Top quark mass & properties

Recent results from ATLAS & CMS

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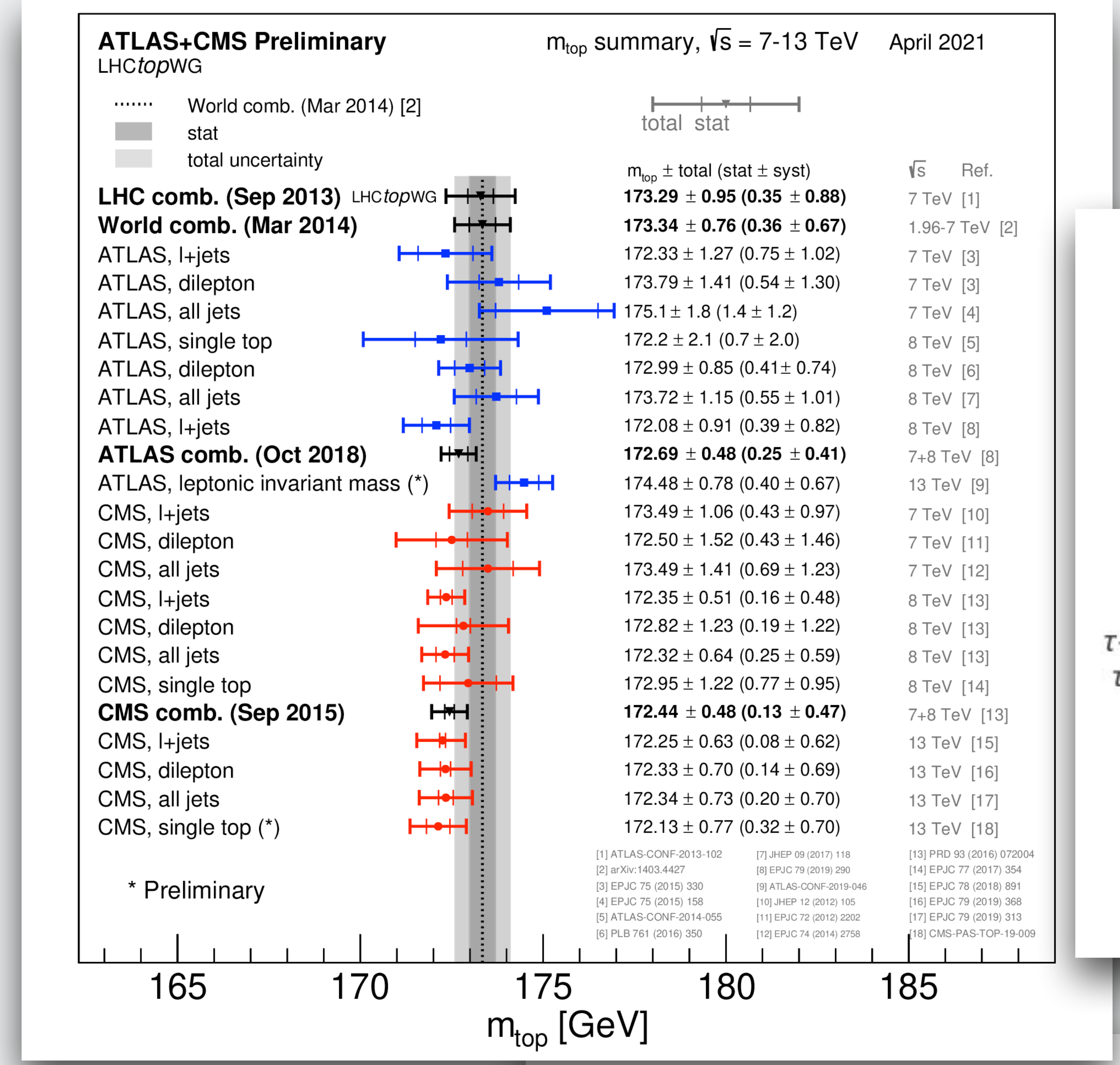
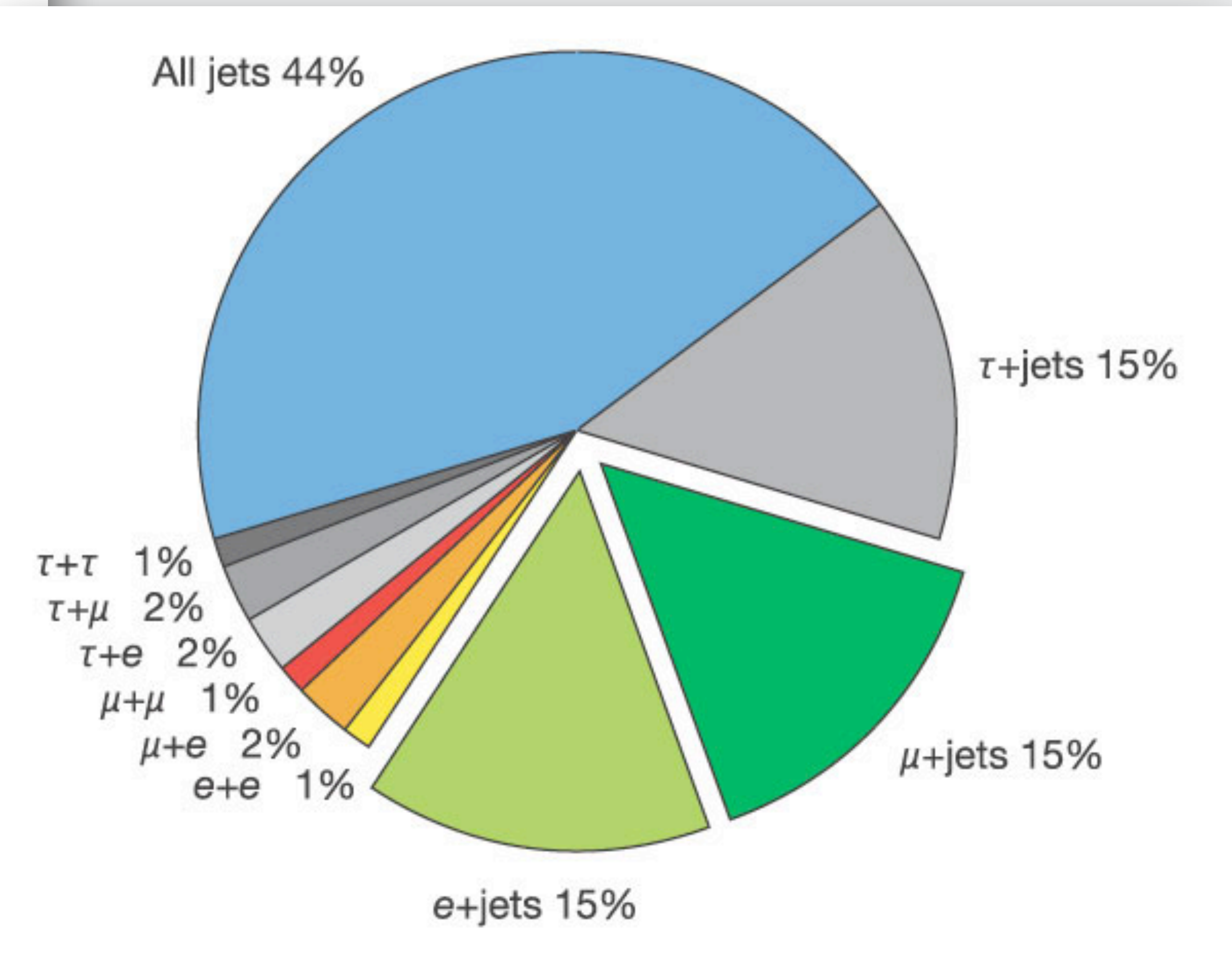
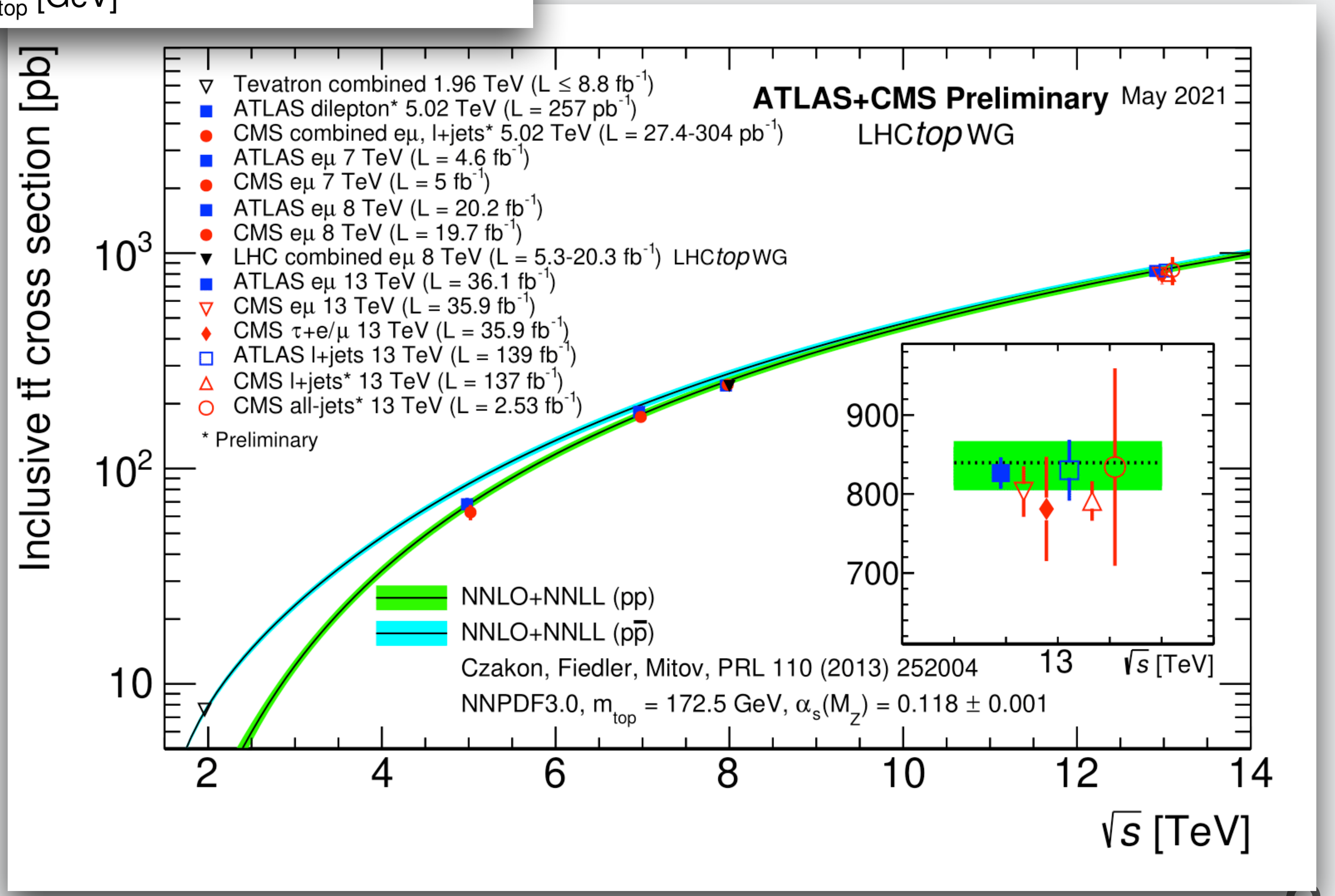
Outline

- Top polarisation and mass from t-channel single-top production
  - ATLAS-CONF-2021-027
  - [TOP-19-009](TOP-19-009)
- MC/pole mass calibration with boosted ttbar
  - ATL-PHYS-PUB-2021-034
- B-fragmentation in a hadronic environment
  - [TOP-18-012](TOP-18-012) / ATLAS-CONF-2020-050
- Energy asymmetry as an EFT probe
  - TOPQ-2019-28-002
- Search for CP violation in l+jets
  - [TOP-20-005](TOP-20-005)
- Test of Lepton Flavour Universality *(see backup)*
  - Nat. Phys. 17, 813-818 (2021)







Top polarisation & mass

from t-channel single top production

Top polarisation: analysis strategy

In ttbar tops are produced unpolarised (QCD is P-preserving) but single tops are highly polarised!

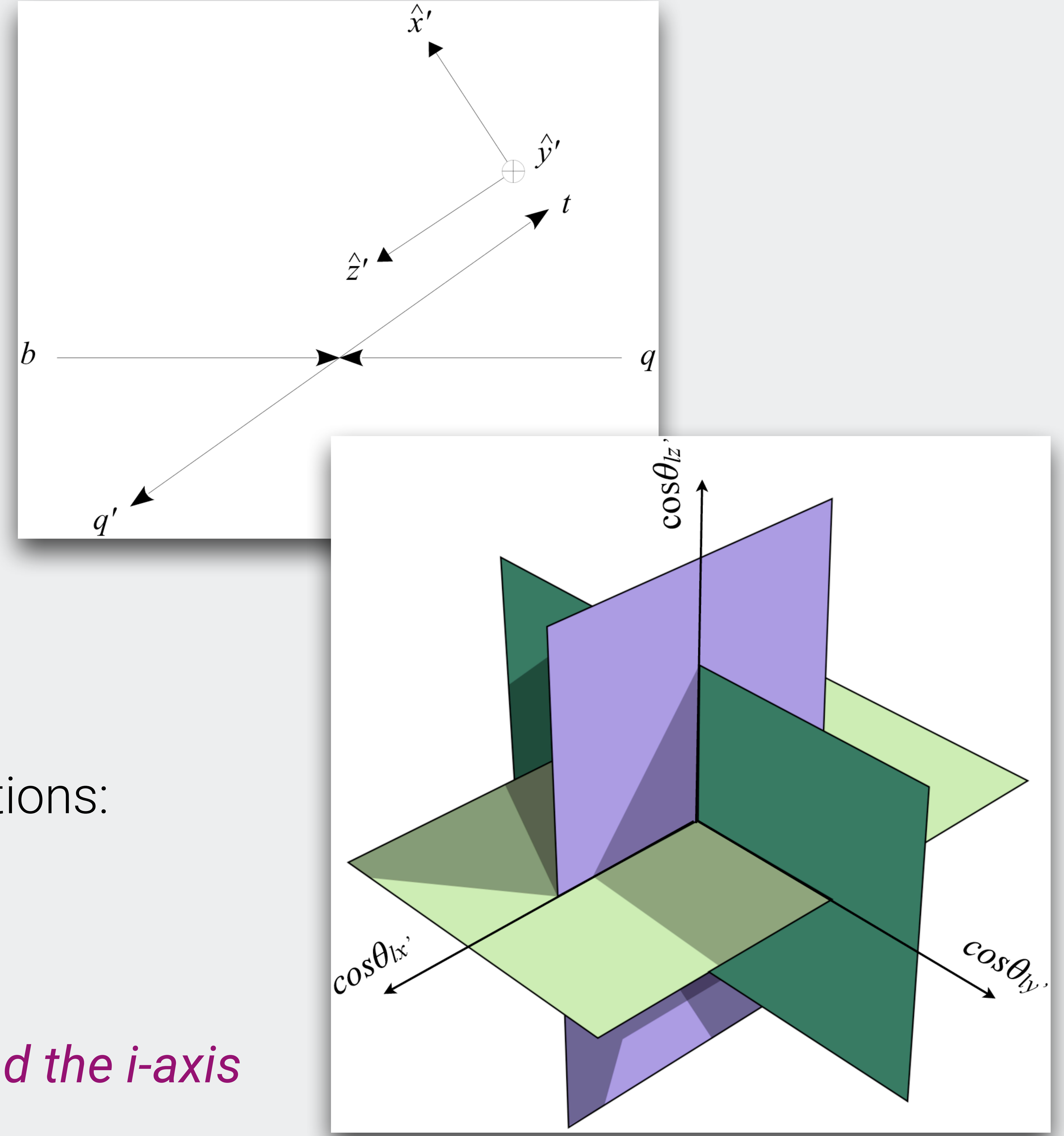
Leptonic t-chan selection: 1e/μ, =2jets, =1bjet@60%, MET>35 GeV, M_T>60 GeV
+ top mass cuts + split into 8 octants, full Run 2 data

➡ Template fit at detector-level to $\{P_x,P_y,P_z\}$ for top/antitop simultaneously

➡ Unfold $\{\cos\vartheta_x,\cos\vartheta_y,\cos\vartheta_z\}$ to particle-level

➡ Constrain dim-6 SMEFT operators that affect top polarisation from the normalised differential distributions: *ctW affects* $\cos\vartheta_x$, *ctWI affects* $\cos\vartheta_y$

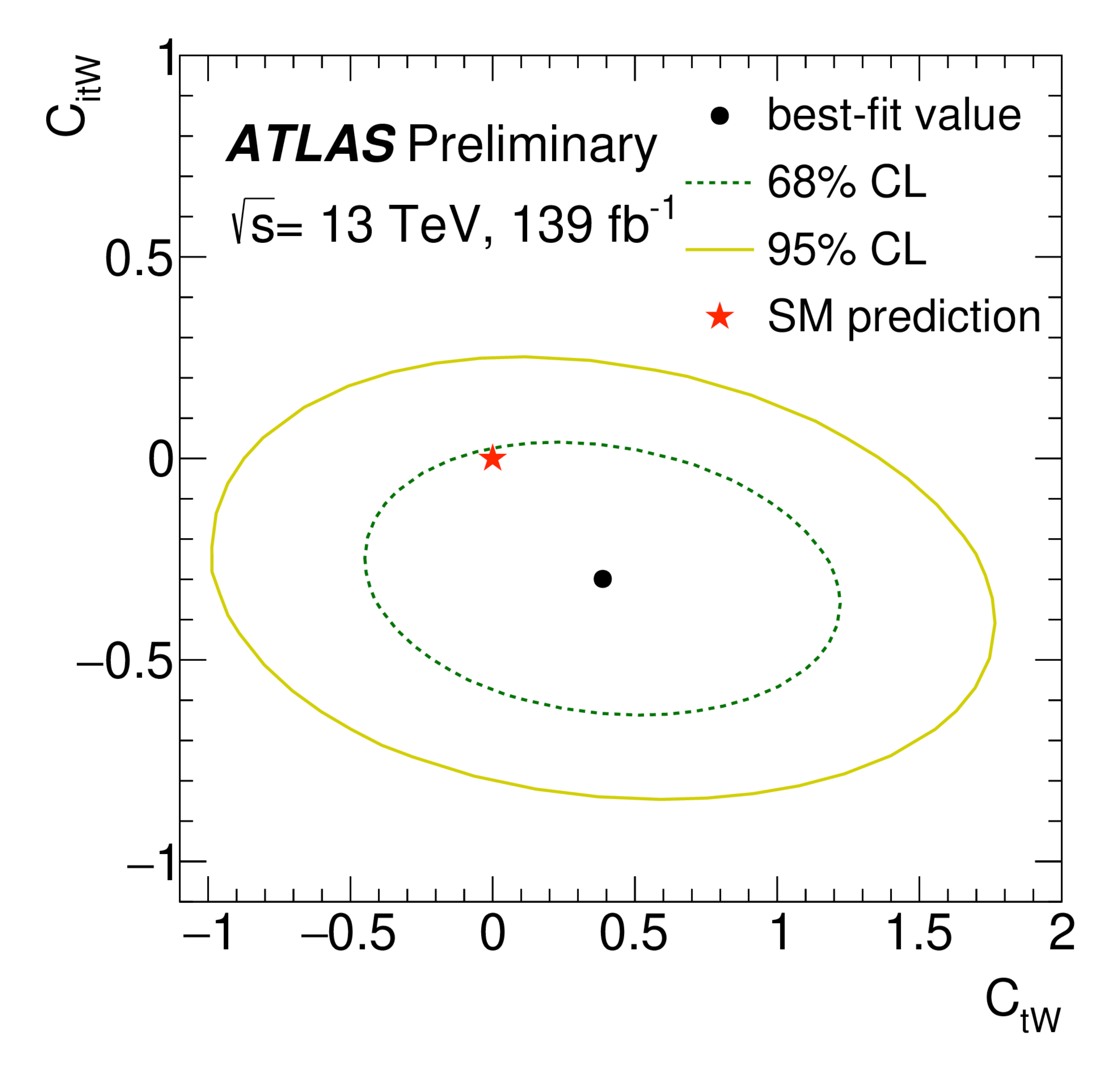
EFT fit: treat data as a multivariate Gaussian in LH



ϑ_i is the polar angle between the charged lepton and the i-axis

Top polarisation: results

Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)



	C_{tW} 68% CL	C_{tW} 95% CL	C_{itW} 68% CL	C_{itW} 95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

Consistent with SM!

- ☞lower stat uncertainty for top (higher σ_t)
- ☞lower P_y uncertainty because ⊥ to production plane

  (leading to cancellations in e.g. JER uncertainties)

TOP-19-009

Top mass: analysis strategy

Measure the top and antitop masses independently using 2015-2016 data.

Leptonic t-chan selection: 1e/μ, =2jets, =1bjet@55%, M_T>50 GeV

➡ MVA approach with 2 BDTs trained on kinematic variables to separate signal

➡ Estimate QCD background from fit to M_T and subtract from data

➡ Map m_t to $y=\ln(m_t/1\ \text{GeV})$ to remove skewness and fit y with a function to extract y_0

➡ Derive mass calibration to correct fitted mass

$$F_l(y;\, y_0,\, f_j) = f_{\text{sig}} F_{\text{sig}}(y;\, y_0) \;+\; f_{t\bar{t}} F_{t\bar{t}}(y;\, y_0) \;+\; f_{\text{EW}} F_{\text{EW}}(y).$$

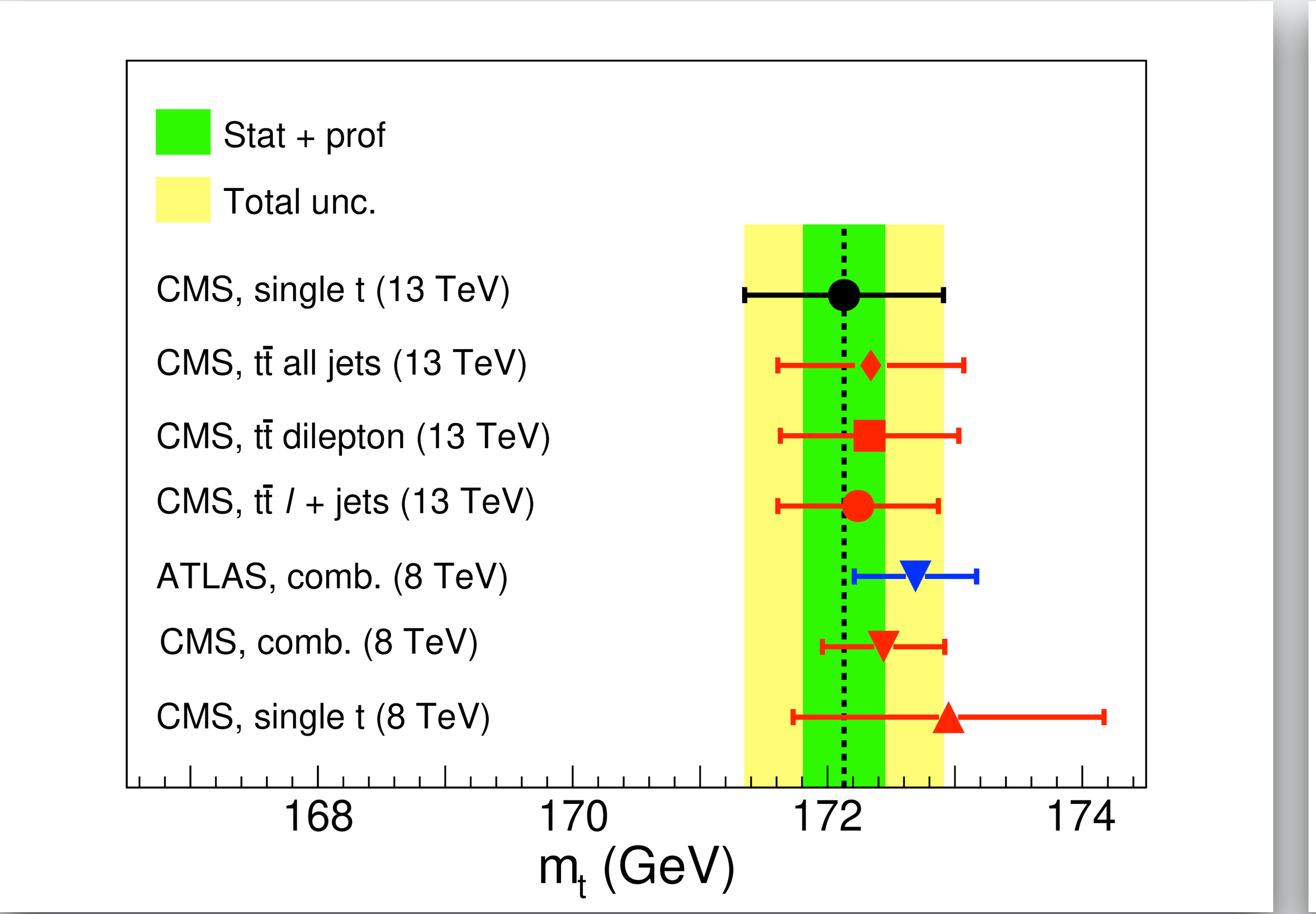
Top mass: results

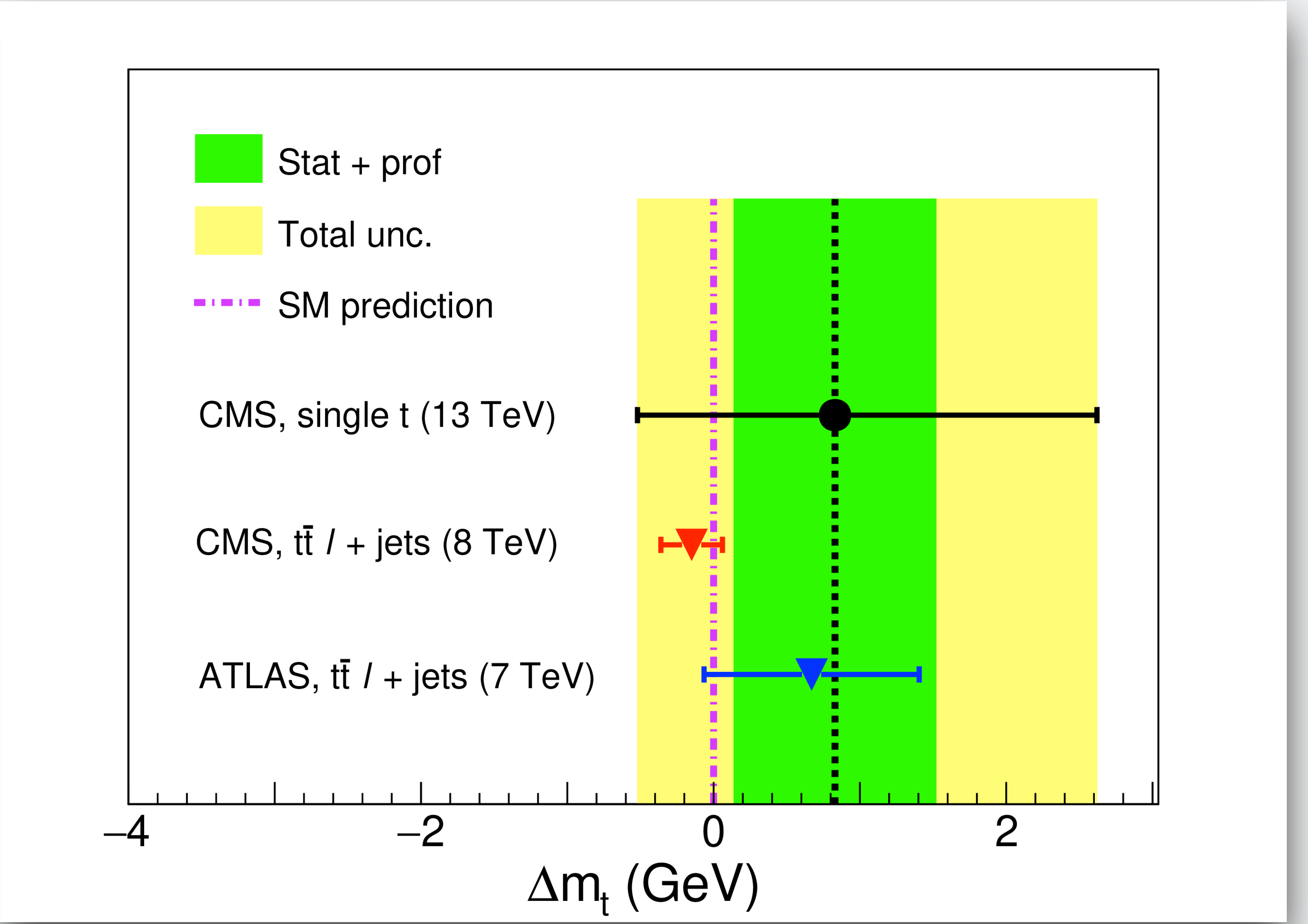
$$m_t = 172.62 \pm 0.37(\text{stat+prof})^{+0.97}_{-0.65}(\text{ext})\ \text{GeV} = 172.62^{+1.04}_{-0.75}\ \text{GeV},$$
$$m_{\bar{t}} = 171.79 \pm 0.58(\text{stat+prof})^{+1.32}_{-1.39}(\text{ext})\ \text{GeV} = 171.79^{+1.44}_{-1.51}\ \text{GeV}.$$

$$m_t = 172.13 \pm 0.32(\text{stat+prof})^{+0.69}_{-0.70}(\text{ext})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}.$$

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.9952 \pm 0.0040(\text{stat+prof})^{+0.0068}_{-0.0096}(\text{ext}) = 0.9952^{+0.0079}_{-0.0104}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69(\text{stat+prof})^{+1.65}_{-1.16}(\text{ext})\ \text{GeV} = 0.83^{+1.79}_{-1.35}\ \text{GeV}$$





30% improvement on previous CMS result!

- ☞by including e-channel and MVA
- ☞JES, CR and FSR most relevant systematics

Using top pairs for tuning

MC/pole mass calibration &
first b-fragmentation measurements in ttbar

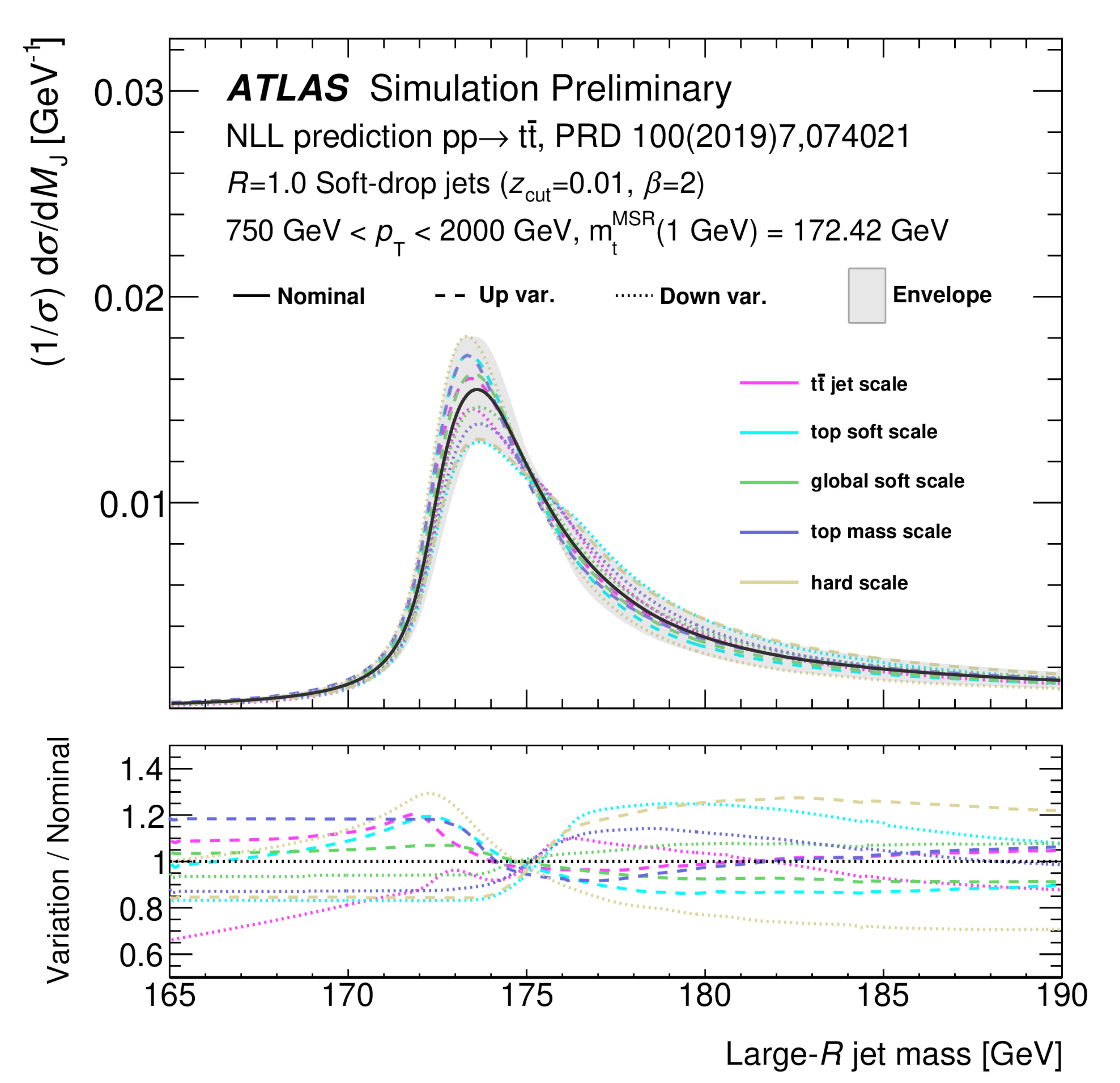
MC/pole calibration: general idea

Top mass not predicted in the SM: direct measurements yield ~0.5 GeV precision, indirect ~2 GeV. PDG average of 172.76 ± 0.3 GeV.

Templates based on MC: **MC top mass identified with pole mass**, *but non pert QCD effects introduce ambiguity of ~0.5 GeV*.

Goal: compare boosted jet mass distribution from hadronic tops in MC to analytical calculation with npQCD effects at particle-level + check modelling in generators

arXiv:1708.02586 SCET: rigorous prediction of $d\sigma_{tt}$ as a function of the jet mass at NLL precision



1. light soft-drop grooming: remove soft-wide radiation
2. highly boosted tops: all decay product captured in a single large R jet
3. 3 free parameters: m_t (pole~MSR), Ω (np-QDC parameter, first moment of hadronic shape function) and x_2 (ratio of second moment to Ω)
4. does not account for UE effects

$$m_{top}^{MC} = m_{top}^{MSR}(1\ GeV) + \Delta m^{MSR} = m_{top}^{pole} + \Delta m^{pole}$$

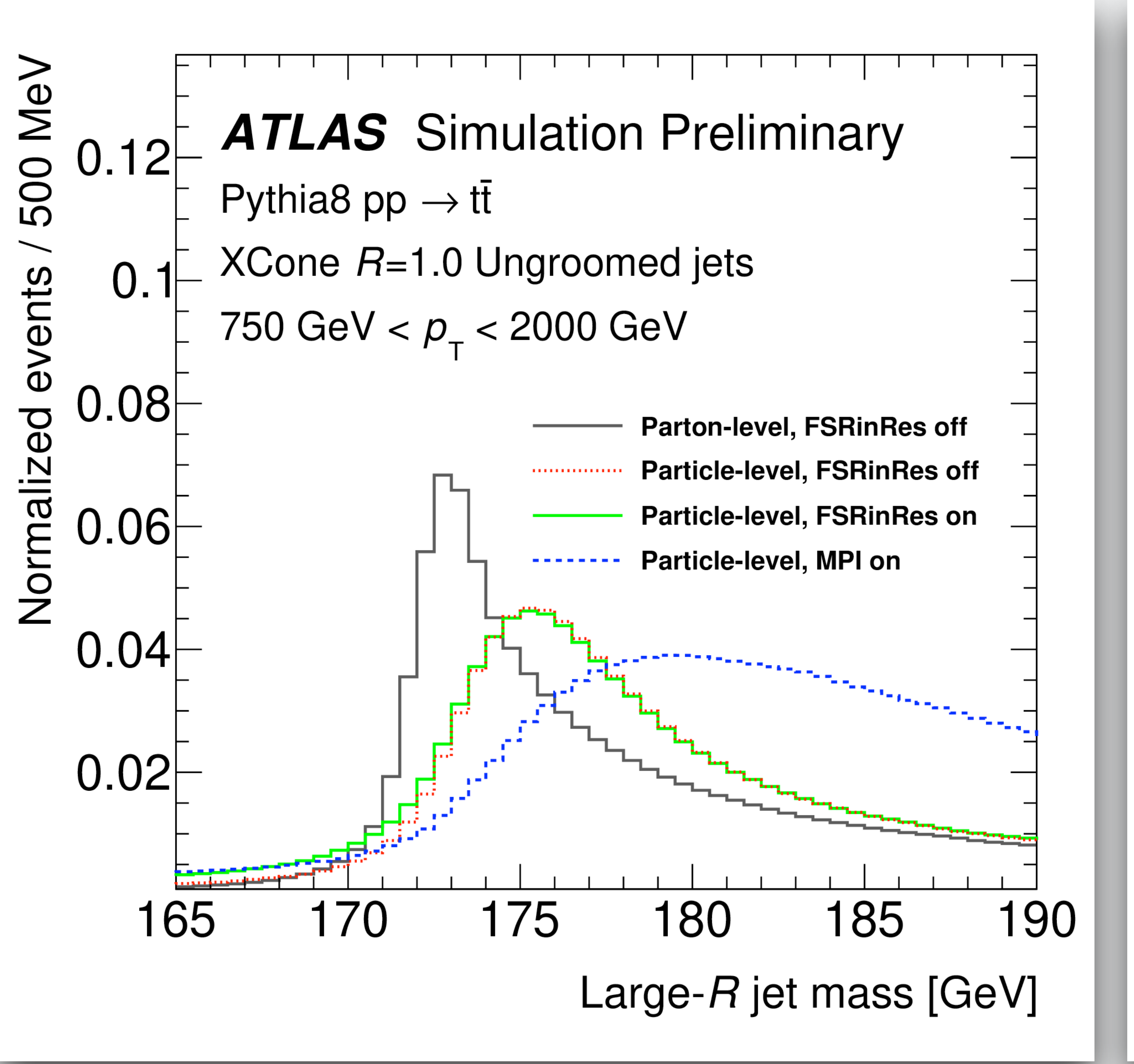
MC/pole calibration: generator setup

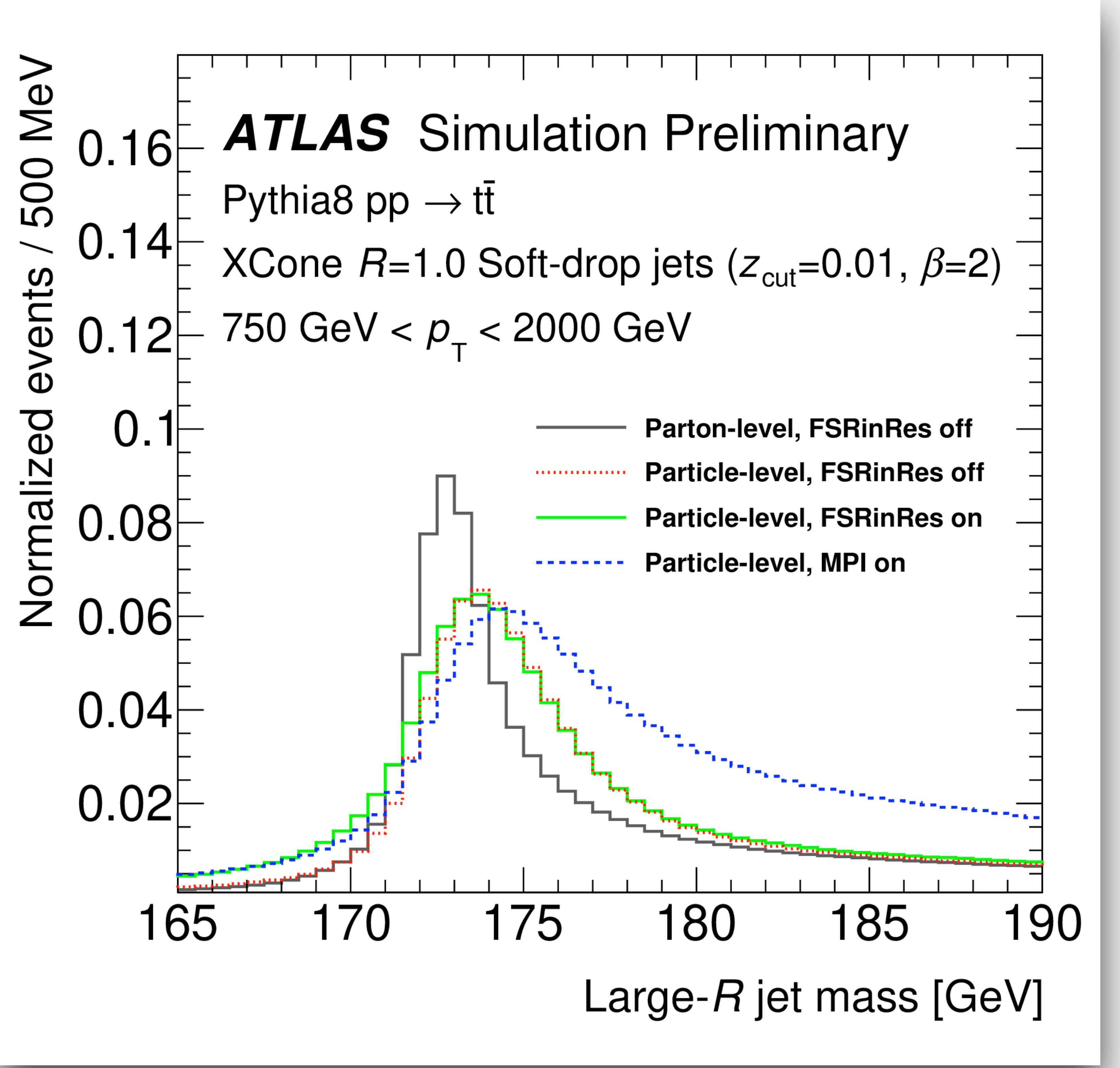
Nominal: Powheg+Pythia8 A14, m_t(MC)=172.5 GeV

Consider also Herwig7, aMC+Pythia8, A14 variations, MEC, h_{damp}, CR, top mass, scale, PDF, α_S variations…

Reconstruction: XCone algorithm with R=1, light soft-drop grooming (z_{cut}=0.01, β=2)

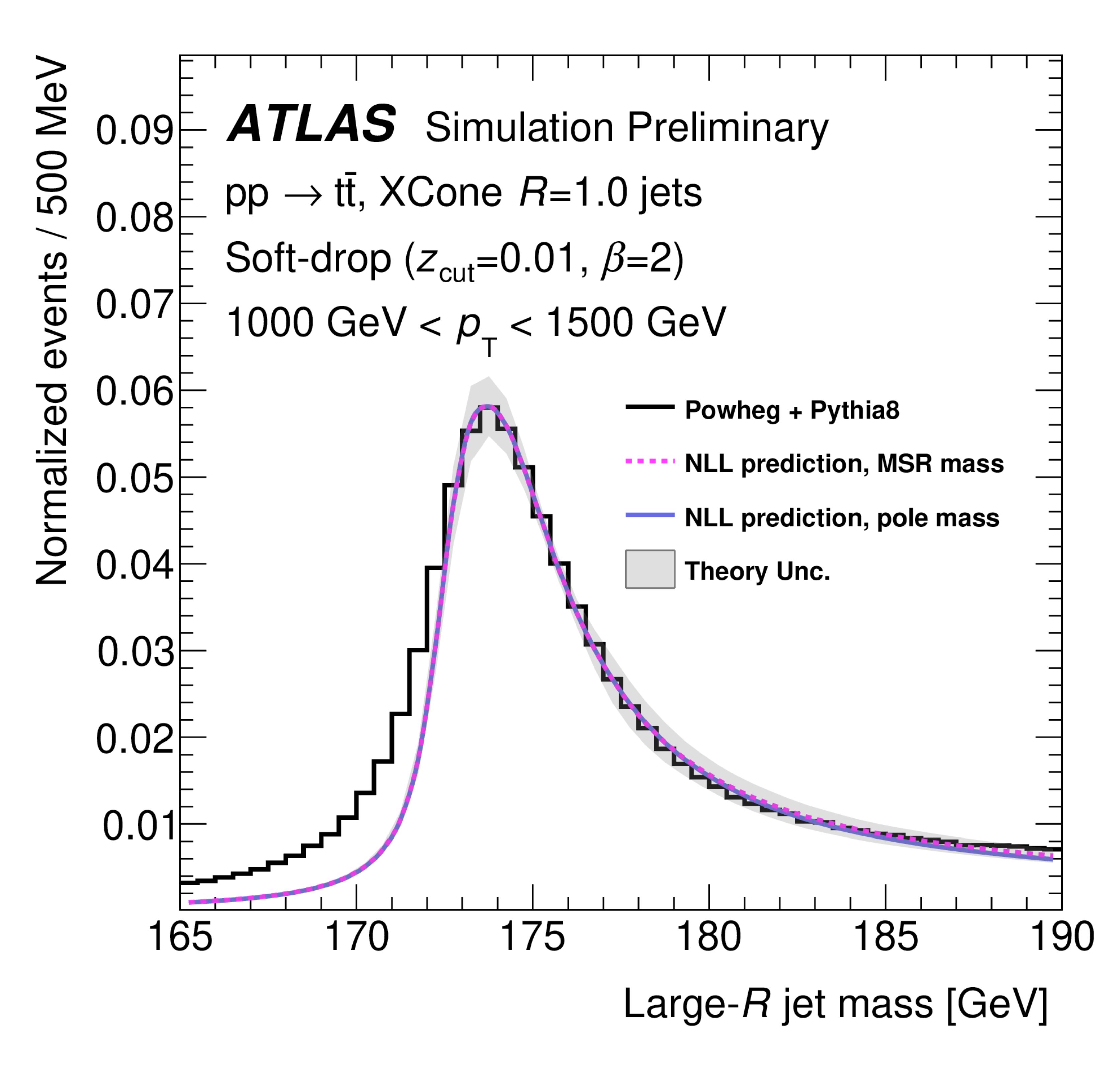
☞ match hadronic top to particle-level large R-jet p_T>750 GeV, build mass distribution in 3 bins of p_T





- ➡ hadronisation shifts and smears the peak (particle-level)
- ➡ radiation from decay products enhances low mass tail (FSR)
- ➡ MPI broadens the distribution and lifts the high mass tail
- ➡ grooming reduces sensitivity to hadronisation and UE effects

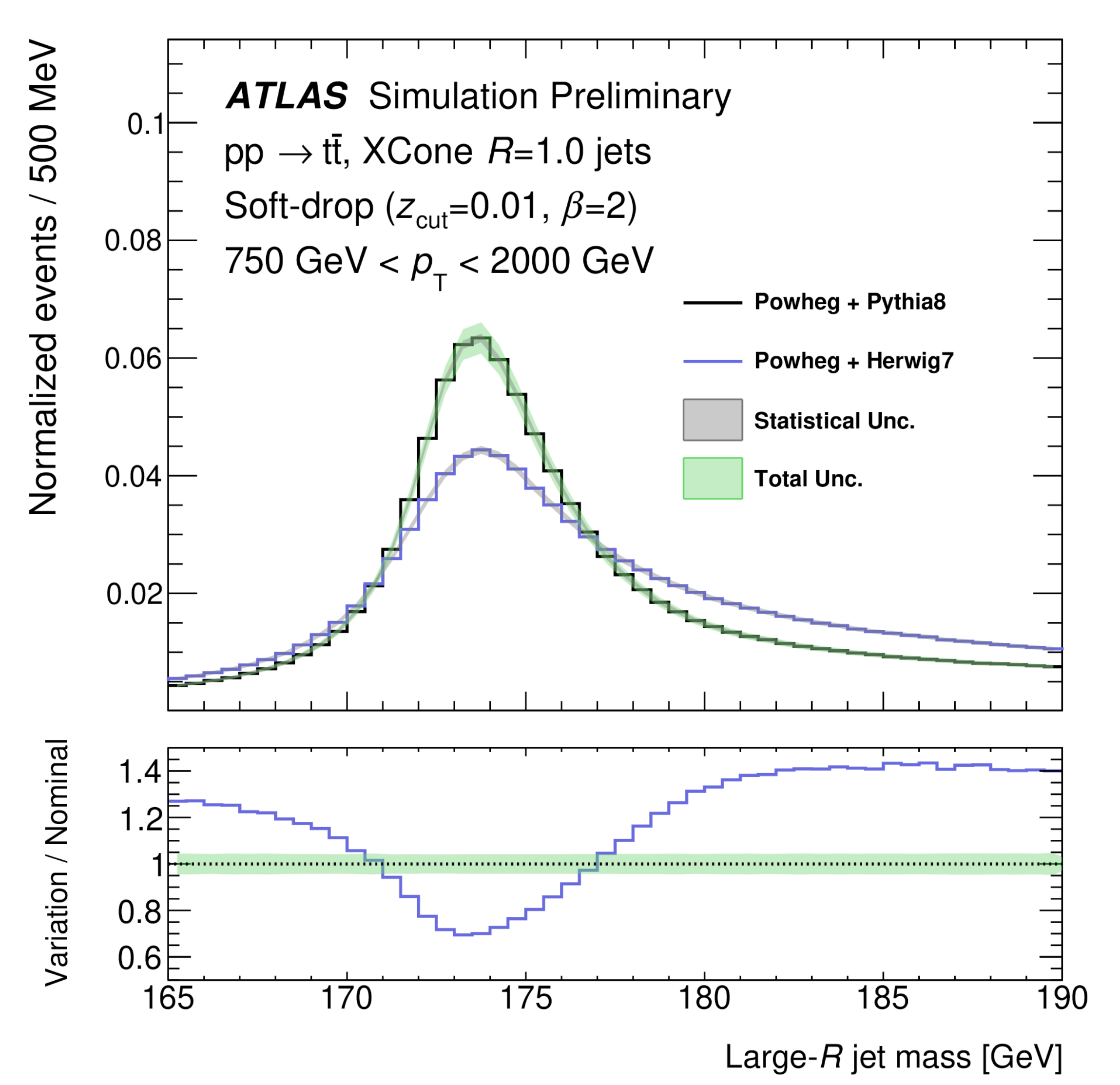
MC/pole calibration: results

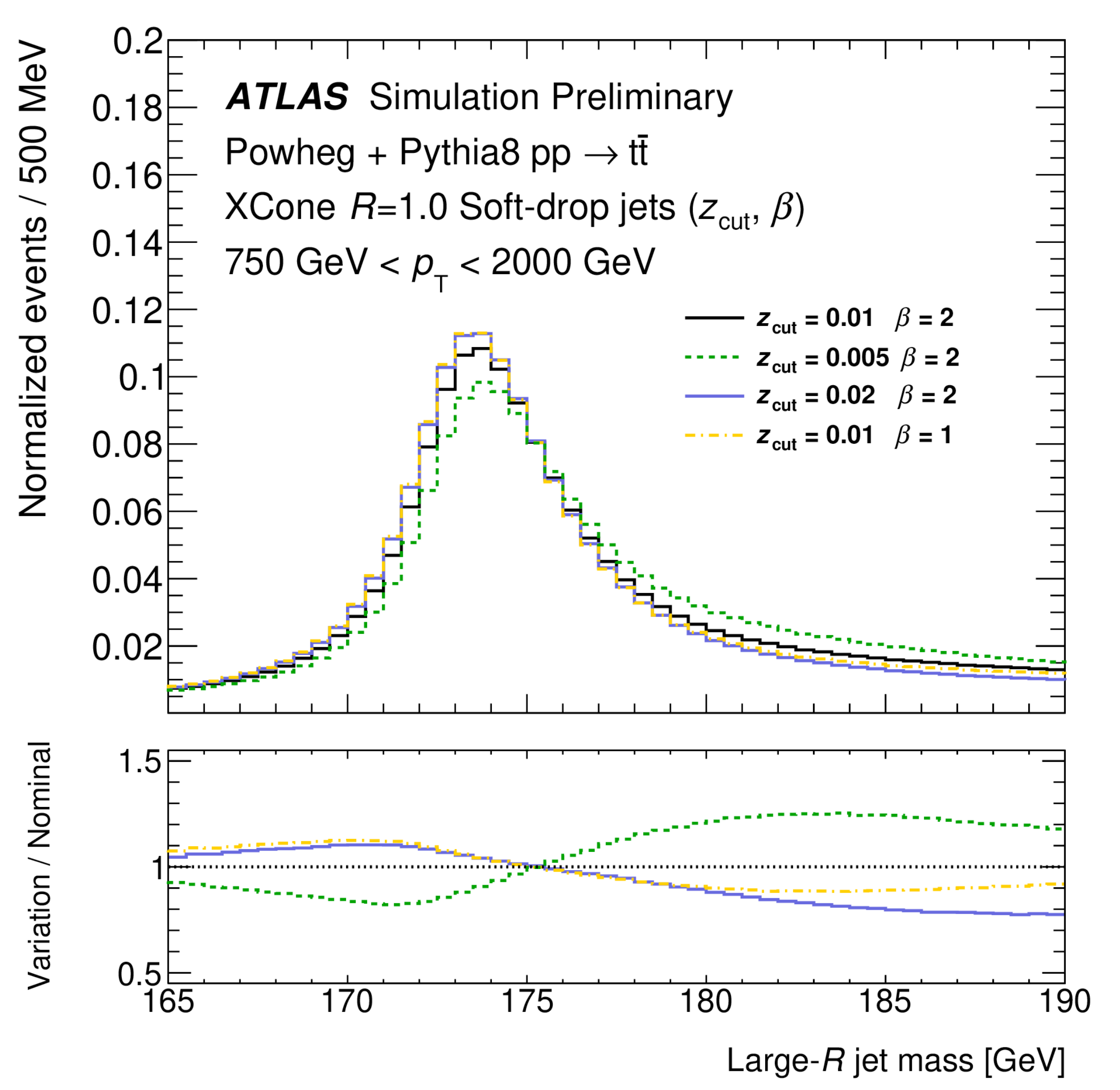


$$m_t^{MSR}(R = 1\ \mathrm{GeV}) = 172.42 \pm 0.10\ \mathrm{GeV},\quad \Omega_{1q}^{\circ\circ} = 1.49 \pm 0.03\ \mathrm{GeV},\quad x_2 = 0.52 \pm 0.09$$

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(1\ \mathrm{GeV}) + 80^{+350}_{-410}\ \mathrm{MeV}$$

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + 350^{+300}_{-360}\ \mathrm{MeV}$$





Source	Size [MeV]	Comment
Theory (higher-order corrections)	$+230/-310$	Envelope of NLL scale variations
Fit methodology	± 190	Choice of fit range, p_{T} bins
Underlying Event model	± 155	A14 eigentune variations, CR models
Total Systematic	**$+340/-340$**	
Statistical Uncertainty	± 100	
Total Uncertainty	**$+350/-410$**	

MC/MSR relation found to be universal within 200 MeV

Pole mass interpretation of MC mass is valid within 0.5 GeV

This calibration could be used in future direct mass measurements and provide coverage of common MC settings!

b-fragmentation: analysis strategy

Determine the shape parameter r_b of the Lund-Bowler b-fragmentation function, using c-mesons (D^0 & J/ψ) inside b-jets from ttbar decays

☞ Previously done in LEP and SLD e^+e^- data: *does it depend on the colour environment?*

- ➡ Measure x_b, the fraction of p_T carried by c-meson inside jet, and fit to analytical expression to extract r_b
- ➡ Use single and dilepton ttbar selections, focus on tracks from charged particles inside jets: search for displaced vertices from D^0 and J/ψ
- ➡ Fit meson mass distributions to normalise signal and background
- ➡ For each candidate meson, compute x_b
- ➡ Extract r_b from template fit to x_b

$$f(z) = \frac{1}{z^{1+r_q b m_q^2}}(1-z)^a \exp\left(-\frac{b m_T^2}{z}\right)$$

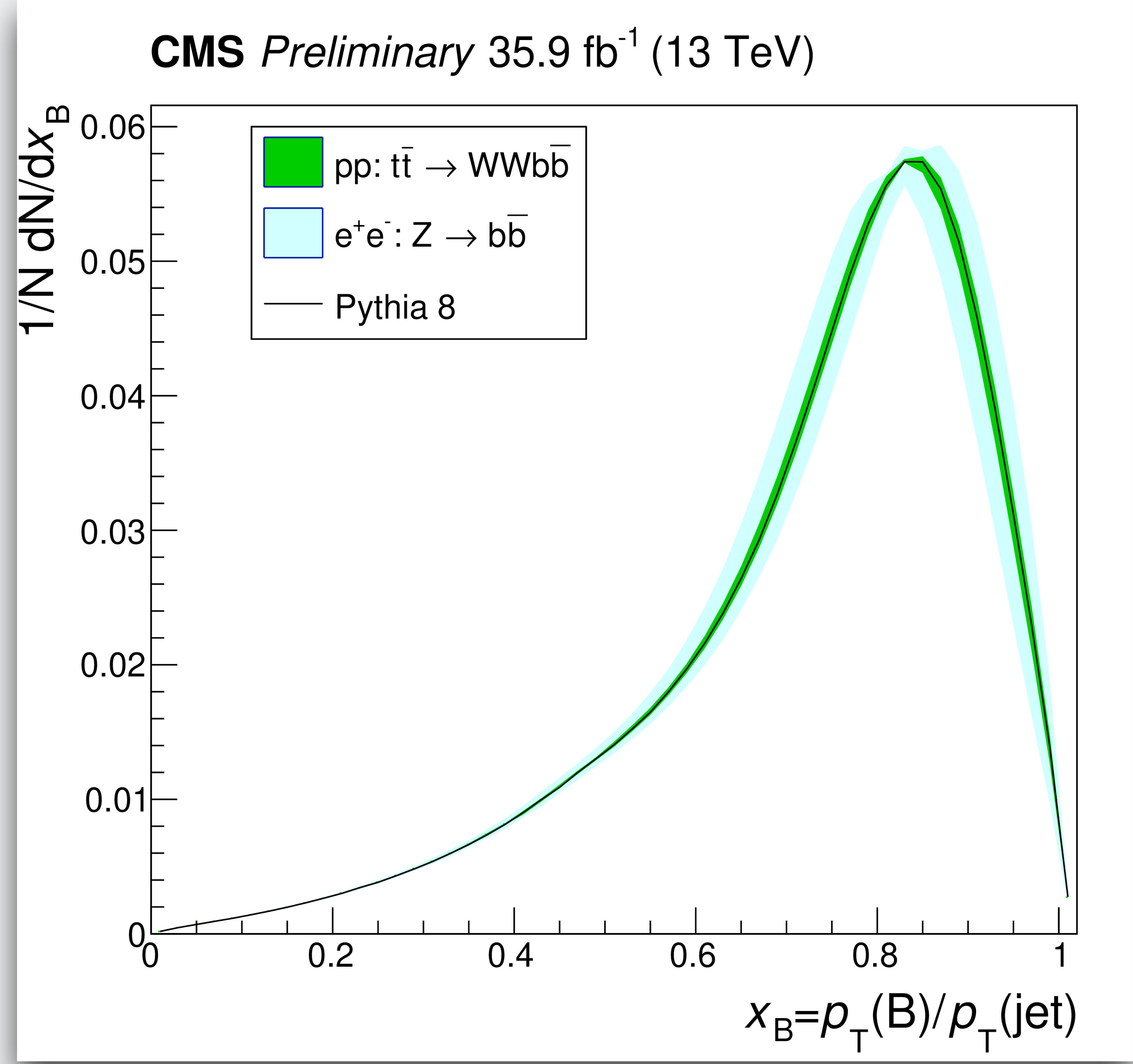
$a=0.68$, $b=0.98$, $m_b=4.78$ GeV
Monash: $r_b=0.855$

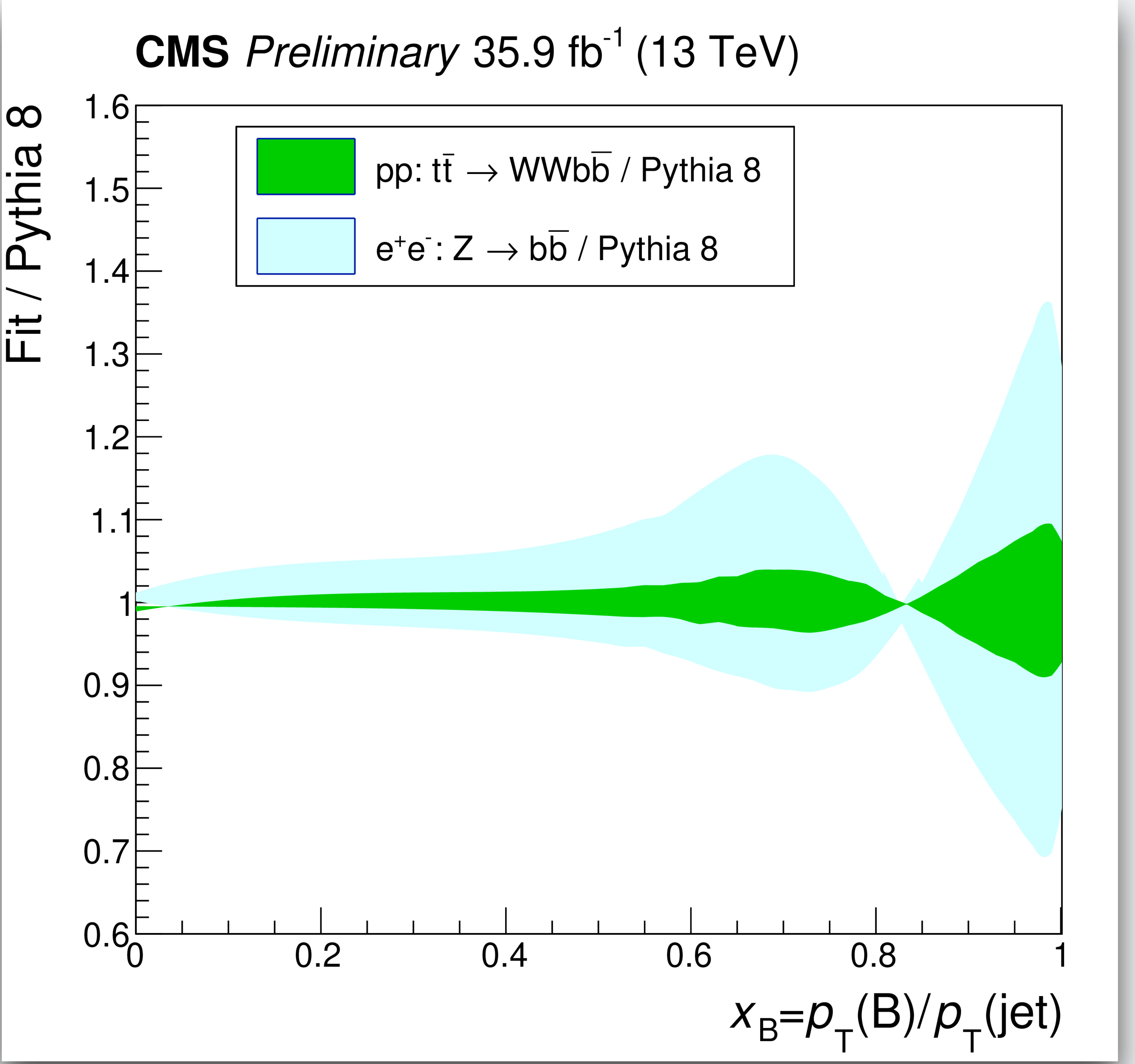
b-fragmentation: results

$$r_b = 0.858 \pm 0.037\,(\text{stat}) \pm 0.031\,(\text{syst})$$

(Monash: r_b=0.855)
(LEP fit: r_b=0.895$^{+0.184}_{-0.197}$)

compare functional forms and uncertainties from this measurement to previous e^+e^- result:





no dependence on the environment!

significant gain in precision!

b-jet moments: analysis strategy

As in the previous CMS measurement: use ttbar production as a clean source of b-jets

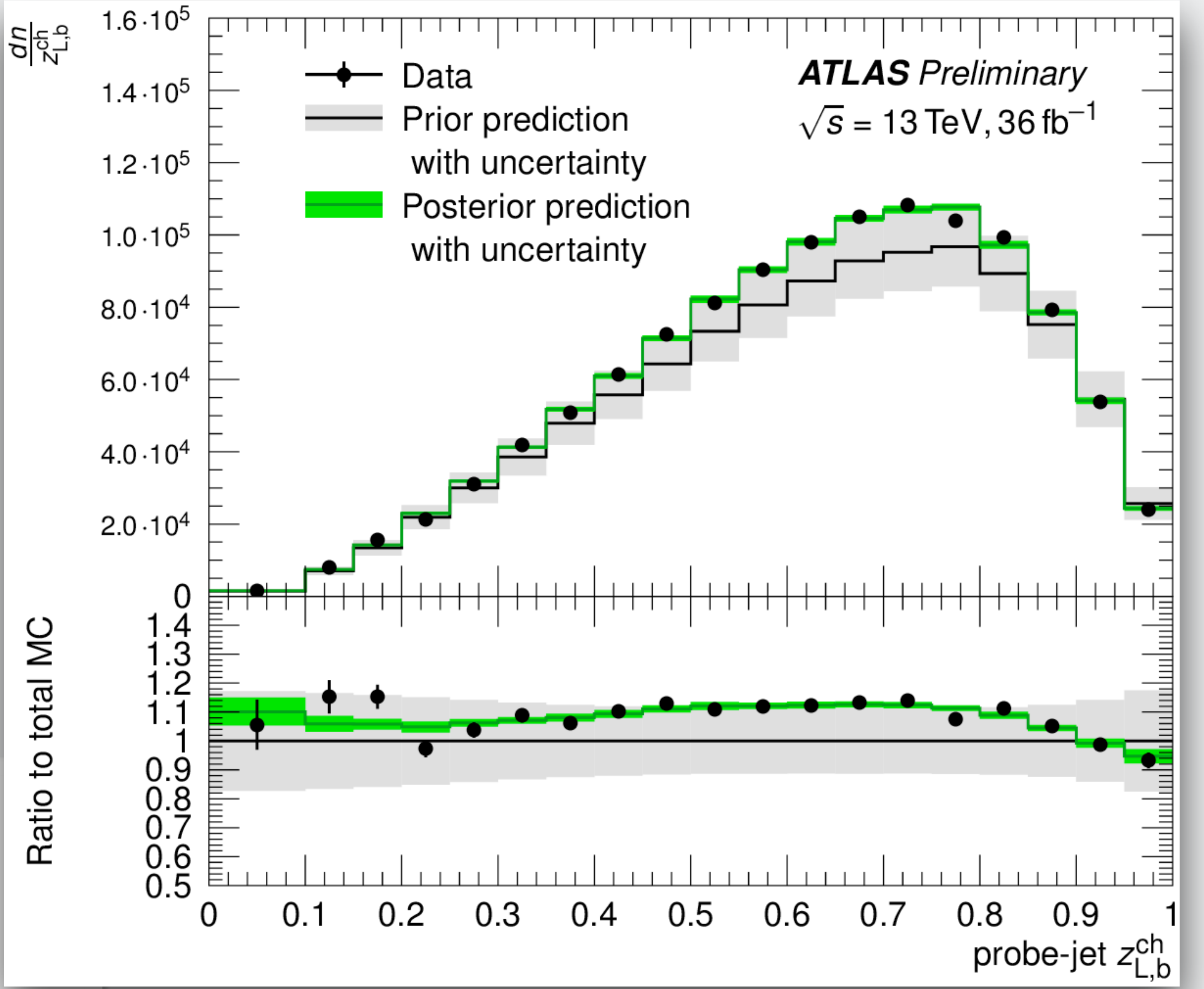
Dilepton selection: eμ with p_T>28 GeV, =2 jets p_T>30 GeV, ≥1 bjet@70%

➡ Use standard b-tagging algorithms and consider the second jet as probe

- only charged particles with p_T>500 MeV are considered
- candidate b-hadrons must have ≥3 charged decay products

➡ Achieve >95% purity: reduce uncertainties to modelling and tracking

➡ Unfold 4 observables to particle-level using FBU



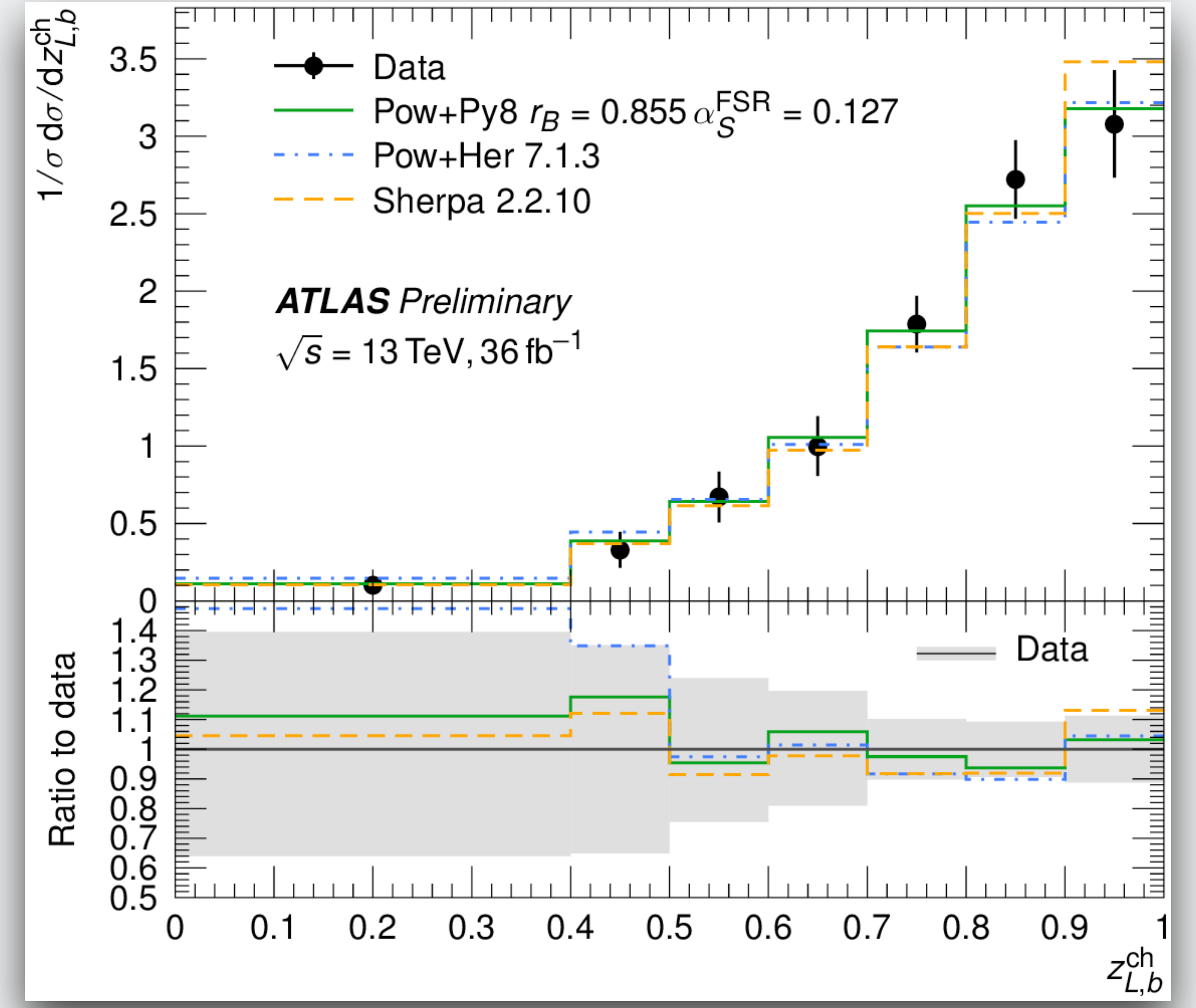
$$\rho = \frac{2p_{\mathrm{T},b}^{\mathrm{ch}}}{p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu}}$$

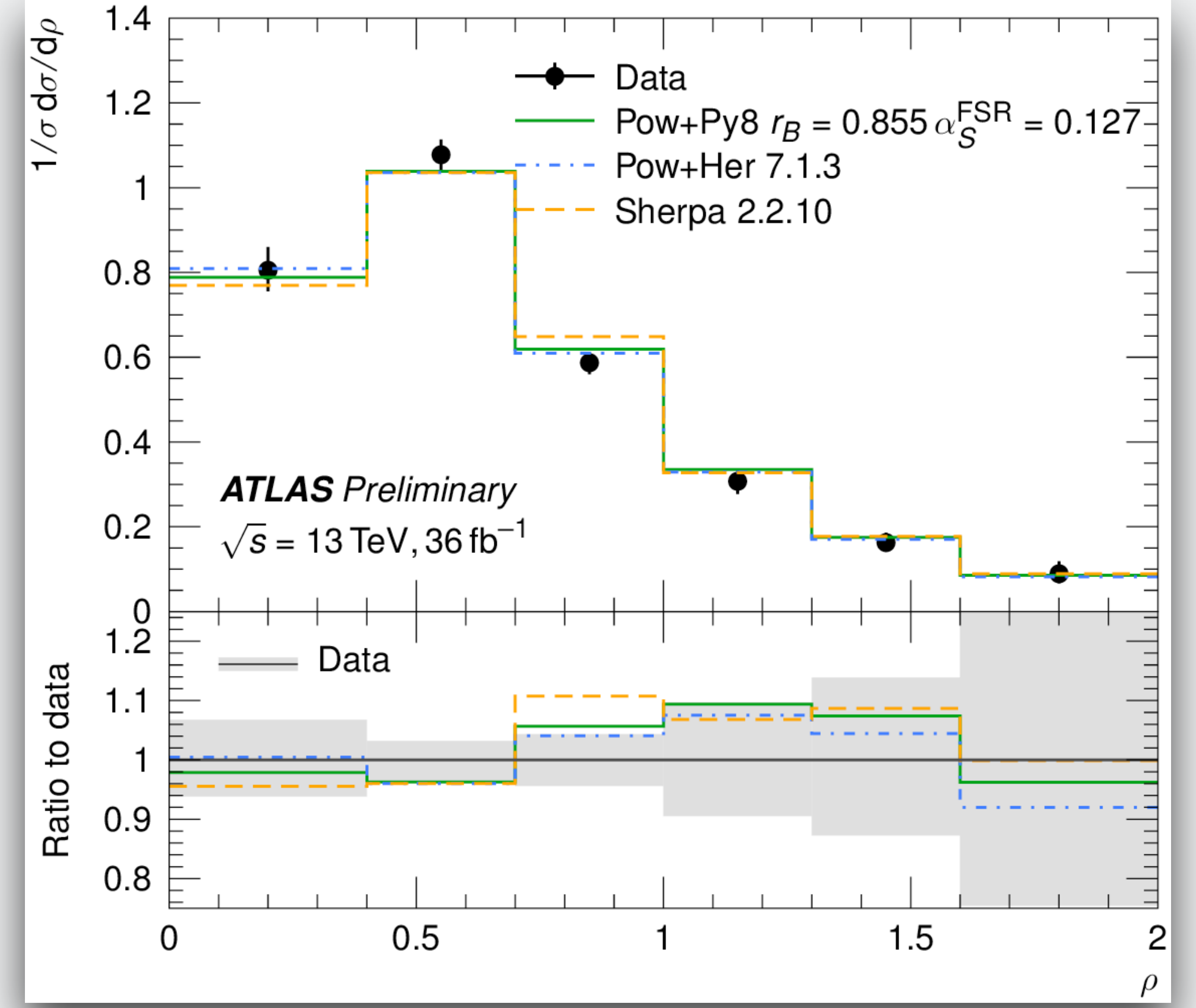
$$n_b^{\mathrm{ch}} = \text{number of fiducial } b\text{-hadron children}$$

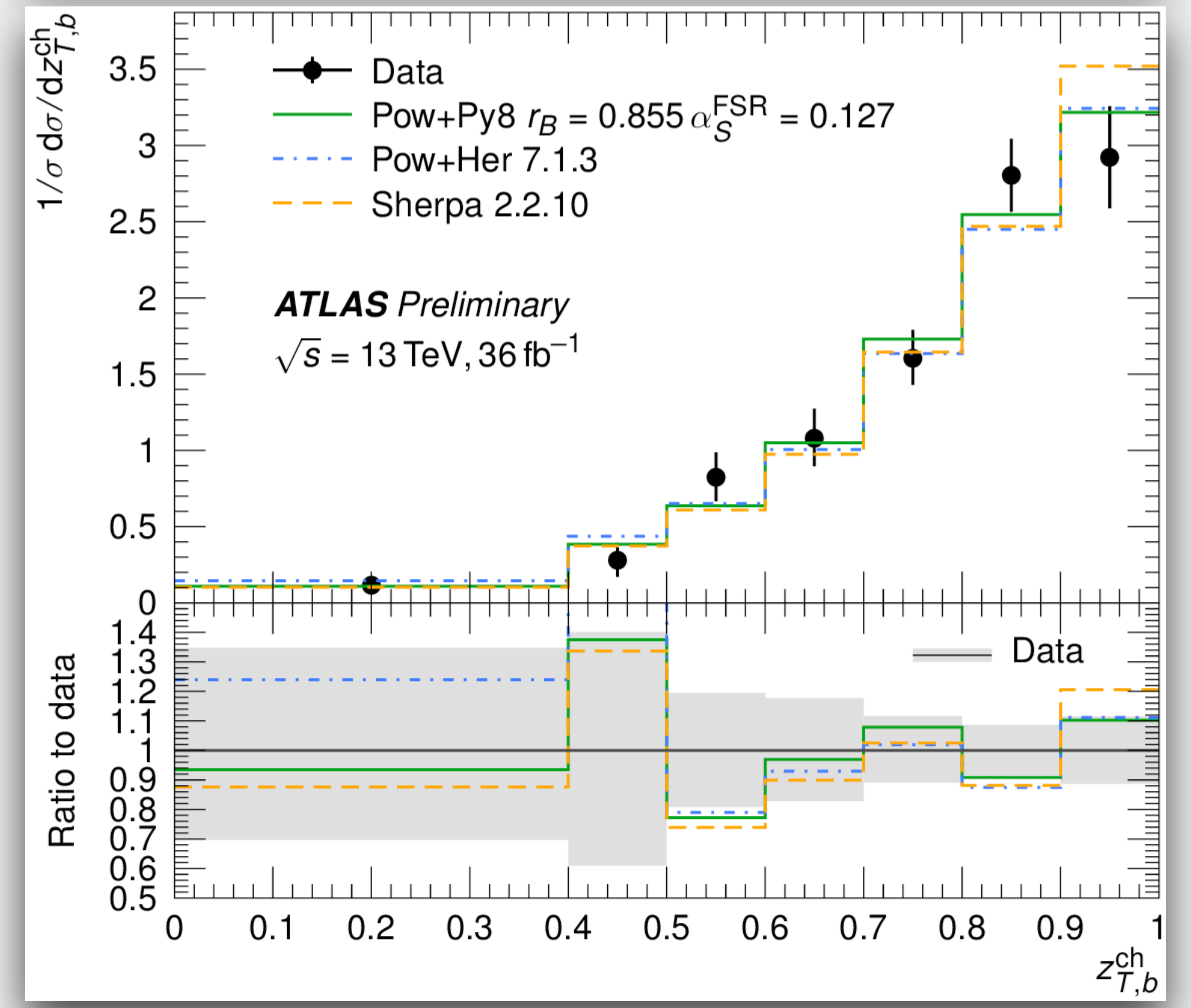
$$z_{\mathrm{T},b}^{\mathrm{ch}} = \frac{p_{\mathrm{T},b}^{\mathrm{ch}}}{p_{\mathrm{T,jet}}^{\mathrm{ch}}}$$

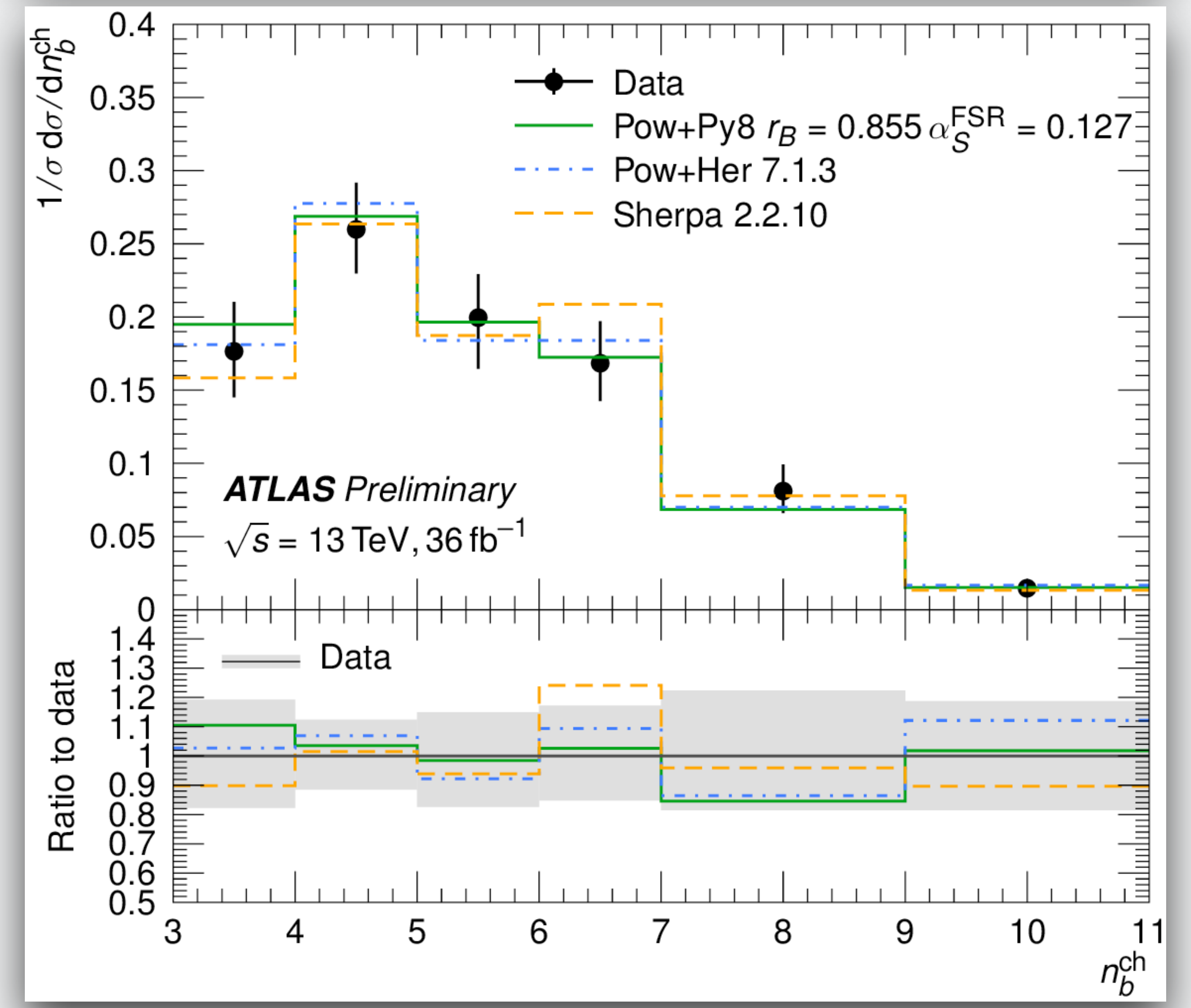
$$z_{\mathrm{L},b}^{\mathrm{ch}} = \frac{\vec{p}_b^{\,\mathrm{ch}} \cdot \vec{p}_{\mathrm{jet}}^{\,\mathrm{ch}}}{|p_{\mathrm{jet}}^{\mathrm{ch}}|^2}$$

b-jet moments: results









Good agreement of the nominal Powheg+Pythia8 (r_b=0.855) setup with data!

- ☞large improvement from Herwig 7.0.4 to Herwig 7.1.3
- ☞difficulty to model ρ properly: sensitive to radiation from top decay products

generator configuration	$z^{ch}_{T,b}$	$z^{ch}_{L,b}$	n^{ch}_b	ρ
POWHEG+PYTHIA8 A14 $r_B = 0.855$ $\alpha_S^{FSR} = 0.127$	0.50	0.98	0.94	0.20
POWHEG+PYTHIA8 A14 $r_B = 0.855$ $\alpha_S^{FSR} = 0.139$	0.13	0.37	0.95	0.31
POWHEG+PYTHIA8 A14 $r_B = 0.855$ $\alpha_S^{FSR} = 0.111$	0.16	0.62	0.95	0.07
POWHEG+PYTHIA8 A14 $r_B = 1.050$ $\alpha_S^{FSR} = 0.127$	0.18	0.60	0.94	0.29
POWHEG+HERWIG7.0.4	0.22	0.50	0.95	0.12
POWHEG+HERWIG7.1.3	0.42	0.84	0.92	0.18
SHERPA2.2.1	0.14	0.45	0.01	0.52
SHERPA2.2.8 ($Z + bb$ tune)	0.004	0.02	0.45	0.24
SHERPA2.2.8	0.32	0.79	0.49	0.11
SHERPA2.2.10	0.27	0.84	0.32	0.08

Precision top physics going Beyond the Standard Model

Energy asymmetry & search for ~~CP~~

Energy asymmetry: analysis strategy

Use energy asymmetry A_E in ttbar+j (driven by gq channel) to probe the SMEFT

l+jets selection: 1e/μ, MET>20 GeV, MET+M_T>60 GeV, >=1bjet@85%,
1 R=0.4 jet p_T>100 GeV, 1 DNN top-tagged R=1 jet p_T>350 (with full Run 2 data)

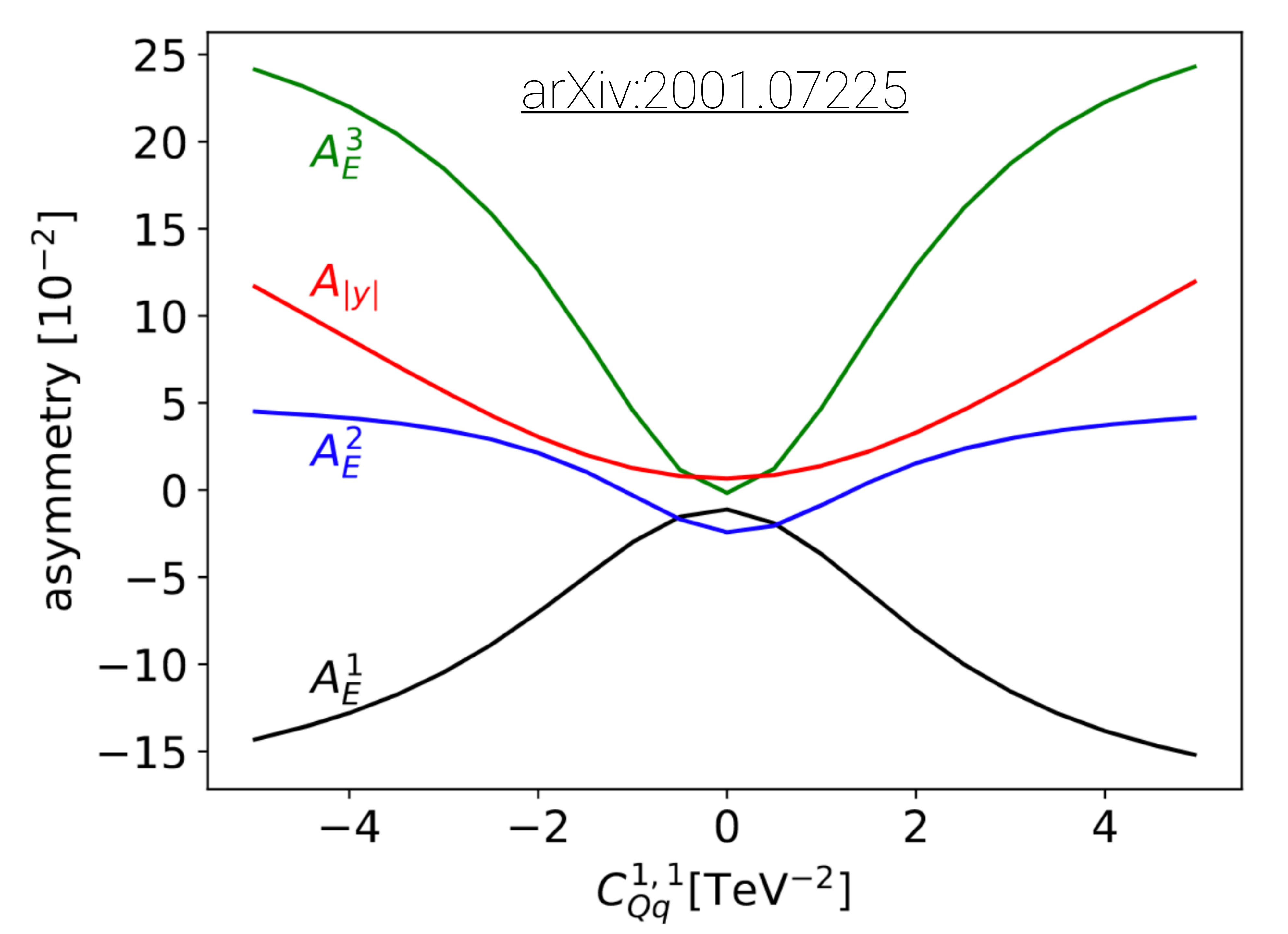
➡ Sensitive to 4-quark operators, complementary to A_y

➡ Unfold to particle-level with FBU

$$A_E(\theta_j) \equiv \frac{\sigma^{\mathrm{opt}}(\theta_j, \Delta E > 0) - \sigma^{\mathrm{opt}}(\theta_j, \Delta E < 0)}{\sigma^{\mathrm{opt}}(\theta_j, \Delta E > 0) + \sigma^{\mathrm{opt}}(\theta_j, \Delta E < 0)}$$

$$\sigma^{\mathrm{opt}}(\theta_j) \equiv \begin{cases} \sigma(\theta_j) & \text{for } y_{t\bar{t}j} > 0 \\ \sigma(\pi - \theta_j) & \text{for } y_{t\bar{t}j} < 0 \end{cases}$$

ϑ_j is the jet scattering angle with respect to the incoming parton in the ttj rest frame

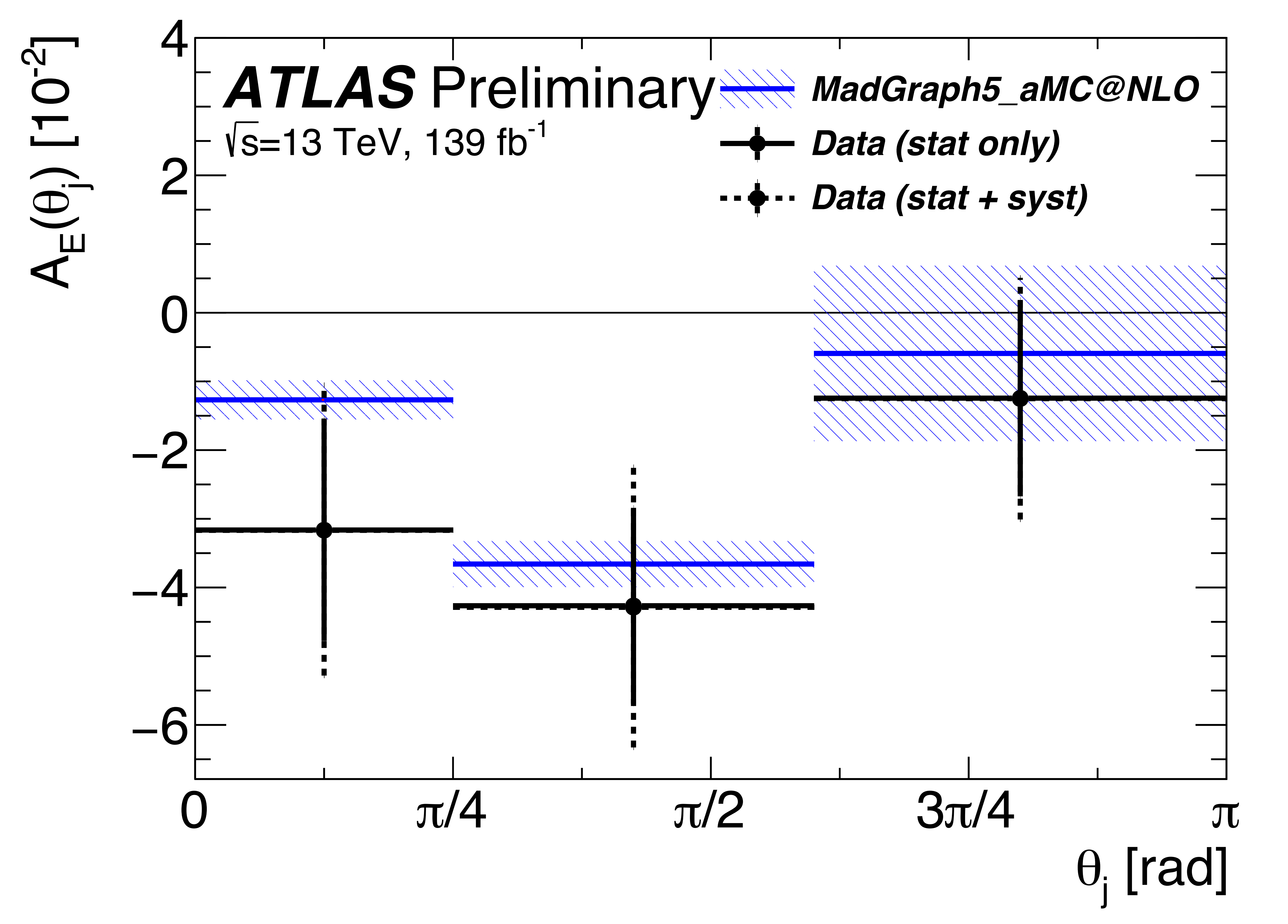


A_y results in ATLAS-CONF-2019-026

Energy asymmetry: SM results

Scenario	$\Delta A_E\,[10^{-2}]$ $0 \le \theta_j < \frac{\pi}{4}$	$\frac{\pi}{4} < \theta_j \le \frac{3\pi}{5}$	$\frac{3\pi}{5} \le \theta_j \le \pi$
Data stat.	1.61	1.43	1.43
$t\bar{t}$ modeling	0.08	0.87	0.34
$t\bar{t}$ response MC stat	0.51	0.42	0.42
W + jets modeling and PDF	0.29	0.49	0.42
Single top modeling	0.28	0.60	0.29
$t\bar{t}$ and singletop PDF	0.08	0.10	0.07
Multijet	0.53	0.54	0.51
Jet energy resolution	0.98	0.40	0.36
Other detector uncertainties	0.42	0.43	0.30
Total	2.11	2.04	1.76

Scenario	$A_E \pm \Delta A_E\,[10^{-2}]$ $0 \le \theta_j \le \frac{\pi}{4}$	$\frac{\pi}{4} \le \theta_j \le \frac{3\pi}{5}$	$\frac{3\pi}{5} \le \theta_j \le \pi$
Data	-3.17 ± 2.11	-4.29 ± 2.04	-1.25 ± 1.76
SM prediction	-1.27 ± 0.28	-3.66 ± 0.33	-0.59 ± 1.28
SM expectation	-1.27 ± 2.05	-3.66 ± 1.95	-0.59 ± 1.61

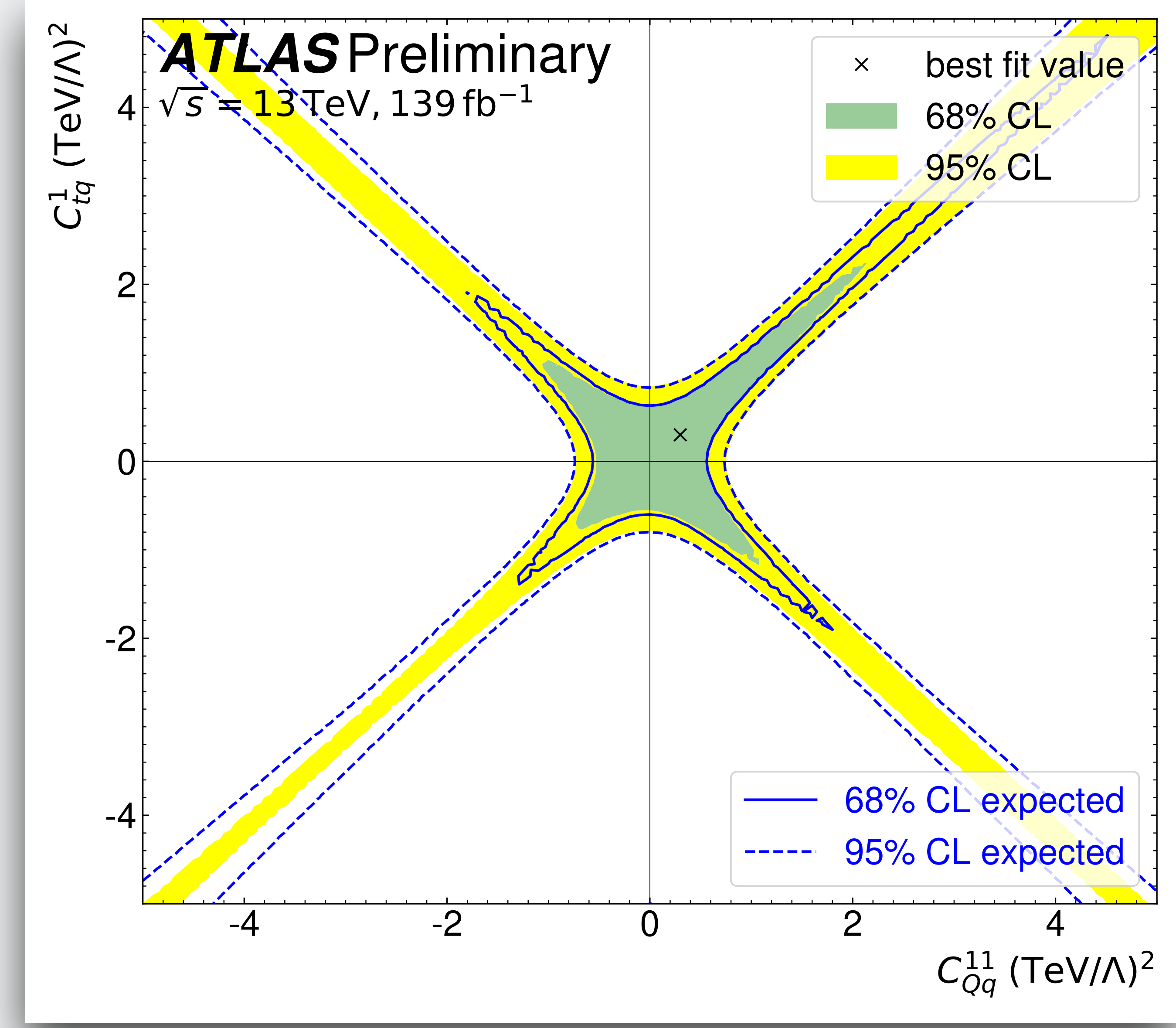


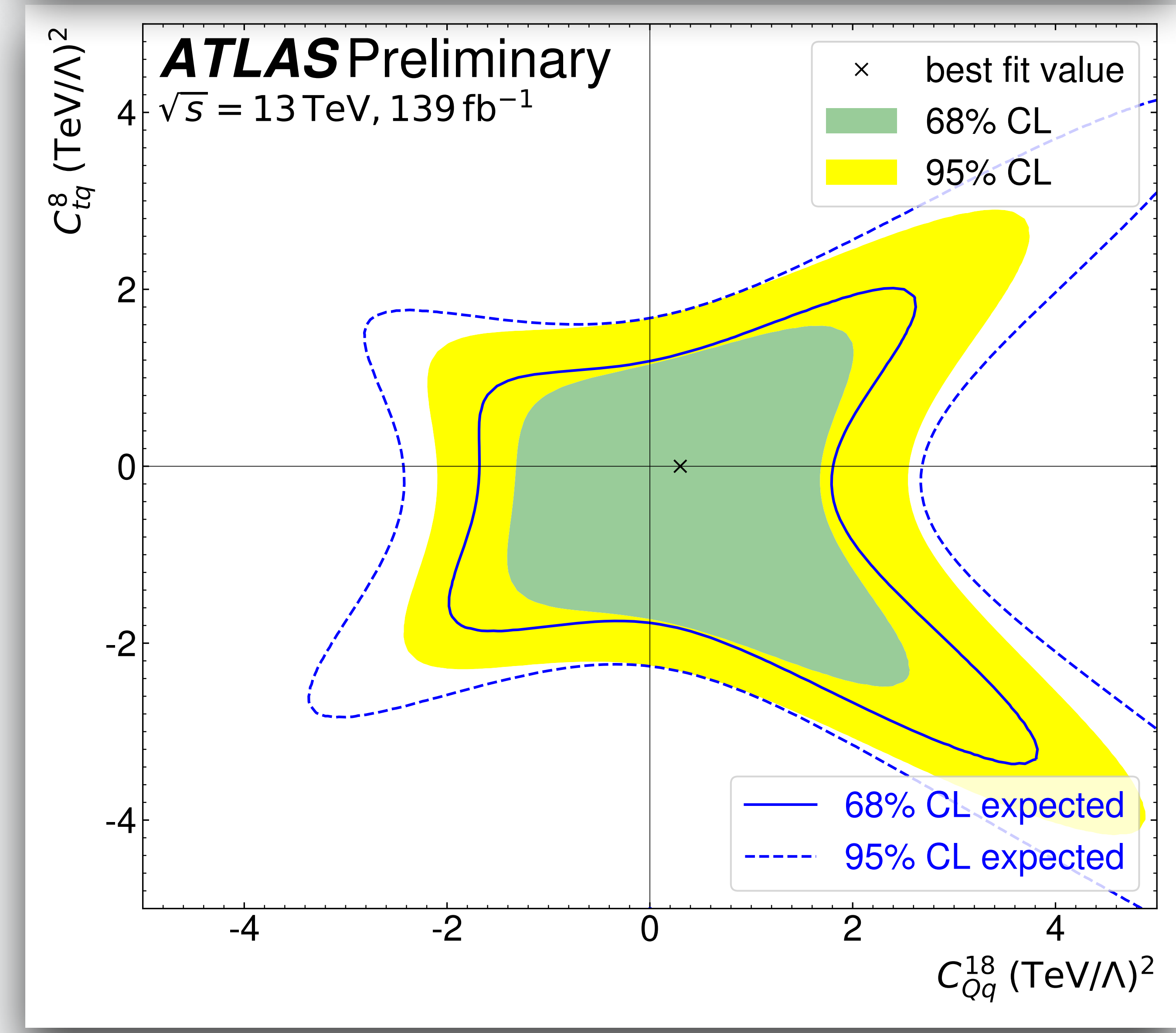
high-purity region: 87% ttbar (61% fiducial), 5% W+jets, <2% fakes+QCD

All bins of ϑ_j are consistent with the SM (p=0.80): dominant uncertainty is statistical

TOPQ-2019-28-002

Energy asymmetry: SMEFT results



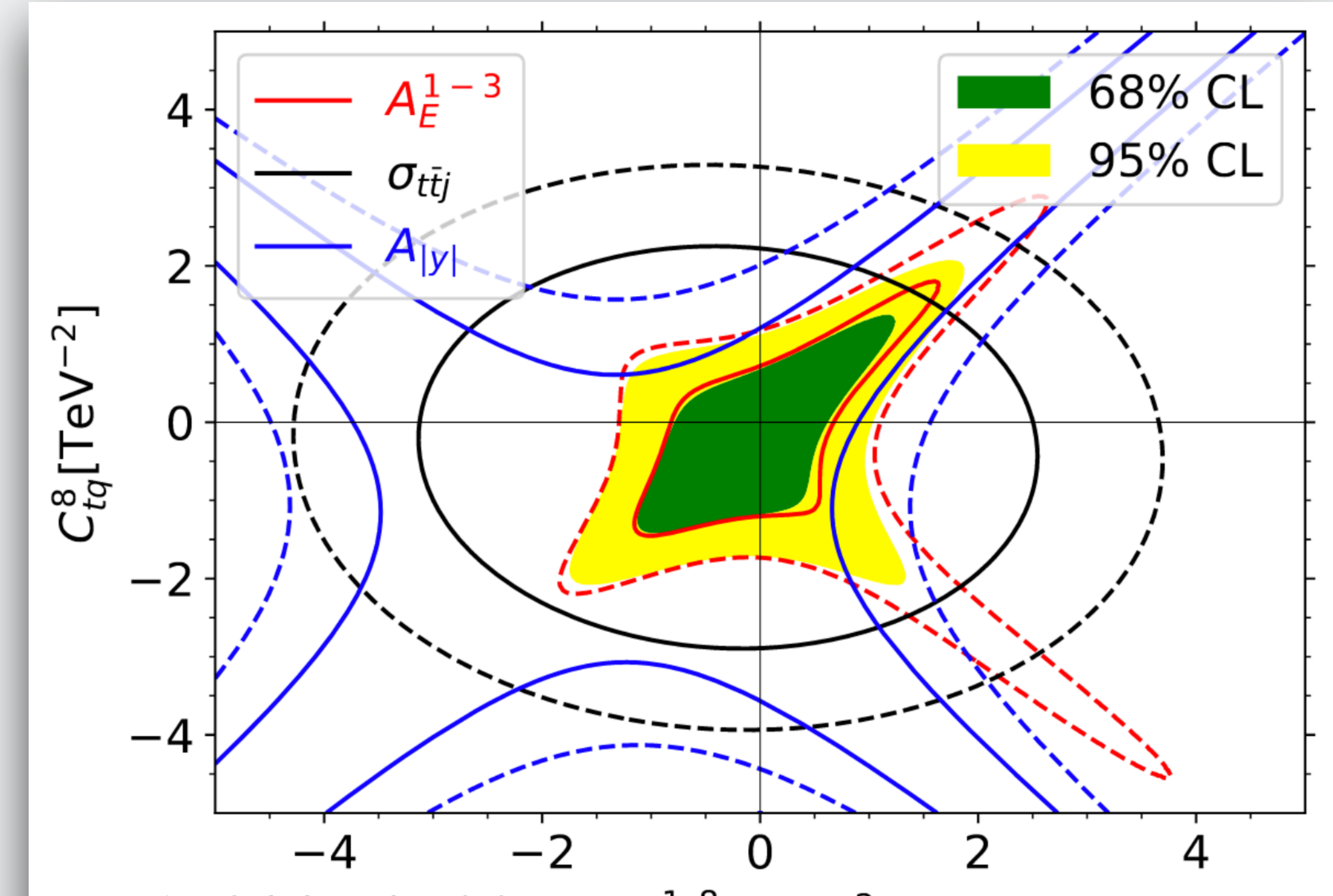


Operators differ only by the chirality of the top quark, blind direction along cQq11=±ctq1, slightly broken by subdominant O(Λ^{-2}) effects

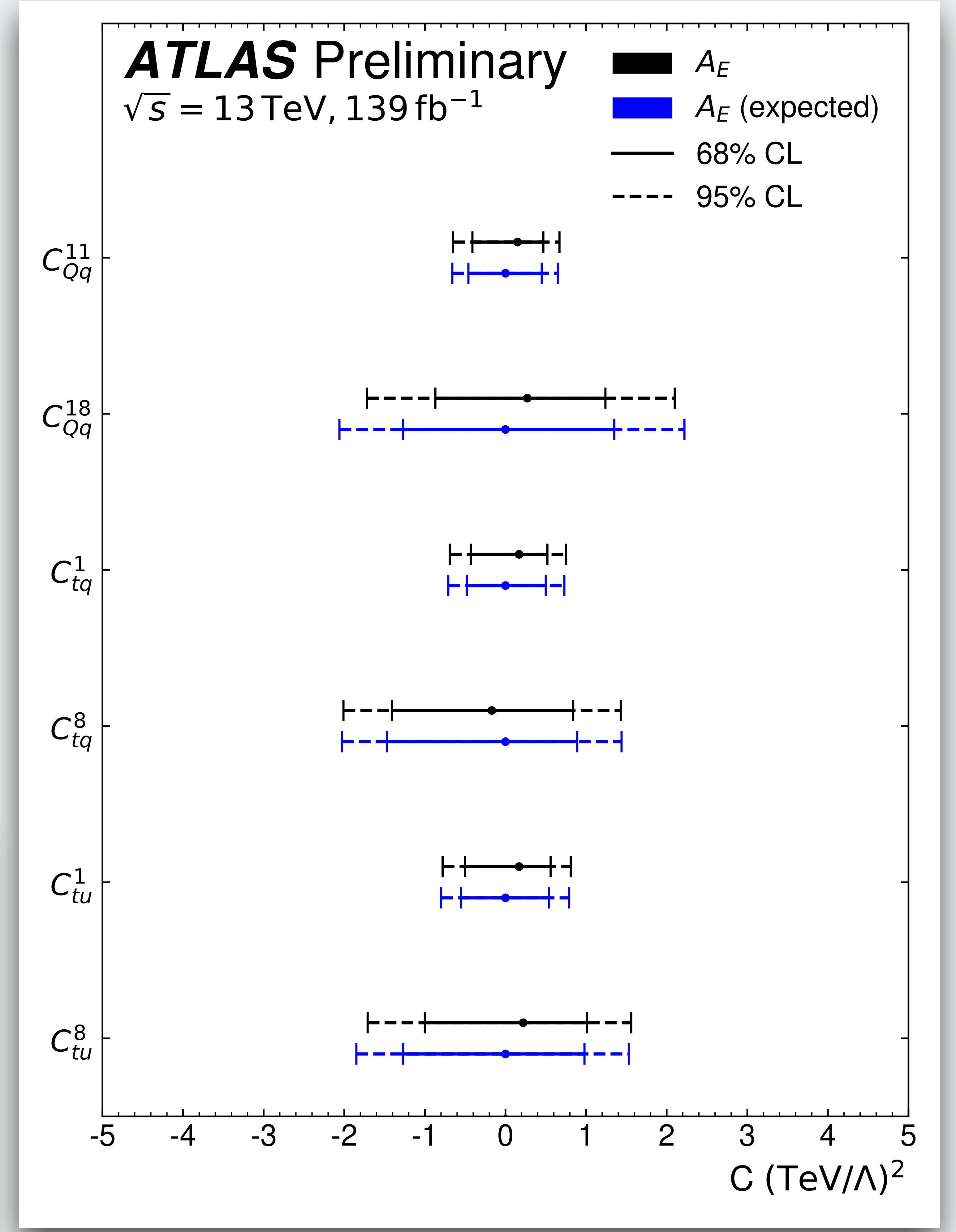
same operators but different colour structure

Colour-octet operators interfere with QCD, no more blind direction!

QCD structure of A_E very different from A_y



arXiv:2001.07225



Tighter bounds for colour singlets, because of colour factors in the amplitude

Search for ~~CP~~: analysis strategy

CP phase in CKM matrix too small to produce visible SM CP violation in ttbar decay:
any asymmetry is a sign of BSM! (e.g. top CEDM or ctGI in SMEFT)

l+jets selection: 1e/μ p_T>30/38 GeV, ≥4 jets p_T>30, =2 bjets@68% (with full Run 2 data)

➡ Look at 4 T-odd observables and define asymmetries

➡ χ^2 top reconstruction + M_{lb}<150 GeV
(higher M_{lb} increases probability of incorrect l-b pairing)

➡ Template fit to M_{lb} to measure signal and background normalisations

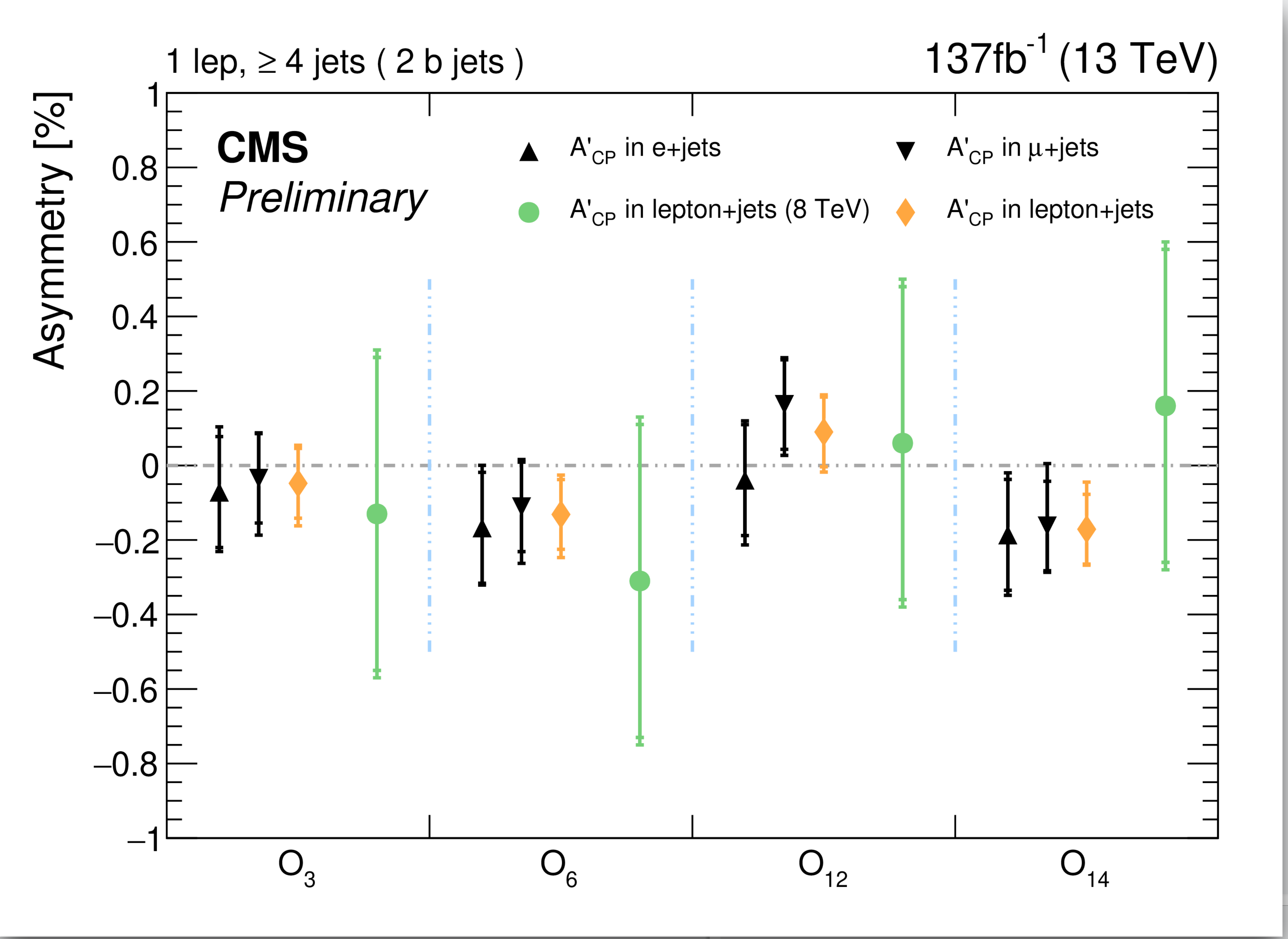
➡ Extract A_{CP} by counting signal events

➡ Correct A_{CP} with dilution factor D to account for migration from detector and top reconstruction effects (~fiducial correction)

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}$$

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_b \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$
$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$
$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

Search for ~~CP~~: results



- ☞ *no discrepancy within 2σ*
- ☞ *factor 3 improvement from 8 TeV measurement!*

	$A'_{CP}(\%)$		
	$e+jets$	$\mu+jets$	*Combined*
O_3	$-0.071 \pm 0.149(\text{stat.})^{+0.092}_{-0.058}(\text{syst.})$	$-0.035 \pm 0.120(\text{stat.})^{+0.022}_{-0.094}(\text{syst.})$	$-0.048 \pm 0.094(\text{stat.})^{+0.041}_{-0.065}(\text{syst.})$
O_6	$-0.167 \pm 0.149(\text{stat.})^{+0.077}_{-0.038}(\text{syst.})$	$-0.111 \pm 0.120(\text{stat.})^{+0.042}_{-0.093}(\text{syst.})$	$-0.131 \pm 0.094(\text{stat.})^{+0.049}_{-0.068}(\text{syst.})$
O_{12}	$-0.039 \pm 0.149(\text{stat.})^{+0.056}_{-0.090}(\text{syst.})$	$+0.163 \pm 0.120(\text{stat.})^{+0.038}_{-0.065}(\text{syst.})$	$+0.090 \pm 0.094(\text{stat.})^{+0.034}_{-0.053}(\text{syst.})$
O_{14}	$-0.186 \pm 0.149(\text{stat.})^{+0.075}_{-0.065}(\text{syst.})$	$-0.162 \pm 0.120(\text{stat.})^{+0.117}_{-0.032}(\text{syst.})$	$-0.171 \pm 0.094(\text{stat.})^{+0.085}_{-0.023}(\text{syst.})$

Conclusion

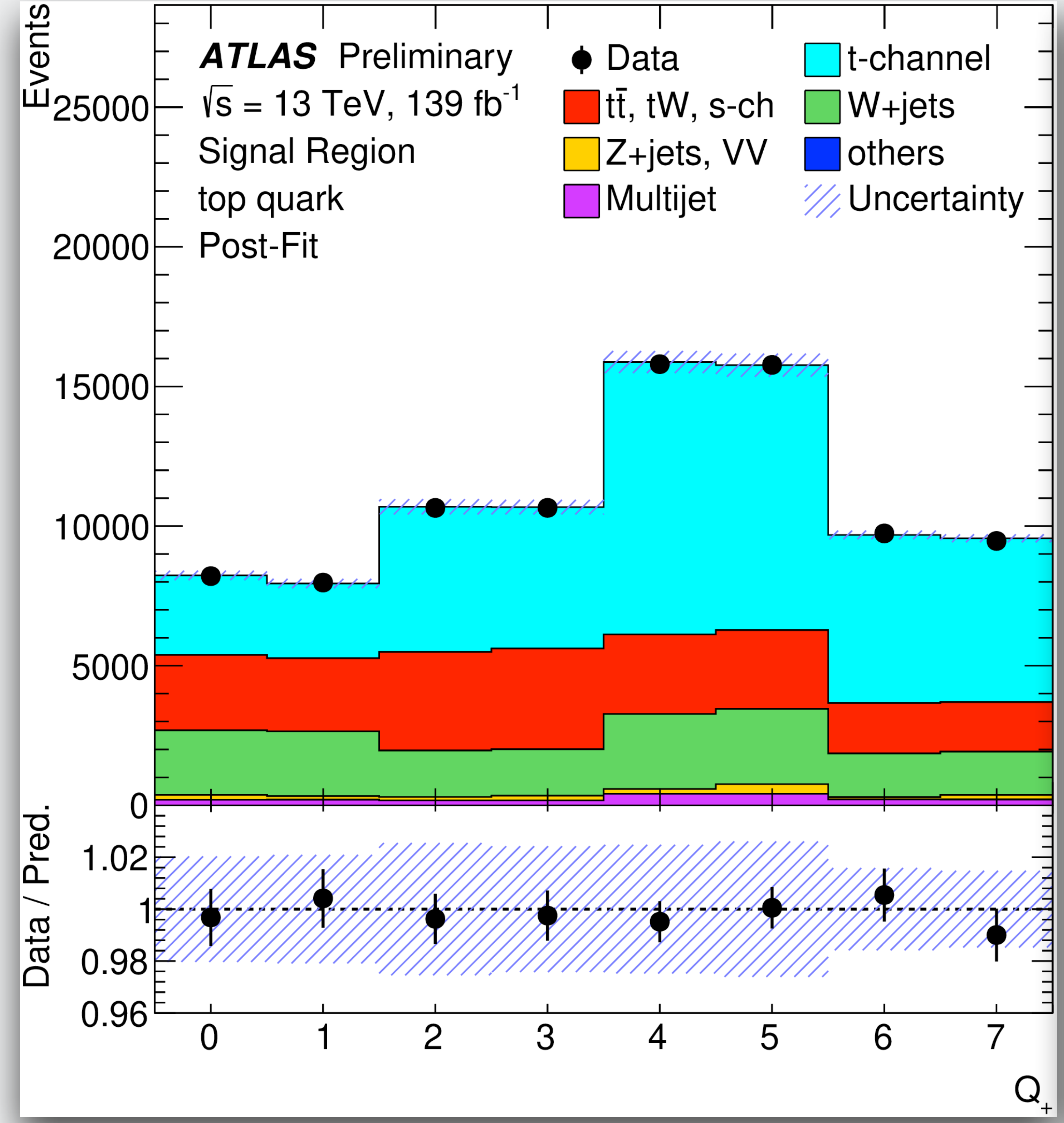
Precision & legacy Run 2 measurements of top physics

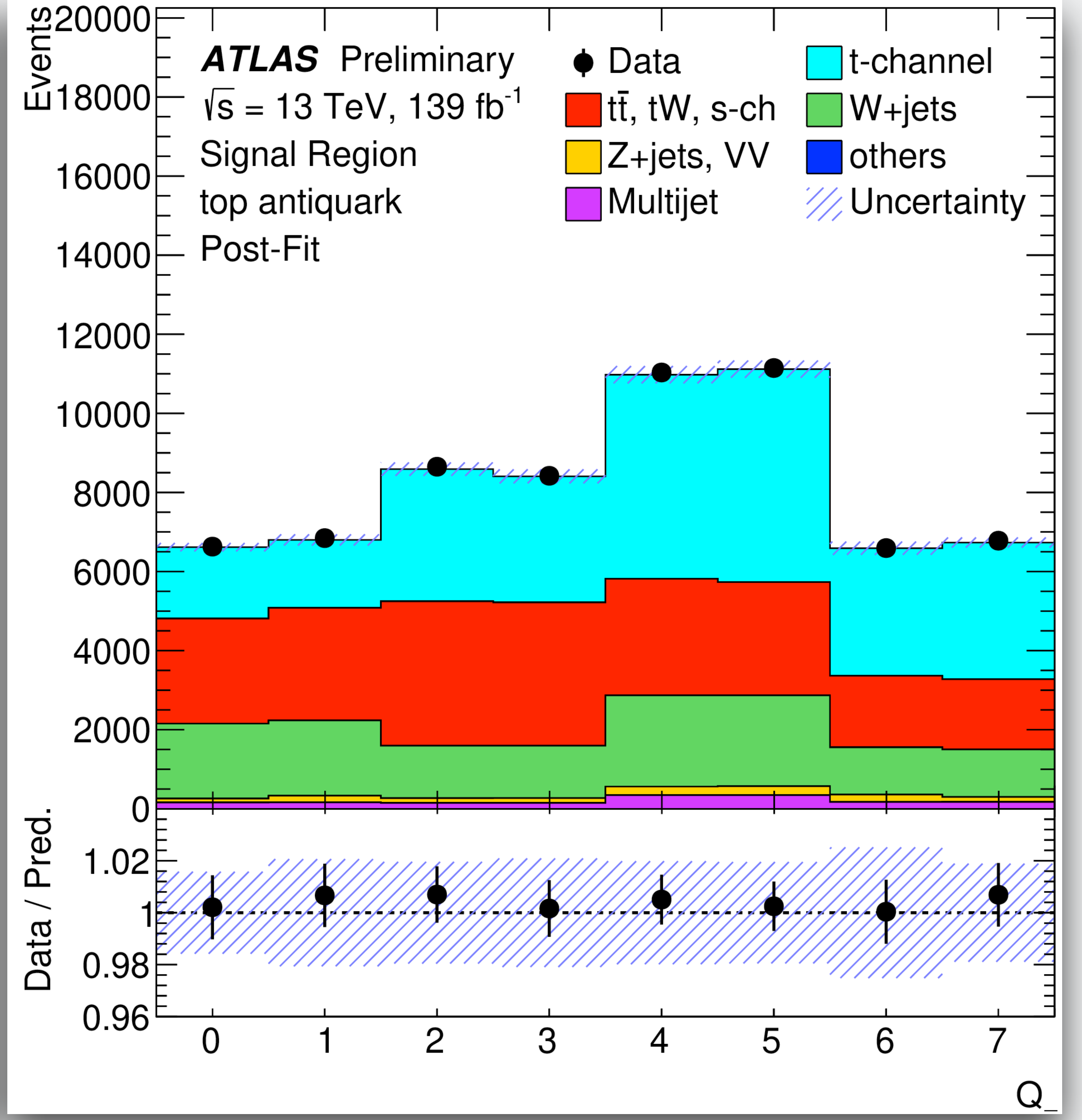
- top polarisation and mass accessible from single-top events
- tuning and calibration from well-controlled ttbar sample
  - *MC/pole mass calibrated and shown to be universal within 200 MeV*
  - *b-fragmentation is environment independent and more precisely determined*
- new tests of BSM physics are possible
  - energy asymmetry able to break blind directions in SMEFT, but no evidence of CP or LFU violation


BACKUP

Top polarisation: detector-level

t-chan signal at LO from PROTOS: allows to obtain separate {Px,Py,Pz} templates





JES/JER can affect frame definition:
JER is considered independently in all octants
+ additional uncertainty from comparing to *single JER shared across octants*

ttbar modelling and MC stats are subleading systematics

Uncertainty source	$\Delta P^{t}_{x'}$	$\Delta P^{\bar{t}}_{x'}$	$\Delta P^{t}_{y'}$	$\Delta P^{\bar{t}}_{y'}$	$\Delta P^{t}_{z'}$	$\Delta P^{\bar{t}}_{z'}$
Modelling						
Modelling (t-channel)	±0.037	±0.051	±0.010	±0.015	±0.061	±0.061
Modelling ($t\bar{t}$)	±0.016	±0.021	±0.004	±0.016	±0.003	±0.016
Modelling (other)	±0.013	±0.031	±0.003	±0.006	±0.026	±0.043
Experimental						
Jet energy scale	±0.045	±0.048	±0.005	±0.007	±0.033	±0.025
Jet energy resolution	±0.166	±0.185	±0.021	±0.040	±0.070	±0.130
Jet flavour tagging	±0.004	±0.002	<0.001	±0.001	±0.007	±0.009
Other experimental uncertainties	±0.015	±0.029	±0.002	±0.007	±0.014	±0.026
Multijet estimation	±0.008	±0.021	<0.001	±0.001	±0.008	±0.013
Luminosity	±0.001	±0.001	<0.001	<0.001	<0.001	<0.001
Simulation statistics	±0.020	±0.024	±0.008	±0.015	±0.017	±0.031
Total systematic uncertainty	±0.174	±0.199	±0.025	±0.048	±0.096	±0.153
Total statistical uncertainty	±0.017	±0.025	±0.011	±0.017	±0.022	±0.034

ttbar and W+jets are the largest backgrounds: normalised in CRs

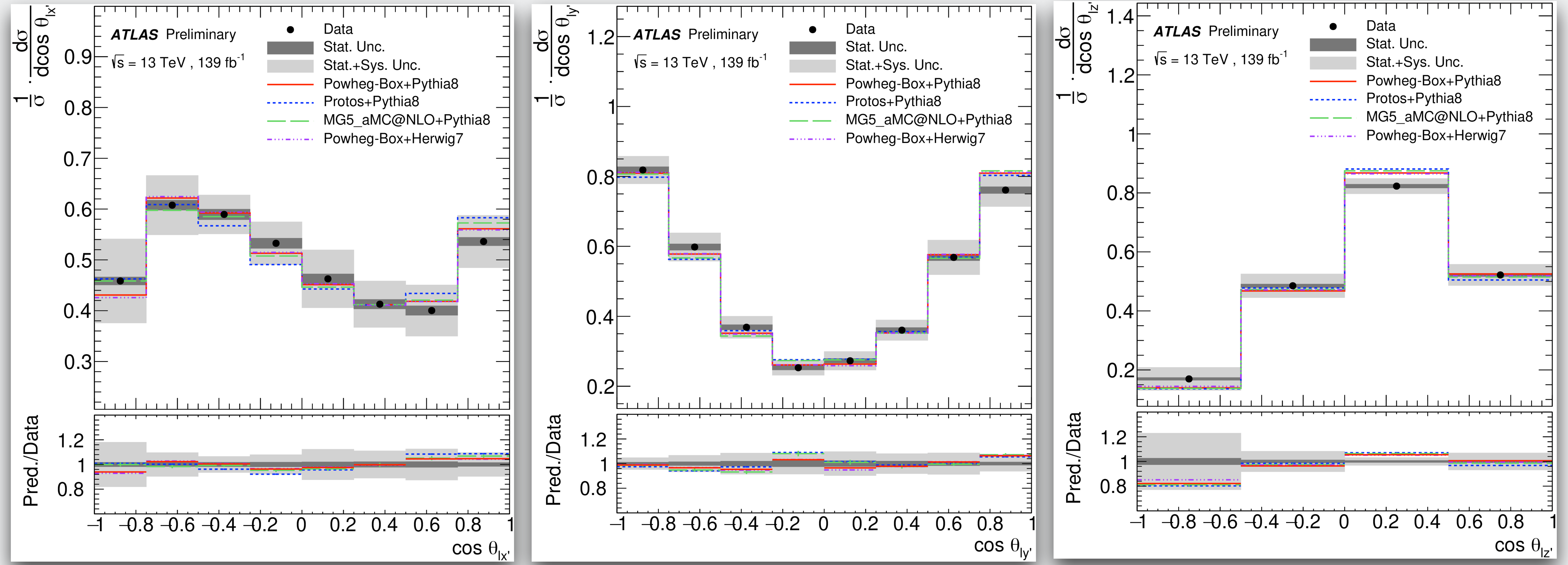
CR-ttbar ☞ add a second b-jet

CR-Wjets ☞ invert SR cuts

(8 octants + 2 CRs) x (top/antitop)
= 20 bins in the fit

Top polarisation: particle-level

t-chan signal at NLO from Powheg-Box 4FS + Pythia8 for unfolding



compared to aMC@NLO and Herwig7

Angular variable	χ^2/NDF	p-value
$\cos\theta_{\ell x'}$	$1.53/7$	0.98
$\cos\theta_{\ell y'}$	$4.25/7$	0.75
$\cos\theta_{\ell z'}$	$2.98/3$	0.39

unfolded with IBU: binning optimised to give >70% along diagonal of migration matrix (3-5 iterations)

MC description is **worst in 1st/3rd bin of cosϑ_z**, *no best generator*

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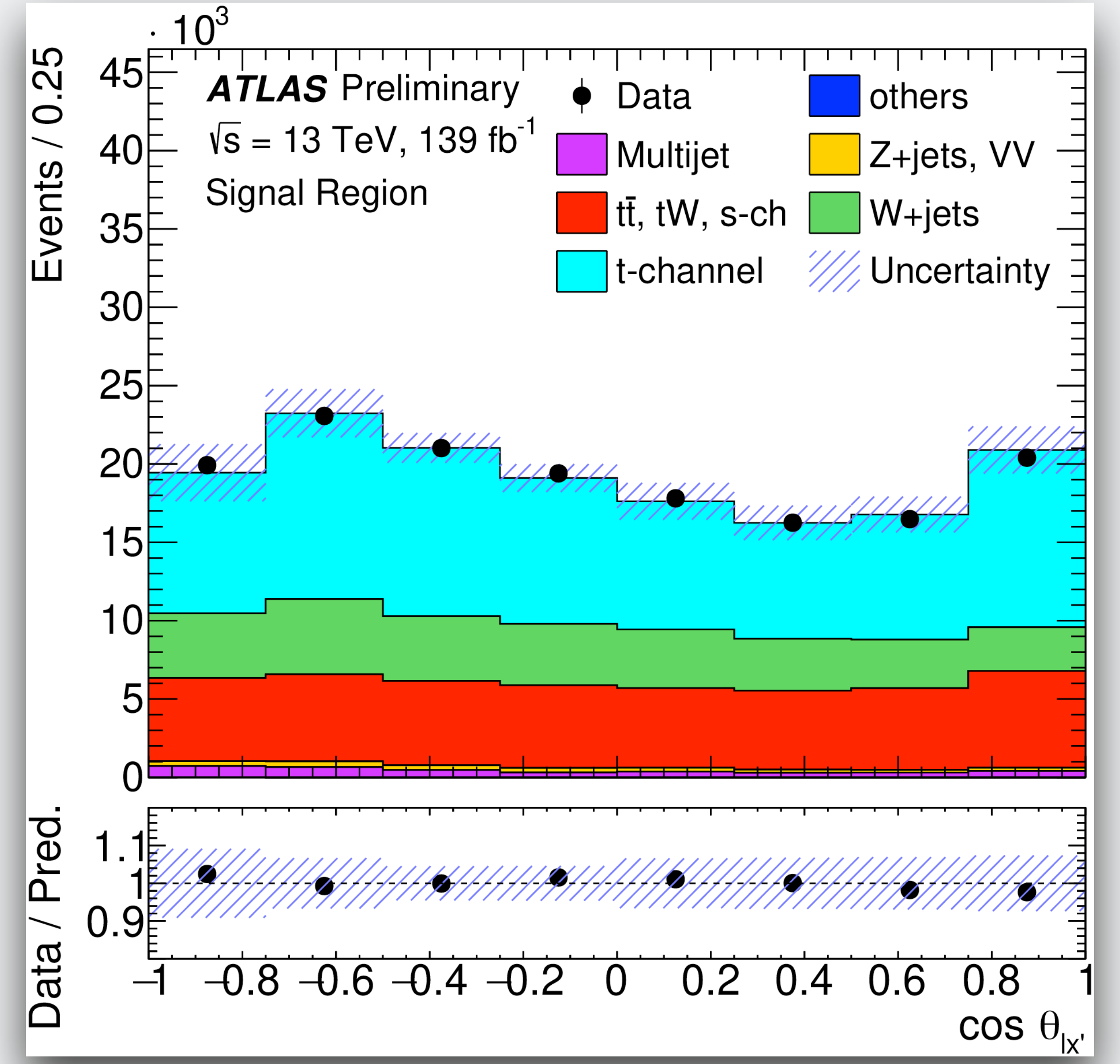
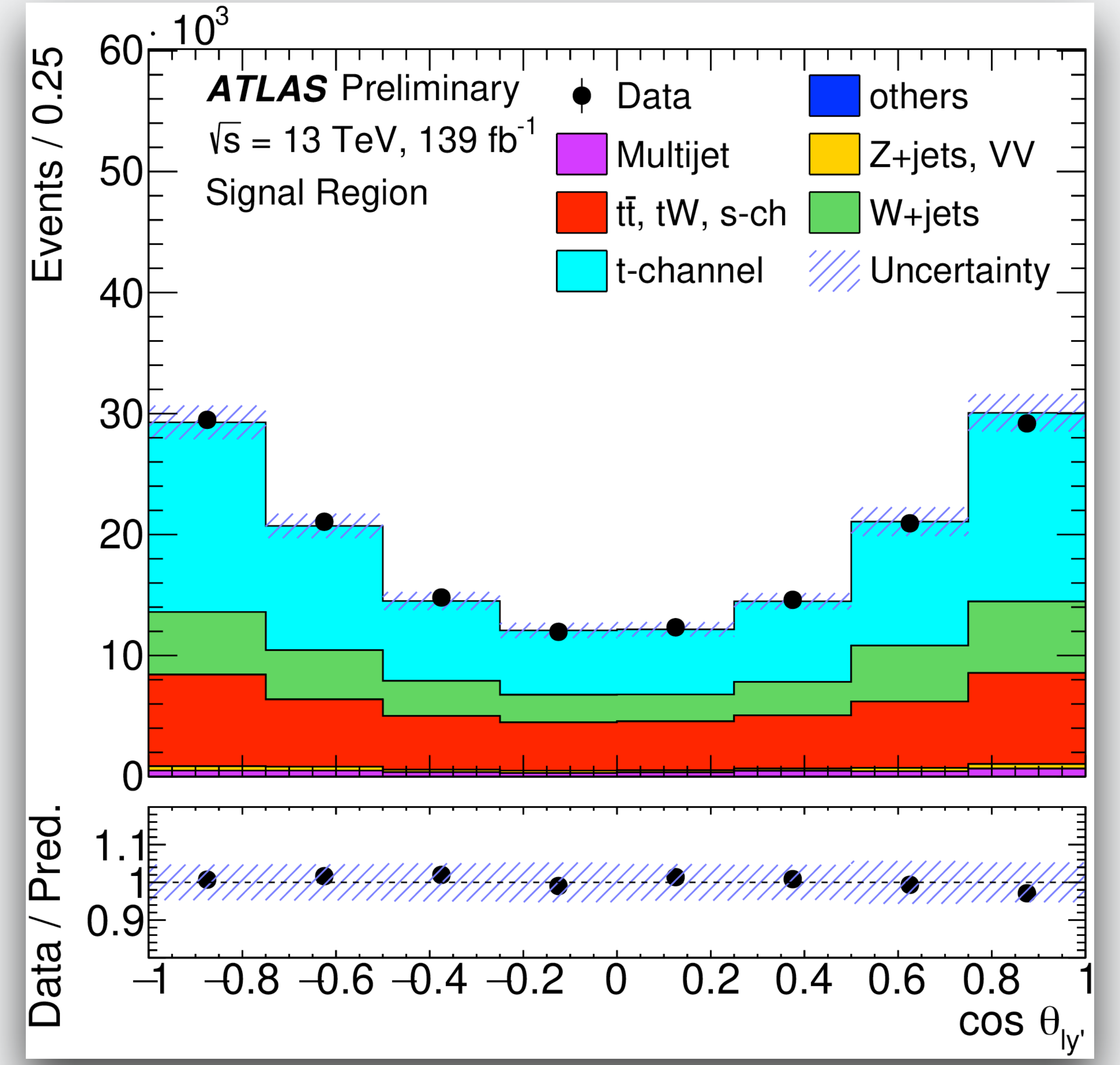
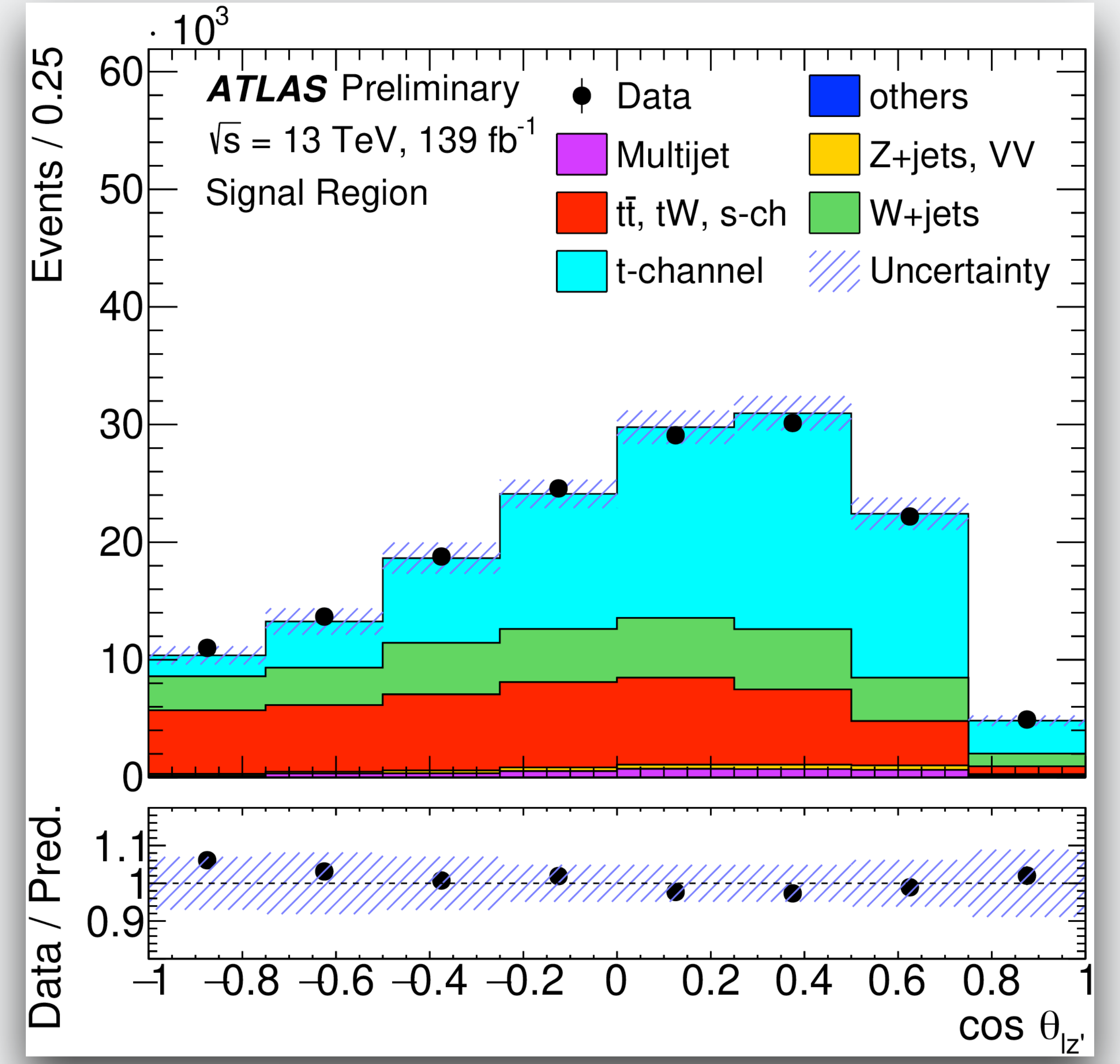
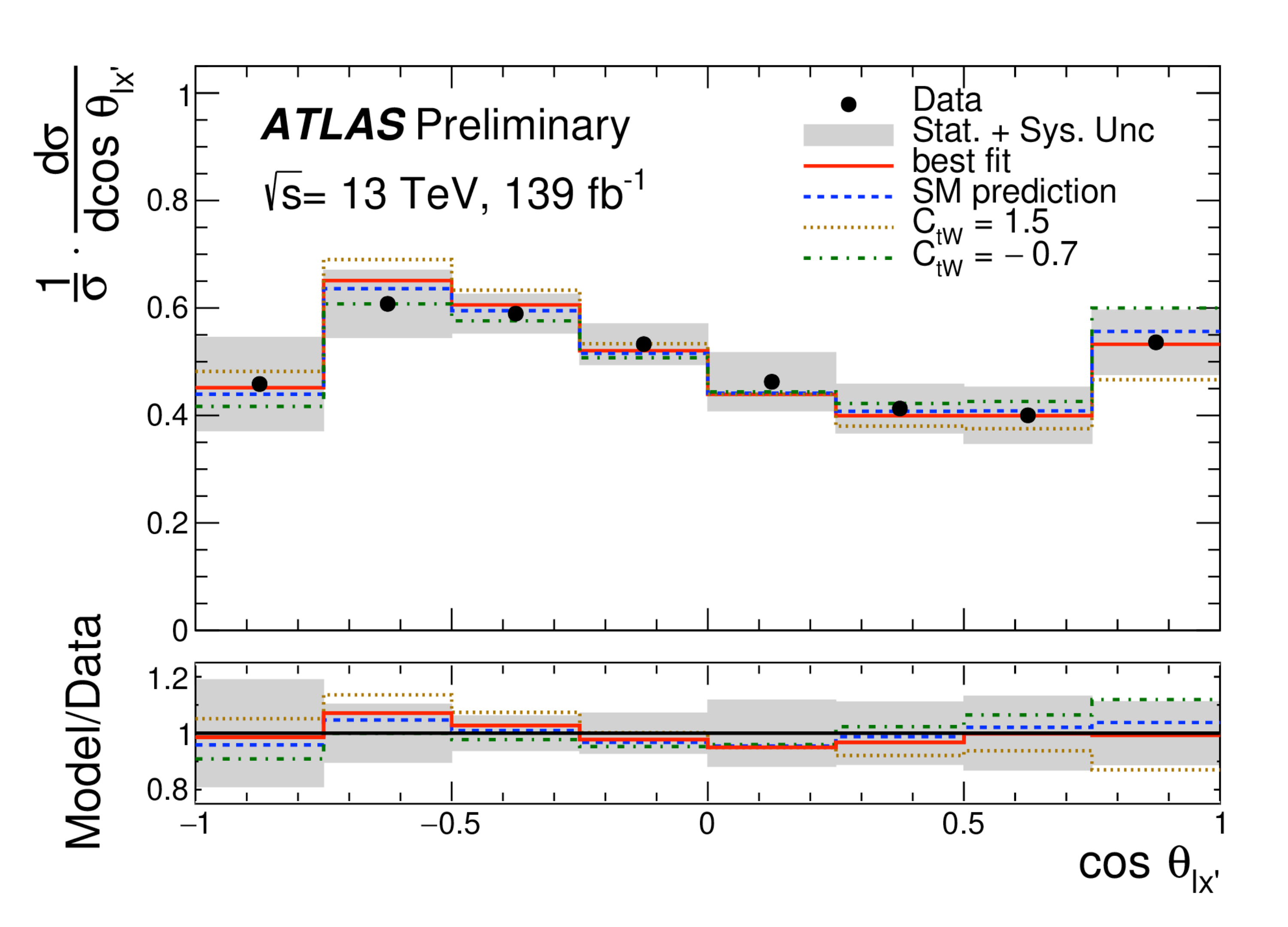
Top polarisation







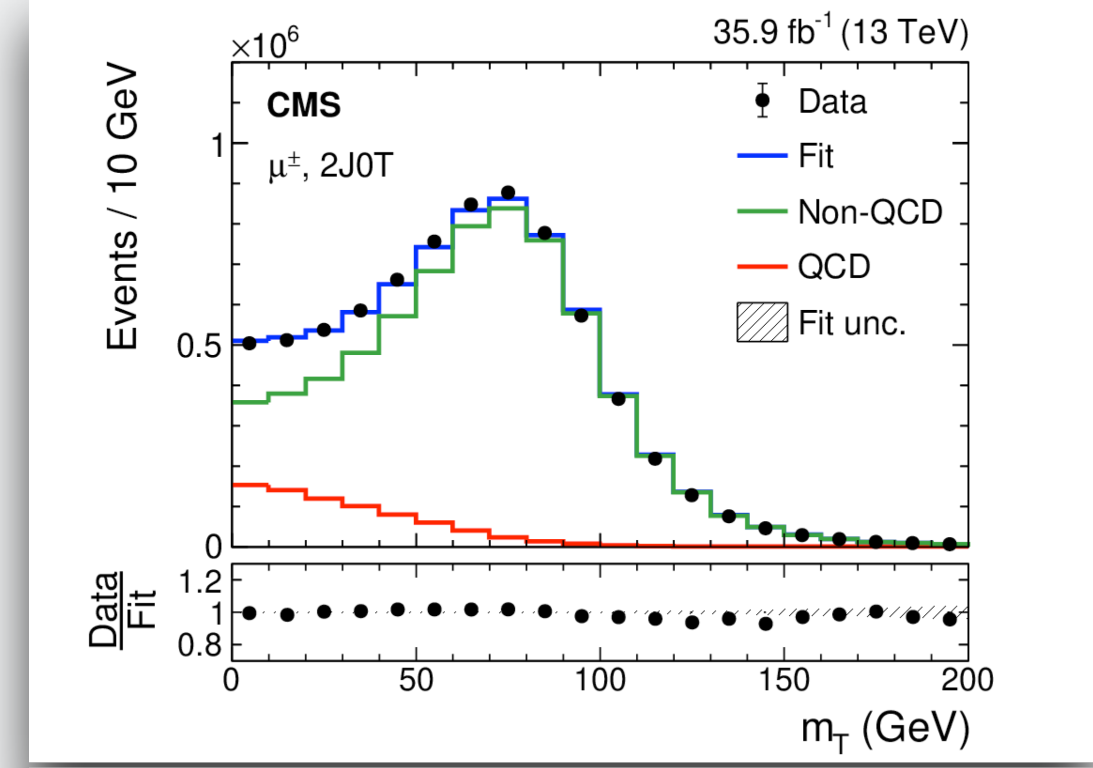
Process	Preselection region	Signal region	$t\bar{t}$ control region	W+jets control region
t-channel	$219\,000 \pm 11\,000$	$70\,600 \pm 3\,500$	$13\,480 \pm 680$	$148\,200 \pm 7\,400$
$t\bar{t}$, tW, s-channel	$736\,000 \pm 39\,000$	$43\,200 \pm 2\,400$	$147\,800 \pm 8\,400$	$693\,000 \pm 37\,000$
W+jets	$590\,000 \pm 200\,000$	$26\,200 \pm 8\,900$	$16\,100 \pm 5\,500$	$560\,000 \pm 190\,000$
Z+jets, diboson	$52\,900 \pm 5\,100$	$2\,120 \pm 350$	$2\,620 \pm 360$	$50\,800 \pm 4\,900$
Others	494 ± 38	30 ± 4	79 ± 6	464 ± 36
Multijet	$52\,000 \pm 10\,000$	$3\,500 \pm 640$	$5\,500 \pm 1\,800$	$48\,500 \pm 9\,400$
Total expected	$1650\,000 \pm 210\,000$	$145\,600 \pm 9\,900$	$186\,000 \pm 10\,000$	$1\,510\,000 \pm 200\,000$
Data	$1\,750\,918$	$154\,361$	$188\,326$	$1\,596\,557$
S/B	0.15 ± 0.02	0.94 ± 0.13	0.08 ± 0.01	0.11 ± 0.02
Data/Prediction	1.06 ± 0.13	1.06 ± 0.07	1.02 ± 0.06	1.06 ± 0.14



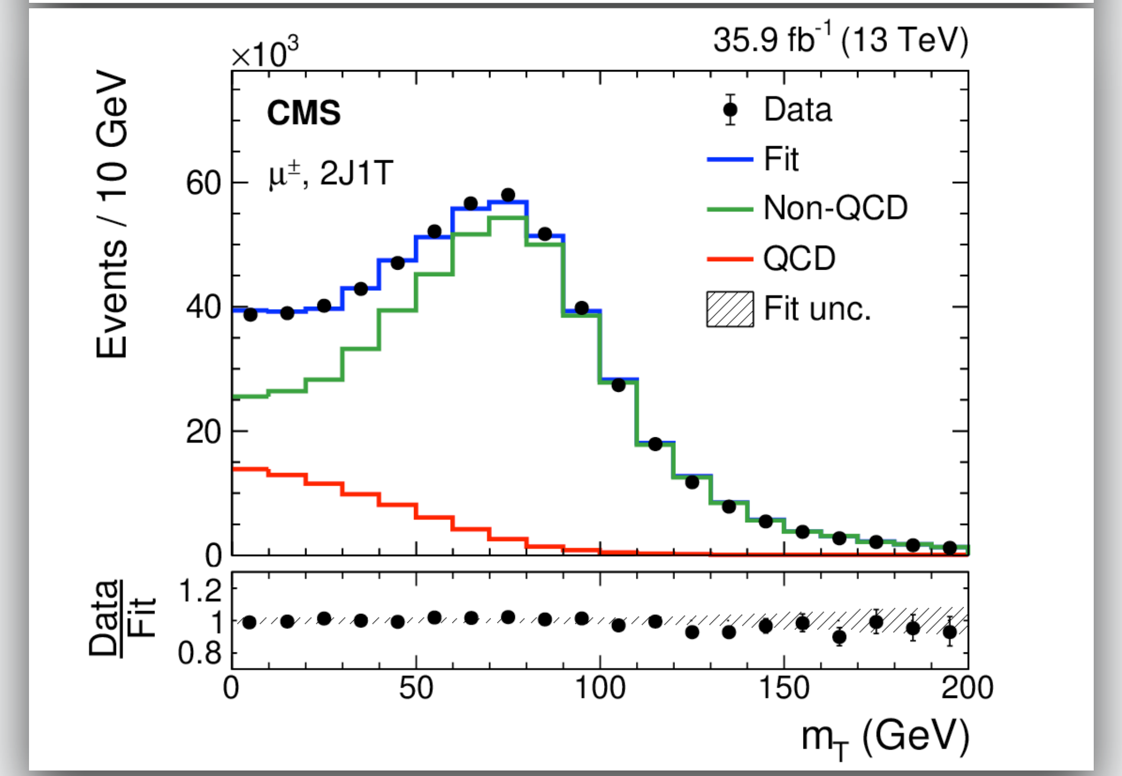
TOP-19-009

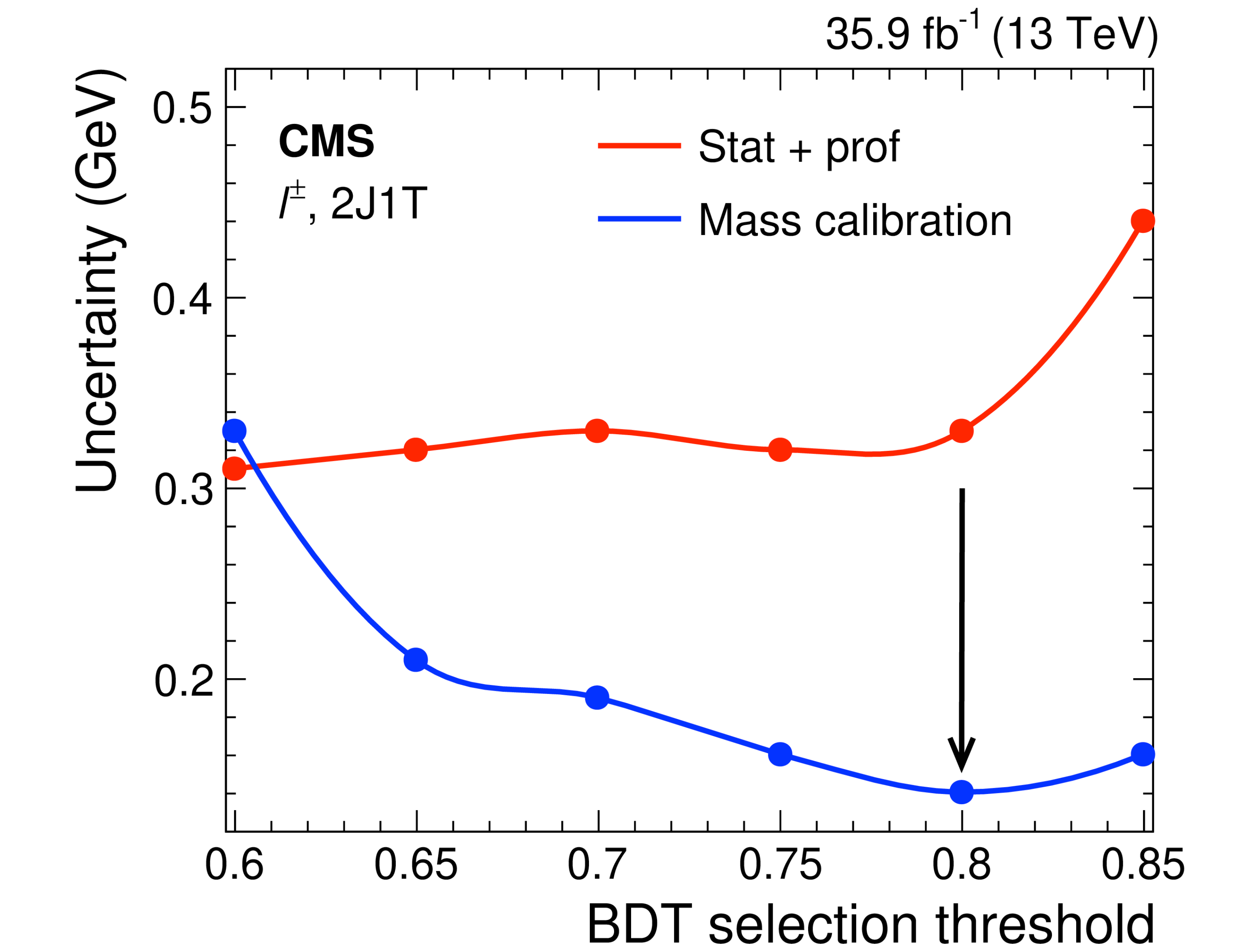
Top mass: QCD estimation & MVA

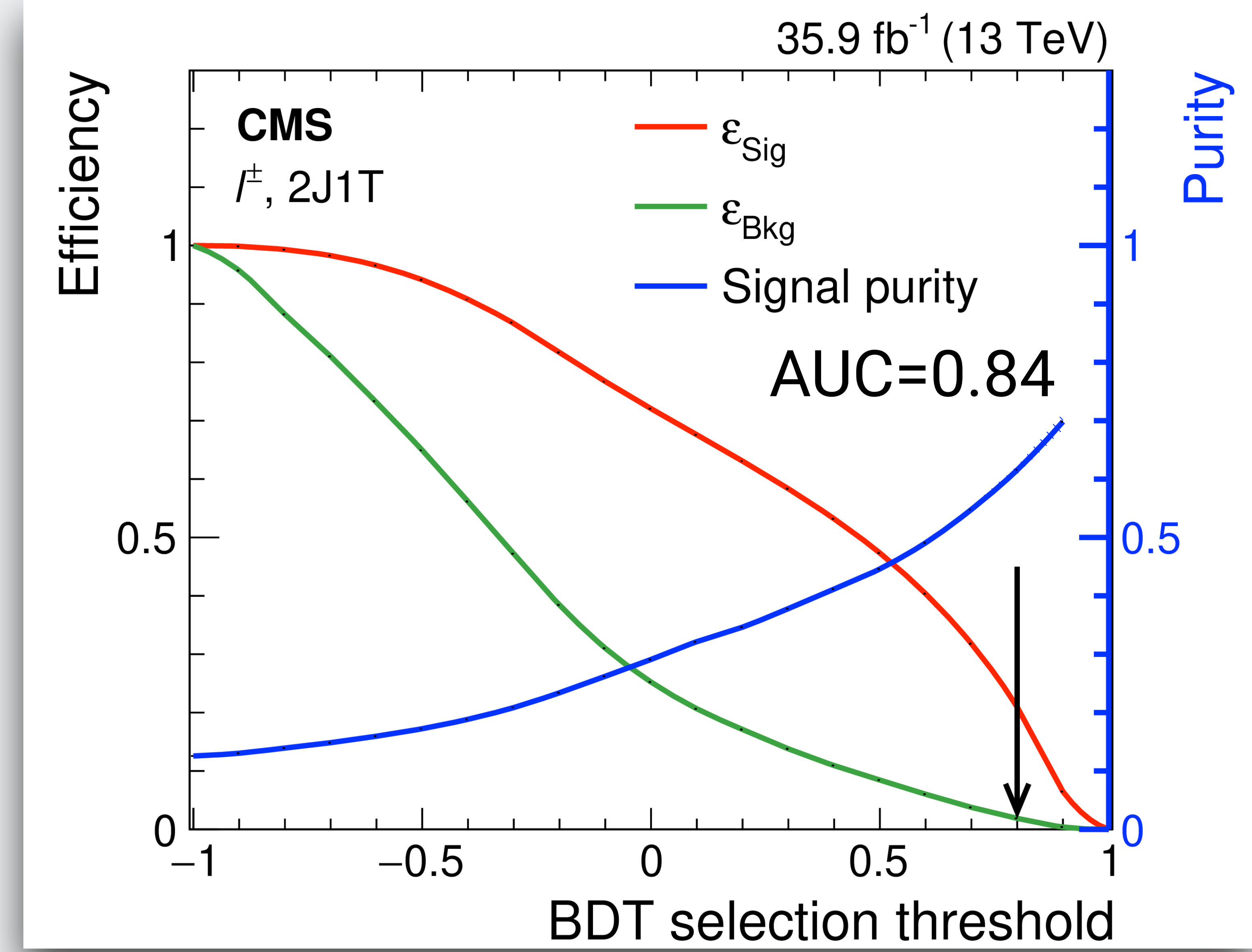
validation region



signal region

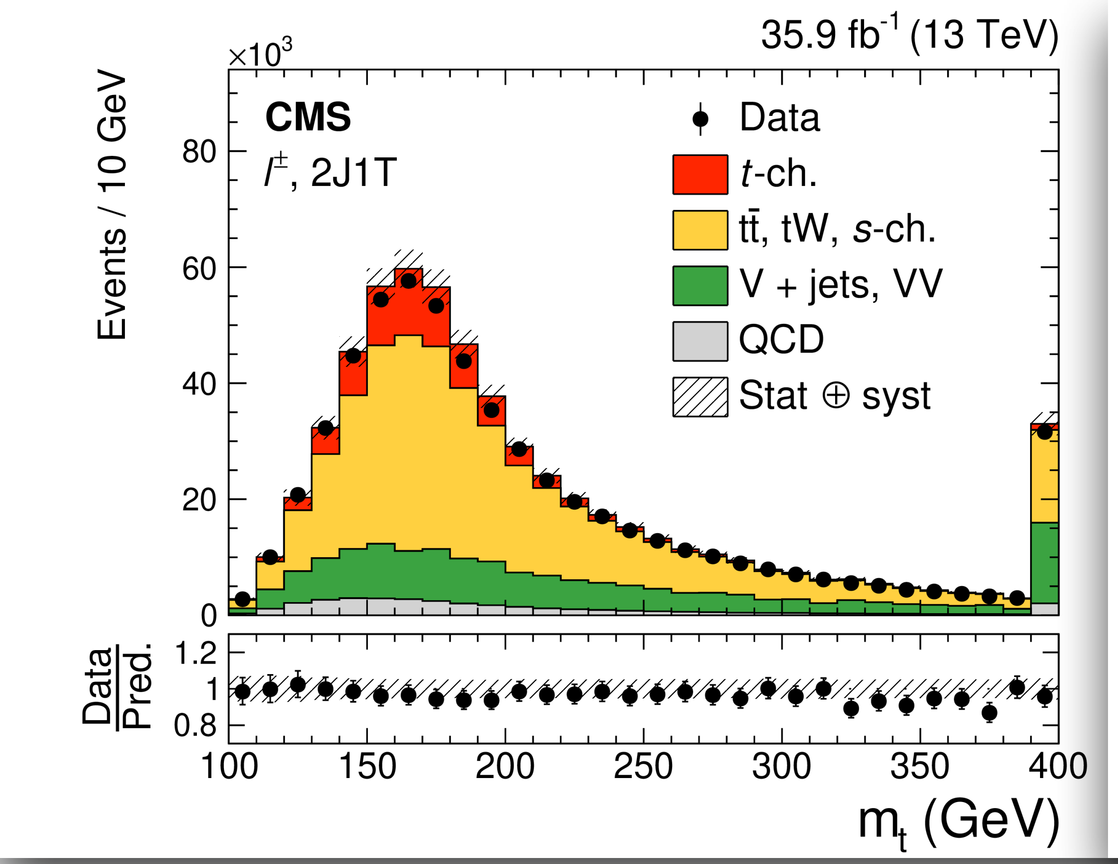




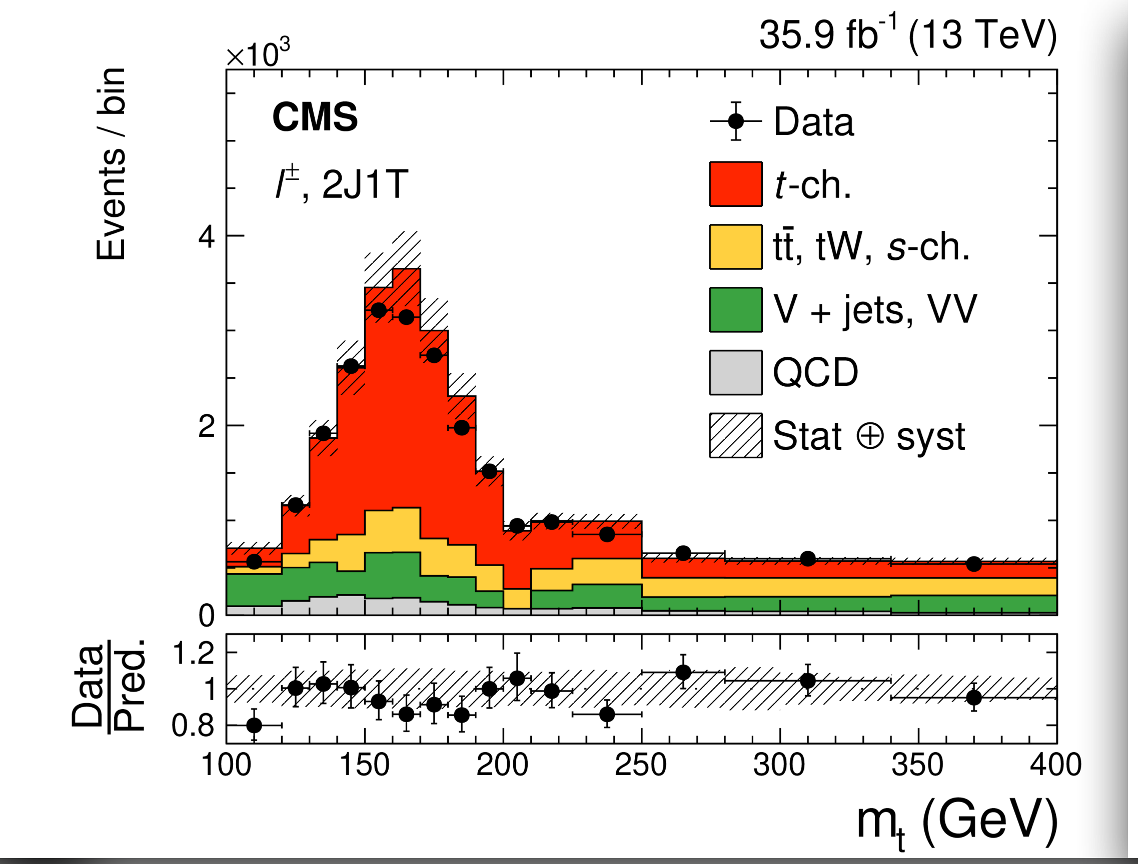


BDT cut optimised to reduce uncertainties

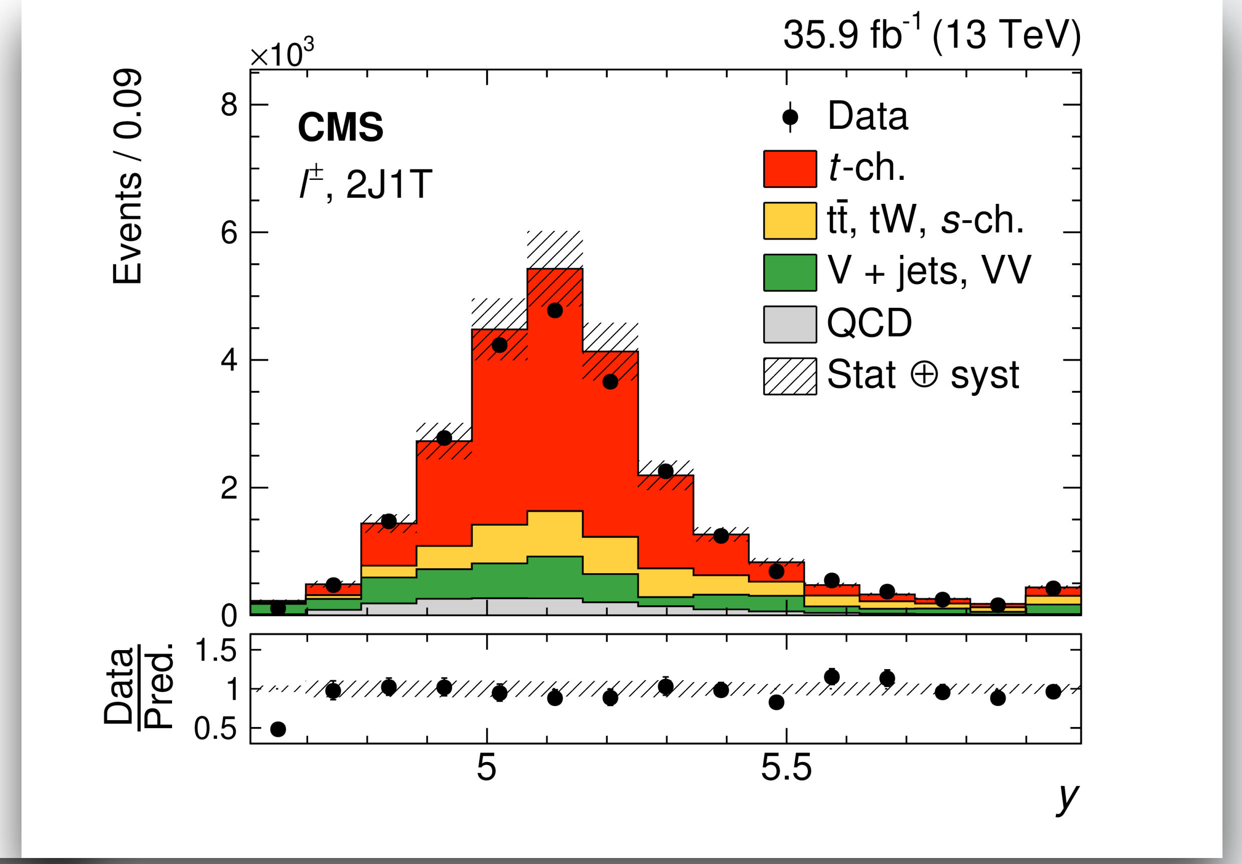
before BDT cut



after BDT cut



log-mapped



<u>QCD-enriched region:</u>

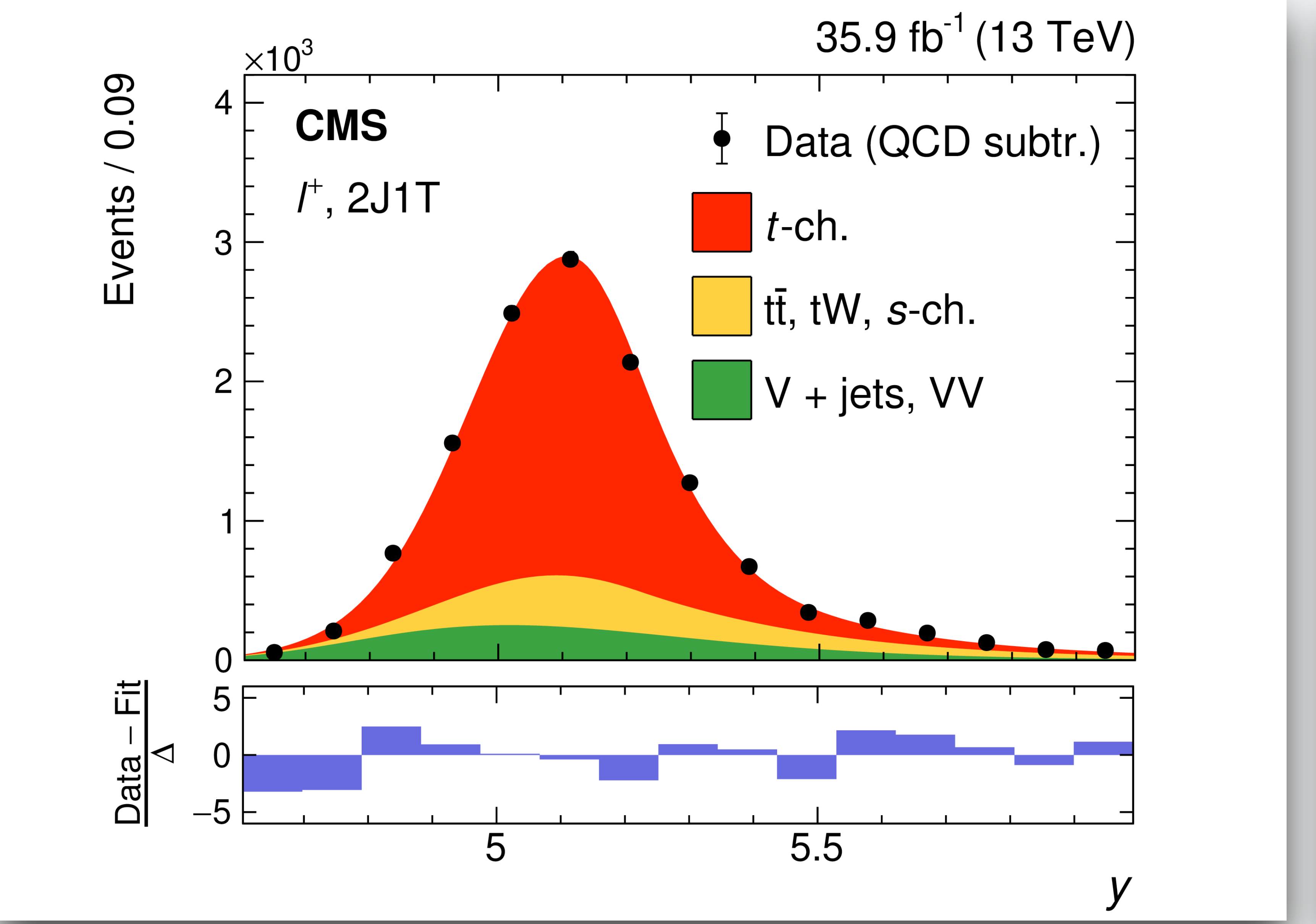
- relax lepton isolation cuts by factor 10 and fail tight electron ID
- define sideband with 70-93% purity after non-QCD subtraction
- binned fit to m_T
- validate in 2J0T before injecting in 2J1T (SR) with a 50% rate+shape uncertainty

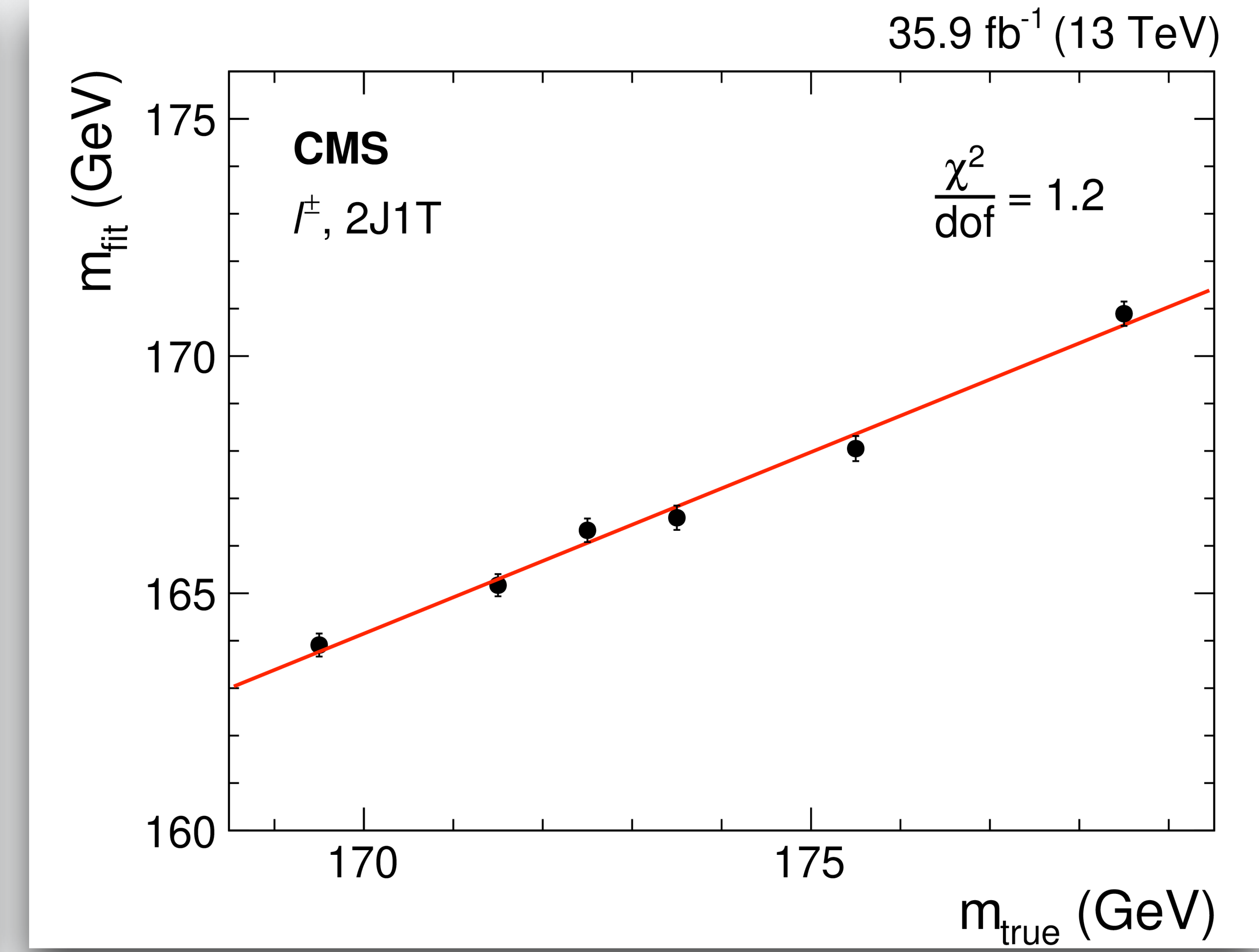
Top mass: shape fit & calibration

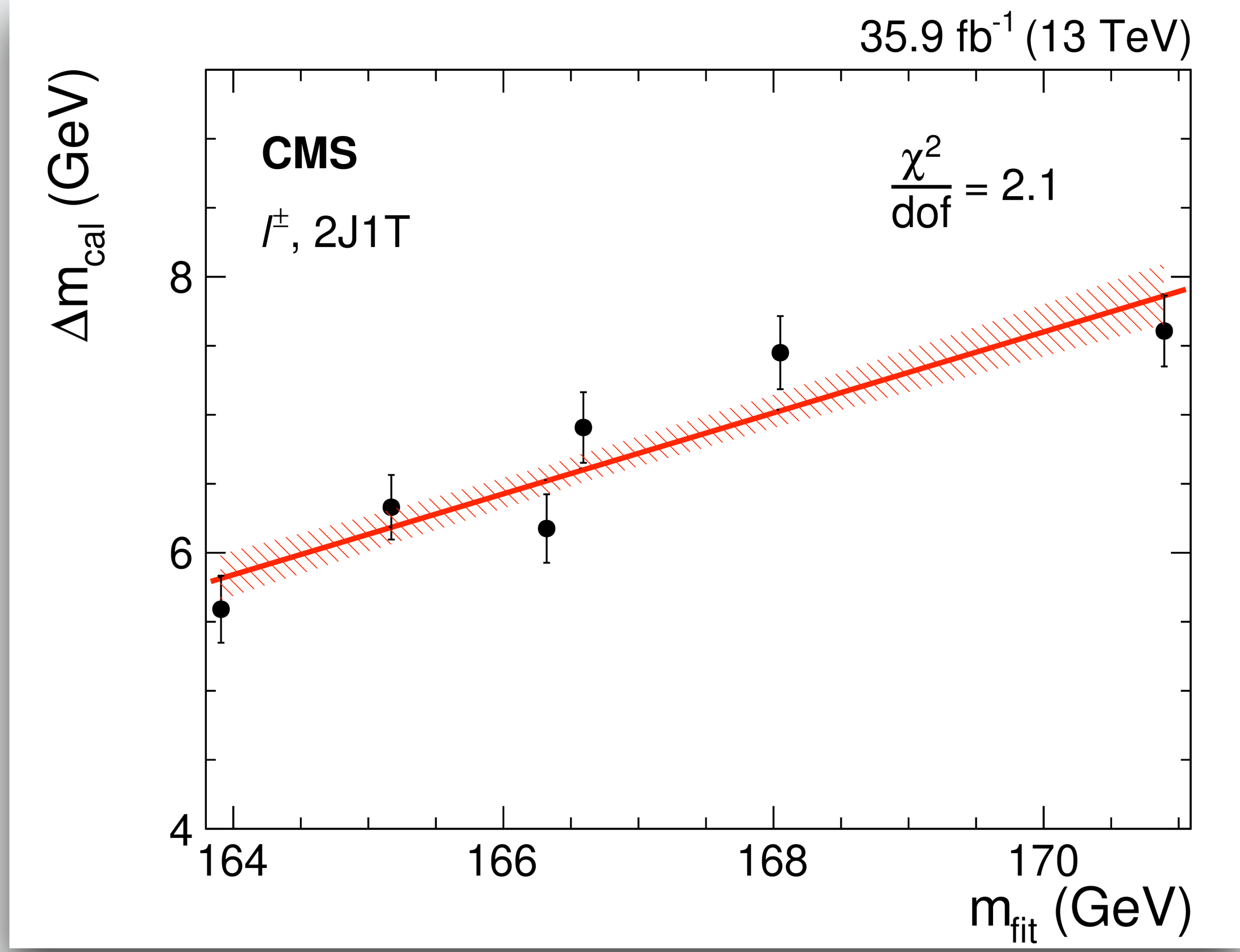
t-chan signal at NLO Powheg 2.0 4FS normalised to 5FS prediction from HATHOR 2.1 to derive calibration

$$F_l(y;\, y_0,\, f_j) = f_{\mathrm{sig}} F_{\mathrm{sig}}(y;\, y_0) \;+\; f_{t\bar{t}} F_{t\bar{t}}(y;\, y_0) \;+\; f_{\mathrm{EW}} F_{\mathrm{EW}}(y)$$

F_{sig}: asymmetric Gaussian core + Landau tail
F_{tt}: crystal ball
F_{EW}: Novosibirsk



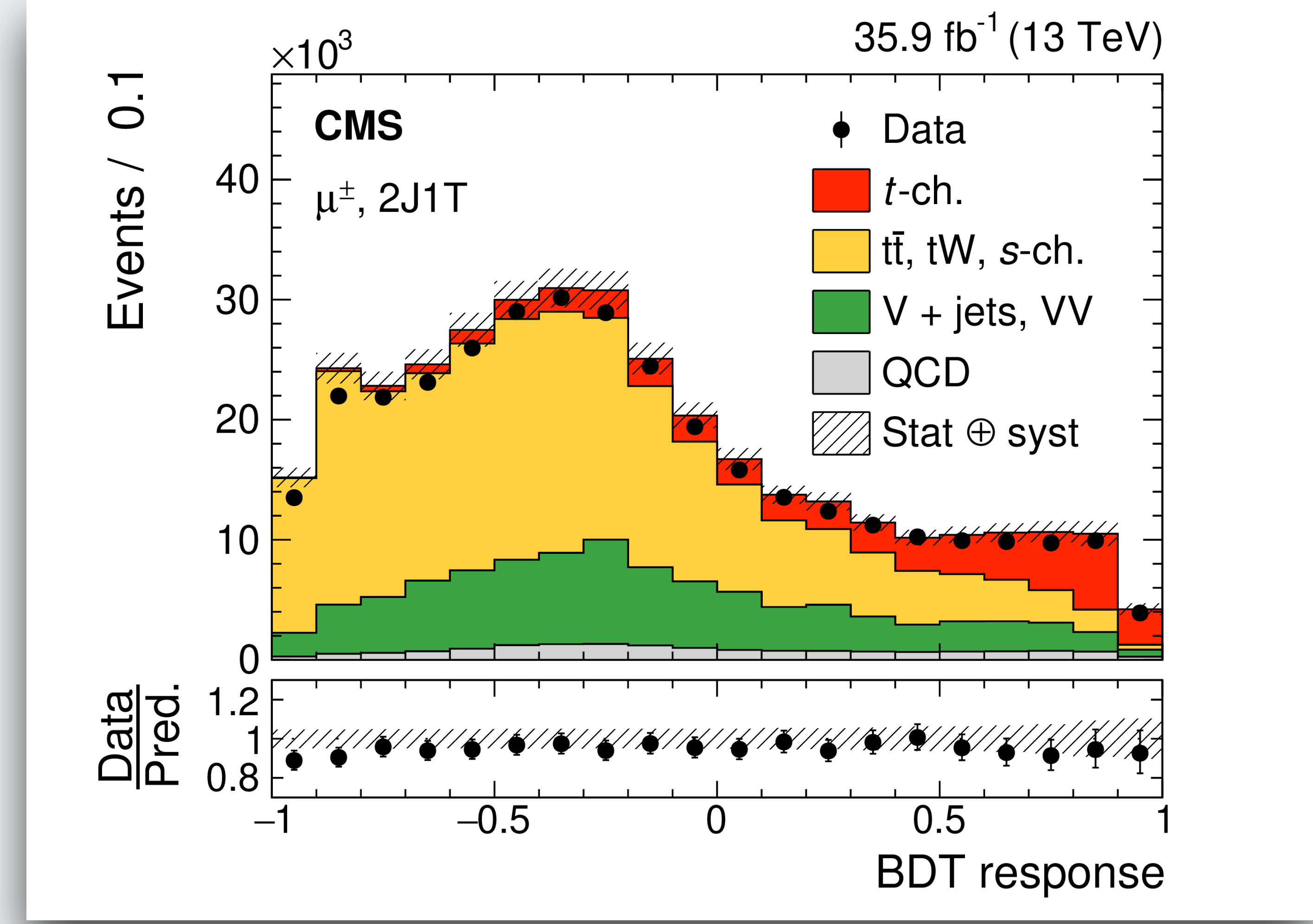


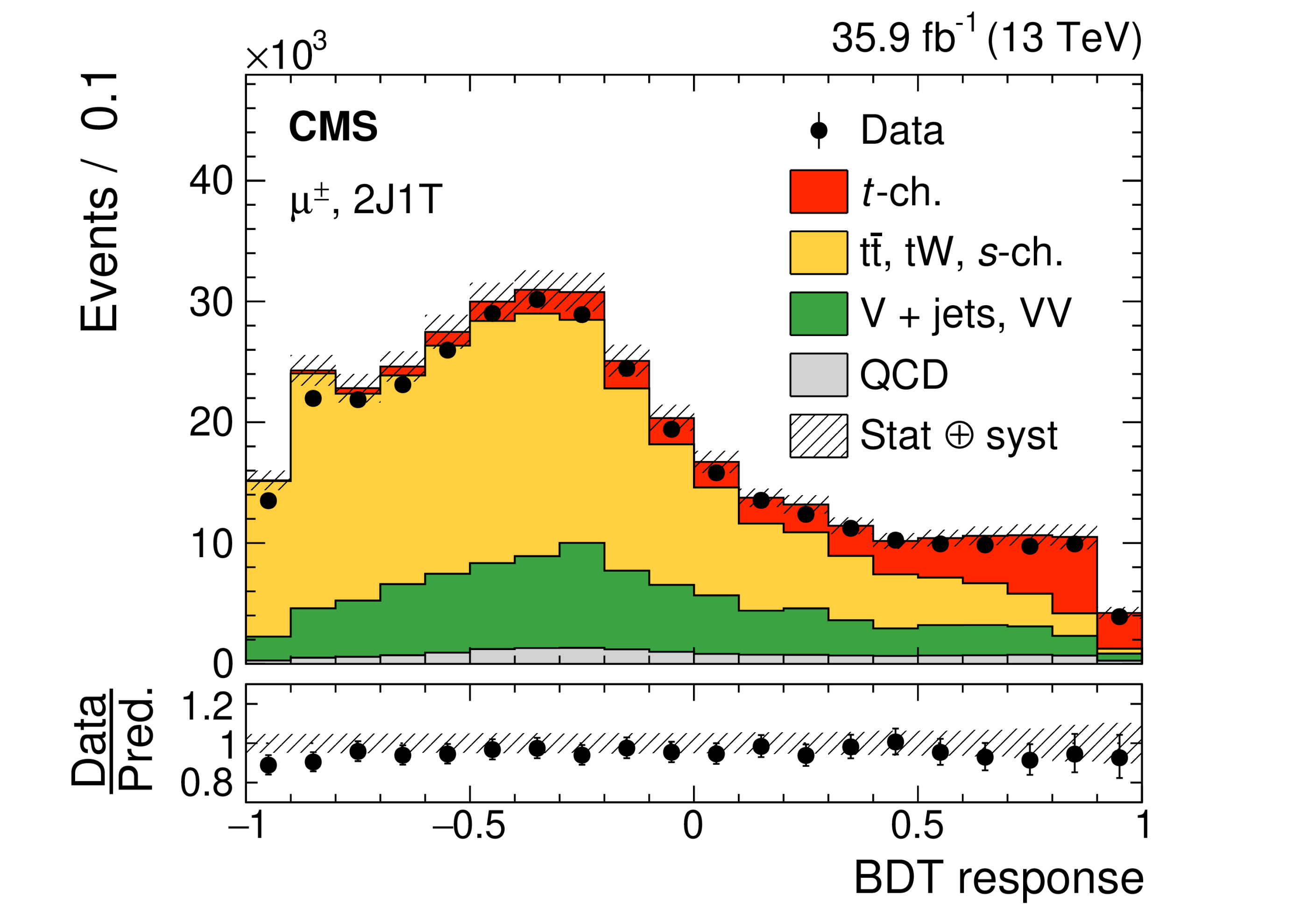


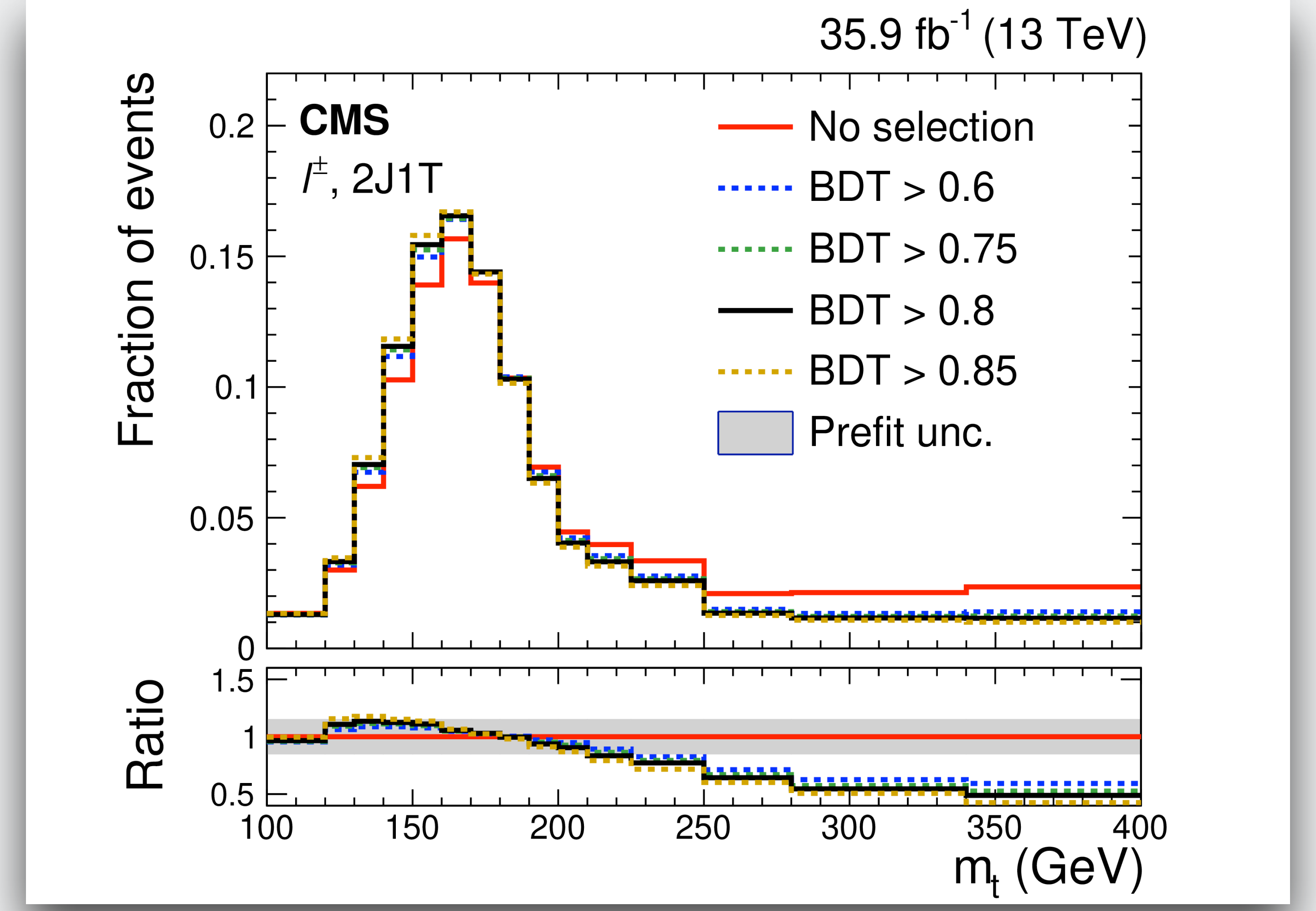
➡ uncertainty on mass calibration (MC stats from alternative m_t samples) not dominant
➡ l^- channel suffers from larger statistical uncertainty and sensitivity to bkg-related uncertainties
➡ JES and JER affect the reconstruction of the untagged jet, which is crucial for the BDT

Top mass

TOP-19-009







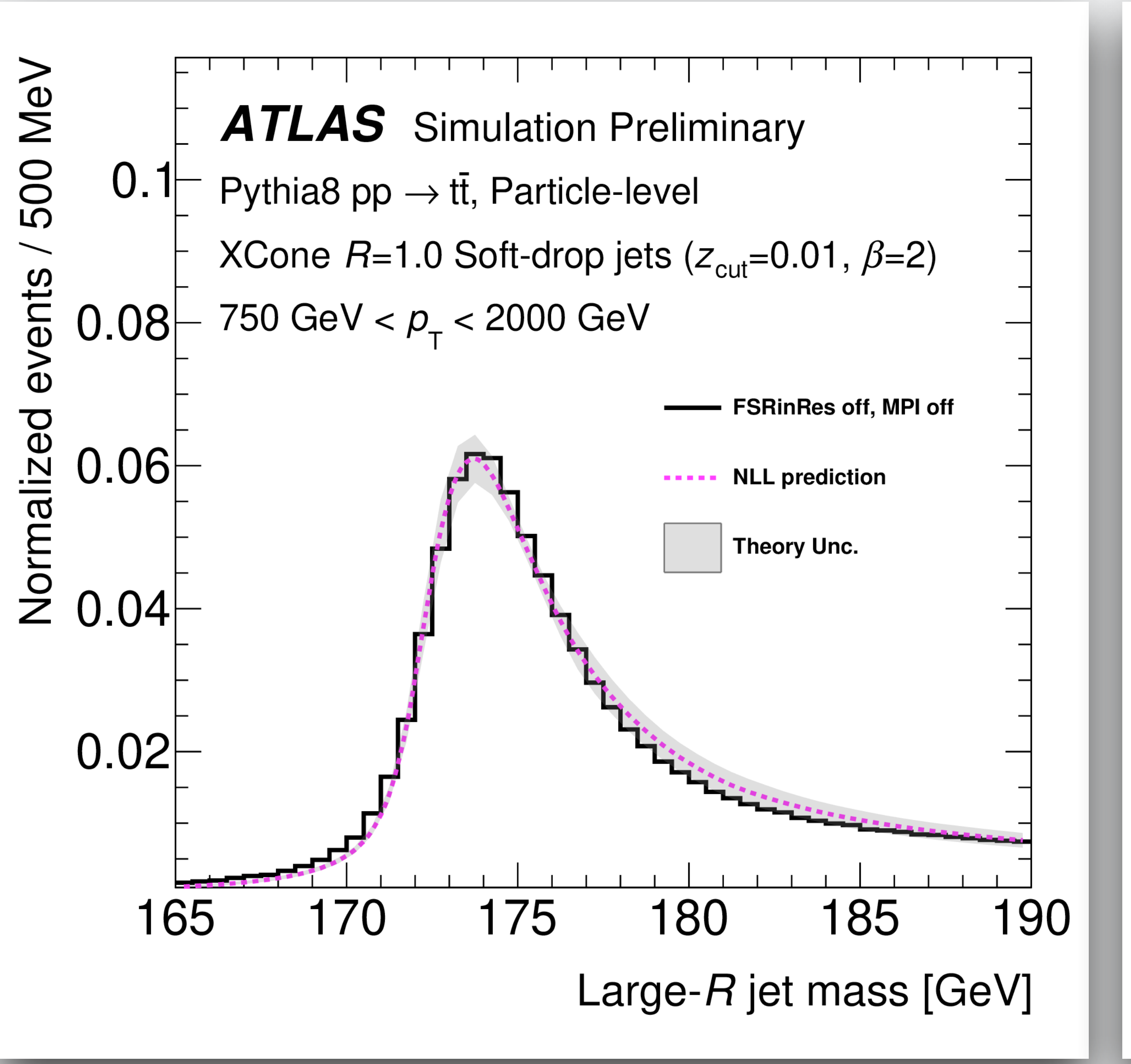
Source		$\delta m_{l^\pm}$	δm_{l^+}	δm_{l^-}
Statistical + profiled systematic		±0.32	±0.37	±0.58
JES	Correlation group intercalibration	±0.09	±0.07	±0.12
	Correlation group MPFInSitu	±0.02	±0.02	±0.01
	Correlation group uncorrelated	±0.39	±0.17	±0.83
	Total (quadrature sum)	±0.40	±0.18	±0.84
JER		<|0.01|	<|0.01|	<|0.01|
Unclustered energy		<|0.01|	<|0.01|	<|0.01|
Muon efficiencies		<|0.01|	<|0.01|	<|0.01|
Electron efficiencies		±0.01	±0.01	±0.01
Pileup		±0.14	±0.04	±0.34
b tagging		±0.20	±0.18	±0.22
QCD multijet background		±0.02	±0.01	±0.02
Mass calibration		±0.11	±0.13	±0.20
Int. luminosity		<|0.01|	<|0.01|	±0.01
CR model and ERD		±0.24 (0.017)	±0.39 (0.027)	±0.68 (0.048)
Flavor-dependent JES	Gluon	+0.52	+0.75	−0.03
	Light quark (uds)	−0.18	+0.18	−0.23
	Charm	+0.01	+0.08	+0.11
	Bottom	−0.48	−0.29	−0.31
	Total (linear sum)	−0.13	+0.72	−0.46
b quark hadronization model	b frag. Bowler–Lund	±0.03	±0.06	±0.08
	b frag. Peterson	+0.14	+0.11	+0.19
	Semileptonic b hadron decays	±0.18	±0.17	±0.19
	Total (quadrature sum)	+0.23 −0.18	+0.21 −0.18	+0.28 −0.21
Signal modeling	ISR	±0.01	±0.01	<|0.01|
	FSR	±0.28	±0.31	±0.20
	μ_R and μ_F scales	±0.09	±0.13	±0.03
	PDF+α_S	±0.06	±0.06	±0.07
	Total (quadrature sum)	±0.30	±0.34	±0.21
$t\bar{t}$ modeling	ISR	±0.11 (0.008)	±0.02 (0.001)	±0.22 (0.016)
	FSR	±0.10 (0.007)	±0.14 (0.010)	±0.40 (0.028)
	ME-PS matching scale	±0.10 (0.007)	±0.10 (0.006)	±0.10 (0.008)
	μ_R and μ_F scales	±0.03	±0.03	±0.01
	PDF+α_S	<|0.01|	<|0.01|	<|0.01|
	Top quark p_T reweighting	−0.04	−0.08	−0.04
	UE	±0.07 (0.005)	±0.04 (0.003)	±0.17 (0.012)
	Total (quadrature sum)	±0.20	+0.18 −0.20	±0.50
Parametric shapes	Signal shape	±0.05	±0.03	±0.04
	$t\bar{t}$ bkg. shape	±0.07	±0.04	±0.05
	EW bkg. shape	±0.03	±0.01	±0.02
	Total (quadrature sum)	±0.09	±0.05	±0.07
Total externalized systematic		+0.69 −0.71	+0.97 −0.65	+1.32 −1.39
Grand total		+0.76 −0.77	+1.04 −0.75	+1.44 −1.51

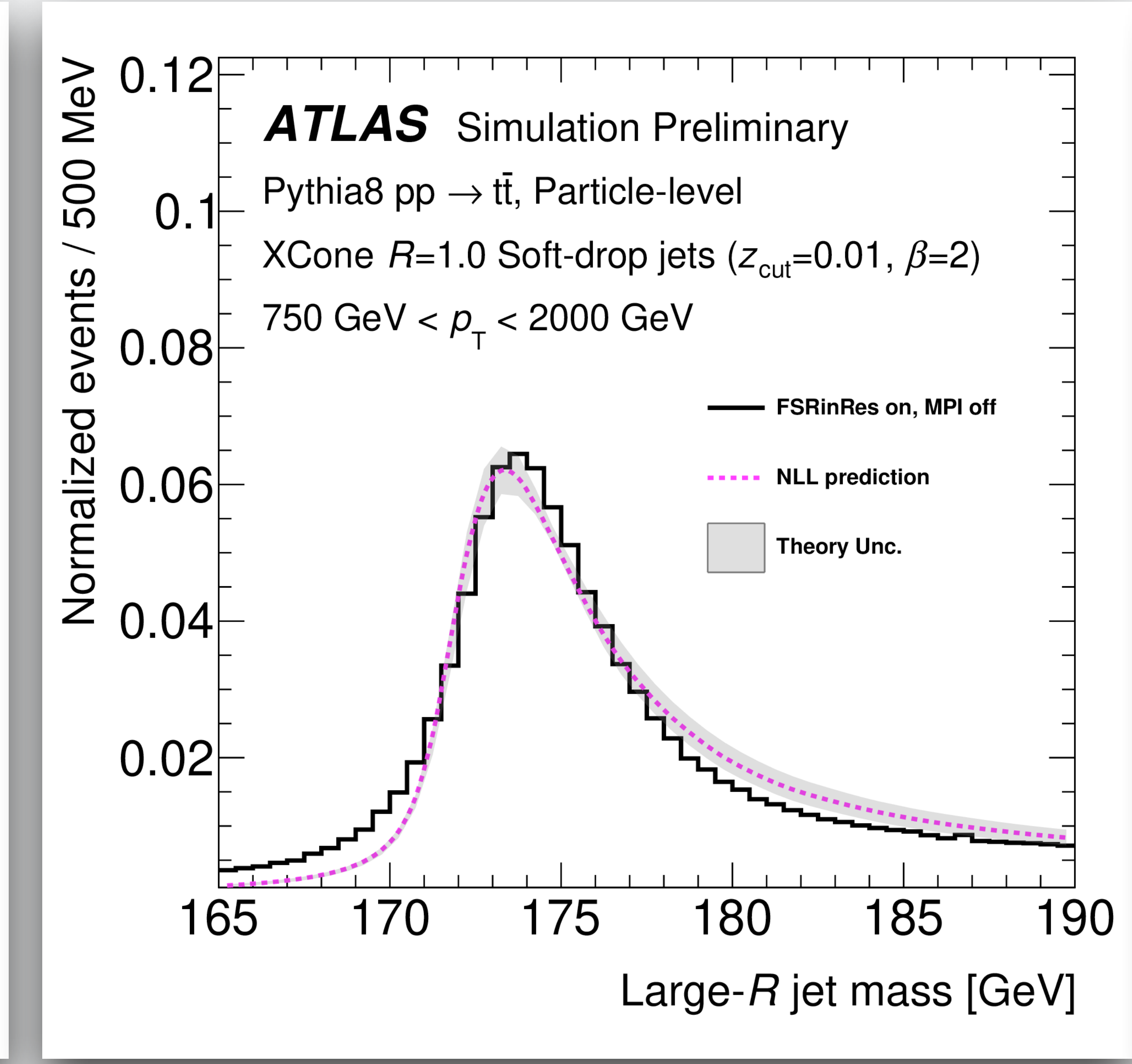
Variable	Rank Muon	Rank Electron	Description
$\Delta R_{bj'}$	1	1	Angular separation in (η, ϕ) space between the b-tagged and untagged jets
Untagged jet $\|\eta\|$ ($\|\eta_{j'}\|$)	2	2	Absolute pseudorapidity of the untagged jet
$m_{bj'}$	3	3	Invariant mass of the system comprising the b-tagged and untagged jets
$\cos\theta^*$	4	4	Cosine of the angle between the lepton and untagged jet in the rest frame of the top quark
m_T	5	5	Transverse mass as defined in Eq. (1)
FW1	—	6	First-order Fox–Wolfram moment [64, 65] (electron final state)
$\|\Delta\eta_{lb}\|$	6	7	Absolute pseudorapidity difference between the lepton and b-tagged jet
$p_T^b + p_T^{j'}$	7	8	Scalar sum of the p_T of the b-tagged and untagged jets
$\|\eta_l\|$	8	—	Absolute pseudorapidity of the lepton (muon final state)

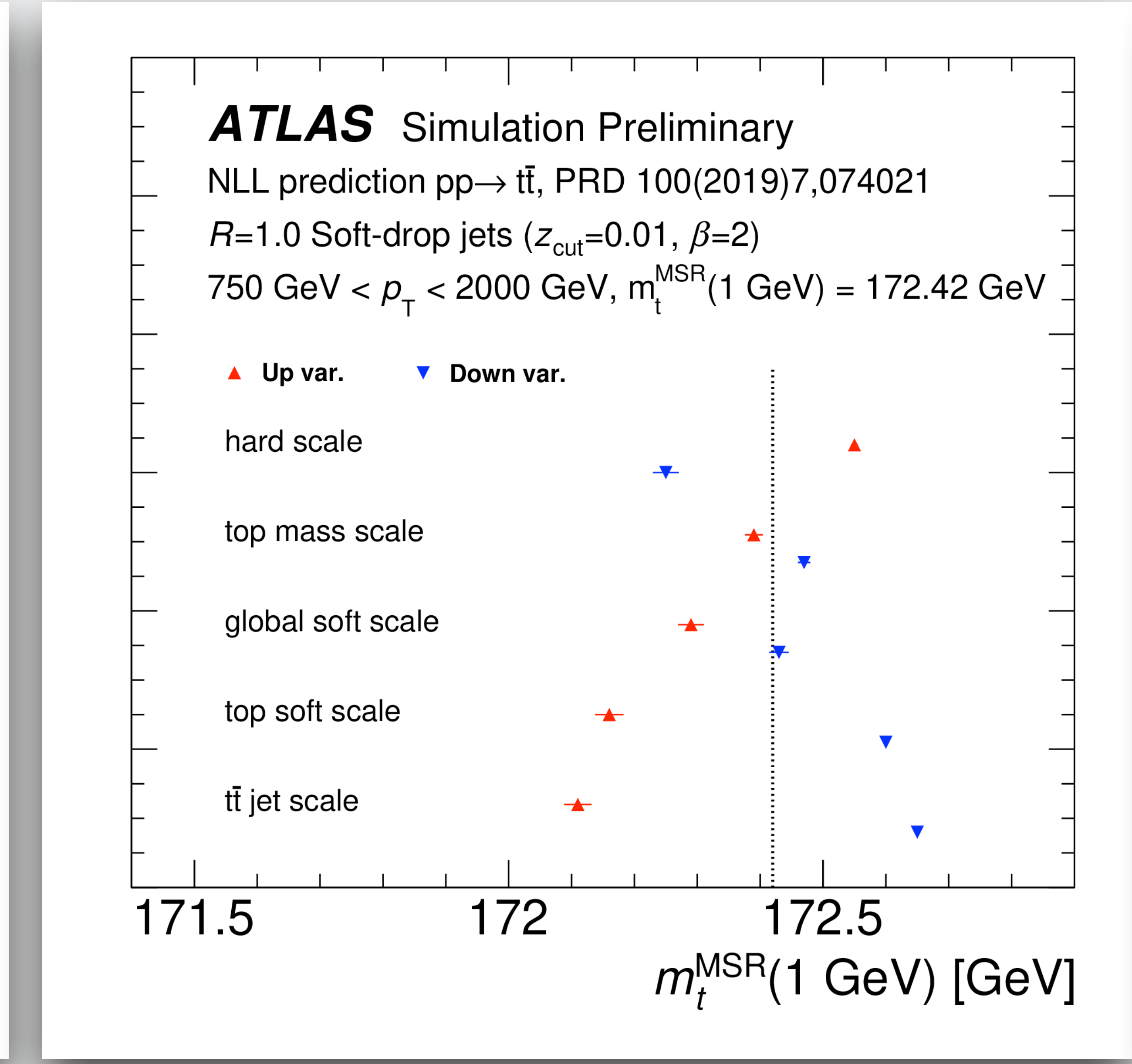
ATL-PHYS-PUB-2021-034

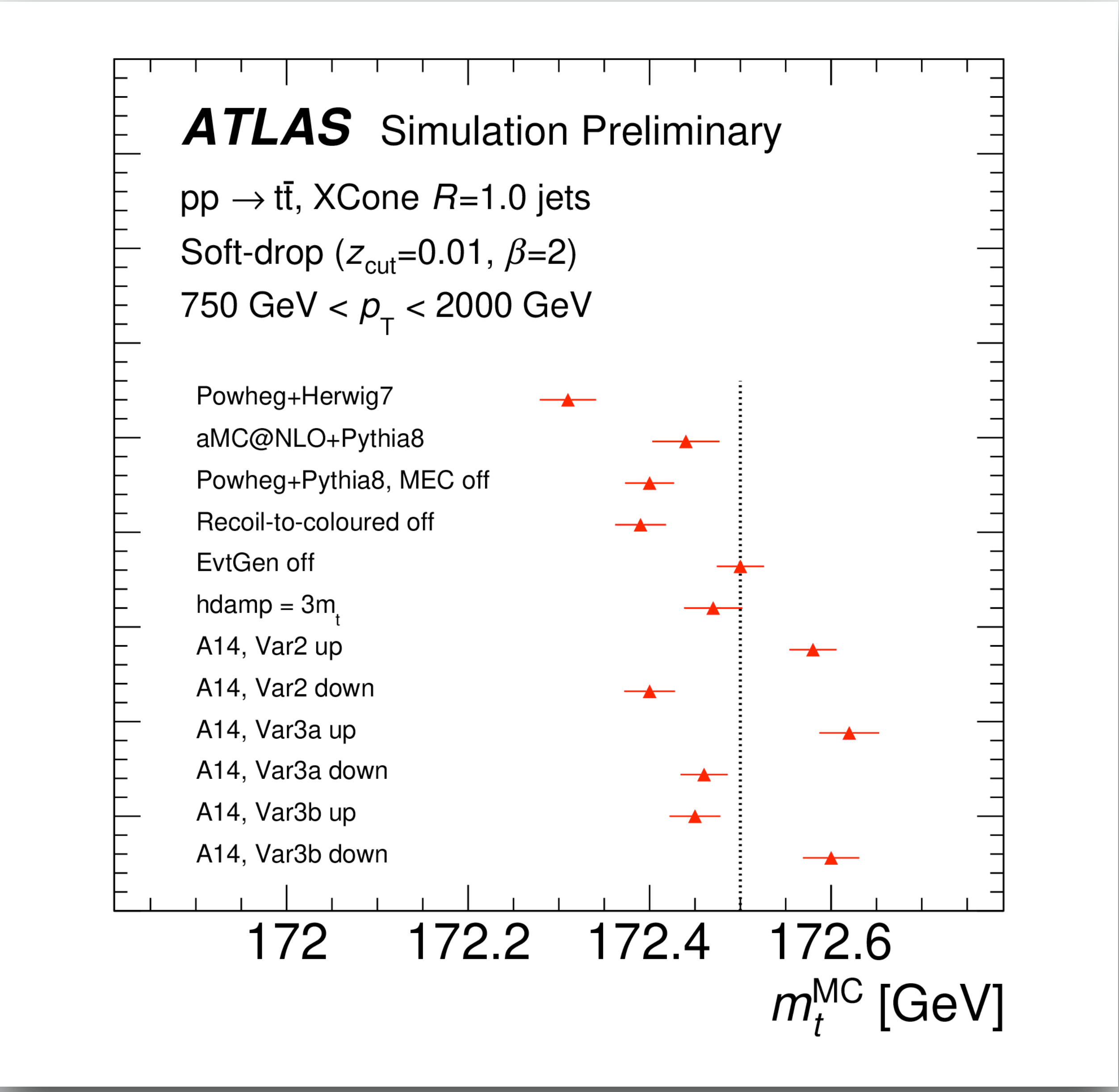
MC/pole calibration: theory vs MC

2.3 million templates in {m_t(MSR),Ω,x_2} are used to fit the MC mass peak [172.5-180 GeV]







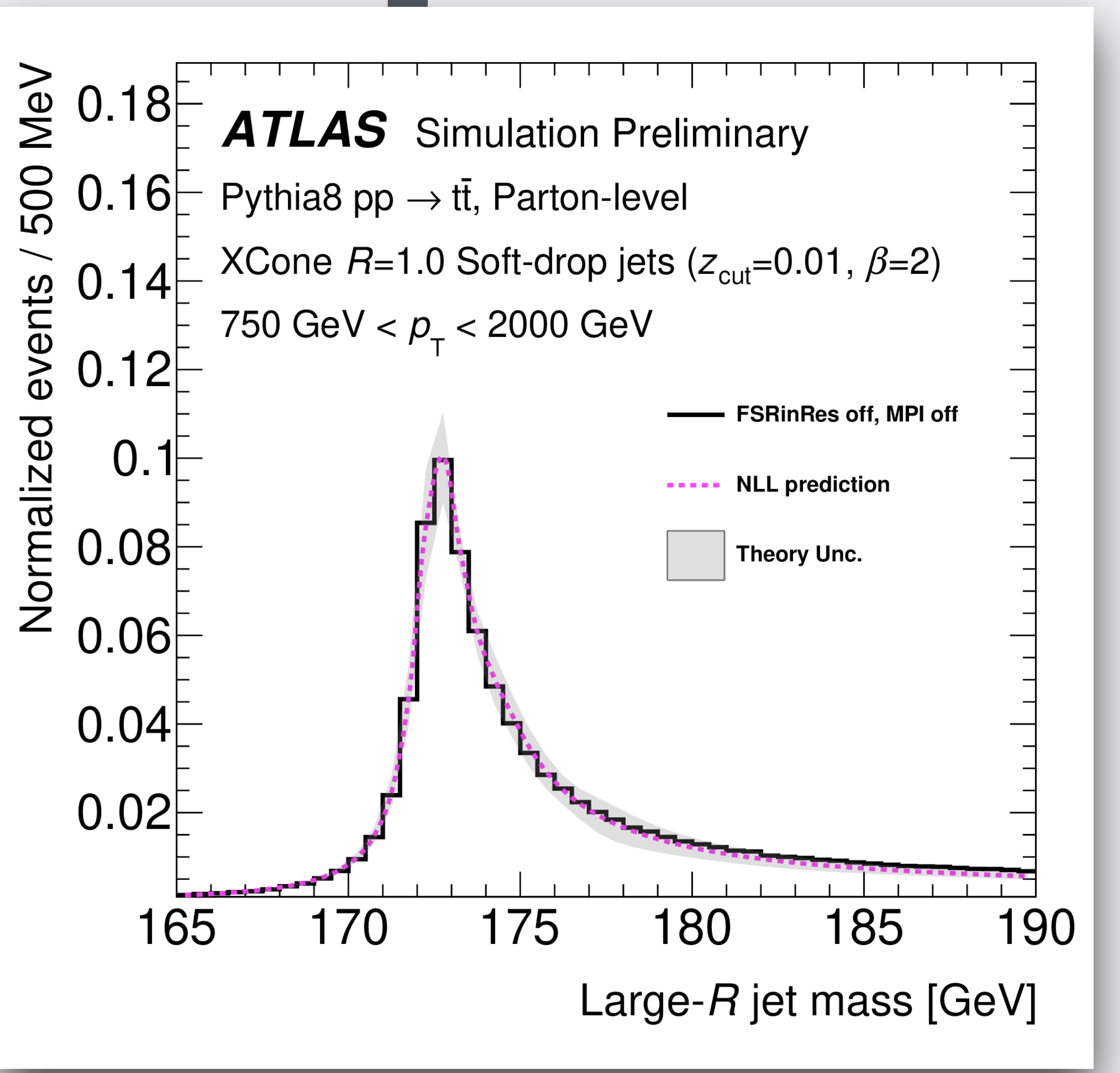


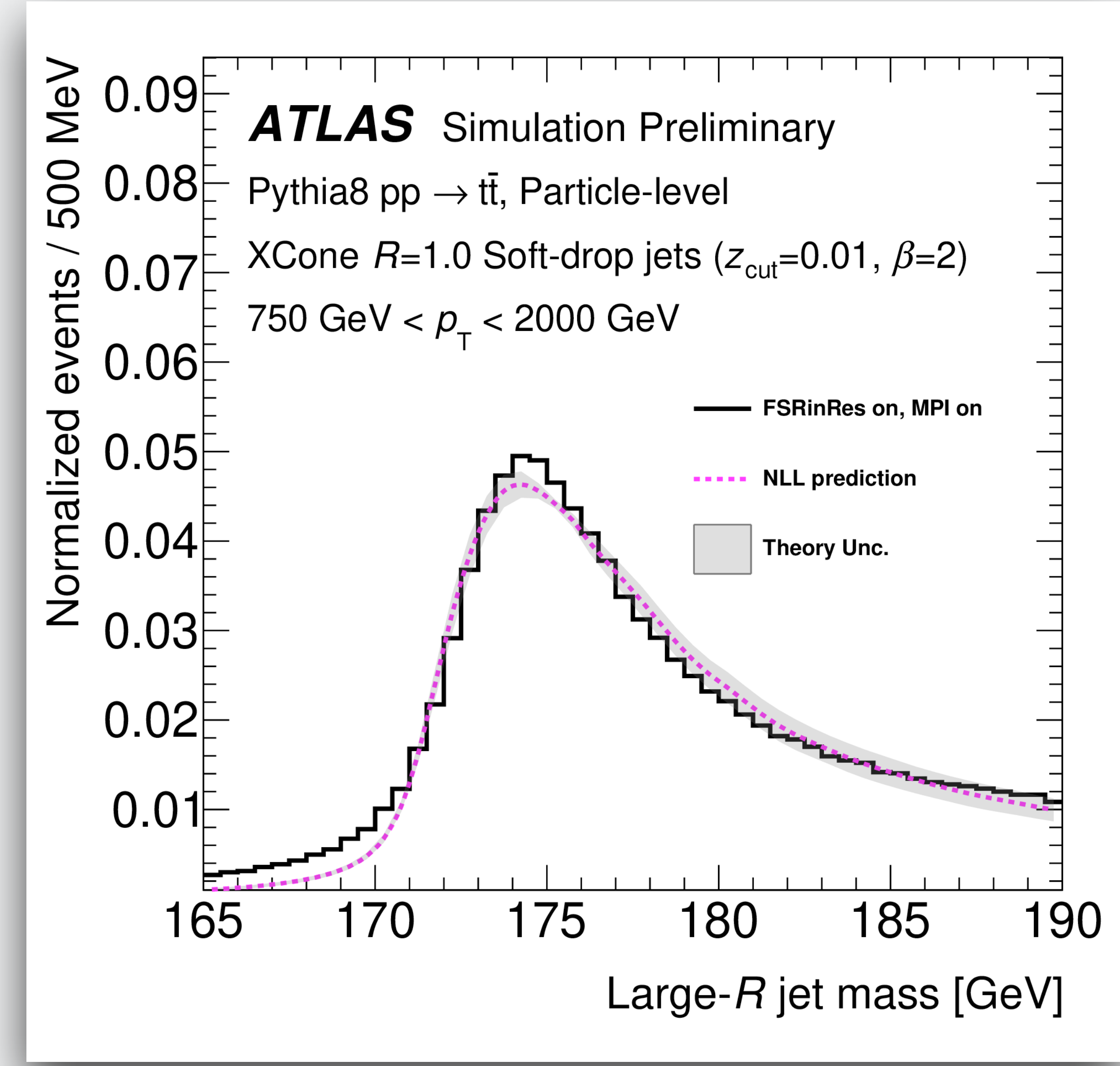
- Excellent agreement at parton-level
- Very good agreement at particle-level without FSR
- **With FSR, discrepancies in the low mass tail:** *theory treats top decays inclusively, so does not allow radiation to be groomed away*

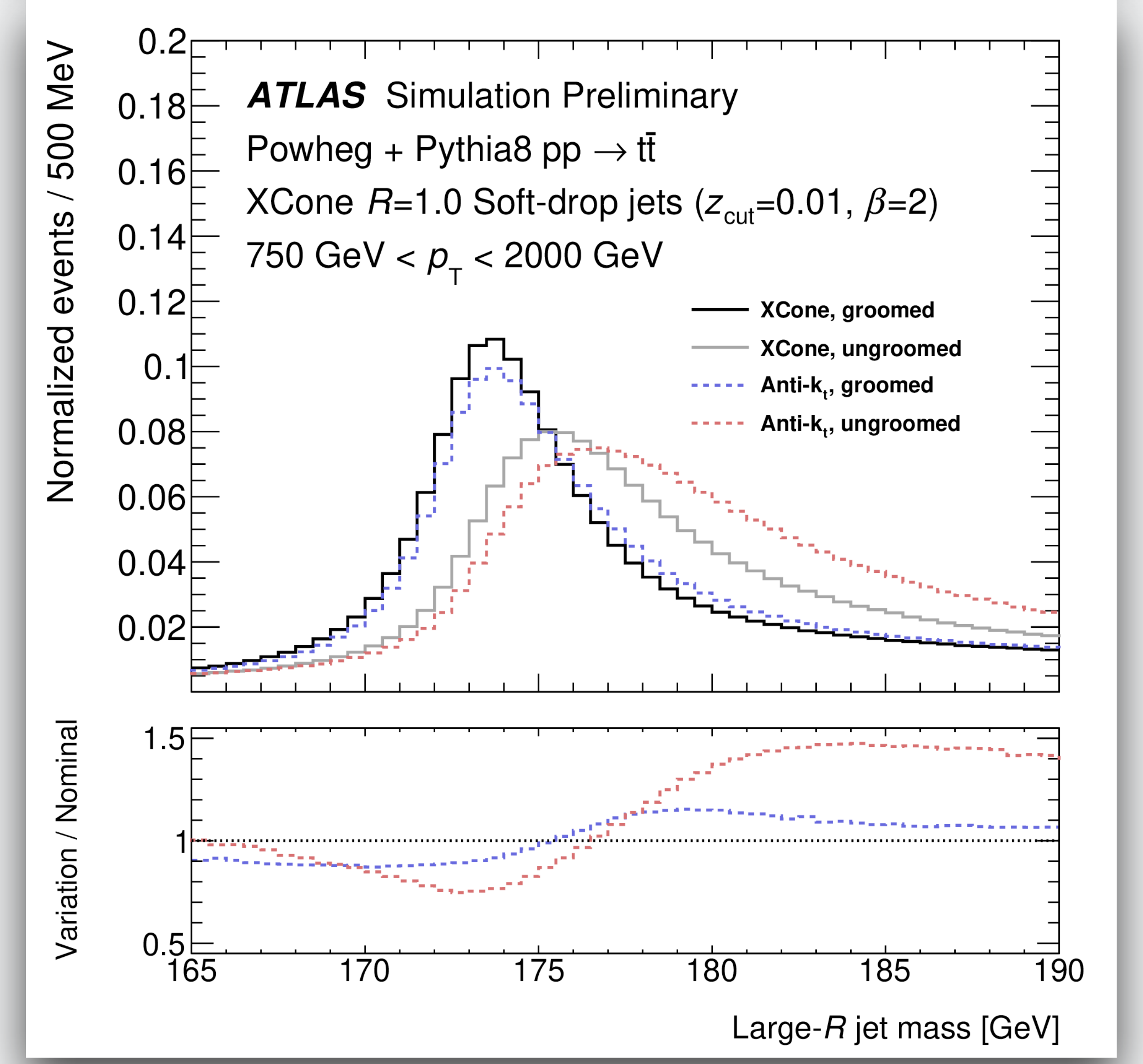
theory uncertainties:
fit nominal NLL with best-fit parameters to scale variations

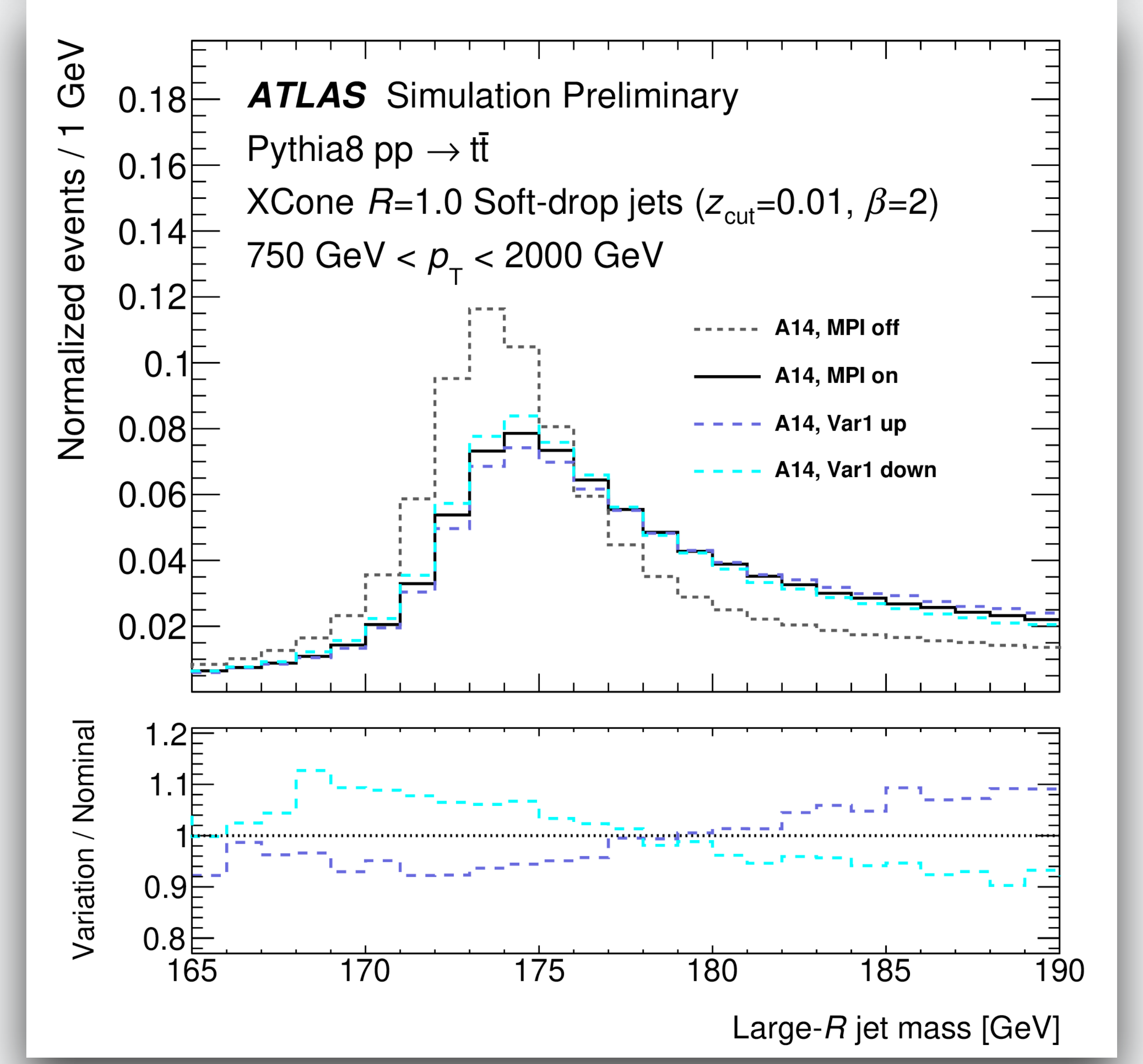
generator uncertainties:
fit nominal MC mass to alternative samples
UE uncertainties:
from A14 Var1 and alternative CR, reweighting parton-level top mass peak

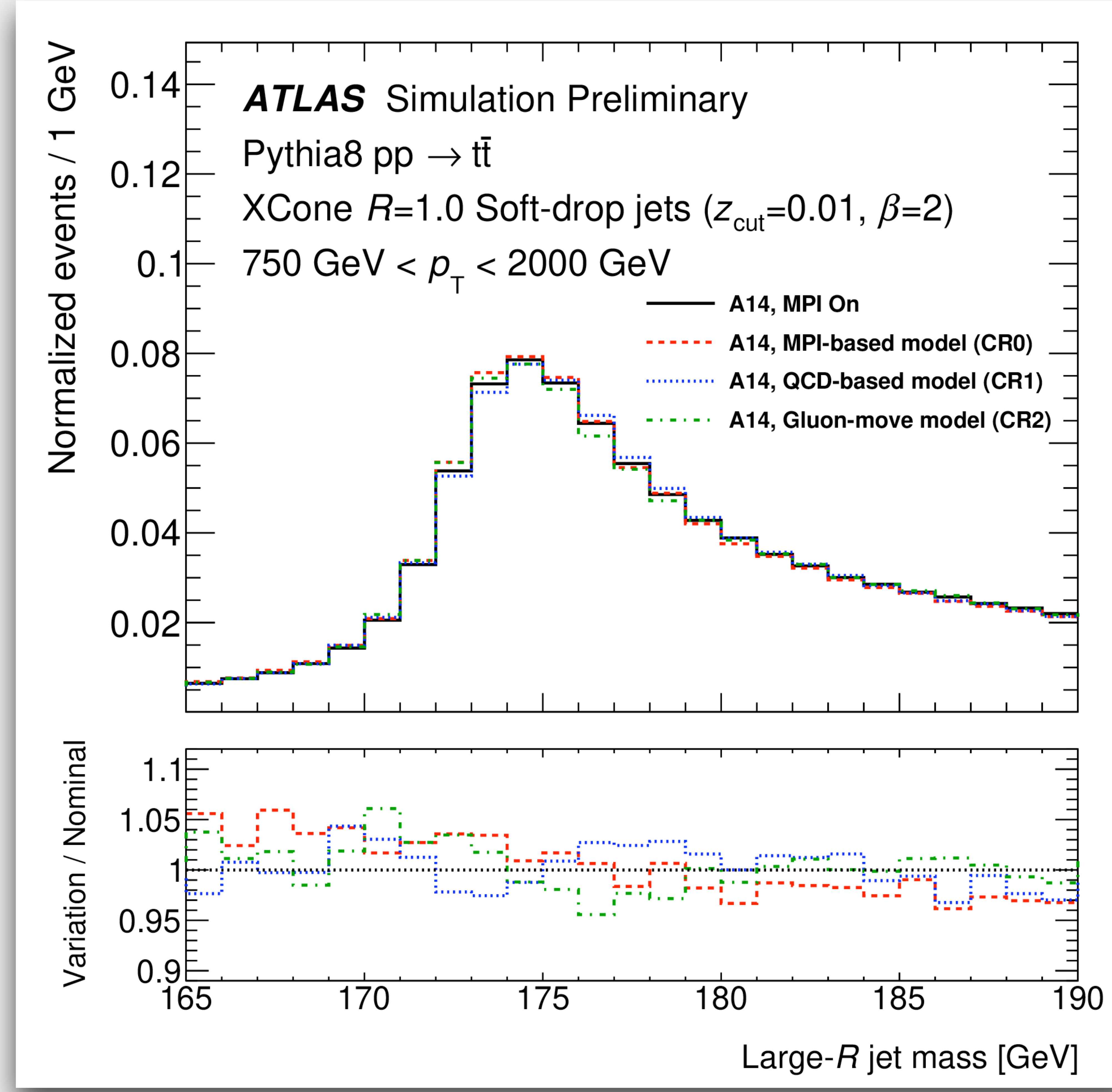
MC/pole calibration



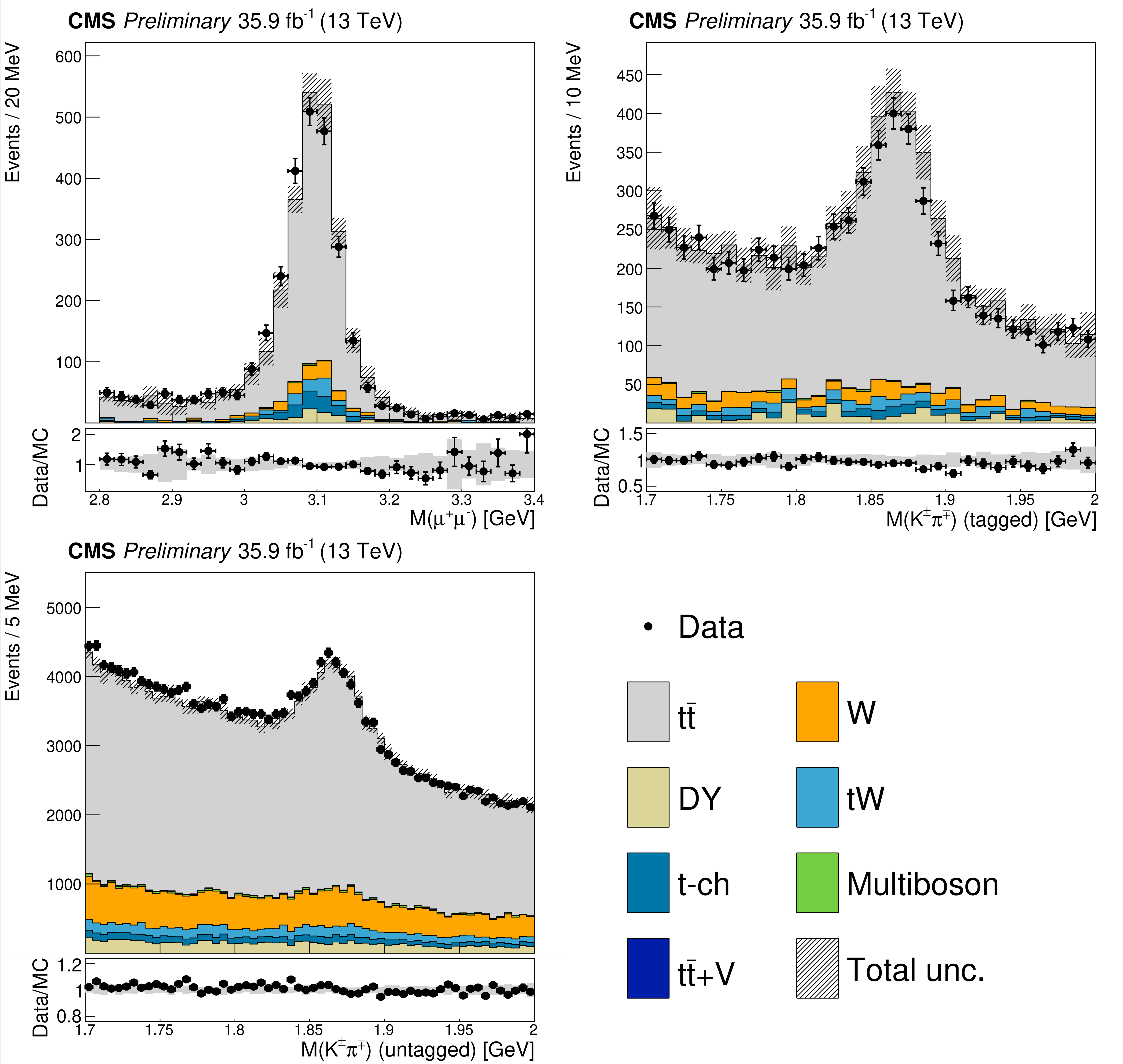








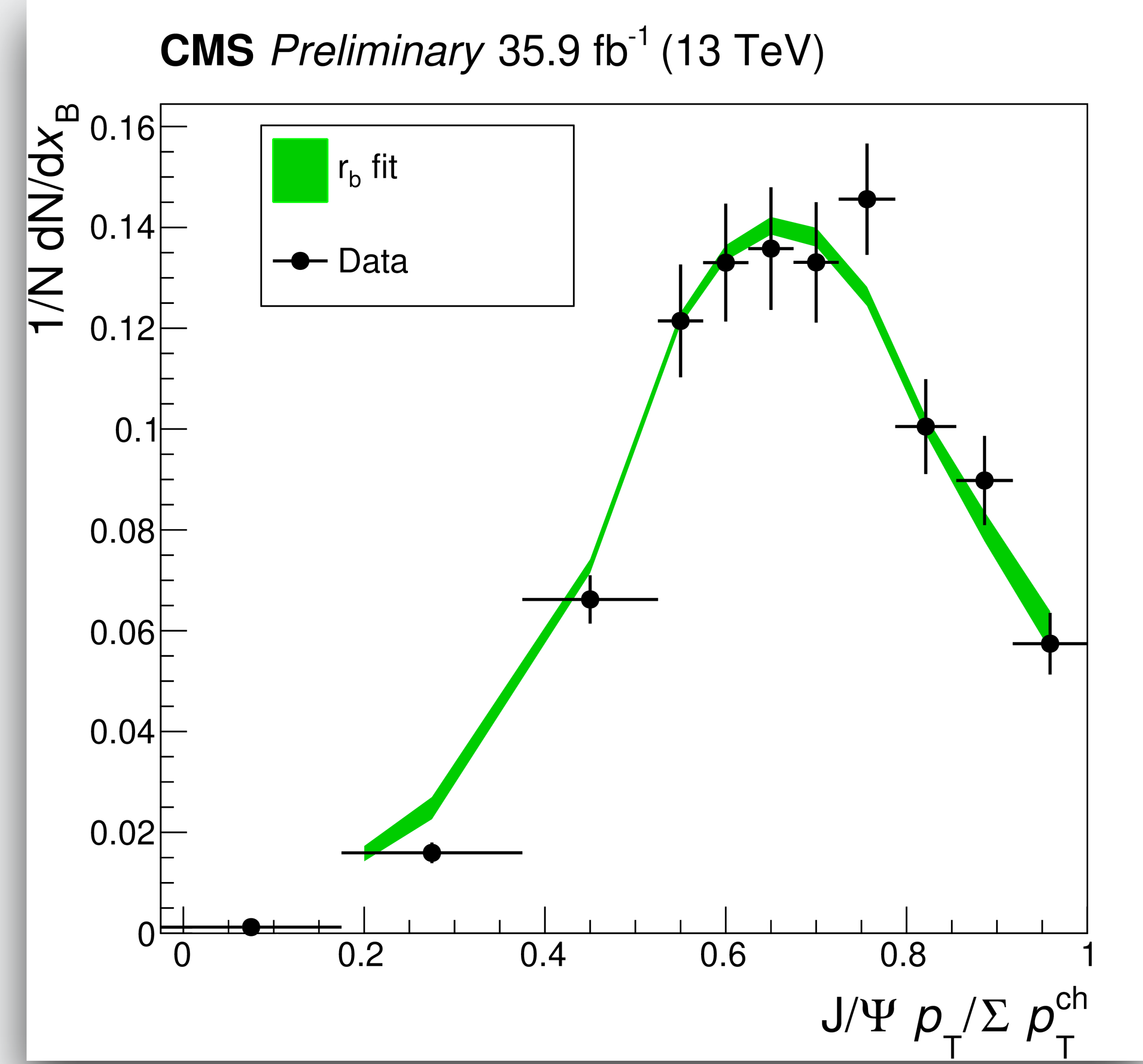
b-fragmentation: meson candidates

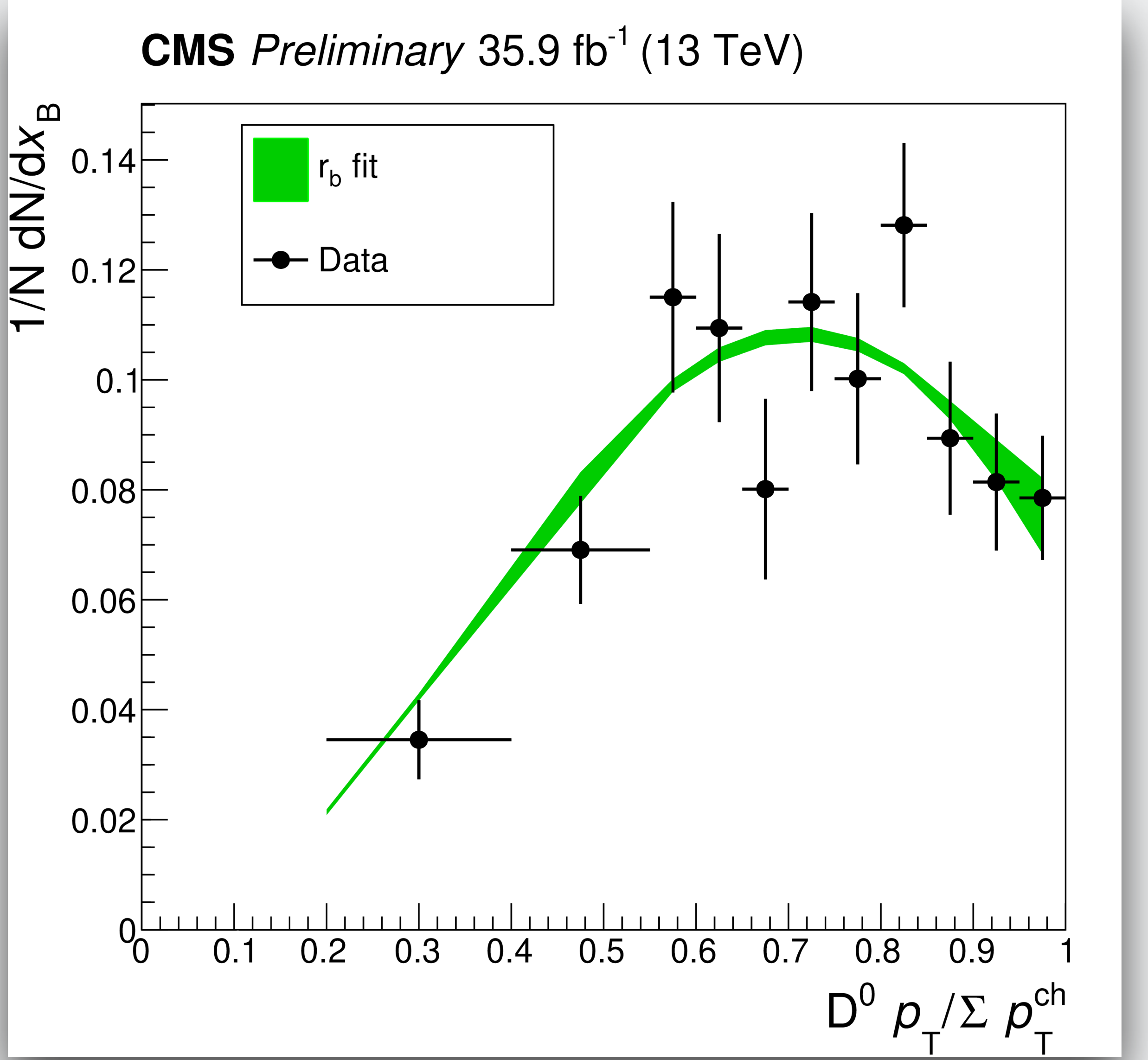


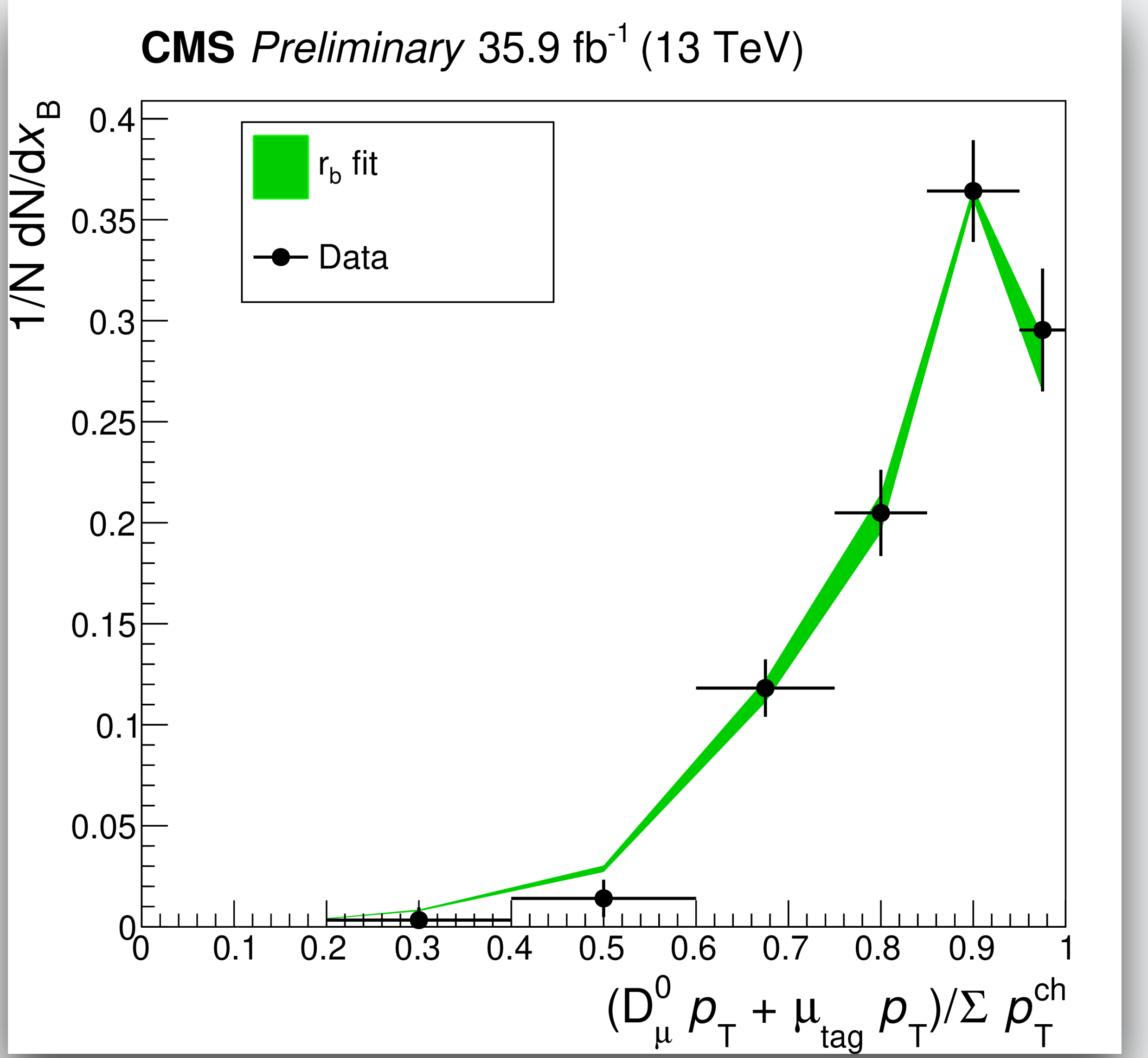
- cut on Kalman Vertex Fitter χ^2/NDF to remove combinatorial background
- cut on decay length significance to remove mesons from prompt production (and some mis-reco tracks)
- cut on H_T to remove W+jets
- **J/ψ candidate:** $\mu^+\mu^-$ with no isolation and p_T>3 GeV
- **D^0 candidate:** 2 OS tracks with p_T>5,1 GeV
- **tagged D^0 candidate:** + non-isolated muon with p_T>3 GeV

- Fit mass distributions with a Gaussian for D^0/D^0_μ and a crystal ball for J/ψ + exponential for the background, to extract probability(signal)
- Subtract background from data taking into account probability(signal)

b-fragmentation: extracting r_b from x_b







minχ^2 fit of x_b from meson candidates using 13 templates in the range $0.655<r_b<1.055$

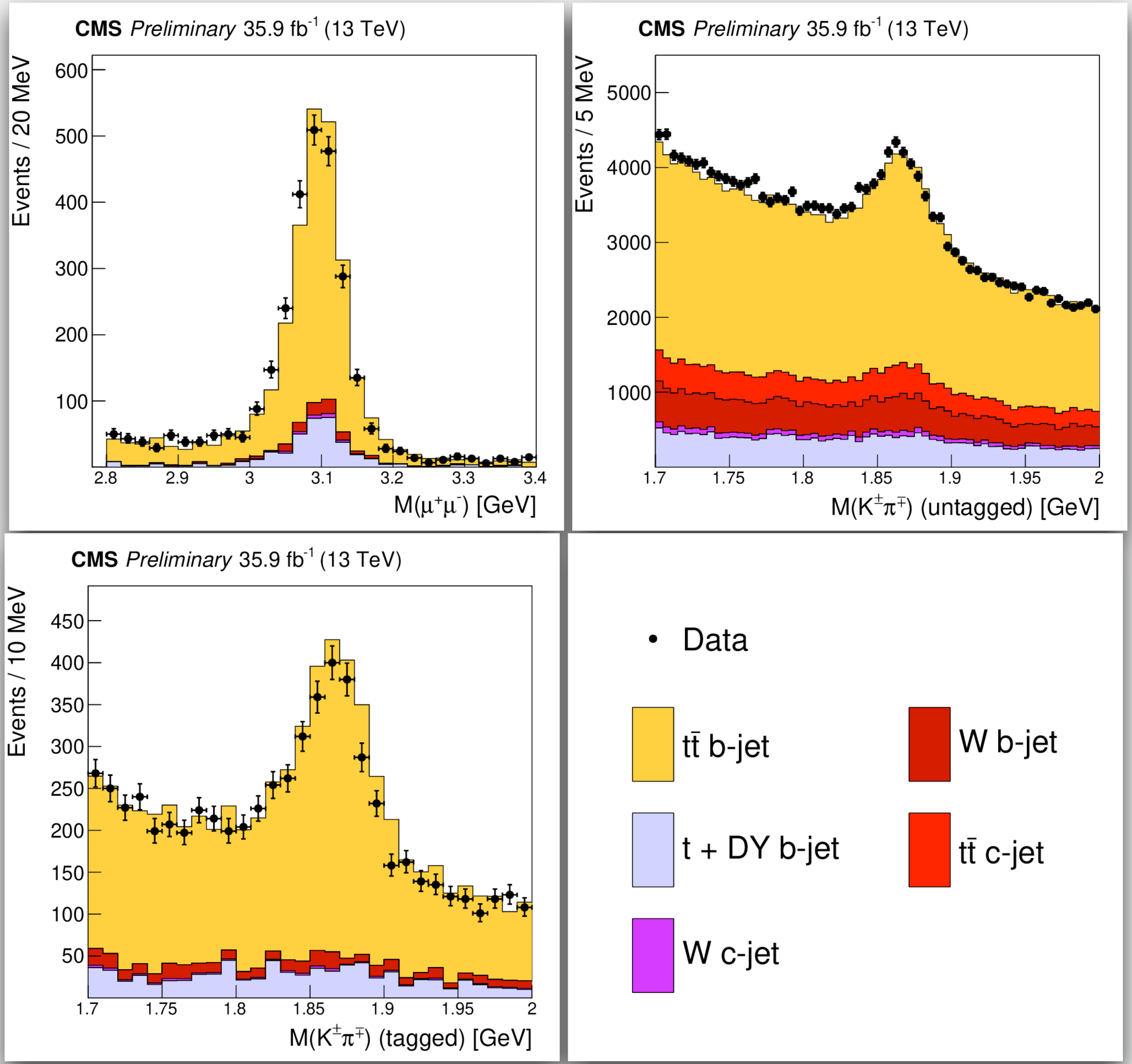
Fitted r_b values from each sample are compatible ☞ combine them!

Source	J/ψ	D^0	$D^0{}_\mu$	Combined
Fit procedure	0.022	0.025	0.025	0.017
Simulated event statistics	0.030	0.042	0.030	0.019
Signal and background functions	0.007	0.021	0.002	0.006
Background subtractions	—	0.010	0.010	0.004
Shape uncertainties	0.013	0.013	0.071	0.016
Total	0.040	0.056	0.081	0.031

Source	J/ψ	D^0	$D^0{}_\mu$	Combined
ISR	—	—	0.014	0.003
FSR	—	0.012	—	0.003
MEPS	0.013	—	0.034	0.010
CR	—	0.006	0.060	0.012
Total	0.013	0.013	0.071	0.016

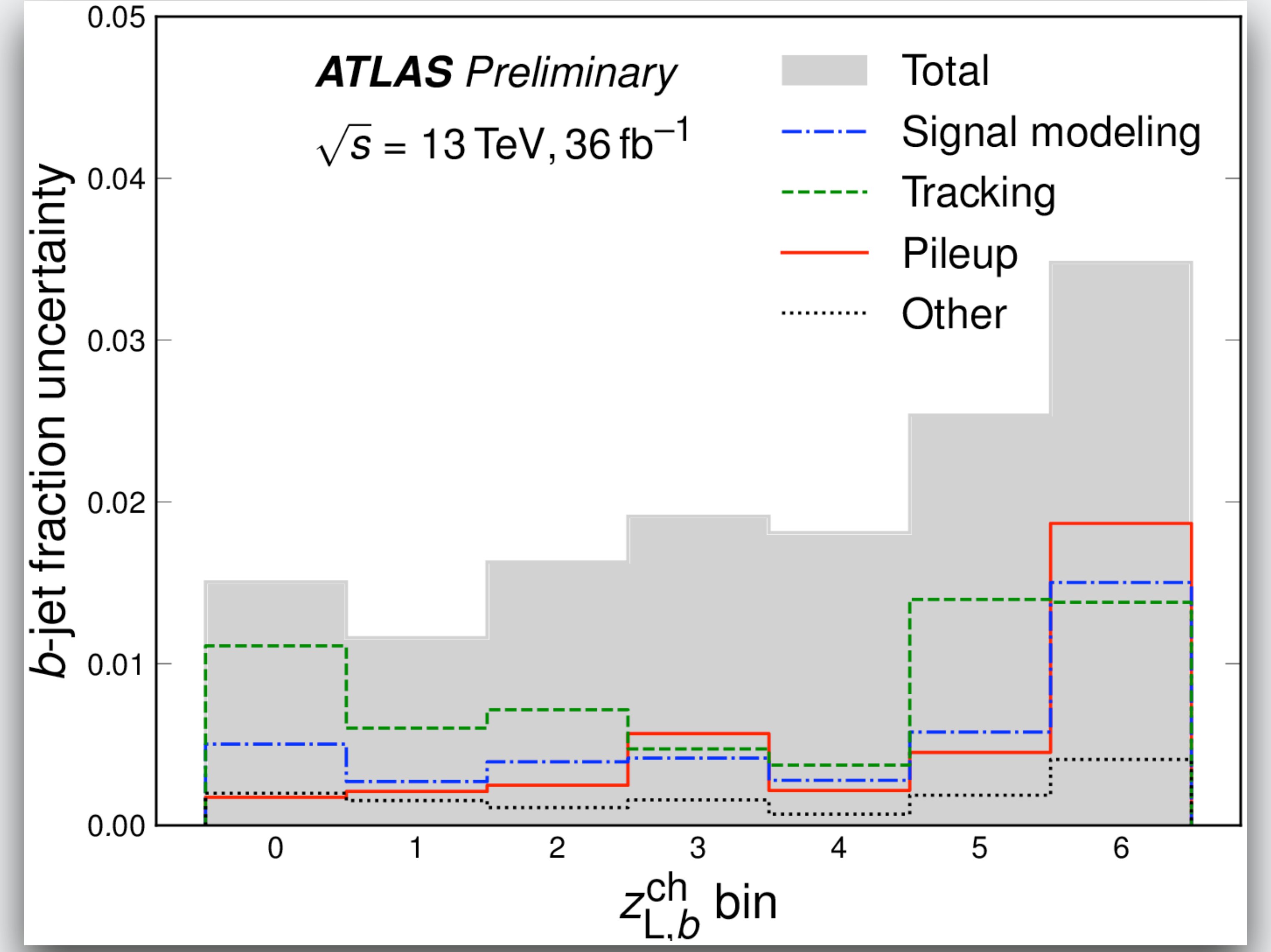
Fit procedure: account for template normalisation, MC statistics and choice of signal/background functions
Background subtractions: vary cross sections by ±25%
Shape uncertainties: variations of Pythia8 b-decay and shower settings

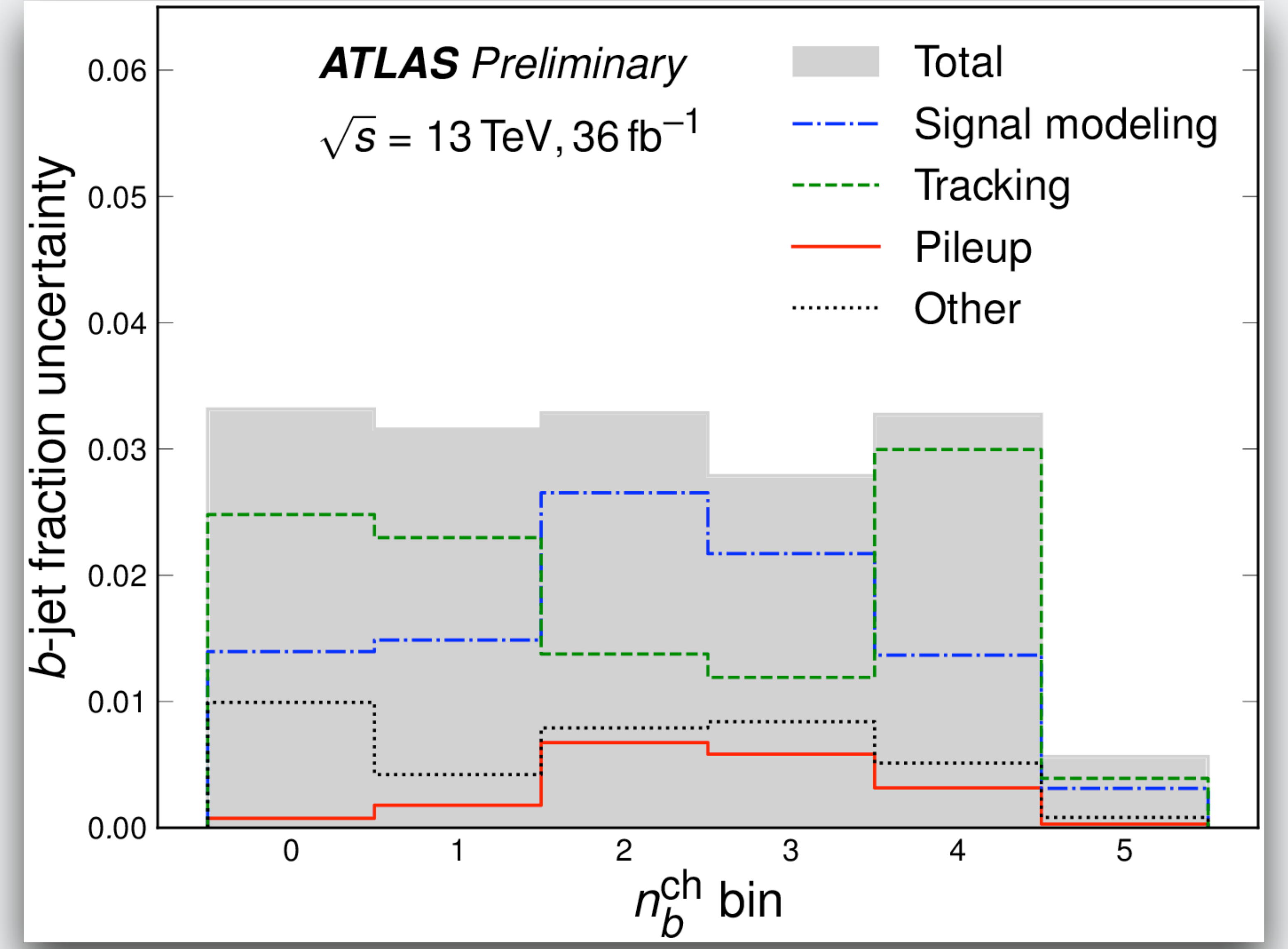
b-fragmentation

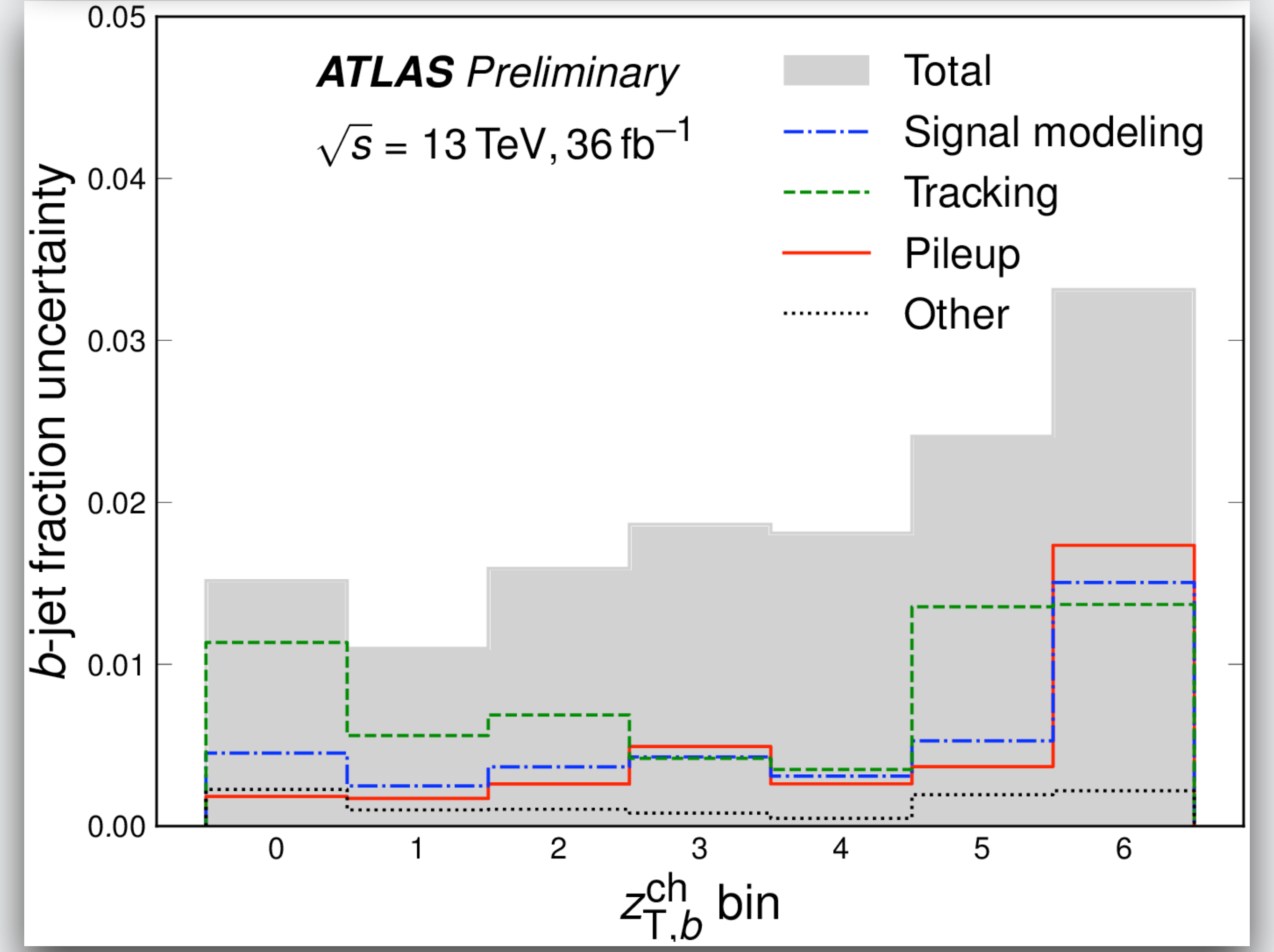


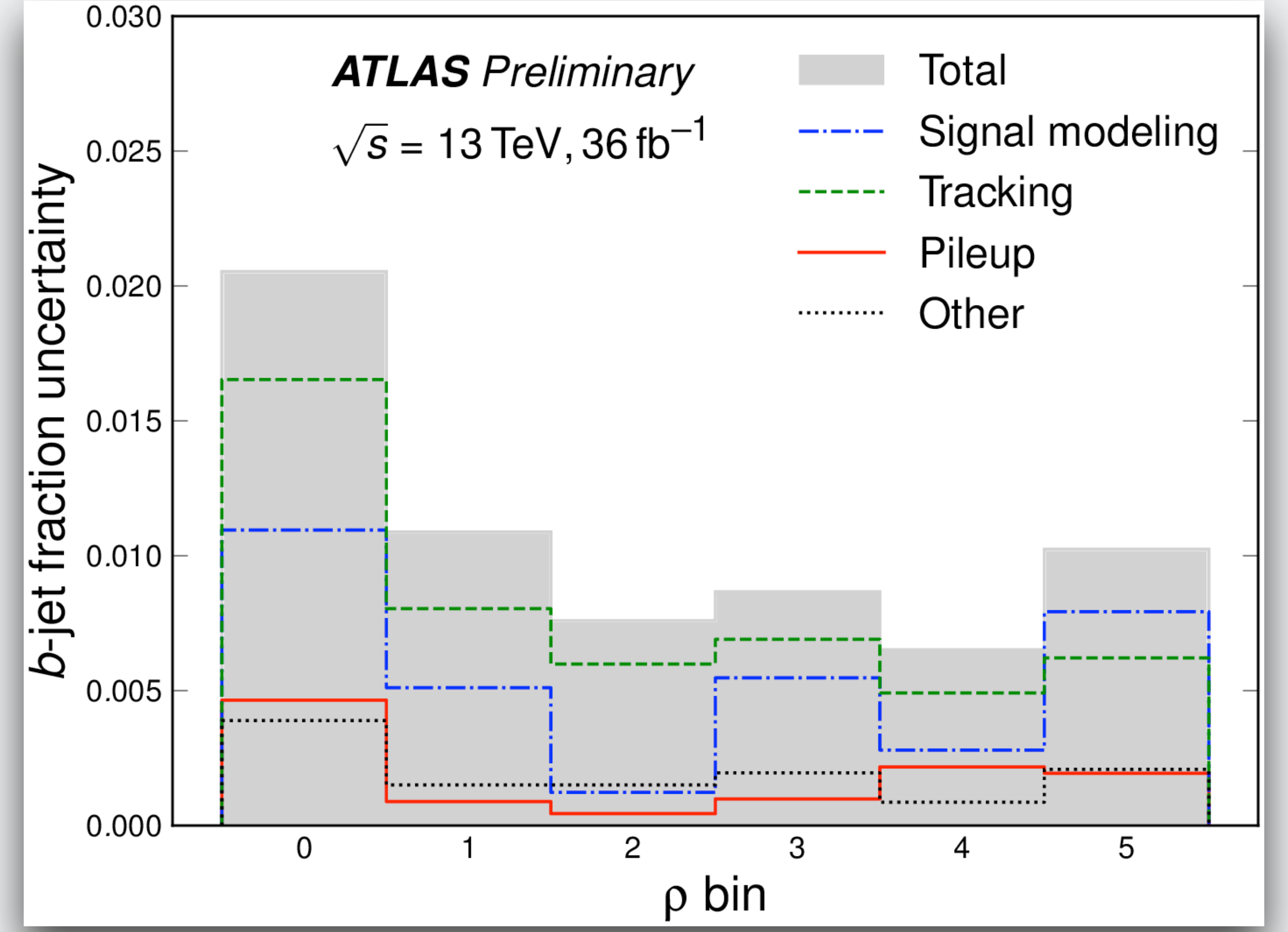
Source	J/ψ	D^0	$D^0{}_\mu$	Combined
b jets from W + jets	—	0.001	0.004	0.001
c jets from W + jets	—	—	—	—
c jets from $t\bar{t}$	—	0.010	—	0.002
b jets from single top	—	0.002	0.009	0.003
Total	—	0.010	0.010	0.004

b-jet moments



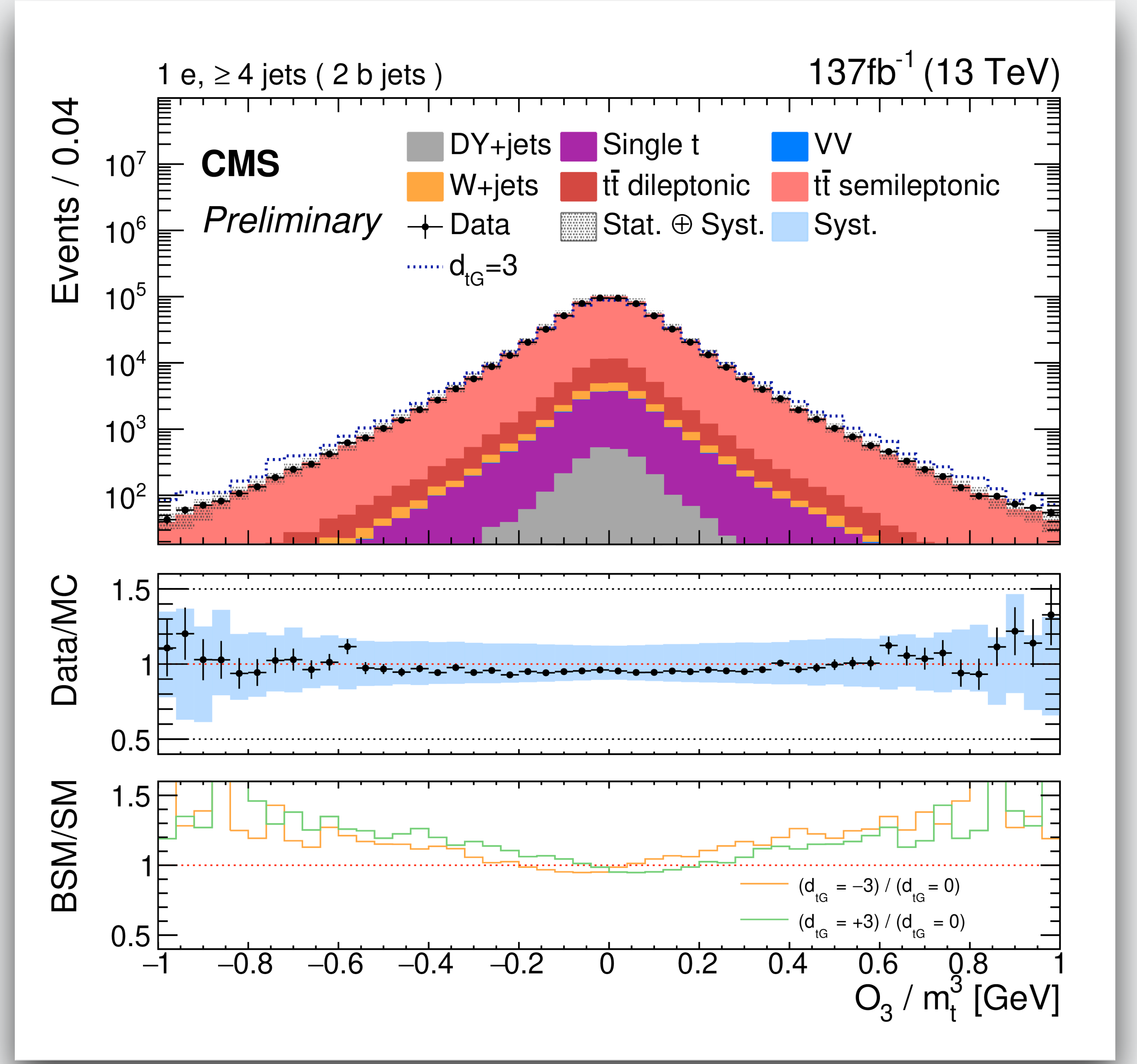




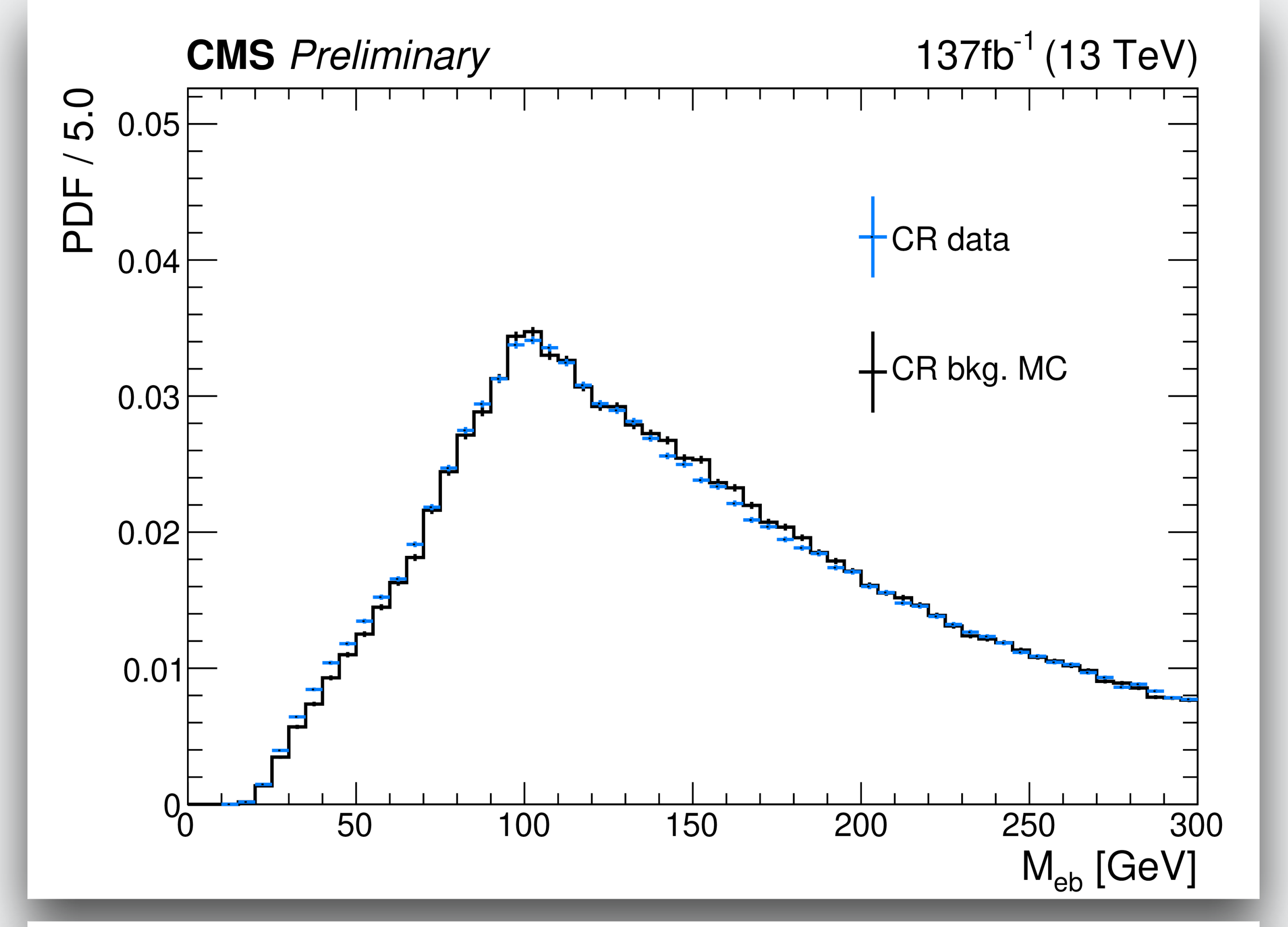


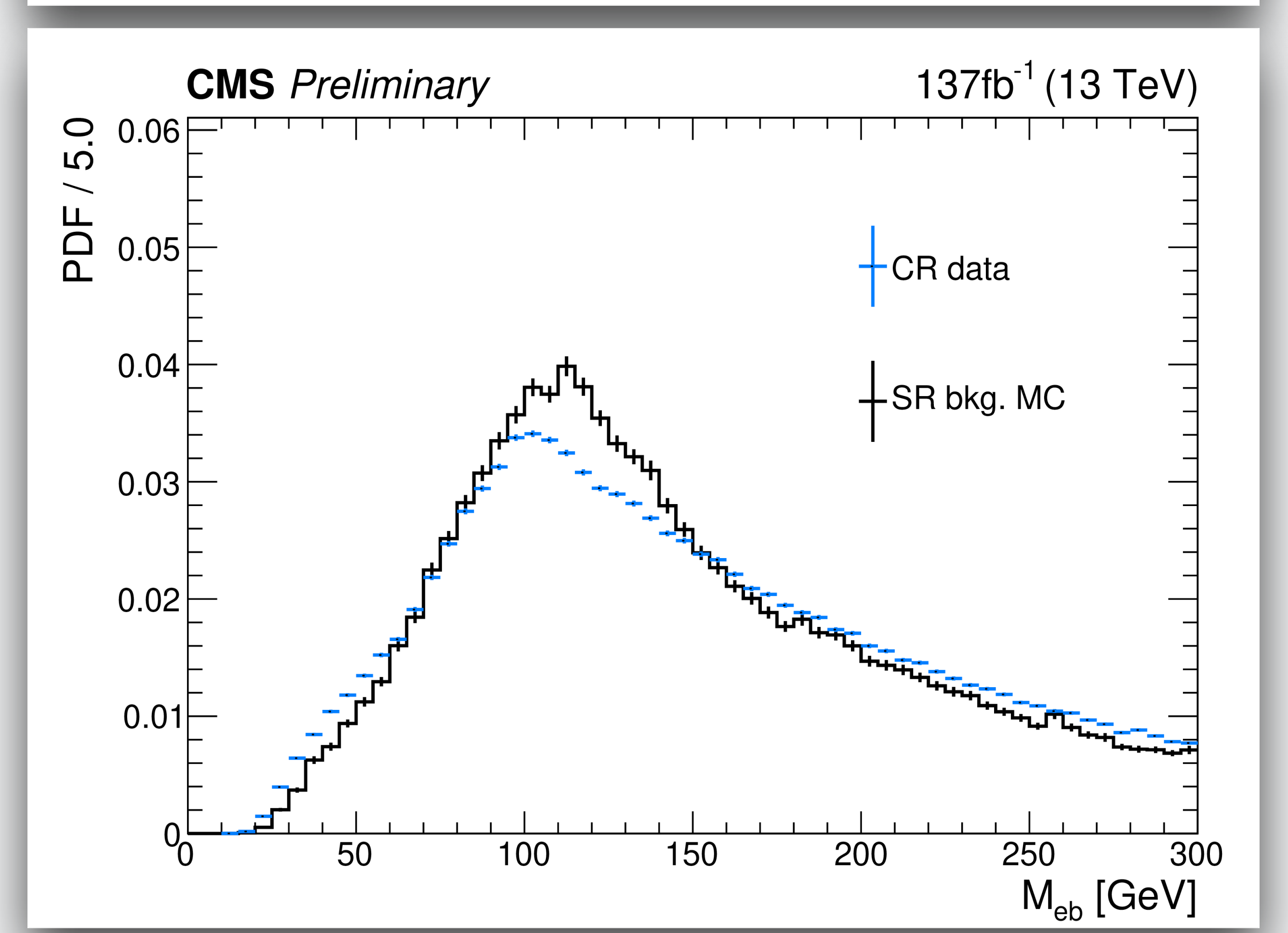
TOP-20-005

Search for ~~CP~~: template fit

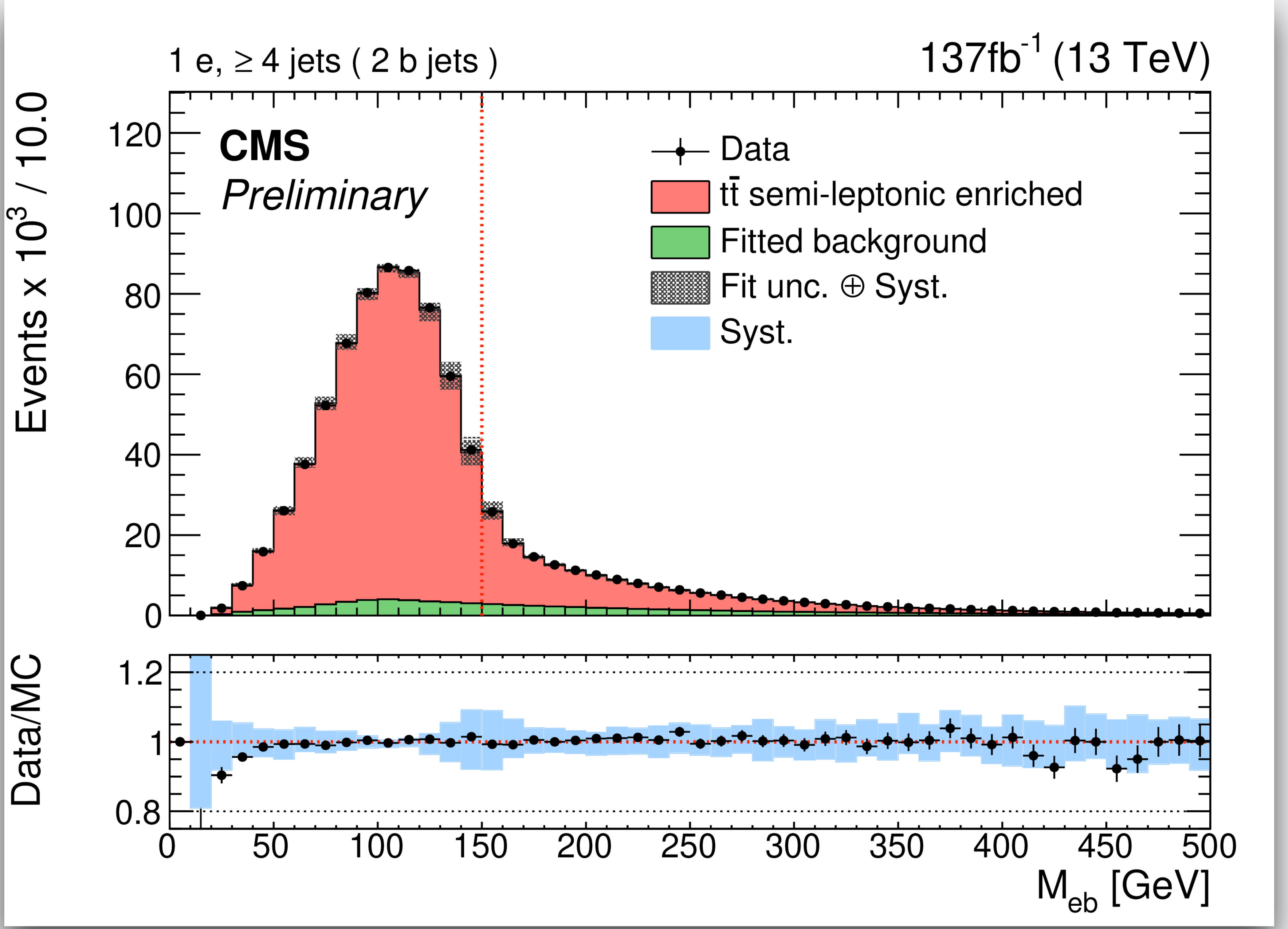


90% purity
W+jets normalisation
from CR with =0bjet





For the template fit, the background shape is taken from the W+jets CR
(non-closure in SR added as uncertainty)



SR extended to M_{lb}<500 GeV to improve fit.
Background template is the largest experimental uncertainty.
UE, MEPS (h_{damp}), FSR and CR are much larger modelling uncertainties.
No biasing of A_{CP} found.

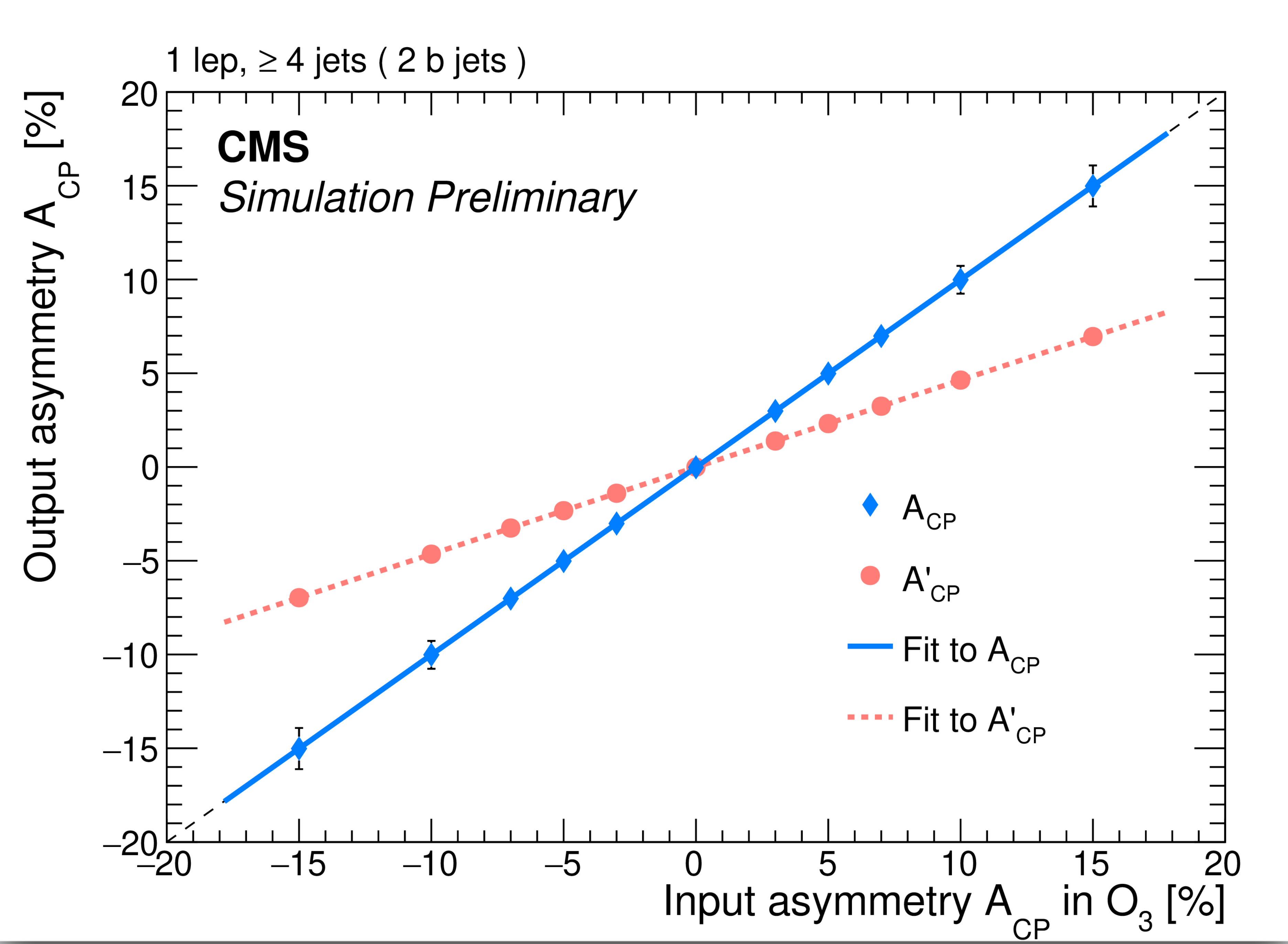
See backup for uncertainties

Search for ~~CP~~: dilution factor

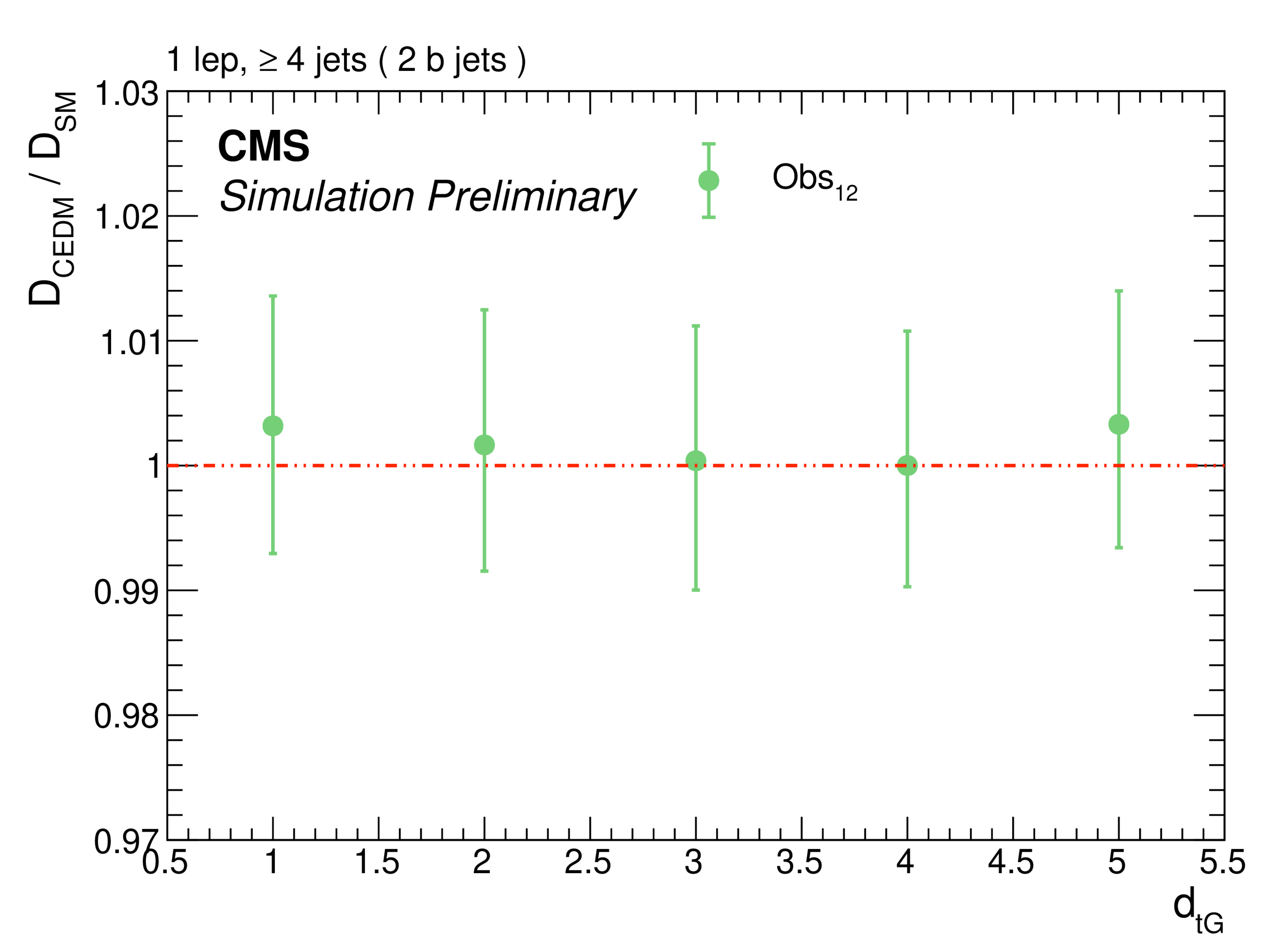
$$D = \epsilon_c - \epsilon_w$$

fractions of events with correct vs wrong sign of O_i

generate arbitrary asymmetries at generator-level and reweight the detector-level distributions, then fit ☞



no BSM model-dependence



Observable	Dilution factor D
O_3	$0.4642^{+0.0007}_{-0.0007}(\text{stat.})\ ^{+0.0135}_{-0.0167}(\text{syst.})$
O_6	$0.4368^{+0.0007}_{-0.0007}(\text{stat.})\ ^{+0.0124}_{-0.0152}(\text{syst.})$
O_{12}	$0.7381^{+0.0006}_{-0.0006}(\text{stat.})\ ^{+0.0129}_{-0.0171}(\text{syst.})$
O_{14}	$0.5989^{+0.0007}_{-0.0007}(\text{stat.})\ ^{+0.0112}_{-0.0143}(\text{syst.})$

TOP-20-005

Search for ~~CP~~

Process	Electron channel (%)	Muon channel (%)
$t\bar{t}$ (semileptonic)	89.92	89.48
$t\bar{t}$ (dileptonic)	5.45	5.48
$t\bar{t}$ (hadronic)	0.06	0.10
Single t	2.89	2.94
QCD	0.18	0.64
DY+jets	0.41	0.22
ZZ / WW / WZ	0.05	0.05
W+jets	1.04	1.08

	Electron channel	Muon channel
Fitted $t\bar{t}$ (semileptonic+dileptonic) events	$604\,700 \pm 1200$	$1\,062\,600 \pm 1500$
Fitted background events	$34\,030 \pm 480$	$58\,490 \pm 820$
Fitted $t\bar{t}$ (semileptonic+dileptonic) fraction (%)	94.67 ± 0.07	94.78 ± 0.06

Syst. source		$A'_{CP}(\%)$			
		O_3	O_6	O_{12}	O_{14}
Experimental uncertainties					
PU re-weight	$+1\sigma$	−0.0008	−0.0003	+0.0023	+0.0040
	-1σ	+0.0010	+0.0007	−0.0017	−0.0044
b-tag scale factor (b and c quark)	$+1\sigma$	+0.0002	+0.0001	+0.0000	+0.0000
	-1σ	−0.0002	−0.0003	−0.0000	−0.0002
b-tag scale factor (light quark)	$+1\sigma$	−0.0003	−0.0003	−0.0009	−0.0007
	-1σ	+0.0004	−0.0000	+0.0007	+0.0005
Lepton	$+1\sigma$	−0.0002	−0.0001	−0.0001	−0.0004
	-1σ	+0.0002	−0.0001	+0.0000	+0.0001
JER	$+1\sigma$	−0.0028	−0.0069	−0.0024	−0.0070
	-1σ	−0.0029	+0.0032	−0.0021	+0.0026
JEC	$+1\sigma$	−0.0051	−0.0046	−0.0046	−0.0062
	-1σ	−0.0018	+0.0065	+0.0011	+0.0041
Bkg. template	-	+0.0061	+0.0050	+0.0139	+0.0016
Theoretical uncertainties					
PDF	$+1\sigma$	+0.0008	−0.0008	+0.0003	+0.0003
	-1σ	−0.0008	+0.0006	−0.0004	−0.0006
μ_R and μ_F	$+1\sigma$	+0.0008	+0.0008	+0.0013	+0.0007
	-1σ	+0.0012	−0.0002	−0.0033	−0.0004
ISR	$+1\sigma$	+0.0006	−0.0005	+0.0017	+0.0024
	-1σ	−0.0004	+0.0004	−0.0015	−0.0021
FSR	$+1\sigma$	−0.0001	−0.0215	+0.0053	−0.0129
	-1σ	−0.0008	+0.0122	−0.0017	+0.0060
Color reconnection	CR1	−0.0162	+0.0186	+0.0091	+0.0384
	CR2	+0.0000	−0.0206	−0.0464	+0.0304
ME-PS matching	$+1\sigma$	−0.0235	−0.0043	−0.0185	+0.0352
	-1σ	+0.0399	+0.0177	+0.0139	+0.0376
Underlying event	$+1\sigma$	−0.0515	−0.0576	−0.0082	+0.0116
	-1σ	−0.0099	+0.0355	+0.0218	+0.0424
Flavour response	$+1\sigma$	−0.0017	−0.0007	−0.0033	−0.0105
	-1σ	−0.0024	+0.0024	−0.0004	+0.0070
Top mass variation	+1 GeV	+0.0049	+0.0152	+0.0119	+0.0082
	−1 GeV	−0.0179	−0.0118	−0.0097	−0.0046
Per event resolution	+10%	−0.0027	−0.0022	+0.0023	−0.0005
	−10%	−0.0004	+0.0040	+0.0014	+0.0048
W+HF enriched	-	−0.0174	−0.0132	−0.0102	−0.0098
w/o Top p_T reweighting	-	−0.0008	−0.0005	−0.0000	−0.0000

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Test of LFU: analysis strategy

Lepton Flavour Universality: $g_e=g_\mu=g_\tau$ in the SM

Test by measuring BR(W→τν)/BR(W→μν) in dilepton ttbar events, considering leptonic τ decays (much better resolution than hadronic τ) in the full Run 2 dataset

Most precise result is LEP ~2.5%, 2.7σ higher than SM

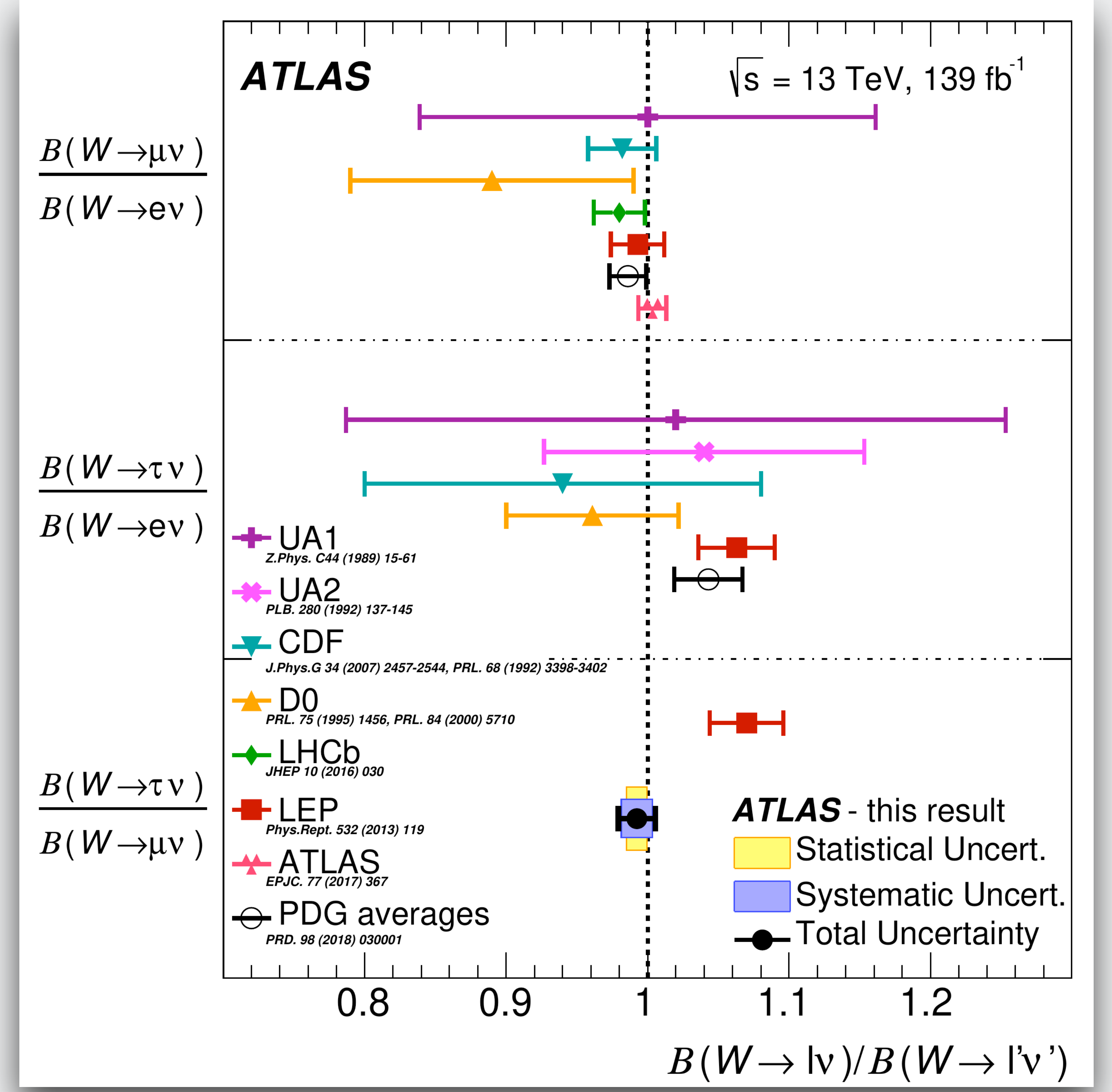
➡Use 1 lepton to trigger and tag event, perform 2D fit of probe muon (p_T vs $|d_0|$)

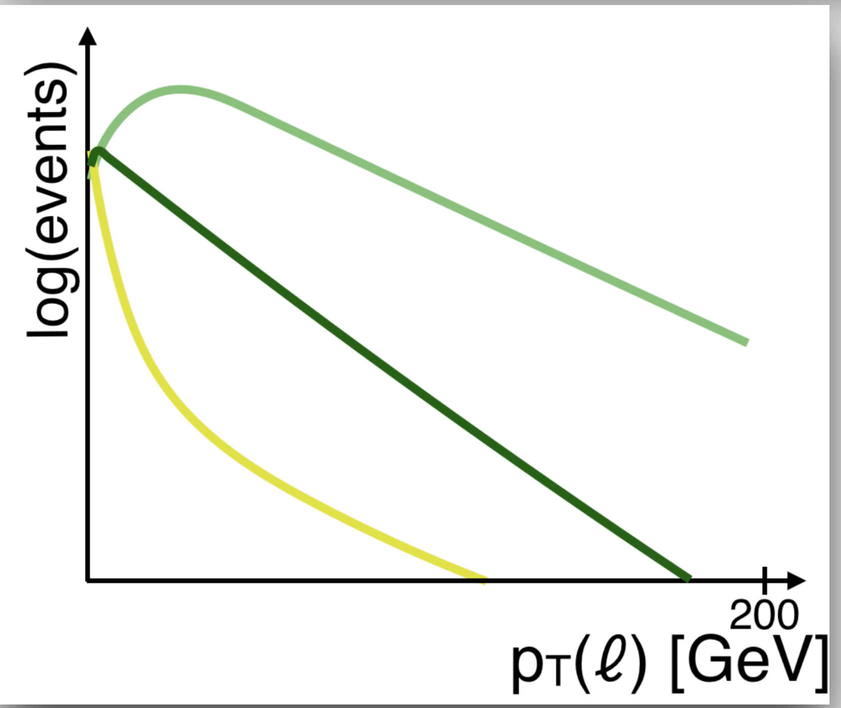
➡Probe muon can be lower p_T and avoids trigger SF uncertainties

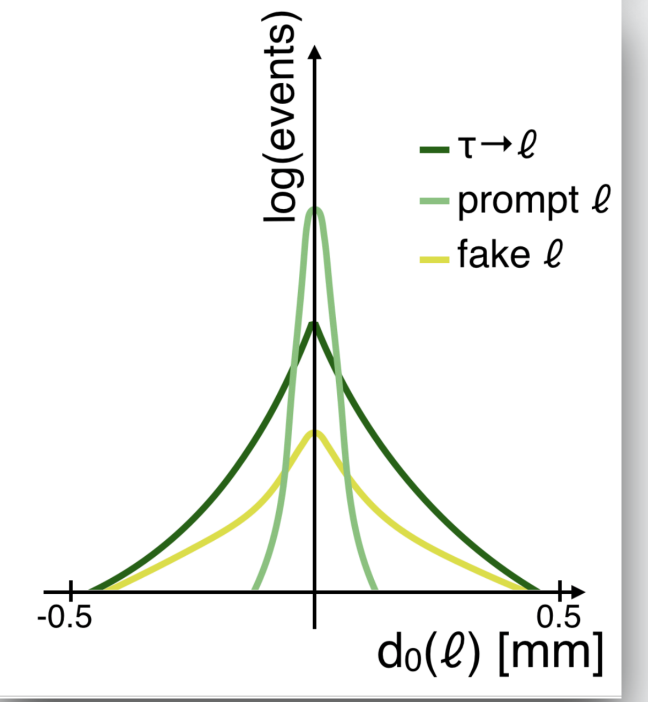
➡*Selection:* single e/μ trigger p_T>27 GeV, probe muons p_T>5 GeV, ≥2 bjets@70% p_T>25 GeV, M(μμ) cuts to remove resonances (Z and <15 GeV)

➡Calibrate $|d_0|$ in Z→μμ events, normalise Z→μμ, hadron→μ, top+V and VV in CRs

➡Profile likelihood fit to extract ttbar normalisation and R(τ/μ)



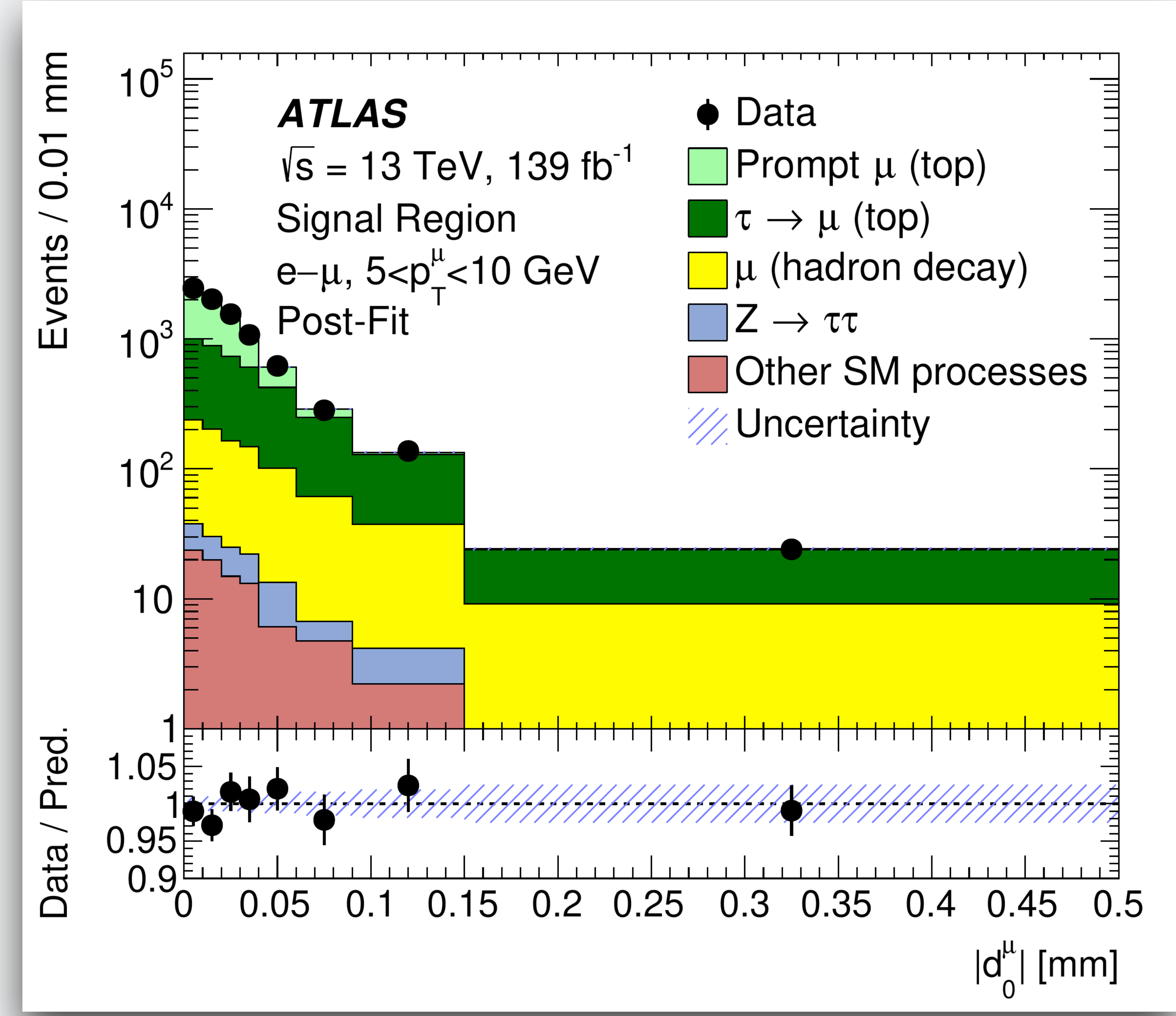


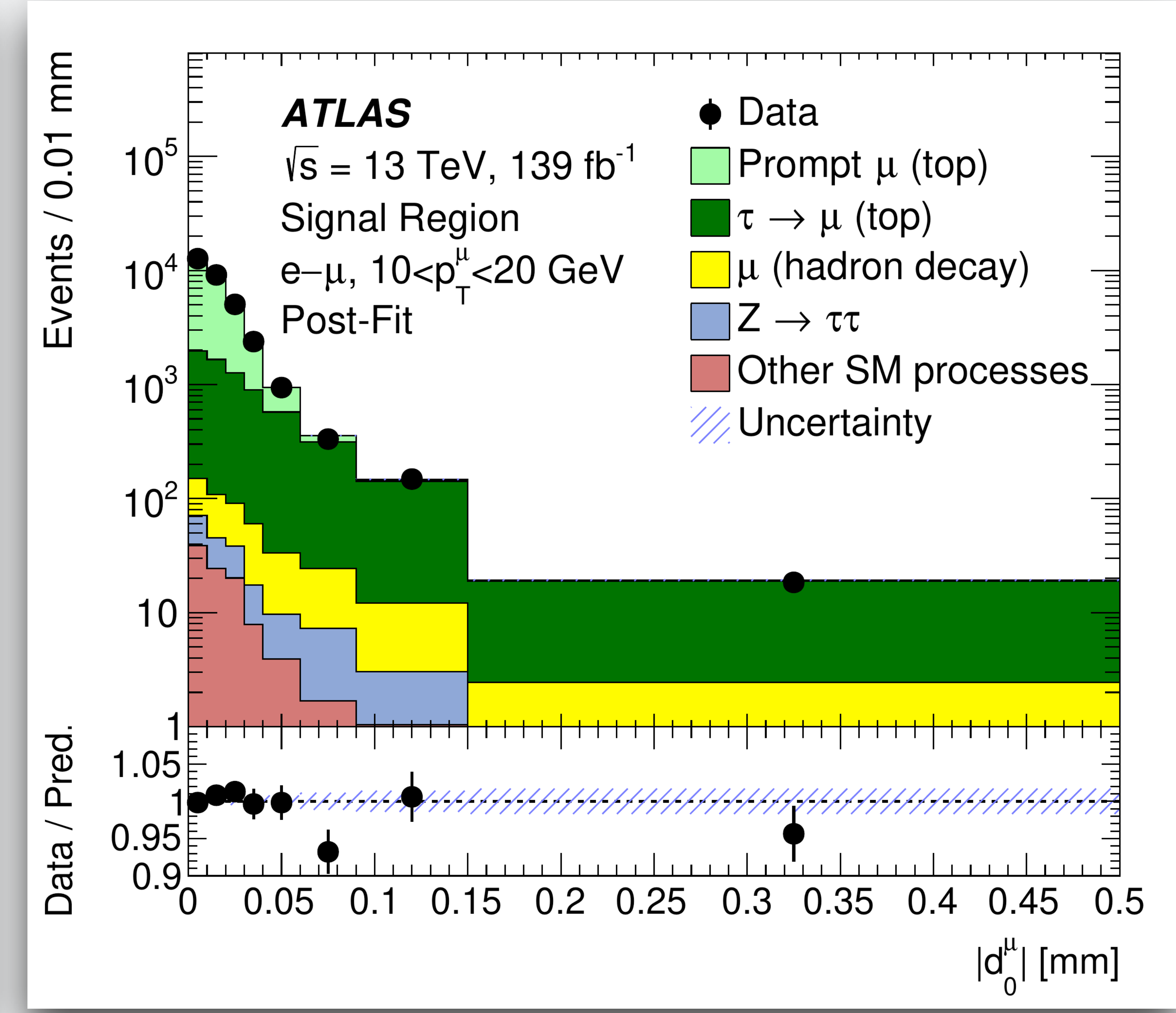


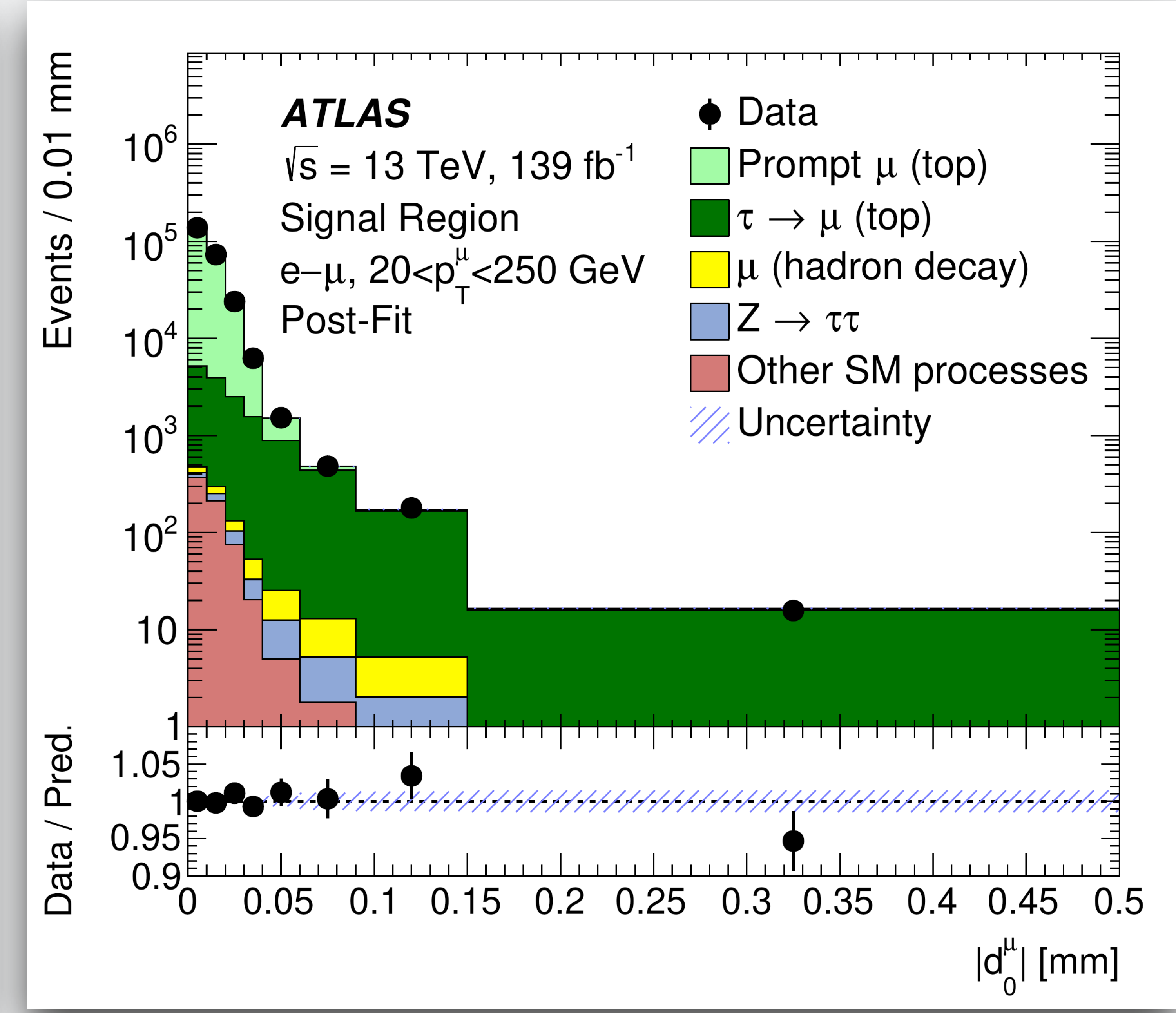
Test of LFU: $|d_0|$ calibration

Define the impact parameter with respect to the beamline rather than PV, so it becomes independent of the resolution of the PV (which is process dependent)

$|d_0|$ calibrated using $Z \rightarrow \mu\mu$ mass peak: 33 bins of p_T and η in 3 data-taking periods







Template uncertainty from small non-closure in ttbar MC vs $Z \rightarrow \mu\mu$ MC, split into 2 components: core+tail

Non-prompt $|d_0|$ resolution found to be similar to prompt resolution in the core

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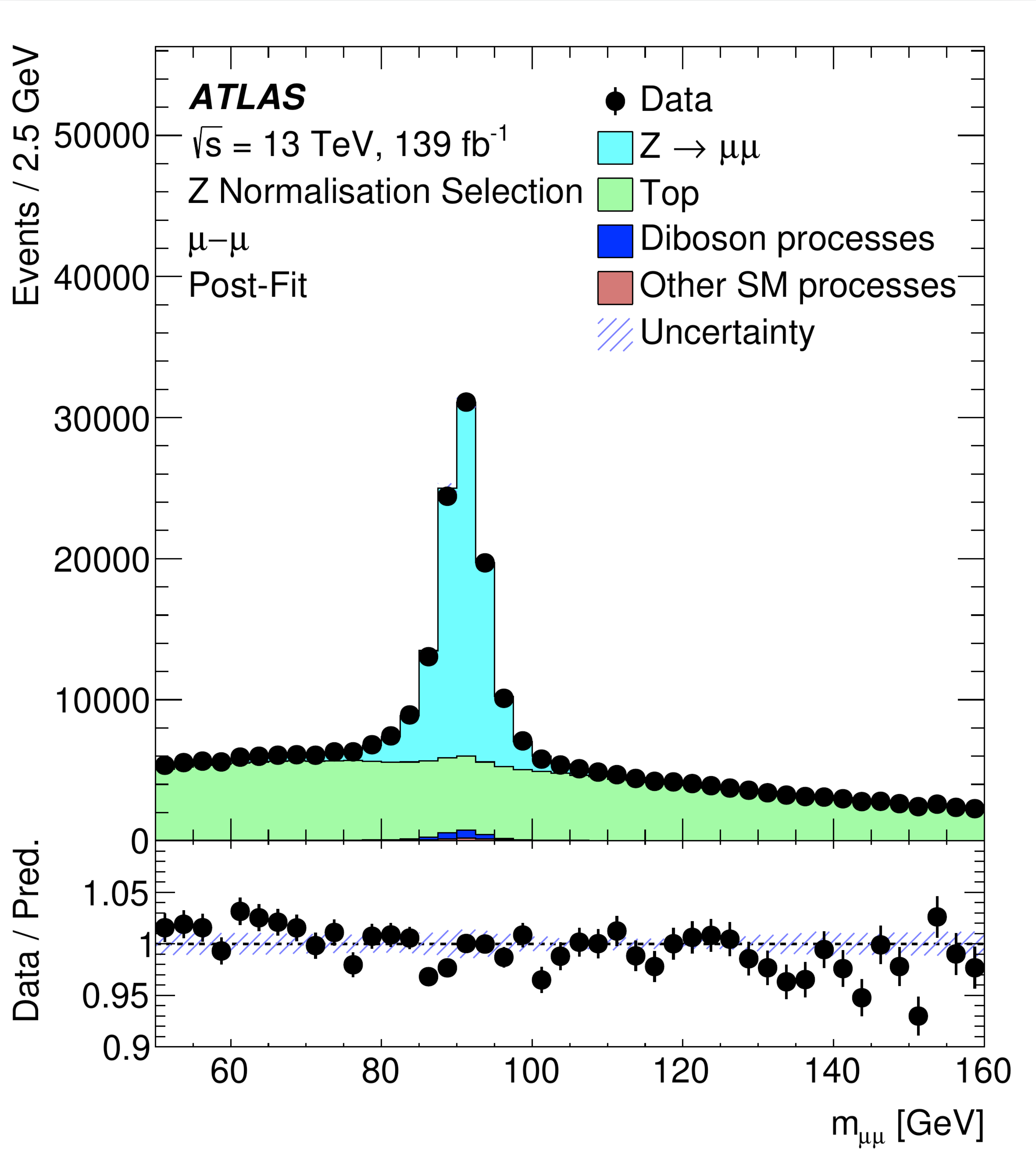
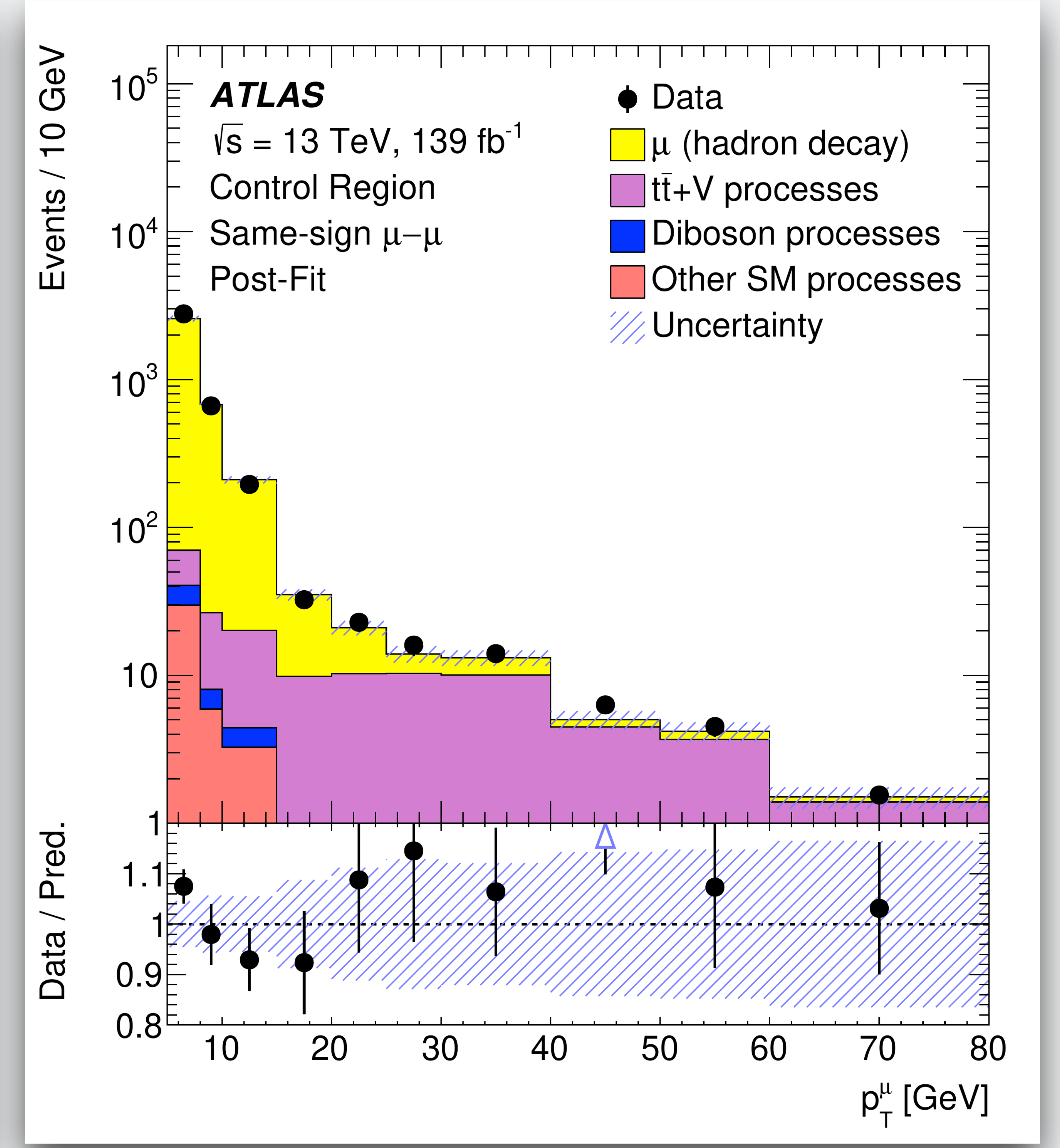
Test of LFU: backgrounds & fit





Z→μμ normalisation from SR minus the Z mass veto

Hadrons→μ normalisation from SR but SS

Also normalise top+V/VV from SS region with $p_T(\mu)$>30 GeV

- 3 bins of p_T x 8 bins of $|d_0|$ x 2 channels (eμ/μμ)=48 bins
- Float R(τ/μ) and ttbar normalisation
- Shower uncertainty uncorrelated between p_T bins: largest impact at high p_T
- Largest systematics from $|d_0|$ tail template.
- Many experimental uncertainties correlated between W→μν and W→τν, and cancel in the ratio

Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

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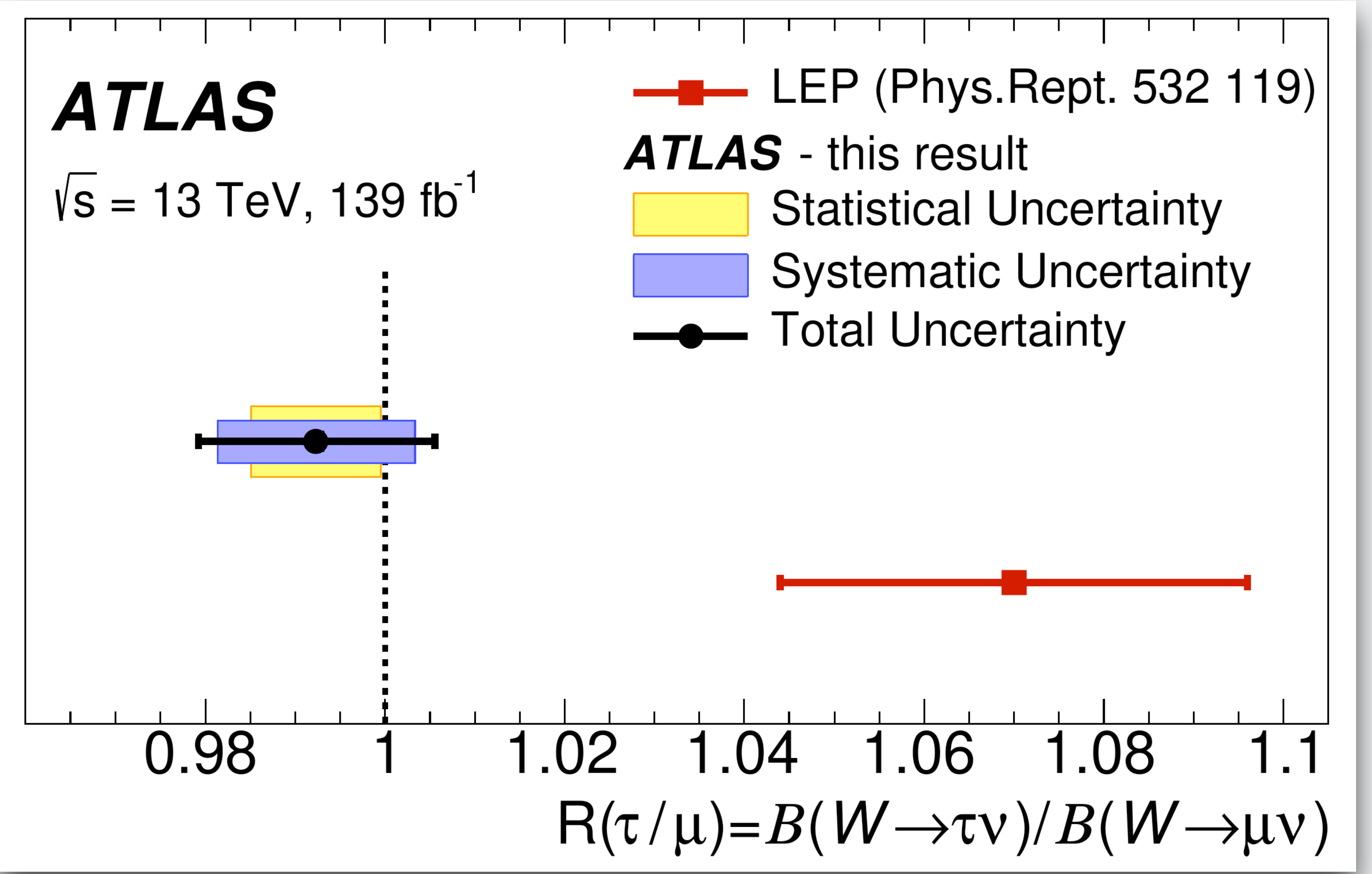
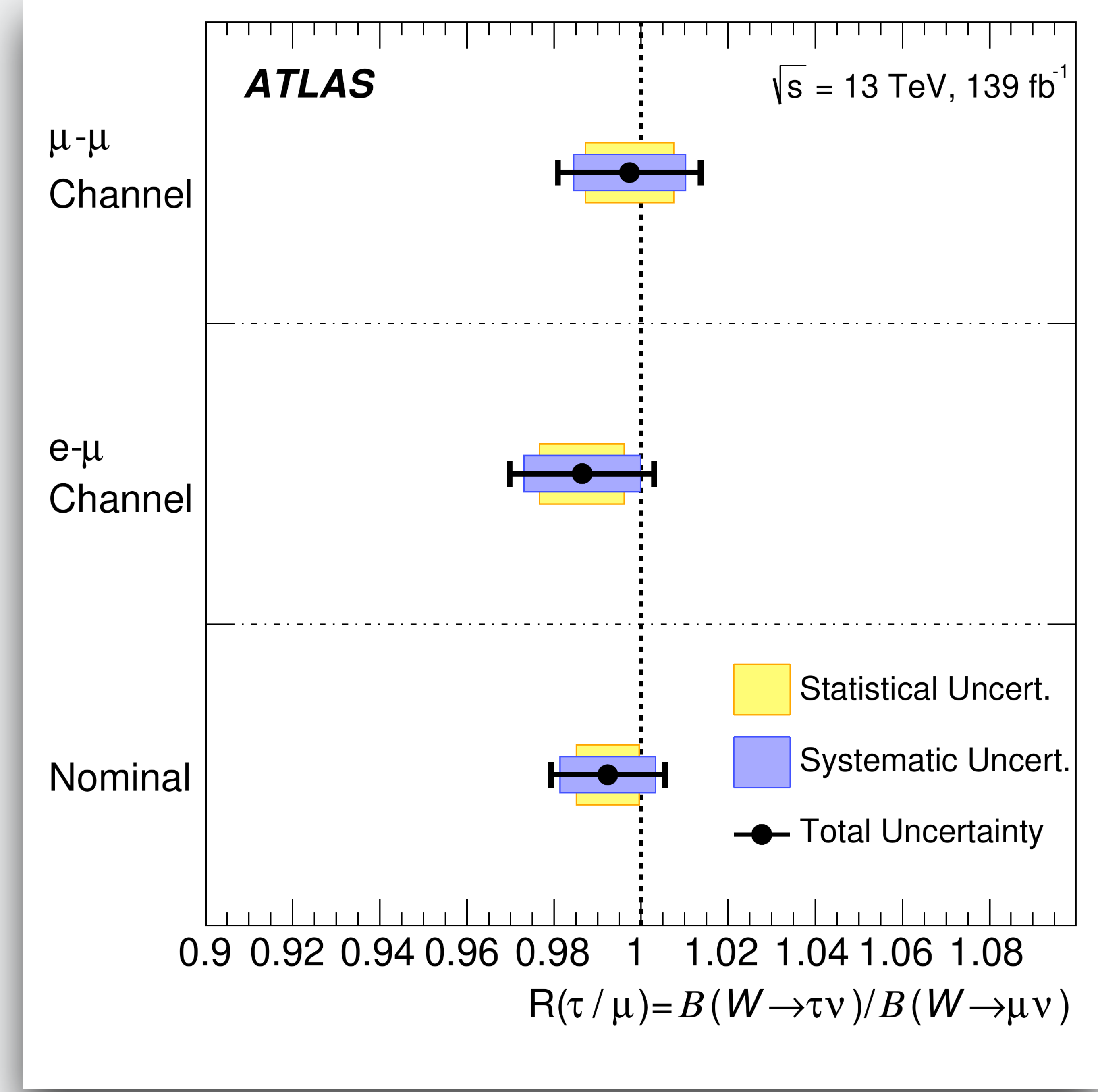
Test of LFU: results



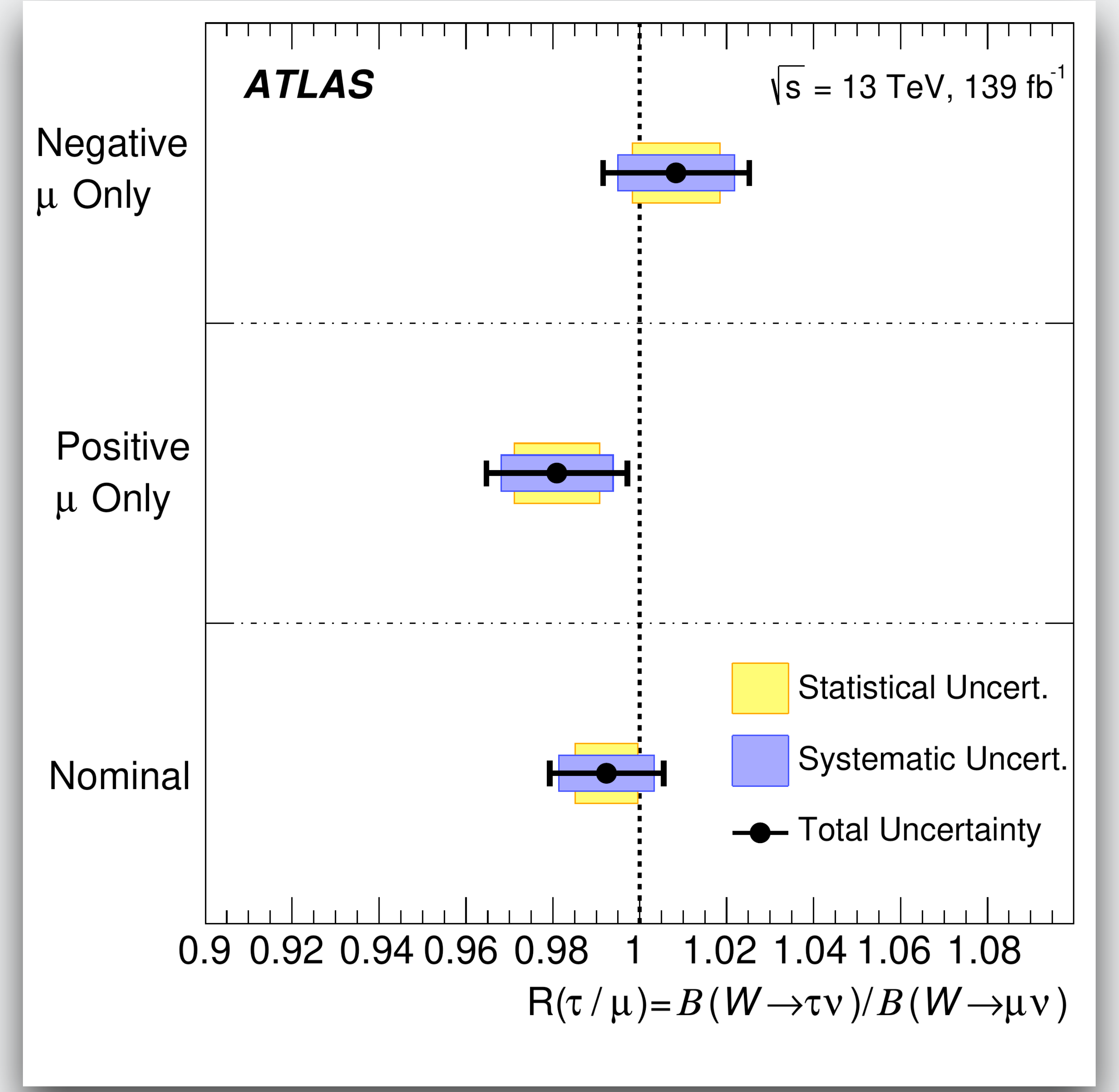
$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat})\ \pm\ 0.011\ (\text{syst})]$$

☞ *Factor >2 improvement from LEP!*

☞ *Consistent with SM LFU*



measurement is robust



Test of LFU

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