SM parameters from top quark measurements at LHC with ATLAS and CMS

14th International Workshop on Top Quark Physics (TOP2021)

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for the ATLAS and CMS collaborations

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13 September 2021

Link to all CMS TOP results

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

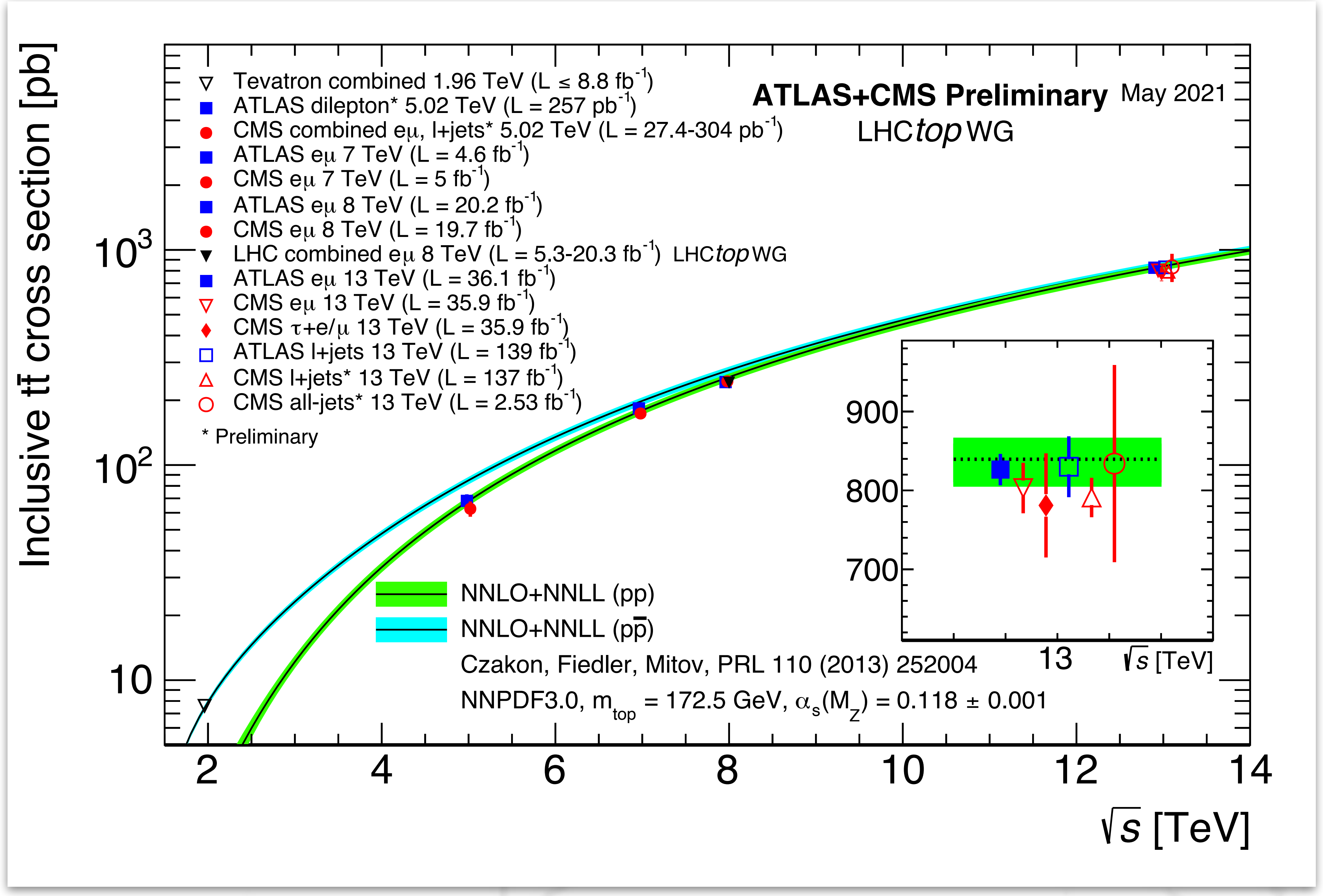
Link to all ATLAS TOP results

Introduction

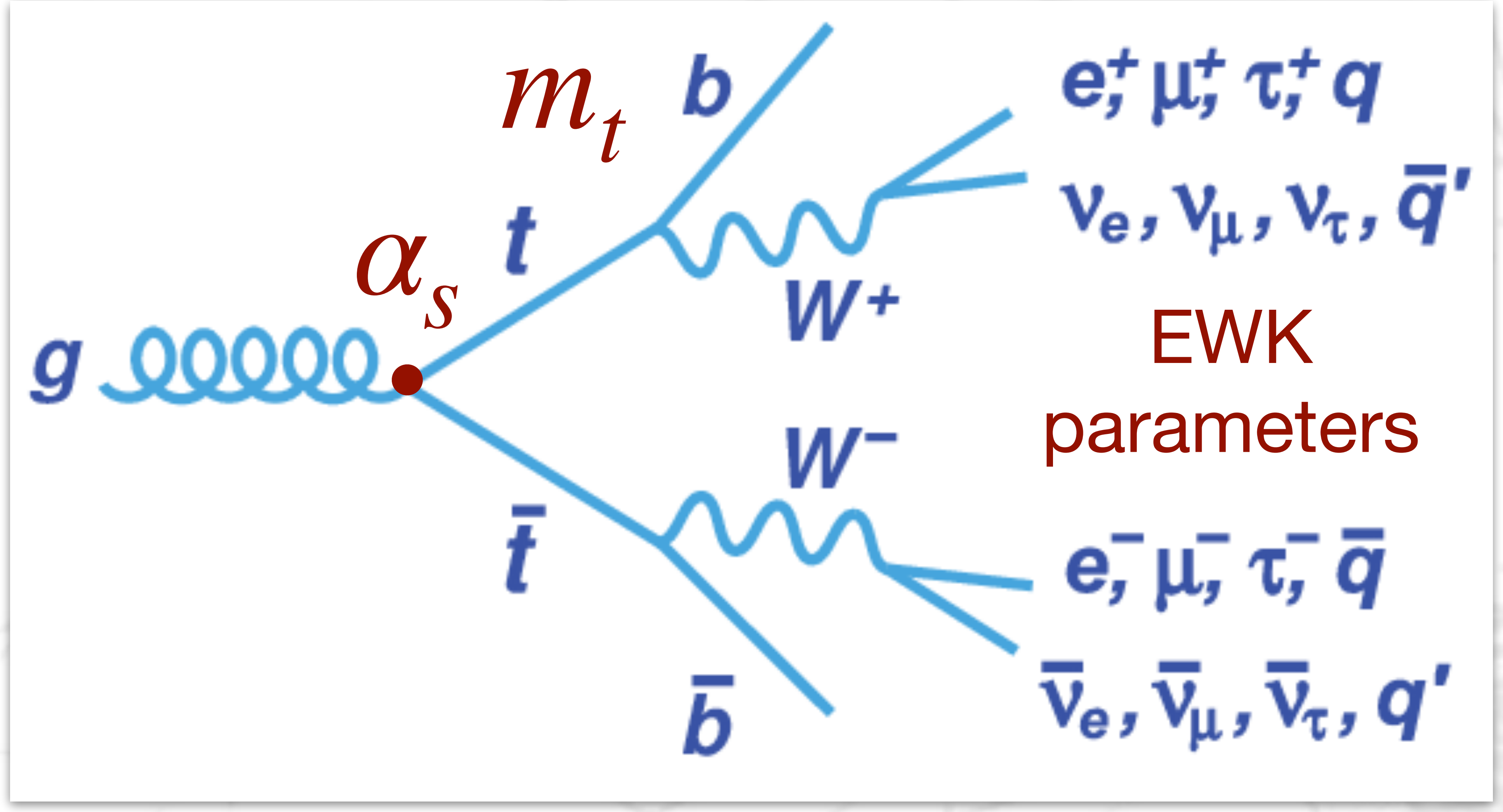
Top quark as a probe for the SM

Reference

- most massive elementary particle known
- Yukawa coupling ~1 to Higgs boson
  - high relevance for the EWK symmetry breaking
- only quark that decays before forming bound states
  - → unique way to study ‘bare’ quark properties



- high production rate at LHC
  - → high precision SM measurements
  - e.g. for $\sigma_{t\bar{t}}$, exp. precision is dominating



- → study QCD + EWK parameters

- multitude of interesting SM/top properties measurements
  - some already covered in James’ talk (top polarization,..)

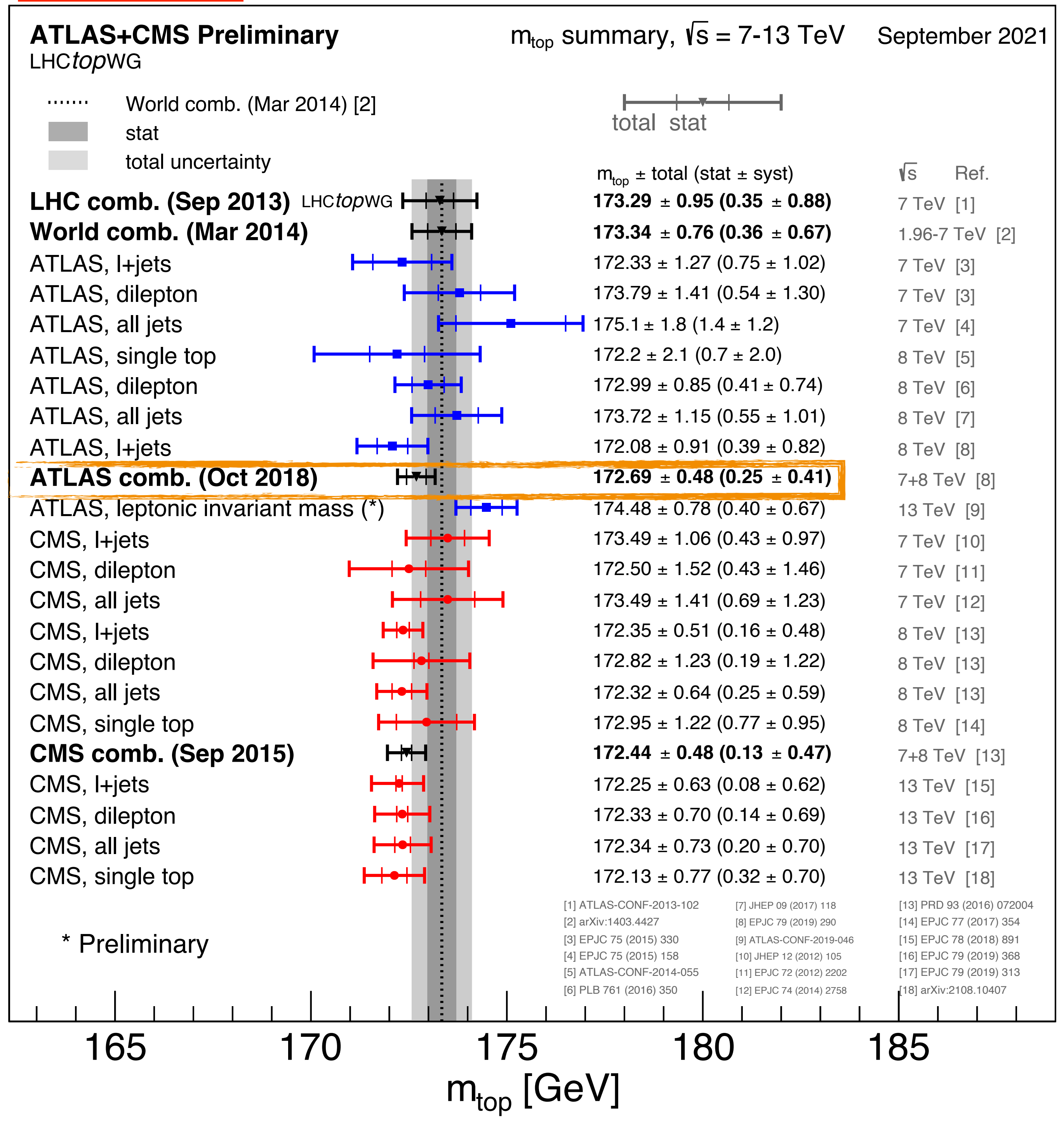
Top quark mass

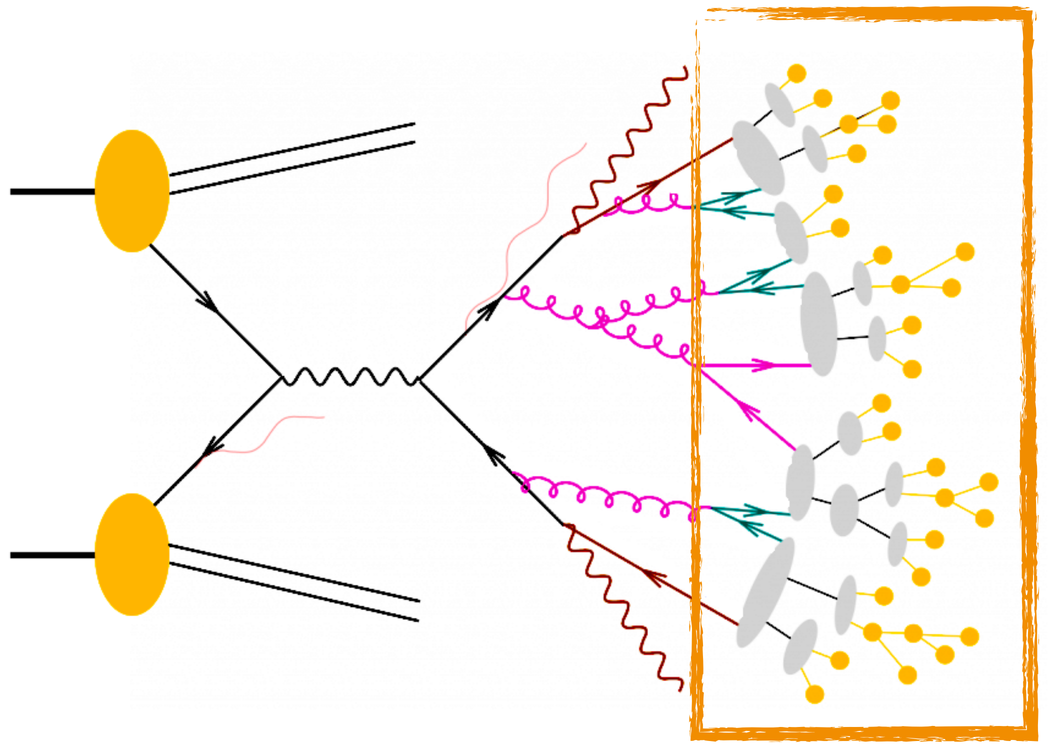
Direct measurements m_t^{MC} ⟷ m_t indirect measurements

- measuring m_t^{MC} using reconstructed decay products
  - very high experimental precision
    - ~0.5 GeV
  - relies on details of MC simulation

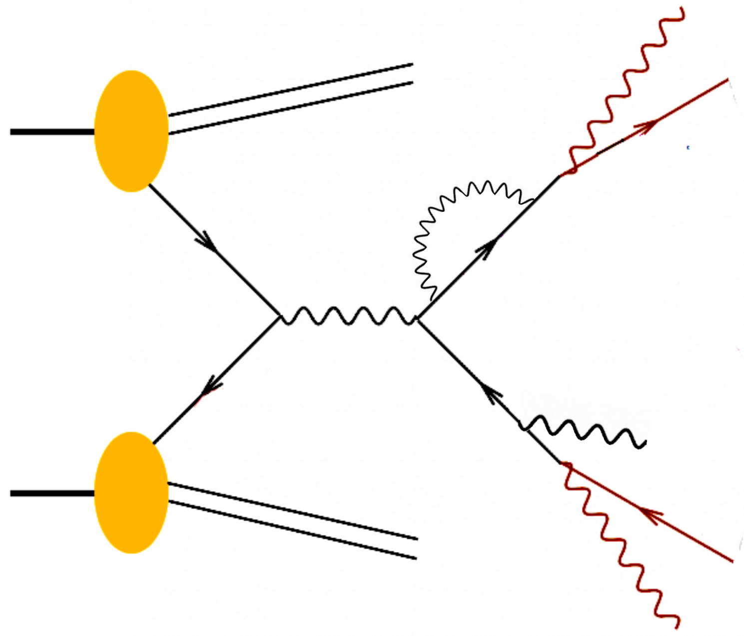
- extract m_t in well defined renormalisation scheme (pole, $\overline{MS}$, …)
- measuring cross section with direct sensitivity to m_t
  - either inclusive or differential

Reference

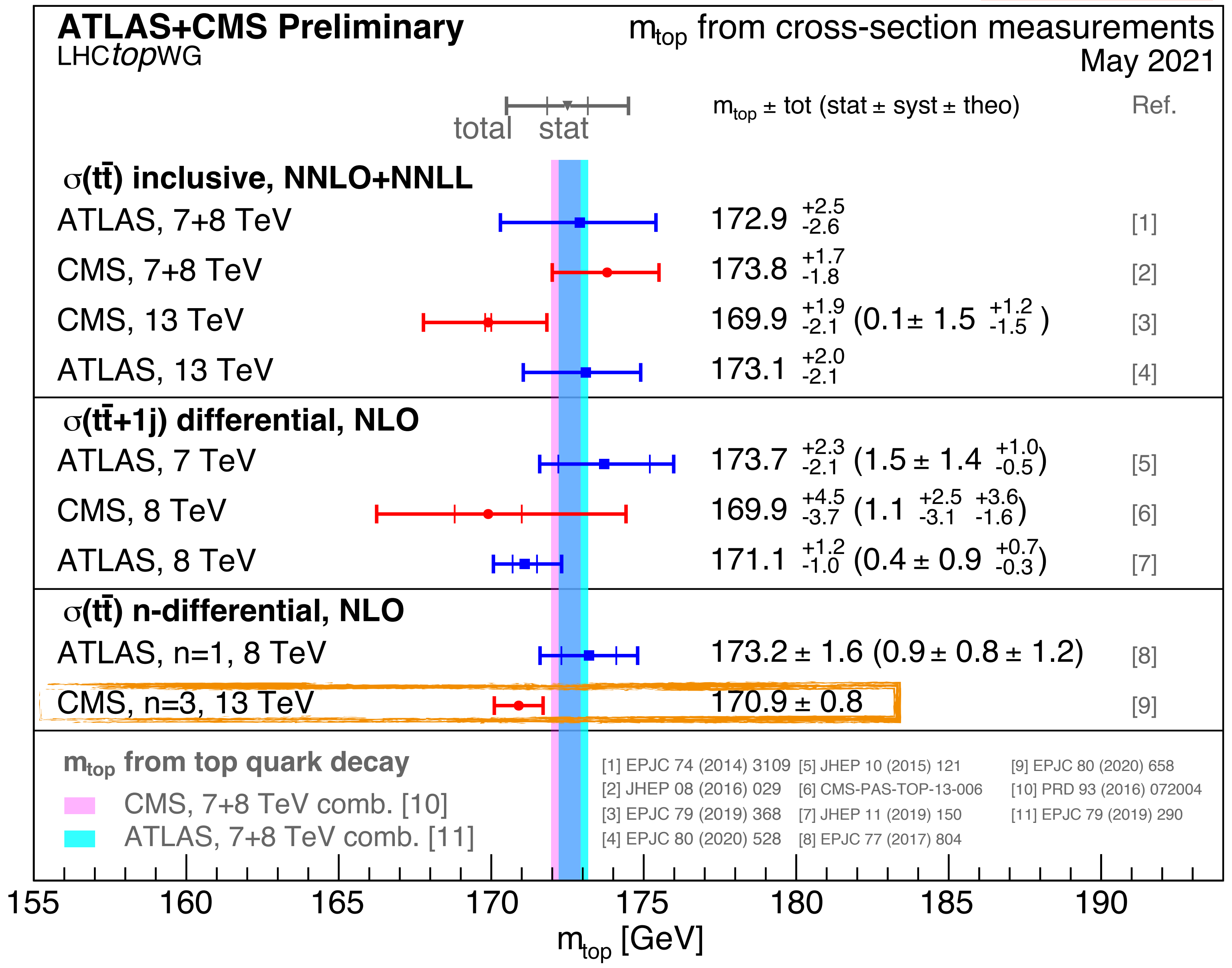




VS.



Reference



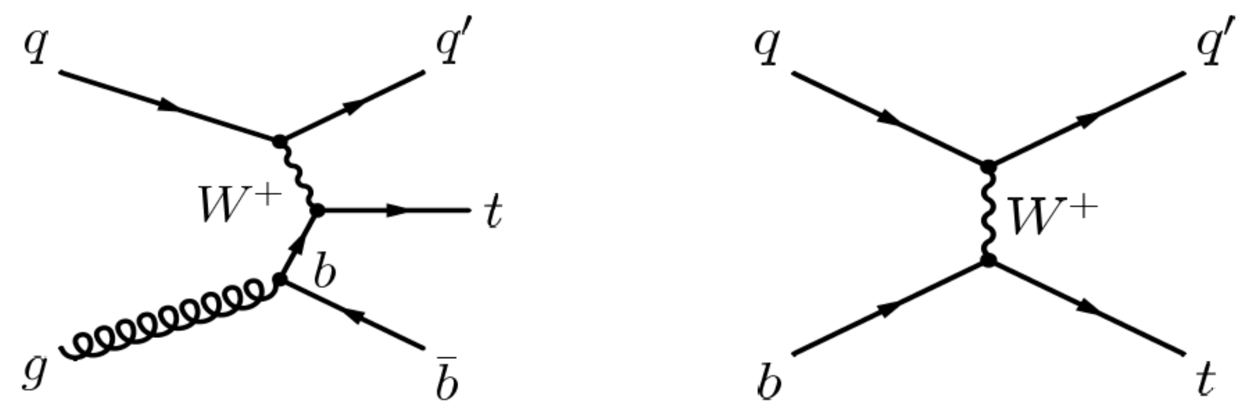
$$m_t^{MC} = m_t^{pole} \pm \Delta_{MC}\, O(1GeV)$$

Top quark mass

Single top t-channel | 2016 data

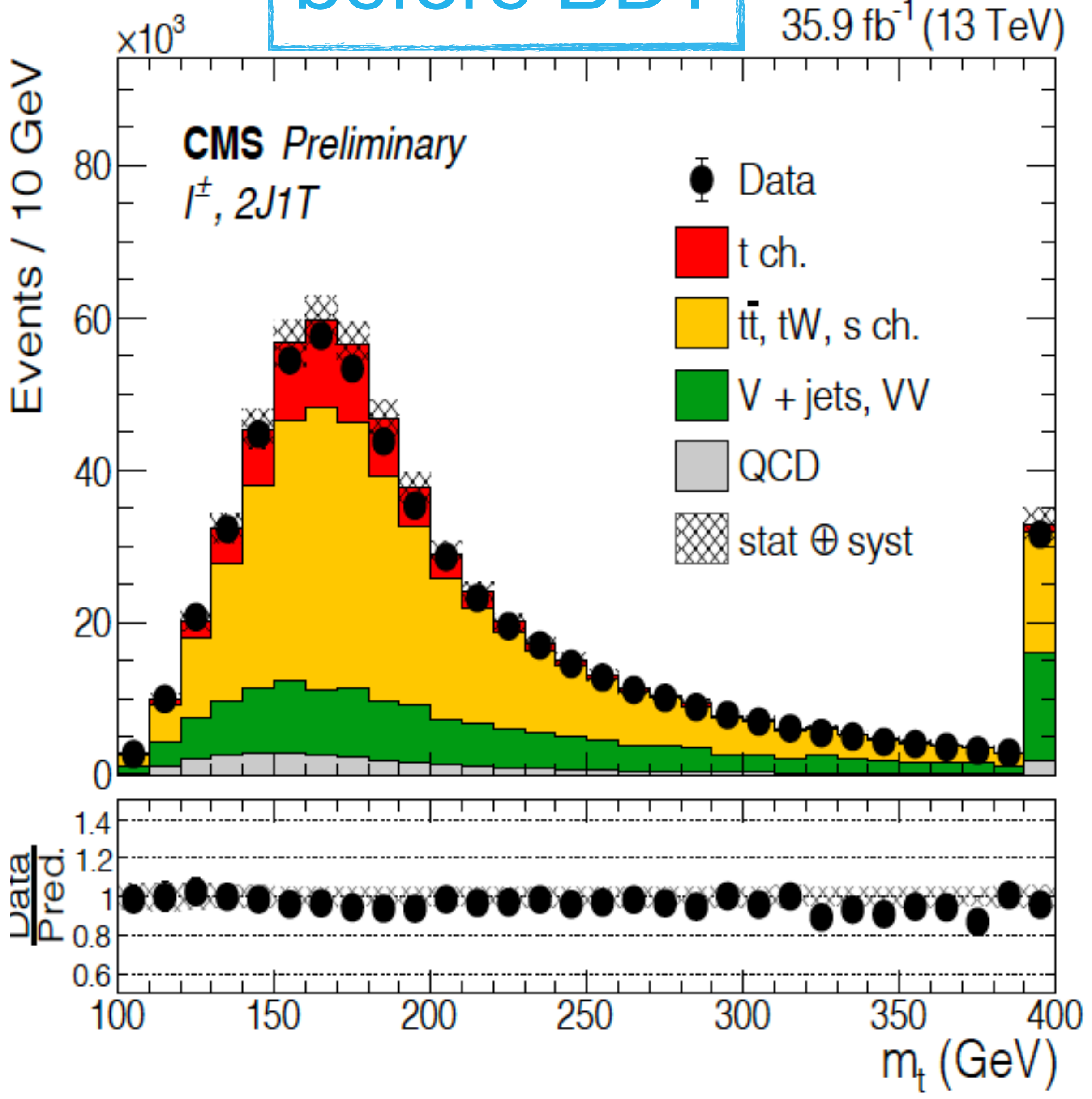
NEW!

- measurement of m_t in a data sample enriched with single top events in lepton+jets channel

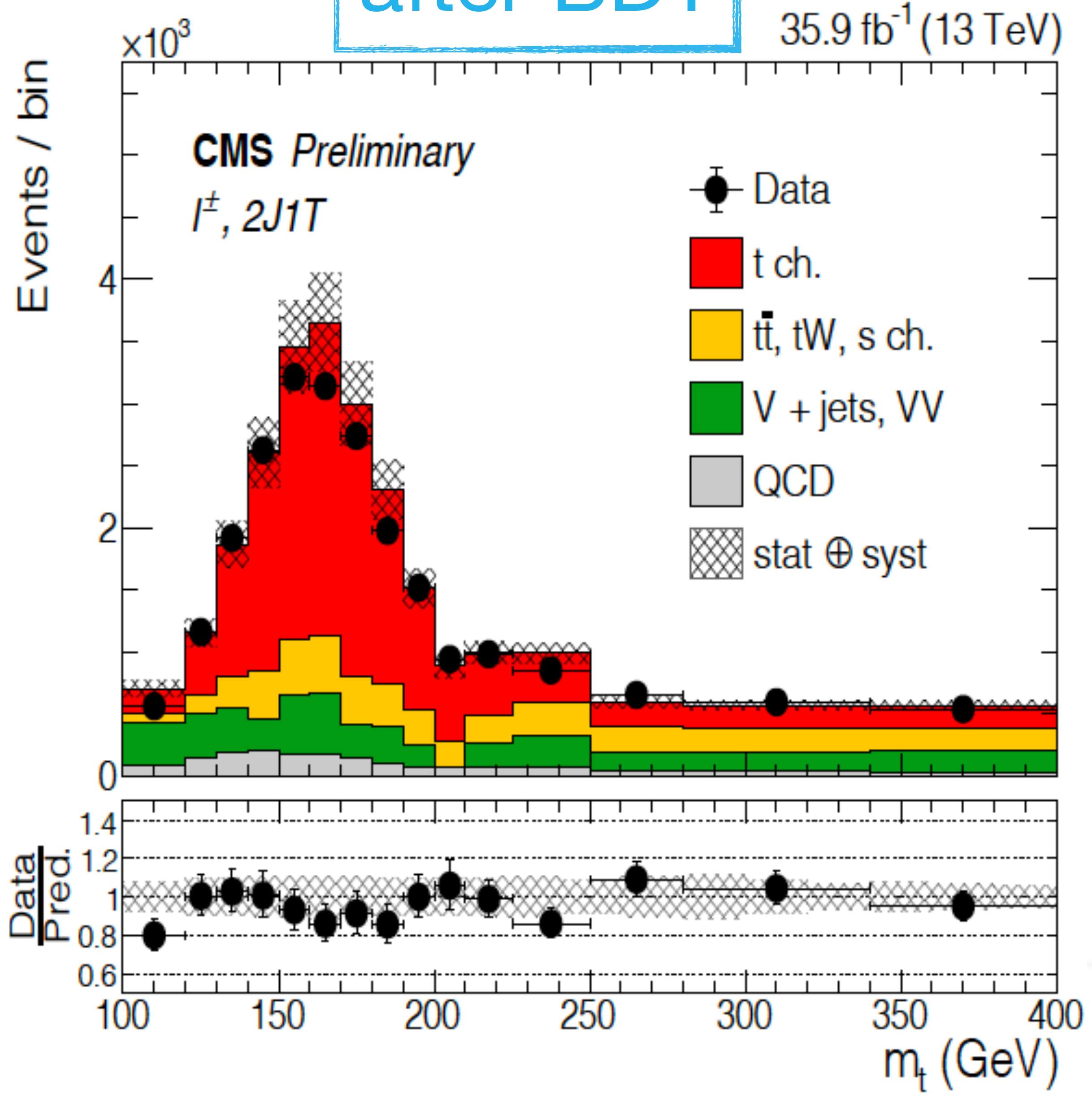


- separated wrt. lepton flavour & charge
  → measure quark/antiquark masses individually

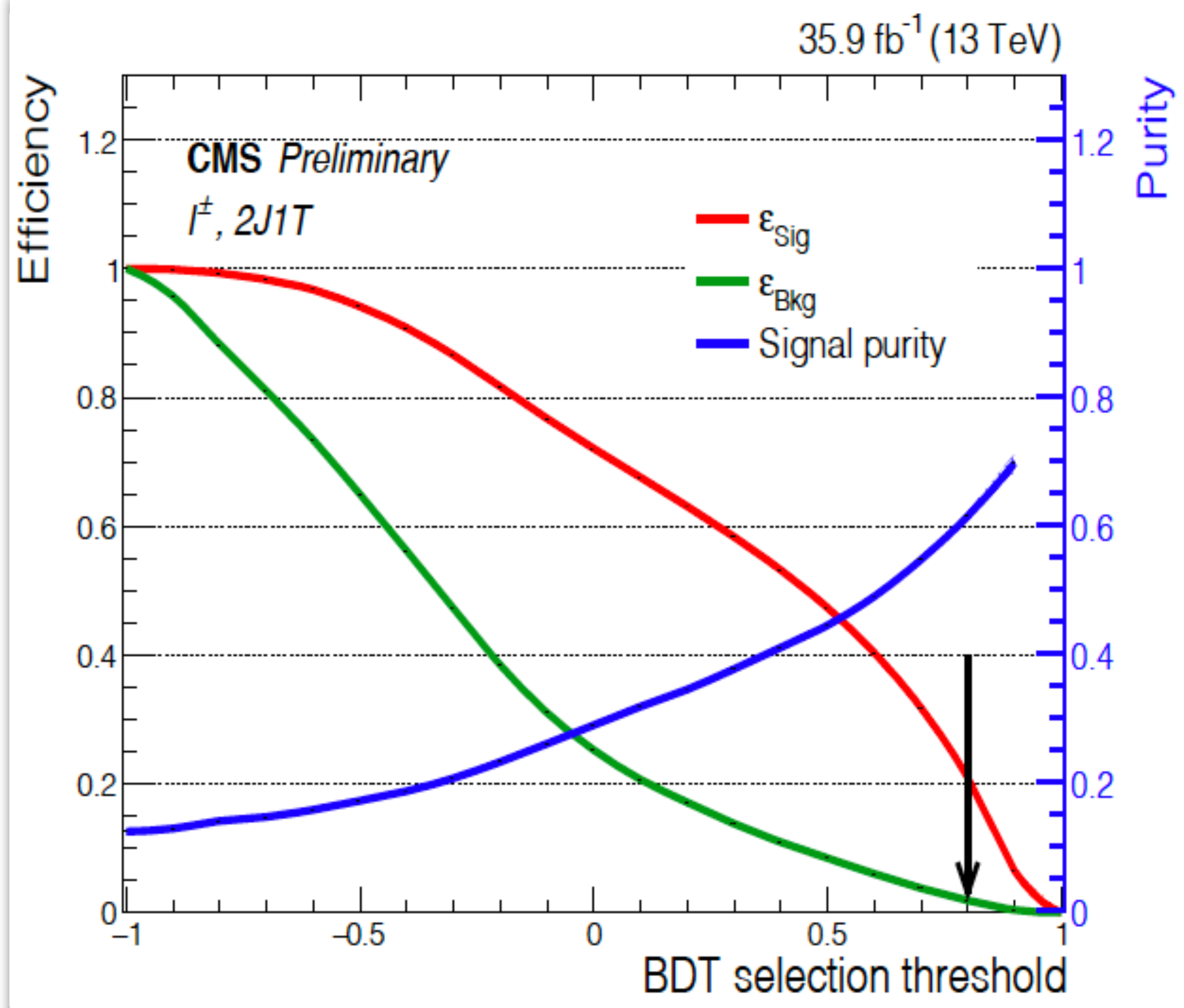
before BDT

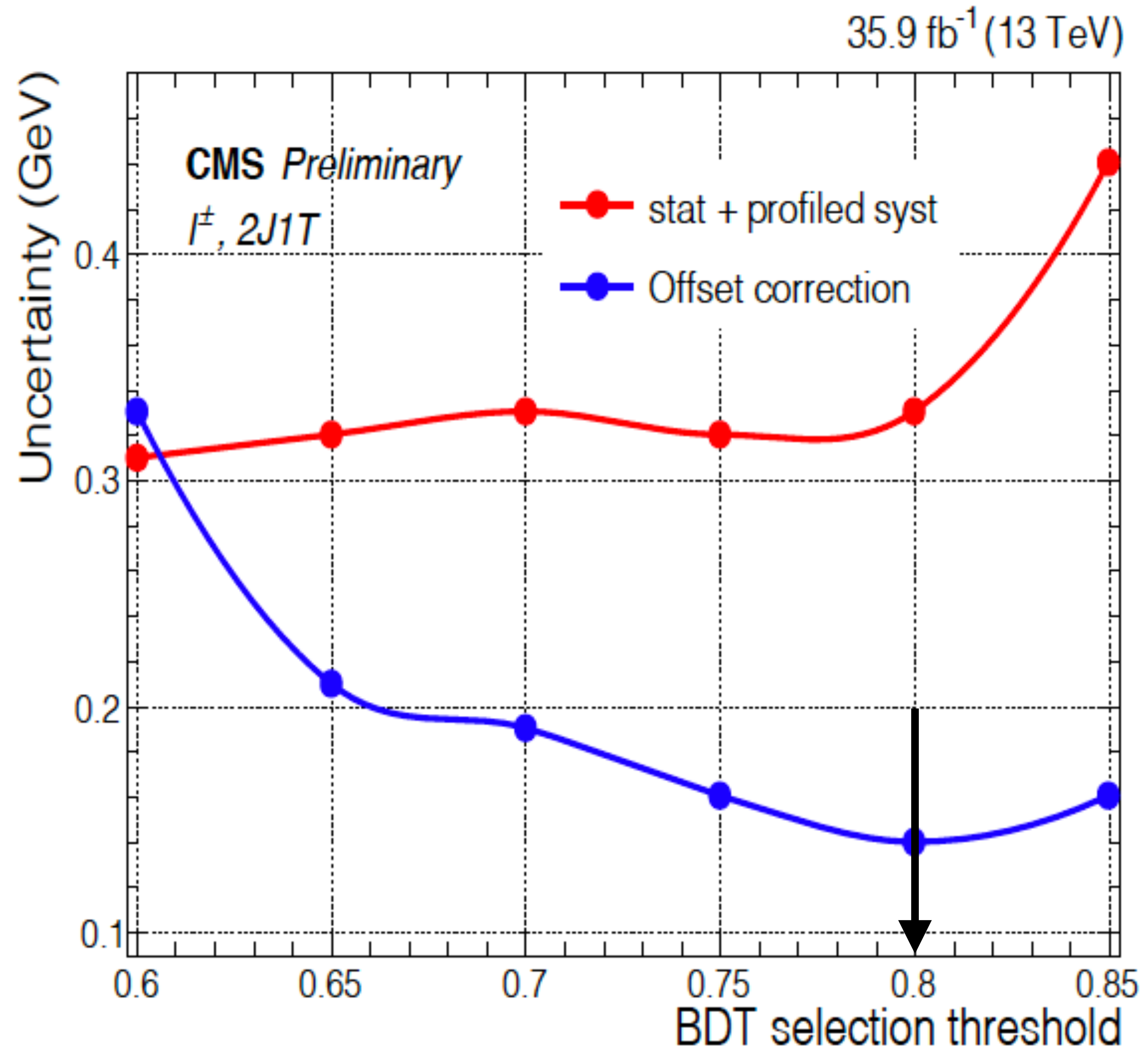


after BDT



CMS-PAS-TOP-19-009





- intensive optimisations of **multivariate** (BDT) discriminators to enrich sample with t-ch. single top
  - reduced correlation to m_t
  - studied bias on m_t
  - calibrations based on final results

Top quark mass
Single top t-channel | 2016 data

NEW!

- extract m_t with parametric fit

$$F(y; y_0 | f_{t-ch}, f_{Top}, f_{EWK}) = f_{t-ch} \cdot F_{t-ch}(y; y_0) + f_{Top} \cdot F_{Top}(y; y_0) + f_{EWK} \cdot F_{EWK}(y)$$

$y_0 = \ln(m_t)$

  - m_t also varied in $t\bar{t}$ background

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

- use of lepton charge to measure quark/antiquark masses

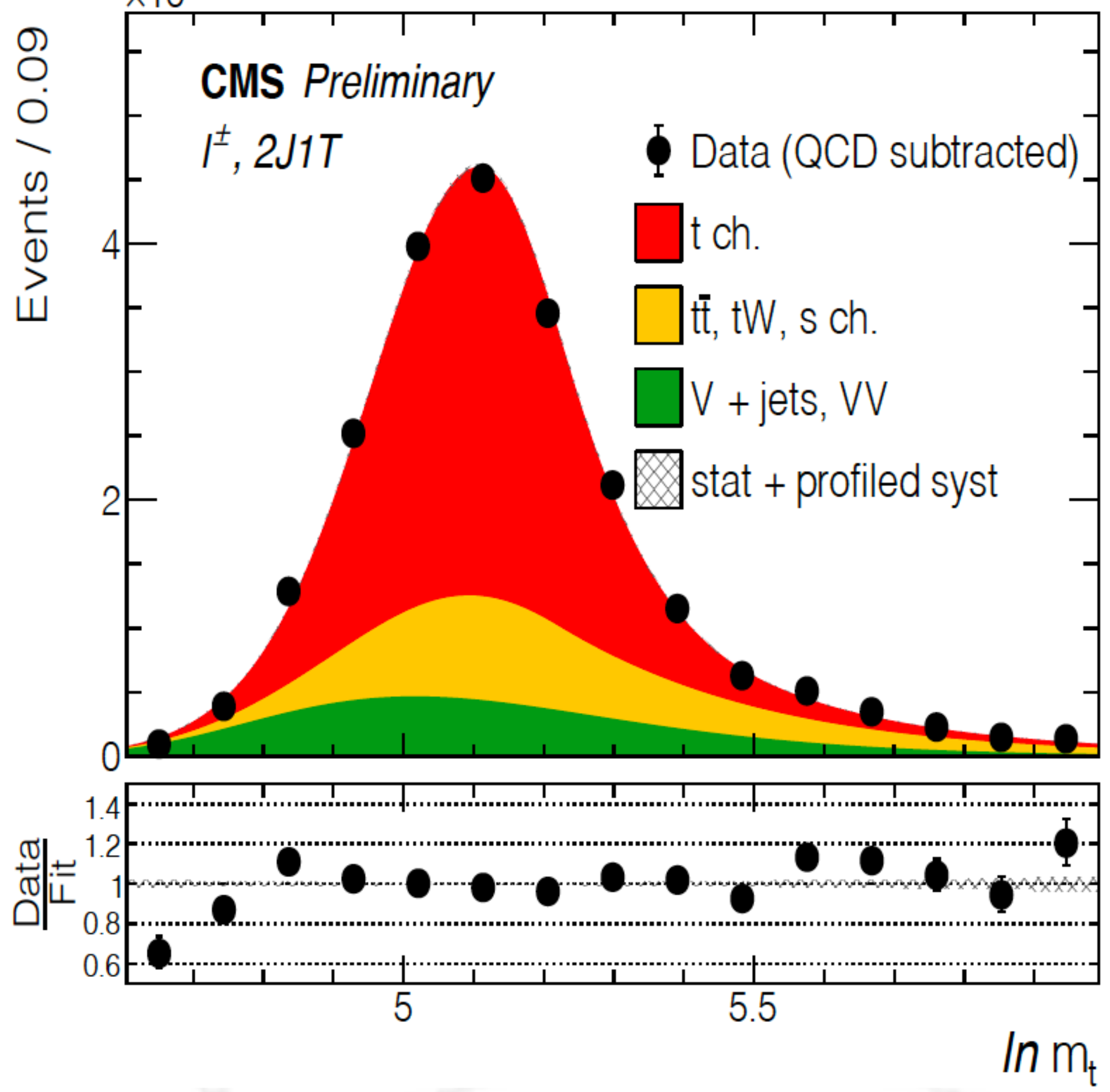
$$m_t = 172.62 \pm 0.37\,(\text{stat} + \text{prof})\,^{+0.97}_{-0.65}\,(\text{syst})\text{ GeV}$$
$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat} + \text{prof})\,^{+1.32}_{-1.39}\,(\text{syst})\text{ GeV}$$

  - difference + ratio in agreement with SM (CPT conservation)

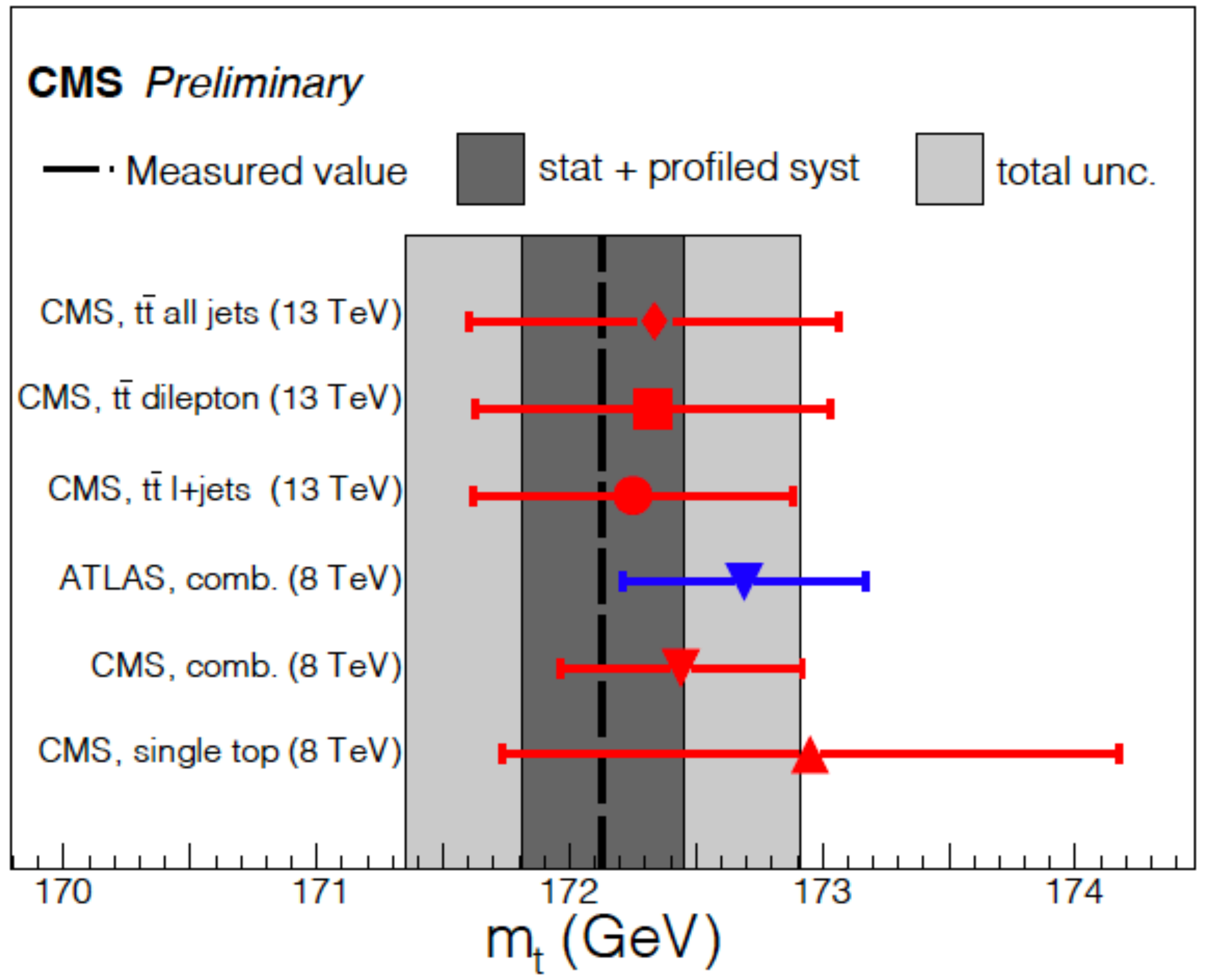
$$\Delta m_t = m_t - m_{\bar{t}} = 0.83^{+0.77}_{-1.01}\text{ GeV} \qquad R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995^{+0.005}_{-0.006}$$

- limited by jet energy scale (JES) and modelling (FSR & CR)

CMS-PAS-TOP-19-009



first time sub-GeV precision in single top phase space

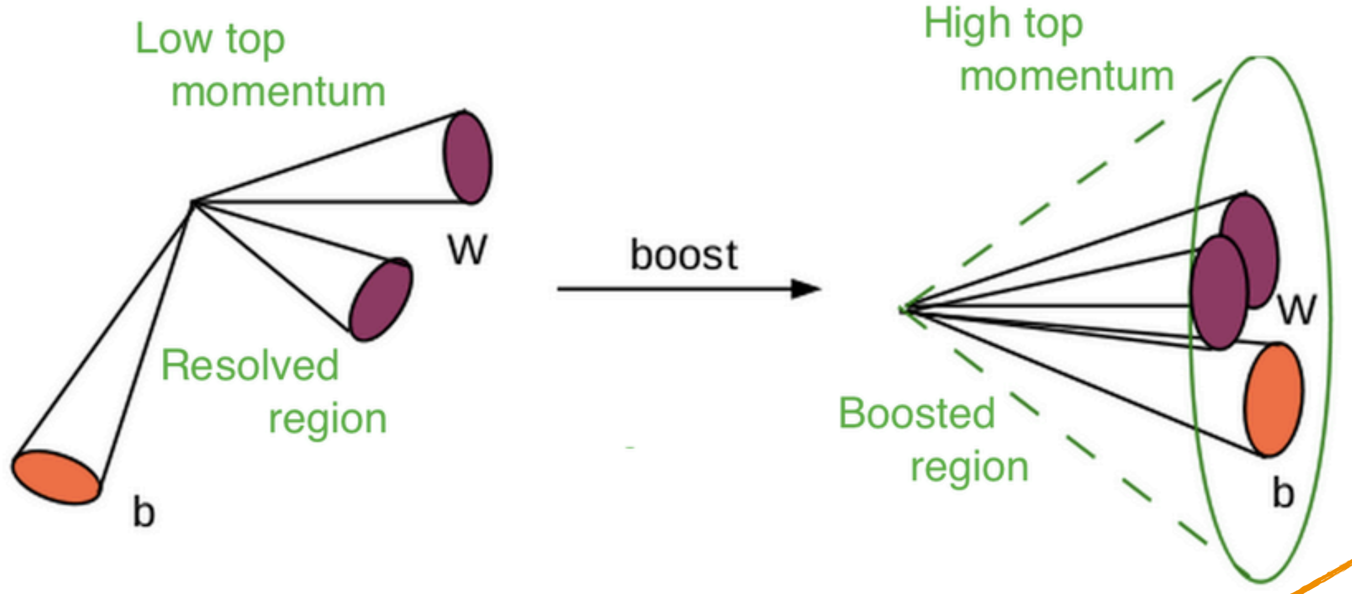


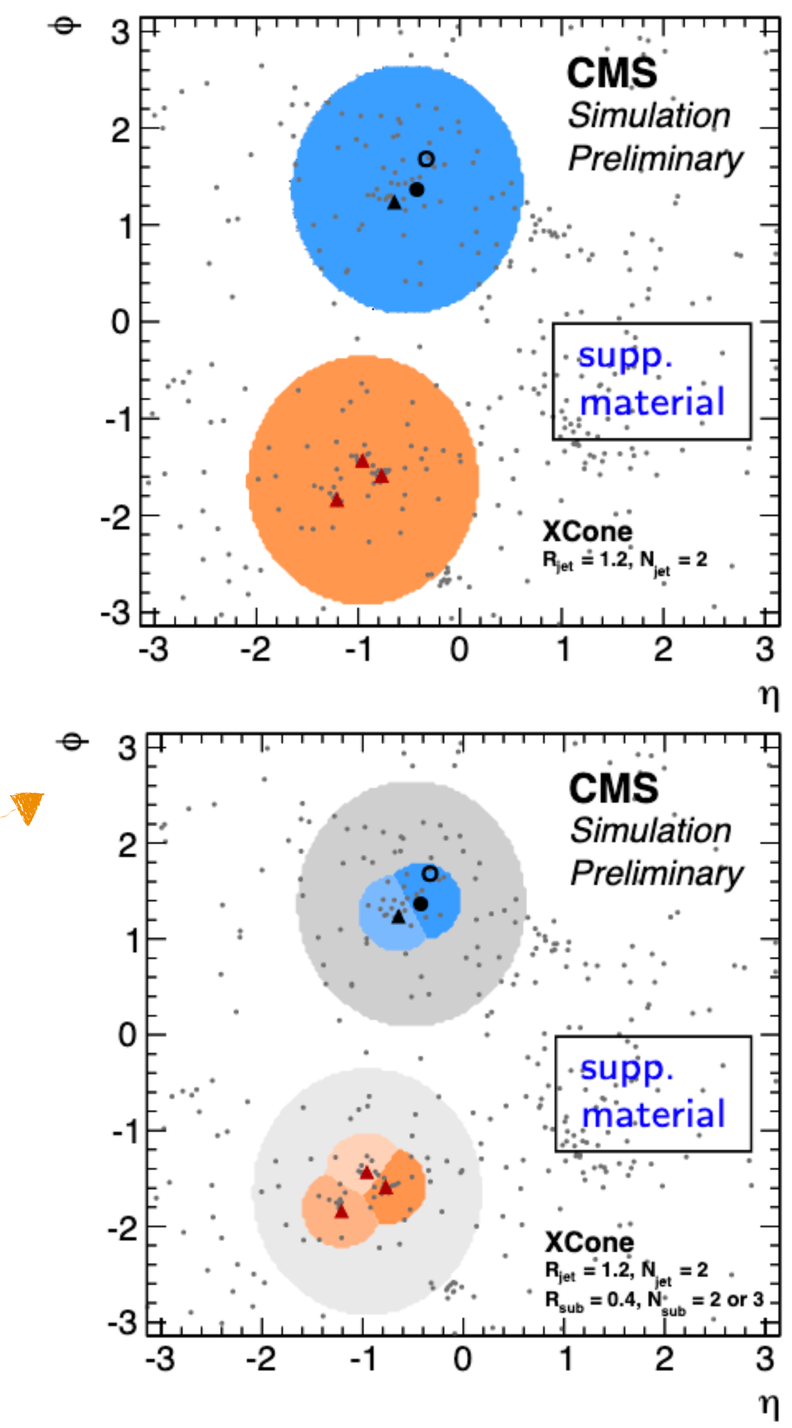
Top quark mass

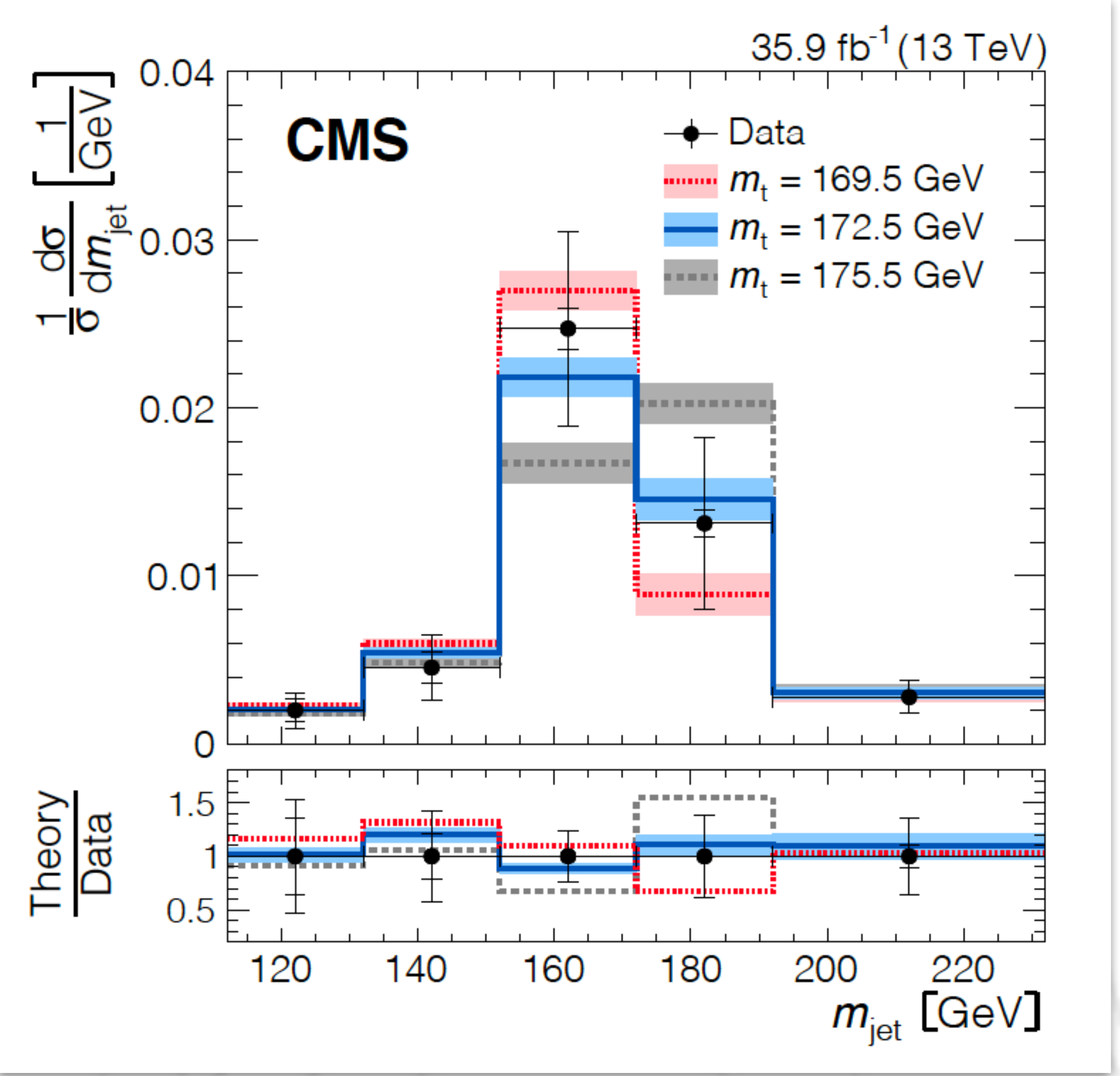
Boosted jets ($t\bar{t}$ l+jets) | 2016 data

Phys. Rev. Lett. 124, 202001 (2020)

- m_t from jet mass in boosted top decays
  - decay products merged in one single jet
  - can be calculated from first principles (SCEFT)







  - using **Xcone algorithm** (first time at LHC)
    - two step procedure (two tops, then decay products)
    - → factor 2 improvement in jet width (particle level & exp. resolution)
    - → factor 4 improvement wrt. previous iteration using Run I data

- dominant syst. uncertainty: JES

  - m_t from comparing to Powheg+Pythia

$$m_t = 172.6 \pm 0.4\,(\text{stat}) \pm 1.6\,(\text{exp}) \pm 1.5\,(\text{model}) \pm 1.0\,(\text{theo})\,\text{GeV}$$

Top quark mass

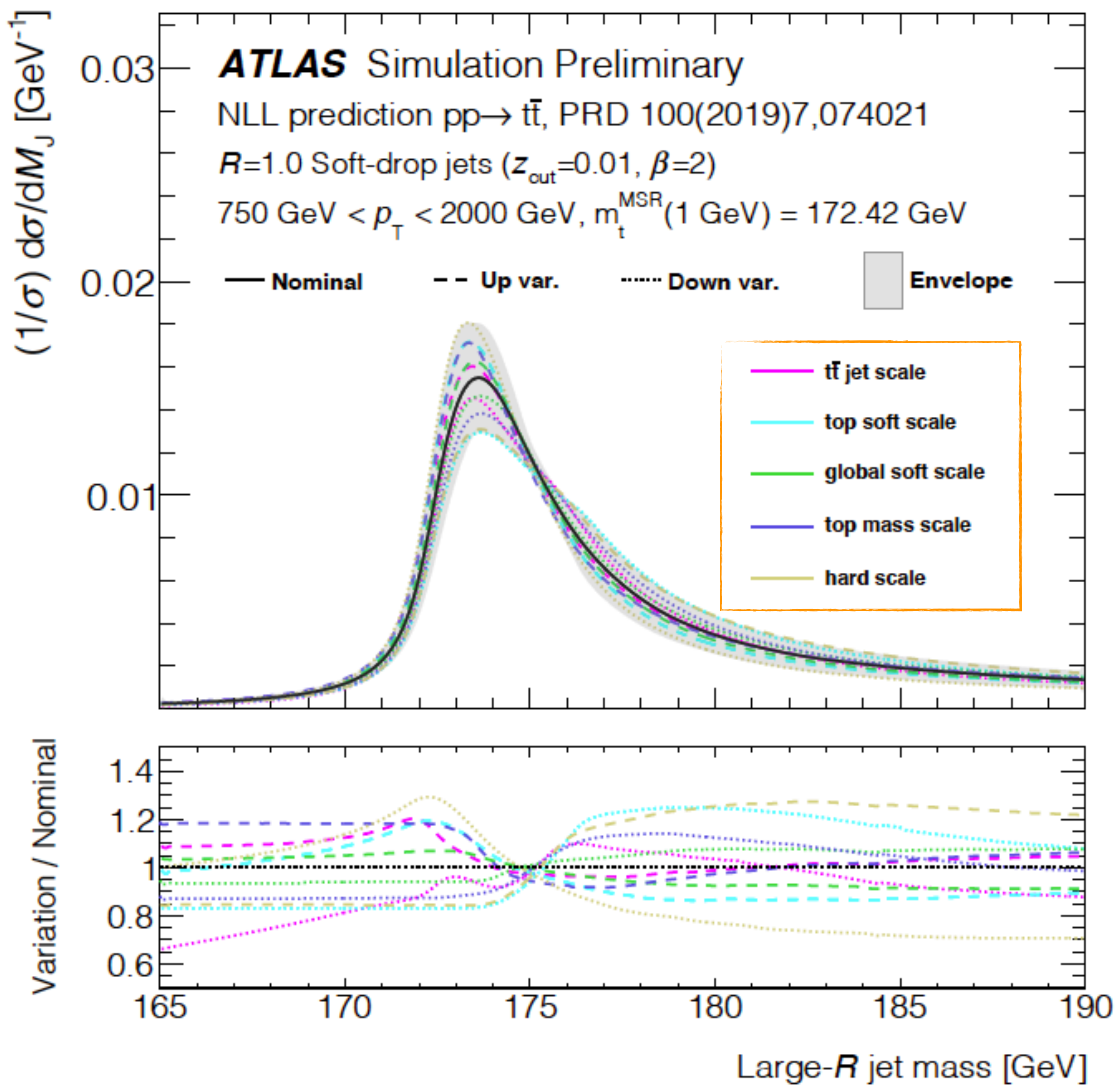
Interpretation in ATLAS MC

NEW!

$$m_t^{MC} = \cancel{m_t^{pole}} \; m_t^{MSR}(1\,GeV) \pm \Delta_{MC}\, O(1GeV)$$

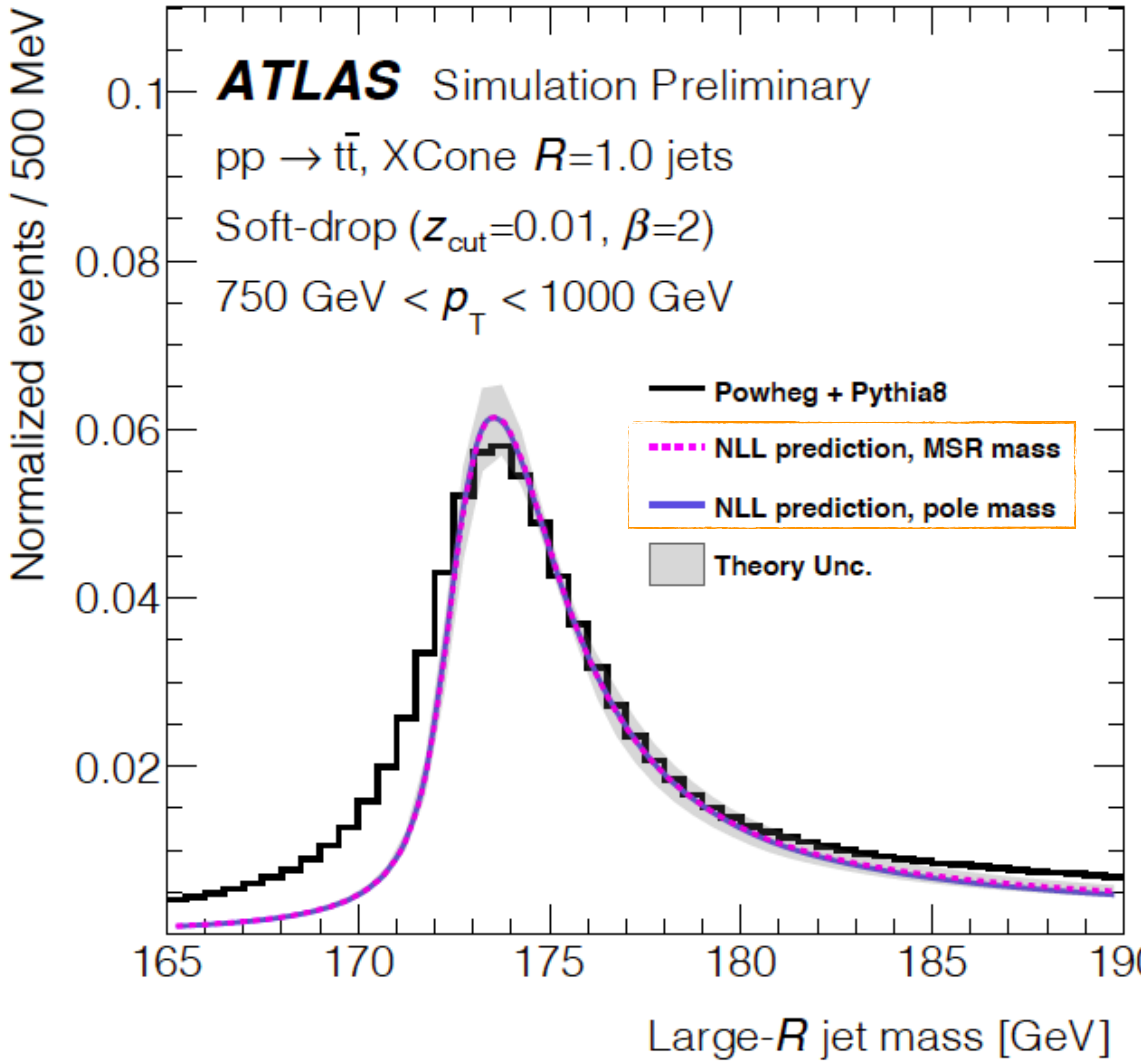
- using the short distance scale dependent **MSR mass** [1]

$$m_t^{MSR}(1\,GeV) \approx m_t^{pole}$$



- NLL calculation at **particle level** for tops reconstructed as light groomed boosted jets (hadronic decays)
  - large jet radius (R=1), using XCone
  - soft-drop algorithm
- χ^2-template fits to ATLAS simulation are performed
  - $m_t^{MSR}(1\,GeV), \Omega_{1q}^{\infty}, x_1$ as free parameters

ATL-PHYS-PUB-2021-034



- best fit results compared to nominal ATLAS MC

pole + MSR

[1] A. Hoang et al, Phys.Rev.Lett.101, 151602 (2008)

Top quark mass

Interpretation in ATLAS MC

NEW!

ATL-PHYS-PUB-2021-034

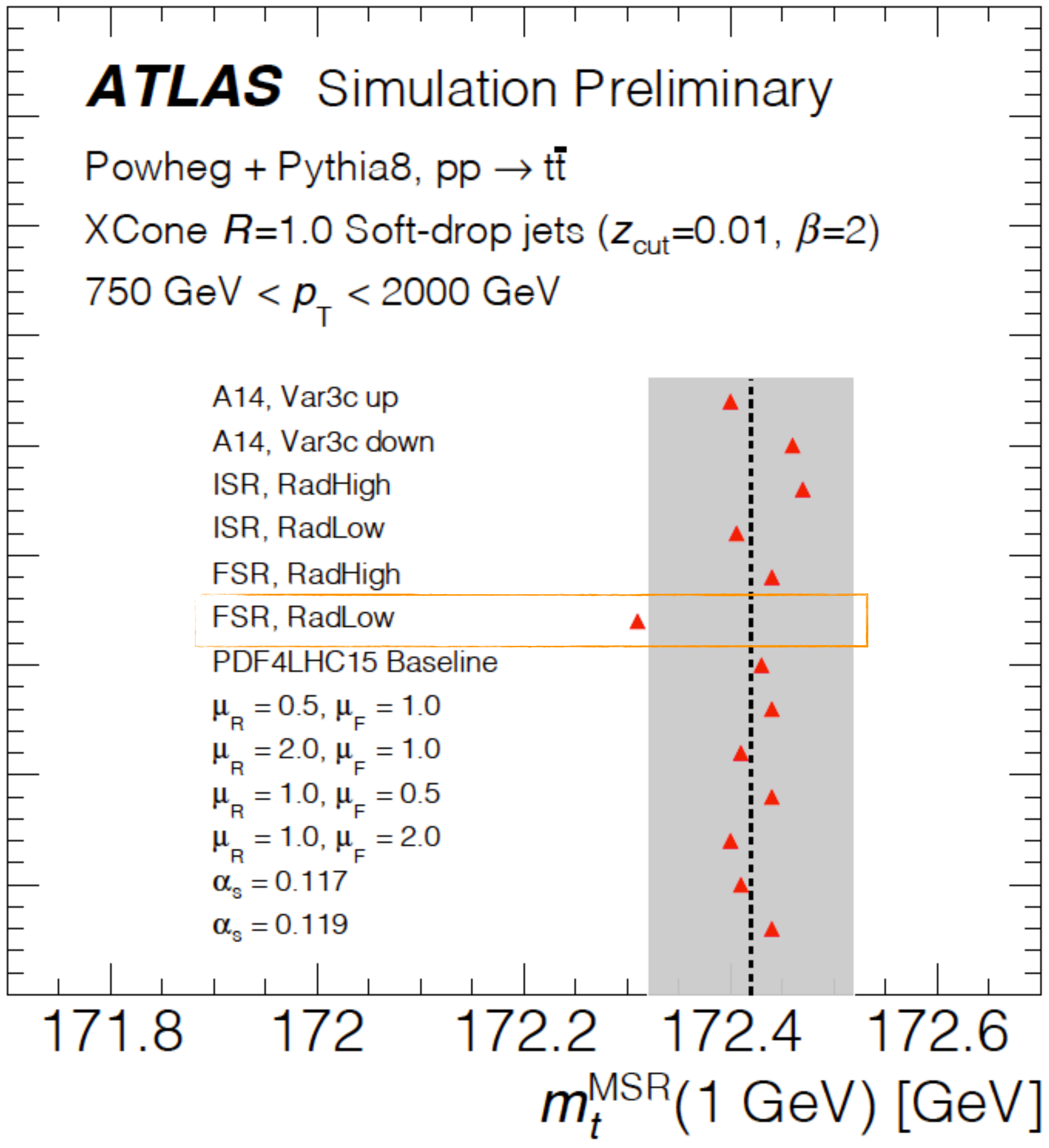
$$m_t^{MC} = m_t^{MSR}(1\text{ GeV}) + 80^{+350}_{-410}\text{ MeV}$$

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**	

- dominated by **theoretical uncertainties**
- similar results for Powheg+Herwig7 & aMC@NLO+Pythia8 simulation

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

- usual mass interpretation validated at order of O(0.5 GeV)



- calibration also performed for common ATLAS sample variations used to access systematic uncertainties

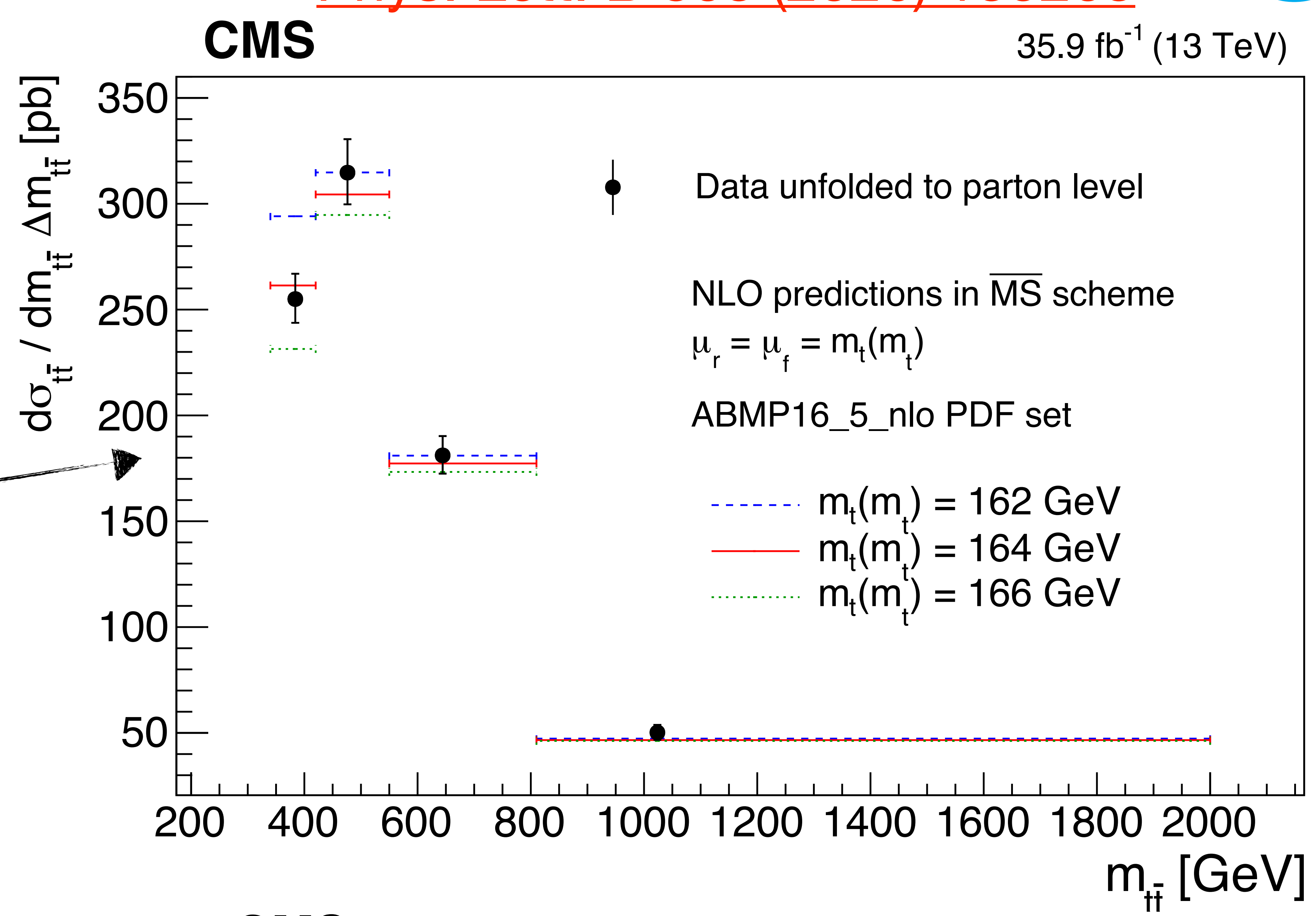
See also YSF talk by Javier Aparisi!

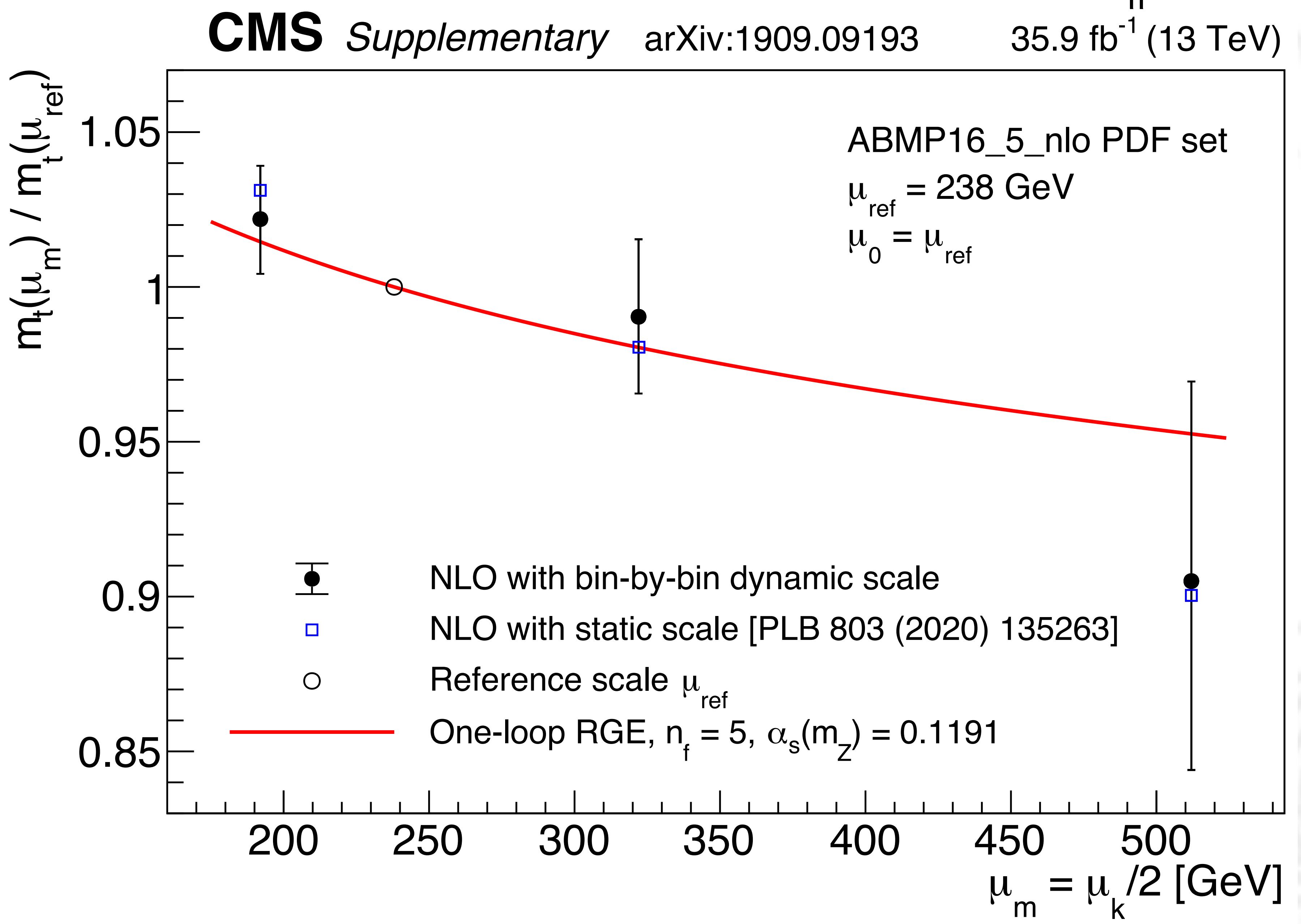
Mass running

$t\bar{t}$ dileptonic final states | 2016 data

[Phys. Lett. B 803 (2020) 135263]

- **first** experimental investigation of the top quark mass running
  - in $\overline{MS}$ scheme, m_t depends on energy scale $m_t(\mu_k)$
  - solution of RGE, like running of α_s
  - shape of invariant mass of $t\bar{t}$ pair
  - all $\sigma_{t\bar{t}}^i$ fitted **simultaneously with m_t^{MC}**
  - extract $m_t(m_t)$ in each bin of $m_{t\bar{t}}$ by comparison to NLO theory and evolve to $m_t(\mu_k)$
  - probe running by comparing to NLO predictions
    - up to a scale of 1 TeV

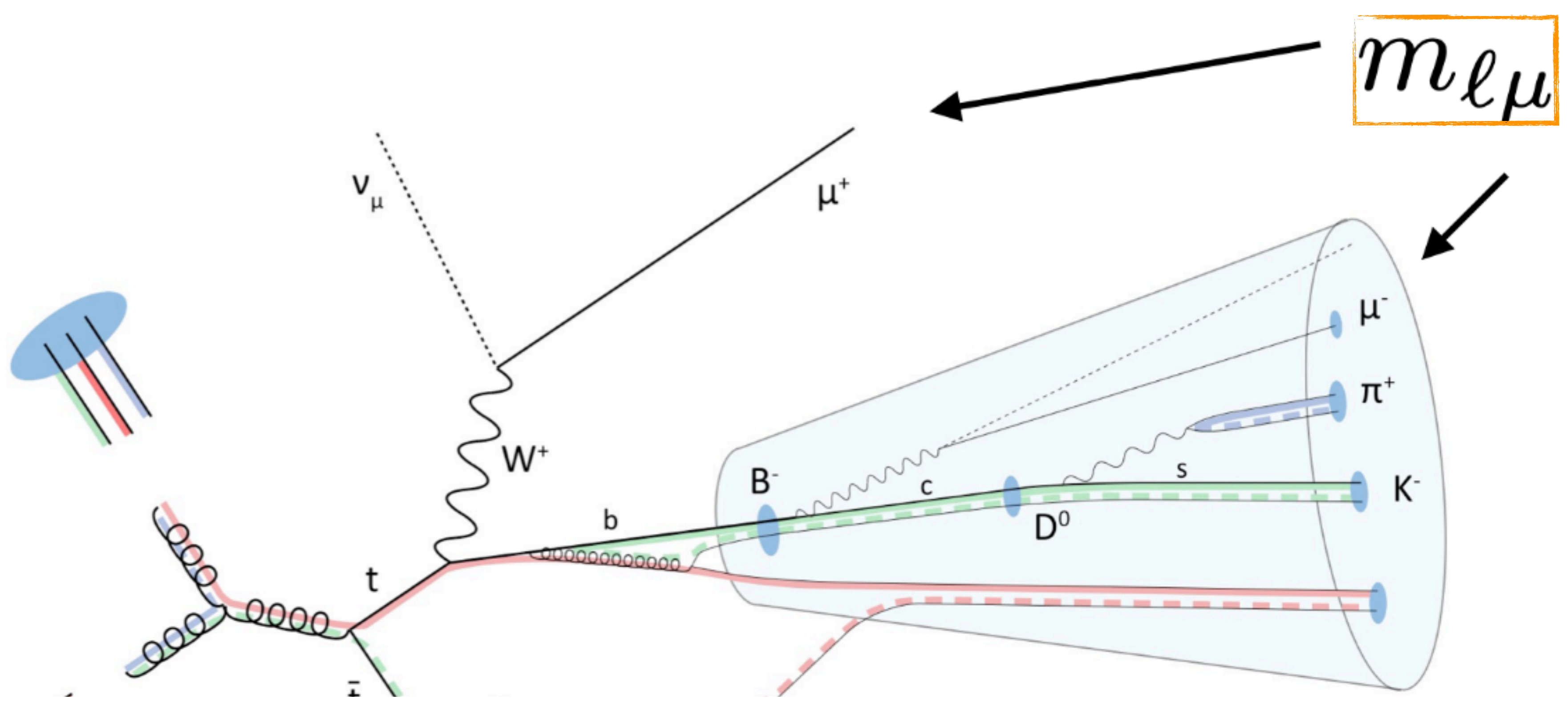


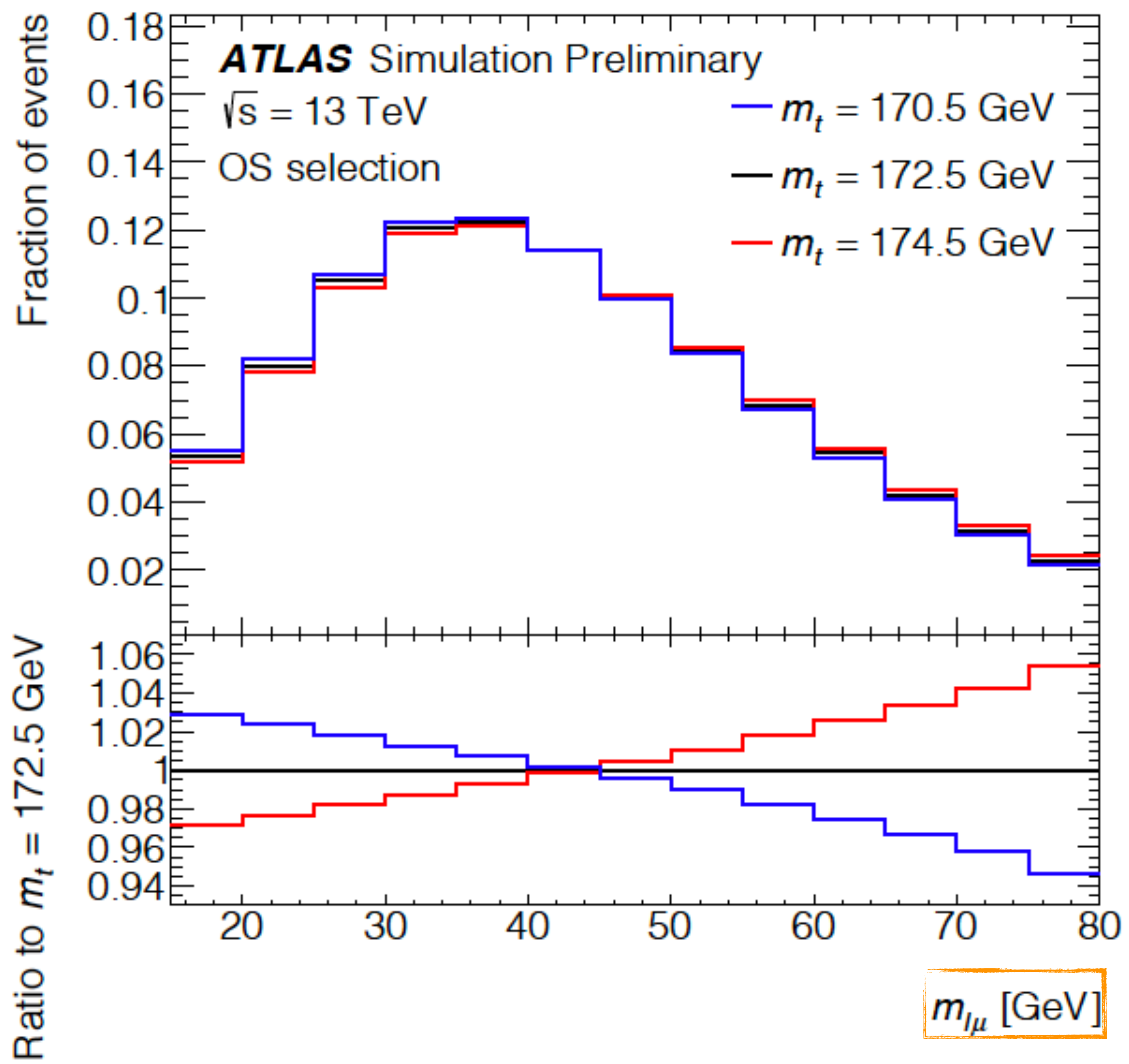


- results in agreement with SM RGE within 1.1σ
- no-running hypothesis excluded at 95% CL

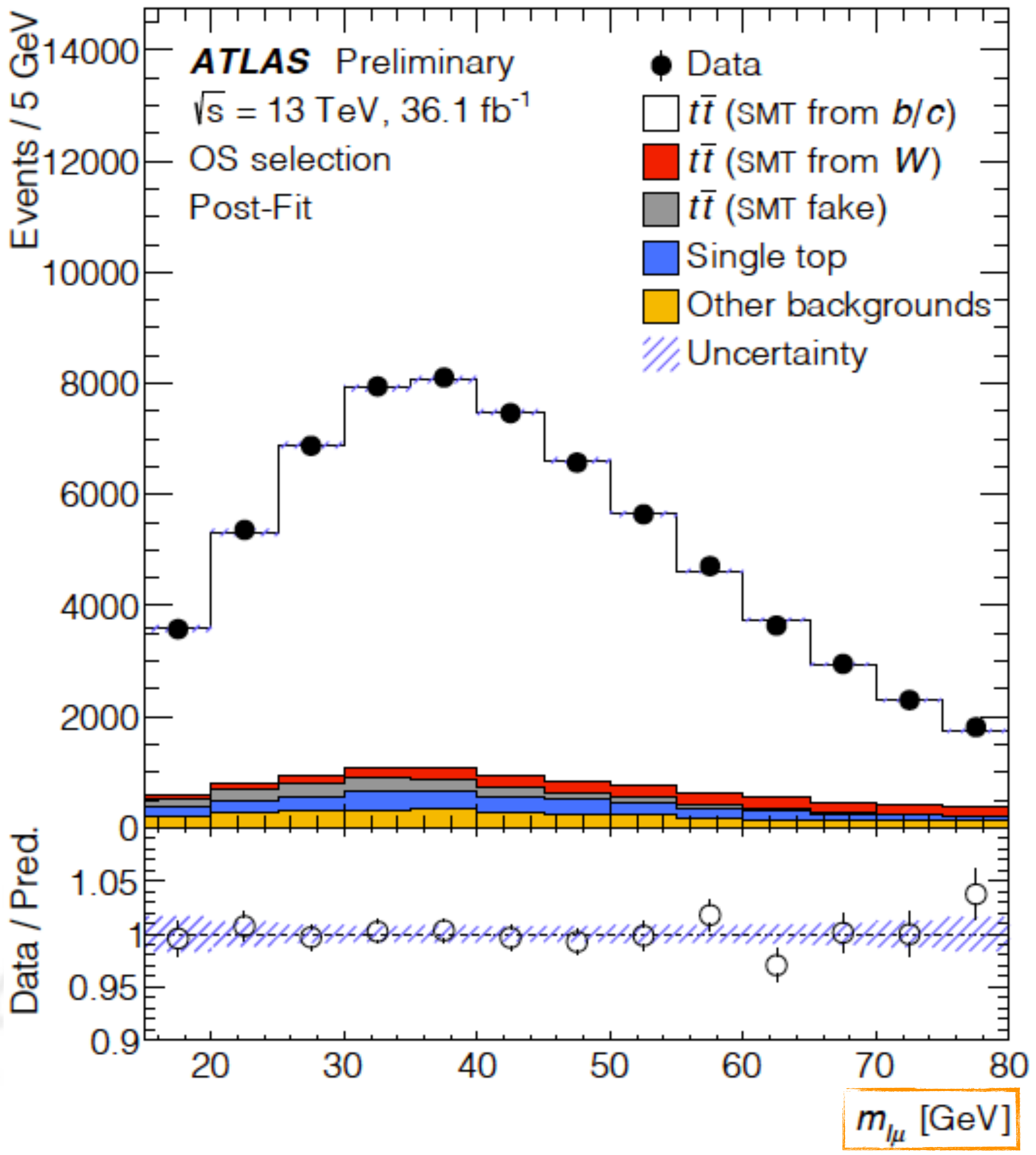
Top quark mass

Soft muons ($t\bar{t}$ l+jets) | 2016 data





ATLAS-CONF-2019-046



- invariant mass of lepton from W decay and soft muon from b quark sensitive to m_t
  - reduced sensitivity to jet calibrations
  - useful for **future combinations**
- retuned simulation using:
  - **recalibrated** b quark fragmentation Bowler-Lund parameter r_b~1.05
  - recent measurements of hadron production and decay fractions
- likelihood template fit to $m_{l\mu}$ spectrum in OS and SS channels

- **dominant** syst. uncertainty: **B hadron branching fractions**
- deviates by 2.2σ from ATLAS average

$$m_t = 174.48 \pm 0.40\,(\text{stat}) \pm 0.67\,(\text{syst})\ \text{GeV}$$

b quark fragmentation

$t\bar{t}$ eμ channel | 2015+16 data

- bottom quarks play vital role in many LHC analyses
  - also top mass measurements!
- fundamental test of pQCD and parton shower formalism
- currently tunes based on e^+e^- data
- at LHC: observables relative to the jet

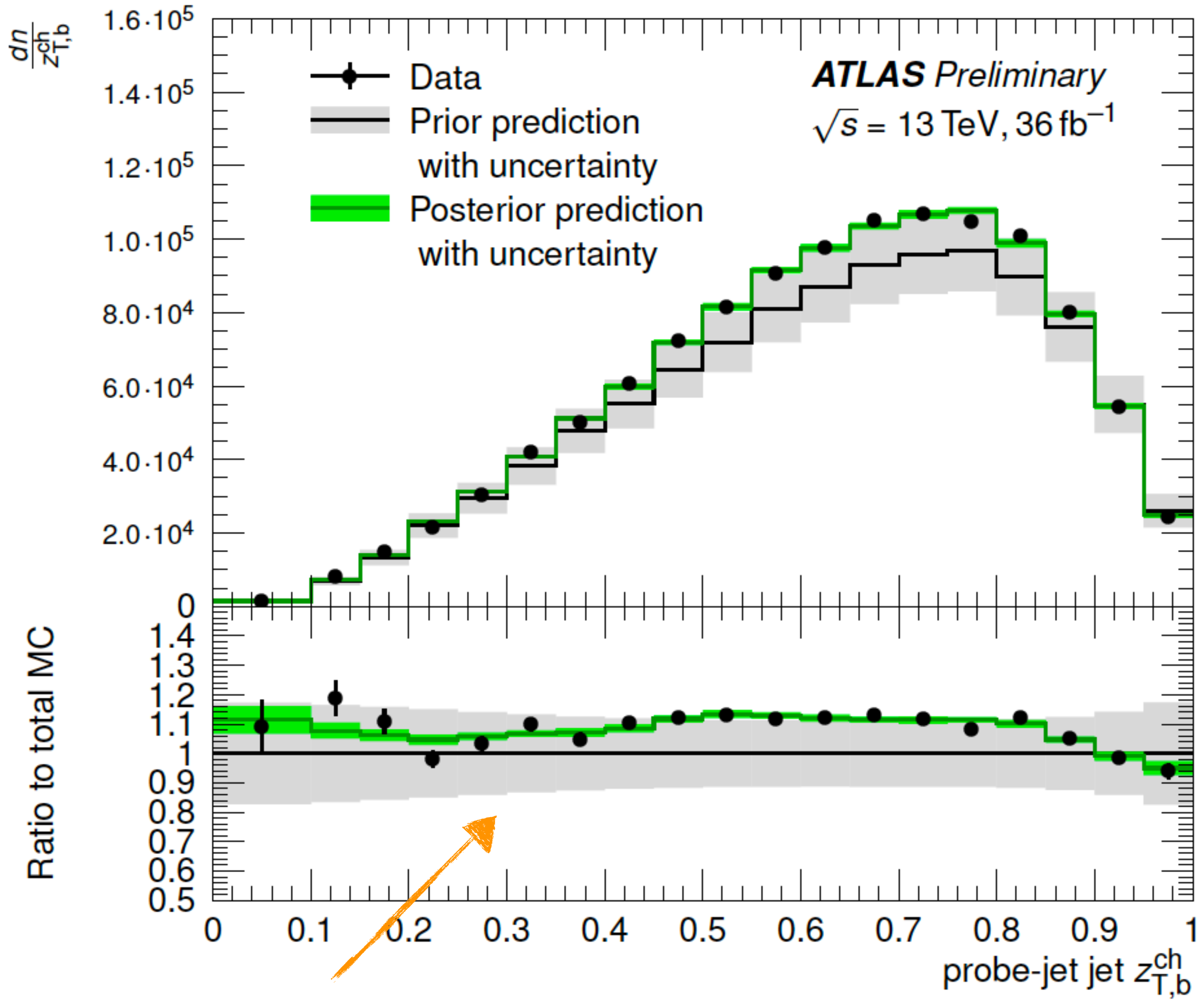
$$z^{ch}_{T,b} = \frac{p^{ch}_{T,b}}{p^{ch}_{T,jet}}$$

$$z^{ch}_{L,b} = \frac{\vec{p}^{\,ch}_{b} \cdot \vec{p}^{\,ch}_{jet}}{|p^{ch}_{jet}|^2}$$

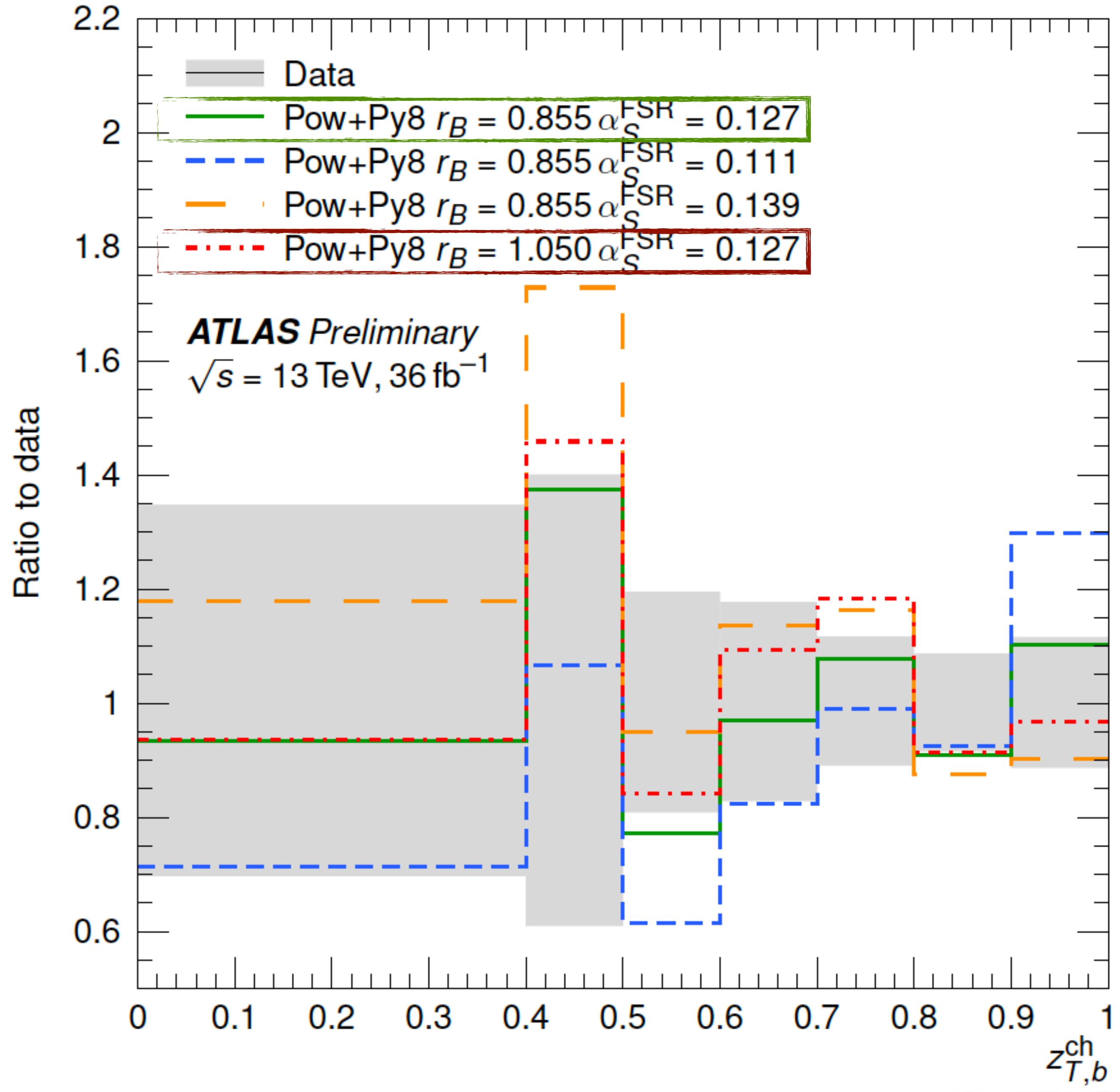
$$\rho = \frac{2p^{ch}_{T,b}}{p^e_T + p^\mu_T}$$

$$n^{ch}_b = \text{number of fiducial } b\text{-hadron children}$$

ATLAS-CONF-2020-050

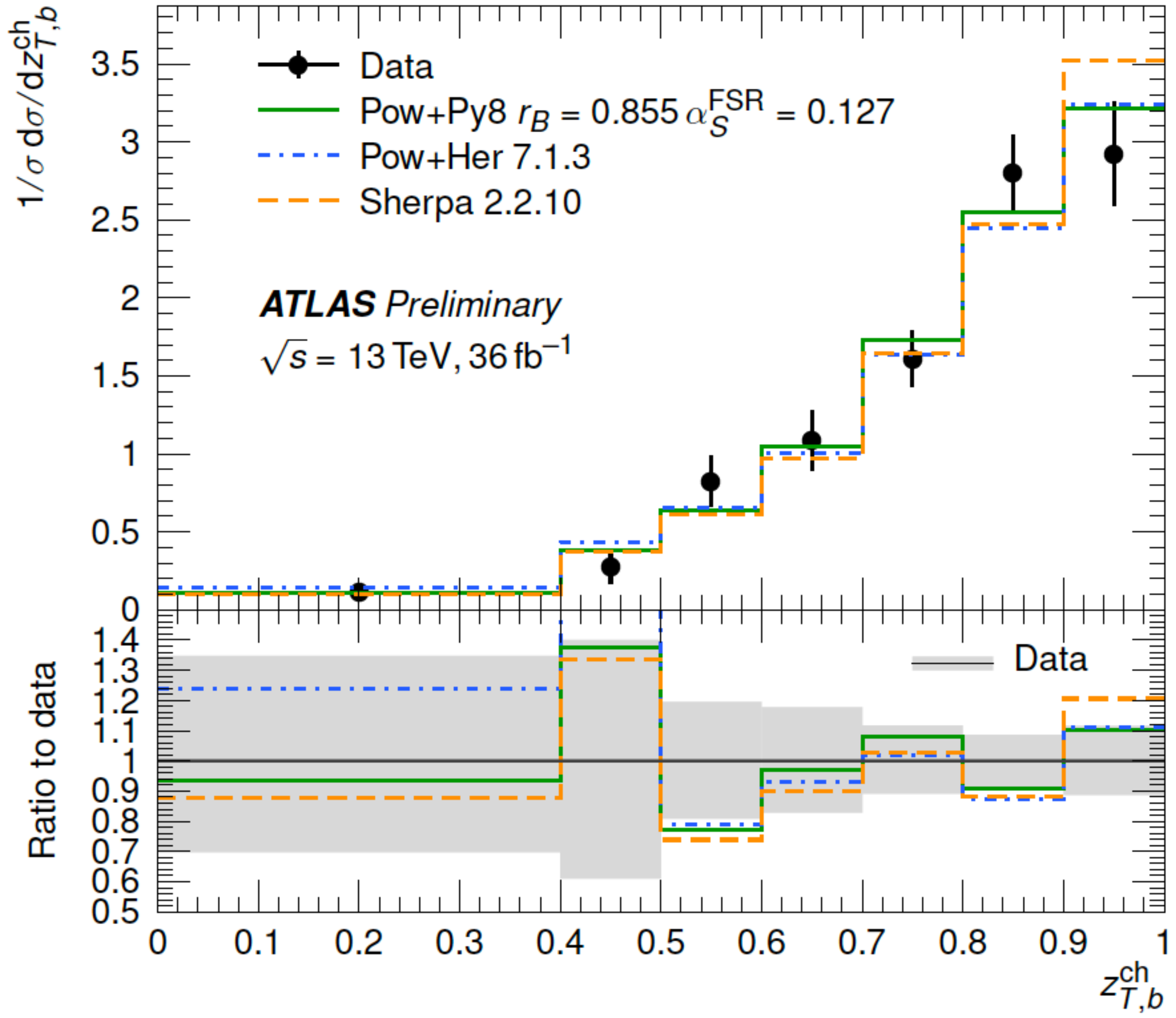


- **likelihood-unfolding** strongly reduces systematic uncertainties



p-values:

- default values preferred
  - also r_b=1.05 (see slide before)



- modern MC generators (Pow+Pyt/Pow+Her/Sherpa) successfully predict shape of observables

b quark fragmentation

NEW!

$t\bar{t}$ channel | 2015+16 data

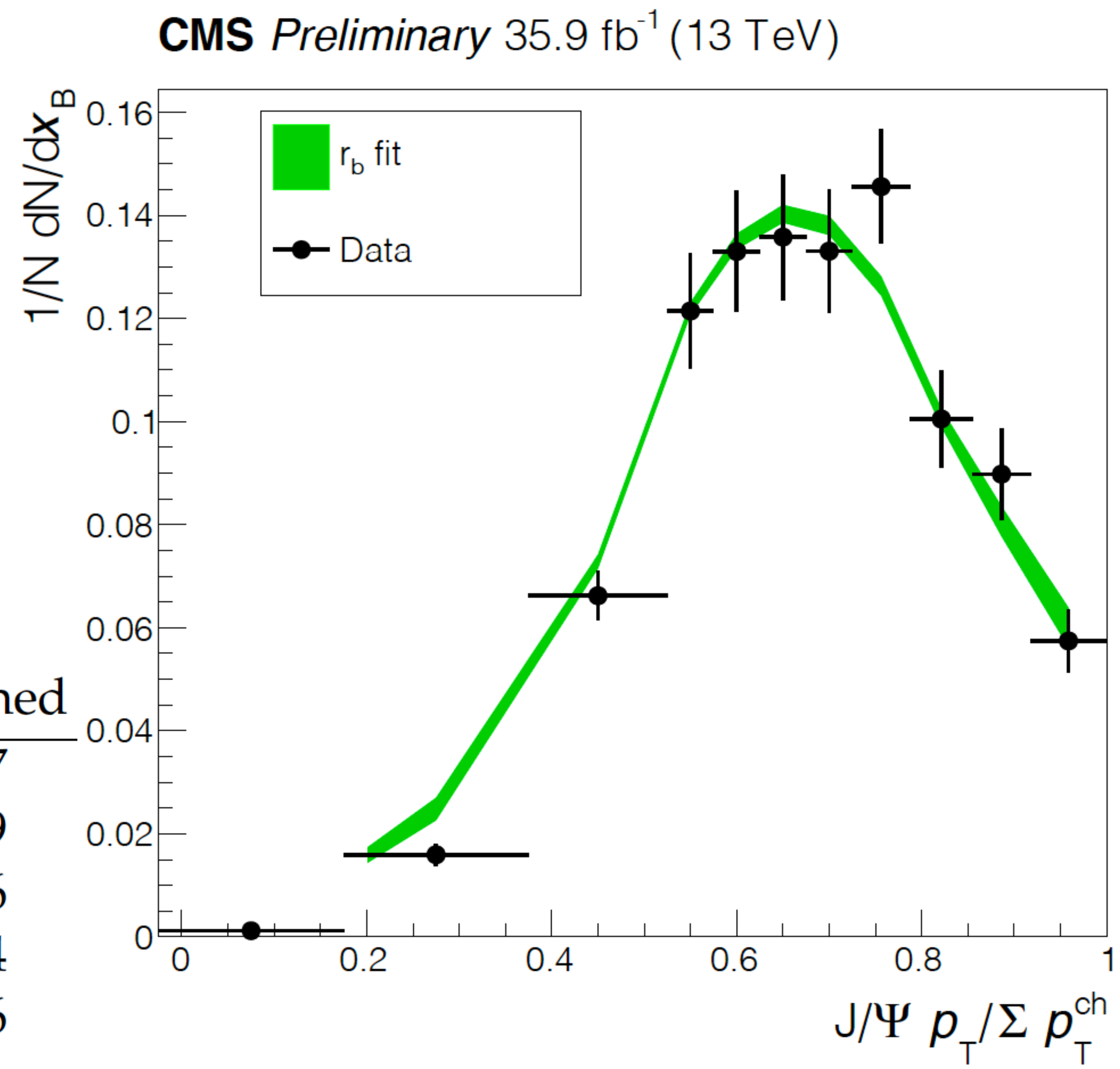
- bottom quarks play vital role in many LHC analyses
  - also top mass measurements!
- fundamental test of pQCD and parton shower formalism
- currently tunes based on e^+e^- data
- at LHC: observables relative to the jet

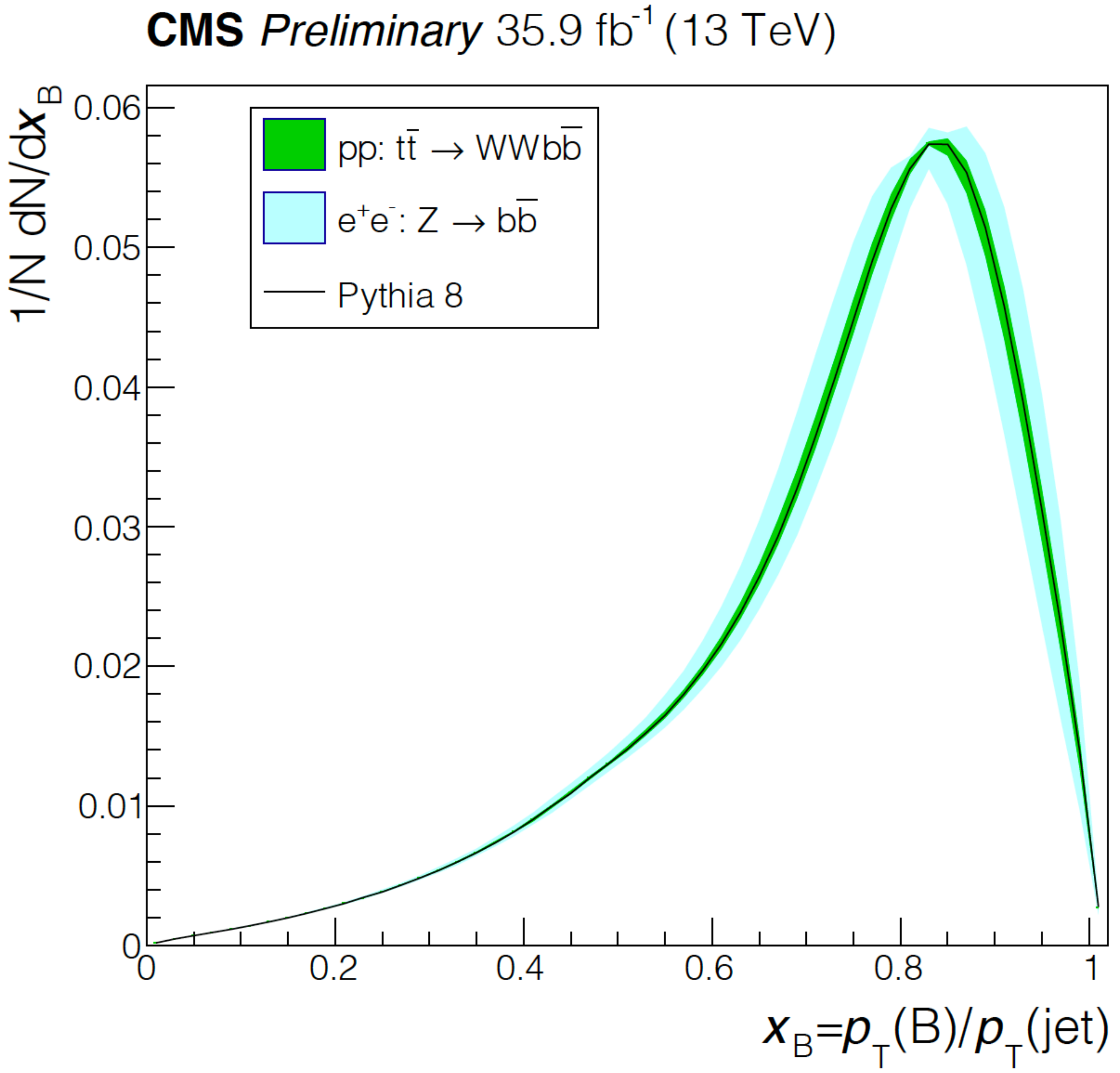
For more details on both, see Gulia Negro's talk!

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

- recent CMS measurement for r_b
  - **first at LHC**
- using charm mesons from B hadron decays as proxies J/ψ or D^0
- template fit to proxy distributions

Source	J/ψ	D^0	D^0_μ	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



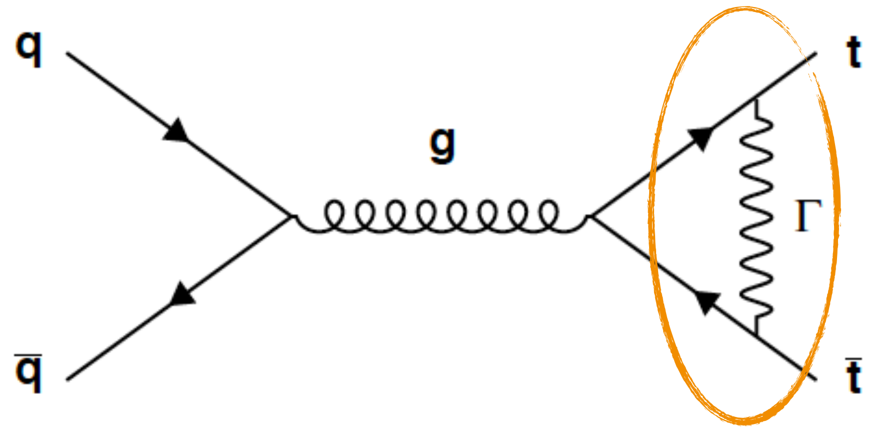


CMS-PAS-TOP-18-012

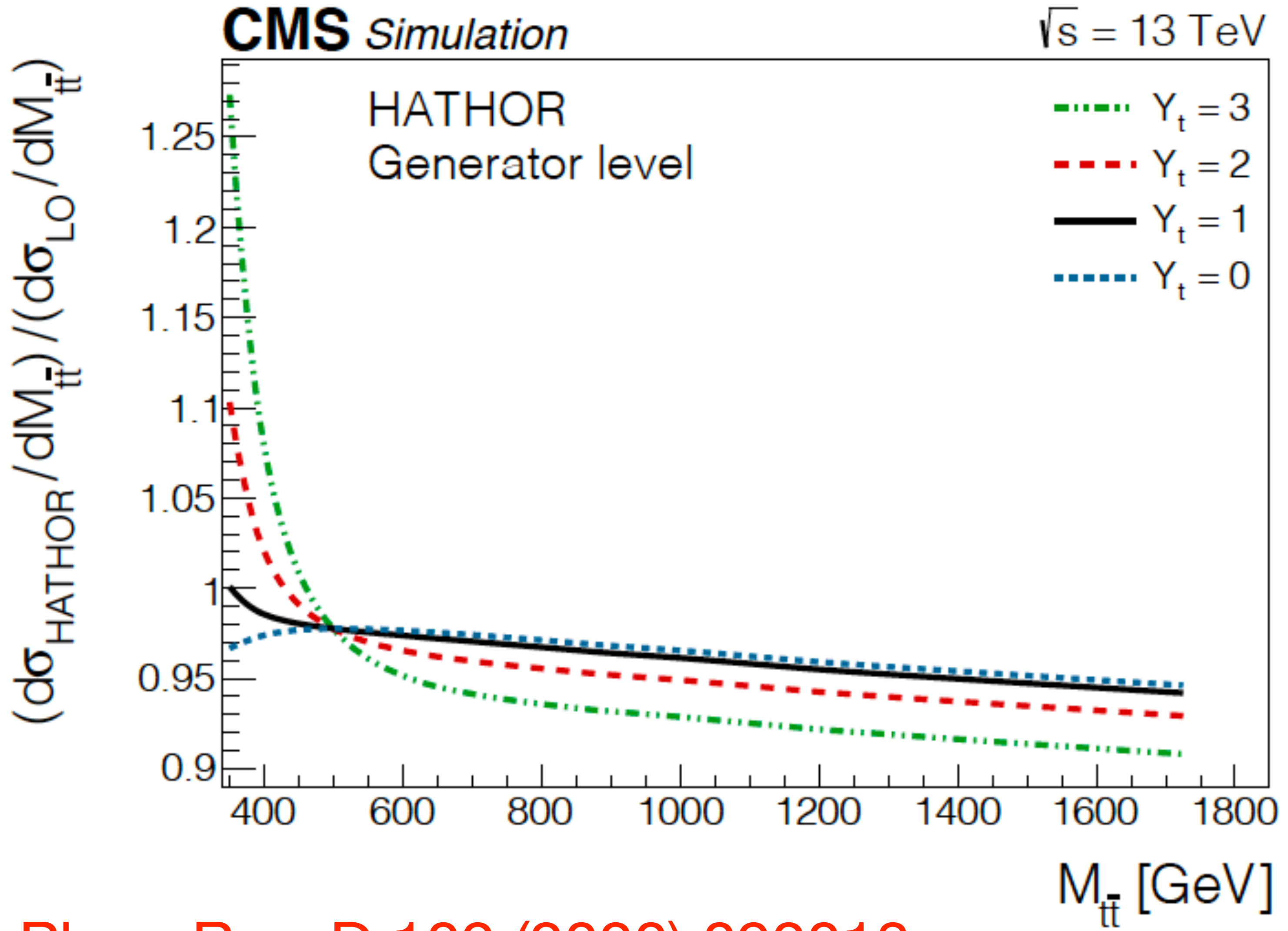
Yukawa coupling

$t\bar{t}$ dileptonic final states | 2016-2018 data

- **EW corrections** affect $t\bar{t}$ production
  - shape of $M_{t\bar{t}}$ and rapidity difference



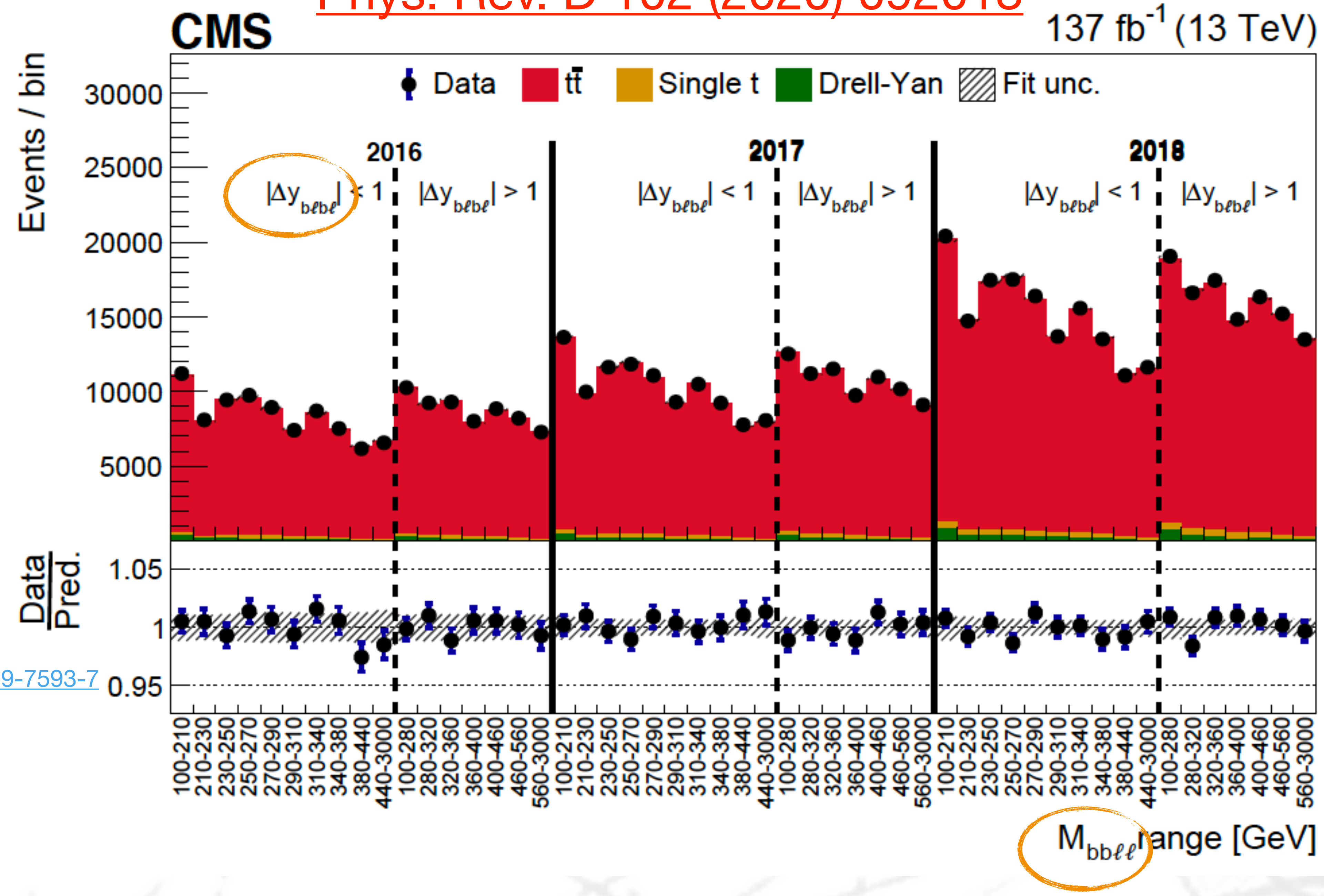
- new analysis in $t\bar{t}$ dileptonic final states
- comparison at detector level by **reweighting NLO Powheg+Pythia** (weights obtained using HATHOR2 in 2D)



- mitigate p_T^{miss} dependence in dilepton channel by exploiting **lepton+b system as proxy** (no $t\bar{t}$ reconstruction)
  - multi differential fit to $M_{bb\ell\ell}\ x\ |\Delta y_{b\ell b\ell}|$

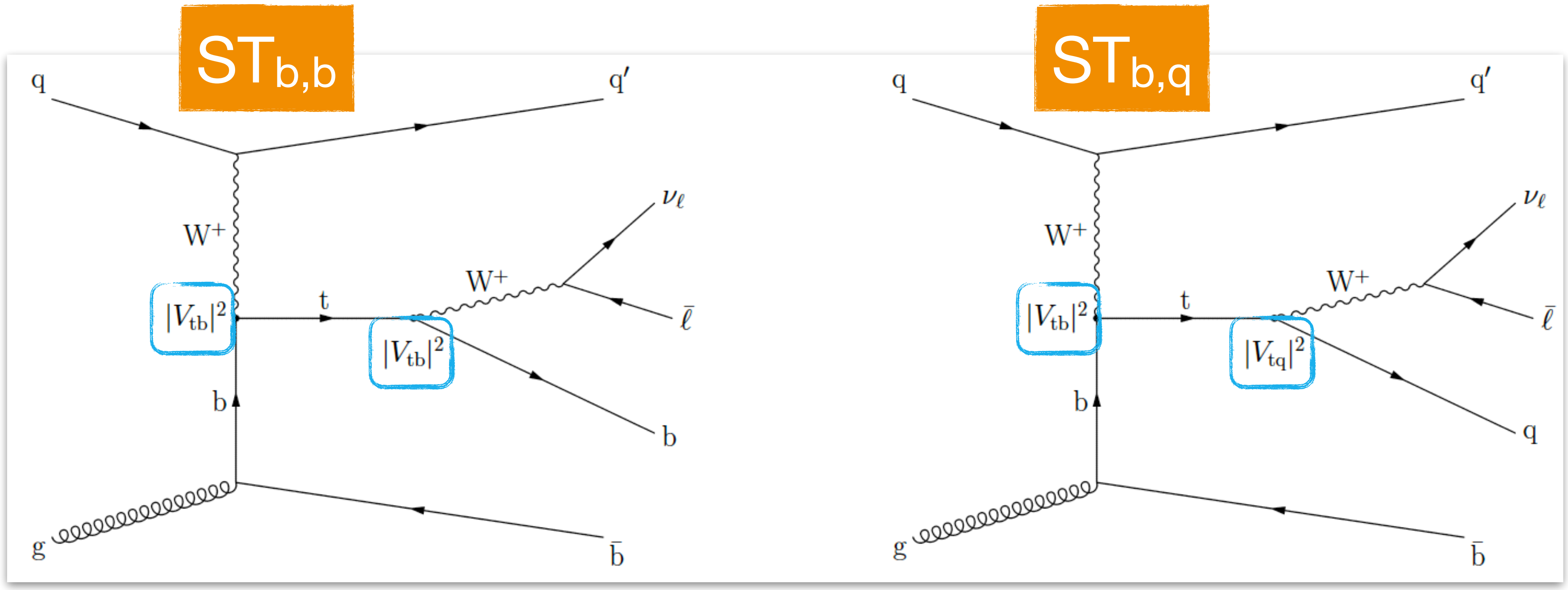
- limit at 95% CL: $Y_t < 1.54$
- best fit: $Y_t = 1.16^{+0.07}_{-0.08}\,(\text{stat})^{+0.23}_{-0.34}\,(\text{syst})$

Phys. Rev. D 102 (2020) 092013



- from combined Higgs measurements: $Y_t = 0.98 \pm 0.14$ 10.1140/epjc/s10052-019-7593-7 (larger model dependence)
- from four tops search: $Y_t < 1.7$ 10.1140/epjc/s10052-019-6909-y

$|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$
Single top t-channel | 2016 data



- first **simultaneous model-independent** measurement of CKM elements

- **three-fold interpretation** of signal strength parameters:
  - assuming SM CKM unitarity:

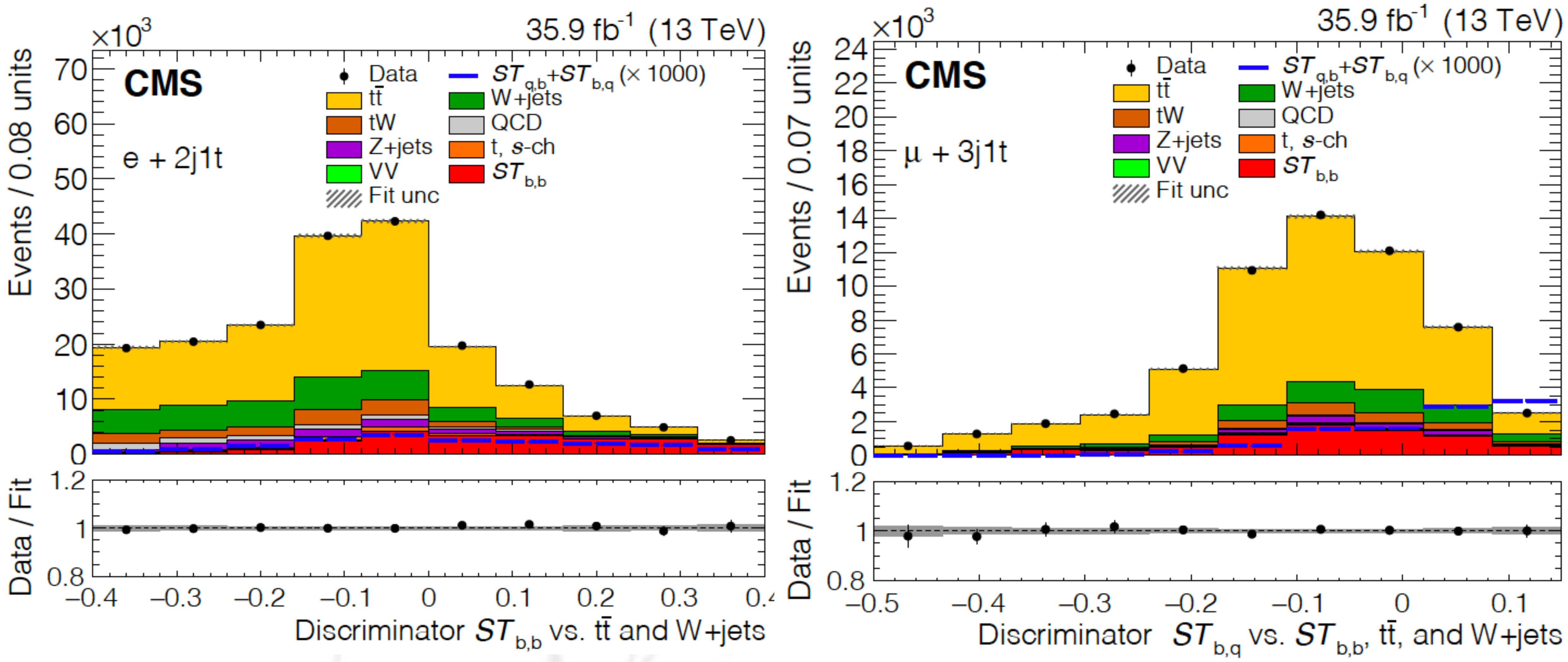
    $|V_{tb}| > 0.970 \qquad |V_{td}|^2 + |V_{ts}|^2 < 0.057$
  - no unitary constraint (add. quark families)

    $|V_{tb}| = 0.988 \pm 0.051 \quad |V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$
  - top quark **total width** unconstrained

    $|V_{tb}| = 0.988 \pm 0.024 \quad |V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06 \quad \frac{\Gamma_t^{obs}}{\Gamma_t} = 0.99 \pm 0.42$

- fitting multiple signals at the same time in different event categories

Phys. Lett. B 808 (2020) 135609



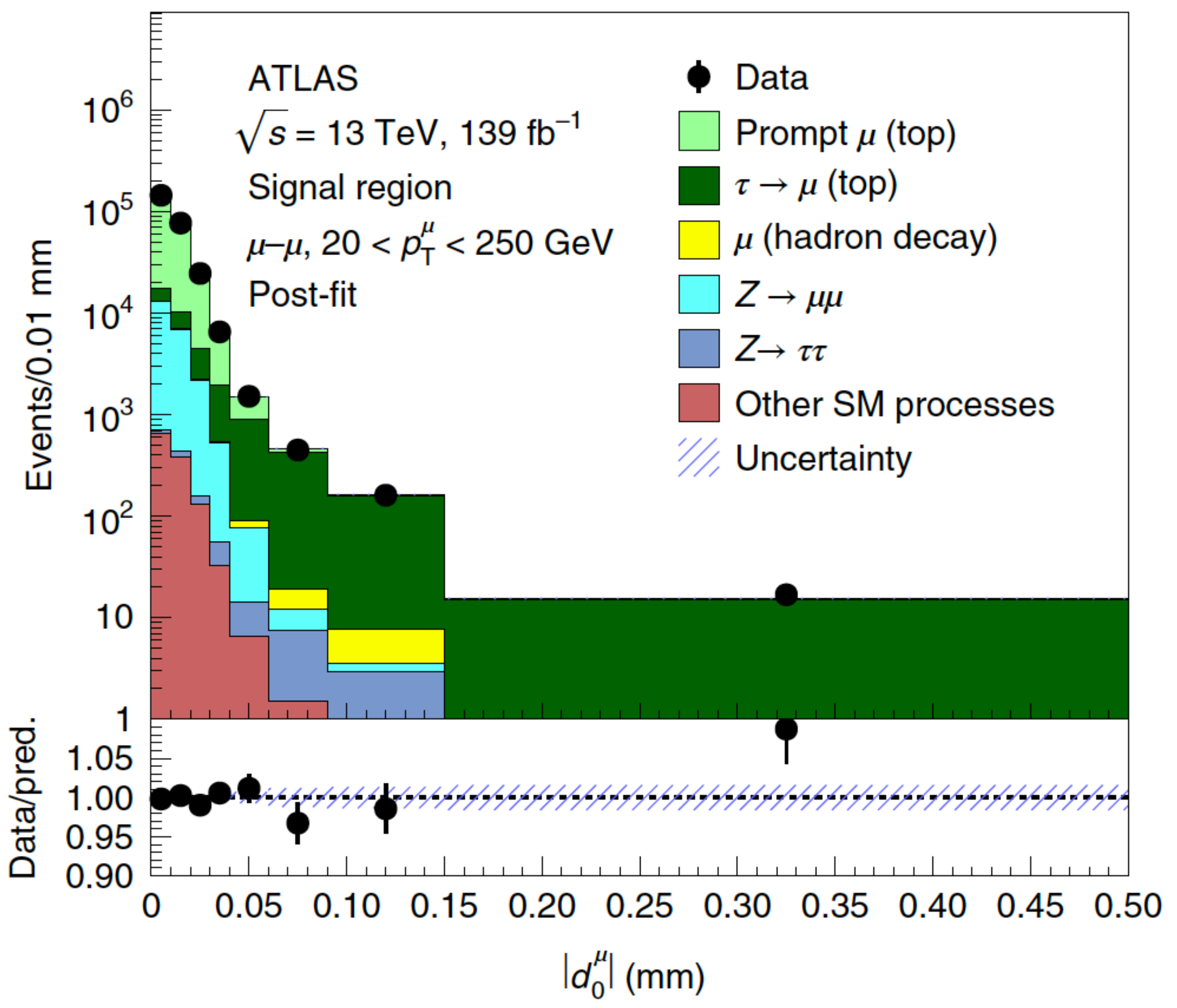
most precise single top measurement of $|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$ limited by modelling

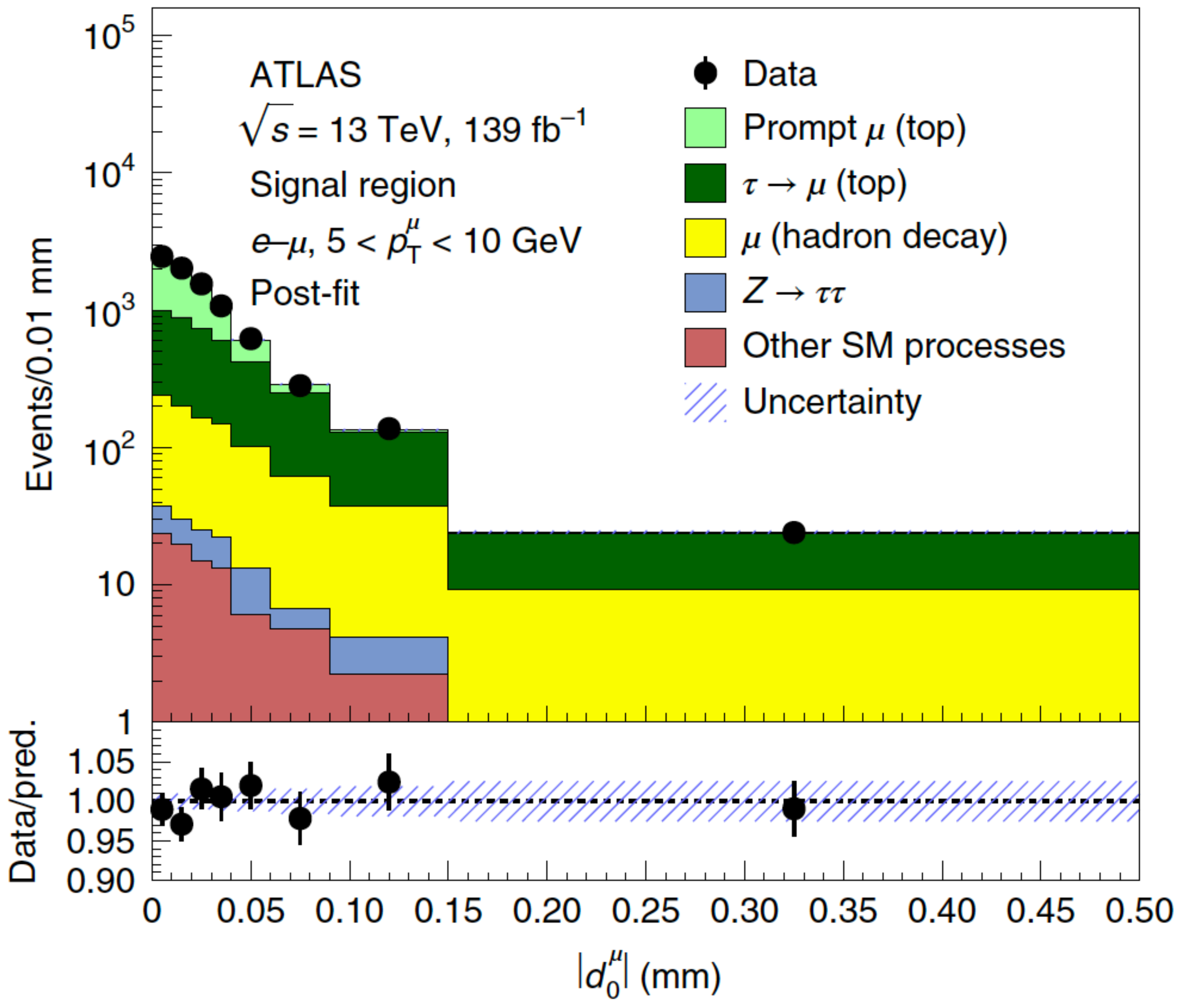
Lepton universality

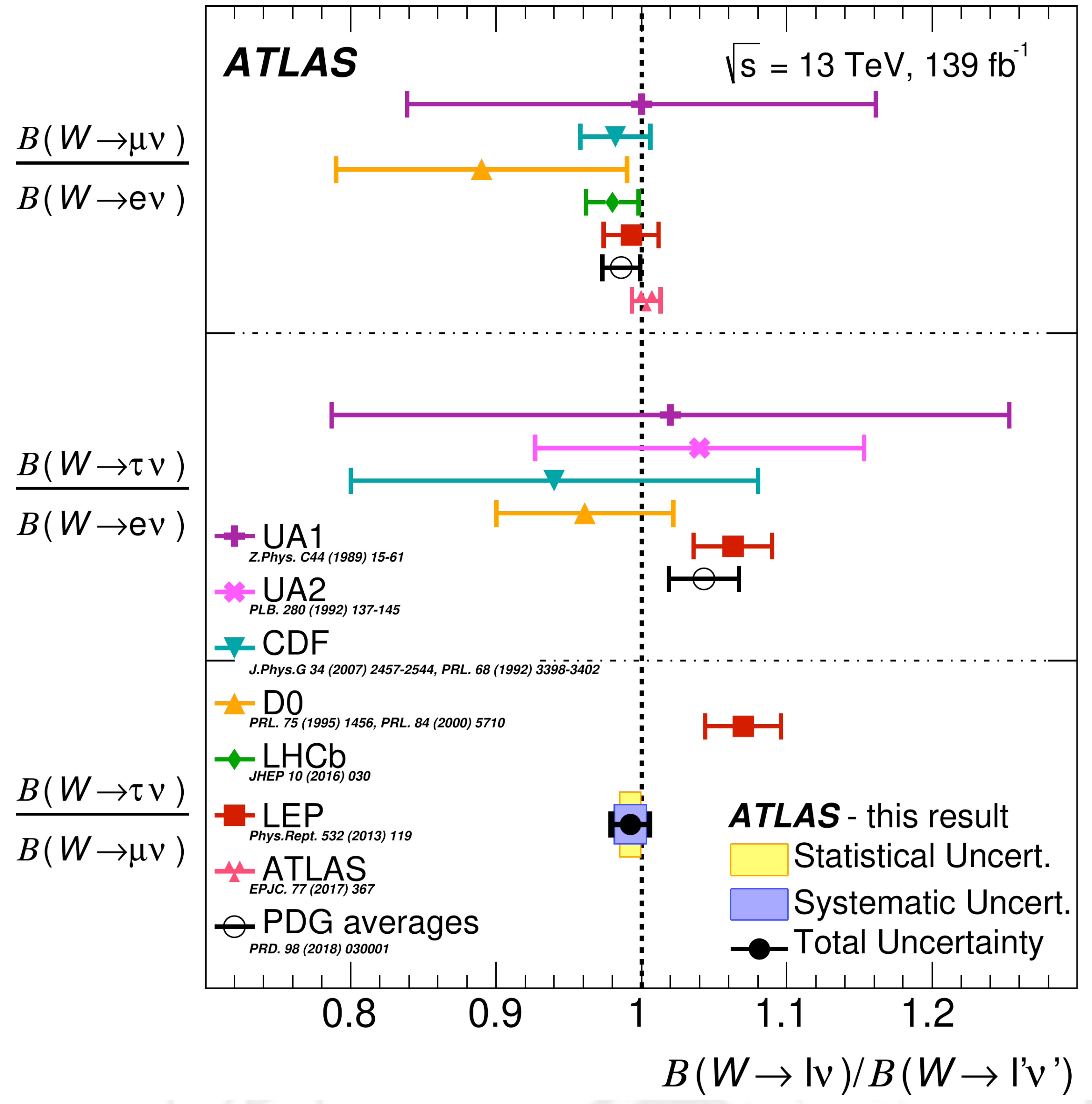
$t\bar{t}$ dileptonic final states | 2016-2018 data

Nature Physics 17, 813–818 (2021)

- universality of couplings of different fermion generations to EWK gauge bosons is a **fundamental assumption in SM** $\frac{B(W\rightarrow\tau\nu)}{B(W\rightarrow\mu\nu)}$
- prompt μ and τ→μ rates determined from multidim. likelihood fit (bins of p_T and $|d_0|$)
- surpass precision of LEP results by **factor ~ 2**







$$R(\tau/\mu) = 0.992 \pm 0.013$$

- muon identification and impact parameter template modelling are dominant uncertainties

Summary

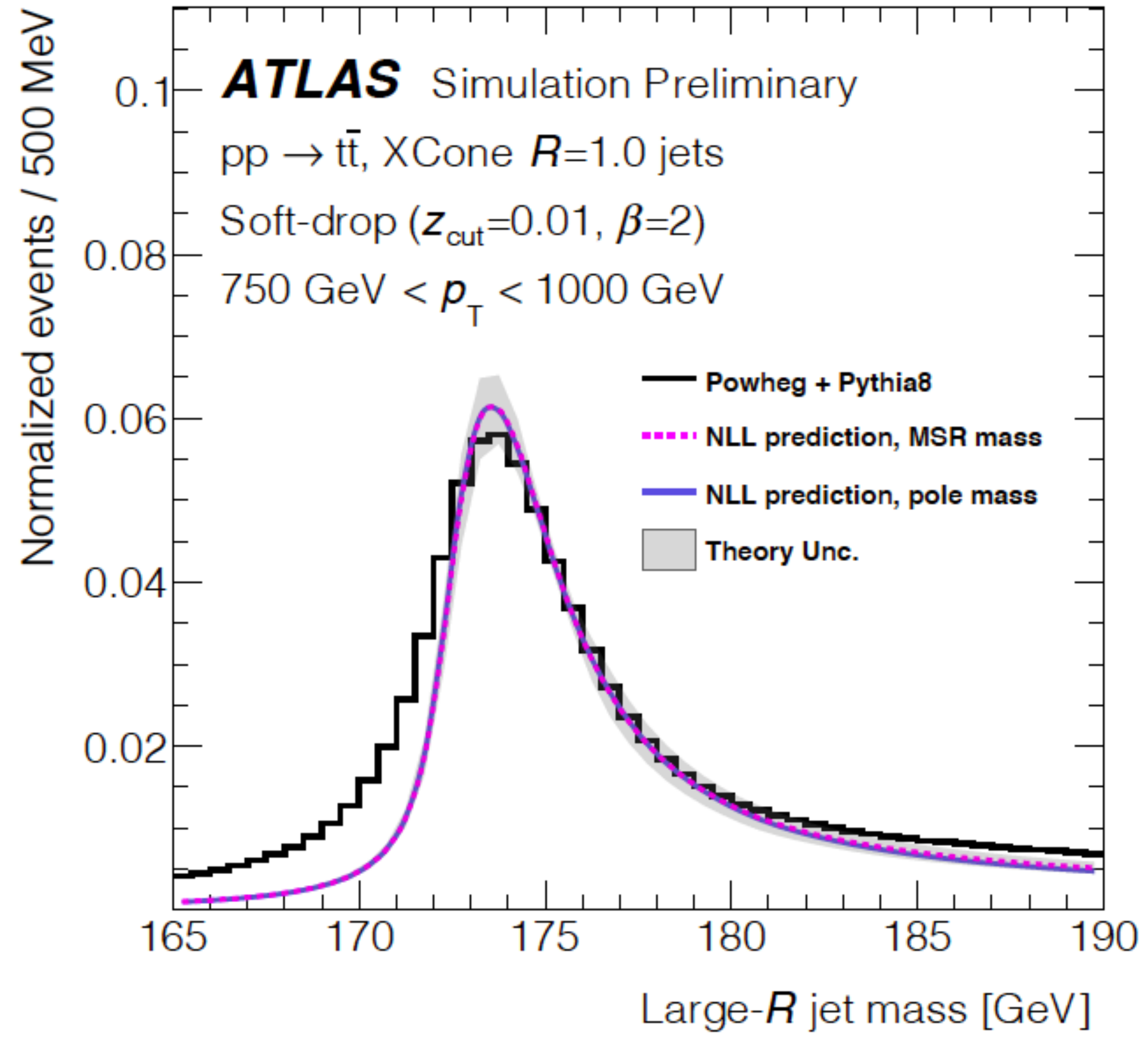
CMS & ATLAS have performed plenty of precision analyses measuring SM properties:

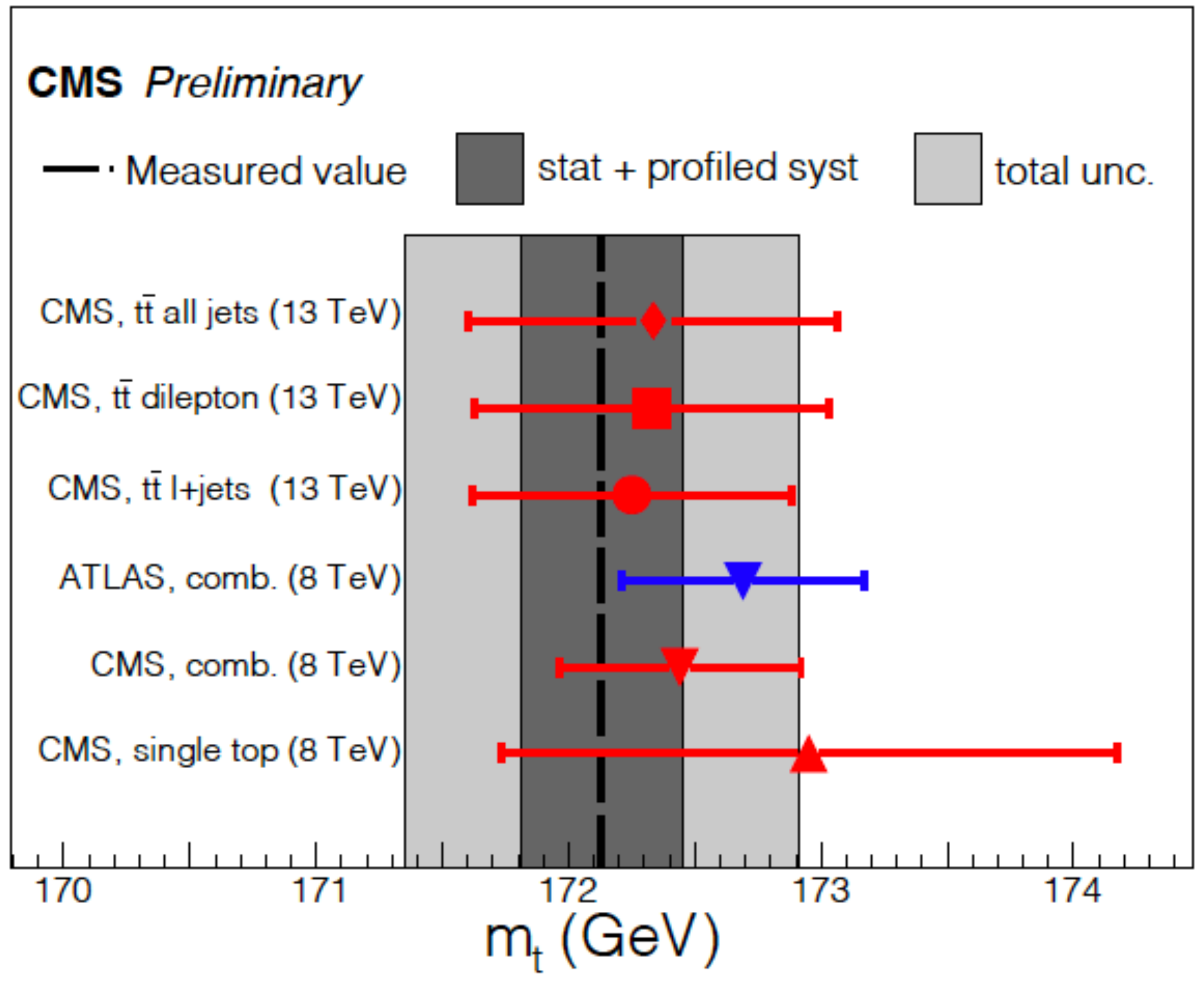
top and QCD sector:

- top quark mass measurements in different phase spaces
  - sub-GeV precision for the first time in the single top enriched sample (CMS)
  - improvement of factor 4 in boosted regime wrt. Run I (CMS)
  - first time using dilepton invariant mass (ATLAS)
- significant improvements in understanding of m_t^{MC} in ATLAS $t\bar{t}$ simulation
- complementing b quark fragmentation measurements with LHC data (ATLAS & CMS)

top and EWK sector:

- Yukawa: indirect studies of the top Yukawa coupling (CMS)
- first direct measurement of V_{tx} elements in the CKM matrix (CMS)
- fundamental test of lepton universality (ATLAS)





Backup