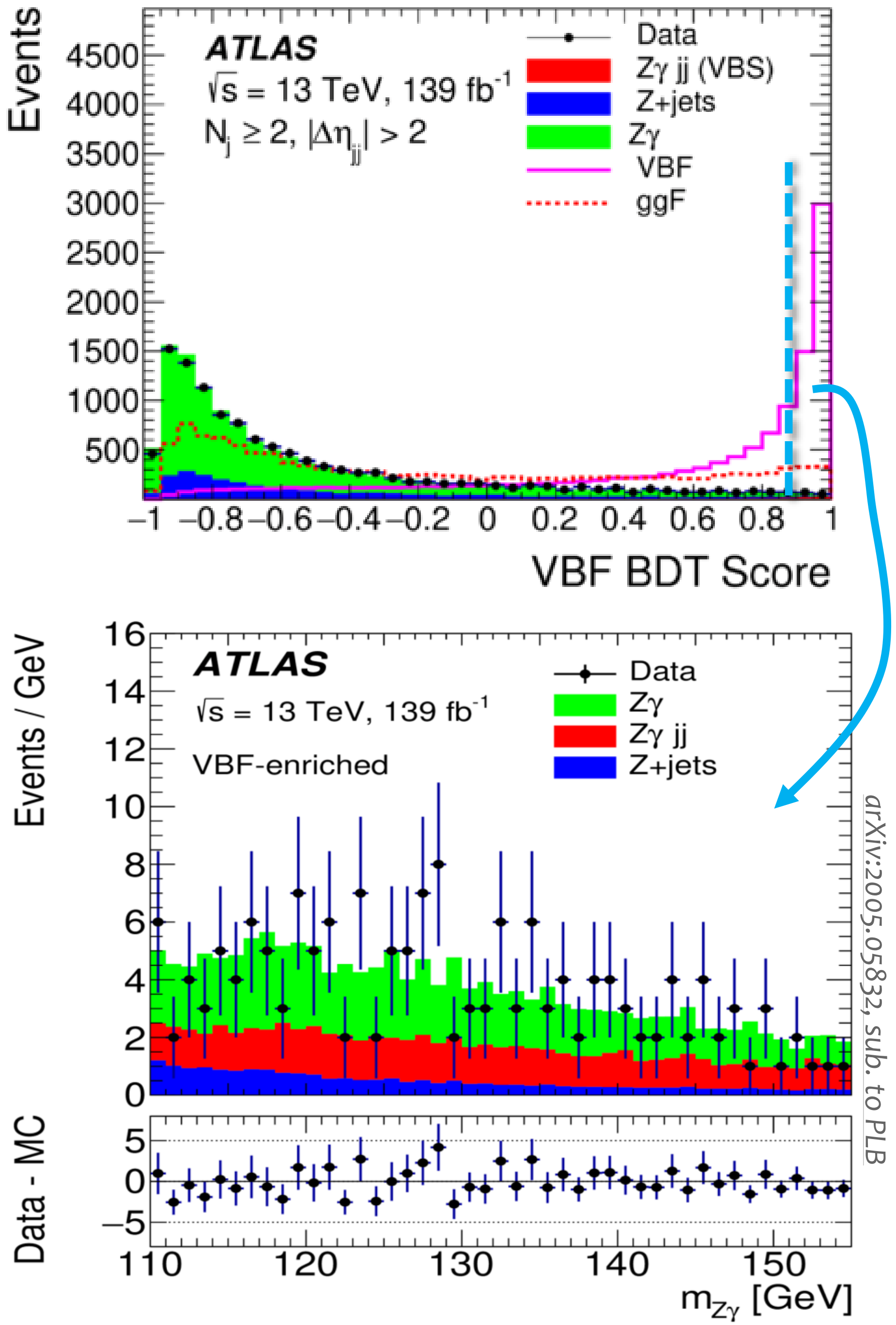
CP studies: fermion couplings

- In CP-violating models, Higgs-fermion interactions can have both $h\bar{\psi}\psi$ and $h\bar{\psi}\gamma_5\psi$
- Multiple recent efforts to probe for them:
  - for top, from ttH & tH production with $H \to \gamma\gamma$
  - for top, or possible BSM heavy quark, from ggH + 2 jets with $H \to 4\ell$
    ($h\bar{\psi}\gamma_5\psi$ yields $hG^{\mu\nu}\tilde{G}_{\mu\nu}$ term in heavy top limit)
  - for tau, from polarization in tau decays

$H \to Z\gamma$

- $SU(2)_L$ symmetry ties together the HWW, HZZ, $H\gamma\gamma$, $HZ\gamma$ interactions
  - If heavy new physics respects $SU(2)_L$, correlated effects across the four
- $BR(H \to Z\gamma \to \ell\ell\gamma) = 0.5 \cdot 10^{-4}$
  - Similar BR to $H \to 4\ell$, but larger background from $Z\gamma$ production
- As in $H \to \mu\mu$, key ingredients are:
  - **Improve signal mass resolution:** FSR recovery, kinematic refit of $Z \to \ell\ell$
  - **Improve S/B via categorization:** BDT targeting VBF production; p_T and p_{Tt}

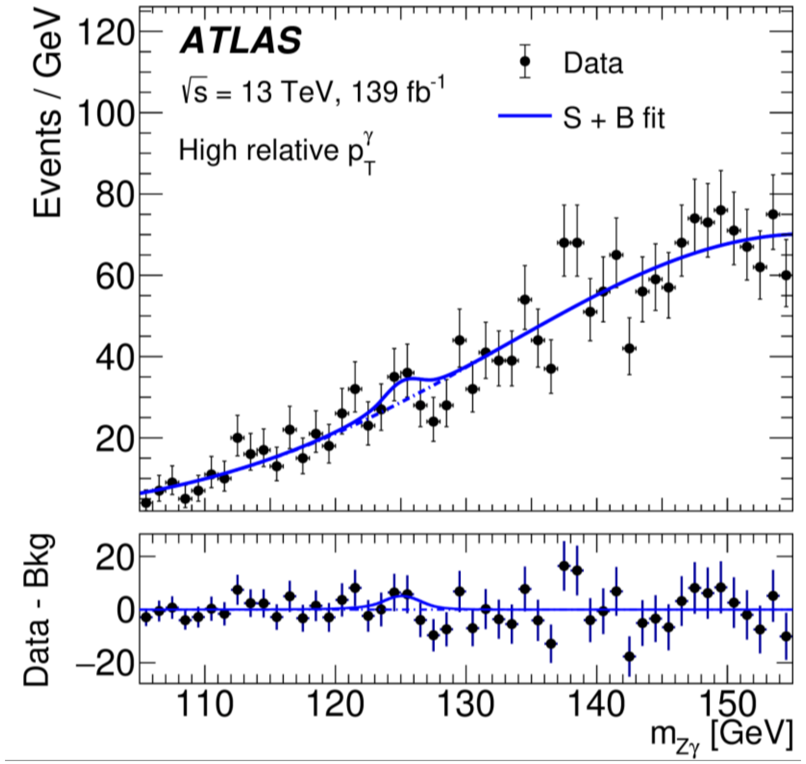
arXiv:2005.05832, sub. to PLB



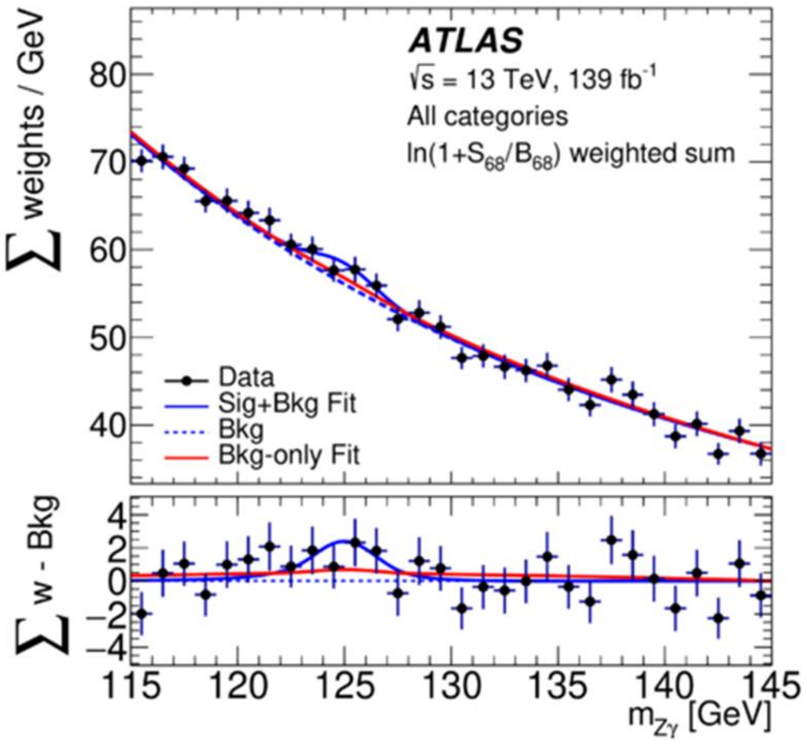
arXiv:2005.05832, sub. to PLB

$H \to Z\gamma$: fit and results

High $p_T^\gamma / m_{Z\gamma}$ category (highest sensitivity)



Sum of all categories (sensitivity-weighted)



Fit results by category and combined

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

arXiv:2005.05832, sub. to PLB

We may be starting to see the first hints of the signal

Also older CMS result on 36 fb⁻¹ for $H \to Z\gamma$ and $H \to \gamma^*\gamma \to \mu\mu\gamma$
Upper limit 3.9 × SM (expected 2.0 × SM). *[JHEP 11 (2018) 152]*