Impact of QCD and PDF uncertainties on SM precision measurements
(at the LHC)

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on behalf of the ATLAS, CMS, and LHCb collaborations

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Overview

Topics covered in this talk

- W boson mass and width
- Weak mixing angle
- Electroweak diboson
- Top quark mass
- Strong coupling α_s
- Higgs $\rightarrow$ Miha (next talk)

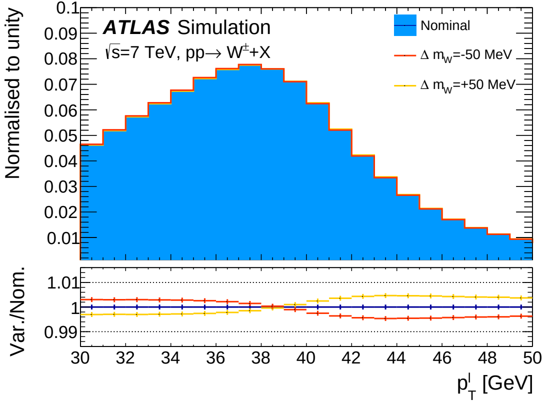
Related plenary talks

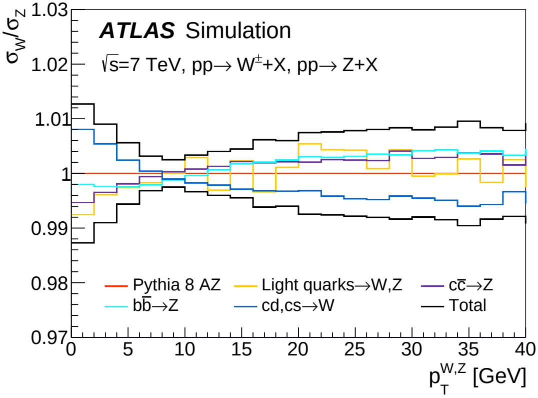
- Valentina Guglielmi: Strong coupling measurements at the LHC (Monday)
- Johannes Erdmann: Status of Higgs boson precision measurements (Tuesday)
- Frederic Derue: Status of electroweak parameter measurements (Tuesday)
- Thorsten Kuhl: Recent experimental results on top and heavy-flavour production (Wednesday)
- Miha Muskinja: Impact of QCD and PDF uncertainties on BSM searches (today)
- ...and even more parallel talks!

First measurement of the W mass at the LHC ($\pm$19 MeV)

ATLAS STDM-2014-18

- Measurement of m_W from lepton p_T requires good control of W p_T

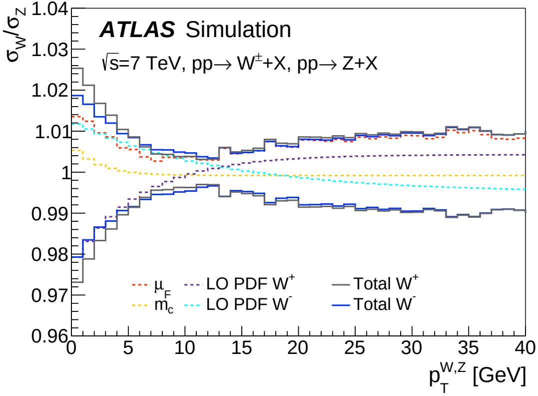


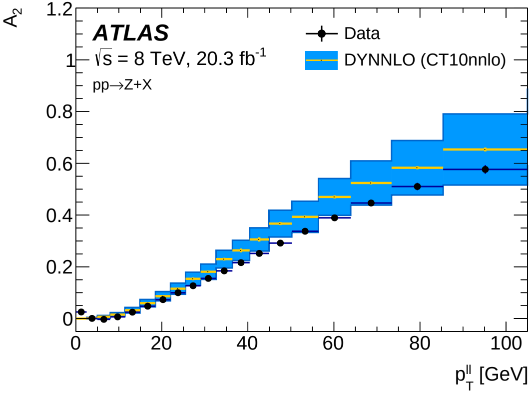


- Prediction by Pythia 8 Tune AZ (LO+ISR MEC), tuned to ATLAS Z p_T data
- Pythia μ_F variations, heavy quark initial states decorrelated between W/Z $\rightarrow$ $\pm$5.0 MeV
  - Uncorrelated light-quark component would give $\pm$30 MeV uncertainty (template fit)

First measurement of the W mass at the LHC ($\pm$19 MeV)

- PDFs uncertainties are the largest: CT10nnlo eigenvectors ($\pm$7.4 MeV) $\oplus$ comparison to MMHT14 and CT14 ($\pm$3.8 MeV)



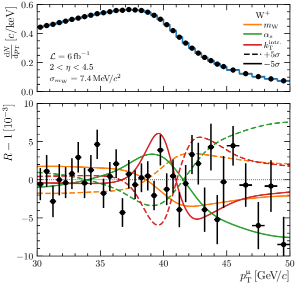


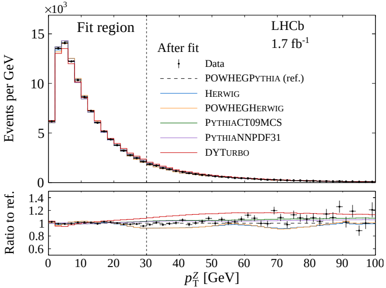
- Uncertainty on angular coefficients A_i from measurement in Z data (5.8 MeV)

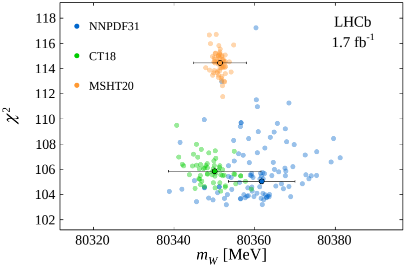
W mass by likelihood fit (± 32 MeV)

LHCb PAPER-2021-024

- Simultaneous fit of W mass, ISR α_s, and intrinsic k_t arXiv 1907.09958







- p_T model: Powheg+Pythia vs Pythia vs Powheg+Herwig $\rightarrow \pm 11$ MeV (after fit)
  - Common intrinsic k_t but ISR α_s decorrelated between W and Z
- PDFs: average of NNPDF3.1, CT18, and MSHT20 $\rightarrow \pm 9$ MeV
- A_i at NNLO but A_3 would be ± 30 MeV. Included in fit $\rightarrow \pm 10$ MeV
- Anti-correlation of LHCb and GPDs, $\rho \simeq -0.5$ arXiv 1508.06954 arXiv 2308.09417

Post-CDF W mass world combination

arXiv 2308.09417

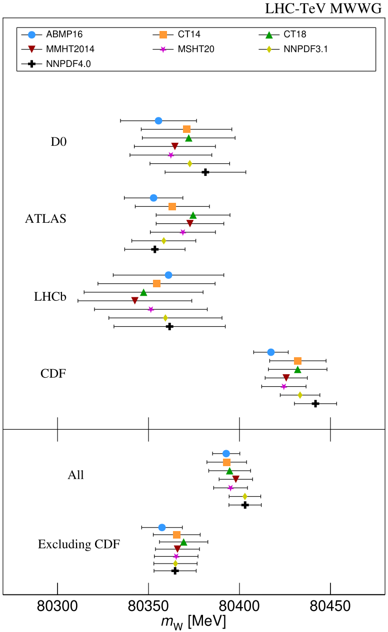
- All results shifted to set of common PDF sets
- Combined with BLUE method for each PDF
- With CDF: largest uncertainty from PDFs

	All experiments (4 d.o.f.)				
PDF set	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$	
ABMP16	80392.7 ± 7.5	3.2	29	0.0008%	
CT14	80393.0 ± 10.9	7.1	16	0.3%	
CT18	80394.6 ± 11.5	7.7	15	0.5%	nominal
MMHT2014	80398.0 ± 9.2	5.8	17	0.2%	
MSHT20	80395.1 ± 9.3	5.8	16	0.3%	
NNPDF3.1	80403.0 ± 8.7	5.3	23	0.1%	largest difference
NNPDF4.0	80403.1 ± 8.9	5.3	28	0.001%	largest difference

  - ABMP: smallest uncertainty due to anti-correlation between ATLAS W+/-
  - 10 MeV between lowest and highest
- W/o CDF: PDF down, total up, fit improved

CT18	80369.2 ± 13.3	6.2	0.5	92%	nominal

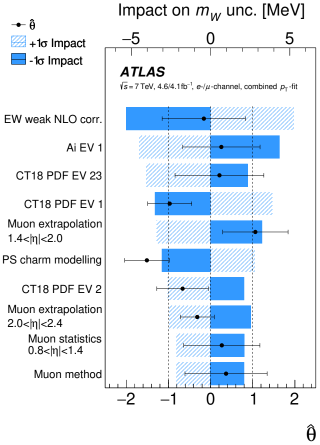
  - 12 MeV difference between lowest and highest

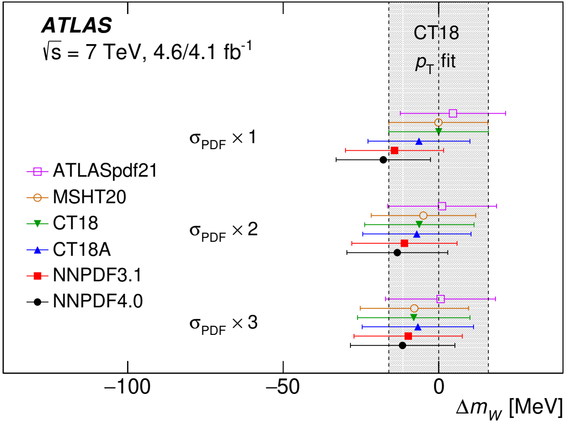


ATLAS reanalysis with profile likelihood fit (± 15.9 MeV)

ATLAS STDM-2019-24

- Fit to lepton p_T, treating all uncertainties as nuisance parameters





- Reduction of PDF uncertainty from 7.4 (CT10) to 4.9 MeV (profiled CT18)
- Difference between PDF sets: up to 18 MeV
  - Reducible by inflating prefit uncertainties but not applied by default

Measurement of the W width

ATLAS STDM-2019-24

W width from lepton p_T

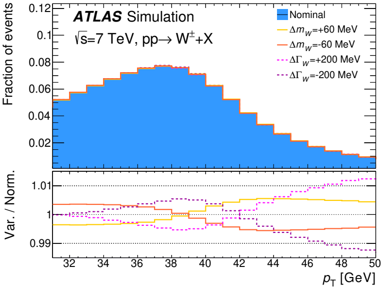
- Huge uncertainty from charm modeling ($m_c \pm 0.5$ GeV)
- Cannot be distinguished from width variation!
- ~~Change systematic variation~~ Consider different observable

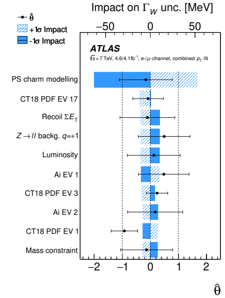
W width from transverse mass m_T

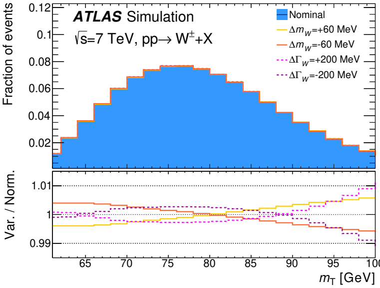
- Impact of charm modeling reduced by factor 4

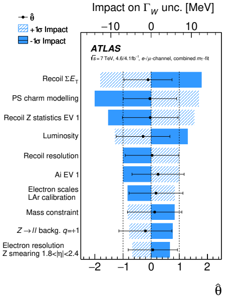
Combined value mostly m_T

- Total uncertainty ± 47 MeV





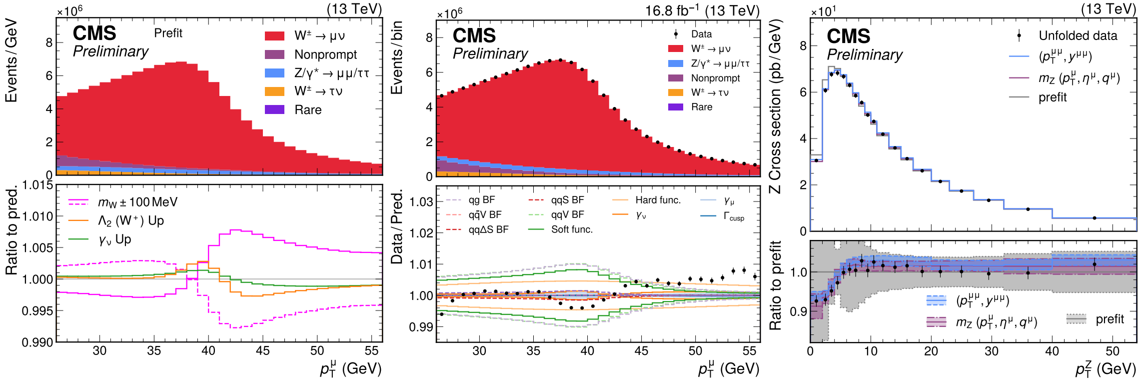




W mass at CMS ($\pm$9.9 MeV)

CMS PAS-SMP-23-002

- Full profile likelihood fit to lepton p_T and η
- Prediction: MiNNLO reweighted to SCETlib+DYTurbo N^{3}LL+NNLO
- TNPs instead of scale variations for resummation Tackmann $\rightarrow p_T^W$ uncertainty $\pm$2 MeV

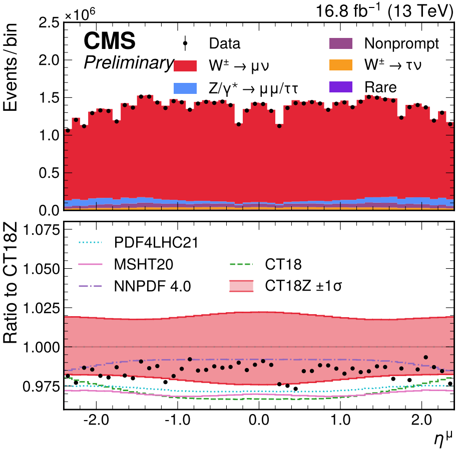


- W-like Z: one muon treated as neutrino $\rightarrow$ good agreement in p_T^Z and m_Z
- MiNNLO scale uncertainties on $A_i \rightarrow \pm$3.2 MeV, larger than p_T^W now

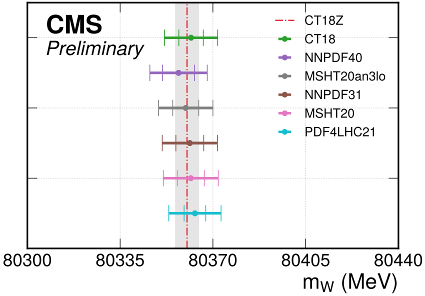
W mass at CMS (± 9.9 MeV): PDF treatment

CMS PAS-SMP-23-002

- CT18Z as default PDF, profiling the eigenvectors $\rightarrow \pm 4.4$ MeV
- Derive scale factors to cover m_W extracted with all other PDF sets



PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0



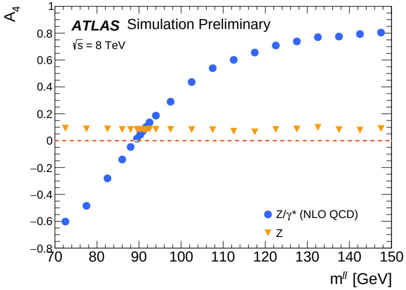
- Very good consistency between PDF sets even before scaling, owed to η^{μ}
- Difference CT18 vs NNPDF4.0 reduced from 5 MeV to 3 MeV

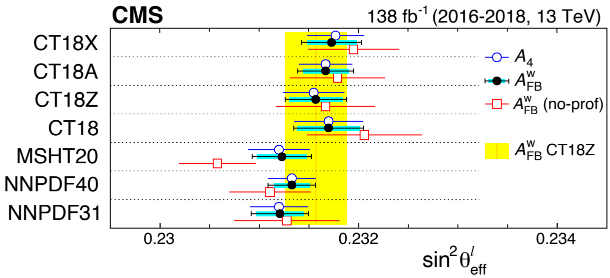
Weak mixing angle at ATLAS and CMS

- Measured by Z/γ^* forward-backward asymmetry, need to infer initial state
- Less dilution at higher Z rapidity $\rightarrow$ use electrons in forward calorimeters

7 TeV ATLAS STDM-2011-34 (total $\pm 12 \times 10^{-4}$) $\rightarrow$ 8 TeV ATLAS CONF-2018-037 (total $\pm 3.6 \times 10^{-4}$)

- PDF treatment: ATLAS-epWZ12 ($\pm 9 \times 10^{-4}$) $\rightarrow$ MMHT14 ($\pm 2.4 \times 10^{-4}$)





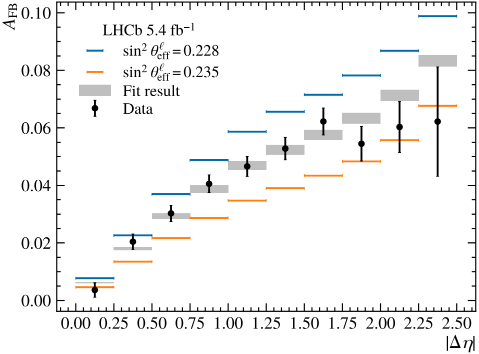
13 TeV measurement CMS SMP-22-010 (total $\pm 3.1 \times 10^{-4}$)

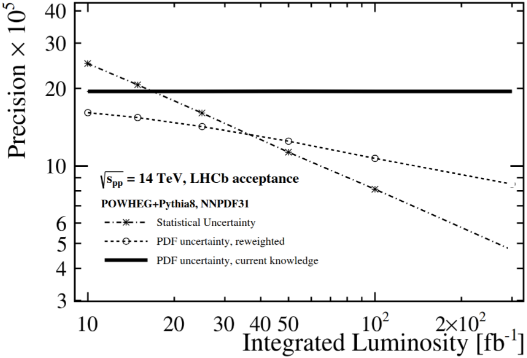
- PDF profiling $\rightarrow$ reduction of differences, decrease of individual PDF uncertainties
- Central value with CT18Z ($\pm 2.7 \times 10^{-4}$), covers other PDF sets

Weak mixing angle at LHCb

LHCb PAPER-2015-039 LHCb PAPER-2024-028

- Advantage: muon reconstruction in the forward region ($2.0 < \eta < 4.5$)
- 7+8 TeV: NNPDF2.3 $\rightarrow \pm 4.3 \times 10^{-4}$ (total $\pm 10.6 \times 10^{-4}$)
- 13 TeV: average of NNPDF3.1, CT18, and MSHT20 $\rightarrow \pm 2.1 \times 10^{-4}$ (total $\pm 4.9 \times 10^{-4}$)





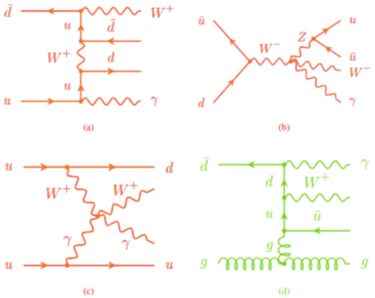
- Dominated by statistical uncertainty, great prospects with more data LHCb PUB-2018-013

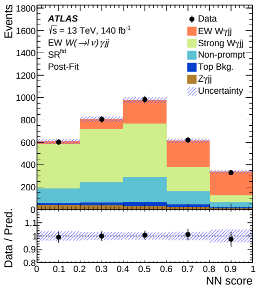
Remark for all $\sin^2\theta$ measurements: $A_{4/FB}$ fully unfolded, available for reinterpretation

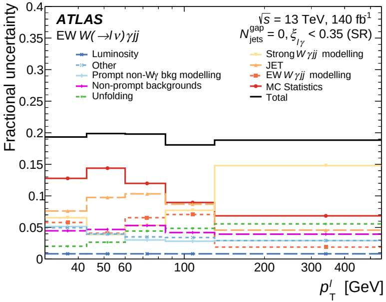
Diboson measurements: electroweak $W\gamma jj$

ATLAS STDM-2018-31

- QCD uncertainties relevant in EW measurements where QCD-induced subtracted
- Using NN to isolate EW from QCD-induced in VBS-enhanced phase space
  $\rightarrow$ observation of electroweak $W\gamma jj$, measured fiducial and differential cross sections





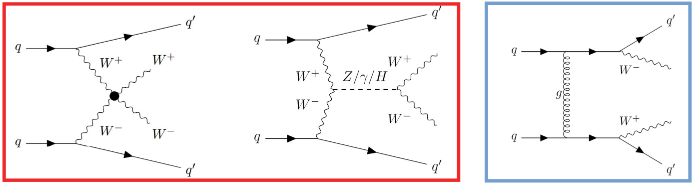


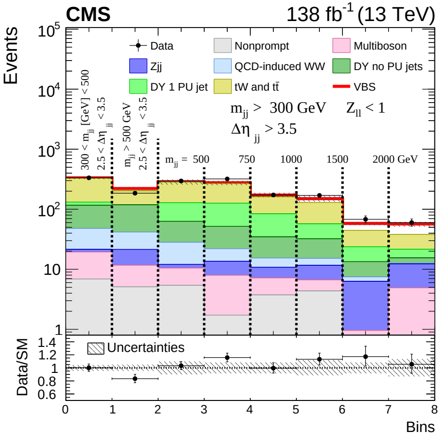
- Strong $W\gamma jj$ modeling uncertainties large at high lepton p_T
  - Sherpa NLO scale uncertainties, Sherpa vs MadGraph5_aMCatNLO
- Corresponding CMS measurement CMS SMP-21-011

Diboson measurements: electroweak W^+W^-

CMS SMP-21-001

- Observation of electroweak W^+W^- production



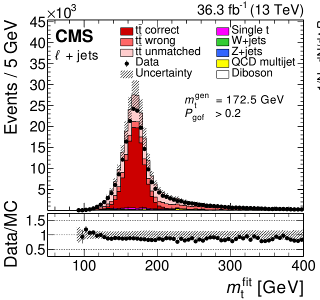


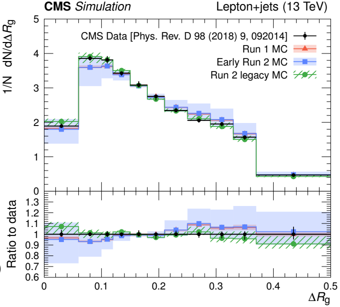
- Selected uncertainties
  - Leading uncertainty: statistical (14.9%)
  - $t\bar{t}$ scale variation (NLO, 5.1%)
  - VBS signal scale variation (WWjj@LO, 4.9%)
  - QCD-induced scale variation (WW@NNLO, 2.1%)
- Modeling might become limiting factor in the future
- Corresponding ATLAS paper ATLAS STDM-2022-06

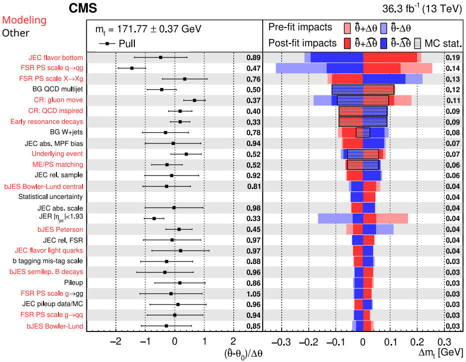
Top quark mass: direct measurements

CMS TOP-20-008

- Direct m_t measurements fit reconstructed top mass peak
- Progress in top quark modeling: switched to NLO generators, improved tunes, using parton shower weights for uncertainties CMS TOP-23-003



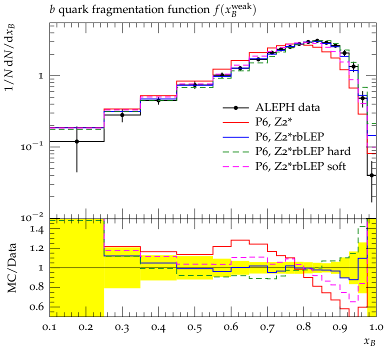


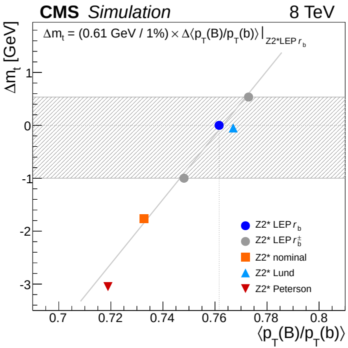


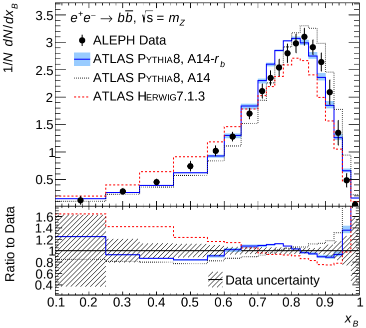
- PDF negligible but leading uncertainties from QCD modeling: Pythia vs Herwig b jet response, FSR scale, color reconnection
- Can we expect higher precision in top decays from NLL showers?

Top quark mass: alternative measurements

- Circumvent jet energy scale uncertainty by using heavy hadrons and leptons
- Large b fragmentation uncertainties in Run 1 CMS measurements
  - $m_{\mathrm{SecVtx},\ell} \to {}^{+1.00}_{-0.64}$ GeV (bfrag) CMS TOP-12-030 , $m_{J/\Psi,\ell} \to \pm 0.3$ GeV (bfrag) CMS TOP-15-014





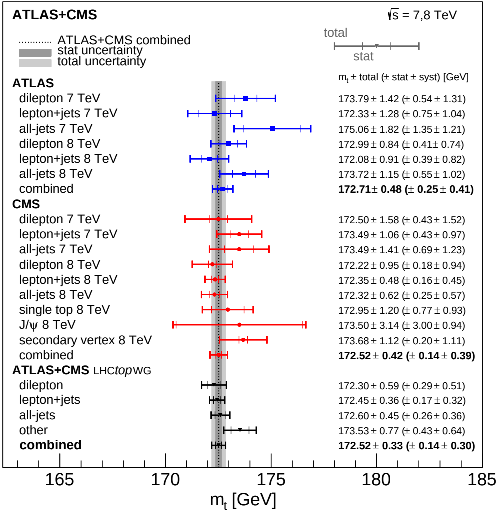


- ATLAS measurement using $m_{\ell\mu}$ with soft μ from b hadron decay ATLAS TOPQ-2017-17
  - Different approach of fitting LEP measurements → ±0.19 GeV (bfrag)
  - Leading uncertainties from b,c-hadron decay BRs (±0.40 GeV) and FSR recoil (±0.25 GeV)
- For all: no standard FSR variations evaluated, huge statistical uncertainties for J/Ψ

LHC Run 1 combination (direct+alternative)

ATLAS+CMS 2402.08713

- Most precise direct value from ATLAS+CMS Run 1 combination → ±0.33 GeV
- CR uncertainty reduced, likely to be effect from limited sample size in each measurement

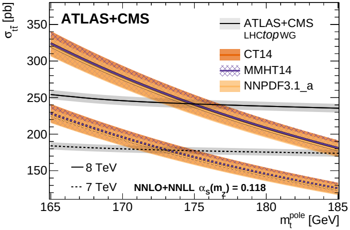


Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

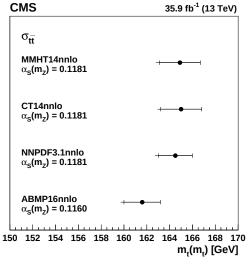
Top pole mass from cross section

ATLAS TOPQ-2013-04 | ATLAS+CMS 2205.13830 | CMS TOP-17-001

- Measured and predicted $\sigma_{t\bar{t}}$ have different dependence on m_t
- Extract m_t in well-defined mass scheme from intersection



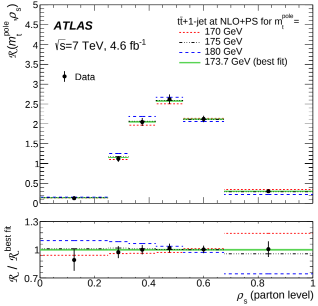
Δm_t^{pole} (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Data statistics	0.6	0.3
Analysis systematics	0.8	0.9
Integrated luminosity	0.7	1.2
LHC beam energy	0.7	0.6
PDF+α_s	1.8	1.7
QCD scale choice	$^{+0.9}_{-1.2}$	$^{+0.9}_{-1.3}$



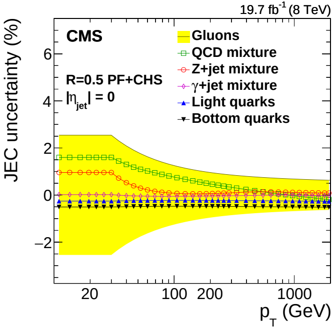
- Largest uncertainties from PDF+α_s and QCD scale (NNLO+NNLL)
  - No breakdown given but $\alpha_s \pm 0.001$ may account for ± 1.5 GeV in m_t
- Most precise result: ATLAS+CMS Run 1 combination: $m_t = 173.4^{+1.8}_{-2.0}$ GeV (NNPDF3.1)
- CMS 13 TeV: 3 GeV downward shift with ABMP16 which uses a lower value of α_s
  $\rightarrow$ pole mass results envelope the direct measurements

Pole mass from $t\bar{t}$ + jet

ATLAS TOPQ-2014-06 CMS TOP-21-008



- Using mass-sensitive observable $\rho = 2m_0/m\,(t\bar{t} + \text{jet})$
- ATLAS measurement at 7 TeV
  - $m_t = 173.7 \pm 1.5\ (\text{stat}) \pm 1.4\ (\text{syst})^{+1.0}_{-0.5}\ (\text{theory})$
  - Large QCD scale uncertainty from NLO $t\bar{t}$ + jet ($^{+0.93}_{-0.44}$ GeV), using fixed scale $\mu = m_t$
- CMS measurement at 13 TeV
  - Dynamic QCD scale choice $H_T^B/2 \rightarrow {}^{+0.51}_{-0.43}$ GeV
  - Largest uncertainty from gluon jet response CMS JME-13-004
  - $m_t = 172.93 \pm 1.36$ GeV (ABM16), $m_t = 172.13 \pm 1.43$ GeV (CT18) ← 0.8 GeV difference

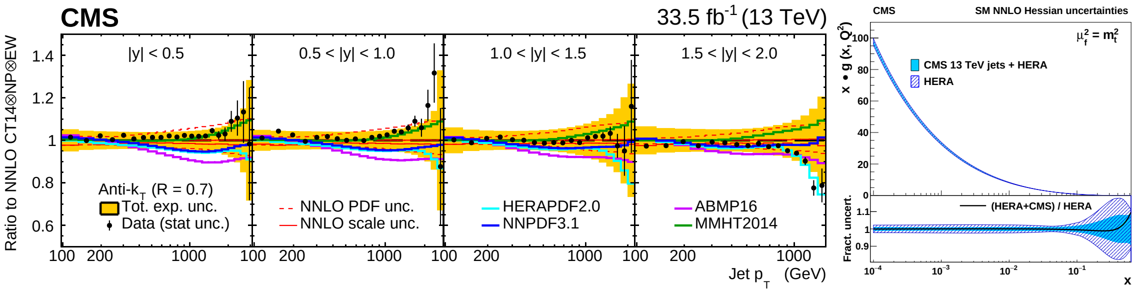


→ wishlist: NNLO calculation, resolve PDF discrepancy, resolve light-quark vs gluon jet response (Pythia vs Herwig)

Strong coupling from jet production

CMS SMP-12-028 CMS SMP-14-001 CMS SMP-20-011

- 7 TeV: $\alpha_s = 0.1185 \pm 0.0028\ (\text{CT10})^{+0.0053}_{-0.0024}\ (\text{NLO scale}) \pm 0.0019\ (\text{exp+NP})$
- 8 TeV: $\alpha_s = 0.1164^{+0.0025}_{-0.0029}\ (\text{CT10})^{+0.0053}_{-0.0028}\ (\text{NLO scale})^{+0.0014}_{-0.0015}\ (\text{exp+NP})$
  - HERA+CMS result: $\alpha_s = 0.1185^{+0.0002}_{-0.0016}\ (\text{model+param})^{+0.0022}_{-0.0018}\ (\text{NLO scale})^{+0.0019}_{-0.0021}\ (\text{exp})$
  - Smaller QCD scale uncertainties due to consistent treatment in PDF and theory prediction

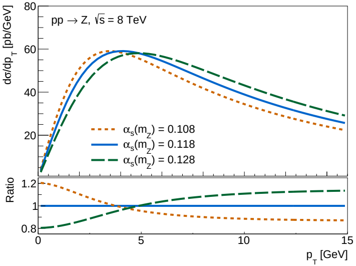


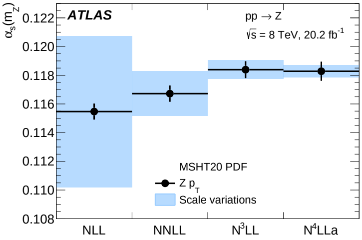
- 13 TeV: main result now HERA+CMS full QCD fit at NNLO
  - $\alpha_s = 0.1170 \pm 0.0007\ (\text{model+param}) \pm 0.0008\ (\text{NNLO scale}) \pm 0.0014\ (\text{exp})$
  - Jet energy response to gluons starts to become an important factor
    $\rightarrow$ new parton showers, or clever idea for calibration?

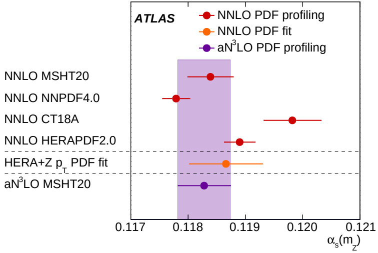
Strong coupling from Z boson recoil

ATLAS STDM-2023-01

- Measurement of Z p_T and rapidity in full phase space (without lepton cuts)
- Fitted using N^{3}LO+aN^{4}LL prediction, profiling MSHT20 PDFs $\rightarrow \alpha_s = 0.1183 \pm 0.0009$
  - Experimental ± 0.44, PDF ± 0.51, scale variation $\pm 0.42 \times 10^{-3}$



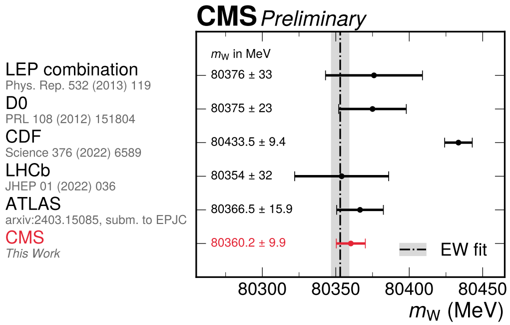


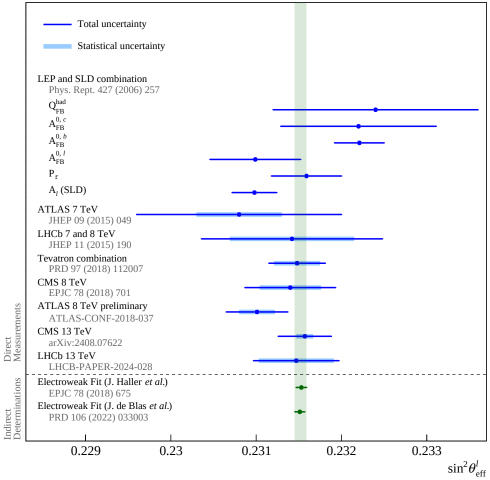


- Cross-check fits at N^{3}LO+N^{3}LL, profiling NNLO PDFs
  - MSHT20 in agreement with NNPDF4.0 and HERAPDF2.0 within PDF uncertainties
  - Value extracted with CT18A significantly higher (0.1198)
- HERA+ATLAS fit $\rightarrow \alpha_s = 0.1187 \pm 0.0010$ with ± 0.0006 from PDF

Summary: W mass and weak mixing angle

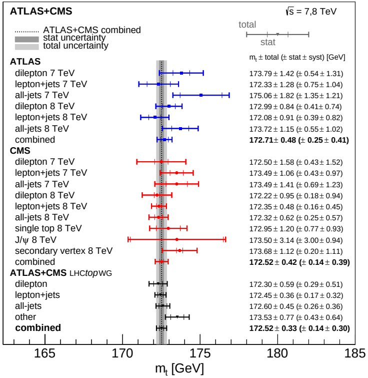
- LHC is a precision machine!
- W boson mass: uncertainties balanced between experimental and modeling

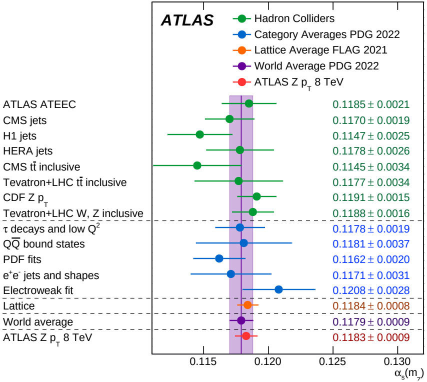




- Weak mixing angle: precision limited by PDFs, good prospects for LHCb with more data

Summary: top quark mass and strong coupling





- Direct m_t: limited by modeling of top quark decay and scheme uncertainty
- m_t from cross section: large uncertainties from PDF, α_s, and QCD scale (NNLO+NNLL)
- α_s: dominated by theory and modeling, genuine detector effects becoming smaller

⇒ further improve precision by collaboration between theory and LHC experiments!