Measurements of event properties and multi-differential jet cross sections and impact of CMS measurements on Proton Structure and QCD parameters

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Introduction

Particle jets:
- produced abundantly in the collisions of protons at the Large Hadron Collider (LHC)
- provide an excellent opportunity for testing the predictions of perturbative Quantum Chromodynamics (pQCD) at high energies
- important backgrounds for many new physics models

Inclusive jet cross section measurement:
- gives important information about the strong coupling constant $\alpha_S$
  \[ \sigma_{i-jet} = \sigma(pp \rightarrow i \text{ jets} + X) \propto \alpha_S \]
- provides a deep insight to understand the proton structure by deriving constraints on the parton distribution functions (PDFs)

Jet properties such as jet shapes, mass, charge etc.: key ingredients of Standard Model (SM) physics measurements and for beyond SM physics searches

![proton - (anti)proton cross sections](http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html)
QCD multijet production
Inclusive jet production

Double-differential cross-section in $p_T$ and $y$:

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \times L_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T (2\Delta|y|)}$$

Measurement at 8 TeV:

- anti-$k_t$ $R = 0.7$
- $21 < p_T < 74$ GeV, upto $|y| = 4.7$ ($\mathcal{L} = 5.6$ pb$^{-1}$)
- $74 < p_T < 2500$ GeV, upto $|y| = 3.0$ ($\mathcal{L} = 19.7$ fb$^{-1}$)

Comparison to NLO parton-level calculations, including electroweak (EWK) and non-perturbative (NP) corrections

Constraints on PDFs together with the fit of $\alpha_S$ [Slide no. 21, 22]

Ratios between different energies 2.76/8 and 7/8: partial reduction of uncertainties
Measurement at 13 TeV:

- anti-$k_t$ R = 0.4 and R = 0.7
- $p_T < 2$ TeV; $|y| < 3$ ($\mathcal{L} = 71$ pb$^{-1}$), $3.2 < |y| < 4.7$ ($\mathcal{L} = 44$ pb$^{-1}$)
- P8+CUETM1 (LO) agrees in shape in $|y| < 1.5$
- Hpp+CUETS1 (LO) agrees in shape in all rapidity bins
- PH+P8 (NLO) shows good agreement

Double-differential cross-section in $p_T$ and $y$:

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \times L_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T \Delta y}$$
Triple-differential dijets

\[
\frac{d^3\sigma}{dp_{T,\text{avg}} dy^* dy_b} = \frac{1}{c \mathcal{L}_{\text{int.eff}} \Delta p_{T,\text{avg}} \Delta y^* \Delta y_b} N
\]

Measurement at 8 TeV:
- anti-\(k_t\) \(R = 0.7\) (\(\mathcal{L} = 19.7\) fb\(^{-1}\))

Cross section as a function of the:
- average transverse momentum, \(p_{T,\text{avg}} = \frac{1}{2}(p_{T,1} + p_{T,2})\)
- half the rapidity separation, \(y^* = \frac{1}{2}|y_1 - y_2|\)
- boost of the two leading jets, \(y_b = \frac{1}{2}|y_1 + y_2|\)

Data are well described in most of the phase spaces but some differences at high \(p_{T,\text{avg}}\) and \(y_b\)

Best suited to constrain PDFs and extract \(\alpha_S\) [Slide no. 21, 22]
Inclusive multijets

Differential cross-section in $H_T, 2 / 2$:

$$\frac{d\sigma}{d(H_T, 2 / 2)} = \frac{1}{\epsilon \mathcal{L}_{\text{int, eff}} N_{\text{event}}} \Delta(H_T, 2 / 2)$$

Measurement at 8 TeV:

- anti-$k_t$ $R = 0.7$ ($\mathcal{L} = 19.7$ fb$^{-1}$)
- 2-jet and 3-jet event cross sections as a function of $H_T, 2 / 2 = \frac{1}{2}(p_T, 1 + p_T, 2)$
- Data are well described by theory predictions within uncertainty.
- EWK corrections explains the increasing excess of the 2-jet data w.r.t. theory ($\sim 1$ TeV)
- 3-jet to 2-jet cross section ratio $R_{32}$: many uncertainties cancel and sensitive to $\alpha_S$ [Slide no. 22]
Azimuthal correlations

Normalized differential cross-section in $\phi$:

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

Measurement at 13 TeV:

- anti-$k_t$ $R = 0.4$ ($\mathcal{L} = 35.9$ fb$^{-1}$)

- Normalized cross sections as a function of the:
  - azimuthal angular separation between the two highest leading $p_T$ jets (2-jet, 3-jet and 4-jet)
  - minimum azimuthal angular separation between any two of the three or four leading $p_T$ 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

- An interesting tool to test the theoretical predictions of multijet production processes

CMS-PAS-SMP-16-014
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
Jet charge

Measurement at 8 TeV:

- anti-$k_t$ $R = 0.5$ ($L = 19.7$ fb$^{-1}$)
- $p_T$-weighted sum of the electric charges of the particles in a jet:
  
  $$Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_i Q_i (p_T^i)^\kappa$$

  $$Q_L^\kappa = \sum_i Q_i \left( p_{\parallel}^i \right)^\kappa / \sum_i \left( p_{\parallel}^i \right)^\kappa$$

  $$Q_T^\kappa = \sum_i Q_i \left( p_{\perp}^i \right)^\kappa / \sum_i \left( p_{\perp}^i \right)^\kappa$$

- Differentiate statistically jets from quarks of different electric charge, or between gluon or quark jets
- Three values of $\kappa = 0.3$, 0.6 and 1.0, provide different sensitivities to the softer and harder particles in the jet
- Broader jet charge distribution on disabling the simulation of FSR in Pythia8

arXiv:1706.05868
(Submitted to JHEP)
Dijet mass

Measurement at 13 TeV:
- anti-$k_t$ $R = 0.8$ ($\mathcal{L} = 2.3$ fb$^{-1}$)
- Double-differential jet cross section as a function of the jet mass and jet $p_T$:
  - **Soft drop (SD)** grooming algorithm removes low energetic constituents
  - For ungroomed jets: MC generators predictions agree with data within uncertainties for intermediate regions ($0.1 < m/p_T < 0.3$)
  - For groomed jets: the jet mass peak is suppressed and the precision in the low and intermediate regions improves
  - Sensitive to QCD parton showering; used in searches for new physics ("boosted" objects)
Electroweak production
**Measurement at 8 TeV:**

- anti-$k_t$ $R = 0.5$ ($\mathcal{L} = 19.6$ fb$^{-1}$)
- $p_T(\ell) > 20$ GeV, $|y(\ell)| < 2.4$, $71 < M(\ell\ell) < 111$ GeV; $\ell = e, \mu$
- $p_T(j) > 30$ GeV, $|y(j)| < 2.4$
- Differential cross sections as functions of the jet $H_T$, $p_T$ and $|y|$ for the leading jet
- Double differential cross sections as a function of $|y|$ and $p_T$, for the leading jet
- A large number of final-state partons should be included in the matrix element calculations in order to correctly describe the kinematics of the leading jets

**Measurement at 13 TeV:**

- anti-$k_t$ $R = 0.4$ ($\mathcal{L} = 2.5$ fb$^{-1}$)
- $p_T(\ell) > 20$ GeV, $|y(\ell)| < 2.4$, $71 < M(\ell\ell) < 111$ GeV; $\ell = \mu$
- $p_T(j) > 30$ GeV, $|y(j)| < 2.4$
- Differential cross sections as a function of jet multiplicity, $p_T$ and $y$ for different jet multiplicities (upto 3 jets)
- Good agreement with NLO and NNLO calculations
Measurement at 8 TeV:
- anti-$k_t$ R = 0.5 ($\mathcal{L} = 19.6 \text{ fb}^{-1}$)
- Differential cross sections as functions of the jet multiplicity, $H_T$, and $p_T$ for different jet multiplicities
- Very good agreement with NLO 0, 1, 2 jets FxFx and NNLO 1 jet
- Important background for other measurements

Measurement at 13 TeV:
- anti-$k_t$ R = 0.4 ($\mathcal{L} = 2.5 \text{ fb}^{-1}$)
- Differential cross sections as a function of jet multiplicity, $p_T$, $y$ and $H_T$ for different jet multiplicities (upto at least 3 jets)
- Good agreement with NLO and NNLO calculations
**Z → ℓ + b jet at 8 TeV:**
- anti-$k_t$ $R = 0.5$ ($\mathcal{L} = 19.8$ fb$^{-1}$)
- b tagging: combined secondary vertex (CSV) algorithm
- Differential cross sections as a function of $p_T$ and $\eta$ of the highest-$p_T$ b jet, Z boson $p_T$, $H_T$, and $\Delta \phi_{Zb}$
- Ratios of the differential cross sections for $Z(1b)$ and $Z+$jets
- $Z(>1b)$ low-$p_T$ region not well described, Z(bb) generally agree with predictions

**W → ℓ + b jet at 8 TeV:**
- anti-$k_t$ $R = 0.5$ ($\mathcal{L} = 19.8$ fb$^{-1}$)
- Exactly one $\ell$ with $p_T(\ell) > 30$ GeV, $|\eta_\ell| < 2.1$,
  Exactly two b jets with $p_T(j) > 25$ GeV, $|\eta_j| < 2.4$
- Cross-section in agreement with Standard Model predictions
  \[ \sigma \rightarrow W(\ell \nu + b \bar{b}) = 0.64 \pm 0.03(\text{stat}) \pm 0.10(\text{syst}) \pm 0.06(\text{theo}) \pm 0.02(\text{lumi}) \]

**arXiv:1611.06507 (Accepted in EPJC)**

**EPJC 77 (2017) 92**

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**Measurement at 8 TeV:**

- anti-$k_t$ R = 0.5 ($\mathcal{L} = 19.7$ fb$^{-1}$)

- **Cross section** $\sigma(pp \rightarrow Z + c + X)$,

- **Cross section ratio** $\frac{\sigma(pp \rightarrow Z + c + X)}{\sigma(pp \rightarrow Z + b + X)}$,

  inclusively and differentially as a function $p_T$ of Z boson and jet with heavy flavour content

- Measurements are in agreement with the LO predictions from MADGRAPH and NLO predictions from MG5_aMC

- Predictions from the MCFM program are lower than the measured $\sigma(Z + c)$, both inclusive and differentially

- Better description in terms of the $Z + c/Z + b$ cross sections ratio

$$\sigma(pp \rightarrow Z + c + X) = 8.6 \pm 0.5{\text{(stat)}} \pm 0.7{\text{(syst)}} \text{ pb}$$

$$\frac{\sigma(pp \rightarrow Z + c + X)}{\sigma(pp \rightarrow Z + b + X)} = 2.0 \pm 0.2{\text{(stat)}} \pm 0.2{\text{(syst)}} \text{ pb}$$
Top Physics
Differential $t\bar{t}$ production cross section, $\ell +$ jets

**Measurement at 8 TeV:**
- anti-$k_t$ R = 0.5 ($\mathcal{L} = 19.7$ fb$^{-1}$)
- Dilepton $e^\pm\mu^\mp$ final state
- Normalized double-differential cross section as a function of six different pairs of kinematic variables:
  \[ p_T(t), y(t), [\Delta y(t), M(t\bar{t})], [\rho_T(t\bar{t}), M(t\bar{t})], [\Delta \phi(t\bar{t}), M(t\bar{t})] \]
- Significant improvement of g at high x as a function of $M(t\bar{t}) - y(t\bar{t})$ [Slide no. 21]

**Measurement at 13 TeV:**
- anti-$k_t$ R = 0.4 ($\mathcal{L} = 2.3$ fb$^{-1}$)
- $\ell+$jets decay channels with a single $\mu$ or $e$ in the final state
- Differential and Double-differential cross sections as a function of jet multiplicity and of kinematic variables of the t and $t\bar{t}$ system
- Measured $p_T(t)$ softer than expected except for Herwig++ MCs, as predicted by the NNLO and the NLO+NNLL' QCD calculation

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*PRD 95 (2017) 092001*
t-channel single top quark production

Measurement at 13 TeV:

- anti-$k_t$ $R = 0.4$ ($\mathcal{L} = 2.2$ fb$^{-1}$)
- Exactly one muon and at least two jets with one b-tagged jet
- Separation between signal and background processes by a MVA technique
- Fit to the distribution of the discriminating variable yields a total cross section:
  \[ \sigma(t\text{-ch.}, t+\bar{t}) = 238 \pm 13\text{(stat)} \pm 29\text{(syst)} \text{ pb} \]
- A ratio of top quark and top antiquark production:
  \[ R_{t\text{-ch.}} = 1.81 \pm 0.18\text{(stat)} \pm 0.15\text{(syst)} \]
- Absolute value of the CKM matrix element $V_{tb}$:
  \[ 1.05 \pm 0.07\text{(exp)} \pm 0.02\text{(theo)} \]
- All results are in agreement with the Standard Model predictions.

arXiv:1610.00678
(Accepted in PLB)
Top mass

Measurement at 8 TeV:
- Cambridge-Aachen R = 1.2 ($\mathcal{L} = 19.7$ fb$^{-1}$)
- Vetoed > 2 jets with $p_T > 150$ GeV
- Highly boosted $t\bar{t}$ events:
  - Semileptonic decay: $t \rightarrow bW$ with $W \rightarrow \ell\nu_\ell$ where $\ell = e$ or $\mu$
  - Fully hadronic decay: $t \rightarrow bW$ with $W \rightarrow q\bar{q}'$
- Differential cross section as a function of jet mass ($m_{\text{jet}}$):
  - Slight overestimation of cross section in simulation.
- Normalized differential cross section as a function of jet mass ($m_{\text{jet}}$):
  - Consistent with other cross section measurements in boosted events.
- Peak position in the $m_{\text{jet}}$ distribution is sensitive to the top quark mass $m_t$
  $$m_t = 170.8 \pm 9.0 \text{ GeV}$$

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Parton Distribution Functions determination

**Inclusive jet:**
- 2D cross sections vs of jet $p_T$ and rapidity
- Probes hadronic parton-parton interaction over a wide range of $x$ and $Q$
- Constraints on PDFs: QCD analysis of data together with HERA DIS measurements, at NLO using HERAFitter
- Significant impact on the gluon distribution in a new kinematic regime

**Triple differential dijets:**
- 3D cross sections vs of jet average $p_T$, rapidity separation and boost
- Use dijet cross section in the QCD analysis in addition to HERA data
- Change in the gluon shape similar as observed in the case of inclusive jet data
- Significant reduction of the uncertainty in $g(x)$ at high $x$

**Double-differential cross sections for top quark pair production:**
- 2d-differential $t\bar{t}$ cross sections
- QCD analysis of data along with HERA inclusive DIS data and CMS W asymmetry, using XFitter 1.2.2
- Best improvement comes from $M(t\bar{t})-y(t\bar{t})$
- Recommend to use both data sets for further improvement of $g(x)$ at high $x$
The strong coupling constant $\alpha_S$

**Inclusive jet [JHEP 03 (2017) 156]**:

- Least square minimization on $p_T(y)$ spectrum using NLO parton level predictions
- Using the CT10 NLO PDF set
  \[ \alpha_S(M_Z) = 0.1164^{+0.0014}_{-0.0015} \text{ (exp)} +^{0.0025}_{-0.0029} \text{ (PDF)} \pm 0.0001 \text{ (NP)} +^{0.0053}_{-0.0028} \text{ (scale)} \]

**Multijets [CMS-PAS-SMP-16-008]**:

- 3-jet to 2-jet cross section ratio, $\mathcal{R}_{32} \propto \alpha_S$
- Insensitive to many theoretical and experimental systematics
- Using the MSTW2008 PDF set
  \[ \alpha_S(M_Z) = 0.1150 \pm 0.0010 \text{ (exp)} \pm 0.0013 \text{ (PDF)} \pm 0.0015 \text{ (NP)} +^{0.0050}_{-0.0000} \text{ (scale)} \]

**Triple differential dijets [arXiv:1705.02628]**:

- Precise $\alpha_S$ extraction together with PDF fit
  \[ \alpha_S(M_Z) = 0.1199 \pm 0.0015 \text{ (exp)} \pm 0.0002 \text{ (mod)} +^{0.0002}_{-0.0004} \text{ (par)} +^{0.0031}_{-0.0019} \text{ (scale)} \]

$\alpha_S^{PDG} = 0.1181 \pm 0.0011$
Jet production in pp collisions is one of the main phenomenological predictions of pQCD. Measurements of characteristics of events with jets, from jet-charge over investigations of shapes to jet mass distributions are presented.

- Compared to theoretical predictions including those matched to parton shower and hadronization.

Multi-differential jet cross-sections over a wide range in transverse momenta from inclusive jets to multi-jet final states are measured.

- Impact on the determination of the strong coupling constant $\alpha_S$ as well as on parton density functions (PDFs)

Electroweak boson production: inclusive or associated with charm or beauty quarks give insight into the flavour separation of the proton sea.

Measurements of cross sections of jet and top-quark pair production are in particular sensitive to the gluon distribution in the proton and $\alpha_S$. 

THANKS!!
Back-Up Slides
Triple-differential dijets

 gg jets (x_g < x_q)
 gq jets (x_g > x_q)
 q_iq_i jets
 q_iq_j jets
 q_iq_i jets
 q_iq_j jets

 Subprocess fraction
 0 \gamma_b < 1
 0 \gamma^* < 1

 1000 200 300 500
 p_T, avg [GeV]
 0.0
 0.2
 0.4
 0.6
 0.8
 1.0

 Subprocess fraction
 0 \gamma_b < 1
 1 \gamma^* < 2

 8 TeV

 gg jets
 gq jets

 Subprocess fraction
 1 \gamma_b < 2
 0 \gamma^* < 1

 2 \gamma^* < 3

 1000 200 300 500
 p_T, avg [GeV]
 0.0
 0.2
 0.4
 0.6
 0.8
 1.0

 Subprocess fraction
 1 \gamma_b < 2
 0 \gamma^* < 1

 2 \gamma^* < 3

 arXiv:1705.02628
Jet charge

CMS

\( p_T > 400 \text{ GeV} \)

\(|\eta| < 1.5 \)

19.7 fb\(^{-1}\) (8 TeV)

\( \frac{1}{N} \frac{dN}{dQ_L} \) [1/e]

\( \frac{1}{N} \frac{dN}{dQ_L} \) [1/e]

\( Q_L < 0.6 \) [e]

\( Q_L < 0.6 \) [e]

Data

MC

0.5

1

1.5

0.8

-0.6

-0.4

-0.2

0

0.2

0.4

0.6

0.8

MC

Data

0.5

1

1.5

0.8

-0.6

-0.4

-0.2

0

0.2

0.4

0.6

0.8

MC

Data

19.7 fb\(^{-1}\) (8 TeV)

\( p_T > 400 \text{ GeV} \)

\(|\eta| < 1.5 \)

\( \frac{1}{N} \frac{dN}{dQ_L} \) [1/e]

\( \frac{1}{N} \frac{dN}{dQ_L} \) [1/e]

\( Q_L < 0.6 \) [e]

\( Q_L < 0.6 \) [e]

Data

MC

0.5

1

1.5

0.8

-0.6

-0.4

-0.2

0

0.2

0.4

0.6

0.8

MC

Data

0.5

1

1.5

0.8

-0.6

-0.4

-0.2

0

0.2

0.4

0.6

0.8

MC

Data

-19.7 fb

CMS

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Parton Distribution Functions determination

HERAPDF method (Hessian)

$Q^2 = 10^4 \text{GeV}^2$

CMS HERA I+II DIS + CMS dijets
HERA I+II DIS + CMS inc. jets

$10^4 \, 10^3 \, 10^2 \, 10^1$

x

0.4
0.2
0.0
0.2
0.4

Rel. uncert.

$\delta xg(x, \mu^2_{\text{ref}}) / xg(x, \mu^2_{\text{ref}})$

CMS

$\mu^2 = 30000 \text{ GeV}^2$ NLO

HERA + CMS $W^\pm$ 8 TeV
$+ y(tt) 8 \text{ TeV}$
$+ [y(tt), M(tt)] 8 \text{ TeV}$

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arXiv:1705.02628