Jet measurements in pp collisions from CMS

11th annual conference on Large Hadron Collider Physics | 22–26 May 2023 | Belgrade, Serbia

Daniel Savoiu on behalf of the CMS Collaboration
Why jets?

jet observables provide valuable experimental input for testing QCD & the Standard Model

- $\alpha_s$ and **parton distributions** of proton (PDFs)
  - **inclusive jet** cross sections → “counting jets”
  - **dijet** cross sections → topology provides handle on parton kinematics

- modeling of higher-order contributions
  - jet production known up to **NNLO** in pQCD
  - additional jets from hard radiation → **multijet** production

- improved understanding of perturbative & nonperturbative regimes
  - impact on **parton shower & hadronization** → jet **substructure**
Why jets?

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**This talk**: personal selection of recent results from CMS
Inclusive jet production at $\sqrt{s} = 13$ TeV

- **double-differential** cross section measured as a function of jet $p_T$ & rapidity $y$ for anti-$k_T$ jets with $R = 0.4$ & 0.7

- good experimental precision, `<5% uncertainty` in main measurement region
  - dominant uncertainty contribution from jet energy scale (JES)

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Inclusive jet production at $\sqrt{s} = 13$ TeV

- comparison to fixed-order pQCD theory at **NNLO & NLO+NLL**
- + corrections for non-perturbative (NP) and electroweak (EW) contributions

- improved description of data at NNLO & reduced scale uncertainty
- some disagreement between global PDF sets, especially in high-$p_T$ region
Inclusive jet production at $\sqrt{s} = 13$ TeV

- determination of PDFs & strong coupling constant up to NNLO
  \[ \alpha_s(m_Z)_{\text{NNLO}} = 0.1166 \] (14) fit (7) model (4) scale (1) param.

  \[ \chi^2 / n_{\text{dof}} = 1302 / 1118 \]

- with $t\bar{t}$ data: limits on Wilson coefficients for four-quark contact interactions
  - multiple coupling structures probed, no significant deviations

**CMS SMEFT NLO 13 TeV jets & $t\bar{t}$ + HERA**

- $\Lambda = 50$ TeV
- 95% CL fit+model+param. unc.
- 68% CL fit+model+param. unc.
- 68% CL fit unc. only
  - Axial vector-like
  - Vector-like
  - Left-handed

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Dijet production at $\sqrt{s} = 13$ TeV

- **double- & triple-differential** cross section measured as a function of **dijet invariant mass $m_{1,2}$ & rapidity** for anti-$k_T$ jets with $R = 0.4$ & 0.8

- disentangle regions of different momentum fractions $x$ carried by partons $\rightarrow$ PDF fits

Dijet production at $\sqrt{s} = 13$ TeV

- comparison to fixed-order theory predictions @ NNLO × NP × EW
- data generally well described by theory (here: $R = 0.8$)
Dijet production at $\sqrt{s} = 13$ TeV

- determination of PDFs & strong coupling constant @ NNLO (preliminary results)

$\alpha_s(m_Z)$

\[ \alpha_s(m_Z)^{2D} = 0.1201 \pm 0.0012 \] (12

\[ \chi^2 / n_{\text{dof}} = 1283 / 1094 \]

\[ \alpha_s(m_Z)^{3D} = 0.1201 \pm 0.0010 \] (10

\[ \chi^2 / n_{\text{dof}} = 1557 / 1167 \]

2D & 3D fit results largely compatible
**Multijet production**

- **jet multiplicity** measured in bins of leading jet $p_T$ & azimuthal separation $\Delta\phi_{1,2}$
  - access up to 7 jets, even in back-to-back region
- compare models using conventional parton showers & **parton-branching** approach (PB) + TMDs
  - higher multiplicities not very well described
  - at low multiplicities, PB-TMD predictions @ NLO have similar accuracy as conventional models

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Multijet production

- jet $p_T$ measured for up to 4 leading jets
  - in general not well described by any model @ LO
  - better description for 3rd & 4th jet with NLO matrix elements

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Measurement of the Lund jet plane density

- **Lund jet plane** represents phase space of emissions inside jets
  - anti-\(k_T\) jets are declustered iteratively using the *Cambridge–Aachen* algorithm
  - the density of emissions is measured as a function of \(\ln(k_T / \text{GeV})\) and \(\ln(1 / \Delta R)\) as:
    \[
    \frac{1}{N_{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d \ln(k_T) d \ln(R/\Delta R)} \approx \frac{2}{\pi} C_R \alpha_s(k_T).
    \]

**Applications**

- improve modeling of parton shower, hadronization, underlying event
- heavy-flavor tagging due to unique signatures of highly boosted color-singlet particles
- test running of \(\alpha_s\) via analytical predictions in perturbative QCD

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Measurement of the Lund jet plane density

- measurement performed for both small ($R = 0.4$) and large-radius jets ($R = 0.8$)
- density measured for jets with $p_T > 700$ GeV & $|y| < 1.7$
  - only charged-particle constituents of jets are used → increased resolution
- multi-dimensional unfolding to obtain density at particle level
Measurement of the Lund jet plane density

- performance of different generators, tunes, parton showers
- measurement can be used as input to further improve these models
Summary

- jet observables are an important experimental probe for SM at highest energy & precision

- many measurements from CMS at $\sqrt{s} = 13$ TeV, targeting wide variety of jet observables
  - inclusive jet and dijet cross sections
  - jet multiplicity & transverse momentum spectra in multijet events
  - jet substructure $\rightarrow$ density of parton emissions in Lund jet plane

- improved precision and extended kinematic reach, beneficial for:
  - determinations of the strong coupling constant $\alpha_s(m_Z)$ and parton distributions (PDFs)
  - probes of extensions to the SM in effective field theory
  - improvement of MC generator modeling of perturbative and non-perturbative effects

Thank you for your attention!
Backup
**Inclusive jet production at $\sqrt{s} = 13$ TeV ($R = 0.4$)**

- comparison to fixed-order pQCD theory at **NNLO & NLO+NLL**
  - corrections for non-perturbative (**NP**) and electroweak (**EW**) contributions
Inclusive jet production at $\sqrt{s} = 13$ TeV (unfolding)

Full 2D unfolding across jet $p_T$ and $|y|$.

Response matrix depicts event migrations between the particle and detector levels.

Statistical correlations on particle-level spectra induced by the unfolding procedure.
Measurement of the Lund jet plane density

**CMS Preliminary**

138 fb⁻¹ (13 TeV)

- **generators**
  - AK4 jets
  - $p_T^{jet} > 700$ GeV, $|y_{jet}| < 1.7$
  - 0.084 < ln($k_T$/GeV) < 0.584
  - 1.09 < $k_T$ < 1.79 GeV
  - Data
  - HERWIG7 CHI
  - PYTHIA8 CP5
  - PYTHIA8 CPS
  - PYTHIA8 CPS (FSR up)
  - PYTHIA8 CPS (ISR down)
  - PYTHIA8 CP5 (FSR down)
  - PYTHIA8 CP5 (ISR down)

- **tunes**
  - PYTHIA8 CUEP8M1
  - PYTHIA8 CP5 (ISR down)

- **recoil schemes**
  - Data
  - HERWIG7 recoil schemes
  - $q$ scheme
  - $q$, $q$
  - $q$, $q'$ + veto

- **parton showers**
  - Data
  - PYTHIA8+DIRE
  - PYTHIA8+VINCIA
  - 0.084 < ln($k_T$/GeV) < 0.584
  - HERWIG7 dipole
  - SHERPA

- **Data**
  - $p_T^{jet} > 700$ GeV, $|y_{jet}| < 1.7$
  - 0.084 < ln($k_T$/GeV) < 0.584
  - 1.09 < $k_T$ < 1.79 GeV

**D. Savoiu**
Measurement of the Lund jet plane density

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Measurement of the Lund jet plane density

D. Savoiu

CMS Preliminary

138 fb⁻¹ (13 TeV)

p_{T,j} > 700 GeV, |y_j| < 1.7

2.333 < ln(R/ΔR) < 2.667

0.056 < ΔR < 0.078

Data

HERWIG7 CH3

PYTHIA8 CP5

PYTHIA8 CP5 (FSR up)

PYTHIA8 CP5 (FSR down)

PYTHIA8 CP5 (ISR up)

PYTHIA8 CP5 (ISR down)

R) < 3.000

2.667 < ln(R/ΔR) < 3.000

0.040 < ΔR < 0.056

Data

HERWIG7 recoil schemes

p scheme

q scheme

q + veto

recoil schemes

PYTHIA8+DIR EXTRACTION

PYTHIA8+VINCIA

HERWIG7 dipole

SHERPA

parton showers

tunes

generators

Measurement of the Lund jet plane density

Measurement of the Lund jet plane density

Measurement of the Lund jet plane density

- comparison to predictions in the soft and collinear limit using the one-loop $\beta$ function for the running of $\alpha_s$
- qualitative description of emission density as a function of emission $k_T$