SM@LHC 2024
Roma May 7-10, 2024

α_S determinations by ATLAS and CMS

Massimo Corradi INFN ROMA

on behalf of the ATLAS and CMS Collaborations

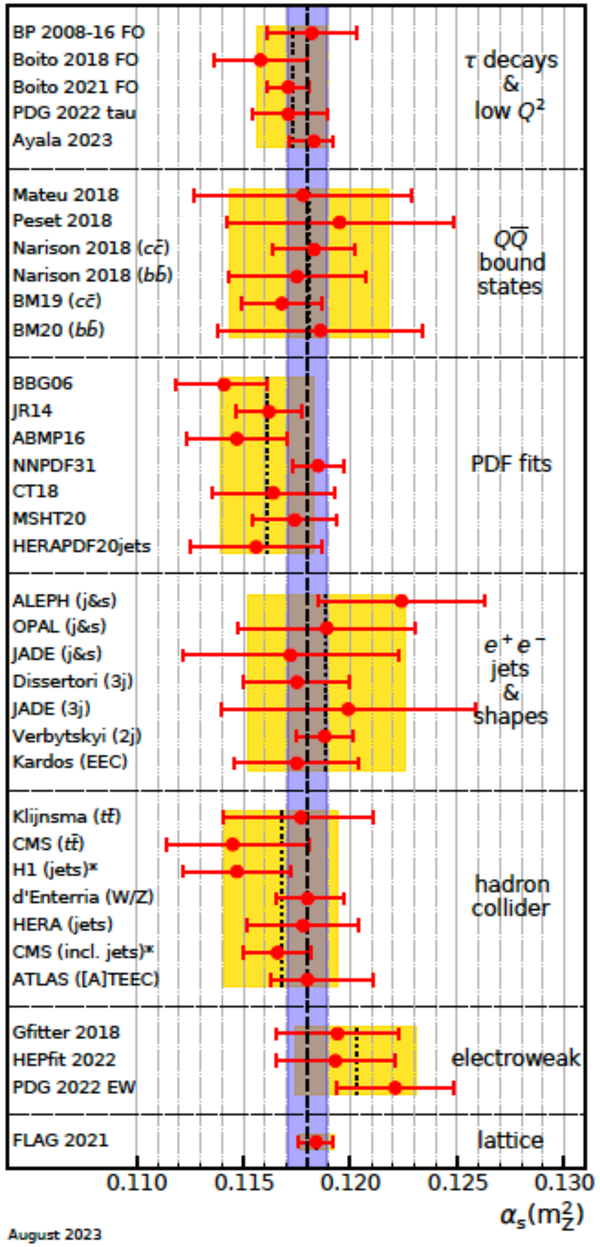
Introduction

- Strong coupling constant α_S is the least known coupling constant in nature
- Its value has implications on SM extrapolation at large scales (GUT…)
- Important uncertainty to many precision measurements

How to extract α_S ?

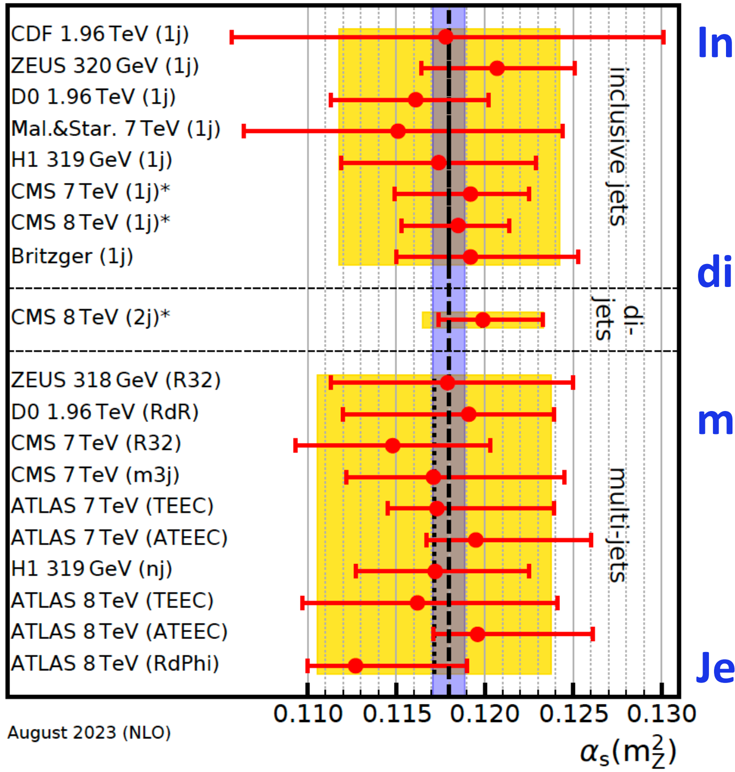
- Approach 1) (Altarelli): extract α_S from few processes with small and well-controlled theoretical uncertainties (e.g. tau decays, DIS scaling violation, e+e- R(hadrons/leptons)) ➔ extract in other processes as a test of the theory (both for testing theoretical approaches to more complex observables and for looking for deviations from SM)
- Approach 2) (PDG): consider many different process together, make a “robust” averages within each category, then average categories to provides a “Word average” which should be the most precise available value.
- current Word Average $\alpha_S(m_Z) = 0.1179 \pm 0.0009$

PDG



α_s determinations at hadronic colliders

PDG 2023 Aug 2023 (α_s from jets)



New results in this presentation :

Inclusive jets :

+ CMS Inclusive jets at 13 TeV JHEP02(2022)142 + JHEP12(2022)035

di-jets :

+ CMS dijets at 13 TeV arXiv:2312.16669

multi-jets :

+ CMS $R_{\Delta\phi}$ at 13 TeV arXiv:2404.16082

+ ATLAS TEEC+ATEEC at 13 TeV JHEP07(2023)085

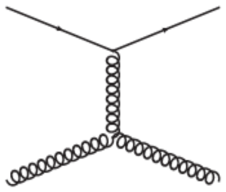
Jet substructure:

+ CMS energy correlations E2C, E3C at 13 TeV arXiv:2402.13864

Drell-Yan

+ ATLAS Zpt at 8 TeV arXiv:2309.12986

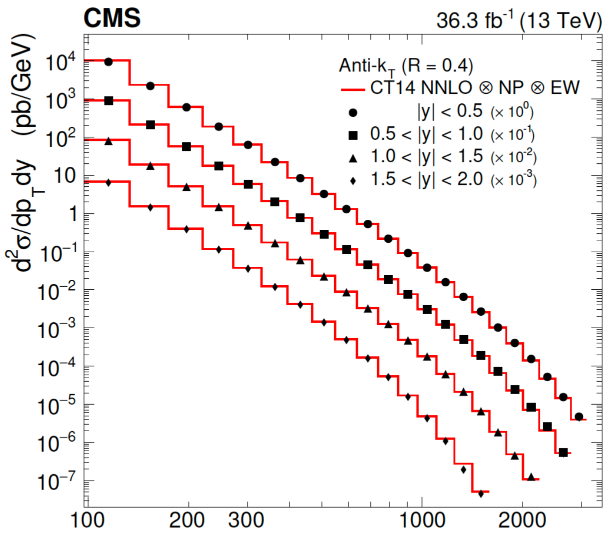
CMS: α_S from inclusive jet cross section

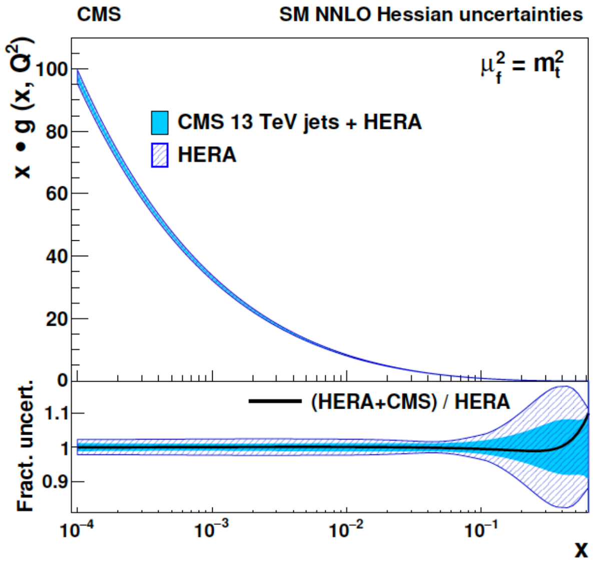


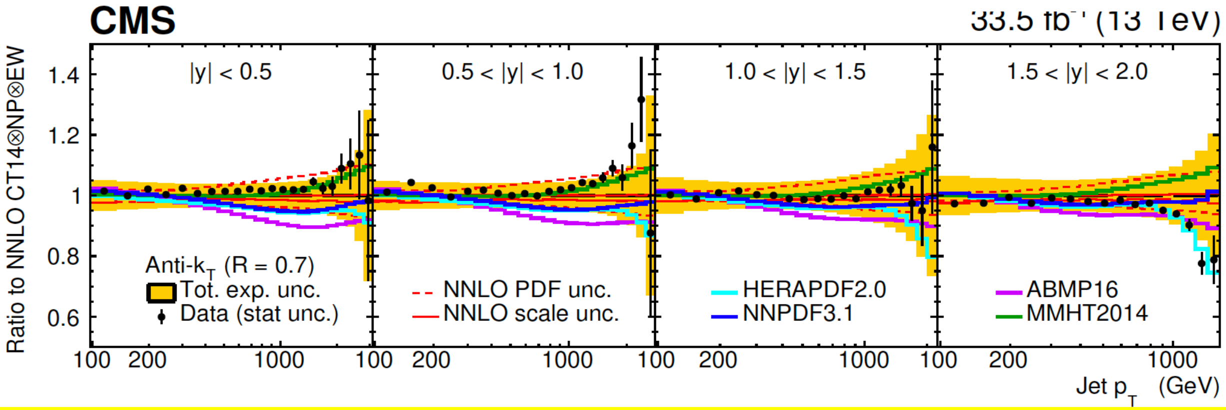
$\sigma_{LO} \propto \alpha^2$

JHEP12(2022)035 (addendum)

- CMS measurement of inclusive jet cross sections at 13 TeV over many orders of magnitude
- Anti-kT R=0.4 and 0.7
- Exp. uncertainty dominated by JES (order 5%)
- Simultaneous extraction of α_s and PDFs from fit of HERA DIS data and CMS jets
- **New analysis** using full NNLO grids (NNLOJETS) rather than k-factors: compatible results with smaller scale uncertainties





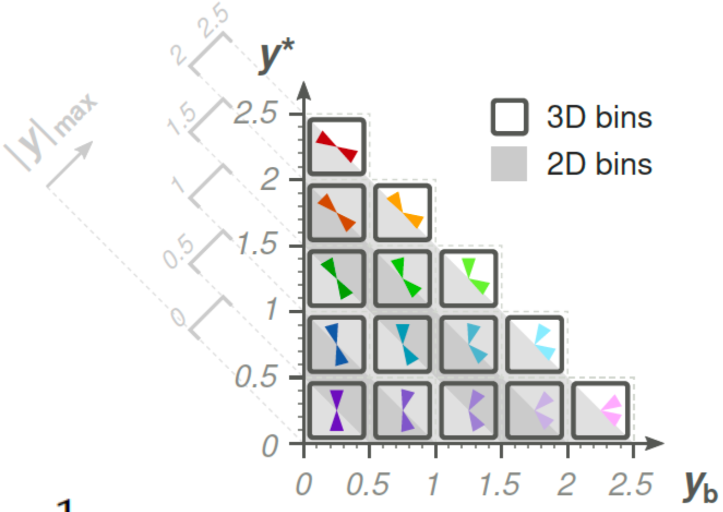


$$\alpha_S(m_Z) = 0.1166 \pm 0.0014\ (fit) \pm 0.0007\ (model) \pm 0.0004\ (scale) \pm 0.0001\ (PDF\ param.)$$

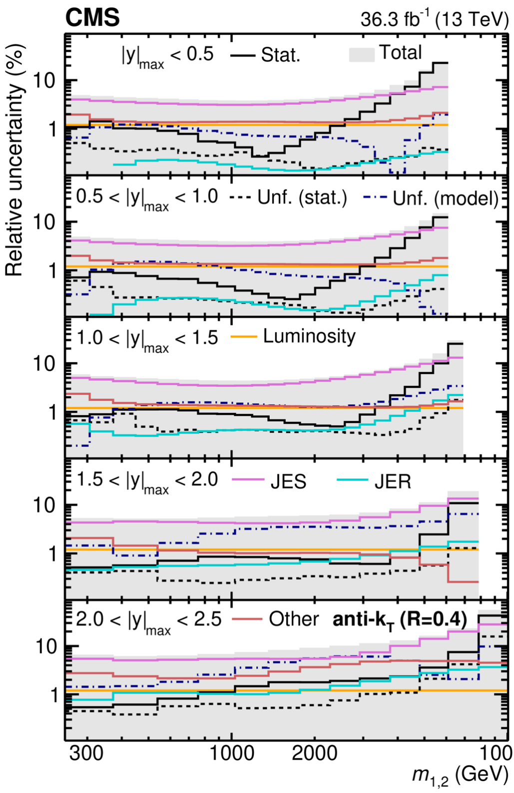
CMS: α_S from di-jet cross section

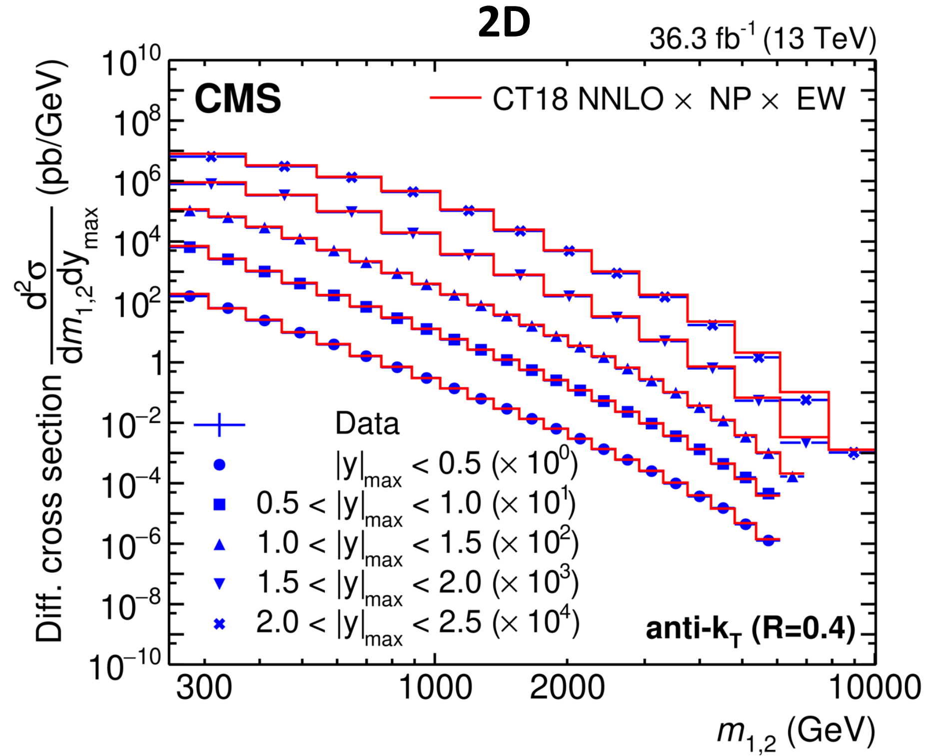
arXiv:2312.16669

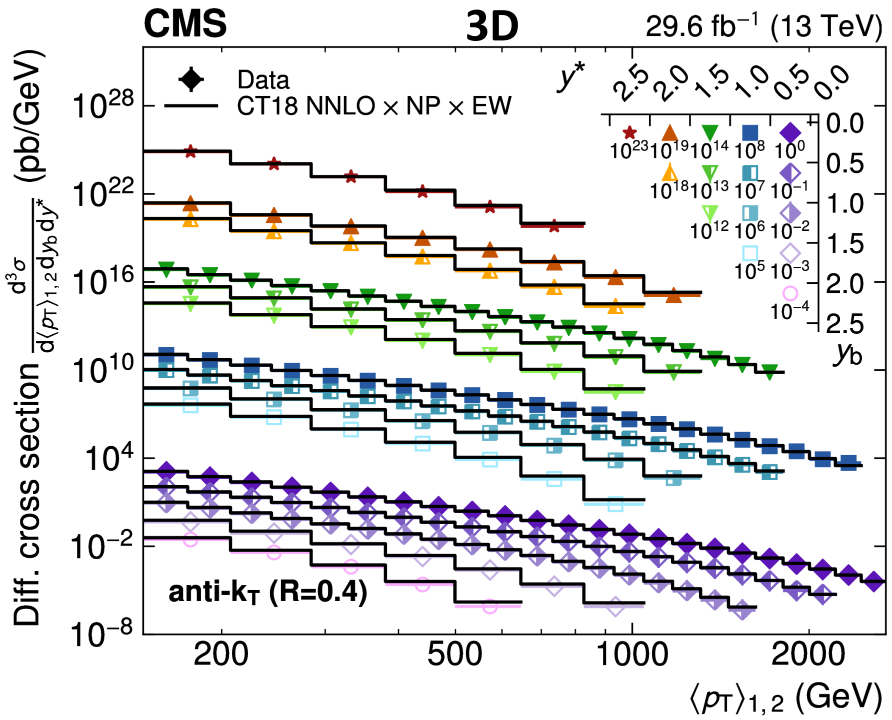
- CMS measurement of di-jet cross sections at 13 TeV (33.5 fb-1)
- 2D in dijet mass ($m_{1,2}$)and maximum rapidity $|y^{max}|$ rapidity
- 3D in average pT ($<p_T>_{1,2}$), (half) rapidity difference y* and mean rapidity y^b
- Experimental uncertainty dominated by JES 5-30%



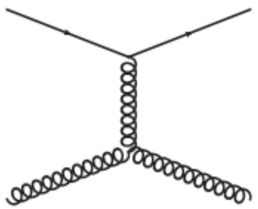
$$y^* = \frac{1}{2}|y_1 - y_2|, \quad y_b = \frac{1}{2}|y_1 + y_2|.$$





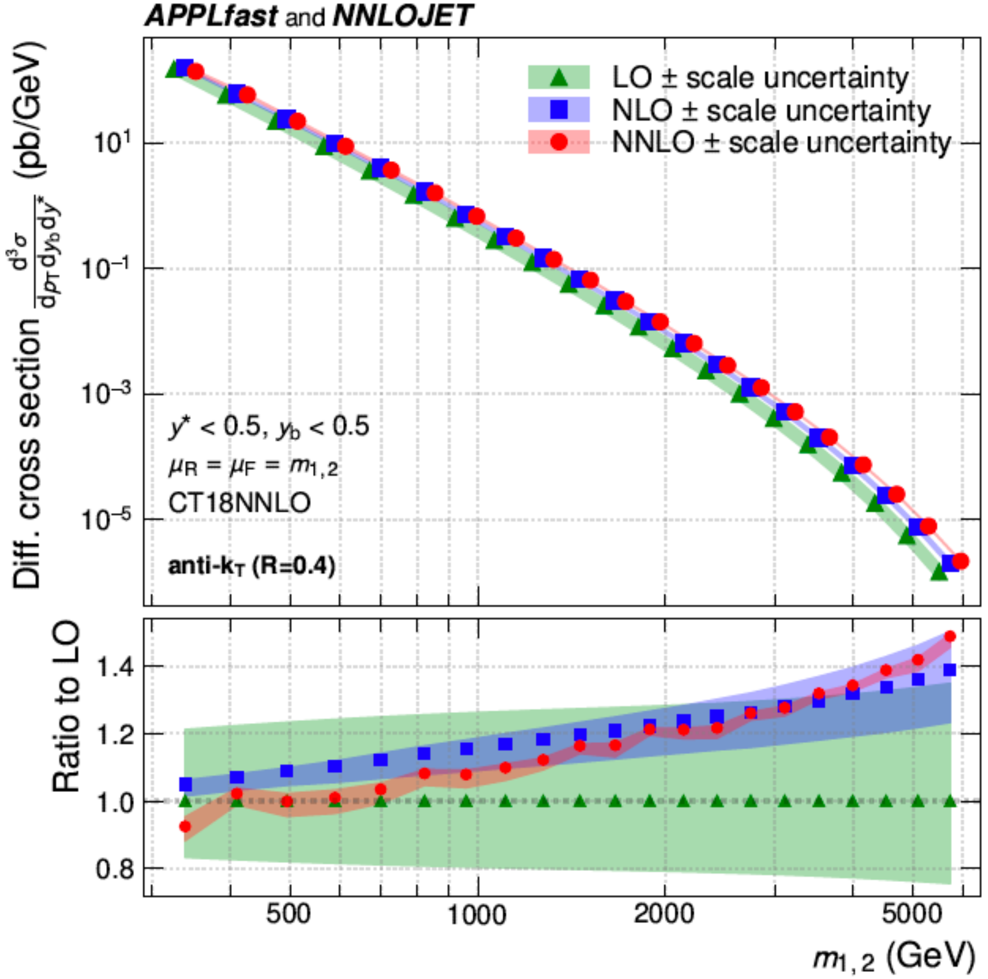


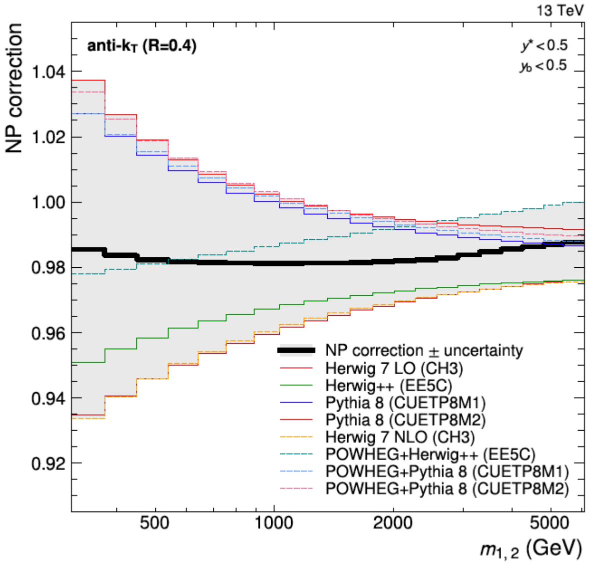
CMS α_s from di-jets : theory

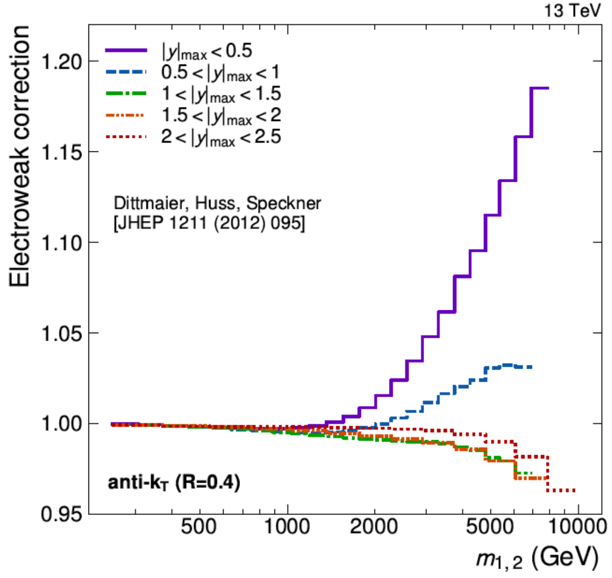


$\sigma_{LO} \propto \alpha^2$

- Therory canclulated a NNLO (NNLOJET): scale uncertainty reduction wrt NLO enables precise α_s measurement
- Non-perturbative corrections calculated as envelope of different hadronization models
- Electroweak correction important at high mass





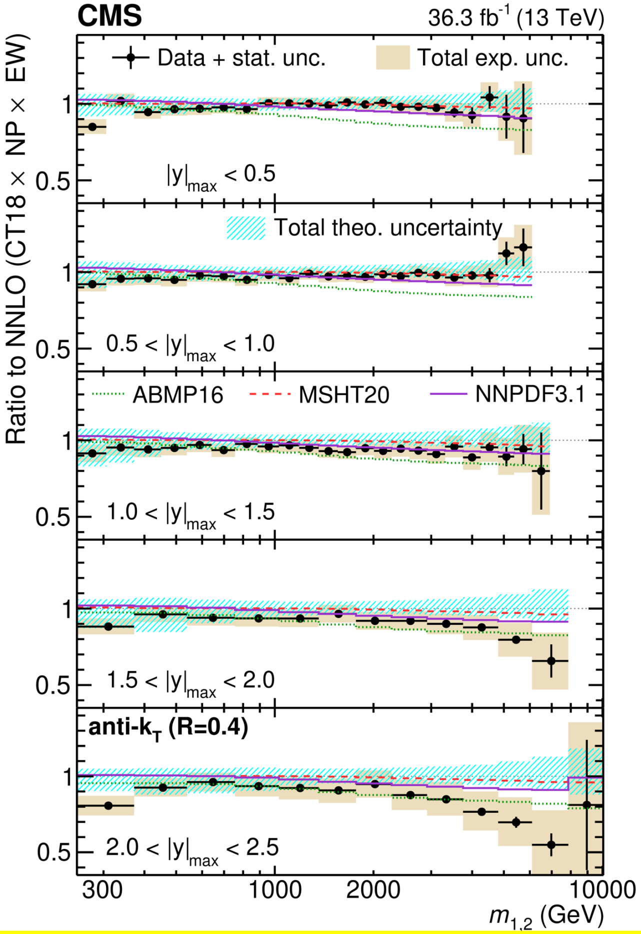


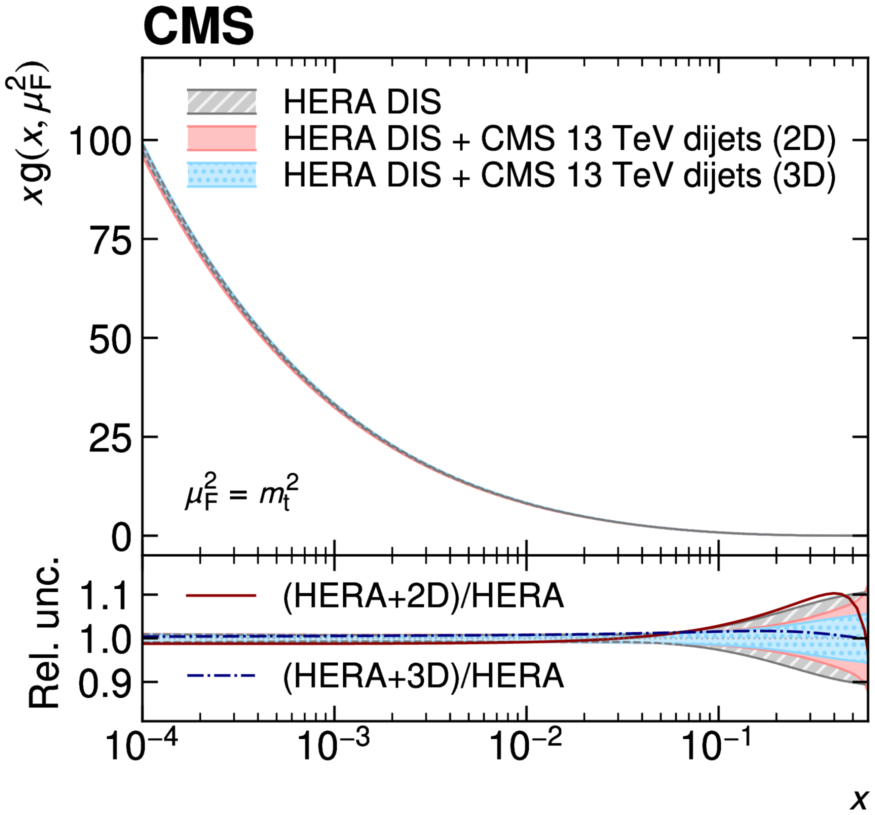
CMS α_S from di-jets : results

- Simultaneous fit of α_S and PDFs using HERA DIS data and CMS dijets, both 2D and 3D
- χ^2 variation from adding dijets to HERA data (2D):

$$\frac{\chi^2}{ndf} : \frac{1161}{1003} \rightarrow \frac{1232}{1081} \; : \; \Delta\frac{\chi^2}{ndf} = \frac{71}{78}$$

- Reduction of PDF errors
- $\alpha_S(m_Z) = 0.1179 \pm 0.0019$





$$2D\colon \alpha_S(m_Z) = 0.1179 \pm 0.0015\,(fit) \pm 0.0008\,(model) \pm 0.0008\,(scale) \pm 0.0001\,(PDF\ param.)$$

$$3D\colon \alpha_S(m_Z) = 0.1181 \pm 0.0013\,(fit) \pm 0.0006\,(model) \pm 0.0009\,(scale) \pm 0.0002\,(PDF\ param.)$$

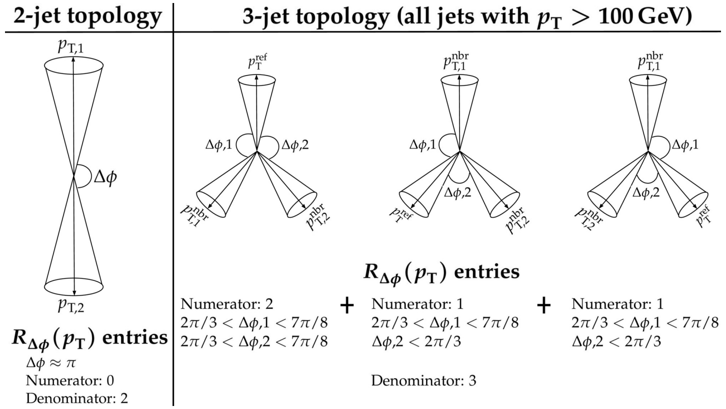
CMS: α_S from Jet Azimuthal Correlation $R_{\Delta\phi}$

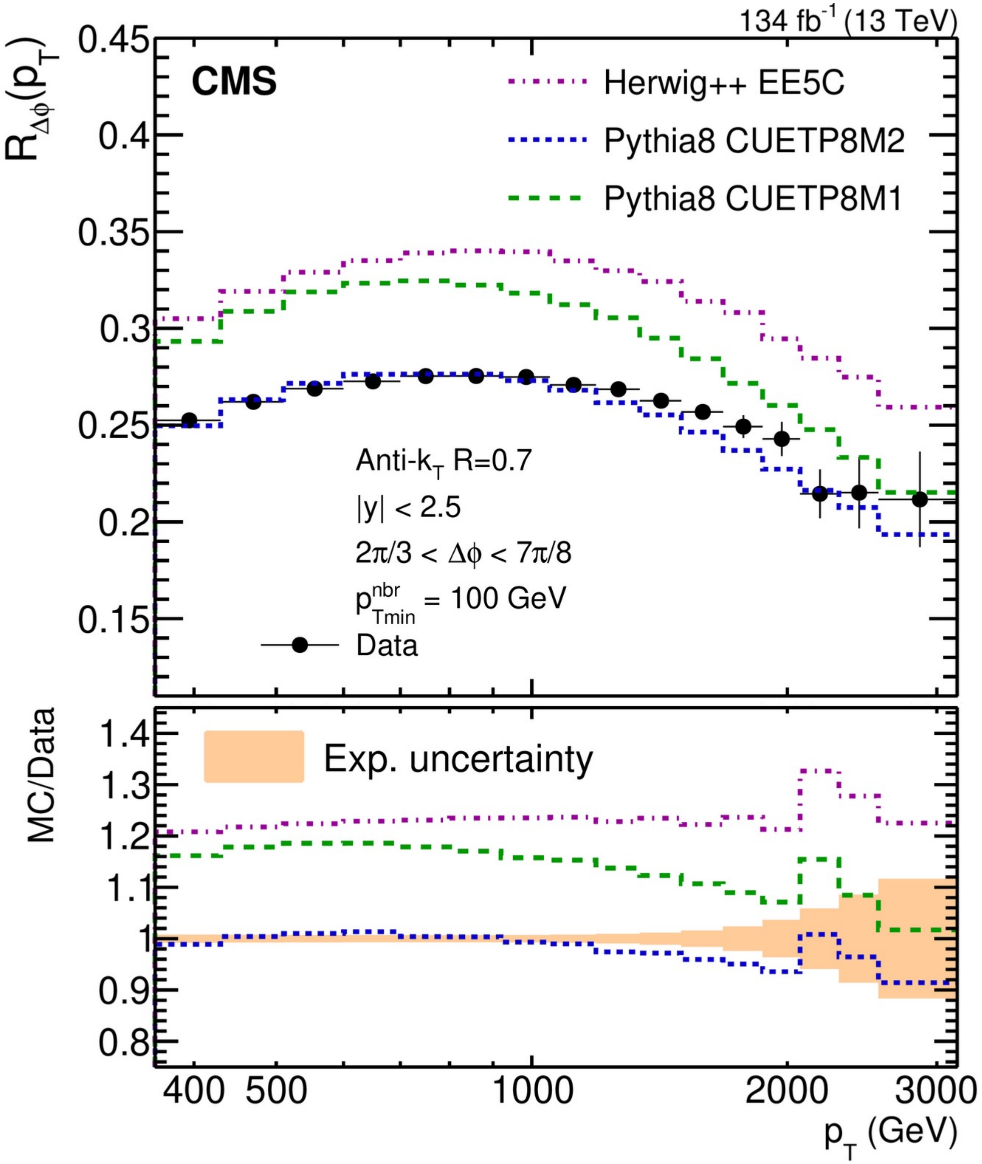
arXiv:2404.16082

- $R_{\Delta\phi}$ is the ratio between the number of jets in a range $\Delta\phi$ from another jet and the total number of jets N$_{\text{jet}}$.

$$R_{\Delta\phi}(p_{\text{T}}) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_{\text{T}})} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{\text{Tmin}}^{\text{nbr}})}{N_{\text{jet}}(p_{\text{T}})}$$

- CMS measurement at 13 TeV, for jets with $p_T^{nbr} > 100$ GeV R=0.4 and $|y| < 2.5$
- The $\Delta\phi$ range is chosen to avoid back-to-back jet topologies: $\frac{2}{3}\pi < \Delta\phi < \frac{7}{8}\pi$: there is a relation with 3/2 jet ratio.
- $R_{\Delta\phi}$ is measured in bins of p$_{\text{T}}$ (one entry per jet)
- Compared to different MC, agreement dependent on MC tuning





CMS $R_{\Delta\phi}$: results

- NLO theory (NLOJET++)
- Extraction of α_S from fit to data using different global PDF sets providing PDFs at different values of of α_S

$$\chi^2 = \sum_{ij}^{N}(D_i - T_i)C_{ij}^{-1}(D_j - T_j),$$

D_i = measuremet, T_i = prediction,

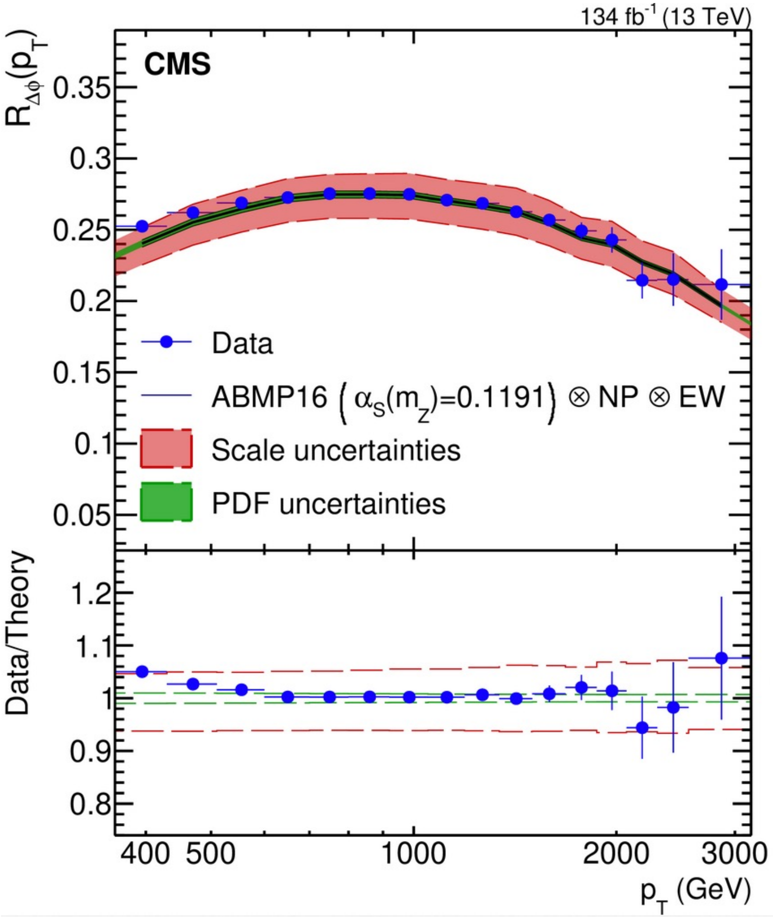
C_{ij} = covariance matrix (including exp. and theor. unc.)

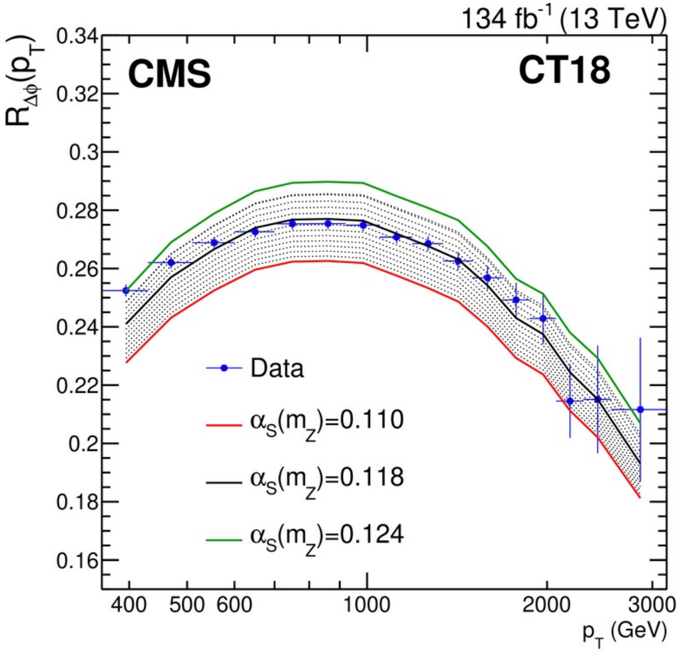
Scale unc. by repeating fit with 6 different μ_r, μ_f

- Uncertainty dominated by scale variation

- Second uncertainty is PDF choice

- $\alpha_S(m_Z) = 0.1177^{+0.0117}_{-0.0074}$





$$\alpha_S(m_Z) = 0.1177^{+0.0114}_{-0.0068}\,(\text{scale.}) \pm 0.0013\,(exp.) \pm 0.0011\,(NP) \pm 0.0010\,(PDF) \pm 0.0003\,(EW) \pm 0.0020\,(PDF\ choice)$$

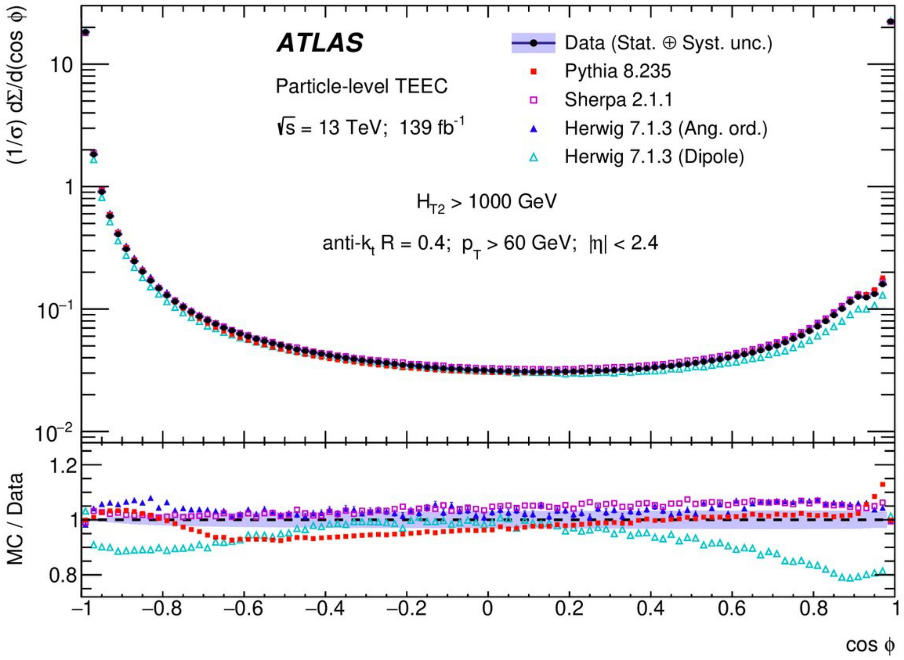
ATLAS: α_S from tranverse energy correlations

JHEP07(2023)085

- Transverse energy-energy correlations (TEEC): transverse energy-weighted angular distribution of jet pairs
- Azimuthal asymmetry (ATEEC)
- ATLAS measurement in 13 TeV data, using jet R=0.4, in bins of the scalar sum of the two leading jets H_{T2}

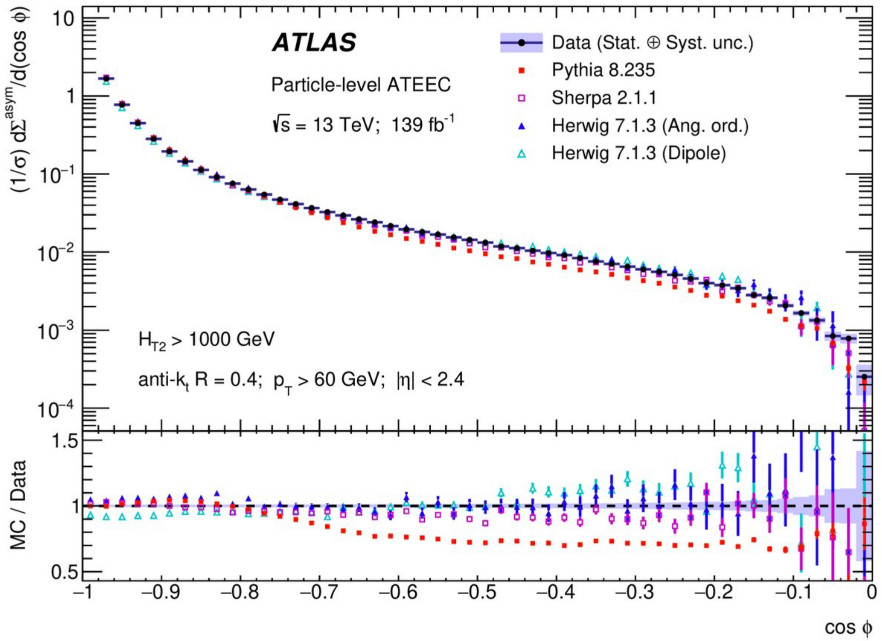
TEEC

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\overset{\text{events}}{\sum_{A=1}^{N}}\;\overset{\text{jets}}{\sum_{ij}}\frac{E^{A}_{\mathrm{T}i}E^{A}_{\mathrm{T}j}}{\left(\sum_k E^{A}_{\mathrm{T}k}\right)^2}\delta(\cos\phi-\cos\phi_{ij})$$



ATEEC

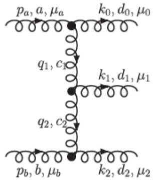
$$\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asym}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$



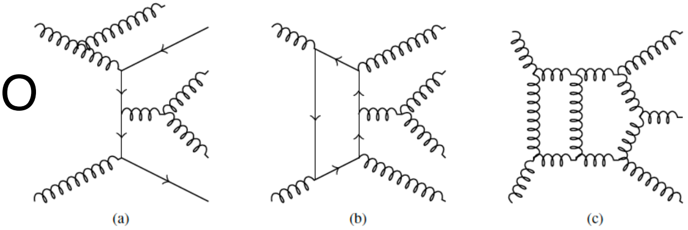
ATLAS: TEEC and ATEEC

- Experimental uncertainty dominated by JES and by angular resolution (TEEC) and energy resolution (ATEEC)
- $|cos\phi| < 0.92$ to avoid 2-jet configurations
- Calculated to NNLO ($= O(\alpha_s^5)$) using OpenLoops2, FivePointAmplitudes and PentagonFunctions++

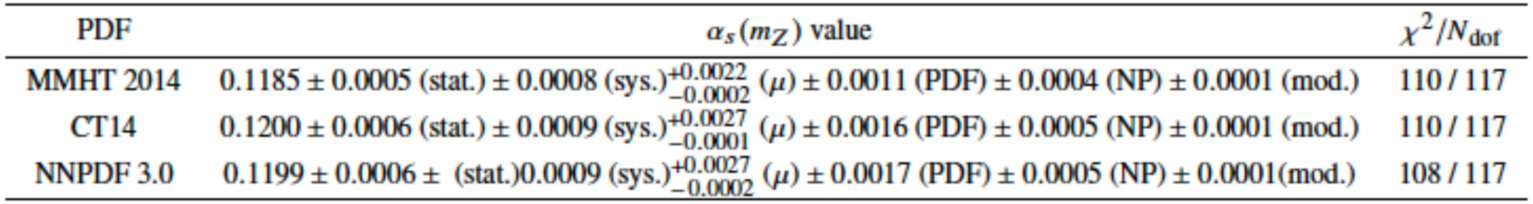
LO



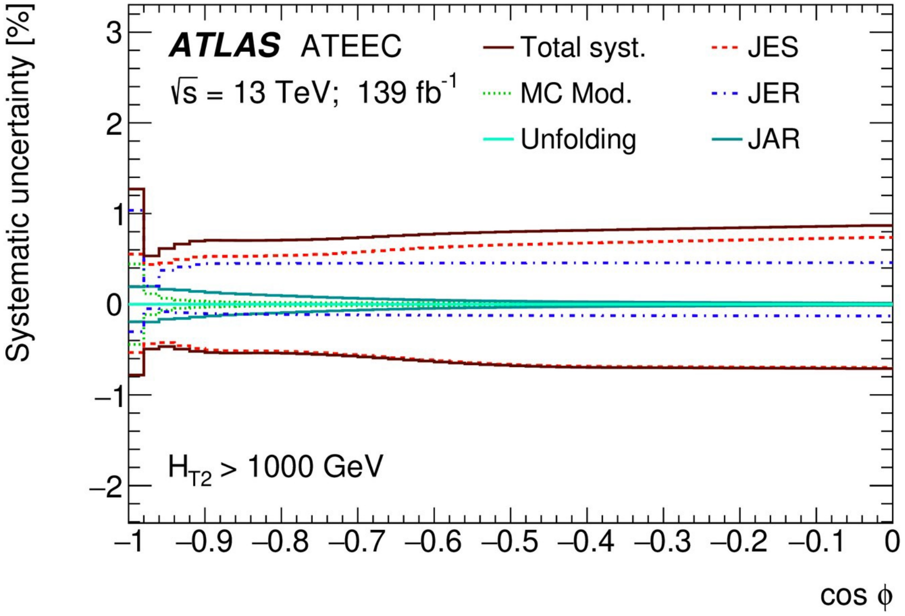
NNLO

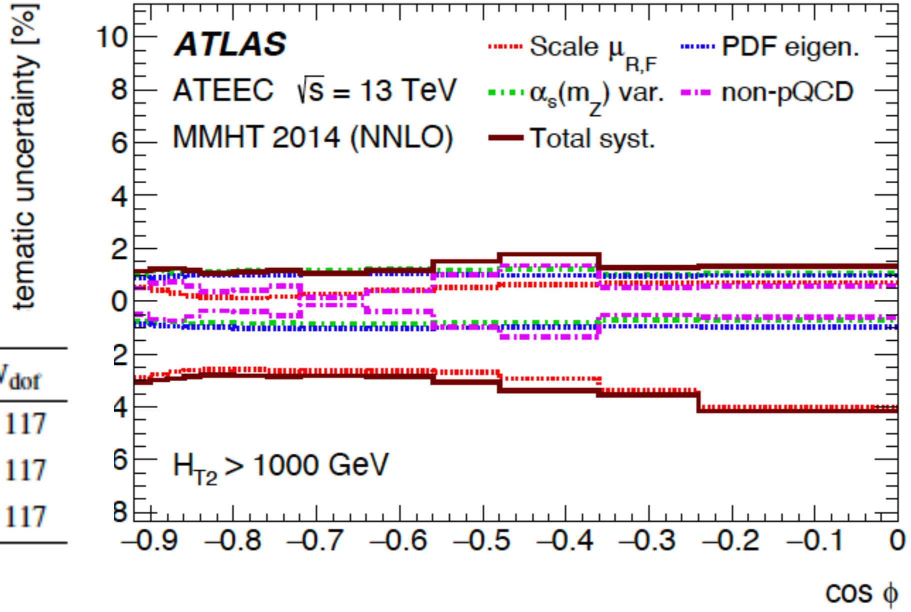


- χ^2 fit to TEEC and ATEEC to extract α_S
  - largest uncertainty from scale variations
  - Results for different NNLO PDFs compatible within PDF uncertainty



PDF	$\alpha_s(m_Z)$ value	$\chi^2/N_{\rm dot}$
MMHT 2014	0.1185 ± 0.0005 (stat.) ± 0.0008 (sys.)$^{+0.0022}_{-0.0002}$ (μ) ± 0.0011 (PDF) ± 0.0004 (NP) ± 0.0001 (mod.)	110 / 117
CT14	0.1200 ± 0.0006 (stat.) ± 0.0009 (sys.)$^{+0.0027}_{-0.0001}$ (μ) ± 0.0016 (PDF) ± 0.0005 (NP) ± 0.0001 (mod.)	110 / 117
NNPDF 3.0	$0.1199 \pm 0.0006 \pm$ (stat.)0.0009 (sys.)$^{+0.0027}_{-0.0002}$ (μ) ± 0.0017 (PDF) ± 0.0005 (NP) ± 0.0001(mod.)	108 / 117





ATLAS: TEEC and ATEEC Results

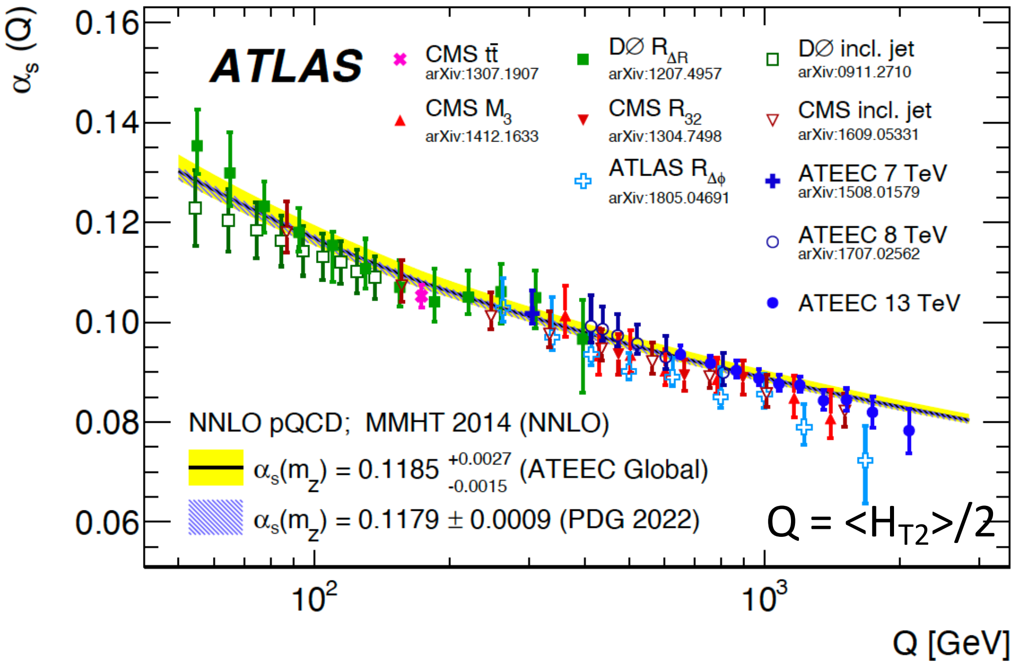
- MMHT 2014 taken as central value :

TEEC: $\alpha_S(m_Z) = 0.1175 \pm 0.0006\ (\text{exp.})\ {}^{+0.0034}_{-0.0017}(\text{theo.})$

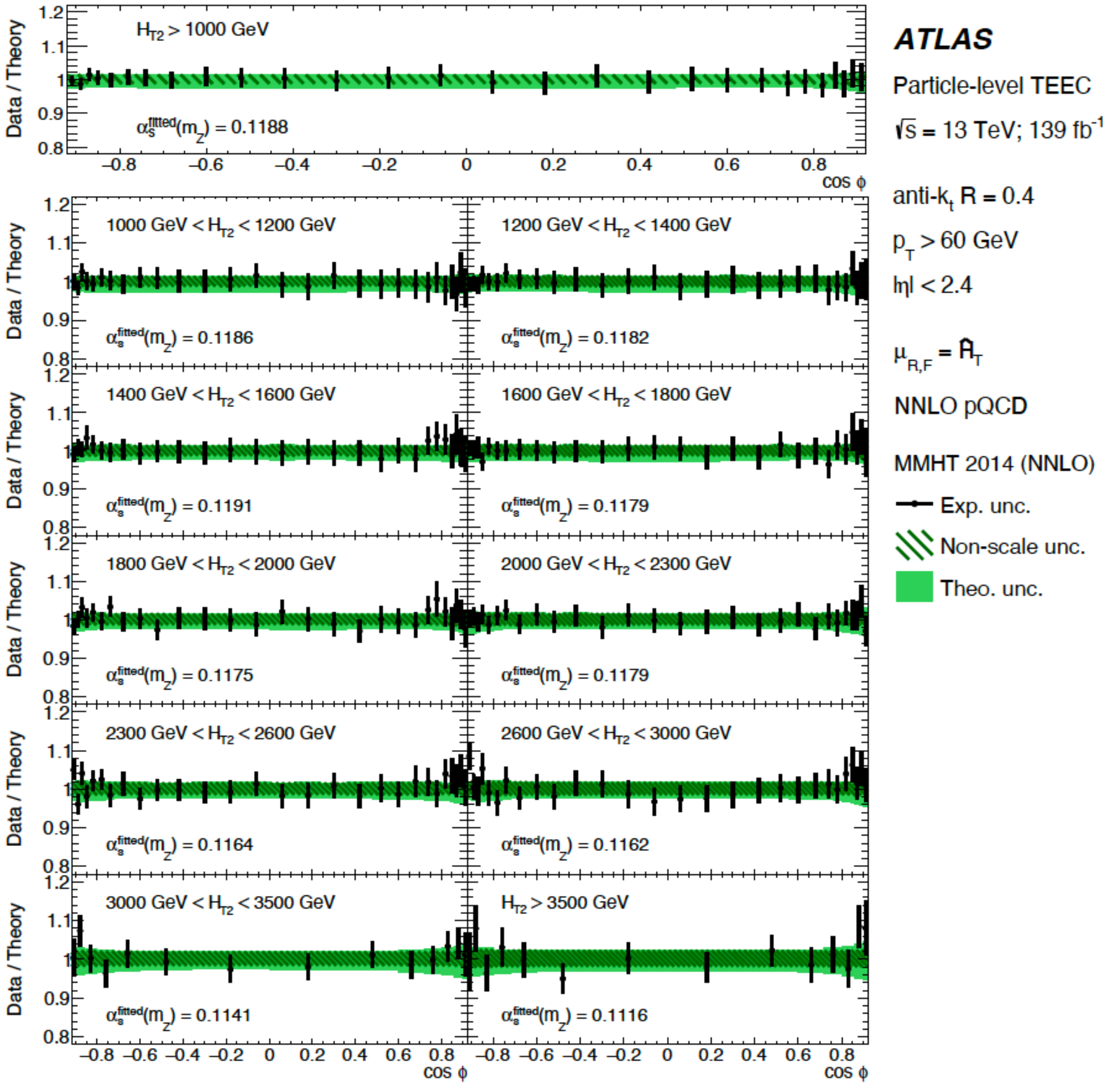
ATEEC: $\alpha_S(m_Z) = 0.1185 \pm 0.0009\ (\text{exp.})\ {}^{+0.0025}_{-0.0012}(\text{theo.})$

Correlation $\rho = 0.86$

- Running of α_S checked up to Q= 2 TeV : no hint of new colored fermions !



TEEC post-fit with MMHT 2014 (NNLO)



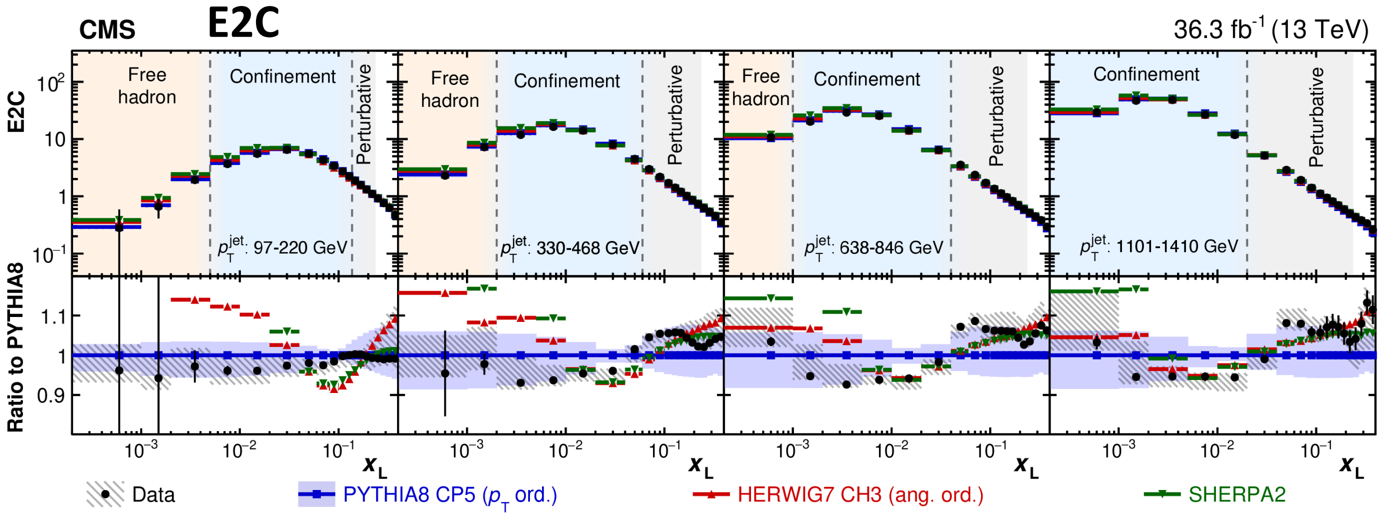
CMS: α_S from Jet substructure: E3C/E2C

arXiv:2402.13864

$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j}),$$

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k})),$$

- Two- and three-point energy correlations for particles inside jets
- Measurement made on dijets at 13 TeV using charged and neutral energy flow objects
- Jet selection: Anti-kT $R = 0.4, |\eta| < 2.1, \quad \Delta\Phi > 2.1,$ $97 < p_T < 1784\ GeV$
- Large-x_L : perturbative region (partons), can be calculated at NLL or approximated NNLL (aNNLL)



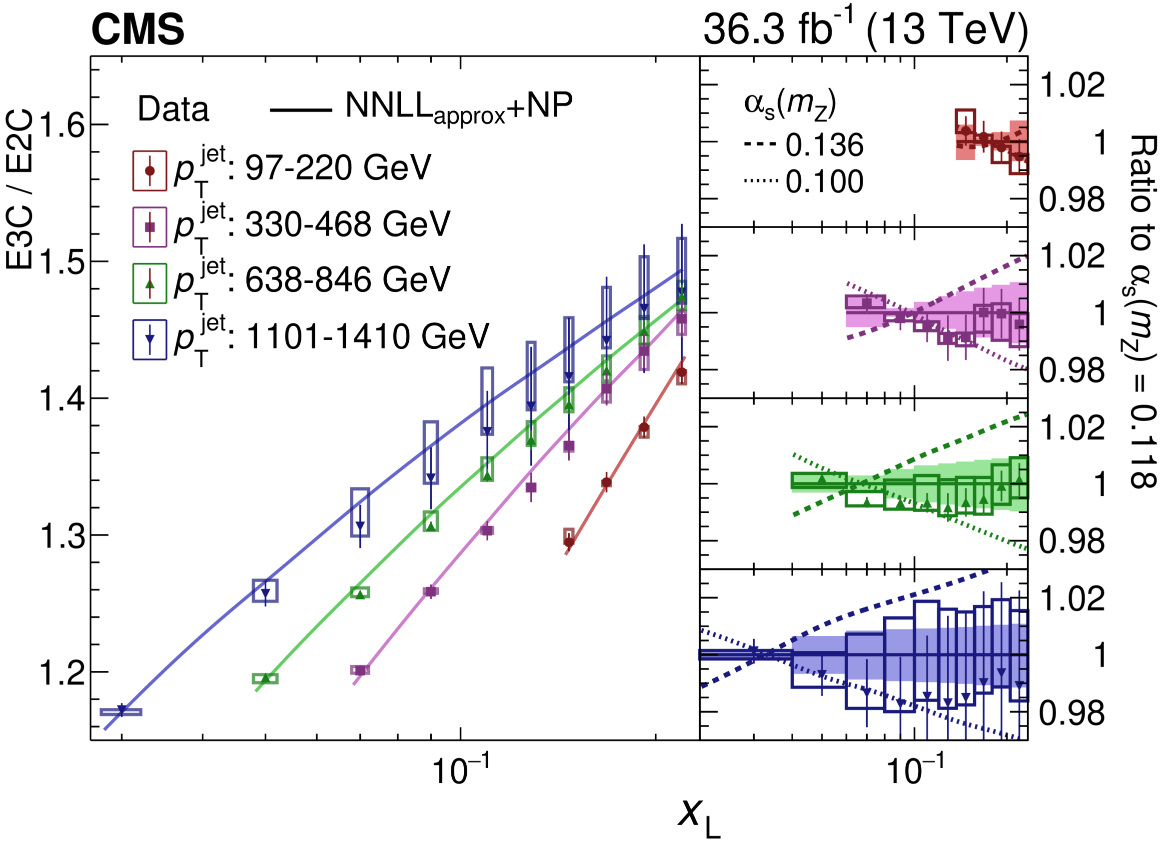
CMS E3C/E2C : results

- The ratio E3C/E2C has a reduced sensitivity to PDF and to NP effects: NP correction uncertainty reduced to 3% on E3C/E2C ratio
- The slope of E3C/E2C is approximately proportional to $\alpha_s(Q^2)$

  -> good observable for α_S measurement
- χ^2 fit to E3C/E2C using approximated NNLL gives

  - Theoretical uncertainty mainly from scale uncertainty
- $\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$

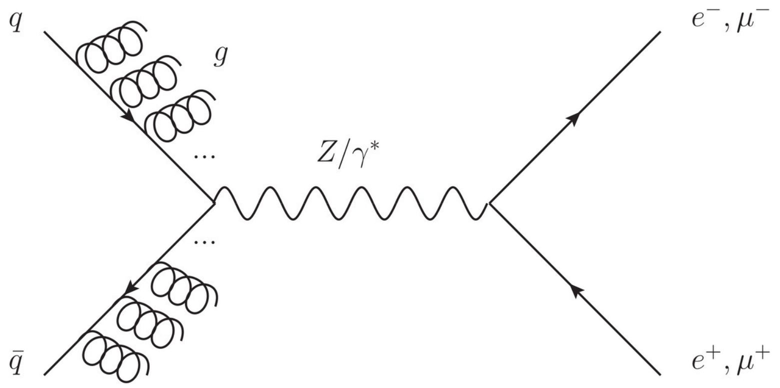
$$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat.})^{+0.0030}_{-0.0033}\,(\text{theo.})^{+0.0023}_{-0.0036}\,(\text{exp.})$$

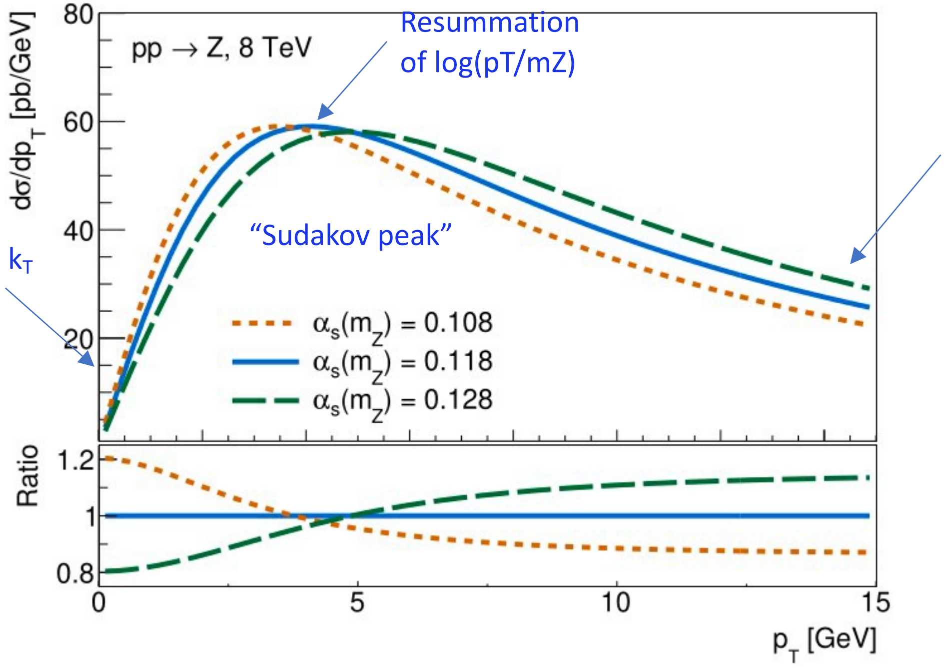


ATLAS: α_S from Z transverse momentum

arXiv:2309.12986

- Z bosons produced in hadron collisions recoil against QCD initial-state radiation
- Z boson p_T distribution can be measured with small exp. uncertainties
- Precise resummed calculation now available up to approximated N^4LL (N^4LLa) matched to N3LO fixed order





Resummation of log(pT/mZ)

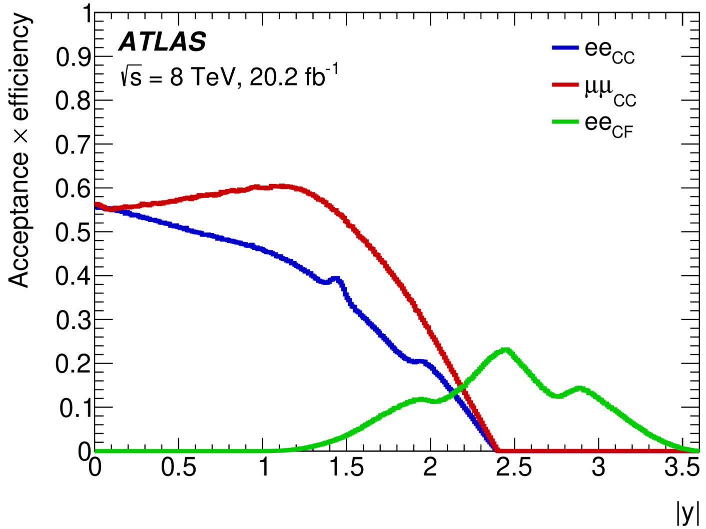
Fixed order

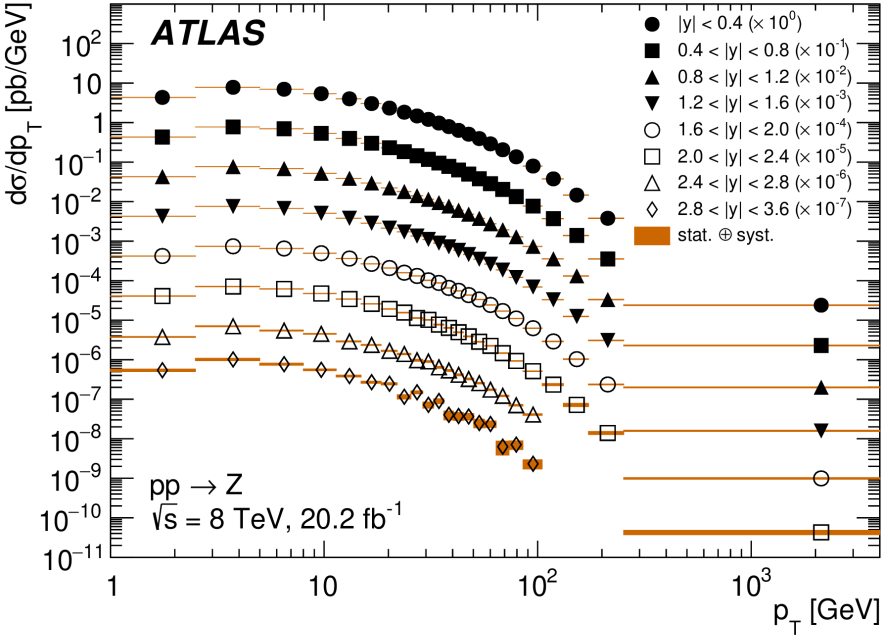
"Sudakov peak"

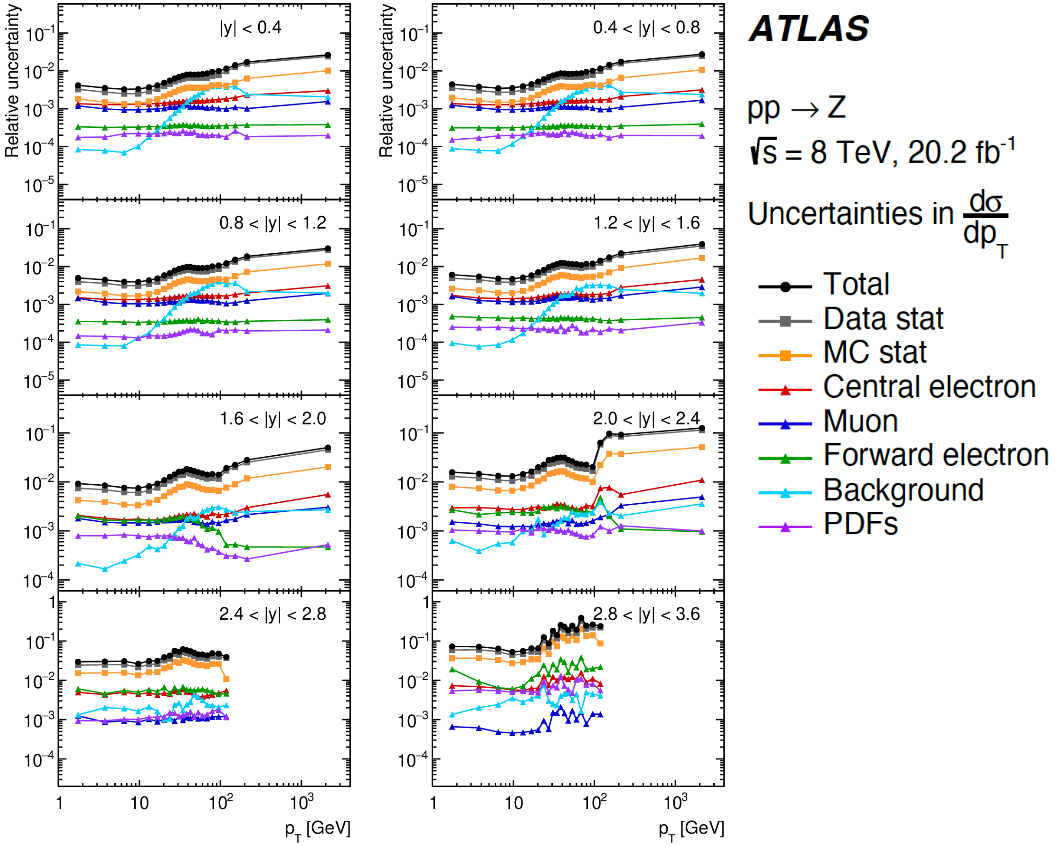
NP intrinsic k_T

ATLAS Z p_T measurement

- Using 8 TeV data (Eur. Phys. J. C 84 (2024) 315)
- Measurement in 3 channels : central $\mu\mu$ and ee, central-forward ee
- Decomposition in angular polynomials used to pass from fiducial measurement to full lepton phase-space
- Uncertainties generally below 1%, stat. dominated !







ATLAS: Zp$_T$ α_s extraction

- N^{4}LLa matched to N3LO fixed order DY calculation (Dyturbo)
- MSTH20 PDF (only set available at N3LO)
- NP “intrinsic parton k$_T$” modeled with gaussian parameters and extracted from the fit, impacts very low p$_T$
- α_S extracted from fit to cross section in y,p$_T$ bins.

exp. ($\beta_{j,exp}$) and PDF ($\beta_{k,th}$) uncertainties treated as nuisance parameters:

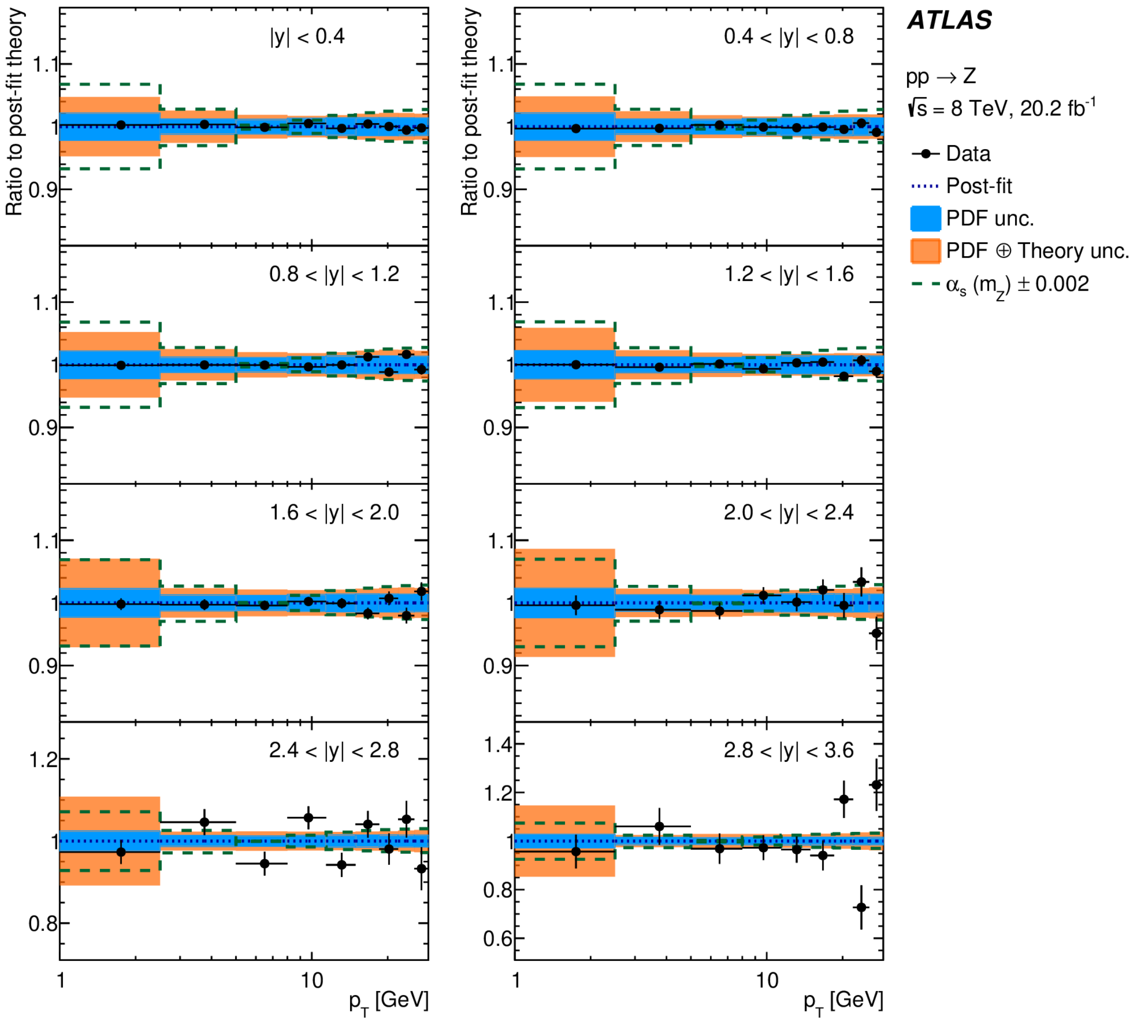
$$\chi^2(\beta_{\rm exp}, \beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 .$$

$\sigma_i^{exp/th}$ *= measured / theoretical cross section*

Δ_i = uncorrelated uncertainty

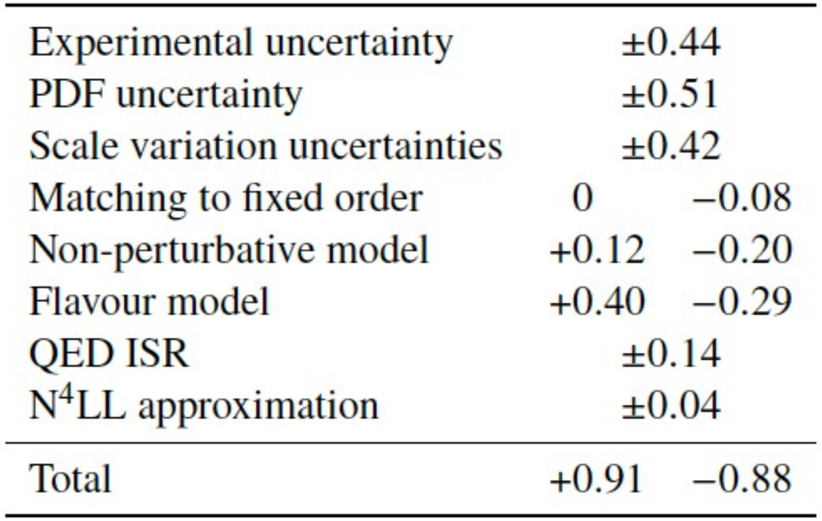
Γij = effect of1 s.d. variation of kth syst. on ith cross section

Post fit



ATLAS: Zp$_T$ results

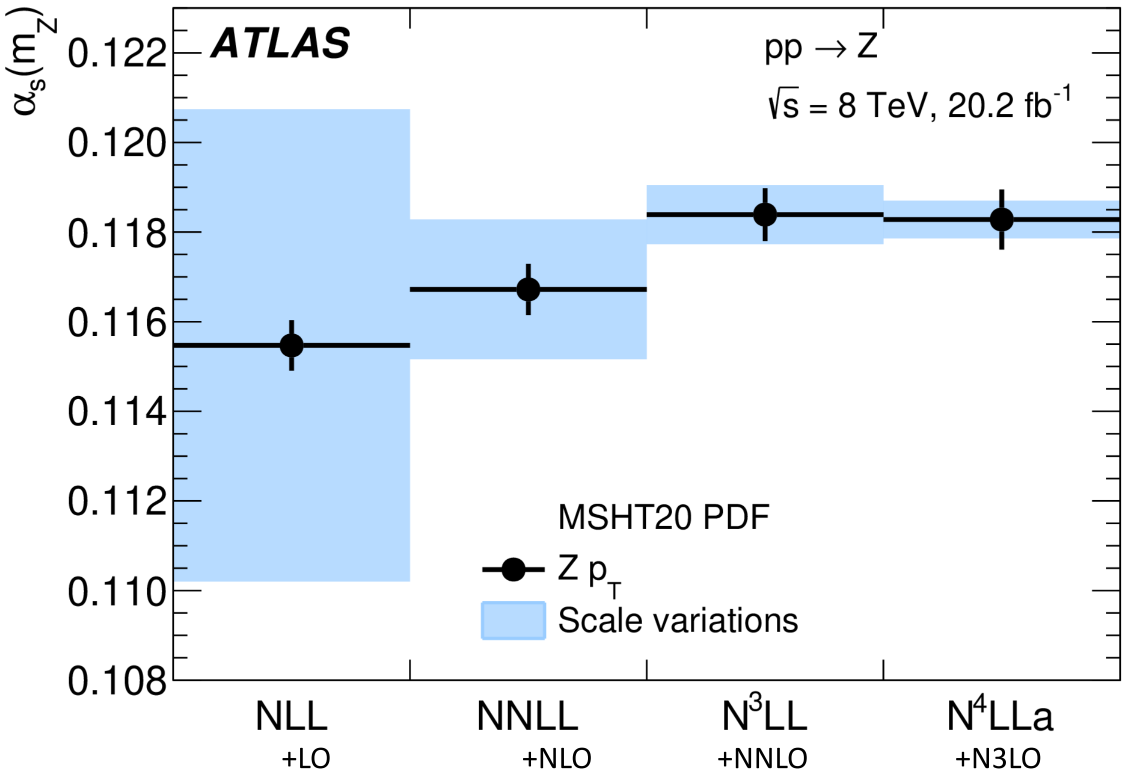
Uncertainties (x 10^{-3})



Experimental uncertainty	±0.44	
PDF uncertainty	±0.51	
Scale variation uncertainties	±0.42	
Matching to fixed order	0	−0.08
Non-perturbative model	+0.12	−0.20
Flavour model	+0.40	−0.29
QED ISR	±0.14	
N^{4}LL approximation	±0.04	
Total	+0.91	−0.88

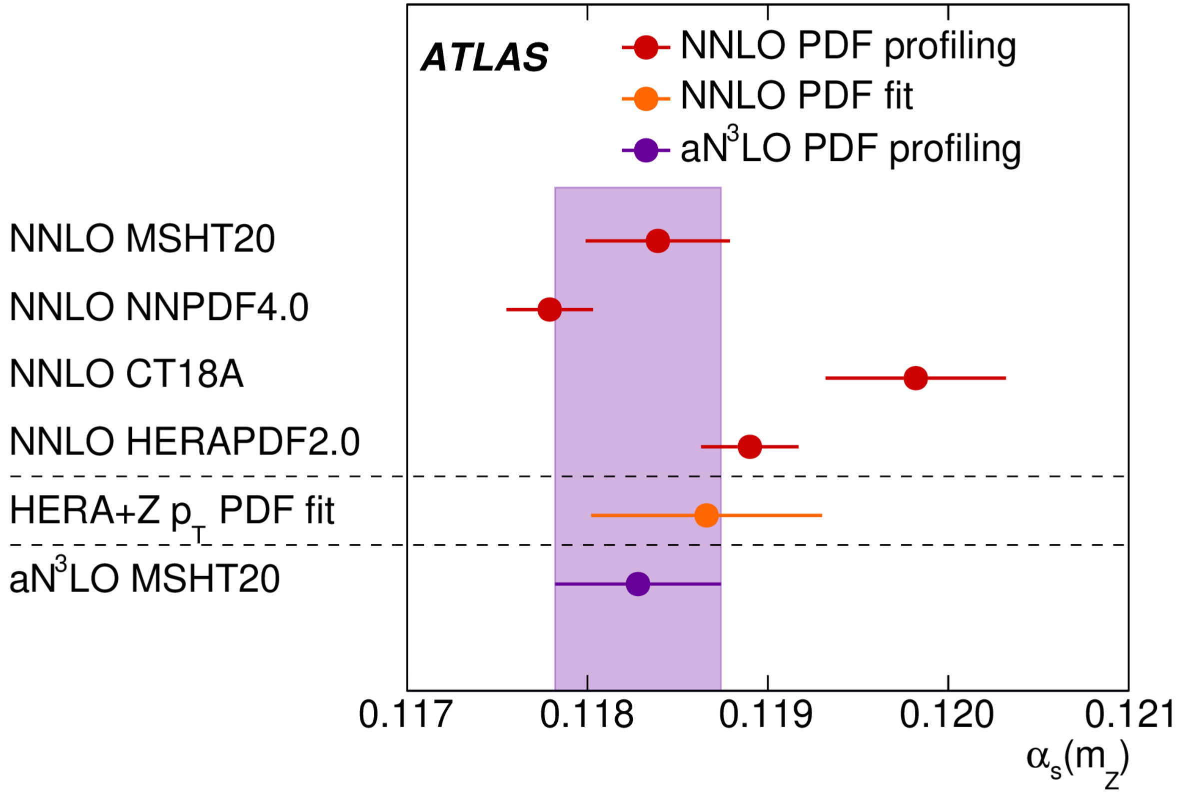
$$\alpha_S(m_Z) = 0.1183 \pm 0.0009$$

- Most precise collider measurement !
- Nice reduction of scale uncertainties observed by performing the fit at different pert. orders



ATLAS: Zp$_T$ alternative α_s extractions

- Alternative fits using different PDFs available at NNLO: some tension between global PDF fits
- NNLO PDF + α_S simultaneous determination from fit of Zp$_T$ and HERA data consistent with aN3LO extraction
- The PDF + α_S fit is probably the cleanest way to extract α_S : only clean processes, real fit rather than nuisance parameter (linearized) approach, to be done at N3LO !



Summary and conclusions

New extractions of $\alpha_S(m_Z)$from ATLAS and CMS :

- From **Inclusive and di-jet cross** sections with simultanaous extraction of PDFs, fitting HERA data:

  $\alpha_S(m_Z) = 0.1166 \pm 0.0016$ (CMS incl. jets, NNLO)

  $\alpha_S(m_Z) = 0.1179 \pm 0.0019$ (CMS dijets, NNLO)

- From **multi-jet correlation observables sensitive to 3rd jet** emission

  $\alpha_S(m_Z) = 0.1177^{+0.0117}_{-0.0074}$ (CMS $R_{\Delta\phi}$, NLO)

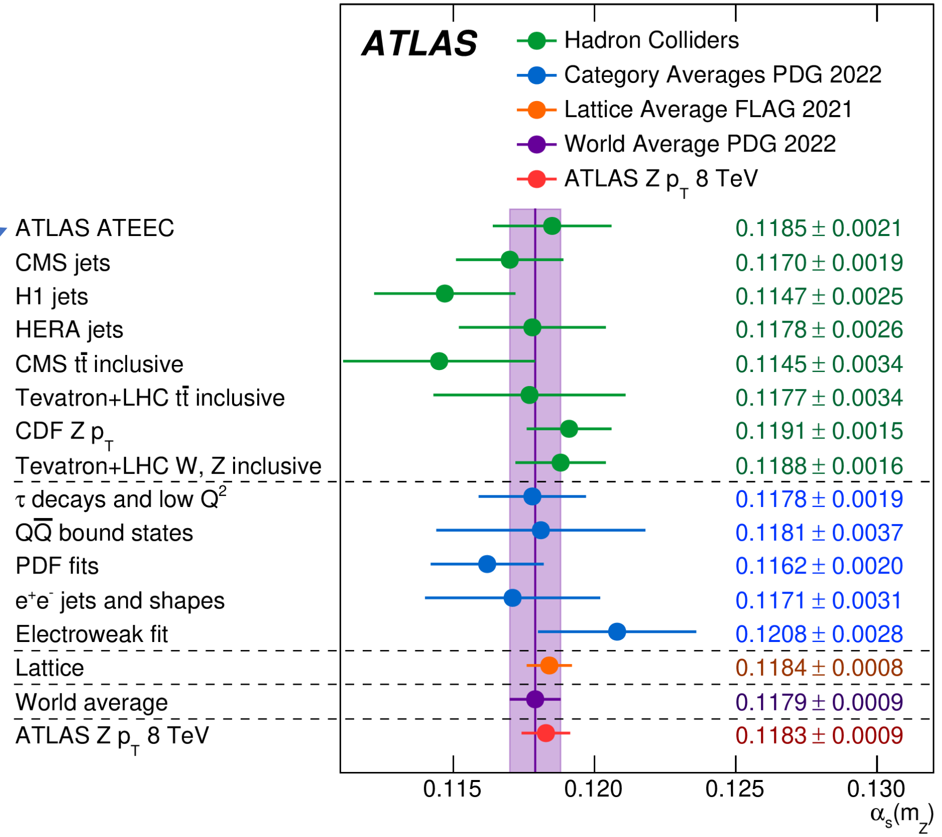
  $\alpha_S(m_Z) = 0.1185^{+0.0027}_{-0.0012}$ (ATLAS ATEEC, NNLO)

- From **jet substructure**

  $\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0070}$ (CMS E3C/E2C, NNLLa)

- From **Z pT** :

  $\alpha_S(m_Z) = 0.1183 \pm 0.0009$ (ATLAS, N4LLa+N3LO)



Summary plot with selection of most precise pp measurements

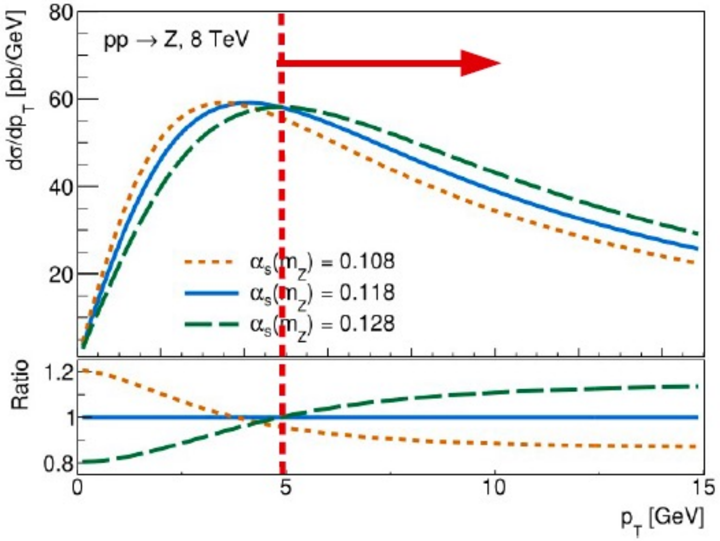
BACKUP SLIDES

Non perturbative QCD model

- The NP model is characterized by a non-perturbative Sudakov form factor and a prescription for regularizing the Landau pole of the α_s running

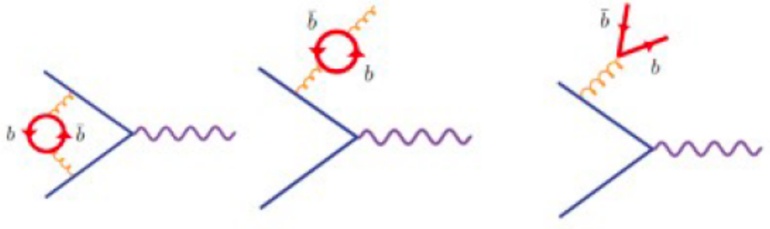
$$S_{\mathrm{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right] \qquad b_\star^2 = \frac{b^2}{1 + b^2/b_{\mathrm{lim}}^2}$$

- The non perturbative model includes a total of 6 parameters which are either fitted to the data or varied to assess an uncertainty



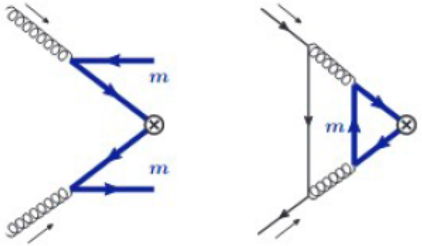
- Fits excluding the region 0-5 GeV yields $\alpha_s(m_Z)$ with a spread of ±0.0002, and fit uncertainty increased from 0.00067 to 0.00071
- Correlation between $\alpha_s(m_Z)$ and g largely reduced
- Demonstrates independence of the result from NP effects and good modelling of NP effects

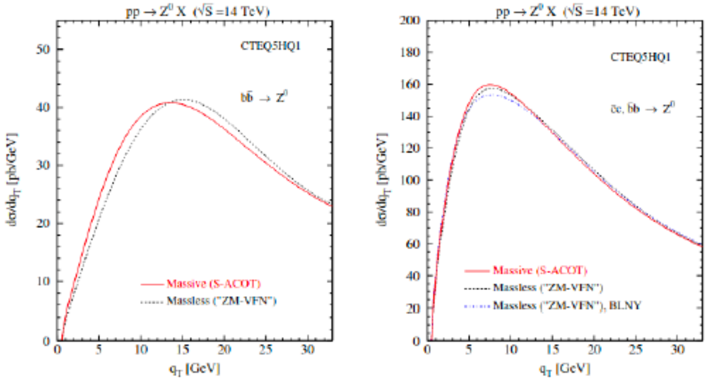
Heavy flavour mass effects



(a) *Double virtual contribution* (b) *Real-virtual Contribution* (c) *Double real Contribution*

- Secondary or final state HF mass effects: softer pT spectrum, estimated $\delta\alpha_s$ of the same order of the VFN evolution, with opposite sign
- Effect covered by flavour model uncertainties
- If both VFN PDFs and HFFS included, their effect would largely cancel

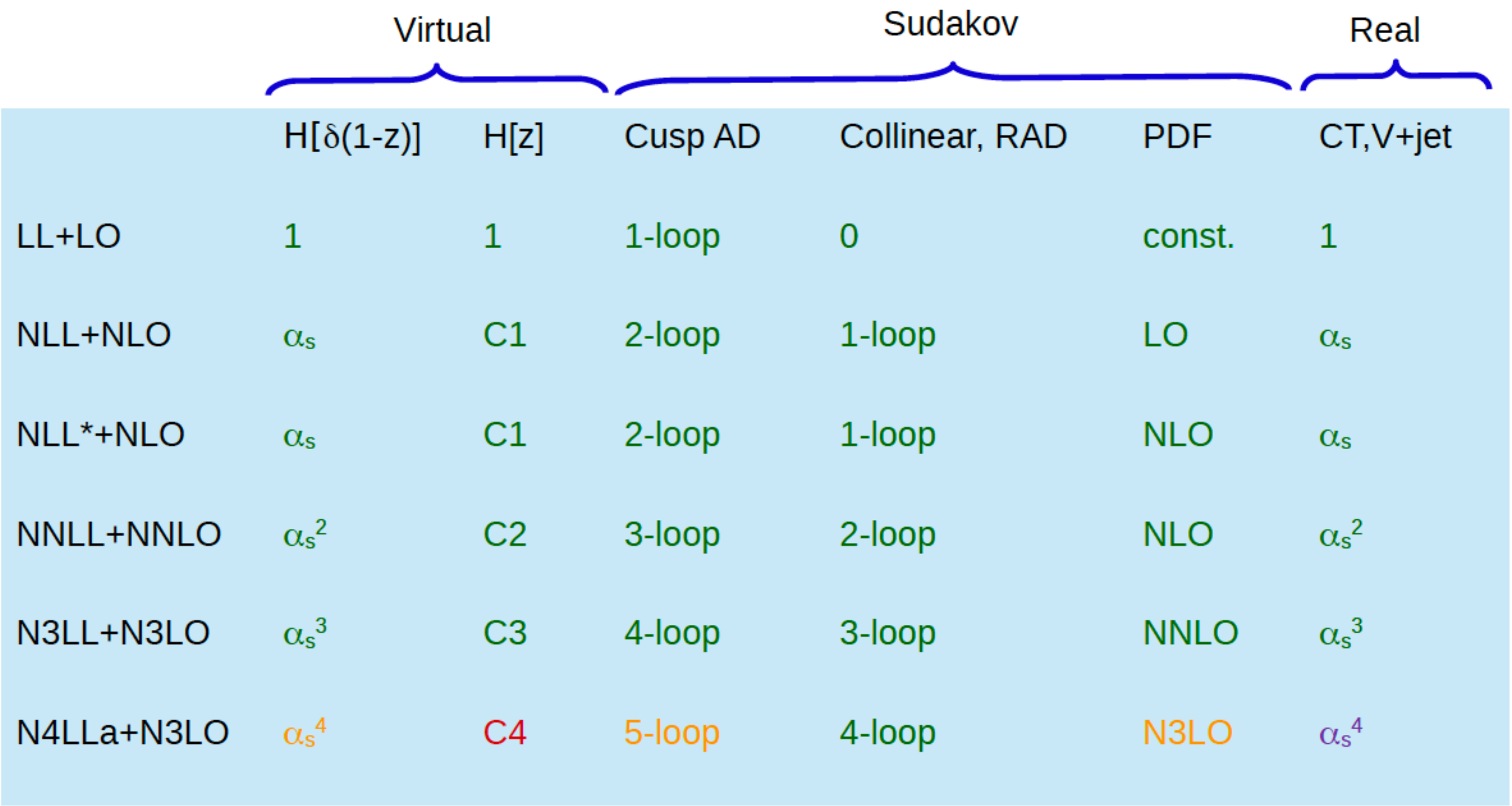




- 2% bb
- 6% cc

- Primary or initial state HF mass effects: softer p_T spectrum in the bb→Z, cc→Z channels
- Expected to be negligible for α_s (but important for the W/Z p_T ratio, and for m_W)

Orders



	Virtual		Sudakov			Real
	H[δ(1-z)]	H[z]	Cusp AD	Collinear, RAD	PDF	CT,V+jet
LL+LO	1	1	1-loop	0	const.	1
NLL+NLO	α_s	C1	2-loop	1-loop	LO	α_s
NLL*+NLO	α_s	C1	2-loop	1-loop	NLO	α_s
NNLL+NNLO	α_s^2	C2	3-loop	2-loop	NLO	α_s^2
N3LL+N3LO	α_s^3	C3	4-loop	3-loop	NNLO	α_s^3
N4LLa+N3LO	α_s^4	C4	5-loop	4-loop	N3LO	α_s^4

Known analytically
Approximated numerically
Unknown, estimated with series acceleration
Not included

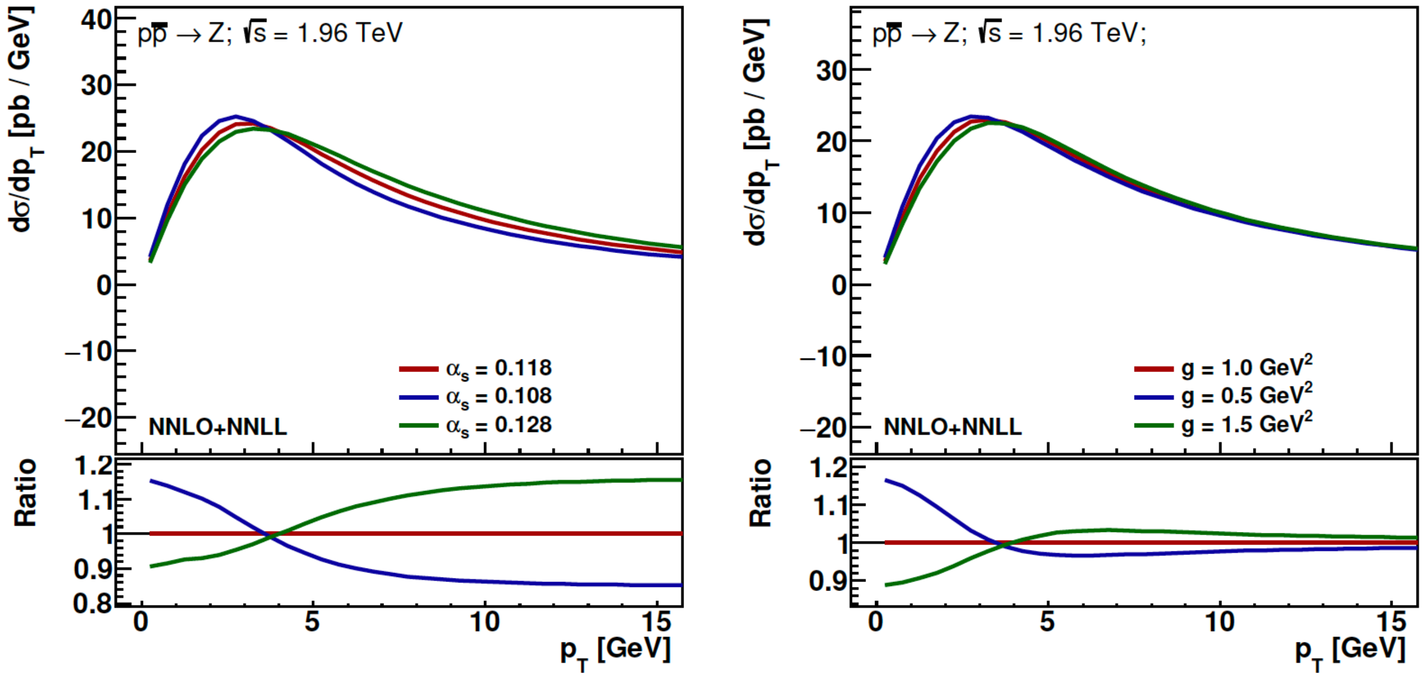
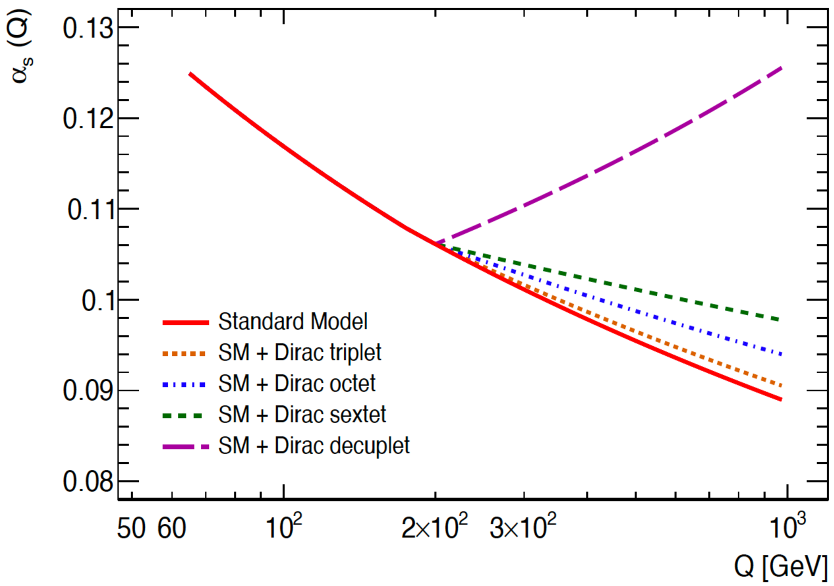


FIG. 32: Sensitivity of the Z-boson transverse-momentum distribution to $\alpha_S(m_Z^2)$ (left) and to the nonperturbative QCD parameter g (right).



$$\frac{\partial \alpha_s}{\partial \log Q^2} = \beta(\alpha_s) = -\alpha_s^2(\beta_0 + \beta_1 \alpha_s + \mathcal{O}(\alpha_s^2))$$

$$\beta_0 = \frac{1}{4\pi}\left(11 - \frac{2}{3}n_f\right); \quad \beta_1 = \frac{1}{(4\pi)^2}\left(102 - \frac{38}{3}n_f\right)$$

The next-to-leading order solutions to the renormalization group equation including a new fermion
with mass mX = 200 GeV transforming under representations of dimension 3, 8, 6 and 10, respectively.

J. Llorente and B. P. Nachman, Nucl. Phys. B 936 (2018) 106, arXiv:1807.00894 [hep-ph].