NEW IDEAS IN JET PHYSICS

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Jets at the LHC

- Jet physics is entering a **golden era**
  - No matter what the LHC sees, we will **need jets** to figure out what it is: Supersymmetry? Extra dimensions? Higgs boson?
  - The LHC is studying jets with **unprecedented precision**

- **New ways** to use jets are being invented every day

- **New theoretical tools** are being developed to calculate jet properties

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**Figure 10:** Comparison of theory to ATLAS data for the $W$ spectra. The red band is the NLO prediction, using $\mu_f = \mu_r = m_W$, as in [cite a paper](#). The N$_{3}^{LL+NLO}$ prediction, in green, is in excellent agreement with the data. Dashed blue lines indicate PDF uncertainties which are of order the scale uncertainties at N$_{3}^{LL+NLO}$ order.
Jet physics I’m interested in

- Jet substructure
- Color flow
- Quark vs gluon jets
  - Gluon tagging
  - Calibration
- Jet charge
- Q-jets
- Jet mass
- N-subjettiness
- Jet physics from static charges in AdS
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Cui, Han, MDS, JHEP 1107 (2011) 127


Gallichio and MDS JHEP 1110 (2011) 103

Krohn, Lin, MDS, Waalewijn., in preparation


Becher, Chien, Kelley, Schabinger, Zhu, various

Feige, MDS, Stewart Thaler, arXiv:1204.3898

Why study jets at the LHC?

New physics at the LHC is expected to be jet-heavy
• Even if new physics is first discovered with leptons, need jets to tell us what it is!

Example: Supersymmetry

6 Jets
Interpreting jets

We want to see quarks and gluons:

We observe jets:

QCD

Can we invert?

Reality: this exists

Jet-to-parton map

- Find jet momenta
- Set quark momenta = jet momenta
What is wrong with the jet-to-parton map?

It treats jets as 4-vectors

- Jets have color, and color connections
  - Used by D0 (published) and ATLAS (Boost 2012, hopefully)

- Quark and gluon jets may be different
  - New physics is quark heavy, backgrounds are gluon heavy
  - Although difficult, quark and gluon discrimination could be extremely useful

- Jets have charge

- Jets from boosted objects have substructure
  - E.g. top-tagging from boosted top jets – used by CMS!
  - Boosted Higgs searches
  - N-subjettiness
JET CHARGE
Jet charge

Can the charge of a jet be measured?

- Could distinguish **up-quark** jets from **down-quark** jets
  - Could help distinguish up squarks from down squarks

- \( W \) prime vs \( Z \) prime

- Many many uses for characterizing new physics (if seen)
How to measure

We consider the energy-weighted jet charge:

$$Q_{\kappa}^i = \frac{1}{E_{\text{jet}}} \sum_{j \in \text{jet}} Q_j (E_j)^{\kappa}$$

• Long history at e+e- colliders and deep-inelastic scattering
• Can it work at the LHC?

$$Z' \rightarrow \bar{u}u$$

jet p_T-weighted charge, min p_T = 50 GeV, Zprime1000_uu.dat
Consistent among flavors

distribution for d-type quarks for different processes

- Zprime1000_ss
- Zprime500_dd
- Zprime1000_dd
- Zprime1000_bb
- Zprime1000_ss
- Zprime500_dd
- Zprime1000_dd
- Zprime1000_bb
- Wprime1000_ud
- Wprime500_udbar
- Wprime200_udbar
Distinguishes W ' from Z '  

Log-likelihood distribution for 1 TeV resonance, various $\kappa$

2$\sigma$ with 30 events  
5$\sigma$ with 200 events
Calibrate on standard model

2D charges (parton level) for different pT

Fractions (parton level)

Jet charge (hadron level)
Test on top quarks

Measure sum of jet charges from $W$ decay products

distribution of jet charge for $W$s from top pairs

- blue: $\kappa = 0.3$
- green: $\kappa = 0.6$
- red: $\kappa = 1$
Calculate in QCD

Mean jet charge

\[ \langle Q^i_{\kappa} \rangle = \frac{1}{16\pi^3} \frac{\tilde{J}_{ij}(E, R, \kappa, \mu)}{J_i(E, R, \mu)} \sum_h Q_h \tilde{D}^h_j(\kappa, \mu) \]

Width of jet charge

\[ \langle (Q^i_{\kappa})^2 \rangle = \sum_j \frac{\tilde{J}_{ij}(E, R, 2\kappa, \mu)}{2(2\pi)^3 J_j(E, R, \mu)} \sum_h Q^2_h \tilde{D}^h_j(2\kappa, \mu) + \int dz_1 dz_2 z_1^\kappa z_2^\kappa \sum_{h_1, h_2} Q_{h_1} Q_{h_2} g^{h_1 h_2}_{ij}(E, R, z_1, z_2, \mu) \]

- Good agreement with Pythia
- Systematically improvable
N-SUBJETTINESSNESS
N-subjettiness

\[ \mathcal{T}_N \equiv \min_{n_1, \ldots, n_N} \sum_{j \in J} \min \{ p_j \cdot n_1, \ldots, p_j \cdot n_N \} \]

\[ \mathcal{T}_1 \approx \frac{m_J^2}{2E_J} \]

\[ \mathcal{T}_2 \approx \frac{m_1^2}{2E_1} + \frac{m_2^2}{2E_2} \]

\[ \mathcal{T}_2 / \mathcal{T}_1 \]

Good discriminant

QCD jet (all \( \tau_n \) small)

Boosted W/Z jet (small \( \tau_2 \), large \( \tau_1 \))
Ratio $\tau_2/\tau_1$

Useful for distinguishing boosted W jets from QCD jets

\[ \tau_2 \approx \frac{m_1^2}{2E_1} + \frac{m_2^2}{2E_2} \]

\[ \tau_1 \approx \frac{m_J^2}{2E_J} \]

65 GeV < $m_j$ < 95 GeV

- **W jets**
- **QCD jets**
Not as good as Qjets (see Tuhin’s talk)

\[ \frac{\epsilon_S}{\sqrt{\epsilon_B}} \]

Qjets + n-subjettiness

n-subjettiness

pruning

W tagging (60-100 GeV window)

- pruned mass
- $\frac{r_y}{r_\tau}$
- $\alpha=0.0001$
- $\alpha=0.001$
- $\alpha=0$
- $\alpha=0.0001 & \frac{r_y}{r_\tau}$

SIC_from_TMVA
Already measured by ATLAS

(March 20, 2012)

With more data, could be a **precision observable**.

Can we **calculate** n-subjettiness more accurately using **QCD**?
Factorization formula

$$\frac{1}{\sigma_0} \frac{d\sigma}{dT_{2/1}} = H \int \frac{d\cos \theta}{2} \int ds_1 ds_2 dk_1 dk_2 S(k_1, k_2, \{n_i\}, \mu)$$

$$\times J(s_1, \mu) J(s_2, \mu) \delta \left( T_{2/1} - \frac{k_1 + k_2}{T_1} - \frac{s_1 E_2 + s_2 E_1}{2 E_1 E_2 T_1} \right)$$

Based on factorization for n-jettiness (Stewart, Tackmann, Waalewijn)

Hard function

Soft function

Jet function

Work done with Iain Stewart, Jesse Thaler and Ilya Fiege
Results

NNNLL Calculation (No Hadronization)

Pythia (No Hadronisation)
Compare to Pythia

![Graphs showing comparison between Pythia and NNLL results with hadronization.](image)

$Ilya$ Feige (Harvard University)

March 29, 2012 13 / 24
Corrections

Real events have
• initial state radiation (ISR)
• Final state radiation (FSR) from other jets
• Underlying event (UE)
• Jet algorithm and size dependence

Power corrections?
Cone and ISR/UE

Cone and ISR/UE effects in Pythia

\( Q = 500 \text{ GeV}, |m_{\text{jet}} - m_Z| < 10 \text{ GeV} \)
Cone and ISR/UE

Cone and ISR/UE effects in Pythia

\( Q = 500 \text{ GeV}, |m_{\text{jet}} - m_Z| < 10 \text{ GeV} \)

\[ \frac{1}{\sigma} \frac{d\sigma}{d\tau_2/1} \]
Cone and ISR/UE effects in Pythia

\[ Q = 500 \text{ GeV}, \ |m_{\text{jet}} - m_Z| < 10 \text{ GeV} \]
Corrections

Real events have
• initial state radiation (ISR)
• Final state radiation (FSR) from other jets
• Underlying event (UE)
• Jet algorithm and size dependence

Key to corrections:
• At large boost, these shift $\tau_1$ and $\tau_2$ in the same way
• For W-jets, $\tau_1 = m_W$ at parton level $\rightarrow$ we know $\Delta \tau$

Slightly modified observable:

$$\tau_{2/1} \equiv \frac{T_2 - T_1 + \hat{T}_1}{T_1 - T_1 + \hat{T}_1} = \frac{T_2 - \Delta \tau}{T_1 - \Delta \tau} \implies (\tau_{2/1})_{ISR/UE} \sim \frac{1}{Q}$$
Cone and ISR/UE effects in Pythia

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Cone and ISR/UE effects in Pythia

\( Q = 500 \text{ GeV}, \mid m_{\text{jet}} - m_Z \mid < 10 \text{ GeV} \)

\[ \frac{1}{\sigma} \frac{d\sigma}{d\tau_2 / 1} \]

- Baseline
- Above + R = 1.0
- Above + ISR/UE
- Above + \( \Delta \tau \)
Cone and ISR/UE effects in Pythia

\( Q = 500 \text{ GeV}, |m_{\text{jet}} - m_Z| < 10 \text{ GeV} \)

\[
\Delta \tau' = \Delta \tau \left( 1 - \frac{\pi m_Z}{2Q} \right)
\]

Subtract off average
Cone and ISR/UE effects in Pythia

\( Q = 1000 \text{ GeV}, \ |m_{\text{jet}} - m_z| < 10 \text{ GeV} \)
Cone and ISR/UE

Cone and ISR/UE effects in Pythia

\( Q = 1000 \text{ GeV}, |m_{\text{jet}} - m_Z| < 10 \text{ GeV} \)

\[ \frac{1}{\sigma} \frac{d\sigma}{d\tau_2/1} \]

- Baseline
- Above + R = 1.0
- Above + ISR/UE
- Above + \( \Delta \tau \)
- Above + \( \Delta \tau ' \)
- NNNLL
QUARKS VS GLUONS
Quark versus Gluon jets

Subtle subject
  • Monte Carlo event generators may not be trustworthy
  • Some data from LEP, but ATLAS and CMS can measure much better

Two parts
  1. Assuming Pythia is correct, how can we distinguish Q from G?
      

  2. How can we validate on data?
      • Where do we find pure samples of quark and gluon jets?
      
      Gallichio and MDS JHEP 1110 (2011) 103
How to compare variables?

- Look at distributions of each variable, normalized to equal area
How to compare variables?

- Look at distributions of each variable, normalized to equal area
- Look at efficiencies as a function of sliding cut

mass/Pt

Sliding Cut
How to compare variables?

This generates the “Receiver Operator Characteristic” (ROC)
We looked at 10,000 variables

The menu, including varying jet size

- Distinguishable particles/tracks/subjets
  - multiplicity, $\langle p_T \rangle$, $\sigma_{p_T}$, $\langle k_T \rangle$,
  - charge-weighted $p_T$ sum

- Moments
  - mass, girth, jet broadening
  - angularities
  - optimal kernel
  - 2D: pull, planar flow

- Subjet properties
  - Multiplicity for different algorithms and $R_{\text{sub}}$
  - First subjet’s $p_T$, 2nd’s $p_T$, etc.
  - Ratios of subjet $p_T$’s.
  - $k_T$ splitting scale

Show [http://jets.physics.harvard.edu/qvg](http://jets.physics.harvard.edu/qvg)
Best Variables in Each Category for 200 GeV Jets

- best group of 5
- charged mult & girth
- charged mult * girth
- charged mult R=0.5
- subjet mult R_{sub}=0.1
- girth R=0.5
- optimal kernel
- 1st subjet R=0.5
- avg k_T of R_{sub}=0.1
- mass/Pt R=0.3
- decluster k_T R_{sub}=0.1
- jet shape Ψ(0.1)
- |pull| R=0.3
- planar flow R=0.3

Gluon Rejection

Gluon rejection as a function of quark jet acceptance. 1/30 = 3% gluon.

40% quarks
We looked at 10,000 variables

Best 2 were

1. Charged particle count
   - Better spatial and energy resolution works better
     - e.g. particles > topoclusters > calorimeter cells > subjets

2. Linear radial moment (girth)
   - Similar to jet broadening

Show http://jets.physics.harvard.edu/qvg
Higher $p_T$ means more tracks and more ‘time’ to establish $C_A/C_F$. 
Girth

Weight $p_T$ deposits by distance from jet center

Radial Moment, or Girth: 

$$g = \frac{1}{p_T^\text{jet}} \sum_{i \in \text{jet}} p_T^i |r_i|$$
2D distributions show that they are fairly uncorrelated
Best Variables in Each Category for 200 GeV Jets

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- planar flow R=0.3

Gluon Rejection

1/30 = 3% gluon

40% quarks
Result

Significance Improvement of \[ \frac{0.4}{\sqrt{1/30}} = 2.19 \]
Conclusions

“These are not your daddy’s jets” -- Steve Ellis

The LHC is so great that we can go well-beyond the jet-to-parton map
  • Detectors can measure jet substructure
  • Need to look at substructure to find new physics in huge backgrounds

Beyond the jet-to-parton map
  • **Jet charge**
    • Measureable, calculable and useful
  • **N-subjettiness**
    • Measureable, calculable and useful as well
  • **Quark** jets and **gluon** jets distinguishable: 40% Q vs 3% G
    • Charge particle count and linear radial moment work best
    • Calculable (beyond Pythia)?
  • ???

A lot of new data is coming soon (by Boost 2012 hopefully)