Dijet Azimuthal Decorrelations

Michael Begel
begel@fnal.gov

University of Rochester

for the DØ Collaboration
Δφ Decorrelation

- Dijet production in lowest order pQCD
  - Jets have equal $p_T$ and $Δφ_{dijet} = π$

Additional soft radiation causes small azimuthal decorrelations.

Additional hard radiation can lead to large azimuthal decorrelations.

$Δφ_{dijet} < jet 1 - jet 2$

$Δφ_{dijet}$ is directly sensitive to higher-order QCD radiation without explicitly measuring third and fourth jets.
\( \Delta \phi \) Decorrelation

- Dijet production in lowest order pQCD
  - jets have equal \( p_T \) and \( \Delta \phi_{\text{dijet}} = \pi \)
- Additional soft radiation causes small azimuthal decorrelations
  - \( \Delta \phi_{\text{dijet}} \sim \pi \)
  - divergent in fixed-order pQCD
**Δφ Decorrelation**

- Dijet production in lowest order pQCD
  - Jets have equal $p_T$ and $Δφ_{dijet} = π$
- Additional soft radiation causes small azimuthal decorrelations
  - $Δφ_{dijet} \sim π$
- Additional hard radiation can lead to large azimuthal decorrelations
  - $k_\perp$ large $⇒$ $Δφ_{dijet} < π$
  - $2\pi / 3 \leq Δφ_{dijet} < π$ for three-jet production
**Δφ Decorrelation**

- Dijet production in lowest order pQCD
  - jets have equal $p_T$ and $Δφ_{dijet} = π$
- Additional soft radiation causes small azimuthal decorrelations
  - $Δφ_{dijet} \sim π$
- Additional hard radiation can lead to large azimuthal decorrelations
  - $k_\perp$ large ⇒ $Δφ_{dijet} < π$

$Δφ_{dijet}$ is directly sensitive to higher-order QCD radiation without explicitly measuring third and fourth jets ⇒ test $O(\alpha_s^4)$ calculations
The Observable

- $\phi$ decorrelation is a *three-jet observable*
- Three-jet NLO pQCD calculations are now available *(NLOJET++)*
  - Same theory calculation used in previous talk
- Tree-level pQCD calculations with up to six jet production are also available *(ALPGEN)*
  - Used extensively in top and higgs analyses
- We can also test parton shower models in HERWIG, PYTHIA, ...
The Measurement

- Inclusive Dijet Sample
  - Discussed in previous talk

- Observable: \( \frac{1}{\sigma_{\text{dijet}}} \cdot \frac{d\sigma_{\text{dijet}}}{d\Delta\phi_{\text{dijet}}} \)

- Results are fully corrected to particle level, including unsmearing in \( p_T \) and position (\(< 20 \) mrad for \( p_T > 80 \) GeV)

- Systematic uncertainties dominated by jet energy calibration. The energy scale contributes \( \approx 7\% \) near \( \pi \) and up to \( 23\% \) at \( \pi/2 \) (larger at small \( \Delta\phi_{\text{dijet}} \) due to \( p_T \) reordering).
The Measurement

- Inclusive Dijet Sample
  - Four bins in leading jet $p_T$: 75, 100, 130, 180 GeV
  - Second leading jet: $p_T > 40$ GeV
  - Both leading jets central: $|y_{\text{jet}}| < 0.5$
  - Increased $\Delta \phi$ correlation with larger $p_{T max}$

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Theory Comparison – NLOJET++

- \[ \frac{1}{\sigma_{\text{dijet}}} \bigg|_{(N)LO} \frac{d\sigma_{\text{dijet}}}{d\Delta\phi_{\text{dijet}}} \bigg|_{(N)LO} \]

- LO pQCD (in 3-jet prod.)
  - Poor agreement
  - no phase space at \( < 2\pi/3 \)
  - divergent at \( \Delta\phi_{\text{dijet}} = \pi \)

- NLO pQCD (in 3-jet prod.)
  - Good description over large range
  - Tree-level only for \( \Delta\phi_{\text{dijet}} < 2\pi/3 \)
  - divergent at \( \Delta\phi_{\text{dijet}} = \pi \)
Theory Comparison – ALPGEN

- Tree-level production for $2 \rightarrow 2, 3, \ldots, 6$ jets
- Uses PYTHIA parton showers
- Mangano’s matching applied to properly add multiplicity bins
- Reasonable description of the data

![Graph showing $1/\sigma_{dijet} \, d\sigma_{dijet}/d\Delta\phi_{dijet}$ for $100 < p_T^{\text{max}} < 130$ GeV]

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Event Generator Comparisons

Third and fourth jets are generated via parton showers (uses soft and collinear approximations)

- HERWIG v6.505
  - very good description
- PYTHIA v6.225
  - poor description

(default parameters)
Event Generator Comparisons

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- PYTHIA v6.225
  - increase $p_T$ cut-off in the ISR parton shower
    PARP (67) = 1 => 4
  - improves description
Event Generator Comparisons

Third and fourth jets are generated via parton showers (uses soft and collinear approximations)

- HERWIG v6.505
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$\text{PARP}(67) = 1 \Rightarrow 4$
Conclusions

- The DØ collaboration has measured the azimuthal decorrelation between the two leading jets at $\sqrt{s} = 1.96$ TeV.
- NLO pQCD describes the data very well.
- LO pQCD fails to describe the data, but a tree-level calculation with up to six jet production is adequate.
- HERWIG v6.505 with default parameters describes the data.
- PYTHIA v6.225 with default parameters does not characterize the data, however, PYTHIA has many handles. In particular, increasing the maximum virtuality of the ISR shower significantly improves agreement at low $\Delta \phi_{\text{dijet}}$. 
DØ Calorimeter

- Uranium–Liquid Argon Calorimeter
  - stable, uniform response, radiation hard
- Compensating: $\epsilon / \pi \approx 1$
- Uniform hermetic coverage
  - $|\eta| \leq 4.2$ [$\eta \equiv -\ln \tan(\theta/2)$]
- Longitudinal Segmentation:
  - 4 EM Layers ($21 X_0$)
  - 4–5 Hadronic Layers ($6 \lambda$)
- Transverse Segmentation:
  - $\Delta \eta \times \Delta \phi = 0.05 \times 0.05$ in EM
  - $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ otherwise

$\eta \quad \phi$

$p_T = 432$ GeV

$p_T = 396$ GeV

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Cone Jet Definition

- **Run I**
  - Add up towers around a “seed”
  - Iterate, using “jets” as seeds, until stable
  - Jet quantities: $E_T$, $\eta$, $\phi$
    $$E_T^{\text{jet}} = \sum_{R_i \leq 0.7} E_T^{\text{tower}}$$

- **Modifications for Run II**
  - Use 4-vector scheme $p_T$ instead of $E_T$
  - Add midpoints between jets as additional seeds
  - Infrared safe
    $$\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2}$$
  - Correct to particle jets...

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Jet Energy Scale

- Measured jet energy is corrected to particle level
  \[ E_{\text{corr}} = \frac{E_{\text{uncorr}}}{R S} - O \]
- \(O\) energy due to previous events, multiple interactions, noise, etc
- \(R\) calorimeter response to hadrons (dead material, non-linearities, etc)
- \(S\) net fraction of particle–jet energy remaining inside jet cone after showering in calorimeter
- \(E_T\) imbalance in \(\gamma + \text{jet}\) events
- Jet transverse shapes
- Large statistical uncertainties and substantial systematic uncertainties (increase with energy due to extrapolation).

\(\gamma + \text{jet}\) statistics up to 200 GeV
Soft Physics

\[ p_T \text{ max} > 180 \text{ GeV} \]
\[ 130 < p_T \text{ max} < 180 \text{ GeV} \]
\[ 100 < p_T \text{ max} < 130 \text{ GeV} \]
\[ 75 < p_T \text{ max} < 100 \text{ GeV} \]