ATLAS EXPERIMENT

INFN Istituto Nazionale di Fisica Nucleare

Recent highlights of top-quark cross-section and properties measurements with the ATLAS detector at the LHC

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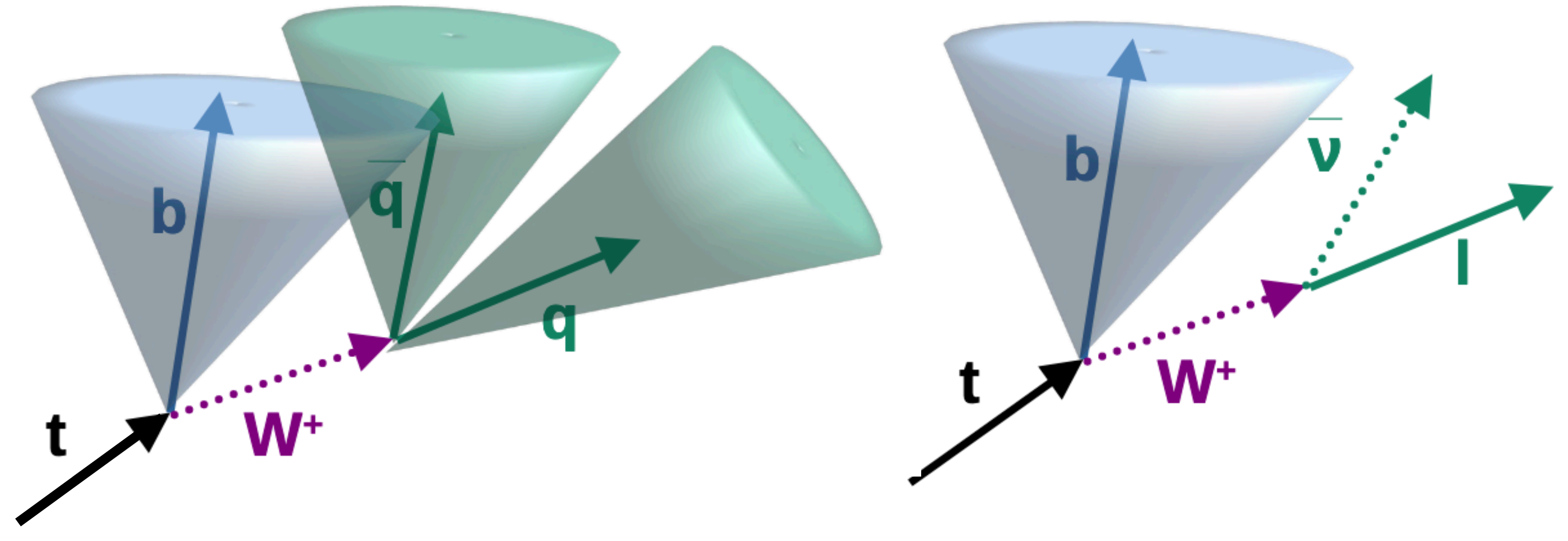
PHENO 2023, University of Pittsburgh, May 8-10 2023

Top physics: motivations and goals

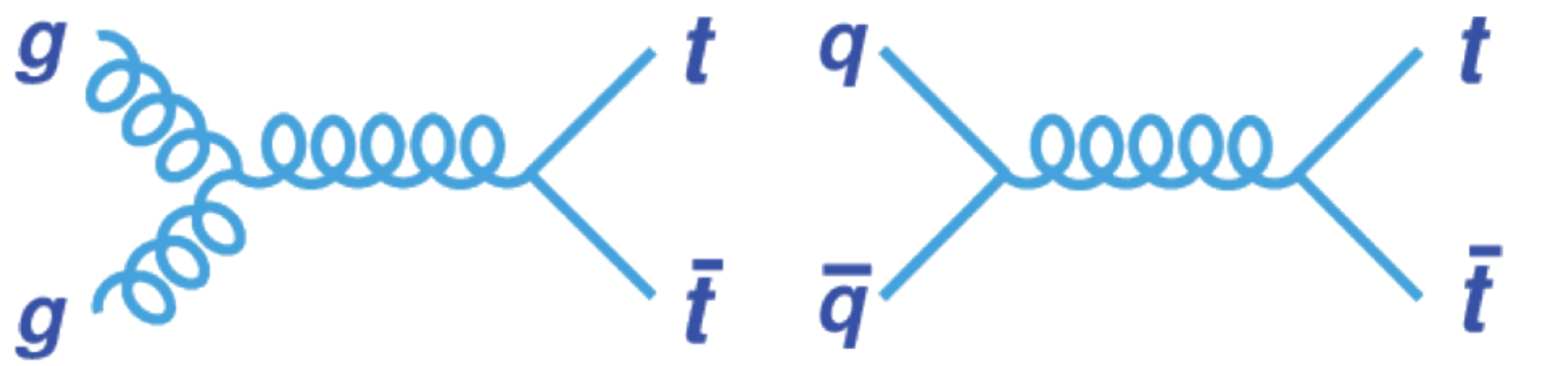
Top-quark has unique properties in the SM:

- heaviest known particle → m_{top} fundamental SM parameter
- large coupling ($\lambda_t \sim 1$) to the Higgs boson → special role in EW symmetry breaking
- short lifetime $\tau_t \sim 10^{-25} < \tau_{had} \sim 10^{-24}$ → unique possibility to probe bare quark properties



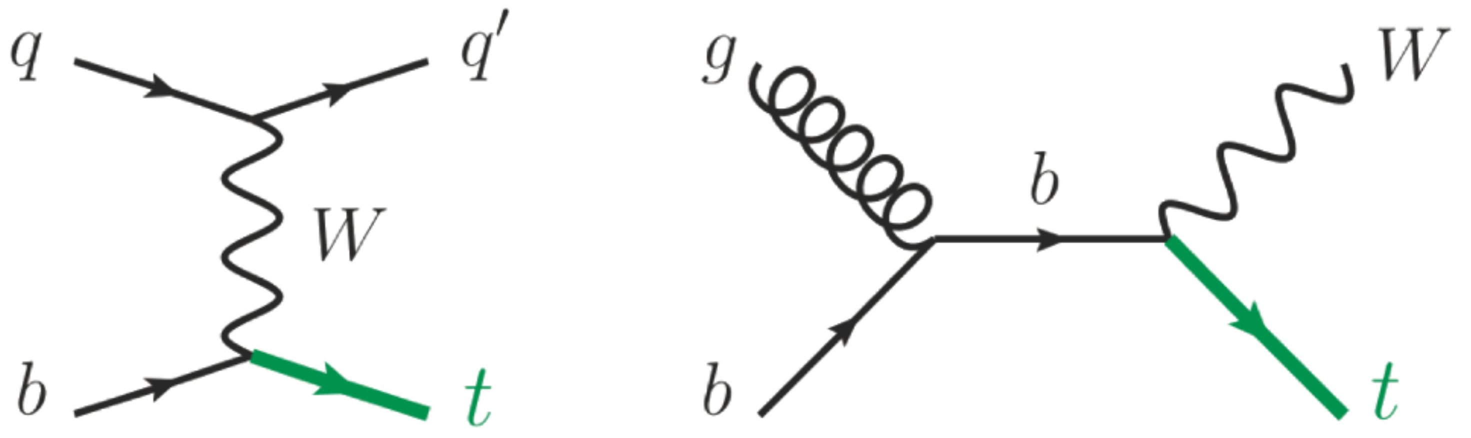
LHC is a top factory: 120M top pairs produced in run2, more are coming in run3

Stringent test of the SM and possible hints for new physics thanks to the large sample, the ever increasing experimental precision and the advances in theoretical calculations.



Pair production via strong interactions (mainly gg), dominant production @ LHC

This talk will present a selected list of recent ATLAS results for top cross-sections, mass and properties. The complete list is available at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults



Single production via EW charge current interactions

Inclusive $t\bar{t}$ cross-section

New measurement @ 5.02 TeV combining di-lepton and l+jets channels

$$\sigma_{t\bar{t}}^{5\mathrm{TeV}} = 67.5 \pm 2.7 \text{ pb } (4\,\%\text{ prec.})$$

- increased $q\bar{q}$ contribution and larger x (new constraint for gluon PDF)
- **better precision than current SM prediction**

$$\sigma_{t\bar{t}}^{NNLO+NNLL} = 68.2 \pm 4.8\ (PDF + \alpha_s)\ {}^{+1.9}_{-2.3}\ (\text{scale})\text{ pb}$$

arXiv:2207.01354 [hep-ex] — 5.02 TeV - 257 pb^{-1}

Most precise result @ 13 TeV exploiting dilepton $e\mu$ final states:

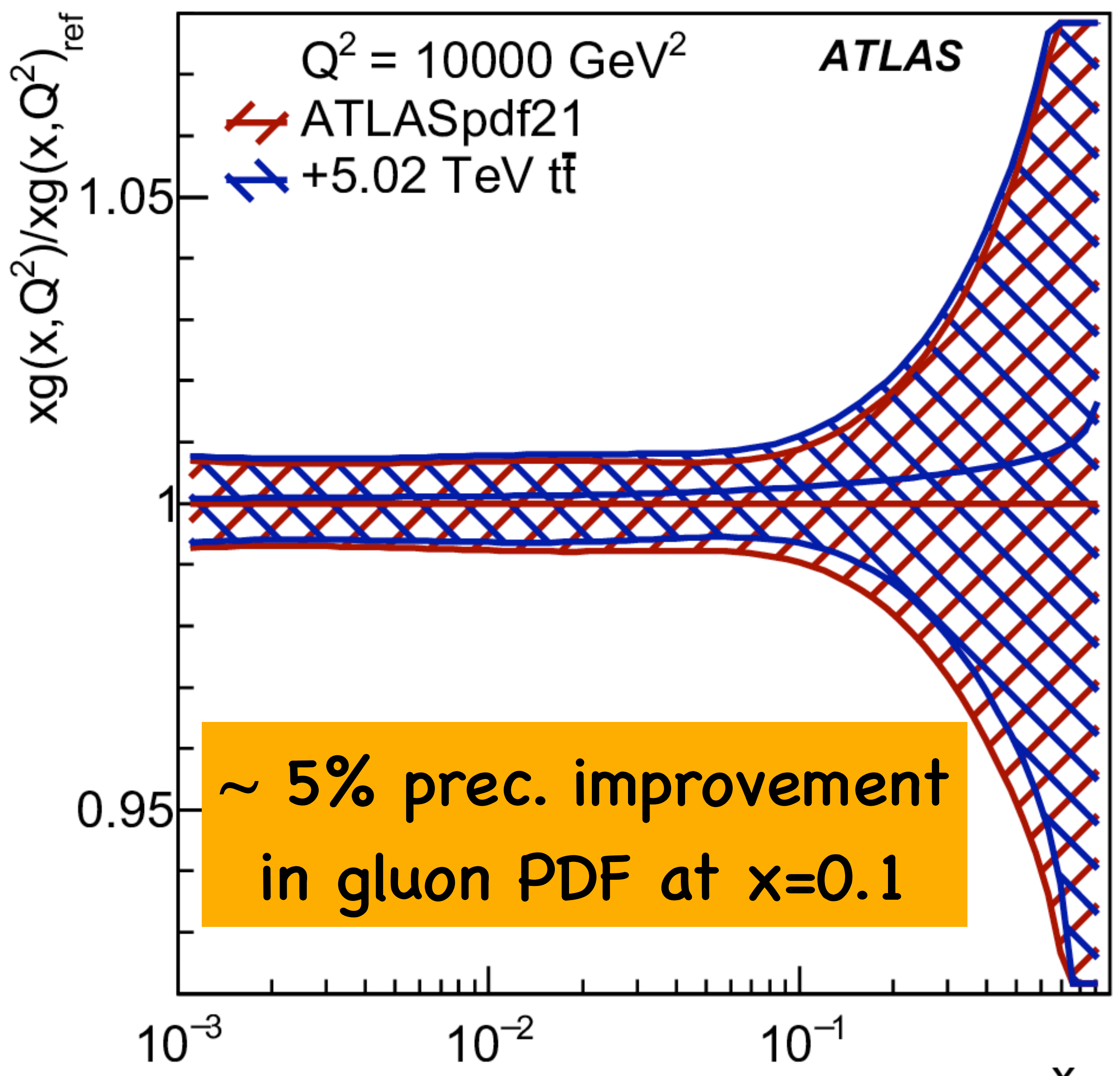
$$\sigma_{t\bar{t}}^{13\mathrm{TeV}} = 829 \pm 1\ (stat) \pm 13\ (syst) \pm 8\ (lumi) \pm 2\ (beam)\text{ pb}$$

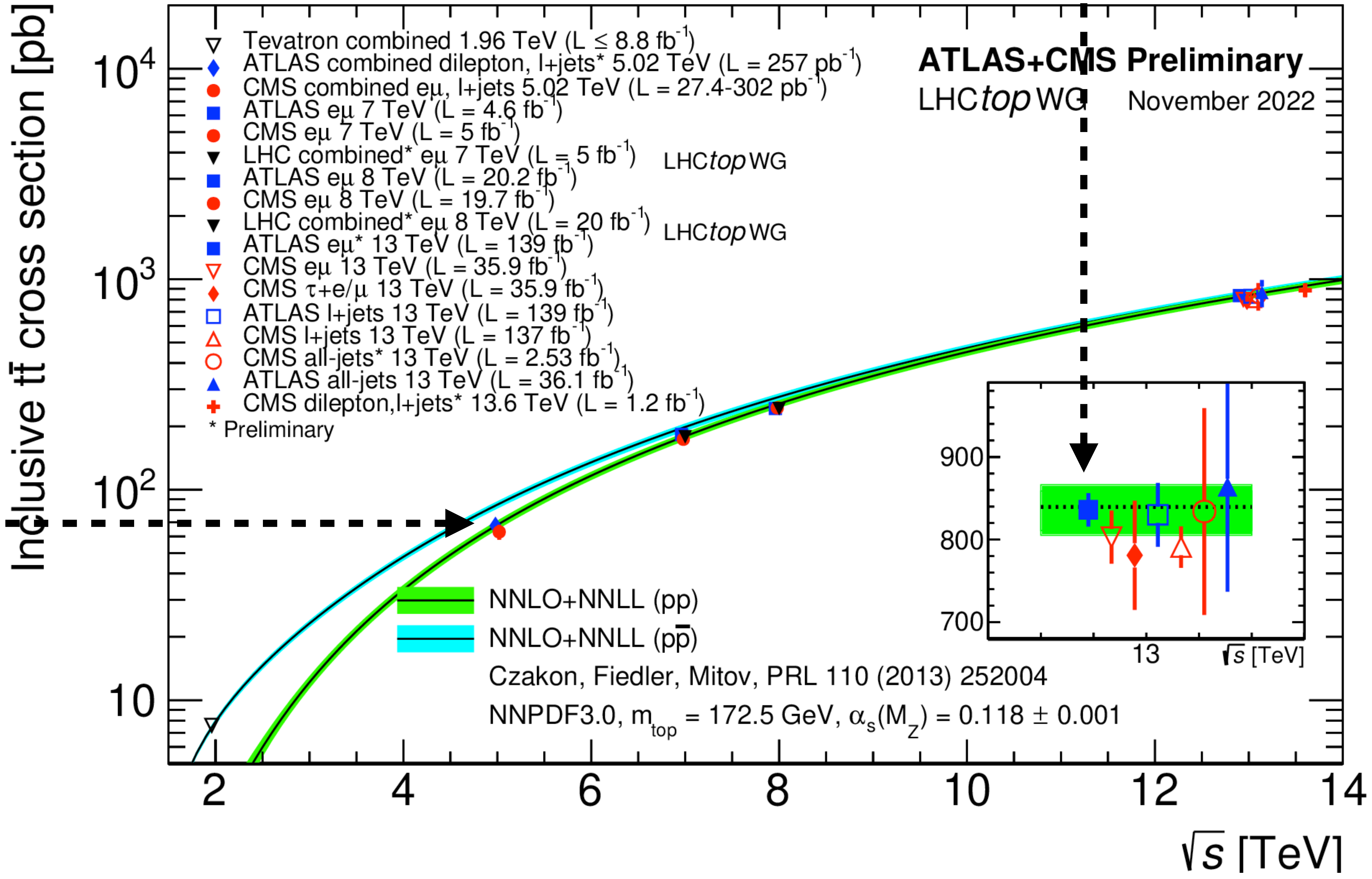
dominant systematics: luminosity (0.93%), top pT reweighing (0.58%), tW bkg. x-sec (0.52%), in-situ electron isolation (0.51%), PDF (0.41%)

1.8% precision! much better than current NNLO+NNLL prediction:

$$\sigma_{t\bar{t}}^{NNLO+NNLL} = 832^{+20}_{-29}\ (scale) \pm 23\ (mass) \pm 35\ (PDF + \alpha_s)\text{ pb}$$

arXiv:2303.15340 [hep-ex], submitted to JHEP —13 TeV - 139 fb^{-1}





First run 3 results: $t\bar{t}$ inclusive cross-section and $t\bar{t}$/Z cross-section ratio

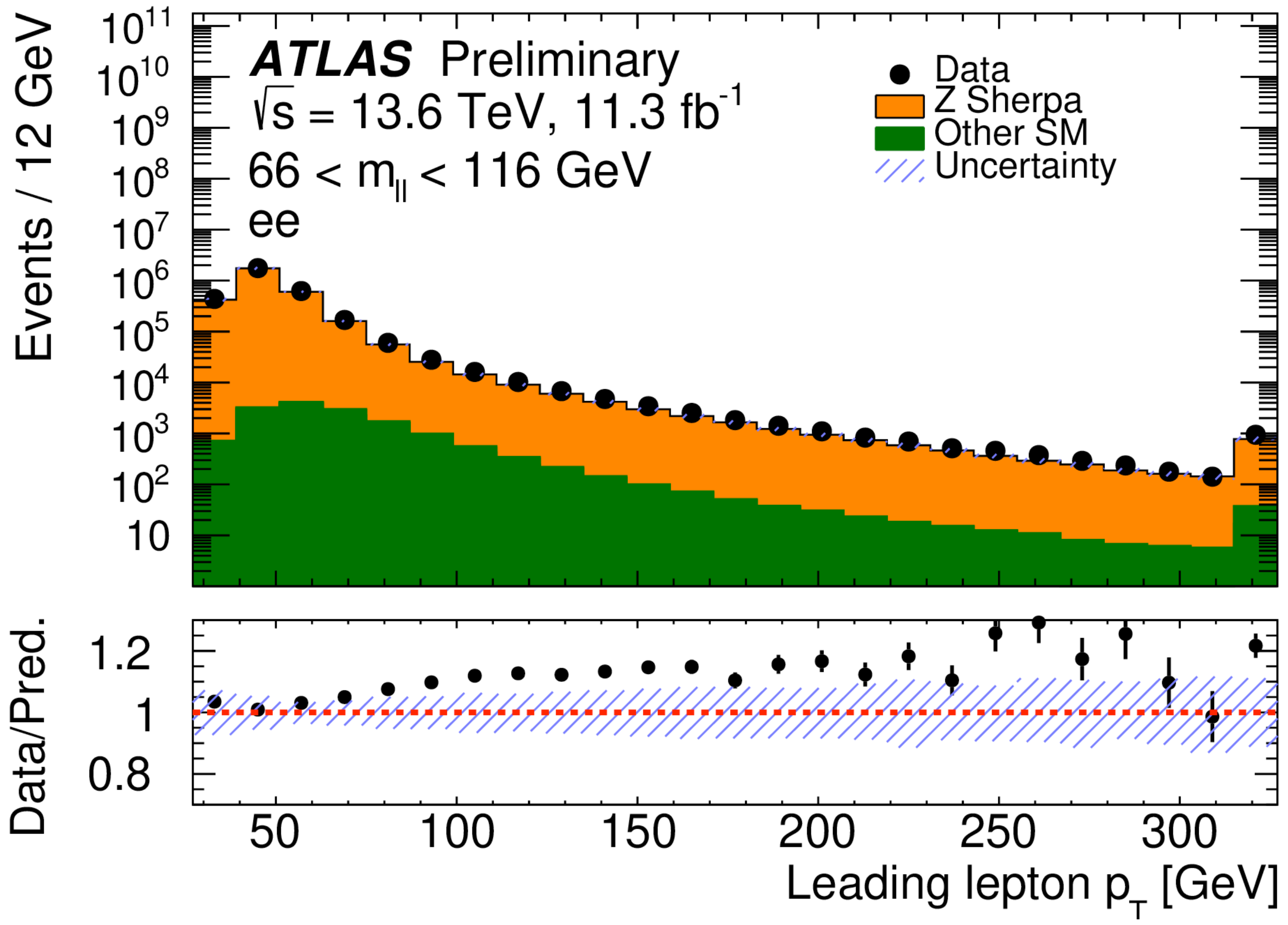
eμ di-lepton channel for $t\bar{t}$

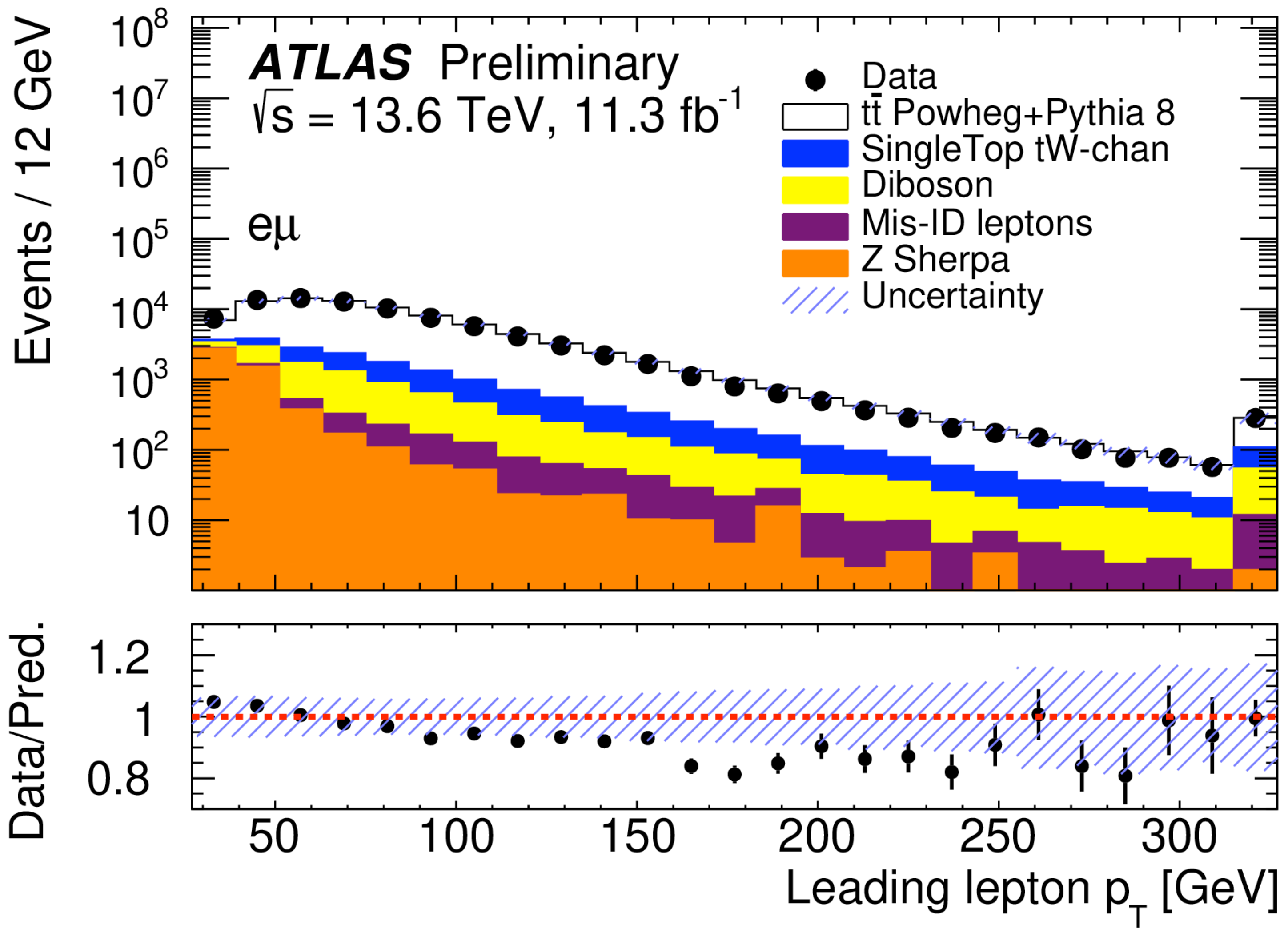
$$\sigma_{t\bar{t}} = 859 \pm 4(stat) \pm 22(syst) \pm 19(lumi)\ \text{pb}\ (3.4\,\%\ \text{prec.})$$

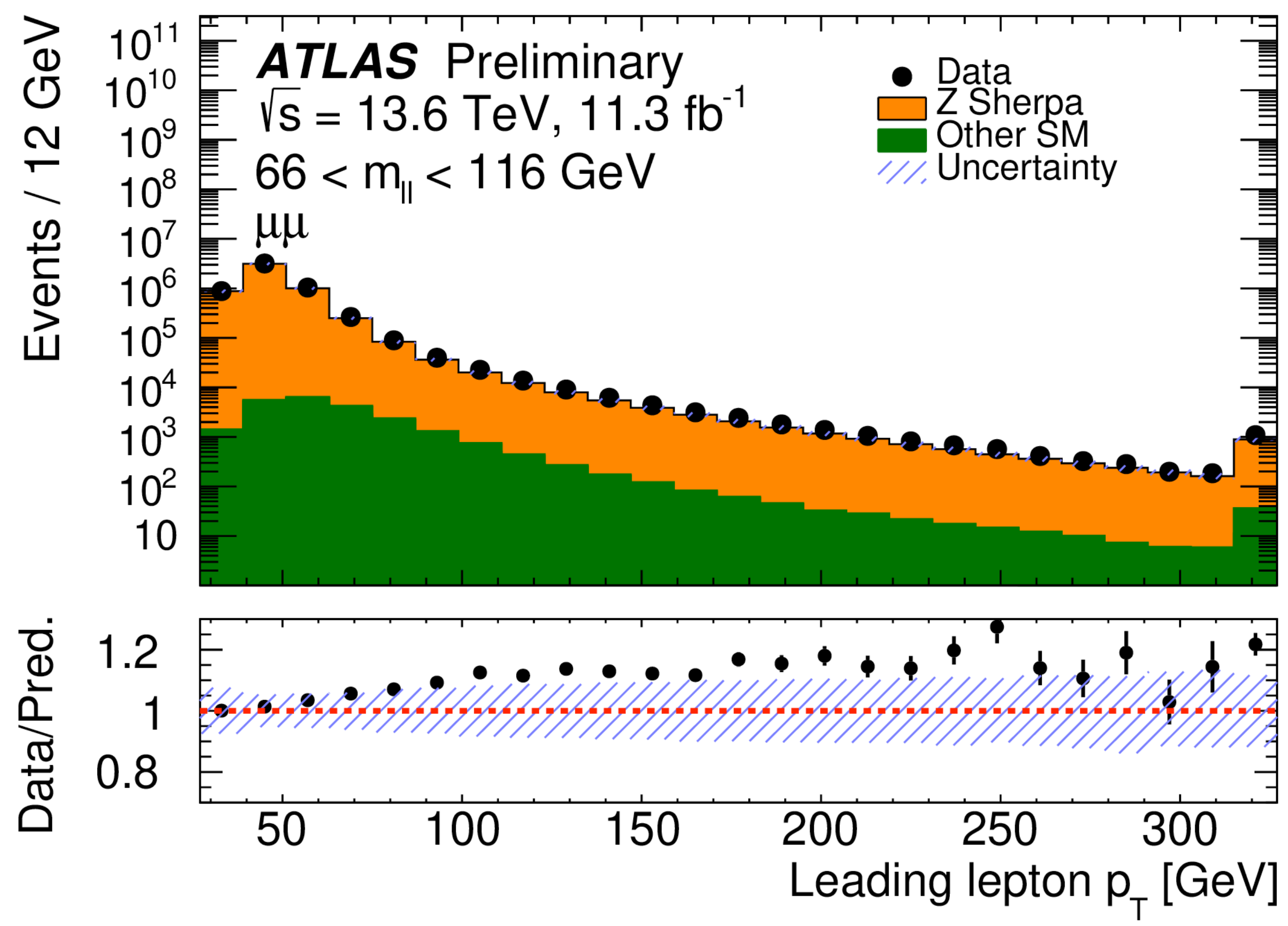
ee/μμ channels for Z, fiducial region 66< $m_{\ell\ell}$ <116 GeV

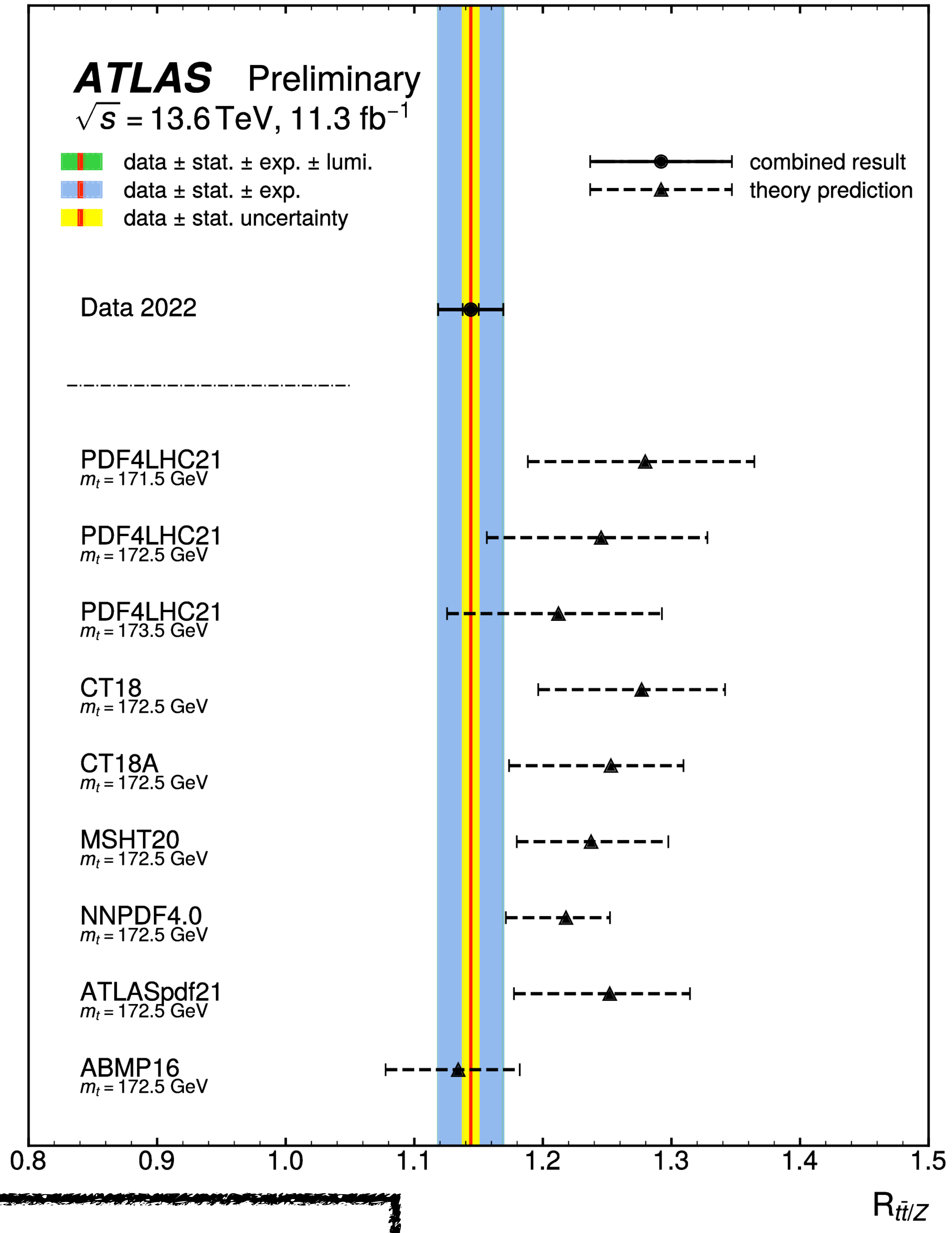
$$\sigma^{\text{fid}}_{Z\to\ell\ell} = 751 \pm 0.3(stat) \pm 15(syst) \pm 17(lumi)\ \text{pb}$$

→ precision of individual results affected by correlated syst. uncertainties









- Binned profile likelihood used to extract the ratio
- Much better precision due to cancelation of correlated systematics

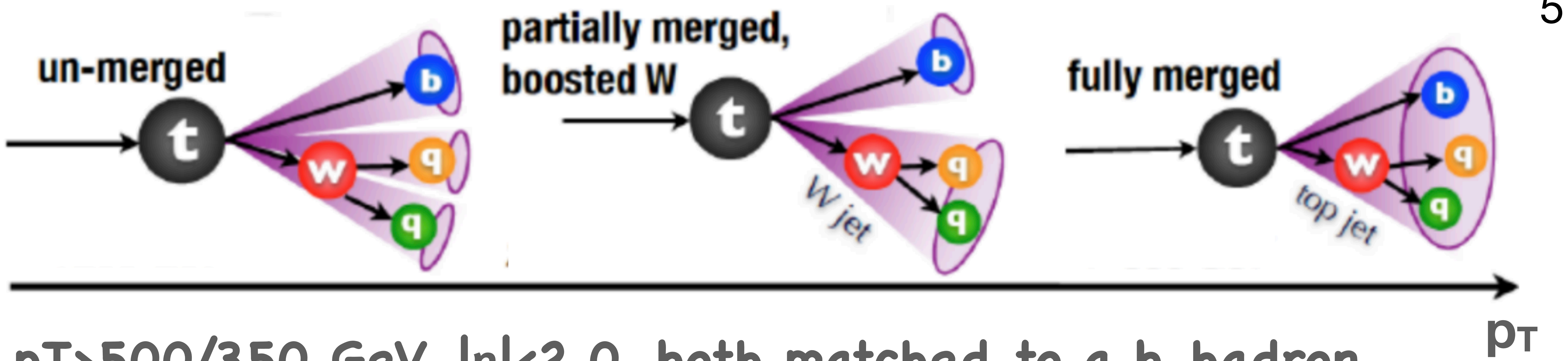
$$R_{t\bar{t}/Z} = 1.144 \pm 0.006(\text{stat}) \pm 0.022(\text{syst}) \pm 0.003(\text{lumi})$$

consistent with SM prediction

ATLAS-CONF-2023-006
13.6 TeV - 11.3 fb^{-1}

Differential $t\bar{t}$ cross-section

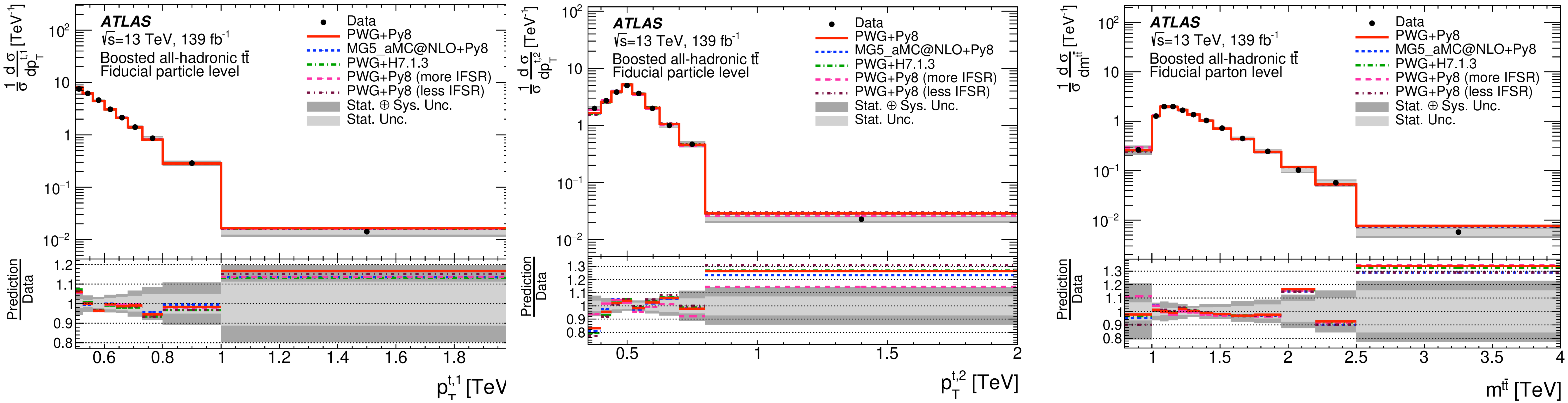
all-had ch. boosted topology



Fiducial region:

particle level → leading/subleading large-R jet: pT>500/350 GeV, |η|<2.0, both matched to a b-hadron

parton level → leading/subleading top-quark: pT>500/350 GeV



Particle level: normalized distributions precision ~ 10%-20%, reasonable agreement with several NLO+PS predictions some discrepancies in the tail of the pT of the second top-quark, as observed in previous ATLAS measurements

Parton level: general better agreement → possible sources of discrepancies: PS, hadronization, ISR/FSR

arXiv:2205.02817 [hep-ex], accepted by JHEP
13 TeV - 139 fb-1

Differential $t\bar{t}$ cross-section

arXiv:2303.15340 [hep-ex], submitted to JHEP
13 TeV - 139 fb^{-1}

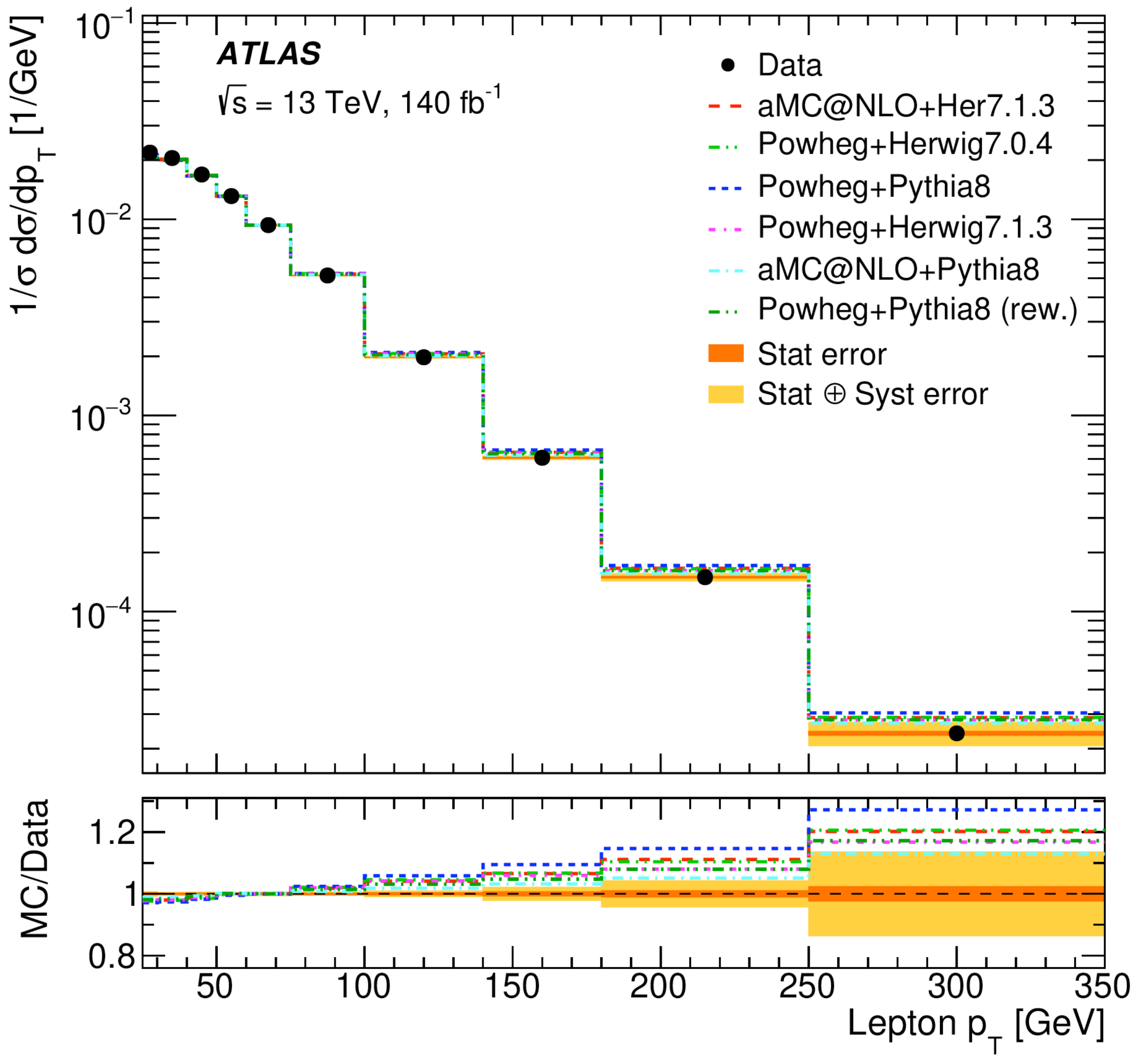
Single and double differential cross-sections in the eμ final states
→ less affected by QCD modeling uncertainties

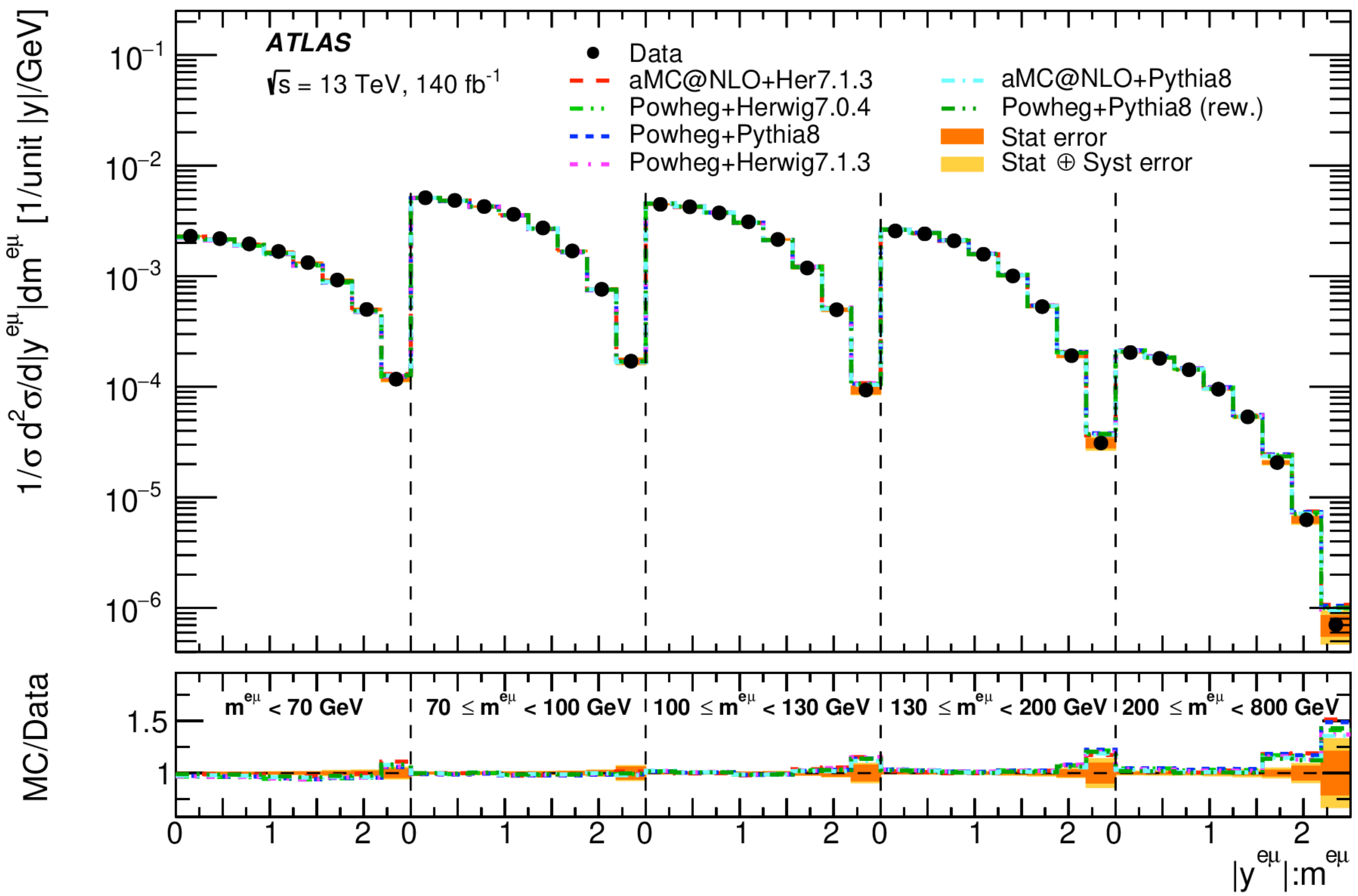
Several leptonic kinematic variables considered and compared with various MC predictions @ NLO+PS p_T^{ℓ}, $|\eta_\ell|$, $m_{e\mu}$, $p_T^{e\mu}$, $|y^{e\mu}|$, $E^e + E^\mu$, $p_T^e + p_T^\mu$, $\Delta\phi^{e\mu}$

Fiducial region at particle level

leptons: e(μ)	jets
$p_T > 27(25)$ GeV $\lvert\eta\rvert < 2.5$	$p_T > 25$ GeV $\lvert\eta\rvert < 2.5$

- Precision ~ 2% (1%) for absolute (normalized) measurements except in the highest energy bins
- No model can describe all distributions within uncertainties, sizable discrepancy especially for the high-energy tail of the distributions → **important inputs for MC modeling improvements**

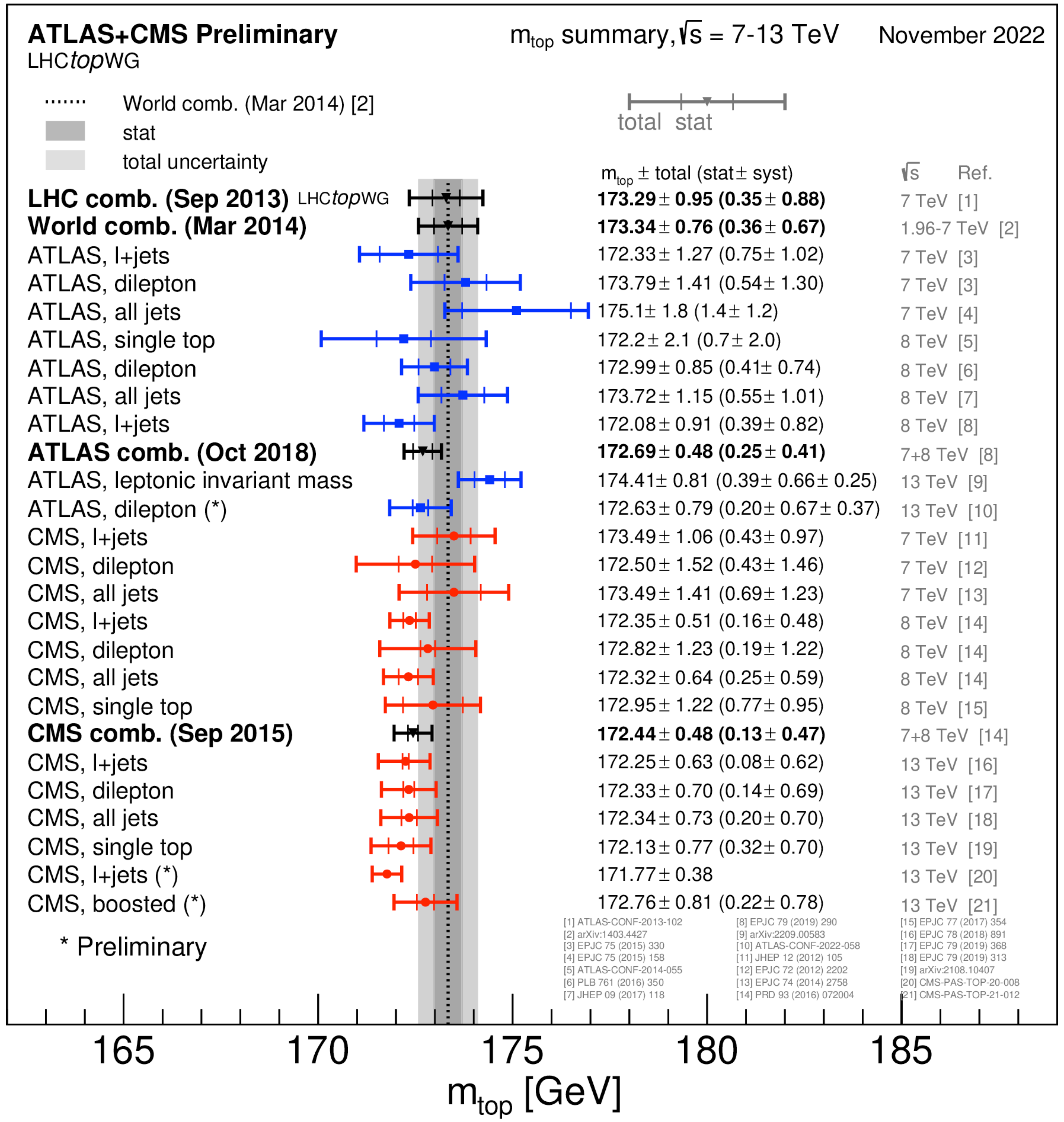




Top-quark mass fundamental parameter of the SM with several implications

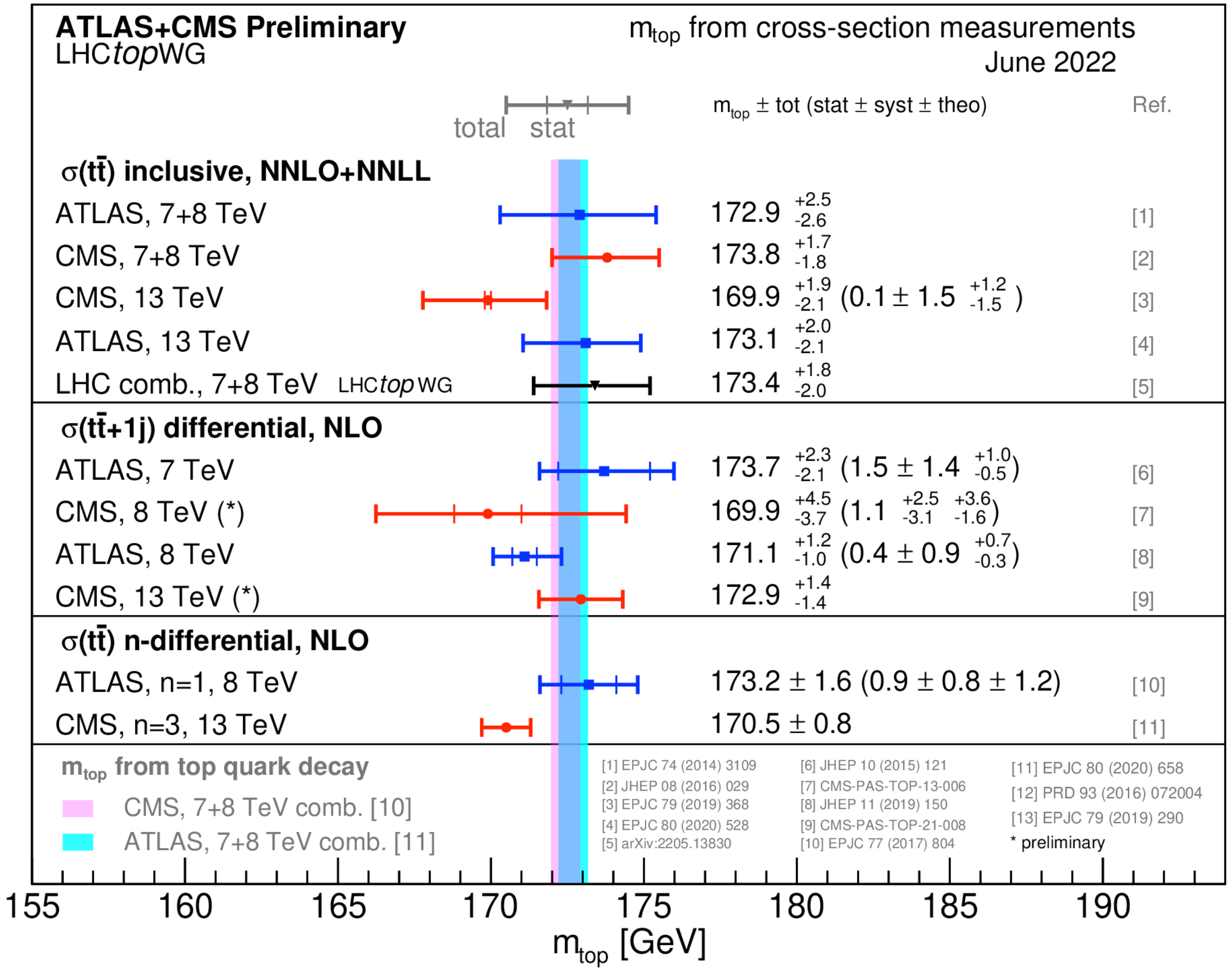
Top-quark not a free particle, mass determined through comparison with calculation

Uncertainty for combinations ~ 0.5 GeV (0.3%)



direct-measurement: invariant mass or other sensitive variables from decay products compared with MC calculation (m_{top}^{MC})

Lower uncertainties ~ 1 GeV (0.6%)

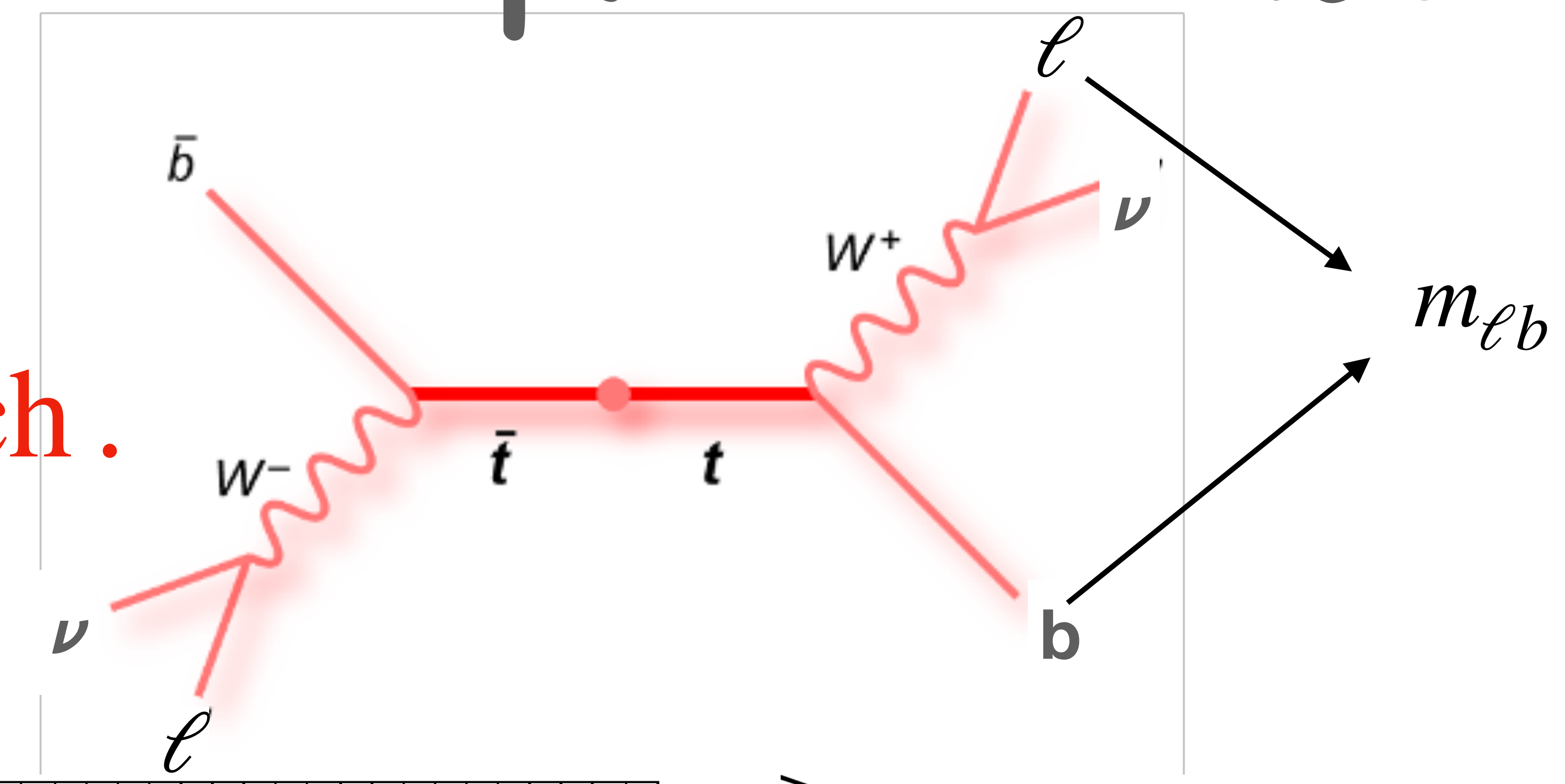


indirect-measurement: production cross-section (dependent from m_{top}) compared with QCD calculation (m_{top}^{pole})

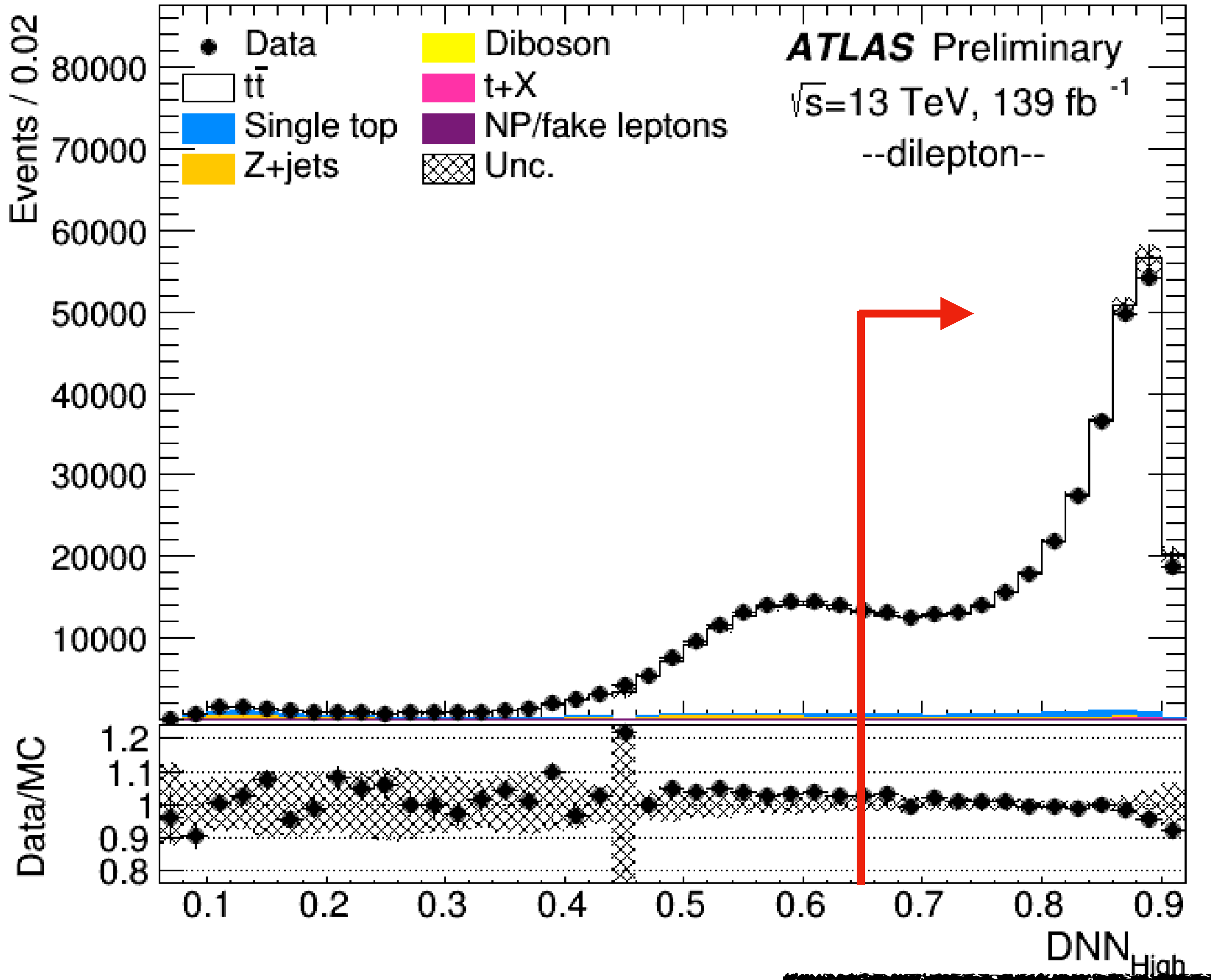
Top mass from template method in $t\bar{t} \rightarrow$ dilepton

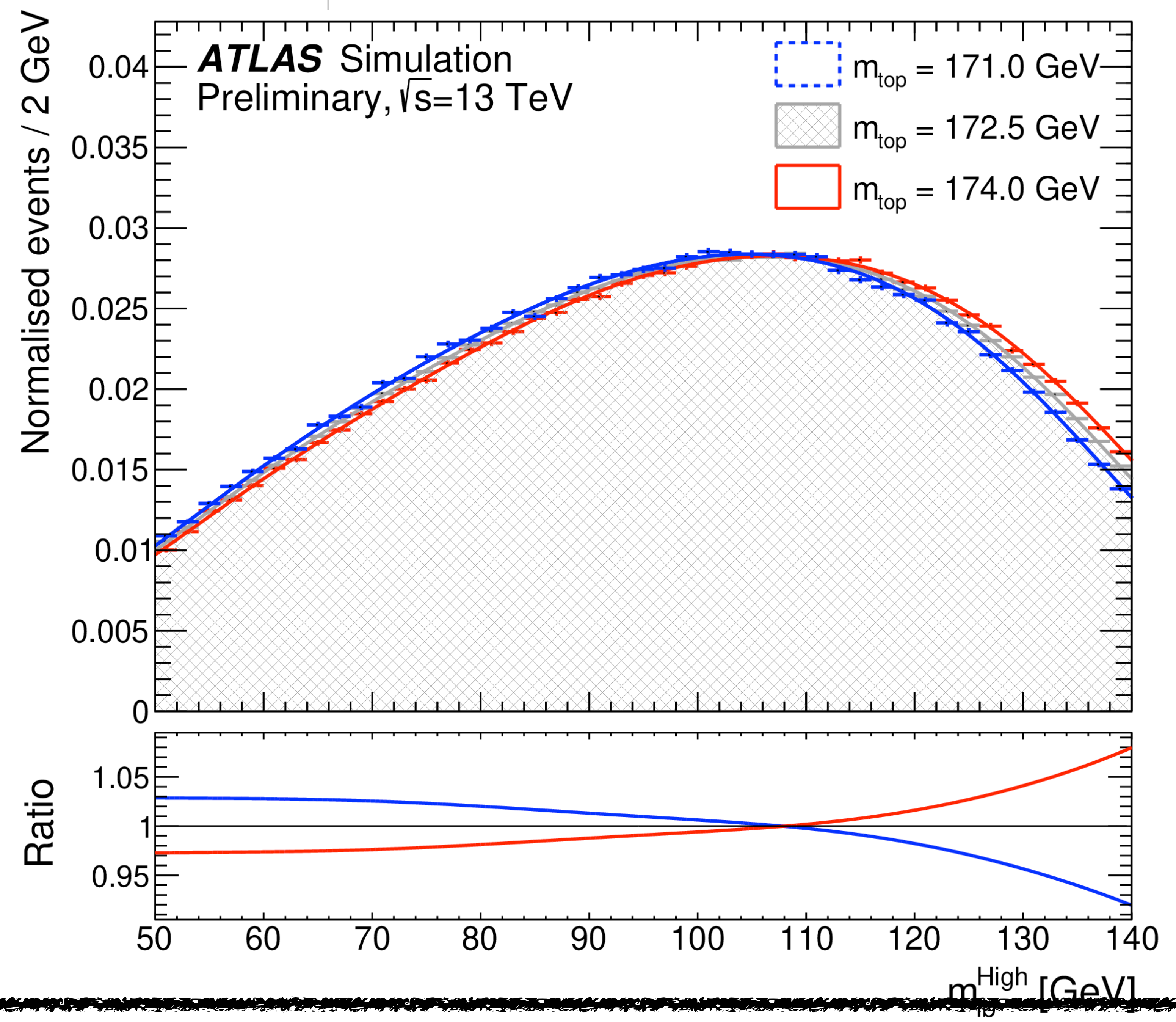
ATLAS-CONF-2022-058
13 TeV - 139 fb^{-1}

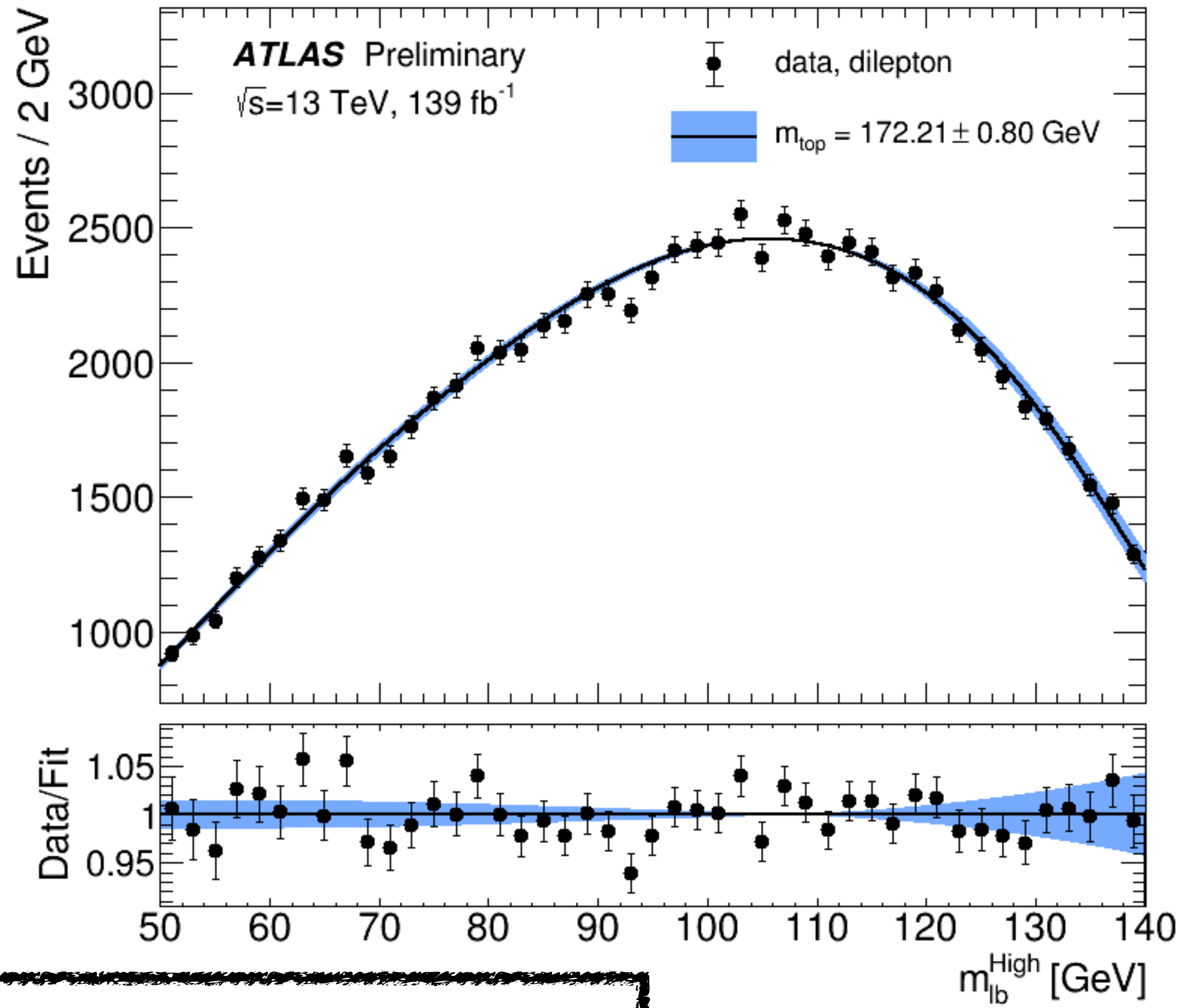
dilepton ch.



- Deep neural network (DNN) for ℓ-b matching
- used ℓ-b pair with larger p_T to reduce signal modeling and jet-related uncertainties
- Template fit to $m_{\ell b}$ distribution







$$m_t = 172.21 \pm 0.20\ (stat)\ \ \pm 0.67\ (syst)\ \ \pm 0.39\ (recoil^*)\ \text{GeV}$$

tot = ±0.80 GeV

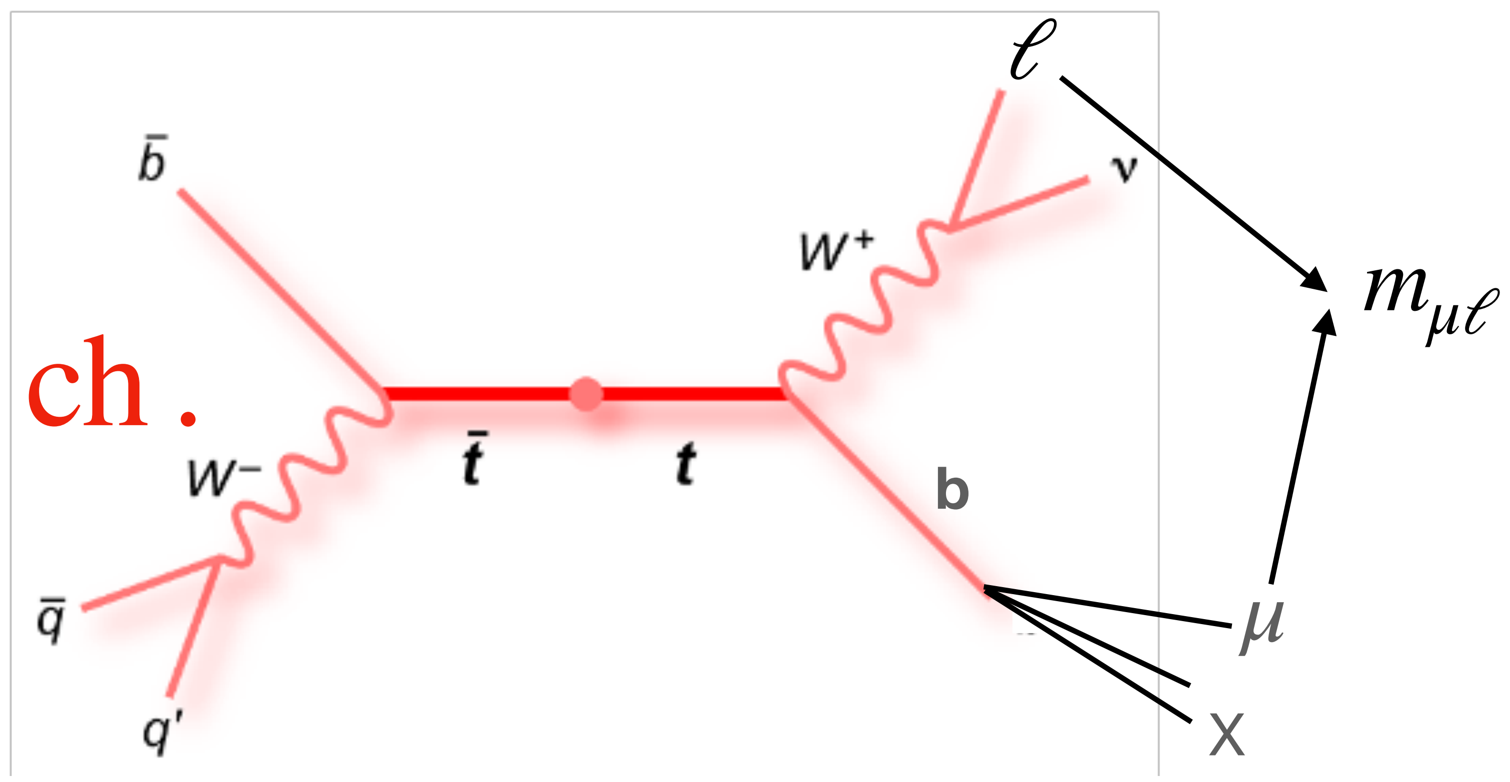
*Effect of different treatments of recoil in gluon emission (against b or t quark) in Pythia quoted separately

Dominant syst uncertainties: ME-PS matching, recoil, JES, color reconnection

Top mass from soft muon tag

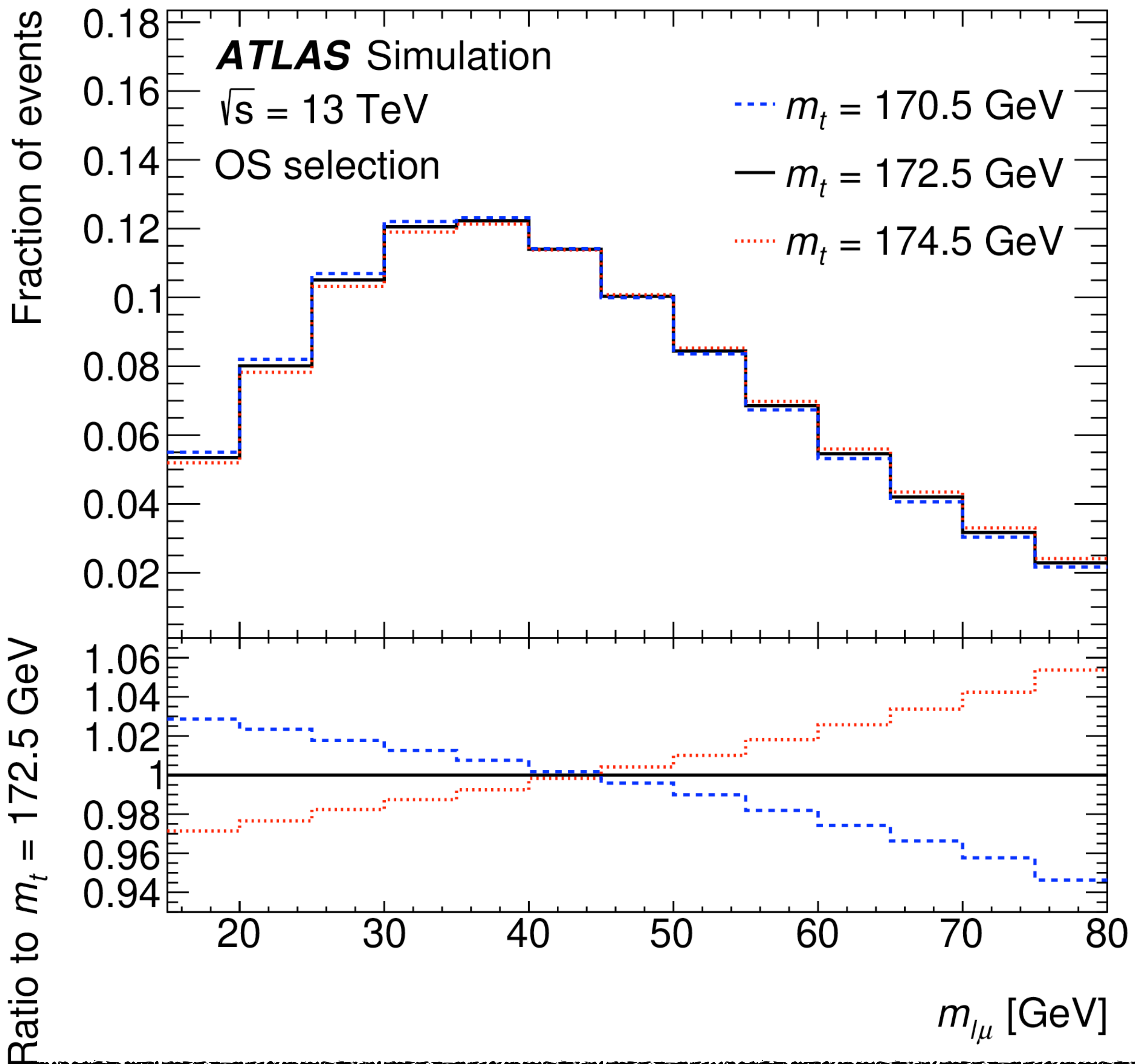
arXiv:2209.00583 [hep-ex]
13 TeV - 36.1 fb^{-1}

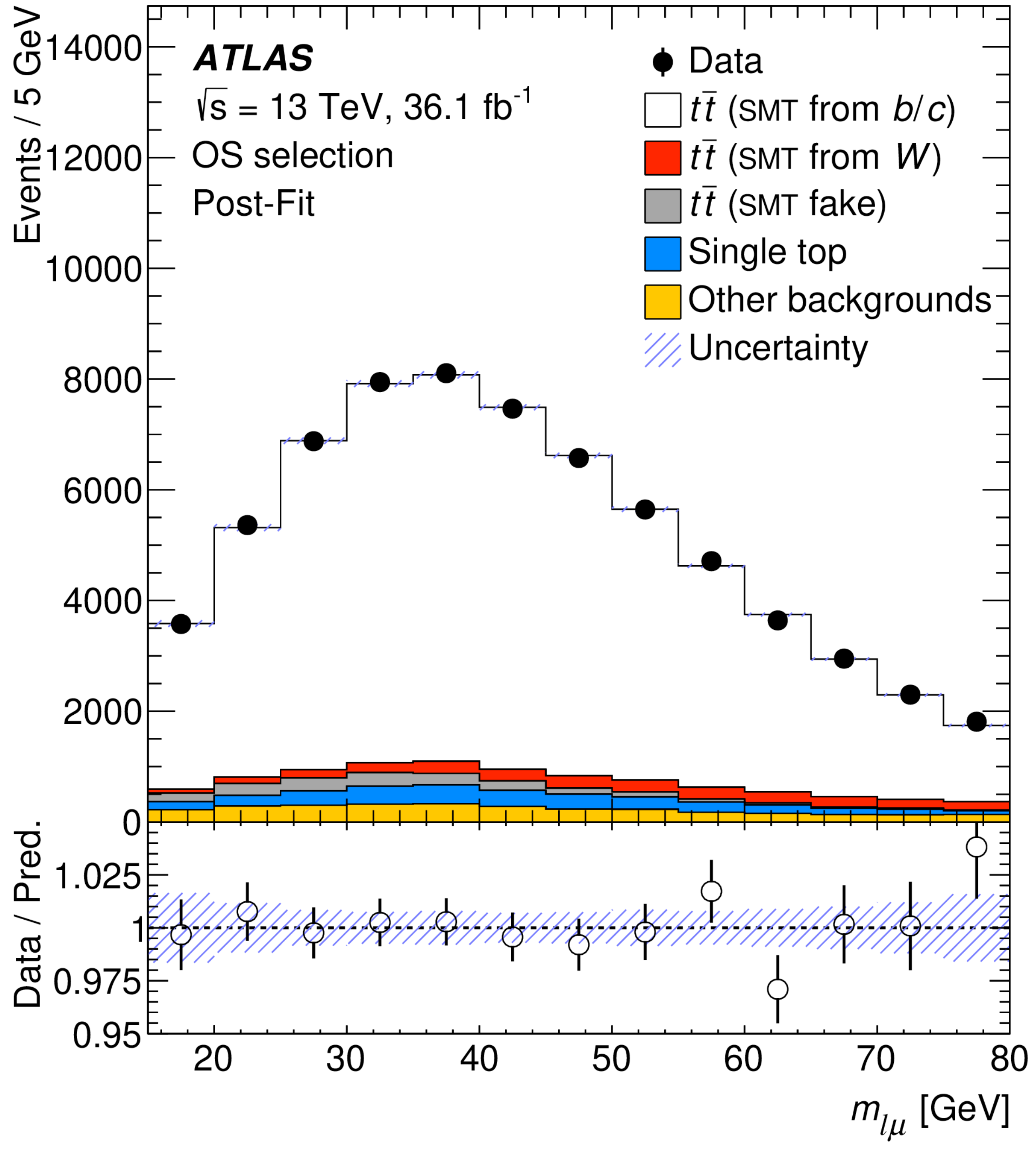
ℓ + jets ch.

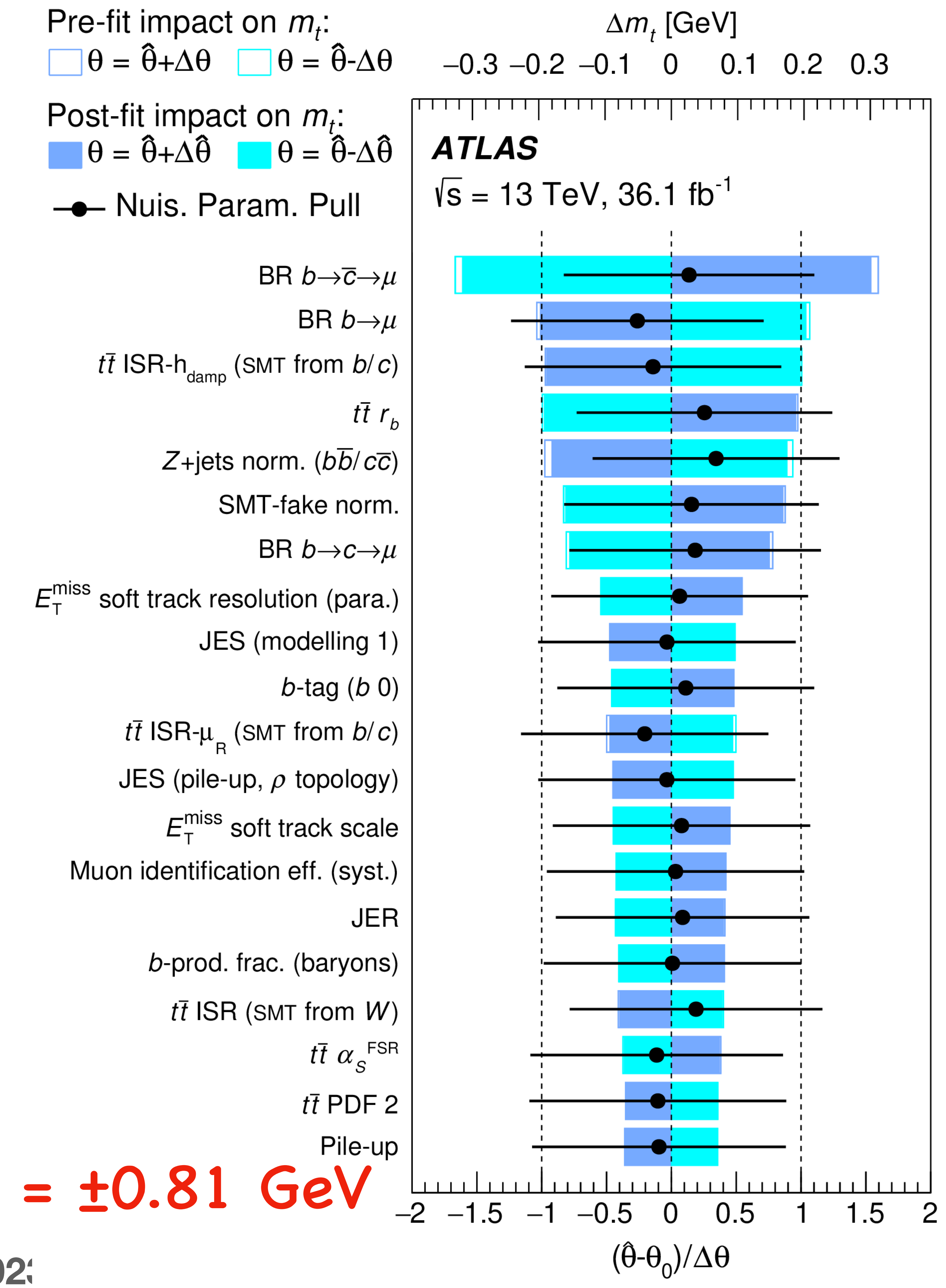


less sensitivity to JES/JER and to $t\bar{t}$ production modeling sensitive to b-fragmentaton, LEP and SLC data used to improve data description → relevant for combination with other methods

Likelihood fit using templates for different m_{top}







$$m_t = 174.41 \pm 0.39\ (stat)\ \pm 0.66\ (syst)\ \pm 0.25\ (recoil)\ \text{GeV}$$

tot = ±0.81 GeV

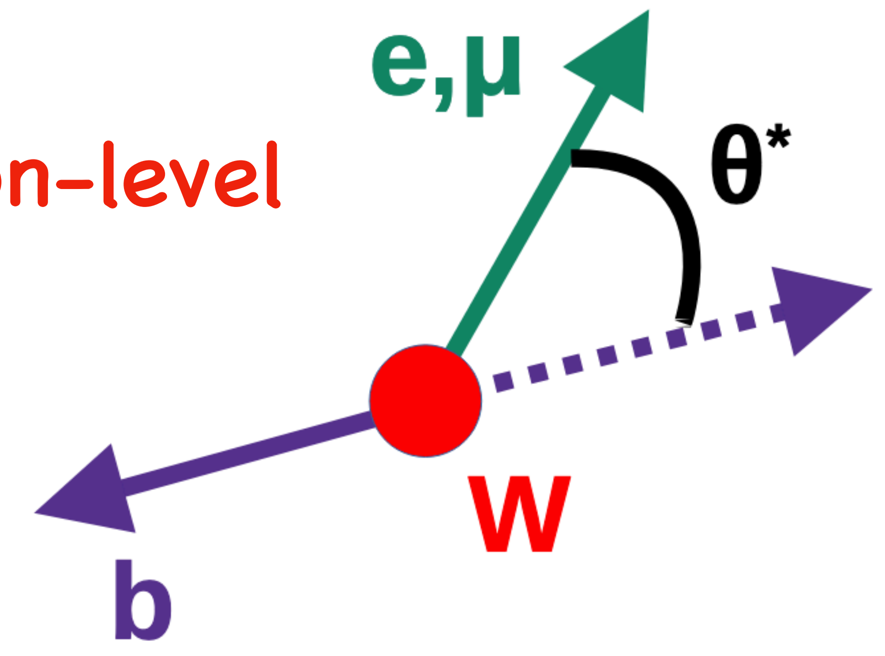
W polarization in top decay

arXiv:2209.14903 [hep-ex]
13 TeV - 139 fb^{-1}

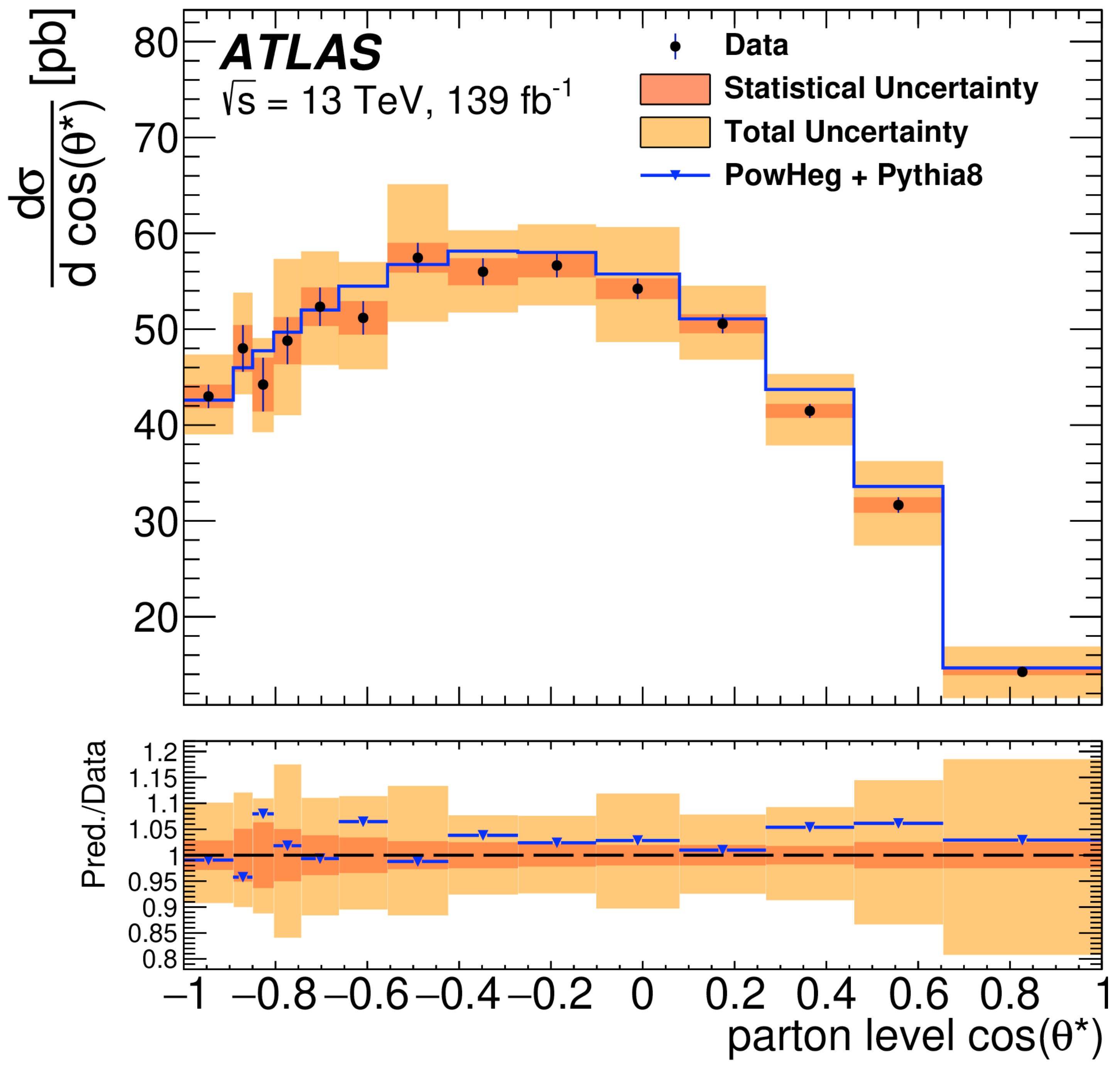
test Wtb properties, determined by the V-A structure of the EW interaction

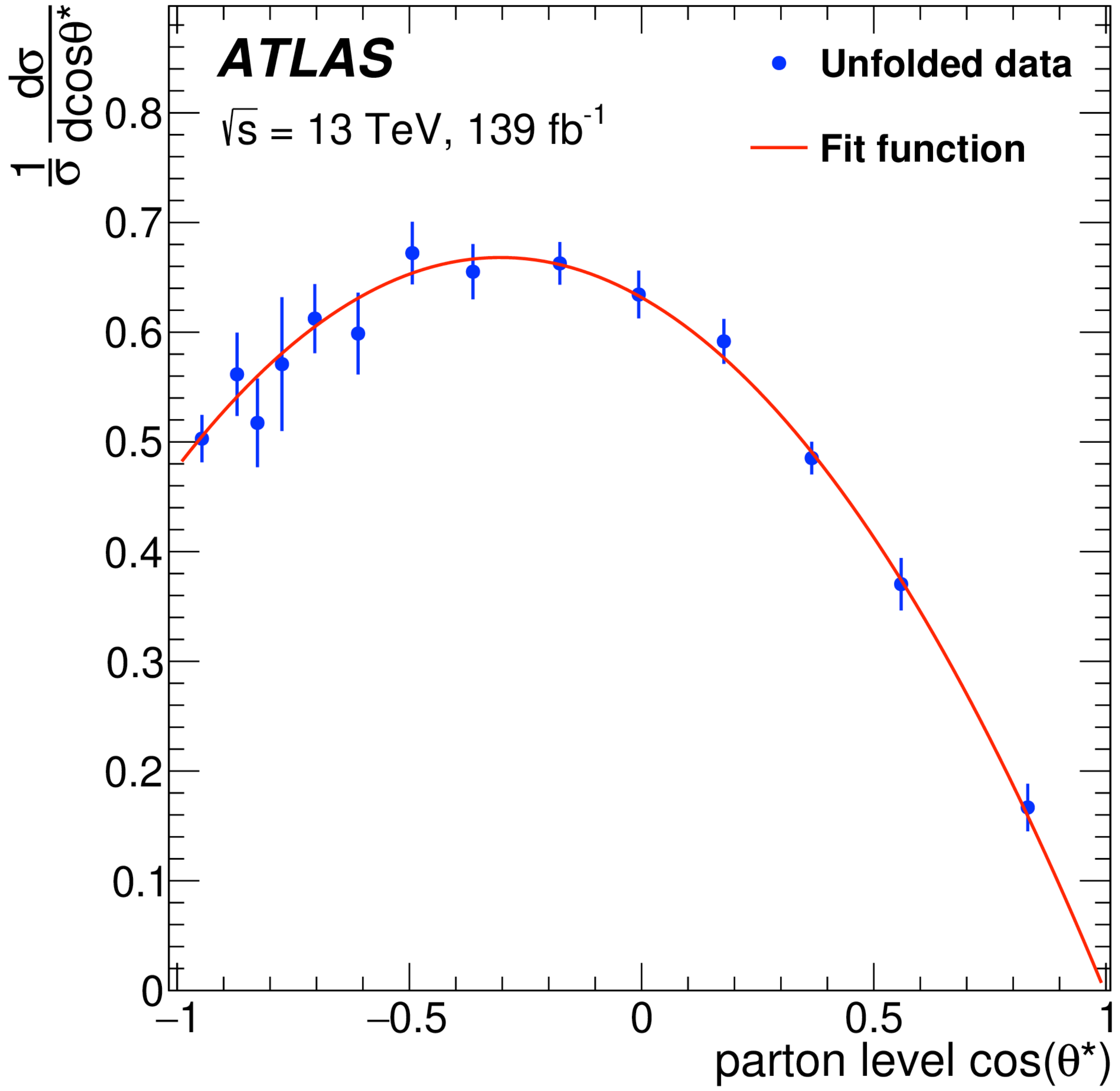
dilepton ch. $\rightarrow \frac{d\sigma}{d\cos\theta^*}$ unfolded at parton-level

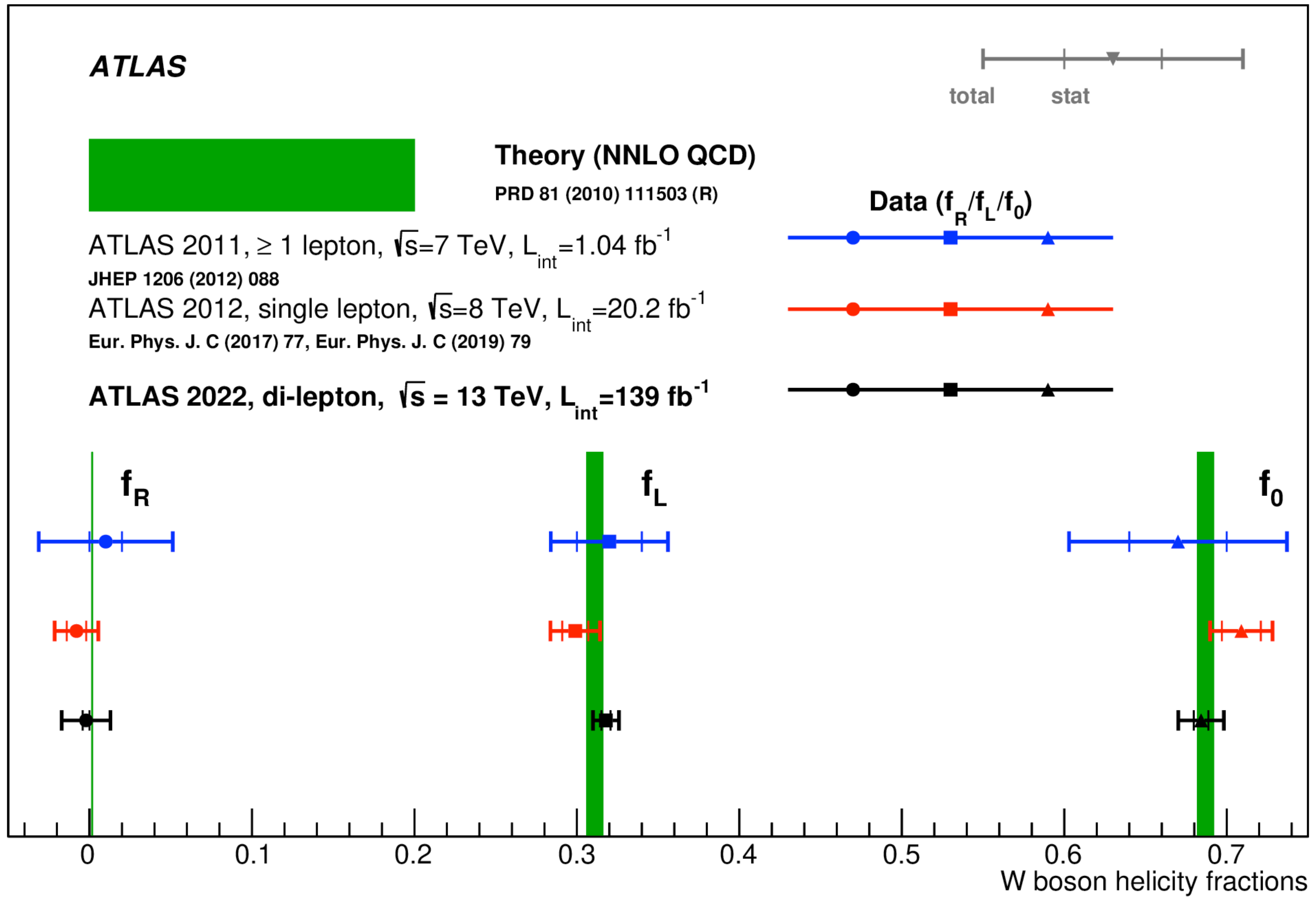
Main systematic uncertainty: $t\bar{t}$ production modelling, jet reconstruction



$$f_0 = 0.684 \pm 0.005(stat) \pm 0.014(syst)$$
$$f_L = 0.318 \pm 0.003(stat) \pm 0.008(syst)$$
$$f_R = -0.002 \pm 0.002(stat) \pm 0.014(syst)$$







Excellent agreement with SM predictions, large improvement in the precision of the measurement

Summary

Top-quark plays a central role in the SM, it is implicated in crucial still open fundamental questions and offers unique opportunities for a better understanding of the microscopic world.

LHC is a top factory, the ideal lab for precision studies of its properties.
An impressive amount of results produced, most of them exhibit a remarkable agreement with the SM predictions:

- Top mass measurements routinely at sub-GeV level

- Differential and fiducial measurements are key input for better MC modeling

Some of the measurements out-perform predictions in precision pushing for further improvements in theoretical calculations

First run 3 results very promising, many new results in the pipeline.

STAY TUNED!

Back-up slides

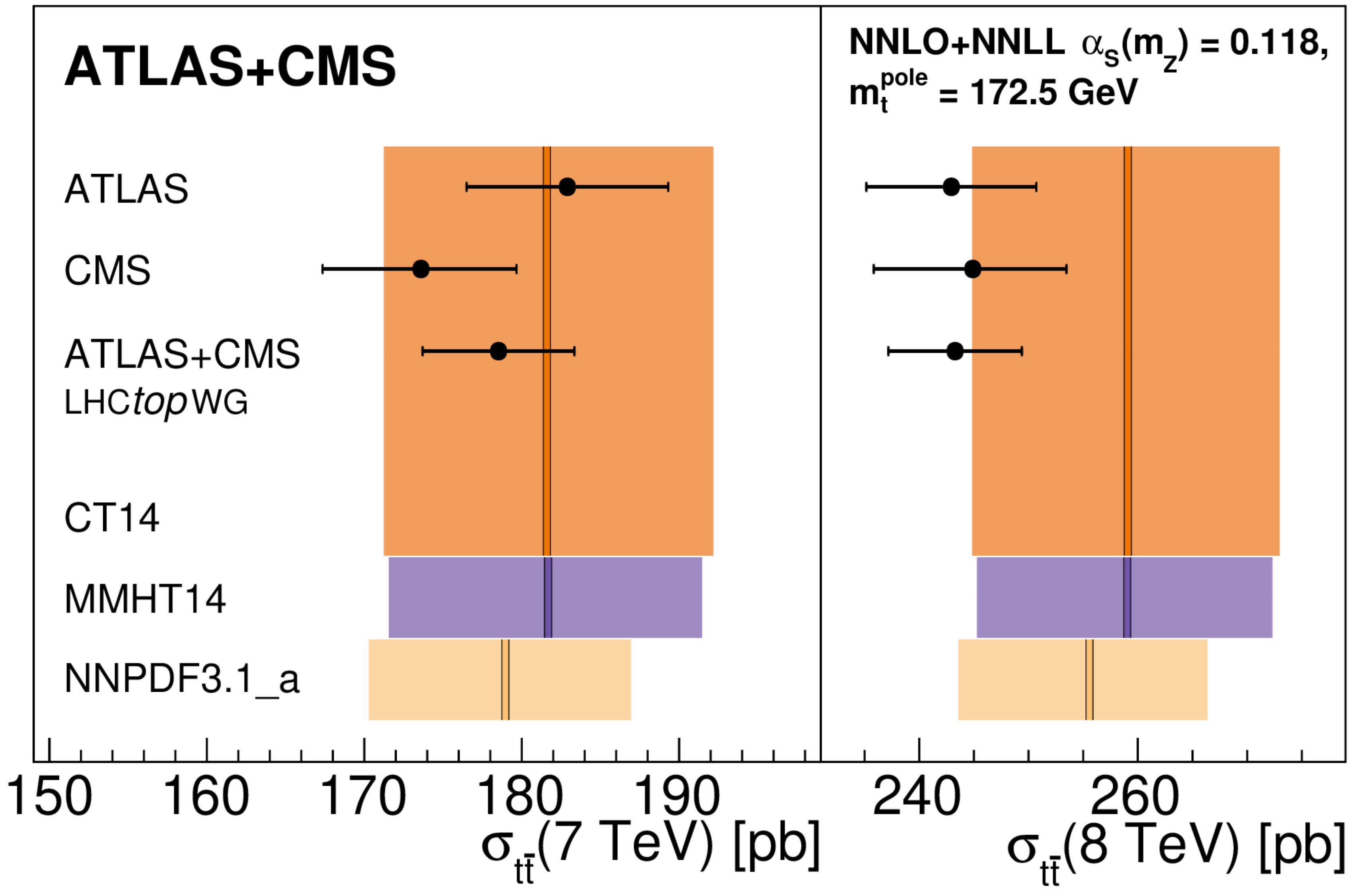
Inclusive $t\bar{t}$ cross-section ATLAS+CMS @ 7 and 8 TeV

eμ di-lepton ch. arXiv:2205.13830 [hep-ex] — 7/8 TeV — 5/20 fb^{-1}

combination performed accounting for correlations between and within the individual measurements:

$$\sigma_{t\bar{t}}^{7\text{ TeV}} = 178.5 \pm 4.7 \text{ pb} \,(2.6\,\%\text{ prec.}) \qquad \sigma_{t\bar{t}}^{8\text{ TeV}} = 243.3^{+6.0}_{-5.9} \text{ pb} \,(2.5\,\%\text{ prec.})$$

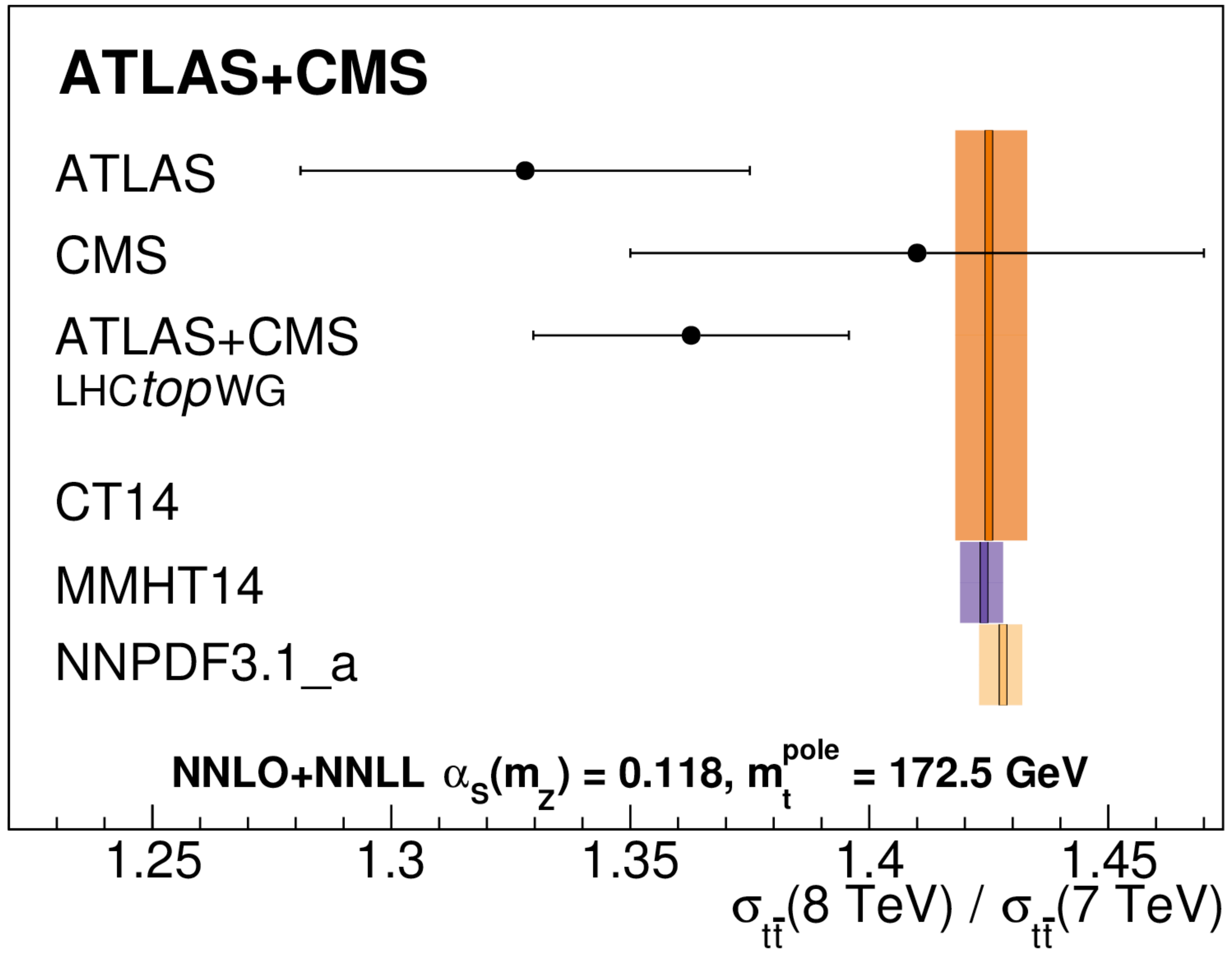
- overall precision improvement in combination → 25 (28)% @ 7 (8) TeV
- luminosity still dominant unc. but reduced ~ 35%, stat. reduced ~ 40%
- most precise measurements to date



$$R_{8/7} = 1.363 \pm 0.032$$

correlated uncertainties cancel in the ratio, improvement ~ 45%

All results in excellent agreement with SM predictions (NNLO+NNLL)



measurements used to determine m_{top}^{pole} and α_s for different PDF sets

most precise value using NNPDF3.1_a:

$$m_t^{pole} = 173.4^{+1.8}_{-2.0} \text{ GeV} \qquad \alpha_s(M_Z) = 0.1170^{+0.0021}_{-0.0018}$$

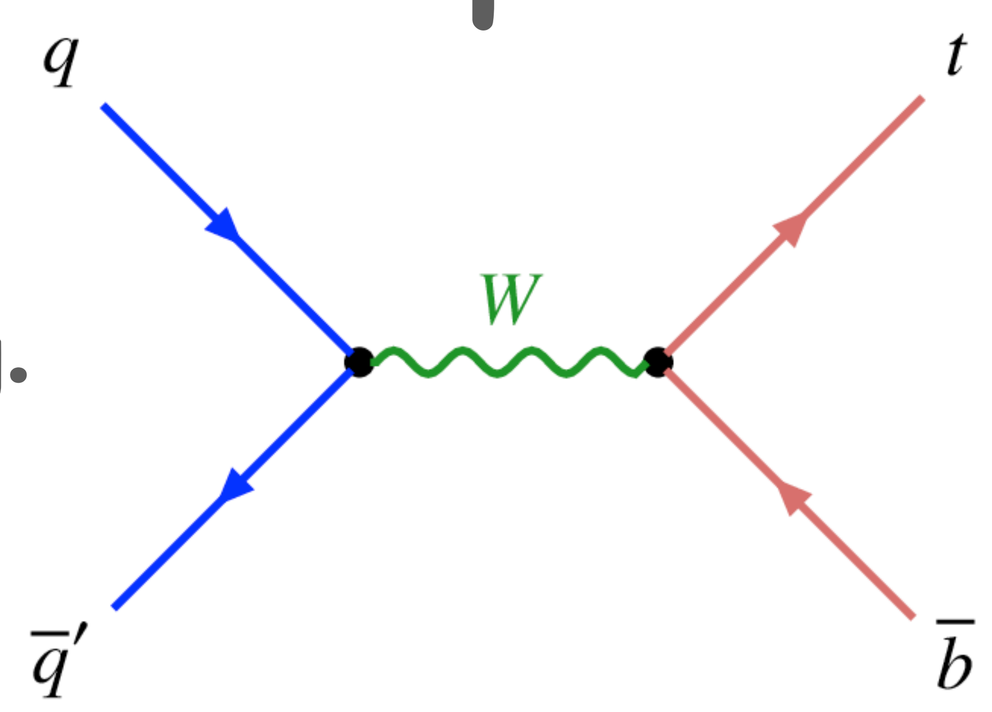
$\alpha_s(M_Z)$ most precise results using top events

Evidence for single top s-channel production

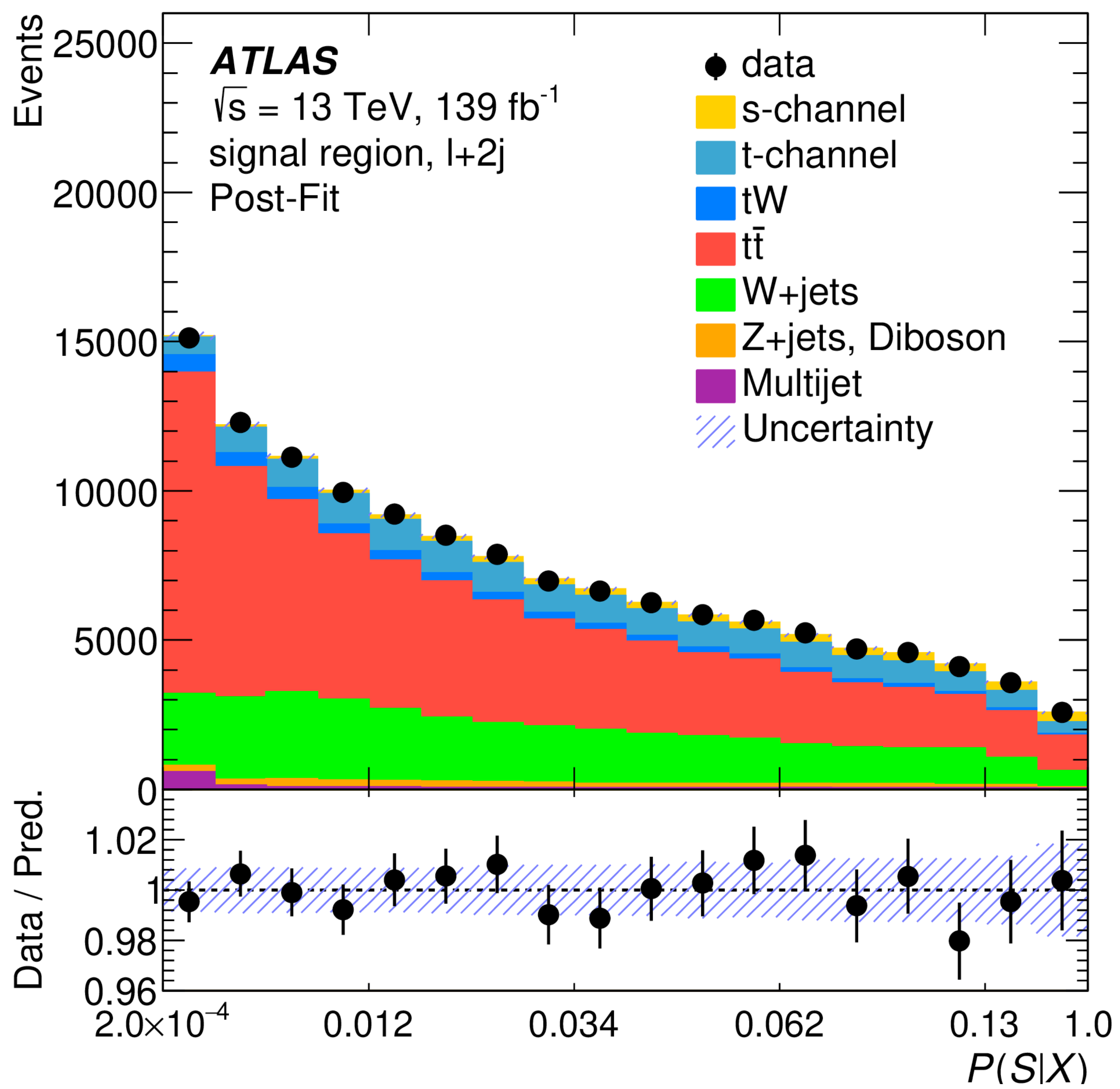
arXiv:2209.08990 [hep-ex]
13 TeV - 139 fb^{-1}

challenging, low xsec, high bkg.

$\sigma_{pred.} = 10.32^{+0.40}_{-0.32}$ pb

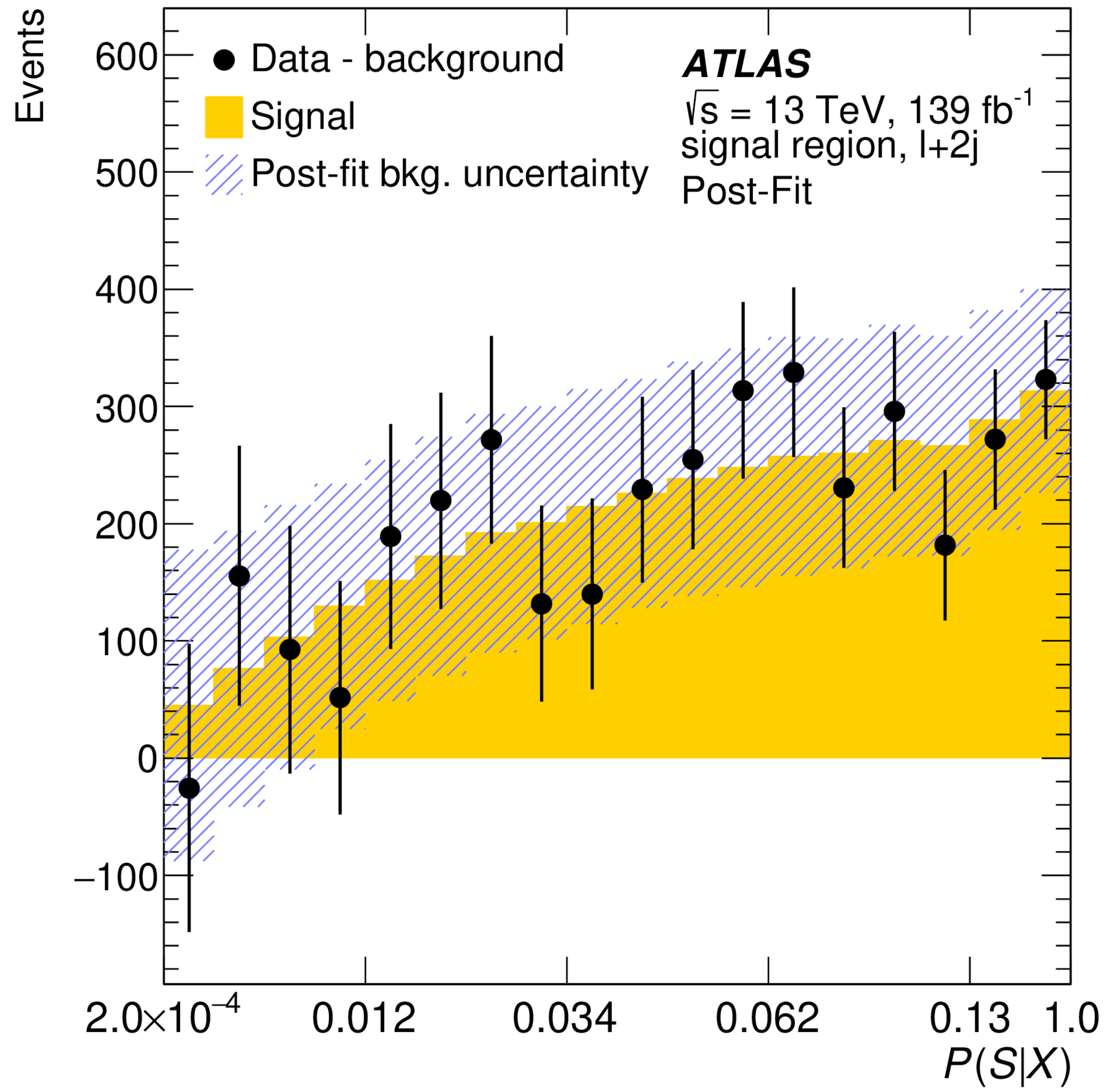


SR	W+jets	$t\bar{t}$
e/μ 2 jets 2 tight b	e/μ 2 jets 1 tight, 1 loose b	e/μ ≥3 jets 2 tight b



- QCD bkg. data driven
- Matrix Element Method and Bayesian discriminant to evaluate signal probability per event P(S|X)

$$\sigma_{s-ch.} = 8.2 \pm 0.6\ (stat)\ ^{+3.4}_{-2.8}\ (syst)\ \text{pb}$$



- Observed (expected) significance over the bkg only hypothesis 3.3 (3.9) s.d.
- dominant syst. $t\bar{t}$ normalization, signal and $t\bar{t}$ modeling, JES, JER

Colour reconnection studies in $t\bar{t}$ events

arXiv:2209.07874 [hep-ex]
13 TeV - 139 fb^{-1}

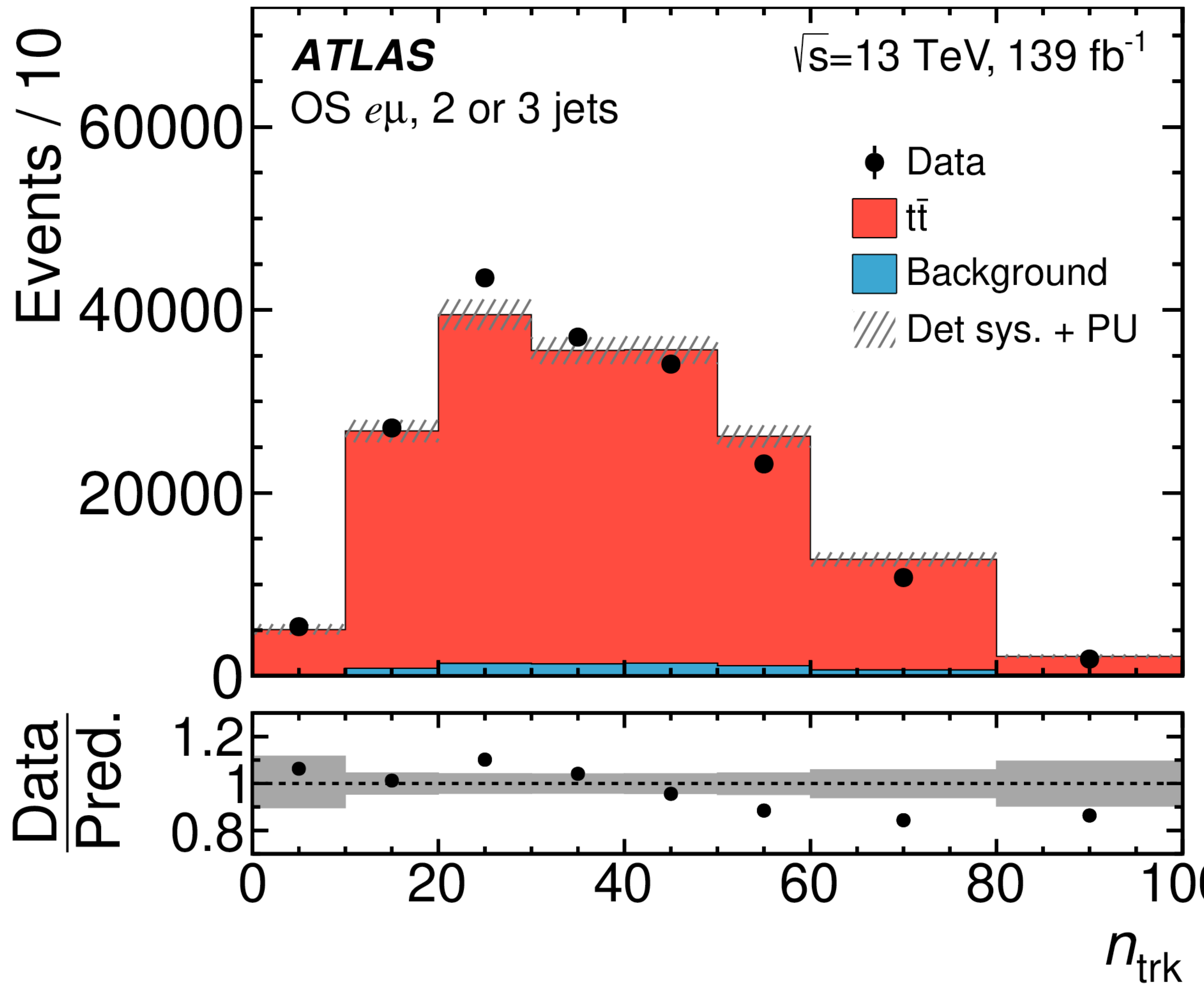
- CR models not from QCD first principles, manage color field interactions during hadronization transition
- currently one of the major systematic uncertainties (~ 300/400 MeV) in top mass measurements

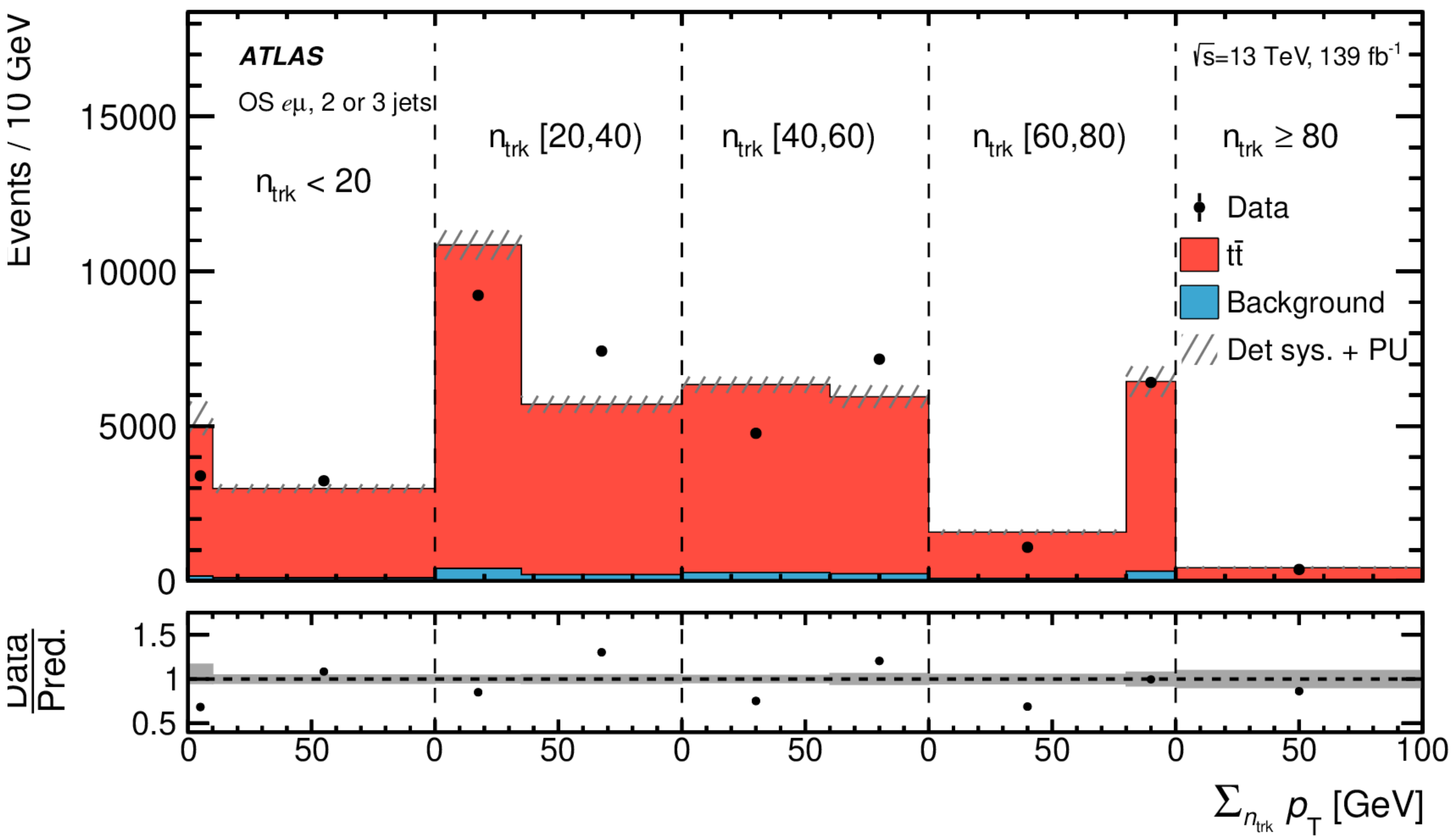
eμ di-lepton ch., 2/3 jets (2 b-tagged)

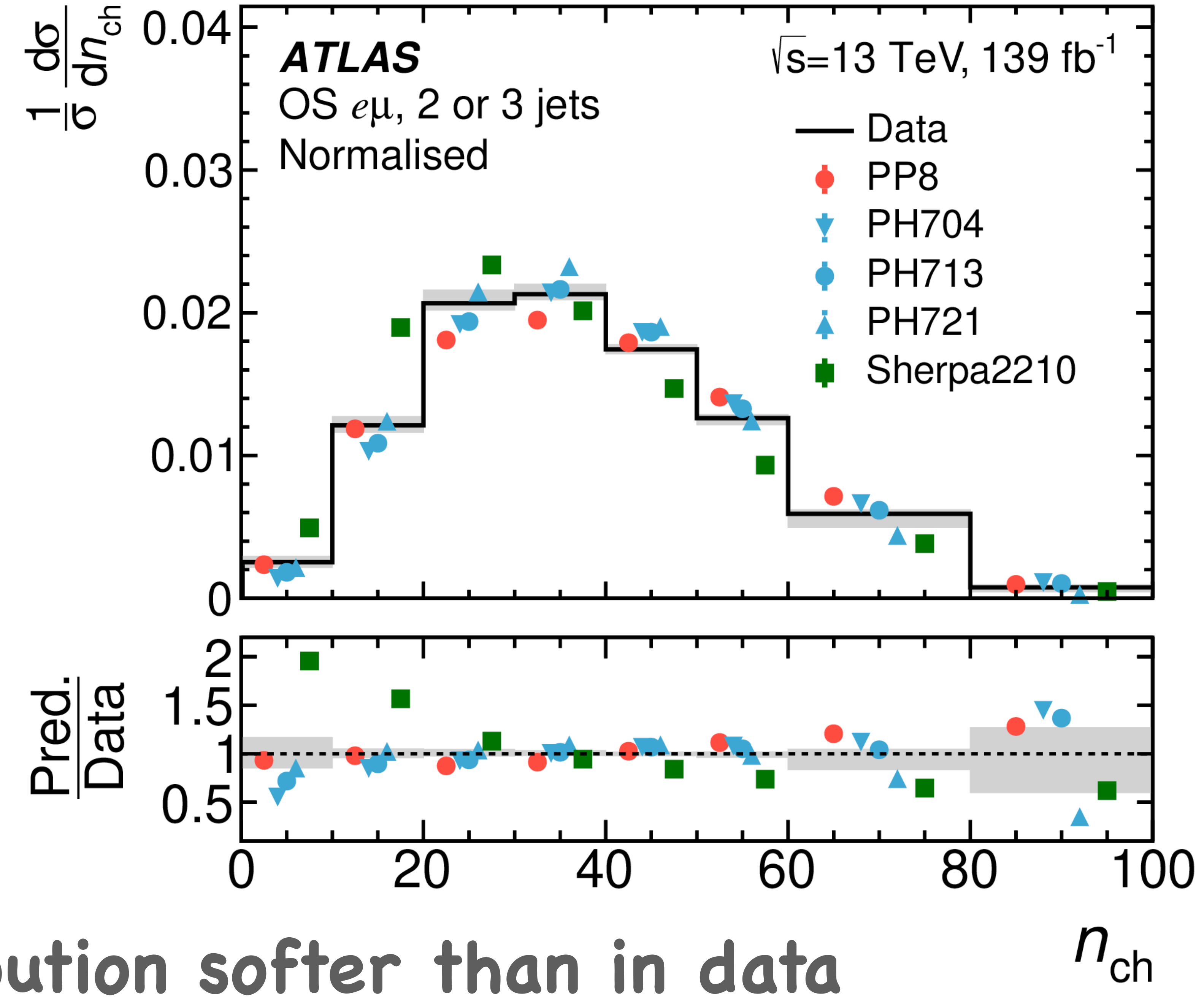
n_{trk} and $\Sigma_{n_{trk}} p_T$ sensitive to CR, compared at particle level to different models implemented in MC generators

Fiducial region particle level

leptons: e-μ	jets
$p_T > 25/27$ GeV, $\lvert\eta\rvert < 2.5$ OS, $m_{\ell\ell}$>15 GeV	2/3 (2 b-jets) $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$







- Sherpa2210 does not contain CR → too few particles and $\Sigma_{n_{ch}} p_T$ distribution softer than in data
- CR models implemented in Pythia8 and Herwig7.2 → better description of the data
- **results to be used as input to future tuning of MC generators for both CR and MPI**

Charge asymmetry in $t\bar{t}$ production

arXiv:2208.12095 [hep-ex]
13 TeV - 139 fb^{-1}

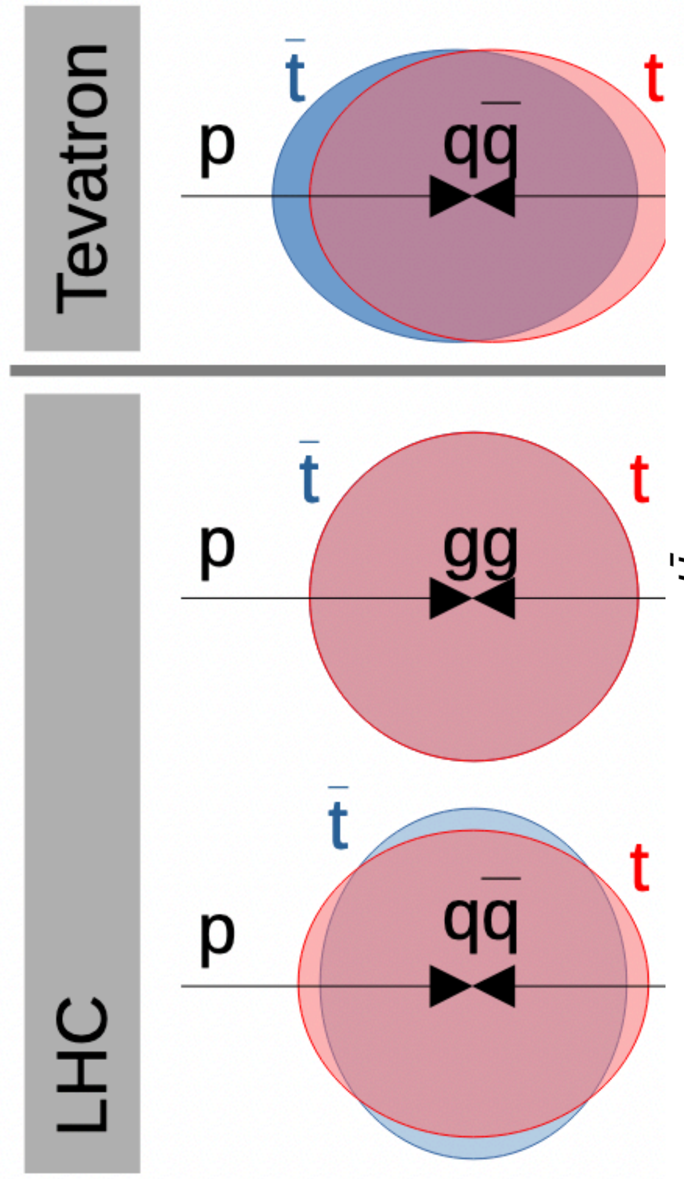
Asymmetry due to higher order contribution in $q\bar{q} \rightarrow t\bar{t}$

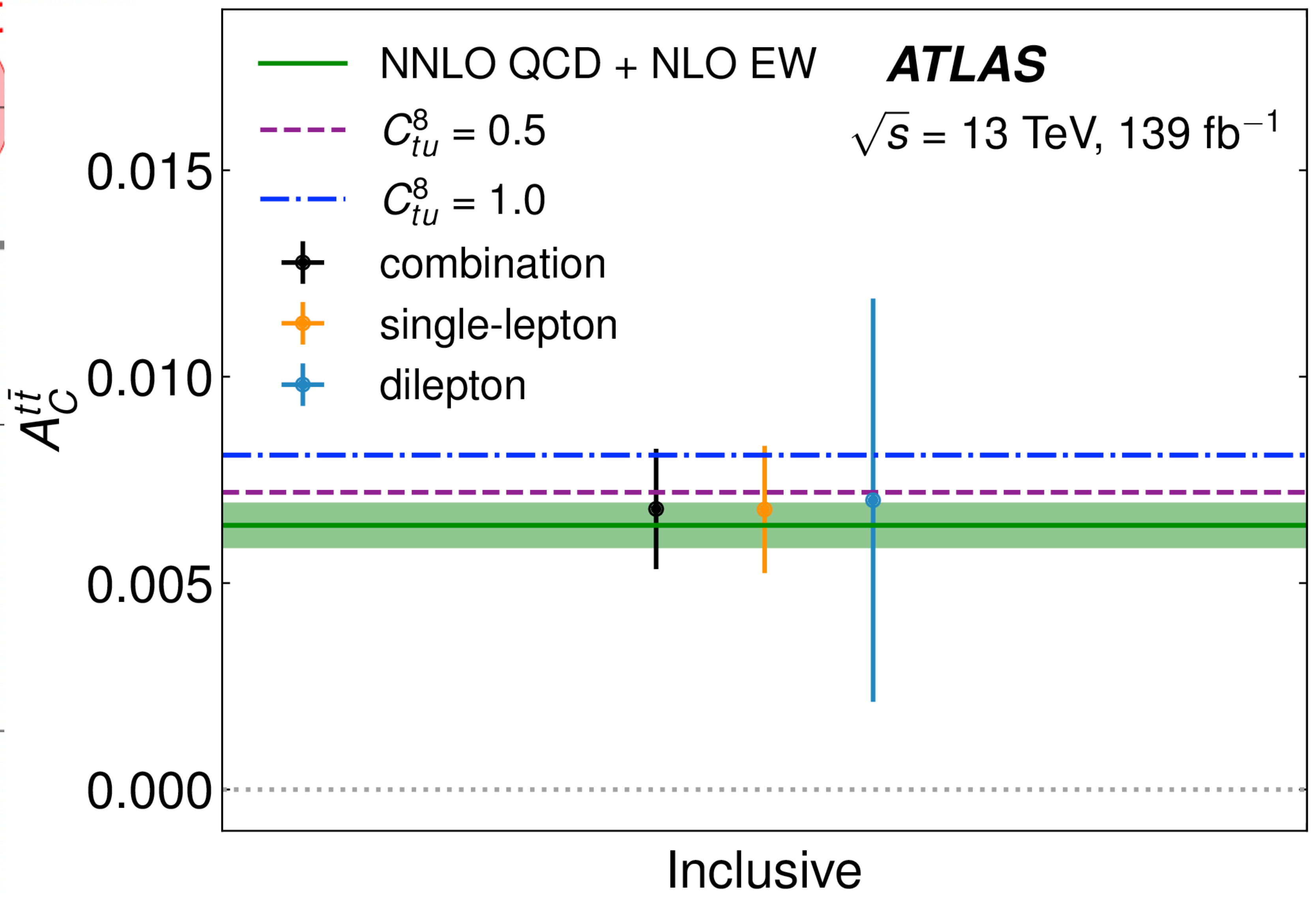
At LHC the main gg production is symmetric

q has on average a larger x than $\bar{q}$ resulting in a more forward distribution for t and more central for $\bar{t}$

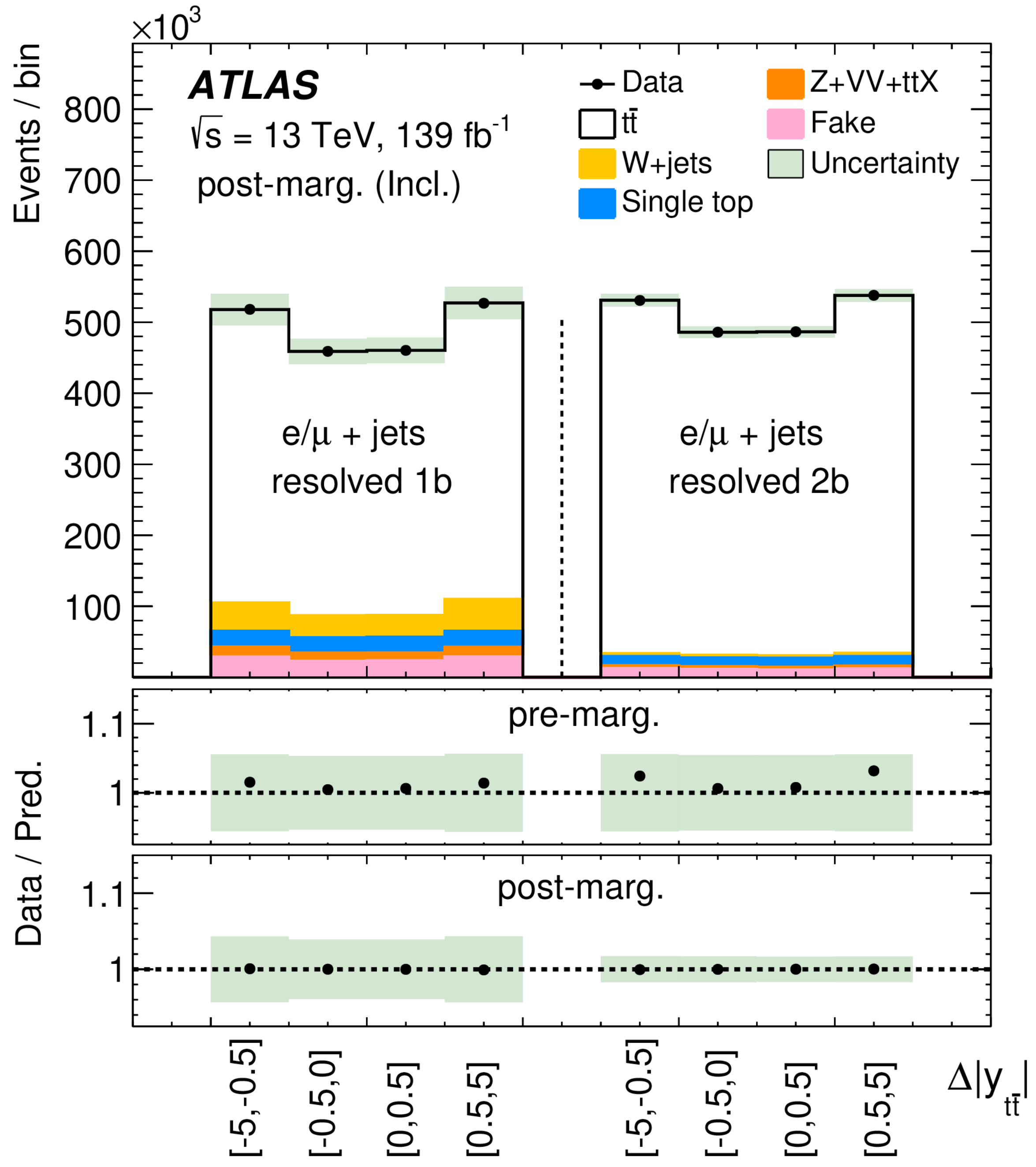
$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}|>0) - N(\Delta|y_{t\bar{t}}|<0)}{N(\Delta|y_{t\bar{t}}|>0) + N(\Delta|y_{t\bar{t}}|<0)} \quad \Delta|y_{t\bar{t}}| = |y_t| - |y_{\bar{t}}|$$

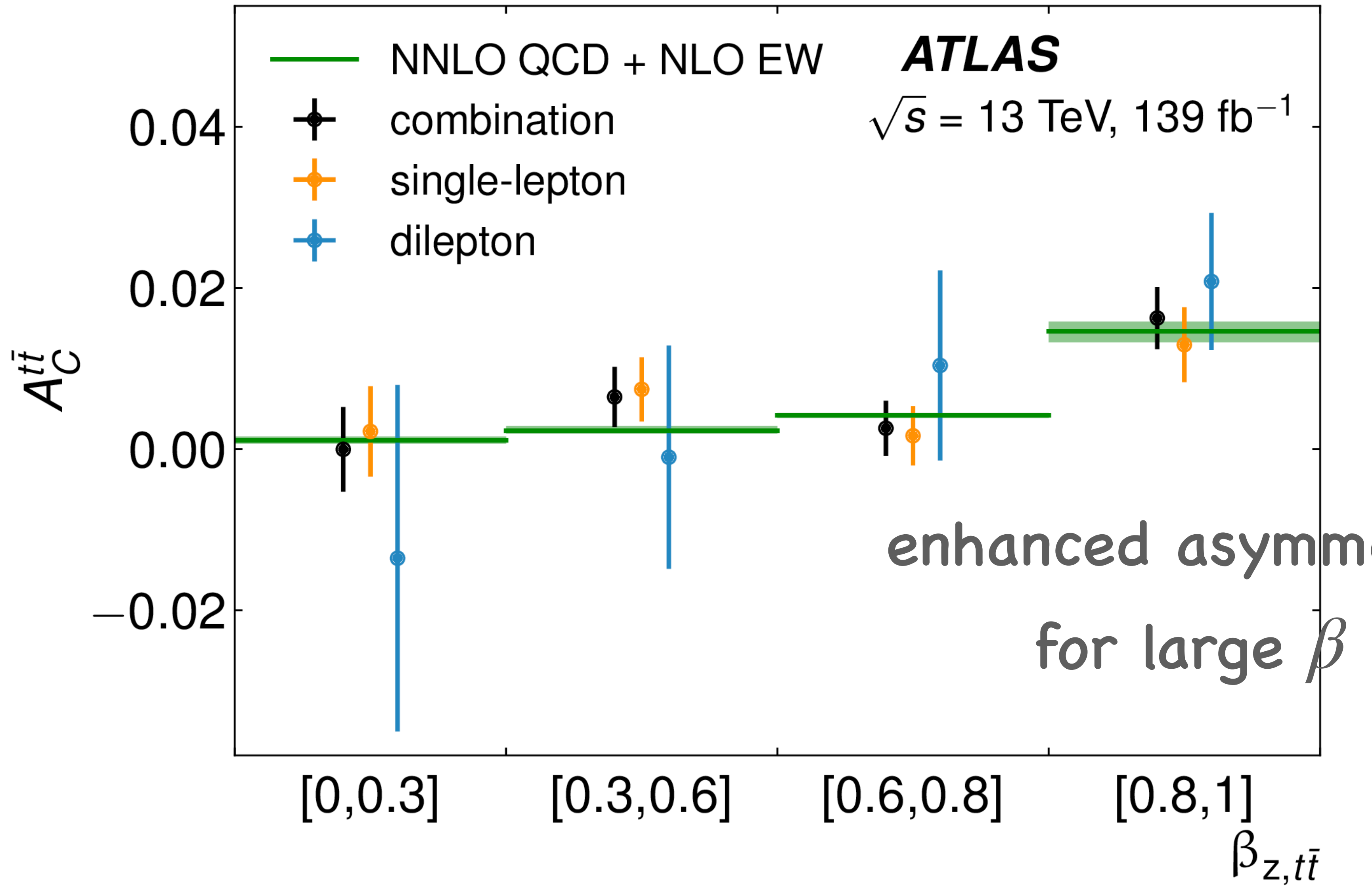
A_C measured inclusively and as a function of $p_T^{t\bar{t}}$, $m_{t\bar{t}}$, $\beta_{z,t\bar{t}}$ in l+jets and dilepton channel resolved and boosted topology



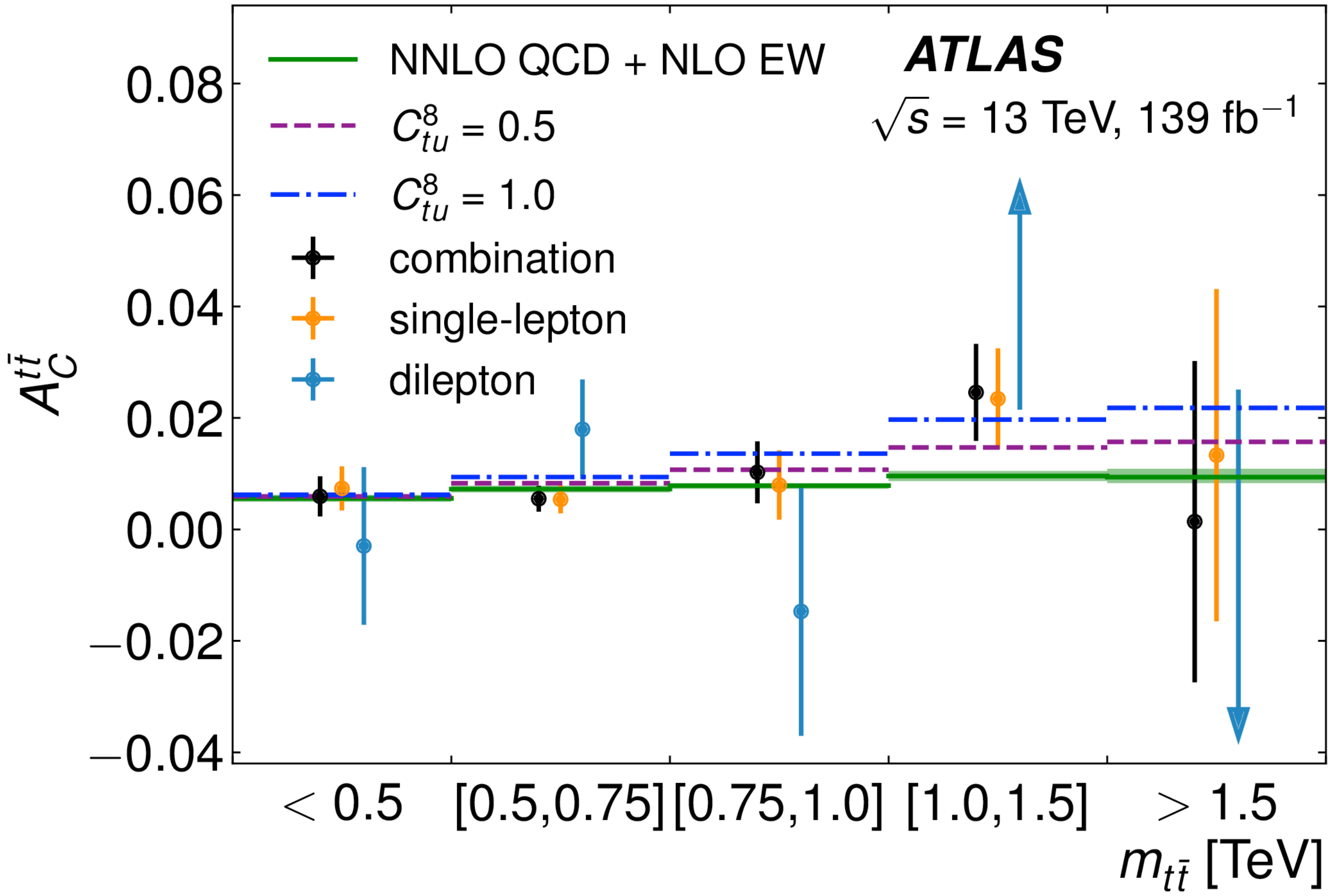


$A_C^{t\bar{t}} = 0.0068 \pm 0.0015$ (stat + sist), 4.7σ significance





enhanced asymmetry for large β



$t\bar{t}$ diff. sec - dilepton ch.

χ^2 values for the comparison of the normalised measured differential cross-sections with different $t\bar{t}$ simulation samples.

Generator	p_T^ℓ	$\lvert\eta^\ell\rvert$	$p_T^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$	$m^{e\mu}$	$\lvert\Delta\phi^{e\mu}\rvert$	$\lvert y^{e\mu}\rvert$
N_{dof}	9	23	9	10	14	20	29	29
Powheg+Pythia 8	196	132	12.0	130	33	102	193	47
Powheg+Pythia 8 - top p_T rew.	51	114	7.8	42	20.4	53	65	45.2
Powheg+Pythia 8 - $h_{damp} \times 2$	228	139	26	167	38	97	121	45.3
Powheg+Pythia 8 - PDF4LHC	186	100	11.5	125	32	93	185	33.6
Powheg+Pythia 8 - ISR up	149	111	17.3	120	34	79	66	50
Powheg+Pythia 8 - ISR down	216	159	10.6	131	30	113	311	44.5
Powheg+Pythia 8 - Rad up	164	115	27	139	38	78	49	47.6
Powheg+Pythia 8 - Rad down	216	159	10.6	131	30	113	311	44.5
Powheg+Pythia 8 - FSR up	216	132	12.5	143	35	106	194	46.8
Powheg+Pythia 8 - FSR down	171	139	9.5	118	30	98	185	49
Powheg+Pythia 8 - MEC off	42	136	41	37	16.5	83	181	42.7
aMC@NLO+Pythia 8	16.5	126	48	14.4	14.3	89	300	50
aMC@NLO+Herwig 7.0.4	98	137	24	74	24.1	29.1	110	54
Powheg+Herwig 7.0.4	113	104	28	82	28	135	271	45.8
Powheg+Herwig 7.1.3	101	107	31	75	25.5	138	259	45.5

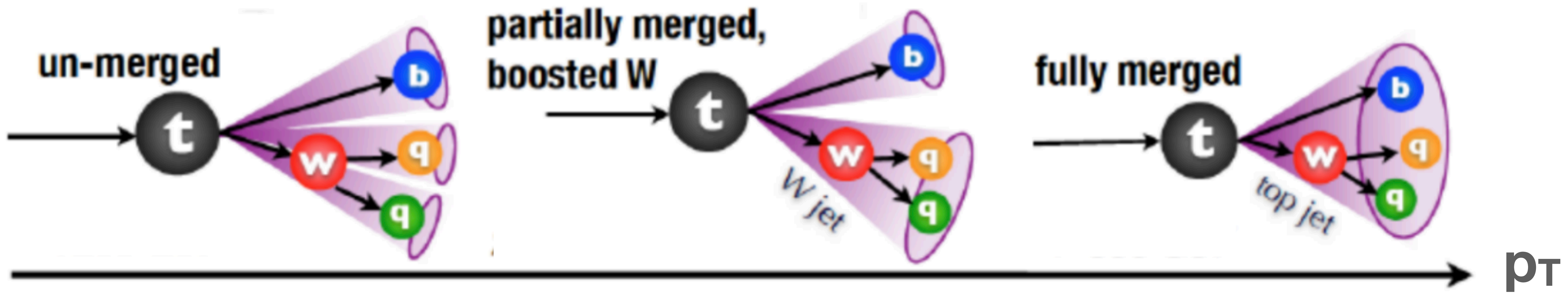
Generator	$\lvert y^{e\mu}\rvert : m^{e\mu}$	$\lvert\Delta\phi^{e\mu}\rvert : m^{e\mu}$	$\lvert\Delta\phi^{e\mu}\rvert : p_T^{e\mu}$	$\lvert\Delta\phi^{e\mu}\rvert : E^e + E^\mu$
N_{dof}	39	39	24	39
Powheg+Pythia 8	131	364	264	263
Powheg+Pythia 8 - top p_T rew.	82	140	81	96
Powheg+Pythia 8 - $h_{damp} \times 2$	129	250	182	183
Powheg+Pythia 8 - PDF4LHC	114	351	252	253
Powheg+Pythia 8 - ISR up	108	153	105	112
Powheg+Pythia 8 - ISR down	143	562	413	409
Powheg+Pythia 8 - Rad up	109	130	90	104
Powheg+Pythia 8 - Rad down	143	562	413	409
Powheg+Pythia 8 - FSR up	137	374	271	268
Powheg+Pythia 8 - FSR down	122	349	247	255
Powheg+Pythia 8 - MEC off	107	276	219	237
aMC@NLO+Pythia 8	108	436	363	386
aMC@NLO+Herwig 7.0.4	95	270	154	162
Powheg+Herwig 7.0.4	151	400	334	345
Powheg+Herwig 7.1.3	147	392	318	336

Differential $t\bar{t}$ cross-section

arXiv:2205.02817 [hep-ex], accepted by JHEP
13 TeV - 139 fb^{-1}

all-had ch. boosted topology

all-had channel → pros: large Br and no final states νs cons: large QCD bkg.

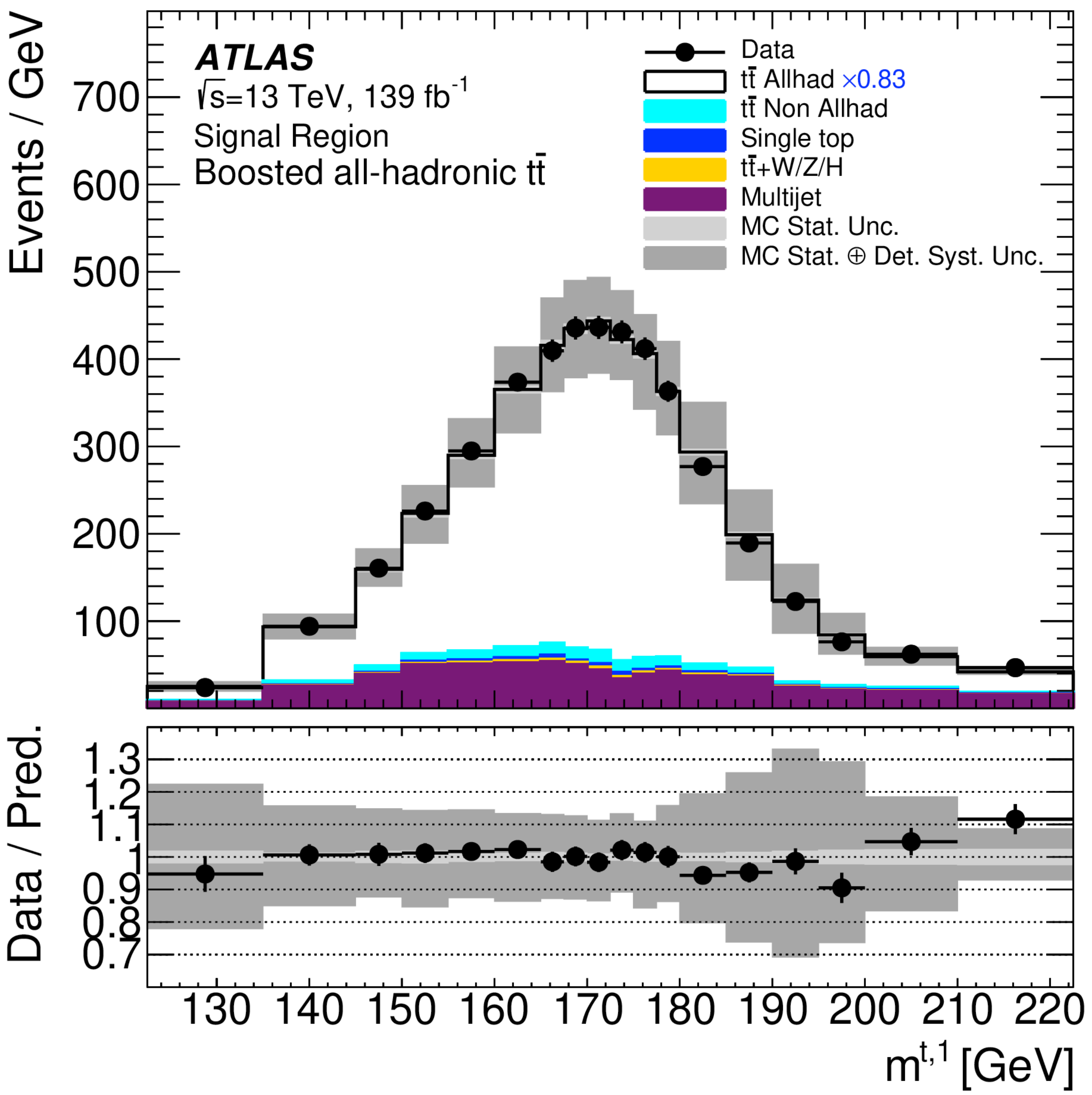


Large top-quark p_T → all decay products collimated in a single large-R jet
Dominant systematic uncertainties top-tagging, JES, JER
→ complementary to other channels

Modeling affected by ISR, FSR, PDFs, ME-PS matching
→ precise QCD tests

single, double and triple differential cross-section measurements for several variables of the $t\bar{t}$ system and of the individual top-quarks

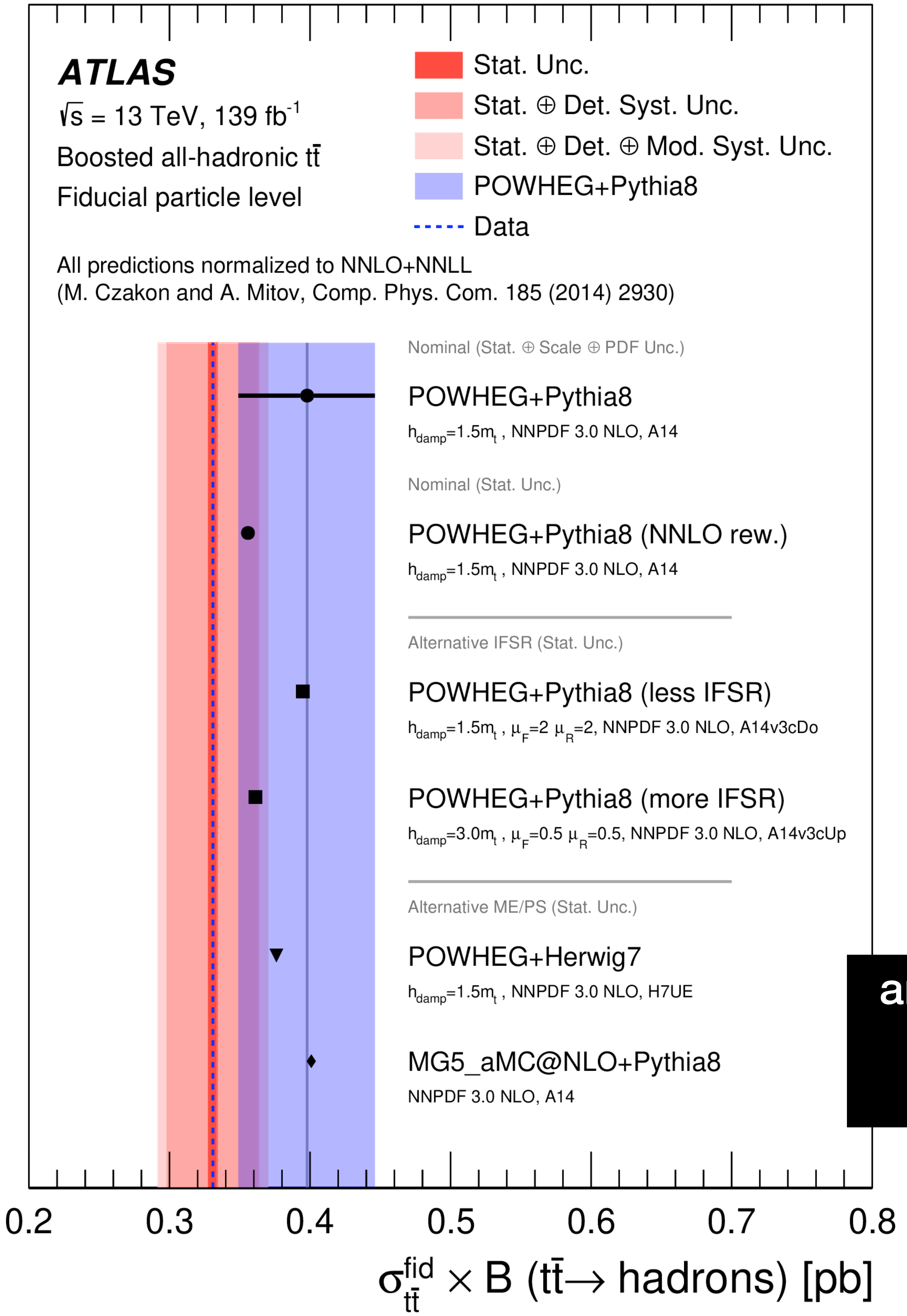
- Particle level: comparison with MC generator at NLO interfaced with PS and hadronization models
- Parton level: direct comparison with fixed order NNLO calculation



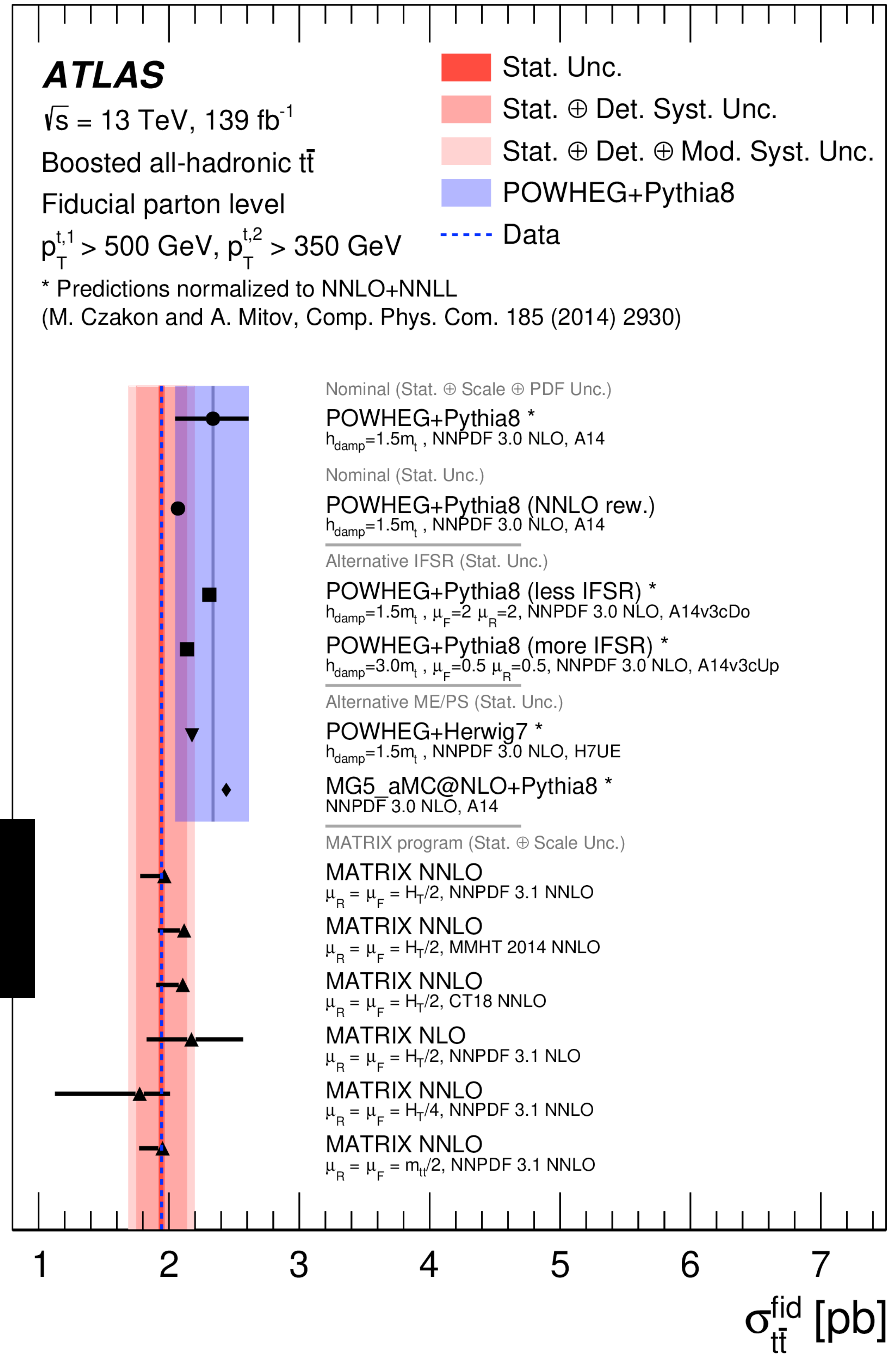
Inclusive $t\bar{t}$ cross-section

all-had ch. boosted topology

parton-level fiducial cross-section with the calculations from several MC generators and the fixed-order NNLO prediction with various PDF sets and dynamical scales obtained using the Matrix program.



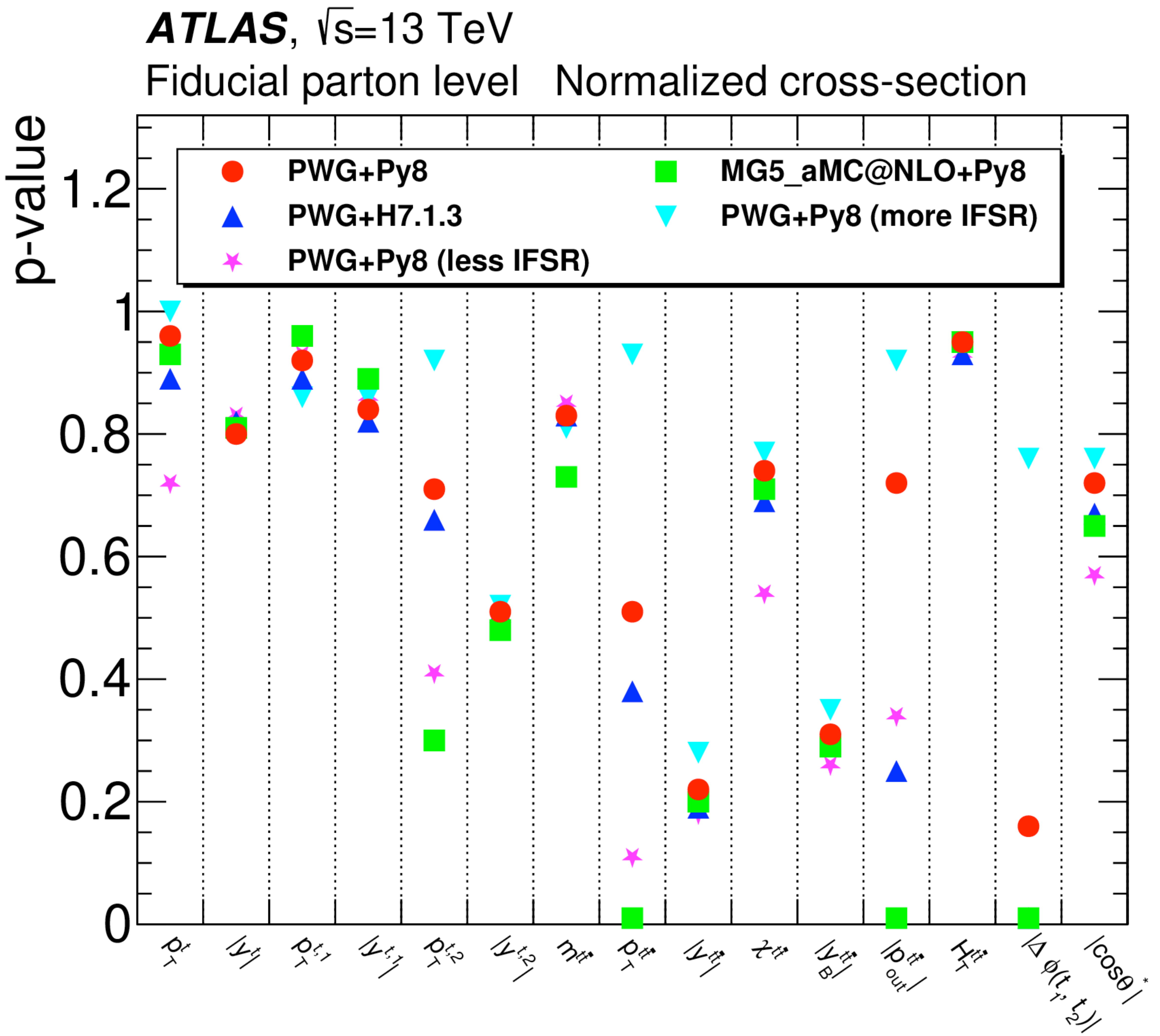
arXiv:2205.02817 [hep-ex]
accepted by JHEP
13 TeV - 139 fb-1

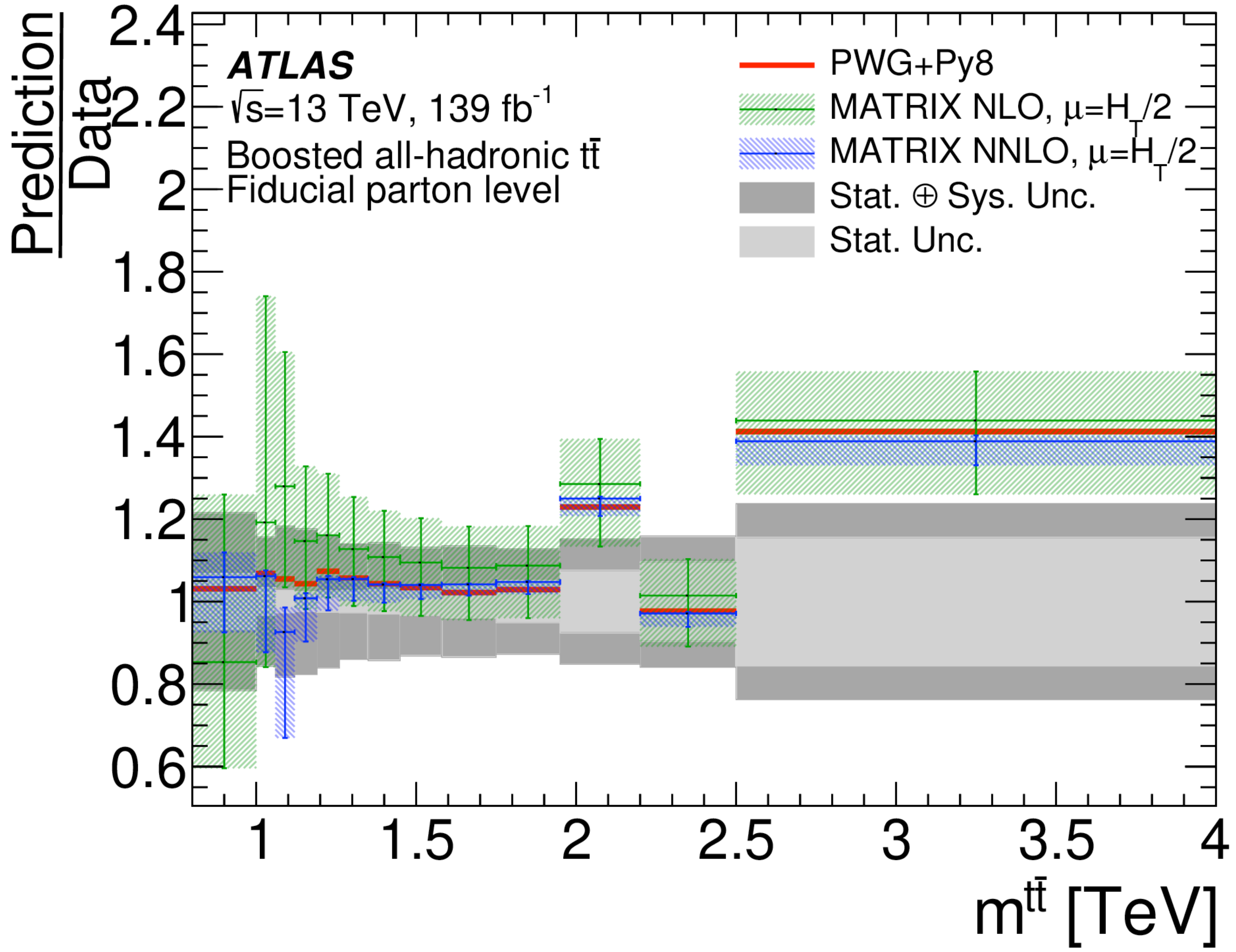


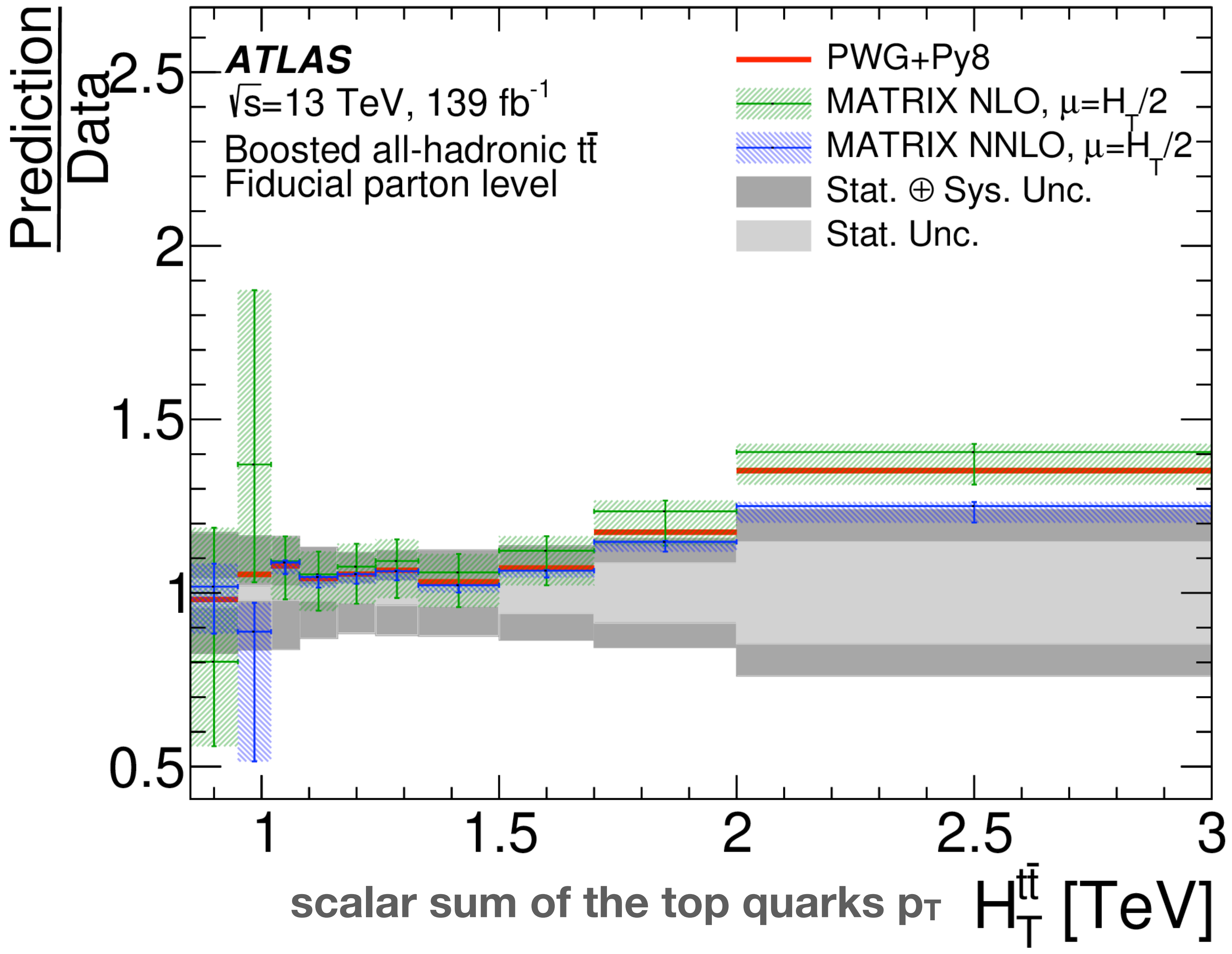
particle-level fiducial cross-section Powheg+Pythia 8 event generator is used as the nominal prediction to correct for detector effects.

Differential tt̄ cross-section

all-had ch. boosted topology







scalar sum of the top quarks pT

Differential $t\bar{t}$ cross-section EFT interpretation

all-had ch. boosted topology

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{B_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots,$$

not considered in this analysis

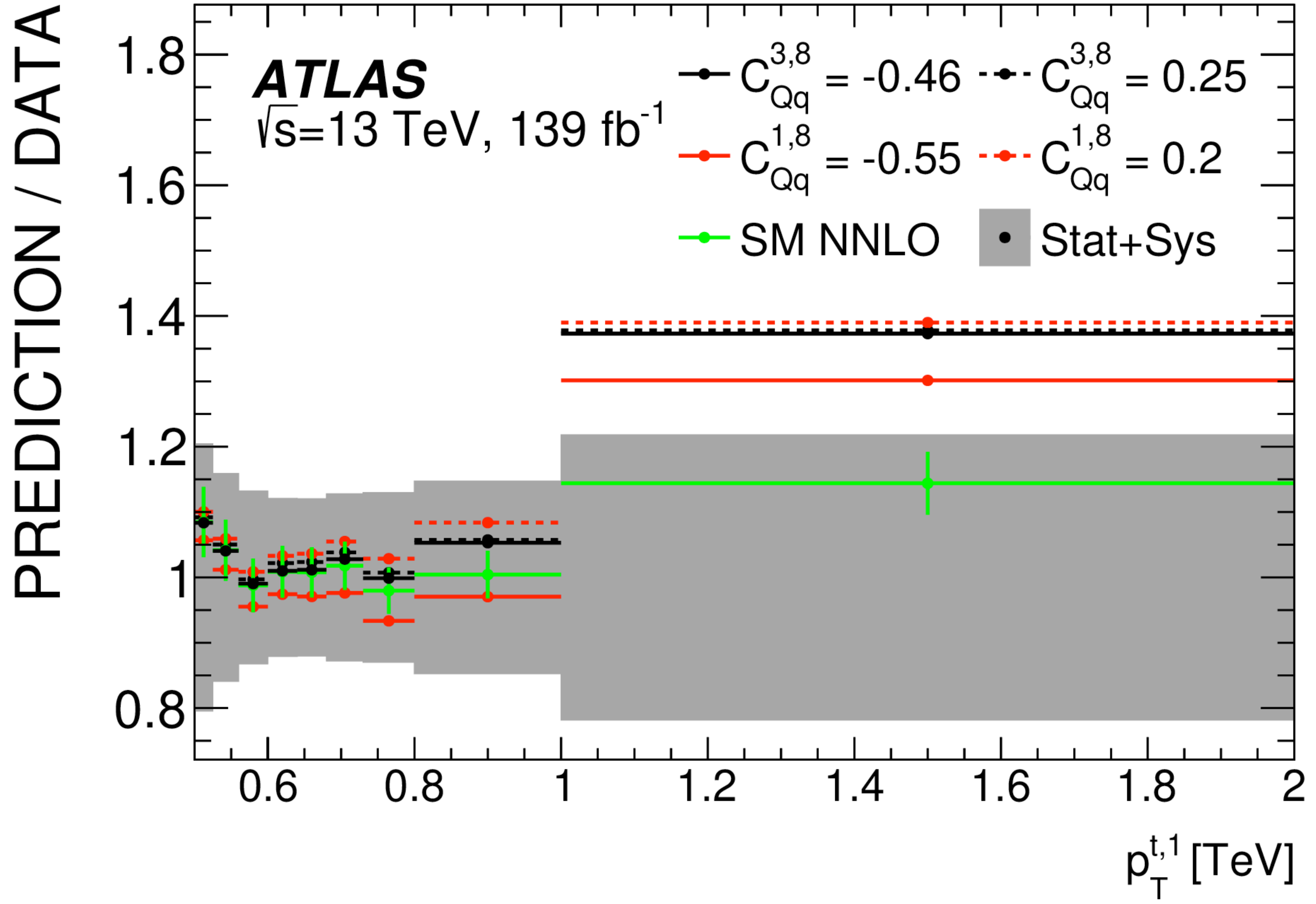
$$\sigma(C_i) = \sigma_{\rm SM} + \sigma_{\rm SM-EFT} + \sigma_{\rm EFT-EFT}$$
$$= \sigma_{\rm SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i C_i + \frac{1}{\Lambda^4}\sum_i \beta_i C_i^2 + \frac{1}{\Lambda^4}\sum_{i,j,i<j}\tilde{\beta}_{ij}C_iC_j,$$

SM-EFT interf. EFT-EFT terms

α and β used to parameterize the cross-section dependence on each Wilson Coefficient

dim6top model used to implement SMEFT at leading order using the Warsaw basis for the operators.

Ratio of various SMEFT predictions to the data. Wilson Coefficients ~ 95%CL limits obtained in this analysis.
The SM NNLO calculation has been obtained by MATRIX including scale uncertainty.



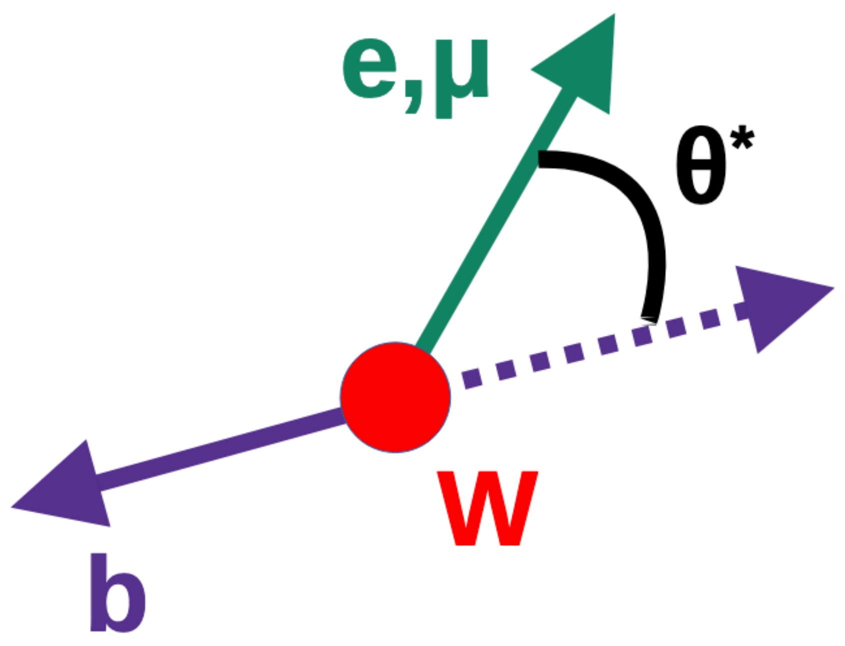
arXiv:2205.02817 [hep-ex], accepted by JHEP
13 TeV - 139 fb-1

W polarization in top decay

- Properties of the top-quark decay vertex Wtb determined by the V-A structure of the EW interactions
- W helicity fractions (longitudinal, left- and right-handed polarization) extracted from the angular distribution of the decay products of the W boson and the top quark → test of SM prediction

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\cdot f_0 + \frac{3}{8}(1-\cos\theta^*)^2\cdot f_L + \frac{3}{8}(1+\cos\theta^*)^2\cdot f_R$$

θ^*: angle between the momentum direction of the charged lepton from W decay and the reversed momentum direction of the b-quark from top decay, computed in the W rest frame



NNLO calculation
PRD 81 (2010) 111503

$f_0 = 0.687 \pm 0.005$

$f_L = 0.311 \pm 0.005$

$f_R = 0.0017 \pm 0.0001$

NNLO calculations compared with ATLAS results in $t\bar{t}$ di-lepton events

arXiv:2209.14903 [hep-ex]
13 TeV - 139 fb^{-1}