MEASURING JETS AT THE LHC

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on behalf of the CMS and ATLAS collaborations

QCD@LHC 2019
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This Talk: Jets

Probe Jet Structure

Probe Hard Scatter
QCD@LHC

New Physics?  tW/Z/H mass  Hard process  Jet algorithm  Jet shape  Jet mass  Heavy quark masses  Temperature in qgp  Diffraction/UE  Hadronization

m_{EW}  p_{T}  p_{TR}  p_{Tr}  m  m_{b,c}  T  \Lambda_{QCD}

Mysteries!!!  > NLO calculations  NLL/resummed calculations  Mysteries?  PDFs  Tuning

H/T Y.-T. Chien, S. Rappoccio
Jet Measurements at the LHC

This Talk

- Jet Measurements at the LHC
- New Physics?
- tW/Z/H mass
- Hard process
- Jet algorithm
- Jet shape
- Jet mass
- Heavy quark masses
- Temperature in qgp
- Diffraction/UE
- Hadronization

- m_{EW}
- p_T
- p_T R
- p_T R
- m
- m_{b,c}
- T
- \Lambda_{QCD}

Mysteries!!!

> NLO calculations
NLL/resummed calculations
Mysteries?

PDFs

Tuning

Caveat: not covering γ+jets, V+jets, top quark measurements
Jet Production Cross Sections

- New Physics?
- $tW/Z/H$ mass
- Hard process
- Jet algorithm
- Jet shape
- Jet mass
- Heavy quark masses
- Temperature in qgp
- Diffraction/UE
- Hadronization

- $m_{EW}$
- $p_T$
- $p_{TR}$
- $p_{TR}$
- $m$
- $m_{b,c}$
- $T$
- $\Lambda_{QCD}$

Mysteries!!!

- $> NLO$ calculations
- NLL/resummed calculations
- Mysteries?

PDFs

Tuning
Test predictions of pQCD at high energy

ATLAS: 13 TeV double differential xs

CMS: 8 TeV triple differential xs

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

JHEP 05 (2018) 195


19.7 fb\(^{-1}\) (8 TeV)
Test predictions of pQCD at high energy

ATLAS: 13 TeV double differential \( \sigma \)

CMS: 8 TeV triple differential \( \sigma \)

Discrepancy at high \( p_T \), boost

\[ y^* = \frac{|y_1 - y_2|}{2} \]

\[ p_{T,\text{avg}} = \frac{(p_{T,1} + p_{T,2})}{2} \]

\[ y_b = \frac{|y_1 + y_2|}{2} \]
Constrain PDFs, measure $\alpha_s$

CMS dijet data reduces gluon PDF uncertainty at high $x$

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

See talks by J. Pekkanen, S. Pflitsch, P. Starovoitov
Inclusive Jet Cross Section

ATLAS, CMS: 13 TeV double differential $\sigma$

Data/prediction appear to agree relatively well

JHEP 05 (2018) 195

Inclusive Jet Cross Section

- Closer look at CMS results
  - Fixed-order NLO predictions + NP, EW corrections (NLOJet++)
    - Overestimates $R=0.4$ due to missing PS, soft-gluon resummation contributions
  - NLO predictions matched to parton showers (PH+P8) more effective overall

![Graphs showing ratio of inclusive jet cross section to NLOJet++ CT14 predictions for different $R$ values and jet $p_T$ ranges.](image-url)
Test dependence of jet production $\times$ on anti-$k_T$ distance parameter

See P. Gunnellini’s talk
Test dependence of jet production $\times s$ on anti-$k_T$ distance parameter

CMS Preliminary

NLO+PS: discrepancy at low $p_T$, large radius

Underlying-event (MPI): $(\delta p_T)_{UE} \sim R^2$

Hadronization: $(\delta p_T)_{HAD} \sim R^{-1}$

Parton shower: $(\delta p_T)_{PS} \sim \ln R^{-1}$

See P. Gunnellini’s talk
Event Shape Variables

ESVs sensitive to flow of energy in hadronic states

Transverse thrust

\[ T_\perp \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}} \]

Complement to \( T_\perp \)

\[ \tau_\perp \equiv 1 - T_\perp \]

Sensitive to hard-scattering

Jet mass

\[ \rho_X \equiv \frac{M_X^2}{p^2} \]

Sensitive to hadronization, NP effects

Jet broadening

\[ B_X \equiv \frac{1}{2p_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2} \]
Event Shape Variables

- Best ESV data/MC agreement at higher energy
  - Partons more boosted, less spherical events
  - $\alpha_s$ decreases, less hard gluon emission

**Pythia8** models energy flow in transverse plane well
(string fragmentation + $p_T$-ordered shower)

**Herwig++** performs well
(cluster fragmentation + angular-ordered shower)
Jet Substructure has emerged as a primary way to look for new physics, and probe QCD at the LHC.

I. Moult
Jet Mass: Dijets

- Groomed vs ungroomed mass: handle on the soft part of the jet (NP regime)
- Investigate multiple soft drop parameters

See A. Parker’s talk
Jet Mass: Dijets

- Groomed vs ungroomed mass: handle on the soft part of the jet (NP regime)

Gluon contribution needs tuning!
→ CMS Z+jets measurement ongoing

![Graph showing quark and gluon likelihood discriminants for Z+jets and Dijets](image-url)
Jet Fragmentation

- Measure track-based jet fragmentation functions
- Charged-particle multiplicity, relative momentum, angular properties of radiation pattern

Measuring jet fragmentation means understanding the emergence of jet structure

\[ \langle n_{ch}^{\text{jet}}(p_T) \rangle = \sum_{p}^{f_p} \int_{\text{threshold}}^{p_{T}^{\text{jet}}} d\zeta D_p^h(\zeta, p_{T}^{\text{jet}}) \]

\[ \zeta = \frac{p_T^{\text{particle}}}{p_T^{\text{jet}}} \]

See A. Buckley's talk
Jet Fragmentation

- Measure track-based jet fragmentation functions
  - Charged-particle multiplicity, relative momentum, angular properties of radiation pattern

Extraction of quark-like fragmentation function components more performant than for gluons

$$\zeta = \frac{p_T^{\text{particle}}}{p_T^{\text{jet}}}$$

See A. Buckley’s talk
Jet Charge

- Measure momentum-weighted sum of the charges of the particles in the jet
- Jet charge probes hadronization, parton shower

Measurements agree with pQCD

Sensitive to hadronization, fragmentation models in Pythia8 and Herwig++

\[ Q^x = \frac{1}{(p_T^\text{jet})^x} \sum_i Q_i(p_T^i)^x \]
• Jet substructure variables used in BSM searches
• Measure in large-R soft drop jets
  • Dijet (quark/gluon), W jets, top jets
  • Goal: improve modeling in MC

\[ D_2: \text{ECF for identifying two-body structures} \]

\[ \text{LHA: provides a measure of jet broadness} \]
Jet Substructure Observables

- Jet substructure variables used in BSM searches
- Measure in large-R soft drop jets
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**Jet Substructure Observables**

- \( D_2 \): ECF for identifying two-body structures
- \( \text{LHA} \): provides a measure of jet broadness

**Here:** Pythia8 outperforms Herwig7
Jet Substructure Observables

- Jet substructure variables used in BSM searches
- Measure in large-R soft drop jets
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\[ D_2: \] ECF for identifying two-body structures
\[ LHA: \] provides a measure of jet broadness

\text{W mass peak shifted: models overestimate gluon radiation}
Color Flow in Jet Pull

- Jet pull encodes parton color connections
  - Poorly constrained area of QCD
  - Potentially useful for distinguishing event topologies

\[ \tilde{\mathcal{P}}(j) = \sum_{i \in j} \frac{\left| \Delta r_i \right| \cdot p_T^i}{p_T^j} \Delta r_i \]

ATLAS measurement at 13 TeV

See S. Marzani’s talk
Default generator does not agree well with data!

Data slightly favors SM over exotic color flow

See S. Marzani’s talk
Jets at the LHC

- Jet measurements give us a handle on QCD
- Which generator is best? Depends on the observable!
  - Can we combine the existing measurements to make MC work for everything?
- Gluon jets not well-understood
  - More measurements needed/ongoing!

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New Physics? | tW/Z/H mass | Hard process | Jet algorithm | Jet shape | Jet mass | Heavy quark masses | Temperature in qgp | Diffraction/UE | Hadronization
---|---|---|---|---|---|---|---|---|---
$\text{m}_{\text{EW}}$ | $\text{p}_{\text{T}}$ | $\text{p}_{\text{T}}\text{R}$ | $\text{p}_{\text{T}}\text{R}$ | $\text{m}$ | $\text{m}_{b,c}$ | $\text{T}$ | $\Lambda_{\text{QCD}}$

Mysteries!!! | > NLO calculations | NLL/resummed calculations | Mysteries?
---|---|---
PDFs | Tuning

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Additional Material
Generators

- **Pythia8**: $2 \rightarrow 2$ parton production @ LO + PS and UE
- **Herwig++ 2.7**: $2 \rightarrow 2$ parton production @ LO + PS and UE
- **Herwig 7**: $2 \rightarrow 2$ parton production @ NLO + PS and UE
- **Madgraph_AMC+NLO+Pythia8**: $2 \rightarrow 2+n$ (with $n<3$) parton production @ LO + PS and UE
- **Powheg+Pythia8**: $2 \rightarrow 2$ parton production @ NLO + PS and UE
- **Powheg+Herwig++**: $2 \rightarrow 2$ parton production @ NLO + PS and UE
- **NLOJet++**: $2 \rightarrow 2$ dijet production @ NLO

Leading order process  Real correction  Virtual correction
CMS Dijet Cross Section

\[ y^* = \frac{1}{2}|y_1 - y_2| \]

\[ y_b = \frac{1}{2}|y_1 + y_2| \]
3D dijets: Theoretical uncertainties

- no uncertainties in the EW corrections are assigned

8 TeV

0 \leq y_b < 1
0 \leq y^* < 1
NNPDF 3.0-NLO

EPJ C 77(2017)746

Pavel Starovoitov (Kirchhoff-Institut für Physik) Experimental measurements of strong couplings QCD@LHC-2019 18/32
CMS Dijets: PDF Uncertainties

- ** CMS \( 0 \leq y_b < 1 \) \( 0 \leq y' < 1 \)
- ** CMS \( 0 \leq y_b < 1 \) \( 2 \leq y' < 3 \)
- ** CMS \( 1 \leq y_b < 2 \) \( 1 \leq y' < 2 \)
- ** CMS \( 1 \leq y_b < 2 \) \( 0 \leq y' < 1 \)
- ** CMS \( 2 \leq y_b < 3 \) \( 0 \leq y' < 1 \)
ATLAS Inclusive: Theory Corrections
Radius Scan

### Fixed order

**CMS Preliminary**

- Anti-$k_t$, CHS
- $R = 0.2$
- $\text{yl} < 0.5$

### Fixed order vs MC with PS resummation

**CMS Preliminary**

- $\Delta R < 35.9 \text{ fb}^{-1} (13 \text{ TeV})$

**NP effects important at low $p_T$**

**Soft radiation effects**

**Effects of hadronization, out-of-cone radiation**

**PS resummation**

- Large impact
Jet Fragmentation

Observables

Fragmentation function $D$ defined as $p_T$ fraction of hadron $h$ wrt its containing jet $p_T$, from parton $p$.

$\Rightarrow$ DGLAP pQCD evolution; mirror image of PDFs

This paper uses charged hadrons, but full (calo) jet

$\Rightarrow \langle n_{ch} \rangle$ and differential $1/N_{jet} \Delta N_{jet}/d\langle n_{ch} \rangle$

+ **summed fragmentation function:**
  differential in $p_T$ fraction $\zeta$ and jet $p_T$ $\Rightarrow$ extract partial fractions, moments & weighted sums

+ Relative transverse momentum
  Radial profile (non-$p_T$-weighted)
Soft Drop

- Recursively decluster jet. Remove the softer component unless the soft drop condition is satisfied.

  \[ \min(p_{T1}, p_{T2}) > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta \]

- Soft wide angle radiation fails the condition
  - As \( z_{\text{cut}} \uparrow \) \( \Rightarrow \) more aggressive grooming
  - As \( \beta \downarrow \) \( \Rightarrow \) more aggressive grooming

- Example \( (z_{\text{cut}} = 0.1) \):
  - If \( \beta = 0 \), remove softer subjet if \( p_T \) fraction < 0.1
    (~equivalent to MMDT)
  - If \( \beta > 0 \), remove softer subjet if \( p_T \) fraction < \( x \), where \( x \) increases with \( \Delta R \) and has maximum value 0.1
  - \( \beta \rightarrow \infty \) no grooming
  - \( \beta < 0 \) soft drop becomes a tagger instead of a groomer
    (finds jets with hard, large angle subjets)

J. Dolen