Higgs Boson fermionic production and decay modes with the ATLAS detector

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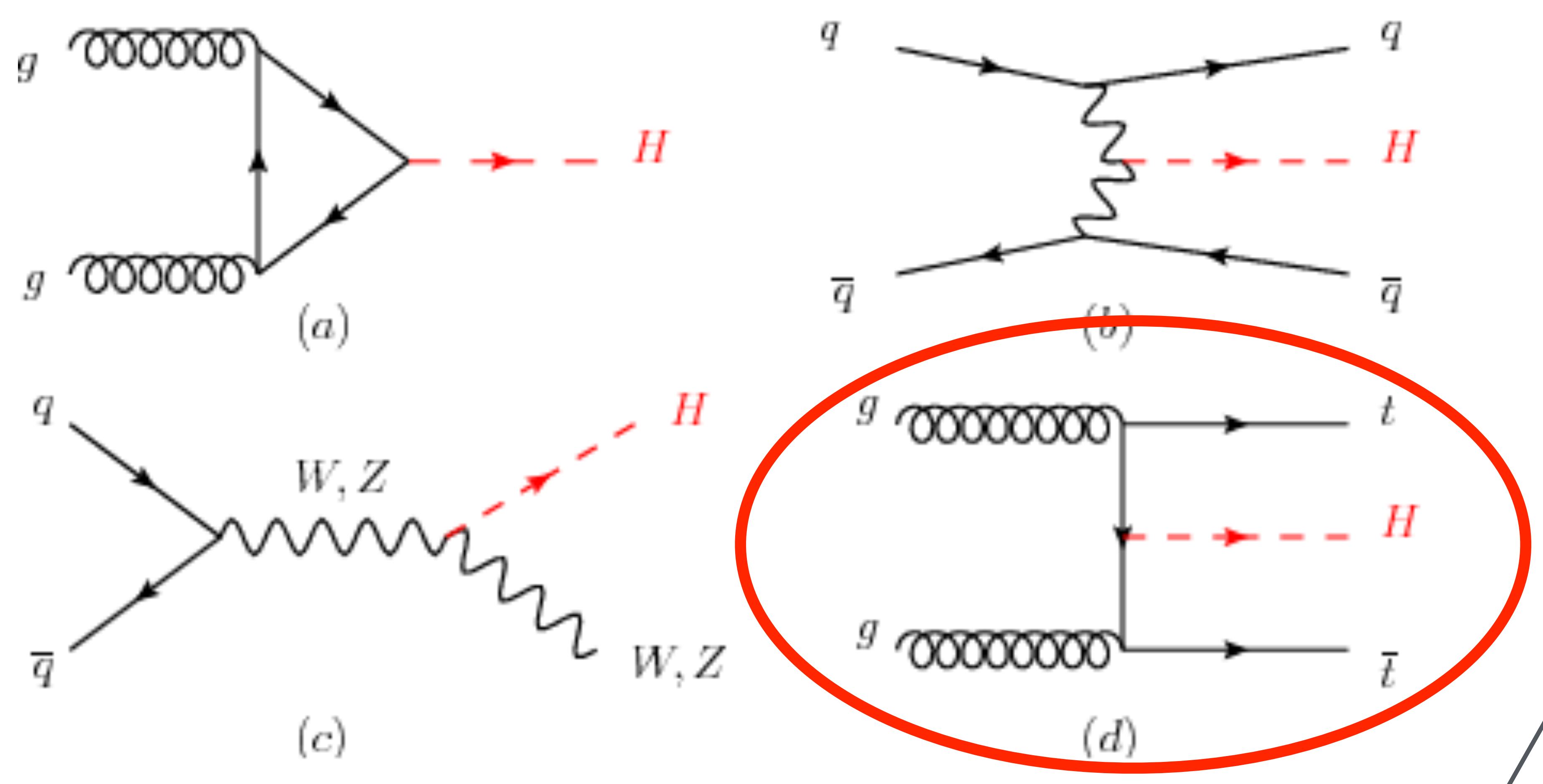
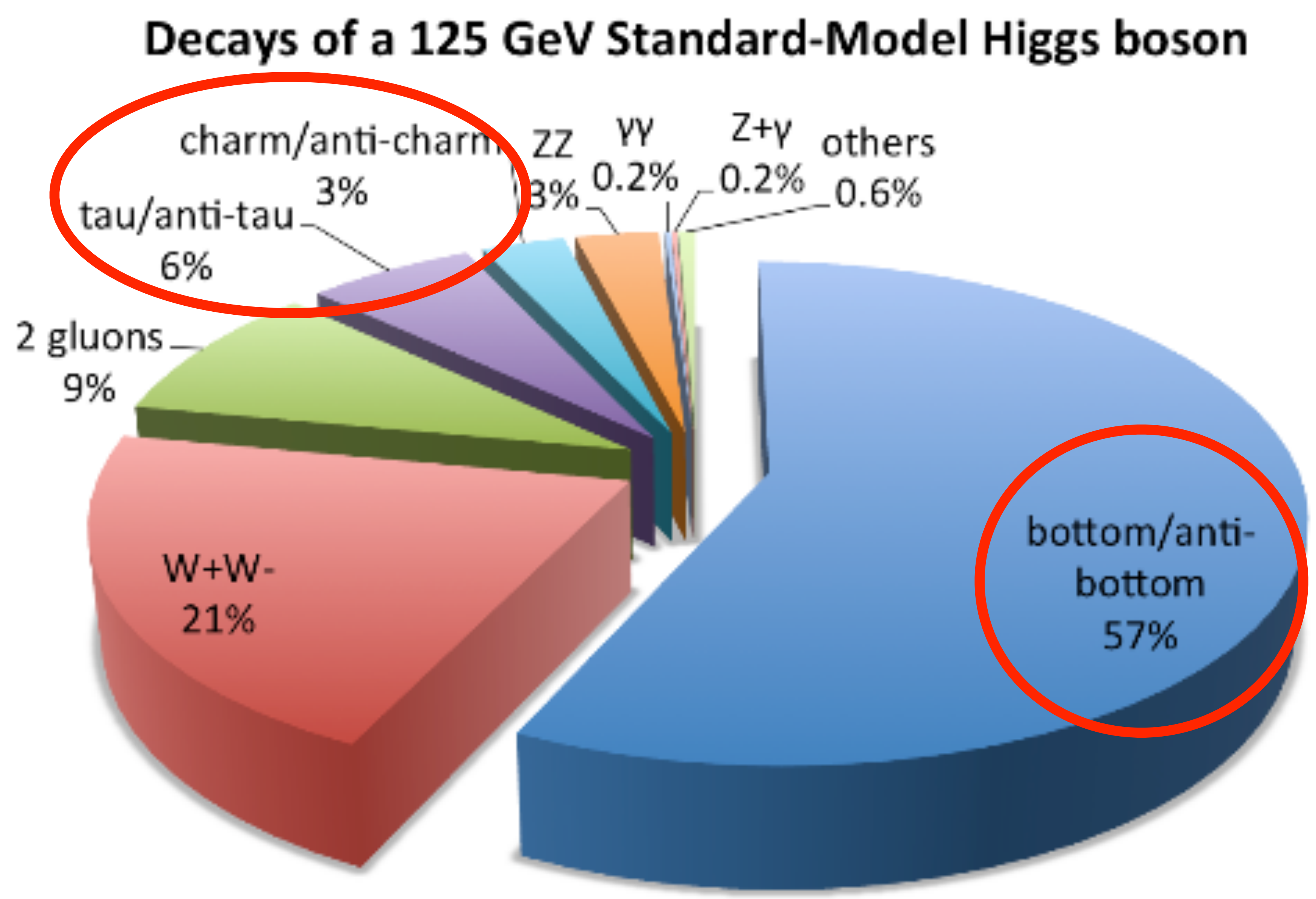
SM HIGGS FERMIONIC PRODUCTION AND DECAY

- Fermionic production: ttH, $\sigma_{SM}(ttH)$ = 507 (+35,-50) fb
  - See Roberto di Nardo's talk for ttH observation!
    - Observed σ(ttH) = 670 fb; combined 6.3σ excess

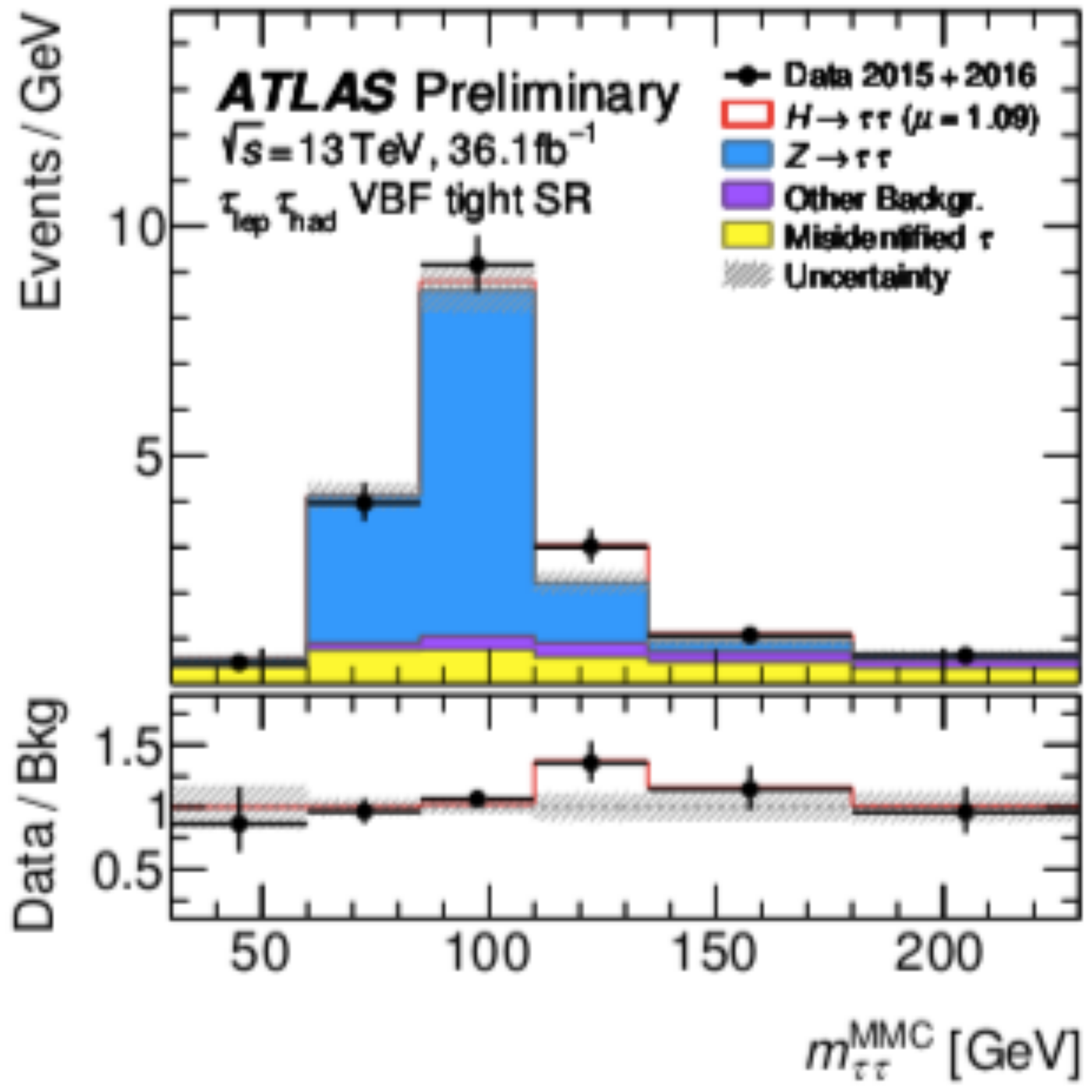




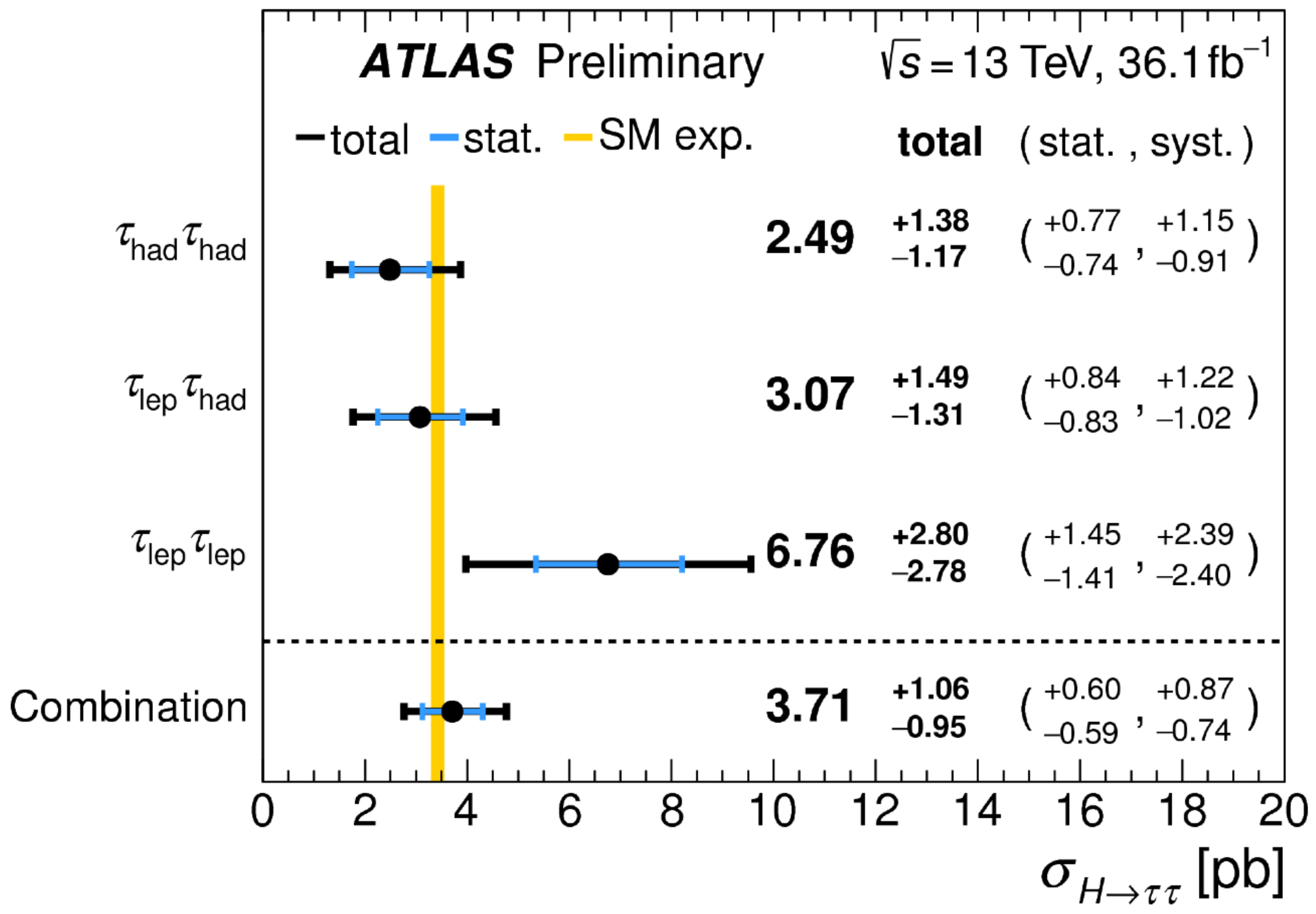
- Decays useful for studying couplings directly
  - At ATLAS, Higgs—>: bb, cc, ττ, μμ

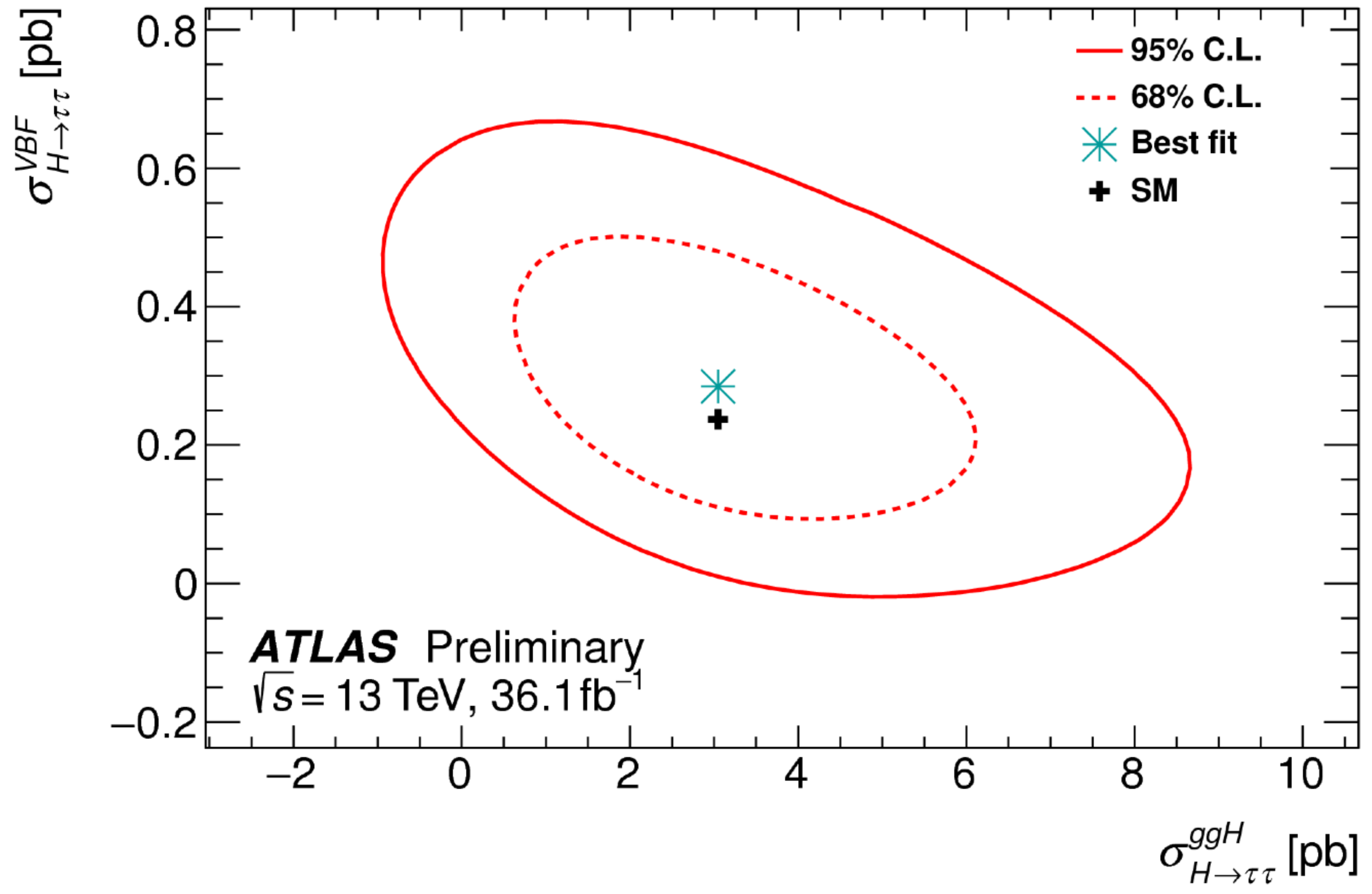
HIGGS LEPTON DECAYS: H—>ττ

- Analysis strategy—separate events based on
  - Leptonic or hadronic decays of tau's (ll, lh, hh)
  - Higgs production (VBF, boosted ggF)
  - Further separation based on $p_T^{\tau\tau}$, $\Delta R_{\tau\tau}$, (and m_{jj} for VBF)
- Simulation and data-driven background estimation techniques
  - Main backgrounds: Z—>ττ, mis-ID'd τ's (multijet, W+jets), top, Z—>ll
- Final discriminant: SR di-tau invariant mass distributions as input to final likelihood fit for total H—>ττ cross section



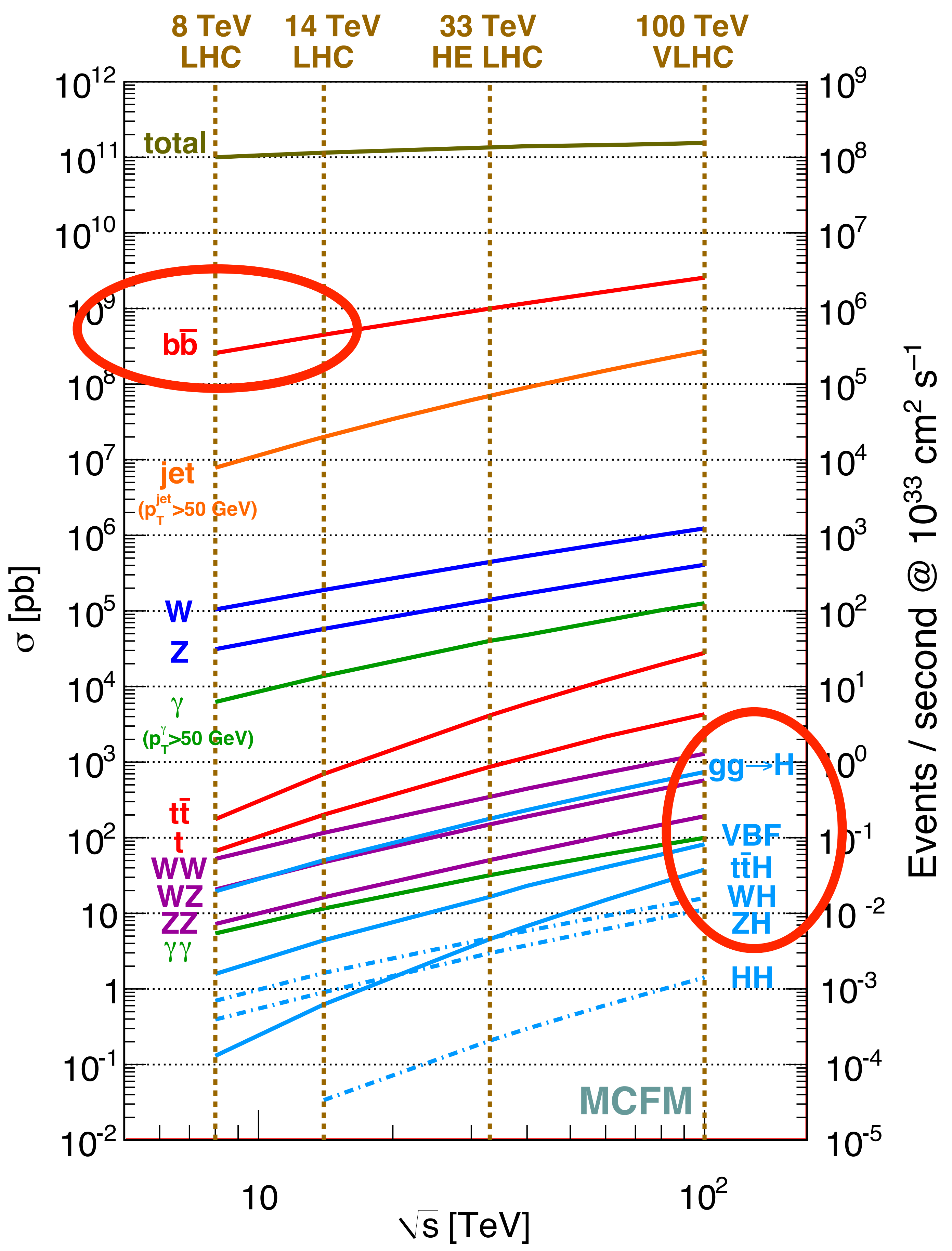
H—>ττ Results

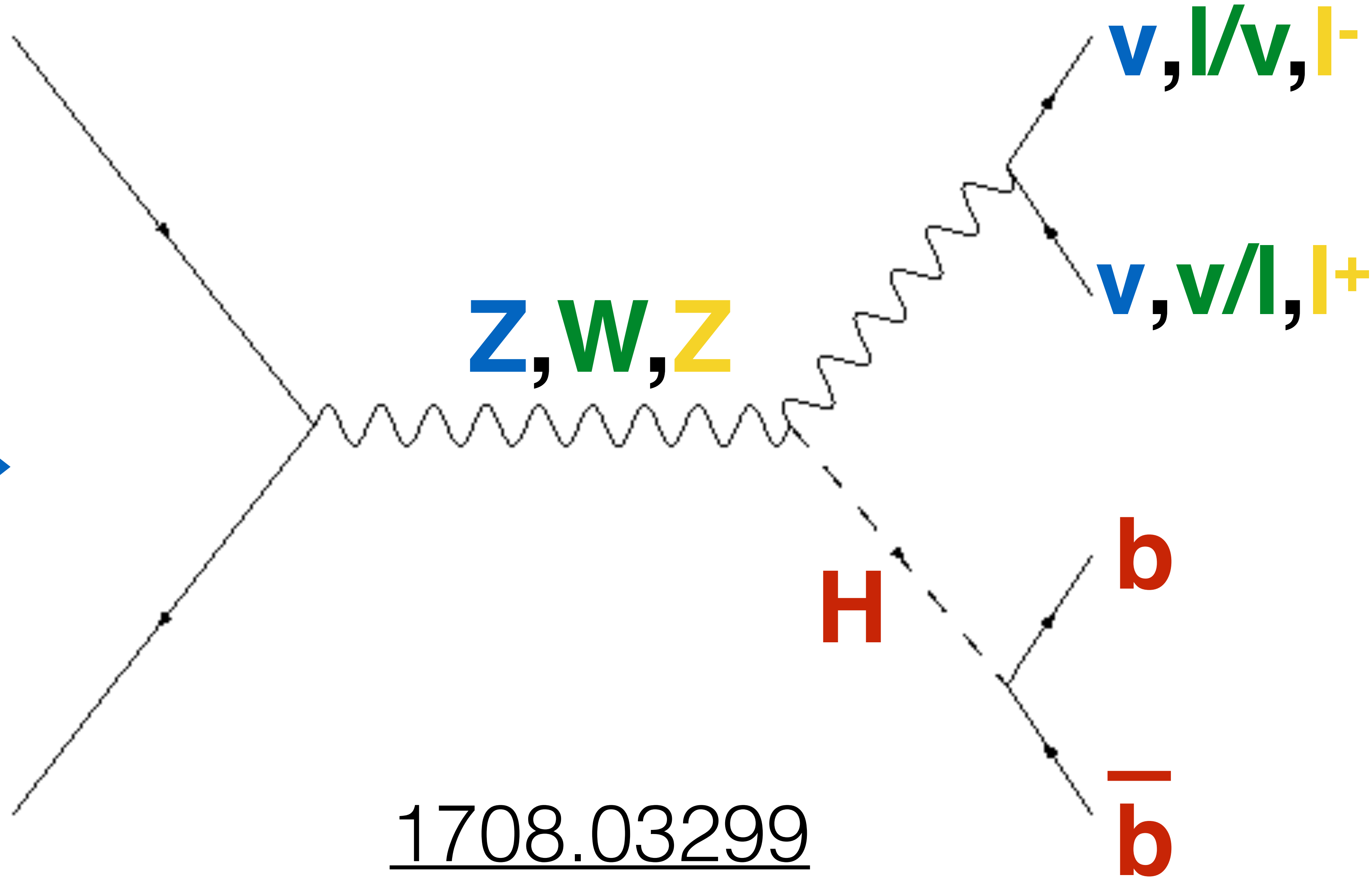




- Total σ(pp—>H—>ττ) = 3.71 (±0.59; stat) (+0.87,-0.74; syst) pb
    - Uncertainty is systematics dominated
        - Signal theory (+14%,-9.0%), BG stats (+11%,-10%), JetEtMiss (+12%,-9%)
    - ggF σ(H—>ττ) = 3.0 pb; VBF σ(H—>ττ) = 0.28 pb
- Combined with Run 1: 6.4σ (5.4σ) observed (expected) excess; observation of H—>ττ!

HIGGS QUARK DECAYS: VH(BB)





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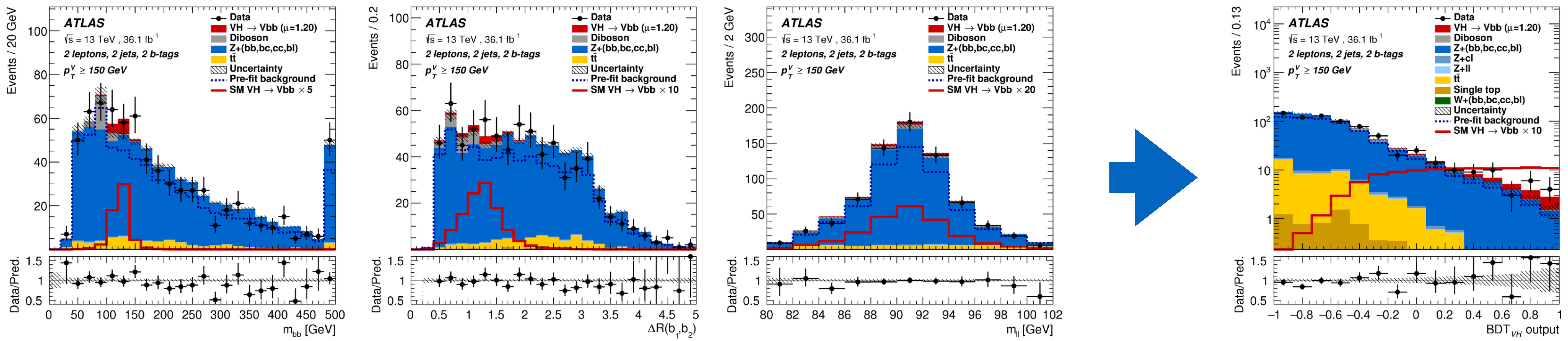
- Next highest Yukawa coupling is to b-quarks
- Focus on VH with leptonically decaying V for trigger/ background suppression
  - Clear signature, no combinatoric ambiguity
  - Good for searching for Hbb

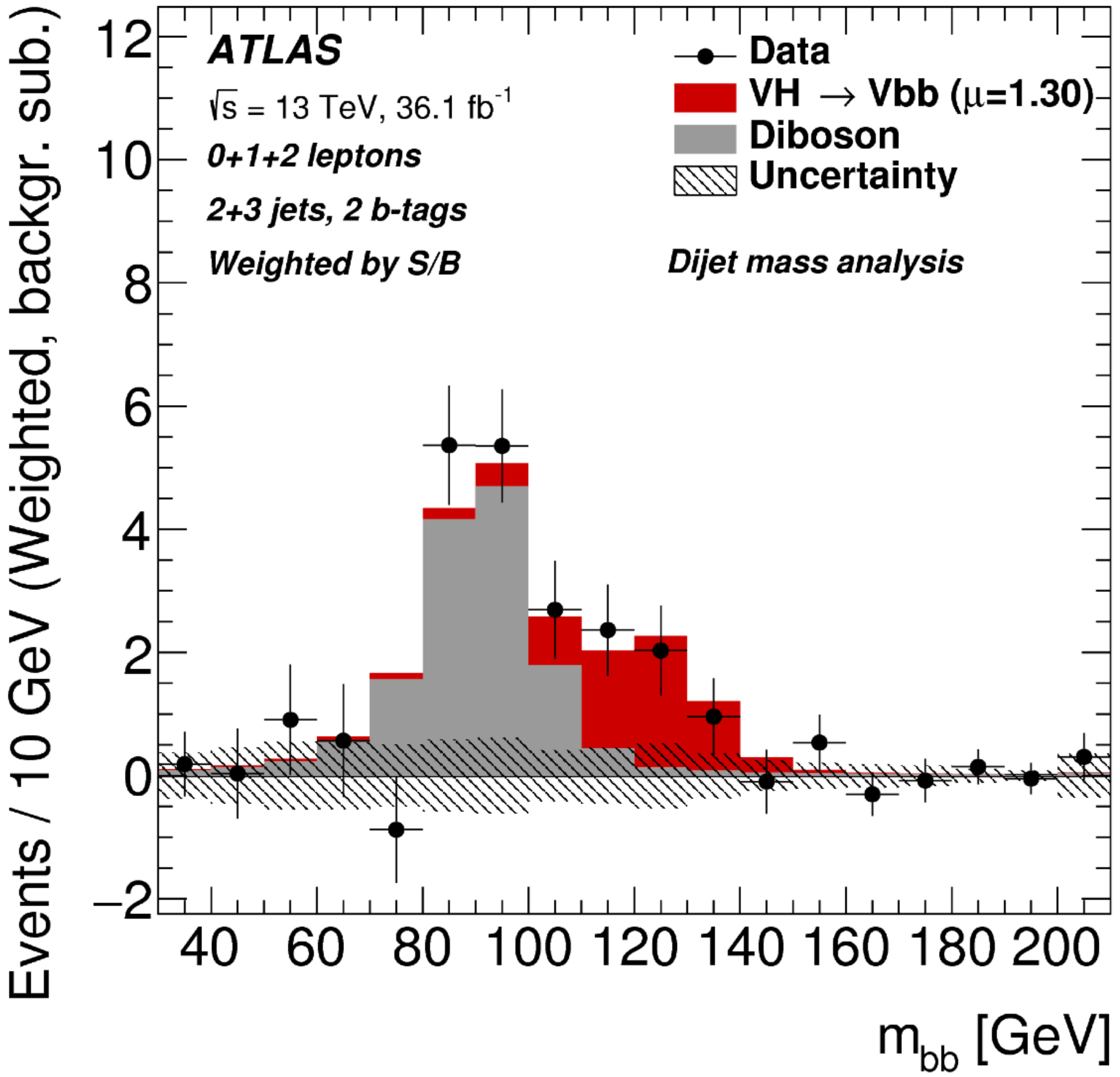
VH(bb) Analysis Strategy

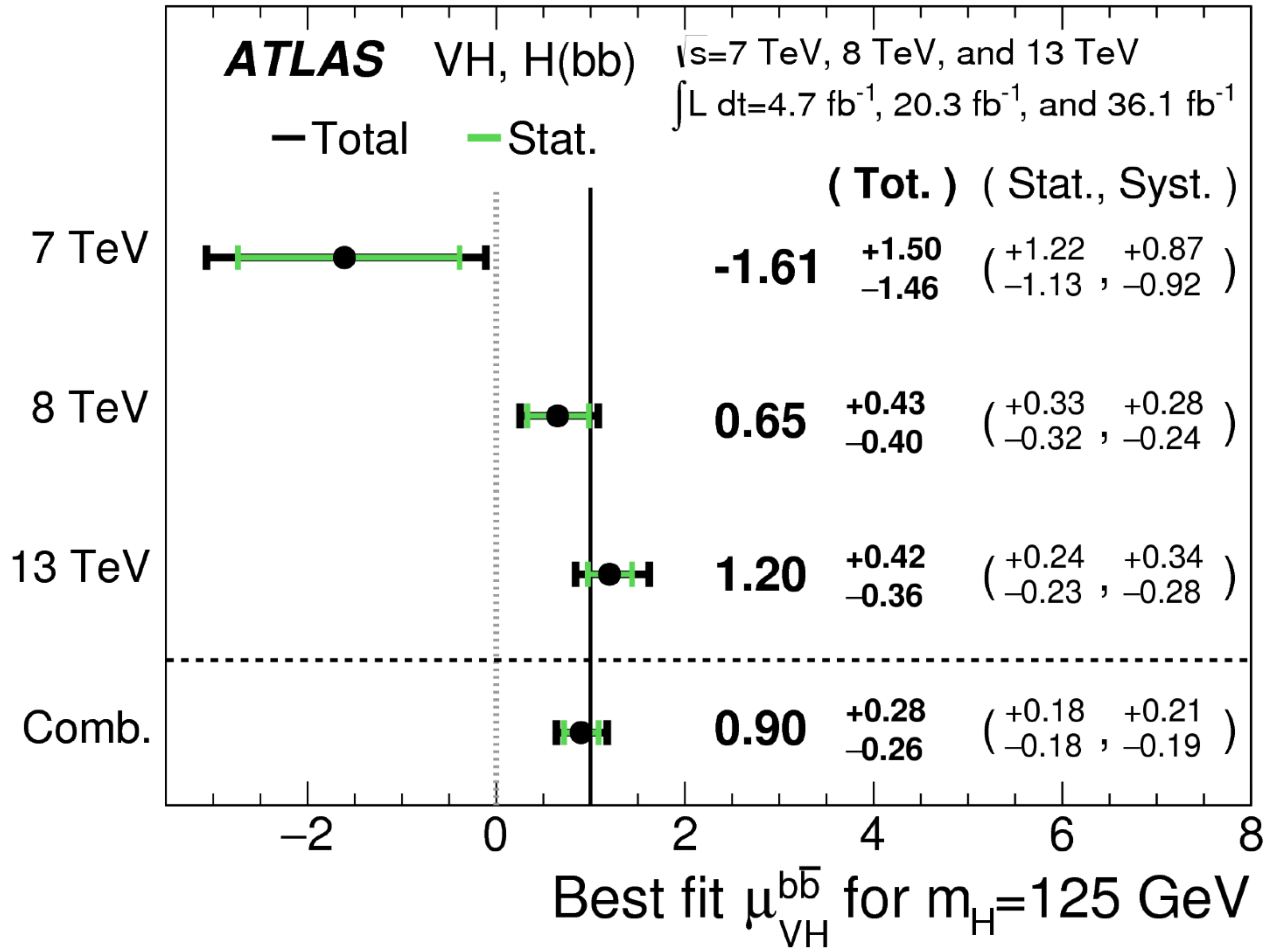


- Signal region selections separated on basis of:
  - Lepton multiplicity in V decay (Z—>νν, W—>lν, Z—>ll) and jet multiplicity
- Main background normalizations are freely floating fit parameters
- Object variables used for fit input BDT's, cross-check by fitting m_{bb} distribution

VH(BB) RESULTS

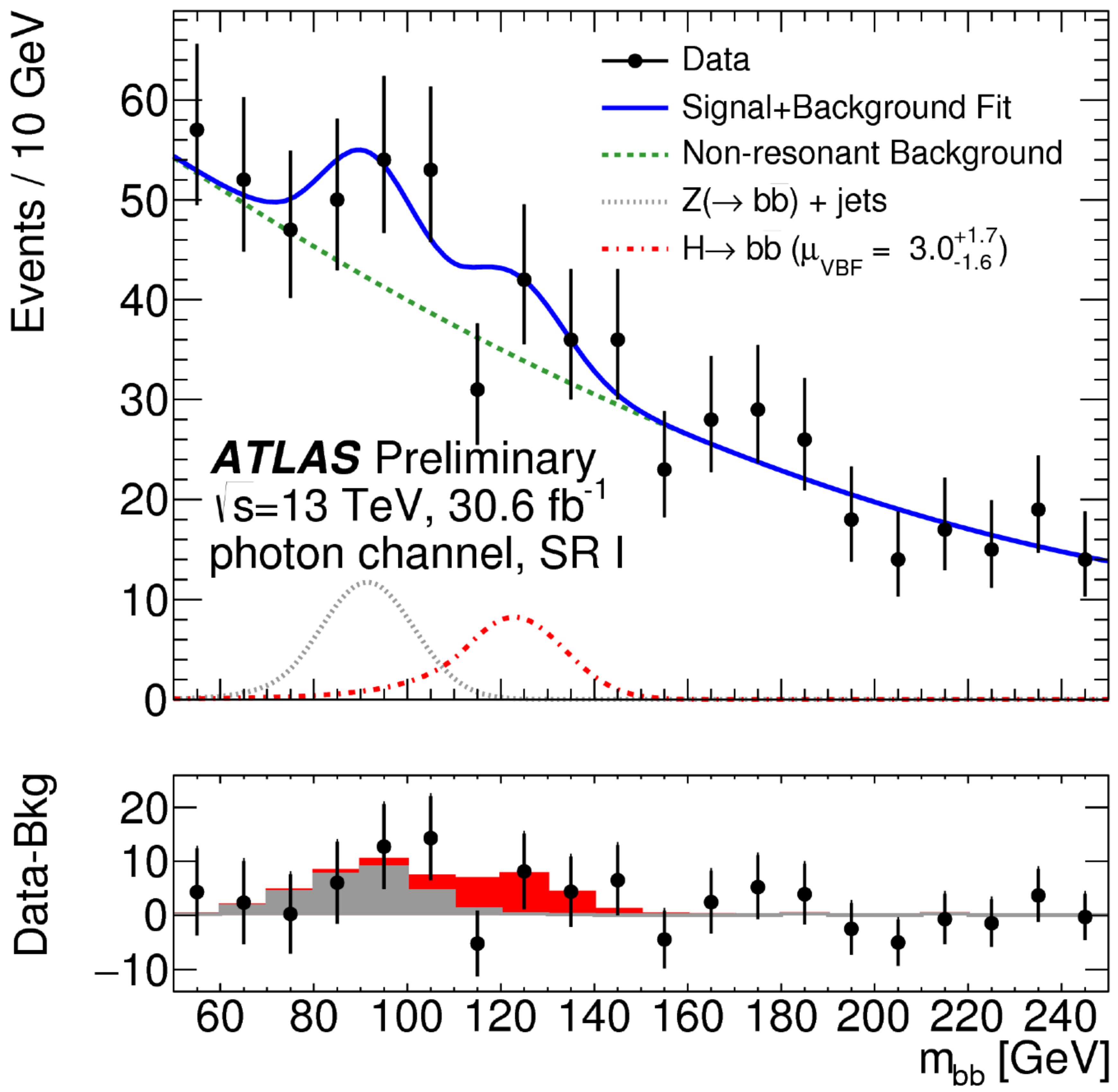
- Run 2 best fit μ=1.2±0.4; corresponds to observed (expected) 3.5σ (3.0σ) excess
  - Signal modeling (0.17), flavor tagging (0.11), also background modeling and MC statistics
- Combine with Run 1 for best fit μ=0.9±0.3; 3.6σ (4.0σ) excess
  - First evidence of Hbb





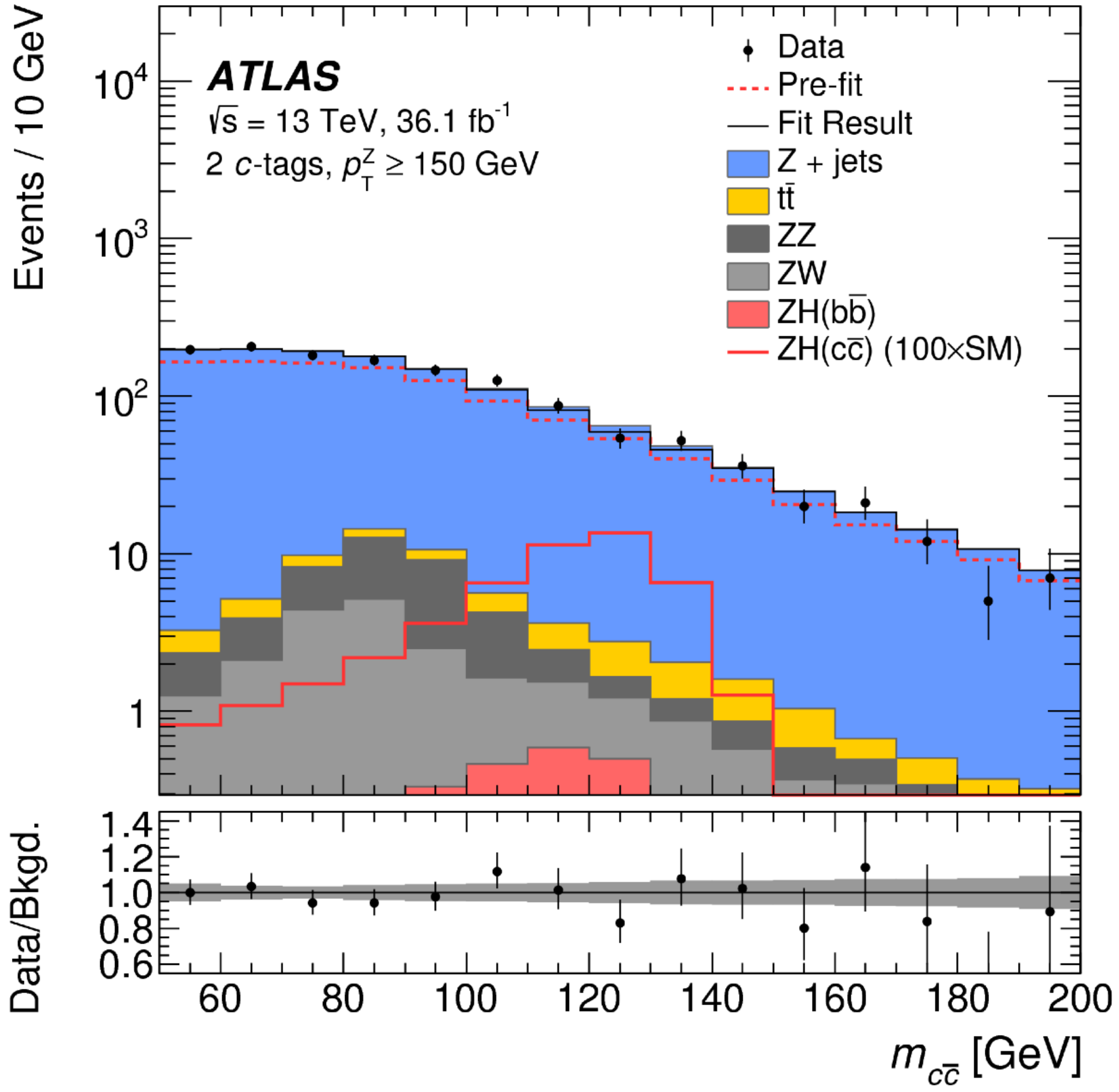
Looking Forward: VBF H(bb)

- Three analysis channels (selections + MVA)
  - All hadronic: two central, four central
  - Associated photon production: cleaner
- SR m_{bb} distributions as input to likelihood fit on signal strength, μ
  - Analytic background models
  - μ_{VBF} = 3.0 (+1.7,-1.6)
  - μ_{H} = 2.7 (+1.4,-1.3)
- No significant excess observed



LOOKING FORWARD: VH(CC)

- Much rarer (~20x) than VH(bb)
  - SM σ(pp—>ZH)xBR(H—>cc) = 26 fb
- Similar strategy to VH(bb) cut-based
  - Charm tagging instead of b-tagging (41% WP instead of 70%)
  - Focus on ZH—>llcc
  - Charm dijet invariant mass is discriminating distribution
- No significant excess
  - 95% CL observed (expected) upper limit on σ x BR of 2.7 (3.9) pb (μ of 110 (150))



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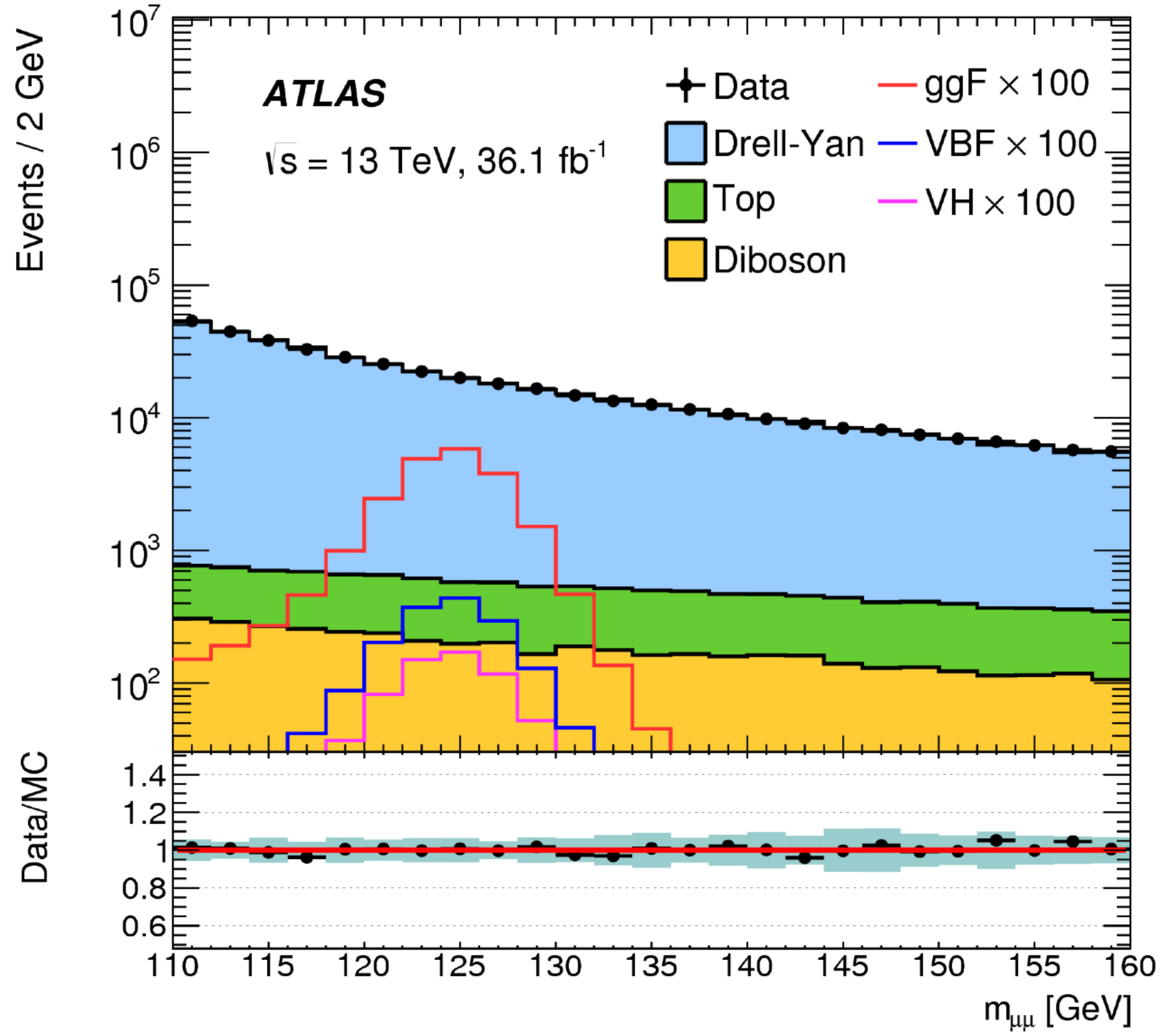
Looking Forward: Higgs to Muons

- Clean, rare (0.022 %) decay
- Analysis strategy:
  - 6 ggF (muon η, pT of dimuon system) + 2 VBF (BDT cut) = 8 SR's
- Analytical $m_{\mu\mu}$ models
  - Main backgrounds: Drell-Yan, top, VV
- Dimuon mass from SR's are likelihood fit input
- No significant excess observed; place upper limit on signal strength, μ
  - 95% CL observed (expected) upper limit 3.0 (3.1)
  - Combine with Run 1: 2.8 (2.9)



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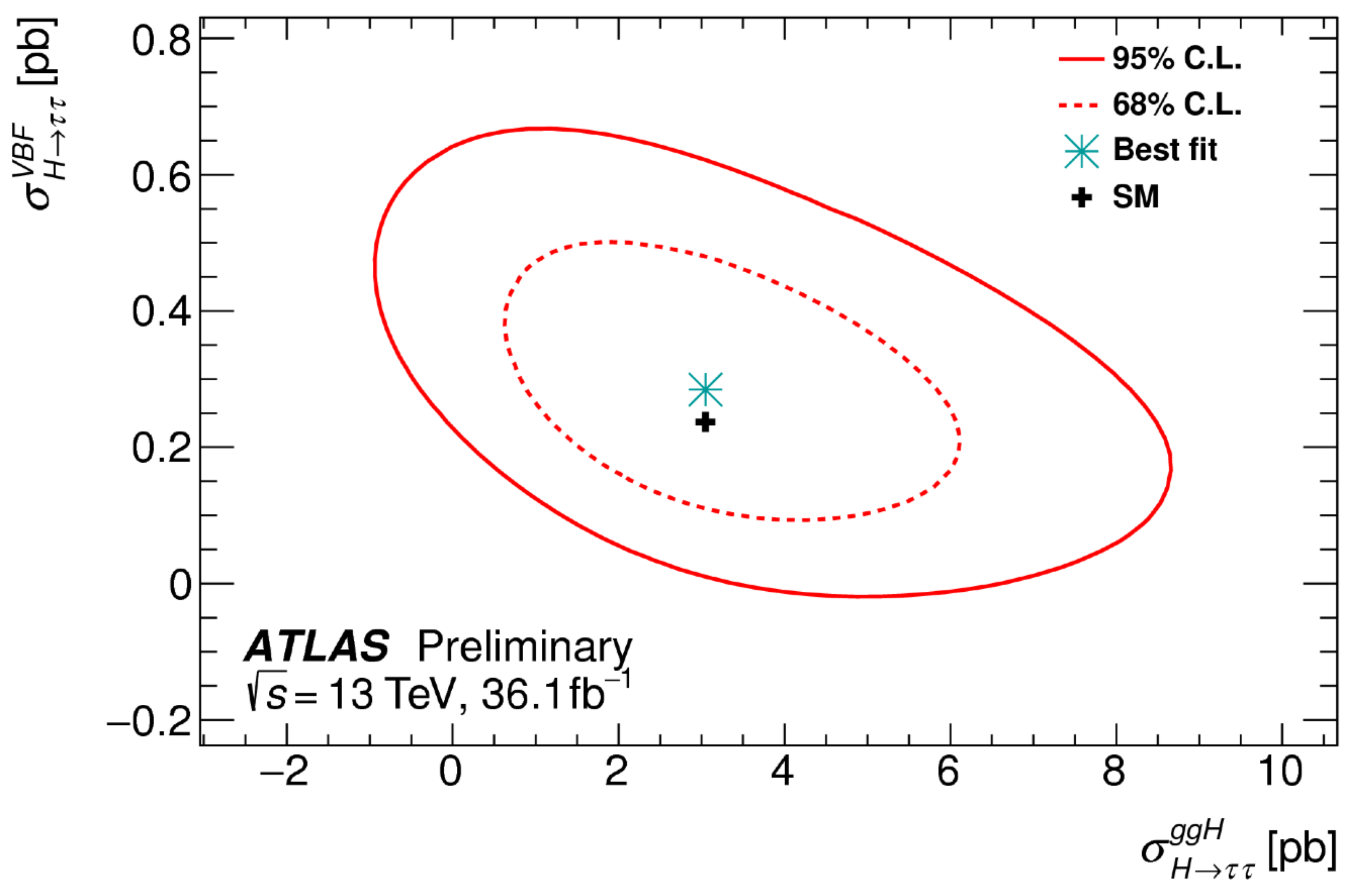
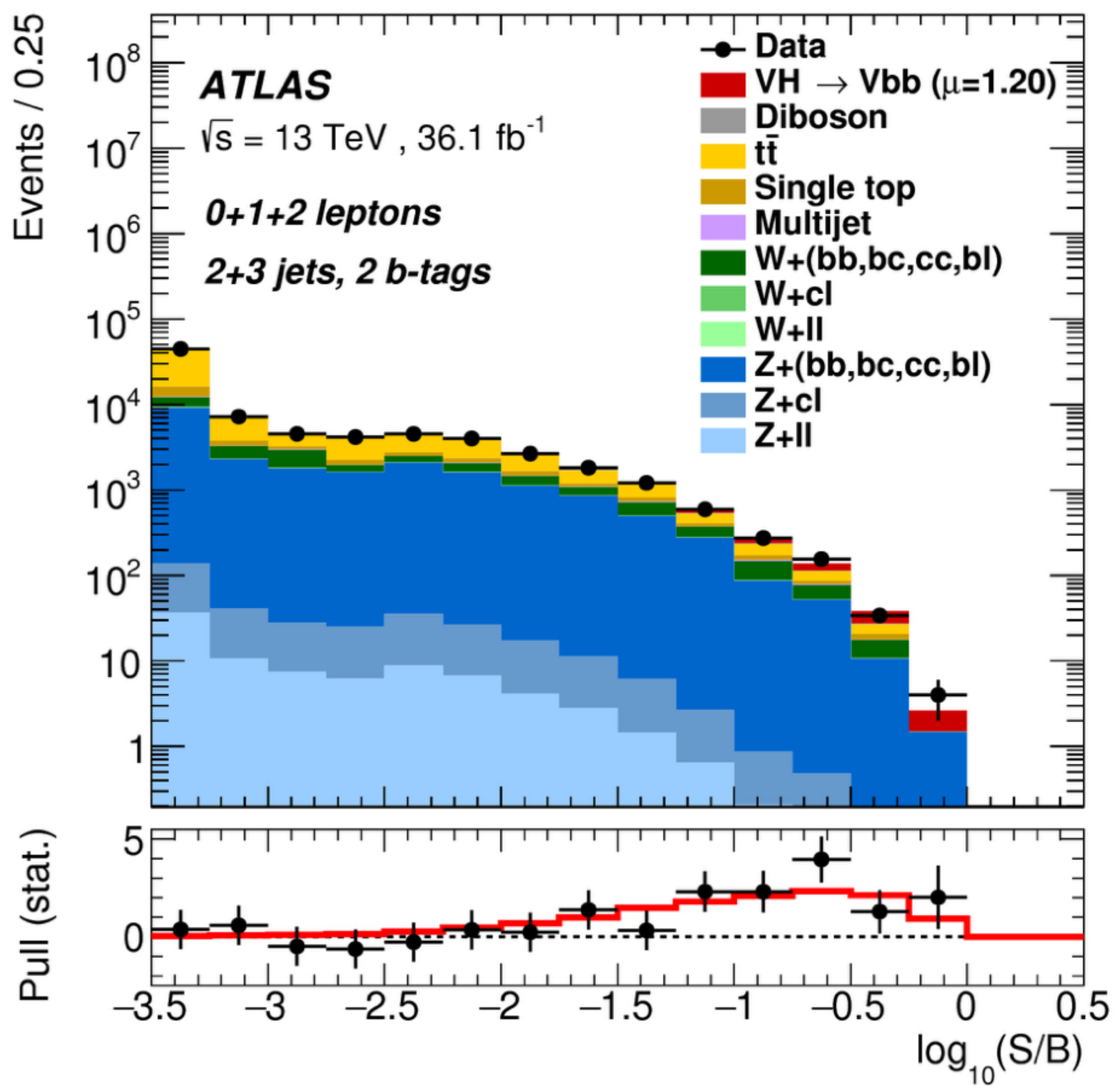
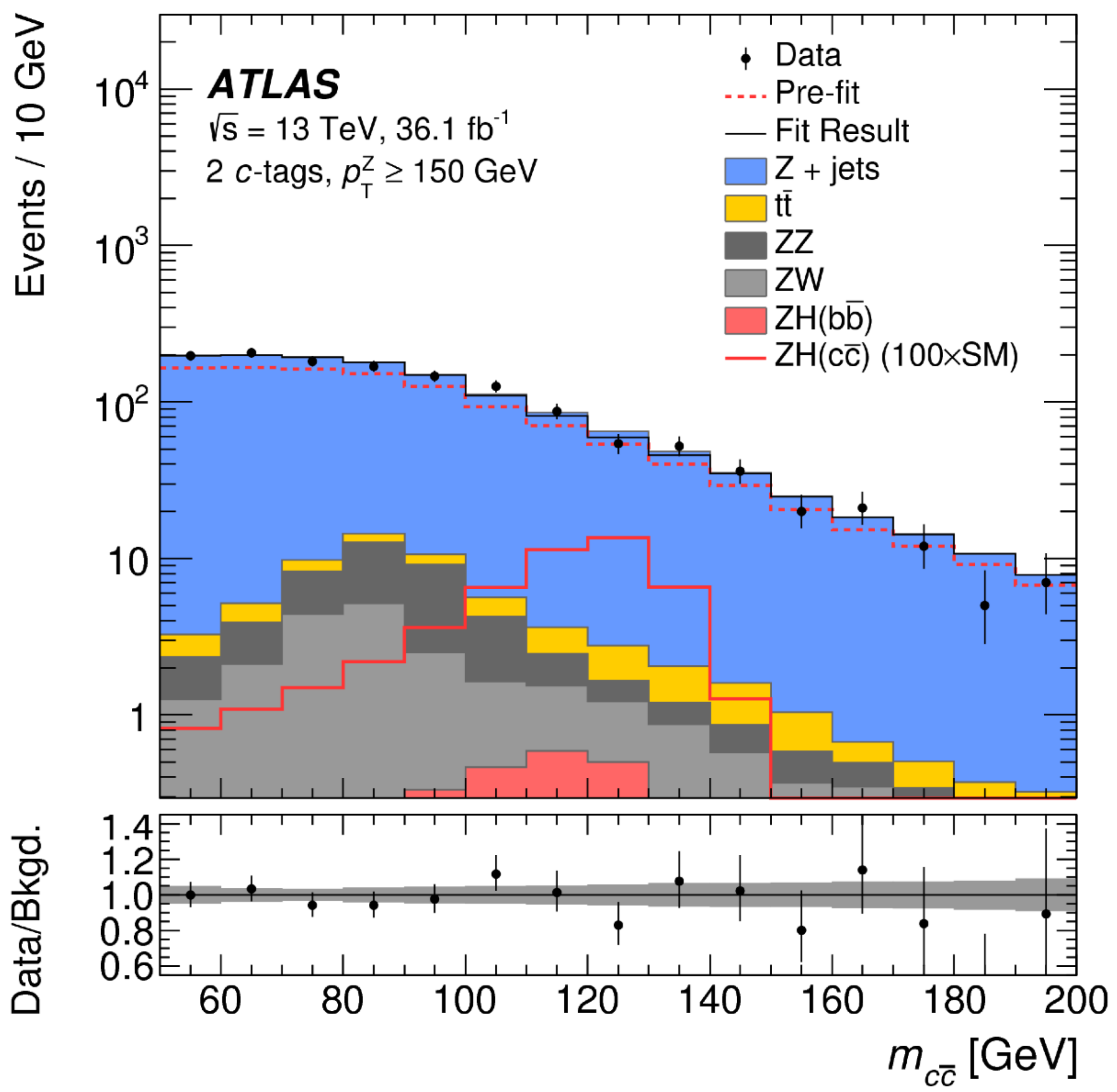
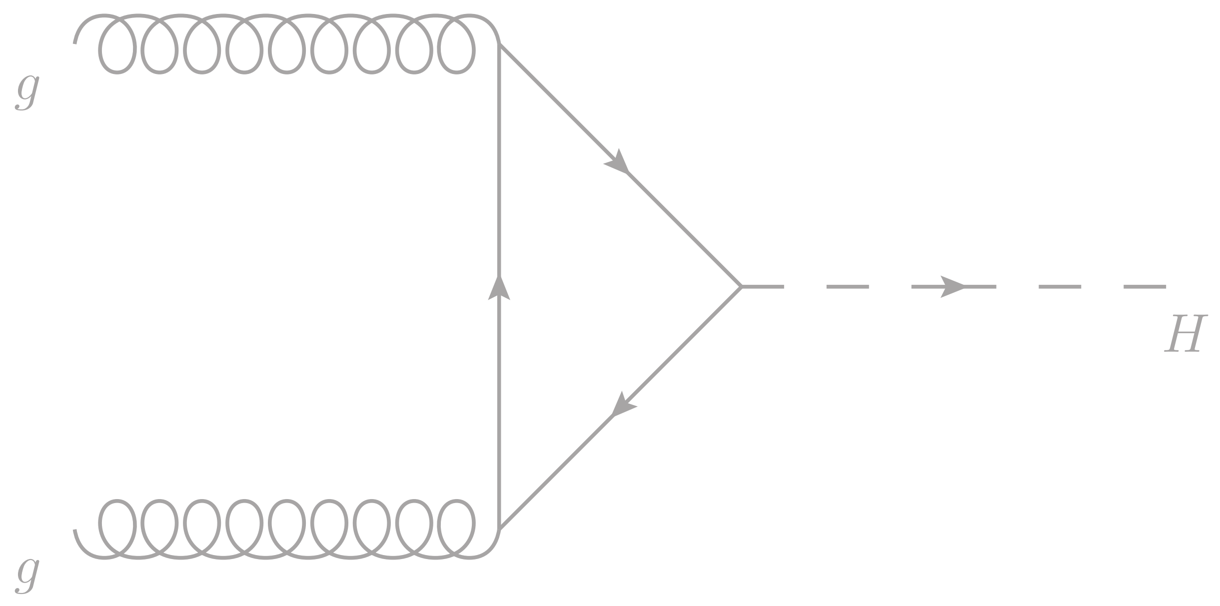
Closing Thoughts

- ATLAS has observed or seen evidence for several direct Higgs fermionic couplings
  - Observation of H—>ττ with Run 1 combination
  - ttH observation
  - First evidence of H—>bb
- Starting to probe the second generation and more challenging channels as well!

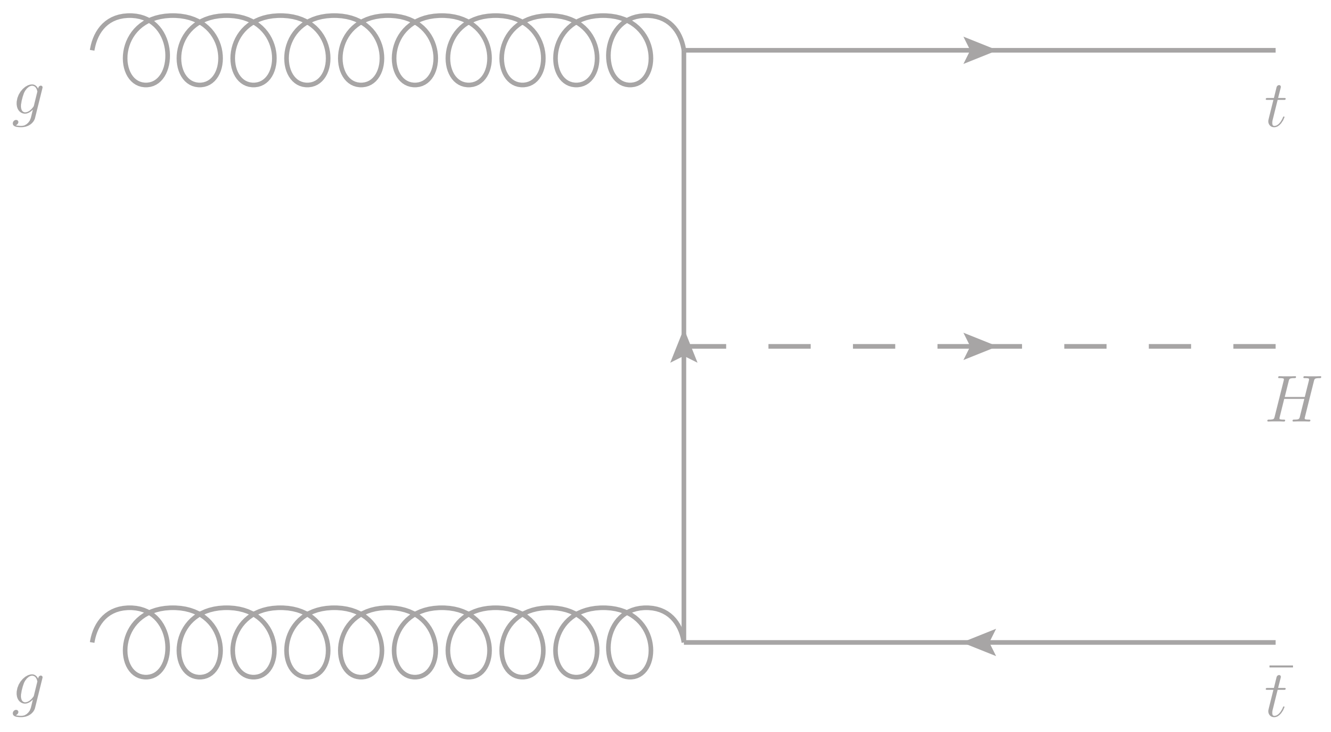






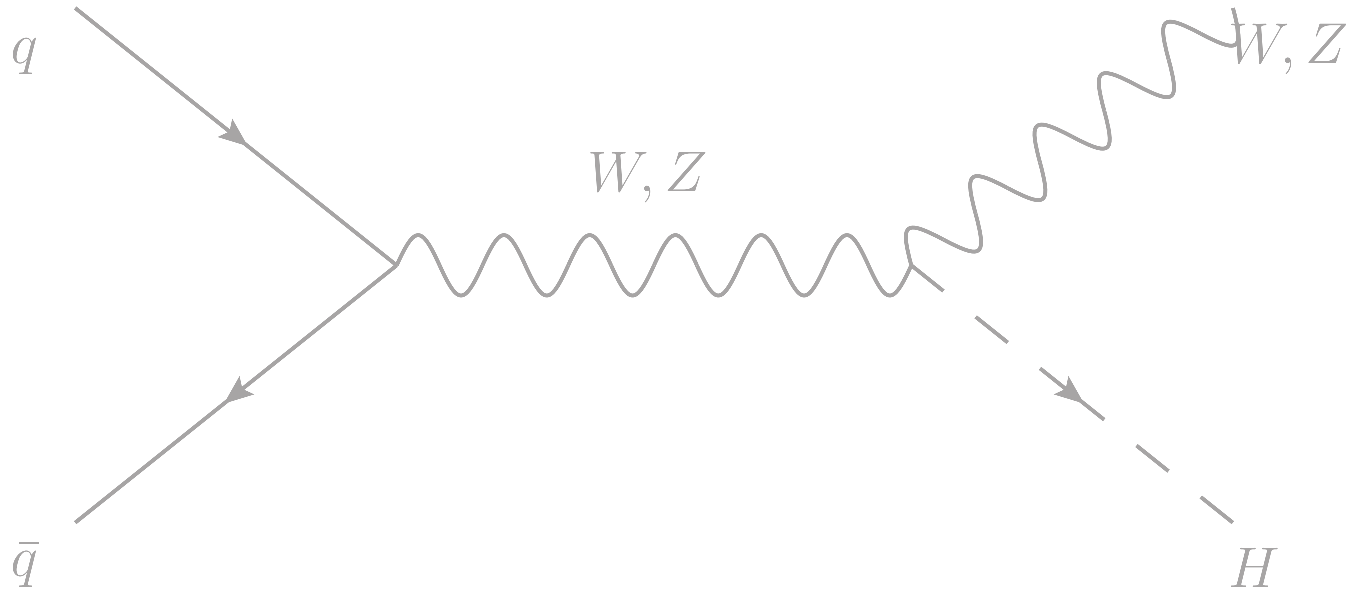


ggF

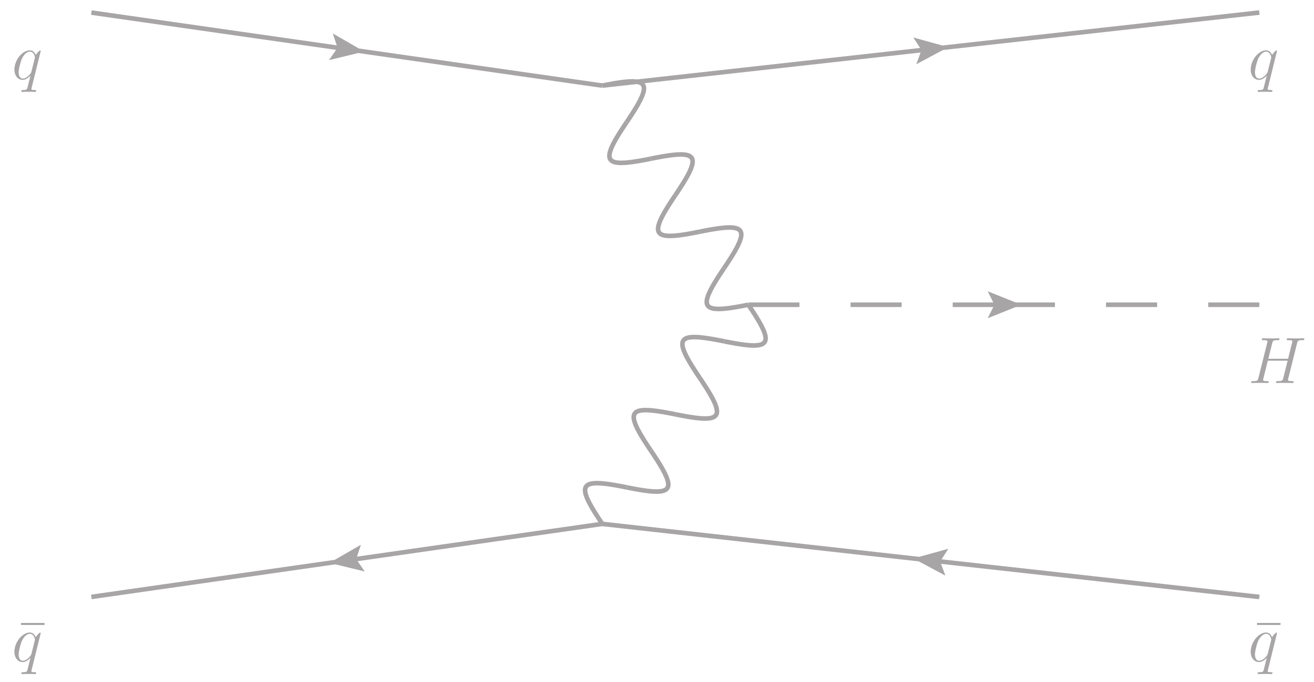


$t\bar{t}H$

Backup



VH



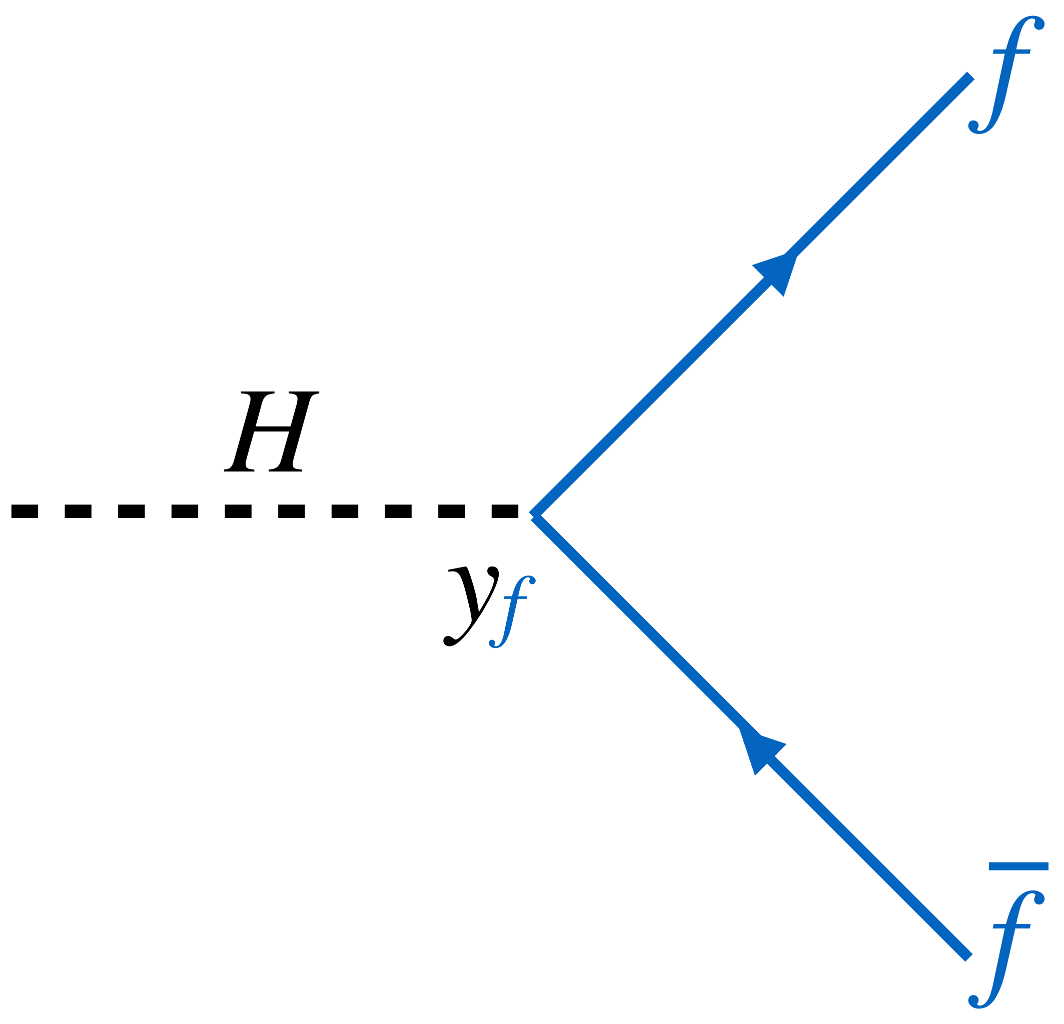
VBF

SM Higgs Coupling to Fermions

- At tree level, the Higgs boson interacts with fermions via a Yukawa coupling:

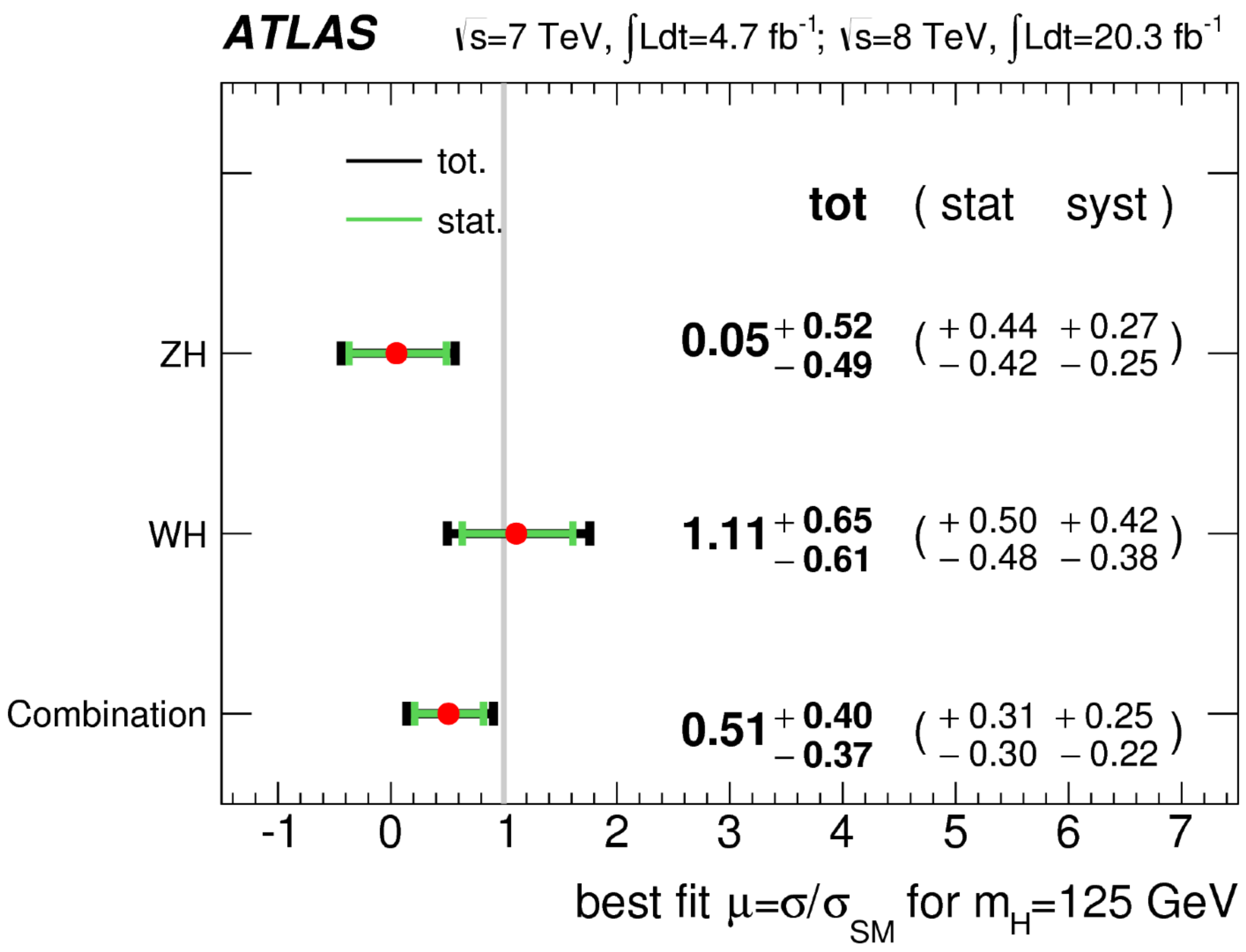
$$y_f = \frac{m_f}{v}$$

  - Coupling to top quarks by far the largest
  - Gives fundamental mass to fermions



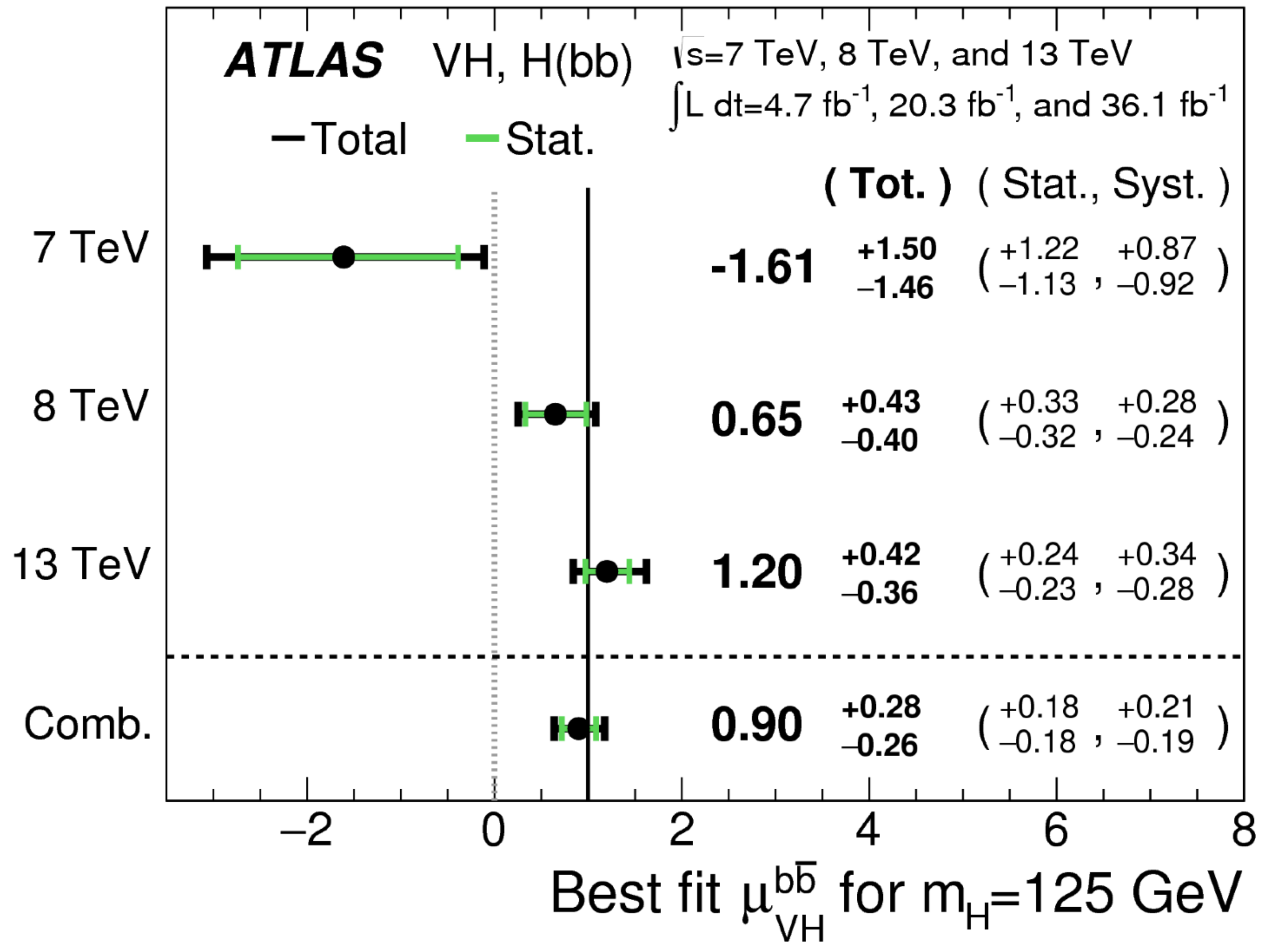
Contextualizing Results: Signal Strengths

- Analysis results often reported in terms of signal strengths, $\mu = \frac{n_{ev,obs}}{n_{ev,exp}}$
  - μ=1 corresponds to data matching (SM) prediction
  - Use to calculate p-values, etc.
- Any significant deviations from μ=1 would suggest Higgs coupling to fermions is more complicated (new physics)
- Lower uncertainties mean stronger tests
  - Amount of data (Stat)
  - Theoretical and experimental systematic uncertainties (Syst)

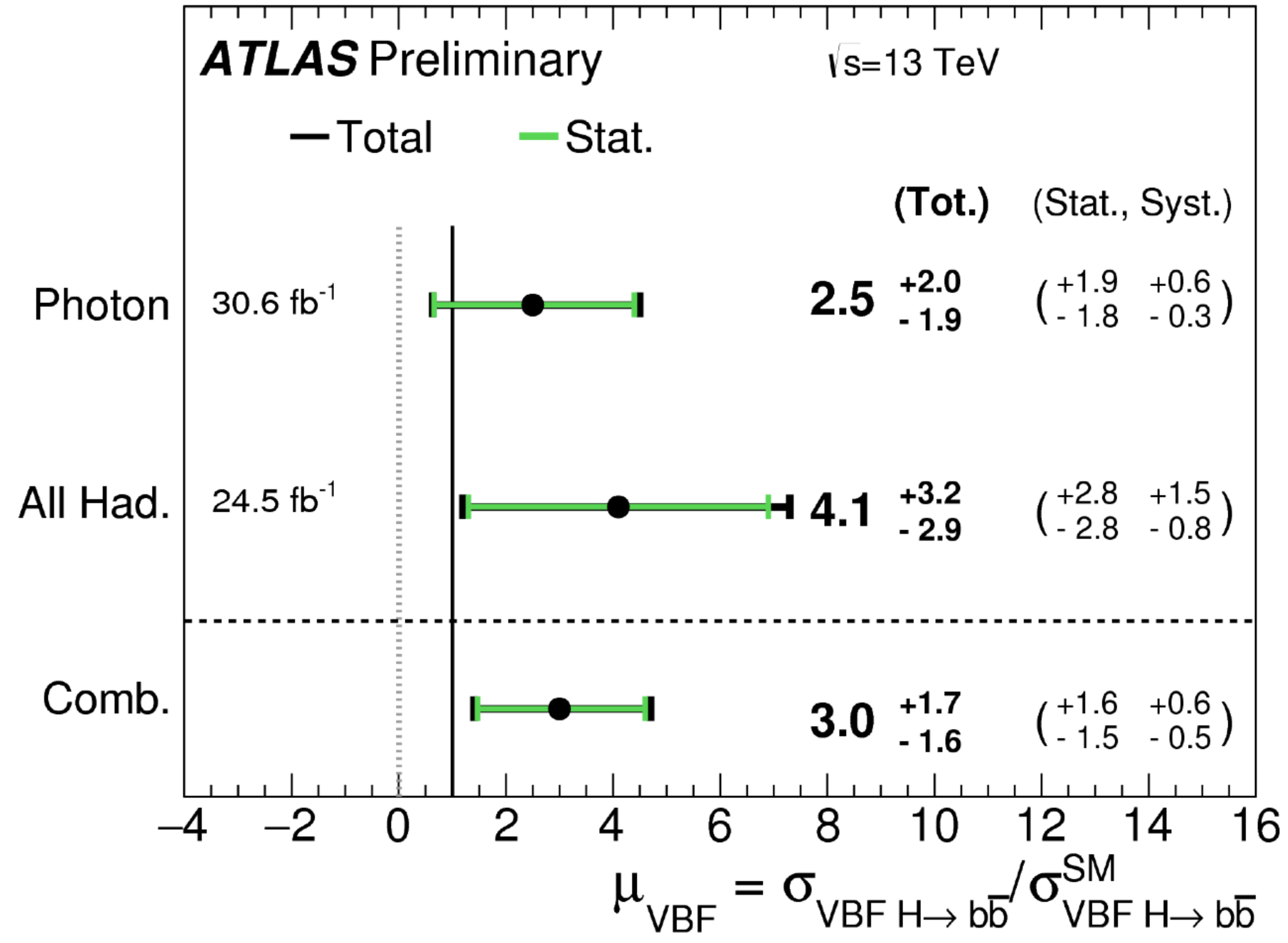


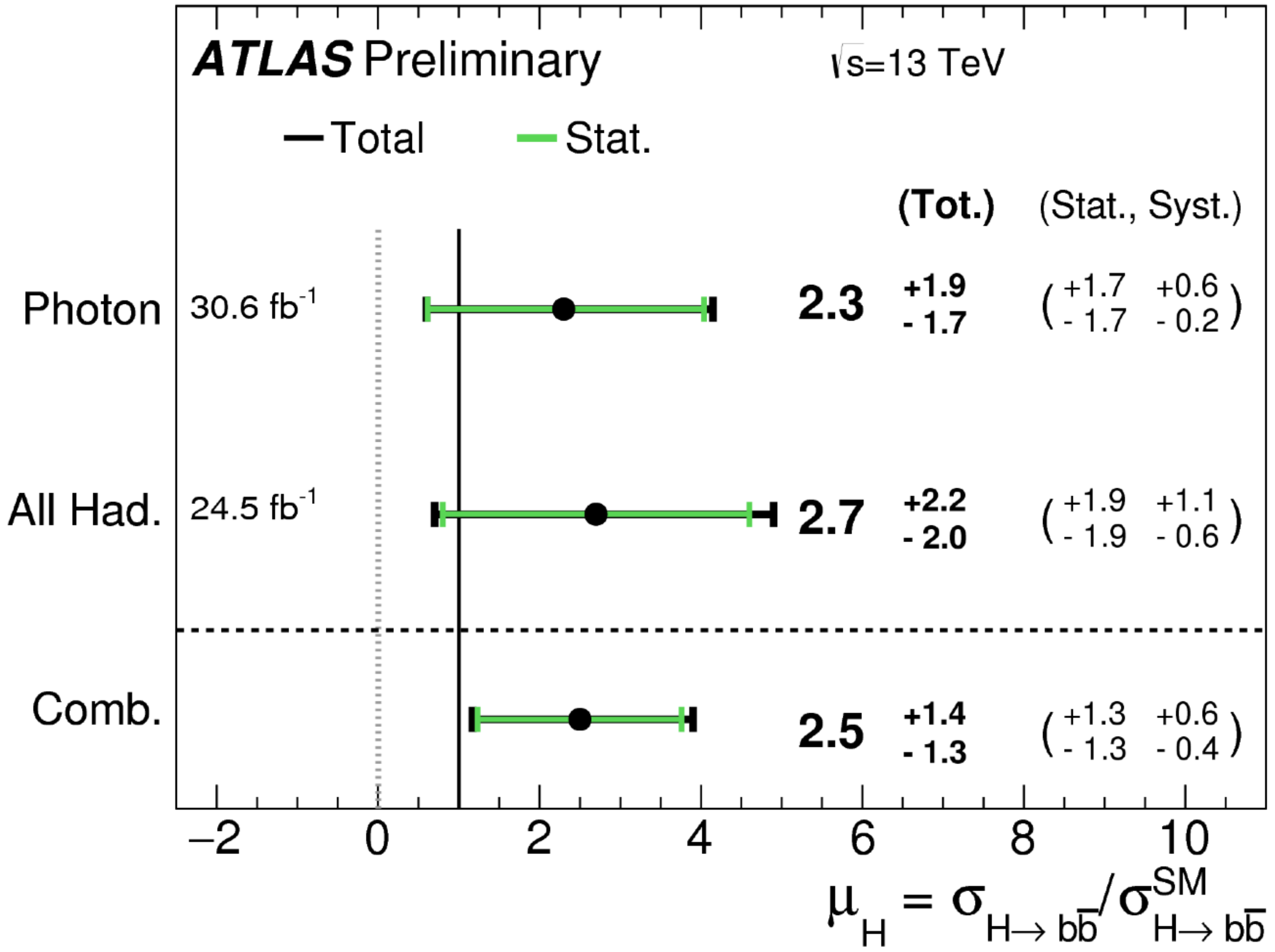
Combination Example: VH(bb) Run1+Run2

- Fit parameter correlations:
  - Correlate signal strength and some signal theory systematics
- Experimental systematics and modeling changed substantially
  - How to correlate? How to check?
  - Ultimately, only *b*-jet energy scale is important
- Combined result: best fit μ=0.9±0.3
  - Corresponds to observed (expected) 3.6σ (4.0σ) excess
  - First evidence of SM VH(bb)



VBF H(bb) Fit Results

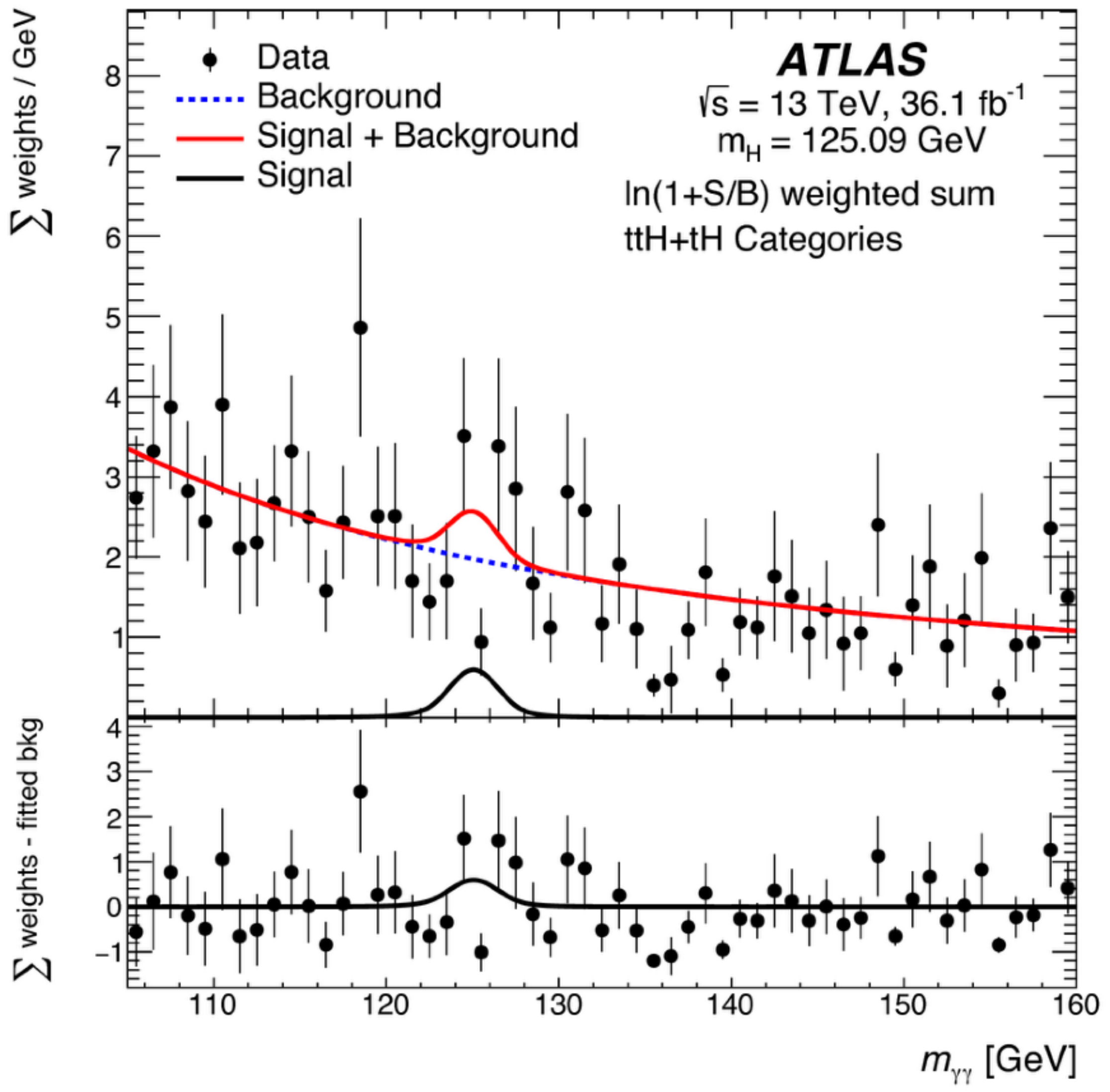




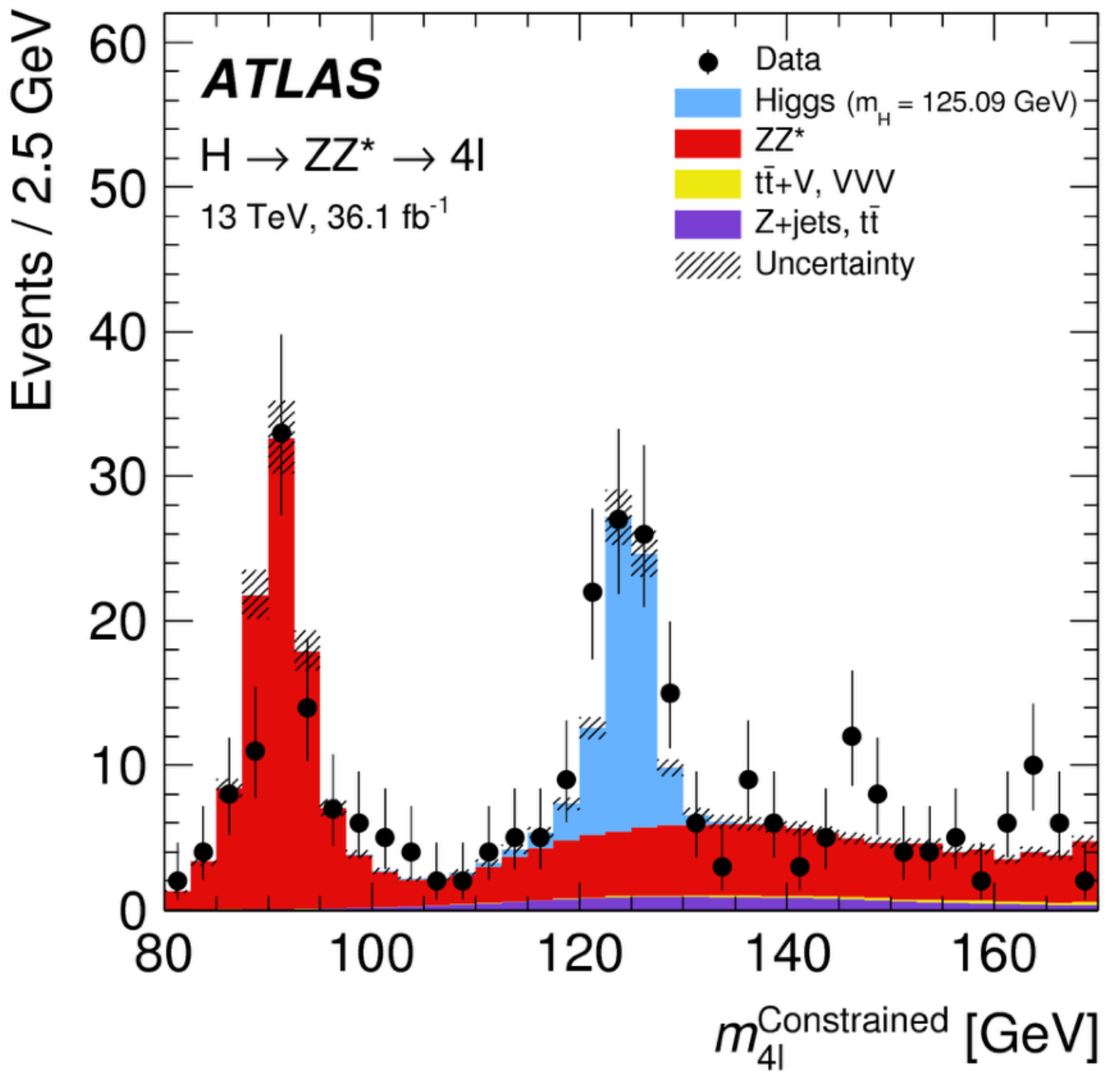
- Statistics limited
- Observed (expected) significances—VBF 1.9σ (0.7σ), Inclusive 1.9σ (0.9σ)
- Leading NP categories: Higgs modeling, JES/JER, b-tagging (all ~±0.2-0.3)

Fermionic Production: ttH

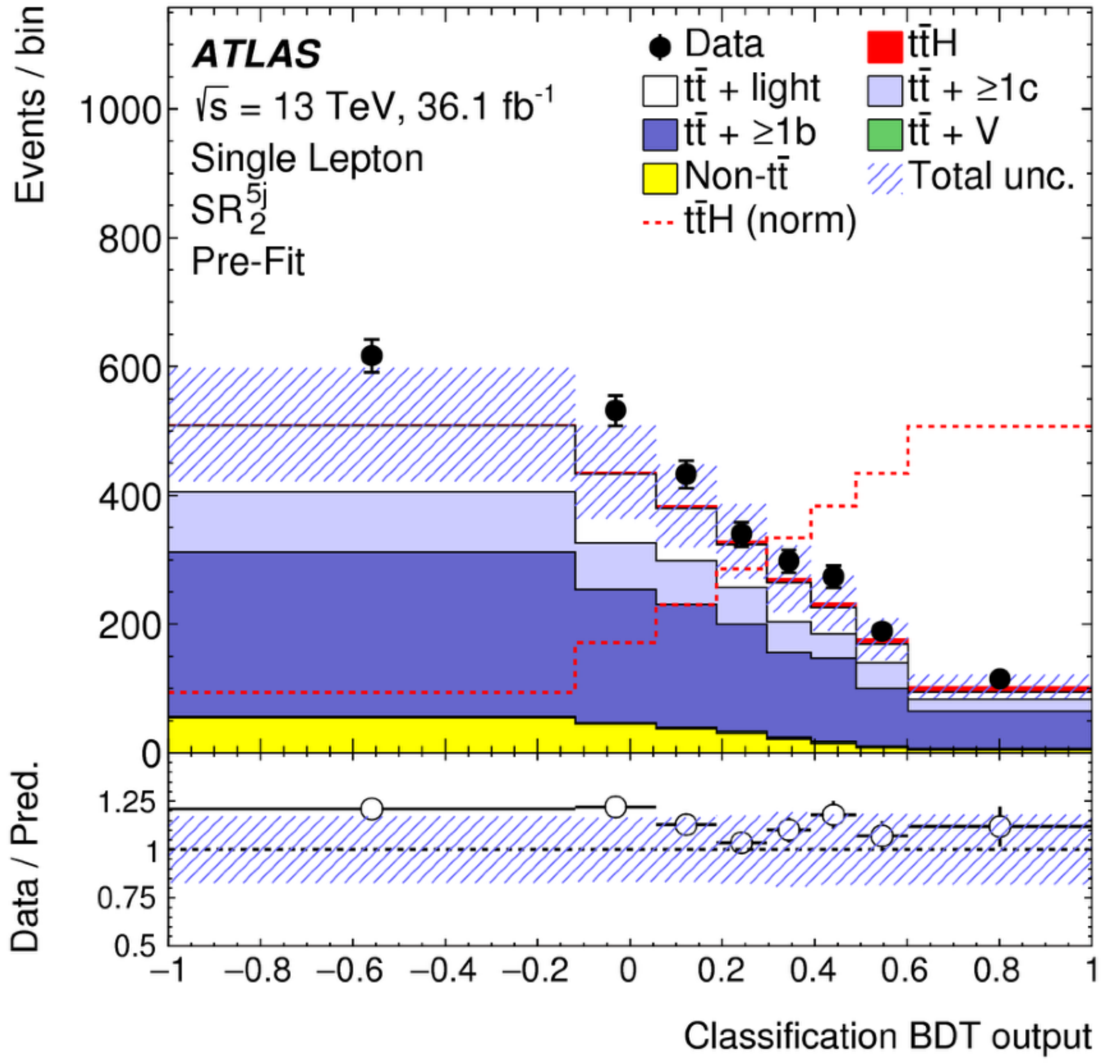
- Different analysis strategy based on Higgs decay
- **ZZ***, γγ: first look for Higgs from decay products, then require additional b-jets for ttH, bump hunt analysis
- WW*, ττ, bb: start by looking for ttbar final state, look for additional Higgs; MVA-based analyses
  - WW*, **bb** have combinatoric ambiguity, cannot do bump hunt
  - WW*, ττ analyzed together in Multilepton (**ML**) analysis



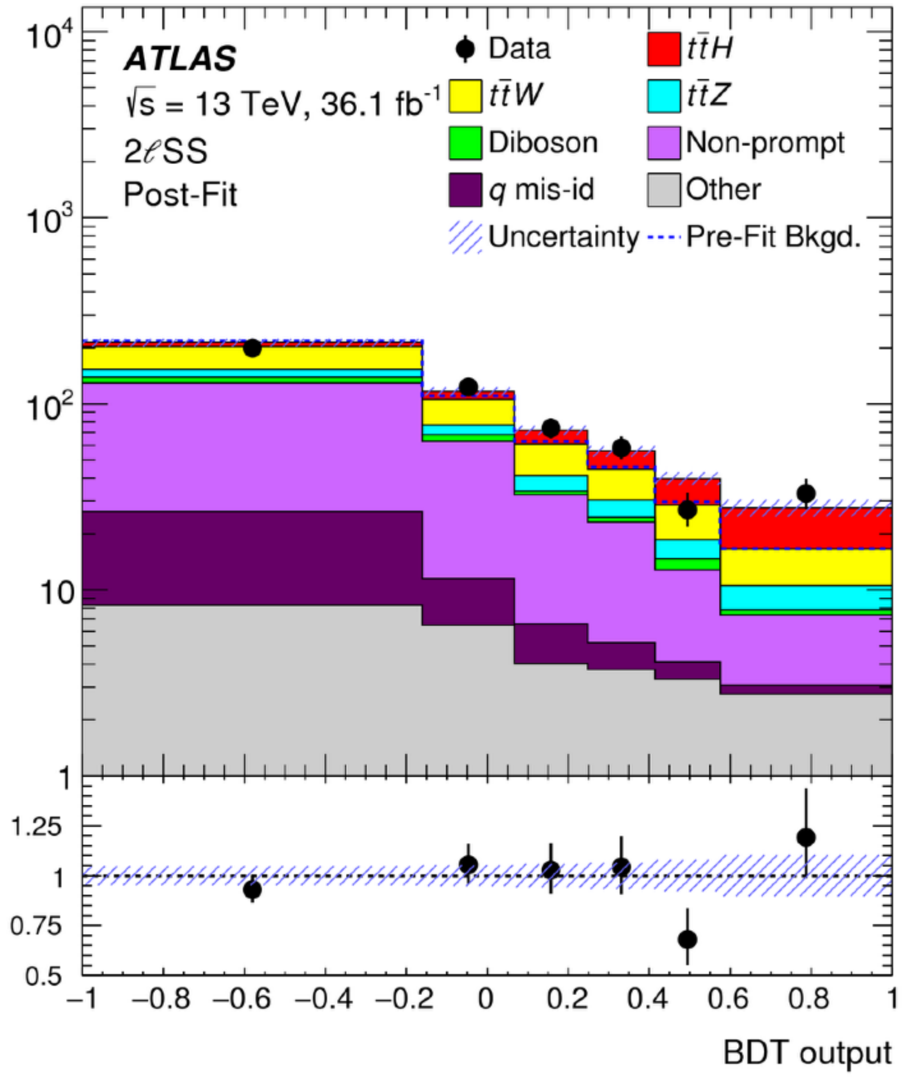
γγ



ZZ*



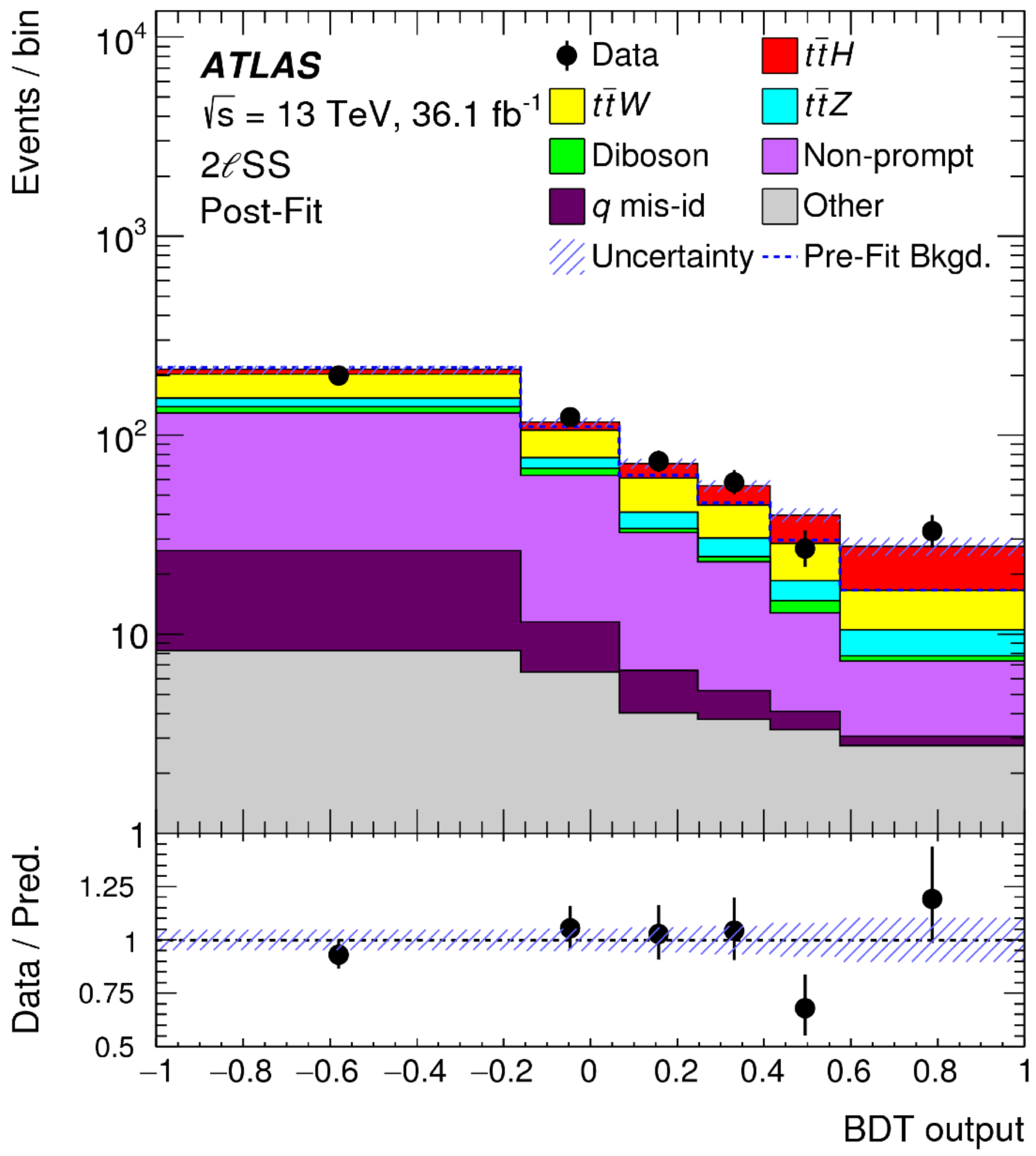
ttHbb



ttH ML

ttH Example: Multilepton (ML)

- Target WW* and ττ (and some ZZ*) decays by looking at final states with leptons
- Signal regions based on e/μ and τ_{had} multiplicity, lepton charge
  - e.g. 2l SS: 2 light *l*eptons with *s*ame *s*ign charge, (no hadronic τ's)
- BDT distributions/yields as fit inputs
- Backgrounds: ttV, VV (MC); fake/non-prompt leptons, charge mis-ID (data-driven)
- Best fit μ=1.6 (+0.6,-0.5) largely agrees with SM; corresponds to a 4.1σ (2.8σ) observed (expected) excess



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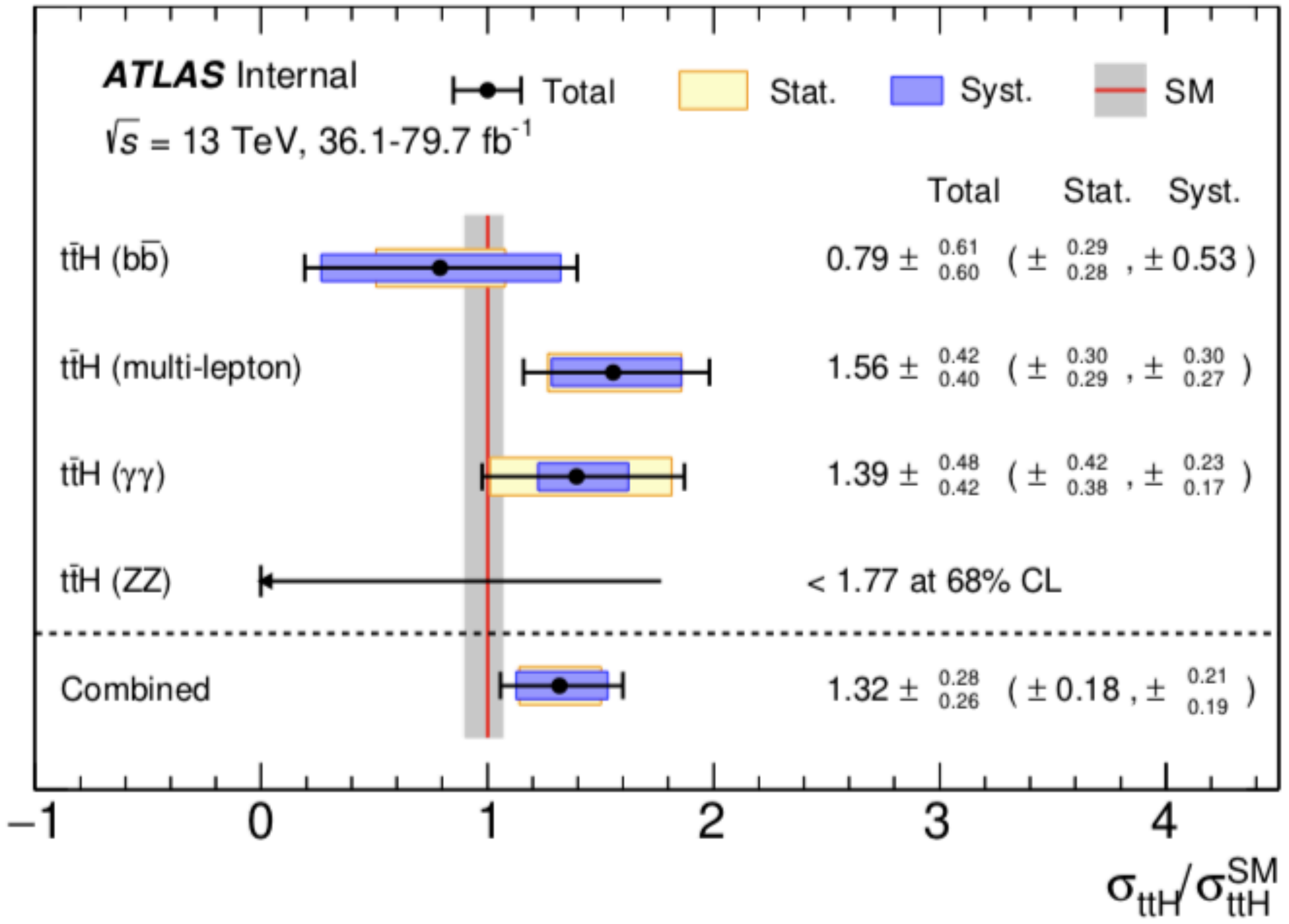
Combined ttH Results



Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Observed significance	Expected significance
$H \to \gamma\gamma$	79.7	$710\ ^{+210}_{-190}$ (stat) $^{+120}_{-90}$ (sys)	4.1	3.7
$H \to$ multilepton	36.1	790 ± 150 (stat) $^{+150}_{-140}$ (sys)	4.1	2.8
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat) $\pm$ 270 (sys)	1.4	1.6
$H \to ZZ^* \to 4\ell$	79.7	<900 (68% CL)	0	1.2
Combined (13 TeV)	≤ 79.7	670 ± 90 (stat) $^{+110}_{-100}$ (sys)	5.8	4.9
Combined (7, 8, 13 TeV)	4.5, 20.3, ≤ 79.7	–	6.3	5.1

- 13 TeV measured σ(ttH) = 670 (±90; stat) (+110,-100; sys) fb agrees with SM
    - Corresponds to observed (expected) 5.8σ (4.9σ) excess; w/Run1: 6.3σ (5.1σ)
    - Dominant systematics: ttbar modeling (9.9%); ttH modeling (6.0%); fake lepton (5.2%)
- Observation of ttH