New results on $t\bar{t}W$ and $t\bar{t}t\bar{t}$ production with the ATLAS experiment

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Windows on the Universe, Quy Nhon

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Why $t\bar{t}W$ and $t\bar{t}t\bar{t}$?

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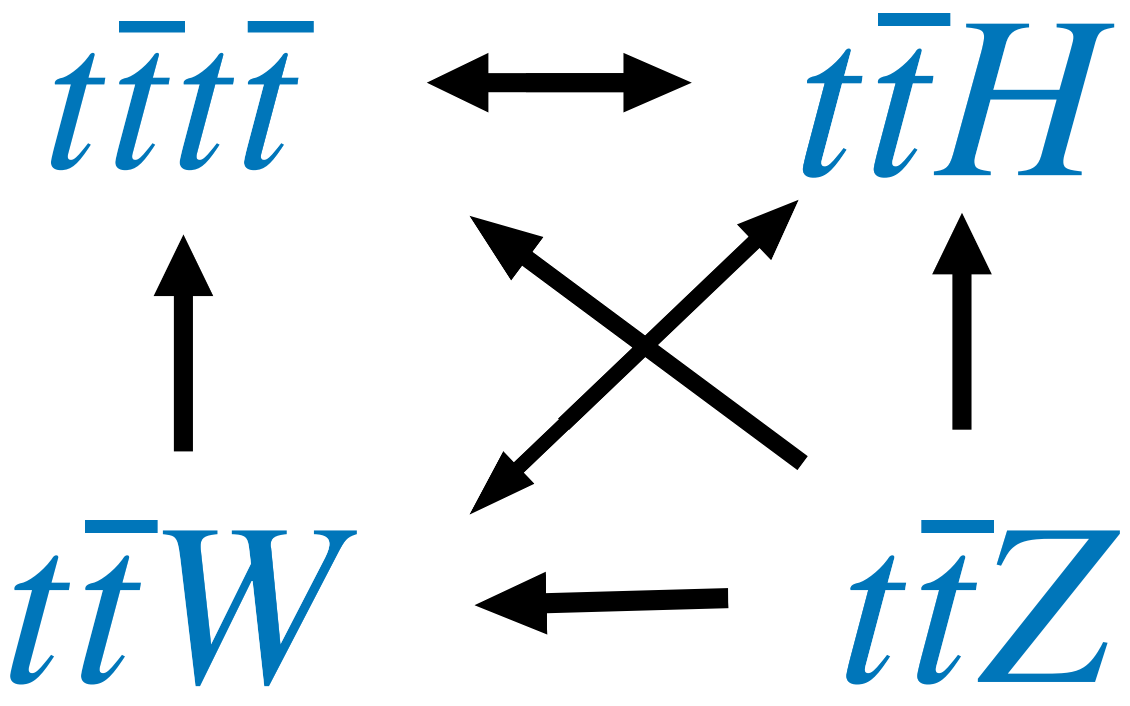
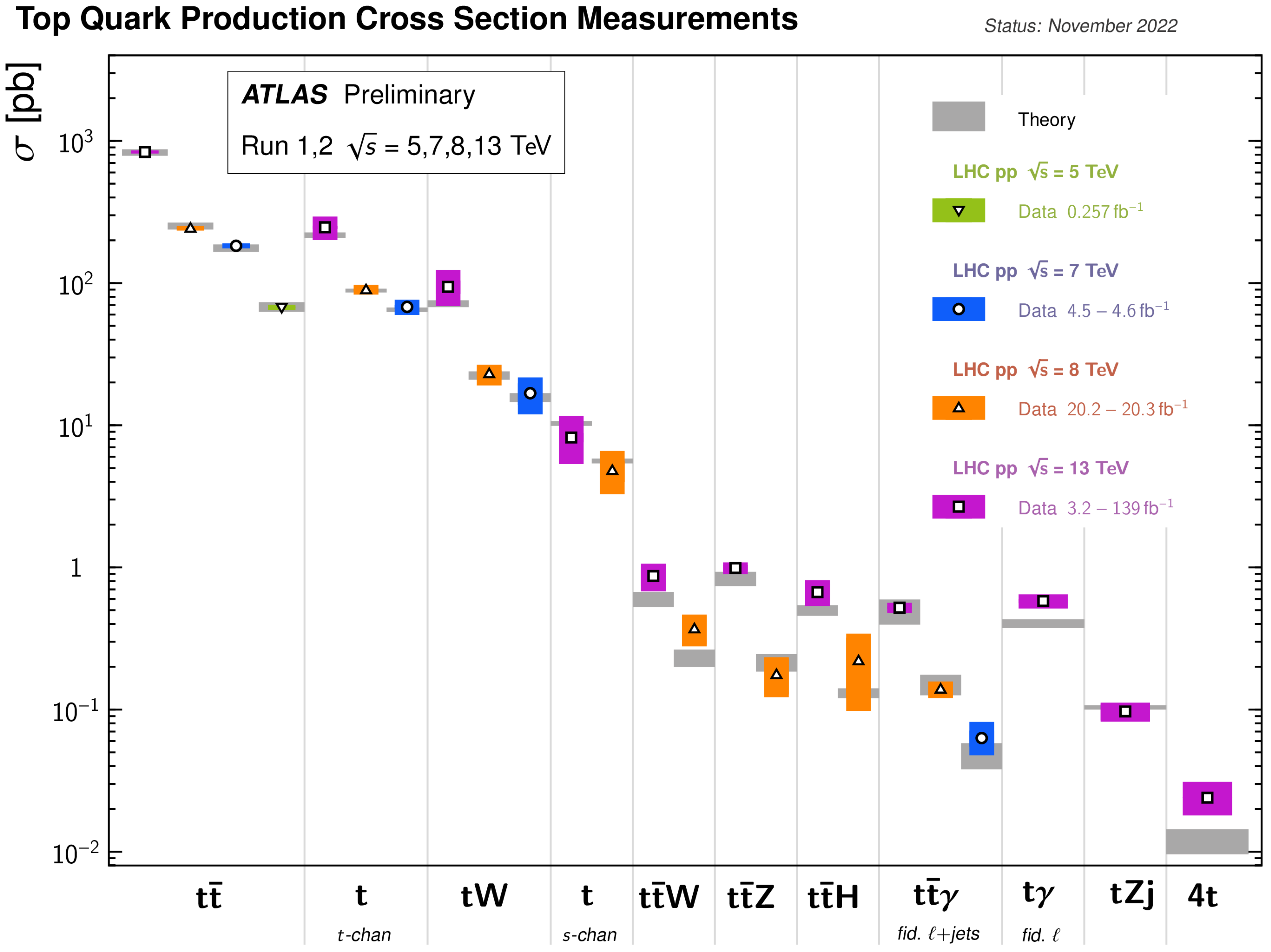
- $t\bar{t}t\bar{t}$: Very rare process, was not observed yet
- $t\bar{t}W$: prediction has been consistently below observation in ATLAS and CMS measurements
- Important to measure rare top processes at high precision to identify any discrepancies in SM

Interdependence between rare top processes in multi lepton channel



Arrows denote dominant backgrounds

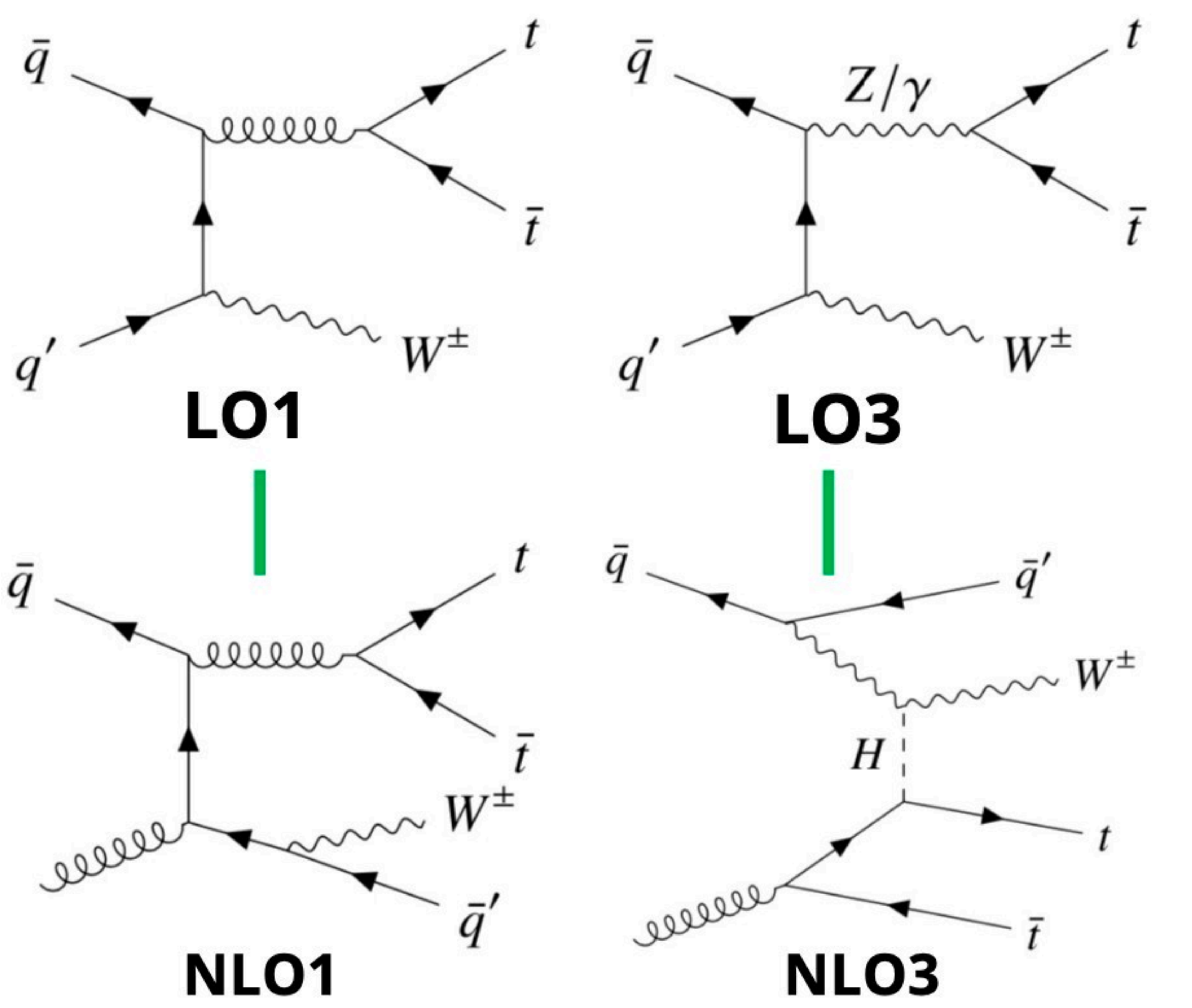


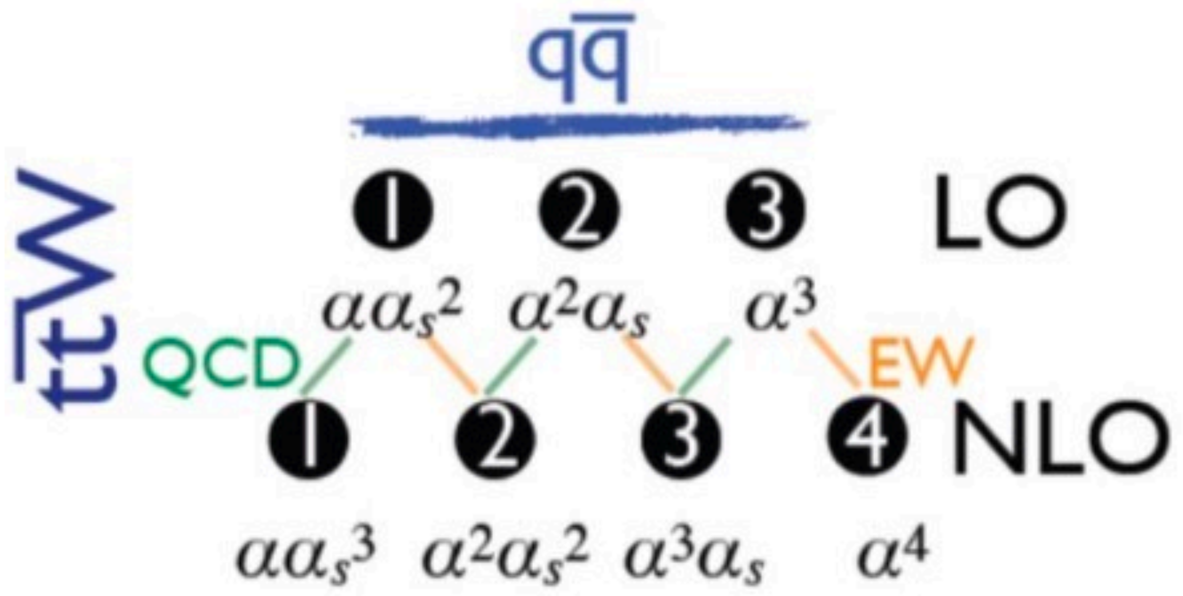
New $t\bar{t}W$ measurement

Overview

- ATLAS and CMS consistently measured 20-50% excess in comparison to SM NLO theory prediction
- Main background in $t\bar{t}t\bar{t}$ and many $t\bar{t}H$ decay channels
- Very challenging process with complex NLO QCD and electroweak contributions
- Theory predictions
  - $\sigma(t\bar{t}W) = 722 \pm 7$ fb JHEP11(2021)029 (NLO with FxFx merging)
  - $\sigma(t\bar{t}W) = 745.3 \pm 6.9$ fb arXiv:2306.16311 (NNLO)
- Mis-modelling observed previously —> First differential measurement

ATLAS-CONF-2023-019





Signal regions

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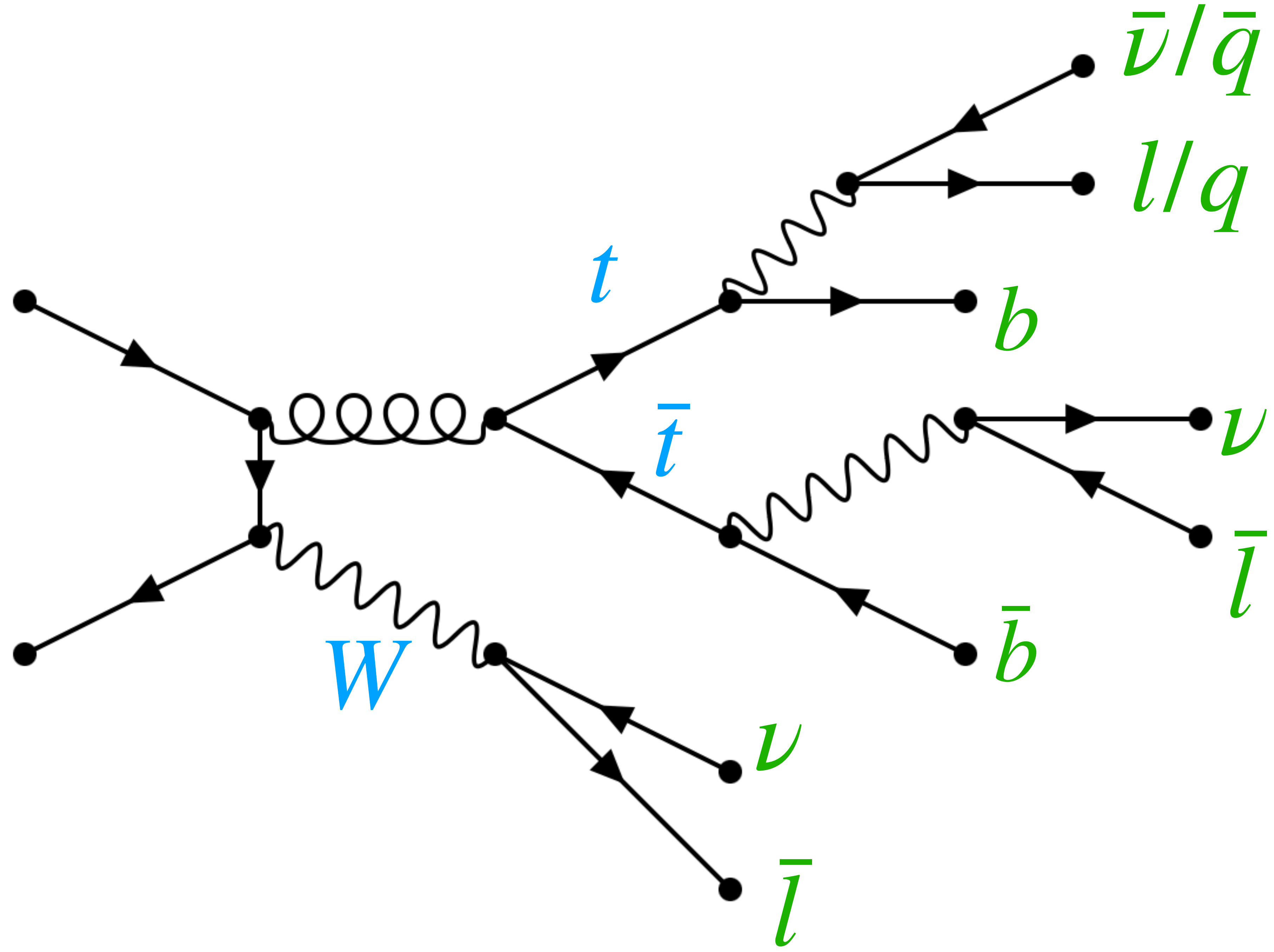
- Using multi lepton final state
  - 2 Same Sign leptons or 3 leptons
- ≥2 jets
- ≥1b-jet 60% or ≥2b-jets 77%
- Remove dominant $t\bar{t}Z$ background by excluding OSSF and 3L pair with mass in Z peak
- For inclusive measurement, events are classified into 56 Signal regions, based on:
  - the number of jets (2/3,4,5+), b-jets(1,2+) and leptons (2,3)
  - total charge of leptons(+1,-1)
  - flavour(e/μ).



Main backgrounds

- Diboson, $t\bar{t}Z$, $t\bar{t}H$
- fake/non-prompt leptons mainly from $t\bar{t}$ production, charge misID (electron)

Control regions

- Dedicated control regions for $t\bar{t}Z$ and Dibosons
- 2 Regions dominated by electron from photon conversion
- 6 regions defined by lepton isolation level and flavour

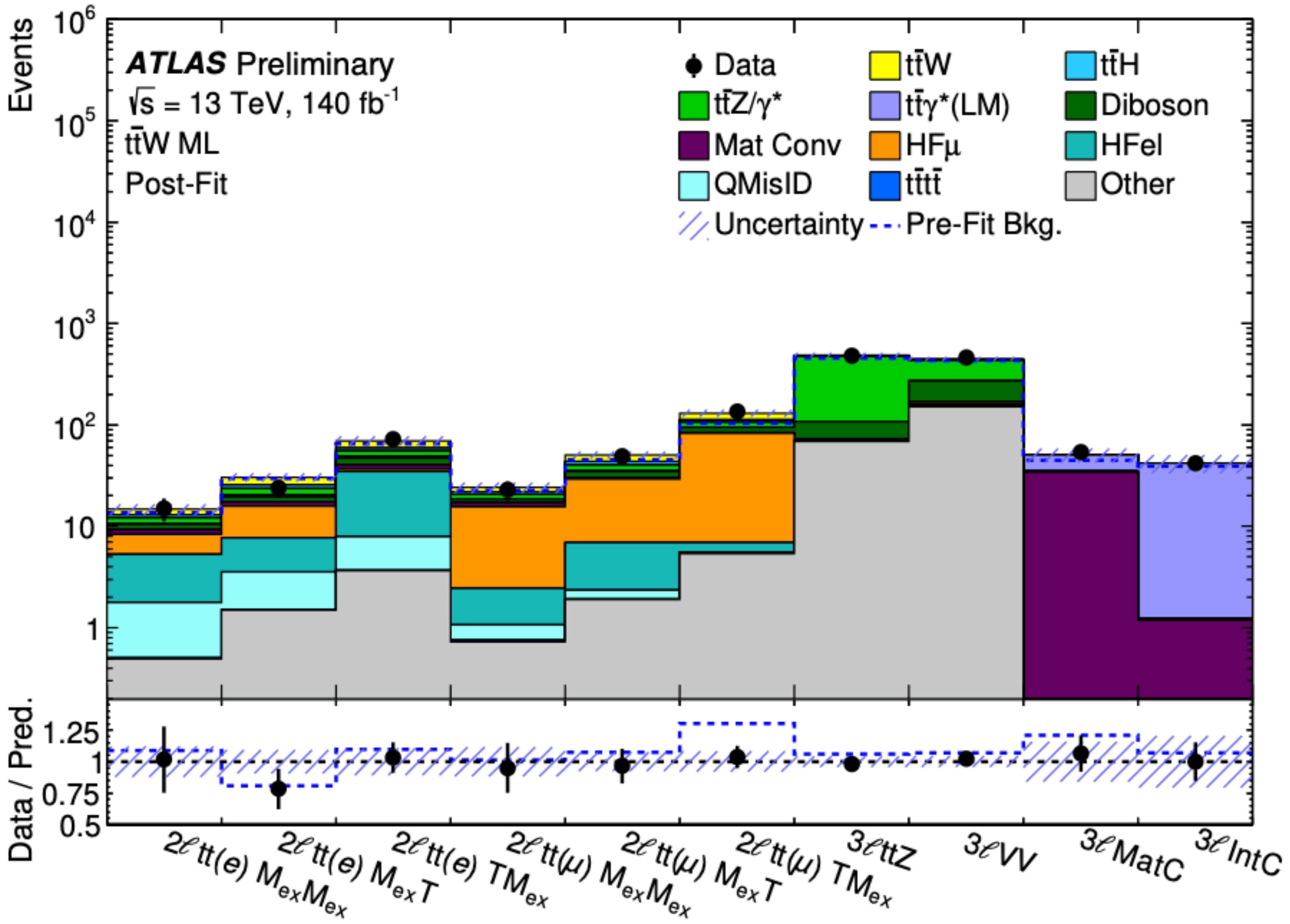
ee+μe	ee+μe	ee+μe	μμ+eμ	μμ+eμ	μμ+eμ
TM	MT	MM	TM	MT	MM
p_T ℓ_1	p_T ℓ_1	p_T ℓ_1	p_T ℓ_1	p_T ℓ_1	p_T ℓ_1

Fake leptons

- Shape from MC modelling
- Normalisation from 4 free parameters included in the signal extraction fit
  - Electrons from HF decays
  - Muons from HF decays
  - material conversions
  - virtual photon conversions

Charge mis-identfication

- Data driven from $Z \rightarrow e^{\pm}e^{\pm}/e^{\pm}e^{\mp}$

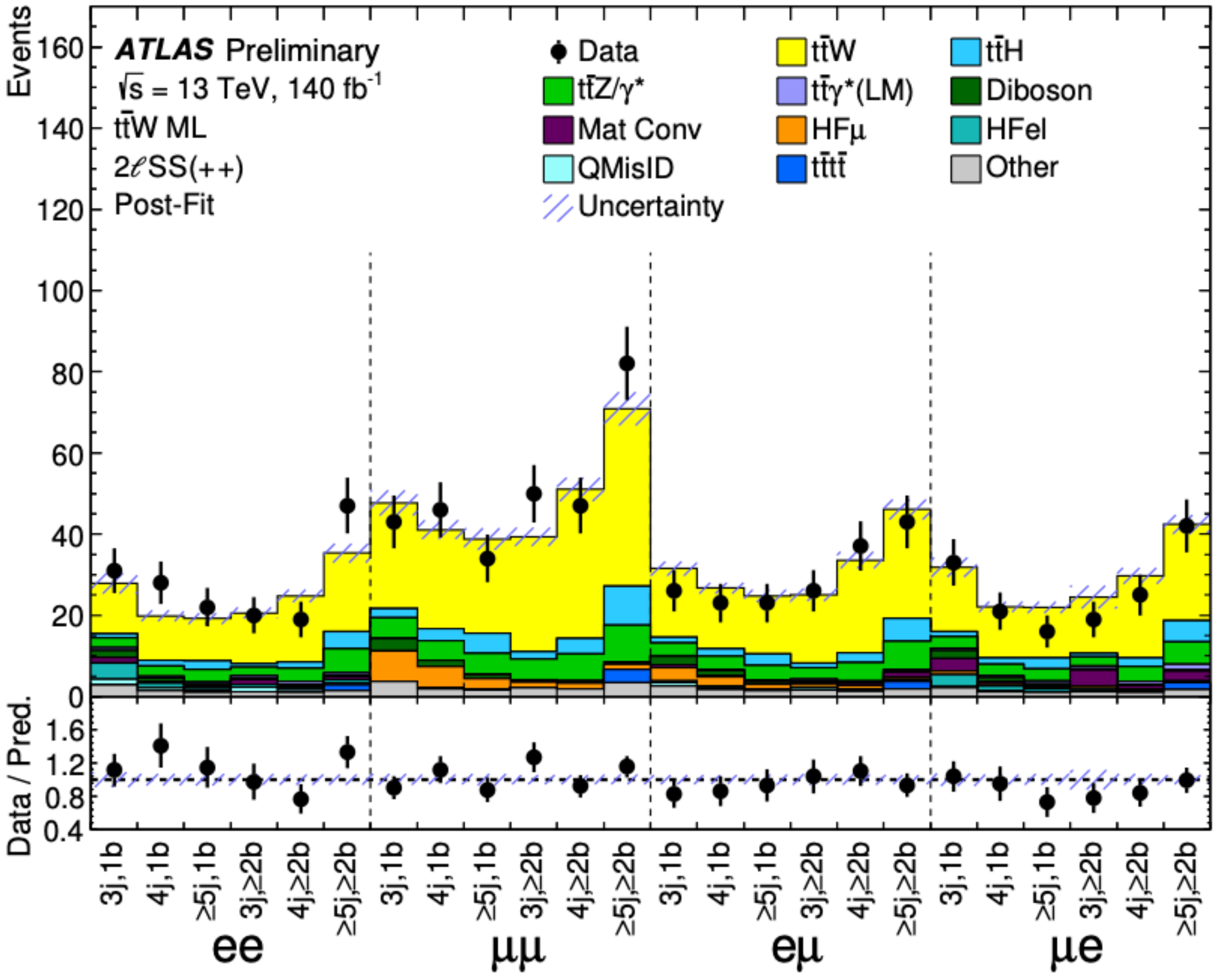


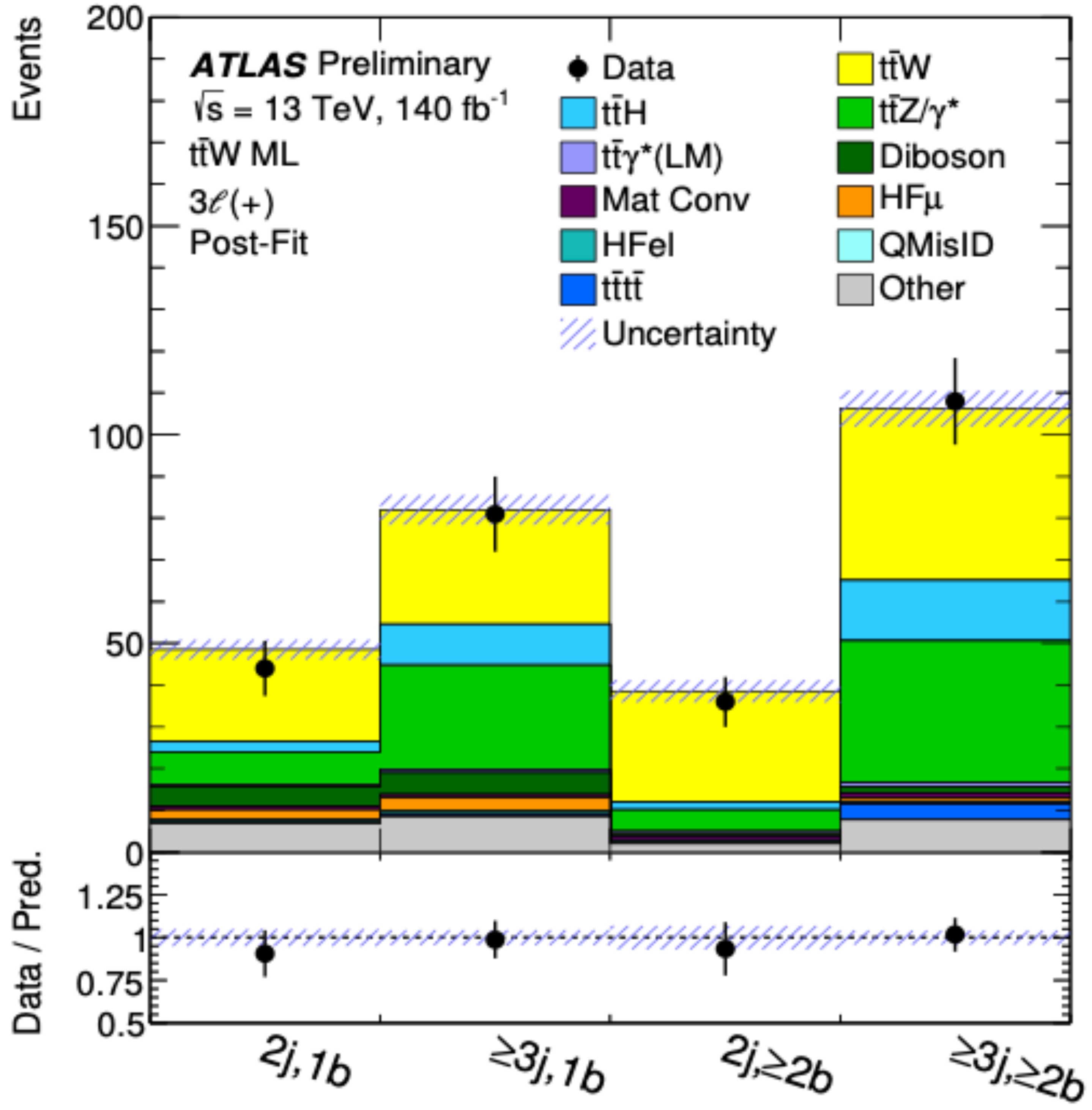
Results - inclusive

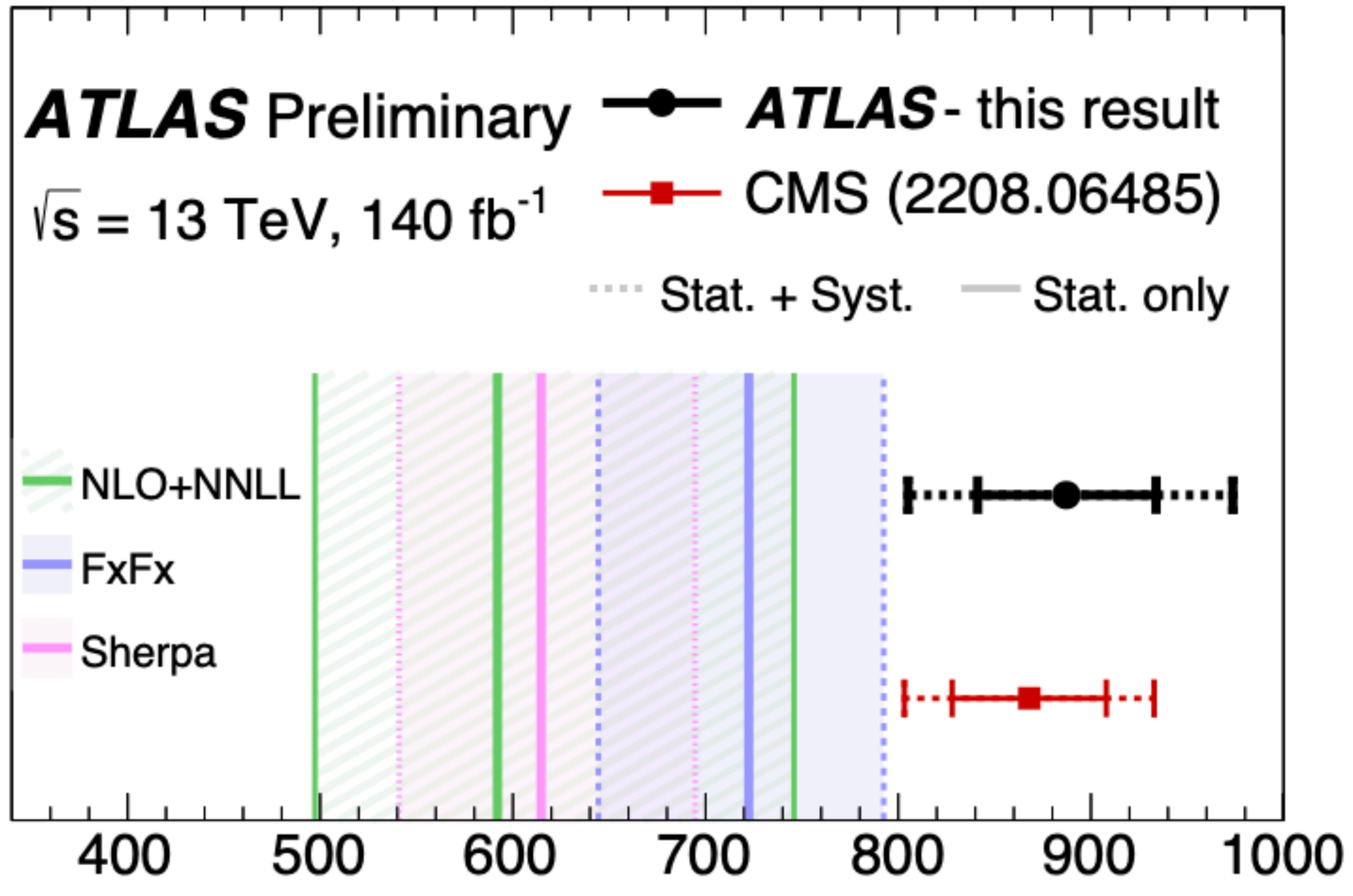
Simultaneous profile likelihood fit to data using event yields in 56 SR and 10 CR with 6 extra free parameters

$$\sigma(t\bar{t}W) = 890 \pm 50\ (\mathrm{stat.})\ \pm 70\ (\mathrm{syst.}) = 890\ \pm 80\ (\mathrm{tot.})\ \mathrm{fb}$$

Consistent with the SM NLO prediction at 1.5σ







$$NF_{mat.\ conv.} \quad 1.15 \pm 0.31$$

$$NF_{Int.\ Conv.} \quad 1.07 \pm 0.24$$

$$NF_{HF\ e} \quad 0.83 \pm 0.31$$

$$NF_{HF\ \mu} \quad 1.01 \pm 0.21$$

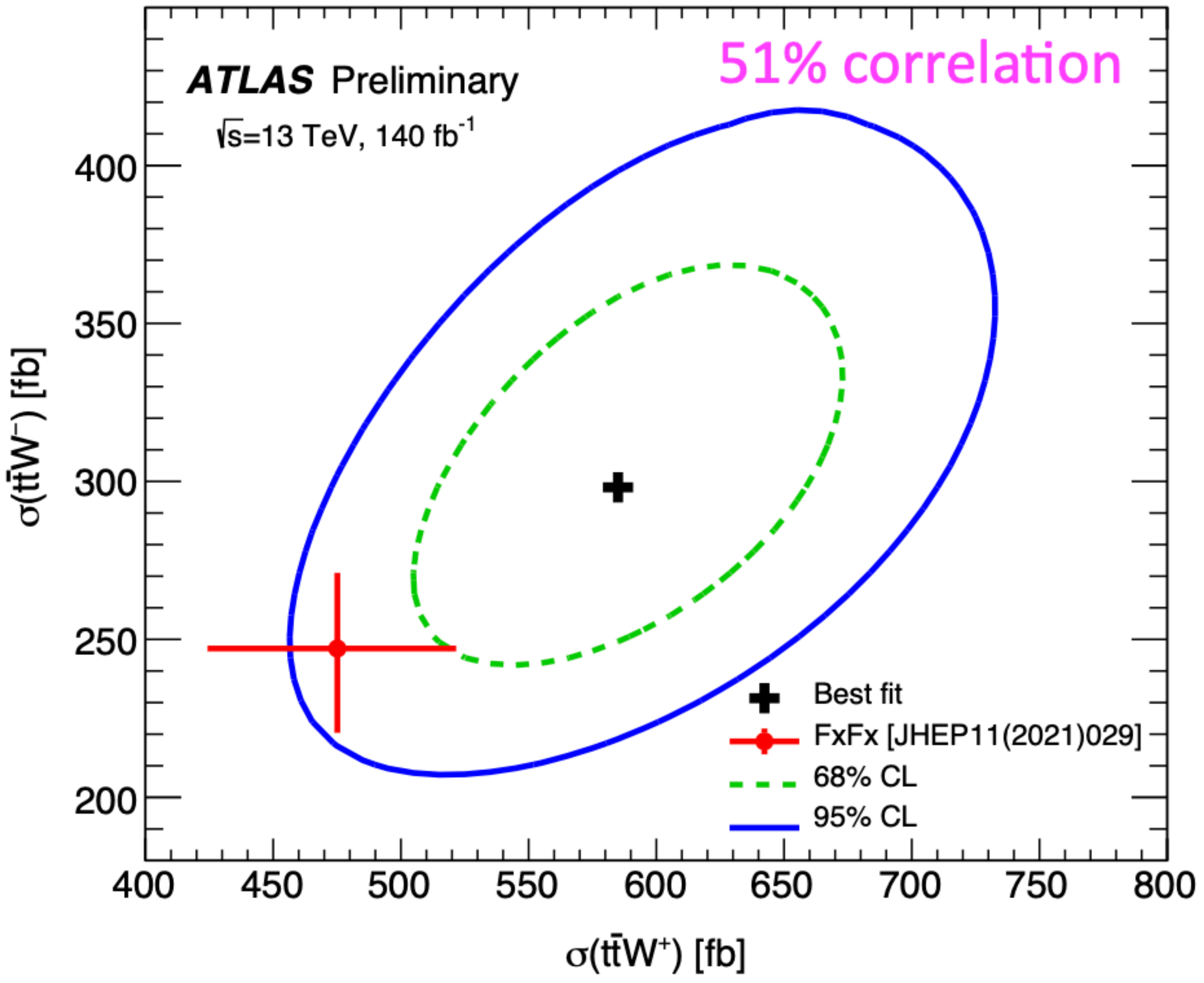
$$NF_{t\bar{t}Z} \quad 1.16 \pm 0.15$$

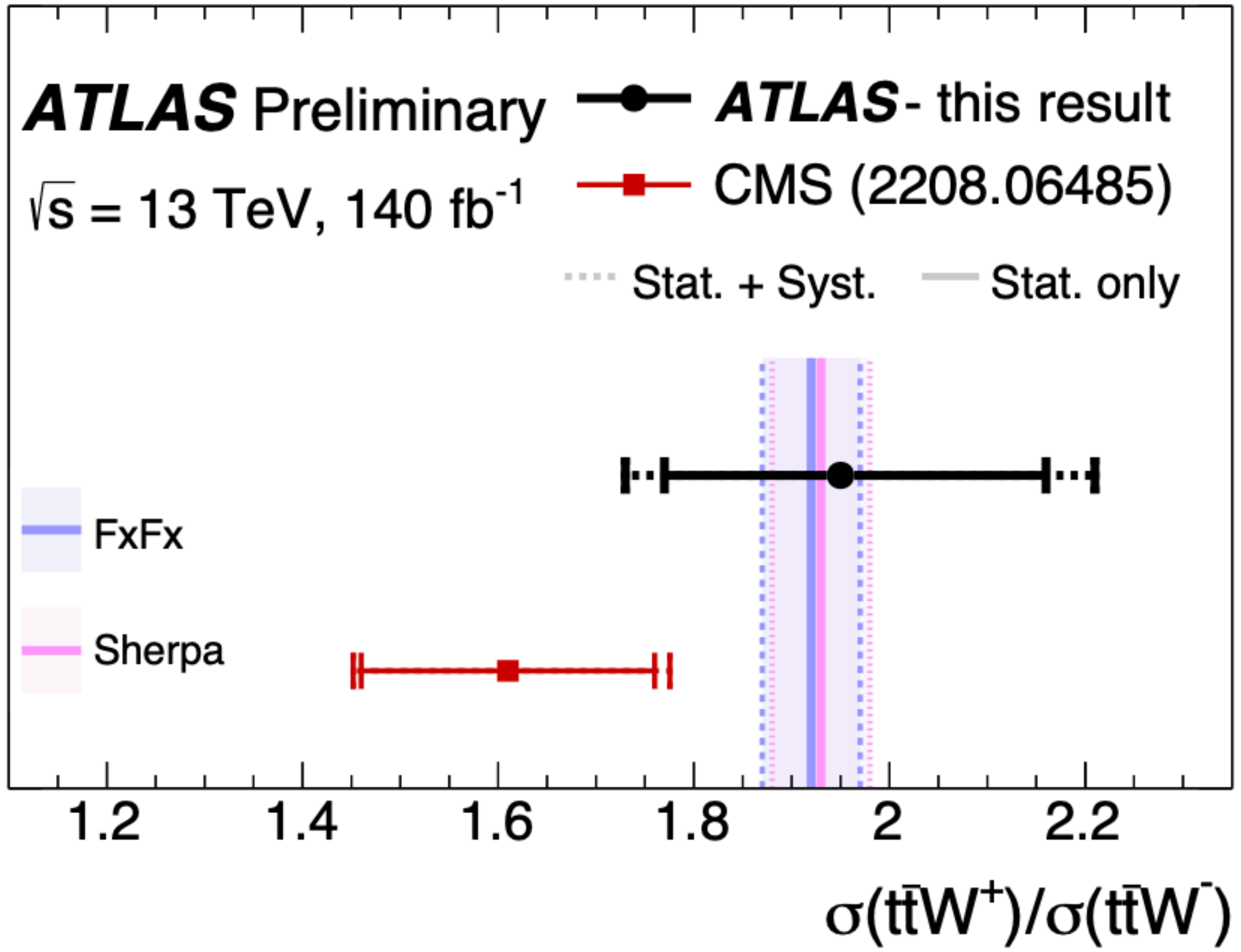
$$NF_{VV} \quad 0.87 \pm 0.33$$

Dominant uncertainties from Signal modelling and Statistics

Results - charge asymmetry

$$\frac{\sigma(t\bar{t}W^+)}{\sigma(t\bar{t}W^-)} = 1.95 \pm 0.21(\textbf{stat}) \pm 0.16(\textbf{syst})$$





$$A_c^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

$$A_C^{rel} = 0.32 \pm 0.05(stat) \pm 0.03(syst)$$

Good agreement with prediction

Results - Differential

- First differential measurement of $t\bar{t}W$ for 7 observables using profile likelihood unfolding
- Consistent with the results from the inclusive measurement
- Unfolded data shows good agreement with all MC in shape

N_{jets}

$H_{\text{T,jets}}$

$H_{\text{T,lep}}$

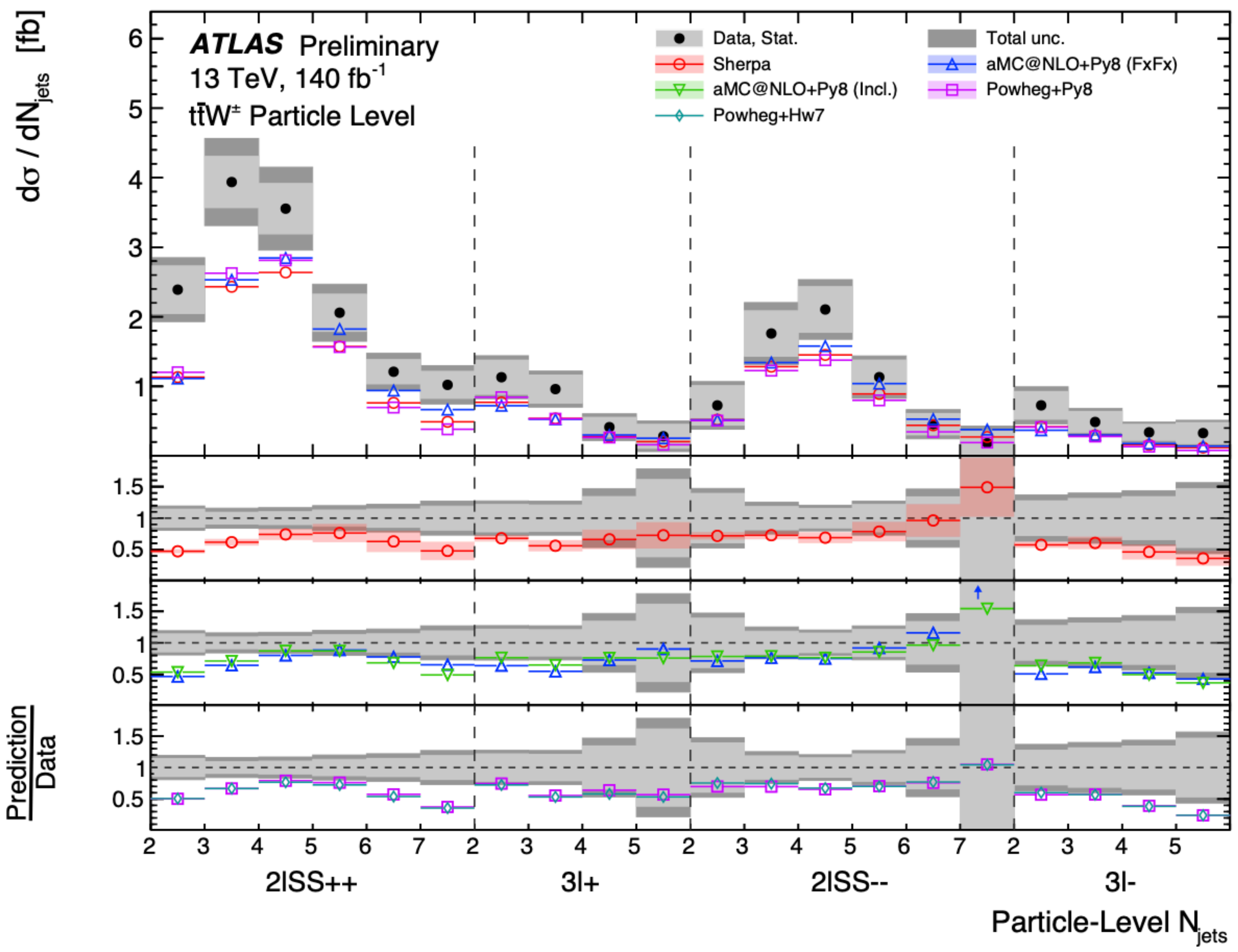
$\Delta R_{\text{lb, lead}}$

$|\Delta\phi_{\text{ll, ss}}|$

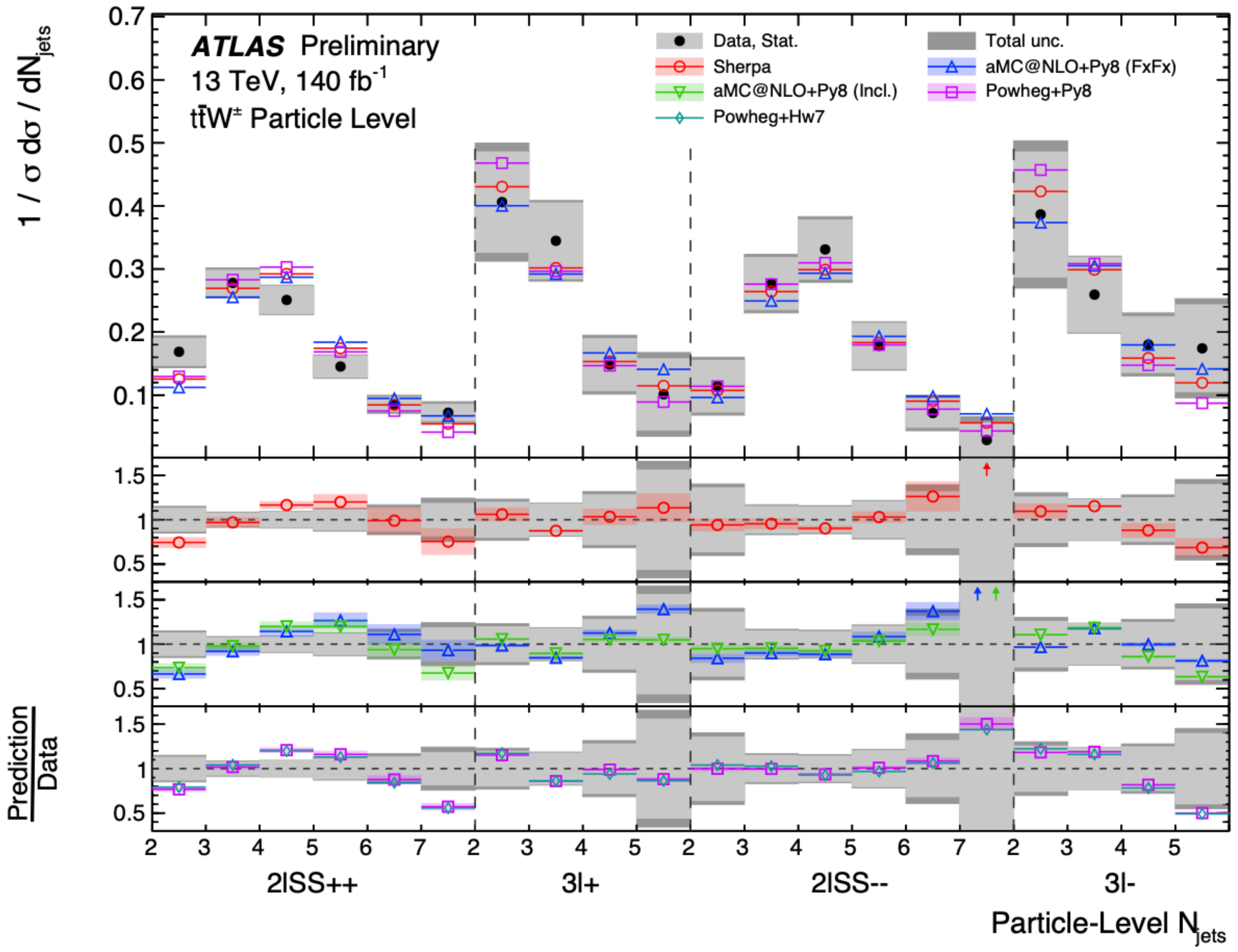
$|\Delta\eta_{\text{ll, ss}}|$

$M_{\text{jj, lead}}$

Absolute Cross-section



Normalised Cross-section



$t\bar{t}t\bar{t}$ production

Overview

EPJC 83 (2023) 496

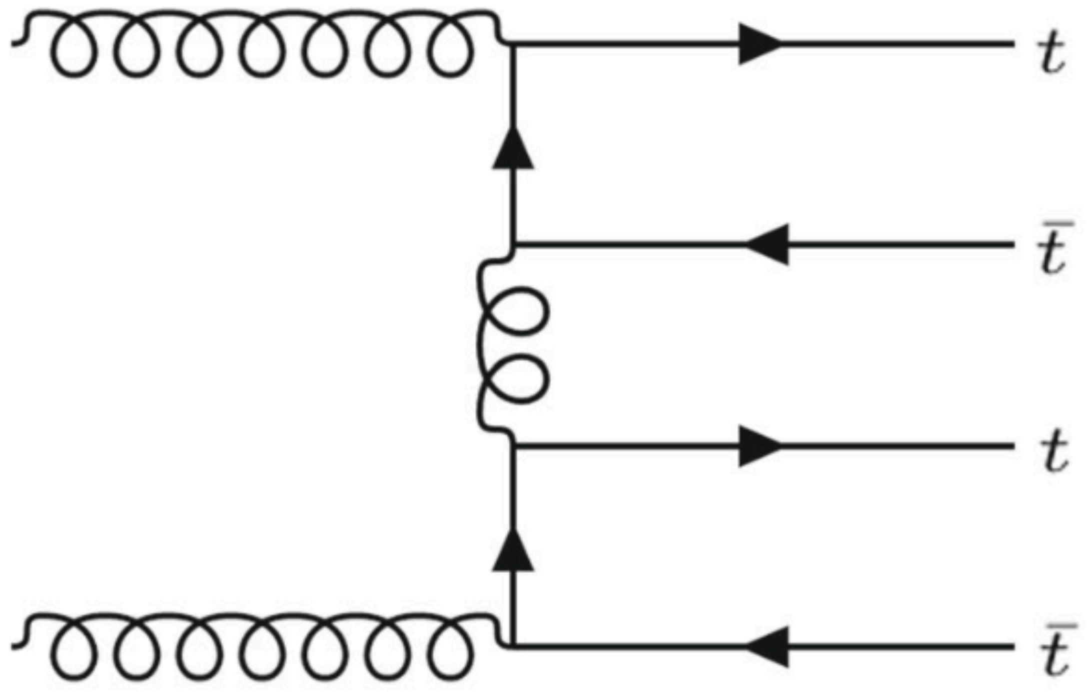
- Extremely rare and heavy final state, first observation in this paper

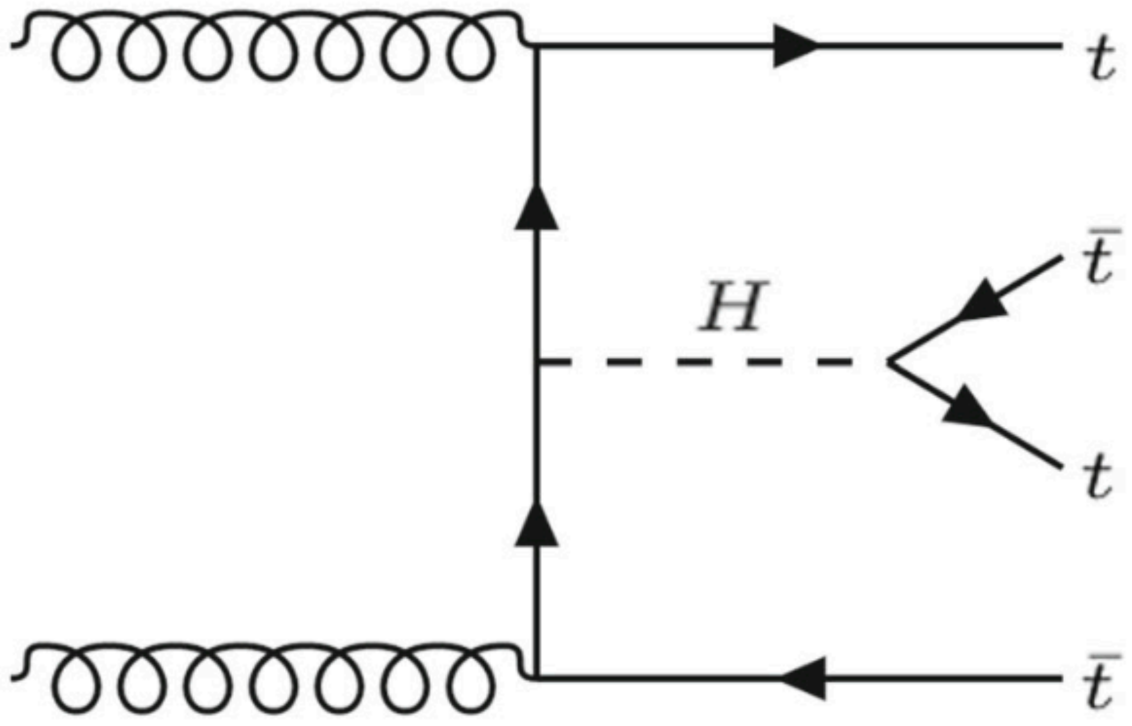
- Predicted:
    - $\sigma(t\bar{t}t\bar{t}) = 12.0 \pm 2.4$ fb JHEP 02 (2018) 031 (NLO QCD)
    - $\sigma(t\bar{t}t\bar{t}) = 13.4^{+1.0}_{-1.8}$ fb arXiv:2212.03259 (NLO+NLL')

- Good candidate for BSM studies —> $t\bar{t}t\bar{t}$ cross-section enhanced

- Sensitive to top-Yukawa coupling

- Sensitive to four-fermion coupling and Higgs oblique parameter



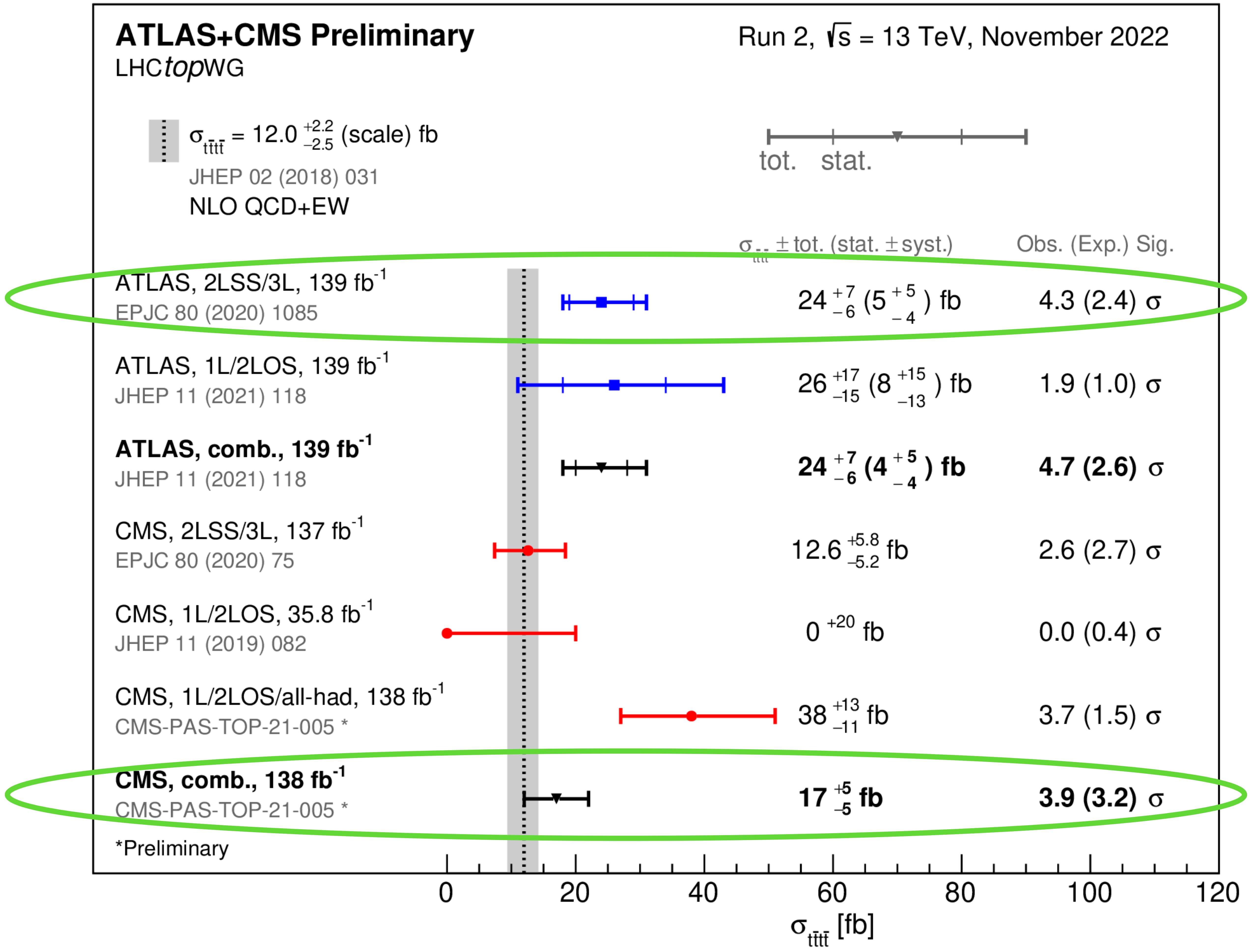


Overview

Evidence for the production of $t\bar{t}t\bar{t}$ was seen by both ATLAS and CMS

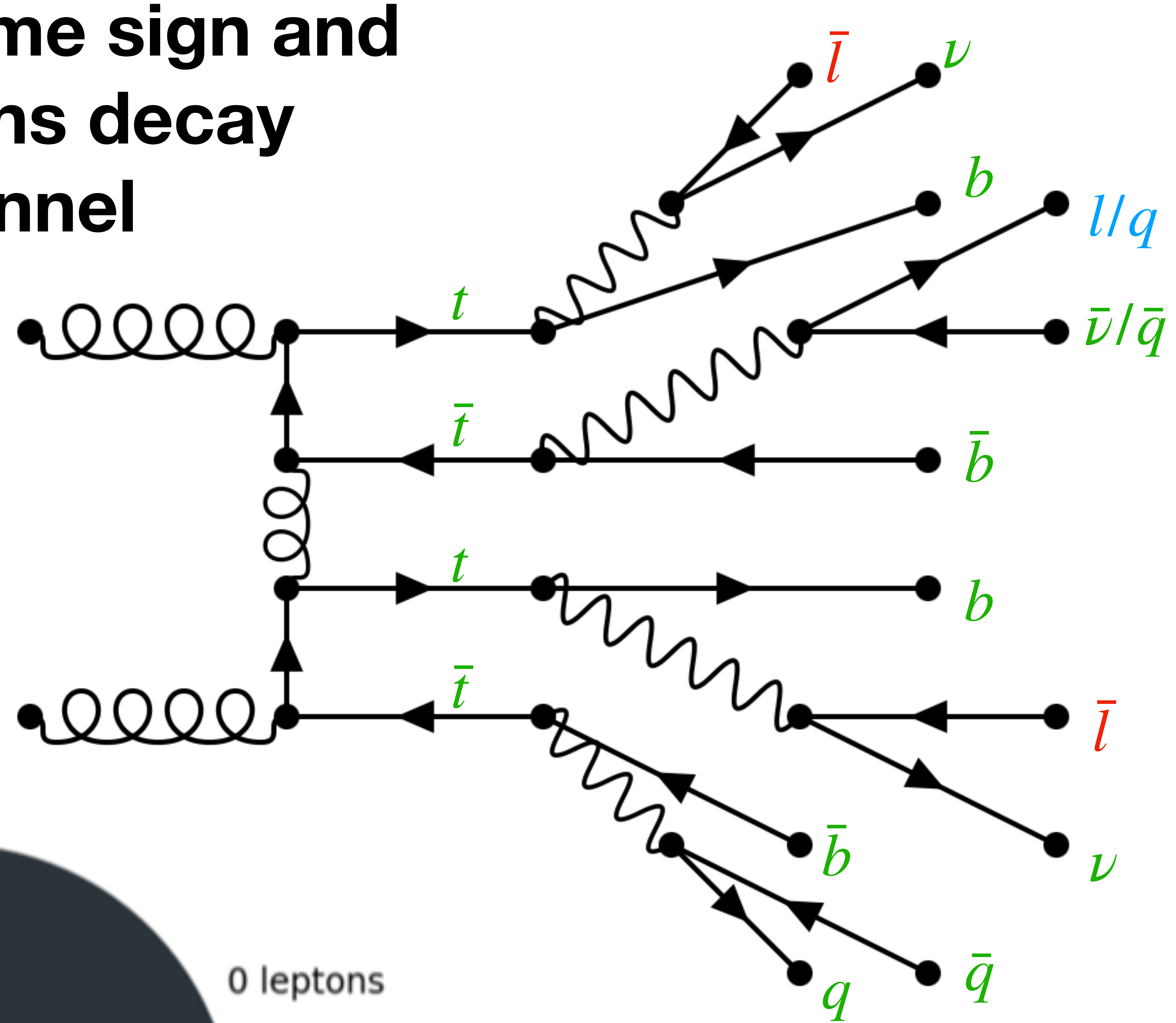
Improvements in this analysis:

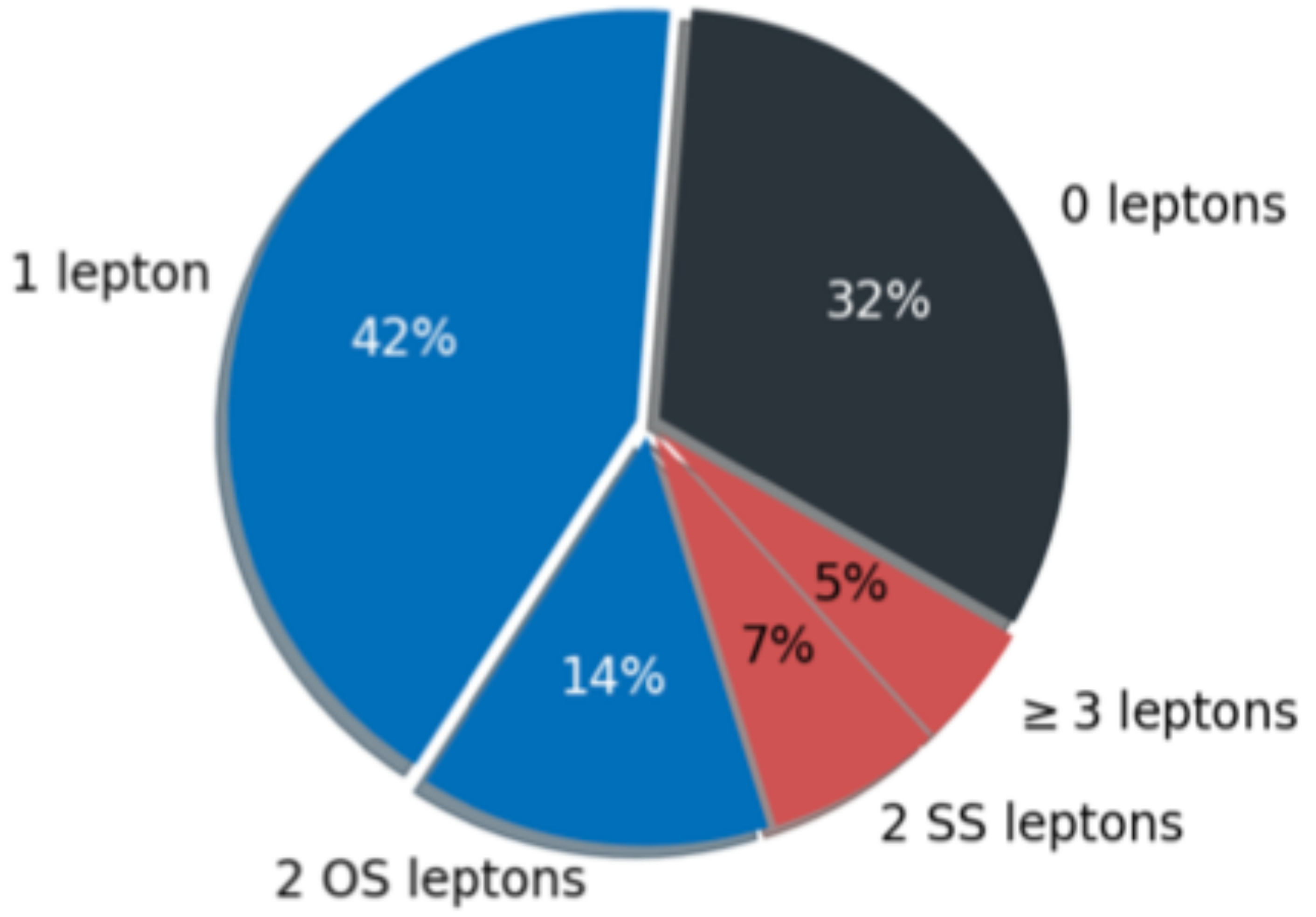
- Includes lower p_T leptons and jets —> increase acceptance
- New improved B-tagging algorithm
- Data driven estimate for the dominant $t\bar{t}W$ background
- Graph Neural Network (GNN) to separate signal and background
- Improved treatment of $t\bar{t}t$
- Updated MC simulation and luminosity calibration



Signal selection

2 lepton same sign and 3+ leptons decay channel



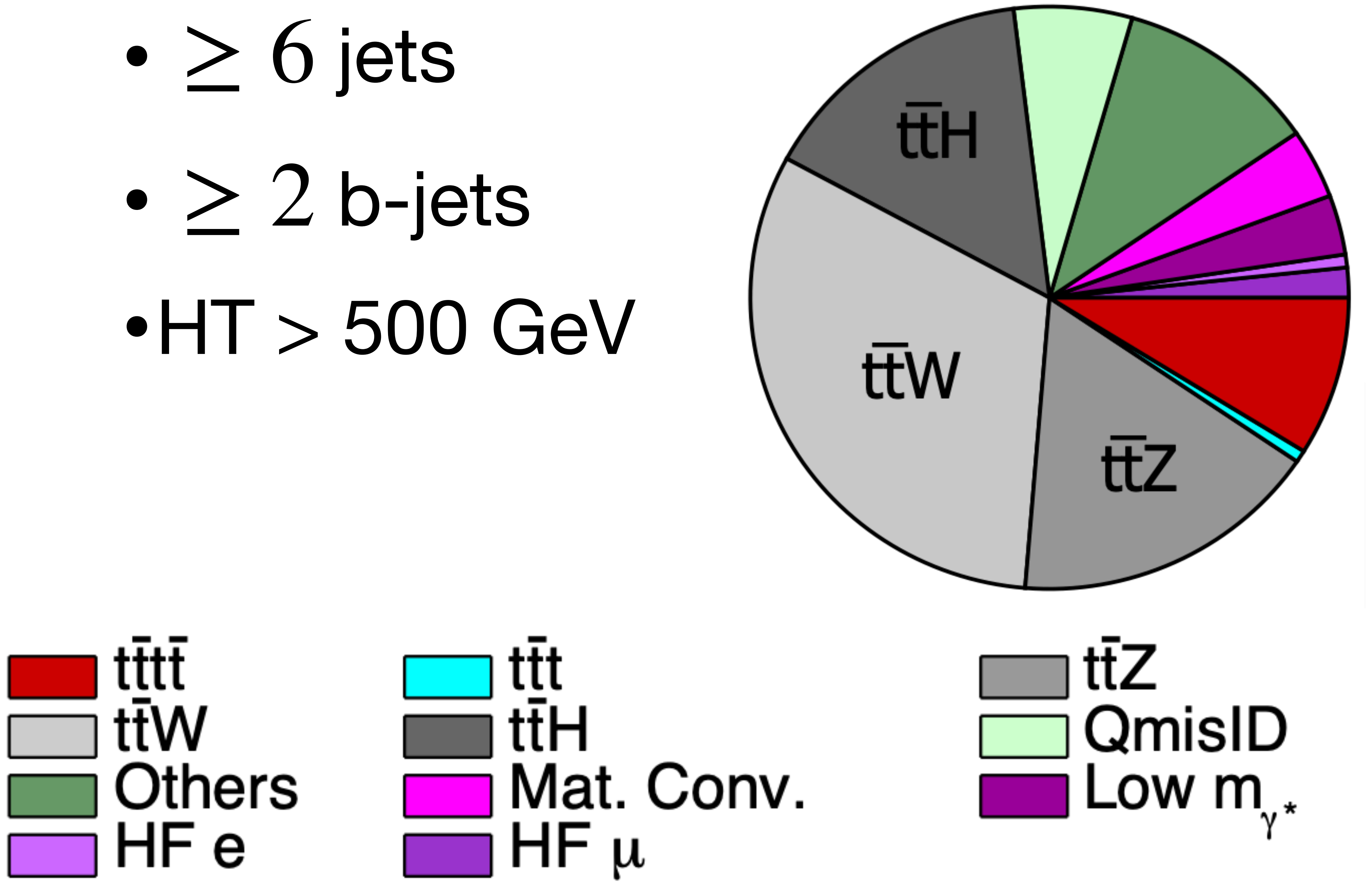


Signal Region (SR)

Definition:

- ≥ 6 jets
- ≥ 2 b-jets
- HT > 500 GeV

Composition:



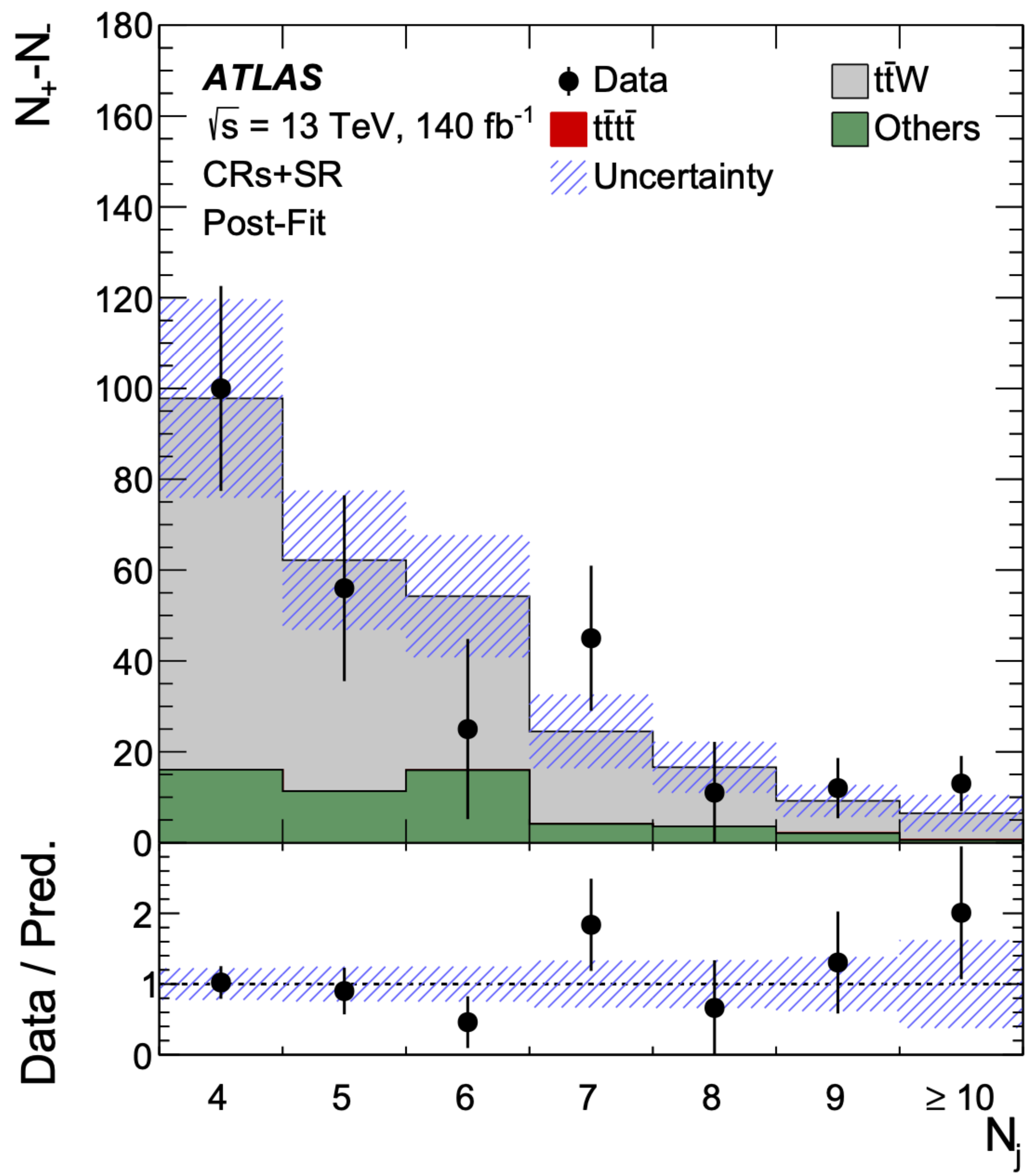
Most sensitive channels, but small branching fractions

Handling $t\bar{t}W$ background

- $t\bar{t}W$ background modelling has large uncertainties, estimated using data in jet multiplicity bins
- 4 dedicated control regions for $t\bar{t}W$ to extract 4 factors, $a_0, a_1, t\bar{t}W^+, t\bar{t}W^-$
- Scale factors a_0, a_1 are defined using:
- $N(j+1) = a_0 * N(j)$ at high jet multiplicity
- $N(j+1) = \dfrac{a_1}{1+n} * N(j)$ at low jet multiplicity

$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$

Validation by removing all charge symmetric backgrounds

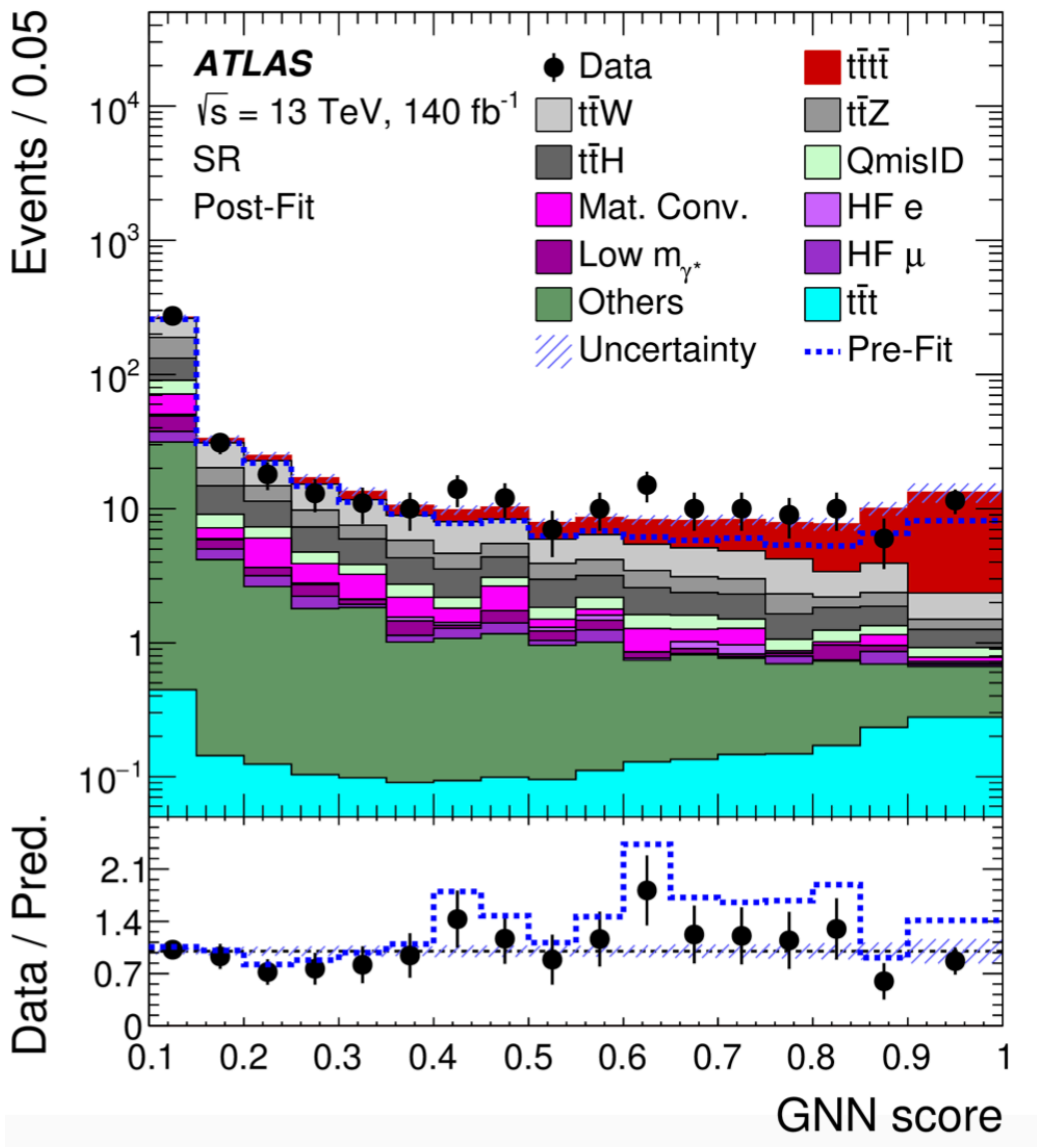


Results

- Graph Neural Network used to distinguish signal and background
- GNN output chosen as observable in signal region
- Signal generator choice and statistical uncertainties largest source of uncertainties
- Observed 6.1σ over background only hypothesis (Expected 4.3σ)

$$\sigma(t\bar{t}t\bar{t}) = 22.5^{+4.7}_{-4.3}\text{(stat)}\ ^{+4.6}_{-3.4}\text{(syst) fb}$$

Consistent with SM prediction (12.0 ± 2.4 fb) at 1.8σ



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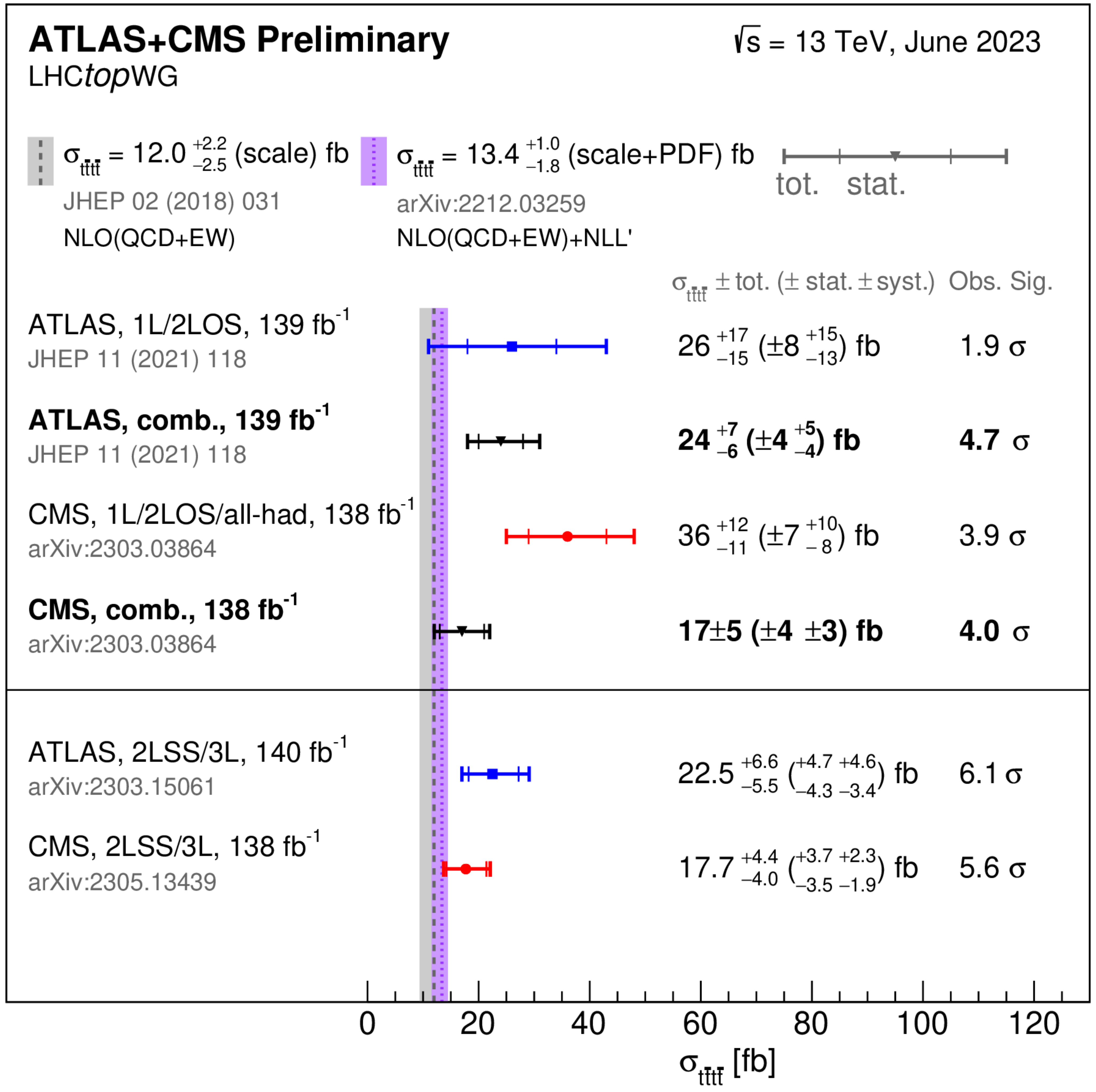
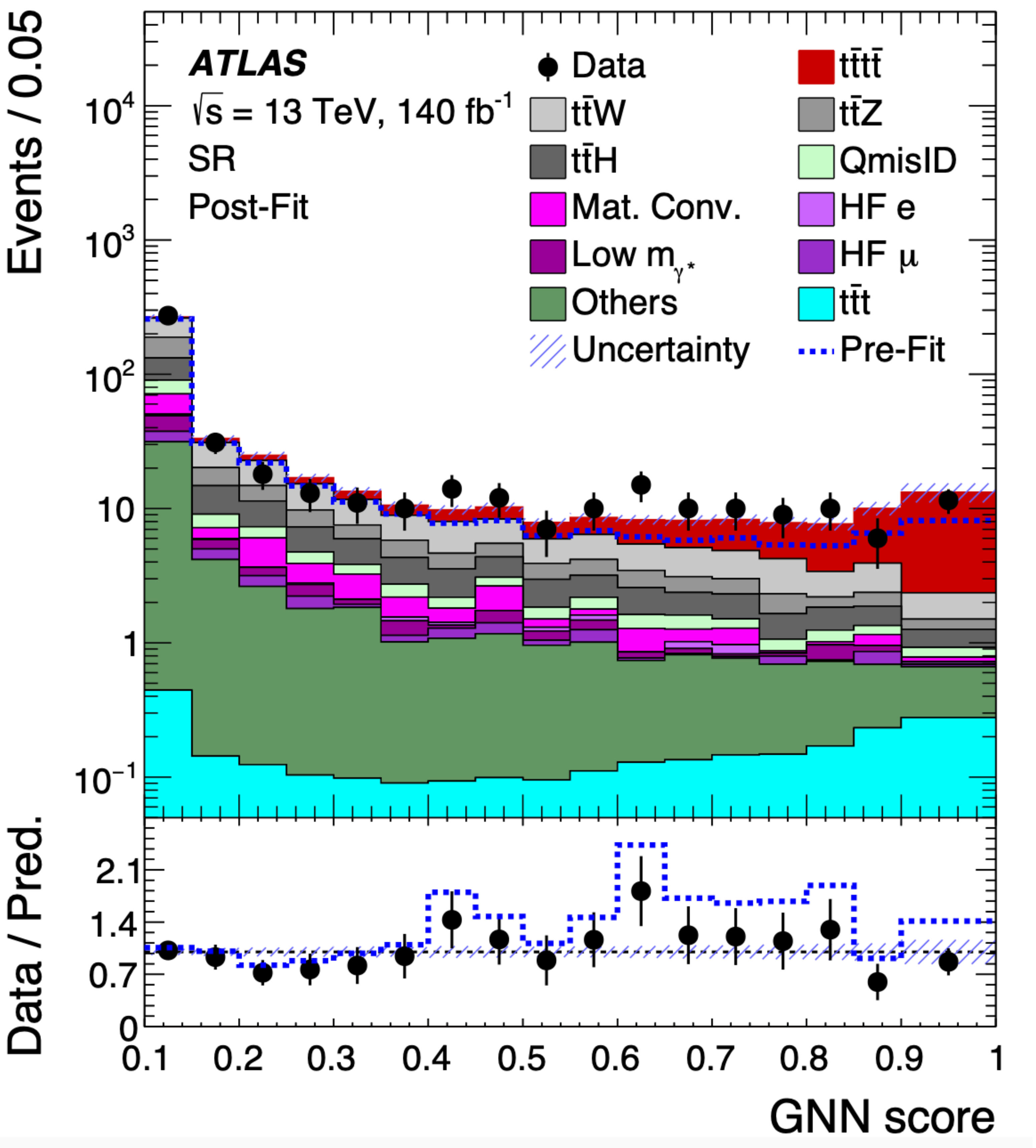
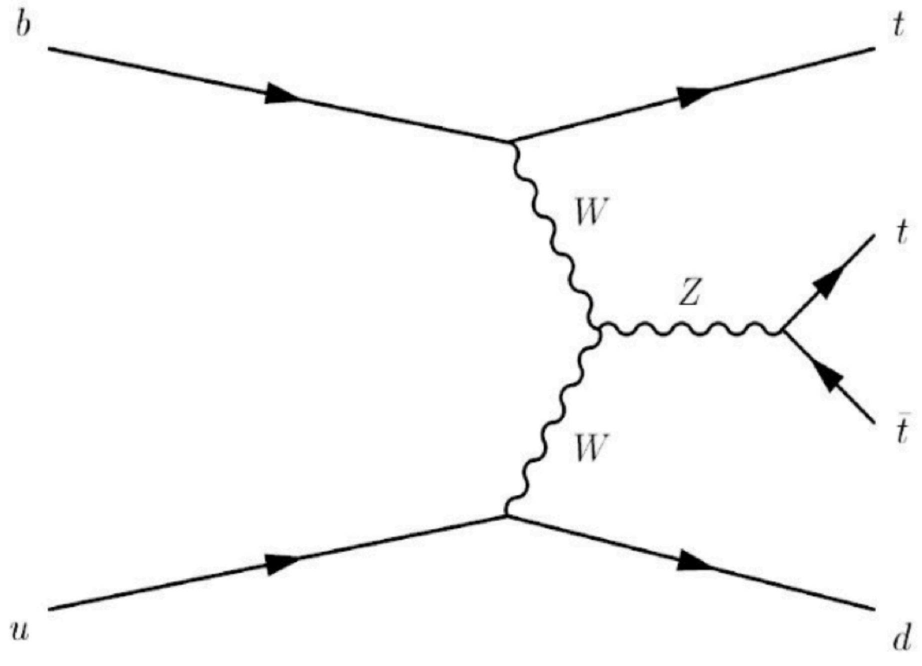


Interpretations - $t\bar{t}t$

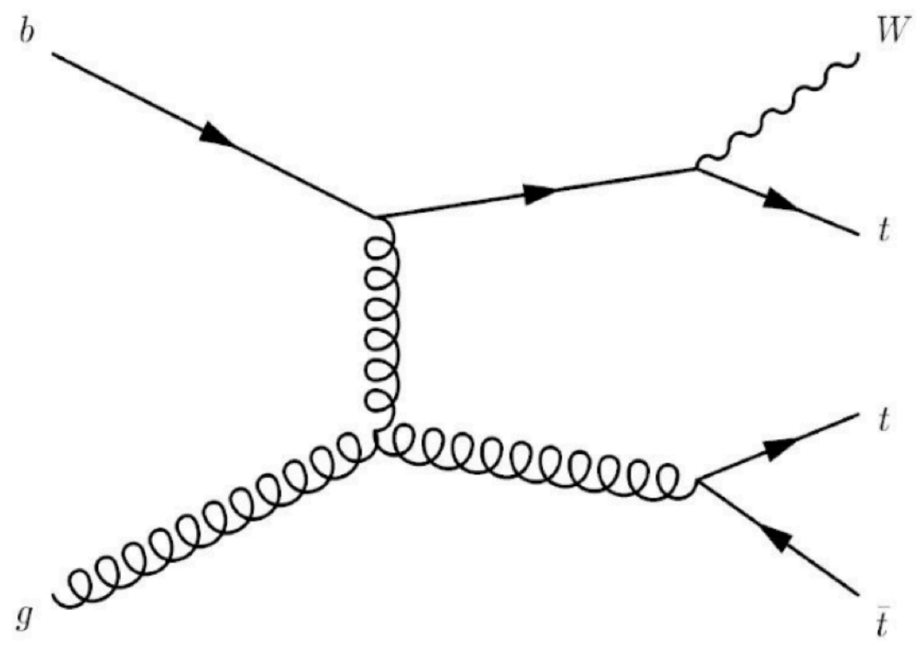
SM three top production

- Cross section ~ 10 times smaller than the four top process
- Significantly populates the signal region



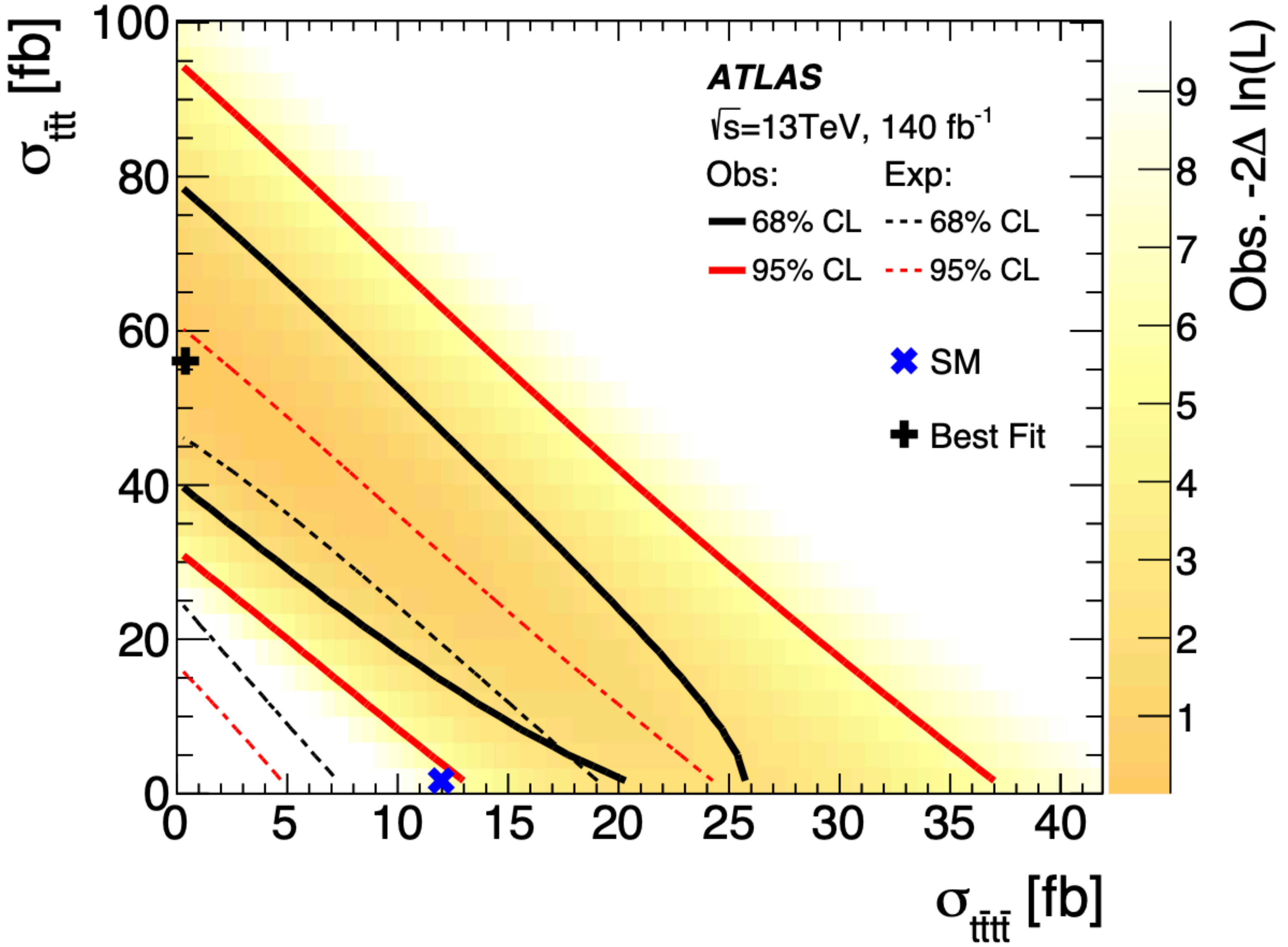


σ(tt̄t q) ~ 0.6 fb



σ(tt̄t W) ~ 1 fb

93% anti-correlation



Cross section [fb]	95% CL interval with $\mu_{t\bar{t}t\bar{t}} = 1$	95% CL interval with $\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

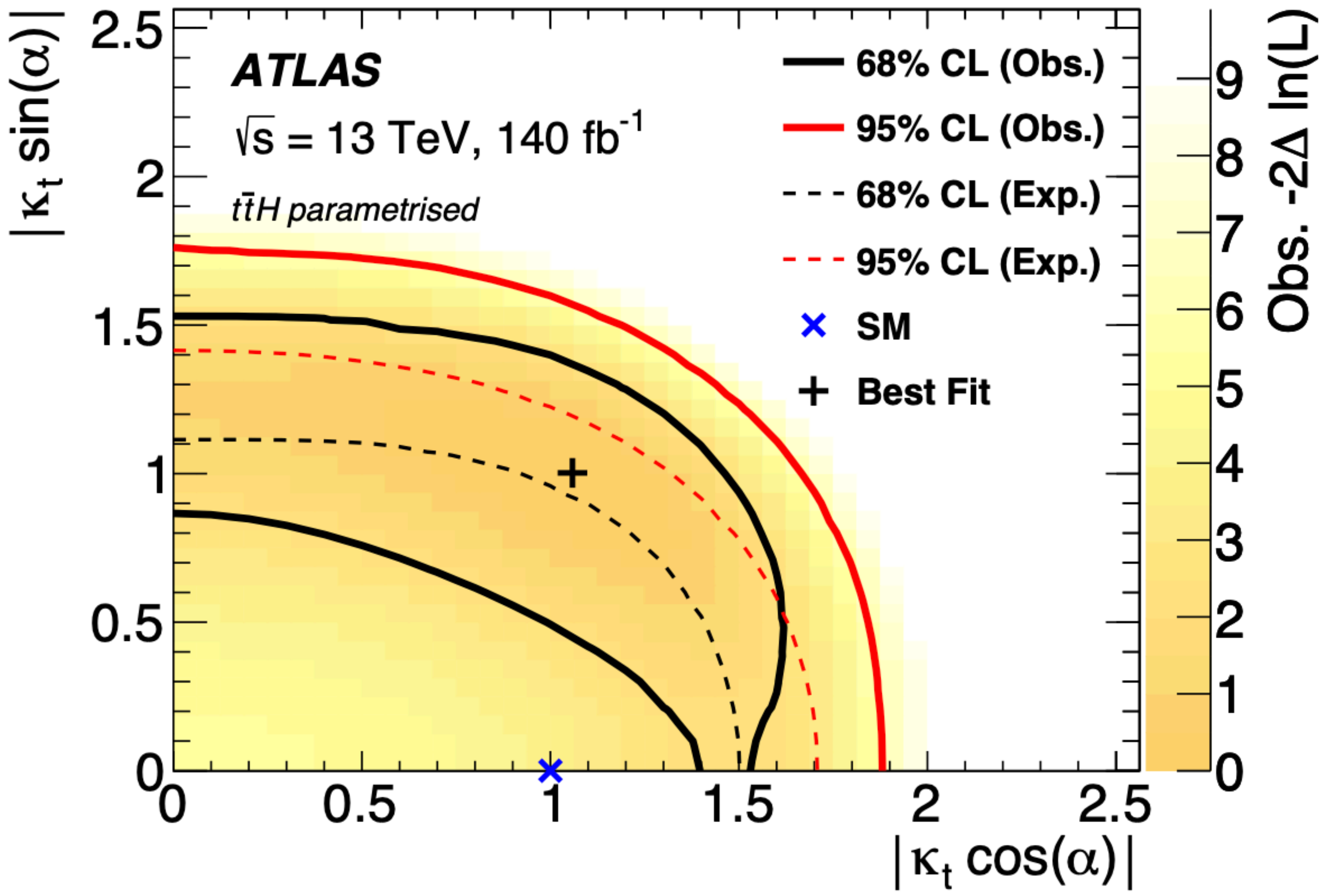
Interpretations - BSM

Top Yukawa coupling

$$\mathscr{L} = 1/\sqrt{2} h_t y_t \bar{t} (\cos\alpha + i \sin(\alpha)\gamma_5) t h$$

CP even **CP odd**

- CP even, obs (exp) |kt|<1.8 (1.6)



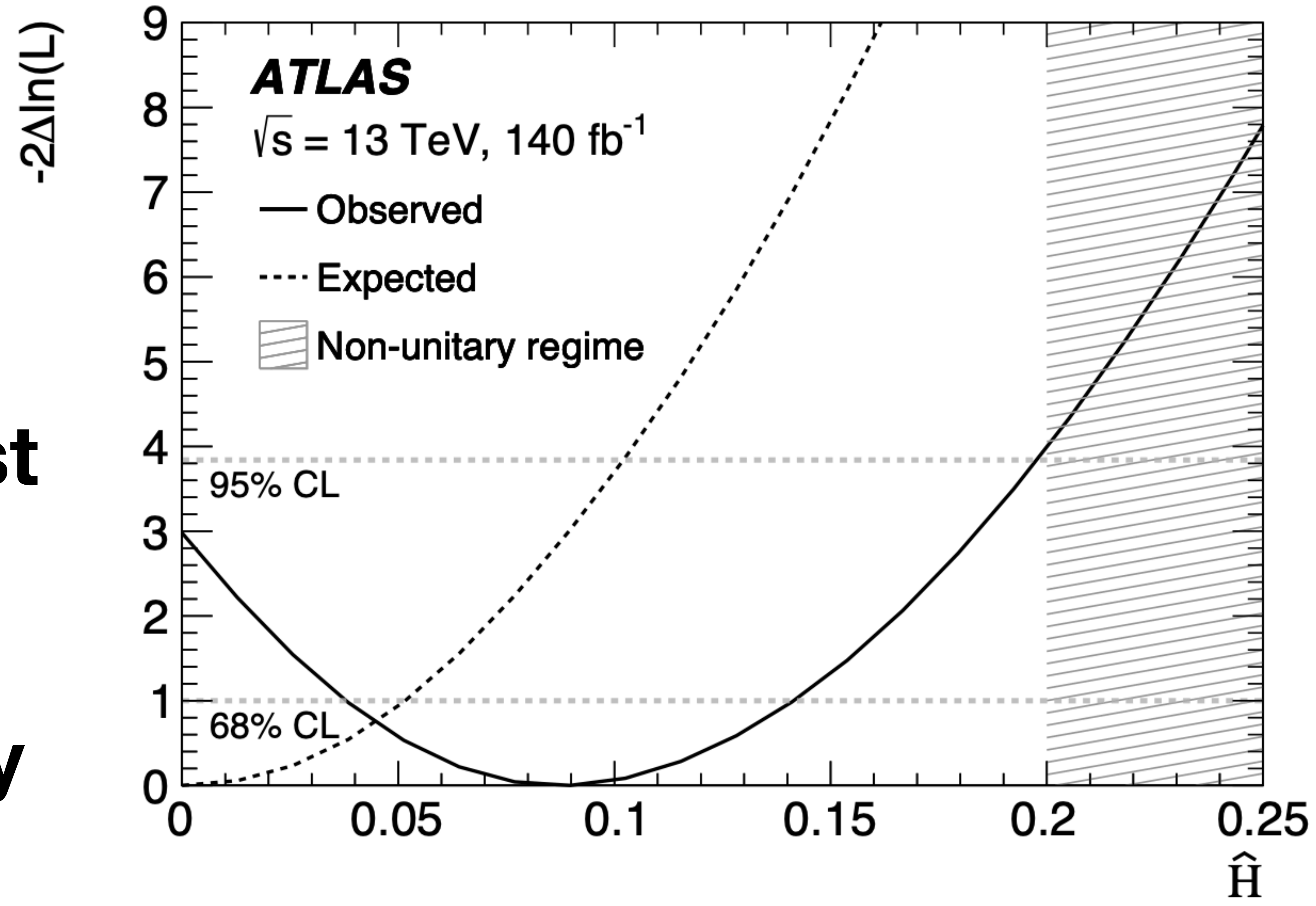
Limits on heavy flavour fermion operators in EFT

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

Higgs oblique parameter

$$\hat{H} < 0.2$$

Upper limit is extracted at largest value preserving unitarity in perturbative theory



Conclusion

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Two very interesting results from the ATLAS collaboration

- Full Run 2 ($140\ \text{fb}^{-1}$) measurement of $t\bar{t}W$ cross-section
  - Consistent with the SM upto 1.5σ
  - First differential cross-section measurement for ttW, performed for 7 observables
- First observation of four top quark production (6.1σ)
  - Limits set on three top cross-section
  - Improvement in the limits of 3 four-fermi operators
  - Upper limit set on Higgs oblique parameter
- Both processes show slight excess in comparison to SM, making it an interesting choice for further investigations especially with more data from Run 3