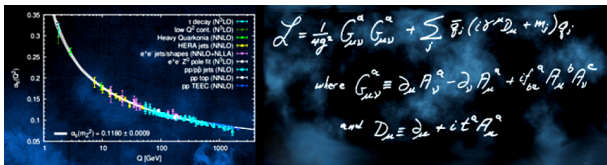


# Determination of $\alpha_S$ from azimuthal correlations among jets

Paris Gianneios

on behalf of the CMS Collaboration



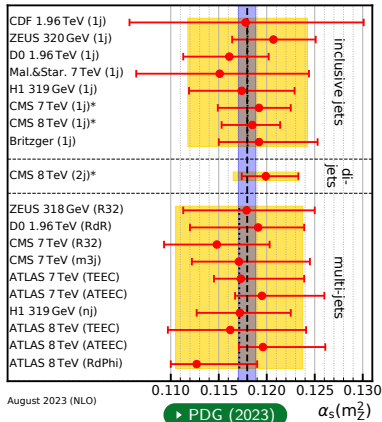
alphas-2024: Workshop on precision measurements of the QCD coupling constant, ECT\*, Trento

- 1 Motivation:  $\alpha_S$  from angular/azimuthal correlations among jets
  - D0  $\rightarrow R_{\Delta R}$  observable, (2012)  $\sqrt{s} = 1.96$  TeV (10.1016/j.physletb.2012.10.003)
  - ATLAS  $\rightarrow R_{\Delta\phi}$  observable, (2018)  $\sqrt{s} = 8$  TeV (10.1103/PhysRevD.98.092004)
  - CMS  $\rightarrow R_{\Delta\phi}$  observable, (2024)  $\sqrt{s} = 13$  TeV (CMS-PAS-SMP-22-005)
- 2 CMS results: determination of  $\alpha_S$  using  $R_{\Delta\phi}$  observable
  - Measurement
  - Theoretical predictions
  - Determination of  $\alpha_S(M_Z)$
  - Investigation of  $\alpha_S(Q)$  evolution

## Multijet cross section ratios

### Goals

- 1 Determination of  $\alpha_S(M_Z)$ .
- 2 Investigation of  $\alpha_S(Q)$  running.



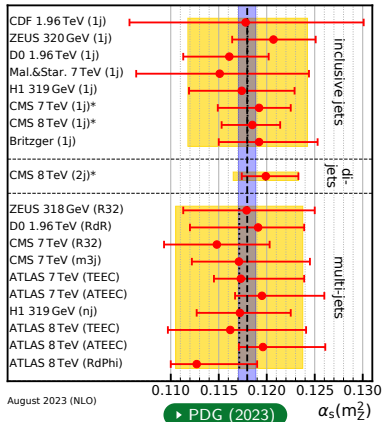
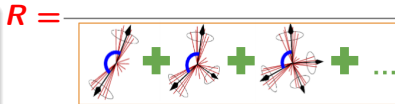
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- **Denominator: topologies with at least 2-jets.**



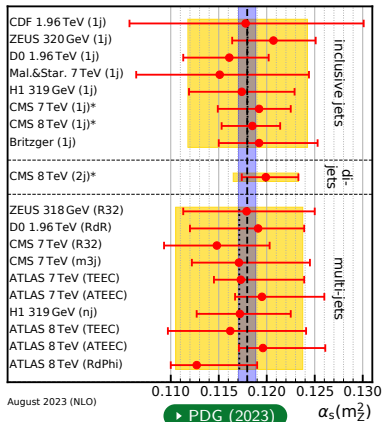
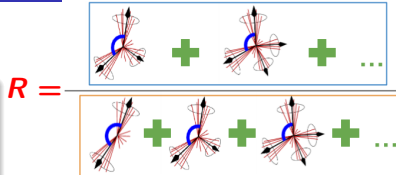
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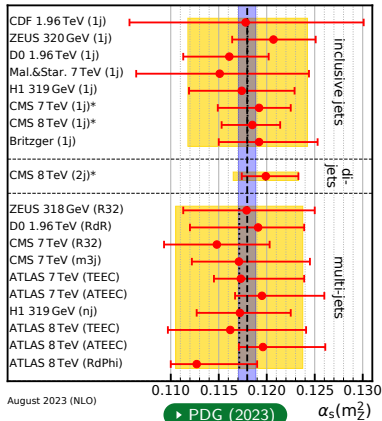
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### Benefits

- ✓ Reduction/cancellation of experimental uncertainties e.g. luminosity.
- ✓ Reduction of theoretical uncertainties e.g. PDF.

$$R = \frac{\text{[Diagrams with 2-jets]} + \text{[Diagrams with 3-jets]} + \dots}{\text{[Diagrams with 2-jets]} + \text{[Diagrams with 3-jets]} + \dots}$$



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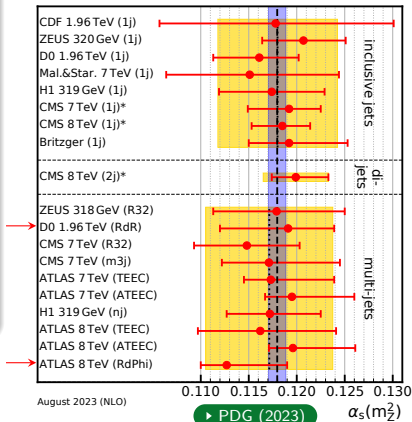
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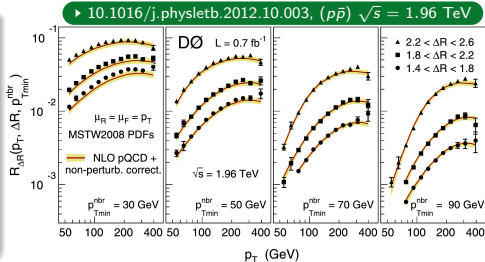
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## (D0) $R_{\Delta R}$ definition

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

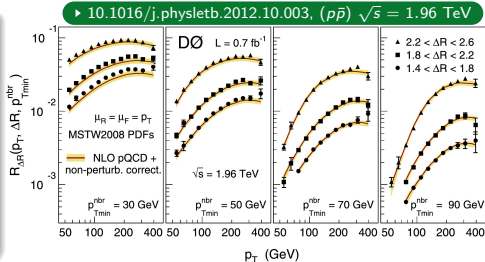
- $N_{jet}$ : inclusive number of jets.
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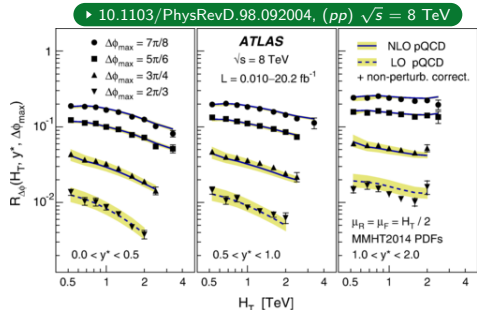
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## (ATLAS) $R_{\Delta\phi}$ definition

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

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



$$R_{\Delta\phi} = \frac{1}{N_{jet}(p_T)}$$

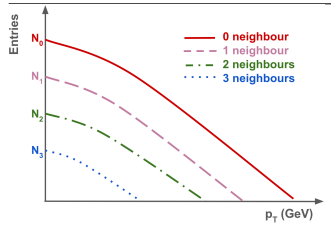
$N_{jet}(p_T)$

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

### 2-jet topology



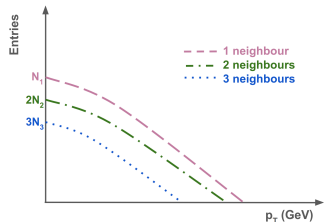
$R_{\Delta\phi}(p_T)$  entries  
 $\Delta\phi \approx \pi$   
 Numerator: 0  
 Denominator: 2



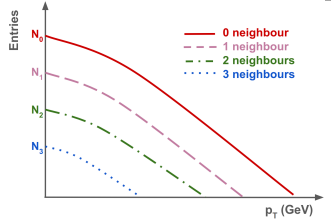
Jets with neighbours within azimuthal separation:  
 $2\pi/3 < \Delta\phi < 7\pi/8$  and  $p_T > 100$  GeV ( $\sim \alpha_s^3$  @LO)

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

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



2-jet topology	3-jet topology (all jets with $p_T > 100$ GeV)		
$R_{\Delta\phi}(p_T)$ entries $\Delta\phi \approx \pi$ Numerator: 0 Denominator: 2	Numerator: 2 $2\pi/3 < \Delta\phi,1 < 7\pi/8$ $2\pi/3 < \Delta\phi,2 < 7\pi/8$	Numerator: 1 $2\pi/3 < \Delta\phi,1 < 7\pi/8$ $\Delta\phi,2 < 2\pi/3$	Numerator: 1 $2\pi/3 < \Delta\phi,1 < 7\pi/8$ $\Delta\phi,2 < 2\pi/3$
	$R_{\Delta\phi}(p_T)$ entries Denominator: 3		



## Experimental data

- Full Run 2:  $\mathcal{L}_{int} = 134 \text{ fb}^{-1}$
- Event sample with jets:
  - anti- $k_T$  with  $R = 0.7$
  - $p_T > 50 \text{ GeV}$ ,  $|y| < 2.5$
- Numerator selection criteria:
  - $(\Delta\phi_{min}, \Delta\phi_{max}) = (2\pi/3, 7\pi/8)$
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Results from: ▶ CMS-PAS-SMP-22-005

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## Theoretical predictions

- Fixed-order predictions pQCD @NLO.
- NLOJet++ (up to 3 jets @NLO)
- Using the **fastNLO** framework.
- $\mu_R = \mu_F = \hat{H}_T/2$ ,  
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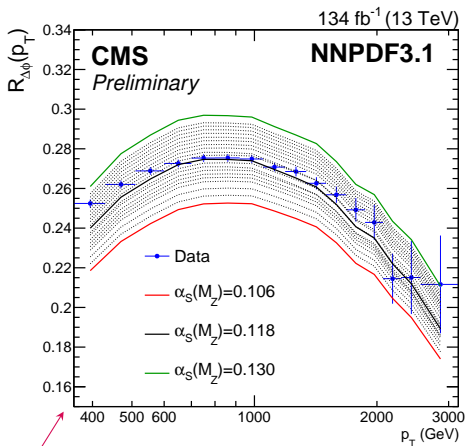
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$R_{\Delta\phi}$  observable has large sensitivity to  $\alpha_S$ .

- **Data Unfolding:** correct the measurement for the detector smearing effects.
- **TUnfold package:** least square minimisation without Tikhonov regularisation:

$$\chi^2 = (Ax + b - y)^T V^{-1} (Ax + b - y)$$

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- Equivalent observable definition using 2D  $N(p_T, n)$  distribution:

$$R_{\Delta\phi} = \frac{\sum_{i=1}^{N_{jet}(p_T)} N_{nbr}^{(i)}(\Delta\phi, p_{Tmin}^{nbr})}{N_{jet}(p_T)} = \frac{\sum_{n=0}^{\infty} n N(p_T, n)}{\sum_{n=0}^{\infty} N(p_T, n)}$$

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

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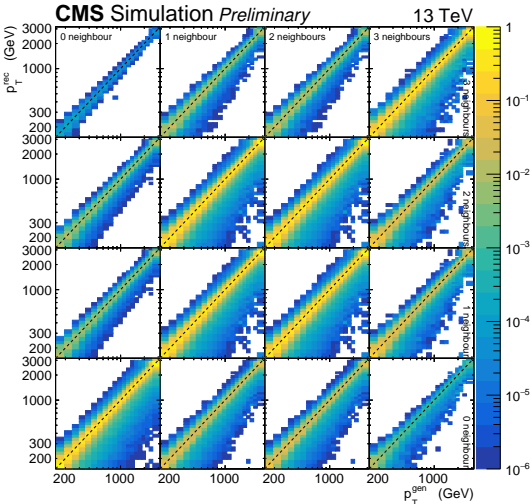
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## Motivation

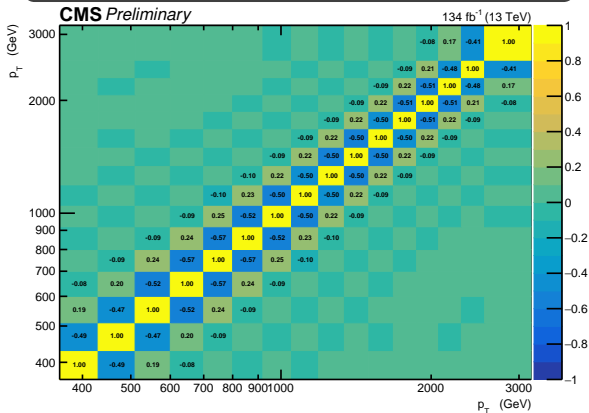
- ✔ Multidimensional unfolding of the  $N(p_T, n)$  distribution.
- ✔ Account for migrations among  $p_T$  bins **and** among  $n$  bins.
- ✔ Account for non-trivial correlations between the numerator and denominator.

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



- Probability matrix built using Pythia8.
  - x axis: generator-level  $p_T$ .
  - y axis: reconstructed-level  $p_T$ .
  - inner cells: neighbouring jet bins.
- Model uncertainties ( $< 0.01\%$ ) investigated using alternative MC models (Madgraph).

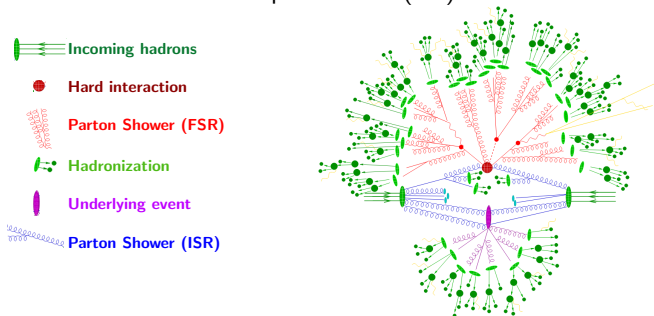
Statistical correlation matrix for  $R_{\Delta\phi}$  after unfolding



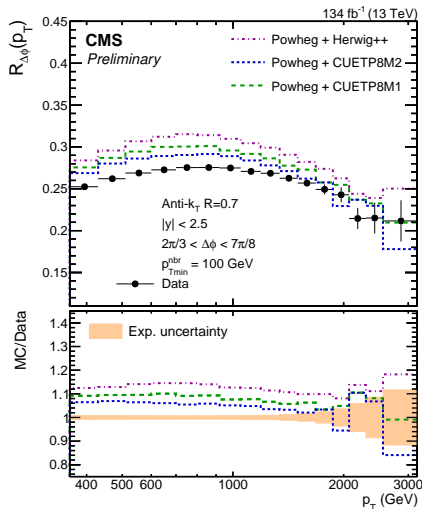
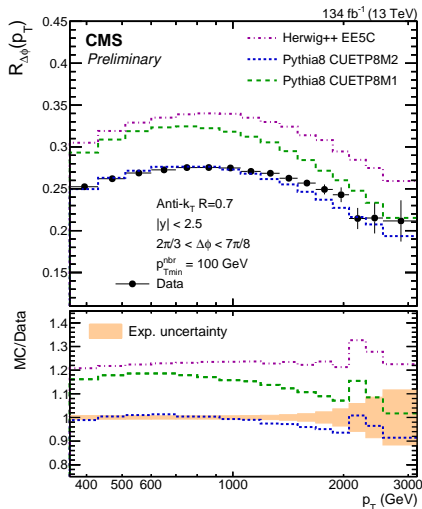
- **Statistical** (< 11%): from the covariance matrix *after* unfolding.
- **JES** (< 5%): **J**et **E**nergy **S**cale uncertainty sources  $\rightarrow p_T = p_T(1 \pm \text{unc. source})$ .
- **JER** (< 0.8%): **J**et **E**nergy **R**esolution smearing process applied to MC samples.
- **Other** (< 1%): Prefiring corrections, PU profile reweighting, MC modeling.

- 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.

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



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

- **Fixed-order pQCD predictions @NLO**

- 4 different 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
MSHT20	0.1200	0.108 - 0.130
NNPDF3.1	0.1180	0.106 - 0.130

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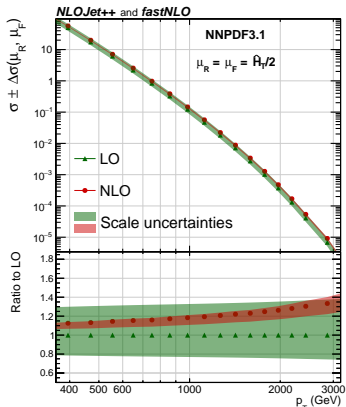
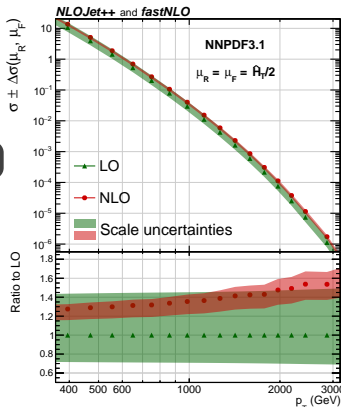
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NLO scale uncertainties

Numerator: 9-17%

Denominator: 5-10%



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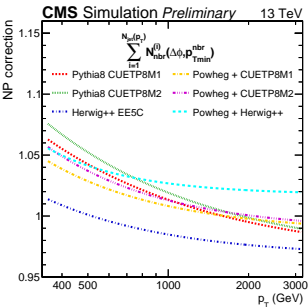
- NP correction factors: 
$$C^{\text{NP}} = \frac{\sigma^{\text{PS+MPI+HAD}}}{\sigma^{\text{PS}}}$$
- Simple polynomial function  $a + b \cdot p_T^c$  for the parametrization of  $C^{\text{NP}}$ .
- Envelope from the predictions of the different MC event generators.

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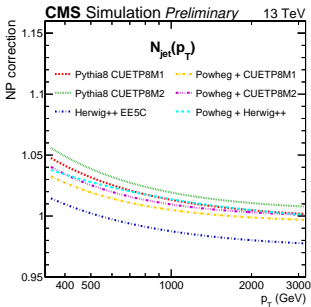
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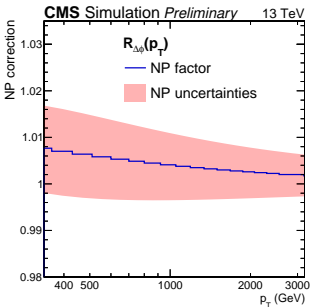
$C^{NP}$  for numerator of  $R_{\Delta\phi}$



$C^{NP}$  for denominator of  $R_{\Delta\phi}$



$C^{NP}$  for  $R_{\Delta\phi}$



- Theoretical predictions are also corrected for the **ElectroWeak** (EW) effects.
- Full NLO corrections to 3-jet production at the LHC [▶ arxiv:1902.01763](https://arxiv.org/abs/1902.01763)  
 $\mathcal{O}(\alpha_s^n \alpha^m)$ , with  $n + m = 2$  and  $n + m = 4$ .

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## Corrections formulation

### Pure NLO EW corrections for n-jet:

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

$\Delta\text{NLO}_1$ : virtual and real EW corrections.

### Combination to QCD process:

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

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

$\Delta\text{NLO}_0$ : virtual and real QCD corrections.

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

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

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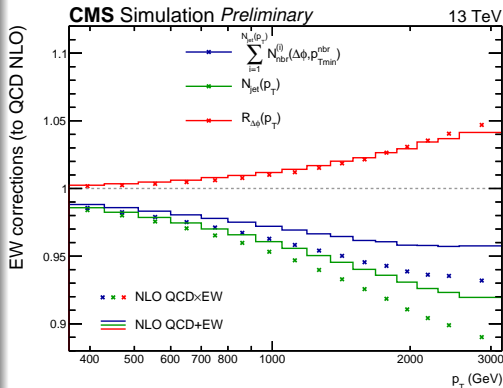
- Additive:**  $\sigma_{nj}^{\text{NLO QCD+EW}}$

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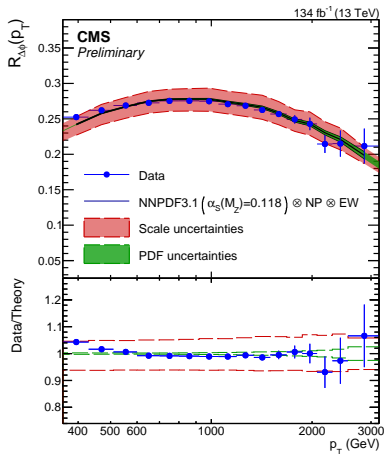
$\Delta\text{NLO}_0$ : virtual and real QCD corrections.

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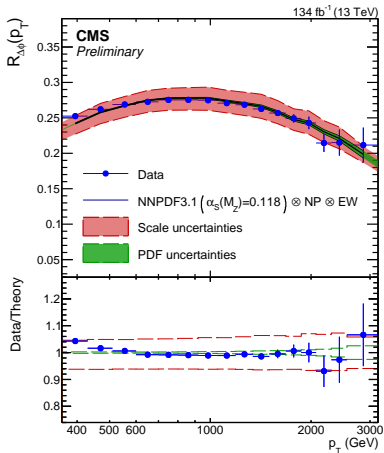
$$\sigma_{nj}^{\text{LO}} \left( 1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_0}}{\sigma_{nj}^{\text{LO}}} \right) \left( 1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_1}}{\sigma_{nj}^{\text{LO}}} \right)$$



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



- Data-theory agreement (within the uncertainties) for all the PDF sets.
- PDF uncertainties: 1-2%.
- Scale uncertainties: 2-8%.



## Determination of $\alpha_S(M_Z)$

- Minimization of:

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

$N$ : number of measurements

$D_i$ : experimental data

$T_i$ : theoretical predictions

$C_{ij}$ : covariance matrix

- Covariance matrix composition:

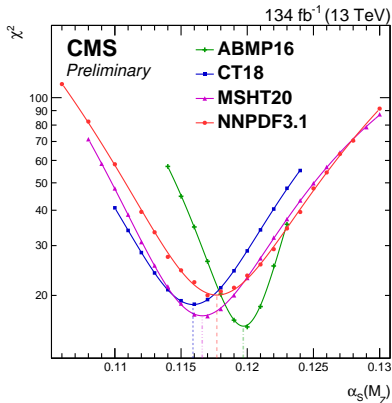
$$C_{ij} = C_{uncor} + C_{exp} + C_{theo}$$

$C_{uncor}$ : numerical precision of FO predictions

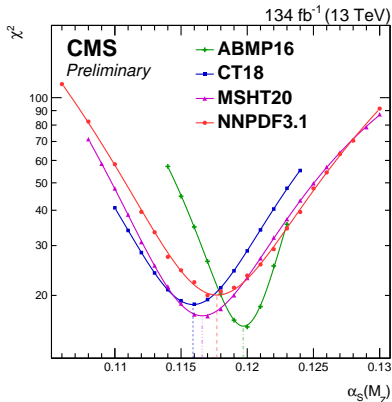
$C_{exp}$ : all the experimental uncertainties

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- Scale uncertainties: 2-8%.

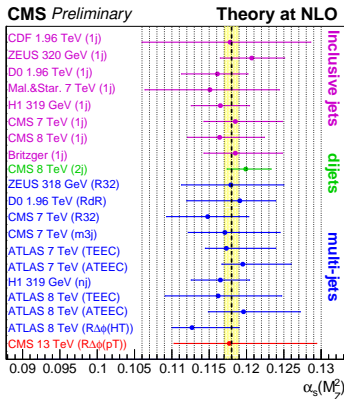
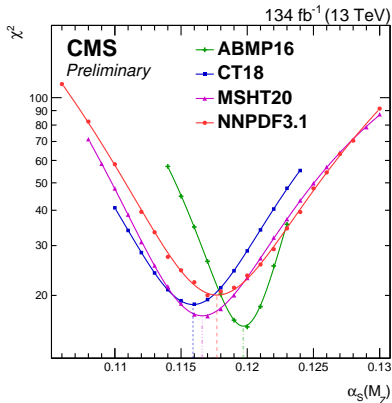


PDF set	$\alpha_S(M_Z)$	Exp	NP	PDF	EW	Scale	Total	$\chi^2/n_{dof}$
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	+0.0043 -0.0042	+0.0045 -0.0044	16/16
CT18	0.1159	0.0013	0.0009	0.0014	0.0002	+0.0099 -0.0067	+0.0101 -0.0070	19/16
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	+0.0112 -0.0063	+0.0114 -0.0066	17/16
NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	+0.0114 -0.0068	+0.0116 -0.0071	20/16



PDF set	$\alpha_s(M_Z)$	Exp	NP	PDF	EW	Scale	Total	$\chi^2/n_{dof}$
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	+0.0043 -0.0042	+0.0045 -0.0044	16/16
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
NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	+0.0114 -0.0068	+0.0116 -0.0071	20/16

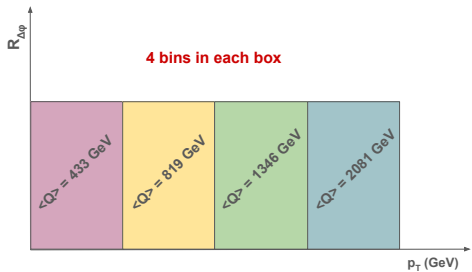
- Scale uncertainties by far the dominant: 4-10%.
- All the  $\alpha_s(M_Z)$  are compatible among each other.



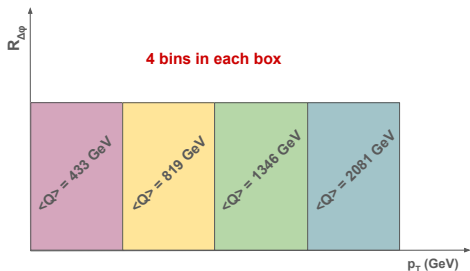
PDF set	$\alpha_S(M_Z)$	Exp	NP	PDF	EW	Scale	Total	$\chi^2/n_{dof}$
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	+0.0043 -0.0042	+0.0045 -0.0044	16/16
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NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	+0.0114 -0.0068	+0.0116 -0.0071	20/16

- Results also compatible with the world average:  $\alpha_S(M_Z) = 0.1180 \pm 0.0009$ .

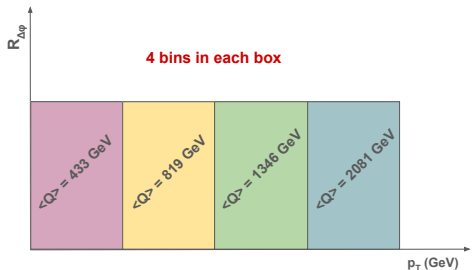
- 1 Split the  $p_T$  range into 4 sub-regions.



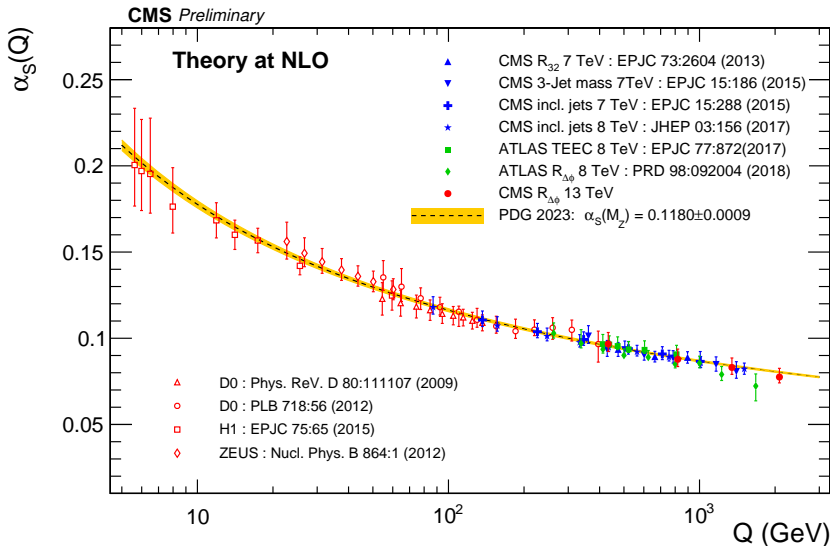
- 1 Split the  $p_T$  range into 4 sub-regions.
- 2 Determination of the  $\alpha_s(M_Z)$  in each sub-region independently.



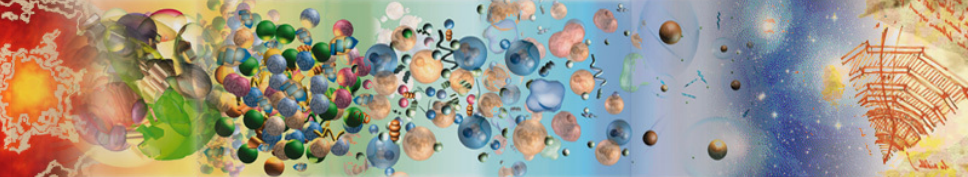
- 1 Split the  $p_T$  range into 4 sub-regions.
- 2 Determination of the  $\alpha_S(M_Z)$  in each sub-region independently.
- 3 Calculation of the cross-section-weighted average  $\langle Q \rangle$  for each sub-region.
- 4 The  $\alpha_S(M_Z)$  values are evolved to  $\alpha_S(Q)$ , using the RGE.



$p_T$ 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	$0.0878^{+0.0060}_{-0.0042}$
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	$0.0775^{+0.0051}_{-0.0034}$



**All the analysis results are consistent with the energy dependence predicted by the RGE and no deviation is observed up to  $\sim 2$  TeV.**



# THANK YOU FOR YOUR ATTENTION



**H.F.R.I.**  
Hellenic Foundation for  
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