Top properties at the LHC

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on behalf of the ATLAS and CMS collaborations

SM@LHC 2021

Introduction

- Heaviest known elementary particle: m_{top} ~ 173 GeV from measurements
  ➣ Sensitive to EWSB mechanism and vacuum stability through radiative corrections

- Top quarks produced in abundance @LHC ⇒ *precision measurements*
  ➣ predominantly in pairs ($t\bar{t}$) via strong interaction (**≈ 10 Hz @ 13 TeV**)
  ➣ alternatively, singly through electroweak interaction (**≈ 1 Hz @ 13 TeV**)

- Unique behavior : Decays ($\boldsymbol{\tau_{decay} \approx 10^{-25}}$ **s**) before hadronization ($\boldsymbol{\tau_{had.} \approx 10^{-24}}$ **s**)
  ➣ Access to **bare quark properties** ⇒ spin-polarization

- Test of perturbative QCD at NLO or NNLO precision (fixed-order)

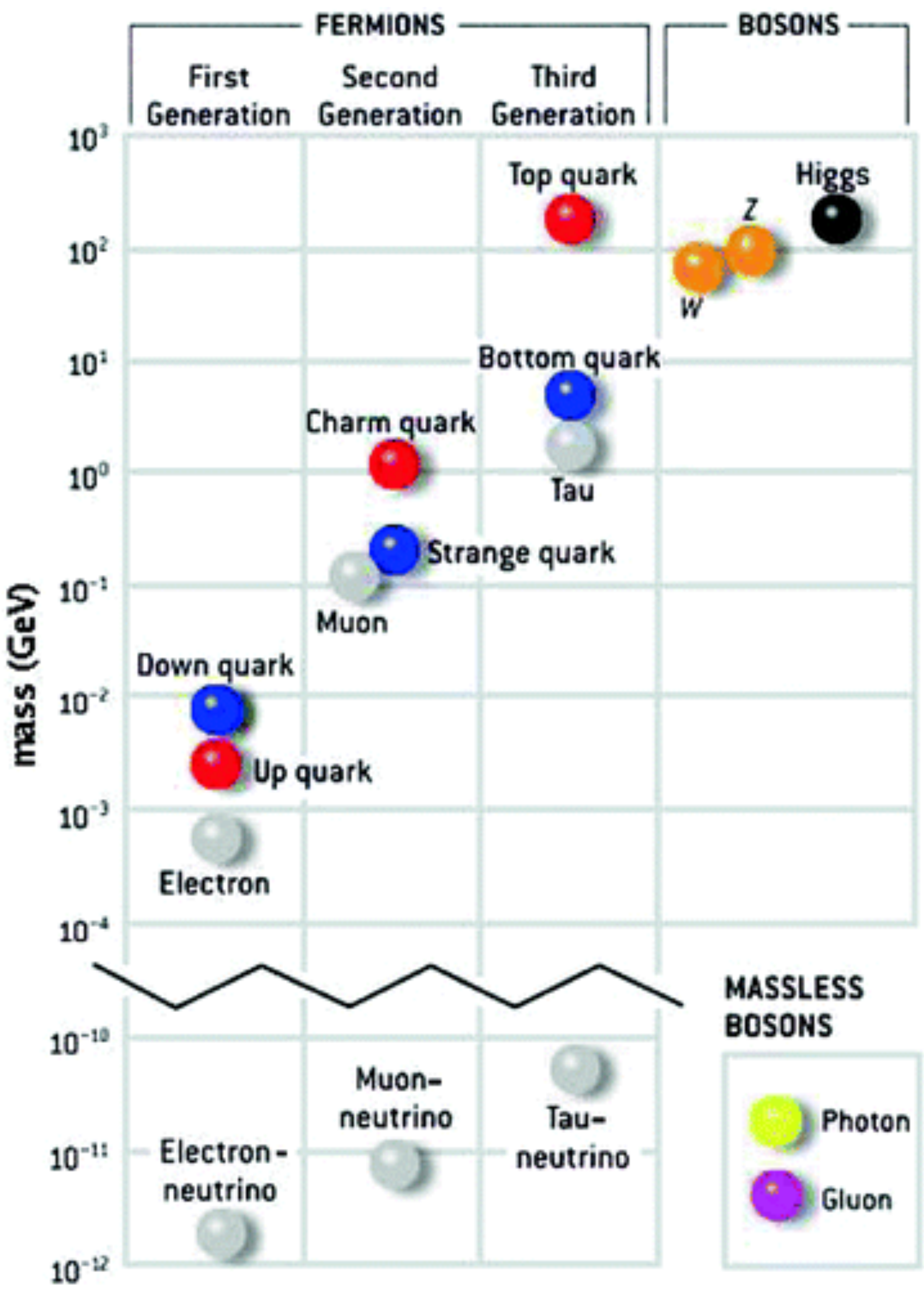
- Constrains proton PDFs, strong coupling, m_t^{pole}

- Access to CKM element $|V_{tb}|$ via tWb vertex at production and decay in the electroweak production mode

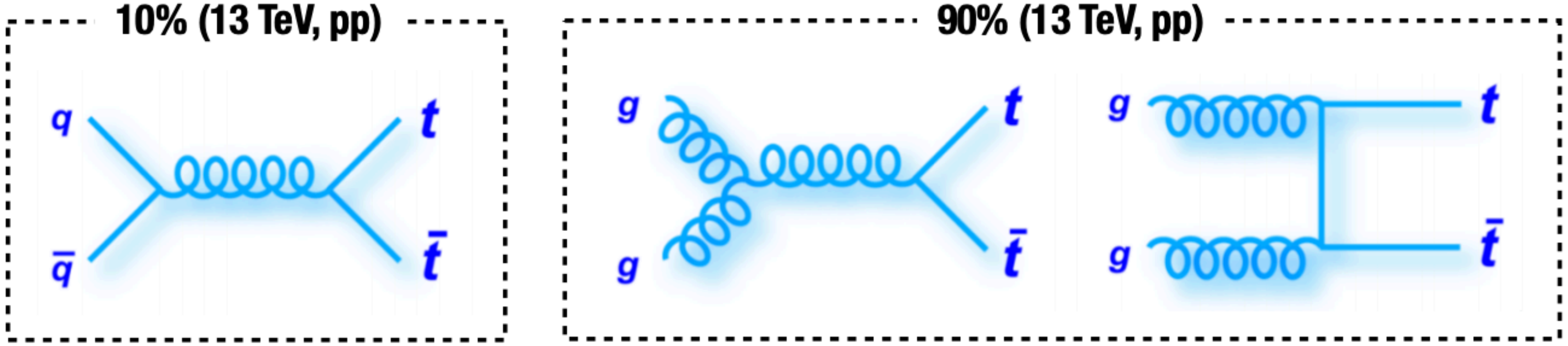
- Window to New Physics via anomalous / EFT couplings

- Constitutes dominant background to multiple BSM resonance searches

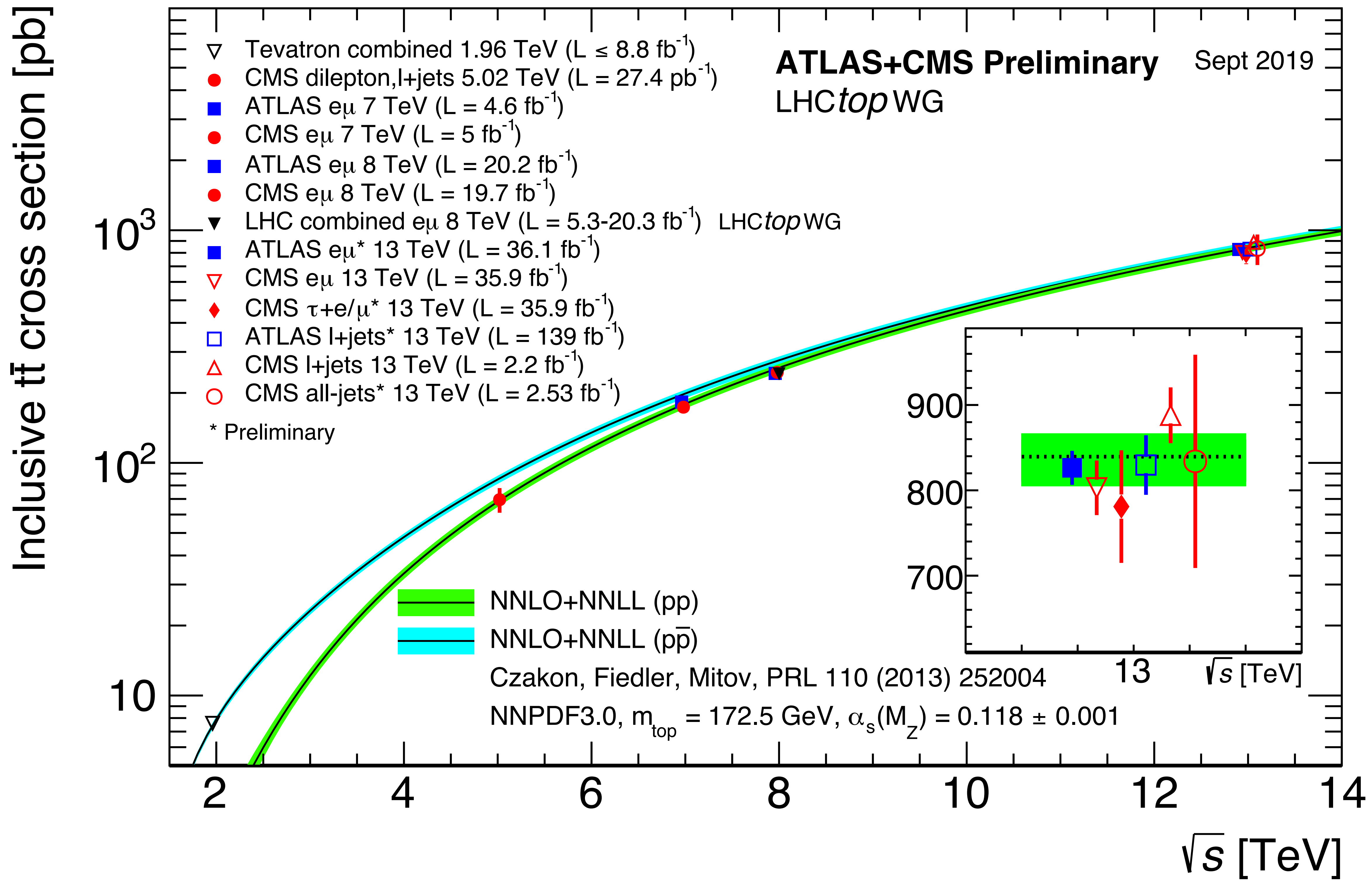
This talk focuses mostly on the selected results from the latest measurements



$t\bar{t}$ production



More details in the talk by M. Owen



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

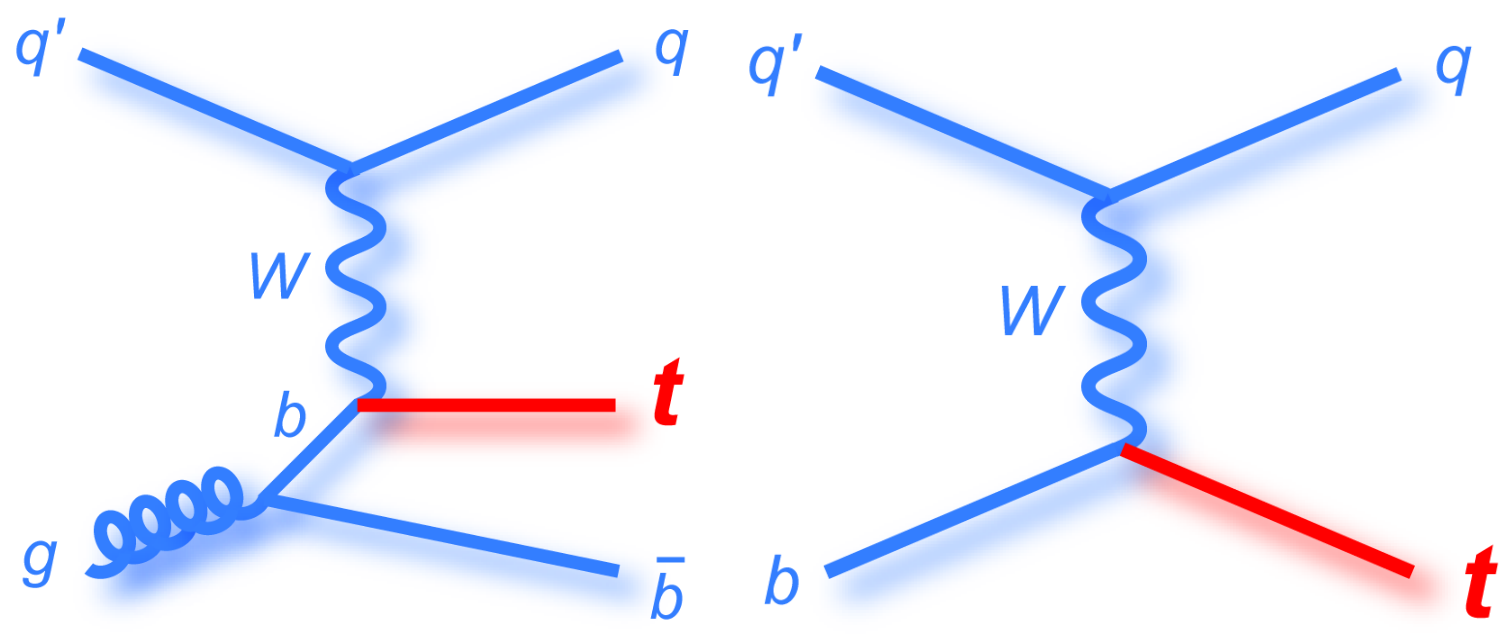
$\sqrt{s}$	$\sigma_{t\bar{t}}$ (NNLO + NNLL)
7 TeV	$177.3^{+10.1}_{-10.8}$ pb (6.6%)
8 TeV	$252.9^{+15.3}_{-16.3}$ pb (6.2%)
13 TeV	$831.8^{+45.5}_{-49.9}$ pb (5.7%)

Theoretical uncertainties shown here correspond to μ_R and μ_F scale, PDF and the strong coupling

Single top quark production

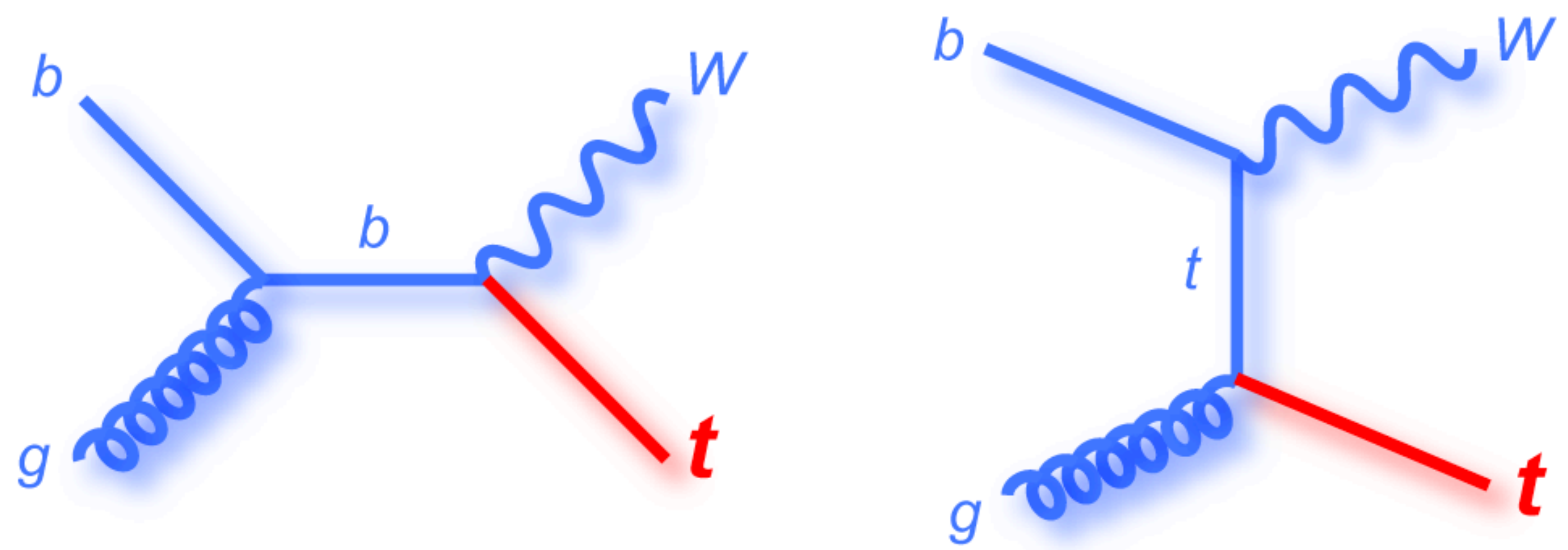
t-channel (~ 73% at LHC)

Golden Channel, sensitive to FCNC



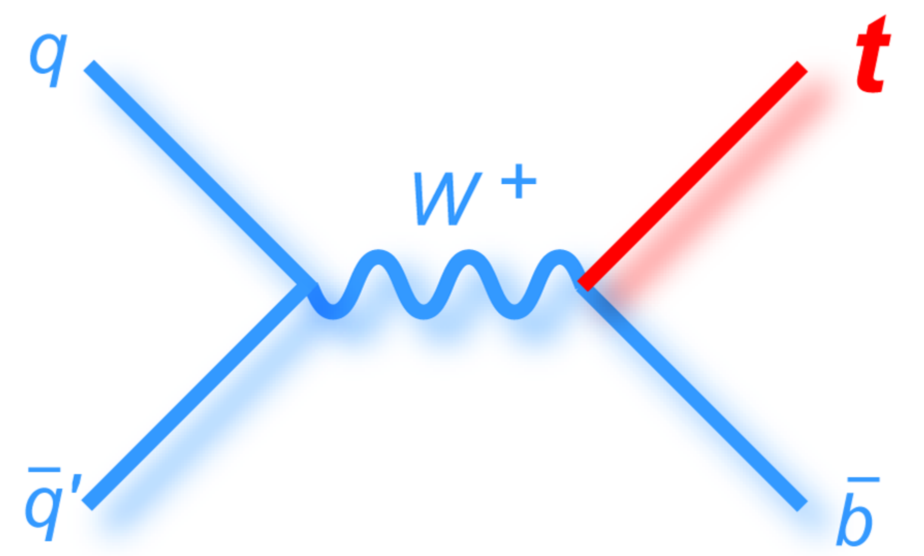
tW (~ 24% at LHC)

Observed at LHC, sensitive to BSM couplings



s-channel (~ 3% at LHC)

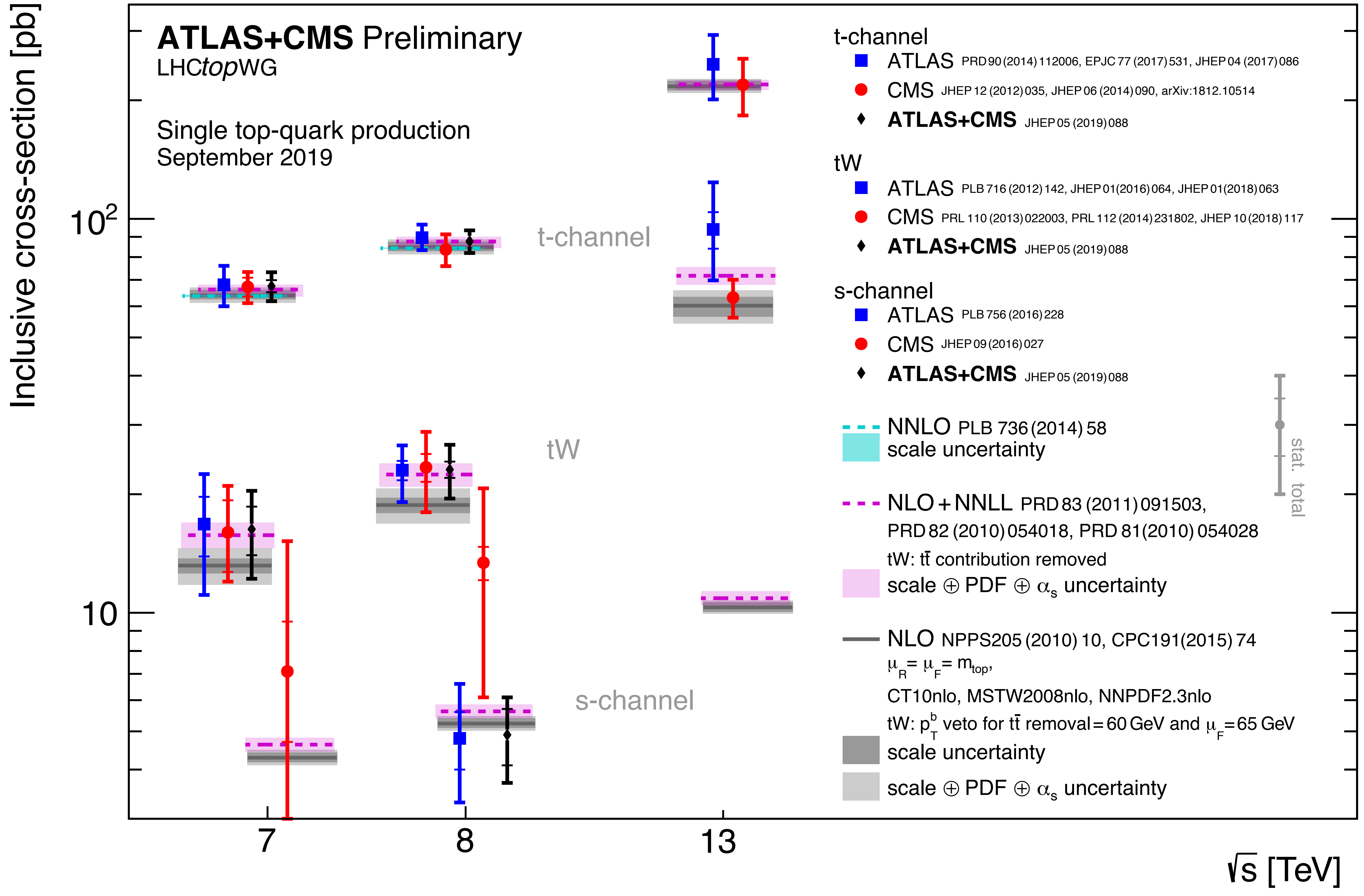
Challenging at LHC



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

$\sqrt{s}$	$\sigma_{t\text{-ch.}}$ (NLO)	σ_{tW} (approx. NNLO)	$\sigma_{s\text{-ch.}}$ (NLO)
7 TeV	$63.9^{+2.9}_{-2.5}$ pb (4.5%)	15.7 ± 1.2 pb (7.6%)	4.3 ± 0.2 pb (4.7%)
8 TeV	$84.7^{+3.8}_{-3.2}$ pb (4.4%)	22.4 ± 1.5 pb (6.7%)	5.2 ± 0.2 pb (3.9%)
13 TeV	$217.0^{+9.0}_{-7.7}$ pb (4.1%)	71.7 ± 3.8 pb (5.3%)	10.3 ± 0.4 pb (3.9%)

Theory uncertainties due to μ_R and μ_F scale, PDF and the strong coupling



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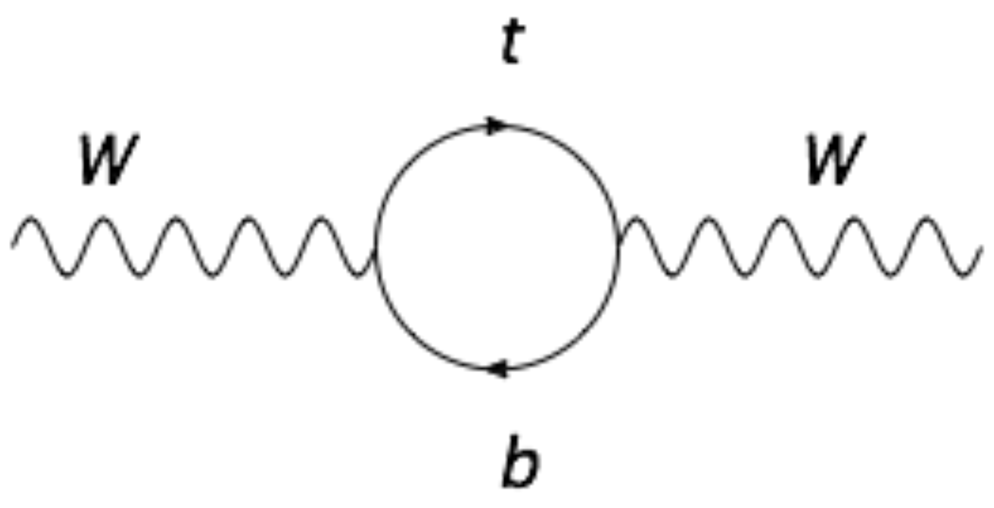
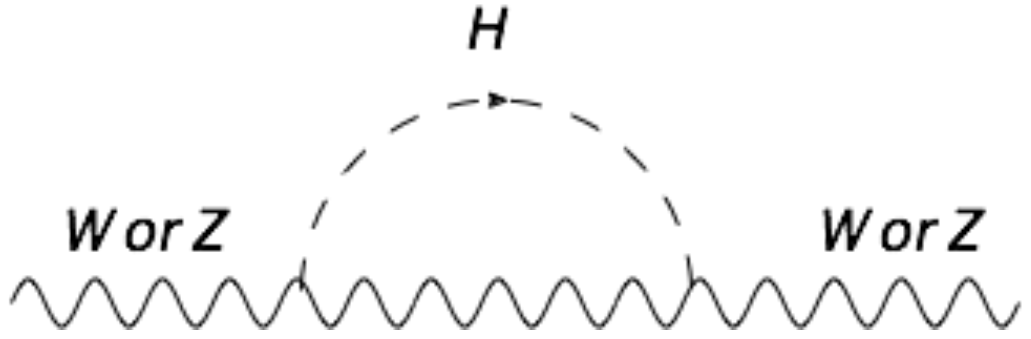
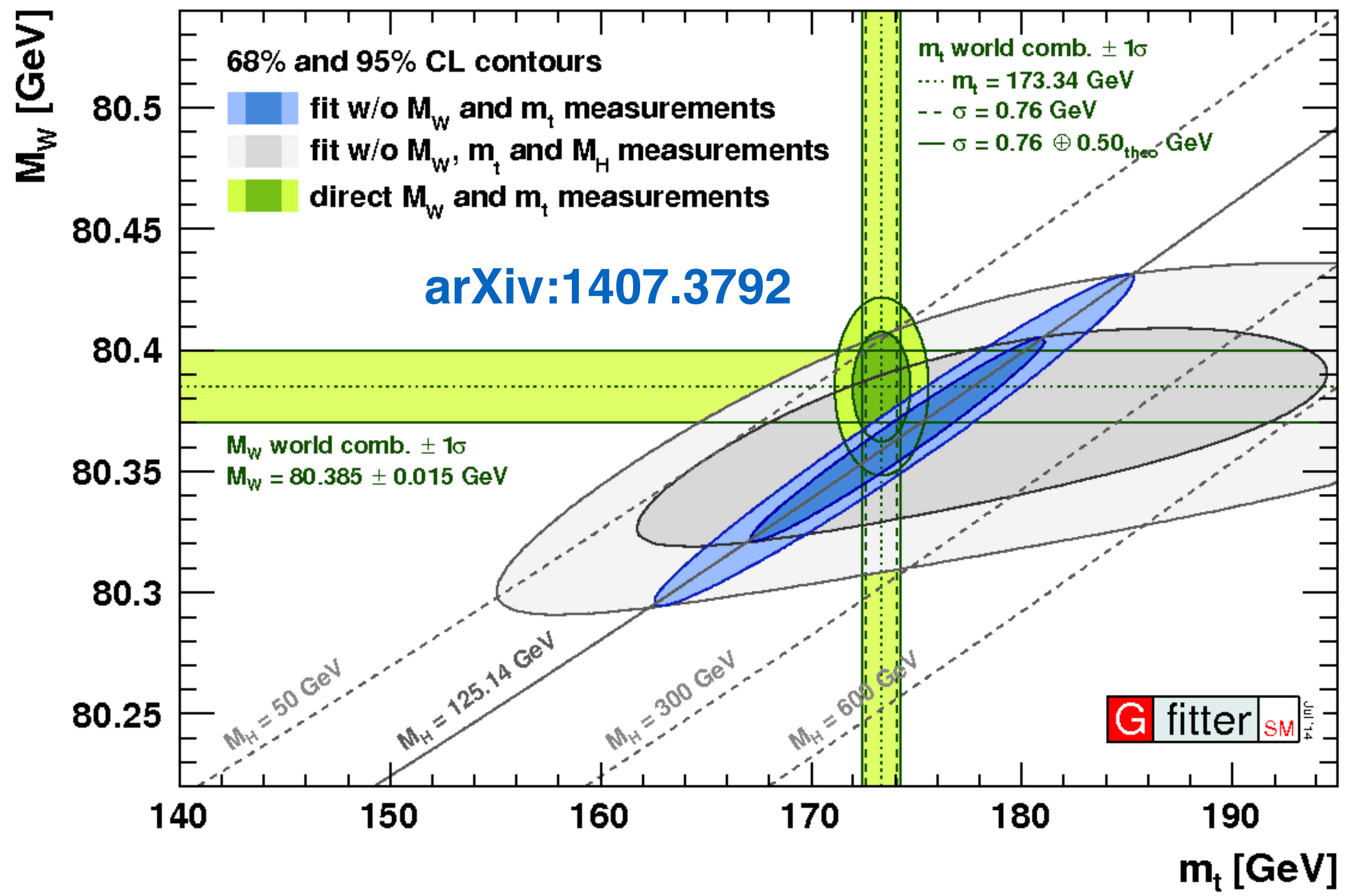
m_t and electroweak symmetry



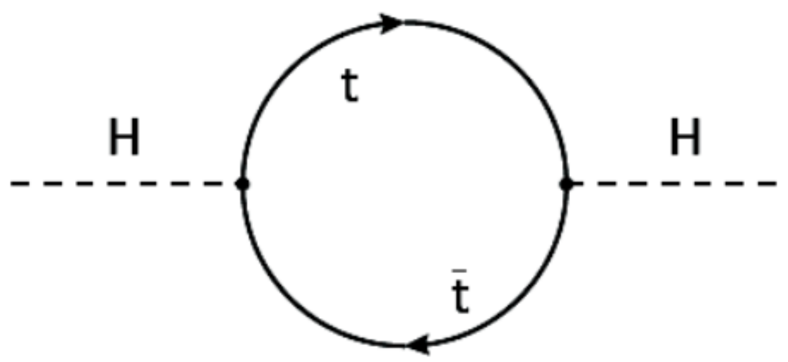
$$\Delta m_W \propto m_t^2$$



$$\Delta m_W \propto \ln m_H$$

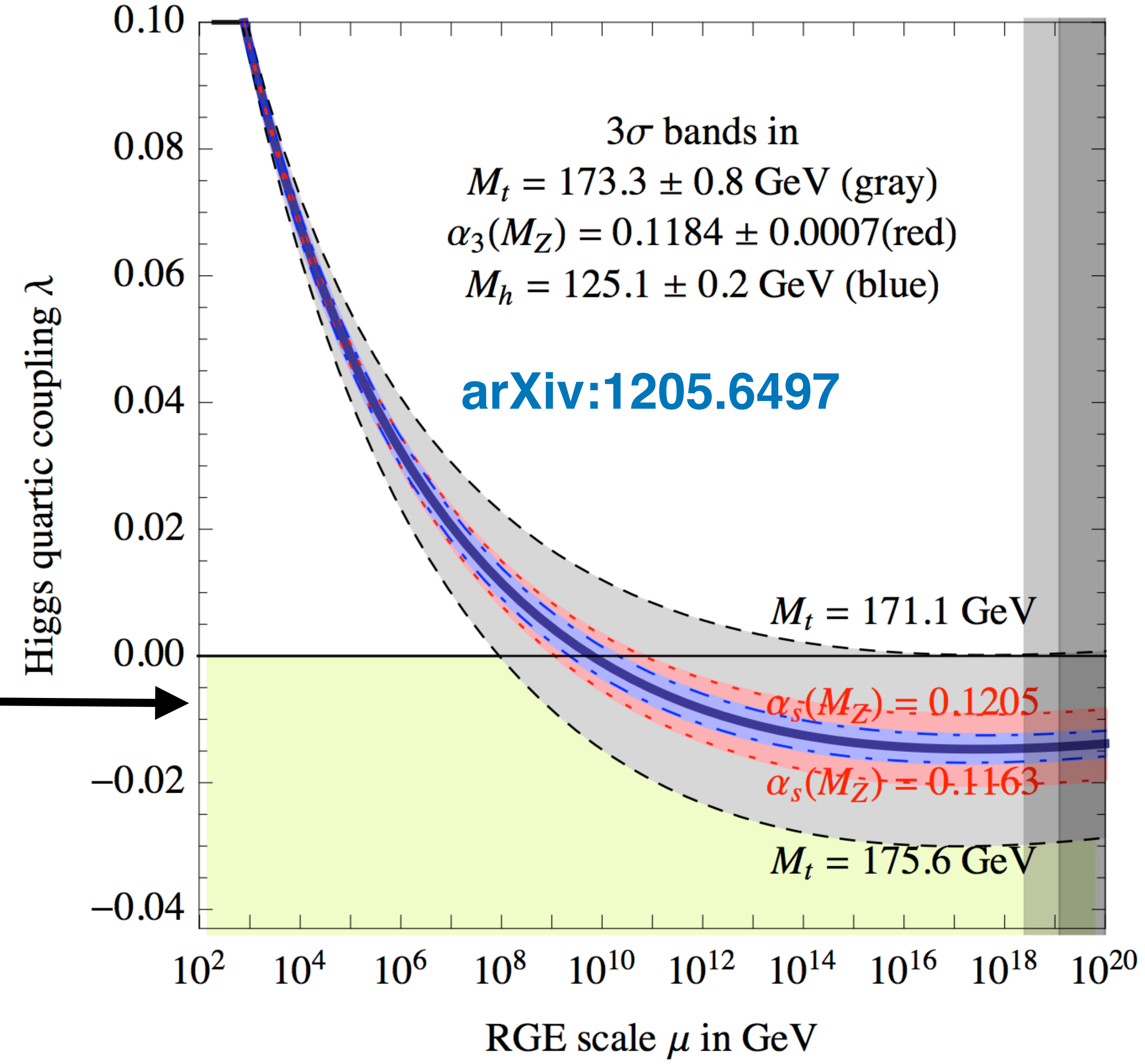


- Higgs Potential: $V(\phi) = -\mu_H^2 \phi^\dagger \phi + \lambda_H (\phi^\dagger \phi)^2$
- Mexican hat only if $\lambda_H > 0$
- $\boldsymbol{\lambda_H}$ receives radiative corrections from all SM particles ➛ mostly from top



$$\lambda_H(\mu) = \lambda_H(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{\mu}{v}$$

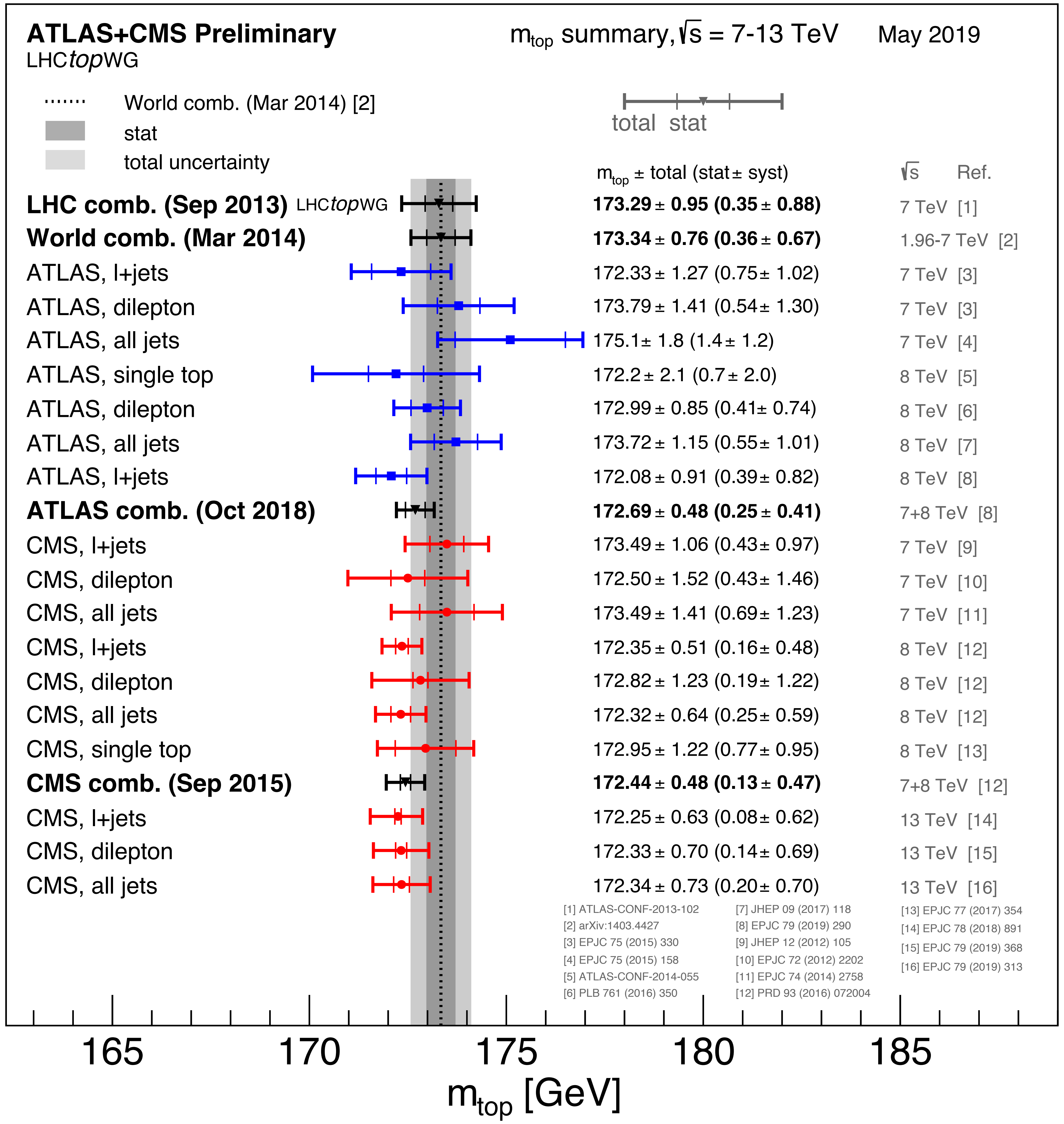
- Evolve $\boldsymbol{\lambda_H}$ up to Planck scale (~10^{19} GeV)
- Knowing the $\boldsymbol{m_t}$ **accurately** might just reveal the **fate of our universe**
- $\Delta m_t = m_t - m_{\bar{t}}$ ➛ test of CPT invariance ⇒ Lorentz symmetry



Summary of m_t measurements (so far)

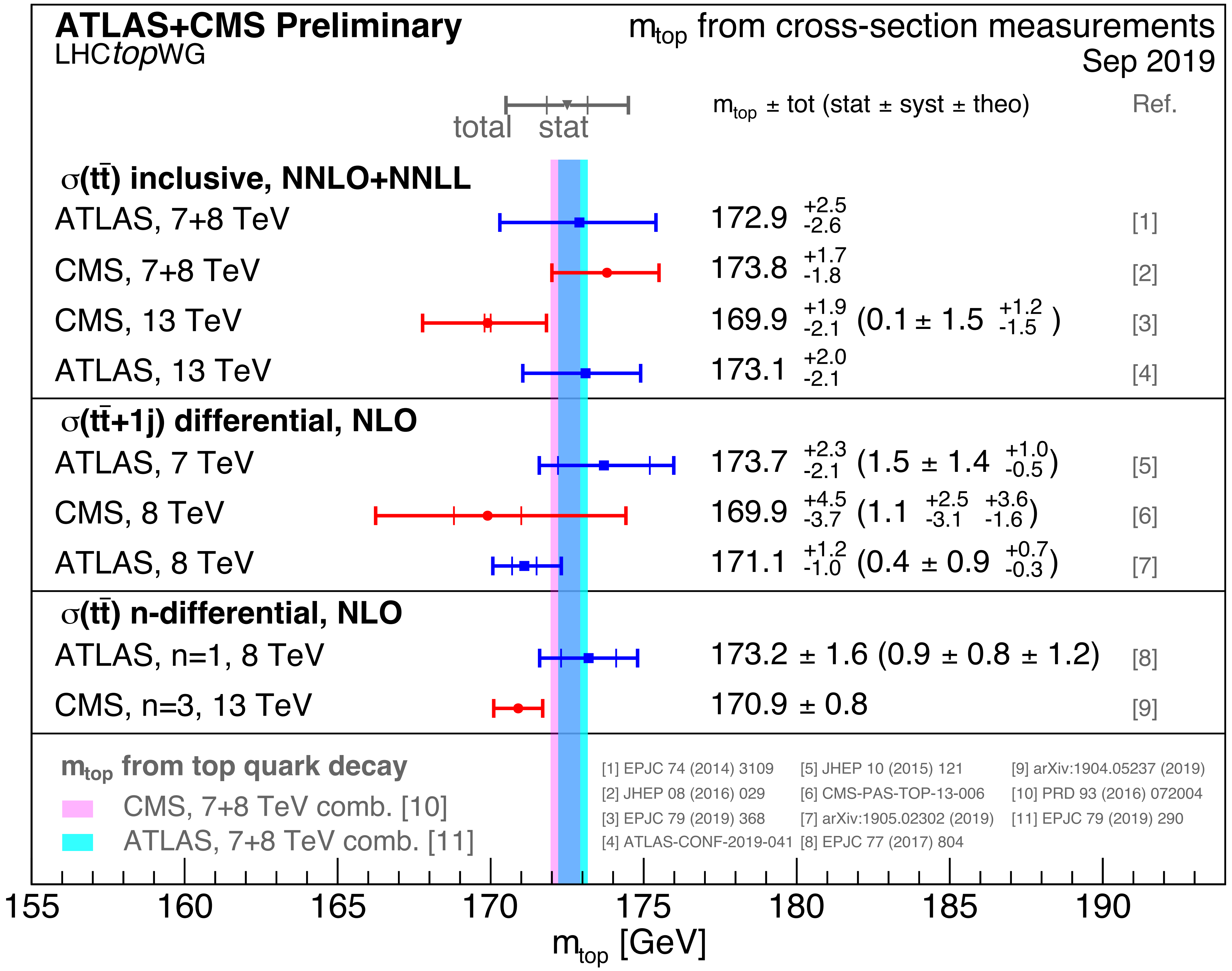
Direct measurements

➣ m_t reconstructed from daughters ⇒ running mass



Indirect measurements

➣ m_t^{pole} determined from cross section measurements



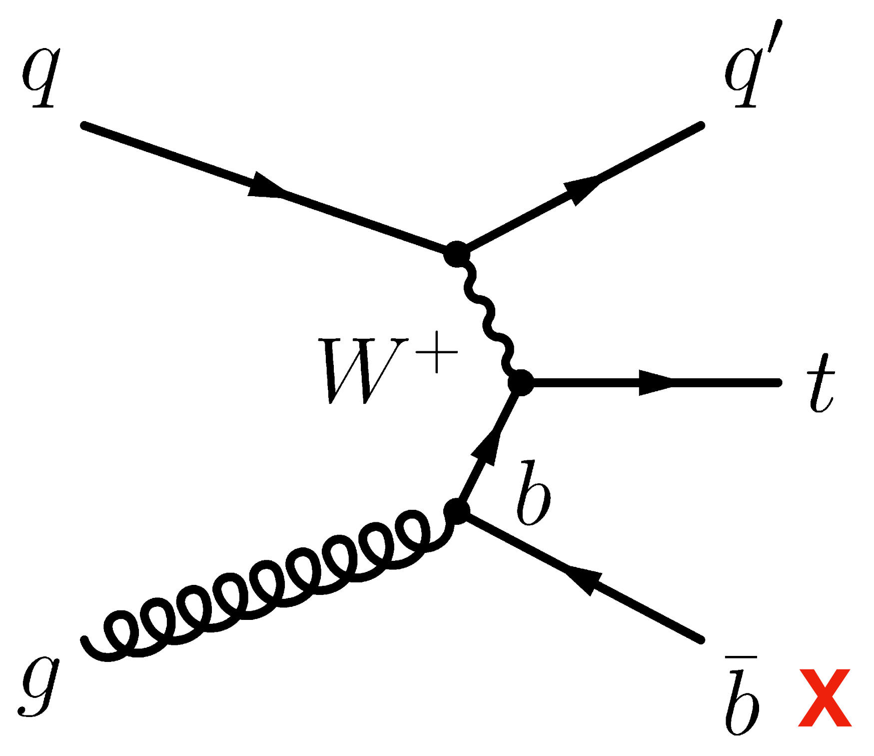
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

m_t from single top *t*-channel at 13 TeV

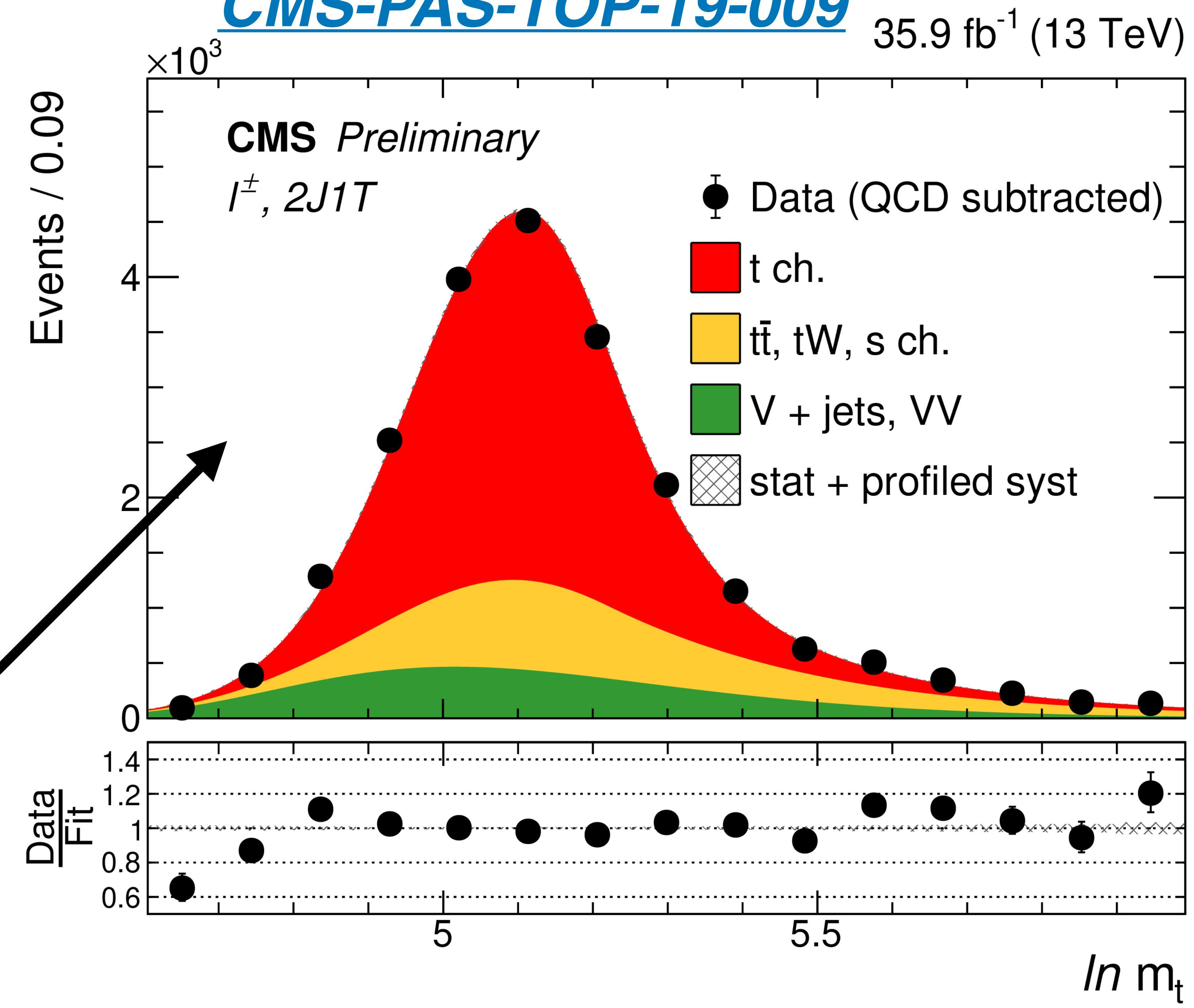
New

[CMS-PAS-TOP-19-009](CMS-PAS-TOP-19-009)

- Complementary phase space (low Q^2 scale) compared to $t\bar{t}$ ⇒ improves combination
- Measurement in events with 1 lepton (*e* and *μ*) + 2J1T (2-jets-1-tagged)
- Multivariate technique employed to select event sample with high signal purity (≈ 60 %) for meas.



- Parametric fit to the reconstructed ***ln m*** distribution (direct measurement)
- Separate fits for the $\ell^{\pm}$, ℓ^{+}, and ℓ^{-} categories ⇒ Measurement of top quark and antiquark masses ➛ test of CPT invariance



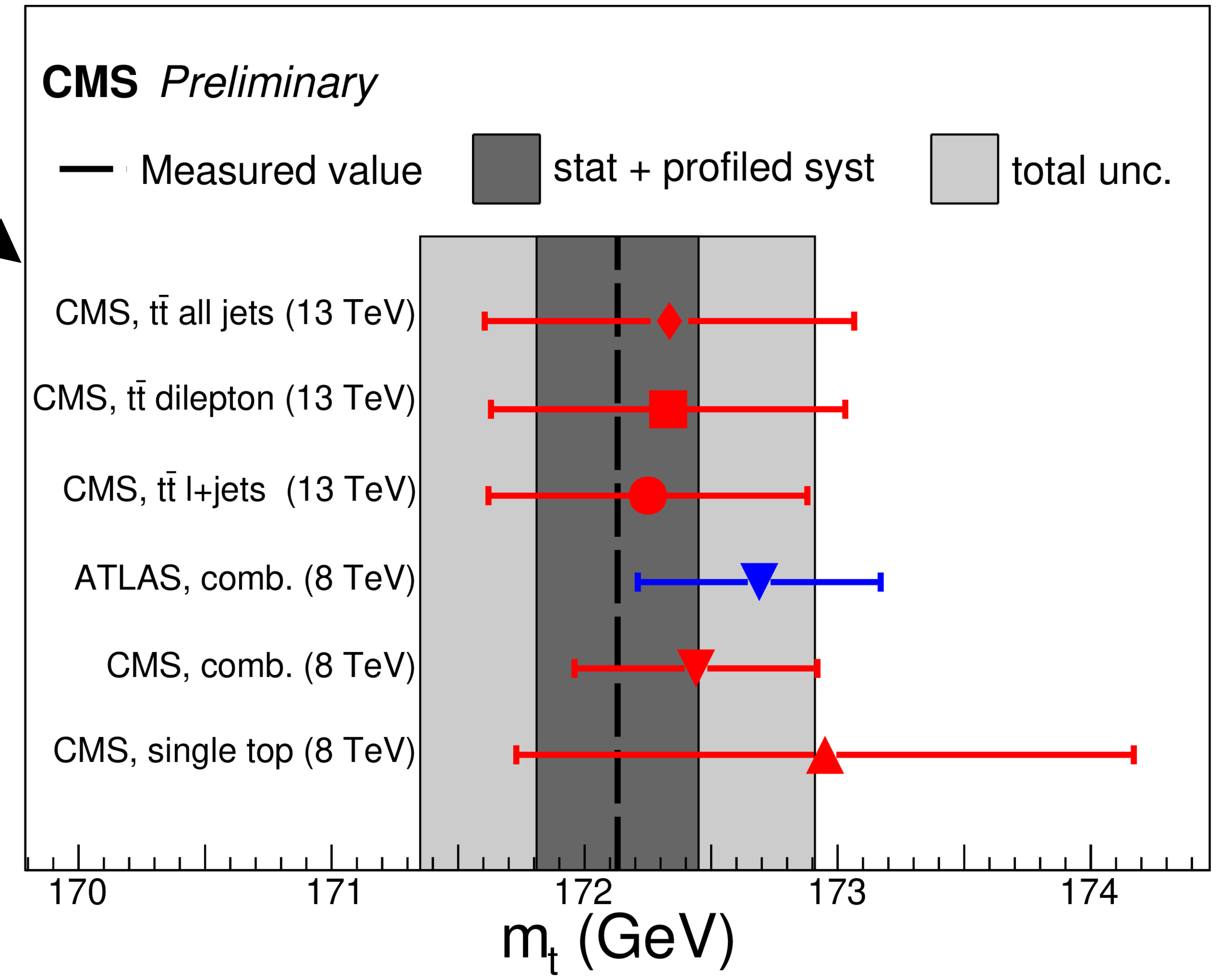
- $\ell^{\pm}$ result: $m_t = 172.13 \pm 0.32\,(\mathrm{stat+prof})\,^{+0.69}_{-0.70}\,(\mathrm{syst})\,\mathrm{GeV} = 172.13^{+0.76}_{-0.77}\,\mathrm{GeV}$

sub-GeV precision achieved first time in single top

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995 \pm 0.004\,(\mathrm{stat+prof})\,^{+0.002}_{-0.004}\,(\mathrm{syst}) = 0.995^{+0.005}_{-0.006}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\mathrm{stat+prof})\,^{+0.35}_{-0.74}\,(\mathrm{syst})\,\mathrm{GeV} = 0.83^{+0.77}_{-1.01}\,\mathrm{GeV}$$

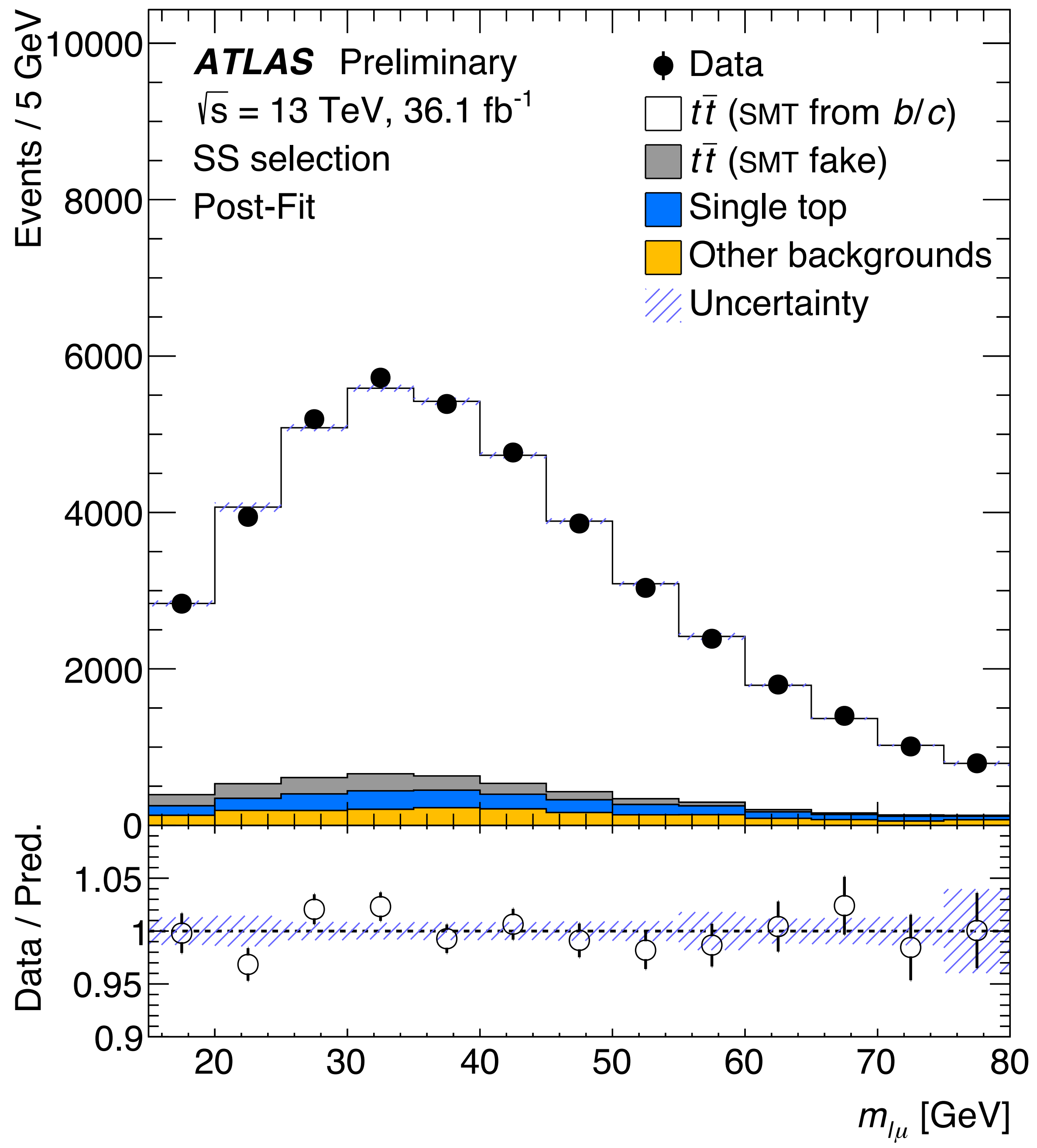
mass ratio and difference consistent with CPT invariance

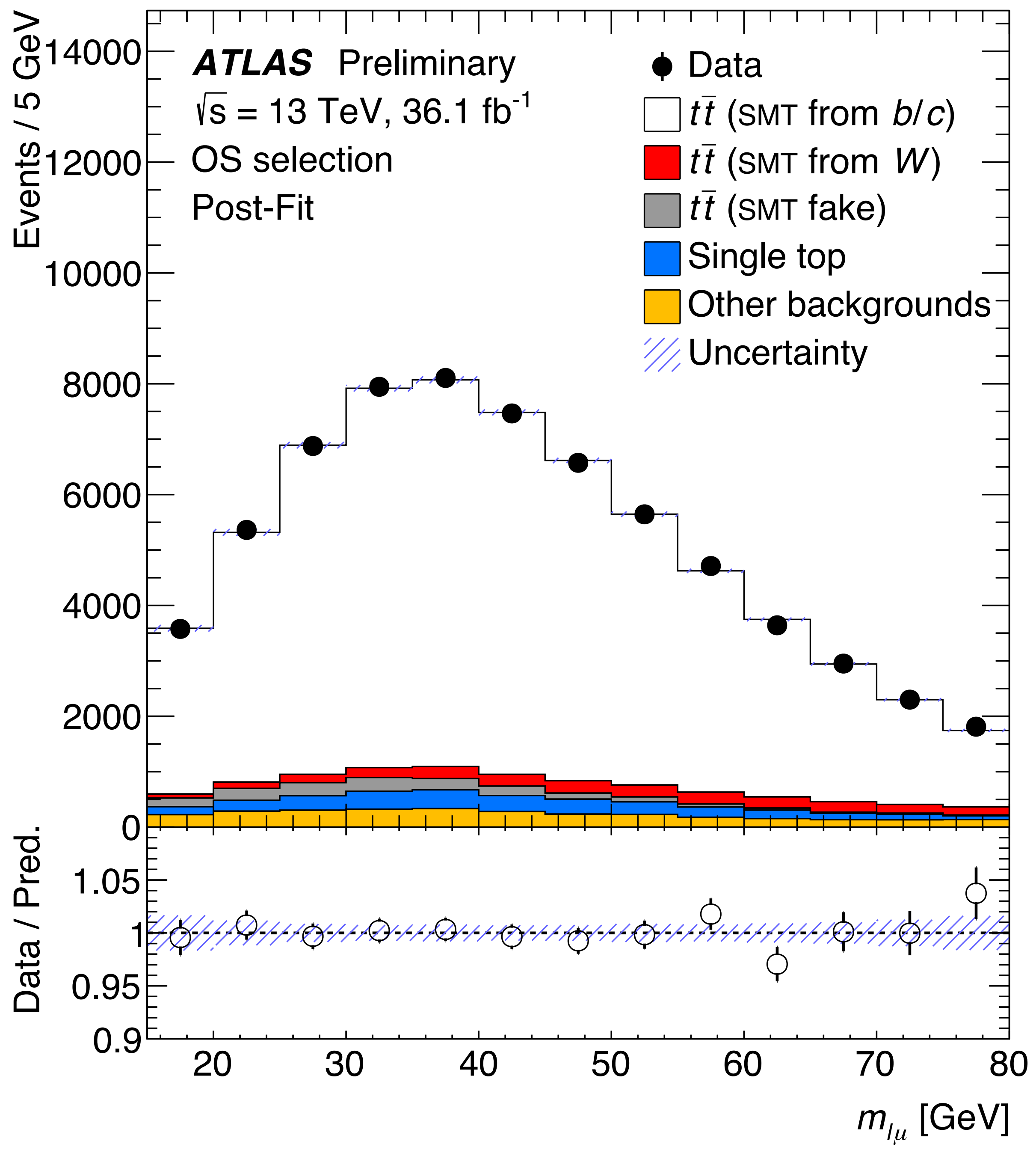


m_t in ℓ+jets with soft-μ

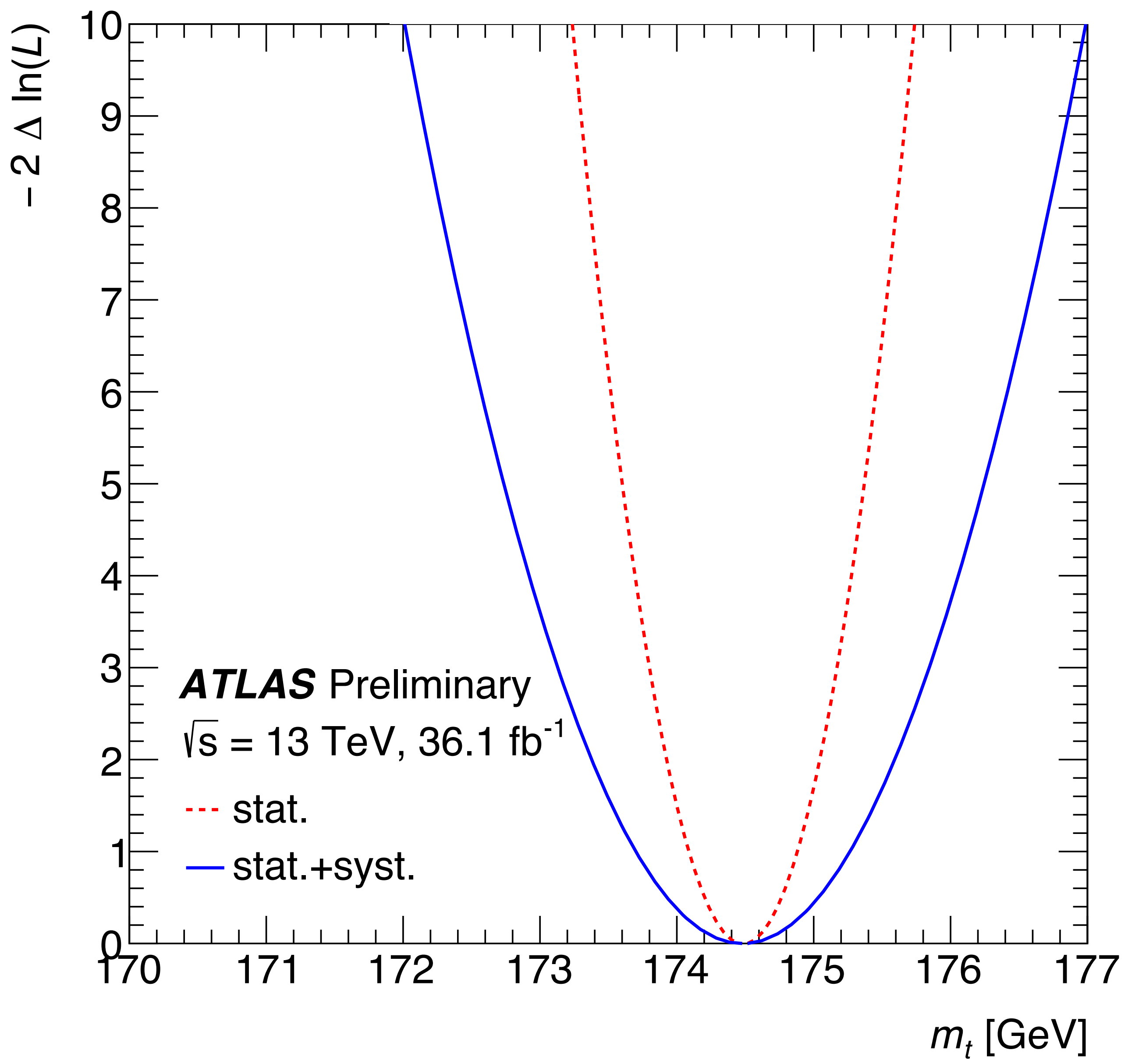
ATLAS-CONF-2019-046

- Analysis with 36.1 fb^{-1} data in $t\bar{t}$ events
- Selection:
  - ➢ 1 e/μ + ≥ 4 jets
  - ➢ ≥ 1 b-tagged jets, one with displaced vertex tag
  - ➢ ≥ 1 soft muon (μ_S) within ΔR < 0.4 of a jet (soft muon tag)
  - ➢ $\Delta R(\ell, \mu_S) < 2$
- SS and OS have different contributions (direct b➢μ decays and chain decays b➢c➢μ); but both depend on m_t
- **m($\ell\mu_S$)** distribution used in a binned template fit to extract the mass ➢ largely reduced sensitivity to JES, JER





$$m_t = 174.48 \pm 0.40\,(\text{stat})\ \pm 0.67\,(\text{syst})\,\text{GeV} = 174.48 \pm 0.78\,\text{GeV}\,(0.45\%)$$



- Dominant systematics:
  - ➢ HF-hadron decay model: 0.39 GeV (0.22%)
  - ➢ Pile up : 0.20 GeV (0.11%)
  - ➢ b-quark hadronization : 0.19 GeV (0.11%)

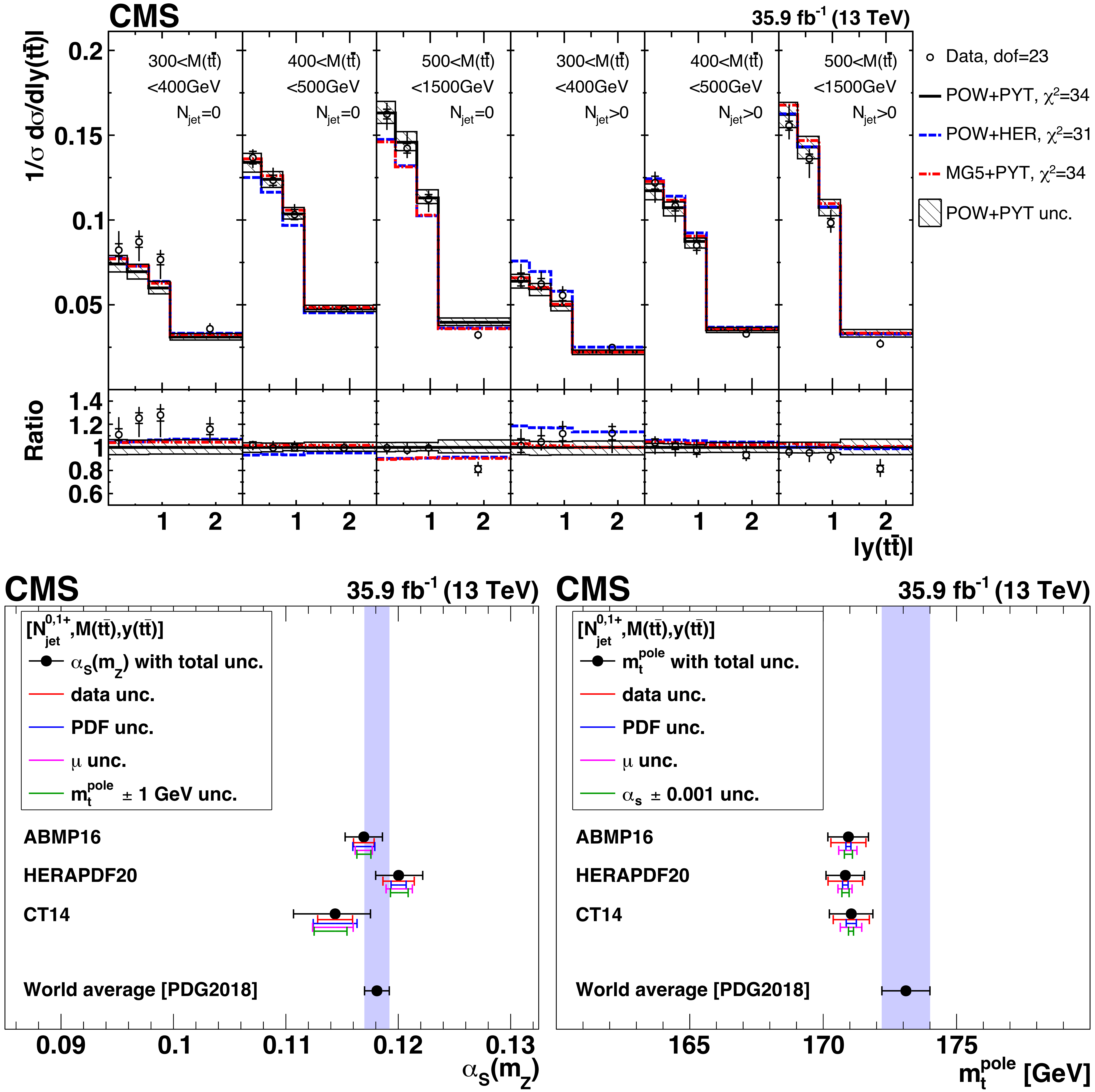
α_S & m_t^{pole} from diff. $\sigma_{t\bar{t}}$

[Eur. Phys. J. C 80 (2020) 658](https://doi.org/10.1140/epjc/s10052-020-7917-7)

- Triple differential cross-section with 35.9 fb^{-1} data
  ➤ measured in bins of M($t\bar{t}$), |y($t\bar{t}$)| and N_{jet}
- Event selection:
  ➤ OS dilepton (ee+μμ+eμ)
  ➤ ≥ 2 jets (≥ 1 b-tagged)
  ➤ N_{jet} additional jets not from $t\bar{t}$ decay (ΔR > 0.4 from leptons and b-quarks)
  ➤ Loose kinematic reconstruction of $t\bar{t}$ system (no m_t constraint)
- α_S and m_t^{pole} extracted from comparison to fixed-order NLO predictions

$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$$

$$m_t^{pole} = 170.5 \pm 0.8\,\text{GeV}\,(0.47\%)$$



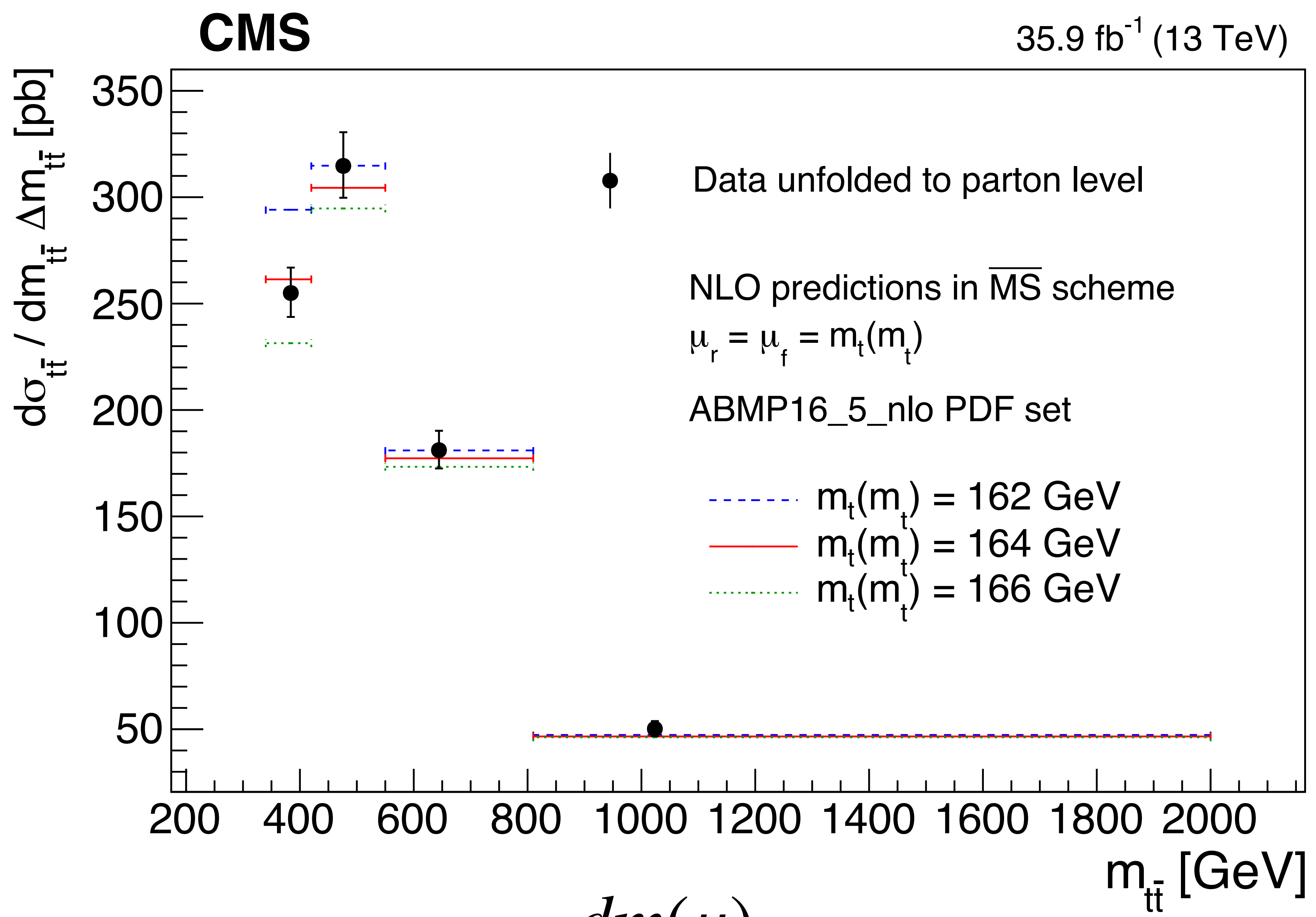
Running of m_t

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

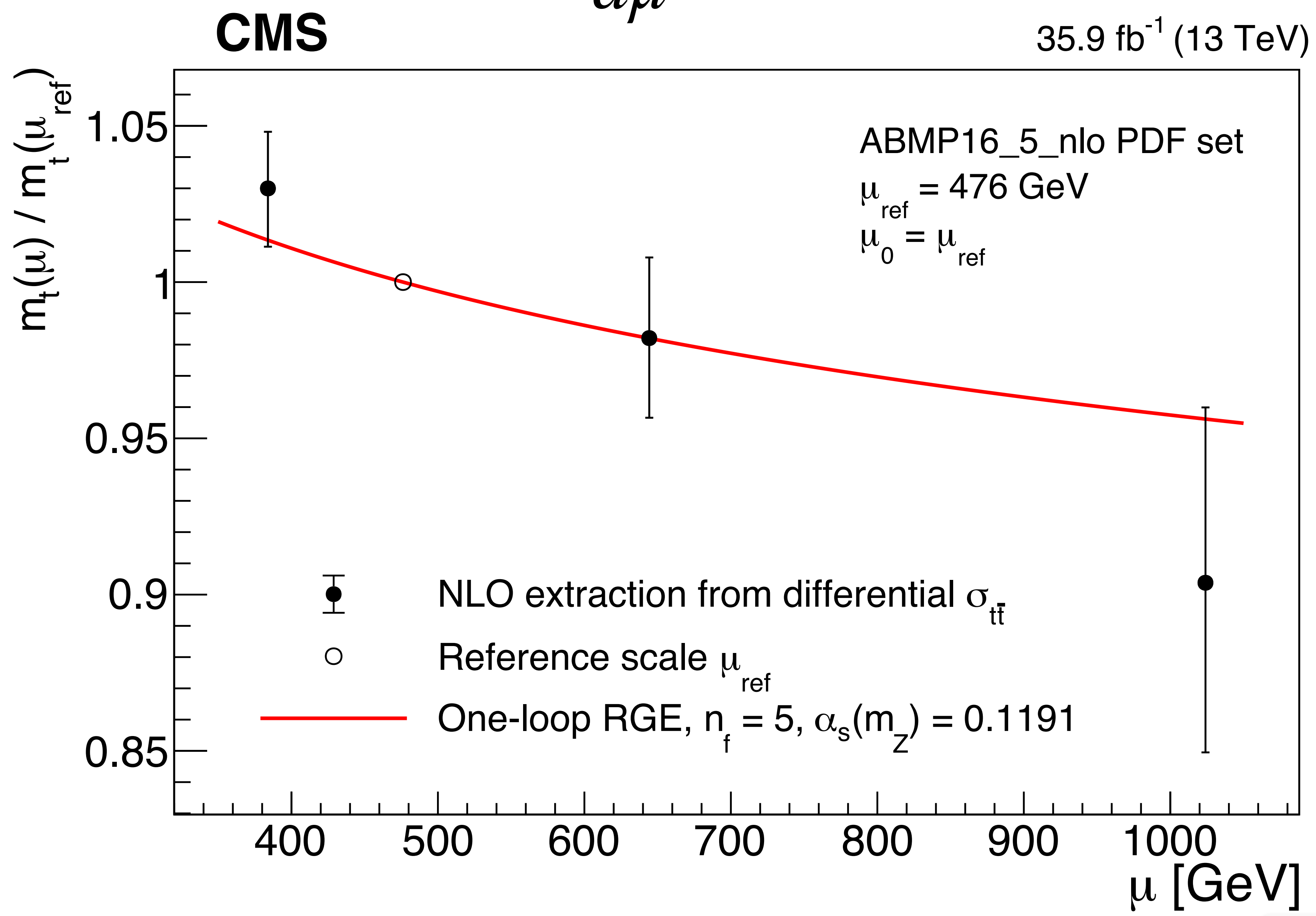
- First measurement of the top mass running with 35.9 fb^{-1} data
- Require 1 OS $e\mu$ pair + ≥ 2 jets
- Kinematic reco. of the $t\bar{t}$ system with m_W and m_t^{MC} constraints
- Diff. cross-section at parton level obtained using ML fit to multi-differential distributions ($m_{t\bar{t}}$, $m_{b\ell}^{min}$, p_T of softest jet)
- 4 $\sigma_{t\bar{t}}$ values obtained as a function of the scale μ in 4 $m_{t\bar{t}}$ bins
- $m_t(\mu)$ in MSbar scheme is determined for each bin independently
- Following 3 ratios extracted in order to reduce systematics

$$\frac{m_t(\mu_1)}{m_t(\mu_2)}, \frac{m_t(\mu_3)}{m_t(\mu_2)}, \frac{m_t(\mu_4)}{m_t(\mu_2)}$$

- Observed evolution agrees with RGE prediction at 1-loop precision within 1.1σ



RGE in $\overline{\text{MS}}$ scheme : $\mu^2 \frac{dm(\mu)}{d\mu^2} = -\gamma(\alpha_S(\mu))\, m(\mu)$

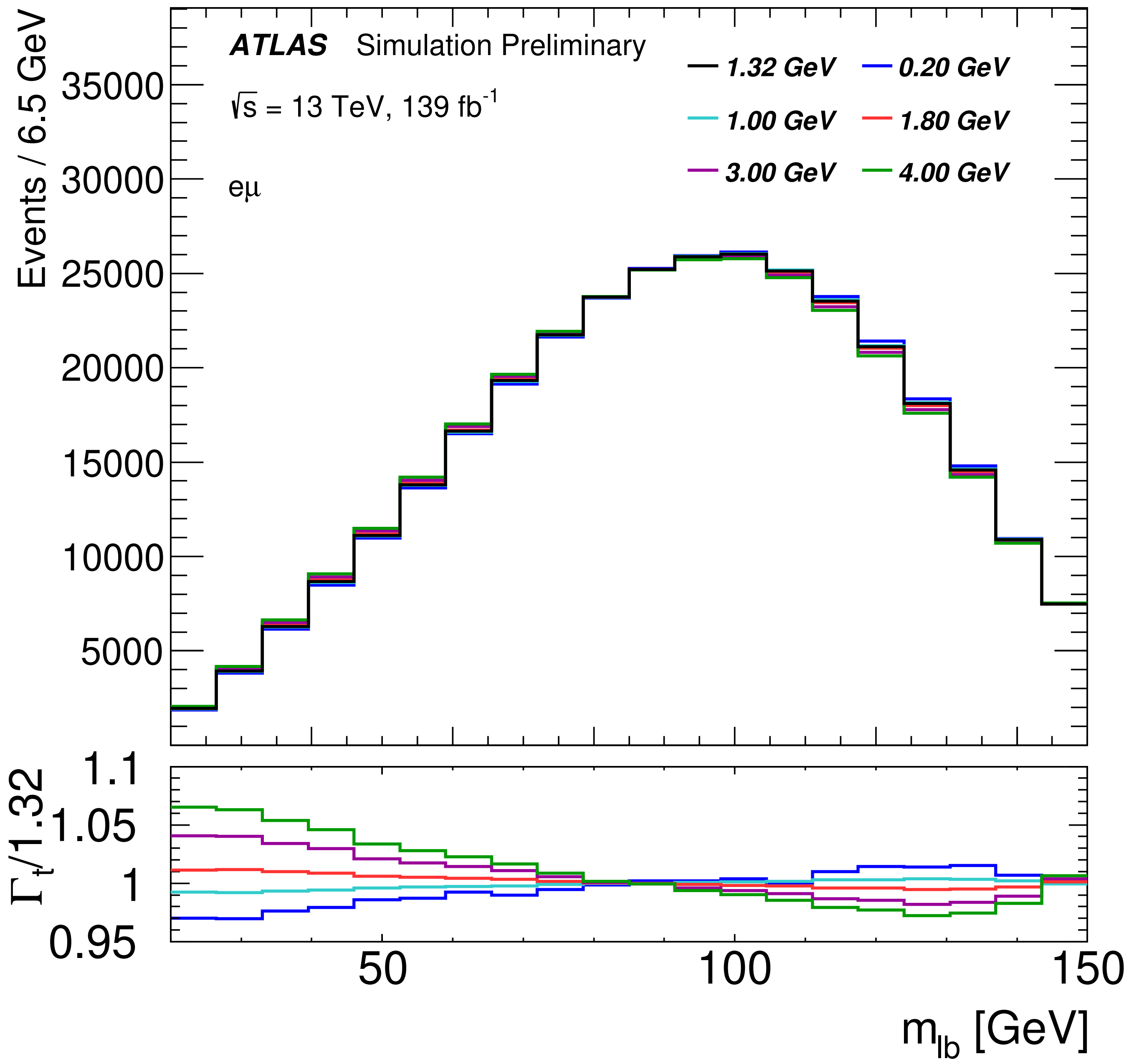


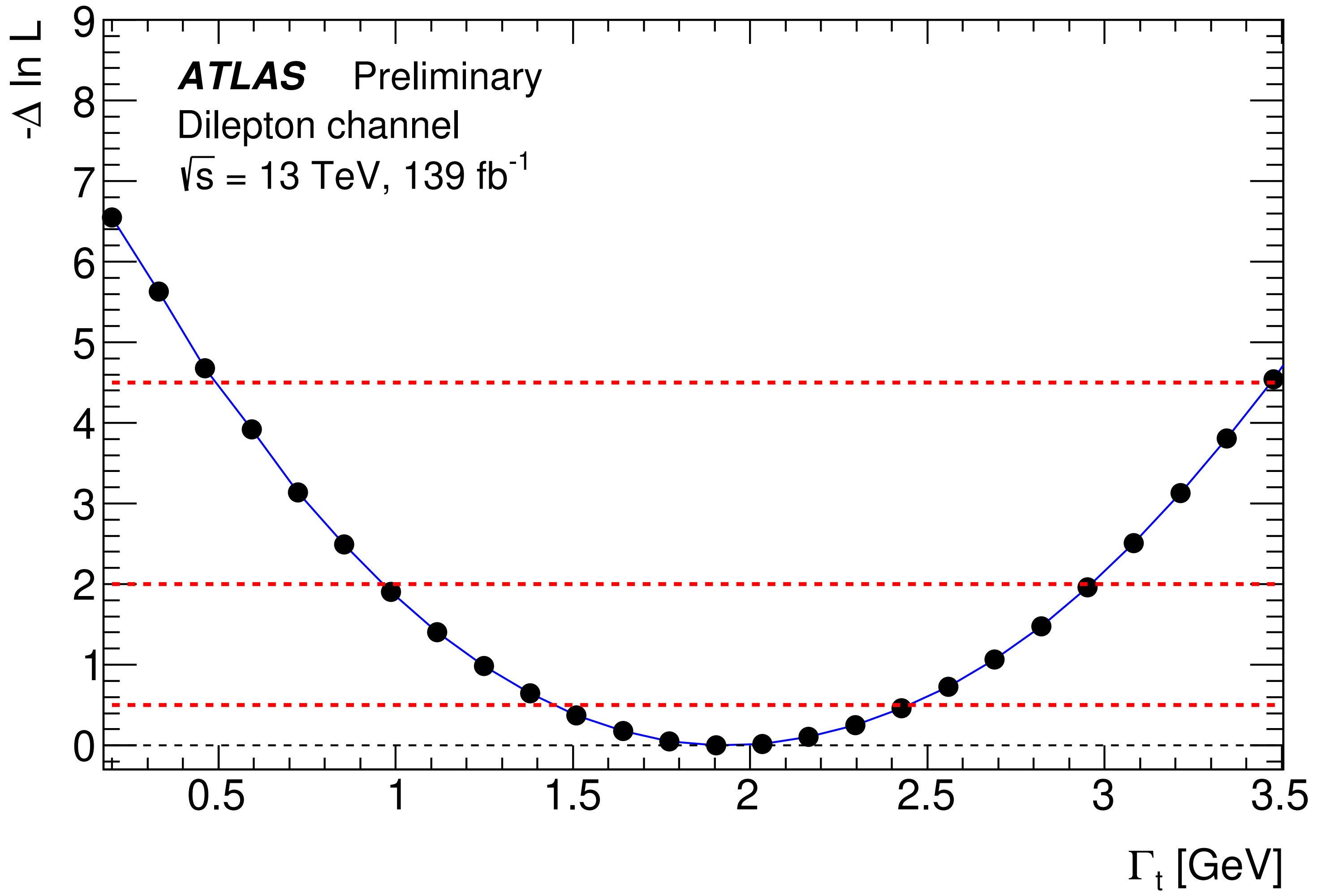
Width (Γ_t)

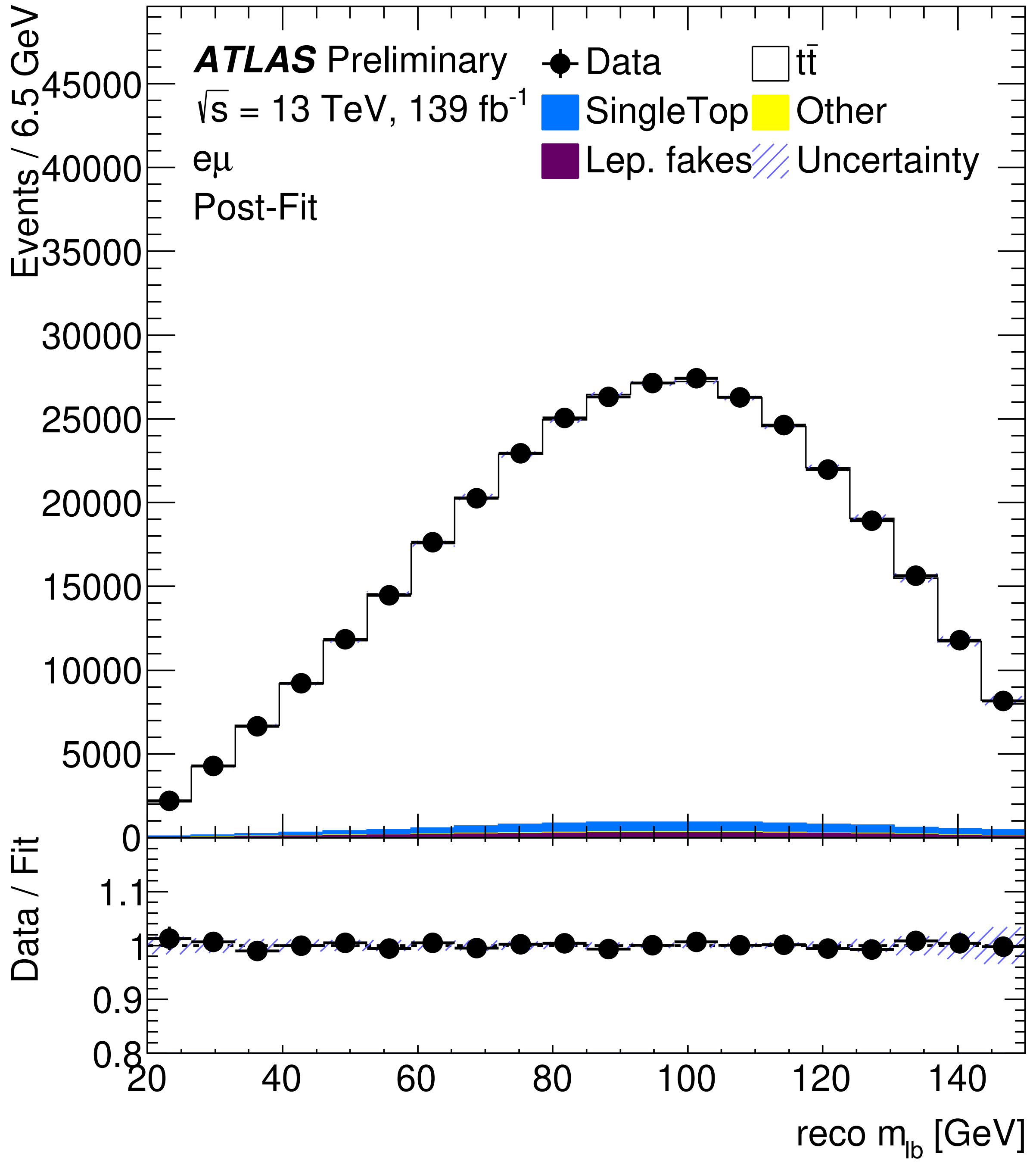
ATLAS-CONF-2019-038

- Direct measurement of top quark decay width in dilepton channel with full Run2 data ≈ 139 fb^{-1}
- MC templates obtained by reweighting nominal $t\bar{t}$ sample
- Profile likelihood fit to
  - ➢ $m_{\ell b}$ template in $e\mu$ channel (high stat.) using both $m_{\ell b}$ candidates
  - ➢ $m_{b\bar{b}}$ template in $ee+\mu\mu$ channel (control region)
- Measured value in agreement with SM prediction within uncertainties

	m_t = 172 GeV		m_t = 172.5 GeV		m_t = 173 GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	+0.53 −0.50	1.94	+0.52 −0.49	1.90	+0.52 −0.48
Theory	1.306	< 1%	1.322	< 1%	1.333	< 1%



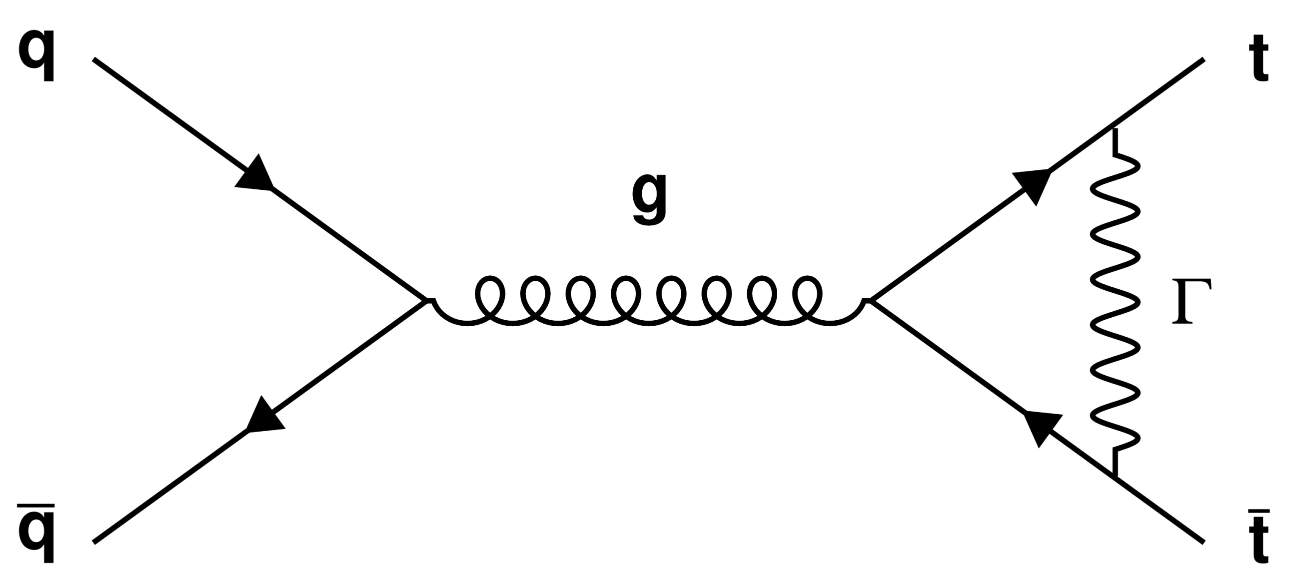




Yukawa coupling

[Phys. Rev. D 102 (2020) 092013](#)

- g_t^{SM} ~ 0.99 for $\Lambda = m_t$, $Y_t = g / g_t^{SM} \neq 1$ for BSM
- EW corrections close to the threshold alters kinematics
- EW corrections determined in $t\bar{t}$ dilepton from multi-differential measurement in $\Delta y_{b\ell b\ell}$ and $M_{bb\ell\ell}$
- Previous limits @ 95% CL: $\boldsymbol{Y_t < 1.7}$ (4 tops [1] and ℓ+jets [2])

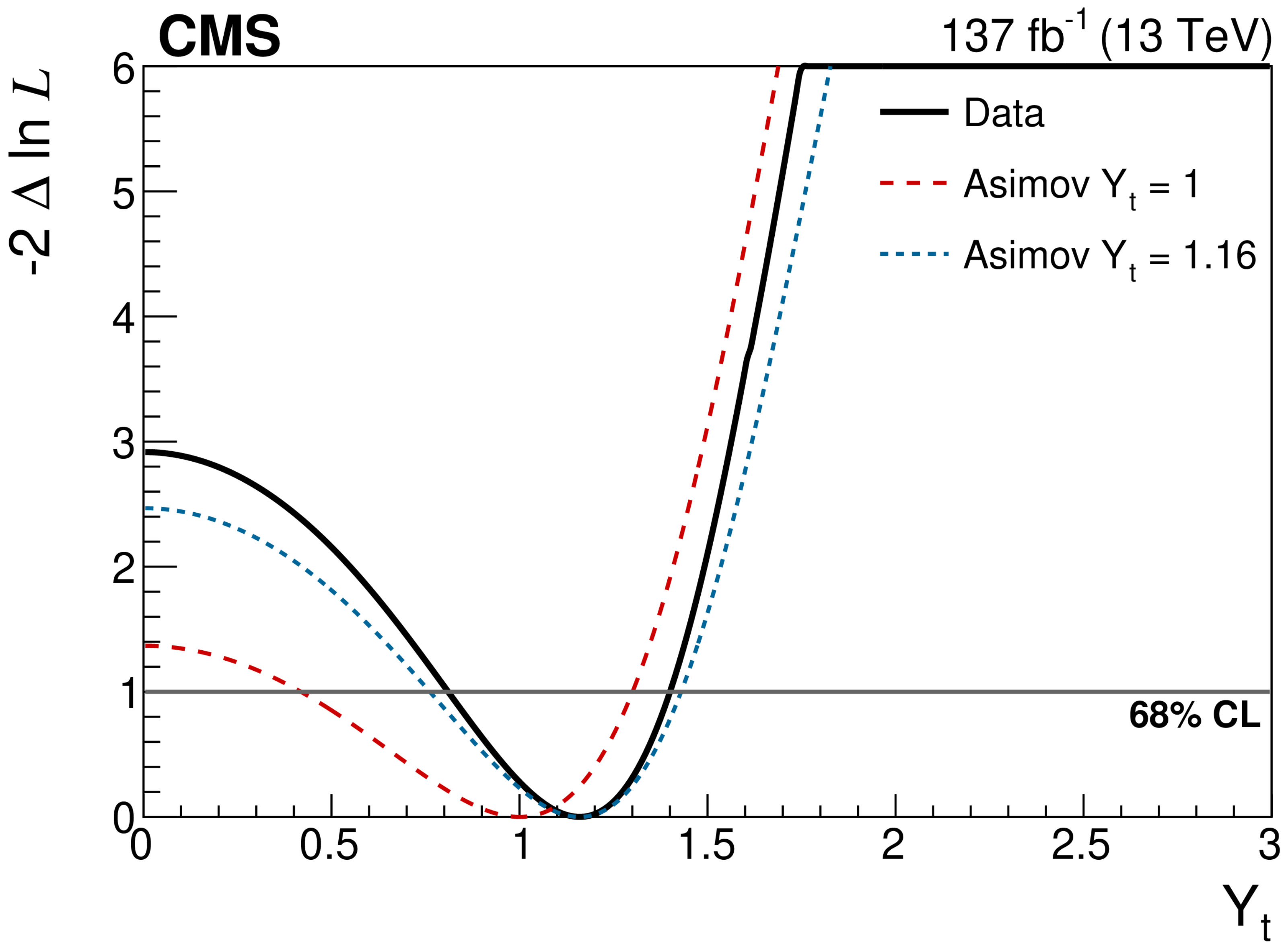


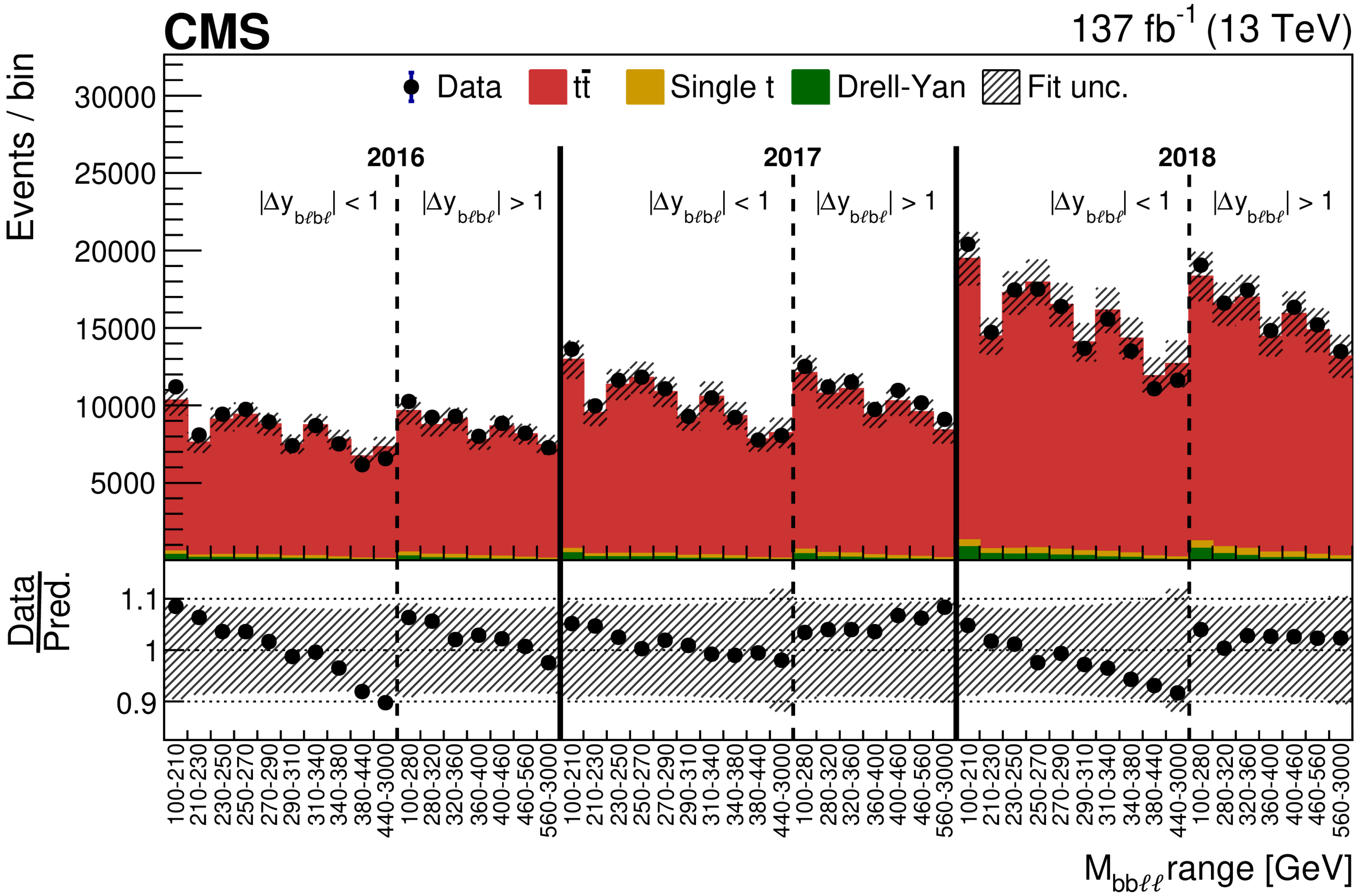
$$Y_t = 1.16^{+0.24}_{-0.35}$$

CMS Higgs comb. [3]

$$Y_t = 0.98 \pm 0.14$$

Higher model dependence





[1] [Eur. Phys. J. C 80 (2020) 75](#)

[2] [Phys. Rev. D 100, 072007 (2019)](#)

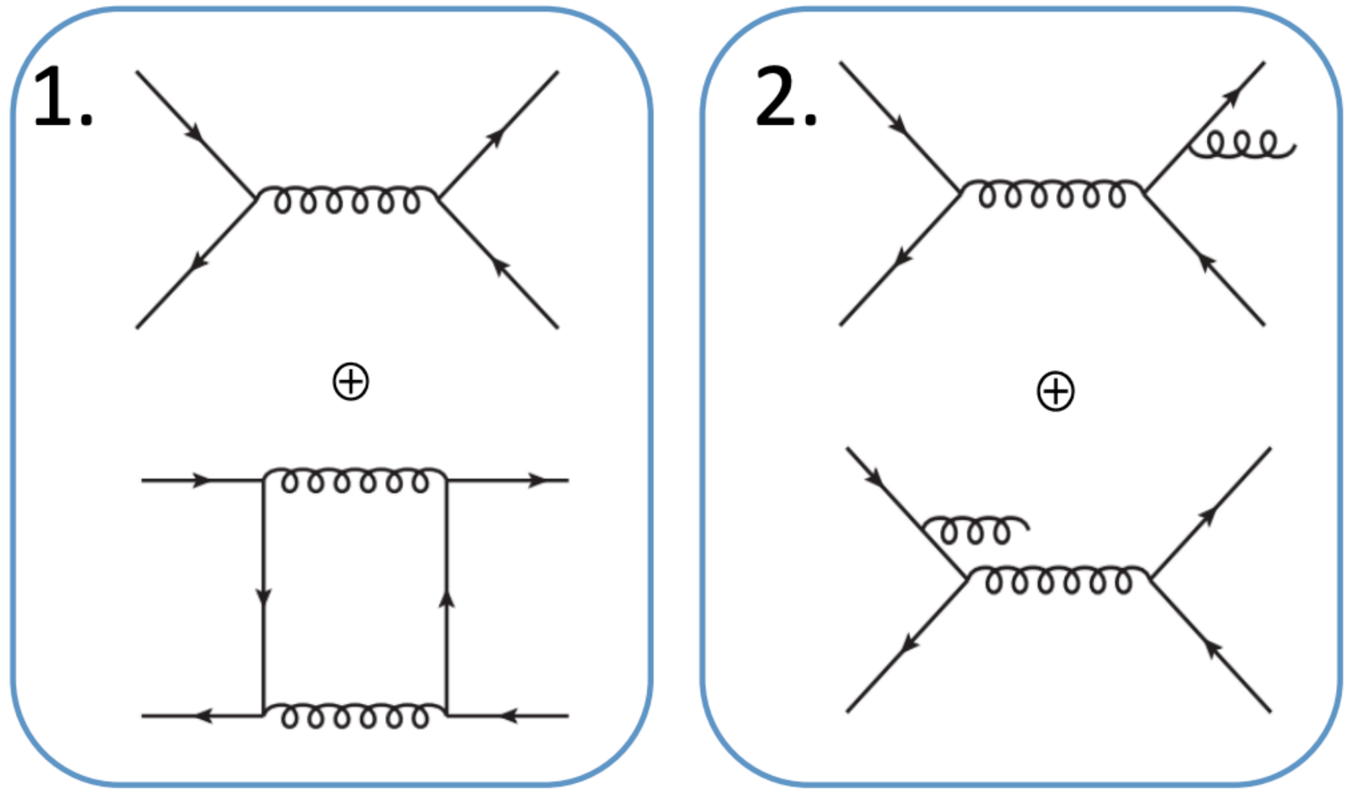
[3] [Eur. Phys. J. C 79 (2019) 421](#)

$t\bar{t}$ asymmetry at LHC

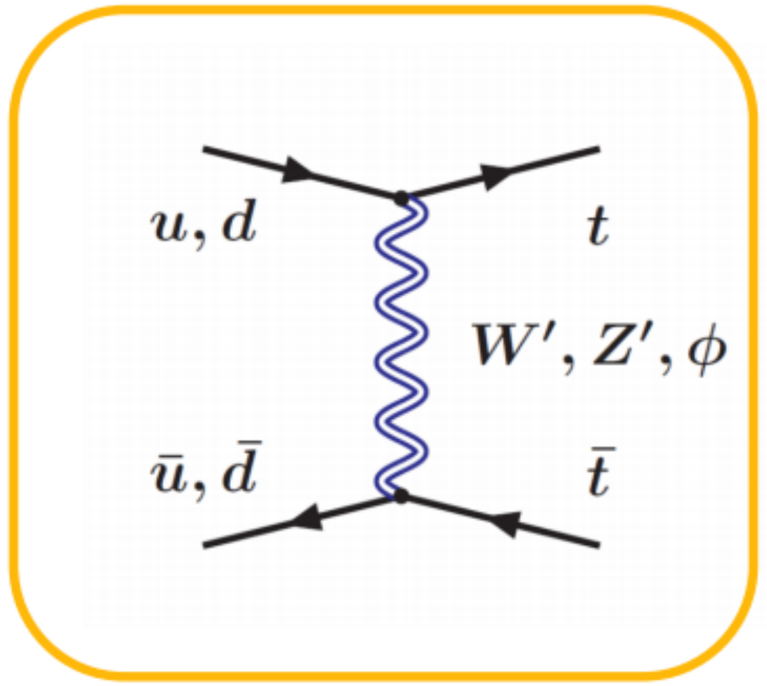
- Production of top quark pairs charge symmetric at LO
- No charge asymmetry in gg ➛ $t\bar{t}$ at all orders, dilutes measurable asymmetry
- Small charge asymmetry at NLO due to QCD $q\bar{q}$ annihilation allowed in SM
  ➛ interference between tree and box diagram
  ➛ interference between gluon ISR and FSR diagrams
- (anti-)top quarks are emitted preferentially in the direction of the incoming (anti-)parton
- LHC being a pp collider ➛ no preferential direction for the incoming (anti-) partons
- High momenta valence quarks collide with sea anti-quarks carrying lower momenta ➛ More forward top quarks and more central anti-top quarks leading to charge asymmetry (A_C)

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

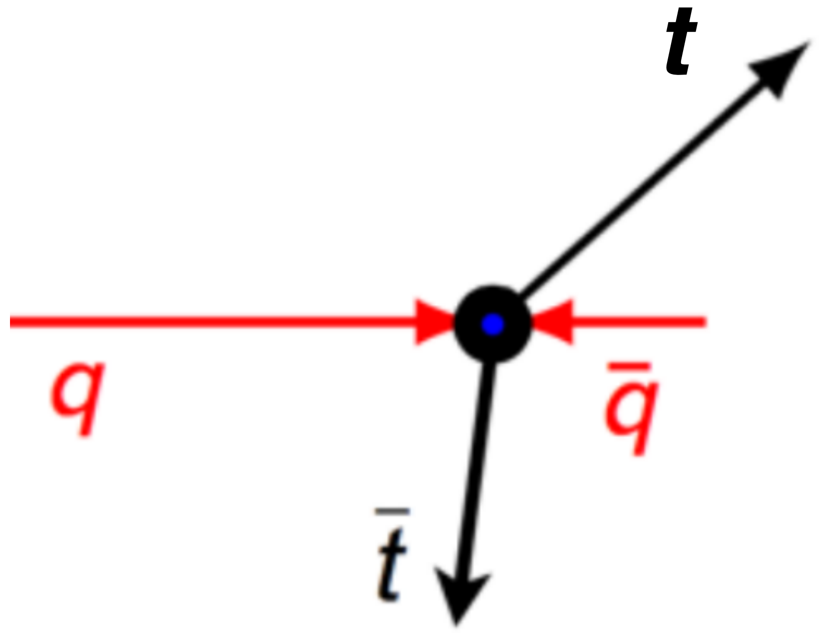
- New Physics models can enhance A_c ➛ indirect search for new physics

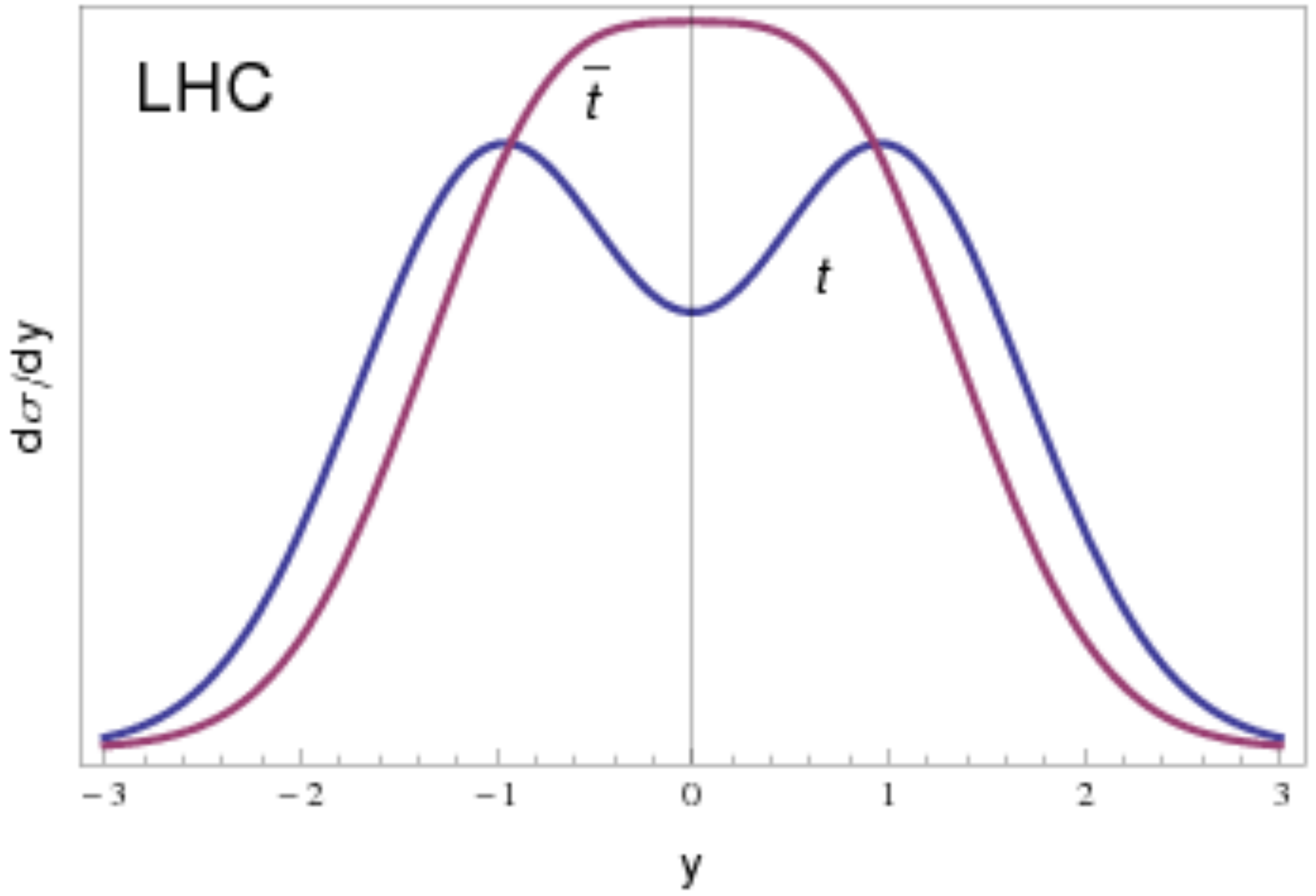


asymmetric QCD



asymmetric BSM



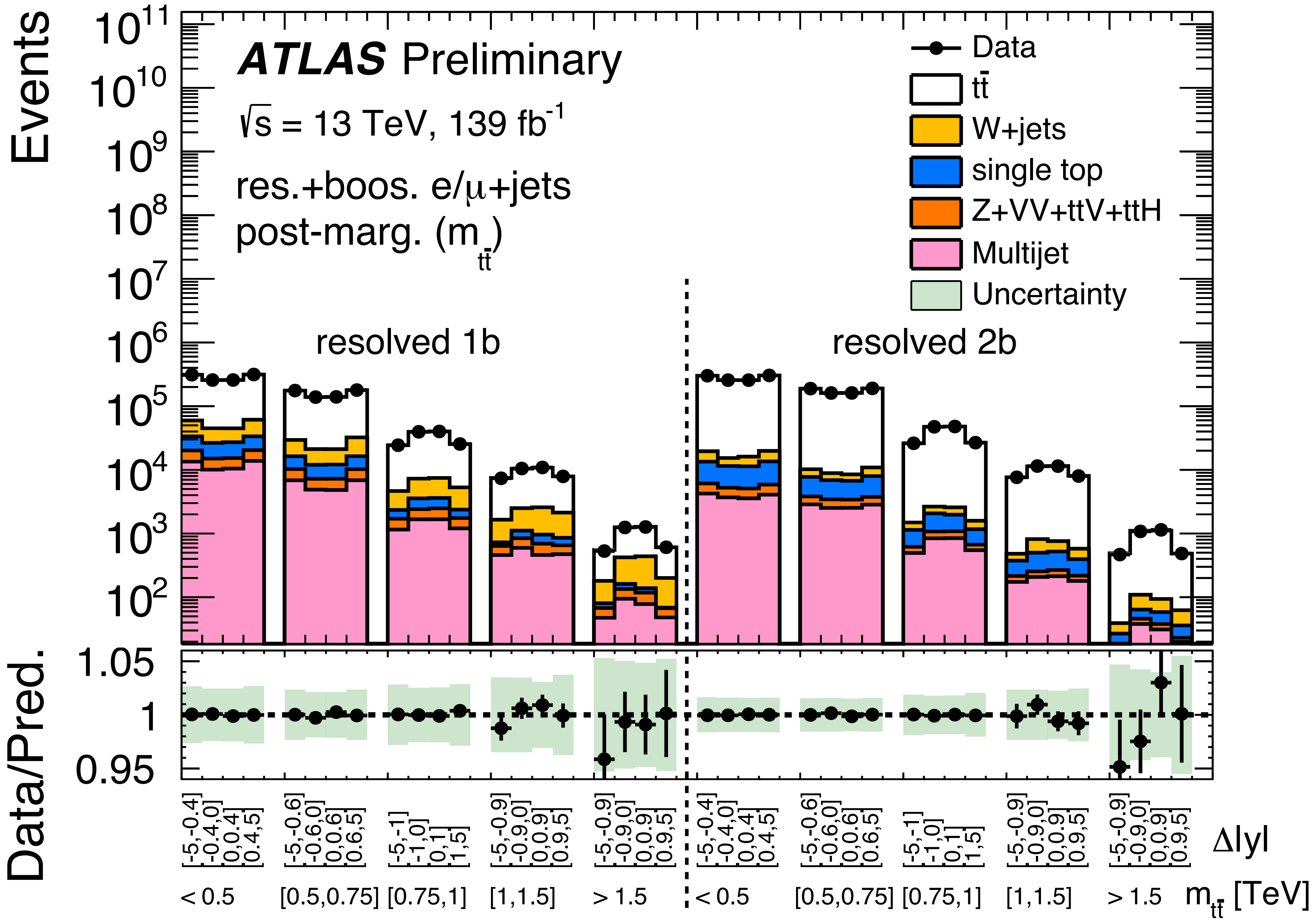


arXiv:1207.0331

Evidence of charge asymmetry (A_C)

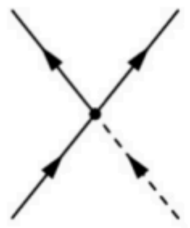
ATLAS-CONF-2019-026

- Measurement with full Run2 data ≈139 fb^{-1}
- Measurement in the ℓ+jets (e and μ) channels with resolved & boosted topologies
- A_C measured inclusively and differentially (in bins of $m_{t\bar{t}}$ & $\beta_{z,t\bar{t}}$)
- First evidence (~ 4σ) of charge asymmetry in pp collisions ➛ consistent with SM prediction with accuracy NNLO QCD + NLO EW
- A_C sensitive to 7 four-fermion operators in the **Warsaw basis** ➛ eventually reduced to 2 by assuming flavour universality

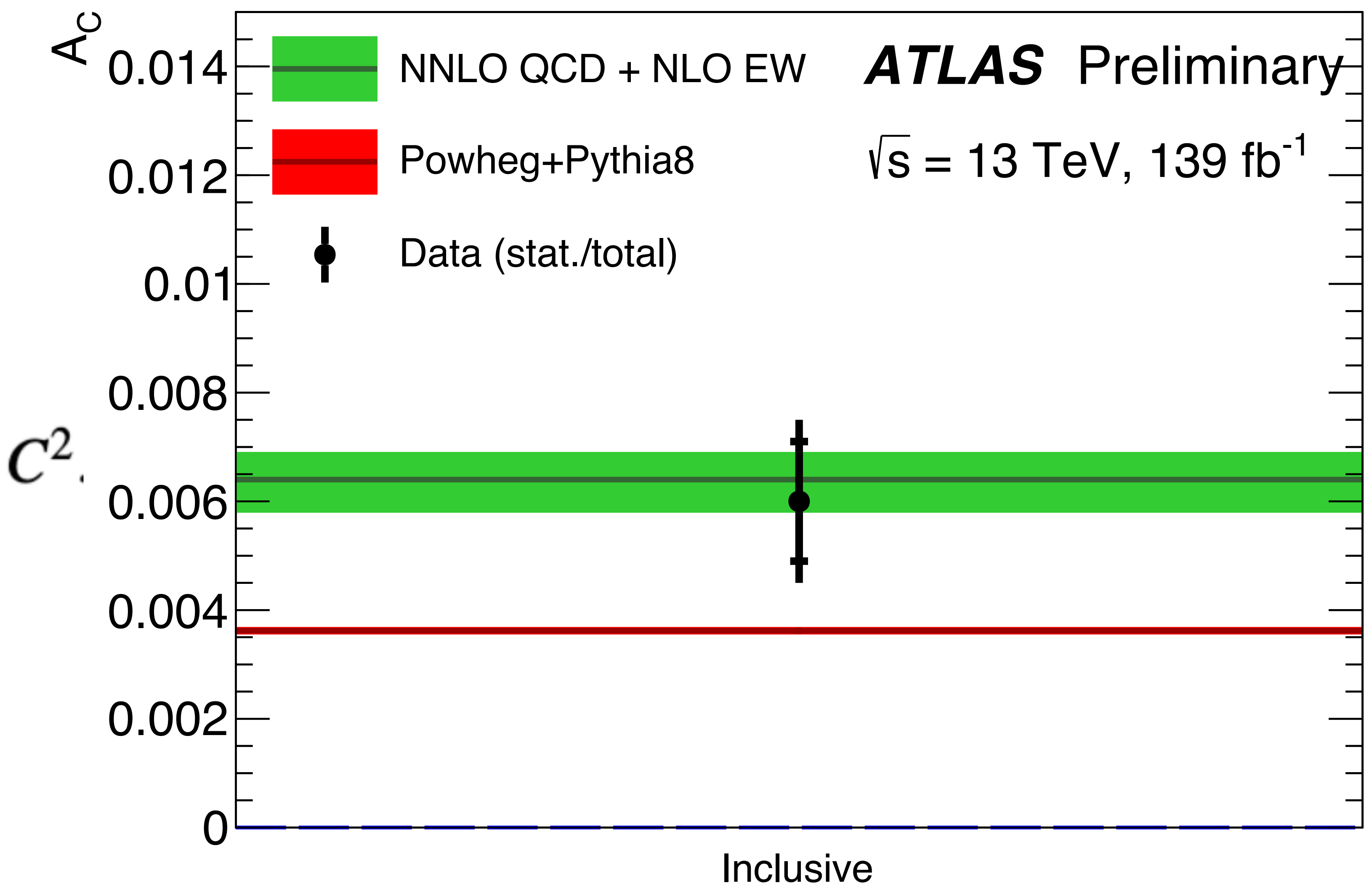


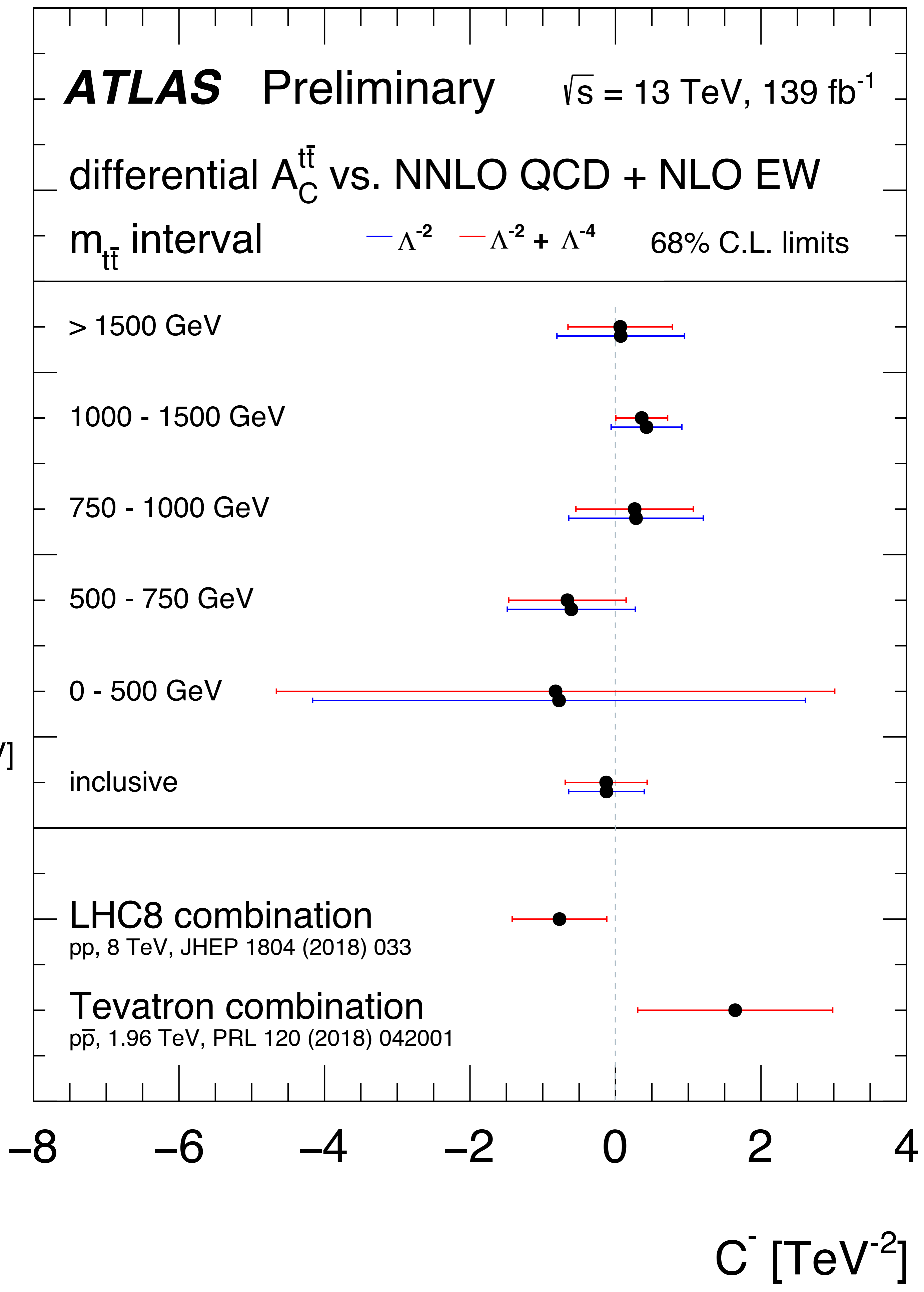
$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

Assumptions:



$$C_u^1 = C_d^1 = C^1$$
$$C_u^2 = C_d^2 = C^2$$
$$C^- = C^1 - C^2$$





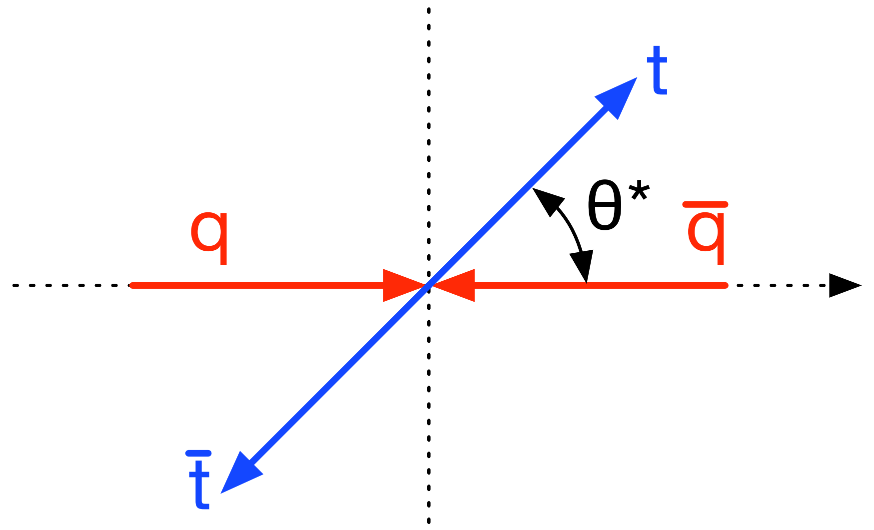
$$A_C = 0.0060 \pm 0.0015\,(\text{stat} + \text{syst})$$

- Tighter bound on C^- than the combination of previous measurements ➛ driven by boosted region

Forward - backward asymmetry (A_{FB})

[JHEP 06 (2020) 146](https://doi.org/10.1007/JHEP06(2020)146)

- The first LHC measurement of A_{FB} using 35.9 fb^{-1} data collected during 2016
- Measurement in the *l* (*e*,*μ*) + jets channels with resolved & boosted topologies
- $q\bar{q}$ initiated process at NLO is isolated using $m_{t\bar{t}}$, x_F and c^*
- $q\bar{q}$ ➛ $t\bar{t}$ diff. cross-section
  ➛ linear combination of symmetric and asymmetric components
  ➛ further expanded as a function of anom. **chromo-magnetic (*μ*)** and **chromo-electric (*d*)** dipole moments and A_{FB}
- Template-based likelihood fits using differential models based on extensions to tree-level cross sections for $q\bar{q}$ and gg initial states



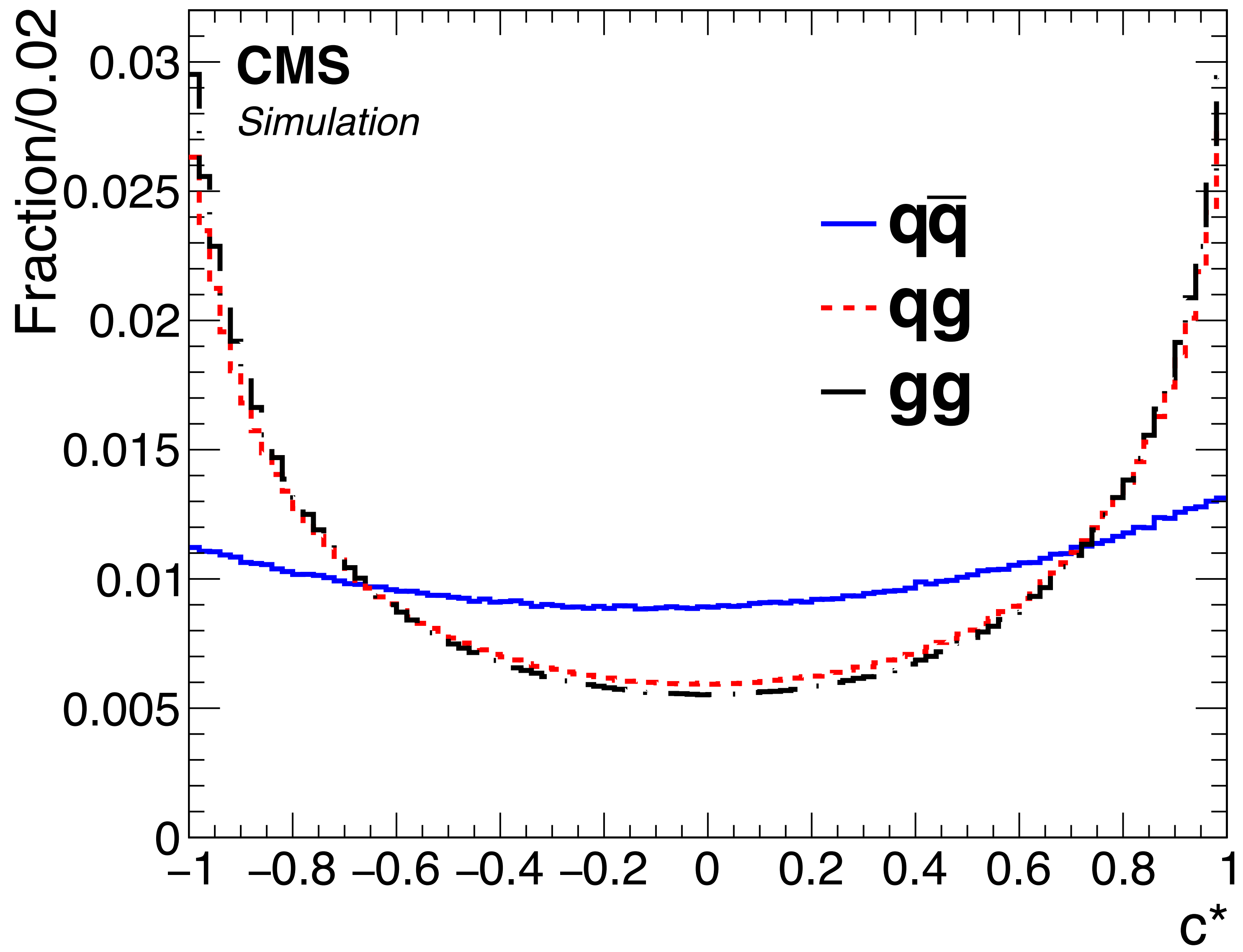
$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}, c^* = \cos\theta^*$$

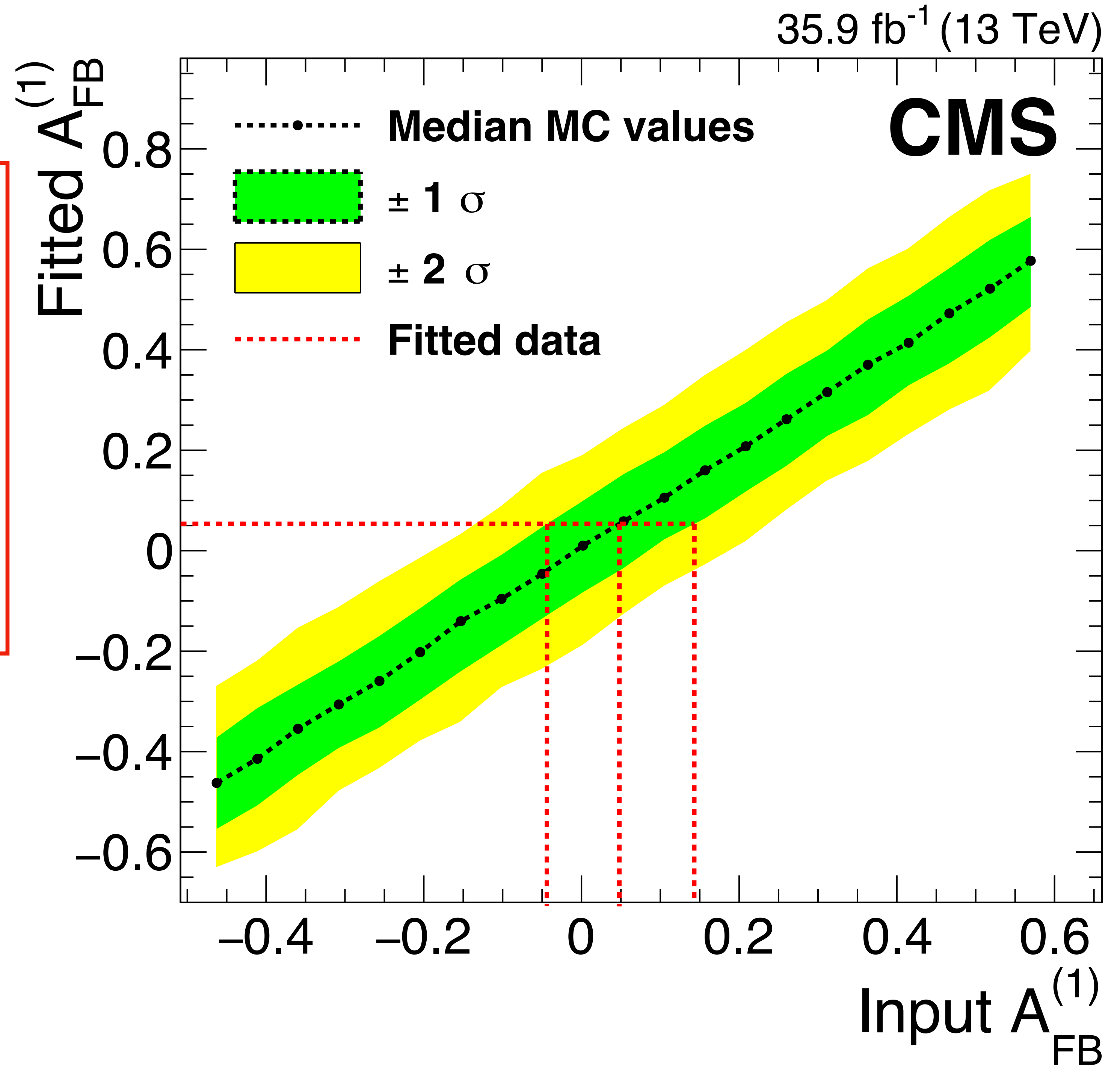
$$x_F = \frac{2p_L}{\sqrt{s}}$$

$$A_{FB} = 0.048^{+0.095}_{-0.087}\,(\text{stat})\,^{+0.020}_{-0.029}\,(\text{syst})$$

$$\mu = -0.024^{+0.013}_{-0.009}\,(\text{stat})^{+0.016}_{-0.011}\,(\text{syst})$$

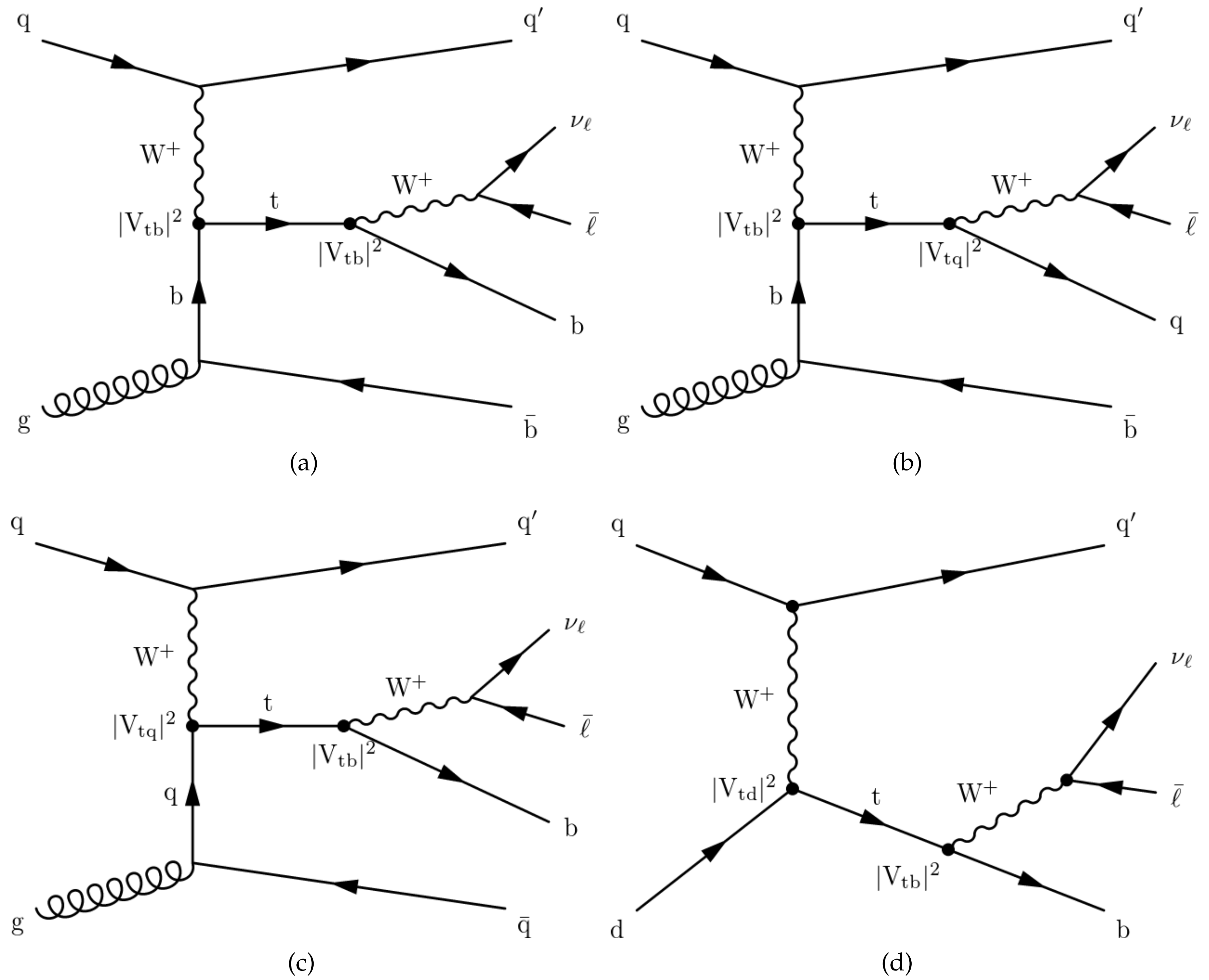
$$d < 0.03\,@\,95\,\%\,\text{CL}$$

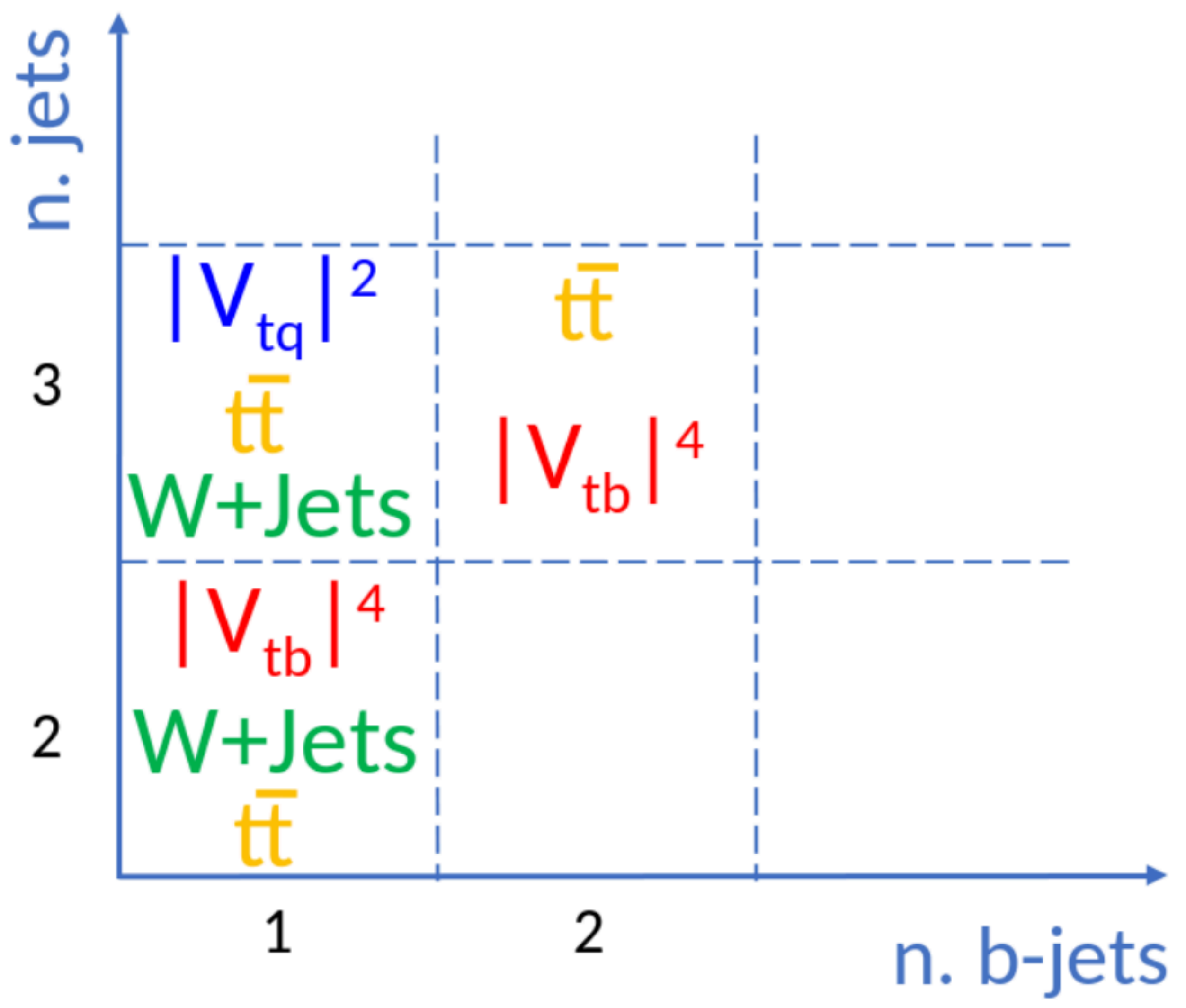


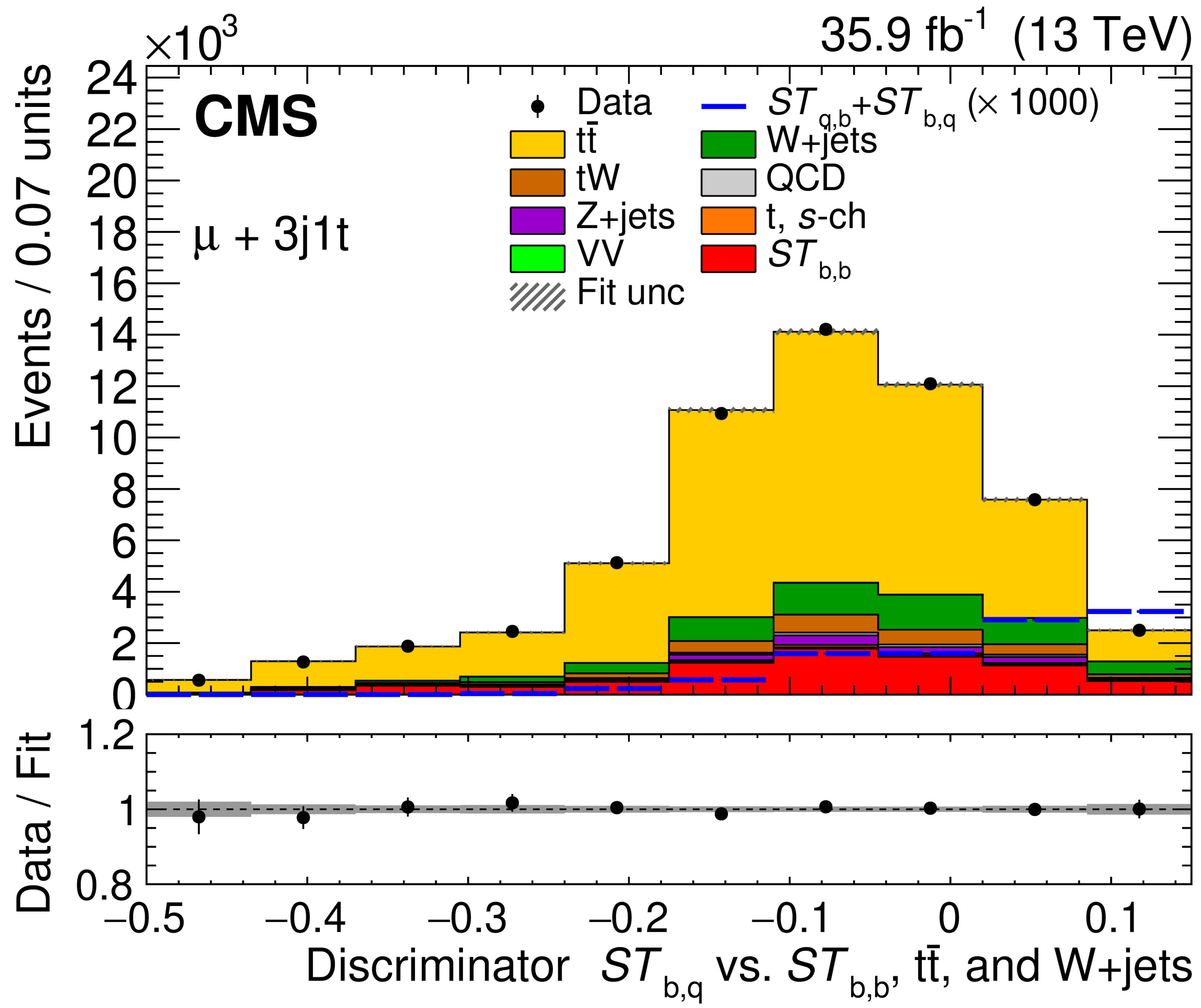


$|V_{tq}|$ in t-channel

Phys. Lett. B 808 (2020) 135609







SM scenario

$$\sum_{q=b,s,d} |V_{tq}|^2 = 1.0$$

$$|V_{tb}| > 0.9$$

$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

BSM scenario 1

Partial widths altered because of modified CKM matrix elements only

$$|V_{tb}| = 0.988 \pm 0.051$$

$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

BSM scenario 2

Partial widths unchanged, but the total width increases due to BSM decays

$$|V_{tb}| = 0.988 \pm 0.024$$

$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

$$\Gamma_t^{Obs}/\Gamma_t = 0.99 \pm 0.42$$

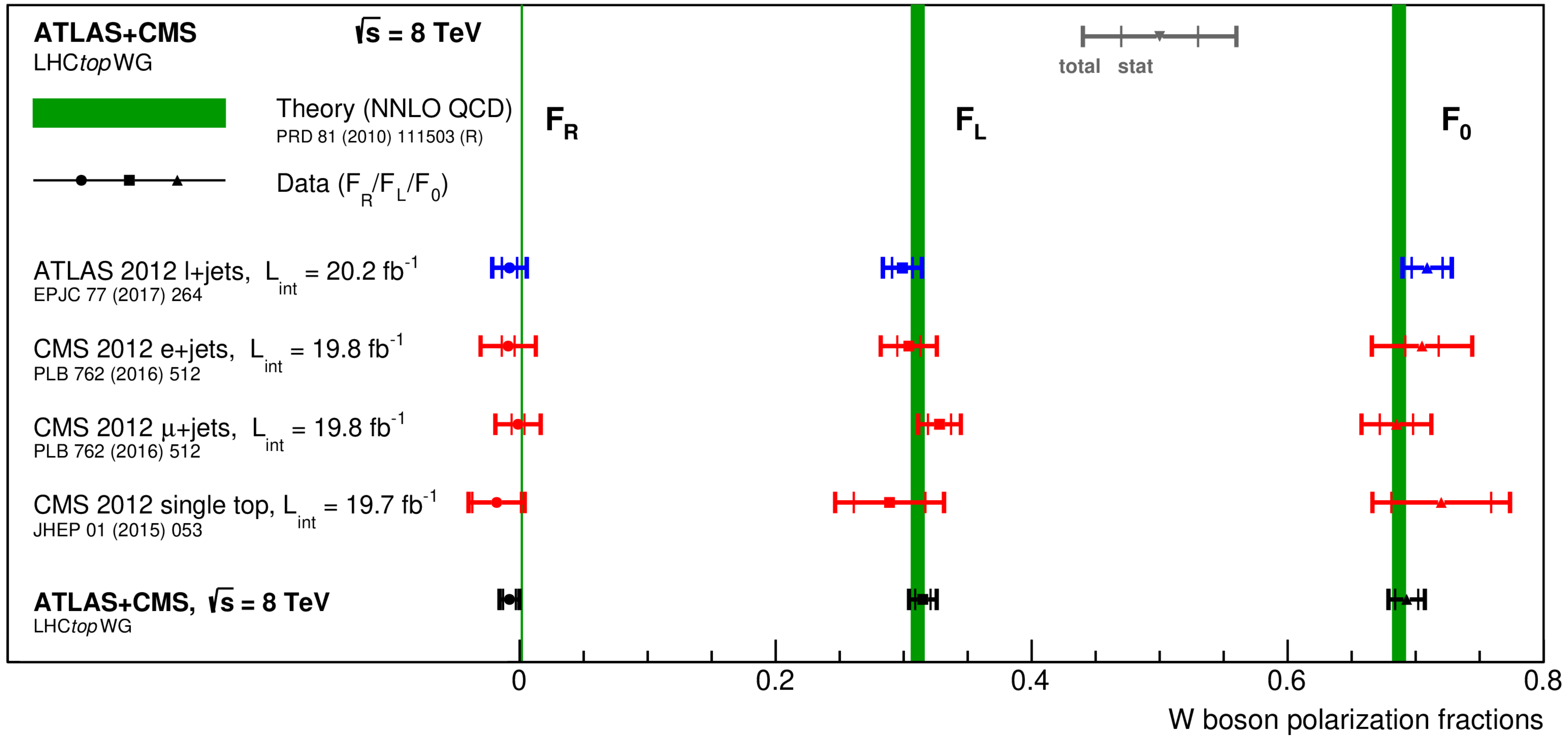
W polarization LHC combination (8 TeV)

JHEP 08 (2020) 051

- Test *V - A* structure of SM using $t \to W(\to \ell\nu)\, b$

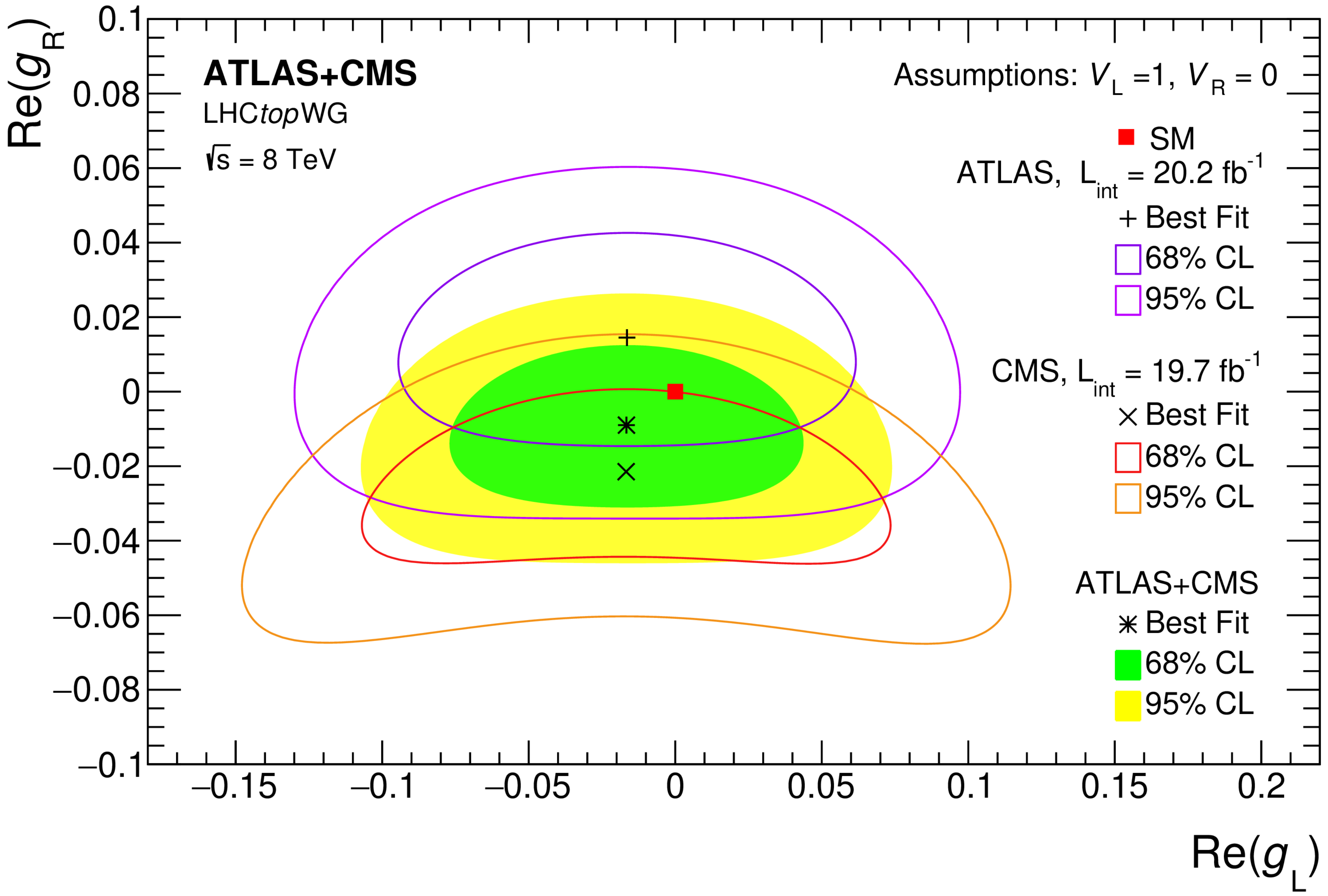
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2F_L + \frac{3}{8}(1+\cos\theta^*)^2F_R$$

- θ^* : ∠ b/w ℓ and *b*-quark (from top decay) in *W* rest frame
- F_0, F_L, and F_R are polarization fractions modify $cos\theta^*$ distributions
- Results from $t\bar{t}$ ℓ+ jets and single top topologies are ***combined***



- Limits on anomalous couplings g_L and g_R are determined
- Results are also interpreted in terms of the EFT couplings

Coefficient	95% CL interval ATLAS	CMS	ATLAS+CMS combination
$C^*_{\phi\phi}$	$[-5.64, 7.68]$	$[-3.84, 4.92]$	$[-3.48, 5.16]$
C^*_{bW}	$[-1.30, 0.96]$	$[-1.06, 0.72]$	$[-0.96, 0.67]$
C_{tW}	$[-0.34, 0.67]$	$[-0.62, 0.19]$	$[-0.48, 0.29]$

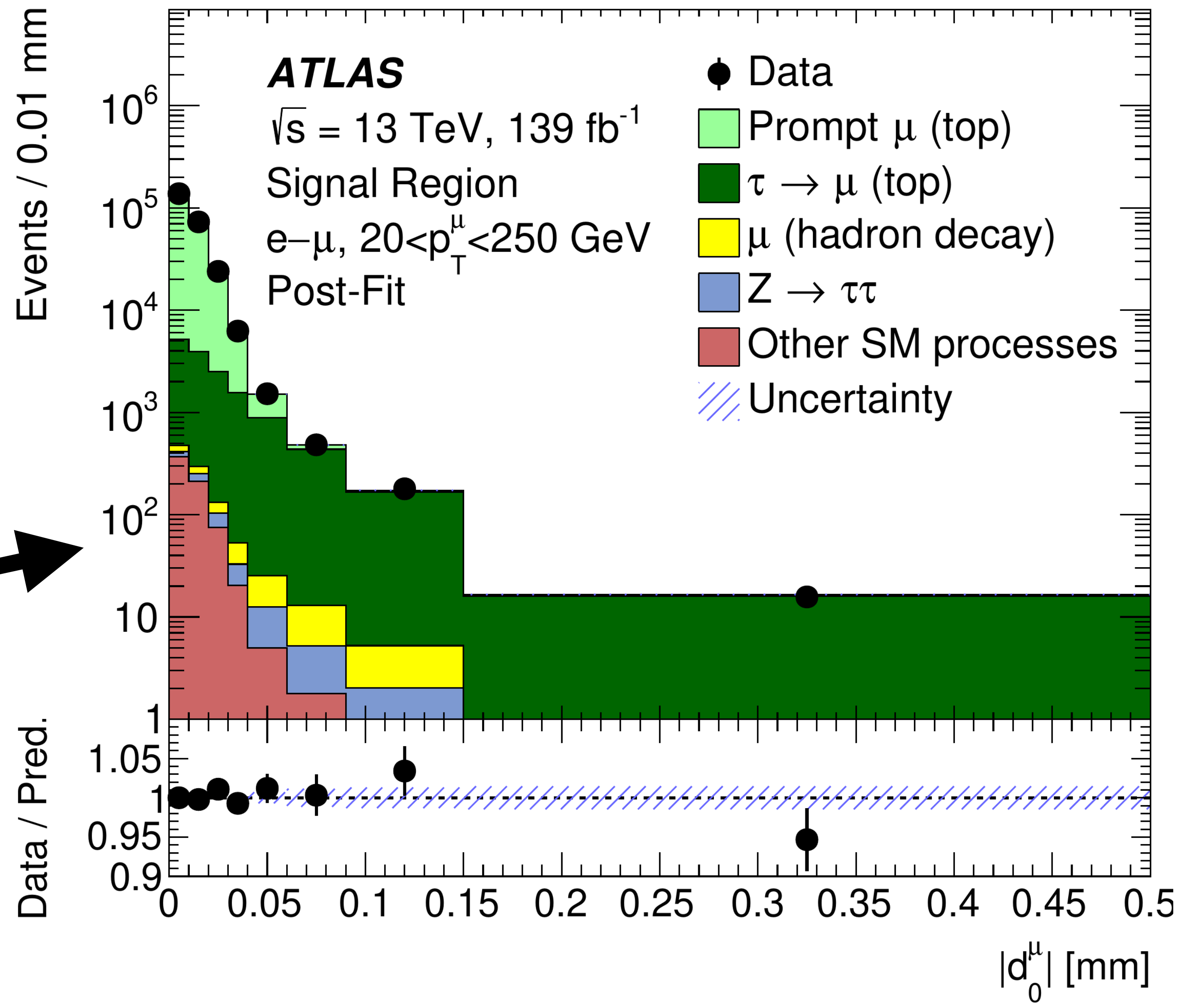


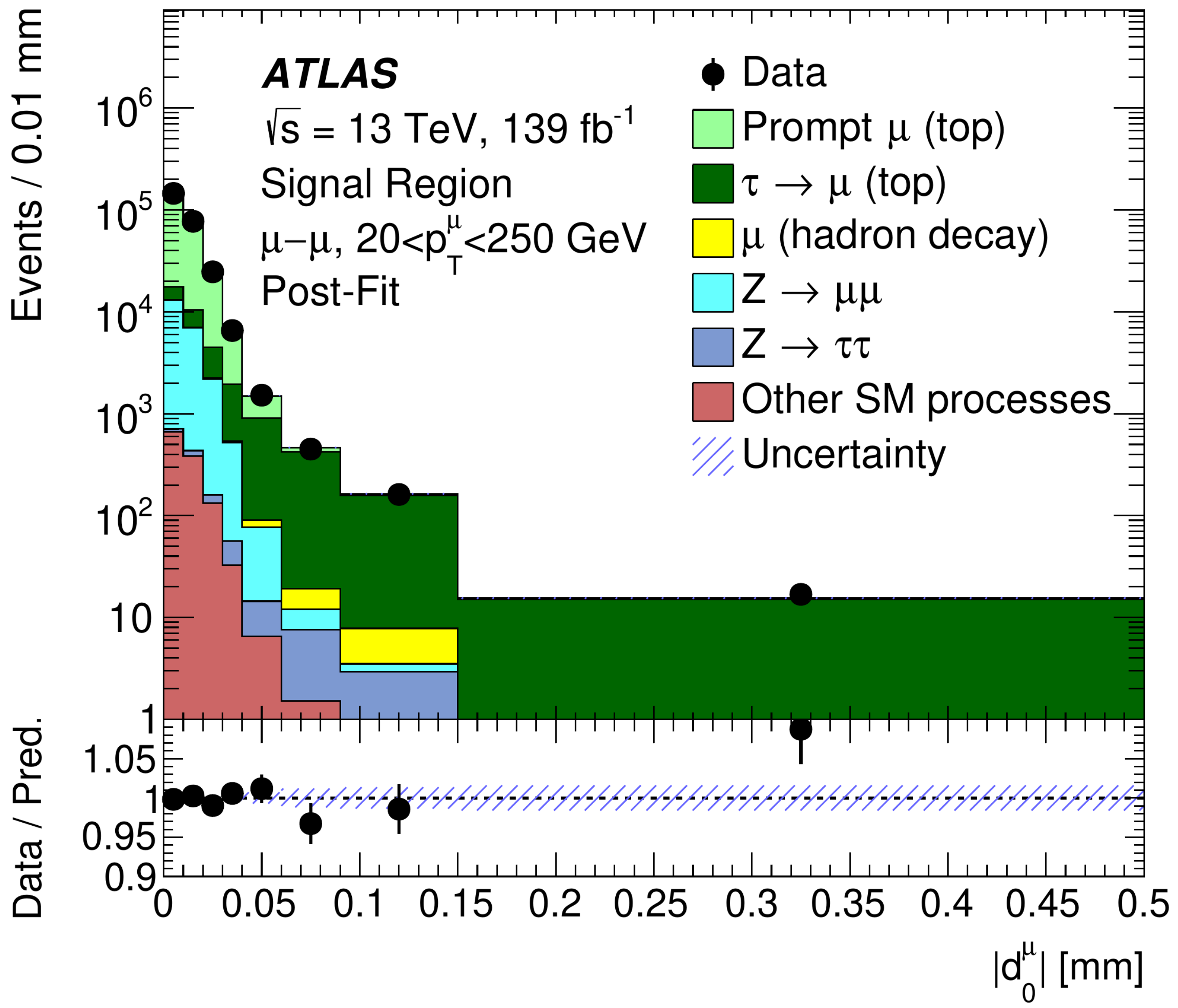
Lepton flavour universality using $t\bar{t}$ events

TOPQ-2018-29

$$R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$$

- Previous LEP result 2.7σ away from SM
- Measurement in $t\bar{t}$ dilepton events using Tag&Probe
  ➛ tight *e/μ , check second μ*
- Impact parameter (d_0) discriminant
  low d_0 : Likely $W \to \mu$
  high d_0 : Likely $W \to \tau \to \mu$

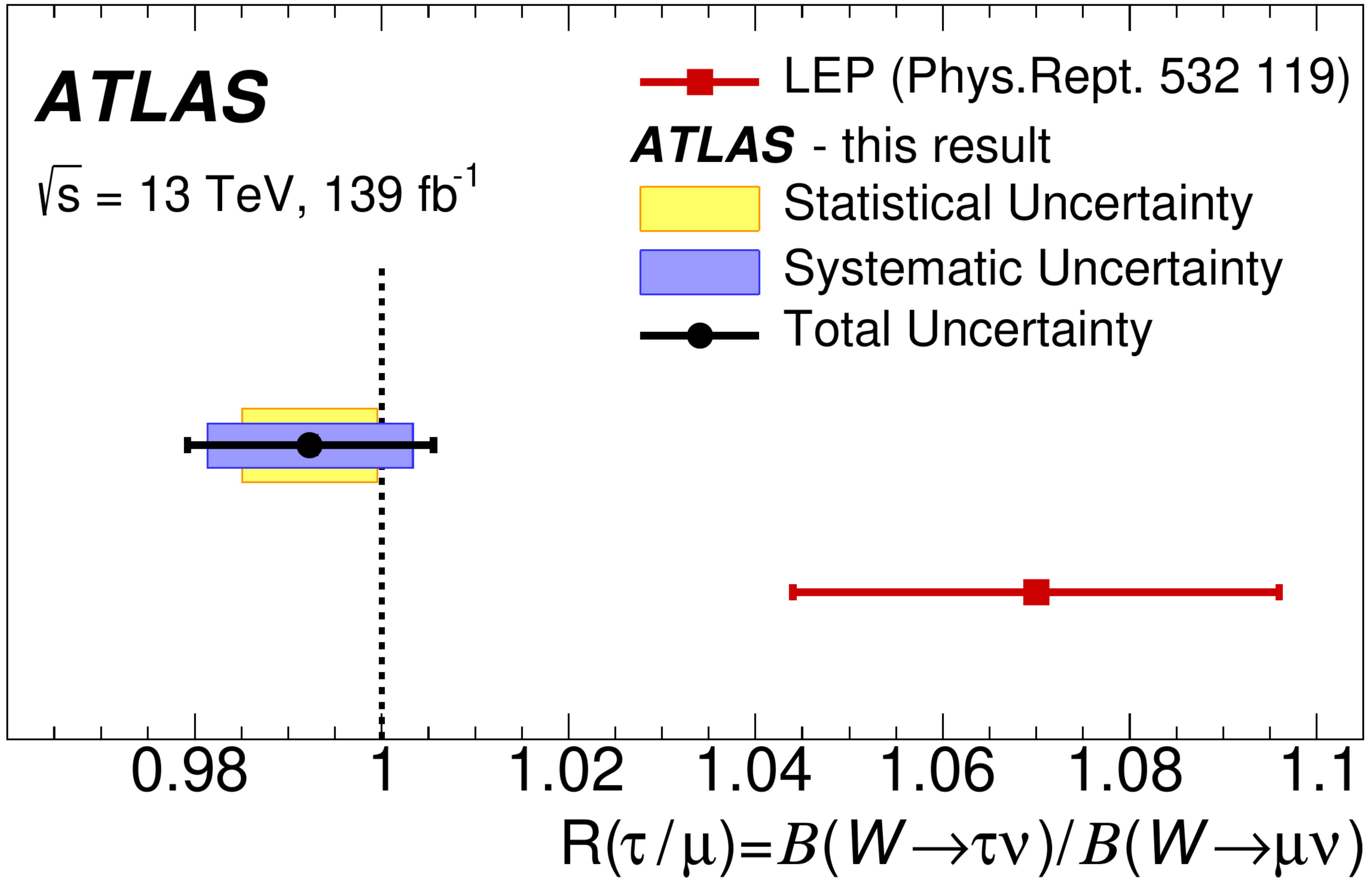




- d_0 calibrated using $Z \to \mu\mu$
- Most Precise result : Unc. dominated by syst.

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

- Dominant syst. sources
  ➛ d_0 template modelling
  ➛ μ isolation and reconstruction
- Recent CMS result (*CMS-PAS-SMP-18-011*) is also found to be consistent with SM prediction ➛ more in backup



Summary and outlook

- LHC ≡ Top Factory ⇒ precision lab for studying top quark properties
- Measurement of top properties ⇒ investigation of SM & BSM
- Most of the measurements agree with SM predictions at a given accuracy
- Systematic bottlenecks in m_t measurements ➛ uncertainties in jet energy estimations and signal modeling
- Extract maximum possible information out of Run2 data
- Preparing towards Run3 and High Lumi. LHC

- More information :

1. ATLAS Top Public Results
2. CMS Top Public Results
3. LHC Top WG

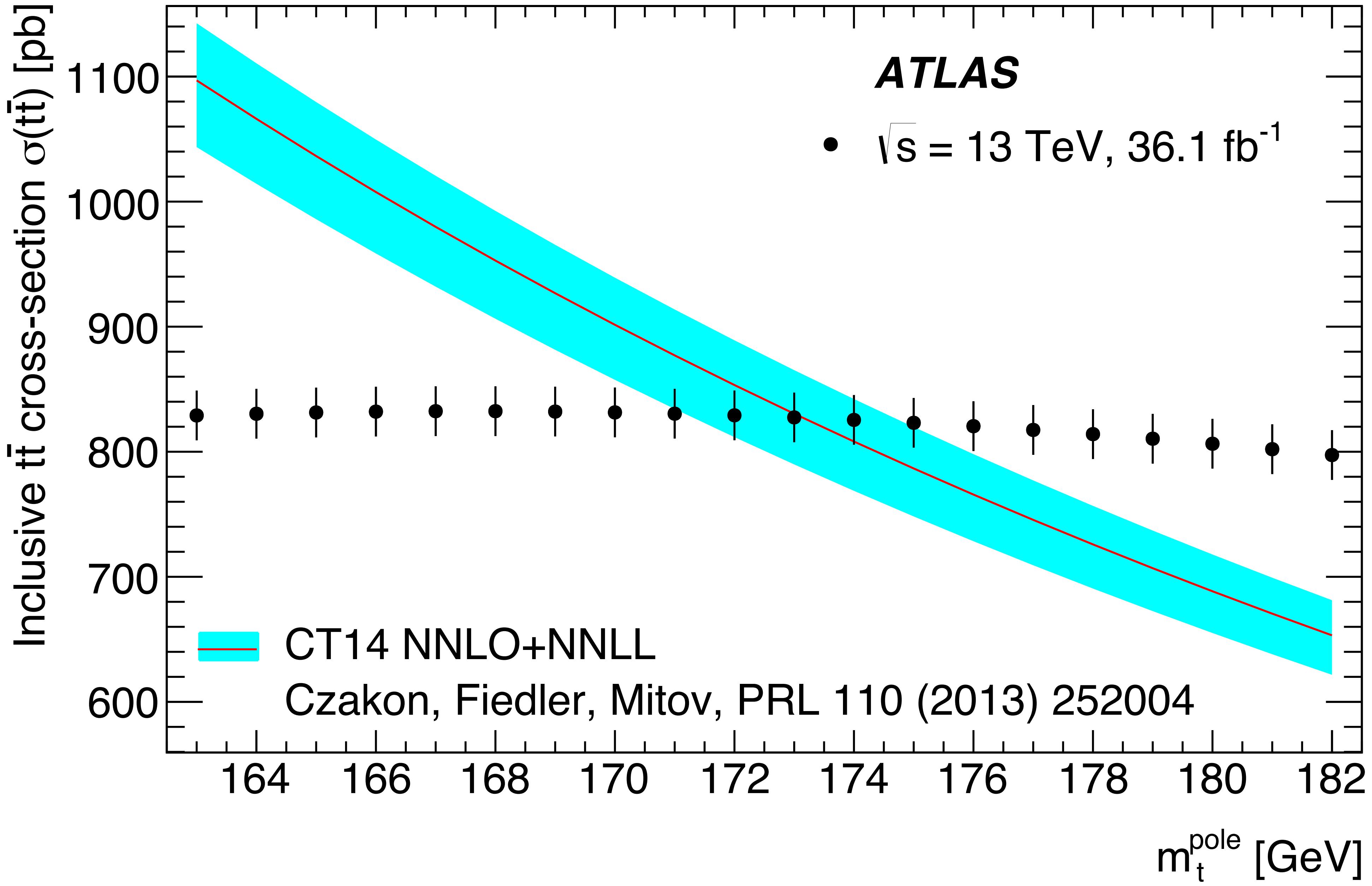
Back Up

m_t^{pole} from $\sigma_{t\bar{t}}$ (eμ)

[Eur. Phys. J. C 80 (2020) 528]

- m_t^{pole} extracted from inclusive $t\bar{t}$ cross-section measurement in dilepton final state using 36.1 fb^{-1} data at 13 TeV

- Selection:
  ➢ 1 OS *eμ* pair
  ➢ 1 or 2 b-tagged jets
  ➢ events with SS *eμ pair* used to control bkg. due to non-prompt leptons



- $\sigma_{t\bar{t}}$ dependence on m_t^{pole} parametrized as:

$$\sigma_{t\bar{t}}^{\text{theo}}(m_t^{\text{pole}}) = \sigma(m_t^{\text{ref}}) \left(\frac{m_t^{\text{ref}}}{m_t^{\text{pole}}}\right)^4 (1 + a_1 x + a_2 x^2)$$

$$\text{where } x = \frac{m_t^{\text{pole}} - m_t^{\text{ref}}}{m_t^{\text{ref}}}, m_t^{\text{ref}} = 172.5\,\text{GeV}$$

$$m_t^{\text{pole}} = 173.1^{+2.0}_{-2.1}\,\text{GeV}$$

Uncertainty source	Δm_t^{pole} [GeV]
Experimental	1.0
PDF+α_S	$^{+1.5}_{-1.4}$
QCD scales	$^{+1.0}_{-1.5}$
Total uncertainty	$^{+2.0}_{-2.1}$

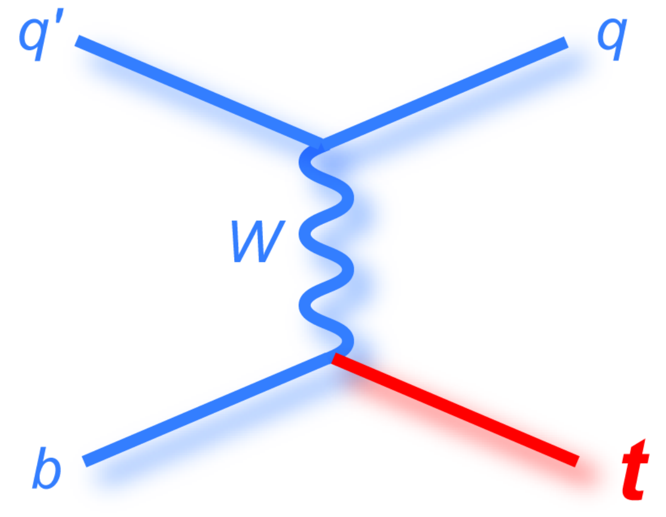
PDF set	m_t^{pole} [GeV]
CT14	$173.1^{+2.0}_{-2.1}$
CT10	$172.1^{+2.0}_{-2.0}$
MSTW	$172.3^{+2.0}_{-2.1}$
NNPDF2.3	$173.4^{+1.9}_{-1.9}$
PDF4LHC	$172.1^{+3.1}_{-2.0}$

t-channel differential measurement (13 TeV)

Eur. Phys. J. C 80 (2020) 370

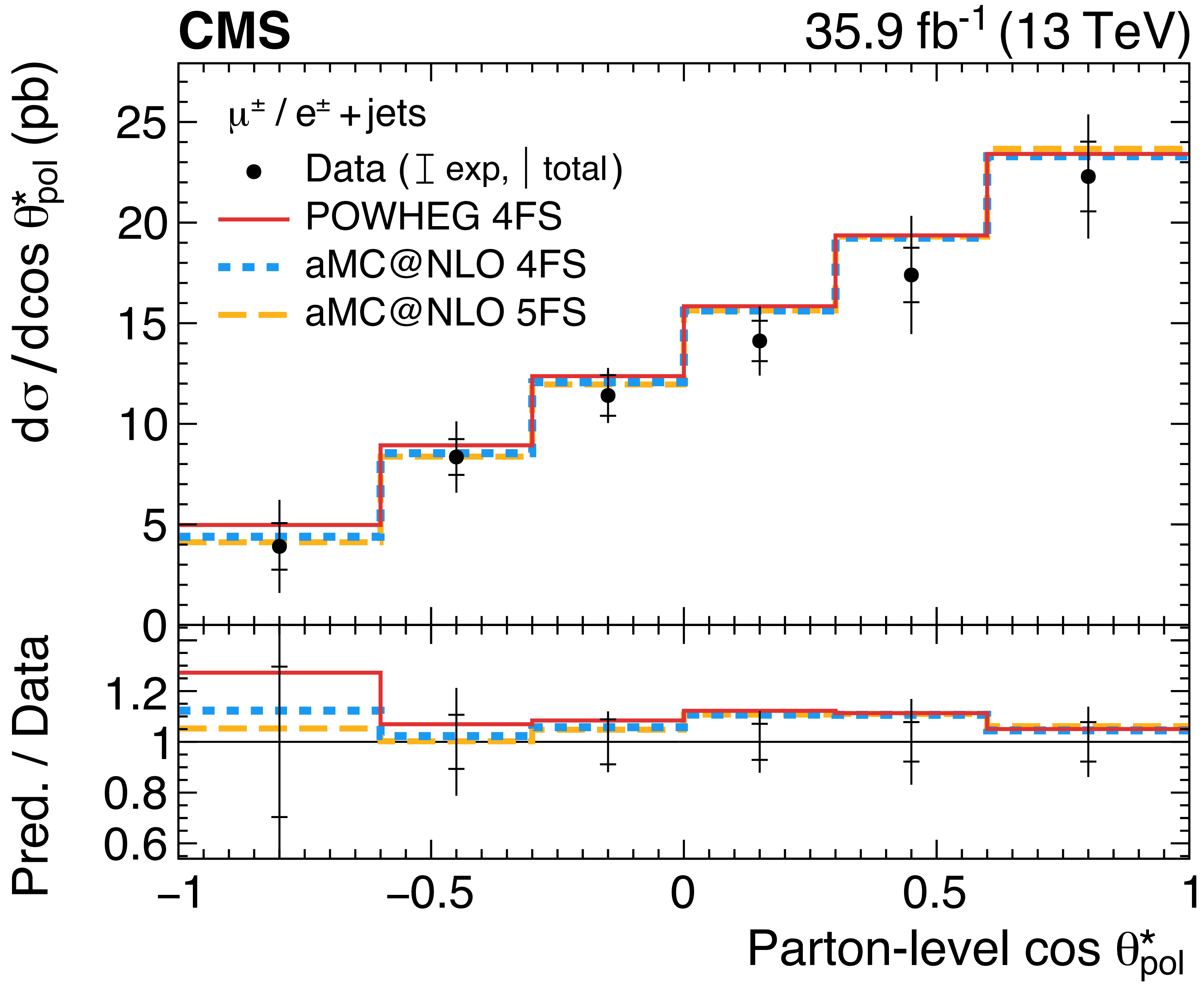
- *t*-channel allows to measure the spin asymmetry of the top quark
  ➛ sensitive to BSM/anomalous couplings
  ➛ top quark highly polarized along the direction of spectator quark

$$A_{\mu+e} = 0.439 \pm 0.032\,(\text{exp}) \pm 0.053\,(\text{theo}) = 0.439 \pm 0.062$$



$$\cos\theta^*_{pol} = \frac{\overrightarrow{p^*_{q'}} \cdot \overrightarrow{p^*_{\ell}}}{|\overrightarrow{p^*_{q'}}||\overrightarrow{p^*_{\ell}}|}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{pol}} = \frac{1}{2}(1 + 2A_\ell \cos\theta^*_{pol})$$

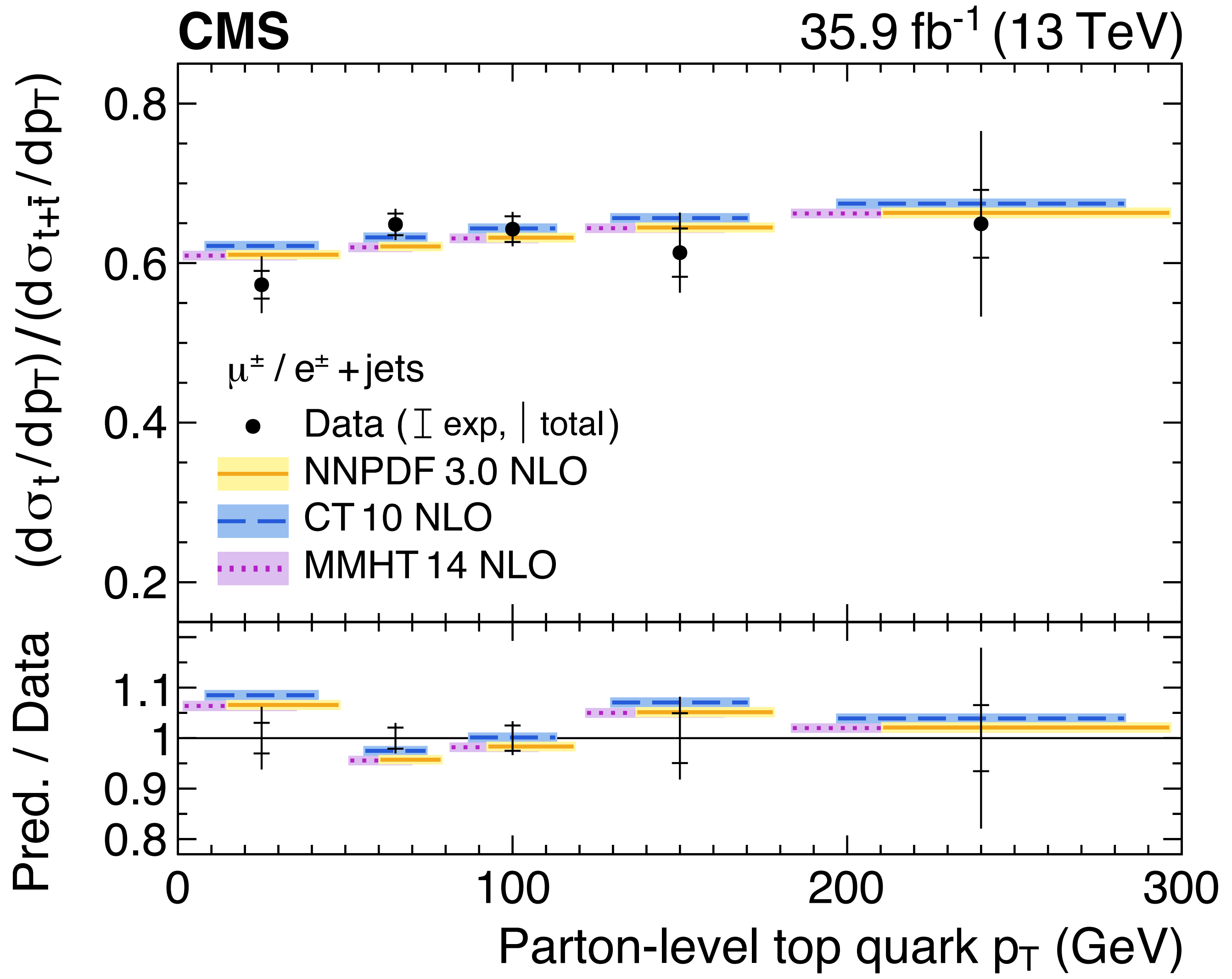


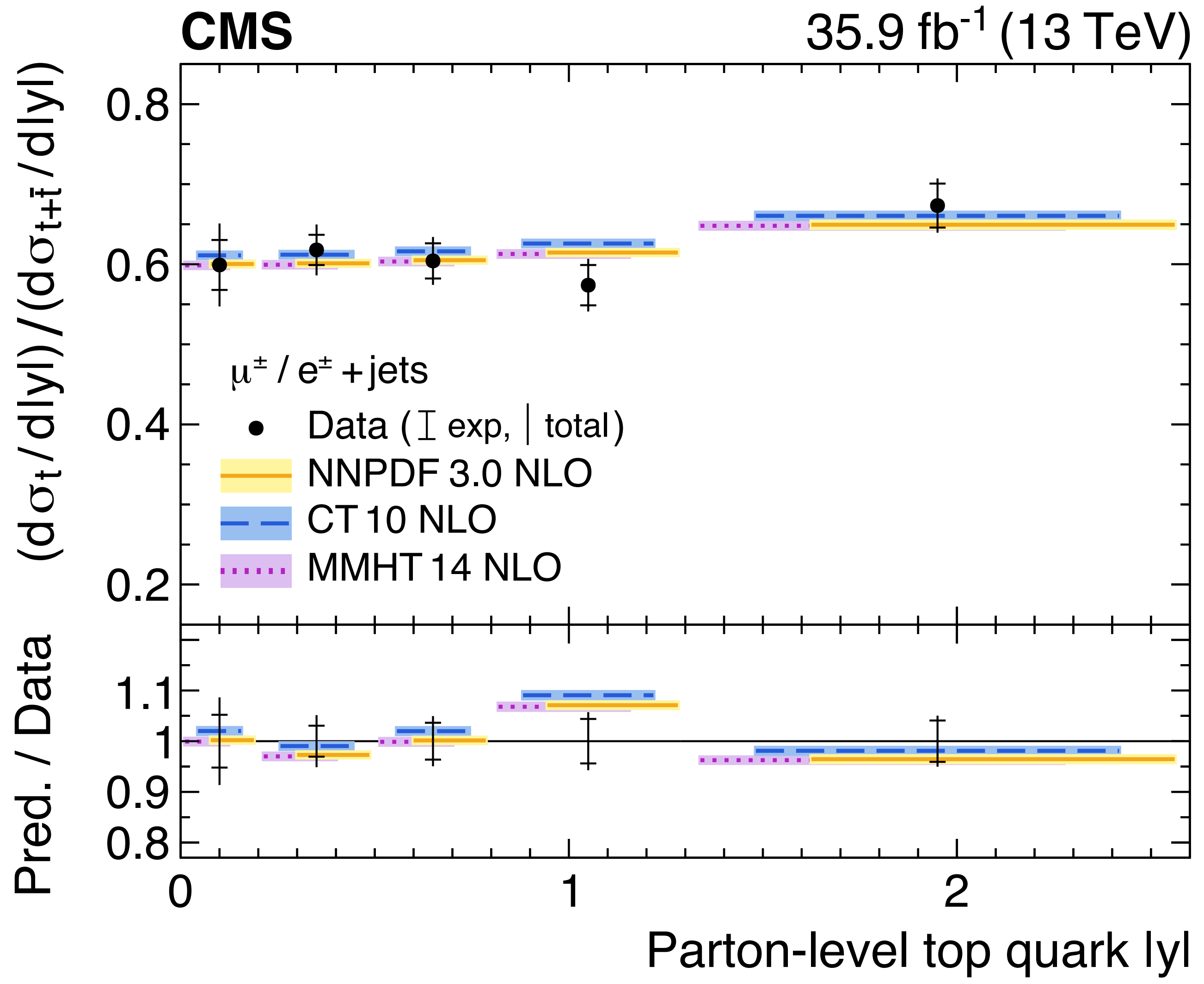
- Measurement compatible with SM expectation (POWHEG NLO): **0.436**
  ➛ deviation observed by CMS at 8 TeV disfavored

- First differential measurement of charge ratio as a function of various observable

- Calculating the ratio of top or anti-top cross-section to total cross-section instead of top quark to antiquark

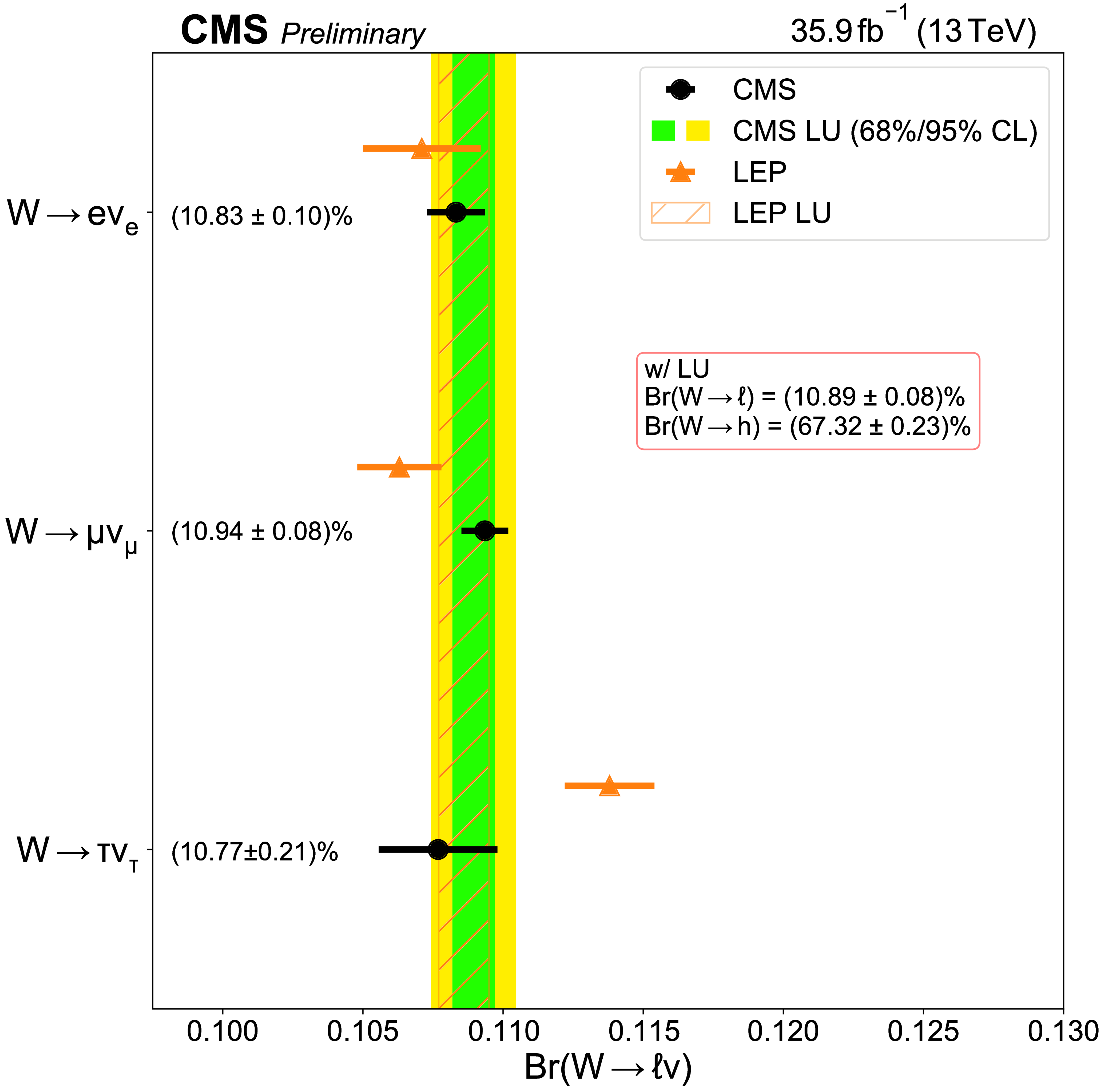
- Results agree with predictions from all PDF sets

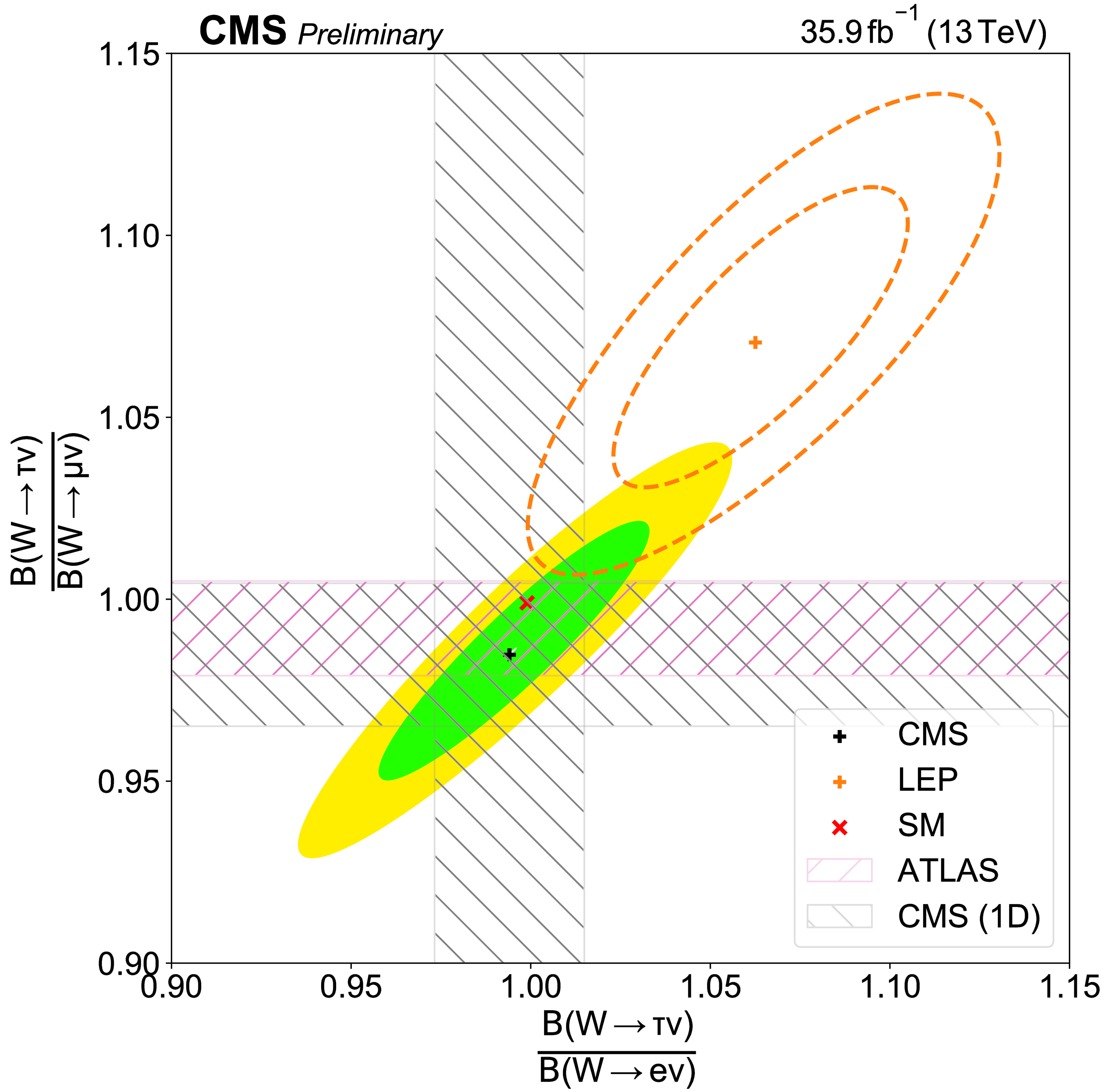




Lepton flavour universality using *WW and W+jets events*

[CMS-PAS-SMP-18-011]





[CMS-PAS-TOP-19-009](CMS-PAS-TOP-19-009)

- Signal and bkg. rates are added as nuisance parameters in the fit
- All other syst. sources externalized ➛ fit repeated with varied templates (conservative approach)
- Dominant sources on the $\ell^{\pm}$ case highlighted by shaded region
- Larger syst. uncertainties in case of ℓ^{-} final state due to higher relative bkg. contribution ➛ charge asymmetry of *W* boson radiated from the initial-state quark in the signal process

Experimental Syst.

Modeling Syst.

Source		$\delta m_{\ell\pm}$	$\delta m_{\ell+}$	$\delta m_{\ell-}$
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 normalization		±0.02	±0.01	±0.02
Offset correction		±0.11	±0.13	±0.20
Luminosity		< ±0.01	< ±0.01	±0.01
CR model and ERD		±0.24	±0.39	±0.68
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 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/μ_F scale	±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	±0.02	±0.22
	FSR	±0.10	±0.14	±0.40
	ME/PS matching scale	±0.10	±0.10	±0.10
	μ_R/μ_F scale	±0.03	±0.03	±0.01
	PDF + α_S	< ±0.01	< ±0.01	< ±0.01
	Top p_T- reweighting	−0.04	−0.08	−0.04
	Underlying event	±0.07	±0.04	±0.17
	total (quadrature sum)	±0.20	$^{+0.18}_{-0.20}$	±0.50
Signal and background shape	signal shape	±0.05	±0.03	±0.04
	Top bkg. shape	±0.07	±0.04	±0.05
	EWK bkg. shape	±0.03	±0.01	±0.02
	total (quadrature sum)	±0.09	±0.05	±0.07
Total systematic		$^{+0.69}_{-0.71}$	$^{+0.97}_{-0.65}$	$^{+1.32}_{-1.39}$
Grand total		$^{+0.76}_{-0.77}$	$^{+1.04}_{-0.75}$	$^{+1.44}_{-1.51}$

ATLAS EXPERIMENT

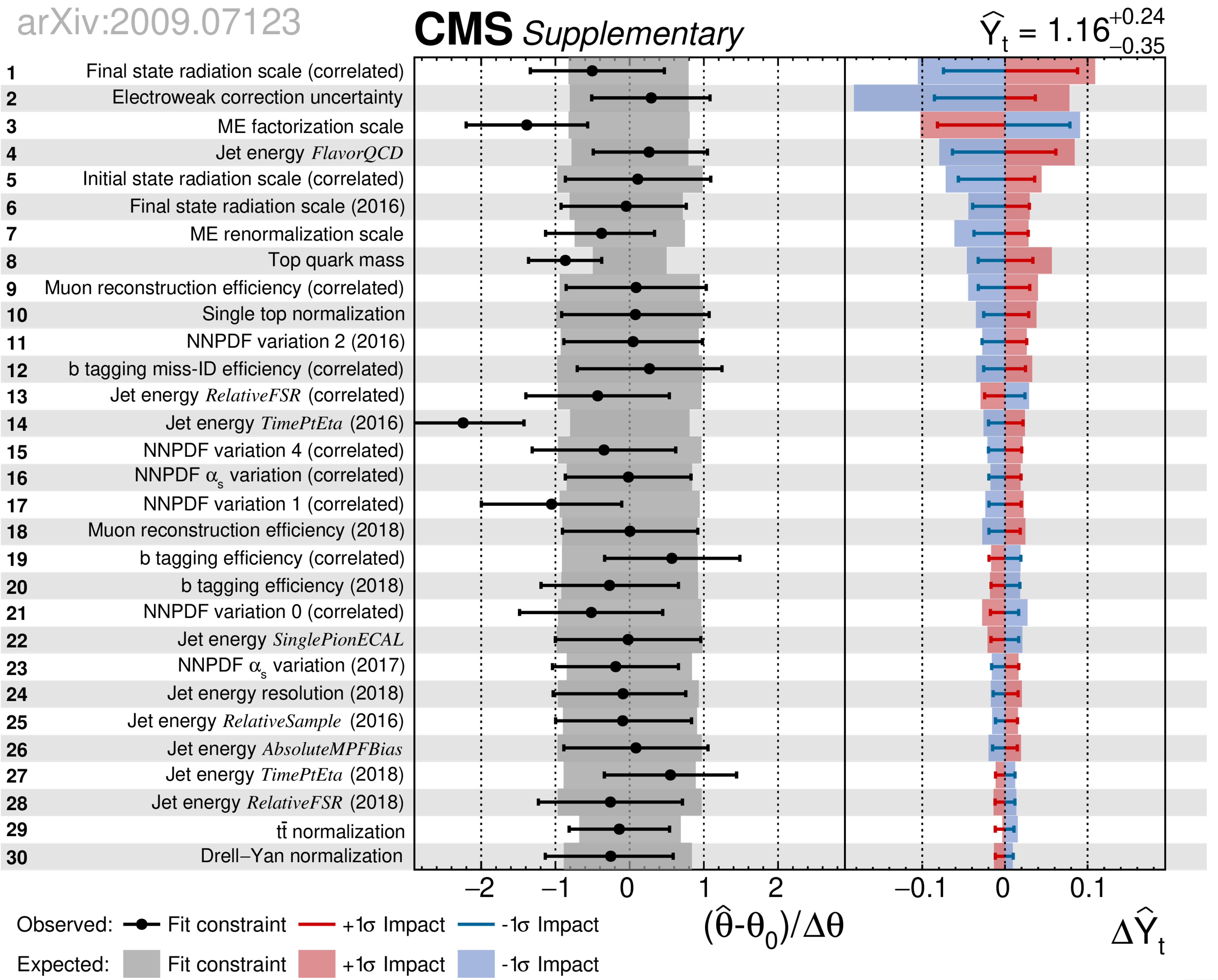
[ATLAS-CONF-2019-038](#)

Source	Impact on Γ_t [GeV]
Jet reconstruction	±0.24
Signal and bkg. modelling	±0.19
MC statistics	±0.14
Flavour tagging	±0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	±0.09
Pile-up and luminosity	±0.09
Electron reconstruction	±0.07
PDF	±0.04
$t\bar{t}$ normalisation	±0.03
Muon reconstruction	±0.02
Fake-lepton modelling	±0.01

[ATLAS-CONF-2019-046](#)

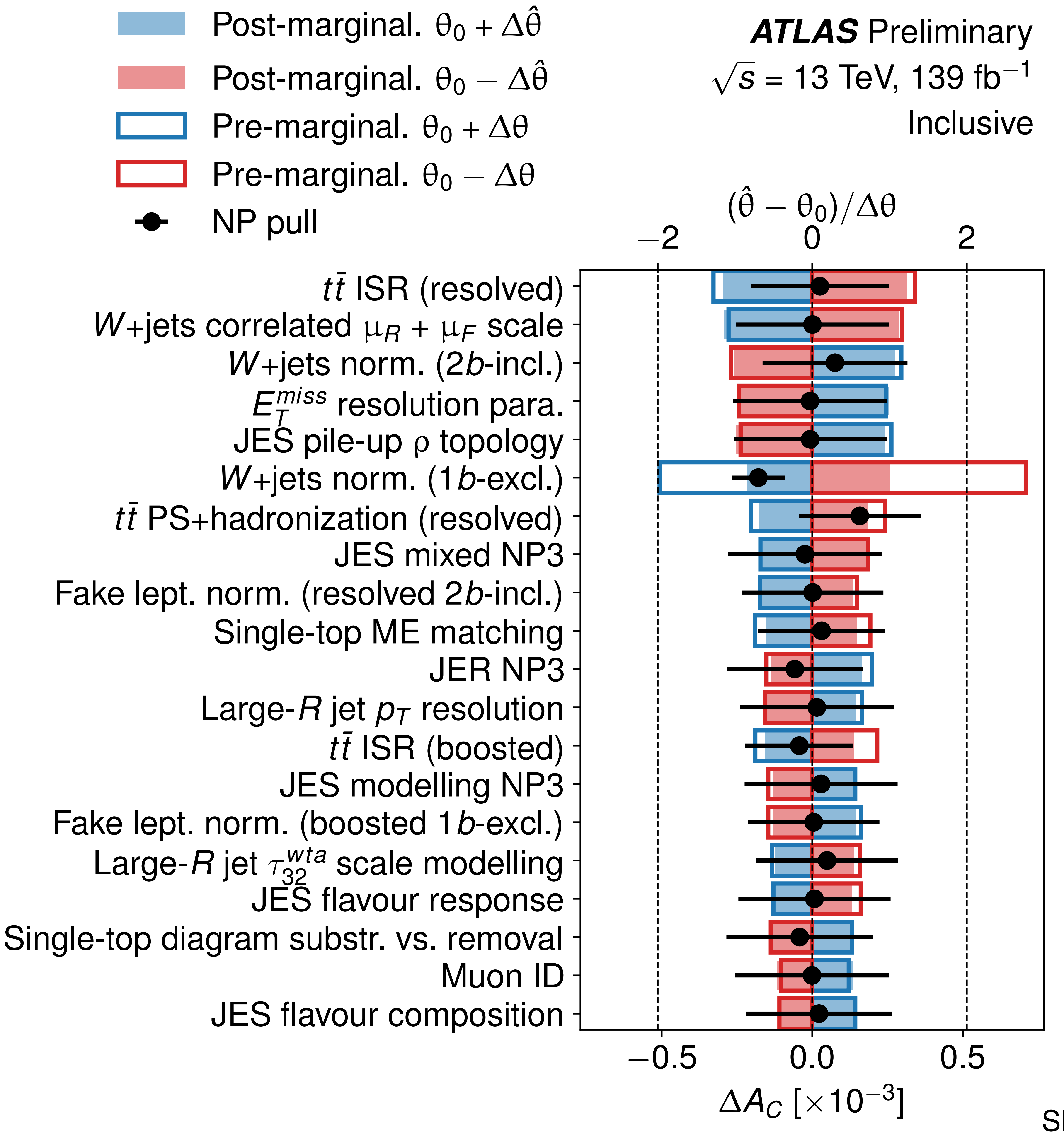
Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
W/Z+jets modelling	0.17	±0.01
Single top modelling	0.01	±0.01
Fake lepton modelling ($t \to W \to \ell$)	0.06	±0.02
Soft muon fake modelling	0.15	±0.03
Jet energy scale	0.12	±0.02
Soft muon jet p_{T} calibration	< 0.01	±0.01
Jet energy resolution	0.07	±0.05
Jet vertex tagger	< 0.01	±0.01
b-tagging	0.10	±0.01
Leptons	0.12	±0.00
Missing transverse momentum modelling	0.15	±0.01
Pile-up	0.20	±0.05
Luminosity	< 0.01	±0.01
Total systematic uncertainty	0.67	±0.04
Total uncertainty	0.78	±0.03

[Phys. Rev. D 102 (2020) 092013](https://doi.org/10.1103/PhysRevD.102.092013)



Dominant uncertainties for A_C and A_{FB} measurements

ATLAS-CONF-2019-026



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Source	Uncertainty in	Type	Size	Affects
Jet energy scale	$\pm1\sigma(p_T, \eta, A)$	N & S	7.6%	All
Jet energy resolution	$\pm1\sigma(\lvert\eta\rvert)$	N & S	3.2%	All
Pileup	$\pm1\sigma(n_{PV})$	N & S	2.9%	All
Boosted μ+jets trigger eff.	$\pm1\sigma(p_T, \eta)$	N & S	0.4%	Type-1/2 μ+jets
Resolved μ+jets trigger eff.	$\pm1\sigma(p_T, \eta)$	N & S	0.1%	Type-3 μ+jets
Boosted e+jets trigger eff.	$\pm1\sigma(p_T, \lvert\eta\rvert)$	N & S	18.6%	Type-1/2 e+jets
Resolved e+jets trigger eff.	$\pm1\sigma(p_T, \eta)$	N & S	2.5%	Type-3 e+jets
Muon ident. eff.	$\pm1\sigma(p_T, \lvert\eta\rvert, n_{PV})$	N & S	0.4%	All μ+jets
Muon PF isolation eff.	$\pm1\sigma(p_T, \lvert\eta\rvert, n_{PV})$	N & S	0.2%	Type-3 μ+jets
Electron ident. eff.	$\pm1\sigma(p_T, \lvert\eta\rvert)$	N & S	1.0%	All e+jets
b tag eff., b jets (loose)	$\pm1\sigma(p_T, \eta)$	N & S	2.5%	Type-1/2
b tag eff., c jets (loose)	$\pm1\sigma(p_T, \eta)$	N & S	1.2%	Type-1/2
b tag eff., light jets (loose)	$\pm1\sigma(p_T, \eta)$	N & S	6.3%	Type-1/2
b tag eff., b jets (medium)	$\pm1\sigma(p_T, \eta)$	N & S	1.9%	Type-3
b tag eff., c jets (medium)	$\pm1\sigma(p_T, \eta)$	N & S	0.8%	Type-3
b tag eff., light jets (medium)	$\pm1\sigma(p_T, \eta)$	N & S	1.2%	Type-3
t tag eff. (merged)	$\pm1\sigma(p_T)$	N & S	1.6%	Type-1
t tag eff. (semimerged)	$\pm1\sigma(p_T)$	N & S	2.2%	Type-1
t tag eff. (not merged)	$\pm1\sigma(p_T)$	N & S	2.8%	Type-1
ISR scale	$\pm1\sigma$	N & S	2.2%	$t\bar{t}$
FSR scale	$\pm1\sigma$	N & S	2.6%	$t\bar{t}$
ME-PS matching (h_{damp})	$\pm1\sigma$	N & S	2.5%	$t\bar{t}$
CUETP8M2T4 tune	$\pm1\sigma$	N & S	2.4%	$t\bar{t}$
Color reconnection	$\pm1\sigma$	S	2.8%	$t\bar{t}$
b fragmentation	$\pm1\sigma(x_b)$	N & S	3.7%	$t\bar{t}$
b branching fraction	$\pm1\sigma$	N & S	1.0%	$t\bar{t}$
Top quark p_T reweighting	$\pm1\sigma(p_T^{gen,t}, p_T^{gen,\bar{t}})$	S	2.5%	$t\bar{t}$
PDF/α_S variation	NNPDF 3.0	S	1.5%	$t\bar{t}$
Renormalization scale μ_R	$\frac{1}{2}\mu_R \to 2\mu_R$	S	2.6%	$t\bar{t}$
Factorization scale μ_F	$\frac{1}{2}\mu_F \to 2\mu_F$	S	1.5%	$t\bar{t}$
Combined μ_R/μ_F scale	$\frac{1}{2} \to 2(\mu_R$ and $\mu_F)$	S	3.8%	$t\bar{t}$ MC
Integrated luminosity	±2.5%	N	—	All
$R_{q\bar{q}}$	±1%	N & S	—	All f_{qp*}/f_{qm*}
R_{W+jets}	±10%	N	—	All W+jets MC
$R_{QCD}^{t/C/R}$ (20 params total)	$\pm1\sigma$ (stat)	N	—	Multijet

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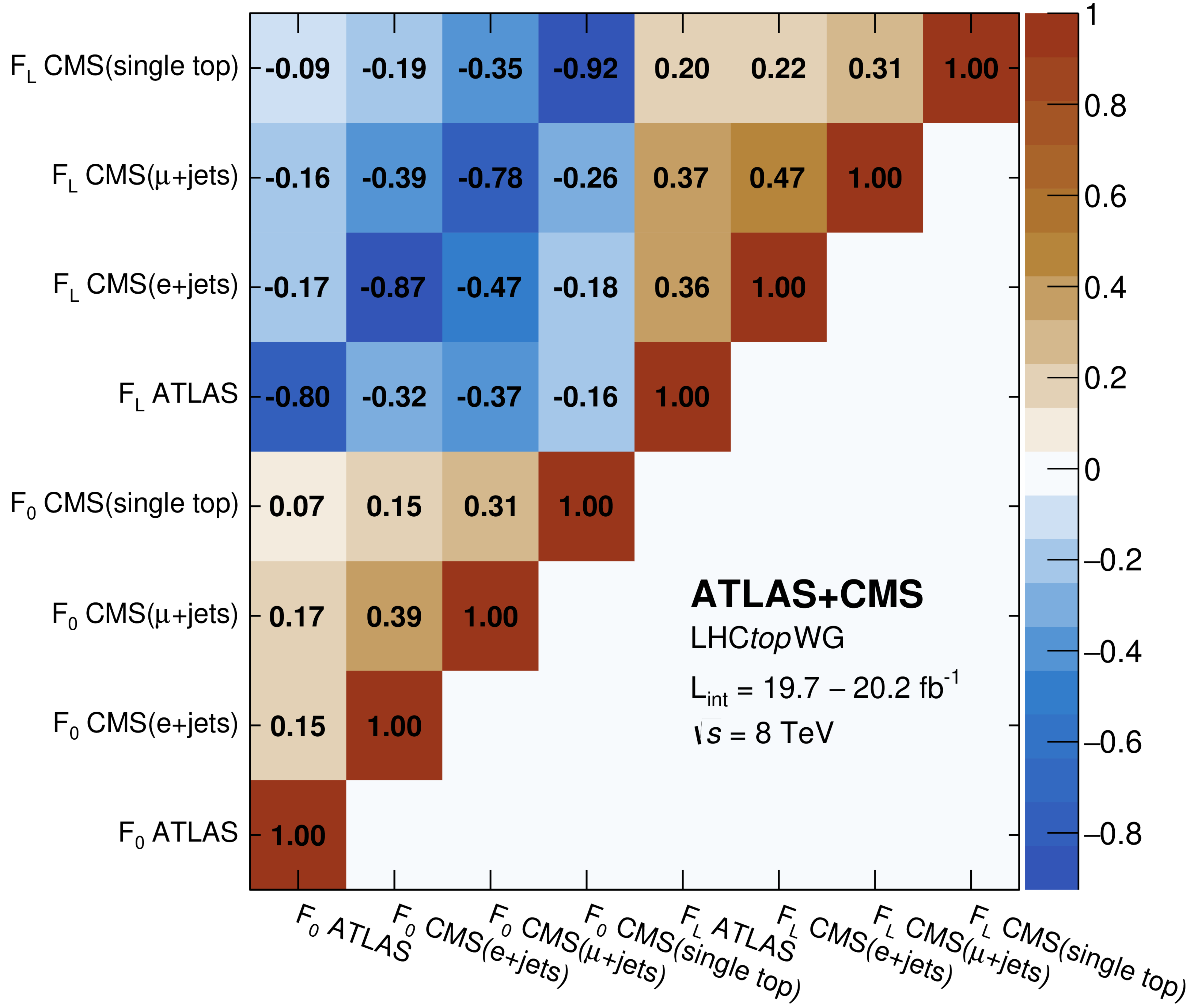
Anomalous coupling :

$$\mathcal{L}_{tWb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \mathrm{h.c.}$$



EFT coupling:

$$L^{\mathrm{eff}} = \mathcal{L}^{\mathrm{SM}} + \Sigma_x \frac{C_x}{\Lambda^2} O_x + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) + \cdots$$

$$O_{\phi\phi} = i(\tilde{\phi}^{\dagger} D_{\mu}\phi)(\bar{t}_R\gamma^{\mu}b_R),$$

$$O_{tW} = (\bar{q}_L\sigma^{\mu\nu}\tau^{I}t_R)\tilde{\phi}W^{I}_{\mu\nu},$$

$$O_{bW} = (\bar{q}_L\sigma^{\mu\nu}\tau^{I}b_R)\phi W^{I}_{\mu\nu},$$

[TOPQ-2018-29](#)

Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^{μ} templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\rightarrow\mu)}$ 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
$\mu_{(\tau\rightarrow\mu)}$ and $\mu_{(had.)}$ d_0^{μ} shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \rightarrow \mu\nu_{\tau}\nu_{\mu})$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**