α_S measurements by ATLAS and CMS

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Content

- ATLAS Collaboration, **"A precise determination of the strong-coupling constant from the recoil of *Z* bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV"**, STDM-2023-01, *submitted to Nature Phys.*, arXiv:2309.12986 [Press Statement]

- CMS Collaboration, **"Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(M_Z)$"**, SMP-22-015, *Phys. Rev. Lett. 133 (2024) 071903*, arXiv:2402.13864 [Physics breafing]

- CMS Collaboration, **"The strong coupling constant and its running from inclusive jet production at CMS"**, CMS-PAS-SMP-24-007

Part I

ATLAS Collaboration, **“A precise determination of the strong-coupling constant from the recoil of *Z* bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV”**, STDM-2023-01, *submitted to Nature Phys.*, arXiv:2309.12986 [Press Statement]

Measure $\alpha_S(M_Z)$ from the $p_T(Z)$ distribution

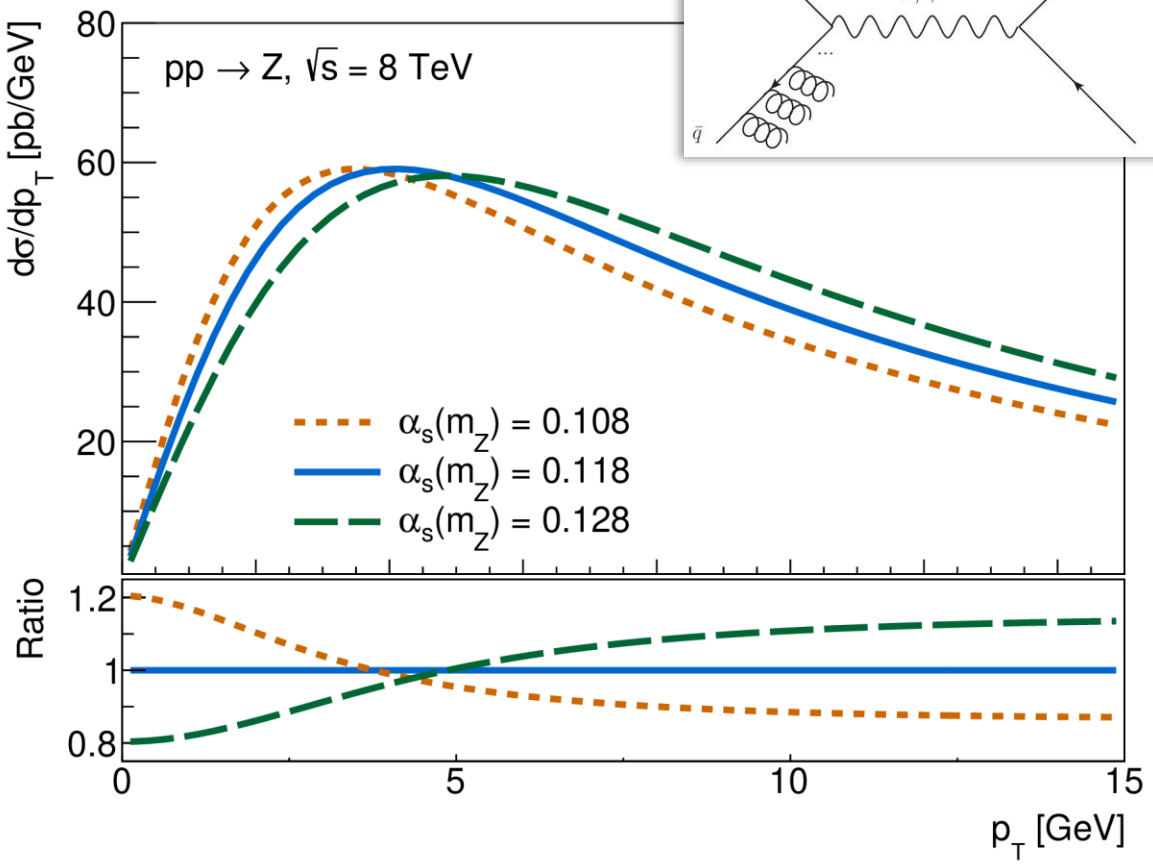
- Z bosons produced in hadron collisions recoil against QCD initial-state radiation

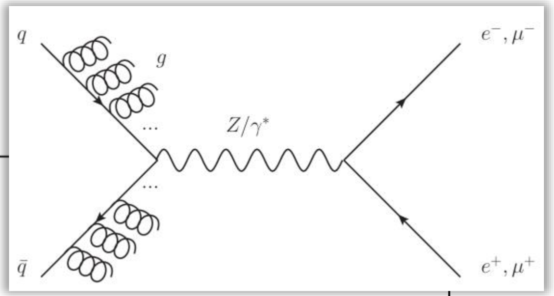
- The Sudakov factor is responsible for the existence of a peak in the Z-boson p_T distribution, at values of approximately 4 GeV

- The position of the peak is sensitive to $\alpha_S(M_Z)$

- Semi-inclusive observable
  - At the phase space boundary
  - Characterized by two energy scales

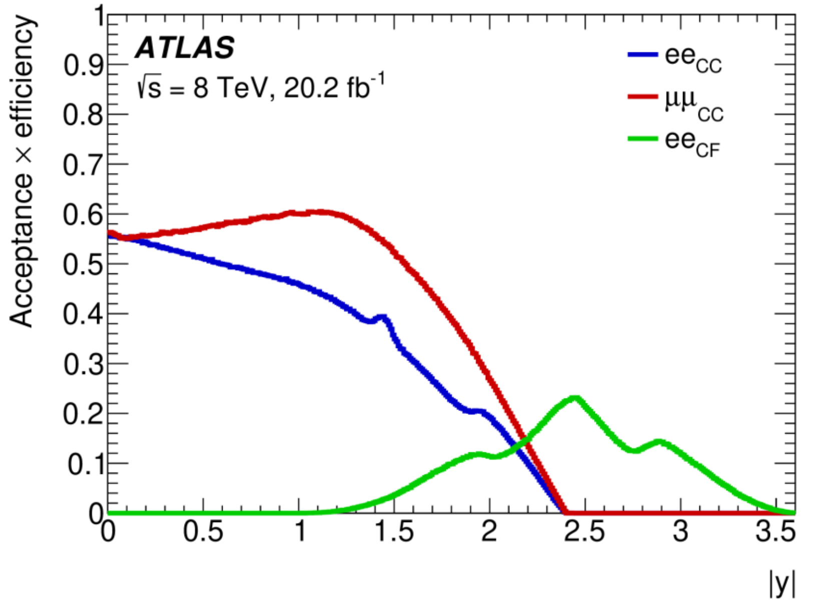
$$\alpha_S^n \frac{M^2}{q_T^2} \ln^m \left(\frac{M^2}{q_T^2}\right)$$

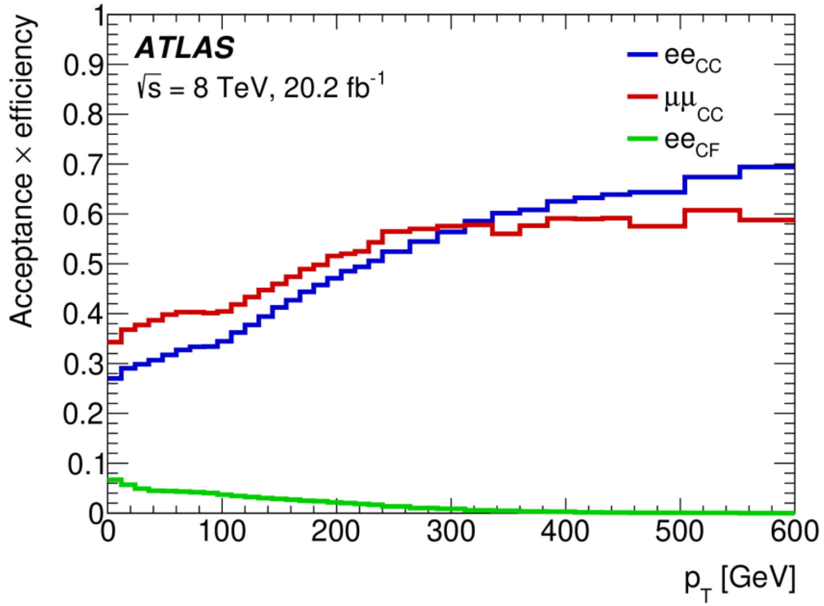




Event selection

- Run-1 8 TeV data, 20.2 fb^{-1} [Eur. Phys. J. C 84 (2024) 315]
- Three channels
  - ➢ eeCC: two central electrons (6.2M events)
    $p_T > 20$ GeV, $|\eta| < 2.4$
  - ➢ μμCC: two muons (7.8M events)
    $p_T > 20$ GeV, $|\eta| < 2.4$
  - ➢ eeCF: central + forward electron (1.2M events)
    Forward e: $2.5 < |\eta| < 4.9$, $p_T > 20$ GeV (25 GeV for the central e)
- $80 < m_{ll} < 100$ GeV





Cross section measurement

- Cross section of the Z boson production in the *full lepton phase space* is extracted using the angular coefficients method

Expected number of events in n-th reco bin:

$$N^n_{\mathrm{exp}}(A, \sigma^{U+L}, \beta, \gamma) = \left\{ \sum_j \sigma_j^{U+L} \times L \times \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} \times t^n_{ij}(\beta) \right] \right\} \times \gamma^n + \sum_B^{\mathrm{bkgs}} T^n_B(\beta),$$

$n = 1 \ldots 22528$: reco bin nr.
$j = 1 \ldots 352$: truth bin nr.
$i = 0 \ldots 7$: index for spherical harmonic P_i
A_{ij}: angular coefficients
σ_j^{U+L}: unpolarised cross section
t^n_{ij}: signal P_i polynomial MC templates
T^n_B: background templates
L: integrated luminosity
β: Gaussian-constrained systematic NPs
γ: Poisson-constrained statistical NPs
(NP = nuisance parameter)

  - 9 parameters of interest A_i $(i = 0 \ldots 7)$ and σ^{U+L} are measured in 352 $(p_{\mathrm{T}}(Z), |y(Z)|)$ bins in a profile likelihood fit
  - Likelihood defined in 22528 $(\cos\theta, \phi, p_{\mathrm{T}}, y)$ bins

Cross section measurement

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Expect

N^n_{exp}

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$$\frac{d\sigma}{dp_T\,dy\,dm\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T\,dy\,dm}\Big\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\sin2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos2\phi+A_3\sin\theta\cos\phi+A_4\cos\theta$$
$$+A_5\sin^2\theta\sin2\phi+A_6\sin2\theta\sin\phi+A_7\sin\theta\sin\phi\Big\}.$$

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Cross section measurement

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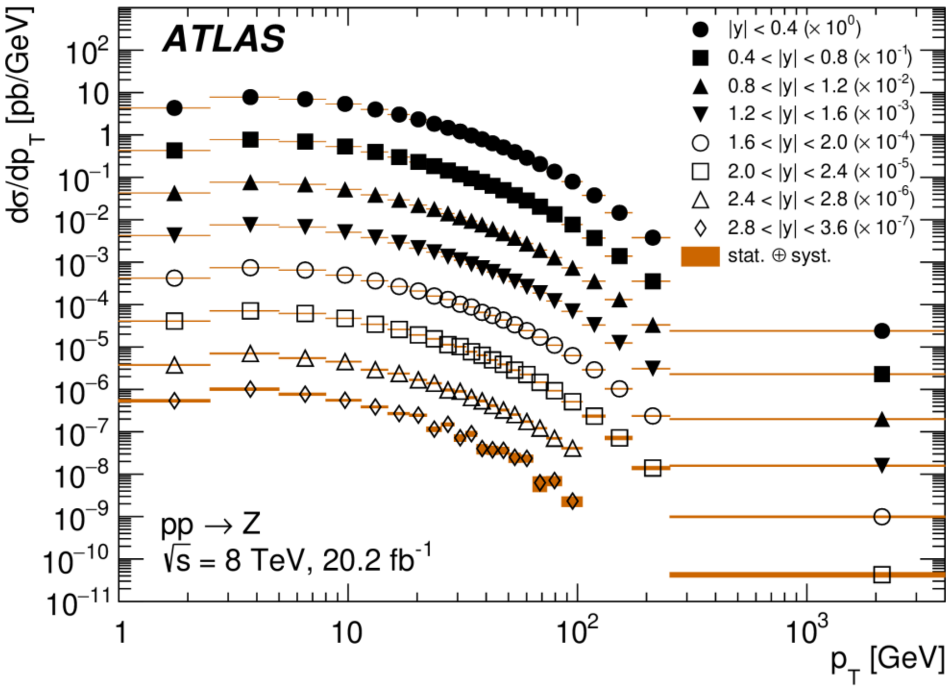
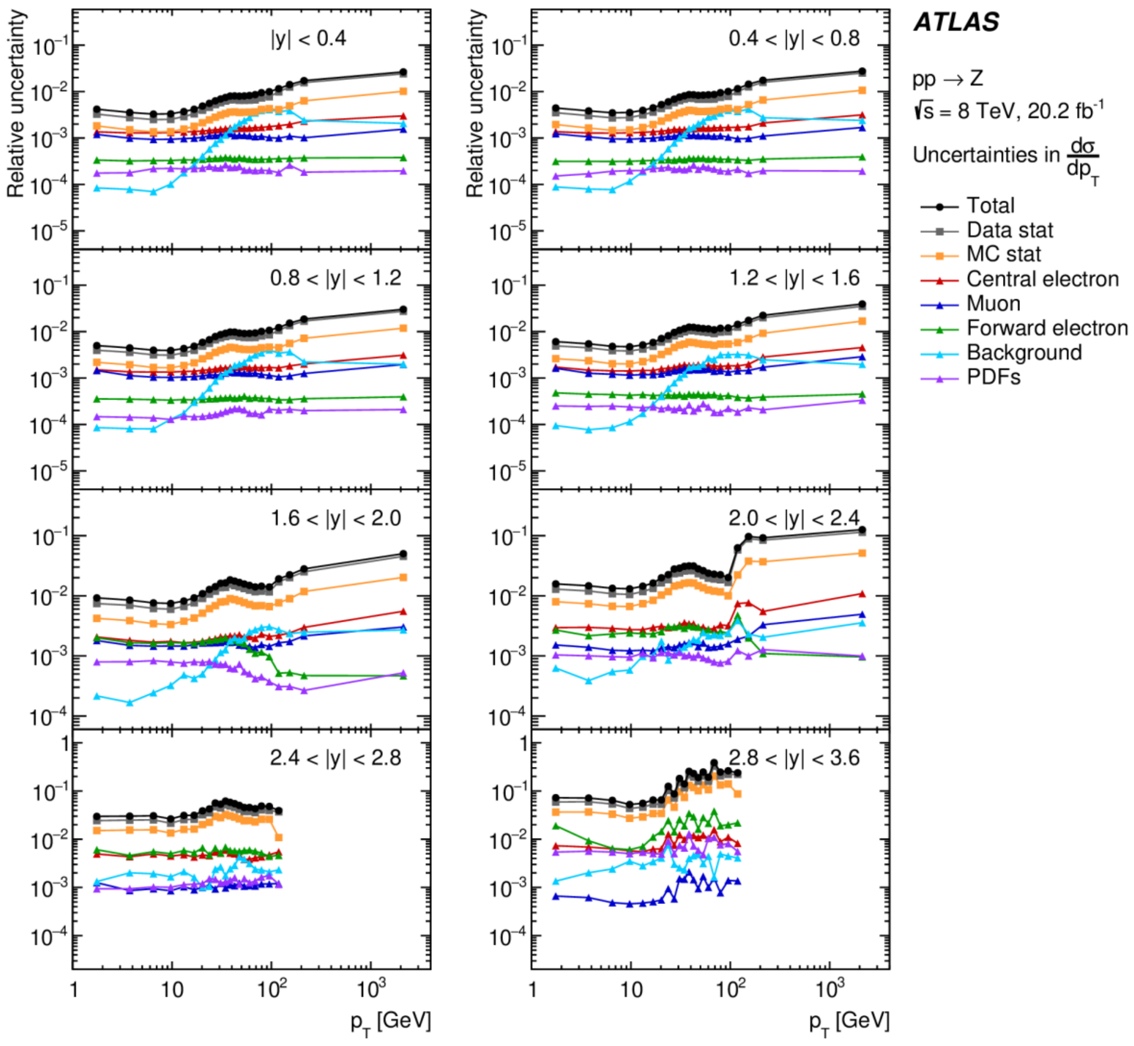
$$\frac{d\sigma}{dp_T\, dy\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T\, dy\, dm}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+\frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$
$$+A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}.$$

- Advantageous method:
  - Model-independent ansatz: cross-section decomposed into 9 terms with various angular dependencies (due to spin-1 nature of the Z)
  - Measurement in the full phase space → avoid theoretical uncertainties related to phase space extrapolation (important for interpretations)
  - Smaller sensitivity to theoretical uncertainties than for the unfolded fiducial measurements
  - Trade systematics for statistics

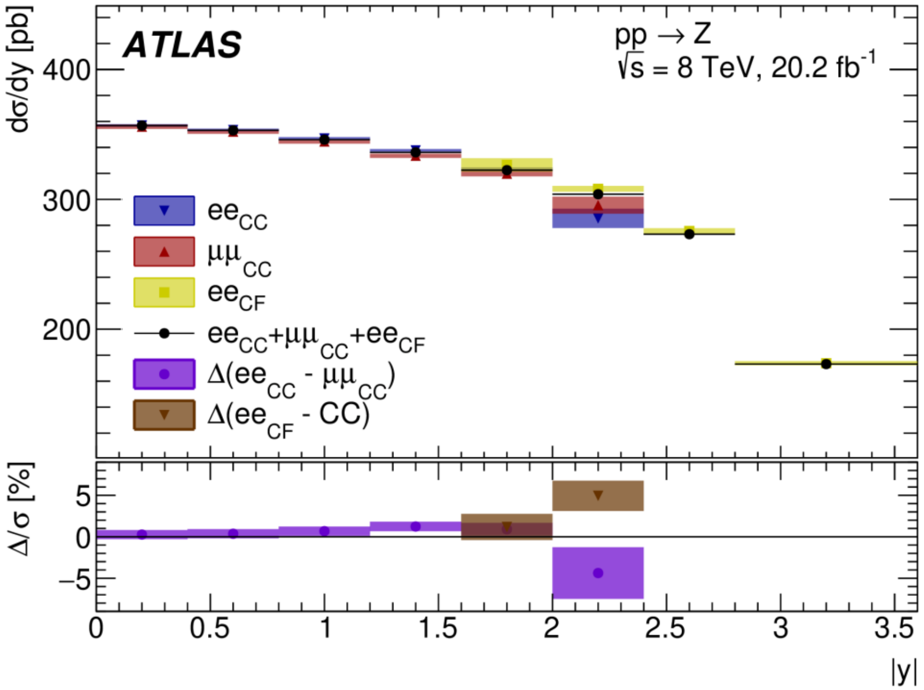
Double-differential Drell-Yan measurement

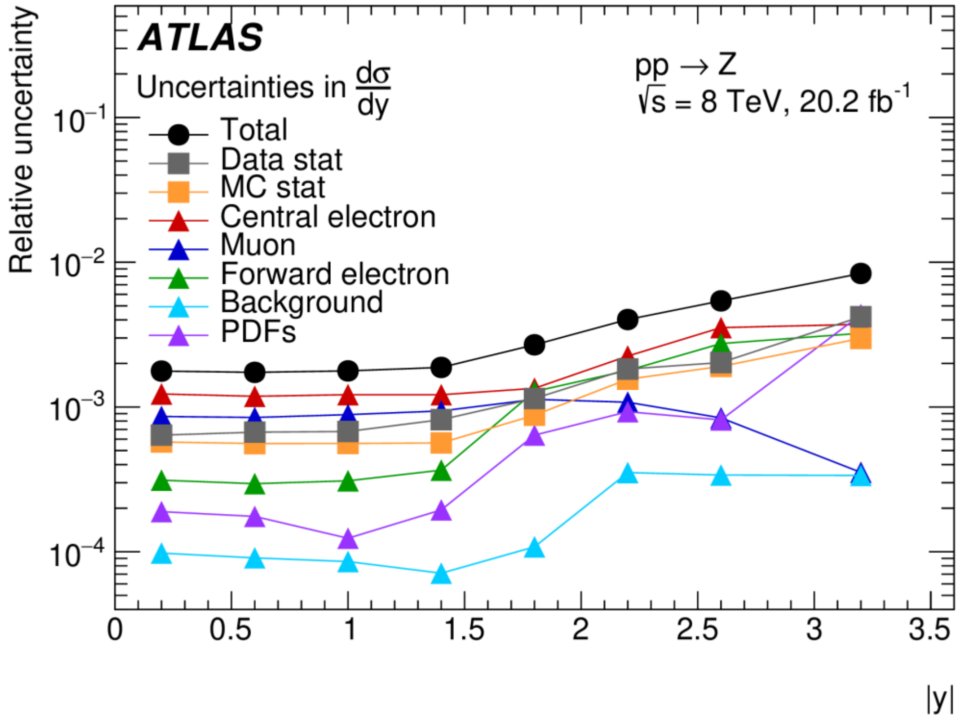




- First doubly-differential measurement at the LHC of full lepton phase space DY cross section
- Statistically dominated measurement
- Negligible theory uncertainties:
  - ➢ Cross-sections are parameters of the fit, not the result of an extrapolation

Comparison of dilepton channels





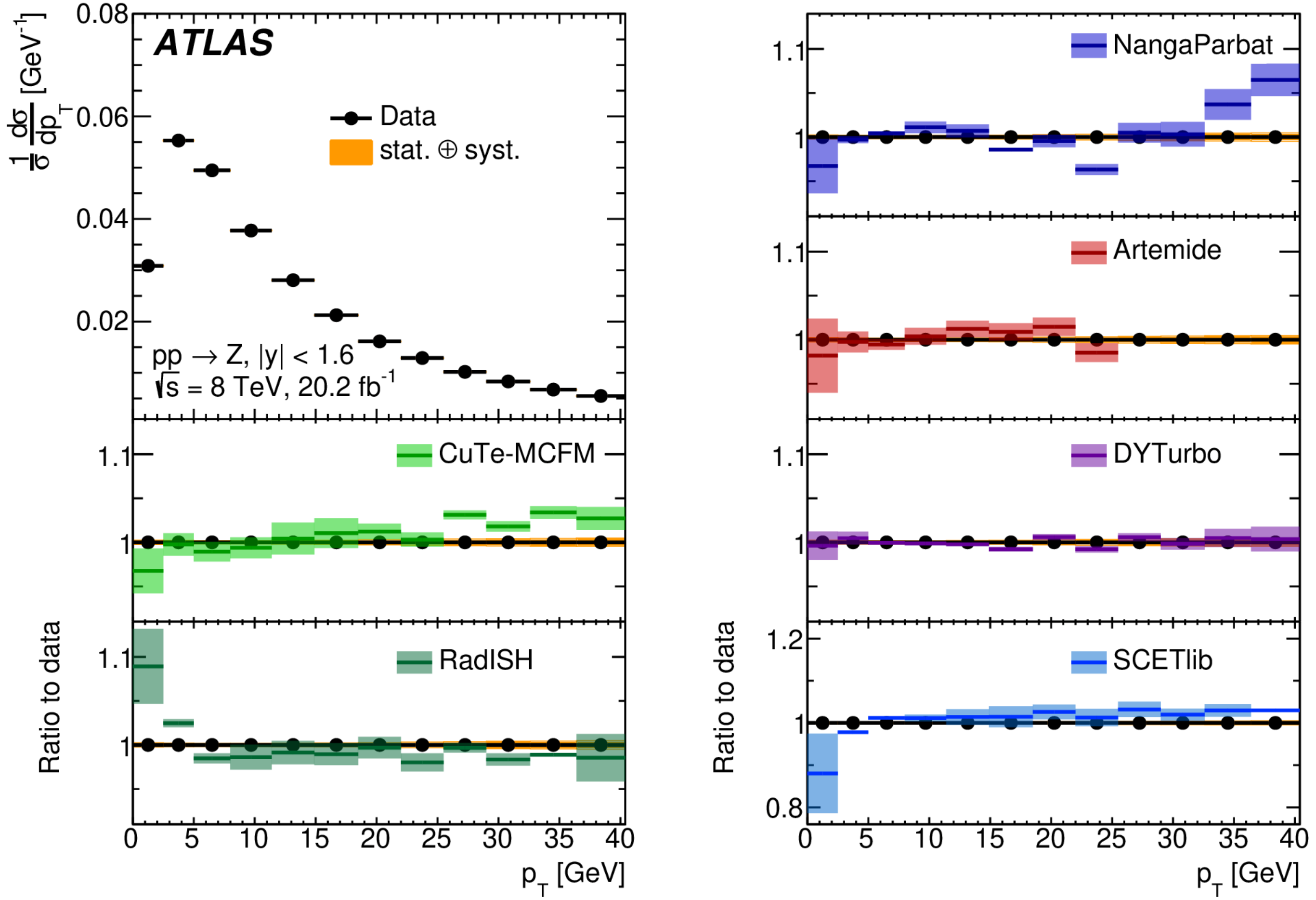
- Results are compatible between eeCC, μμCC, eeCF regions
  - ➢ Important cross check of detector calibration

- Exquisite per-mille level precision in the central region
- Sub-percent uncertainties up to $|y| < 3.6$ thanks to dedicated forward electron calibration

Predictions vs measurement

- Measurement compared to predictions employing N^{4}LL$_{\text{approx}}$ logarithmic accuracy resummed calculations at low p_{T}
  - ➢ Matched to $O(\alpha_S^3)$ from MCFM at high p_{T}

- Excellent agreement between data and predictions
  - ➢ Impressive progress understanding of the boson p_{T} modelling from experimental and theoretical points of view



Extraction of α_S: methodology

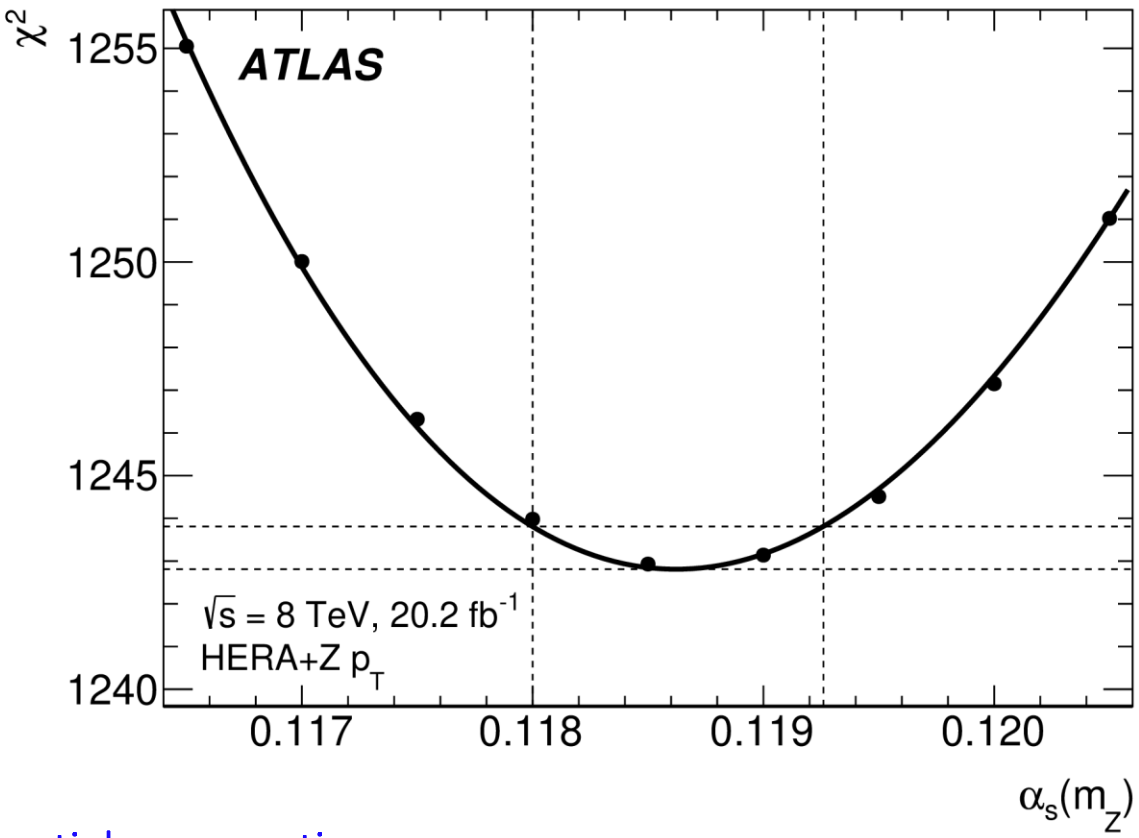
PLB 845 (2023) 138125

- Theory expectation from DYTurbo at $\text{N}^4\text{LL}_{\text{approx}}$ and N^3LO
- Use the region of $p_{\mathrm{T}}(Z) < 29$ GeV
- At each value of α_S, use the corresponding N^3LO MSHT20 PDF set (the only set available at N^3LO)

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

PDF profiling

Fit using xFitter



Γ_{ij}^{exp} encodes covariance matrix of the measured double-differential cross section

Γ_{ik}^{th} covers nuisance parameters of the PDF Hessian uncertainties and of the non-perturbative form-factor

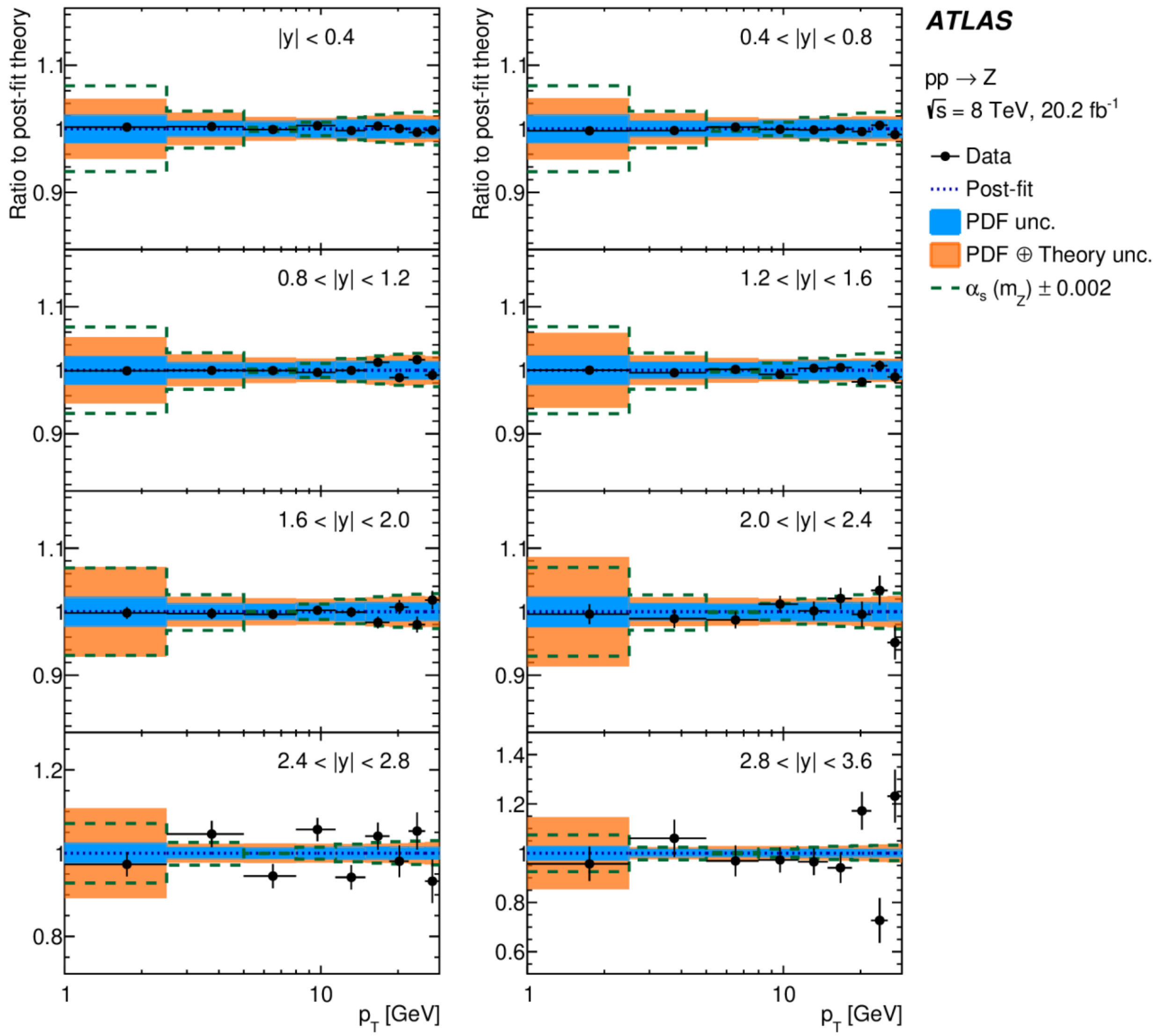
β: Experimental and theoretical NP vectors

Fit result

- Postfit $\frac{\chi^2}{ndf} = \frac{82}{72}$ $(p = 0.2)$

- Figure shows the ratio between the measurement and post-fit prediction

- Blue band shows the the PDF uncertainty of the prediction, constrained in the fit
  - ➢ Pulls and constraints of the PDF uncertainties are below 1σ and 30%, respectively -> new minimum close to the original one



Uncertainties

- PDF Hessian uncertainties
- Scale variations: independent μ_R, μ_F and Q (resummation scale) variations
- Flavour model: use variable-flavour number scheme in the PDF evolution/α_S running in the Sudakov region; charm and bottom threshold variations; include effect of the gluon splitting into massive $c\bar{c}$, $b\bar{b}$ pairs → take envelope

Uncertainty of α_S in units of 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^4LL approximation	± 0.04	
Total	$+0.91$	-0.88

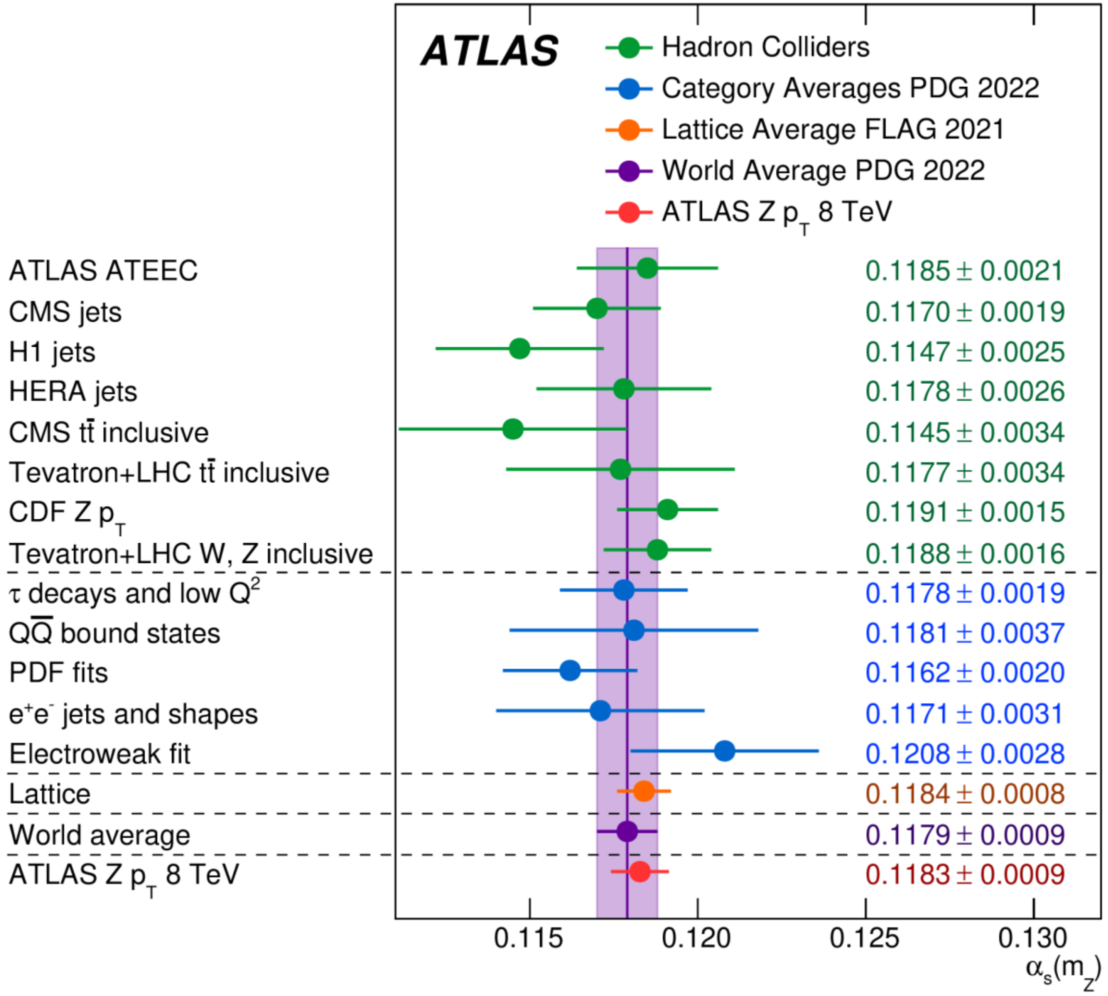
Final result

0.8%

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

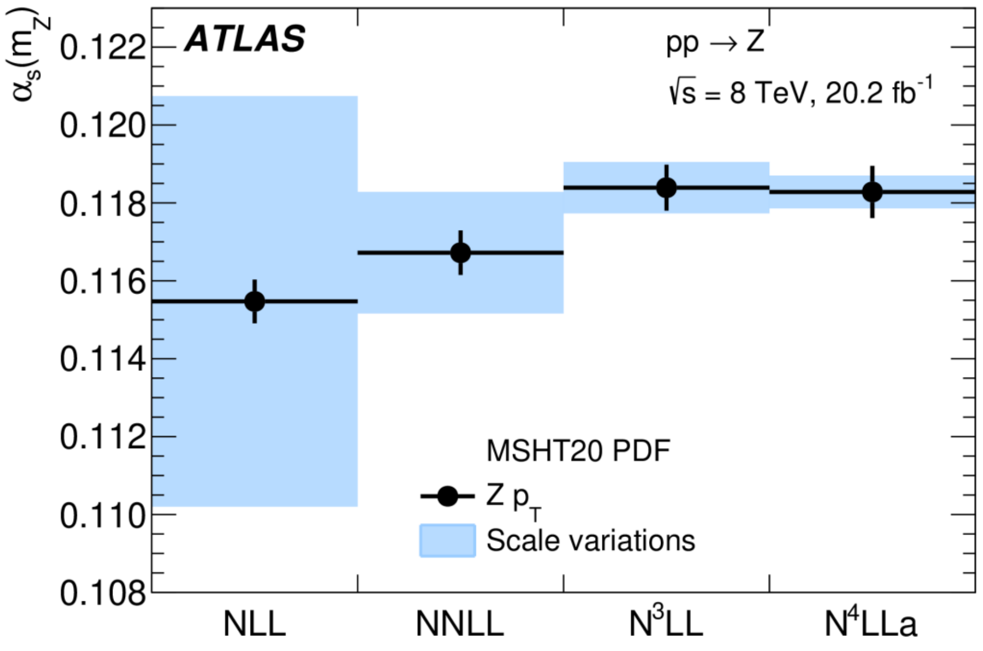
- The most precise determination of α_S
  - As precise as PDG and Lattice world averages

- First $\alpha_S(m_Z)$ determination at N^{3}LO + N^{4}LL$_{approx}$
- Using $p_T(Z)$ cross section in the full phase space
- Clean experimental signature (leptons) with highest exp sensitivity
- α_S measured directly at $m(Z)$ scale (as in LEP event shapes)



Cross-checks (a selection)

- Repeat fit using lower orders (also with MSHT20)
  - α_S at higher orders is always within uncertainties of lower orders
  - good convergence of the perturbative series



- At order N^4LL_{approx}+N^3LO, only one N^3LO PDF set available: MSHT20aN3LO
  - Study the dependence of the results on the choice of PDF set by fitting one order lower, i.e. N^3LL + N^3LO using NNLO PDFs
  - Observed spread of ± 0.00102 using PDF profiling

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g $[GeV^2]$	q $[GeV^4]$
MSHT20 [37]	0.11839	0.00040	0.44	−0.07
NNPDF4.0 [84]	0.11779	0.00024	0.50	−0.08
CT18A [29]	0.11982	0.00050	0.36	−0.03
HERAPDF2.0 [65]	0.11890	0.00027	0.40	−0.04

- Simultaneous PDF + α_S fit using HERA DIS and ATLAS $p_T(Z)$ data at N^3LL + N^3LO yields the exp & PDF (total) uncertainty of ± 0.00064 (± 0.0010)

Part II

CMS Collaboration, **“Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(M_Z)$”**

SMP-22-015, *Phys. Rev. Lett. 133 (2024) 071903*, arXiv:2402.13864

[Physics breafing]

Energy-energy correlators

- New jet substructure observables proposed to describe multiparticle energy correlations within jets Phys. Rev. D 102, 054012 (2020)
- Evolved from the event shape energy-energy correlator (EEC) extensively studied in e^+e^- experiments
- Derived from energy flow operators; collinear- and infrared-safe
- Analytical predictions at NLO+NNLL$_{\text{approx}}$ can be achieved

Energy-energy correlators: definition

- Two- and three-particles correlators (E2C, E3C) within jets

E2C: for each pair of particles (i, j) within a jet, fill the distribution of x_L

$$x_L = \Delta R_{ij} = \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$$

- Jet with n particles contributes with n^2 entries, each having a weight $\frac{E_i E_j}{E^2}$

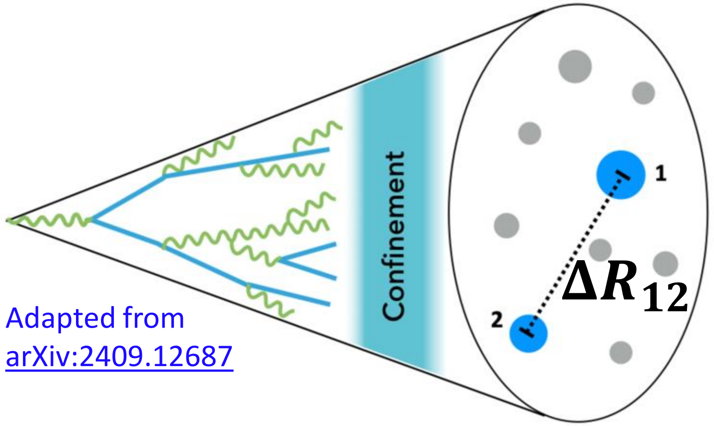
E3C: for each triplet of particles (i, j, k), fill the distribution of

$$x_L = \max\{\Delta R_{ij}, \Delta R_{jk}, \Delta R_{ik}\}$$

- Jet with n particles contributes with n^3 entries, each with a weight $\frac{E_i E_j E_k}{E^3}$

- General properties:
  - The E2C and E3C distributions are normalized to the number of jets in the event sample
  - E2C and E3C are insensitive to soft radiation

Energy-energy correlators



Adapted from arXiv:2409.12687

Momentum exchange between 1 and 2:
$\propto p_T^{jet} x_L = p_T^{jet} \Delta R_{12}$

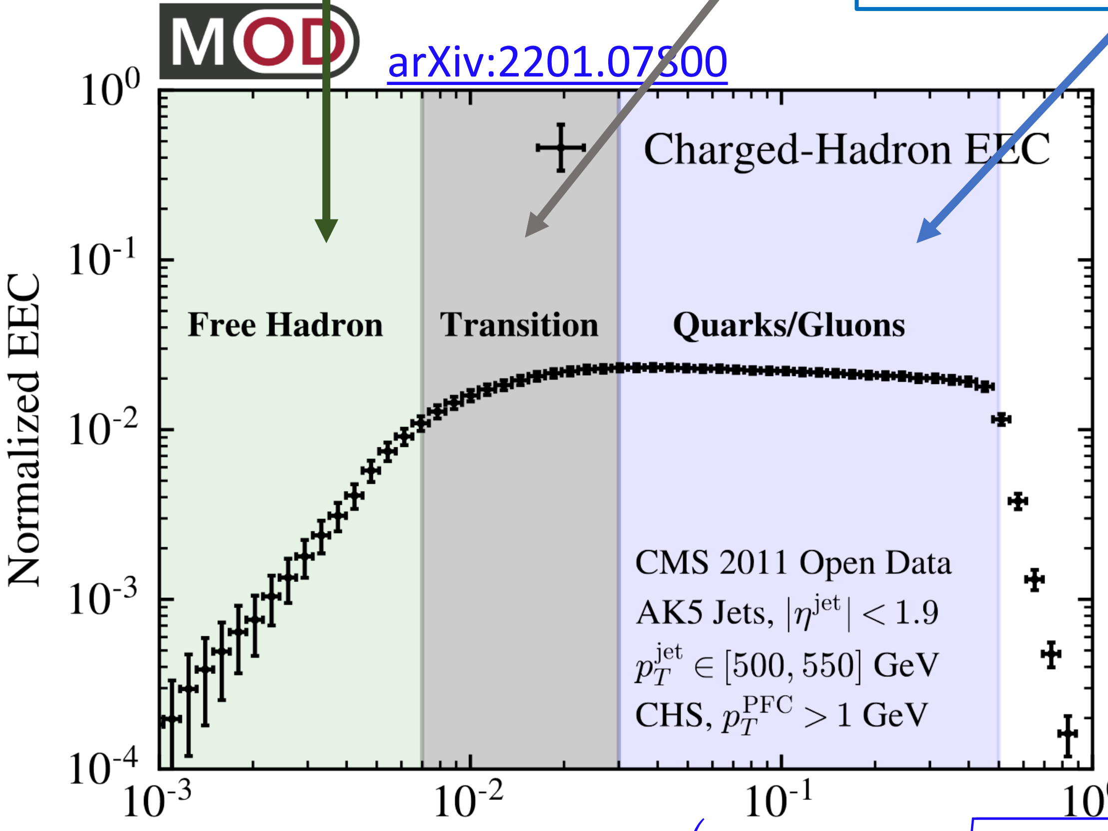
- Different x_L regions probe the dynamics of jet formation:
  - ➢ Perturbative (Quarks/Gluons)
  - ➢ Confinement (Transition)
  - ➢ Free hadron
- Time scale of splitting:

$$\tau \sim \frac{1}{\left(p_{\mathrm{T}}^{\mathrm{jet}} \cdot x_L\right)^2}$$

$R_L \frac{d\sigma}{dR_L} \propto R_L^2$

Hadron formation

E3C/E2C $\propto \alpha_S \ln x_L$

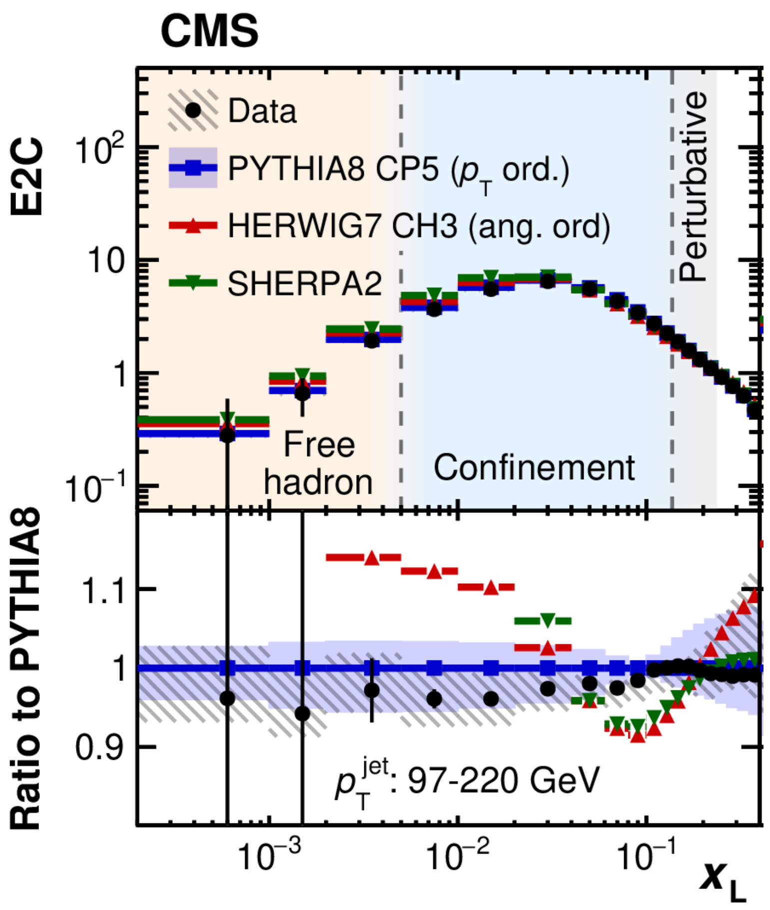


$\left(= x_L = \Delta R_{ij} = \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}\right)$

Event selection and unfolding

- 2016 pp data at $\sqrt{s} = 13$ TeV, 36.3 fb^{-1}
- At least two anti-k$_T$ jets (R=0.4) with $p_T > 97$ GeV and $|\eta| < 2.1$
  - ➢ Central jets for good reconstruction of jet constituents
- Two leading jets are back-to-back with $|\Delta\phi| > 2$
- Only two leading jets are used for building E2C and E3C

- Iterative D'Agostini unfolding to particle level
  - ➢ Matching of particles to reconstructed objects
  - ➢ Matching efficiency:
    - – 80-84% for charged particles
    - – 54-70% for photons
    - – 20-35% for neutral particles



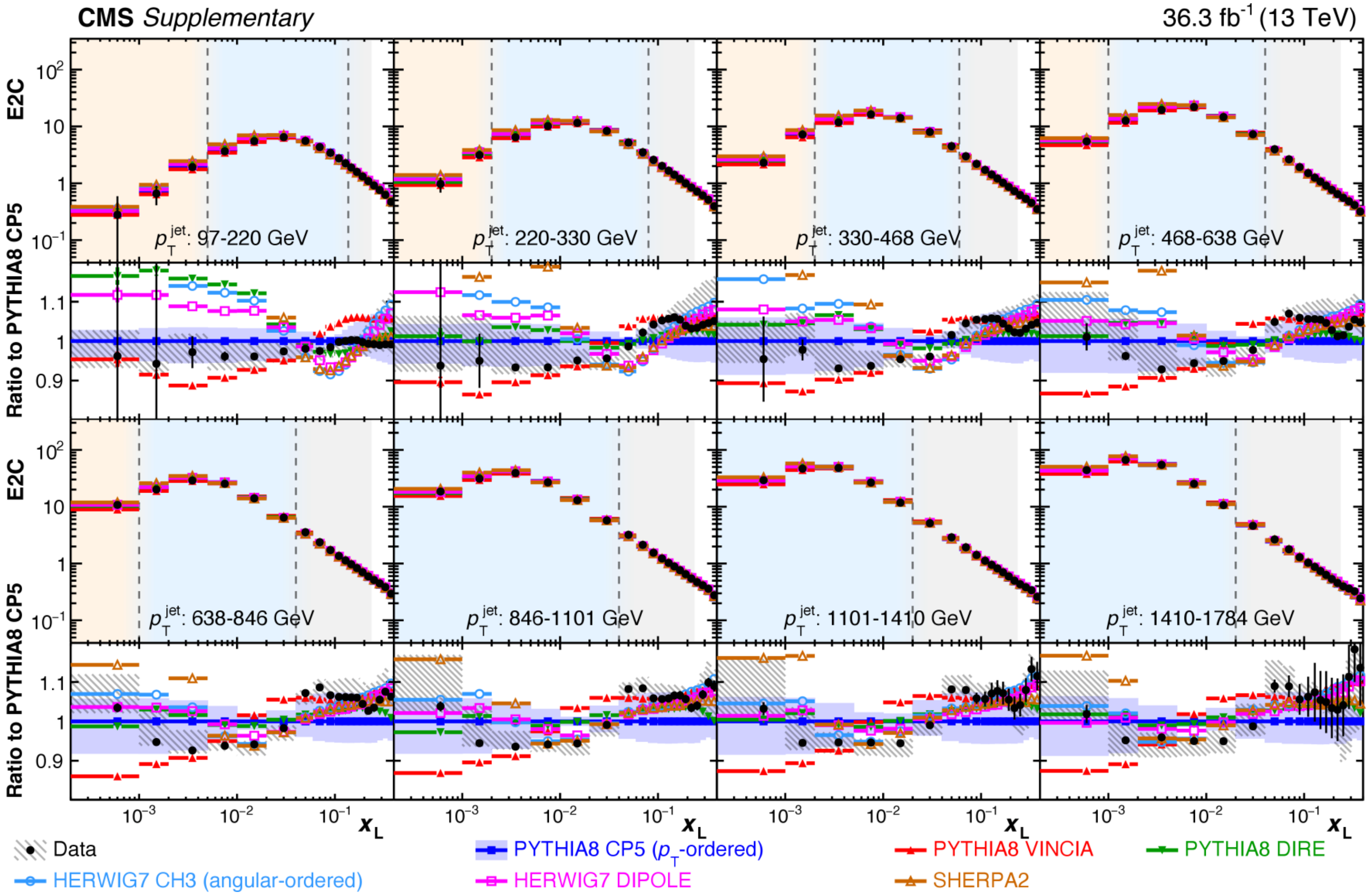
- Correlation between bins (each jet contributes multiple entries) are preserved, ~40% on average
  - ➢ Data are split into two halves for computing E2C and E3C, for simplicity

Unfolded E2C distributions

- Nominal prediction by Pythia8.240 (CP5 tune) describes data well and is used for unfolding to particle level

- MC generators differ in parton shower and hadronization modelling, tuning of the parameters, and fixed-order matrix element calculation

- Difference between unfolded results when using response matrix from various MC generators is the largest source of uncertainty of the E2(3)C distributions



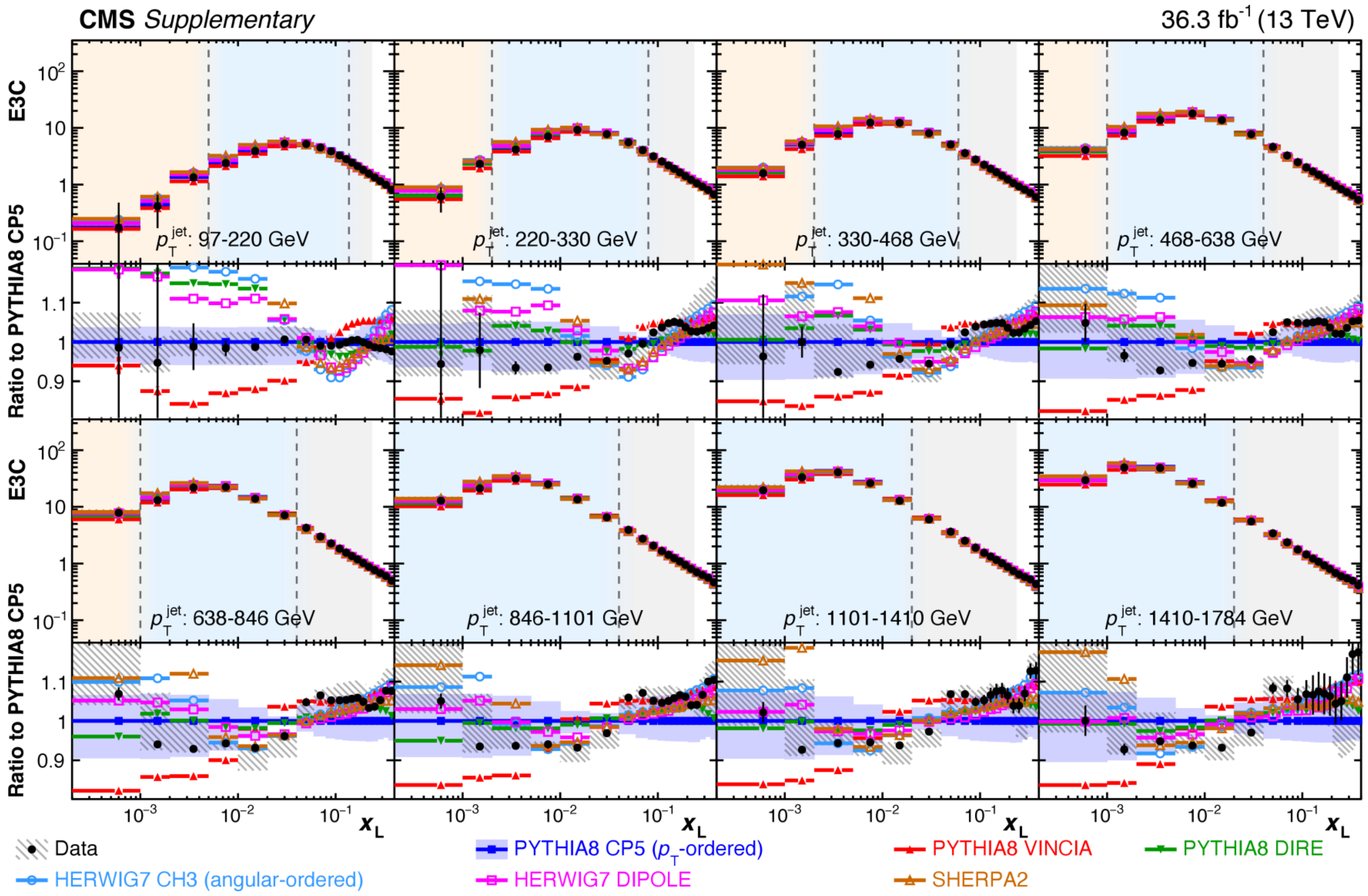
Unfolded E3C distributions

Experimental systematics:

- Unfolding (see previous page)
- Energy scale of the jet constituents: 3% for γ, 1% (3%) for charged (neutral) particles
- Track reconstruction efficiency (3%)

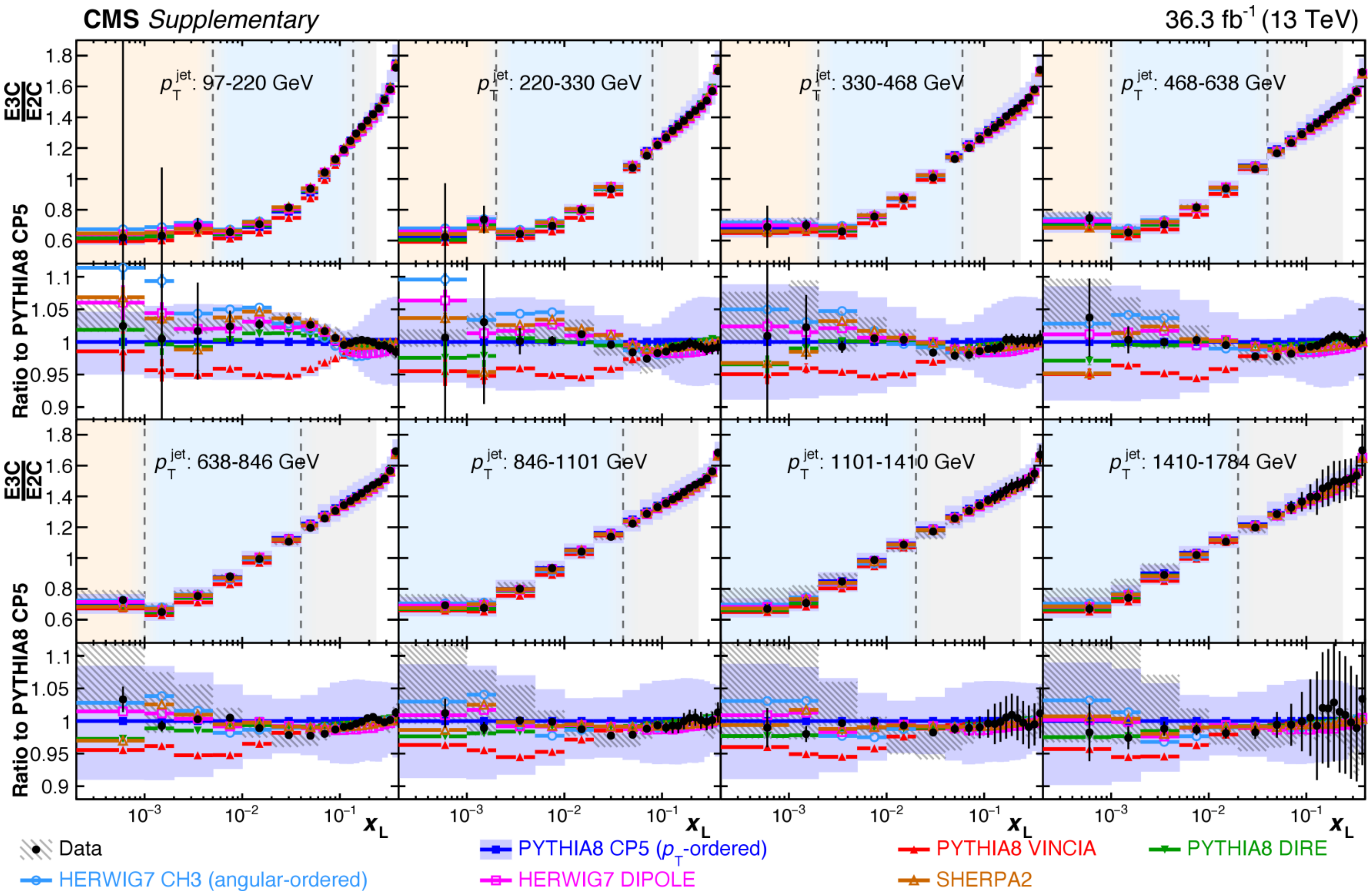
Theory uncertainties (blue band):

- μ_F and μ_R variation by factors 0.5, 2
- PDF uncertainty
- Variation of the nonsingular term coefficient in Pythia PS splitting kernels by ± 2
- Difference between CP5 and Monash tune

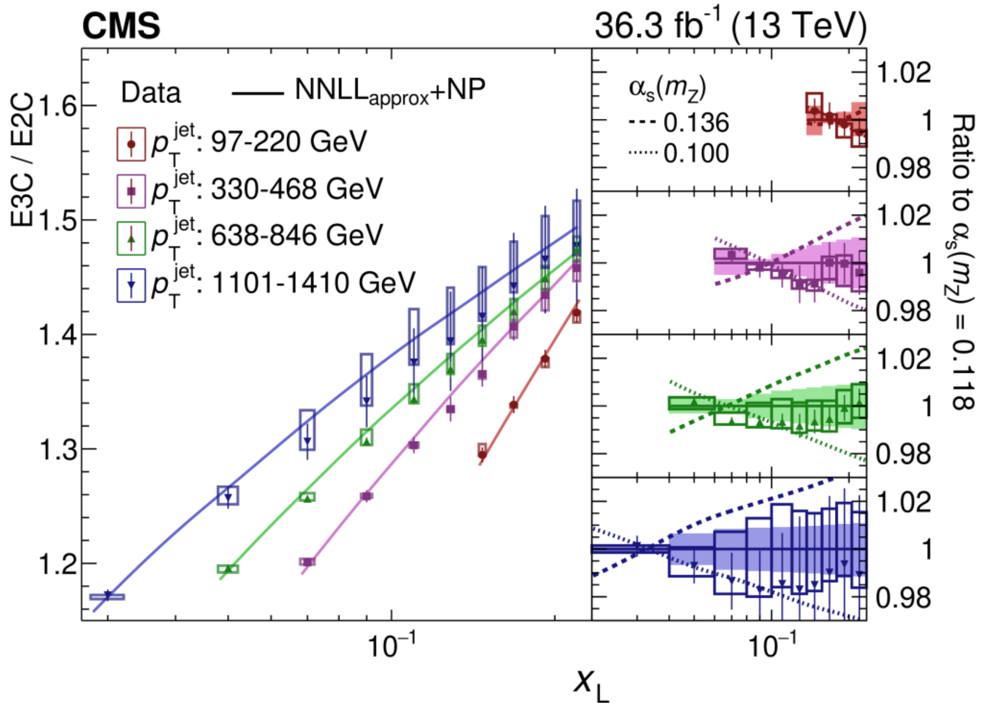


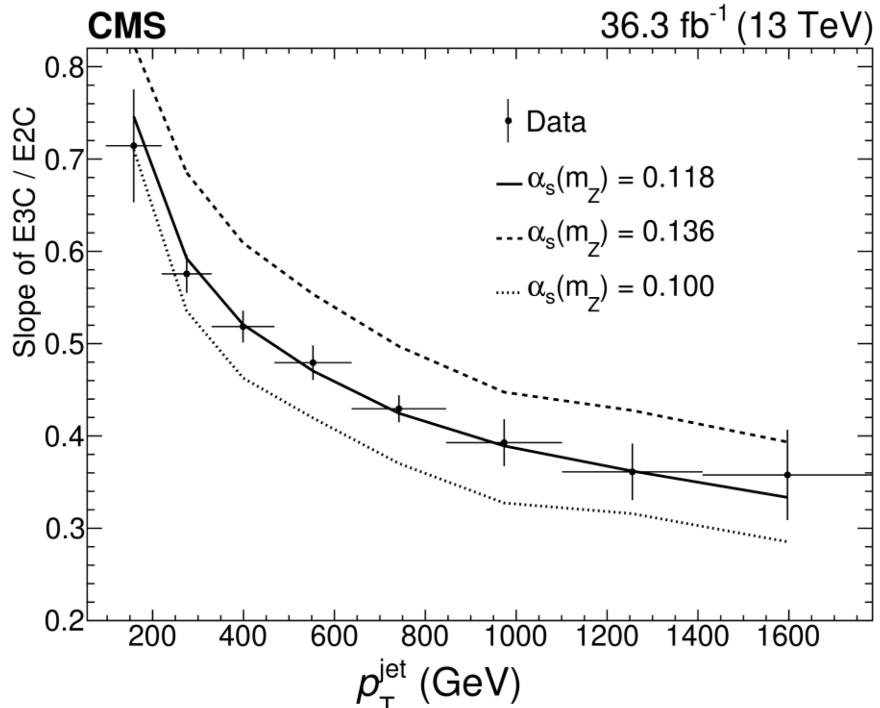
E3C/E2C ratio

- Most of E2C and E3C experimental systematic uncertainties cancel out in the ratio:
  - Exp. Syst.: ~8% → ~3%
- Sensitivity to modelling of non-perturbative effects in MC is strongly reduced
- Very good agreement between all MC generators and data in the perturbative region



Extraction of α_S





- Only the perturbative region is used; x_L <0.234 to avoid boundary effects of the jet clustering algorithm
- E3C/E2C $\propto \alpha_S \ln x_L$
  - ➢ Decreasing slope for larger p_T^{jet} reflects the running of α_S
- Theory predictions at NLO + NNLO$_{approx}$ JHEP05 (2024) 043
- Hadronisation and UE correction (5-40% on E2(3)C) extracted from Pythia and Herwig and applied to perturbative calculation
  - ➢ Largely cancels out in the E3C/E2C ratio (below 3%)

Extraction of α_S

$$\chi^2 = [\vec{v}_{\rm m}(\vec{\theta}) - \vec{v}_{\rm th}(\alpha_{\rm S}, \vec{\theta})]^{\intercal} V_{\rm m}^{-1} [\vec{v}_{\rm m}(\vec{\theta}) - \vec{v}_{\rm th}(\alpha_{\rm S}, \vec{\theta})] + \sum_j \theta_j^2$$

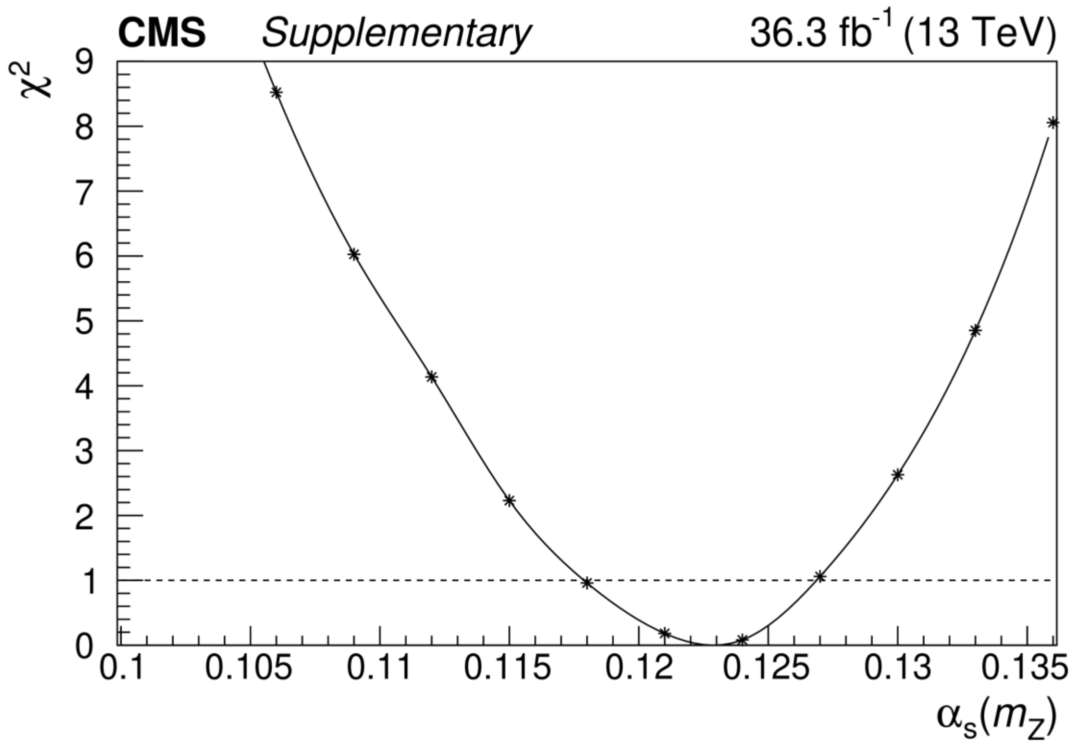
- For each value of α_S, the χ^2 is minimized vs NPs $\vec{\theta}$ encoding experimental and theory systematics
- V_m: covariance matrix of the unfolded data

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

$$\alpha_S(M_Z) = 0.1229^{+0.0040}_{-0.0050}$$ (3%) (4%)

- Most precise α_S determination using jet substructure observables

- The measurement is systematics dominated, with largest contributions from
  - Renormalization scale variation of the prediction (2.4%)
  - Energy scales of the jet constituents (2.3%)



New!

Part III

CMS Collaboration, **“The strong coupling constant and its running from inclusive jet production at CMS”**

CMS-PAS-SMP-24-007

α_S from inclusive jet data

- QCD analysis (simultaneous PDF and α_S fit) using measurements of inclusive jet production   Fit using xFitter

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	N_{dp}	p_T [GeV]	$\|y\|$
2.76	0.0054	80	74–592	0.0–3.0
7	5.0	130	114–2116	0.0–2.5
8	20	165	74–1784	0.0–3.0
13	33.5	78	97–3103	0.0–2.0

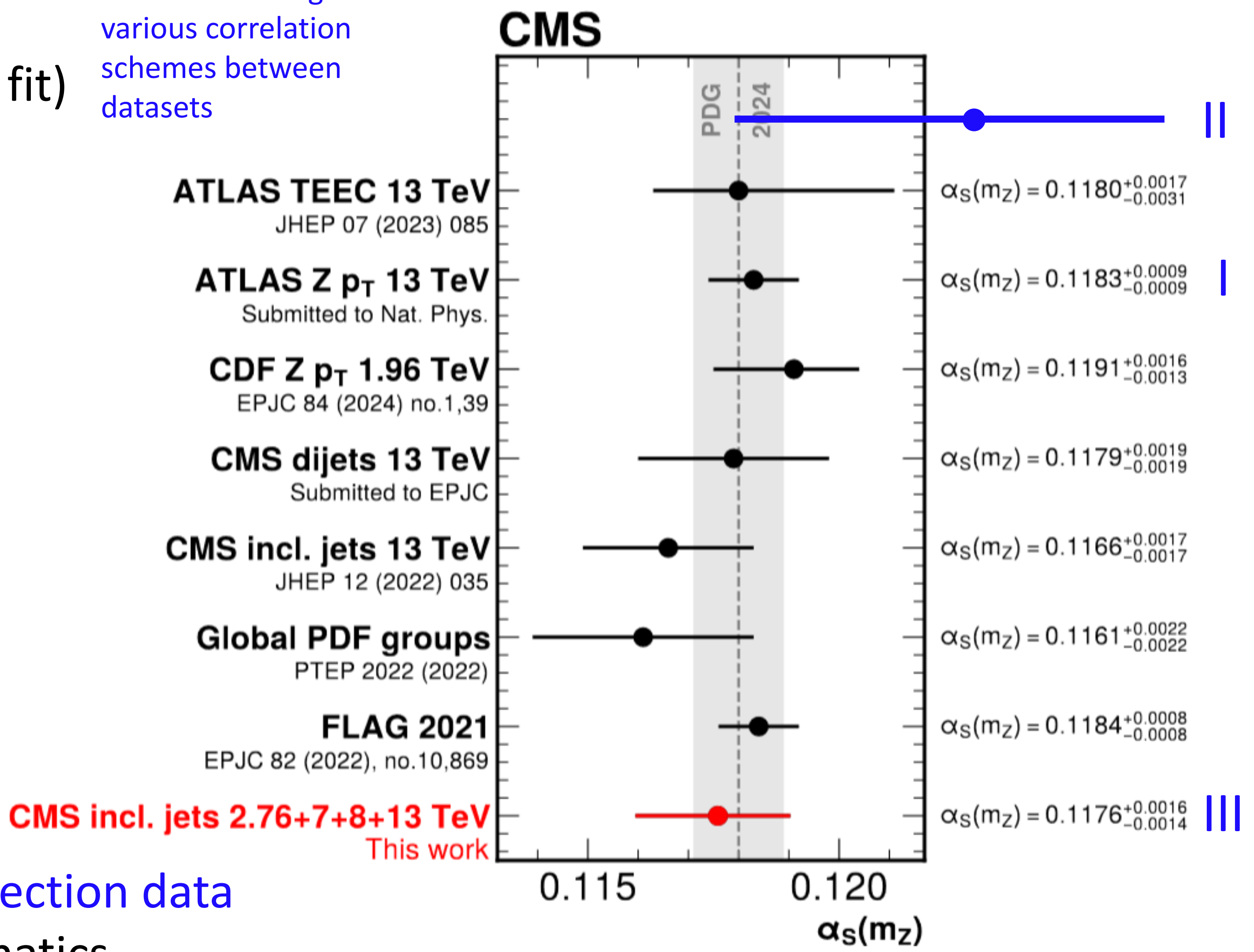
- Using NNLO predictions from NNLOJET

Phys. Rev. Lett. 118 (2017) 072002

- Final result:

$$\alpha_S(M_Z) = 0.1176^{+0.0014}_{-0.0016}$$ (1.2%) (1.4%)

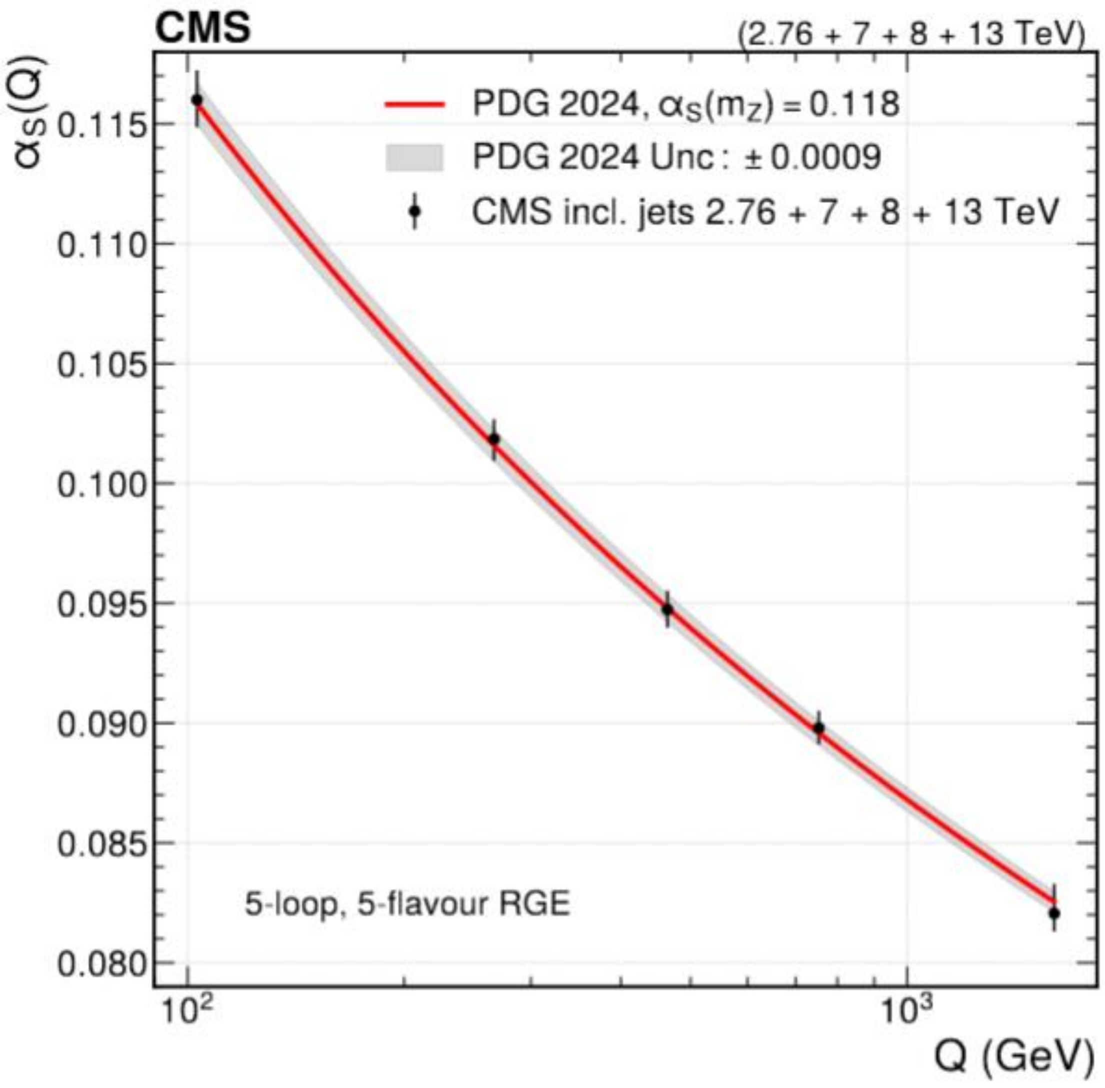
Results stable against various correlation schemes between datasets



- ➢ Most precise results based on jet cross section data
- ➢ Uncertainty dominated by theory systematics

Test of α_S running

- α_S extracted in five mutually exclusive $\mu_{\mathrm{R}} = p_{\mathrm{T}}^{\mathrm{jet}}$ regions
- Observed running of α_S is in agreement with the QCD five-loop five-flavour RGE



Summary

- Three most precise α_S results by ATLAS and CMS Collaborations; two of them based on novel methods:

  - ATLAS: most precise $\alpha_S(M_Z)$ measurement
    - Using *Z* boson recoil novel
    - Based on precision double-differential Drell-Yan cross section measurement in the full dilepton phase space

  - CMS: most precise $\alpha_S(M_Z)$ measurement based on jet substructure
    - Using new observables: energy-energy correlators of particles within jets novel
    - $\alpha_S(M_Z)$ extracted from the ratio E3C/E2C

  - CMS: most precise $\alpha_S(M_Z)$ measurement from inclusve jet cross sections
    - QCD analysis of CMS inclusive jet data at 2.76, 7, 8, 13 TeV
    - Test of α_S running for energy scales between 100 and 1600 GeV