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Higgs properties with the ATLAS detector

Latest-and-greatest results with full Run-2 data

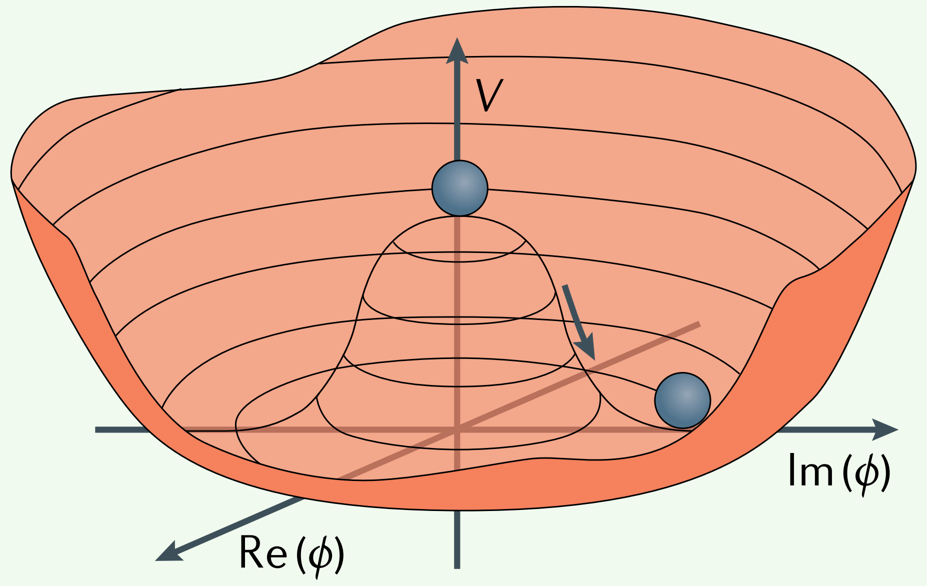
Mohamed Aly obo the ATLAS collaboration, 27.08.2024

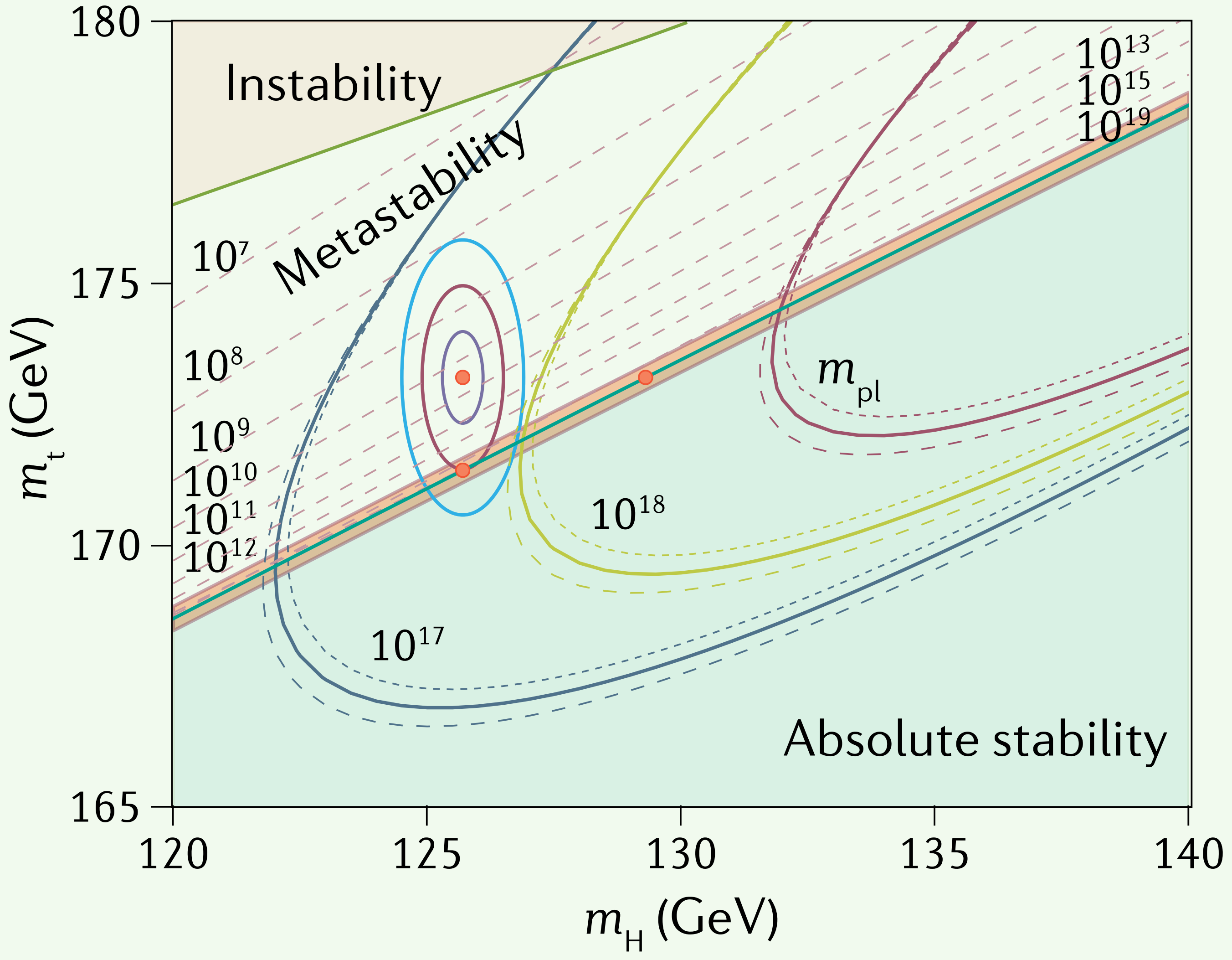
ICNFP 2024, Crete

Overview

What makes a Higgs "the" Higgs

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$





Mass

$$m_H^2 = -2\mu^2$$

Fundamental (free) parameter of the SM

⬇

- Only depends on $V(\phi)$ parameters
- Linked to stability of universe

Width

$\Gamma_H^{SM} \approx 4$ MeV

Sensitive to un-observed massive particles

Coupling

Coupling of other particles to Higgs modified by new physics

⬇

New physics parameterisation with SMEFT and Kappa frameworks

CP structure

CP-violation in SM is not enough to explain matter-antimatter asymmetry

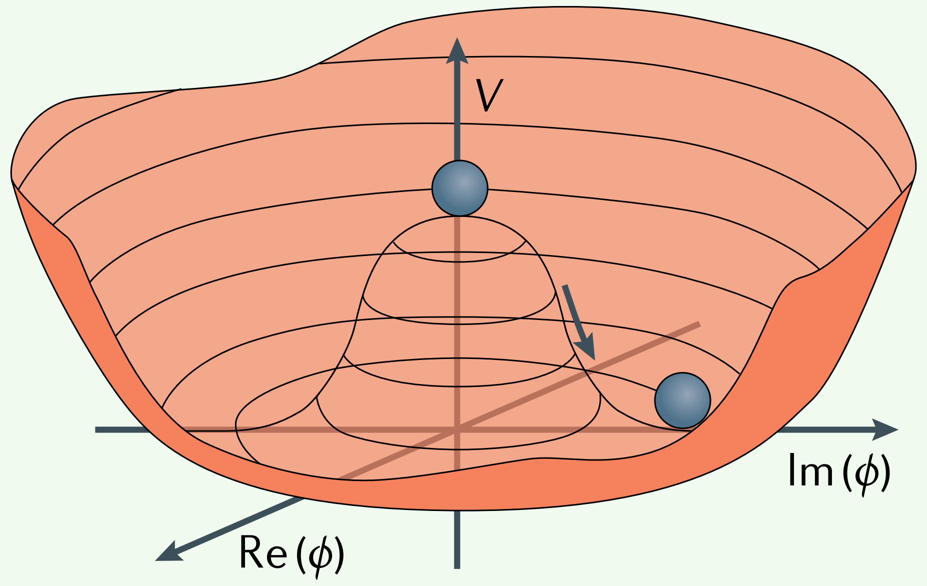
⬇

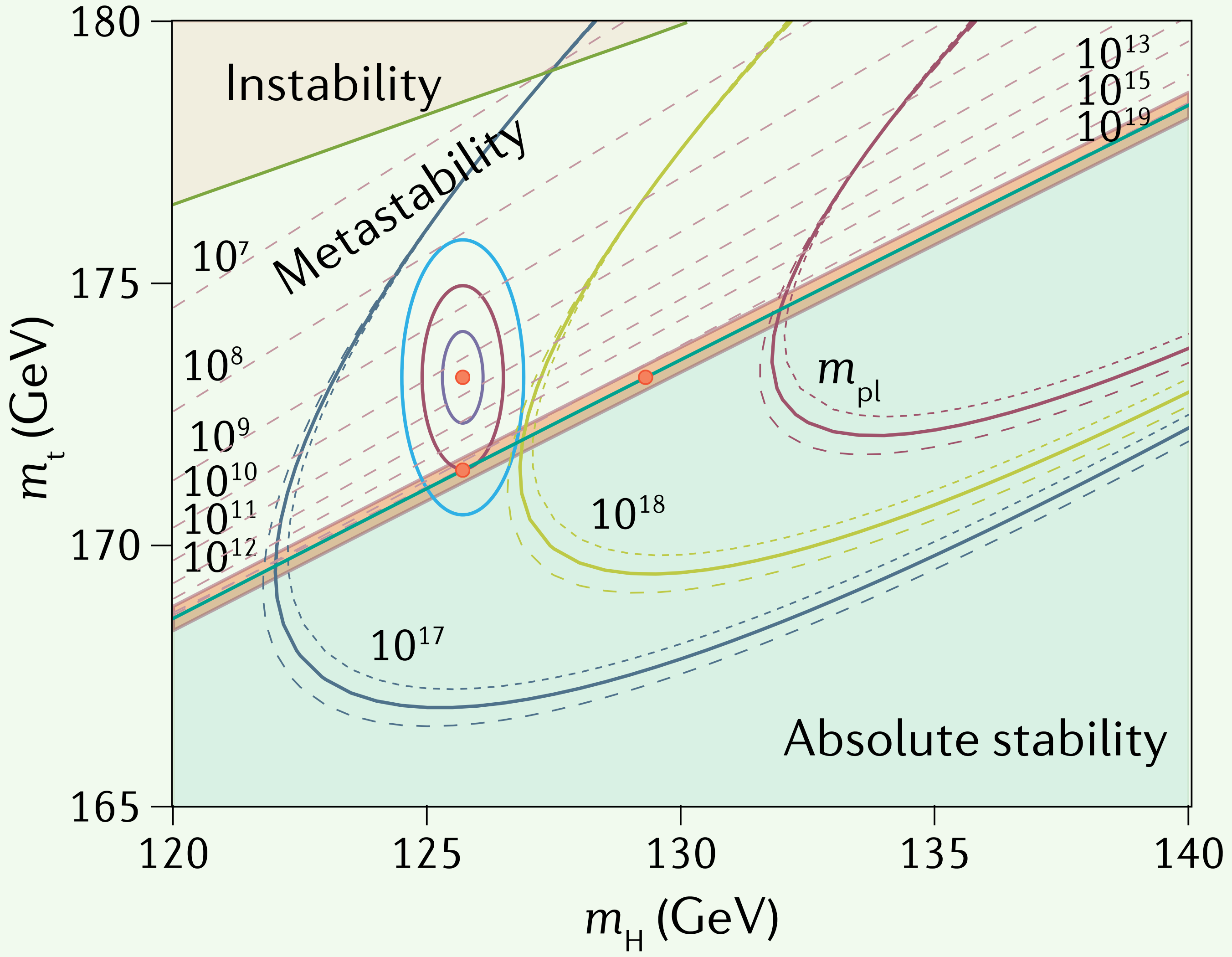
- Higgs sector in SM is CP-conserving
- CP-violation in Higgs sector hiding?

Overview

What makes a Higgs "the" Higgs: this talk

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$





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See talk by Y. Zhu

New physics parameterisation with SMEFT and Kappa frameworks

CP structure

CP-violation in SM is not enough to explain matter-antimatter asymmetry

- Higgs sector in SM is CP-conserving
- CP-violation in Higgs sector hiding?

Higgs mass

Probed with $H \to \gamma\gamma$ and $H \to ZZ^\star \to 4\ell$

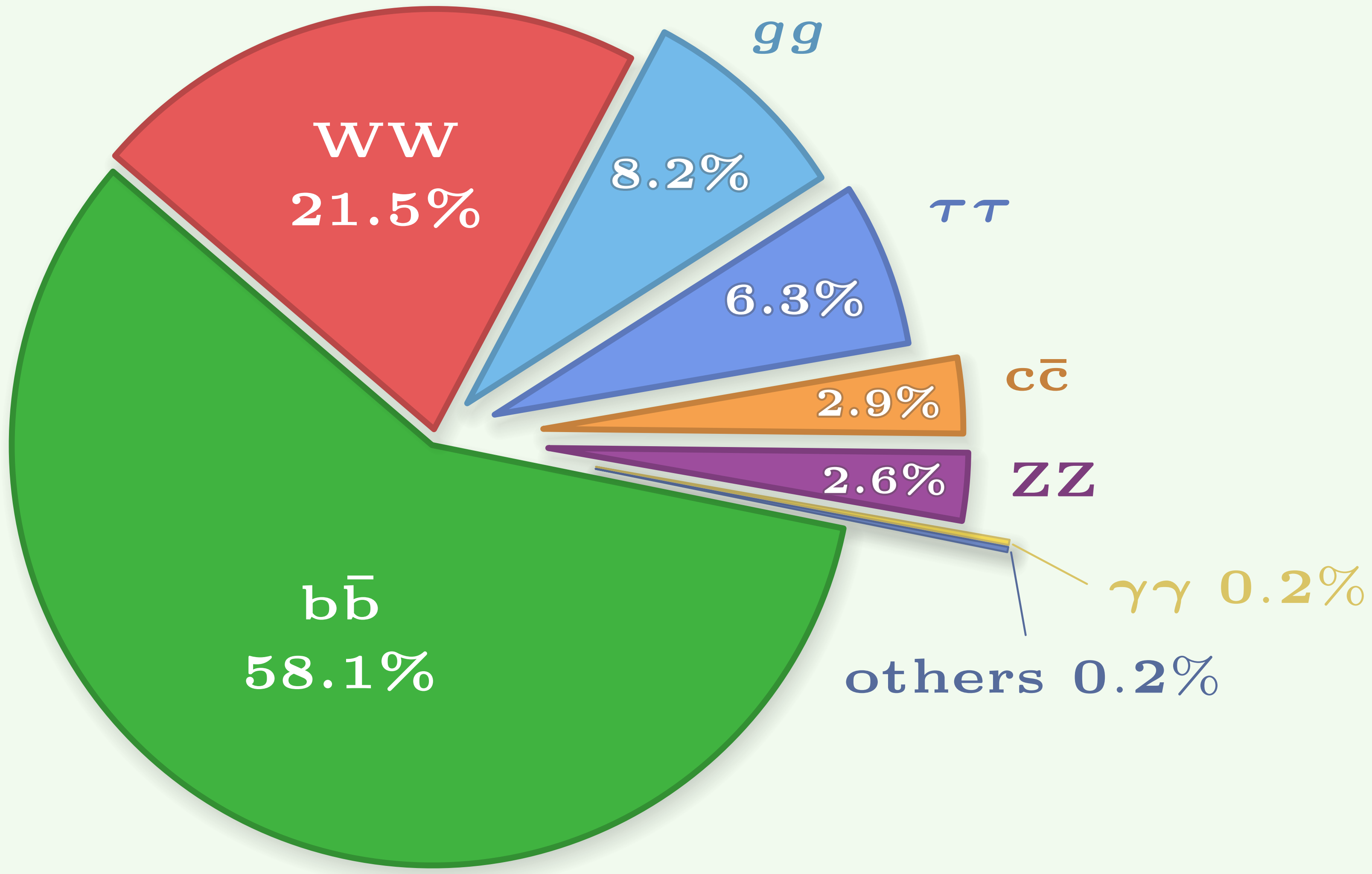
$H \to \gamma\gamma$: Phys. Lett B 847 (2023) 138315 — aux material

$H \to ZZ^\star$: Phys. Lett. B 843 (2023) 137880

Choices to be made

The Higgs mass: decay channels

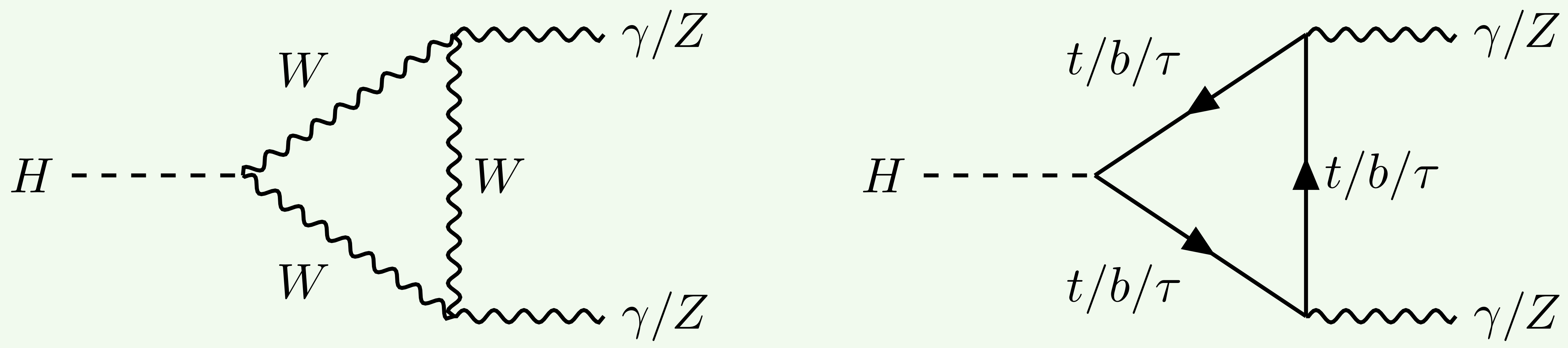
Higgs mass = invariant mass of decay products



$H \to ZZ/\gamma\gamma$

- Manageable backgrounds
- *Easy* reconstruction
- High resolution

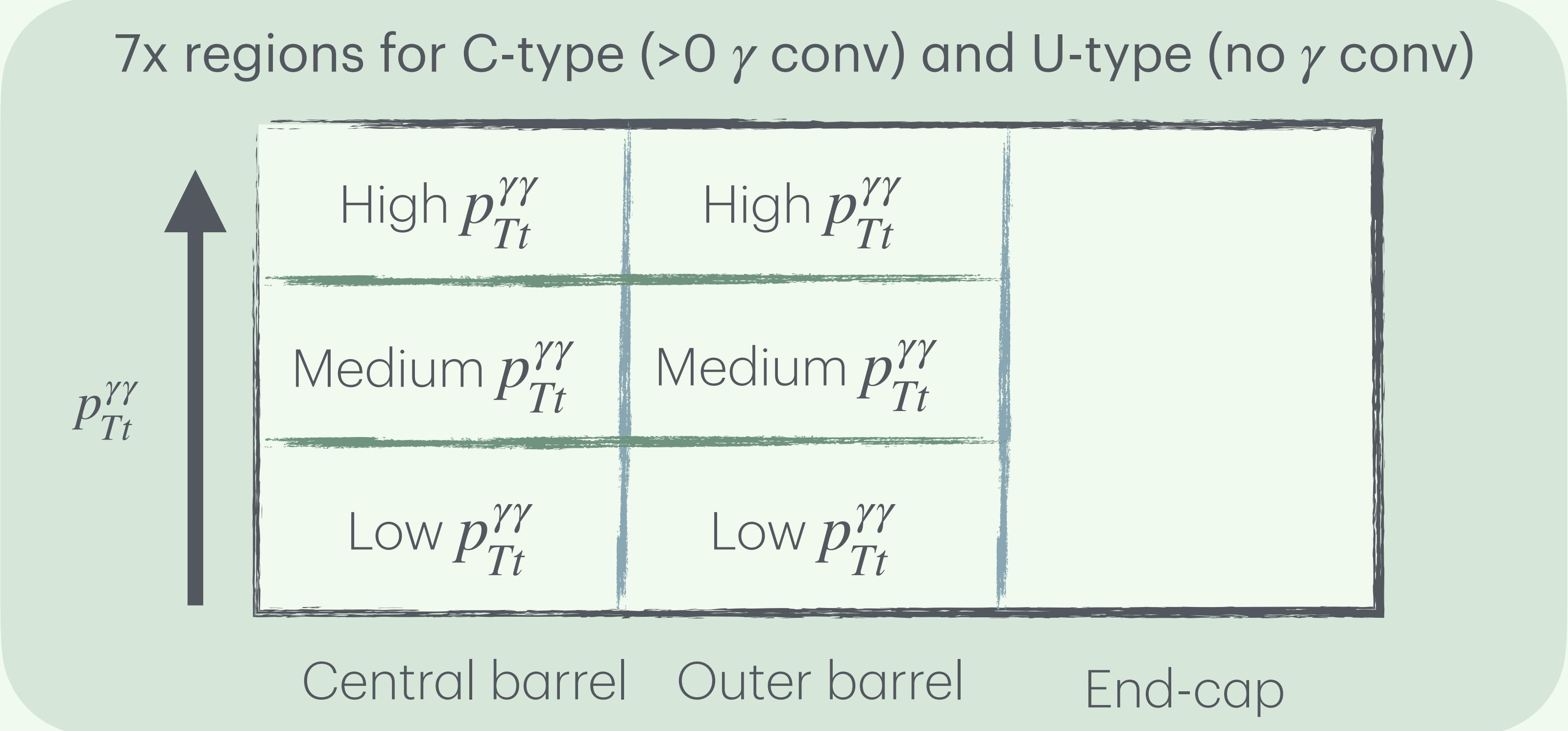
$H \to \gamma\gamma$



Mass with $H \to \gamma\gamma$

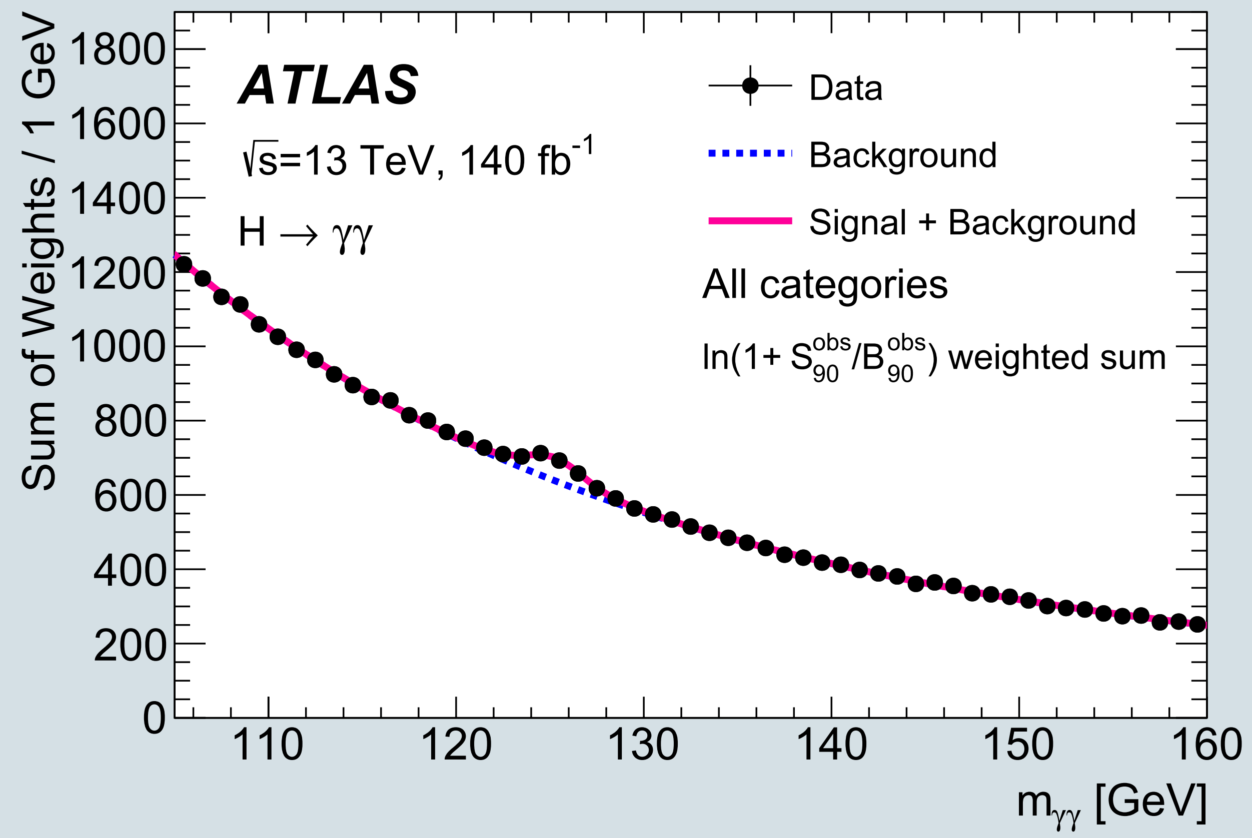
Full Run-2 (140 fb^{-1}): setup

Phys. Lett B 847 (2023) 138315 — aux material



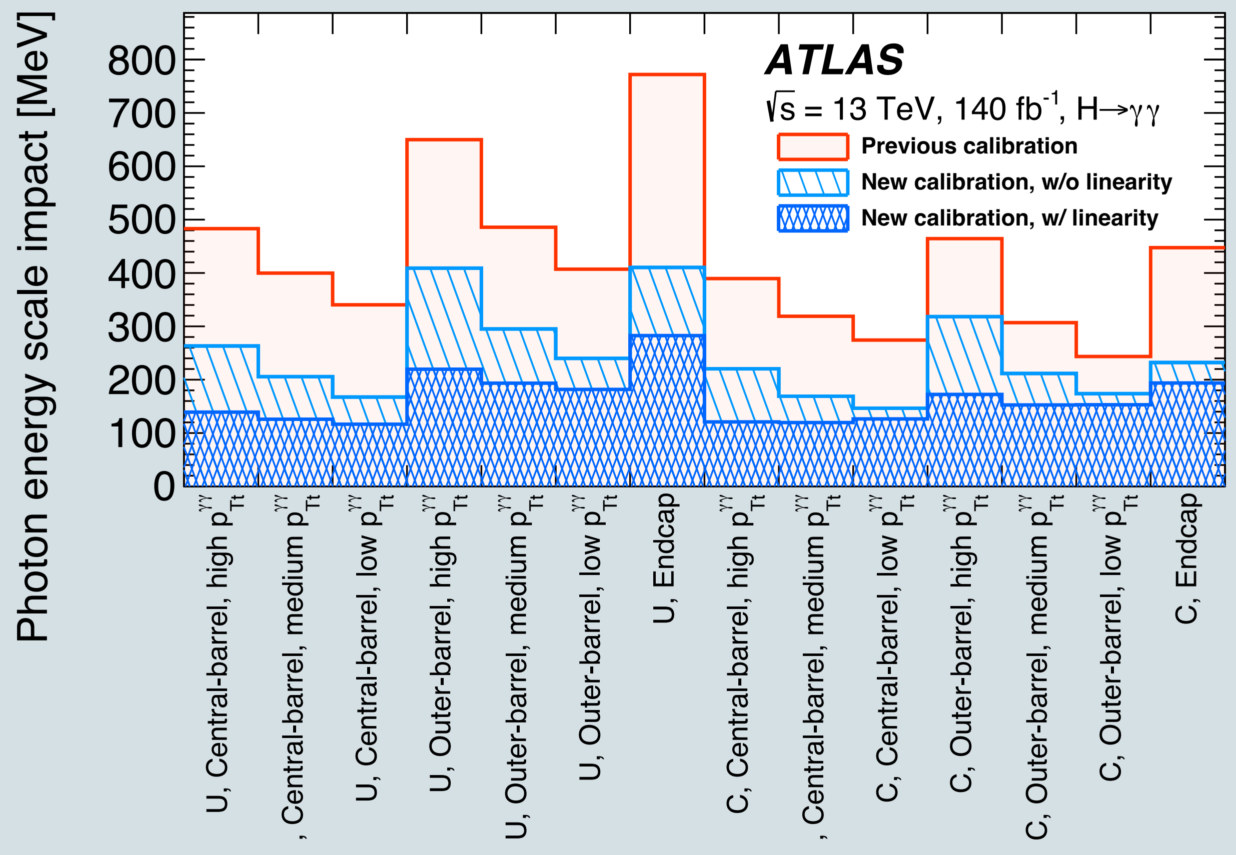
Categorisation

- Regions based on photon kinematics with **improved γ reconstruction**
  - Optimised to reduce Higgs mass uncertainty
  - **Improved mass precision** by 6% w.r.t partial Run-2



Modelling

- Signal modelled with **double-sided Crystal Ball**
- Background modelled empirically with **exponentials and polynomials**
- **Better γ energy scale**: improved detector model w.r.t partial Run-2



Mass with $H \to \gamma\gamma$

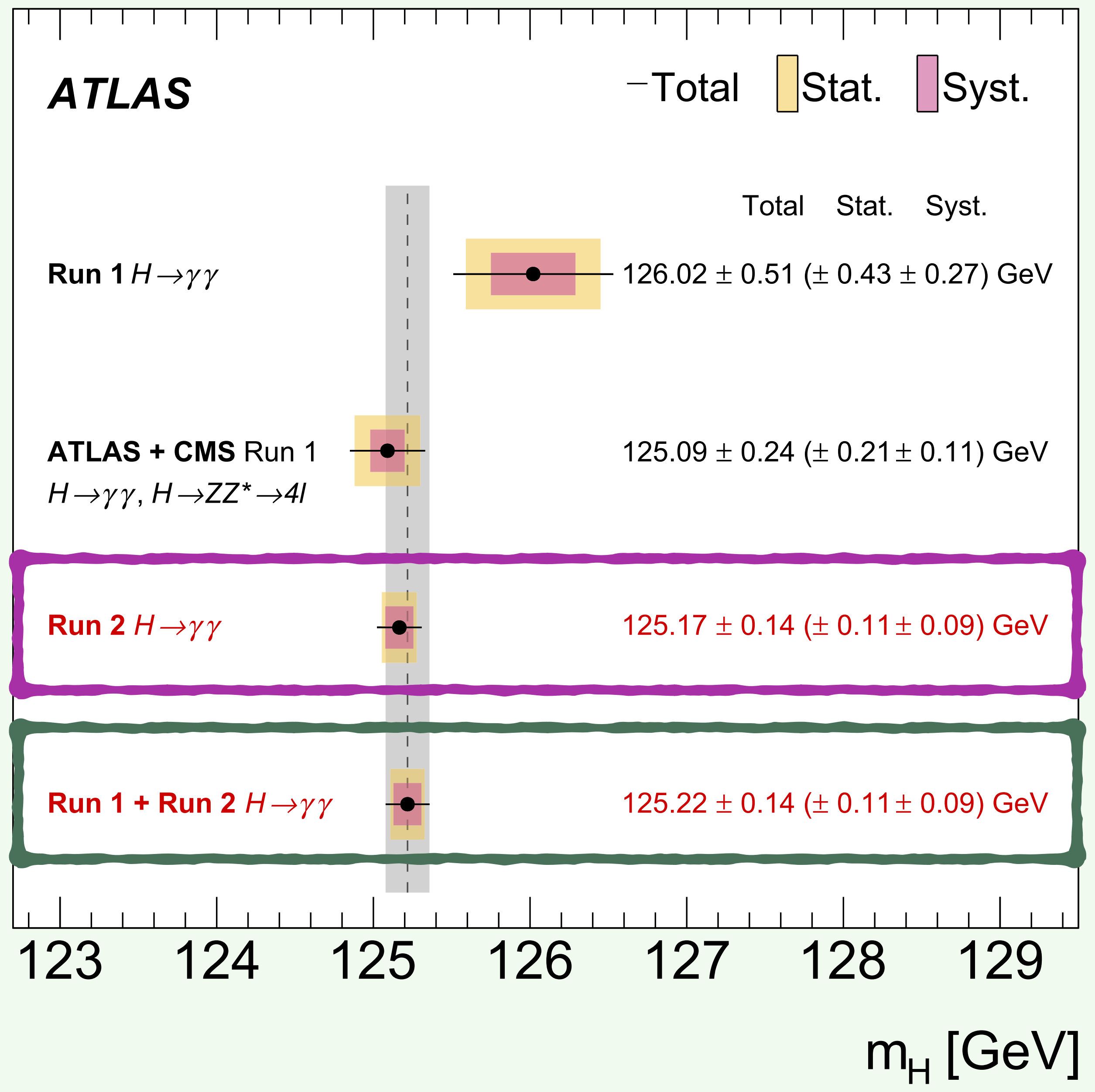
Full Run-2 (140 fb^{-1}): result

Phys. Lett B 847 (2023) 138315 — aux material

Fitting

- Simultaneous maximum-likelihood fit in all categories

Precision x3 better than partial Run-2



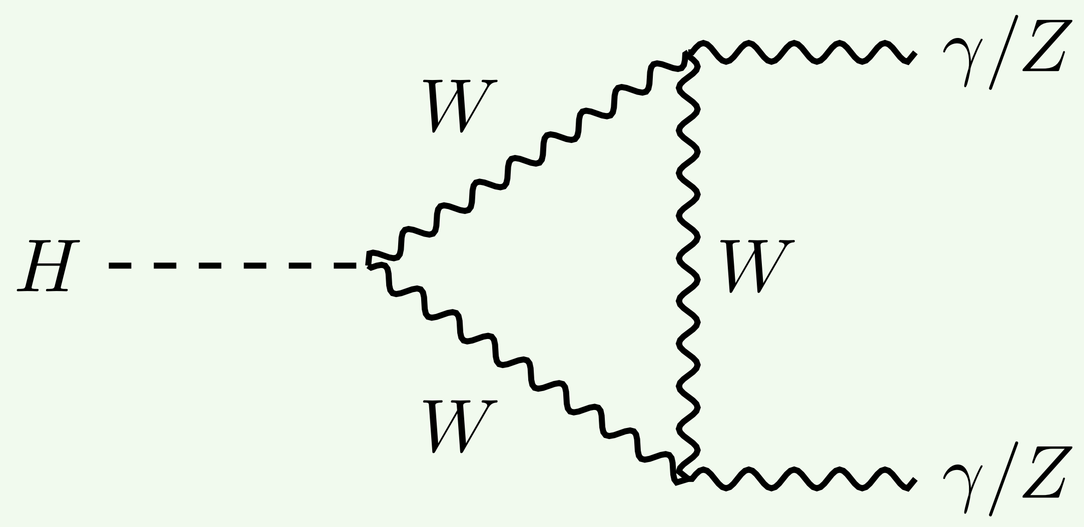
Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

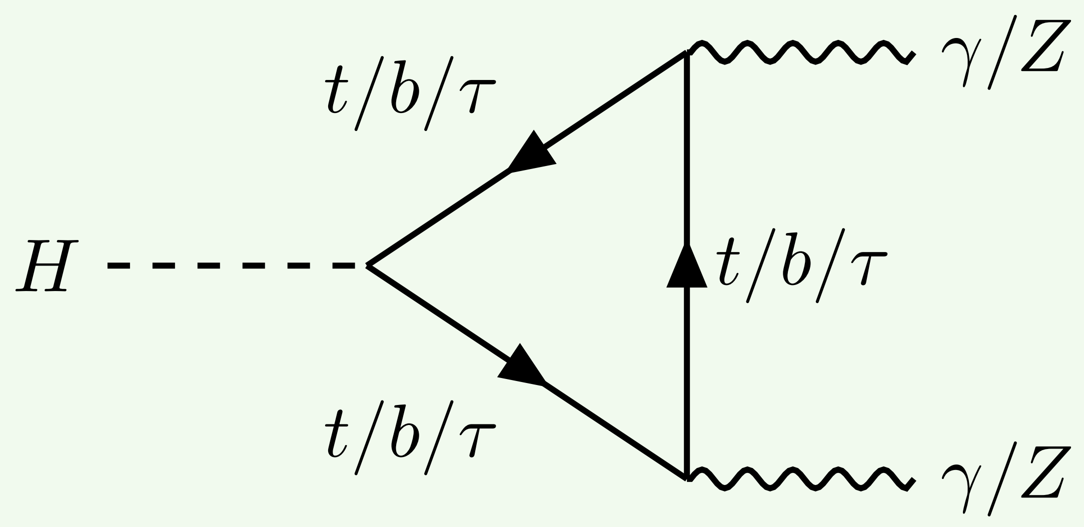
x4 smaller than partial Run-2

Run 1 + Run 2:

$$m_H = 125.22 \pm 0.14 \text{ GeV} \quad [\pm 0.11 \text{ (stat.)} \pm 0.09 \text{ (syst.)}]$$

$H \to ZZ$





Mass with $H \rightarrow ZZ^{\star} \rightarrow 4\ell$

Full Run-2 (140 fb^{-1}): setup

Phys. Lett. B 843 (2023) 137880

Categorisation

- 4 channels split by leading/sub-leading lepton flavours
  - 4μ ,$2e2\mu$,$2\mu 2e$,$4e$

Modelling

- Signal PDF combine 3 distributions:
  - 4-lepton mass
  - Signal/background DNN score
  - Per-event mass resolution (with Quantile Regression NN)
- Background PDF based on smoothed MC predictions
- **Improved μ momentum scale** by 20% w.r.t partial Run-2

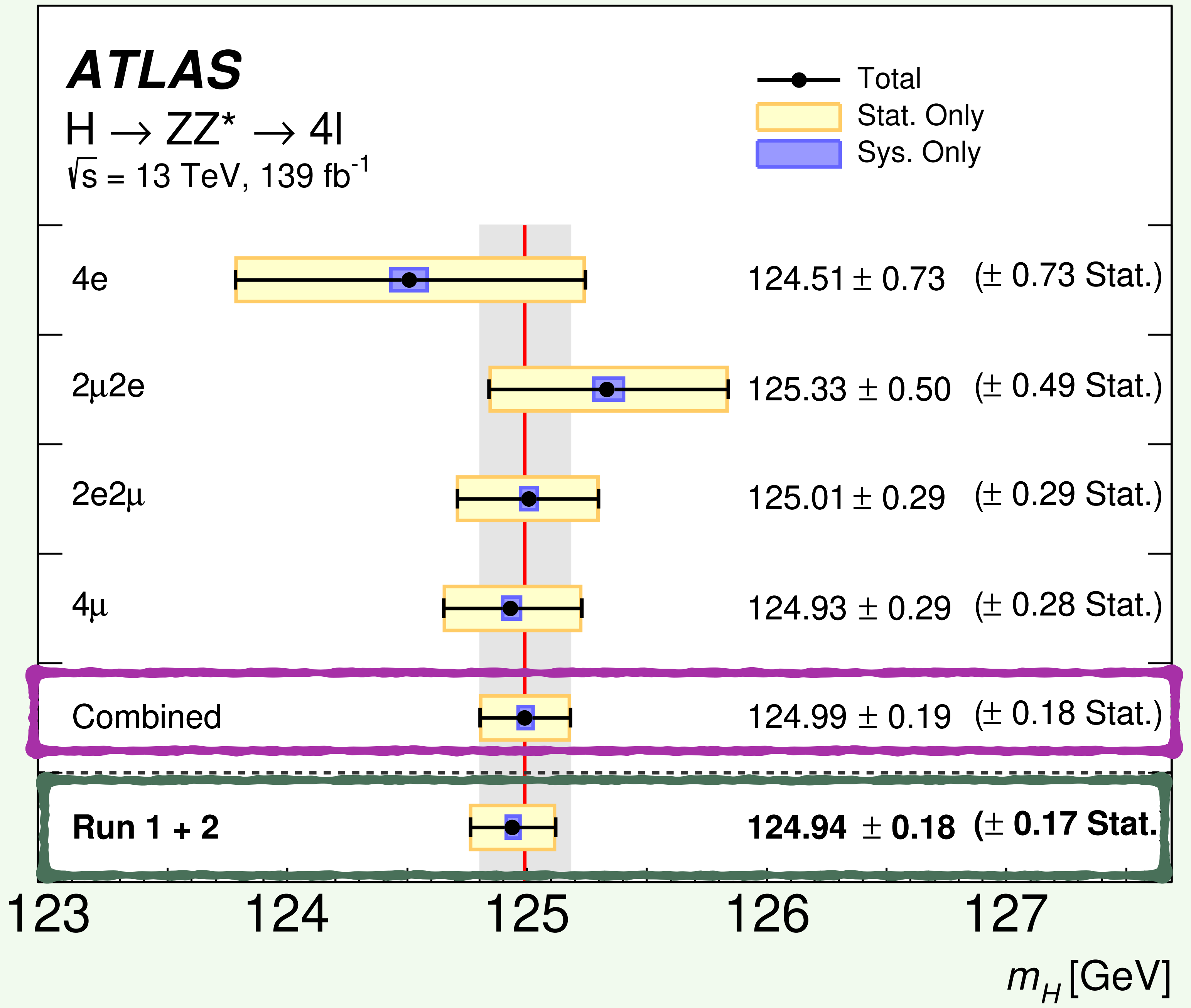
Mass with $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): result

Phys. Lett. B 843 (2023) 137880

Fitting

- Un-binned maximum likelihood fit in each channel then combine



Statistically limited, tiny systematics
↓
improvement in Run-3

Run 1 + Run 2:

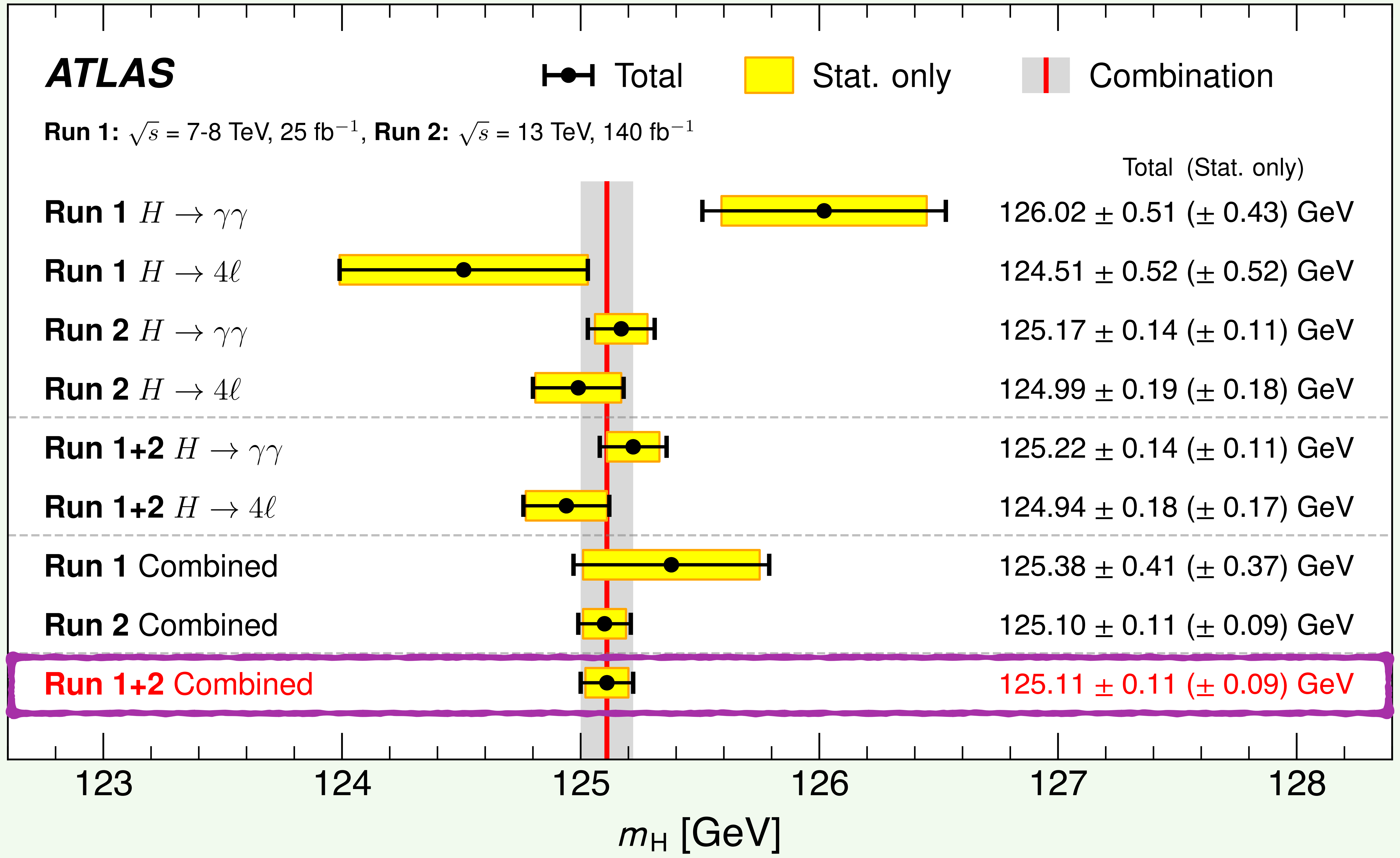
$$m_H = 124.94 \pm 0.18 \text{ GeV } \left[\pm 0.17 \text{ (stat.)} \pm 0.03 \text{ (syst.)}\right]$$

Combination

Mass with ATLAS

Combined ATLAS results with full Run-2 data

Phys. Lett. B 131 (2023) 251802 — aux material



< 0.1% precision

Most precise m_H measurement to-date!

Higgs width

Probed with on-shell to off-shell ratios

$H \to ZZ$: Phys. Lett. B 846 (2023) 138223 — aux material

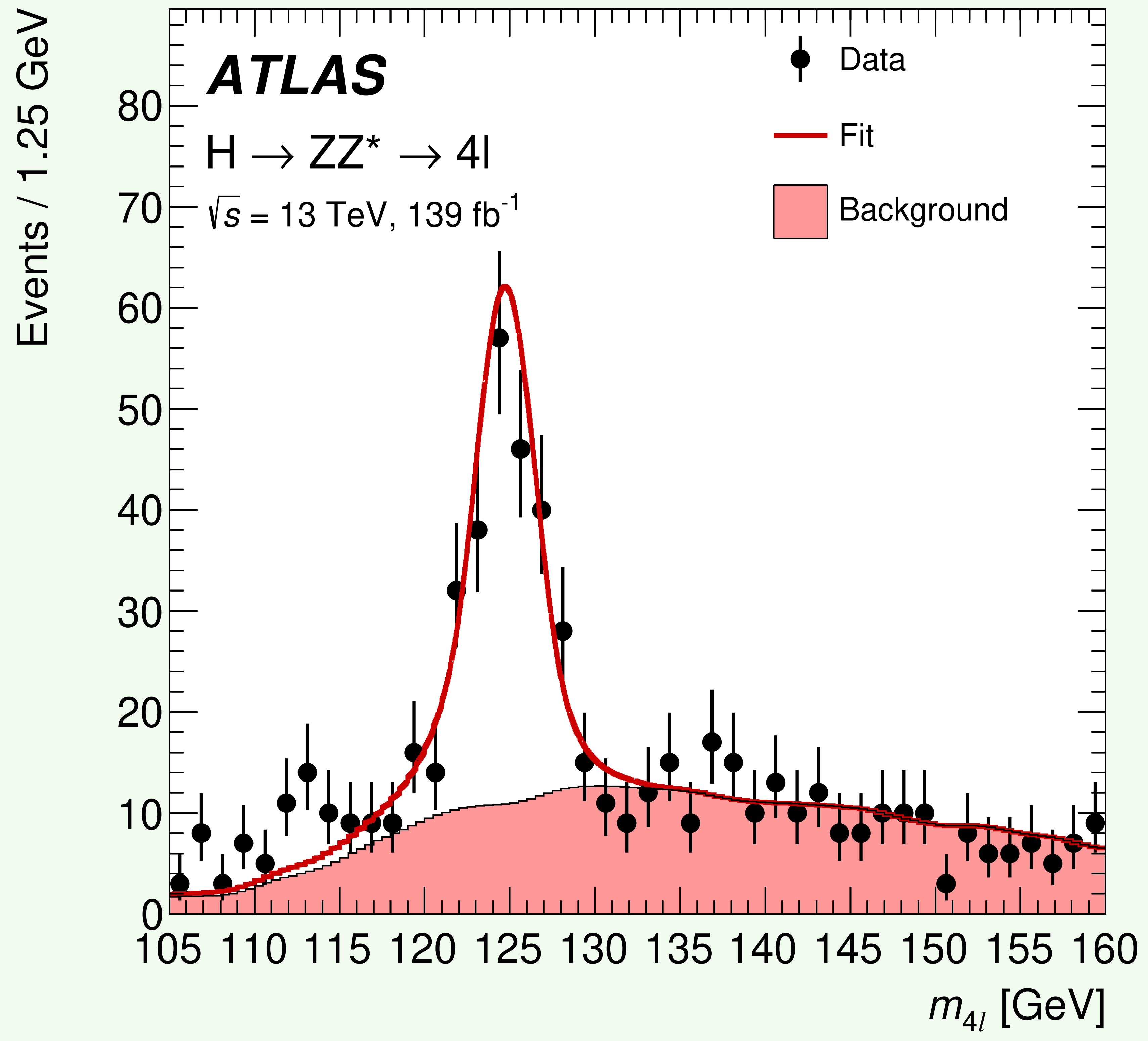
$t\bar{t}t\bar{t}$ and $t\bar{t}H$: arXiv:2407.10631 **(see backup)**

Extracting the total width

The challenge of detector resolution

Challenge

- SM Higgs width is $\Gamma_H^{SM} = 4.1$ MeV
- 1000x times smaller than reconstructed mass resolution



Extracting the total width

The challenge of detector resolution

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- SM Higgs width is $\Gamma_H^{SM} = 4.1$ MeV
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Solution

$$\frac{d\sigma_{i \to H \to f}}{dM^2} \sim \frac{\kappa_i^2 g_i^2 \cdot \kappa_f^2 g_f^2}{(M^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

κ is a coupling modifier
g is SM coupling

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on-shell measurements constrain κ/Γ

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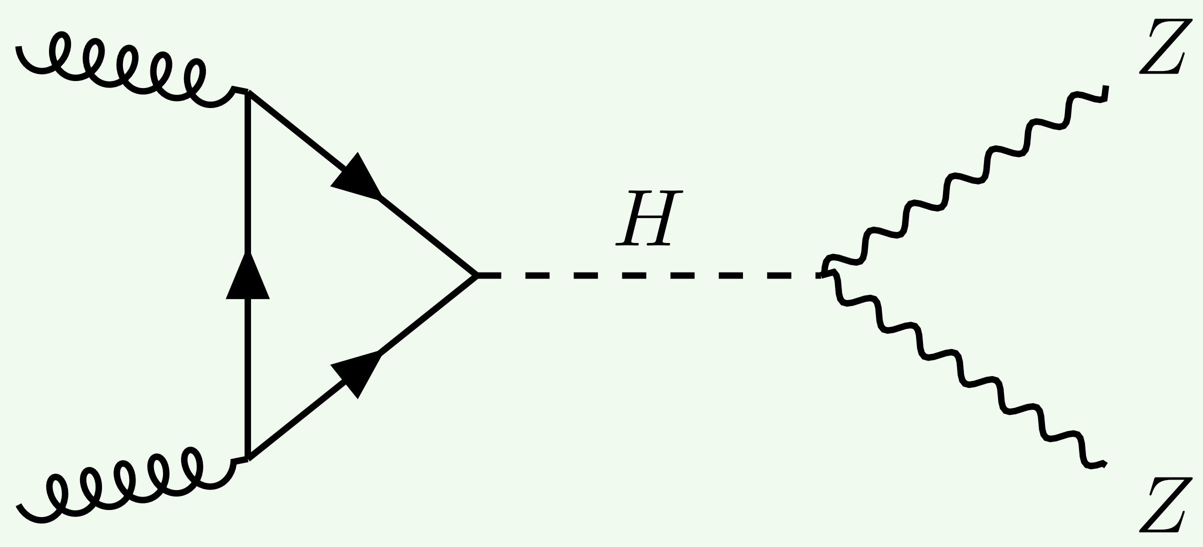
κ is a coupling modifier
g is SM coupling

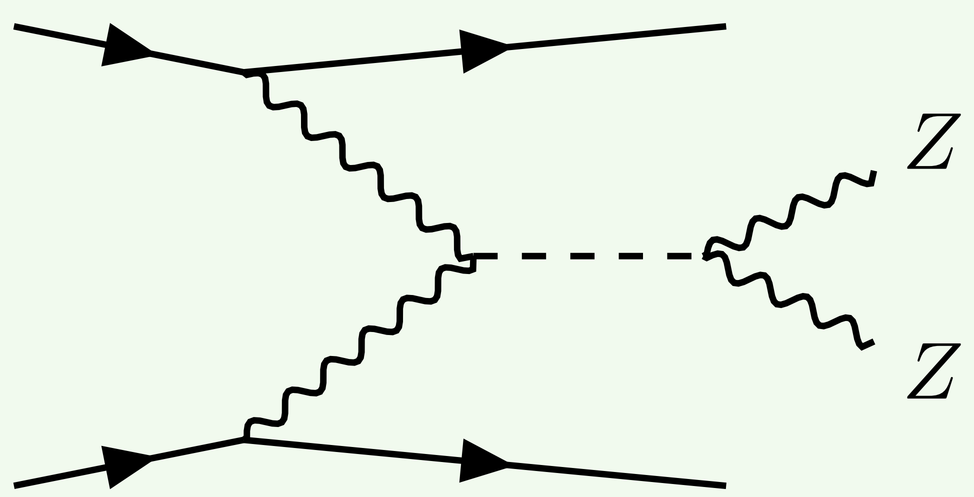
off-shell measurements constrain κ

on-shell measurements constrain κ/Γ

$$\frac{\sigma_{\text{on-shell}} / \sigma^{SM}_{\text{on-shell}}}{\sigma_{\text{off-shell}} / \sigma^{SM}_{\text{off-shell}}} \to \frac{\mu_{\text{on-shell}}(\kappa, \Gamma)}{\mu_{\text{off-shell}}(\kappa)} \sim \Gamma_H/\Gamma_H^{\text{SM}}$$

$$H^\star \to ZZ \text{ and } H \to ZZ^\star$$





Width from $H^{\star} \rightarrow ZZ \rightarrow 4\ell/2\ell 2\nu$

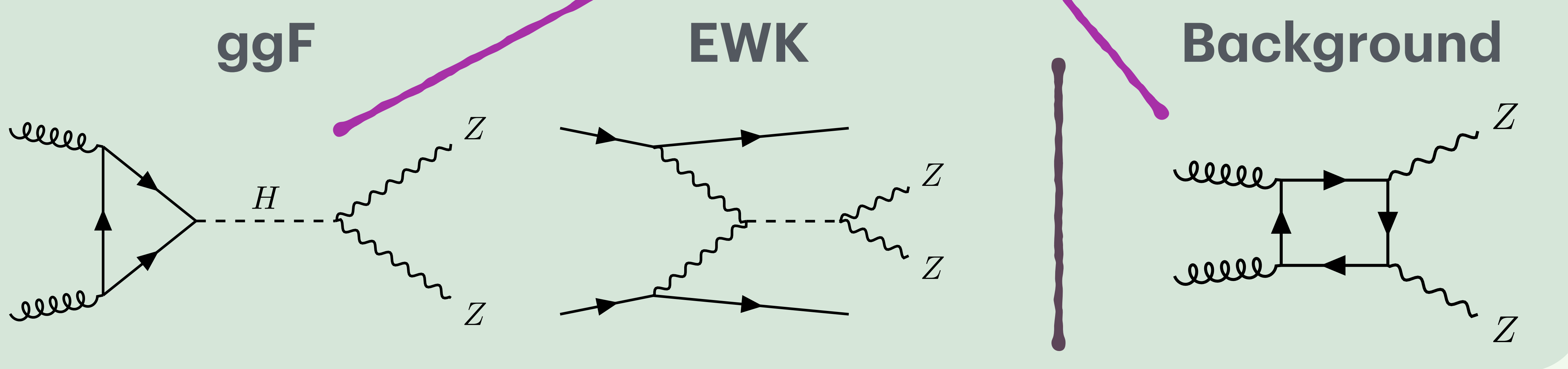
Full Run-2 (140 fb^{-1}): setup

Phys. Lett. B 846 (2023) 138223 — aux material

Large destructive interference for off-shell signal

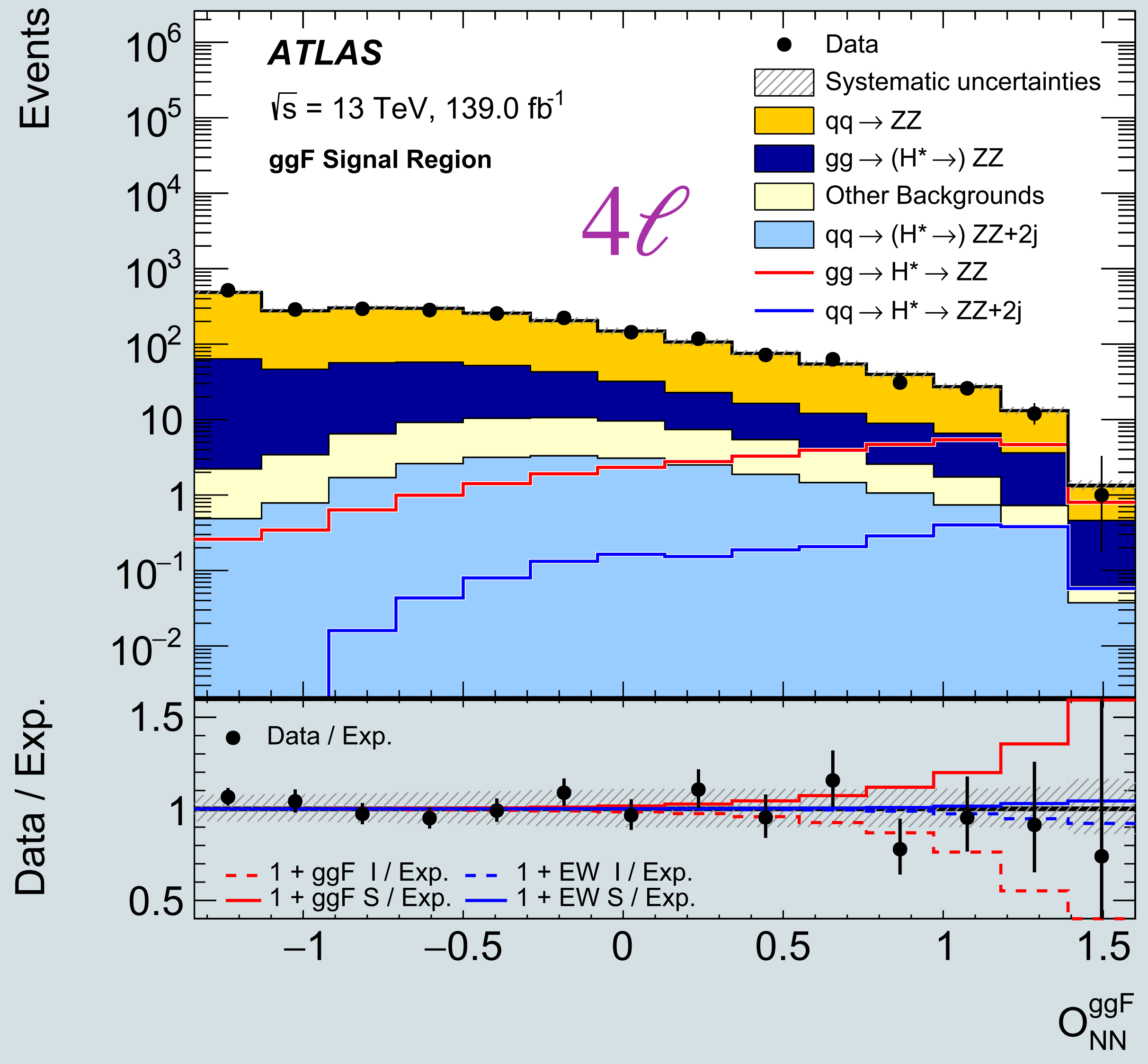
Categorisation

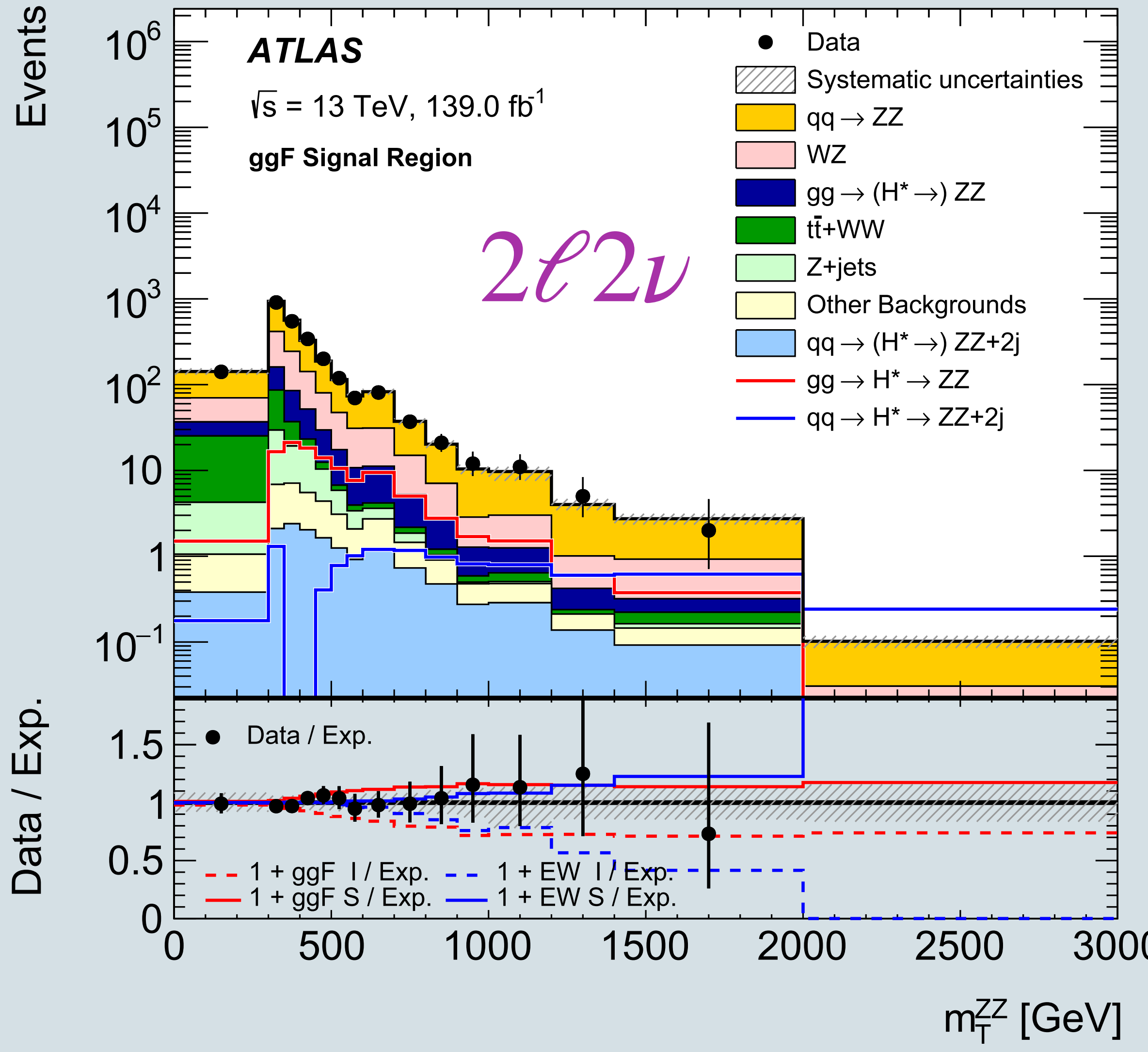
- 2 channels: 4ℓ, $2\ell 2\nu$
  - 3 SRs in each channel: ggF, EWK and mixed



Fit variables

- 4ℓ channel
  - **S/B NN score** — 1x for EWK and 1x for ggF
- $2\ell 2\nu$ channel
  - **Di-boson transverse mass**





Width from $H^{\star} \to ZZ \to 4\ell/2\ell2\nu$

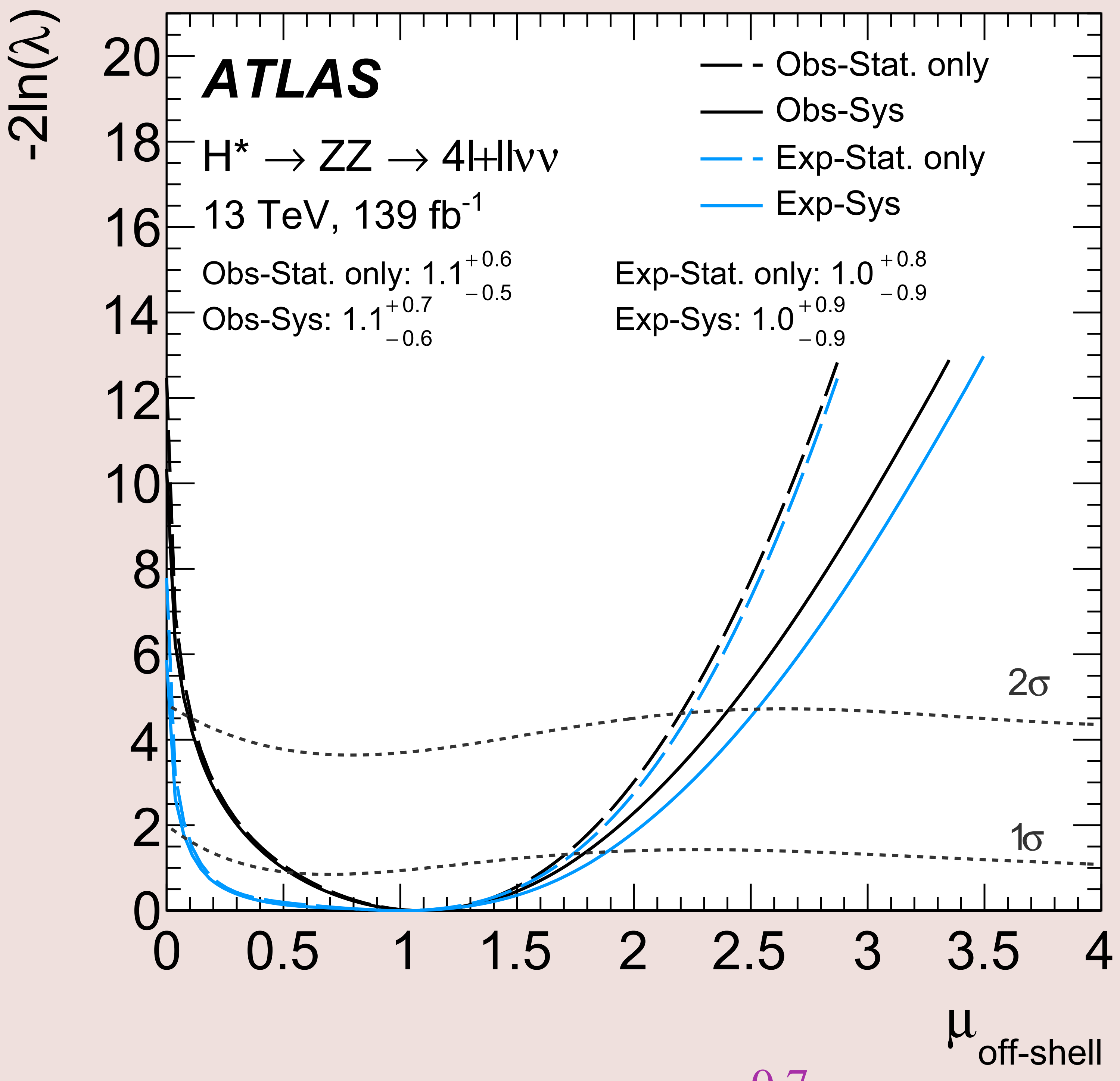
Full Run-2 (140 fb^{-1}): result

Phys. Lett. B 846 (2023) 138223 — aux material

Fitting

- Binned maximum likelihood fit in channels → combine

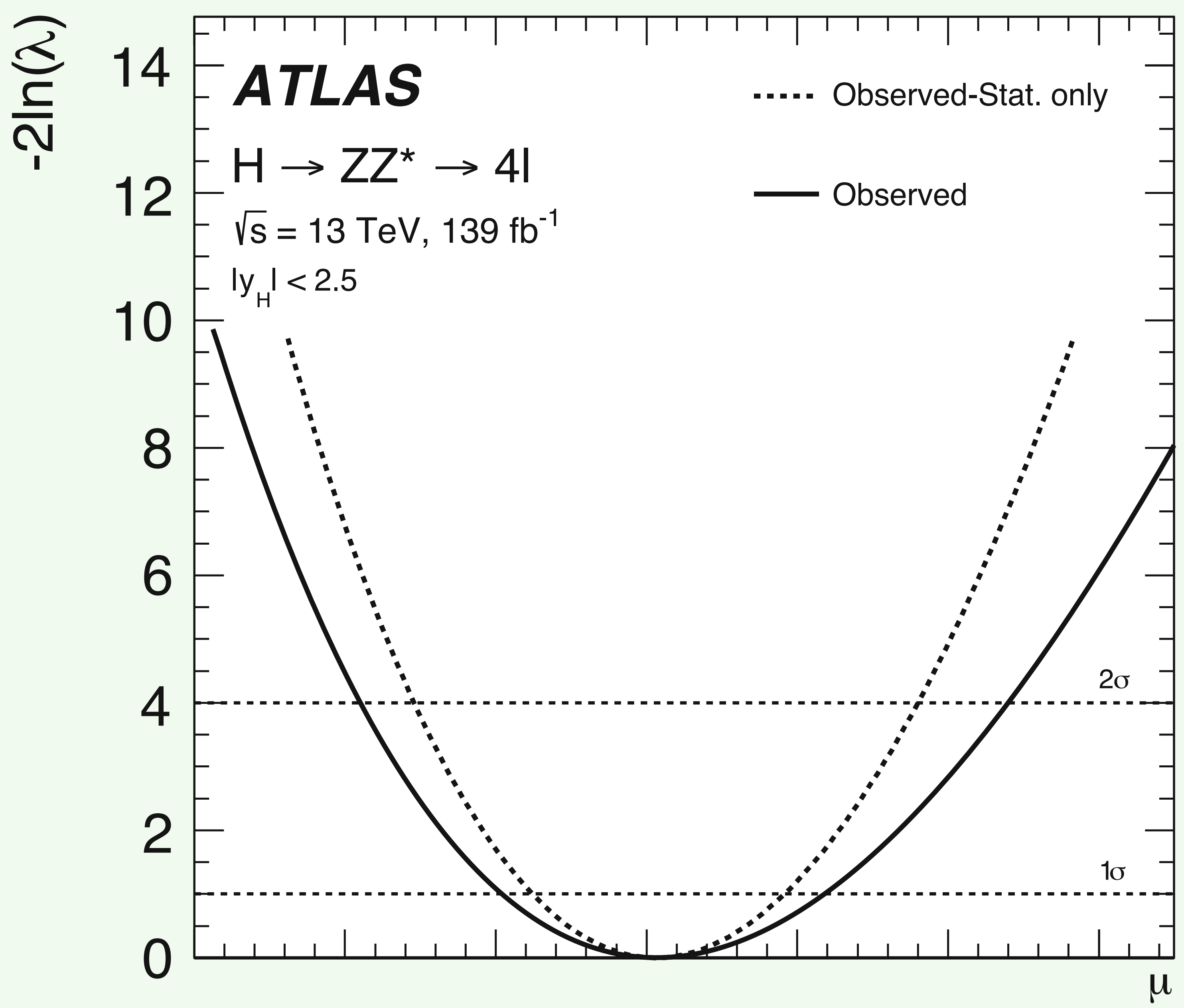
Off-shell



$\mu_{\text{off-shell}} = 1.1^{0.7}_{-0.6}$

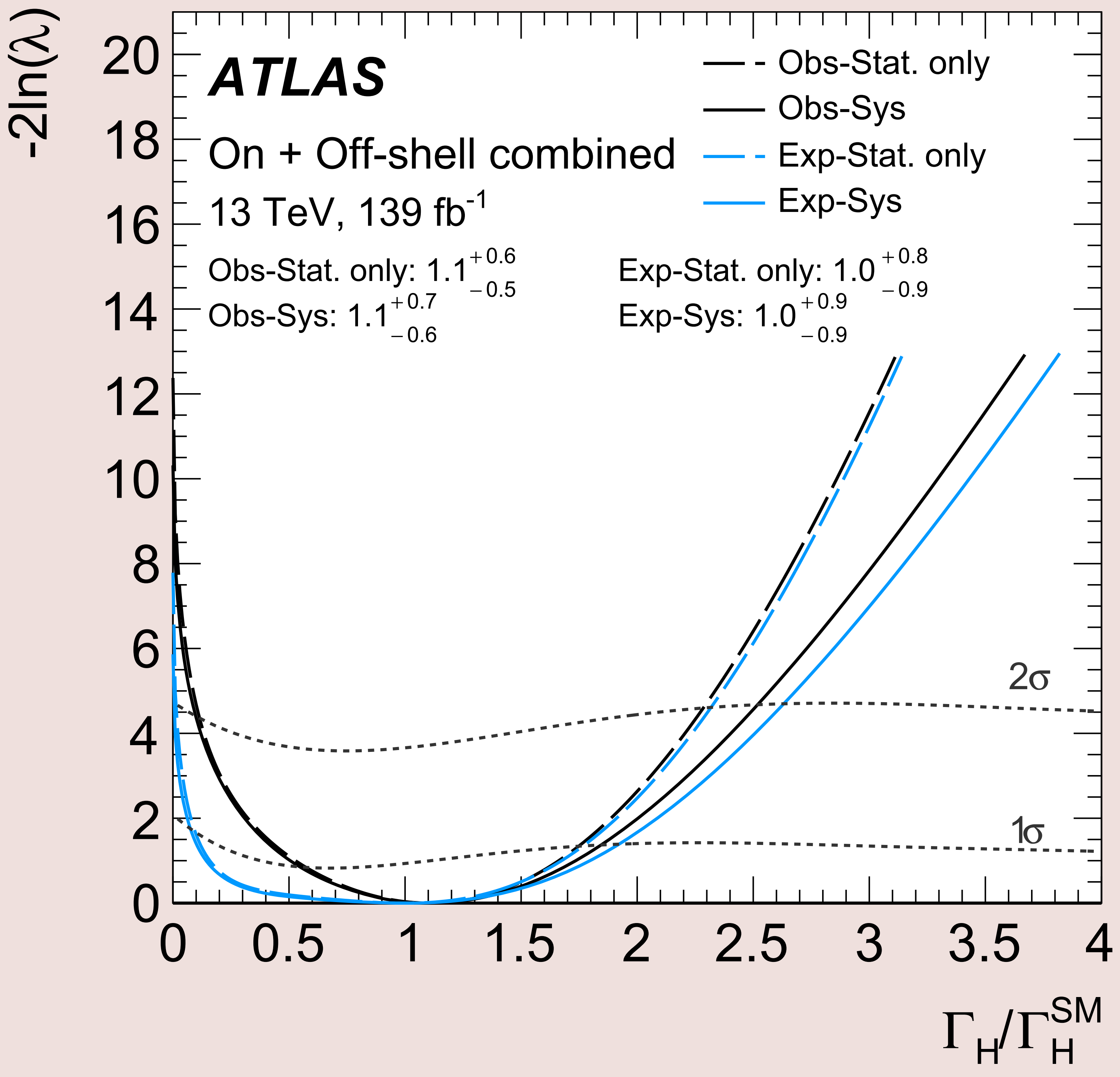
On-shell

Eur. Phys. J. C 80 (2020) 957



$\mu_{\text{on-shell}} = 1.01 \pm 0.11$

Width



$\Gamma_H^{\text{SM}} = 4.2\,\text{MeV} \quad \Gamma_H = 4.5^{+3.3}_{-2.5}\,\text{MeV}$

Statistically limited

CP violation and Higgs

Probed with bosons and fermions

VBF $H \to \gamma\gamma$: Phys. Rev. Lett. 131 (2023) 061802 — aux material

VBF $H \to ZZ$: JHEP 05 (2024) 105 — aux material

$H \to \tau\tau$: Eur. Phys. J. C 83 (2023) 563 — aux material

$t\bar{t}H(\to b\bar{b})$: Phys. Lett. B 849 (2024) 138469 — aux material

CP-violating models

Recipes to include CP-violation in the Higgs sector

Higgs to bosons

Higgs to fermions

CP-violating models

Recipes to include CP-violation in the Higgs sector

Higgs to bosons SMEFT

Wilson coefficients

New physics operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

New physics mass scale

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New physics mass scale

Measure c_i associated with CP-violating Higgs coupling operators $\mathcal{O}_i$

- Higgs basis
- Warsaw basis
- HISZ basis (simple)

Higgs to fermions

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Optimal observable

- Interference in $|\mathcal{M}_{\text{SMEFT}}|^2$
- Sensitive to CP-violation
- Model independent

$$\mathcal{OO} = \frac{2\Re\left(\mathcal{M}^{\star}_{\text{SM}}\mathcal{M}_{\text{BSM}}\right)}{|\mathcal{M}_{\text{SM}}|^2}$$

Higgs to fermions

CP-violating models

Recipes to include CP-violation in the Higgs sector

Higgs to bosons — SMEFT

Wilson coefficients

New physics operators

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Higgs to fermions — Kappa

Fermion mass

Yukawa coupling

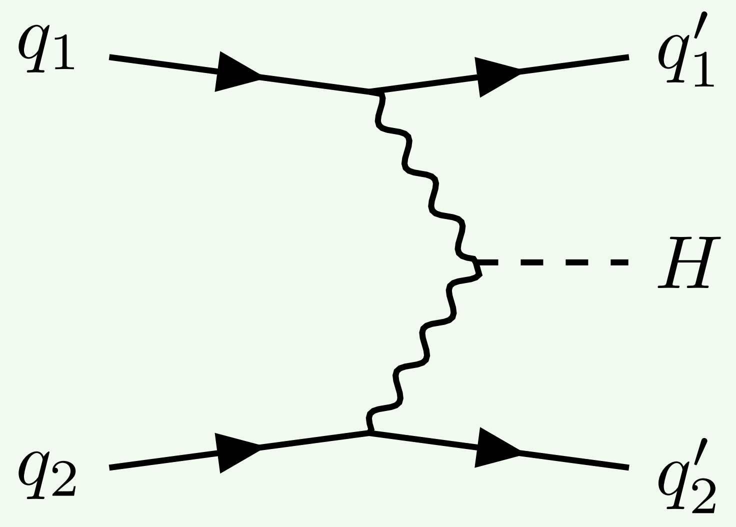
CP mixing angle

$$\mathcal{L}_{Hff} = -\frac{m_f}{v}\kappa_f\left(\cos\phi_f\,\bar{f}f + i\sin\phi_f\,\bar{f}\gamma_5 f\right)H$$

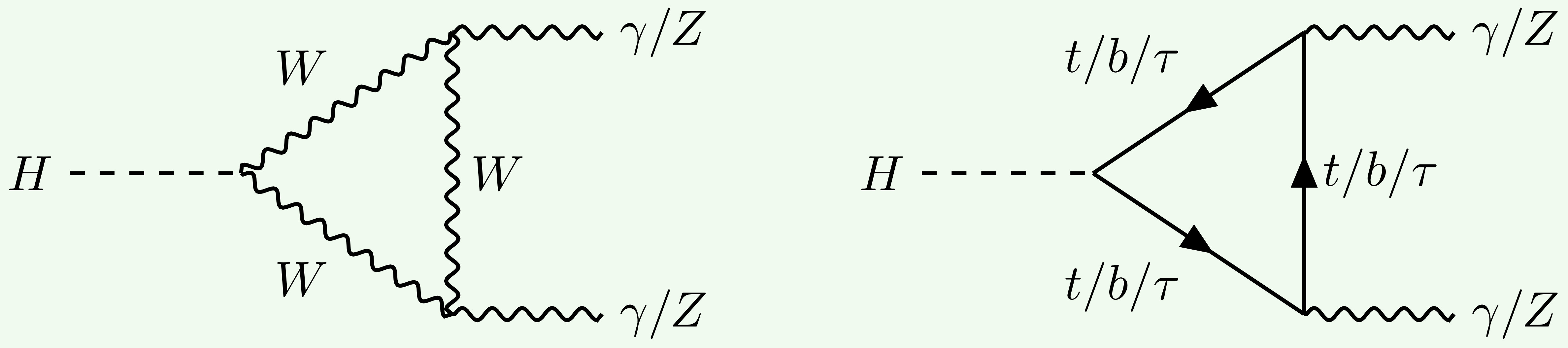
CP-violating interactions at tree level

CP structure in $H \to VV$

VBF $\boldsymbol{H \to \gamma\gamma}$



Production-side

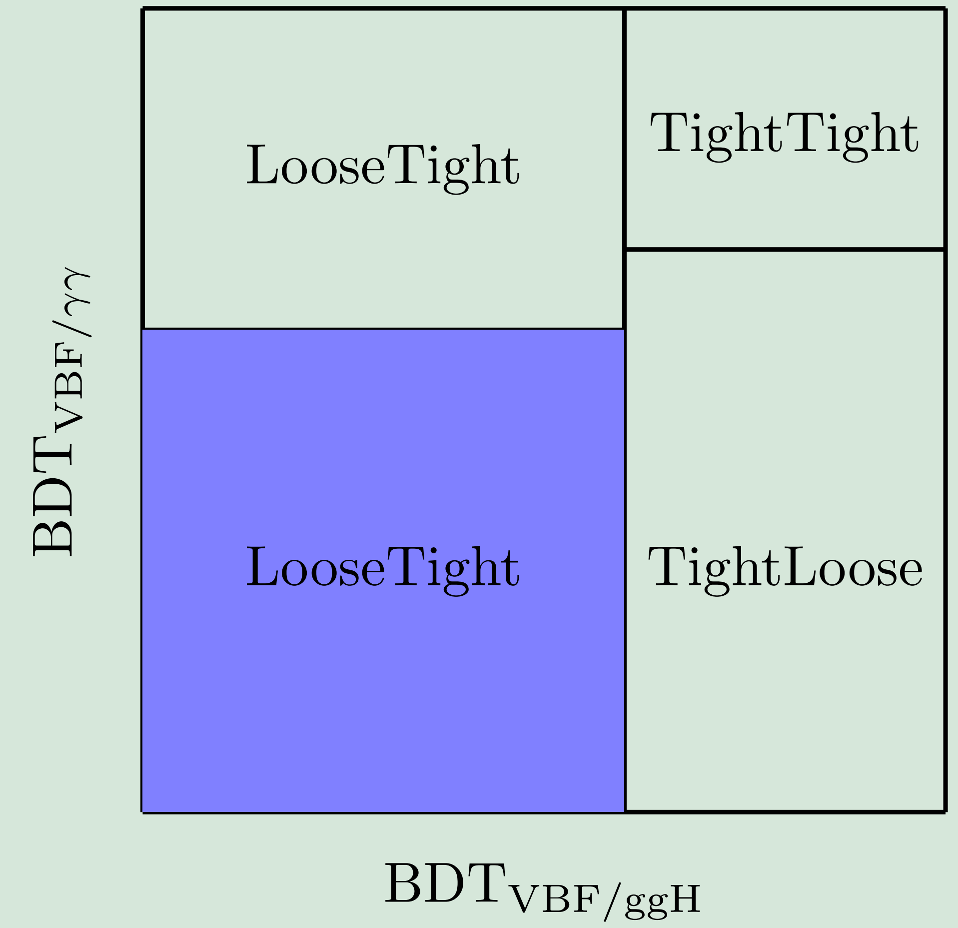


Decay-side

VBF $H \to \gamma\gamma$

Full Run-2 (140 fb^{-1}): setup

Phys. Rev. Lett. 131 (2023) 061802 — aux material

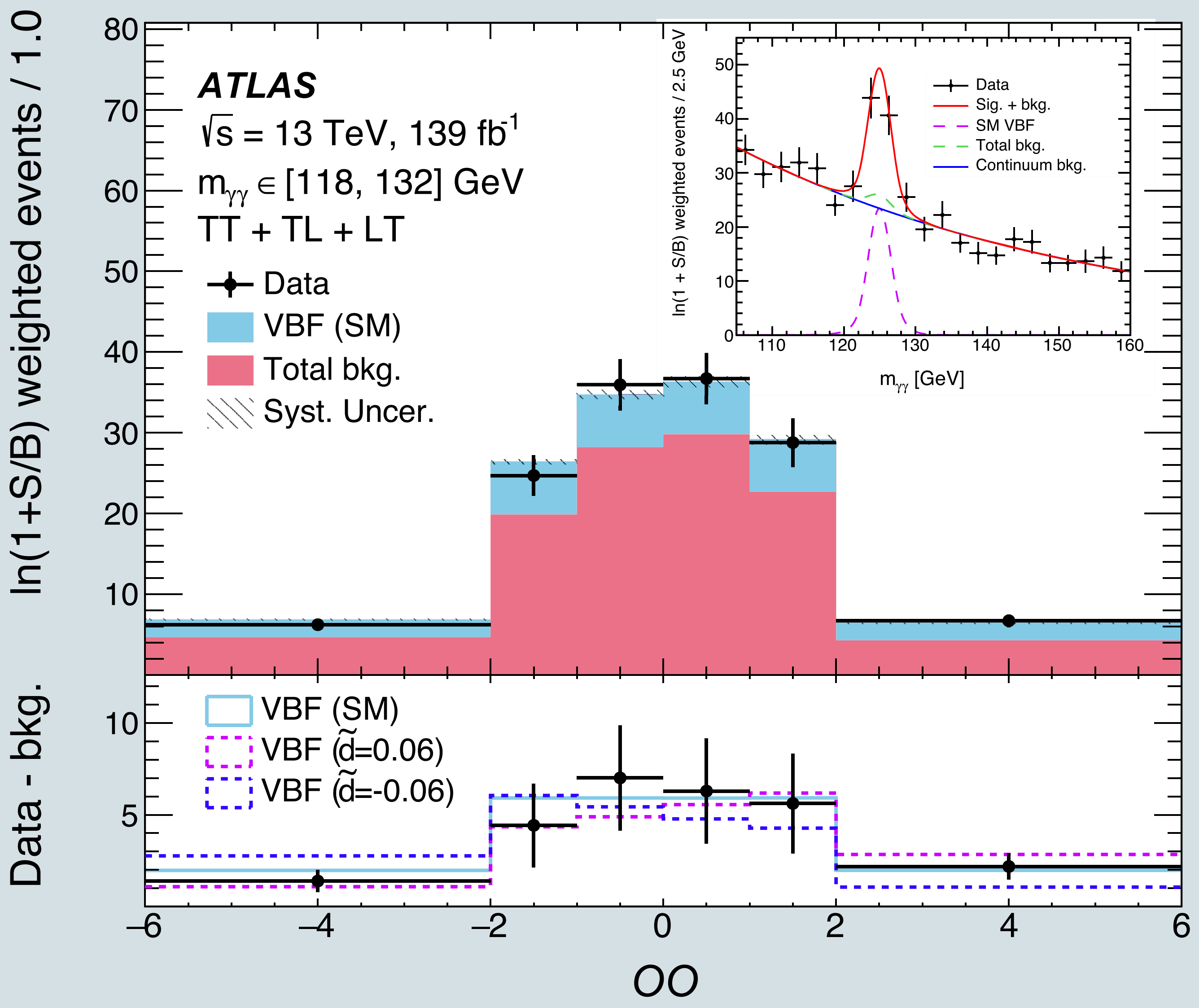


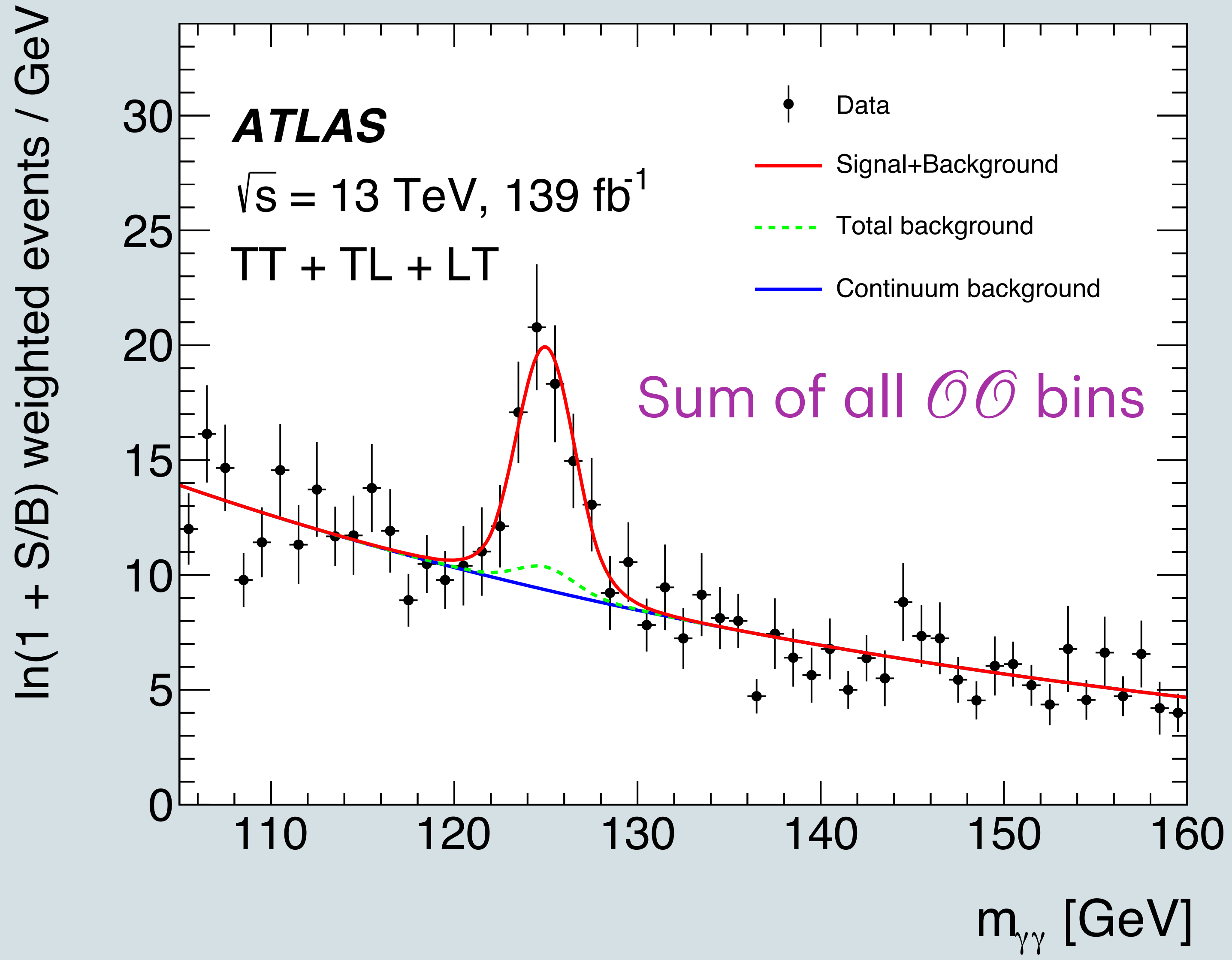
Categorisation

- 3 SRs in 2D BDT-score space
  - Signal vs: ($\gamma\gamma$) and (ggF)
- Compute $\mathcal{OO}$ in each SR → six bins → six regions (total 18 regions)

Fit variables

- Di-photon mass





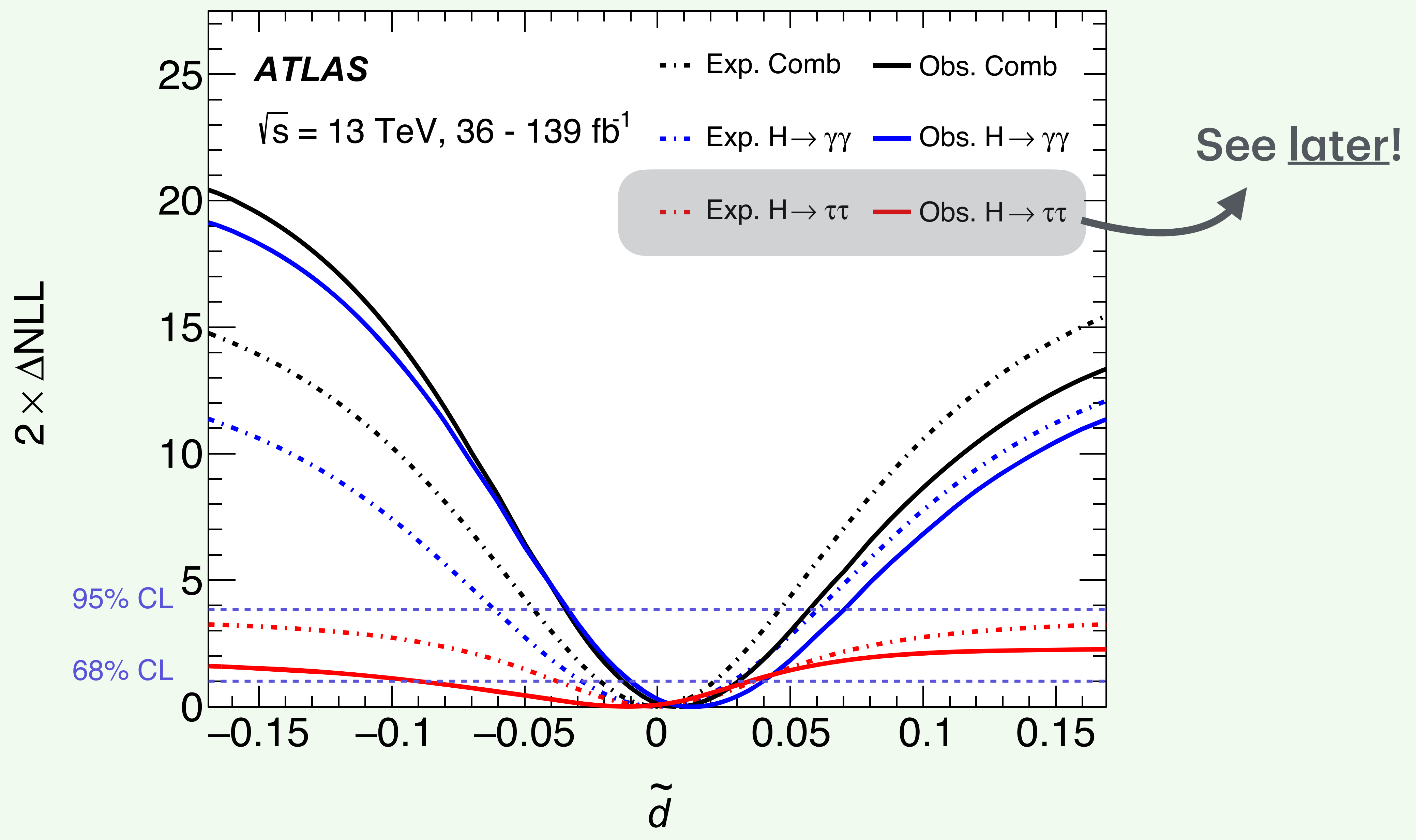
VBF $H \to \gamma\gamma$

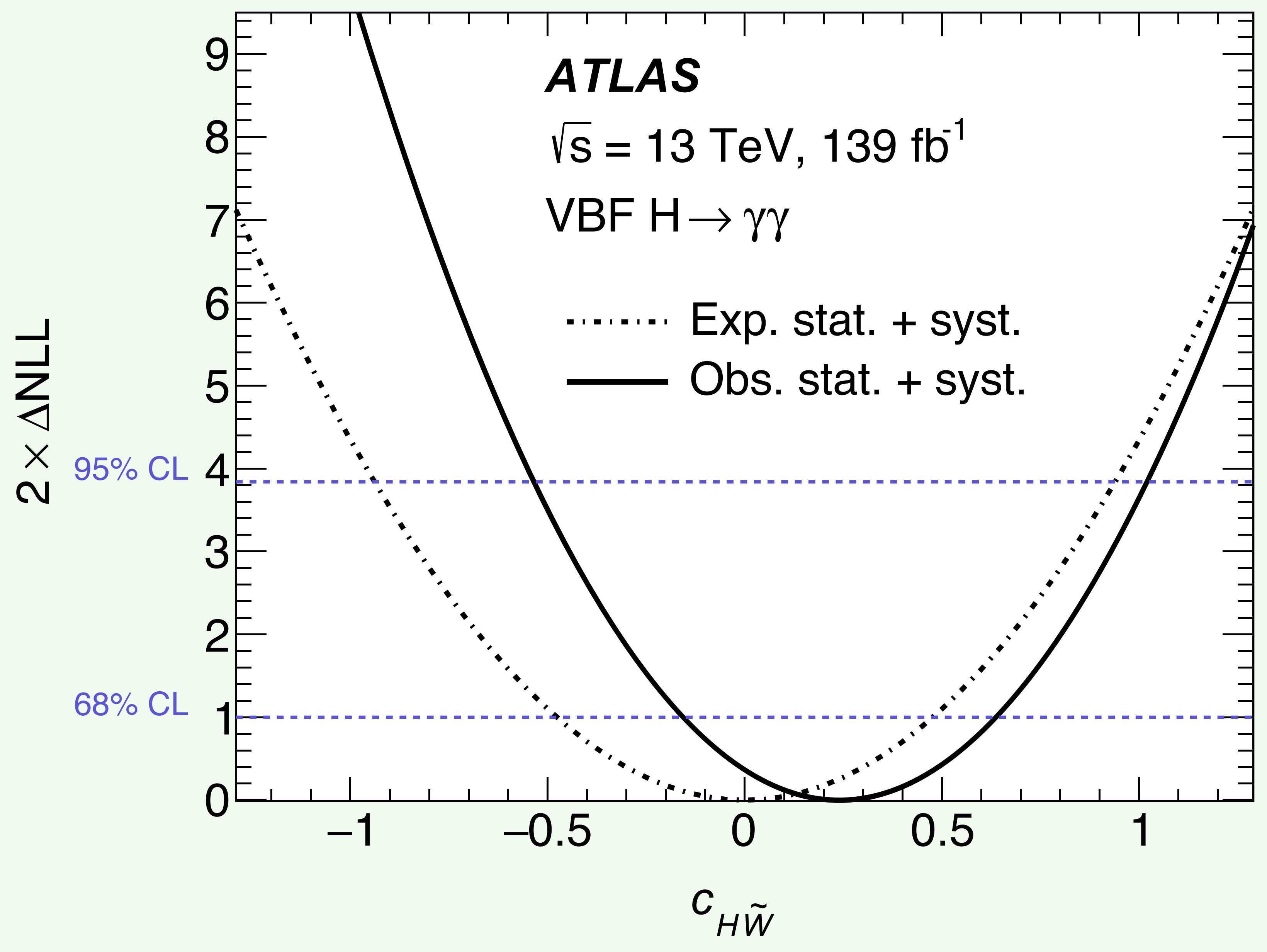
Full Run-2 (140 fb^{-1}): result

Phys. Rev. Lett. 131 (2023) 061802 — aux material

Fitting

- Un-binned maximum likelihood fit in all regions
- Free-float signal normalisation
  - $\mathcal{OO}$ only probes shape effects due to CP-violation

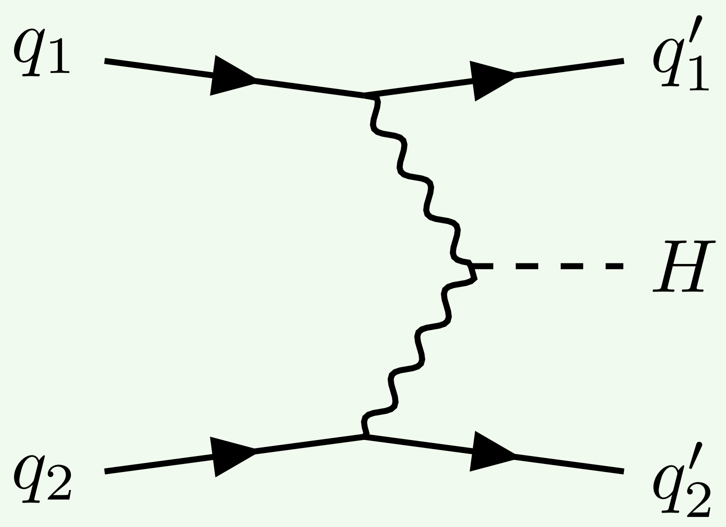




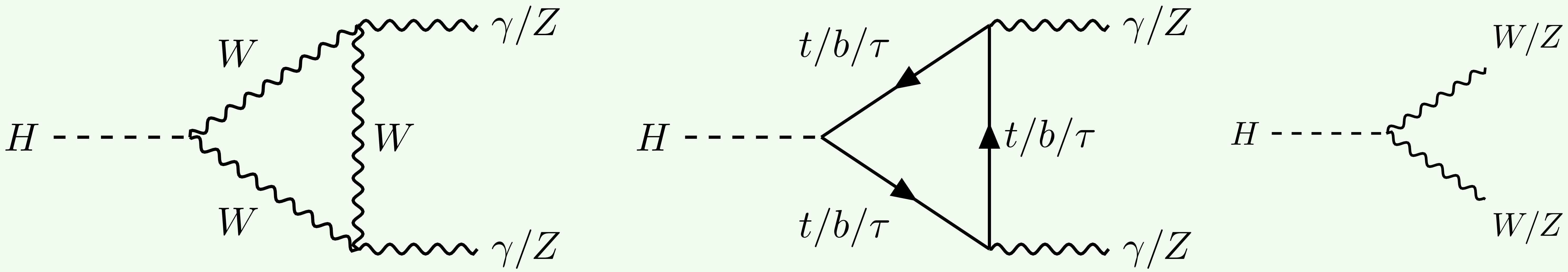
Constraint at 95% CL: $-0.034 < \tilde{d} < 0.071$ $\quad -0.55 < c_{H\tilde{W}} < 1.07$

no CP-violation observed

VBF $H \rightarrow ZZ^{\star} \rightarrow 4\ell$



Production-side

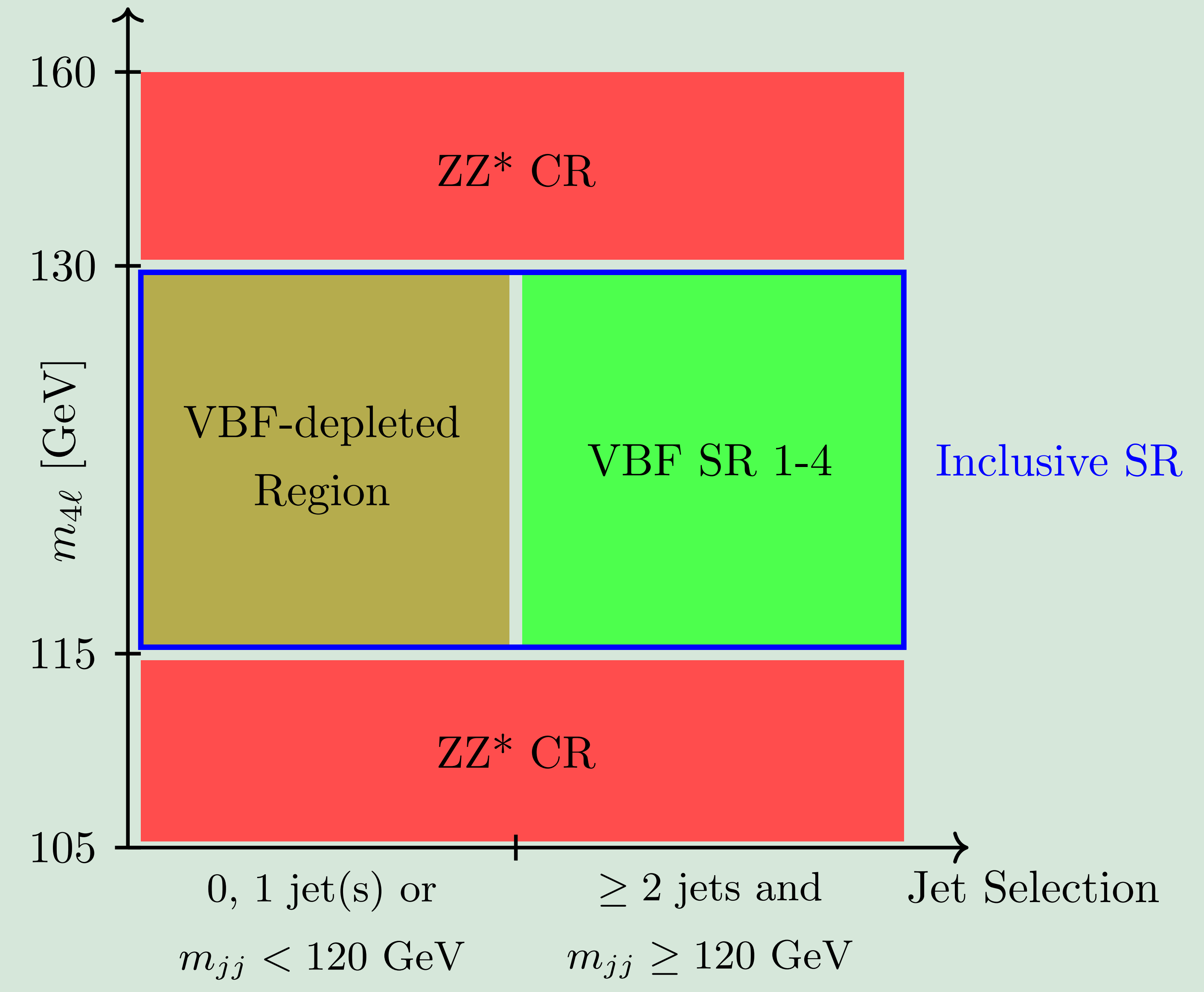


Decay-side

VBF $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): setup

JHEP 05 (2024) 105 — aux material

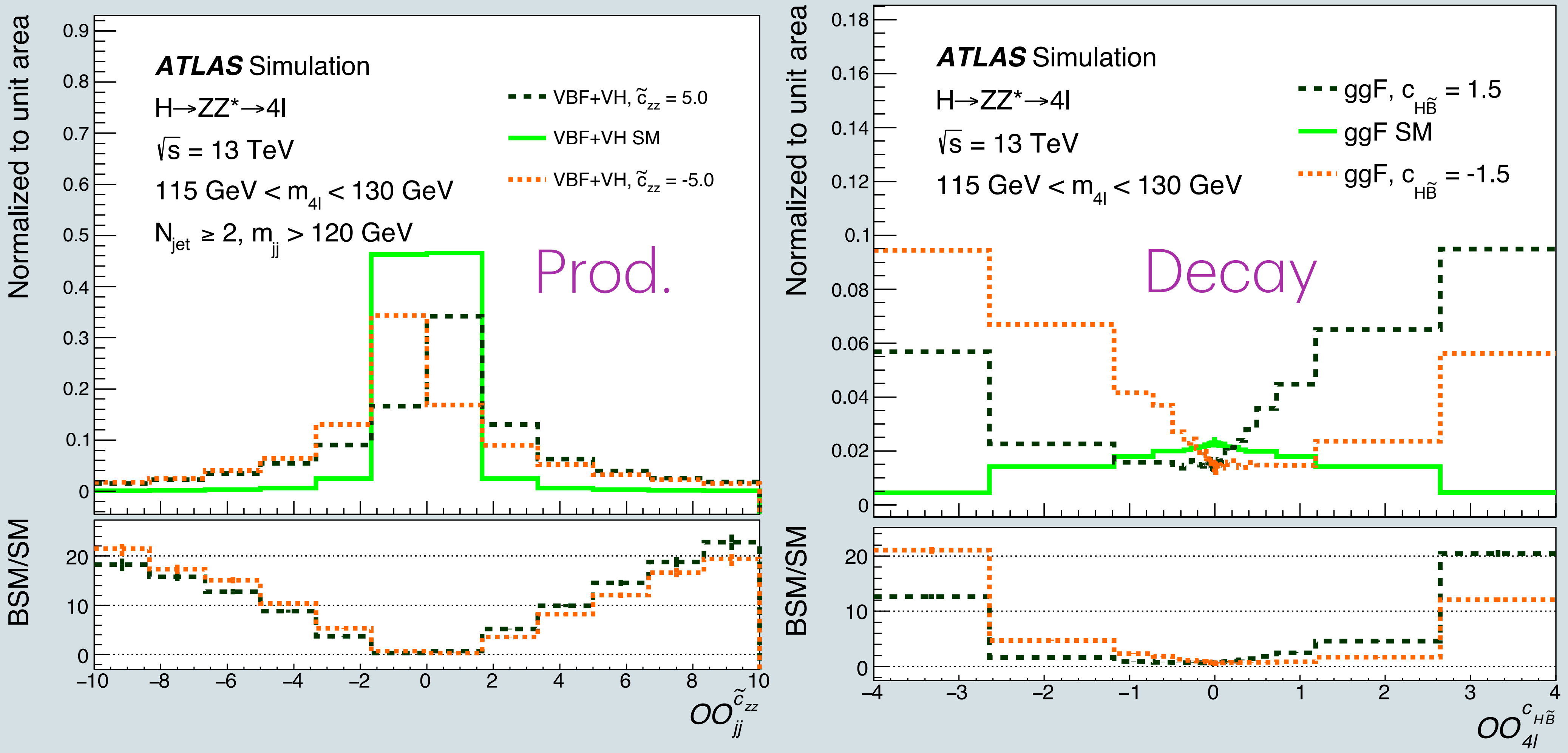


Categorisation

- Split phase-space by kinematic selections into
  - $ZZ^\star$ CR
  - VBF-enriched SR (useful for production-side CP-violation)
    - Split to 4 regions by S/B DNN score
  - VBF-depleted SR (useful for decay-side CP-violation)

Fit variables

- Compute two sets of optimal observables:
  - **Production-level:** use VBF production ME (decay-agnostic)
  - **Decay-level:** use Higgs decay ME (production-agnostic)
- 7x Wilson coefficients of-interest → 7x observables of each type
- $\mathcal{OO}$ for a signal (combo of active Wilson coeffs) by *morphing method*



VBF $H \to ZZ^\star \to 4\ell$

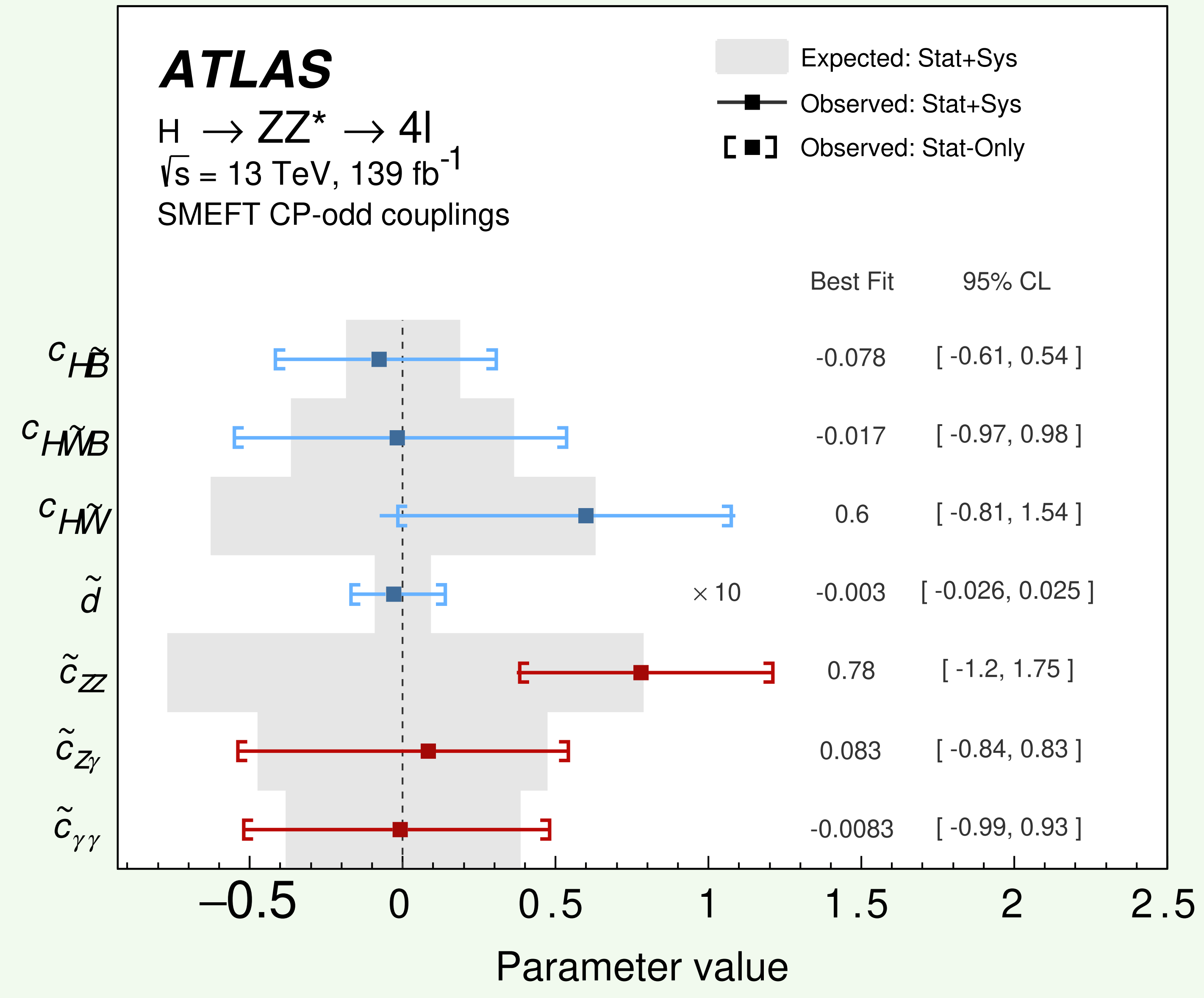
Full Run-2 (140 fb^{-1}): result

JHEP 05 (2024) 105 — aux material

EFT coupling	Expected 95% CL		
	production-only	decay-only	combined
$c_{H\tilde{B}}$	–	±0.37	–
$c_{H\widetilde{W}B}$	–	±0.72	–
$c_{H\widetilde{W}}$	±4.8	±1.34	±1.27
$\tilde{d}$	±0.63	±0.018	±0.019
$\tilde{c}_{zz}$	±2.4	–	–
$\tilde{c}_{z\gamma}$	±6.6	±0.76	±0.80
$\tilde{c}_{\gamma\gamma}$	–	±0.76	–

Fitting — Direct coupling measurement

- Three fits are performed
  - **Production-only**, **Decay-only** and **combined**
  - Different combos of SRs/CRs and $\mathcal{OO}$-type to fit
- Float signal normalisation to probe shape-only effects



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JHEP 05 (2024) 105 — aux material

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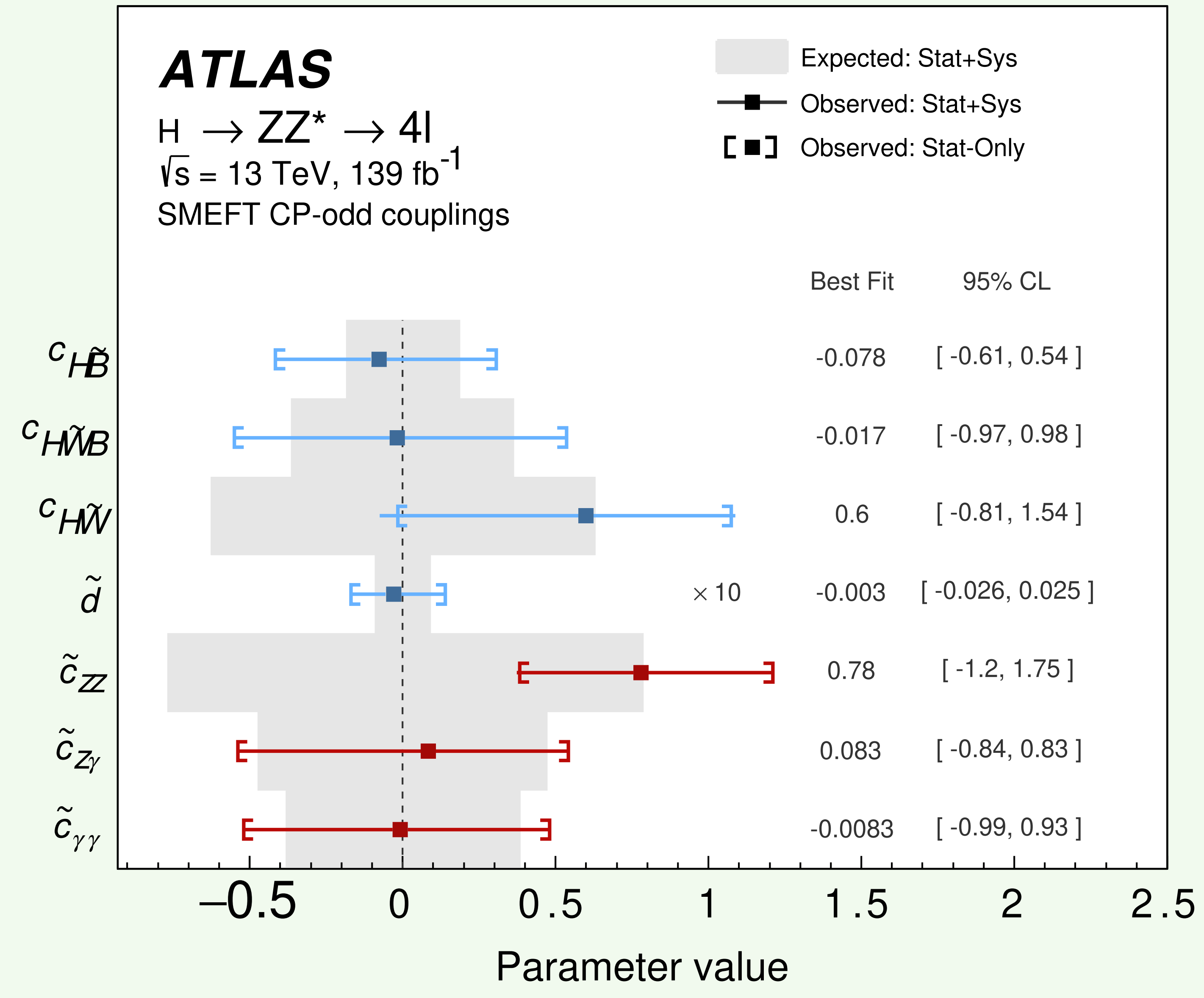
$c_{H\tilde{W}B}$	–	±0.72	–
$c_{H\tilde{W}}$	±4.8	±1.34	±1.27
$\tilde{d}$	±0.63	±0.018	±0.019
$\tilde{c}_{zz}$	±2.4	–	–
$\tilde{c}_{z\gamma}$	±6.6	±0.76	±0.80
$\tilde{c}_{\gamma\gamma}$	–	±0.76	–

Fitting — Direct coupling measurement

- Three fits are performed
  - **Production-only**, **Decay-only** and **combined**
  - Different combos of SRs/CRs and $\mathcal{OO}$-type to fit
- Float signal normalisation to probe shape-only effects



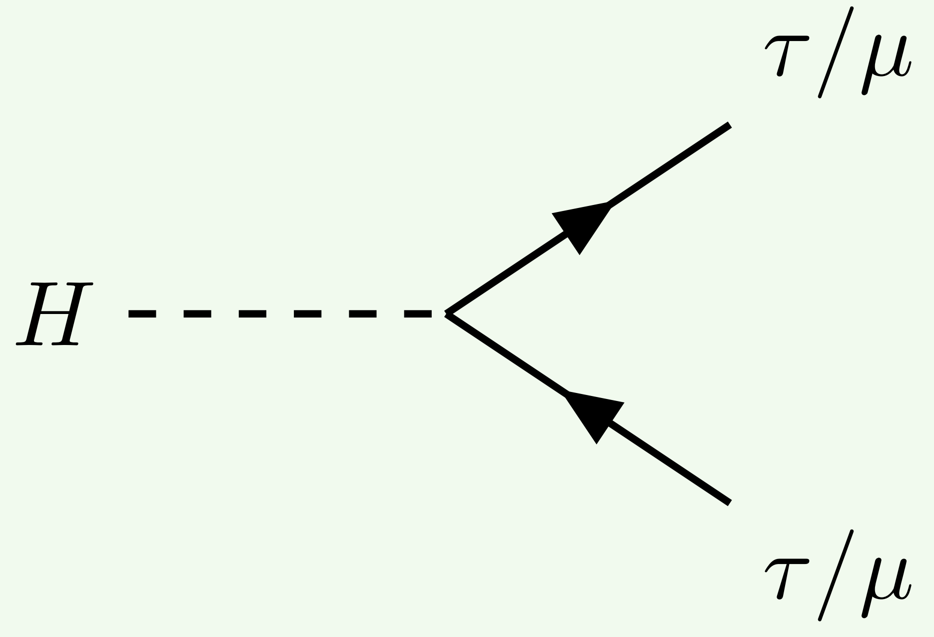
Fitting — Differential XS measurements

- Unfold $\mathcal{OO}$
- Fit $m_{4\ell}$ in each bin

no CP-violation observed

CP structure in $\boldsymbol{H} \to f\bar{f}$

$H \rightarrow \tau\tau$



$H \to \tau\tau$

Full Run-2 (140 fb^{-1}): setup

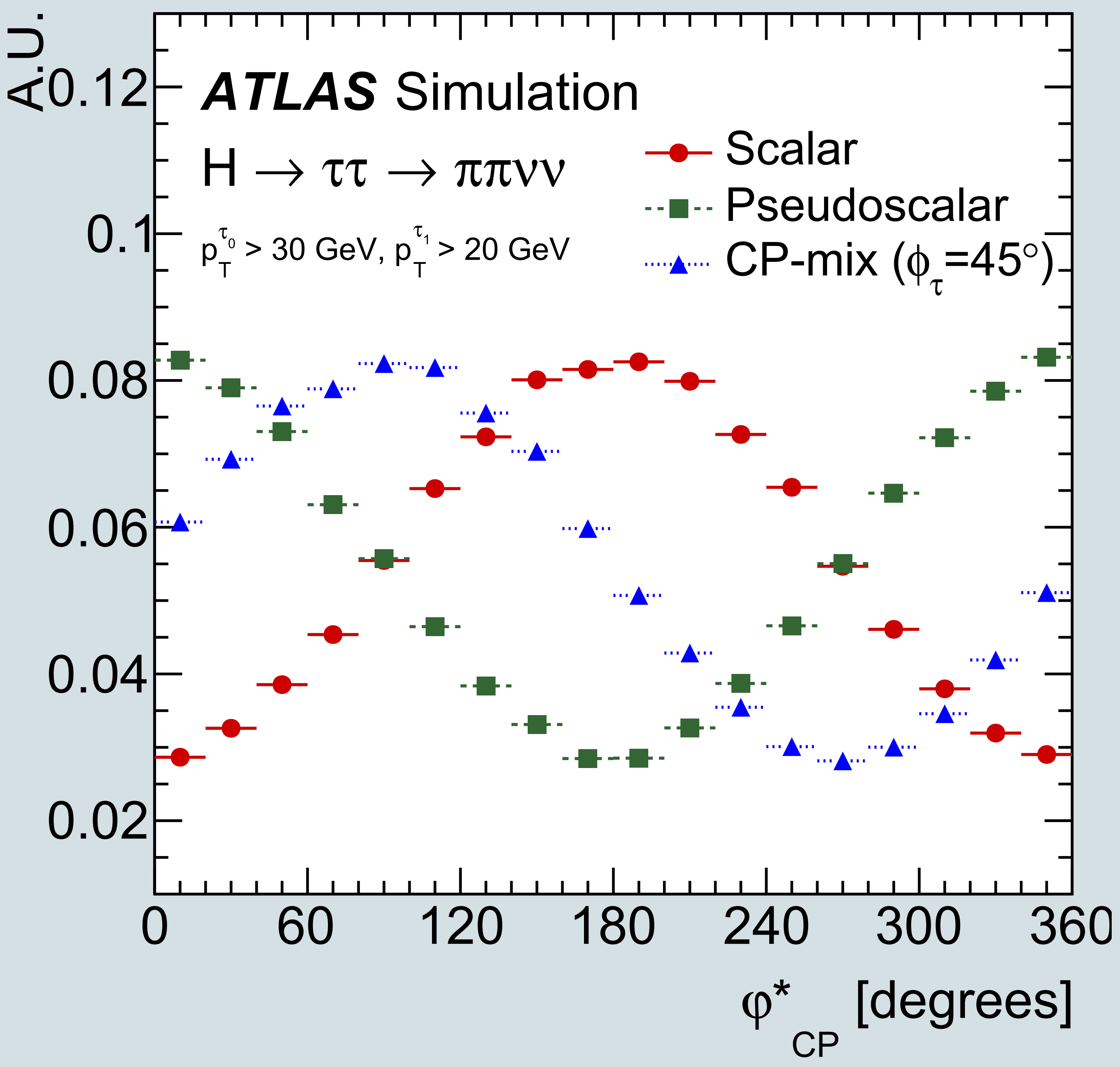
Eur. Phys. J. C 83 (2023) 563 — aux material

Categorisation

- 2 channels: $\tau_{\mathrm{had}}\tau_{\mathrm{lep}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
  - Split to VBF and ggF enriched regions
    - VBF and ggF SRs split by BDT scores / kinematics
- SRs split by impact parameters and spin-analysing functions

Fit variables

- Signed a-coplanarity angle φ_{CP}
  - Angle between τ decay planes
    - Reconstruction method depends on $\pi^{\pm}/\pi^{0}$ multiplicities
  - Sensitive to CP-mixing angle ϕ_{τ}



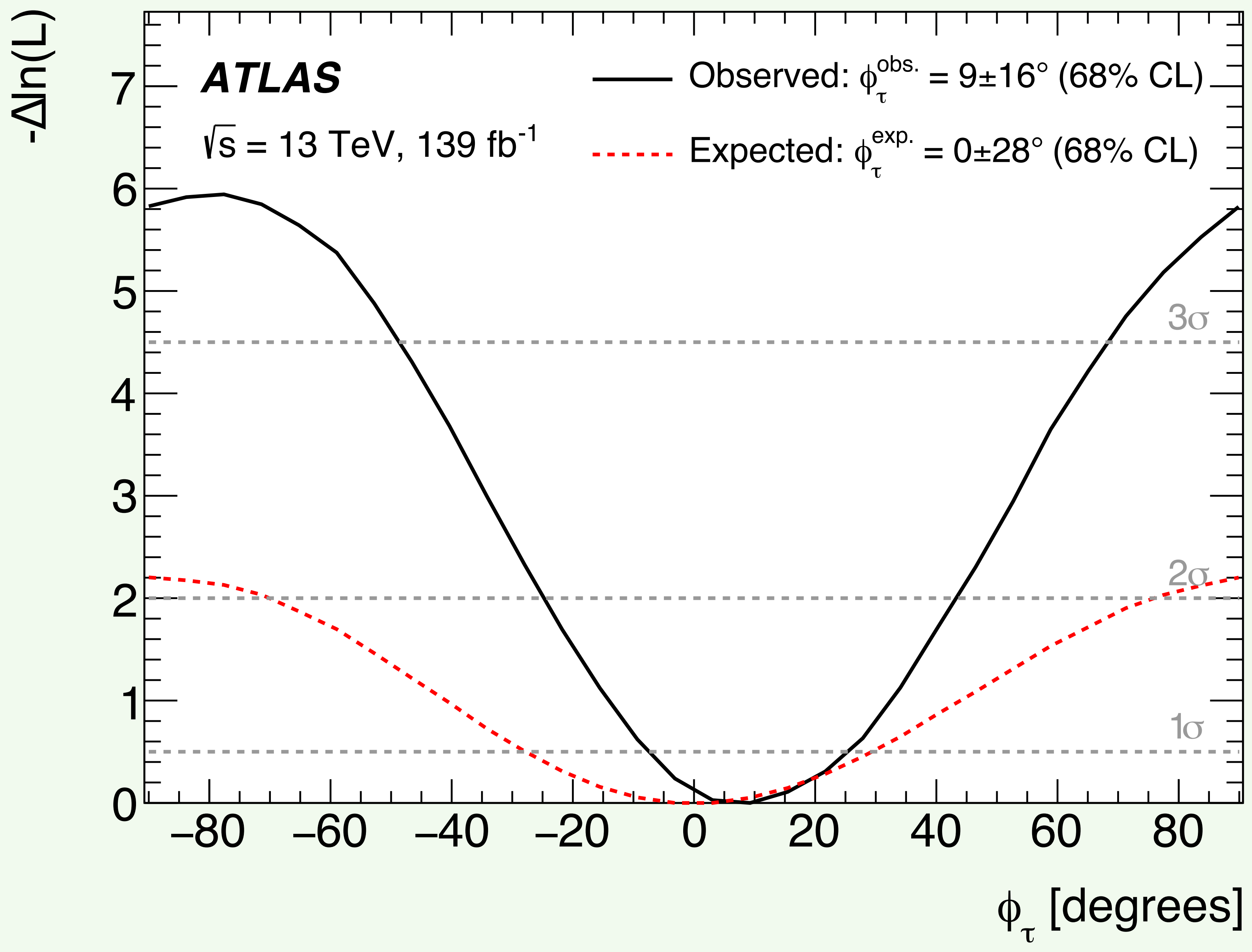
$H \to \tau\tau$

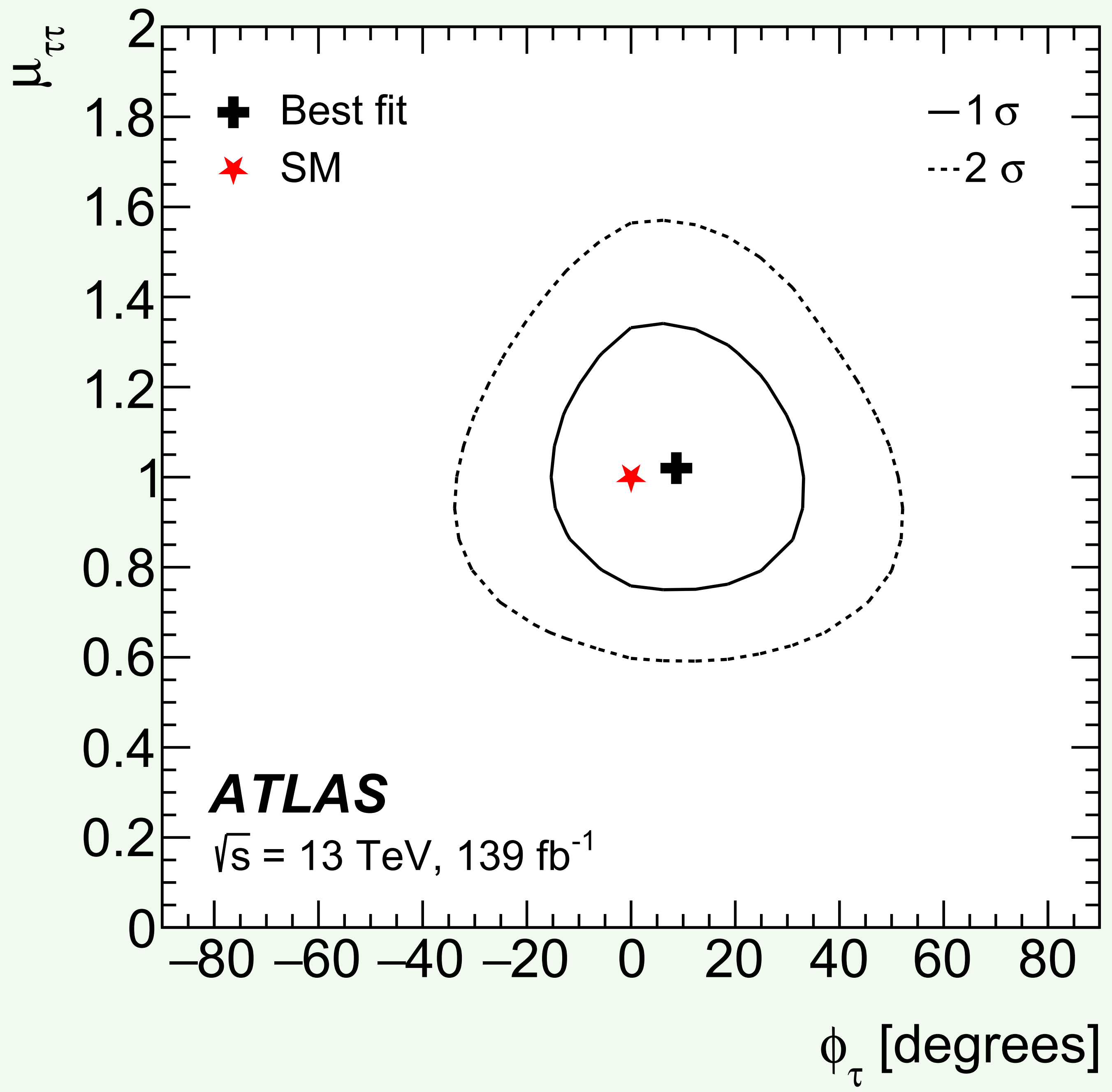
Full Run-2 (140 fb^{-1}): setup

Eur. Phys. J. C 83 (2023) 563 — aux material

Fitting

- Binned maximum likelihood fit in all regions
- Free-float ϕ_τ and $\mu_{H\to\tau\tau}$

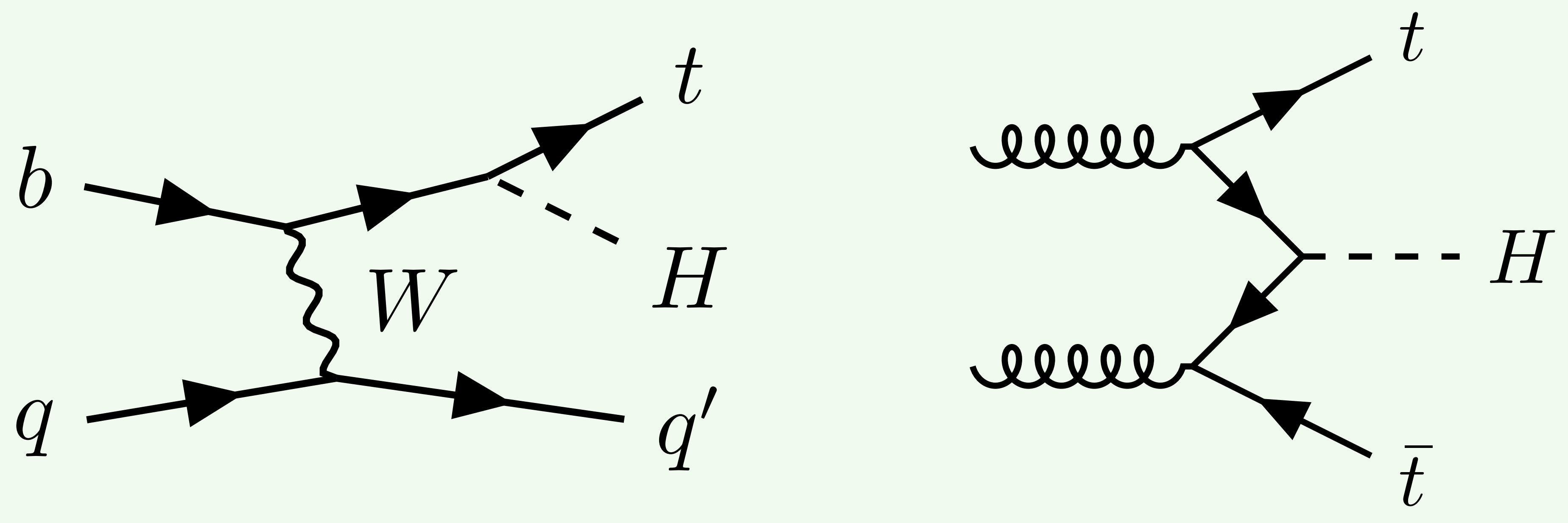




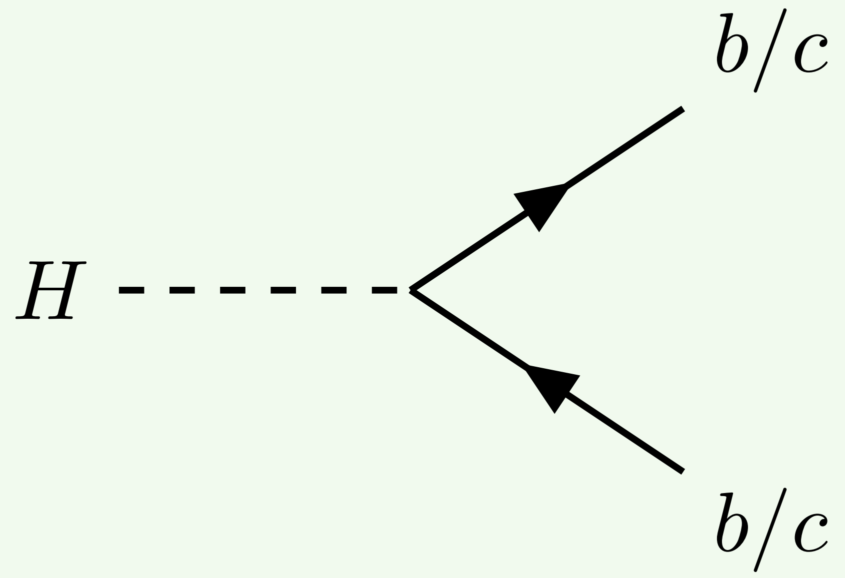
$\phi_\tau = 9 \pm 16^\circ$ and $\phi_\tau = 90^\circ$ excluded at 3.4σ

no CP-violation observed

$H \to bb$ in $t\bar{t}H$ and tHq



Production-side



Decay-side

$t\bar{t}H(\to b\bar{b})$ and $tH(\to b\bar{b})q$

Full Run-2 (140 fb^{-1}): setup

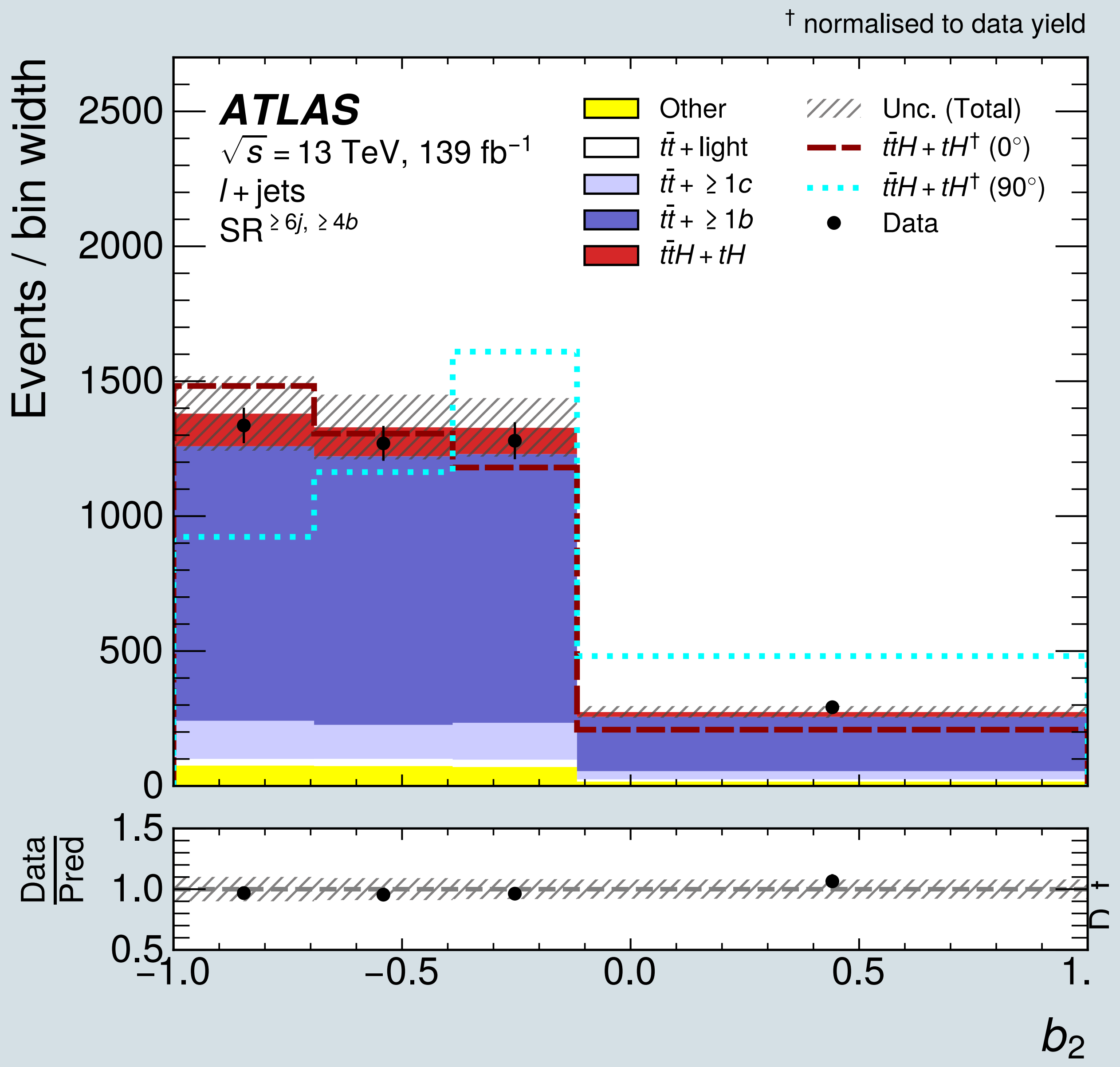
Phys. Lett. B 849 (2024) 138469 — aux material

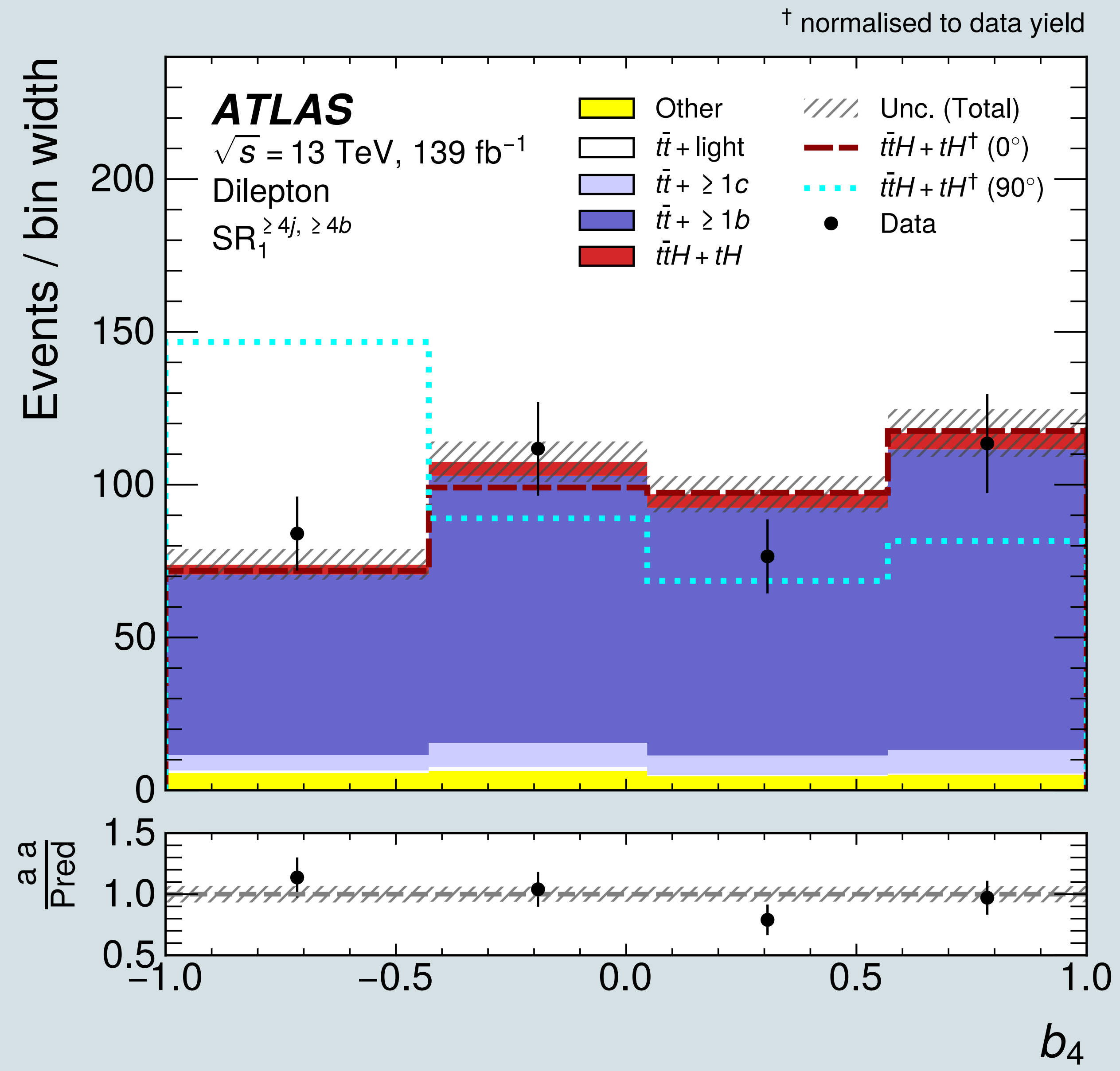
Categorisation

- 2 channels: 1ℓ and 2ℓ
  - Split regions in each channel by jet multiplicity and S/B BDT score
  - Split 1ℓ channel to resolved and boosted

Fit variables

- Build CP-sensitive observables based on top-quark kinematics
- Use reconstruction BDT to build Higgs and top
- Fit b_2 and b_4 in resolved regions





$t\bar{t}H(\to b\bar{b})$ and $tH(\to b\bar{b})q$

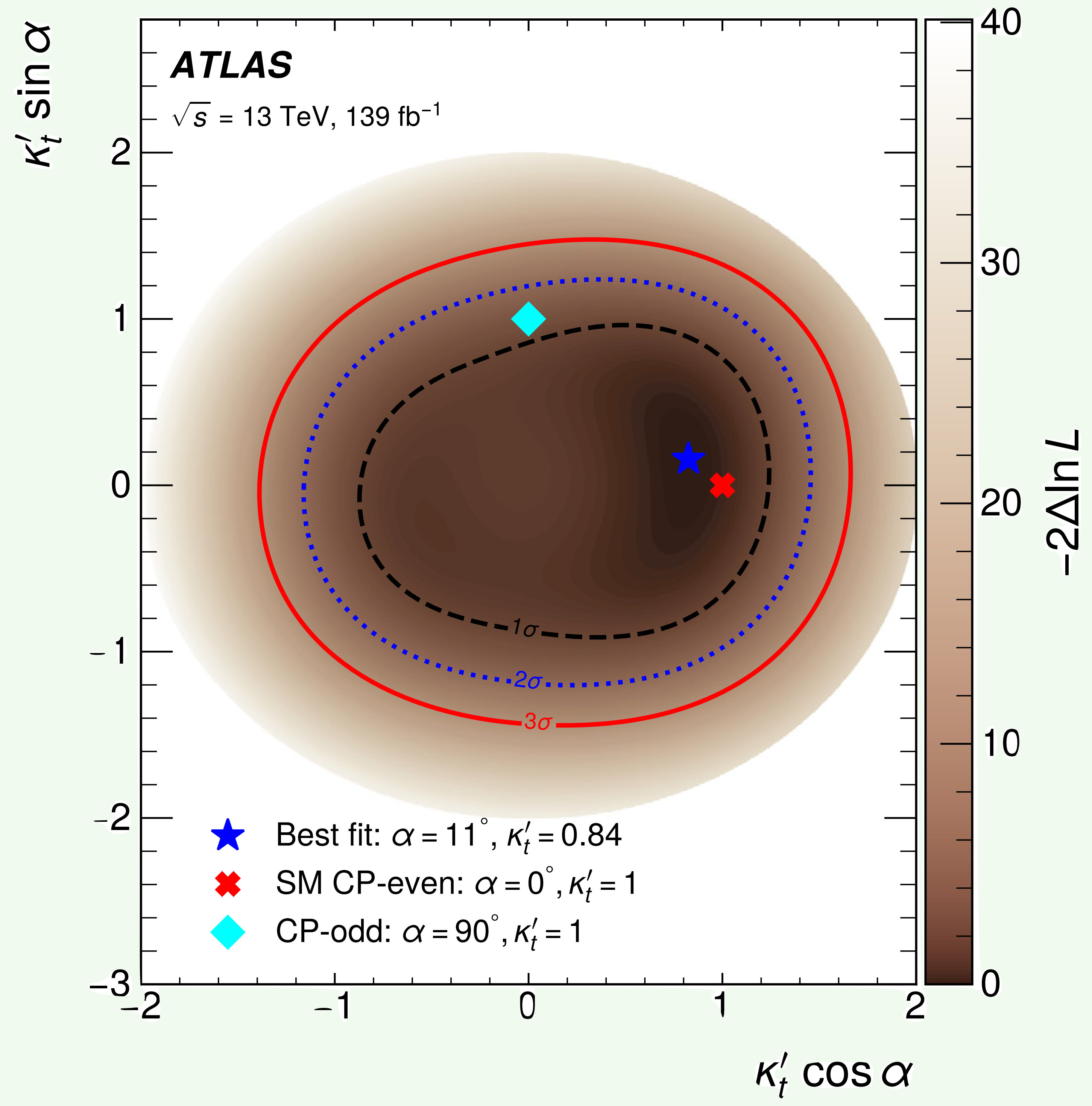
Full Run-2 (140 fb^{-1}): setup

Phys. Lett. B 849 (2024) 138469 — aux material

Fitting

- Binned max-likelihood fit in all regions
- Free-float α and κ_t'

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t \left(\cos\alpha + i\gamma_5 \sin\alpha\right) \psi_t$$



$\alpha = 11^{+52^\circ}_{-73^\circ}$

$\alpha = 90^\circ$ excluded at 1.2σ

Uncertainty source	$\Delta\alpha\,[^\circ]$	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+23	-37
$t\bar{t}+\geq 1b$ NLO matching	+22	-33
$t\bar{t}+\geq 1b$ fractions	+14	-21
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+16	-24
$t\bar{t}+\geq 1b$ $p_T^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t}+\geq 1b$ ISR	+14	-24
$t\bar{t}+\geq 1c$ modelling	+6.6	-11
$t\bar{t}$ + light modelling	+2.5	-4.7

Systematics dominated

Conclusions

- Wide range of Higgs boson properties measured at ATLAS with full Run-2 data
- **Mass measurements** with $H \to \gamma\gamma$ and $H \to ZZ^{\star} \to 4\ell$ reach 0.1% precision
  - Best in the world!
- **Width measurements** with $H \to ZZ^{\star}$ moving closer to a precise value
  - Expected precision improvements with more data in Run-3
- **CP structure** measured for Higgs interactions with bosons ($\gamma\gamma$, ZZ) and fermions ($\tau\tau$, $b\bar{b}$)
  - With interpretations in the SMEFT and kappa frameworks

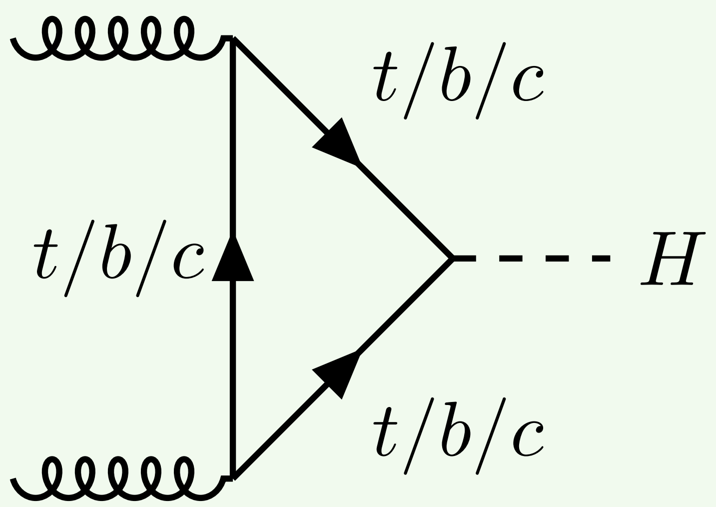
Thanks for listening!

Overview

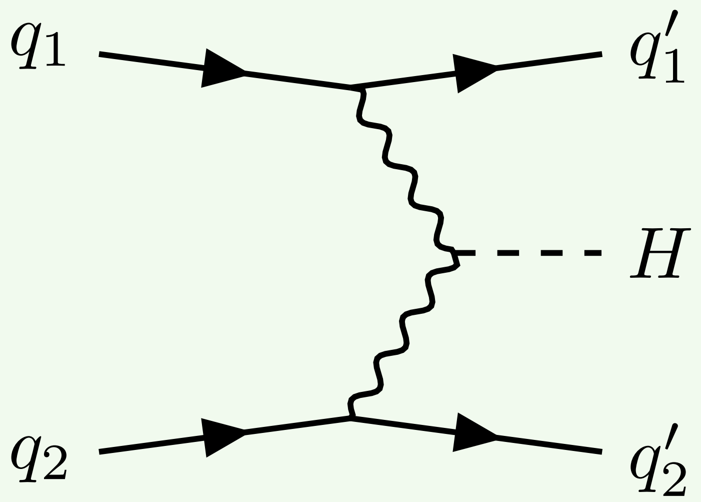
How we get Higgs and how we lose it

Production

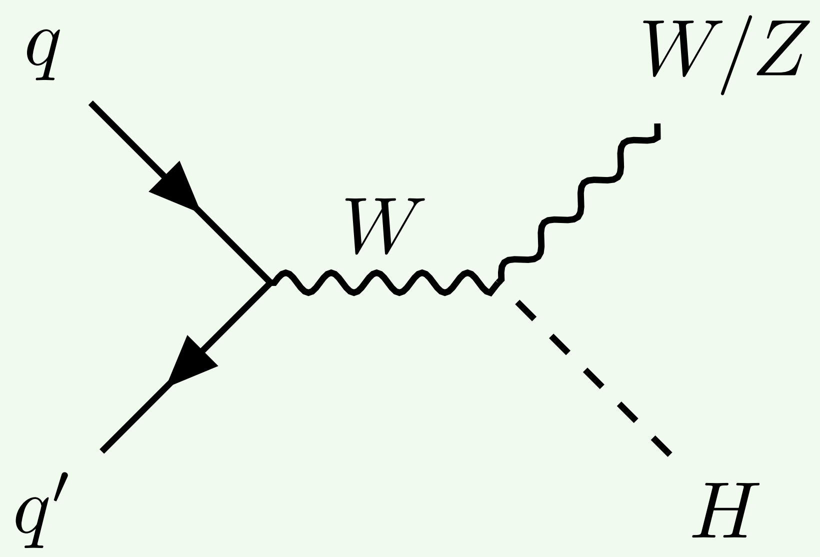
Cross-sections from LHCWG at 13 TeV for $m_H = 125$ GeV



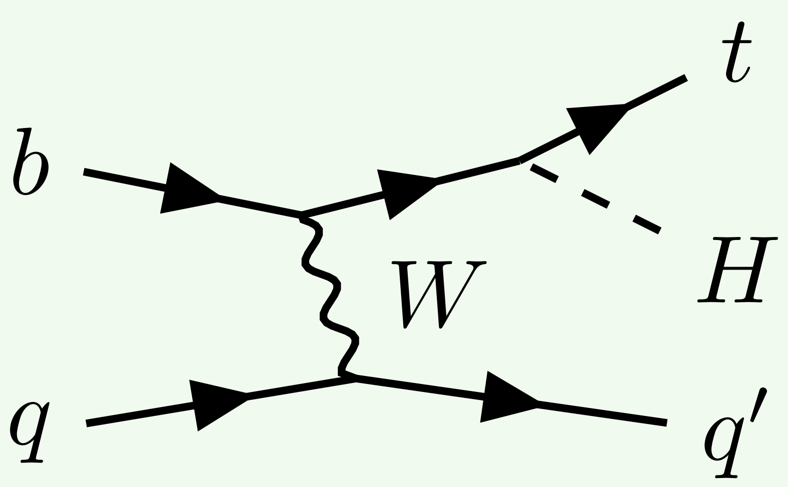
ggF ($\sigma = 48.6$ pb)



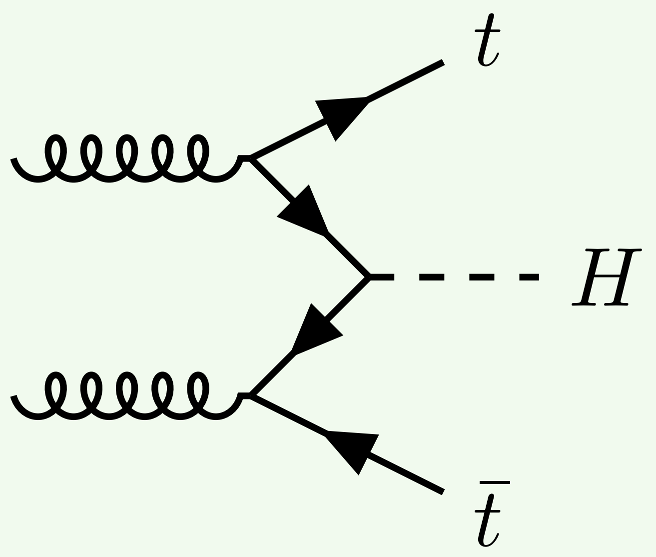
VBF ($\sigma = 3.93$ pb)



VH ($\sigma = 2.26$ pb)

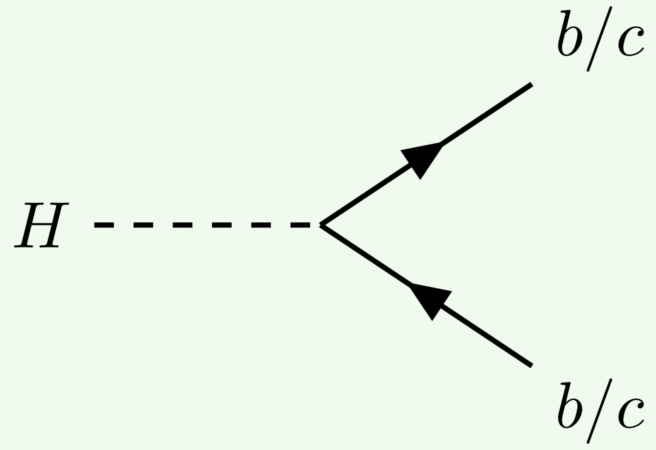


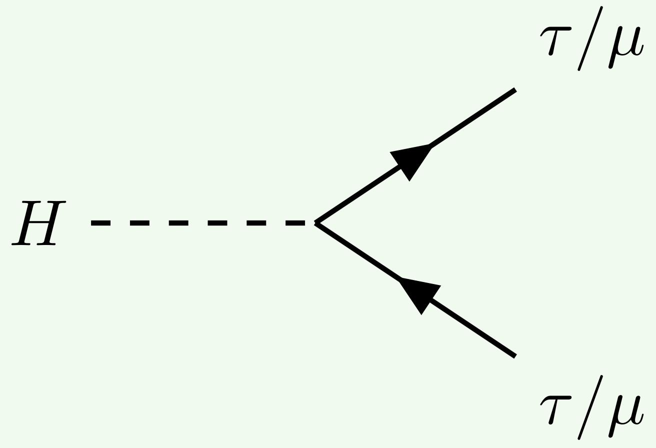
tHq ($\sigma = 0.077$ pb)

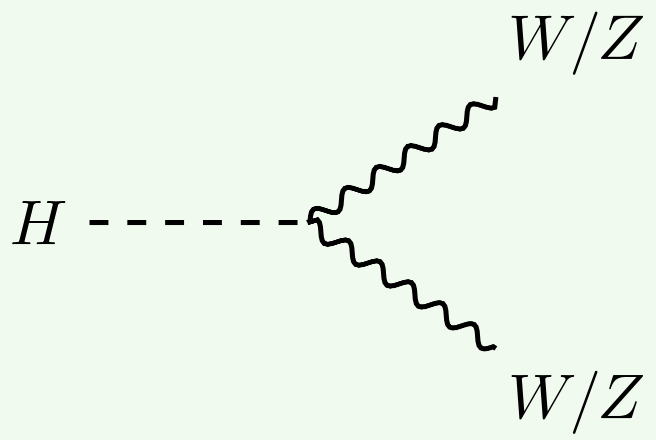


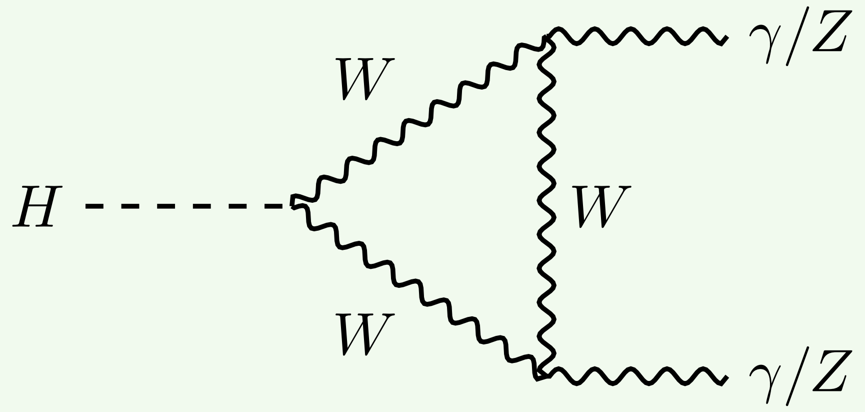
$t\bar{t}H$ ($\sigma = 0.50$ pb)

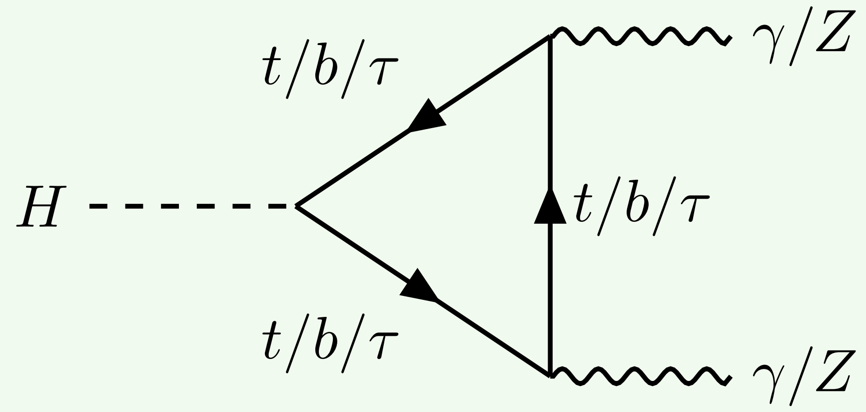
Decay









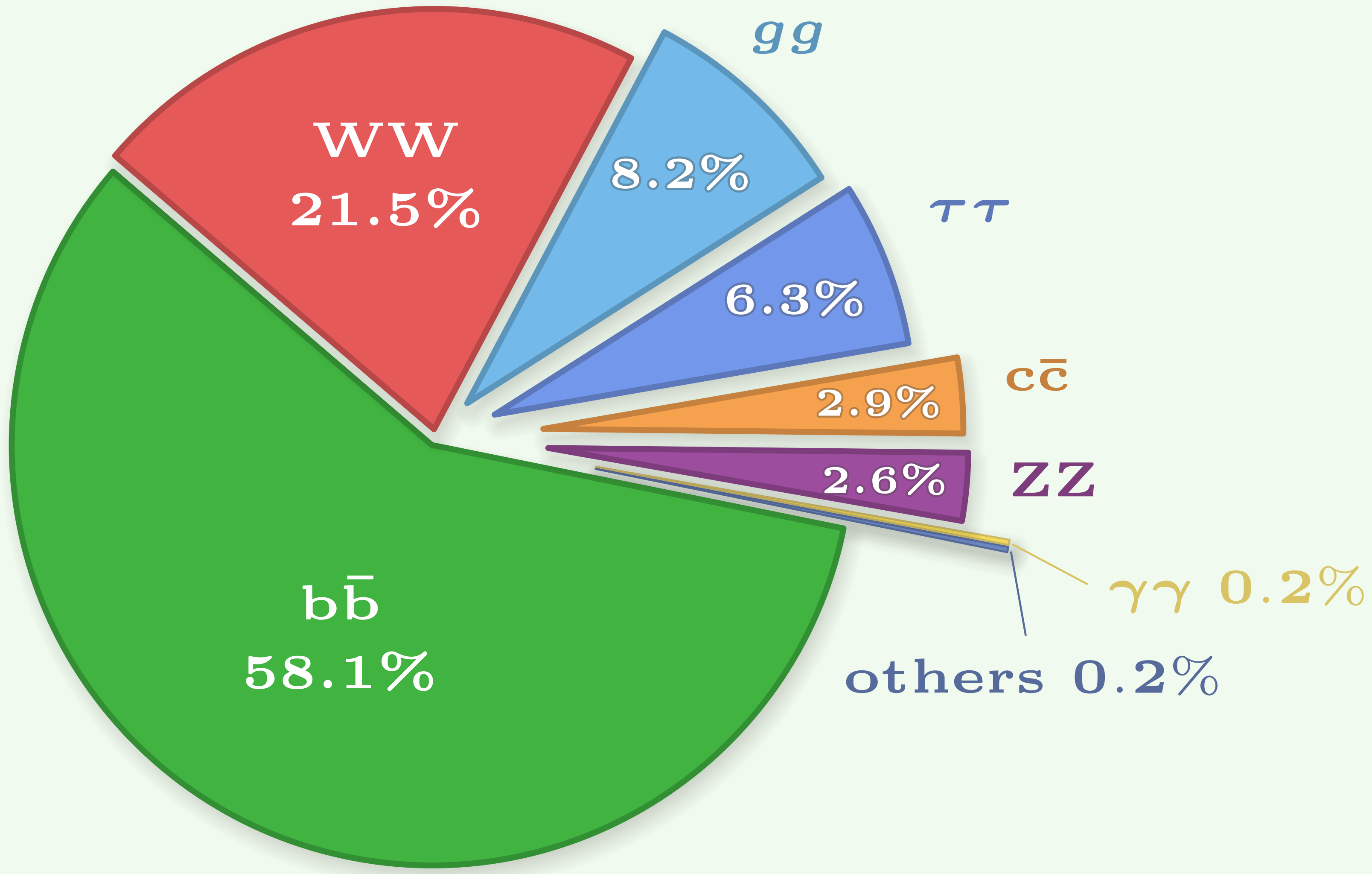


.Higgs mass

Choices to be made

The Higgs mass: decay channels

Higgs mass = invariant mass of decay products



$H \rightarrow$ bb/cc/gg
- Difficult to reconstruct hadronic final states with high resolution

$H \rightarrow$ WW/$\tau\tau$
- Neutrinos in final-state are invisible

$H \rightarrow \mu\mu/ee/Z\gamma$
- Low branching ratios, large backgrounds

$H \rightarrow ZZ/\gamma\gamma$
- Manageable backgrounds
- *Easy* reconstruction

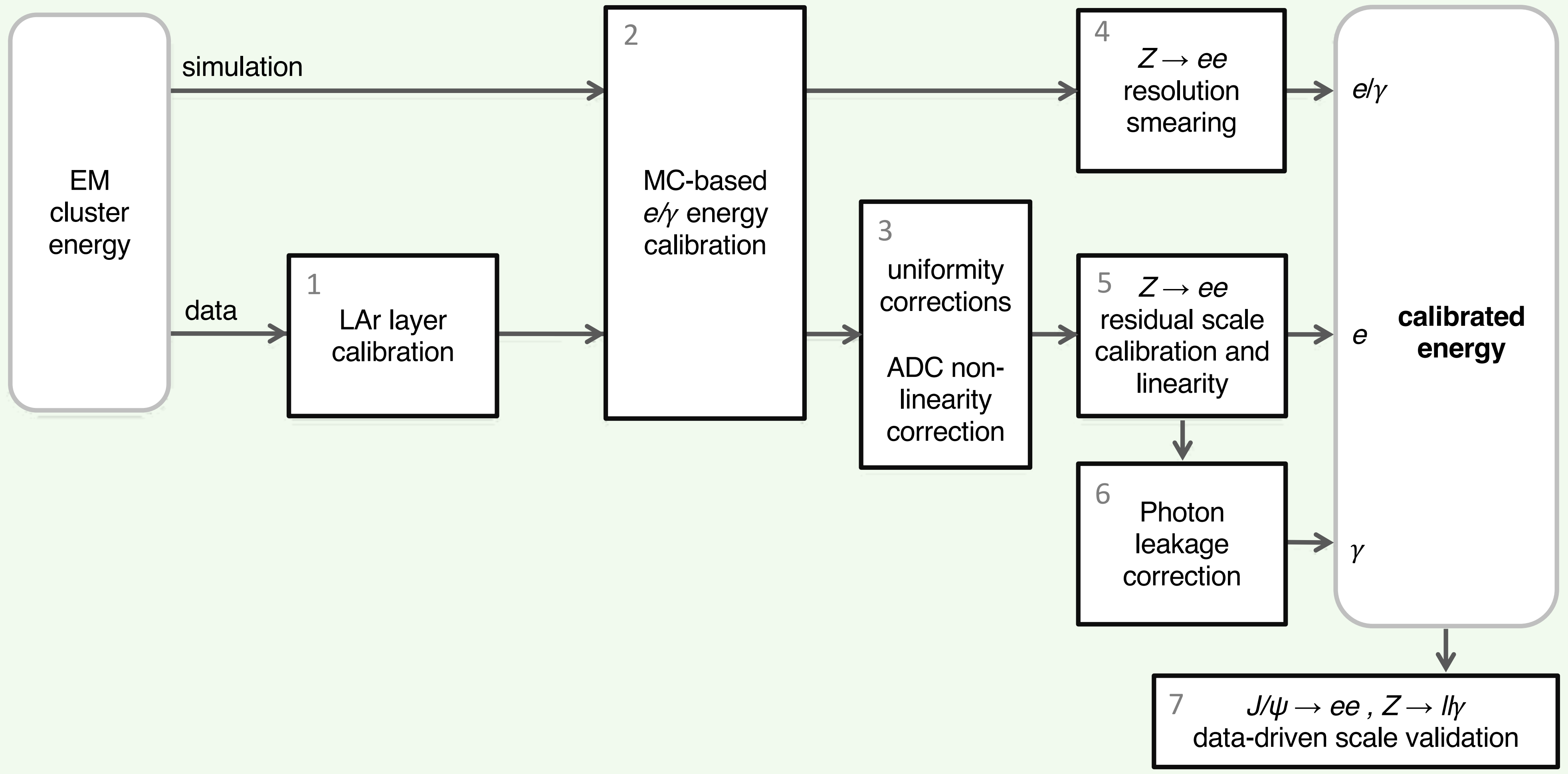
$$H \to \gamma\gamma$$

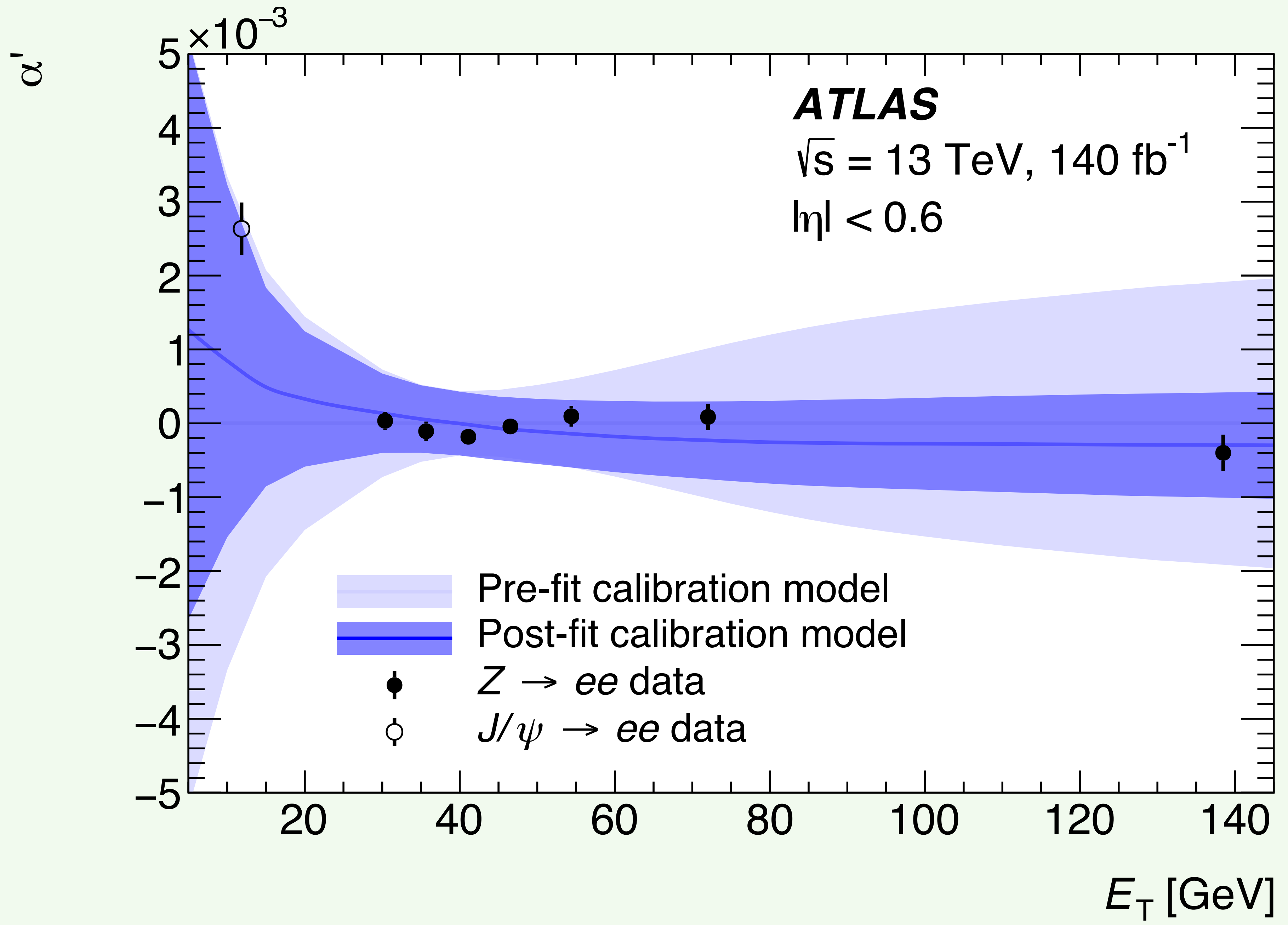
Mass with $H \rightarrow \gamma\gamma$

Photon energy scale improvement

JINST 19 (2024) P02009

- The photon energy scale measurement combines has improved:
  - Material modelling → 3x better
  - On-detector electronics non-linearity modelling → 2x better
  - Electron-to-photon scale extrapolation → 2x better
- $Z \rightarrow ee$ calibration scale-factors parameterised in p_T and η





$$H \to ZZ$$

Mass with $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): misc

Phys. Lett. B 843 (2023) 137880

$$\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i \mid m_H) = \mathcal{P}(m_{4\ell} \mid D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} \mid \sigma_i, m_H) \cdot \mathcal{P}(\sigma_i \mid m_H)$$
$$\simeq \mathcal{P}(m_{4\ell} \mid D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} \mid m_H)$$

Crystal-ball

Gaussian core parametrised for a channel λ with $a^\lambda \cdot (m_H - 125\,\text{GeV}) + b^\lambda(D_{NN})$, b^λ is 2^{nd} order poly. $a^\lambda \approx 1$ Determined from separate ML fit

Core stdev expressed as function of σ_i and parametrised as function of DNN

NN independent of m_h

Determined by interpolation across neighbouring simulated mass points

Neglected because it's same for signal and background around mass peak

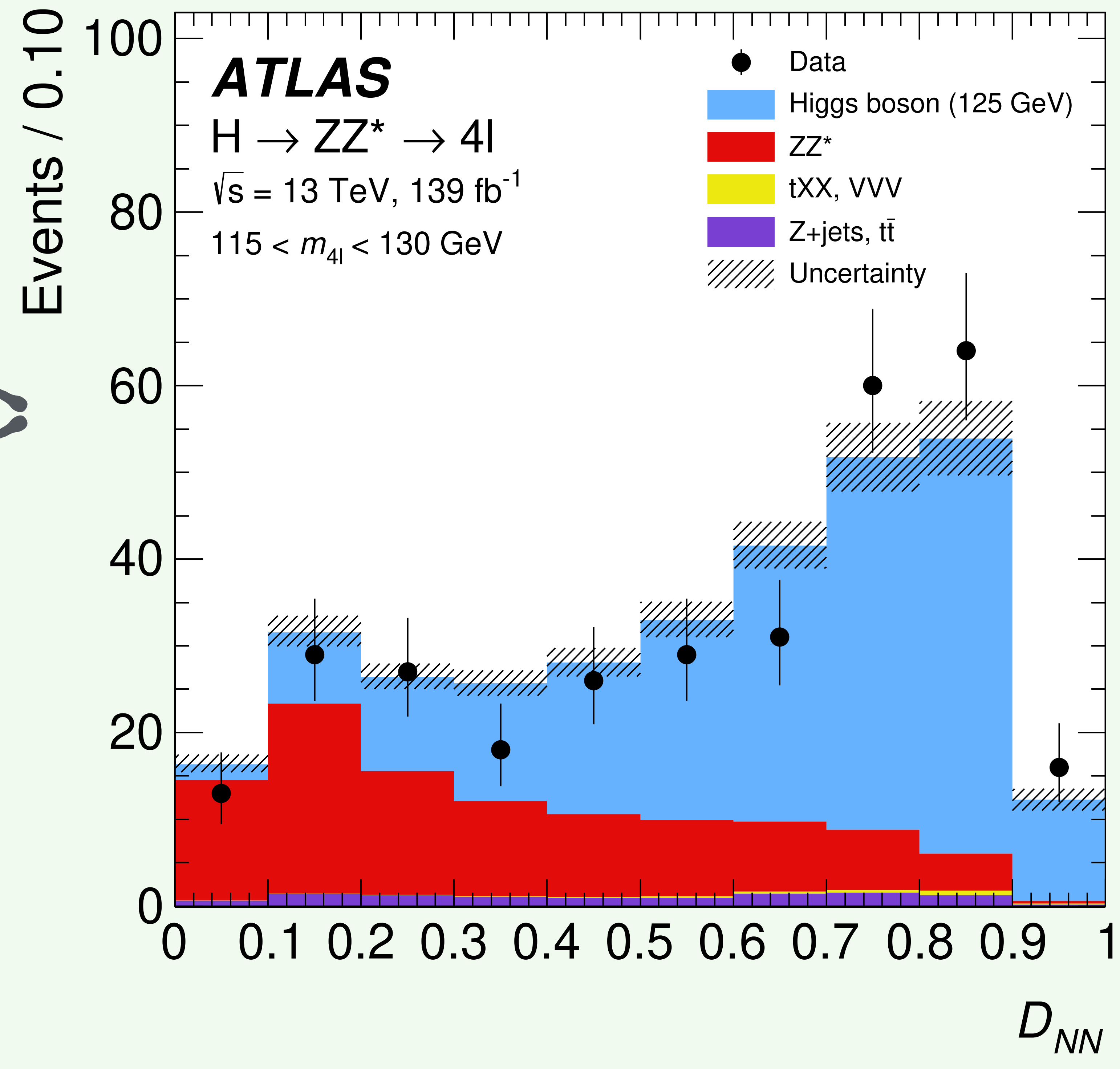
Mass with $H \rightarrow ZZ^{\star} \rightarrow 4\ell$

Full Run-2 (140 fb^{-1}): misc

Phys. Lett. B 843 (2023) 137880

Four-lepton kinematics

$$\ln\left(\frac{|\mathcal{M}_{HZZ^*}|^2}{|\mathcal{M}_{ZZ^*}|^2}\right)$$



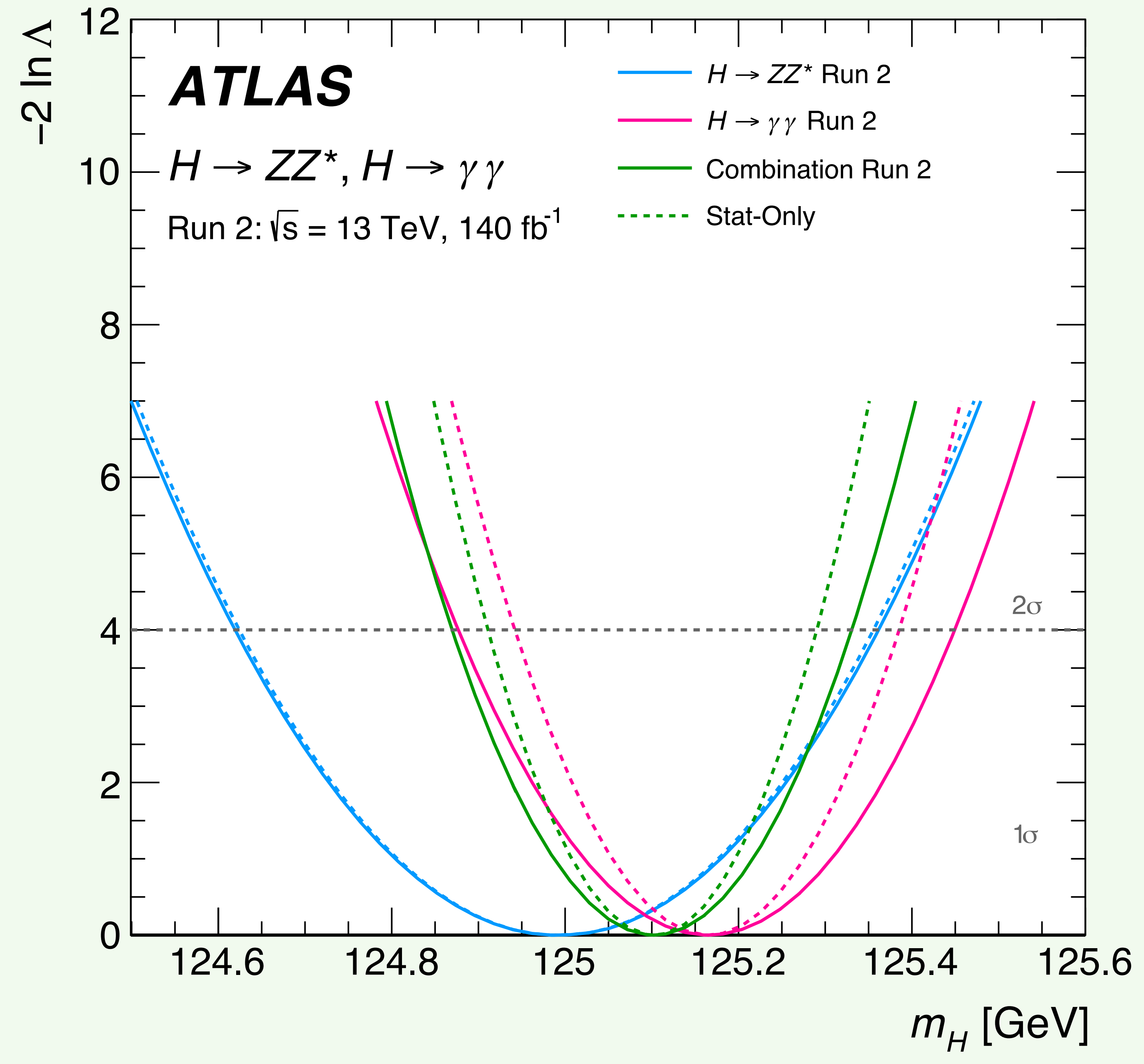
Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	± 28
Electron energy scale	± 19
Signal-process theory	± 14

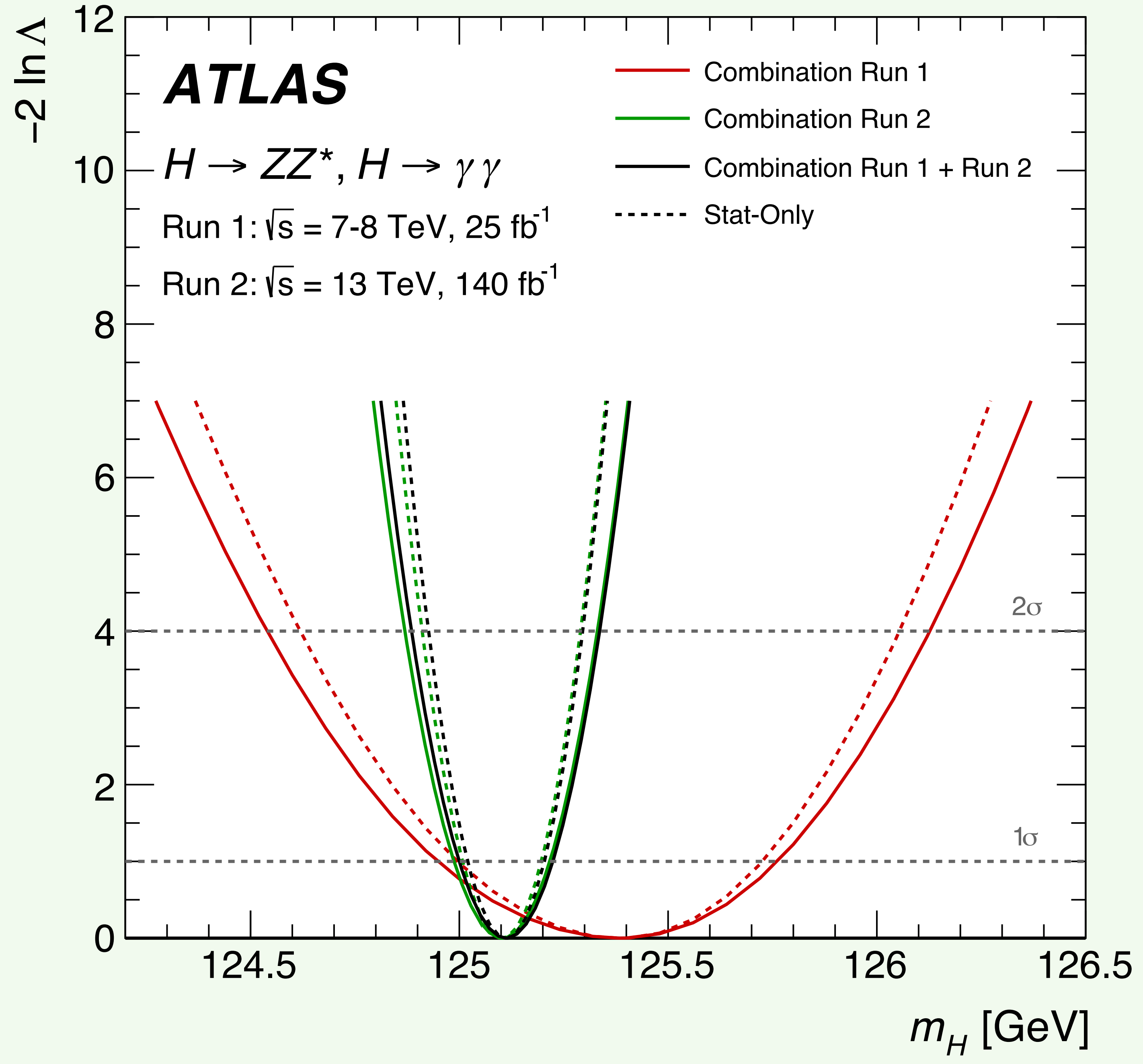
Combination

Mass with ATLAS

Combined results with full Run-2 data: misc

Phys. Lett. B 131 (2023) 251802 — aux material





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

.Higgs width

$$H^\star \to ZZ \text{ and } H \to ZZ^\star$$

VBF $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): misc.

JHEP 05 (2024) 105 — aux material

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2},$$

$$\begin{aligned}
\nu^{\text{ggF}}(\mu^{\text{ggF}}_{\text{off-shell}}, \boldsymbol{\theta})
&= \mu^{\text{ggF}}_{\text{off-shell}} \cdot n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) \\
&\quad + \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}} \cdot (n^{\text{ggF}}_{\text{SBI}}(\boldsymbol{\theta}) - n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) - n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta})) + n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta}) \\
&= (\mu^{\text{ggF}}_{\text{off-shell}} - \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}}) \cdot n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) \\
&\quad + \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}} \cdot n^{\text{ggF}}_{\text{SBI}}(\boldsymbol{\theta}) + (1 - \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}}) \cdot n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta})
\end{aligned}$$

Systematic Uncertainty Fixed	$\mu_{\text{off-shell}}$ value at which $-2\ln\lambda(\mu_{\text{off-shell}}) = 4$
Parton shower uncertainty for $gg \to ZZ$ (normalisation)	2.26
Parton shower uncertainty for $gg \to ZZ$ (shape)	2.29
NLO EW uncertainty for $qq \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $qq \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

$H^\star \to t\bar{t}$ and $t\bar{t}H$

Multi-top united for width

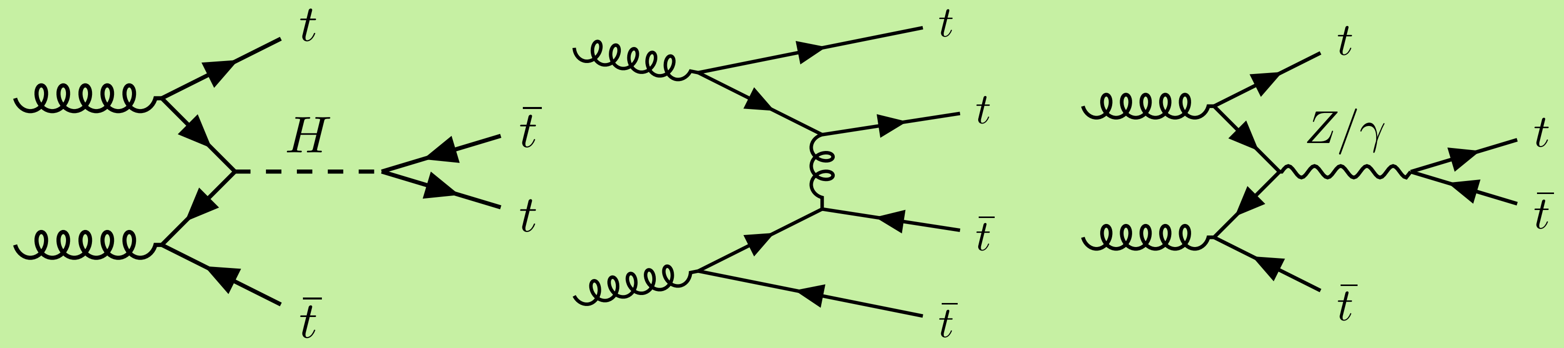
The idea

Phys. Rev. D 99, 113003 (theory)

arXiv:2407.10631 — **submitted to PLB**

Off-shell

4-tops

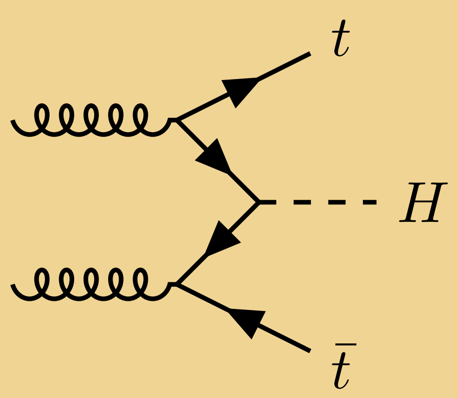


$$\mu_{t\bar{t}t\bar{t}} = A + B\kappa_t^2 + C\kappa_t^4$$

$g + Z/\gamma$ — interference — Higgs

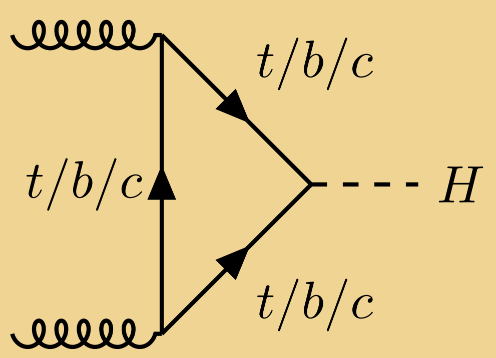
On-shell

$t\bar{t}H$



$\propto \kappa_t^2/\Gamma^2$

$gg \rightarrow H$



$\propto \kappa_g^2(\kappa_t, \kappa_V)/\Gamma^2$

Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \rightarrow \gamma\gamma$
$t\bar{t}H + tH$	$H \rightarrow b\bar{b}$
WH, ZH	$H \rightarrow b\bar{b}$
VBF	$H \rightarrow b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow ZZ$
ggF, VBF	$H \rightarrow WW$
WH, ZH	$H \rightarrow WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \rightarrow \mu\mu$
Inclusive	$H \rightarrow Z\gamma$

$\propto \kappa_i^2(\kappa_t, \kappa_V)\kappa_f^2(\kappa_t, \kappa_V)/\Gamma^2$

Combination

- Aggregate statistical model from all ATLAS Higgs measurements
  - Except $t\bar{t}H(\rightarrow$ leptons)
- Perform a fit using the aggregated model
- Free-float:
  - tree-level κ (e.g. $\kappa_t, \kappa_b, \ldots$)
  - effective loop κ (e.g. $\kappa_g, \kappa_\gamma, \ldots$)
- Allow Higgs width to float for all models

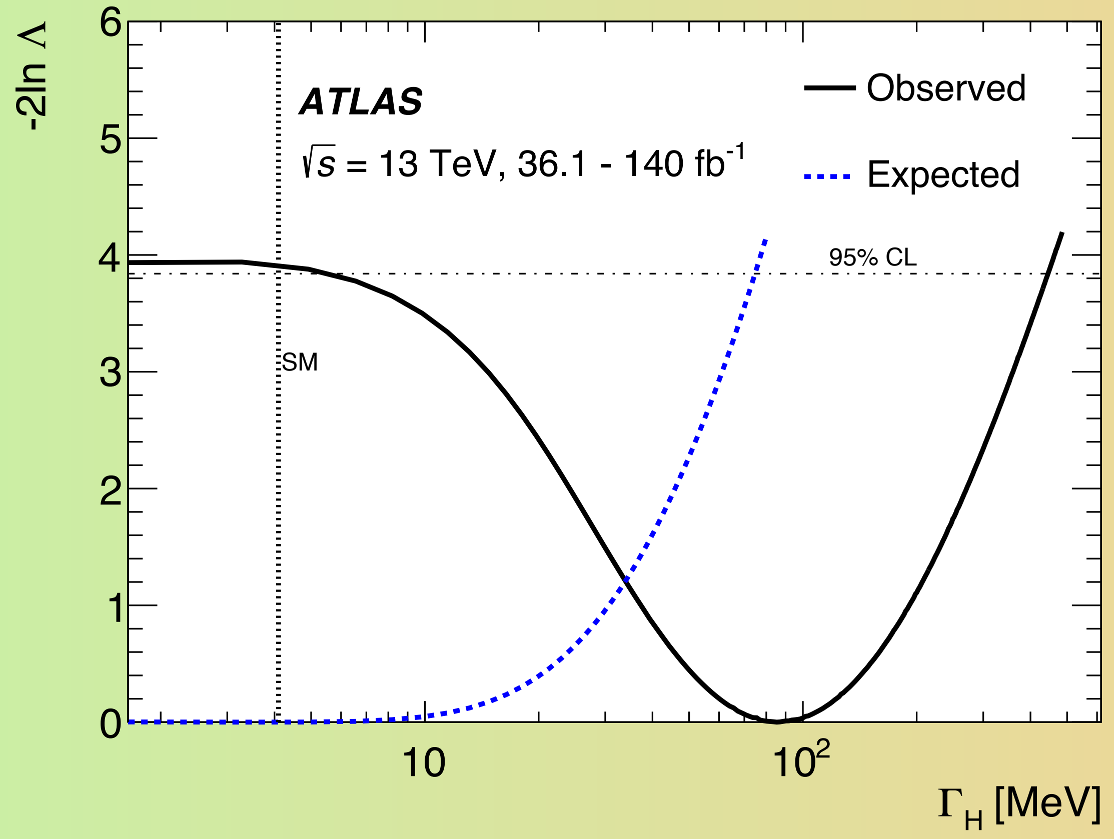
Multi-top united for width

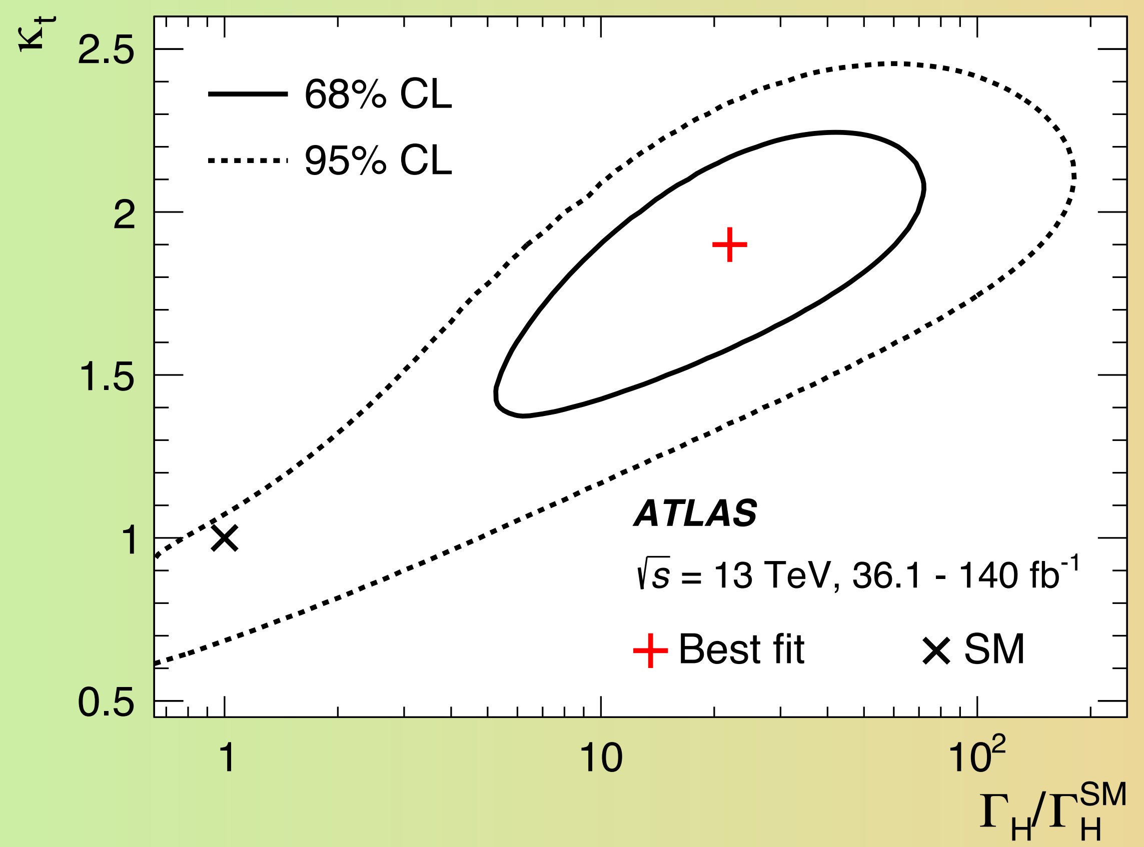
The result

Phys. Rev. D 99, 113003 (theory)

arXiv:2407.10631 — **submitted to PLB**

Combination



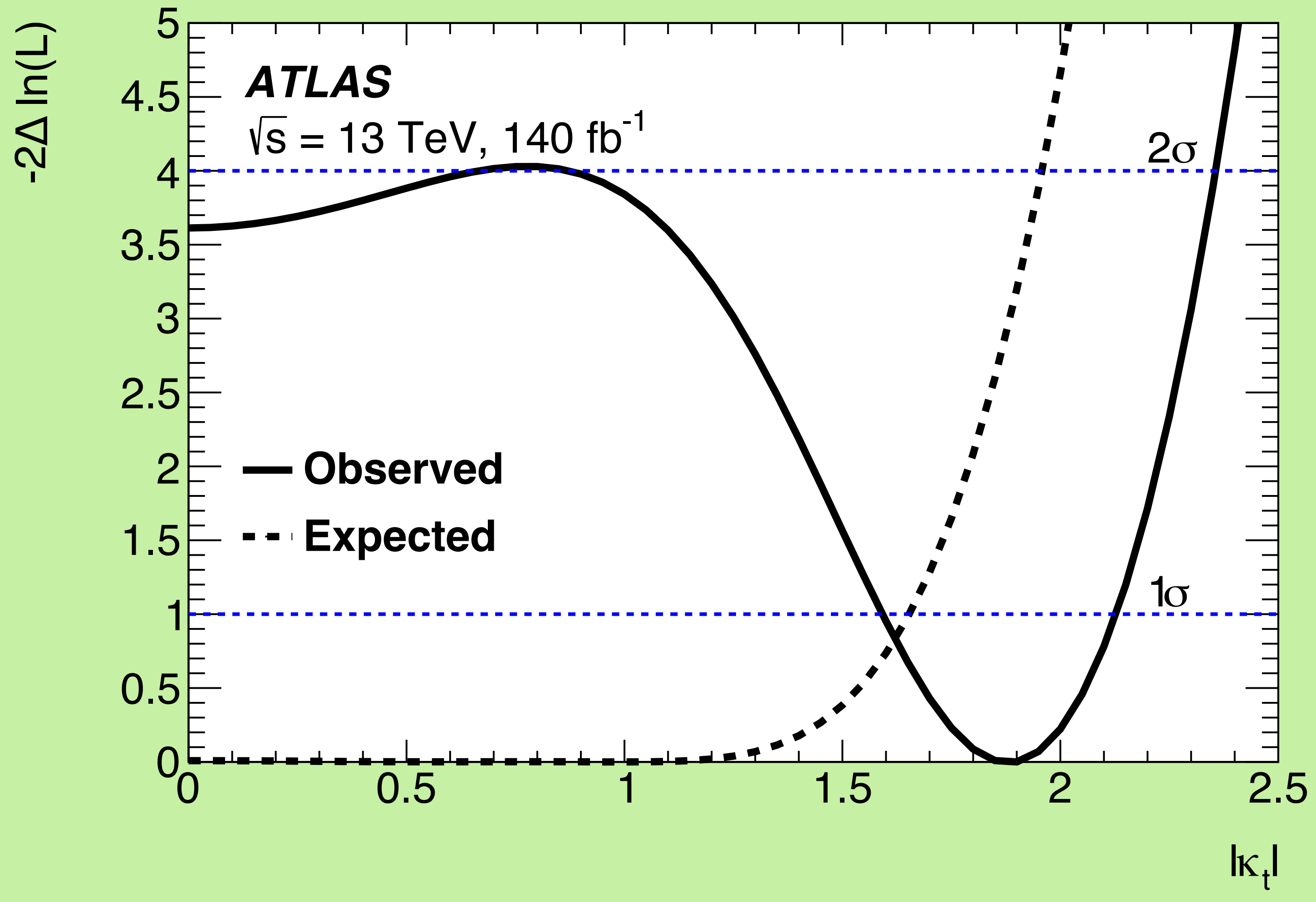


$\Gamma_H < 450\,(75)$ MeV @ 95% CL

Resolve loop κ ⤷ $\Gamma_H < 157\,(55)$ MeV

Off-shell

4-tops — multi-lepton final state



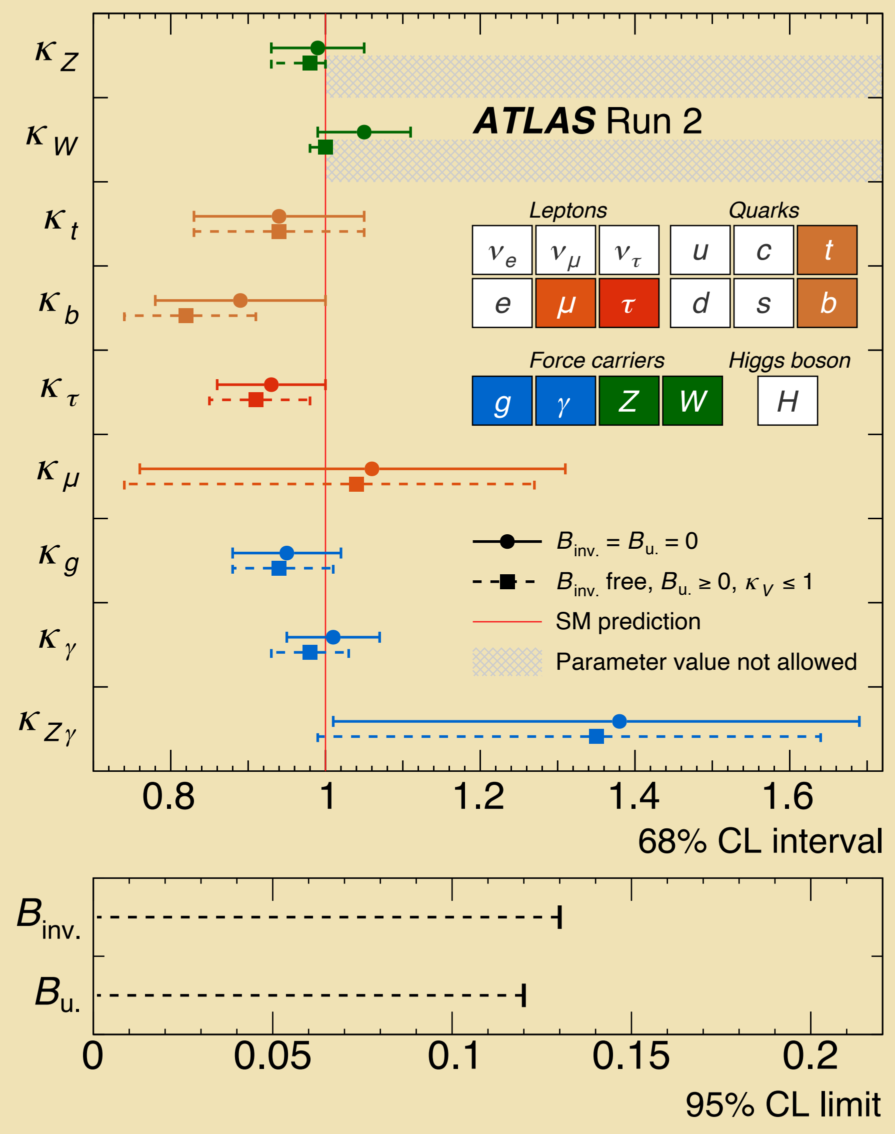
Limit obs (exp): $|\kappa_t| < 2.3(1.9)$ @ 95% CL

Eur. Phys. J. C 83 (2023) 496 / erratum — aux material

On-shell

Higgs combination model

Nature 607, 52–59 (2022)



$|\kappa_t| = 0.94 \pm 0.10$

Remove $t\bar{t}H(\to ML)$ ⤷ $|\kappa_t| = 0.86 \pm 0.13$

.CP violation and Higgs

CP structure in $H \to VV$

Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
Higgs Basis		
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

HISZ basis

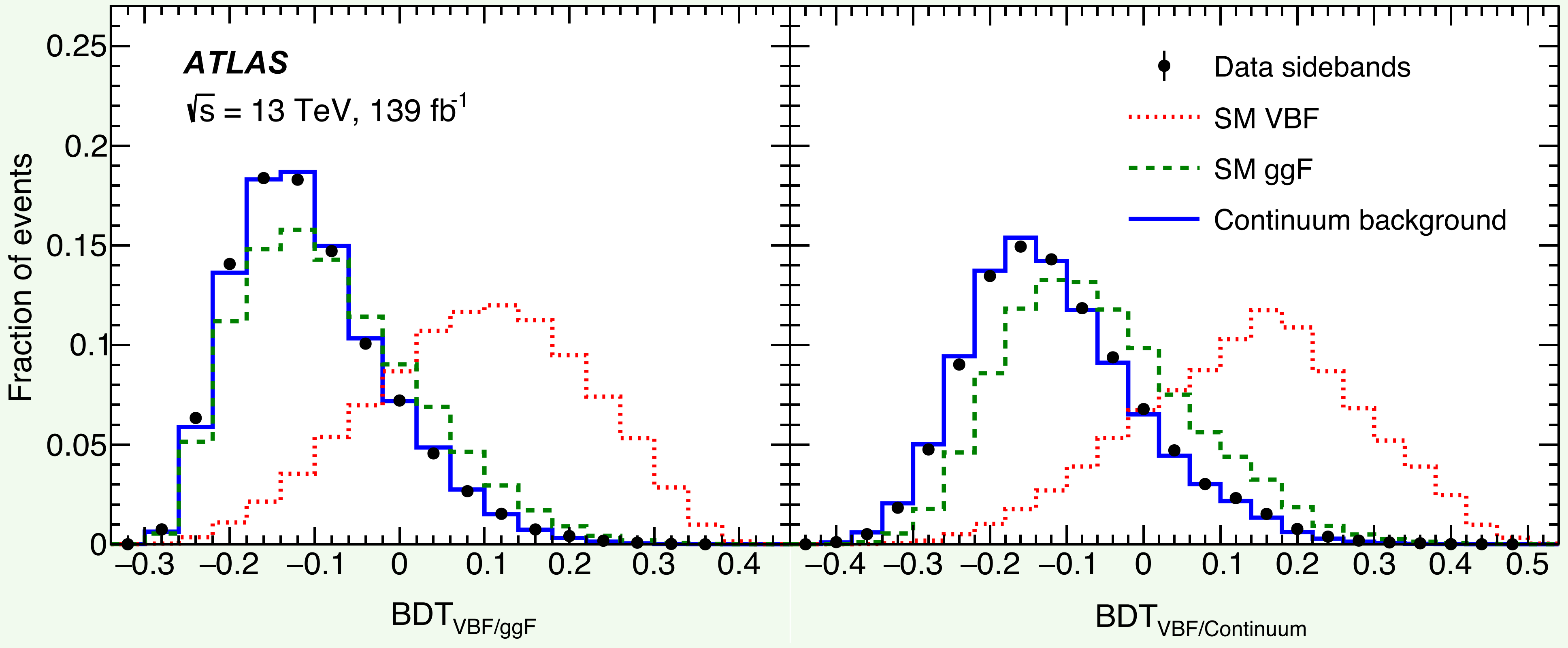
$$\tilde{d}: \quad \tilde{c}_{HW\tilde{B}} = 0, \quad \tilde{c}_{HW} = \tilde{c}_{HB\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d},$$

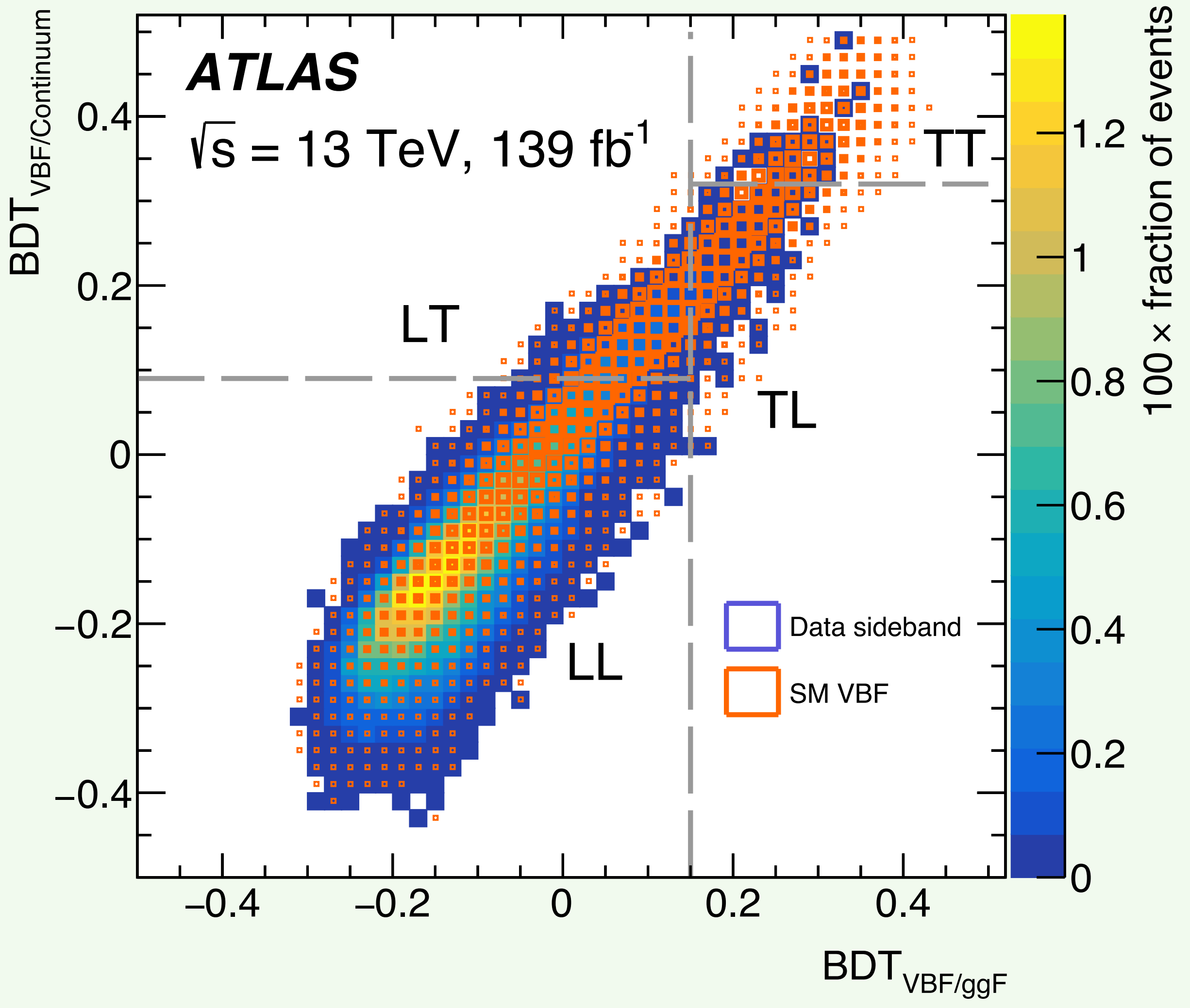
$$\tilde{c}_{Z\gamma} = 0, \quad \tilde{c}_{\gamma\gamma} = \sin^2\theta_W \cos^2\theta_W \tilde{c}_{ZZ} \propto \tilde{d}$$

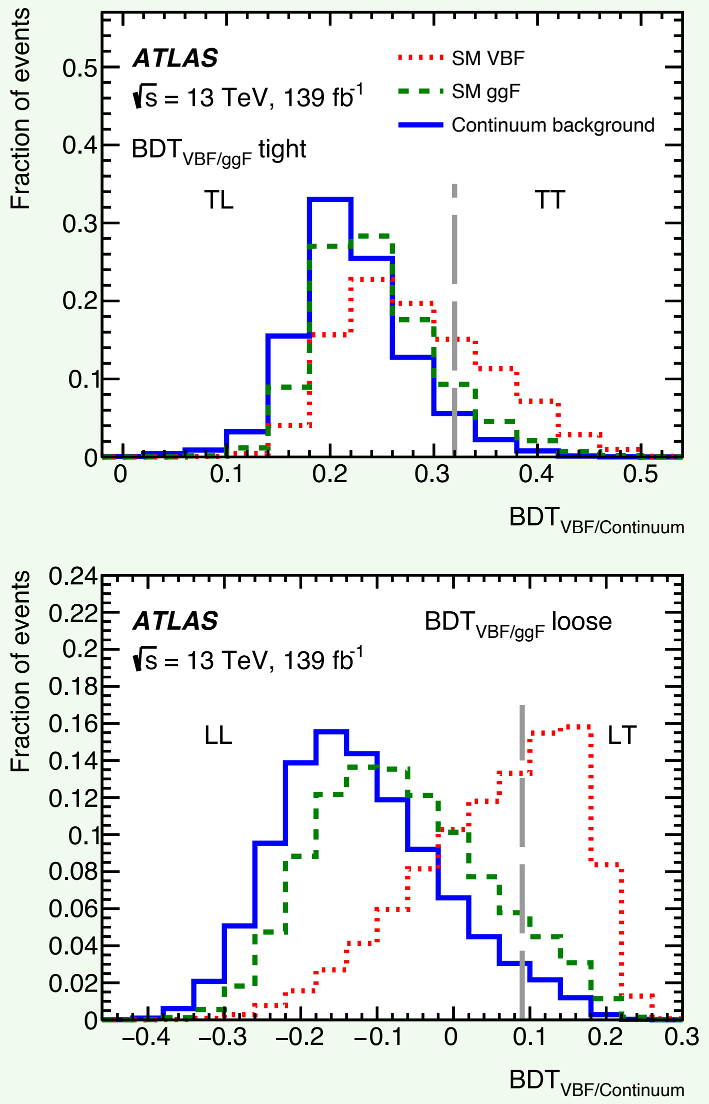
$\mathrm{VBF}\ \boldsymbol{H} \rightarrow \gamma\gamma$

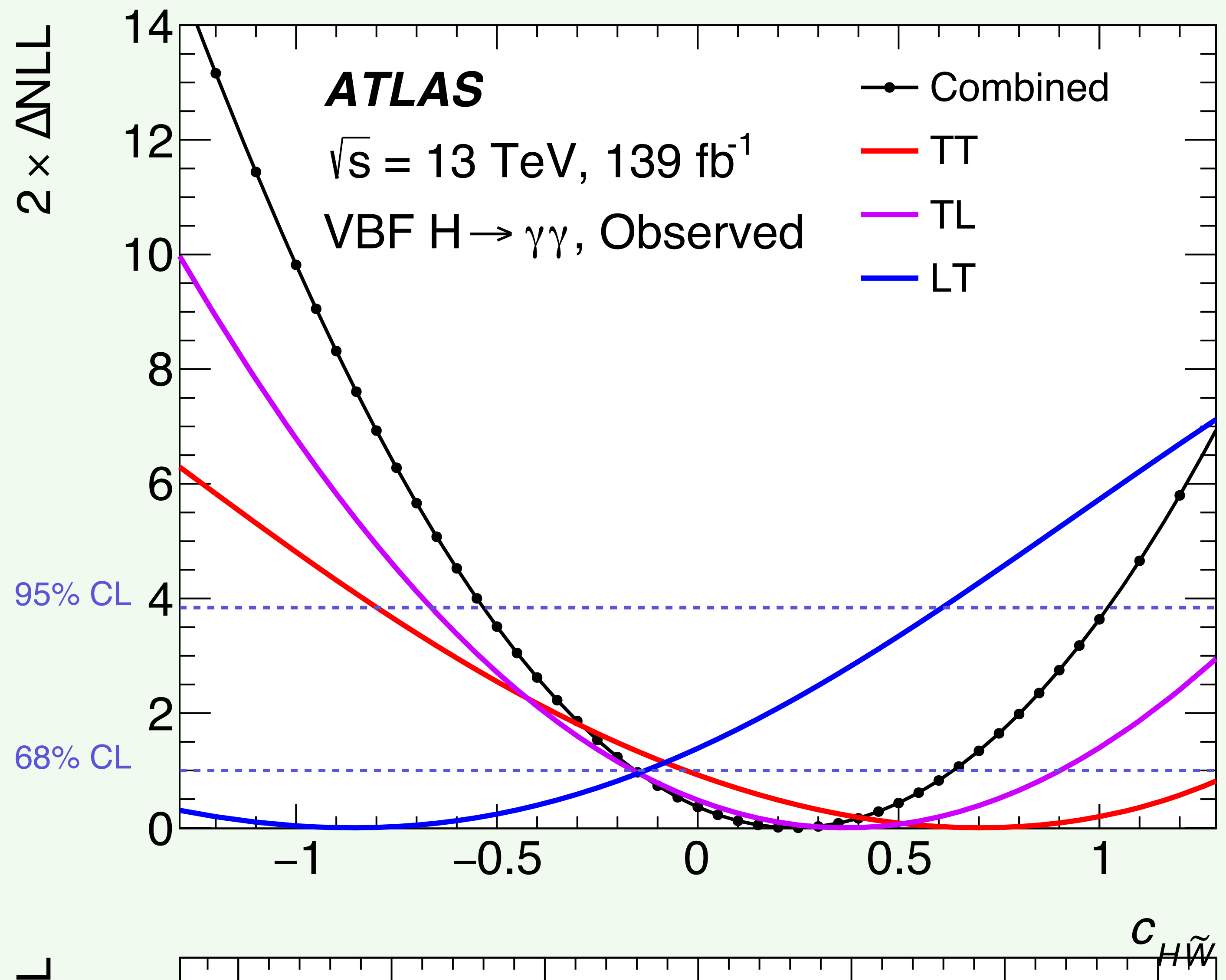
VBF $H \to \gamma\gamma$

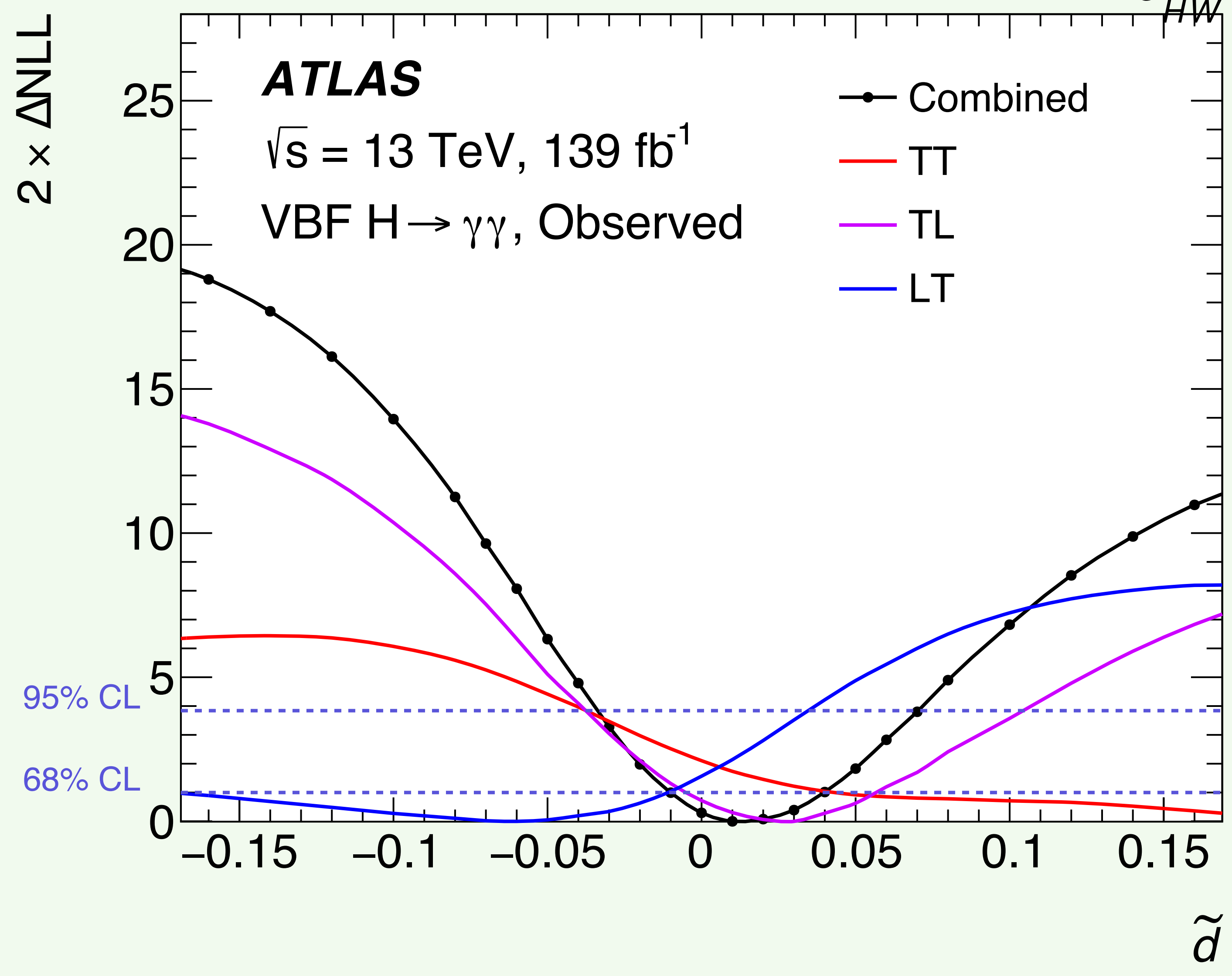
Full Run-2 (140 fb^{-1}): setup









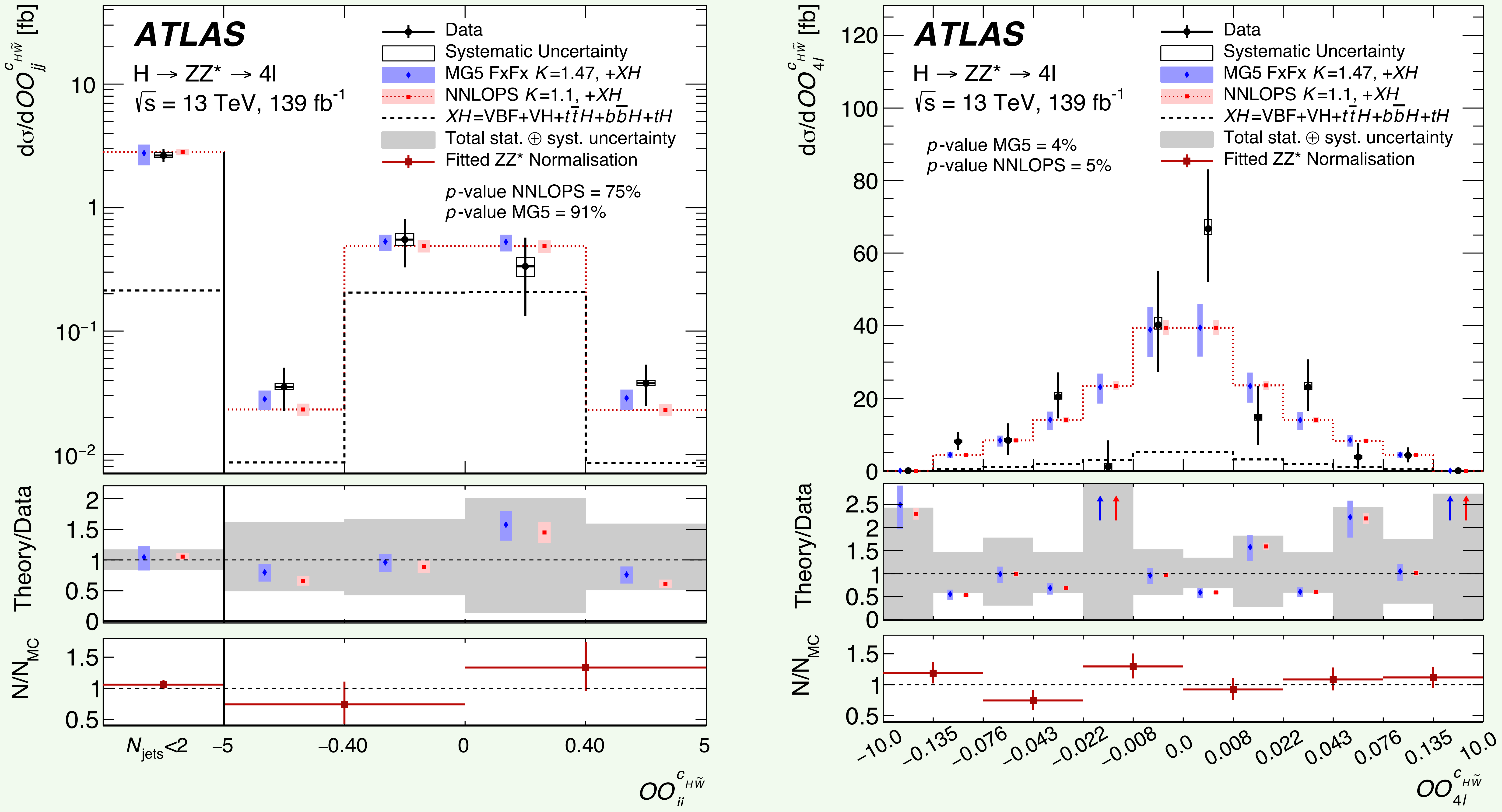


$$\text{VBF}\, \boldsymbol{H} \to ZZ^{\star} \to 4\ell$$

VBF $H \to ZZ^{\star} \to 4\ell$

Full Run-2 (140 fb^{-1}): differential measurement

JHEP 05 (2024) 105 — aux material



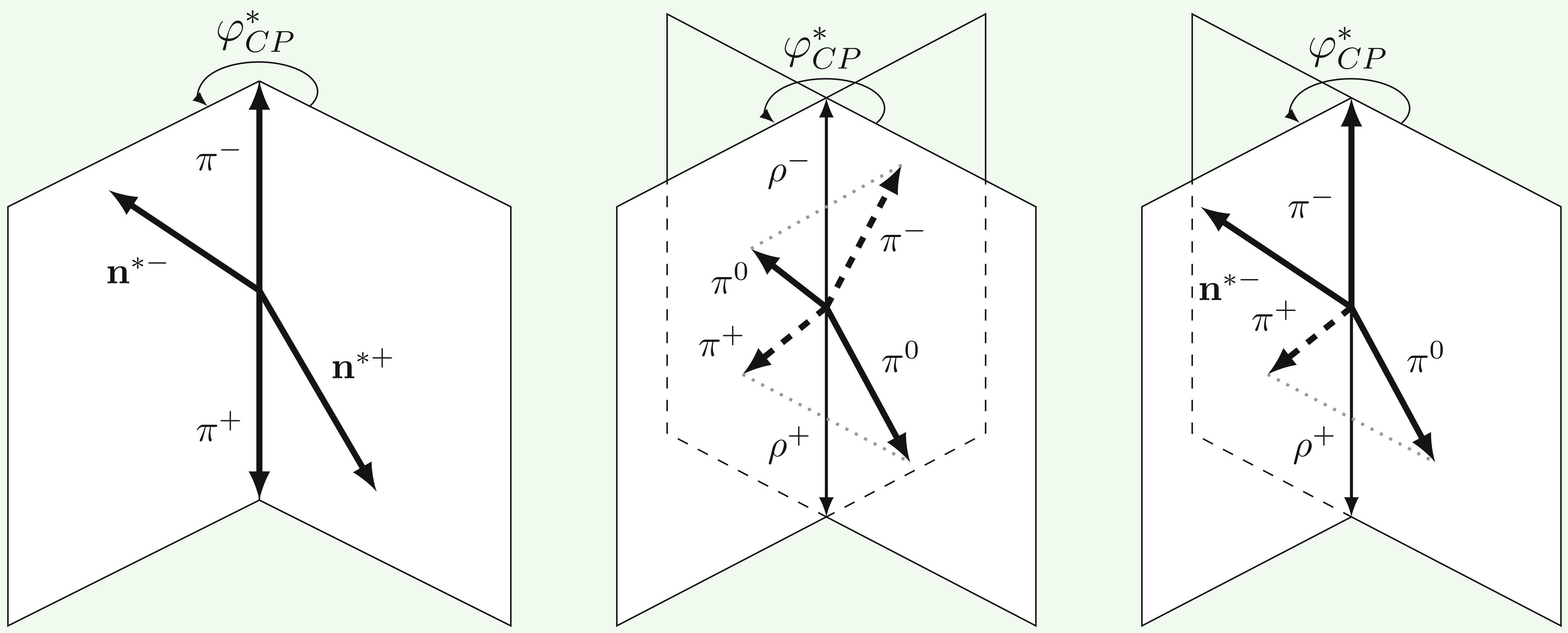
$$H \rightarrow \tau\tau$$

$H \to \tau\tau$

Full Run-2 (140 fb^{-1}): setup

Eur. Phys. J. C 83 (2023) 563 — aux material

IP-method | ρ-method | mixed



(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$ | (b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$ | (c) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$

one $\pi^\pm$ per τ | > 0 π^0 per τ | > 0 π^0 for one τ, zero for the other

$H \to \tau\tau$

Full Run-2 (140 fb^{-1}): setup

Eur. Phys. J. C 83 (2023) 563 — aux material

$$\mathrm{d}\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

Decay channel	Decay mode combination	Method	Fraction in all τ-lepton-pair decays
$\tau_{lep}\tau_{had}$	ℓ–1p0n	IP	8.1%
	ℓ–1p1n	IP–ρ	18.3%
	ℓ–1pXn	IP–ρ	7.6%
	ℓ–3p0n	IP–a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n–1p0n	IP	1.3%
	1p0n–1p1n	IP–ρ	6.0%
	1p1n–1p1n	ρ	6.7%
	1p0n–1pXn	IP–ρ	2.5%
	1p1n–1pXn	ρ	5.6%
	1p1n–3p0n	ρ–a_1	5.1%

Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{lep}\tau_{had}$	High	ℓ–1p0n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$
		ℓ–1p1n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$
	Medium	ℓ–1pXn	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{\rho}(\tau_{1pXn})\rvert > 0.1$
		ℓ–3p0n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{a_1}(\tau_{3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{had}\tau_{had}$	High	1p0n–1p0n	$\lvert d_0^{sig}(\tau_1)\rvert > 1.5$ $\lvert d_0^{sig}(\tau_2)\rvert > 1.5$
		1p0n–1p1n	$\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$ $\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$
		1p1n–1p1n	$\lvert y^{\rho}(\tau_1)y^{\rho}(\tau_2)\rvert > 0.2$
	Medium	1p0n–1pXn	$\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$ $\lvert y^{\rho}(\tau_{1pXn})\rvert > 0.1$
		1p1n–1pXn	$\lvert y^{\rho}(\tau_{1p1n})y^{\rho}(\tau_{1pXn})\rvert > 0.2$
		1p1n–3p0n	$\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$ $\lvert y^{a_1}(\tau_{3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

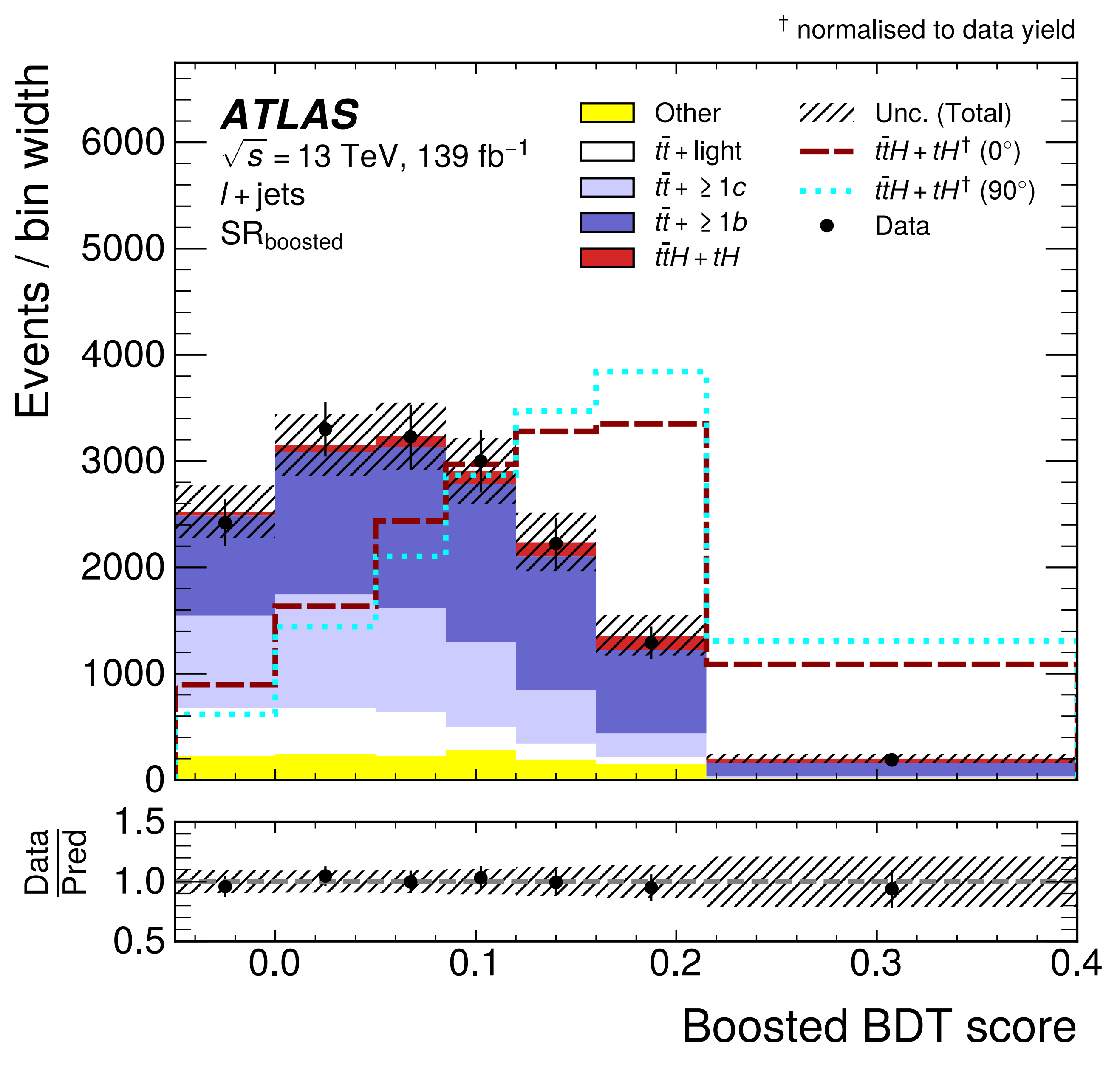
Set of nuisance parameters	Impact on ϕ_τ [degrees]
Jet energy scale	3.4
Jet energy resolution	2.5
Pile-up jet tagging	0.5
Jet flavour tagging	0.2
E_T^{miss}	0.4
Electron	0.3
Muon	0.9
τ_{had} reconstruction	1.0
Misidentified τ	0.6
τ_{had} decay mode classification	0.3
π^0 angular resolution and energy scale	0.2
Track ($\pi^\pm$, impact parameter)	0.7
Luminosity	0.1
Theory uncertainty in $H \to \tau\tau$ processes	1.5
Theory uncertainty in $Z \to \tau\tau$ processes	1.1
Simulated background sample statistics	1.4
Signal normalisation	1.4
Background normalisation	0.6
Total systematic uncertainty	5.2
Data sample statistics	15.6
Total	16.4

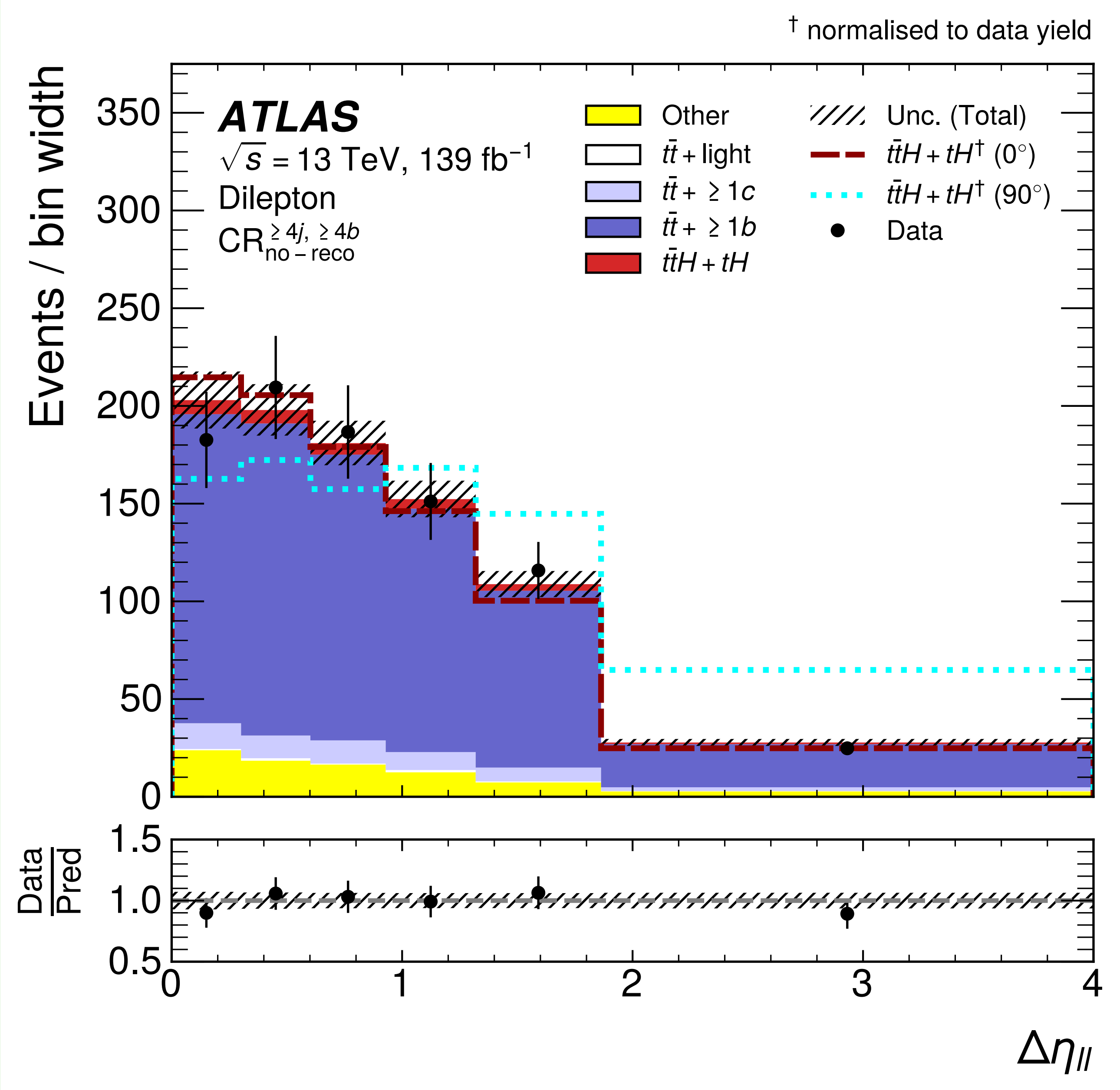
$H \to bb$ in $t\bar{t}H$ and tHq

$t\bar{t}H(\to b\bar{b})$ and $tH(\to b\bar{b})q$

Full Run-2 (140 fb^{-1}): setup

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\text{TR}^{\geq 4j,\geq 4b}$)	$\text{CR}^{\geq 4j,\geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	$\text{CR}^{\geq 4j,\geq 4b}$	$\text{BDT}^{\geq 4j,\geq 4b} \in [-1, -0.086)$	b_4
	$\text{SR}^{\geq 4j,\geq 4b}_1$	$\text{BDT}^{\geq 4j,\geq 4b} \in [-0.086, 0.186)$	b_4
	$\text{SR}^{\geq 4j,\geq 4b}_2$	$\text{BDT}^{\geq 4j,\geq 4b} \in [0.186, 1]$	b_4
ℓ+jets ($\text{TR}^{\geq 6j,\geq 4b}$)	$\text{CR}^{\geq 6j,\geq 4b}_1$	$\text{BDT}^{\geq 6j,\geq 4b} \in [-1, -0.128)$	b_2
	$\text{CR}^{\geq 6j,\geq 4b}_2$	$\text{BDT}^{\geq 6j,\geq 4b} \in [-0.128, 0.249)$	b_2
	$\text{SR}^{\geq 6j,\geq 4b}$	$\text{BDT}^{\geq 6j,\geq 4b} \in [0.249, 1]$	b_2
ℓ+jets ($\text{TR}_{\text{boosted}}$)	$\text{SR}_{\text{boosted}}$	$\text{BDT}^{\text{boosted}} \in [-0.05, 1]$	$\text{BDT}^{\text{boosted}}$





Uncertainty source	$\Delta\alpha\,[°]$	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+23	-37
$t\bar{t}+\geq 1b$ NLO matching	+22	-33
$t\bar{t}+\geq 1b$ fractions	+14	-21
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+16	-24
$t\bar{t}+\geq 1b$ $p_{\text{T}}^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t}+\geq 1b$ ISR	+14	-24
$t\bar{t}+\geq 1c$ modelling	+6.6	-11
$t\bar{t}$ + light modelling	+2.5	-4.7
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+8.7	-15
c-mis-tag rates	+6.7	-11
l-mis-tag rates	+2.3	-2.7
Jet energy scale and resolution		
b-jet energy scale	+1.6	-3.8
Jet energy scale (flavour)	+7.8	-11
Jet energy scale (pileup)	+5.2	-7.9
Jet energy scale (remaining)	+8.1	-13
Jet energy resolution	+5.7	-9.3
Luminosity	$\leq \pm 1$	
Other sources	+4.9	-8
Total systematic uncertainty	+41	-54
$t\bar{t}+\geq 1b$ normalisation	+8.2	-13
κ_t'	+17	-33
Total statistical uncertainty	+32	-49
Total uncertainty	+52	-73

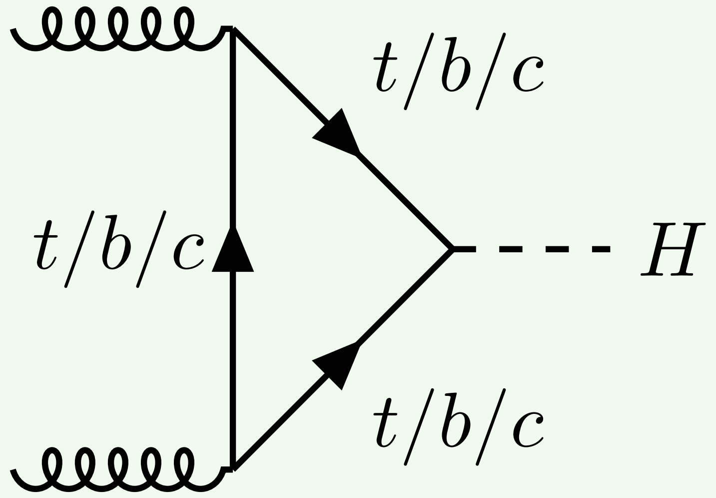
Backup

Overview

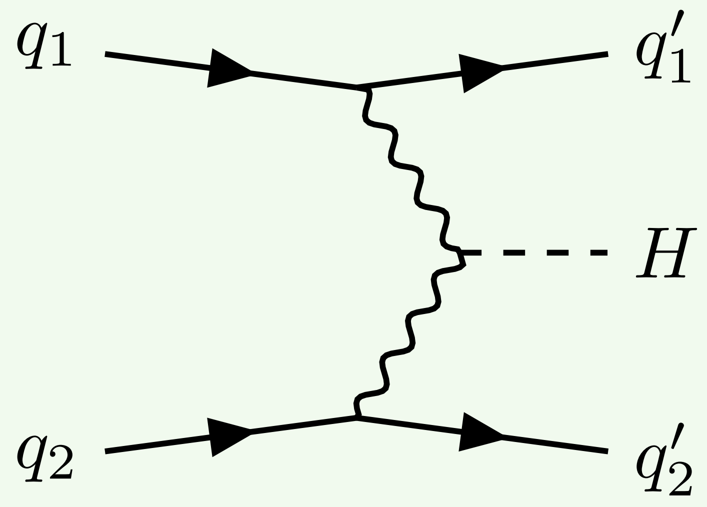
How we get Higgs and how we lose it

Production

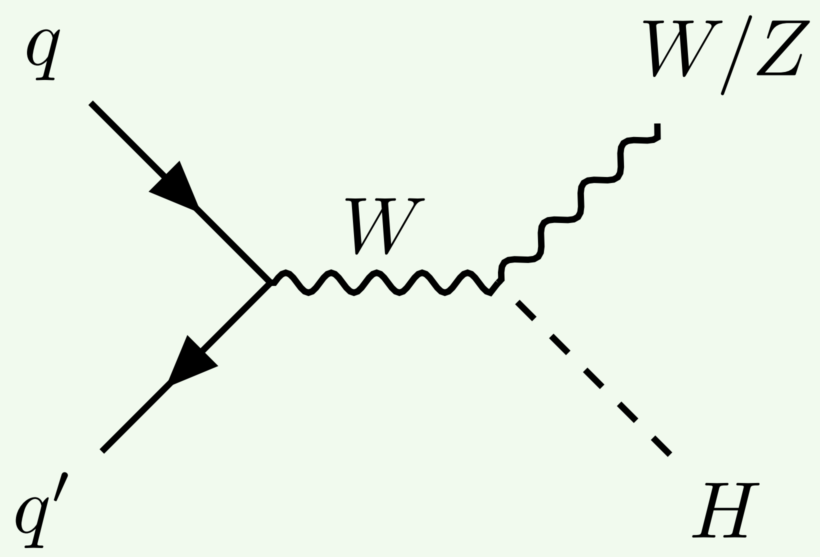
Cross-sections from LHCWG at 13 TeV for $m_H = 125$ GeV



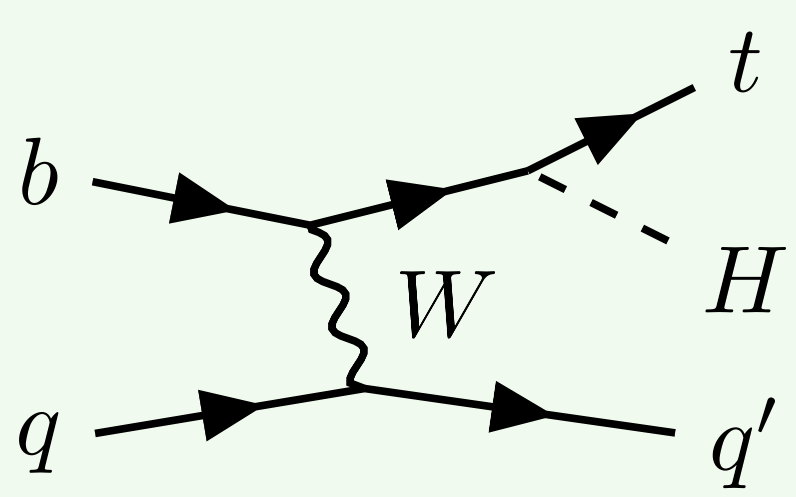
ggF ($\sigma = 48.6$ pb)



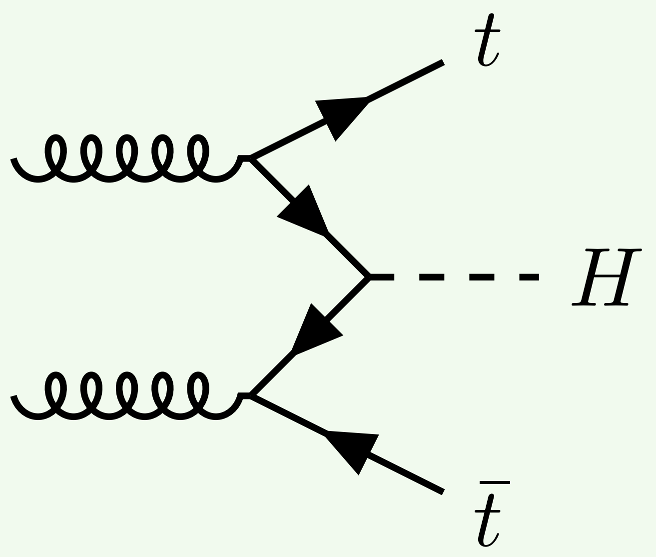
VBF ($\sigma = 3.93$ pb)



VH ($\sigma = 2.26$ pb)

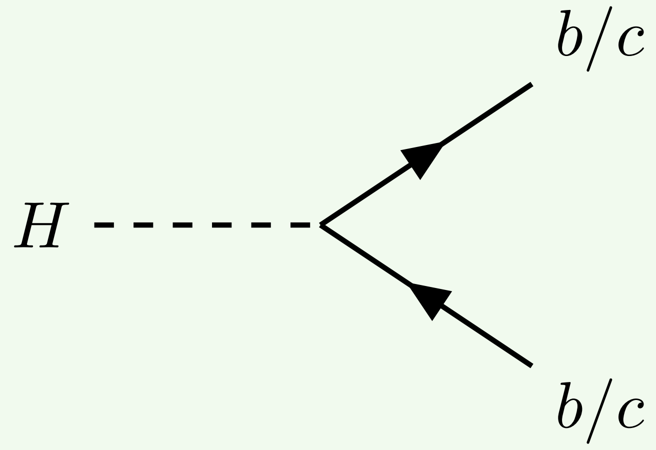


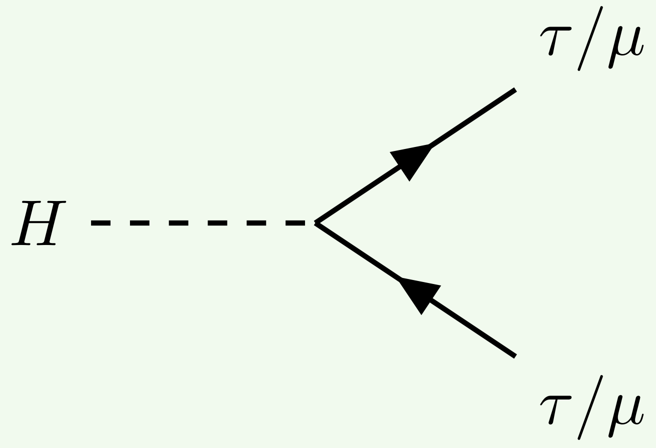
tHq ($\sigma = 0.077$ pb)

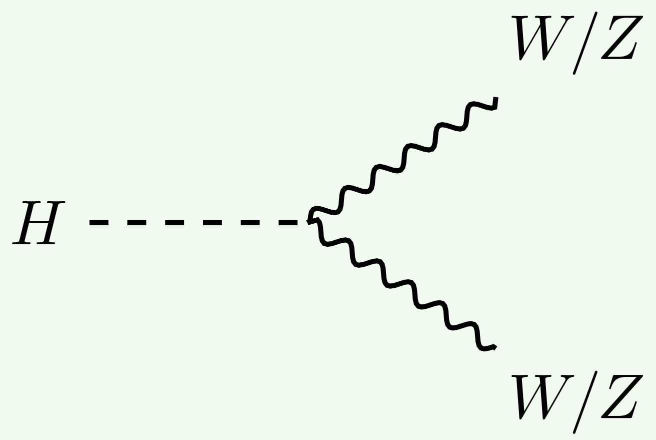


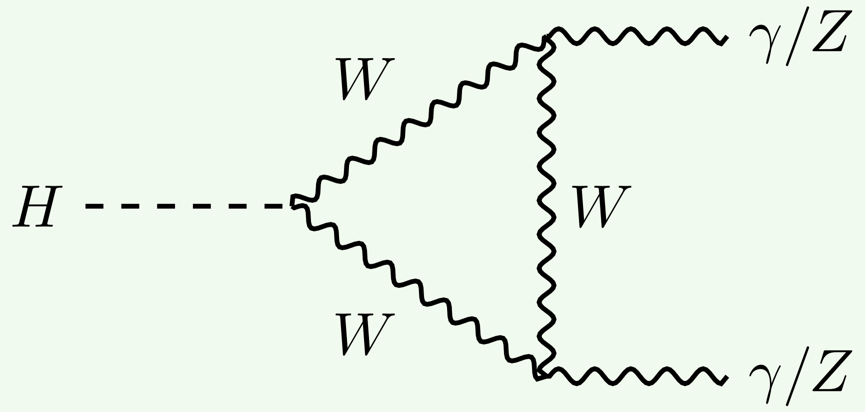
$t\bar{t}H$ ($\sigma = 0.50$ pb)

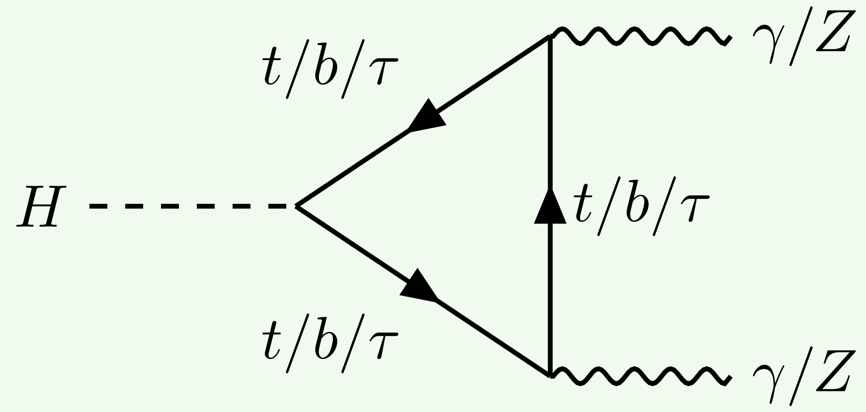
Decay









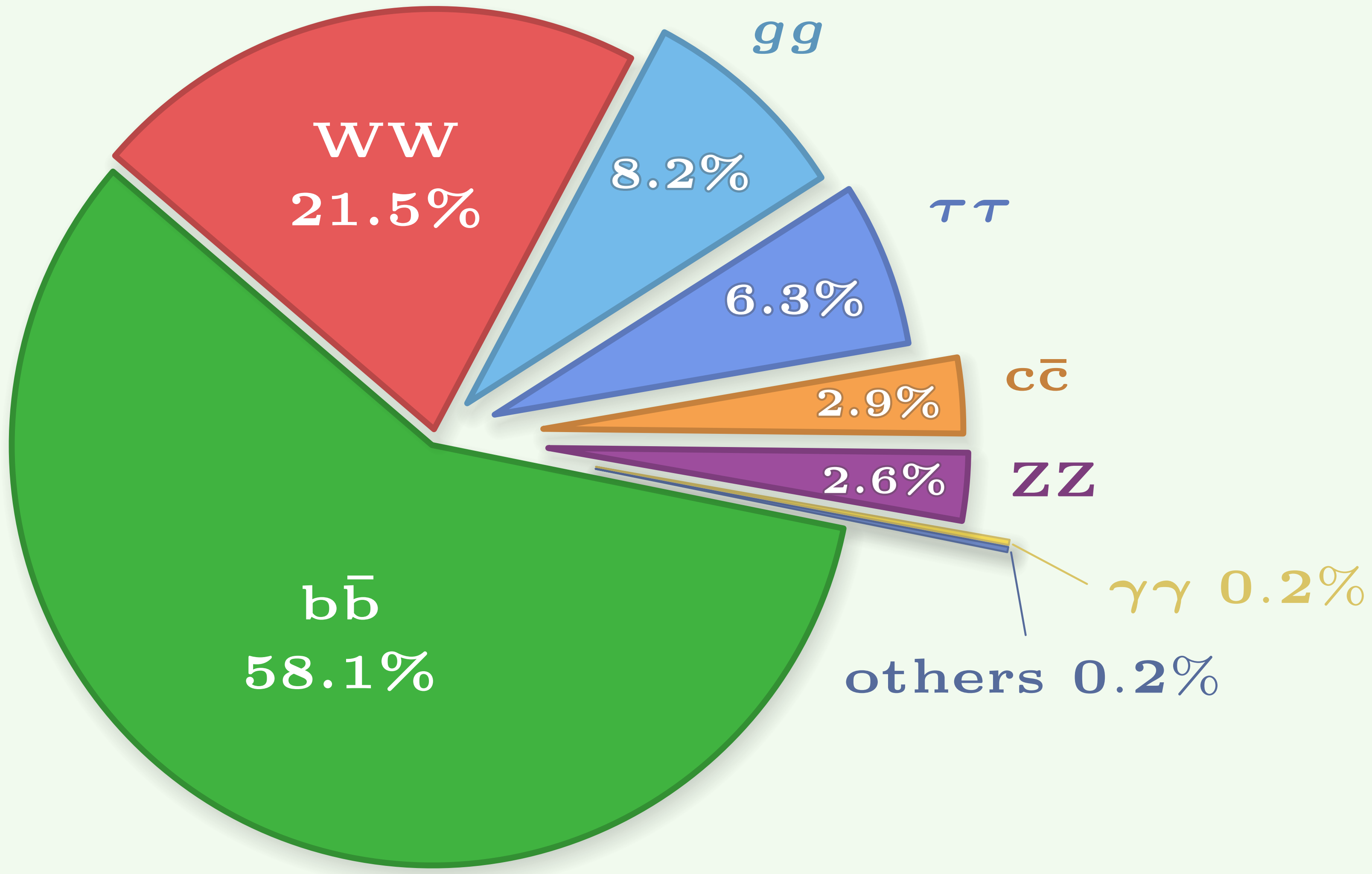


.Higgs mass

Choices to be made

The Higgs mass: decay channels

Higgs mass = invariant mass of decay products



$H \rightarrow$ bb/cc/gg

- Difficult to reconstruct hadronic final states with high resolution

$H \rightarrow$ WW/$\tau\tau$

- Neutrinos in final-state are invisible

$H \rightarrow \mu\mu/ee/Z\gamma$

- Low branching ratios, large backgrounds

$H \rightarrow ZZ/\gamma\gamma$

- Manageable backgrounds
- *Easy* reconstruction

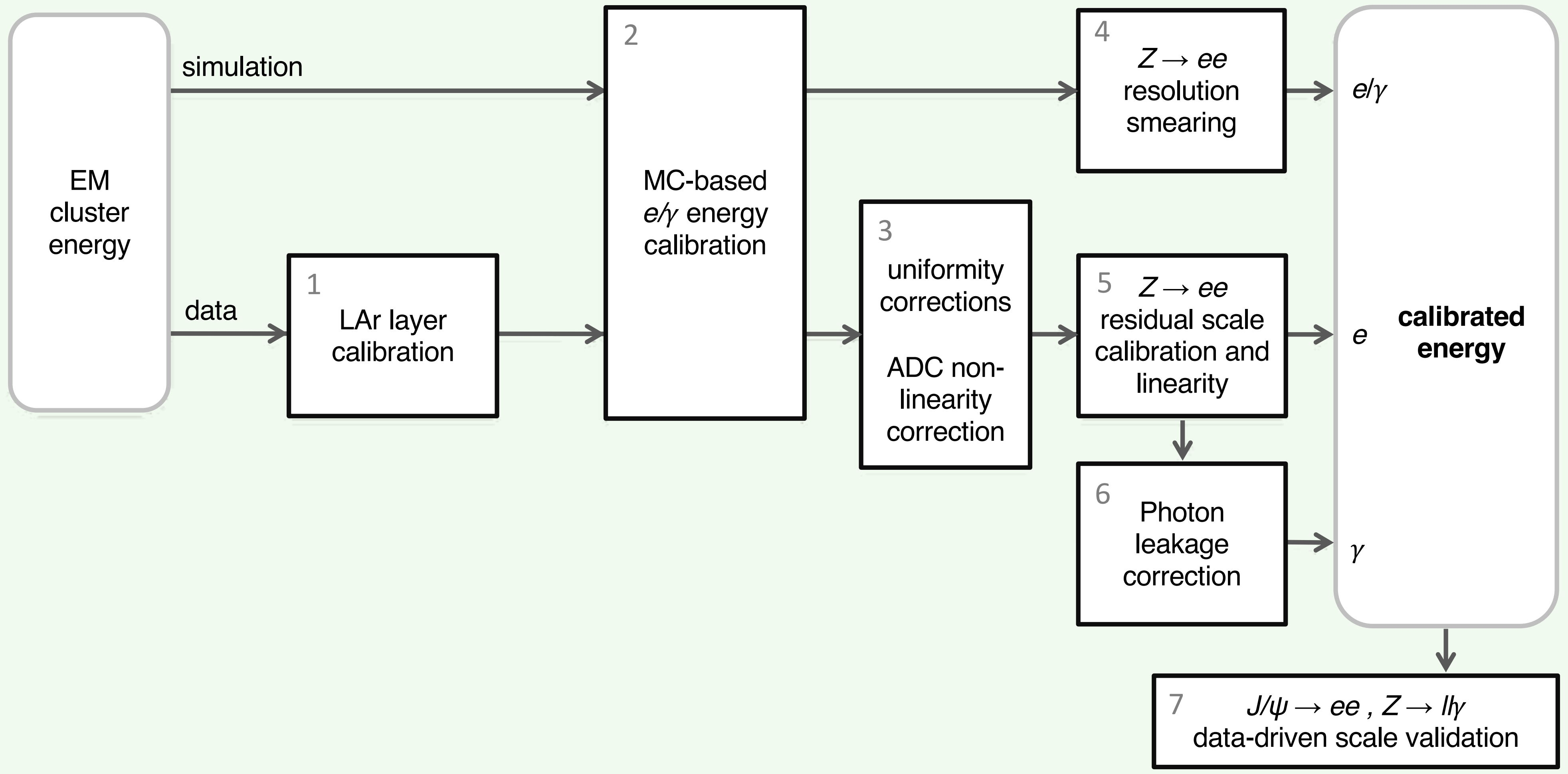
$$H \to \gamma\gamma$$

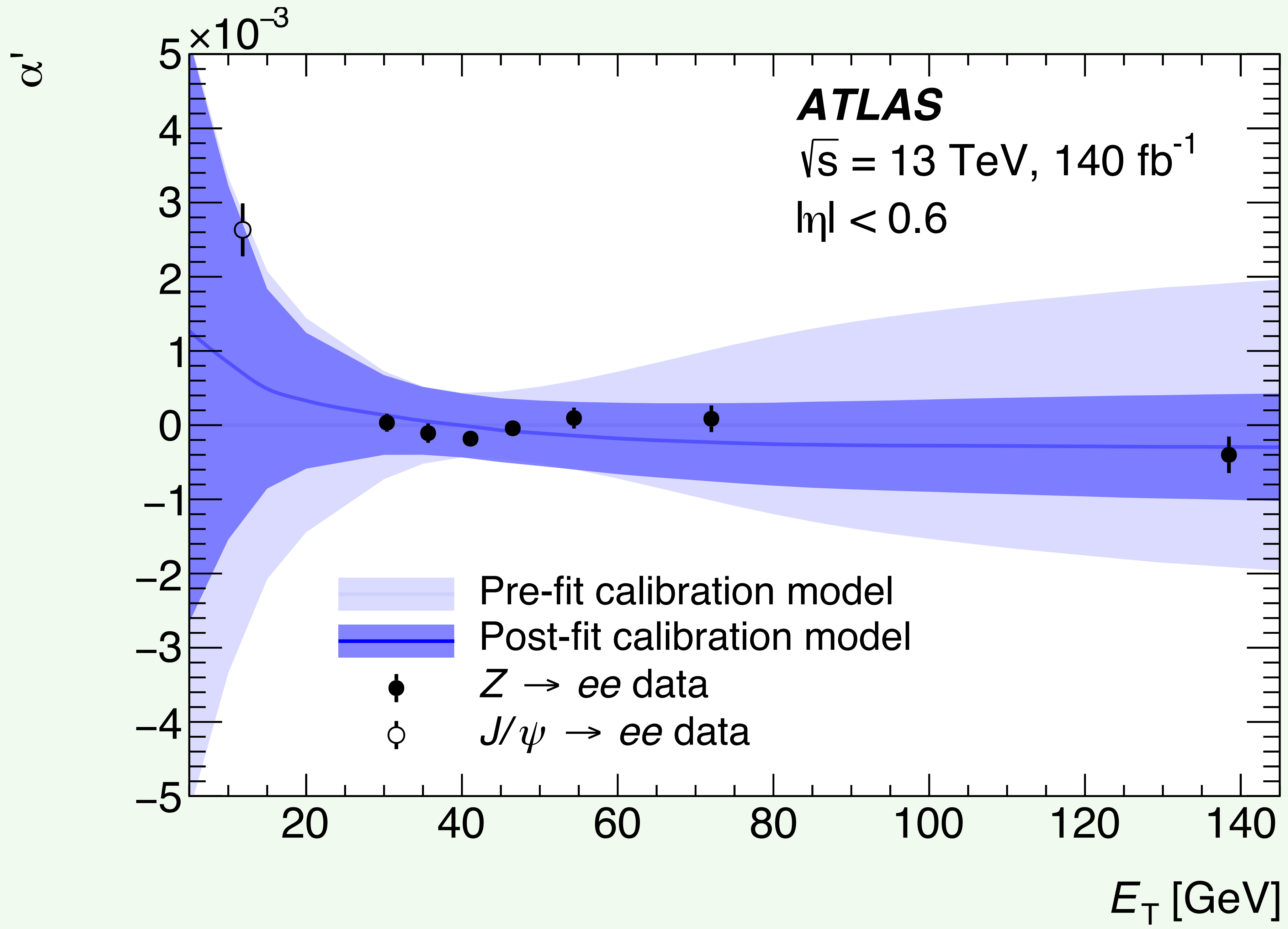
Mass with $H \to \gamma\gamma$

Photon energy scale improvement

JINST 19 (2024) P02009

- The photon energy scale measurement combines has improved:
  - Material modelling → 3x better
  - On-detector electronics non-linearity modelling → 2x better
  - Electron-to-photon scale extrapolation → 2x better
- $Z \to ee$ calibration scale-factors parameterised in p_T and η





$$H \to ZZ$$

Mass with $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): misc

Phys. Lett. B 843 (2023) 137880

$$\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i \mid m_H) = \mathcal{P}(m_{4\ell} \mid D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} \mid \sigma_i, m_H) \cdot \mathcal{P}(\sigma_i \mid m_H)$$
$$\simeq \mathcal{P}(m_{4\ell} \mid D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} \mid m_H)$$

Crystal-ball

Gaussian core parametrised for a channel λ with $a^\lambda \cdot (m_H - 125\,\text{GeV}) + b^\lambda(D_{NN})$, b^λ is 2^{nd} order poly. $a^\lambda \approx 1$ Determined from separate ML fit

Core stdev expressed as function of σ_i and parametrised as function of DNN

NN independent of m_h

Determined by interpolation across neighbouring simulated mass points

Neglected because it's same for signal and background around mass peak

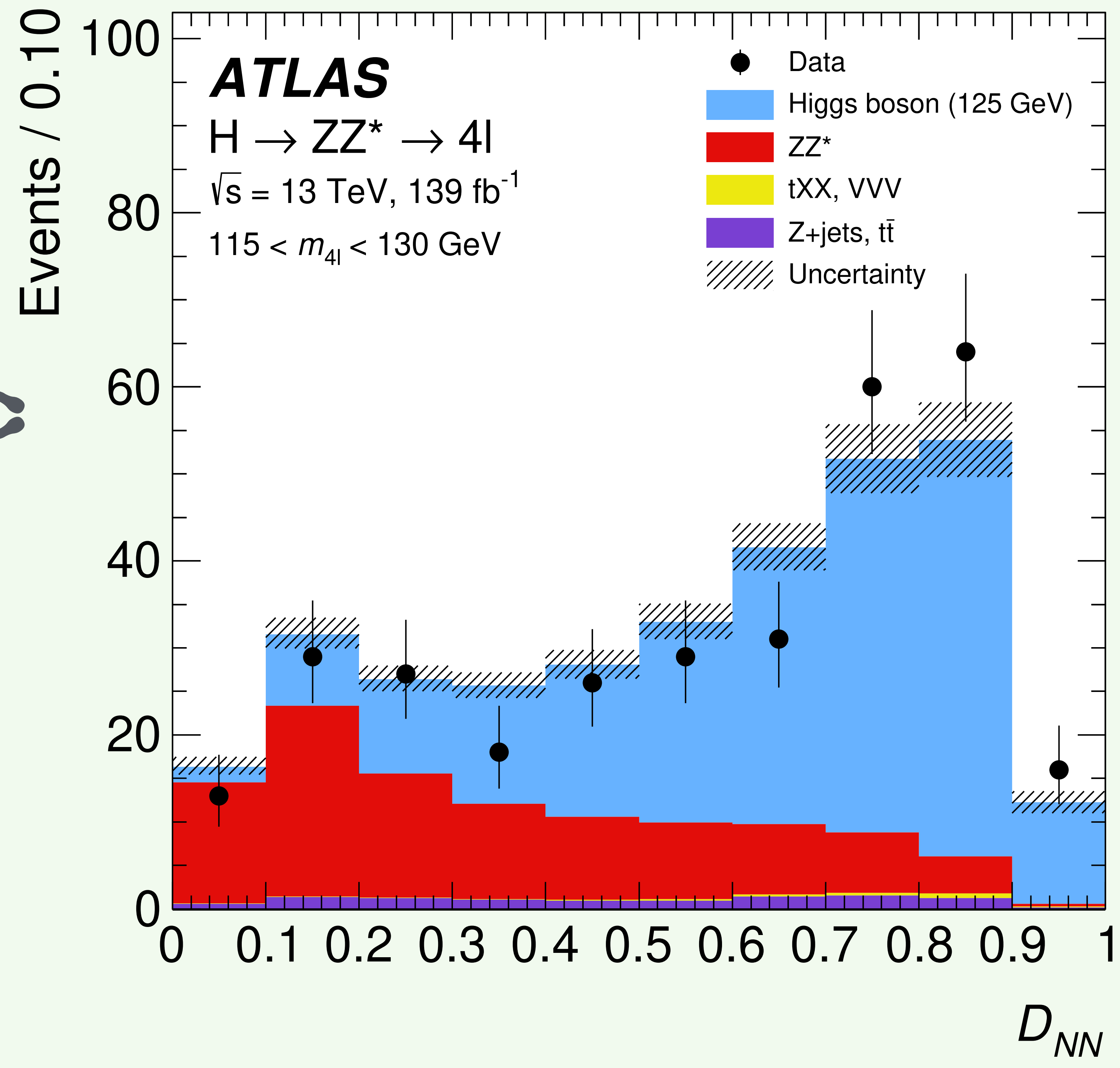
Mass with $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): misc

Phys. Lett. B 843 (2023) 137880

Four-lepton kinematics

$$\ln\left(\frac{|\mathcal{M}_{HZZ^*}|^2}{|\mathcal{M}_{ZZ^*}|^2}\right)$$



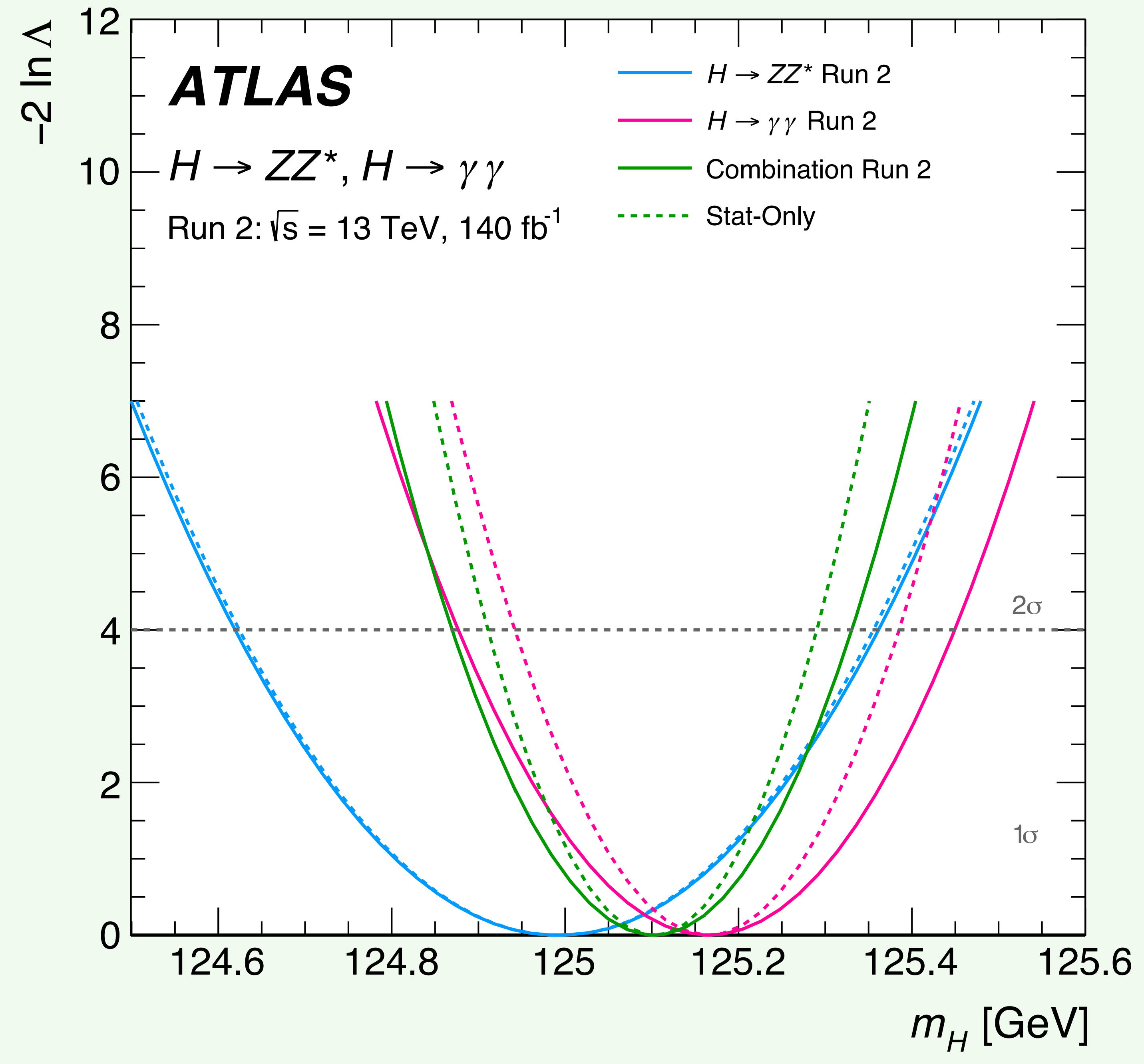
Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

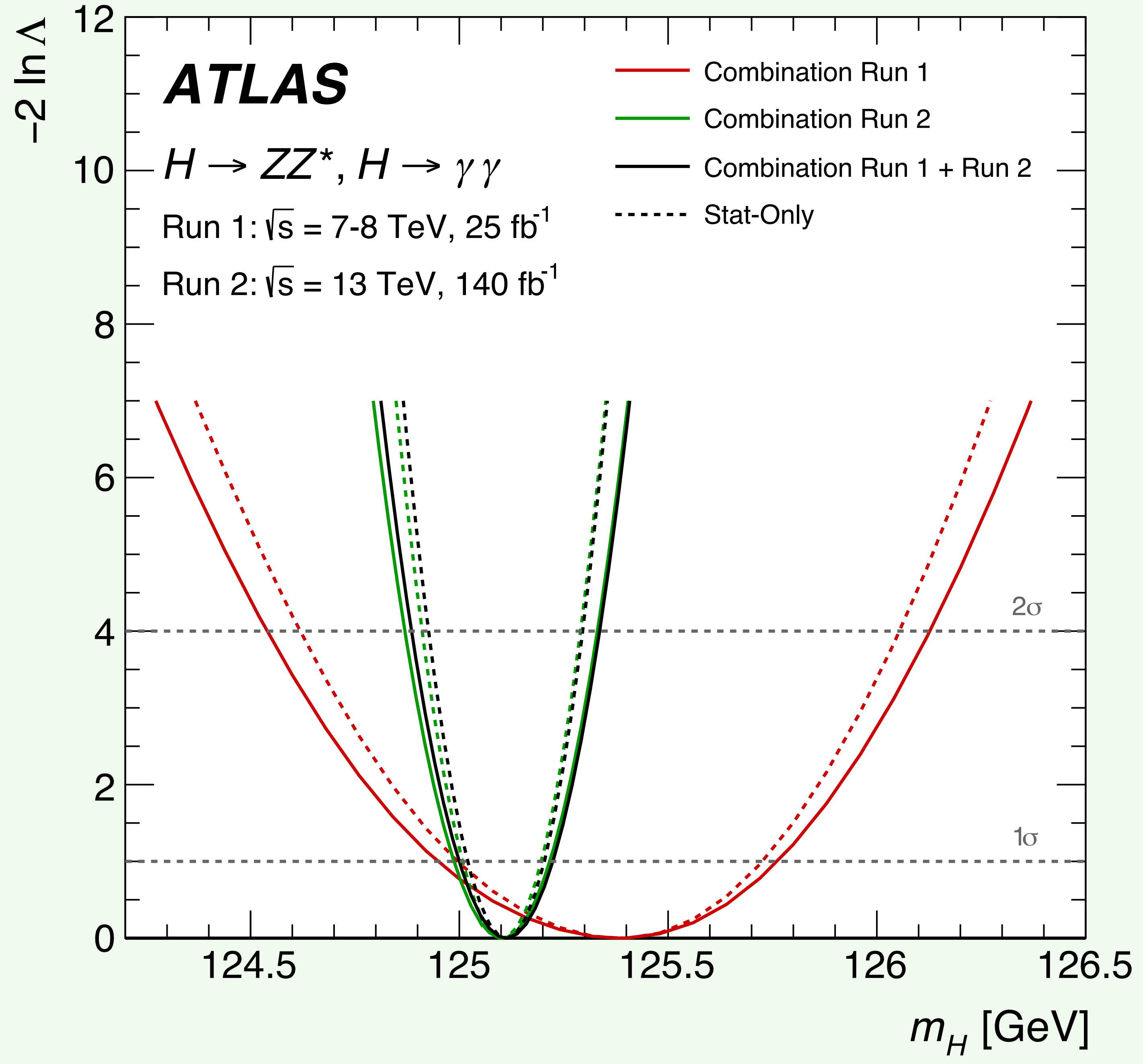
Combination

Mass with ATLAS

Combined results with full Run-2 data: misc

Phys. Lett. B 131 (2023) 251802 — aux material





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

.Higgs width

$$H^\star \to ZZ \text{ and } H \to ZZ^\star$$

VBF $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): misc.

JHEP 05 (2024) 105 — aux material

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2},$$

$$\begin{aligned}
&\nu^{\text{ggF}}(\mu^{\text{ggF}}_{\text{off-shell}}, \boldsymbol{\theta}) \\
&\quad = \mu^{\text{ggF}}_{\text{off-shell}} \cdot n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) \\
&\qquad + \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}} \cdot (n^{\text{ggF}}_{\text{SBI}}(\boldsymbol{\theta}) - n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) - n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta})) + n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta}) \\
&\quad = (\mu^{\text{ggF}}_{\text{off-shell}} - \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}}) \cdot n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) \\
&\qquad + \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}} \cdot n^{\text{ggF}}_{\text{SBI}}(\boldsymbol{\theta}) + (1 - \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}}) \cdot n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta})
\end{aligned}$$

Systematic Uncertainty Fixed	$\mu_{\text{off-shell}}$ value at which $-2\ln\lambda(\mu_{\text{off-shell}}) = 4$
Parton shower uncertainty for $gg \to ZZ$ (normalisation)	2.26
Parton shower uncertainty for $gg \to ZZ$ (shape)	2.29
NLO EW uncertainty for $qq \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $qq \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

$$H^{\star} \rightarrow t\bar{t} \text{ and } t\bar{t}H$$

Multi-top united for width

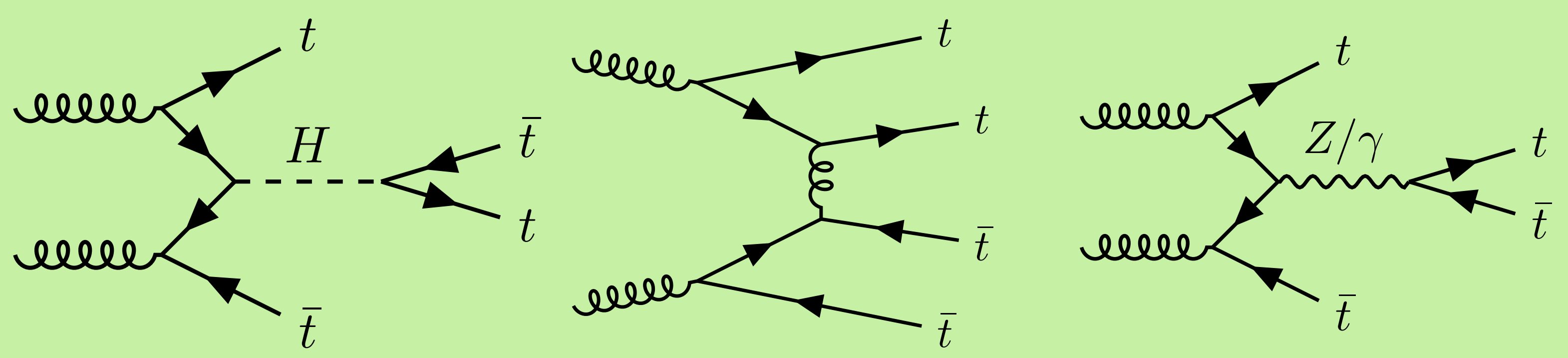
The idea

Phys. Rev. D 99, 113003 (theory)

arXiv:2407.10631 — **submitted to PLB**

Off-shell

4-tops

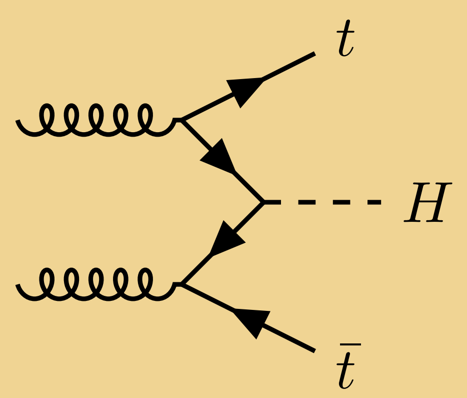


$$\mu_{t\bar{t}t\bar{t}} = A + B\kappa_t^2 + C\kappa_t^4$$

$g + Z/\gamma$ — interference — Higgs

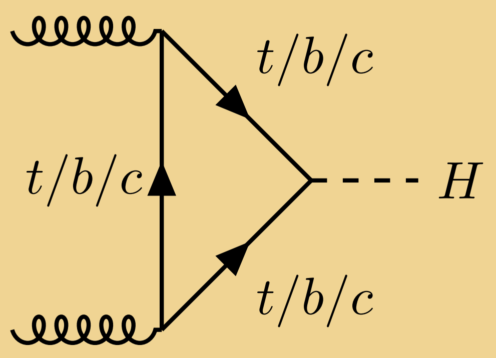
On-shell

$t\bar{t}H$



$\propto \kappa_t^2/\Gamma^2$

$gg \rightarrow H$



$\propto \kappa_g^2(\kappa_t, \kappa_V)/\Gamma^2$

Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \rightarrow \gamma\gamma$
$t\bar{t}H + tH$	$H \rightarrow b\bar{b}$
WH, ZH	$H \rightarrow b\bar{b}$
VBF	$H \rightarrow b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow ZZ$
ggF, VBF	$H \rightarrow WW$
WH, ZH	$H \rightarrow WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \rightarrow \mu\mu$
Inclusive	$H \rightarrow Z\gamma$

$$\propto \kappa_i^2(\kappa_t, \kappa_V)\kappa_f^2(\kappa_t, \kappa_V)/\Gamma^2$$

Combination

- Aggregate statistical model from all ATLAS Higgs measurements
  - Except $t\bar{t}H(\rightarrow$ leptons)
- Perform a fit using the aggregated model
- Free-float:
  - tree-level κ (e.g. $\kappa_t, \kappa_b, \ldots$)
  - effective loop κ (e.g. $\kappa_g, \kappa_\gamma, \ldots$)
- Allow Higgs width to float for all models

Multi-top united for width

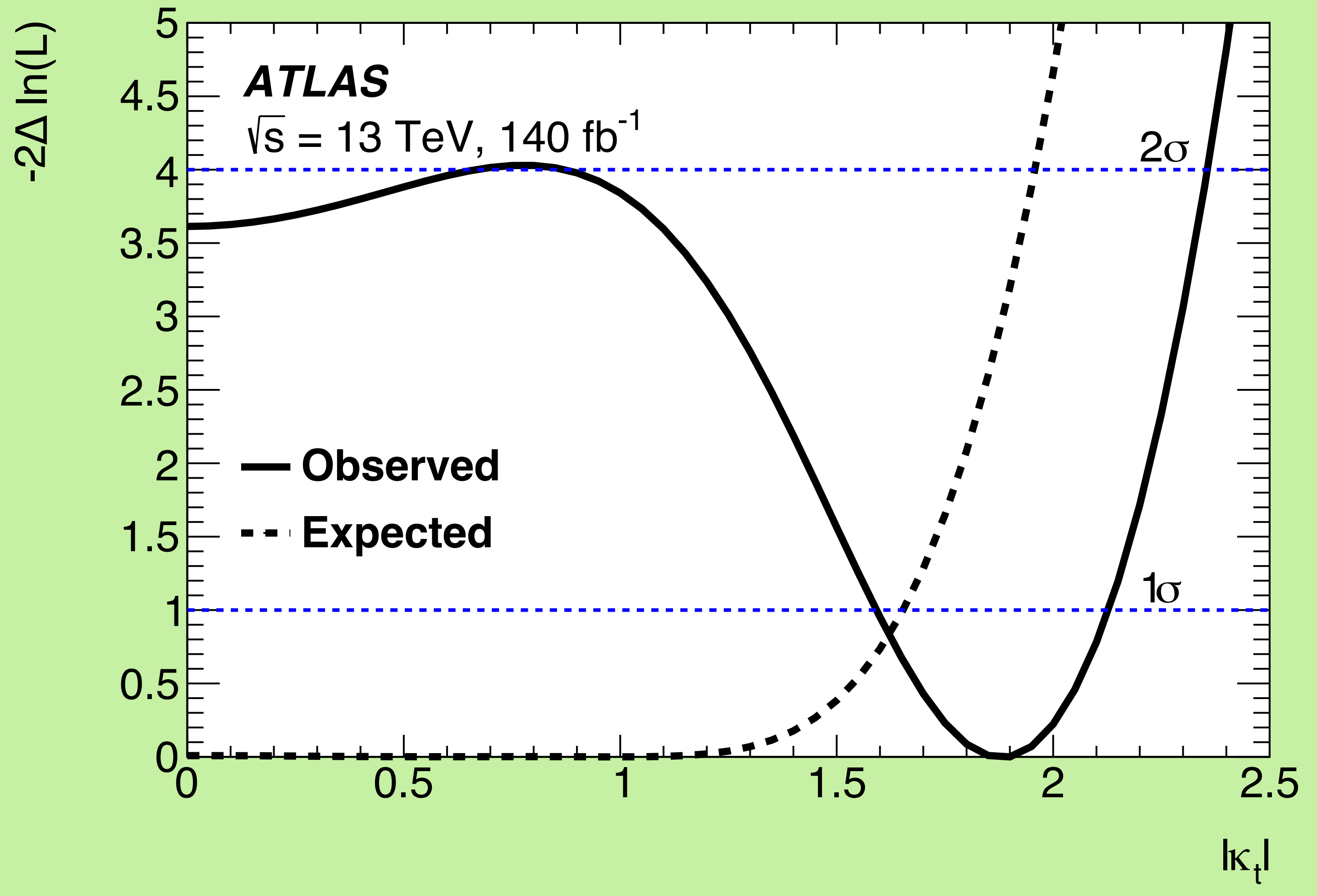
The result

Phys. Rev. D 99, 113003 (theory)

arXiv:2407.10631 — **submitted to PLB**

Off-shell

4-tops — multi-lepton final state



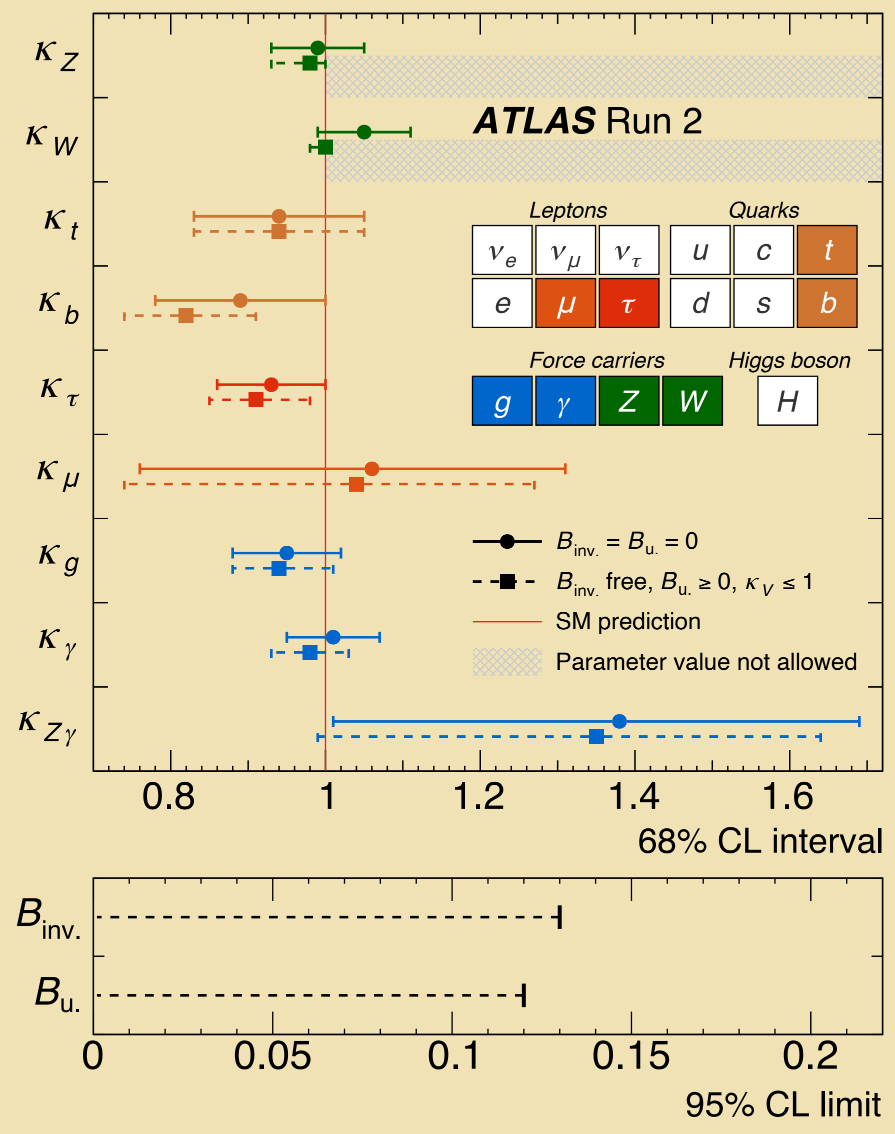
Limit obs (exp): $|\kappa_t| < 2.3(1.9)$ @ 95% CL

Eur. Phys. J. C 83 (2023) 496 / erratum — aux material

On-shell

Higgs combination model

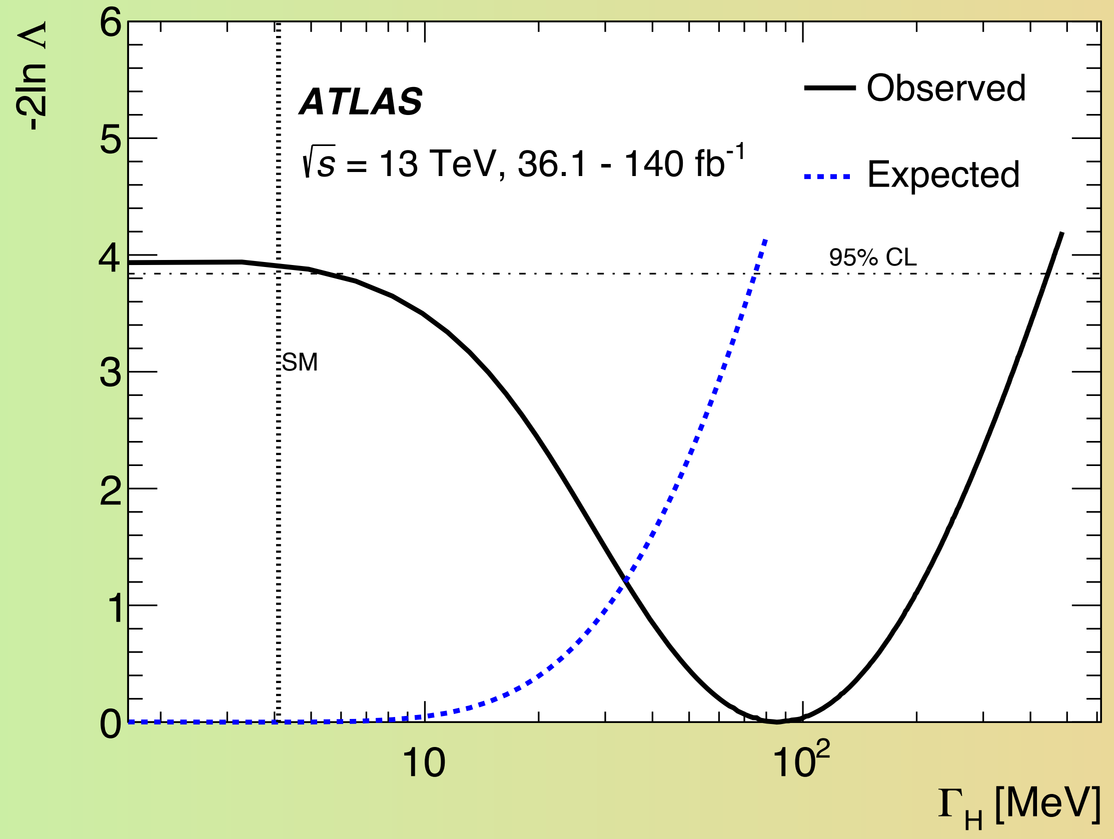
Nature 607, 52–59 (2022)

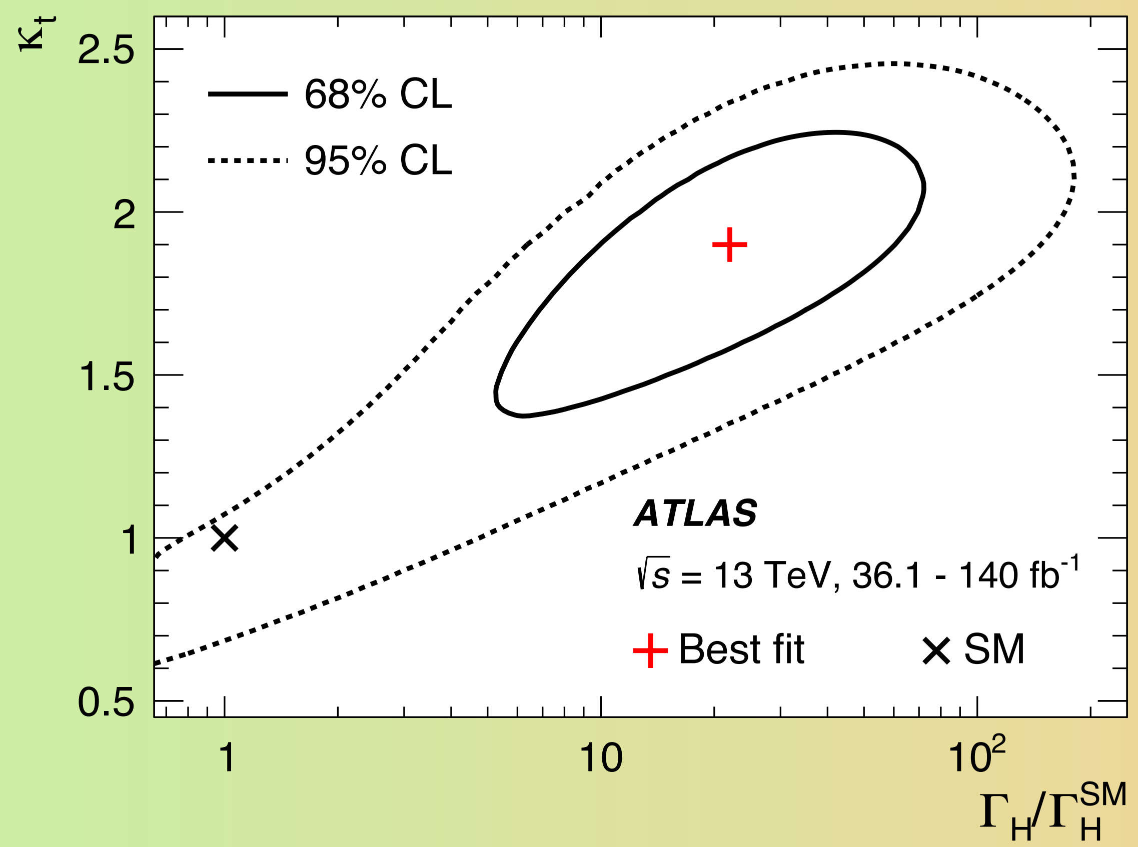


$|\kappa_t| = 0.94 \pm 0.10$

Remove $t\bar{t}H(\rightarrow ML)$ ⤷ $|\kappa_t| = 0.86 \pm 0.13$

Combination





$\Gamma_H < 450\,(75)$ MeV @ 95% CL

Resolve loop κ ⤷ $\Gamma_H < 157\,(55)$ MeV

.CP violation and Higgs

CP structure in $\boldsymbol{H \to VV}$

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\widetilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\widetilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\widetilde{c}_{\gamma\gamma}$

HISZ basis

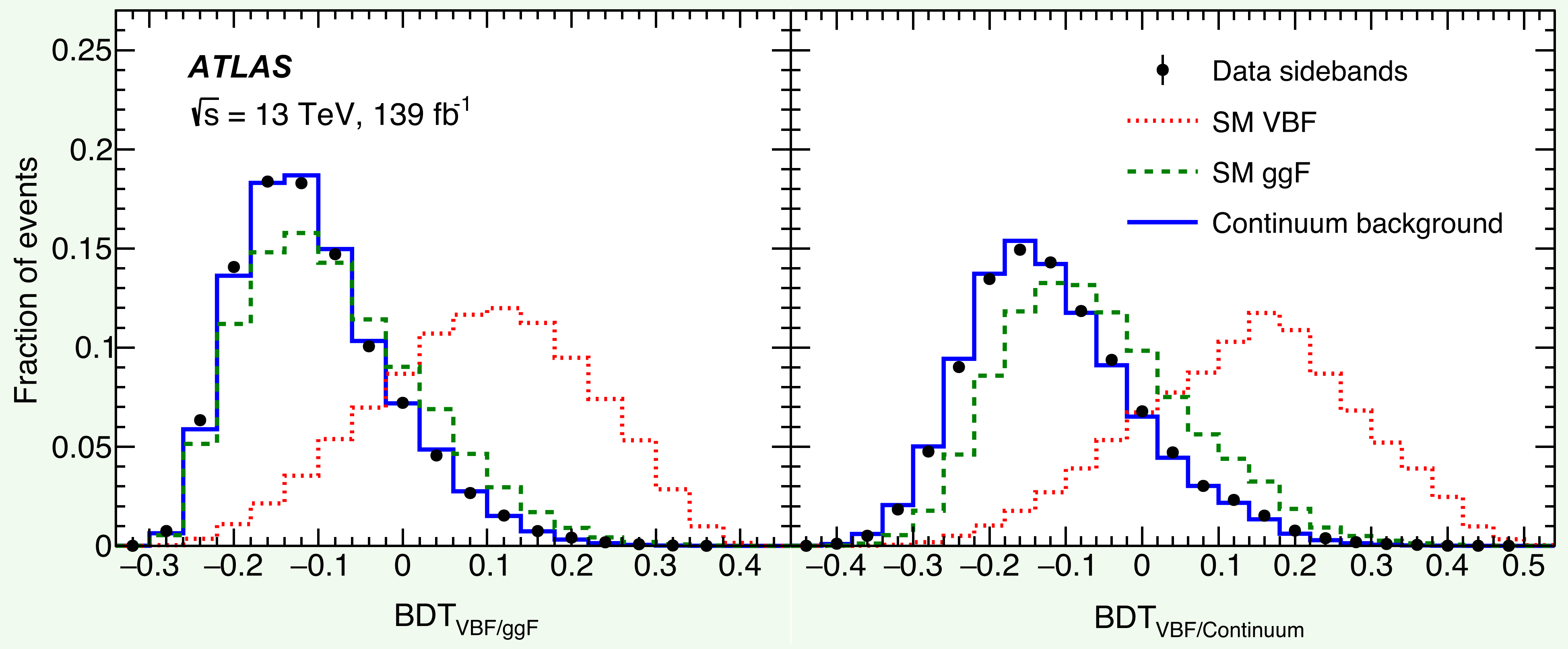
$$\tilde{d}: \quad \tilde{c}_{HW\tilde{B}} = 0, \quad \tilde{c}_{HW} = \tilde{c}_{HB\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d},$$

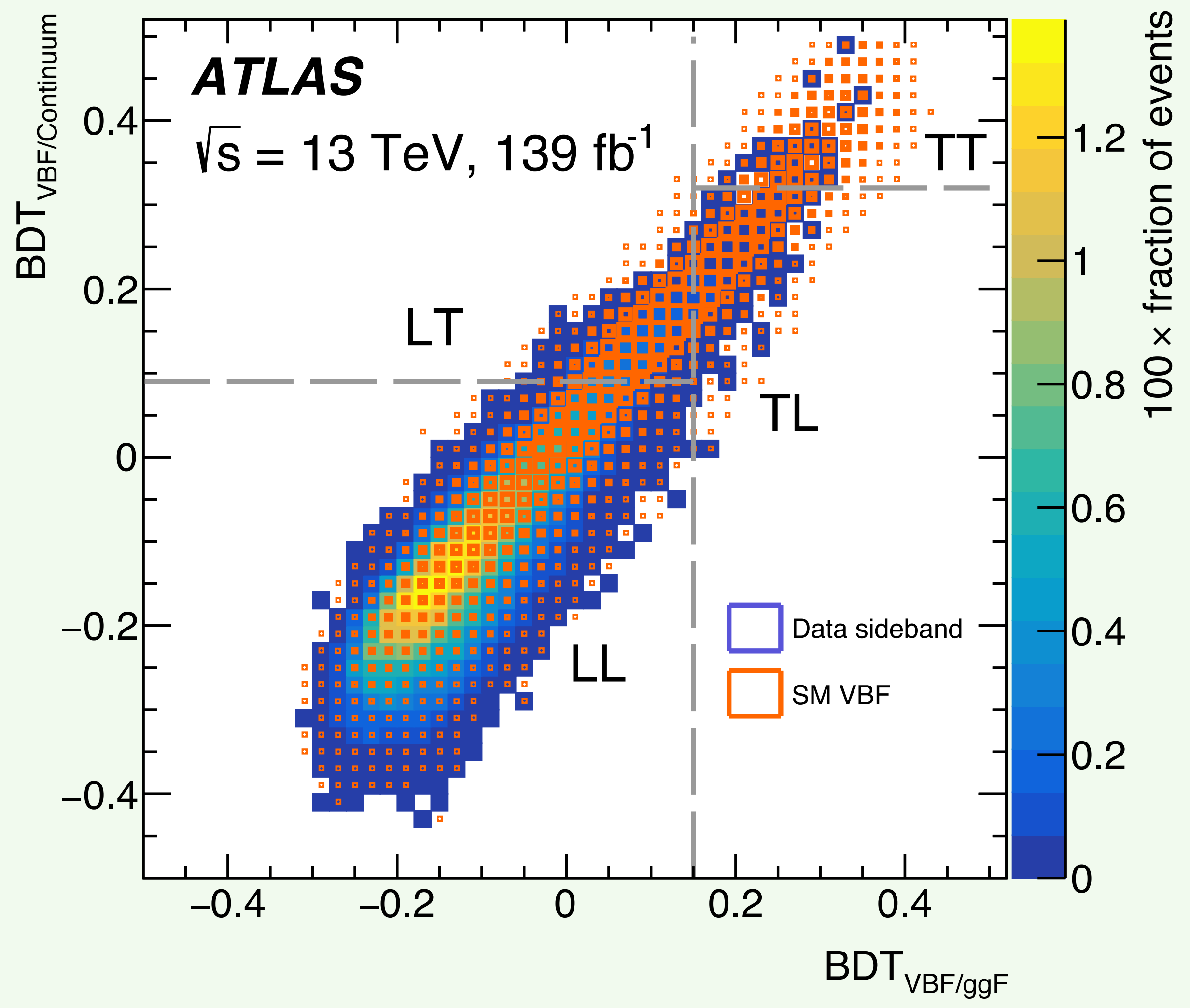
$$\tilde{c}_{Z\gamma} = 0, \quad \tilde{c}_{\gamma\gamma} = \sin^2\theta_W \cos^2\theta_W \tilde{c}_{ZZ} \propto \tilde{d}$$

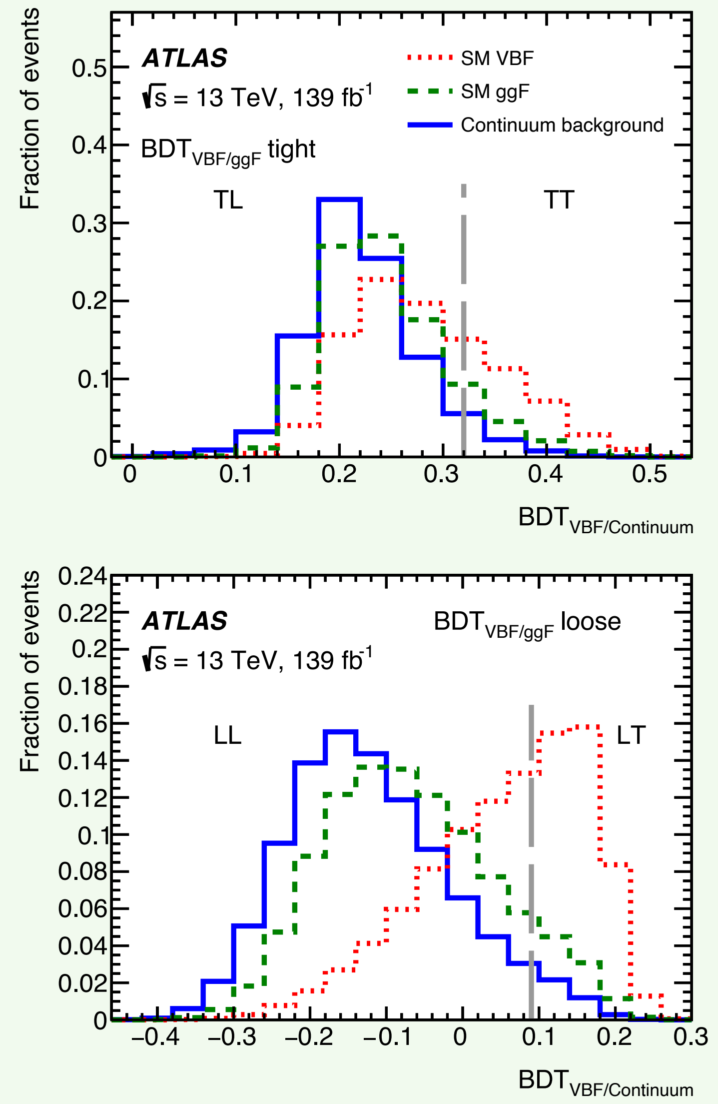
$$\mathrm{VBF}\; \boldsymbol{H} \to \gamma\gamma$$

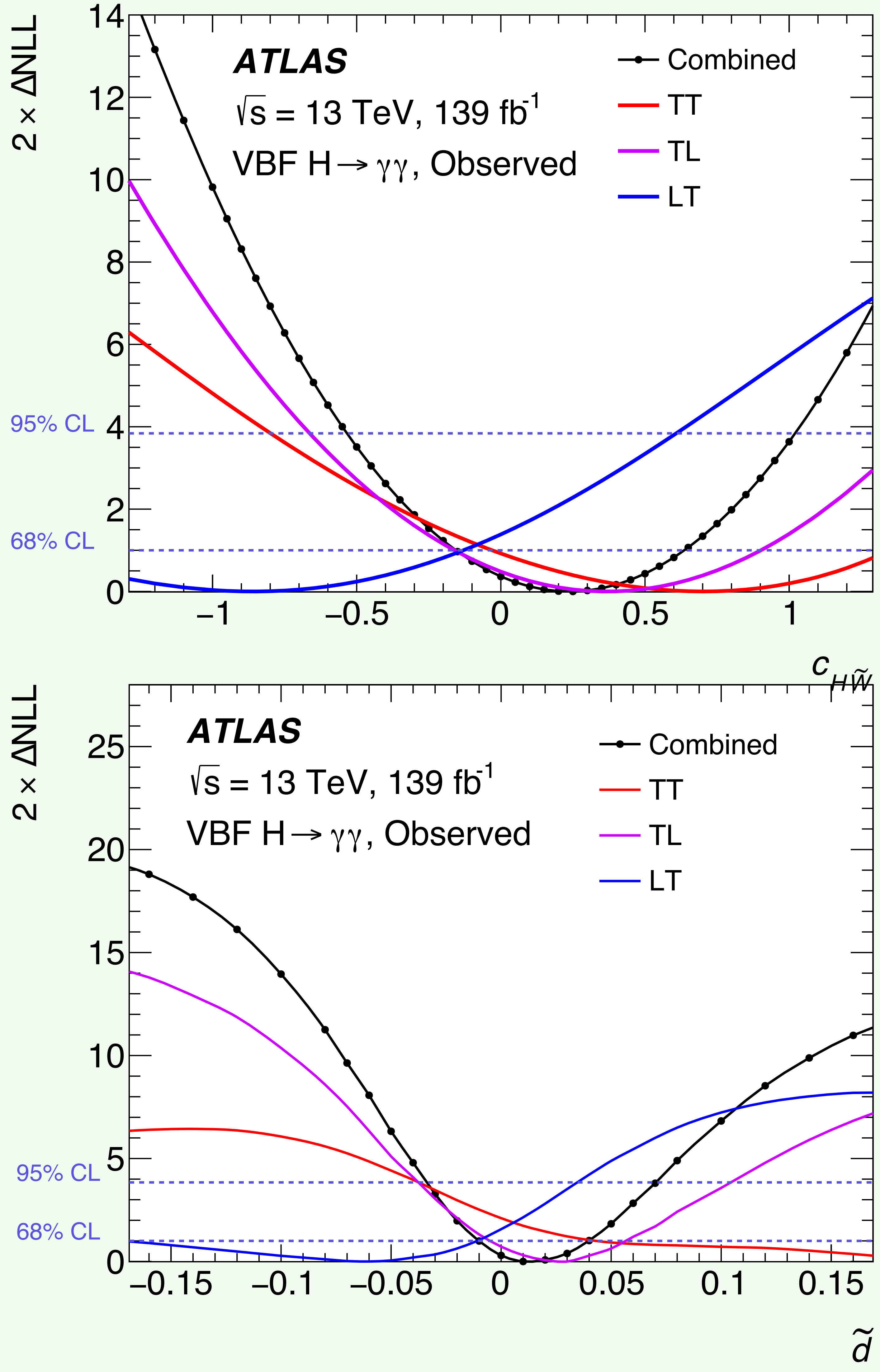
VBF $H \to \gamma\gamma$

Full Run-2 (140 fb^{-1}): setup









$$\mathrm{VBF}\ \boldsymbol{H} \to ZZ^{\star} \to 4\ell$$

VBF $H \to ZZ^\star \to 4\ell$

Full Run-2 (140 fb^{-1}): differential measurement

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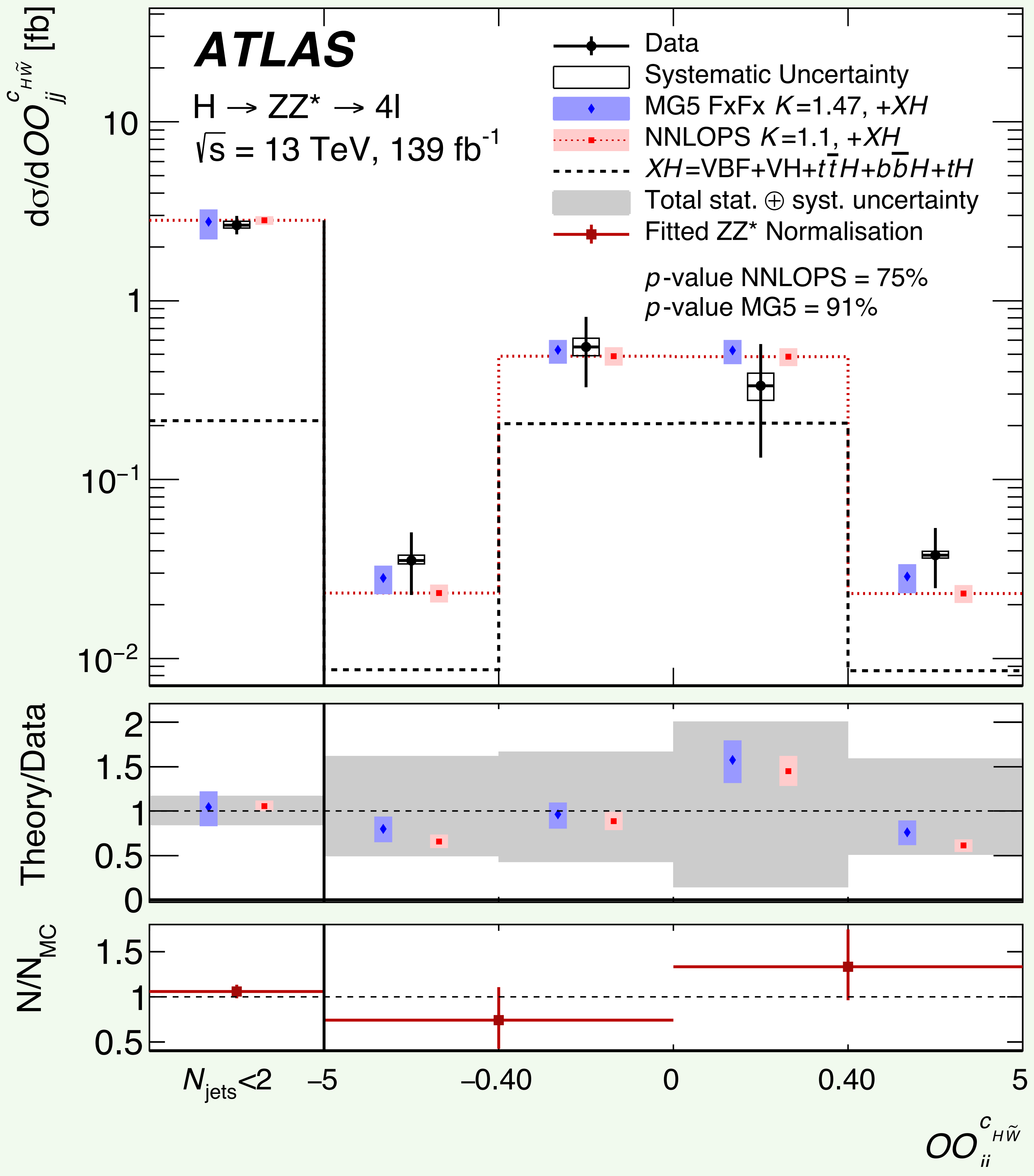

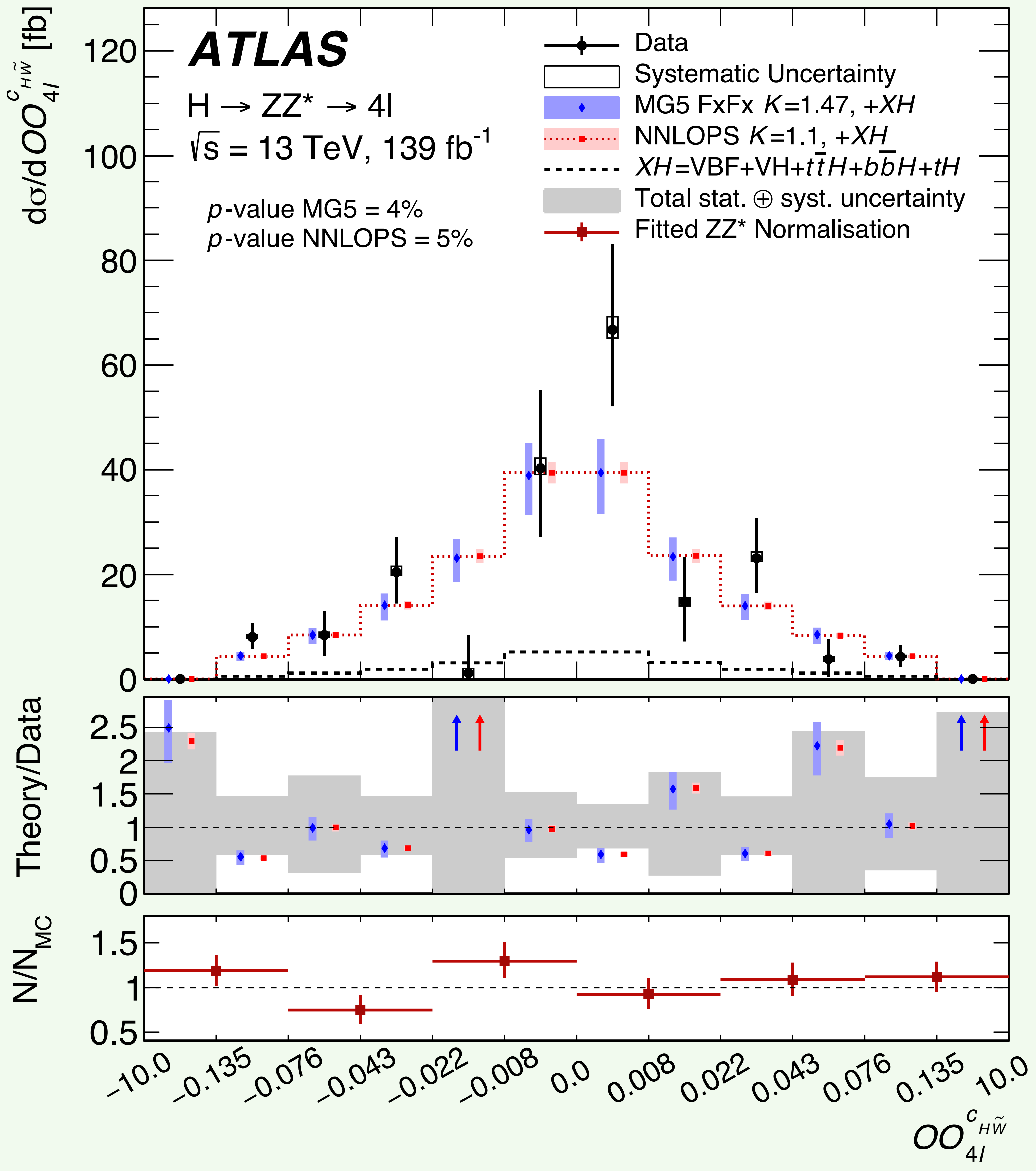

$$H \rightarrow \tau\tau$$

$H \to \tau\tau$

Full Run-2 (140 fb^{-1}): setup

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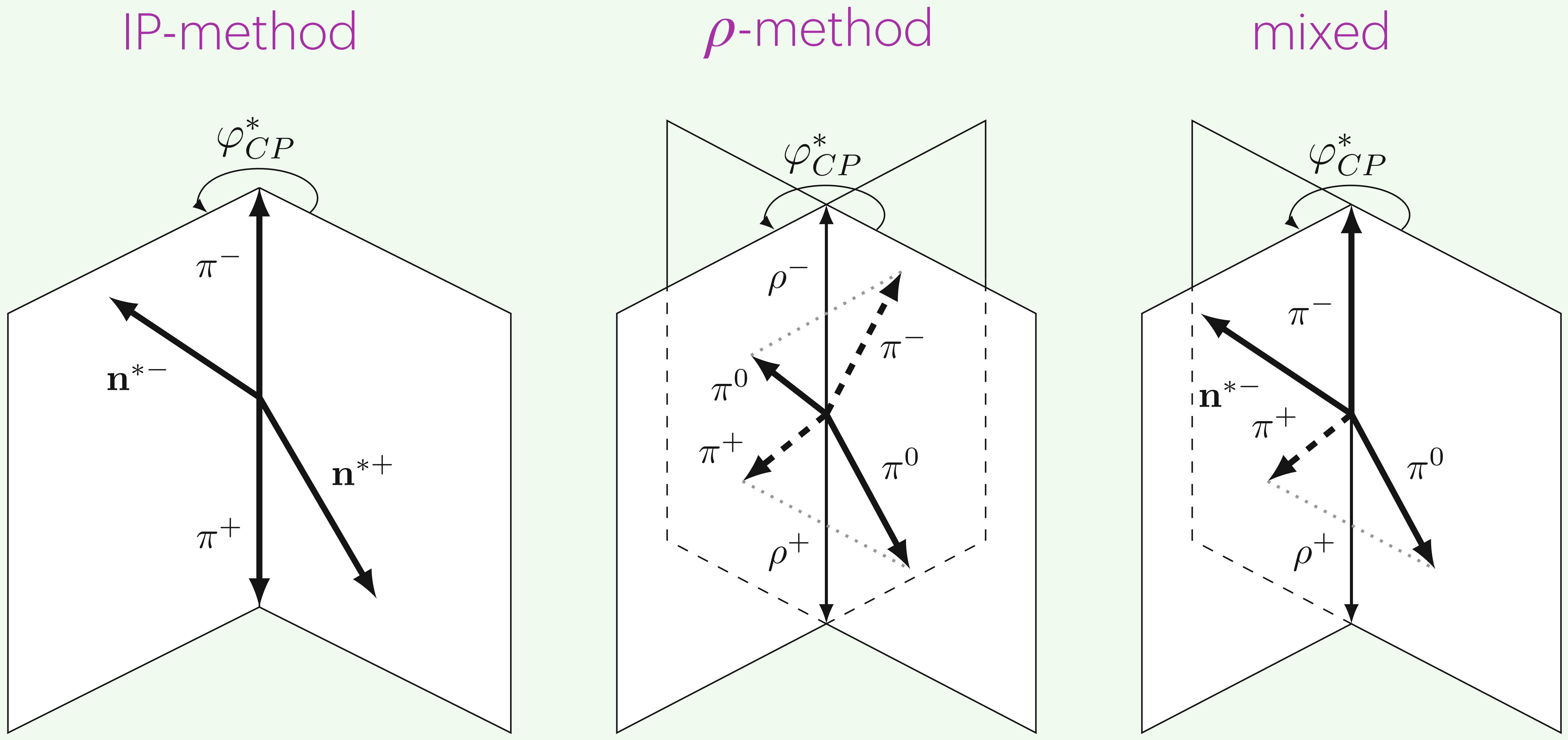

(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$

(b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$

(c) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$

one $\pi^\pm$ per τ

> 0 π^0 per τ

> 0 π^0 for one τ, zero for the other

$H \to \tau\tau$

Full Run-2 (140 fb^{-1}): setup

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

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Decay channel	Decay mode combination	Method	Fraction in all τ-lepton-pair decays
$\tau_{lep}\tau_{had}$	ℓ–1p0n	IP	8.1%
	ℓ–1p1n	IP–ρ	18.3%
	ℓ–1pXn	IP–ρ	7.6%
	ℓ–3p0n	IP–a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n–1p0n	IP	1.3%
	1p0n–1p1n	IP–ρ	6.0%
	1p1n–1p1n	ρ	6.7%
	1p0n–1pXn	IP–ρ	2.5%
	1p1n–1pXn	ρ	5.6%
	1p1n–3p0n	ρ–a_1	5.1%

Set of nuisance parameters	Impact on ϕ_τ [degrees]
Jet energy scale	3.4
Jet energy resolution	2.5
Pile-up jet tagging	0.5
Jet flavour tagging	0.2
E_T^{miss}	0.4
Electron	0.3
Muon	0.9
τ_{had} reconstruction	1.0
Misidentified τ	0.6
τ_{had} decay mode classification	0.3
π^0 angular resolution and energy scale	0.2
Track ($\pi^\pm$, impact parameter)	0.7
Luminosity	0.1
Theory uncertainty in $H \to \tau\tau$ processes	1.5
Theory uncertainty in $Z \to \tau\tau$ processes	1.1
Simulated background sample statistics	1.4
Signal normalisation	1.4
Background normalisation	0.6
Total systematic uncertainty	5.2
Data sample statistics	15.6
Total	16.4

Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{lep}\tau_{had}$	High	ℓ–1p0n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$
		ℓ–1p1n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$
	Medium	ℓ–1pXn	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{\rho}(\tau_{1pXn})\rvert > 0.1$
		ℓ–3p0n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{a_1}(\tau_{3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

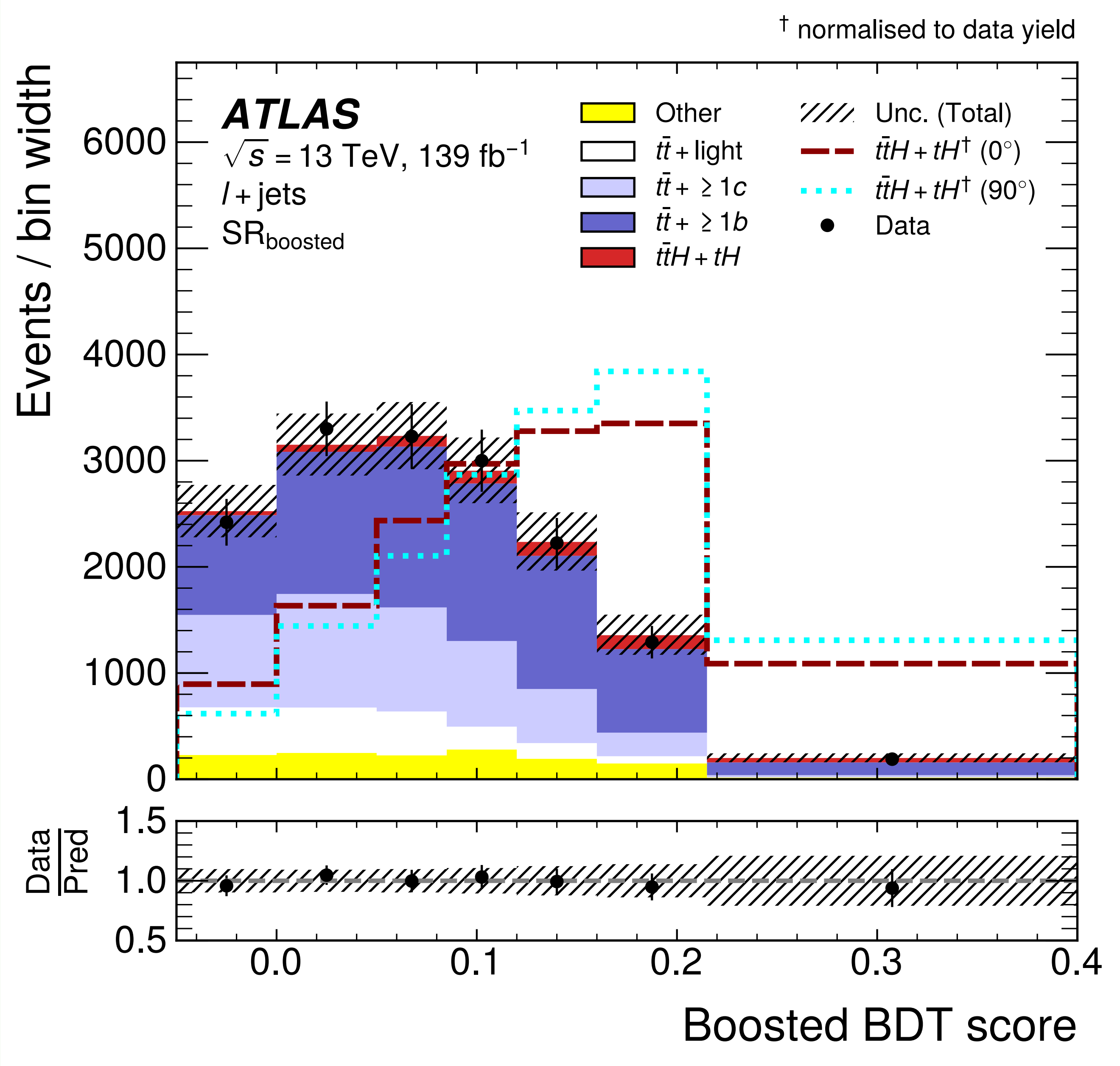
Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{had}\tau_{had}$	High	1p0n–1p0n	$\lvert d_0^{sig}(\tau_1)\rvert > 1.5$ $\lvert d_0^{sig}(\tau_2)\rvert > 1.5$
		1p0n–1p1n	$\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$ $\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$
		1p1n–1p1n	$\lvert y^{\rho}(\tau_1)y^{\rho}(\tau_2)\rvert > 0.2$
	Medium	1p0n–1pXn	$\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$ $\lvert y^{\rho}(\tau_{1pXn})\rvert > 0.1$
		1p1n–1pXn	$\lvert y^{\rho}(\tau_{1p1n})y^{\rho}(\tau_{1pXn})\rvert > 0.2$
		1p1n–3p0n	$\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$ $\lvert y^{a_1}(\tau_{3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

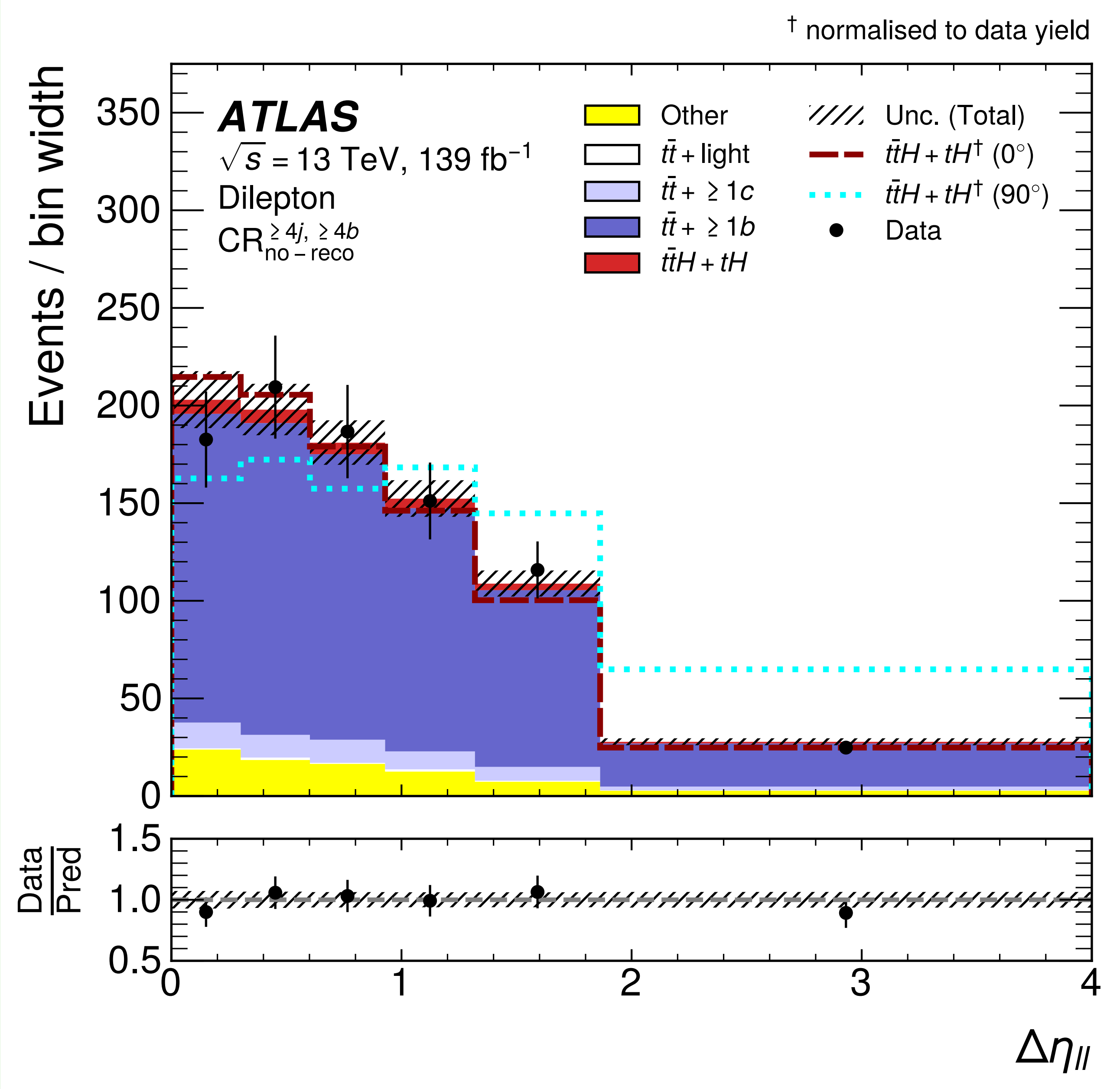
$H \to bb$ in $t\bar{t}H$ and tHq

$t\bar{t}H(\rightarrow b\bar{b})$ and $tH(\rightarrow b\bar{b})q$

Full Run-2 (140 fb^{-1}): setup

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{TR}^{\geq 4j,\geq 4b}$)	$\mathrm{CR}^{\geq 4j,\geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [-1, -0.086)$	b_4
	$\mathrm{SR}^{\geq 4j,\geq 4b}_1$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [-0.086, 0.186)$	b_4
	$\mathrm{SR}^{\geq 4j,\geq 4b}_2$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [0.186, 1]$	b_4
ℓ+jets ($\mathrm{TR}^{\geq 6j,\geq 4b}$)	$\mathrm{CR}^{\geq 6j,\geq 4b}_1$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [-1, -0.128)$	b_2
	$\mathrm{CR}^{\geq 6j,\geq 4b}_2$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [0.249, 1]$	b_2
ℓ+jets ($\mathrm{TR}_{\text{boosted}}$)	$\mathrm{SR}_{\text{boosted}}$	$\mathrm{BDT}^{\text{boosted}} \in [-0.05, 1]$	$\mathrm{BDT}^{\text{boosted}}$





Uncertainty source	$\Delta\alpha\,[°]$	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+23	-37
$t\bar{t}+\geq 1b$ NLO matching	+22	-33
$t\bar{t}+\geq 1b$ fractions	+14	-21
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+16	-24
$t\bar{t}+\geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t}+\geq 1b$ ISR	+14	-24
$t\bar{t}+\geq 1c$ modelling	+6.6	-11
$t\bar{t}+$light modelling	+2.5	-4.7
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+8.7	-15
c-mis-tag rates	+6.7	-11
l-mis-tag rates	+2.3	-2.7
Jet energy scale and resolution		
b-jet energy scale	+1.6	-3.8
Jet energy scale (flavour)	+7.8	-11
Jet energy scale (pileup)	+5.2	-7.9
Jet energy scale (remaining)	+8.1	-13
Jet energy resolution	+5.7	-9.3
Luminosity	$\leq \pm 1$	
Other sources	+4.9	-8
Total systematic uncertainty	+41	-54
$t\bar{t}+\geq 1b$ normalisation	+8.2	-13
κ_t'	+17	-33
Total statistical uncertainty	+32	-49
Total uncertainty	+52	-73