ATLAS Results on Higgs Physics and Electroweak Symmetry Breaking

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on behalf of the ATLAS Collaboration

Columbia University
in the City of New York

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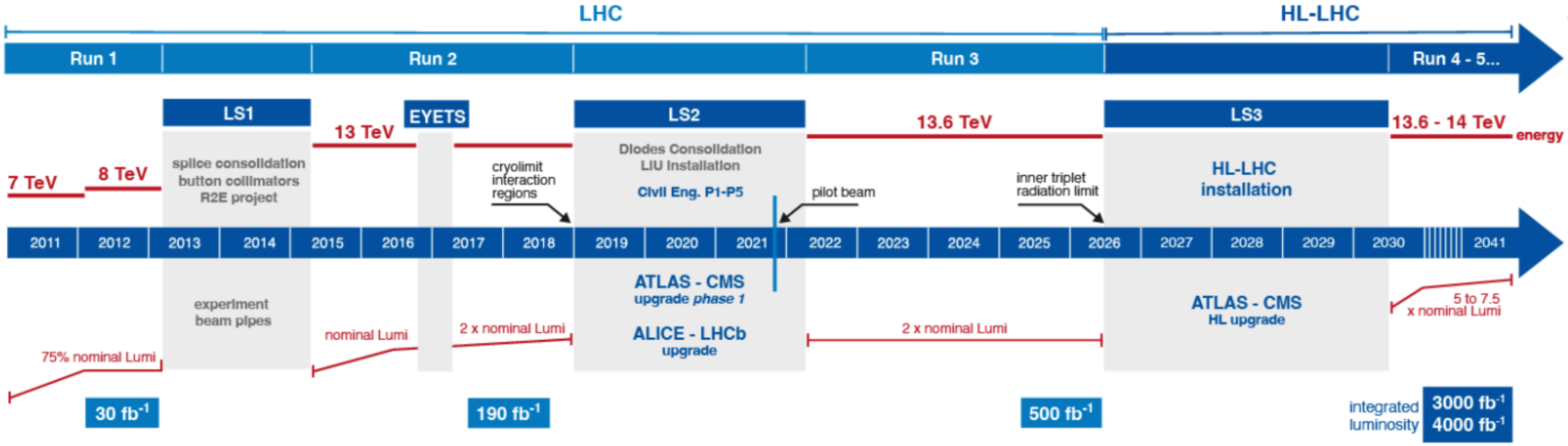
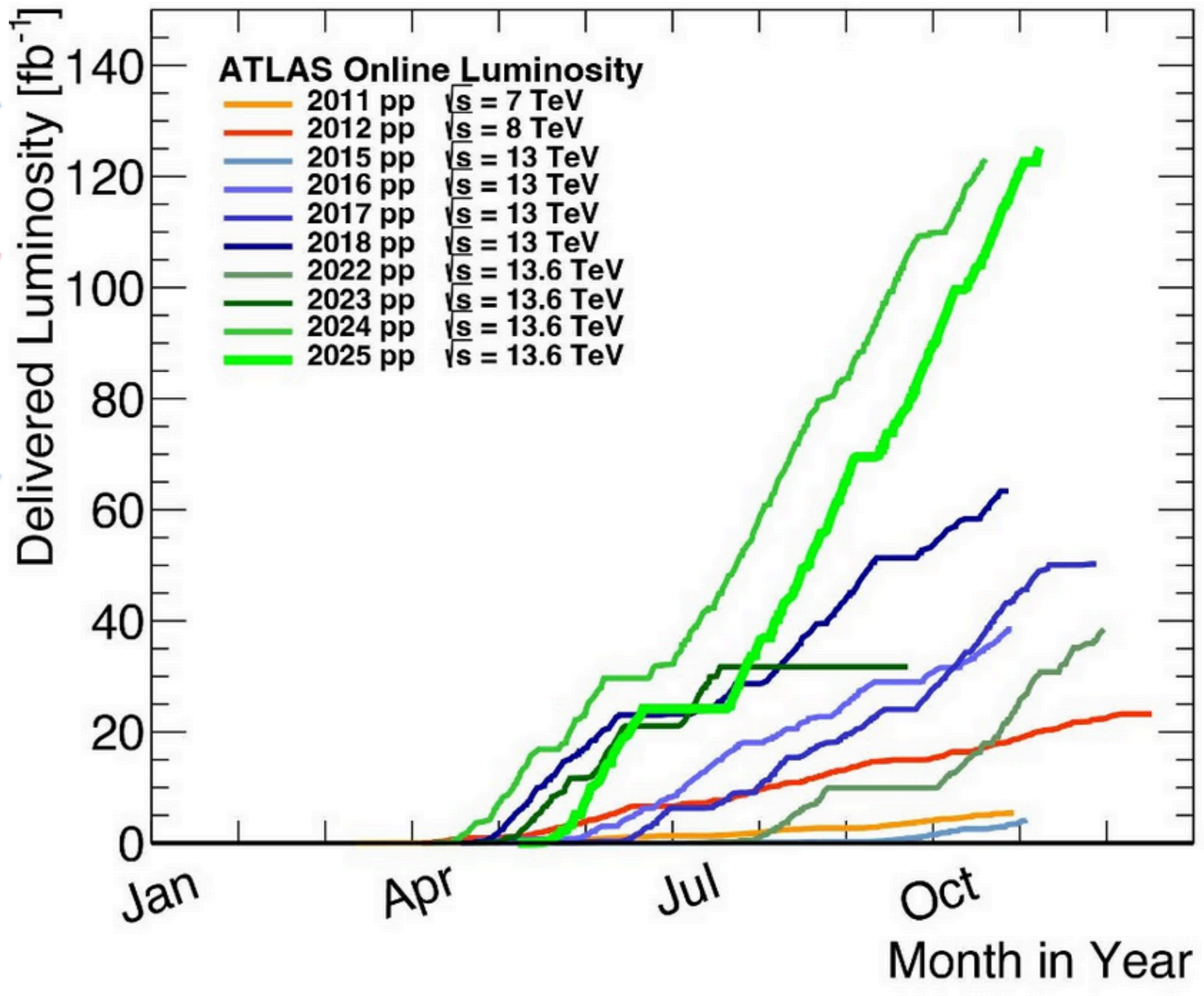
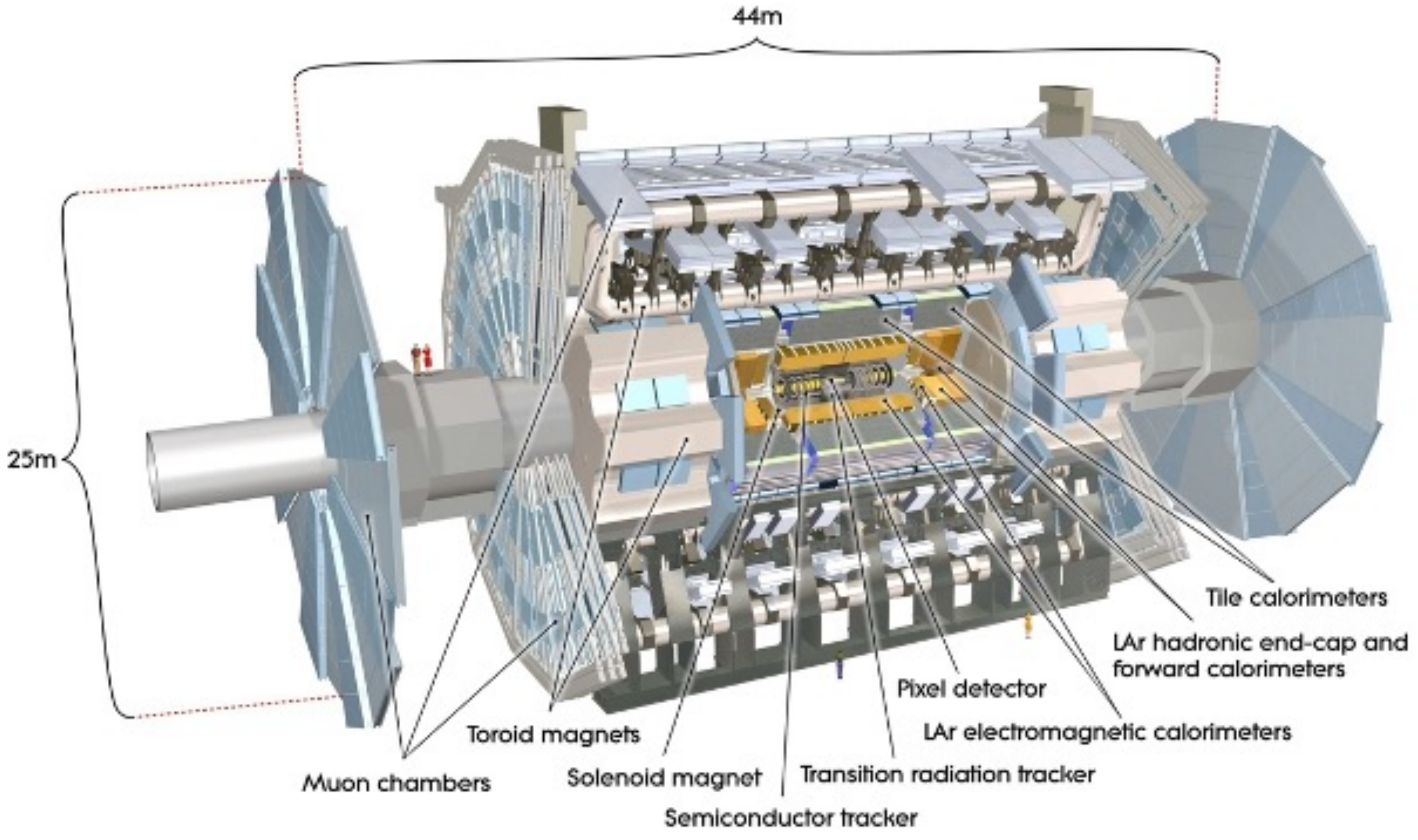
Outline

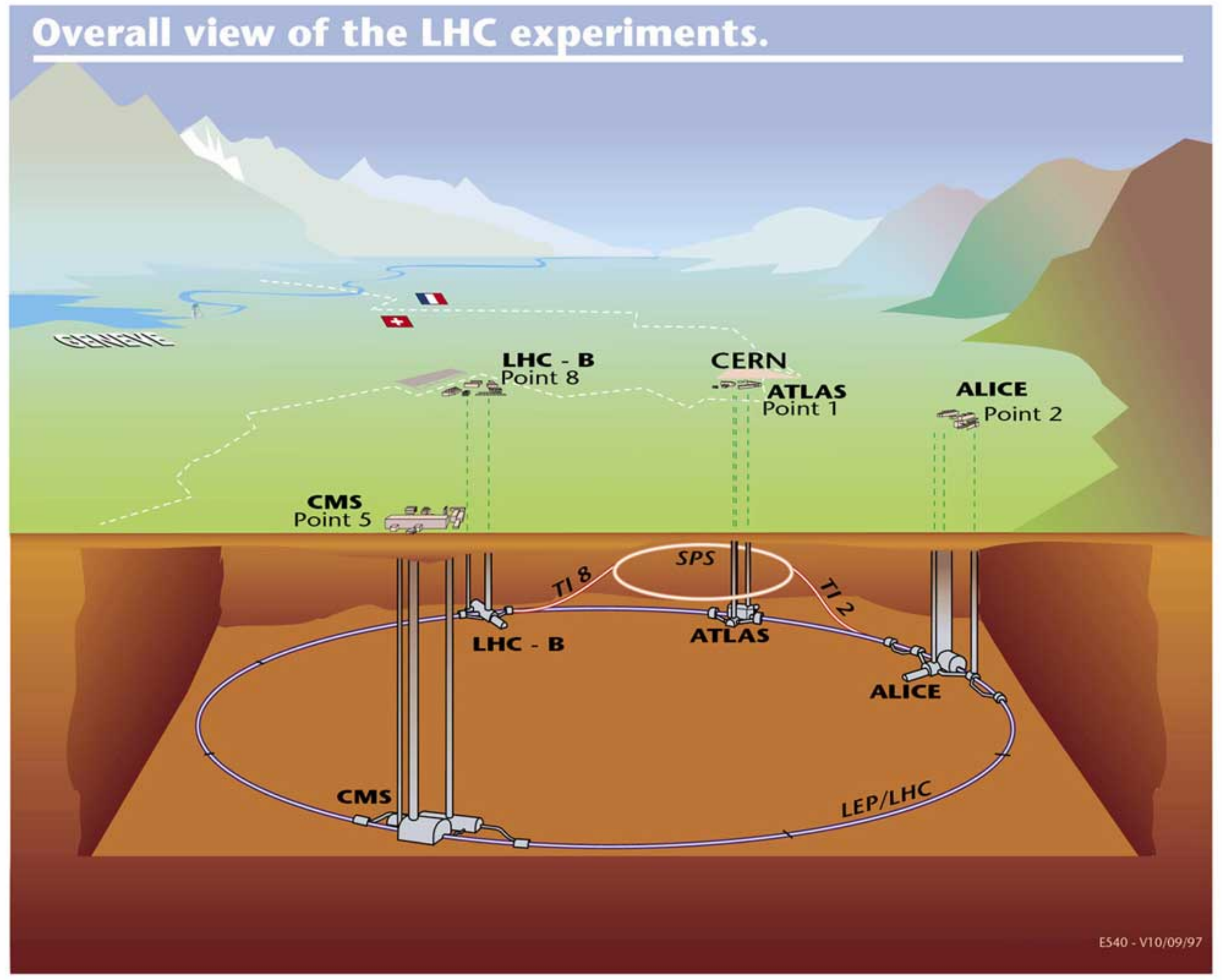
- Electroweak Symmetry Breaking
- Vector Boson Scattering
- Higgs Boson Properties
  - Higgs-Top Coupling *Sign*?
- Higgs Boson Rare Decays
  - $H \to \mu\mu$
  - $H \to Z\gamma$
- The Higgs Potential
  - Multi-Higgs Boson Production
- Concluding Remarks

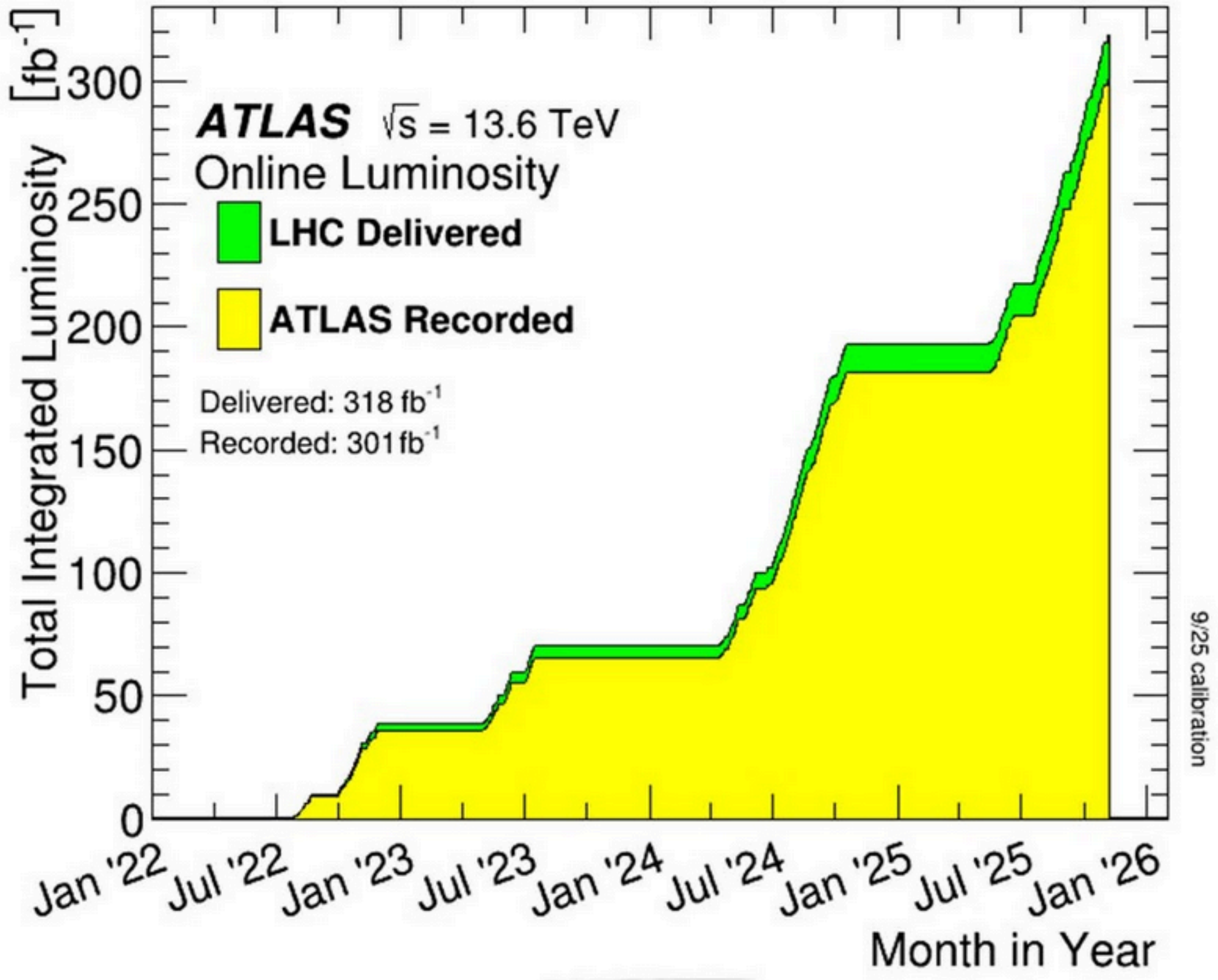
The LHC, ATLAS, Data







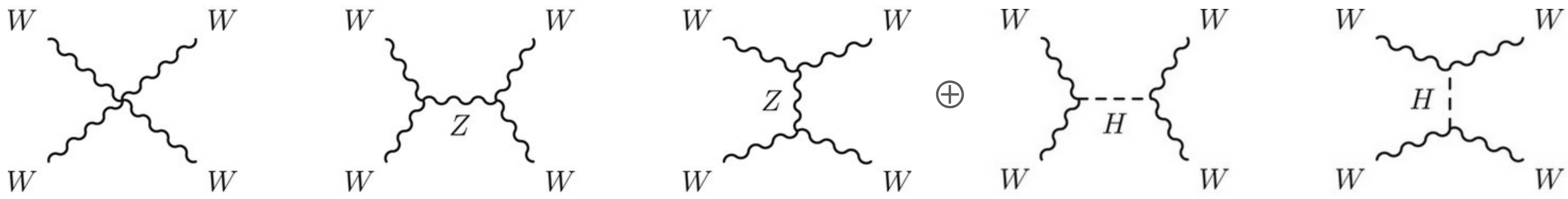




Electroweak Symmetry Breaking

- Without a Higgs boson, or other new physics, $\sigma(WW \to WW) \sim s$
  - This is similar to e.g. low energy neutrino scattering, where this behavior is "regulated" by the W boson propagator as the energy increases
  - To solve this for WW scattering, introduce an even-spin boson with $m \lesssim 1$ TeV

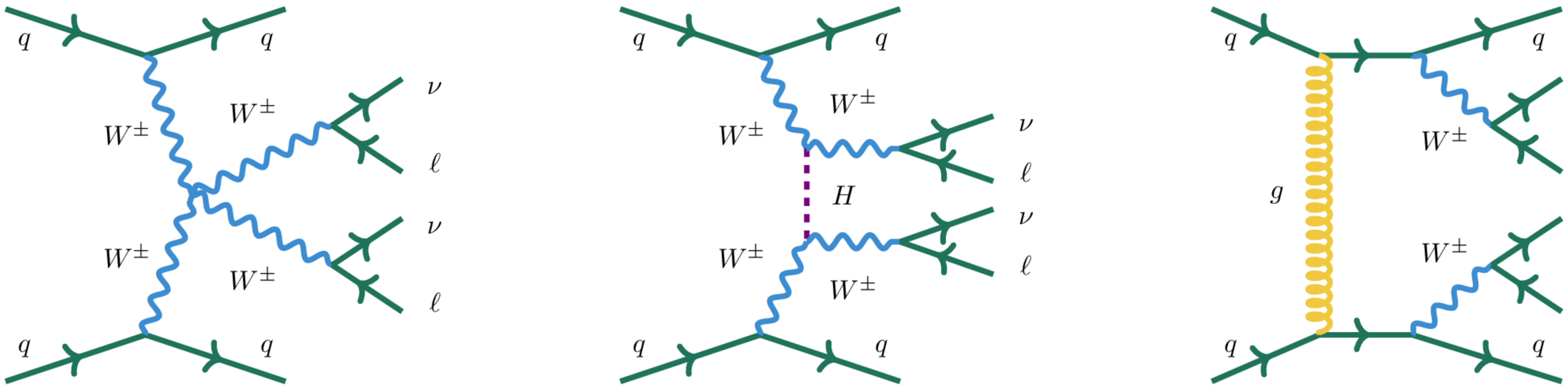
Lee, Quigg, Thacker, 1977



- A similar, but "softer", issue arises in fermion scattering: $\sigma(f\bar{f} \to WW) \sim m_f \sqrt{s}$
  - To be economical, solve both problems at once: new boson needs to be a neutral, colorless scalar $\Longrightarrow$ quantum numbers of the vacuum!
- From a Standard Model lagrangian point of view, it needs to be embedded in (at least) an $SU(2)_L$ doublet…

Probe #1: Vector Boson Scattering

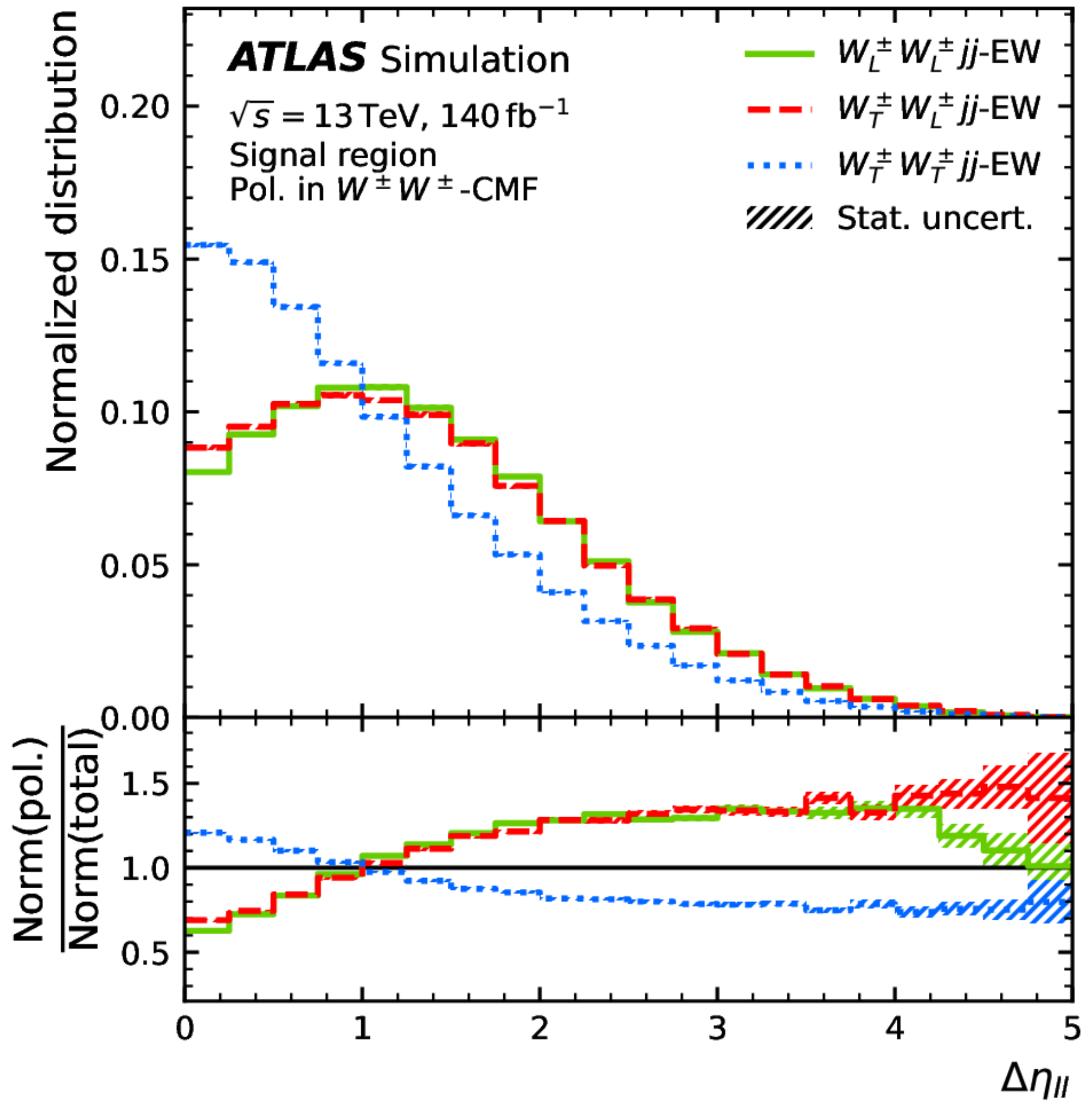
- Before the Higgs boson observation, vector boson scattering formed the basis of the no-lose theorem: something had to happen in VBS
  - In particular, scattering of longitudinally polarized vector bosons, since these are the degrees of freedom that only exist because of non-zero vector boson mass
  - At hadron colliders, W/Z bosons can be radiated from incoming quarks
    - Vector boson scattering (and fusion) is characterized by two “forward” jets
      – Jet transverse momentum (p_T) is $O(m_W/2)$

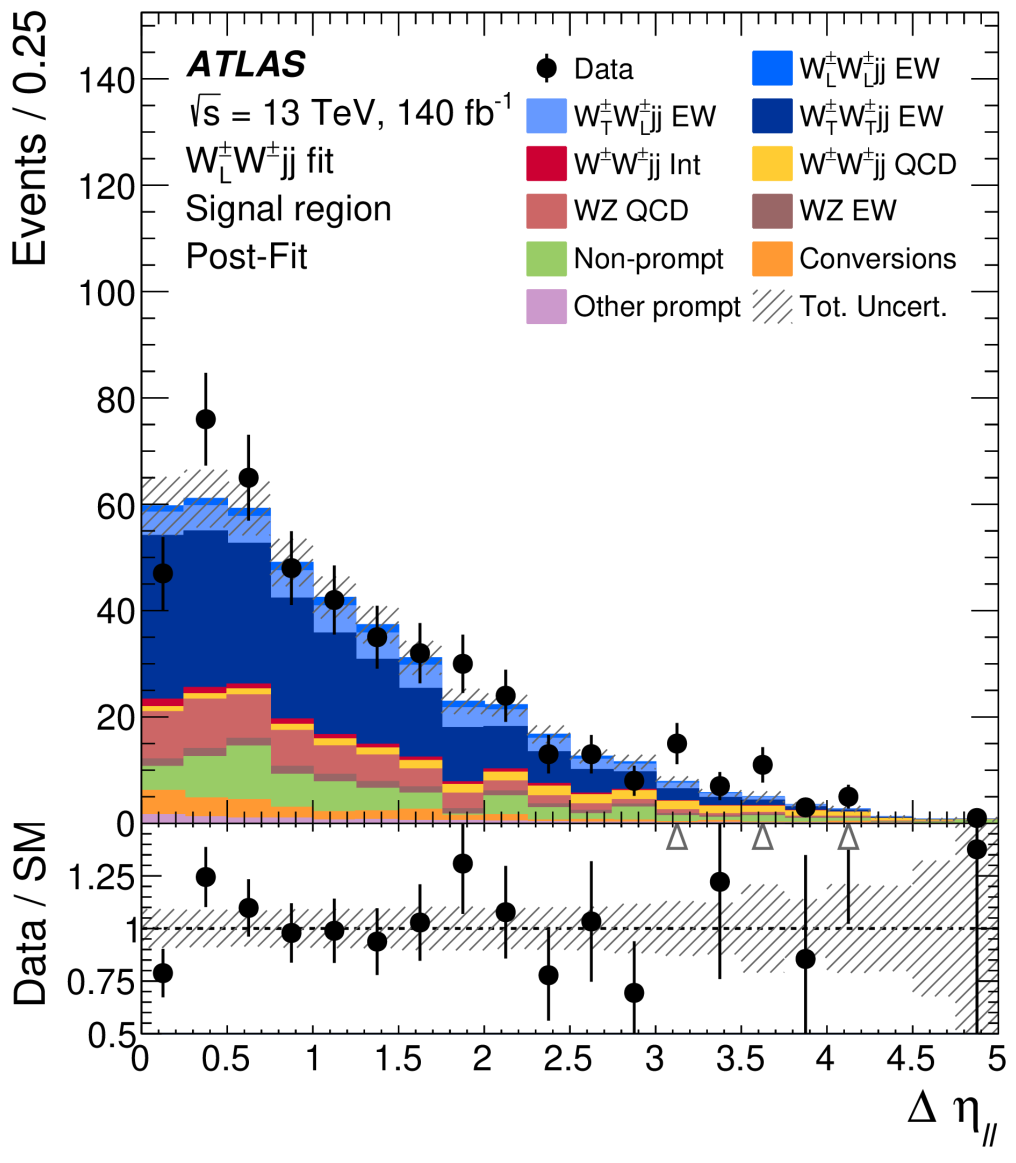


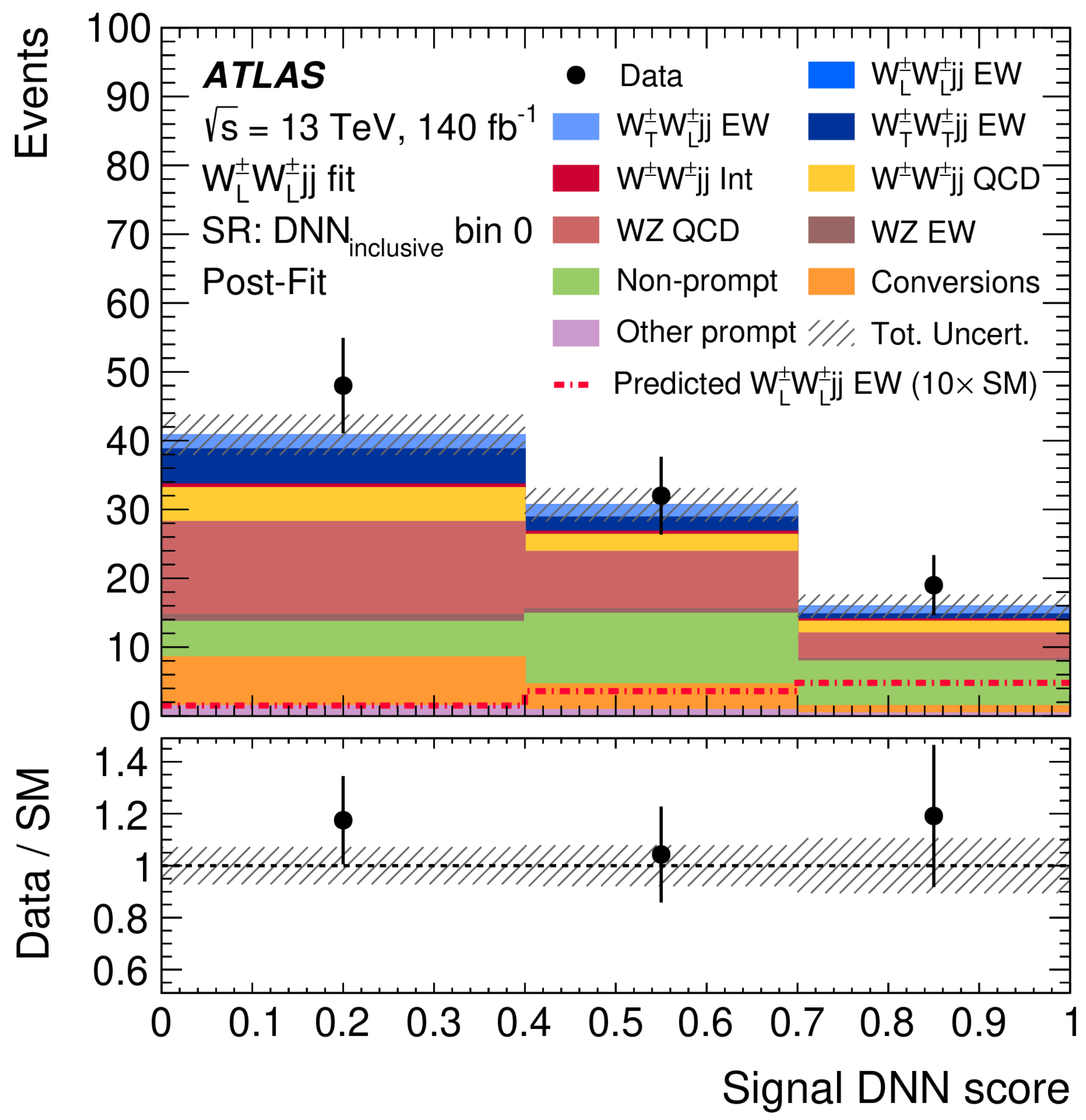
ATLAS Search for $W_L W_L$ Scattering

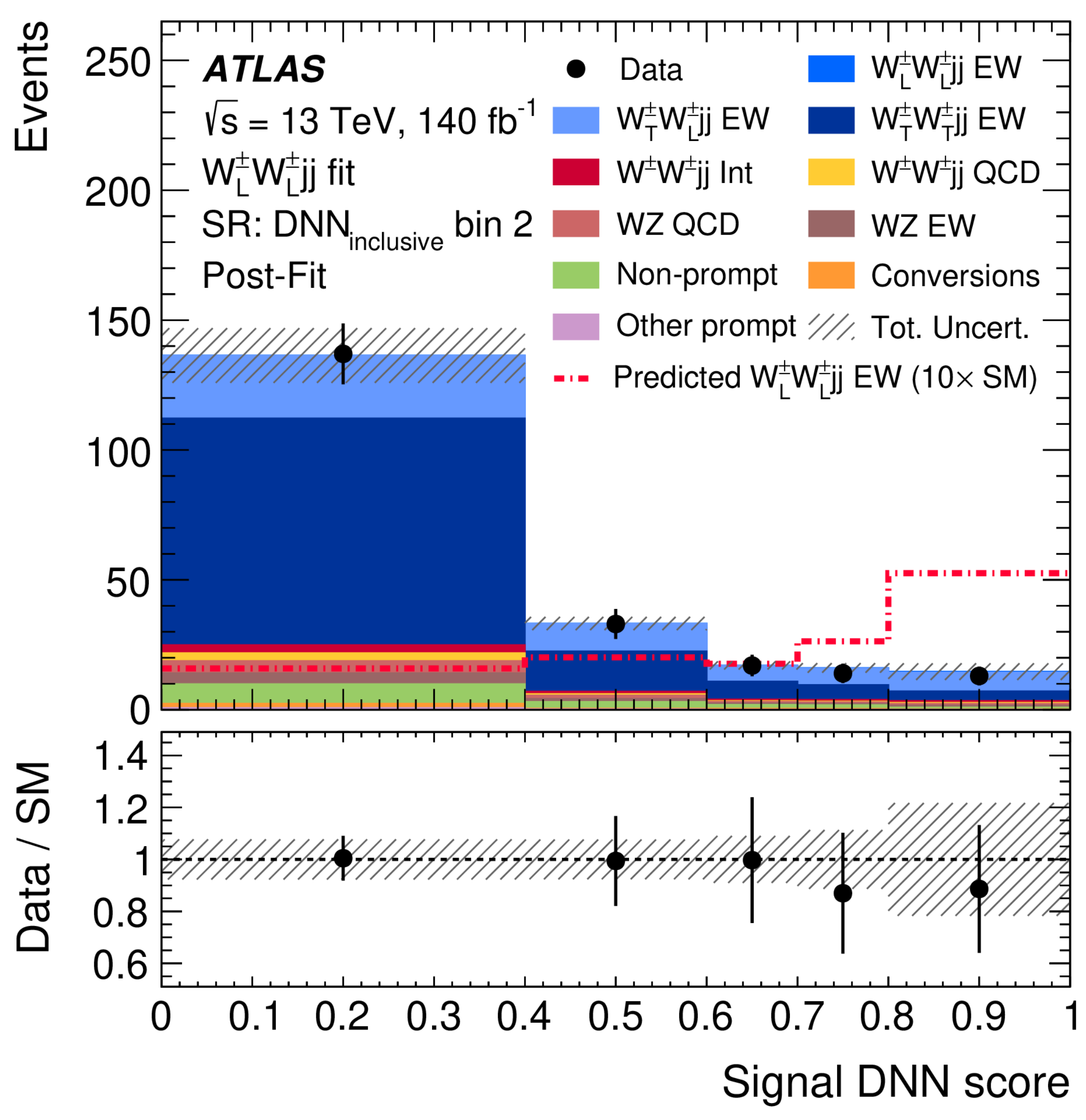
- To minimize backgrounds, look for same-sign $W^{\pm}W^{\pm}$ scattering, with each boson decaying to an electron or muon and a neutrino:
  - A pair of same-charge leptons, large MET, a pair of forward jets with large m_{jj}
- Then two-component analysis:
  - NN to separate WW scattering signal from non-VBS backgrounds, 3 bins
  - NNs to separate $W_L W_L$ from $W_T W$ and $W_L W$ from $W_T W_T$
  - Use all NN outputs in final fit

Phys. Rev. Lett. 135 (2025) 111802
ATLAS webpage with plots









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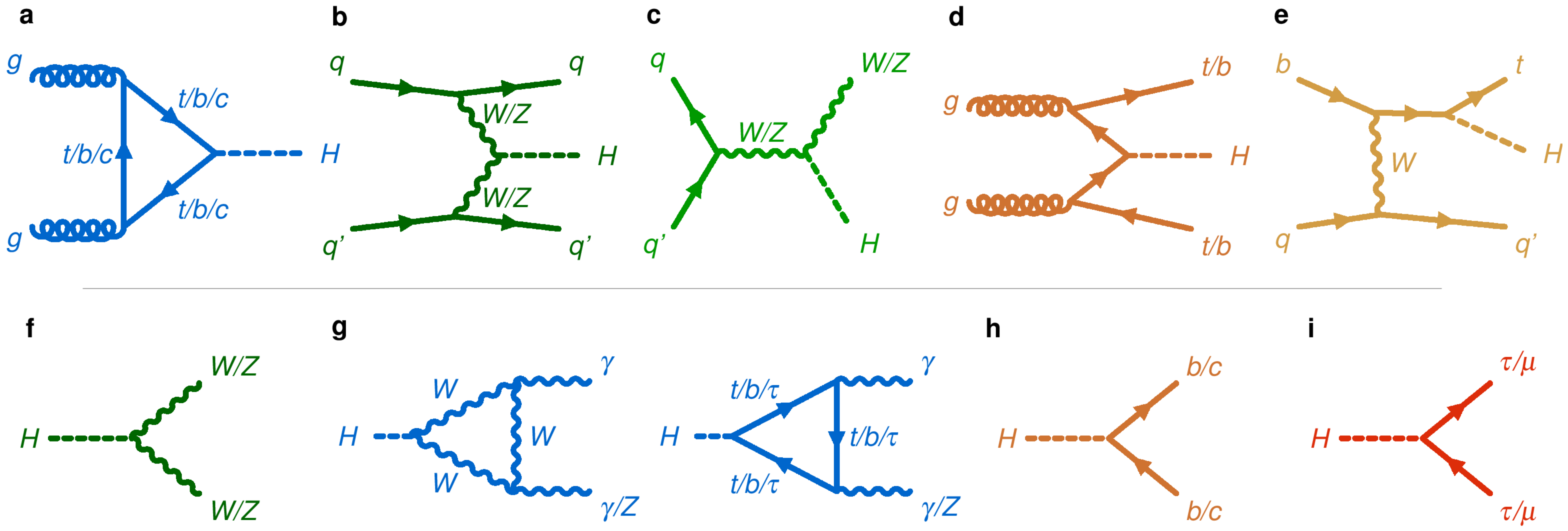
Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)	Uncertainty breakdown (fb)
$W_L^{\pm}W_L^{\pm}jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)	± 0.20 (stat.) ± 0.02 (mod. syst.) ± 0.05 (exp. syst.)
$W_T^{\pm}W^{\pm}jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)	± 0.30 (stat.) ± 0.08 (mod. syst.) ± 0.16 (exp. syst.)
$W_L^{\pm}W^{\pm}jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)	± 0.28 (stat.) ± 0.05 (mod. syst.) ± 0.08 (exp. syst.)
$W_T^{\pm}W_T^{\pm}jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)	± 0.30 (stat.) ± 0.05 (mod. syst.) ± 0.12 (exp. syst.)

3σ evidence for VBS with at least one longitudinally polarized W boson

"Legacy" Run 2 Higgs Measurements

- Combination of Run 2 (2015-2018) results to constrain the properties of the observed Higgs boson, and compare with SM expectations



- Probes multiple production and decay modes
  - Given the significant contributions of loops in both production and decay, combination adds significant constraining power

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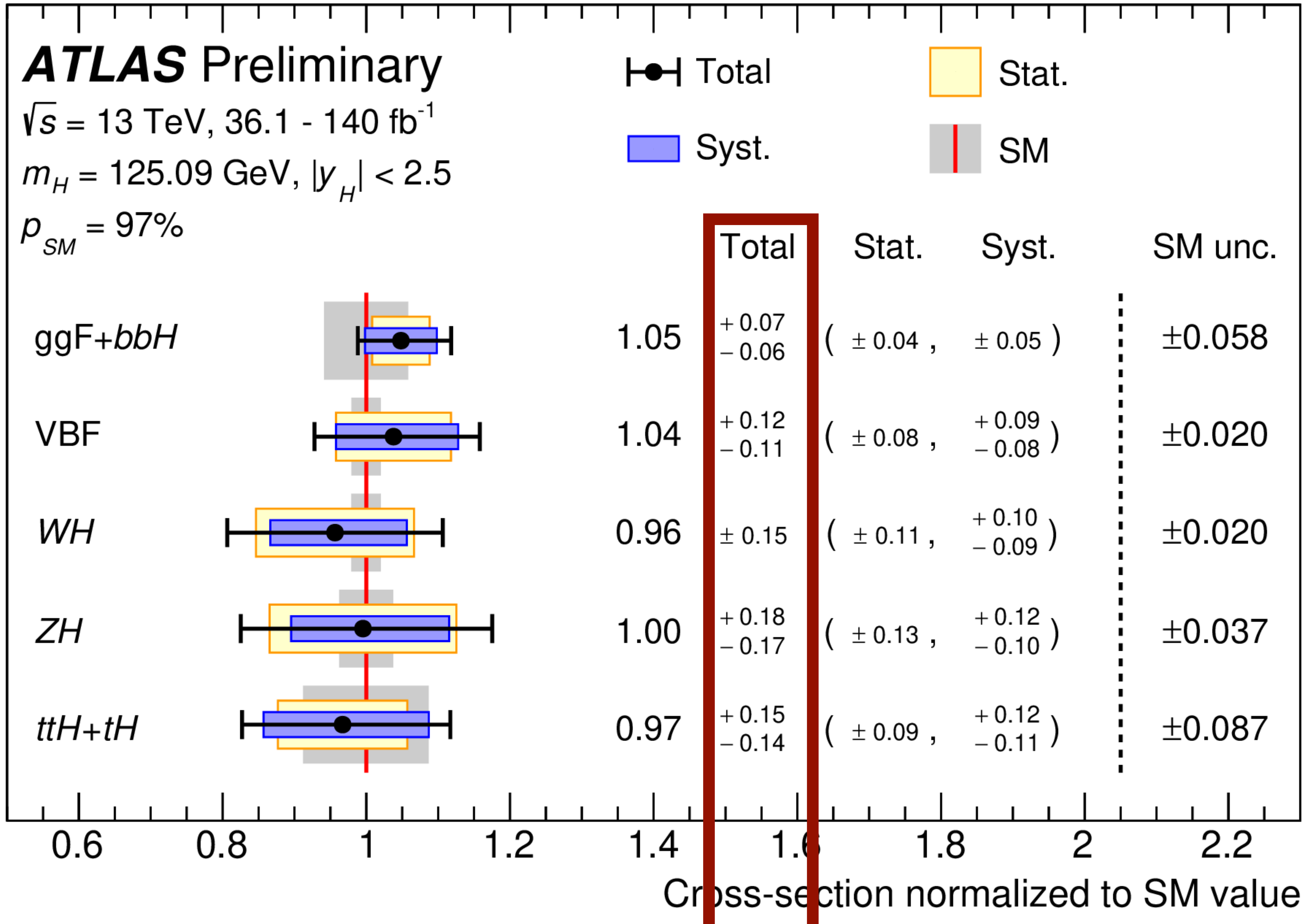
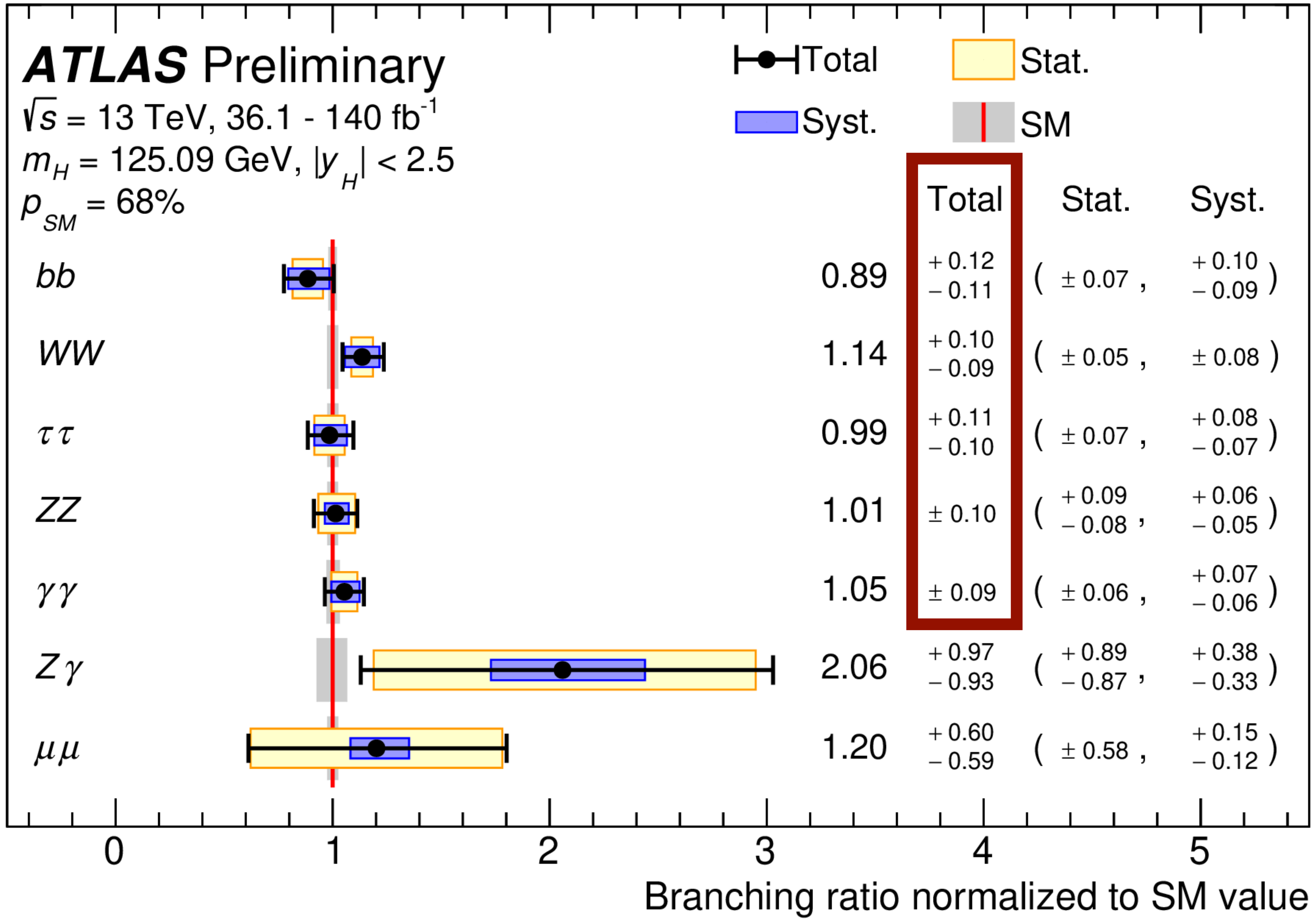
[ATLAS webpage with Plots](#)

Production and Decay



10-20%



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~10%

Couplings

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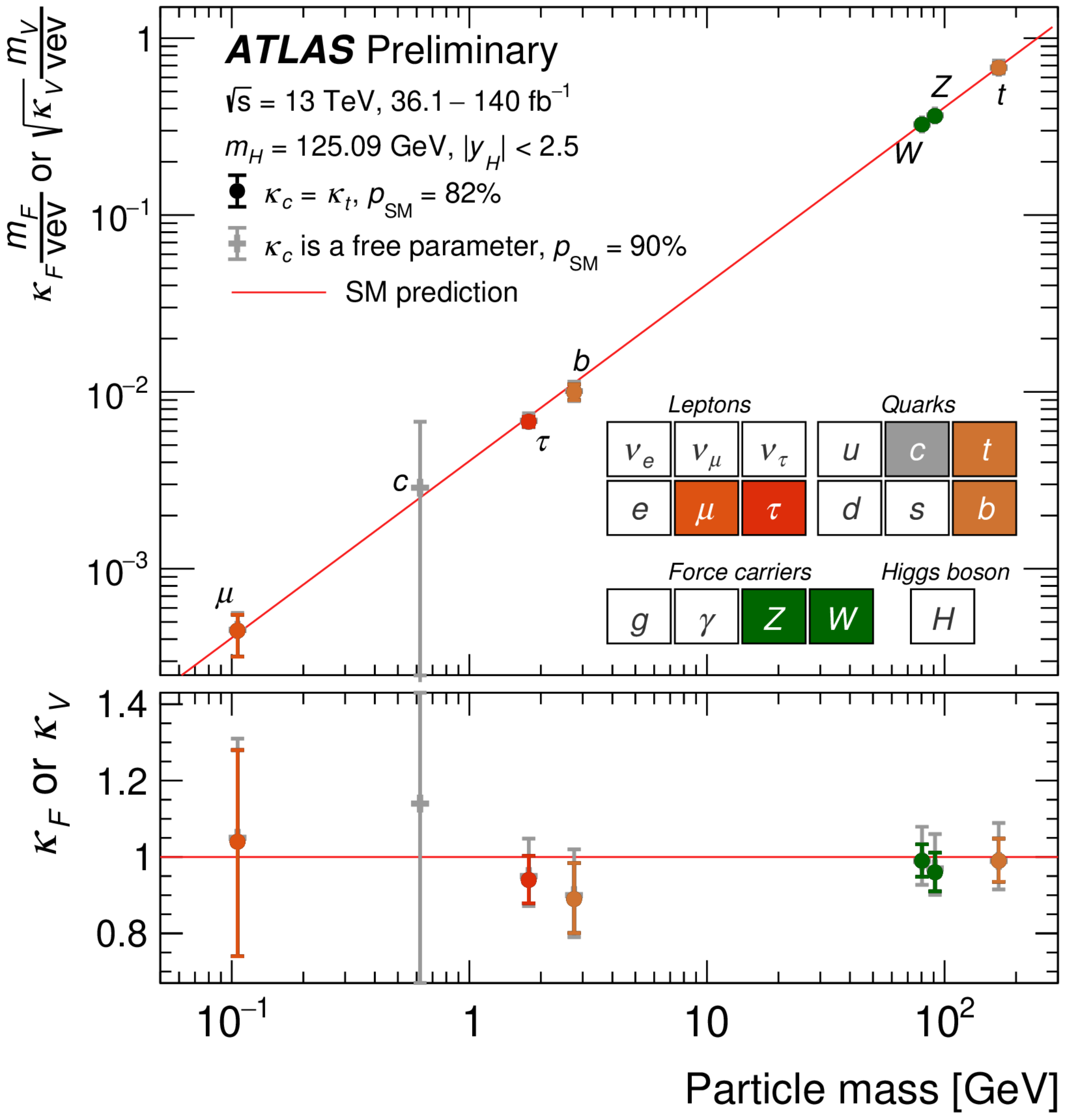
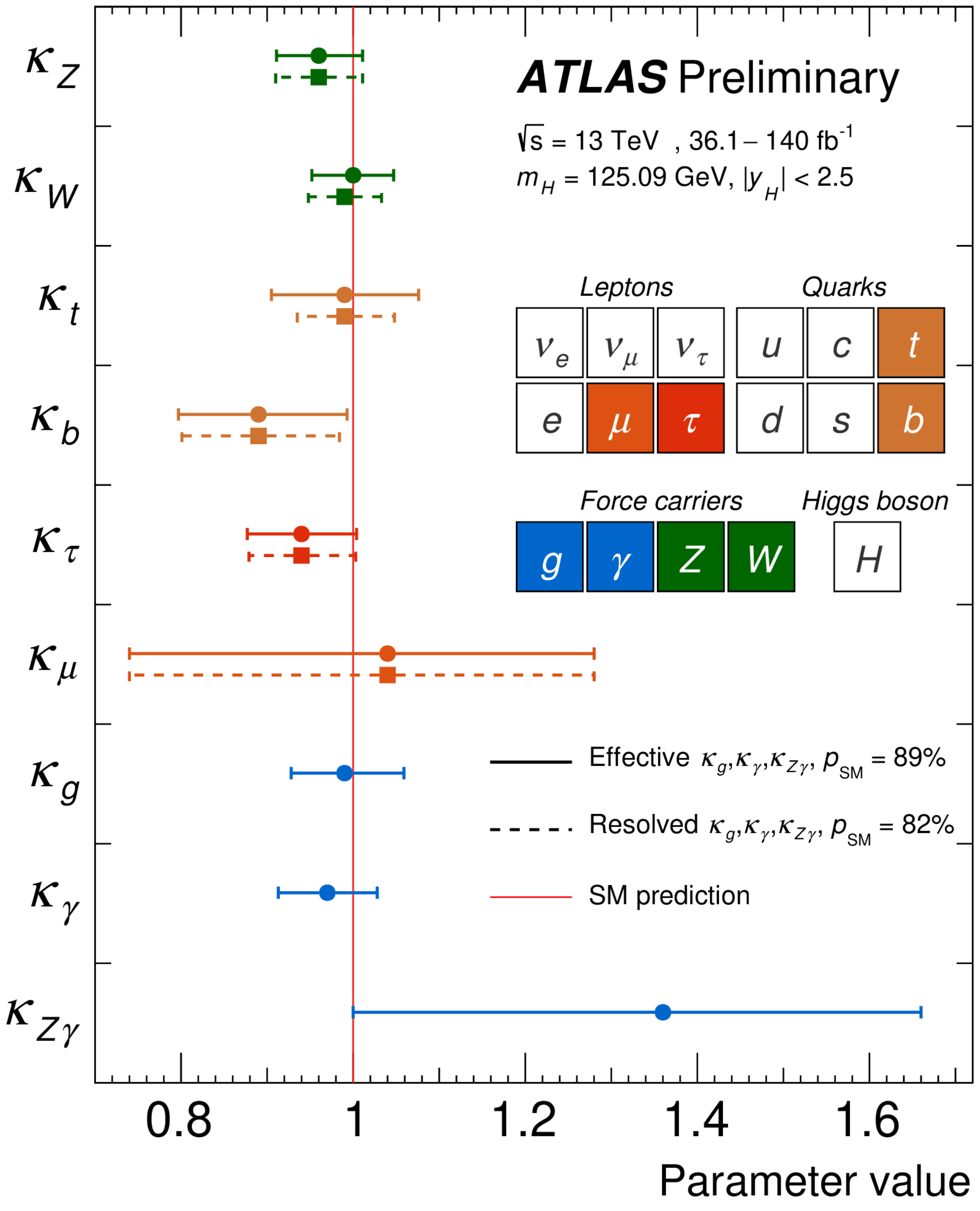
Proportionality



Coupling "Modifiers"



Couplings

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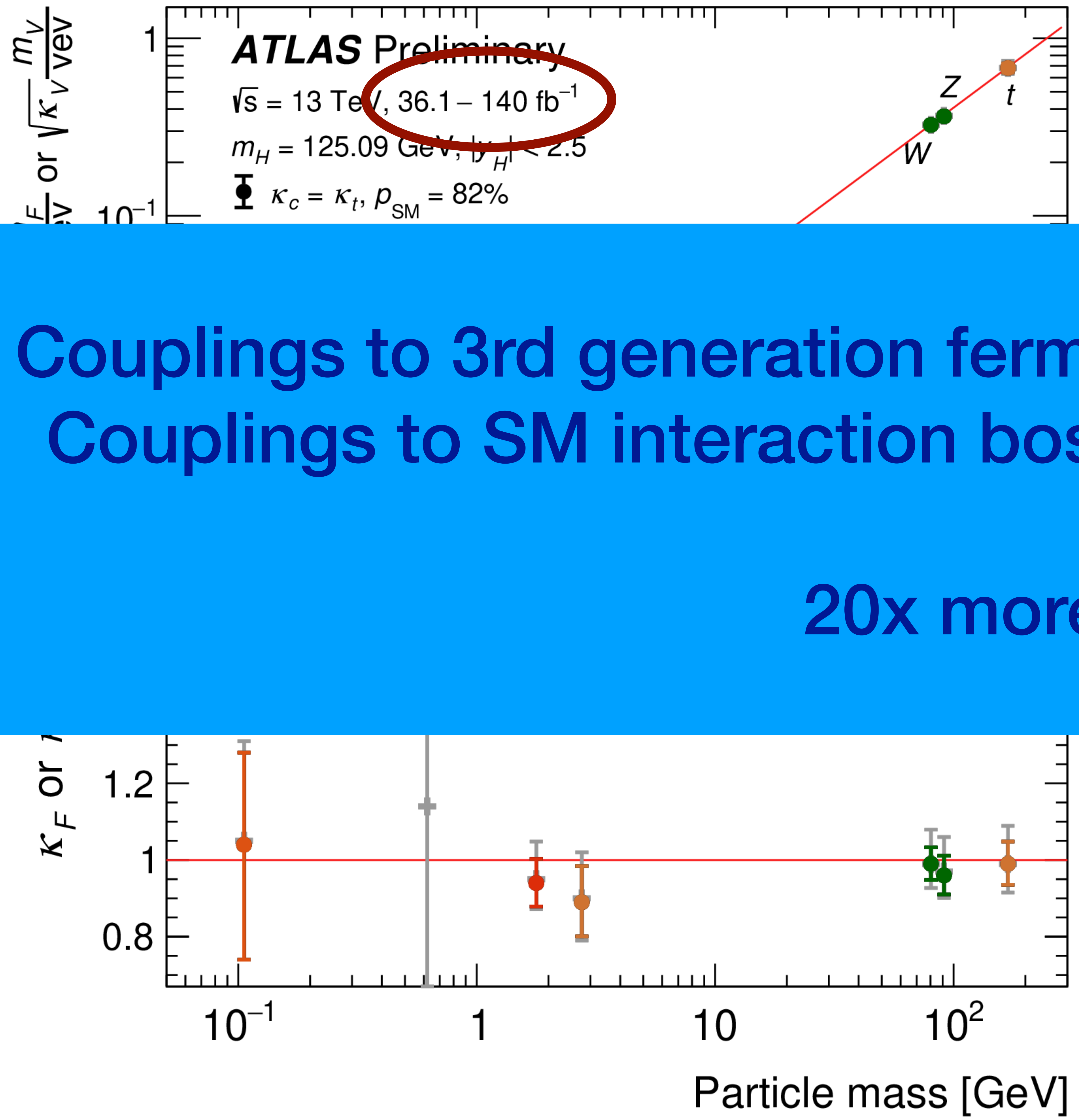

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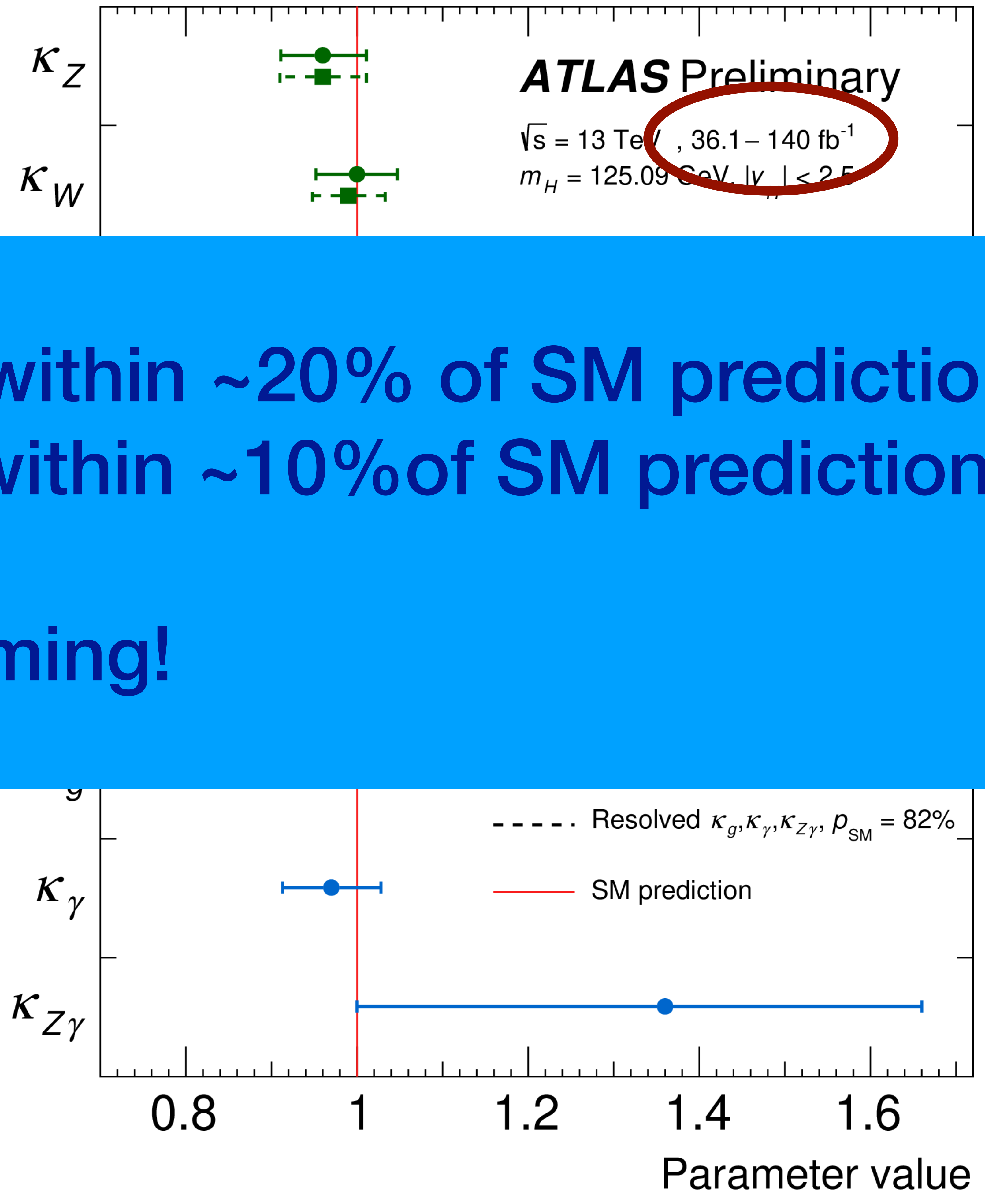
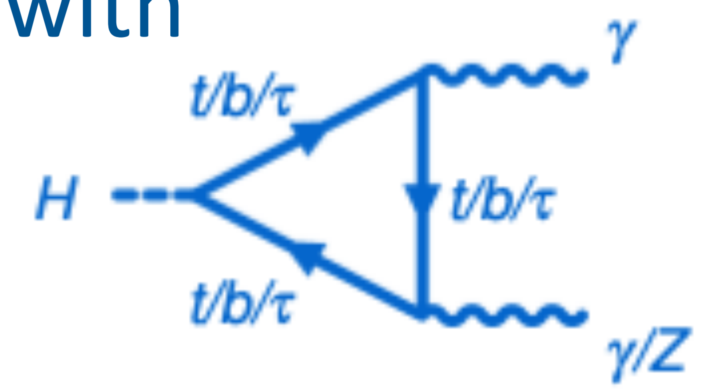


Couplings to 3rd generation fermions are within ~20% of SM prediction
Couplings to SM interaction bosons are within ~10%of SM prediction

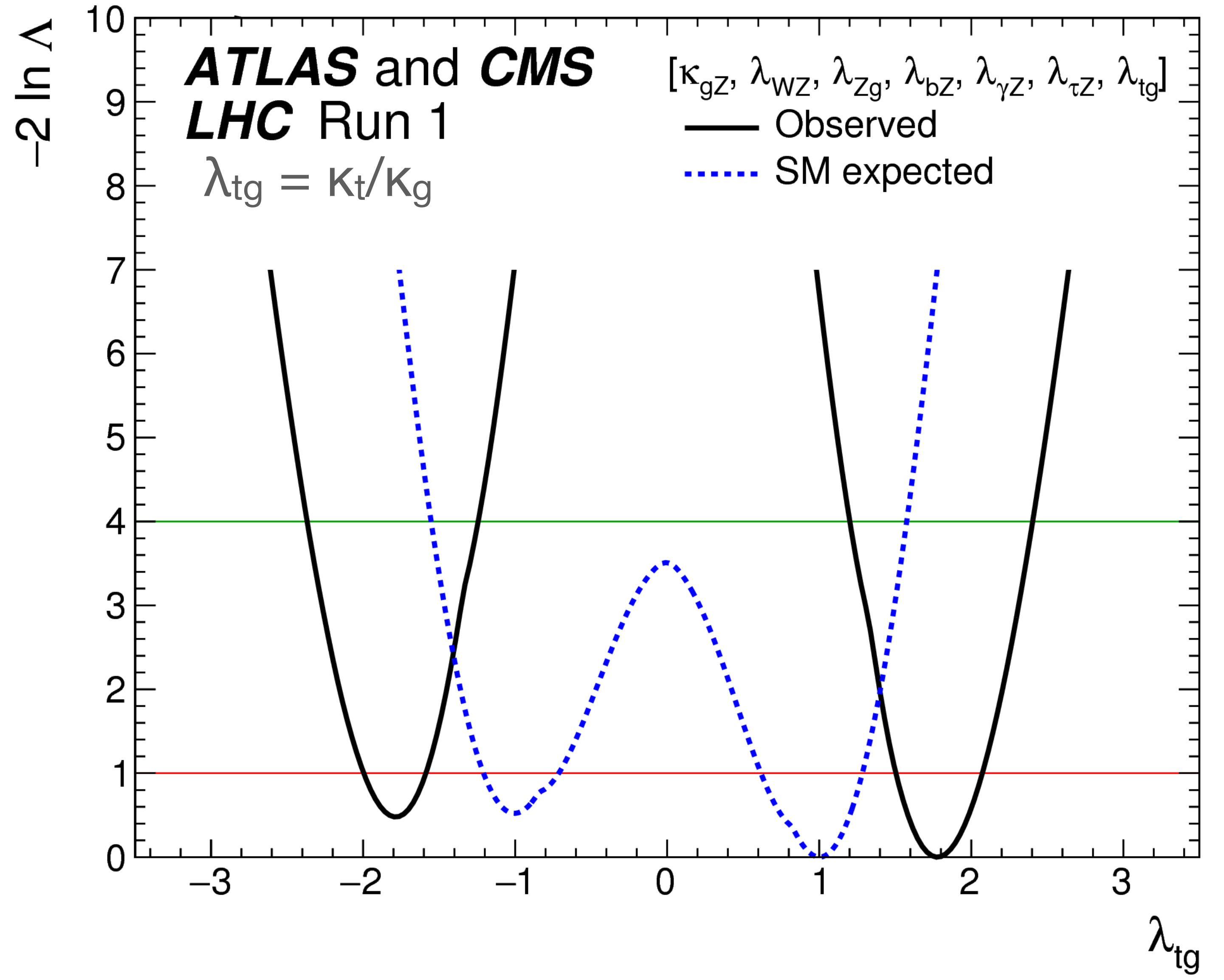
20x more data coming!

tH Production: y_t Sign

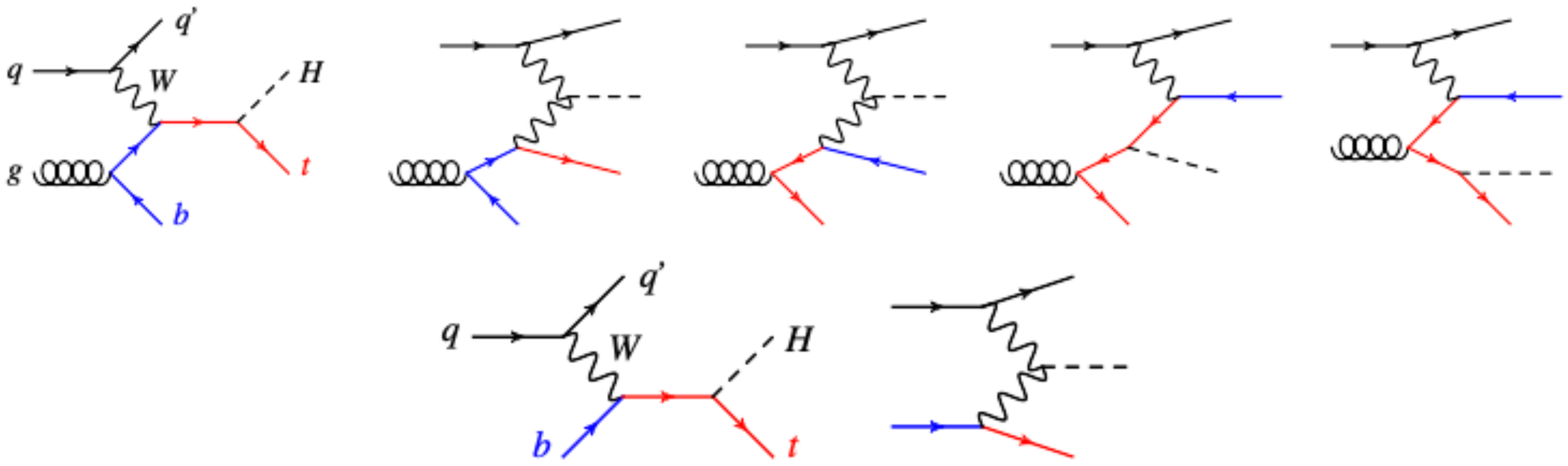
- Higgs coupling strength to the top quark (y_t) gets probed through multiple processes: not just $t\bar{t}H$, but also e.g. H → γγ or gluon fusion H production (top loop)
  - These processes are mainly sensitive to $(y_t)^2$ - to probe a coupling's sign one needs a process with interference
    - H → γγ (t-b interference) and ggF H production (t-W) have some sensitivity



- tH production however, is small in the SM ***because*** of significant destructive interference: with opposite sign the interference becomes constructive and σ(tH) increases x 10



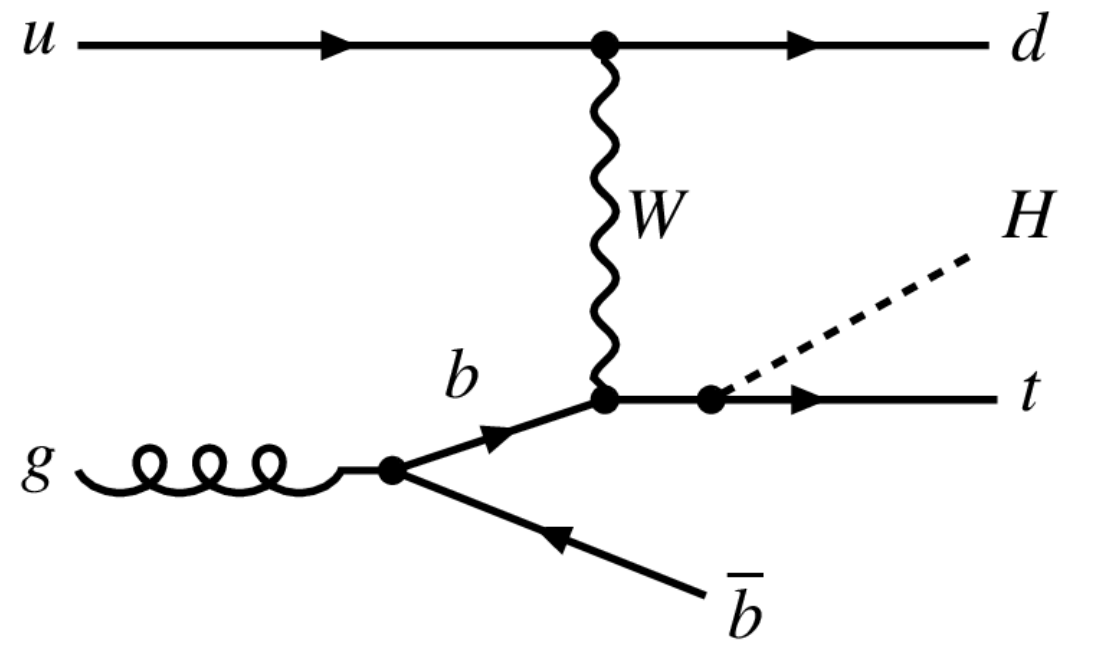
ATLAS+CMS Run 1 (7-8 TeV), **no tH**, JHEP 08 (2016) 045

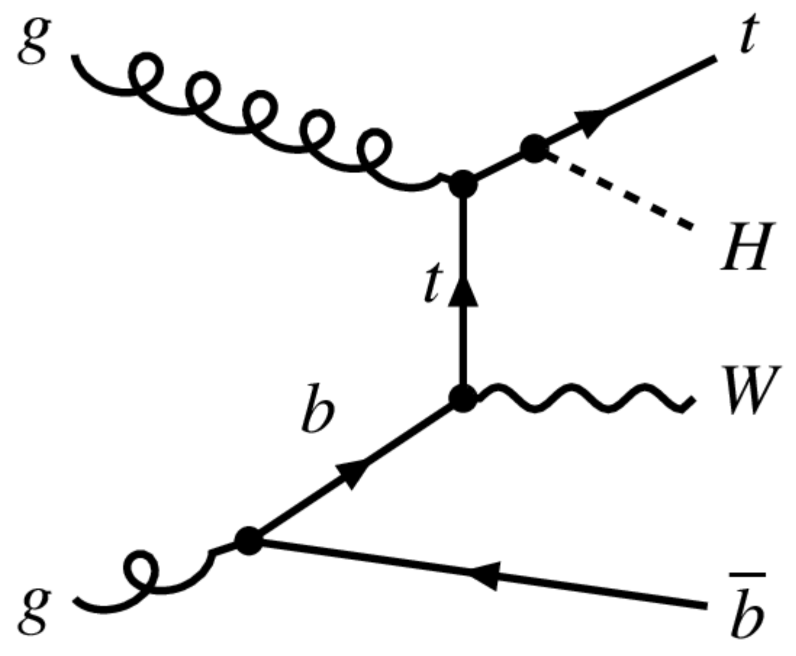


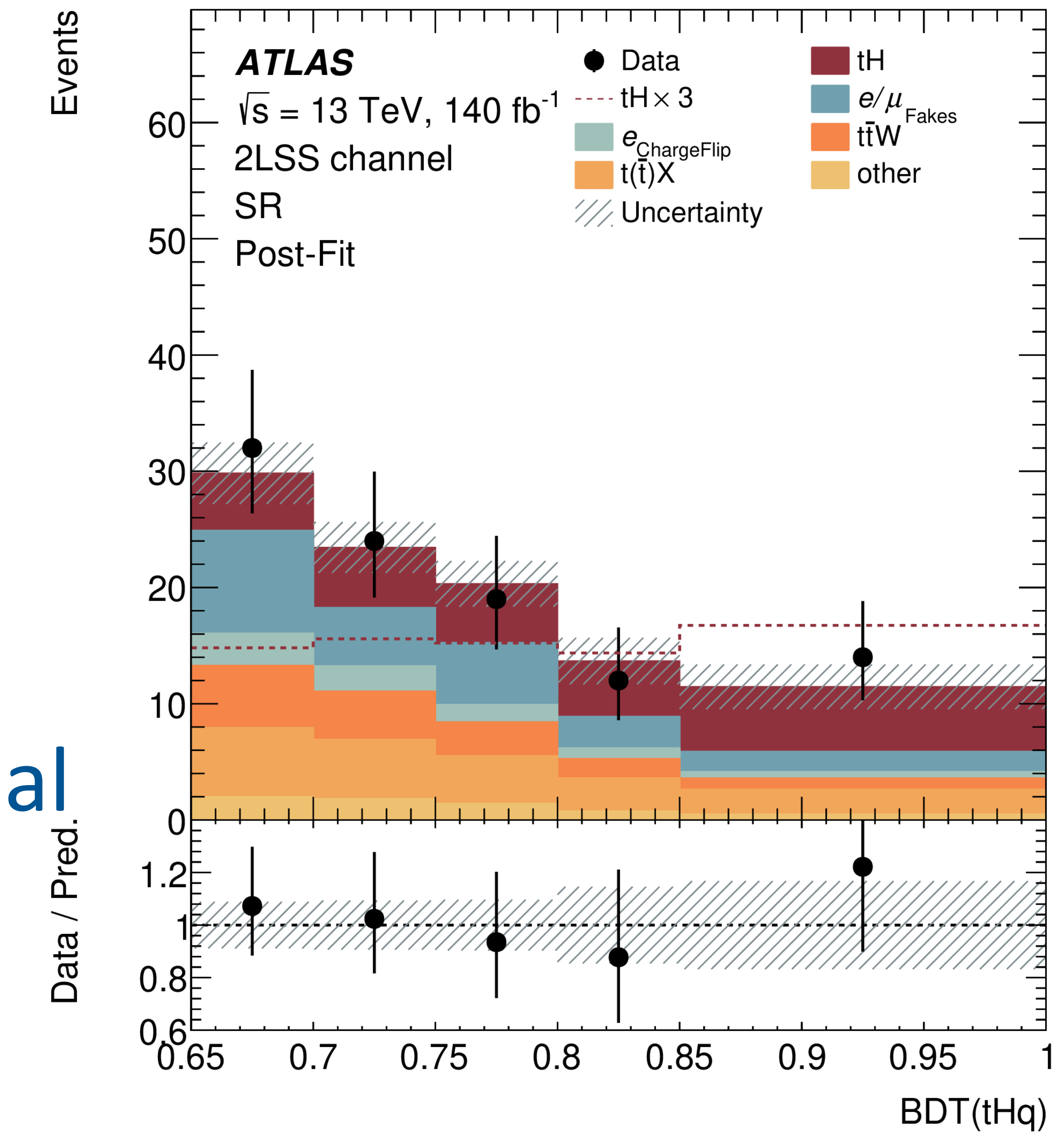
From Demartin et al, Eur.Phys.J.C 75 (2015) 6, 267

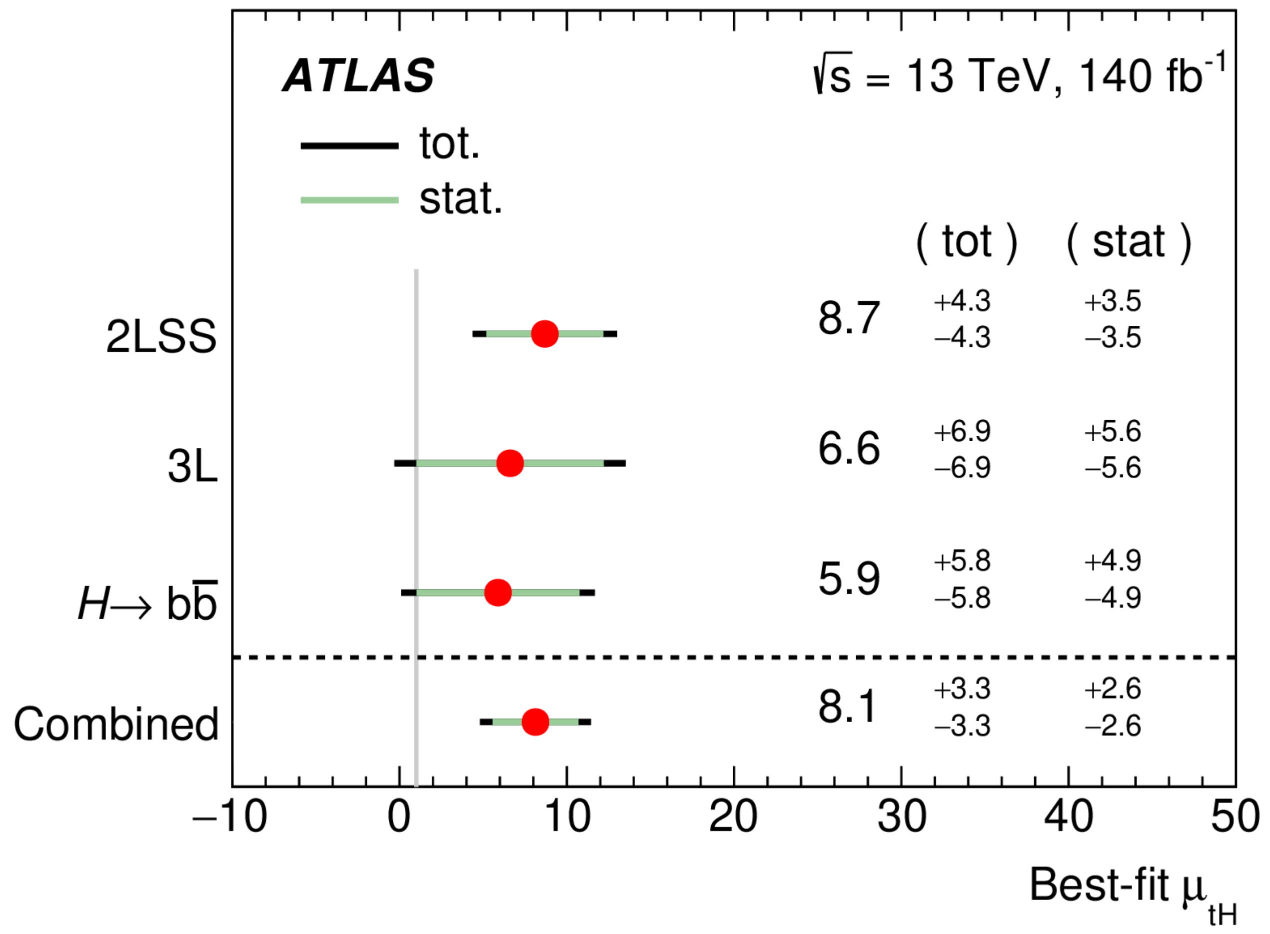
ATLAS Search for tH Production

- tHq and tHW yield distinct topologies
  - !tHW is same final state as tt̄H!
- Separate by number of leptons
  - 1 lepton (H → bb̄)
  - 2 same-charge leptons (mainly H → WW*)
  - 3 leptons (mainly H → WW*)
- Dedicated signal and control regions to constrain tt̄+b, tt̄W, "fake" leptons
- BDTs to separate signal from backgrounds
  - Only train to separate tHq from background: tHW is too close to tt̄H and including it in signal weakens separation!
    - But of course tHW contribution fully taken into account as signal









2.8σ significance!
0.4σ expected…

ATLAS, arXiv:2508.14695
ATLAS webpage with Plots etc

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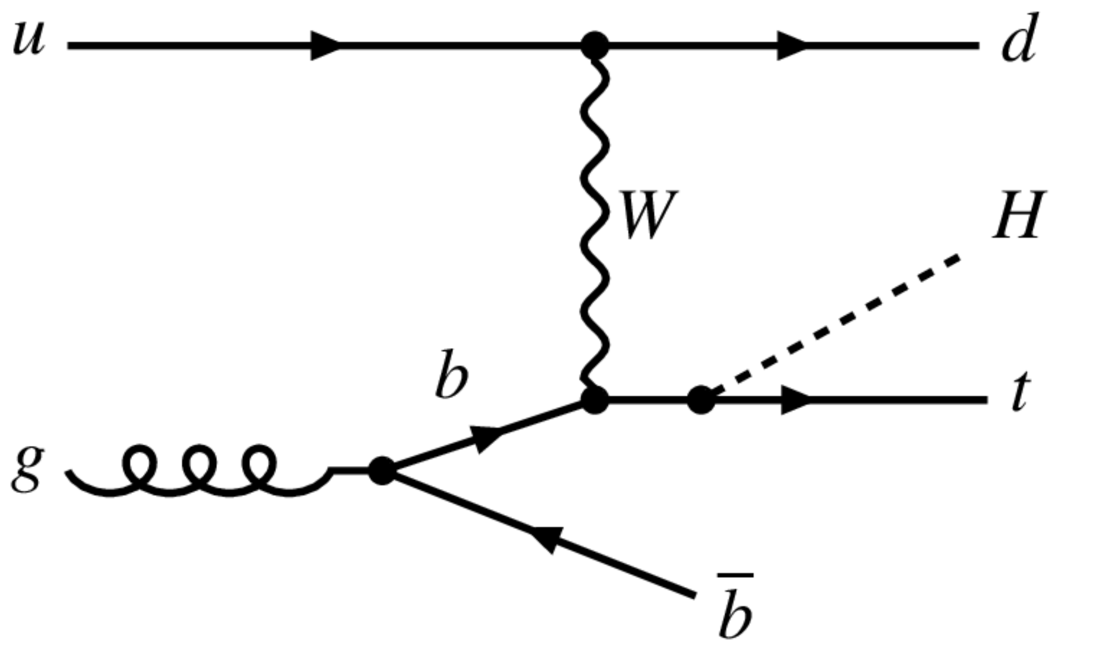
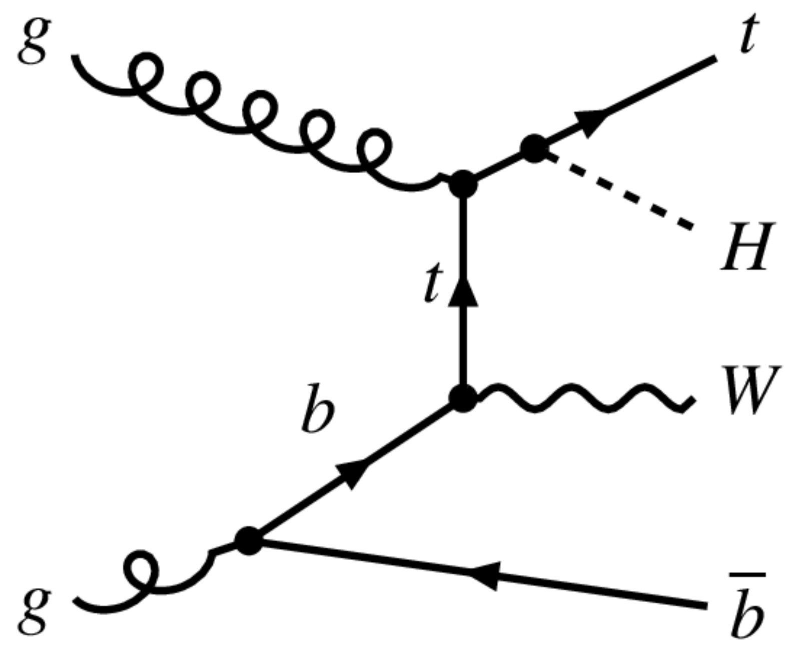
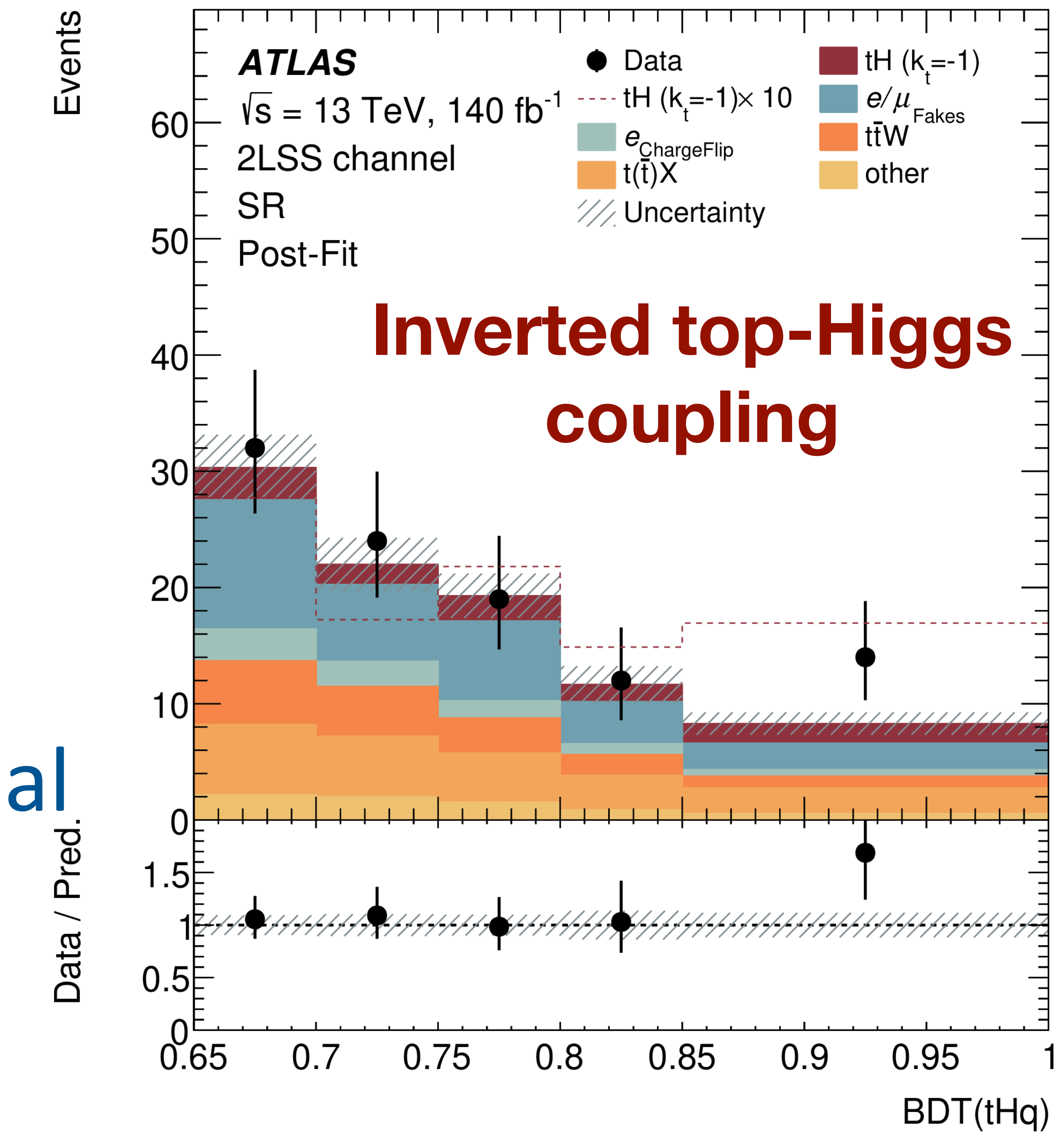
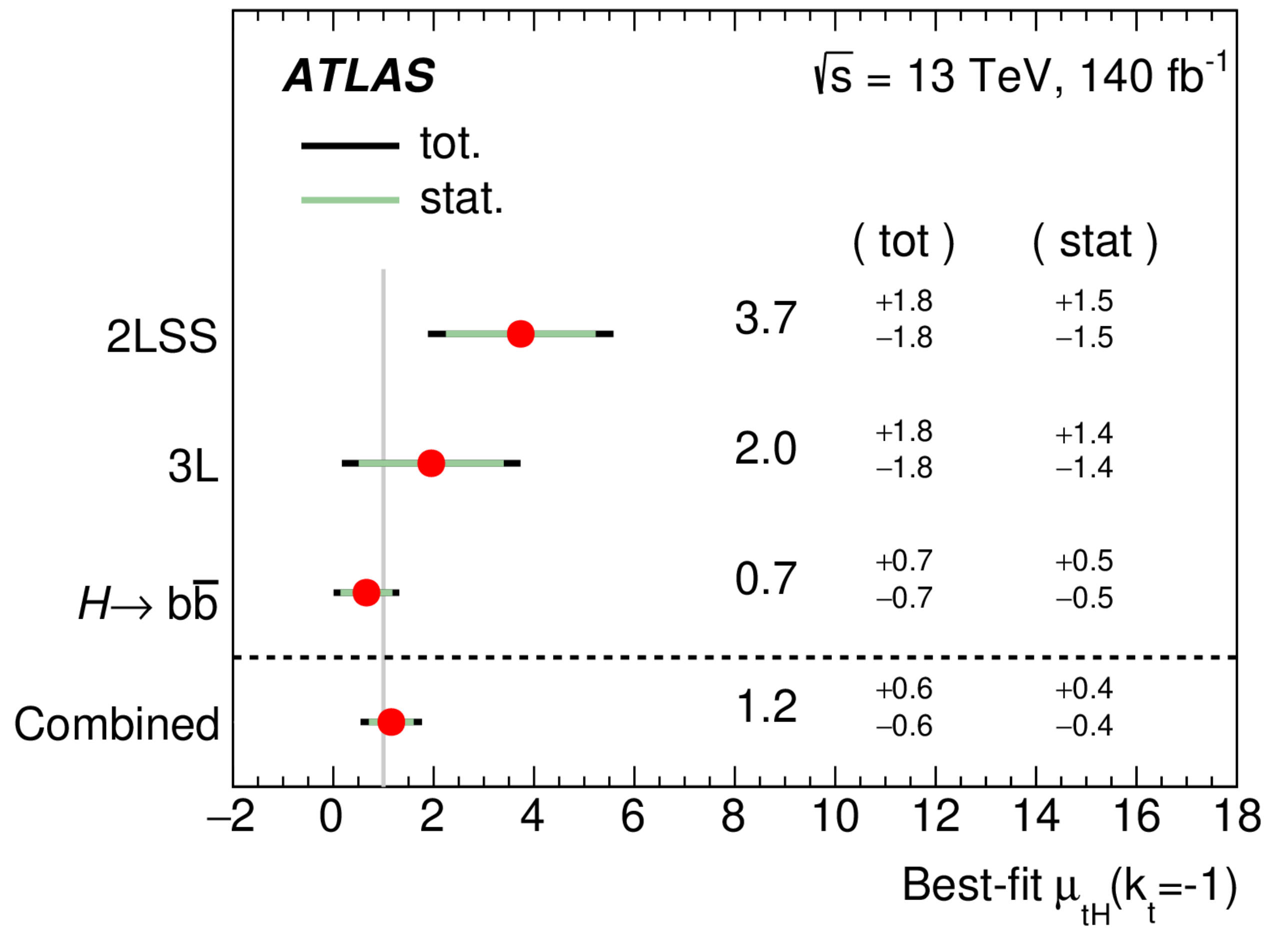






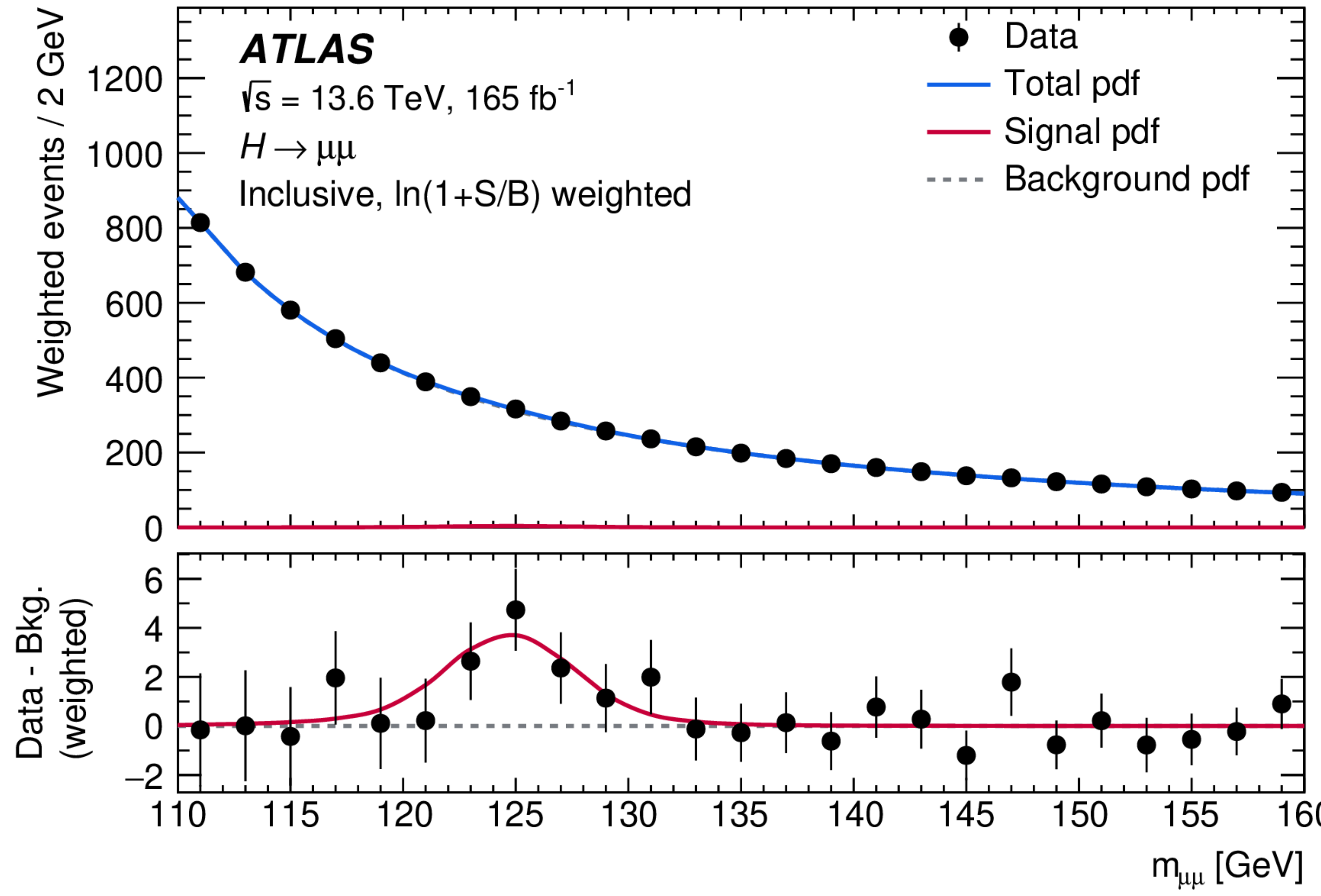


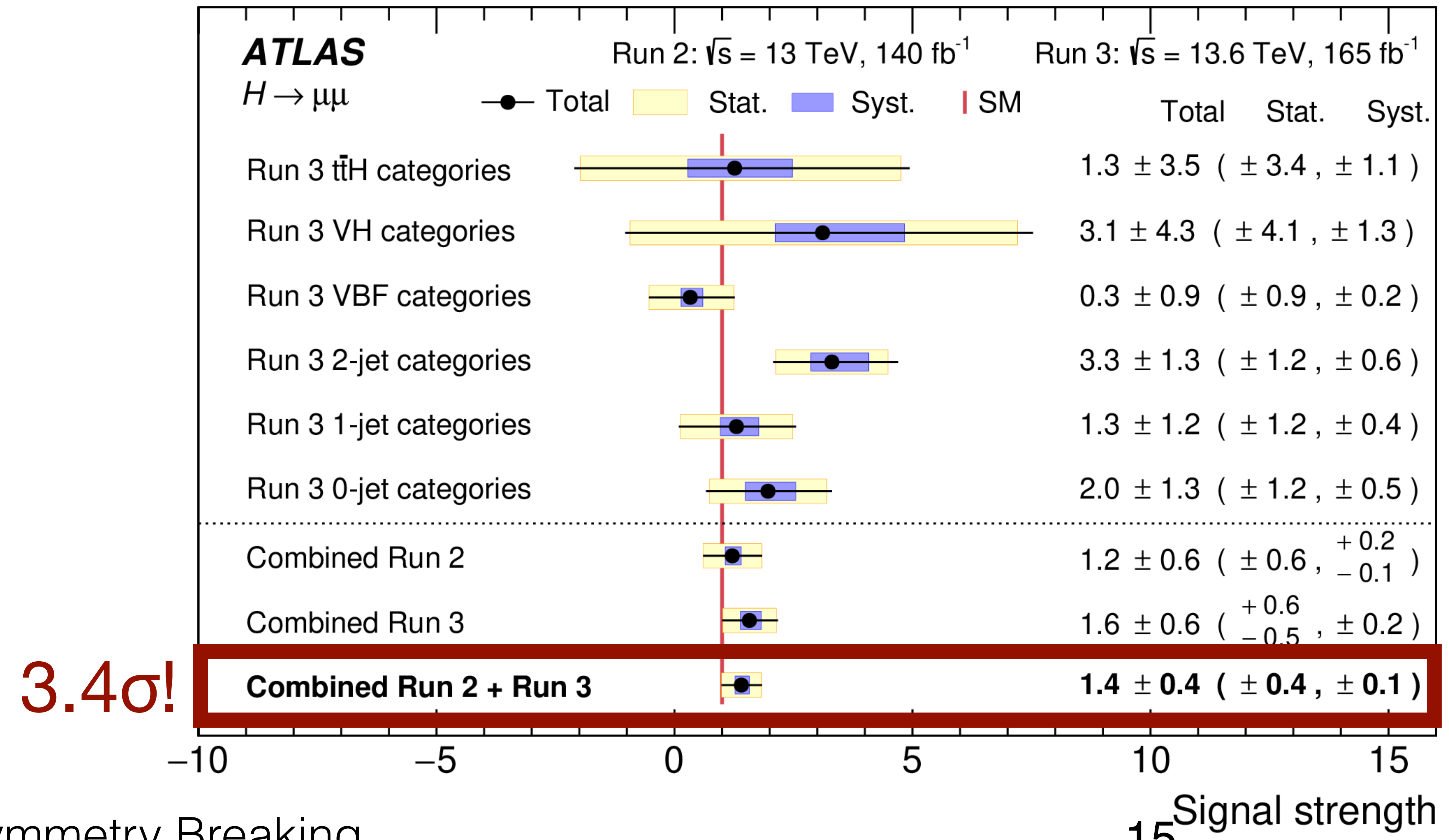
BDTs not retrained, biggest changes in multi-l channels

ATLAS, arXiv:2508.14695
ATLAS webpage with Plots etc

Rare Decays: H → μμ

- Total Higgs production cross-section is > 50 pb, so 300 fb^{-1} of data ⟹ 15x10^{6} Higgs bosons produced
  - Now enough luminosity to probe rare decays: in the SM, H → μμ branching ratio is ~2x10^{-4}
    - That's 3000 potential H → μμ events, reduced by detector acceptance and selection & reconstruction efficiency factors (47% for Run 3 data)
    - Primary background is Drell-Yan continuum μμ production
- New analysis improves background description (huge DY MC sample), mass resolution from improved μμ vertex fit; adds VH/ttH events with V/tt decaying hadronically; new NN for ttH event categorization
- 23 categories: separate events by production process and purity based on process-specific BDT or NN score
  - Fitted simultaneously

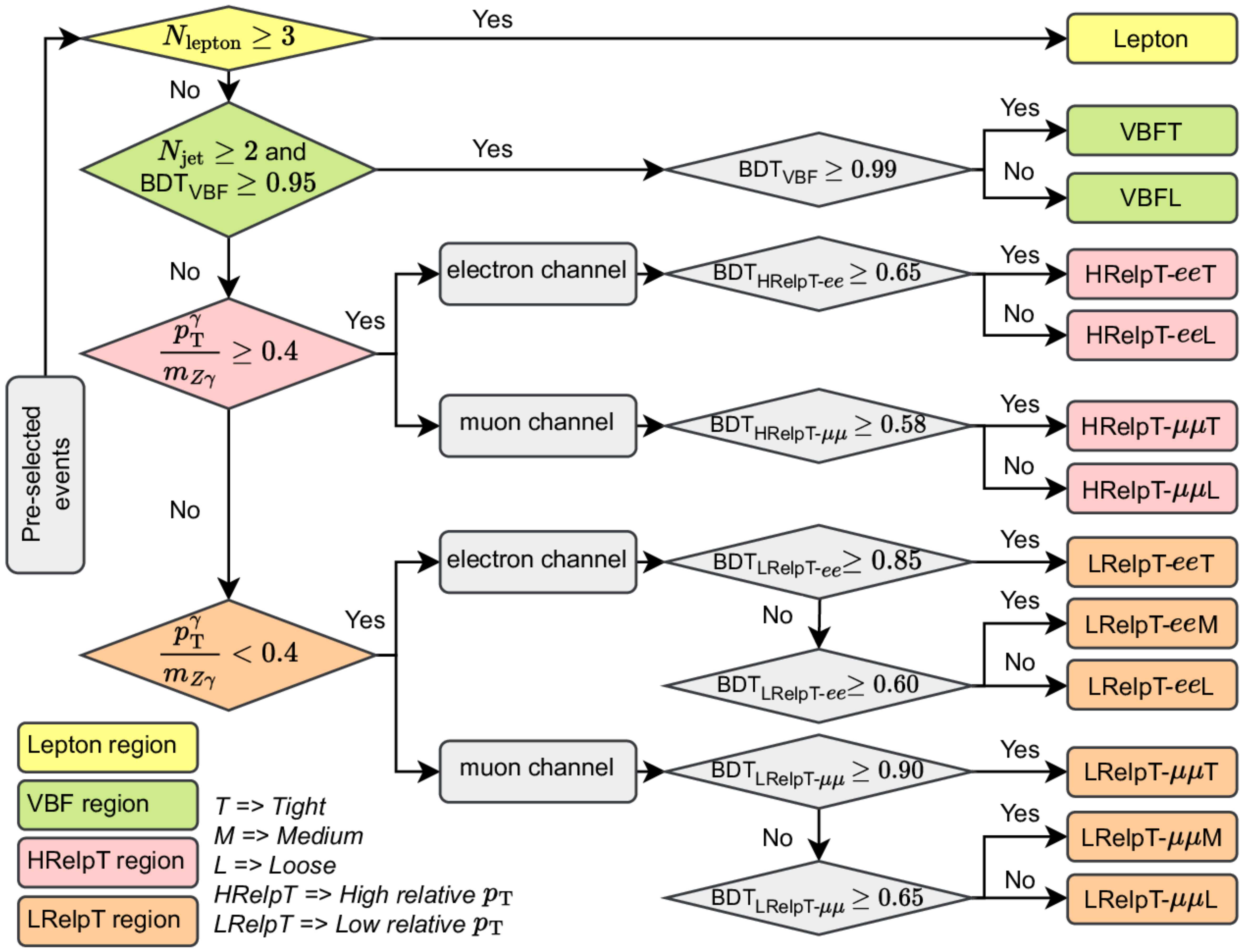




ATLAS, arXiv:2507.03595
ATLAS webpage with plots

Rare Decays: H → Zγ

- In the SM, BR(H→Zγ) = 1.5×10^{-3}, so 10x larger than μμ
  - But this is loop-induced, so more sensitive to new heavy particles running in loops, and BR(H→Zγ)/BR(H→γγ) makes for a particularly sensitive probe
- Experimentally harder than H→μμ: to suppress very large γ+jets backgrounds, best option is Z→ee/μμ, but those BRs are just 3.4%
  - And decay products are "softer", since effectively a 3-body decay
  - Classify events based on number of leptons and jets, and photon p_T
    - Background dominated by Zγ and Z+jets



ATLAS, arXiv:2507.12598
ATLAS webpage with plots

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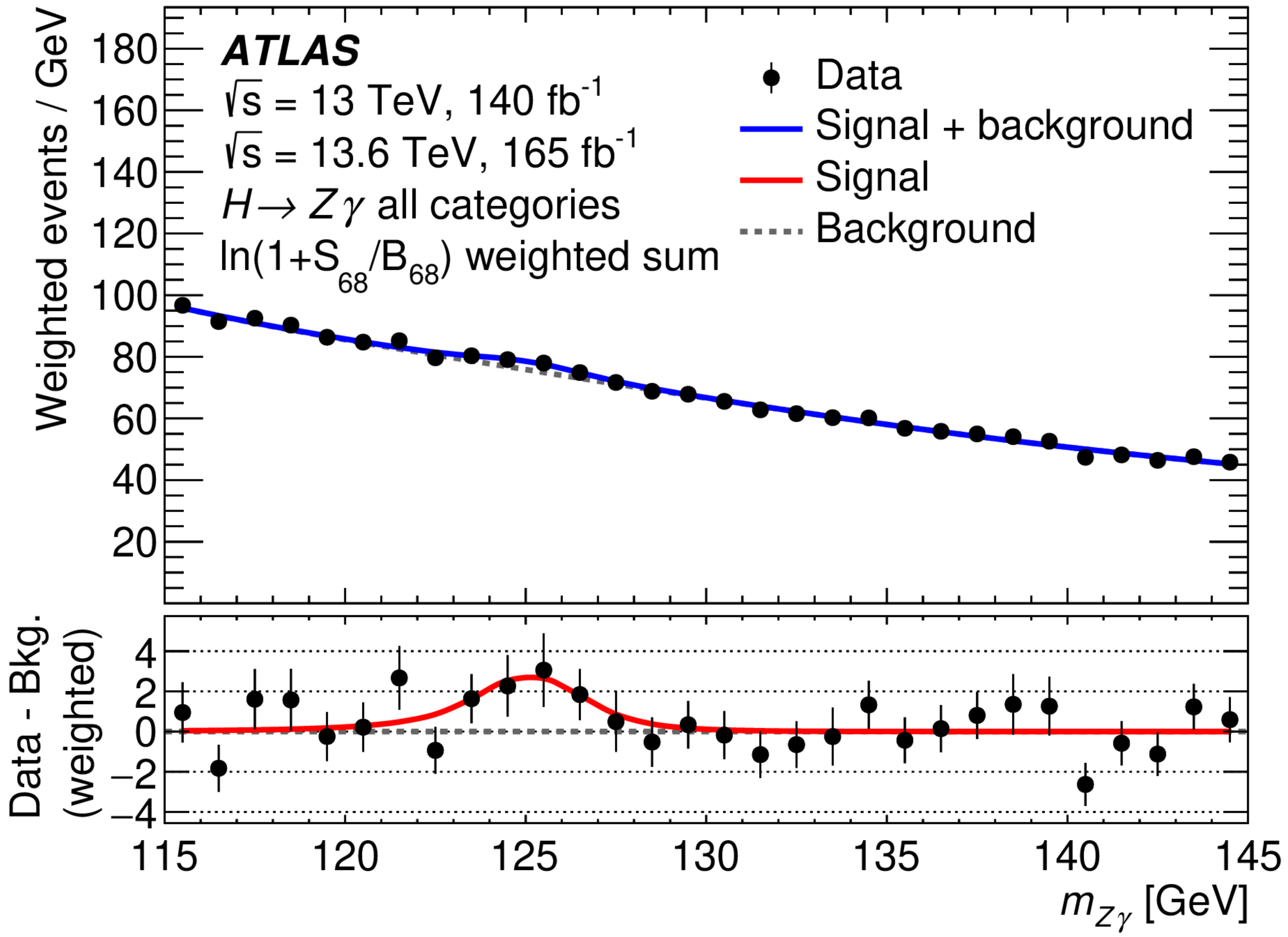
Category	S_{68}^{exp}	B_{68}^{exp}	N_{68}	w_{68} [GeV]	$S_{68}^{exp}/\sqrt{S_{68}^{exp}+B_{68}^{exp}}$
Lepton	1.5 ± 1.1	76.3 ± 2.8	78	4.4	0.17
VBFT	1.5 ± 1.1	1.2 ± 0.4	3	3.8	0.91
VBFL	2.8 ± 2.0	27.6 ± 1.8	23	4.0	0.51
HRelpT-eeT	1.2 ± 0.8	6.6 ± 0.9	11	3.1	0.43
HRelpT-eeL	3.0 ± 2.1	54.10 ± 1.8	77	4.0	0.40
HRelpT-$\mu\mu$T	2.4 ± 1.7	20.3 ± 1.7	33	3.9	0.50
HRelpT-$\mu\mu$L	2.4 ± 1.7	56.5 ± 1.7	72	4.1	0.31
LRelpT-eeT	9 ± 6	234 ± 6	251	3.8	0.57
LRelpT-eeM	29 ± 20	2 591 ± 19	3 806	4.1	0.56
LRelpT-eeL	24 ± 17	13 260 ± 50	17 435	4.5	0.21
LRelpT-$\mu\mu$T	4.9 ± 3.4	96 ± 4	127	3.9	0.49
LRelpT-$\mu\mu$M	34 ± 24	2 545 ± 19	3 133	4.1	0.67
LRelpT-$\mu\mu$L	37 ± 26	16 960 ± 40	19 331	4.4	0.28
Inclusive	150 ± 110	35 930 ± 70	44 380	4.0	1.81

ATLAS, arXiv:2507.12598
ATLAS webpage with plots

Rare Decays: $H \to Z\gamma$

- Signal extraction done through S+B fit to $m_{Z\gamma}$ spectrum:



ATLAS, arXiv:2507.12598
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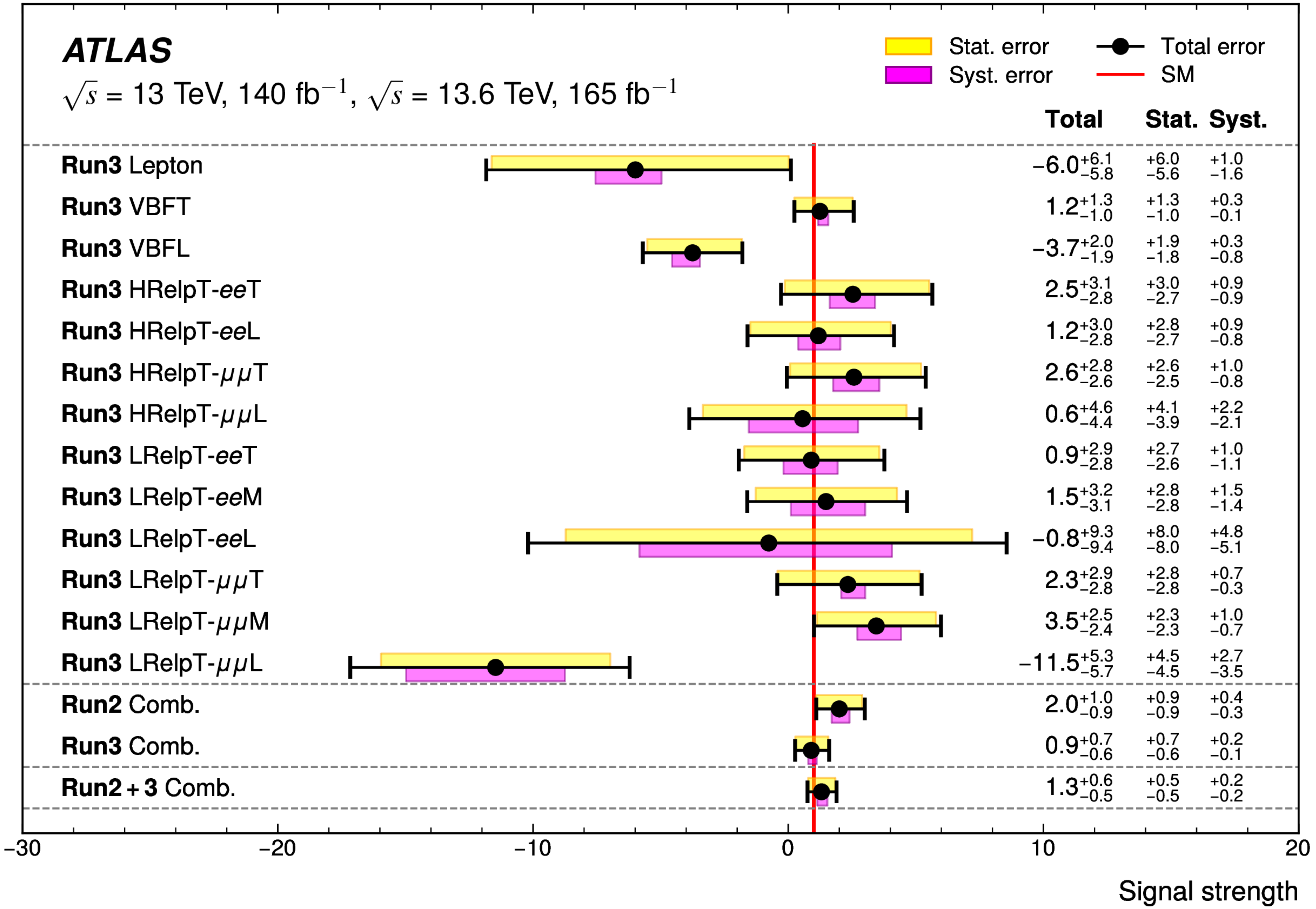
- For the background, parametrize using an analytic function:
  - Require decent fit, spurious signal < 20% of expected signal statistical uncertainty
    - While minimizing the number of free parameters
- Then do unbinned ML fit to $m_{Z\gamma}$ across all categories simultaneously

Rare Decays: H → Zγ



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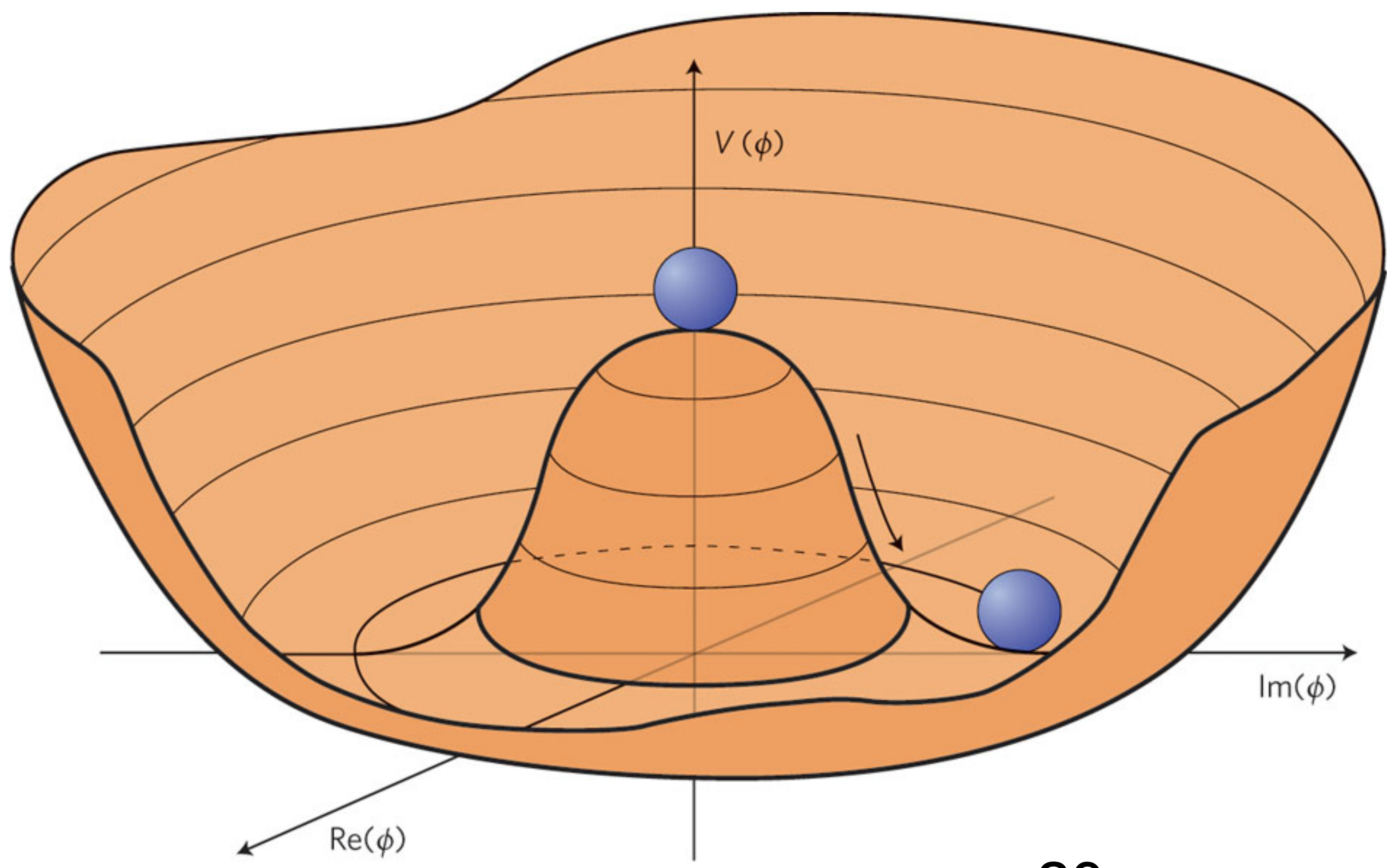
2.5σ

(Run 2 ATLAS+CMS combination was 3.4 σ)

The Higgs Potential

- WW scattering, and WW pair production from fermion annihilation, strongly pointed to the existence of a Higgs-like object
  - The most economical way to solve both problems
- From a more technical point of view, replacing $m_f\overline{\psi}_L\psi_R$ with $y_f\overline{\psi}_L\phi\psi_R$ requires ϕ to be (at least) a (complex) $SU(2)_L$ doublet
  - 3 degrees of freedom are the longitudinal W/Z components, the 4th the Higgs boson
- But for all this to work, and masses to be generated, the Higgs doublet needs to acquire a vacuum expectation value; need a potential term with multiple minima
  - From a human point of view, 4th order polynomial with only even terms is the most economical $\Longrightarrow V = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$ with $\mu^2 < 0$ and $\lambda > 0$ yields the desired result
    - m_H and v (246 GeV) determine μ and λ



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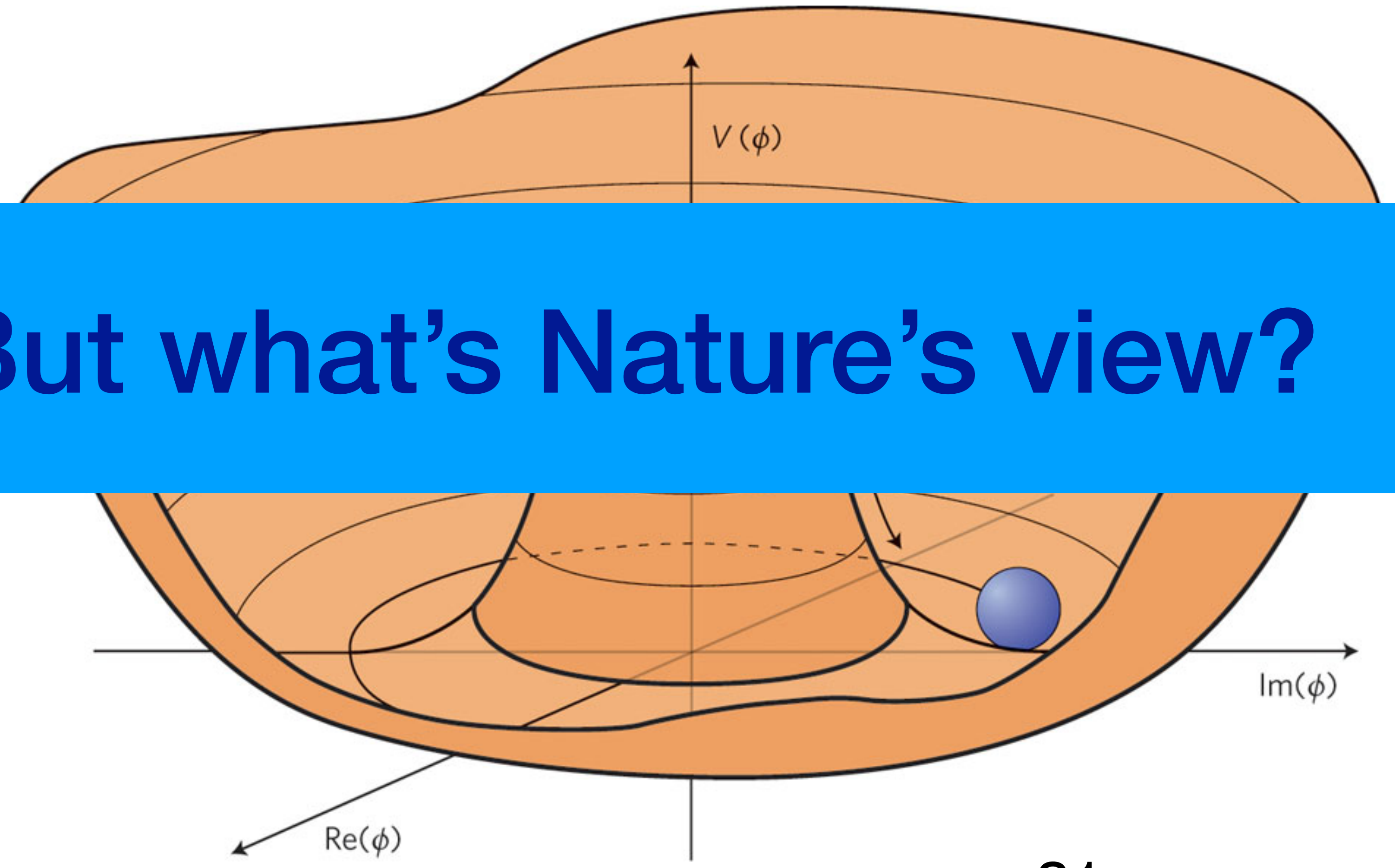
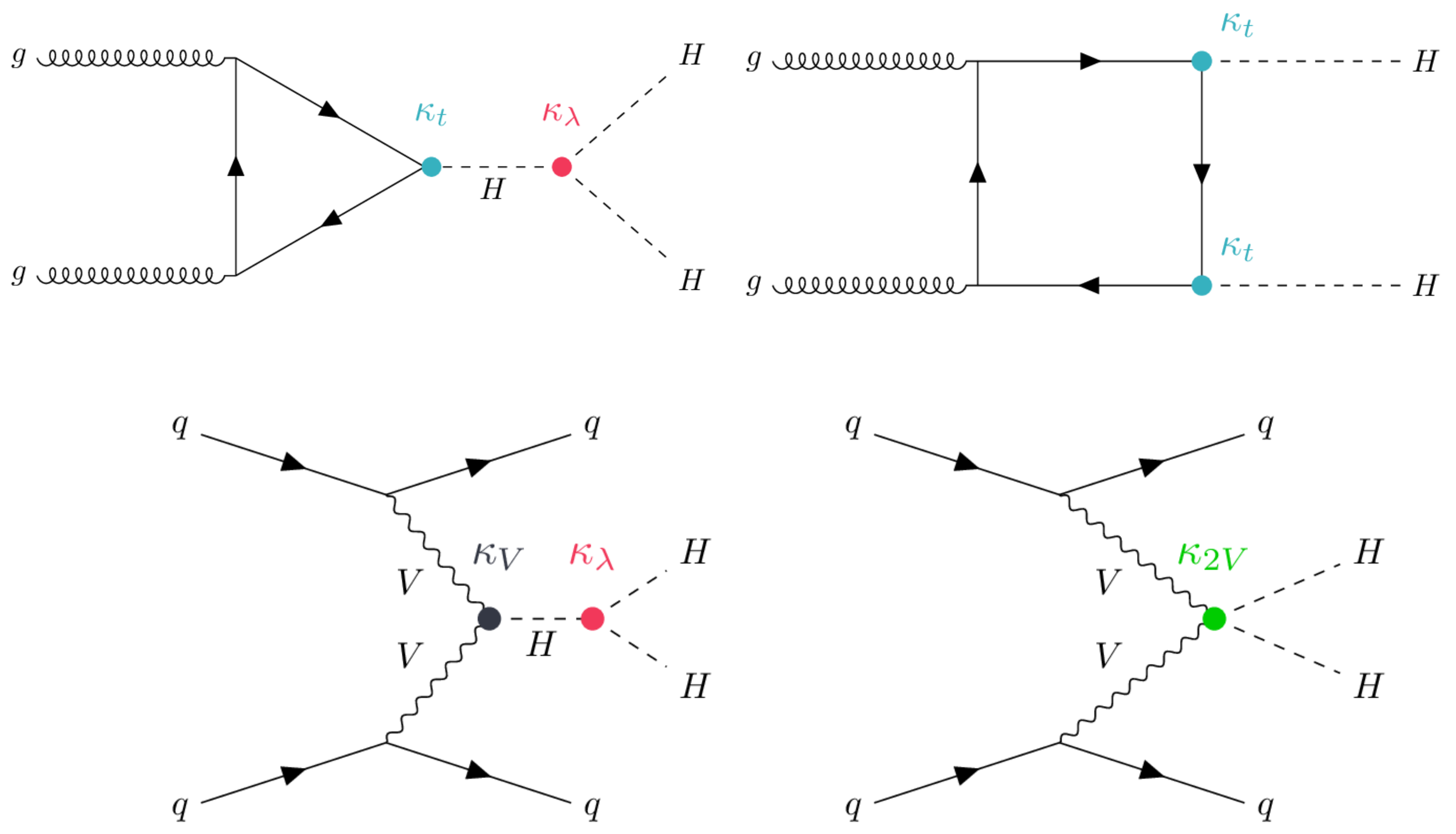
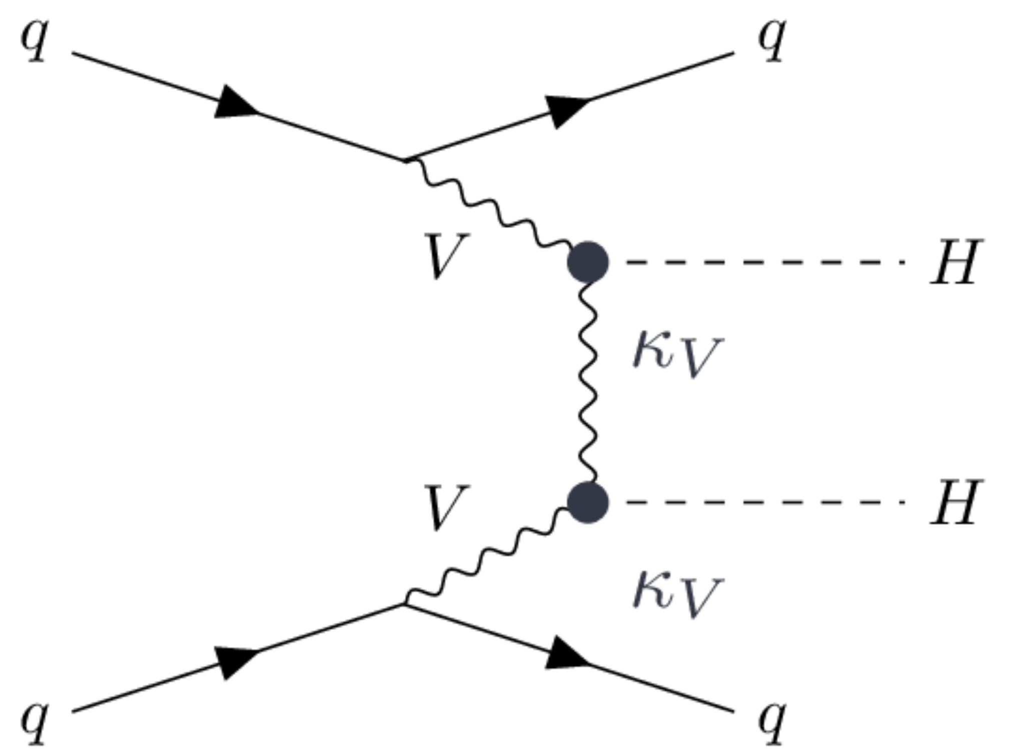


But what's Nature's view?

Probing V(ϕ): Di-Higgs Production

- Probing Higgs potential requires processes with multi-Higgs vertices
  - Most sensitive is di-Higgs production
- Whether through gluon fusion or vector boson fusion, there is destructive interference $\Longrightarrow$ tiny cross-sections (31 and 2 fb) ($\Longrightarrow$ HL-LHC!)
  - Also sensitivity to deviations from SM primarily close to threshold, hardest region to probe experimentally
    - HH → 4b yields 4 b-jets with p = O(60 GeV)
  - But deviation from SM typically means less destructive interference





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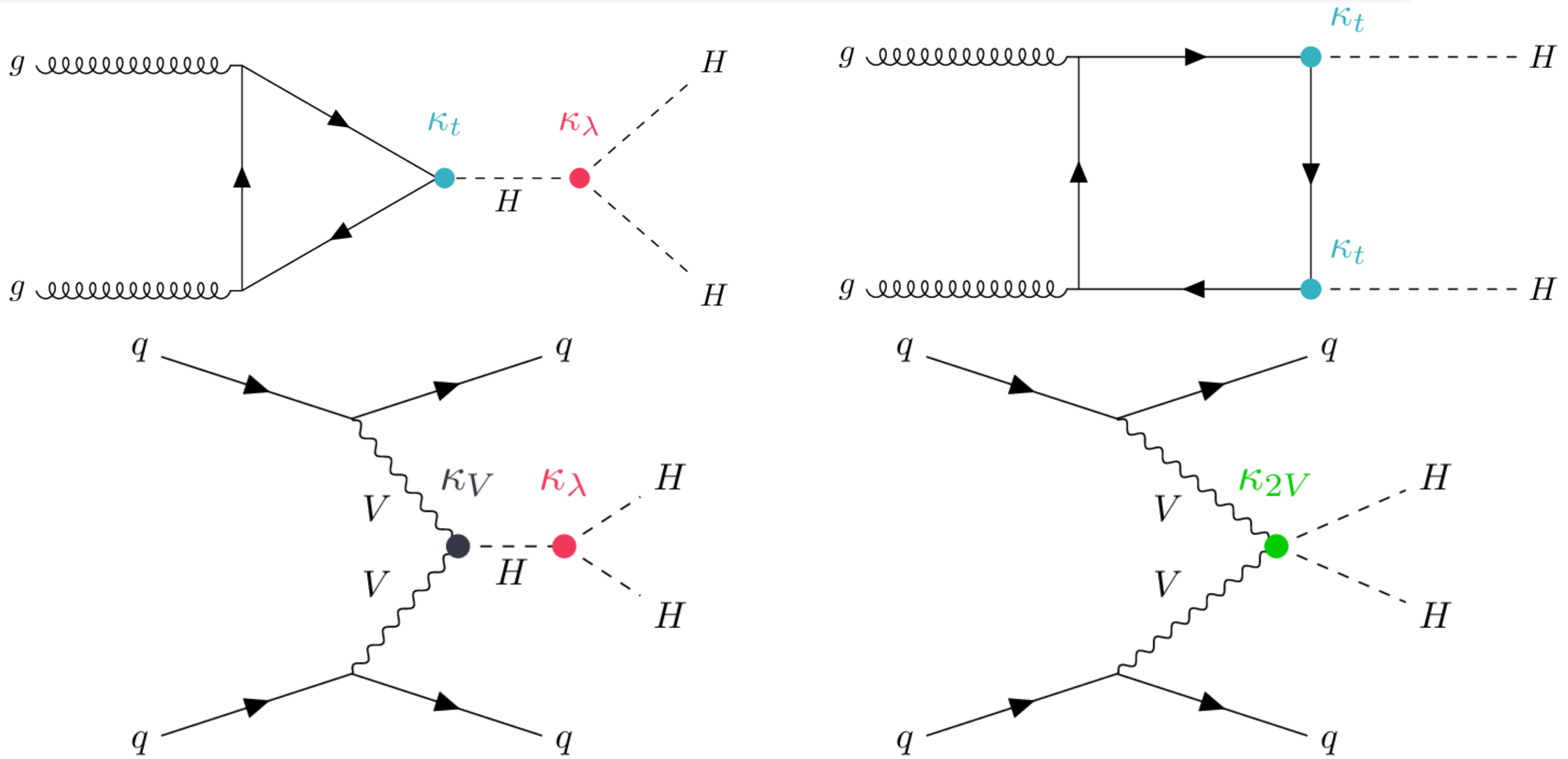
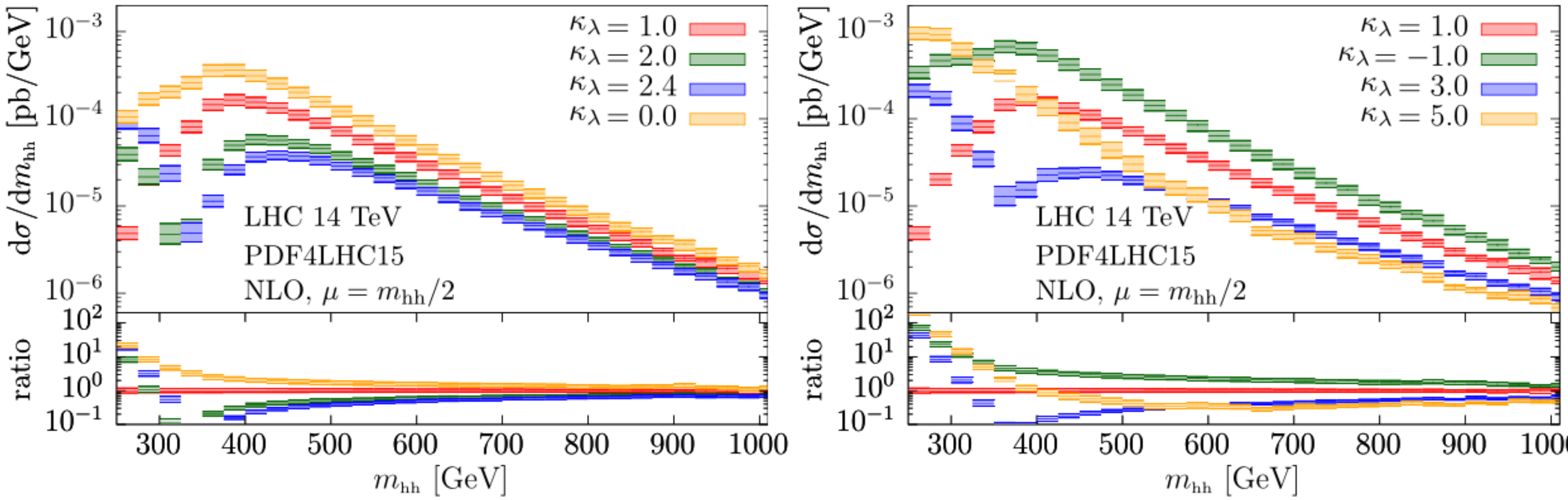
  - But deviation from SM typically means less destructive interference





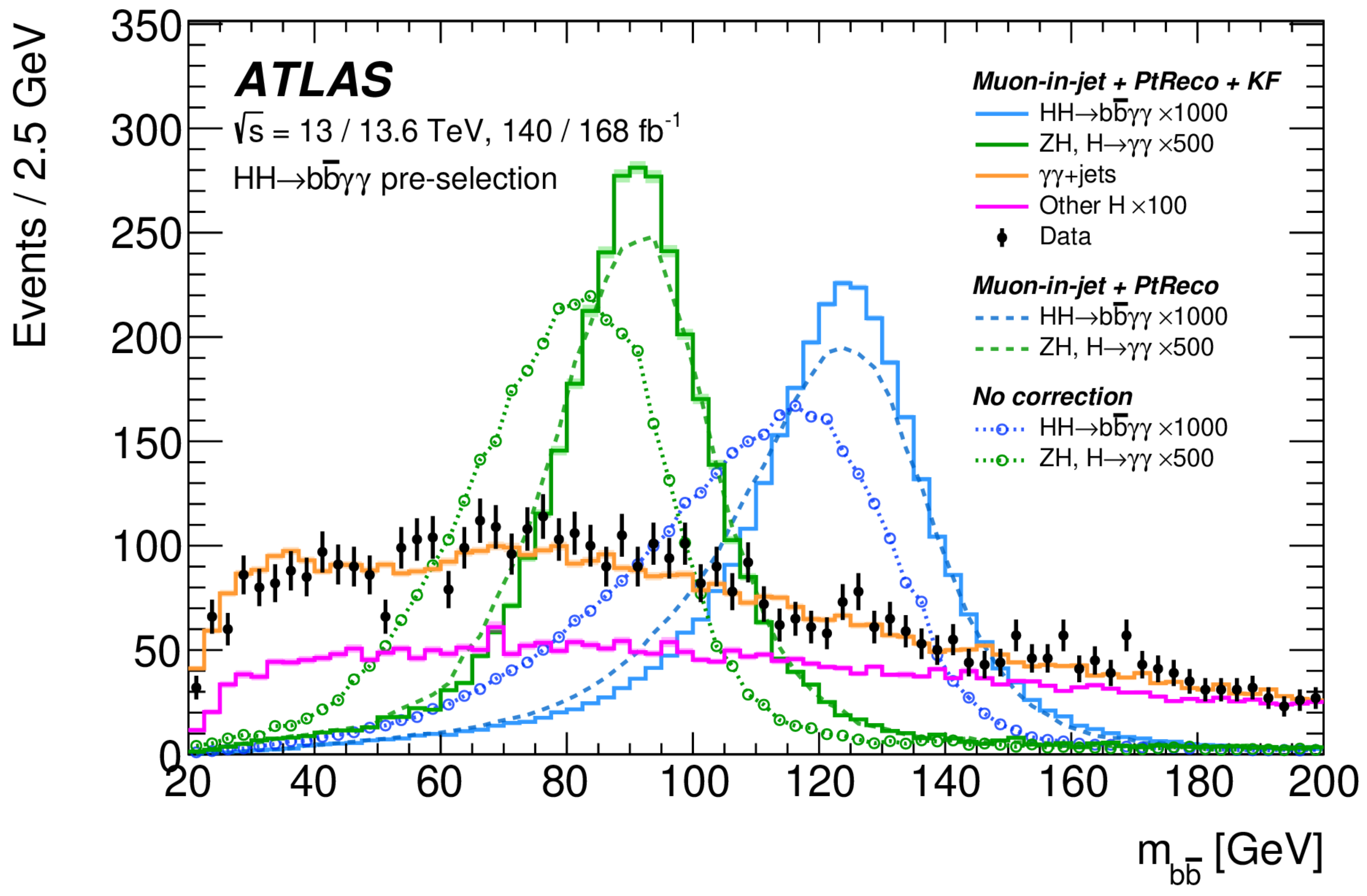
B. Di Micco, M. Gouzevitch, J. Mazzitelli, C. Vernieri (eds) et al, arXiv:1910.00012

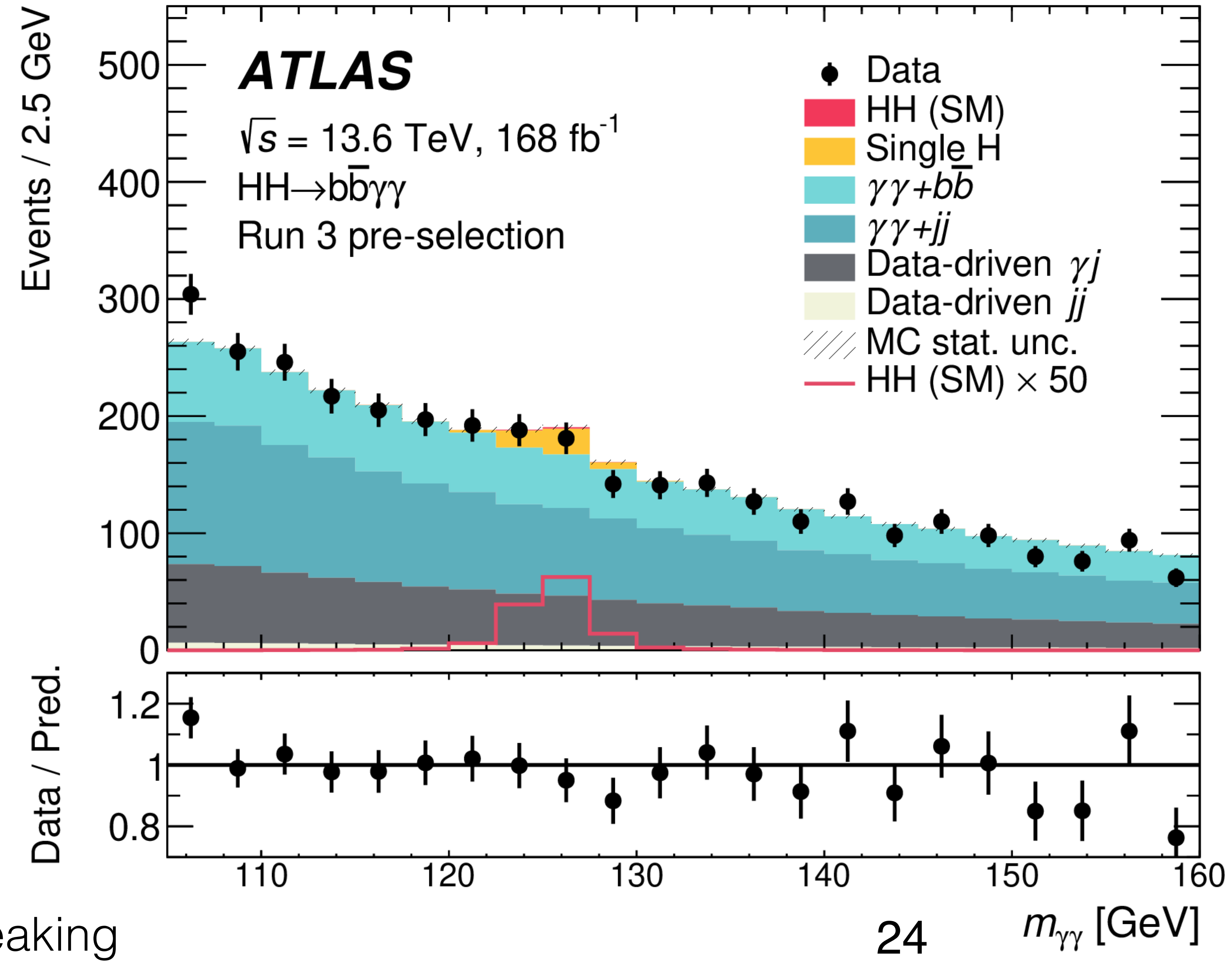
= κλ

Di-Higgs with 300 fb^{-1}

- New ATLAS bbγγ result
  - bbγγ channel has the best sensitivity near threshold: can trigger on photons and exploit excellent diphoton mass resolution
  - Dominant background is γγ + (b-)jets
    - Use kinematic fit to improve bb mass: aim for event balance in transverse plane, including (in a second step) a term $(m_{bb} - 125\ \text{GeV})^2$

ATLAS, arXiv:2507.03495
[ATLAS webpage with plots]()

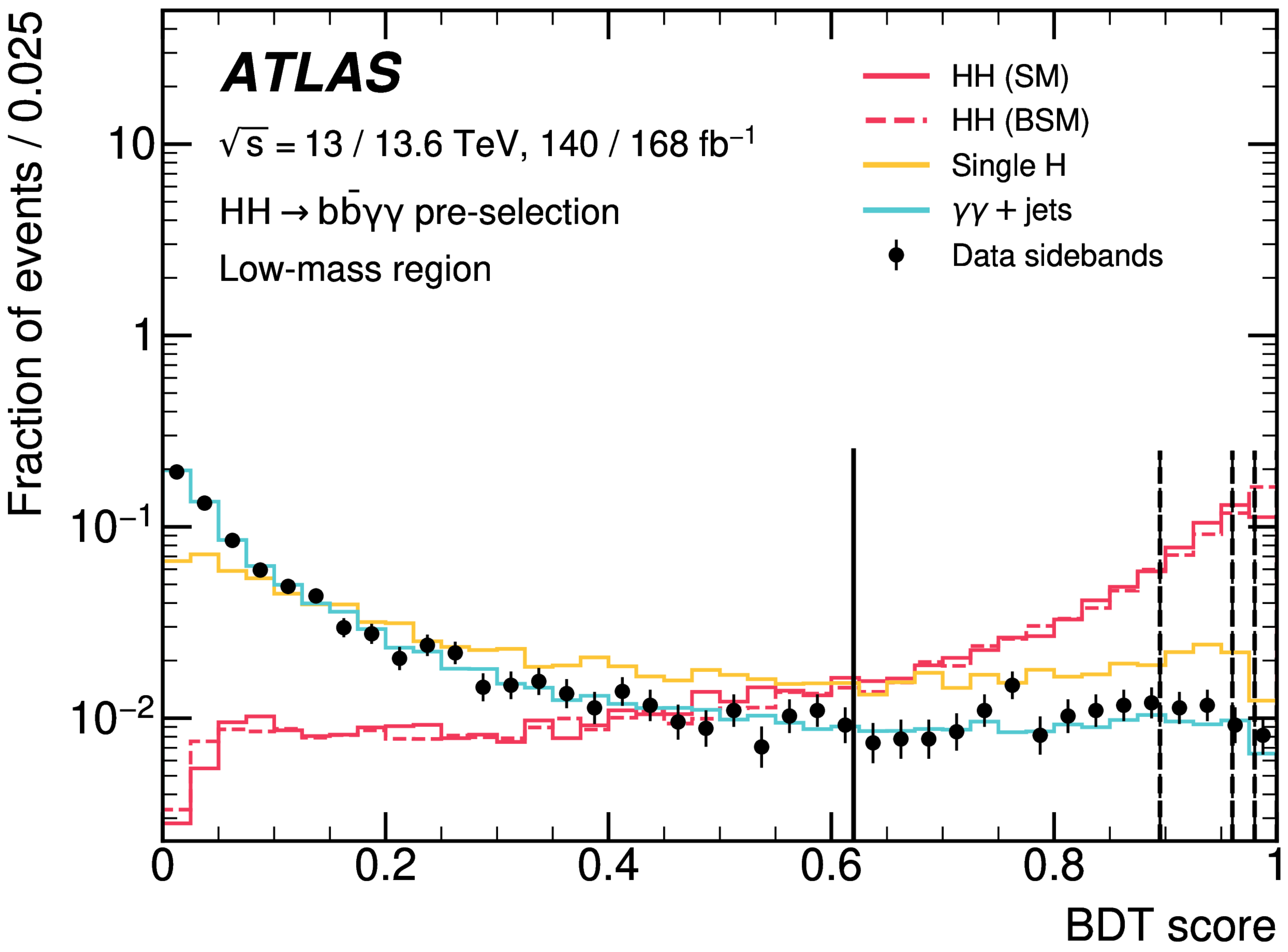


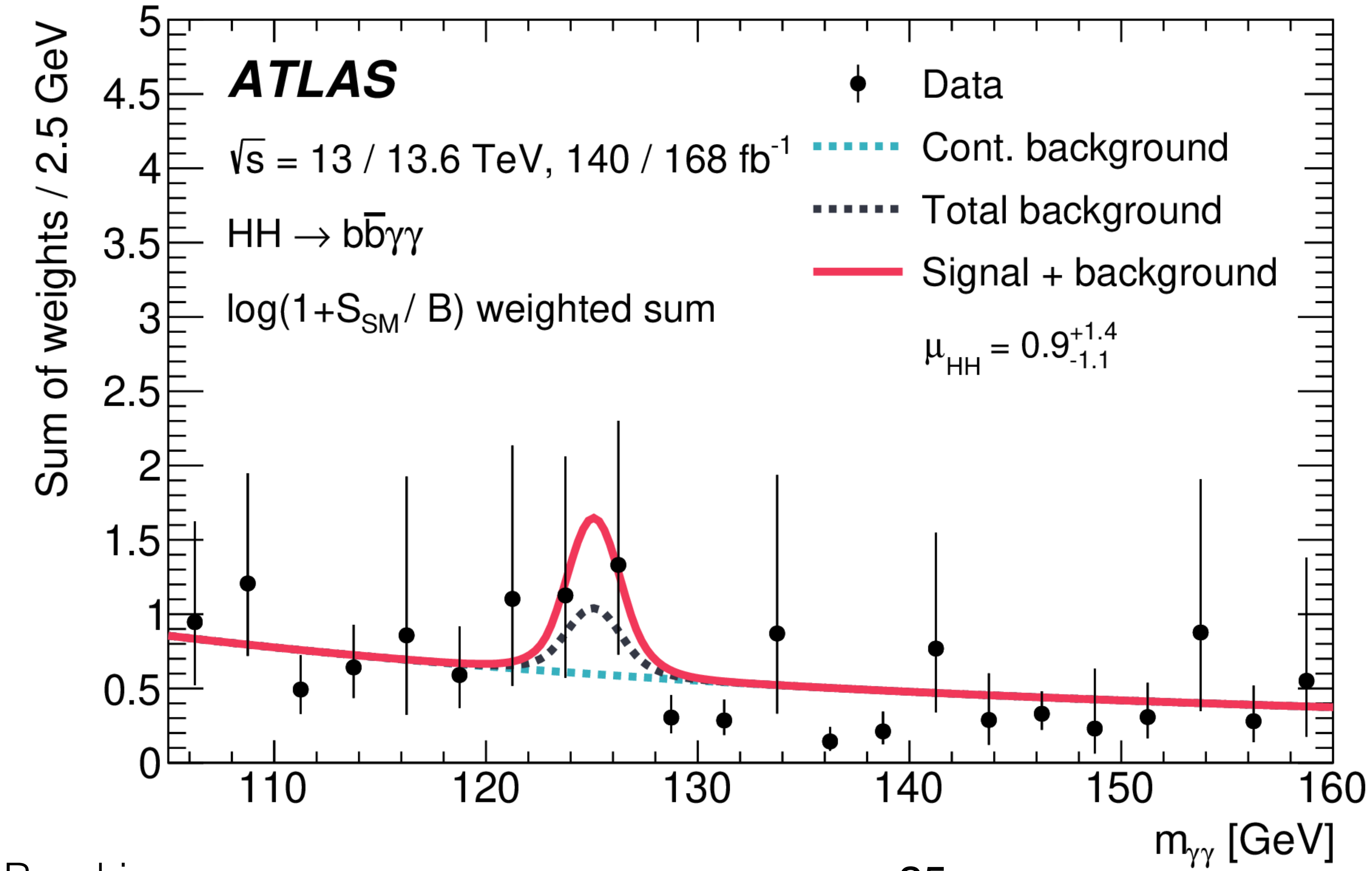


Di-Higgs with 300 fb^{-1}

- New ATLAS bbγγ result
  - Split sample in two mass regions (for sensitivity to κ_λ and κ_{2V}), then use BDTs to separate signal from background (fitted from side bands/simulation), and define regions with different purities
  - Final fit to all categories simultaneously
    - Find $\mu_{HH} = 0.9^{+1.4}_{-1.1}$ (statistics dominated)

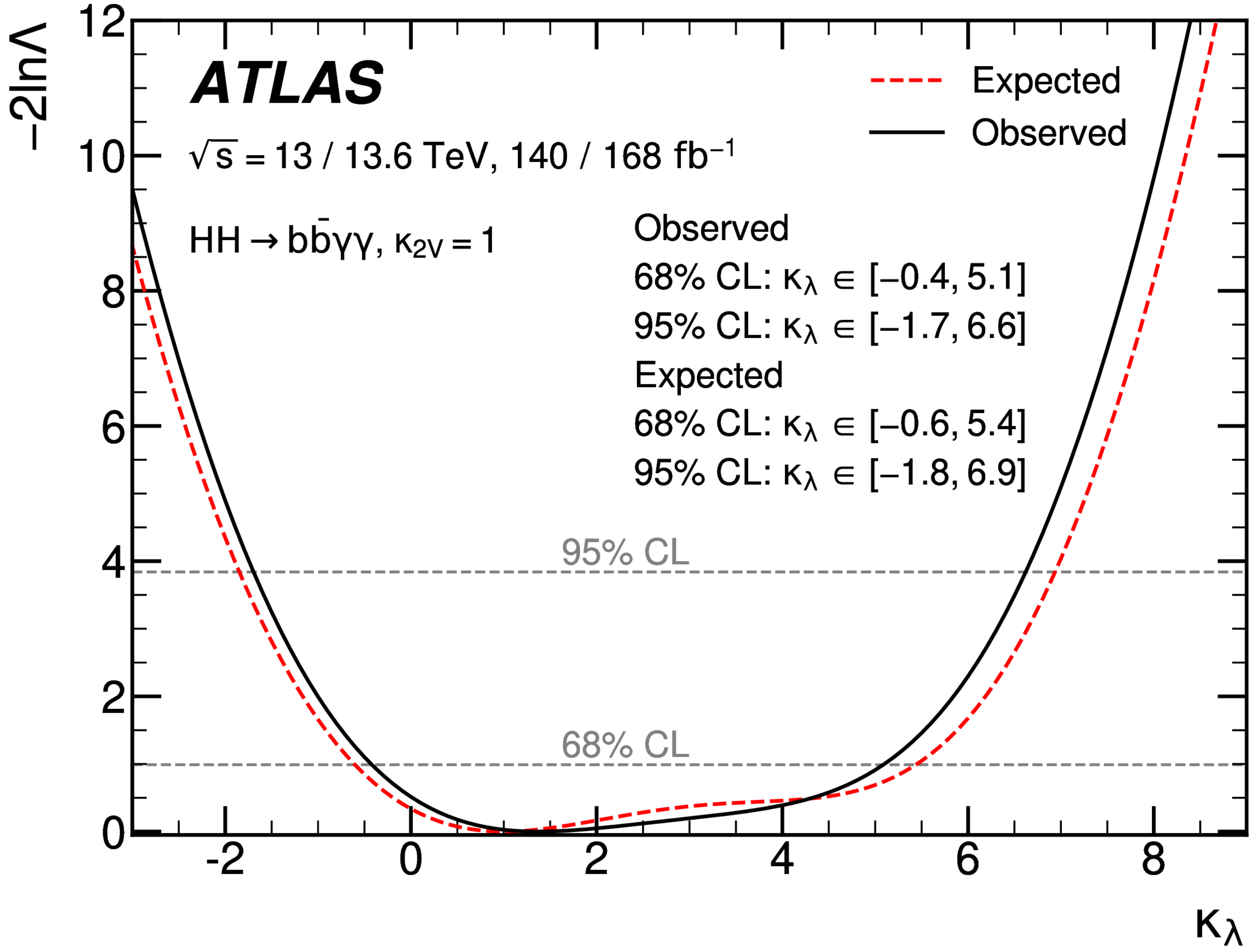
ATLAS, arXiv:2507.03495
ATLAS webpage with plots



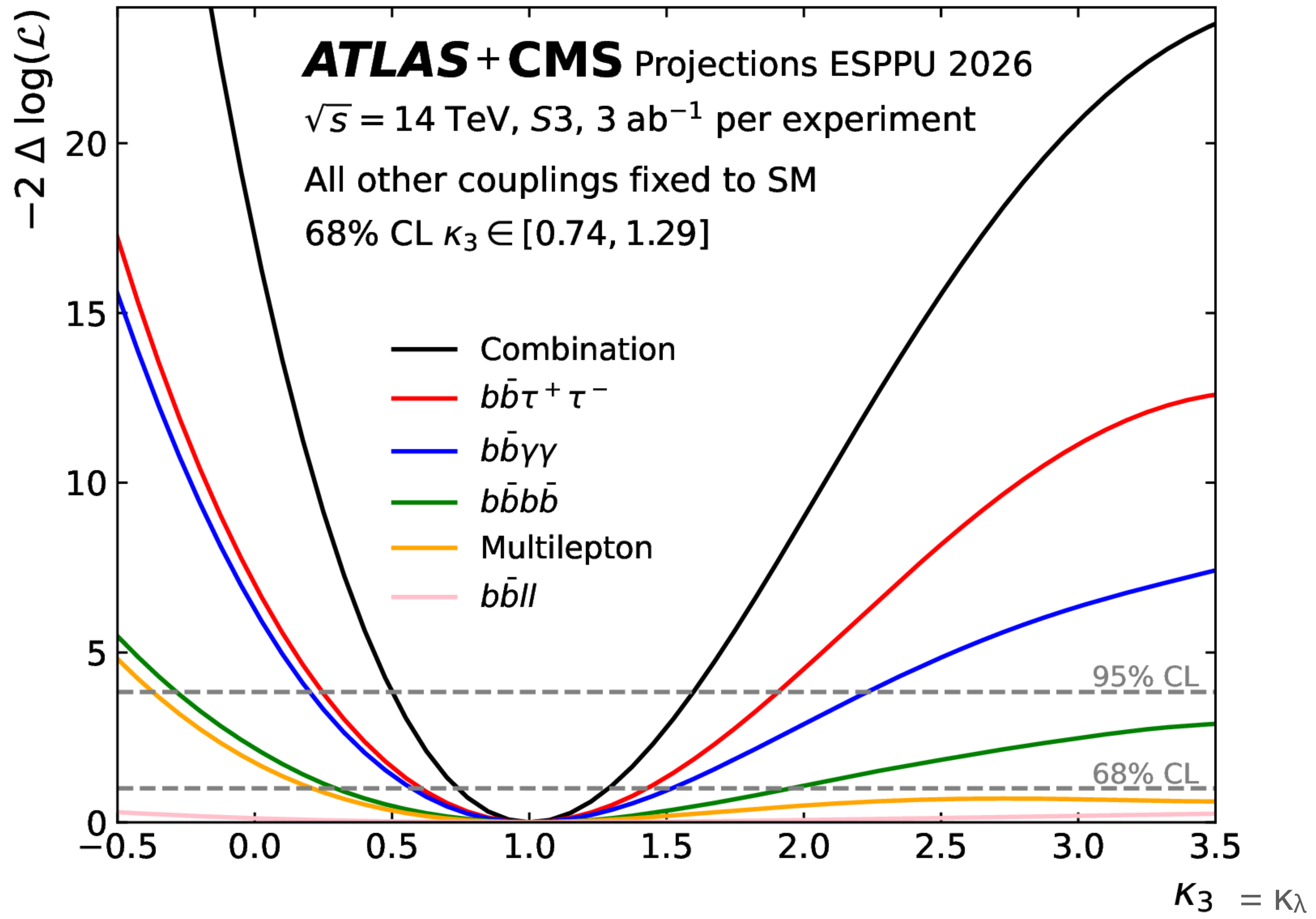


Di-Higgs with 300 fb^{-1}, 3 ab^{-1}

- Still improving analyses, more channels, and 10x more data to come with HL-LHC



ATLAS, arXiv:2507.03495
ATLAS webpage with plots



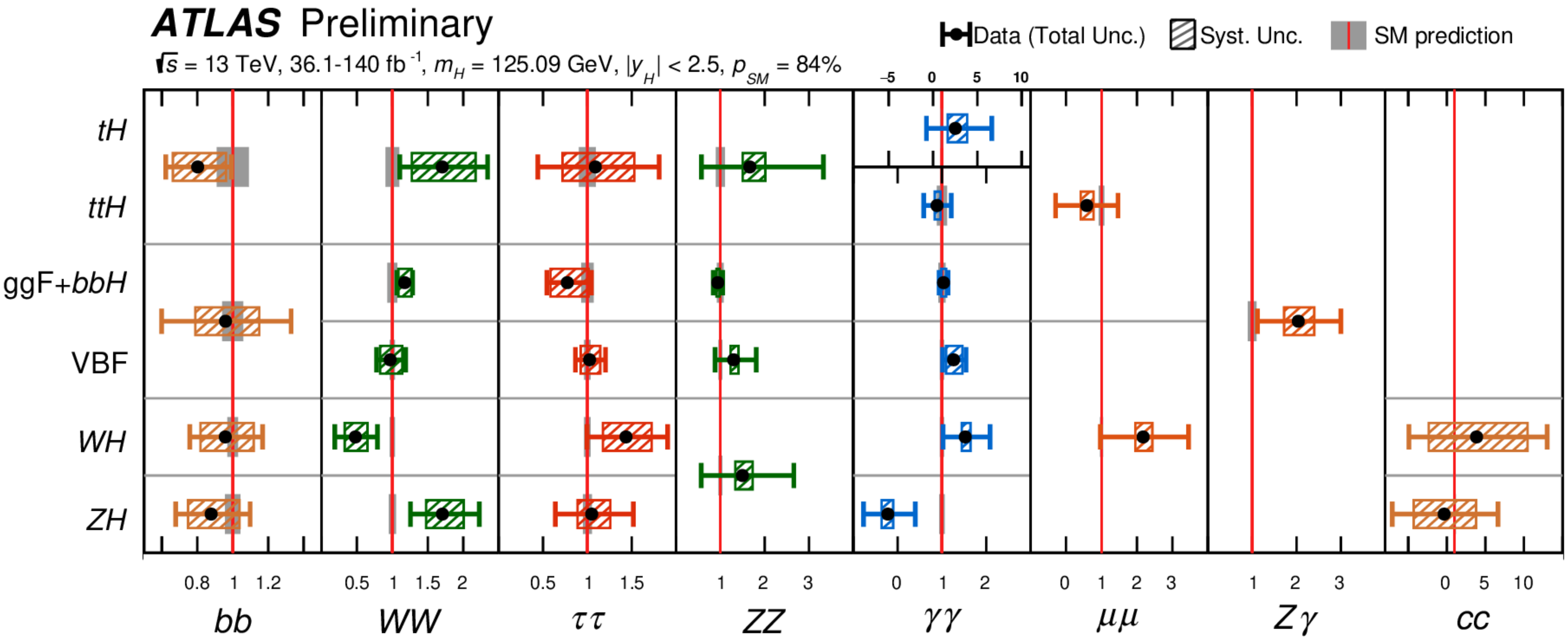
ATLAS & CMS
ATL-PHYS-PUB-2025-018

Closing Remarks

- Higgs boson was first observed a little over a decade ago
  - Most economical way to realize electroweak symmetry breaking
- We are very lucky its mass is 125 GeV
  - Almost hardest point for discovery… but many observable production and decay channels
  - Now extensively probed: couplings to SM interaction bosons and third generation fermions are within ~15% of SM predictions
    - And we are starting to probe couplings to muon and charm quark
    - Also 10-120x more data coming!
- Next big endeavor is probing Higgs potential
  - SM prediction is just “simplest” form that meets requirements
  - Observing multi-Higgs production is key to probing $V(\phi)$
  - Improving analyses, so far consistent with SM, but uncertainties are large
    - BSM typically leads to larger total cross-section, but in kinematic range that’s hardest to probe

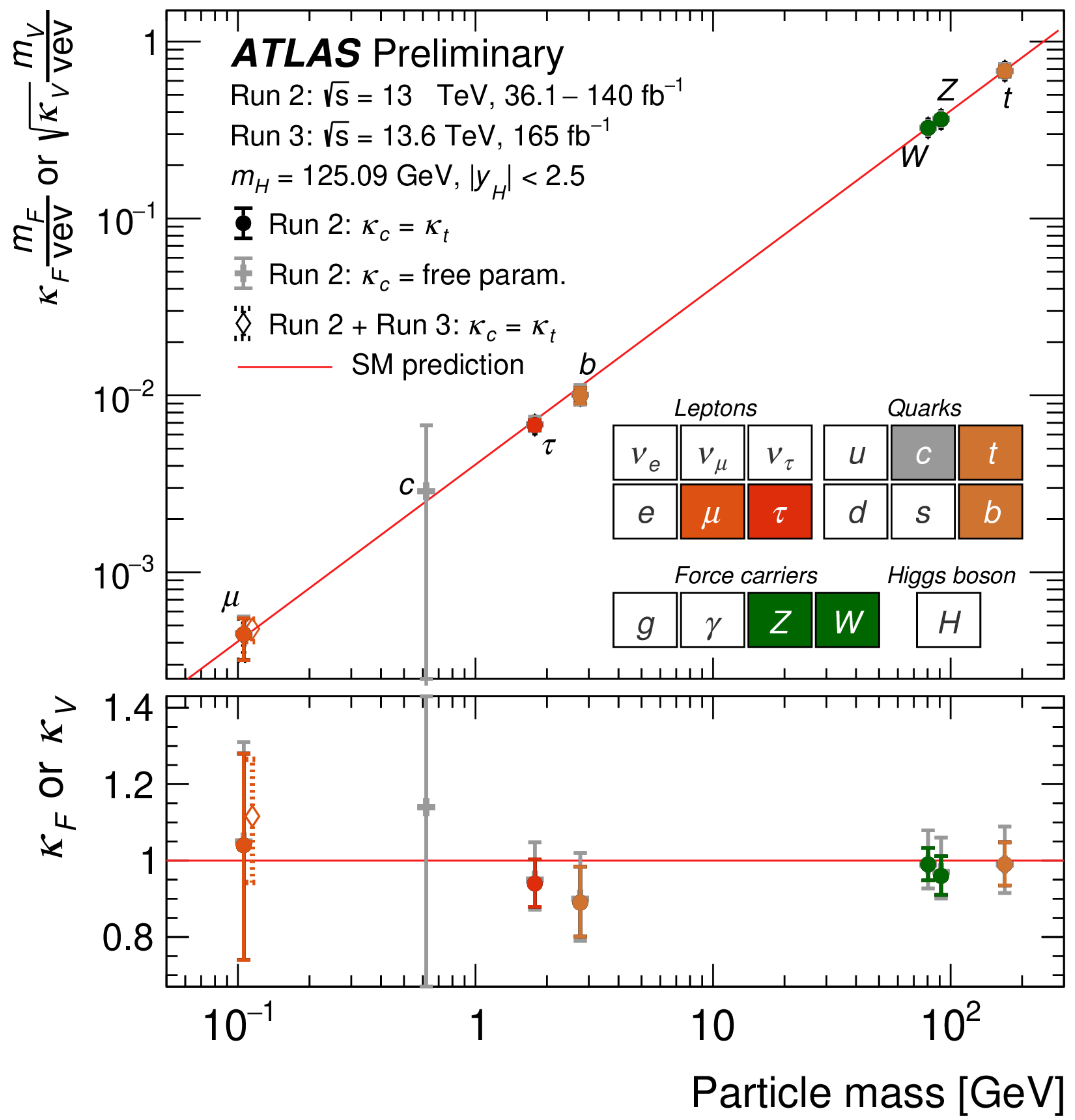
Just In Case

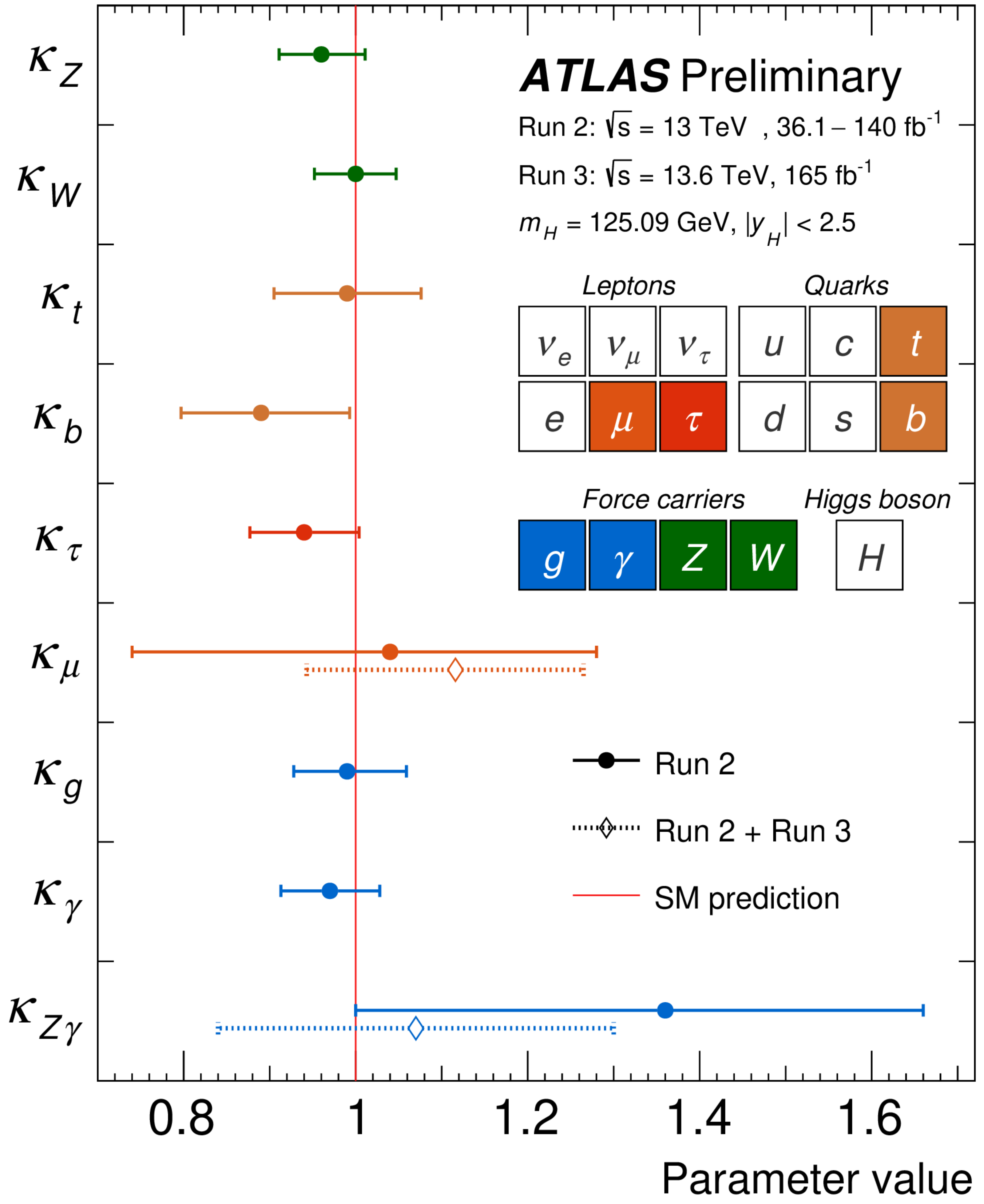
At Detailed Level



[ATLAS-CONF-2025-006](#)
[ATLAS Webpage with Plots](#)

Couplings, Run 2 + Early Run 3

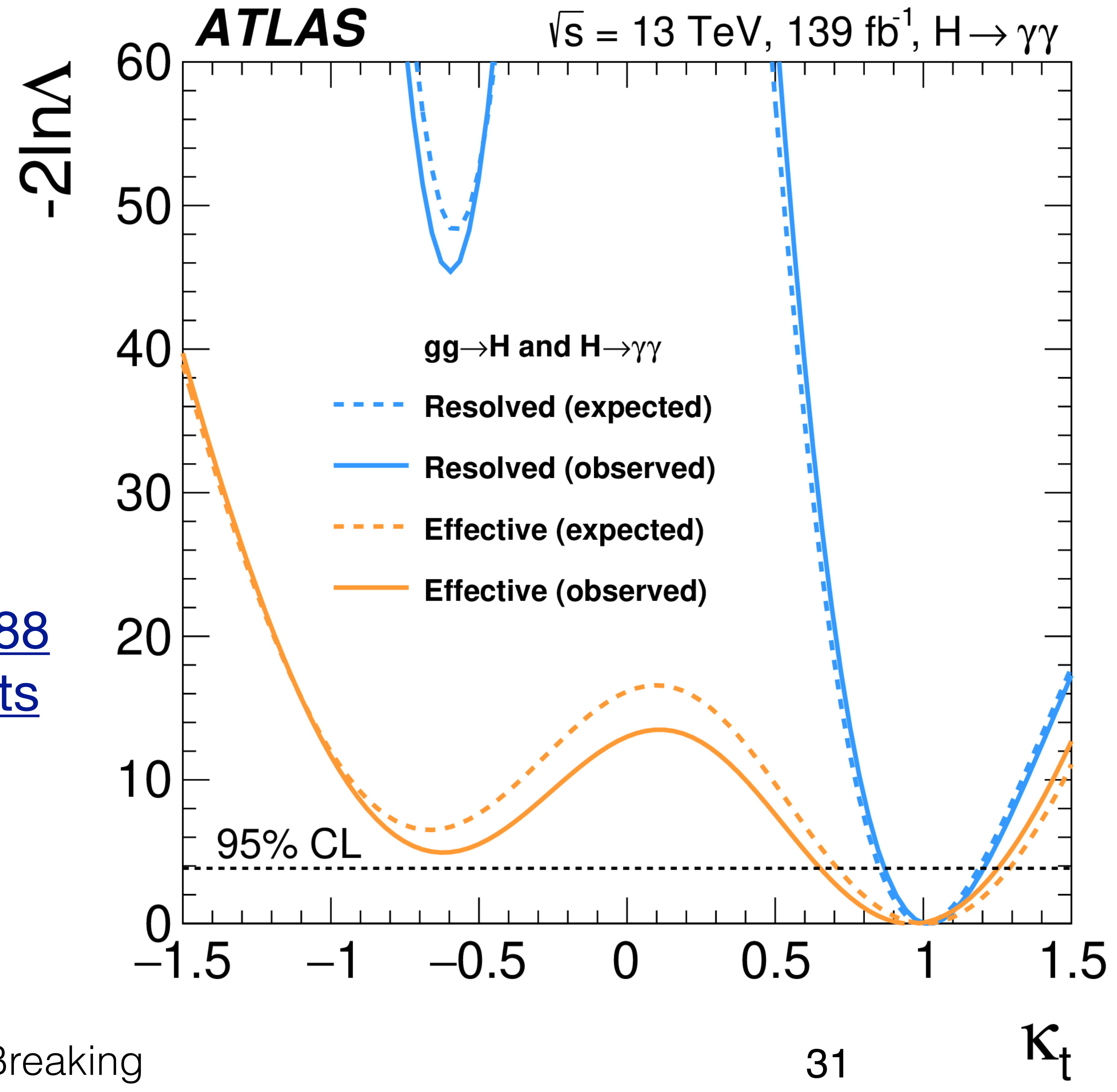




κ_t from H → γγ

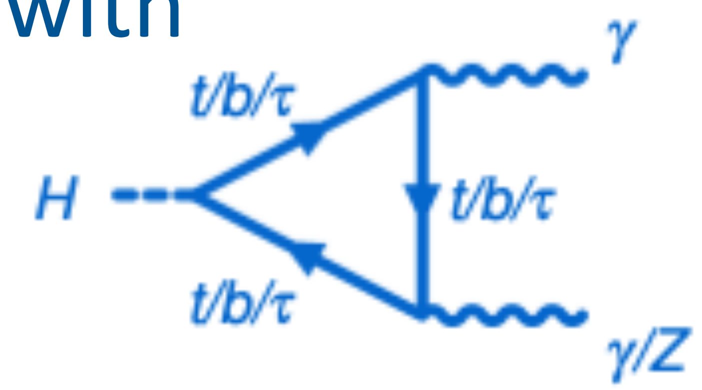
- Can parametrize gg → H and H → γγ as a function of the couplings in the loop, and constrain κ_t, fixing all other couplings to their SM values
- Or can parametrize using effective κ_g and κ_γ and extract κ_t (with sensitivity mainly from tH production)
- $\kappa_t < 1$ is excluded by first approach

ATLAS, JHEP 07 (2023) 088
ATLAS webpage with plots

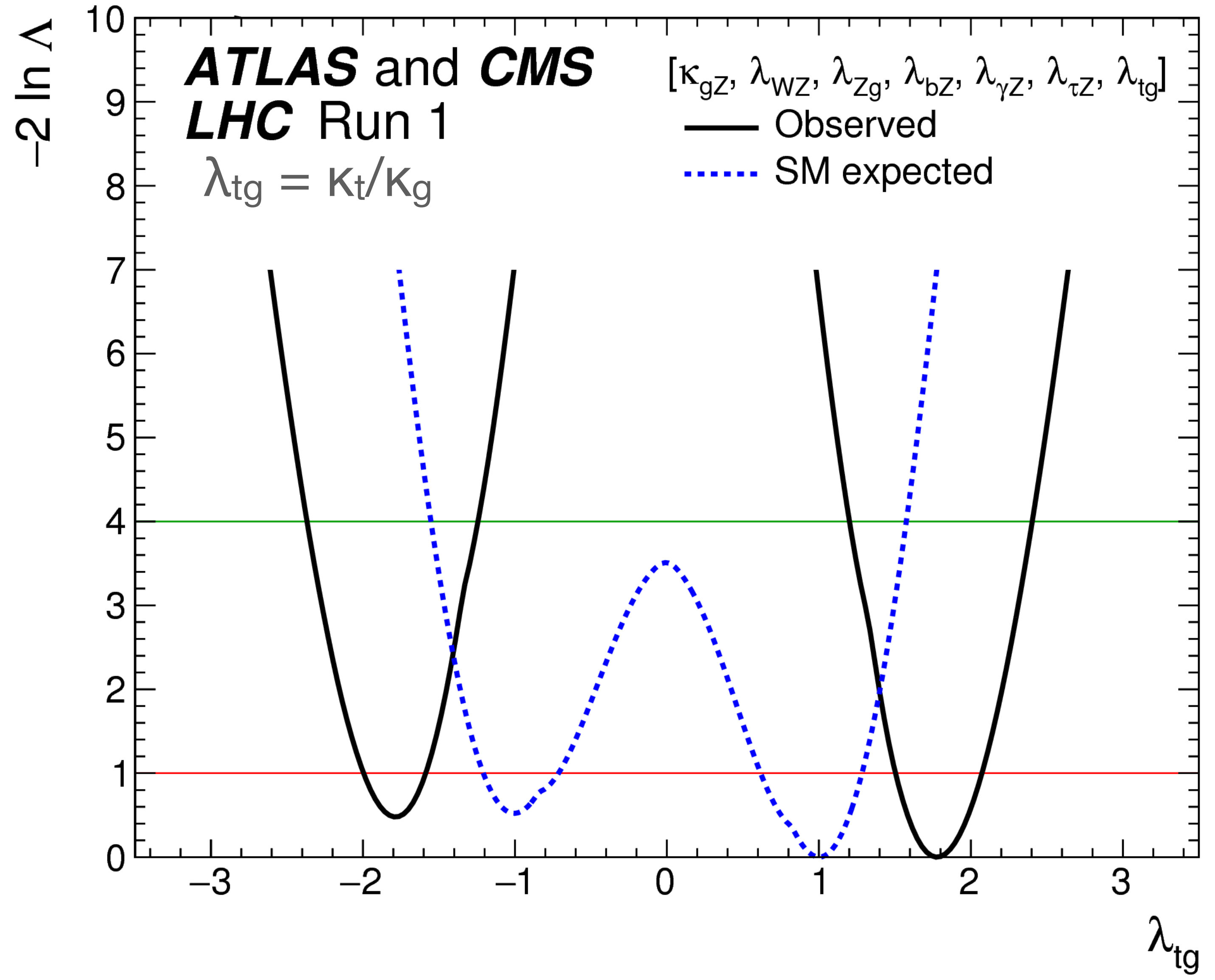


tH Production: y_t Sign

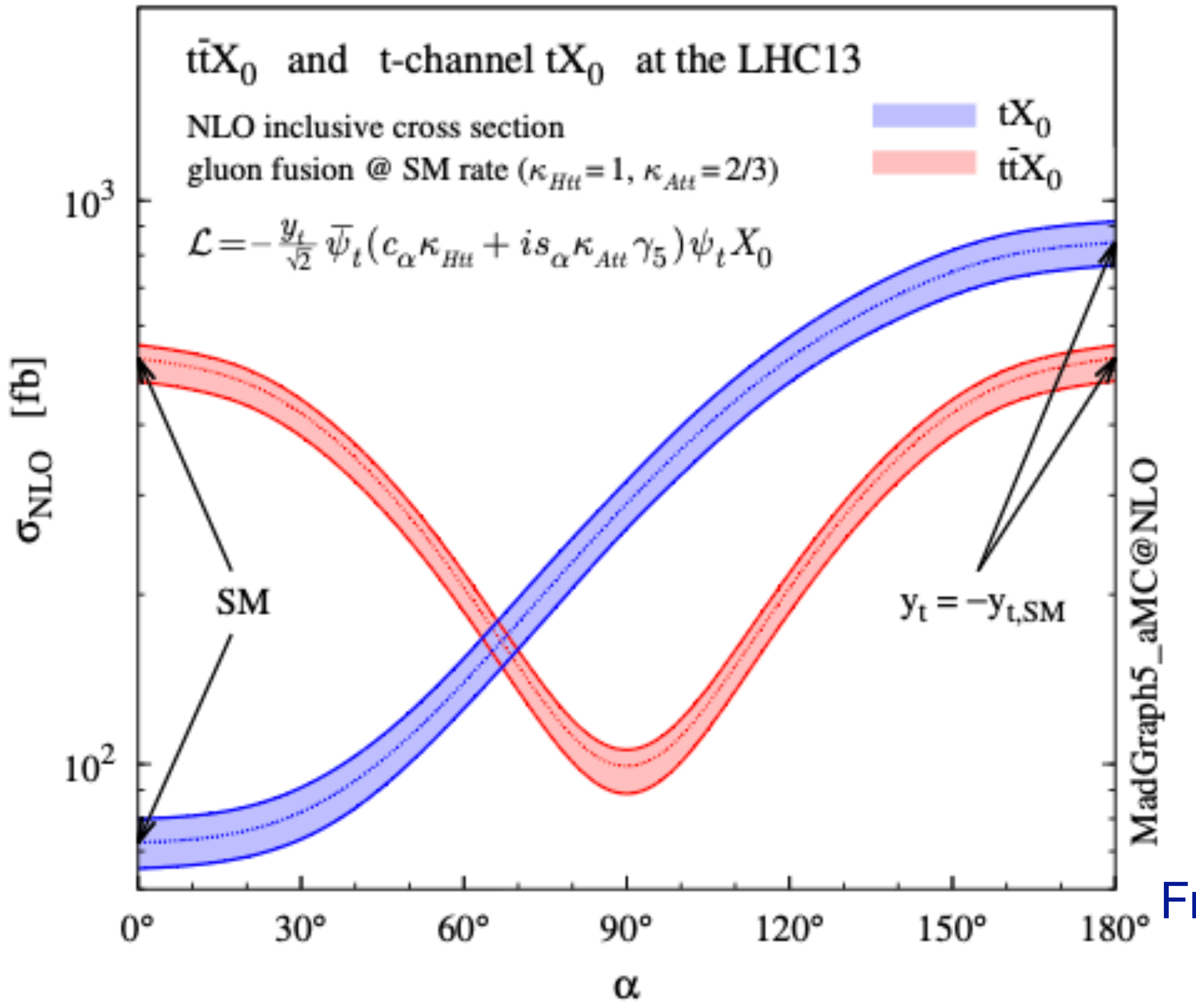
- Higgs coupling strength to the top quark (y_t) gets probed through multiple processes: not just $t\bar{t}H$, but also e.g. $H \to \gamma\gamma$ or gluon fusion H production (top loop)
  - These processes are mainly sensitive to $(y_t)^2$ - to probe a coupling's sign one needs a process with interference
    - $H \to \gamma\gamma$ (t-b interference) and ggF H production (t-W) have some sensitivity



- tH production however, is small in the SM ***because*** of significant destructive interference: with opposite sign the interference becomes constructive and σ(tH) increases x 10



ATLAS+CMS Run 1 (7-8 TeV), no tH, JHEP 08 (2016) 045

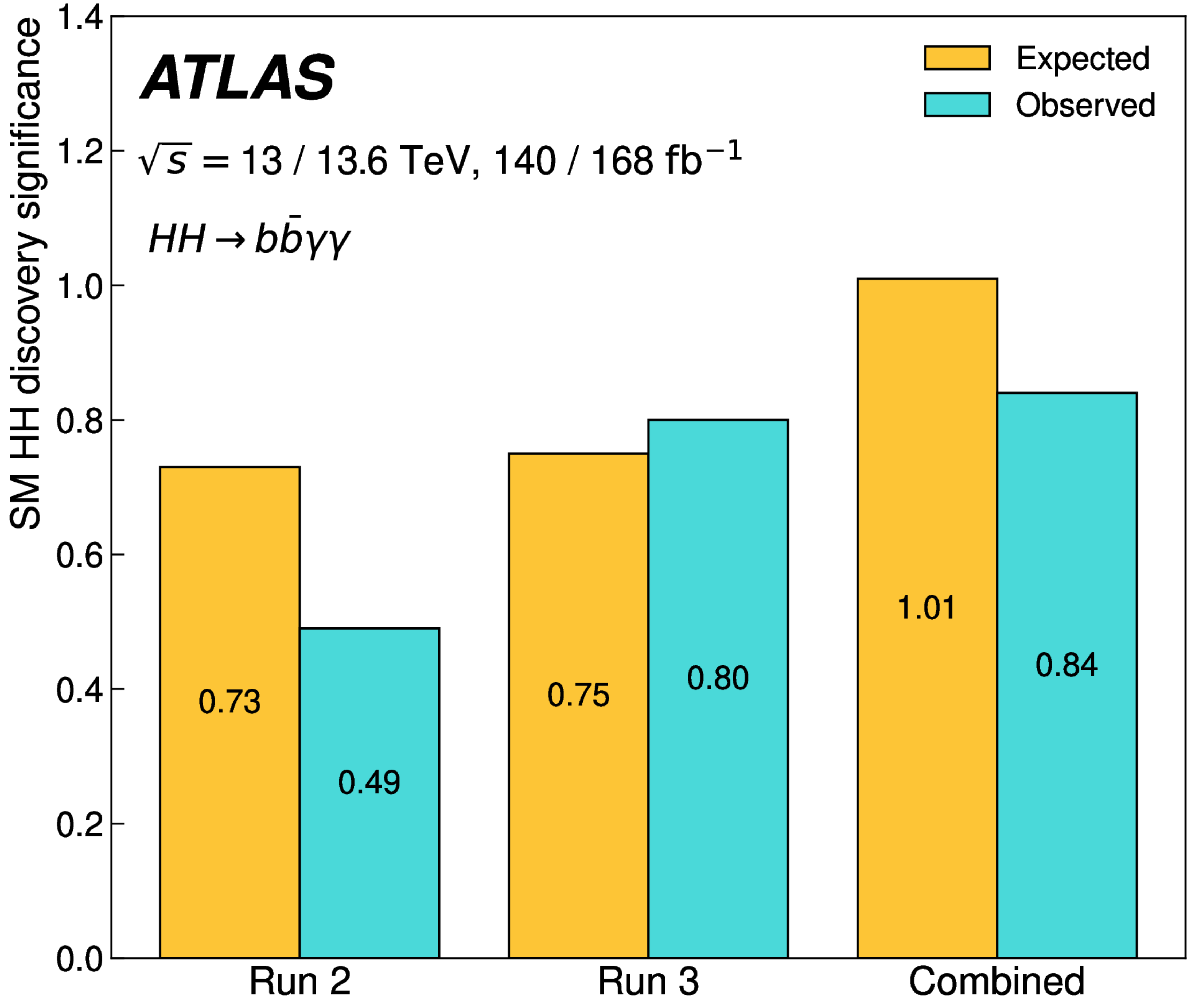


From Demartin et al, Eur.Phys.J.C 75 (2015) 6, 267

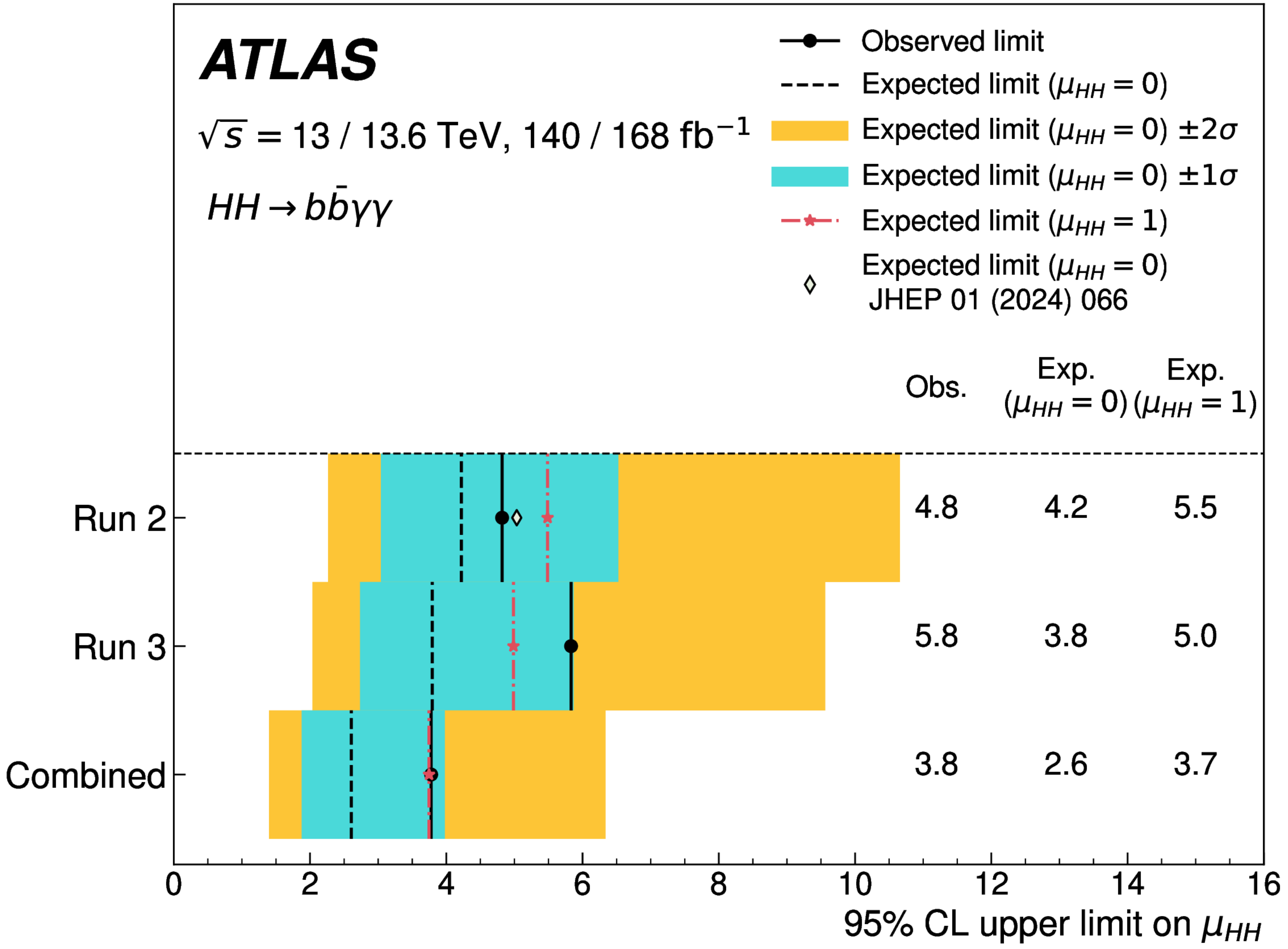
ATLAS Search for tH Production

Channel	Region	BDT score	Conversion cut	Jets	Leptons flavour (p_T ordered)	Other
$H \to b\bar{b}$	SR	-	-	$N^{70}_{\text{not-}b} < 2$ $N^{\text{jet}}_{\text{forward}} \geq 1$	-	-
	CR($t\bar{t}+ \geq 1b$)	-	-	$N^{70}_{\text{not-}b} \geq 2$ $N^{\text{jet}}_{\text{forward}} = 0$	-	
2ℓ SS	SR	BDT(tHq) > 0.65 BDT($t\bar{t}$) < 0.5 BDT($t\bar{t}W$) < 0.6 and BDT(VV) < 0.8	yes	-	-	-
	CR(μ_{HF})	BDT(tHq) < 0.65 BDT($t\bar{t}$) > 0.3 BDT($t\bar{t}W$) < 0.6 and BDT(VV) < 0.9	yes	-	$\mu\ \mu$	-
	CR(e_{HF})	BDT(tHq) < 0.65 BDT($t\bar{t}$) > 0.3 BDT($t\bar{t}W$) < 0.6 and BDT(VV) < 0.9	yes	-	$\mu\ e$, $e\ e$	$H_T(\ell) < 225$ GeV
	CR(e_{conv})	BDT($t\bar{t}$) > 0.3	inverted	-	$\mu\ e$, $e\ e$	m($\ell\ell$) < 150 GeV
	CR($t\bar{t}W$)	BDT($t\bar{t}W$) > 0.6 BDT($t\bar{t}$) < 0.3	yes	-	-	-
3ℓ	SR	BDT(tHq) > 0.7 BDT($t\bar{t}$) < 0.9 BDT($t\bar{t}W$) < 0.8	yes	-	-	-
	CR(μ_{HF})	BDT(tHq) < 0.7 BDT($t\bar{t}$) > 0.5 BDT($t\bar{t}W$) < 0.8	yes	-	$\mu\ \mu\ \mu$, $e\ \mu\ \mu$, $\mu\ e\ \mu$, $e\ e\ \mu$	-
	CR(e_{HF})	BDT(tHq) < 0.7 $BDT(t\bar{t}) > 0.5$ $BDT(t\bar{t}W) < 0.8$	yes	-	$\mu\ \mu\ e$, $e\ \mu\ e$ $\mu\ e\ e$, $e\ e\ e$	-
	CR(e_{conv})	-	inverted	-	$\mu\ \mu\ e$, $e\ \mu\ e$, $\mu\ e\ e$, $e\ e\ e$	-
	CR($t\bar{t}W$)	BDT($t\bar{t}W$) > 0.8	yes	-	-	-

Di-Higgs



ATLAS
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 168 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma$
Expected
Observed
SM HH discovery significance
0.73
0.49
0.75
0.80
1.01
0.84
Run 2
Run 3
Combined



ATLAS
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 168 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma$
Observed limit
Expected limit ($\mu_{HH} = 0$)
Expected limit ($\mu_{HH} = 0$) $\pm 2\sigma$
Expected limit ($\mu_{HH} = 0$) $\pm 1\sigma$
Expected limit ($\mu_{HH} = 1$)
Expected limit ($\mu_{HH} = 0$)
JHEP 01 (2024) 066
Obs.
Exp. ($\mu_{HH} = 0$)
Exp. ($\mu_{HH} = 1$)
Run 2
Run 3
Combined
4.8
4.2
5.5
5.8
3.8
5.0
3.8
2.6
3.7
95% CL upper limit on μ_{HH}

Di-Higgs at HL-LHC

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

$$\lambda_3 = \lambda_4 = \lambda_{SM} = \frac{m_H^2}{2v^2}$$