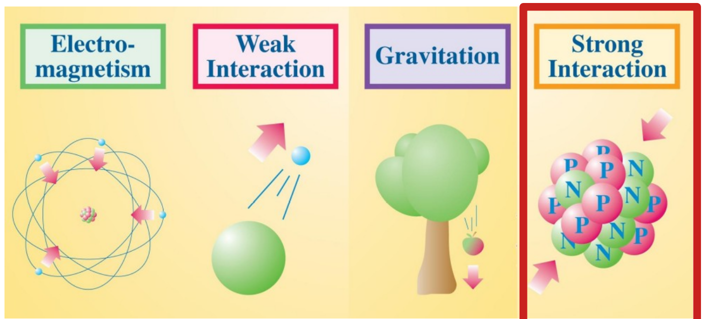
Recent α_s determinations from the LHC

QCD@LHC
Durham
4-8 September 2023

Stefano Camarda

The strong-coupling strength $\alpha_s(m_Z)$

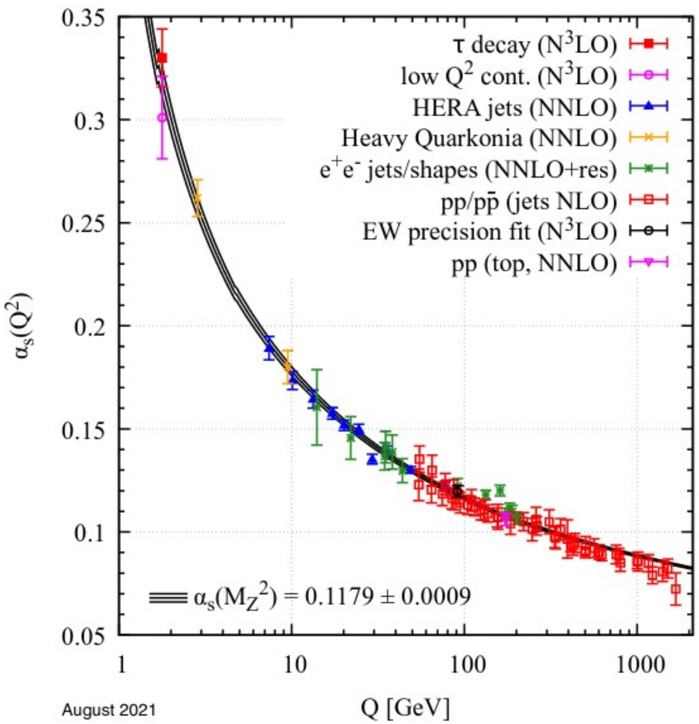
The strong coupling is the least known fundamental force of nature

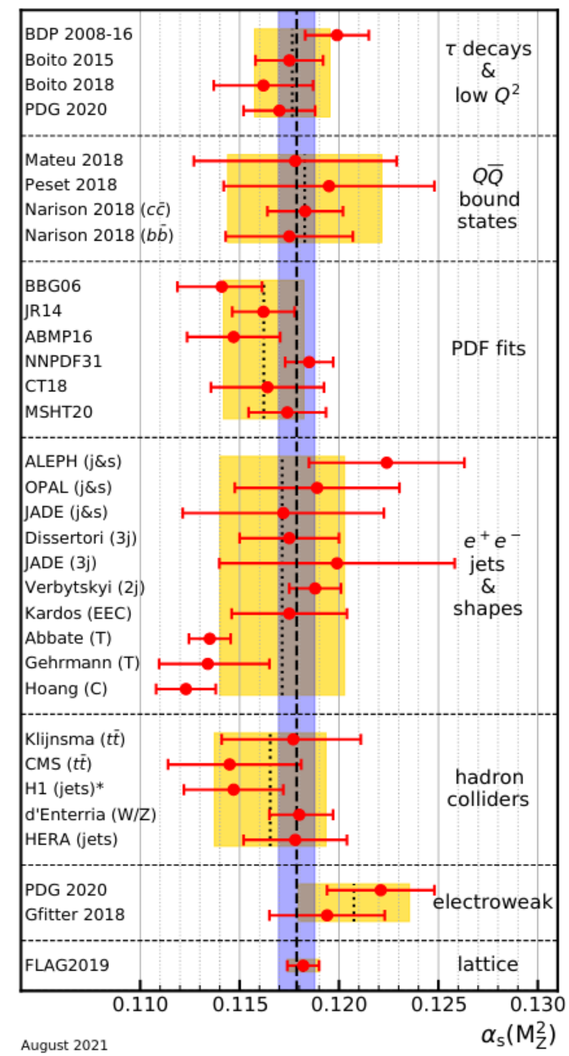


Relative uncertainty	10^{-10}	10^{-7}	10^{-5}	10^{-2}

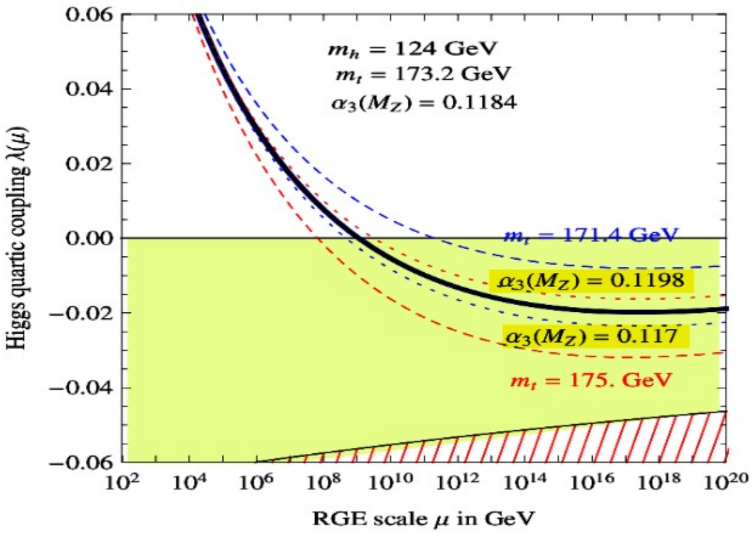
World average:
$\alpha_s(m_Z) = 0.1179 \pm 0.0009$

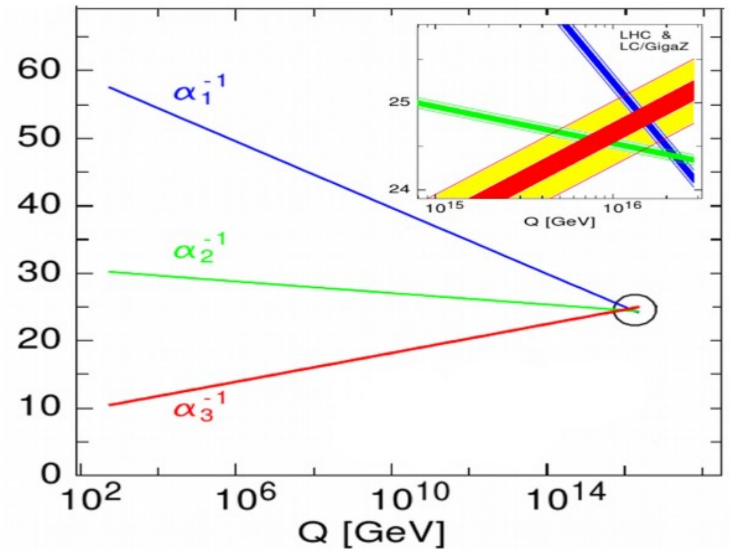
- Single free parameter of QCD in the $m_q \rightarrow 0$ limit
- Conventionally determined at the reference scale $Q = m_Z$
- Decreases ("runs") as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$





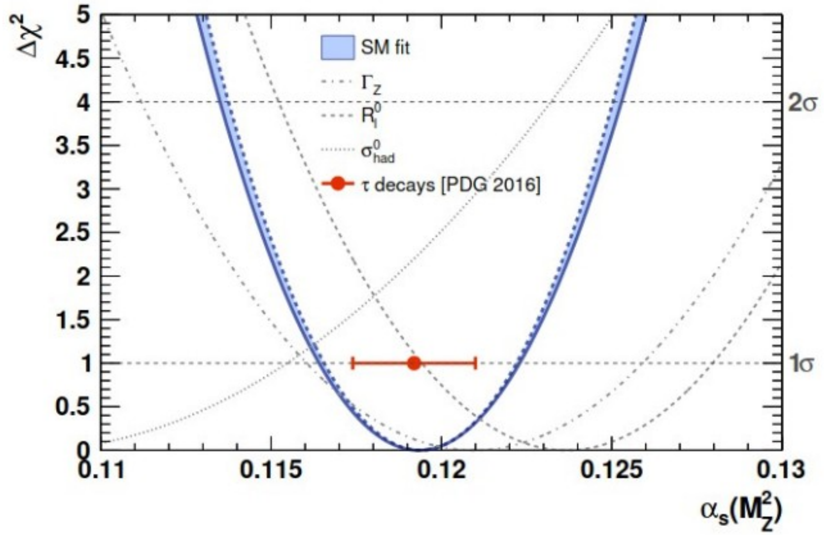
The strong-coupling constant - Motivation





- The strong-coupling constant impacts physics at the Planck scale: EW vacuum stability, GUT

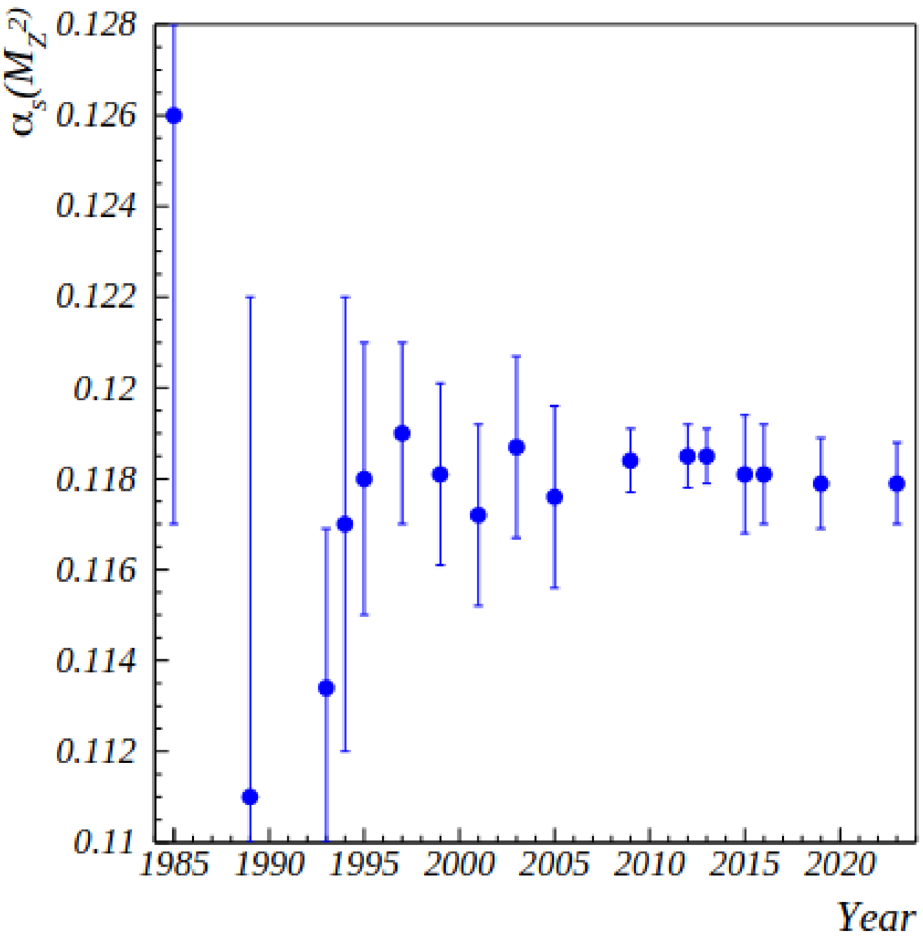
arXiv:1803.01853



- The strong-coupling constant is among the dominant uncertainties of several precision measurements at colliders
  - Higgs couplings at the LHC
  - EWPO at e+e- colliders as the total and hadronic Z width, m_t from threshold scan

History plot

arXiv:2303.00723

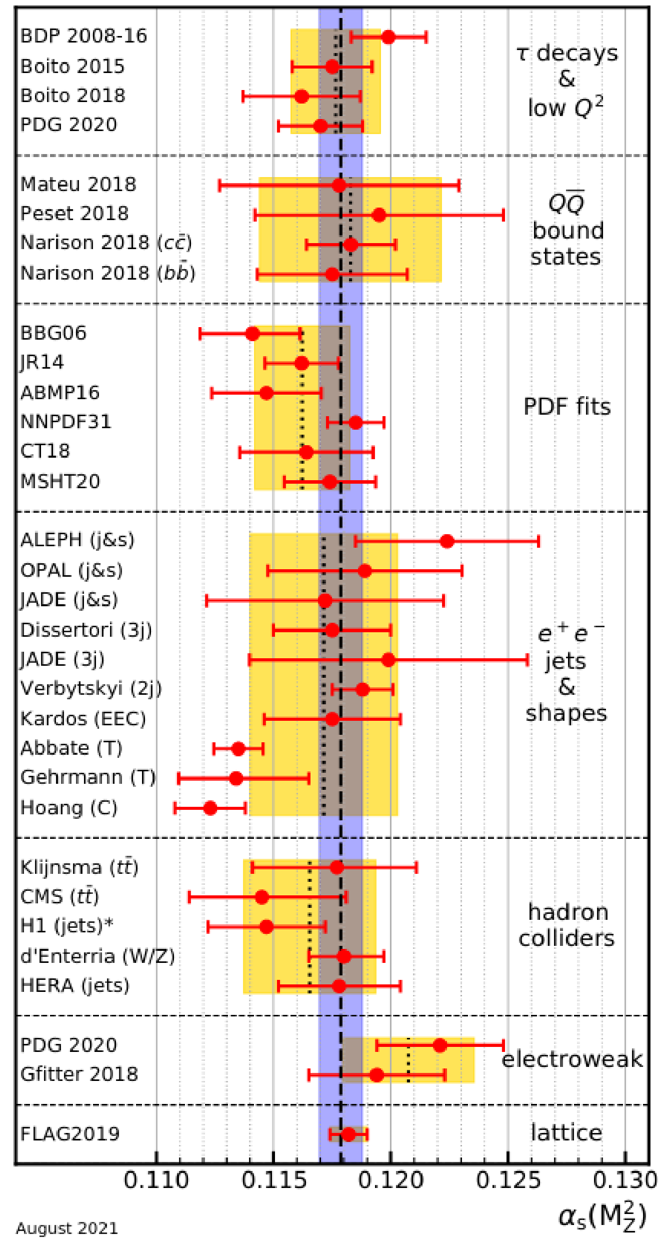


- The effort of measuring the strong coupling constant has a long history of more than 35 years
- Improving the precision of $\alpha_s(m_Z)$ is not always a linear process

State-of-the-art for the strong coupling $\alpha_s(m_Z)$

Category	$\alpha_s(m_Z)$	$\delta\alpha_s(m_Z)$	Rel. Unc.	Results
Tau decays and low Q^2	0.1178	0.0019	1.6%	4
$Q\overline{Q}$ bound states	0.1181	0.0037	3.1%	4
DIS and PDF fits	0.1162	0.0020	1.7%	6
e+e- jets and shapes	0.1171	0.0031	2.6%	10
Hadron colliders	0.1165	0.0028	2.4%	5
Electroweak boson decays	0.1208	0.0028	2.4%	2
Lattice QCD (FLAG 21)	0.1184	0.0008	0.7%	11
PDG 22 World Average	0.1179	0.0009	0.8%	39

- 7 PDG categories
- Most precise determinations from lattice QCD and tau decays



How to best determine $\alpha_s(m_Z)$

- PDG approach: set selection criteria (NNLO QCD, published result, standard theory uncertainty) and combine sets of correlated measurements through unweighted pre-averages

  → Test of QCD, unbiased result, but total uncertainty affected by unresolved tensions

- Critical view: select a smaller set of *clean* $\alpha_s(m_Z)$ measurements to achieve better precision:

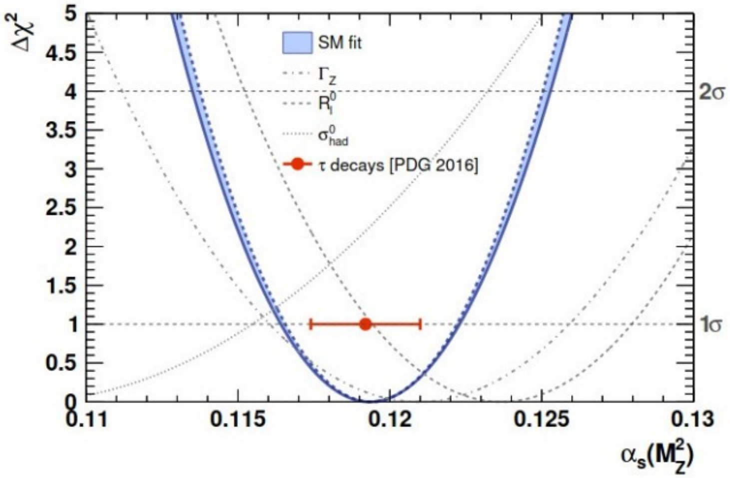
  [...] *one should select few theoretically simplest processes for measuring α_s and consider all other ways as tests of the theory (G. Altarelli)* arXiv:1303.6065

Desirable features of a clean $\alpha_s(m_Z)$ determination

- Large observable's sensitivity to α_s as compared to the experimental precision
- High (perturbative) accuracy of the perturbative prediction → At least NNLO
- Small size of non-perturbative effects
- The scale at which the measurement is performed

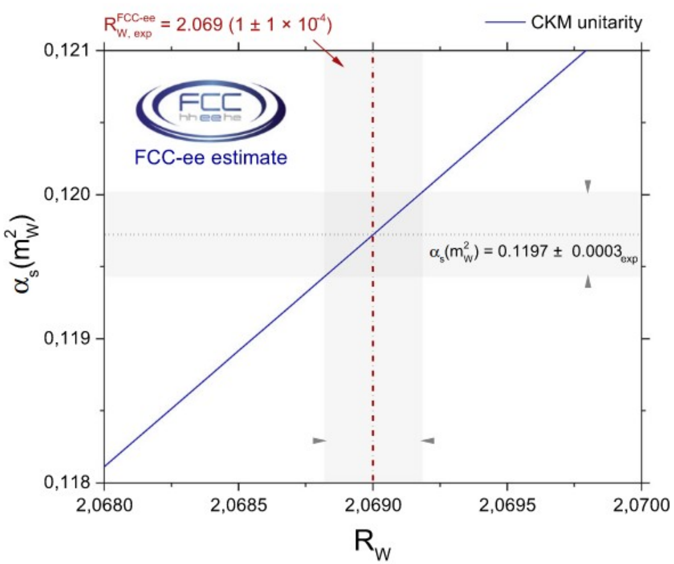
Clean $\alpha_s(m_Z)$ determination at 0.1%

arXiv:1803.01853

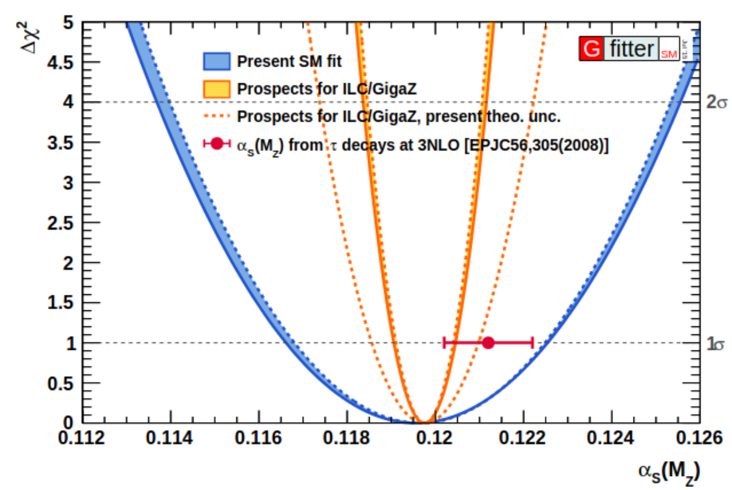


- Cleanest determination of $\alpha_s(m_Z)$ from hadronic decays of W and Z bosons
- Current determination from LEP measurements have large ~3% uncertainties, limited by experimental uncertainties
- Prospects for measuring $\alpha_s(m_Z)$ at permille level precision from R_Z, R_W at the FCC-ee
- Model dependent determination → sensitive to new physics if confronted with a model independent determination of similar precision

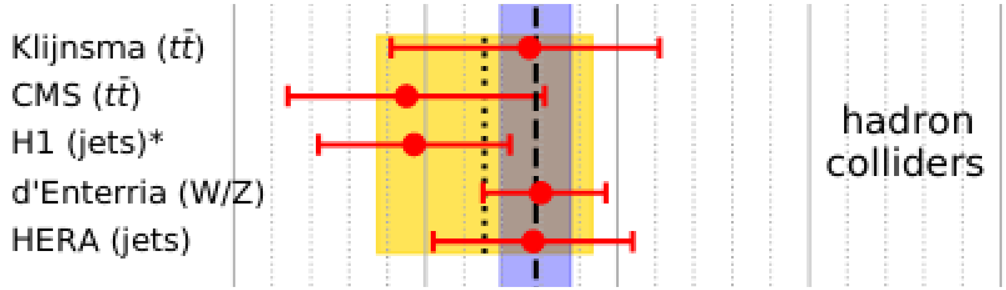
arXiv:1905.05078



arXiv:1512.05194



$\alpha_s(m_Z)$ at the LHC



- Top pairs
  - Inclusive cross section
- Jets
  - TEEC
  - Inclusive jets
  - Dijets

LHC determinations from

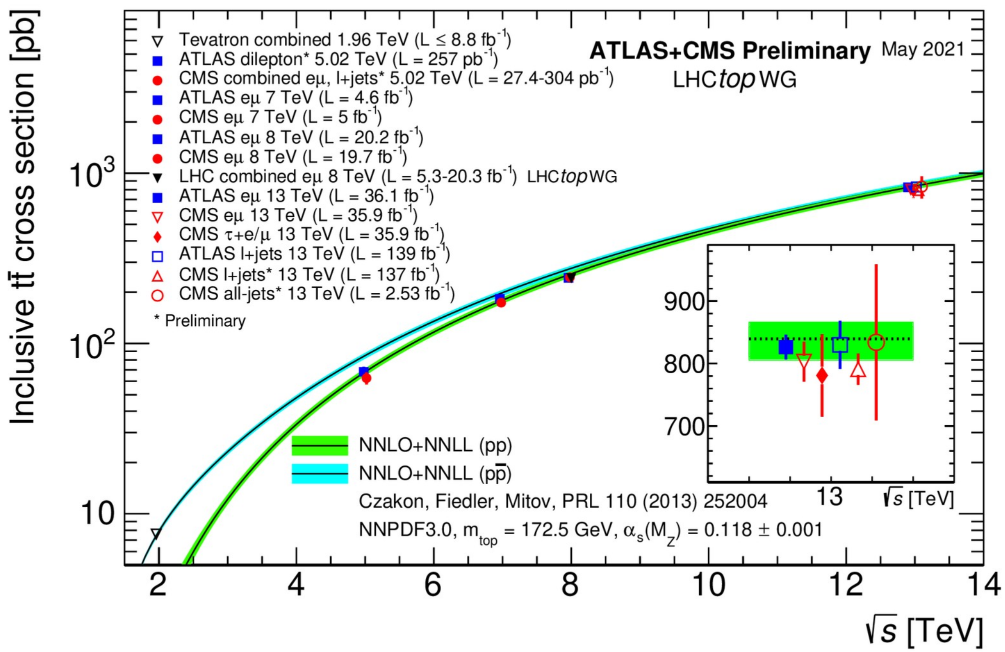
- Drell-Yan
  - Inclusive W/Z
  - Z pT

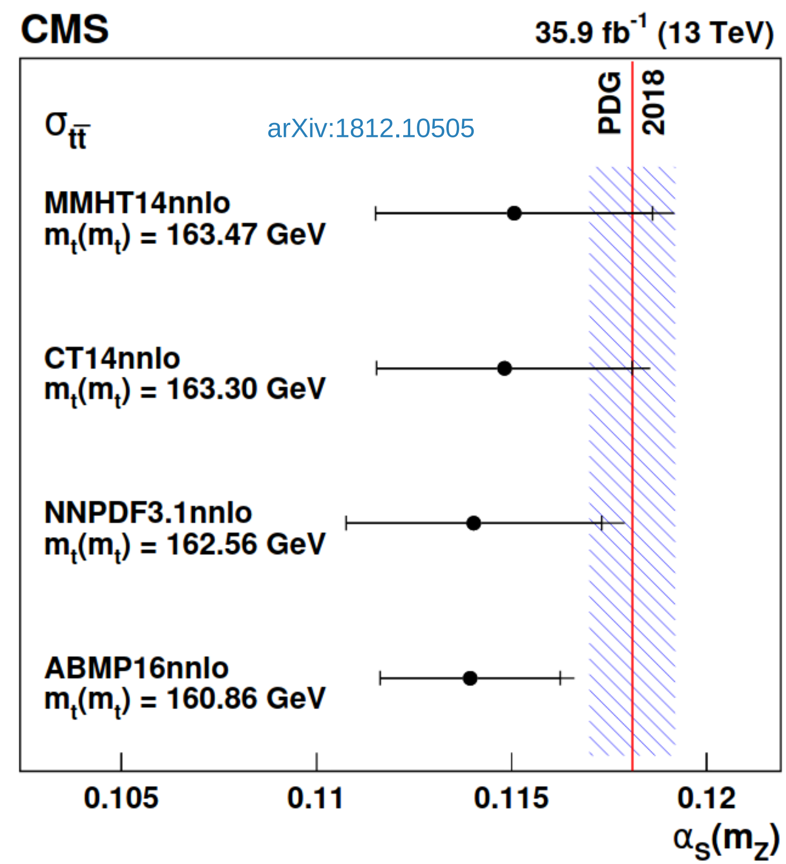
- Recent LHC results for $\alpha_s(m_Z)$ at NNLO
  - ATLAS TEEC
  - CMS Inclusive jets
  - CMS dijets
  - ATLAS Z p_T

4 new candidate results for the hadron colliders category of the PDG world average

Other NLO measurements not discussed here: dijets, 3-jet mass, R_{32} cross-section ratios, V+jets, differential $t\bar{t}$

Top quark production inclusive cross section



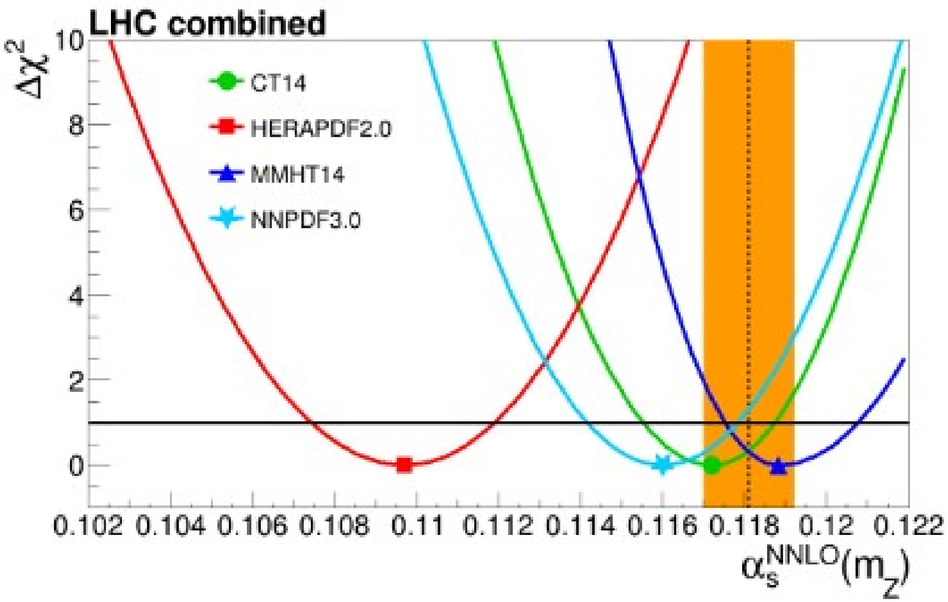


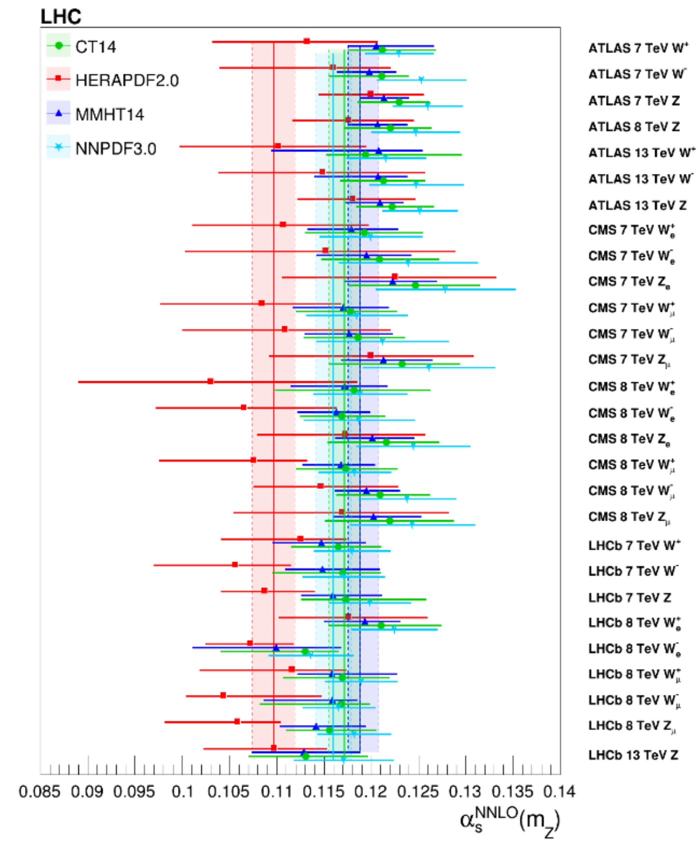
- Inclusive cross section is sensitive to PDFs, $a_s(m_Z)$ and top mass
- Allows determination of $a_s(m_Z)$ with a NNLO QCD analysis
- Large theory uncertainties related to gluon PDF and scale variations
- Was the first hadron collider process opening a new category in the PDG

PDF set	$\alpha_S(m_Z)$
ABMP16	0.1139 ± 0.0023 (fit + PDF) $^{+0.0014}_{-0.0001}$ (scale)
NNPDF3.1	0.1140 ± 0.0033 (fit + PDF) $^{+0.0021}_{-0.0002}$ (scale)
CT14	0.1148 ± 0.0032 (fit + PDF) $^{+0.0018}_{-0.0002}$ (scale)
MMHT14	0.1151 ± 0.0035 (fit + PDF) $^{+0.0020}_{-0.0002}$ (scale)

Strong-coupling constant from W,Z cross section

arXiv:1912.11733





- First determination of $\alpha_s(m_Z)$ with the DY process, combined fit of 28 datasets
- Result compatible with the PDG world average: $\alpha_s(m_Z)$ = 0.1180+-0.0016
- Measurement dominated by PDF and luminosity uncertainties
- Advantage wrt to global PDF fits → single out the sensitivity to $\alpha_s(m_Z)$ of inclusive DY cross sections, which is an experimentally and theoretically clean signature
- The analysis could be upgraded to N3LO in the near future

PDF	$\alpha_s(m_Z)$
CT14	$0.1172^{+0.0015}_{-0.0017}$
HERAPDF2.0	$0.1097^{+0.0022}_{-0.0023}$
MMHT14	$0.1188^{+0.0019}_{-0.0013}$
NNPDF3.0	0.1160 ± 0.0018

Hint of tension with DIS-only PDF fit (or PDF parametrisation bias?)

Transverse energy-energy correlations

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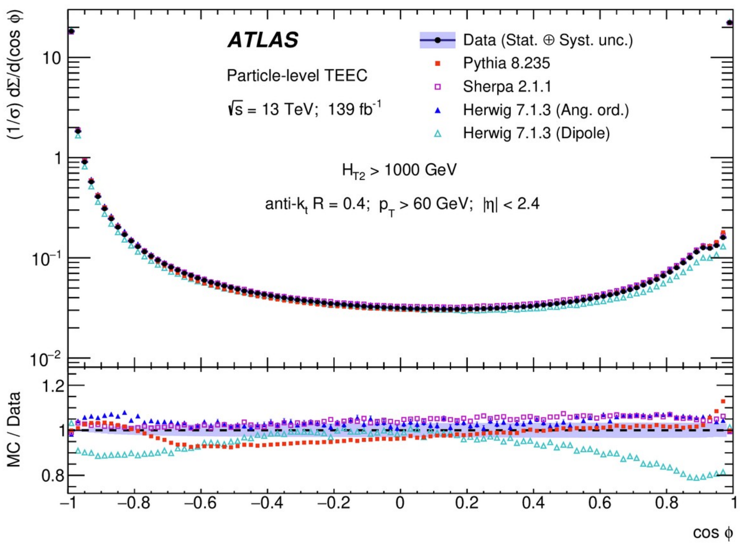
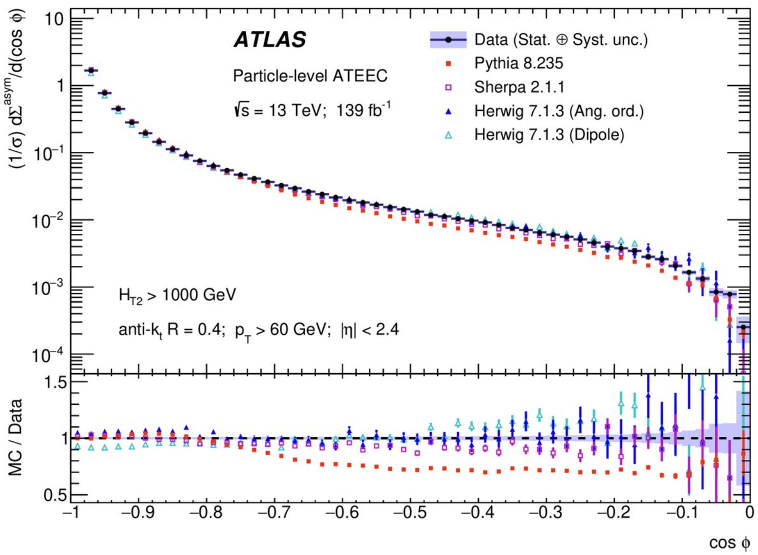
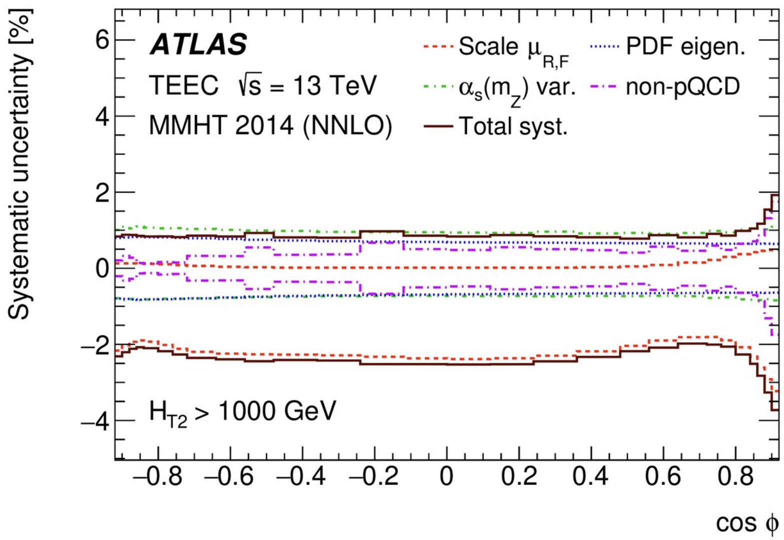




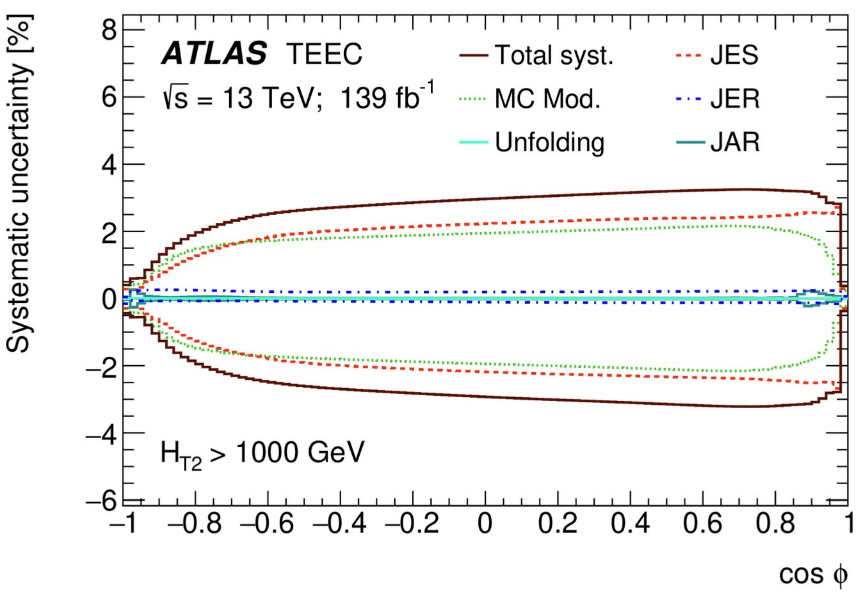
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

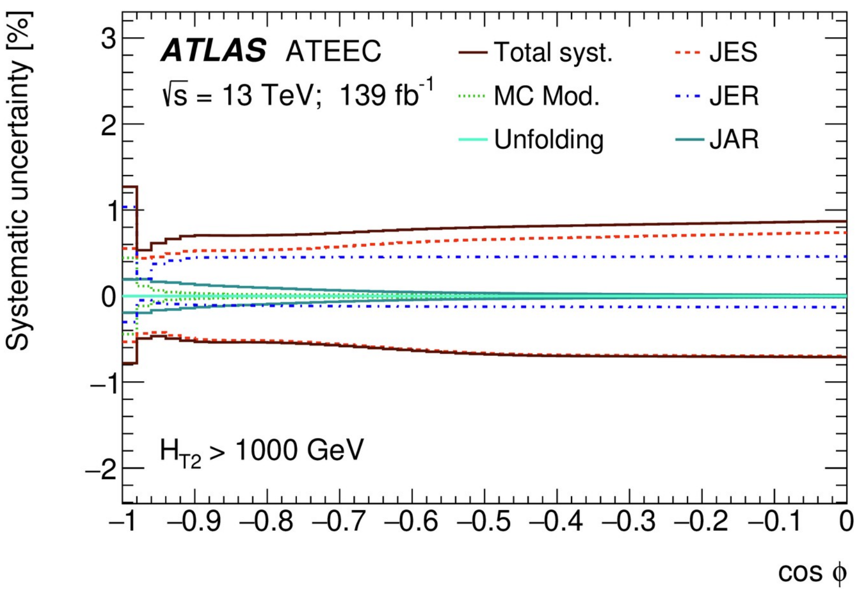
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

- Transverse energy-energy correlations (TEEC) are the transverse energy-weighted angular distribution of jet pairs
- TEEC and their azimuthal asymmetry (ATEEC) are generalisation for hadron colliders of EEC and AEEC
- Sensitive to gluon radiation and to $\alpha_s(Q)$

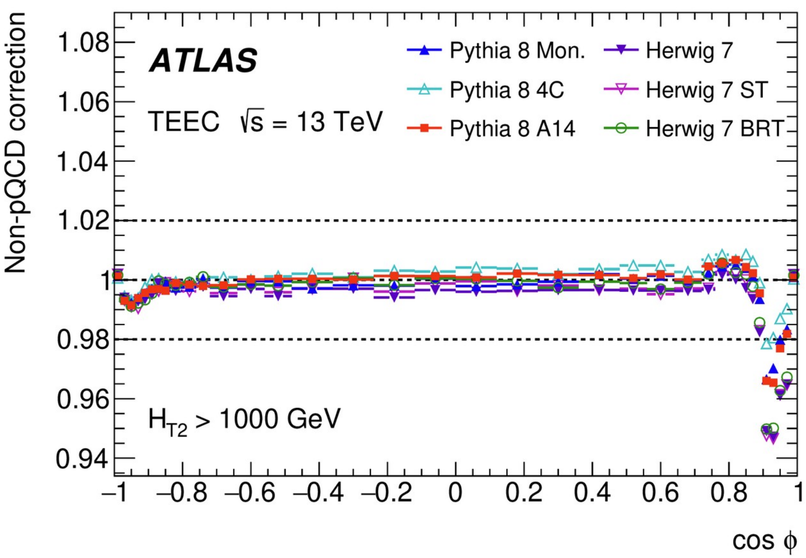


Transverse energy-energy correlations



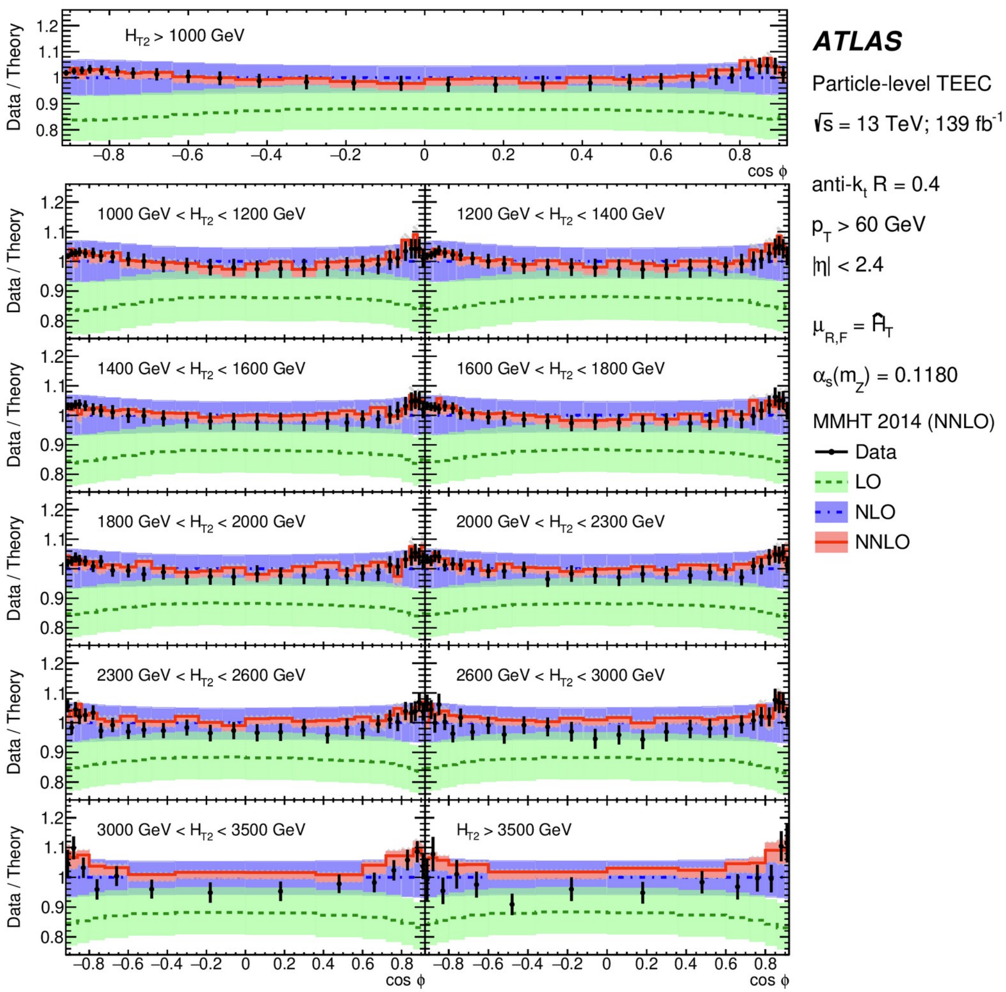


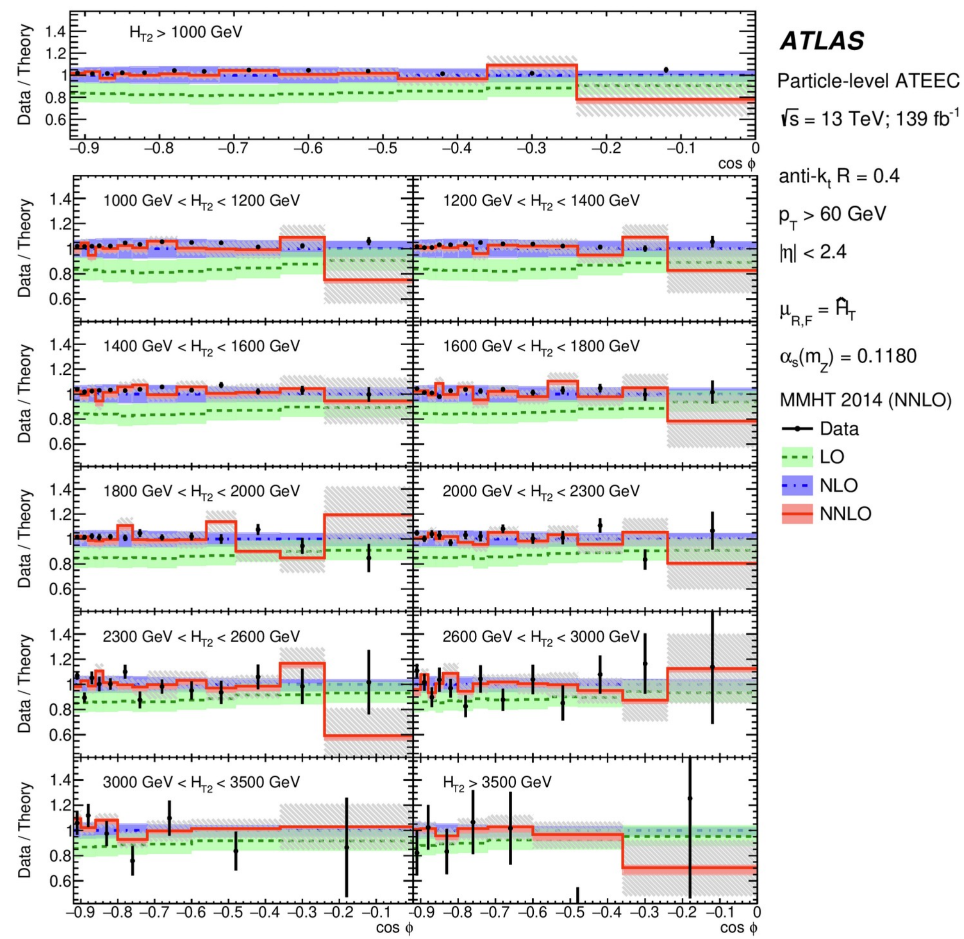
- Full Run 2 dataset: 139 fb^{-1}
- Anti-k_T calibrated PF jets with p_T > 60 GeV and $|\eta|$ < 2.4
- Measured performed in 10 bins of H_{T2}, the scalar sum of p_T of the two leading jets, from 1 to 3.5 TeV
- Experimental uncertainties dominated by jet modeling and JES/JER
- Small size of parton-to-particle corrections, except in the collinear region



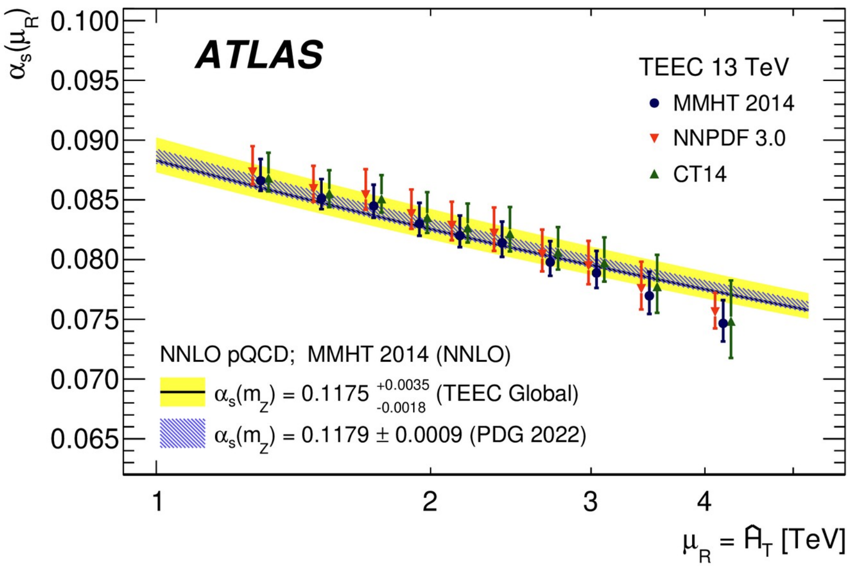
Transverse energy-energy correlations

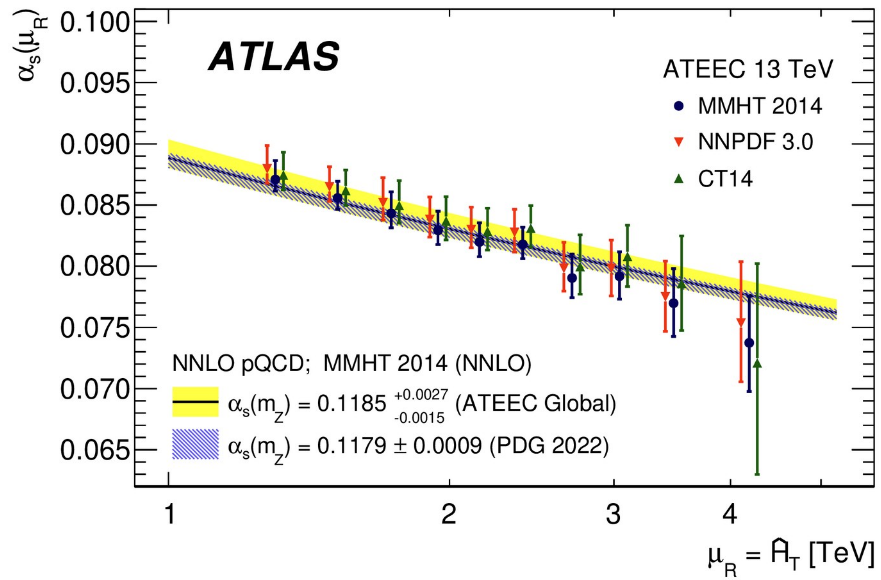
- Strong coupling determination based on NNLO 3-jets calculation
- Improved agreement with data and significant reduction of scale variations at NNLO





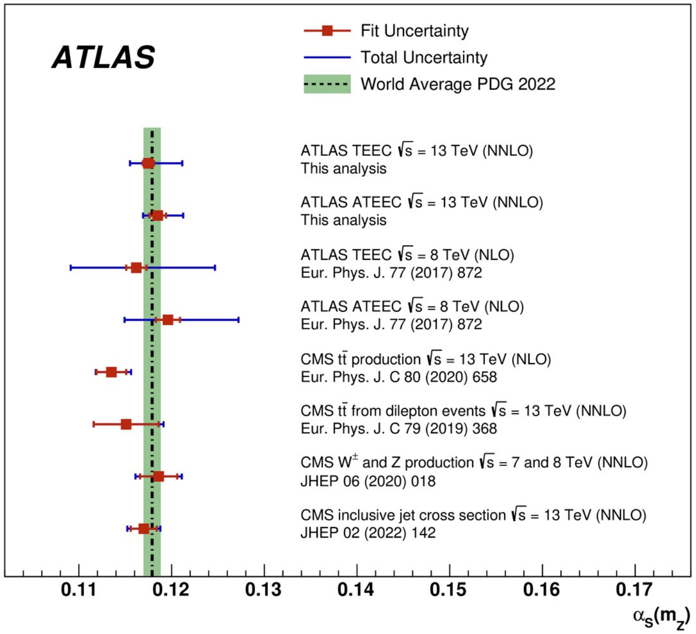
Transverse energy-energy correlations





$$\alpha_s(m_Z)^{TEEC} = 0.1175 \pm 0.0006(\text{exp.})^{+0.0034}_{-0.017}(\text{theo.})$$

$$\alpha_s(m_Z)^{ATEEC} = 0.1185 \pm 0.0009(\text{exp.})^{+0.0025}_{-0.012}(\text{theo.})$$



- Agreement with the RGE predictions up to the highest energy scales
- Determined value of $\alpha_s(m_Z)$ in agreement with PDG world average

CMS $\alpha_s(m_Z)$ from jet production

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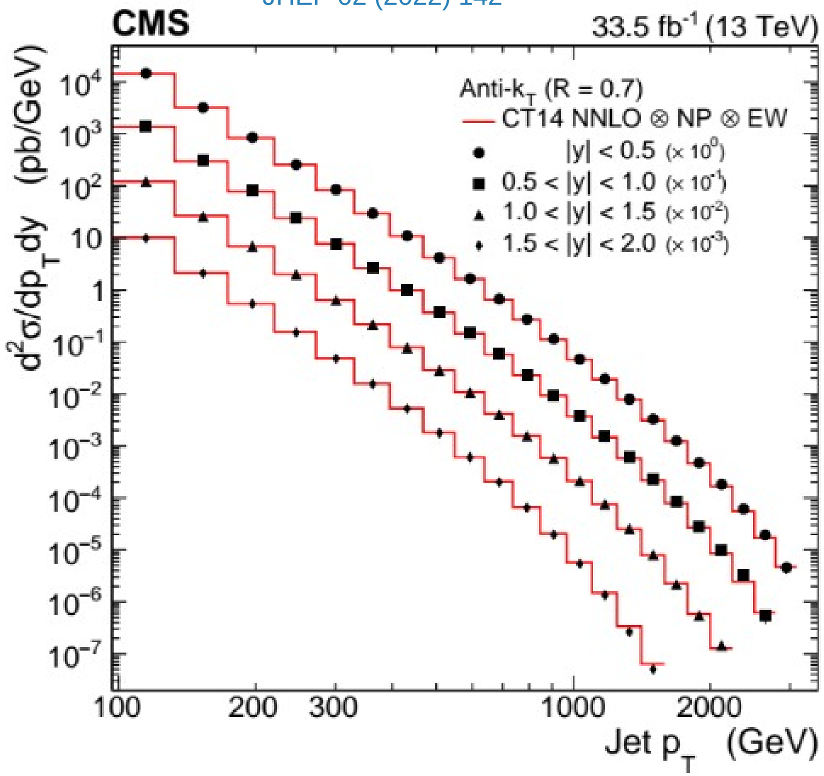
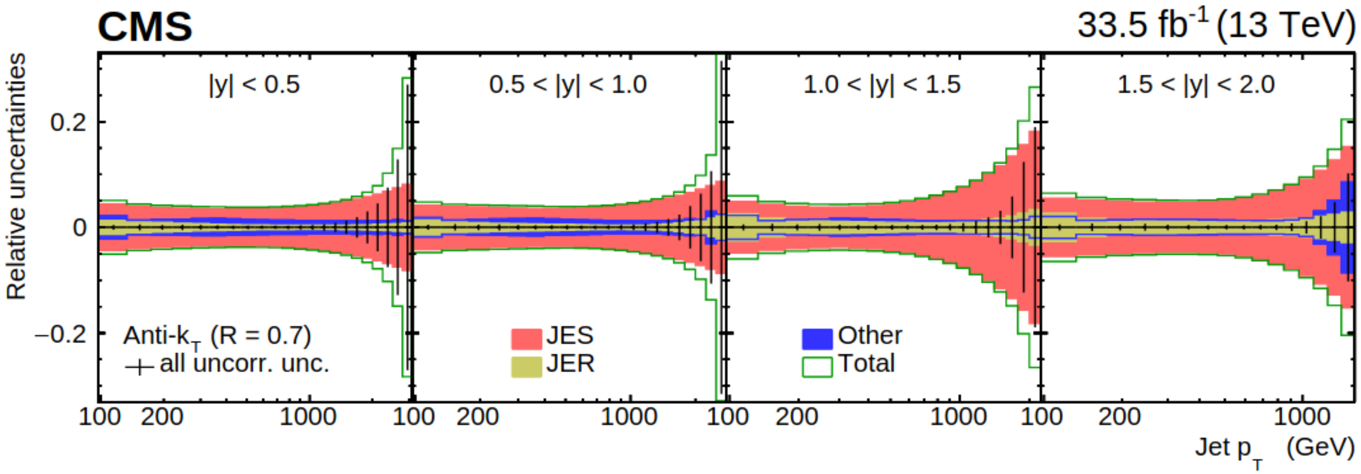
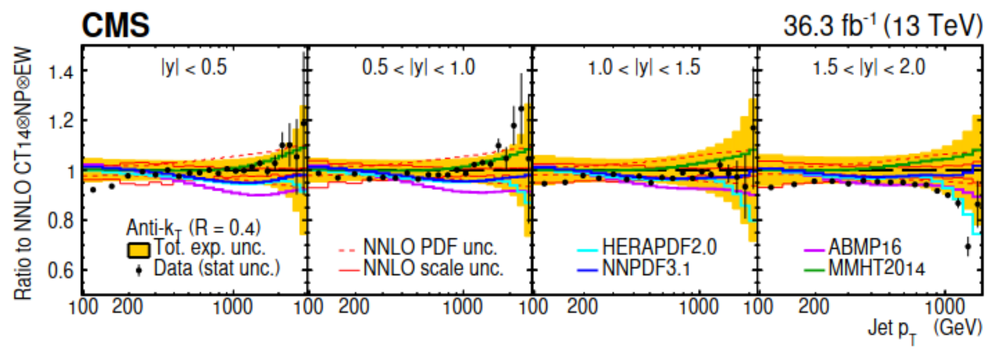
- Double differential cross sections as functions of p_T and rapidity for anti-k_T jets with R = 0.4, 0.7
- Experimental uncertainties dominated by JES

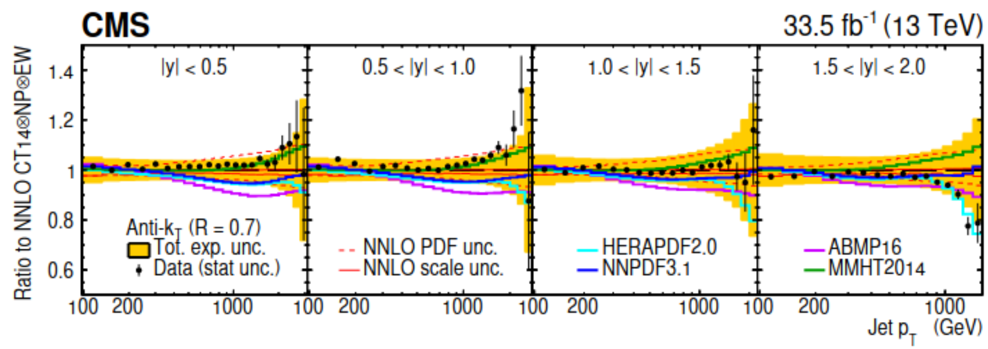


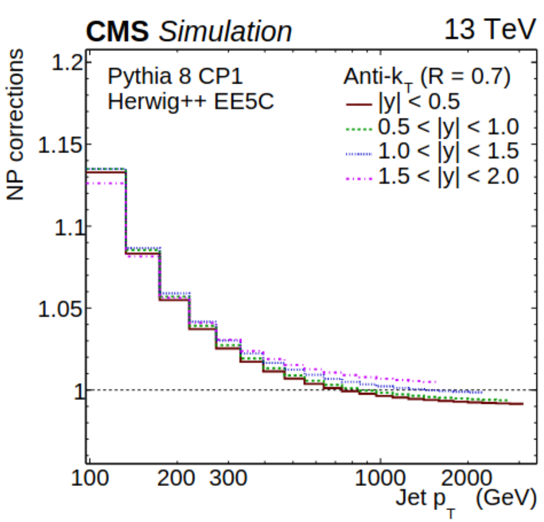


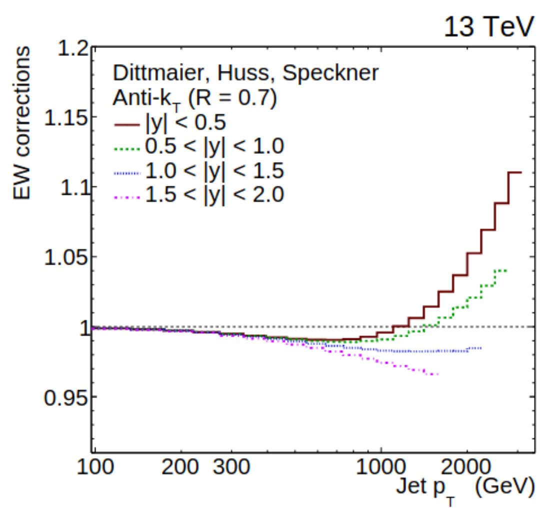
CMS $\alpha_s(m_Z)$ from jet production

- Comparison to NNLO perturbative QCD and to NLO+NLL threshold and small R joint resummation
- Non-perturbative QCD and EW corrections included in the comparison

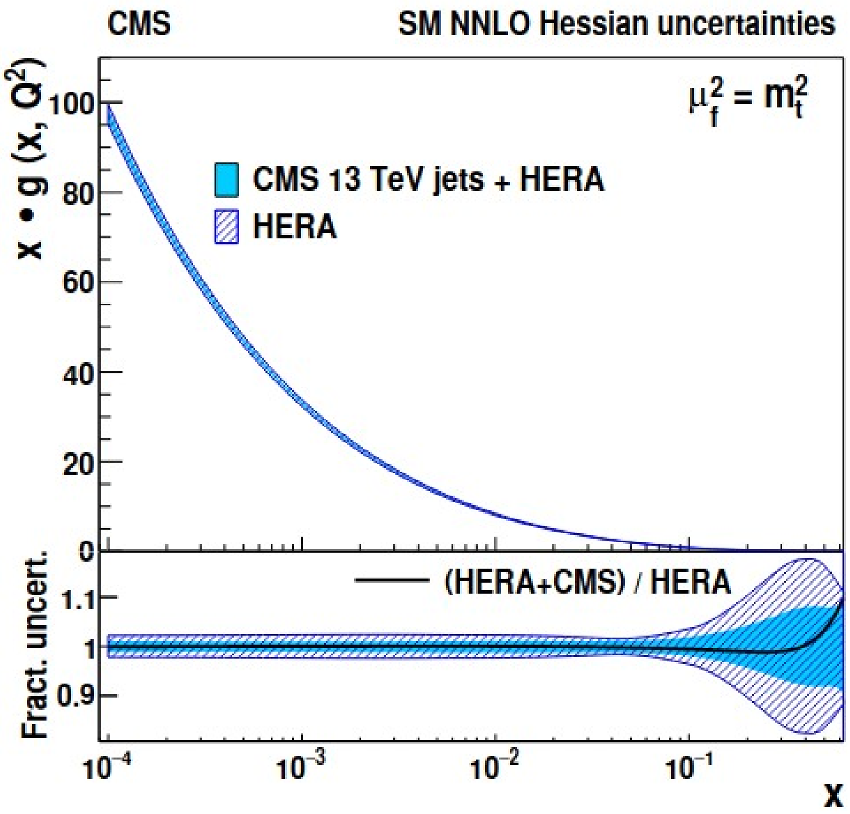








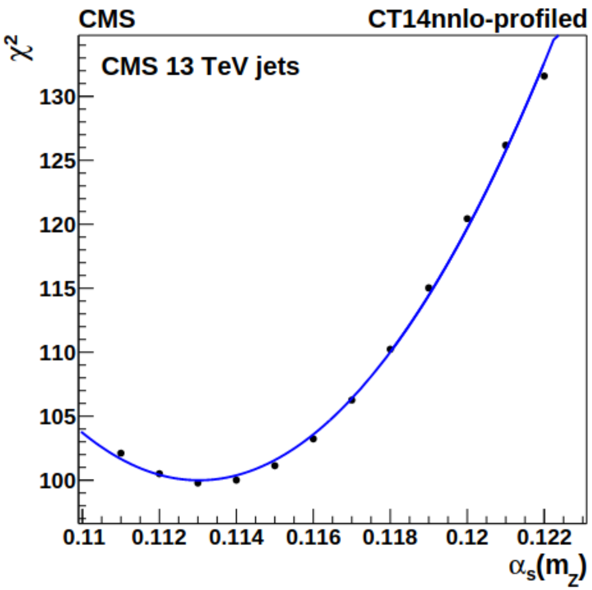
CMS $\alpha_s(m_Z)$ from jet production



- Fit to Inclusive jet cross sections at 13 TeV and HERA data with a NNLO analysis
- Significant reduction of the gluon PDF uncertainty at high x
- Simultaneous PDF+α_s fit:

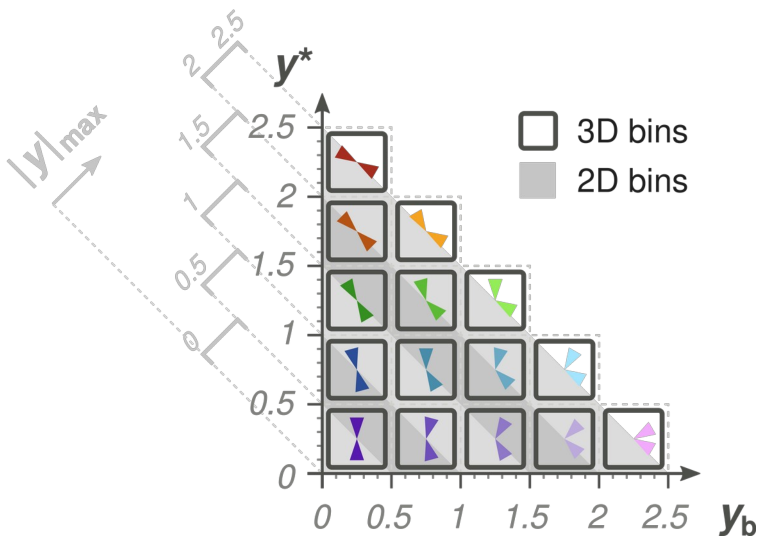
  $\alpha_s(m_Z) = 0.1166 \pm 0.0016$
- Profiling analysis with CT14nnlo:

  $\alpha_s(m_Z) = 0.1130 \pm 0.0021$

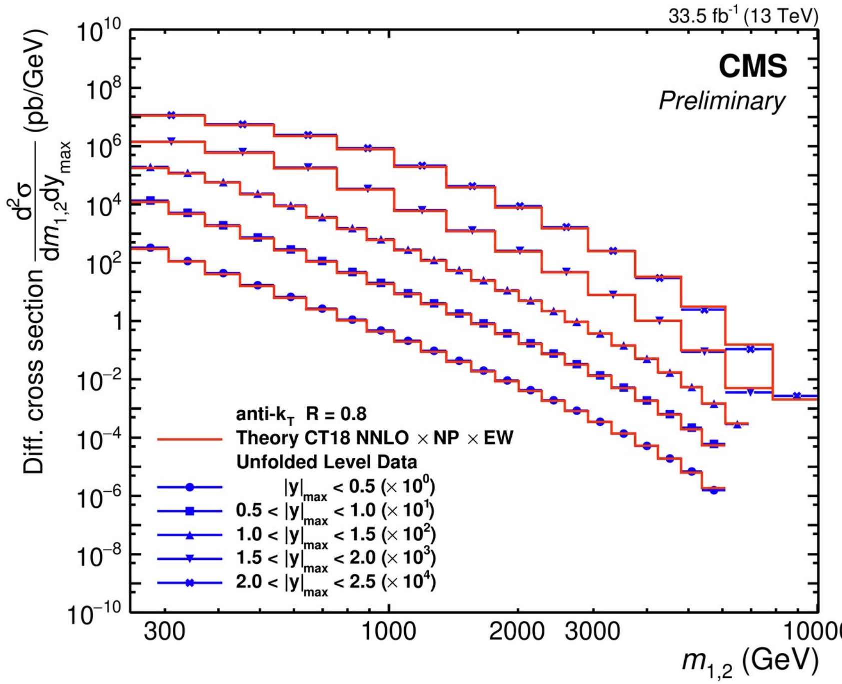


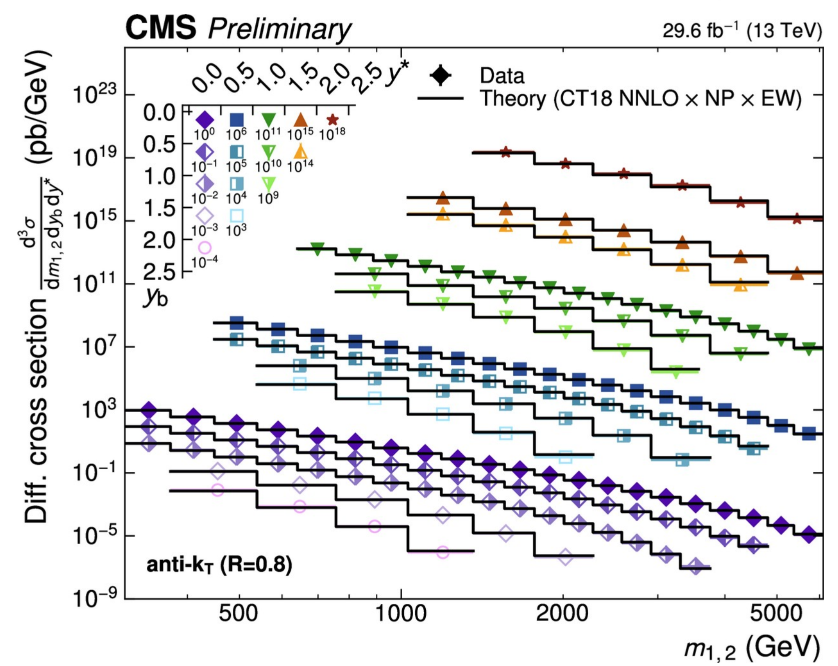
CMS $\alpha_s(m_Z)$ from dijet production

- Double and triple differential cross sections measured as a function of dijet invariant mass and and rapidity of anti-k_T jets with R = 0.4, 0.8



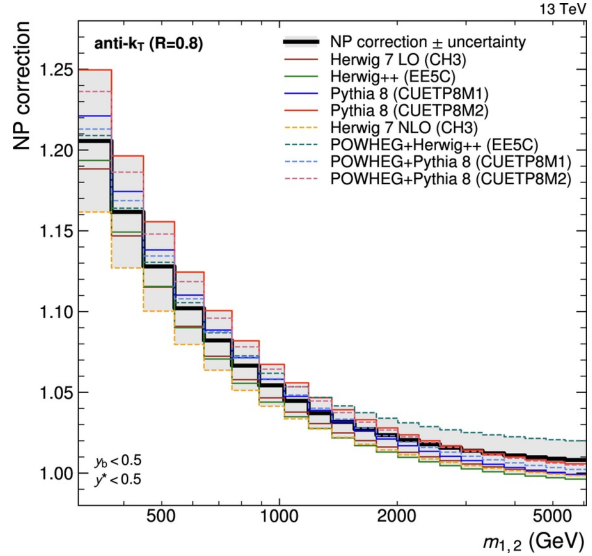
$$y^* = \frac{1}{2}|y_1 - y_2|, \quad y_b = \frac{1}{2}|y_1 + y_2|$$

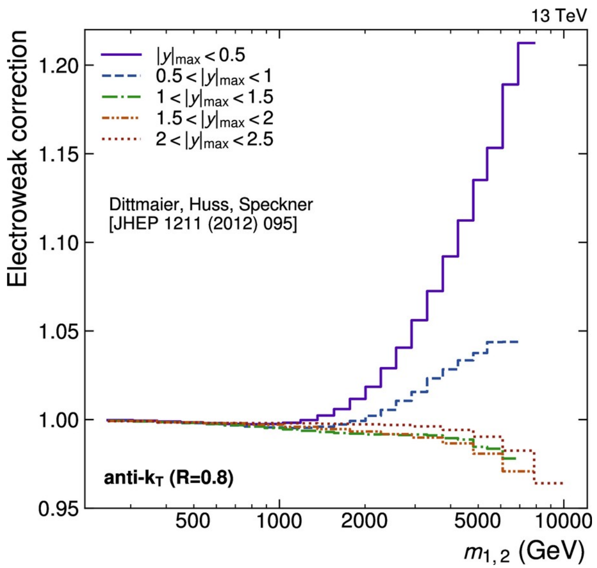


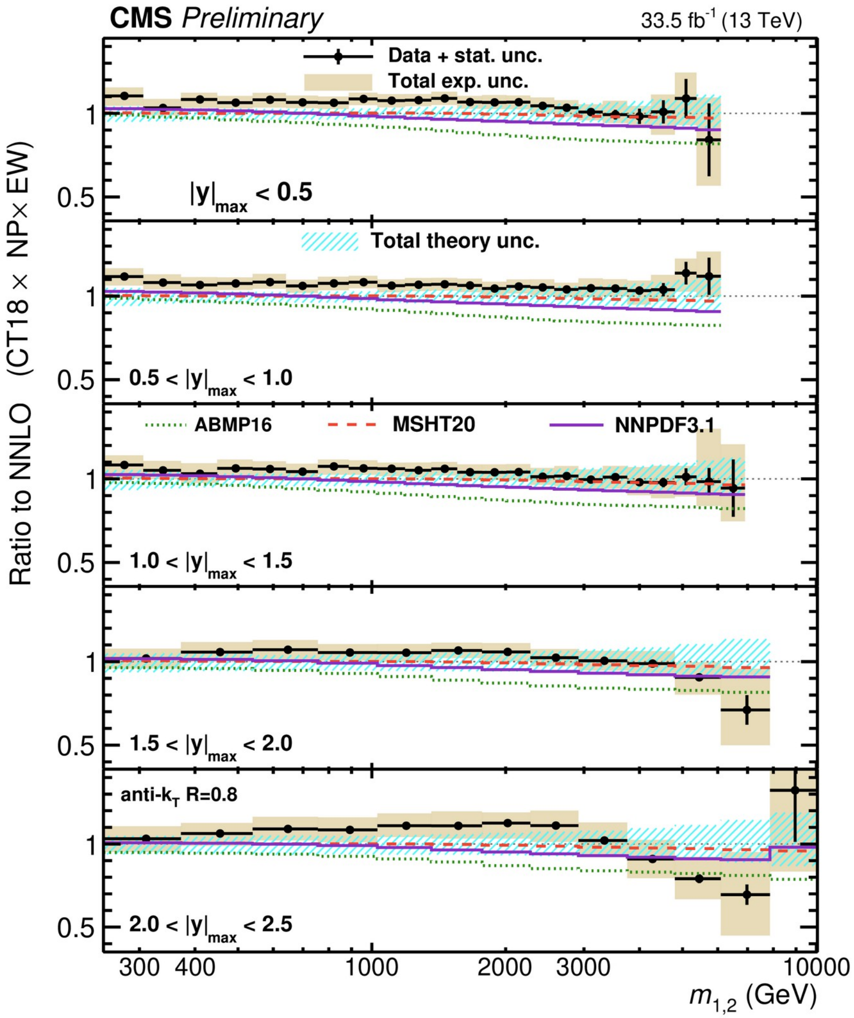


CMS $\alpha_s(m_Z)$ from dijet production

- Comparison to NNLO QCD predictions
- Including NP and EW corrections



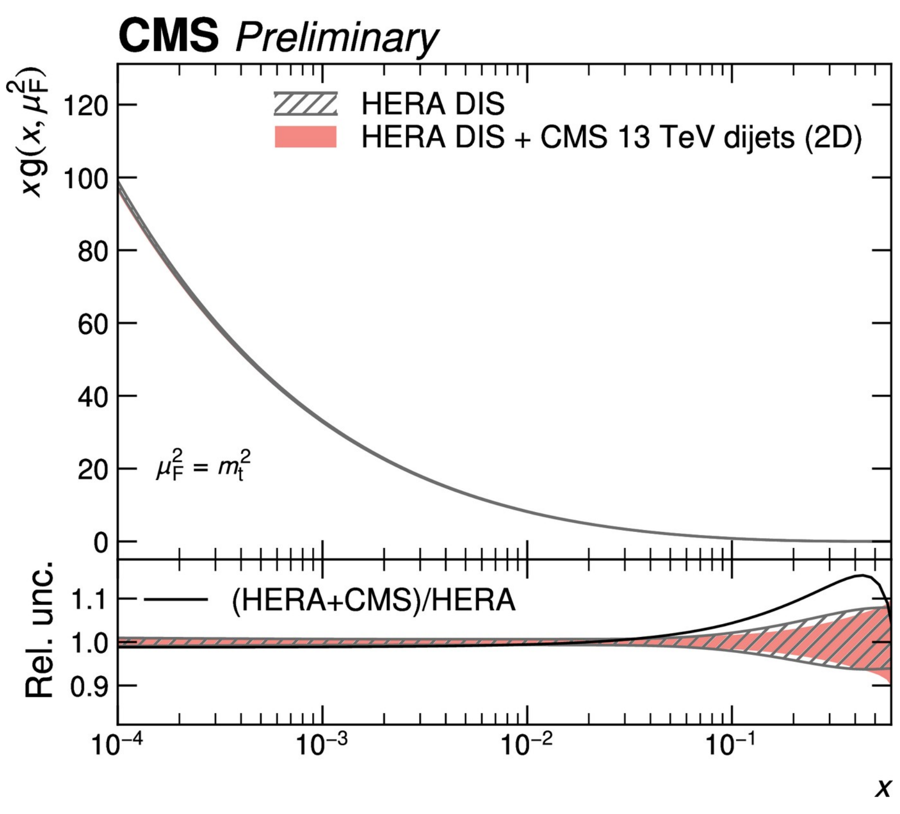


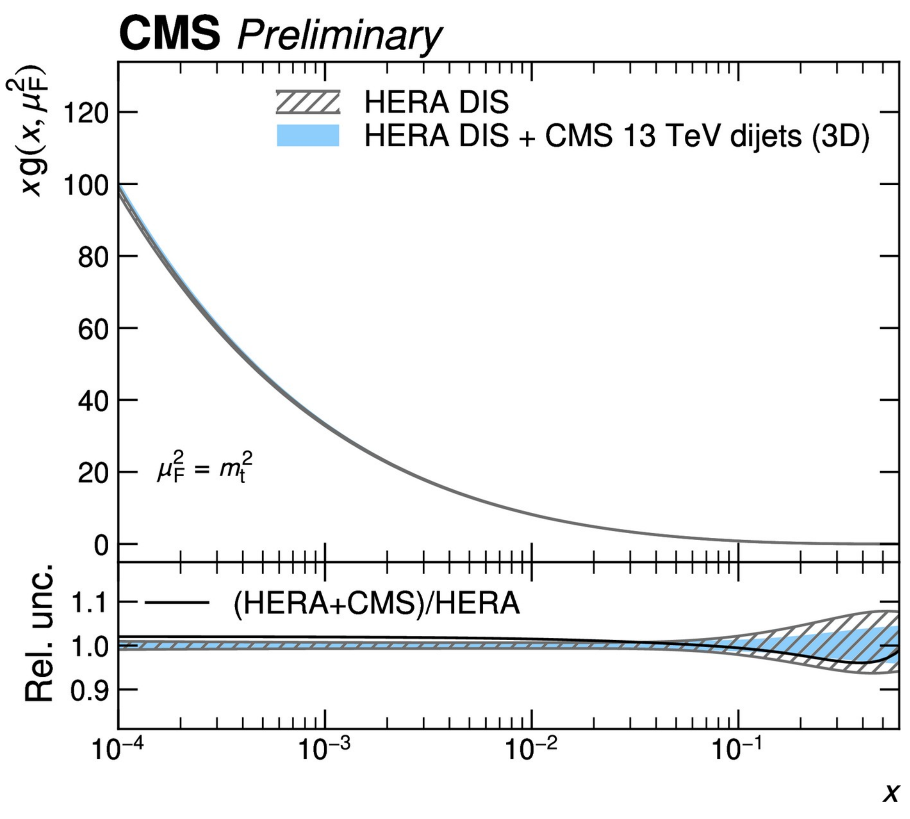


CMS $\alpha_s(m_Z)$ from dijet production

- Determination of PDFs and $\alpha_s(m_Z)$ at NNLO
- $\alpha_s(m_Z)$ is 1.6σ higher than inclusive jets determination (0.1166 +- 0.0016)
- Dominant experimental systematics (JES) expected to be largely correlated → tension in theory predictions?

$$\alpha_s(m_Z) = 0.1201 \pm 0.0010\,(\text{fit}) \pm 0.0005\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0006\,(\text{param.}) = 0.1201 \pm 0.0020\,(\text{total}),$$



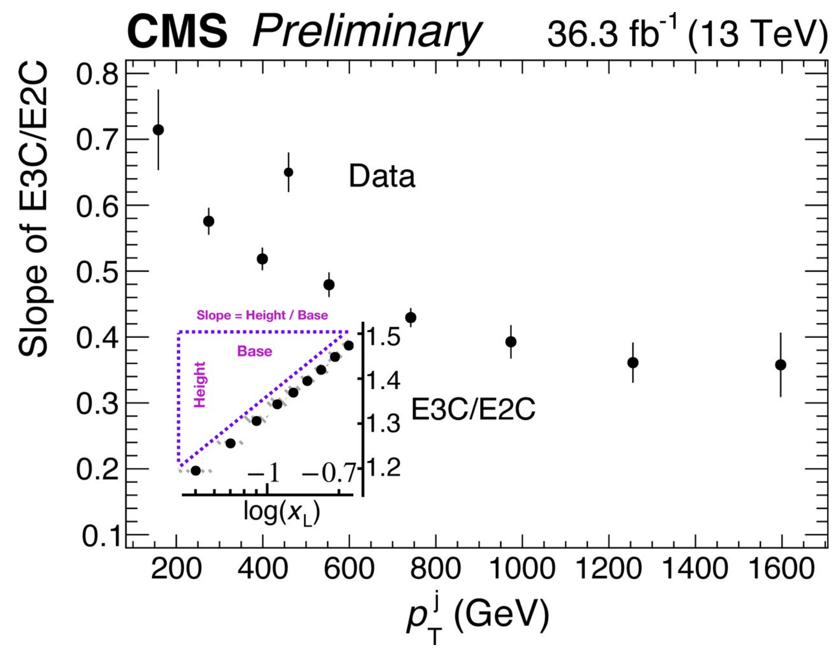


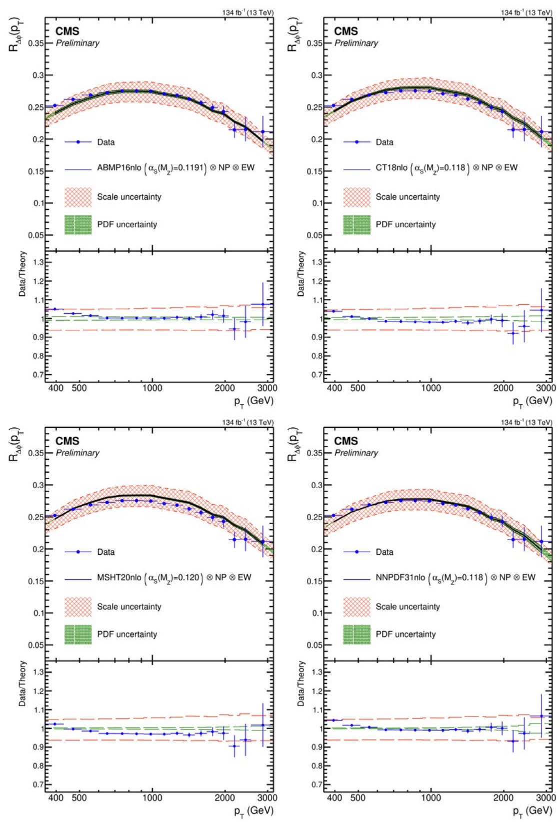
CMS $\alpha_s(m_Z)$ at NLO

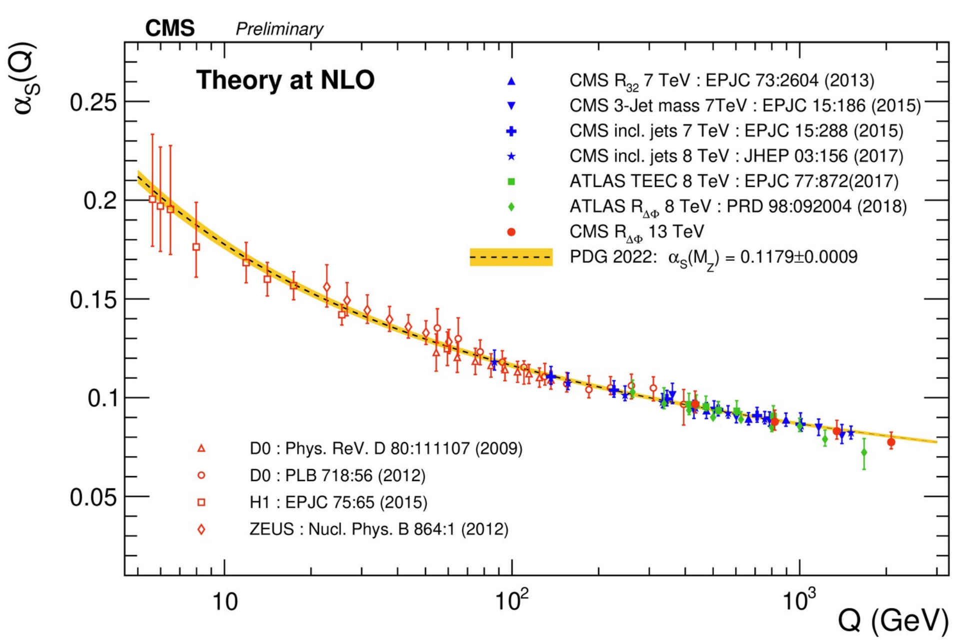
- NLO determinations of $\alpha_s(m_Z)$
  - From ratio of energy correlators inside jets

    $\alpha_s(m_Z) = 0.1129^{+0.0040}_{-0.0050}$
  - From azimuthal correlations

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

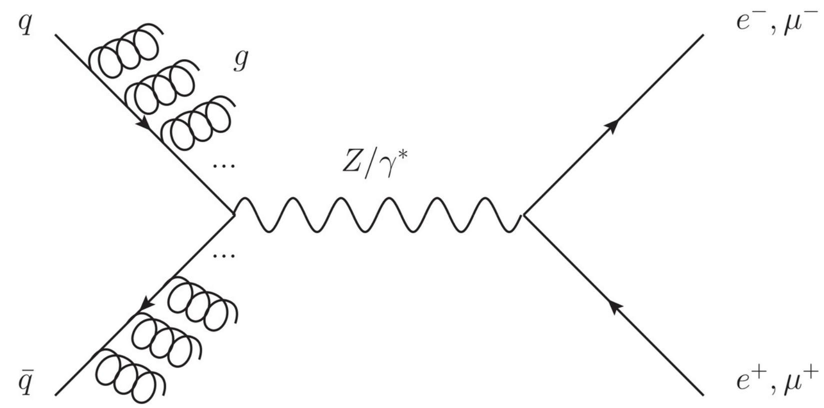


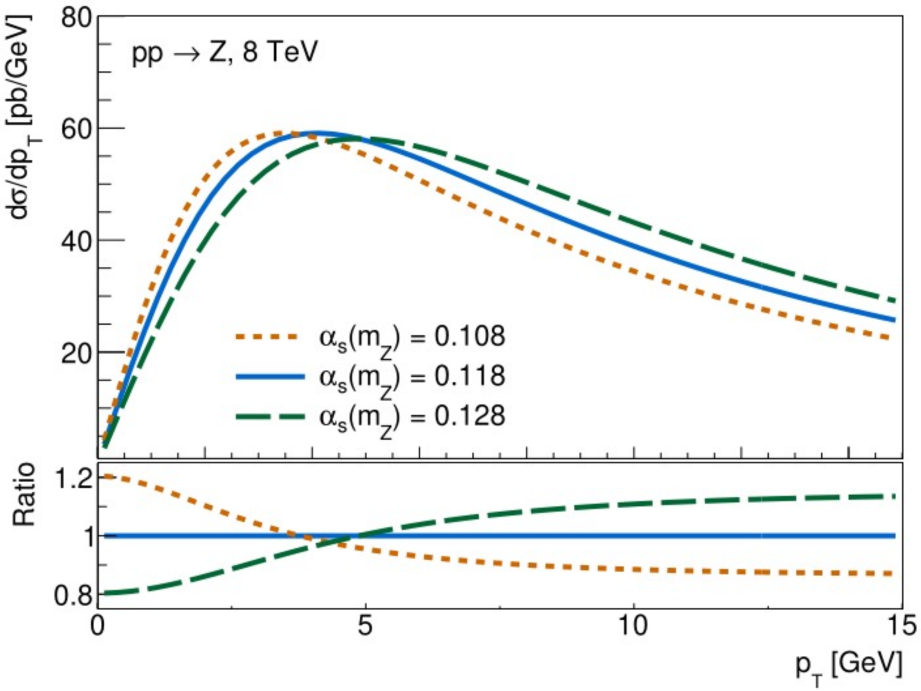




ATLAS $\alpha_s(m_Z)$ from the Z p_T distribution

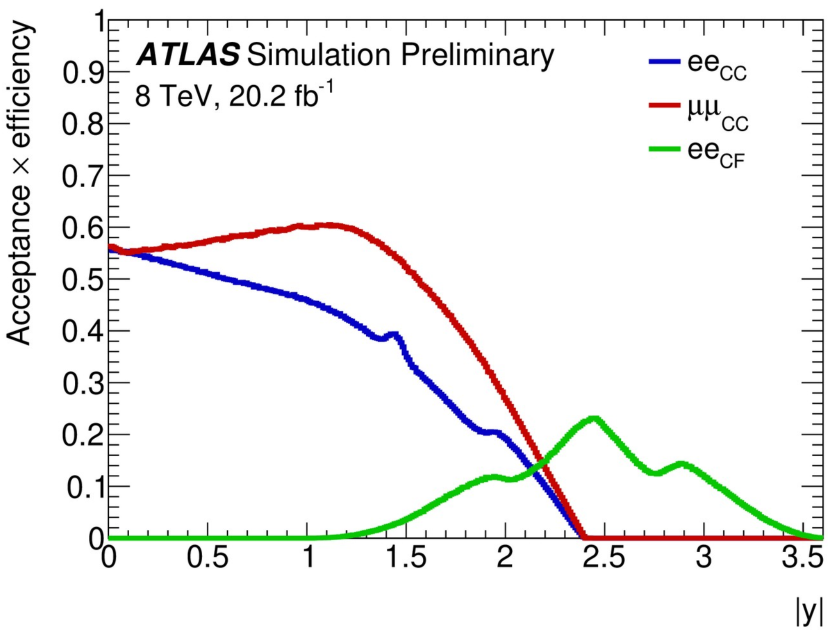
- Z bosons produced in hadron collisions recoil against QCD initial-state radiation: by momentum conservation, ISR gluons will boost the Z in the transverse plane
- The Sudakov factor is responsible for the existence of a peak in the Z-boson p_T distribution, at values of approximately 4 GeV
- The Sudakov region of the p_T distribution has a linear sensitivity to $\alpha_s(m_Z)$
- Semi-inclusive (radiation inhibited) observable, requires resummation

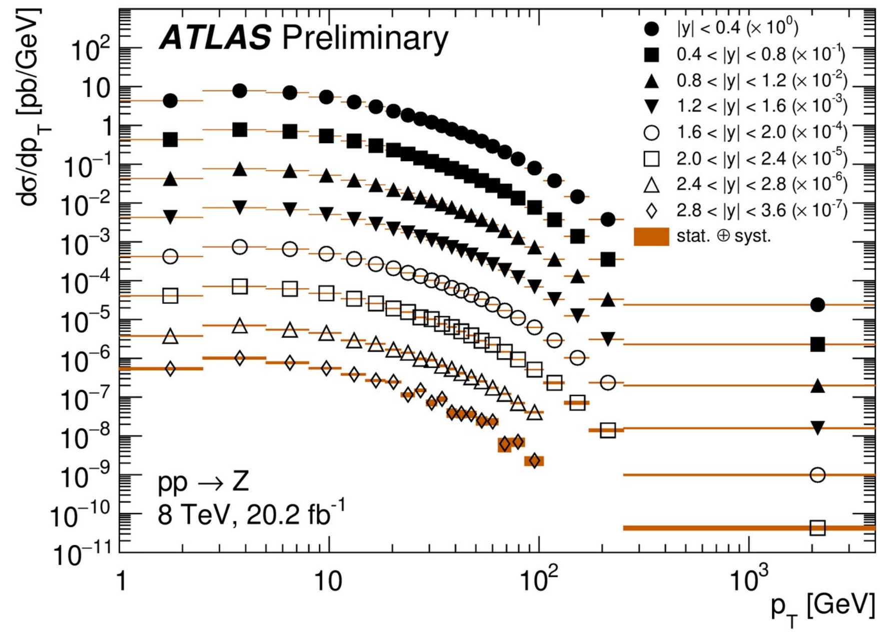




ATLAS $\alpha_s(m_Z)$ from Z p_T

- $\sqrt{s}$ = 8 TeV, L = 20.2 fb^{-1}
- Three channels: ee_{CC}, $\mu\mu_{CC}$, ee_{CF}:
- Central electron/muons with p_T > 25 GeV, $|\eta|$ < 2.4, forward electron with p_T > 20 GeV, 2.5 < $|\eta|$ < 4.9
- 80 < m_{ll} < 100 GeV
- Double differential p_T, y cross section, |y| < 3.6





Expected Yield

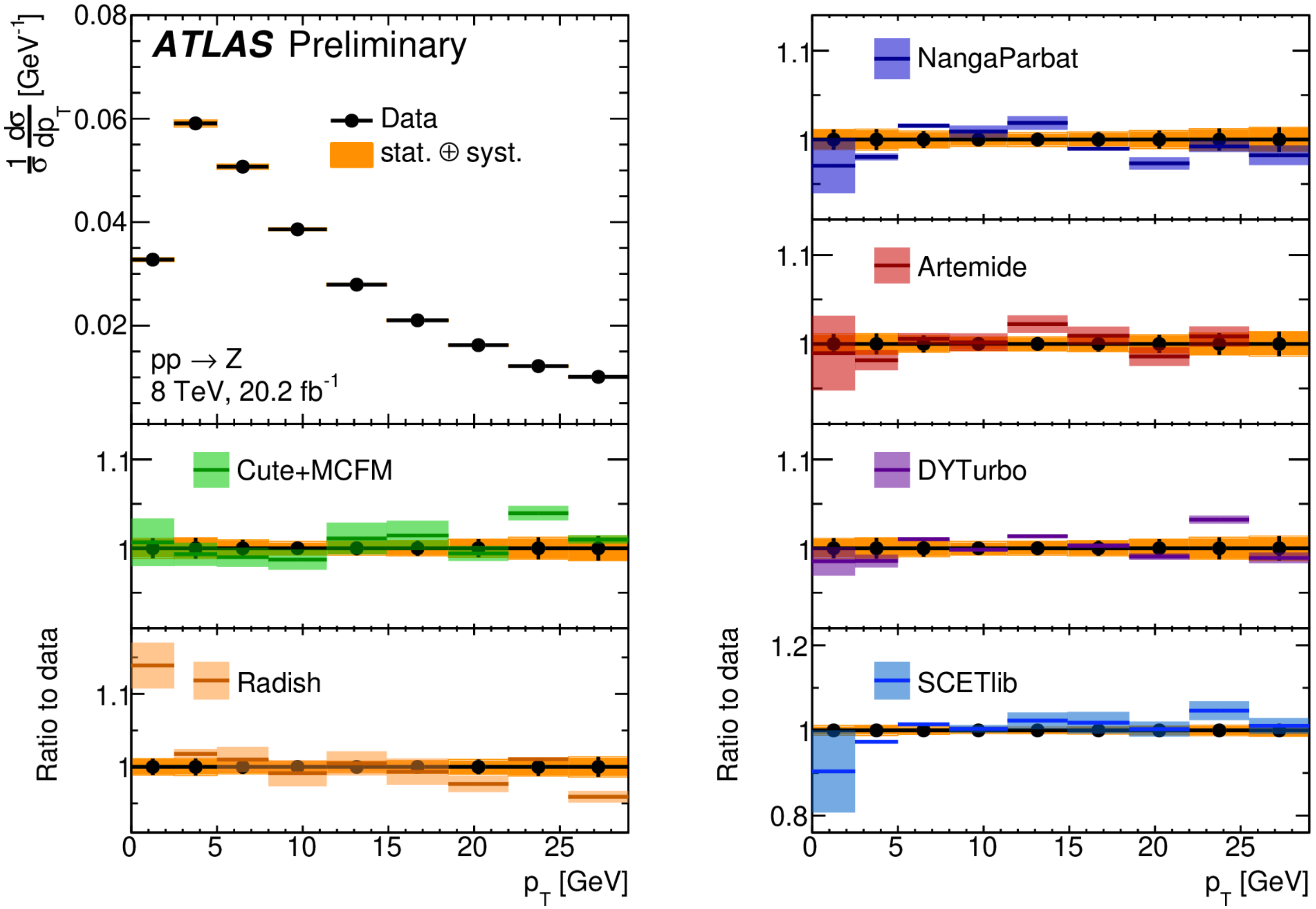
Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

$$N^n_{\mathrm{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=1}^{N^{ana}_{\mathrm{bins}}} \mathcal{L}\sigma_j \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} t^n_{ij}(\beta) \right] \right\} \gamma^n + \sum_{B}^{\mathrm{bkgs}} T^n_B(\beta)$$

Cross section — Background template — Truth (p_T^Z, y^Z, m^Z) bin — Angular coefficient — Templated polynomial

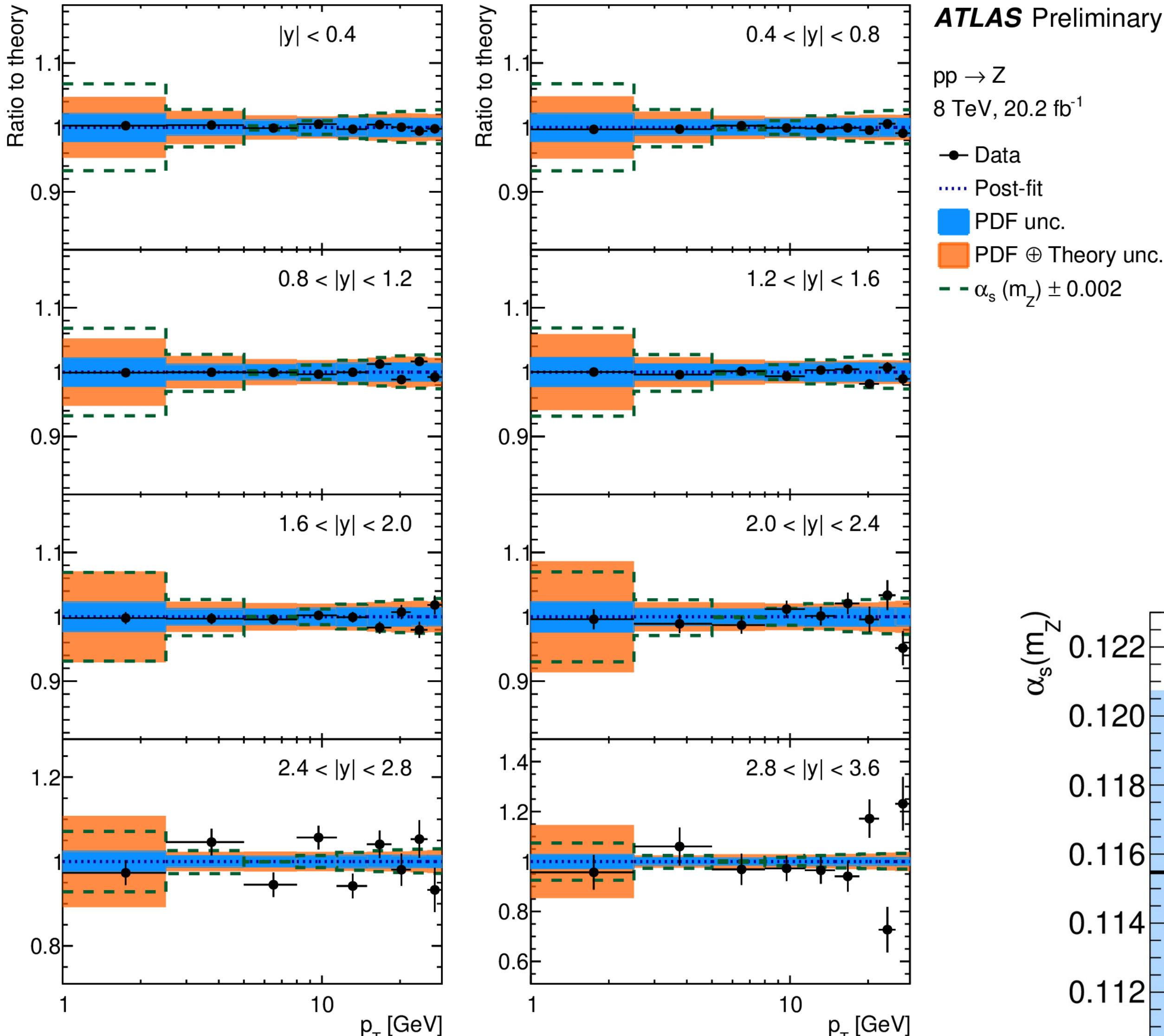
- First measurement at the LHC of full-lepton phase space cross sections

Comparison to p_T-resummation

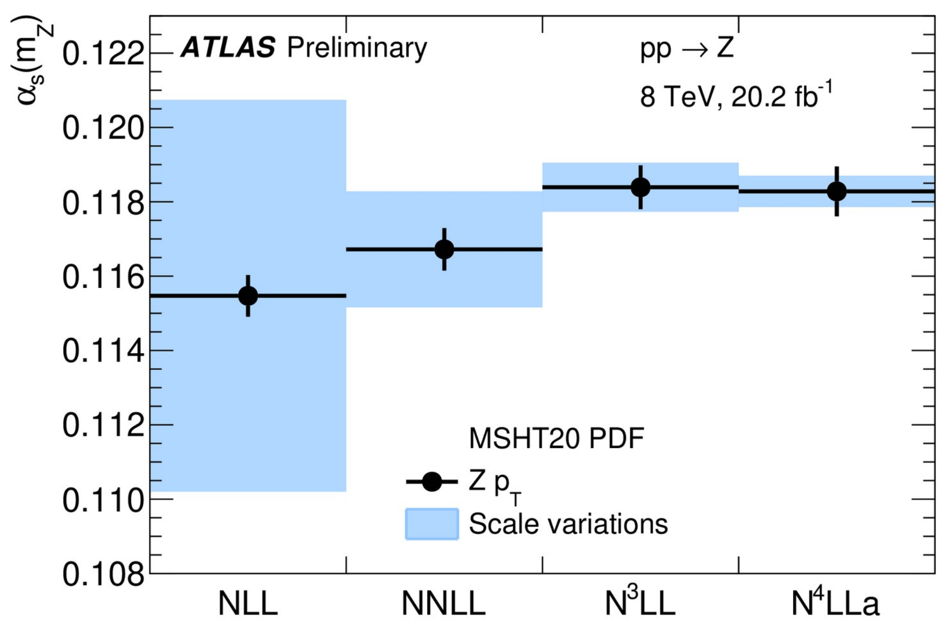


- Rapidity-integrated cross sections in the low p_T region
- Excellent agreement between data and all predictions
  - The result of an impressive progress in the understanding of the boson p_T modelling from the experimental and theoretical points of view

Determination of $\alpha_s(m_Z)$ from p_T Z at 8 TeV



- $\alpha_s(m_Z)$ from a fit to the double-differential p_T-y Z cross section measured in full-lepton phase space
- Experimental sensitivity evaluated with pseudodata: $\Delta\alpha_s/\alpha_s = 0.05\%$
- Postfit χ^2/dof = 82/72
- Determination performed at lower orders demonstrating convergence of the perturbative series



α_s = 0.11828 ± 0.00067(fit) ± 0.00042 (scales)

Theory uncertainties

Experimental uncertainty	+0.00044	-0.00044	Fit unc.
PDF uncertainty	+0.00051	-0.00051	
Scale variations uncertainties	+0.00042	-0.00042	
Matching to fixed order	0	-0.00008	
Non-perturbative model	+0.00012	-0.00020	
Flavour model	+0.00021	-0.00029	
QED ISR	+0.00014	-0.00014	
N4LL approximation	+0.00004	-0.00004	
Total	+0.00084	-0.00088	

- PDFs is the single largest source of uncertainties
- QED ISR uncertainty from half the LL corrections, validated at NLL
- Matching uncertainty estimated by removing the unitarity constraint (canonical logarithms)
- Uncertainty of the N4LL approximation one order of magnitude smaller than missing higher order uncertainties from scale variations
- Heavy flavour model uncertainties dominated by VFN PDF evolution and VFN α_s running

NNLO PDF sets

- At N4LL+N3LO only one N3LO PDF set is available: MSHT20an3lo
- Different PDF sets can be studied at N3LL+N3LO, where the spread of NNLO PDFs is ±0.00102, driven by NNPDF4.0-CT18A difference (with CT14 the spread would be a factor of 2 smaller)

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
MSHT20 [32]	0.11839	0.00040	0.44	-0.07
NNPDF40 [78]	0.11779	0.00024	0.50	-0.08
CT18A [79]	0.11982	0.00050	0.36	-0.03
HERAPDF20 [63]	0.11890	0.00027	0.40	-0.04

- Adding HERA data to the fit (counted twice), the spread is reduced to ±0.00016, around a central value of 0.11804
- Indication that the large spread is due to the tension in the gluon PDF between different datasets, and how this is solved by each PDF group
- MSHT20an3lo analysis shows that the gluon PDF tension is much reduced at N3LO

Summary and conclusions

- The strong-coupling constant is a keystone of QCD, improving its knowledge has far-reaching implications in the quest for new phenomena
- A large variety of $\alpha_s(m_Z)$ determinations are currently being pursued, leading to a much improved overall understanding of QCD. Some of these determinations have prospects to reach 0.1% uncertainty in the near future
- Several recent determinations at the LHC have reached percent-level uncertainty and begin to have an impact on the PDG world average

	$\alpha_s(m_Z)$	$\delta\alpha_s(m_Z)$	Rel. Unc.
ATLAS ATEEC	0.1185	0.0021	1.7%
CMS inclusive jets	0.1166	0.0016	1.4%
CMS dijets	0.1201	0.0020	1.7%
ATLAS Z pT	0.1183	0.0009	0.7%

- Most problematic issue in considering LHC determinations as “clean” measurements of $\alpha_s(m_Z)$ is related to PDFs. Most precise LHC determinations would clearly benefit from significant advancements in the understanding of the gluon PDF, may be possible in the near future with N3LO PDF fits

BACKUP

Theory predictions at approximate N4LL

- Theory predictions evaluted with DYTurbo, implementing CdFG q_T-resummation in b-space arXiv:1910.07049

$$\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2} = \frac{d\hat{\sigma}^{(\mathrm{res.})}_{F\,ab}}{dq_T^2} + \frac{d\hat{\sigma}^{(\mathrm{fin.})}_{F\,ab}}{dq_T^2}$$

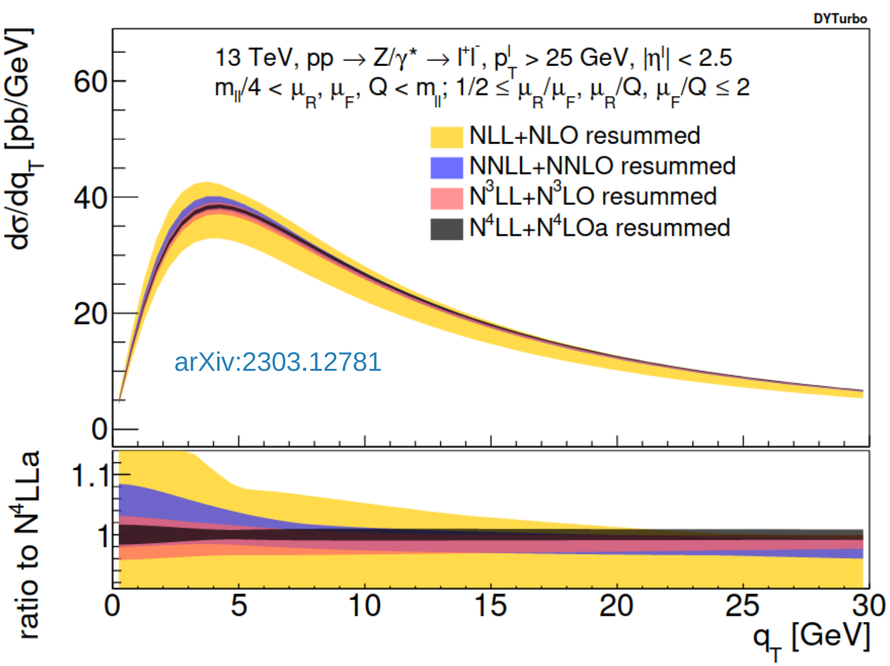
$$\mathrm{d}\sigma^{\mathrm{res}} = \mathrm{d}\hat{\sigma}^{V}_{\mathrm{LO}}(q_{\mathrm{T}}) \times \mathcal{H}^{V} \times \exp\{\mathcal{G}(\alpha_s, L)\}$$

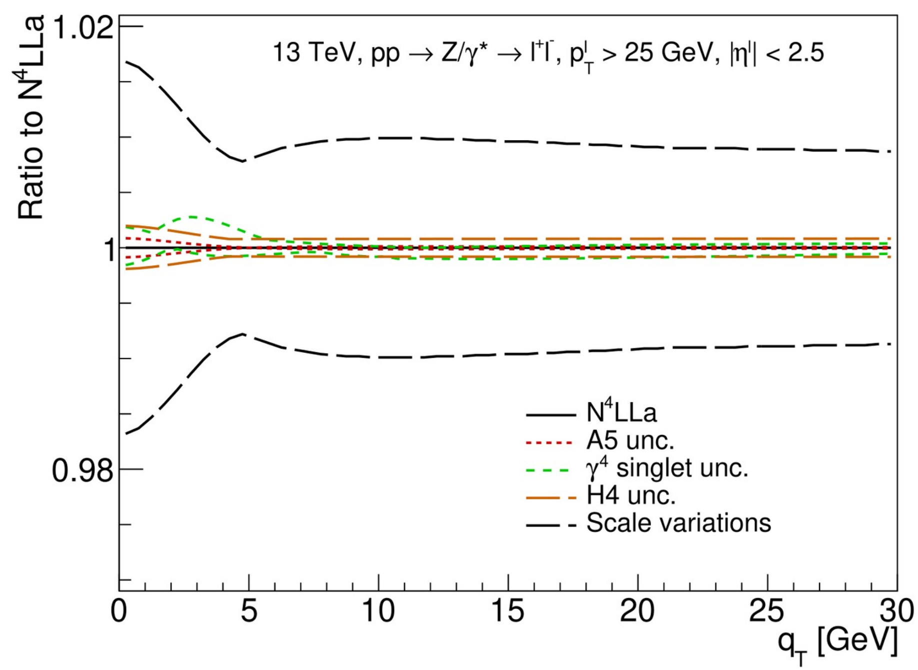
Born cross section

Hard virtual

perturbative Sudakov form factor

Sensitivity to α_s





- N4LL approximations are much smaller than missing higher order uncertainties

Non perturbative QCD model

- NP model is generally determined from the data, parameters values depend on the chosen prescription to avoid the Landau pole in b-space

$$b_\star = \frac{b}{1 + b^2/b_{\mathrm{lim}}^2}$$

$$S_{\mathrm{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right]$$

$$\begin{cases} g_j(b) = \dfrac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \mathrm{sign}(q)\left(1 - \exp\left[-|q|\,b^4\right]\right) \\ g_K(b) = g_0\left(1 - \exp\left[-\dfrac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\,b_{\mathrm{lim}}^2}\right]\right) \end{cases}$$

- g_j functions include a quadratic and a quartic term, with g and q free parameters of the fit
- The theory should not depend on b_{lim} (freezing scale) and Q_0 (starting scale of the TMD evolution), provided S_{NP} is flexible enough. Q_0 and b_{lim} are varied to assess a parameterisation uncertainty
- g_0 controls the very high b (very small p_T) behaviour, should be fitted to data, but there is no sensitivity to it, so it is varied
- λ controls the transition from Gaussian (quadratic) to exponential (linear), set to 1 GeV^{-2} and varied by factor of 2 up and down
- Total of 6 NPQCD parameters which are either fitted to the data or varied to assess an uncertainty

Transverse energy-energy correlations

arXiv:1205.1689