Summary of Top measurements at LHC

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on behalf of the CMS and ATLAS collaboration

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Introduction

- Heaviest known elementary particle
  ➛ Sensitive to EWSB mechanism and vacuum stability through radiative corrections

- At LHC, top quarks are produced
  ➛ 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 ($\tau_{decay} \approx 10^{-25}$ s) before hadronization ($\tau_{had.} \approx 10^{-24}$ s)
  ➛ Access to bare quark properties such as spin-polarization

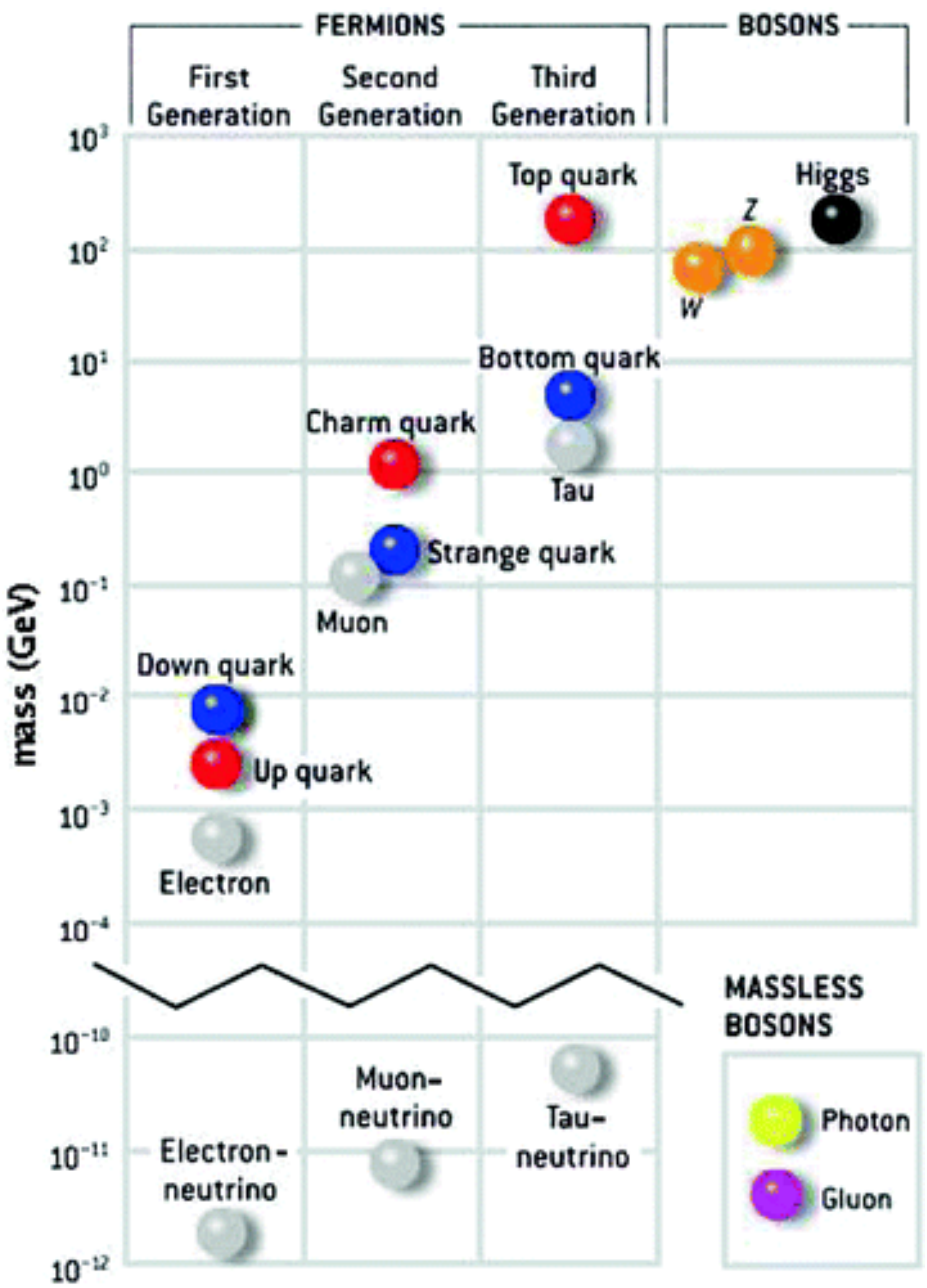
- Allows test of pQCD at NLO or NNLO precision (fixed-order)

- Constrains proton PDFs, strong coupling, top-quark pole mass

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

- Window to New Physics via anomalous or EFT couplings

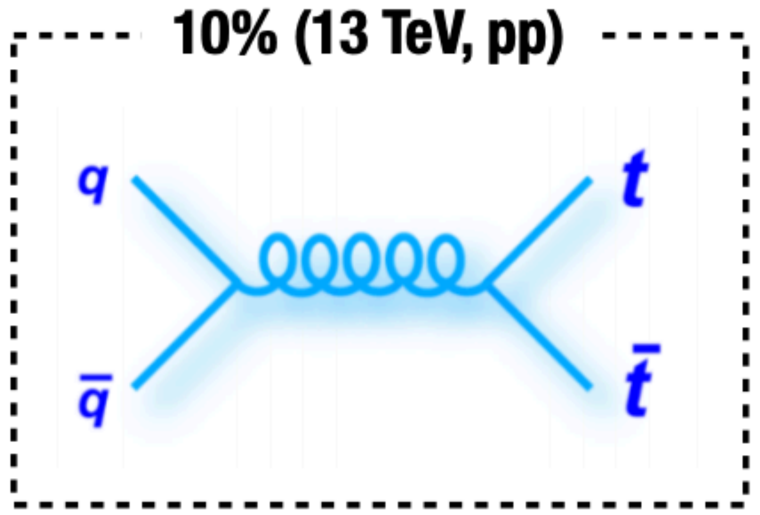
- Constitutes dominant background to multiple BSM resonance searches

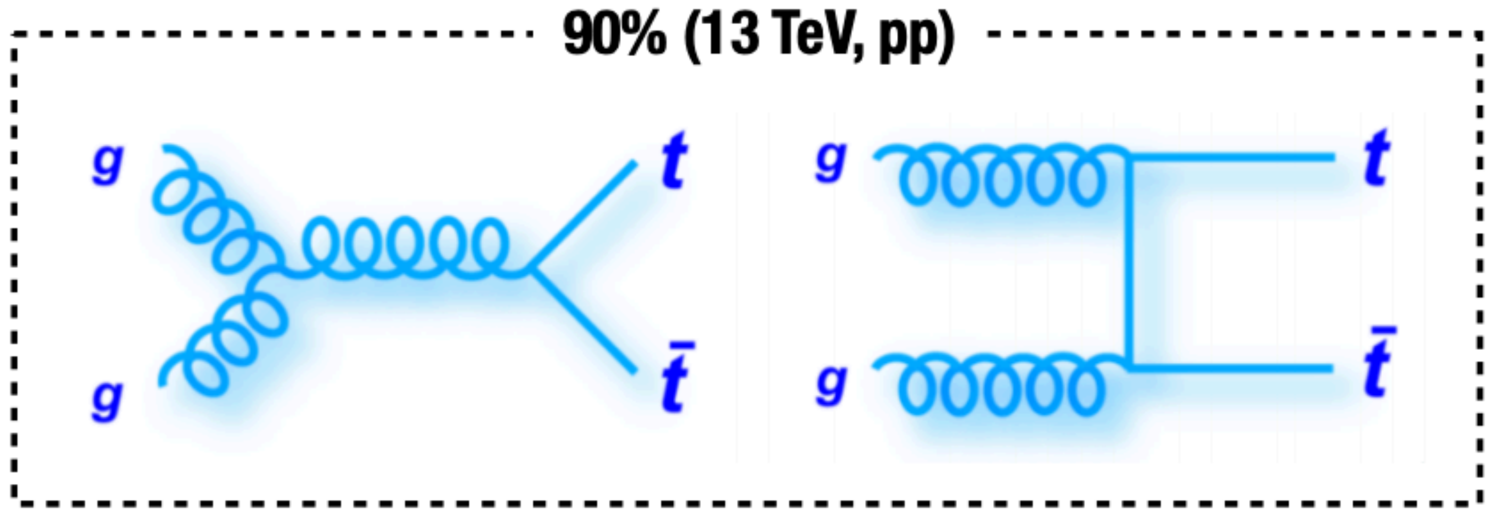


This talk focuses mostly on my picks from all the latest results using Run2 (13 TeV) data

Top pair measurements

Inclusive $\sigma_{t\bar{t}}$ measurements





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

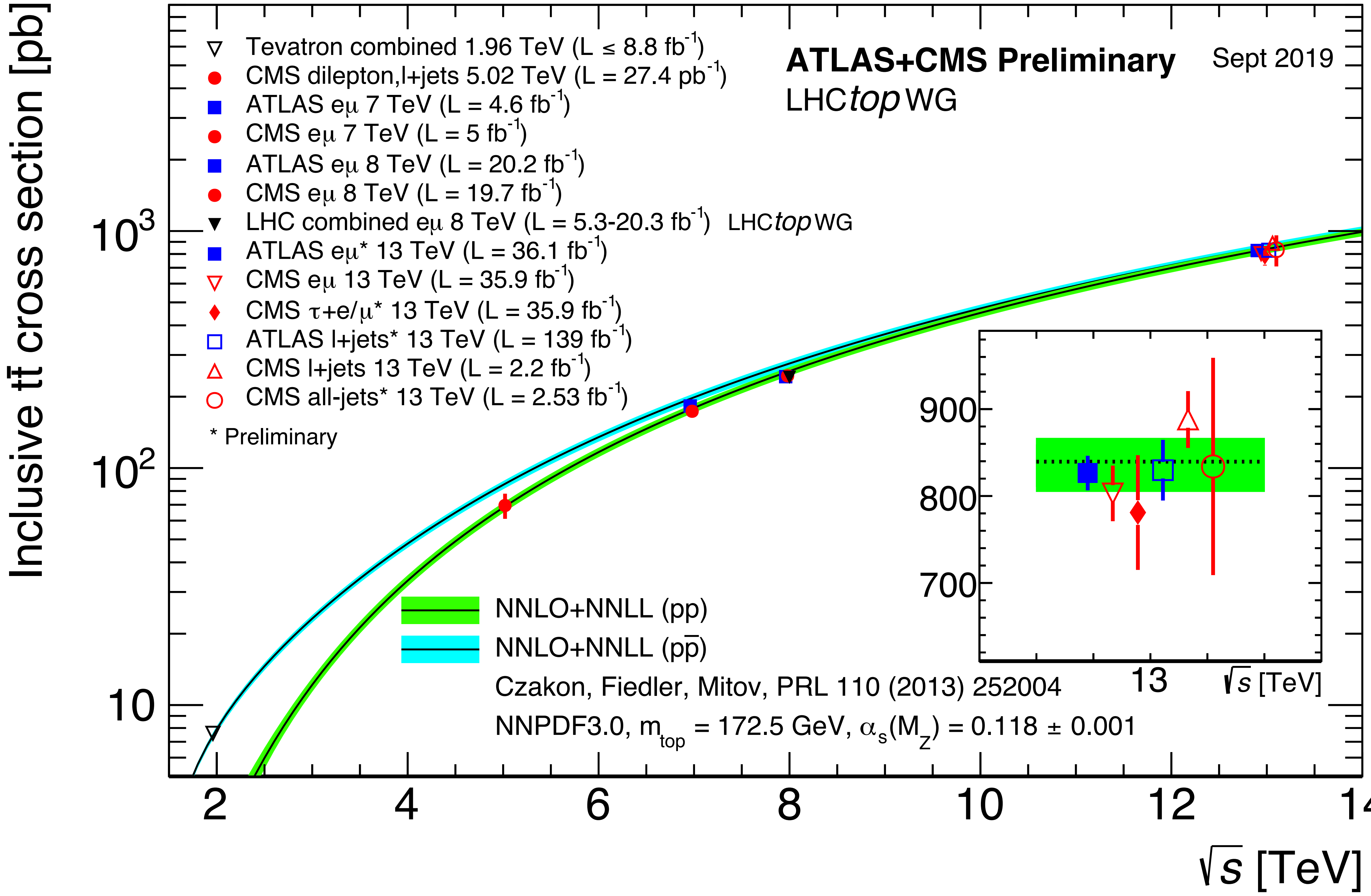
- Most precise (2.4%) result by ATLAS (arXiv:1910.08819) in events with OS $e\mu$ pair + 1 or 2 b-tagged jets

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\text{stat}) \,\pm 11.5\,(\text{syst}) \,\pm 15.7\,(\text{lumi}) \,\pm 1.9\,(\text{beam})\,\text{pb}$$

- Dominant systematics:
  - ➛ Luminosity(1.9%),
  - ➛ *tW* bkg. cross-section (0.52%),
  - ➛ $t\bar{t}$ shower/had. model (0.49%),
  - ➛ $t\bar{t}$ PDF (0.45%),
  - ➛ $t\bar{t}$ ISR/FSR model (0.45%)

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

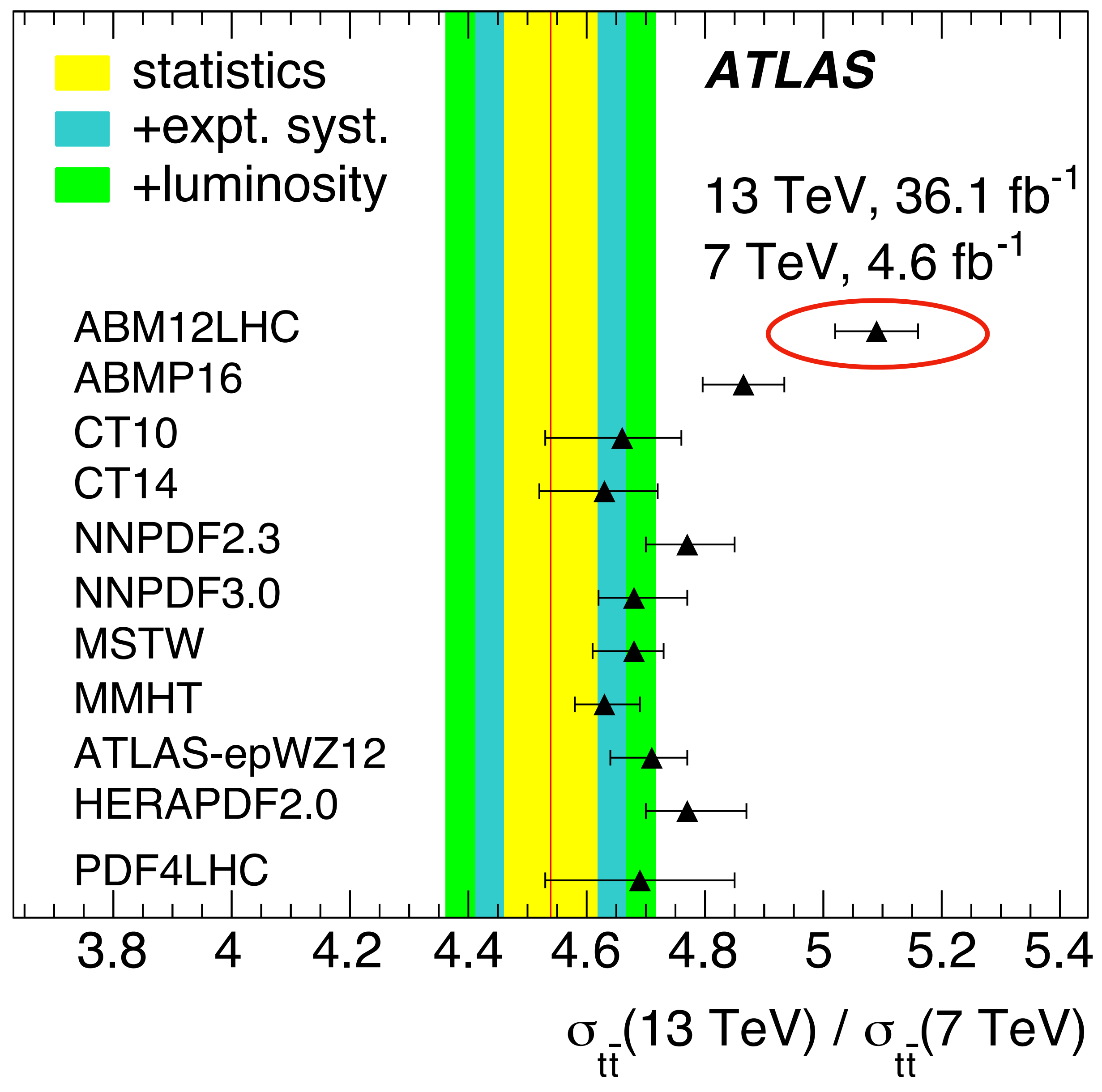
$\sqrt{s}$	$\sigma_{t\bar{t}}$ (NNLO + NNLL)
7 TeV	$177.3^{+10.1}_{-10.8}$ pb (6.6%)
8 TeV	$252.9^{+15.3}_{-16.3}$ pb (6.2%)
13 TeV	$831.8^{+45.5}_{-49.9}$ pb (5.7%)

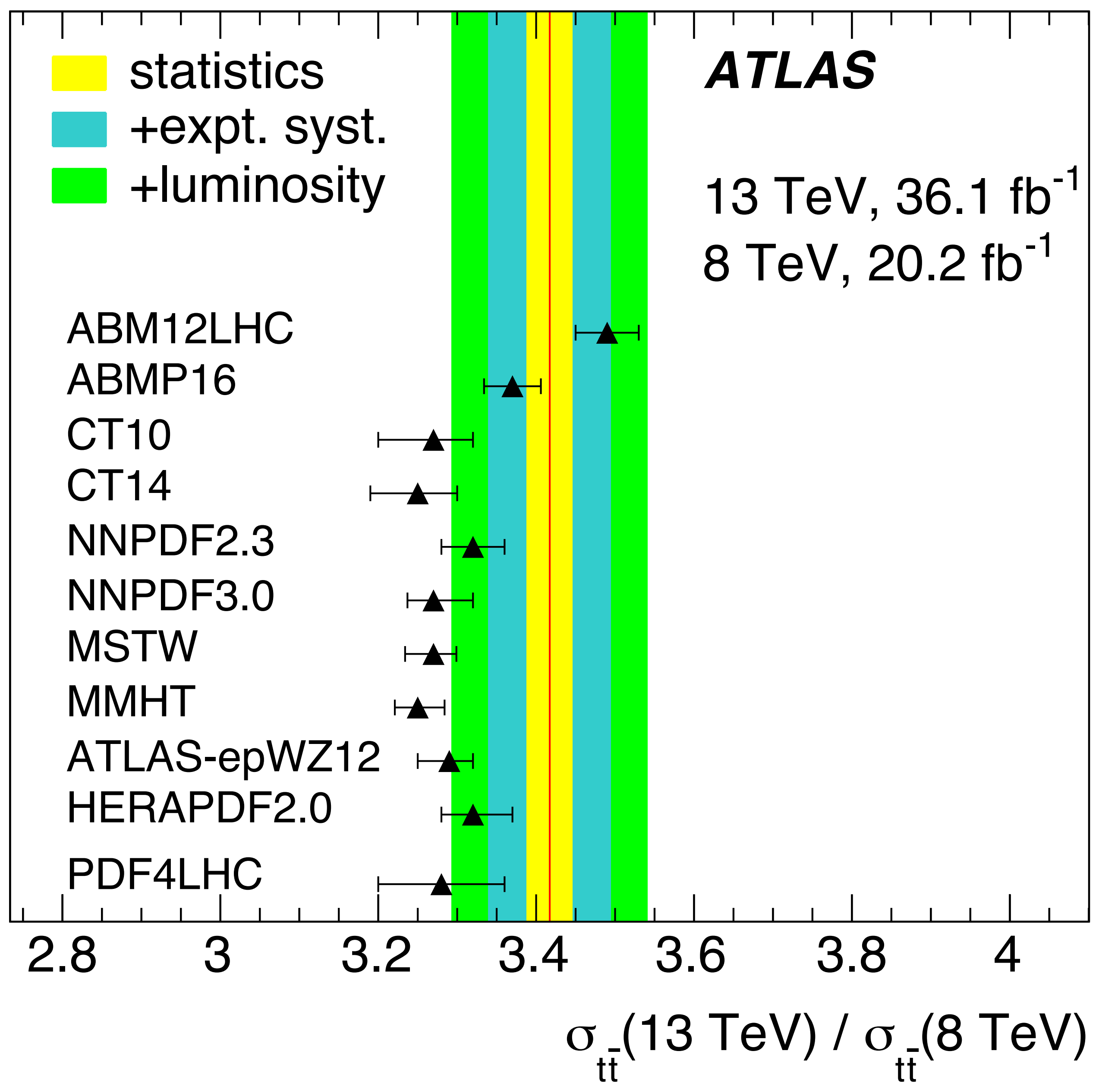


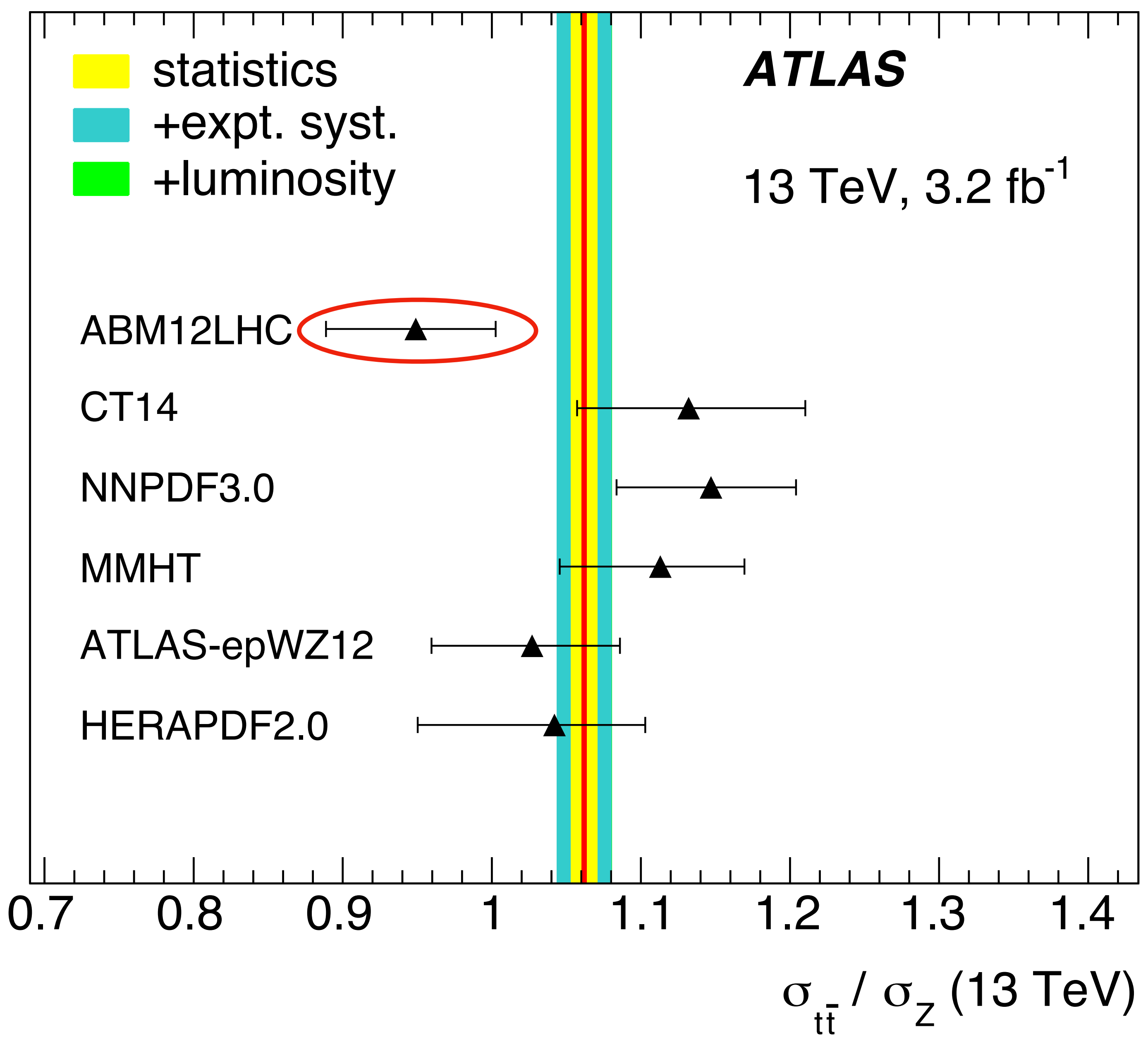
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

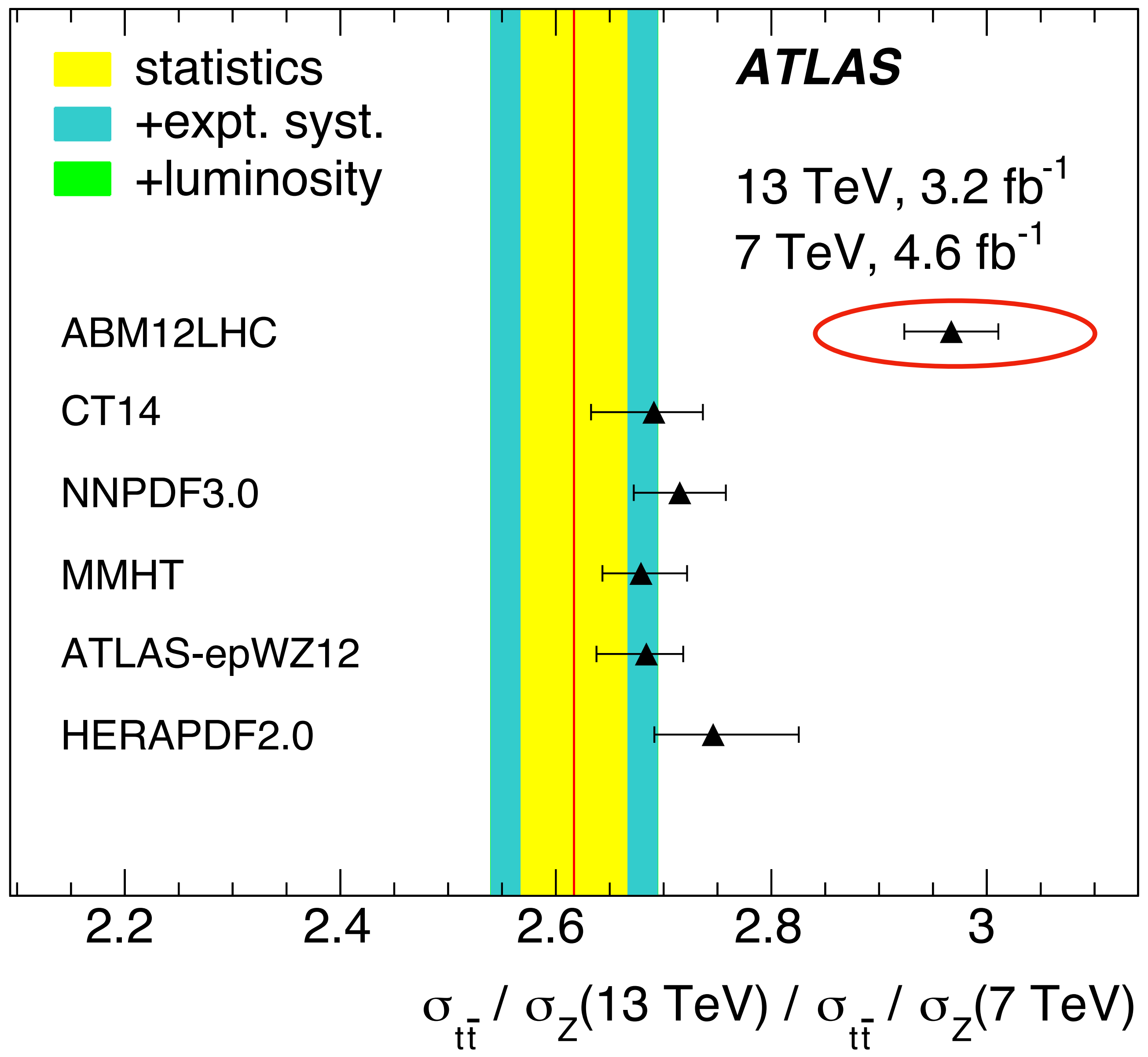
Cross-section ratios

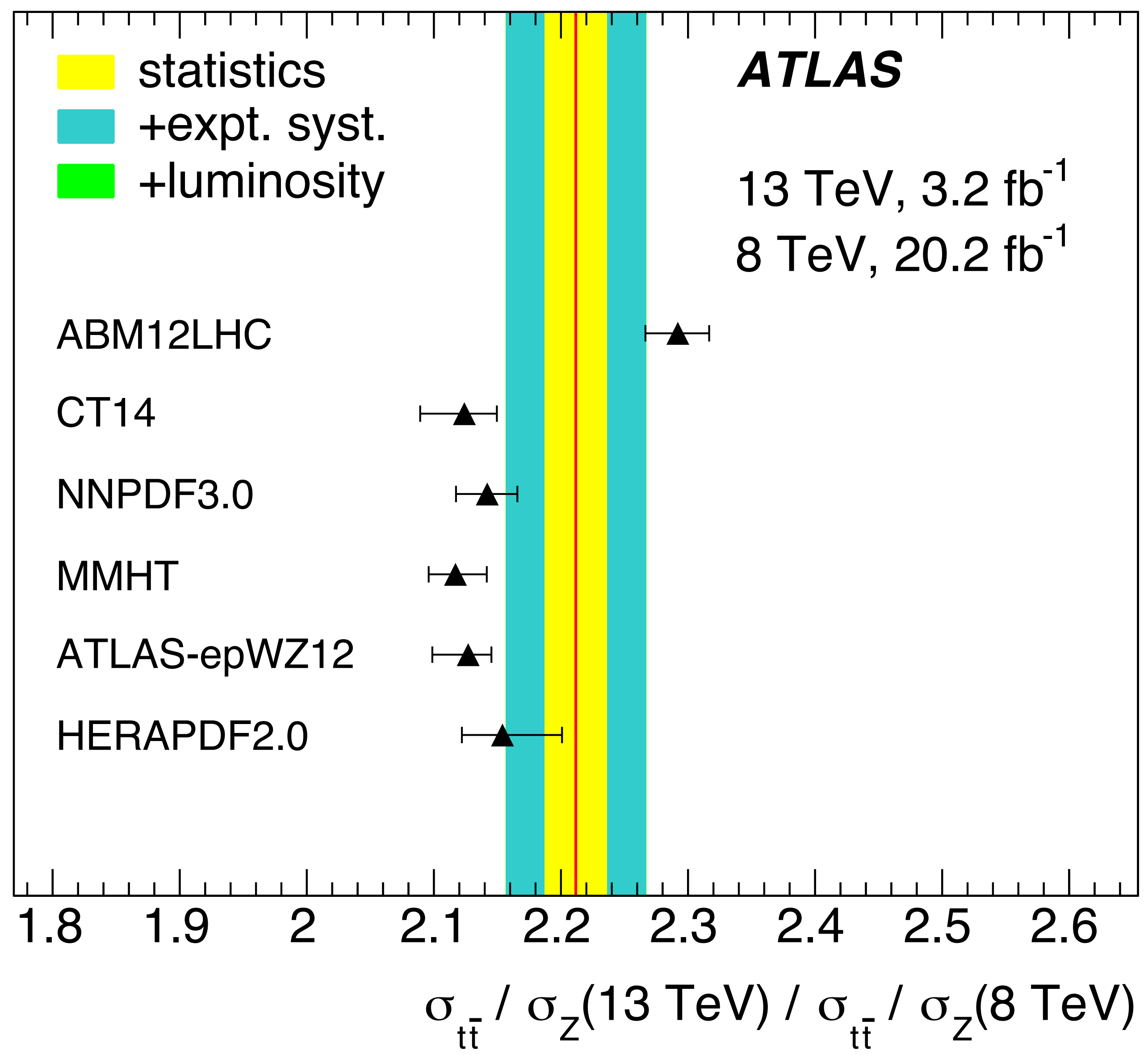
arXiv:1910.08819











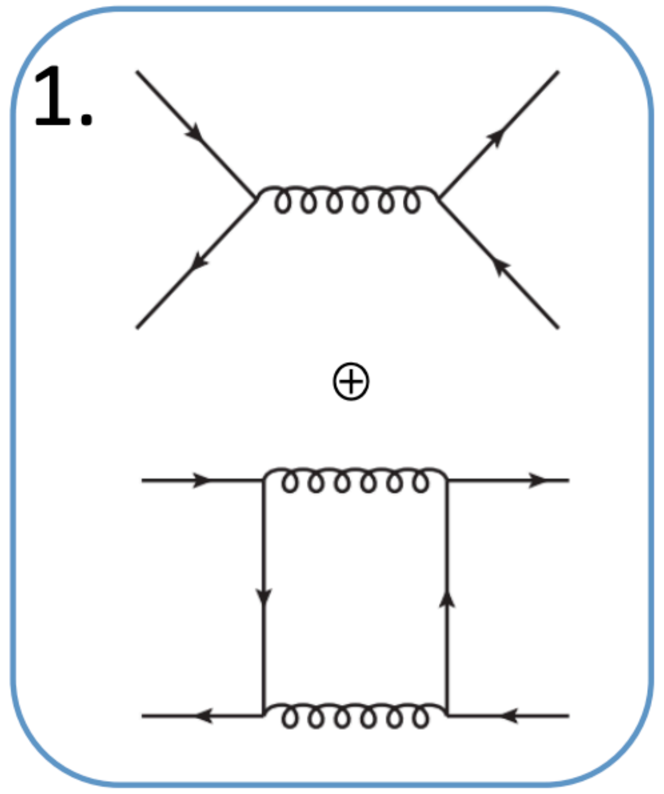
- $t\bar{t}$ cross-section ratios and double ratios ($t\bar{t}$/Z) at different $\sqrt{s}$ are estimated and compared with various PDF predictions
- Results agree within 2 s.d with most predictions
- Only exception being ABM12LHC
  ➢ attributed to lower gluon density at high Bjorken-x for ABM12LHC compared to other PDFs

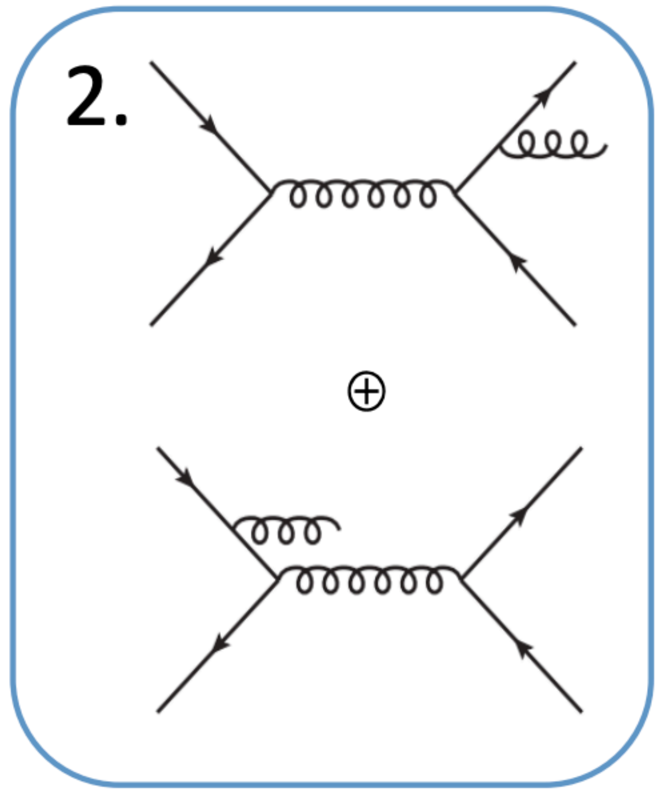
Charge asymmetry at LHC

- Production of top quark pairs charge symmetric at LO

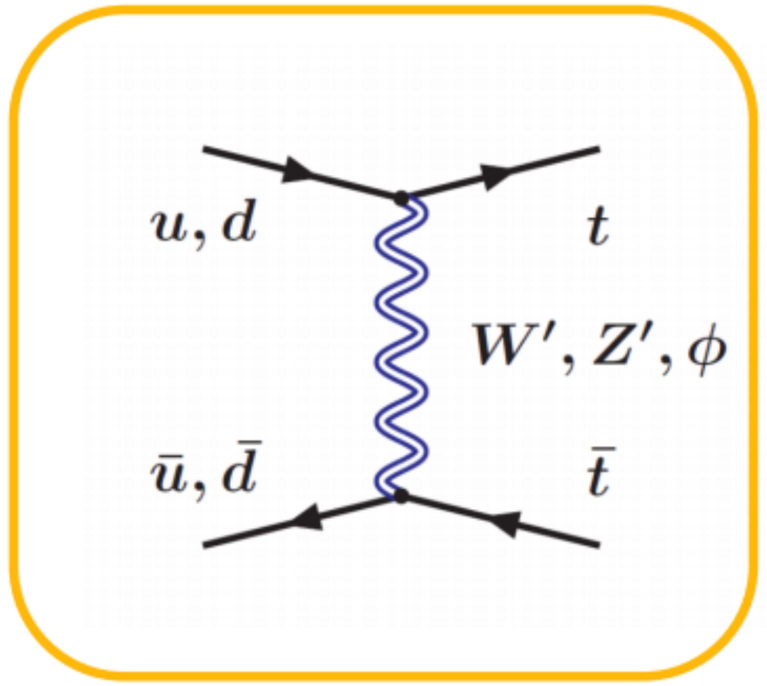
- No charge asymmetry in gg ➛ $t\bar{t}$ at all orders, dilutes measurable asymmetry

- 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





asymmetric QCD

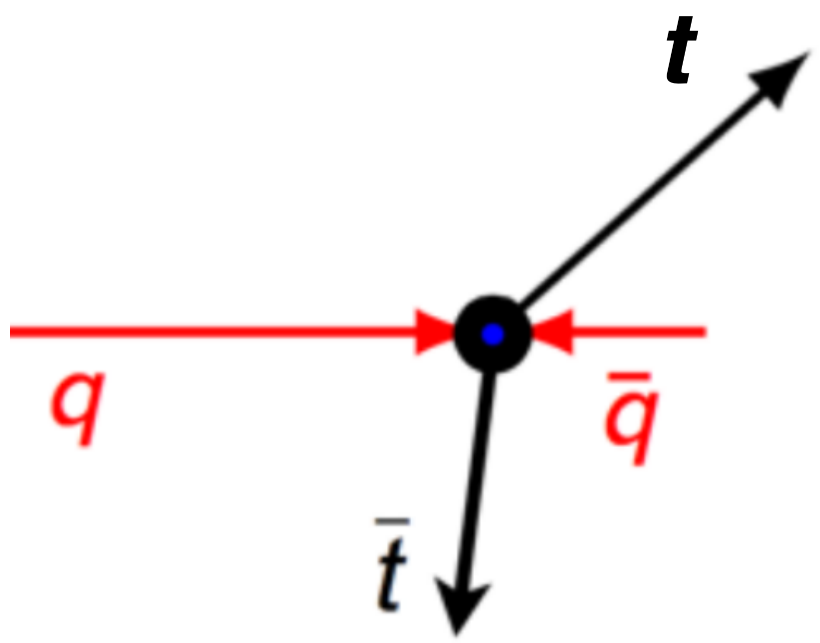


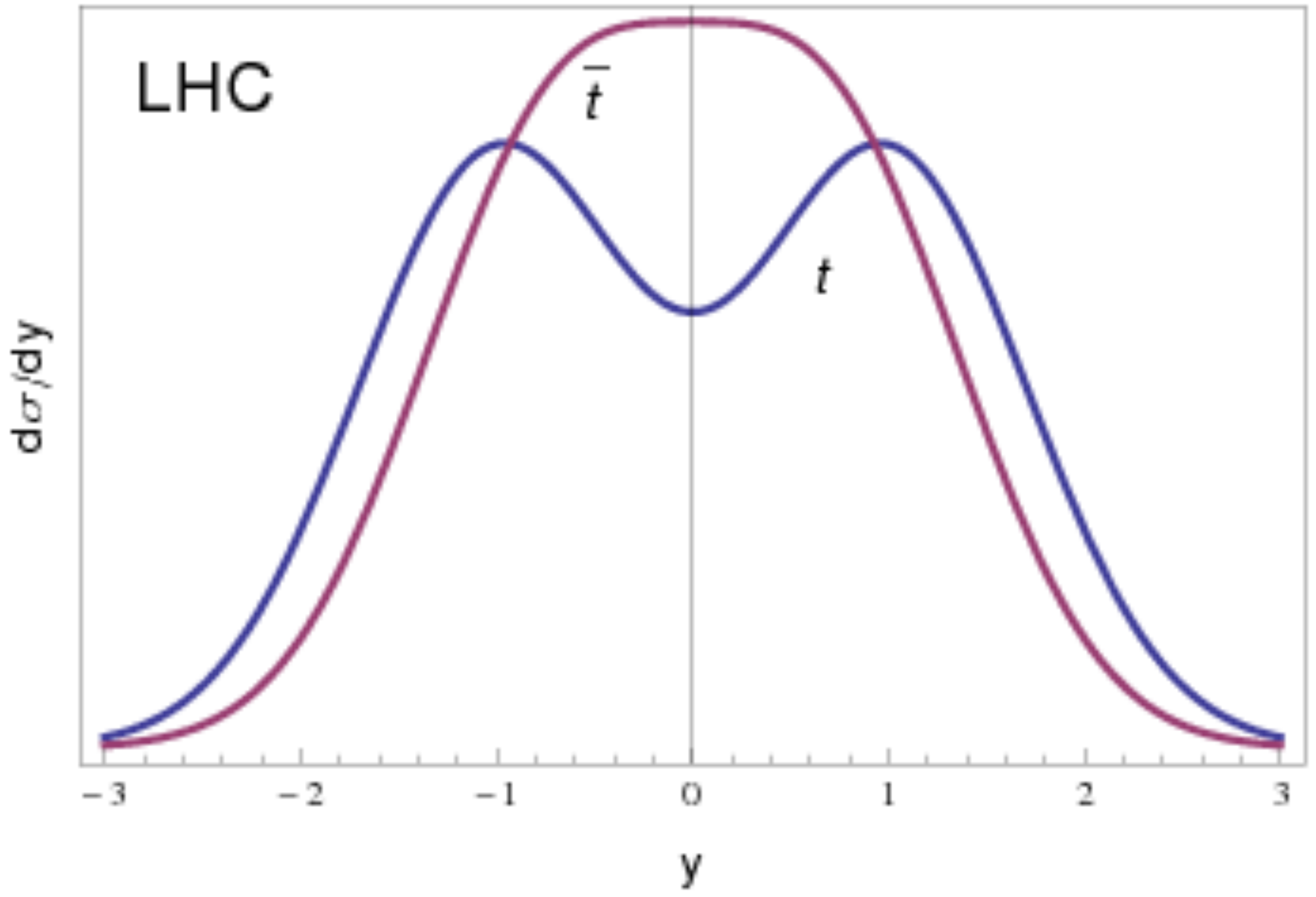
asymmetric BSM

- (anti-)top quarks are emitted preferentially in the direction of the incoming (anti-)parton

- No preferential direction for the incoming (anti-)partons at LHC

- High momenta valence quarks collide with sea anti-quarks carrying lower momenta ➛ More forward top quarks and more central anti-top quarks





arXiv:1207.0331

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

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

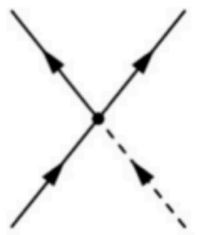
Evidence of charge asymmetry

ATLAS-CONF-2019-026

- Measurement using full Run 2 data (139 fb^{-1})
- Measurement in the l+jets (e and μ) channels with resolved & boosted topologies
- Results unfolded to parton level
- A_C measured inclusively and differentially (in bins of $m_{t\bar{t}}$ & $\beta_{z,t\bar{t}}$)
- Evidence of charge asymmetry at the level of 4 s.d ➛ 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 flavor universality

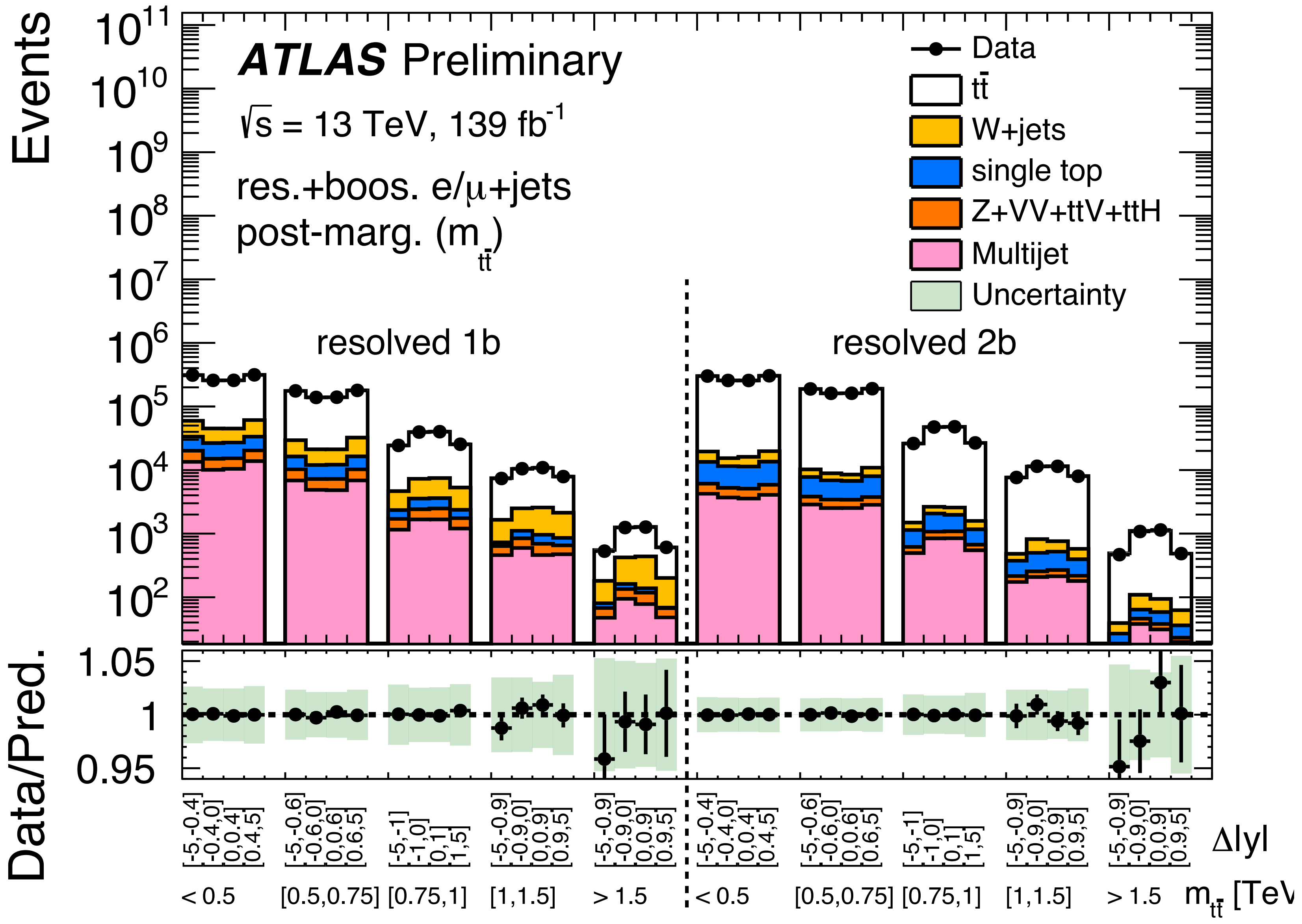
$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

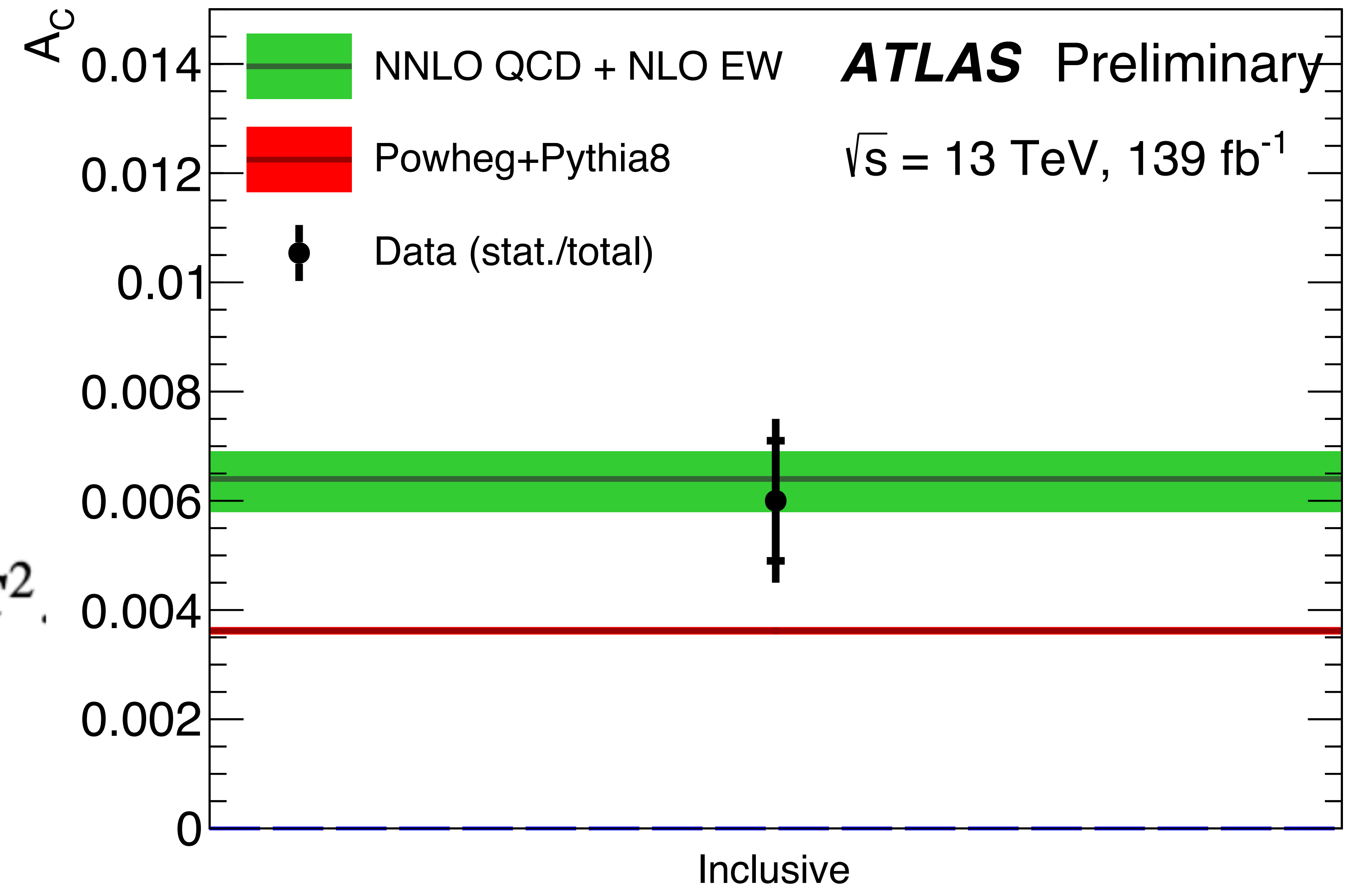
Assumptions:

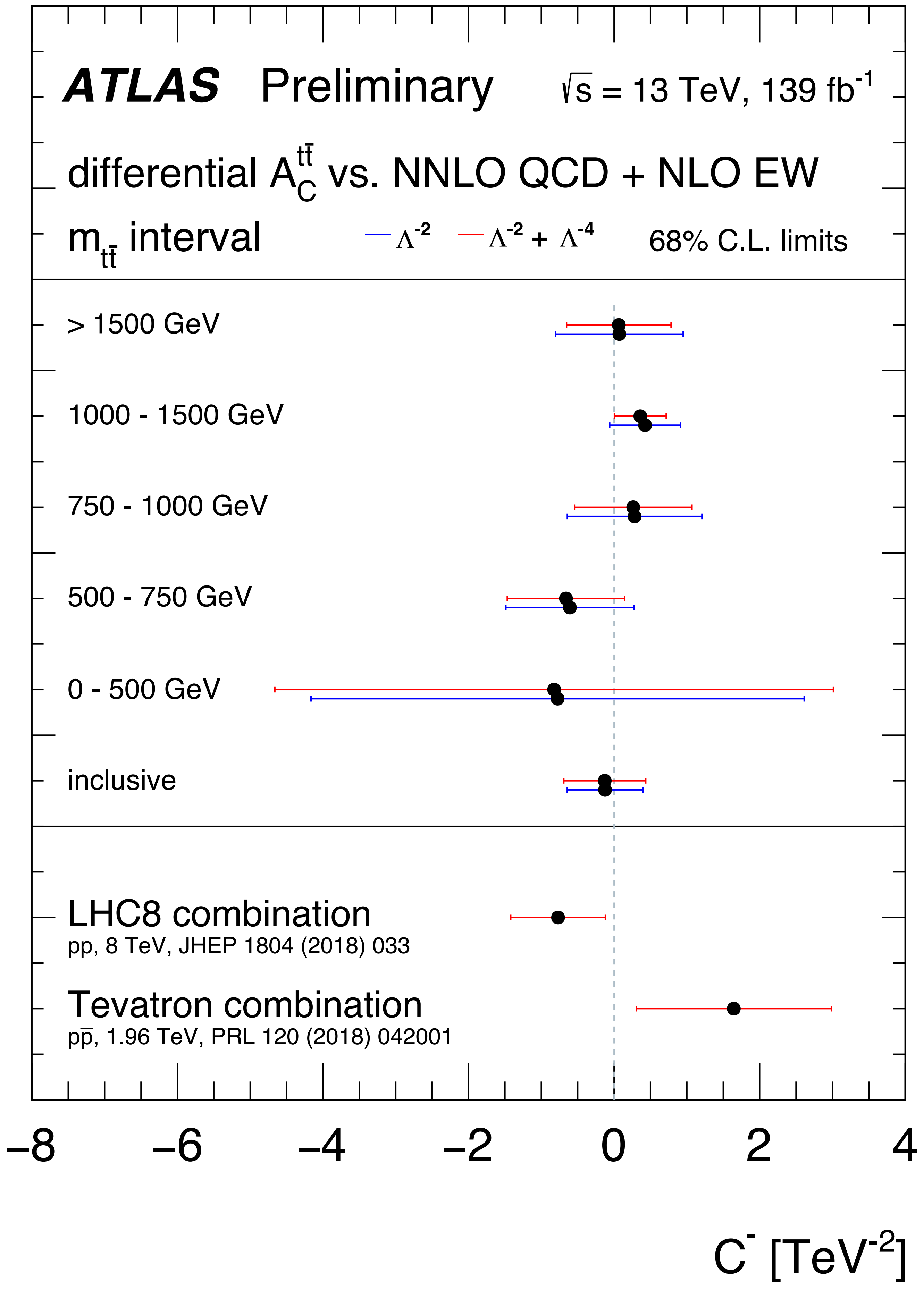


$$C_u^1 = C_d^1 = C^1 \qquad C^- = C^1 - C^2$$
$$C_u^2 = C_d^2 = C^2$$

- Tighter bound on C^- than the combination of previous measurements





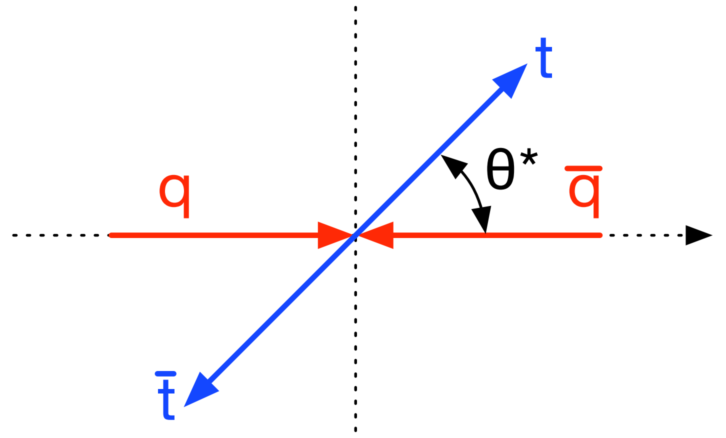


$$A_C = 0.0060 \pm 0.0015\,(\text{stat} + \text{syst})$$

Forward - Backward asymmetry

arXiv:1912.09540

- 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. chromomagnetic (μ) and chromoelectric (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



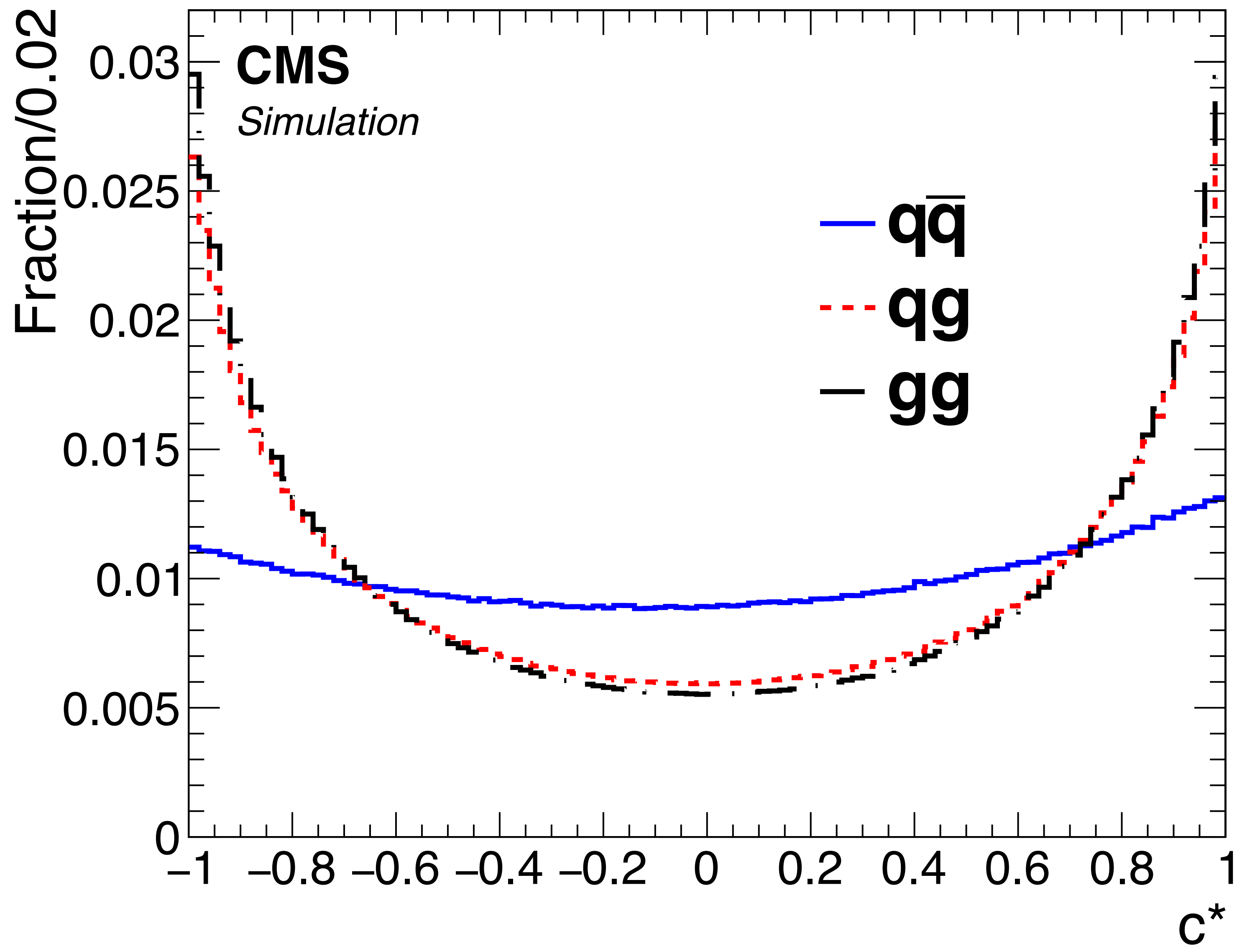
$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}, c^* = \cos\theta^*$$

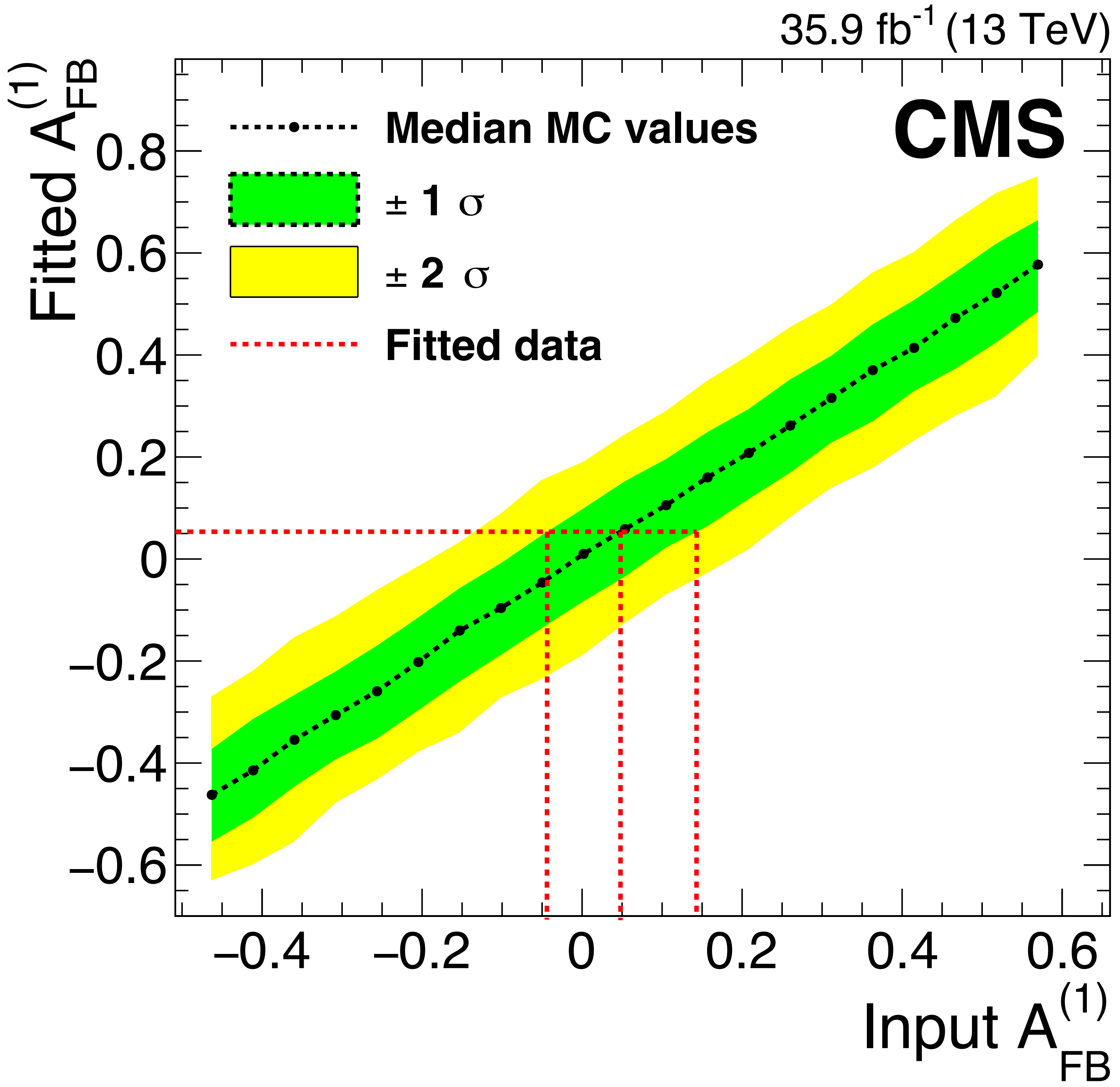
$$x_F = \frac{2p_L}{\sqrt{s}}$$

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

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

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





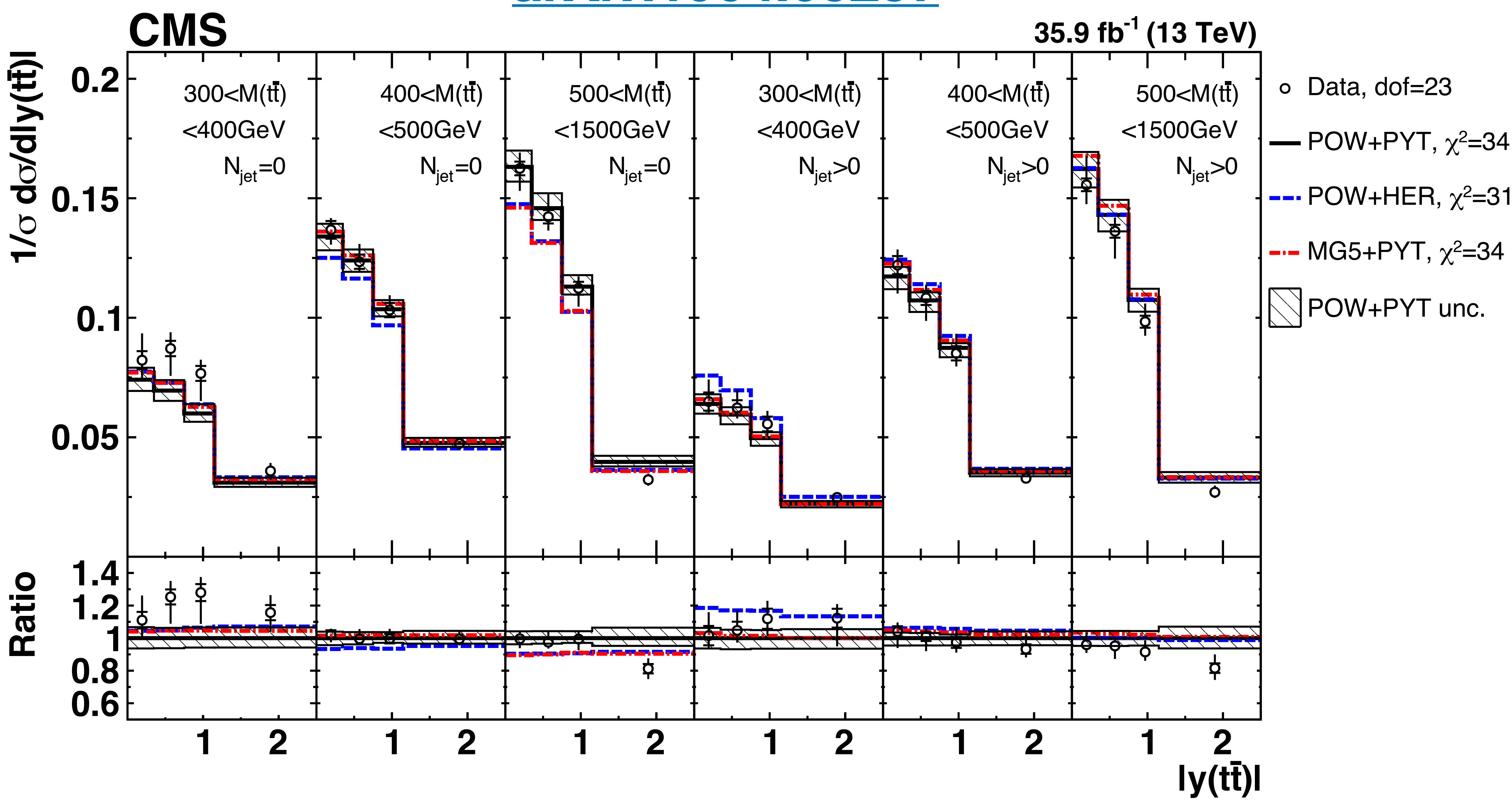
α_S & m_t^{pole} from differential cross-section

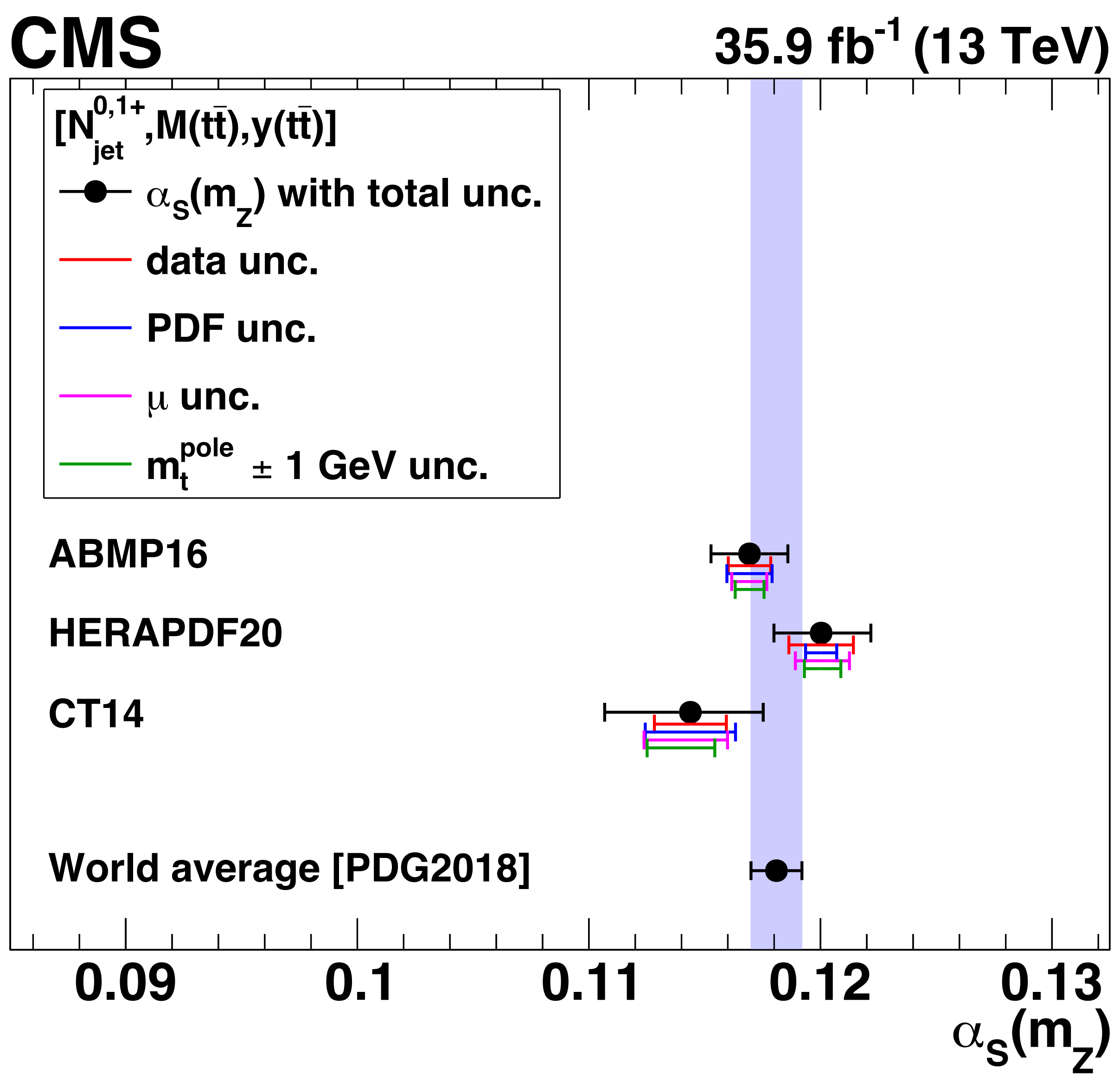
arXiv:1904.05237

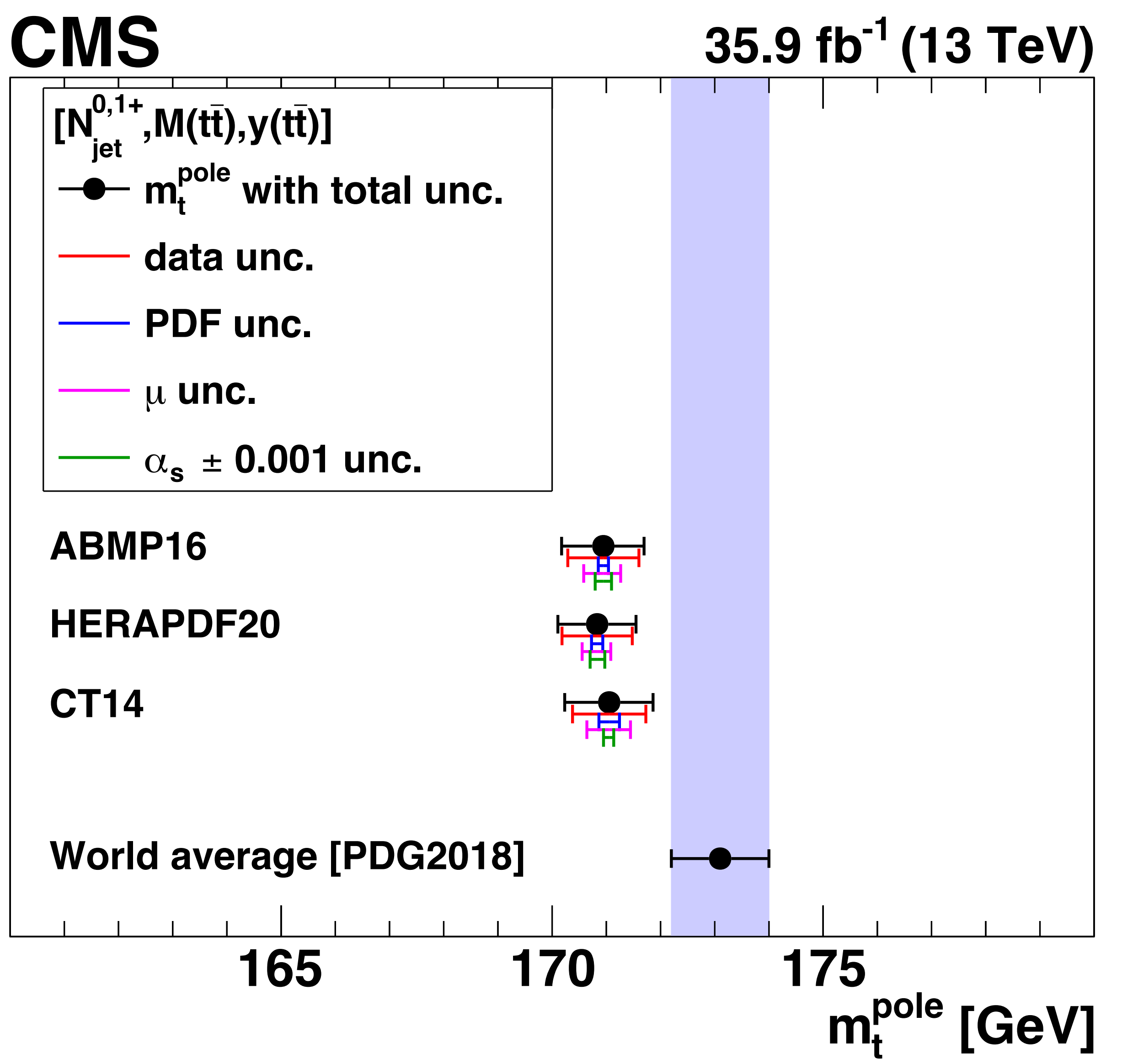
- Triple differential cross-section measured in bins of $M(t\bar{t})$, $|y(t\bar{t})|$ and N_{jet} with 35.9 fb^{-1} data
- Event selection:
  - ➛ OS dilepton (ee+μμ+eμ)
  - ➛ ≥ 2 jets (≥ 1 b-tagged)
  - ➛ N_{jet} additional jets not from $t\bar{t}$ decay (ΔR > 0.4 from leptons and b-quarks)
  - ➛ Loose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

$$\alpha_S(m_Z) = 0.1135 \pm 0.0016\,(\text{fit})^{+0.0002}_{-0.0004}\,(\text{model})^{+0.0008}_{-0.0001}\,(\text{param})^{+0.0011}_{-0.0005}\,(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}$$

$$m_t^{pole} = 170.5 \pm 0.7\,(\text{fit}) \pm 0.1\,(\text{model})\,^{+0.0}_{-0.1}\,(\text{param}) \pm 0.3\,(\text{scale})\,\text{GeV} = 170.5 \pm 0.8\,\text{GeV}\,(0.47\%)$$







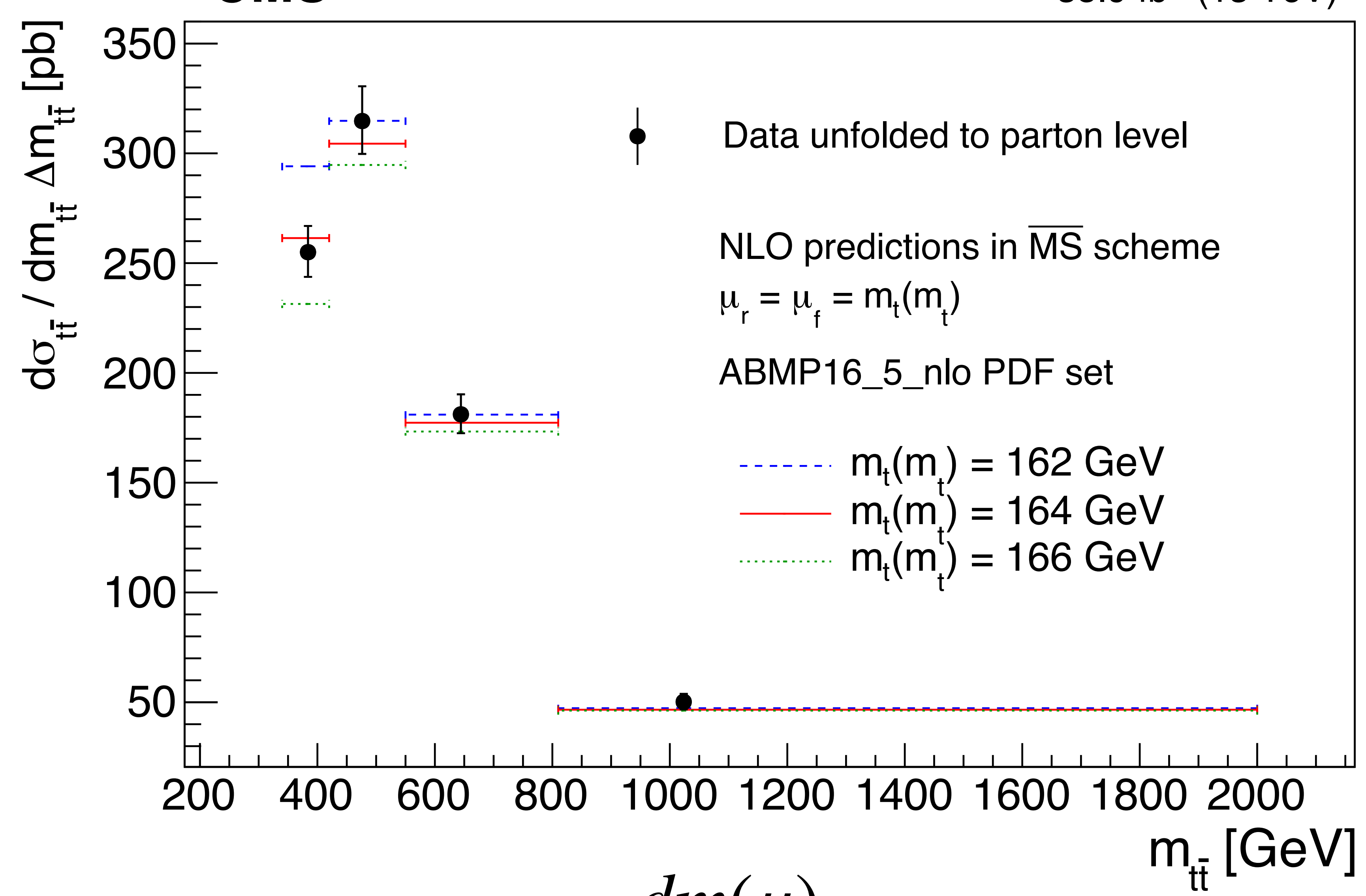
Running of m_t

- First measurement of the top mass running with 35.9 fb^{-1} data
- Require 1 OS eμ 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_{lb}^{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

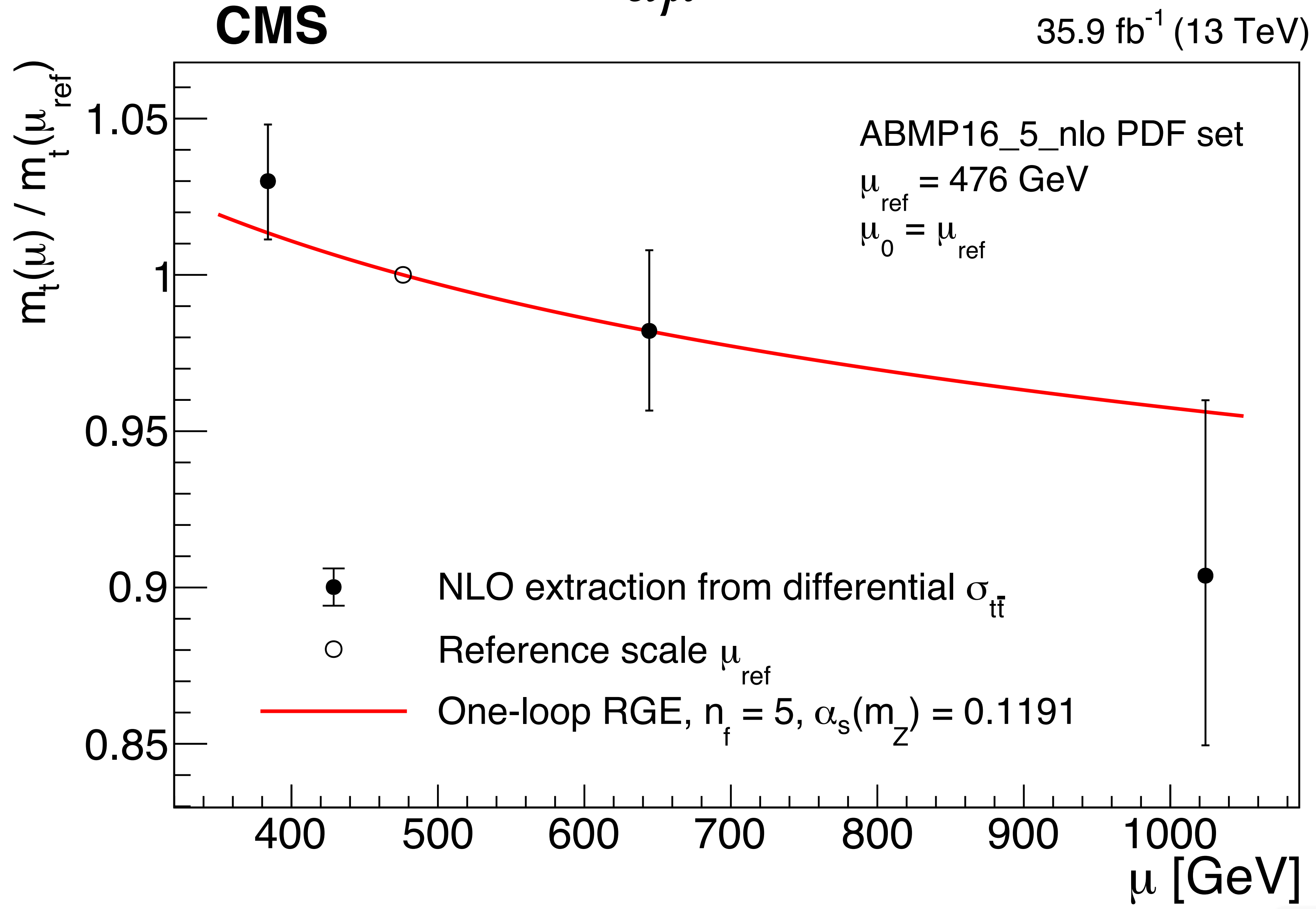
$$\frac{m_t(\mu_1)}{m_t(\mu_2)}, \frac{m_t(\mu_3)}{m_t(\mu_2)}, \frac{m_t(\mu_4)}{m_t(\mu_2)}$$

- Observed evolution agrees with RGE prediction at 1-loop precision within 1.1 s.d

arXiv:1909.09193



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



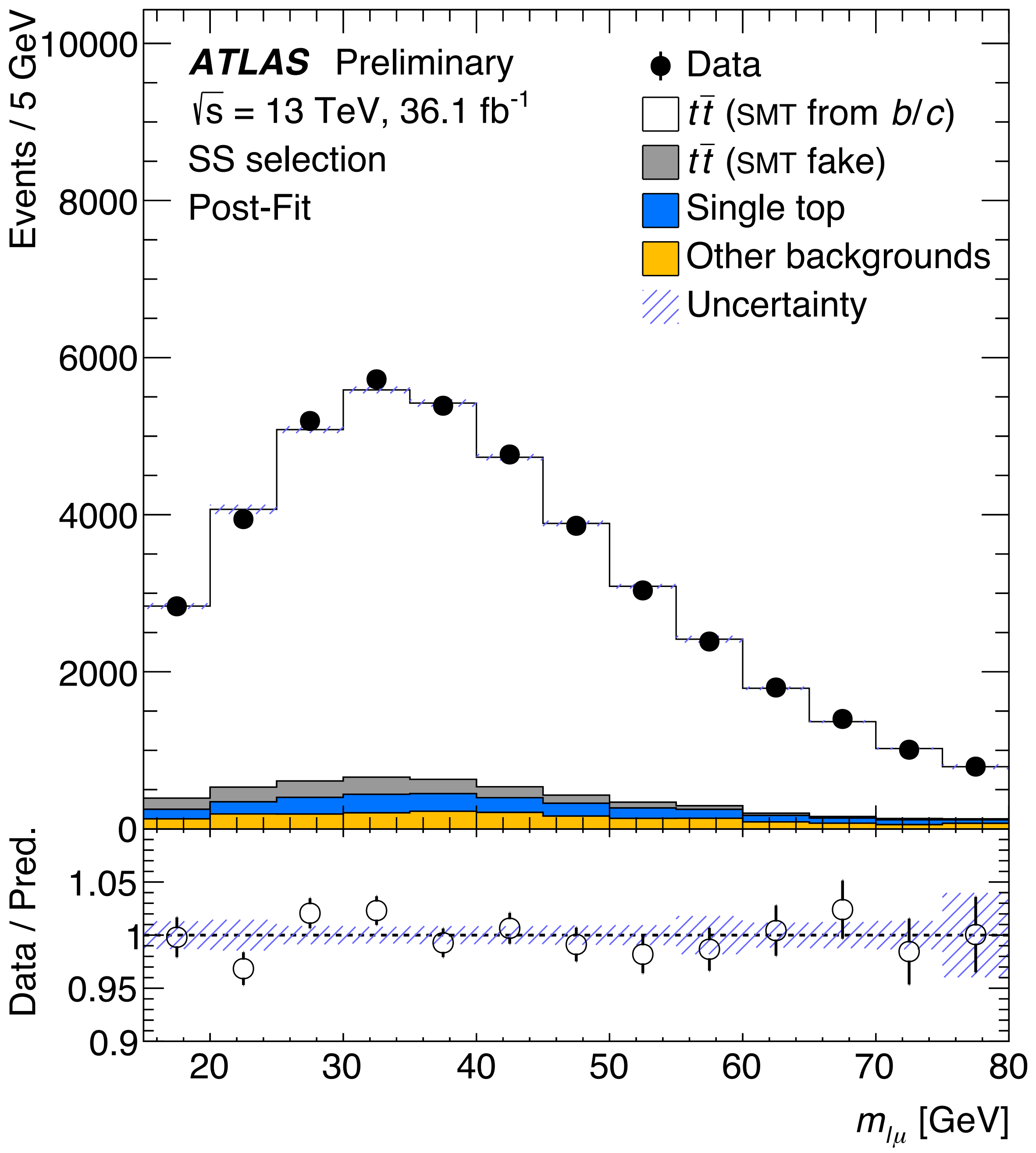
m_t in lepton+jets with soft-μ

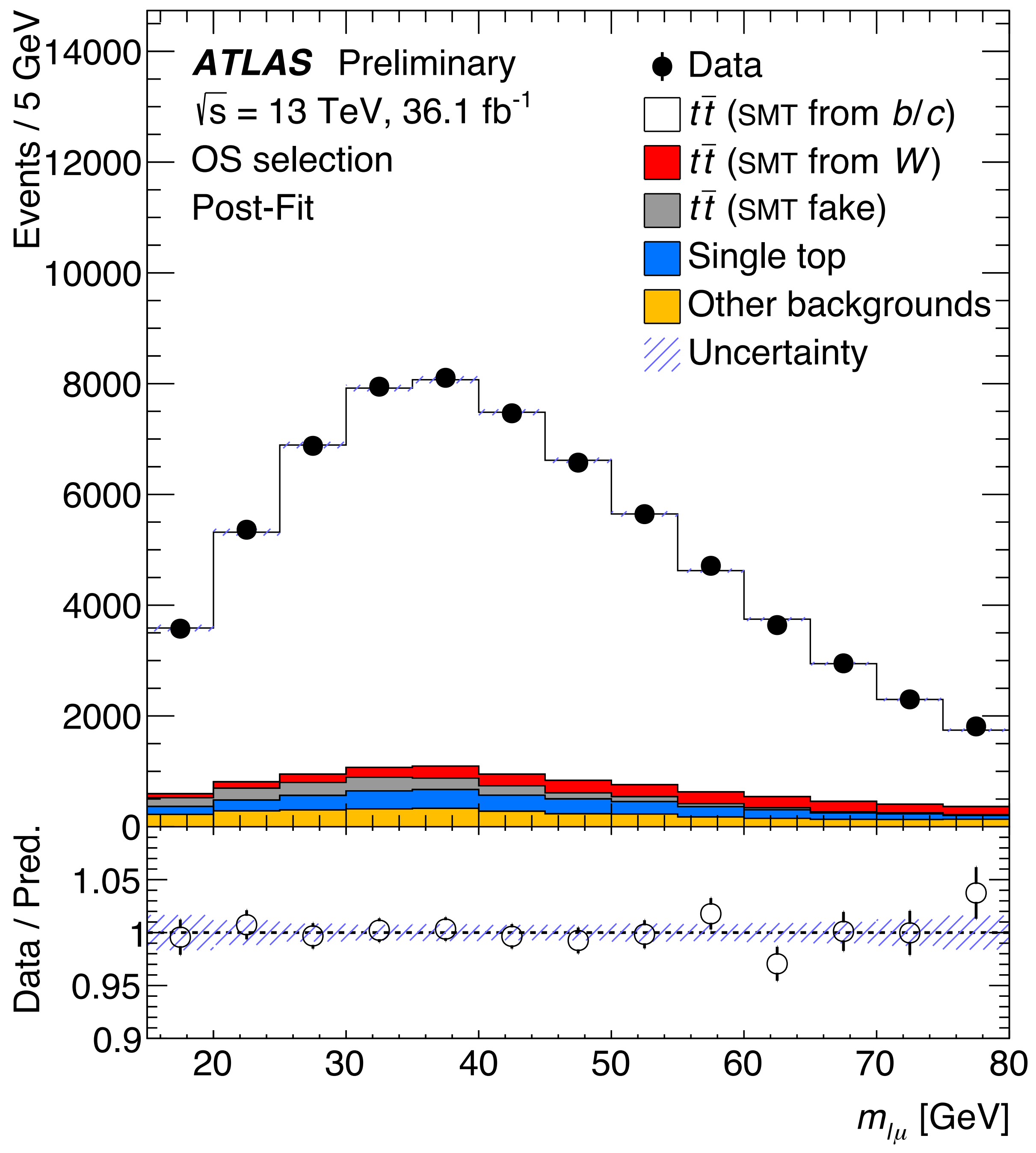
ATLAS-CONF-2019-046

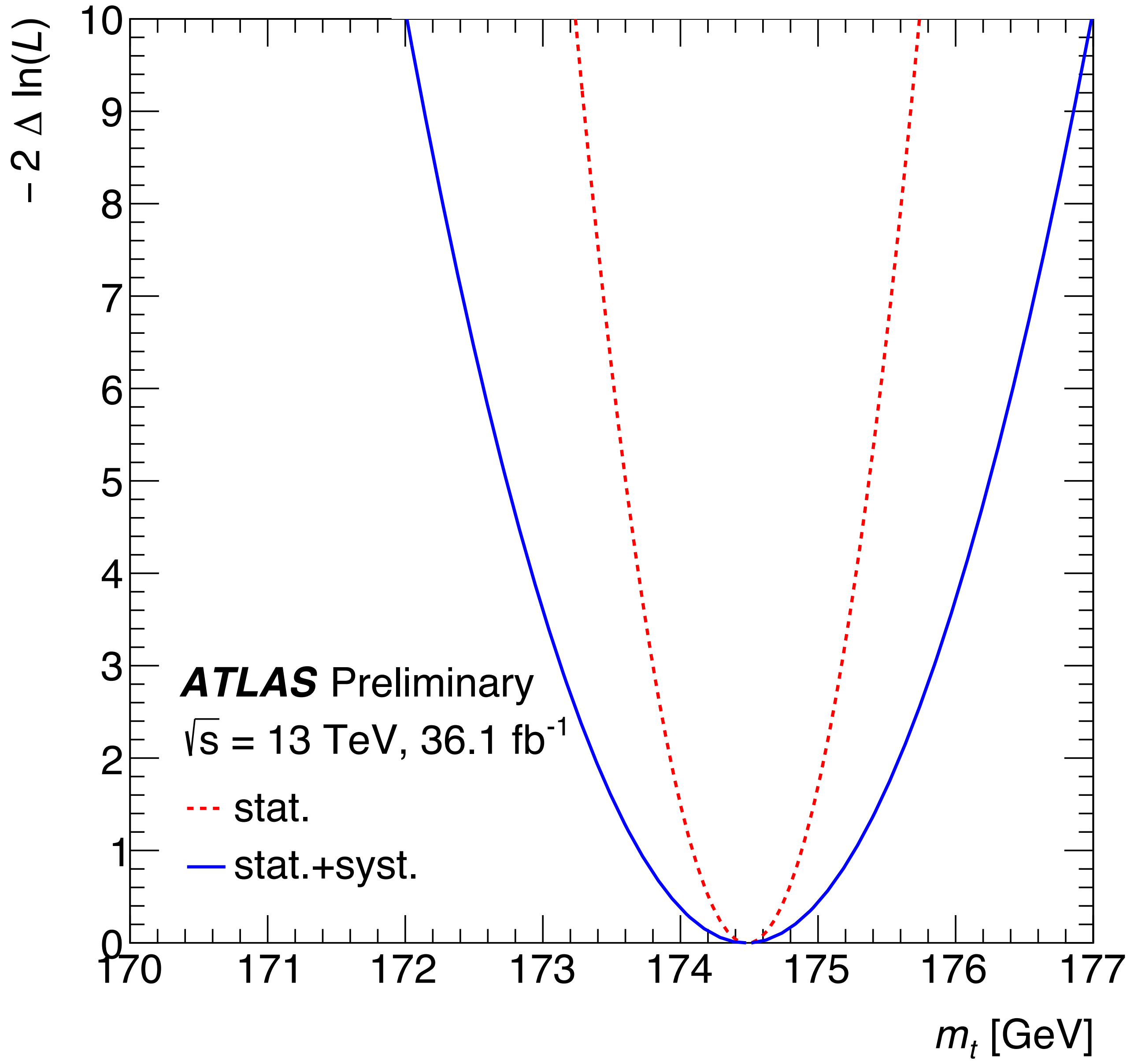
- Analysis with 36.1 fb^{-1} data
- Selection:
  ➢ 1 e/μ + ≥ 4 jets
  ➢ ≥ 2 b-tagged jets, one with displaced vertex tag, one with soft Muon tag (μ_S)
  ➢ $\Delta R(\ell, \mu_S) < 2$ (good for boosted jets)
- SS and OS have different contributions but both depend on m_t
- $m(\ell\mu_S)$ distribution 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%)



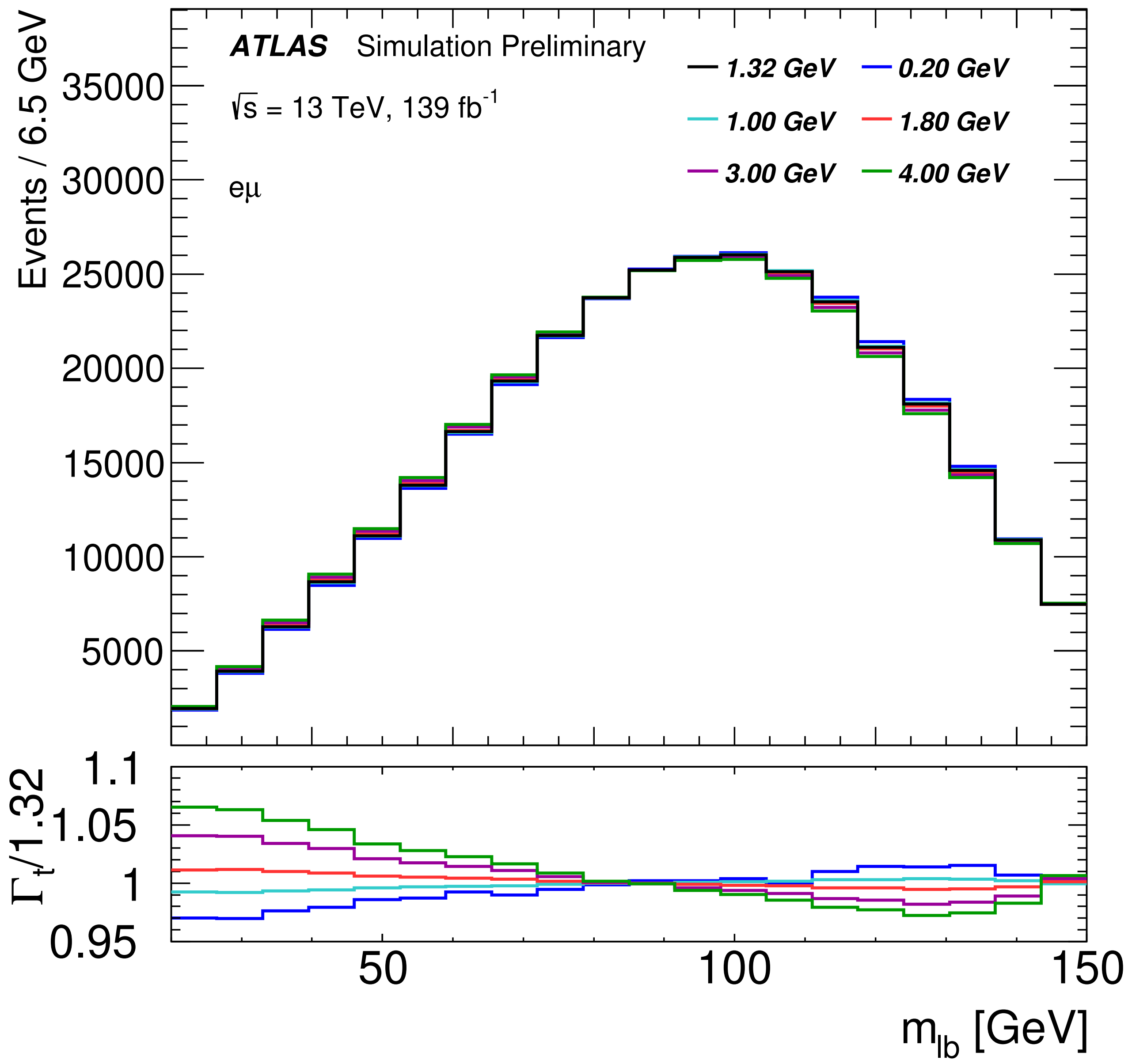


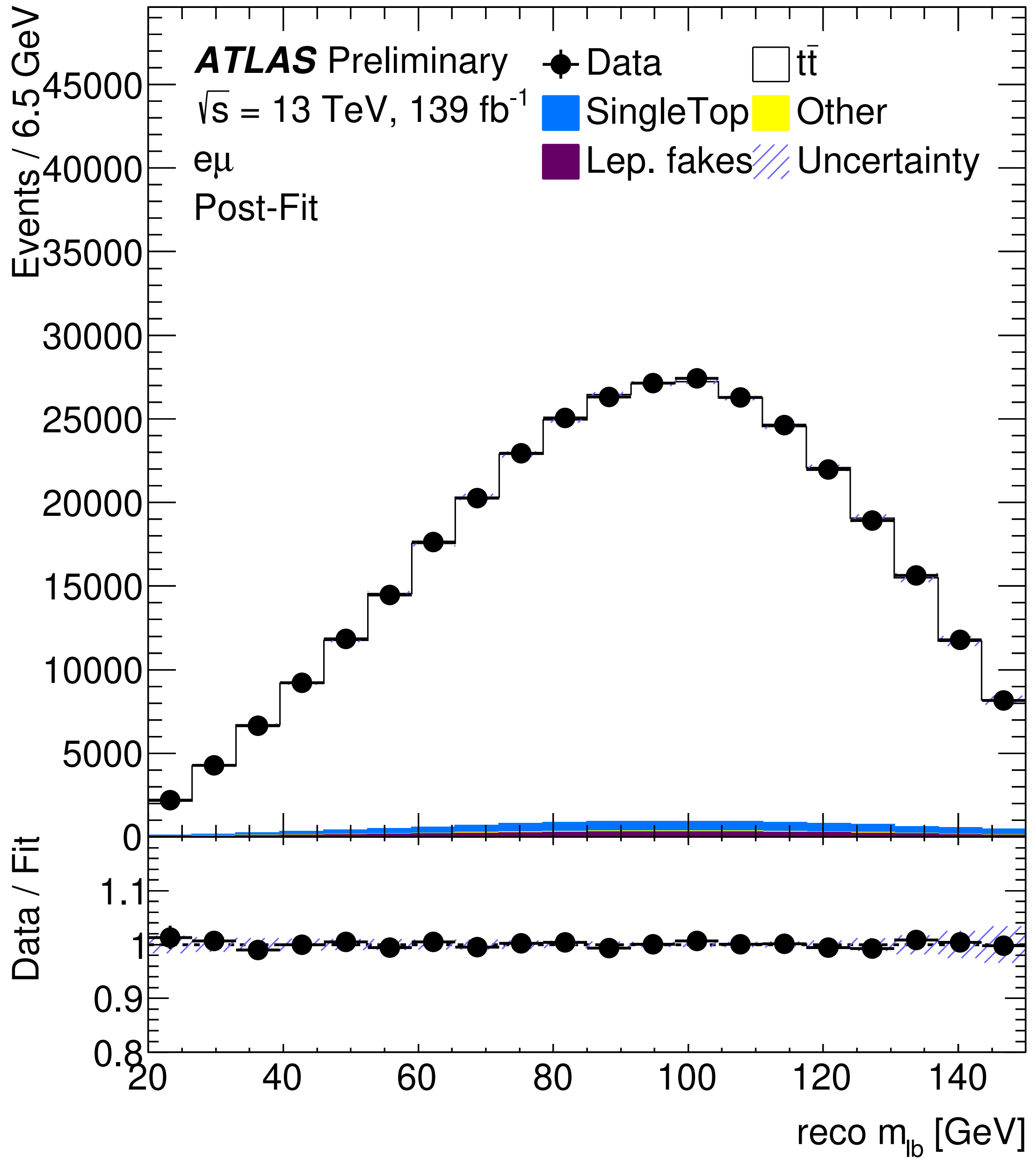


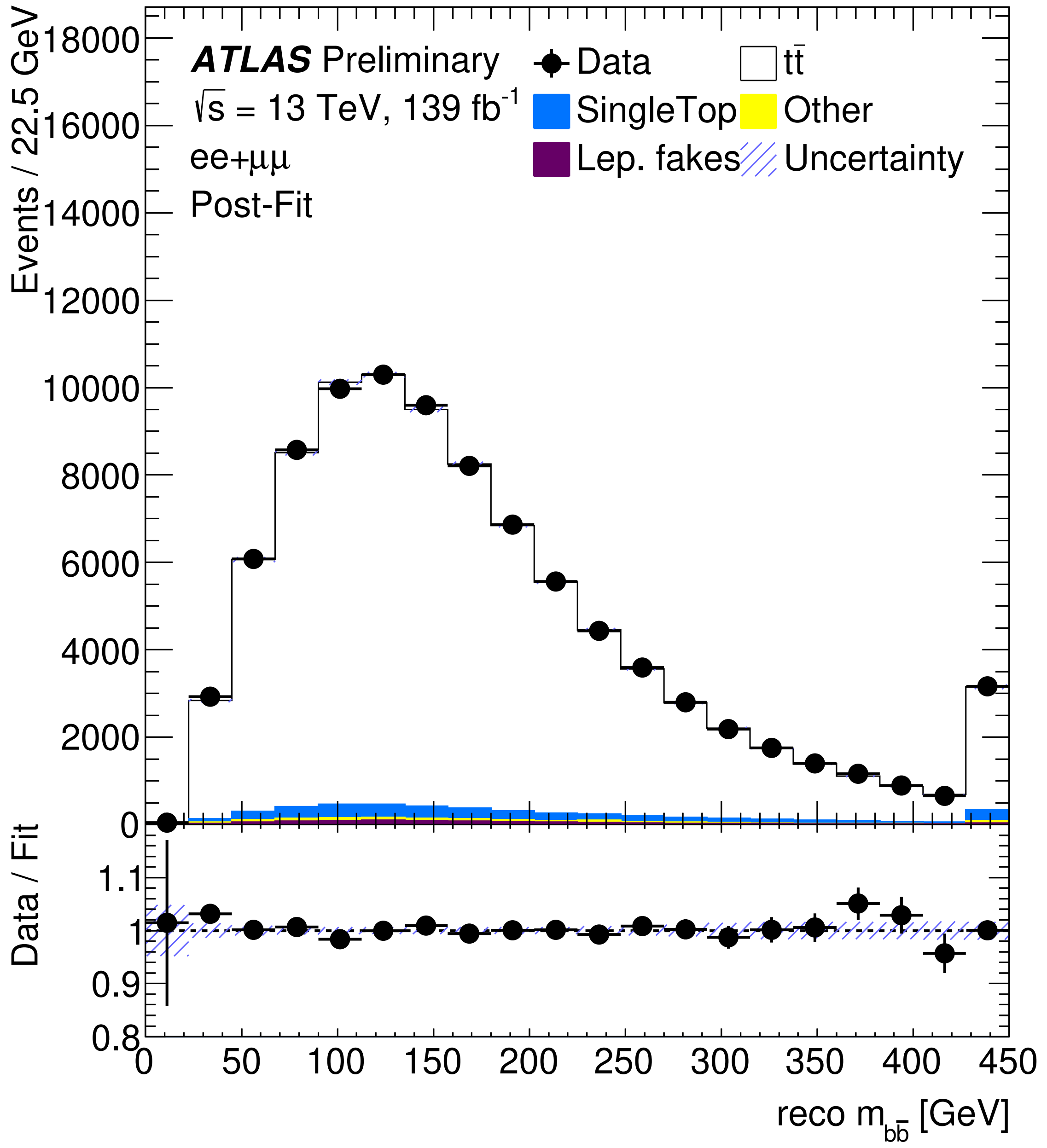
Top Width

ATLAS-CONF-2019-038

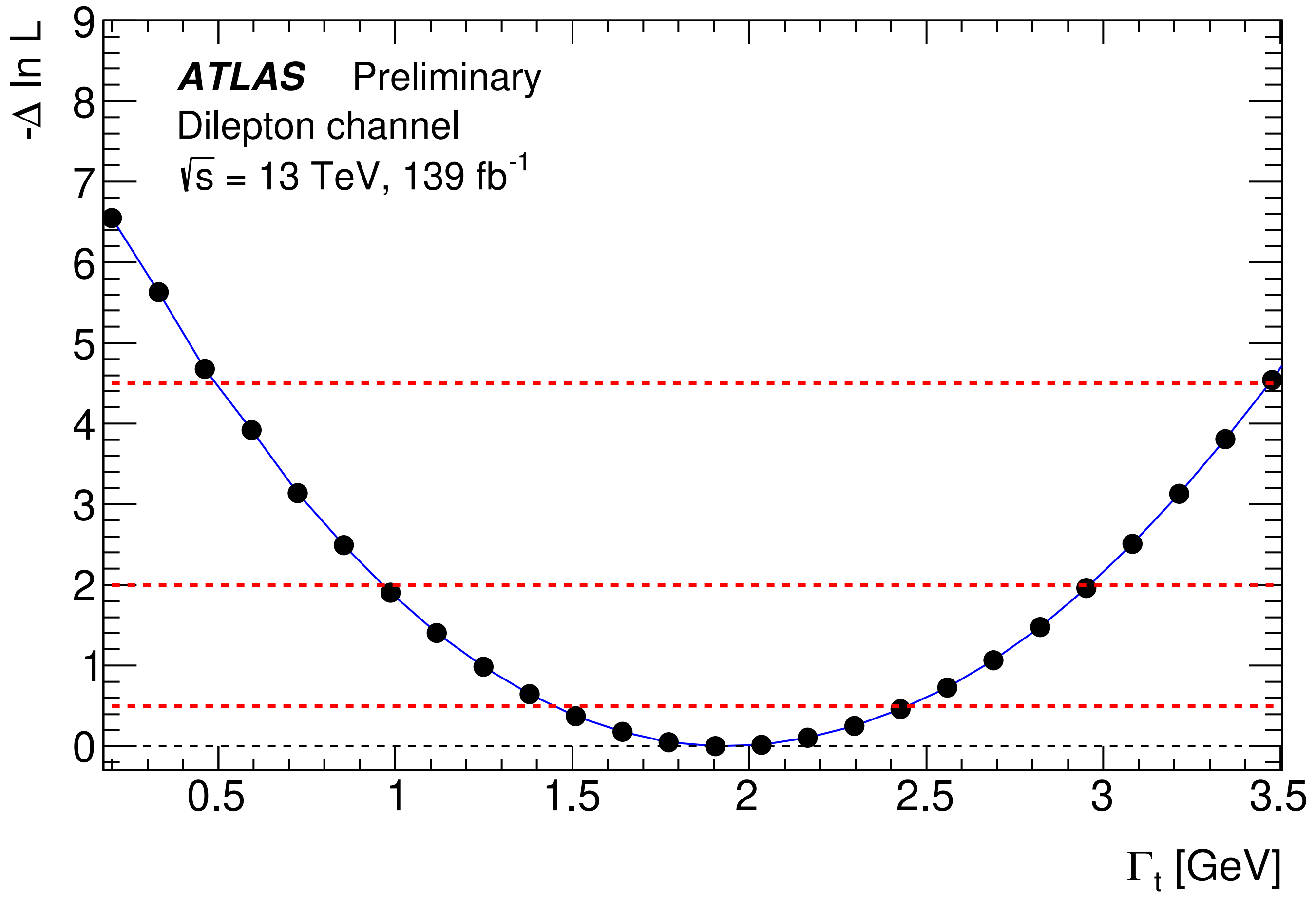
- Direct measurement of top quark decay width in dilepton channel with full Run 2 data (139 fb^{-1})
- MC templates obtained by reweighing nominal $t\bar{t}$ sample (Γ_t = 1.32 GeV)
- Profile likelihood fit to
  - ➢ m_{lb} template in *eμ* channel (high stat.)
  - ➢ $m_{b\bar{b}}$ template in *ee+μμ* 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%

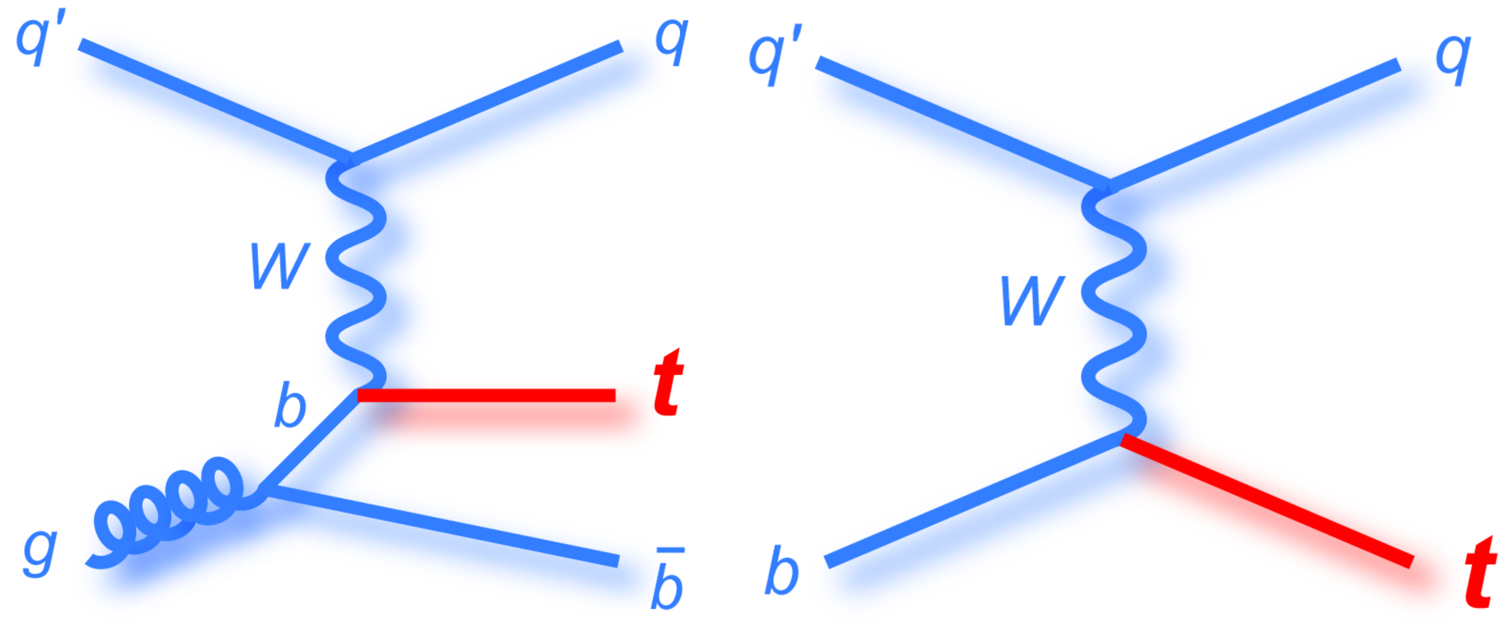


Single top measurements

Inclusive single top-quark cross-section measurements

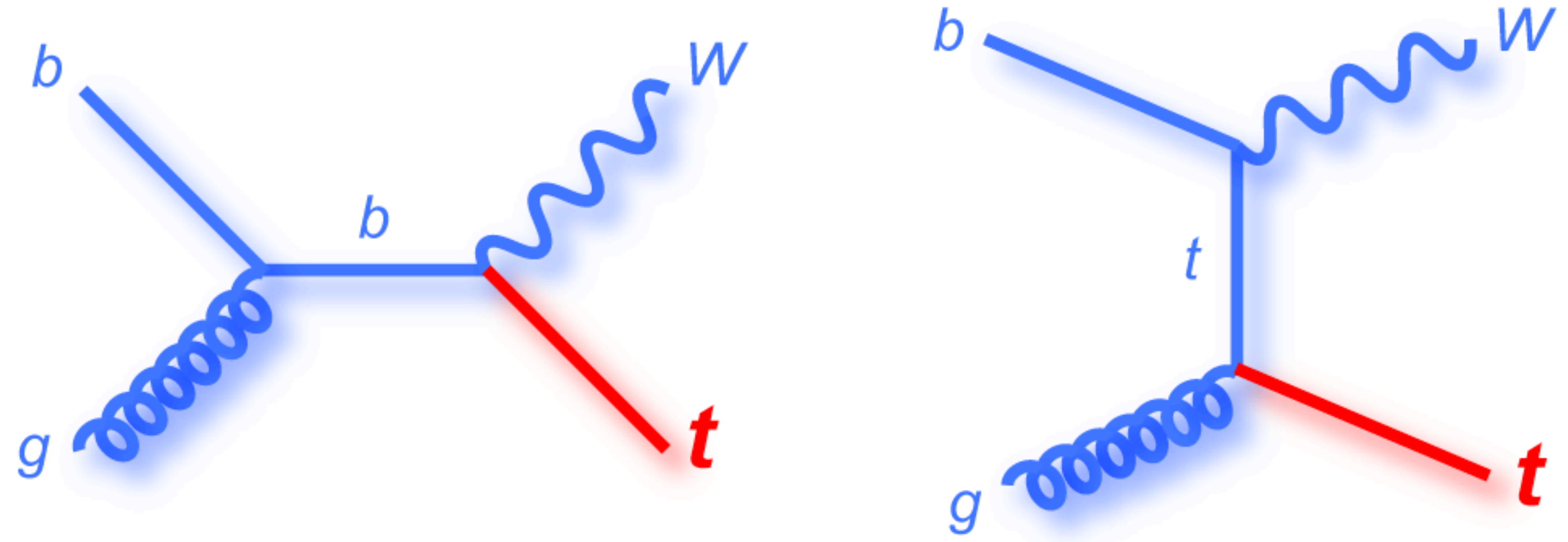
t-channel (~ 73% at LHC)

Golden Channel, sensitive to FCNC



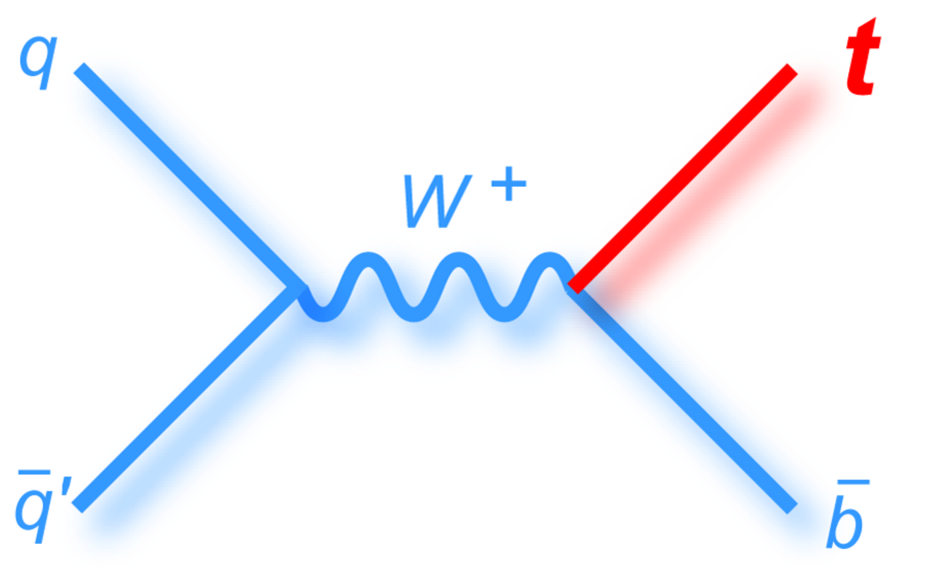
tW (~ 24% at LHC)

Observed at LHC, sensitive to BSM couplings



s-channel (~ 3% at LHC)

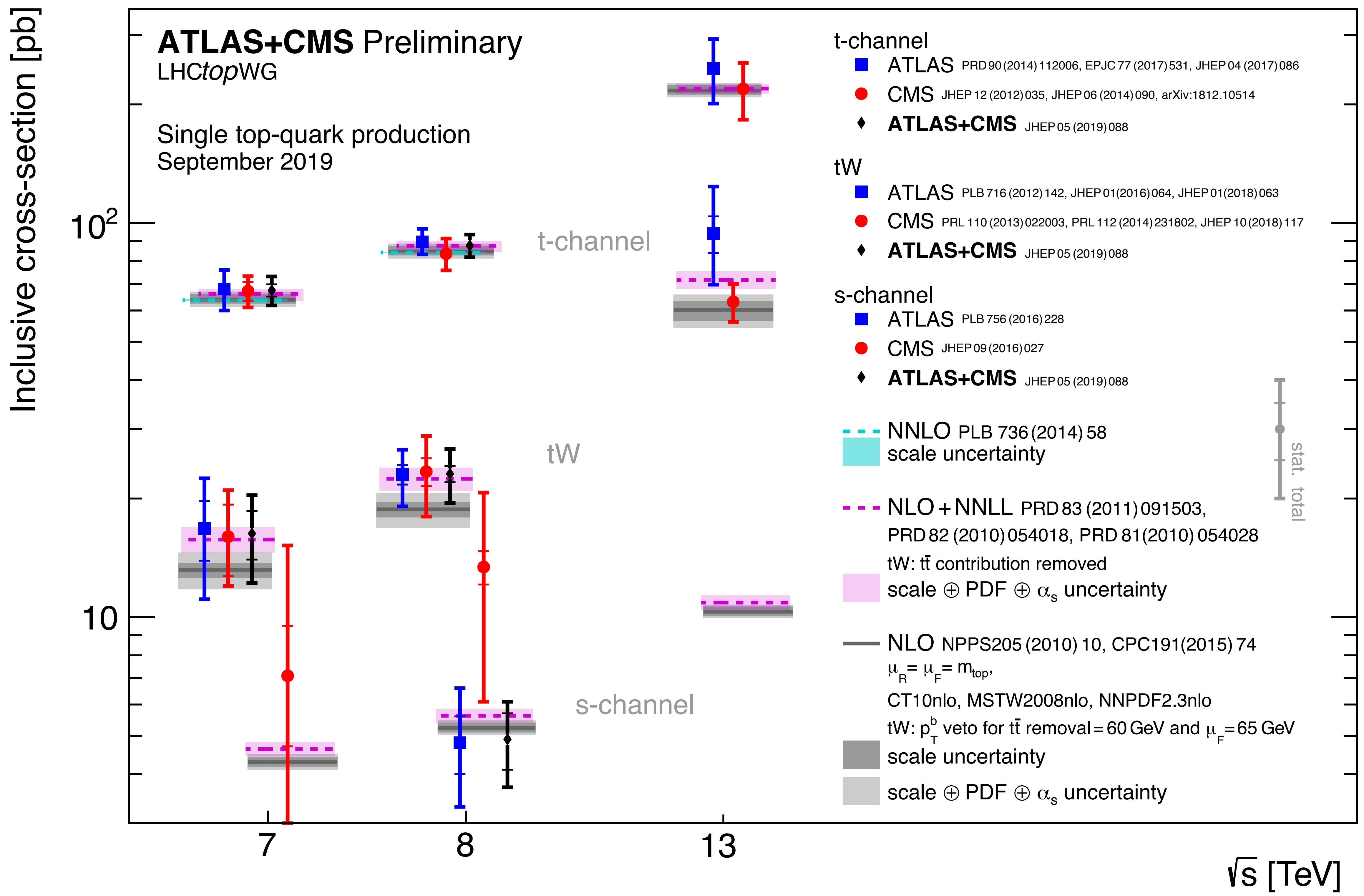
Challenging at LHC



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

√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%)

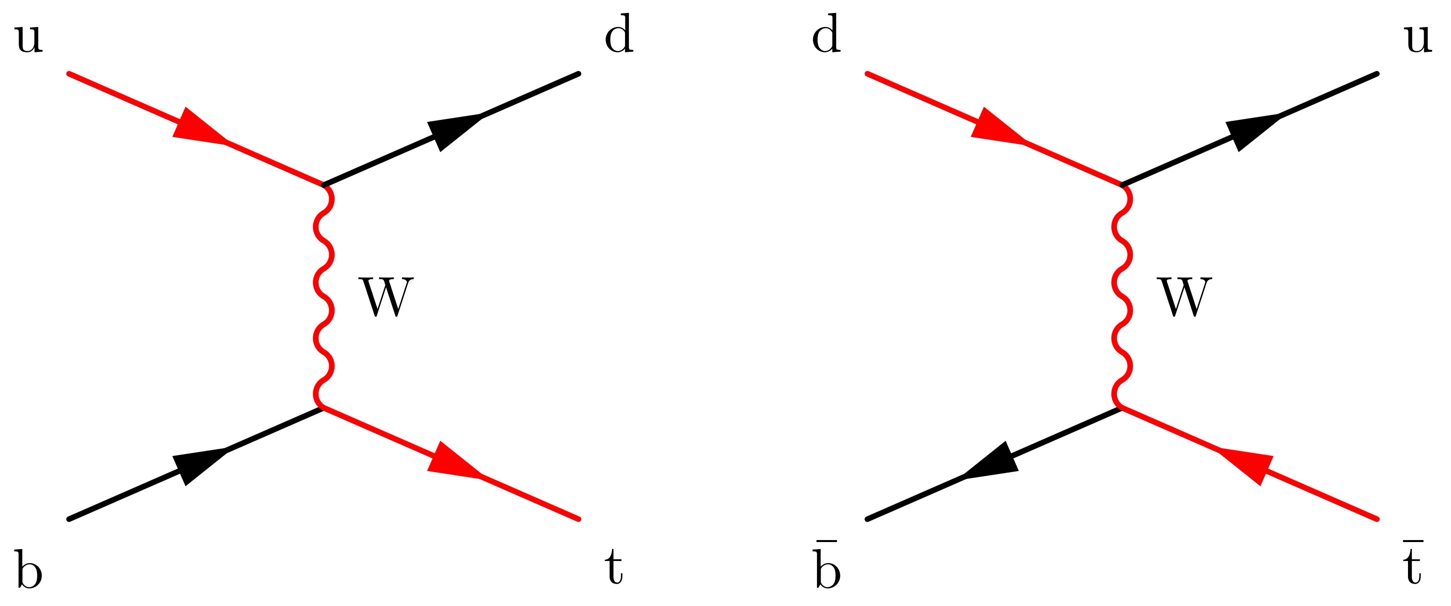
Theory uncertainties due to μ_R and μ_F scale, PDF and the strong coupling



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

t-channel inclusive and differential measurement @13 TeV

- Different production rate of t and $\bar{t}$ due to proton PDF
- Direct sensitivity to $|V_{tb}|$
- Event selection: 1 e or μ and multiple jets
- Events categories depending on jet and b-tag multiplicity
- Likelihood fit to BDT discriminator in all regions simultaneously to extract $\sigma_{t\text{-ch}}$ and $R_{t\text{-ch}}$ from data
- Dominant unc. sources: PS scale, PDF, μ_R and μ_F scale
- Unfolded data matched to signal predictions at parton or particle level ➛ better agreement with aMC@NLO 4FS



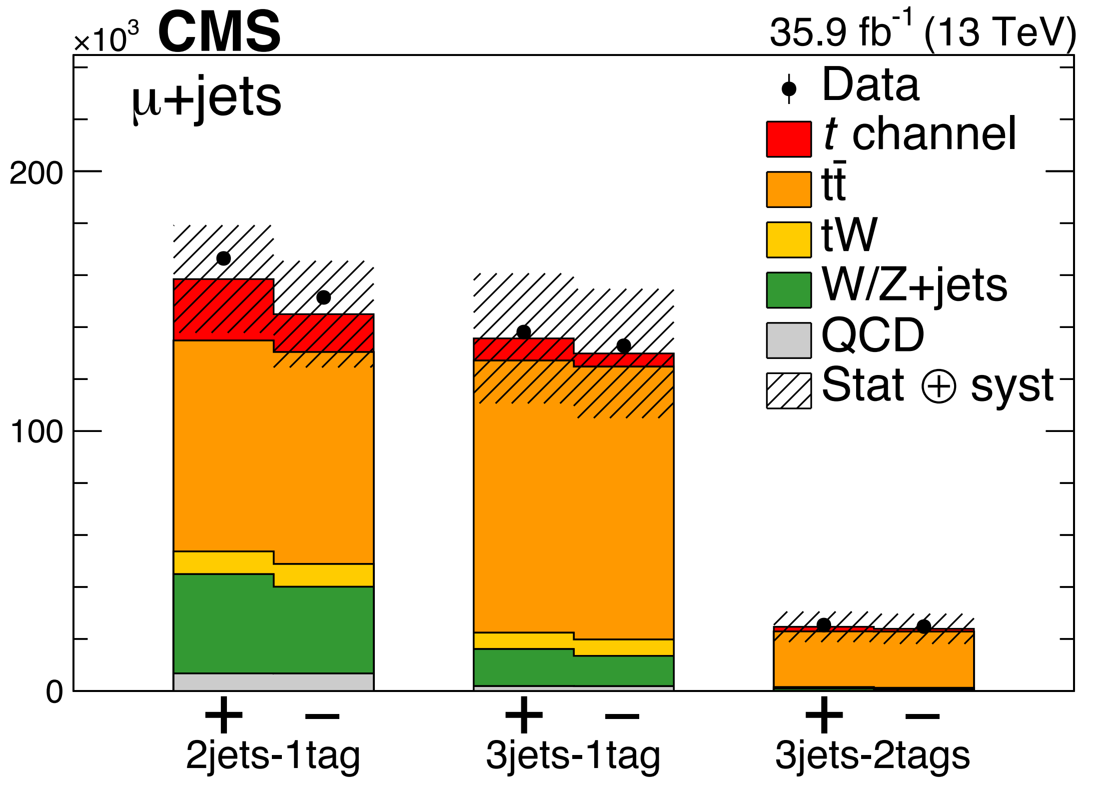
$$\sigma_{t\mathrm{-ch,t}} = 130 \pm 1\,(\mathrm{stat}) \pm 19\,(\mathrm{syst})\,\mathrm{pb} = 130 \pm 19\,\mathrm{pb}$$

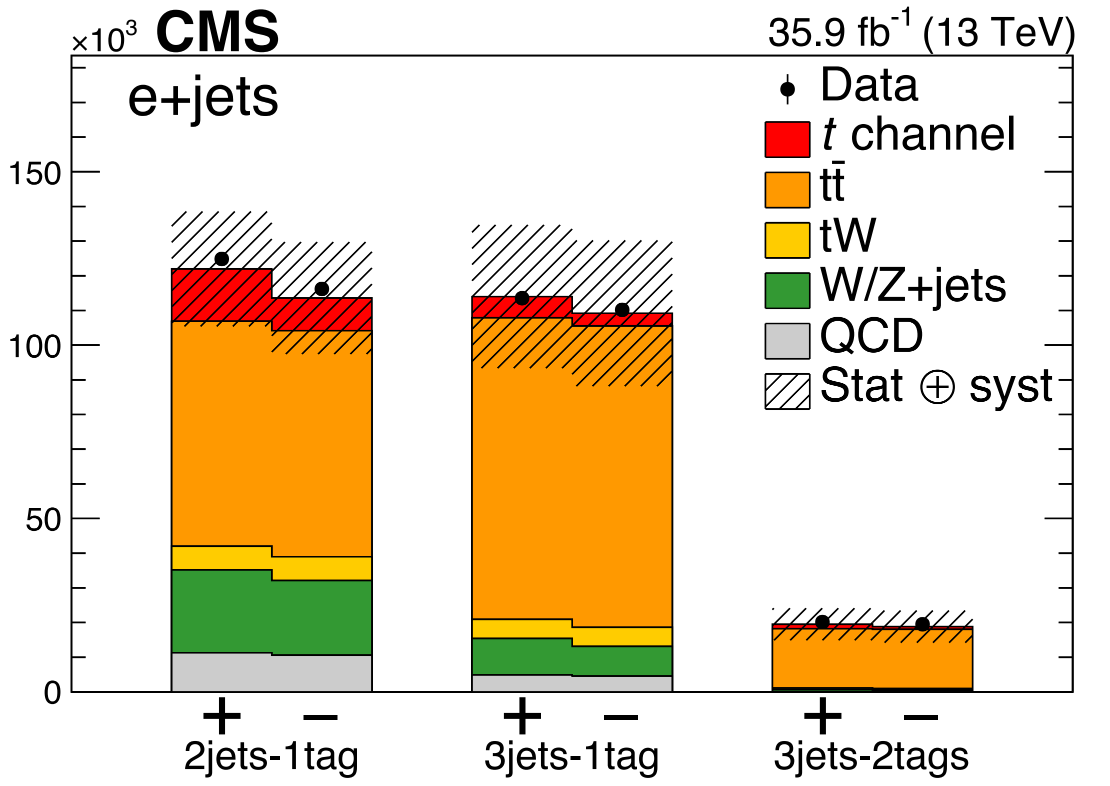
$$\sigma_{t\mathrm{-ch,\bar{t}}} = 77 \pm 1\,(\mathrm{stat}) \pm 12\,(\mathrm{syst})\,\mathrm{pb} = 77 \pm 12\,\mathrm{pb}$$

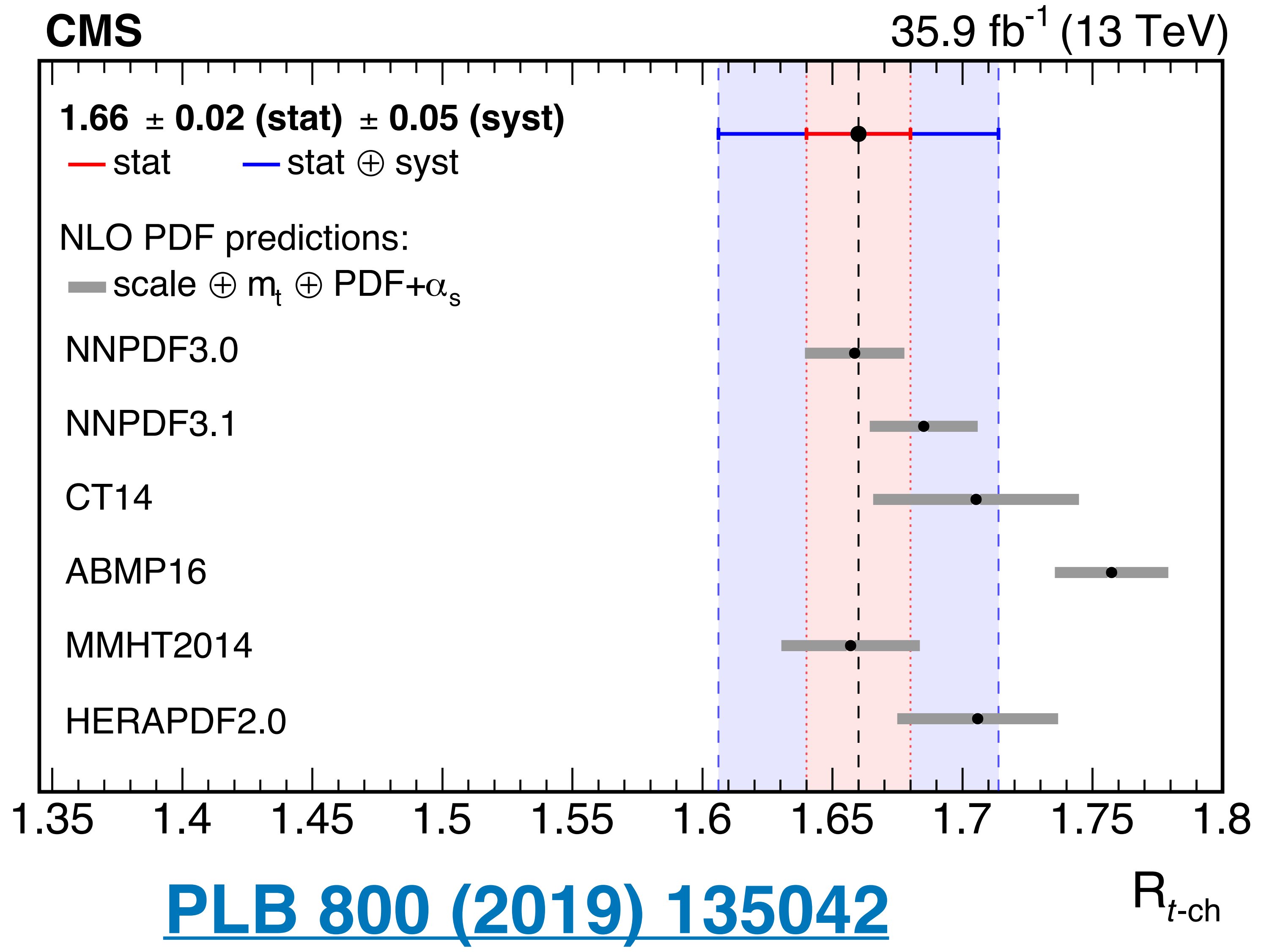
$$\sigma_{t\mathrm{-ch,t+\bar{t}}} = 207 \pm 2\,(\mathrm{stat}) \pm 31\,(\mathrm{syst})\,\mathrm{pb} = 207 \pm 31\,\mathrm{pb}$$

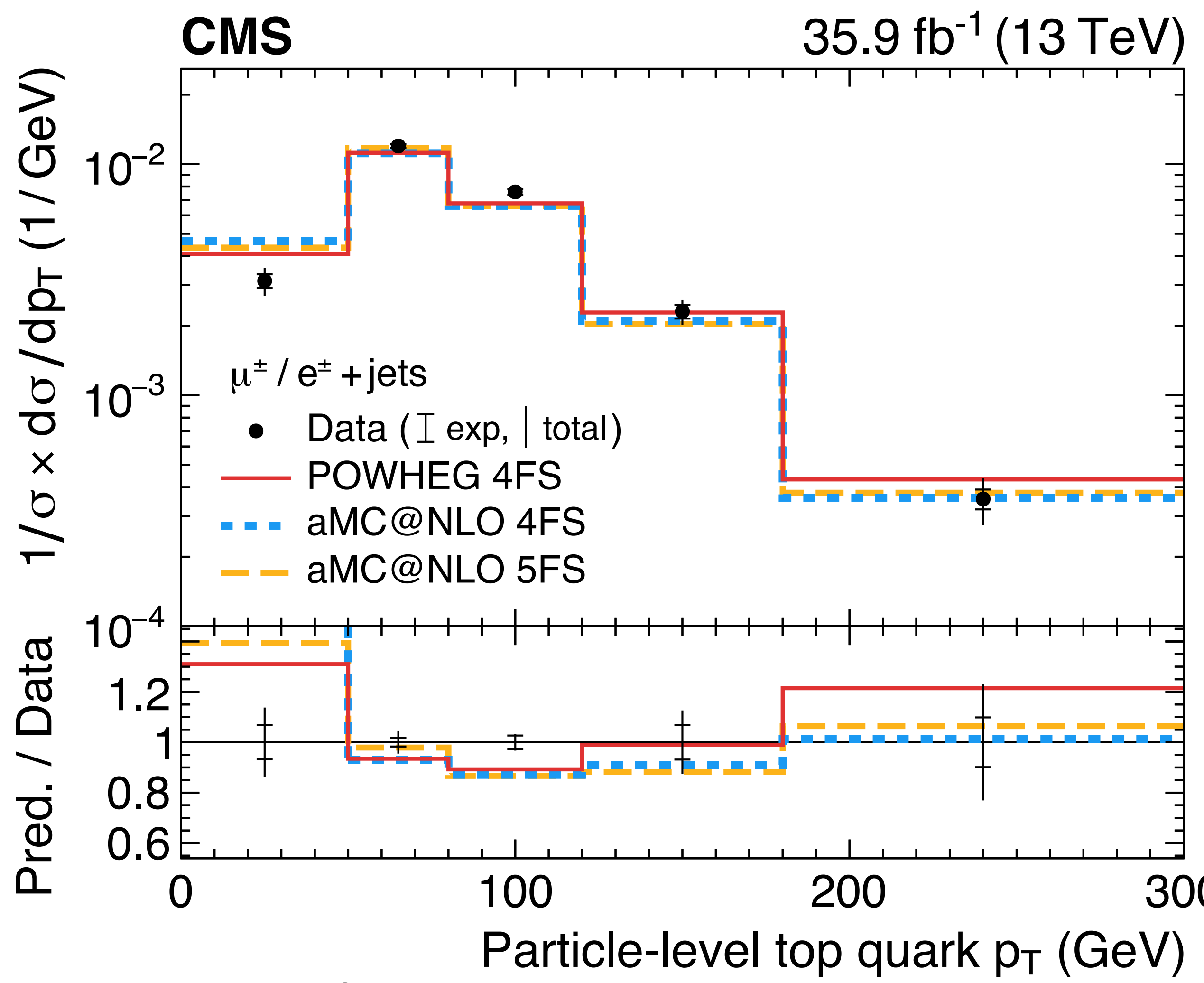
$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{t\mathrm{-ch,t+\bar{t}}}}{\sigma^{\mathrm{theo}}_{t\mathrm{-ch,t+\bar{t}}}}} = 0.98 \pm 0.07\,(\mathrm{exp}) \pm 0.02\,(\mathrm{theo})$$

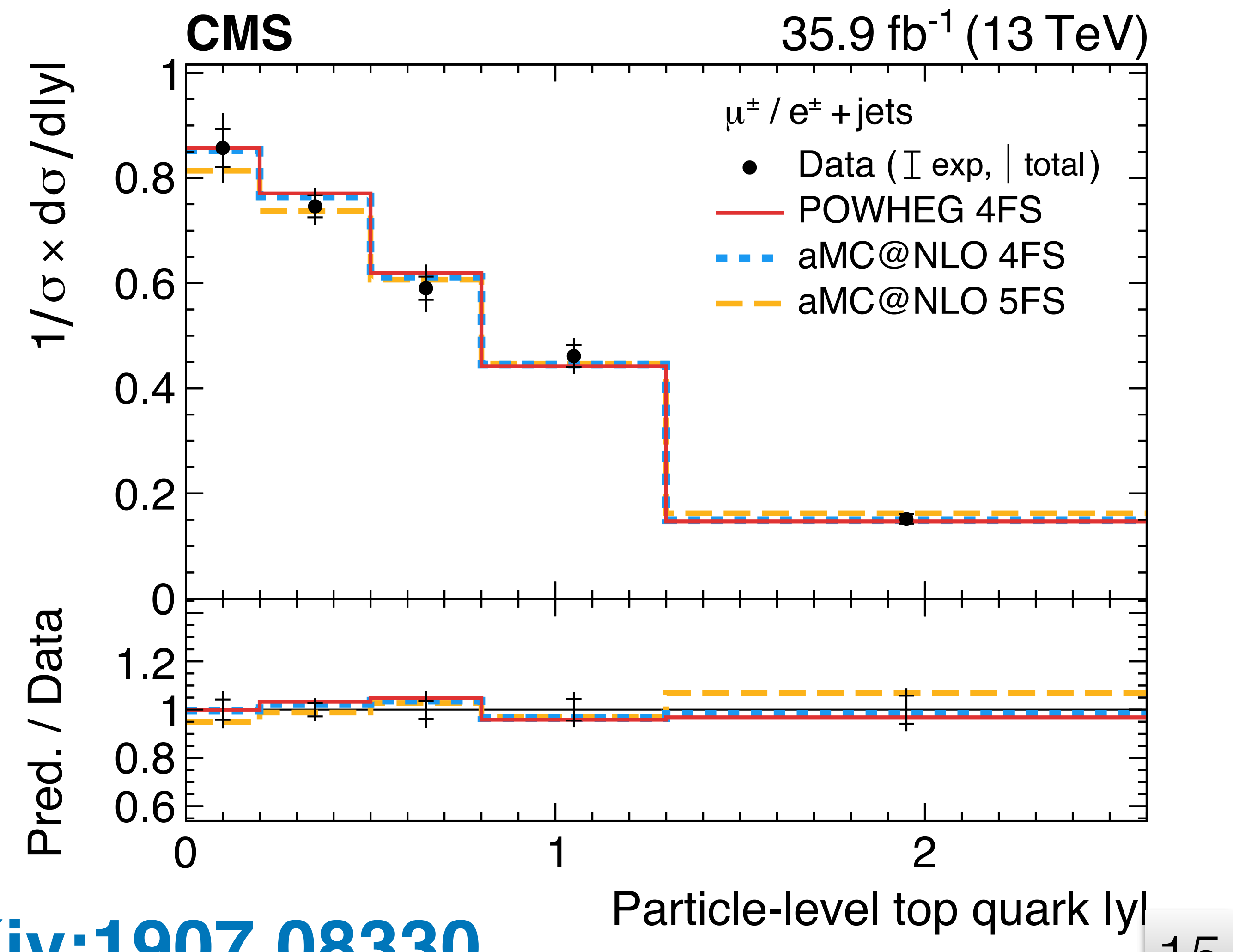
$$R_{t\mathrm{-ch}} = 1.68 \pm 0.02\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}) = 1.68 \pm 0.06$$











PLB 800 (2019) 135042

arXiv:1907.08330

t-channel differential measurement @13 TeV

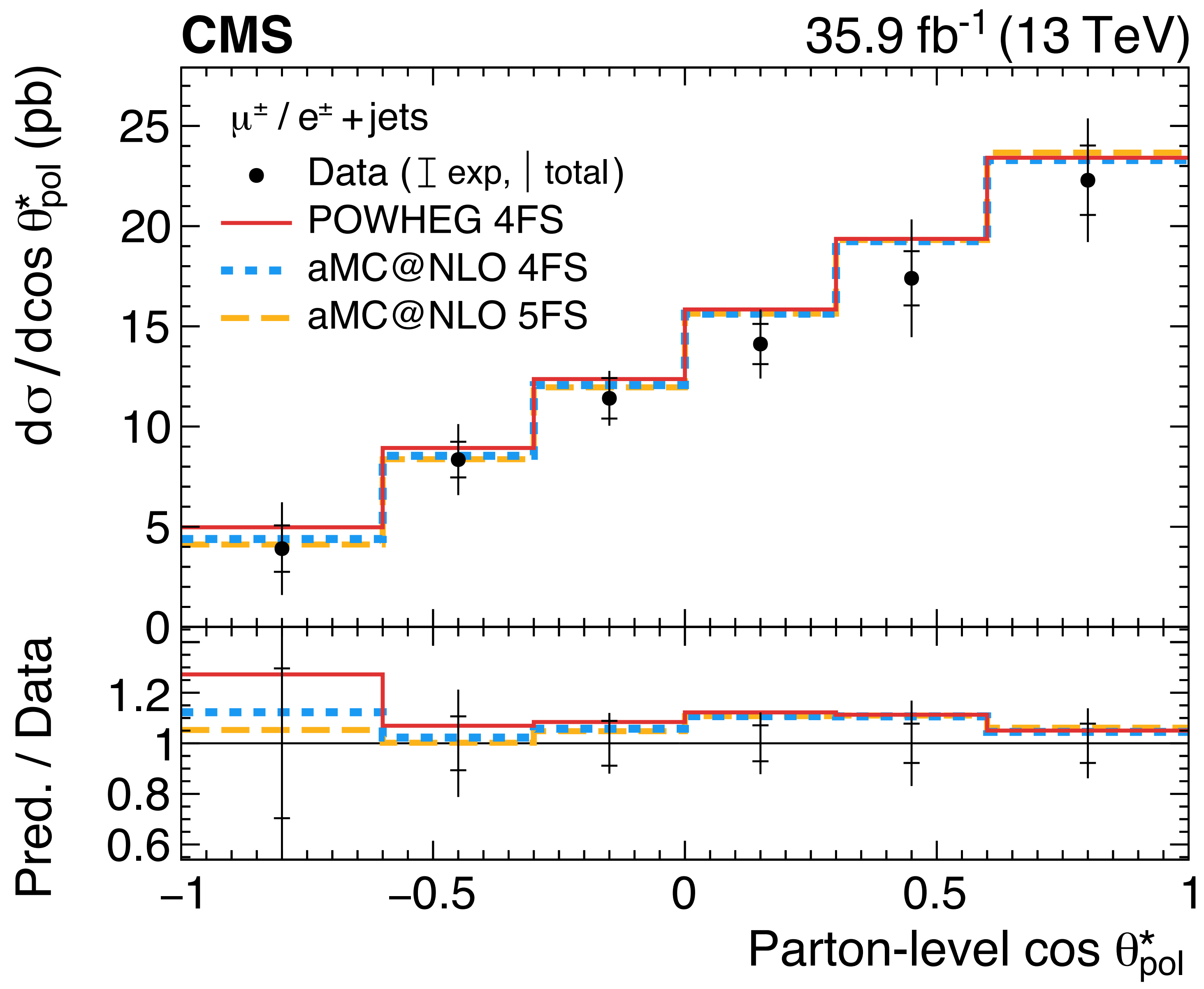
arXiv:1907.08330

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

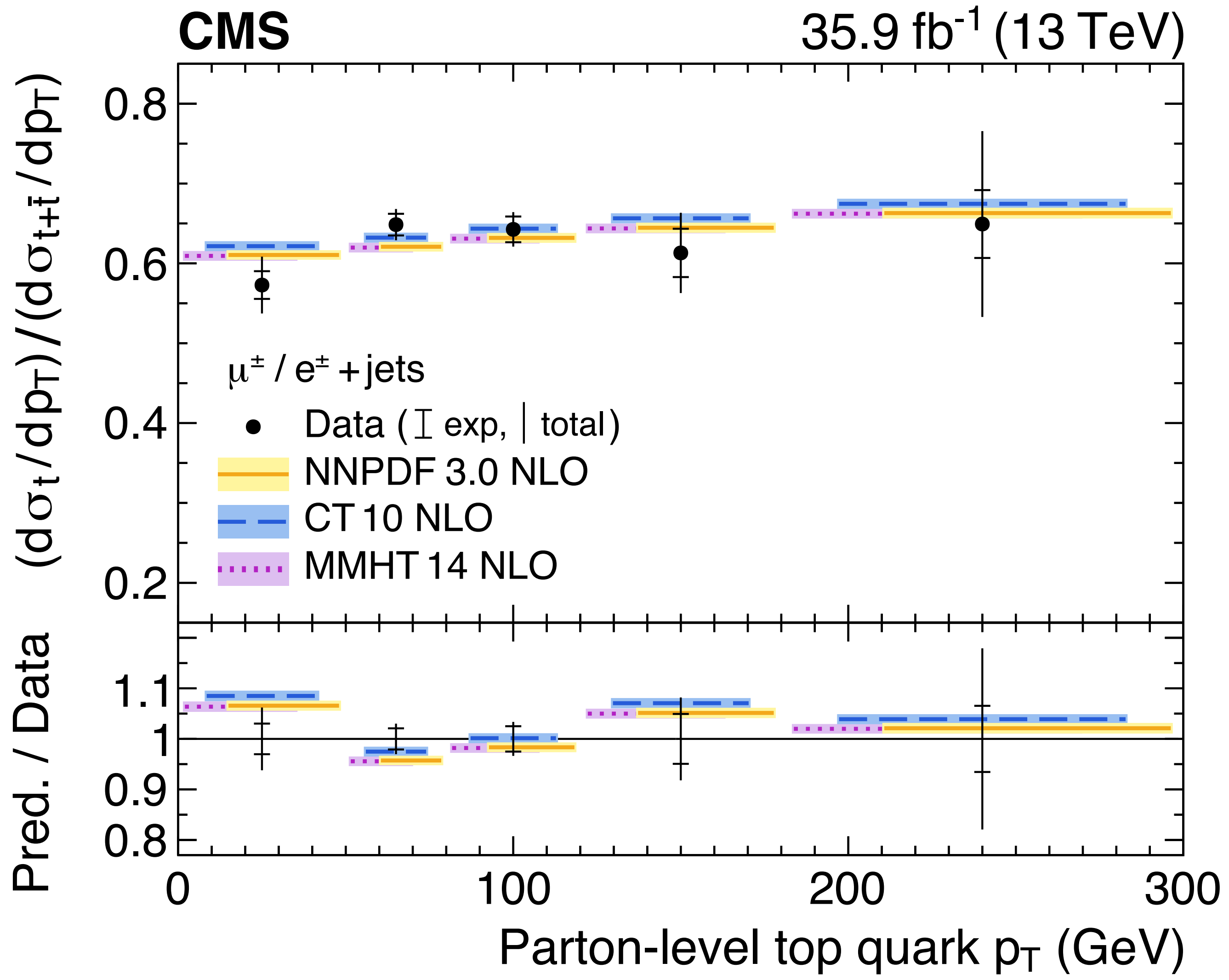
$$\cos\theta^*_{pol} = \frac{\overrightarrow{p^*_{q'}} \cdot \overrightarrow{p^*_{\ell}}}{|\overrightarrow{p^*_{q'}}|\,|\overrightarrow{p^*_{\ell}}|}$$

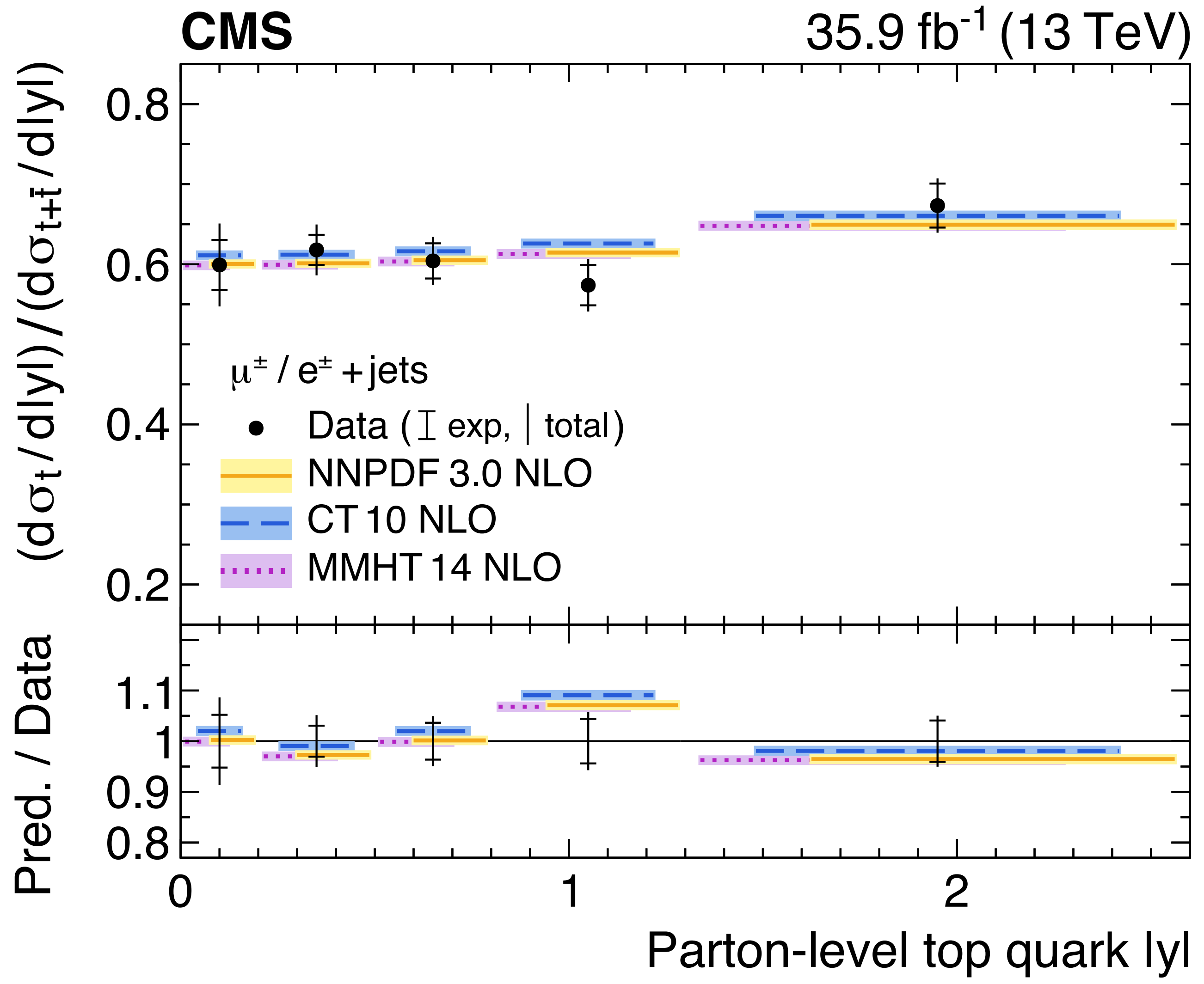
$$A_{\mu+e} = 0.439 \pm 0.032\,(\text{exp}) \pm 0.053\,(\text{theo}) = 0.439 \pm 0.062$$

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



- 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 to anti-top
- Results agree with prediction from all PDF sets

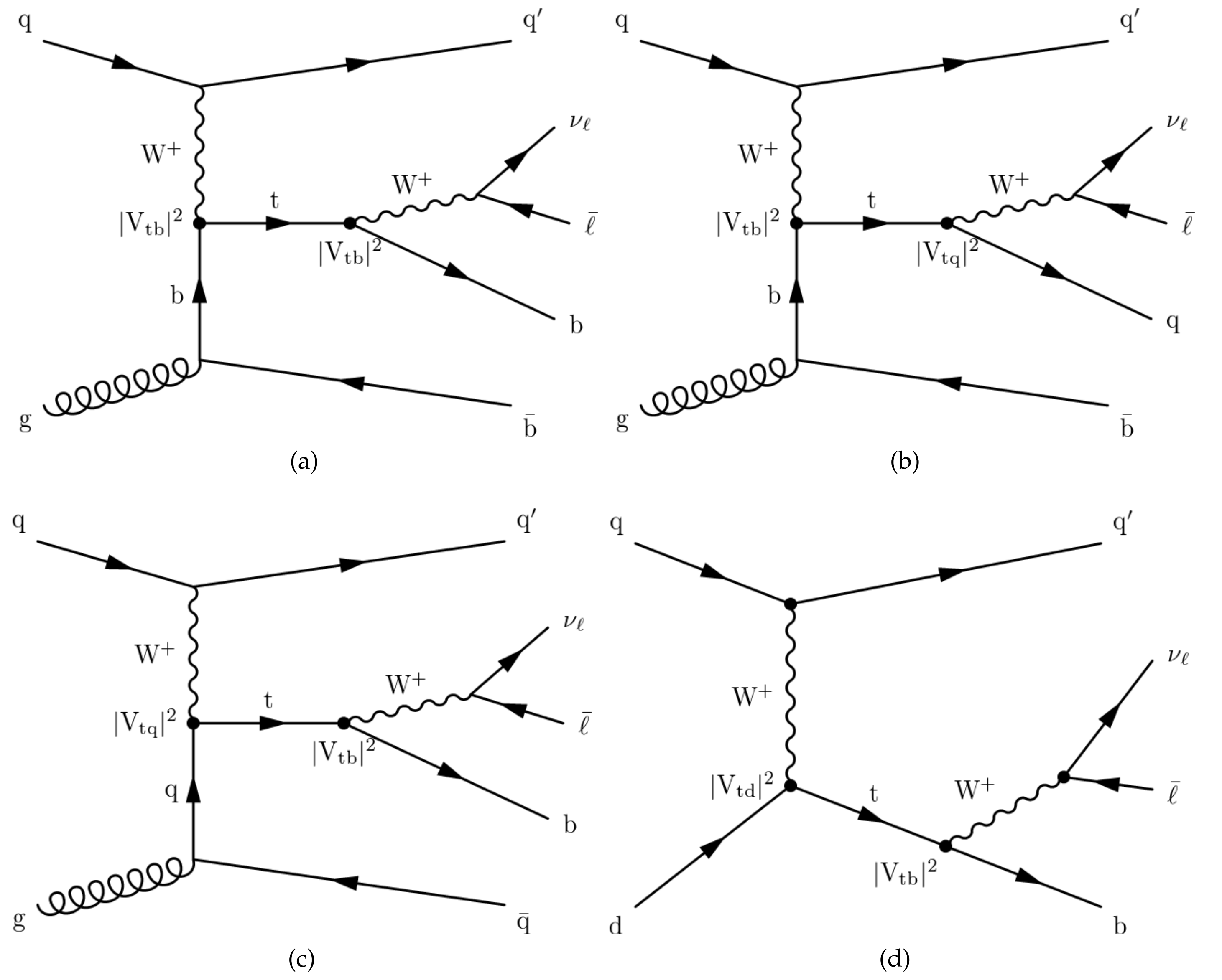


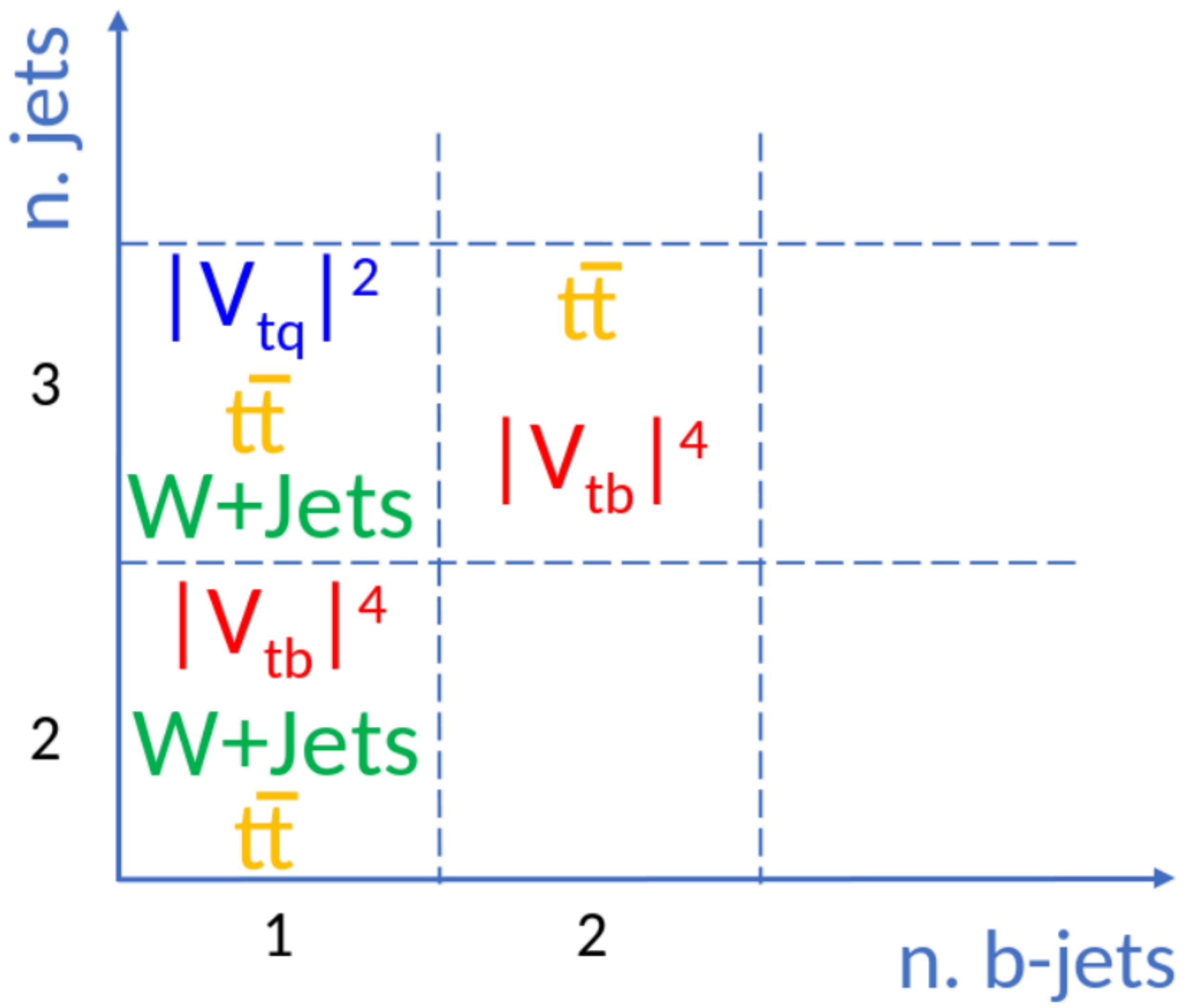


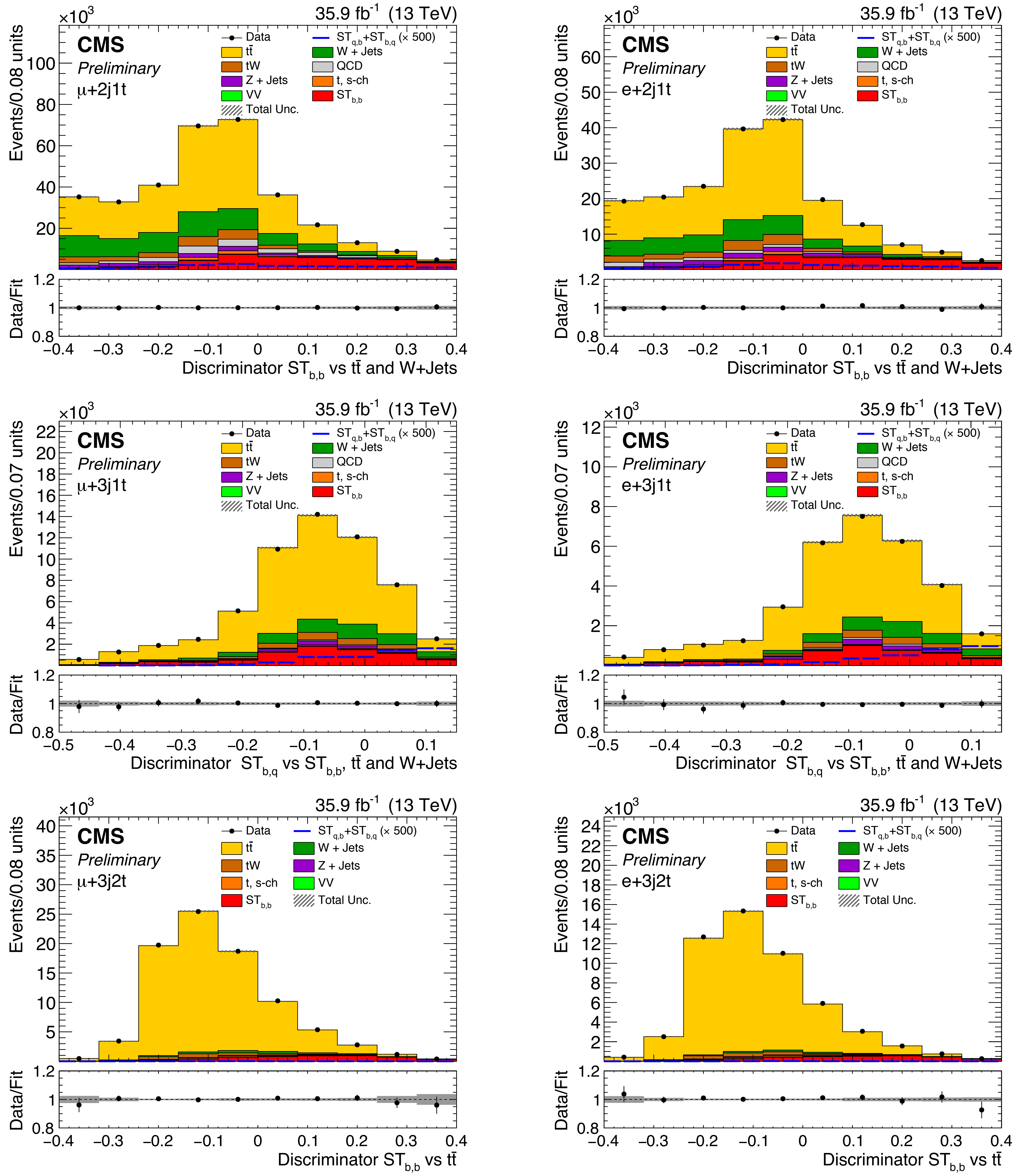
$|V_{tq}|$ in t-channel

New

CMS-PAS-TOP-17-012







Unconstrained Scenario

$$|V_{tb}| = 1.00 \pm 0.01\,(\text{stat} + \text{syst}) \pm 0.03\,(\text{nonprofiled})$$

$$|V_{tb}|^2 = 0.99 \pm 0.02\,(\text{stat} + \text{syst}) \pm 0.06\,(\text{nonprofiled})$$

$$|V_{td}|^2 + |V_{ts}|^2 < 0.17\,@\,95\,\%\,\text{CL}$$

With SM CKM unitarity constraint

$$|V_{tb}| = 0.980^{+0.014}_{-0.011}\,(\text{stat} + \text{syst}) \pm 0.031\,(\text{nonprofiled})$$

$$|V_{td}|^2 + |V_{ts}|^2 = 0.040^{+0.023}_{-0.028}\,(\text{stat} + \text{syst}) \pm 0.059\,(\text{nonprofiled})$$

Observation of SM tZq process

ATLAS-CONF-2019-043

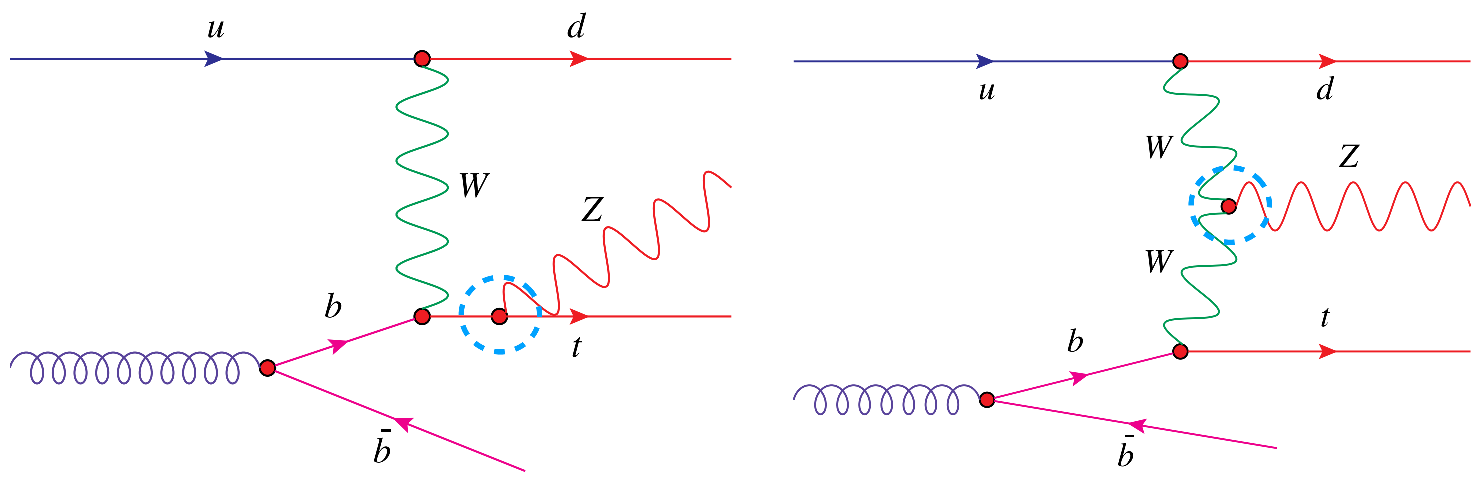
- Observation of SM tZq with full Run2 data (139 fb^{-1}) by ATLAS

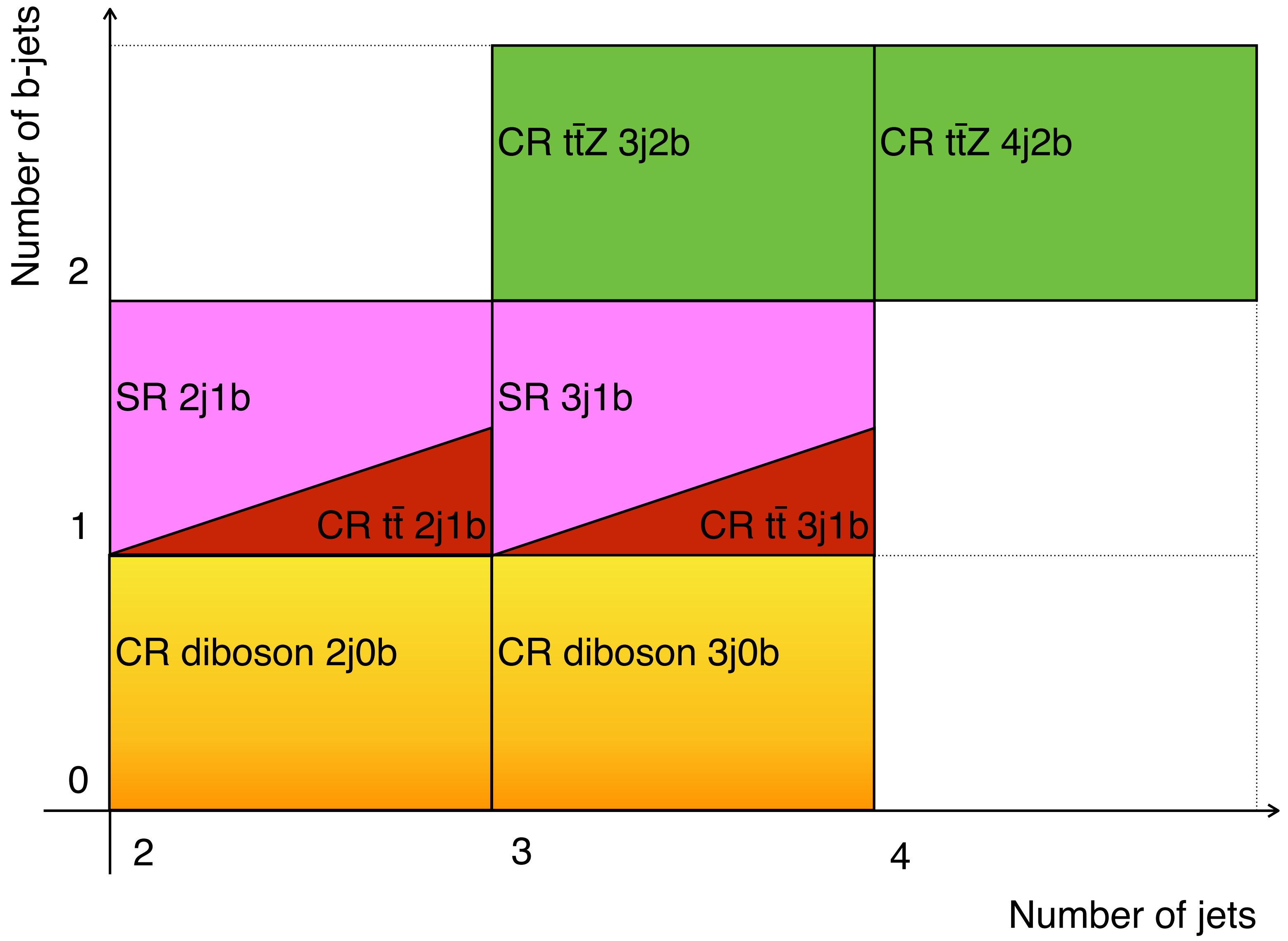
- CMS observation earlier with 77 fb^{-1} data (2016+2017) with significance ~ 8 s.d (PRL122(2019) 132003)

- Events selection:
  - ➛ OR of single electron/muon triggers
  - ➛ exactly 3 leptons (1 OSSF pair) & $|m_{\ell\ell} - m_Z| < 10$ GeV
  - ➛ ≥ 2 jets with $p_T > 35$ GeV and $|\eta| < 4.5$; out of which exactly 1 central ($|\eta| < 2.5$) b-jet

- Separate NN for each signal region (SR) designed using several kinematic variables

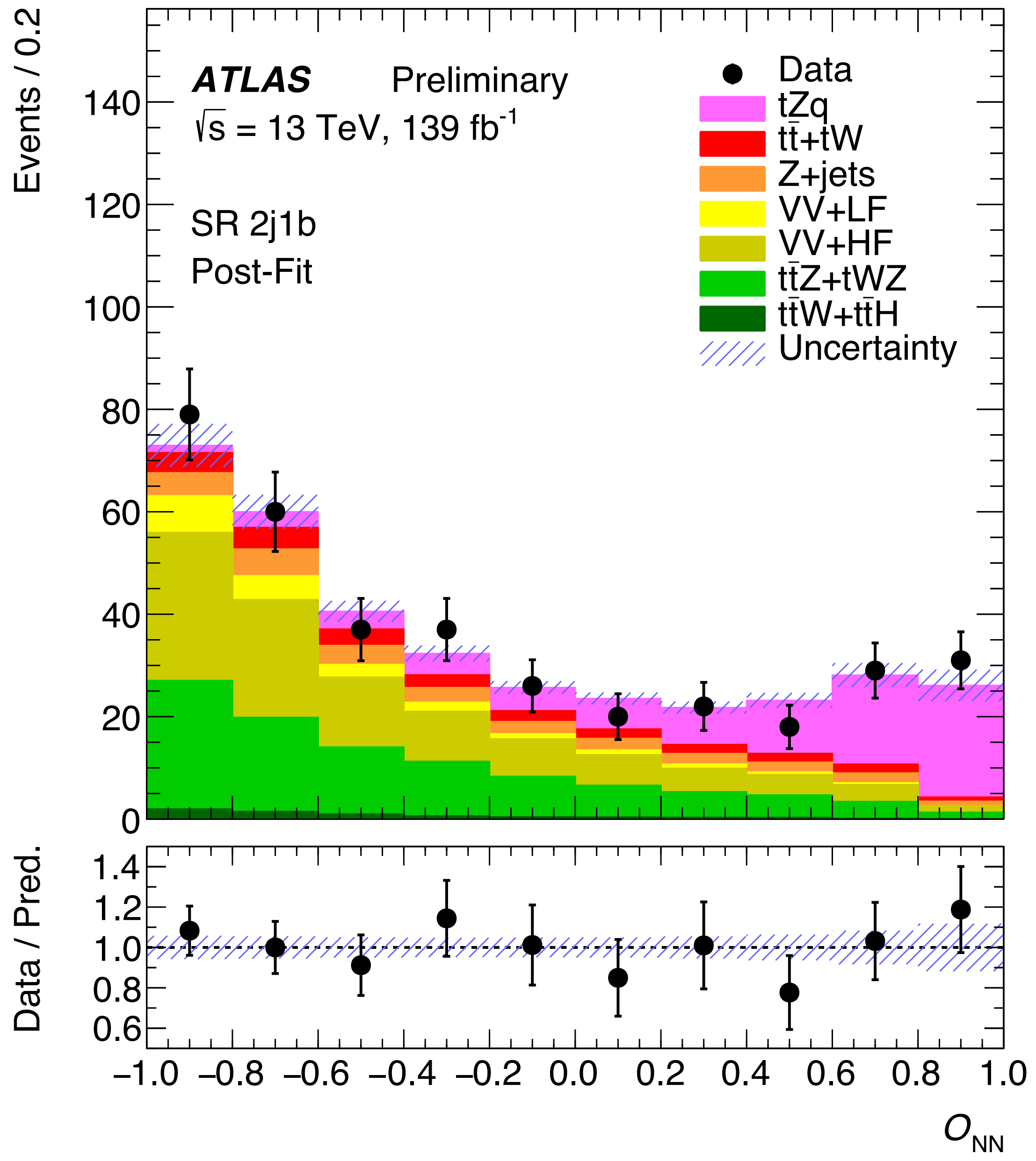
- Simultaneous PLH fits to data in SRs and control regions (CRs) to extract $\sigma(t\ell^+\ell^- q)$
  - ➛ NN in SRs, NN in $t\bar{t}Z$ CR, event yield in $t\bar{t}$ CR, $m_T(\ell, E_T^{miss})$ in diboson CR

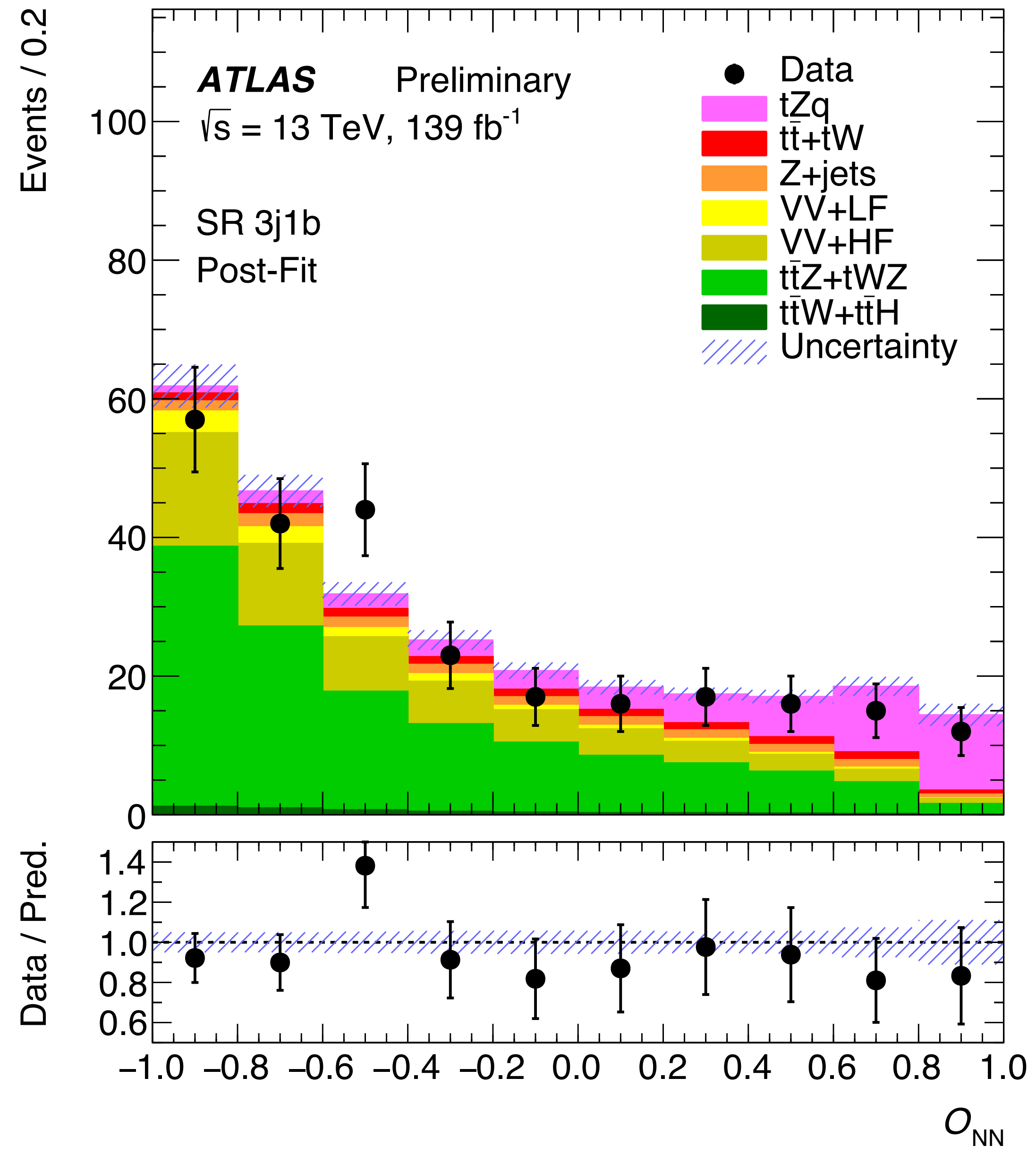




$$\left.\begin{aligned}\sigma(t\ell^+\ell^- q) &= 98 \pm 12\,(\text{stat}) \pm 8\,(\text{syst})\,\text{fb}\,(15\%)\\ \sigma_{\text{SM}} &= 102^{+5}_{-2}\,\text{fb}\end{aligned}\right\}\quad m_{\ell\ell} > 30\,\text{GeV}$$

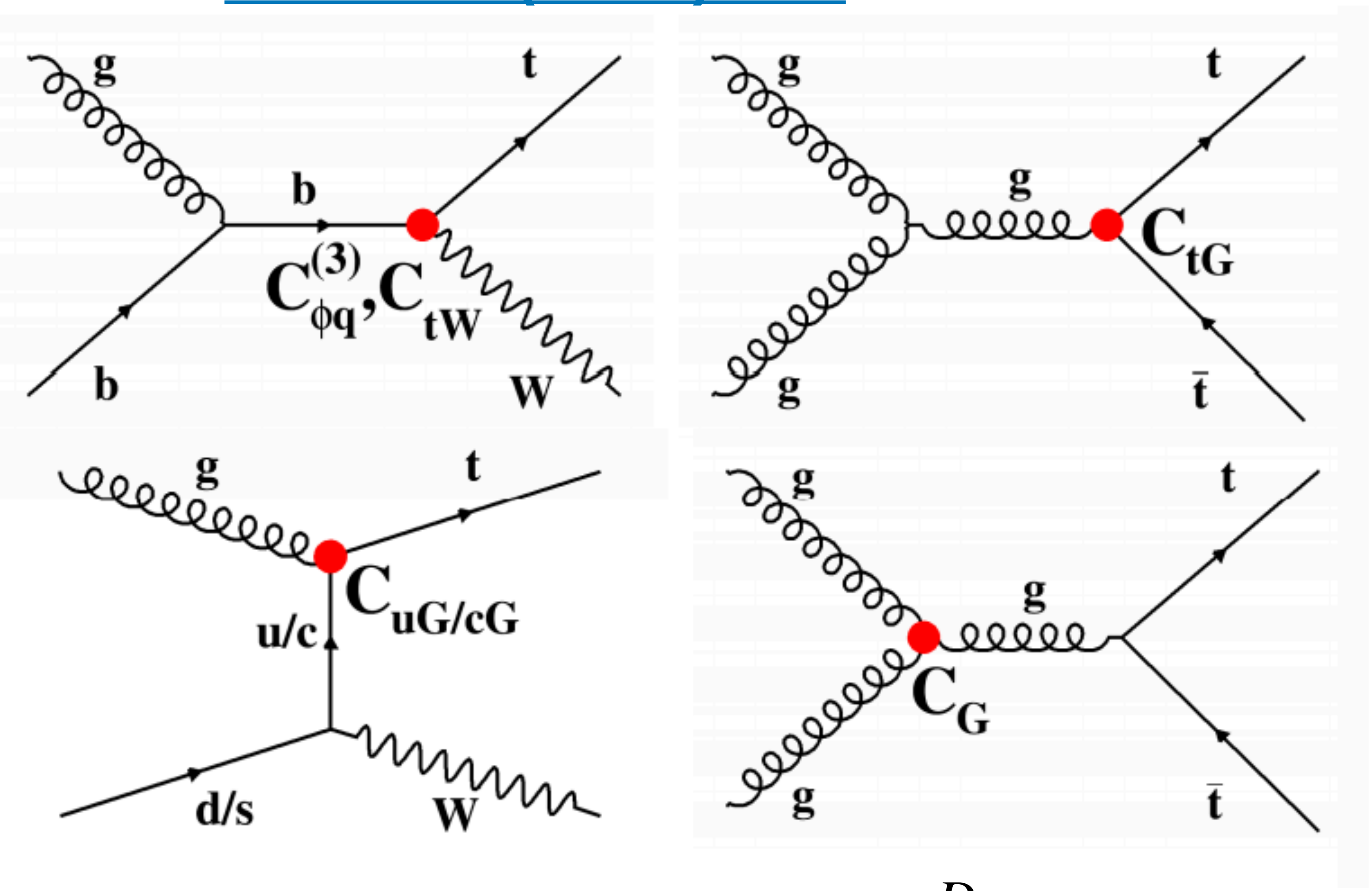
- Observation with 15% uncertainty ➛ dominated by stat. component





New Physics in $tW + t\bar{t}$ production in dilepton final states

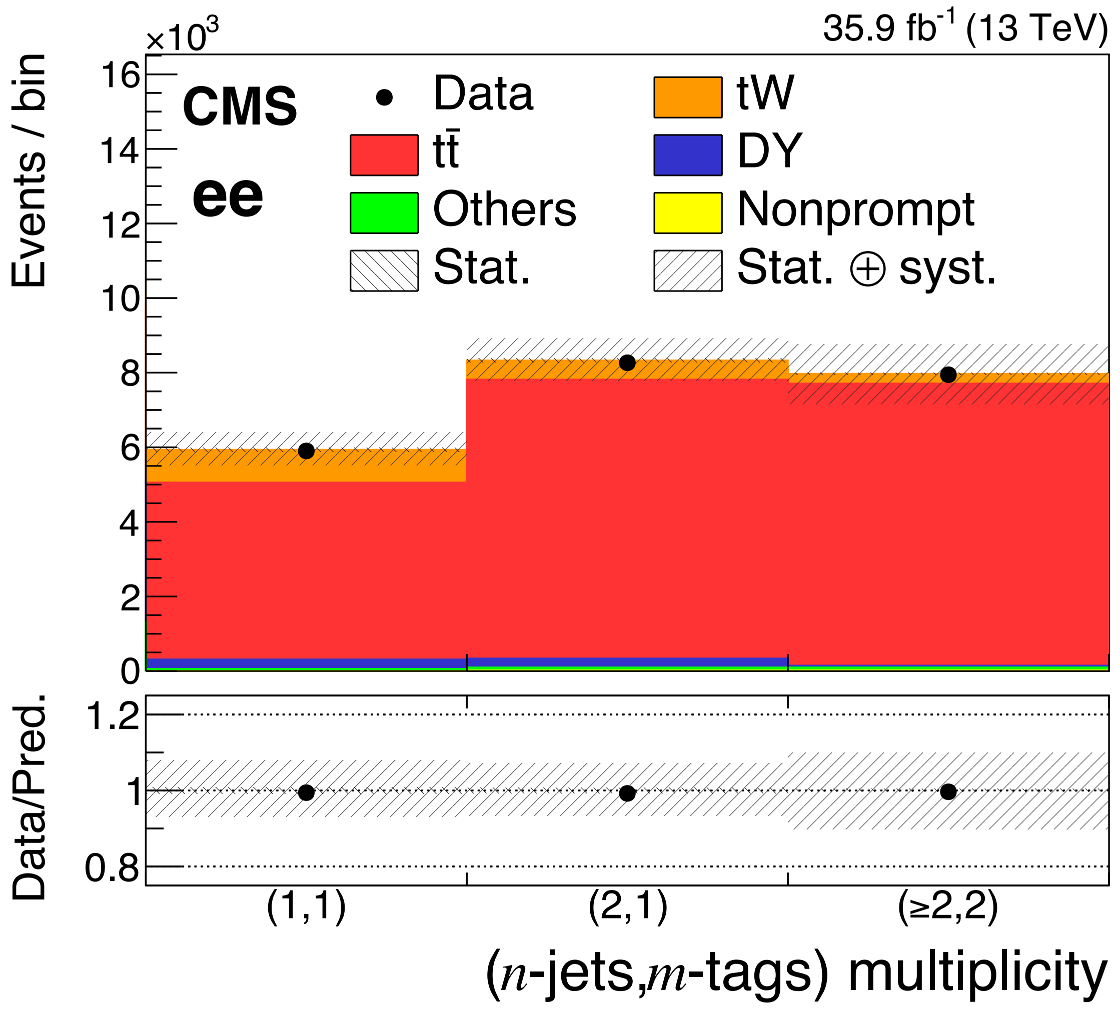
EPJC 79 (2019) 886

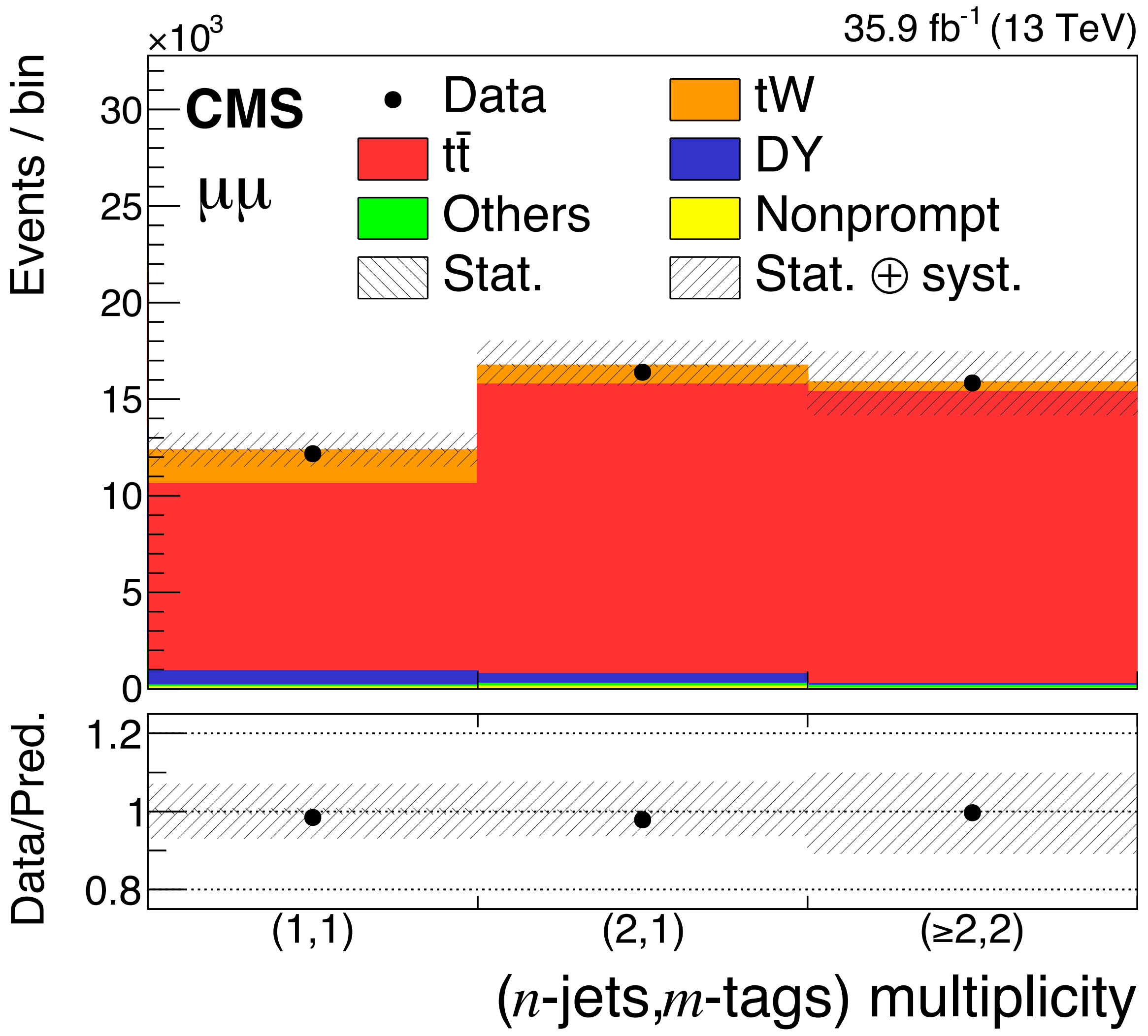


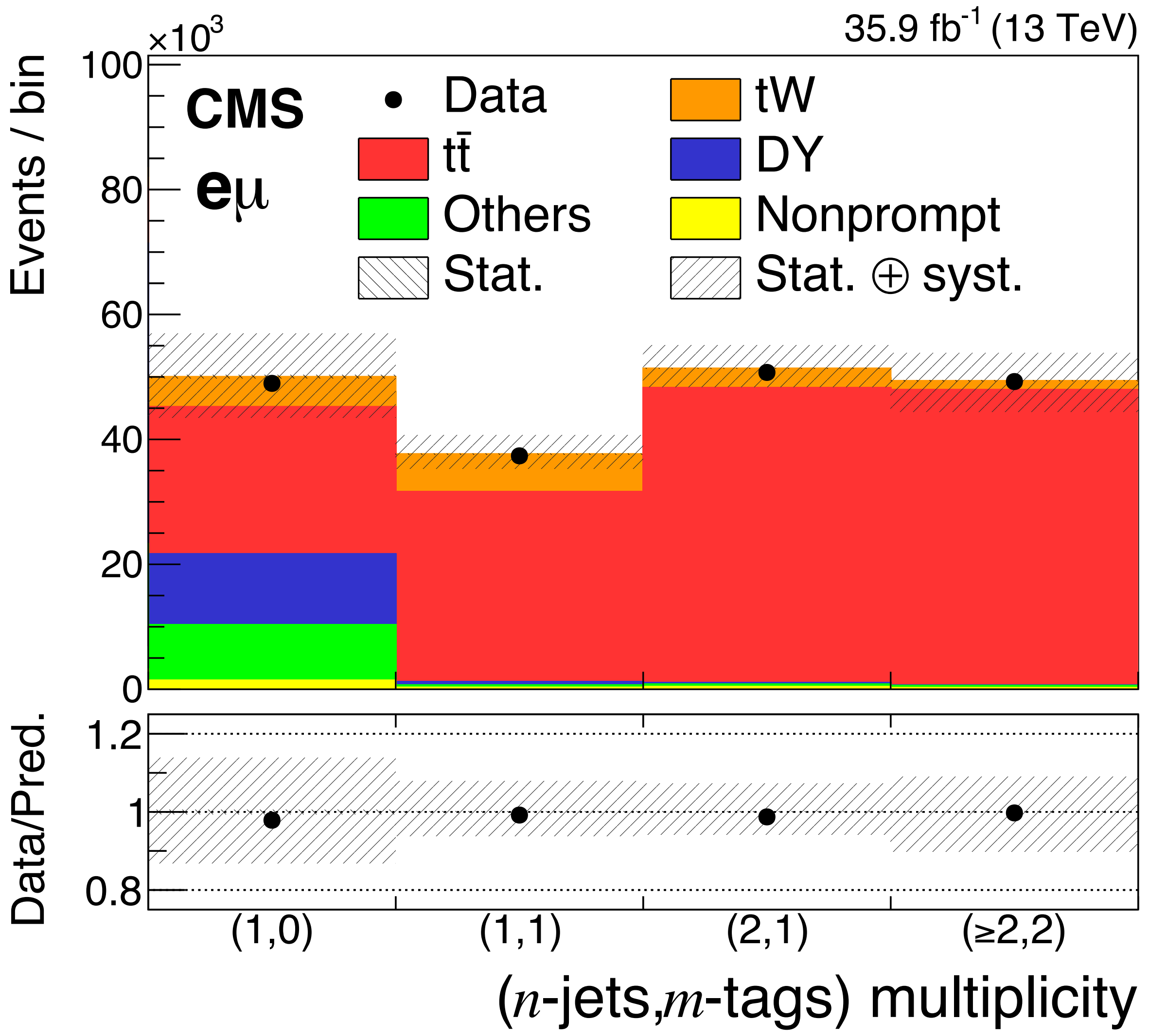
- Analysis with 35.9 fb^{-1} data
- Event Selection: di-lepton (***ee, eμ, μμ***) + jets events
  ➛Separated by lepton flavor , $t\bar{t}$: ≥ 2 jets (2 b-jets), tW : 1-2 jets (0-1 b-jet)
- Signal extraction is performed using channel dependent NN
- First experimental bound on C_G coupling
- Limits on C_{uG} and C_{cG} translated to observed (expected) ULs on FCNC BRs @95% CLs

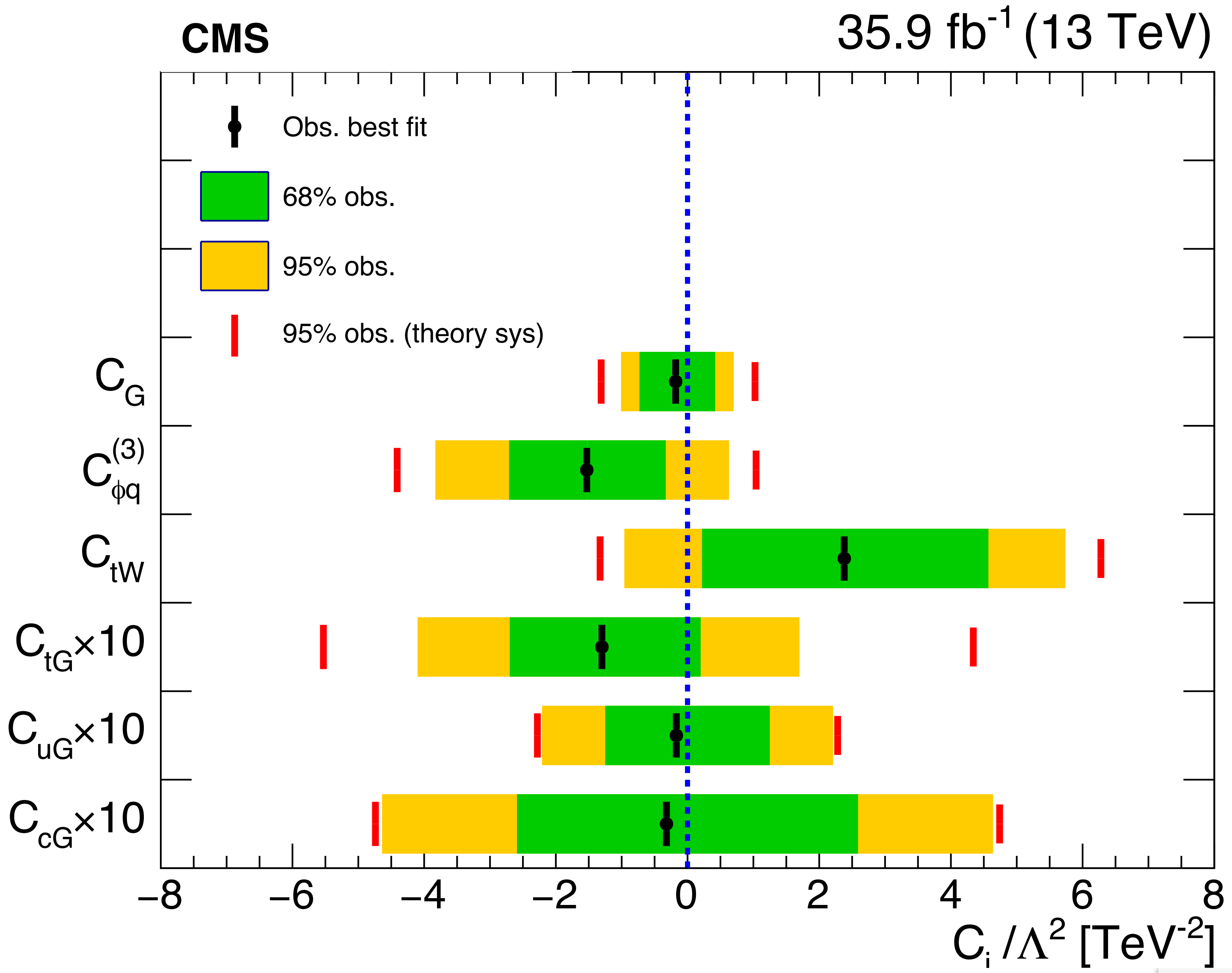
$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

$$\mathscr{B}(t \to ug) < 0.12\,(0.22)\,\%\,,\ \mathscr{B}(t \to cg) < 0.53\,(1.05)\,\%$$









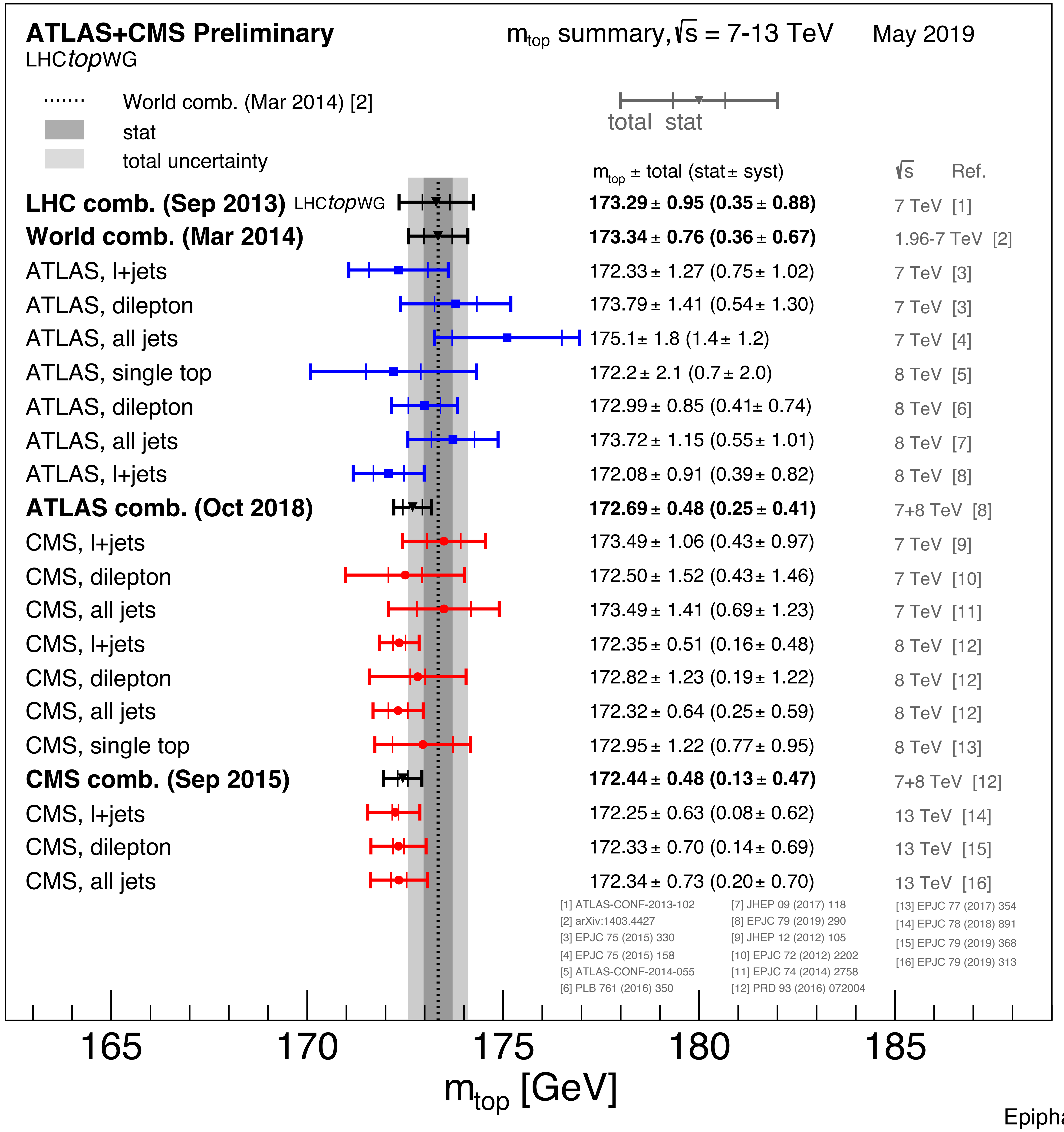
Summary

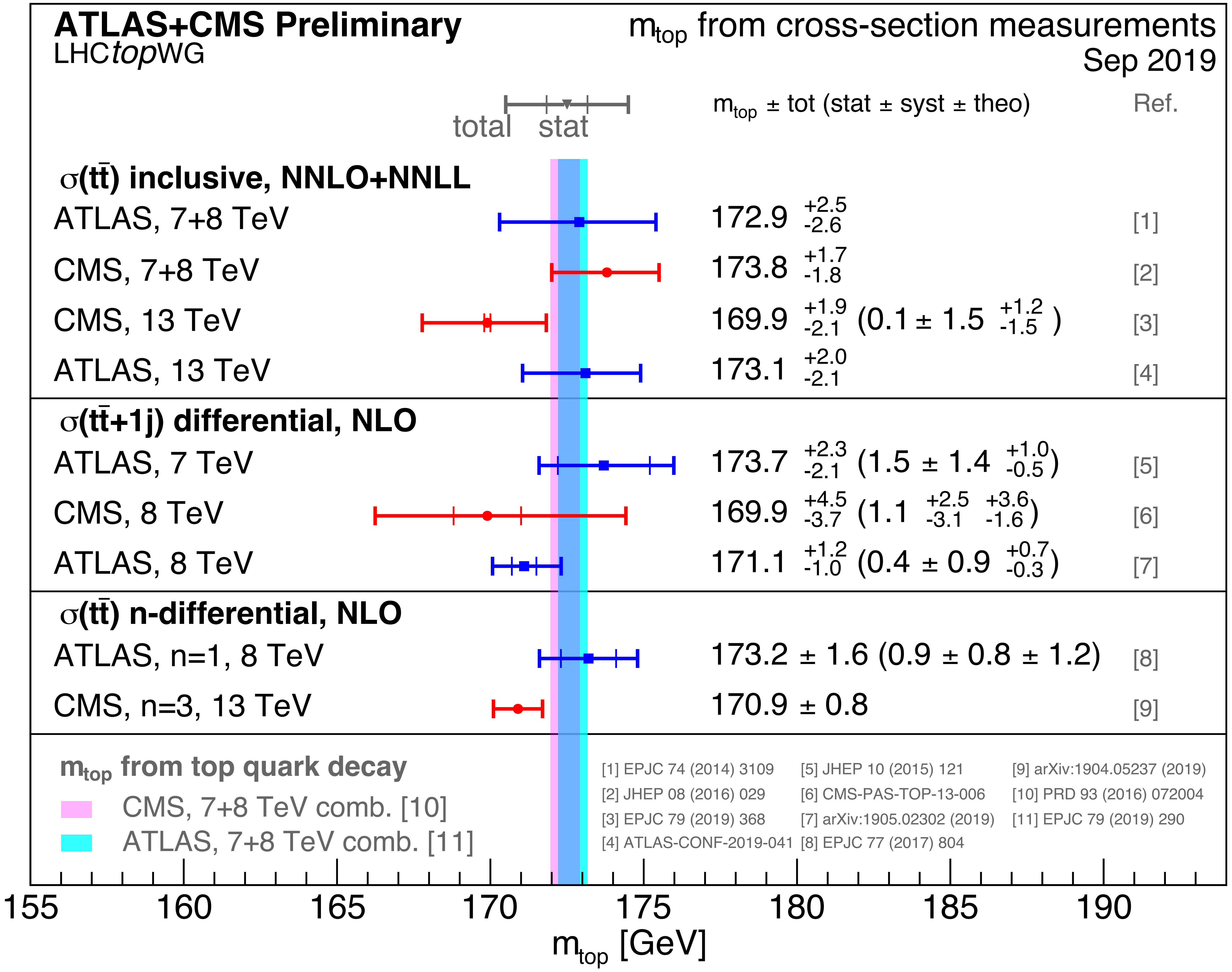
- Several results with full or partial Run2 data
- Measurements agree with SM prediction at a given accuracy
- Measurements are performed with unprecedented precision
- Provides good understanding of the various modeling aspects such as PDF, hadronization and parton shower etc.
- Stringent limits on couplings are placed with EFT interpretation
- Need to exploit the full potential of the Run2 data (~140 fb^{-1})

Back Up

Summary of m_{top} measurements at LHC

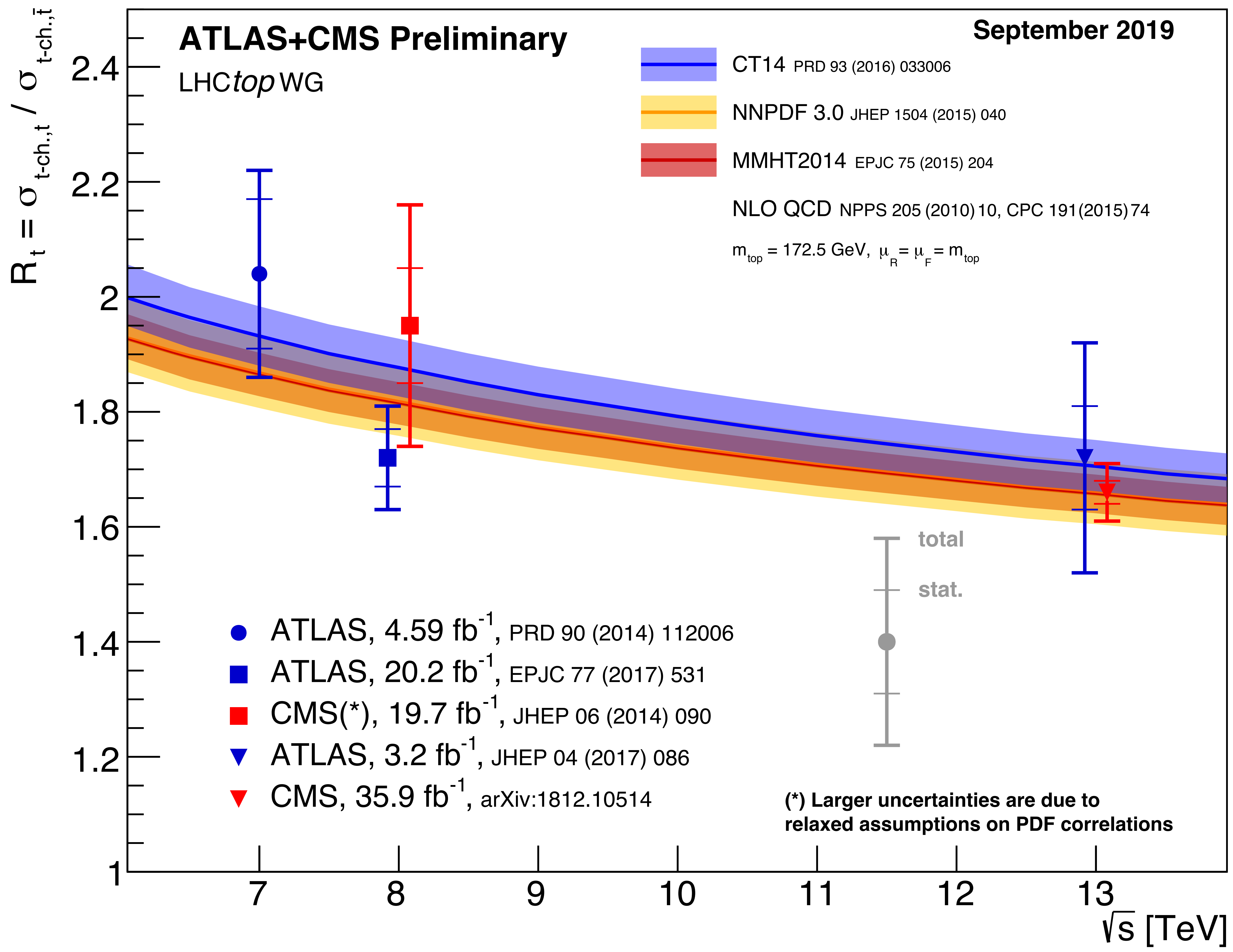
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

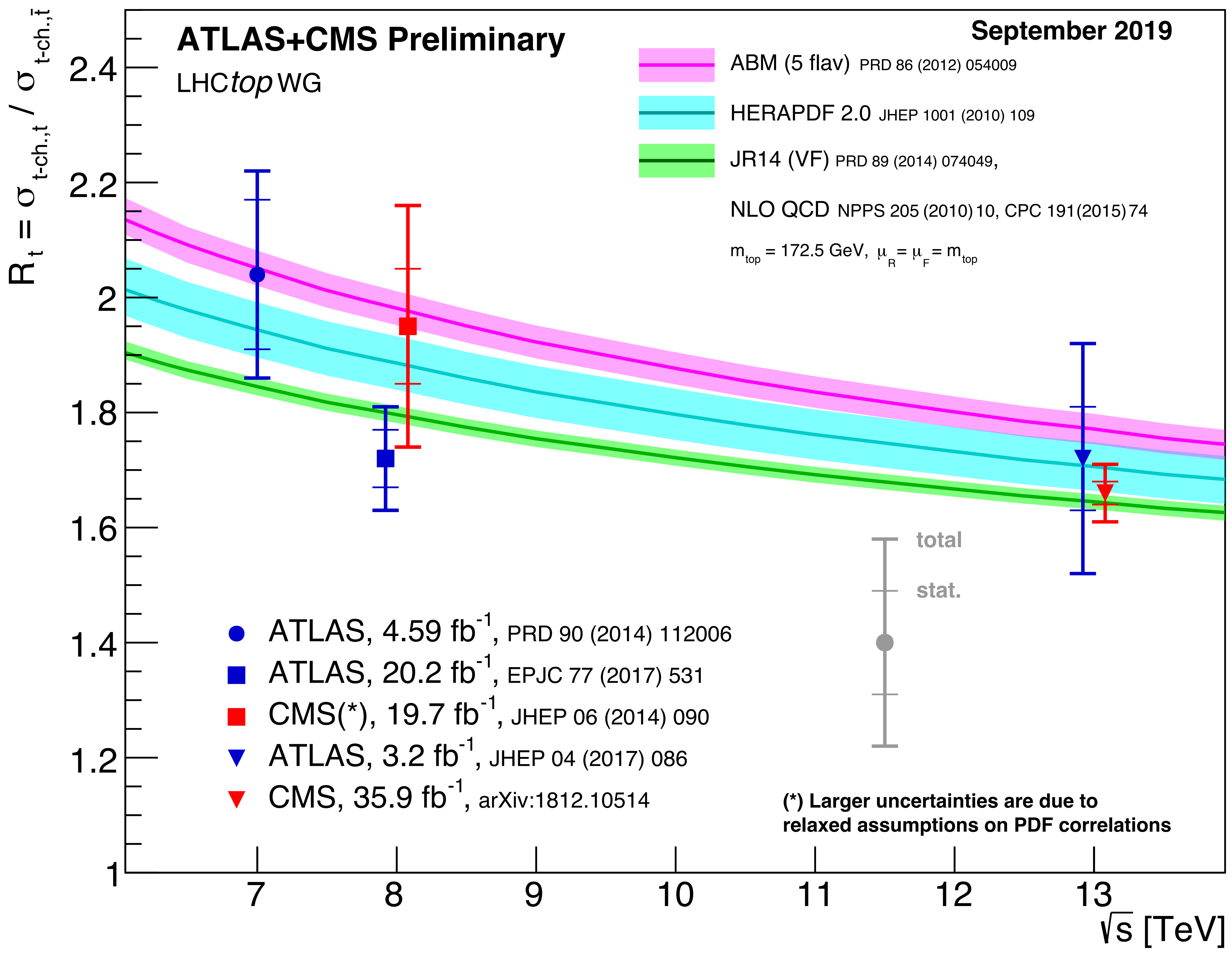




Summary of $R_{t\text{-ch.}}$ measurements at LHC

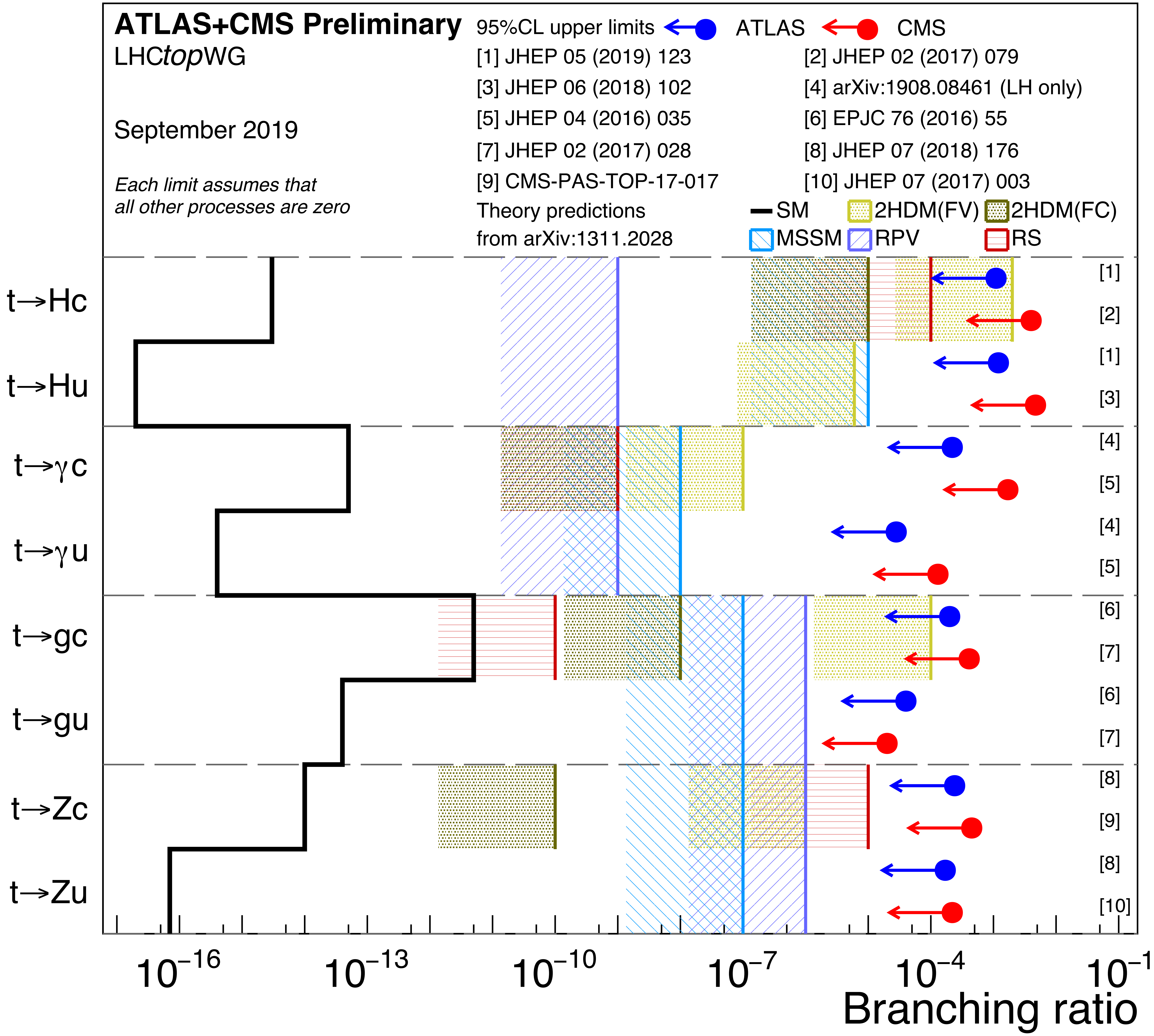
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots



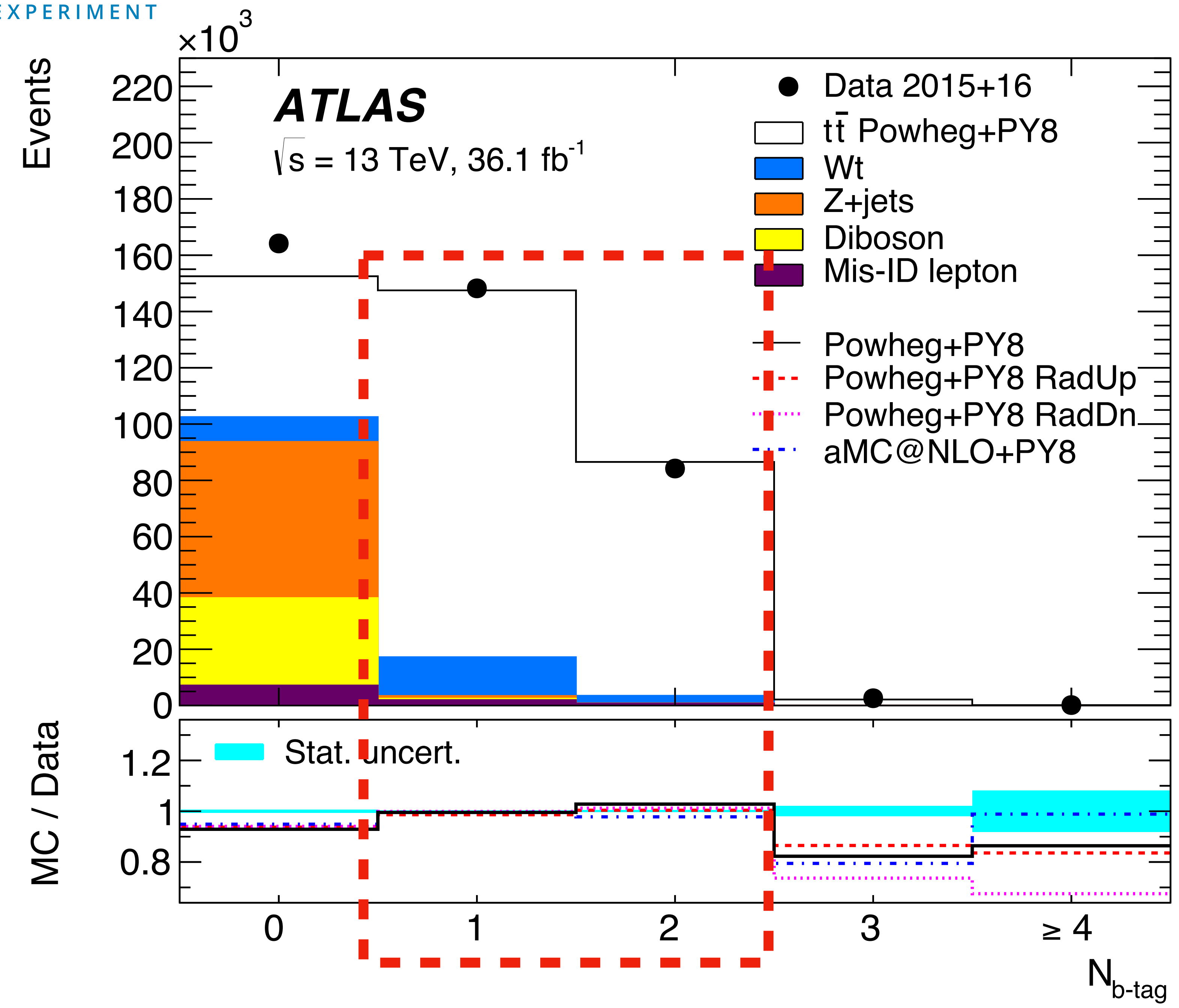


Summary of FCNC searches at LHC

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



$\sigma_{t\bar{t}}$ (eμ)



$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}}$$

- $\epsilon_{e\mu}$ = efficiency for a $t\bar{t}$ event to pass the OS selection
- ϵ_b = combined probability for a jet coming from top decay within the acceptance, passing the reco. criteria and p_T threshold and being b-tagged
- C_b = tagging correlation coefficient

$\sqrt{s}$ values [TeV]	Measured cross-section ratio	NNLO+NNLL prediction
13/7	4.54 ± 0.08 ± 0.10 ± 0.12 (0.18)	4.69 ± 0.16
13/8	3.42 ± 0.03 ± 0.07 ± 0.10 (0.12)	3.28 ± 0.08
8/7	1.33 ± 0.02 ± 0.02 ± 0.04 (0.05)	1.43 ± 0.01

$\sqrt{s}$ value [TeV]	$t\bar{t}/Z$ cross-section ratio	CT14 prediction
13	1.062 ± 0.009 ± 0.016 ± 0.002 (0.018)	$1.132^{+0.078}_{-0.075}$
$\sqrt{s}$ values [TeV]	**$t\bar{t}/Z$ cross-section double ratio**	
13/7	2.617 ± 0.049 ± 0.060 ± 0.007 (0.078)	$2.691^{+0.045}_{-0.058}$
13/8	2.212 ± 0.024 ± 0.049 ± 0.006 (0.055)	$2.124^{+0.026}_{-0.035}$

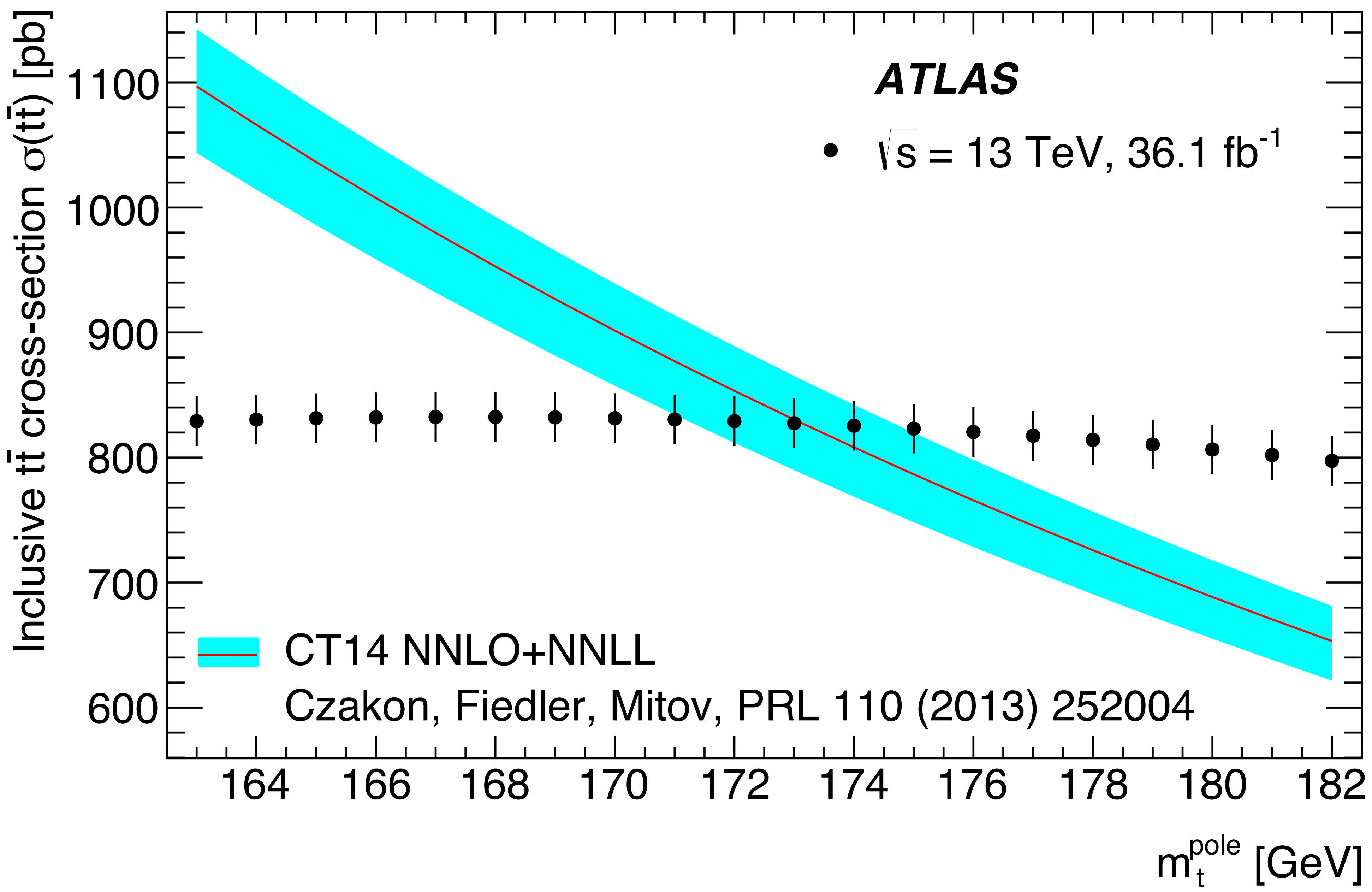
arXiv:1910.08819

	Uncertainty source	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta G_{e\mu}/G_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ (%)
	Data statistics				0.44	0.44
$t\bar{t}$ mod.	$t\bar{t}$ generator	0.38	0.05	0.05	0.43	0.10
	$t\bar{t}$ hadronisation	0.24	0.42	0.25	0.49	0.67
	Initial/final-state radiation	0.30	0.26	0.16	0.45	0.41
	$t\bar{t}$ heavy-flavour production	0.01	0.01	0.26	0.26	0.26
	Parton distribution functions	0.44	0.05	-	0.45	0.07
	Simulation statistics	0.22	0.15	0.17	0.22	0.18
Lept.	Electron energy scale	0.06	0.06	-	0.06	0.06
	Electron energy resolution	0.01	0.01	-	0.01	0.01
	Electron identification	0.34	0.34	-	0.37	0.37
	Electron charge mis-id	0.09	0.09	-	0.10	0.10
	Electron isolation	0.22	0.22	-	0.24	0.24
	Muon momentum scale	0.03	0.03	-	0.03	0.03
	Muon momentum resolution	0.01	0.01	-	0.01	0.01
	Muon identification	0.28	0.28	-	0.30	0.30
	Muon isolation	0.16	0.16	-	0.18	0.18
	Lepton trigger	0.13	0.13	-	0.14	0.14
Jet/b	Jet energy scale	0.02	0.02	0.06	0.03	0.03
	Jet energy resolution	0.01	0.01	0.04	0.01	0.01
	Pileup jet veto	-	-	-	0.02	0.02
	b-tagging efficiency	-	-	0.04	0.20	0.20
	b-tag mistagging	-	-	0.06	0.06	0.06
Bkg.	Single-top cross-section	-	-	-	0.52	0.52
	Single-top/$t\bar{t}$ interference	-	-	-	0.15	0.15
	Single-top modelling	-	-	-	0.34	0.34
	Z+jets extrapolation	-	-	-	0.09	0.09
	Diboson cross-sections	-	-	-	0.02	0.02
	Diboson modelling	-	-	-	0.03	0.03
	Misidentified leptons	-	-	-	0.43	0.43
	Analysis systematics	0.91	0.75	0.44	1.39	1.31
L/E_b	Integrated luminosity	-	-	-	1.90	1.90
	Beam energy	-	-	-	0.23	0.23
	Total uncertainty	0.91	0.75	0.44	2.40	2.36

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

arXiv:1910.08819

- 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

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

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

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

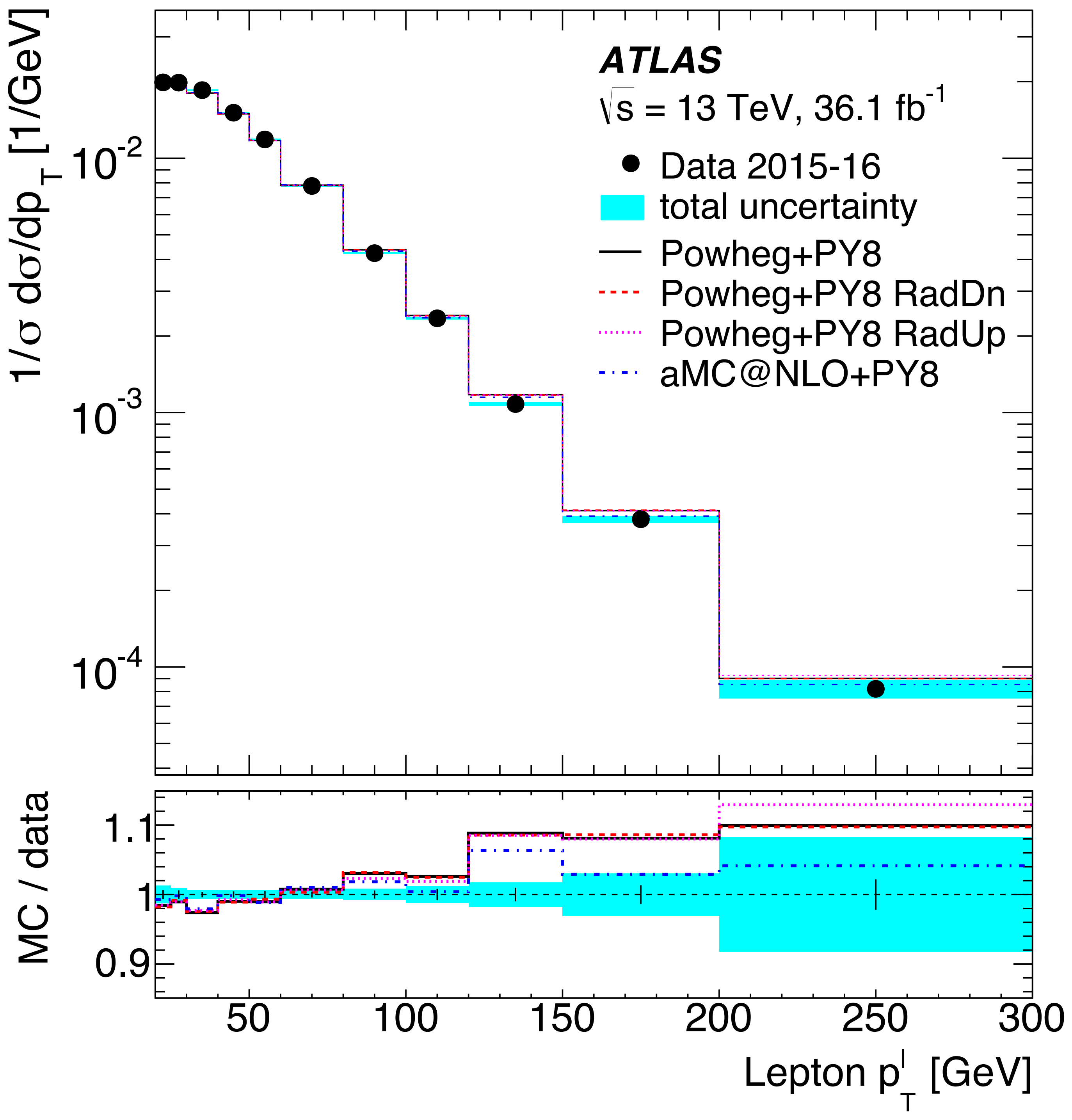
Uncertainty source	Δm_t^{pole} [GeV]
Experimental	1.0
PDF+α_S	$^{+1.5}_{-1.4}$
QCD scales	$^{+1.0}_{-1.5}$
Total uncertainty	$^{+2.0}_{-2.1}$

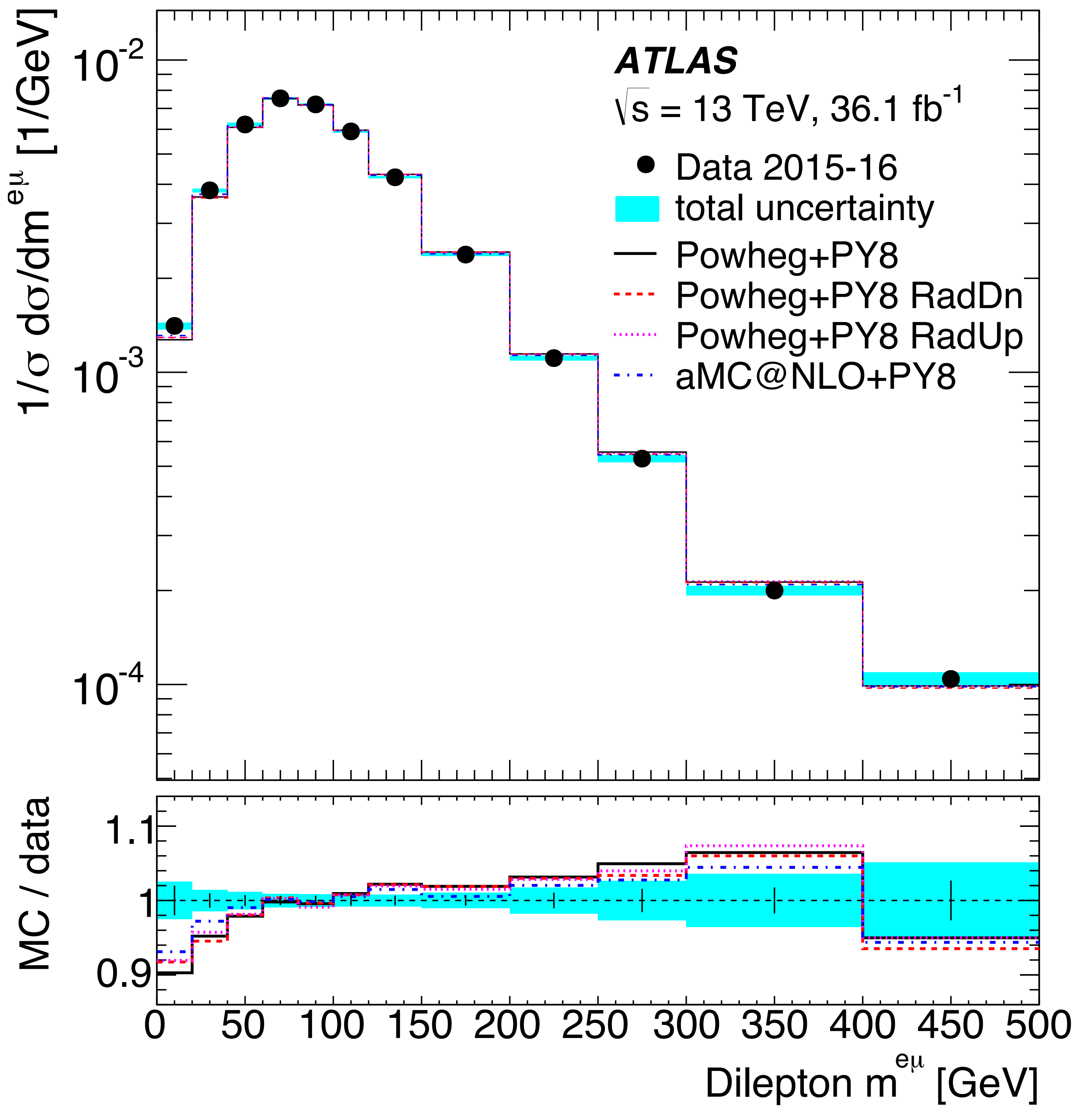
PDF set	m_t^{pole} [GeV]
CT14	$173.1^{+2.0}_{-2.1}$
CT10	$172.1^{+2.0}_{-2.0}$
MSTW	$172.3^{+2.0}_{-2.1}$
NNPDF2.3	$173.4^{+1.9}_{-1.9}$
PDF4LHC	$172.1^{+3.1}_{-2.0}$

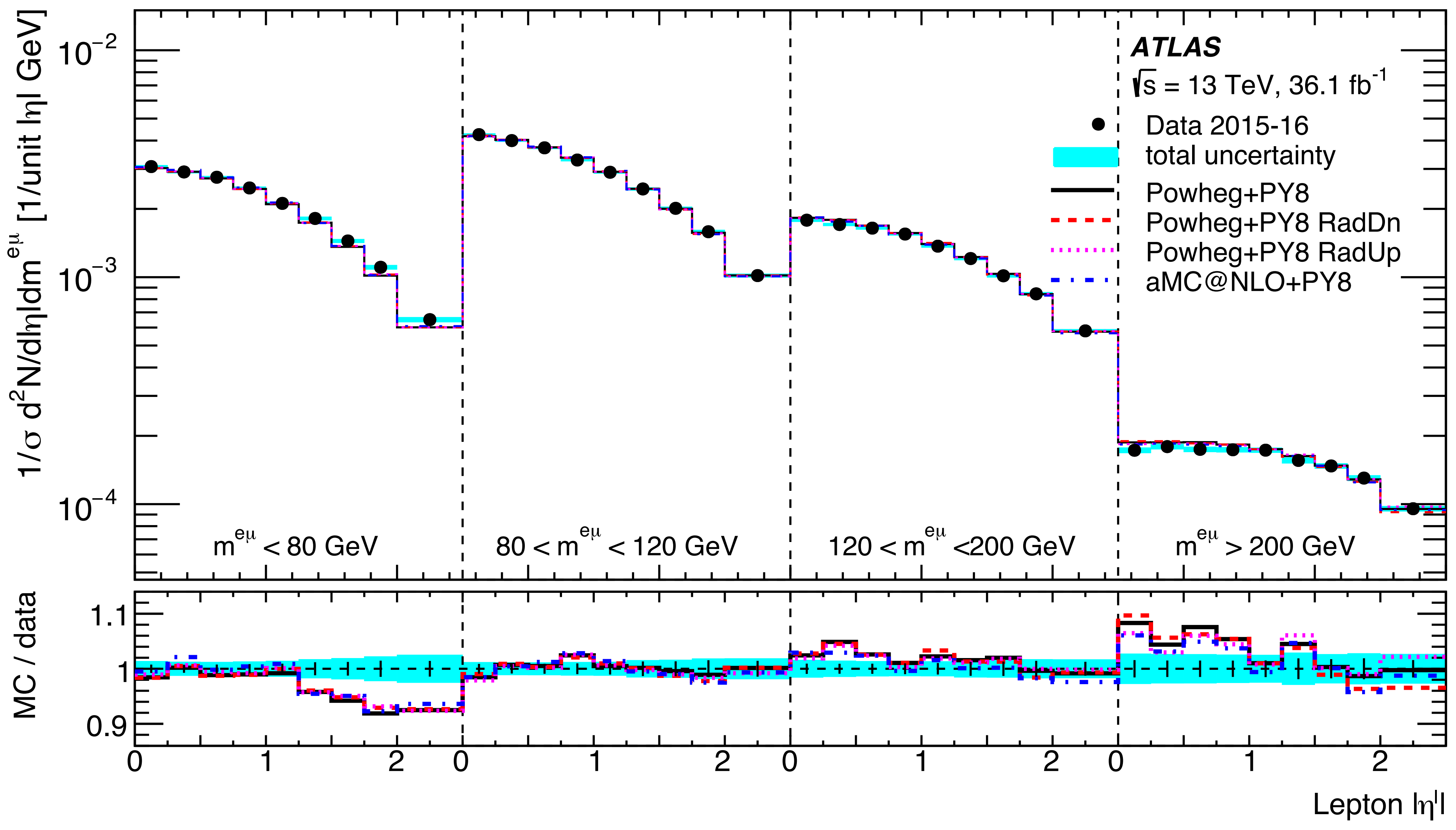
Differential $\sigma_{t\bar{t}}$ (eμ)

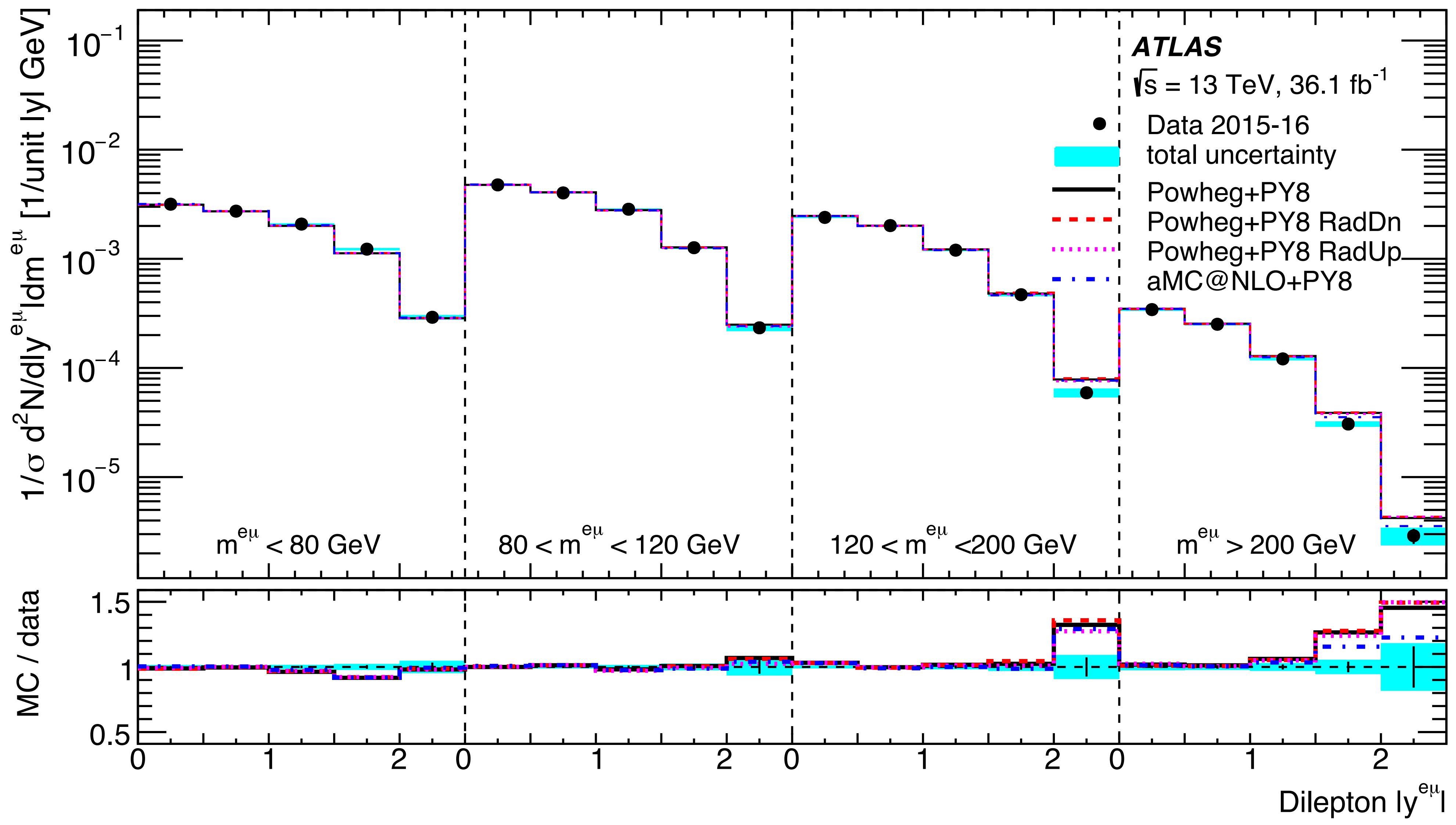
arXiv:1910.08819

- 1D and 2D normalized diff. cross-section measurement as a function of lepton and dilepton kinematic variables and compared with several MC generators
- Disagreements between unfolded data and MC predictions are found mostly in the tails (lower or higher) of leptonic and dileptonic observables









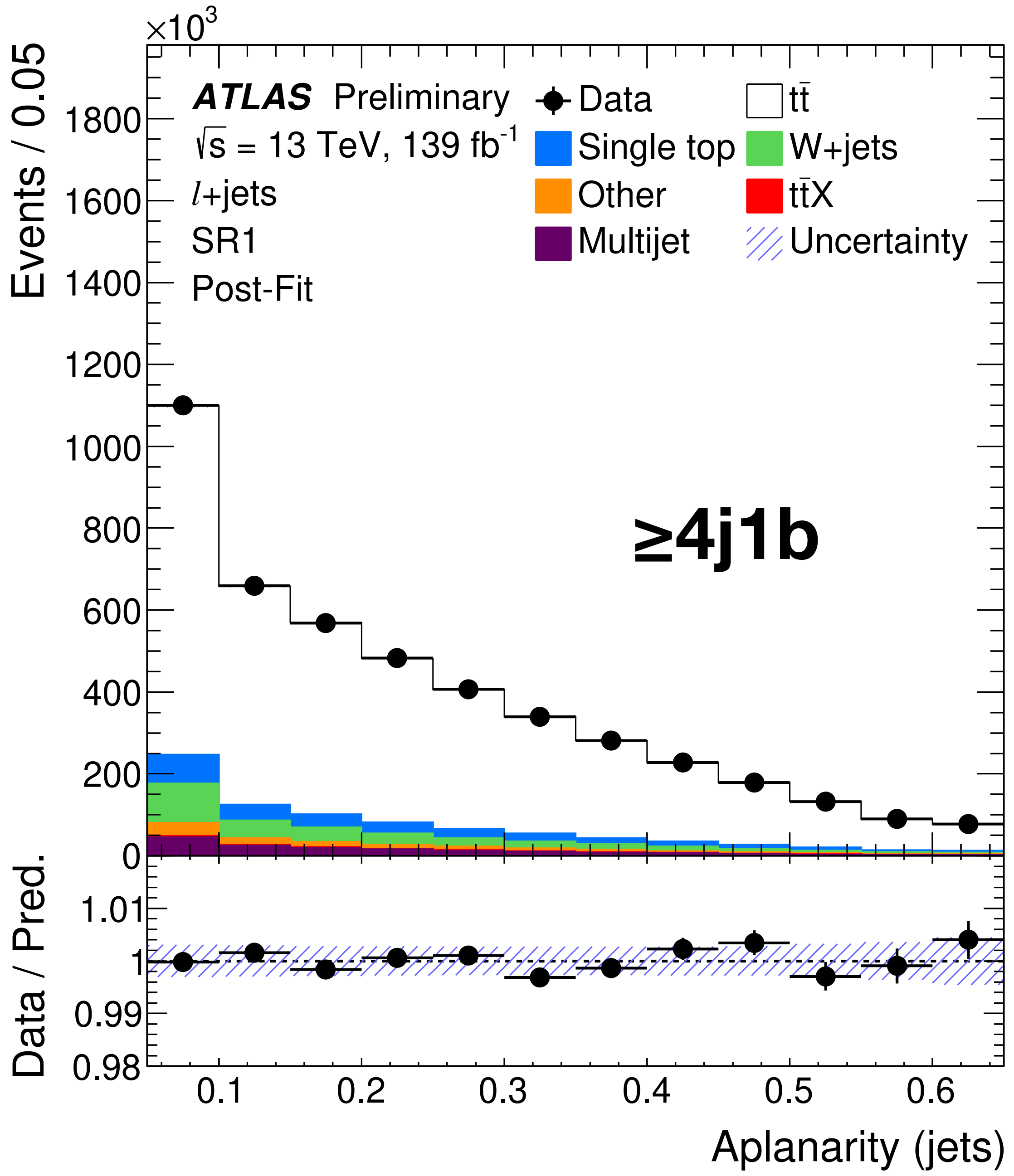
$\sigma_{t\bar{t}}$ (ℓ + jets)

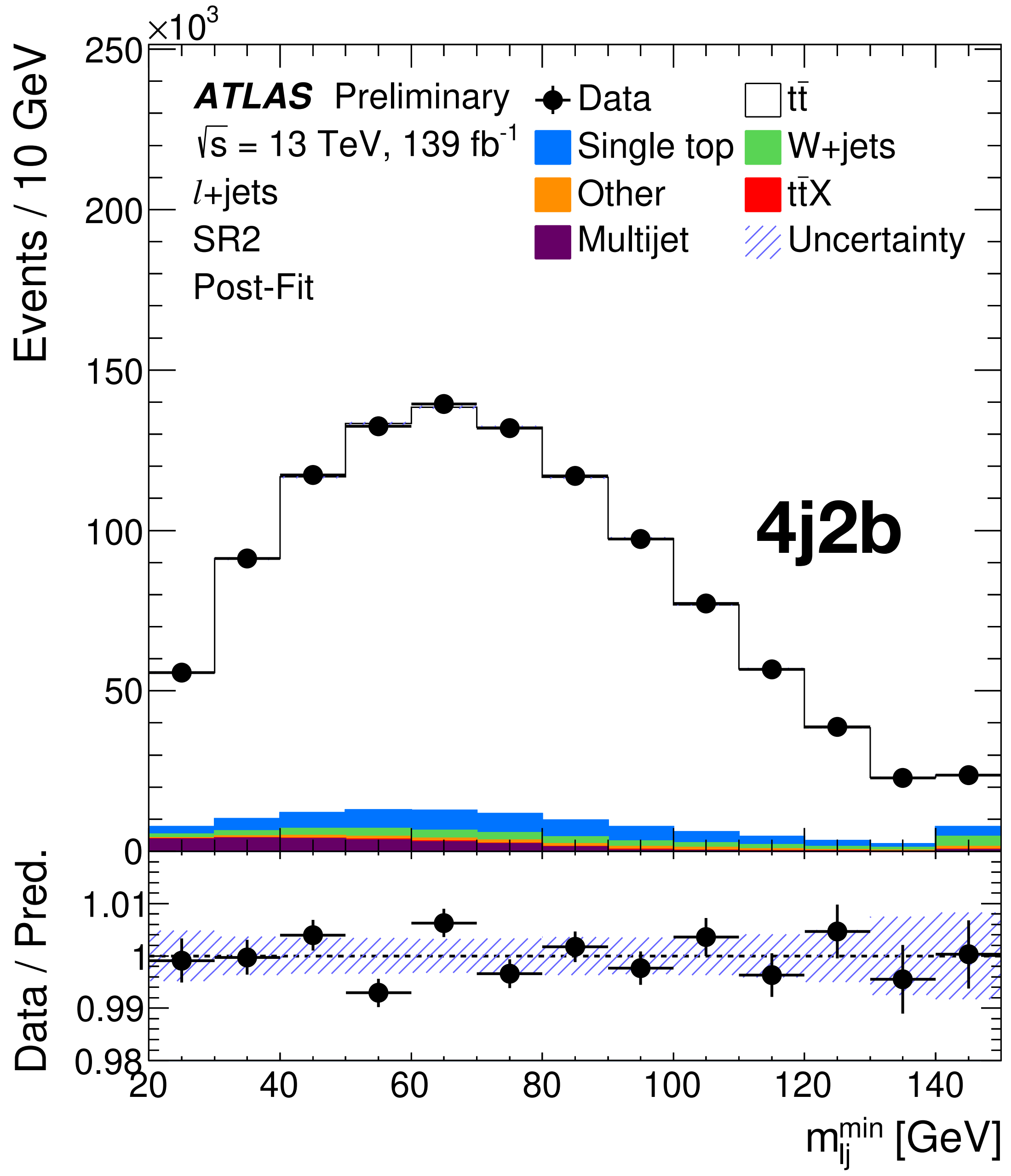
ATLAS-CONF-2019-044

- Analysis with full Run2 data (139 fb^{-1})
- Event Selection:
  ➛ 1 lepton (e or μ) + ≥ 4 jets (≥ 1 b-jet)
- PLH fit to different distributions in 3 signal-enriched regions (≥4j1b, 4j2b, ≥5j2b)
  ➛ small sensitivity to $t\bar{t}$ modeling uncertainties
- Systematic sources included as nuisance parameters and constrained in the fit

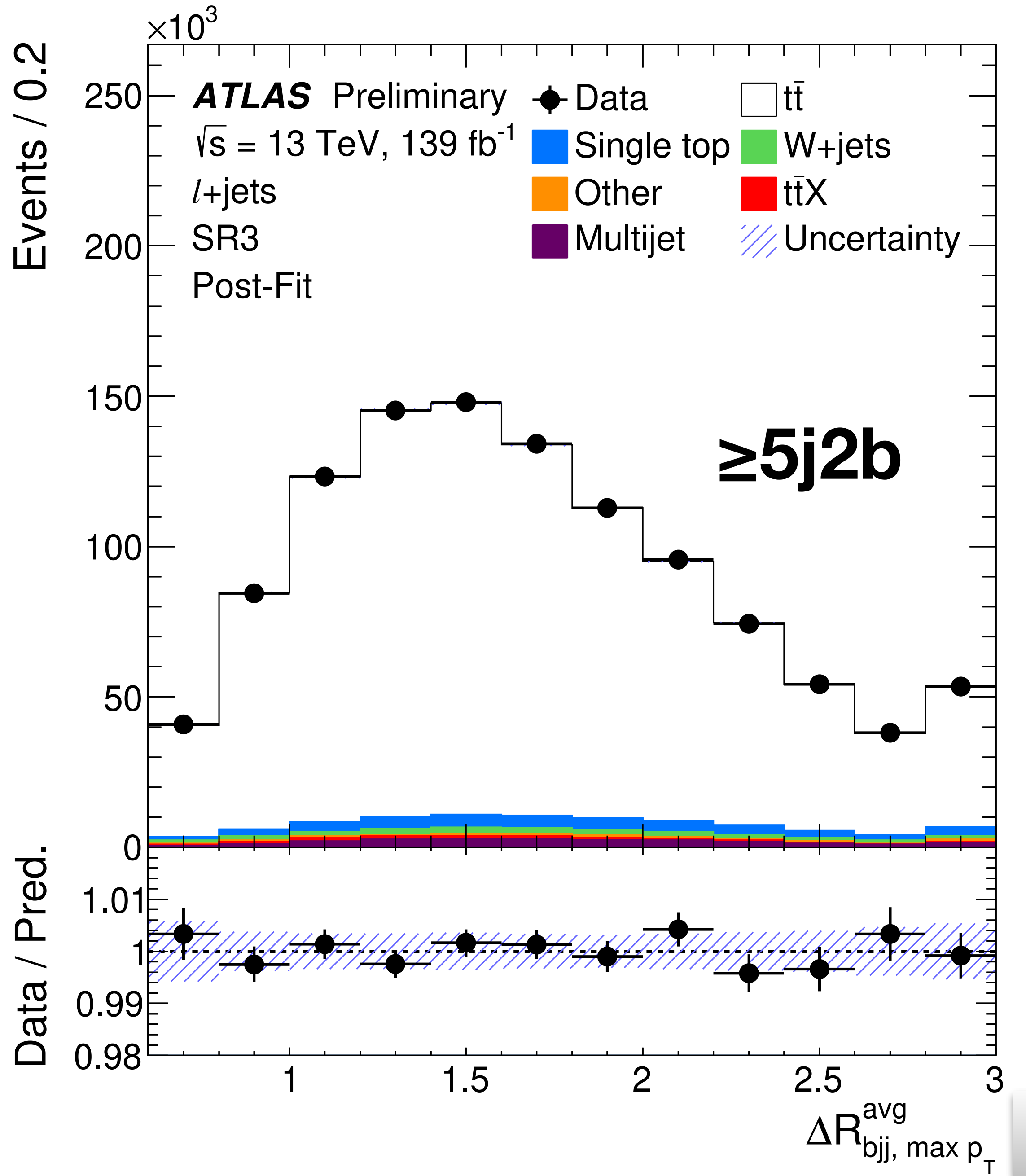
$$\sigma_{t\bar{t}}(\ell + \text{jets}) = 829.7 \pm 0.4\,(\text{stat})^{+35.3}_{-34.5}\,(\text{syst})\,\text{pb}\,(4.6\%)$$

- Similar level of uncertainty obtained in the measured σ_{fid}
- In agreement with NNLO + NNLL prediction (unc. 5.7%)





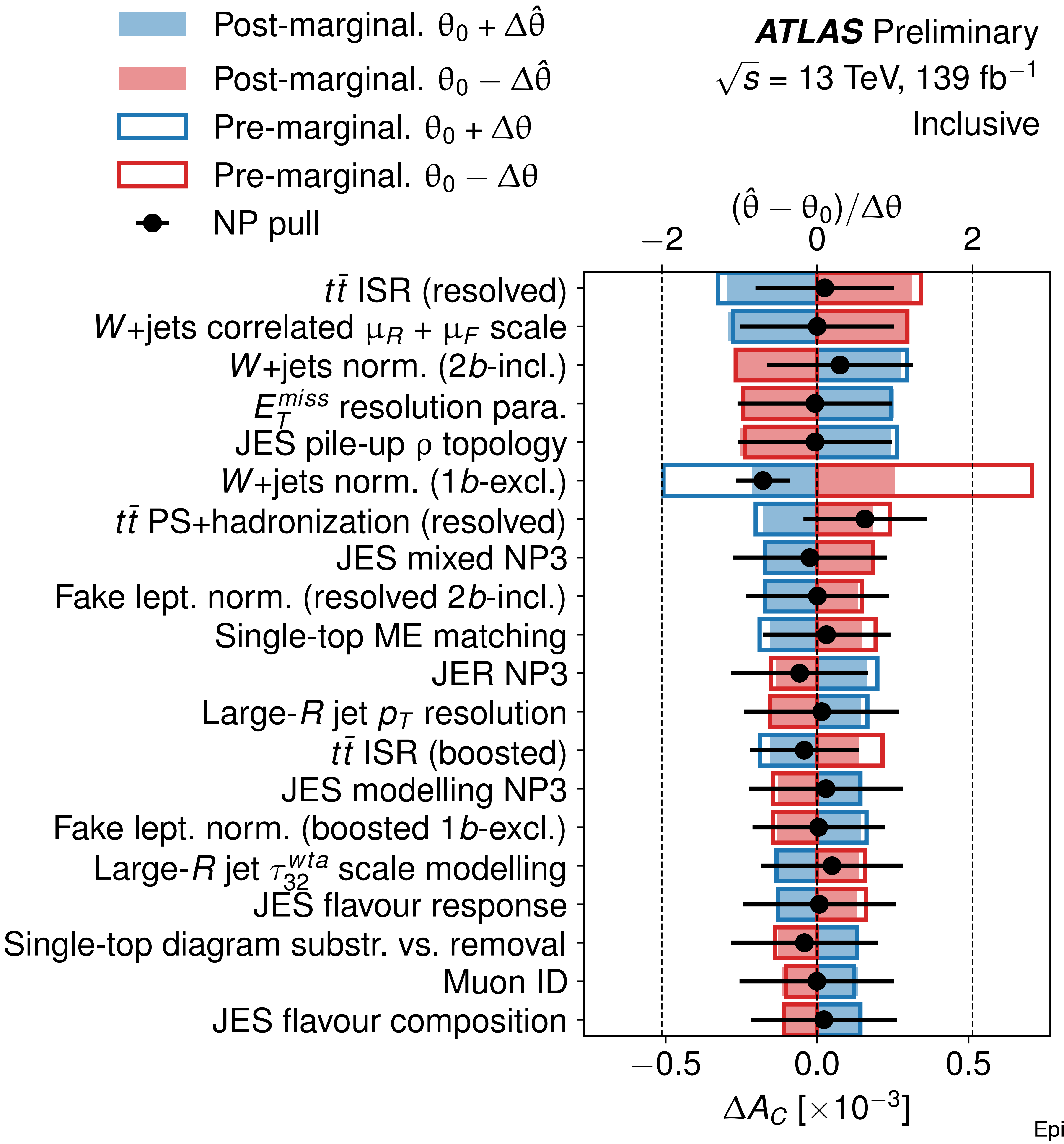
Category	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]		$\frac{\Delta\sigma_{\text{inc}}}{\sigma_{\text{inc}}}$ [%]	
Signal modelling				
$t\bar{t}$ shower/hadronisation	+2.1	−1.9	+2.7	−2.7
$t\bar{t}$ scale variations	+2.0	−1.8	+2.5	−2.6
Background modelling				
MC background modelling	+1.8	−1.7	+1.6	−1.8
Multijet background	+0.5	−0.6	+0.6	−0.7
Detector modelling				
Jet reconstruction	+2.4	−2.3	+2.5	−2.3
Luminosity	+1.8	−1.7	+1.8	−1.6
Flavour tagging	+1.4	−1.4	+1.5	−1.4
E_T^{miss} + pile-up	+0.3	−0.2	+0.5	−0.5
Muon reconstruction	+0.4	−0.6	+0.4	−0.5
Electron reconstruction	+0.4	−0.2	+0.2	−0.4
Simulation stat. uncertainty	+0.7	−0.6	+0.9	−0.9
Total systematic uncertainty	+4.1	−3.9	+4.6	−4.5
Data stat. uncertainty	+0.05	−0.05	+0.05	−0.05
Total uncertainty	+4.1	−3.9	+4.6	−4.5



Dominant uncertainties for A_C and A_{FB} measurements

ATLAS-CONF-2019-026

arXiv:1912.09540



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

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

Comparison between CMS and ATLAS measurements of SM tZq

ATLAS-CONF-2019-043

$$\sigma(t\ell^+\ell^-q) = 98 \pm 12\,(\text{stat}) \pm 8\,(\text{syst})\,\text{fb}\,(15\%)$$

Uncertainty source	$\Delta\sigma/\sigma$ [%]
tZq PDF	4.2
Prompt lepton background modelling and normalisation	3.4
Non-prompt lepton background modelling and normalisation	2.3
Jets+E_T^{miss}	2.1
Luminosity	1.7
Lepton reconstruction and calibration	1.7
Pile-up	1.2
MC statistics	1.0
tZq QCD radiation	0.8
b-tagging	0.4
Total systematic uncertainty	8.0
Statistical uncertainty	12

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$$\sigma(t\ell^+\ell^-q) = 111 \pm 13\,(\text{stat})^{+11}_{-9}\,(\text{syst})\,\text{fb}\,(15\%)$$

Uncertainty	Impact (%)
Experimental	
lepton selection	3.2
trigger efficiency	1.4
jet energy scale	3.3
b-tagging efficiency	1.7
nonprompt normalization	4.1
$t\bar{t}$Z normalization	1.0
luminosity	1.7
pileup	1.9
other	1.3
Theoretical	
final-state radiation	2.0
tZq QCD scale	2.0
$t\bar{t}$Z QCD scale	1.4

BDT inputs for ATLAS measurement of SM tZq

ATLAS-CONF-2019-043

Variable	Rank SR 2j1b	Rank SR 3j1b	Definition
$m_{b\mathrm{j_f}}$	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\lvert\eta(\mathrm{j_f})\rvert$	3	3	Absolute value of the η of the $\mathrm{j_f}$ jet
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	4	4	Transverse mass of the W boson
b-tagging score	5	11	b-tagging score of the b-jet
H_{T}	6	–	Scalar sum of the p_{T} of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W-boson decay
$\lvert\eta(\ell_W)\rvert$	8	12	Absolute value of the η of the lepton from the W-boson decay
$p_{\mathrm{T}}(W)$	9	15	p_{T} of the reconstructed W boson
$p_{\mathrm{T}}(\ell_W)$	10	14	p_{T} of the lepton from the W-boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$\lvert\eta(Z)\rvert$	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(\mathrm{j_f}, Z)$	13	7	ΔR between the $\mathrm{j_f}$ jet and the reconstructed Z boson
$E_{\mathrm{T}}^{\mathrm{miss}}$	14	–	Missing transverse momentum
$p_{\mathrm{T}}(\mathrm{j_f})$	15	10	p_{T} of the $\mathrm{j_f}$ jet
$\lvert\eta(\mathrm{j_r})\rvert$	–	5	Absolute value of the η of the $\mathrm{j_r}$ jet
$p_{\mathrm{T}}(Z)$	–	6	p_{T} of the reconstructed Z boson
$p_{\mathrm{T}}(\mathrm{j_r})$	–	9	p_{T} of the $\mathrm{j_r}$ jet

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Variable	Description
Light-quark jet $\|\eta\|$	Absolute value of the pseudorapidity of the light-quark jet
Dijet mass	Invariant mass of the light-quark jet and the b-tagged jet associated to the top quark decay
Top quark mass	Invariant mass of the top quark reconstructed from the lepton, the neutrino and the b-tagged jet associated to the top quark decay
ΔR (lepton, b jet)	ΔR between the momentum vectors of the lepton and the b-tagged jet associated to the top quark decay
$\cos(\theta^*)$	Cosine of the angle between the lepton and the light-quark jet in the rest frame of the top quark
Jet p_{T} sum	Scalar sum of the transverse momentum of the light-quark jet and the b-tagged jet associated to the top quark decay
$m_{\mathrm{T}}^{\mathrm{W}}$	Transverse mass of the W boson
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing momentum in the transverse plane of the event
ΔR (light jet, b jet)	ΔR between the momentum vectors of the light-quark jet and the b-tagged jet associated to the top quark decay
Lepton $\|\eta\|$	Absolute value of the pseudorapidity of the selected lepton
W boson $\|\eta\|$	Absolute value of the pseudorapidity of the reconstructed W boson
Light-quark jet mass	Invariant mass of the light-quark jet

	$\Delta R_{t\text{-ch}}/R_{t\text{-ch}}$	$\Delta\sigma/\sigma(\mathrm{t})$	$\Delta\sigma/\sigma(\bar{\mathrm{t}})$
Nonprofiled uncertainties			
$\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ scale t channel	0.1	6.2	6.5
ME-PS scale matching t channel	0.5	2.9	2.3
PS scale t channel	0.6	12.9	13.3
PDF t channel	2.4	7.1	9.5
Luminosity	—	2.5	2.5
Profiled uncertainties			
JES	0.5	1.7	2.1
JER	0.2	0.1	0.3
Unclustered energy	0.2	0.1	0.3
b tagging	0.1	1.2	1.2
Muon and electron efficiencies	0.2	1.1	1.0
Pileup	0.4	0.9	1.2
QCD bkg. normalization	0.2	0.3	0.5
MC sample size	2.6	2.3	3.3
$\mathrm{t\bar{t}}$ bkg. model and normalization	0.6	1.1	1.5
Top quark p_{T}	< 0.1	0.5	0.5
tW bkg. normalization	0.1	0.4	0.5
W/Z+jets bkg. normalization	0.2	0.3	0.5
$\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ scale $\mathrm{t\bar{t}}$, tW, W/Z+jets	0.8	0.3	0.5
PDF $\mathrm{t\bar{t}}$, W/Z+jets	0.6	0.2	0.7

CMS-PAS-TOP-17-012

Treatment	Uncertainty	$\Delta\sigma/\sigma(\%)$
Profiled	Lepton trigger and reconstruction	0.50
	Limited size of samples of simulated events	3.13
	$t\bar{t}$ modelling	0.66
	Pileup	0.35
	QCD background normalization	0.08
	W+jets composition	0.13
	Other backgrounds μ_R/μ_F	0.44
	PDF for background processes	0.42
	b-tagging	0.73
	Total profiled	3.4
Nonprofiled	Luminosity	2.6
	JER	2.8
	JES	8.0
	PDF for signal process	3.8
	Signal μ_R/μ_F	2.4
	ME-PS matching	3.7
	Parton shower scale	6.1
	Total nonprofiled	11.5
Total uncertainty		12.0

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$$O_{\phi q}^{(3)} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q),$$

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

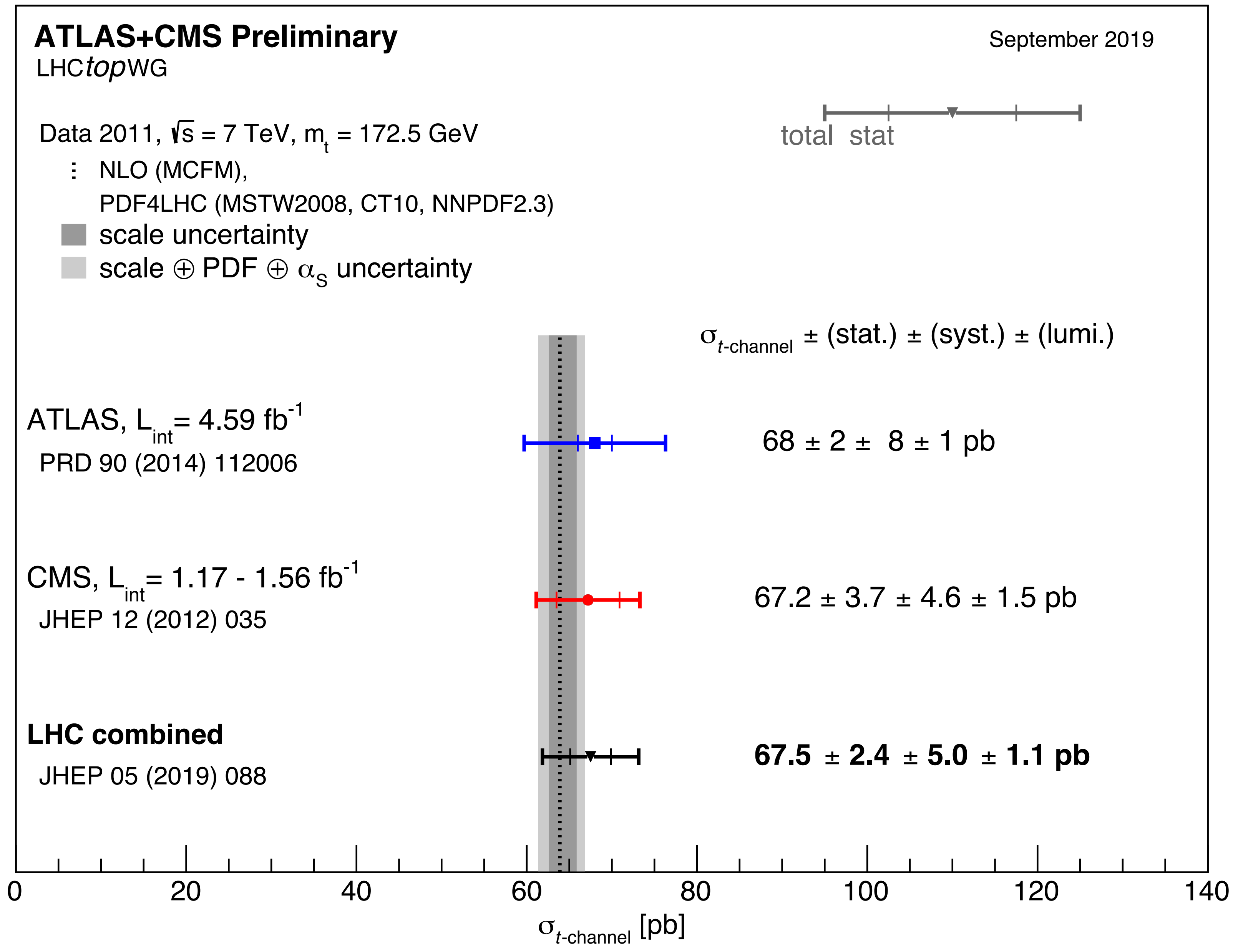
$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu},$$

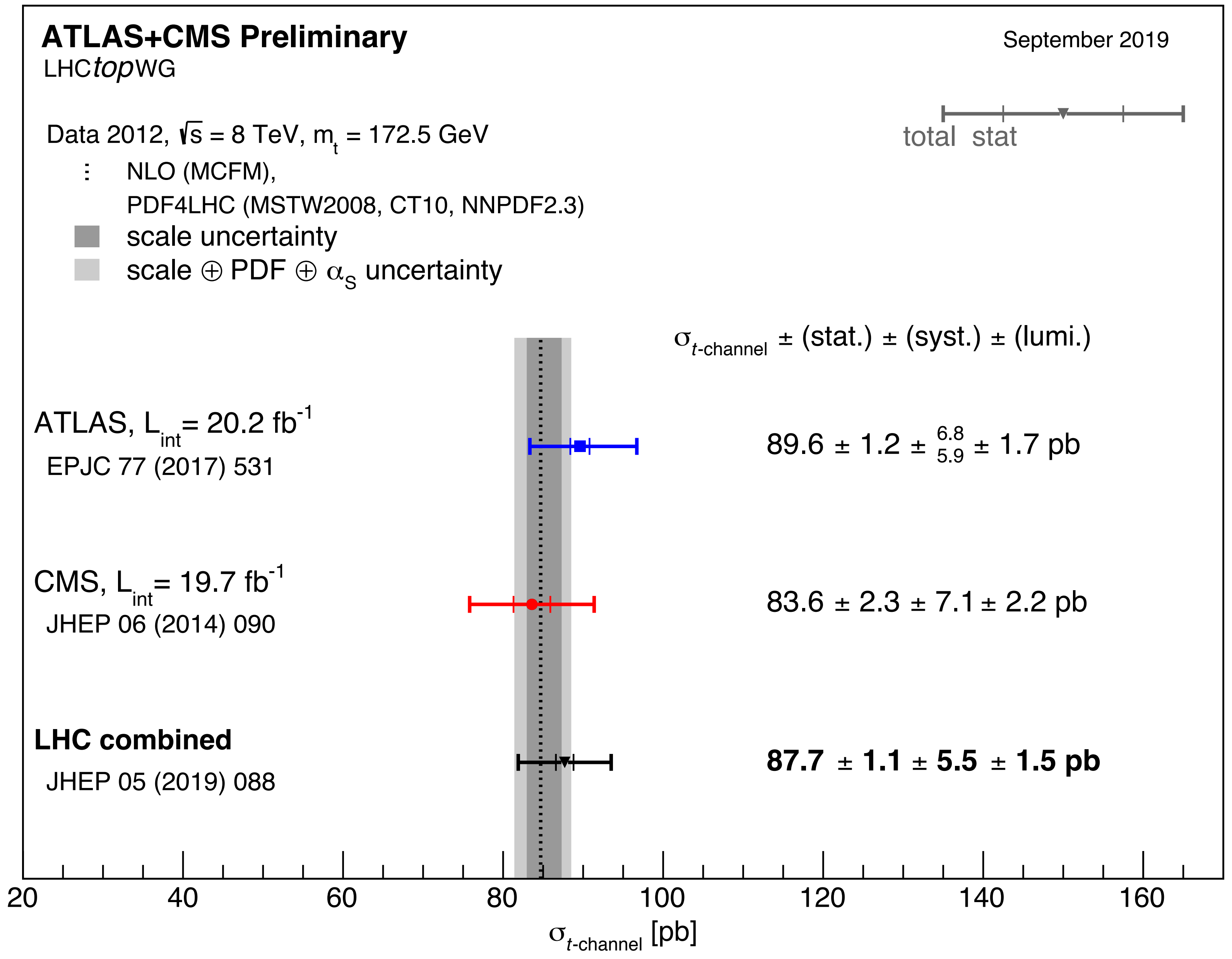
$$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu},$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu},$$

Run1 combination of $\sigma_{t\text{-ch.}}$ measurements at LHC

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





$\sigma_{t\text{-chan.}}, \sqrt{s} = 7$ TeV		
Combined cross-section	67.5 pb	
Uncertainty category	Uncertainty [%]	Uncertainty [pb]
Data statistical	3.5	2.4
Simulation statistical	1.4	0.9
Integrated luminosity	1.7	1.1
Theory modelling	5.1	3.5
Background normalisation	1.9	1.3
Jets	3.4	2.3
Detector modelling	3.4	2.3
Total syst. unc. (excl. lumi.)	7.5	5.0
Total syst. unc. (incl. lumi.)	7.6	5.2
Total uncertainty	8.4	5.7

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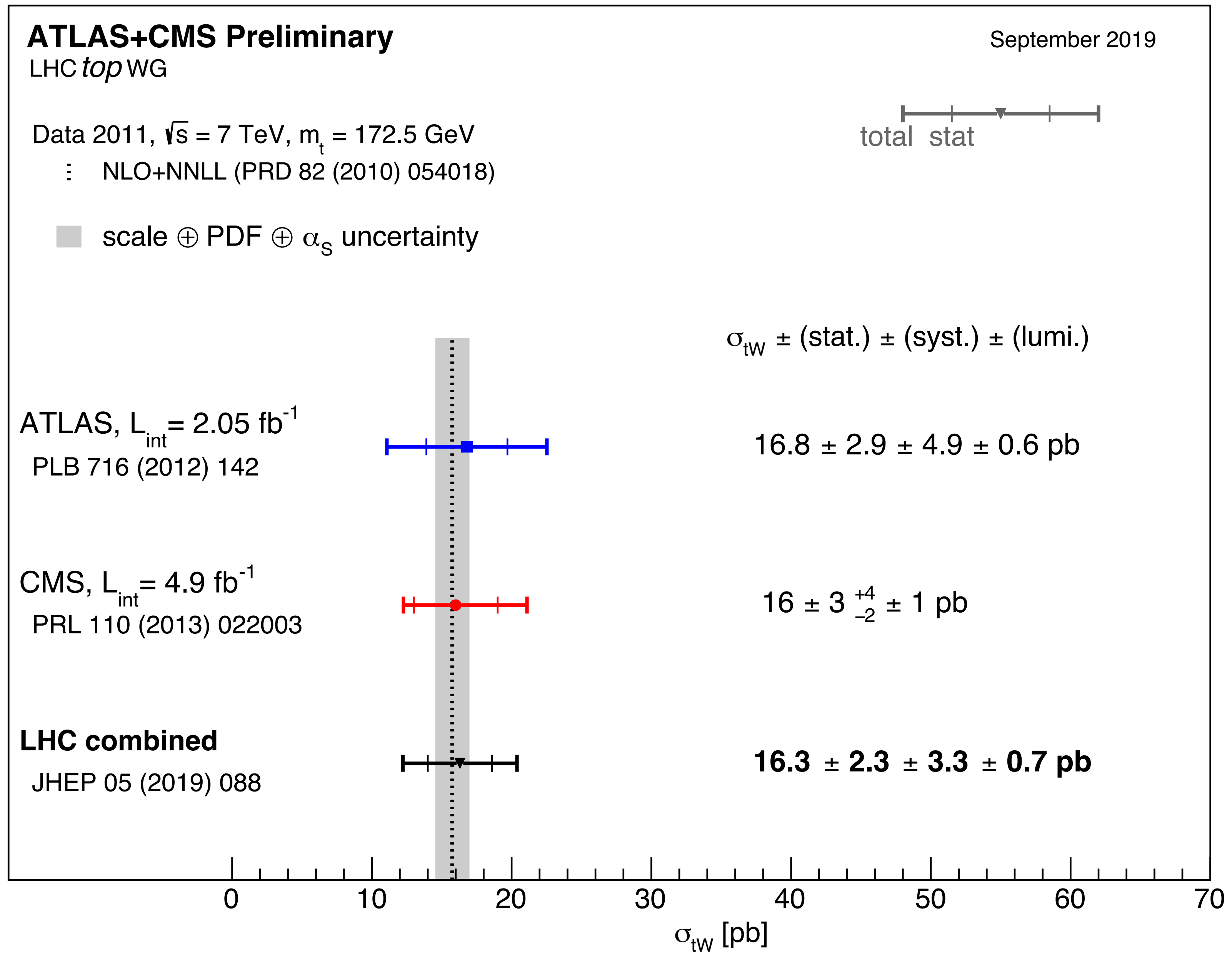
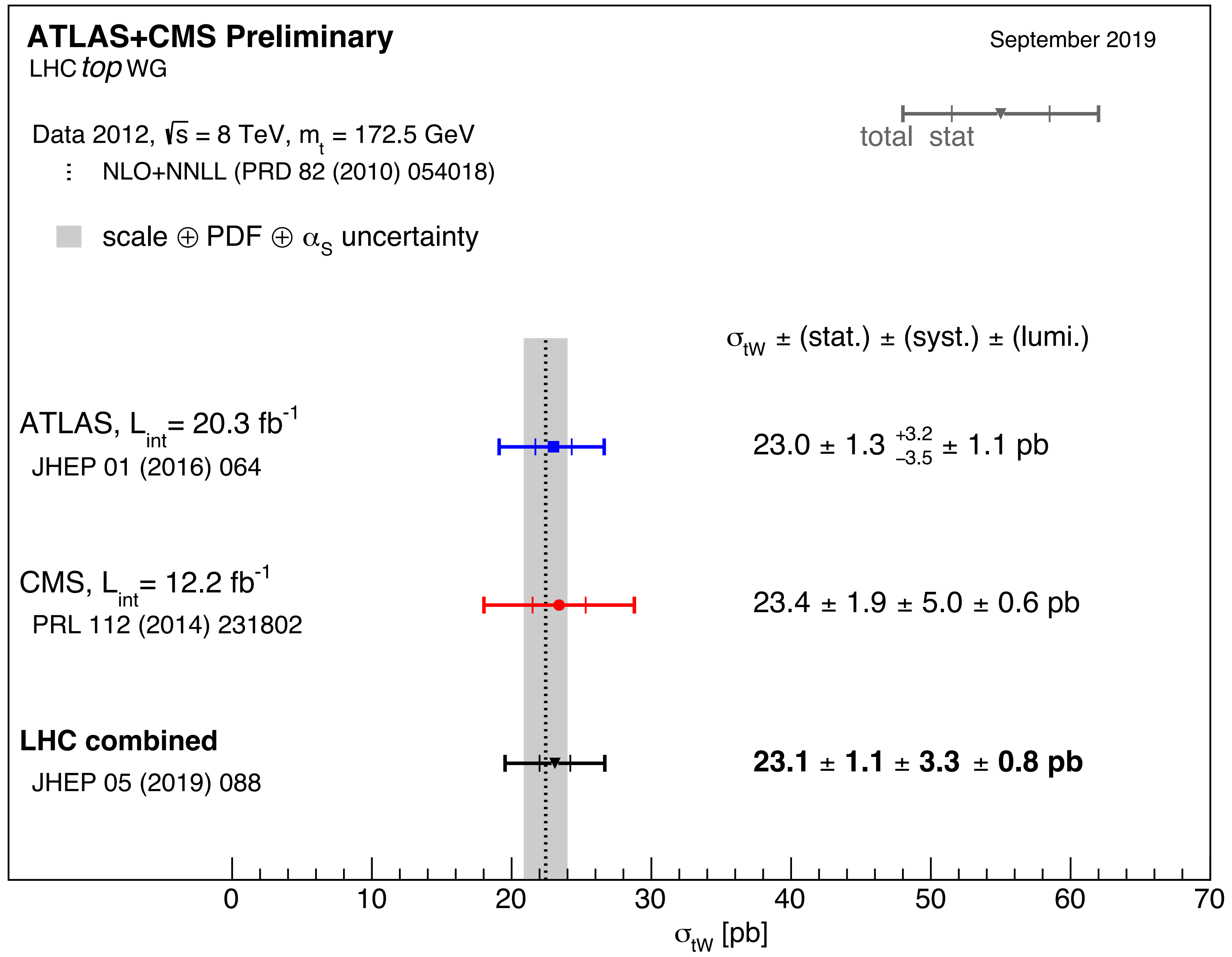
$\sigma_{t\text{-chan.}}, \sqrt{s} = 8$ TeV		
Combined cross-section	87.7 pb	
Uncertainty category	Uncertainty [%]	Uncertainty [pb]
Data statistical	1.3	1.1
Simulation statistical	0.6	0.5
Integrated luminosity	1.7	1.5
Theory modelling	5.3	4.7
Background normalisation	1.2	1.1
Jets	2.6	2.3
Detector modelling	1.8	1.6
Total syst. unc. (excl. lumi.)	6.3	5.5
Total syst. unc. (incl. lumi.)	6.5	5.7
Total uncertainty	6.7	5.8

Run1 combination of σ_{tW} measurements at LHC

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





σ_{tW}, $\sqrt{s} = 7$ TeV

Combined cross-section	16.3 pb	
Uncertainty category	Uncertainty [%]	Uncertainty [pb]
Data statistical	14.0	2.3
Simulation statistical	0.8	0.1
Integrated luminosity	4.4	0.7
Theory modelling	13.9	2.3
Background normalisation	6.0	1.0
Jets	11.5	1.9
Detector modelling	6.2	1.0
Total syst. unc. (excl. lumi.)	20.0	3.3
Total syst. unc. (incl. lumi.)	20.5	3.3
Total uncertainty	24.8	4.1

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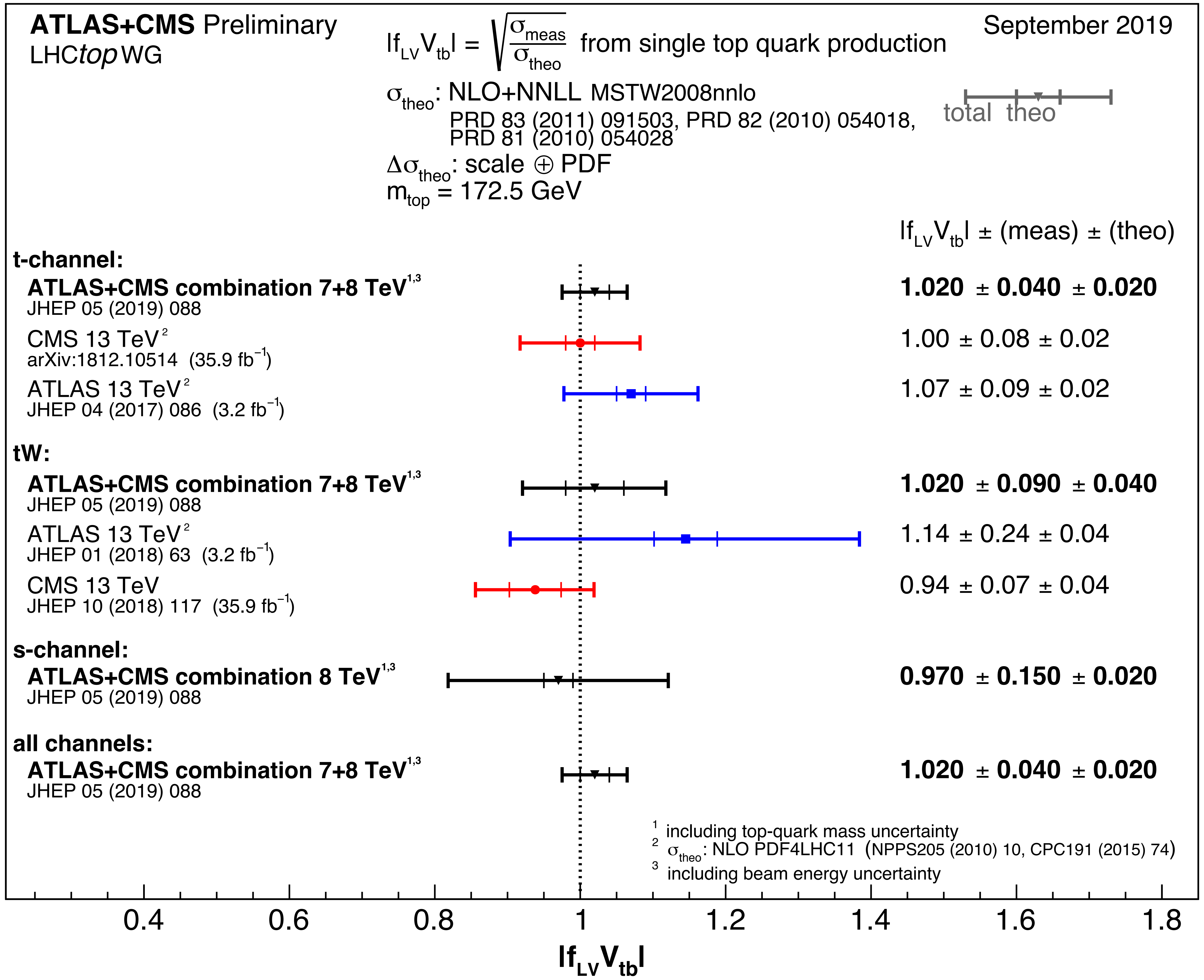
σ_{tW}, $\sqrt{s} = 8$ TeV

Combined cross-section	23.1 pb	
Uncertainty category	Uncertainty [%]	Uncertainty [pb]
Data statistical	4.7	1.1
Simulation statistical	0.8	0.2
Integrated luminosity	3.6	0.8
Theory modelling	11.8	2.7
Background normalisation	2.2	0.5
Jets	6.2	1.4
Detector modelling	4.9	1.1
Total syst. unc. (excl. lumi.)	14.4	3.3
Total syst. unc. (incl. lumi.)	14.8	3.4
Total uncertainty	15.6	3.6

Run1 combination of $|V_{tb}|$ measurements at LHC

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



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Combined $|f_{LV}V_{tb}|^2$	1.05	
Uncertainty category	Uncertainty	
	[%]	$\Delta|f_{LV}V_{tb}|^2$
Data statistical	1.8	0.02
Simulation statistical	0.9	0.01
Integrated luminosity	1.3	0.01
Theory modelling	4.5	0.05
Background normalisation	1.3	0.01
Jets	2.6	0.03
Detector modelling	1.6	0.02
Top-quark mass	0.7	0.01
Theoretical cross-section	4.3	0.04
Total syst. unc. (excl. lumi.)	7.1	0.07
Total syst. unc. (incl. lumi.)	7.2	0.08
Total uncertainty	7.4	0.08

Evidence of *s*-ch. single top process at 8 TeV

[PLB 756 (2016) 228 -246](PLB 756 (2016) 228 -246)

- Lepton + 2 b-jet final state (2j2b) with 20.3 fb^{-1} data at $\sqrt{s}$ = 8 TeV
- Dominant backgrounds :
  ➛ $t\bar{t}$, *t*-ch. single top, W+bb
- Matrix-element-method to separate signal from bkgs.
  ➛approximate signal probability P(S|X)
- Profile likelihood fit of signal and bkg. templates of P(S|X)
- Test of B vs S+B hypotheses
  ➛ evidence with 3.2σ

$$\sigma = 4.8 \pm 0.8\,(\mathrm{stat})^{+1.6}_{-1.3}\,(\mathrm{syst})\,\mathrm{pb}$$

$$\sigma_{\mathrm{SM}} = 5.2 \pm 0.2\,\mathrm{pb}$$

- Precision limited by data statistics