Measurements of jet production in CMS

The 5th Annual Conference on Large Hadron Collider Physics Shanghai 2017

Patrick L.S. Connor

on behalf of the CMS collaboration

Deutsches Elektronen-Synchrotron

15 May 2017

Introduction

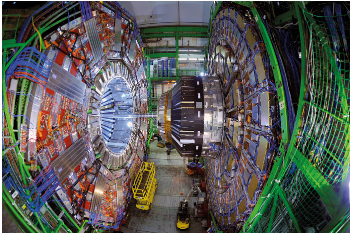
- Review the latest precision measurements in pp collisions:
  - inclusive jet production (8 and 13 TeV) [1, 2]
  - multijet production (8 TeV) [3]
  - triple differential cross section (8 TeV) [4]
  - azimuthal correlations (8 and 13 TeV) [5, 6]
- New constraints on PDFs [1, 4]
- Various measurements of α_S [1, 3, 4]

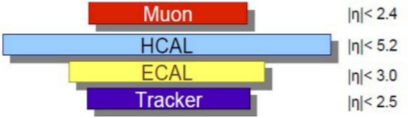
Introduction

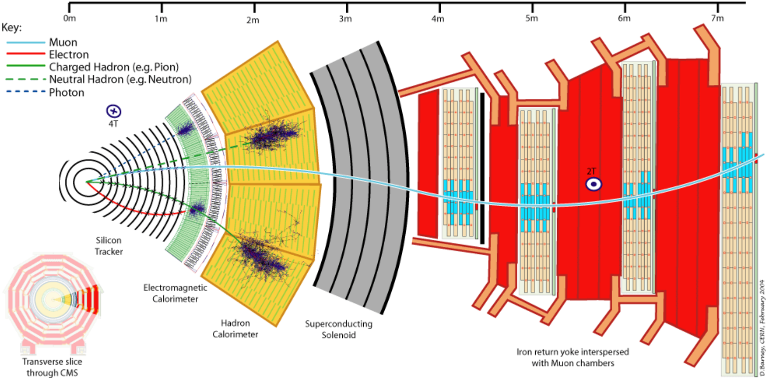
- Review the latest precision measurements in pp collisions:
  - inclusive jet production (8 and 13 TeV) [1, 2]
  - multijet production (8 TeV) [3]
  - triple differential cross section (8 TeV) [4]
  - azimuthal correlations (8 and 13 TeV) [5, 6]
- New constraints on PDFs [1, 4]
- Various measurements of α_S [1, 3, 4]

The anti-k_T algorithm is used to reconstruct the jets [7], with cone radius $R = 0.4$ or $R = 0.7$.

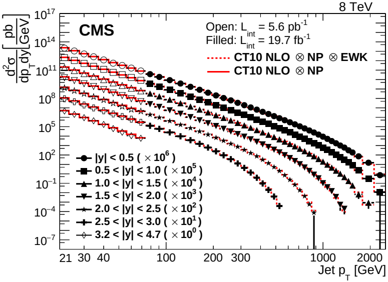
CMS in a nutschell

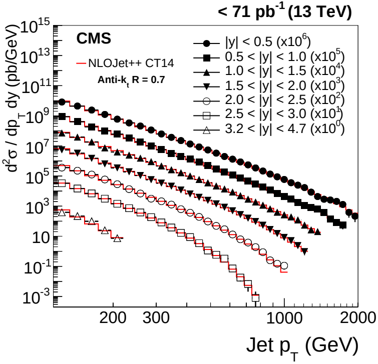






Inclusive jet analysis

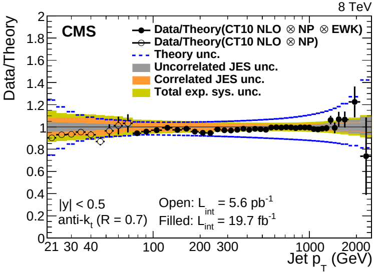


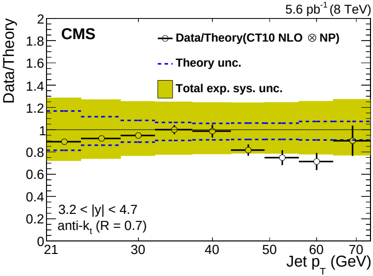


- Measurements at 8 and 13 TeV
- Two cone size radii for 13 TeV
- The TeV scale is now reached!
- Large rapidity coverage

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\,\mathrm{d}y} = \frac{1}{\epsilon\mathcal{L}_{\text{int}}^{\text{eff}}}\frac{N_{\text{jets}}}{\Delta p_T \Delta|y|}$$

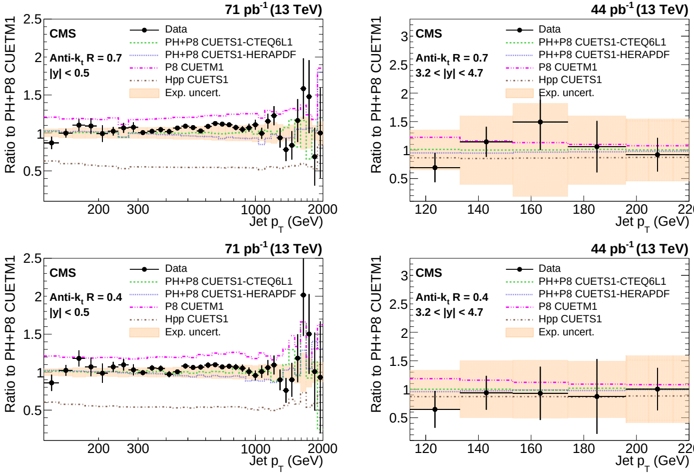
Inclusive jet analysis, 8 TeV





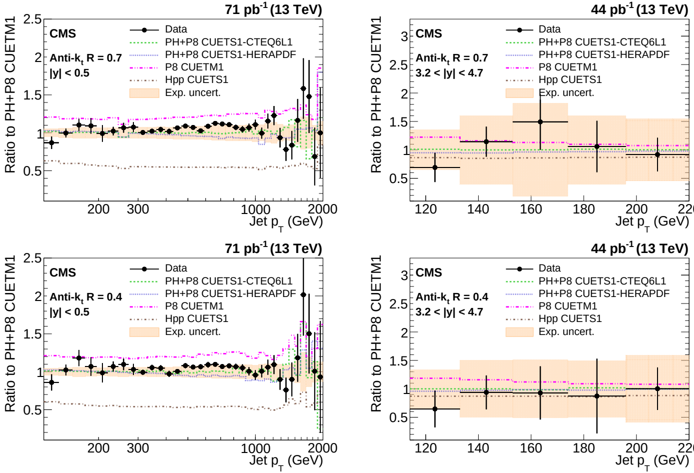
- Comparison to NLO parton-level calculation, including EWK and NP corrections.
- JES uncertainties at the order of the percent in the central region
  $\longrightarrow$ this is an achievement!
- Agreement with measurement on two orders of magnitude!
- New constraints on PDFs together with fit of α_S
  $\longrightarrow$ see later in the talk...

Inclusive jet analysis, 13 TeV



- P8+CUETM1 (LO) agrees in shape in $|y| < 1.5$
- Hpp+CUETS1 (LO) agrees in shape in all rapidity bins
- PowHeg+P8 (NLO) shows good agreement

Inclusive jet analysis, 13 TeV



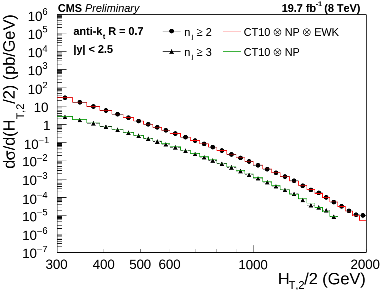
- P8+CUETM1 (LO) agrees in shape in $|y| < 1.5$
- Hpp+CUETS1 (LO) agrees in shape in all rapidity bins
- PowHeg+P8 (NLO) shows good agreement

$\longrightarrow$ **no significant slope!**

Multijet analysis, 8 TeV

$$\frac{d\sigma}{d(H_{T,2}/2)} = \frac{1}{\epsilon \mathcal{L}_{\text{int}}^{\text{eff}}} \frac{N_{\text{events}}}{\Delta(H_{T,2}/2)}$$

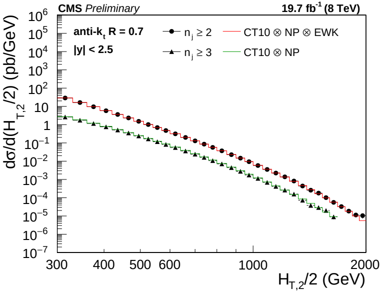
- $H_{T,n} = \sum_{i=1}^{n} p_{T,i}$
- α_S can be safely extracted from $R_{mn} = \frac{\sigma_{m-\text{jet}}}{\sigma_{n-\text{jet}}} \propto \alpha_S^{m-n}$
  $\longrightarrow$ see later in the talk...
- $p_T > 150\,\text{GeV}$ and $|y| < 2.5$

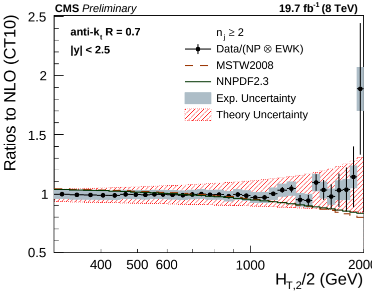


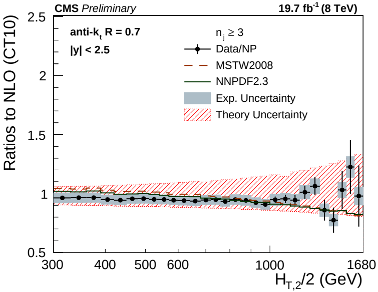
Multijet analysis, 8 TeV

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

- $H_{T,n} = \sum_{i=1}^{n} p_{T,i}$
- α_S can be safely extracted from $R_{mn} = \frac{\sigma_{m-\textbf{jet}}}{\sigma_{n-\textbf{jet}}} \propto \alpha_S^{m-n}$
  $\longrightarrow$ see later in the talk...
- $p_T > 150\,\mathrm{GeV}$ and $|y| < 2.5$





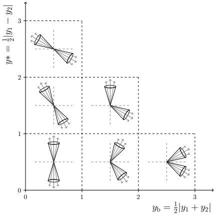


$\longrightarrow$ good agreement over the full range!

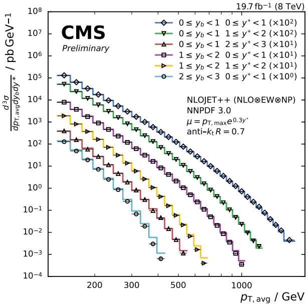
Triple differential cross section 8 TeV

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{T,\text{avg}}\,\mathrm{d}y^*\,\mathrm{d}y_b} = \frac{1}{\epsilon\mathcal{L}_{\text{int}}^{\text{eff}}}\frac{N_{\text{dijet events}}}{\Delta p_{T,\text{avg}}\Delta y^*\Delta y_b}$$

- $p_{T,\text{avg}} = \frac{1}{2}(p_{T,1} + p_{T,2})$
- $y_b = \frac{1}{2}|y_1 + y_2|$
- $y^* = \frac{1}{2}|y_1 - y_2|$



- $p_{T,\text{jet}} > 50$ GeV
- $|y_{\text{jet}}| < 3.0$
- $p_{T,\text{avg}} > 133$ GeV



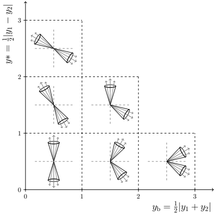
Triple differential cross section

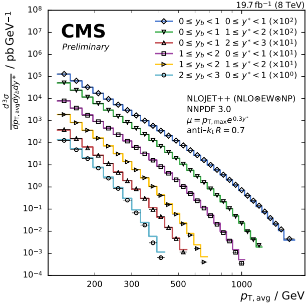
8 TeV

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{T,\mathbf{avg}}\ \mathrm{d}y^*\ \mathrm{d}y_b} = \frac{1}{\epsilon\mathcal{L}_{\mathbf{int}}^{\mathbf{eff}}}\frac{N_{\mathbf{dijet\ events}}}{\Delta p_{T,\mathbf{avg}}\Delta y^*\Delta y_b}$$

- $p_{T,\mathbf{avg}} = \frac{1}{2}(p_{T,1} + p_{T,2})$
- $y_b = \frac{1}{2}|y_1 + y_2|$
- $y^* = \frac{1}{2}|y_1 - y_2|$

- $p_{T,\mathbf{jet}} > 50\ \mathrm{GeV}$
- $|y_{\mathbf{jet}}| < 3.0$
- $p_{T,\mathbf{avg}} > 133\ \mathrm{GeV}$





This measurement is very well suited to extract PDFs and α_S:

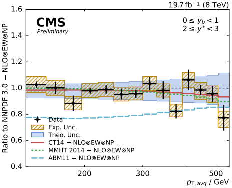
central region most suited for α_S extraction at high energy scales

boosted region high-x region of PDFs can be better constrained

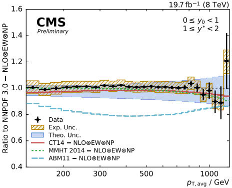
large rapidity separation PDF and detector effects can be better disentangled

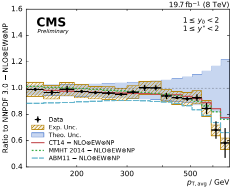
⟶ see later in the talk...

Triple differential cross section 8 TeV

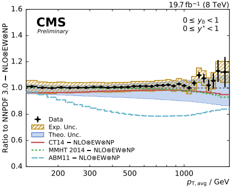


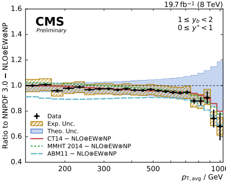
- Good agreement with NLO calculation with NNPDF 3.0.
- Good agreement also with CT14 and MMHT2014.
- However AMB11 PDF underestimates the predictions.

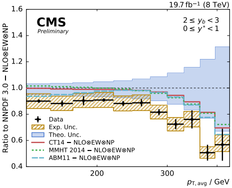


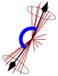


- $p_{T,\mathbf{jet}} > 50$ GeV
- $|y_{\mathbf{jet}}| < 3.0$
- $p_{T,\mathbf{avg}} > 133$ GeV

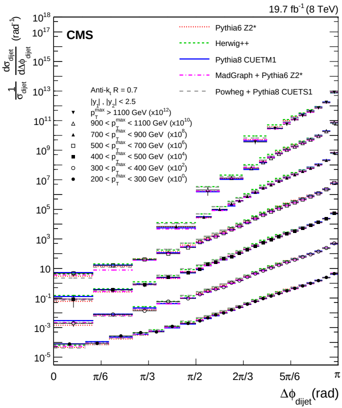


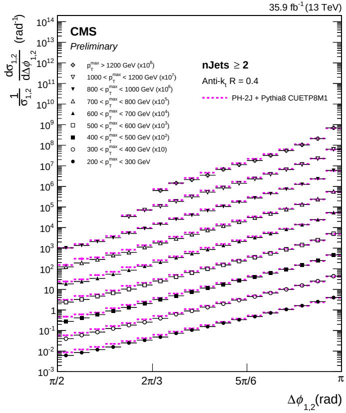






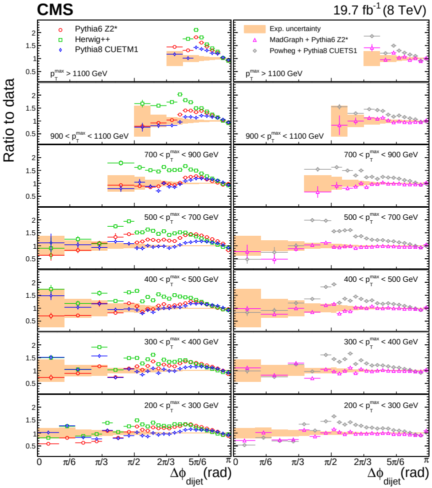
Azimuthal correlations





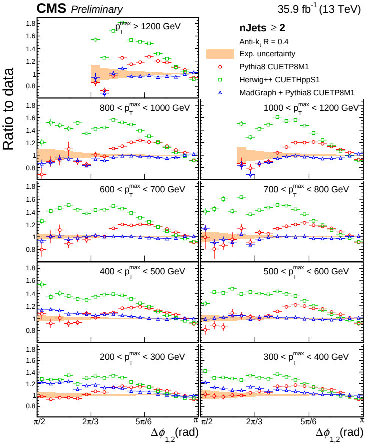
- The more extra radiations, the less correlated the two leading jets $\longrightarrow$ good test for matching ME+PS.
- At 8 and 13 TeV, measurement of azimuthal correlation between the two leading jets $\Delta\phi_{12}$ (but different cone sizes).
- At 13 TeV, additional measurement of minimum azimuthal correlations of the 2nd with the 3rd or 4th jet: $\Delta\phi_{2j}^{\text{min}}$.

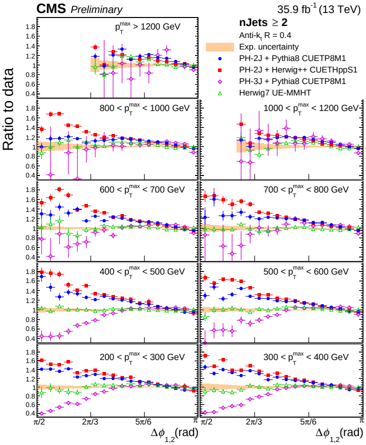
Azimuthal correlations at 8 TeV



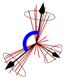
- For event generators, best agreement is given by tree-level multiparton generator MadGraph+Pythia 6 (RHS).
- Among the LO dijet event generators, Pythia 8 agrees best, while Herwig++ overshoots most.
- Also fixed-order NLO parton-level calculation in back-up.

Azimuthal correlations 13 TeV, $\Delta\phi_{12}^{2-\text{jet}}$

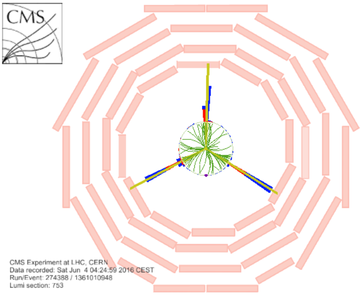


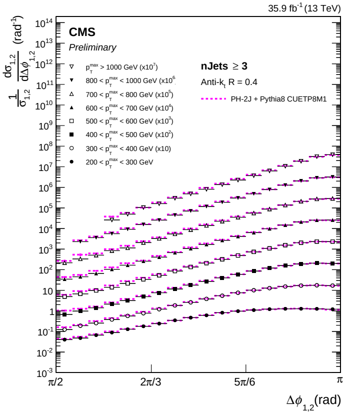


- MadGraph+Pythia 8 agrees best; Herwig++ overshoots again.
- Best agreement is given by Herwig7.
- PH-2J gives better results when matched with P8 than Herwig++.
- PH-3J+P8 is generally lower than PH2J+P8.



Azimuthal correlations
13 TeV, $\Delta\phi_{12}^{3-\text{jet}}$

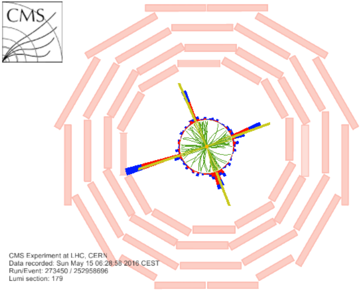


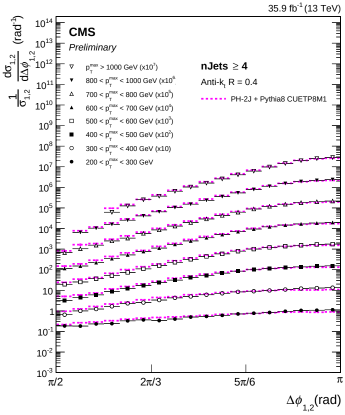


1. $p_T = 709\,\text{GeV},\ y = -0.396,\ \phi = 1.544$
2. $p_T = 709\,\text{GeV},\ y = 0.343,\ \phi = -2.655$
3. $p_T = 703\,\text{GeV},\ y = -0.304,\ \phi = -0.561$

- Spectrum gets flatter, as dijet events are no more included.
- More sensitive to parton shower.
- Conclusions are similar as for 2-jet case.

Azimuthal correlations 13 TeV, $\Delta\phi_{12}^{4-\text{jet}}$

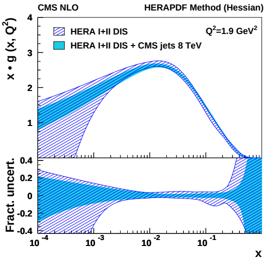


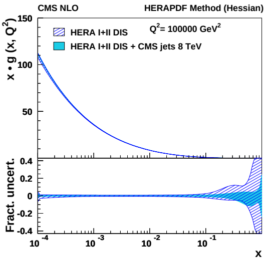


1. $p_T = 234\,\text{GeV},\ y = -0.714,\ \phi = -2.820$
2. $p_T = 224\,\text{GeV},\ y = 1.477,\ \phi = 0.349$
3. $p_T = 216\,\text{GeV},\ y = 0.375,\ \phi = 1.977$
4. $p_T = 196\,\text{GeV},\ y = -0.823,\ \phi = -1.199$

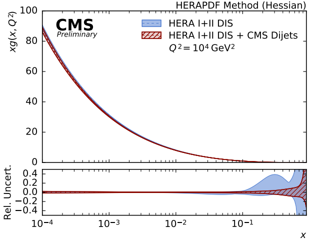
- Spectrum gets even flatter.
- Even more sensitive to parton shower.
- And conclusions are similar as for 2- and 3-jet cases.

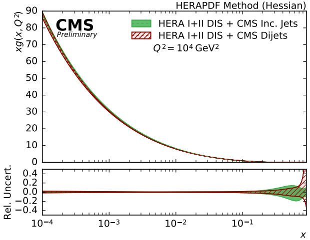
PDFs from jet measurements





α_S extracted treated as free parameter





Fit combines HERA and CMS data:

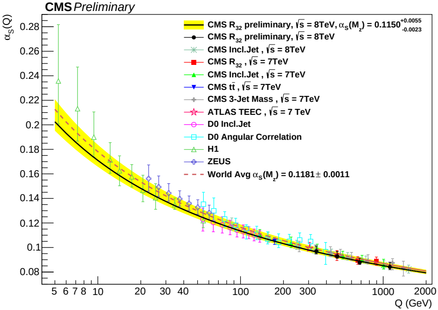
1. inclusive jet at 8 TeV
2. dijet at 8 TeV

Strong coupling

inclusive jet least square minimisation on $p_T(y)$ spectrum using NLO parton-level predictions

multijet id. on $R_{32} = \sigma_{3-\text{jet}}/\sigma_{2-\text{jet}}$

triple differential cross section together with PDF fit



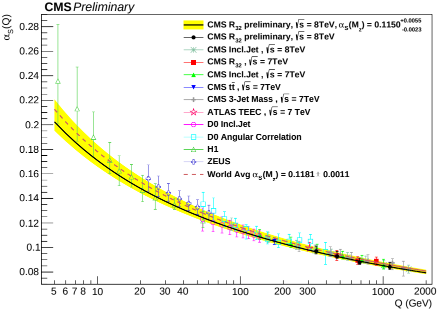
method	$\alpha_S(M_Z)$	scale unc.	exp. unc.	PDF unc.	total unc.
incl. jet	0.1164	$^{+0.0053}_{-0.0028}$	$^{+0.0015}_{-0.0016}$	$^{+0.0025}_{-0.0029}$	$^{+0.0093}_{-0.0073}$
multijet	0.1150	$^{+0.0050}_{-0.0000}$	± 0.0025	± 0.0013	$^{+0.0088}_{-0.0038}$
trip. diff. σ	0.1194	$^{+0.0031}_{-0.0019}$	$^{+0.0015}_{-0.0015}$	$^{+0.0004}_{-0.0006}$	$^{+0.0050}_{-0.0040}$

Strong coupling

inclusive jet least square minimisation on $p_T(y)$ spectrum using NLO parton-level predictions

multijet id. on $R_{32} = \sigma_{3-\text{jet}}/\sigma_{2-\text{jet}}$

triple differential cross section together with PDF fit



method	$\alpha_S(M_Z)$	scale unc.	exp. unc.	PDF unc.	total unc.
incl. jet	0.1164	$^{+0.0053}_{-0.0028}$	$^{+0.0015}_{-0.0016}$	$^{+0.0025}_{-0.0029}$	$^{+0.0093}_{-0.0073}$
multijet	0.1150	$^{+0.0050}_{-0.0000}$	± 0.0025	± 0.0013	$^{+0.0088}_{-0.0038}$
trip. diff. σ	0.1194	$^{+0.0031}_{-0.0019}$	$^{+0.0015}_{-0.0015}$	$^{+0.0004}_{-0.0006}$	$^{+0.0050}_{-0.0040}$

$\longrightarrow$ **all compatible with world average** $\alpha_S^{\text{PDG}} = 0.1181 \pm 0.0011$! [8]

Summary

- We presented the latest results on jet measurements at 8 and 13 TeV.
- The TeV scale is reached in the p_T and H_T spectra, and a large rapidity range is covered, opening up new regions of the phase space.
- Detailed comparisons with LO/NLO+PS and NLO parton-level calculations are available.
  - The NLO parton-level calculations are in very good agreement for $R = 0.7$ in all the analyses.
  - Among the MC event generators, PowHeg gives the best description of the inclusive jet, and MadGraph+Pythia and Herwig7 give nice agreement in the azimuthal correlations.
- Gluons PDFs can better be constrained, especially for high x values.
- We have various measurements of α_S.

Summary

- We presented the latest results on jet measurements at 8 and 13 TeV.
- The TeV scale is reached in the p_T and H_T spectra, and a large rapidity range is covered, opening up new regions of the phase space.
- Detailed comparisons with LO/NLO+PS and NLO parton-level calculations are available.
  - The NLO parton-level calculations are in very good agreement for $R = 0.7$ in all the analyses.
  - Among the MC event generators, PowHeg gives the best description of the inclusive jet, and MadGraph+Pythia and Herwig7 give nice agreement in the azimuthal correlations.
- Gluons PDFs can better be constrained, especially for high x values.
- We have various measurements of α_S.

Thanks a lot!

References I

Vardan Khachatryan et al.
Measurement and QCD analysis of double-differential inclusive jet cross sections in pp collisions at $\sqrt{s} = 8$ TeV and cross section ratios to 2.76 and 7 TeV.
JHEP, 03:156, 2017.

Vardan Khachatryan et al.
Measurement of the double-differential inclusive jet cross section in proton–proton collisions at $\sqrt{s} = 13$ TeV.
Eur. Phys. J., C76(8):451, 2016.

CMS Collaboration.
Determination of the strong coupling constant from the measurement of inclusive multijet event cross sections in pp collisions at $\sqrt{s} = 8$ TeV.
Technical Report CMS-PAS-SMP-16-008, 2017.

CMS Collaboration.
Measurement of Triple-Differential Dijet Cross Sections at $\sqrt{s} = 8$ TeV with the CMS Detector and Constraints on Parton Distribution Functions.
Technical Report CMS-PAS-SMP-16-011, 2016.

Vardan Khachatryan et al.
Measurement of dijet azimuthal decorrelation in pp collisions at $\sqrt{s} = 8$ TeV.
Eur. Phys. J., C76(10):536, 2016.

CMS Collaboration.
Measurements of inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in pp collisions at $\sqrt{s} = 13$ TeV.
Technical Report CMS-PAS-SMP-16-014, 2017.

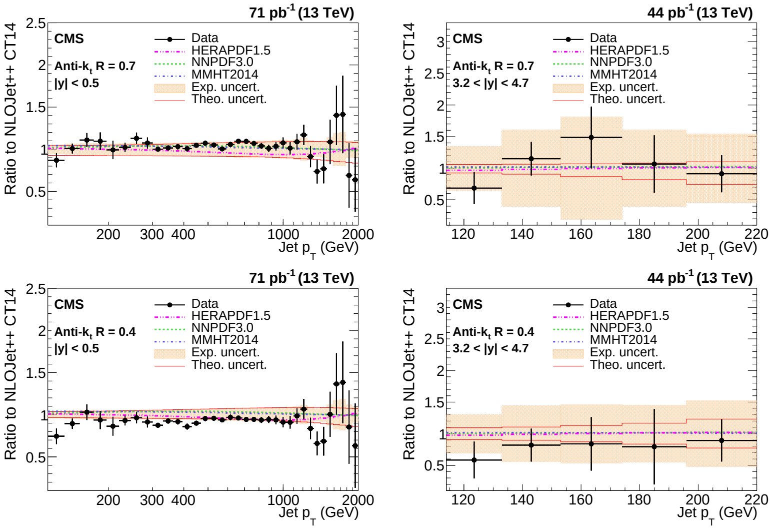
References II

Matteo Cacciari, Gavin P. Salam, and Gregory Soyez.
The Anti-k(t) jet clustering algorithm.
JHEP, 04:063, 2008.

C. Patrignani et al.
Review of Particle Physics.
Chin. Phys., C40(10):100001, 2016.

Back-up

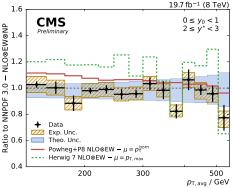
Inclusive jet analysis, 13 TeV



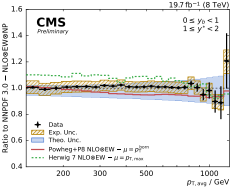
Agreement is better for large than small cone sizes

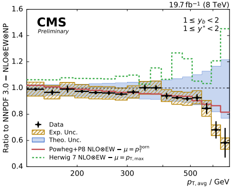
$\longrightarrow$ missing PS and soft-gluon resummation in fixed order calculations

Triple differential cross section 8 TeV

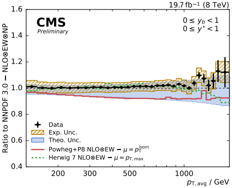


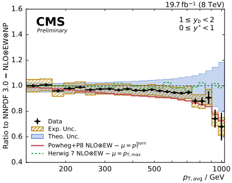
- Herwig 7 (NLO) shows better agreement in central region
- while Pythia 8 + PS (LO) shows better agreement in forward region

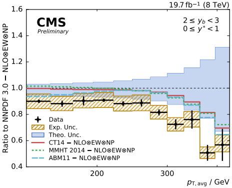




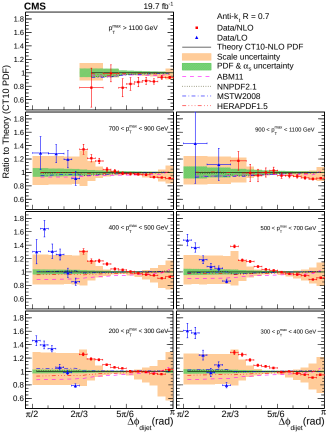
- $p_{T,\mathrm{jet}} > 50$ GeV
- $|y_{\mathrm{jet}}| < 3.0$
- $p_{T,\mathrm{avg}} > 133$ GeV





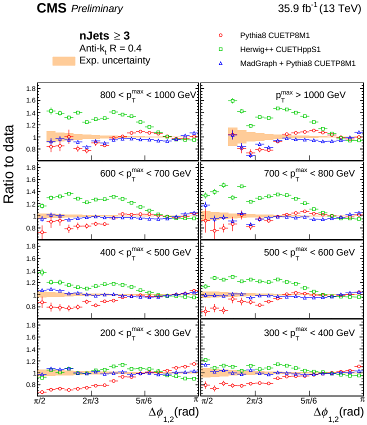


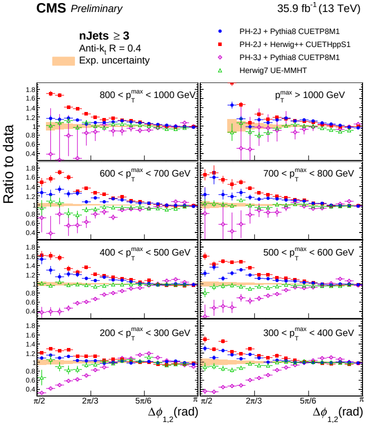
Azimuthal correlations at 8 TeV



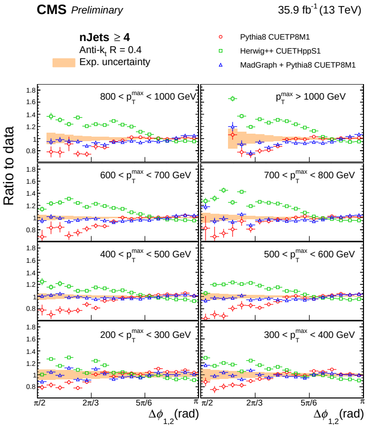
- Fixed-order calculations agree with data except from $5\pi/6$ for the highest p_T^{max} region
- Discontinuity comes from matching LO and NLO.

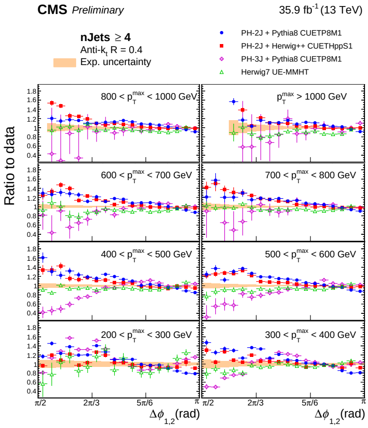
Azimuthal correlations 13 TeV, $\Delta\phi_{12}$



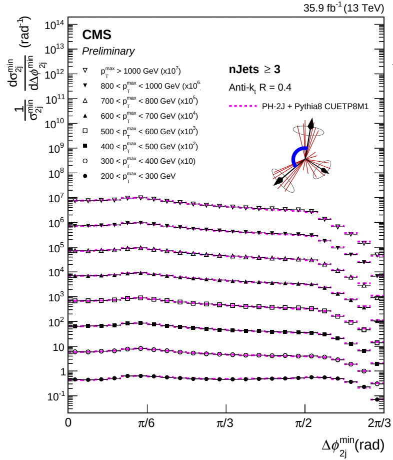


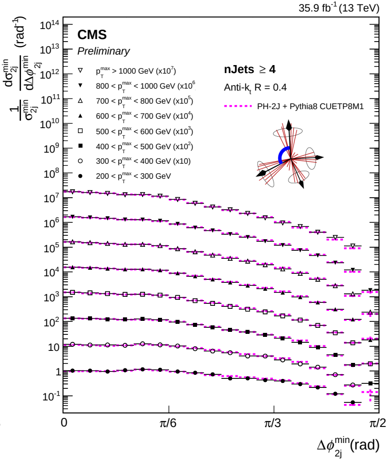
Azimuthal correlations 13 TeV, $\Delta\phi_{12}$



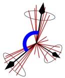


Azimuthal correlations 13 TeV, $\Delta\phi_{2j}^{\min}$

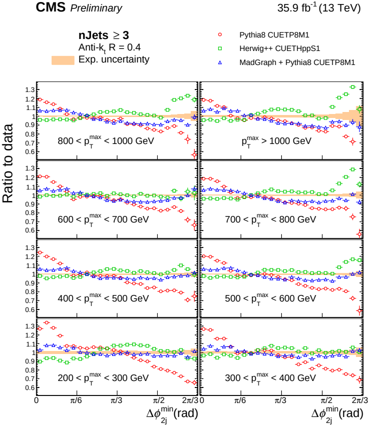


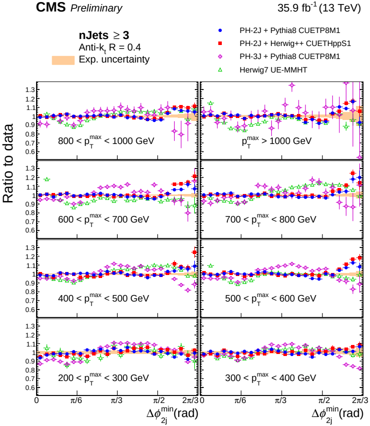


- 3-jet (4-jet) distributions have maximum at $2\pi/3$ ($\pi/2$) $\longrightarrow$ typical, as shown in previous event displays
- Little change at 0.4 is related cone size $R = 0.4$.

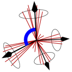


Azimuthal correlations 13 TeV, $\Delta\phi_{2j}^{\text{min}}$



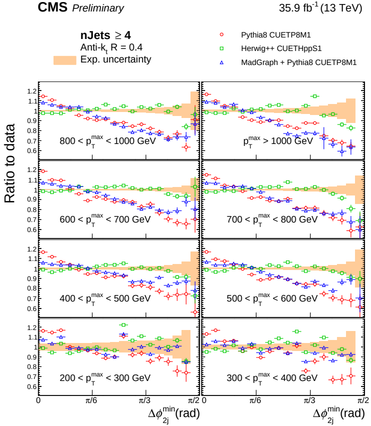


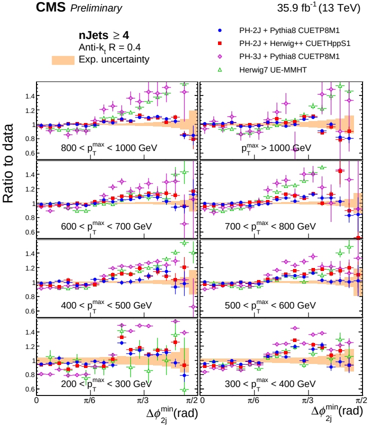
- MG+P8 and Herwig++ give reasonable description but P8 fails.
- PH-2J has best agreement.
- PH-3J+P8 suffers from statistical accuracy.
- Feature at low values in Herwig7 is related to some non-physical cut.



Azimuthal correlations

13 TeV, $\Delta\phi_{2j}^{\min}$





- Here however P8 and MG+P8 are both off.
- Herwig7 exhibits large deviations.
- Other conclusions are the same.