# Measurements of the strong coupling constant at the LHC and perspectives

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# Introduction

- The strong coupling, one of the main free parameters in QCD, is known with least precision than any other SM coupling, $\alpha_s(m_Z) = 0.1181 \pm 0.0011$
- Uncertainties in $\alpha_s$ are important in theoretical calculations of
  - Higgs boson production cross sections and decay widths,
  - top quark mass
  - EW precision observables
  - physics at Planck/GUT scales
- At hadron colliders the only observable known at NNLO accuracy used so far for determination of the strong coupling is $\sigma(t\bar{t})$,

New measurements considered this year:

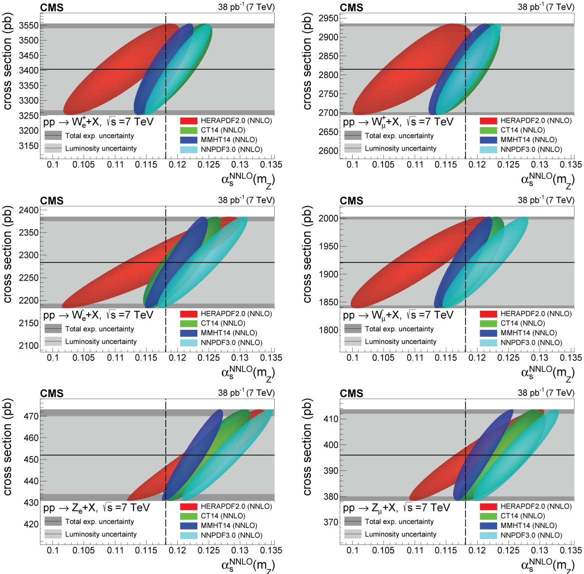
- CMS: Determination of $\alpha_s(M_Z)$ from inclusive $W^{\pm}$ and $Z$ boson production in $p-p$ at 7 and 8 $TeV$ (JHEP 06 (2020) 018 )
- ATLAS : Determination of $\alpha_s(M_Z)$ and test of asymptotic freedom from Transverse Energy-Energy Correlations (TEEC) at 13 $TeV$ (ATLAS-CONF-2020-025 )

The table below shows a summary of the twelve $W^{\pm}$ and $Z$ boson fiducial cross sections in the $e, \mu$ decay channels at 7 TeV (38.0 $pb^{-1}$) and 8 TeV (18.2 $pb^{-1}$) together with their uncertainties : (JHEP 06 (2020) 018 )

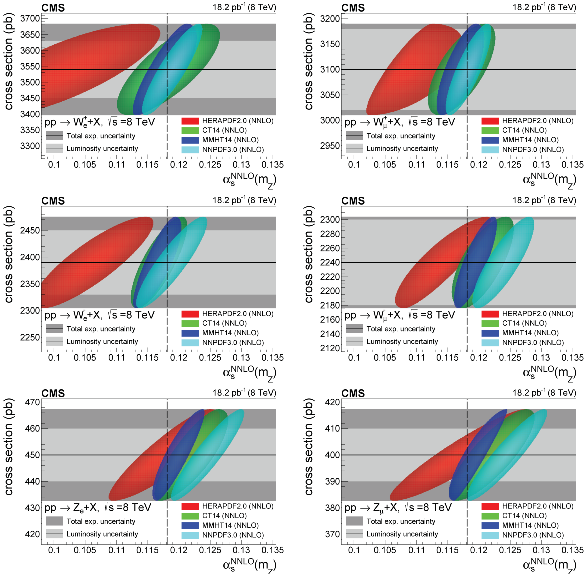
| Measurement | Fiducial cross section |
|---|---|
| pp at $\sqrt{s} = 7$ TeV [? ] | |
| $W_e^+$, $p_T^e > 25$ GeV, $\|\eta^e\| < 2.5$ | $3404 \pm 12\,(\text{stat}) \pm 67\,(\text{syst}) \pm 136\,(\text{lumi})$ pb $= 3404 \pm 152$ pb |
| $W_e^-$, $p_T^e > 25$ GeV, $\|\eta^e\| < 2.5$ | $2284 \pm 10\,(\text{stat}) \pm 43\,(\text{syst}) \pm 91\,(\text{lumi})$ pb $= 2284 \pm 101$ pb |
| $Z_e$, $p_T^e > 25$ GeV, $\|\eta^e\| < 2.5$, $60 < m_Z < 120$ GeV | $452 \pm 5\,(\text{stat}) \pm 10\,(\text{syst}) \pm 18\,(\text{lumi})$ pb $= 452 \pm 21$ pb |
| $W_\mu^+$, $p_T^\mu > 25$ GeV, $\|\eta^\mu\| < 2.1$ | $2815 \pm 9\,(\text{stat}) \pm 42\,(\text{syst}) \pm 113\,(\text{lumi})$ pb $= 2815 \pm 121$ pb |
| $W_\mu^-$, $p_T^\mu > 25$ GeV, $\|\eta^\mu\| < 2.1$ | $1921 \pm 8\,(\text{stat}) \pm 27\,(\text{syst}) \pm 77\,(\text{lumi})$ pb $= 1921 \pm 82$ pb |
| $Z_\mu$, $p_T^\mu > 20$ GeV, $\|\eta^\mu\| < 2.1$, $60 < m_Z < 120$ GeV | $396 \pm 3\,(\text{stat}) \pm 7\,(\text{syst}) \pm 16\,(\text{lumi})$ pb $= 396 \pm 18$ pb |
| pp at $\sqrt{s} = 8$ TeV [? ] | |
| $W_e^+$, $p_T^e > 25$ GeV, $\|\eta^e\| < 1.44$, $1.57 < \|\eta^e\| < 2.5$ | $3540 \pm 20\,(\text{stat}) \pm 110\,(\text{syst}) \pm 90\,(\text{lumi})$ pb $= 3540 \pm 140$ pb |
| $W_e^-$, $p_T^e > 25$ GeV, $\|\eta^e\| < 1.44$, $1.57 < \|\eta^e\| < 2.5$ | $2390 \pm 10\,(\text{stat}) \pm 60\,(\text{syst}) \pm 60\,(\text{lumi})$ pb $= 2390 \pm 90$ pb |
| $Z_e$, $p_T^e > 25$ GeV, $\|\eta^e\| < 1.44$, $1.57 < \|\eta^e\| < 2.5$, $60 < m_Z < 120$ GeV | $450 \pm 10\,(\text{stat}) \pm 10\,(\text{syst}) \pm 10\,(\text{lumi})$ pb $= 450 \pm 20$ pb |
| $W_\mu^+$, $p_T^\mu > 25$ GeV, $\|\eta^\mu\| < 2.1$ | $3100 \pm 10\,(\text{stat}) \pm 40\,(\text{syst}) \pm 80\,(\text{lumi})$ pb $= 3100 \pm 90$ pb |
| $W_\mu^-$, $p_T^\mu > 25$ GeV, $\|\eta^\mu\| < 2.1$ | $2240 \pm 10\,(\text{stat}) \pm 20\,(\text{syst}) \pm 60\,(\text{lumi})$ pb $= 2240 \pm 60$ pb |
| $Z_\mu$, $p_T^\mu > 25$ GeV, $\|\eta^\mu\| < 2.1$, $60 < m_Z < 120$ GeV | $400 \pm 10\,(\text{stat}) \pm 10\,(\text{syst}) \pm 10\,(\text{lumi})$ pb $= 400 \pm 20$ pb |

- Calculations at NNLO accuracy with MCFM (R. Boughezal et al., EPJ C 77 (2017) 7 ) interfaced with LHAPDF (CT14, MMHT14, NNPDF3.0 and HERAPDF2.0) and $\mu_R = \mu_F = m_W, m_Z$
- EW corrections are taken into account with the code MCSANC (S.G. Bondarenko and A.A. Sapronov, Comp. Phys. Comm. 184 (2013) 2343 )

Experimental fiducial x-sections on the Y-axis are shown at 7 TeV together with joint probability densities for 4 PDF sets as a function of $\alpha_s(M_Z)$ on the X-axis

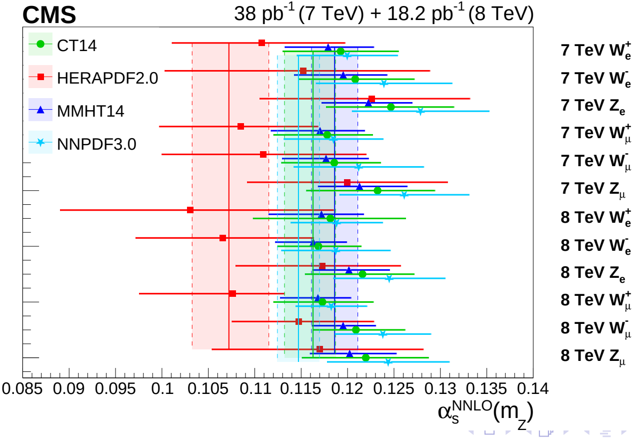


Experimental fiducial x-sections on the Y-axis are shown at 8 TeV together with joint probability densities for 4 PDF sets as a function of $\alpha_s(M_Z)$ on the X-axis



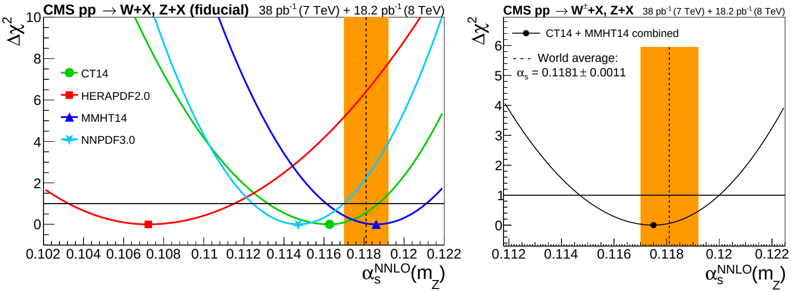
- From previous two figures: predictions using the HERAPDF2.0 set, which is obtained from fits to DIS data only, tend to be above the data
- Those using NNPDF3.0 tend to be systematically below
- While MMHT14 and CT14 overlap

These features translate into these values of $\alpha_s(m_Z)$ extracted for each channel and for each PDF separately



Results for $\alpha_s(m_Z)$ extracted from a global fit

| PDF | $\alpha_S(m_Z)$ | $\delta$(stat) | $\delta$(lumi) | $\delta$(syst) | $\delta$(PDF) | $\delta$(scale) | $\delta$(num) | $\chi^2$/ndf |
|---|---|---|---|---|---|---|---|---|
| CT14 | $0.1163^{+0.0024}_{-0.0031}$ | 0.0007 | 0.0013 | 0.0010 | $^{+0.0016}_{-0.0022}$ | 0.0009 | 0.0006 | 13.3/11 |
| HERAPDF2.0 | $0.1072^{+0.0043}_{-0.0040}$ | 0.0012 | 0.0027 | 0.0012 | $^{+0.0027}_{-0.0020}$ | 0.0012 | 0.0009 | 14.2/11 |
| MMHT14 | $0.1186 \pm 0.0025$ | 0.0003 | 0.0018 | 0.0009 | 0.0013 | 0.0007 | 0.0002 | 10.2/11 |
| NNPDF3.0 | $0.1147 \pm 0.0023$ | 0.0009 | 0.0008 | 0.0007 | 0.0014 | 0.0006 | 0.0010 | 29.2/11 |



- Event shapes have been measured in $e^+e^-$, $e-p$ and hadron colliders
- One particularly interesting example of event shapes : TEEC and ATEEC
- Measured by ATLAS at 7 TeV (158 $pb^{-1}$) and 8 TeV (20.2 $fb^{-1}$)

Extension at 13 TeV desirable because

- The interaction scale is extended from below 1 TeV to 4 TeV
- Improved statistical accuracy from 1.5% to 0.5%
- Reduction of systematic uncertainties from 5% to 2%
- Reduction in JES and JER uncertainties due to combined use of tracking and calorimetric information (ATLAS Coll., CERN-EP-2020-083 )
- Aim: leave as a legacy a measurement which supersedes those from LEP

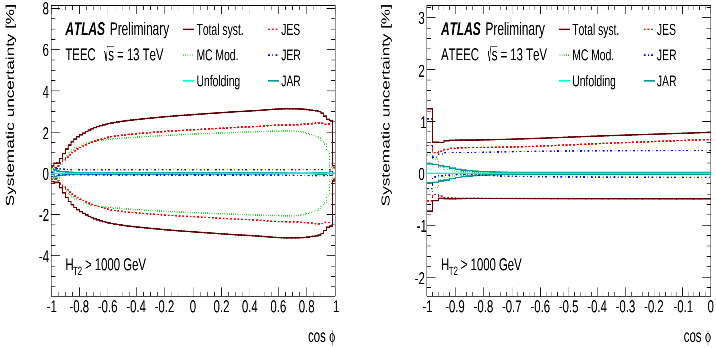
For a sample of $N$ multijet events, the TEEC funcion is defined as :

$$\frac{1}{\sigma'}\frac{d\Sigma'}{dcos\phi} = \frac{1}{N}\sum_{A=1}^{N}\frac{1}{\Delta cos\phi}\sum_{\substack{a,b=1 \\ pairs\ \ in\ \ \Delta cos\phi}}^{N_{jets}}\frac{2E^A_{T_a}E^A_{T_b}}{(E^A_T)^2} \tag{1}$$

The ATEEC is defined as its forward-backward asymmetry

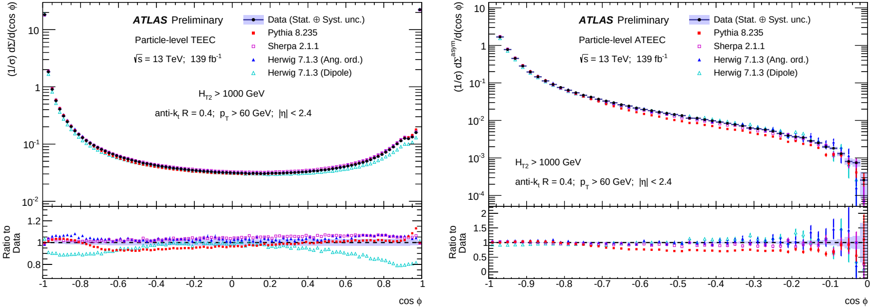
- Full Run 2 data set at $\sqrt{s} = 13\ TeV$ with an integrated luminosity of $139\ fb^{-1}$
- $HLT\_j460$ unprescaled single jet trigger
- Jet clustering: particle flow objects
- Jet reconstruction: anti-$k_T$ algorithm with $R = 0.4$
- Event and jet cleaning algorithms applied
- Jet selection: $p_T > 60\ GeV$ and $|\eta| < 2.4$ for each jet
- Event selection : $H_{T2} = p_{T1} + p_{T2} > 1\ TeV$
- Ten bins in $H_{T2}$ considered: From $1.0 < H_{T2} < 1.2\ TeV$ up to $H_{T2} > 3.5\ TeV$

Data unfolded with an iterative Bayesian procedure
The plots below show the systematic uncertainties for the inclusive TEEC (left) and ATEEC (right)

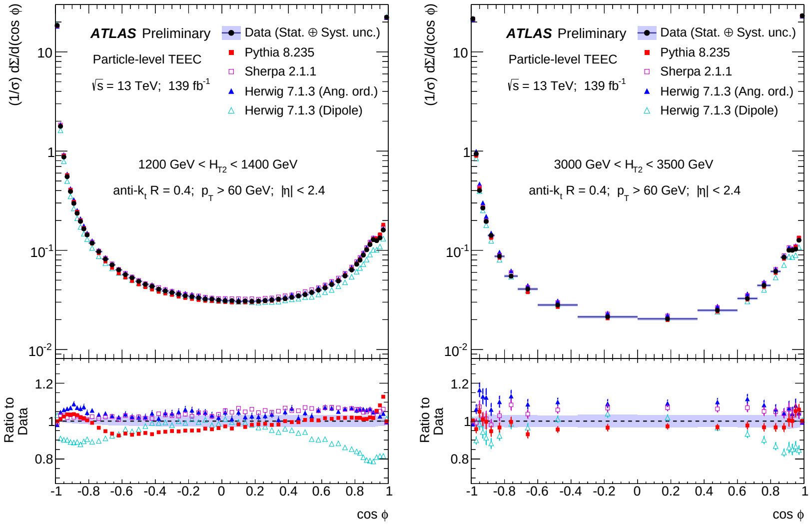



- Dominant systematic sources are the JES and MC modelling
- They amount to $1 - 2\%$ in the central plateau for any $H_{T2}$ bin

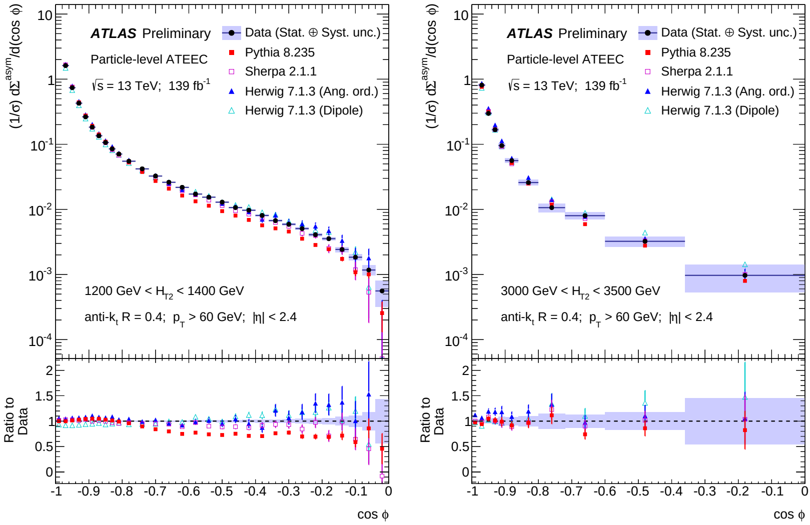
# ATLAS Inclusive TEEC (lhs) and ATEEC (rhs) at particle level and comparison with Monte Carlo models




- LO SHERPA ($2 \to 2$ and $2 \to 3$) and NLO HERWIG 7 (angular ordered PS) give similar overall good description of the data
- LO PYTHIA 8 ($2 \to 2$) underestimates the asymmetry at large angles
- NLO HERWIG 7 (dipole PS) needs a better tune

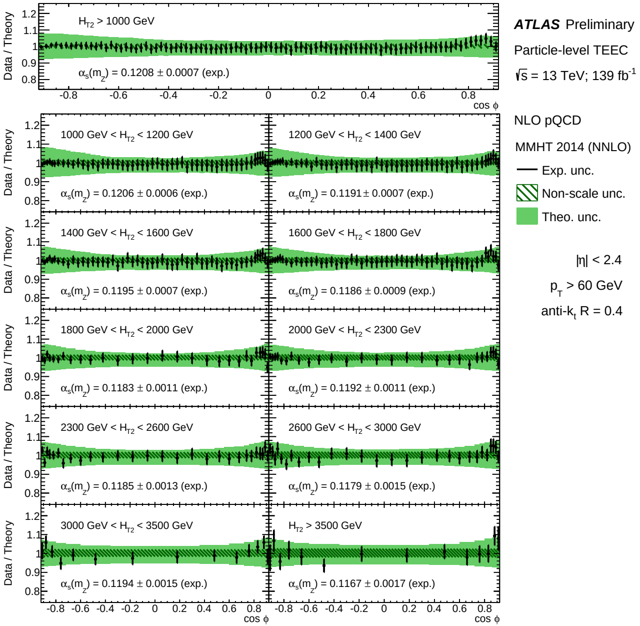

ATLAS Preliminary
Particle-level TEEC
√s = 13 TeV; 139 fb-1
Data (Stat. ⊕ Syst. unc.)
Pythia 8.235
Sherpa 2.1.1
Herwig 7.1.3 (Ang. ord.)
Herwig 7.1.3 (Dipole)
1200 GeV < HT2 < 1400 GeV
3000 GeV < HT2 < 3500 GeV
anti-kt R = 0.4; pT > 60 GeV; |η| < 2.4
(1/σ) dΣ/d(cos ϕ)
Ratio to Data
cos ϕ

# ATLAS ATEEC at particle level for two representative $H_{T2}$ bins

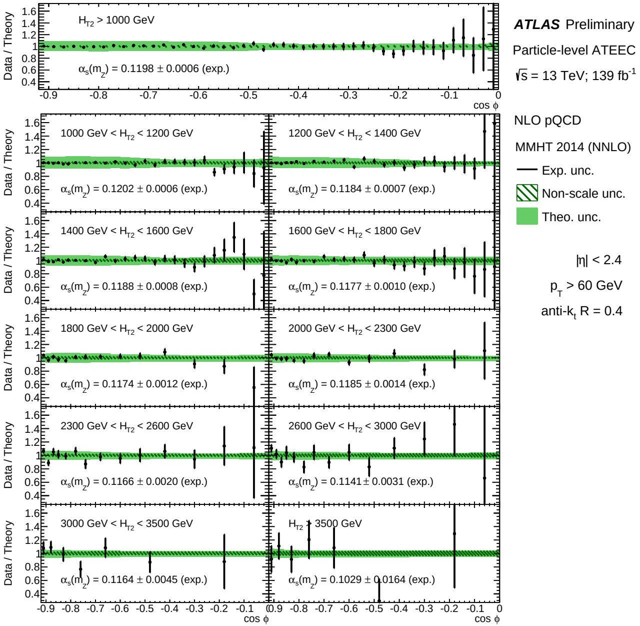


# TEEC at 13 TeV: Fixed order predictions at NLO in pQCD

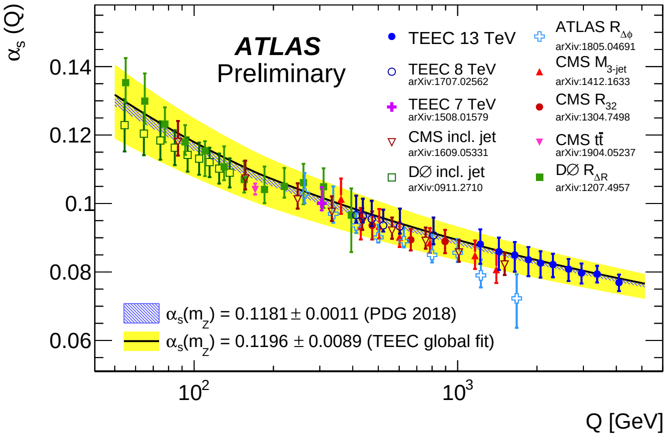
- Analogue of the EEC in $e^+e^-$ annihilation is the transverse EEC: (A. Ali, E. Pietarinen and W.J. Stirling, PL B141 (1984) 447 )
- NLO corrections are found moderate : (A. Ali, F.B., J. Llorente and W. Wang., Phys. Rev. D86 (2012) 114017 )
- Theoretical predictions computed at parton level using NLOJET++ (Z. Nagy, Phys. Rev. D 68 (2003) 094002 )
- Collinear emissions are controlled with the cut $|cos\phi| < 0.92$
- Renormalization scale choice $\mu_R = \hat{H}_T = \sum_i p_{Ti}$
- Cross sections are convoluted with NNLO PDF sets available from LHAPDF namely MMHT 2014, NNPDF 3.0 and CT14
- Factorization scale $\mu_F = \mu_R/2$
- Jets are reconstructed with FASTJET
- Non perturbative corrections are computed with PYTHIA 8.240 with Tune A14, compatible with unity within 1%
- Scale uncertainty is the dominant theoretical uncertainty source $O(6\%)$
- PDF uncertainties obtained fom variations of the PDF group eigenvectors are subdominant $O(1\%)$


H_T2 > 1000 GeV
αs(mZ) = 0.1208 ± 0.0007 (exp.)
1000 GeV < H_T2 < 1200 GeV
αs(mZ) = 0.1206 ± 0.0006 (exp.)
1200 GeV < H_T2 < 1400 GeV
αs(mZ) = 0.1191 ± 0.0007 (exp.)
1400 GeV < H_T2 < 1600 GeV
αs(mZ) = 0.1195 ± 0.0007 (exp.)
1600 GeV < H_T2 < 1800 GeV
αs(mZ) = 0.1186 ± 0.0009 (exp.)
1800 GeV < H_T2 < 2000 GeV
αs(mZ) = 0.1183 ± 0.0011 (exp.)
2000 GeV < H_T2 < 2300 GeV
αs(mZ) = 0.1192 ± 0.0011 (exp.)
2300 GeV < H_T2 < 2600 GeV
αs(mZ) = 0.1185 ± 0.0013 (exp.)
2600 GeV < H_T2 < 3000 GeV
αs(mZ) = 0.1179 ± 0.0015 (exp.)
3000 GeV < H_T2 < 3500 GeV
αs(mZ) = 0.1194 ± 0.0015 (exp.)
H_T2 > 3500 GeV
αs(mZ) = 0.1167 ± 0.0017 (exp.)
Data / Theory
cos ϕ
ATLAS Preliminary
Particle-level TEEC
√s = 13 TeV; 139 fb-1
NLO pQCD
MMHT 2014 (NNLO)
Exp. unc.
Non-scale unc.
Theo. unc.
|η| < 2.4
pT > 60 GeV
anti-kt R = 0.4

# $\alpha_S(M_Z)$ determined from fits to ATLAS ATEEC particle level data

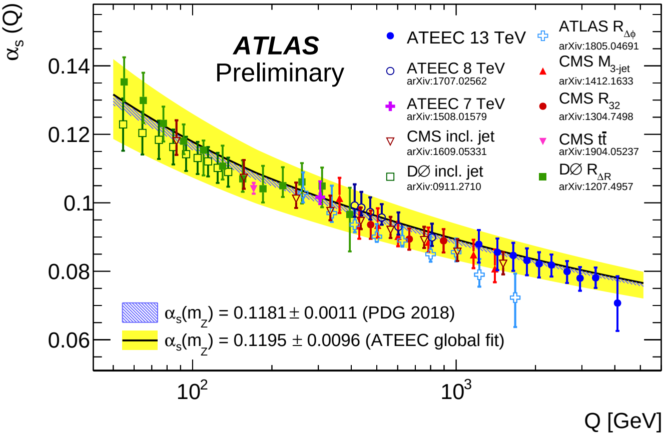


# Test of the running of the strong coupling from ATLAS TEEC




These data could be used to improve limits on masses for new coloured fermions obtained by J. Llorente and B. Nachman, Nucl. Phys. B936 (2018) 106 using previous measurements at 8 TeV.

# Test of the running of the strong coupling from ATLAS ATEEC



# Summary and Outlook

- CMS has measured $W^{\pm}$ and $Z$ boson production x-sections in the $e, \mu$ channels at 7 and 8 TeV
- Comparisons with MCFM calculations at NNLO accuracy interfaced with LHAPDF $\Rightarrow$ extracted $\alpha_s(m_Z) = 0.1186 \pm 0.0025$ with MMHT 14

- ATLAS measured TEEC and ATTEC at 13 TeV
- Comparison with NLOJET++ predictions $\Rightarrow$ extracted $\alpha_s(Q)$ with Q in the range $1 - 4\ TeV$
- From a global fit to the TEEC data $\Rightarrow$ $\alpha_s(m_Z) = 0.1196 \pm 0.0004(exp) \pm 0.0089(theo)$
- NNLO corrections needed to bring down the scale systematic uncertainties