Patrick Connor

Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



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

LHCP2017

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up



- $\hfill \bullet$ 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

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Patrick Connor

Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



$\hfill \bullet$ 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.

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up





CMS in a nutschell





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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

- Summary References
- Back-up





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

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

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up





- 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...

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up





- 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

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up



Inclusive jet analysis, 13 TeV 71 pb⁻¹ (13 TeV) 44 pb⁻¹ (13 TeV) 2.5 Ratio to PH+P8 CUETM1 Data Ratio to PH+P8 CUETM — Data CMS CMS 3 PH+P8 CUETS1-CTEQ6L1 PH+P8 CUETS1-CTEQ6L1 PH+P8 CUETS1-HERAPDE PH+P8 CUETS1-HERAPDE 2 Anti-k, R = 0.7 Anti-k. R = 0.7 25 P8 CUETM1 P8 CUETM1 |y| < 0.5 3.2 < |y| < 4.7 HDD CUETS1 Hpp CUETS1 1.5 Exp. uncert. Exp. uncert. .5 0.5 0.5 200 300 1000 2000 120 140 160 180 200 220 Jet p_ (GeV) Jet p_ (GeV) 71 pb⁻¹ (13 TeV) 44 pb⁻¹ (13 TeV) 2.5 Ratio to PH+P8 CUETM1 Ratio to PH+P8 CUETM1 Data Data CMS CMS PH+P8 CUETS1-CTEQ6I 1 PH+P8 CUETS1-CTEQ6L1 PH+P8 CUETS1-HERAPDE PH+P8 CUETS1-HERAPDE 2 Anti-k, R = 0.4 Anti-k. R = 0.4 2 P8 CUETM1 P8 CUETM1 |y| < 0.5 3.2 < IVI < 4.7 Hpp CUETS1 Hpp CUETS1 1.5 Exp. uncert Exp. uncert .5 0.5 0.5Ē Jet p_T (GeV) 200 300 1000 140 160 180 220 Jet p_ (GeV)

- 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
- \rightarrow no significant slope!

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Introduction

Latest analyses

Inclusive jet analysis

Multijet analysis

Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



Multijet analysis, 8 TeV

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

•
$$H_{T,n} = \sum_{i=1}^{n} p_{T,i}$$

•
$$\alpha_S$$
 can be safely extracted
from $R_{mn} = \frac{\sigma_{m-jet}}{\sigma_{n-jet}} \propto \alpha_S^{m-n}$
 \longrightarrow see later in the talk...

•
$$p_T > 150 \, \text{GeV}$$
 and $|y| < 2.5$



Patrick Connor

Introduction

Latest analyses

Inclusive iet analysis

Multiiet analysis

Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summarv References Back-up



Multijet analysis, 8 TeV

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

•
$$H_{T,n} = \sum_{i=1}^{n} p_{T,i}$$

CMS Preliminary

IVI < 2.5

anti-k. R = 0.7

400 500 600

2.5

1.5

0.5

Ratios to NLO (CT10)

 α_S can be safely extracted from $R_{mn} = \frac{\sigma_{m-jet}}{\sigma_{n-jet}} \propto \alpha_S^{m-n}$ \rightarrow see later in the talk...

•
$$p_T > 150 \,\mathrm{GeV}$$
 and $|y| < 2.5$



n, ≥ 2

ASTW2008

Exp. Uncertainty

7 Theory Uncertainty

1000

NNPDF2 3



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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis

Triple differential cross section Azimuthal

Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



Triple differential cross section 8 TeV







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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis

Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



Triple differential cross section 8 TeV



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

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis

Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



19.7 fb=1 (8 TeV) CMS $0 \le y_0 < 1$ $2 \le y^* < 3$ 1.4 Exp. Unc Theo, Unc. 0.6 CT14 - NLOSEWSNP MMHT 2014 - NLOSEWANP ABM11 - NLOGEWONP 200 300 500 р_{т, жир} / GeV 19.7 fb=1 (8 TeV) CMS + Exp Linc CT14 - NLOSEWSNE MMHT 2014 - NLOREWRNP pt, avg / GeV 19.7 fb-1 (8 TeV) CMS $0 \le y_0 < 1$ $0 \le y' < 1$ NLO®EW®NF NPDF Data Exp Linc Theo, Linc 80.6 CT14 - NLOREWRNF MMHT 2014 - NLOBFWANF ADM11 - NIGETWEND 300 PT and / GeV

Triple differential cross section

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









- The more extra radiations, the less correlated the two leading jets \rightarrow 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: $\Delta \phi_{2i}^{\min}$.

10/17

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Latest

analyses

analysis

Multiiet

analysis

differential

Azimuthal

Triple

PDFs

Strong

coupling

Summarv

Back-up

Patrick Connor

Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up





Azimuthal correlations at 8 TeV

- CMS 19.7 fb⁻¹ (8 TeV) Exp. uncertainty Pythia6 72* MadGraph + Pythia6 Z2* Herwig++ Pythia8 CLIFTM Powheg + Pythia8 CUETS1 p_max > 1100 GeV p_ms > 1100 GeV Ratio to data 900 < p^{max} < 1100 GeV 900 < p^{max} < 1100 GeV 700 < p^{max} < 900 GeV 700 < p^{max} < 900 GeV ----500 < p^{max} < 700 GeV 500 < p____ < 700 GeV ********* 400 < p_____ < 500 GeV 400 < p_____ < 500 GeV 300 < p____ < 400 GeV 300 < p_max < 400 GeV ·******** 200 < p_____ < 300 GeV 200 < p_max < 300 GeV $\Delta \phi_{dijet}$ (rad) ∆¢__(rad
- 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.

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up



12/17



Azimuthal correlations



- 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.

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Data recorded: Sat Jun 4 04:24:59 2016 CES

Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal

correlations PDFs

Strong coupling

- Summary References
- Back-up



13/17



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



- Spectrum gets flatter, as dijet events are no more included.
- More sensitive to parton shower.

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 $p_T = 703 \,\text{GeV}, \, y = -0.304, \, \phi = -0.561$

• Conclusions are similar as for 2-jet case.

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CMS Experiment at LHC, CERN Data recorded: Sun May 15 06:28:58 2016 CER

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal

correlations

PDFs

- Strong coupling
- Summary References
- Back-up



14/17



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



3 $p_T = 216 \text{ GeV}, \ y = 0.375, \ \phi = 1.977$ **4** $p_T = 196 \text{ GeV}, \ y = -0.823, \ \phi = -1.199$

1 $p_T = 234 \,\text{GeV}, \, y = -0.714, \, \phi = -2.820$

2 $p_T = 224 \text{ GeV}, y = 1.477, \phi = 0.349$

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

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



PDFs from jet measurements





Fit combines HERA and CMS data:

1 inclusive jet at 8 TeV

2 dijet at 8 TeV

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summary References

Back-up



inclusive jet least square minimisation on $p_T(y)$ spectrum using NLO parton-level predictions multijet id. on $R_{32} = \sigma_{3-jet}/\sigma_{2-jet}$ triple differential cross section together with PDF fit

Strong coupling



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	$^{+0.0031}_{-0.0019}$	$+0.0015 \\ -0.0015$	$+0.0004 \\ -0.0006$	$+0.0050 \\ -0.0040$

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Introduction

Latest analyses

Inclusive iet analysis Multiiet analysis Triple differential cross section Azimuthal correlations

PDFs

Strong coupling

Summarv References

Back-up



inclusive jet least square minimisation on $p_T(y)$ spectrum using NLO parton-level predictions multijet id. on $R_{32} = \sigma_{3-jet}/\sigma_{2-jet}$ triple differential cross section together with PDF fit

Strong coupling



-0.0015

-0.0006

-0.0040

[8]

-0.0019PDG \rightarrow all compatible with world average α_{S}^{PI} $= 0.1181 \pm 0.0011!$

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up



- 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 .

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Introduction

Latest analyses

Inclusive jet analysis Multijet analysis Triple differential cross section Azimuthal correlations

PDFs

- Strong coupling
- Summary References
- Back-up



17/17

• We presented the latest results on jet measurements at 8 and 13 TeV.

Summary

- 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.
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- Gluons PDFs can better be constrained, especially for high x values.
- We have various measurements of α_S .

Thanks a lot!



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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations

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References II

References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations



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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations





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References

Back-up

Inclusive jet analysis Triple

differential cross section Azimuthal correlations



Agreement is better for large than small cone sizes \rightarrow missing PS and soft-gluon resummation in fixed order calculations



21/17

Inclusive jet analysis, 13 TeV

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References

Back-up

Inclusive jet analysis

Triple differential cross section Azimuthal correlations





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







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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations





Azimuthal correlations at 8 TeV



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

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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations



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





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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations



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





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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations



Azimuthal correlations

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

DESY

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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations



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



- 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.

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References

Back-up

Inclusive jet analysis Triple differential cross section Azimuthal correlations





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