Determination of α_s from azimuthal correlations among jets at CMS

Paris Gianneios

on behalf of the CMS Collaboration

Parallel session talk - Strong Interactions and Hadron Physics

July 18, 2024

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CMS

Outline

1. Introduction - Motivation
2. $\mathrm{R}_{\Delta\phi}$ observable definition and event selection
3. $\mathrm{R}_{\Delta\phi}$ measurement with CMS
4. Fixed Order pQCD predictions
5. Determination of $\alpha_s(\mathrm{m_z})$ and $\alpha_s(\mathrm{Q})$ evolution

Talk based on arXiv: 2404.16082*

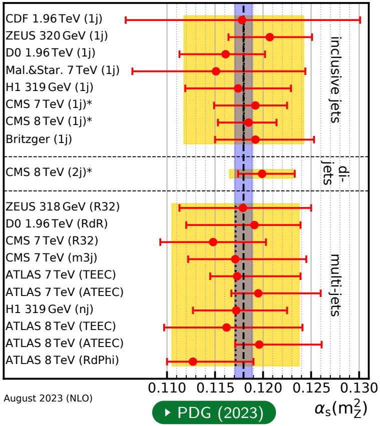
**Accepted by EPJC*

Introduction - Motivation

Multijet cross section ratios

Goals

1. Determination of the strong coupling constant $\alpha_s(\mathrm{m_z})$.
2. Investigation of the energy scale (Q) dependence $\alpha_s(\mathrm{Q})$.



PDG (2023)

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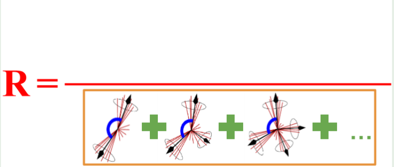

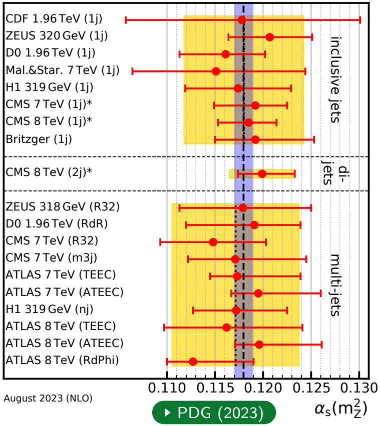

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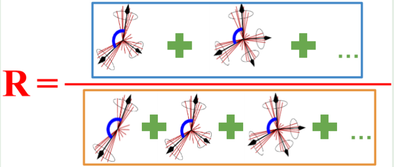

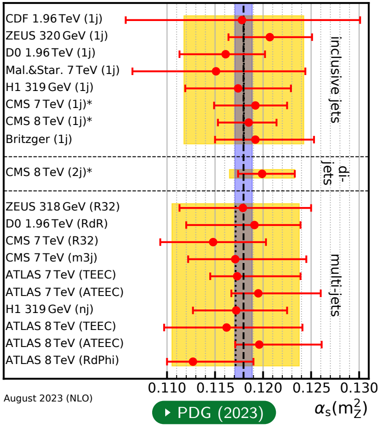

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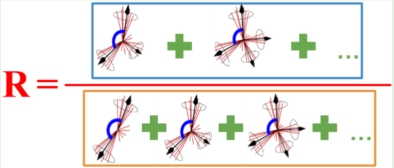
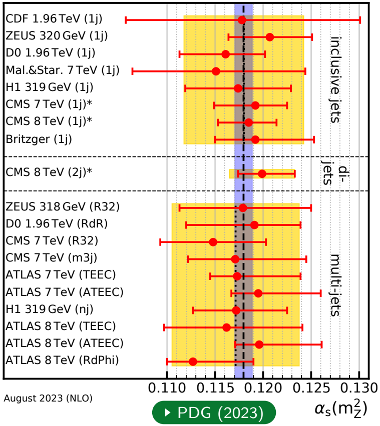


Benefits

✔ Reduction/cancellation of systematic effects e.g. luminosity.
✔ Reduction of theoretical uncertainties e.g. non-perturbative.



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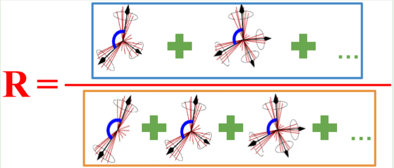

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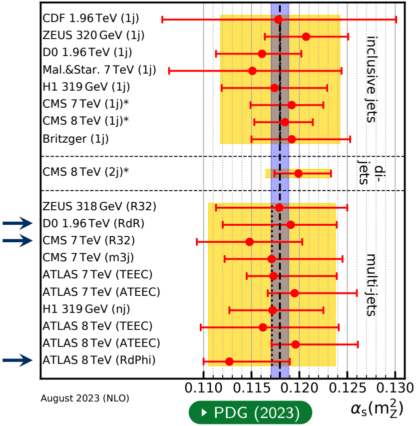
Examples

- $\mathrm{R}_{\Delta\mathrm{R}}$ (D0, 1.96 TeV) ▸ PLB 718:1 (2012)
- R_{32} (CMS, 7 TeV) ▸ EPJC 73:2604 (2013)
- $\mathrm{R}_{\Delta\phi}$ (ATLAS, 8 TeV) ▸ PRD 98:092004 (2018)

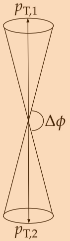


▸ PDG (2023)

$R_{\Delta\phi}$ observable definition

$$\mathbf{R}_{\boldsymbol{\Delta}\phi} = \frac{}{N_{\text{jet}}(p_T)}$$

Number of jets in a jet p_T bin ($\sim \alpha_s^2$ @LO)

2-jet topology	
 $R_{\Delta\phi}(p_T)$ entries $\Delta\phi \approx \pi$ Numerator: 0 Denominator: 2	

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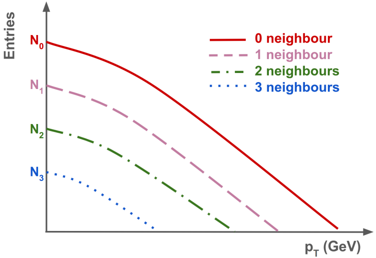

$R_{\Delta\phi}$ observable definition

Jets with neighbours within azimuthal separation:
$2\pi/3 < \Delta\phi < 7\pi/8$ and $p_T > 100$ GeV ($\sim \alpha_s^3$ @LO)

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

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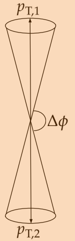
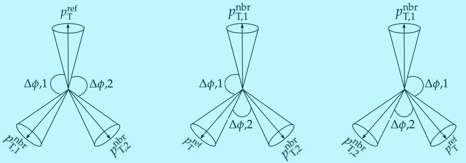


$R_{\Delta\phi}(p_T)$ entries
$\Delta\phi \approx \pi$
Numerator: 0
Denominator: 2

3-jet topology (all jets with $p_T > 100$ GeV)



$R_{\Delta\phi}(p_T)$ entries

Numerator: 2
$2\pi/3 < \Delta\phi,1 < 7\pi/8$
$2\pi/3 < \Delta\phi,2 < 7\pi/8$

+

Numerator: 1
$2\pi/3 < \Delta\phi,1 < 7\pi/8$
$\Delta\phi,2 < 2\pi/3$

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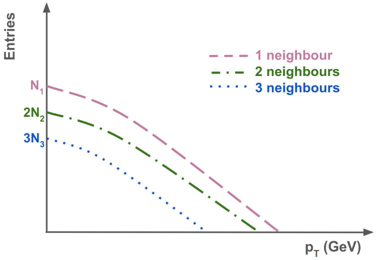
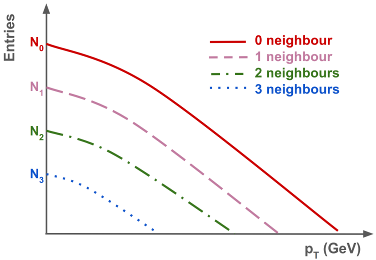
Denominator: 3

$R_{\Delta\phi} =$





Event selection - α_s sensitivity

Experimental data

- Full Run 2: $\mathcal{L}_{\text{int}} = 134\ \text{fb}^{-1}$
- Event sample with jets:
  - anti-k_T with $R = 0.7$
  - $p_T > 50$ GeV, $|y| < 2.5$
- Numerator selection criteria:
  - $(\Delta\phi_{\min}, \Delta\phi_{\max}) = (2\pi/3, 7\pi/8)$
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Results from: arXiv: 2404.16082

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Theoretical predictions

- Fixed-Order predictions pQCD @NLO.
- **NLOJet++** (up to 3 jets @NLO)
- Using the fastNLO framework.
- $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \hat{\mathrm{H}}_{\mathrm{T}}/2$, with $\hat{\mathrm{H}}_{\mathrm{T}} = \sum_{i \in \text{partons}} p_{\mathrm{T},i}$

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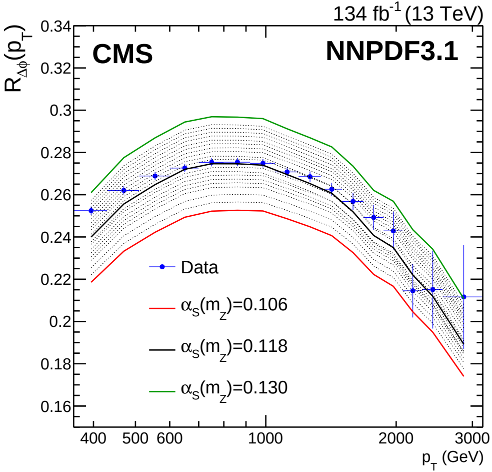
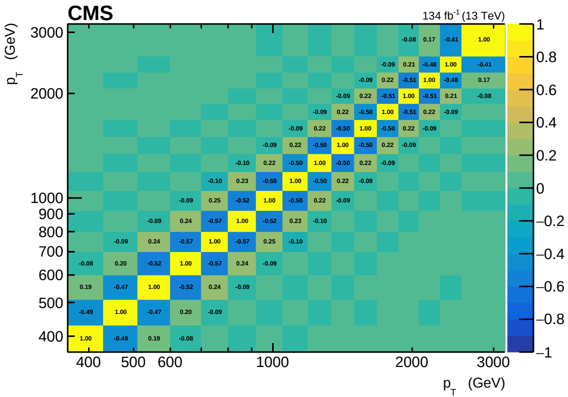


$R_{\Delta\phi}$ observable has large sensitivity to α_s.

Measurement: uncertainties

Statistical correlation matrix for $R_{\Delta\phi}$ *after* unfolding



- **Statistical** (0.18 – 10.49 %): from the covariance matrix *after* unfolding.
- **JES** (0.65 – 5.00 %): **J**et **E**nergy **S**cale uncertainty sources $\rightarrow p_T = p_T(1 \pm \text{unc. source})$.
- **JER** (0.04 – 0.77 %): **J**et **E**nergy **R**esolution smearing process applied to MC samples.
- **Other** ($< 1\%$): Prefiring corrections, PU profile reweighting, MC modeling.

Theoretical predictions

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  - 4 different NLO PDF sets.
- **PDF uncertainties**
  - 68% CL Hessian/MC methods.
- **Scale uncertainties**
  - $\frac{1}{2} \leq \mu_R/\mu_F \leq 2$

PDFs available via LHAPDF

PDF set	Default $\alpha_s(m_z)$	Alternative $\alpha_s(m_z)$
ABMP16	0.1191	0.114 - 0.123
CT18	0.1180	0.110 - 0.124
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NLO scale uncertainties

(3-jet) Numerator : 9 – 17 %
(2-jet) Denominator : 5 – 10 %

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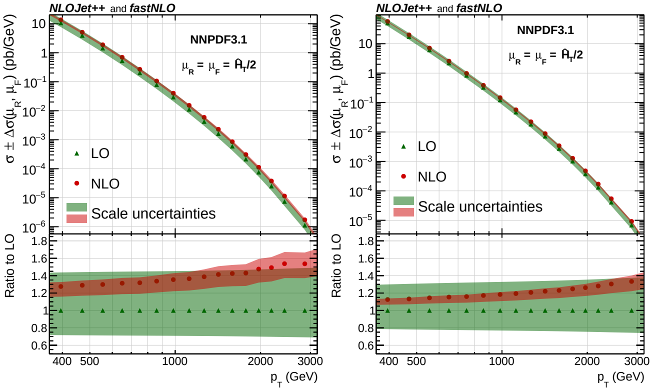

Non-Perturbative corrections

- Fixed Order pQCD predictions are available at parton level only: non-perturbative (NP) corrections account for multiple parton interactions (MPI) and hadronization (HAD) effects:

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  - Envelope from the predictions of the different MC event generators.

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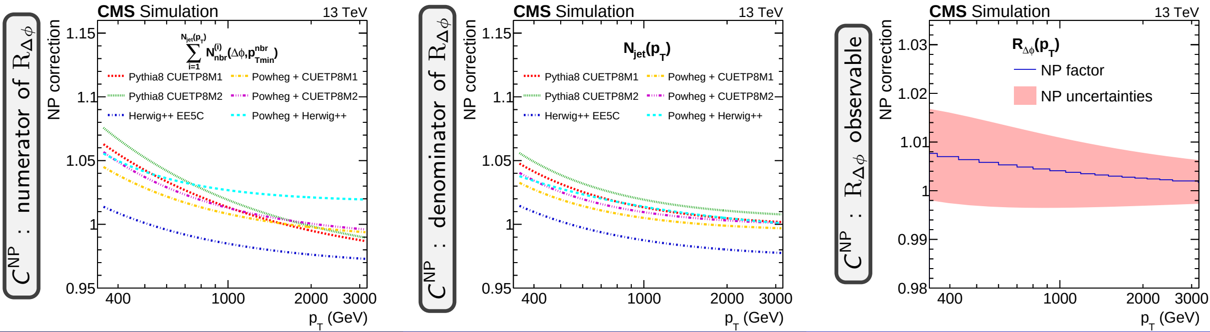

ElectroWeak corrections

- Fixed Order pQCD predictions are also corrected for the **E**lectro**W**eak (EW) effects.
- *Full NLO corrections to 3-jet production and* R_{32} *at the LHC*
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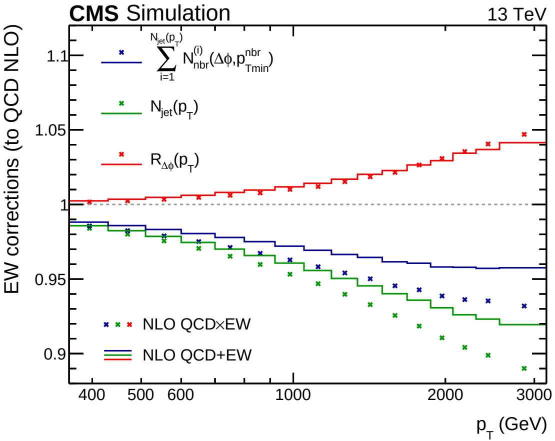
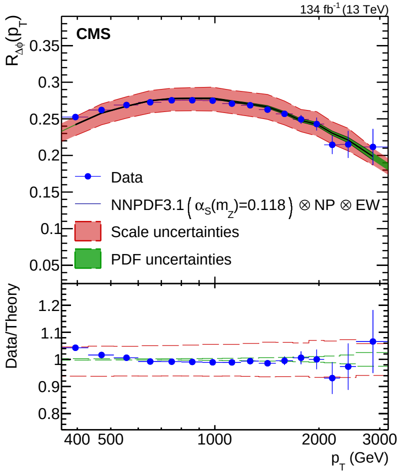


EW corrections for $R_{\Delta\phi} < 5\%$ and EW correction uncertainties $< 0.6\%$.

Determination of $\alpha_s(m_z)$



- **Agreement between data and theory (within the uncertainties) for all the PDF sets.**
- **Uncertainties: PDF: 1 − 2 % , Scale: 2 − 8 %**

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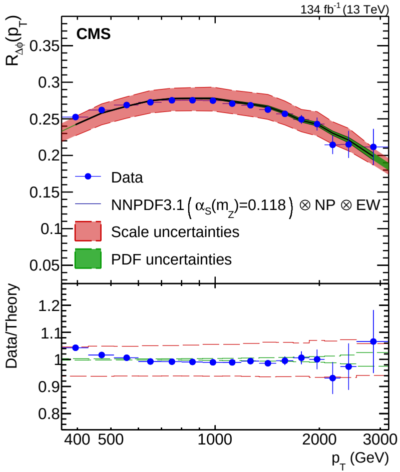

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Determination of $\alpha_s(m_z)$

- **Minimization of:**

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

N: number of measurements
D_i: experimental data
T_i: theoretical predictions
C_{ij}: covariance matrix

- **Covariance matrix composition:**

$$C_{ij} = C_{\mathrm{uncor}} + C_{\mathrm{exp}} + C_{\mathrm{theo}}$$

C_{uncor} : numerical precision of FO predictions
C_{exp} : all the experimental uncertainties
C_{theo} : all the theoretical uncertainties

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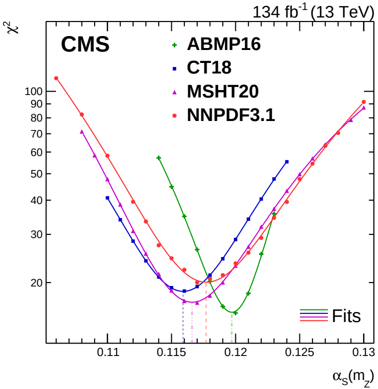

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CT18	0.1159	0.0013	0.0009	0.0014	0.0002	$^{+0.0099}_{-0.0067}$	$^{+0.0101}_{-0.0070}$	19/16
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	$^{+0.0112}_{-0.0063}$	$^{+0.0114}_{-0.0066}$	17/16
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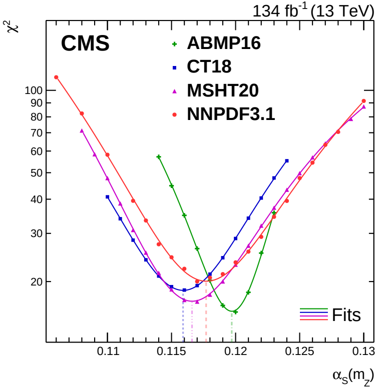

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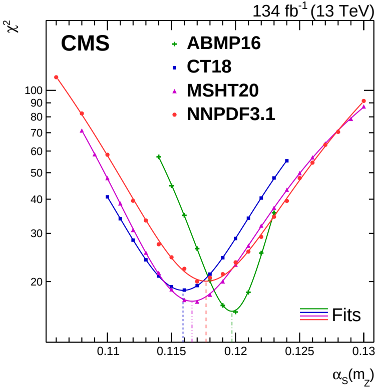
- **Extracted $\alpha_s(m_z)$ are compatible among each other within the uncertainties.**

Determination of $\alpha_s(m_z)$



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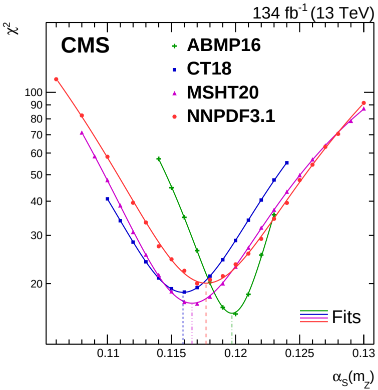
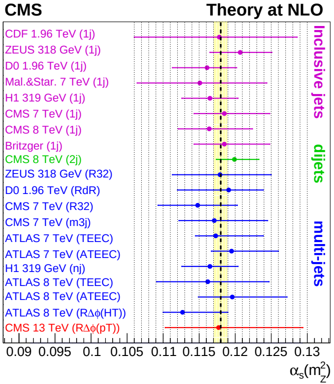
- **Scale uncertainties (theoretical) by far the dominant: $4-10$ %.**

Determination of $\alpha_s(m_z)$





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- **Results also compatible with the world average: $\alpha_s(m_z) = 0.1180 \pm 0.0009$.**

$\alpha_s(Q)$ evolution

Evolution of α_s as a function of the energy scale (Q).

$\alpha_s(\mathrm{Q})$ evolution

Evolution of α_s as a function of the energy scale (Q).

1. $\alpha_s(\mathrm{m_z})$ determination in 4 $\mathrm{p_T}$ ranges.
2. $\langle \mathrm{Q} \rangle$: cross-section-weighted average.
3. $\alpha_s(\mathrm{m_z})$ evolution to $\alpha_s(\mathrm{Q})$ via RGE.

$\mathrm{p_T}$ range (GeV)	$\alpha_s(\mathrm{m_z})$	$\langle \mathrm{Q} \rangle$ (GeV)	$\alpha_s(\mathrm{Q})$
360 – 700	$0.1177^{+0.0104}_{-0.0067}$	433.0	$0.0967^{+0.0066}_{-0.0044}$
700 – 1190	$0.1162^{+0.0108}_{-0.0073}$	819.0	$0.0878^{+0.0060}_{-0.0042}$
1190 – 1870	$0.1159^{+0.0112}_{-0.0077}$	1346.0	$0.0830^{+0.0055}_{-0.0040}$
1870 – 3170	$0.1118^{+0.0110}_{-0.0070}$	2081.0	$0.0775^{+0.0051}_{-0.0034}$

Evolution of α_s as a function of the energy scale (Q).

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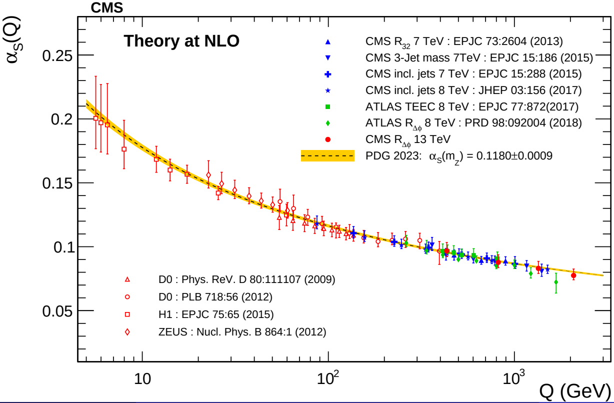
700 – 1190	$0.1162^{+0.0108}_{-0.0073}$	819.0	$0.0878^{+0.0060}_{-0.0042}$
1190 – 1870	$0.1159^{+0.0112}_{-0.0077}$	1346.0	$0.0830^{+0.0055}_{-0.0040}$
1870 – 3170	$0.1118^{+0.0110}_{-0.0070}$	2081.0	$0.0775^{+0.0051}_{-0.0034}$



$\alpha_s(Q)$ evolution

Evolution of α_s as a function of the energy scale (Q).

1. $\alpha_s(m_z)$ determination in 4 p_T ranges.
2. $\langle Q \rangle$: cross-section-weighted average.
3. $\alpha_s(m_z)$ evolution to $\alpha_s(Q)$ via RGE.

p_T range (GeV)	$\alpha_s(m_z)$	$\langle Q \rangle$ (GeV)	$\alpha_s(Q)$
360 − 700	$0.1177^{+0.0104}_{-0.0067}$	433.0	$0.0967^{+0.0066}_{-0.0044}$
700 − 1190	$0.1162^{+0.0108}_{-0.0073}$	819.0	$0.0878^{+0.0060}_{-0.0042}$
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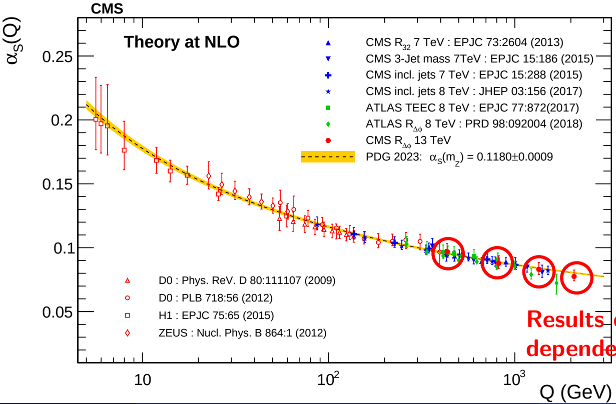

Results consistent with the energy dependence predicted by the RGE.

$\alpha_s(Q)$ evolution

Evolution of α_s as a function of the energy scale (Q).

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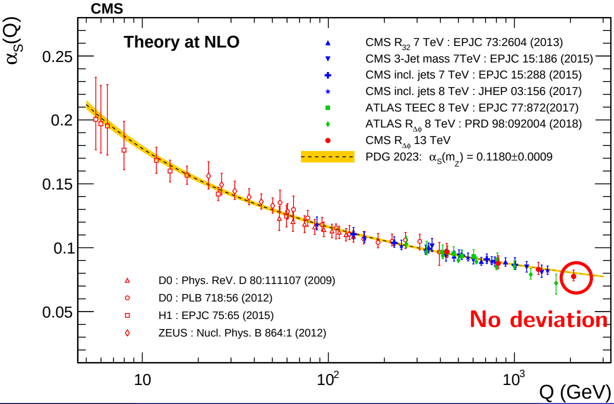
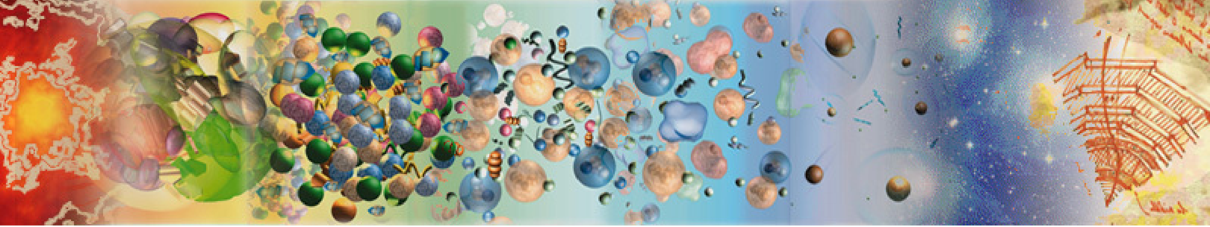


No deviation is observed up to ∼ 2 TeV.



THANK YOU FOR YOUR ATTENTION

BACK UP

$R_{\Delta R}$ and $R_{\Delta\phi}$ observables

(D0) $R_{\Delta R}$ definition

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

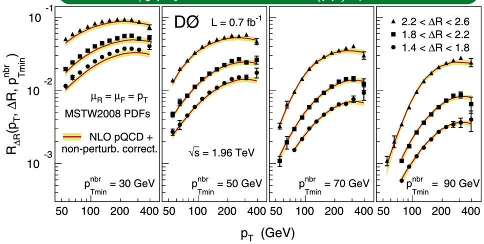
- N_{jet}: inclusive number of jets.
- N_{nbr}: jets with neighbours within angular separation interval ΔR and $p_T > p_{Tmin}^{nbr}$.

(ATLAS) $R_{\Delta\phi}$ definition

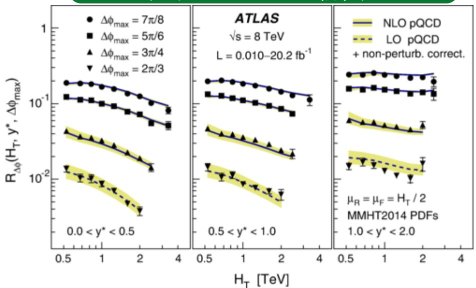
$$R_{\Delta\phi} = \frac{\dfrac{d^2\sigma_{dijet}(\Delta\phi_{dijet} < \Delta\phi_{max})}{dH_T\,dy^*}}{\dfrac{d^2\sigma_{dijet}(\text{inclusive})}{dH_T\,dy^*}}$$

- σ_{dijet}: inclusive dijet sample.
- H_T: $\sum_{i\in\text{jets}} p_{T,i}$, y^*: $|y_1 - y_2|/2$.

10.1016/j.physletb.2012.10.003, $(p\bar{p})$ $\sqrt{s} = 1.96$ TeV



10.1103/PhysRevD.98.092004, (pp) $\sqrt{s} = 8$ TeV



Measurement: data unfolding

Equivalent observable definition

$$\mathbf{R}_{\Delta\phi} = \frac{\sum_{i=1}^{N_{\mathrm{jet}}(p_T)} N_{\mathrm{nbr}}^{(i)}(\Delta\phi, p_{T\mathrm{min}}^{\mathrm{nbr}})}{N_{\mathrm{jet}}(p_T)} = \frac{\sum_n n N(p_T, n)}{\sum_n N(p_T, n)}$$

where n is the number of neighbours and p_T is jet's transverse momentum.

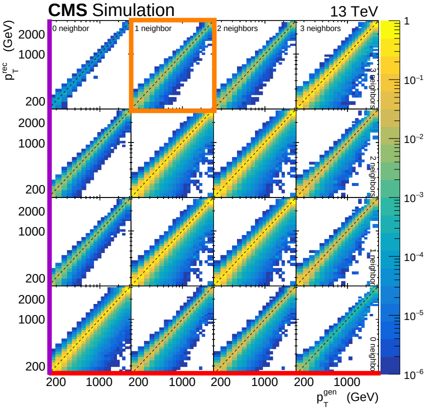
Motivation

- 2D unfolding of $N(p_T, n)$ distribution.
- ✔ Migrations among p_T **and** among n bins.
- ✔ Account for non-trivial numerator-denominator correlations.

Matrix structure

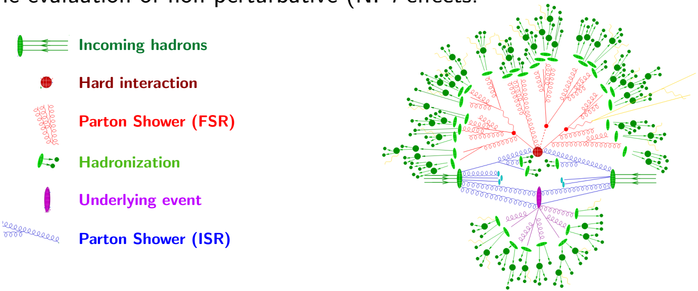
- **x axis: generator-level p_T.**
- **y axis: reconstructed-level p_T.**
- **inner cells: neighbouring jet bins.**

Probability matrix for the 2D $N(p_T, n)$



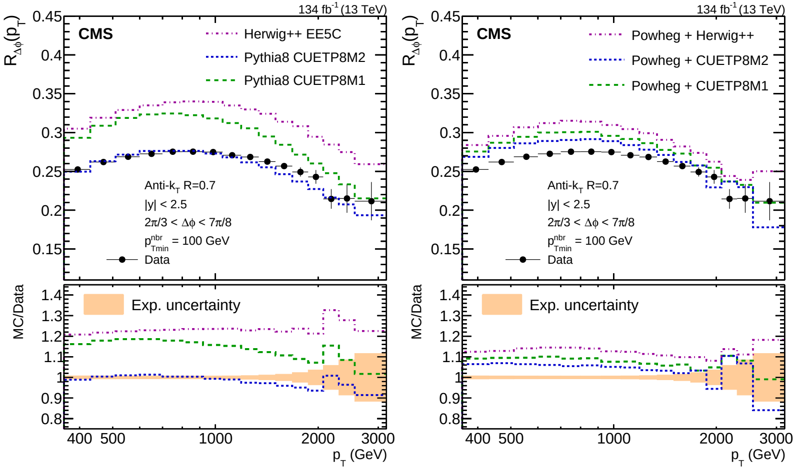
Monte Carlo predictions

- Predictions from MC event generators at particle level using RIVET toolkit.
  - For the comparison with experimental data.
  - For the evaluation of non-perturbative (NP) effects.



MC	Matrix Element	Parton Shower	Hadronization	Tune	PDF set
PYTHIA8	$2 \to 2$ (LO)	p_T ordered	Lund string	CUETP8M1	NNPDF2.3
				CUETP8M2	NNPDF3.0
HERWIG++	$2 \to 2$ (LO)	Angular ordered	Cluster model	EE5C	CTEQ6.1M
POWHEG	$2 \to 2$ (NLO), $2 \to 3$ (LO)	PYTHIA8	PYTHIA8	CUETP8M1	NNPDF3.0
		PYTHIA8	PYTHIA8	CUETP8M2	NNPDF3.0
		HERWIG++	HERWIG++	EE5C	NNPDF3.0

Monte Carlo predictions



- Predictions from Powheg overestimate the measurement by ∼5-12%.
- Herwig++ EE5C (Pythia8 CUETP8M1) overestimate $R_{\Delta\phi}$ by ∼ 20% (∼12-18%).
- Nice description from (LO) Pythia8 tune CUETP8M2T4.

Electroweak corrections

Combination of QCD and EW corrections

Pure NLO EW corrections for n-jet:

$$\sigma_{nj}^{\text{NLO EW}} = \sigma_{nj}^{\text{LO}} + \sigma_{nj}^{\Delta\text{NLO}_1}$$

ΔNLO_1: virtual and real EW corrections.

Combination to QCD process:

1. **Additive:** $\sigma_{nj}^{\text{NLO QCD+EW}}$

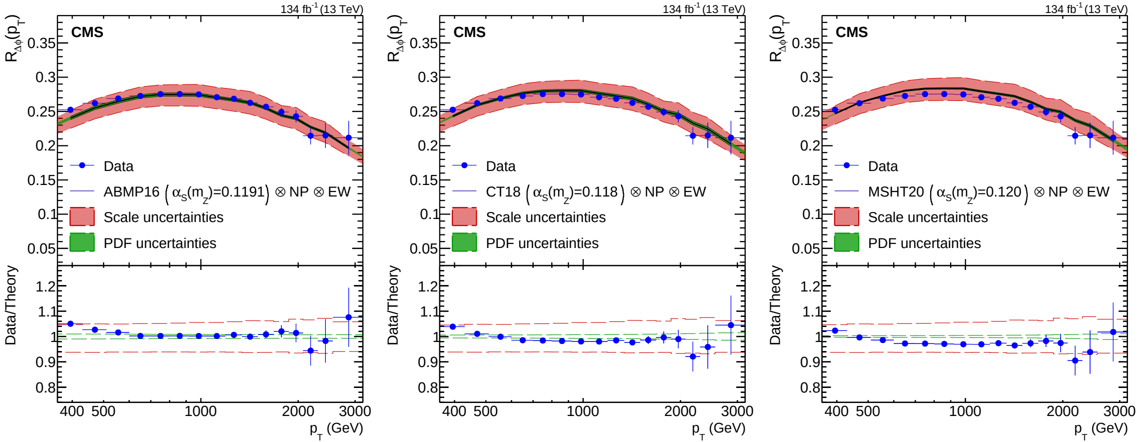
$$\sigma_{nj}^{\text{LO}} + \sigma_{nj}^{\Delta\text{NLO}_0} + \sigma_{nj}^{\Delta\text{NLO}_1}$$

ΔNLO_0: virtual and real QCD corrections.

2. **Multiplicative:** $\sigma_{nj}^{\text{NLO QCD}\times\text{EW}}$

$$\sigma_{nj}^{\text{LO}} \left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_0}}{\sigma_{nj}^{\text{LO}}}\right) \left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_1}}{\sigma_{nj}^{\text{LO}}}\right)$$

Data vs Theory



Sensitivity to α_s