JET
FRAGMENTATION

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OUTLINE

• Physics introduction
  • Introduction to jet physics
  • Jets in heavy-ion-collisions
  • Jet reconstruction

• Paper discussion
  • The CMS experiment
  • Data selection and track/jet reconstruction
  • Analysis
  • Physics outcome
Proton substructure is described by Parton distribution functions.

Parton distribution functions give the probability to find a parton with a given momentum fraction

\[ x = \frac{p_{\text{parton}}}{p_{\text{hadron}}} \]

in the proton.

Deep inelastic scattering @ HERA (1992-2007)
Production of Jets in hadron collisions:

- Scattering of partons inside the hadrons
- Subsequent fragmentation of the scattered partons will lead to hadron-spray: Jets
- Only back-to-back in $\phi$ due to different momenta of initial partons
HADRONISATION MODELLING

• QCD potential: \( V(r) \sim -\frac{1}{r} + \kappa r \) with \( \kappa \sim 1 \frac{GeV}{fm} \)

• \( q\bar{q} \) connected via flux tube („string“)

• String can break into new \( q\bar{q} \) pairs

Lund string model: (1983)

→ Default model in Pythia!
HIGH $p_T$ HADRON PRODUCTION

- QCD asymptotic freedom: $\alpha_s(Q^2 \to \infty) \to 0$

- High energy parton-parton scattering $\to$ pQCD

- QCD factorization theorem: High-$p_T$ hadron production cross-section in hadron-hadron collisions can be written (to some order):

$$d\sigma_{AB \to h}^{\text{hard}} = f_{a/A}(x_1, Q^2) \otimes f_{b/B}(x_2, Q^2) \otimes d\sigma_{ab \to c}^{\text{hard}}(x_1, x_2, Q^2) \otimes D_{c \to h}(z, Q^2)$$

- Fragmentation functions encode the probability of a parton to fragment into a hadron with a momentum fraction

$$Z = \frac{p_{\text{hadron}}}{p_{\text{parton}}}$$

Also useful:

$$\xi = ln\frac{1}{Z}$$
• High-$p_T$ partons are produced early in the collision

• They will propagate through the entire medium

• Jet quenching → „Smoking gun“ of QGP formation
JET QUENCHING

- A parton traversing the medium will lose energy by scattering or bremsstrahlung.
- Energy loss will depend on particle and plasma properties.

BDMPS approach: (Rad. E loss)

\[ \Delta E \propto \alpha_s C_F \hat{q} L^2 \]

Energy loss \( \Delta E \) in a static medium of length \( L \) for \( E \to \infty \)

\[ C_F = \begin{cases} 
3 & \text{for gluon jets} \\
4/3 & \text{for quark jets} 
\end{cases} \]

Medium parameter \( \hat{q} = \frac{\mu^2}{\lambda} \)

- \( \mu^2 \): Typical momentum transfer from the medium to the parton
- \( \lambda \): Mean free path
FRAGMENTATION FUNCTIONS IN THE MEDIUM

- Some models of jet quenching predict an effective change of the shape of the fragmentation function.
- Changes of the fragmentation function would give access to the properties of the medium.

„Kinematic rescaling“: Fragmentation in the vacuum with rescaled energy.

„Q-Pythia“:
JET RECONSTRUCTION

- Idea: Reconstruct energy and direction of initial parton
- Two main classes of jet finding algorithms:

**Cone algorithms:**
Sum up all momenta in cone with given radius around seed particle $i$

**Sequential recombination:**
Merge hadrons which have smallest difference in transverse momentum

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 < R^2$$
SEQUENTIAL RECOMBINATION

- Introduce distances

\[ d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \]

\[ d_{iB} = k_{ti}^{2p} \]

- Find smallest of the distances and

| p=1: \( k_T \) | p=0: Cambridge/Aachen | p=-1: Anti-\( k_T \) |

if it is a \( d_{ij} \) \rightarrow recombine entities

(e.g. add 4-momenta)

if it is a \( d_{iB} \) \rightarrow move entities to list of jets

- Procedure is repeated until no entities are left

- Anti-\( k_T \): Soft particles will tend to cluster with hard ones long before clustering among themselves
COMPARISON OF DIFFERENT ALGORITHMS:
• Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{S_{NN}} = 2.76$ TeV

THE CMS EXPERIMENT

CMS: Compact Muon Solenoid

Used in this analysis
DATA SELECTION

- Use 2010/11 $E_{cmsNN} = 2.76 \text{ TeV}$ pp and PbPb Data
- Use HLT to select events containing high $p_T$ jets in calorimeters (pp: $p_T > 40 \text{ GeV}/c$, PbPb: $p_T > 35 \text{ GeV}/c$)
- Standard event selection criteria
- Determine centrality from transverse energy in HF

HO: Hadron Outer calorimeter
HB: Hadron Barrel calorimeter
HE: Hadron Endcap calorimeter
HF: Hadron Forward calorimeter

$3 \leq |\eta| \leq 5.2$
**TRACK AND JET RECONSTRUCTION**

- **Particle-flow approach:** Reconstruct all stable particles first using tracking and calorimetric information.
- **In PbPb:** Subtract underlying event with iterative pile-up method:
  - Calculate average tower energies in rings of $\eta$ and subtract from event.
  - Find jets and recalculate average energy using initial towers outside jet.
  - Subtract new average energy from initial event and find jets again.

- Reconstruct jets with **Anti-$k_T$** algorithm with $R=0.3$.
SYSTEMATIC UNCERTAINTIES

• Jet finding efficiency:  >95% for jets with $p_T > 40 \text{ GeV/c}$
  >99% for jets with $p_T > 50 \text{ GeV/c}$

• Jet momentum resolution:  pp: 19%(13%) at $p_T = 40(100) \text{ GeV/c}$
  central PbPb: 24%(16%) at $p_T = 40(100) \text{ GeV/c}$

• Reconstructed jet momenta are corrected to final state stable particle level using factors derived from PYTHIA

• Jet energy scale uncertainty:
  pp: 3% → per-bin-yield uncertainty: 15%
  peripheral PbPb: 4% → per-bin-yield uncertainty: 20%
  central PbPb: 5% → per-bin-yield uncertainty: 25%

• Track finding efficiency:  60-70% → reweighting of tracks

• Track momentum reconstruction resolution:  ~1-3%
ANALYSIS

- Leading jet: $p_{T,1} > 100 \text{ GeV}/c$  \hspace{1cm} |$\eta$| < 2
- Subleading jet: $p_{T,2} > 40 \text{ GeV}/c$  \hspace{1cm} $\Delta\phi_{12} > \frac{2}{3}\pi$
- Compare to Pythia (pp) and Pythia events embedded in Hydjet PbPb collision

Observation of parton energy loss in central PbPb collisions
Fragmentation functions:

\[ z = \frac{p_{||}^{\text{track}}}{p_{\text{jet}}} \]

\[ \xi = \ln \frac{1}{z} \]

- Momentum components and angles are calculated in dijet centre-of-mass frame.
- Estimate remaining UE contribution by selecting tracks in background cone obtained by flipping the jet cone around \( \eta = 0 \).

Reduce UE contribution:

\[ p_T^{\text{track}} > 4 \text{ GeV}/c \]
Comparison of fragmentation functions in pp and PbPb

- Take momentum resolution deterioration in PbPb into account
  → Smear reconstructed $p_T$ of jets in pp data by quadratic difference of UE contribution

- Match $p_T$ distributions → apply $p_T$ dependent reweighting to pp data
  (Compare FF for matching $p_T$ spectra)

Shape of fragmentation functions in pp and PbPb agree within uncertainties
OTHER SOURCES OF SYSTEMATIC UNCERTAINTIES

• Uncertainties in jet response
  • Smearing of jet energy due to fluctuations
  • Miscalibration of the overall energy scale
  • Residual offset in jet energy

• Uncertainties from track reconstruction
  • Failure to reconstruct high- $p_T$ charged particle
  • Momentum resolution of reconstructed charged particle tracks

→ Study with Monte-Carlo
→ Combine all uncertainties in quadrature
Fragmentation of the most central events in different dijet momentum asymmetry classes:

CMS, PbPb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV}, L_{\text{int}} = 6.8 \mu\text{b}^{-1} \)

1/N_{\text{jet}} dN_{\text{track}}/d\xi

1/N_{\text{jet}} dN_{\text{jet}}/dp_{T}^{\text{jet}}

\( \xi = \ln(1/z) \)

\( 0 < A_{J} < 0.13 \)
\( 0.13 < A_{J} < 0.24 \)
\( 0.24 < A_{J} < 0.35 \)
\( A_{J} > 0.35 \)

Also in agreement with 1
PHYSICS OUTCOME

- Partons in PbPb collisions are reconstructed as jets with significantly reduced momentum.

- The partition of the smaller momentum that remains within the jet cone into $p_T > 4 \text{GeV}/c$ particles corresponds within the uncertainties to that observed for jets fragmenting in the vacuum (pp).