ATLAS+CMS Combined Measurement of the Higgs Boson Properties

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on behalf of the ATLAS and CMS Collaborations

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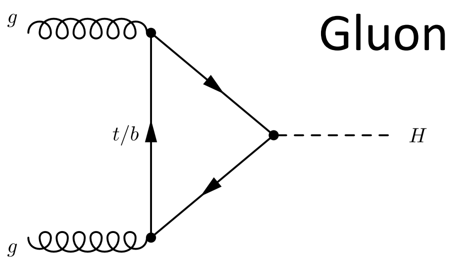
Introduction

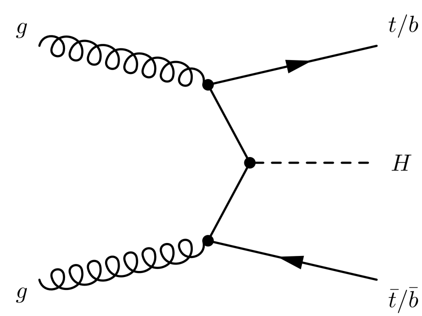
- Higgs boson is a window into possible new phenomena like SUSY
- ATLAS and CMS have measured together its mass, which is a free parameter, to be about 125 GeV
- Angular distributions consistent with spin 0 and even parity
  - In SUSY, CP is generally violated through loops so 125 GeV state could be CP admixture of light h and heavy A/H
- Crucial to measure Higgs couplings as major deviations predicted in BSM models like SUSY
  - Two Higgs doublets modify direct couplings to massive particles
  - Superpartners modify loop-induced couplings to gluons & photons
  - Higgs may decay invisibly to LSP (dark matter candidate)
- **Describe today final ATLAS+CMS combined Run 1 measurements of Higgs couplings that have just been submitted to JHEP:** http://arxiv.org/abs/1606.02266
  - Denote 125 GeV state as "H" (not "h") and will clarify whenever referring explicitly to heavy Higgs instead

Combination of channels

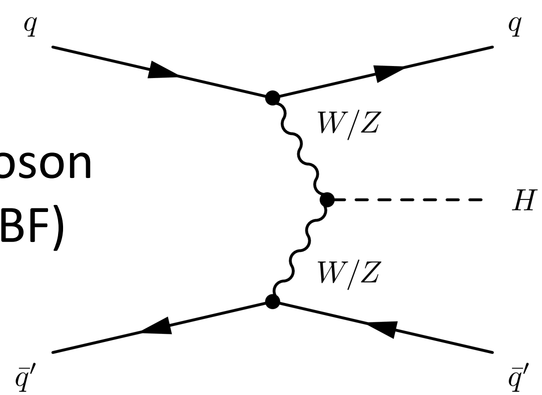
- Combined fit of measurements from all major Higgs production and visible decay modes measured by ATLAS and CMS
  - Include numerous correlations in theory uncertainties, background estimates, experimental systematics, etc (4200 nuisance parameters)
- Production modes mediated by fermions (ggF, ttH) or vector bosons (VBF, VH)
- Measure rates in "units" of SM value: $\mu_i = \sigma_i / \sigma_{i\,,\,SM}$ (SM: μ_i=1)
- Measure couplings in "units" of SM value: $\kappa_i^2 = \sigma_i / \sigma_{i\,,\,SM}$ (SM: κ_i=1)



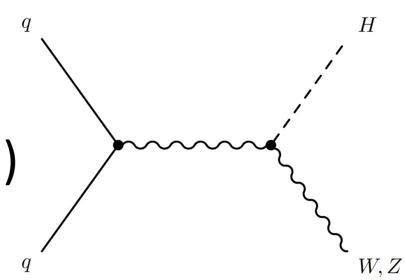
Gluon fusion (ggF)



ttbar associated (ttH)



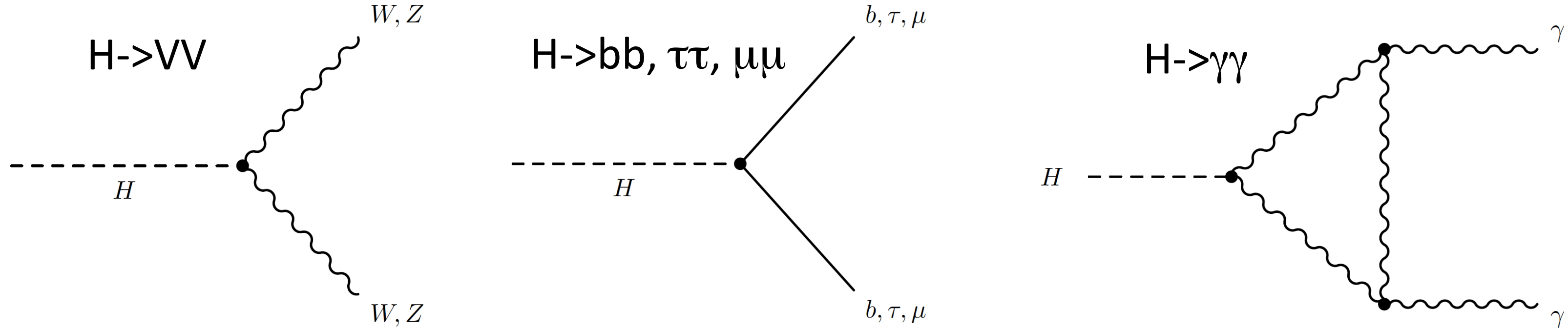
Vector boson fusion (VBF)



Vector boson associated (VH)

From rates to couplings

- Similarly for branching ratios in main decay modes γγ, ZZ, WW, ττ, bb, μμ



- Total width characterized with scale factor: $\kappa_H^2 = \Sigma\, \kappa_i^2 / (1 - B_{BSM})$
  - B_{BSM} is BR for BSM (invisible or undetected) decays
- Example:

$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- Photon and gluon loop-induced couplings can be resolved if desired:

$$\kappa_\gamma^2 = 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

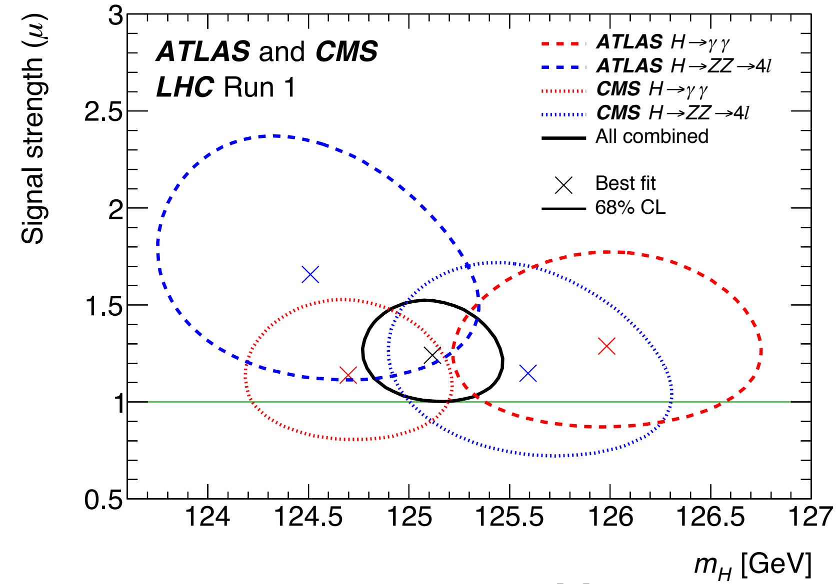
- Relations would be modified if new particles like stops, staus, etc enter loops, so can also consider κ_g and κ_g as "effective" couplings to be less model-dependent

Mass

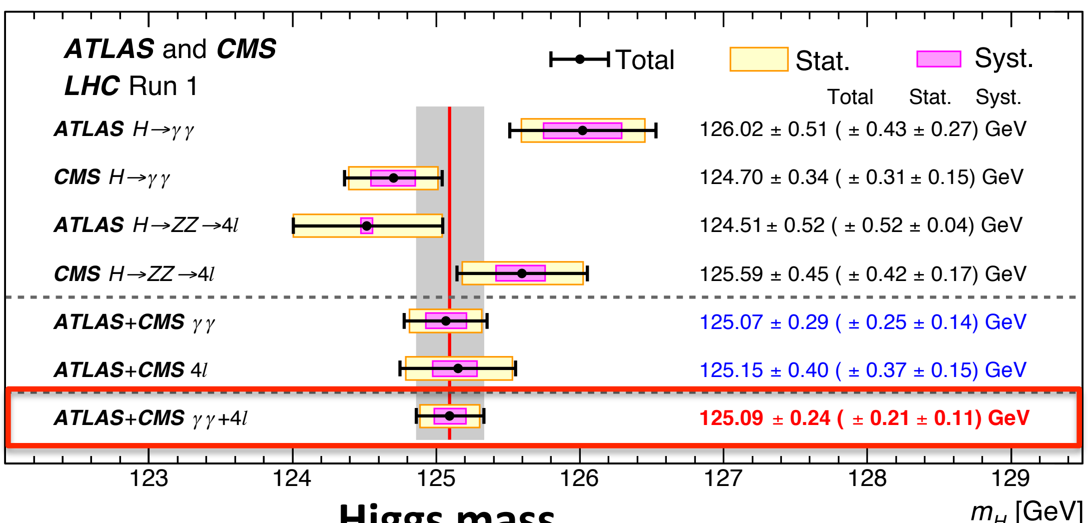
- ATLAS + CMS combined mass measurement: **m_H = 125.09 ± 0.24 GeV**
- Using high-resolution H->γγ and H->ZZ->4l channels

PRL 114 (2015) 191803

Rate



Mass



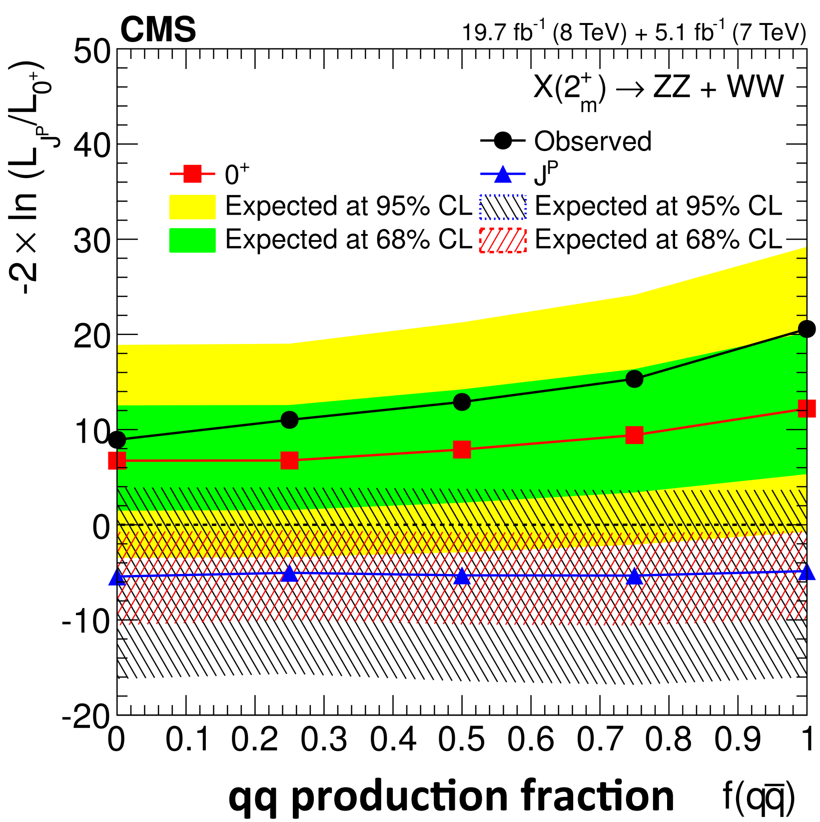
Higgs mass

- Statistical uncertainty still dominates and can be further reduced in future

Spin and parity

- Various spin-2 and spin-1 models, as well as a large pseudoscalar fraction, in H->VV decays are independently disfavored by both CMS & ATLAS data
- Thus in couplings analysis, assume single narrow spin-0 CP-even resonance with mass of 125.09 GeV

PRD 92 (2015) 012004



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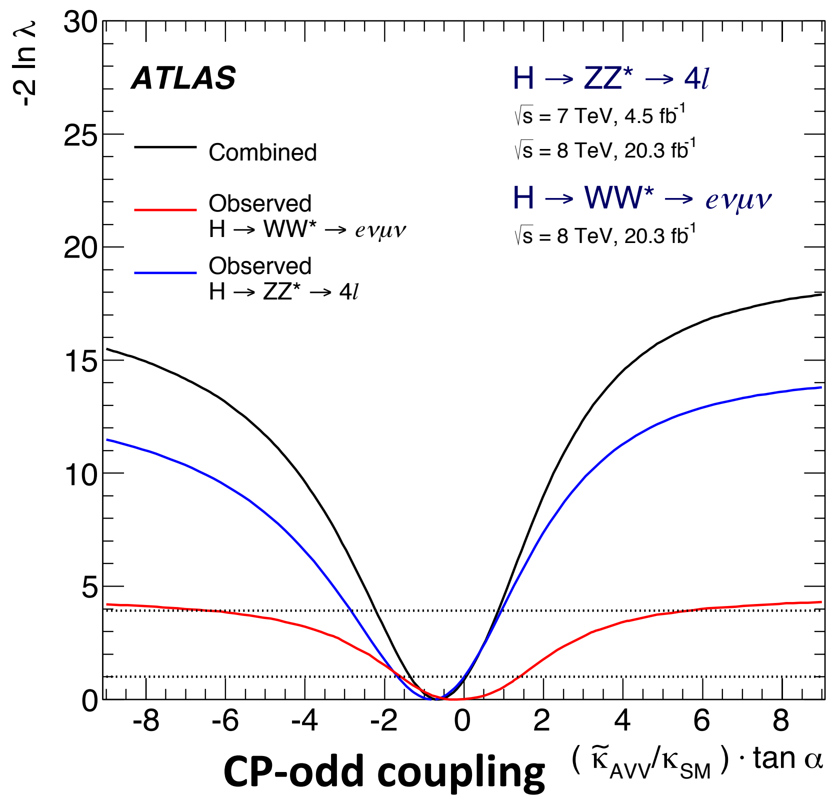
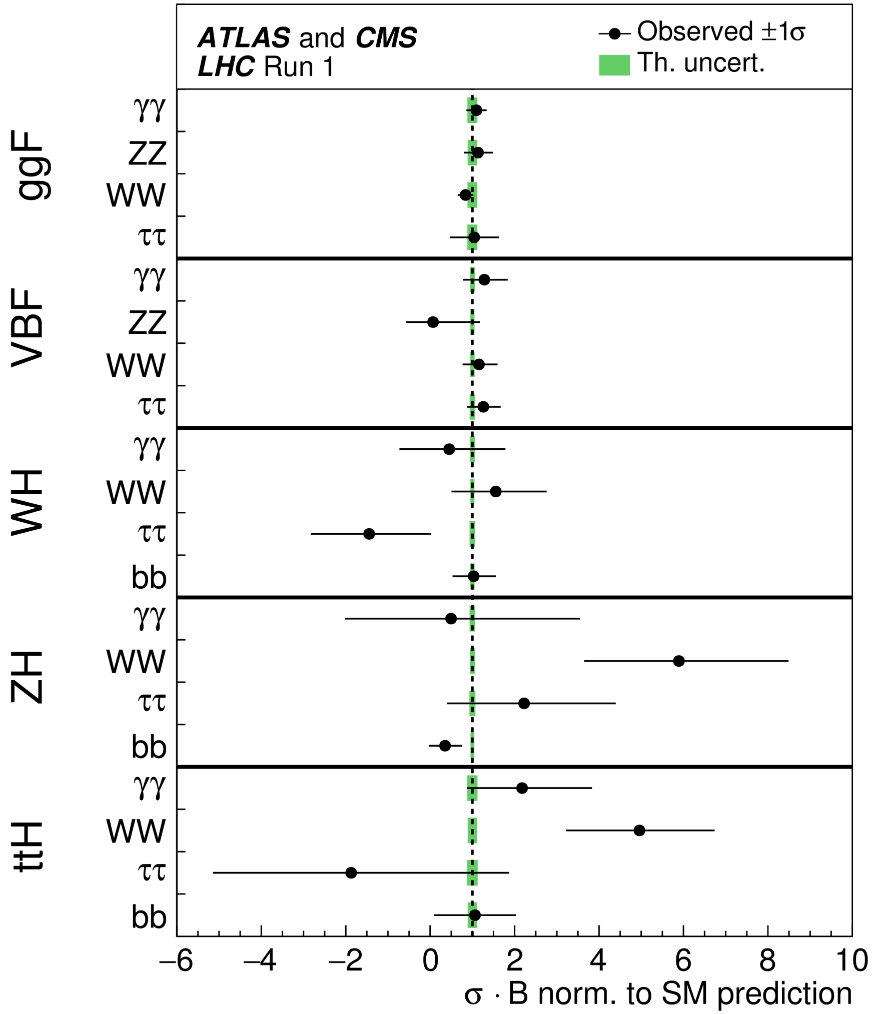


Production and decay rates

- No significant deviation in rates observed in any individual channel of production and decay
  - Mild excesses for ttH (multileptons) and ZH in decay modes with large statistical uncertainties
- Gluon fusion measurements, e.g. in H->WW decays, starting to approach SM theory uncertainties
  - Overall measured rate for Higgs production and decays dominated by theory uncertainty on inclusive cross-section



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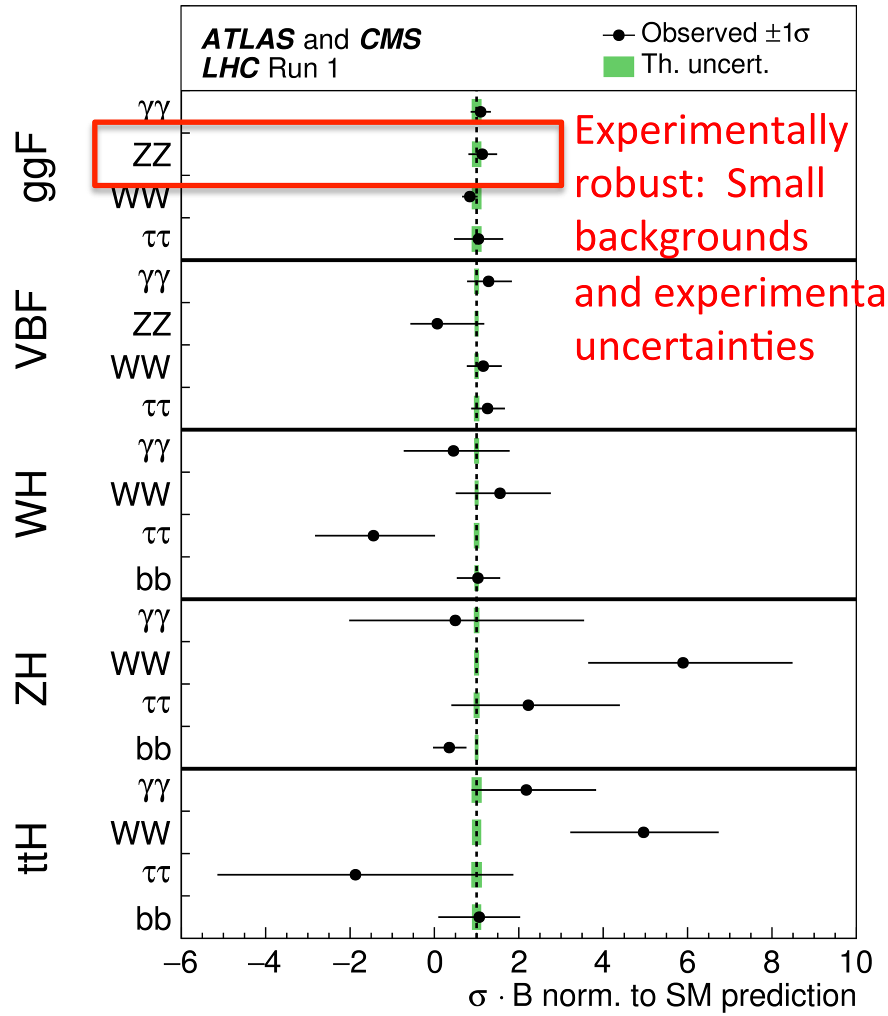
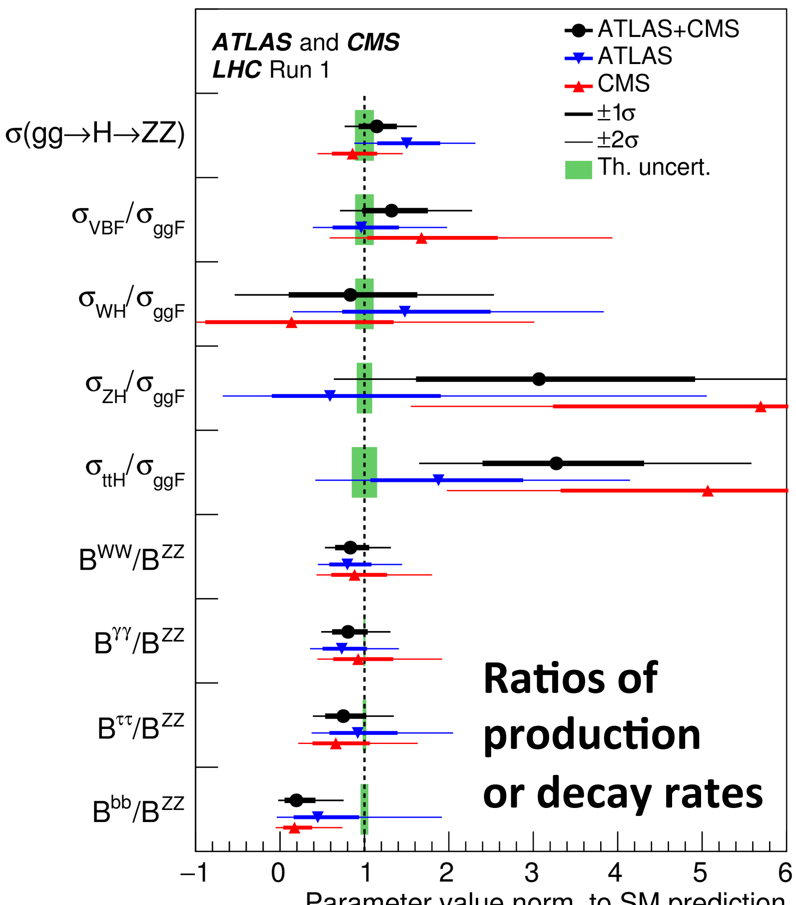


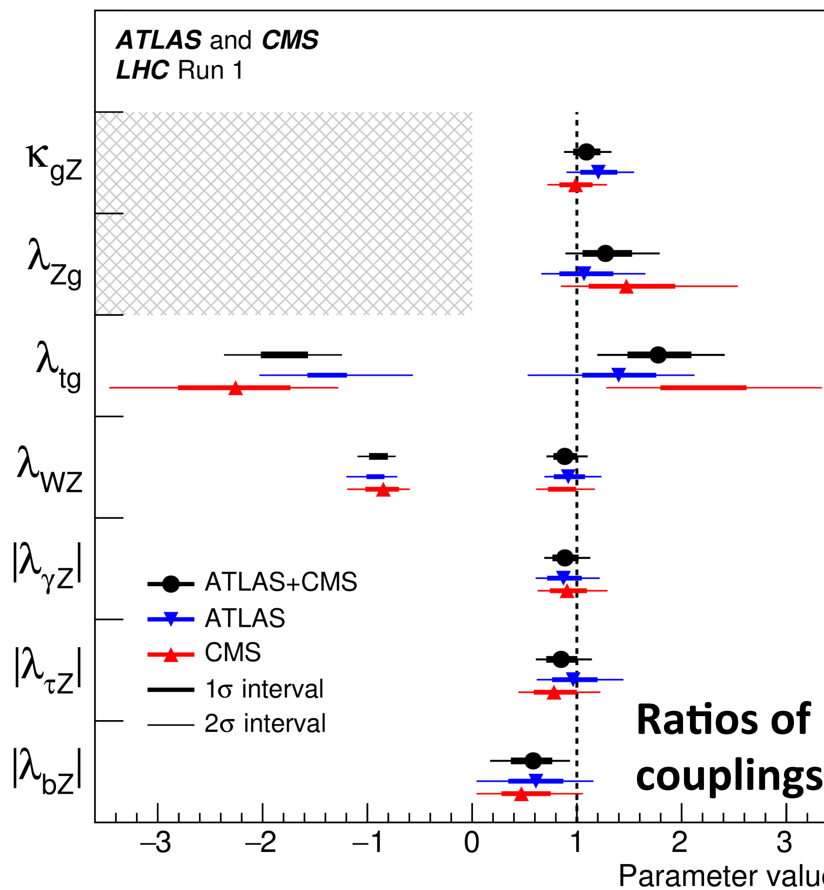
Production & decay rate

Ratios of rates or couplings

- Treat all production & decay rates independently to minimize model dependence
  - Measured ratios of them wrt σ(ggF) and BR(H->ZZ) to cancel out systematic uncertainties: consistent with SM, again with large stat. unc. in ttH and ZH
- Re-fit fewer couplings to actual particles as ratios to Z and gluon, $\lambda_{ij} = \kappa_i/\kappa_j$

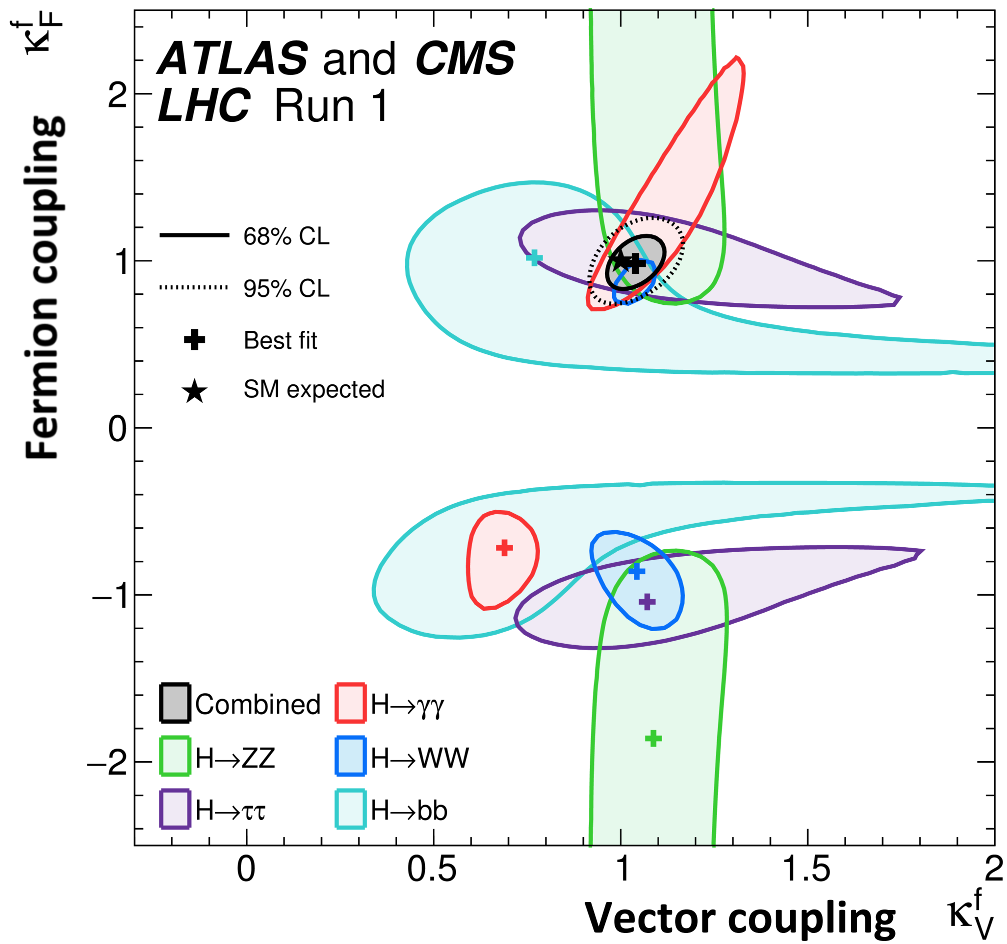


Refit



Vector and fermion couplings

- Simple parametrization $[\kappa_V, \kappa_F]$ with unified couplings to vectors (W, Z) or fermions (t, b, τ, μ)
  - Probes Two-Higgs-doublet-model (2HDM) Type I i.e."Fermiophobic"
  - Fewer parameters enables higher-precision test
- No deviation observed wrt SM
- H->$\gamma\gamma$ channel provides sensitivity to relative sign of vector and fermion couplings through interference of loops in decays to photons



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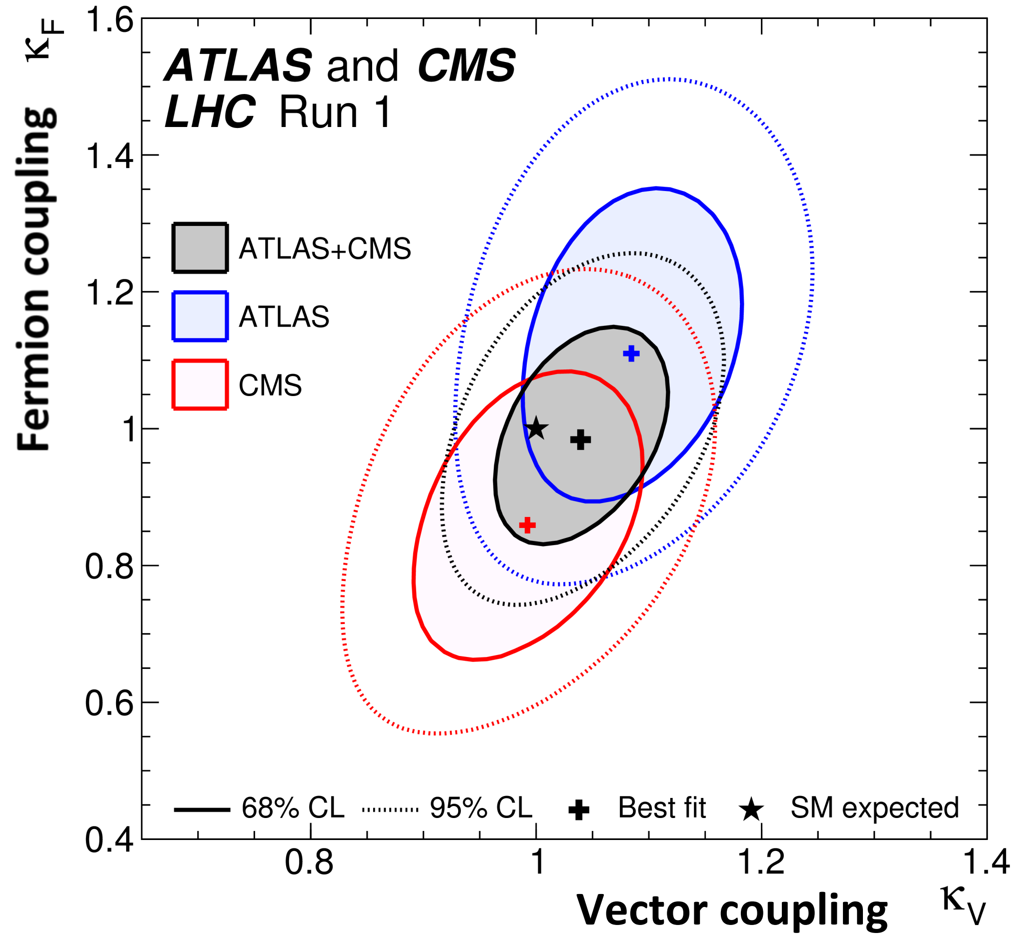
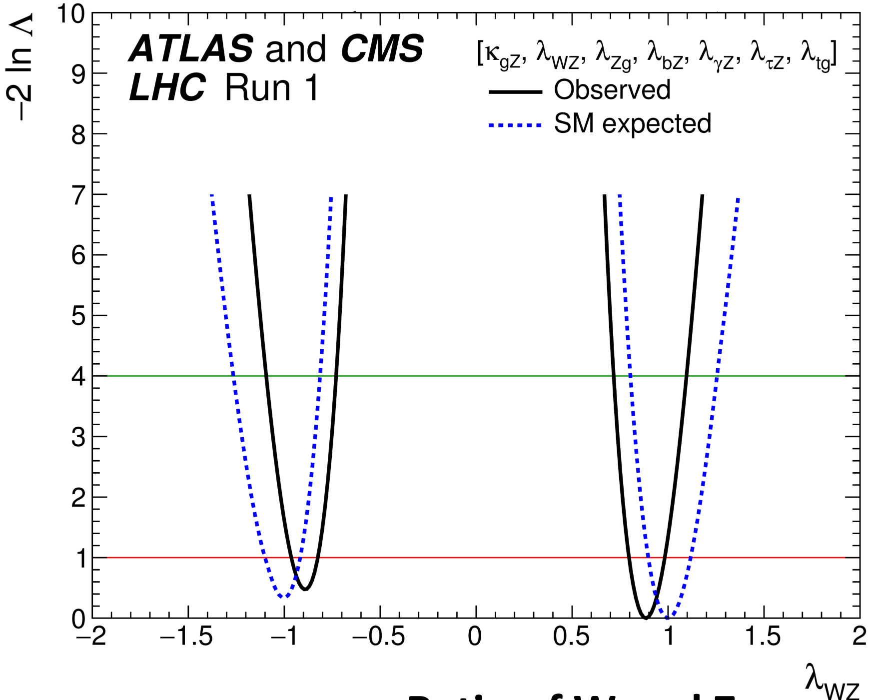


Weak boson couplings

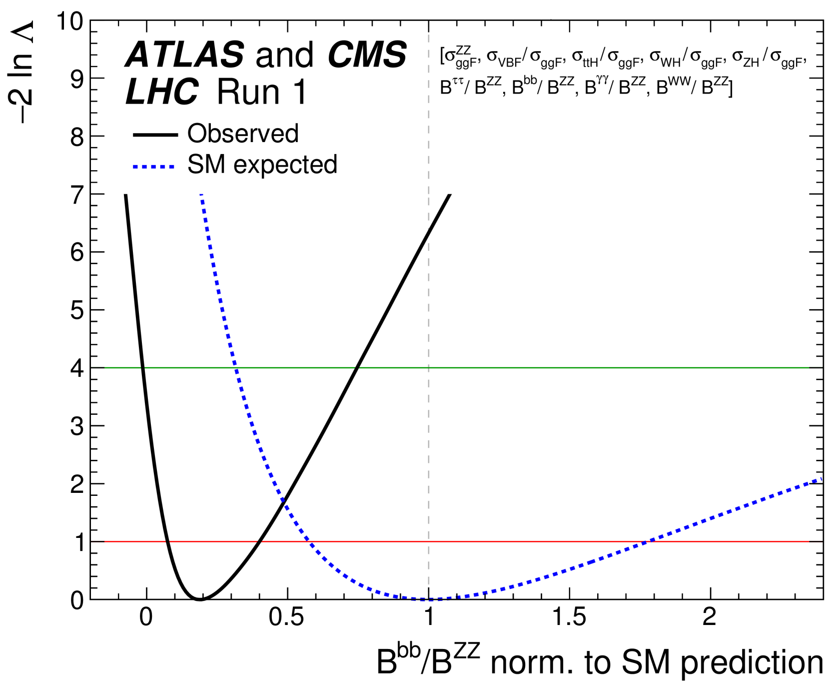
- In MSSM (or more generally, 2HDM Type II) W and Z couplings can be reduced away from "alignment limit" of SM-like couplings
- Ratio of W and Z couplings consistent with SM when tested with ~10% precision
  - Compatible with alignment, but need not imply that additional Higgs bosons are very heavy (decoupling limit)
- No deviation in absolute W and Z couplings either



Ratio of W and Z couplings

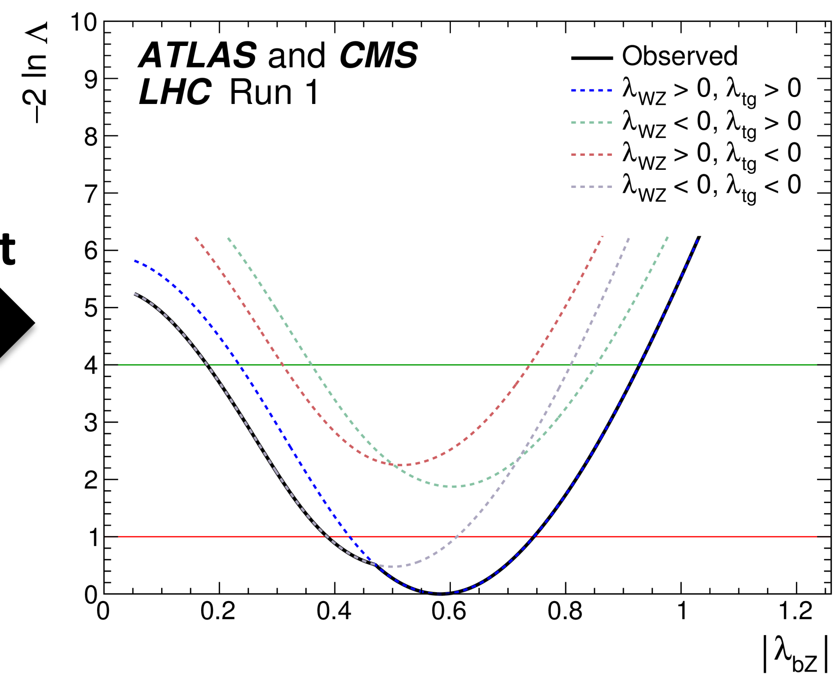
b-quark coupling

- At large tan β, large enhancements to b-quark, τ, and muon couplings
- Measured ratio B(H->bb)/B(H->ZZ) using independent production & decay rates to reduce model dependence as before
    - *Smaller* than expected, but consistent with SM within about 2.5σ
- After relating couplings to particles (fewer parameters), re-fit ratio of b-quark and Z couplings shows similar agreement with ~25% frac. unc.
- Higher-precision tests possible by reducing parameters further as follows



Ratio of BRs to bb and ZZ

Refit

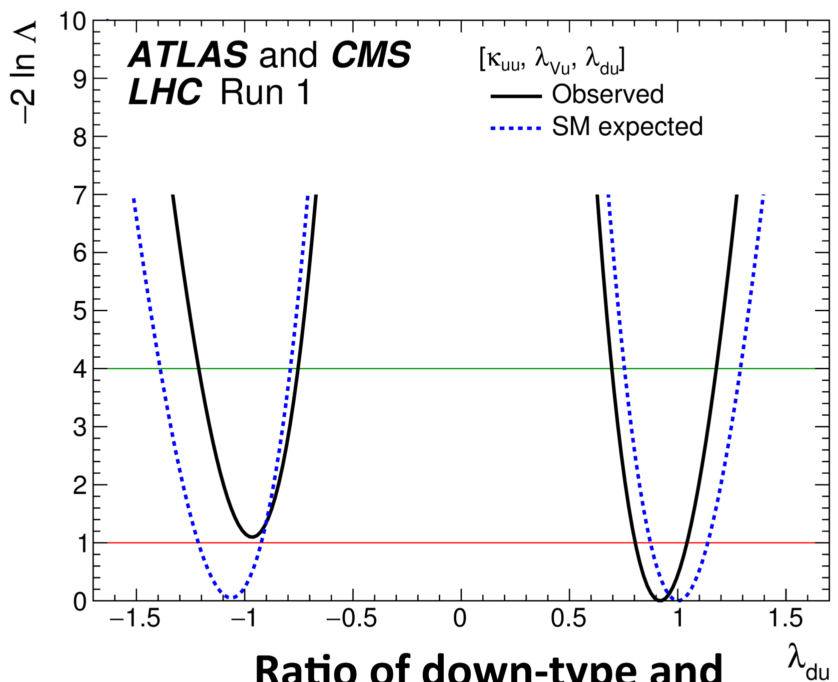


Ratio of couplings to b and Z

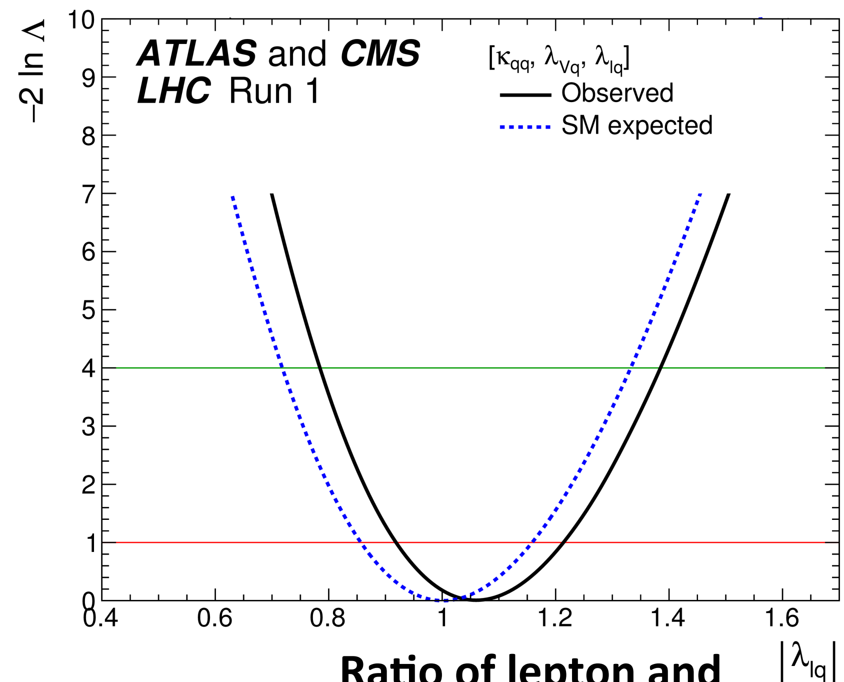
Fermion couplings

- In MSSM / 2HDM Type II [κ_V, κ_d, κ_u], ratio of down-type (b, τ, μ) and up-type (t) fermion couplings is tested with ~10% precision
- No enhancement observed wrt SM, i.e. consistent with alignment limit

- In 2HDM Lepton-Specific [κ_V, κ_l, κ_q], ratio of lepton (τ, μ) and quark couplings (t, b) would be enhanced at large tan β
- Also good agreement with SM



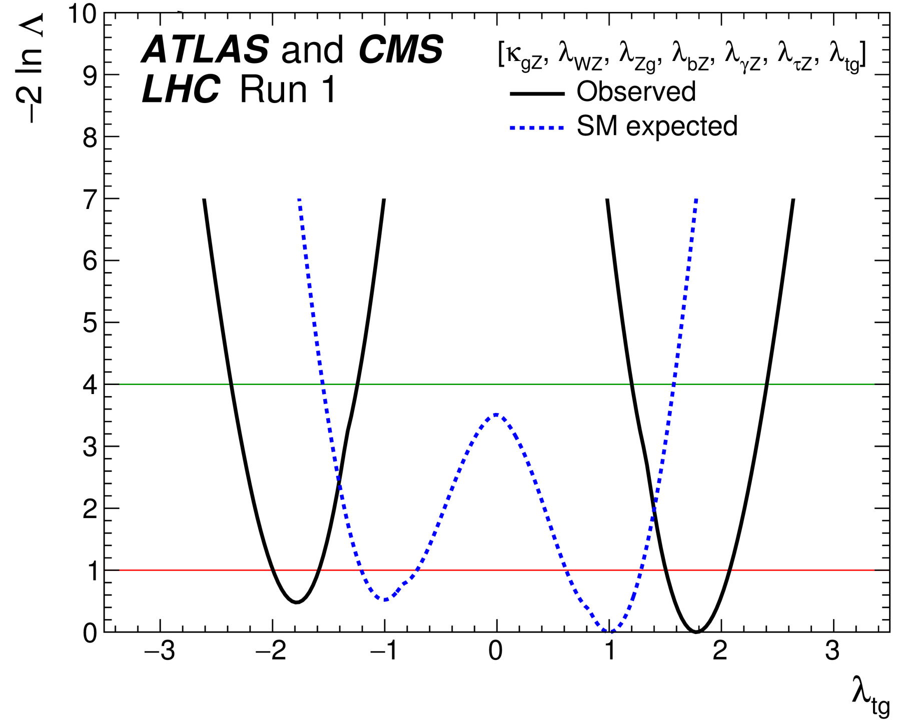
Ratio of down-type and up-type fermion couplings



Ratio of lepton and quark couplings

Resolving the gluon fusion loop

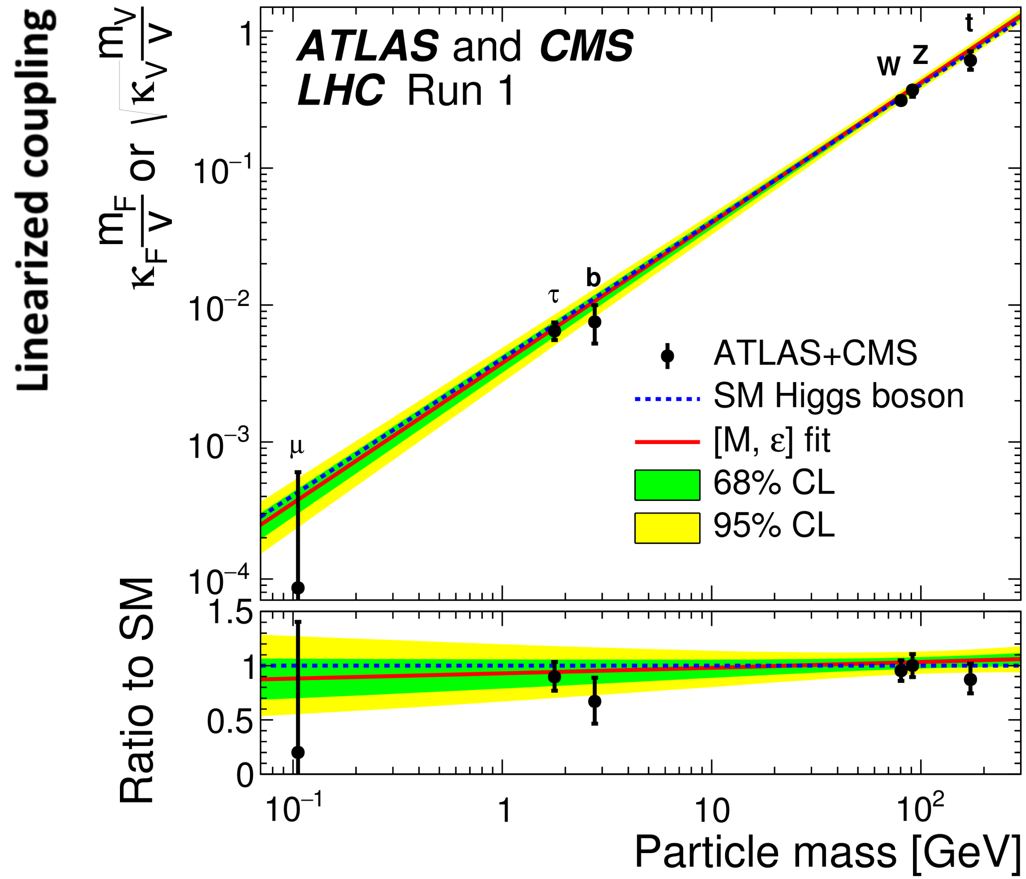
- Light stops, sbottoms, etc can enhance gluon fusion production (and also H->gg decays) via loops
  - Absorb into effective coupling to gluons, κ_g
- Ratio of direct top (ttH) and loop-induced gluon (ggF) couplings, with latter dominated by top in SM
  - Mild *excess* wrt SM (MSSM predicts deficit), but again consistent within uncertainties
  - Very mild preference for relative sign of top quark and gluon couplings from tH and gg->ZH
- Again precision could be improved by tailoring parameters to specific models



Ratio of top and gluon couplings

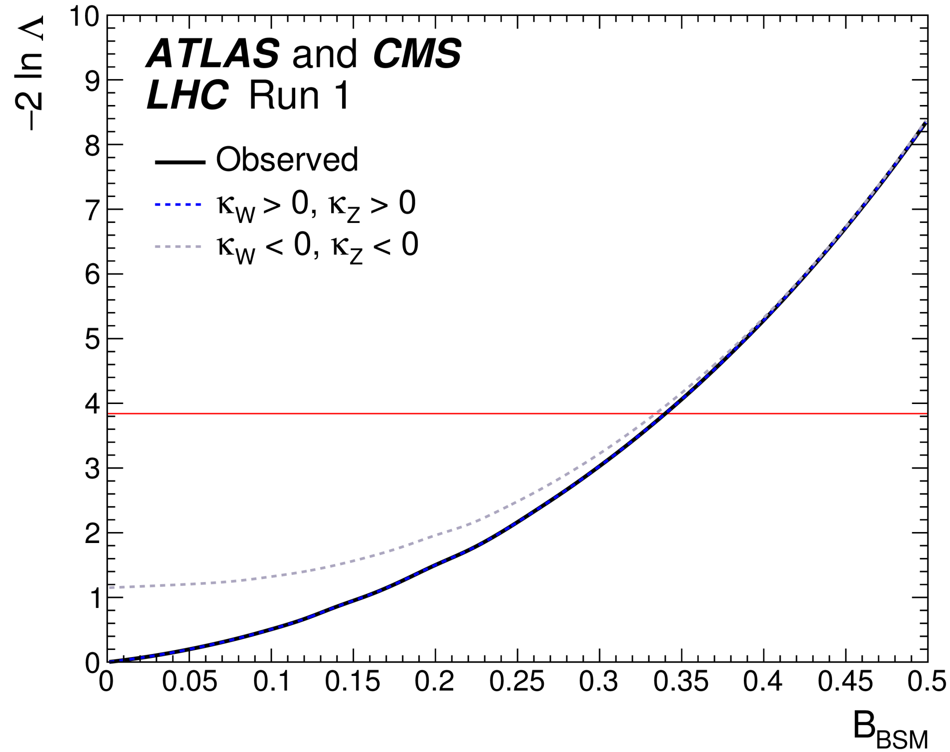
Coupling vs. mass

- Linearized couplings to massive particles, with resolved loops to g and γ
- Test non-linearity ε and "VEV" normalization parameter M (SM: ε=0, M~246 GeV)
- All measurements are consistent with mass dependence expected for SM-like Higgs boson



Invisible or undetected decays

- Higgs boson may decay invisibly to LSP e.g. lightest neutralino, a dark matter candidate
- Branching ratio for invisible or "undetected" (typically due to low signal-to-background, e.g. H->cc) decays can be tested assuming $|\kappa_V| \leq 1$, which is satisfied in MSSM at tree level
  - No excess observed: $B_{BSM} < 34\%$ at 95% CL
- Taking $|\kappa_V| \leq 1$ or $B_{BSM} = 0$, all absolute couplings consistent with SM



BR for BSM decays

Conclusions and outlook

- Final combined ATLAS+CMS Run 1 measurements of Higgs boson couplings submitted to JHEP in arXiv:1606.02266
  - Precision usually better by ~1/√2 wrt single experiment
  - Gluon fusion measurements approaching precision of SM theory predictions in some cases
- All rates of Higgs production and visible/invisible decay, couplings, and ratios are consistent with SM within 2.5σ or less
  - But plenty of Higgs coupling parameter space left for BSM deviations in future, which in SUSY are often expected to be small
- Significantly higher precision in many channels, particularly ttH and VH production, anticipated with higher-energy 13 TeV data
  - Run 2 data flowing in rapidly, so stay tuned for exciting updates on future Higgs property measurements!

EXTRA SLIDES