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Soft QCD Phenomena in High-$E_T$ Jet Events at Tevatron

**JET FRAGMENTATION**
- hard scattered partons
- final state radiation
- hadronization

**UNDERLYING EVENT (UE)**
- initial state radiation (IR)
- multi-parton interactions (MPI)
- proton/antiproton remnants
- hadronization

ALL ENTANGLED WITH COLOR CONNECTIONS (!)
Jet Fragmentation

Driven by soft QCD ($k_T << 1$ GeV)

Why bother?

- Good stuff:
  - Lots of phenomena
  - Theoretical challenge (pQCD at $k_T \sim \Lambda_{QCD}$)
  - Hadronization stage remains a mystery
- Many high-$E_T$ physics analyses depend on good understanding of jet properties

Tools available

- Re-summed pQCD approximations
  - analytic, but only for a few observables
- Monte Carlo generators
  - generic, but many tuning knobs

$k_T=1$ GeV/c
Underlying Event

Underlying event processes
- IR, MPI, pp remnants, hadronization
- all are very soft

Why bother?
- Physics is poorly understood:
  - Implementations in MC’s are very different
  - Default predictions for LHC vary wildly
  
- UE pollutes many analyses and is source of systematic errors

Tools available
- any analytic predictions?
  - hardly any… (color flow away from jets)
- Monte Carlo generators
  - generic, but many (too many?) tuning knobs

LHC:
- 25 events per bunch crossing
- Jet cone pollution (R=0.7):
  - 15 GeV
  - 10 charged particles

Different MC’s disagree by more than a factor of 2
Results presented in this talk

Jets Fragmentation ↔ NLLA
- Momentum distribution of charged particles in jets
- Multiplicities of charged particles in g- and q-jets

Underlying Event ↔ MC
- Energy flow in transverse direction away from a jet
- Charged particle multiplicity flow away from a jet
- Momenta of away-from-jet charged particles
Jet fragmentation: doing it analytically

- **Parton shower development: NLL**
  - Modified Leading Log Approximation
    - with one $k_T$-cutoff parameter: $k_T > Q_{\text{cutoff}} = \Lambda_{\text{QCD}} (= Q_{\text{eff}})$
  - Various next-to-NLL extensions

- **Hadronization: LPHD**
  - Hypothesis of Local Parton Hadron Duality
    - with one parameter $K_{\text{LPHD}} = N_{\text{hadrons}} / N_{\text{partons}}$

- **MLLA+LPHD**
  - cannot describe all details...
  - but all analytical...
  - and works surprisingly well...
**Moments of charged particles in jets**

*(MLLA+LPHD, next-to-NLL normalization corrections)*

**Measurement**
- Central dijet events with $M_{jj} \sim 80-600$ GeV
- Di-jet center of mass frame: $E_{jet} = \frac{1}{2}M_{jj}$
- Charged particles in cones with opening angle $\theta$ from ~0.3 to ~0.5 rad
- Energy scale $Q = 2E_{jet}\tan(\theta/2) \approx E_{jet}\theta$

**Results**


- $Q_{eff} = 240 \pm 40$ MeV
  - $k_T$-cutoff can be set as low as $\Lambda_{QCD}$
- $K_{LPHD(\pm)} = 0.56 \pm 0.10$
  - Number of hadrons $\approx$ number of partons
$Q_{\text{eff}}$ at CDF vs Other Experiments

$Q_{\text{eff}}$ for all 9 $M_{jj}$'s and 3 opening angles $\theta_{\text{cone}}$'s
Jets: multiplicities in quark & gluon jets

**Ratio** \[ r = \frac{N_{ch}(\text{gluon jet})}{N_{ch}(\text{quark jet})} \]

- **CDF**
- **HRS**
- **OPAL**
- **SLD**
- **ALEPH**
- **DELPHI**
- **CLEO**
- **CDF**

**Graphical Data**

- **Legend**:
  - HRS
  - OPAL
  - SLD
  - ALEPH
  - DELPHI
  - CLEO
  - CDF

**Equation**

\[ C_A / C_F = 9/4 \]
Jets: multiplicities in quark & gluon jets

**Theory:**
- Next-Leading-Log extensions
- $r = \frac{N_{\text{ch}}(\text{gluon jet})}{N_{\text{ch}}(\text{quark jet})} = 1.5-1.8$ (Q=20-100 GeV)

**$e^+e^-$ Data:**
- 15+ papers (mostly last 10 yrs)
- Results range from 1.0 to 1.6
- Diversity of results:
  - biases due to using events of different topologies (qqg and qq)
  - energy scale confusion
  - “catch-22” analyses
  - model-dependent analyses
  - recent unbiased/model-independent
Gluon vs Quark jets at Tevatron

- Dijet and $\gamma$-jet events with $M_{jj}$ and $M_{\gamma j}$ ~80-100 GeV
  - tracks are not used in jet reconstruction
- di-jet events (~60% gluon jets) and $\gamma$-jet events (~80% quark jets)
  - very stable for the energies used
- di-jet or $\gamma$-jet center of mass frame: $E_{\text{jet}} = \frac{1}{2}M_{jj}$ or $\frac{1}{2}M_{\gamma j}$
- $N_{\text{ch}}$ multiplicity in cones with opening angle $\theta$ from ~0.3 to ~0.5 rad
- Energy scale $Q = 2E_{\text{jet}} \tan(\theta/2) \approx E_{\text{jet}}\theta$

Leading diagrams for dijet events

Leading diagrams for $\gamma$-jet events
N\textsubscript{ch} multiplicities in gluon and quark jets

- Tevatron and e\textsuperscript{+}e\textsuperscript{-} data (except for CLEO) agree
- Tevatron and e\textsuperscript{+}e\textsuperscript{-} data (except for CLEO) follow 3NLL trends
$N_{ch}$ multiplicities in gluon and quark jets

- Tevatron: Ratio $r=1.6\pm0.2$ for typical $Q\approx20$ GeV
- Tevatron and recent OPAL “unbiased” data ($r=1.51\pm0.04$ at $Q=80$ GeV) agree and follow trends obtained in the recent NLL extensions
- CLEO “unbiased” results at small $Q\sim7$ GeV fall out…

CDF Preliminary
Event sample:
- min-bias
- central jet events

In direction transverse to the leading jet, we measure:
- \( n = \frac{dN}{dA} \) -- average density of charged particles:
- \( \frac{dn}{dp_T} \) -- \( p_T \) spectrum of charged particles:
- \( \frac{dP_T^{\text{sum}}}{dA} \) -- average density of energy flow (summed over charged particles):
- compare sides with maximum and minimum activities

Confront Monte Carlo with Data:
- identify relevant importance of various Monte Carlo knobs/parameters
**UE: Default Pythia 6.206 fails to reproduce data**

- Number of charged tracks in transverse direction is underestimated
- $P_T$ distribution of charged tracks in transverse direction is OK
- Average energy flow in transverse direction is no good

![Graph showing the comparison between CDF Data and Pythia 6.206 predictions for the number of charged particles in transverse direction.](image)

- $E_T$(jet)
- Leading Jet
- $\Delta \phi$
- "Transverse"
UE: Default Herwig 6.4 fails to reproduce data

✓ Number of charged tracks in transverse direction is OK
✗ No (or too soft) tail in the spectrum for particles in transverse direction in minbias events and events with small $E_T$ jets
→ missing multi-parton interaction being added...
✓ Average energy flow in transverse direction is more or less OK

Spectrum of charged particle momenta in transverse direction

CDF Preliminary Min-Bias Data, 1.8 TeV
Herwig "Soft" Min-Bias at 0.63, 1.8, and 14 TeV
**UE: Tune Pythia to match CDF data**

<table>
<thead>
<tr>
<th>CDF Tune A vs. Pythia 6.206 default parameters</th>
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<tbody>
<tr>
<td>- <strong>Enhance initial state radiation</strong></td>
</tr>
<tr>
<td>- from PARP(67) =1 to 4</td>
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<td>- <strong>Smooth out probability of Multi-Parton Interactions vs. impact parameter</strong></td>
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<tr>
<td>- from solid opaque disk to 50-50 double-Gaussian distribution ($r=0.4R$)</td>
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<tr>
<td>- <strong>Make more di-gluons than q-qbar pairs in Multi-Parton Interactions</strong></td>
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<tr>
<td>- from 66% to 95%</td>
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<tr>
<td>- <strong>Enhance color connection probability for MPI gluons and p-pbar remnants</strong></td>
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<tr>
<td>- from 33% to 90%</td>
</tr>
<tr>
<td>- <strong>Reduce Multi-Parton Interaction dependence on CM Energy</strong></td>
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<tr>
<td>- to better connect Tevatron and lower energy data</td>
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<td>- this approximately halves the LHC underlying event activity…</td>
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UE: Pythia Tune A describes Data

Number of Charged Particles \( n = \frac{dN}{dA} \)

CDF Preliminary data uncorrected

- CDF Run 1 Min-Bias
- CDF Run 1 JET20
- CDF Run 2
- PY Tune A

\[ |\eta| < 1.0 \text{ PT} > 0.5 \text{ GeV/c} \]
UE: Pythia Tune A describes Data

-Charged Energy Flow $dP_T^{\text{sum}}/dA$

CDF Preliminary

| $|\eta|<1.0$ $\text{PT}>0.5 \text{ GeV/c}$

| CDF Run 1 Min-Bias |
| CDF Run 1 JET20 |
| CDF Run 2 |
| PY Tune A |

PT(charged jet#1) (GeV/c)

"Transverse" PT sum Density (GeV)
UE: Pythia Tune A describes Data

Number of Charged Particles $n = \frac{dN}{dA}$

CDF Preliminary

| $|\eta| < 1.0$ | $0 < PT < 0.5$ GeV/c |
|-------------|---------------------|
| CDF Run 1 Min-Bias |
| CDF Run 1 JET20 |
| CDF Run 2 |
| PY Tune A |

Charged Energy Flow $\frac{dP_{T \sum}}{dA}$

CDF Preliminary

| $|\eta| < 1.0$ | $0 < PT < 0.5$ GeV/c |
|-------------|---------------------|
| CDF Run 1 Min-Bias |
| CDF Run 1 JET20 |
| CDF Run 2 |
| PY Tune A |

$P_{T}$ spectrum of charged particles $\frac{dn}{dP_{T}}$

CDF Preliminary

PYTHIA Tune A 1.96 TeV

| $30 < P_{T(chgjet#1)} < 70$ GeV/c |
| $70 < P_{T(chgjet#1)} < 95$ GeV/c |

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ISMD 2003

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Jet fragmentation

- Momenta of charged particles in jets are well described by NLLA pQCD:
  - MLLA $k_T$-cutoff $Q_{\text{eff}} = 240 \pm 40$ MeV
  - $k_T$-cutoff can be set as low as $\sim \Lambda_{\text{QCD}}$
  - LPHD $N_{\text{hadrons}}/N_{\text{partons}} = K_{\text{KPHD}}(\pm) = 0.56 \pm 0.10$
  - Number of hadrons ~ number of partons

- Ratio of charged particle multiplicities in gluon/quark jets $r = 1.6 \pm 0.2$
  - Multiplicities and their ratio agree with next-to-NLLA and recent LEP data

Underlying event

- MC generators with default parameters do not quite work, but can be tuned to match data...
  - Pythia tuned for Run I continues to work in Run II for broader range...
  - Did we gain any insights into UE physics?
    -- Need to compare Pythia Tune A and Herwig Tune “X” (work in progress)