Measurement of Higgs Boson mass and width with LHC run2 data at the ATLAS experiment

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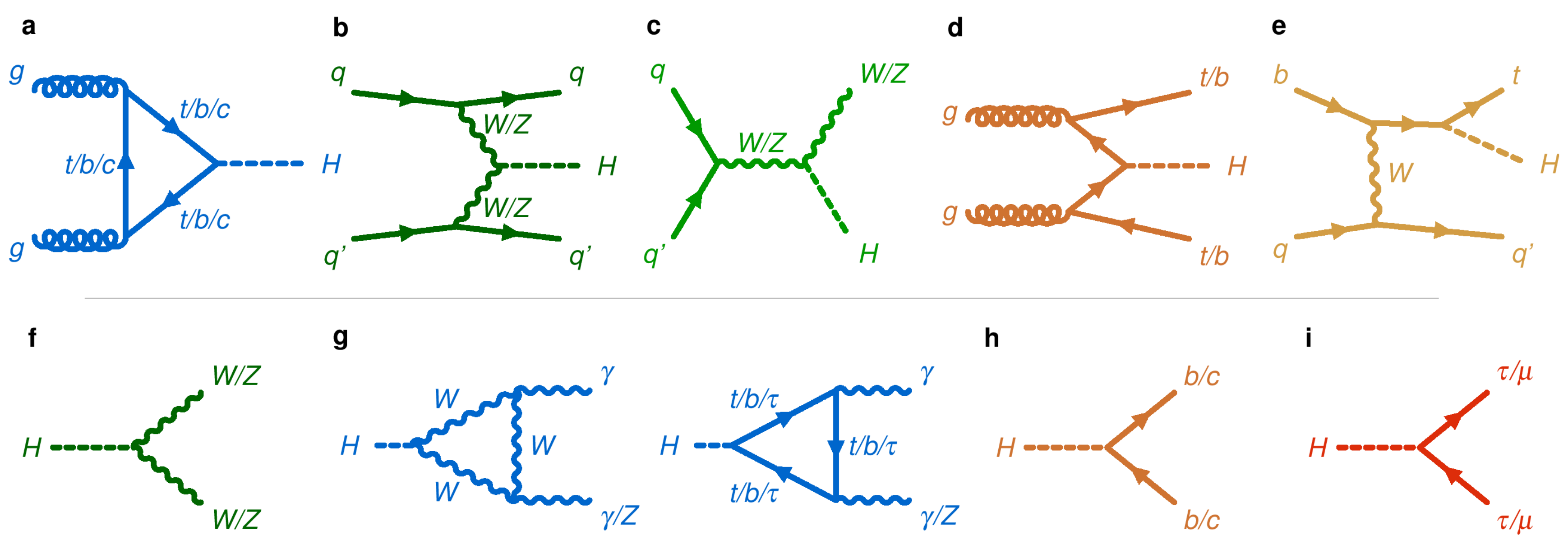
Introduction

Higgs production rates



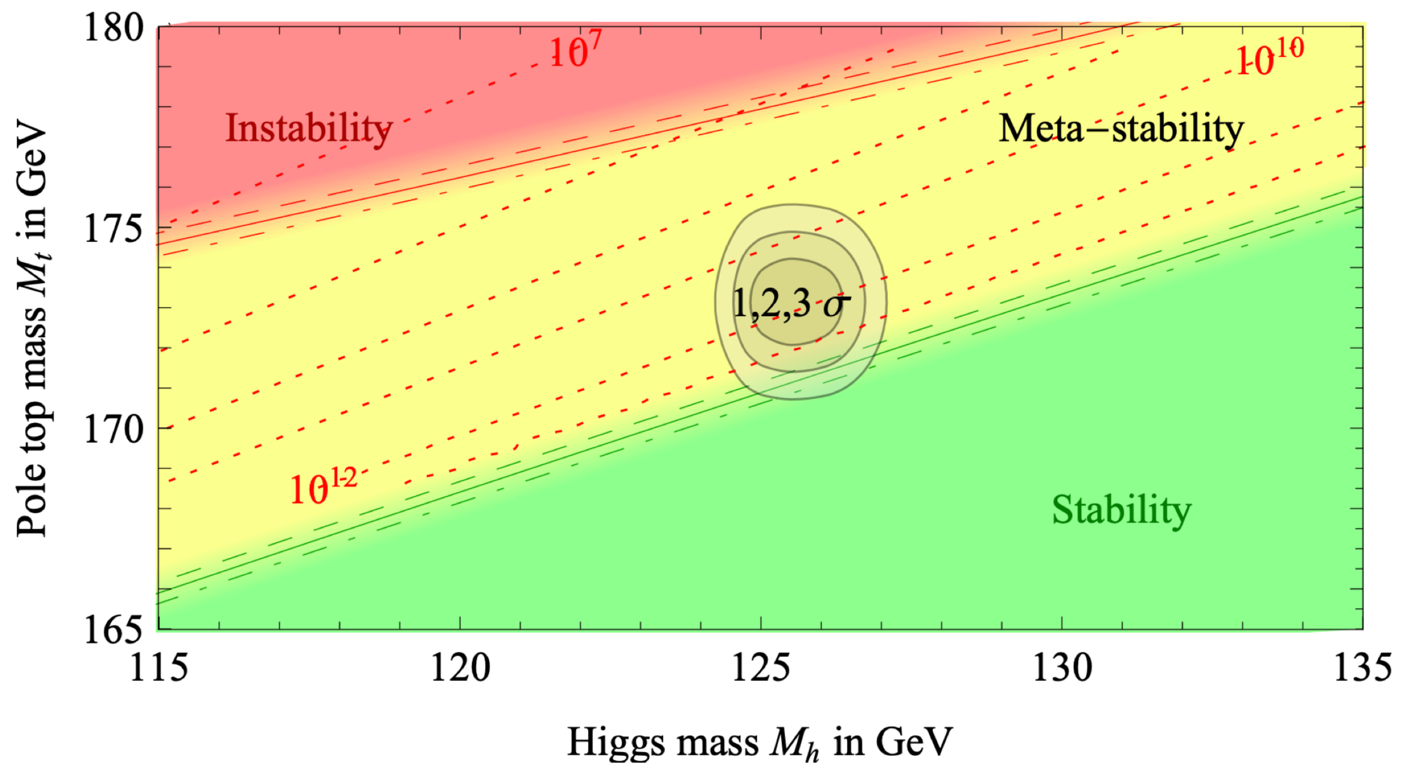
Fundamental parameter in Standard Model

Higgs mass
m_H

However it's **NOT** predicted by theory

Higgs decay branching ratios

Electroweak vacuum stability

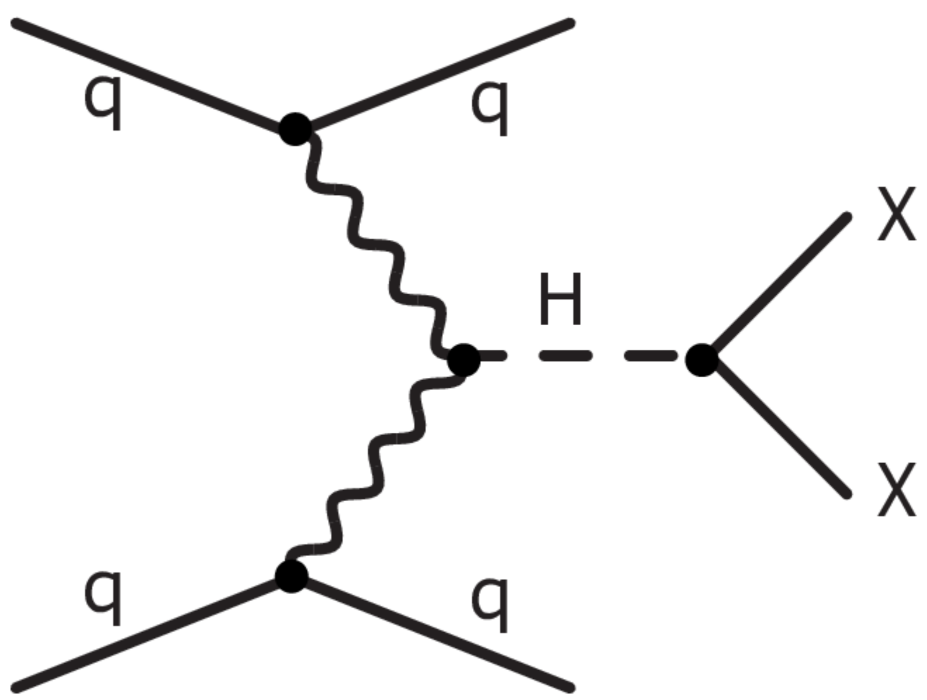


SM internal consistency

Higgs width Γ_H : Predicted by theory once m_H is given

→ Deviation from predicted value will indicate new physics

Such as the composite Higgs model and Higgs invisible decay into light dark matter

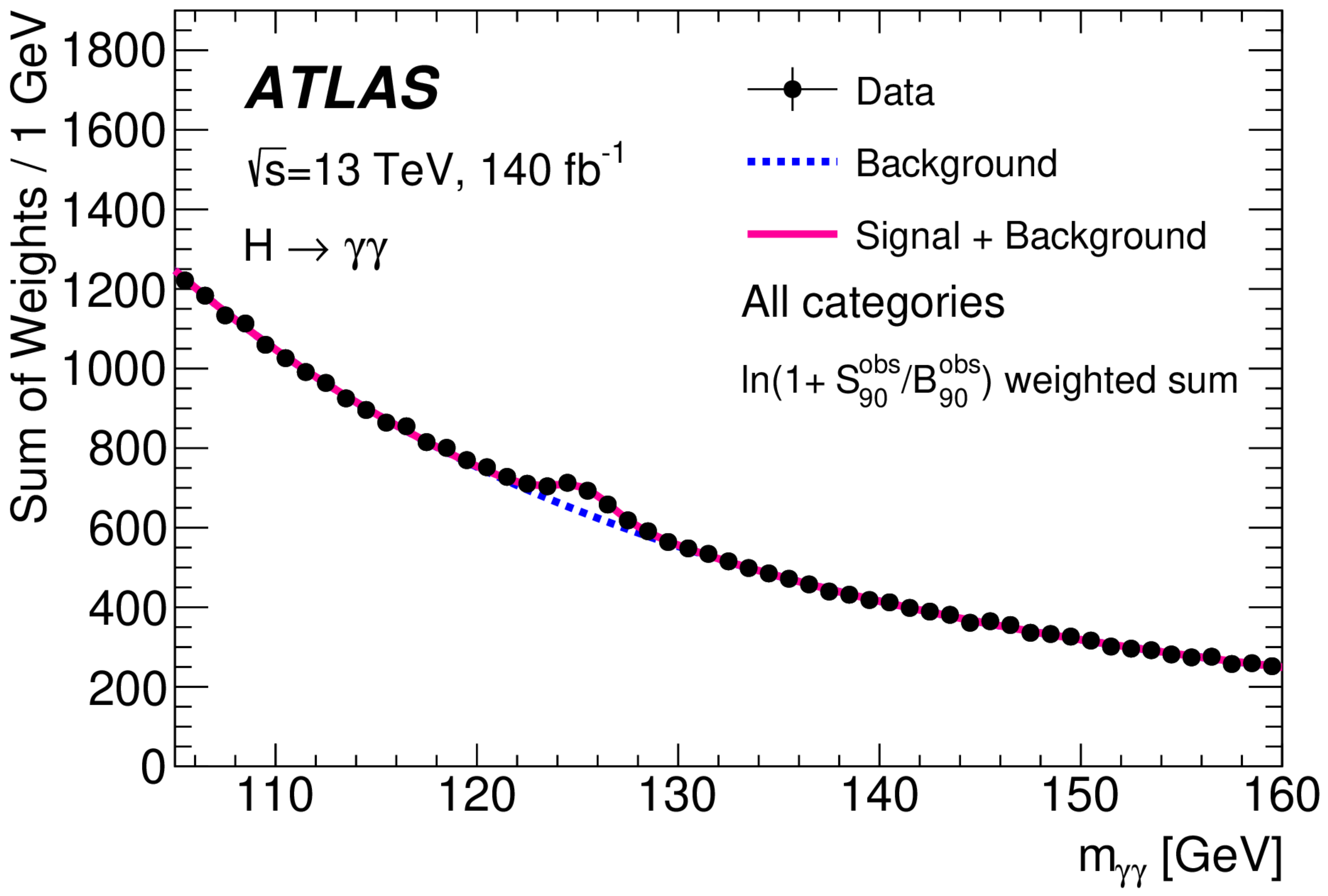


Experimental measurement for Higgs mass and width is important

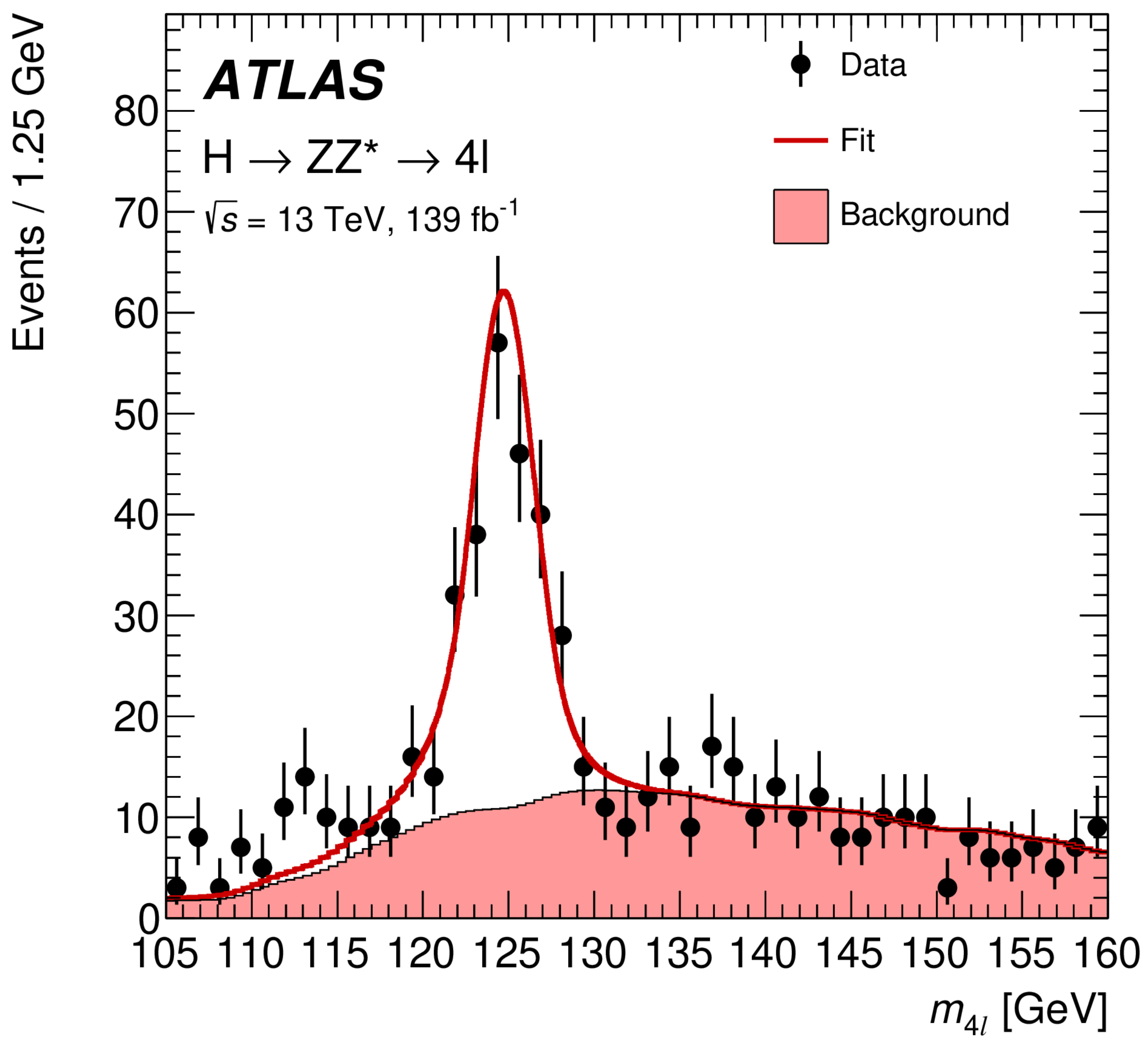
Higgs Mass Measurement

Golden channels on LHC: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$

Due to model independence and good resolution



Run2 $H \to \gamma\gamma$, Phys. Lett. B 847 (2023) 138315



Run2 $H \to ZZ^* \to 4l$, Phys. Lett. B 843 (2023) 137880

$m_H = 125.17 \pm 0.11(\text{stat.}) \pm 0.09\,(\text{syst.})$ GeV

$m_H = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})$ GeV

Benefit from the new linearity fit method for e/γ energy scale calibration!

Statistical dominant

Combined measurement for m_H

- Combine 4 Input measurements: (Run1, Run2)×($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$)

Float parameters	$H \rightarrow ZZ^* \rightarrow 4l$	$H \rightarrow \gamma\gamma$
Run1	Higgs mass, 1 global signal strength for all production modes	Higgs mass, 2 signal strengths for ggF+ttH and VBF+VH production
Run2	Higgs mass, 4 signal strengths for different categories	Higgs mass, 14 signal strengths for different categories

- Signal yield normalization float independently among categories and channels in order to reduce model dependence

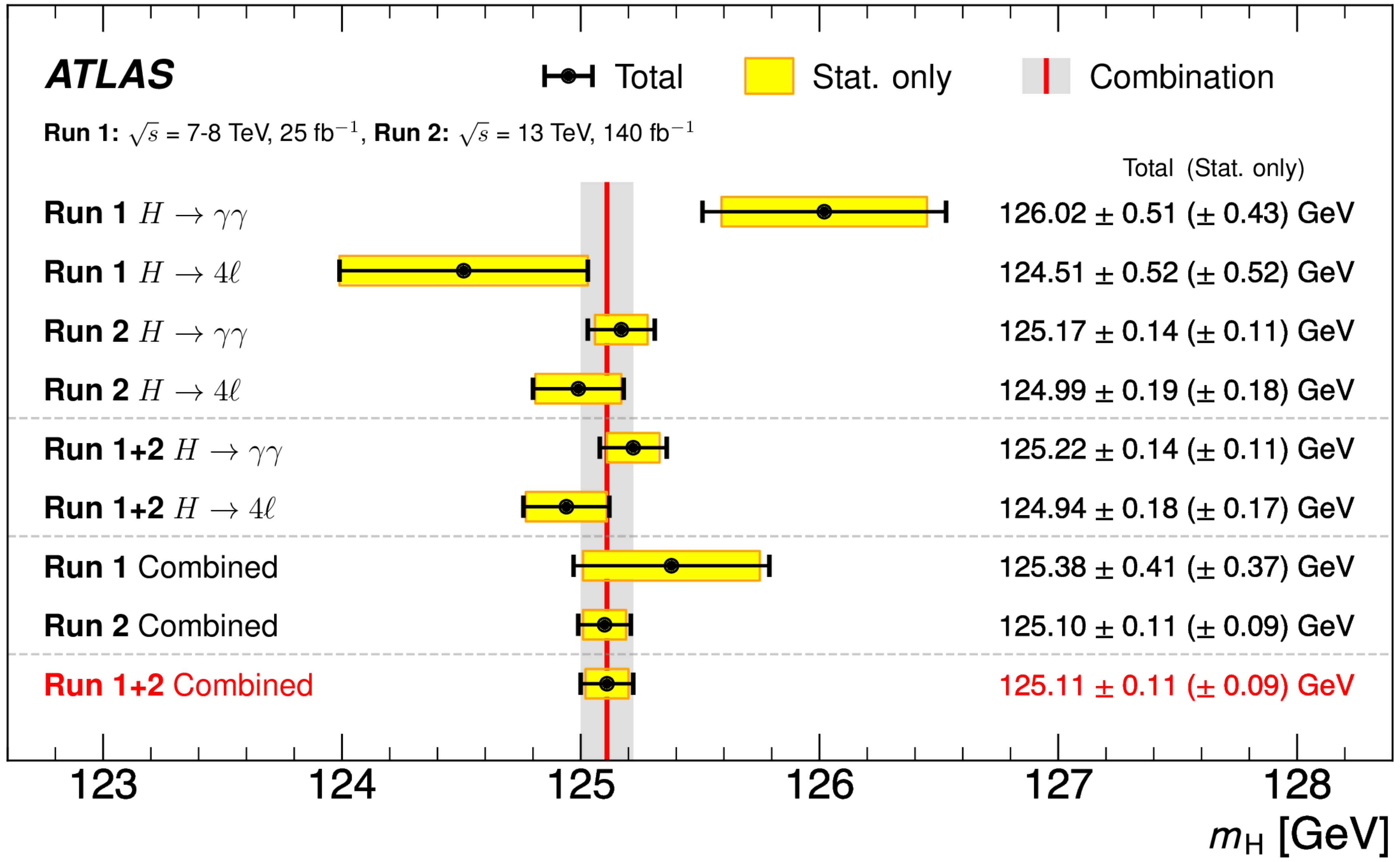
Higgs Mass Results

- By combining all 4 individual analysis: Phys. Rev. Lett. 131 (2023) 251802

$$m_H = 125.11 \pm 0.11 = 125.11 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})\ \text{GeV}$$

→ 0.09% precision: The most precise result up to date!

- Good compatibility of 4 input measurements: p-value = 18%

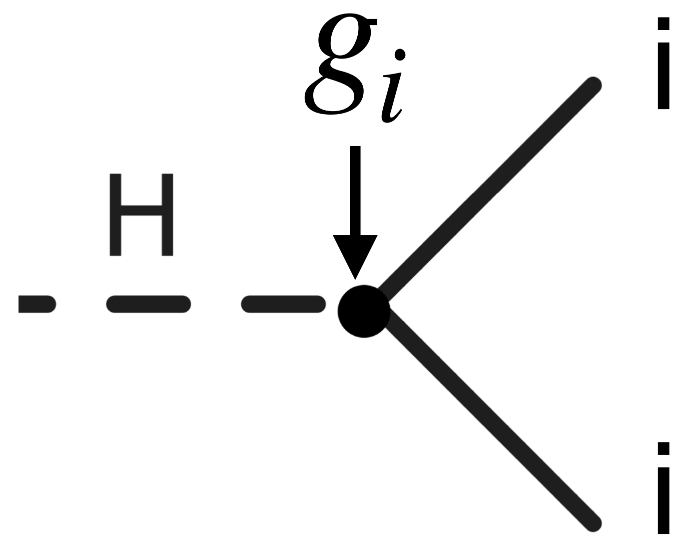


Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

Systematic uncertainty decomposition

Higgs Width Measurement

Kappa modifier: $\kappa_i = \frac{g_i}{g_{i,SM}}$



$$\frac{d\sigma}{dm^2} = \frac{g_{i,SM}^2 g_{f,SM}^2 \kappa_i^2 \kappa_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

On-shell ⇩ $R_\Gamma = \frac{\Gamma_H}{\Gamma_{H,SM}}$ ⇩ Off-shell

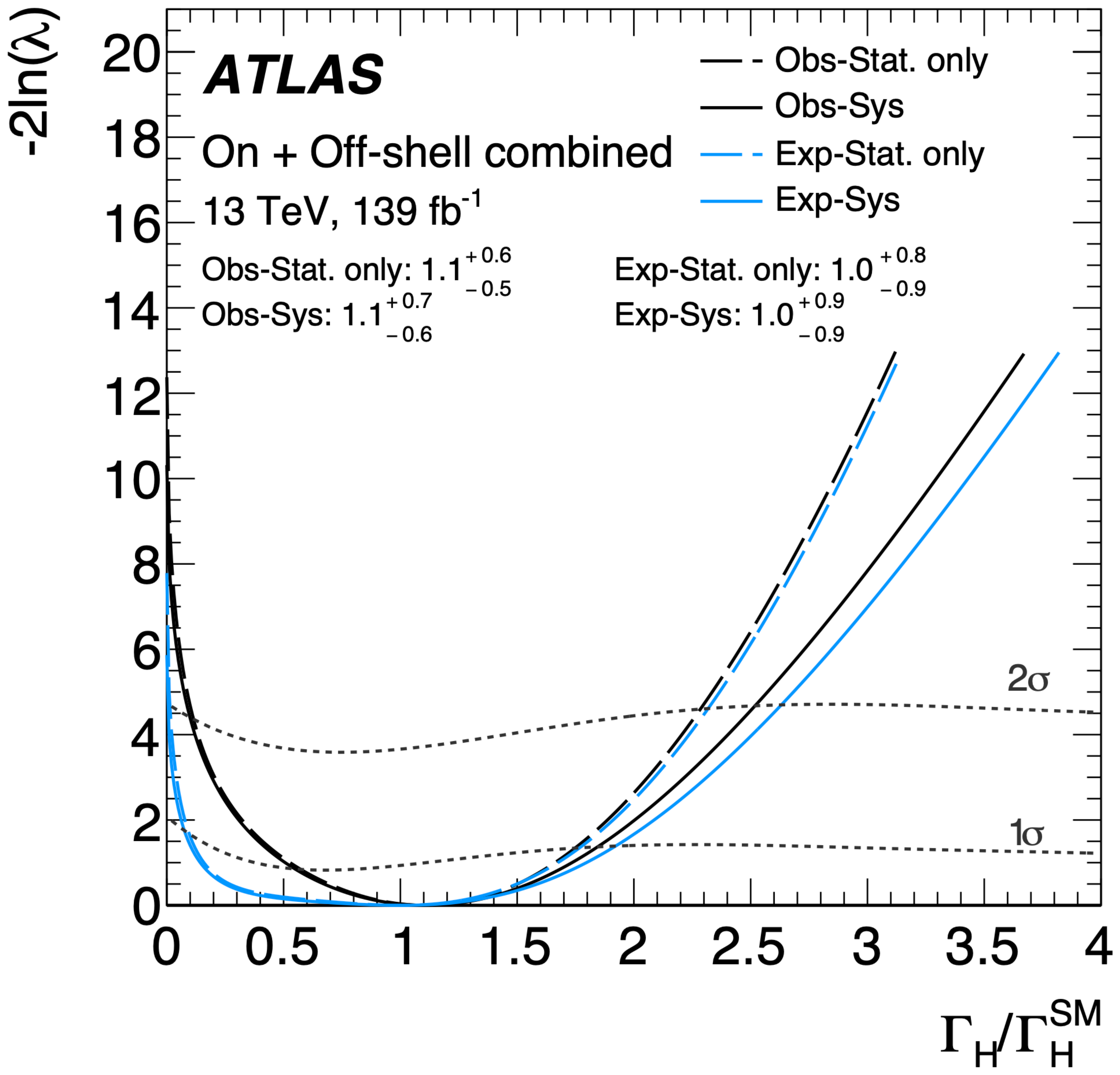
$$\mu_{i\to H\to f} = \frac{\kappa_i^2 \kappa_f^2}{R_\Gamma}$$

$$\mu_{i\to H\to f} = \kappa_i^2 \kappa_f^2$$

Depend on Higgs width

Not depend on Higgs width

- Combining on- and off-shell measurements allows us to measure κ and Higgs width simultaneously
  - Previously done by ATLAS and CMS with $H\to ZZ^*$ and $H^*\to ZZ$
  - $H \to WW$ done in Run1

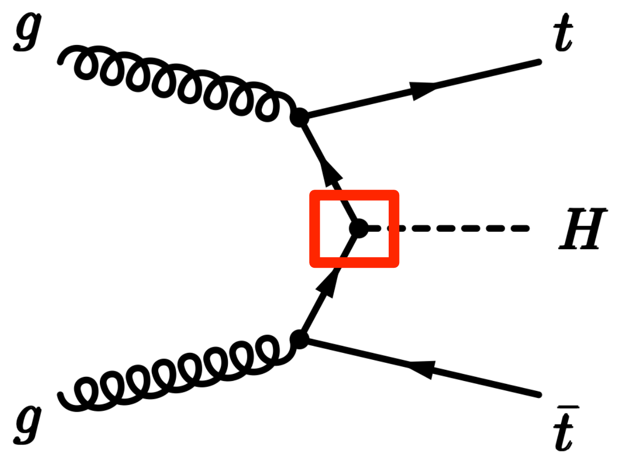


Higgs width from $H \to ZZ$ channel

95% CL upper limt: 10.2 MeV

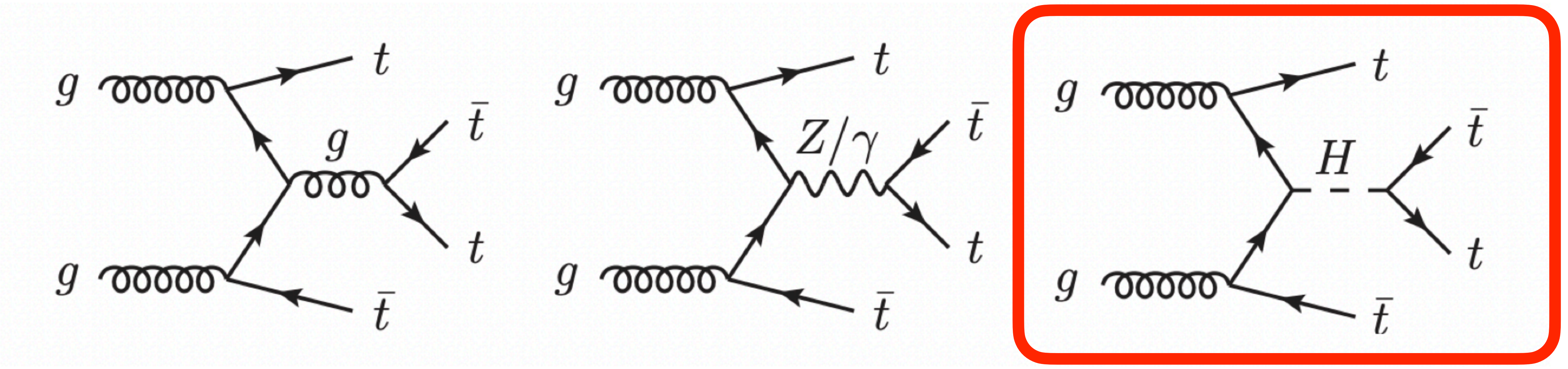
Γ_H from κ_t with Four-Top and On-Shell Higgs

- Different from the existing analysis, we rely on **tree-level Higgs-Top Yukawa coupling**
  - Unlike the current $H \to ZZ$ or $H \to WW$ analysis, it's not affected by the presence of unknown colored particles
- On-shell measurement has constraint from $t\bar{t}H$ production



Higgs-top vertex

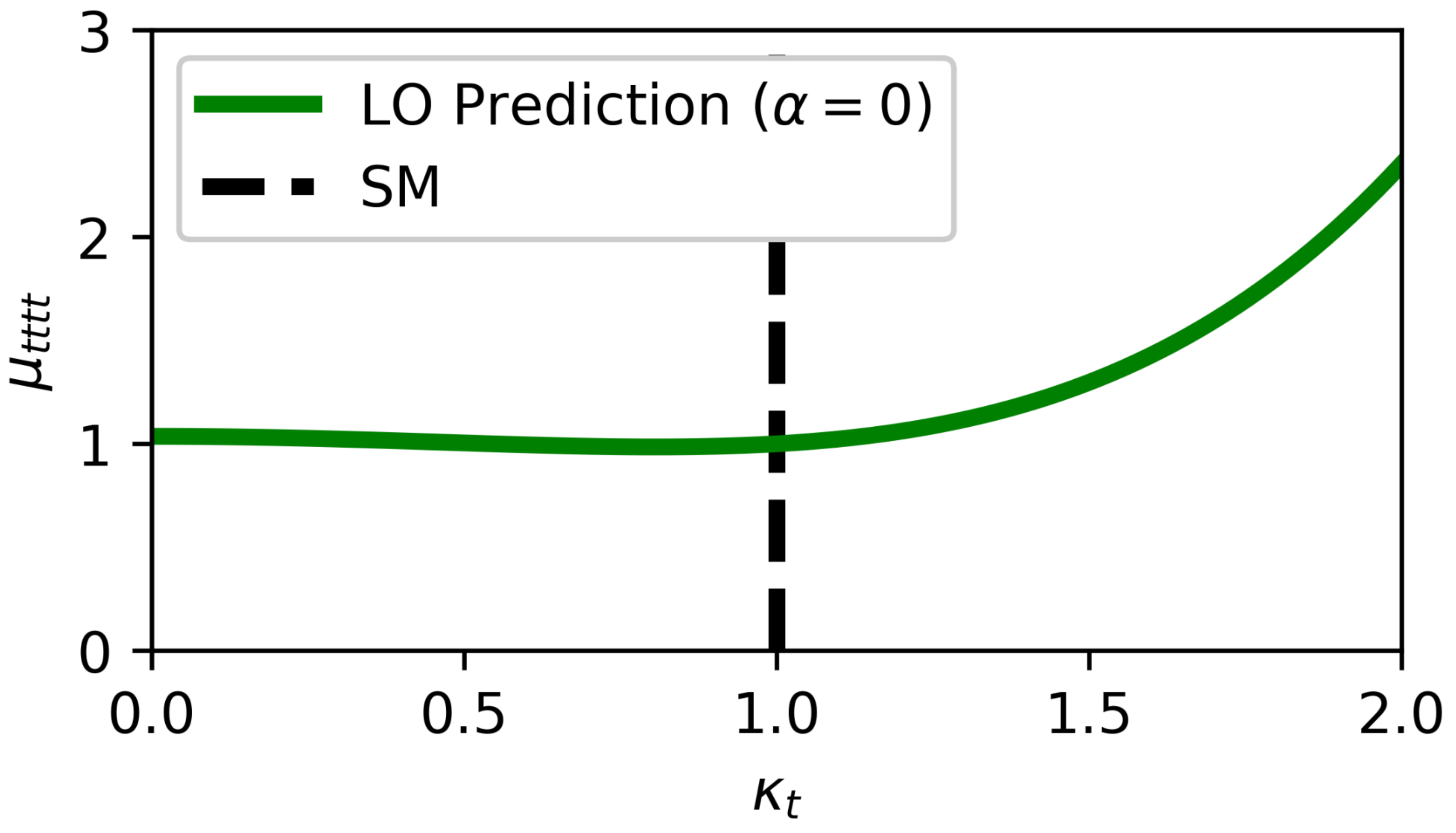
- Four-top cross-section depends on κ_t due to off-shell Higgs contribution



Pure H contribution is quartic, interference is quadratic

Inclusive normalized cross-section parameterized into κ_t:

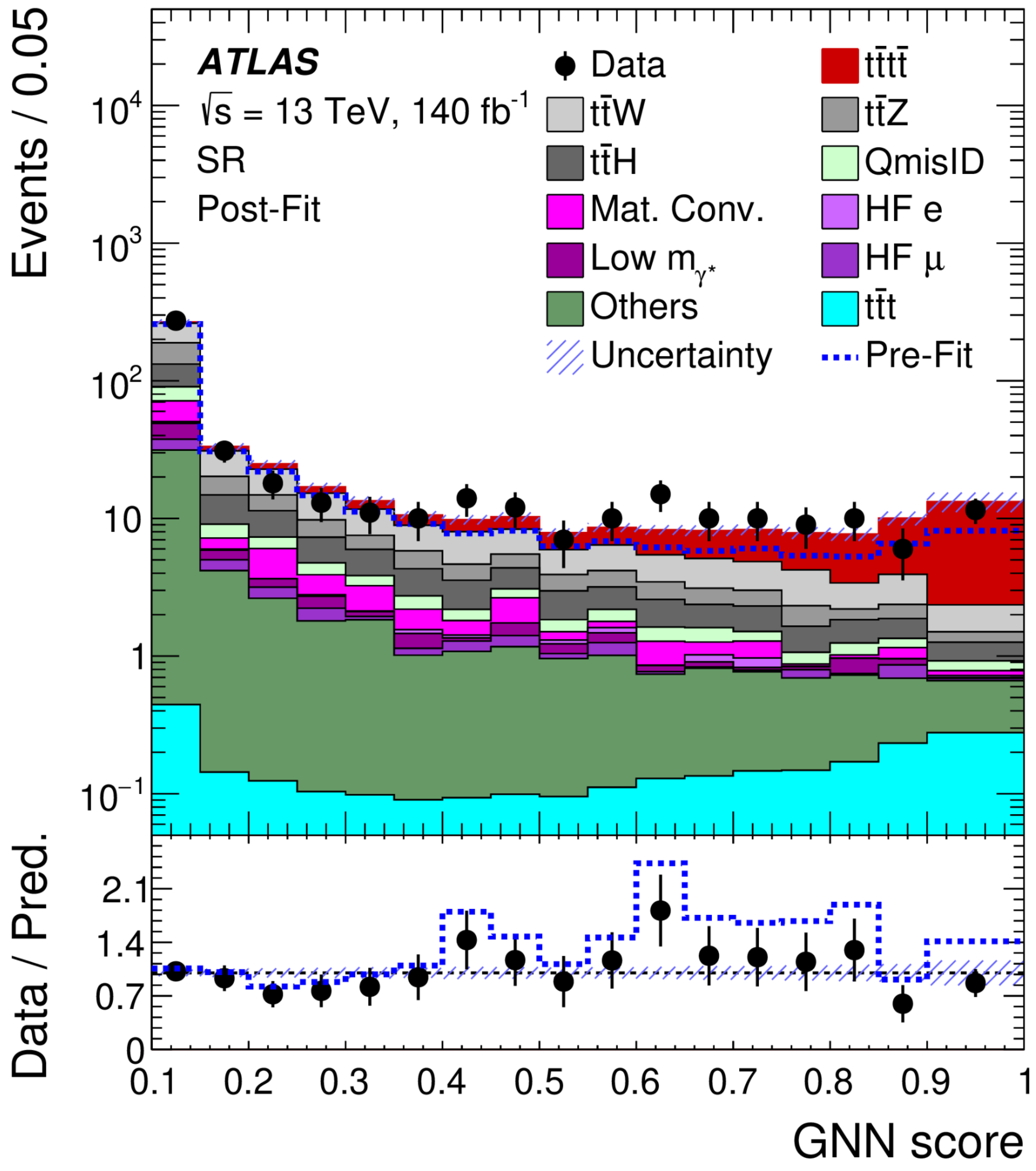
$$\mu_{t\bar{t}t\bar{t}} = 1.04 - 0.16\kappa_t^2 + 0.12\kappa_t^4$$



Q.-H. Cao, S.-L. Chen, Y. Liu, R.Zhang and Y. Zhang, Phys. Rev. D 99 (2019) 113003

Off-shell part: Four-Top Overview

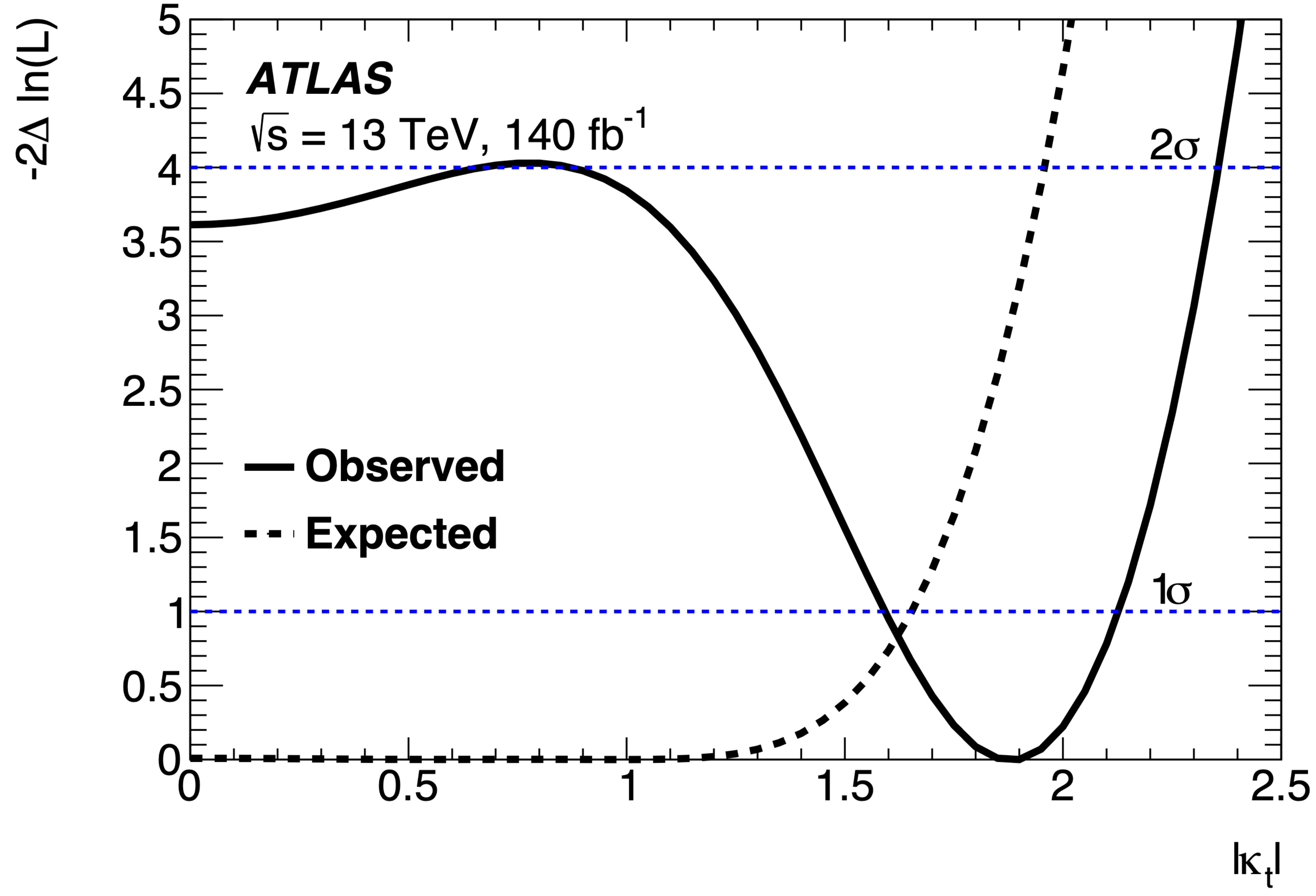
- Target at Multi-lepton final state
- Use Graph Neuron Network to separate signal and background processes



First observation with 6σ significance!

Eur. Phys. J. C 83 (2023) 496

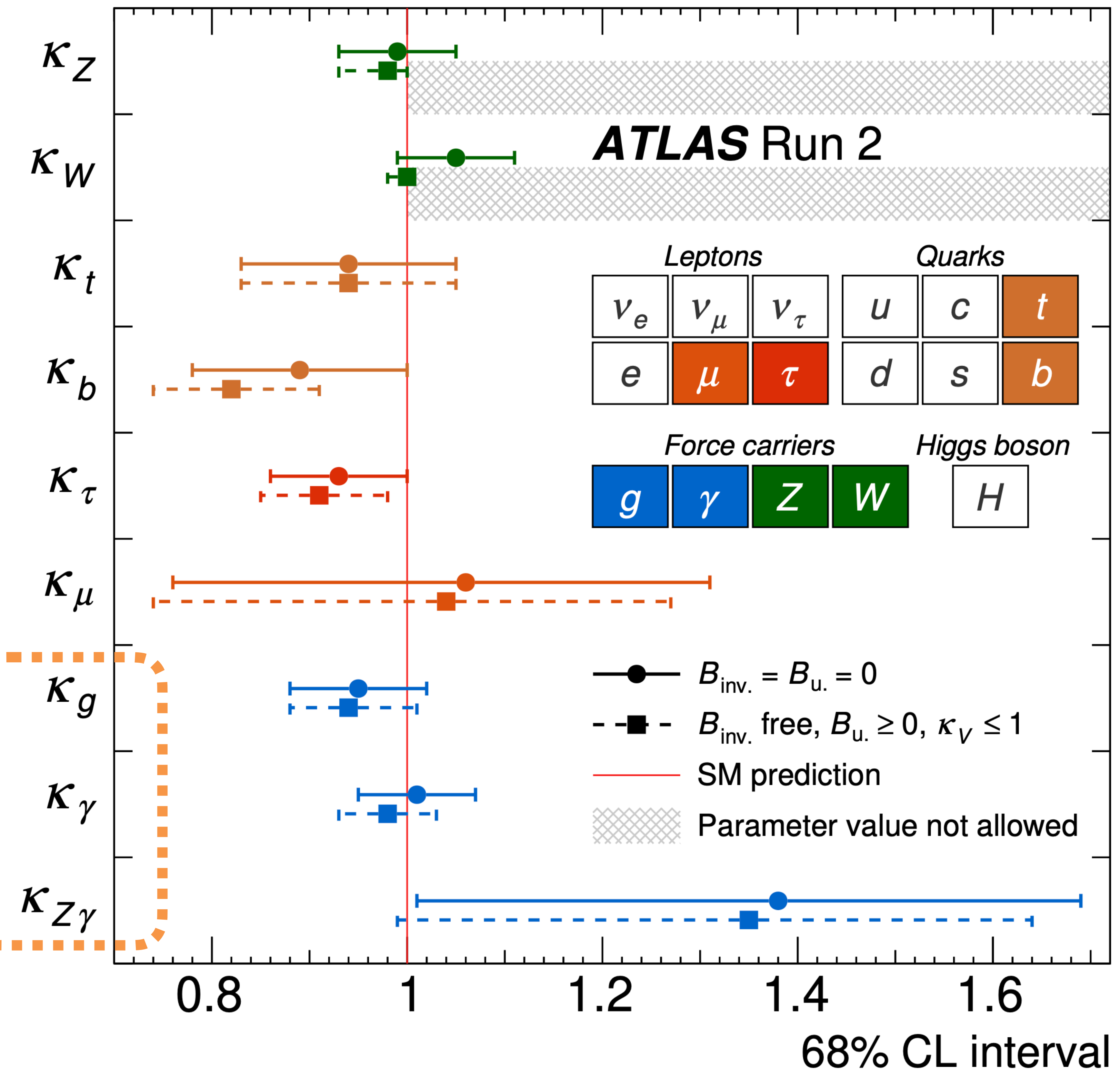
Interpreted into κ_t measurement:



95% CL upper limt: 2.3

- Covering all major Higgs production and decay modes at LHC. Nature 607 52 (2022)

Loop-induced, BSM particles can enter the loops

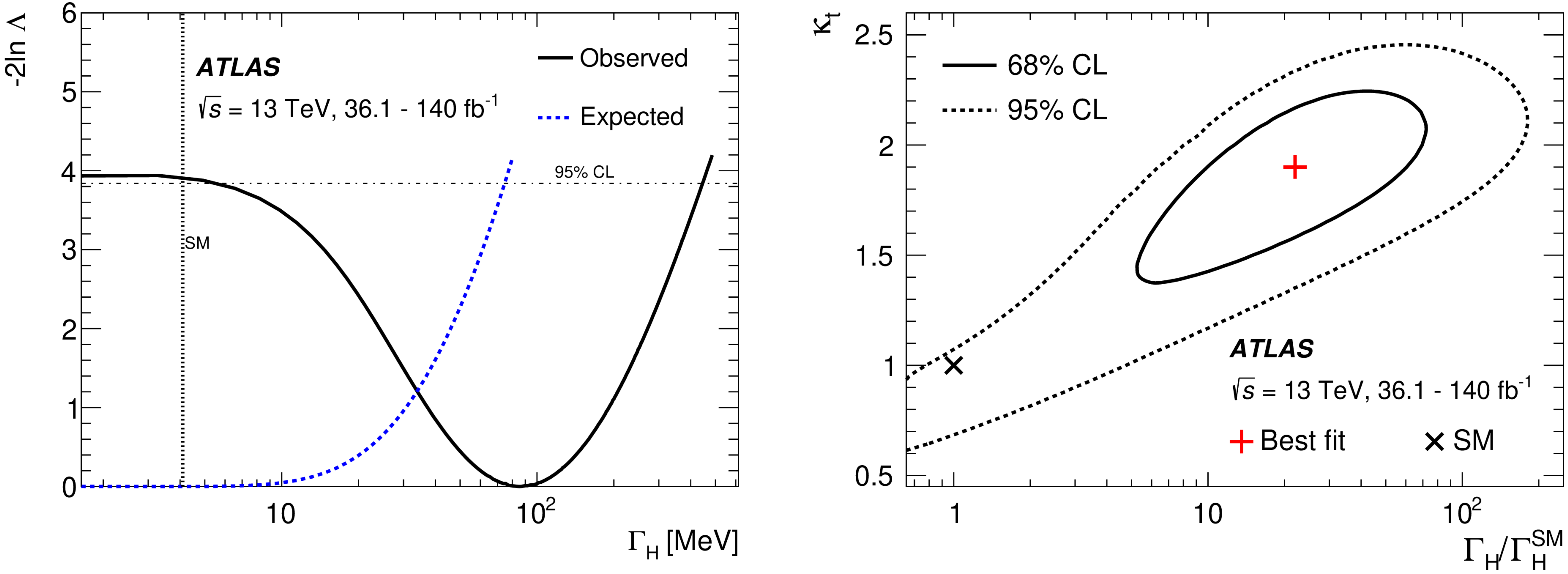


Target processes		Ref.
Off-shell measurements		
$pp \to t\bar{t}t\bar{t}$		[23]
On-shell measurements		
Production	Decay	
ggF, VBF, WH, ZH, $t\bar{t}$H, tH	$H \to \gamma\gamma$	[24]
$t\bar{t}$H + tH	$H \to b\bar{b}$	[25]
WH, ZH	$H \to b\bar{b}$	[26, 27]
VBF	$H \to b\bar{b}$	[28]
ggF, VBF, WH + ZH, $t\bar{t}$H + tH	$H \to ZZ$	[29]
ggF, VBF	$H \to WW$	[30]
WH, ZH	$H \to WW$	[31]
ggF, VBF, WH + ZH, $t\bar{t}$H + tH	$H \to \tau\tau$	[32]
ggF + $t\bar{t}$H + tH, VBF + WH + ZH	$H \to \mu\mu$	[33]
Inclusive	$H \to Z\gamma$	[34]

- To combine with four-top measurement, $t\bar{t}H \to$ Multi-lepton channel is removed from the on-shell part due to non-trivial overlap between them

Upper limit on Γ_H

Submitted to PLB



Tension with SM: 2.0 σ

	Observed	Expected
95% CL upper limit [MeV]	445	75

Impact of systematic uncertainties

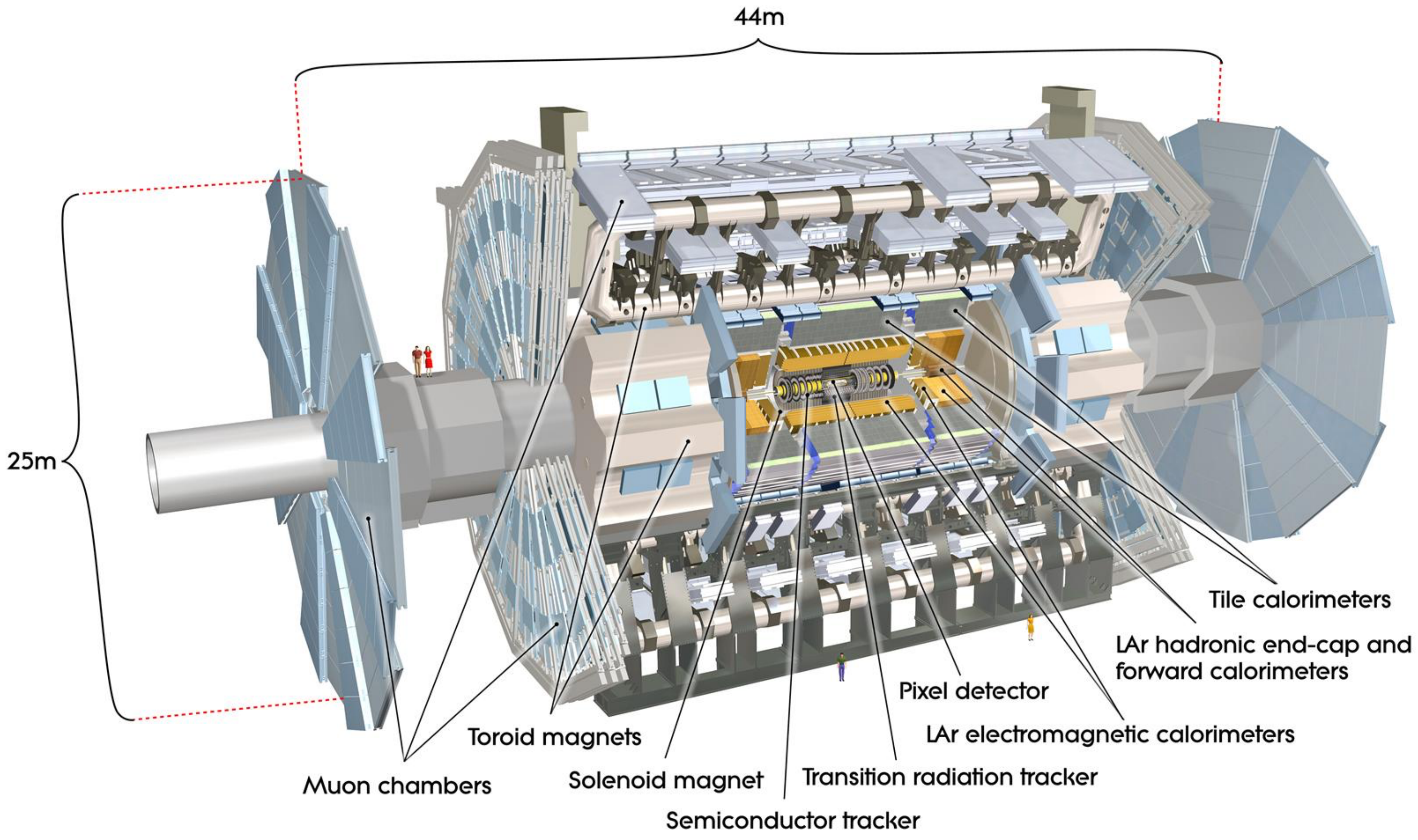
Systematic uncertainty	Impact on 95% CL upper limit of Γ_H Expected [%]	Impact on 95% CL upper limit of Γ_H Observed [%]
Theory	37	33
$t\bar{t}t\bar{t}$ theory	25	13
Higgs boson theory	5	6
Other theory	10	16
Experimental	2	2
Jet flavor tagging	2	1
Jet and missing transverse energy	< 1	< 1
Leptons and photons	< 1	< 1
All other systematic uncertainties	< 1	< 1

Summary

- Higgs Boson mass is measured from a combination of LHC Run1 and Run2 data in $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels in ATLAS experiment: $m_H = 125.11 \pm 0.11$ GeV, which is the most precise measurement up to date
- A first measurement on Higgs Boson width based on tree-level Higgs-top Yukawa coupling is performed. The observed (expected) 95% CL upper limit for Γ_H is 445 (75) MeV
- Outlook:
  - Higgs mass: LHC combination to provide input for future Higgs analysis
  - Higgs width:
    - Improvement of four-top measurement during Run3 and High-Lumi LHC
    - Add $t\bar{t}$ measurement to constrain off-shell κ_t
    - Design $t\bar{t}H \to$ Multi-lepton to be orthogonal with four-top and constrain on-shell κ_t

Back up

ATLAS experiment



- Large Hadron Collider (LHC)
  - The largest and highest energy particle collider in the world
  - Proton beams collide at center-of-mass energy up to 13.6 TeV

  → Suitable to study Higgs boson physics

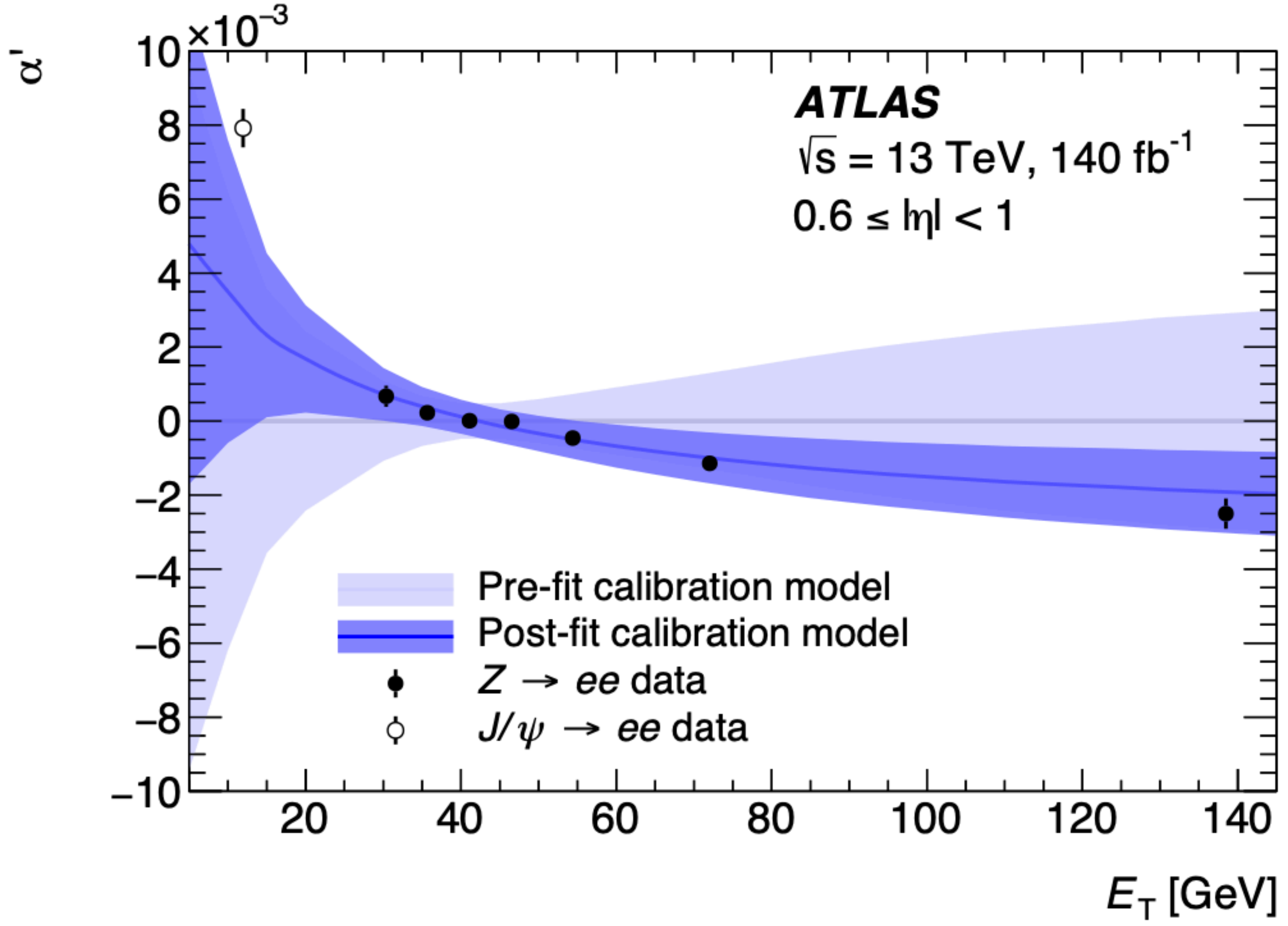
- A Toroidal LHC Apparatus (ATLAS)
  - Largest particle detector in the world
  - Inner solenoid + outer toroidal magnetic field
  - Various sub-detectors to measure and reconstruct particle information

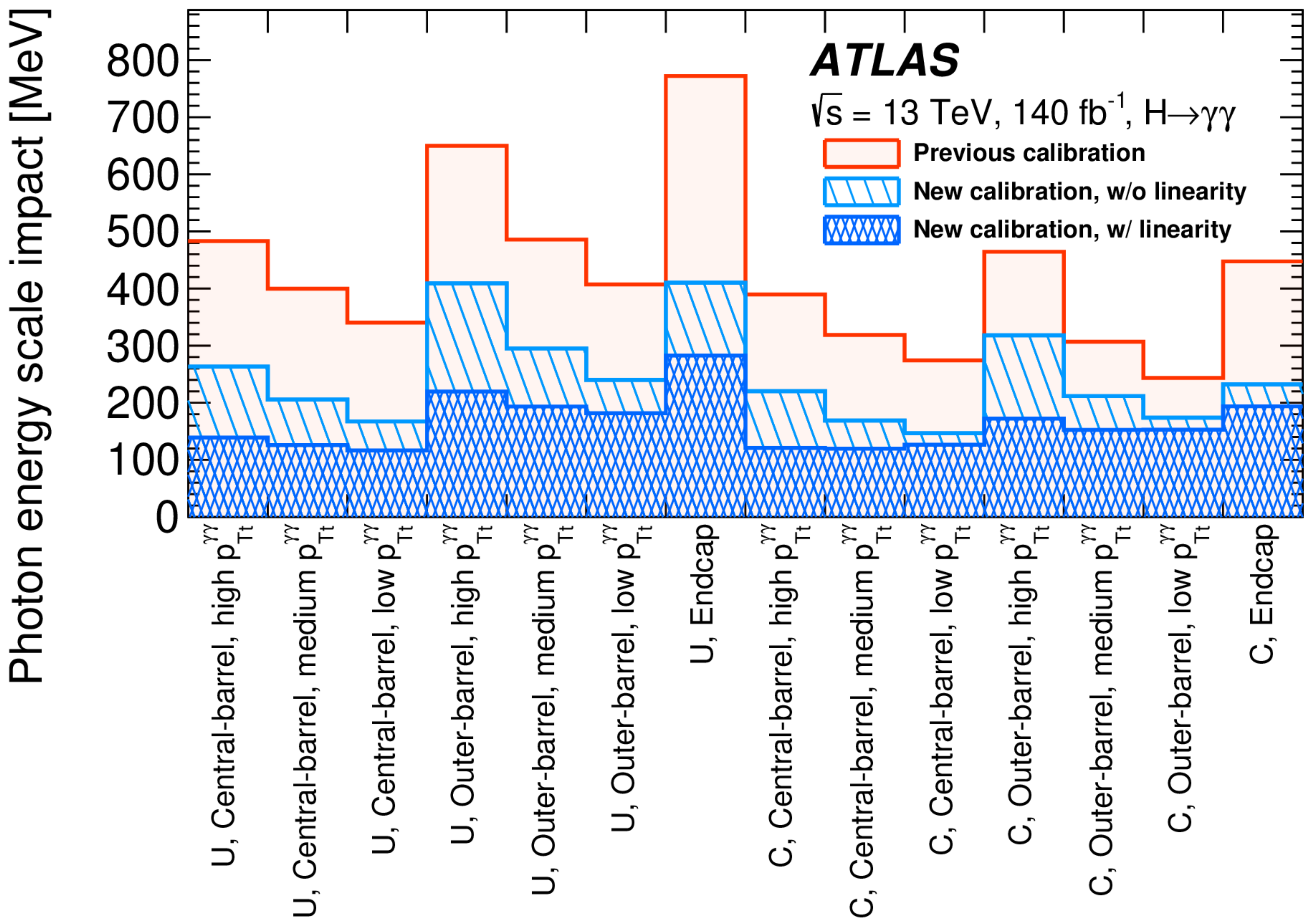
Linearity fit

$$E^{\text{data,corr}} = E^{\text{data}}/[(1+\alpha_i)(1+\alpha'_j)]$$

α: energy scale factor from standard calibration

α': extra factor for E_T dependent energy scale calibration





Systematic uncertainty correlation scheme

- $H \to \gamma\gamma$ Run1+Run2: Correlate some NPs for energy scale, resolution and theoretical uncertainties

  - Energy scale systematics uncertainties:

ATLAS_EG_SCALE_ZEESYST	↔	ATLAS_EM_ES_Z
ATLAS_PH_SCALE_CONVRADIUS	↔	ATLAS_EM_ConvRadius

  - Resolution systematics uncertainties:

ATLAS_EG_RESOLUTION_MATERIAL_RUN1_RUN2	↔	ATLAS_EM_mRes_MAT
ATLAS_EG_RESOLUTION_SAMPLINGTERM	↔	ATLAS_EM_mRes_ST
ATLAS_EG_RESOLUTION_ZSMEARING	↔	ATLAS_EM_mRes_CT

  - Theoretical uncertainties:

ATLAS_QCDscale_ggH	↔	ATLAS_QCDscale_ggH
ATLAS_QCDscale_VBF	↔	ATLAS_QCDscale_qqH
ATLAS_QCDscale_ttH	↔	ATLAS_QCDscale_ttH

Measurement Scenarios

- Generic Kappa - Primary result. Couplings generated by loops are parameterized independently of the tree-level couplings.
  - Minimal model dependence in the treatment of the loop couplings.
- Resolved Kappa - Secondary result. Loop level couplings are parameterized in terms of the tree level coupling modifiers.
  - Increased sensitivity from resolving the $H\to\gamma\gamma$ and $gg\to H$ loops.

Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(gg\to H)$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(qq'\to qq'H)$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qqZH)$	-	-	-	κ_Z^2
$\sigma(ggZH)$	✓	t–Z	-	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t - 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t + 0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b - 0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2

Higgs Combination Without *ttH*(ML)

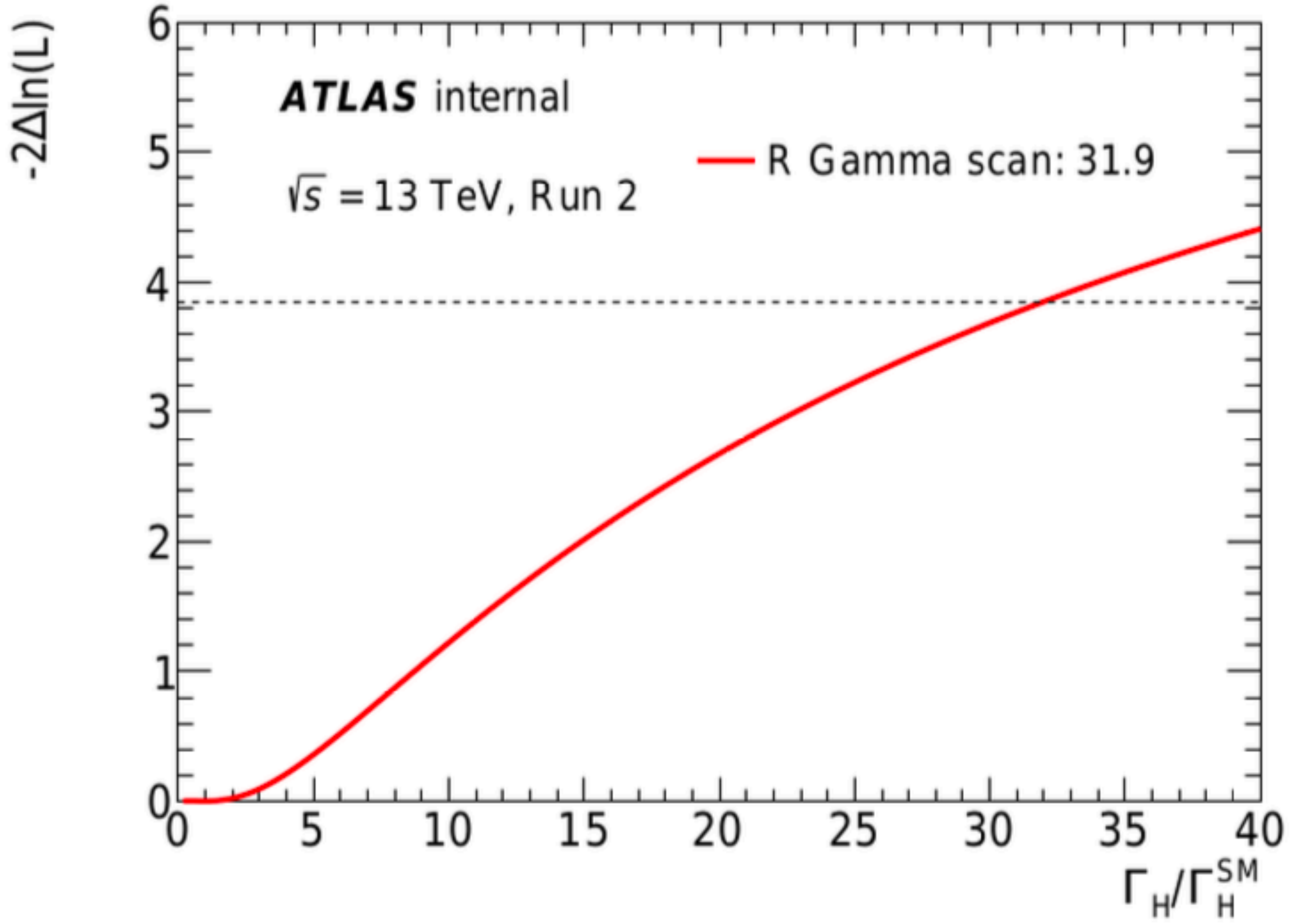
- We remove the *ttH*(ML) input from the Higgs combination due to non-trivial overlap with the *tttt* measurement
  - The same sign lepton signature used to measure four tops enters 5 of the 7 signal regions of the *ttH*(ML) analysis, including the sensitive 2LSS and 3L channels
- The measurement of κ_t is slightly affected

POI	Published Result	Result without $t\bar{t}H$ ML
κ_W	$1.05^{+0.06}_{-0.06}$	$1.05^{+0.06}_{-0.06}$
κ_Z	$0.99^{+0.06}_{-0.06}$	$1.00^{+0.05}_{-0.06}$
κ_{Zy}	$1.38^{+0.31}_{-0.37}$	$1.39^{+0.31}_{-0.37}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.91^{+0.12}_{-0.11}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.96^{+0.08}_{-0.07}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.07^{+0.25}_{-0.31}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.93^{+0.07}_{-0.07}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.86^{+0.13}_{-0.13}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$1.02^{+0.06}_{-0.06}$

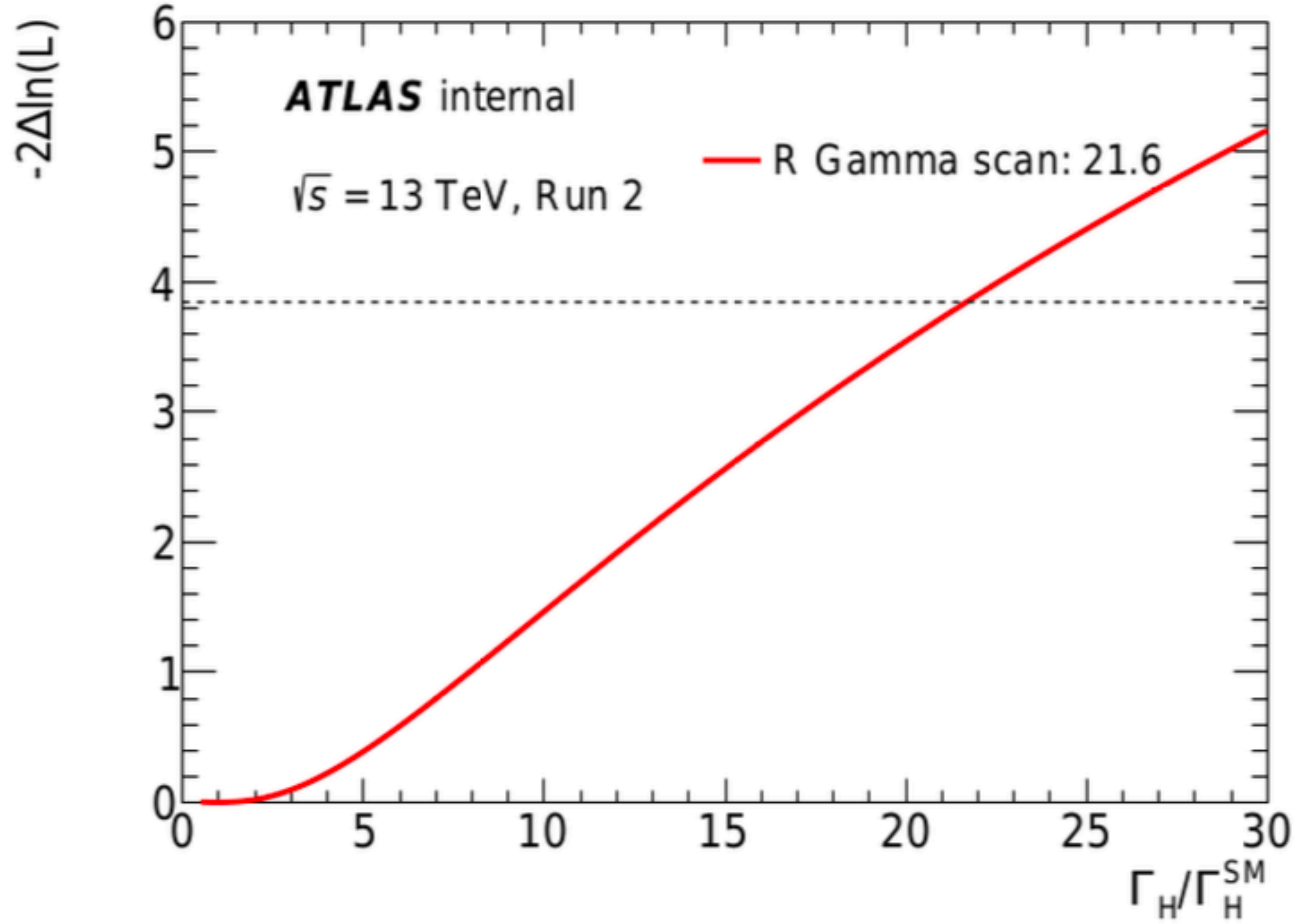
Relative weight of ttHyy and ttHbb

Test on asimov, nominal upper limit = 18.2

Remove ttH/tH categories in ttH$\gamma\gamma$

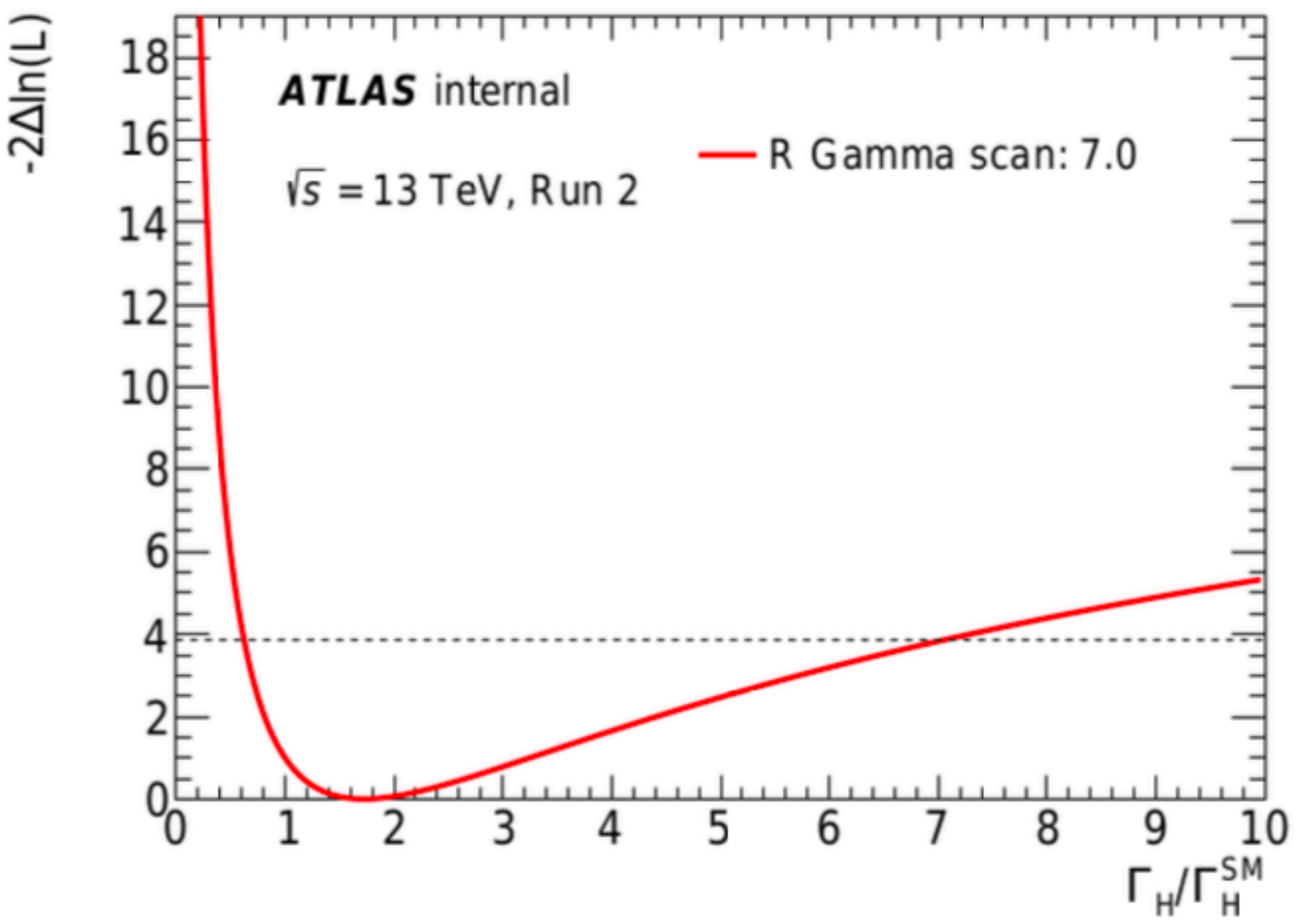


Remove ttHbb

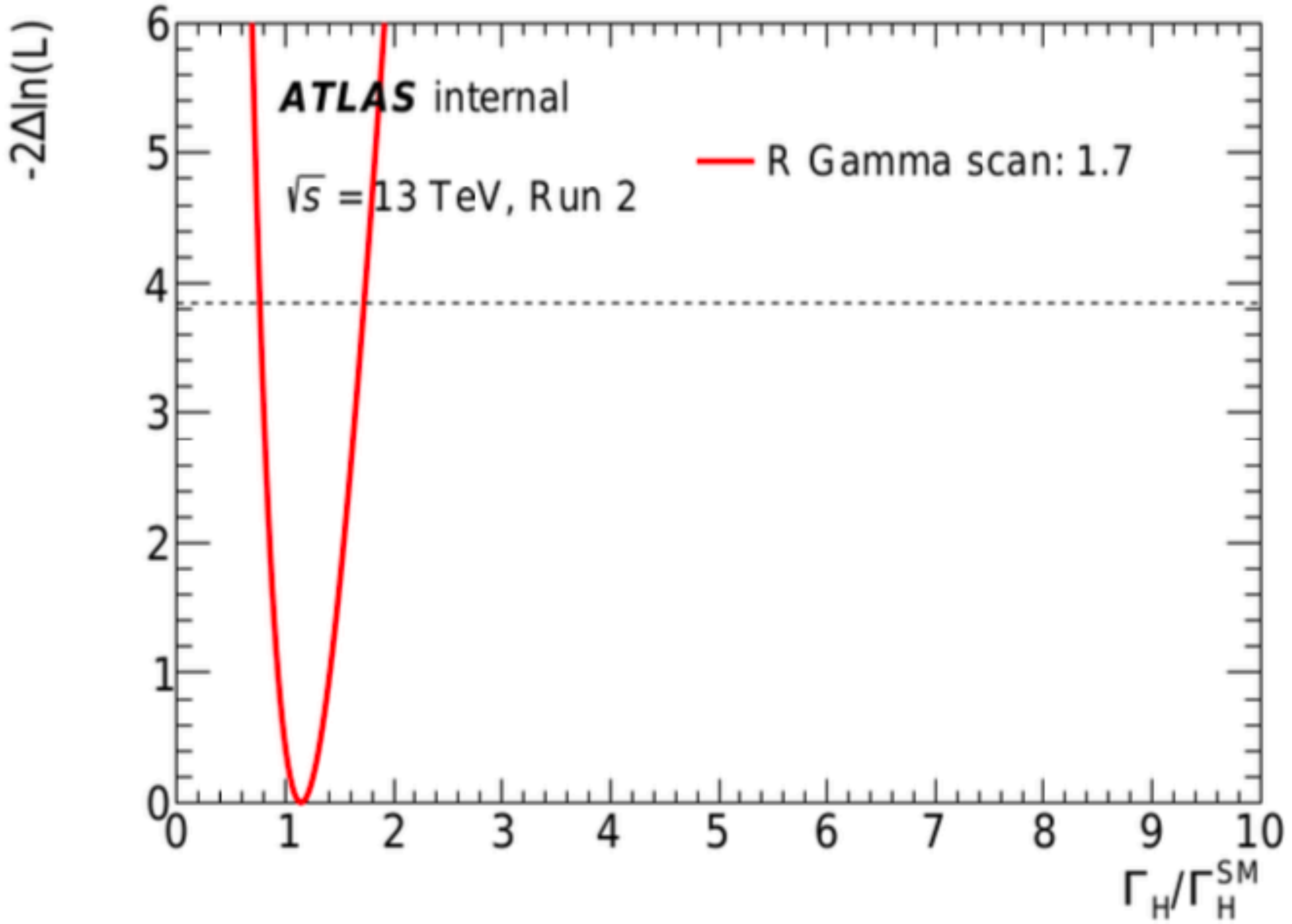


κ_t fixed at 1

GenericKappa:

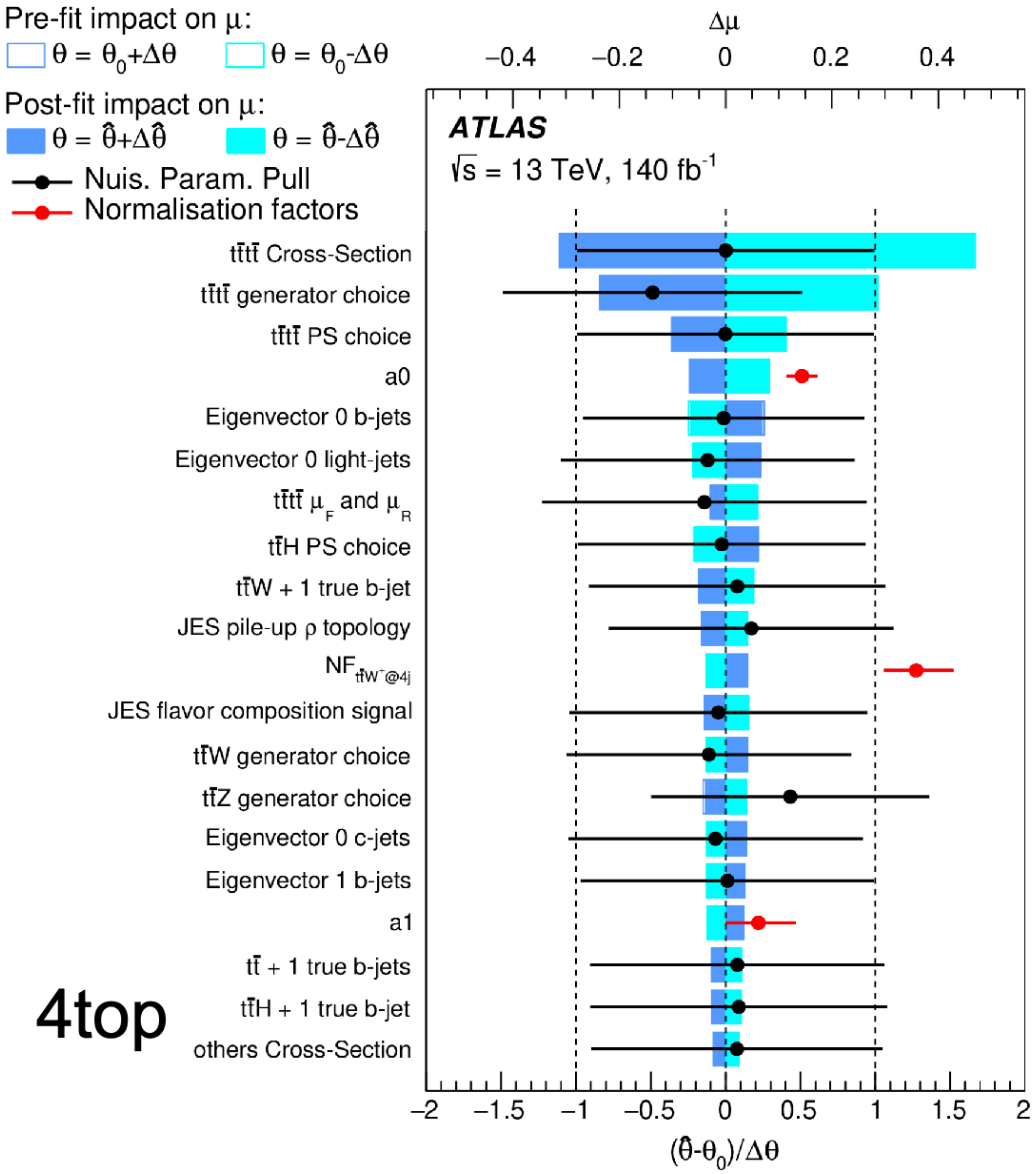


ResolvedKappa:

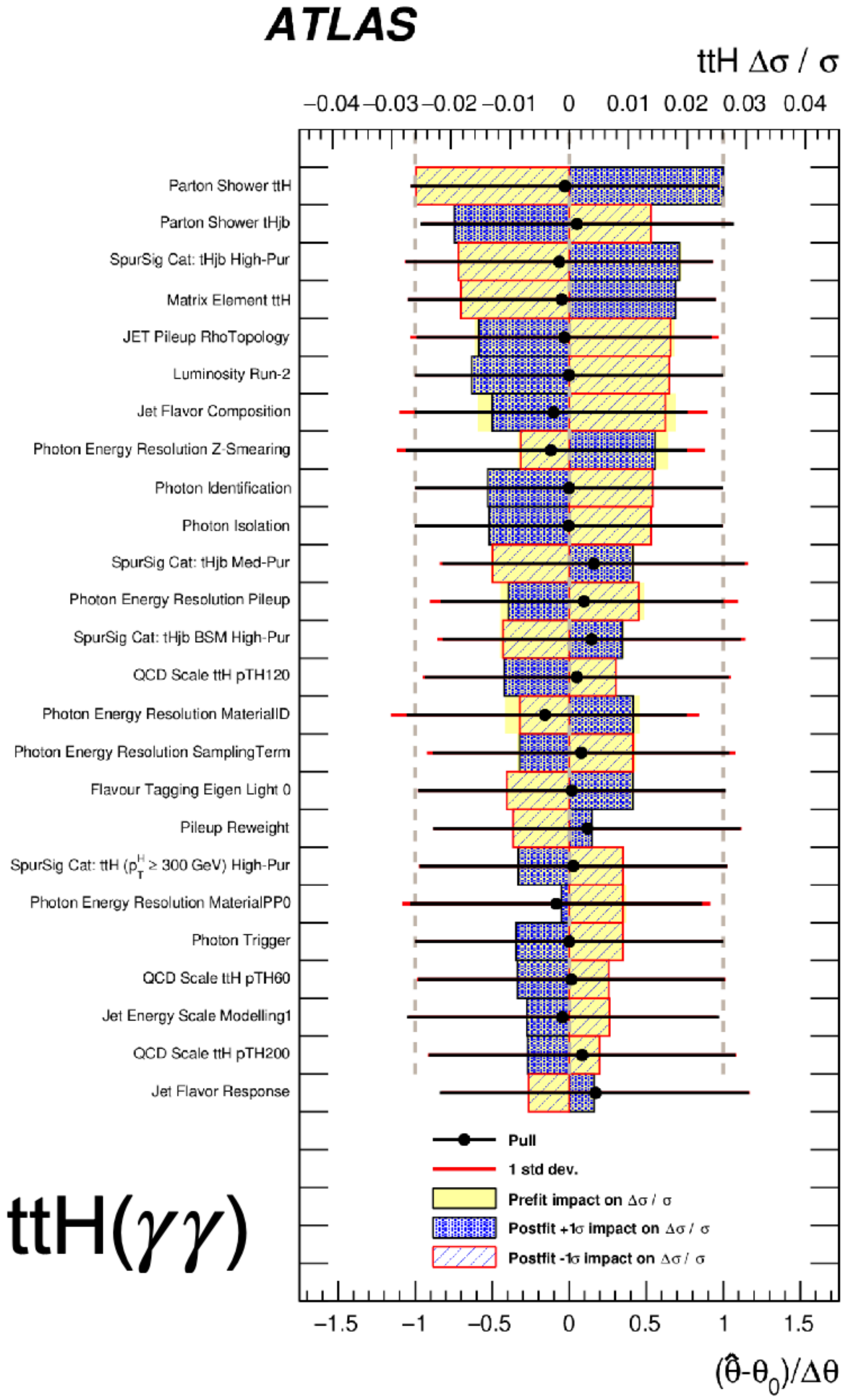


Dominant Systematics in Signal Strength Fits Before Combination

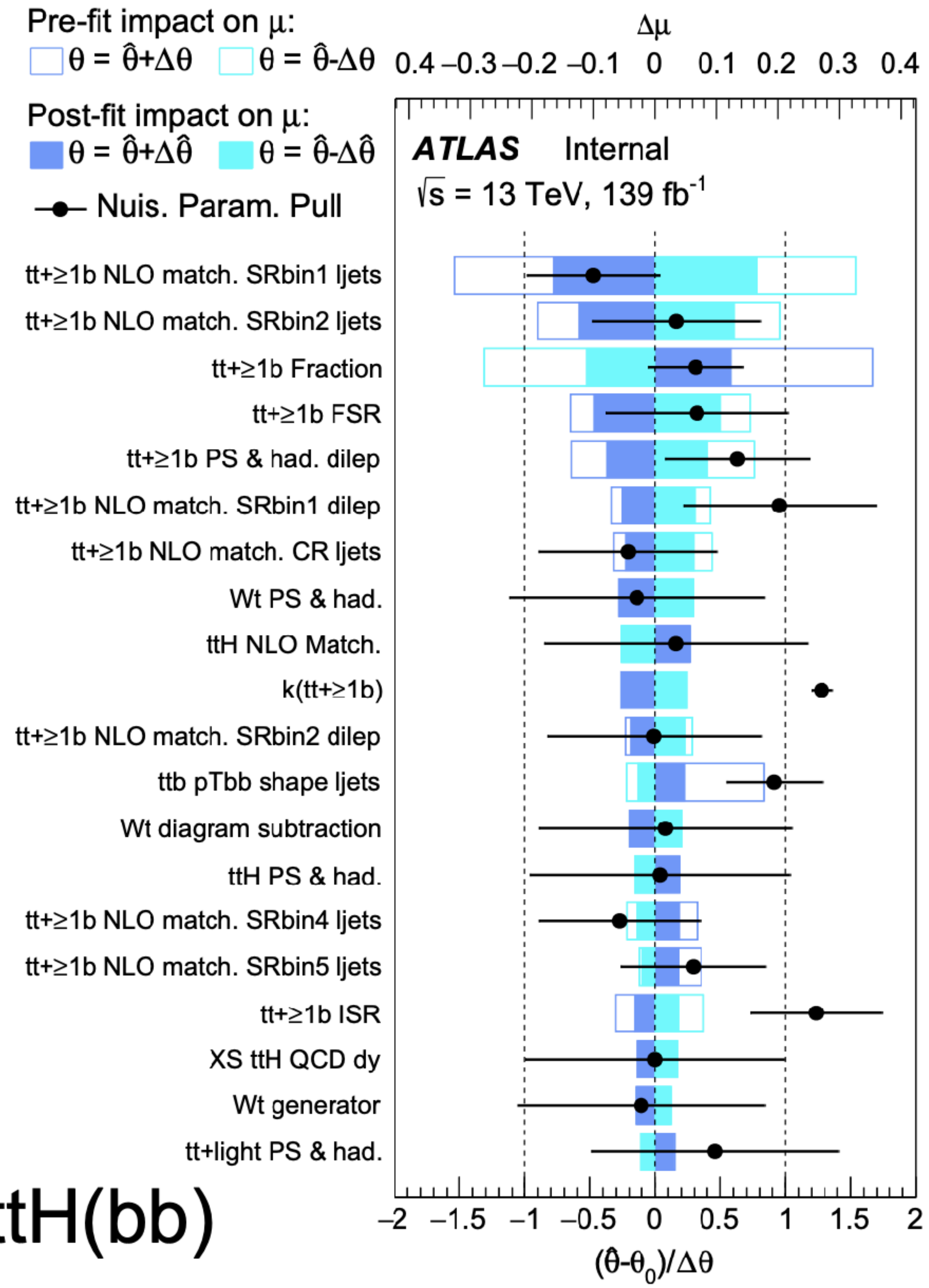
Highest ranked uncertainties are generally theoretical.



4top



ttH(γγ)



ttH(bb)

Systematics Correlation - Theoretical

- Processes playing a major role in multiple input channels have correlated theoretical systematic uncertainties
- *ttH*, *tttt*, and *ttZ* are affected, details in backup
- The nominal and alternate *ttW* samples are different between the inputs, so we don't correlate the systematics
  - *ttH*(bb) uses MadGraph as nominal, Sherpa as alternate. Four-top uses Sherpa as nominal, FxFx as alternate
- The cross-section and PDF uncertainties do not have the same values, but the impact is expected to be small

NP Name in the 4 tops WS	NP Name in the Nature WS	Ranking in 4 tops fit	Ranking in $t\bar{t}H(b\bar{b})$
alpha_ttH_Gen	Theorysig_ME_ttH	> 30	9
alpha_ttH_PDF	TheorySig_PDF_ttH	> 30	> 20
alpha_ttH_PS	TheorySig_UEPS_ttH	5	14
alpha_ttH_Xsec	TheorySig_QCDscale_ttH_mu	> 30	18
alpha_ttH_varRF	TheorySig_ttH_Rad	> 30	> 20
alpha_tttt_Xsec	BkgTheory_tttt_XS_ttHbb	1	> 20
alpha_ttZ_Gen	BkgTheory_ttZ_Gen_ttHMLbb*	15	> 20
alpha_ttZ_PDF	BkgTheory_ttZ_XS_PDF_ttHMLbb*	> 30	> 20
alpha_ttZ_Xsec	BkgTheory_ttZ_XS_QCDscale_ttHMLbb*	> 30	> 20

Systematic Uncertainty Correlation

- Theoretical:
  - Shared uncertainties of $t\bar{t}H$, $t\bar{t}t\bar{t}$ and $t\bar{t}Z$ processes are correlated
- Luminosity:
  - Assigned extra uncertainty to cover the luminosity difference in different calibration schemes
  - Split the total uncertainty into 4 components to correlate different datasets

	δ_0	δ_1	δ_2	δ_3	$\sqrt{\Sigma_i \delta_i^2}$	Original δ
2015-2016	0.575%	0.101%	0.641%	0.074%	0.87%	0.87%
2015-2018	0.816%	0.143%	0.102%	0.019%	0.83%	0.83%

- Other experimental:
  - Correlate the shared uncertainties for jet, pileup reweighting, missing E_T, e/γ, lepton and so on

Treatment of ttH in four-top

- Four-top measurement has ttH as background
- We leave the normalization of the *ttH* process floating in the four-top workspace because the decay modes are not separated
- A full parameterization would have a <2% impact on the expected limit
  - Learn from ttH(ML) analysis: mostly WW and $\tau\tau$ decay
  - Studied by assuming either 100% WW or 100% $\tau\tau$ decay

	$t\bar{t}H$ profiled	$t\bar{t}H$ resolved as $t\bar{t}H$WW	$t\bar{t}H$ resolved as $t\bar{t}H\tau\tau$
Expected upper limit on Γ_H/Γ_{SM}	18.2	17.9	17.9

- Also tested on observed data: 6% impact on the upper limit

Treatment of four-top in ttHbb

- ttHbb measurement has four-top as background
- We leave the normalization of the four-top process fixed to the SM with a 50% cross-section uncertainty in the *ttH*(bb) workspace
- Four-top is a small background and the impact of changing the parameterization is negligible.
  - Studied by the inclusive parameterization for four-top cross-section in ttHbb

$$\mu_{t\bar{t}t\bar{t}} = 1.04 - 0.16\kappa_t^2 + 0.12\kappa_t^4$$

  - correlate κ_t with four-top analysis
  - Caveat: four-top analysis used bin-by-bin parameterization instead of the inclusive one

	Expected upper limit on Γ_H/Γ_{SM}
$t\bar{t}t\bar{t}$ in Nature workspace fixed to SM	18.2
$t\bar{t}t\bar{t}$ in Nature workspace correlated with $t\bar{t}t\bar{t}$ analysis	18.3

Understand the observed best-fit value

- Fit on observed data gives $\Gamma_H/\Gamma_H^{SM} = 21$ as best-fit
- Other POIs are also pulled away from 1
  - κ_t mostly pulled by four-top measurement
  - R_Γ and other κ pulled via on-shell relationship

POI	Best-fit value
R_Γ	20.963
κ_t	1.877
κ_Z	2.183
κ_W	2.308
κ_b	2.000
κ_τ	2.037
κ_μ	2.356
κ_g	2.094
κ_γ	2.235
$\kappa_{Z\gamma}$	3.040

Detailed systematic impact study

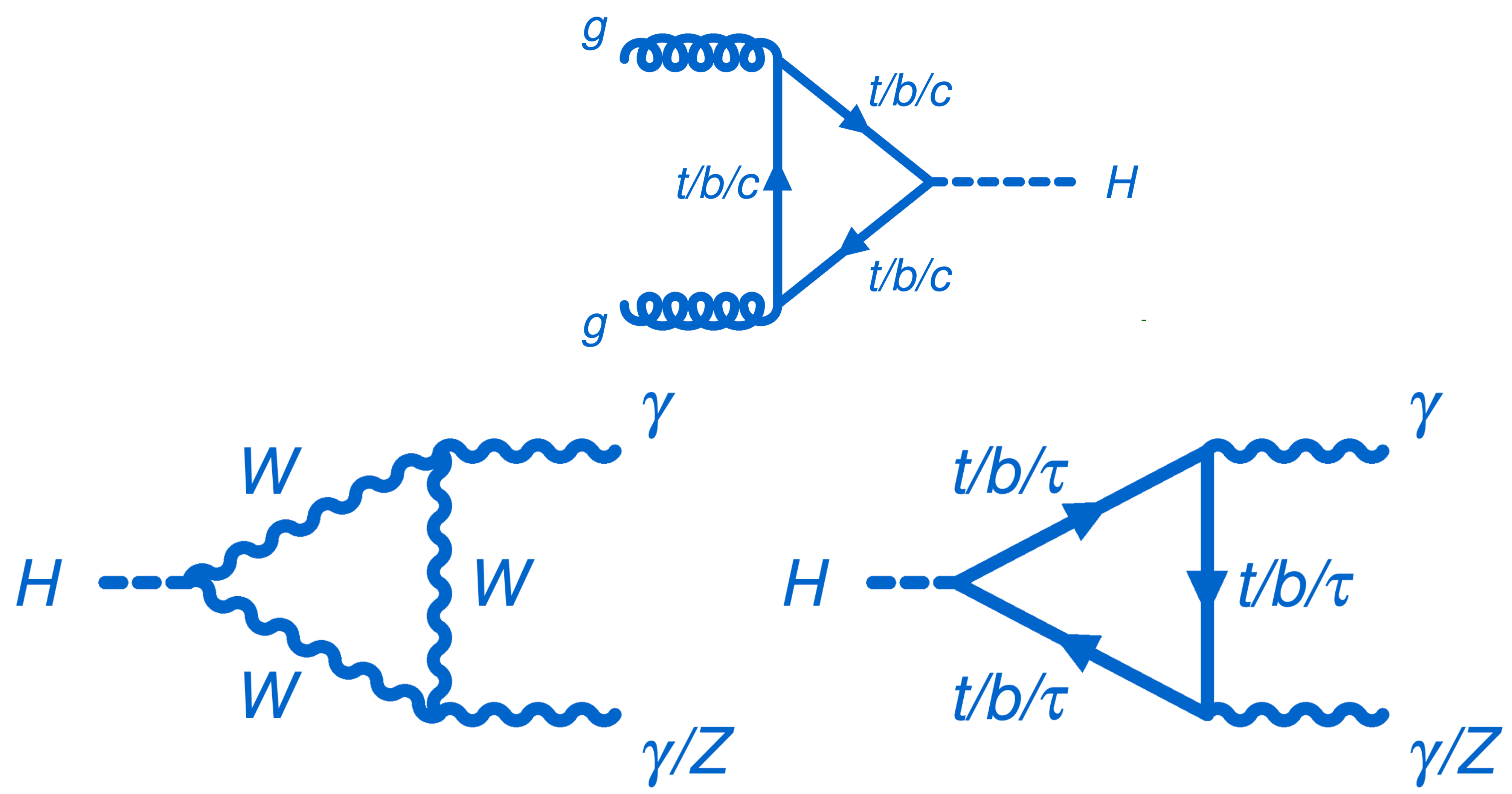
Systematics Model	Observed Limit on R_Γ (**GenericKappa**)	Expected Limit on R_Γ (**GenericKappa**)
Nominal	108.6	18.2
Remove All Theory	72.5 (33.2%)	11.5 (37%)
Remove $t\bar{t}t\bar{t}$ Theory	94.2 (13.3%)	13.7 (25%)
Remove $t\bar{t}t\bar{t}$ Cross-section Theory	98.7 (9.1%)	15.4 (15.4%)
Remove $t\bar{t}t\bar{t}$ Generator Theory	105.3 (3.0%)	17.1 (6.0%)
Remove $t\bar{t}t\bar{t}$ Parton Shower Theory	107.9 (<1%)	18.0 (1.1%)
Remove other $t\bar{t}t\bar{t}$ Theory	108.5 (<1%)	18.2 (<1%)
Remove Background Theory	91.1 (16.1%)	16.4 (9.9%)
Remove Background Theory in ttHbb	92.5 (14.8%)	16.7 (8.2%)
Remove Background $t\bar{t}+\geqslant 1b$ Theory	95.3 (12.2%)	17.0 (6.6%)
Remove Higgs Theory	102.2 (5.9%)	17.3 (4.9%)
Remove All Experiment	106.2 (2.2%)	17.8 (2.2%)
Remove FTAG	107.2 (1.3%)	17.9 (1.6%)
Remove Jet+MET	108.2 (<1%)	18.1 (<1%)
Remove Lepton+Photon	108.3 (<1%)	18.2 (<1%)
Remove Others	107.6 (<1%)	18.1 (<1%)
Stat-Only	67.8 (37.6%)	10.8 (41%)

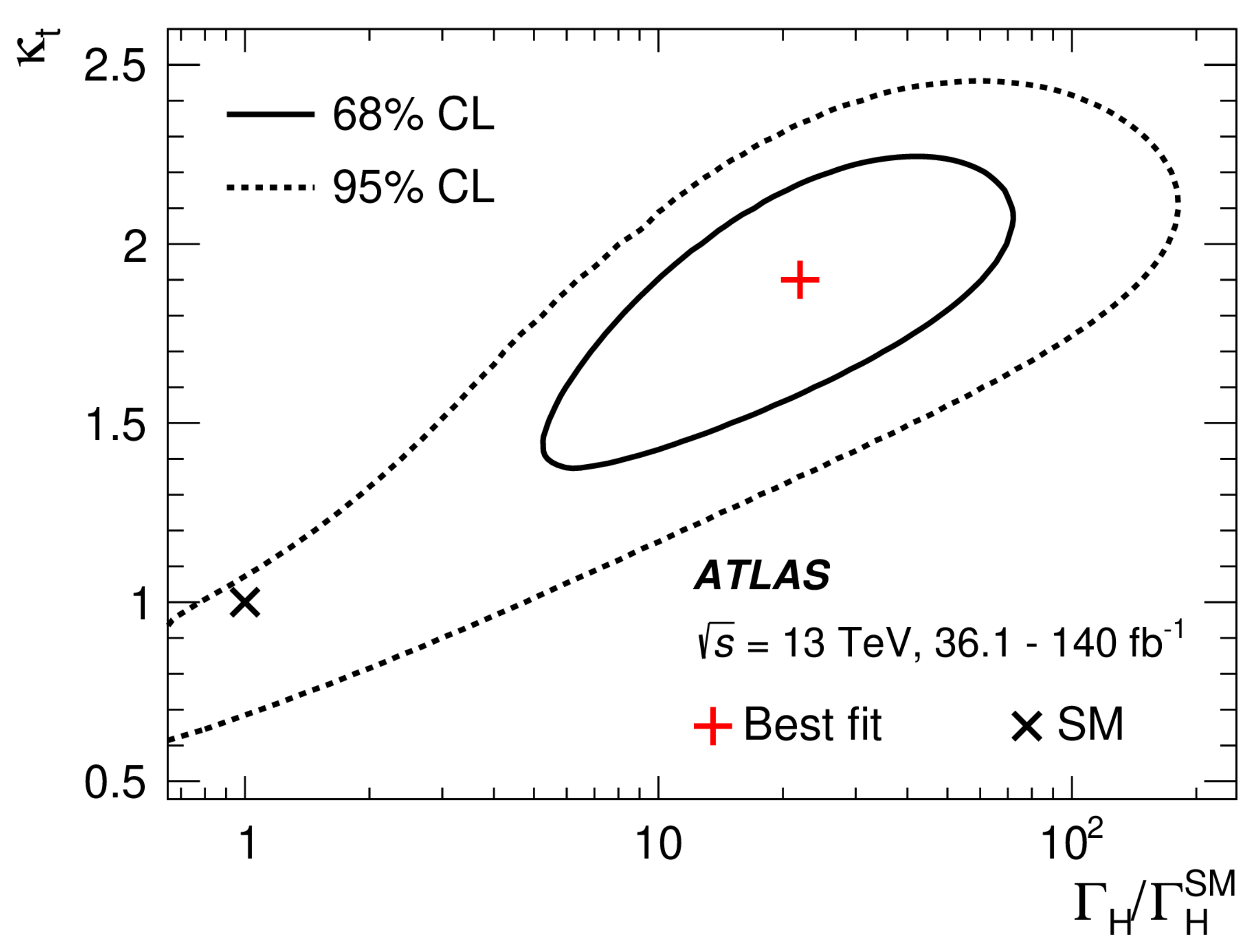
Further resolve the loops

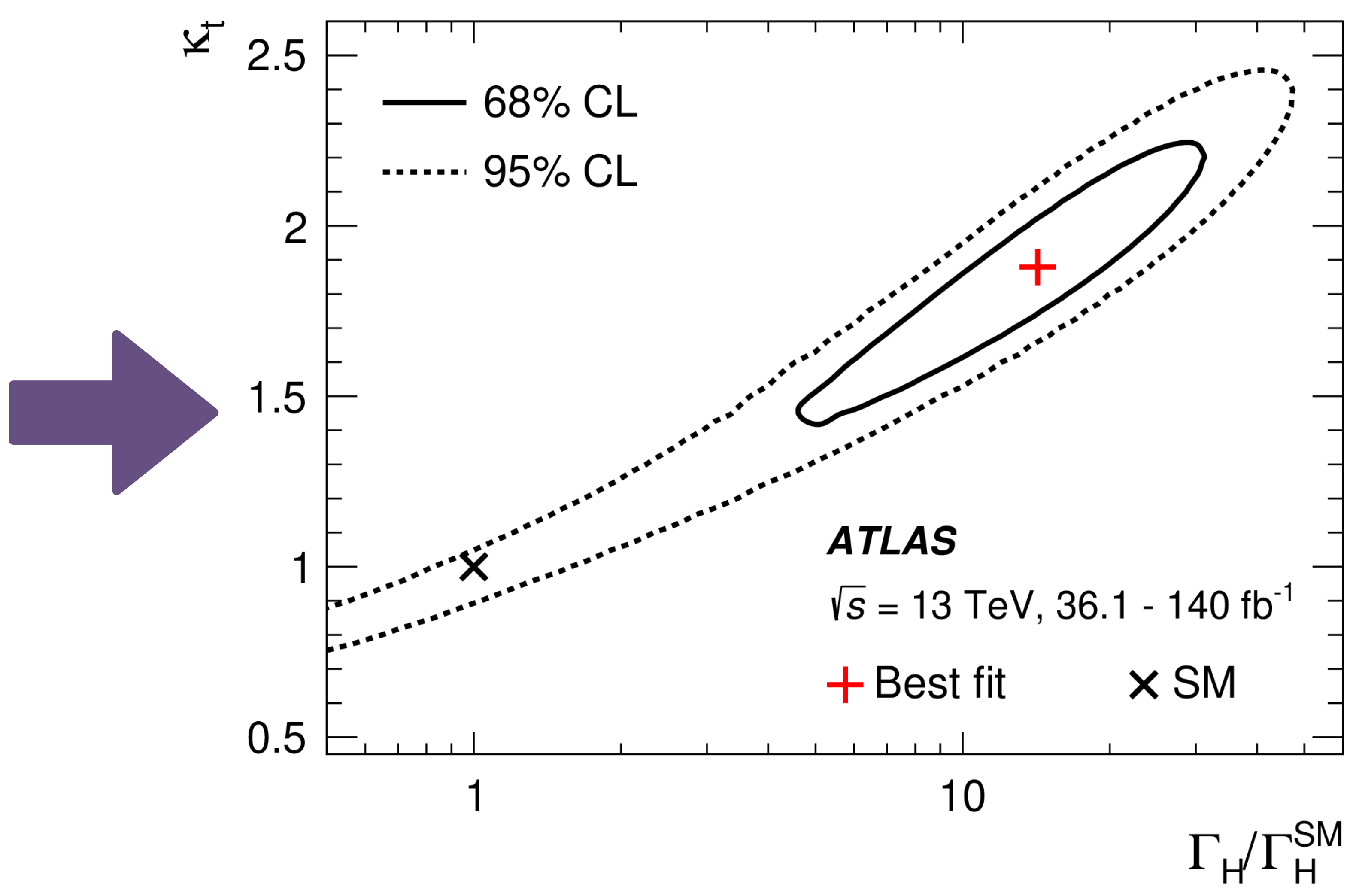
- ggF, $H \to \gamma\gamma$ and $H \to Z\gamma$ loops contain the contribution from top-quark
- Can resolved them into couplings with SM particles

→ 95% CL upper limit decreases from 445 MeV to 157 MeV after resolving the loops

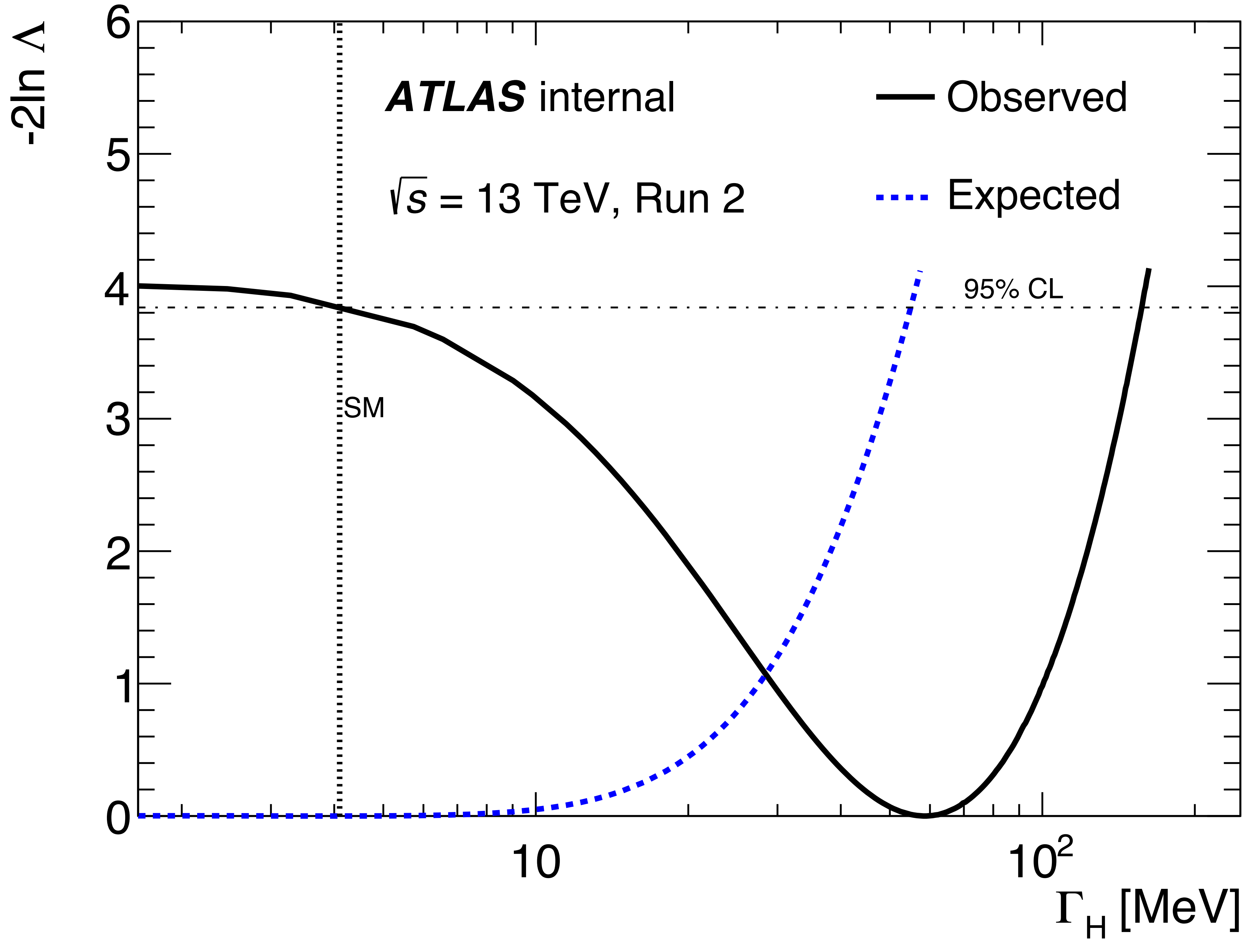
  - Improvement due to stronger assumptions

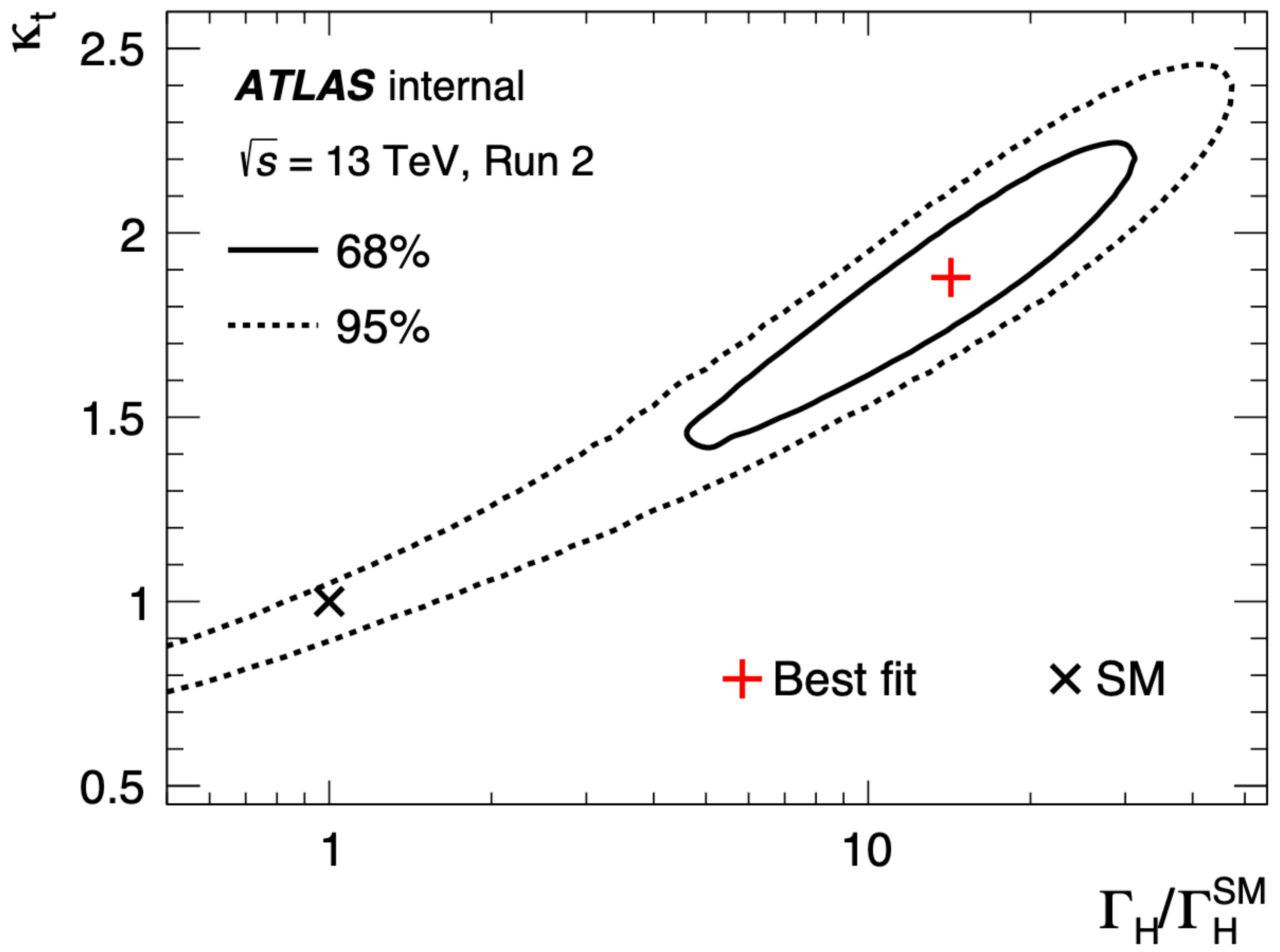






The 2-dim contour's shape shrinks in κ_t direction after resolving the loops
→ ggF and $H \to \gamma\gamma$ loops introduce extra constraint on κ_t





Tension with SM: 2.0 σ

	Observed	Expected
95% CL upper limit [MeV]	157	55