

Measurement of azimuthal correlations of jets and determination of the strong coupling in pp collisions at 13 TeV with CMS



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Outline

- 1 Motivation
- 2 Measurement
- 3 Theoretical predictions
- 4 Determination of the strong coupling



Motivation

QCD studies

- ① Test the validity of the SM of particle physics up to unprecedented energy scales.
 - Comparison between experimental data and theoretical predictions.
- ② High precision measurements of SM QCD processes.
 - Determination of the strong coupling, PDF constraints etc.
- ③ Significant background
 - Other SM measurements.
 - Searches for new physics.



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Strong coupling constant α_s

- ▶ Not a physical observable itself.
- ▶ The value of α_s must be inferred from experimental measurements.
- ▶ Usage of observables sensitive to α_s .

Standard practice:

- ▶ Determination of $\alpha_s(M_Z)$ and test of $\alpha_s(Q)$ running via the RGE.



Motivation

QCD studies

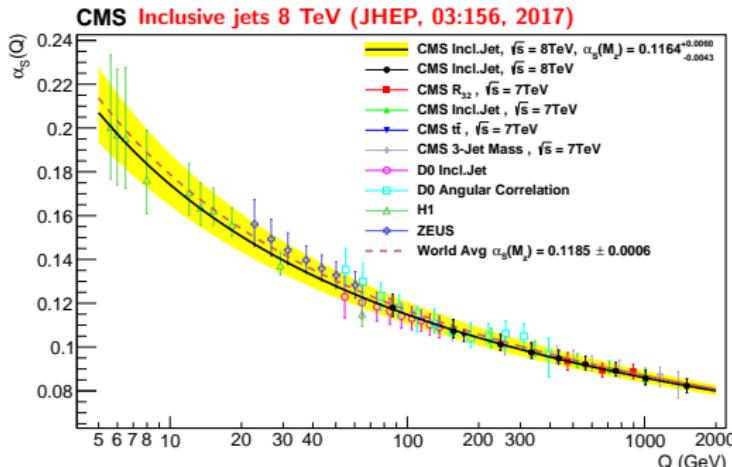
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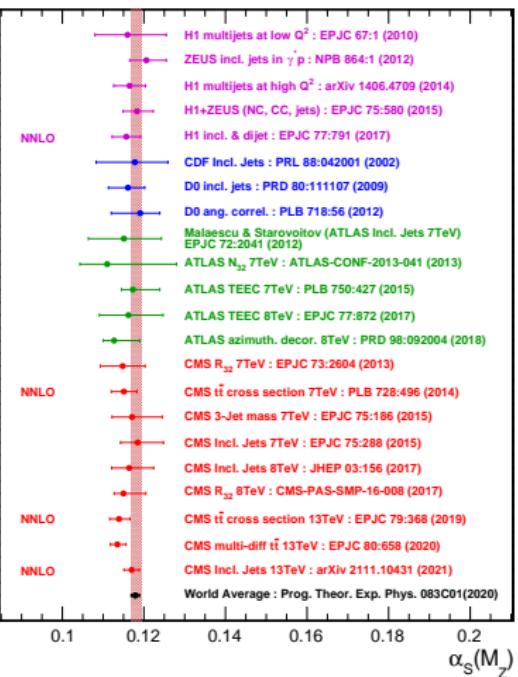




Motivation

Previous determinations of $\alpha_s(M_Z)$ using hadrons physics.

\sqrt{s} (TeV)	Collaboration (year)	Observable
1.96	CDF (2002)	Inclusive jet cross section
1.96	D0 (2009)	Inclusive jet cross section
1.96	D0 (2012)	Jet angular correlations
7	ATLAS (2012)	Inclusive jet cross section
7	CMS (2013)	3- over 2-jet inclusive jet ratio (R_{32})
7	CMS (2014)	$t\bar{t}$ production cross section
7	CMS (2015)	3-jet differential cross section
7	CMS (2015)	Inclusive jet cross section
7	ATLAS (2015)	Transverse Energy-Energy Correlations
8	CMS (2017)	Inclusive jet cross section
8	CMS (2017)	Triple differential dijet cross section
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8	ATLAS (2018)	Dijet azimuthal decorrelations ($R_{\Delta\phi}$)
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13	CMS (2020)	$t\bar{t}$ multi-differential cross sections
13	CMS (2021)	Inclusive jet cross section

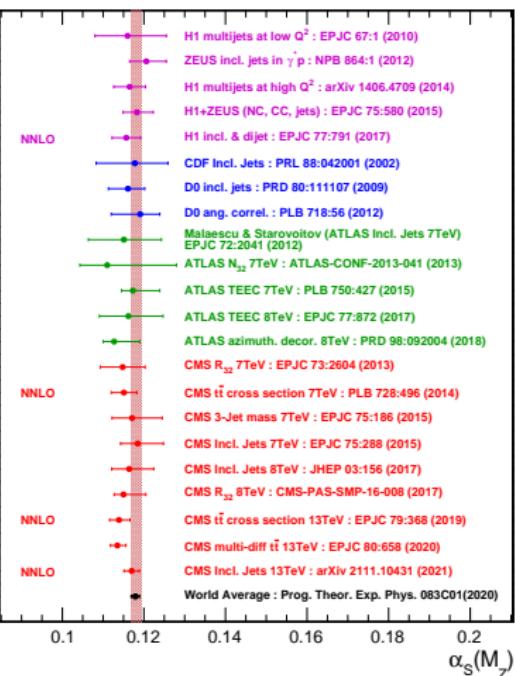




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Analysis goals

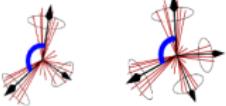
- 1 $\alpha_s(M_Z)$ determination at $\sqrt{s} = 13$ TeV using full Run II dataset
→ comparison with the α_s world average.
- 2 $\alpha_s(Q)$ running test for $Q > 1.5$ TeV
→ comparison with the energy dependence predicted by the RGE.



Observable

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

Topologies with at least 3 jets
 $(\sim \alpha_s^3)(LO)$



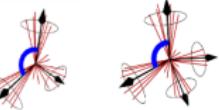
N_{jet} : number of inclusive jets in a jet p_T bin
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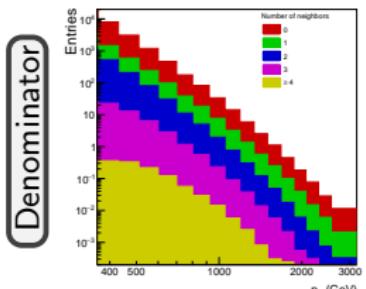
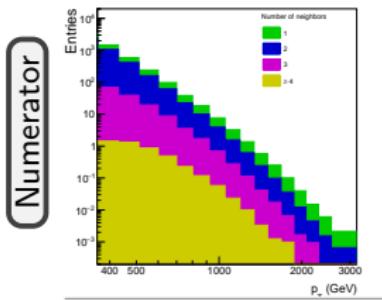
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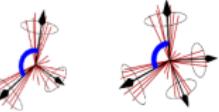




Observable

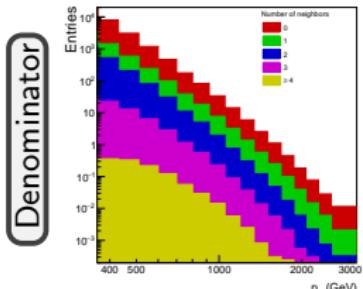
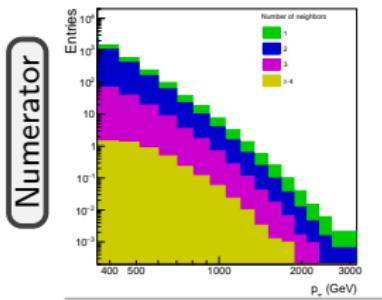
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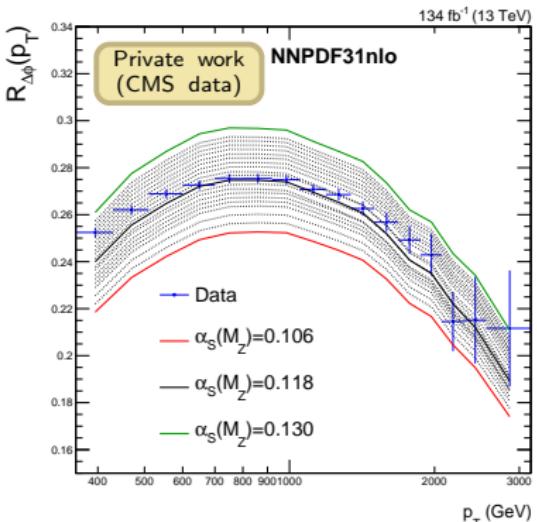


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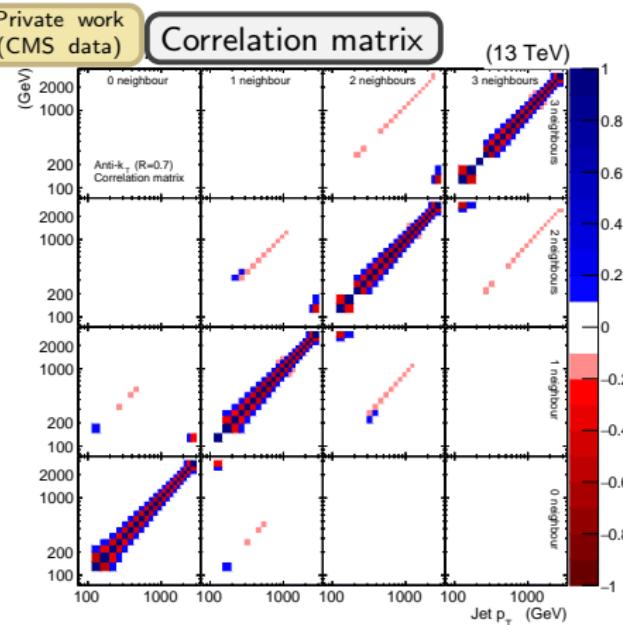
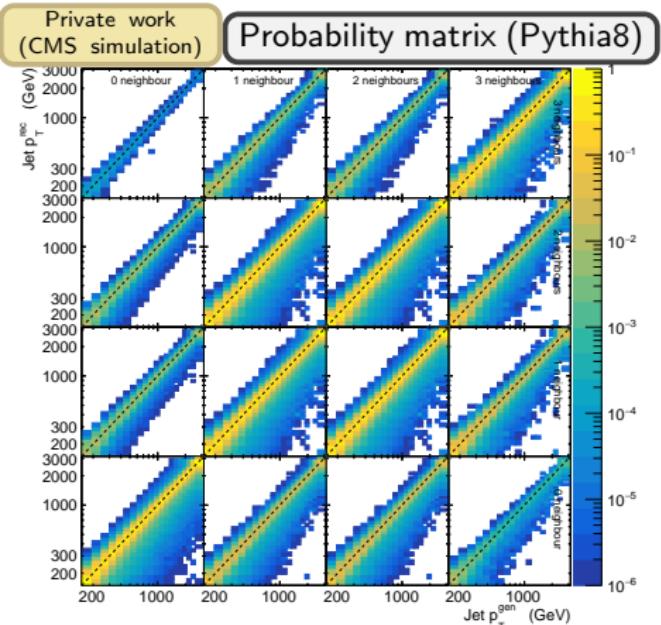
$R_{\Delta\phi}$ sensitivity to α_s





Unfolding

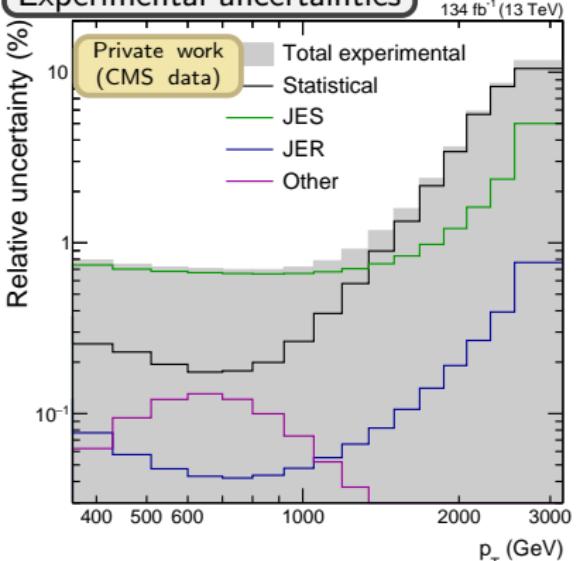
- Data Unfolding: correct the measurement for the detector smearing effects.
- TUNFOLD package: least square minimisation without Tikhonov regularisation,
$$\chi^2 = (Ax + b - y)^T V^{-1} (Ax + b - y)$$
- Equivalent observable definition using 2D $N(p_T, n)$ distribution $\Rightarrow \frac{\sum_{n=0}^{\infty} n N(p_T, n)}{\sum_{n=0}^{\infty} N(p_T, n)}$
where n is the number of neighbours and p_T is jet's transverse momentum.



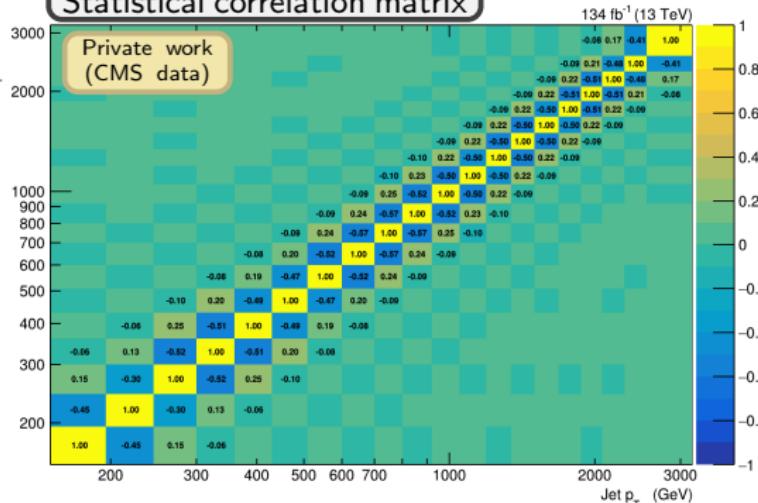


Experimental uncertainties

Experimental uncertainties



Statistical correlation matrix



- **Statistical** (< 11%): from the covariance matrix *after* unfolding.
- **JES** (< 5%): 27 mutually uncorrelated JEC uncertainty sources which are estimated by varying jet p_T : $p_T = p_T(1 \pm \text{unc. source})$
- **JER** (< 0.8%): jet resolution smearing process applied to MC, so that the reconstructed jet p_T resolution matches the one in data.
- **Other** (< 1%): Prefiring corrections, PU profile reweighting, modeling, miss/fakes.

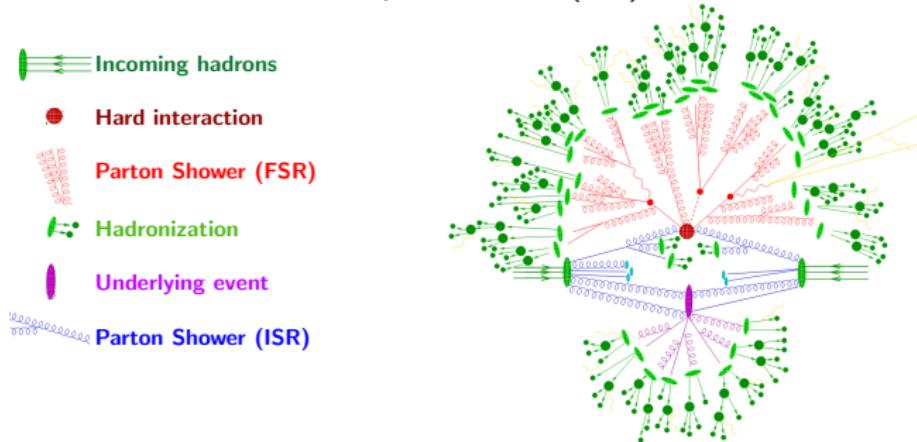


Monte Carlo event generators

- 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.

Monte Carlo event generators

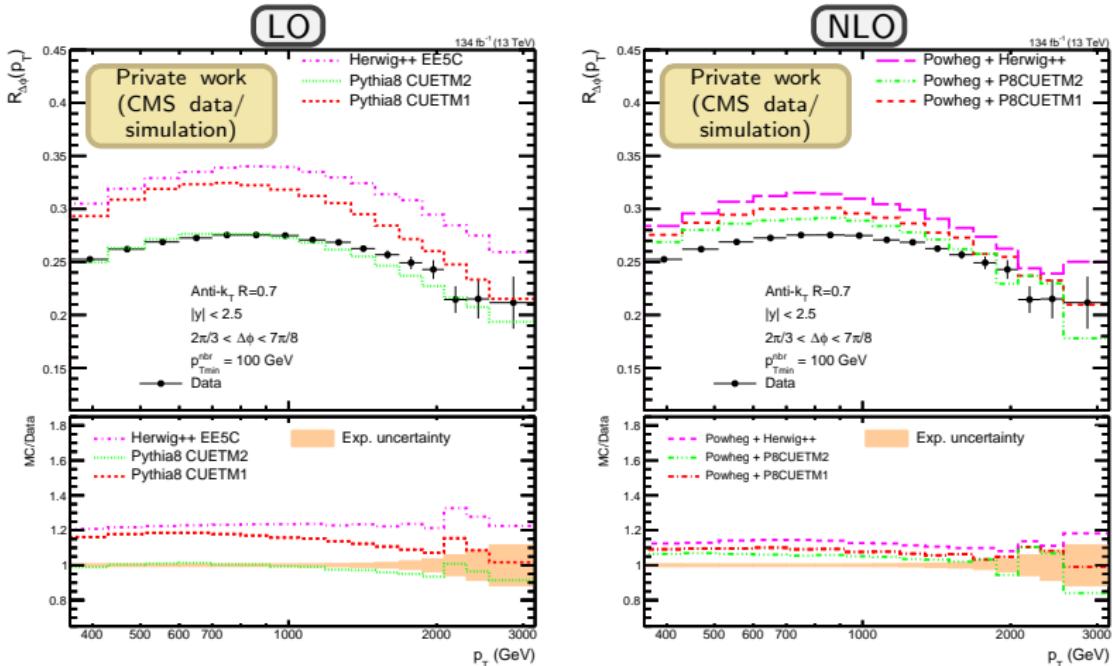
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MC	Matrix Element	Parton Shower	Hadronization	Tune	PDF set
PYTHIA8	2 → 2 (LO)	p_T ordered	Lund string	CUETP8M1	NNPDF2.3
HERWIG++	2 → 2 (LO)	Angular ordered	Cluster model	CUETP8M2	NNPDF3.0
POWHEG	2 → 2 (NLO), 2 → 3 (LO)	PYTHIA8 PYTHIA8 HERWIG++	PYTHIA8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



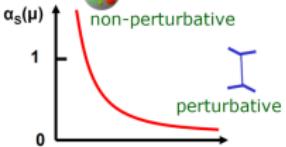
Monte Carlo event generators



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



Cross section predictions

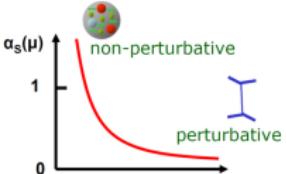


Factorisation theorem of QCD

$$\sigma_{pp \rightarrow X} = \sum_{a,b} \int_0^1 dx_a dx_b f_{a/h_1}(x_a, \mu_f) f_{b/h_2}(x_b, \mu_f) \hat{\sigma}_{ab \rightarrow X}(\mu_f, \mu_r)$$



Cross section predictions



Factorisation theorem of QCD

$$\sigma_{pp \rightarrow X} = \sum_{a,b} \int_0^1 dx_a dx_b \left[f_{a/h_1}(x_a, \mu_f) f_{b/h_2}(x_b, \mu_f) \right] \hat{\sigma}_{ab \rightarrow X}(\mu_f, \mu_r)$$

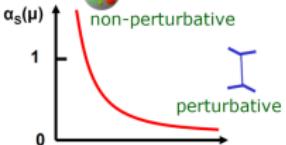
PDFs available via LHAPDF

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
NNPDF31	0.1180	0.106 - 0.130

+ PDF uncertainties using Hessian/eigenvector methods.



Cross section predictions



Factorisation theorem of QCD

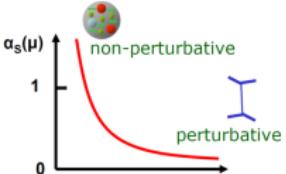
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Fixed Order QCD predictions (parton level)

- $\hat{\sigma}$ is calculated with NLOJET++ package
(up to 3 jets @NLO)



Cross section predictions



Factorisation theorem of QCD

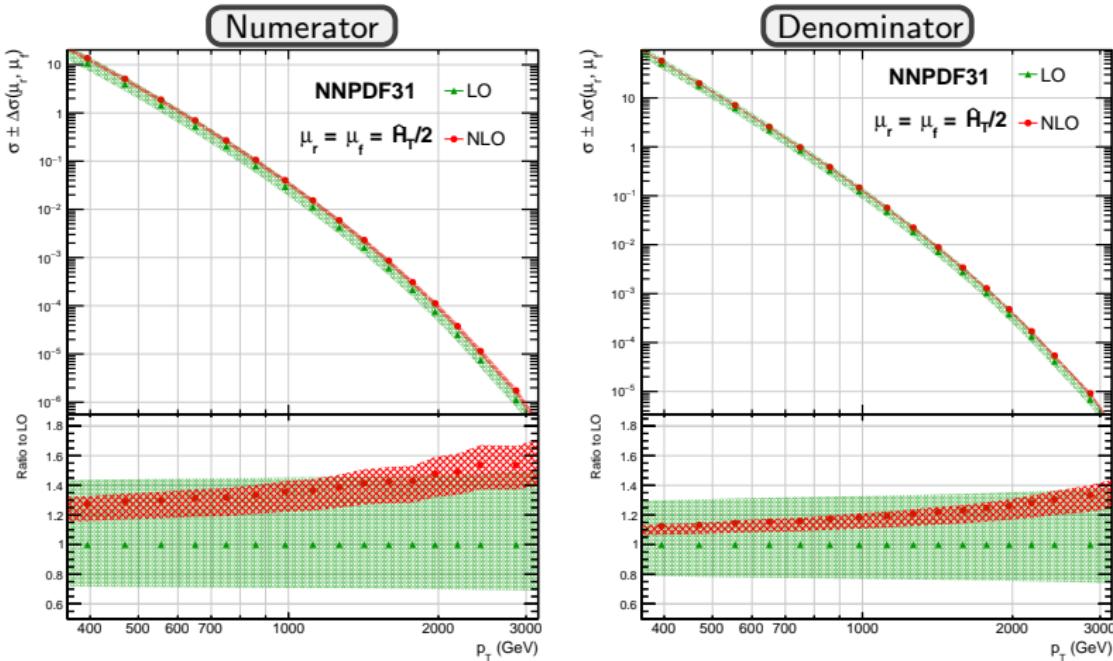
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Fixed Order QCD predictions (parton level)

- $\hat{\sigma}$ is calculated with NLOJET++ package (up to 3 jets @NLO)
- **fastNLO** framework for the evaluation of LO, NLO cross sections (σ).
- $\mu_r = \mu_f = \hat{H}_T/2$, where $\hat{H}_T = \sum_{i \in \text{partons}} p_{T,i}$
- Scale uncertainties: $\frac{1}{2} \leq \mu_r/\mu_f \leq 2$



Cross section predictions



- K factors (NLO/LO): 1.30-1.55 for numerator and 1.20-1.35 for denominator.
- NLO scale uncertainties: 9-17% for numerator and 5-10% for denominator.

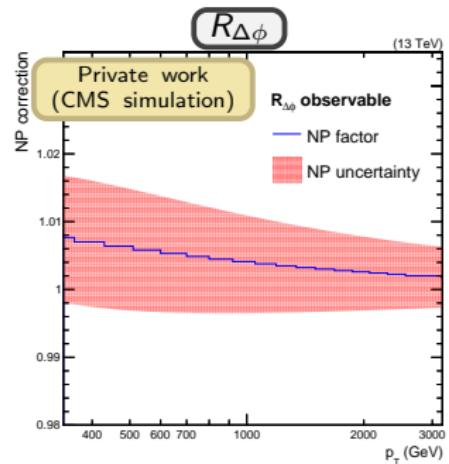
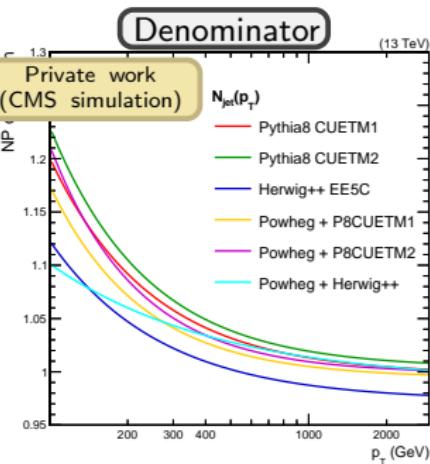
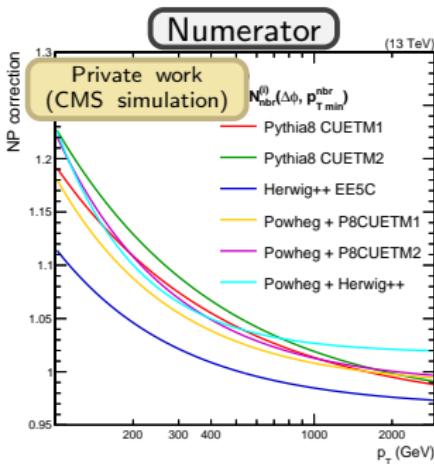
Non-perturbative corrections

- Fixed order QCD predictions are available at parton level only
→ they should be corrected for the non-perturbative (NP) effects of multiple parton interactions (MPI) and hadronization (HAD).

- NP correction factors:

$$C^{\text{NP}} = \frac{\sigma^{\text{PS+MPI+HAD}}}{\sigma^{\text{PS}}}$$

- A simple polynomial function $a + b \cdot p_T^c$ is used for the parametrization of C^{NP} .
- An envelope is constructed from the predictions of different MC event generators.





Electroweak corrections

- To improve the accuracy of theoretical predictions the electroweak (EW) corrections are also considered.
- 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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NLO EW corrections formulation

Pure NLO EW corrections for n-jet production:

$$\sigma_{nj}^{\text{NLO EW}} = \sigma_{nj}^{\text{LO}} + \sigma_{nj}^{\Delta\text{NLO}_1}, \quad (1)$$

ΔNLO_1 : virtual and real EW corrections.

Additive combination to QCD process:

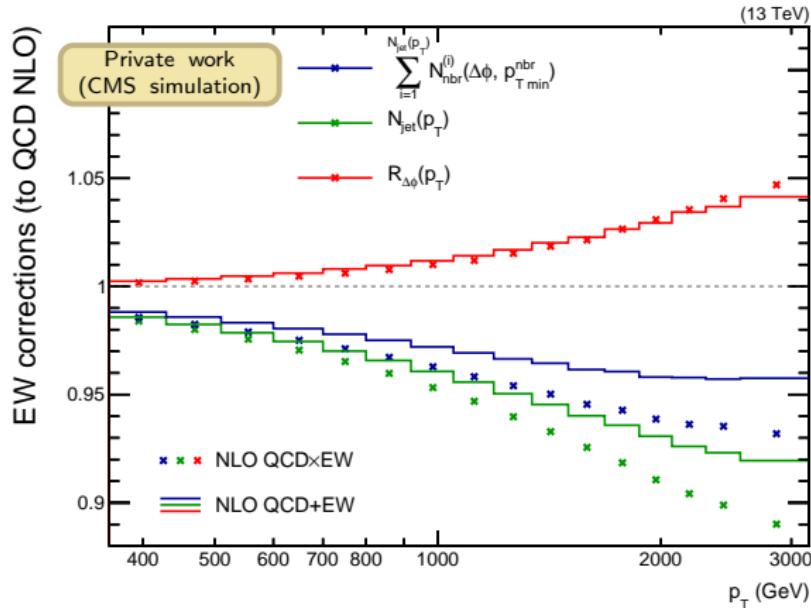
$$\sigma_{nj}^{\text{NLO QCD+EW}} = \sigma_{nj}^{\text{LO}} + \sigma_{nj}^{\Delta\text{NLO}_0} + \sigma_{nj}^{\Delta\text{NLO}_1}, \quad (2)$$

ΔNLO_0 : virtual and real QCD corrections. Multiplicative combination to QCD process:

$$\sigma_{nj}^{\text{NLO QCD}\times\text{EW}} = \sigma_{nj}^{\text{LO}} \left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_0}}{\sigma_{nj}^{\text{LO}}} \right) \left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_1}}{\sigma_{nj}^{\text{LO}}} \right) \quad (3)$$

Electroweak corrections

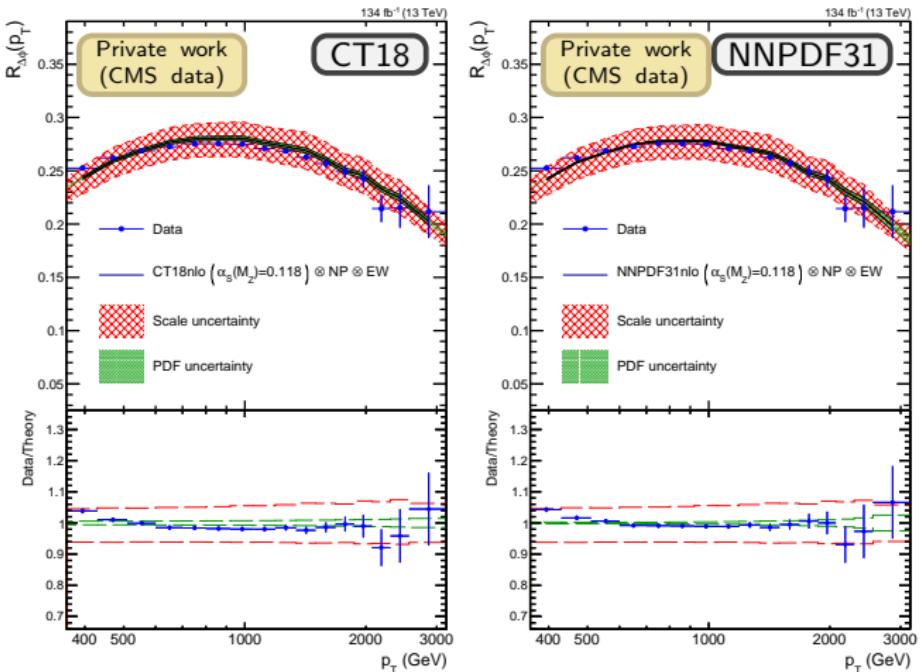
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- EW corrections for $R_{\Delta\phi} < 5\%$, EW uncertainties $< 0.6\%$.



Data-Theory comparison



- Good agreement between data and theoretical predictions for all the PDF sets.
- PDF uncertainties are of the order of 1-2%.
- Scale uncertainties are dominant: 2-8%.



Determination of $\alpha_s(M_Z)$

- Minimization of $\chi^2 = \sum_{ij}^N (D_i - T_i) C_{ij}^{-1} (D_j - T_j)$ between the N measurements D_i and theoretical predictions T_i (corrected for the NP & EW effects).



Determination of $\alpha_s(M_Z)$

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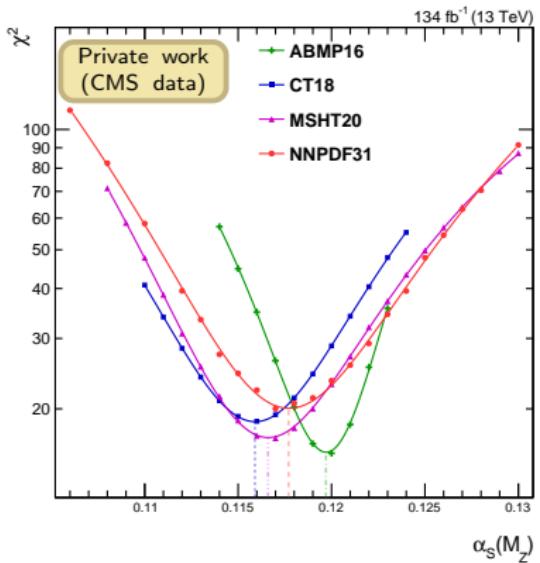
and theoretical predictions T_i (corrected for the NP & EW effects).

The covariance matrix C_{ij} is composed as:

$$C = C_{\text{stat}} + C_{\text{uncor}} + \left(\sum_{\text{sources}} C_{\text{JES}} \right) + C_{\text{unfold}} + C_{\text{pref}} + C_{\text{NP}} + C_{\text{PDF}} + C_{\text{EW}}$$

Experimental uncertainties

100% correlated among p_T bins & treated as multiplicative

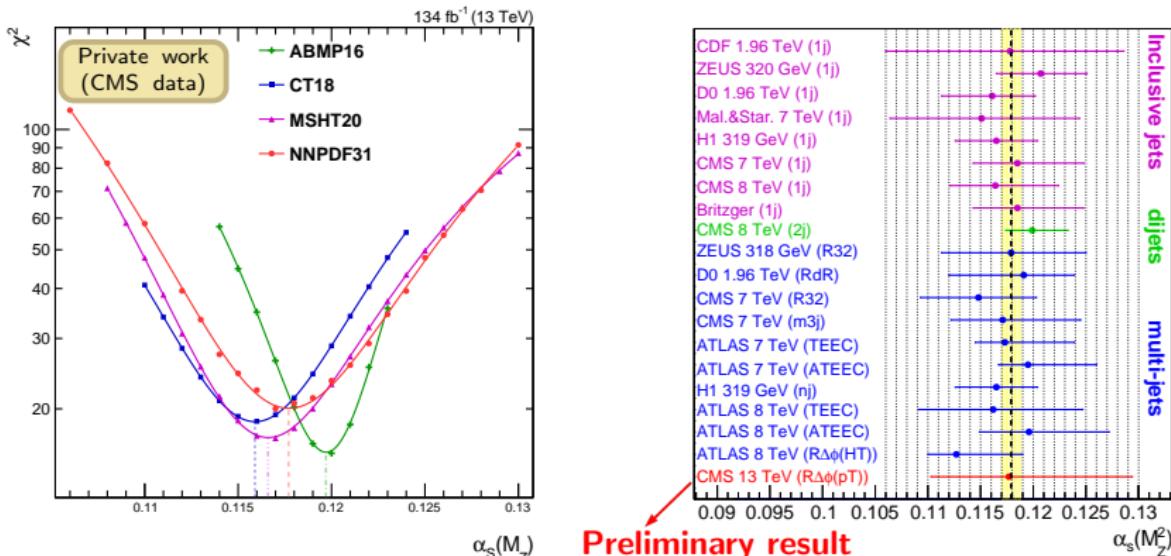
Determination of $\alpha_s(M_Z)$ 

PDF set	$\alpha_s(M_Z)$	Exp	NP	PDF	EW	Scale	Total	χ^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
NNPDF31	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.

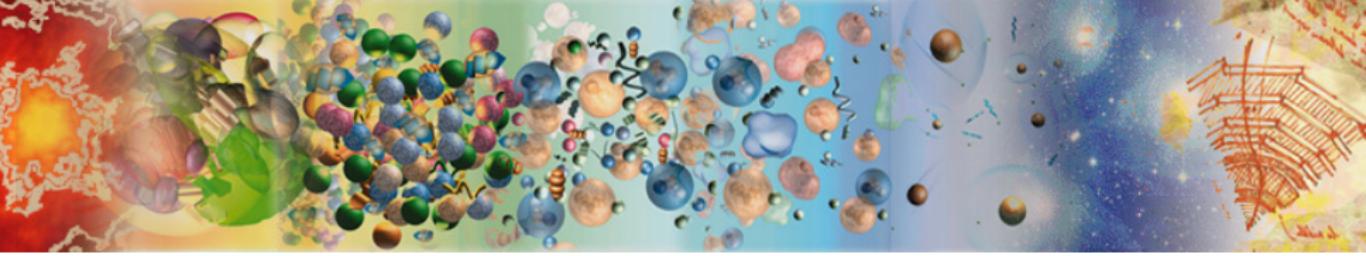


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NNPDF31	0.1177	0.0013	0.0011	0.0010	0.0003	+0.0114 -0.0068	+0.0116 -0.0071	20/16

- Results also compatible with the world average: $\alpha_s(M_Z) = 0.1179 \pm 0.0009$.



THANK YOU FOR YOUR ATTENTION



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Hellenic Foundation for
Research & Innovation

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