Jet Measurements at DØ

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Outline

- Tevatron & DØ
- Experimental Jets
  - Jet algorithms
  - Jet Energy Scale Calibration
- Jet Measurements
Fermi National Accelerator Laboratory, Batavia, Illinois, USA

Tevatron accelerator

- $\sqrt{s} = 1.96\text{TeV}$
- $\mathcal{L}_{\text{max}} = 2.95 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$
- 2 collider experiments
Comparison of hadron colliders

Past - CERN

- ISR($pp$), $\sqrt{s} = 62\text{GeV}$, $L_{\text{record}} = 140 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$
- $Spp\bar{p}S(pp)$, $\sqrt{s} = 540\text{GeV}$, $L \sim 2 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$

Present - Fermilab

- TeVatron($pp$), $\sqrt{s} = 1.96\text{TeV}$ (Run II),
  $L_{\text{record}} = 295 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$ (Run IIb)

Future - CERN

- LHC($pp$) (scheduled to start in 2008), $\sqrt{s} = 14\text{TeV}$,
  $L_{\text{plan}} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$
Jets are collections of highly collimated particles

- **Calorimeter jet**
  - interaction of hadrons with calorimeter
  - collection of calorimeter cell energies

- **Particle jet**
  - after hadronization and fragmentation
  - effect of hadronization is soft ⇒ allows comparison between particle and parton jets

- **Parton jet**
  - hard scattering
  - additional showers
Why Jets?

- Jet production cross-section is dominant part of the total cross-section
- Described by pQCD (?)
  - Structure of hadrons (protons)
  - Parton showering
  - $\alpha_S$
  - ...

- Background to other interesting processes
  - SM - top, Higgs
  - Beyond SM - SUSY & others $\rightarrow$ multijets, lepton(s) + jets, jets + missing energy topologies
Jet Algorithms - Experimental Issue

Compare nice dijet event with some noisy one (more than 20 'jets' on the right!!) - need a common tool for jet finding
List of requirements on the algorithm (hep-ex/0005012)

1. The same algorithm for both theory and experiment

2. Theoretical requirements

3. Experimental requirements
   - Detector independence
   - CPU efficiency
   - Easy to calibrate

Two (main) classes of jet algorithms at hadron colliders - cone vs kT

DØ uses RunII Cone Algorithm:

\[ \Delta R \leq \sqrt{(y_{ptcl} - y_{jet})^2 + (\phi_{ptcl} - \phi_{jet})^2} \], \quad \Delta R = 0.5, 0.7

See backup slides for details
Jet Energy Scale Correction

\[ E^{\text{corr}} = \frac{E^{\text{meas}} - O}{R \cdot S} \]

- Offset \((O)\) coming from calorimeter noise, underlying event, multiple interactions and pile-up
- Response \((R)\) of the calorimeter to jets
- Showering \((S)\) is a fraction of energy deposited outside the jet cone

RunIIa Preliminary JES error 2-3%
RunIIa Final JES aims at 0.5-1.5% (for \(\gamma+\)jet sample)

NB: In some cases, JES is no longer the dominant uncertainty
1. Calibrate EM calorimeter
   - $Z \rightarrow e^+ e^-$ (fixed to LEP values)
   - Correct $\gamma$ for differences between $e$ and $\gamma$

2. Subtract offset energy coming from underlying event, multiple interactions, noise or pile-up - estimated by measuring the average energy in the calorimeter in zero and minimum bias data

3. Measure calorimeter response to hadronic jets in $\gamma$+jet events
   - EM Scale calibrated
   - 'Clean events' - jet and photon balanced in $p_T$
   - Limited by max photon $p_T \sim 250\text{GeV} \Rightarrow$ extrapolate towards higher $p_T$
   - Use dijets for endcap calorimeters - one jet in central (calibrated) is balanced by second jet in endcap

4. Correct for showering outside the jet cone due to detector effects

See: http://www-d0.fnal.gov/phys_id/jes/public/plots_v7.1/
Jet Measurements at DØ

1. Inclusive Jet Cross-section

2. Dijets
   - Dijet mass
   - Dijet angular distribution
   - Dijet azimuthal decorrelations

3. Multijets
   - Threejets + more

4. Jets + Vector Bosons

5. Jets + $\slashed{E}_T$

NB: Results not presented can be found at:

http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
Curiosity of excess of high $p_T$ jets by CDF in RunI

PDF not well constrained at high $x$ (especially gluon) - increased gluon density can explain the CDF result

Highest energy available - jet $p_T > 600$GeV

The nature of the basic interaction between quarks and gluons

Possible new physics - quark substructure, ...
Inclusive Jet Cross-section

\[ \frac{d^2\sigma}{dp_T dy} (\text{pb}/(\text{GeV/c})) \]

- \(|y_{\text{jet}}| < 0.4\) (x10)
- \(0.4 < |y_{\text{jet}}| < 0.8\)

\(\sqrt{s} = 1.96\ \text{TeV}\)

- \(L = 0.9\ \text{fb}^{-1}\)
- \(R_{\text{cone}} = 0.7\)

**NLO pQCD**

- plus threshold corrections (2-loop)
- Hadronization corrections applied

**CTEQ6.1M**

- \(\mu_R = \mu_F = p_T\)

**DØ Run II preliminary**

- Total error
- JES
- JES statistical error
- Resolution
- ID and trigger efficiency
- MC vs. ansatz unsmeareding

\(|y_{\text{jet}}| < 0.4\)

**DØ Run II preliminary**

- \(\text{data} / \text{theory}\)

- NLO \(\mu_{R,F} = p_T\) CTEQ6.1M \(R_{\text{cone}} = 0.7\)

- Hadronization corrections applied

- with threshold corrections (2-loop)
- PDF uncertainty
- without threshold corrections (2-loop)
Dijet System

\[ M_{JJ}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 \]

\[ \Delta \phi \]

\[ \chi_{\text{dijet}} = \exp(|y_1 - y_2|) \]
Dijet Mass and Dijet Angular Distribution

To be updated & approved

\[ \chi_{\text{dijet}} = \exp(|y_1 - y_2|), \]

\[ y = \frac{1}{2} \ln\left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right), \quad \beta = \frac{|\vec{p}|}{E} \]
Dijet Azimuthal Decorrelations ($\Delta \phi$)

LO QCD - two back-to-back jets. Any additional radiation causes decorrelation in $\Delta \phi$ - sensitive to higher order corrections without measuring the additional jet(s).
Threejets

- Theory also available at NLO
- 8 variables needed to describe the final state in its CMS

\[ M_{3\text{jet}} \] - mass of 3 jets, in CMS

\[ M_{3\text{jet}} = E_3 + E_4 + E_5 \]

\[ X_3, X_4 \] - distribution of energies among the 3 jets

\[ X_i = \frac{2E_i}{M_{3\text{jet}}} \] (because of \( \sum_i X_i = 2 \), \( X_5 \) is not independent)

- Angles:

\[ \cos \theta_3 = \frac{\vec{P}_{AV} \cdot \vec{P}_3}{|\vec{P}_{AV}| \cdot |\vec{P}_3|}, \cos \psi_3 = \frac{(\vec{P}_3 \times \vec{P}_{AV}) \cdot (\vec{P}_4 \times \vec{P}_5)}{|\vec{P}_3 \times \vec{P}_{AV}| \cdot |\vec{P}_4 \times \vec{P}_5|}, \vec{P}_{AV} = \vec{p} - \vec{\bar{p}} \]

- Masses of individual jets (dimensionless)

\[ f_i = \frac{m_i}{M_{3\text{jet}}}, \quad i = 3, 4, 5 \]
Jets $+\gamma$, $W$, $Z$

- Jet and VB balanced in $p_T \Rightarrow$ calibration purposes $\Rightarrow$ important to understand higher order corrections, test of MC generators
- $W + c$ jet - sensitivity to $s$ quark PDF
- Background to various processes

$Z+$jet(s) - Pythia/Sherpa comparison

Zdeněk Hubáček (CTU Prague)
Other Jet Measurements

SM: top quark pair production, single top, Higgs searches - jets everywhere ;-)

Beyond the SM (SUSY, LED, . . . ) are tested and limits for new particles masses are set in various channels:

- SUSY, LED - multijets + \( E_T \)
- Technicolor \( p\bar{p} \rightarrow e^- + 2\text{jets} \)
- Leptoquarks
- . . .

(Search for squarks and sgluininos in mSUGRA)
Jets dominate the final states at hadron colliders ⇒ their understanding is essential - many searches for the Higgs boson and physics beyond the Standard Model involve jets.

DØ Jet Energy Scale under development should reduce uncertainties in QCD measurements.

QCD theory well proved in inclusive jet $p_T$ spectrum measurement, dijet system, $\gamma+$ jet ⇒ going to multijets.
Back-up slides
DØ RunII Cone Algorithm

Proceeds in two steps:

1. Preclustering - to find seeds for the main algorithm (DØ specific values for example)
   - Get list of items (calorimeter towers, MC particles, MC partons) ordered by $p_T$
   - Take the leading item with $p_T > 500\text{MeV}$, form a cone with $\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2} = 0.3$
   - Remove all items with $p_T > 1\text{MeV}$ lying in the cone from the initial list and put it into a new precluster
   - Compute precluster properties (using E-scheme)
   - Continue until there are no available items in the initial list
   - Keep preclusters with $p_T > 1\text{GeV}$

2. RunII Cone Algorithm
   - Takes two lists - list of preclusters and the complete list of items
   - Preclusters serve as seeds where the algorithm starts in $y \times \phi$ plane
   - **Protojets** are found by an iterative procedure - cone of radius $R_{\text{cone}}$ is formed around the seed, all items in the cone are added to a protojet-candidate and the candidate’s axis is computed. If the axis differs from the original one, the original protojet is replaced by the protojet-candidate and procedure is repeated until a stable solution is found
   - Procedure is repeated for the remaining list of seeds
   - **Midpoints** are added to reduce sensitivity to soft radiation. Between each pair of protojets, new seeds are added and the same procedure as for seeds is repeated
   - In RunII Cone Algorithm, the items are not removed from the initial list - the same item can end up in more than one protojet → **splitting/merging** condition is applied to decide which item will end up in which jet
   - Finally, the jet parameters are recomputed using the E-scheme

Main parameters:
- Radius of Cone ($R_{\text{cone}} = 0.5, 0.7$)
- splitting/merging fraction (50% - if two protojets share more than 50% of the lower $p_T$ protojet, they will be merged, otherwise the common items will be split into two separated jets
- Minimal jet $p_T = 6\text{GeV}$