Top Quark Properties

Efe Yazgan (National Taiwan University)
on behalf of ATLAS and CMS Collaborations

The Top Quark

- The most massive elementary particle known to date.
  - Very short lifetime.

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5 \times 10^{-24} s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda^2_{QCD}} \sim 3 \times 10^{-21} s << \tau_b \sim 10^{-12} s$$

$$\tau_t < \tau(\text{hadronization}) < \tau(\text{spin-decorrelation}) << \tau_b$$

No hadronic bound states
—> quark properties accessible

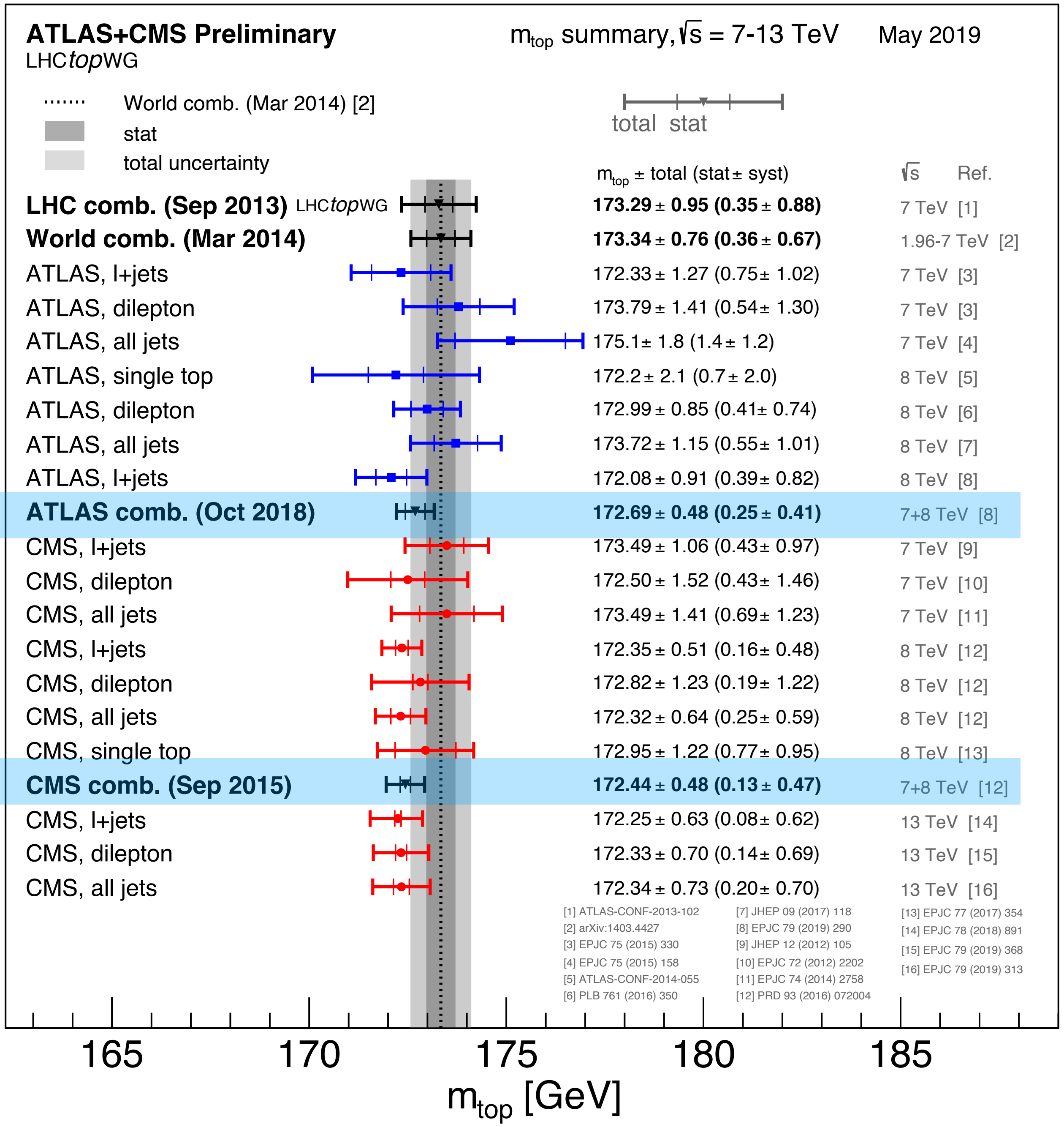
top quark spins
stay correlated

All public results at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Recent measurements from ATLAS and CMS

Top quark mass and width - Yukawa coupling - CKM matrix elements - Asymmetries - Spin correlations- W boson polarization

Top Quark Mass Extraction from Decay (« Direct »)



- More recent measurements not included yet:
- ATLAS: l+jets at 13 TeV
  - from soft muon tags

ATLAS-CONF-2019-046

$$m_t = 174.48 \pm 0.78\ GeV$$
$$(rel.unc. = 0.45\%)$$

(more details later)

- CMS: all-jets + l+jets at 13 TeV
  - m_t determined simultaneously with JES (for both channels) in a joint likelihood fit

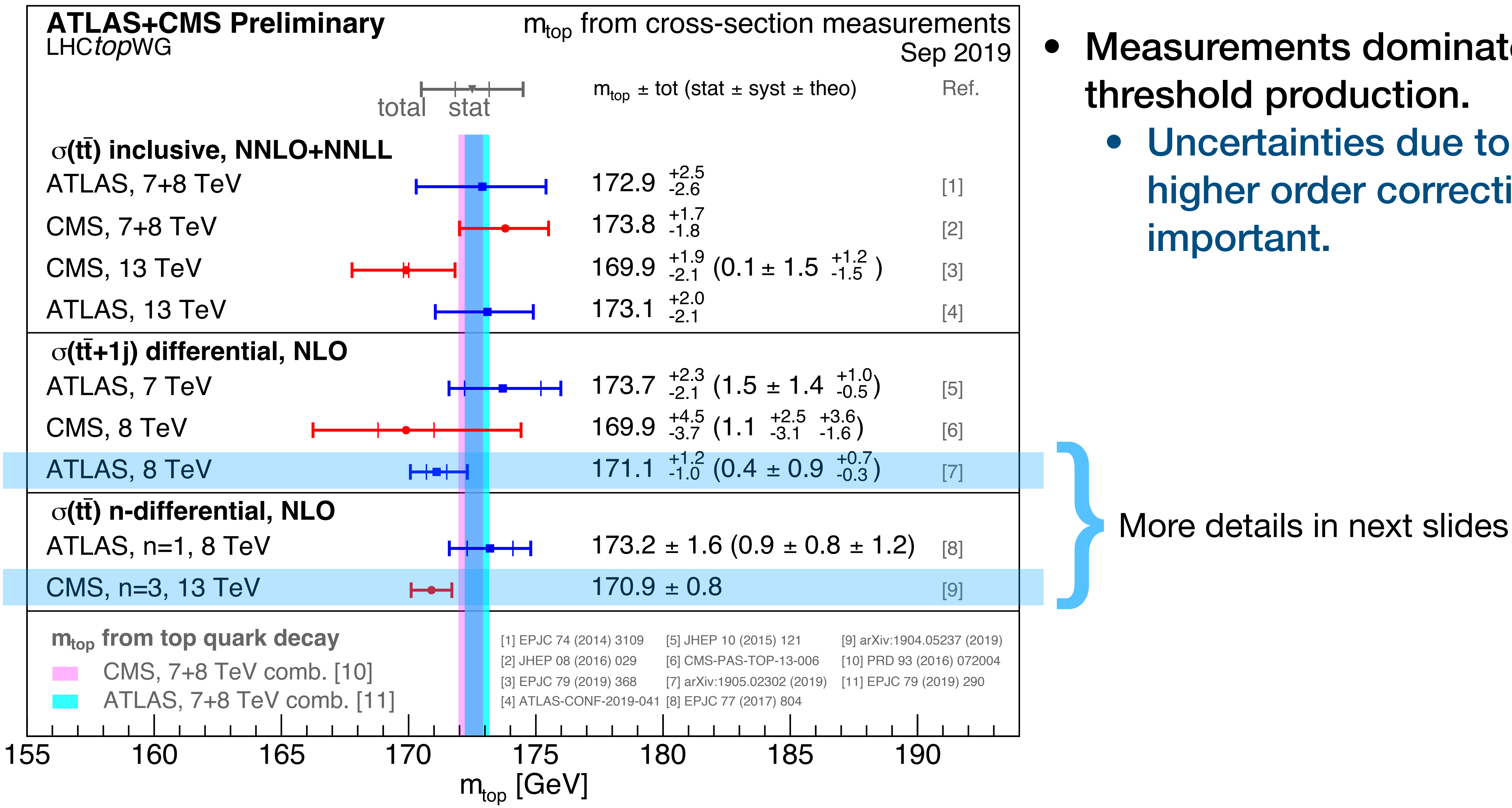
$$m_t = 172.26 \pm 0.61\ GeV$$
$$(rel.\ unc. = 0.36\%)$$

EPJ C 79 (2019) 313

- Combined measurements precision ~ 500 MeV —> 0.28% (ATLAS & CMS)
  - Limited by jet energy scale calibration, b-tagging and modelling uncertainties.
- Many individual measurements with < 1 GeV uncertainty at Run I and Run II.
- Interpretation of top mass measurements is complicated by non-perturbative effects ~0.5-1 GeV.
  - Important to measure top mass in well-defined mass schemes and with independent methods.

Top Mass Extraction from Production Observables

total and differential ttbar cross sections



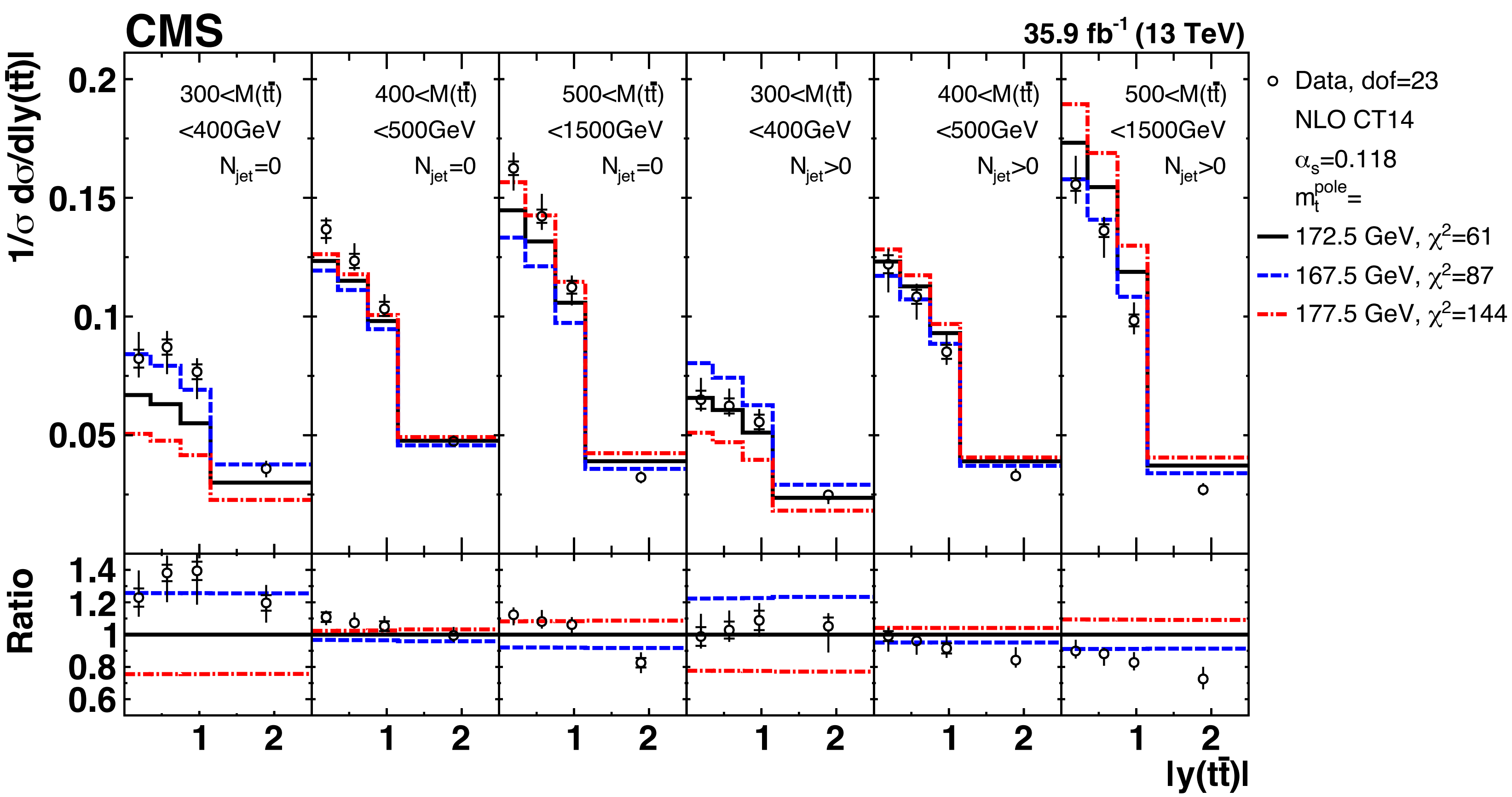
- **Measurements dominated by tt threshold production.**
  - **Uncertainties due to PDFs and higher order corrections are important.**

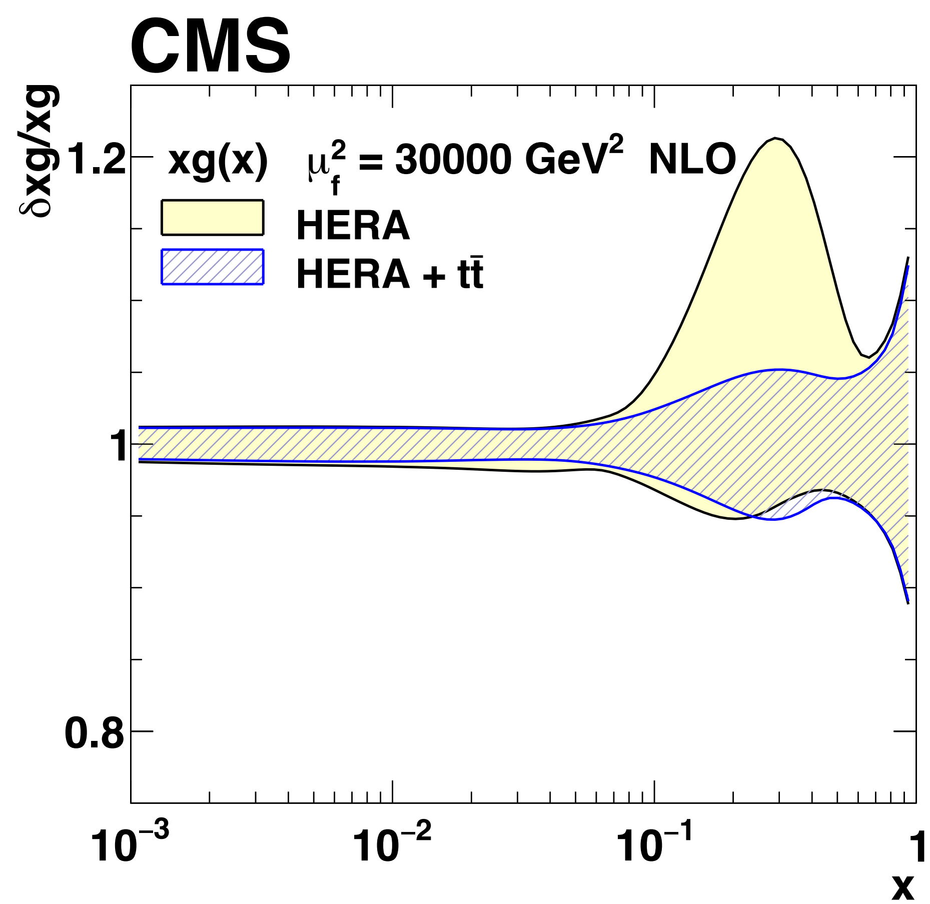
Top Mass from Multi-Differential Cross Sections

arXiv:1904.05237
Accepted by EPJC

Triple-differential normalised cross sections
$N_{jet}^{0,1+}, \ M(t\bar{t}), \ y(t\bar{t})$
+ HERA DIS data

} Simultaneous fit of PDF, α_s and m_t at NLO





Most (but not the only) sensitive region: $M_{t\bar{t}} \sim 2m_t$

Significant impact on the gluon PDF at high x.

$$m_t^{pole} = 170.5 \pm 0.8 \ \mathrm{GeV}$$

$$\alpha_s = 0.1135^{+0.0021}_{-0.0017}$$

Precision = 0.5%

Dominated by experimental and modelling uncertainties.

(possible effects from Coulomb and soft-gluon resummation near $2m_t$ are not studied in detail - effects known only with large uncertainty in cross section.)

Piclum & Schwinn, JHEP 03 (2018) 164

Top Mass from differential distributions

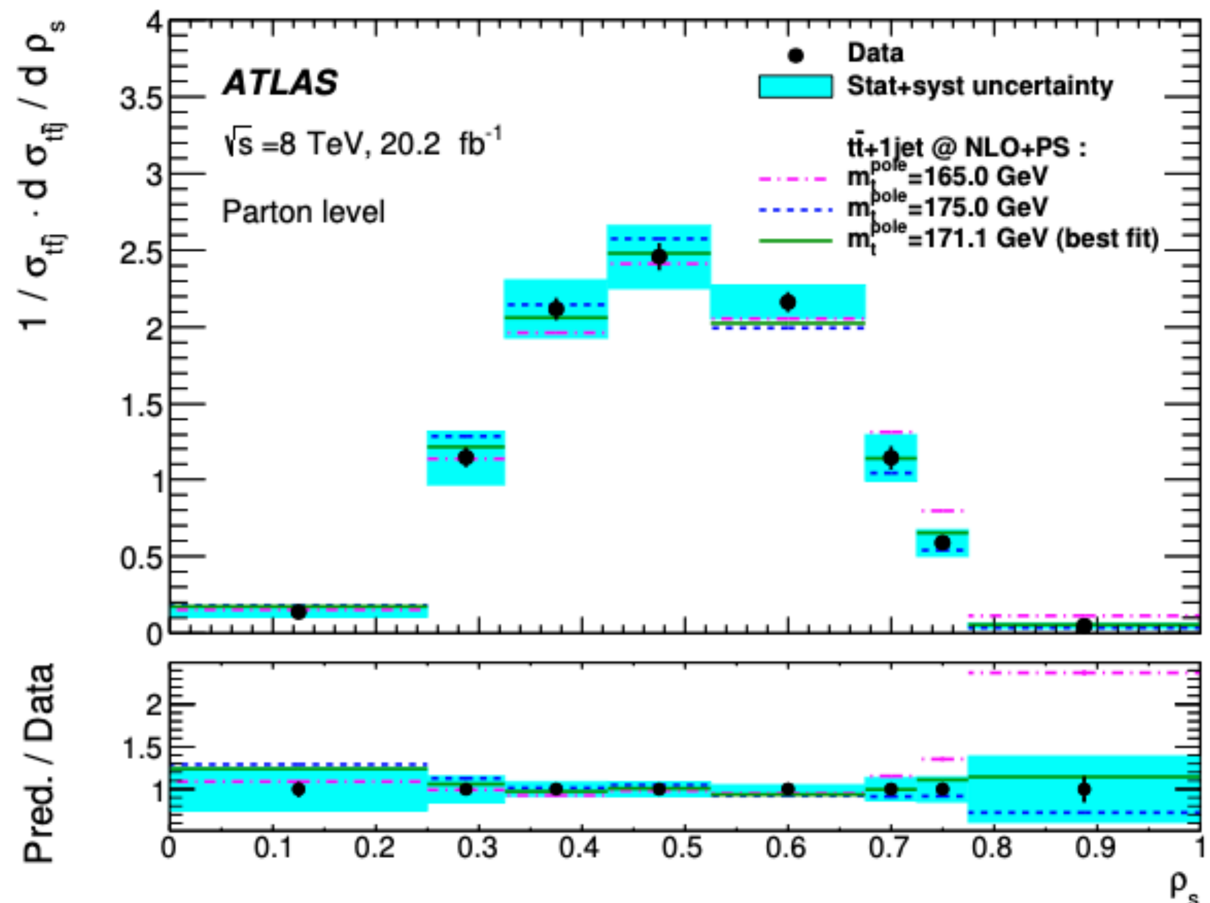
JHEP 11 (2019) 150

- Extract top mass using tt+1 jet events in lepton+jets channel.
- Parton level distribution is compared with QCD NLO+PS calculations to extract MSbar and pole mass.

$$R(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1jet}} \frac{d\sigma_{t\bar{t}+1jet}}{d\rho_s}$$

$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1\ \mathrm{jet}}}, \quad m_0 = 170\ \mathrm{GeV}$$

Reconstruction: b-jets + W boson candidates + the additional jet.



$$m_t(m_t) = 162.9 \pm 0.5(stat) \pm 1.0(syst)^{+2.1}_{-1.2}(theo)\ GeV$$
$$m_t^{pole} = 171.1 \pm 0.4(stat) \pm 0.9(syst)^{+0.7}_{-0.3}(theo)\ GeV$$

$$m_t^{\mathrm{pole}} = m_t(m_t)\left(1 + \frac{4}{3}\frac{\alpha_s(\mu = m_t)}{\pi}\right) + \mathcal{O}(\alpha_s^2)$$

$m_t(m_t)$ translated to m_t^{pole} is in good agreement w/ the extracted value.

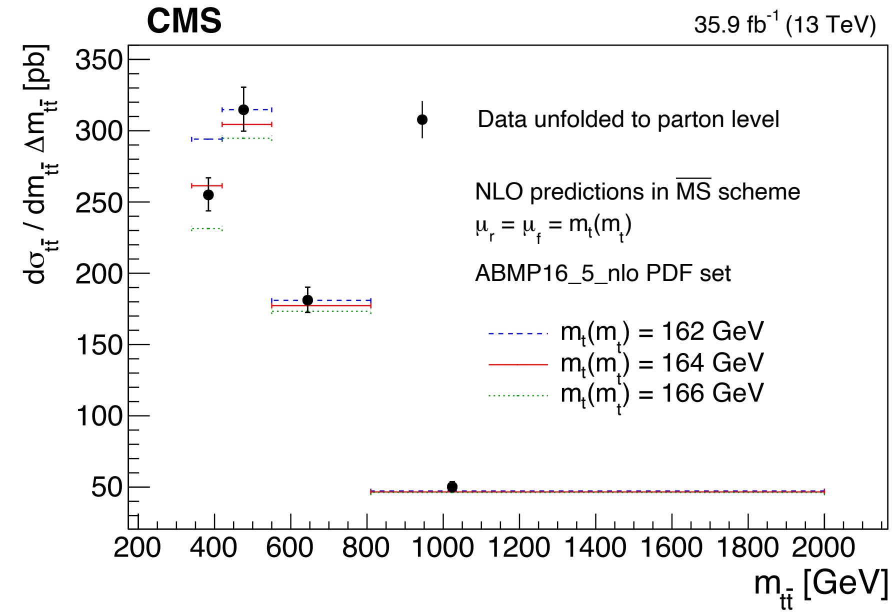
Scales, PDFs, parton shower, color reconnection, and jet energy scale are the dominant uncertainties.

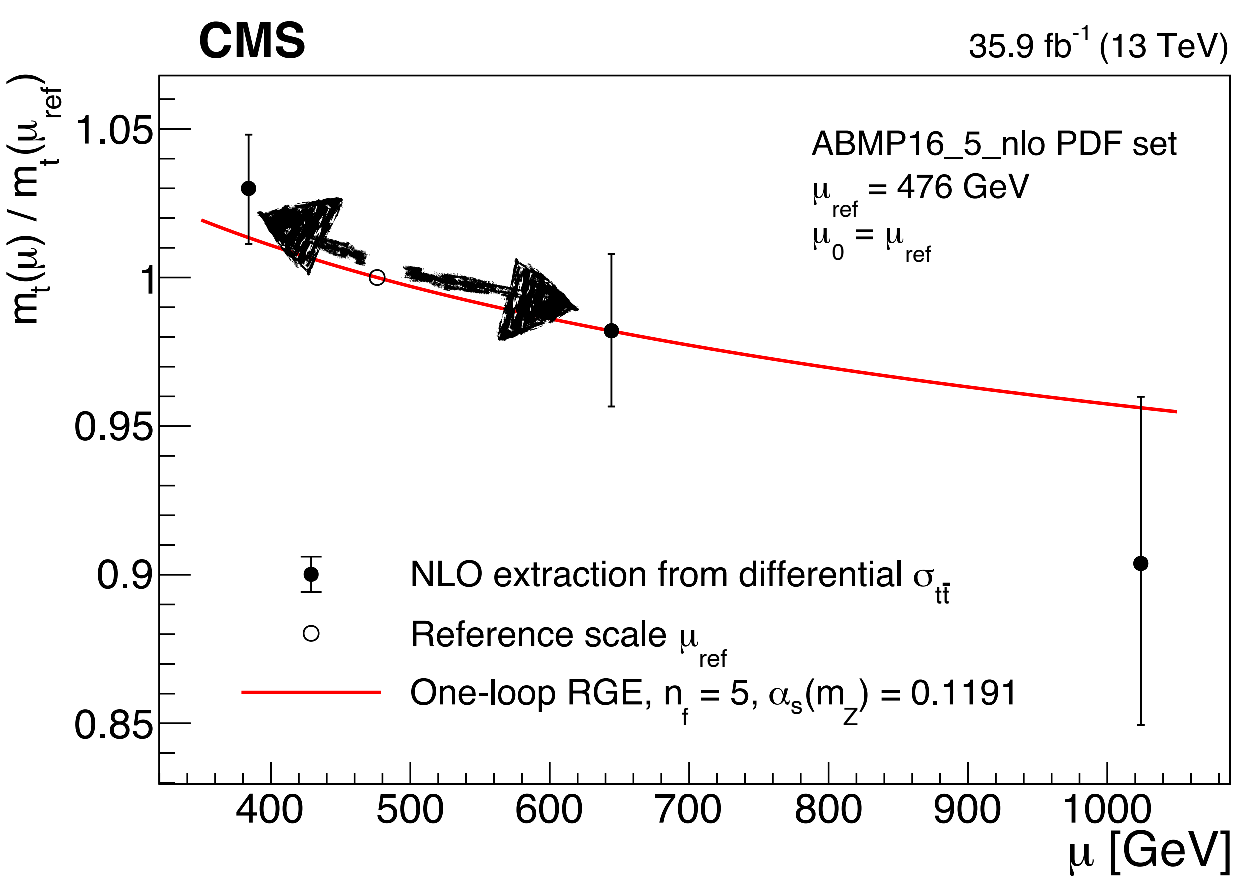
—> $m_t(m_t)$ has larger theory uncertainty due to the larger dependence on renorm. & fact. scales at ~$2m_t$.

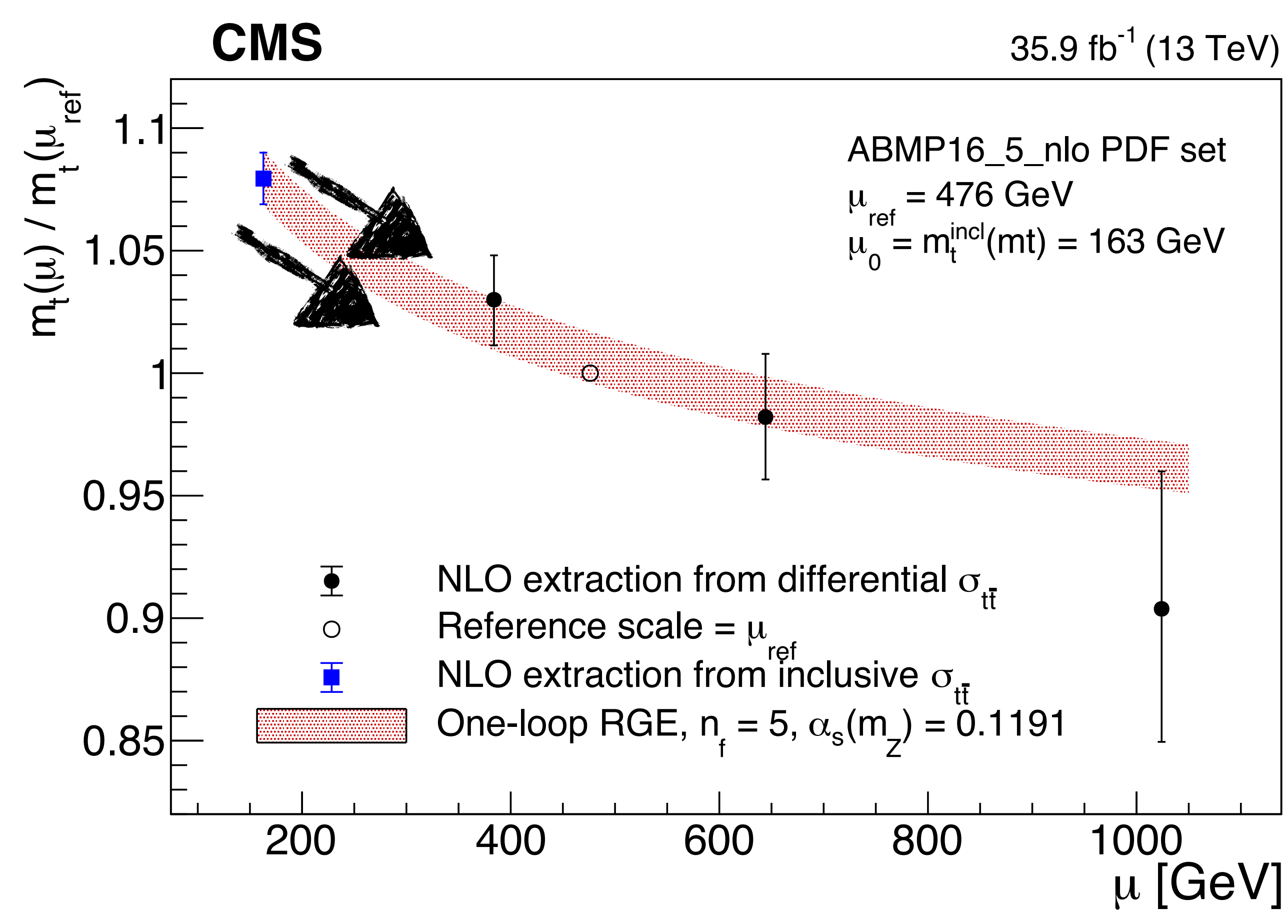
The first experimental investigation of the running of the top mass

PLB 803 (2020) 135263

- Running mass $m_t(\mu)$ extracted at one-loop precision as a function of m(tt) by comparing NLO calculations to the measurement corrected to the parton level in the eμ-channel.
- The extracted running of m_t up to ~1 TeV is in agreement with the scale dependence predicted by the renormalization group equation (RGE) within 1.1σ.
- No-running scenario excluded at above 95% CL.







- Precision limited by integrated luminosity, lepton id, JES/JER and signal modelling.
- For improving the measurement, NNLO calculations in the MSbar scheme needed to allow extraction of the running at two-loop precision.

Top quark mass from boosted top-jet mass in lepton+jets channel

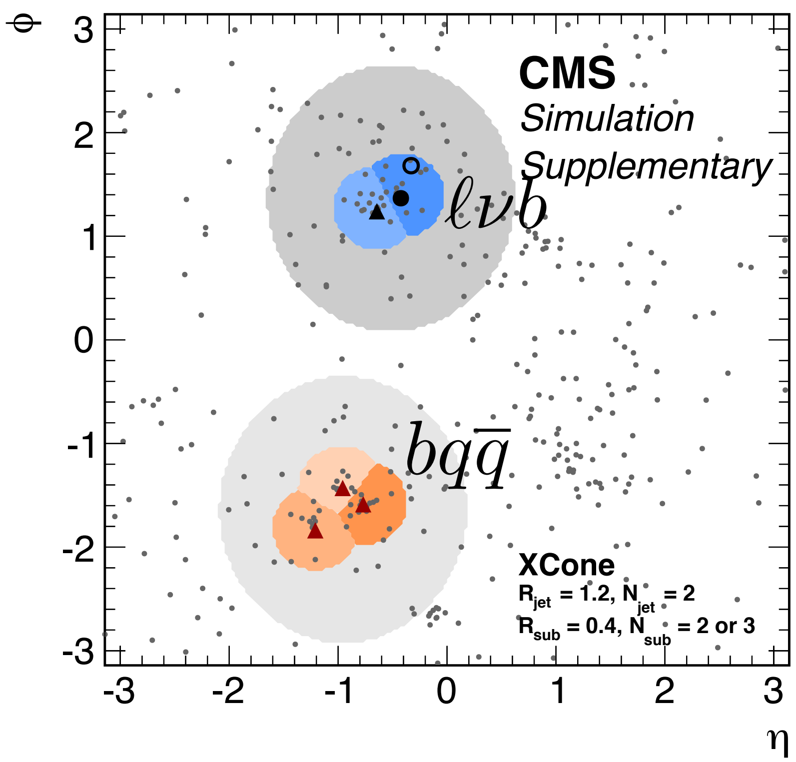
PRL 124 (2020) 202001

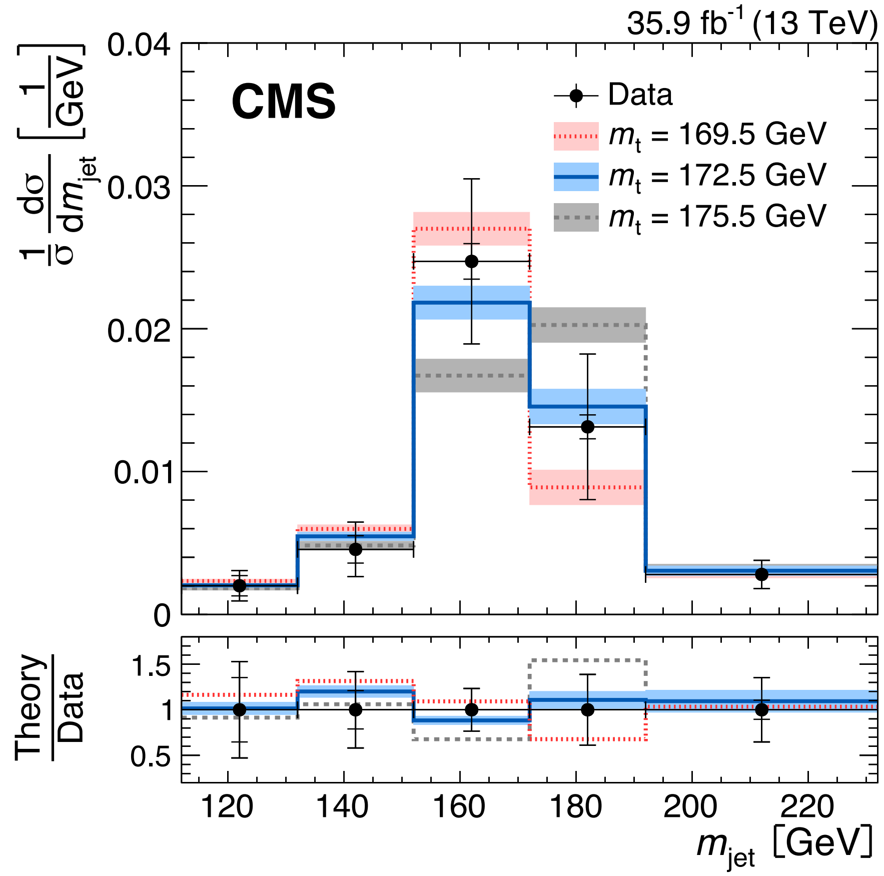
- XCone jet mass = invariant mass of all particle-flow candidates in the 3 XCone subjets.

JHEP 11 (2015) 072

Particle level

2 large-radius XCone jets (p_T^j>400 GeV) with 3 XCone subjets (p_T^j>30 GeV)





unfolded measurement
—> Aim for analytical m_t determination in the boosted regime in soft-collinear effective theory.
—> Help understanding the ambiguities between MC and pole masses.

Hoang et al. PRD 100 (2019) 074021

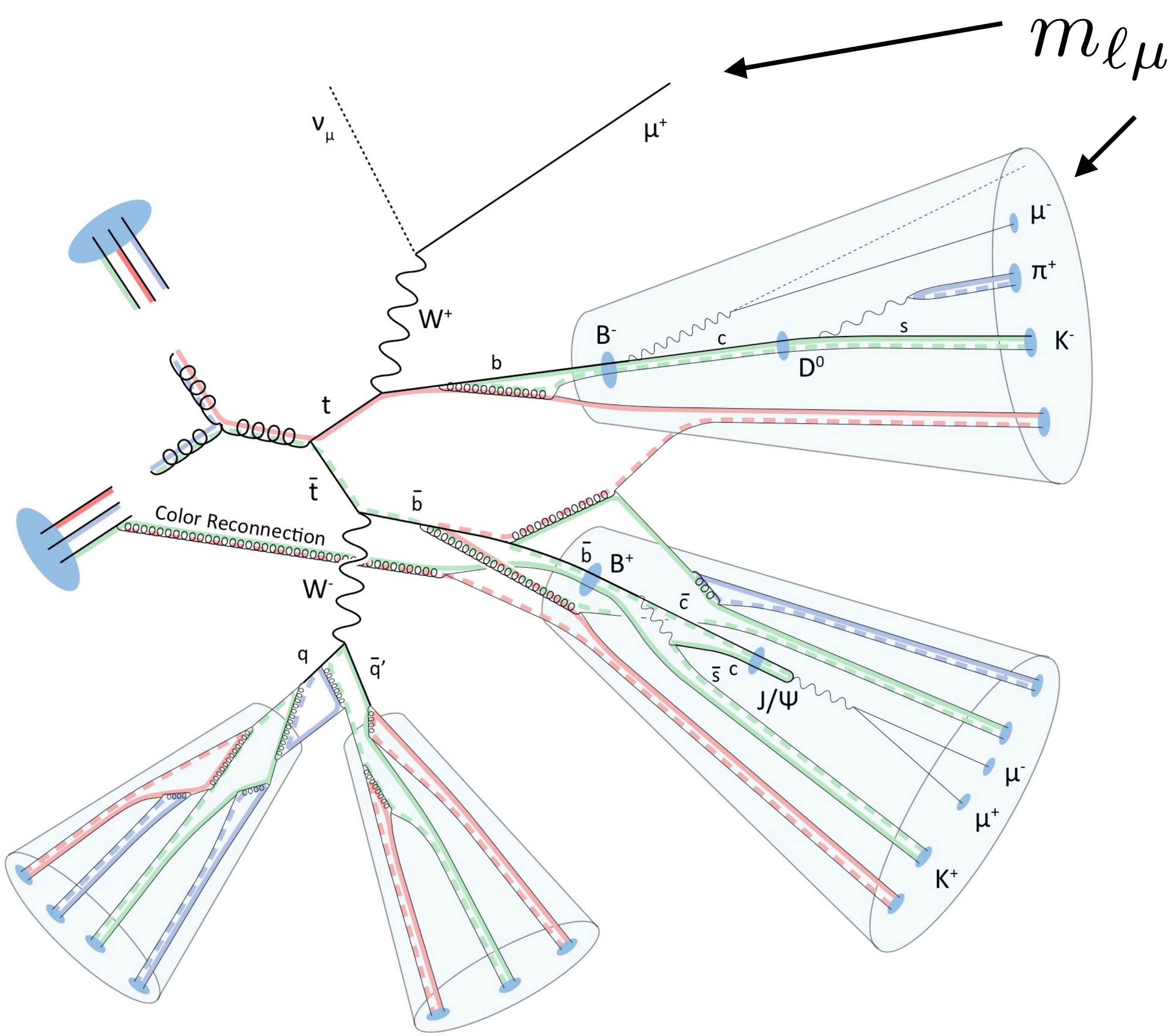
$$m_t = 172.6 \pm 0.4(stat) \pm 1.6(exp) \pm 1.5(model) \pm 1.0(theo)\ GeV$$

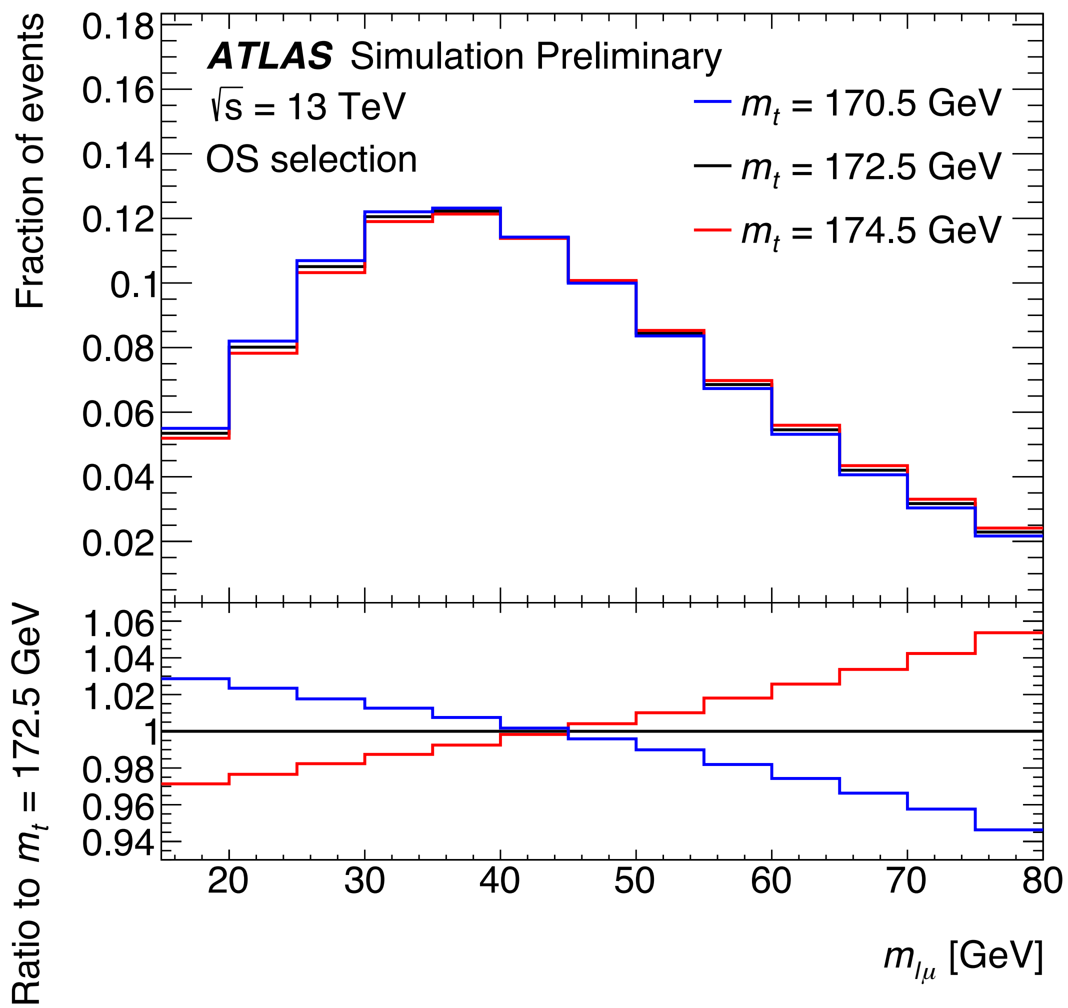
precision~1.4%

Experimental: JES, JER, XCone jet energy correction, …
Model: FSR, color reconnection, UE tune, top mass value, …

—> Average energy scale ~480 GeV >> the scale in other m_t measurements.

Top Quark Mass using soft muon tags ATLAS-CONF-2019-046





	OS [%]	SS [%]
Processes involving a μ from a t or $\bar{t}$		
$t \to B \to \mu$	73.6	51.2
$t \to B \to D \to \mu$	16.7	44.2
$t \to B \to \tau \to \mu$	2.0	1.3
$t \to B \to D \to \tau \to \mu$	0.8	0.8
Processes involving a μ not from a t or $\bar{t}$		
$B \to \mu$	0.6	0.9
$D \to \mu$	5.8	1.4
$\tau \to \mu$	0.5	0.1

- e/μ + ≥4 jets
- ≥ 2 b-tagged jets: One with displaced vertex, One with soft muon tag
- Simultaneous template fit to $m_{l\mu}$ distributions from same-sign and opposite-sign samples

Top Quark Mass using soft muon tags ATLAS-CONF-2019-046

- The fragmentation function in PYTHIA8 is improved by determining the r_b parameter based in the b-quark fragmentation measured in e+e- data and extrapolated to pp collisions.
- b and c hardon decay branching ratios are adjusted to match those of the previous measurements (DELPHI, CLEO, ALEPH).

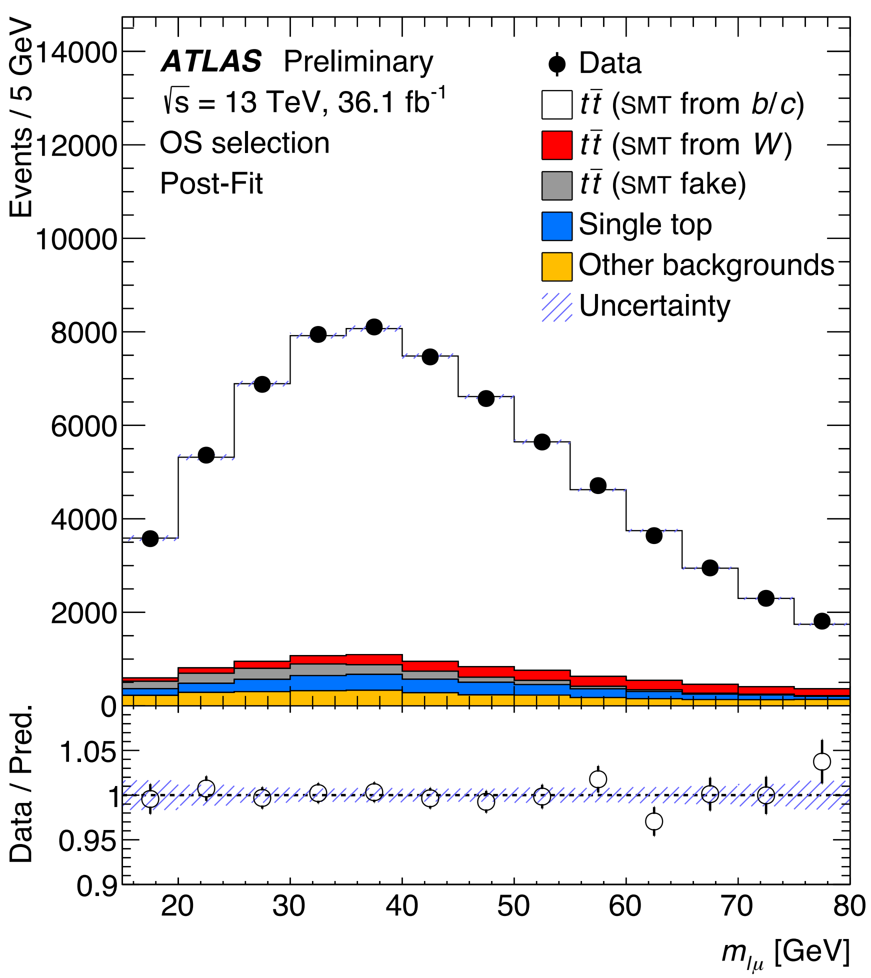
$$f(z) = \frac{1}{z^{1+r_q b m_q^2}}(1-z)^a exp(-\frac{b m_T^2}{z})$$

fit to LEP and SLD data is performed using

$x_B = 2p_B p_Z/m_Z^2$ using $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ events.

$$\rightarrow r_b = 1.05 \pm 0.02$$

Hadron	PDG	POWHEG+PYTHIA8	Scale Factor
$b \rightarrow \mu$	$0.1095^{+0.0029}_{-0.0025}$	0.106	1.032
$b \rightarrow \tau$	0.0042 ± 0.0004	0.0064	0.661
$b \rightarrow c \rightarrow \mu$	0.0802 ± 0.0019	0.085	0.946
$b \rightarrow \bar{c} \rightarrow \mu$	$0.016^{+0.003}_{-0.003}$	0.018	0.888
$c \rightarrow \mu$	0.082 ± 0.005	0.084	0.976



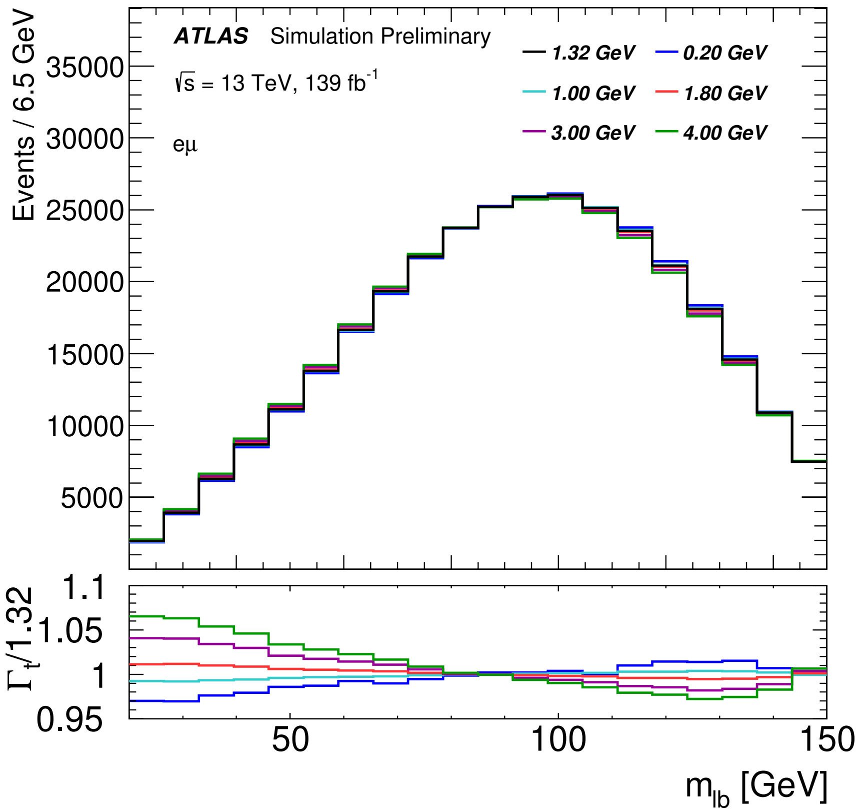
$$m_t = 174.48 \pm 0.40(stat) \pm 0.67(sys)\ GeV$$

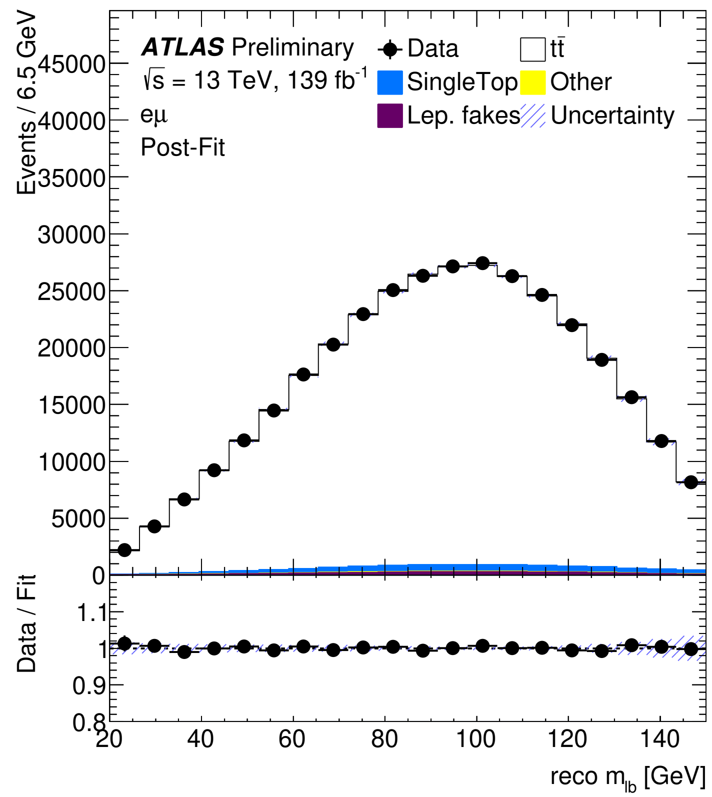
- **precision~0.45%**
- sensitive to different modelling effects which is also useful for combinations:
  - HF-hadron decay modeling: 0.39 GeV
  - Pile-up: 0.20 GeV
  - b-quark fragmentation: 0.19 GeV

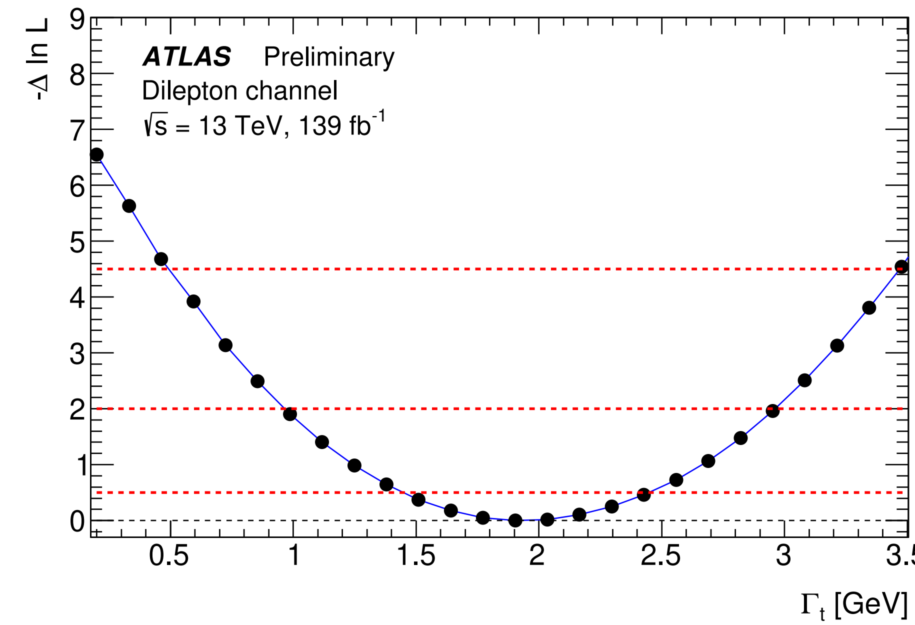
Top Quark Width

ATLAS-CONF-2019-038

- Direct measurement using a profile-likelihood template fit to m(l,b) distribution in the dilepton channel **using full run2 data**.







	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%

Dominant uncertainties: jet reconstruction, signal and bkg. modeling, MC stats., flavor tagging, …

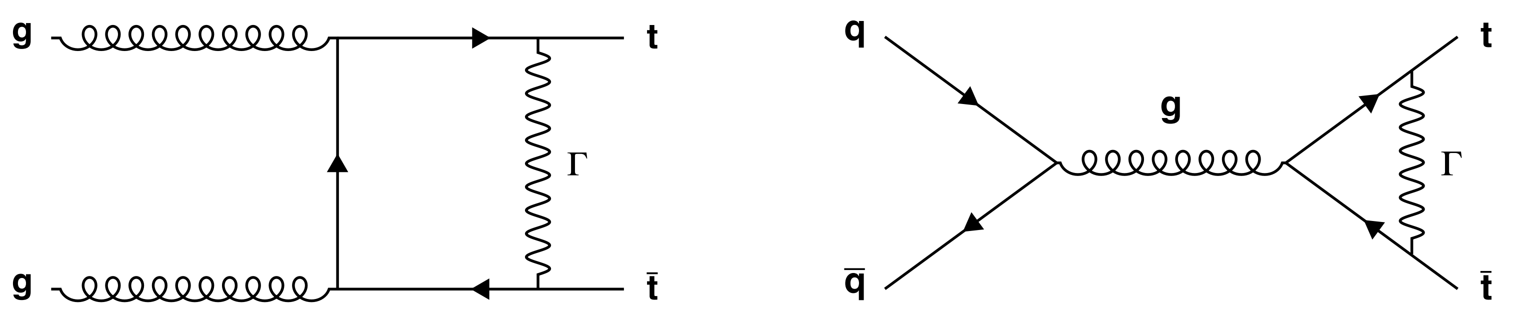
Agreement with NNLO predictions.

Gao et al. PRL 110 (2013) 042001

Yukawa Coupling

CMS-PAS-TOP-19-008

NEW



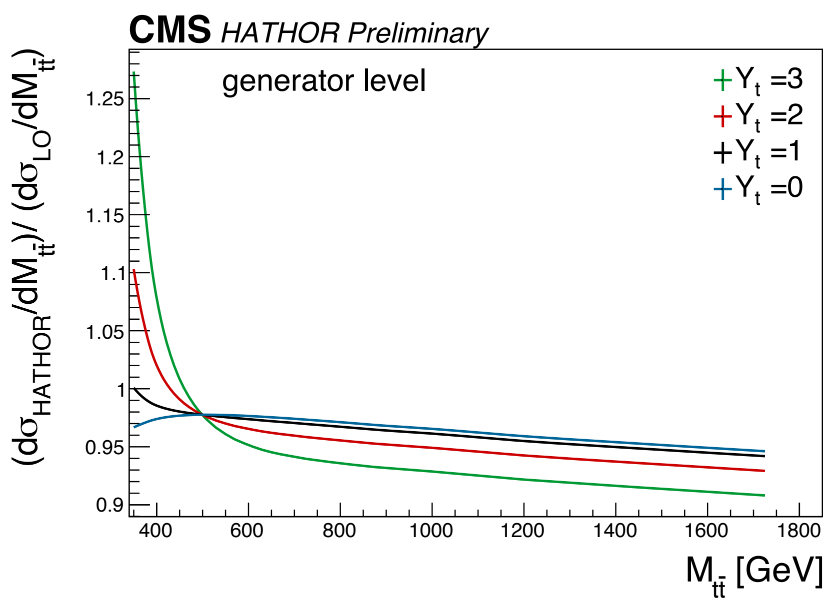
- Weak corrections ($\alpha_s^2\alpha$) from vector or scalar bosons modify differential distributions at ~2m_t if Yukawa coupling (g_t) is larger than 1.

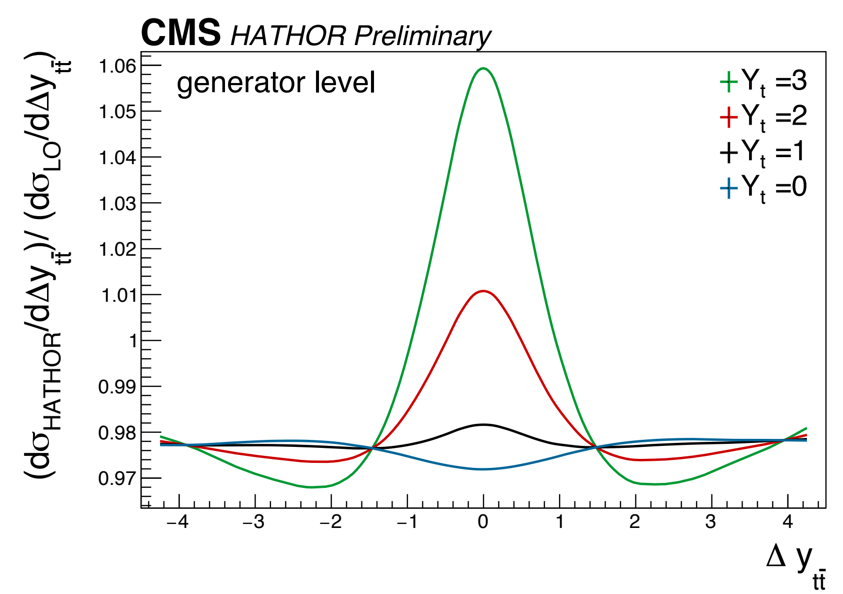
Yukawa coupling strength ⟶ $g_f = \frac{\sqrt{2}m_f}{v}$

$$Y_t = \frac{g_t}{g_t^{SM}}$$

Weak corrections as a function of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ at various Yukawa parameter values

$$Y_t = \frac{g_t(HATHOR)}{g_t(SM)}$$





to all ttbar samples so that their kinematics remain dependent on Y_t.

Yukawa Coupling

CMS-PAS-TOP-19-008 **NEW**

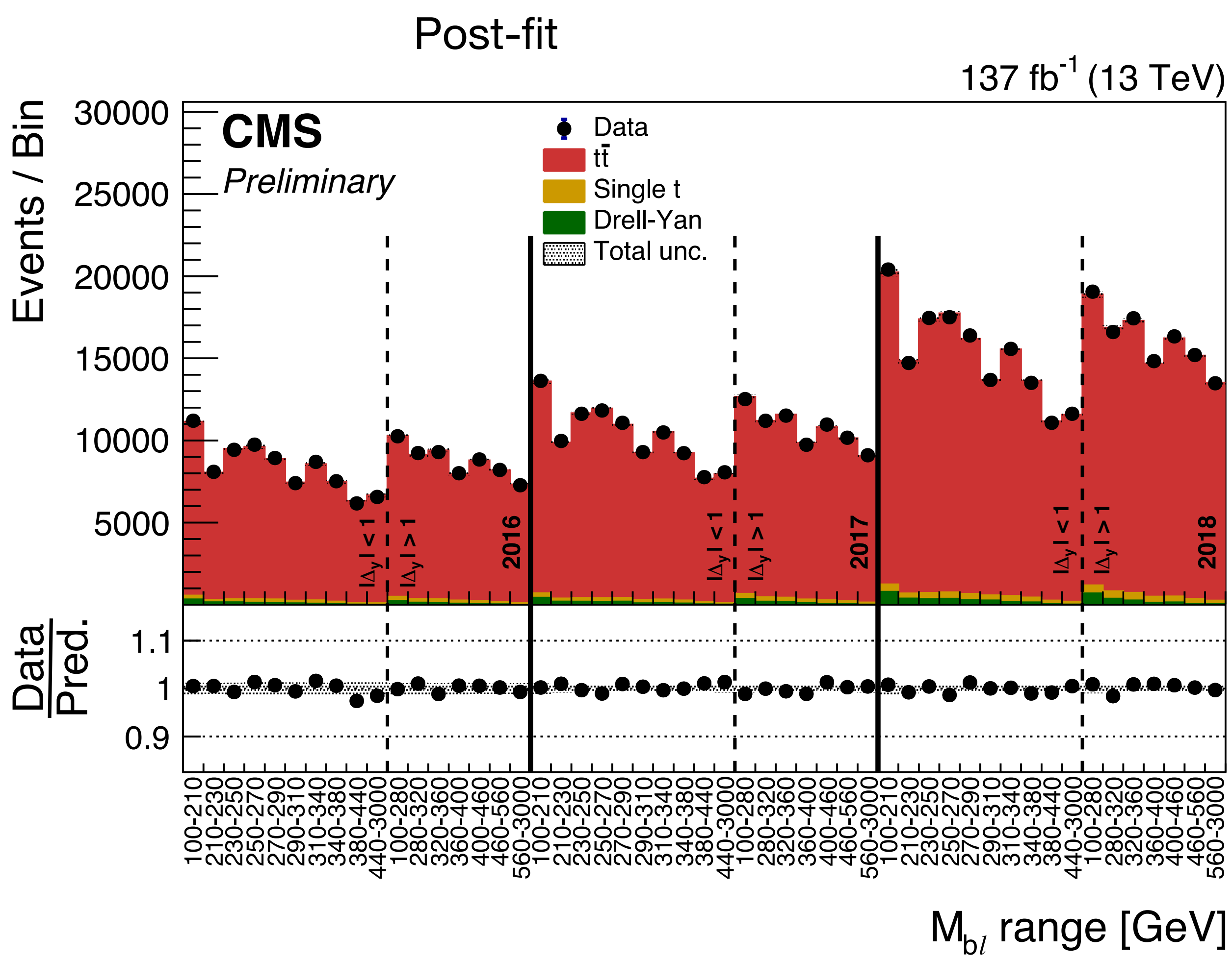
Measurement in the dilepton channel: 2 opposite-sign leptons and 2 b-jets.

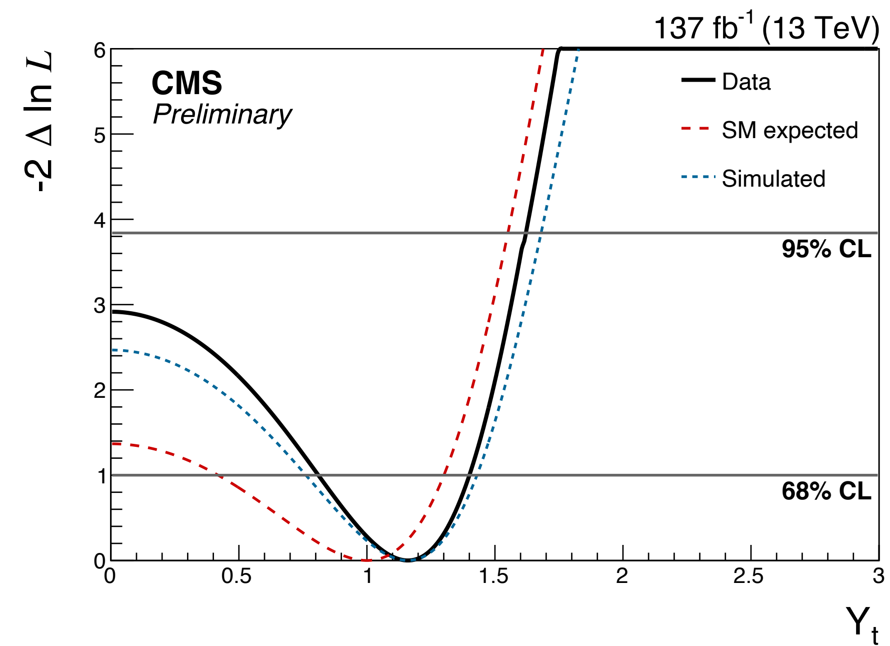
Partial reconstruction results in a more sensitive measurement than using $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$

$$M_{b\ell} = M(b + \bar{b} + \ell + \bar{\ell})$$

$$|\Delta y|_{b\ell} = |y(b + \bar{\ell}) - y(\bar{b} + \ell)|$$

Requires each jet to be matched to the correct lepton through a kinematic fit.





Dominant unc.: EW correction, PS, ME scales, JES flavor

full run2 data

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

$$68\%\ \mathrm{CL}: \quad [0.81, 1.40]$$

$$95\%\ \mathrm{CL}: \quad [0.00, 1.62]$$

A bit more sensitive than the only CMS result that exclusively depend on the top Yukawa coupling from 4top production cross section:

EPJ C 80 (2020) 75 $Y_t < 1.7\ @95\%\ CL$

CMS Higgs combination: $Y_t = 0.98 \pm 0.14$

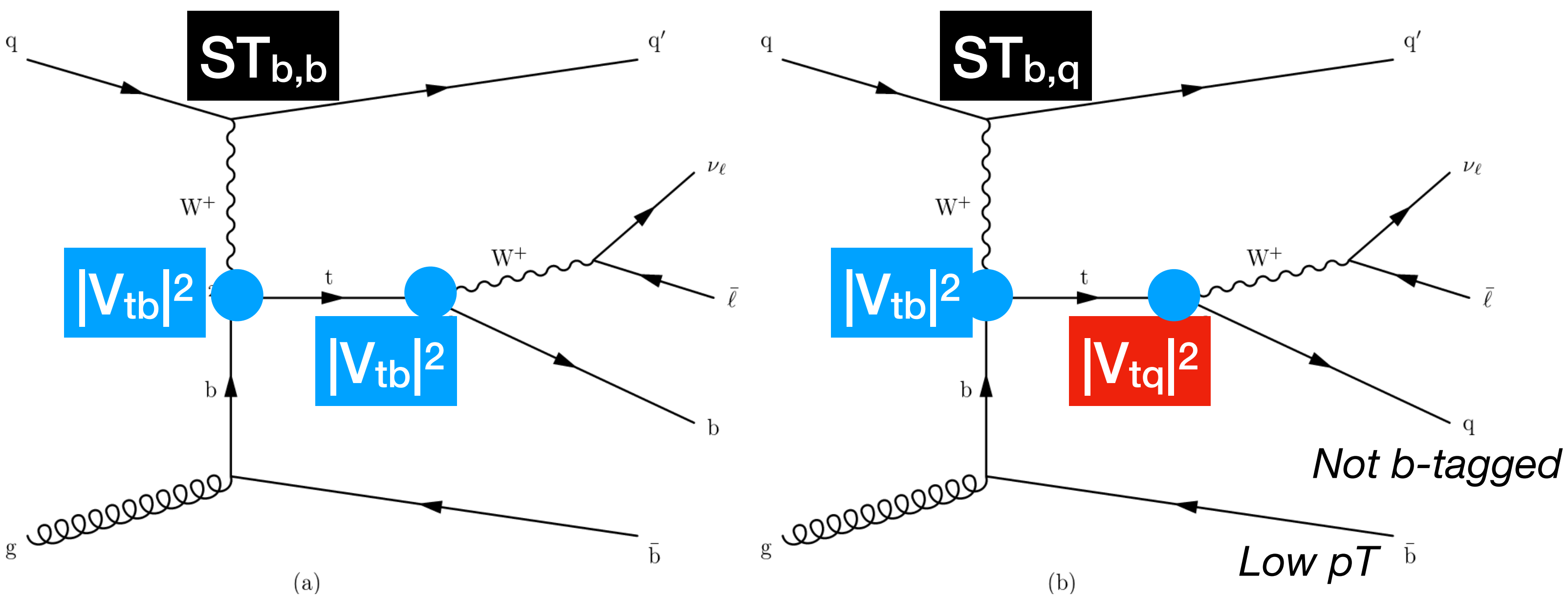
but it is model dependent: assumes couplings of Higgs to particles other than top EPJ C 79 (2019) 421

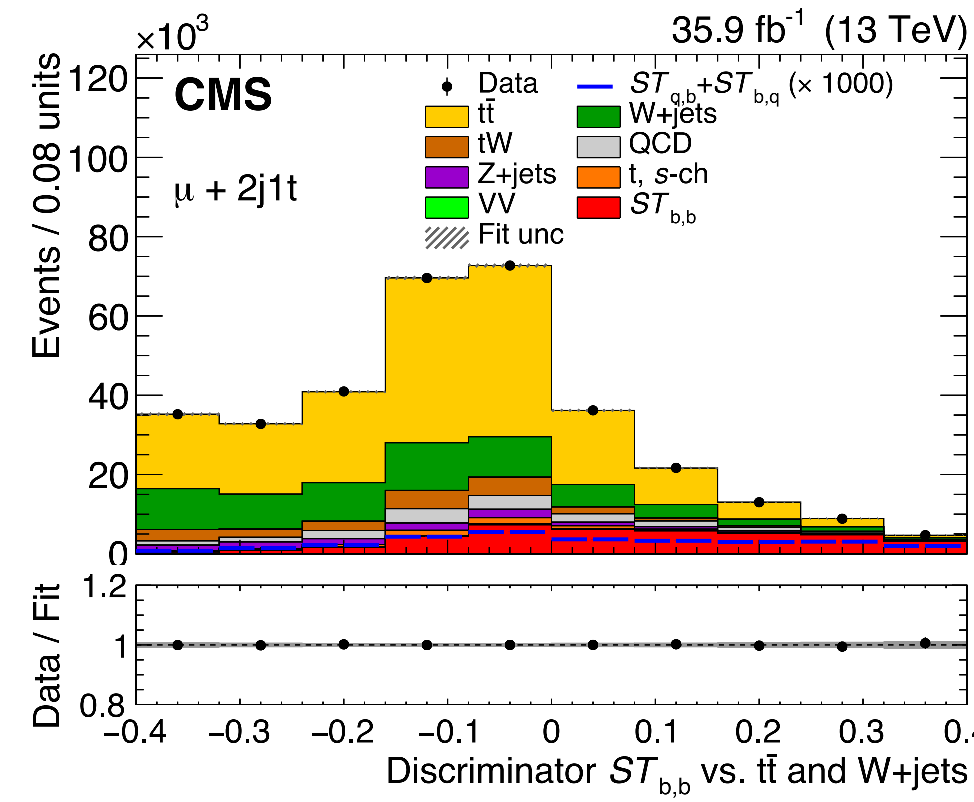
CKM Matrix Elements from single top quark t-channel

arXiv:2004.12181

NEW

- Processes directly sensitive to V_{tb}, V_{td}, and V_{ts} matrix elements in production and decay.





- The yields of different signals extracted through a simultaneous fit to data in different event categories
- CKM matrix elements inferred from the signal strengths $= \dfrac{\sigma_{t-chan} \times BR(meas)}{\sigma_{t-chan} \times BR(theo)}$

Category	Enriched in	Cross section × branching fraction
2j1t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$
3j1t	$ST_{b,q}$, $ST_{q,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wq)$, $\sigma_{t\text{-ch,q}}\mathcal{B}(t \to Wb)$
3j2t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$

Most discriminating vars.

2j1t: $|\eta_{j'}|$, m(l,b)
3j1t: MET, MVA b tagger
3j2t: $|\eta_{j'}|$, m(l,j')

CKM Matrix Elements from single top quark t-channel

arXiv:2004.12181

NEW

- Signal strength from the fit $\mu_b = 0.99 \pm 0.12$
- Assuming CKM unitarity of SM $|V_{tb}| > 0.970$ @ 95% $C.L.$

$$|V_{td}|^2 + |V_{ts}|^2 < 0.057 \text{ @ } 95\% \; C.L.$$

- *BSM1:* Assuming additional quark families with m > m_t
  - No CKM unitarity but SM top quark decay channels.
  - Assume partial width of each top decay varies b/c of a modified CKM element.

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

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

- BSM2**: top quark width left unconstrained** under the assumption that contributions to the total width from the mixing of the three families are negligible.

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

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

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

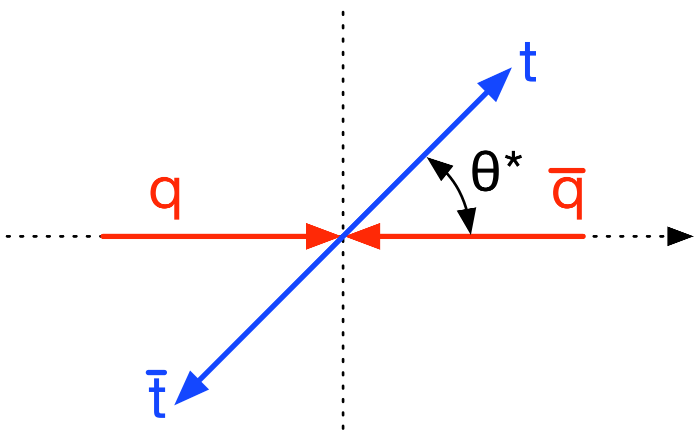
Modeling uncertainties dominate.

==> The first direct, model-independent measurements of the CKM matrix elements for the third-generation quarks, and provide the best determination of these fundamental SM parameters via single top quark measurements.

First Forward-Backward Asymmetry Measurement at the LHC

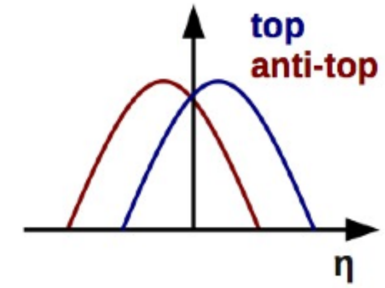
arXiv:1912.09540
Accepted by JHEP

- Asymmetry due to NLO interference terms between qqbar diagrams —> leads to a slightly positive asymmetry.



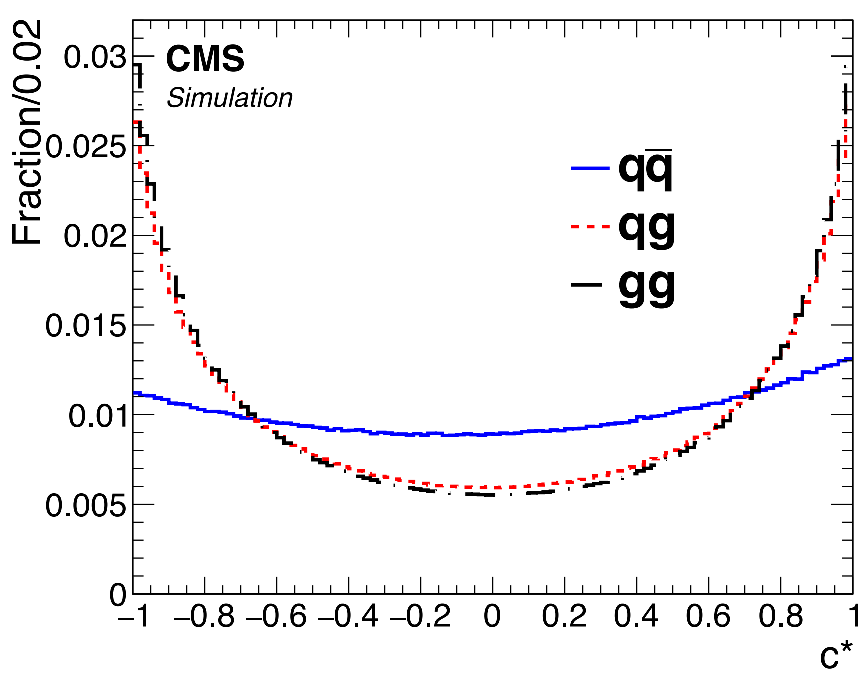
$$c^* = cos\theta^* \qquad A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

(analogous to Drell-Yan A_{FB})

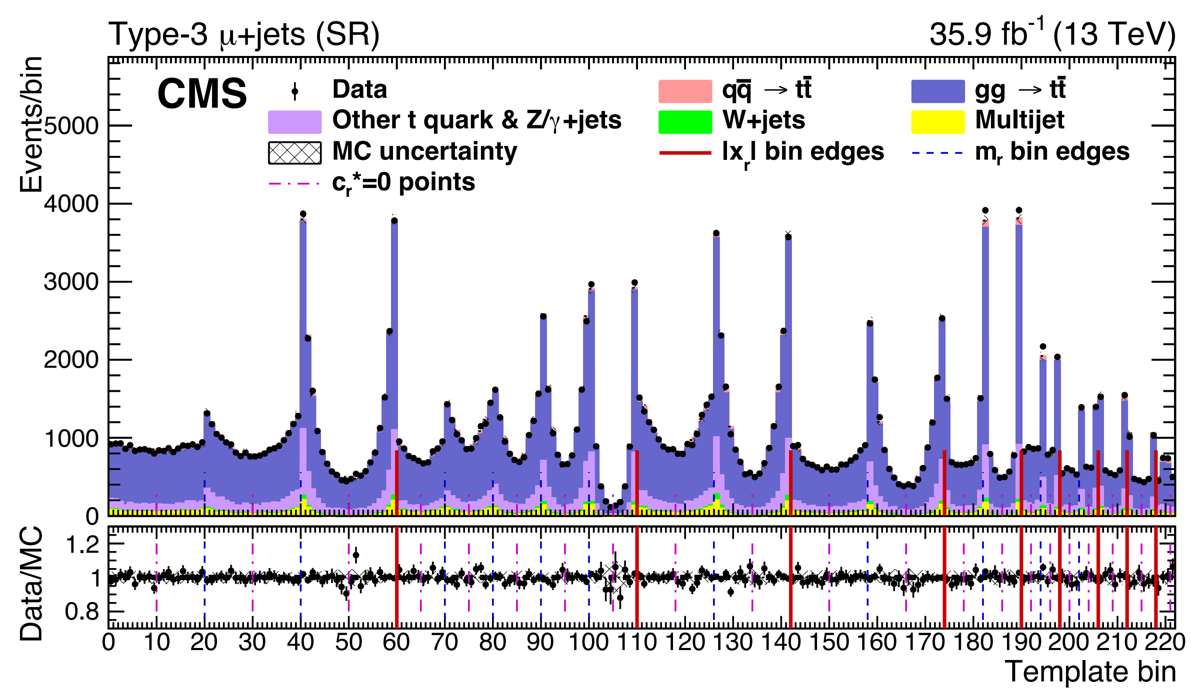


- Lepton+jets final states with « resolved » and « boosted » topologies selected and reconstructed through a kinematic fit.
- The parameters extracted from template-likelihood fits to the data based in differential models of extensions of LO tree-level cross sections for qqbar and gg initial states.

POWHEG v2



Multi-dimensional fit to $c^*,\ m_{t\bar{t}},\ x_F = 2p_L/\sqrt{s}$



r=reco

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}(stat)^{+0.016}_{-0.011}$$

$$|\hat{d}_t| < 0.03 \text{ @ } 95\% \ C.L.$$

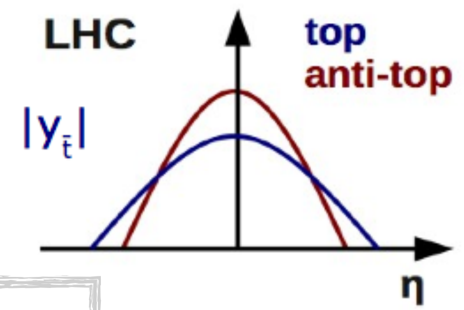
$$A_{FB}^{(1)} = 0.048^{+0.095}_{-0.087}(stat)^{+0.020}_{-0.029}$$

Agrees well with Tevatron, and (N)NLO QCD and with CMS spin correlation measurements in the dilepton channel.

Evidence of Charge Asymmetry ATLAS-CONF-2019-026

- lepton+jets combining resolved and boosted topologies **using full run II data**.

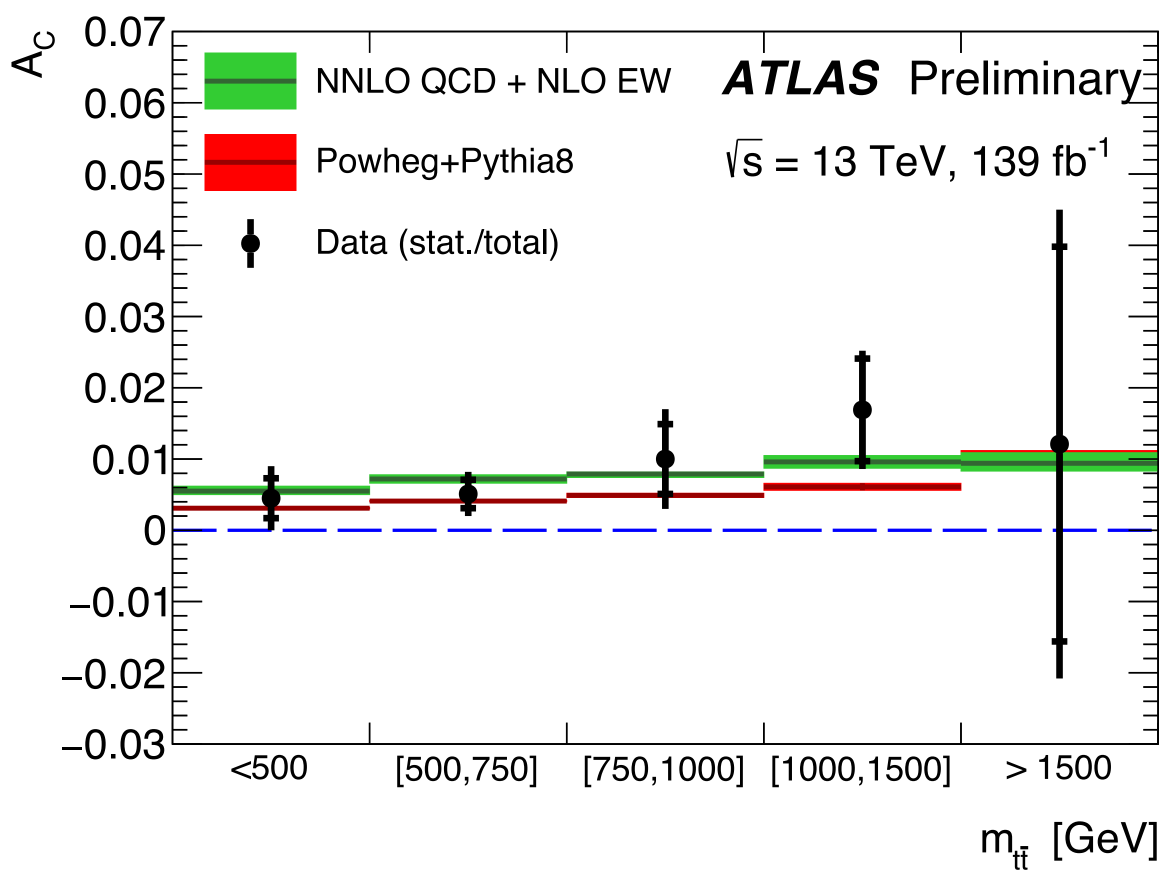
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$



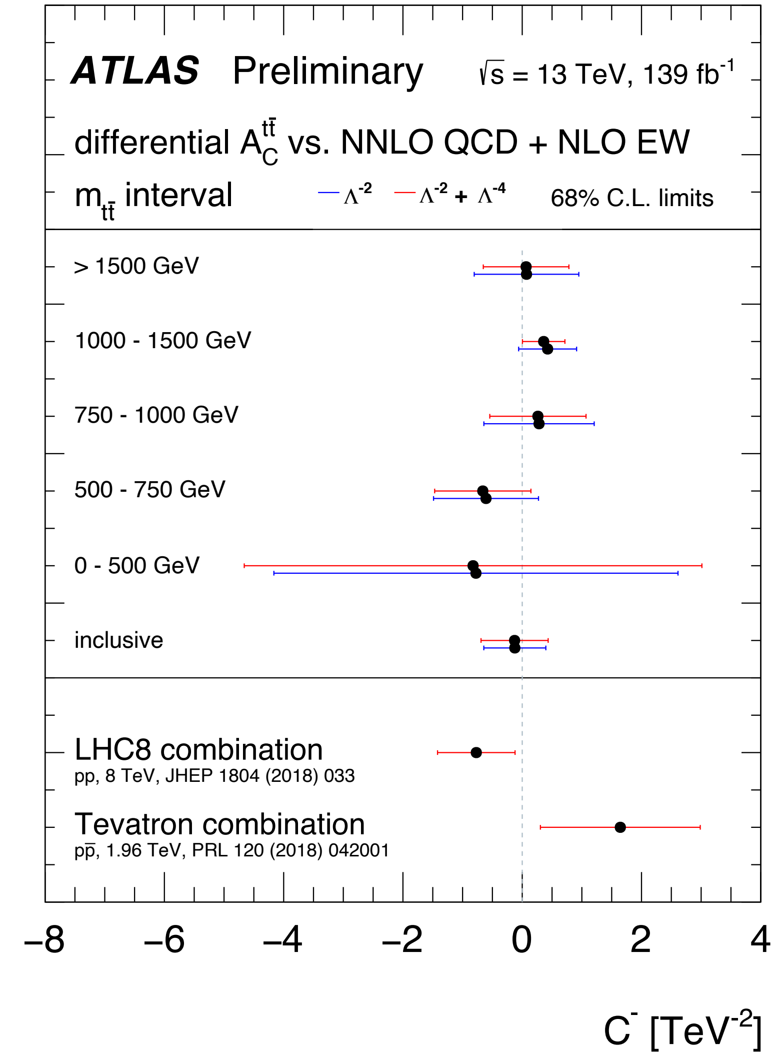
PDF effect: On average, P(valence quark) > P(sea anti-quark)
→ top quark rapidity broader than the anti-quark rapidity

$A_C = 0.0060 \pm 0.0015$ differs 4σ from zero

$$A_C^{NNLO} = 0.0064^{+0.0005}_{-0.0006}$$



Inclusive and differential measurements consistent with QCD NNLO + EWK NLO.



Limits on linear combination of Wilson coefficients of dim-6 EFT operators.

Spin Correlations

PRD 100 (2019) 072002

$$|M(q\bar{q}/gg \to t\bar{t} \to \ell^+ \nu b \ell^- \bar{\nu} \bar{b})|^2 \propto \rho R \bar{\rho}$$

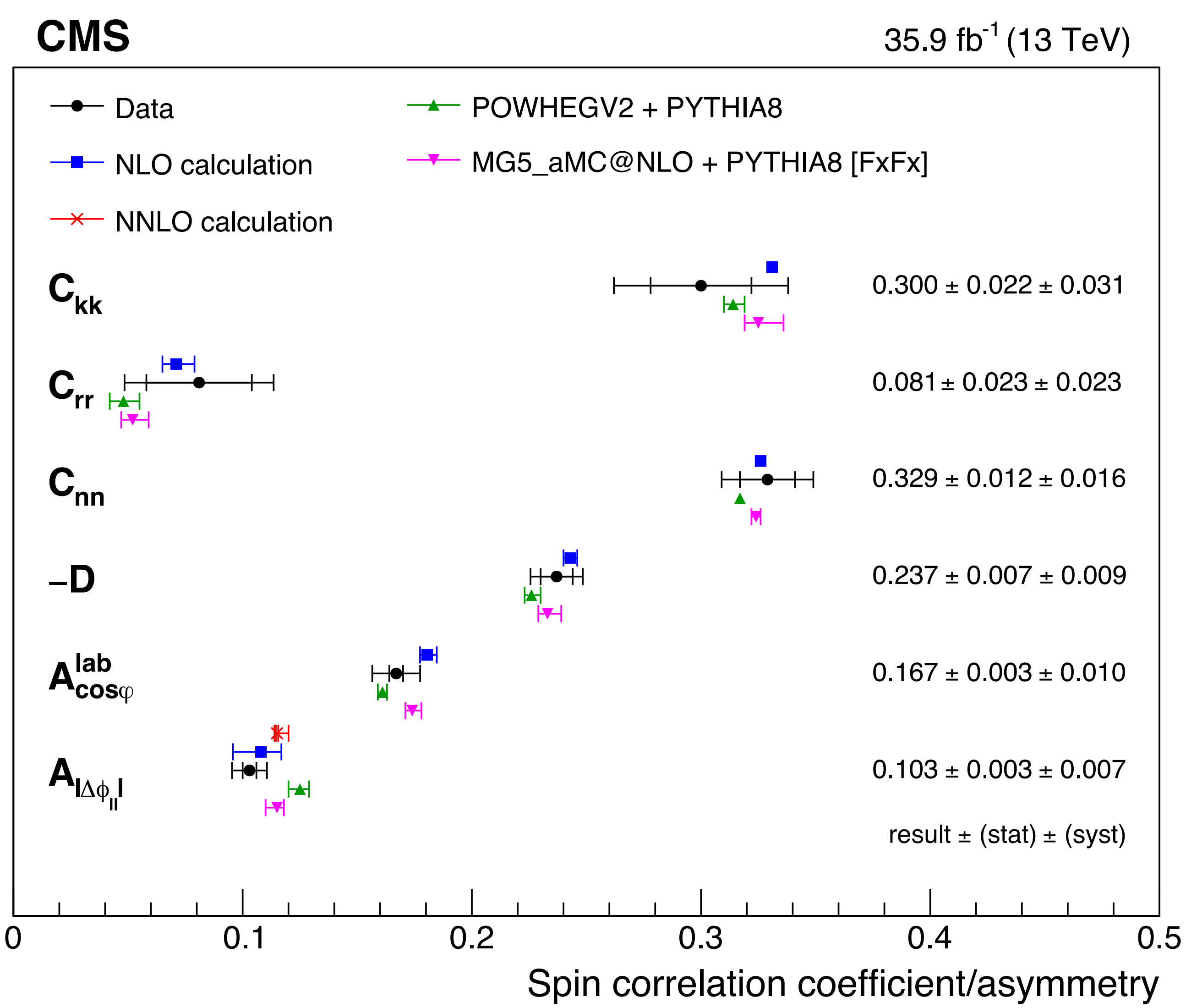
$$R \propto \tilde{A}\mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^+ \sigma^i \otimes \mathbb{1} + \tilde{B}_i^- \mathbb{1} \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j$$

Cross section
And kinematics

Polarization

Spin correlation

- R = spin density matrix parametrized by 15 coefficients that fully characterise spin dependence of top quark pair production.
- Coefficients determined by 1D angular distributions unfolded to parton level in dilepton events.
- Lab frame asymmetries are also measured (not directly relate to the coefficients)



- All distributions and extracted parameters agree with the SM.
- No indication of new physics through anomalous couplings.

Spin Correlations

arXiv:1903.07570

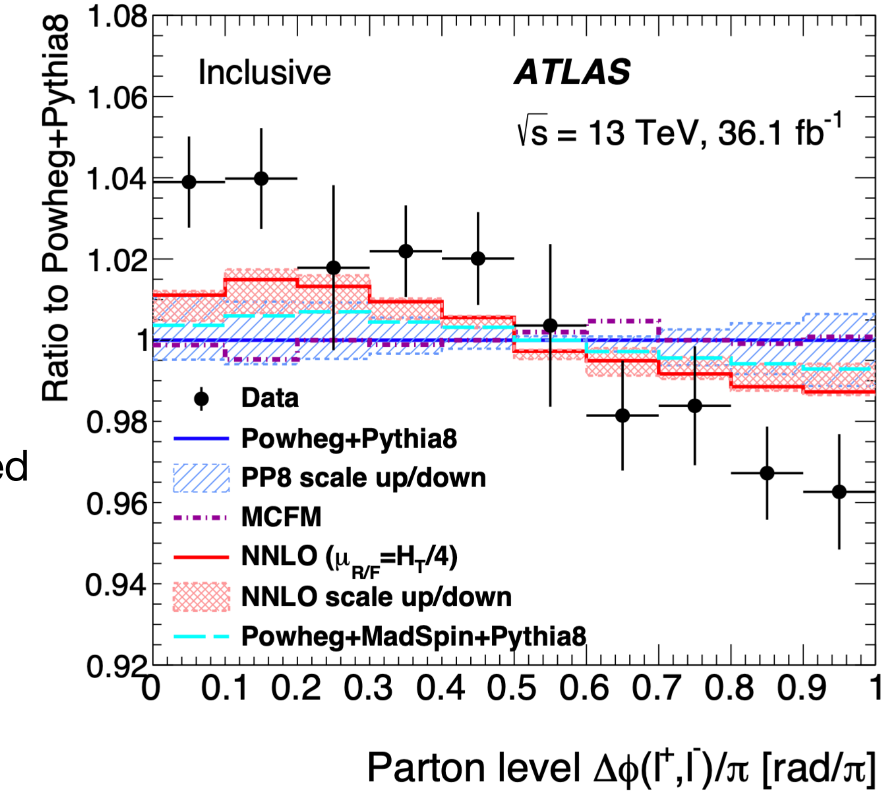
- Δϕ, Δη, Δϕ vs m(tt) in the eμ channel.
- *fraction of SM-like spin correlation* extracted using hypothesis templates that are fitted to the parton-level distributions using spin-correlated and -uncorrelated hypotheses

$$f_{SM} = \frac{N_{\text{spin}}}{N_{\text{spin}} + N_{\text{nospin}}}, \; f_{SM} = 1$$

$$f_{SM} = 1.249 \pm 0.024(stat) \pm 0.061(sys)^{+0.067}_{-0.090}(theo)$$

dom. uncertainties: ISR/FSR, scale settings

2.2σ difference between POWHEG + PYTHIA8 prediction and data.

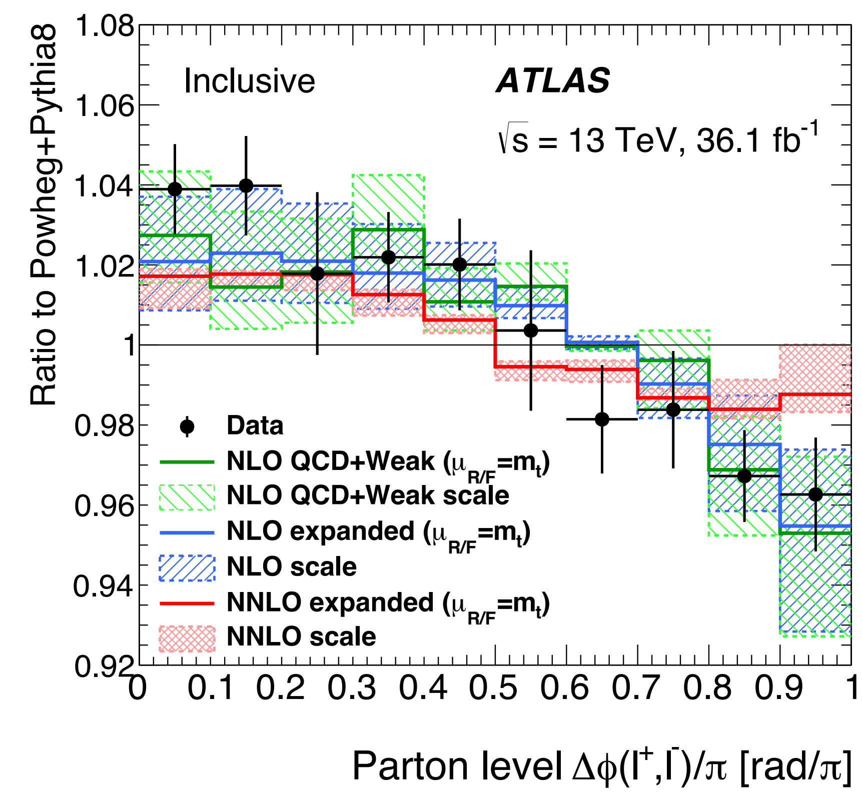


Alternative differential predictions with NLO QCD+Weak couplings / NNLO QCD using an expansion of the normalised diff. distribution in powers of the couplings. Bernreuther, Si, PLB 725 (2013) 115, PLB 744 (2015) 413 Behring et al, arXiv:1901.05407 Behring et al, arXiv:1901.05407 Bernreuther, Si, NPB 837 (2010) 90 Bernreuther, et al. JHEP 12 (2015) 026

$$f_{SM} = 1.03 \pm 0.07(stat)^{+0.10}_{-0.14}(scale)$$

(extracted using NLO (QCD + Weak expanded, μ=m$_t$) template.

—> consistent w/ Powheg+Pythia8, SM, CMS.
—> NNLO expanded less consistent w/ data.

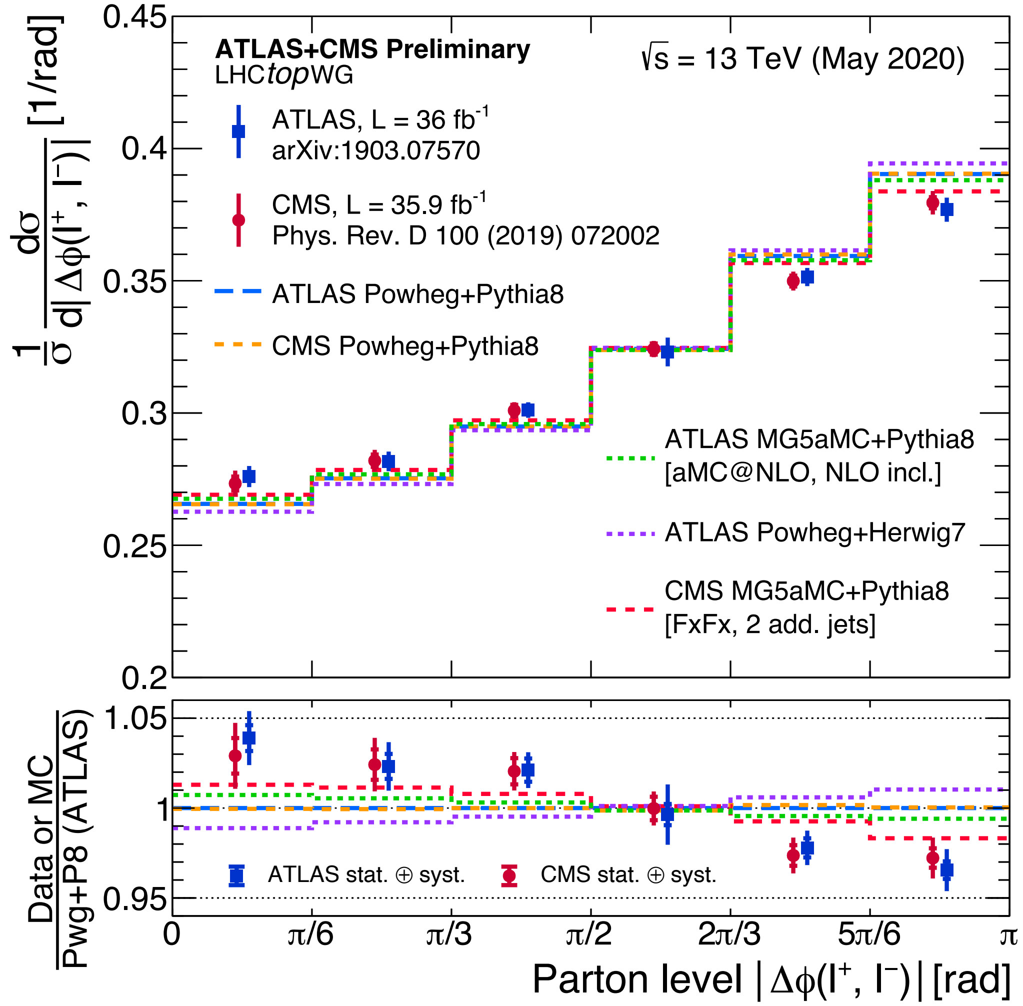


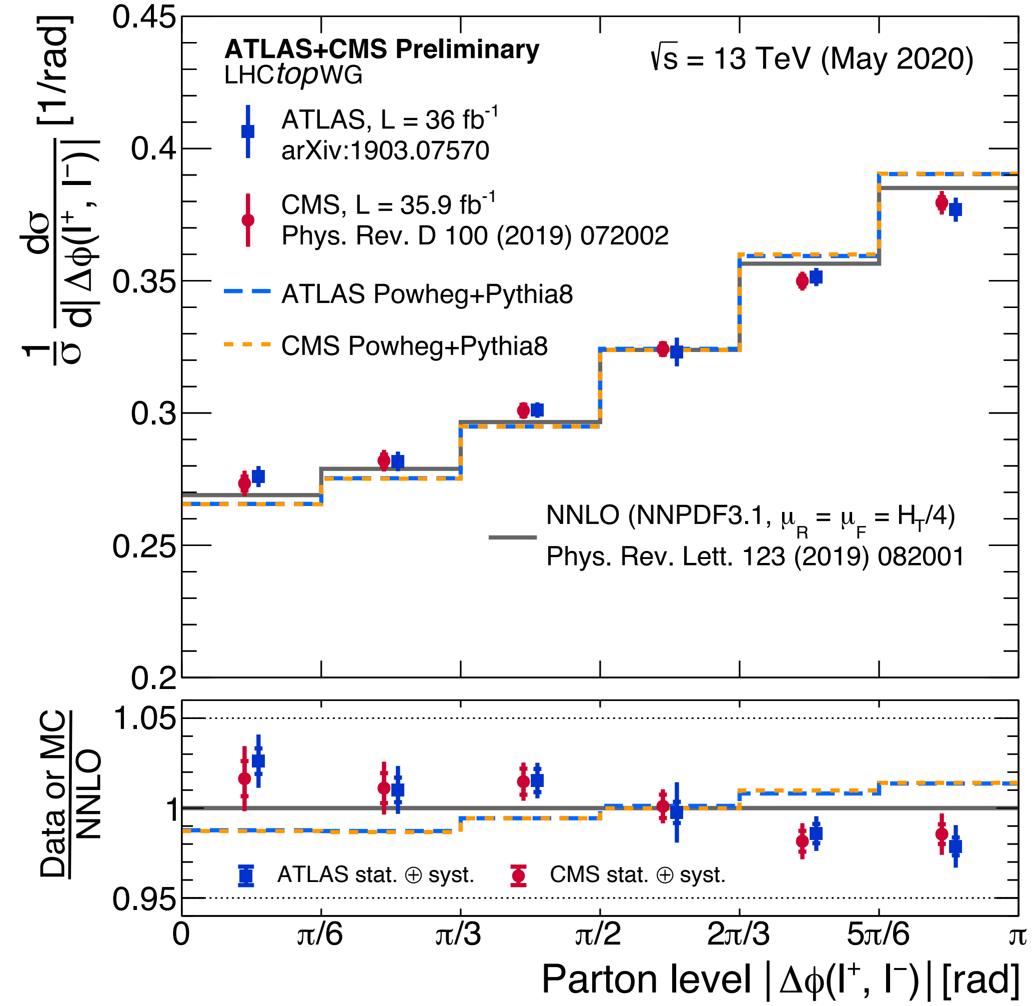
And no top squarks in m=170-230 GeV from $\tilde{t}_1\bar{\tilde{t}}_1$ production using Δϕ in bins of Δη.

Spin Correlation

NEW

Normalized cross sections at the parton level.





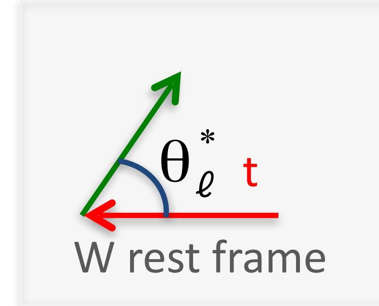
- Very good agreement between ATLAS and CMS data and between ATLAS and CMS main MC predictions.
- Good agreement of data with MG5_aMC@NLO with FXFX merging (2 additional jets from the matrix element).
- Fair agreement with the NNLO calculation.
- Paves the way for first 13 TeV ATLAS+CMS combination from TOPLHCWG.

https://lpcc.web.cern.ch/lhc-top-wg-wg-top-physics-lhc

W Boson Polarization

arXiv:2005.03799

NEW

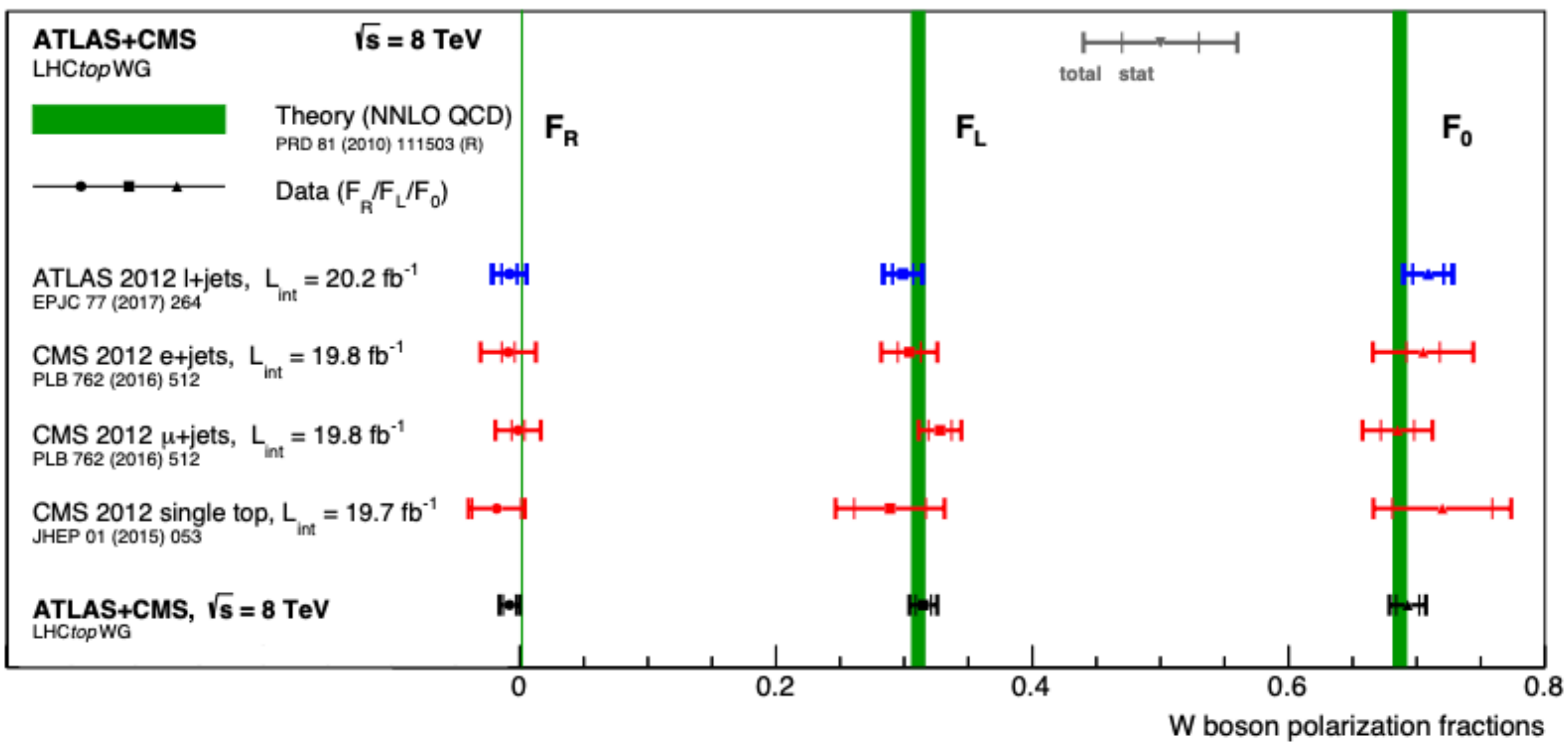


- W helicity fractions (F_X) sensitive to the Wtb (V-A) vertex structure.
- New **ATLAS+CMS 8 TeV ttbar and single top combination** with 20.2 and 19.7 fb^{-1}.

$$\frac{d\sigma}{d\cos\theta^*} \approx \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0 + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

F_L~0.3	F_0~0.7	F_R~0
Left-handed (negative helicity)	longitudinal (zero helicity)	Right-handed (positive helicity)

- BLUE (Best Linear Unbiased Estimate) method used for combination.
- Correlation assumptions studied in detail; drastic variation of correlation assumptions result in deviations covered by uncertainties of the combined measurement.
- Results dominated by statistical, background, radiation/scales, and MC statistics uncertainties.



- results in agreement with NNLO QCD.
- Precision ~2 % in F_0 and 3.5% for F_L.
- improvement in precision of 25 % for F_0 and 29% for F_L wrt the most precise single measurement.
- Limits on anomalous couplings and Wilson coefficients.

Conclusions

- New Run II LHC top mass and properties results with increased precision (up to *NNLO+NLO EWK level)*, new methods, new observables.
  - Top quark mass
    - Combinations ~500 MeV uncertainty.
    - From (multi-) differential cross-section measurements.
    - With an average energy scale of ~480 GeV from boosted top-jet mass.
    - From soft-muon tags.
    - All the top mass definitions tested with the LHC data look consistent.
    - Running of the top quark mass tested up to 1 TeV.
  - Top quark width using full run II data.
  - Yukawa coupling with full run II data.
  - First ttbar forward-backward asymmetry measurement at the LHC.
  - First evidence of ttbar charge asymmetry with full run II data.
  - Precise spin correlation measurements and comparisons between ATLAS and CMS.
  - ATLAS+CMS W boson polarisation combinations at 8 TeV.
  - Limits on new physics from many of the measurements.

More results to come w/ full Run 2 data
Run 3 ~ 2x more ttbar events
HL-LHC ~ 20x more ttbar events

→ More precise measurements —> better understanding of some top properties and increased reach for new physics through direct searches and effective field theory.

Additional Slides

The first experimental investigation of the running of the top quark mass

PLB 803 (2020) 135263

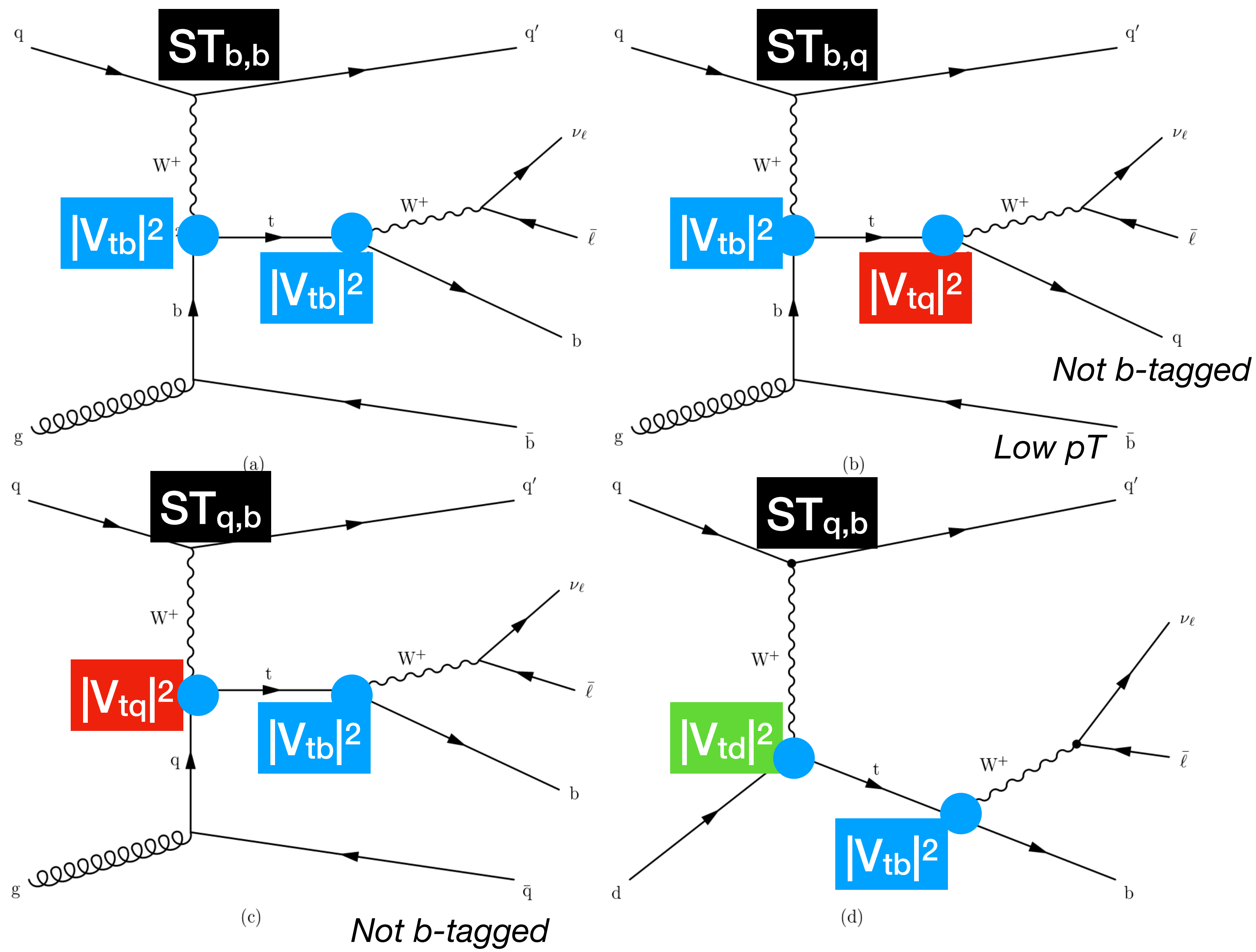
Input distributions to the fit in the different event categories. The number of jets, the number of b-tagged jets, the number of events, and the p_T of the softest jet are denoted with N_{jets}, N_b, N_{events}, and "jet p_T^{min}", respectively, while the category corresponding to the bin k in $m_{t\bar{t}}^{reco}$ is indicated with "$m_{t\bar{t}}^{reco}$ k".

	$N_b = 1$	$N_b = 2$	Other N_b
$N_{jets} < 2$	N_{events}	n.a.	N_{events}
$m_{t\bar{t}}^{reco}$ 1	$m_{\ell b}^{min}$	jet p_T^{min}	N_{events}
$m_{t\bar{t}}^{reco}$ 2	$m_{\ell b}^{min}$	jet p_T^{min}	N_{events}
$m_{t\bar{t}}^{reco}$ 3	$m_{\ell b}^{min}$	jet p_T^{min}	N_{events}
$m_{t\bar{t}}^{reco}$ 4	N_{events}	N_{events}	N_{events}

Bin	$m_{t\bar{t}}$ [GeV]	Fraction [%]	μ_k [GeV]
1	<420	30	384
2	420–550	39	476
3	550–810	24	644
4	>810	7	1024

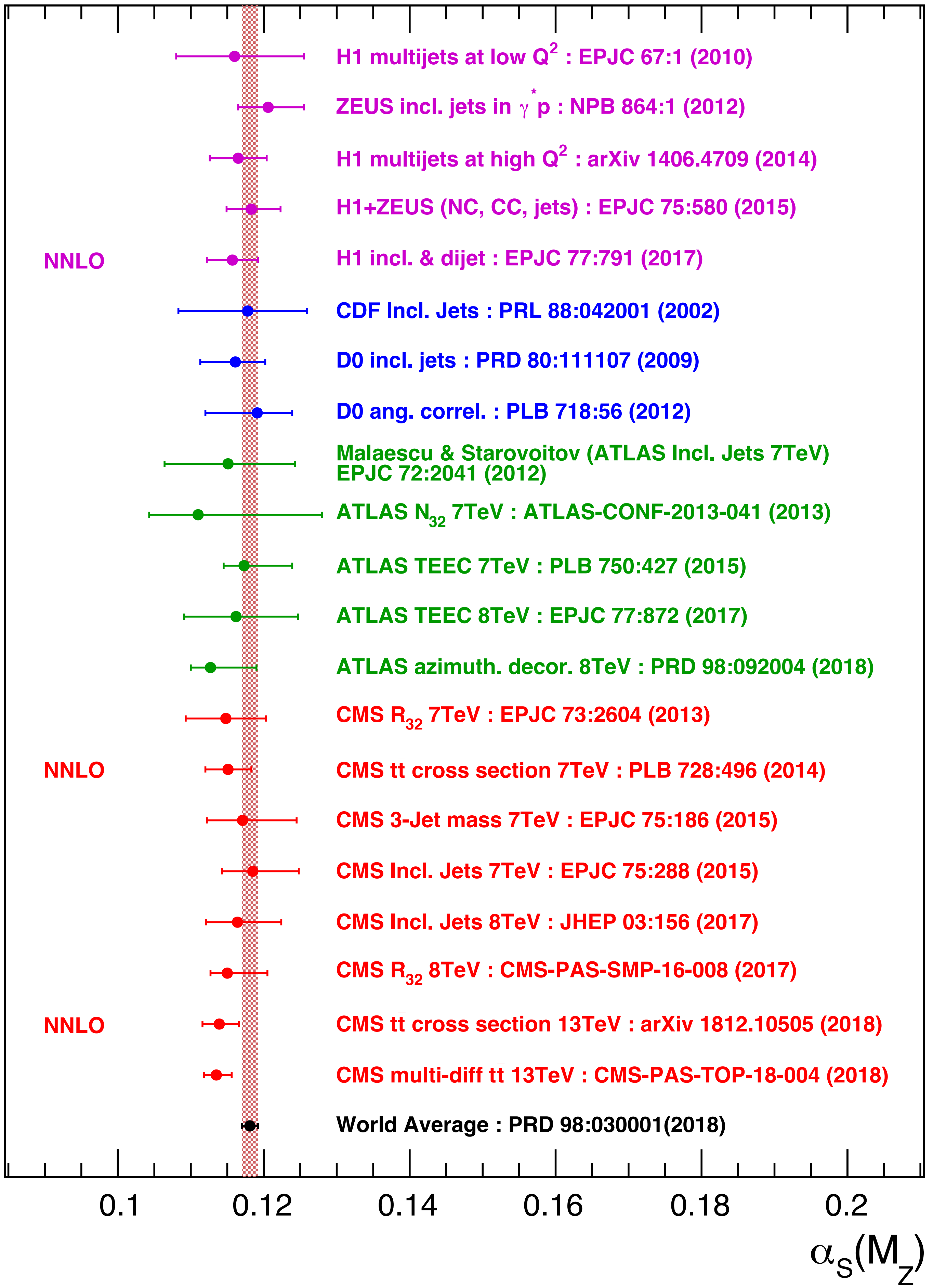
CKM Matrix Elements from single top quark t-channel

arXiv:2004.12181

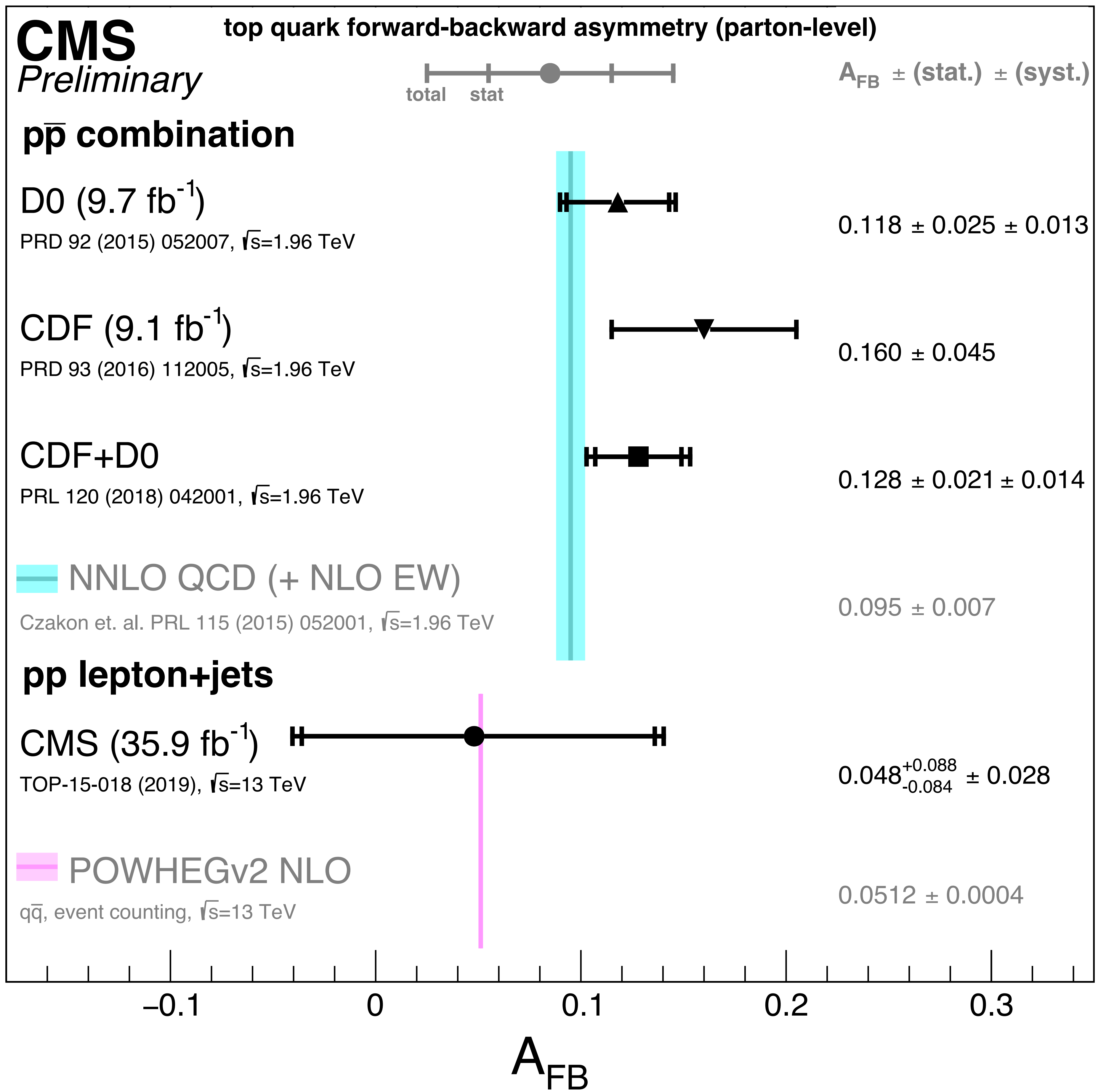


Signal regions

Category	Enriched in	Cross section × branching fraction	Feynman diagram
2j1t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$	1a
3j1t	$ST_{b,q}$, $ST_{q,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wq)$, $\sigma_{t\text{-ch,q}}\mathcal{B}(t \to Wb)$	1b, 1c, 1d
3j2t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$	1a



H1 multijets at low Q^2 : EPJC 67:1 (2010)
ZEUS incl. jets in $\gamma^* p$: NPB 864:1 (2012)
H1 multijets at high Q^2 : arXiv 1406.4709 (2014)
H1+ZEUS (NC, CC, jets) : EPJC 75:580 (2015)
NNLO
H1 incl. & dijet : EPJC 77:791 (2017)
CDF Incl. Jets : PRL 88:042001 (2002)
D0 incl. jets : PRD 80:111107 (2009)
D0 ang. correl. : PLB 718:56 (2012)
Malaescu & Starovoitov (ATLAS Incl. Jets 7TeV) EPJC 72:2041 (2012)
ATLAS N_{32} 7TeV : ATLAS-CONF-2013-041 (2013)
ATLAS TEEC 7TeV : PLB 750:427 (2015)
ATLAS TEEC 8TeV : EPJC 77:872 (2017)
ATLAS azimuth. decor. 8TeV : PRD 98:092004 (2018)
CMS R_{32} 7TeV : EPJC 73:2604 (2013)
NNLO
CMS $t\bar{t}$ cross section 7TeV : PLB 728:496 (2014)
CMS 3-Jet mass 7TeV : EPJC 75:186 (2015)
CMS Incl. Jets 7TeV : EPJC 75:288 (2015)
CMS Incl. Jets 8TeV : JHEP 03:156 (2017)
CMS R_{32} 8TeV : CMS-PAS-SMP-16-008 (2017)
NNLO
CMS $t\bar{t}$ cross section 13TeV : arXiv 1812.10505 (2018)
CMS multi-diff $t\bar{t}$ 13TeV : CMS-PAS-TOP-18-004 (2018)
World Average : PRD 98:030001(2018)
0.1
0.12
0.14
0.16
0.18
0.2
$\alpha_S(M_Z)$



CMS
Preliminary
top quark forward-backward asymmetry (parton-level)
total
stat
A_{FB} ± (stat.) ± (syst.)
$p\bar{p}$ combination
D0 (9.7 fb^{-1})
PRD 92 (2015) 052007, $\sqrt{s}$=1.96 TeV
0.118 ± 0.025 ± 0.013
CDF (9.1 fb^{-1})
PRD 93 (2016) 112005, $\sqrt{s}$=1.96 TeV
0.160 ± 0.045
CDF+D0
PRL 120 (2018) 042001, $\sqrt{s}$=1.96 TeV
0.128 ± 0.021 ± 0.014
NNLO QCD (+ NLO EW)
Czakon et. al. PRL 115 (2015) 052001, $\sqrt{s}$=1.96 TeV
0.095 ± 0.007
pp lepton+jets
CMS (35.9 fb^{-1})
TOP-15-018 (2019), $\sqrt{s}$=13 TeV
$0.048^{+0.088}_{-0.084}$ ± 0.028
POWHEGv2 NLO
$q\bar{q}$, event counting, $\sqrt{s}$=13 TeV
0.0512 ± 0.0004
−0.1
0
0.1
0.2
0.3
A_{FB}

W Boson Polarization arXiv:2005.03799 NEW

Limits on tWb anomalous couplings

Coupling	ATLAS	CMS	ATLAS+CMS combination
	95% CL interval		
Re(V_R)	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$[-0.11, 0.16]$
Re(g_L)	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$[-0.08, 0.05]$
Re(g_R)	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$[-0.04, 0.02]$

Limits on Wilson coefficients

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