EFFECTIVE FIELD THEORY INTERPRETATIONS OF ATLAS HIGGS DATA

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Overview

- Introduction
- Reminder of CMS+ATLAS Run 1 Higgs results
- Interpretation using simple coupling modifiers
- Introduction to Effective Field Theory (EFT) approach
- Some ATLAS results from diphoton differential Run1 and Run2 measurements
- Projections for achievable precision of EFT fits with full ATLAS dataset
- EFT studies of CP mixing in tau and weak boson channels
- Some recent ATLAS results in ZZ*

disclaimer: not discussing simplified template cross sections scheme!

How we “see” Higgs Bosons

Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.577 ± 0.016	0.703 ± 0.018
ZH	0.334 ± 0.013	0.414 ± 0.016
[$ggZH$]	0.023 ± 0.007	0.032 ± 0.010
ttH	0.086 ± 0.009	0.129 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
bbH	0.156 ± 0.021	0.203 ± 0.028
Total	17.4 ± 1.6	22.3 ± 2.0

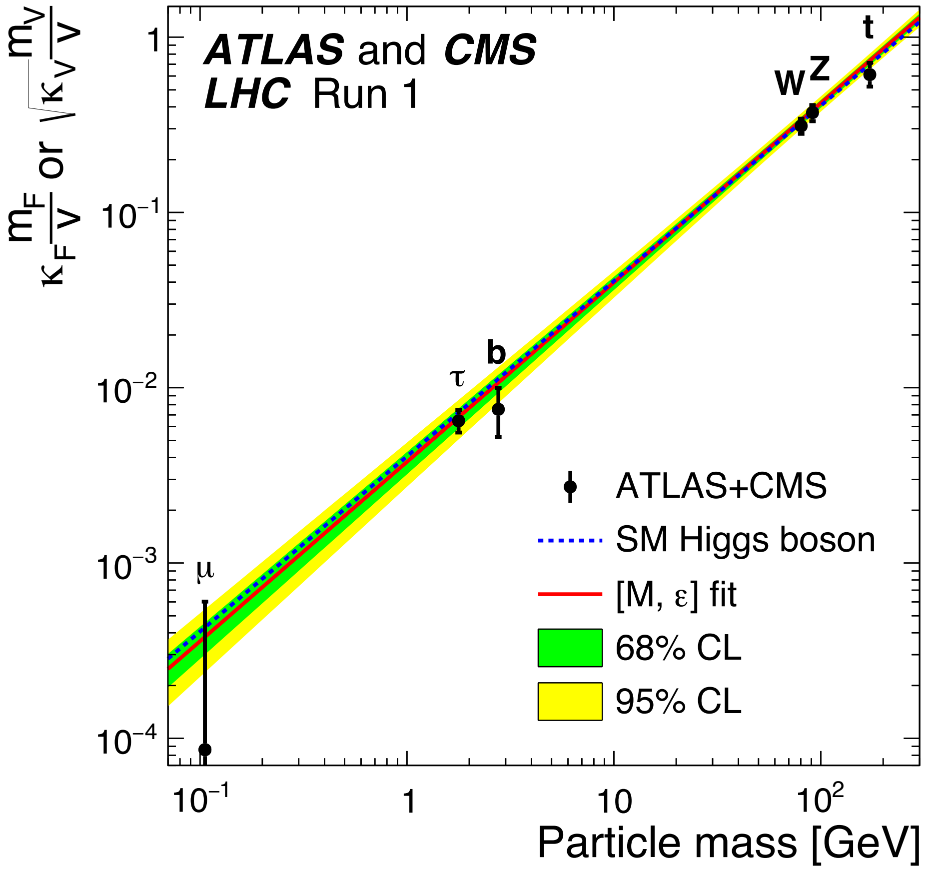
- **Production modes:**
- Main mode is gluon fusion
- Rare modes have characteristic signatures

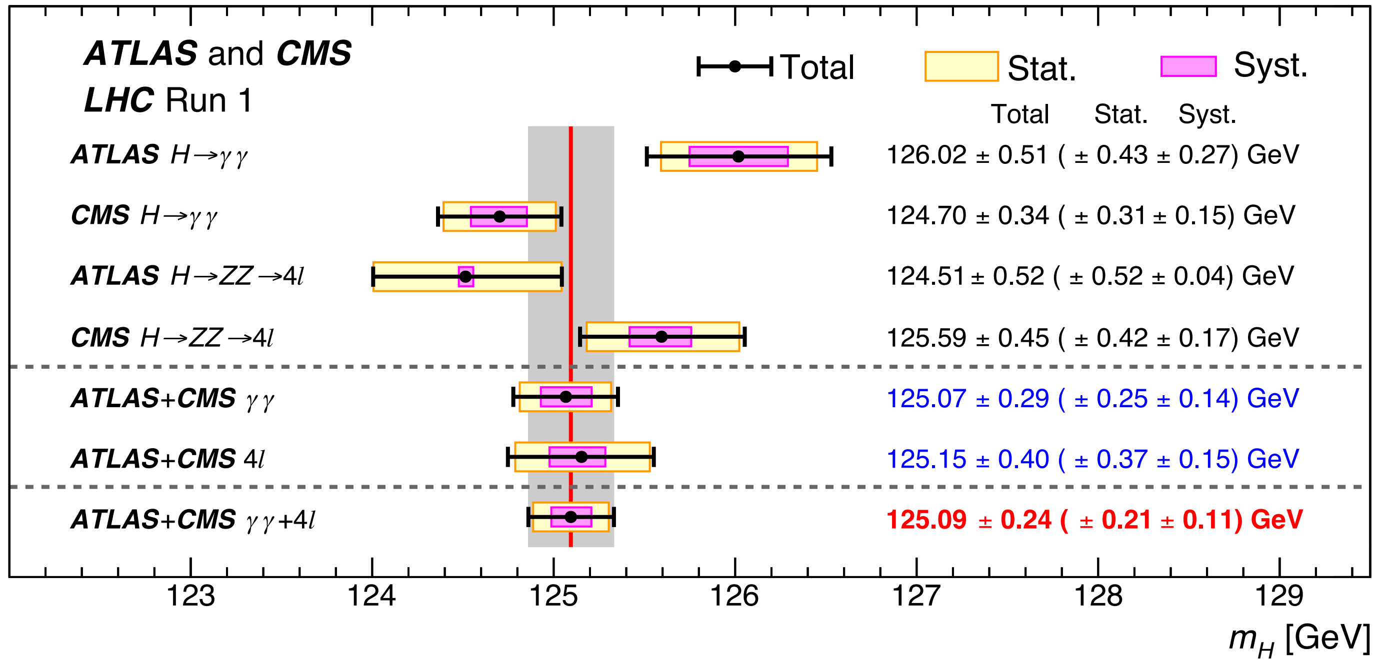
- **Decay modes:**
  - ZZ, γγ: low branching fractions (BR), clean signal
  - WW: good sensitivity, difficult backgrounds
  - ττ, bb: medium-high BR, fermion couplings, very difficult backgrounds

Decay mode	Branching fraction [%]
$H \rightarrow bb$	57.5 ± 1.9
$H \rightarrow WW$	21.6 ± 0.9
$H \rightarrow gg$	8.56 ± 0.86
$H \rightarrow \tau\tau$	6.30 ± 0.36
$H \rightarrow cc$	2.90 ± 0.35
$H \rightarrow ZZ$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\mu$	0.022 ± 0.001

JHEP 1608 (2016) 045
Phys. Rev. Lett. 114, 191803

Basic Properties



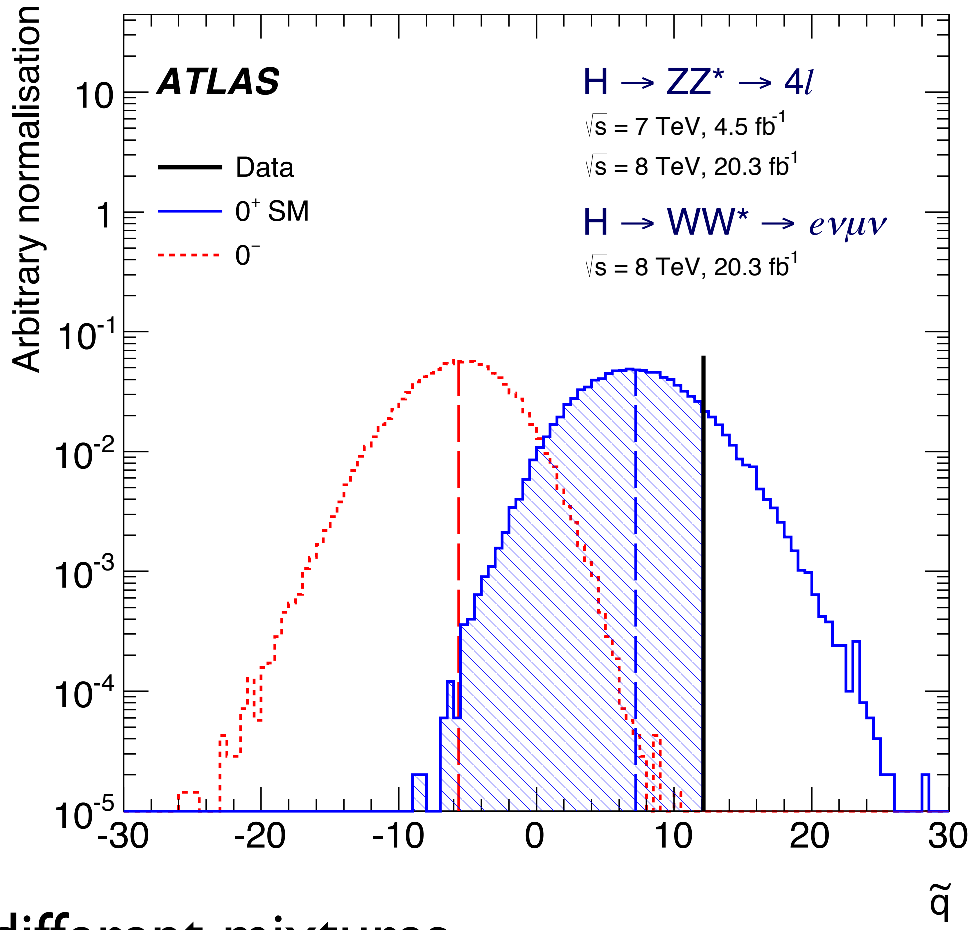


- Confirmed scaling of coupling with mass
- Precise mass measurement in γγ and ZZ* channels

Eur. Phys. J. C75 (2015) 476

Limits on alternative Spin/CP Hypotheses

Tested Hypothesis	$p^{\mathrm{alt}}_{\mathrm{exp},\mu=1}$	Obs. $\mathrm{CL_s}$ (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$



- **Channels:** γγ, ZZ* and WW
- **Signal models:** 0^- quark-induced, $1^{+/-}$ gluon-induced, 2^+ different mixtures
- **Results:** All hypotheses except 0^+ excluded at >99.9% confidence level

Couplings: Fit Model

- Derive couplings from event yields n in the different analysis channels k
- Parameters of interest are the "signal strengths" $\mu_{i,f}$ for production and decay modes
- Defined such that $\mu_{i,f} = 1$ represents signal strength consistent with the SM
- Other parameters need to be measured in each channel k for all production and decay modes

SM production cross section — selection efficiency — integrated Lumi

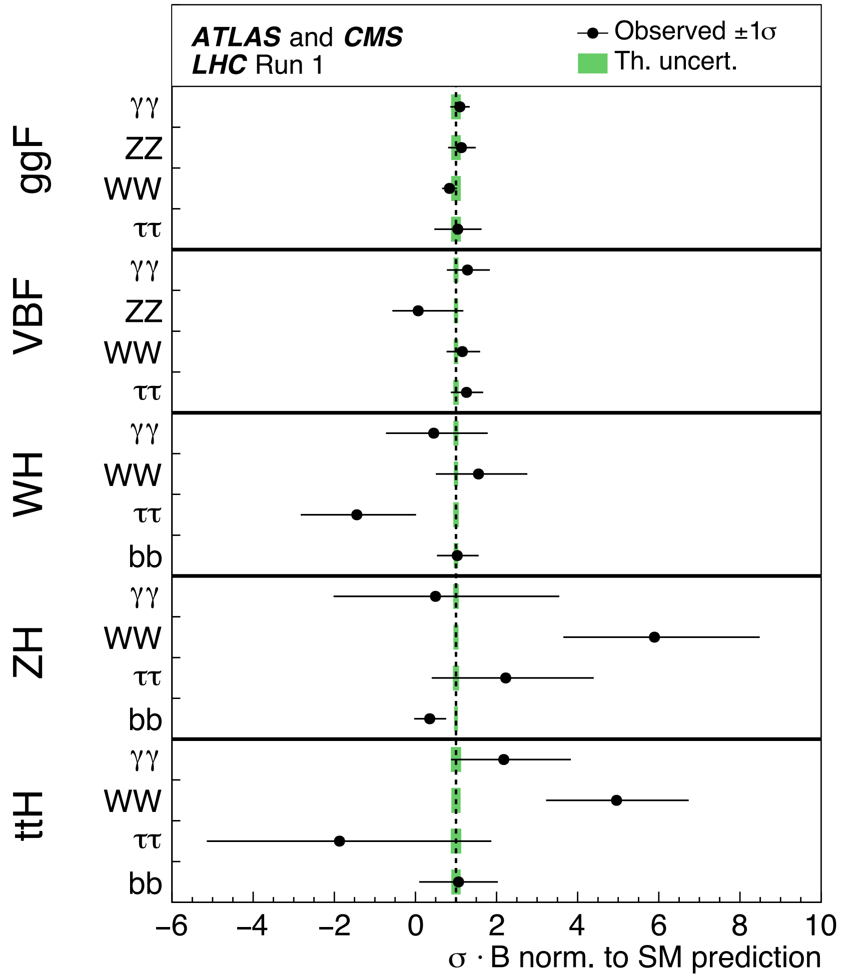
$$n^k_{\text{signal}} = \left(\sum_i \mu_i \boxed{\sigma_{i,\text{SM}}} \times \boxed{A^k_{if}} \times \boxed{\varepsilon^k_{if}} \right) \times \mu_f \times \boxed{B_{f,\text{SM}}} \times \mathcal{L}^k$$

detector acceptance — SM branching ratio

Fit Inputs

- Measured signal strength in units of SM cross section x branching ratio
- Not possible to measure either by itself without theory assumptions
- In all decay channels signal strength agrees with SM expectation within 1-2 σ

Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.14^{+0.27}_{-0.25}$	$1.11^{+0.25}_{-0.23}$	5.0	5.6
	$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.23}_{-0.21}\right)$	(4.6)	(5.1)
$H \to ZZ$	$1.52^{+0.40}_{-0.34}$	$1.04^{+0.32}_{-0.26}$	7.6	7.0
	$\left(^{+0.32}_{-0.27}\right)$	$\left(^{+0.30}_{-0.25}\right)$	(5.6)	(6.8)
$H \to WW$	$1.22^{+0.23}_{-0.21}$	$0.90^{+0.23}_{-0.21}$	6.8	4.8
	$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.36}$	$0.88^{+0.30}_{-0.28}$	4.4	3.4
	$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	$0.62^{+0.37}_{-0.37}$	$0.81^{+0.45}_{-0.43}$	1.7	2.0
	$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	$-0.6^{+3.6}_{-3.6}$	$0.9^{+3.6}_{-3.5}$		
	$\left(^{+3.6}_{-3.6}\right)$	$\left(^{+3.3}_{-3.2}\right)$		
ttH production	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
	$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.9}_{-0.8}\right)$	(1.6)	(1.3)



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The Kappa Framework

- First attempt to parametrize deviations of Higgs couplings from SM expectations
- In narrow width approximation production cross sections and branching ratios factorize

$$\sigma_i \cdot \mathrm{B}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

- Then introduce kappa parameters to scale cross section or partial widths

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$$

- Can reduce complexity by correlating kappa parameters, e.g. one k for all fermions or bosons
- By construction only modifies event rates, not shapes
- Does not predict where deviations from SM could occur

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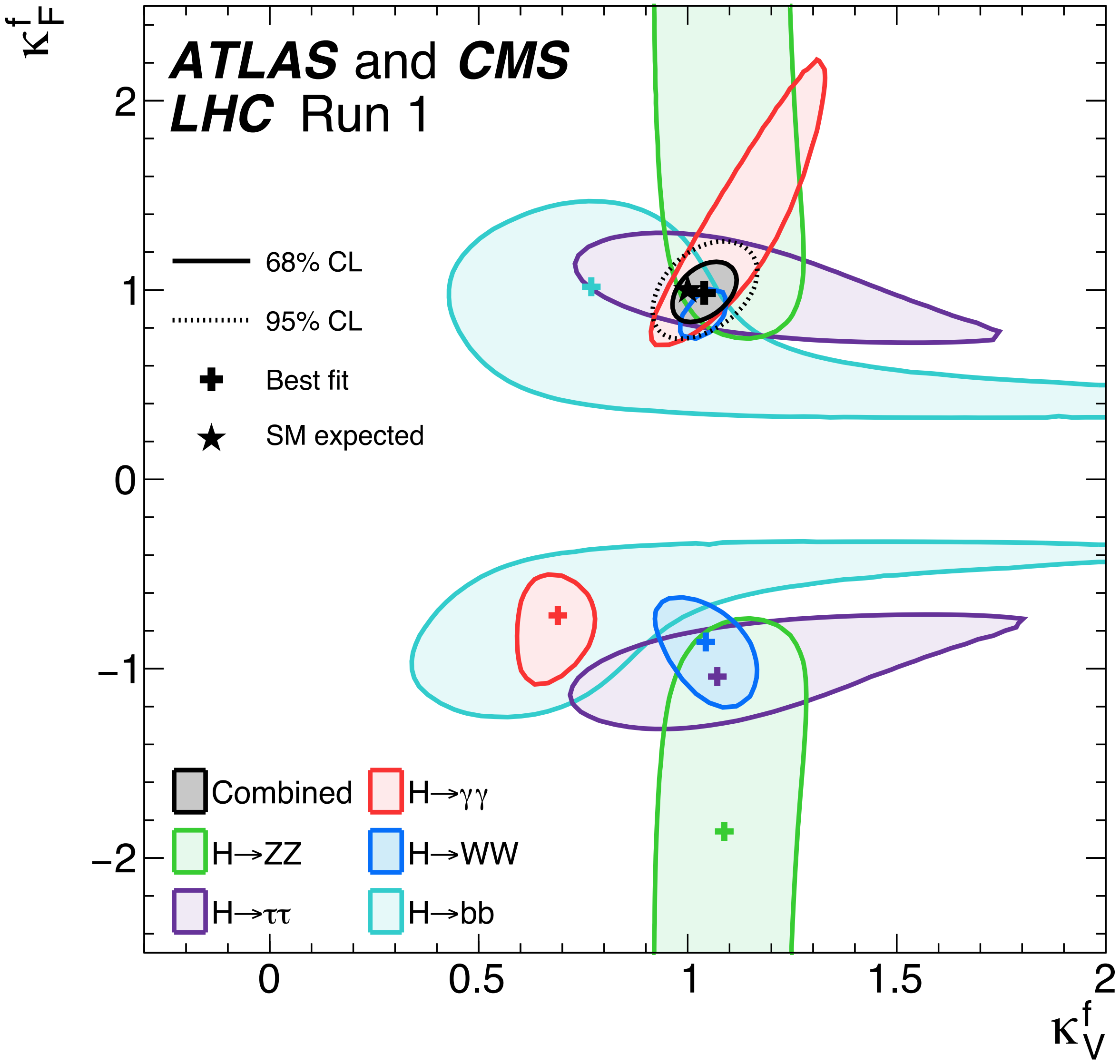
Couplings: K_V vs. K_f

- Scale all vector boson couplings with k_V and fermion couplings with k_f
- New physics could change ratio and relative sign
- Measurement compatible with SM and positive sign preferred
- top and W loops in diphoton decay lift degeneracy of sign



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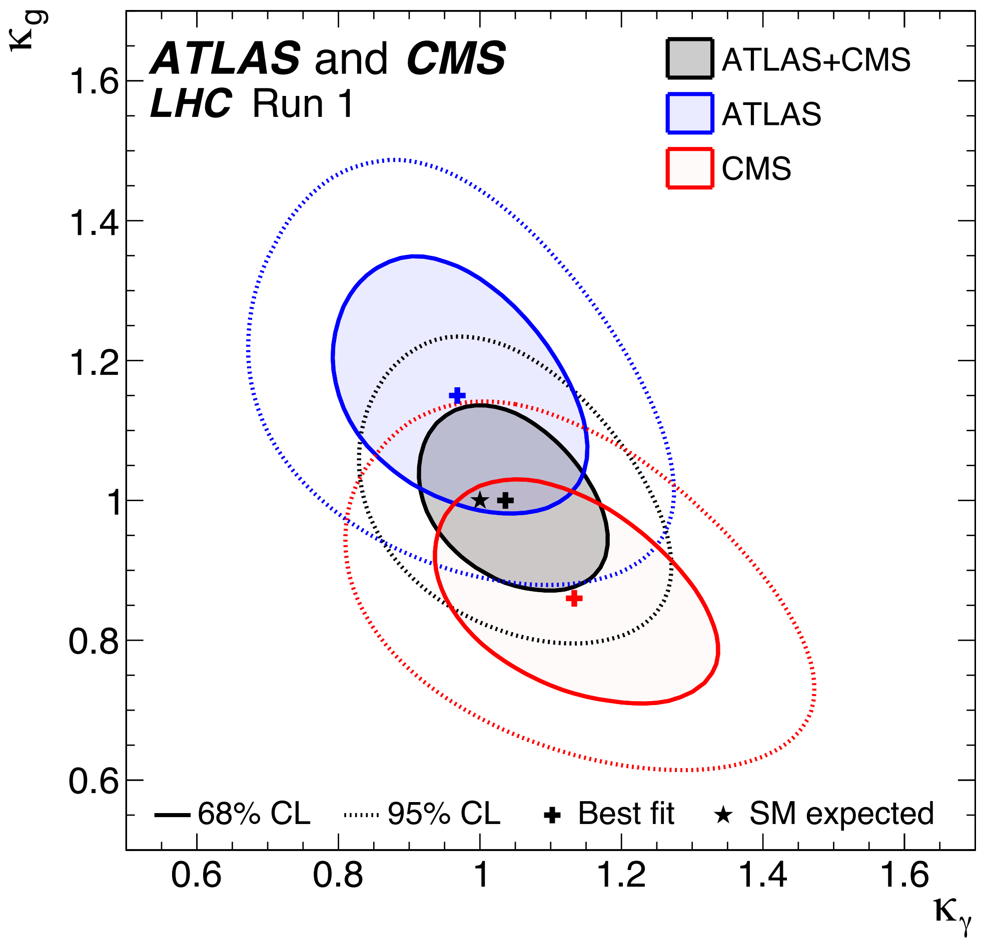
Couplings: K_g vs. K_γ

- gluon and photon coupling sensitive to new particles through loops
- Set all other couplings to SM values
- SM values for k_g and k_γ firmly within 1σ boundary
- P-value for SM case 82%



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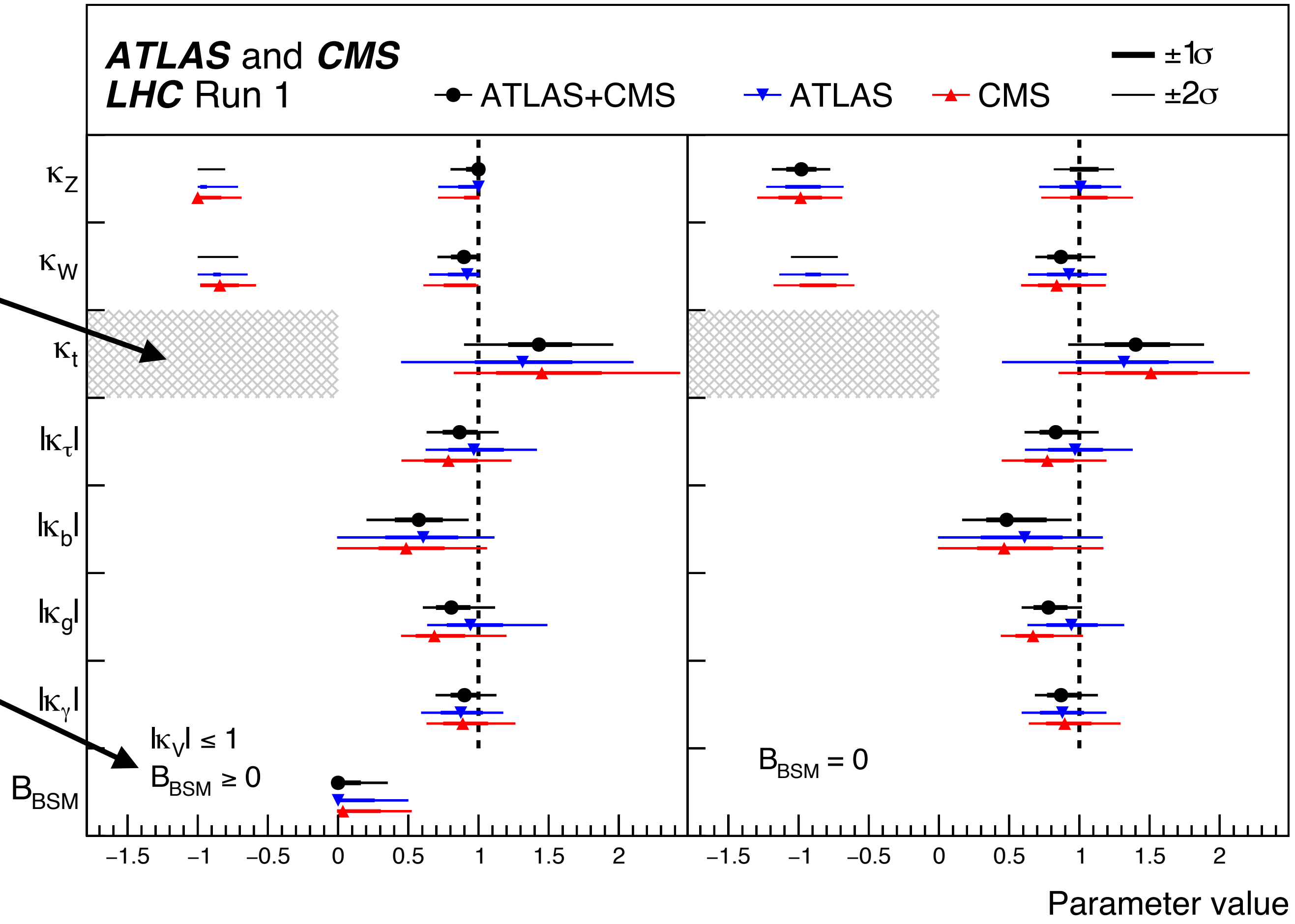
Couplings: 8D Fit

- Can also allow for individual k-factors for all measurable couplings
- Assume positive k_t, no loss of generality
- Results depend on whether the fit allows for a non-zero BSM contribution to width
- Then k_Z and k_W <= 1 and same sign
- Compatibility with SM is 11%
- Non-SM width constrained to $B_{BSM} < 0.34$



Effective Field Theory

- Kappa framework is useful to tell us where deviations from SM predictions occur
  - Only takes into account rate information
  - Assumptions on correlations in couplings need to be put into fit by hand
- Effective field theory (EFT) approach starts from:
  - Construct effective Lagrangian with all possible operators up to dimension six [JHEP 1010:085,2010]
  - Require lepton and baryon number conservation and Lorentz invariance
  - Wilson coefficients describe strength of effective coupling
- Directly gives coherent predictions of modified differential cross sections

The SILH Basis

- Many possible bases, popular example is “strongly interacting light higgs” (SILH) [JHEP 1307 (2013) 035]

$$\Delta\mathcal{L}^{(6)} = \boxed{\Delta\mathcal{L}_{SILH}} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

16 operators

(12 CP even, 4 CP odd)

SILH operators

Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} \\
& + \frac{i\tilde{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) \tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) \tilde{B}_{\mu\nu} \\
& + \frac{\tilde{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} \tilde{G}^{a\mu\nu}
\end{aligned}$$

brazenly stolen from here

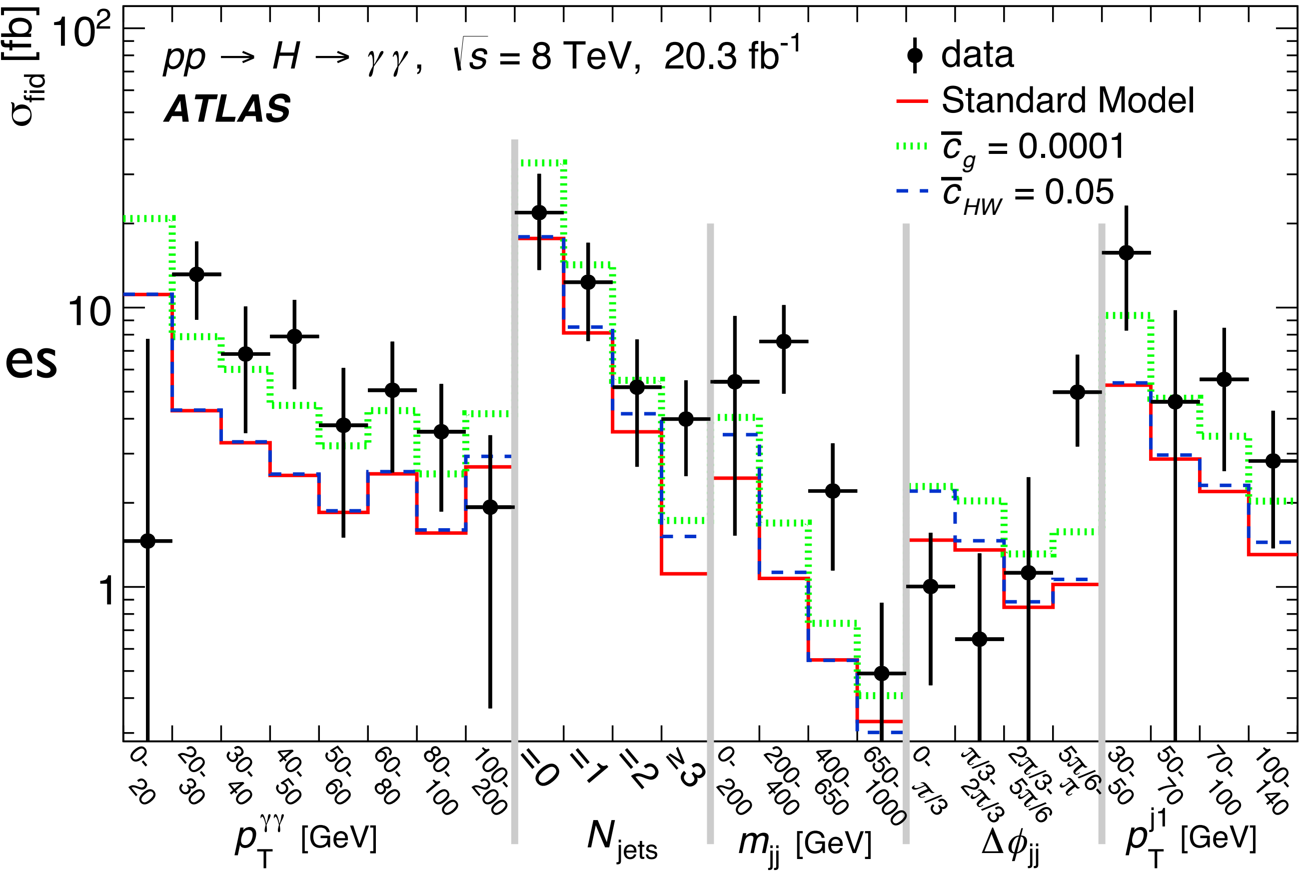
Ingredients for EFT Fit

- Several groups provide predictions for EFT models for some operators natively (HAWK arXiv:0707.0381,1412.5390 VBFNLO arXiv:0811.4559,…)
- But also full EFT models available in so-called universal FeynRules output (UFO) format
- Can use this generate signal models using generators with UFO support (MadGraph, Sherpa) [JHEP 06 (2011) 128 , Eur.Phys.J. C75 (2015) 135]
  - Usually renormalize partial widths to SM prediction from HDecay
- Using these signal predictions hypothesis tests can be done with fit framework of your choice (SFitter widely used in theory community)

Physics Letters B 753 (2016) 69-85

H→γγ EFT Interpretation

- Using Run I H→γγ differential measurements
- Interpretation in SILH basis
- EFT models formulated in universal FeynRules output (UFO) format
- Use this to produce signal predictions with Madgraph
- Information both from total and differential XS dependence on Wilson coefficients



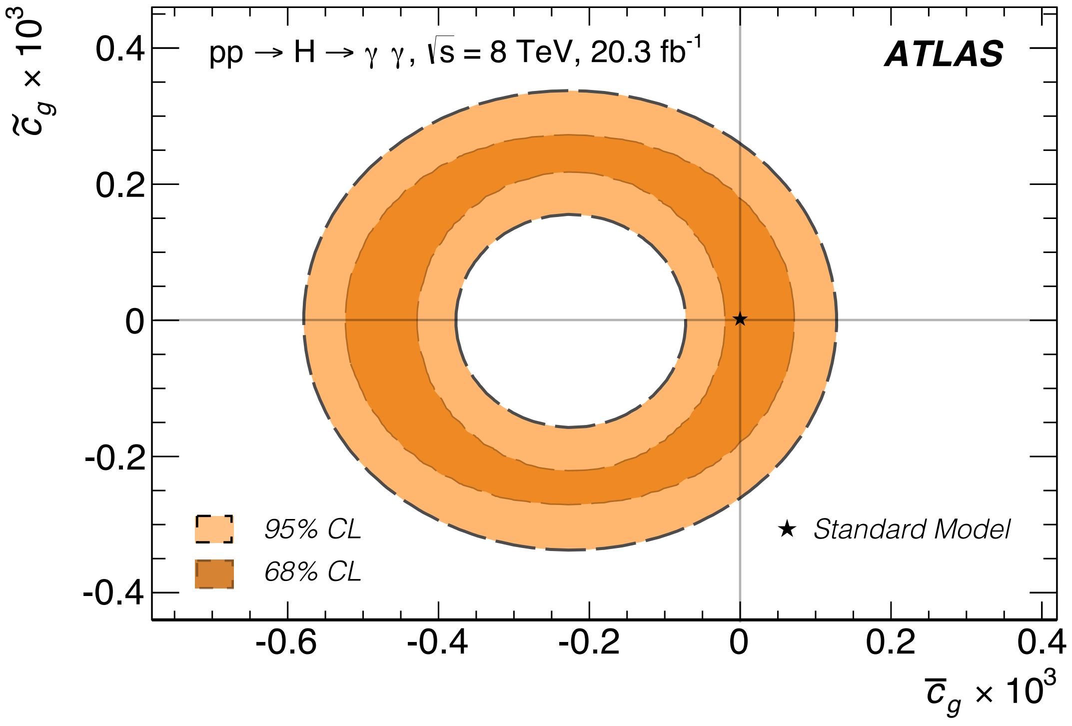
involvement by Desy, Bonn

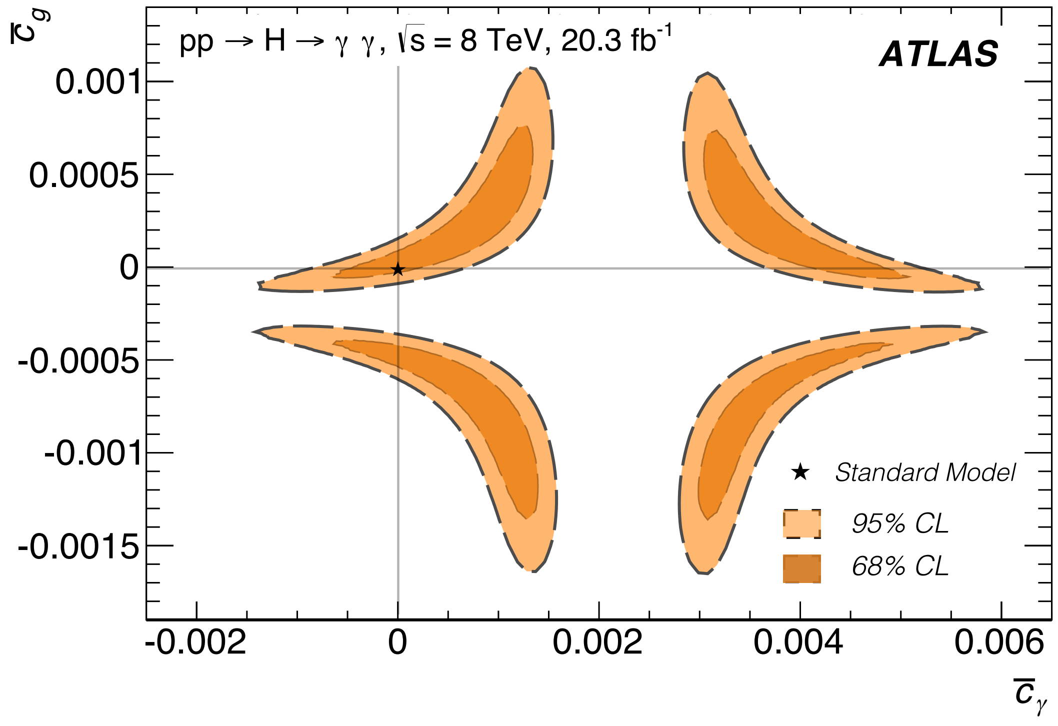
Physics Letters B 753 (2016) 69-85

H->γγ EFT Interpretation

- Sensitive mainly to dim. 6 operators involving photons, gluons
- But also W and Z via vector boson fusion and associated production
- Both in CP even (bar) and odd (tilde) variants due to including $\Delta\Phi_{jj}$

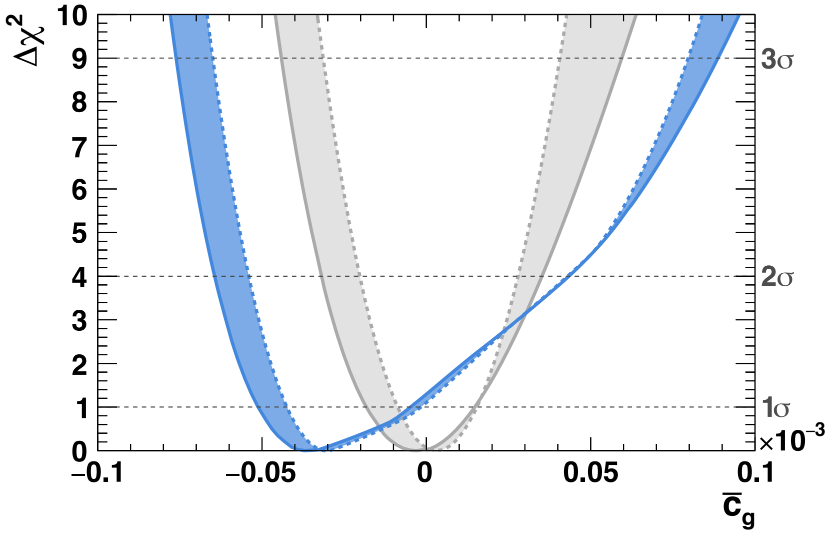
$$\begin{aligned}\mathcal{L}_{\text{eff}} =\ & \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} \\ +\ & \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},\end{aligned}$$



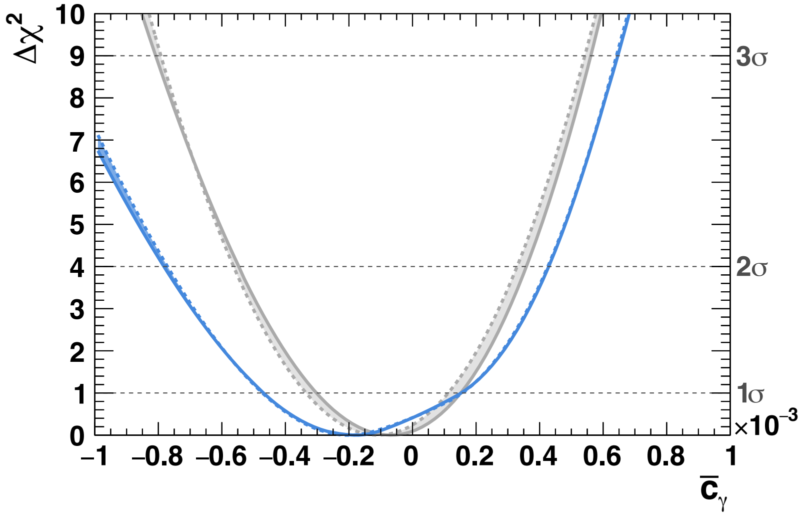


How Theorists do it

- Several theorists already take ATLAS data and feed it to working EFT frameworks
- Here use one example that can be directly compared to the ATLAS H->γγ EFT result
    - Also uses SILH basis
    - Signal predictions with modified version of VBFNLO using FeynRules
- Includes all production modes apart from di-Higgs
- Fitted Decay modes cover all ATLAS Run 1 results
- Results in slightly tighter limits on gluon and photon Wilson coefficients due to including other channels



arxiv: 1511.05170

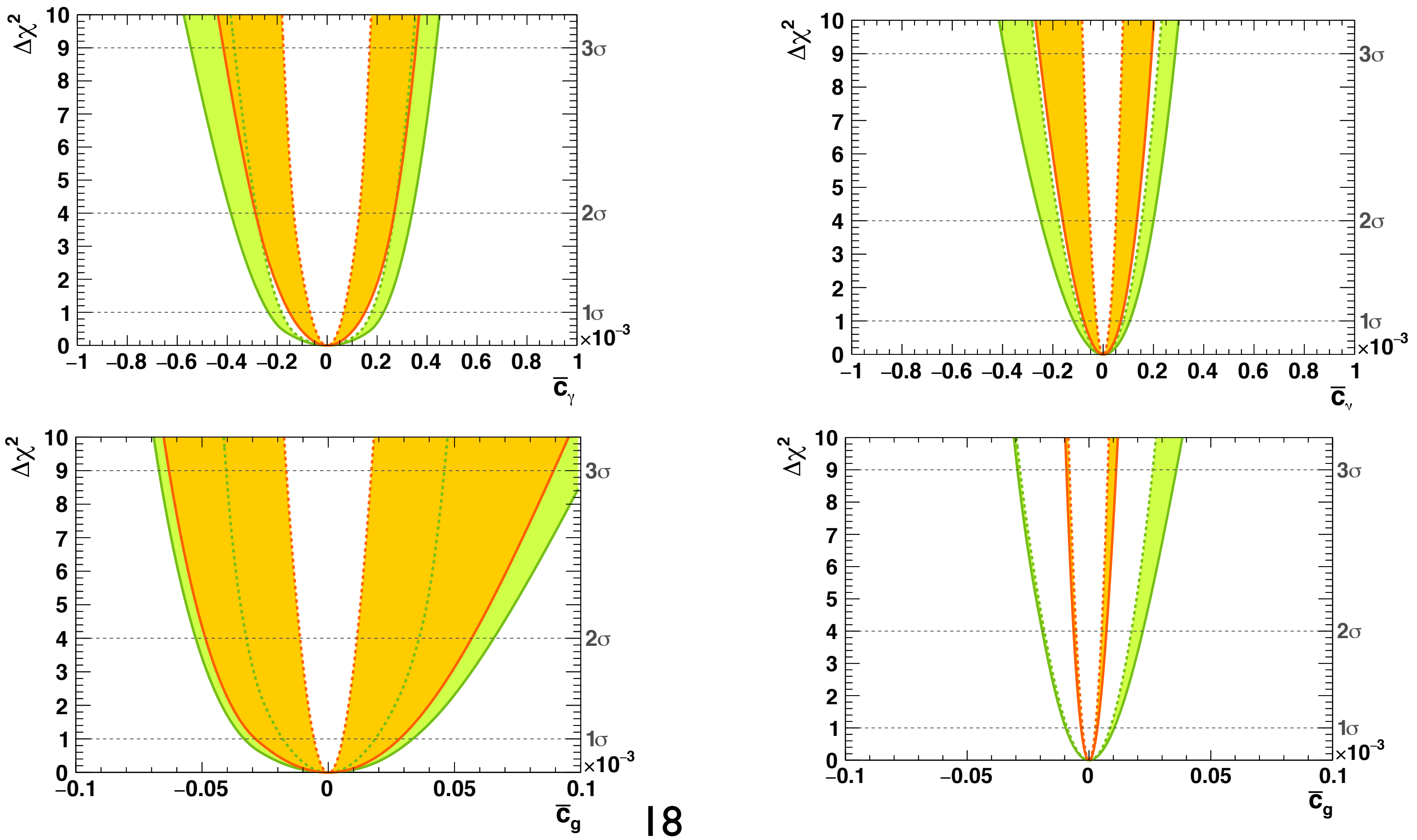


$$\bar{c}_g \in [\,-0.64,\, 0.43\,] \times 10^{-4}$$
$$\bar{c}_\gamma \in [\,-7.8,\, 4.3\,] \times 10^{-4}\,.$$

also arxiv: 1410.7703v1 , 1505.05516v1

Full LHC Dataset Projections

- Extrapolate to 300 (green) and 3000 (orange) fb-1 using
  - Published object selection efficiencies for production and decay
  - Estimates of background levels and systematic uncertainties
- Comparison of fits with only rate information (left) and full differential $p_{T,H}$ (right)

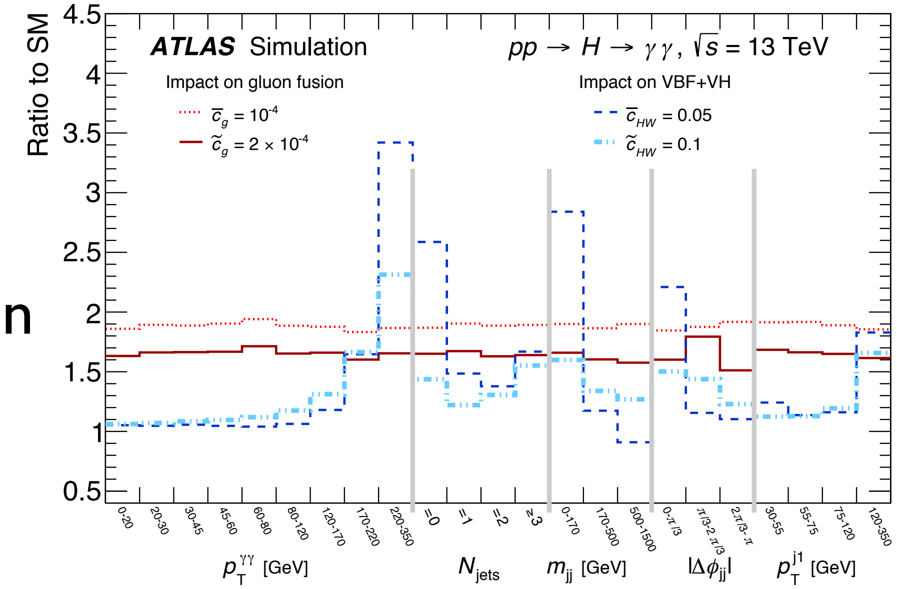


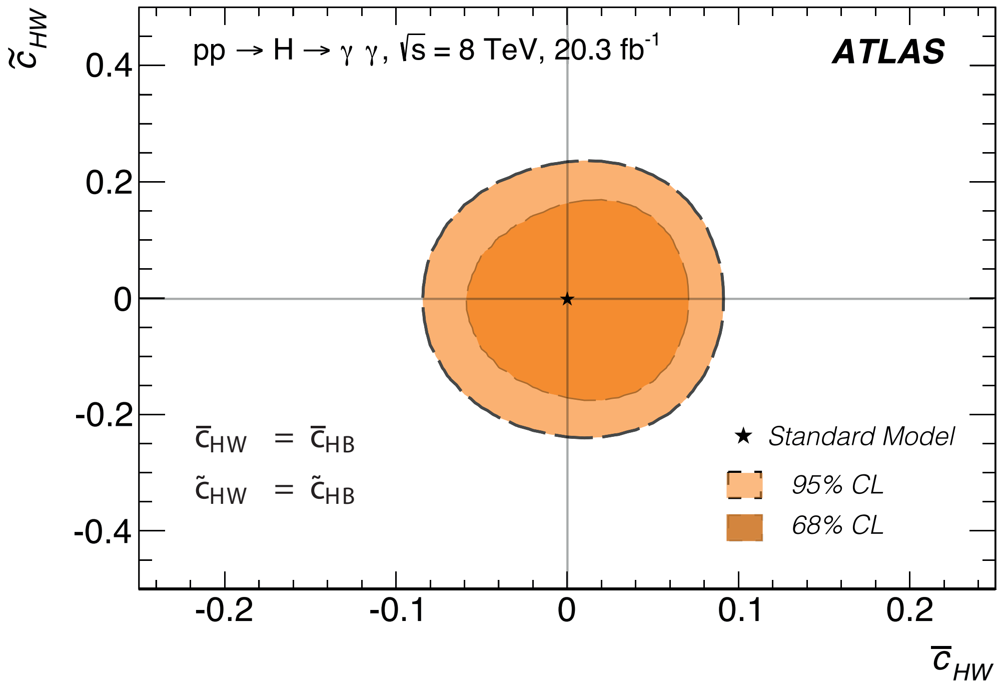
arxiv: 1511.05170

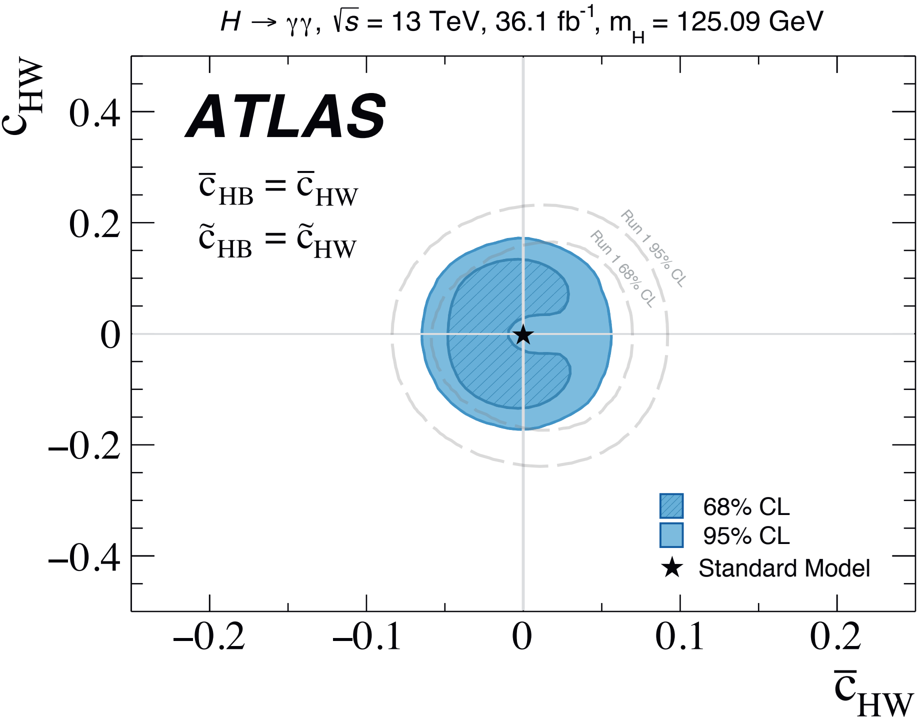
arxiv: 1802.04146

H->γγ: ATLAS strikes back

- ATLAS published the Run 2 version of this analysis in February 2018
- Again sensitivity is obtained from simultaneous fit of differential cross sections in multiple observables
- Limits in Wilson coefficients improve significantly
  - but again heavily dependent on rate information
  - sensitivity mostly from m_{jj} and pT(γγ)

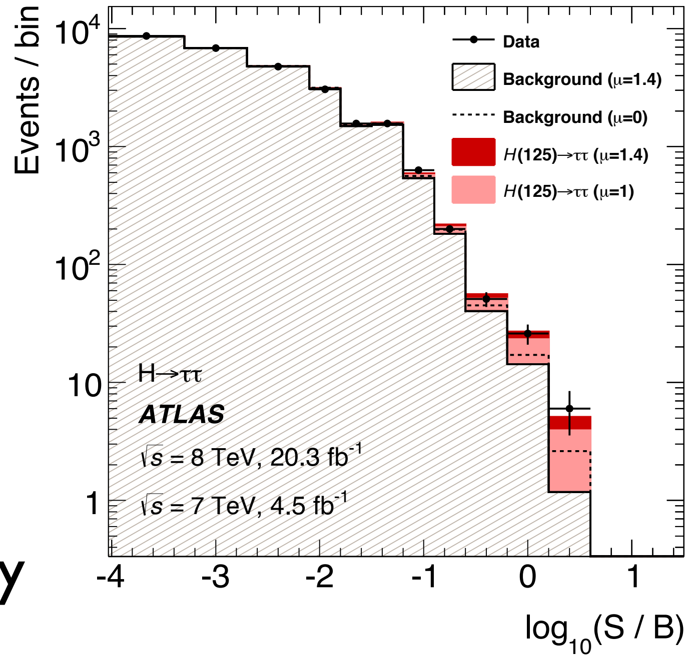






CP Mixing in Higgs Sector

- ATLAS and CMS have published >99.9% confidence level (CL) exclusion limits on pure CP-odd behaviour of new scalar boson
- But CP mixing still possible
- Look for small admixtures of CP-odd state to discovered scalar boson
- Can look at HVV coupling in vector boson fusion (VBF) production
    - Using Hττ decay mode due to relatively large VBF sample
- CP-mixing in HVV vertex also studied in H→WW and ZZ decay
    - results of both will be compared here
- Disclaimer: won't be discussing CP mixing in Hττ vertex



arxiv: 1602.04516

HVV in Effective Field Theory

- Most general, Lorentz-invariant tensor structure of HVV vertex

$$\begin{aligned} T^{\mu\nu}(q_1,q_2) = {} & a_1(q_1,q_2)\, g^{\mu\nu} && \text{(SM: } CP \text{ even)} \\ & + a_2(q_1,q_2)\, [q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}] \\ & && (CP \text{ even}) \\ & + a_3(q_1,q_2)\, \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma} && (CP \text{ odd}) \end{aligned}$$

- With a3 = 0 in SM and != 0 in CP-mixed case

- Yields effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

- Wilson coefficients g proportional to d-tilde parameter from HAWK EFT model

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2} \tilde{g}_{HWW} = \frac{g}{2m_W} \tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

Expressed in terms of the parameters used for the HWW/HZZ CP analysis (E.P. J. C75 (2015) 476):

$$\tilde{d} = -\hat{\kappa}_Z = -\hat{\kappa}_W = -\tilde{\kappa}_W/\kappa_{SM} \tan\alpha$$

HVV Matrix Element in EFT

- Using the EFT Lagrangian from previous page, the VBF matrix element can be written as:

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

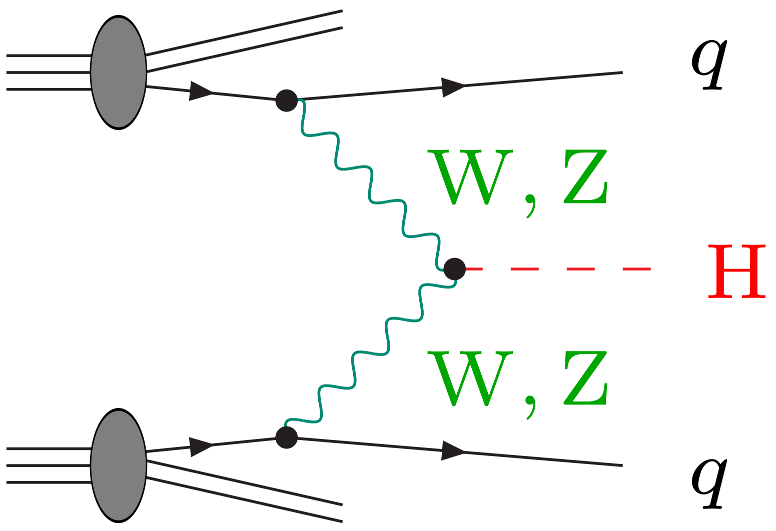
- Squaring M gives three terms. Only term linear in d-tilde is cp-violating:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

- Quadratic term only affects total yield, but no contribution to CP violation
- Not exploiting yield information in this analysis
- In principle can also have CP-violation other Higgs coupling
  - here assume SM couplings (also for gluon fusion production), but could have additional interpretation with additional non-SM couplings

arxiv: 1602.04516

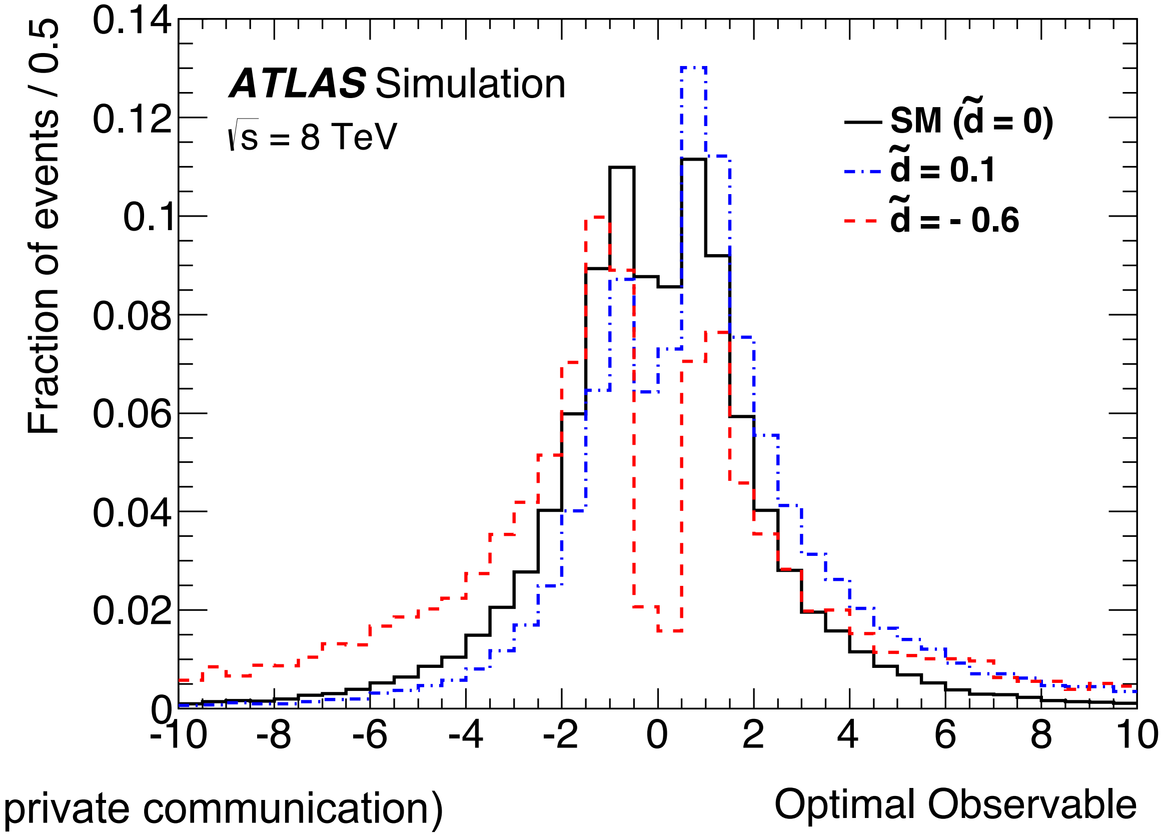
Optimal Observable



- Use all kinematic information of VBF final state
  - Reconstructed 4-vectors of tagging jets and Higgs
  - Bjorken $x_{1/2}^{\text{reco}} = \frac{m_{Hjj}}{\sqrt{s}} \mathrm{e}^{\pm y_{Hjj}}$
- Combine into ratio of matrix elements

$$\mathcal{OO} = \frac{2\,\mathrm{Re}(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- Matrix elements calculated at leading order using HAWK 2.0

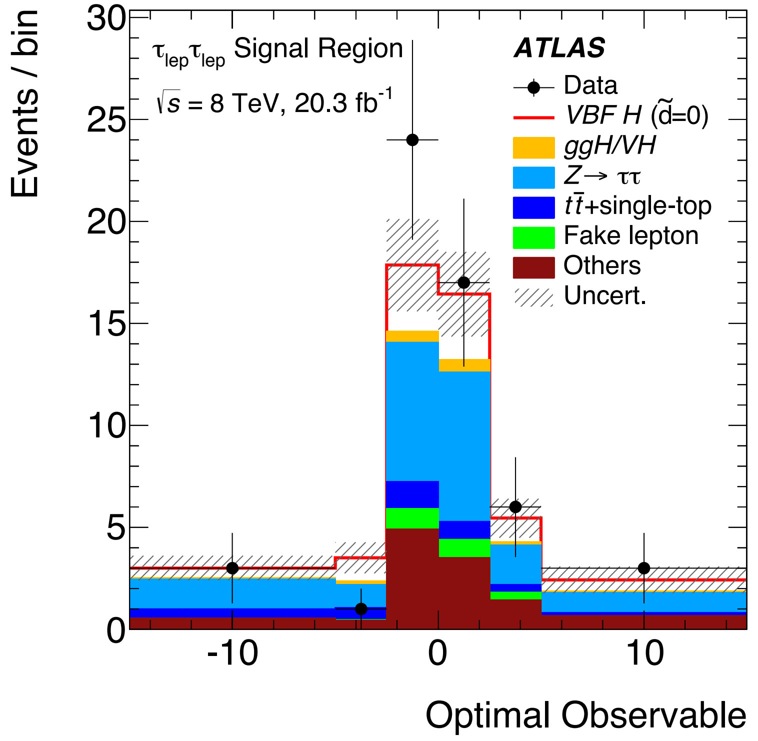


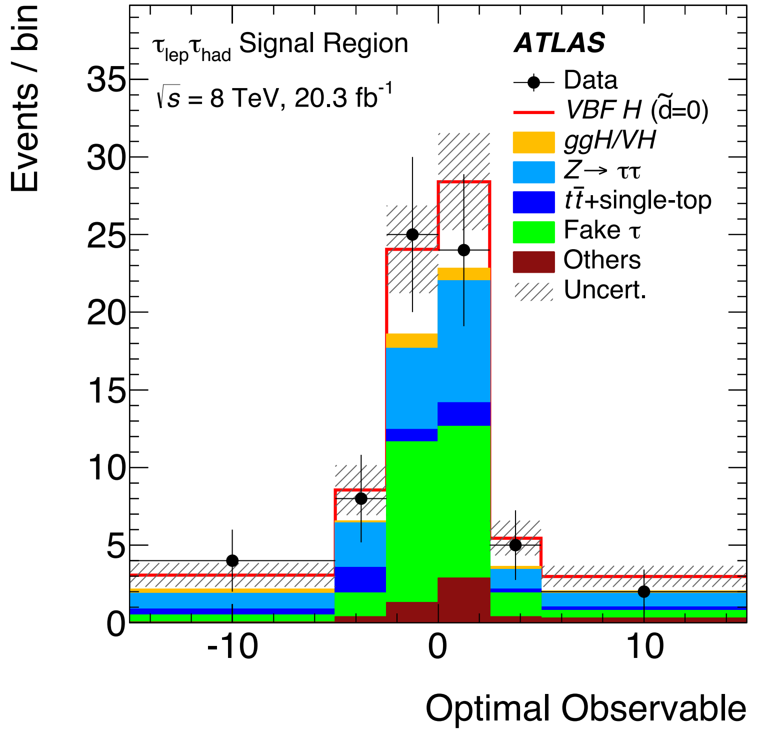
(Ciccolini et al arXiv:0707.0381, Denner at al. arXiv:1412.5390 and private communication)

VBF H→ττ Fit Model

- Signal strength fitted in binned, maximum likelihood fit
- No constraint on signal strength from CP-odd signal predictions
- Control regions enter to constrain nuisance parameters (NPs)
    - Top (and Z->ll) CR as single bin to constrain normalization
    - Low-BDT CR binned in BDT score: constrain shape NP's

Process	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$
Data	54	68
VBF $H \to \tau\tau/WW$	9.8±2.1	16.7±4.1
$Z \to \tau\tau$	19.6±1.0	19.1±2.2
Fake lepton/τ	2.3±0.3	24.1±1.5
$t\bar{t}$ +single-top	3.8±1.0	4.8±0.7
Others	11.5±1.7	5.3±1.6
ggH/VH, $H \to \tau\tau/WW$	1.6±0.2	2.5±0.7
Sum of backgrounds	38.9±2.3	55.8±3.3



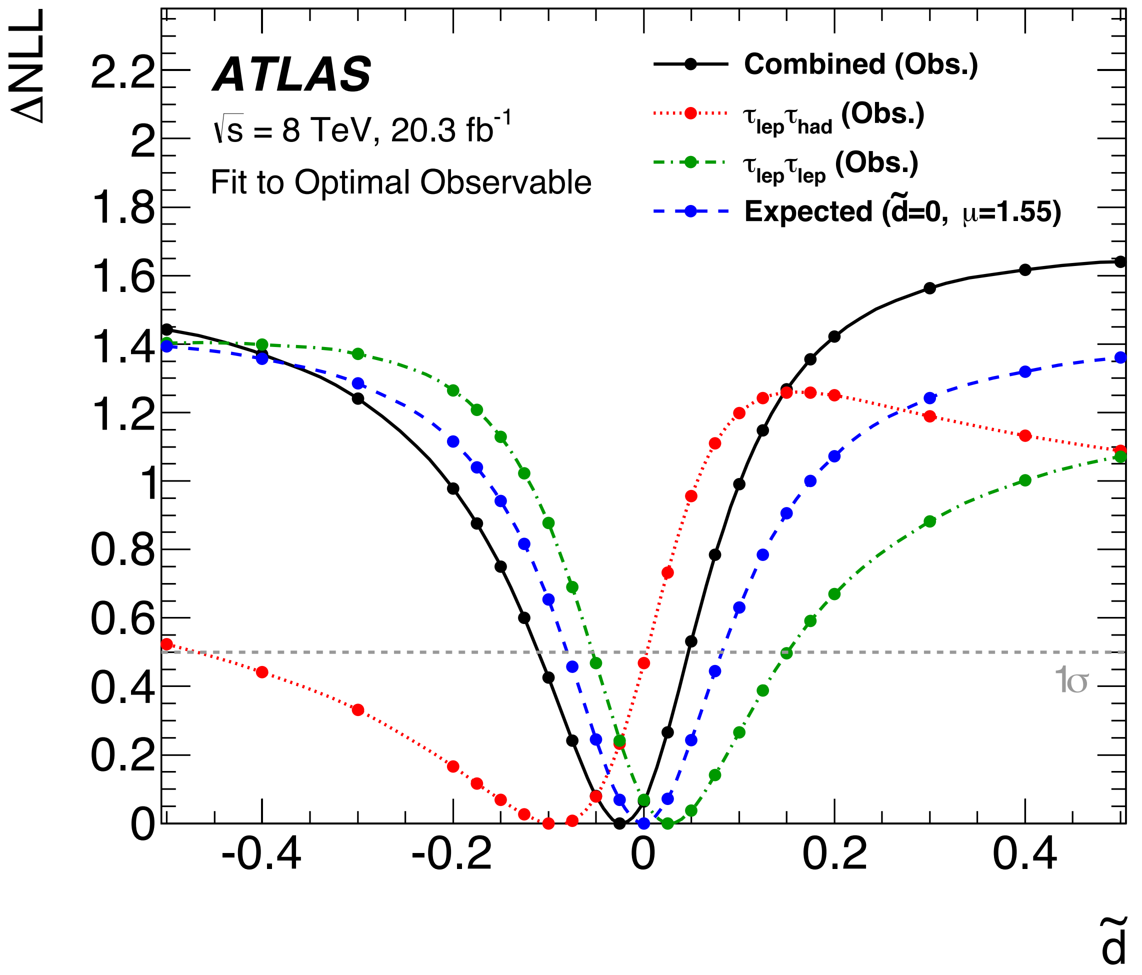


involvement by Freiburg, Göttingen

arxiv: 1602.04516

VBF H→ττ Fit Interpretation

- Reminder pure CP-odd already excluded and high mixing therefore also unlikely
  - Focus on small values of d-tilde
- Mean of OO consistent with zero
  - → No sign of CP-violation
- Perform signal strength fit for various d-tilde values
- d-tilde outside [-0.11,0.05] excluded at 68% CL



EPJC 75 (2015) 476

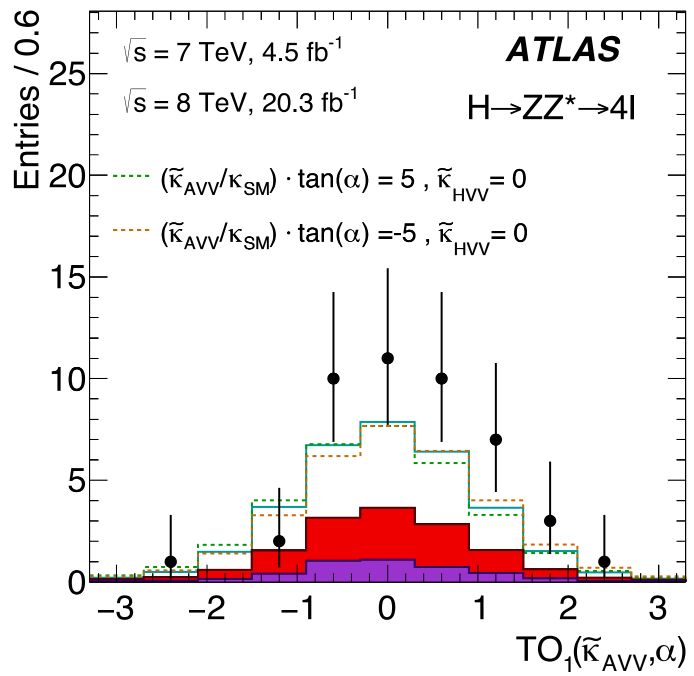
Comparison with H→Bosons

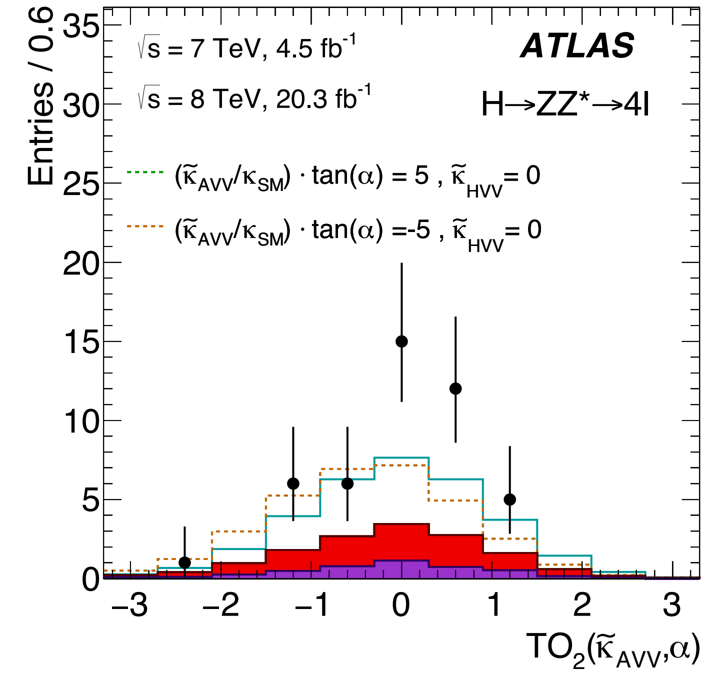
- Limits on CP-mixing also extracted from combination of WW and ZZ channels
    - EFT model predictions derived from MadGraph
- Approach for WW analogous to analysis used to exclude spin 1,2 hypotheses
- In ZZ a matrix element method is used also based on ratios of CP-odd and even matrix elements

$$\frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- Main difference is inclusion of second order term that grows quadratically with CP-mixing parameter

$$\frac{|\mathcal{M}_{\text{CP-odd}}|^2}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

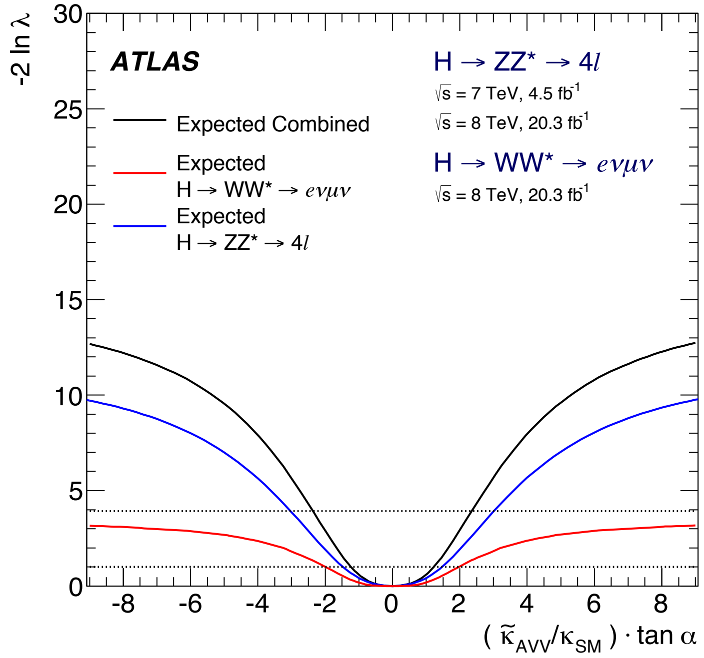


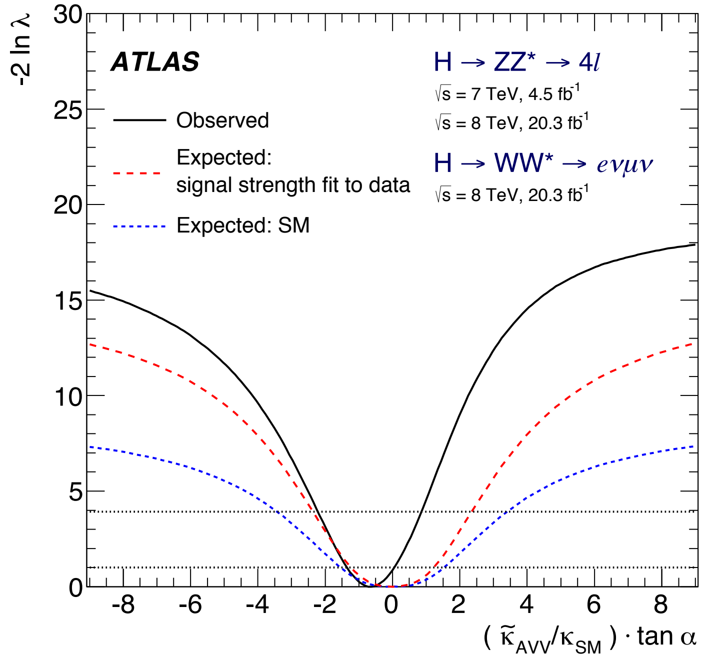


EPJC 75 (2015) 476

CP-Mixing limits from H→Bosons

- Extraction of limits from DNLL curves
- 95% CL limits given, also on additional CP even coupling
- At 95% CL these limits naturally exceed the VBF production analysis
    - Though 68% CL interval for VBF analysis more narrow
- Production and decay information complementary → combine





Coupling ratio Combined	Best-fit value Observed	95% CL Exclusion Regions Expected	 Observed
$\tilde{\kappa}_{HVV}/\kappa_{\rm SM}$	-0.48	$(-\infty,-0.55]\bigcup[4.80,\infty)$	$(-\infty,-0.73]\bigcup[0.63,\infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\rm SM})\cdot\tan\alpha$	-0.68	$(-\infty,-2.33]\bigcup[2.30,\infty)$	$(-\infty,-2.18]\bigcup[0.83,\infty)$

Expressed in terms of the parameters used for the HWW/HZZ CP analysis (E.P. J. C75 (2015) 476):

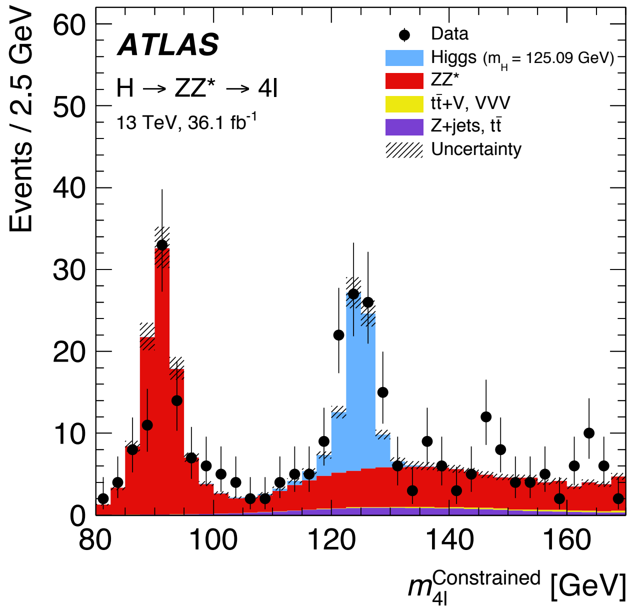
$$\tilde{d} = -\hat{\kappa}_Z = -\hat{\kappa}_W = -\tilde{\kappa}_W/\kappa_{SM}\tan\alpha$$

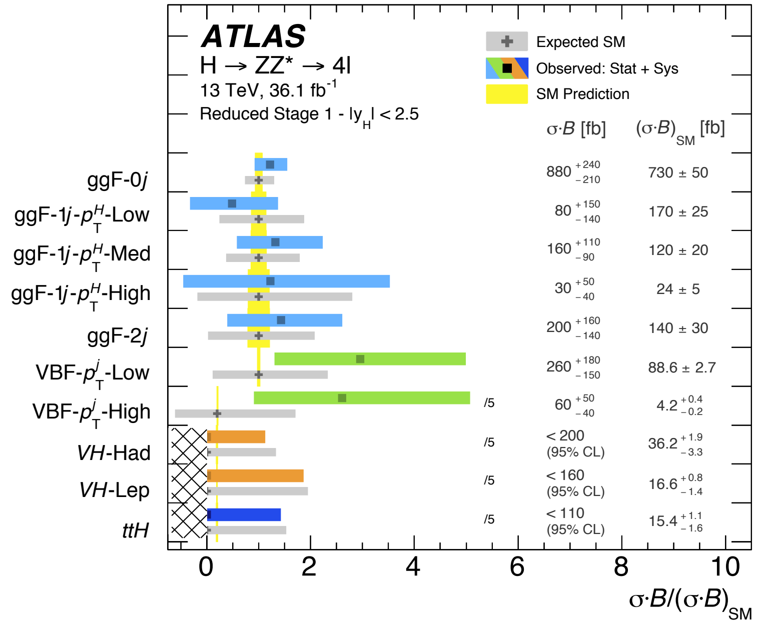
involvement by Freiburg, Munich, Mainz

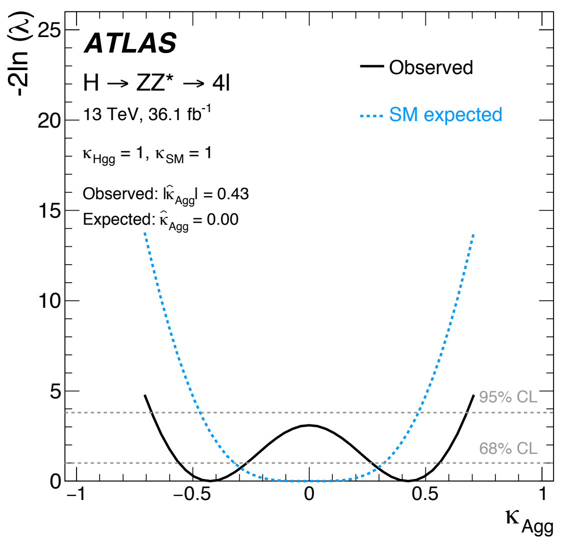
JHEP 03 (2018) 095

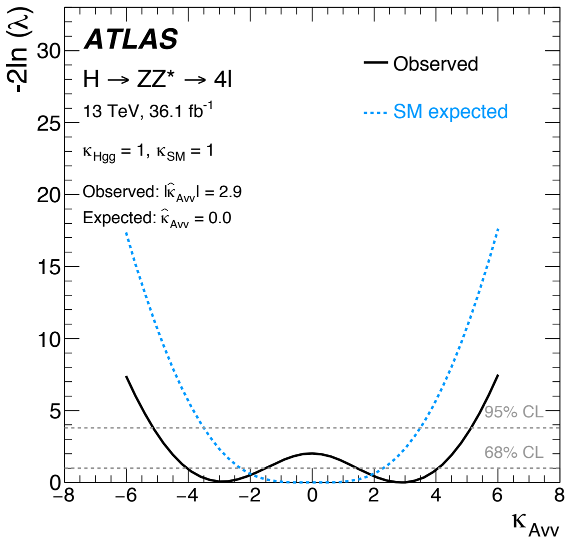
Run 2Update from H→ZZ*

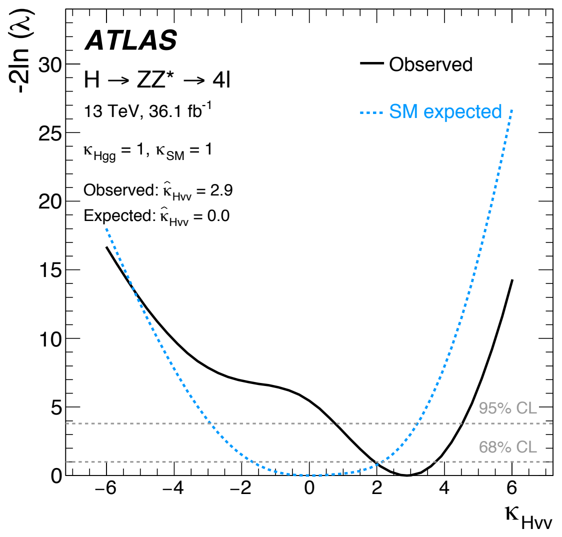
- Analysis using 2015+16 dataset
- More events than Run1 but split across a lot of categories
    - “Symptom” of STXS trend
- From rate in each category, derive sensitivity to EFT parameters
- much less sensitive than Run1-style matrix element analysis
    - to be fair also missing WW* final state still







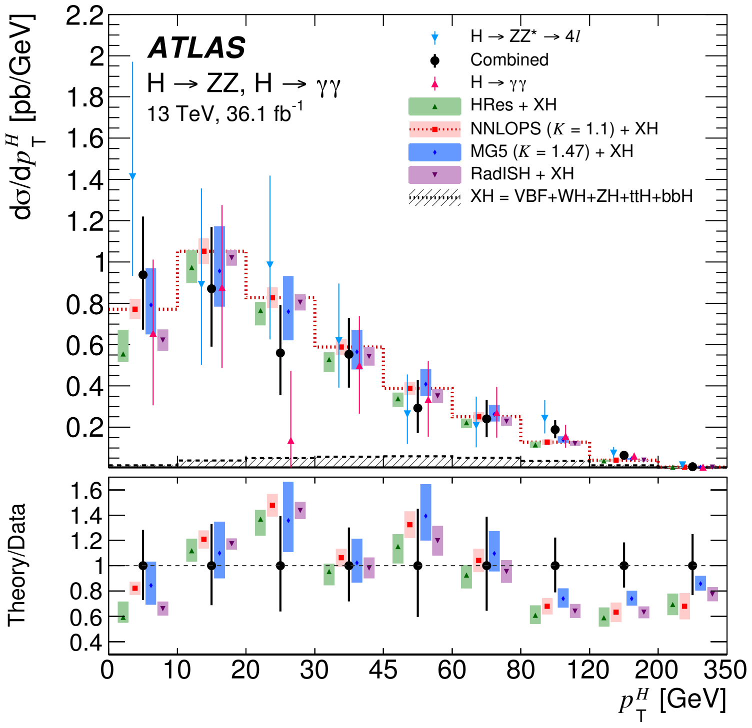


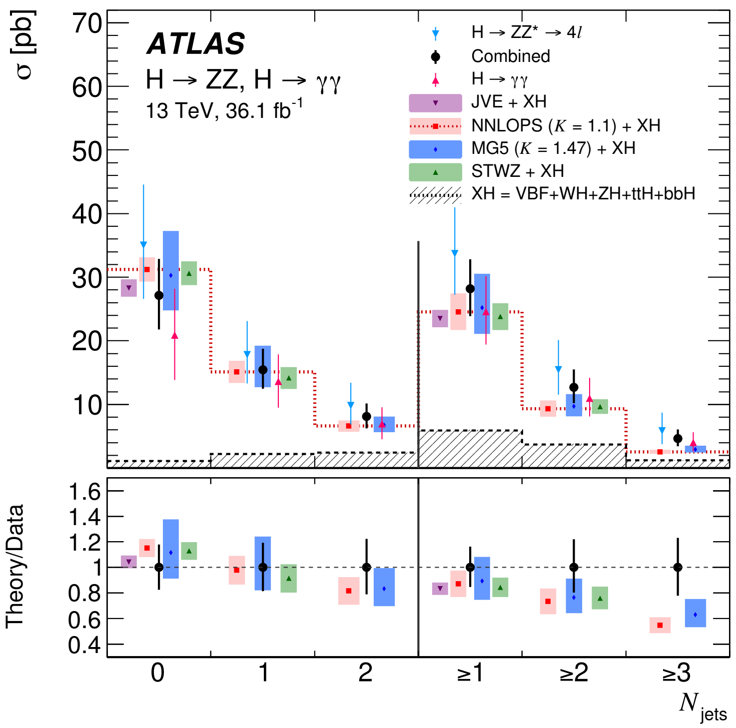


arxiv: 1805.10197v1

what’s up in Run 2 ?

- A lot of effort went into “rediscovery” of Higgs at 13 TeV
- WW* published only recently on 2015+16 dataset, H→ττ
- ATLAS recently combined differential measurements in γγ and ZZ*
- So far only stating combined differential cross sections
    - no combined interpretation w.r.t. BSM Higgs theory
- Hope for proper EFT interpretation in combination with further channels





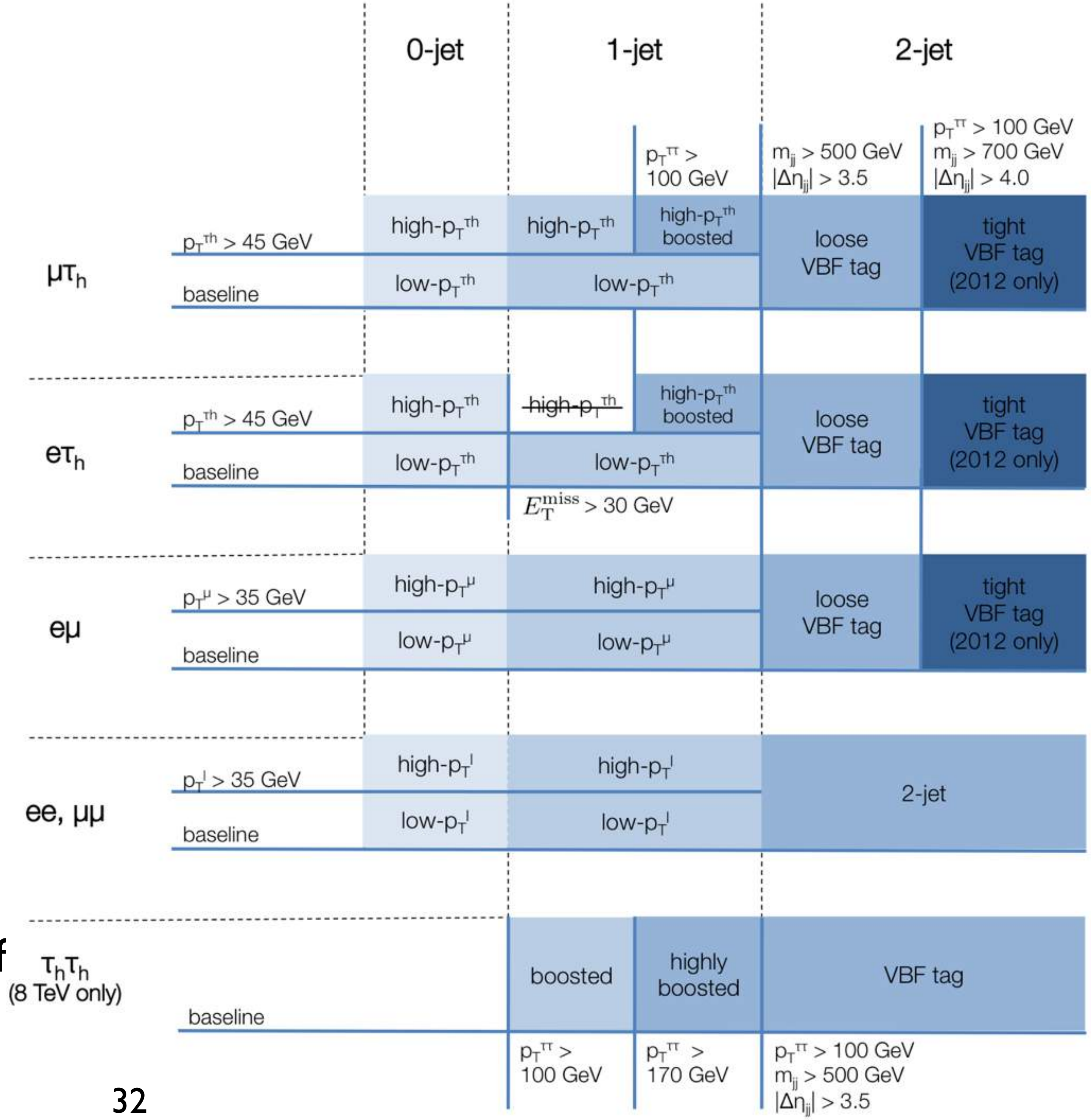
Summary

- (non-comprehensive and biased) review of Higgs measurements at LHC
- CMS and ATLAS provide fits of some well motivated coupling modifications
  - using only rate information, not considering predictions for correlations
- EFT approach provides complete set of possible modifications of rate and shapes
- Run1 data has been also interpreted in EFT approach, but in uncoordinated way
- Several theorists using Run 1 inputs and even making predictions for Run 2
  - Should collaborate more closely to ensure valid systematics treatment
- First results appearing for EFT interpretation of Run2 data

Backup

“Tagging” Production Modes

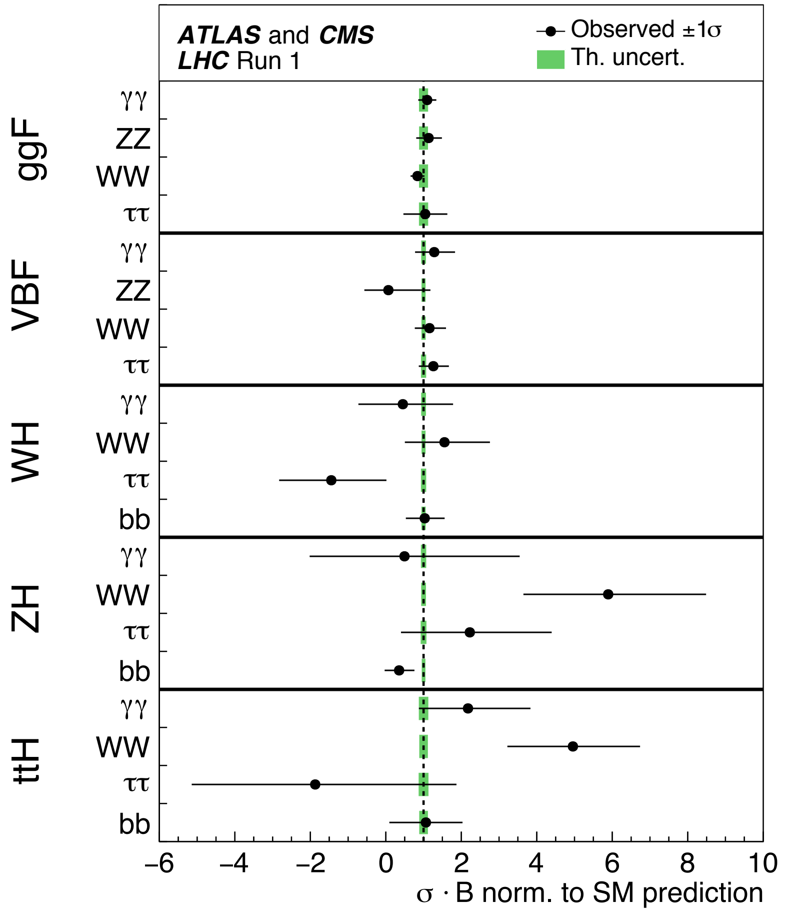
- separating production modes by jet multiplicity
- 2-jet categories enriched with VBF
- Increase purity with selections on $\Delta\eta_{jj}$, m_{jj} and similar variables
- Third-Jet veto sometimes used, but introduces large theory uncertainties
- high Higgs-candidate p_T improves sensitivity
- Higgs from gluon fusion (ggF) has large theory uncertainties on p_T spectrum
- QCD-scale uncertainties on ggF one of the dominant uncertainties in all channels



Fit Inputs

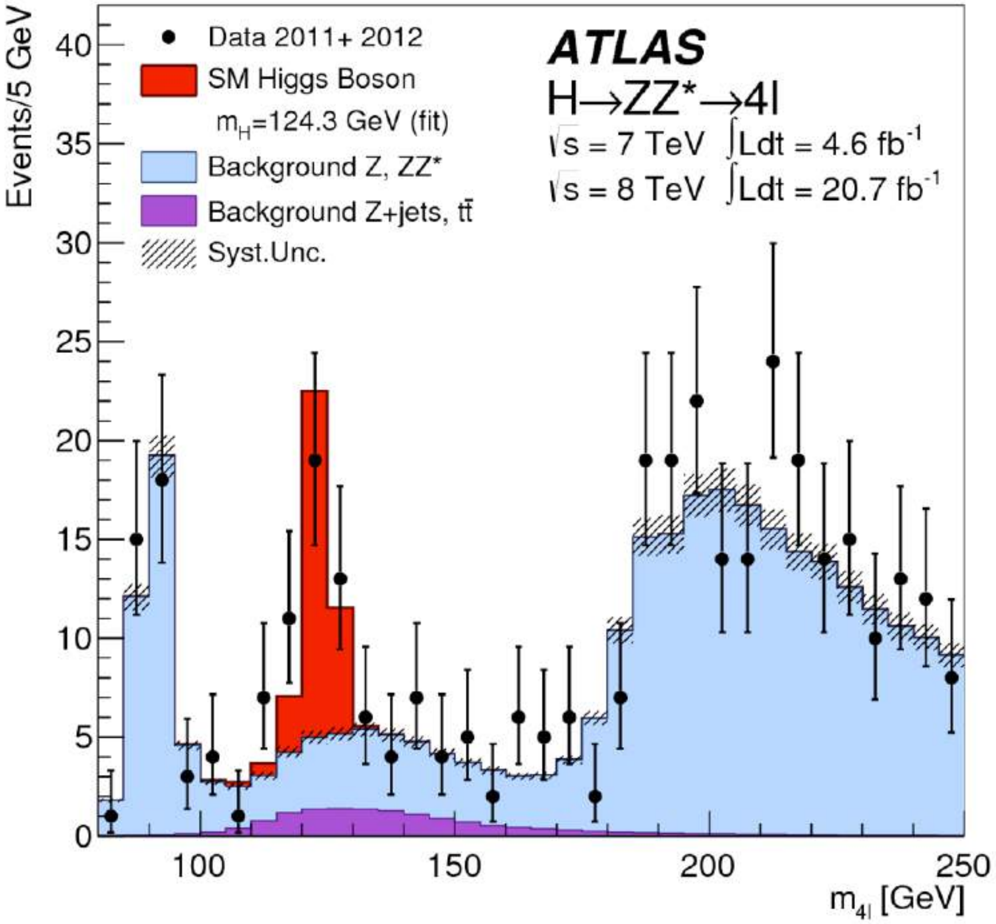
- Measured signal strength in units of SM cross section x branching ratio
- Not possible to measure either by itself without theory assumptions
- In all decay channels signal strength agrees with SM expectation within 1-2 σ

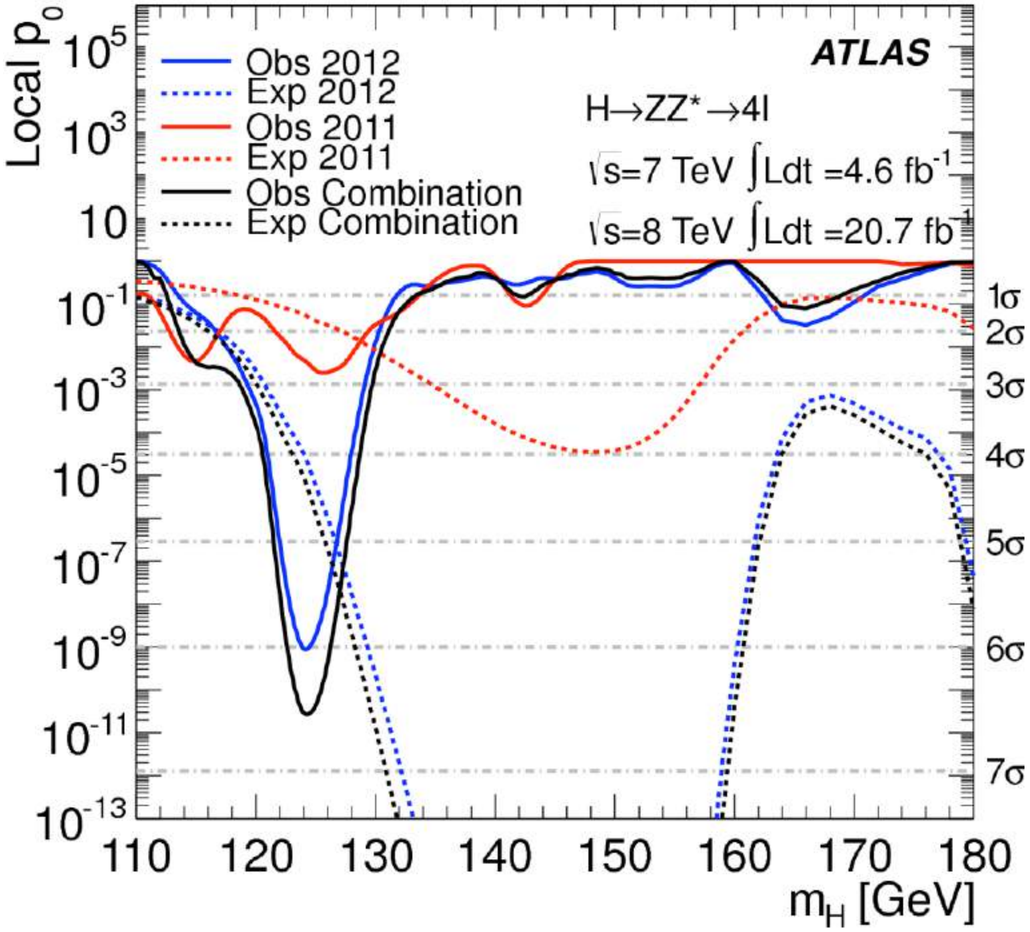
Channel	References for individual publications		Signal strength [μ] Signal significance [σ] from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[92]	[93]	$1.14^{+0.27}_{-0.25}$ $\left(\begin{smallmatrix}+0.26\\-0.24\end{smallmatrix}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(\begin{smallmatrix}+0.23\\-0.21\end{smallmatrix}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[94]	[95]	$1.52^{+0.40}_{-0.34}$ $\left(\begin{smallmatrix}+0.32\\-0.27\end{smallmatrix}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(\begin{smallmatrix}+0.30\\-0.25\end{smallmatrix}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[96, 97]	[98]	$1.22^{+0.23}_{-0.21}$ $\left(\begin{smallmatrix}+0.21\\-0.20\end{smallmatrix}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(\begin{smallmatrix}+0.23\\-0.20\end{smallmatrix}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[99]	[100]	$1.41^{+0.40}_{-0.36}$ $\left(\begin{smallmatrix}+0.37\\-0.33\end{smallmatrix}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(\begin{smallmatrix}+0.31\\-0.29\end{smallmatrix}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[101]	[102]	$0.62^{+0.37}_{-0.37}$ $\left(\begin{smallmatrix}+0.39\\-0.37\end{smallmatrix}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(\begin{smallmatrix}+0.45\\-0.43\end{smallmatrix}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[103]	[104]	$-0.6^{+3.6}_{-3.6}$ $\left(\begin{smallmatrix}+3.6\\-3.6\end{smallmatrix}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(\begin{smallmatrix}+3.3\\-3.2\end{smallmatrix}\right)$		
ttH production	[78, 105, 106]	[108]	$1.9^{+0.8}_{-0.7}$ $\left(\begin{smallmatrix}+0.7\\-0.7\end{smallmatrix}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(\begin{smallmatrix}+0.9\\-0.8\end{smallmatrix}\right)$	2.7 (1.6)	3.6 (1.3)



ATLAS-CONF-2013-013 / PLB 726, pp 88-119

H → ZZ*

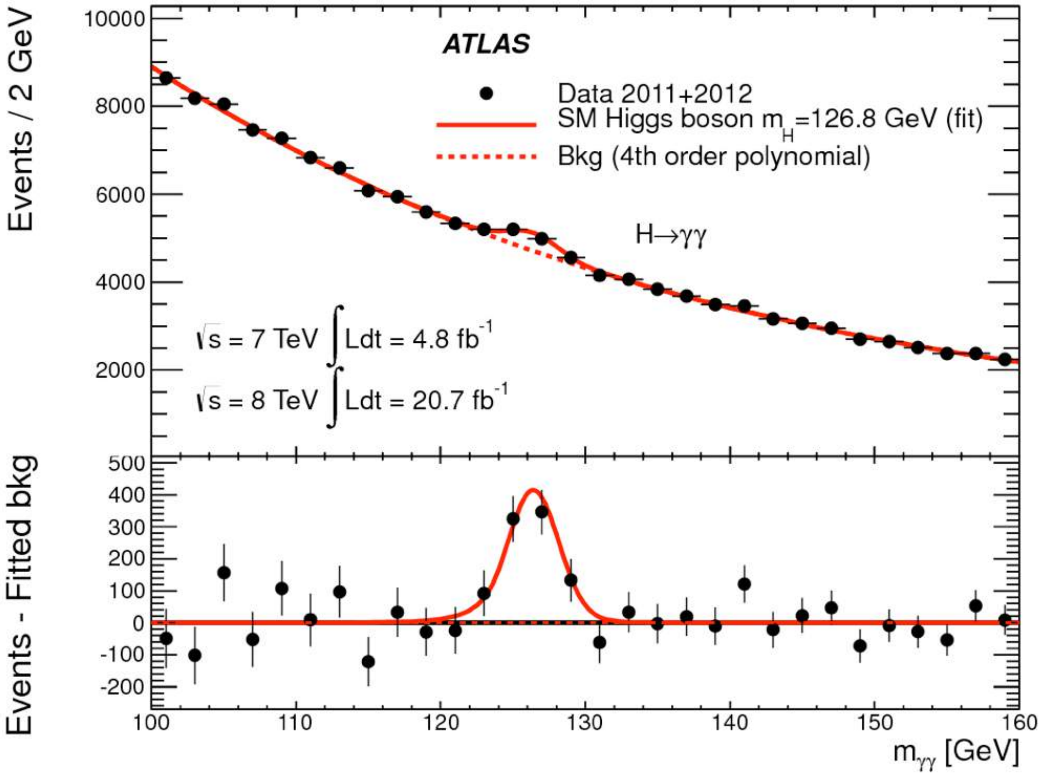


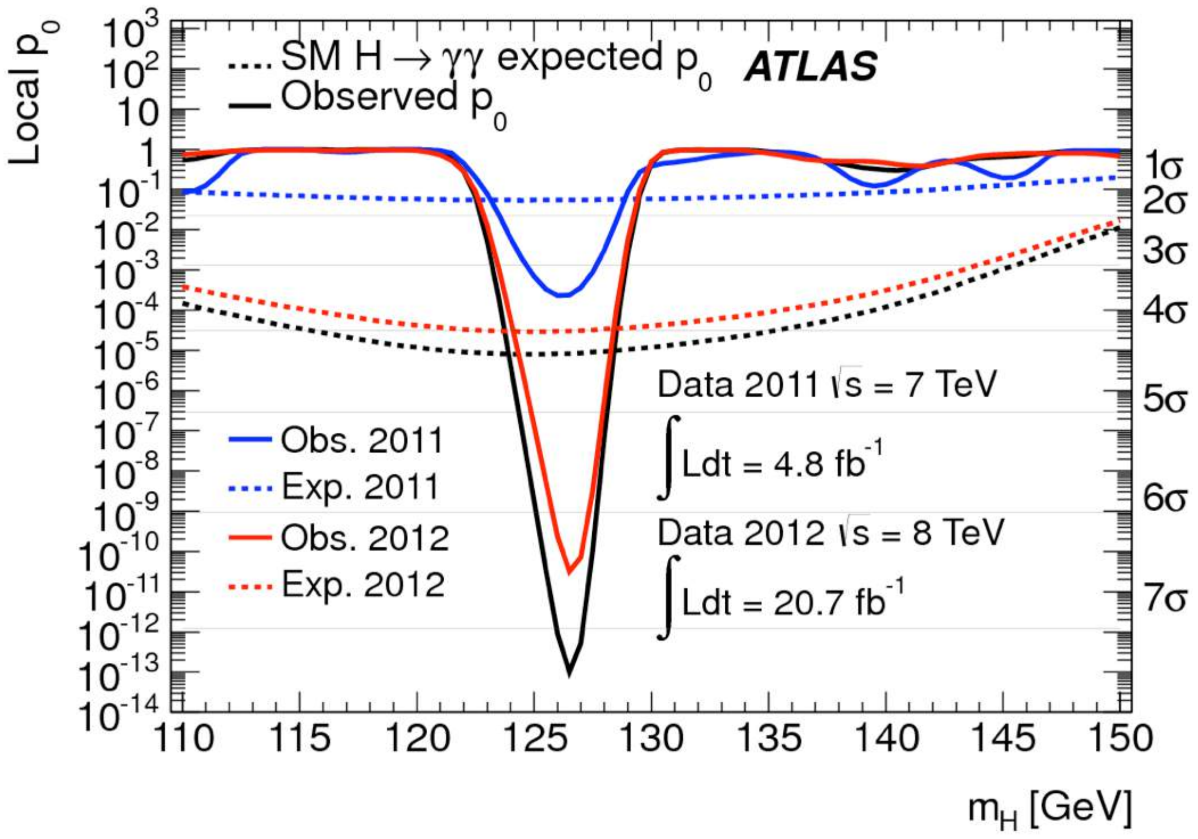


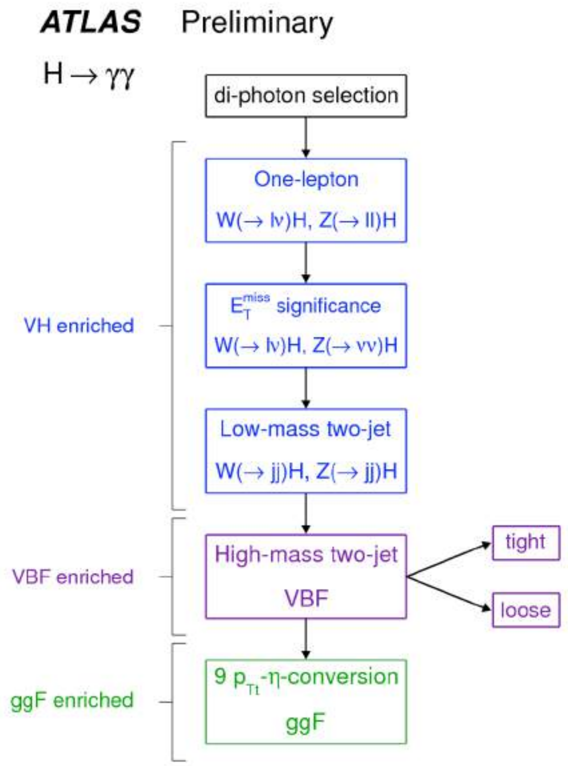
- **Selection:** 2 pairs of isolated, opposite sign leptons, lead pair consistent with Z mass
- **Categorization:** one each for VBF, ggF and VH
- **Backgrounds:** ZZ* continuum, Z+jets and ttbar
- **Main Results:** obs. (exp.) 6.6 (4.4) σ at 124.3 GeV, corresponding to $\mu = 1.7^{+0.5}_{-0.4}$

ATLAS-CONF-2013-013 / PLB 726, pp 88-119

$H \rightarrow \gamma\gamma$







ATLAS Preliminary

$H \rightarrow \gamma\gamma$

di-photon selection

VH enriched

One-lepton
$W(\rightarrow l\nu)H$, $Z(\rightarrow ll)H$

E_T^{miss} significance
$W(\rightarrow l\nu)H$, $Z(\rightarrow \nu\nu)H$

Low-mass two-jet
$W(\rightarrow jj)H$, $Z(\rightarrow jj)H$

VBF enriched

High-mass two-jet
VBF

tight

loose

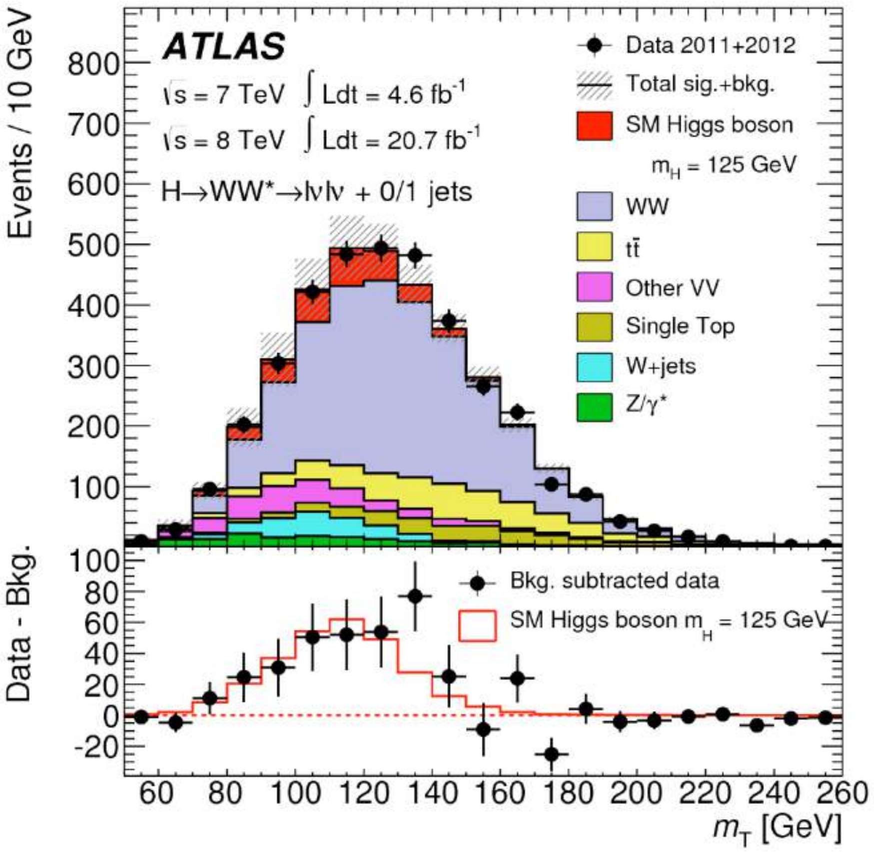
ggF enriched

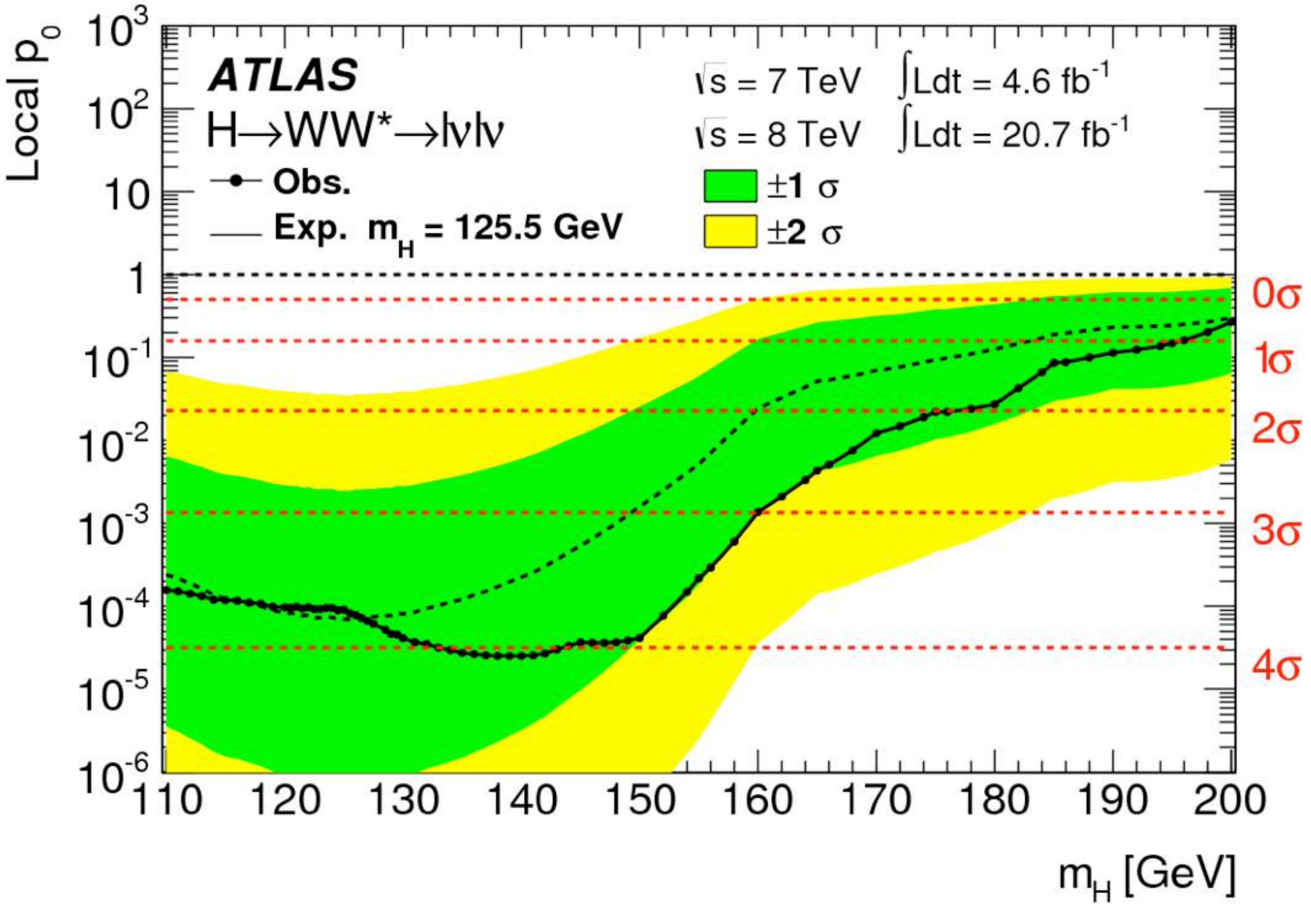
9 p_{Tt}-η-conversion
ggF

- **Selection:** 2 high E_T, isolated photons
- **Categorization:** split 14 ways by production mode and sensitivity
- **Backgrounds:** γ-γ, γ-jet, jet-jet and Drell-Yan fit in mass sidebands
- **Main Results:** obs. (exp.) 7.4 (4.1) σ at 126.8 GeV, corresponding to $\mu = 1.65^{+0.35}_{-0.30}$

ATLAS-CONF-2013-013 / PLB 726, pp 88-119

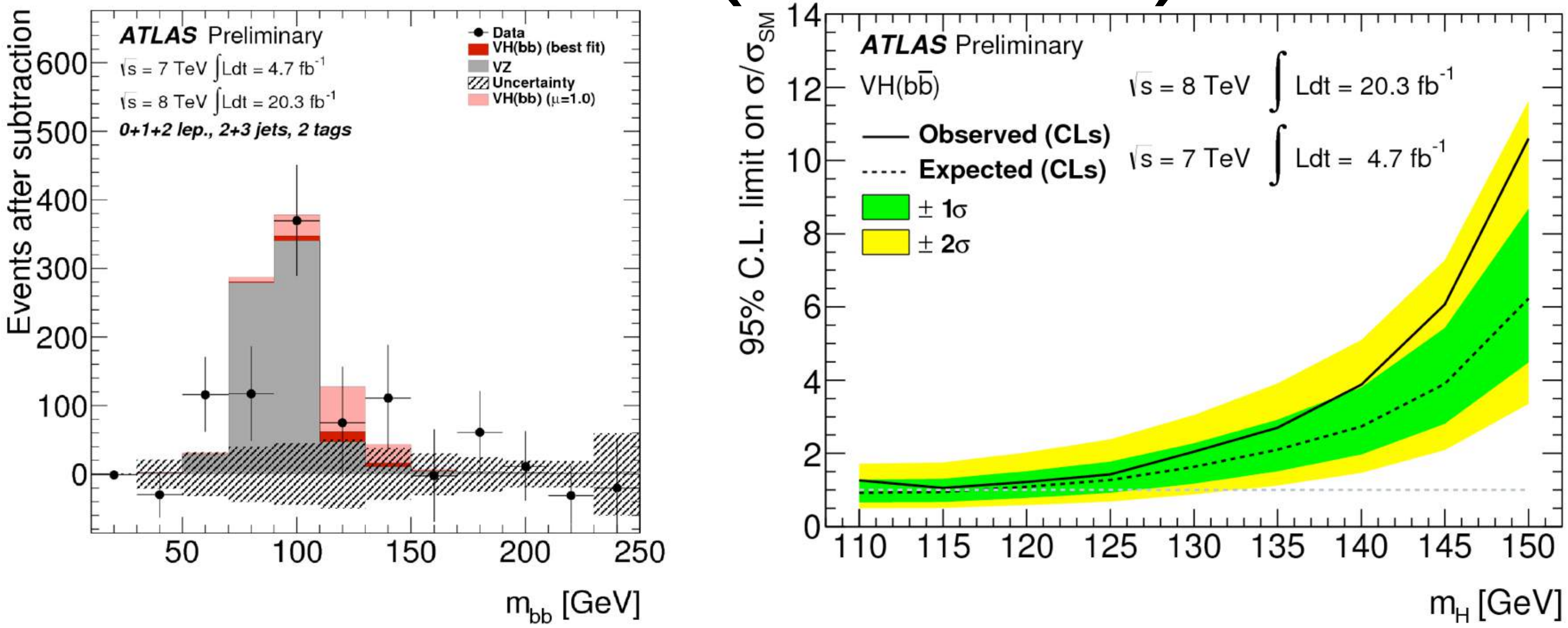
H → WW(lνlν)





- **Selection:** 2 isolated, opposite sign leptons, large E_T^{Miss}
- **Categorization:** VBF and ggF split by jet multiplicity
- **Backgrounds:** WW continuum, other VV, top, V+jets
- **Main Results:** obs. (exp.) 3.8 (3.7) σ at 125 GeV, corresponding to $\mu = 1.01^{+0.31}_{-0.31}$

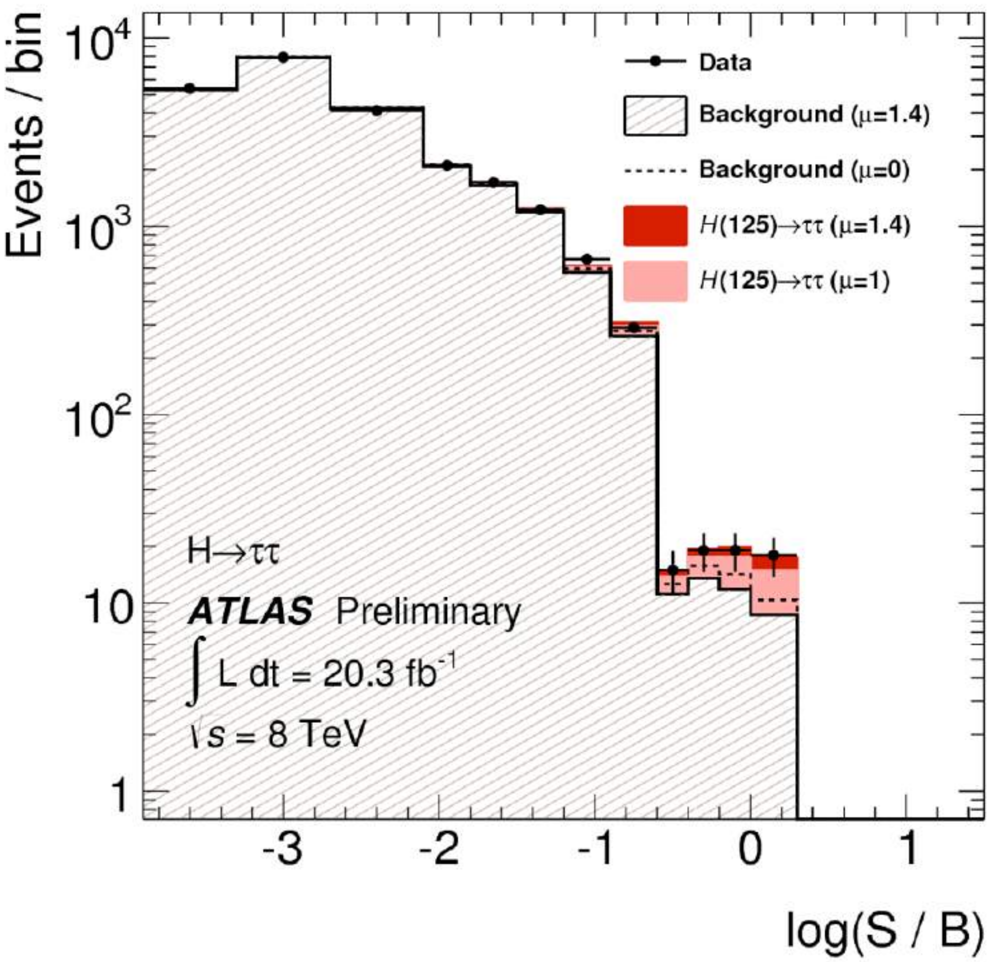
VH →(ll,lν,νν)bb

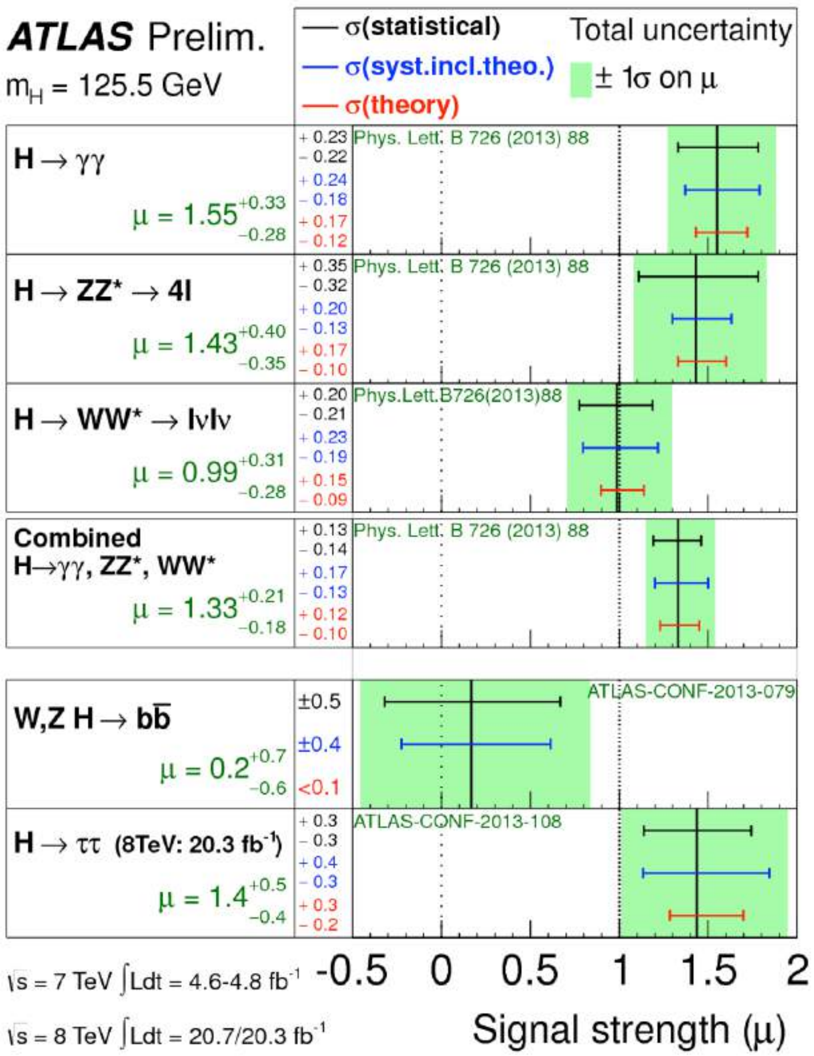


- **Selection:** 2 b-tagged jets and either large E_T^{Miss} or 1-2 leptons
- **Categorization:** split by W/Z decay, jet multiplicity and di-jet system p_T
- **Backgrounds:** ttbar, V+heavy flavour, VV, QCD multijet
- **Main Results:** obs. (exp.) 95% CL 1.4 (1.3) x SM at 125 GeV, $\mu = 0.2^{+0.7}_{-0.6}$

ATLAS-CONF-2013-108

$H \rightarrow \tau\tau$





- **Selection:** 2 opposite sign τ lepton decays (all modes)
- **Categorization:** VBF and boosted category, split by decay mode of τ lepton
- **Backgrounds:** Z→ττ, ttbar, VV Depending on tau decay: Drell-Yan, W+jets, QCD multijet
- **Main Results:** obs. (exp.) 4.1 (3.2) σ at 125 GeV, corresponding to $\mu = 1.4^{+0.5}_{-0.4}$

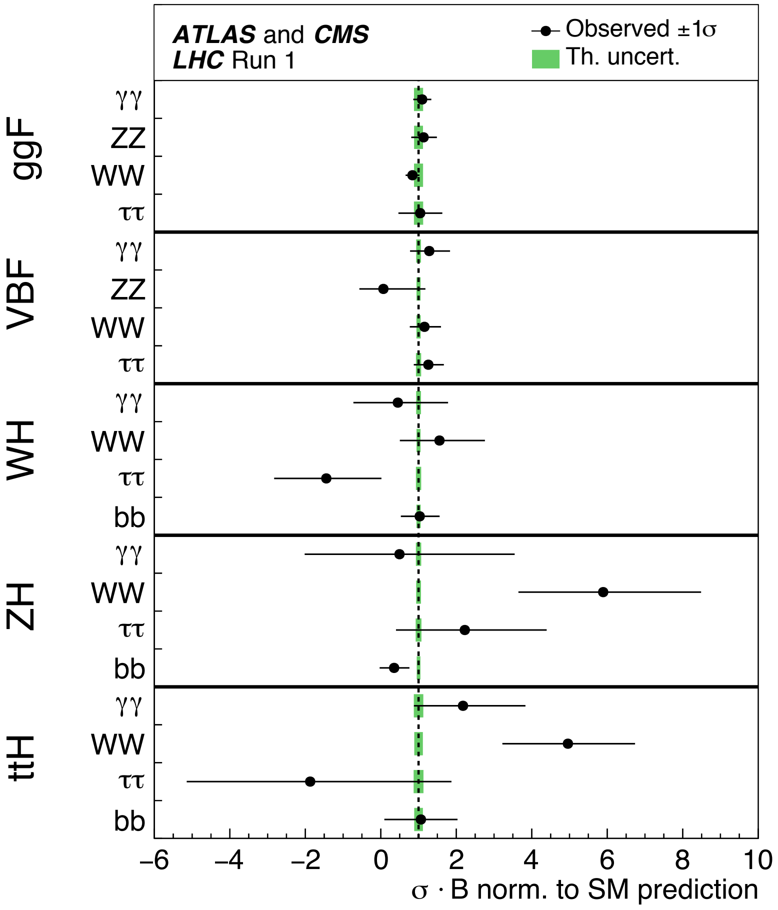
Property Measurements

JHEP 1608 (2016) 045

Fit Inputs

- Measured signal strength in units of SM cross section x branching ratio
- Not possible to measure either by itself without theory assumptions
- In all decay channels signal strength agrees with SM expectation within 1-2 σ

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[92]	[93]	$1.14\,^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11\,^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[94]	[95]	$1.52\,^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04\,^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[96, 97]	[98]	$1.22\,^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90\,^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[99]	[100]	$1.41\,^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88\,^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[101]	[102]	$0.62\,^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81\,^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[103]	[104]	$-0.6\,^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9\,^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[78, 105, 106]	[108]	$1.9\,^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9\,^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)



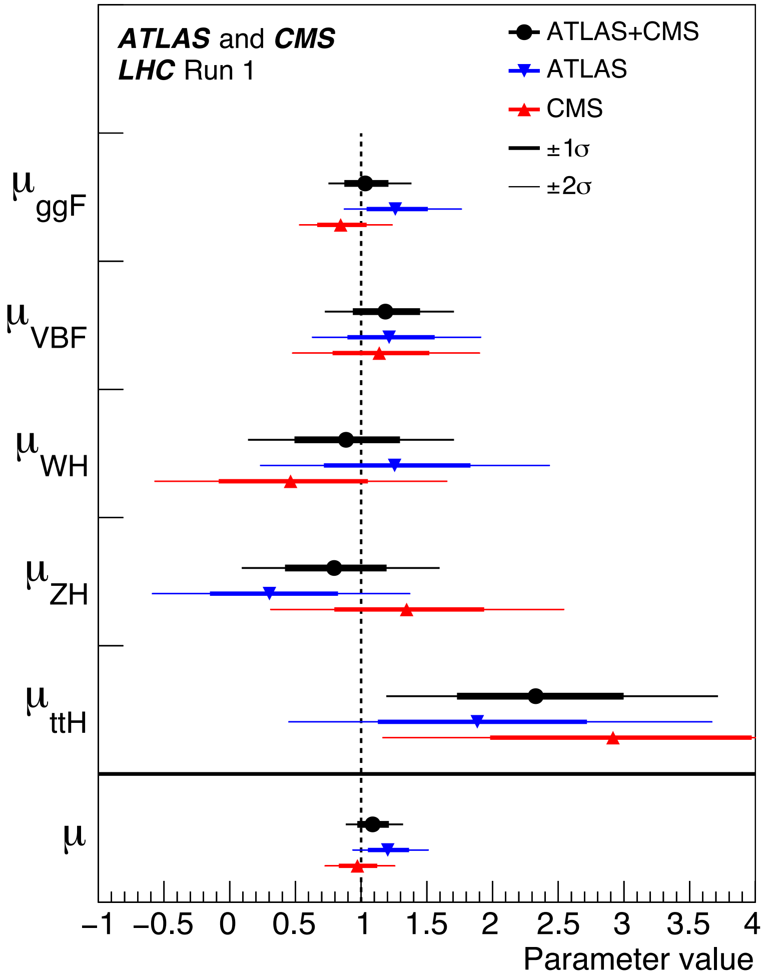
Couplings: Fit Model

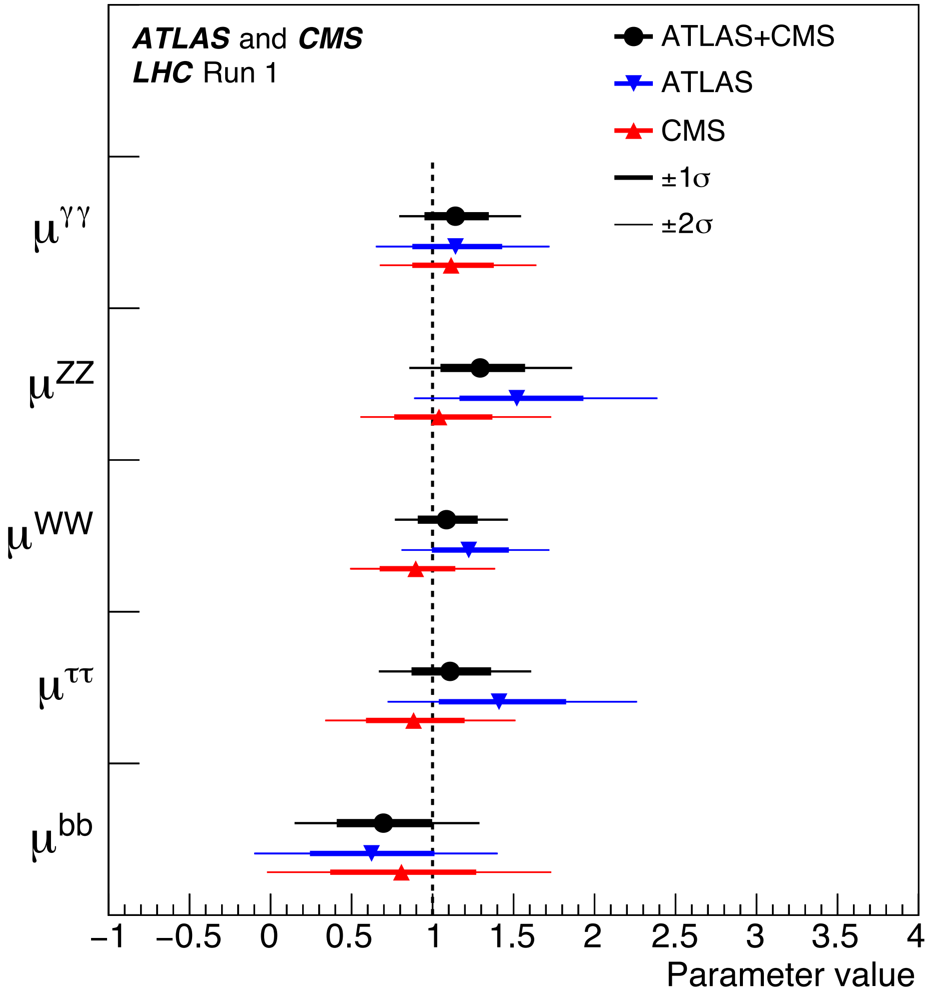
$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

- We derive couplings from event yields n in the different analysis channels k
- Parameters of interest are the "signal strengths" μ_i for production and μ_f for decay modes
- These are defined such that $\mu_{i,f} = 1$ represents signal strength consistent with the SM
- Other parameters are:
    - $\sigma_{i,SM}$,$B_{f,SM}$: standard model production cross section and branching ratios
    - A^k_{if} : detector acceptance for production mode i, decay mode f and analysis channel k
    - ε^k_{if} : selection efficiency for production mode i, decay mode f and analysis channel k
    - L^k : integrated luminosity analysed in channel k

Production vs. Decay

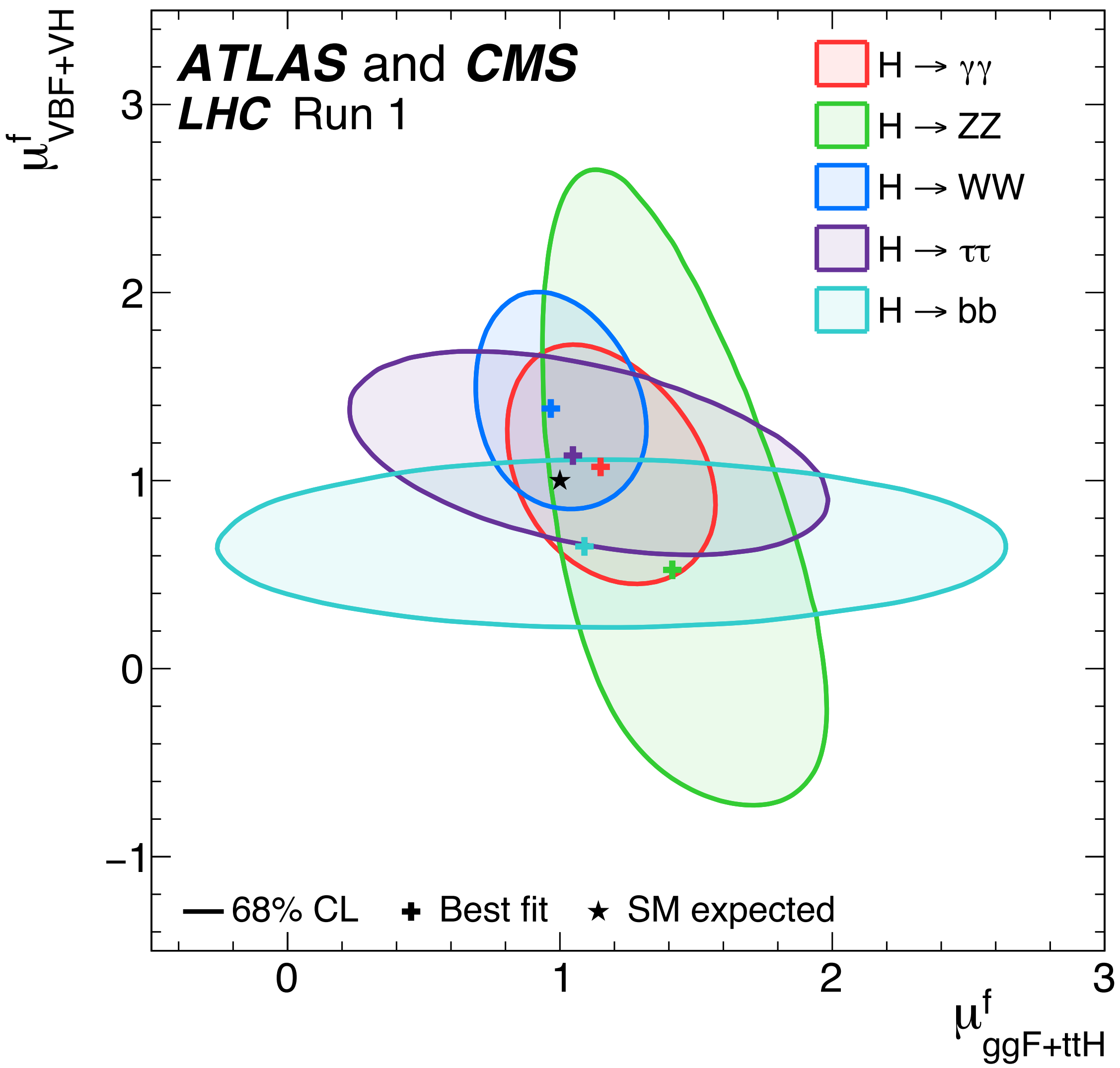
- Possible to fit production and decay rates separately, assuming SM values for the other part
- Production modes compatible with SM, though large ratio of ttH to for example ggH
- All decay channels signal strength agrees with SM expectation within 1-2 σ





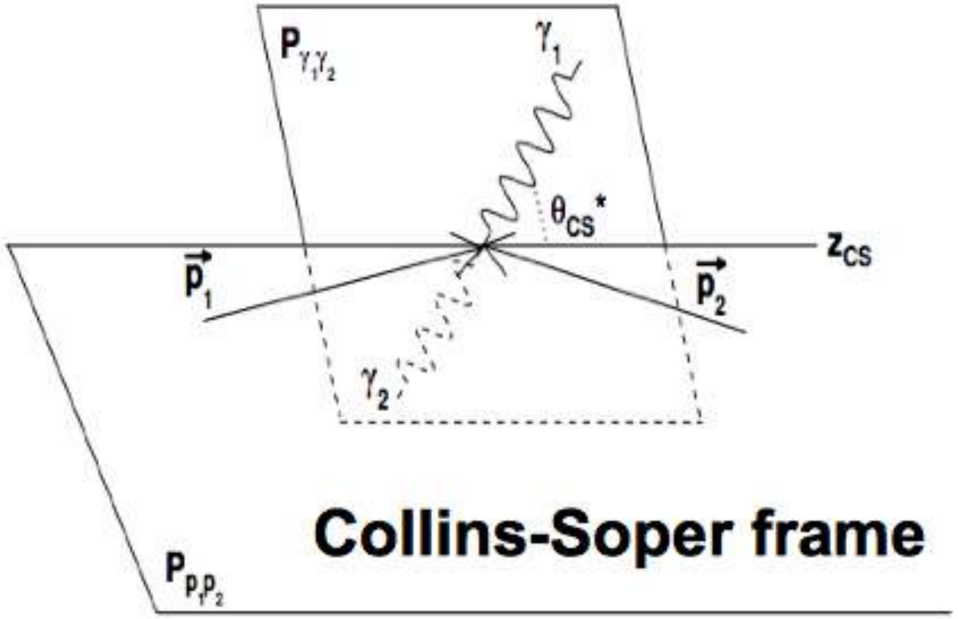
Production Couplings

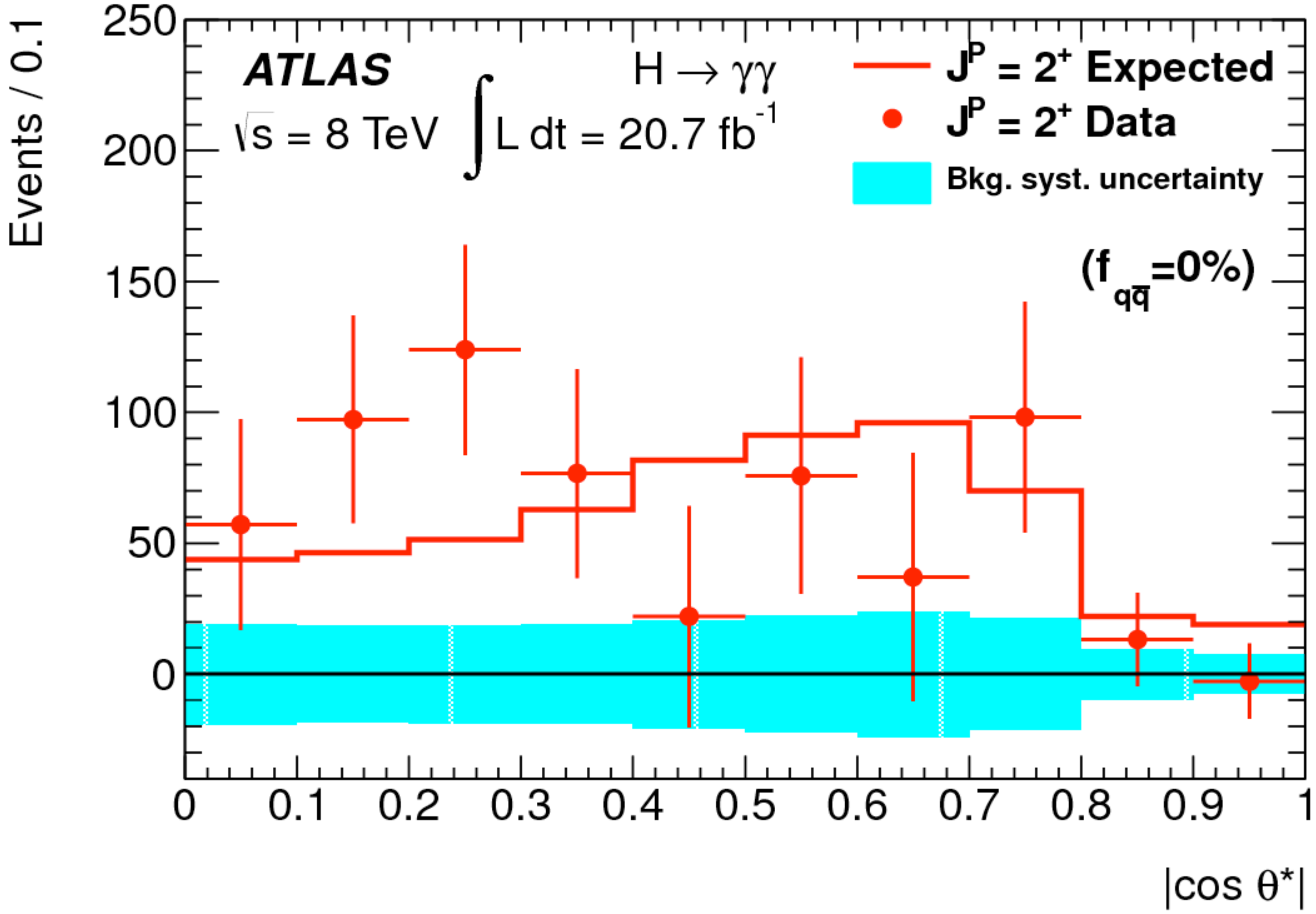
- separately fit couplings in production
- fix decay BR to SM values
- simplify production couplings
    - VBF = VH :“VBF+VH”
    - ttH = ggF : “ggF+ttH”



PLB 726, pp 120-144

γγ: Spin/CP





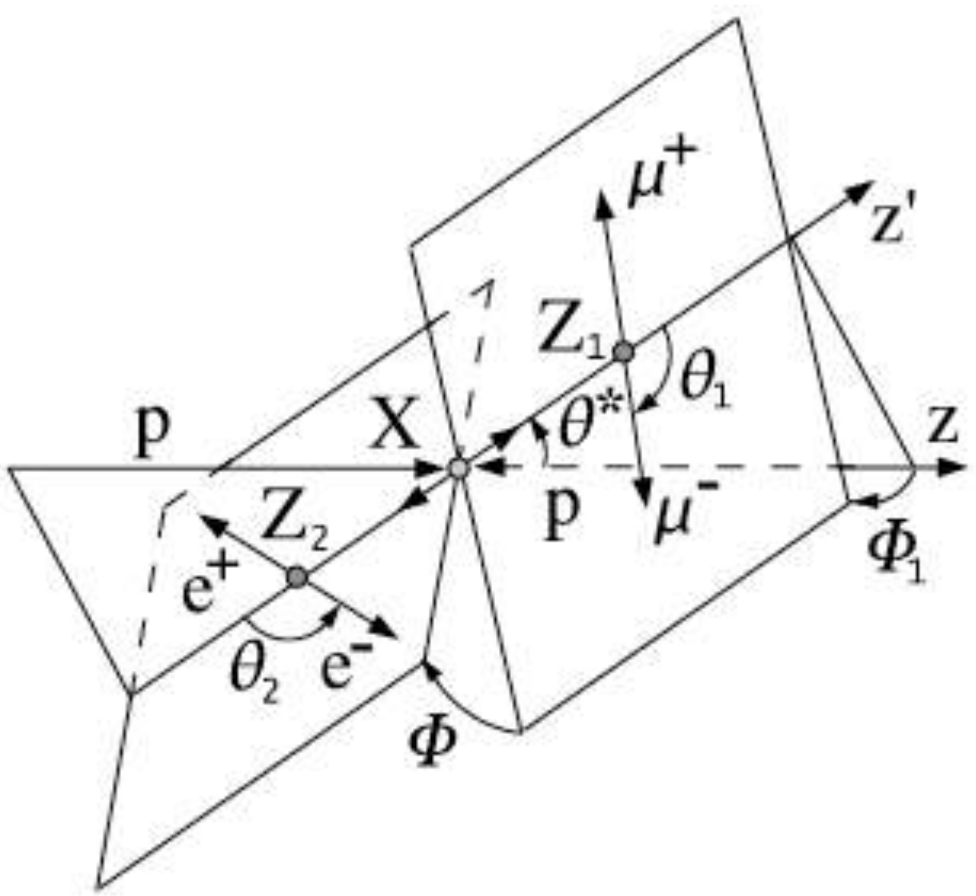
- **Sensitivity:** only sensitive to 0^+ and 2^+
- **Variables:** $P_{T,\gamma\gamma}$ and cos(θ*) in Collins-Soper frame

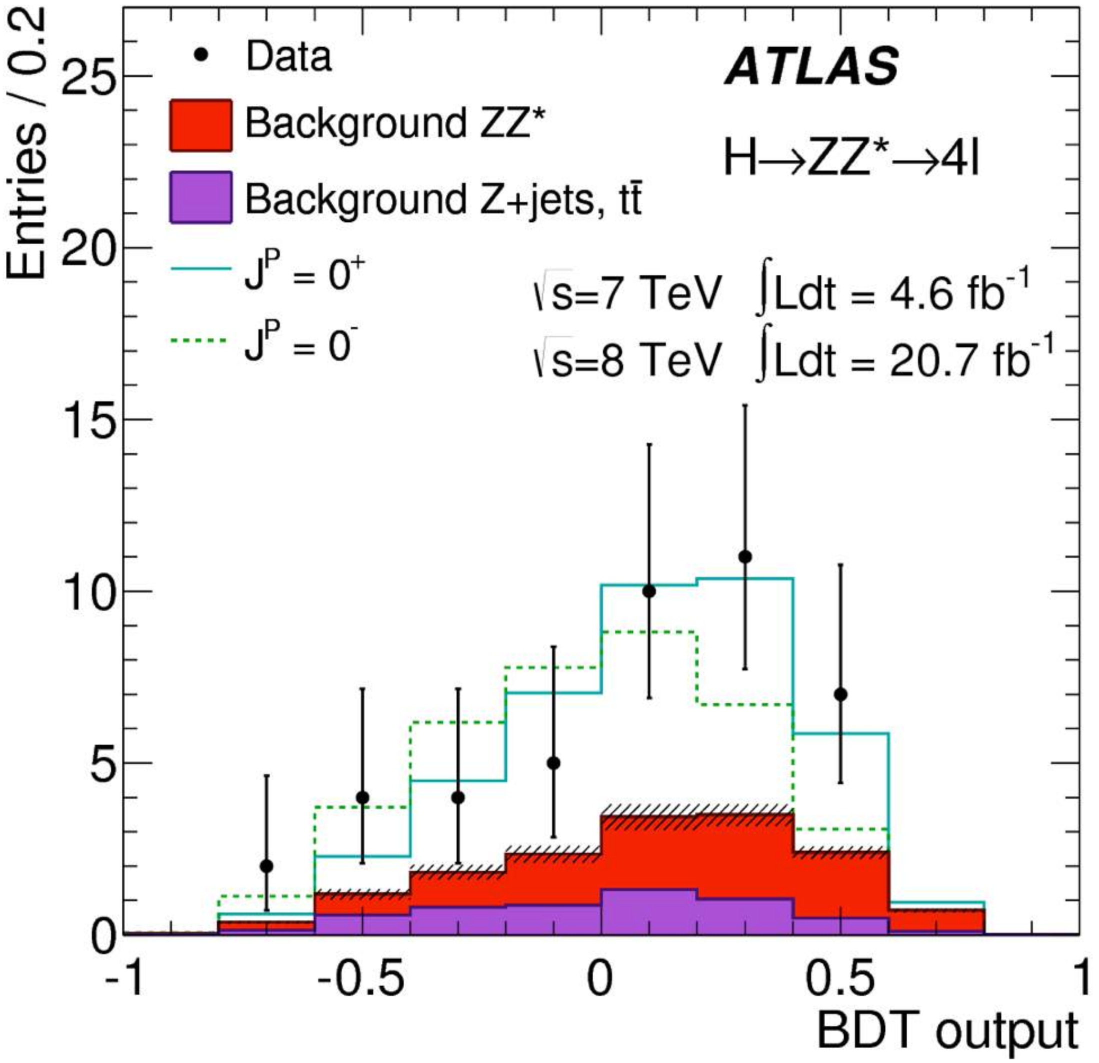
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

- **Unique feature:** observation of this decay strongly disfavors spin 1 (Landau-Yang theor.)

PLB 726, pp 120-144

ZZ*: Spin/CP

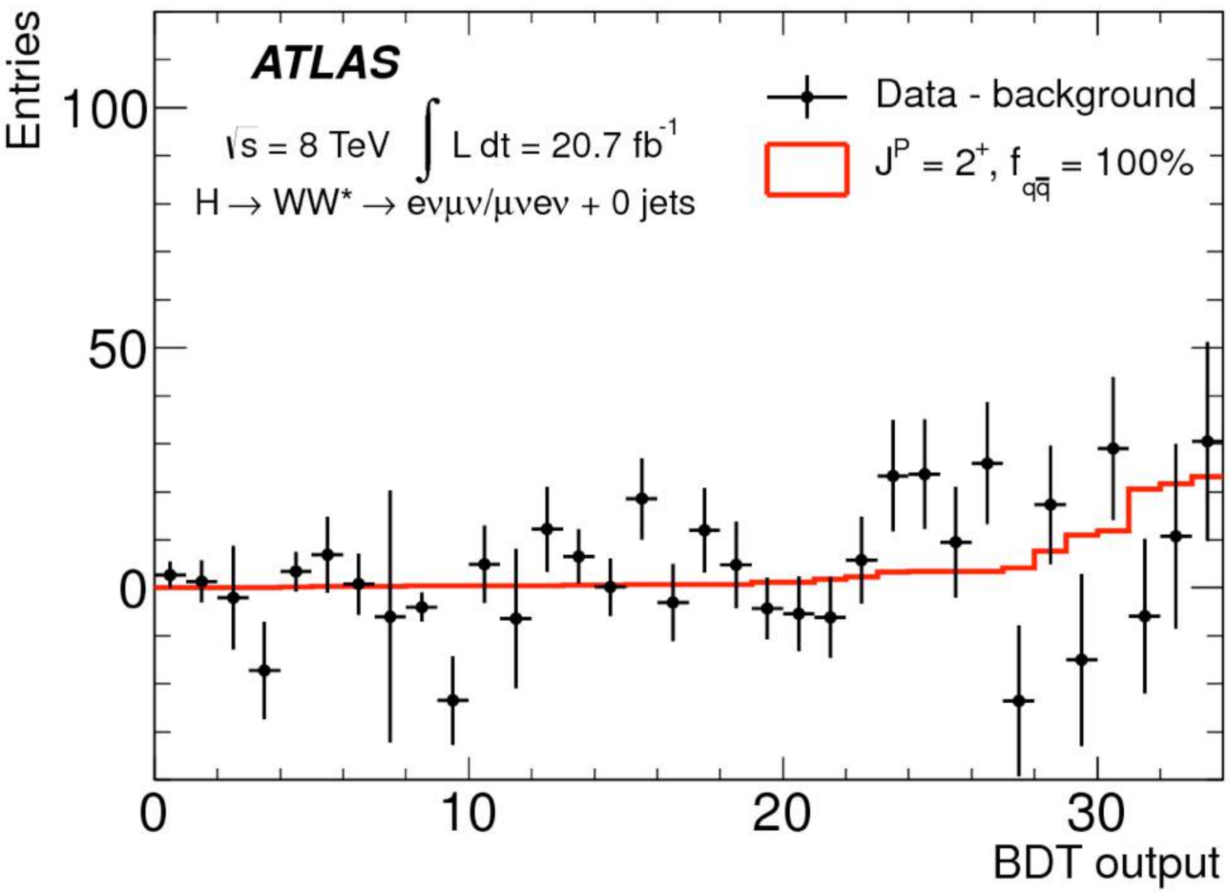


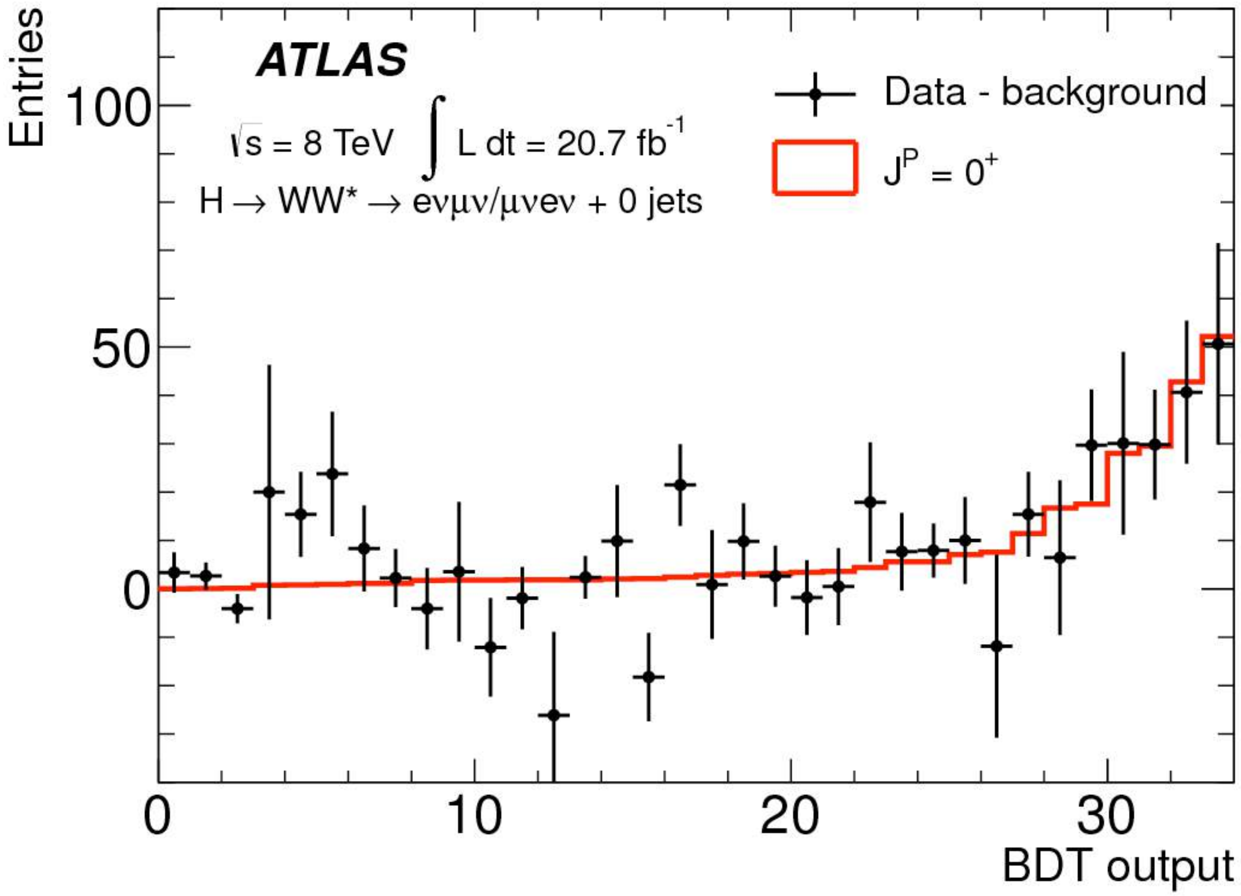


- **Sensitivity:** all J^P hypotheses
- **Variables:** full 4 lepton decay kinematics available, combined into BDT
- **Unique feature:** Dominant channel wrt sensitivity to 0^- vs 0^+

PLB 726, pp 120-144 and Eur. Phys. J. **C75** (2015) 231

WW: Spin/CP





- **Sensitivity:** all Jp hypotheses, but only small separation between 0^+ and 0^-
- **Variables:** $\Delta p_T(ll)$, $\Delta\varphi(ll)$, $p_T(ll)$, $m(ll)$, $E_{ll\nu\nu}$ and m_T, combined into several BDT's
- **Unique feature:** higher event yields than ZZ*, but difficult due to E_T^{Miss}

Eur. Phys. J. C75 (2015) 476

Limits on alternative Spin/CP Hypotheses

Tested Hypothesis	$p^{\mathrm{alt}}_{\mathrm{exp},\mu=1}$	$p^{\mathrm{alt}}_{\mathrm{exp},\mu=\hat{\mu}}$	$p^{\mathrm{SM}}_{\mathrm{obs}}$	$p^{\mathrm{alt}}_{\mathrm{obs}}$	Obs. $\mathrm{CL_s}$ (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\mathrm{T}} < 300\ \mathrm{GeV})$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_{\mathrm{T}} < 125\ \mathrm{GeV})$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\mathrm{T}} < 300\ \mathrm{GeV})$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\mathrm{T}} < 125\ \mathrm{GeV})$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

- **Channels:** γγ, ZZ* and WW
- **Signal models:** 0^- quark-induced, $1^{+/-}$ gluon-induced, 2^+ different mixtures
- **Results:** All hypotheses except 0^+ excluded at >99.9% confidence level

arxiv: 1602.04516

HVV in Effective Field Theory

- Most general, Lorentz-invariant tensor structure of HVV vertex

$$\begin{aligned} T^{\mu\nu}(q_1,q_2) = {} & a_1(q_1,q_2)\, g^{\mu\nu} && (\text{SM: } CP \text{ even}) \\ & + a_2(q_1,q_2)\, [q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}] && (CP \text{ even}) \\ & + a_3(q_1,q_2)\, \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma} && (CP \text{ odd}) \end{aligned}$$

- With SM values of: $a_1 = \frac{2m_V^2}{v}, a_2 = 0, a_3 = 0$
- To add CP violation one needs: $a_1 = \frac{2m_V^2}{v}, a_2 = 0, a_3 \neq 0$
- Yields effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

- with the couplings given by:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$

- assuming d-tilde = d-tilde_b simplifies this to:

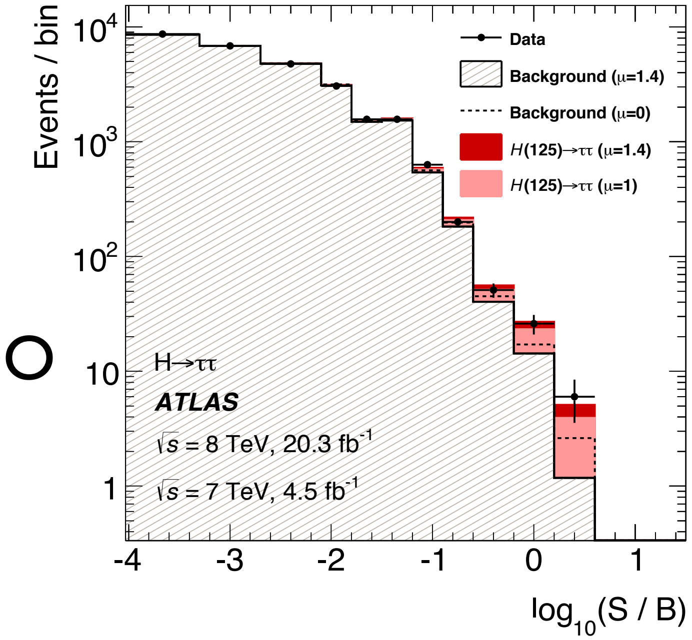
$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

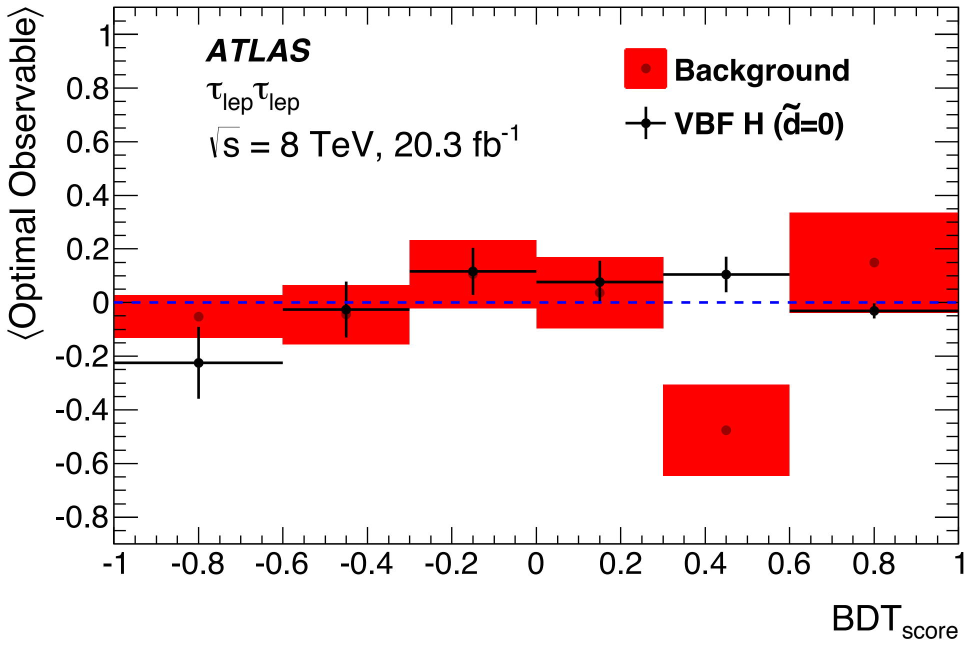
Expressed in terms of the parameters used for the HWW/HZZ CP analysis (E.P. J. C75 (2015) 476):

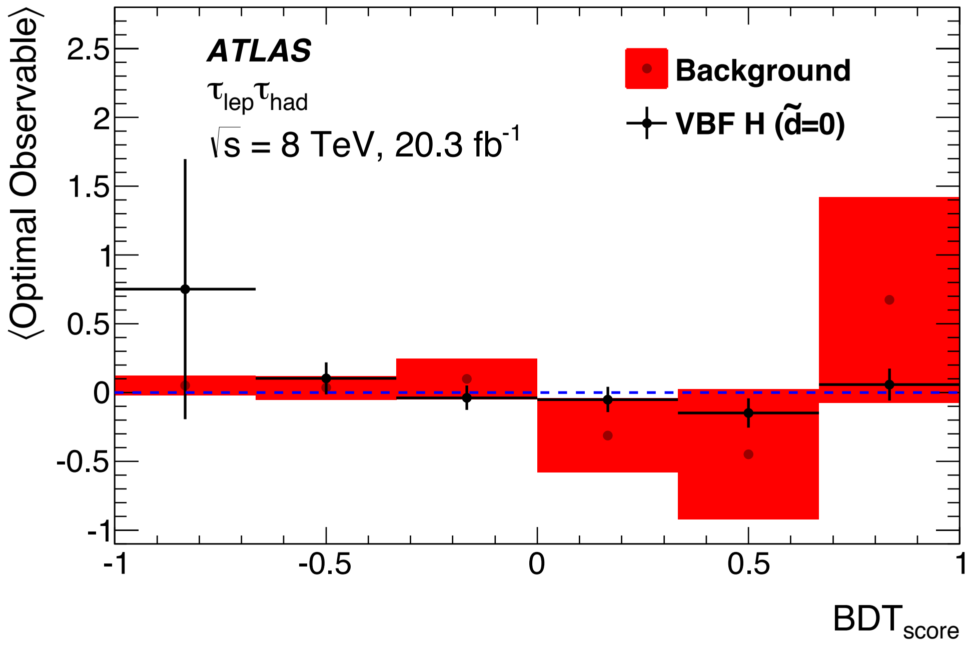
$$\tilde{d} = -\hat{\kappa}_Z = -\hat{\kappa}_W = -\tilde{\kappa}_W/\kappa_{SM}\tan\alpha$$

The H→ττ Decay Channel

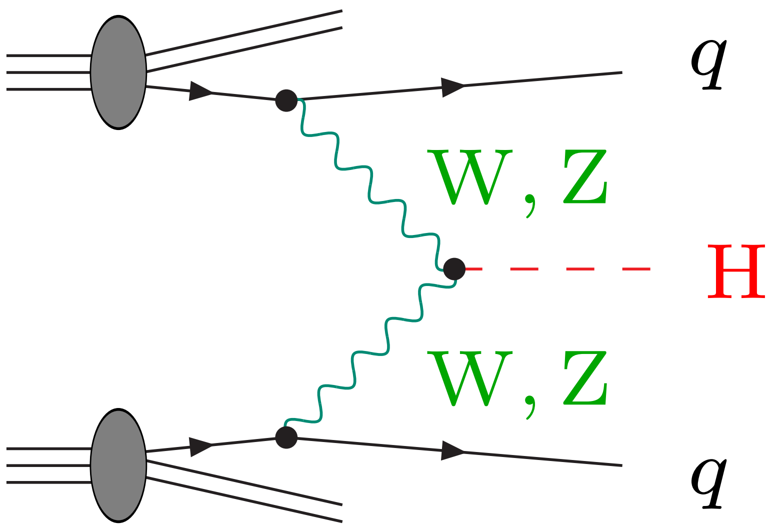
- Utilize H→ττ due to relatively large VBF sample
- But method independent of Higgs decay, so could include more channels in Run2
- Based on Run1 H→ττ ATLAS analysis (JHEP 04 (2015) 117)
- same background (BG) models and multivariate classifier (BDT)
- But instead of fitting BDT score distribution, cut on score and fit OO
- Prove that BDT score and optimal observable are uncorrelated



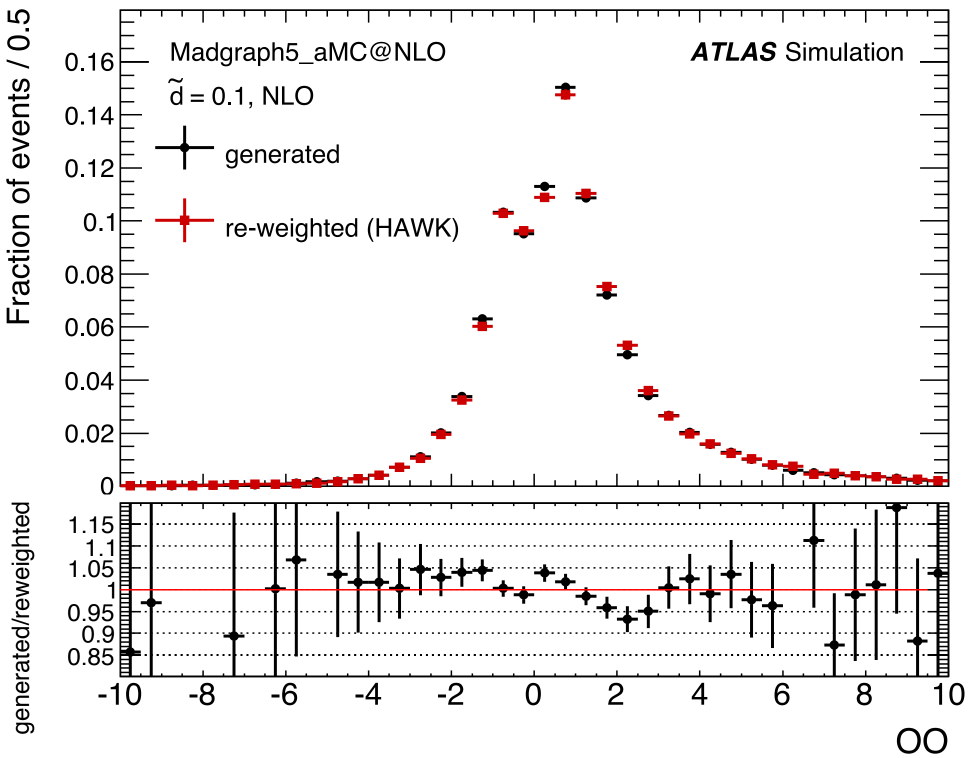




Generating Signal Models

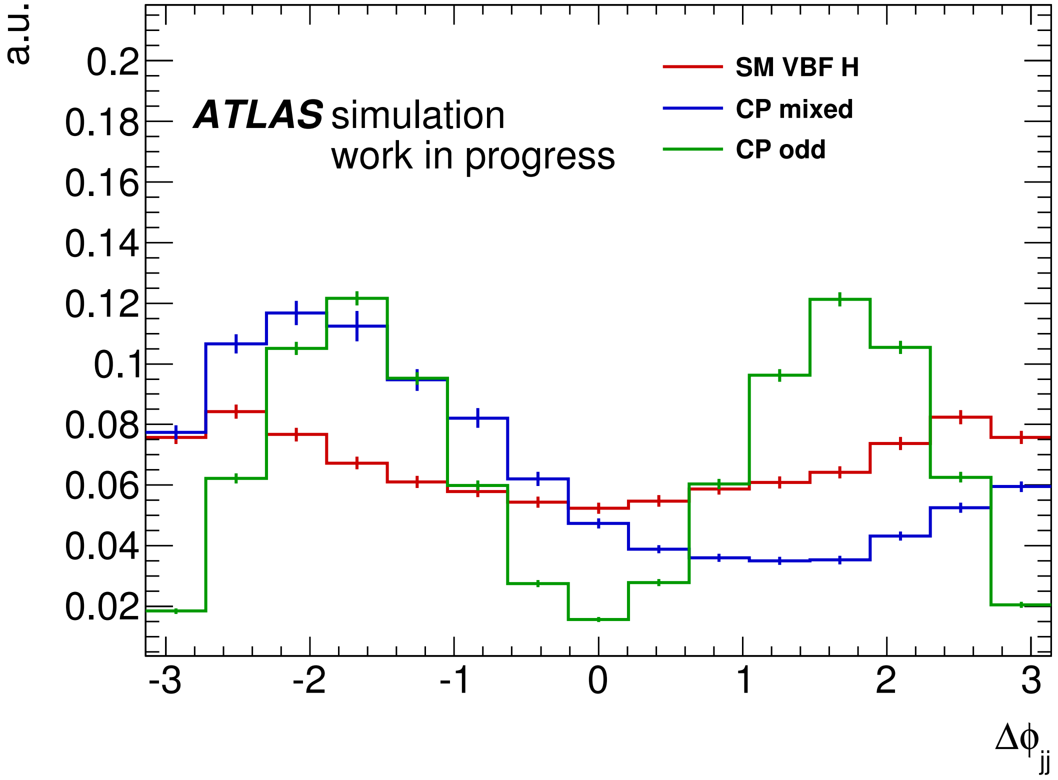


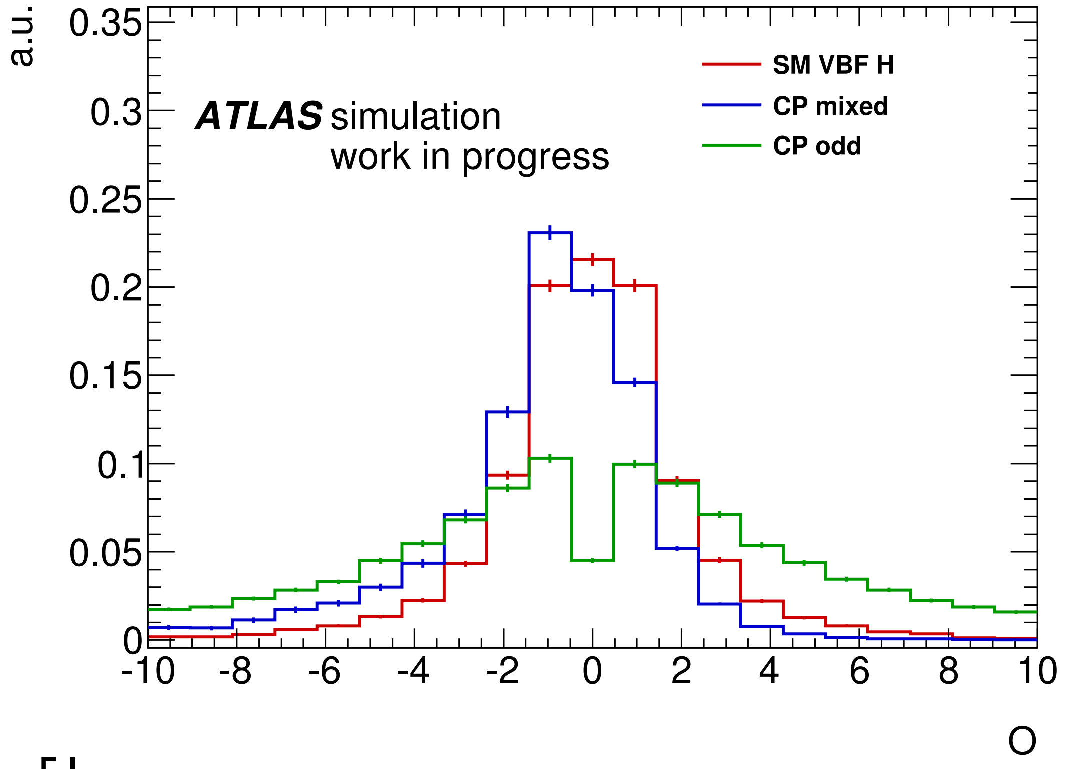
- Generating signals for continuous CP-mixing parameter is CPU- and disk-intensive
- Prefer to re-weight SM signal sample with large number of events
- Use final state kinematics at generator level to calculate weight based on ratio of CP-odd and SM matrix elements
- Matrix elements calculated at leading order using HAWK 2.0
- Leading-order calculation validated against NLO calculation with Madgraph 5



Testing for CP Violation

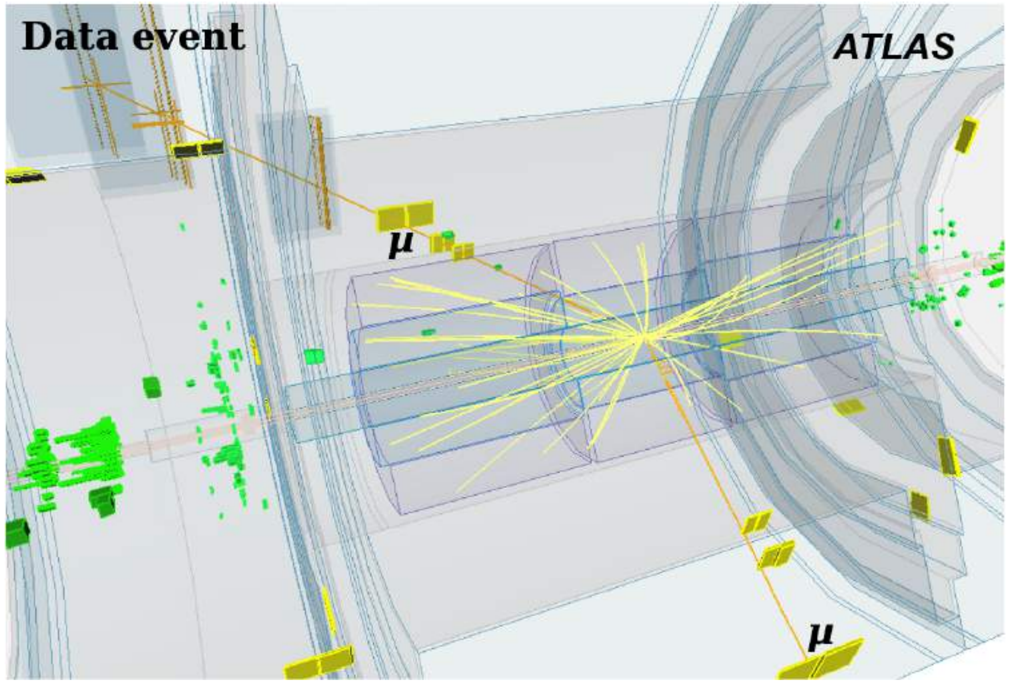
- Define CP odd observable X
- <X> != 0 → CP violation
- Possible Observables:
  - ”Optimal” observable
  - Signed $\Delta\Phi_{jj} = \Phi_{+} - \Phi_{-}$: Φ_{+} is Φ of the jet in positive z-direction



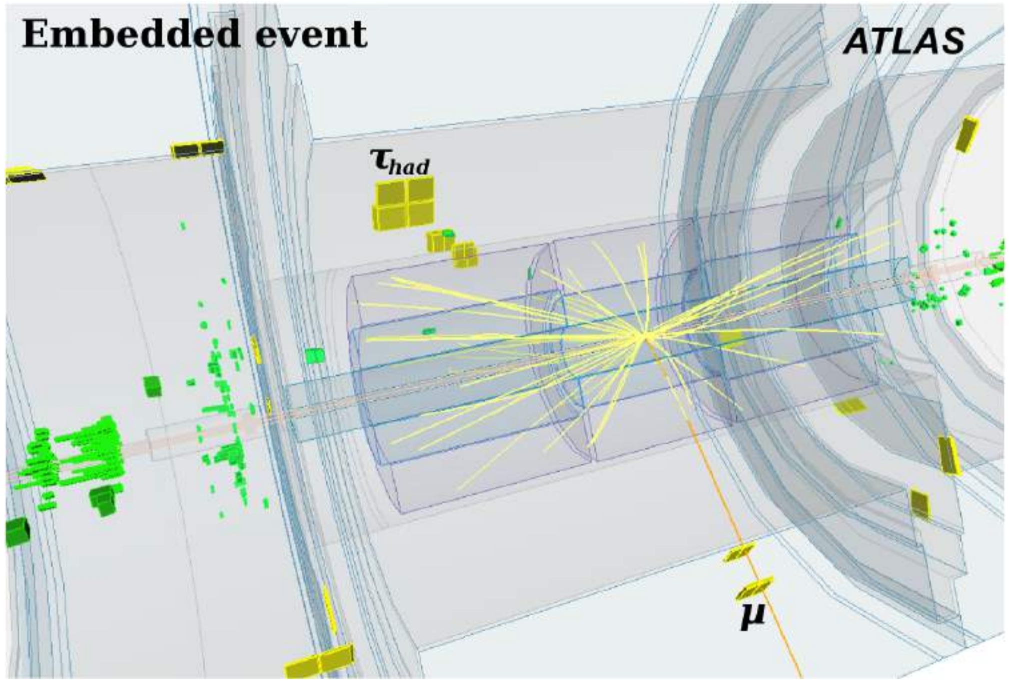


Embedding

- Feel a bit cheeky talking about embedding in Bonn, just wanted to say it's important also for this analysis
- Large irreducible background from $Z \rightarrow \tau\tau$ decays
- Complex final states (boosted, VBF) want to rely as little as possible on simulation
- Cannot select pure $Z \rightarrow \tau\tau$ control region in data, but we can get a very pure $Z \rightarrow \mu\mu$

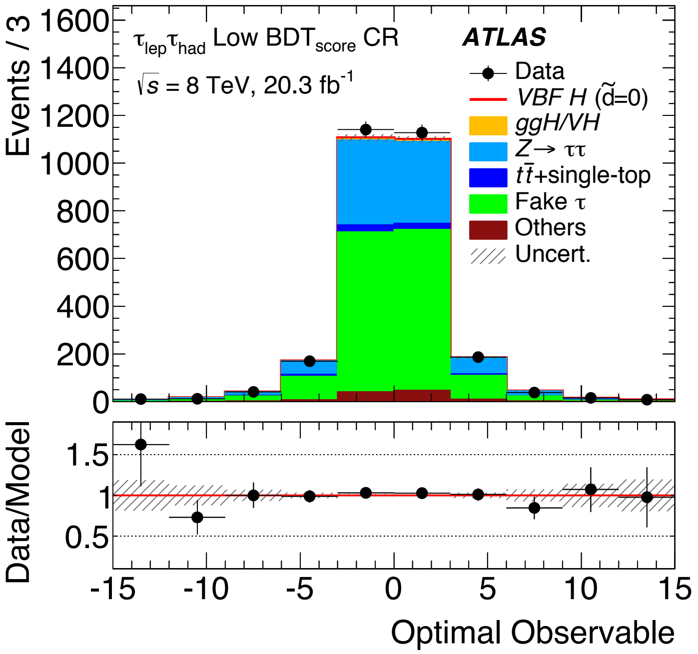


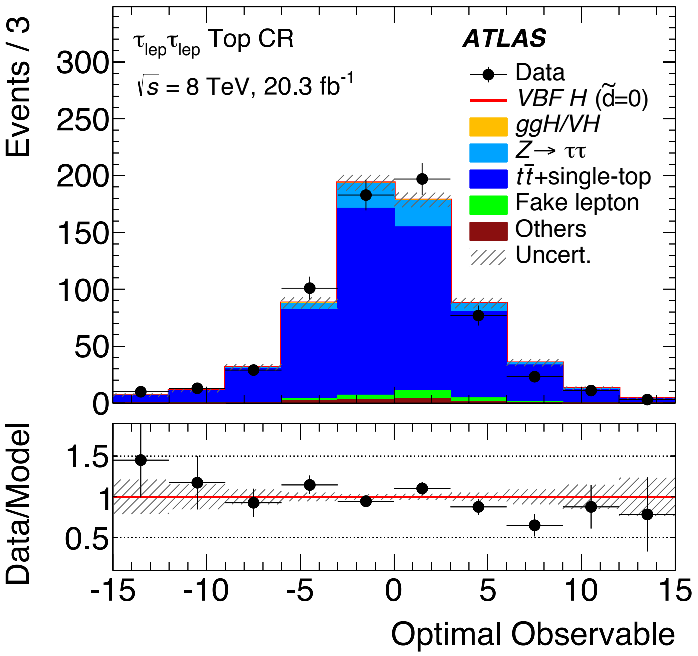
→

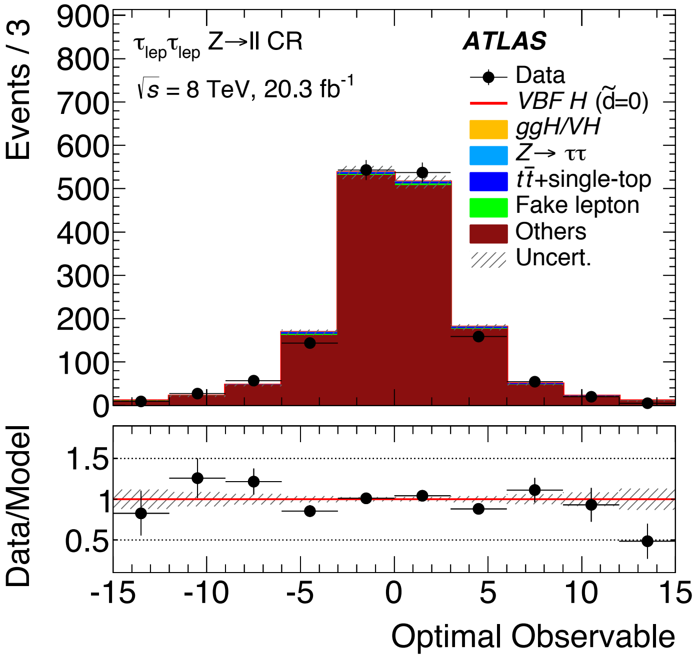


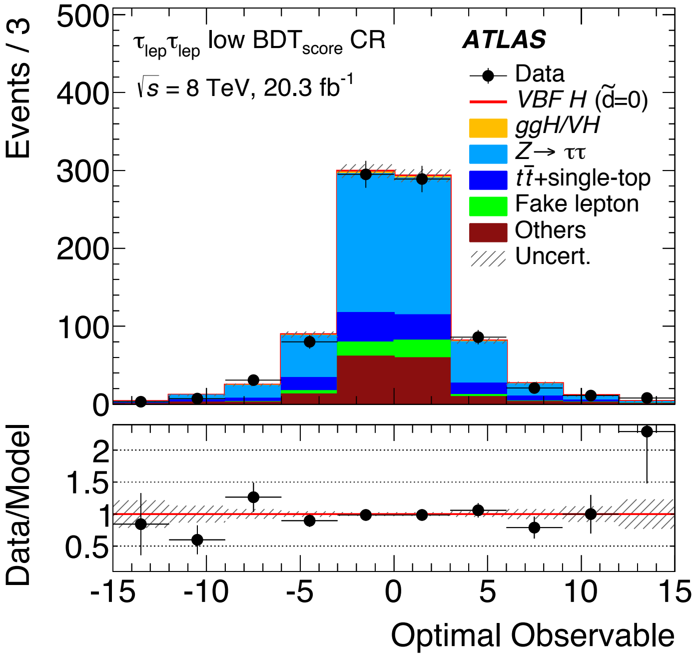
Confirm BG Model

- Control Regions:
  - Low BDT-score region (Z→ττ, Fakes)
  - Inverted b-veto (ttbar)
  - Z→ll mass-window (only leplep channel)



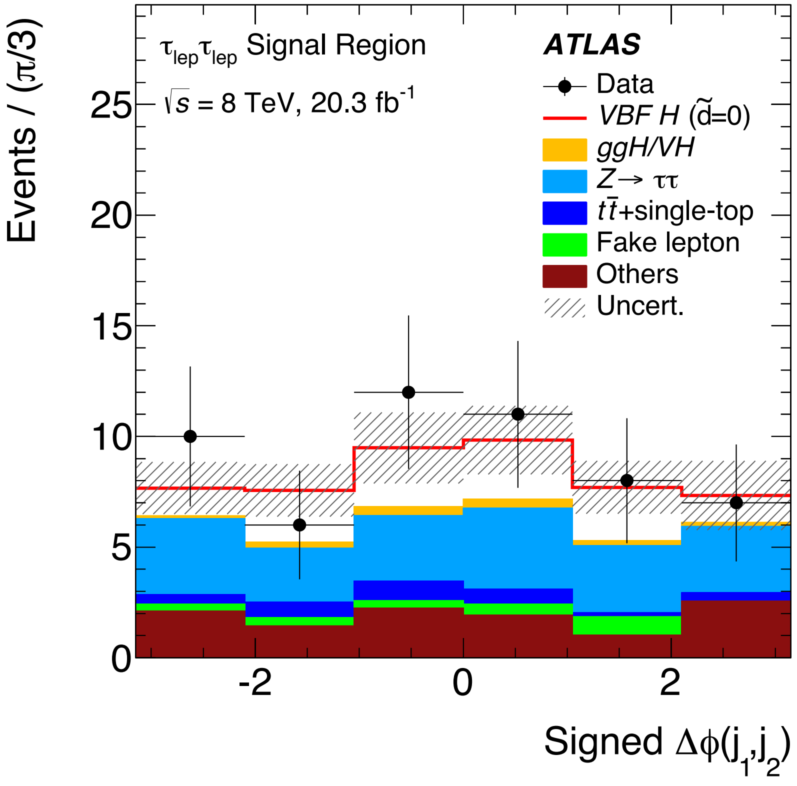


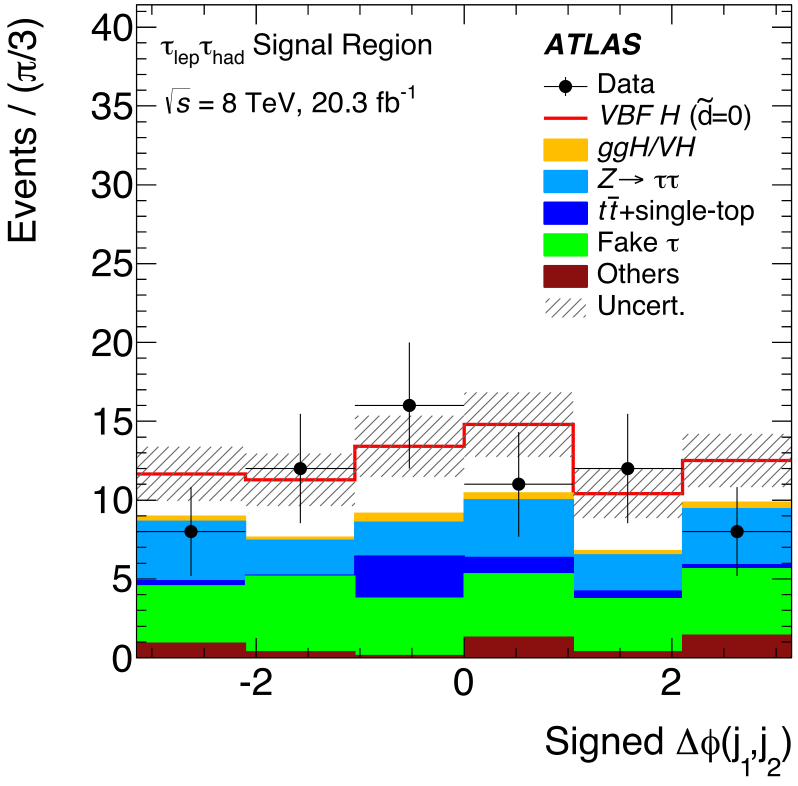


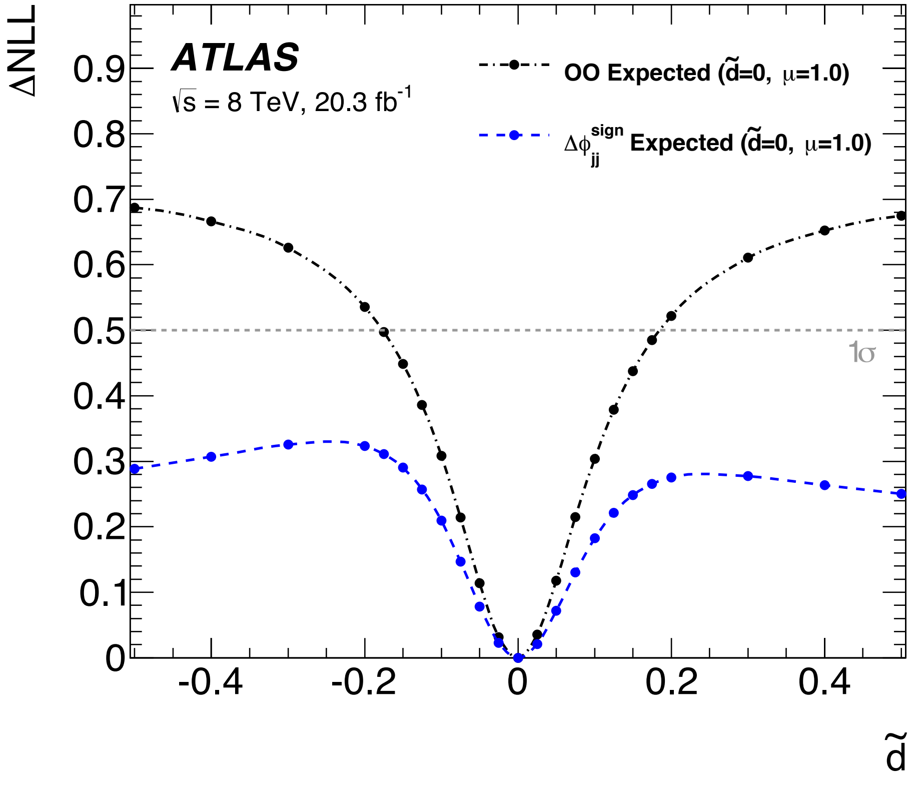


Signed ΔΦjj Analysis

- Signed $\Delta\Phi_{jj} = \Phi_{+} - \Phi_{-}$: Φ_{+} is Φ of the jet in positive z-direction
- CP-odd observable proposed previously in Phys. Rev. D74 (2006) 095001
- Significantly better performance of optimal observable







Comparison with Decay Analyses

- Reminder of effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

- To be compared with:

$$\begin{aligned} \mathcal{L}_0^V = \quad & \Big\{ \cos(\alpha)\kappa_{\text{SM}} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0 \end{aligned}$$

- With some simplifications

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{\text{v}}{\Lambda}\kappa_{AVV} \quad \text{and} \quad \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{\text{v}}{\Lambda}\kappa_{HVV}$$

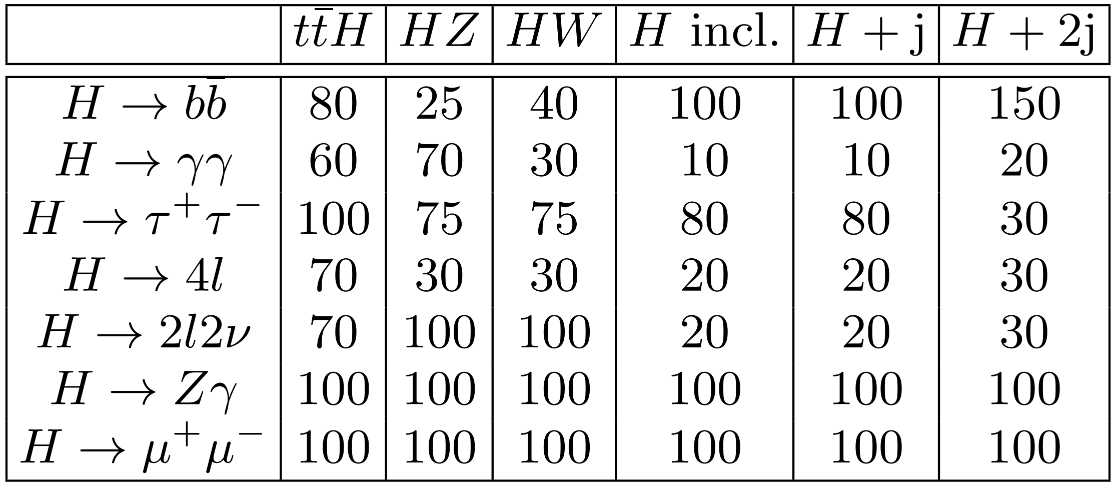
$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

- This leads to:
-

Expressed in terms of the parameters used for the HWW/HZZ CP analysis (E.P. J. C75 (2015) 476):

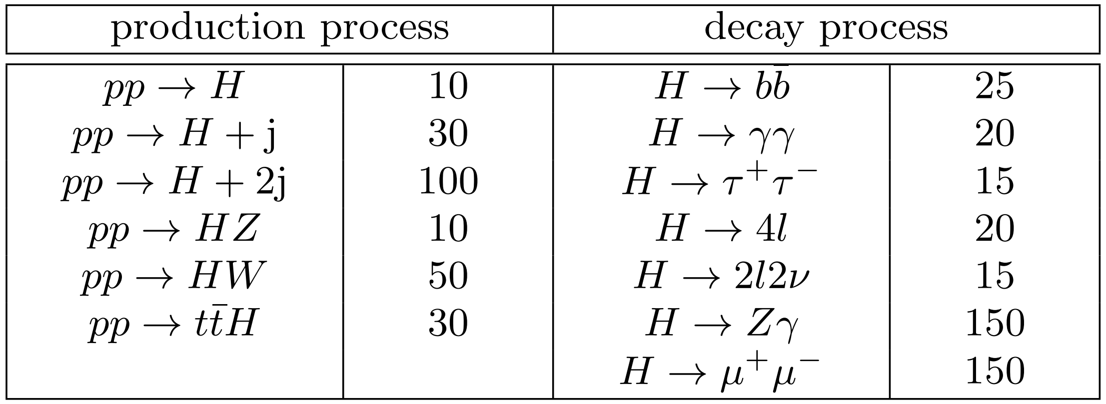
$$\tilde{d} = -\hat{\kappa}_Z = -\hat{\kappa}_W = -\tilde{\kappa}_W / \kappa_{SM} \tan\alpha$$

Full LHC Dataset Projections



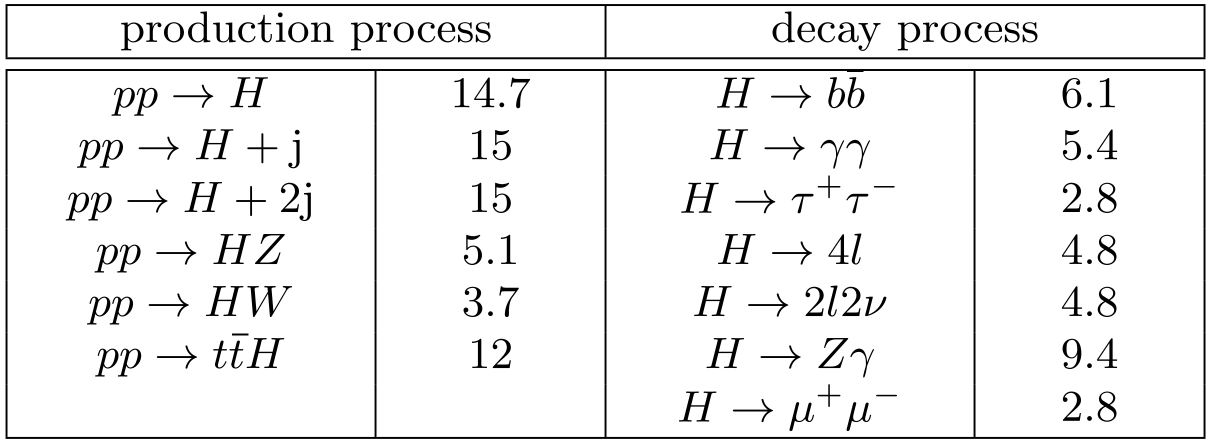
	$t\bar{t}H$	HZ	HW	H incl.	$H+\mathrm{j}$	$H+2\mathrm{j}$
$H \to b\bar{b}$	80	25	40	100	100	150
$H \to \gamma\gamma$	60	70	30	10	10	20
$H \to \tau^+\tau^-$	100	75	75	80	80	30
$H \to 4l$	70	30	30	20	20	30
$H \to 2l2\nu$	70	100	100	20	20	30
$H \to Z\gamma$	100	100	100	100	100	100
$H \to \mu^+\mu^-$	100	100	100	100	100	100

TABLE III: Relative systematic uncertainties for each production times decay channel in %.



production process		decay process	
$pp \to H$	10	$H \to bb$	25
$pp \to H+\mathrm{j}$	30	$H \to \gamma\gamma$	20
$pp \to H+2\mathrm{j}$	100	$H \to \tau^+\tau^-$	15
$pp \to HZ$	10	$H \to 4l$	20
$pp \to HW$	50	$H \to 2l2\nu$	15
$pp \to t\bar{t}H$	30	$H \to Z\gamma$	150
		$H \to \mu^+\mu^-$	150

TABLE II: Relative systematic uncertainties due to background processes for each production and decay channel in %.



production process		decay process	
$pp \to H$	14.7	$H \to b\bar{b}$	6.1
$pp \to H+\mathrm{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H+2\mathrm{j}$	15	$H \to \tau^+\tau^-$	2.8
$pp \to HZ$	5.1	$H \to 4l$	4.8
$pp \to HW$	3.7	$H \to 2l2\nu$	4.8
$pp \to t\bar{t}H$	12	$H \to Z\gamma$	9.4
		$H \to \mu^+\mu^-$	2.8

TABLE IV: Theoretical uncertainties for each production and decay channel in %.

EPJC 75 (2015) 476

Comparison with H→Bosons

- Limits on CP-mixing also extracted from combination of WW and ZZ channels
    - EFT model predictions derived from MadGraph
- Approach for WW analogous to analysis used to exclude spin 1,2 hypotheses
- In ZZ a matrix element method is used also based on ratios of CP-odd and even matrix elements

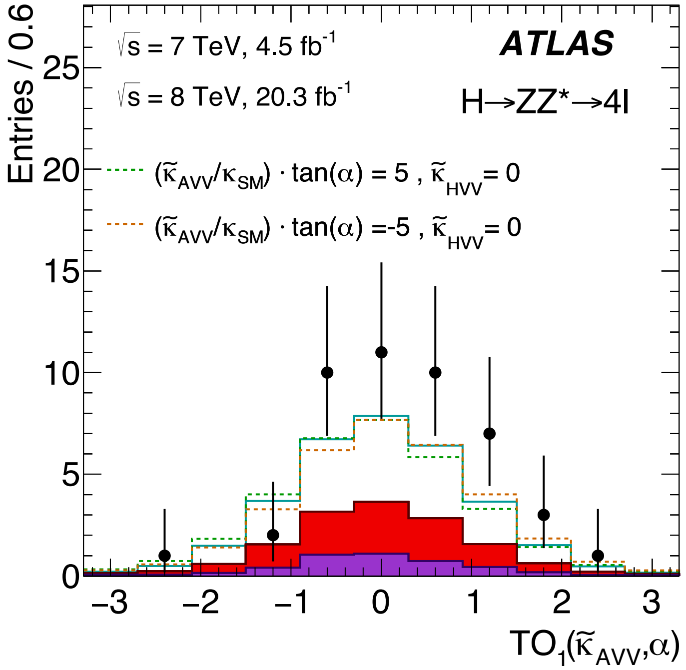
$$O_1(\kappa_{AVV},\alpha) = \frac{2\Re[\mathrm{ME}(\kappa_{\mathrm{SM}}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)^*\cdot \mathrm{ME}(\kappa_{AVV}\neq 0;\ \kappa_{\mathrm{SM}},\kappa_{HVV}=0;\ \alpha=\pi/2)]}{|\mathrm{ME}(\kappa_{\mathrm{SM}}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)|^2},$$

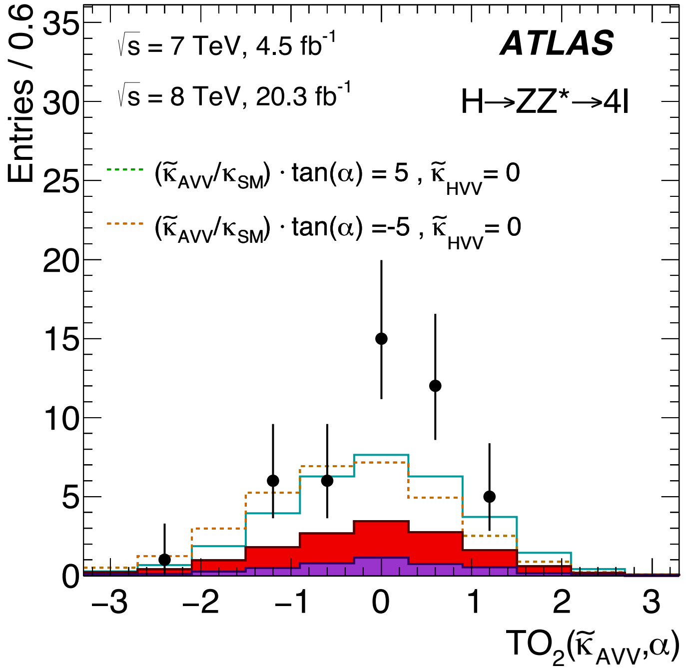
$$O_2(\kappa_{AVV},\alpha) = \frac{|\mathrm{ME}(\kappa_{AVV}\neq 0;\ \kappa_{\mathrm{SM}},\kappa_{HVV}=0;\ \alpha=\pi/2)|^2}{|\mathrm{ME}(\kappa_{\mathrm{SM}}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)|^2}.$$

- Main difference is inclusion of second order term that grows quadratically with CP-mixing parameter
- Reminder:

Expressed in terms of the parameters used for the HWW/HZZ CP analysis (E.P. J. C75 (2015) 476):

$$\tilde{d} = -\hat{\kappa}_Z = -\hat{\kappa}_W = -\tilde{\kappa}_W/\kappa_{SM}\tan\alpha$$

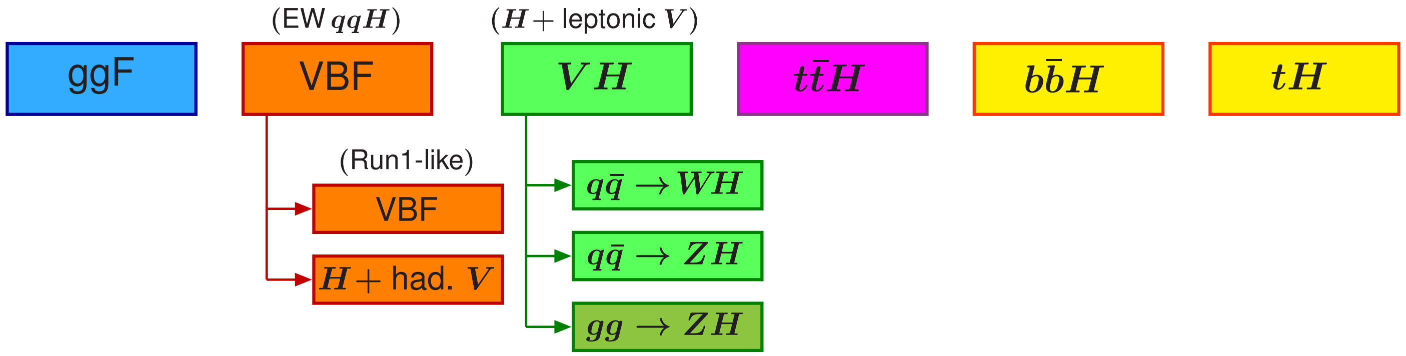




Simplified Template Cross Sections (STXS)

- Evolution of Run 1 coupling framework
  - Measure ***cross sections***, instead of signal strengths
- Allows for global combination across all decay modes

Stage-0 categories: separated into production modes



(EW qqH) ($H+$ leptonic V)

ggF | VBF | VH | $t\bar{t}H$ | $b\bar{b}H$ | tH

(Run1-like) VBF

$H+$ had. V

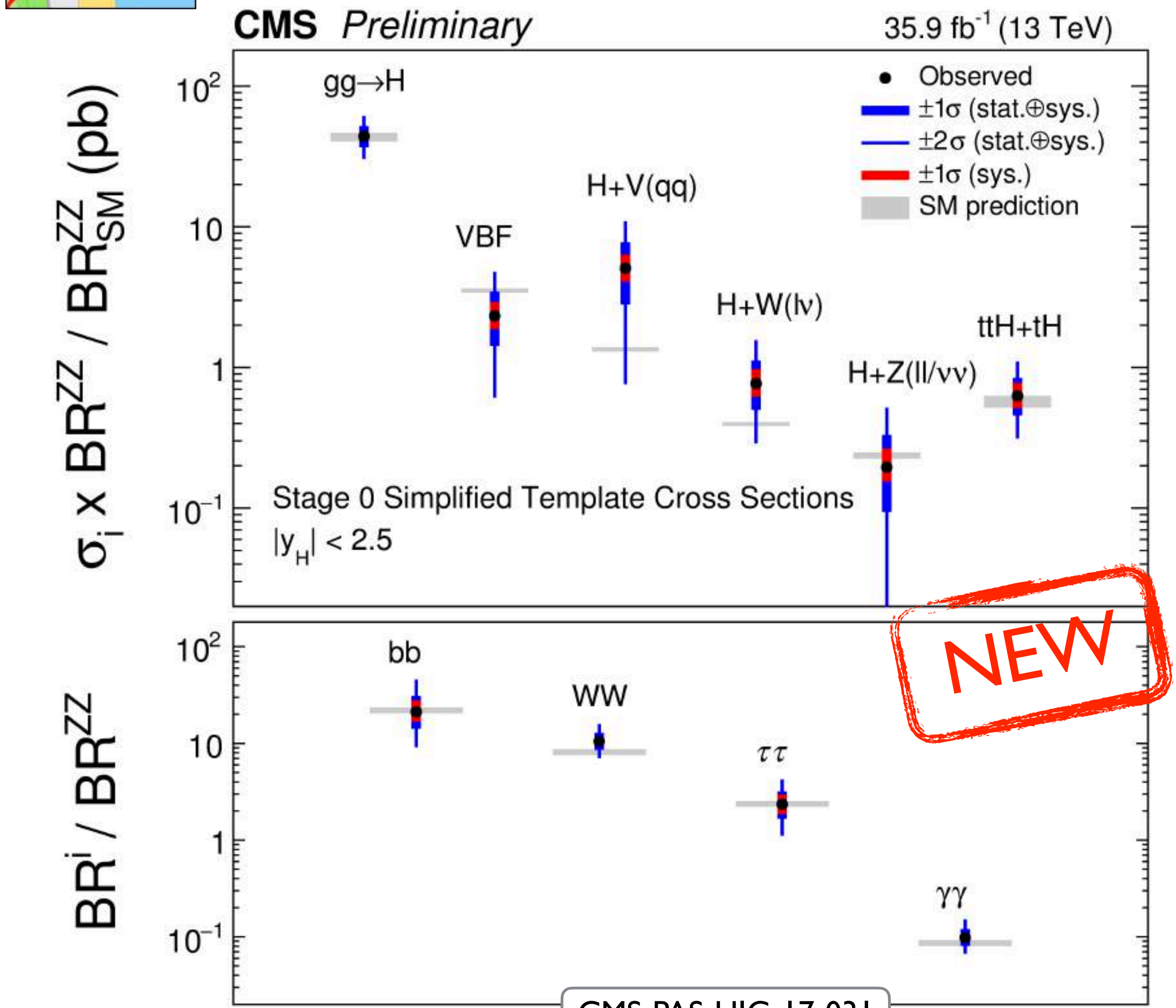
$q\bar{q}\to WH$

$q\bar{q}\to ZH$

$gg\to ZH$

arxiv:1610.07922

Stage-0 analysis: Combination of main channels



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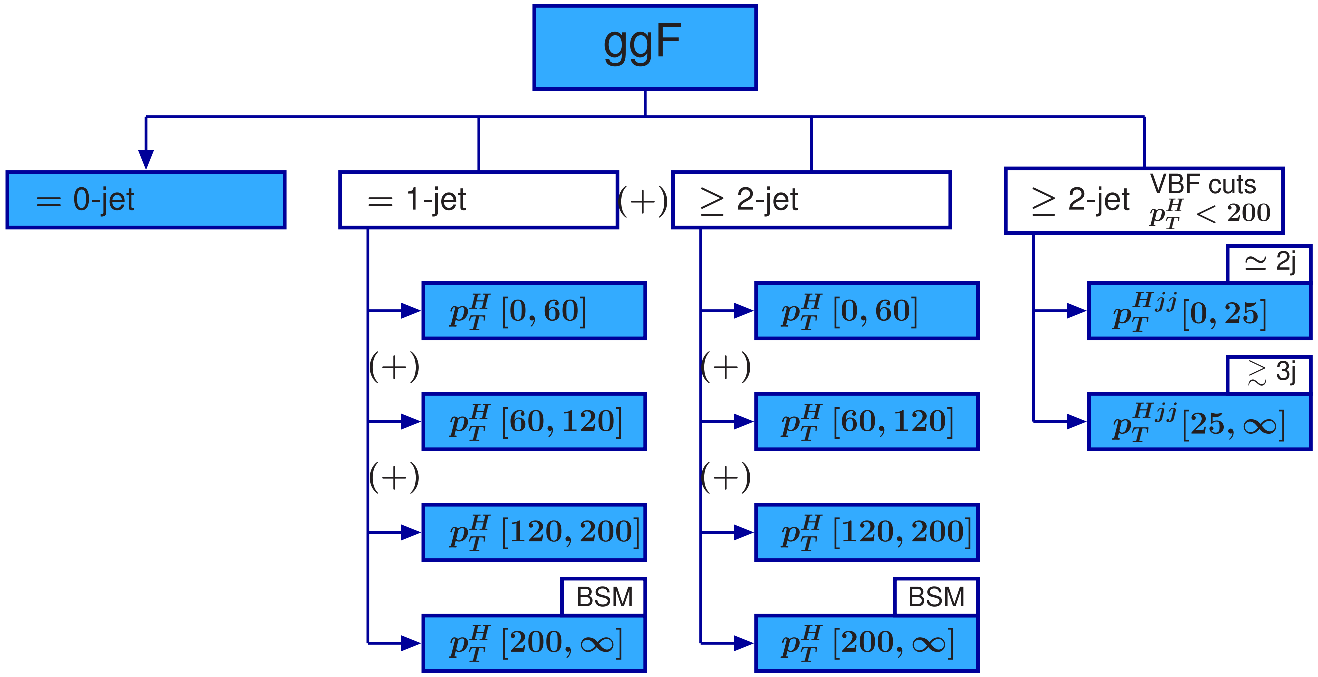
Simplified Template Cross Sections (STXS)

Stage-1 ggF categories: exclusive phase spaces



ggF

$= 0$-jet

$= 1$-jet $(+)$ ≥ 2-jet

≥ 2-jet VBF cuts $p_T^H < 200$

$p_T^H\,[0, 60]$ $(+)$ $p_T^H\,[60, 120]$ $(+)$ $p_T^H\,[120, 200]$ BSM $p_T^H\,[200, \infty]$

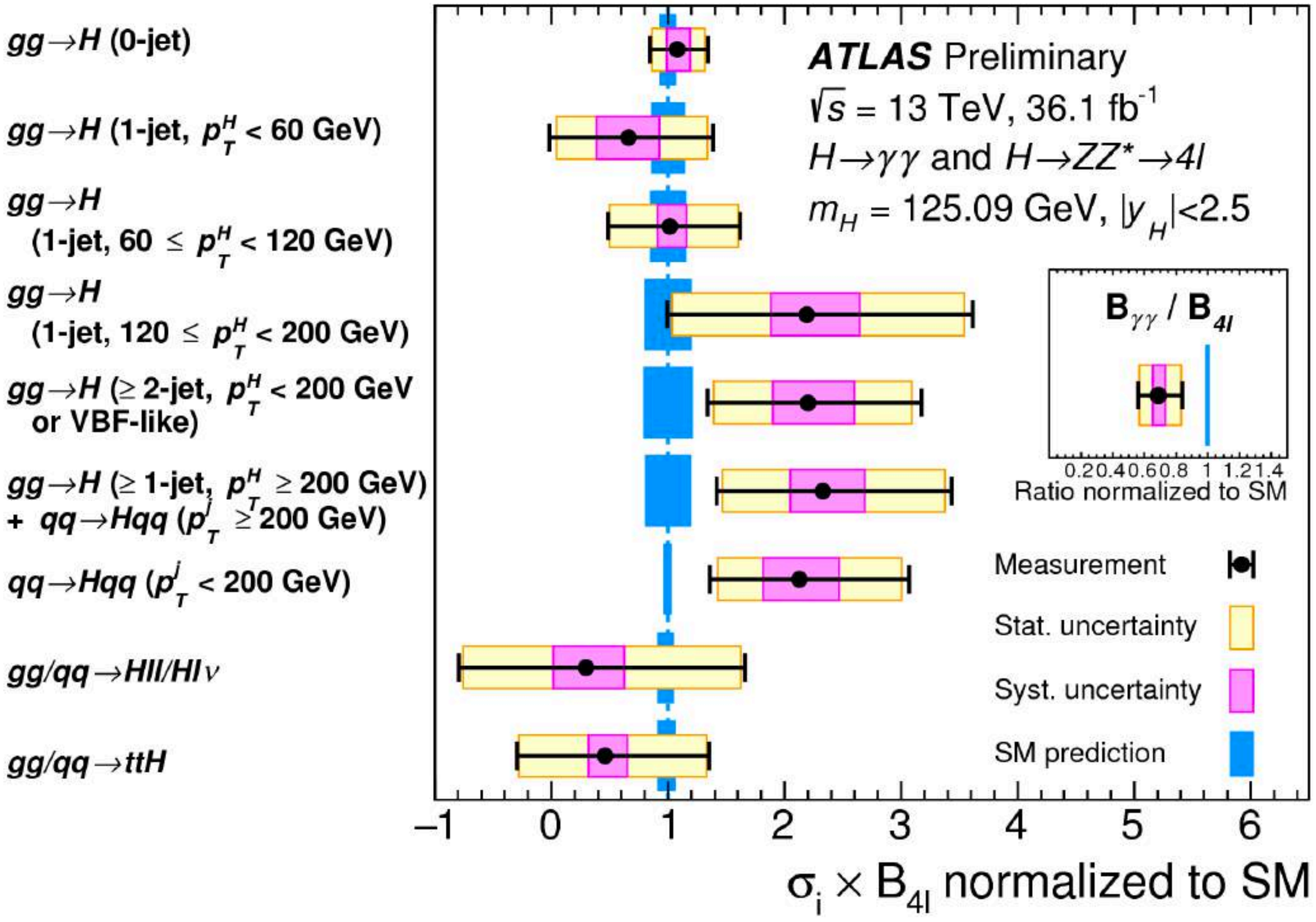
$p_T^H\,[0, 60]$ $(+)$ $p_T^H\,[60, 120]$ $(+)$ $p_T^H\,[120, 200]$ BSM $p_T^H\,[200, \infty]$

$\simeq 2$j $p_T^{Hjj}\,[0, 25]$

$\gtrsim 3$j $p_T^{Hjj}\,[25, \infty]$

arxiv:1610.07922

Stage-1 analysis: Combination of H → $\gamma\gamma$ and H → ZZ* → 4ℓ



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