# Higgs boson measurements: where theory uncertainties matter

ATLAS+Theory SLAC group jamboree
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# Outline

- Higgs combination
  - Leading uncertainties
  - Final results from ATLAS+CMS Run-1 combination
- Background simulation for complex searches
  - The case of VH(bb): recent progress

Higgs combination
(arXiv 1606.02266v1,
submitted to JHEP 6 days ago)

# Inputs to the combination

| Channel | References for individual publications | | Signal strength [$\mu$] from results in this paper (Section 5.2) | | Signal significance [$\sigma$] | |
|---|---|---|---|---|---|---|
| | ATLAS | CMS | ATLAS | CMS | ATLAS | CMS |
| $H \to \gamma\gamma$ | [91] | [92] | $1.14\,^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$ | $1.11\,^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$ | 5.0 (4.6) | 5.6 (5.1) |
| $H \to ZZ$ | [93] | [94] | $1.52\,^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$ | $1.04\,^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$ | 7.6 (5.6) | 7.0 (6.8) |
| $H \to WW$ | [95, 96] | [97] | $1.22\,^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$ | $0.90\,^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$ | 6.8 (5.8) | 4.8 (5.6) |
| $H \to \tau\tau$ | [98] | [99] | $1.41\,^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$ | $0.88\,^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$ | 4.4 (3.3) | 3.4 (3.7) |
| $H \to bb$ | [100] | [101] | $0.62\,^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$ | $0.81\,^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$ | 1.7 (2.7) | 2.0 (2.5) |
| $H \to \mu\mu$ | [102] | [103] | $-0.6\,^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$ | $0.9\,^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$ | | |
| $ttH$ production | [77, 104, 105] | [107] | $1.9\,^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$ | $2.9\,^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$ | 2.7 (1.6) | 3.6 (1.3) |

# Signal theory input

| Production process | Cross section [pb] $\sqrt{s} = 7$ TeV | Cross section [pb] $\sqrt{s} = 8$ TeV | Order of calculation |
|---|---|---|---|
| $ggF$ | $15.0 \pm 1.6$ | $19.2 \pm 2.0$ | NNLO(QCD) + NLO(EW) |
| VBF | $1.22 \pm 0.03$ | $1.58 \pm 0.04$ | NLO(QCD+EW) + APPROX. NNLO(QCD) |
| $WH$ | $0.577 \pm 0.016$ | $0.703 \pm 0.018$ | NNLO(QCD) + NLO(EW) |
| $ZH$ | $0.334 \pm 0.013$ | $0.414 \pm 0.016$ | NNLO(QCD) + NLO(EW) |
| $[ggZH]$ | $0.023 \pm 0.007$ | $0.032 \pm 0.010$ | NLO(QCD) |
| $ttH$ | $0.086 \pm 0.009$ | $0.129 \pm 0.014$ | NLO(QCD) |
| $tH$ | $0.012 \pm 0.001$ | $0.018 \pm 0.001$ | NLO(QCD) |
| $bbH$ | $0.156 \pm 0.021$ | $0.203 \pm 0.028$ | 5FS NNLO(QCD) + 4FS NLO(QCD) |
| Total | $17.4 \pm 1.6$ | $22.3 \pm 2.0$ | |

- Uncertainty from sum in quadrature of QCD scale, PDF unc. and $\alpha_S$.

- Many improvements since discovery
  - Thanks to interaction with theorists (esp. within Higgs xSec WG)
- In general, tried to use most updated calculation / tools.

| Production process | Event generator ATLAS | Event generator CMS |
|---|---|---|
| $ggF$ | POWHEG [79–83] | POWHEG |
| VBF | POWHEG | POWHEG |
| $WH$ | PYTHIA8 [84] | PYTHIA6.4 [85] |
| $ZH$ ($qq \to ZH$ or $qg \to ZH$) | PYTHIA8 | PYTHIA6.4 |
| $ggZH$ ($gg \to ZH$) | POWHEG | See text |
| $ttH$ | POWHEL [87] | PYTHIA6.4 |
| $tHq$ ($qb \to tHq$) | MADGRAPH [89] | aMC@NLO [78] |
| $tHW$ ($gb \to tHW$) | aMC@NLO | aMC@NLO |
| $bbH$ | PYTHIA8 | PYTHIA6.4, aMC@NLO |

# Most general fits (I)

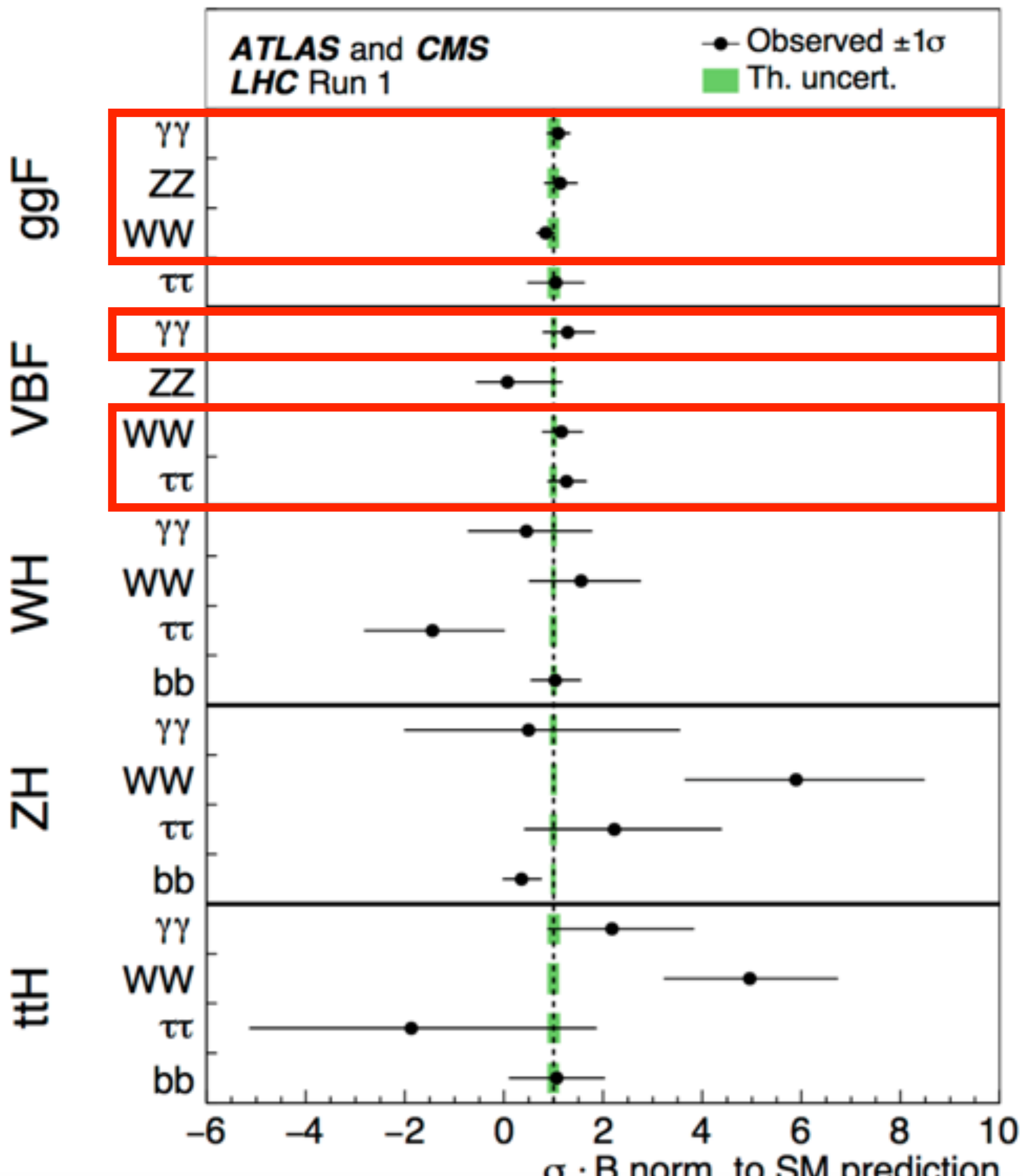
| Production process | Decay channel | | | | |
|---|---|---|---|---|---|
| | $H \to \gamma\gamma$ | $H \to ZZ$ | $H \to WW$ | $H \to \tau\tau$ | $H \to bb$ |
| $ggF$ | $\boxed{(\sigma \cdot B)^{\gamma\gamma}_{ggF}}$ | $\boxed{(\sigma \cdot B)^{ZZ}_{ggF}}$ | $\boxed{(\sigma \cdot B)^{WW}_{ggF}}$ | $(\sigma \cdot B)^{\tau\tau}_{ggF}$ | – |
| VBF | $\boxed{(\sigma \cdot B)^{\gamma\gamma}_{VBF}}$ | $(\sigma \cdot B)^{ZZ}_{VBF}$ | $\boxed{(\sigma \cdot B)^{WW}_{VBF}}$ | $\boxed{(\sigma \cdot B)^{\tau\tau}_{VBF}}$ | – |
| $WH$ | $(\sigma \cdot B)^{\gamma\gamma}_{WH}$ | $(\sigma \cdot B)^{ZZ}_{WH}$ | $(\sigma \cdot B)^{WW}_{WH}$ | $(\sigma \cdot B)^{\tau\tau}_{WH}$ | $(\sigma \cdot B)^{bb}_{WH}$ |
| $ZH$ | $(\sigma \cdot B)^{\gamma\gamma}_{ZH}$ | $(\sigma \cdot B)^{ZZ}_{ZH}$ | $(\sigma \cdot B)^{WW}_{ZH}$ | $(\sigma \cdot B)^{\tau\tau}_{ZH}$ | $(\sigma \cdot B)^{bb}_{ZH}$ |
| $ttH$ | $(\sigma \cdot B)^{\gamma\gamma}_{ttH}$ | $(\sigma \cdot B)^{ZZ}_{ttH}$ | $(\sigma \cdot B)^{WW}_{ttH}$ | $(\sigma \cdot B)^{\tau\tau}_{ttH}$ | $(\sigma \cdot B)^{bb}_{ttH}$ |

$$i \to H \to f$$

$$\sigma_i \cdot B^f$$

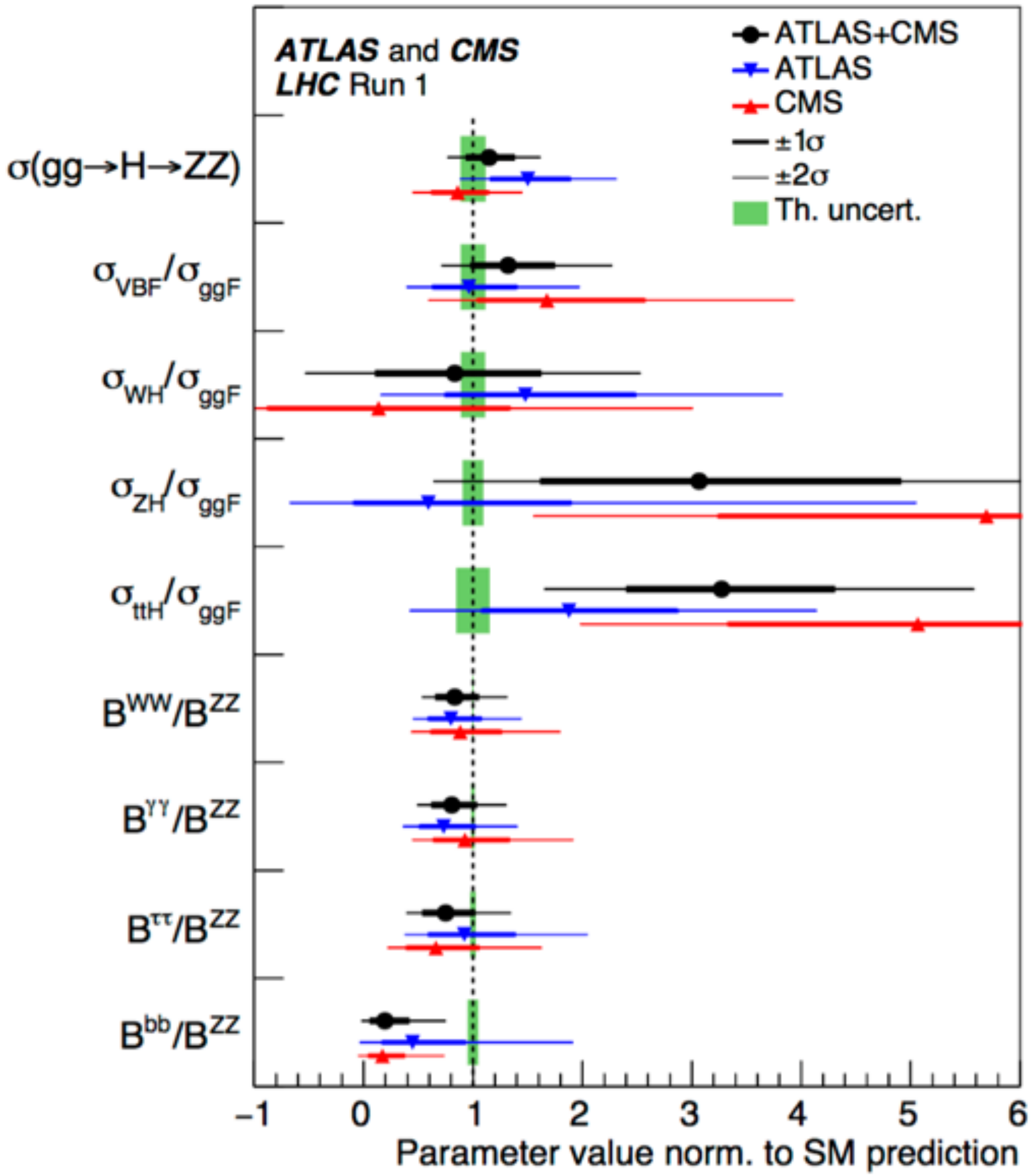
- In practice not all combinations are available
- And some have limited precisions (highlighted are the ones with precision better than 40%)
- But most model independent result…

# Most general fits (II)




- In general good compatibility with SM, with some tensions here and there.
- Theory uncertainty start to play a leading role in the highest stat channels, especially in ggF.

# Next-to-most generic fits (I)




- Make use of narrow-width approximation to factorize production and decay mode, e.g.

$$\sigma(gg \to H \to ZZ) = \sigma_{ggF} \cdot \mathrm{B}^{ZZ}$$

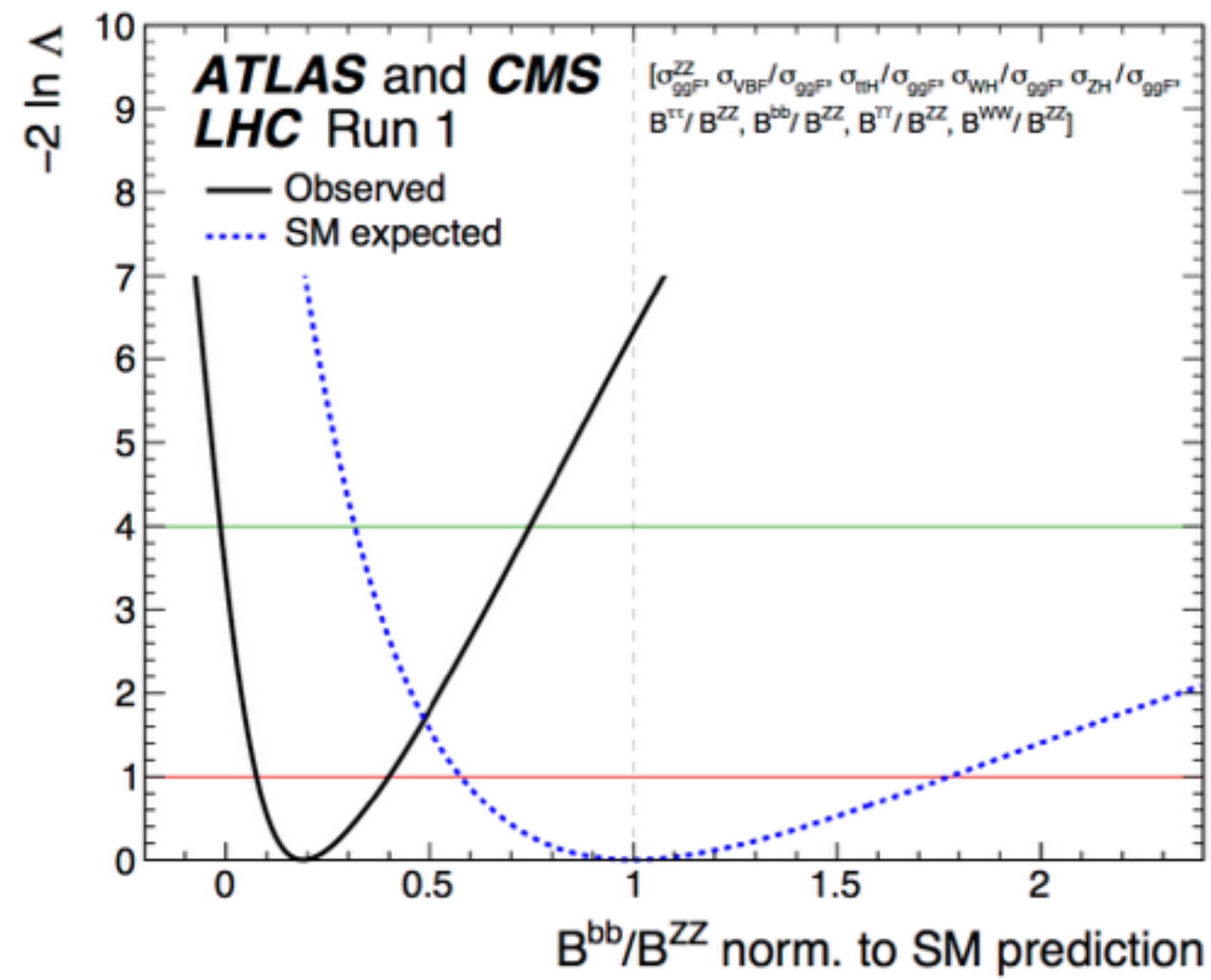
- Normalize cross sections and branching fractions to a reference channel, $(\sigma_{x}BR)_{ZZ}$:

$$\sigma_i \cdot \mathrm{B}^f = \sigma(gg \to H \to ZZ) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{\mathrm{B}^f}{\mathrm{B}^{ZZ}}\right)$$

- Uncertainties on $(\sigma_{x}BR)_{ZZ}$ reduced by factor of ~2
- Overall compatibility with SM ~16%.

# Next-to-most generic fits (II)

- Other highlights:
  - $\sigma_{ttH} / \sigma_{ggF}$ at +3.0σ w.r.t. SM prediction (mainly from multi-lepton categories)
  - $B_{bb}/B_{ZZ}$ =0.2 +0.2 -0.1, 2.5σ from SM prediction (mainly due to high values found for production σ of ZH and ttH)




- Theory vs exp. uncertainty
  - Unc(BR) negligible, import: $\sigma_{GGF}$

| Parameter | SM prediction | Best fit value | Uncertainty Stat | Uncertainty Syst |
|---|---|---|---|---|
| | | ATLAS+CMS | | |
| $\sigma(gg \to H \to ZZ)$ [pb] | $0.51 \pm 0.06$ | $0.59\,^{+0.11}_{-0.10}$ | $^{+0.11}_{-0.10}$ | $^{+0.02}_{-0.02}$ |
| | ~12% | ~17% | | |

Theory error will be dominant in Run-2

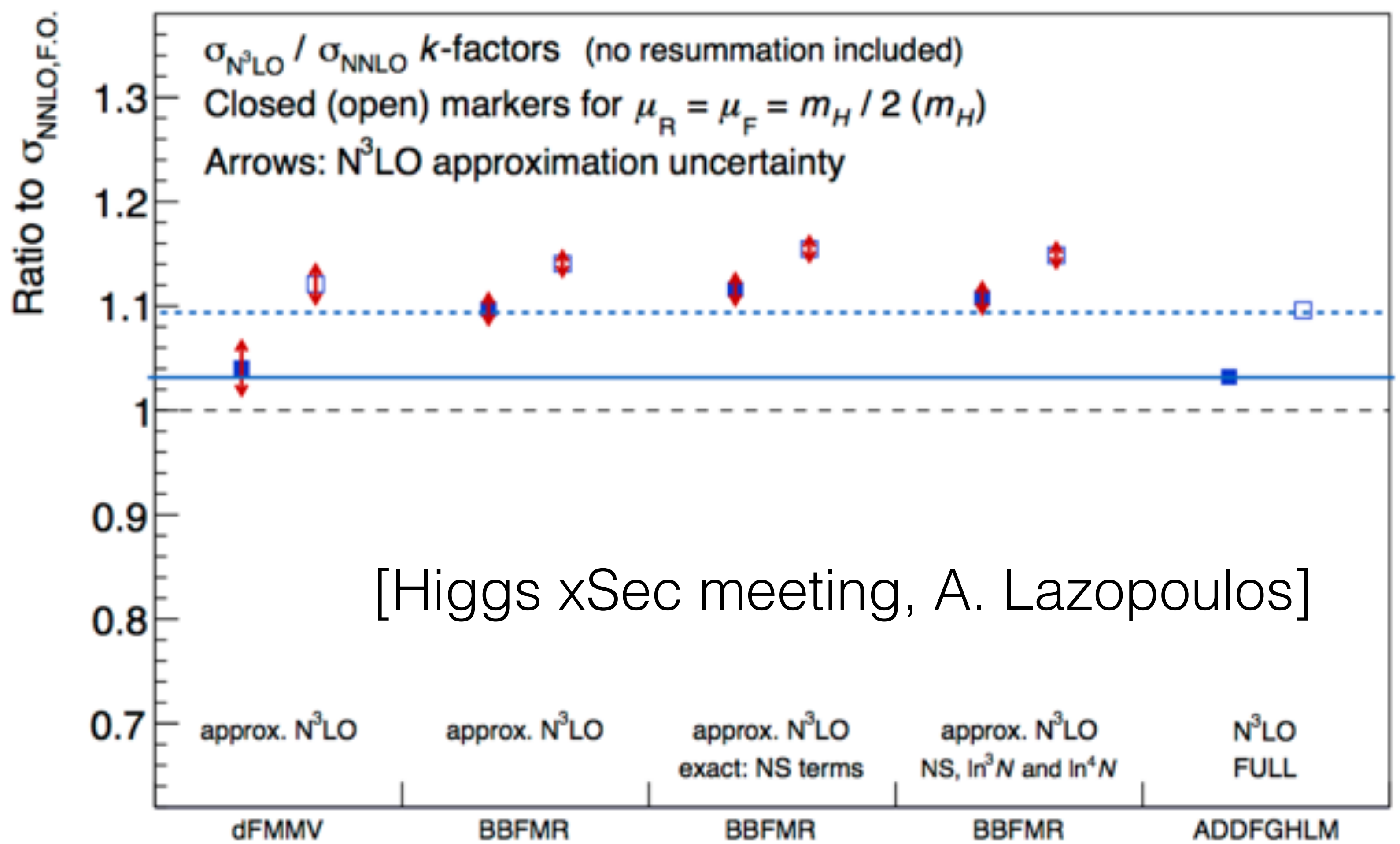
# Global signal strength fit

| | Best fit $\mu$ | Uncertainty | | | | |
|---|---|---|---|---|---|---|
| | | Total | Stat | Expt | Thbgd | Thsig |
| ATLAS + CMS (measured) | 1.09 | $^{+0.11}_{-0.10}$ | $^{+0.07}_{-0.07}$ | $^{+0.04}_{-0.04}$ | $^{+0.03}_{-0.03}$ | $^{+0.07}_{-0.06}$ |
| ATLAS + CMS (expected) | | $^{+0.11}_{-0.10}$ | $^{+0.07}_{-0.07}$ | $^{+0.04}_{-0.04}$ | $^{+0.03}_{-0.03}$ | $^{+0.07}_{-0.06}$ |
| ATLAS (measured) | 1.20 | $^{+0.15}_{-0.14}$ | $^{+0.10}_{-0.10}$ | $^{+0.06}_{-0.06}$ | $^{+0.04}_{-0.04}$ | $^{+0.08}_{-0.07}$ |
| ATLAS (expected) | | $^{+0.14}_{-0.13}$ | $^{+0.10}_{-0.10}$ | $^{+0.06}_{-0.05}$ | $^{+0.04}_{-0.04}$ | $^{+0.07}_{-0.06}$ |
| CMS (measured) | 0.97 | $^{+0.14}_{-0.13}$ | $^{+0.09}_{-0.09}$ | $^{+0.05}_{-0.05}$ | $^{+0.04}_{-0.03}$ | $^{+0.07}_{-0.06}$ |
| CMS (expected) | | $^{+0.14}_{-0.13}$ | $^{+0.09}_{-0.09}$ | $^{+0.05}_{-0.05}$ | $^{+0.04}_{-0.03}$ | $^{+0.08}_{-0.06}$ |

- Experimental: **7%** stat error, **4%** exp. uncertainties (e.g. jet energy scale)
- Theory: **3%** from background estimates, **7%** from signal predictions
  - For ggF: +7/-8% scale unc., +7/-7% PDF+$\alpha_S$ uncertainty (PDF+$\alpha_S$ uncertainty reduced to ~3% with new PDF4LHC prescription)

# ggF total cross-section

- Uncertainty being further reduced by N3LO (!) computation (C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog, A. Lazopoulos, B. Mistlberger)



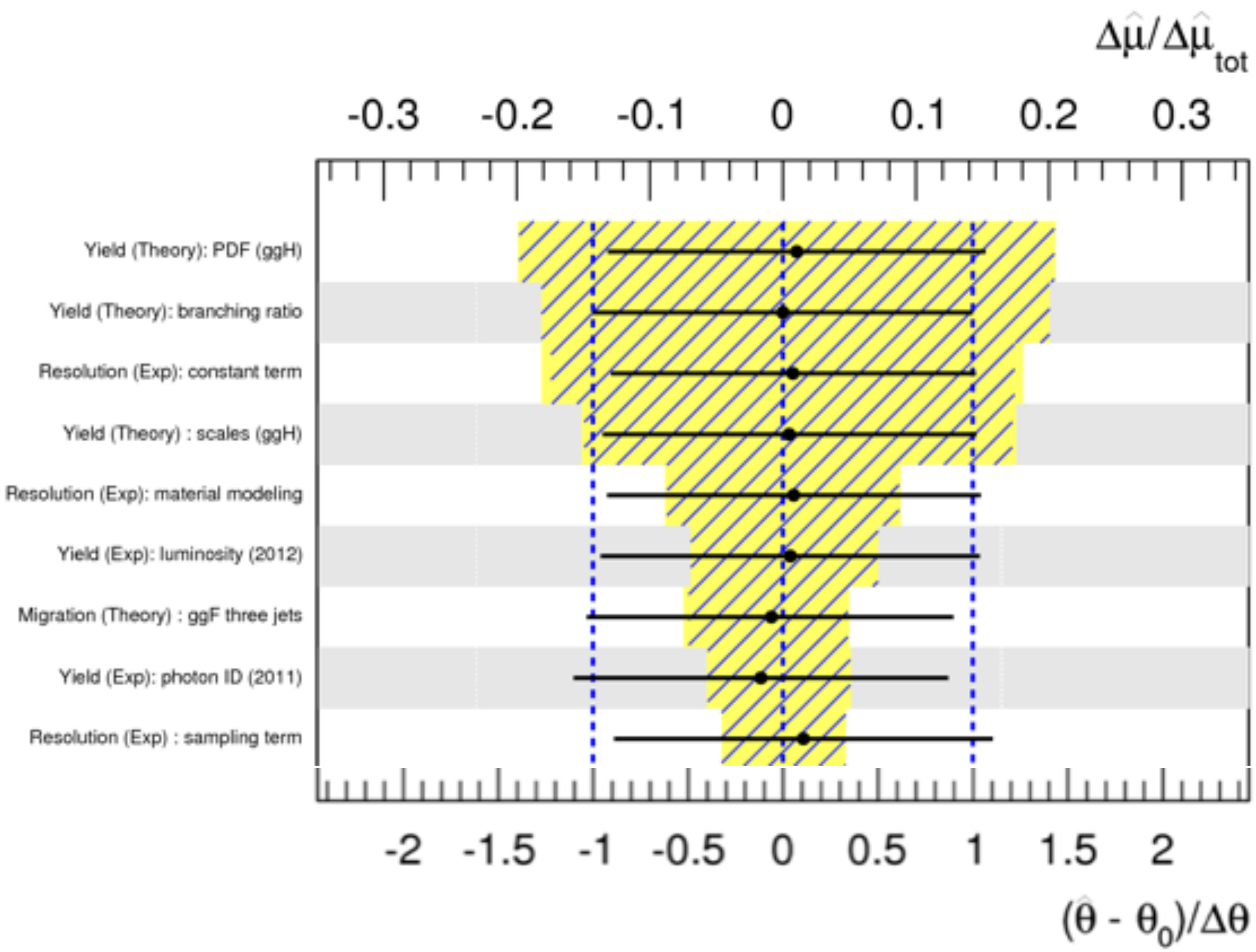

Talk by Falko later

- This is for 13 TeV, but still seems to go in direction of bring exp. result closer to theory…

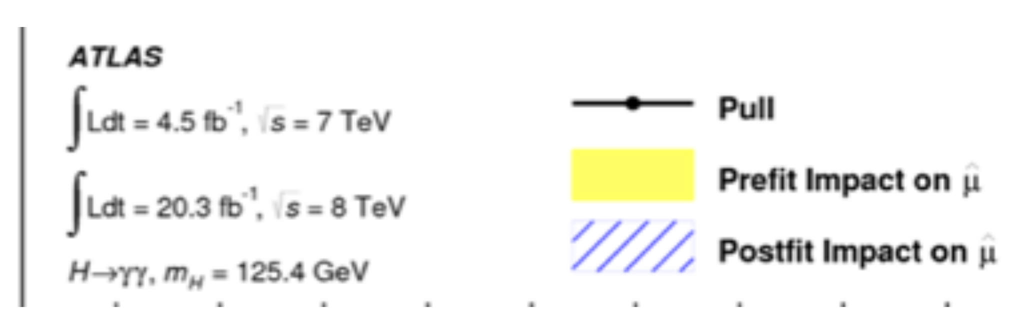
# Other theory uncertainties

- Differential distributions (mainly scale variations + matching to PS/res.)
  - E.g. for ggF
    - differential pT spectrum rescaled to HRes2.1 (NNLO+NNLL)
    - H+2 jet bin reweighed to MiNLO H+jet MC estimate
  - Differences in PS model/UE tunes
- Higgs boson branching fraction
  - Subleading in general, except when considering ratios of couplings
- In some cases a neglected NNLO effect can significantly change the result
  - E.g. in WH/ZH, H to bb the gg to ZH contribution was initially "neglected" by CMS
  - This changed the μ(VH to Vbb) result from 1+/-0.5 to 0.81+/- 0.44!

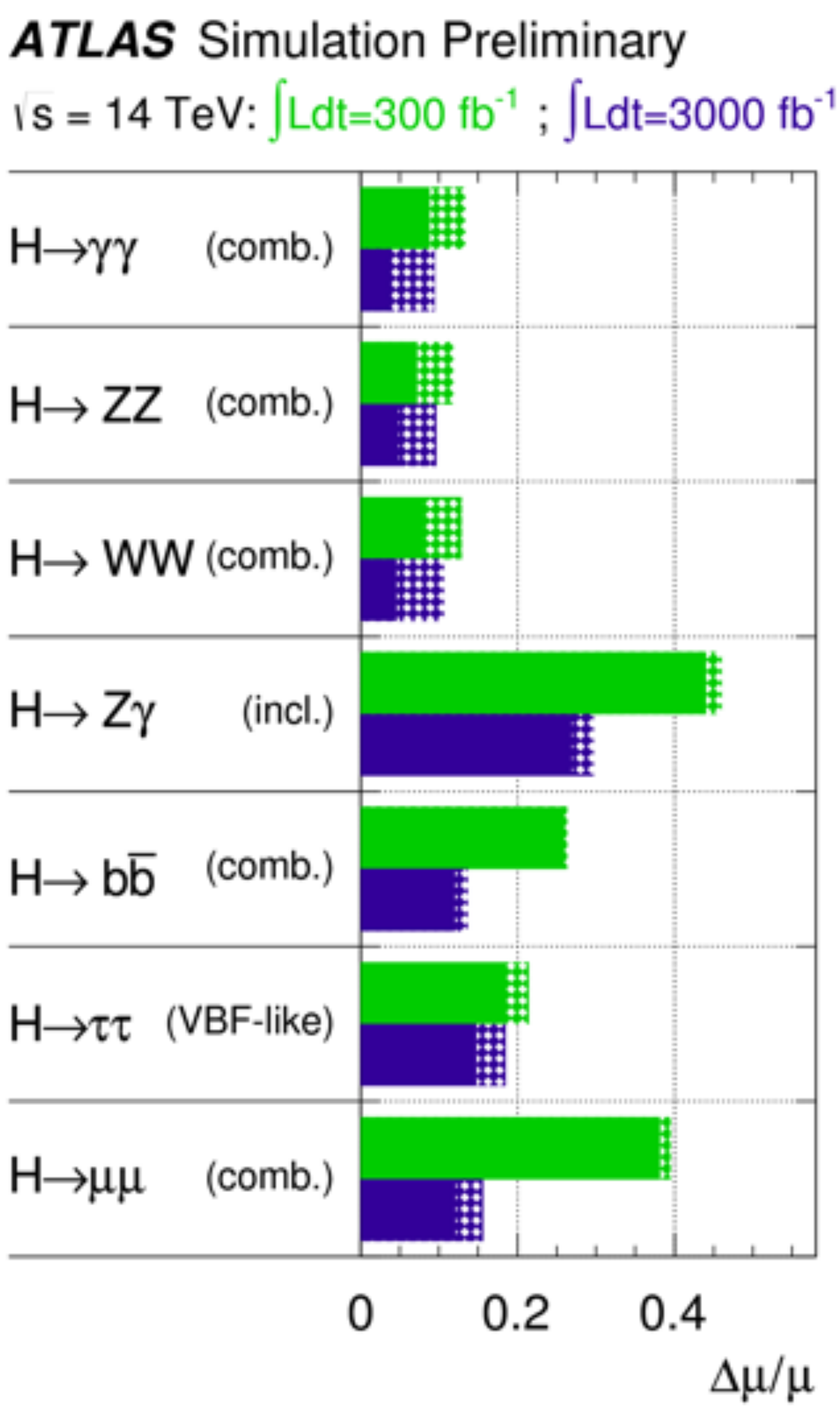
# Example: H →γγ




- Theory uncertainties among leading ones
- Differential uncertainties sub-leading in H →γγ



# Projections for HL-LHC




- Approximate projections for HL run of LHC in note ~end of 2014
- Difference between full and dashed are is due to (current) theory uncertainties
- Clearly ultimately the limiting factor to precise coupling measurements!

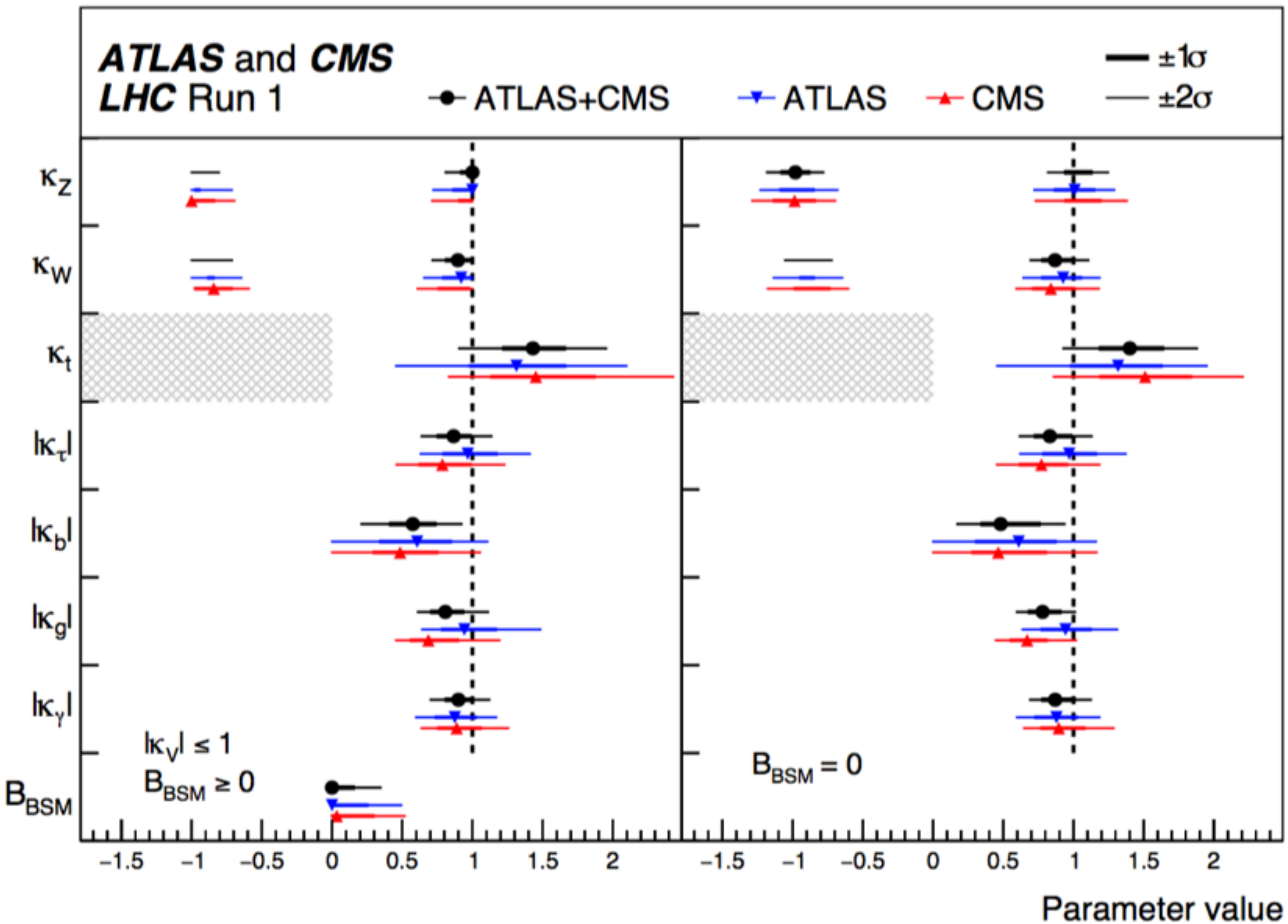
# Coupling fits ("κ" framework)

| Production | Loops | Interference | Effective scaling factor | Resolved scaling factor |
|---|---|---|---|---|
| $\sigma(ggF)$ | ✓ | $t$–$b$ | $\kappa_g^2$ | $1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$ |
| $\sigma(\mathrm{VBF})$ | – | – | | $0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$ |
| $\sigma(WH)$ | – | – | | $\kappa_W^2$ |
| $\sigma(qq/qg \to ZH)$ | – | – | | $\kappa_Z^2$ |
| $\sigma(gg \to ZH)$ | ✓ | $t$–$Z$ | | $2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$ |
| $\sigma(ttH)$ | – | – | | $\kappa_t^2$ |
| $\sigma(gb \to tHW)$ | – | $t$–$W$ | | $1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$ |
| $\sigma(qq/qb \to tHq)$ | – | $t$–$W$ | | $3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$ |
| $\sigma(bbH)$ | – | – | | $\kappa_b^2$ |
| Partial decay width | | | | |
| $\Gamma^{ZZ}$ | – | – | | $\kappa_Z^2$ |
| $\Gamma^{WW}$ | – | – | | $\kappa_W^2$ |
| $\Gamma^{\gamma\gamma}$ | ✓ | $t$–$W$ | $\kappa_\gamma^2$ | $1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$ |
| $\Gamma^{\tau\tau}$ | – | – | | $\kappa_\tau^2$ |
| $\Gamma^{bb}$ | – | – | | $\kappa_b^2$ |
| $\Gamma^{\mu\mu}$ | – | – | | $\kappa_\mu^2$ |
| Total width ($B_{\mathrm{BSM}} = 0$) | | | | |
| $\Gamma_H$ | ✓ | – | $\kappa_H^2$ | $0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$ |

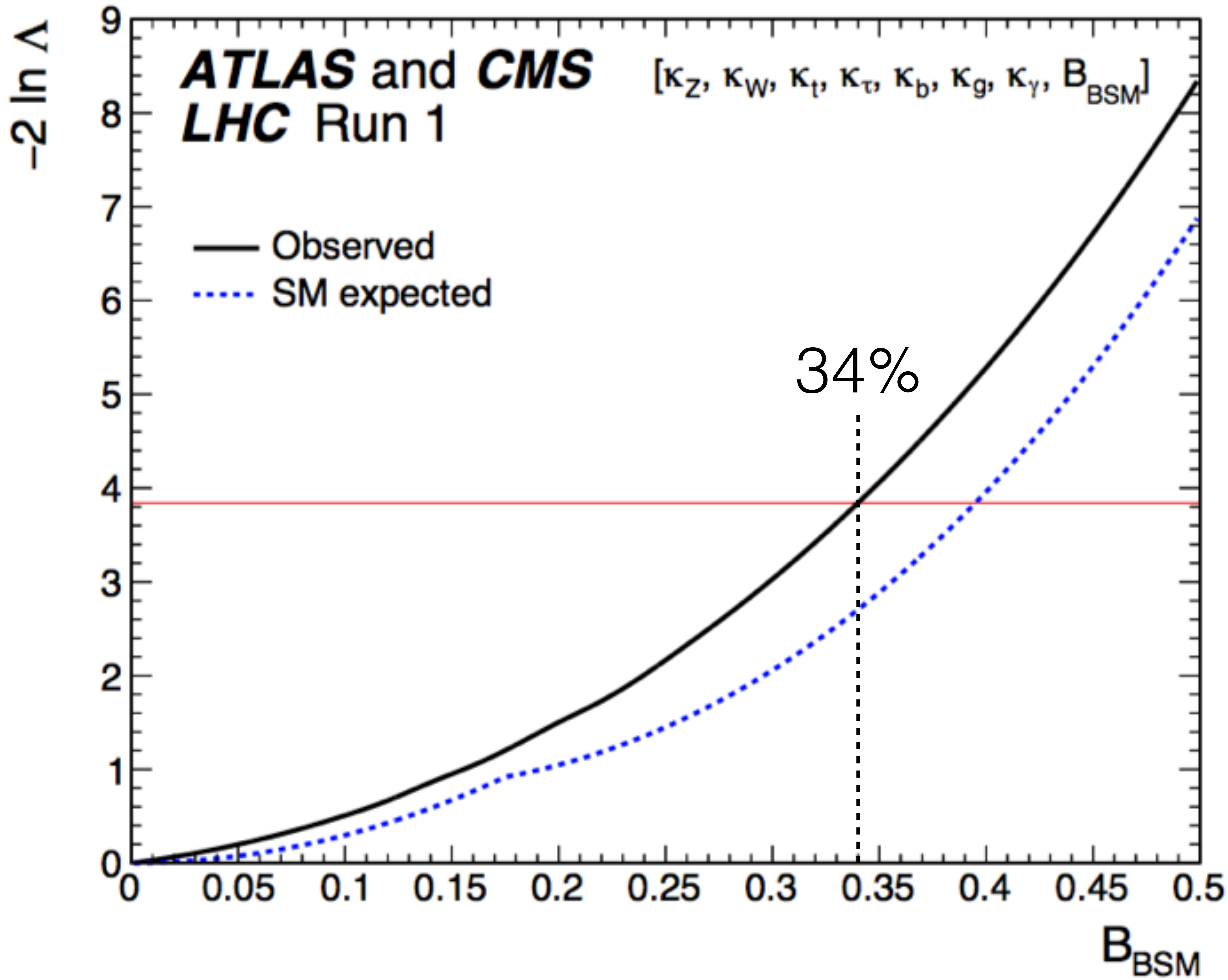
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - B_{\mathrm{BSM}}}$$

- Based on this parameterization, results are derived in many different scenarios
- Ratios of couplings also considered
- Will only show some of the results in the following

# Coupling fits results (I)



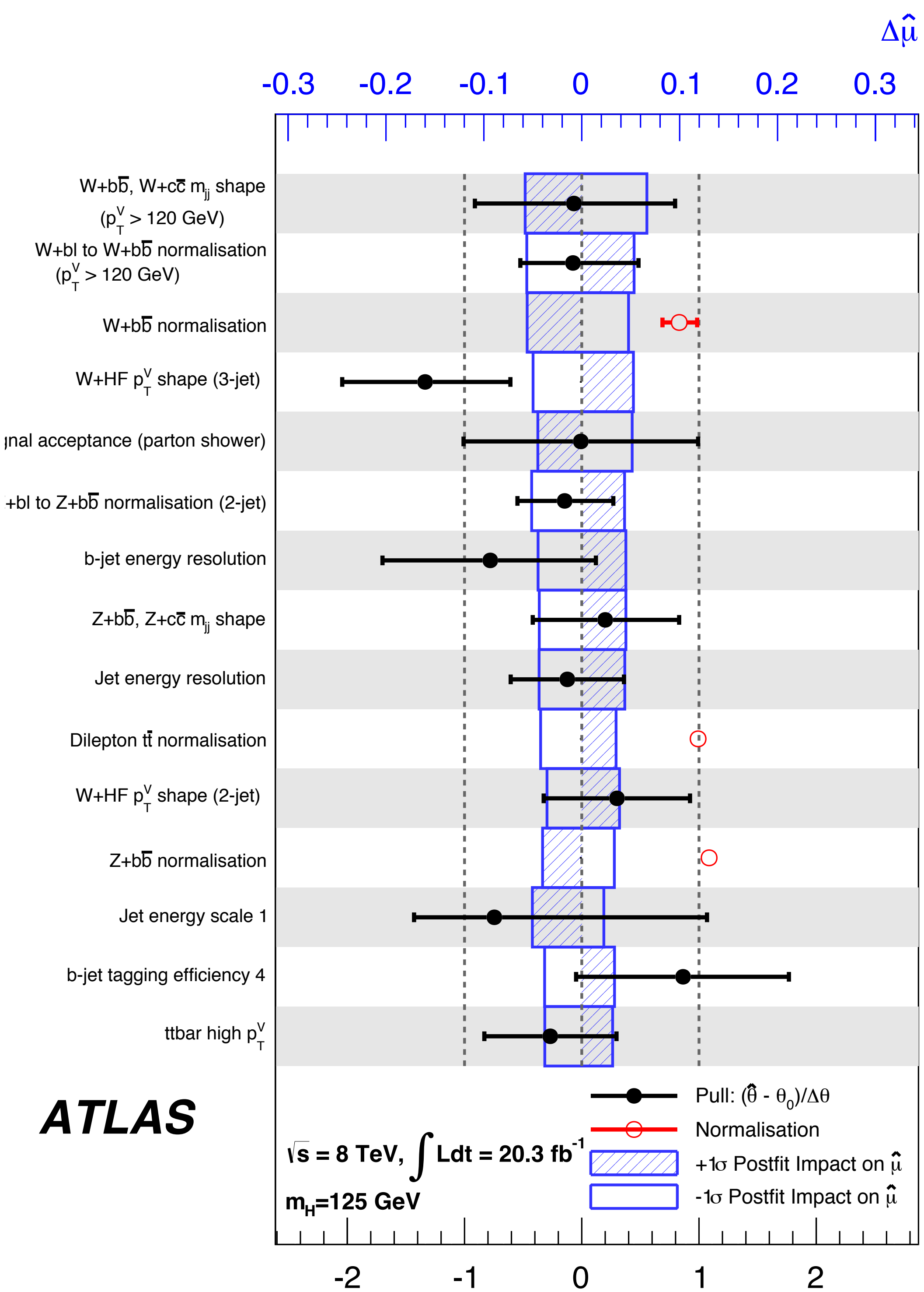
# Coupling fits results (II)




- $B_{BSM}$ is basically the non-SM contribution allowed to Higgs decay width
- Dominated by H to bb
- Competitive with direct searches for H to invisible
  - <25% in ATLAS
  - <58% (44%) observed (expected) in CMS

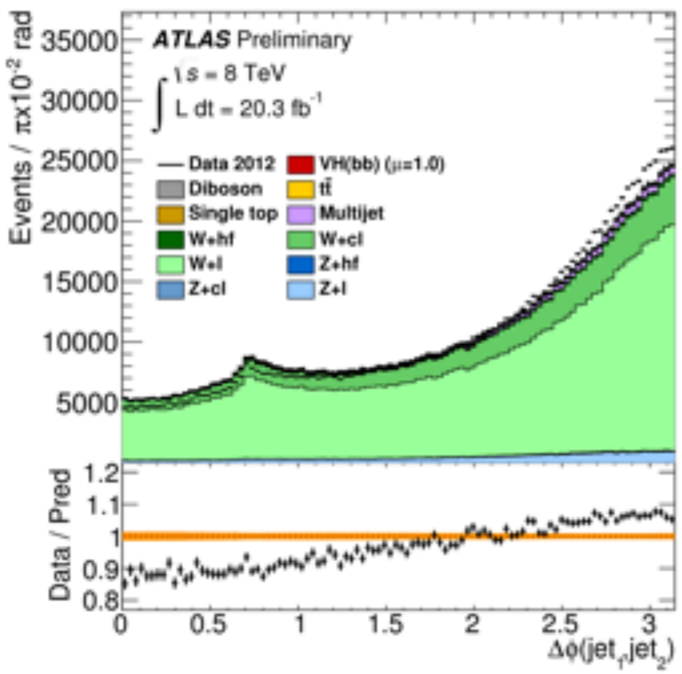
# Background modeling in H to bb searches

# The case of VH to Vbb

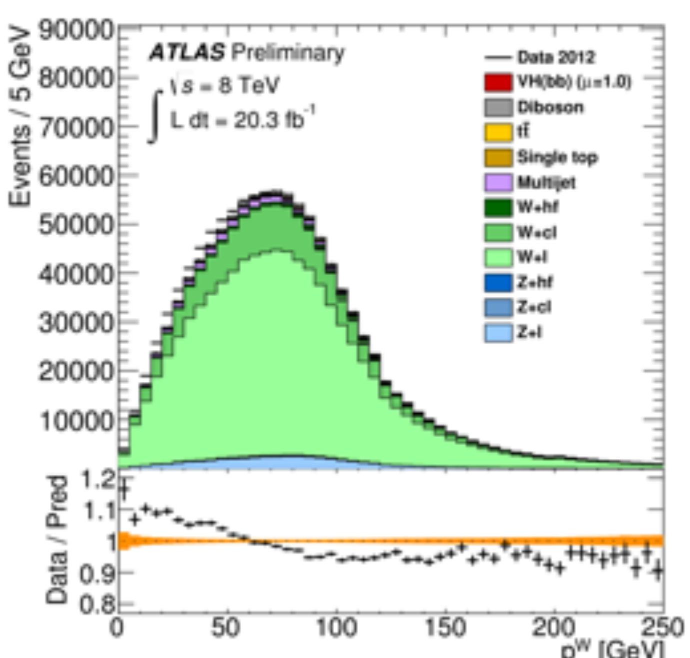


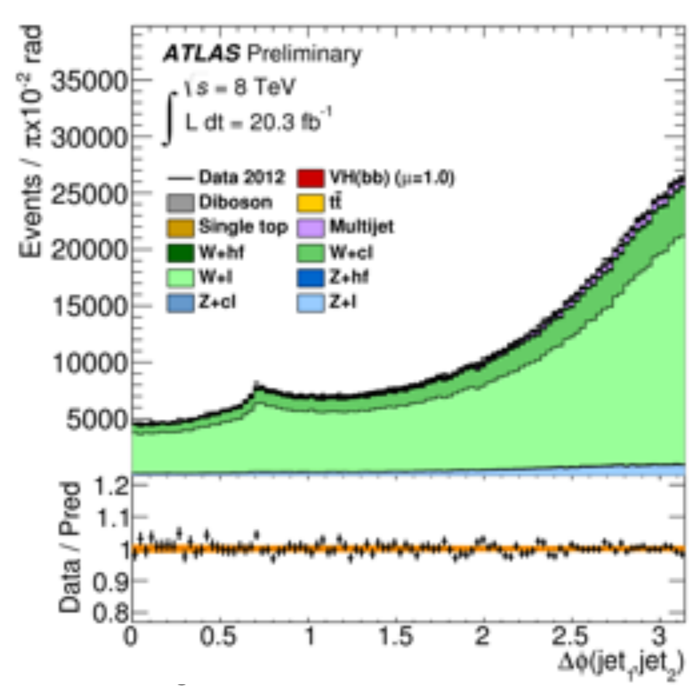

- Very difficult to define “clean” data control regions for certain backgrounds (e.g. W+bb, single top)
  - Theory predictions used for differential distributions, fit to control regions to normalize to data
- With such an approach, systematic uncertainties degraded sensitivity by ~25% in Run-1
- Leading uncertainties:
  - **W+b/c theory** (shapes + flavor composition)
  - Signal theory (parton shower)
  - Jet energy resolution
- It will be hard to reach 5σ discovery without better theory predictions for the leading backgrounds

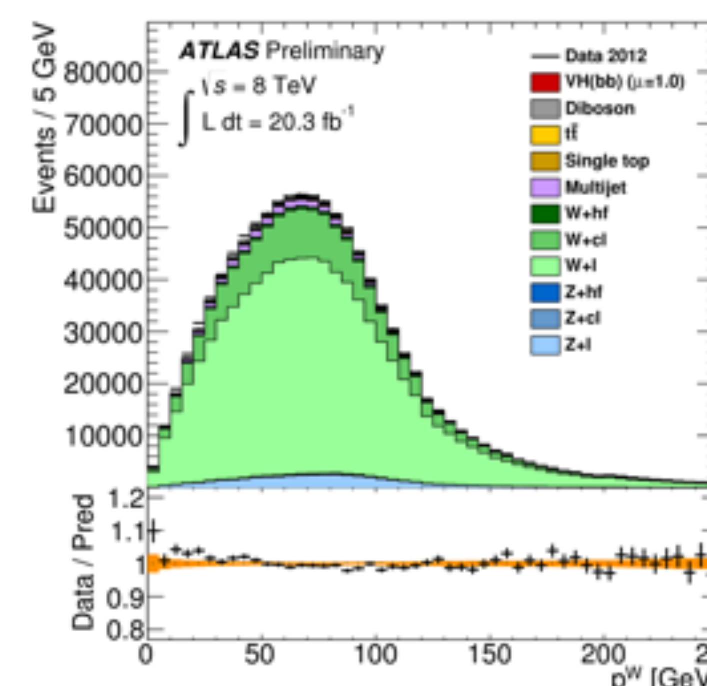
# W+jets: Run-1 approach




- Used Sherpa v1.4.1 for W/Z+jets
- Significant data/MC discrepancy in pT(V=W/Z) and Δφ(jet,jet)
- In Run-1 used re-weighting + ad-hoc uncertainties (incl. diff. to Alpgen)

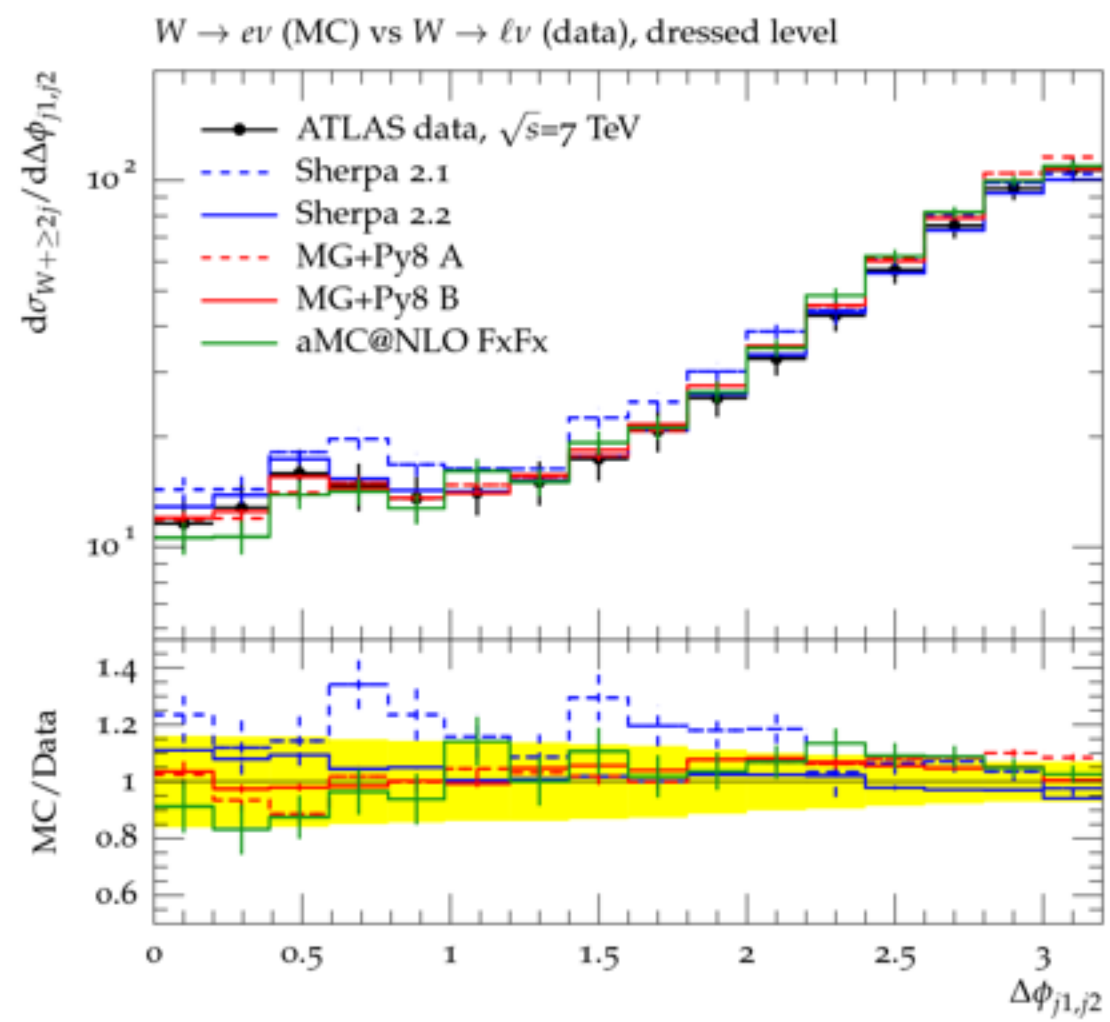


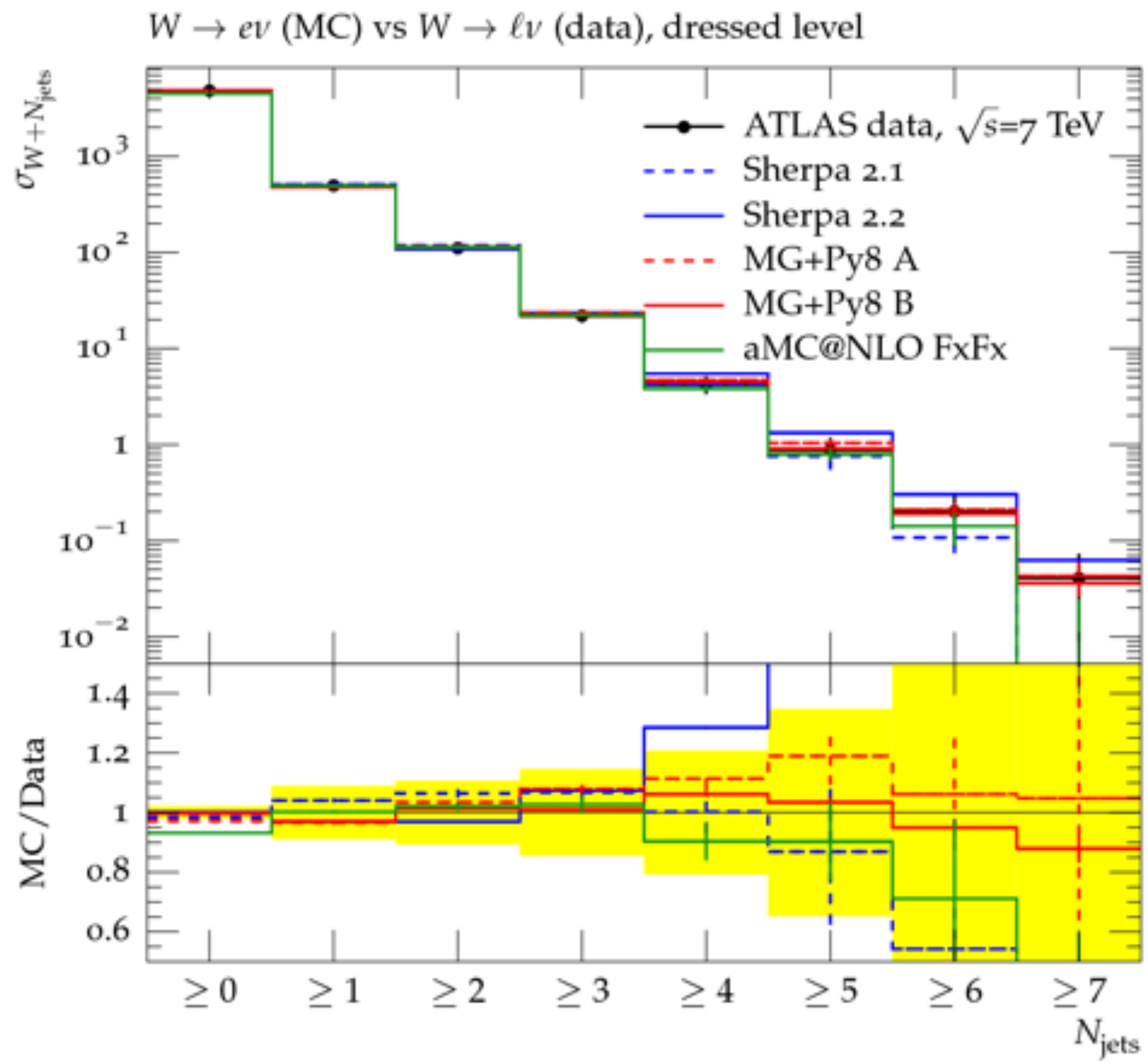
# W+jets: Run-2 status (1)

- Several improvements went into v2 of Sherpa
  - ATLAS uses NLO matched to PS for up to 2 jets, then LO beyond 2 (although for W+jets up to W+3 jets would be very desirable!)
  - Comparisons to ATLAS W+jets 7 TeV data in note ATL-PHYS-PUB-2016-003
  - Significant problem found with Sherpa v2.1: MET distribution not correctly described (can't show here!)
    - Traced down to modeling of soft activity in forward region
    - Led to Sherpa v2.2



# W+jets: Run-2 status (2)

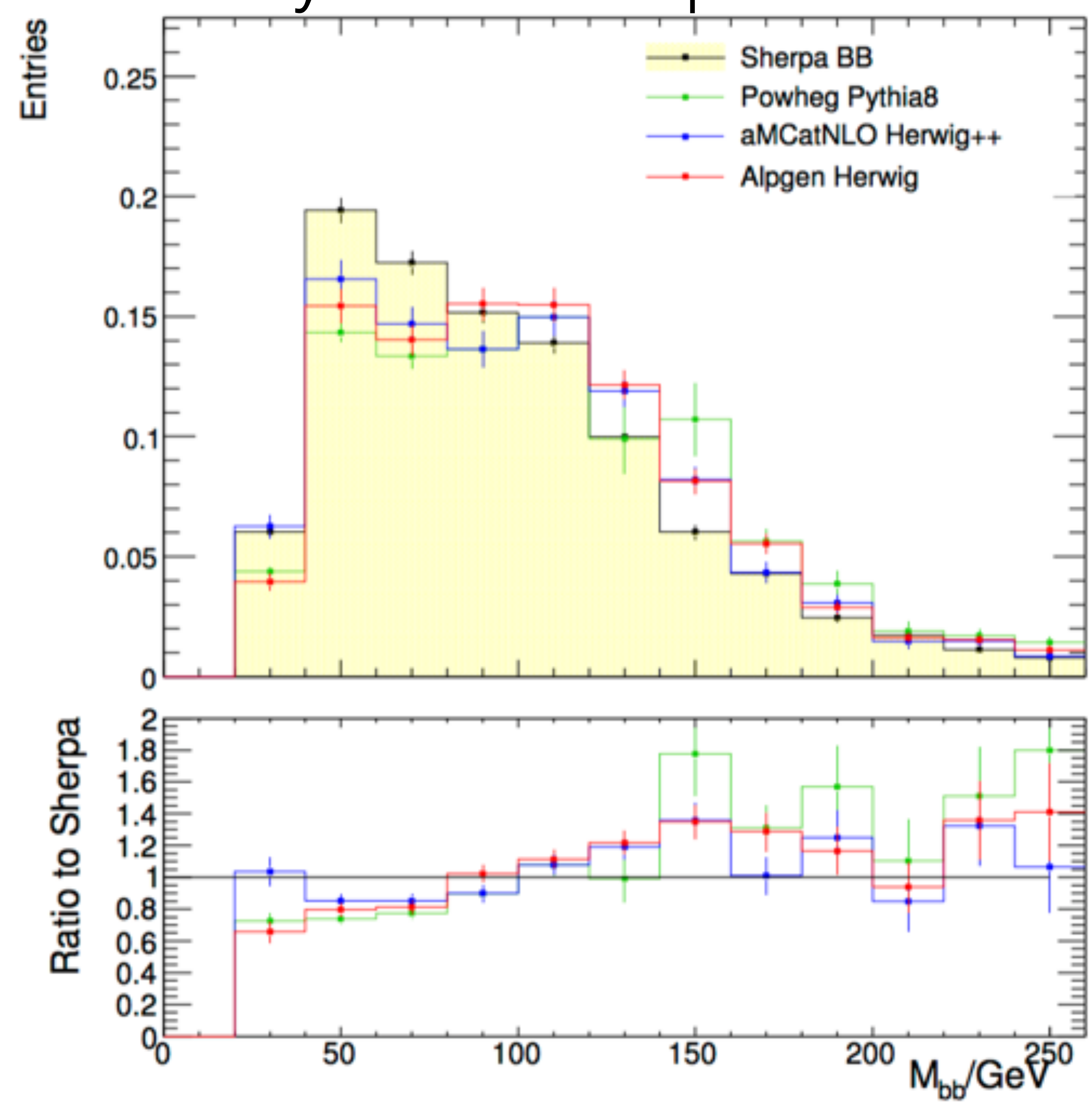
- However, Sherpa v2.2 samples didn't reproduce well jet multiplicity
- Traced down to ATLAS settings for Sherpa (choice of ME Truncated Shower scale)
  - We used approximate scale ("loose") also in event generation
- Recipe made available to re-weight jet multiplicity at truth level
  → now used for ICHEP analyses



# W+jets: Run-2 status (3)

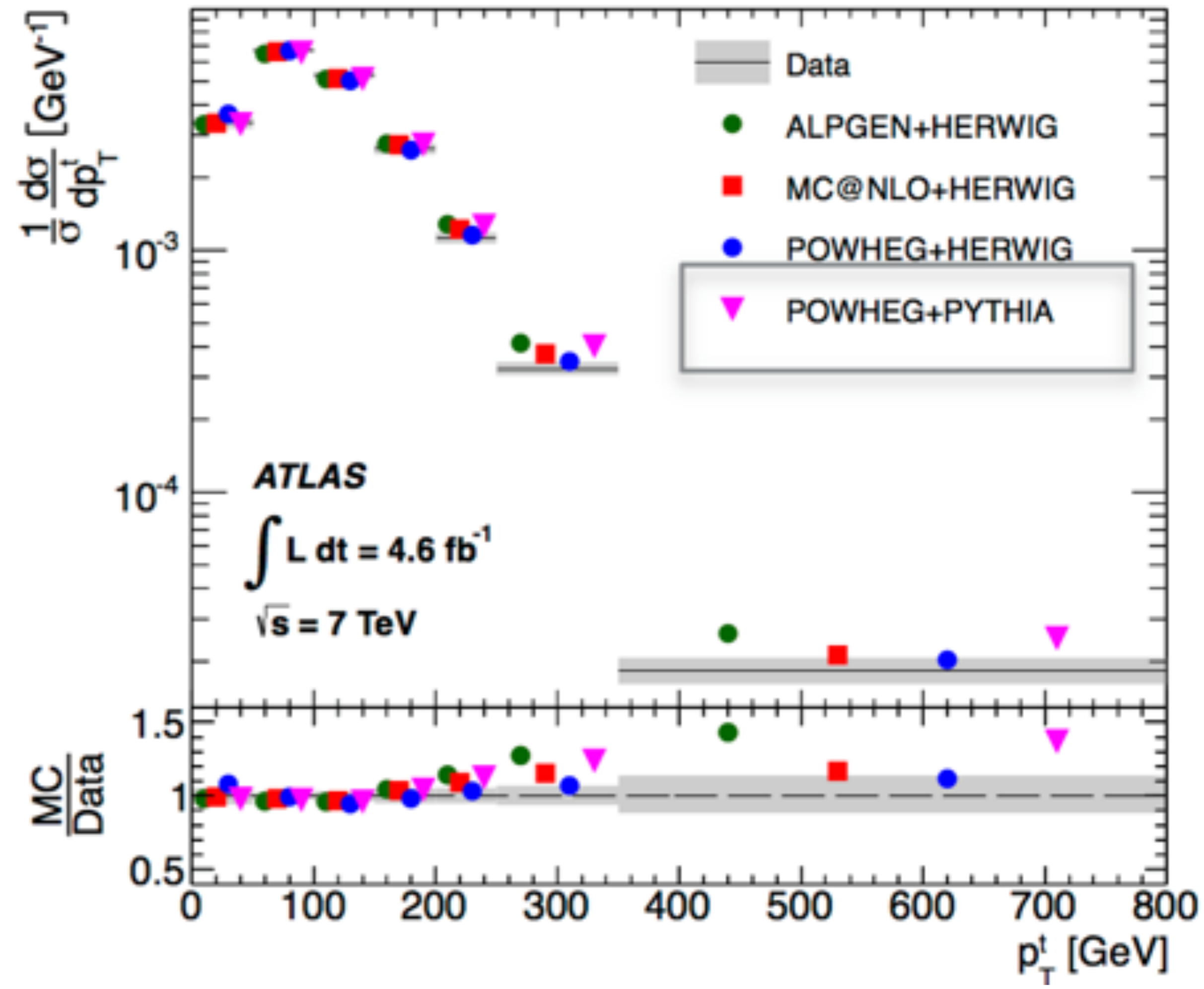
- Residual issue
  - NLO accuracy is great, but many events with high positive or negative weights, that reduce effective statistics significantly
  - Can this be improved for the future?
- The main V+jet samples in ATLAS are now:
  - Sherpa (used as nominal in VHbb)
  - Madgraph
- Description of heavy flavor component presently under study
  - Most crucial for H bb signal extraction

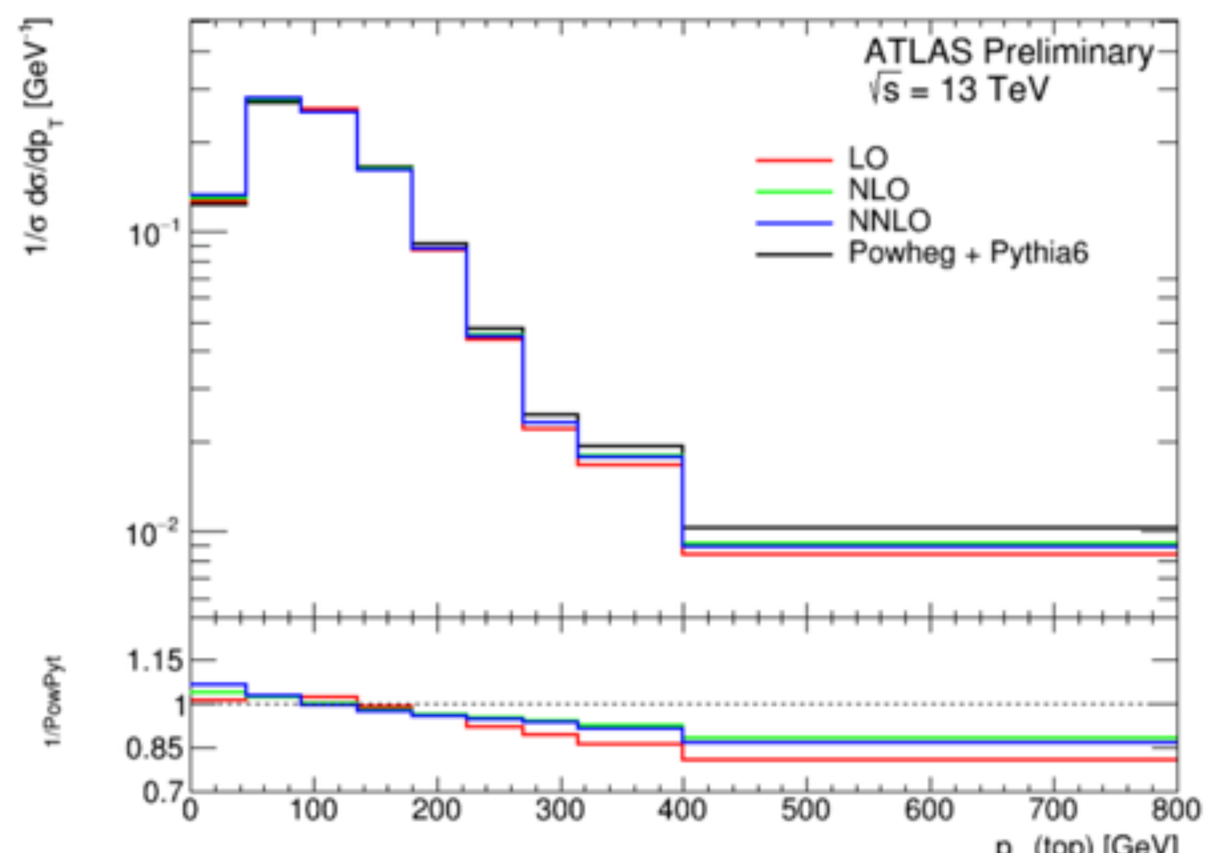
Theory level comp. for Run-1



# Top modeling

- One of main top background acceptance systematics is due to pT(top) modeling
- It seems that re-weighting to FO NNLO solves most of the discrepancy
- Perhaps NLO up to ttbar+1 or 2 jets would provide a similarly accurate result?



# Conclusions

- Increasing precision of coupling fits allows exclusion of an increasingly amount of new physics scenarios (e.g. with Higgs boson decays to invisible) - complementary to direct searches!
- First high-stats Run-2 Higgs results soon!
- Theory input essential
  - for modeling signal acceptance
  - to reliably estimate backgrounds in most complex searches, e.g. with H to bb