Determination of the strong coupling constant from TEEC in multijet events at 13 GeV with the ATLAS detector

Fernando Barreiro
On behalf of the ATLAS Collaboration

Universidad Autónoma de Madrid

α_s-2024, Trento, Feb 5-9,2024

Introduction

- The strong coupling, one of the main free parameters in QCD, is known with least precision than any other SM coupling, $\alpha_s(m_Z) = 0.1180 \pm 0.0009$
- Uncertainties in α_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:

- ATLAS : Determination of the strong coupling from Transverse Energy-Energy Correlations (TEEC) in multijet events at 13 *TeV* (JHEP 07 (2023) 085)

Transverse Energy-Energy Correlations (TEEC) at 13 TeV with ATLAS

- 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 function is defined as :

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

The ATEEC is defined as its forward-backward asymmetry

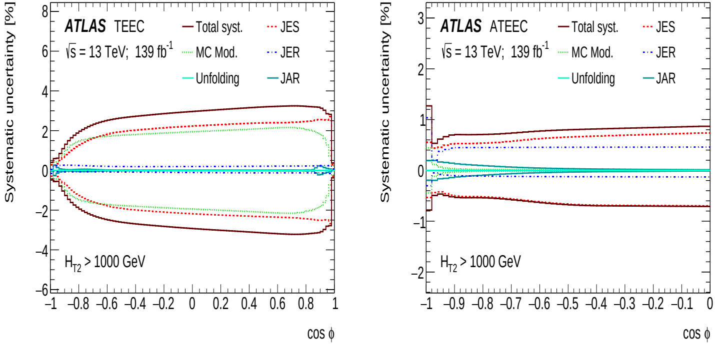
TEEC at 13 TeV with ATLAS : Data and event selection, MC samples

- 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 : $H_{T2} = p_{T1} + p_{T2} > 1\ TeV$
- 60M events in ten bins in H_{T2} : From $1.0 < H_{T2} < 1.2\ TeV$, $1.2 < H_{T2} < 1.4\ TeV$ up to $3.0 < H_{T2} < 3.5\ TeV$ and $H_{T2} > 3.5\ TeV$
- Table below : MC generators used in the analysis

Generator	ME order	ME partons	PDF set	Parton shower	Scales μ_R, μ_F	$\alpha_s(m_Z)$
Pythia 8	LO	2	NNPDF 2.3 LO	p_T-ordered	$(m_{T3}^2 \cdot m_{T4}^2)^{\frac{1}{2}}$	0.140
Sherpa	LO	2,3	CT14 NNLO	CSS (dipole)	$H(s,t,u)$ [2 → 2] CMW [2 → 3]	0.118
Herwig 7	NLO	2,3	MMHT2014 NLO	Angular-ordered Dipole	$\max\{p_{Ti}\}_{i=1}^{N}$	0.120

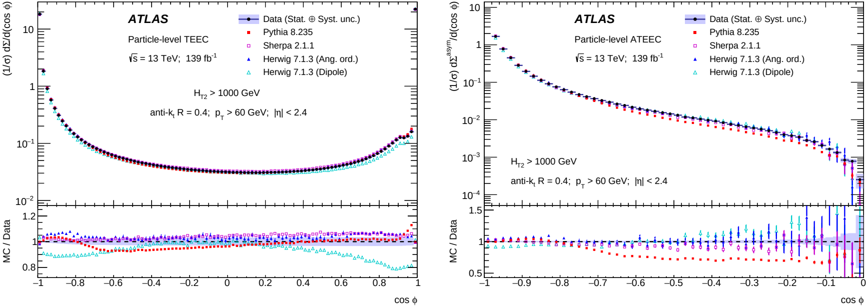
ATLAS TEEC at 13 TeV: Unfolding and experimental systematic uncertainties

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



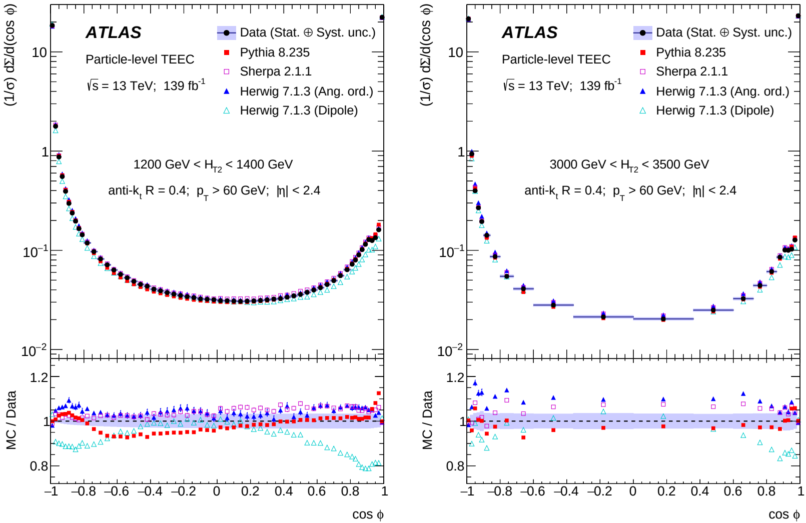
- Dominant systematic sources are the JES and MC modelling
- They amount to $1-2\%$ in the central plateau for any H_{T2} bin

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

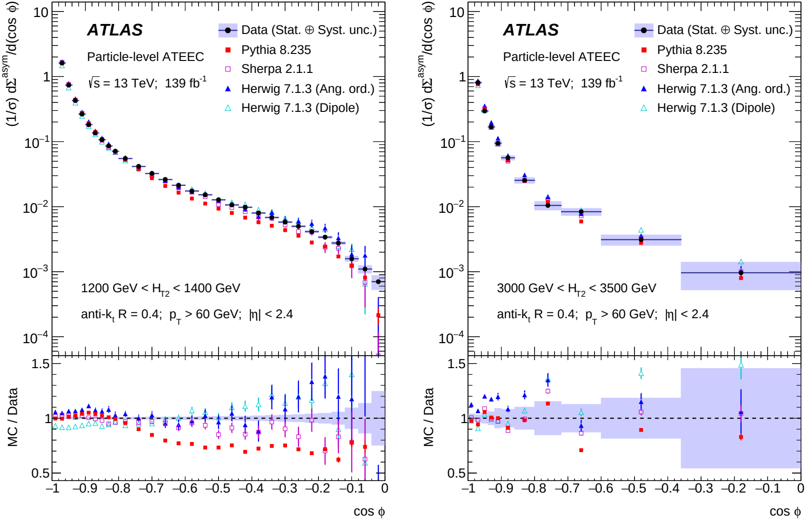


- LO SHERPA (2 → 2 and 2 → 3) and NLO HERWIG 7 (angular ordered PS) give similar overall good description of the data
- LO PYTHIA 8 (2 → 2) underestimates the asymmetry at large angles
- NLO HERWIG 7 (dipole PS) needs a better tune

ATLAS TEEC at particle level for two representative H_{T2} bins



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

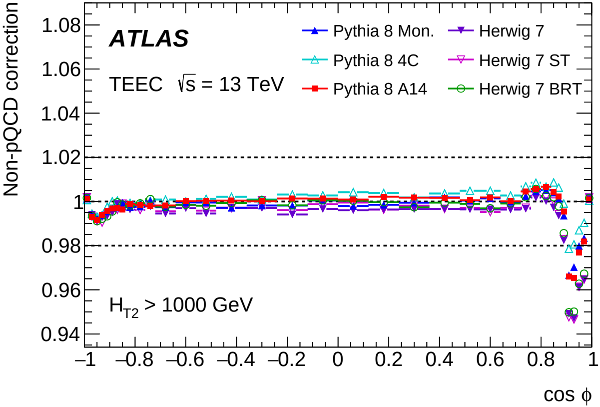


TEEC at 13 TeV: Fixed order predictions at NLO in pQCD

- 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 0.5%
- Scale uncertainty is the dominant theoretical uncertainty source $O(6\%)$
- PDF uncertainties obtained fom variations of the PDF group eigenvectors are subdominant $O(1\%)$
- Results presented in ICHEP-2020 Prague: (ATLAS-CONF-2020-025)

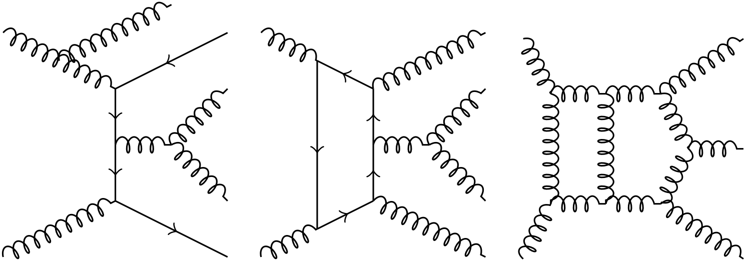
Non-perturbative corrections

Calculated as ususal as the ratio between MC expectations with fragmentation and underlying event effects switched on and off



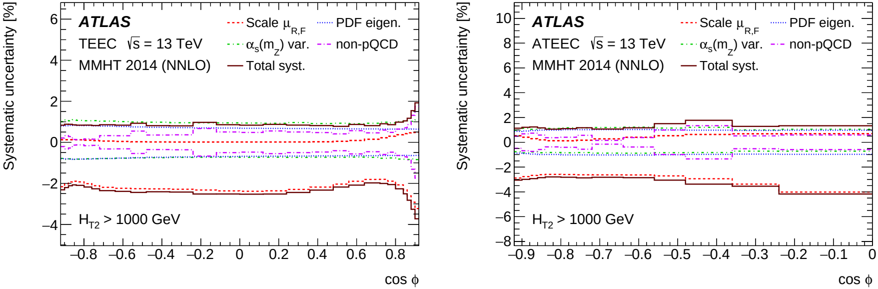
TEEC at 13 TeV: Fixed order predictions at NNLO in pQCD

- M. Czakon, A. Mitov and R. Poncelet, PRL 127 (2021) 152001
- 5×10^{13} events generated, 200 M CPU hours at the WLCG
- $2 \rightarrow 3$ subprocesses at NNLO, $2 \rightarrow 4$ subprocesses at NLO and $2 \rightarrow 5$ subprocesses at LO
- Mixed flavour scheme assumed
- $\mu_R = \mu_F = \hat{H}_T$
- 1M Feynman diagrams computed, sample diagrams for real-real (l.h.s.), real-virtual (center) and virtual-virtual (r.h.s.) are shown below
- Partial statistics: M. Alvarez, J. Cantero, M. Czakon, J. Llorente, A. Mitov and R. Poncelet, JHEP 03 (2023) 129)

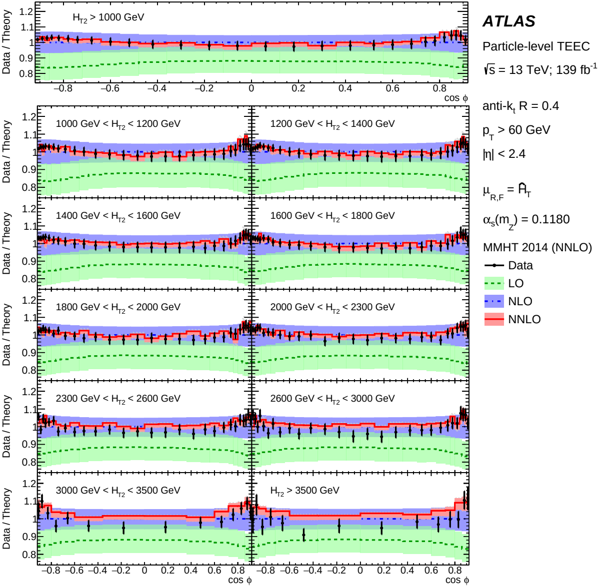


Theoretical uncertainties at NNLO

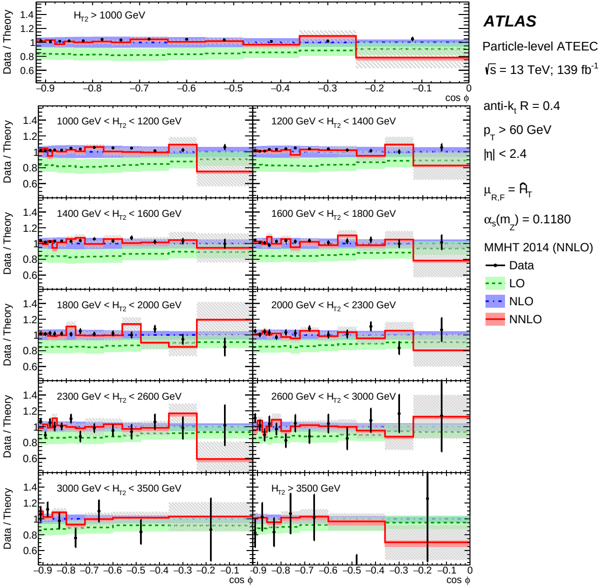
- NNLO corrections are found small at large angles
- Main improvement : scale uncertaintis are reduced by factor 2-3 w.r.t NLO calculations



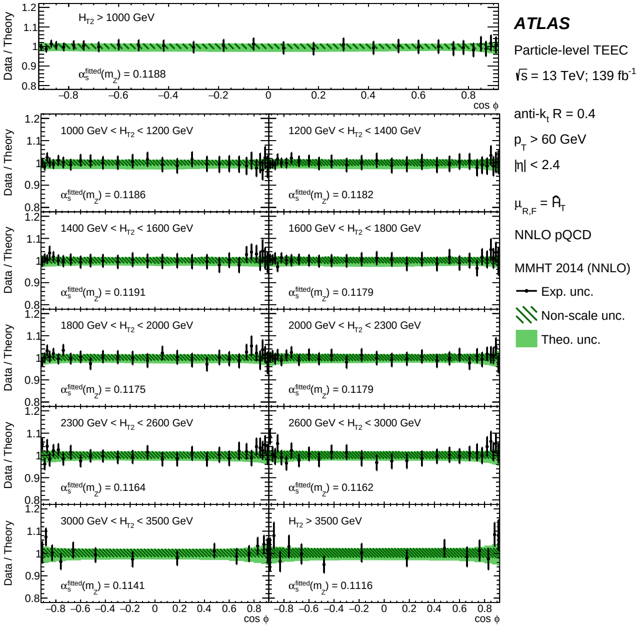
Ratios to NLO predictions for fixed coupling : TEEC



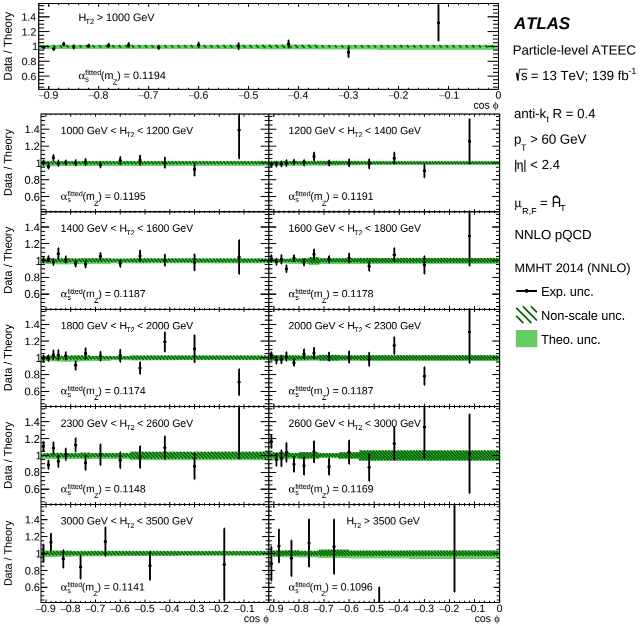
Ratios to NLO predictions for fixed coupling: ATEEC



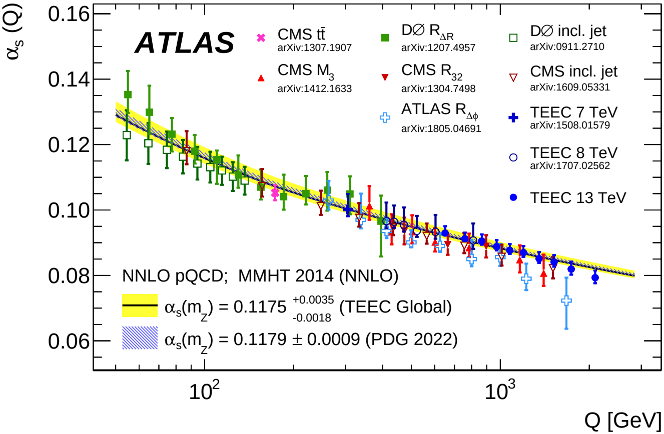
$\alpha_S(M_Z)$ determined from fits to ATLAS TEEC particle level data



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

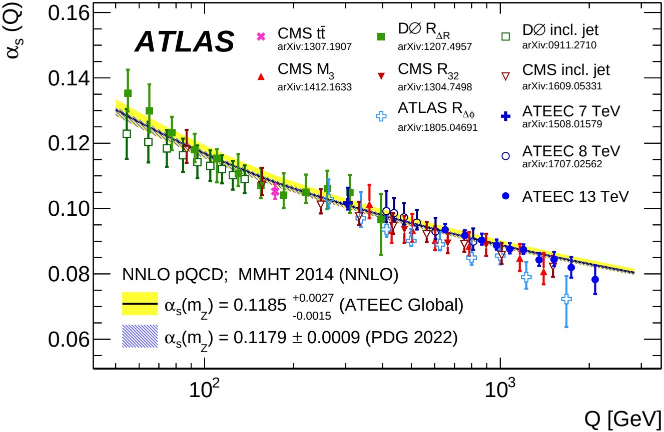


Test of the running of the strong coupling from ATLAS TEEC



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.

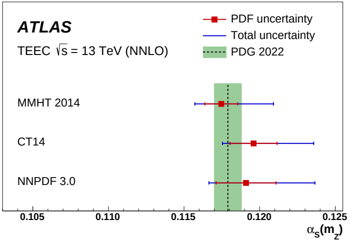
Test of the running of the strong coupling from ATLAS ATEEC

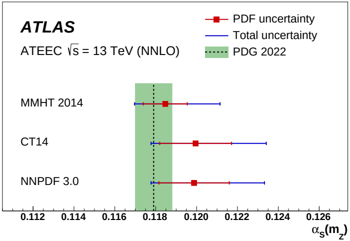


Summary and Outlook

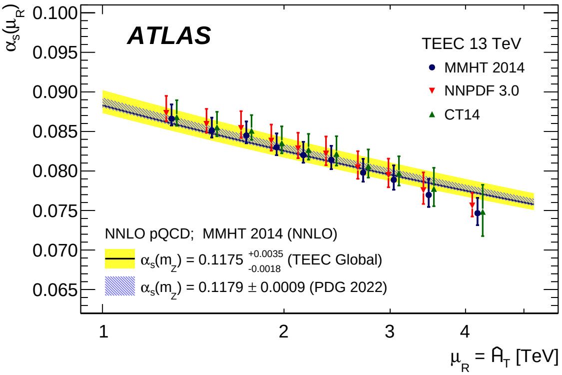
- ATLAS measured TEEC and ATTEC at 13 TeV
- Comparison with NNLOJET predictions ⇒ extracted $\alpha_s(Q)$ with Q in the range $1-4\ TeV$
- From a global fit to the TEEC data ⇒ $\alpha_s(m_Z) = 0.1175 \pm 0.0006(exp)^{+0.0034}_{-0.0017}(theo)$
- From a global fit to the ATEEC data ⇒ $\alpha_s(m_Z) = 0.1185 \pm 0.0009(exp)^{+0.0025}_{-0.0012}(theo)$
- Including NNLO corrections brings down theoretical scale uncertainties at NLO by a factor 2-3
- Recent world average $\alpha_s(m_Z) = 0.1180 \pm 0.0009$

Backup 1


ATLAS
TEEC √s = 13 TeV (NNLO)
PDF uncertainty
Total uncertainty
PDG 2022
MMHT 2014
CT14
NNPDF 3.0
0.105
0.110
0.115
0.120
0.125
$\alpha_s(m_Z)$


ATLAS
ATEEC √s = 13 TeV (NNLO)
PDF uncertainty
Total uncertainty
PDG 2022
MMHT 2014
CT14
NNPDF 3.0
0.112
0.114
0.116
0.118
0.120
0.122
0.124
0.126
$\alpha_s(m_Z)$

Backup 2


ATLAS
TEEC 13 TeV
● MMHT 2014
▼ NNPDF 3.0
▲ CT14
NNLO pQCD; MMHT 2014 (NNLO)
$\alpha_s(m_Z) = 0.1175\,^{+0.0035}_{-0.0018}$ (TEEC Global)
$\alpha_s(m_Z) = 0.1179 \pm 0.0009$ (PDG 2022)
$\alpha_s(\mu_R)$
0.100
0.095
0.090
0.085
0.080
0.075
0.070
0.065
1
2
3
4
$\mu_R = \hat{H}_T$ [TeV]