# Differential jet cross sections at the CMS experiment

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on behalf of the CMS Collaboration

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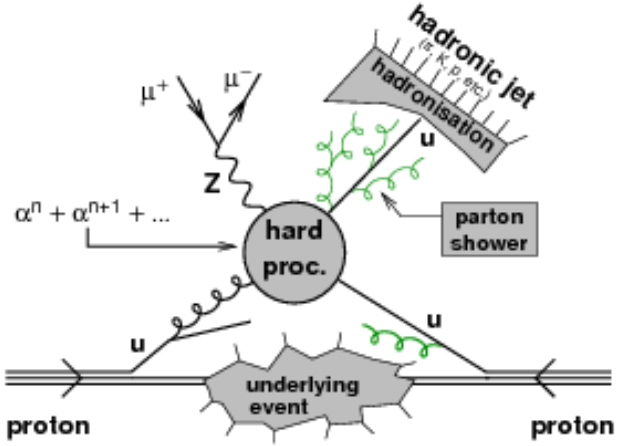
## Jets :

- key component to extend our understanding of the Standard Model physics
- signatures of large momentum transfers at short distances, belong primarily to perturbative domain of Quantum Chromodynamics (pQCD)
- produced abundantly in the collisions of protons at the Large Hadron Collider (LHC)
- important backgrounds for many new physics models

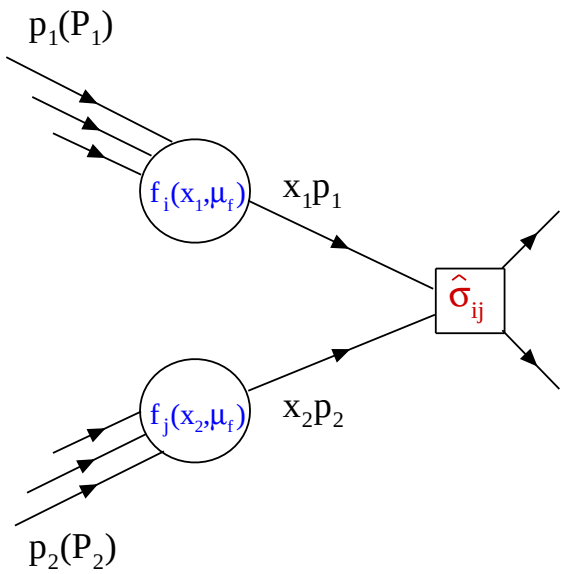



## Inclusive jet cross section measurement :

- gives important information about the strong coupling constant $\alpha_S$

$$\sigma_{\text{i-jet}} = \sigma(\text{pp} \to \text{i jets + X}) \propto \alpha_S^{\text{i}}$$

- provides a deep insight to understand the proton structure by deriving constraints on the parton distribution functions (PDFs)




$$\sigma_{P_1 P_2 \to X} = \sum_{i,j} \int dx_1 dx_2 f_{i,P_1}(x_1, \mu_f) f_{j,P_2}(x_2, \mu_f) \times \hat{\sigma}_{ij \to X}\left(x_1 p_1, x_2 p_2, \alpha(\mu_r^2), \frac{Q^2}{\mu_f^2}\right)$$

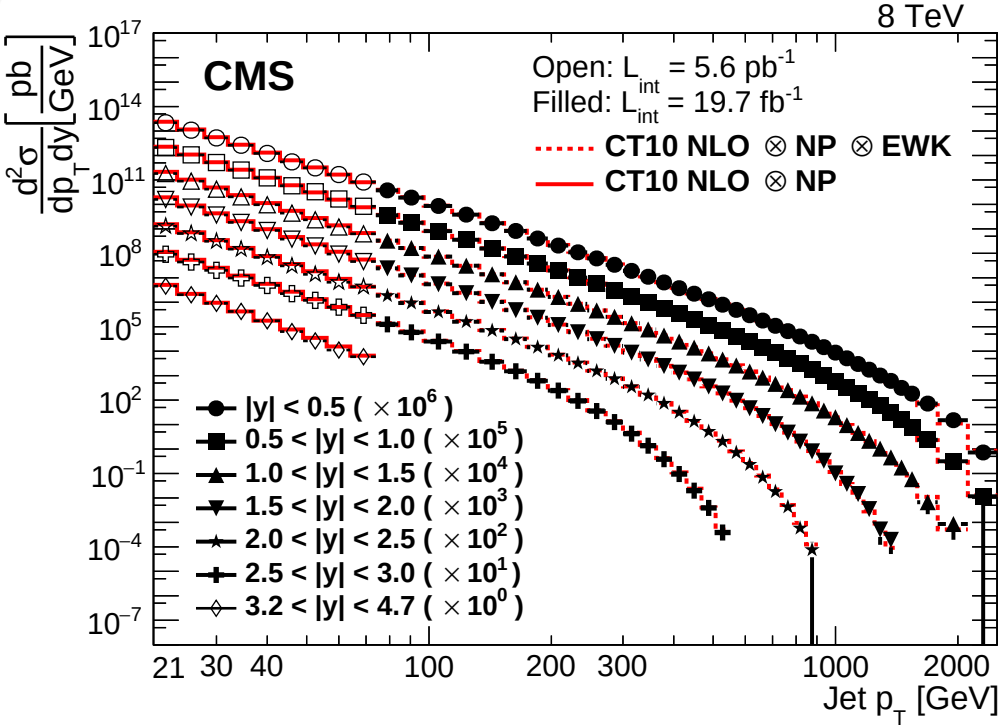
# Inclusive jet production @ 8 TeV

**Double-differential cross-section**

$$\frac{d^2\sigma}{dp_{\mathrm{T}}dy} = \frac{1}{\epsilon\ \mathcal{L}_{\mathrm{int,eff}}} \frac{N_{\mathrm{jets}}}{\Delta p_{\mathrm{T}}(2\Delta|y|)}$$

- Measurement at 8 TeV
  $\mathcal{L} = 19.7\ \mathrm{fb}^{-1}$ and $\mathcal{L} = 5.6\ \mathrm{pb}^{-1}$
- anti-$k_t$ jets with R = 0.7
- $21 \leq p_{\mathrm{T}} < 74$ GeV, upto $|y| = 4.7$

  $74 \leq p_{\mathrm{T}} < 2500$ GeV, upto $|y| = 3.0$
- Theoretical NLO calculations :
  - using CT10 PDF set
  - corrected for non-perturbative (NP) and electroweak (EWK) effects

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# Inclusive jet production @ 8 TeV

## Data/theory using the CT10 NLO PDF :

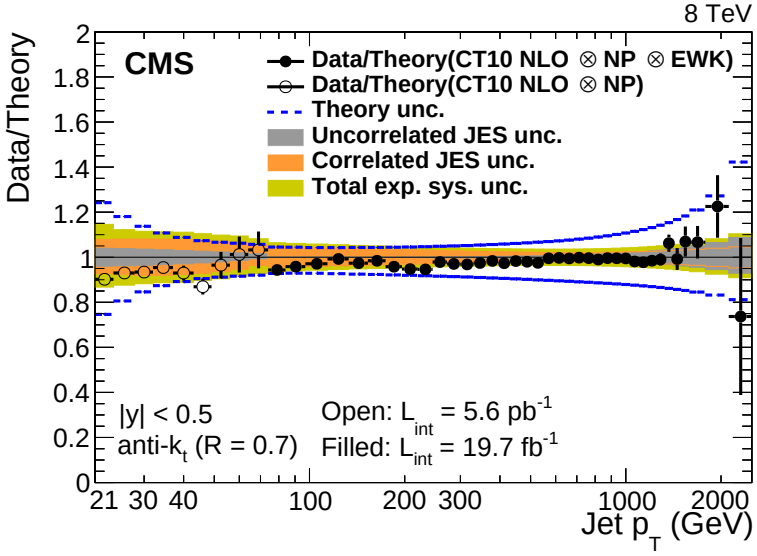
- Good agreement except low-$p_T$ region
- Data uncertainties : jet energy scale (1-45%), lumi (2.6%)
- NLO uncertainties : scale (5-40%), PDF (10-100%)

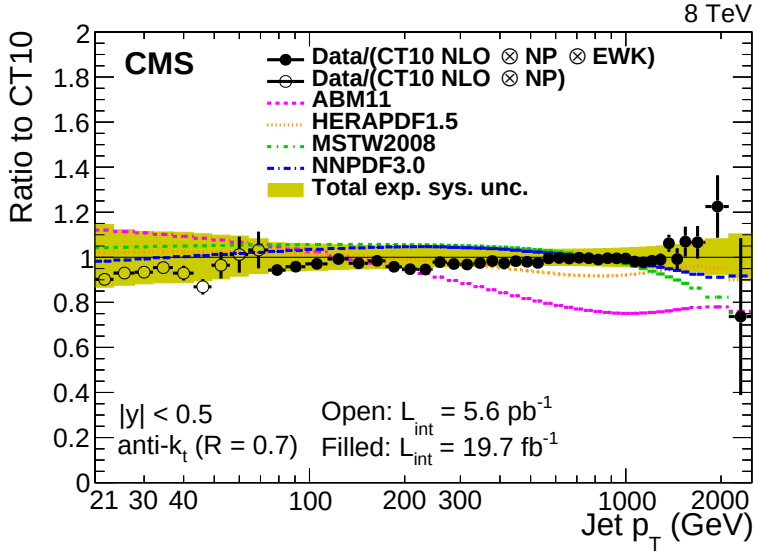
## Ratios to CT10 PDF :

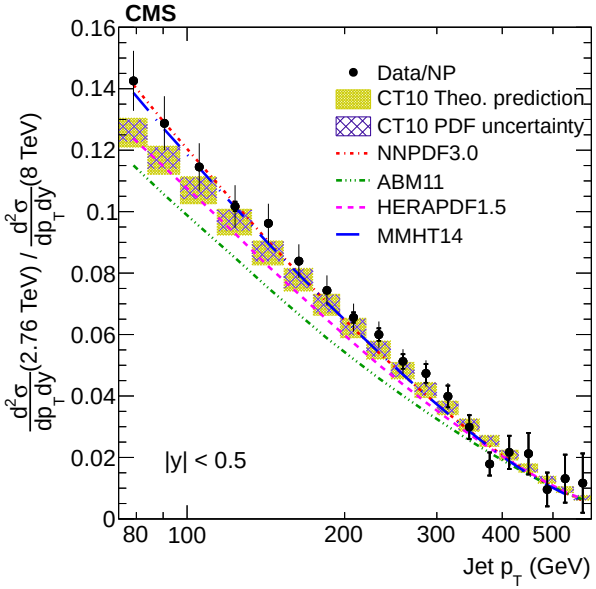
- Significant discrepancies with ABM11 PDF

## Ratios 2.76/8 TeV, 7/8 TeV :

- Partial reduction of uncertainties → better sensitivity to PDFs

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## QCD analysis using HeraFitter (1.1.1)

- Inclusive cross sections + HERA inclusive DIS :
  - probes hadronic parton-parton interaction over a wide range of $x$ and $Q$
  - constraints on PDFs
  - significant improvement of the gluon distribution

## Extraction of $\alpha_S$

- Least square minimization on $p_{\mathrm{T}}(y)$ spectrum :
  - using the CT10 NLO PDF set

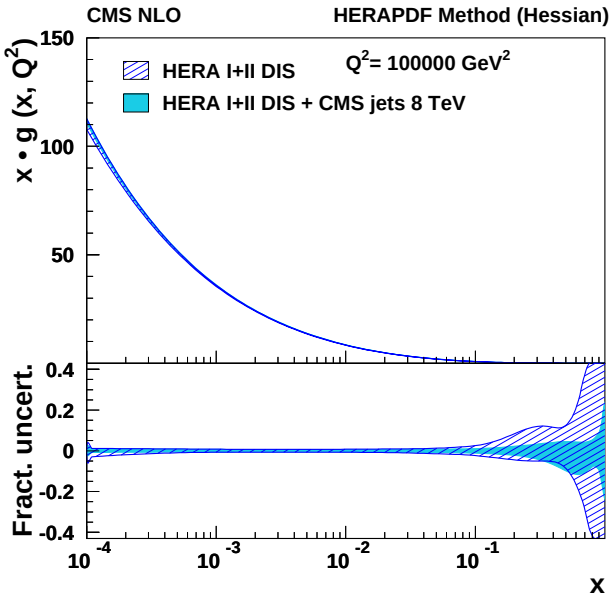
$$\alpha_S(M_Z) = 0.1164\ ^{+0.0060}_{-0.0043}$$

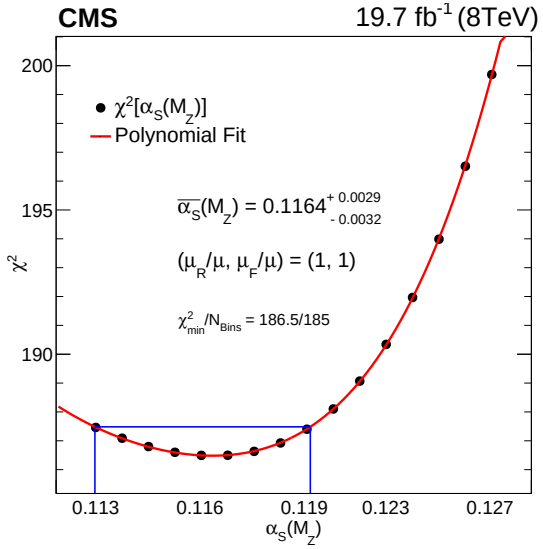
  - using the NNPDF3.0 NLO PDF set

$$\alpha_S(M_Z) = 0.1172\ ^{+0.0083}_{-0.0075}$$

- Consistent with the world average value :

$$\alpha_S(M_Z) = 0.1181 \pm 0.0011$$

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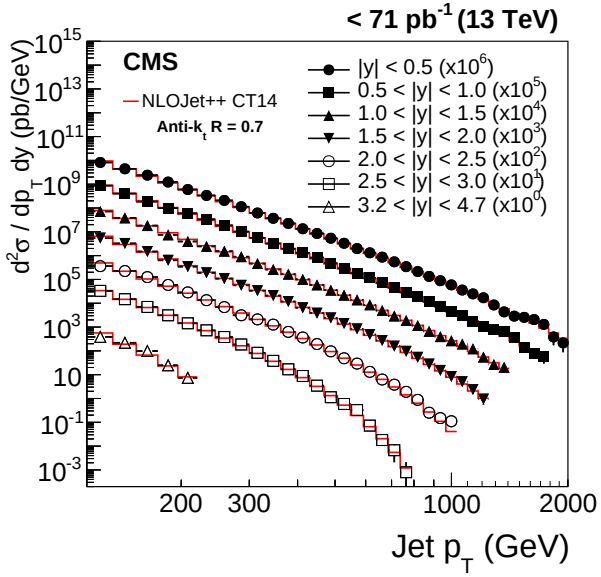
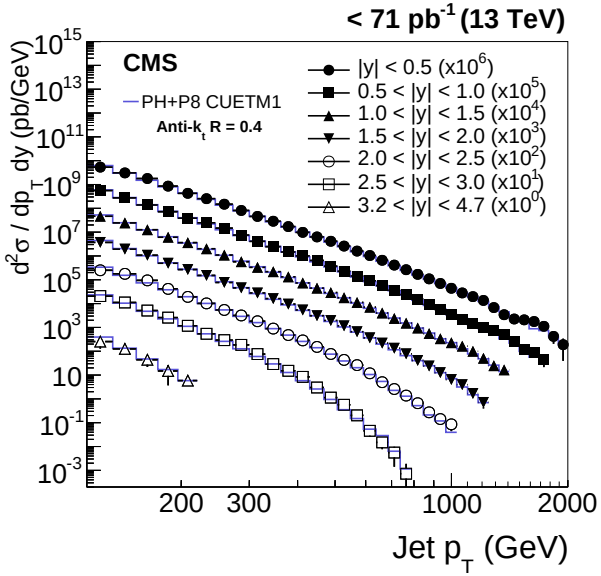
# Inclusive jet production @ 13 TeV

**Double-differential cross-section**

$$\frac{d^2\sigma}{dp_{\mathrm{T}}\,dy} = \frac{1}{\epsilon\ \mathcal{L}_{\mathrm{int,eff}}}\frac{N_{\mathrm{j}}}{\Delta p_{\mathrm{T}}\Delta y}$$

- Measurement at 13 TeV
  $\mathcal{L} = 71\ \mathrm{pb}^{-1}$ and $\mathcal{L} = 44\ \mathrm{pb}^{-1}$
- anti-$k_t$ jets with R = 0.4 and R = 0.7
- $p_{\mathrm{T}} < 2$ TeV
- Large rapidity coverage : $|y| < 3$, $3.2 < |y| < 4.7$
- Theoretical NLO calculations :
  - using CT14 PDF set
  - corrected for non-perturbative (NP) and electroweak (EWK) effects
- x-sections accuratey described for R = 0.7, while for R = 0.4 theory overestimates by 5–10%

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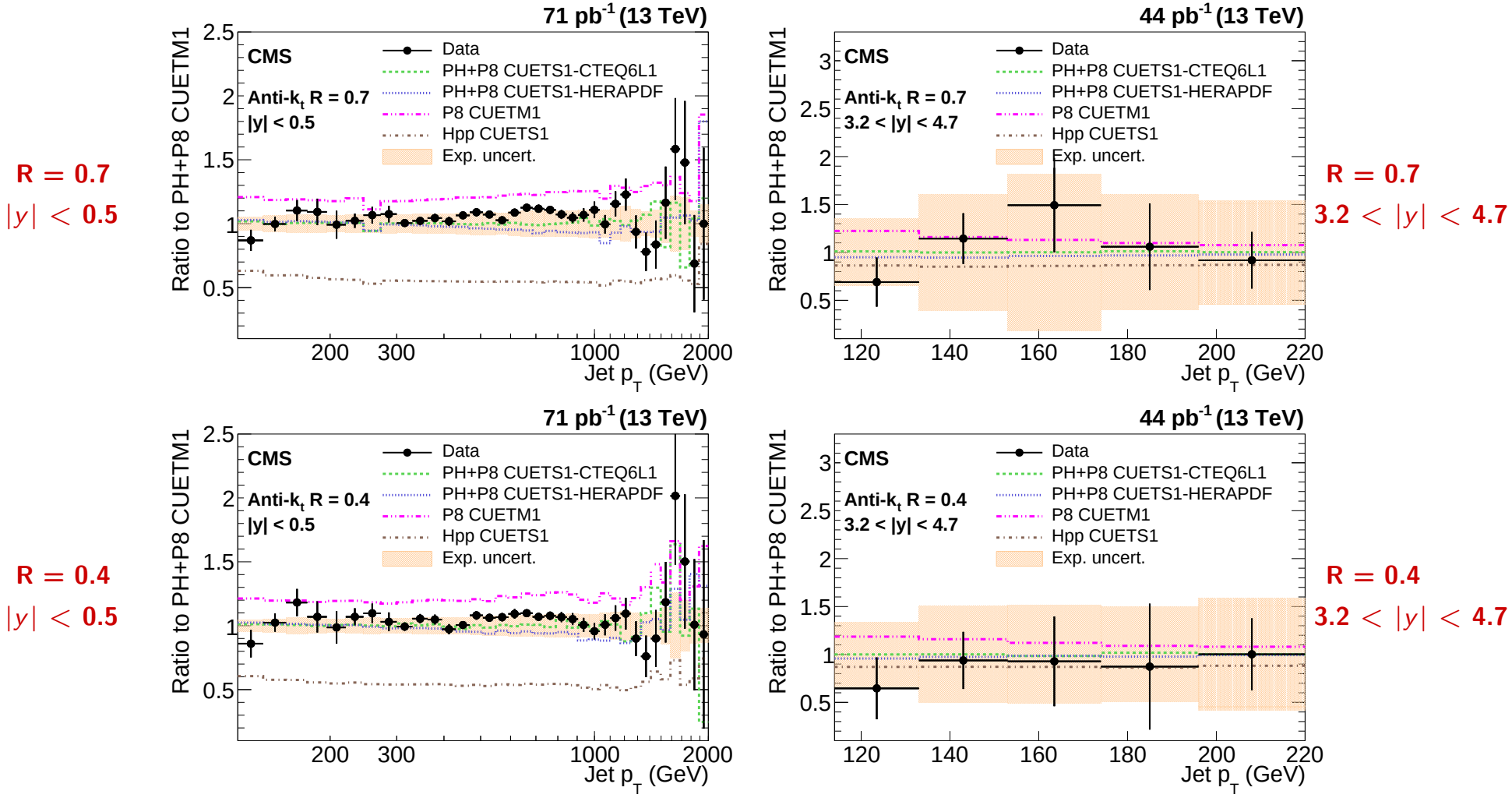
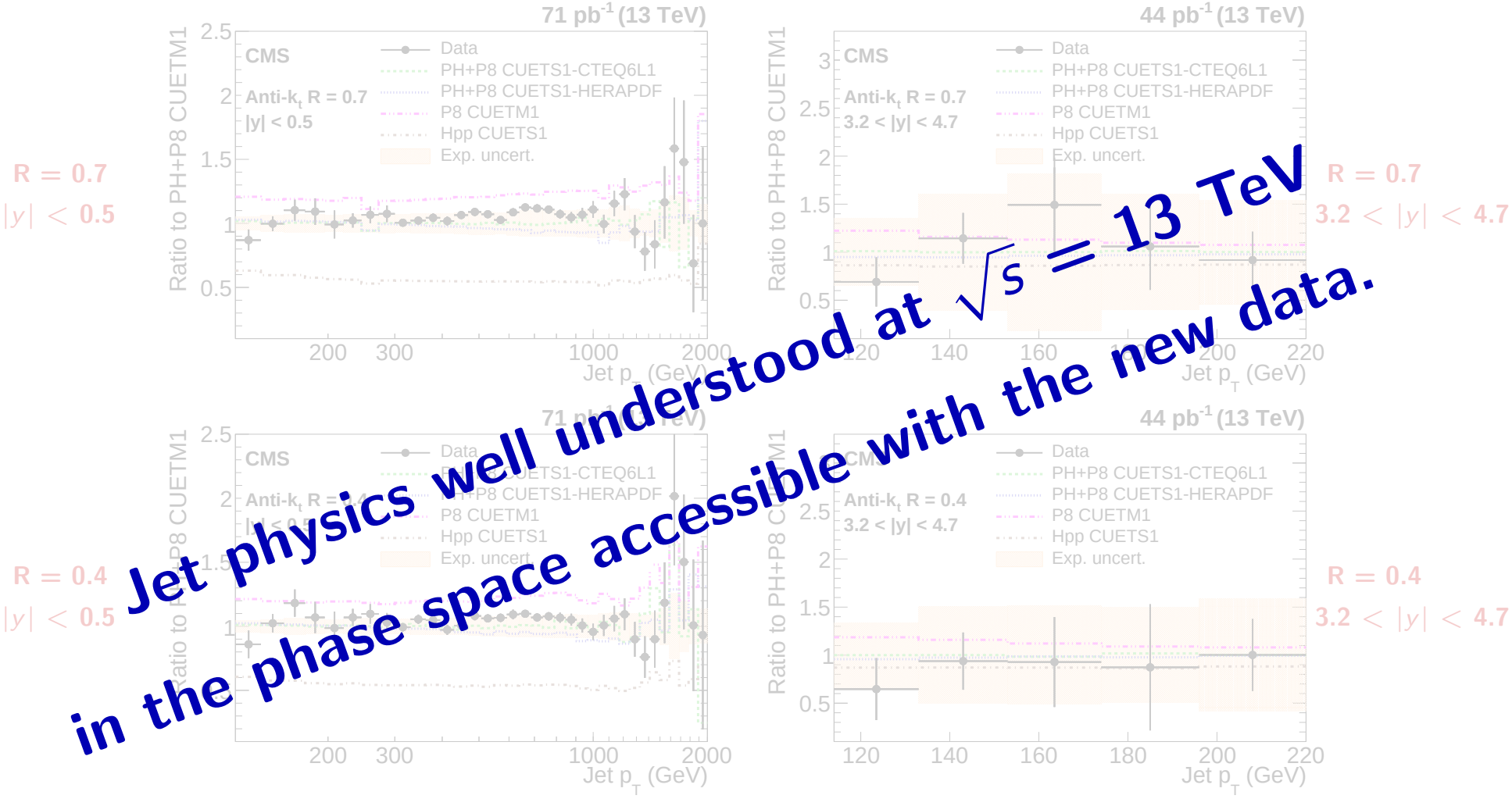
# Inclusive jet production @ 13 TeV




- PYTHIA8 CUETM1 (LO) agrees well in shape for only |y| < 1.5.
- HERWIG++ CUETS1 (LO) agrees in shape for all rapidity bins.
- POWHEG+PYTHIA8 (NLO) with various tunes show good agreement for both R.

# Inclusive jet production @ 13 TeV



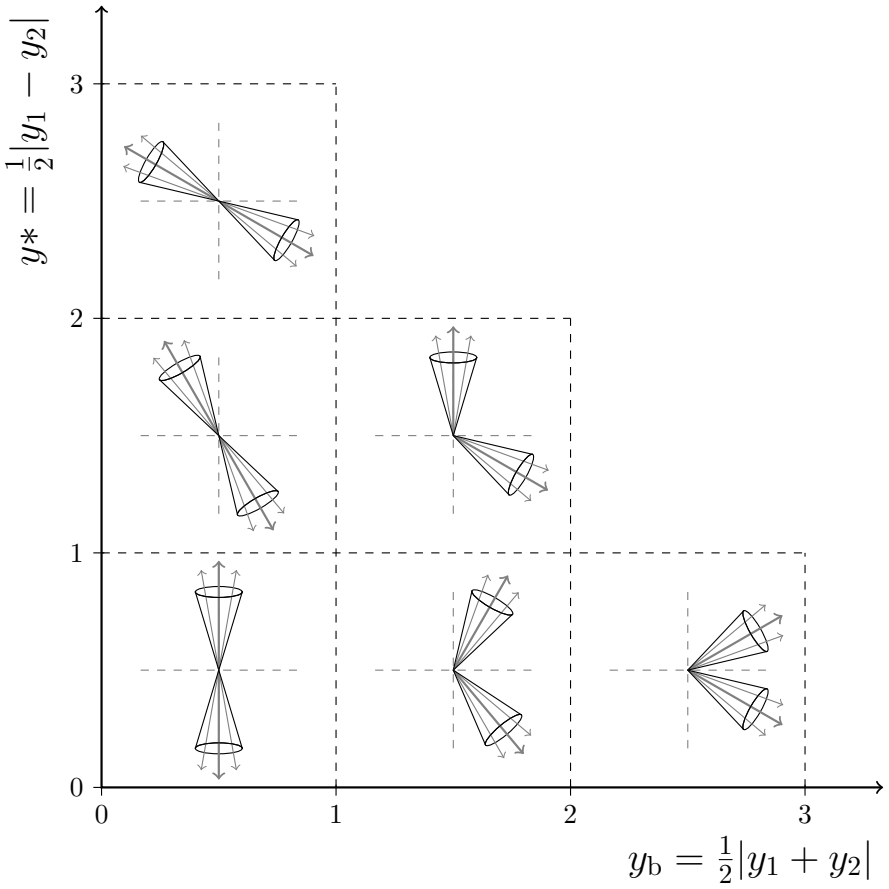

**Jet physics well understood at $\sqrt{s} = 13$ TeV in the phase space accessible with the new data.**

- PYTHIA8 CUETM1 (LO) agrees well in shape for only |y| < 1.5.
- HERWIG++ CUETS1 (LO) agrees in shape for all rapidity bins.
- POWHEG+PYTHIA8 (NLO) with various tunes show good agreement for both R.

**Triple differential cross-section**

$$\frac{d^3\sigma}{dp_{\mathrm{T,avg}}\,dy^\star\,dy_b} = \frac{1}{\epsilon\ \mathcal{L}_{\mathrm{int}}^{\mathrm{eff}}}\frac{N}{\Delta p_{\mathrm{T,avg}}\Delta y^\star\Delta y_b}$$

- Measurement at 8 TeV, $\mathcal{L} = 19.7\ \mathrm{fb}^{-1}$
- anti-$k_t$ jets with R = 0.7
- **Cross section as a function of the :**
  - average transverse momentum,
    $p_{\mathrm{T,avg}} = \frac{1}{2}(p_{\mathrm{T},1} + p_{\mathrm{T},2})$
  - half the rapidity separation,
    $y^\star = \frac{1}{2}|y_1 - y_2|$
  - boost of the two leading jets,
    $y_b = \frac{1}{2}|y_1 + y_2|$

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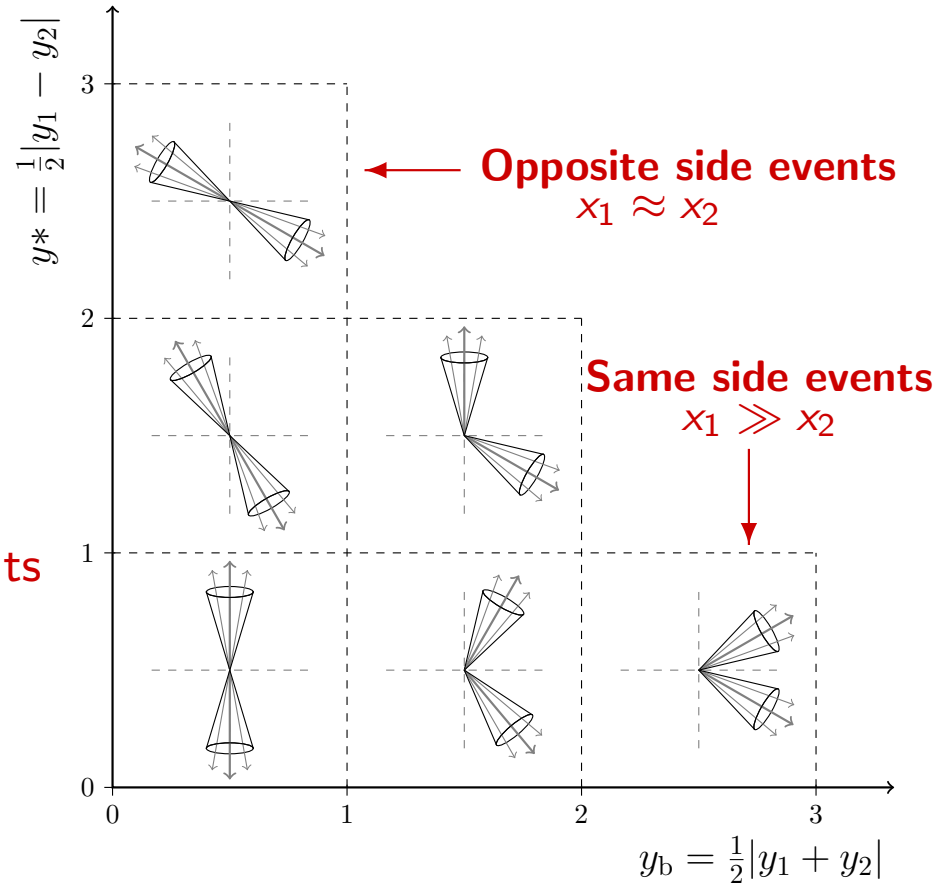
**Triple differential cross-section**

$$\frac{d^3\sigma}{dp_{\mathrm{T,avg}}\,dy^\star\,dy_b} = \frac{1}{\epsilon\ \mathcal{L}_{\mathrm{int}}^{\mathrm{eff}}}\frac{N}{\Delta p_{\mathrm{T,avg}}\Delta y^\star\Delta y_b}$$

- Dijet rapidities and the parton momentum fractions are related :

$$x_{1,2} = \frac{p_{\mathrm{T}}}{\sqrt{s}}\left(e^{\pm y_1} + e^{\pm y_2}\right)$$

- For small $y_b$, $x_1 \approx x_2 \rightarrow$ Opposite side events
- For large $y_b$, $x_1 \gg x_2 \rightarrow$ Same side events (Boosted region)

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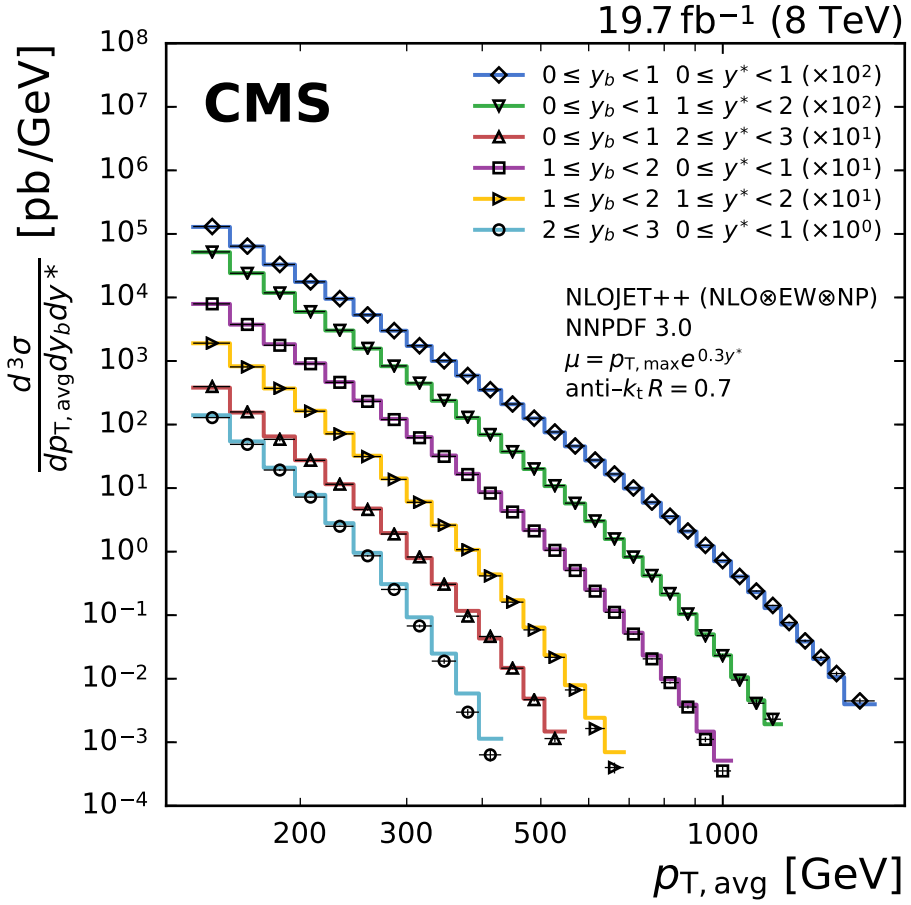
# Triple-Differential dijets

- $p_{\mathrm{T,avg}}$ spectrum for six phase-space regions in $y^{\star}$ and $y_b$
- Theoretical NLO predictions :
  - using NLOJET++ with NNPDF 3.0 PDF set
  - corrected for non-perturbative (NP) and electroweak (EW) effects
- Data are well described by NLO predictions except for the boosted region.

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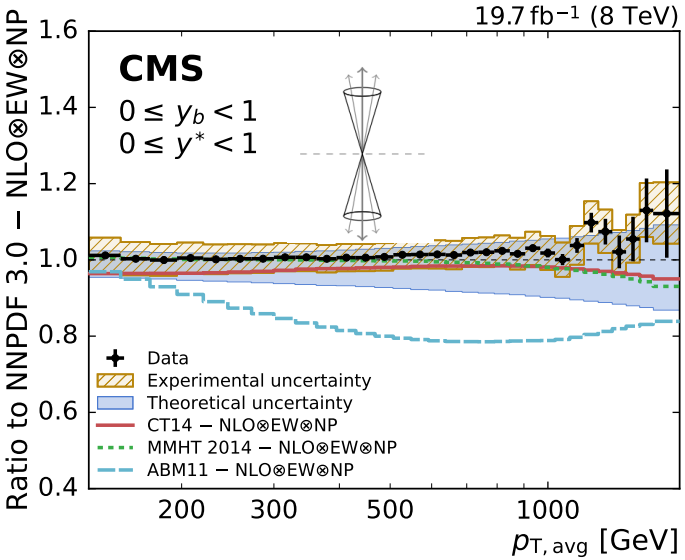
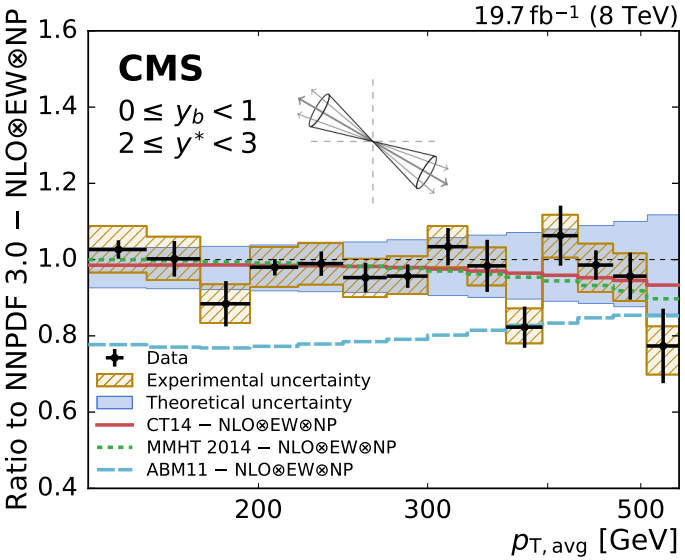
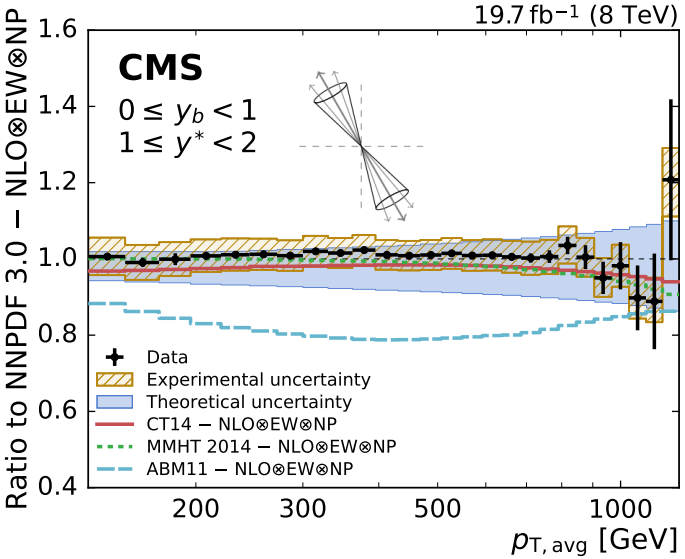
# Triple-Differential dijets

- Ratios to NNPDF 3.0 - NLO $\otimes$ EW $\otimes$ NP
- **Data points with statistical uncertainty**
- Experimental uncertainty
- Theoretical uncertainty (PDF, Scale and NP)
- Good agreement with MMHT2014 and CT14 PDF NLO calculations
- ABM11 PDF underestimates the predictions

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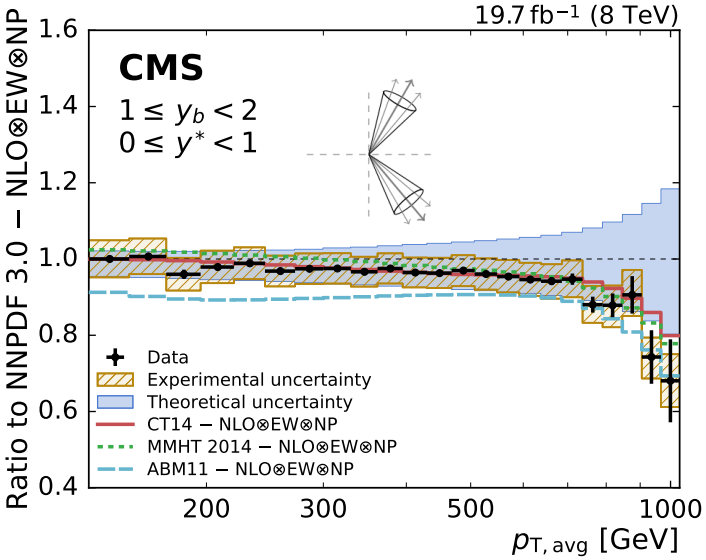
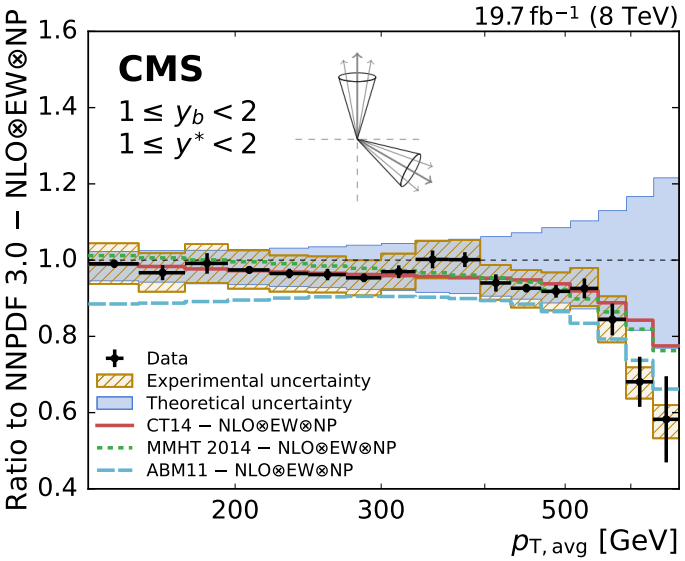
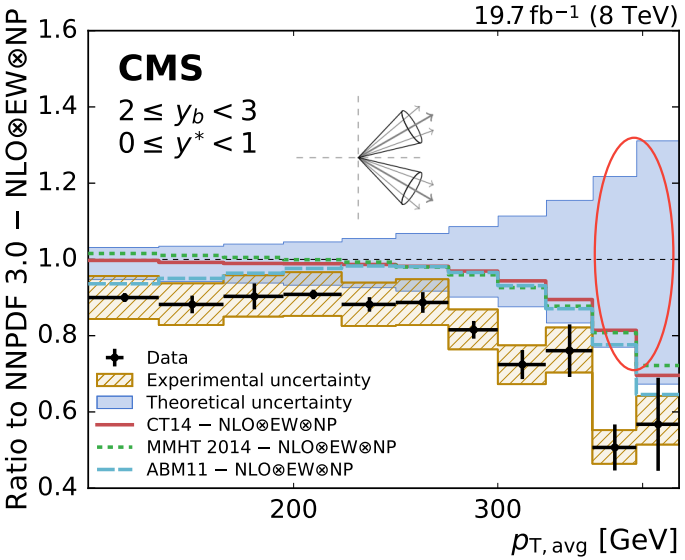
# Triple-Differential dijets

- Data are well described in most of the analysed phase spaces.
- Differences observed at high $p_{\mathrm{T,avg}}$ and $y_b$ : less known high $x$ region of the PDFs is probed.
- Smaller data uncertainties : potential to constrain the PDFs.

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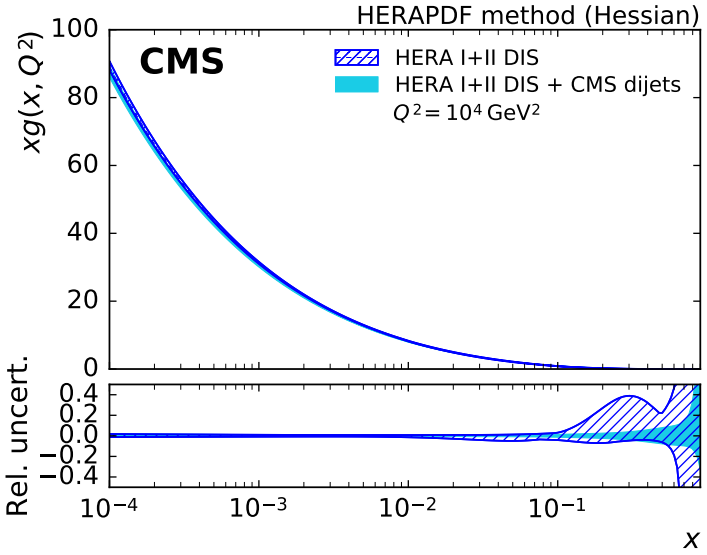
## QCD analysis using XFitter (1.2.2)

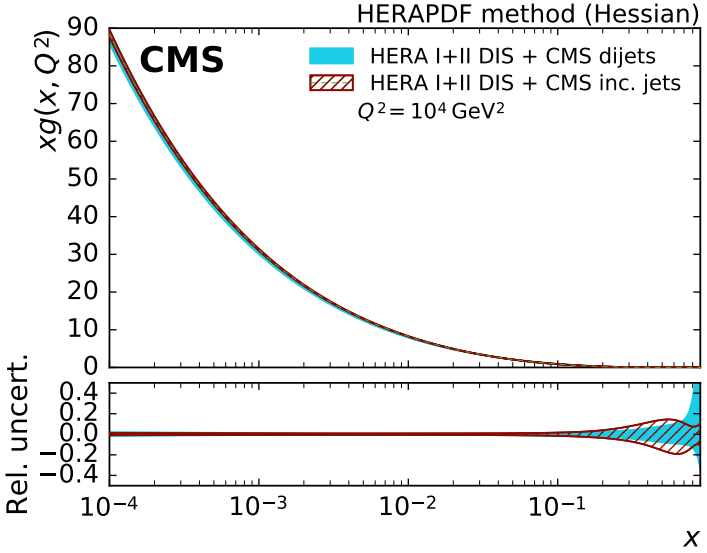
- Dijet cross sections + HERA inclusive DIS :
  - an increased gluon PDF at high $x$ with reduced uncertainties of the PDFs
  - change in shape especially at low $Q^2$
- Comparison of gluon PDFs with inclusive jet data :
  - similar shapes of the PDFs and the uncertainties
- Precise $\alpha_S$ extraction together with PDF fit :

$$\alpha_S(M_Z) = 0.1199 \pm 0.0015(\text{exp})\ ^{+0.0031}_{-0.0020}(\text{theo})$$

- Agreement with the world average value :

$$\alpha_S(M_Z) = 0.1181 \pm 0.0011$$

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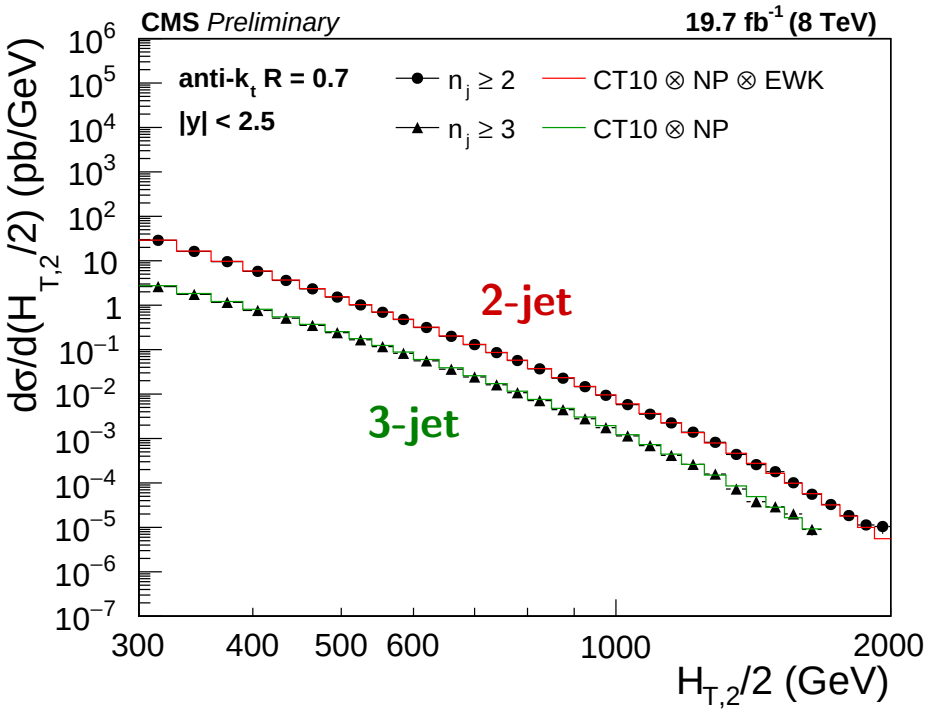
**Differential cross-section**

$$\frac{d\sigma}{d(\mathrm{H_{T,2}}/2)} = \frac{1}{\epsilon\ \mathcal{L}_{\mathrm{int,eff}}} \frac{N_{\mathrm{event}}}{\Delta\left(\mathrm{H_{T,2}}/2\right)}$$

- Measurement at 8 TeV, $\mathcal{L} = 19.7\ \mathrm{fb}^{-1}$
- anti-$k_t$ jets with R = 0.7
- **2-jet and 3-jet event cross sections as a function of :**

$$\mathrm{H_{T,2}}/2 = \frac{1}{2}(p_{\mathrm{T},1} + p_{\mathrm{T},2})$$

- Theoretical NLO calculations :
  - using CT10 PDF set
  - corrected for non-perturbative (NP) and electroweak (EWK) effects



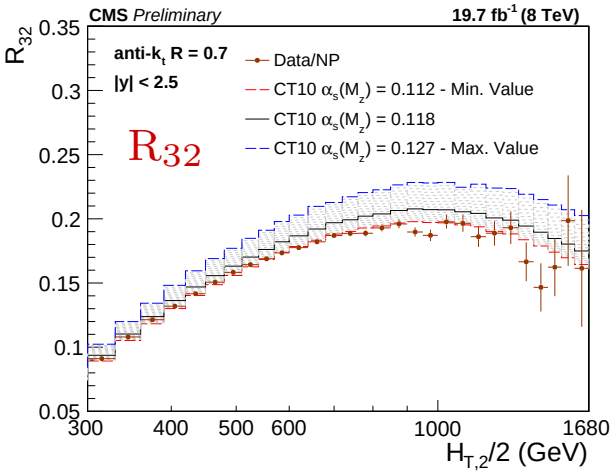

CMS-PAS-SMP-16-008

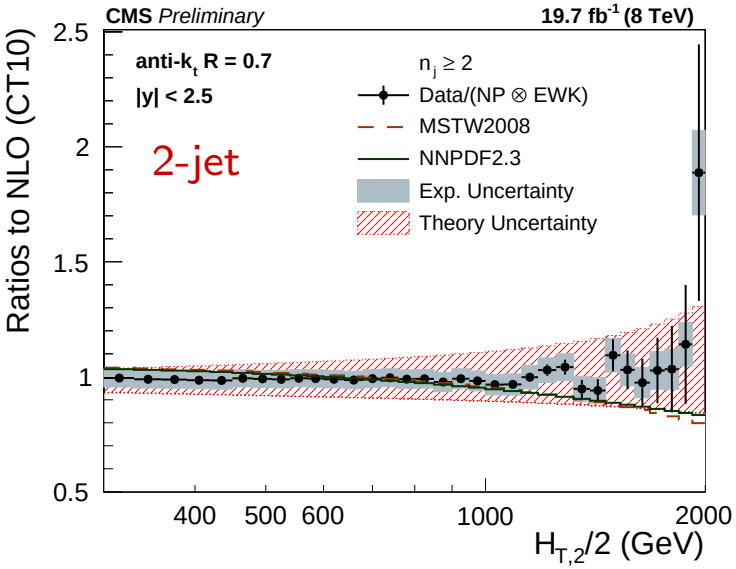
## Multijet cross sections

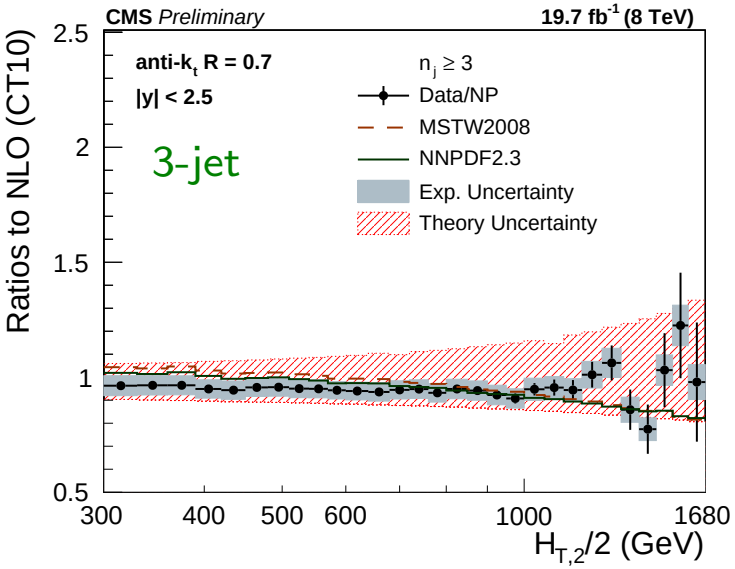
- Data are well described by theory predictions within uncertainty.
- EWK corrections explain the increasing excess of the 2-jet data w.r.t. theory (∼1 TeV).

## Cross section ratio

- $R_{32} = \frac{\sigma_{3\text{-jet}}}{\sigma_{2\text{-jet}}} \sim \alpha_S$
- Experimental uncertainties, theory uncertainties due to NP effects, PDFs, scale choice, EWK corrections may cancel partially or fully
- Better tool to extract $\alpha_S$

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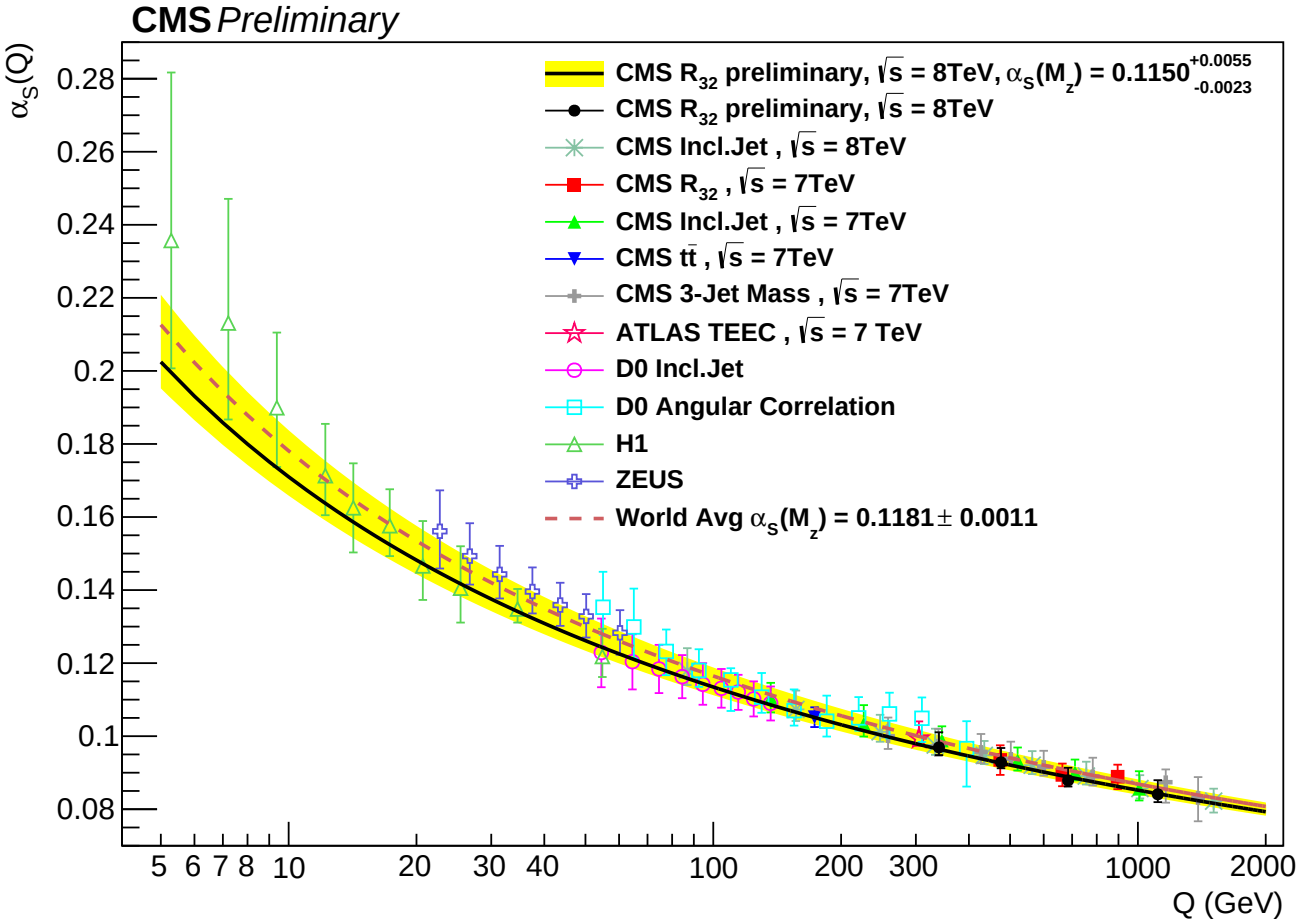
## Determination of $\alpha_S$

- By minimizing the $\chi^2$ between the measurement and the theory
- In a fit to $\mathrm{R}_{32}$, using the MSTW2008 PDF set : $\alpha_S(M_Z) = 0.1150 \pm 0.0023(\text{all except scale})\ ^{+0.0050}_{-0.0000}(\text{scale})$
- $\alpha_S(M_Z)$ extracted in ranges of $\mathrm{H}_{\mathrm{T},2}/2 \rightarrow$ evolved to $\alpha_S(Q)$

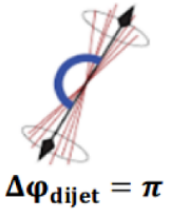


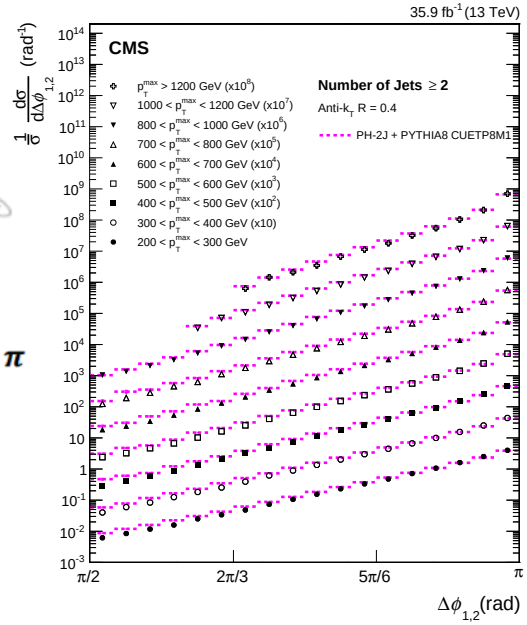
# Azimuthal correlations

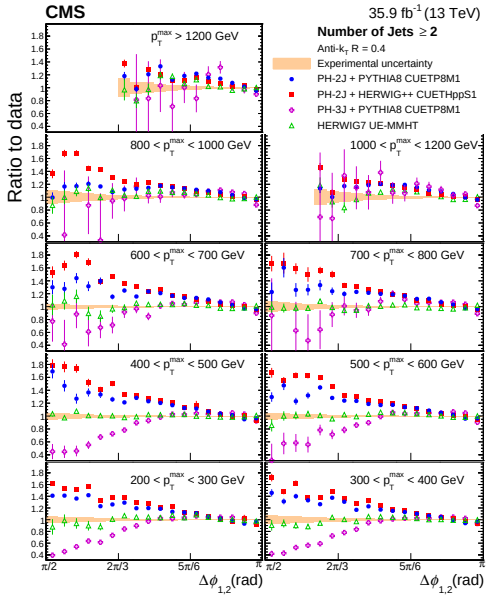
**Normalized differential cross-section**

$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi_{1,2}}, \quad \frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi_{2j}^{min}}(\text{3-jet and 4-jet})$$

- Measurement at 13 TeV, $\mathcal{L} = 35.9$ fb$^{-1}$
- anti-$k_t$ jets with R = 0.4
- **Normalized cross sections as a function of the :**
  - **azimuthal angular separation** between the two highest leading $p_{\mathrm{T}}$ jets
  - **minimum azimuthal angular separation** between any two of the three or four leading $p_{\mathrm{T}}$ jets (3-jet and 4-jet)
- Spectrum gets flatter and become more sensitive to parton shower on moving from 2-jet to 3-jet to 4-jet
- Best agreement is given by Herwig7
- POWHEG-2J gives better results when matched with Pythia8 than Herwig++
- POWHEG-3J+Pythia8 is generally lower than POWHEG-2J+Pythia8

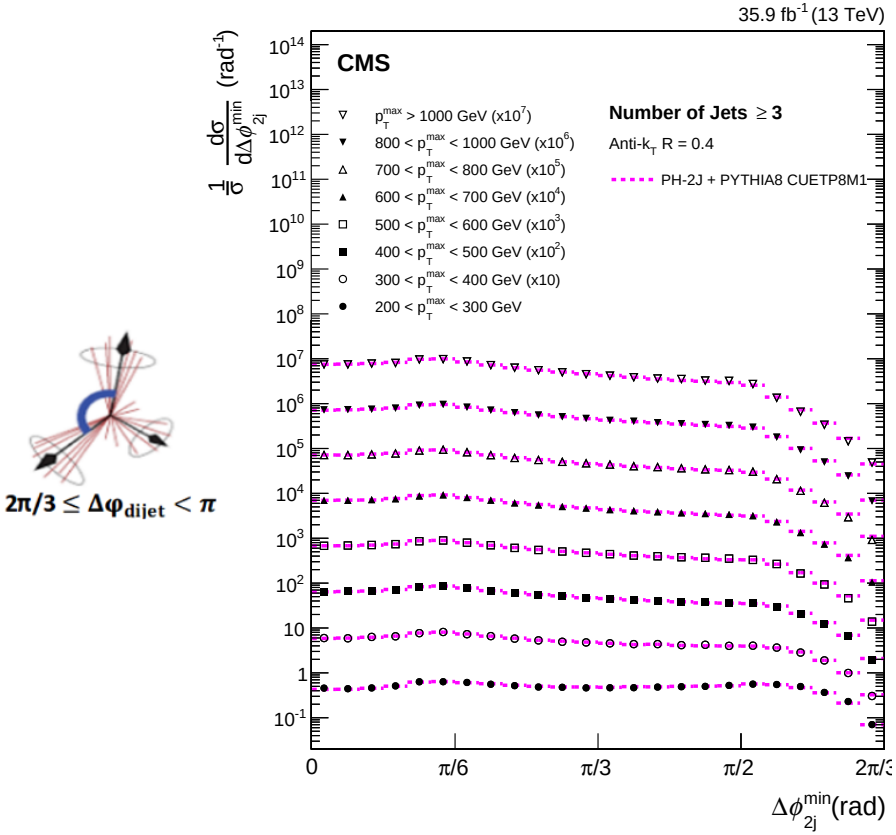


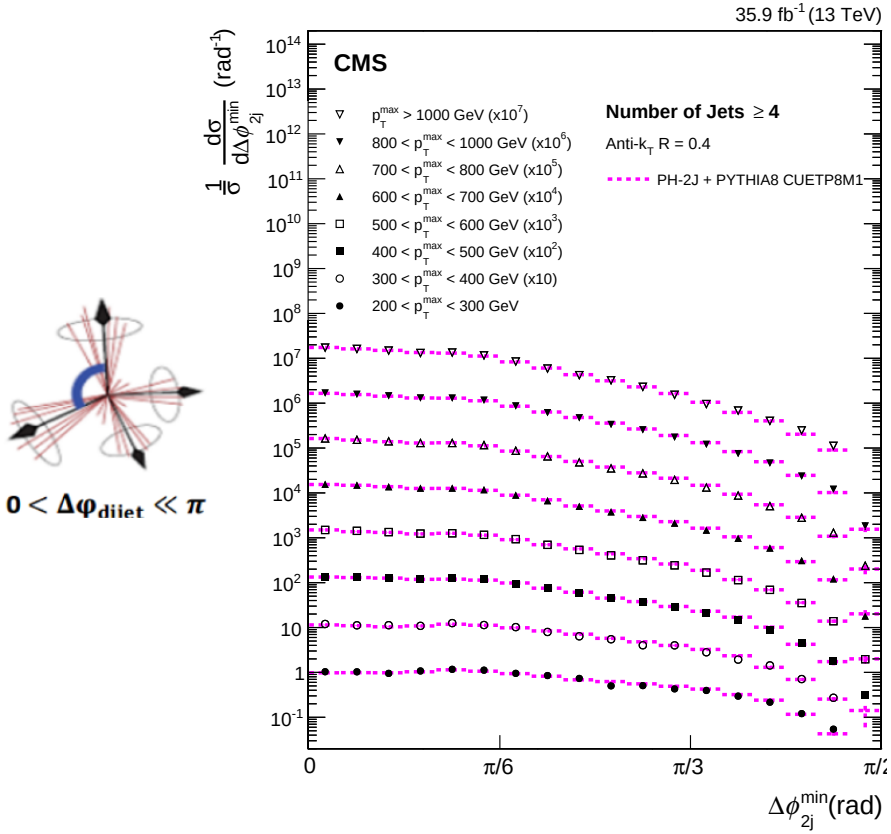




arXiv:1712.05471 (Submitted to EPJC)

# Azimuthal correlations




- **Pythia8 (LO)** exhibits small deviations from the $\Delta\phi_{1,2}$ and fails to describe $\Delta\phi_{2j}^{min}$
- **Herwig++** exhibits the largest deviations from the $\Delta\phi_{1,2}$ but provides a reasonable description of the $\Delta\phi_{2j}^{min}$
- **MADGRAPH+Pythia8** provides a good overall description of the measurements except for $\Delta\phi_{2j}^{min}$ in 4-jet case
- An interesting tool to test the theoretical predictions of multijet production processes

## Summary

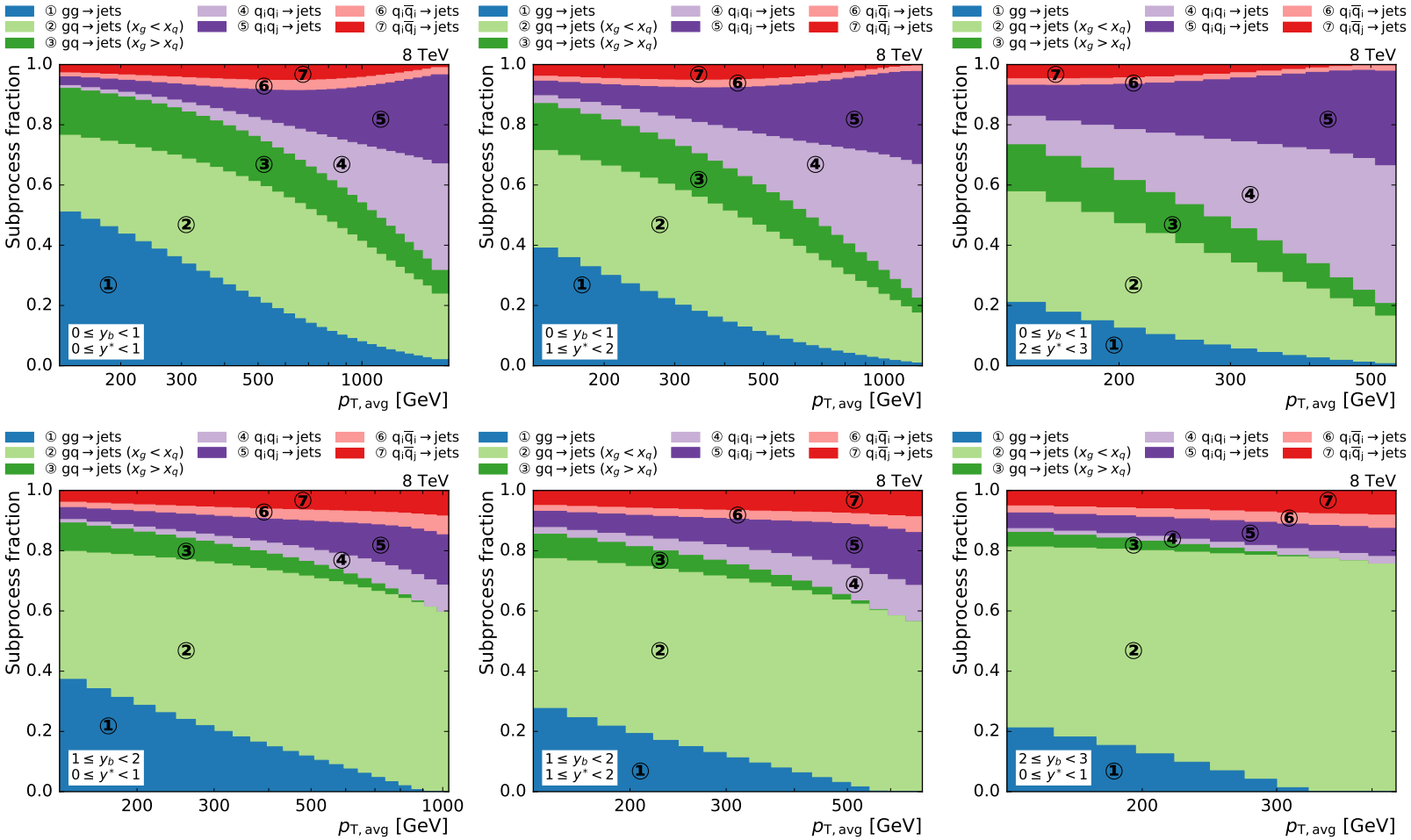
- Jet production in pp collisions is one of the main phenomenological predictions of pQCD.
- Many interesting results from CMS*, reaching new levels of precision and exploring new regions of phase space :
  - Measurements of differential jet cross sections over a wide range in transverse momenta from inclusive jets to multi-jet final states are presented.
  - Compared to theoretical predictions including those matched to parton shower and hadronization.
  - Impact on the determination of the strong coupling constant $\alpha_S$ as well as on parton density functions (PDFs) are reported.
- Wide range of jet measurements at various collision energies improve our understanding of QCD.

**THANKS!!**

*http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

# Back-Up Slides

# Triple-differential dijets

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# Triple-differential dijets

| | | HERA data | | HERA & CMS data | |
|---|---|---|---|---|---|
| Data set | $n_{\text{data}}$ | $\chi^2_{\text{p}}$ | $\chi^2_{\text{p}}/n_{\text{data}}$ | $\chi^2_{\text{p}}$ | $\chi^2_{\text{p}}/n_{\text{data}}$ |
| NC HERA-I+II $e^+p$ $E_p = 920\,\text{GeV}$ | 332 | 382.44 | 1.15 | 406.45 | 1.22 |
| NC HERA-I+II $e^+p$ $E_p = 820\,\text{GeV}$ | 63 | 60.62 | 0.96 | 61.01 | 0.97 |
| NC HERA-I+II $e^+p$ $E_p = 575\,\text{GeV}$ | 234 | 196.40 | 0.84 | 197.56 | 0.84 |
| NC HERA-I+II $e^+p$ $E_p = 460\,\text{GeV}$ | 187 | 204.42 | 1.09 | 205.50 | 1.10 |
| NC HERA-I+II $e^-p$ | 159 | 217.27 | 1.37 | 219.17 | 1.38 |
| CC HERA-I+II $e^+p$ | 39 | 43.26 | 1.11 | 42.29 | 1.08 |
| CC HERA-I+II $e^-p$ | 42 | 49.11 | 1.17 | 55.35 | 1.32 |
| CMS triple-differential dijet | 122 | — | — | 111.13 | 0.91 |
| Data set(s) | $n_{\text{dof}}$ | $\chi^2$ | $\chi^2/n_{\text{dof}}$ | $\chi^2$ | $\chi^2/n_{\text{dof}}$ |
| HERA data | 1040 | 1211.00 | 1.16 | — | — |
| HERA & CMS data | 1162 | — | — | 1372.52 | 1.18 |

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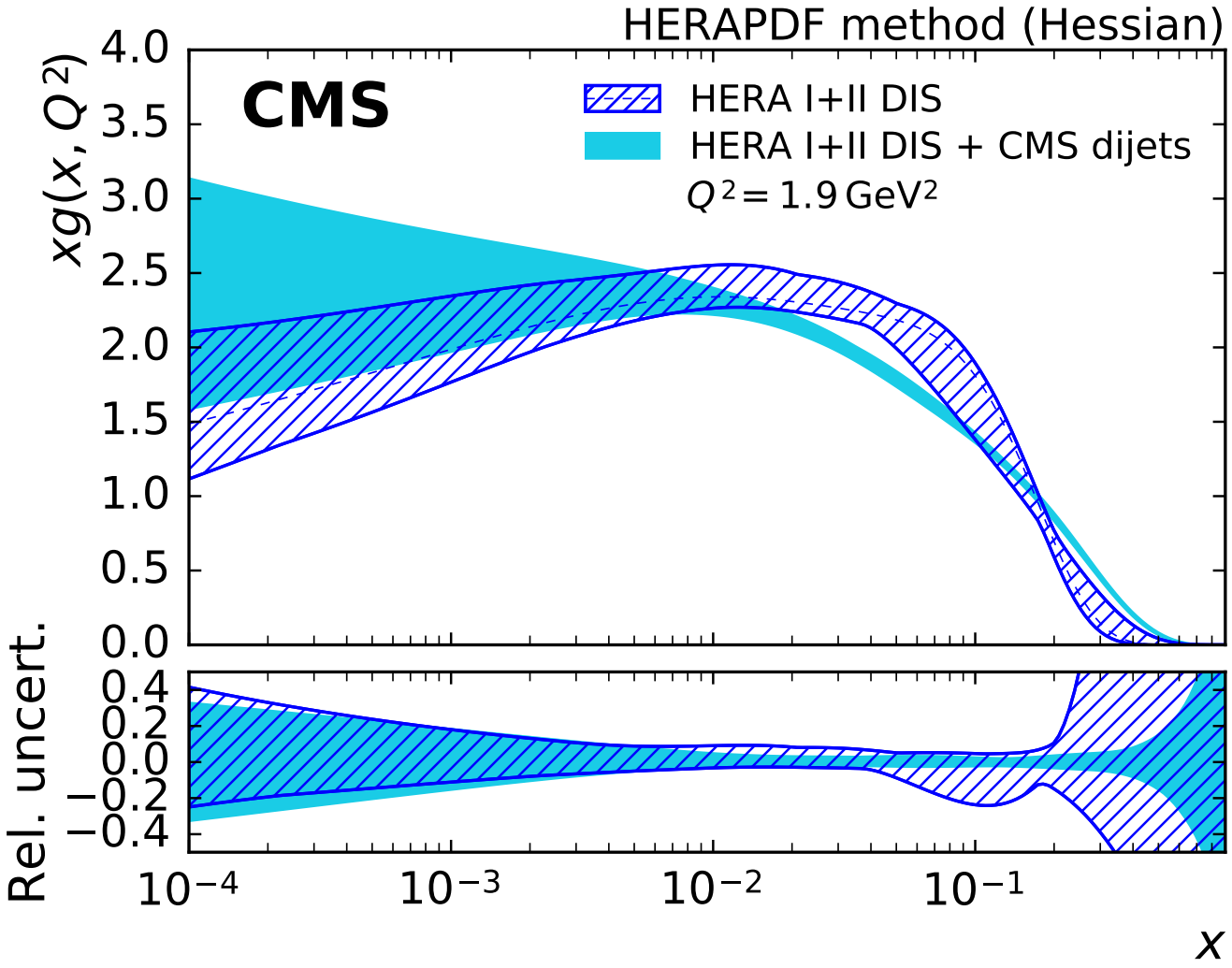
# Triple-differential dijets

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