Overview of the $t\bar{t}W$ process and its measurements by the ATLAS experiment

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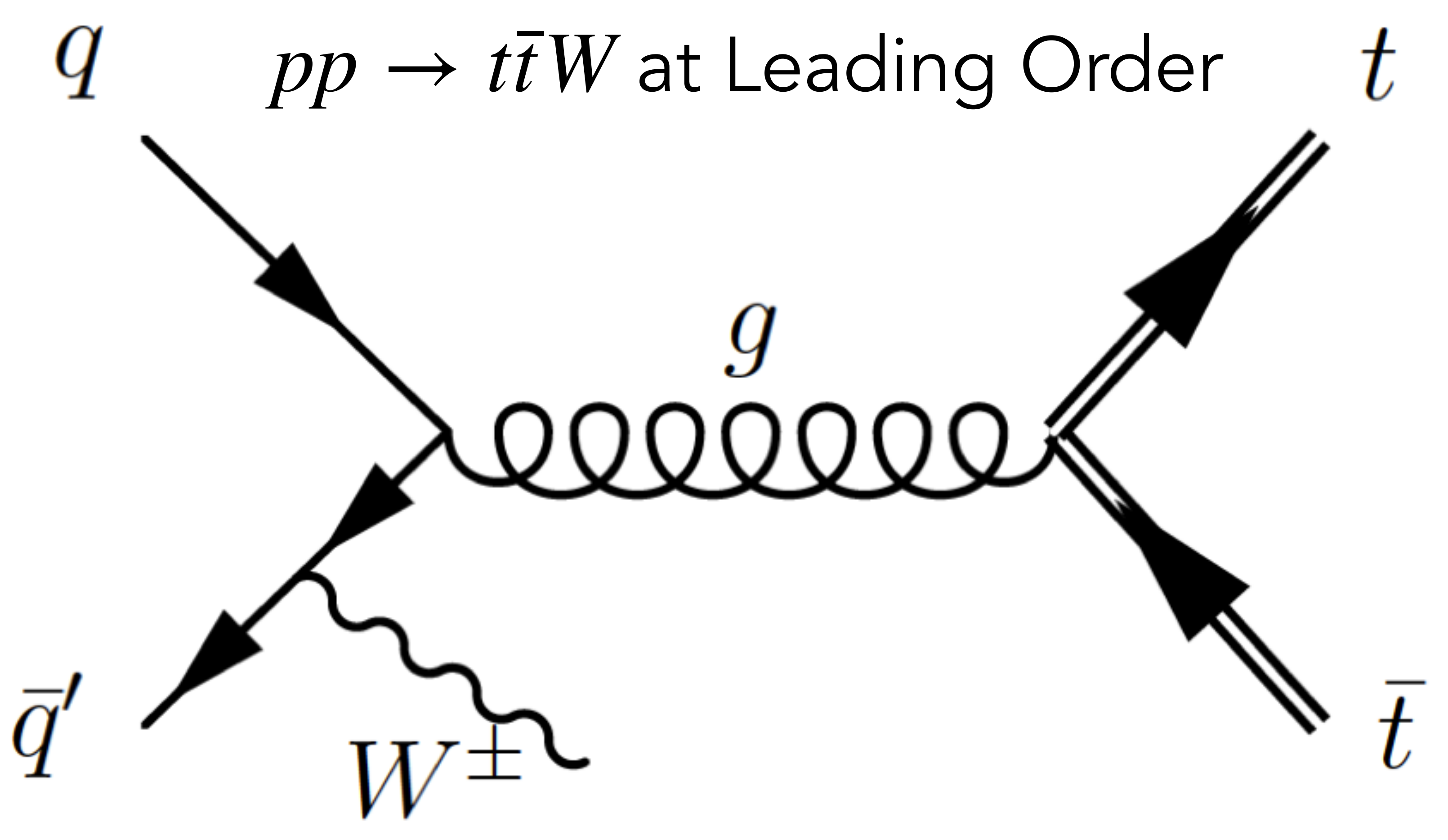
on behalf of the ATLAS Collaboration

Young Scientist Forum
Higgs Hunting 2022
Orsay/Paris, France

The landscape of $t\bar{t} + X$



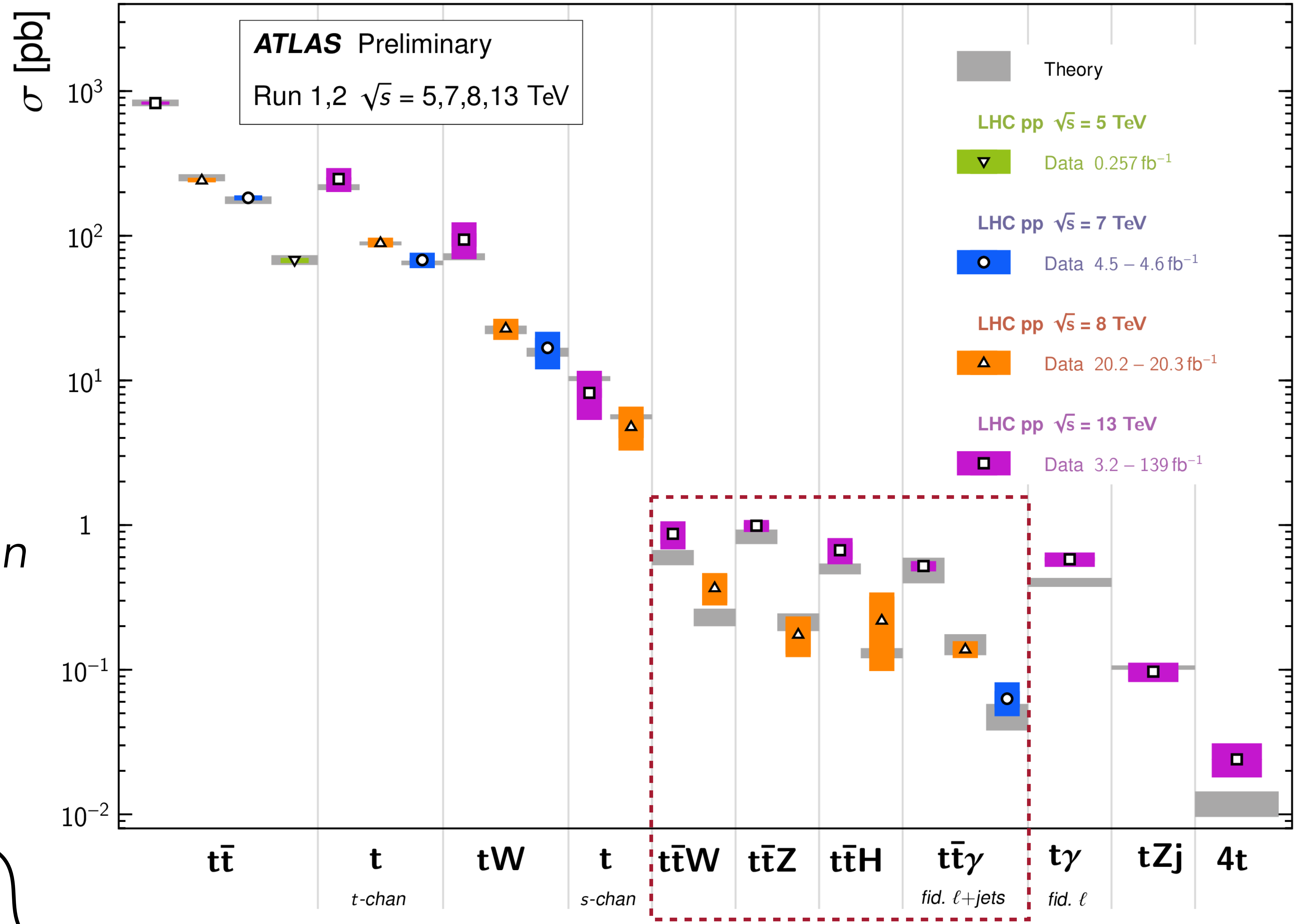
Unlike $t\bar{t}H$, $t\bar{t}Z$, and $t\bar{t}\gamma$, $t\bar{t}W$ has *no sensitivity* to top coupling to heavy boson

…but inclusive cross section ~20-50% higher than predictions!

NLO+NNLL	592^{+155}_{-97} fb	2001.03031
NLO+FxFx	722^{+71}_{-78} fb	2108.07826
ATLAS (36 fb^{-1})	870 ± 190 fb	1901.03584
CMS (36 fb^{-1})	770^{+180}_{-160} fb	1711.02547
CMS (138 fb^{-1})	868 ± 65 fb	2208.06485

Need NNLO!

Top Quark Production Cross Section Measurements ATL-PHYS-PUB-2022-031



$t\bar{t}H$-ML limited by $t\bar{t}W$

ATLAS-CONF-2019-045

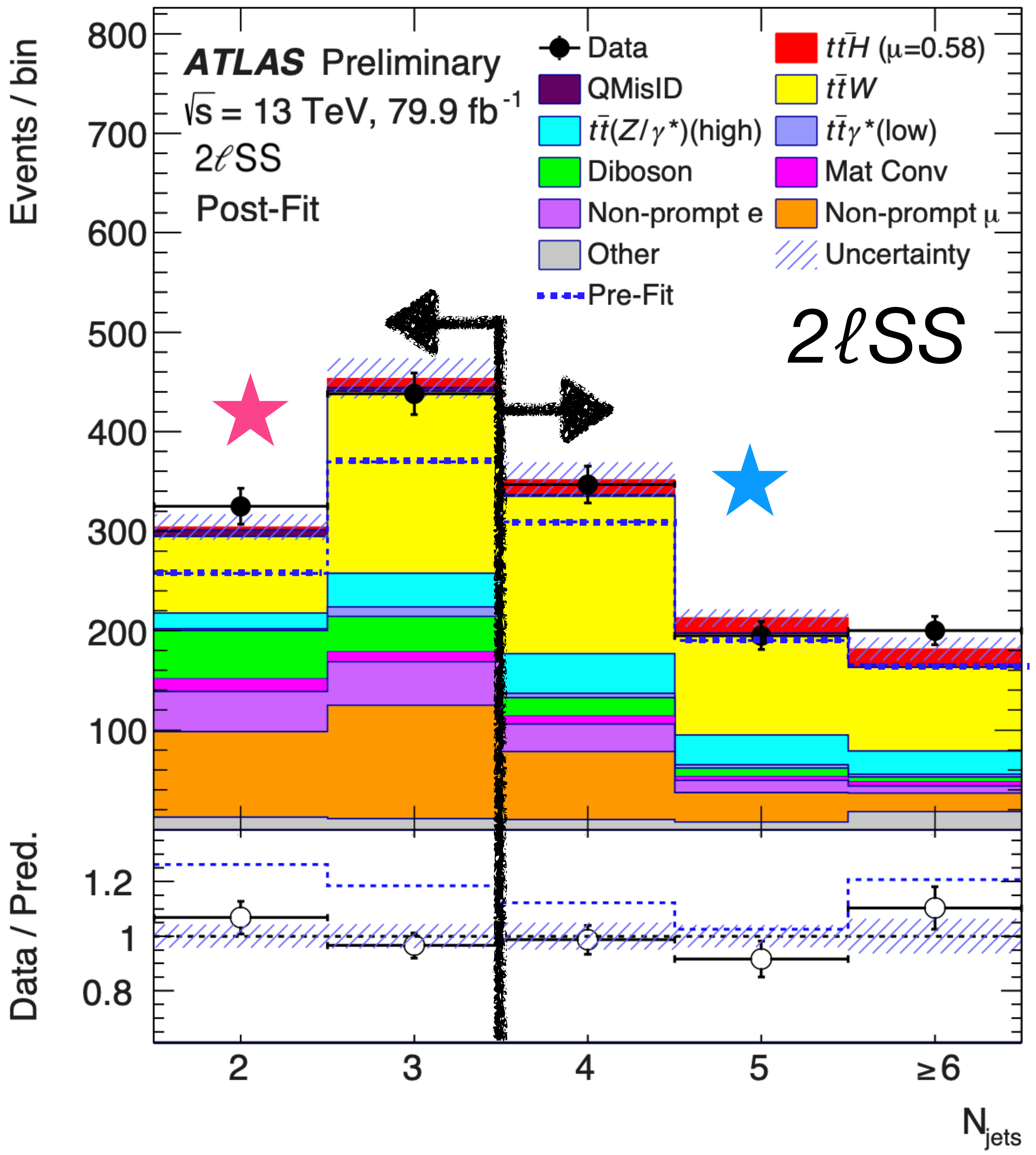
Ad-hoc ttW normalization factors

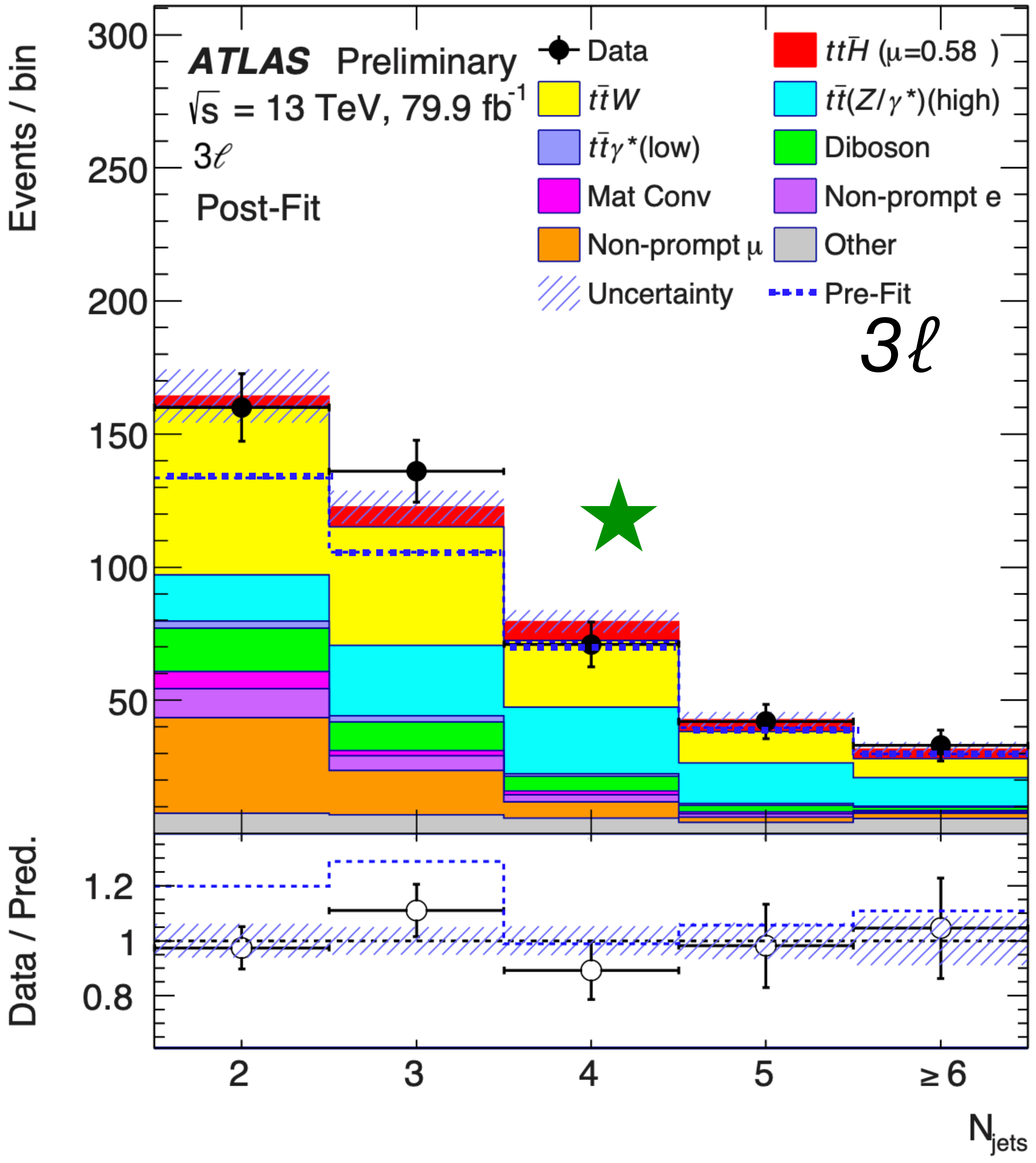
$$\lambda_{t\bar{t}W}^{2\ell,N=2,3} = 1.56^{+0.30}_{-0.28}$$

$$\lambda_{t\bar{t}W}^{2\ell,N\geq4} = 1.26^{+0.19}_{-0.18}$$

$$\lambda_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28}$$

+ NPs for charge-asymmetric, high $N_{b\text{-jet}}$ data/MC disagreement





→ Need to pin down N_{jets}, $N_{b\text{-jets}}$ in $t\bar{t}W^{\pm}$ production

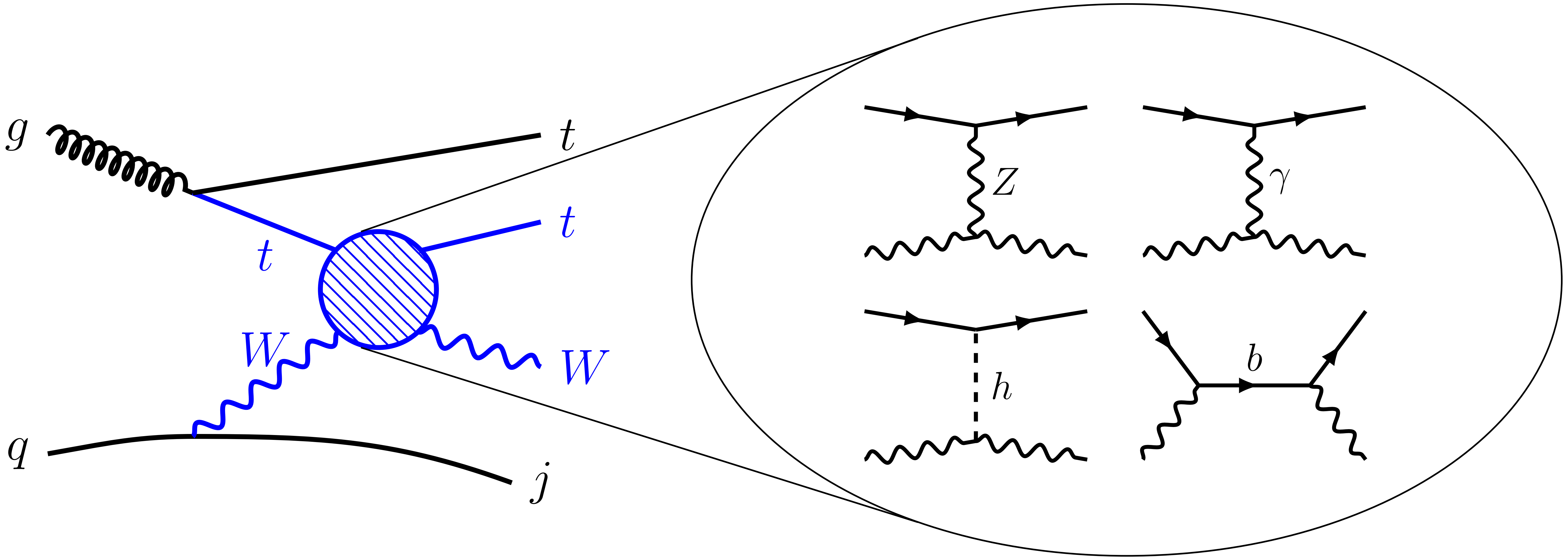
$t\bar{t}W$ as a BSM test bed - EW effects

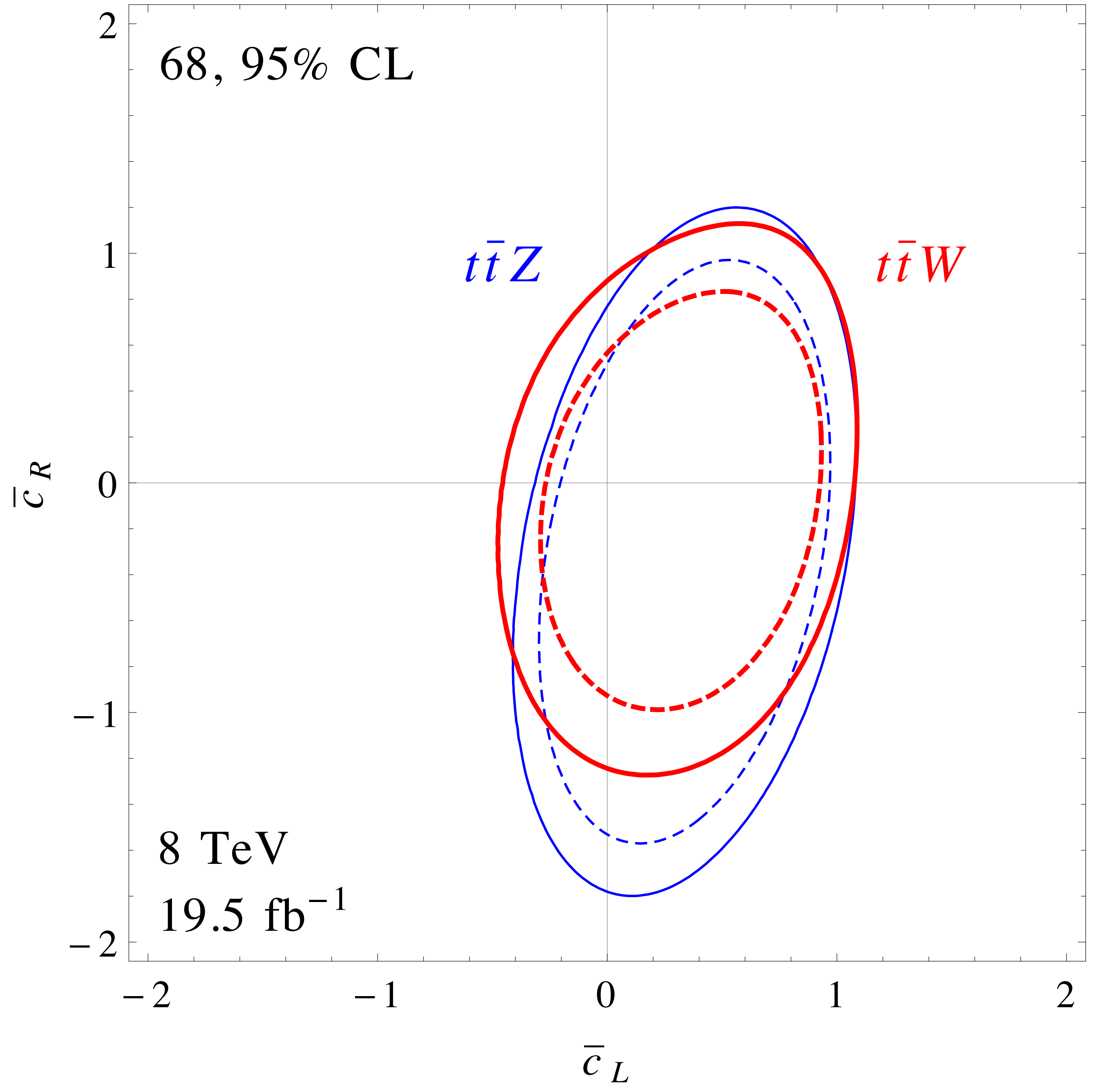
Even though $t\bar{t}W$ is not fully understood, can use it to probe BSM physics

$tW \rightarrow tW$ scattering accessible via $pp \rightarrow t\bar{t}Wj$

$\rightarrow$ complementary sensitivity to $t - Z$ and $t - H$ couplings

~5-10% of total $t\bar{t}W$ cross section





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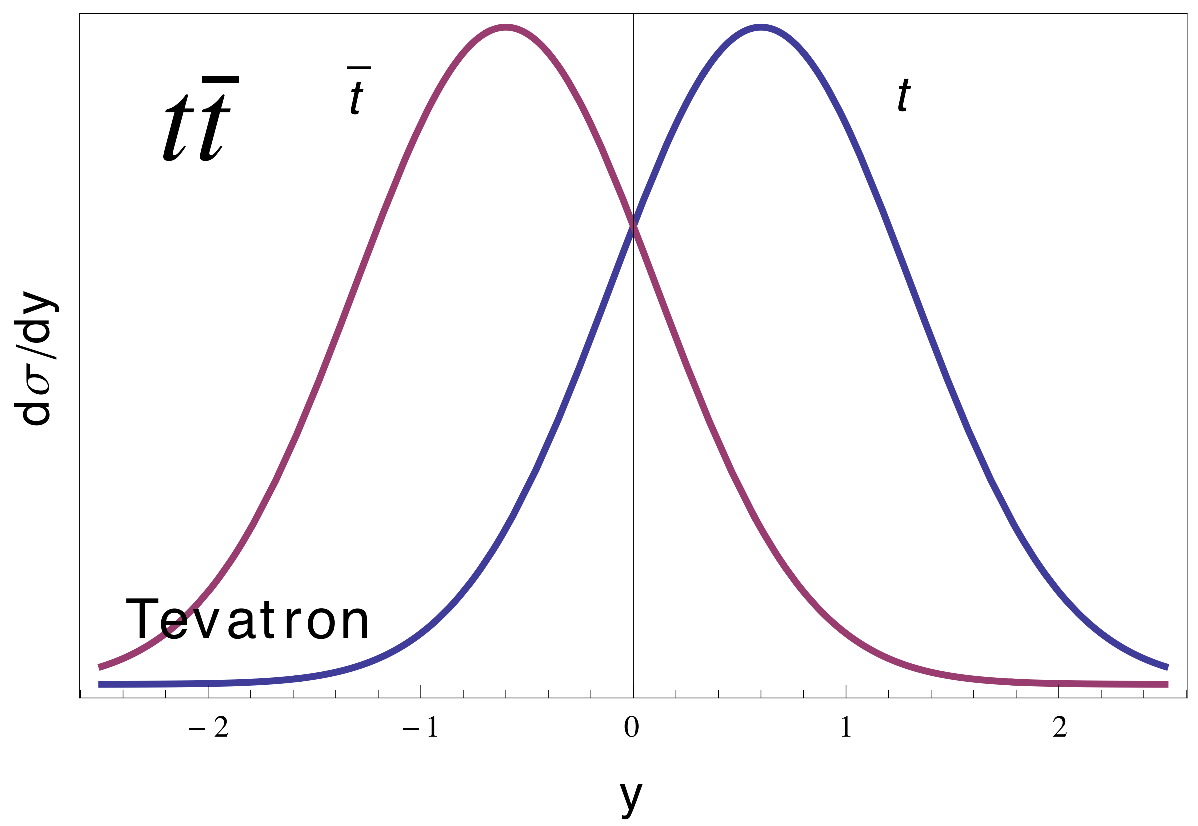
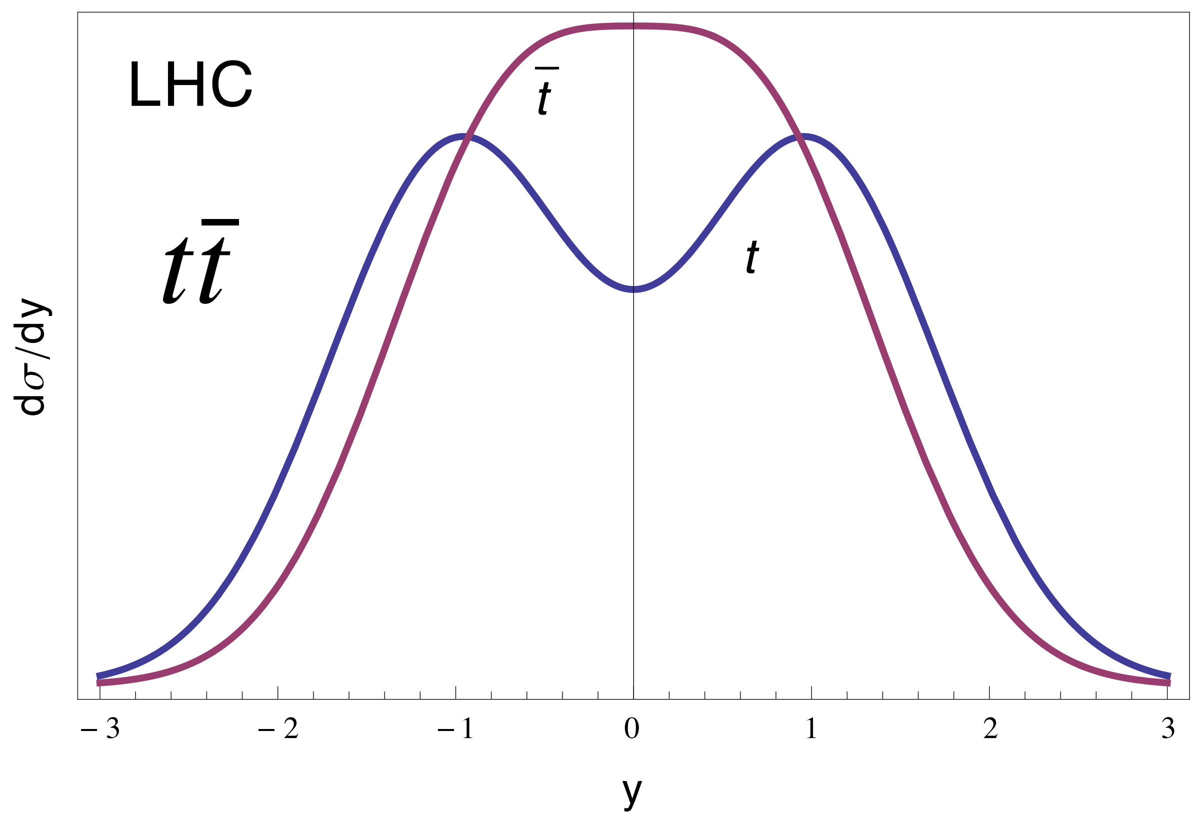
$t\bar{t}W$ as a BSM test bed - QCD effects

Even though $t\bar{t}W$ is not fully understood, can use it to probe BSM physics

Top quark rapidity asymmetry





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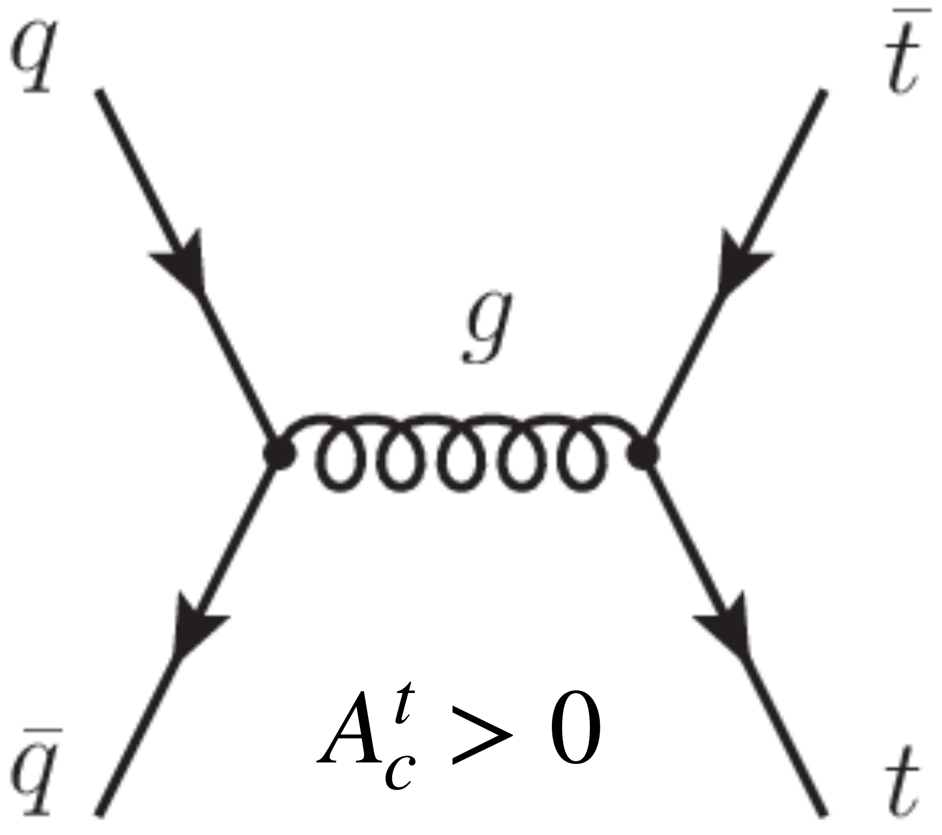
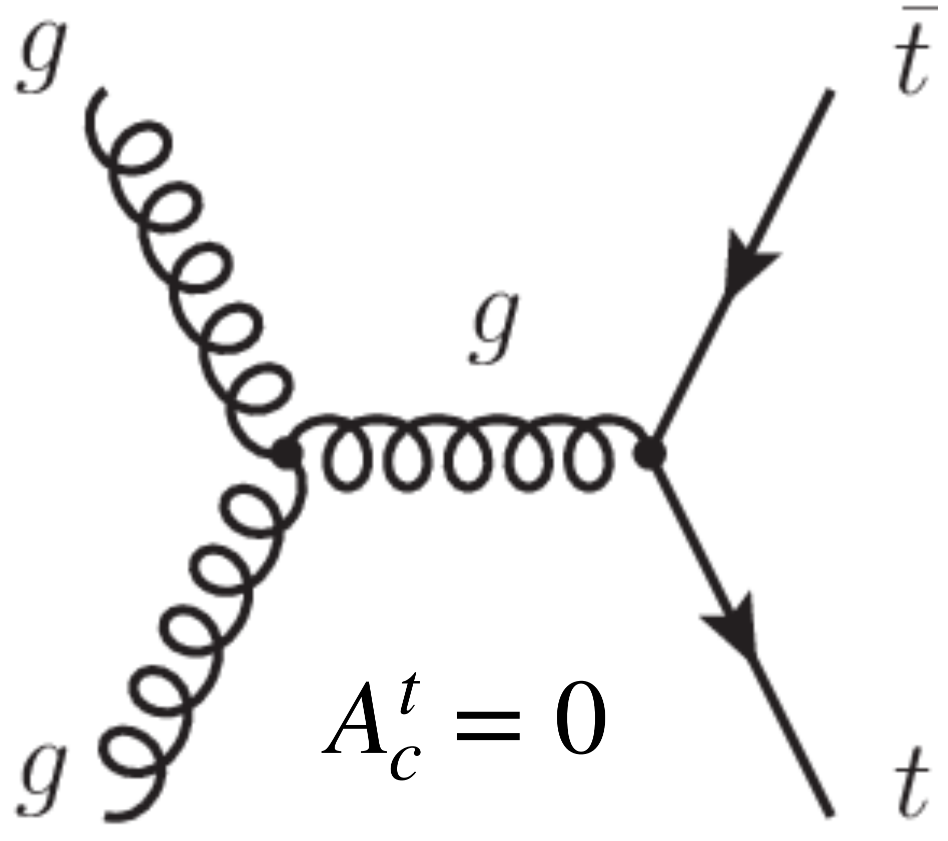
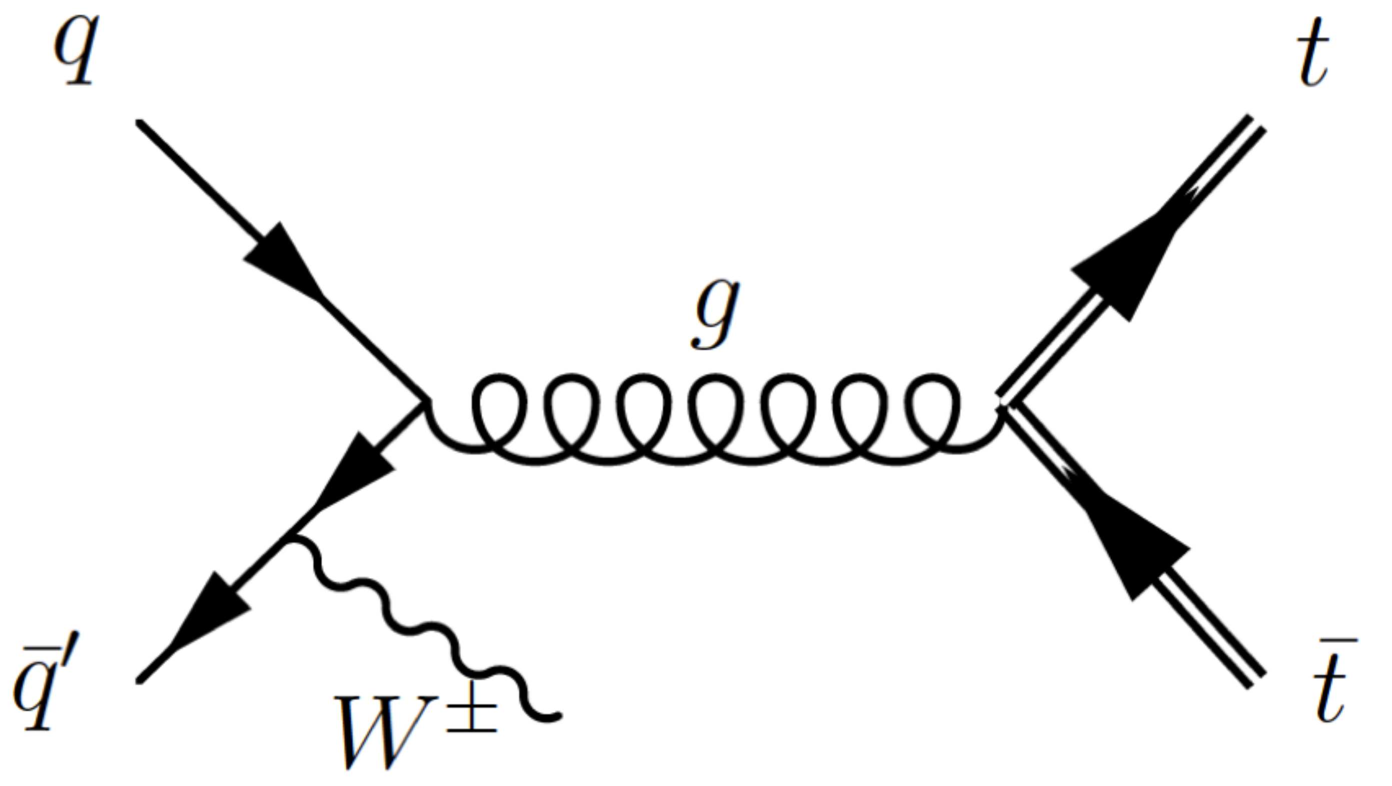




Asymmetry masked by large $gg \to t\bar{t}$ contribution at LHC

→ Enhanced asymmetry with $W^{\pm}$ ISR!

	A_c^t [%]	σ [pb]
$t\bar{t}$	$0.45^{+0.09}_{-0.06}$	661^{+99}_{-86}
$t\bar{t}W^{\pm}$	$2.24^{+0.43}_{-0.32}$	$0.587^{+0.076}_{-0.070}$



1406.3262

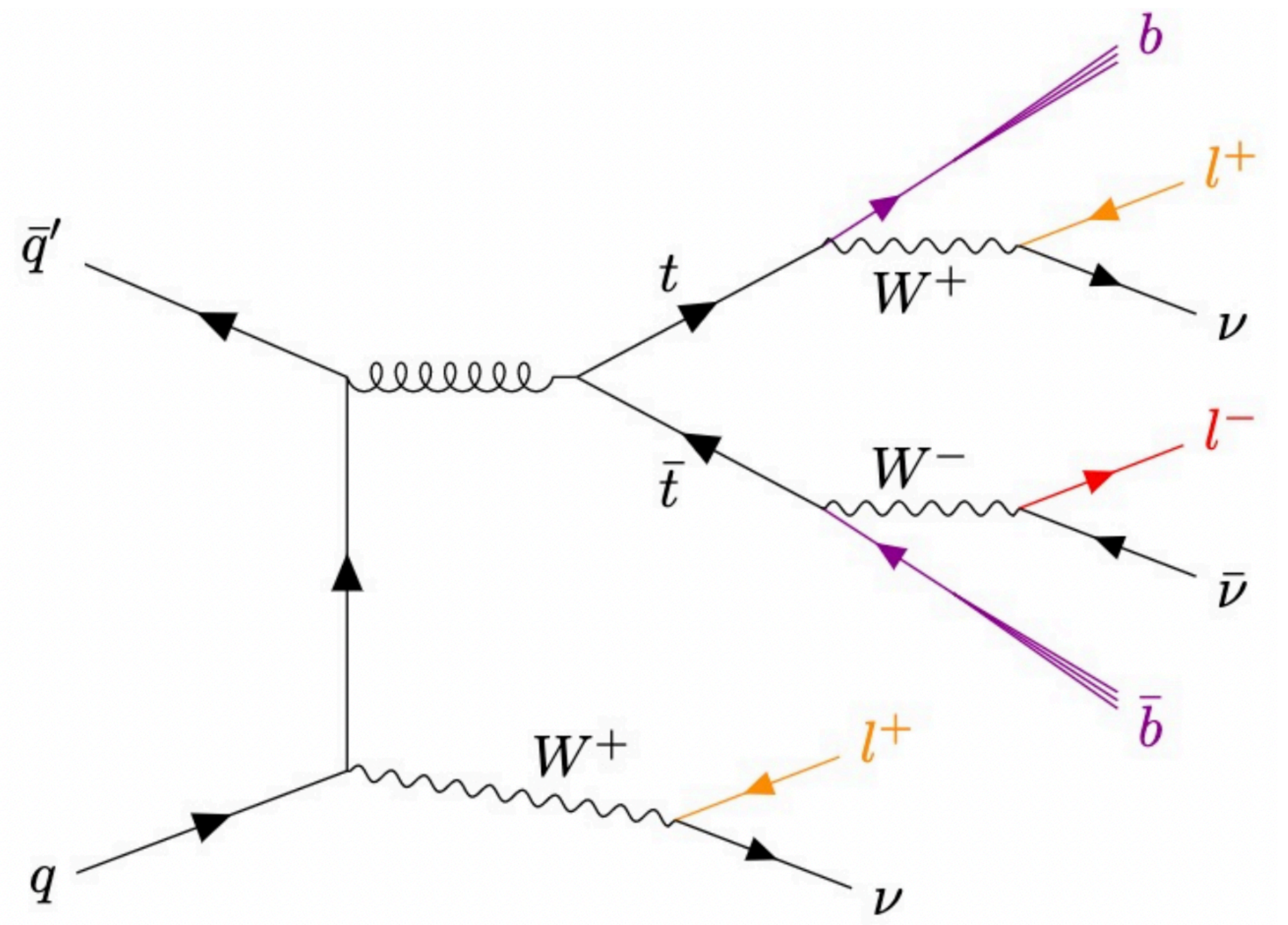
Search for leptonic CA in $t\bar{t}W$ by ATLAS

- Manifests in leptonic charge asymmetry

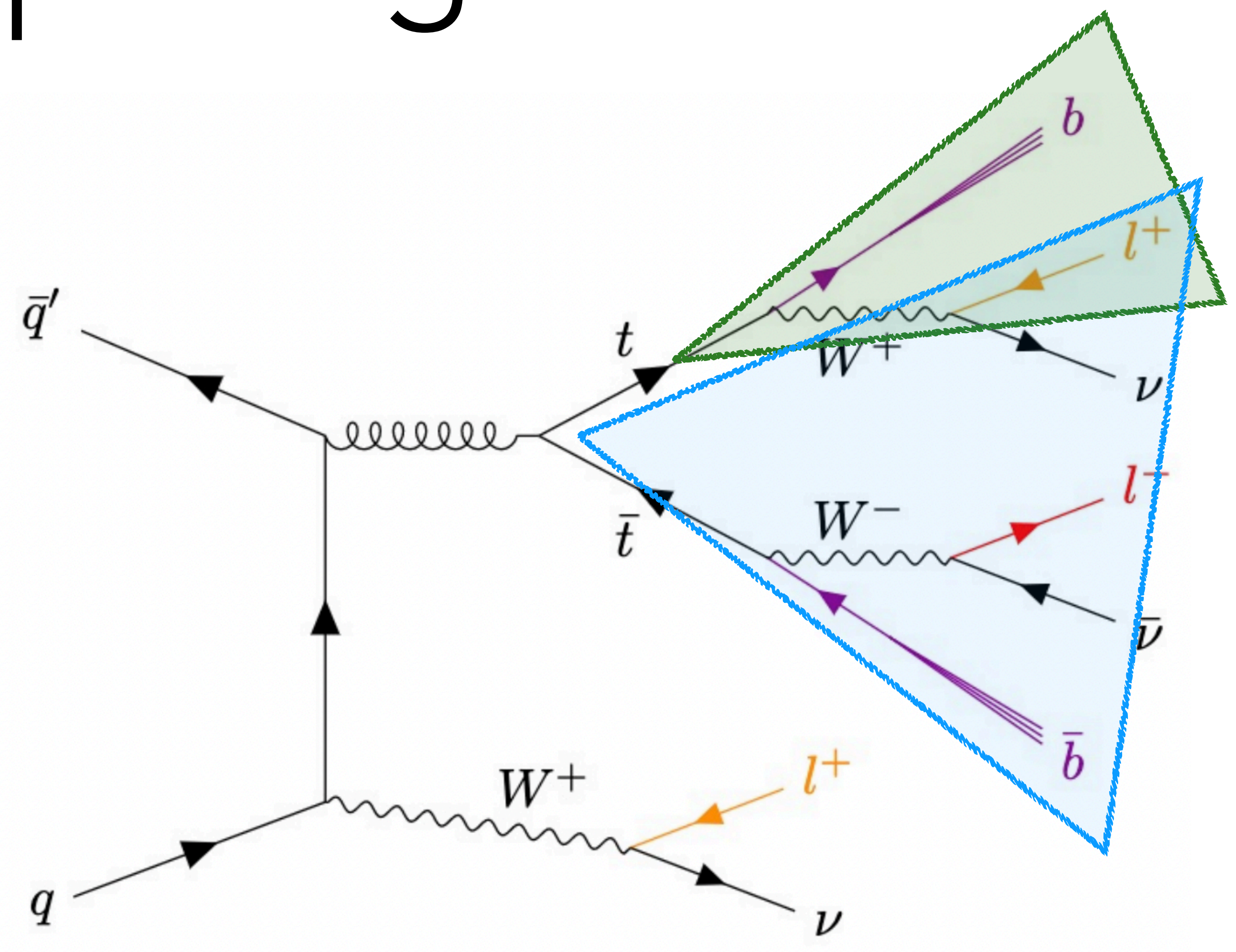
$$A_c^\ell = \frac{N(\Delta_y^\ell > 0) - N(\Delta_y^\ell < 0)}{N(\Delta_y^\ell > 0) + N(\Delta_y^\ell < 0)}, \quad \Delta_y^\ell = |y_{\ell^+}| - |y_{\ell^-}|$$

- Select events with 3 leptons, $\Sigma Q \pm 1$, ≥ 1b
  - Small fraction of total decays $t\bar{t}W$ (~1%)
  - Use BDT to associate same sign lepton to top quark
- Define CR to constrain dominant backgrounds
  - $t\bar{t}Z$, $t\bar{t}H$; fake leptons (HF, γ-conversions)
- Extract A_c^ℓ at detector-level, use profile likelihood unfolding to get fiducial A_c^ℓ at particle level

ATLAS-CONF-2022-062



Top assignment from with BDT



B-jets ordered in ΔR to lepton

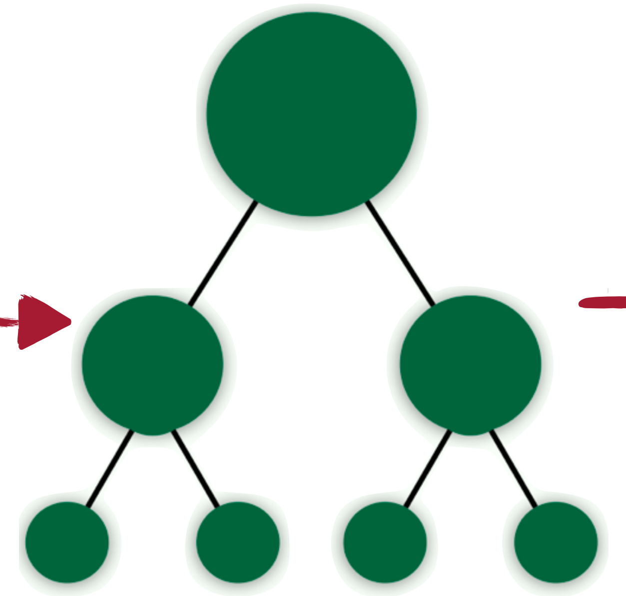
★ m_{lb_0}

m_{lb_1}

ΔR_{lb_0}

ΔR_{lb_1}

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

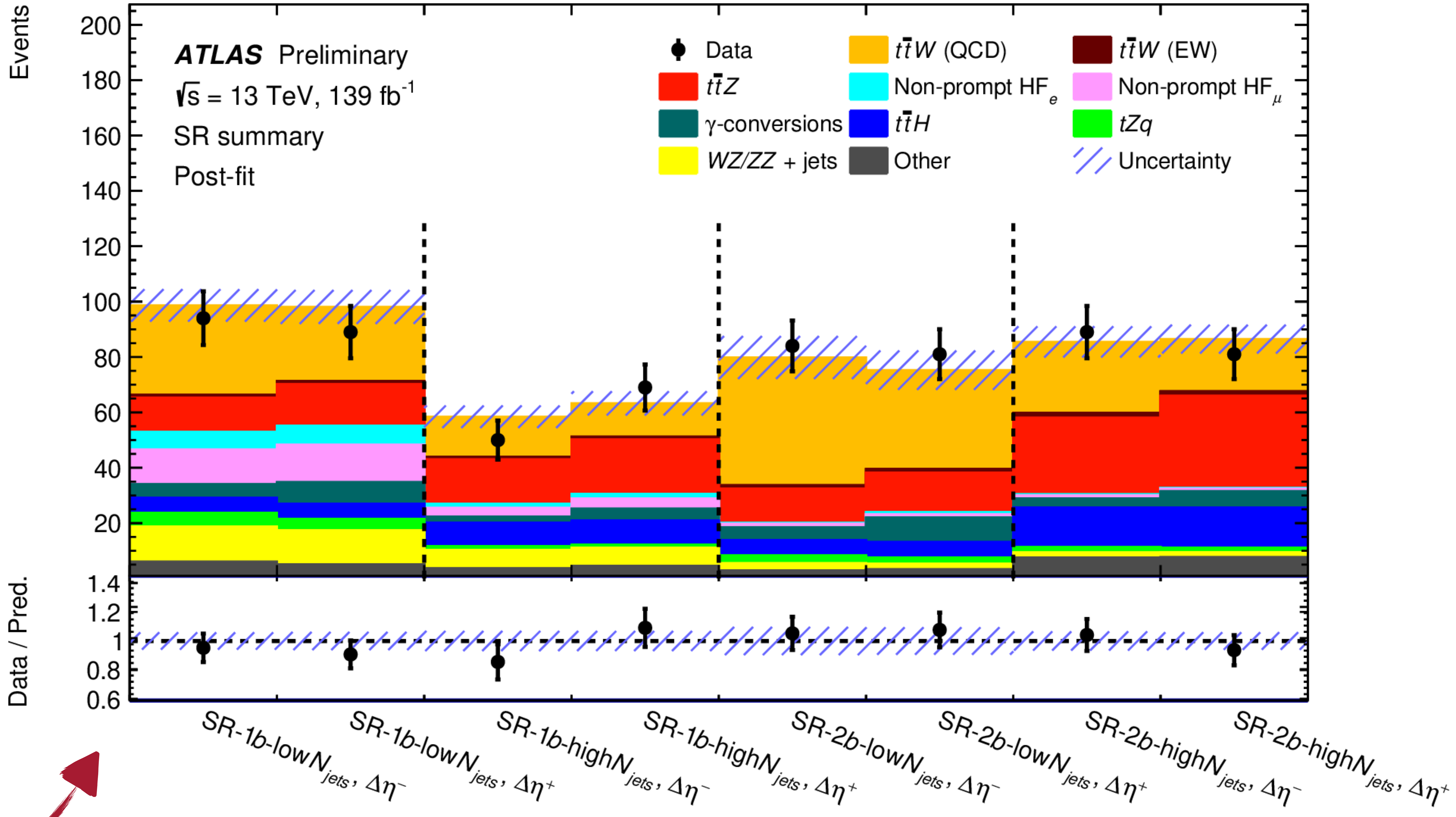


71% accurate!

Top-association score

Winning SS lepton + OS lepton form $t\bar{t}$ lepton candidates

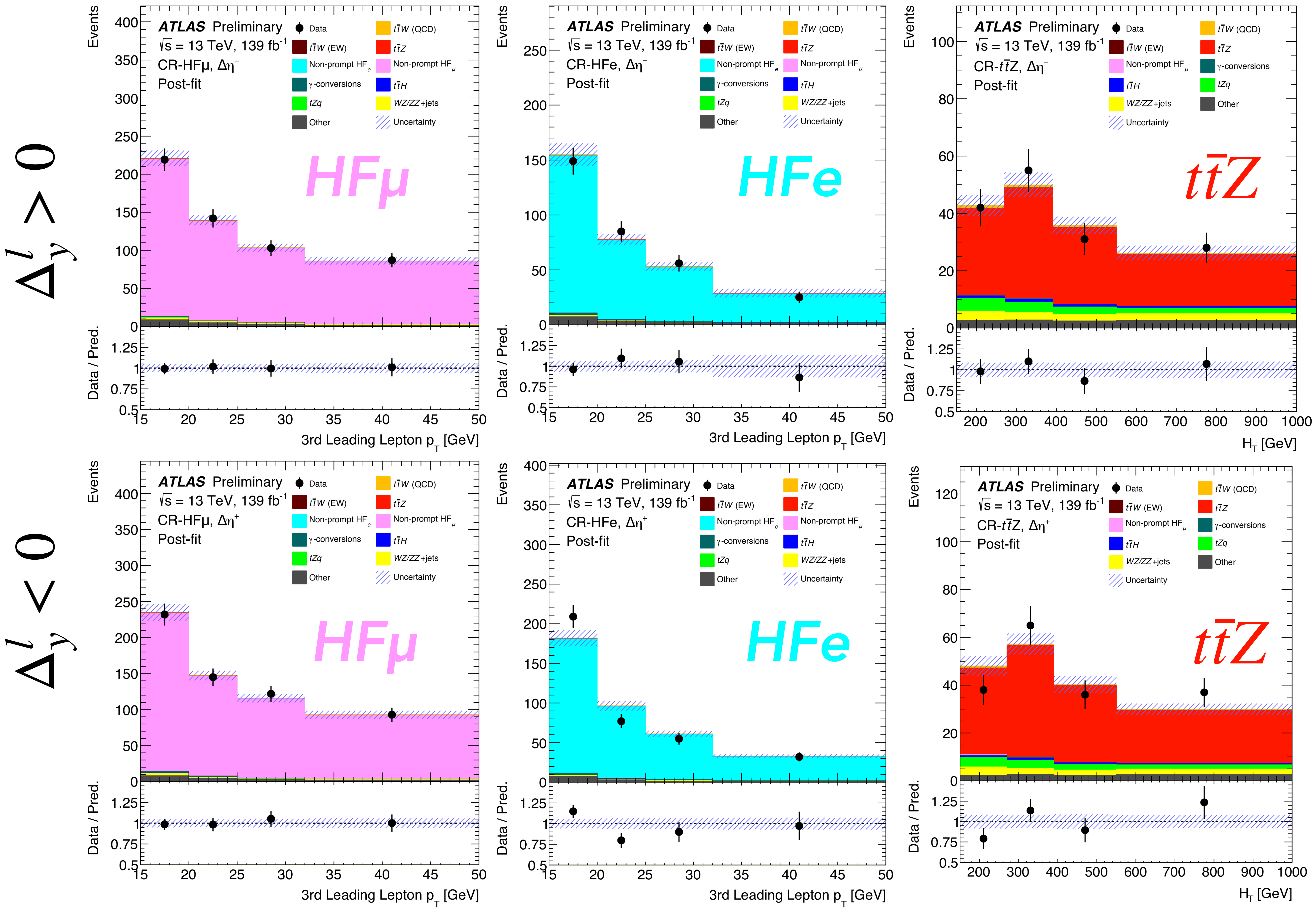
Signal regions split by (b-)jet multiplicities



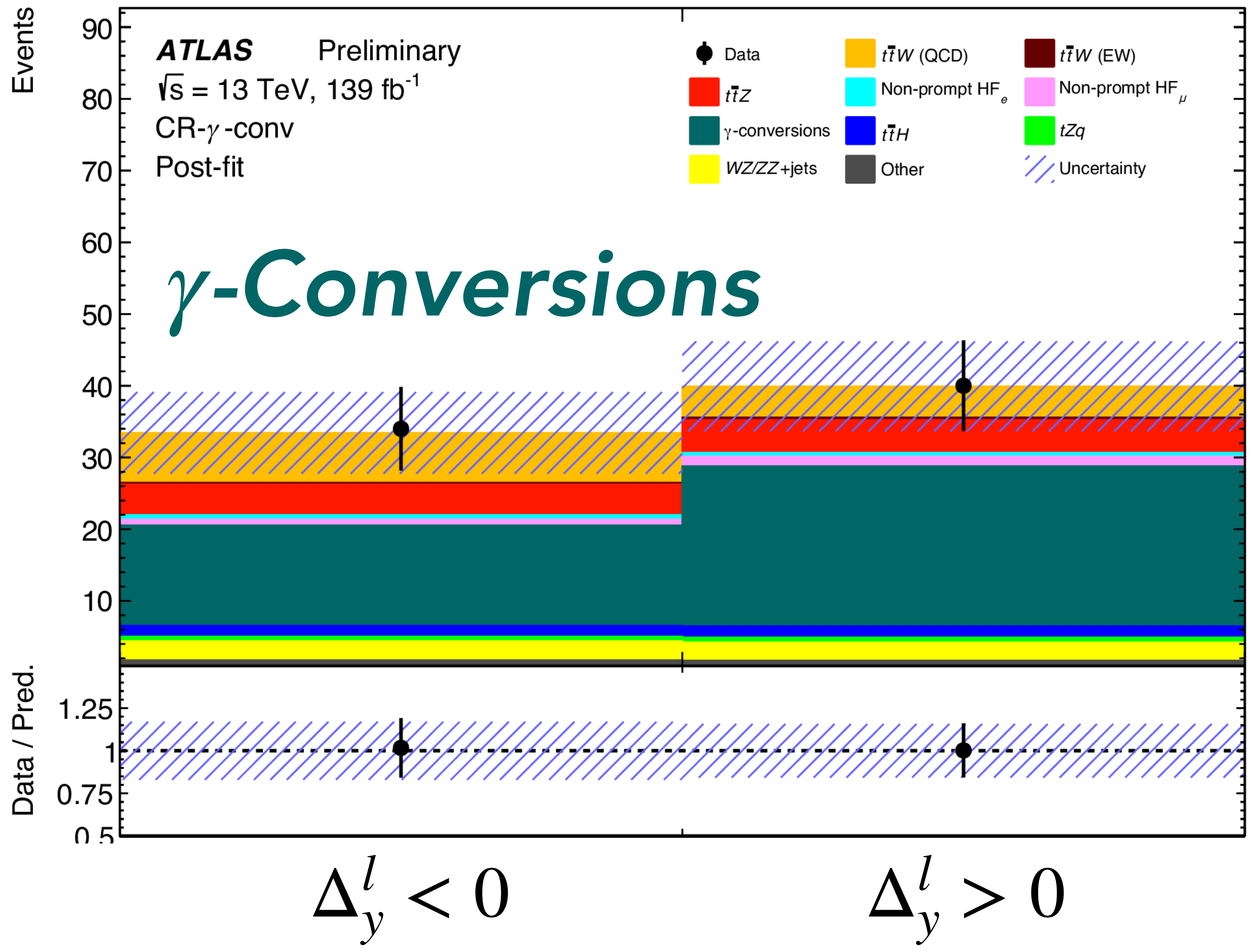
Split SRs by sign of

$$\Delta_y^\ell = |y_{\ell^+}| - |y_{\ell^-}|$$

Control regions



- → target dominant backgrounds with CR, split by the sign of Δ_y^l
- → fit NF to data with A_c^l



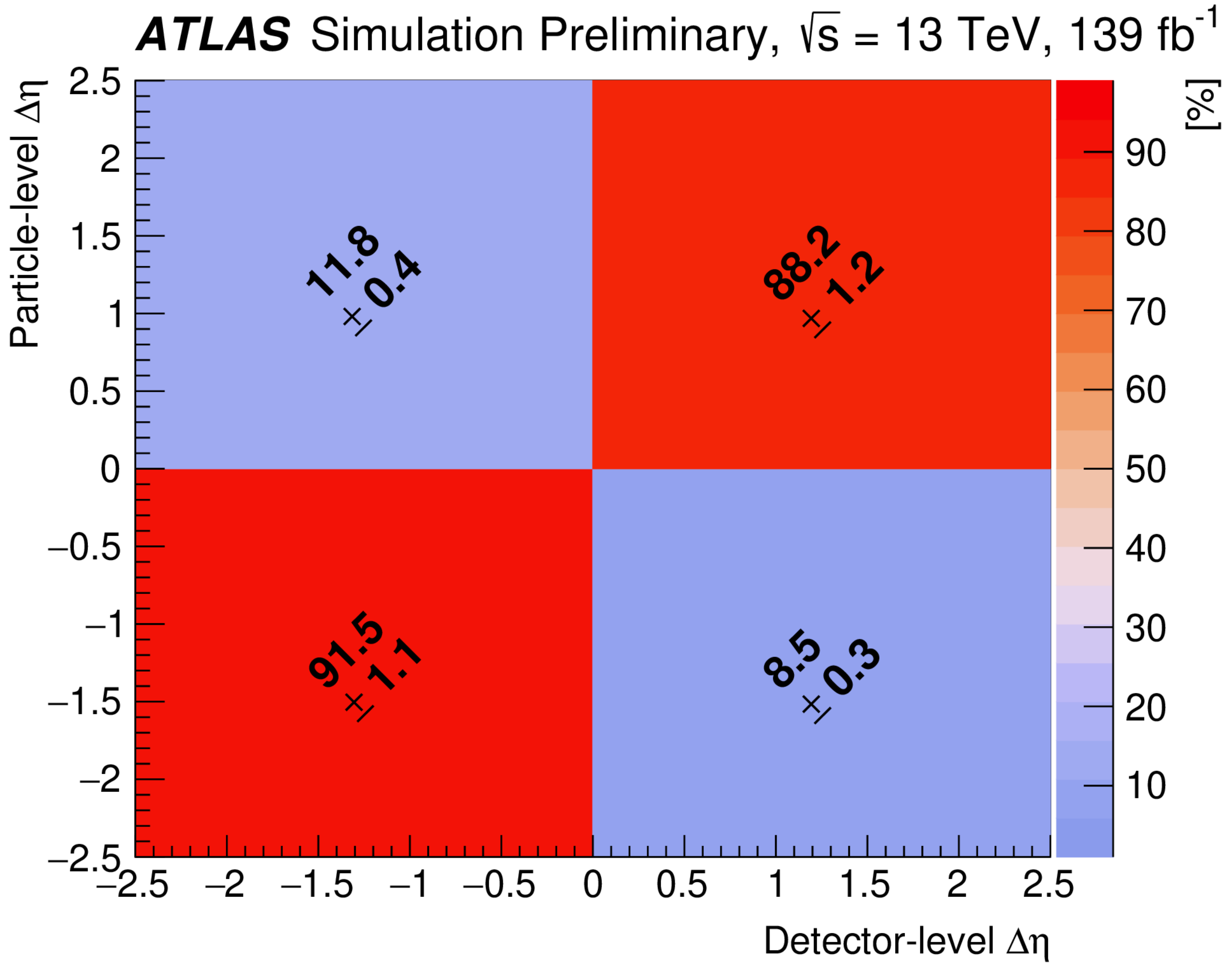
Particle-level unfolding

- Fiducial region slightly looser than detector-level
  - Top-assignment by $m_{\ell b_0}$ nearest true $m_{\ell b}^{t\to b\ell\nu}$ peak
- Profile likelihood unfolding, no regularization
  - Injection tests of $t\bar{t}W$ asymmetry to test bias

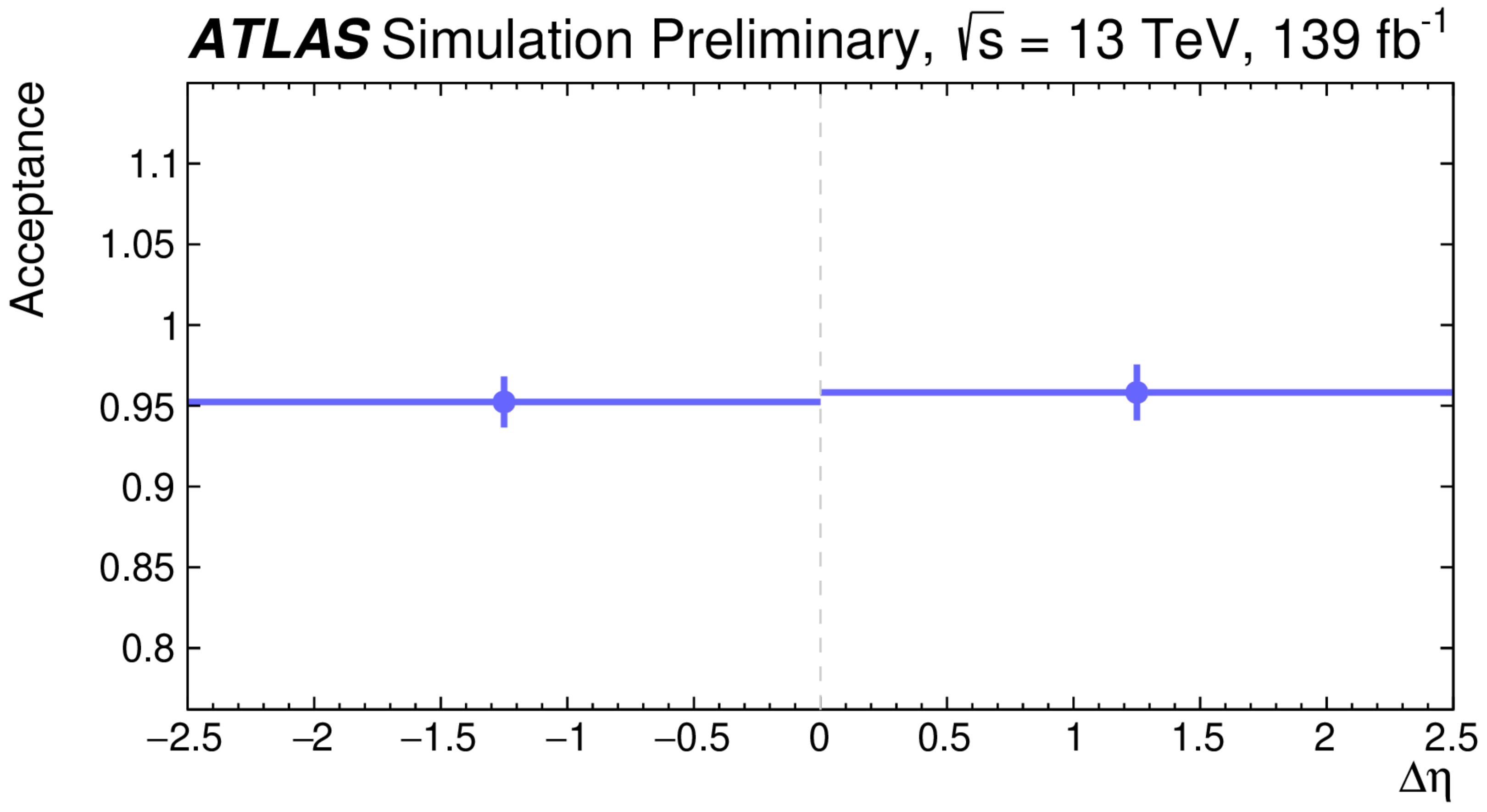
Response $$N_i^{\text{folded}} = \underbrace{\frac{1}{\alpha_i}\sum_j \varepsilon_j M_{ij}}_{R_{ij}} N_j^{\text{fid}}$$

Migration Matrix

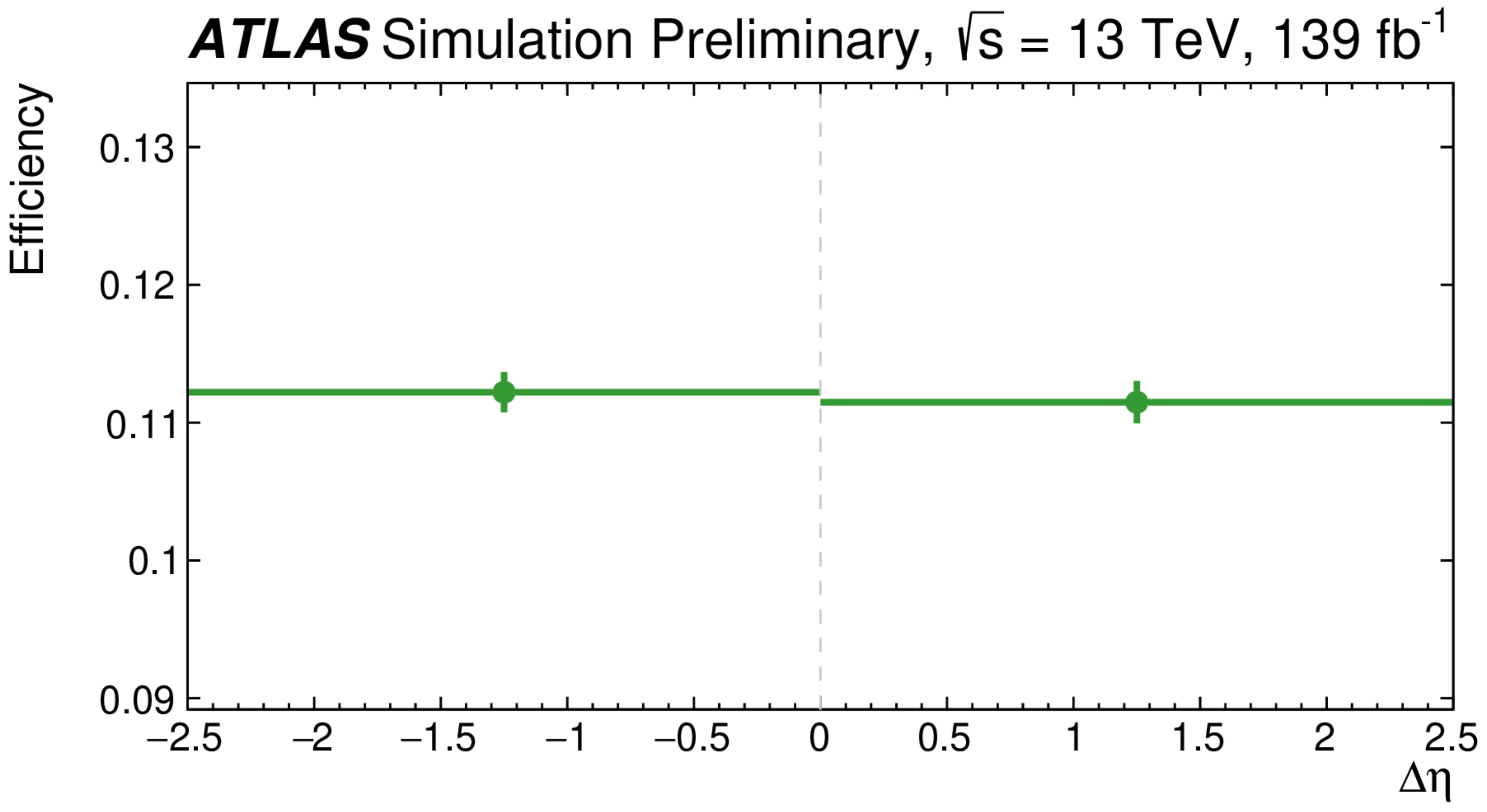
SR-2b-low-N_{jet}



Acceptance



Efficiency



Results

- ✦ Leading uncertainties come from decorrelating background NF in $\Delta\eta$ bins
  - Modeling uncertainties for $t\bar{t}W$, $t\bar{t}Z$

Detector-level

$$A_c^\ell(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.})$$

Expected: $A_c^\ell(t\bar{t}W)_{\text{MC}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$

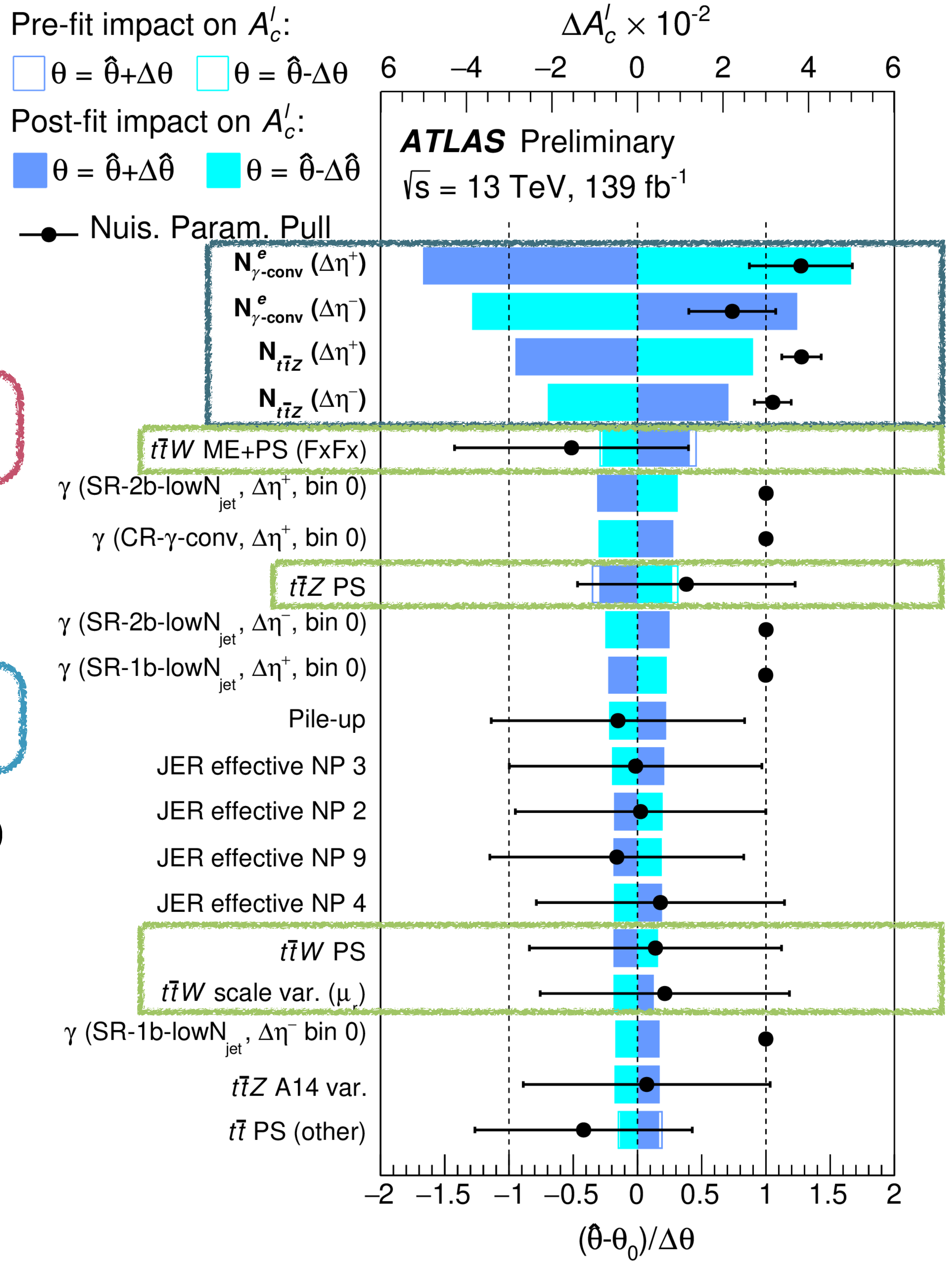
Particle-level

$$A_c^\ell(t\bar{t}W)_{\text{PL}} = -0.112 \pm 0.170\,(\text{stat.}) \pm 0.055\,(\text{syst.})$$

Expected: $A_c^\ell(t\bar{t}W)_{\text{MC}} = -0.063\,^{+0.007}_{-0.004}\,(\text{scale}) \pm 0.004\,(\text{MC stat.})$

- ✦ Dominated by statistical uncertainties
  - Trade-off in $\sigma \cdot \text{BR}$ for cleaner asymmetry environment only gets better in Run III and beyond!

Detector-level



Summary

- The $t\bar{t}W$ process anomalously large cross section in data in tension with best models
  - Spurred many developments in phenomenology community
  - Until $t\bar{t}W$ is better understood (NNLO calculation), challenging for ML analyses (e.g. $t\bar{t}H$-ML, $t\bar{t}t\bar{t}$)
- ATLAS collaboration pursuing robust program of measurements of $t\bar{t}W$ process
  - Presented **first search** of leptonic charge asymmetry of $t\bar{t}W$ at the LHC!
- Ancillary $N_{t\bar{t}W}(\Delta\eta^{-}) = 1.59 \pm 0.40$ consistent with ATLAS/CMS measurements
  - Differential cross sections with full Run II dataset will help resolve tensions

Thanks for your attention!

Backup

Signal Regions

- Lepton selections
  - Use single and di-lepton triggers - increase efficiency
  - Standard quality requirements (impact parameters, vertex association, calorimeter coverage, isolation BDT)

	Pre-selection			
N_ℓ ($\ell = e/\mu$)	$= 3$			
p_{T}^{ℓ} ($1^{\mathrm{st}}/2^{\mathrm{nd}}/3^{\mathrm{rd}}$)	≥ 30 GeV, ≥ 20 GeV, ≥ 15 GeV			
$\sum$ lep. charges	± 1			
$m_{\ell\ell}^{\mathrm{OSSF}}$	≥ 30 GeV			
	Region-specific requirements			
	SR-1b-lowN_{jets}	SR-1b-highN_{jets}	SR-2b-lowN_{jets}	SR-2b-highN_{jets}
N_{jets}	[2, 3]	≥ 4	[2, 3]	≥ 4
$N_{b\text{-jets}}$	$= 1$	$= 1$	≥ 2	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}$	≥ 50 GeV	≥ 50 GeV	–	–
$N_{Z\text{-cand.}}$	$= 0$			
Tight leptons	TTT			
e/γ ambiguity-cuts	all pass			

Sherpa signal samples

Nominal: Sherpa 2.2.10 NLO QCD+EW (+1j@NLO, +2,3,4j@LO) + Sherpa PS

Alternate: MG5_aMC@NLO NLO QCD+EW (+1j@NLO, +2j@LO) + Pythia PS w/ FxFx

Control region definitions

	Pre-selection
N_ℓ ($\ell = e/\mu$)	$= 3$
p_{T}^{ℓ} ($1^{\mathrm{st}}/2^{\mathrm{nd}}/3^{\mathrm{rd}}$)	$\geq 30\,\mathrm{GeV}$, $\geq 20\,\mathrm{GeV}$, $\geq 15\,\mathrm{GeV}$
Sum of lepton charges	± 1
$m_{\ell\ell}^{\mathrm{OSSF}}$	$\geq 30\,\mathrm{GeV}$

	CR-$t\bar{t}Z$	**CR-HF$_e$**	**CR-HF$_\mu$**	**CR-γ-conv**
$\ell^{1\mathrm{st}/2\mathrm{nd}/3\mathrm{rd}}$	$\ell\ell\ell$	$\ell\ell e$	$\ell\ell\mu$	$\ell\ell e$, $\ell e\ell$, $e\ell\ell$
N_{jets}	≥ 4	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$	≥ 2	$= 1$	$= 1$	≥ 1
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	$< 50\,\mathrm{GeV}$	$< 50\,\mathrm{GeV}$	$< 50\,\mathrm{GeV}$
$N_{Z\text{-cand.}}$	$= 1$	$= 0$	$= 0$	$= 0$
Tight leptons	TTT	TT$\overline{\mathrm{T}}$	TT$\overline{\mathrm{T}}$	TTT
e/γ ambiguity-cuts	all pass	all pass	all pass	≥ 1 fail

Systematics breakdown

- Leading uncertainty is background asymmetry estimation
- Additional MC sensitivity in PL due to response matrix bins
- Statistical uncertainties larger due to bin-to-bin correlations

Detector-level

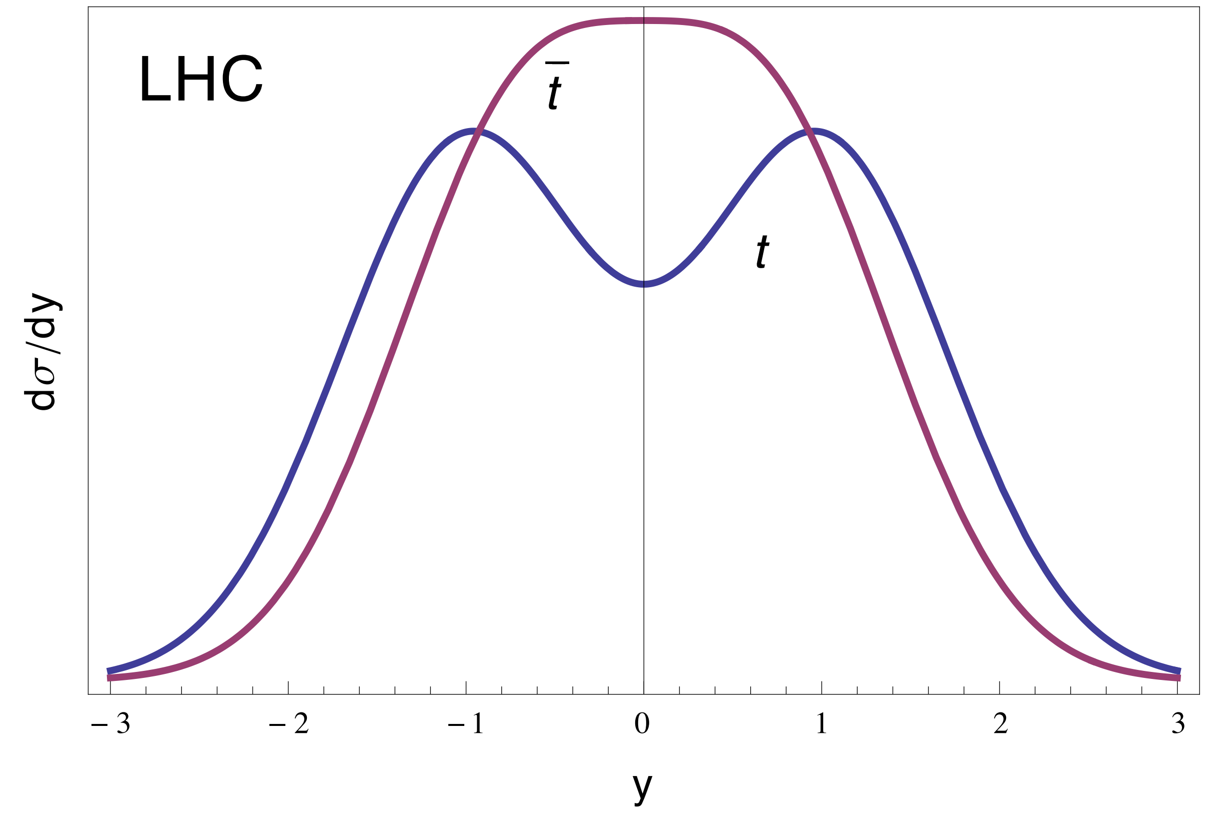
	$\Delta A_c^{\ell}(t\bar{t}W)$
Experimental uncertainties	
Jet energy resolution	0.013
Pile-up	0.007
b-tagging	0.005
Leptons	0.004
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.004
Jet energy scale	0.003
Luminosity	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.013
$t\bar{t}Z$ modelling	0.010
Non-prompt modelling	0.006
$t\bar{t}H$ modelling	0.005
Other uncertainties	
$\Delta\eta^{\pm}$ dependency	0.046
MC statistical uncertainty	0.019
Data statistical uncertainty	0.136
Total uncertainty	0.145

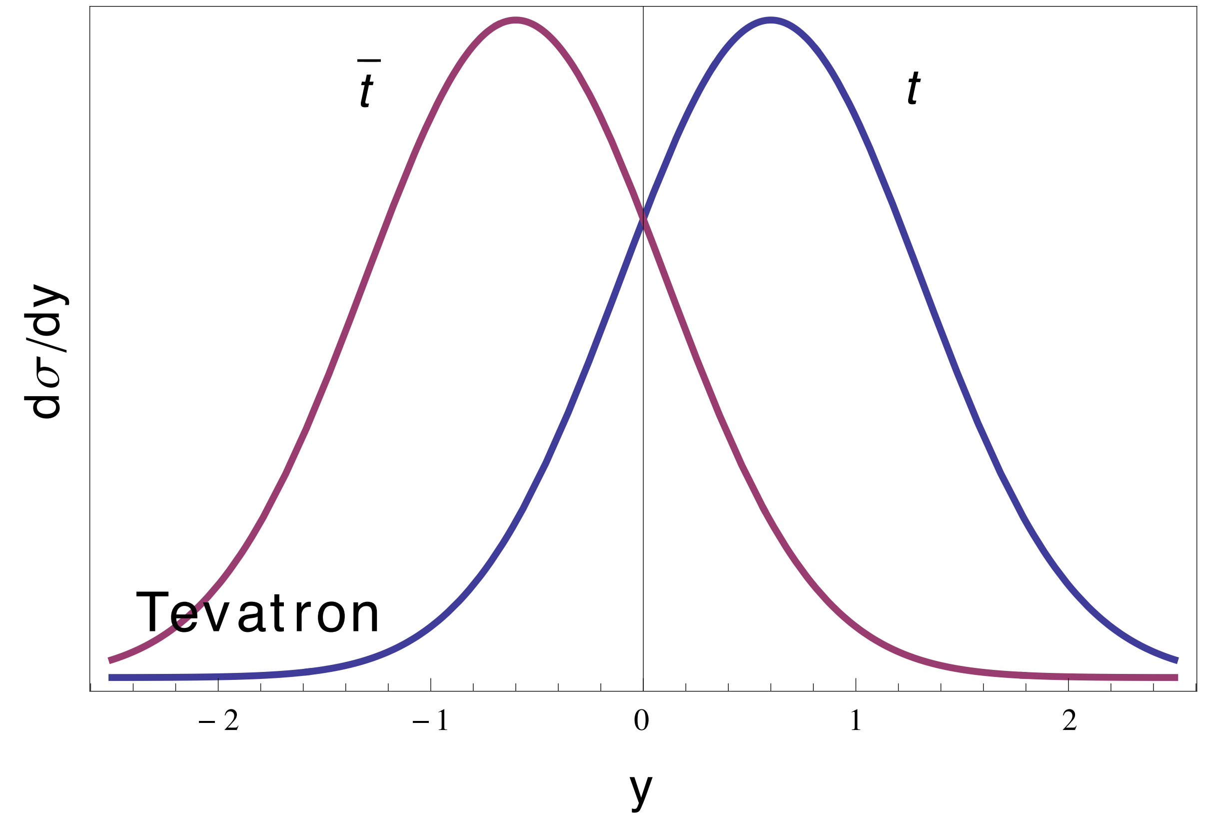
Particle-level

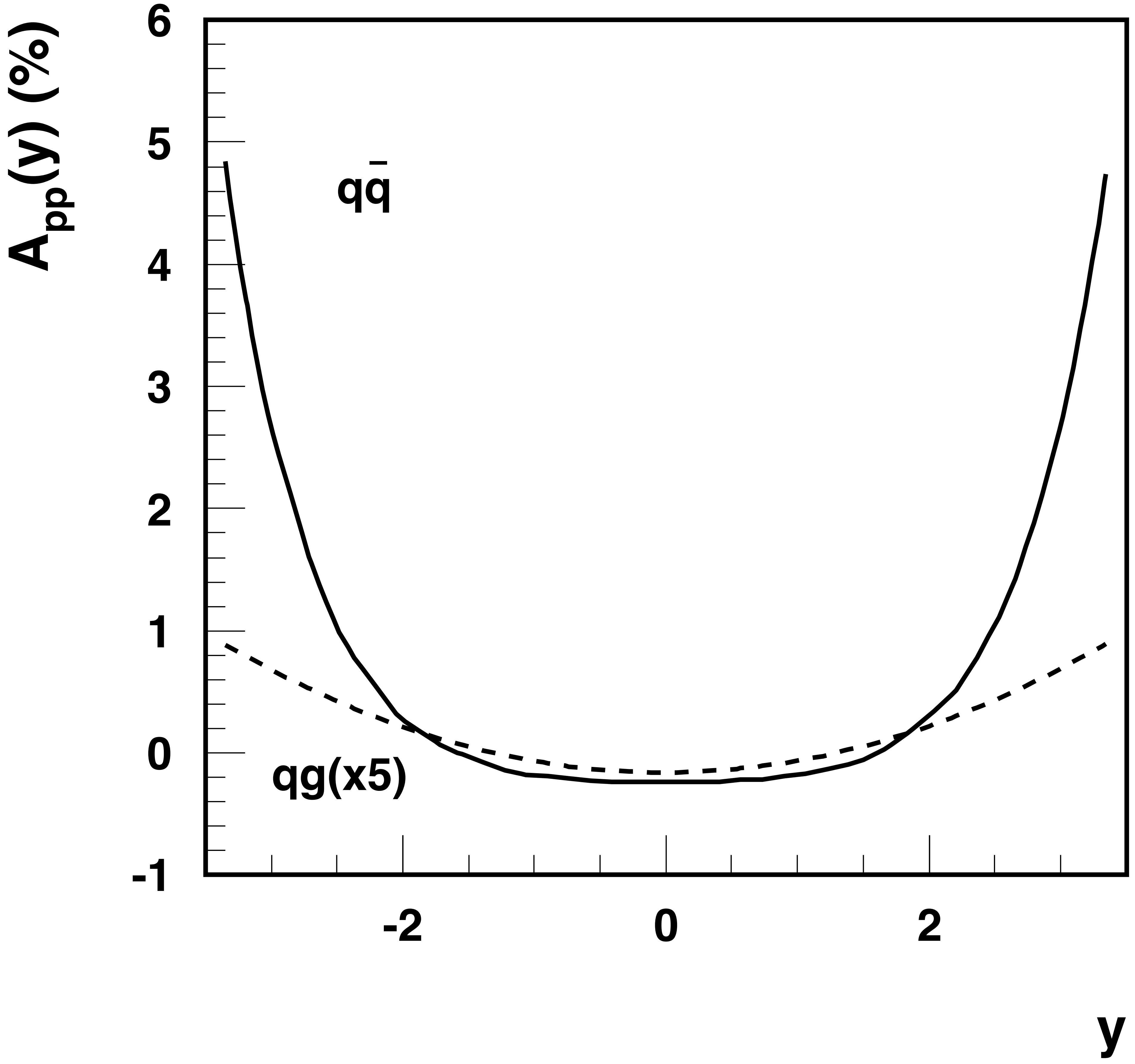
	$\Delta A_c^{\ell}(t\bar{t}W)^{\mathrm{PL}}$
Experimental uncertainties	
Leptons	0.014
Jet energy resolution	0.011
Pile-up	0.008
Jet energy scale	0.004
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.002
Luminosity	0.001
Jet vertex tagger	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.022
$t\bar{t}Z$ modelling	0.017
Non-prompt modelling	0.015
Others modelling	0.015
$WZ/ZZ+$jets modelling	0.014
$t\bar{t}H$ modelling	0.006
Other uncertainties	
Unfolding bias	0.011
$\Delta\eta^{\pm}$ dependency	0.039
MC statistical uncertainty	0.027
Response matrix	0.009
Data statistical uncertainty	0.170
Total uncertainty	0.179

Top quark asymmetry

- Same underlying dynamics manifest differently at Tevatron ($p\bar{p}$) and LHC (pp)







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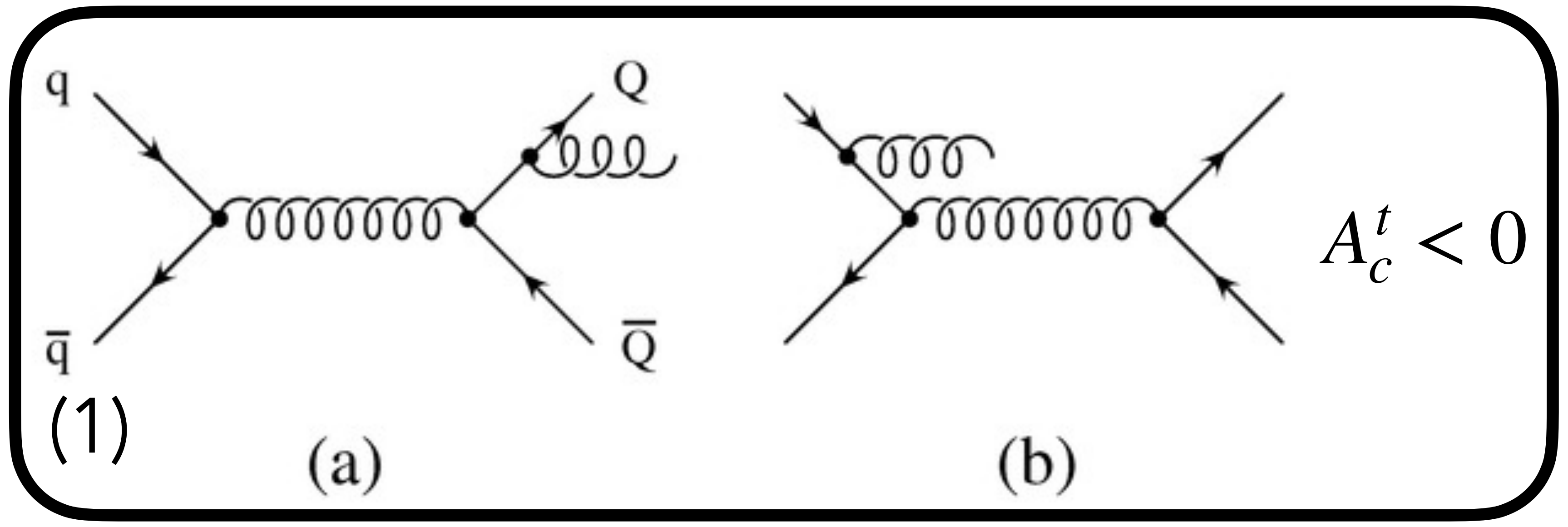
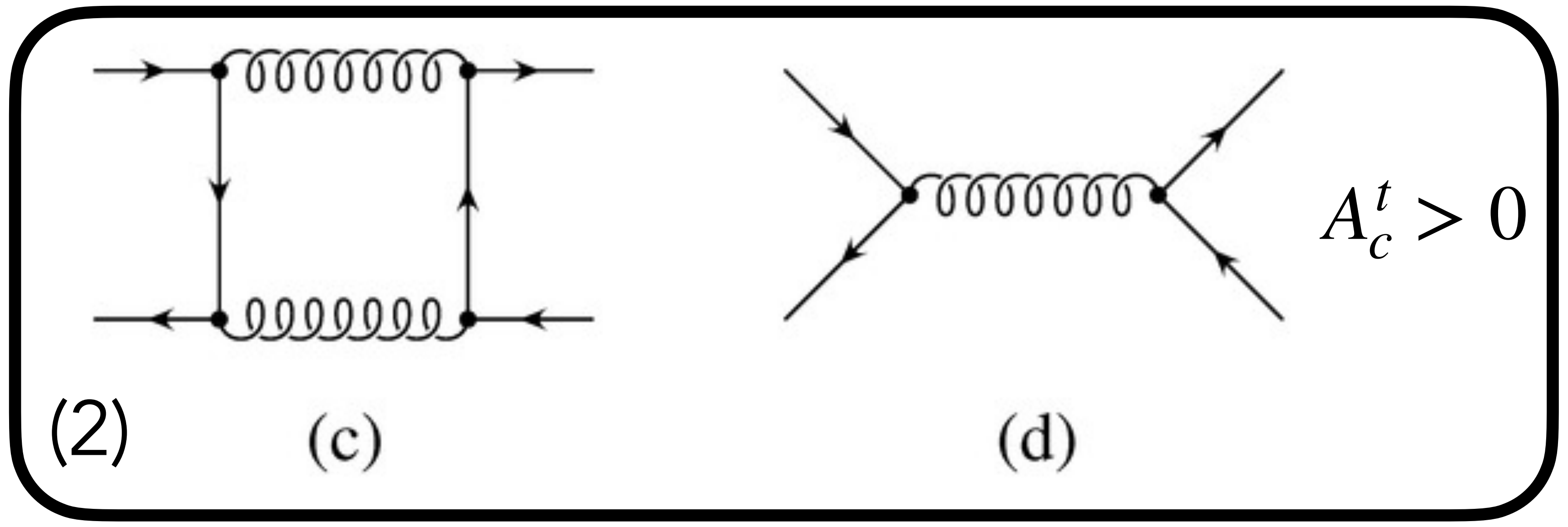
Asymmetry arises from interference effects at NLO QCD

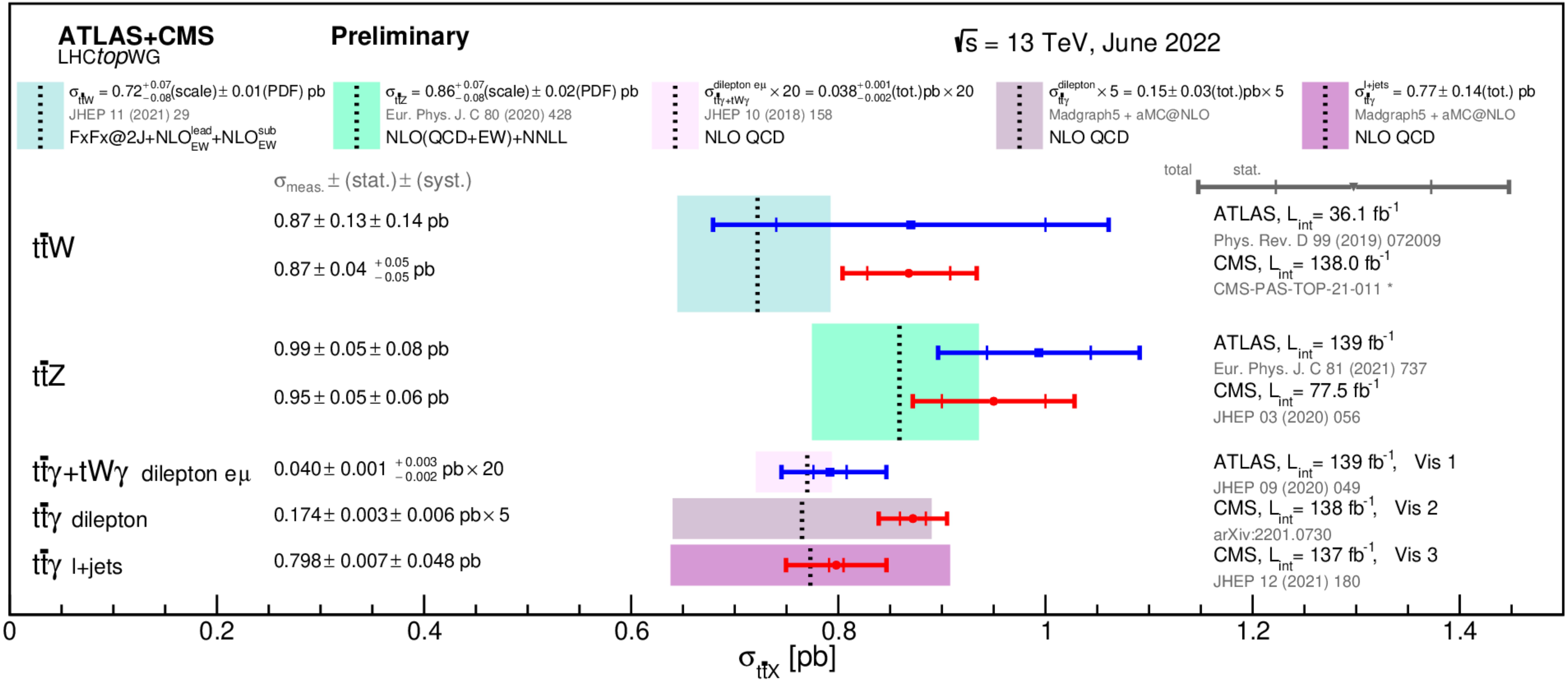




Effect of (2) is dominant, leading to overall positive asymmetry at LHC

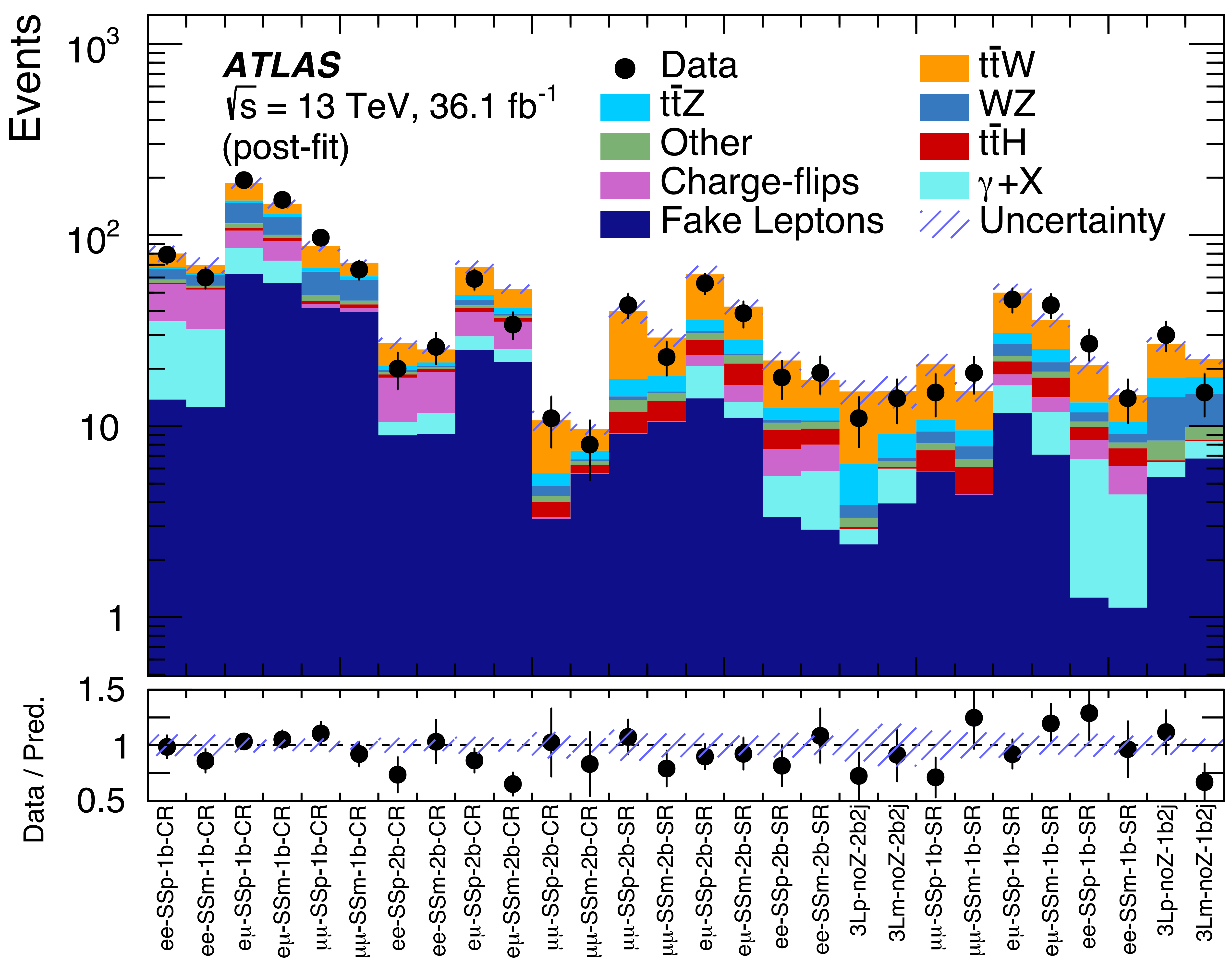
LHCTopWG $t\bar{t}+X$ Summary

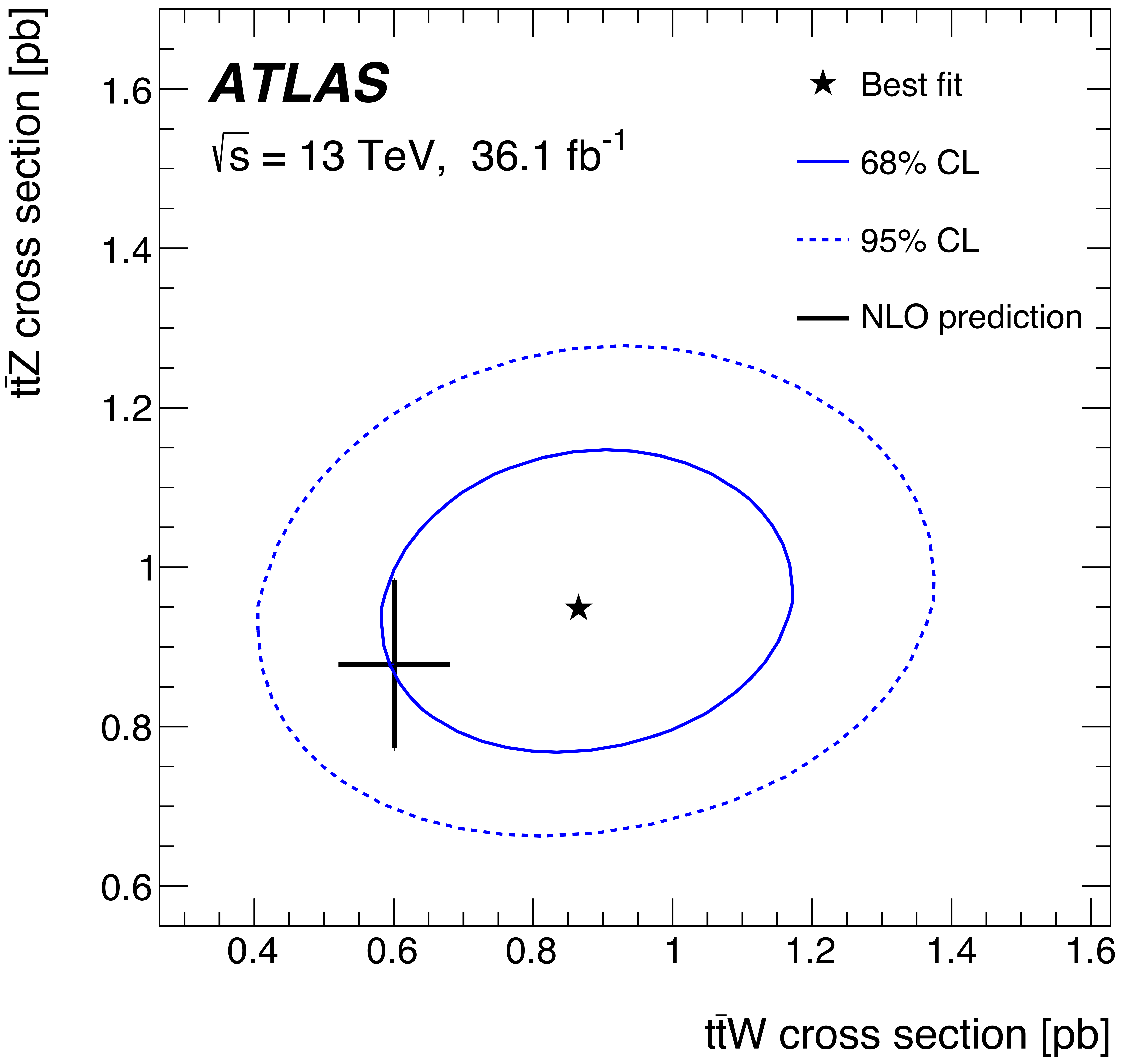
ATL-PHYS-PUB-2022-030



Partial Run II Inclusive Cross Section by ATLAS

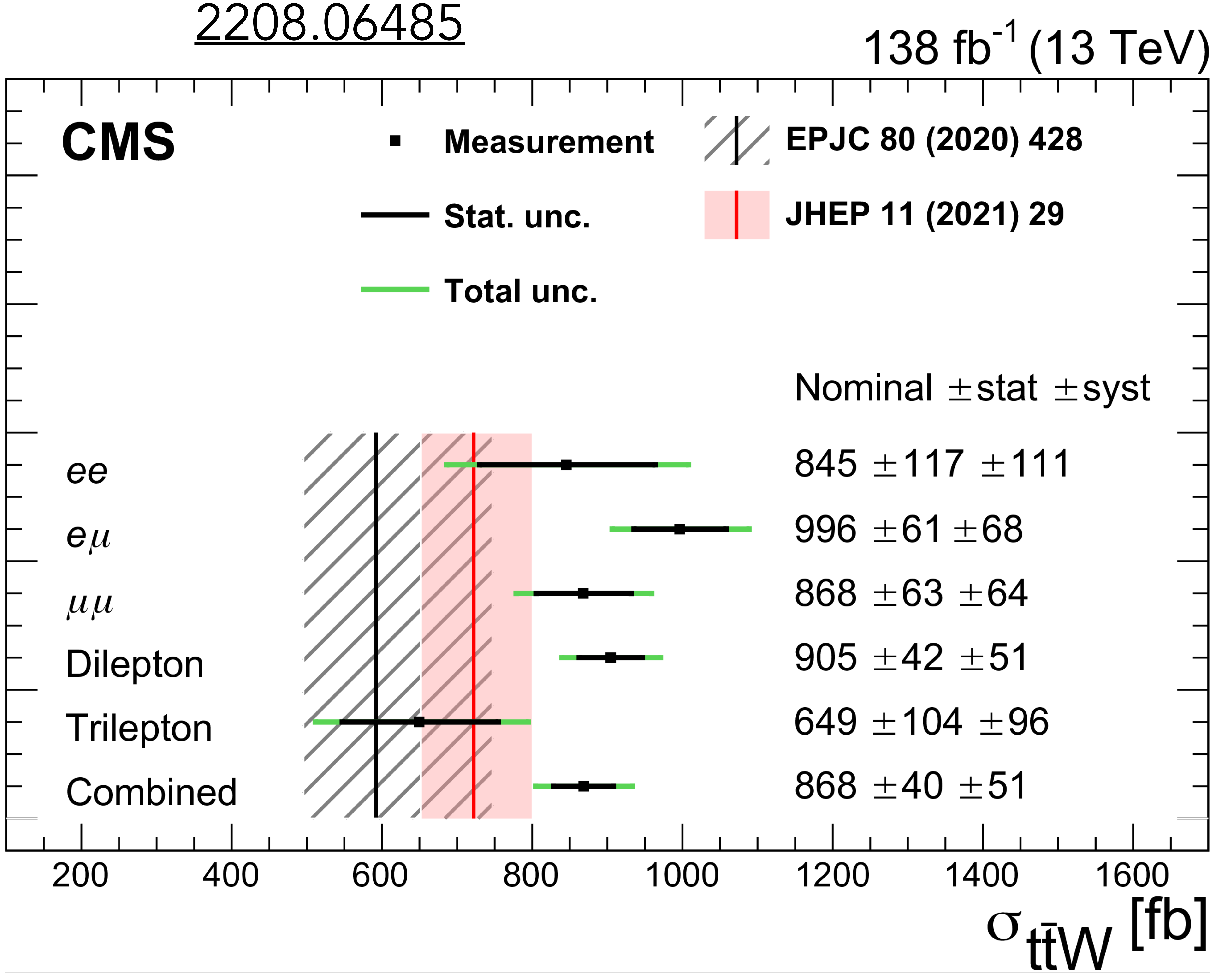
1901.03584

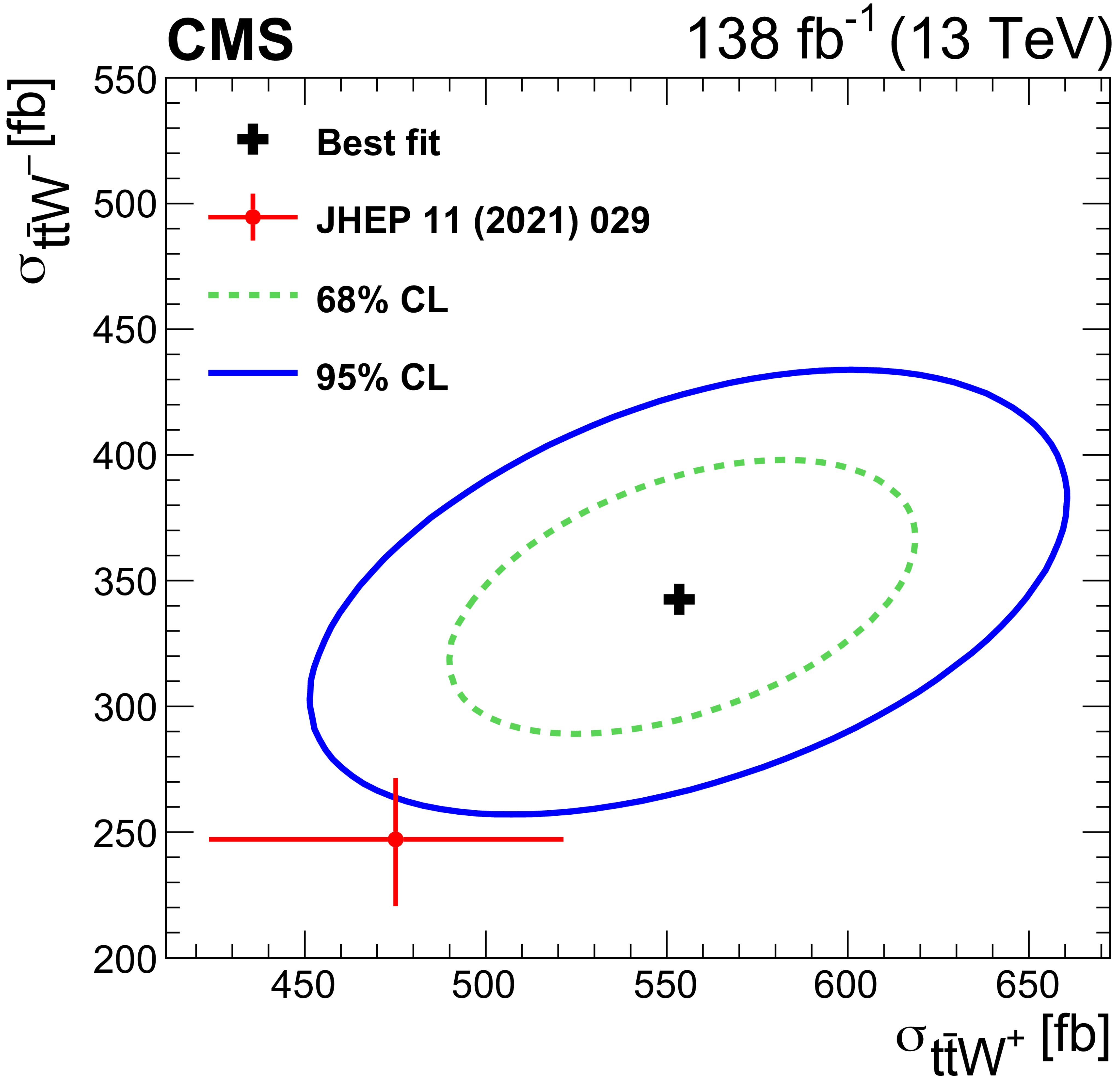




Full Run II Inclusive Cross Section by CMS

2208.06485

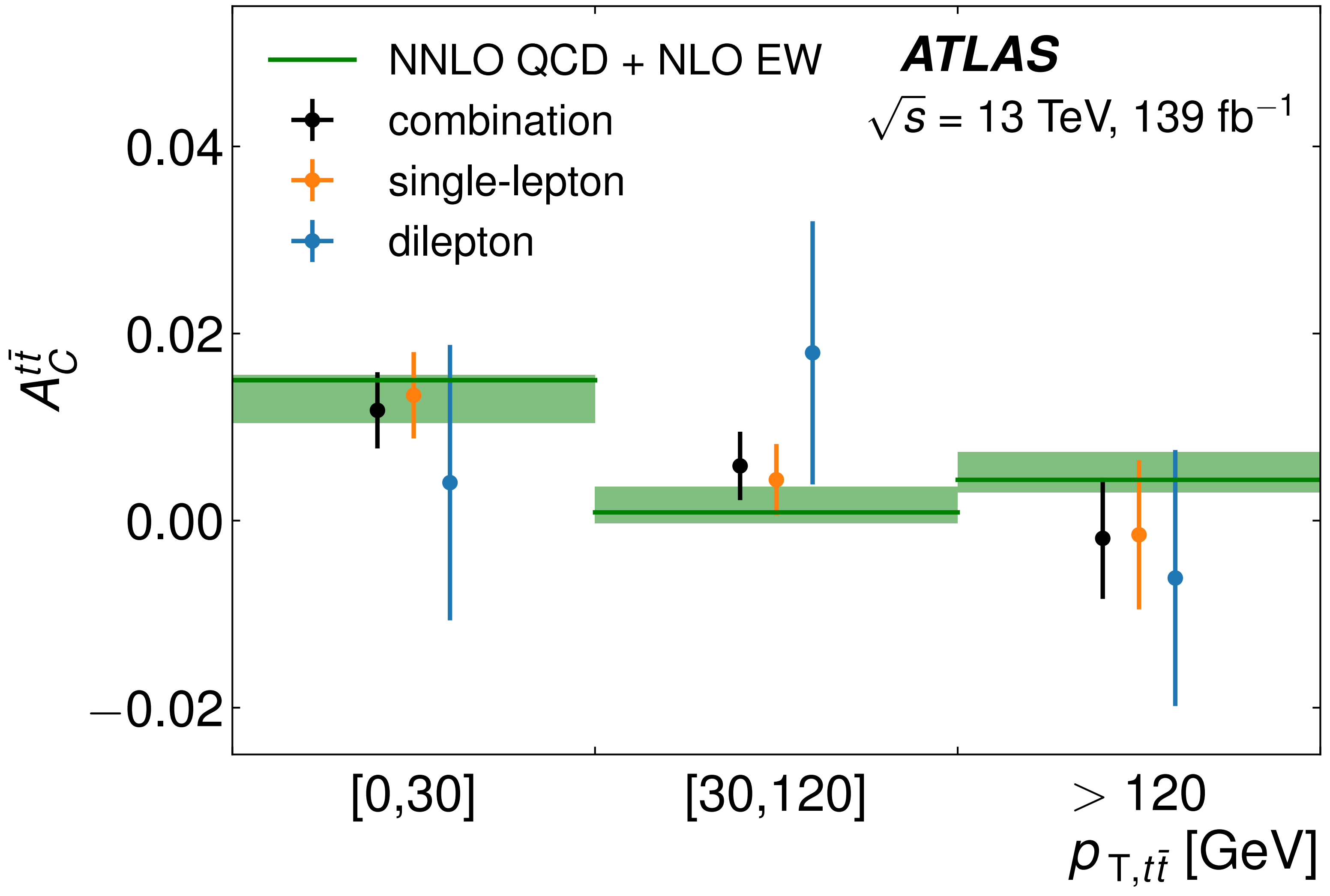


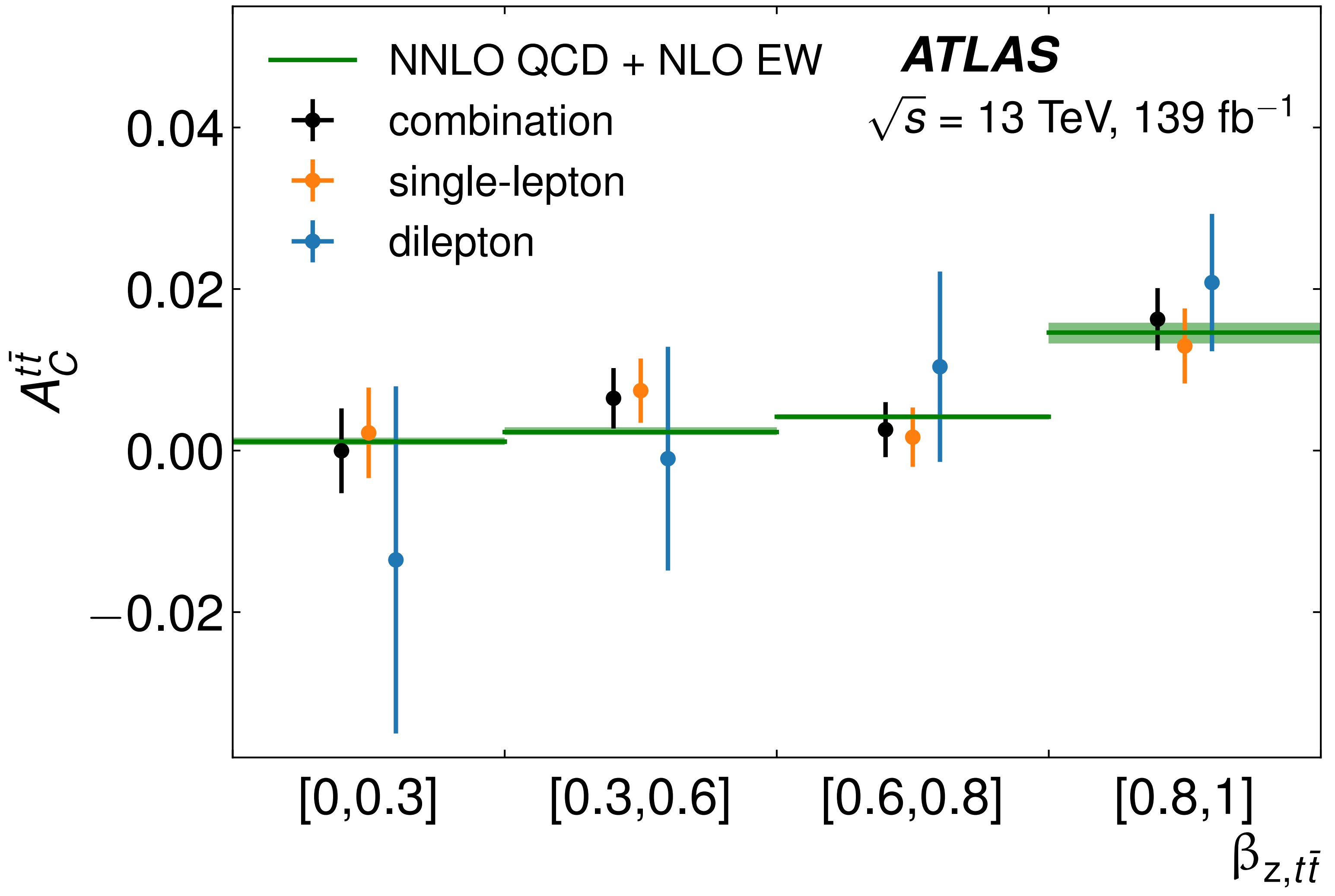


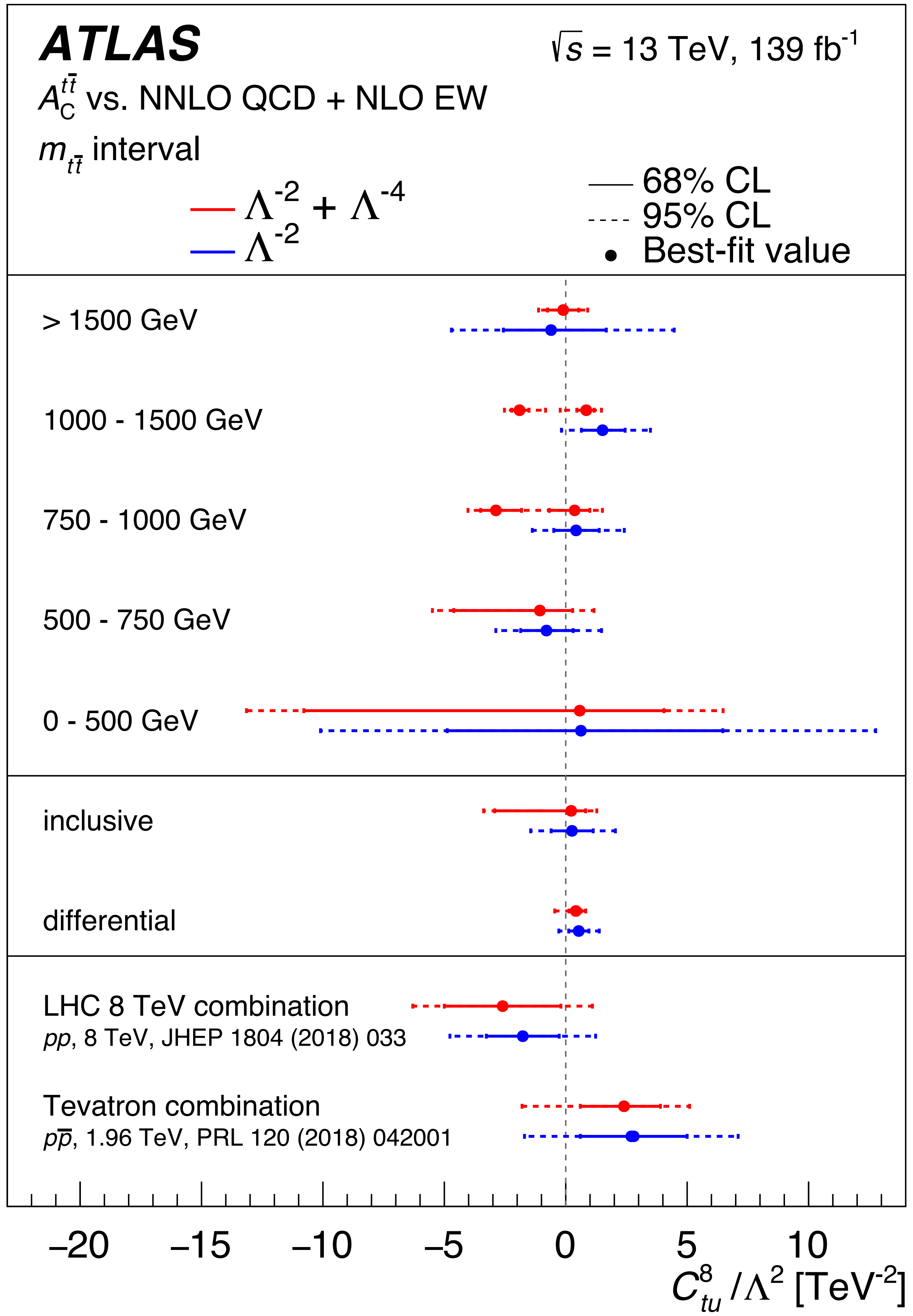
$t\bar{t}$ Charge Asymmetry at the LHC

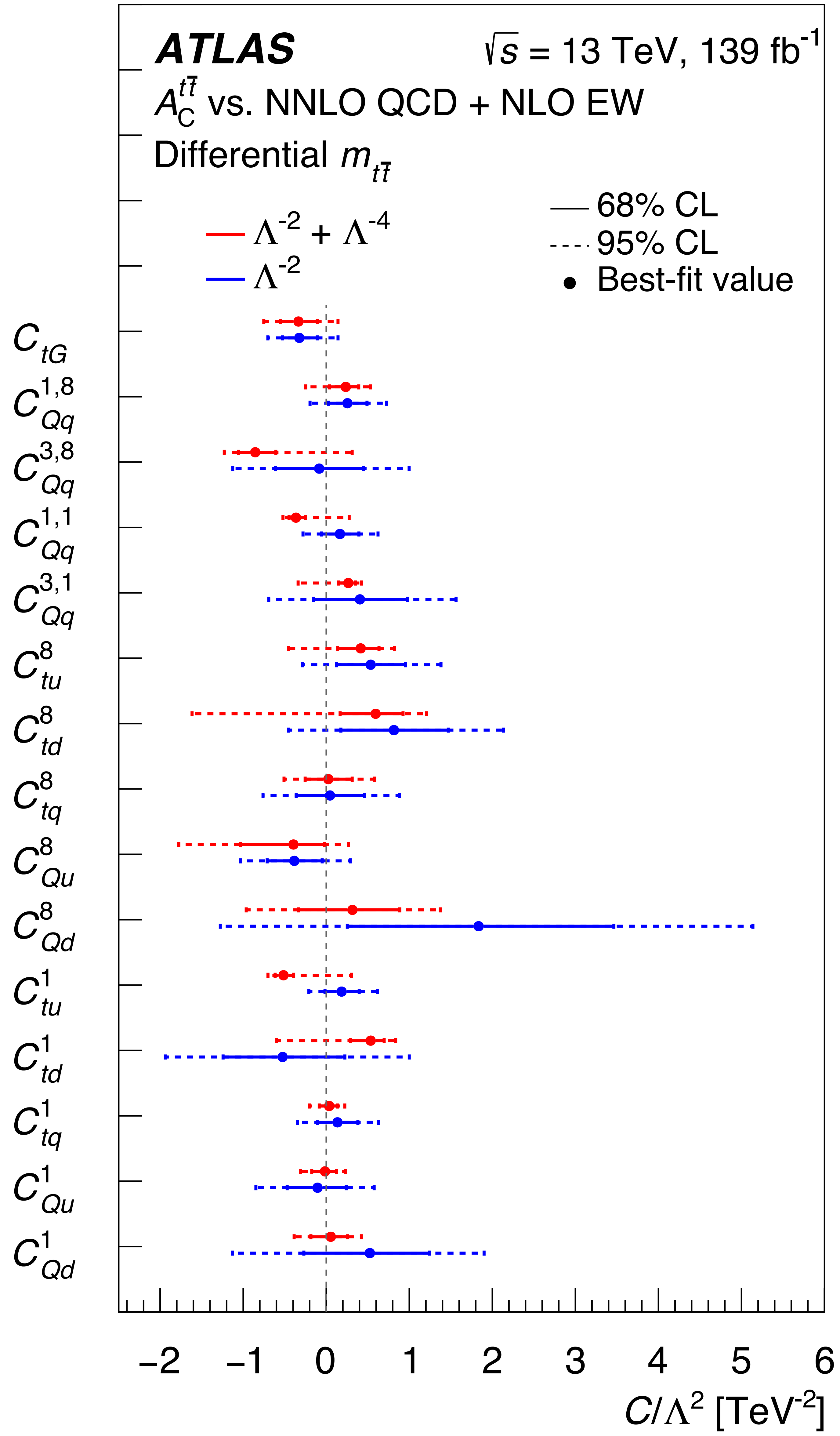
2208.12095

4.7σ evidence of $A_C^{t\bar{t}} \neq 0$!



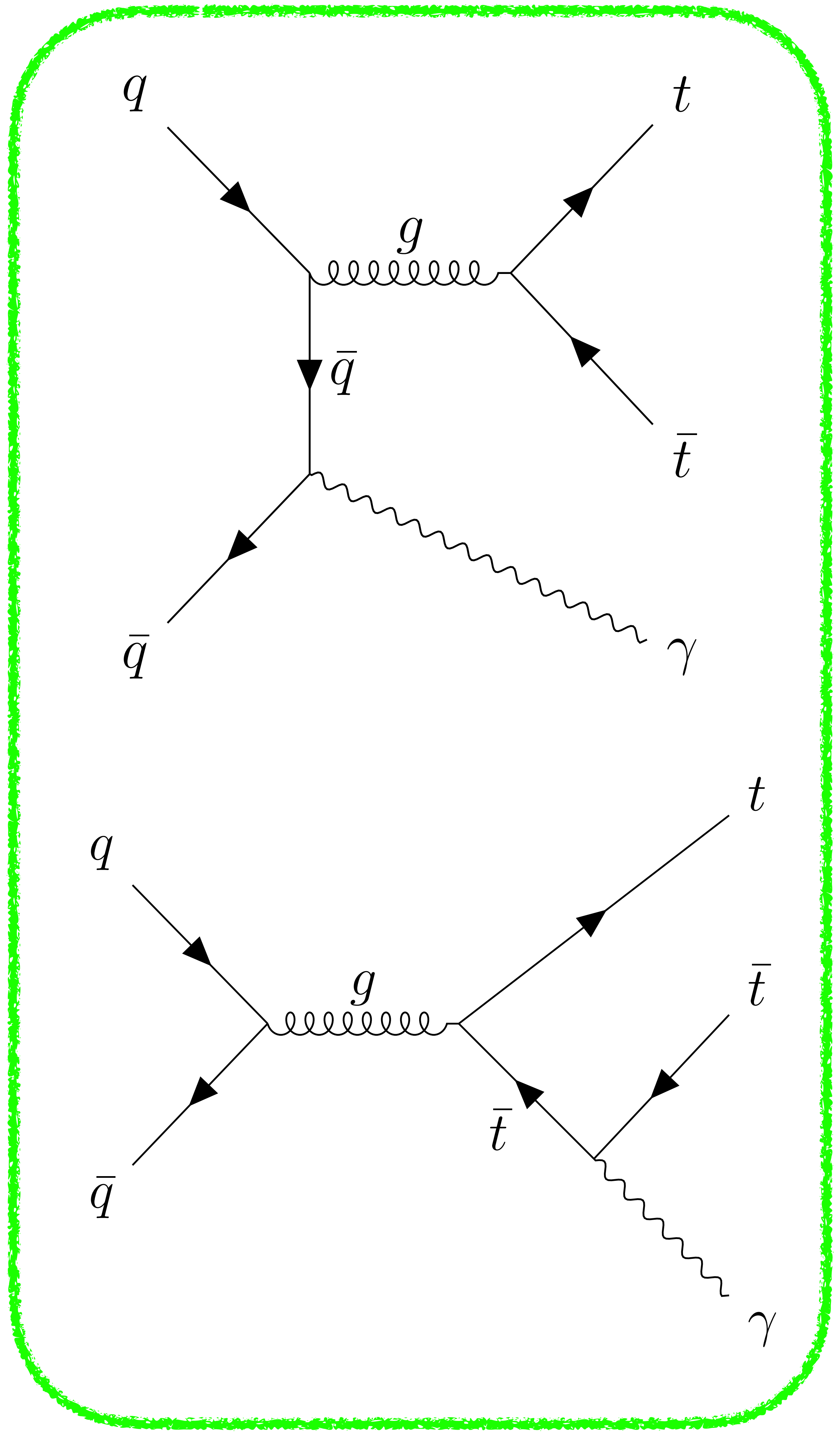


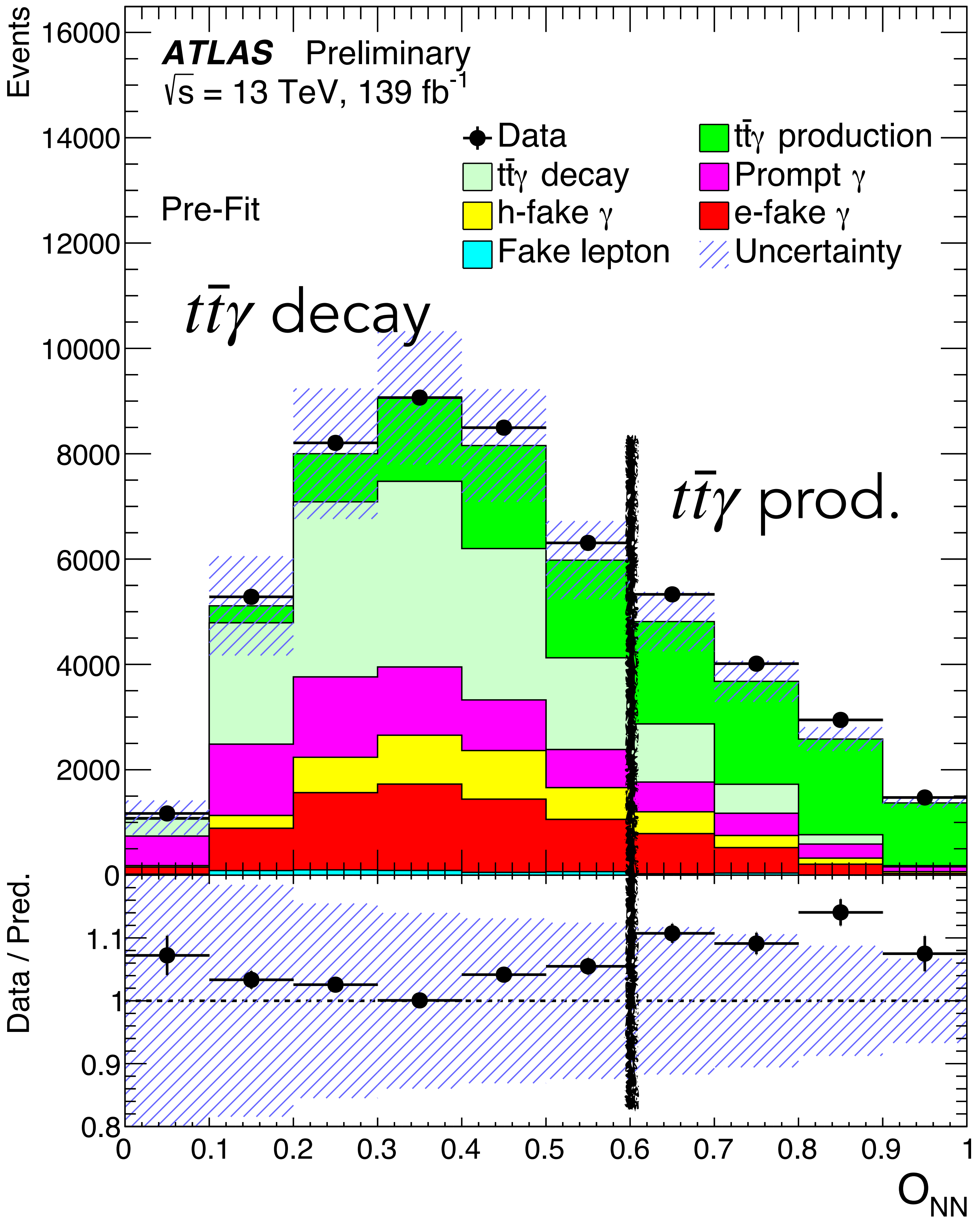




$t\bar{t}+\gamma$ Charge Asymmetry at the LHC

ATLAS-CONF-202-049





Profile-likelihood unfolding (no regularization)

$$A_C^{NLO} = -0.014 \pm 0.001 \text{ (scale)}$$

$$A_C = -0.006 \pm 0.024 \text{ (stat)} \pm 0.018 \text{ (syst)}$$