Top quark mass and properties with the ATLAS detector

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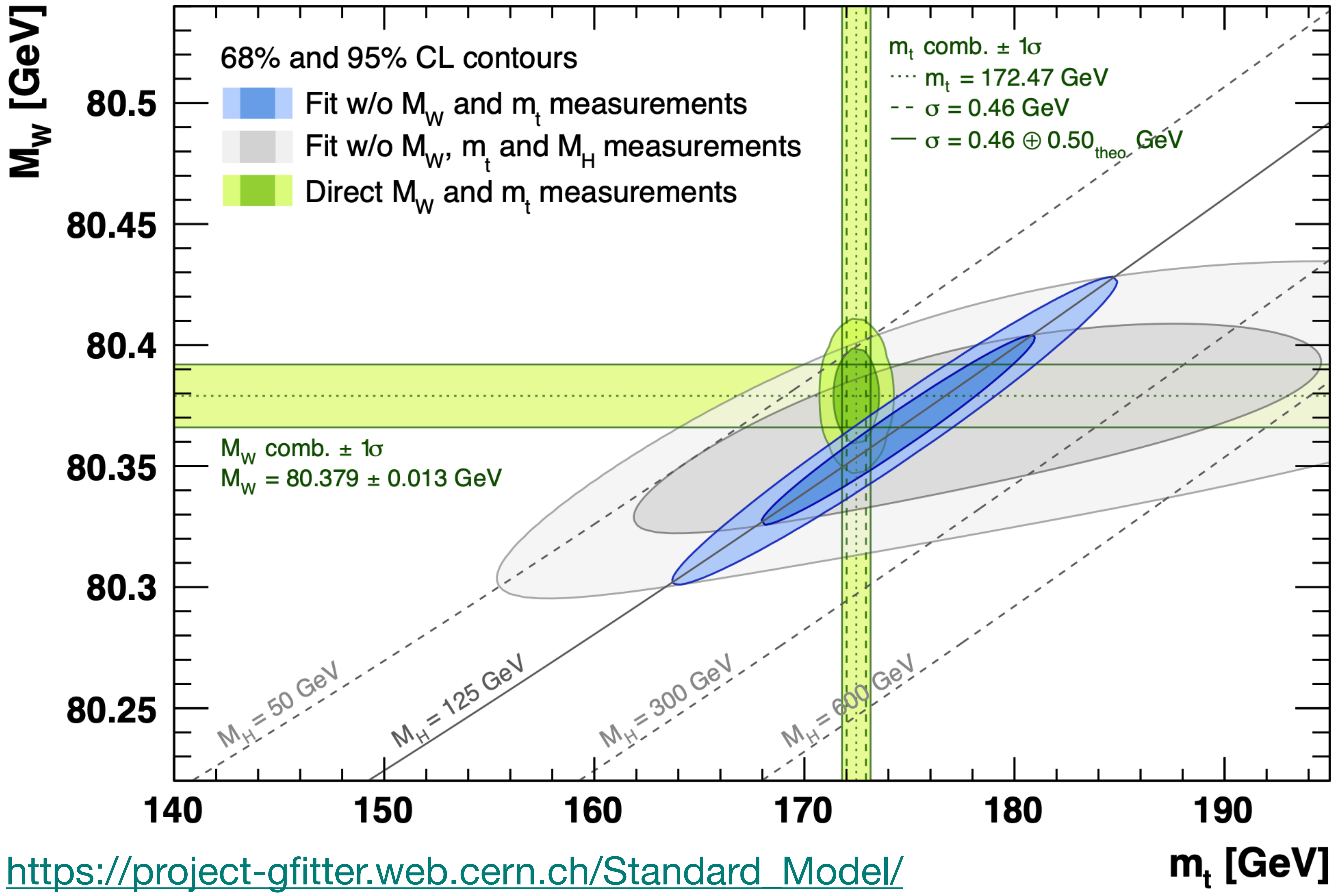
Top mass

Why measure top quark mass

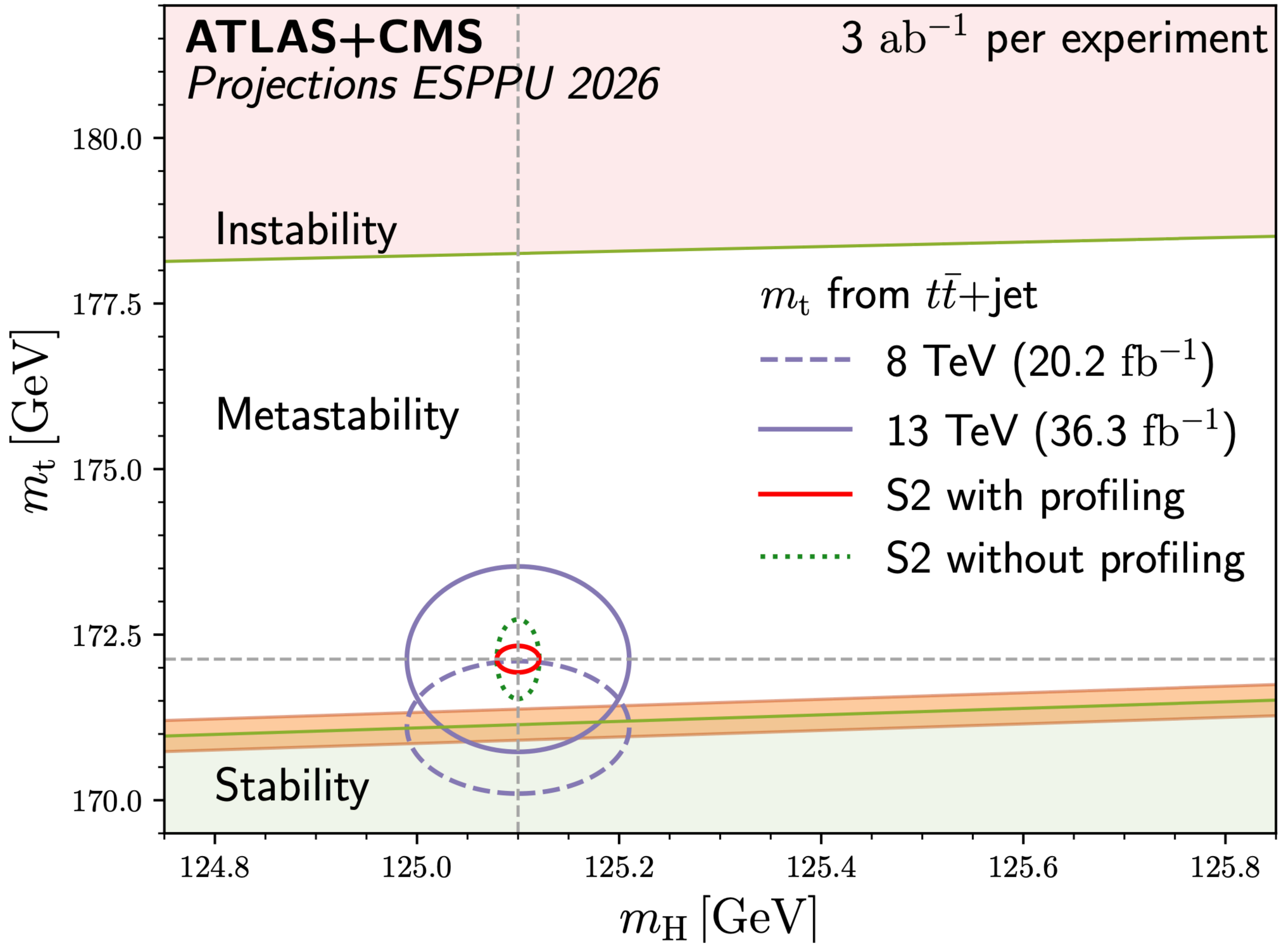
- Free Standard Model (SM) parameter
- Input to the SM prediction of the top Yukawa coupling
- Affects the dynamics of elementary particles via loop diagrams
- Important parameter to assess the SM consistency at the electroweak scale and probe possible extensions

precision measurements of m_t provide information for global fits of electroweak parameters



https://project-gfitter.web.cern.ch/Standard_Model/

w/o new physics up to the Planck scale, the electroweak vacuum stability strongly depends on m_H and m_t



HL-LHC physics projections arXiv:2504.00672

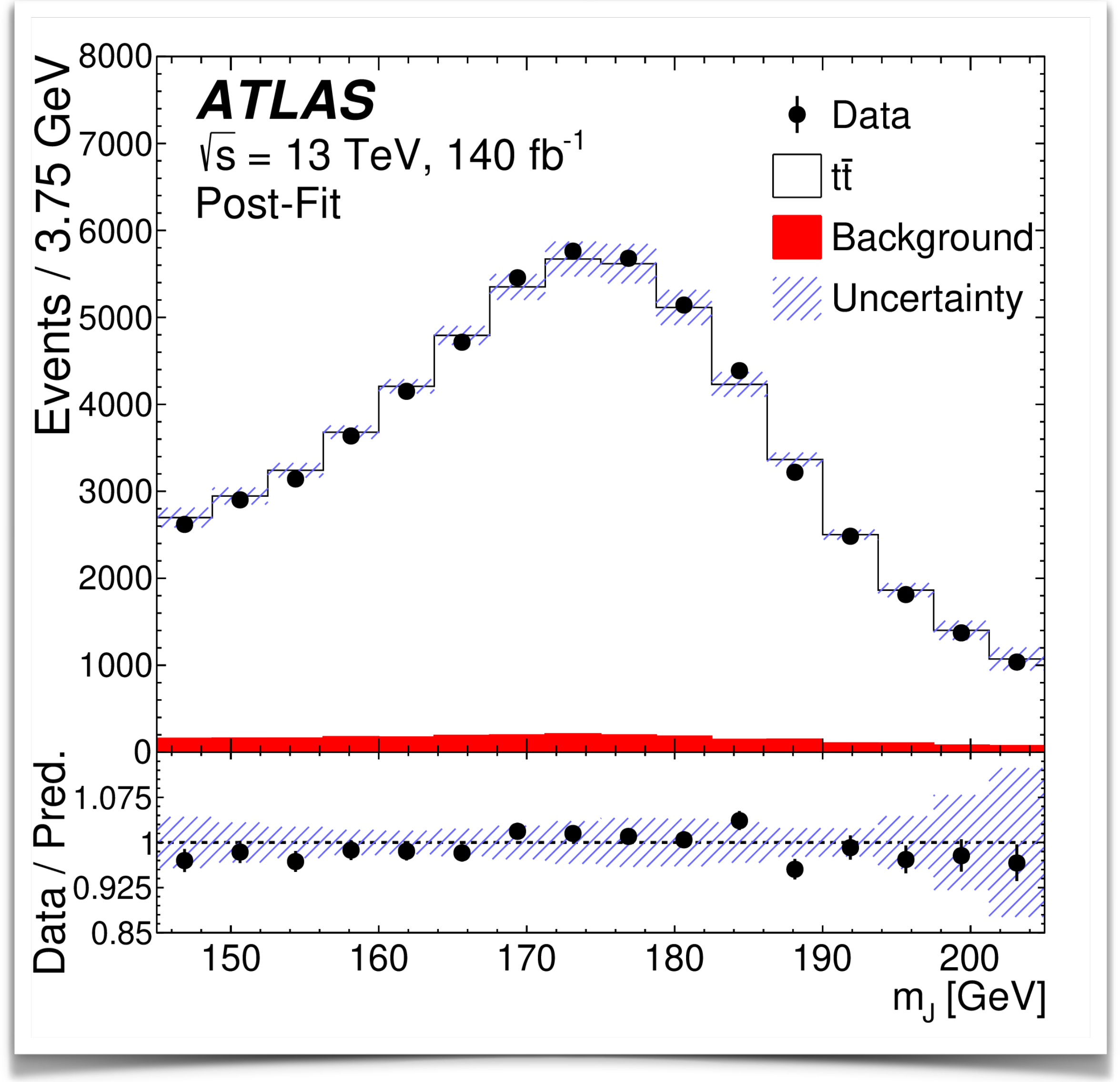
How to measure top quark mass

Direct measurements

- Reconstruct the top quark from the decay products
- Compare the distribution of reconstructed m_t (or a sensitive observable) to its MC prediction
- Ambiguity exists in identifying the measured mass as pole mass

✳ Recent Run2 result: top quark mass using boosted $t\bar{t}$ events [PLB 867 (2025) 139608]

- *First ATLAS result with boosted top quarks*
- *Most precise top quark mass measurement from ATLAS in a single channel*

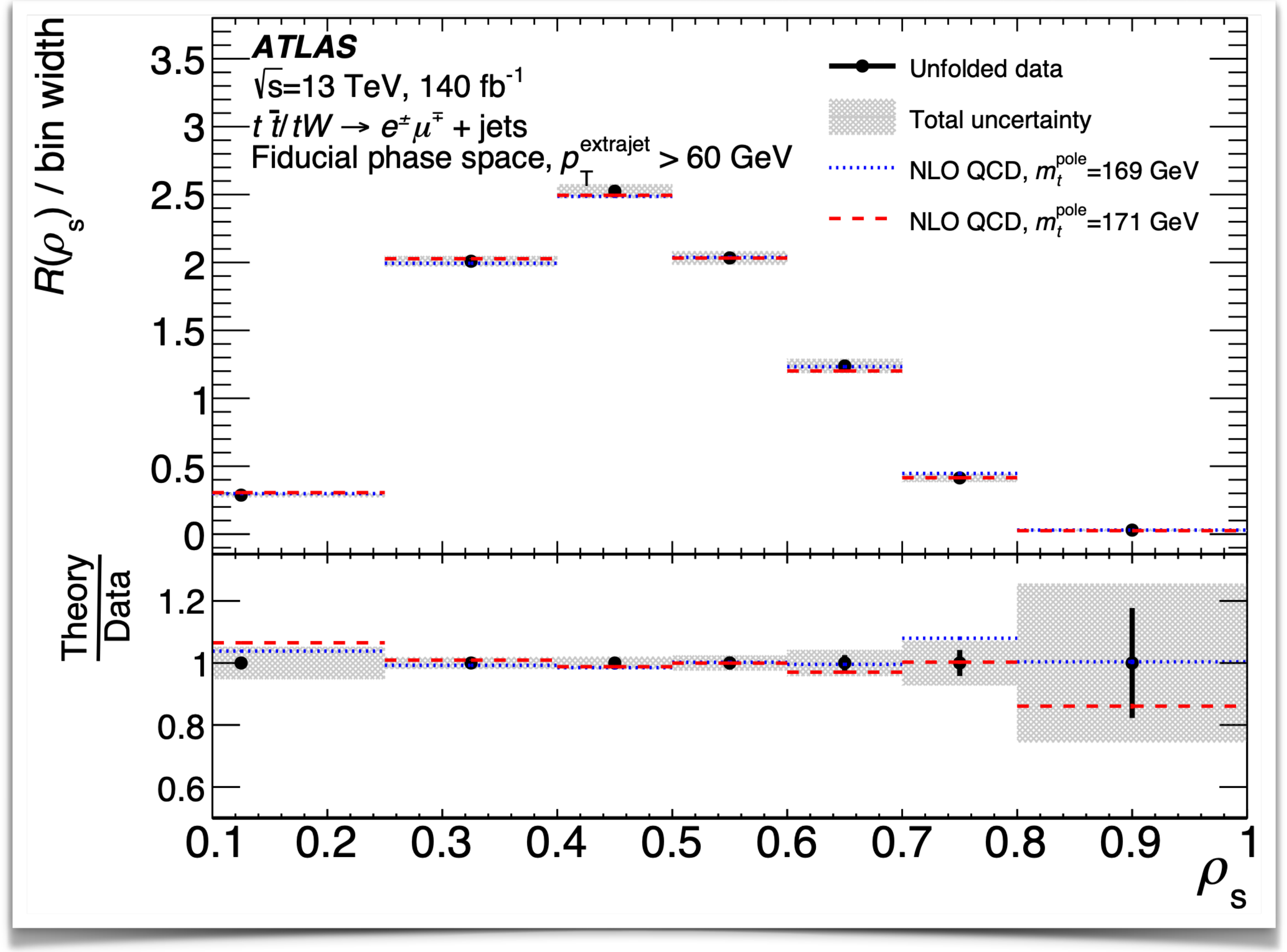


Indirect measurements

- Compare the measured $t\bar{t}$ production observables (e.g. cross-section) to its fixed-order calculation in a certain normalisation scheme (pole, $\overline{MS}$)

★ **New Run2 result**: top quark pole mass in dilepton $t\bar{t}$ + 1jet events [arXiv:2507.02632]

- *First result in this channel with full Run2 data*
- *Using improved fixed-order calculations*



Top quark pole mass in dilepton $t\bar{t} + 1$jet events

arXiv:2507.02632

extra jet enhances sensitivity to m_t

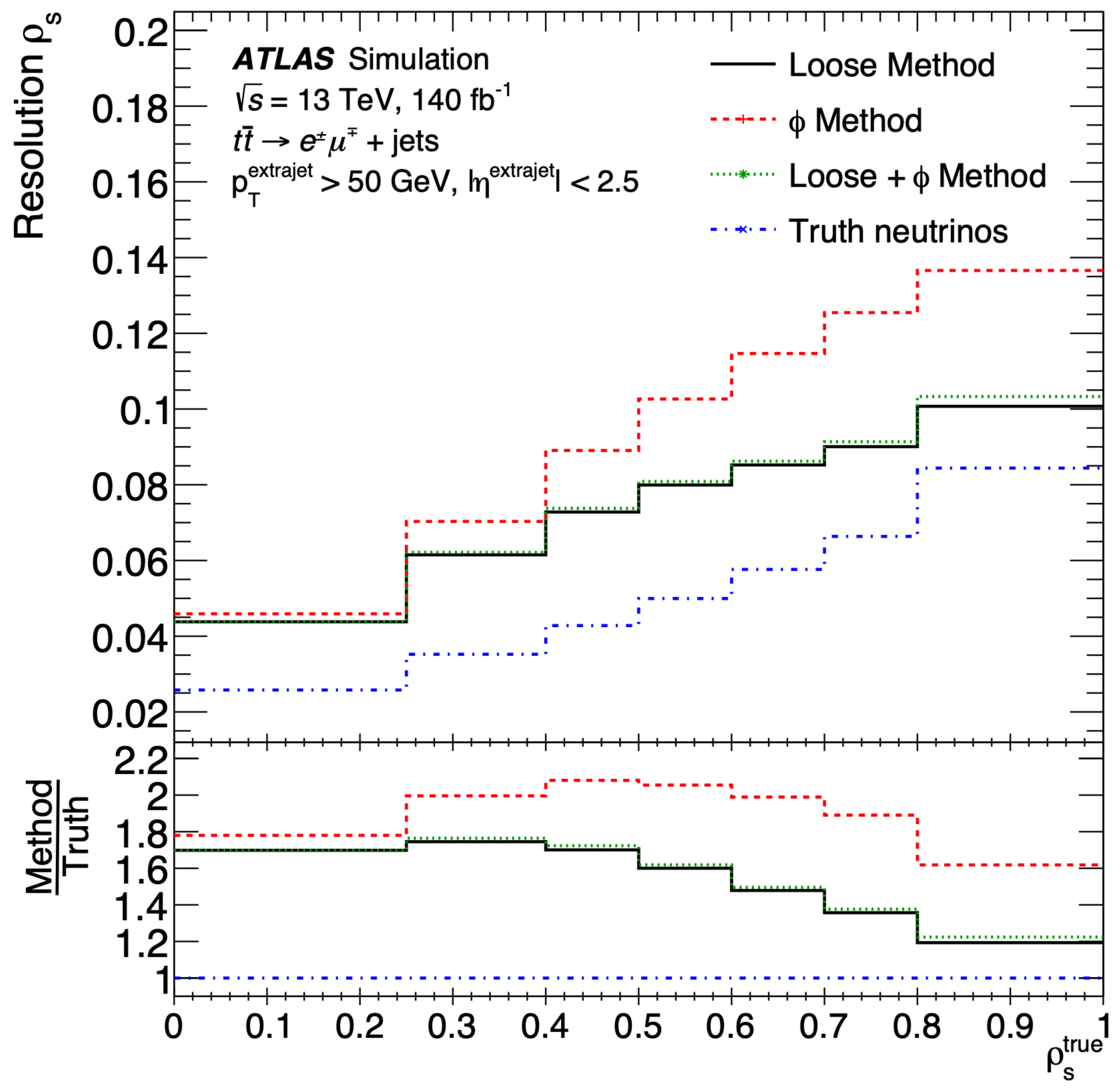
Extract the top quark mass from the normalised cross-section

$$\mathcal{R}(\rho_s; m_t^{\text{pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s} \quad \text{, with} \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

- $1e + 1\mu$ of opposite charge
- 2 b-tagged jets
- Additional jet with $p_T > 50\ (60)$ GeV ← *to match the theory prediction we are comparing to*
- $E_T^{\text{miss}} > 30$ GeV
- $m_{lb} < 200$ GeV ← *avoid the region difficult to model, reduce the $t\bar{t}/tW$ interference uncertainty*

Reconstruct the $t\bar{t}$ system using a combination of 2 methods:

- **Loose kinematic reconstruction** EPJC 80 (2020) 658
  - Reconstruct $\nu\bar{\nu}$ system as a whole
- **ϕ-weighting reconstruction** PRD 79 (2009) 072005
  - $\phi(\nu_{1,2})$ is scanned with 100 random values from a uniform distribution
  - Minimise $\chi^2_\phi = (m_{\nu\bar{l}b} - m_{\bar{\nu}l\bar{b}})/(m_{\nu\bar{l}b} + m_{\bar{\nu}l\bar{b}})$



resolution of the ρ_S observable for the different reconstruction methods

Top quark pole mass in dilepton $t\bar{t}$ + 1jet events

Correct the data to parton level → compare to fixed-order NLO QCD predictions

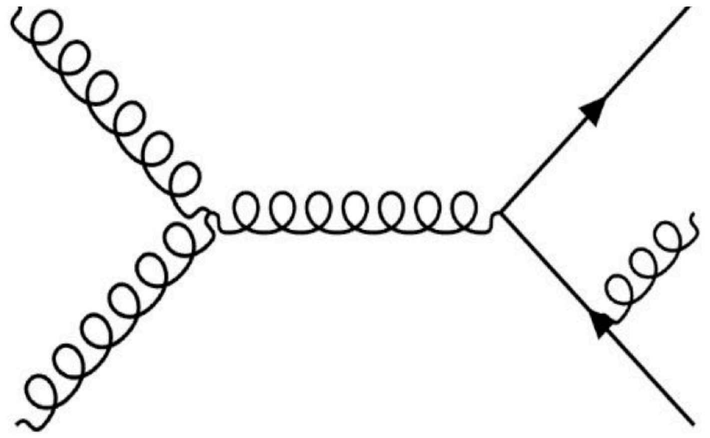
- Iterative Bayesian Unfolding:

$$\frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(\rho_s)^{\text{parton}}_{\text{data}} = \mathcal{M}^{unf} \otimes \left[\frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(\rho_s)^{\text{det}}_{\text{data}} \cdot f^{\text{acc}}\right] \cdot f^{\text{eff}^{-1}}$$

Two final states considered:

- Stable top quarks → compare to the calculation for $pp \rightarrow t\bar{t}$ + 1jet

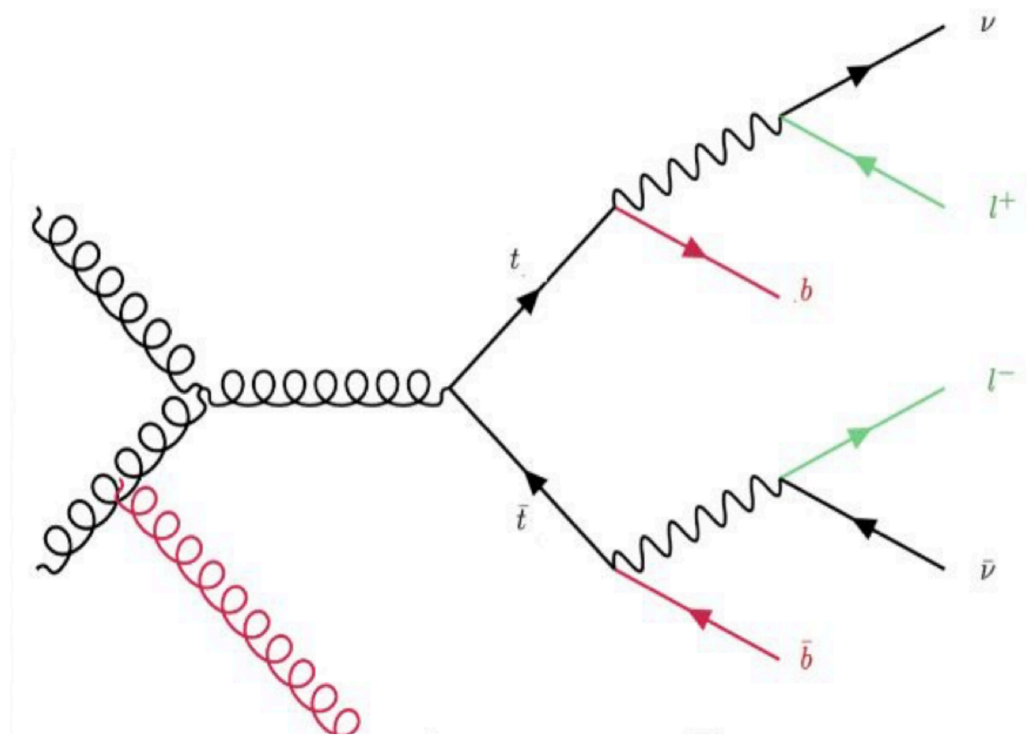
JHEP 05 (2022) 146



2→3 process

- Leptons, ν, jets (before hadr.) → compare to the calculation for $pp \rightarrow b\bar{b}l^+\nu l^-\bar{\nu}j$

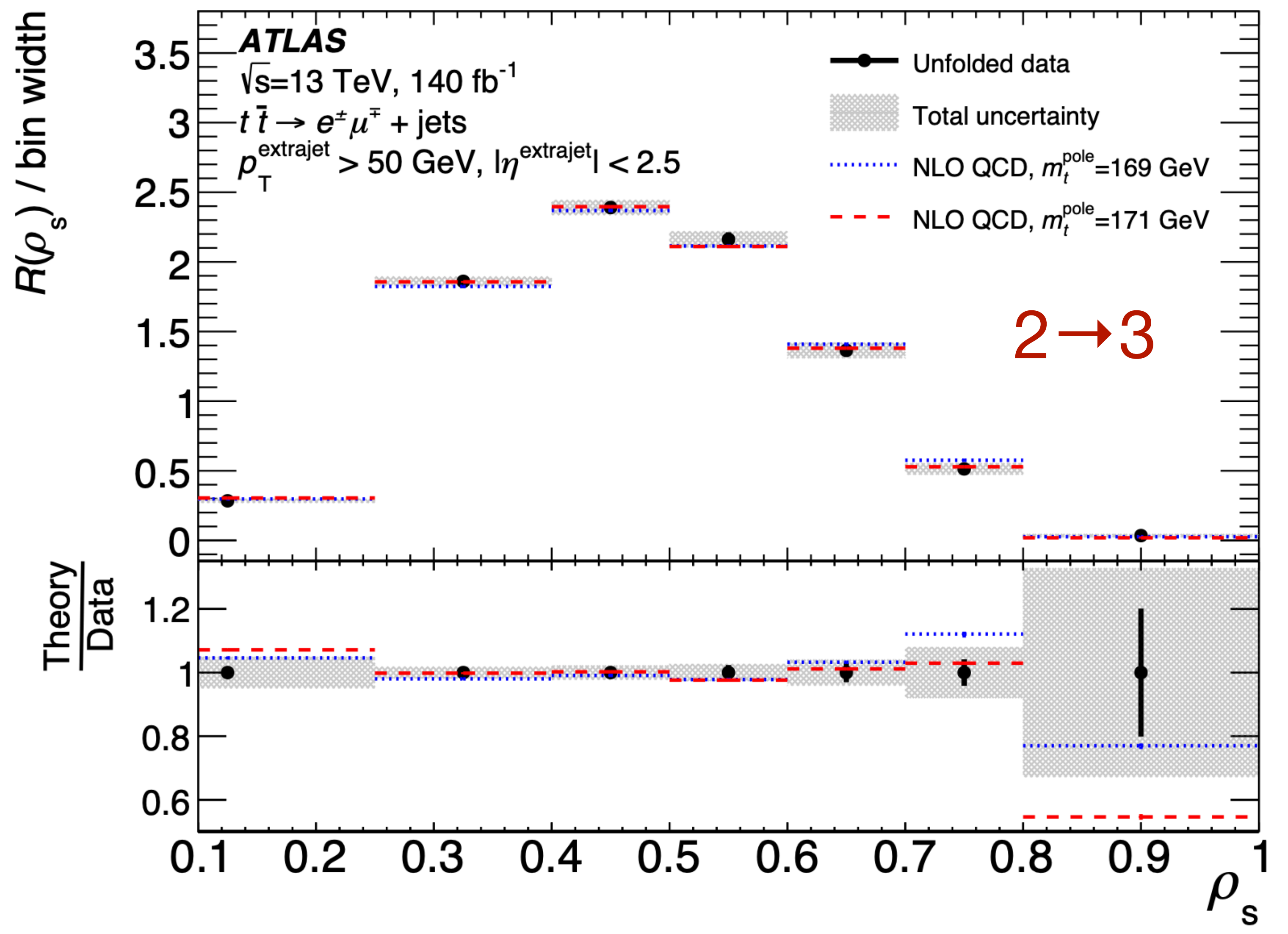
JHEP 11 (2016) 098

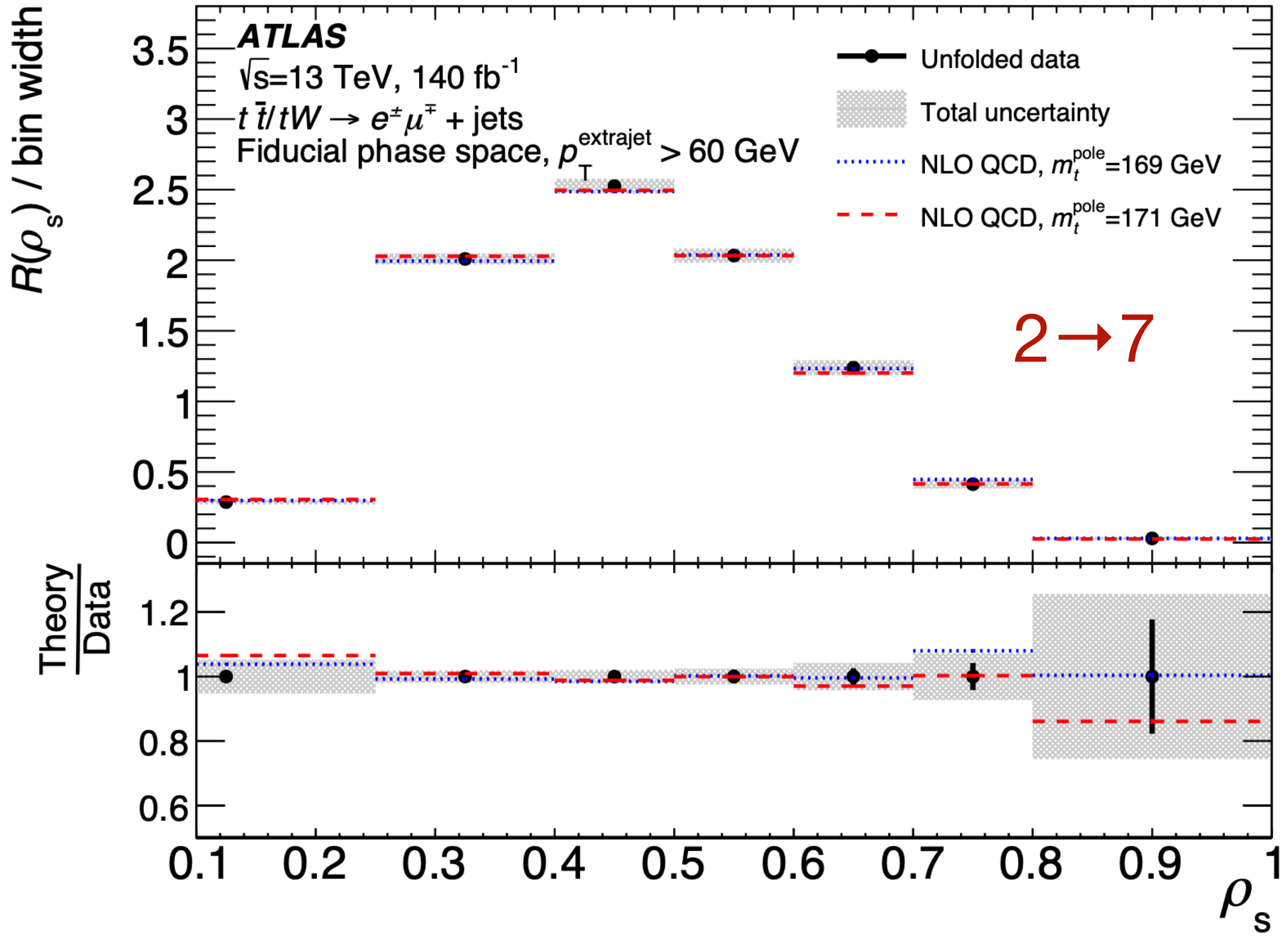


2→7 process

+ single- and non-resonant diagrams

unfolded ρ_S distribution





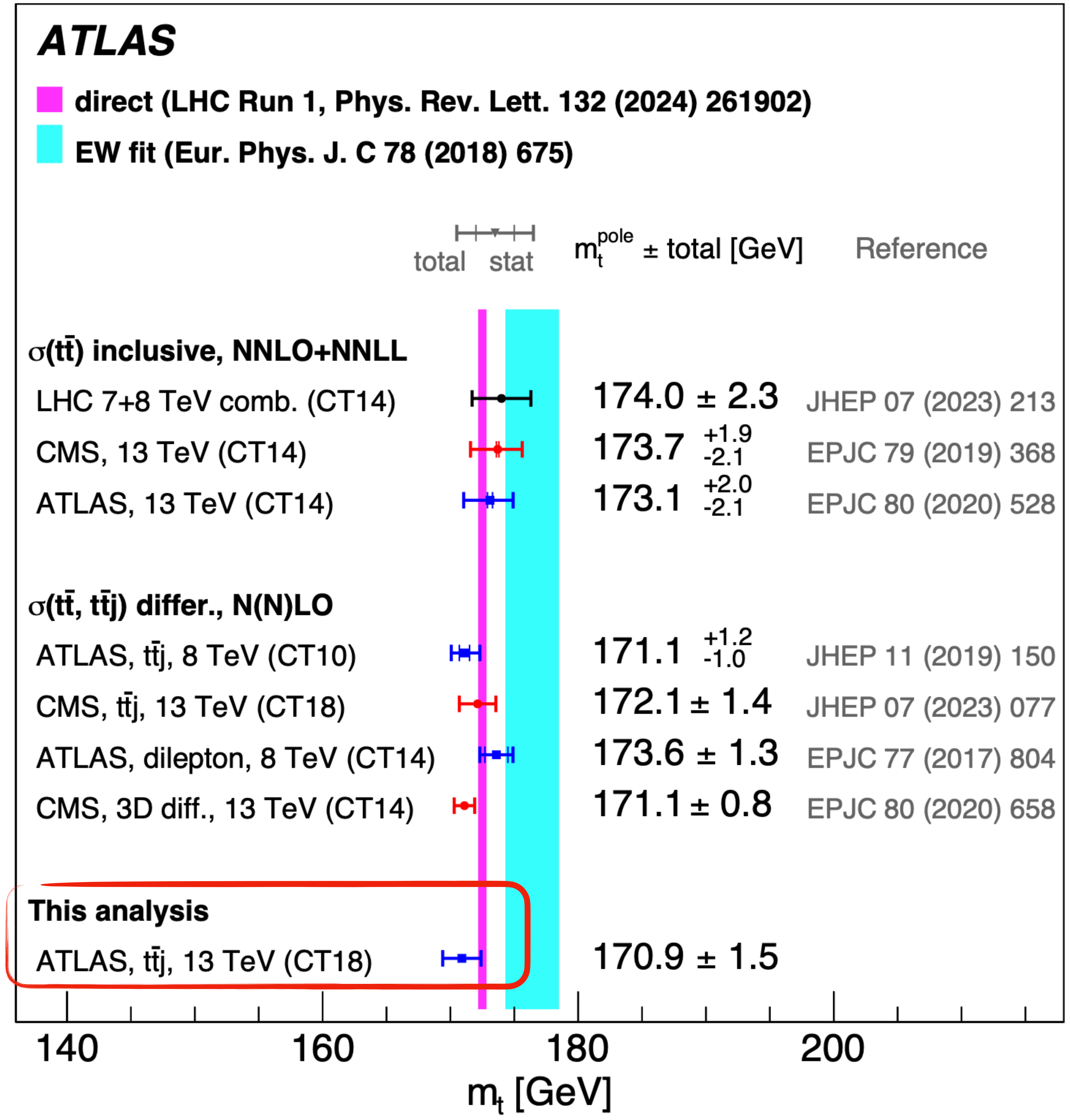
Top quark pole mass in dilepton $t\bar{t}$ + 1jet events

arXiv:2507.02632

- Extracting the top quark pole mass using the least-squares method:
  - Statistical & systematic uncertainties: included in the covariance matrix
  - Theory uncertainties: change in m_t^{pole} when varying theory predictions
- **2→3 approach (main result)**:

$$m_t^{\text{pole}} = 170.73 \pm 0.33\,(\text{stat.}) \pm 1.36\,(\text{syst.})\,^{+0.28}_{-0.34}\,(\text{scale})\,^{+0.24}_{-0.24}\,(\text{PDF} + \alpha_s)\ \text{GeV}$$

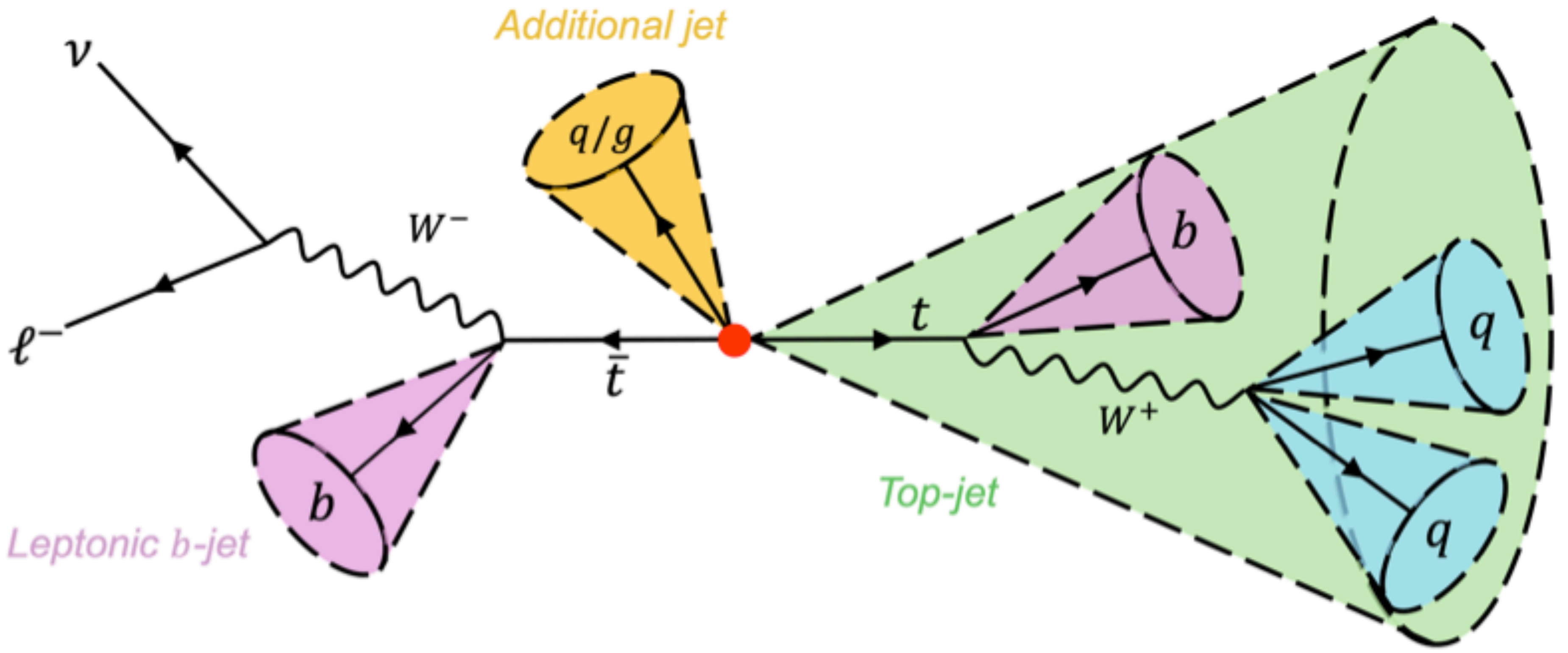
- Precision comparable to other complementary measurements
- <u>Dominant systematic uncertainties:</u>
  - Experimental: *b*-tagging, jet-response calibration
  - Modelling: parton shower choice and recoil model



PDF set here (CT18) is different from the one in the main result (PDF4LHC21)

Top quark mass using boosted $t\bar{t}$ events

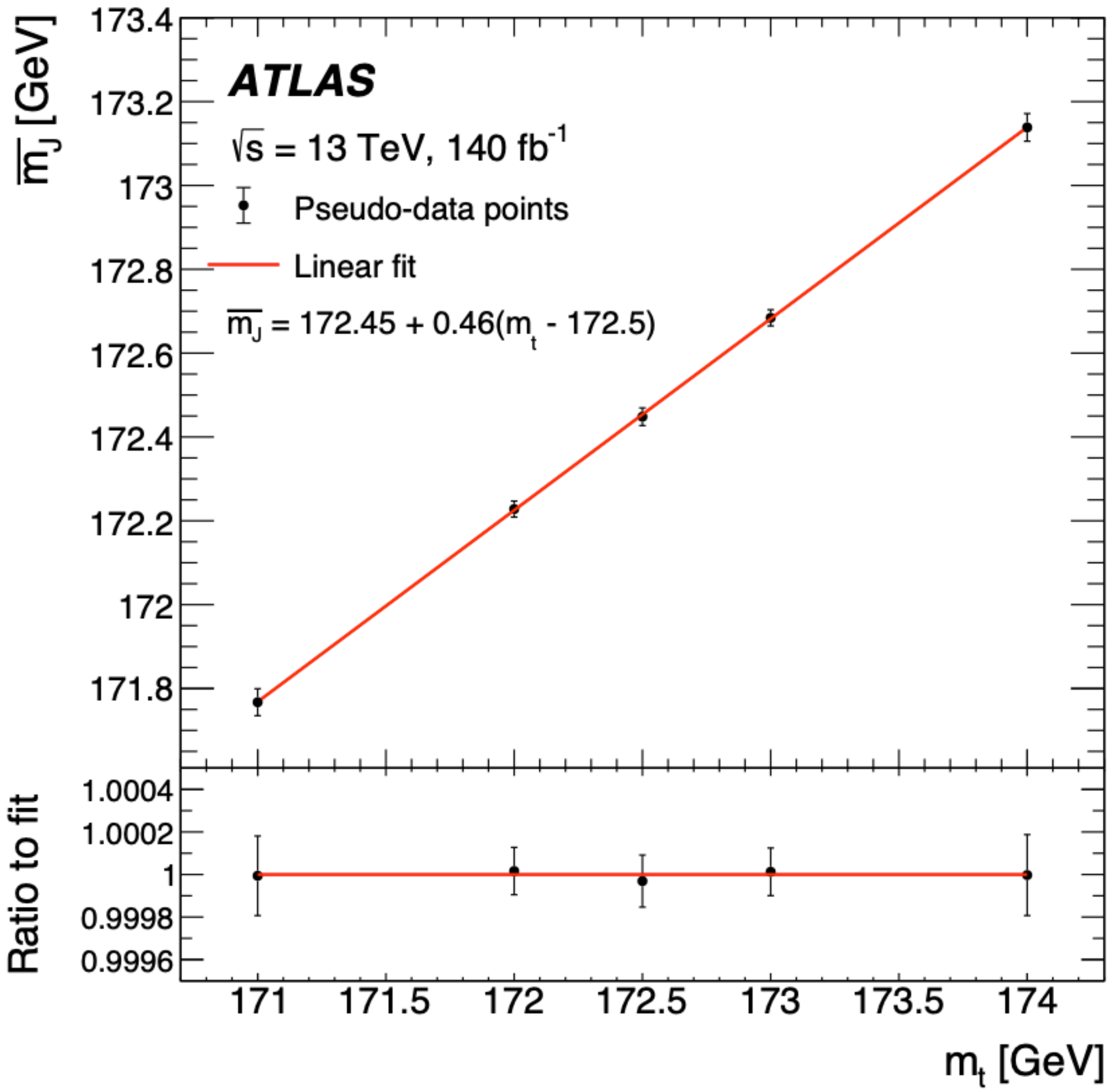
PLB 867 (2025) 139608



- Boosted top quark regime
  - Simplifies the reconstruction of hadronically decaying top quarks
  - May offer the possibility to connect to hadron-level calculations where m_t is unambiguously defined [arXiv:2004.12915] [arXiv:2309.00547]

- Targeting $t\bar{t}$ events in the lepton+jets channel
- Reconstruct hadronically decaying top quark using a large-R jet (top-jet)
  - Top-jet formed by reclustering $R = 0.4$ jets
  - At least 2 small-R jets, where at least 1 is *b*-tagged

- Top quark mass is obtained from a profile-likelihood fit to three observables:
  1. $\overline{m_J}$: average top-jet mass
     - linearly dependent on the top quark mass →
  2. m_{jj}: invariant mass of the 2 leading light jets inside the top-jet
     - sensitive to the jet energy scale
  3. m_{tj}: invariant mass of the semi-leptonic top and the closest jet
     - sensitive to the radiation from the *b*-quark from the top decay
- Using additional variables m_{jj} and m_{tj} to control the systematic uncertainties



Top quark mass using boosted $t\bar{t}$ events

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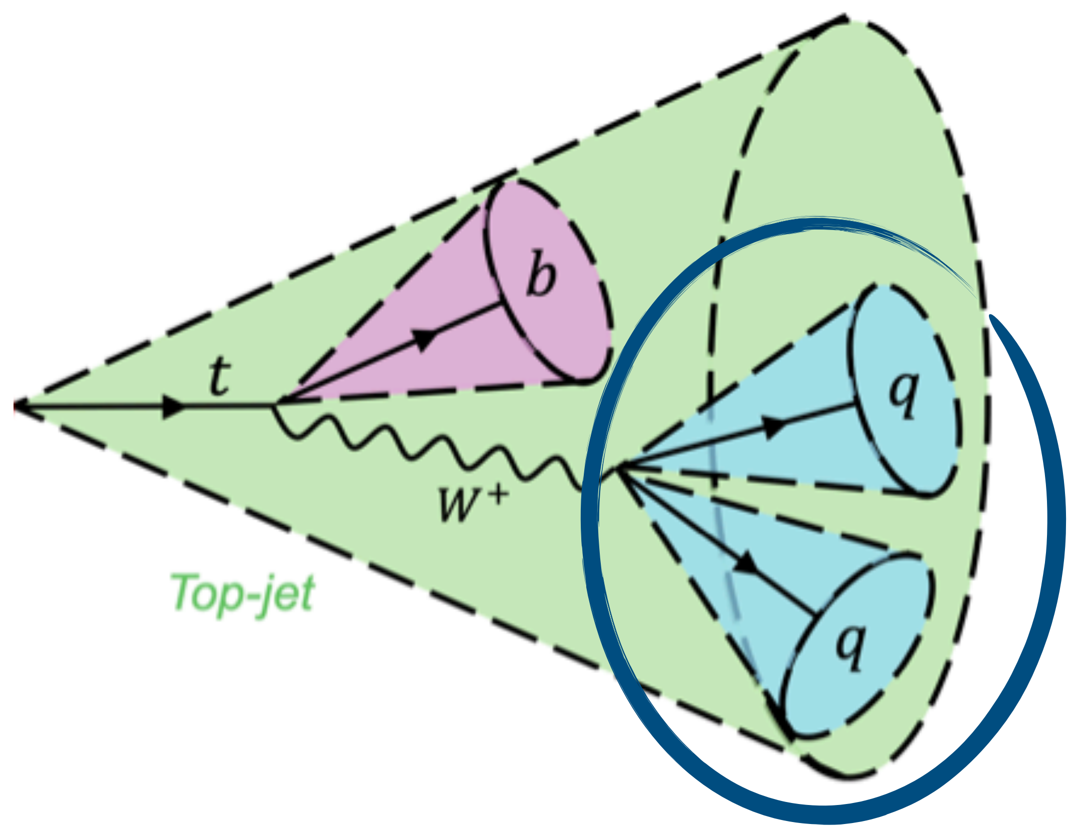
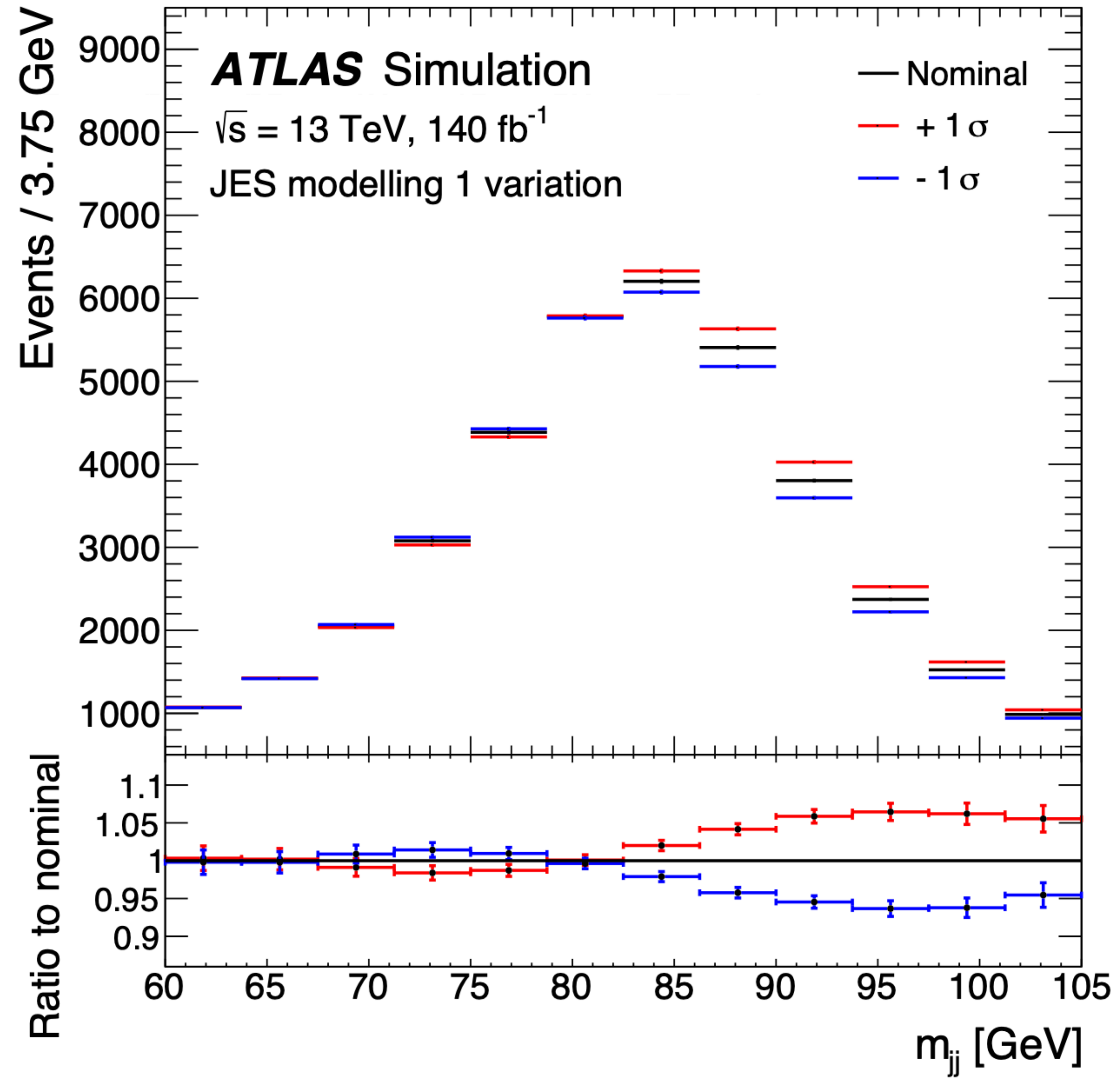
Jet energy scale (JES) uncertainties:

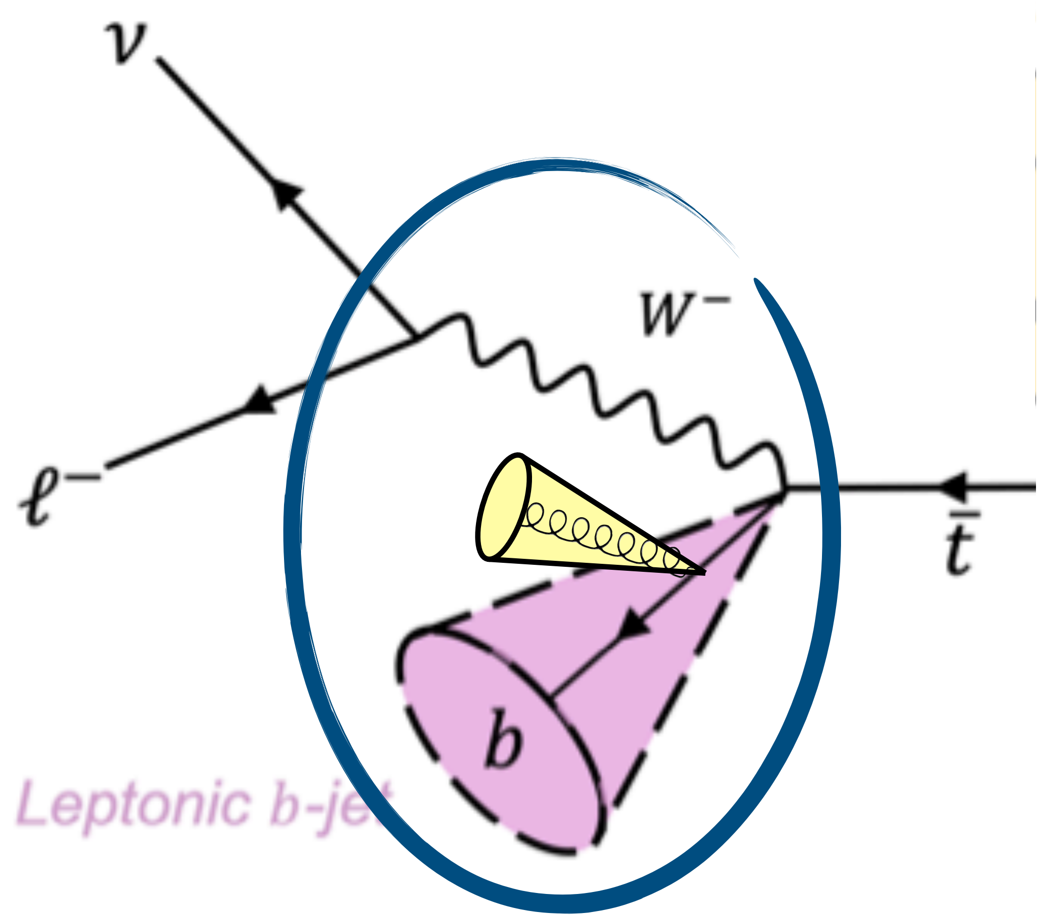
- Measurement relies on jets ⟶ JES uncertainties dominate
- Need an observable sensitive to changes in JES but not in m_t
  - ➡ Reconstruct the W boson mass, m_{jj}

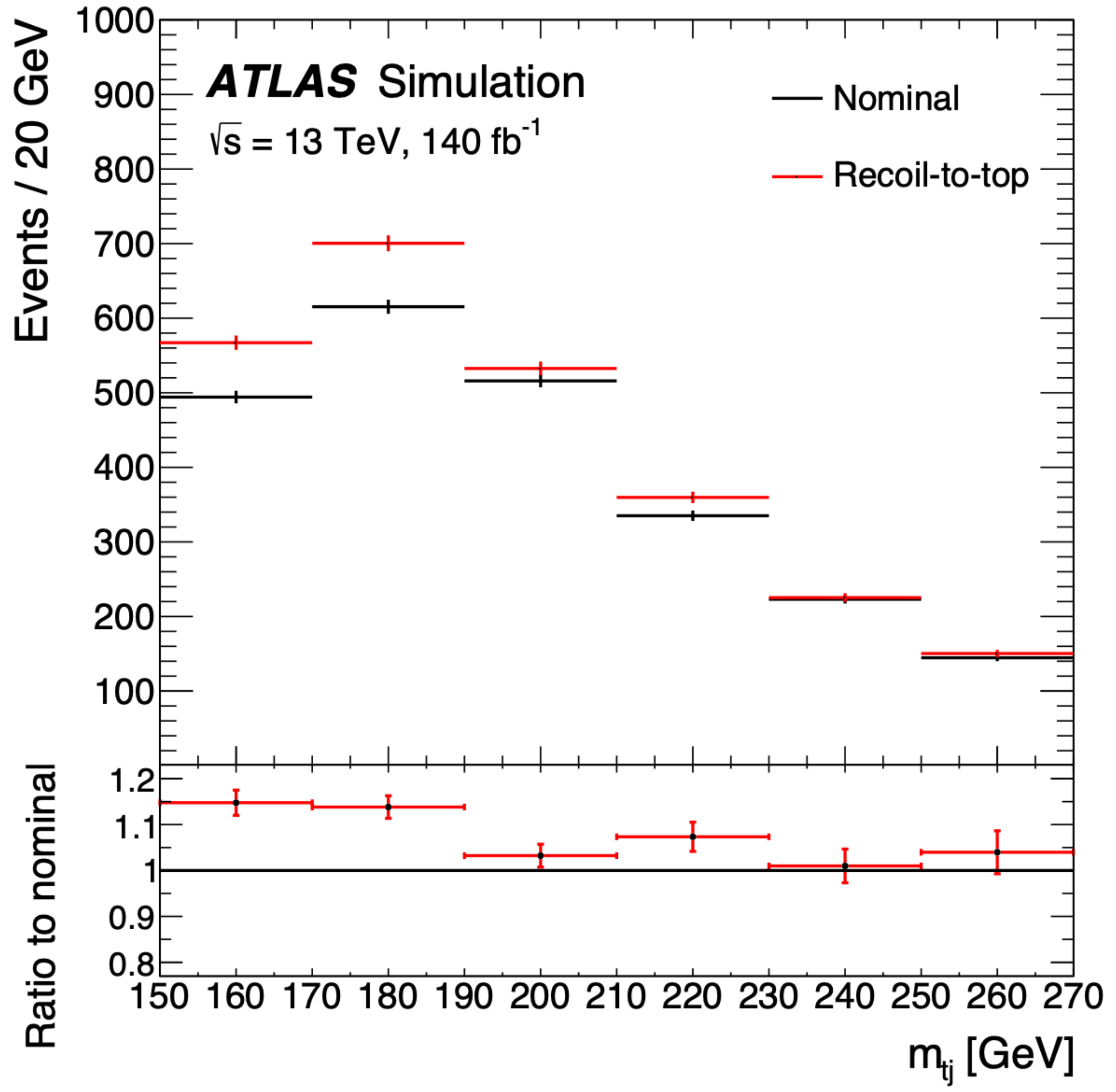




Recoil uncertainty:

- Alternative Pythia model for the radiation off the *b*-quark *(red histogram on the plot)*
  - Increased wide-angle radiation
  - More events with extra jet close to semi-leptonic top
- Need an observable sensitive to recoil effects but not to m_t
  - ➡ Reconstruct the invariant mass of the leptonic top and the closest jet, m_{tj}





Top quark mass using boosted $t\bar{t}$ events

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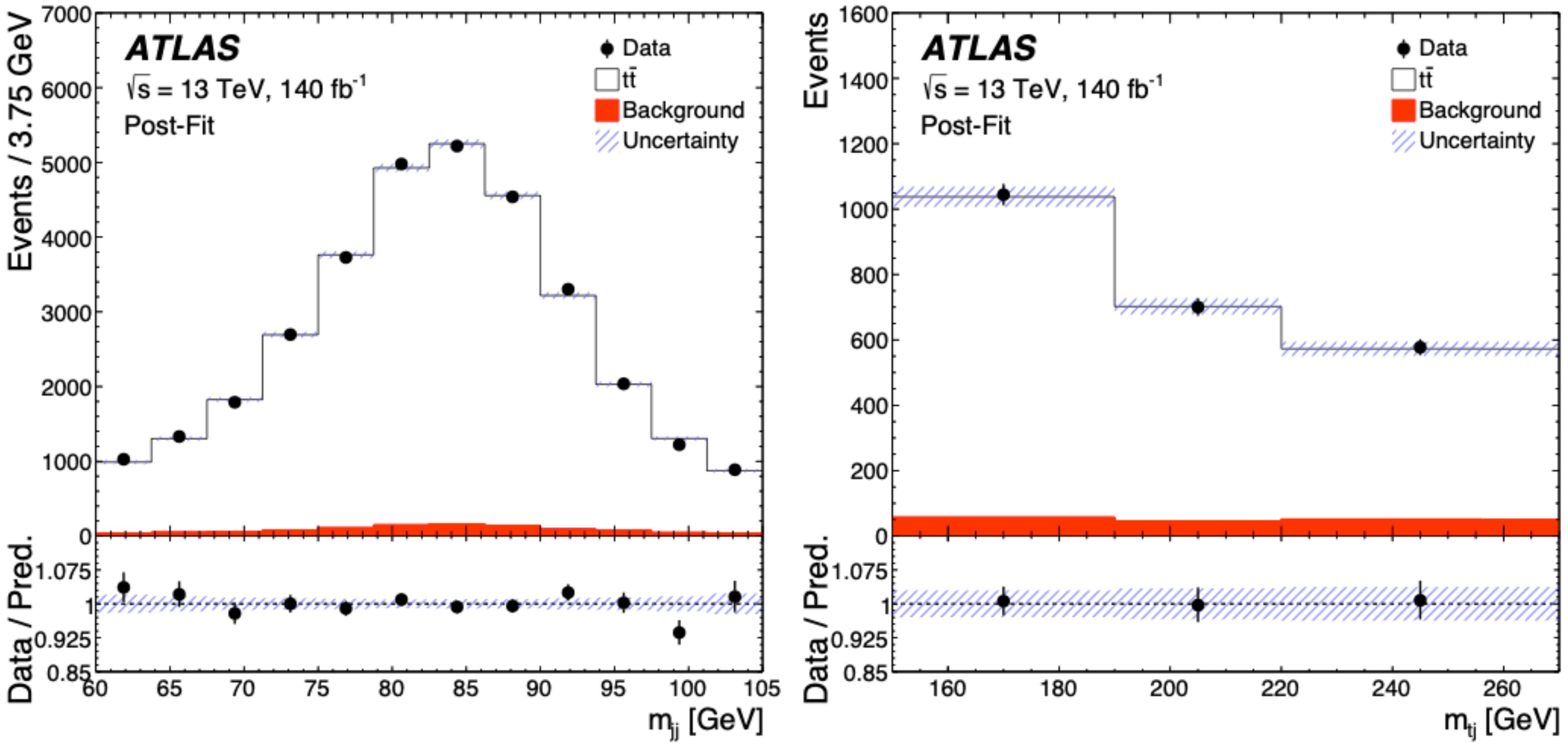
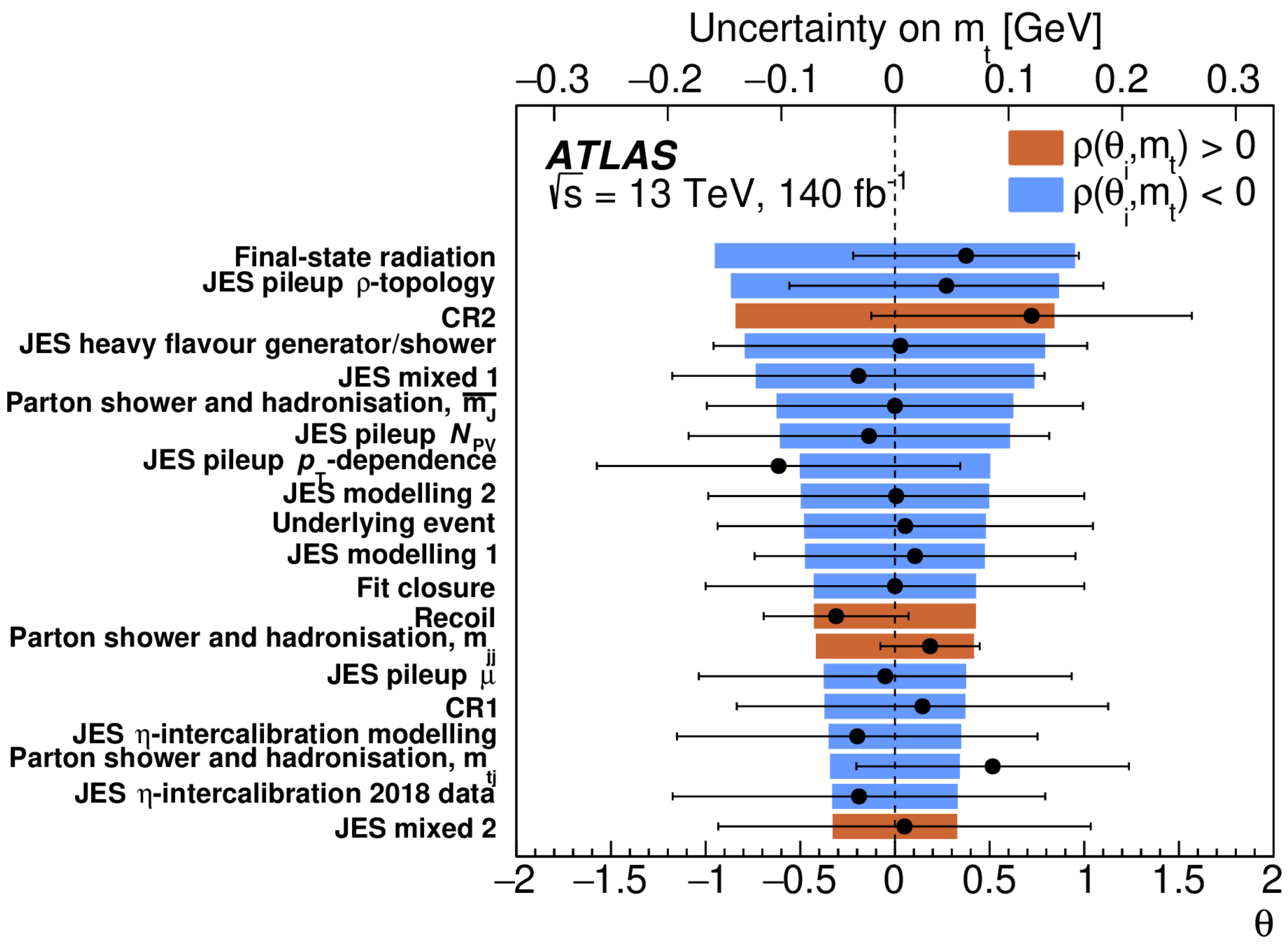
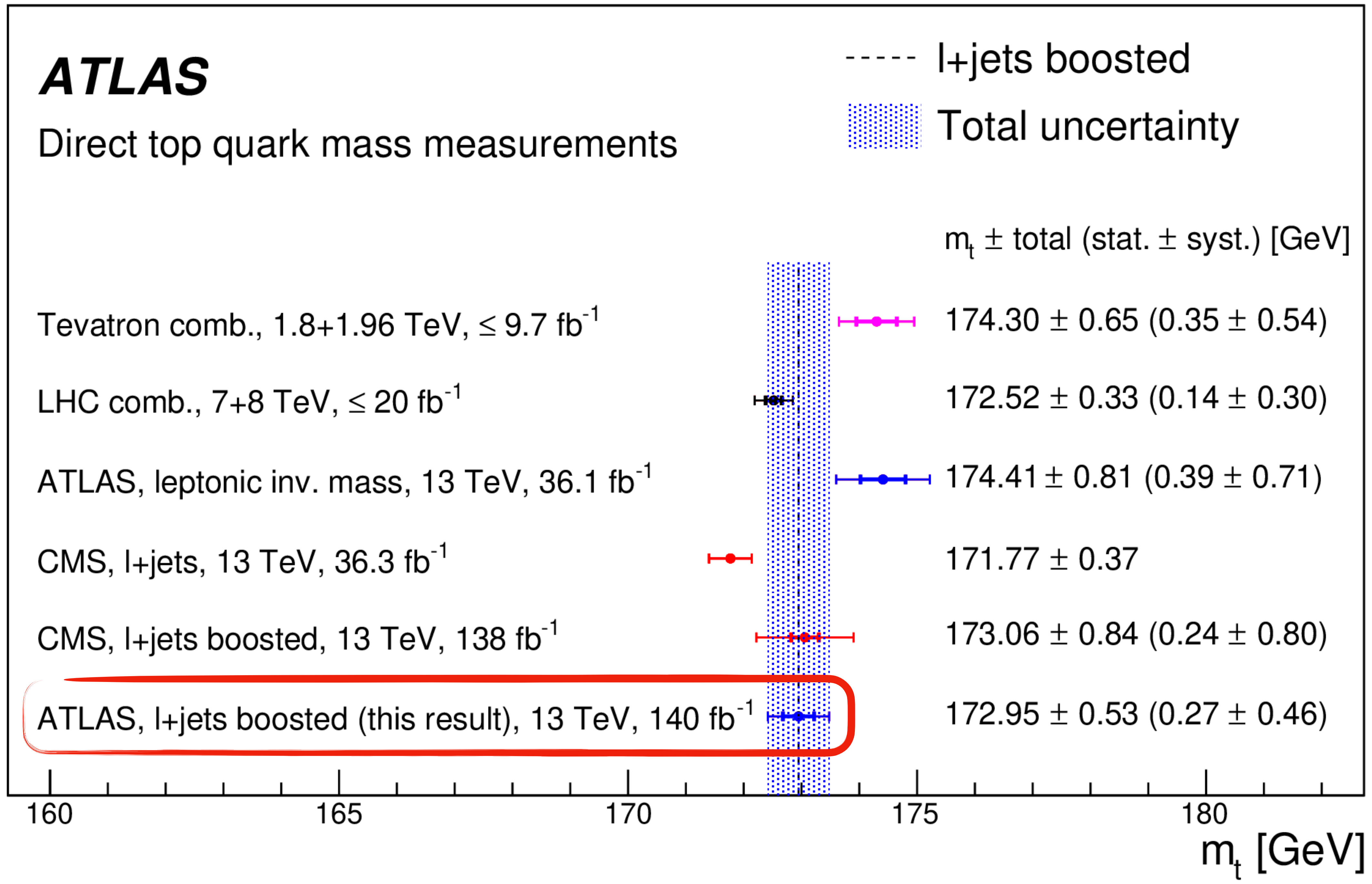
- Profile likelihood fit: m_t and signal strength floating
- Inclusion of m_{jj} and m_{tj} improves the total unc. from 1.7 to 0.51 GeV
  - JES uncertainty reduced from 1.4 to 0.26 GeV
  - ISR/FSR uncertainty reduced from 0.82 to 0.14 GeV
- Extracted mass: $m_t = 172.95 \pm 0.27\ \text{(stat)} \pm 0.46\ \text{(syst)}\ \text{GeV}$
- Dominant systematic uncertainties: JES, $t\bar{t}$ modelling





the most precise ATLAS measurement in a single channel



Top properties

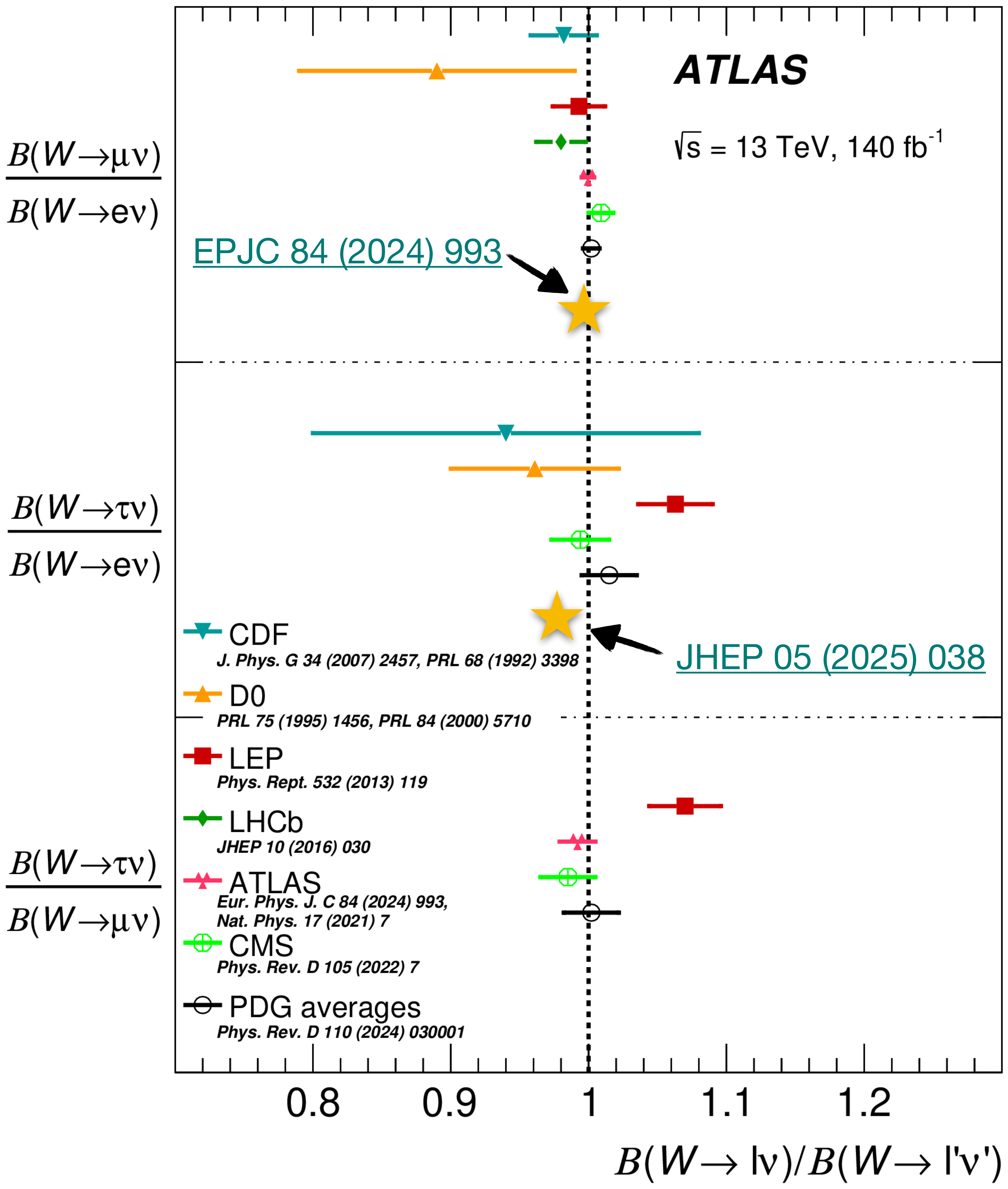
Lepton flavour universality (LFU) in top-quark decay

- **LFU: equality of e, μ, τ couplings to electroweak bosons**
- Violation of LFU would be a direct evidence of the new physics
- Tested in τ, π, K decays to ~0.1% level and in real W decays to % level
- 13 TeV $t\bar{t}$ events provide a big sample of $tt \rightarrow WbWb \rightarrow l\nu bl\nu b$
  - LFU can be tested by measuring $R_W^{l_1/l_2} = B(W \rightarrow l_1\nu_1)/B(W \rightarrow l_2\nu_2)$

✴ **Two recent ATLAS Run2 measurements**:

- $R_W^{\tau/e}$ JHEP 05 (2025) 038 — *first ATLAS $R_W^{\tau/e}$ measurement using top decays as a source of W bosons*
- $R_W^{\mu/e}$ EPJC 84 (2024) 993 — *most precise $R_W^{\mu/e}$ measurement to date*

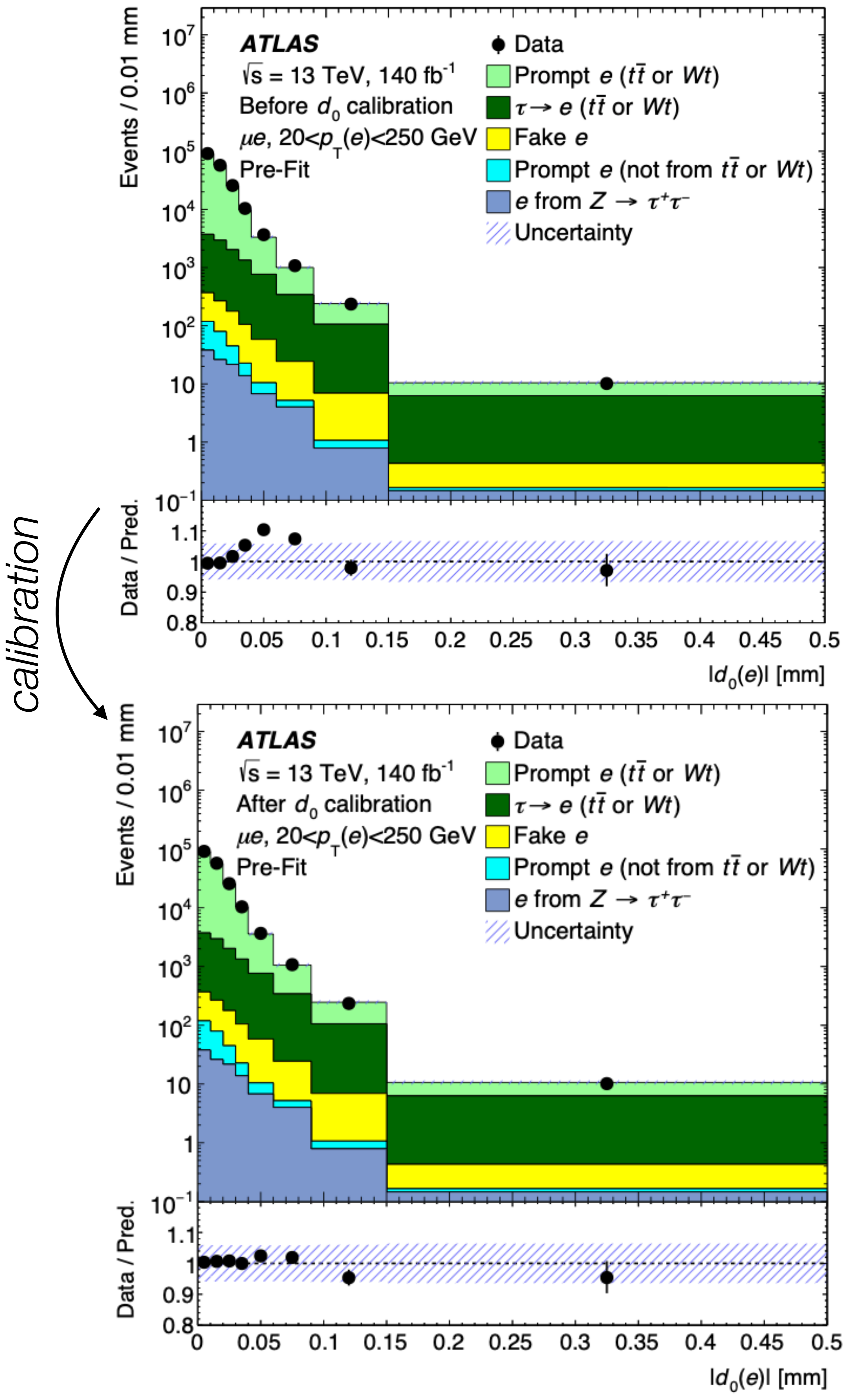
Both analyses select 2 opposite-charge leptons and 1 or 2 b-tagged jets



e/τ universality in top decays

- Mesure $R_{\tau/e} = \Gamma(W \to \tau\bar{\nu}_\tau)/\Gamma(W \to e\bar{\nu})$
- Consider $\tau \to e\nu\bar{\nu}$ decays ⟶ electrons in both final states ($W \to \tau\nu$ and $W \to e\nu$)
  - ➡ Many uncertainties cancel in $R_{\tau/e}$
- Tag-and-probe method:
  - **tag**: electron or muon with $p_\mathrm{T} > 27$ GeV
  - **probe**: electron with $p_\mathrm{T} > 7$ GeV; fitting its p_T and $|d_0|$

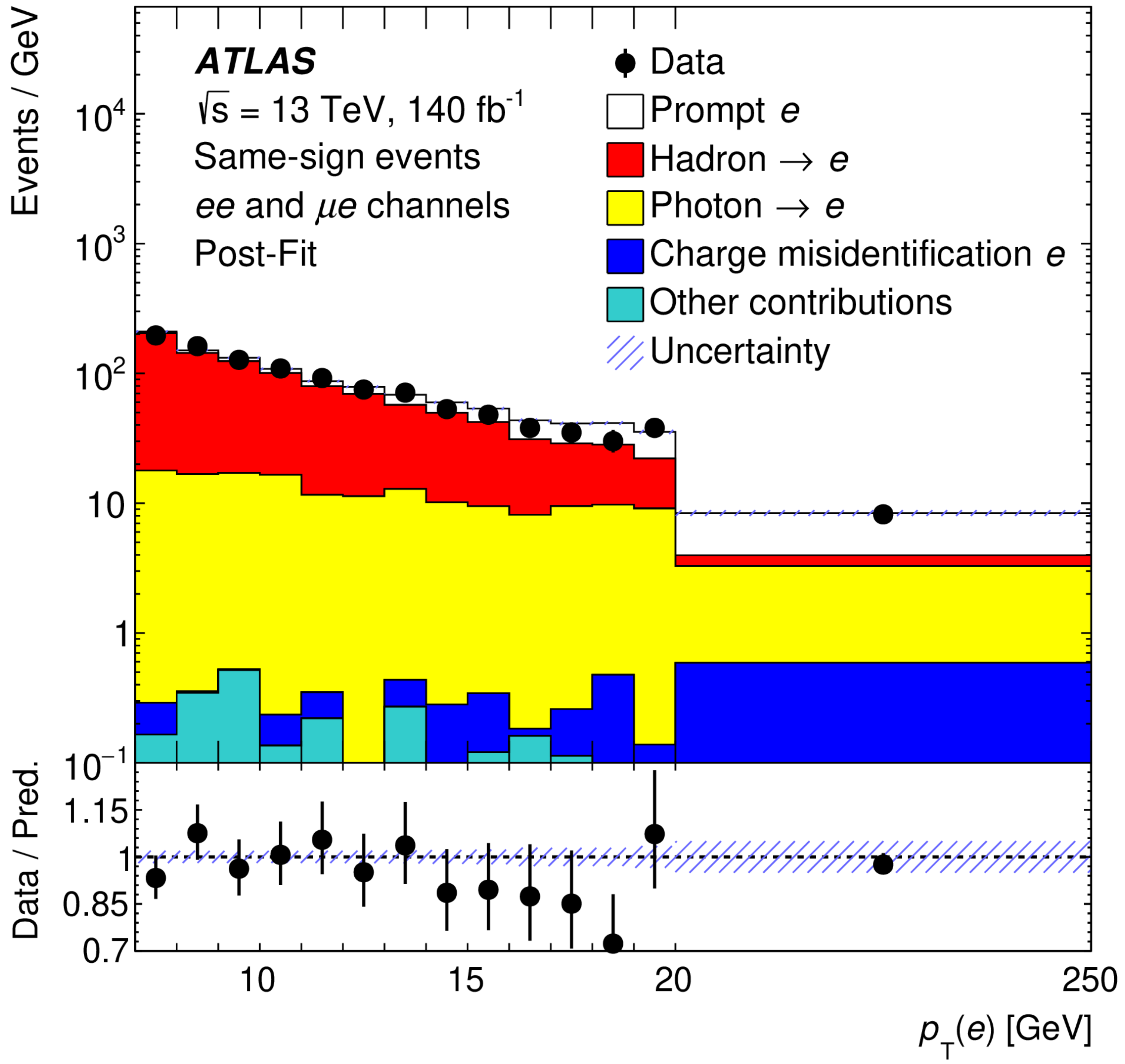
  ⟵ *separate μe and ee channels*
- Electrons from τ decays, compared to the prompt ones, have
  - lower p_T ⟵ *energy loss to neutrinos*
  - larger $|d_0|$ ⟵ *non-zero τ lifetime*
- Calibrate d_0 of prompt electrons using $Z \to ee$ events
- d_0 for electrons from τ decays taken from simulation + apply a resolution correction



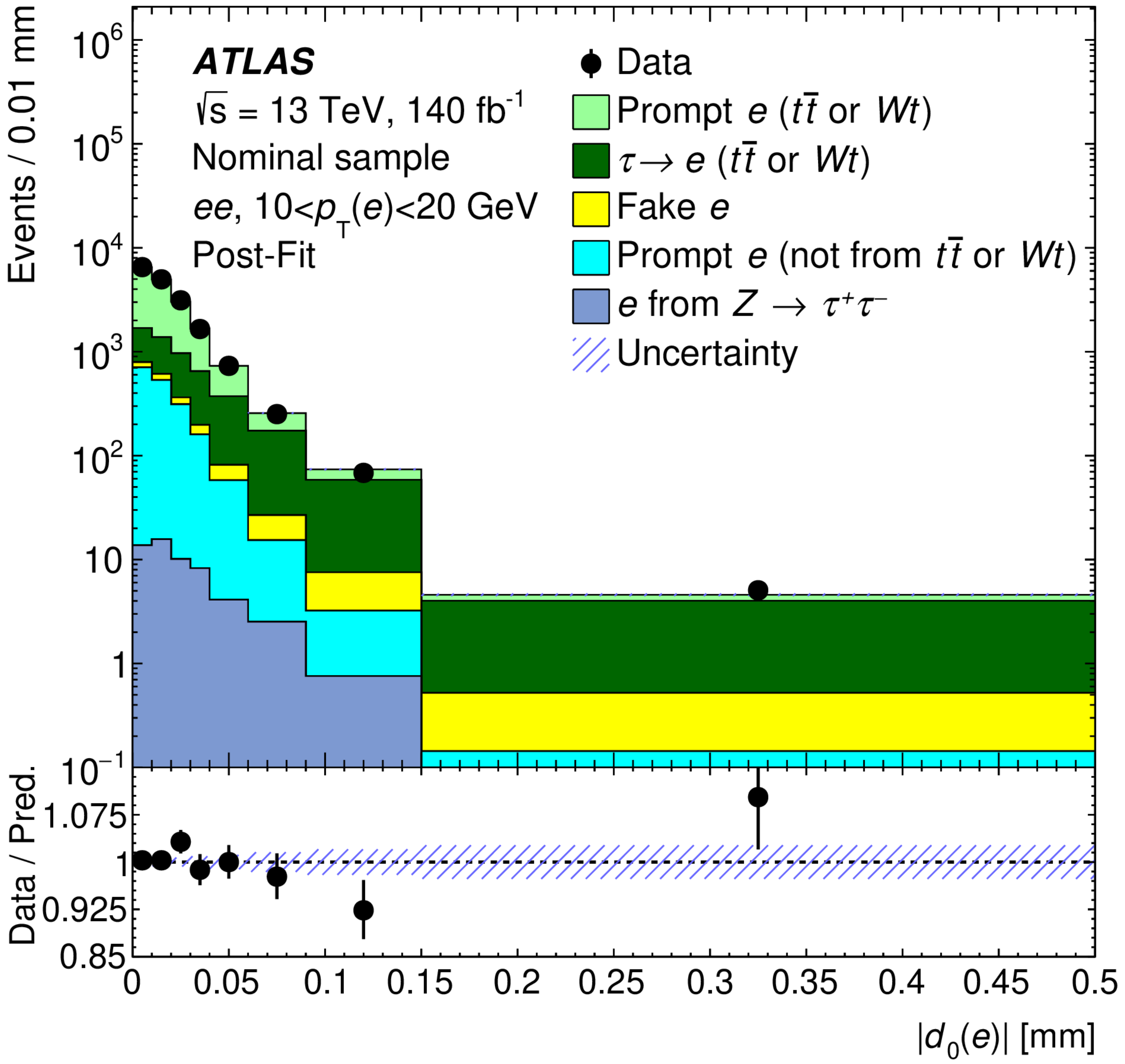
e/τ universality in top decays

Backgrounds

- **$Z \to ee$**: removed by applying a Z-mass window veto in the signal region
- **Non-resonant e^+e^-**: estimate from a control region w/o Z-mass window veto
- **Fake electrons**: get correction factors from a same-sign control region

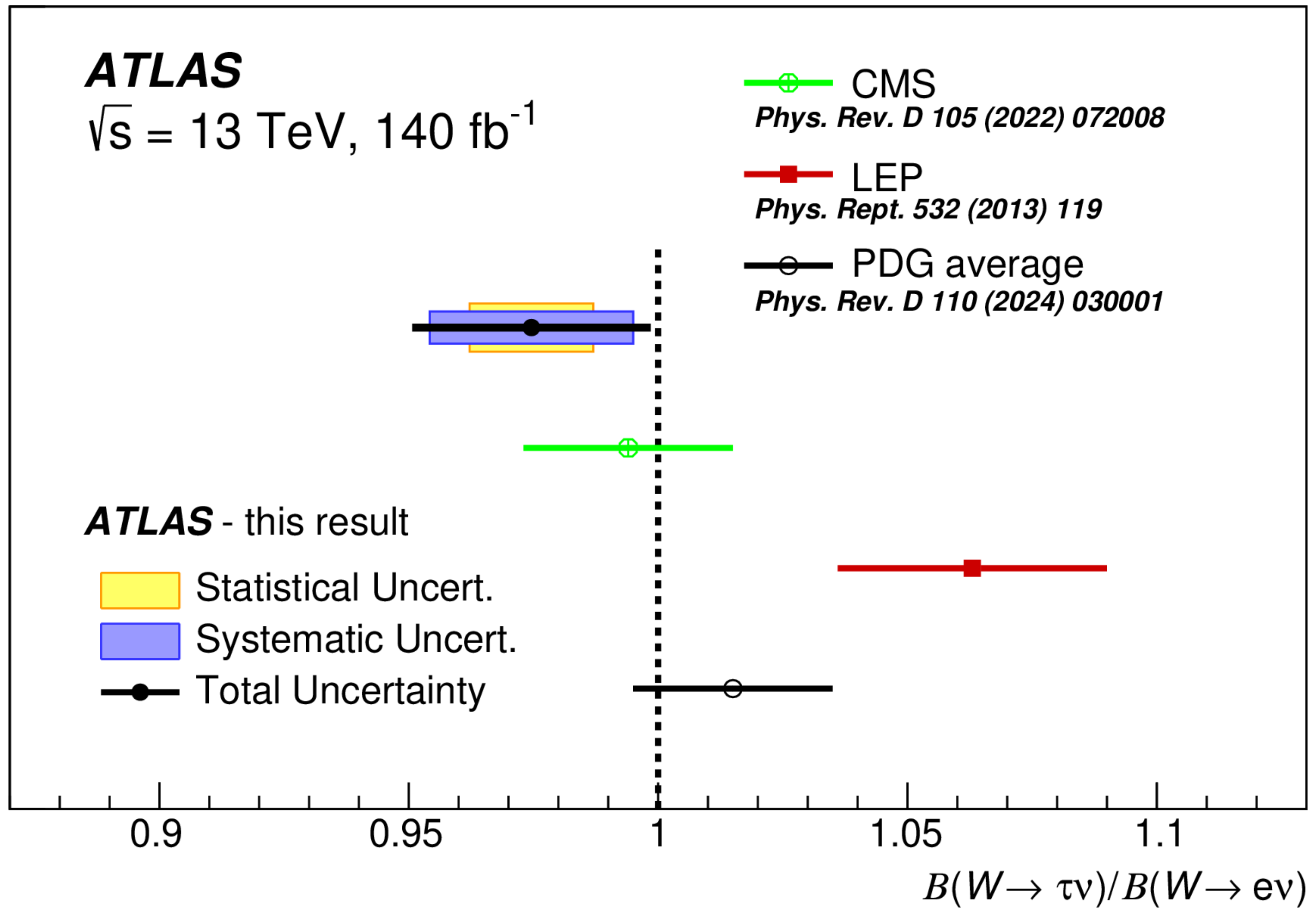


SS events with correction factors applied



fitted d_0 distribution in one of the p_T bins

Results



- Profile likelihood fit to $p_T(e)$ and $|d_0(e)|$

$$R_{\tau/e} = 0.975 \pm 0.012\ (\text{stat}) \pm 0.020\ (\text{syst})$$

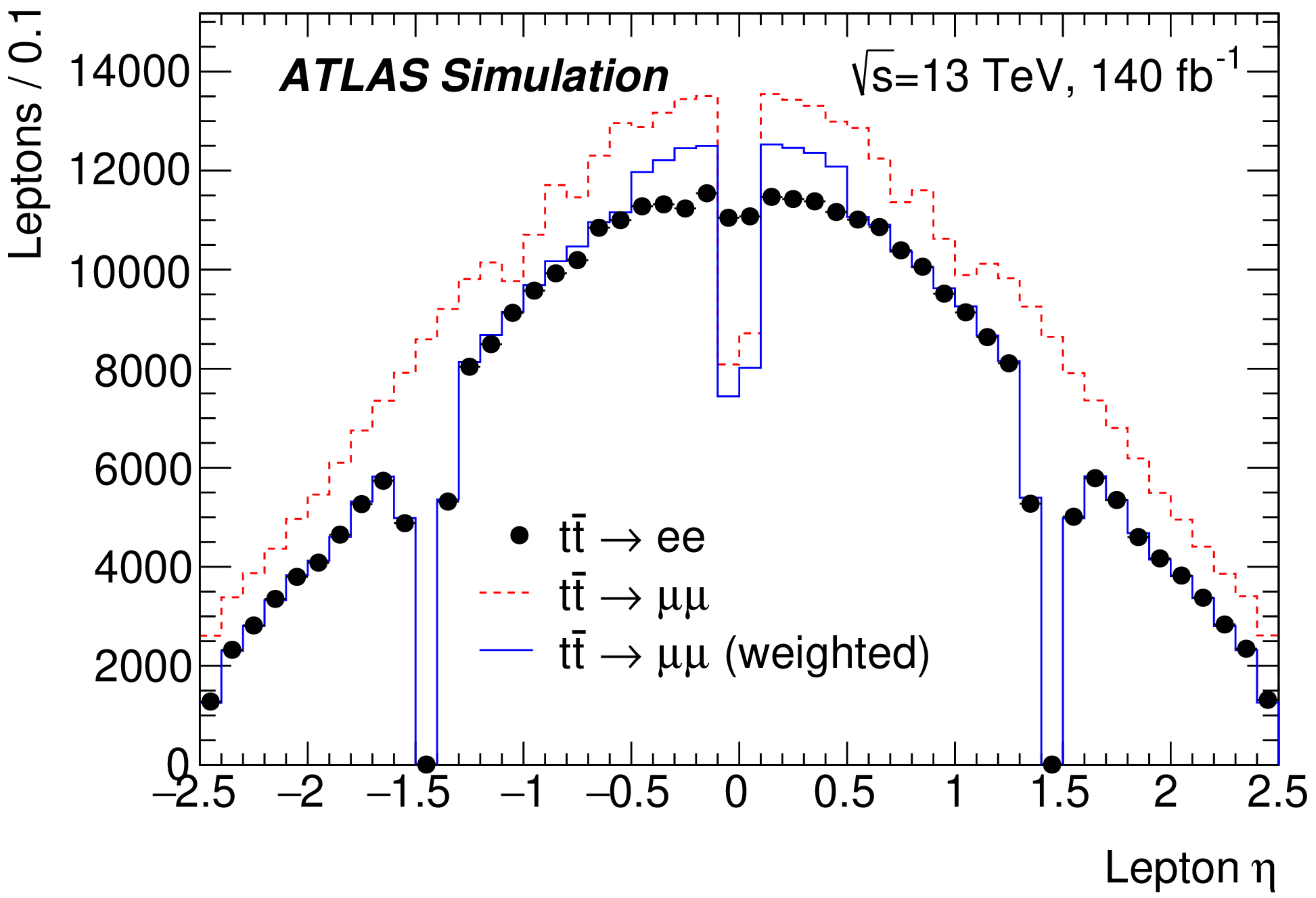
- Dominant uncertainties:
  $t\bar{t}$ modelling, d_0 calibration, background evaluation, electron reconstruction

e/μ universality in top decays

EPJC 84 (2024) 993

by-product measurements:
$\sigma_{t\bar{t}}$, $\sigma_{Z\to ll}$

- Measure $R_W^{\mu/e} = \Gamma(W \to \mu\bar{\nu}_\mu)/\Gamma(W \to e\bar{\nu})$
  - Derive from a comparison of the $t\bar{t}$ cross-section in ee, $\mu\mu$ and $e\mu$ channels
- **Reduce the e/μ ID uncertainties** by simultaneously measuring $R_Z^{\mu\mu/ee} = \Gamma(Z \to \mu\mu)/\Gamma(Z \to ee)$
  - Parameter-of-interest becomes $R_{WZ}^{\mu/e} = R_W^{\mu/e}/\sqrt{R_Z^{\mu\mu/ee}}$
- **Reduce physics modelling uncertainties** by weighting muons vs $(p_\mathrm{T}, |\eta|)$
  - Kinematic acceptance in $ee/\mu\mu$ events becomes almost the same

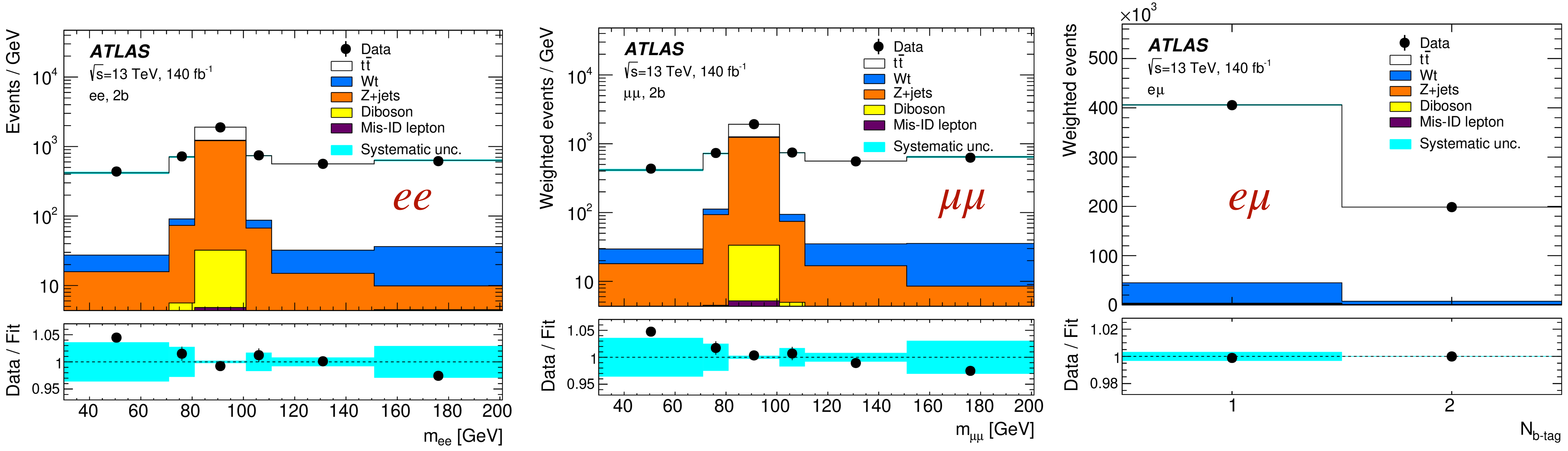


- Jet/*b*-tagging efficiency determined from data separately for $ee/\mu\mu/e\mu$ events
- Dedicated in-situ lepton isolation efficiency measurements for $Z \to ll$ and $t\bar{t}$
- Normalisations factors for $Z + 1b$ and $Z + 2b$ determined from the fit

e/μ universality in top decays

[EPJC 84 (2024) 993]

results of the fit to data

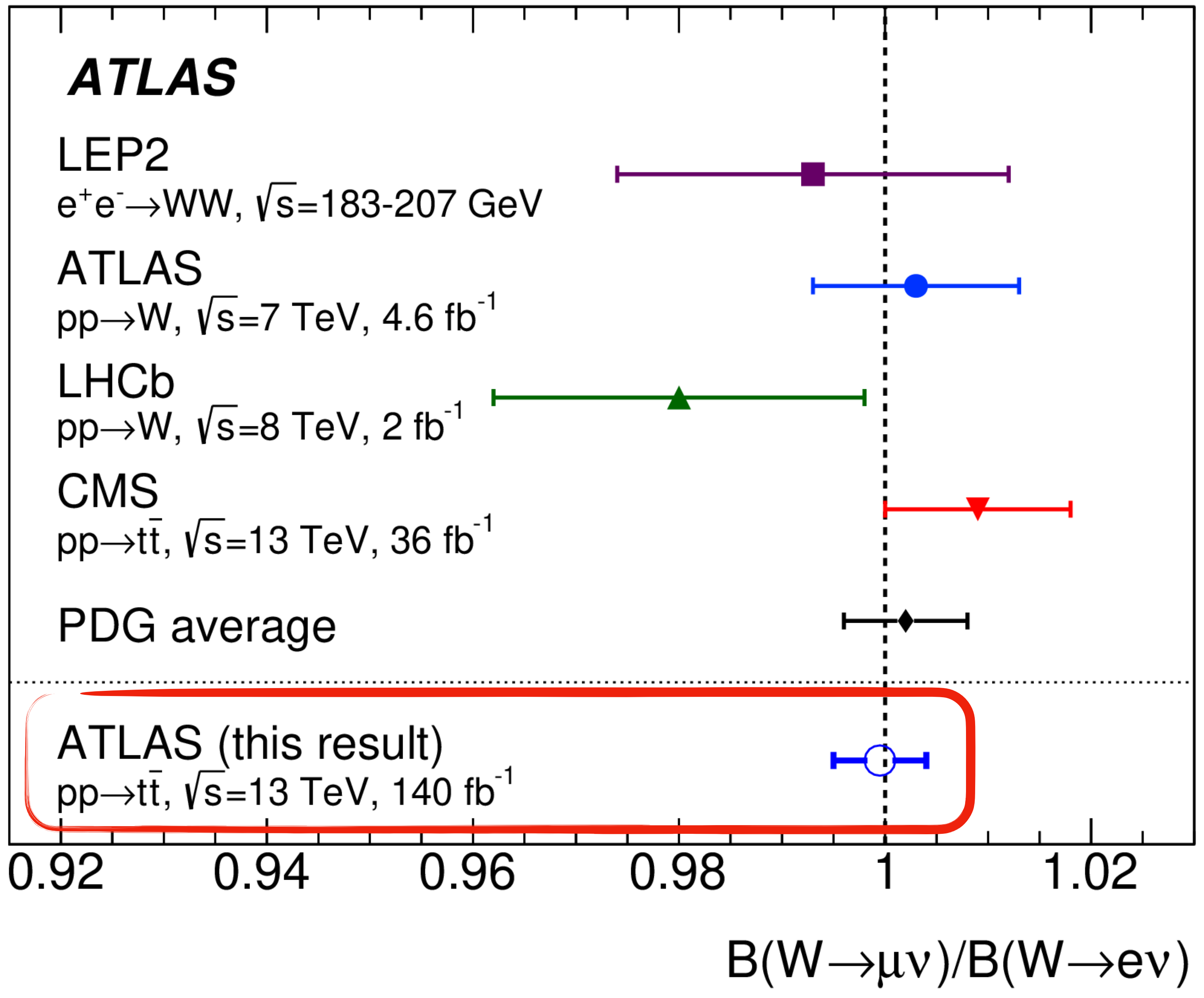


$$R^{\mu/e}_{WZ} = 0.9990 \pm 0.0022(\text{stat}) \pm 0.0036(\text{syst})$$
$$R^{\mu\mu/ee}_{Z} = 0.9913 \pm 0.0002(\text{stat}) \pm 0.0045(\text{syst})$$

- Take $R^{\mu\mu/ee}_{Z} = 1.0009 \pm 0.0028$ from LEP/SLD [PDG 2022] for the final result:

$$R^{\mu/e}_{W} = R^{\mu/e}_{WZ}\sqrt{R^{\mu\mu/ee}_{Z-\text{ext}}} = 0.9995 \pm 0.0022(\text{stat}) \pm 0.0036(\text{syst}) \pm 0.0014(\text{ext})$$

- **The most precise $R^{\mu/e}_{W}$ measurement to date**
  - ✓ Uncertainty is smaller than that of the previous world average



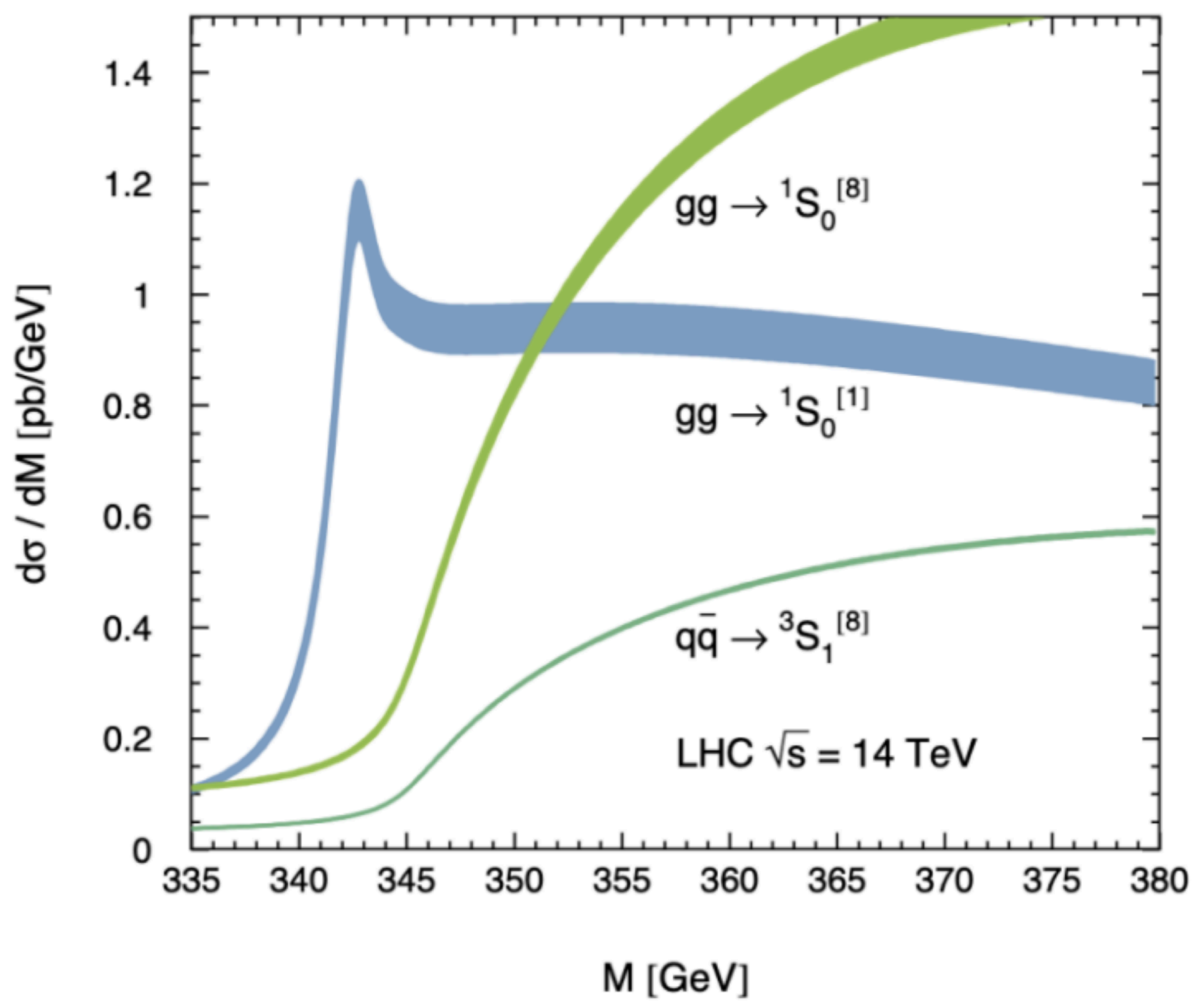
Conclusions

- Top quark measurements continue providing useful input to assess the SM consistency
- Latest top quark mass measurements are in good agreement with the previous results
- No sign of violation of lepton flavour universality
- Various ways to reach higher precision
  - Use improved theoretical predictions
  - Introduce additional variables sensitive to systematic variations
  - Object calibration using auxiliary measurements
- So far, talking about Run 2 results — stay tuned for Run 3 measurements!

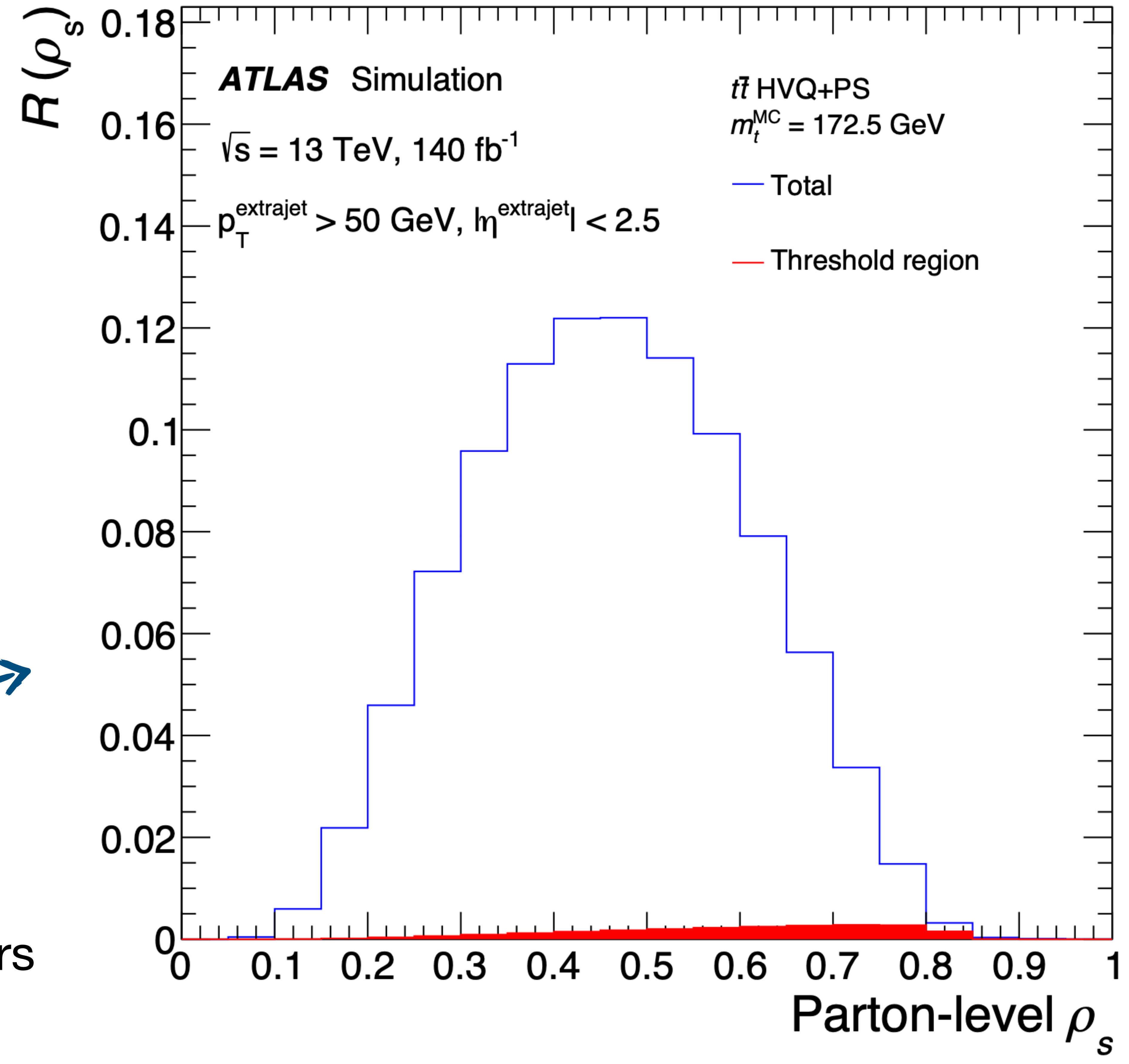
Back-up

Top quark pole mass in dilepton $t\bar{t}$ + 1jet events

EPJC 60 (2009) 375



Threshold region affected by Coulomb corrections: $340 < m_{t\bar{t}} < 355$ GeV



- Normalised parton-level ρ_S distribution from the nominal Ph+Py8 sample
  - Blue: all events passing $p_{\mathrm{T}}^{\mathrm{extrajet}} > 50$ GeV
  - Red: threshold region
- Threshold region is affected by effects not included in the mainstream MC generators
  - Coulomb corrections
  - "Toponium" pseudo-bound state
- **Threshold enhancement is smeared out over the ρ_S range**

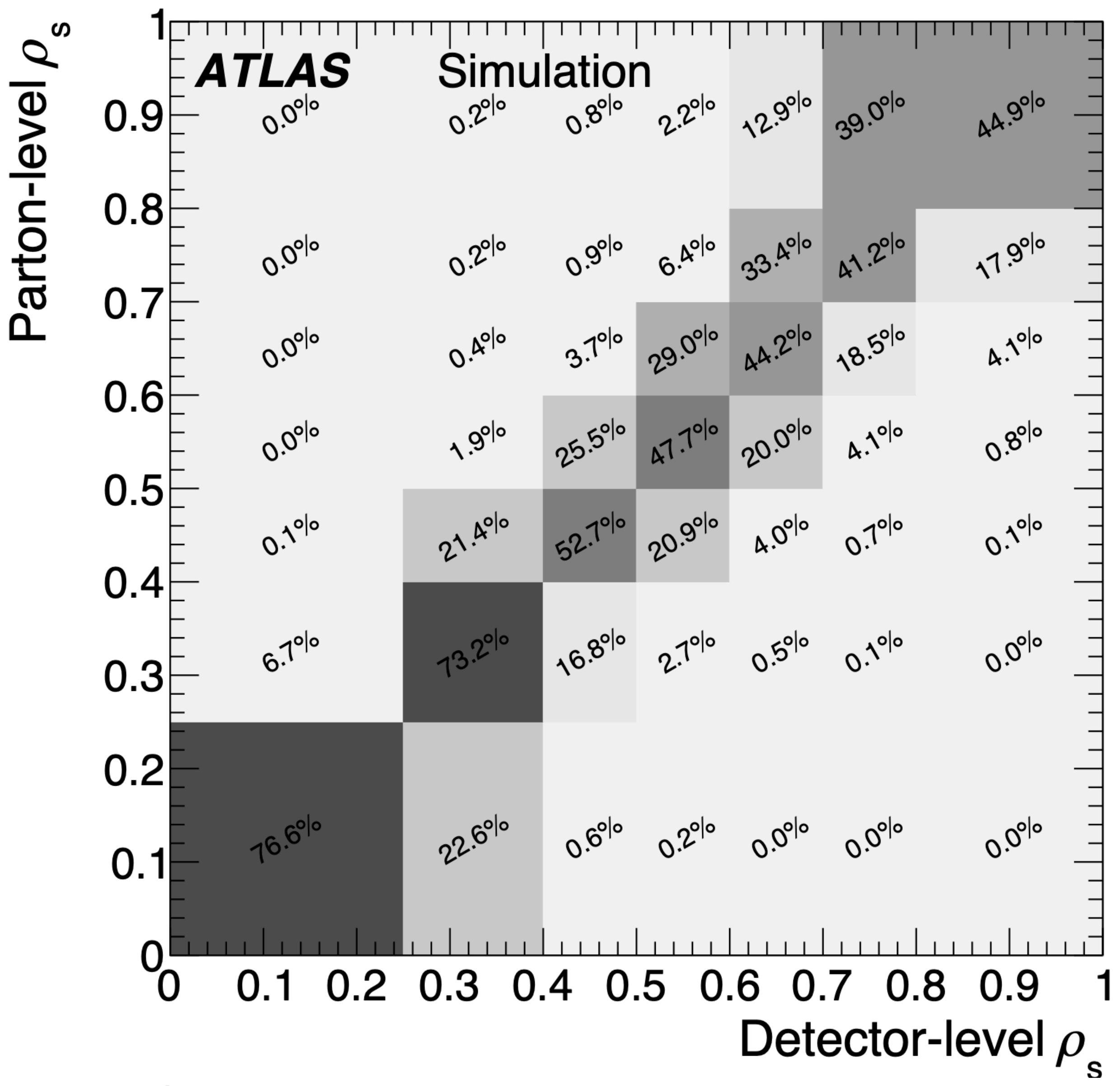
Top quark pole mass in dilepton $t\bar{t}$ + 1jet events: unfolding

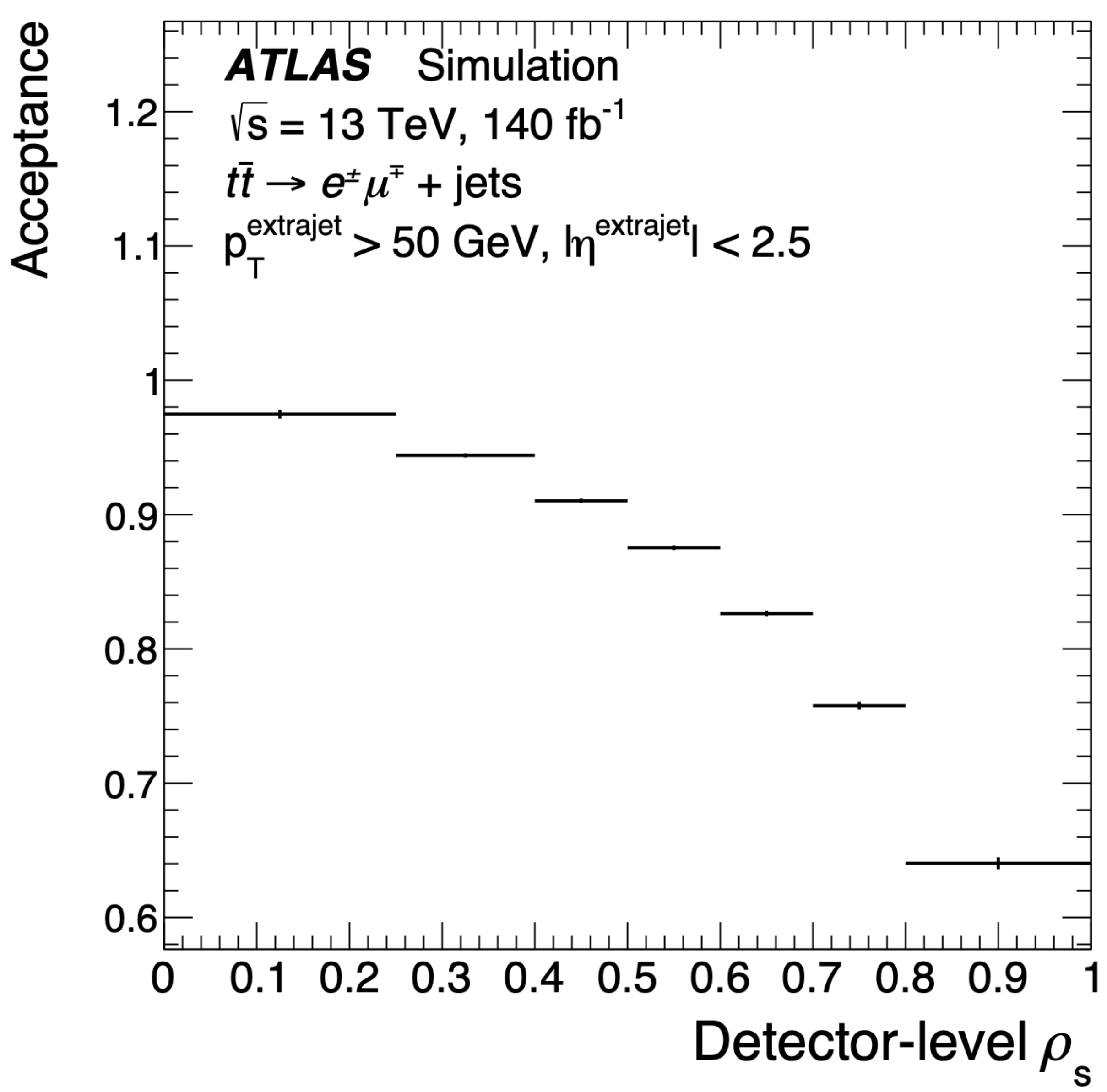
migration matrix

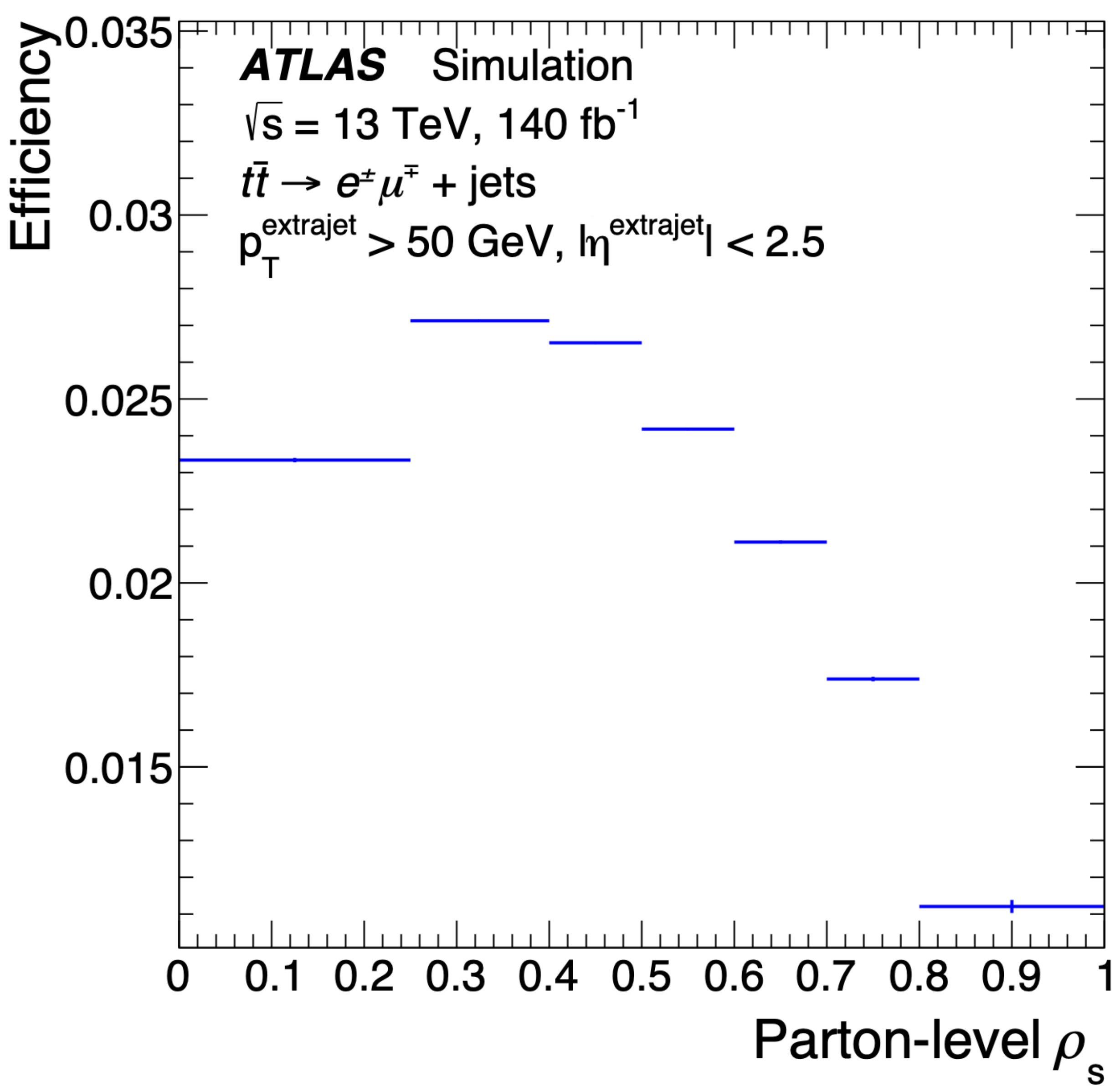
acceptance

efficiency

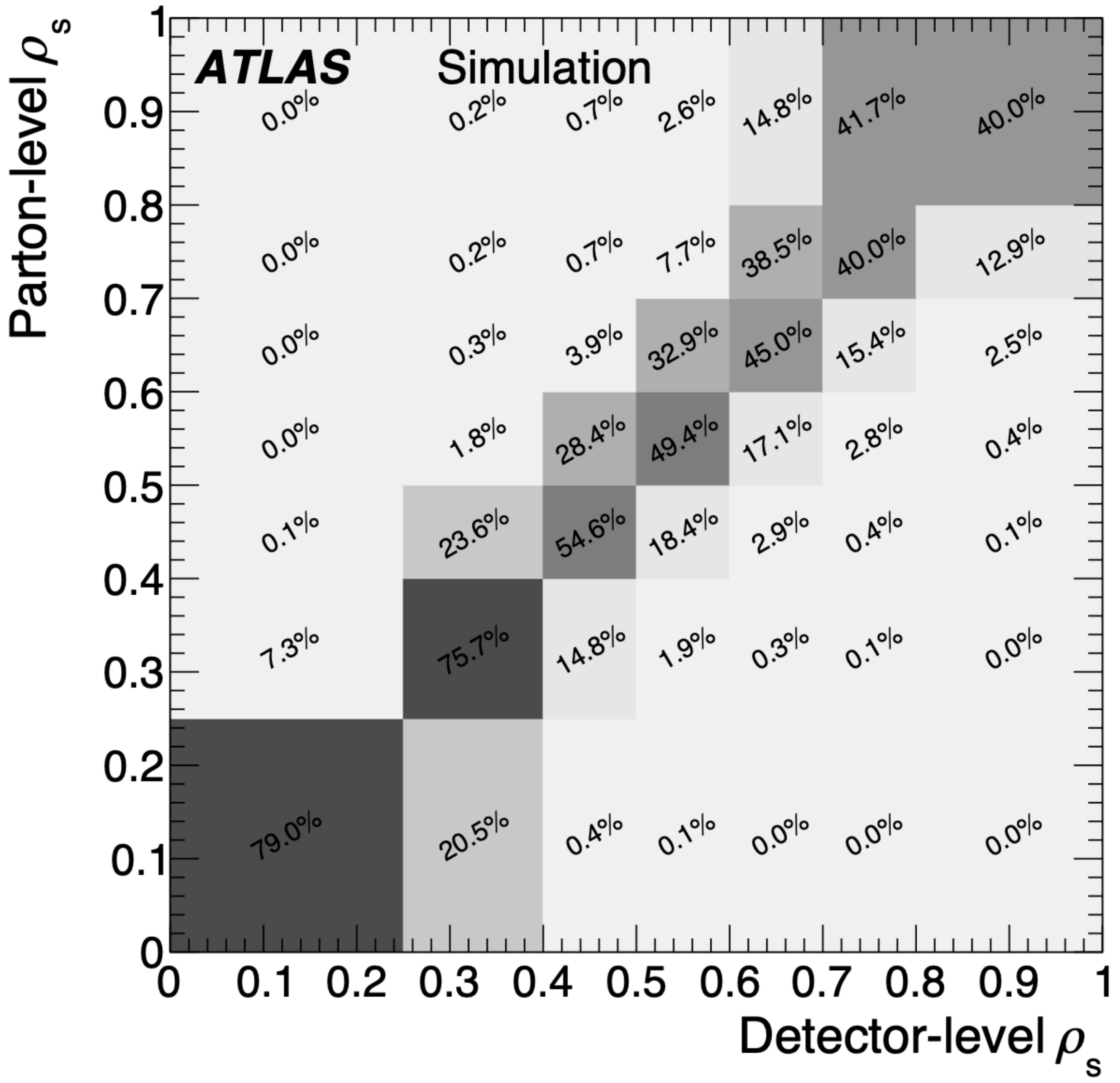
unfolding to 2→3

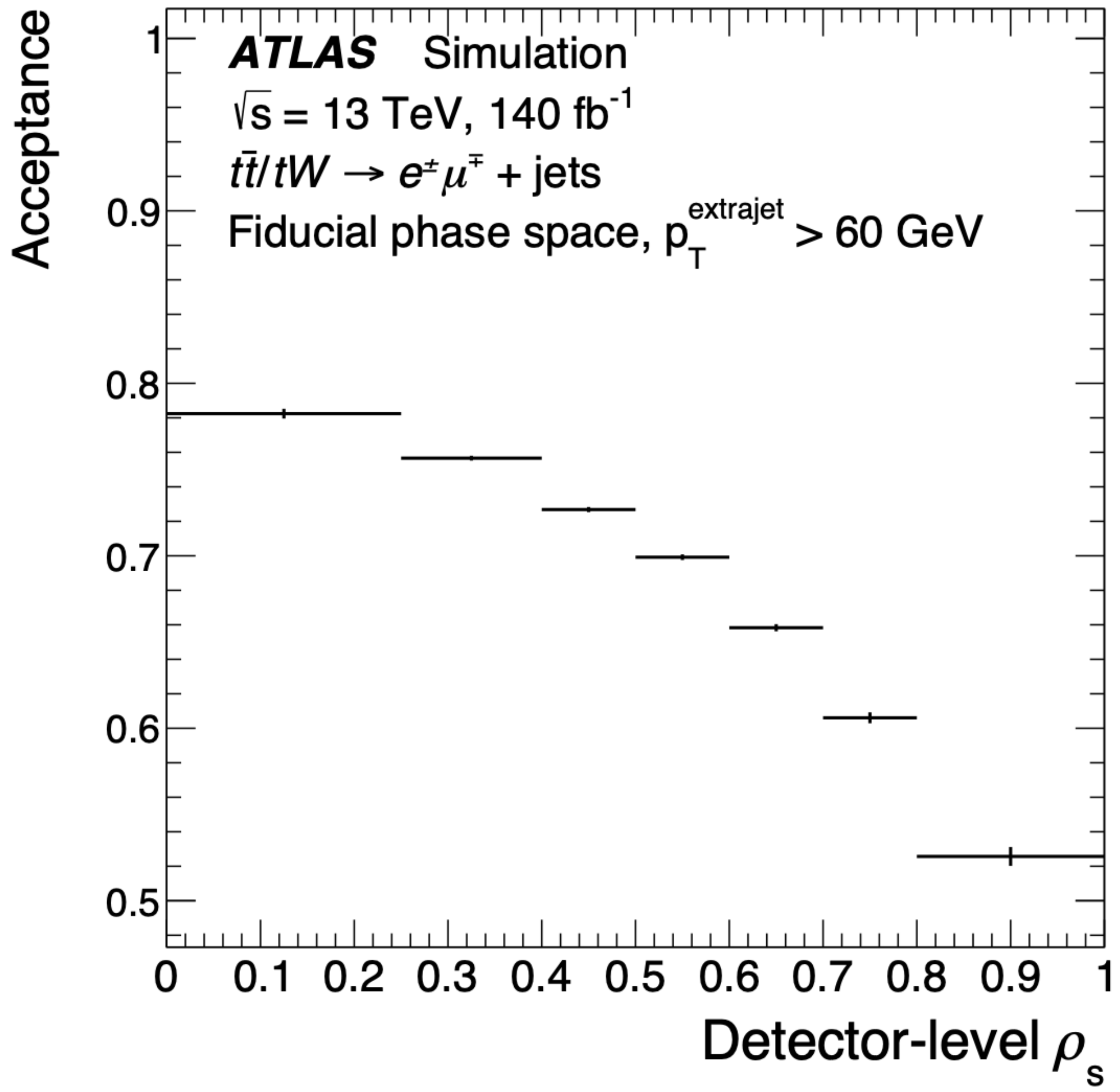


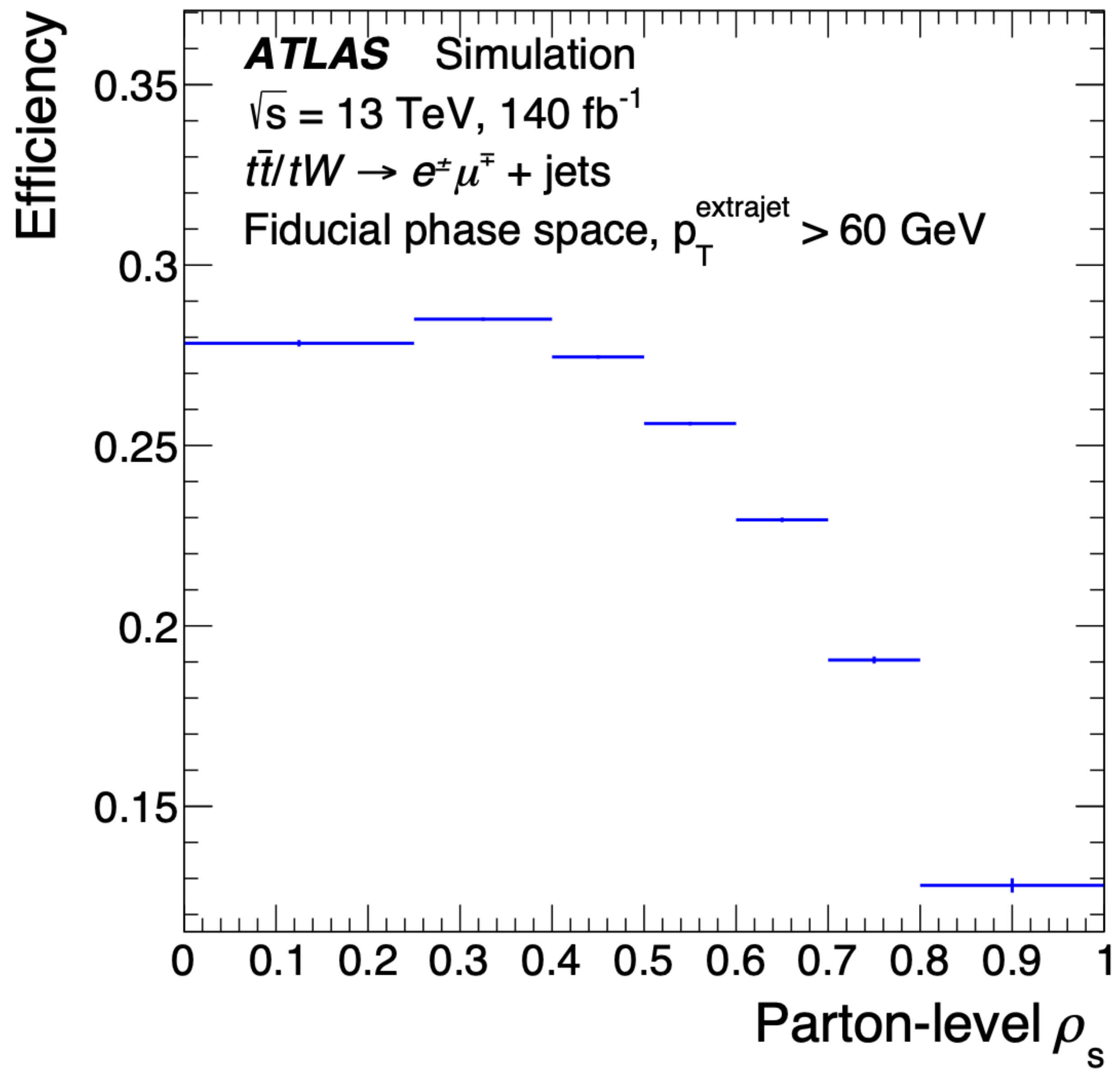




unfolding to 2→7

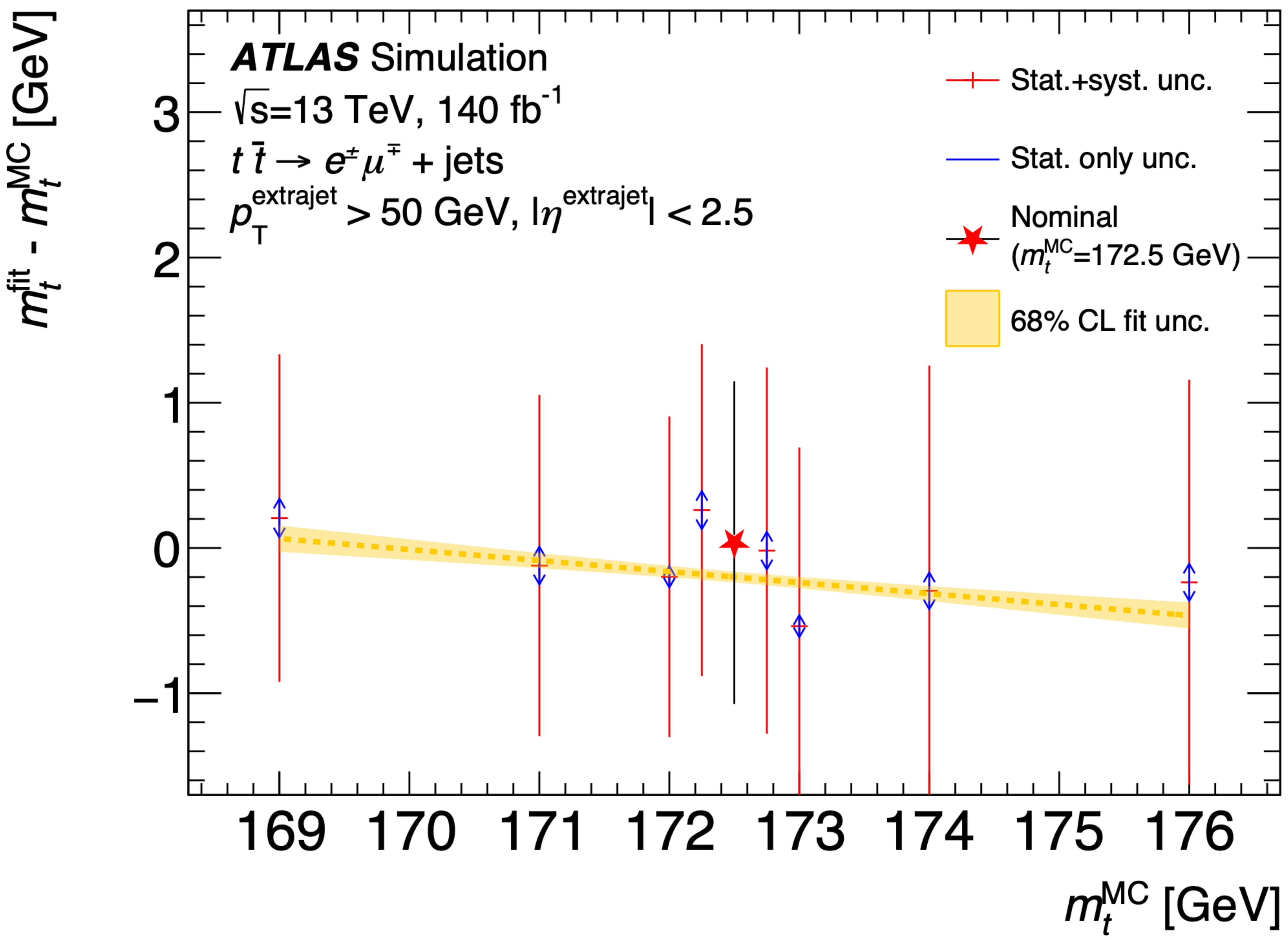




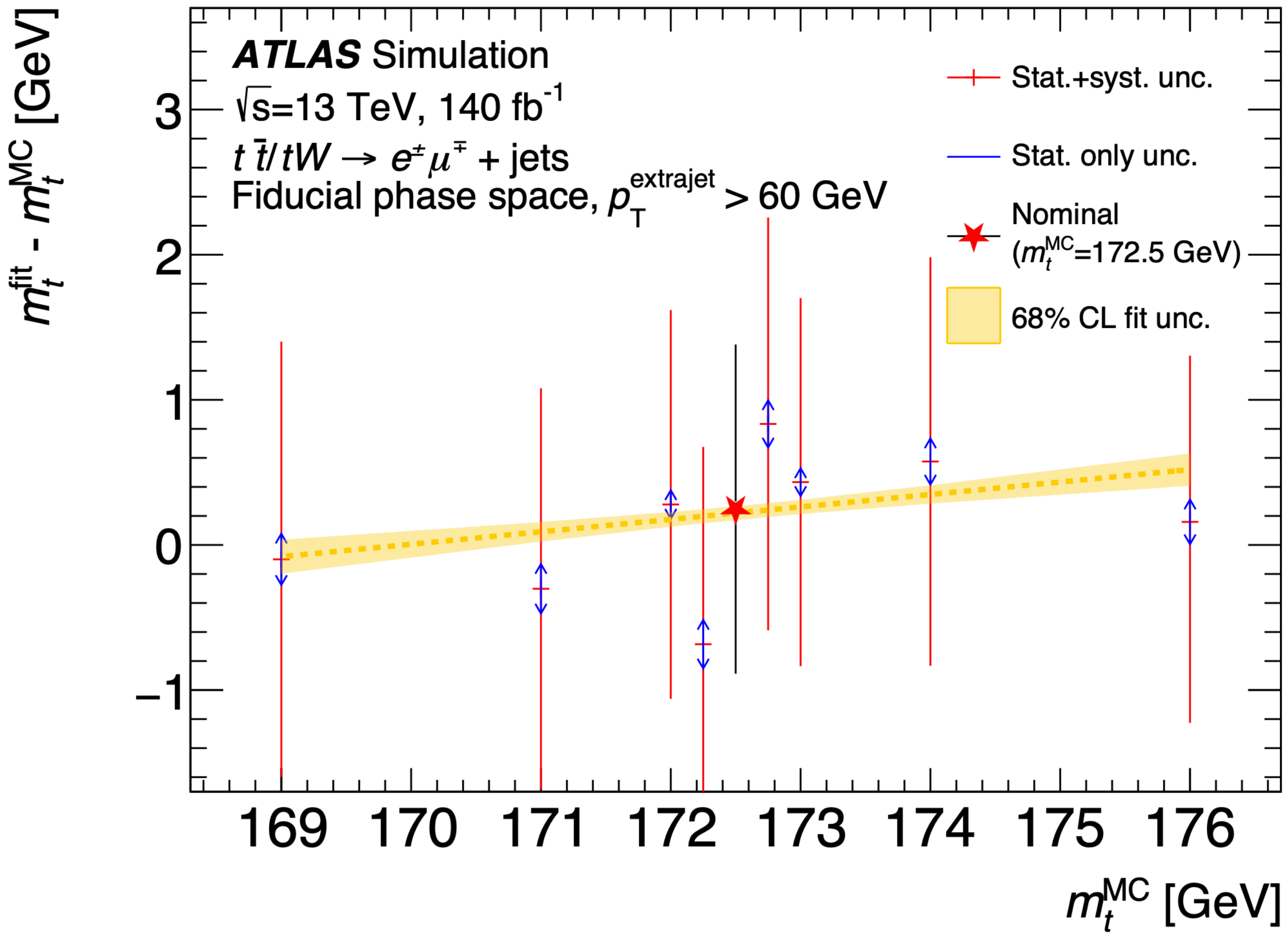


Top quark pole mass in dilepton $t\bar{t}$ + 1jet events: linearity

unfolding to 2→3



unfolding to 2→7



Top quark pole mass in dilepton $t\bar{t}$ + 1jet events: uncertainty breakdown

Uncertainty source	Δm_t^{pole} [GeV]	MC stat. unc. [GeV]
Data statistics	0.33	-
Detector unc.		
b-tagging and mistag	0.44	0.06
Jets	0.65	0.06
Leptons	0.25	0.06
Others	0.18	0.06
Modeling unc.		
MC statistical uncertainty	0.08	-
Backgrounds normalization	0.02	-
Single-top modeling	0.03	0.06
m_t^{MC} dependence	0.10	0.09
PS Recoil model	0.68	0.06
Parton shower	0.43	0.14
Underlying event	0.39	0.12
Color reconnection	0.13	0.08
ME+PS matching: p_T^{hard}	0.09	0.06
ME+PS matching: h_{damp}	0.26	0.06
ME+PS matching: line shape	0.38	0.12
3D NNLO reweight	0.21	0.06
PDF	0.26	0.06
Initial-state radiation	0.24	0.06
Final-state radiation	0.04	0.16
Factorization scales	0.09	0.06
Renormalization scales	0.03	0.06
Theory unc.		
Scale variations	+0.34 -0.28	+0.05 -0.06
PDF $\oplus$ α_S	0.24	+0.06 -0.06
Total	+1.47 -1.44	-

fit to 2→3 predictions

Uncertainty source	Δm_t^{pole} [GeV]	MC stat. unc. [GeV]
Data statistics	0.41	-
Detector unc.		
MC statistical uncertainty	0.12	-
b-tagging and mistag	0.47	0.08
Jets	0.91	0.08
Leptons	0.28	0.08
Others	0.19	-
Modeling unc.		
Backgrounds normalization	0.07	-
Single-top modeling	0.11	0.08
m_t^{MC} dependence	0.30	0.12
PS recoil model	0.21	0.08
Parton Shower	0.87	0.19
Underlying event	0.16	0.15
Color reconnection	-0.25	0.1
ME+PS matching: p_T^{hard}	0.05	0.08
ME+PS matching: h_{damp}	0.74	0.08
ME+PS matching: line shape	0.17	0.15
3D NNLO reweight	0.11	0.08
PDF	0.57	-
Initial-state radiation	0.14	0.08
Final-state radiation	0.12	0.22
Factorization scales	-0.14	0.08
Renormalization scales	0.11	0.08
Theory unc.		
Scale variations	+0.66 -1.34	+0.05 -0.1
PDF $\oplus$ α_S	+0.49 -0.46	+0.06 -0.06
Total	+1.92 -2.24	-

fit to 2→7 predictions

Top quark mass using boosted $t\bar{t}$ events

$$L\left(\overline{m_J}^{\mathrm{data}}, \boldsymbol{n}_{\boldsymbol{m_{jj}}}, \boldsymbol{n}_{\boldsymbol{m_{tj}}} \middle| m_t, \mu_{t\bar{t}}, \boldsymbol{\theta}\right)$$

sensitive to m_t

$$= G\left[\overline{m_J}^{\mathrm{data}} \middle| \overline{m_J}(m_t, \mu_{t\bar{t}}, \boldsymbol{\theta}), \sigma_{\overline{m_J}}\right]$$

likelihood for $\overline{m_J}$, assumed to follow a Gaussian

control and reduce systematics

$$\times \prod_i P\left(n_{m_{jj},i} \middle| \nu_i(\mu_{t\bar{t}}, \boldsymbol{\theta})\right)$$

likelihood for m_{jj}

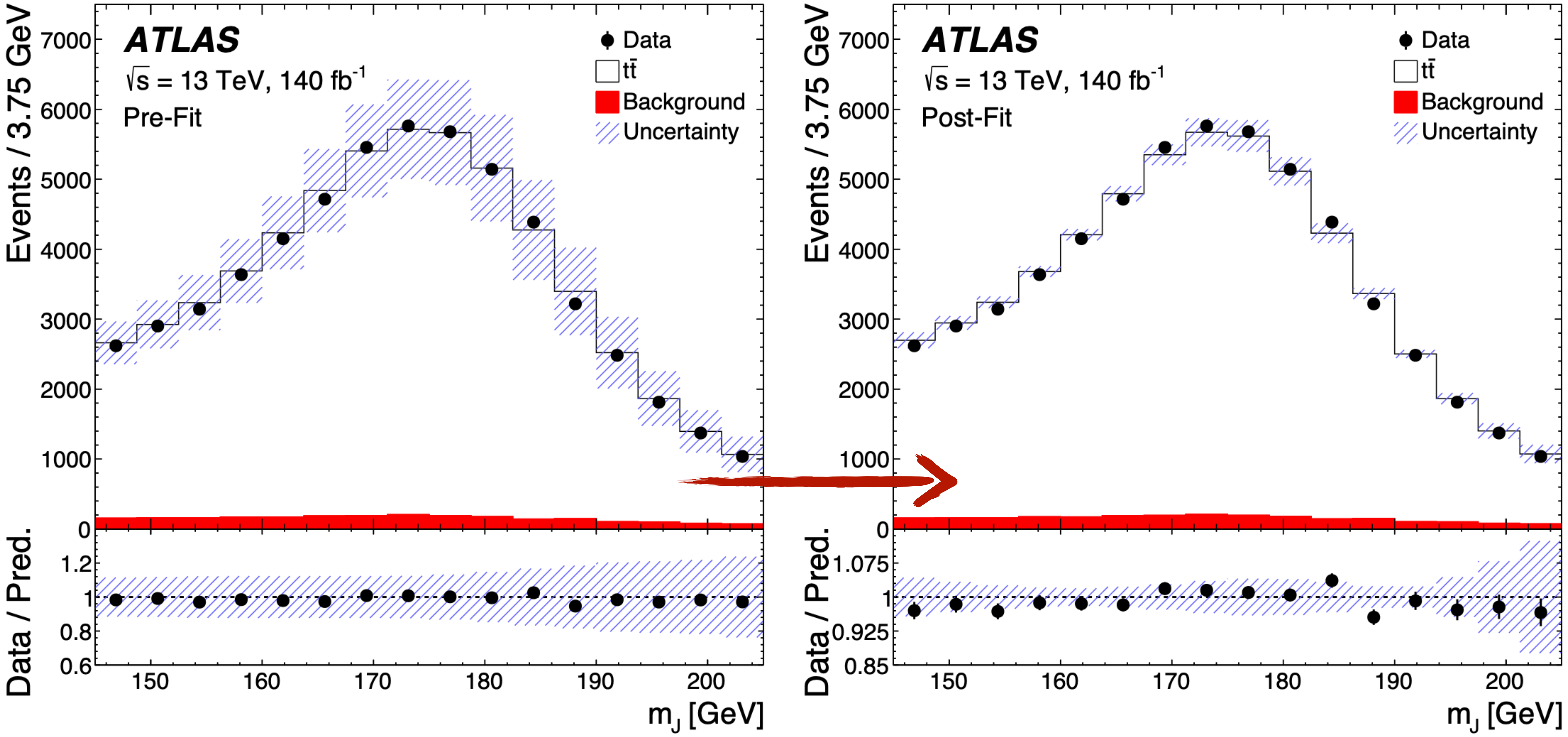
$$\times \prod_k P\left(n_{m_{tj},k} \middle| \rho_k(\mu_{t\bar{t}}, \boldsymbol{\theta})\right)$$

likelihood for m_{tj}

Poisson probabilities for bin contents

$$\times \prod_s G(\alpha_s | \theta_s, 1)$$

Gaussian terms for NP constraints

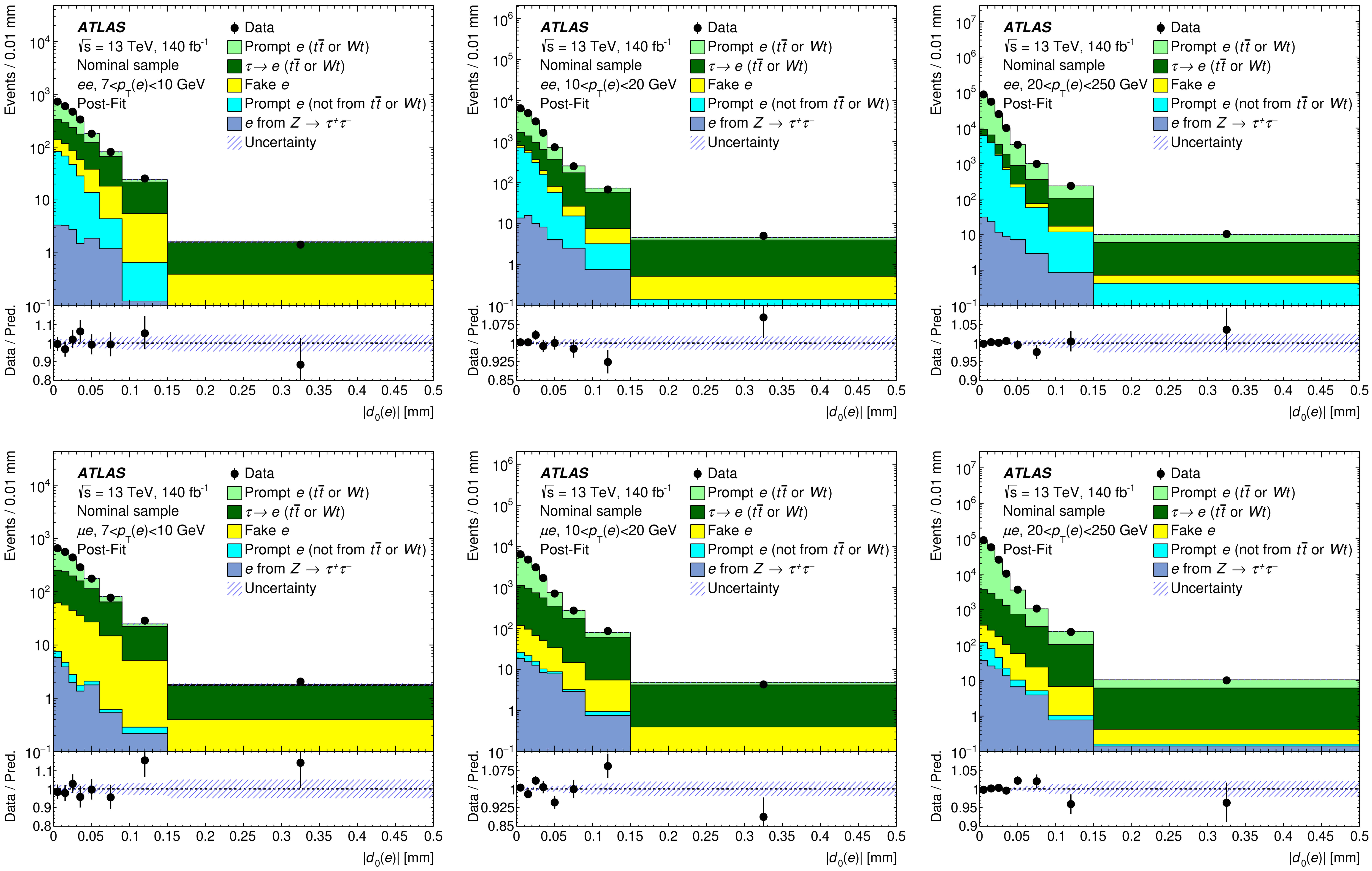


Source	Uncertainty [GeV]
JES	± 0.29
Radiation (ISR and FSR)	± 0.17
Colour reconnection (CR1 and CR2)	± 0.15
JES heavy flavour	± 0.14
Parton shower and hadronisation model	± 0.14
JER	± 0.10
MC statistics	± 0.08
Underlying event	± 0.08
Recoil	± 0.07
Fit closure	± 0.07
Background modelling	± 0.05
Matrix element matching ($p_T^{\mathrm{hard}} = 1$)	± 0.04
b-tagging	± 0.04
Higher-order corrections	± 0.02
E_T^{miss}	± 0.02
Pileup	± 0.01
JVT	± 0.01
PDF	± 0.01
Leptons	± 0.01
Luminosity	< 0.01
Total statistical	± 0.27
Total systematic	± 0.46
Total	± 0.53

e/τ universality in top decays: fitted distributions

ee

μe



e/τ universality in top decays

Object selection

electrons	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$ *probe:* $7 < p_T < 250$ GeV *tag:* $p_T > 27$ GeV
muons	$p_T > 27.3$ GeV, $\|\eta\| < 2.5$
b-tagged jets	$p_T > 25$ GeV, $\|\eta\| < 2.5$, b-tagging DL1r 70%

Event selection

Dilepton flavour	ee, eμ
DIlepton inv. mass	$m_{ll} > 15$ GeV, $\|m_{ee} - m_Z\| > 5$ GeV
b-tagged jet mult.	1 or 2

Measured values of $R^{\tau/e}$ in the different p_T bins

p_T bin	$R_{\tau/e}$
$7 < p_T < 10$ GeV	1.13 ± 0.11 (stat) ± 0.07 (syst)
$10 < p_T < 20$ GeV	0.93 ± 0.04 (stat) ± 0.02 (syst)
$20 < p_T < 250$ GeV	0.98 ± 0.04 (stat) ± 0.02 (syst)

Uncertainty breakdown

Uncertainty group	$\sigma(R_{\tau/e})$
Modelling of $t\bar{t}$ and Wt	0.011
d_0 calibration	0.006
Background estimation	0.005
Electron reconstruction, identification, and isolation	0.005
Electron energy scale	0.003
Electron energy resolution	0.002
Jet energy resolution	0.004
Jet energy scale	0.003
Jet b-tagging	0.002
Muon reconstruction, identification, and isolation	0.001
Other sources	0.002
Variation of k_{sig} and $k(\mu/e)$	0.003
Finite size of simulated samples	0.003
$B(W \to \tau\nu_\tau \to e\nu_e\nu_\tau\nu_\tau)$	0.002
Total systematical uncertainty	0.020
Data statistical uncertainty	0.012
Total uncertainty	0.024

e/μ universality in top decays

Object selection		
Electrons	$p_T > 27.3$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	
Muons	$p_T > 27.3$ GeV, $\|\eta\| < 2.5$	
b-tagged jets	$p_T > 30.0$ GeV, $\|\eta\| < 2.5$, b-tagging DL1r 70%	
Event selection	$t\bar{t} \to \ell\ell b\bar{b}\nu\bar{\nu}$	$Z \to \ell\ell$
Dilepton flavour ($\ell^+\ell^-$)	ee, $e\mu$, $\mu\mu$	ee, $\mu\mu$
Dilepton invariant mass	$m_{\ell\ell} > 30$ GeV	66 GeV $< m_{\ell\ell} <$ 116 GeV
b-tagged jet multiplicity	1 or 2	–

Summary of the fitted distributions

Event selection	Variable	Bins	Event count
$e\mu$+1 or 2 b-tagged jets	$N_{b\text{-tag}}$	2	$N_1^{e\mu}$, $N_2^{e\mu}$
ee+1 b-tagged jet	$m_{\ell\ell}$	6	$N_{1,m}^{ee}$
ee+2 b-tagged jets	$m_{\ell\ell}$	6	$N_{2,m}^{ee}$
$\mu\mu$+1 b-tagged jet	$m_{\ell\ell}$	6	$N_{1,m}^{\mu\mu}$
$\mu\mu$+2 b-tagged jets	$m_{\ell\ell}$	6	$N_{2,m}^{\mu\mu}$
$Z \to ee$ or $\mu\mu$	channel	2	N_Z^{ee}, $N_Z^{\mu\mu}$

Uncertainty breakdown

Uncertainty [%]	$\sigma_{t\bar{t}}$	$\sigma_{Z\to\ell\ell}$	$R_{WZ}^{\mu/e}$	$R_Z^{\mu\mu/ee}$
Data statistics	0.13	0.01	0.22	0.02
$t\bar{t}$ modelling	1.68	0.03	0.10	0.00
Top-quark p_T modelling	1.42	0.00	0.06	0.00
Parton distribution functions	0.67	0.68	0.15	0.03
Single-top modelling	0.65	0.00	0.05	0.00
Single-top/$t\bar{t}$ interference	0.54	0.00	0.09	0.00
Z(+jets) modelling	0.06	0.73	0.13	0.20
Diboson modelling	0.05	0.04	0.01	0.00
Electron energy scale/resolution	0.05	0.06	0.10	0.11
Electron identification	0.10	0.07	0.04	0.13
Electron charge misidentification	0.06	0.06	0.01	0.13
Electron isolation	0.09	0.02	0.08	0.04
Muon momentum scale/resolution	0.04	0.02	0.06	0.04
Muon identification	0.18	0.12	0.11	0.23
Muon isolation	0.09	0.01	0.07	0.01
Lepton trigger	0.09	0.12	0.01	0.23
Jet energy scale/resolution	0.08	0.00	0.03	0.00
b-tagging efficiency/mistag	0.14	0.00	0.00	0.00
Misidentified leptons	0.17	0.02	0.15	0.05
Simulation statistics	0.04	0.00	0.06	0.00
Integrated luminosity	0.93	0.83	0.00	0.00
Beam energy	0.23	0.09	0.00	0.00
Total uncertainty	2.66	1.32	0.42	0.45