Jet Reconstruction
and applications...

Mateusz Ploskon
Outline

• What is a jet and what does it mean to reconstruct it?
• Jets in elementary, hadronic and HI collisions
• Why to reconstruct jets?
• Utilizing jets in heavy-ion collisions
• Jet related observables
• Outlook
What is a jet?

A spray of collimated showers/particles
- Hardly ever better defined...

- Direct indication of fragmenting parton
- **Good assumption**: approximate parton/jet energy by reconstructing energy of individual particles/constituents
- Jets (unlike single hadrons) are objects which are “better” understood/calculable within pQCD

Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...
Jets at collider experiments

1/22/2010

Hirschegg 2010, MPloskon
Jets at collider experiments

\[ \sigma(e^+ + e^-) = \sigma(e^+ + e^-) \otimes J_1 \otimes J_2 \]
Tevatron, RHIC and already at LHC

These are hadron colliders!

ATLAS Nov/Dec 2009

$\sqrt{s}=2.36$ TeV

Tevatron:

CDF

RHIC p+p @ $\sqrt{s}=200$ GeV

STAR TPC Event Display

xy plane

Jet1: $E_T$ (EM scale) $\sim 16$ GeV, $\eta = -2.1$
Jet2: $E_T$ (EM scale) $\sim 6$ GeV, $\eta = 1.4$

1/22/2010
What really happens in hadronic collisions...
Hadronic collisions and pQCD

\[ E \frac{d^3 \sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\rightarrow cd}}{dt} \otimes D_{h/c}(z_c, Q^2) \]

pQCD factorization:
- parton distribution fn \( f_{a/A} \)
- partonic cross section
- fragmentation fn \( D_{h/c} \)
Hadronic collisions and interaction at different scales

- Distance scale set by $d \sim 1/s$
- Distance scale set by $d \sim 1/m_T$
- Distance scale set by $d \sim 1/\lambda$
- Various scales involved

Theory needs to answer how to isolate perturbative piece (jet finding algorithm has to identify it).
Why jets?

- Complete jet reconstruction (in terms of energy flow at a given resolution scale)
  - Significantly reduces uncertainties (fragmentation)
  - Allows for much better comparison/understanding of experimental results with theory

\[
\frac{d\sigma}{dp_T} = (PDF) \otimes (\text{hard } x - \text{ sec}) \otimes (\text{fragmentation})
\]
Examples of h-h processes calculable within pQCD

\[ \sigma(p + p \rightarrow X + e^+ + e^-) = f_q \otimes f_q \otimes \sigma(q + q \rightarrow e^+ + e^-) \]

Drell-Yan

\[ \sigma(p + e^- \rightarrow X + e^-) = f_q \otimes \sigma(q + e^- \rightarrow q + e^-) \]

Deep Inelastic Scattering

CTEQ6

Q=2 GeV

Hirschegg 2010, MPloskon
Event shape studies

\[ \sigma(e^+ + e^- \rightarrow \text{hadrons}) = \sigma(e^+ + e^- \rightarrow q + q) \otimes J_1 \otimes J_2 \otimes S \]

\[ \sigma(p^+ + p^- \rightarrow \text{jets}) = f_q \otimes f_q \otimes \sigma(q^+ + q^- \rightarrow q + q) \otimes J_1 \otimes J_2 \otimes S \]
Focus of this talk

\[ \sigma(h + h \rightarrow jet + X) = f_q \otimes f_q \otimes \sigma(q + q \rightarrow jet + X) \otimes J \]

Properties of jet finding

-> Jet definition
Finding jets

Particles \( \{ p_i \} \) \rightarrow Jets \( \{ j_k \} \)
Finding jets

Jet definition

- Recombination scheme
- Algorithm
- Resolution parameter

Particles \{p_i\} \rightarrow \text{Jets} \{j_k\}

Note: jets=hard partons, however definition of a parton in terms of a jet is ambiguous -> multiple jet definitions.
Optimum jet finder algorithm

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.
QCD divergences and jet finders

QCD probability for gluon bremsstrahlung at angle $\theta$ and $\perp$-mom. $k_t$:

$$dP \propto \alpha_s \frac{d\theta}{\theta} \frac{dk_t}{k_t}$$

Two divergences:

Collinear

Soft

For pQCD to make sense, the (hard) jets should not change when

- one has a collinear splitting
  - i.e. replaces one parton by two at the same place $(\eta, \phi)$

- one has a soft emission i.e. adds a very soft gluon
More on jet finders

• Some “bad” jet properties
  – Multiplicity (not well understood in theory and not easily measured)
  – Charge (pair from vacuum dilutes significance; fractional q charge)

• Jet equivalence:
\[ J(\vec{p}_{\text{partons}}) \approx J(\vec{p}_{\text{shower}}) \approx J(\vec{p}_{\text{hadrons}}) \approx J(\vec{p}_{\text{cells/tracks}}) \]

• Jets are four-vectors with mass
  – modulo \( p \)-recombination scheme

• Different algorithms give/may different answers
  – However, if analysis is very sensitive to algorithm – something must be wrong(!) – still a learning curve in HI

• Jet size is process dependent(!) – need theory input on optimal size (resolution parameter).
Modern algorithms

- Colinear and infrared safe
- Improved performance
- Rigorous definition of jet area
- Different algorithms -> different response to the underlying event
  - Developed for uniform bg subtraction (pile-up) at LHC

\[ p_T^{jet} = p_T^{cluster} - \rho \times Area \]

Two main classes of algorithms: recombination (kt, Cambridge/Aachen, anti-kt) and cone (Mid point cone, CDF, SIScone)
Example: Kt-like algorithms

1.1 $k_t$ jet algorithm

The definition of the inclusive $k_t$ jet algorithm that is coded is as follows:

1. For each pair of particles $i$, $j$ work out the $k_t$ distance

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2) \Delta R_{ij}^2 / R^2$$

with $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, where $k_{ti}$, $y_i$ and $\phi_i$ are the transverse momentum, rapidity and azimuth of particle $i$ and $R$ is a jet-radius parameter usually taken of order 1; for each parton $i$ also work out the beam distance $d_{iB} = k_{ti}^2$.

2. Find the minimum $d_{\text{min}}$ of all the $d_{ij}, d_{iB}$. If $d_{\text{min}}$ is a $d_{ij}$ merge particles $i$ and $j$ into a single particle, summing their four-momenta (this is $E$-scheme recombination); if it is a $d_{iB}$ then declare particle $i$ to be a final jet and remove it from the list.

3. Repeat from step 1 until no particles are left.

Anti-kt: $k_t^2$ is replaced by $k_t^{-1}$

Background subtraction

\[ p_{T}^{jet} = p_{T}^{\text{cluster}} - \rho \times \text{Area} \]

\[ p_{T}^{jet} = p_{T}^{\text{true}} \otimes \delta \rho \]

- \( \rho \): median pT per unit area of the diffuse background in an event – measured using background “jets” as found by kT algorithm
- \( A \): area of the jet – measured using number of artificially injected infinitely soft particles of finite “size” into an event that are clustered into the jet
- \( \delta \rho \): uncertainty due to noise fluctuations – non-uniformity of the event background
Other approaches possible

- Seedless, infrared and collinear safe
- Optimizes S/B (focus on the “core” of the jet)
- Robust against background

\[
\int d\eta' d\phi' p_T(\eta', \phi') \exp \left[-\frac{(\eta - \eta')^2 + (\phi - \phi')^2}{2\sigma^2}\right] = \text{max!}
\]

Results from PHENIX

Tevatron, RHIC and already at LHC

Star TPC Event Display

ATLAS Nov/Dec 2009

\[ \sqrt{s} = 2.36 \text{ TeV} \]

Tevatron: CDF

RHIC p+p @ \( \sqrt{s} = 200 \text{ GeV} \)

STAR TPC Event Display

Jet1: \( E_T \) (EM scale) \( \sim 16 \text{ GeV}, \eta = -2.1 \)

Jet2: \( E_T \) (EM scale) \( \sim 6 \text{ GeV}, \eta = 1.4 \)

Hirschegg 2010, MPloskon
Testing/exercising the theory...
Tevatron

Very good agreement with NLO pQCD

Multiple algorithms used converging to consistent results
pQCD at RHIC

\[ d\sigma \propto (PDF) \otimes (HARD) \]

p+p collision

STAR TPC Event Display

xy plane

Hirschegg 2010, MPloskon
Jet cross-sections in p+p at RHIC

\[ \frac{1}{(2\pi)} \frac{d^2\sigma}{d^2p_T} \] (pb (GeV/c)^4)

\[ \frac{1}{(2\pi)} \frac{d^2\sigma}{d^2p_T} \] (mb (GeV/c)^2)

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p+p: Cross-section ratio $R=0.2/R=0.4$

STAR Preliminary

Au+Au and p+p at $\sqrt{s_{NN}}=200$ GeV/c

Solid lines: Pythia – particle level

Illustration: Gaussian 1D profile

$p+p$: “Narrowing” of the jet structure with increasing jet energy
p+p: cross-section ratio R=0.2/R=0.4

STAR Preliminary

NLO Calculation
W. Vogelsang – priv. comm. 2009

Narrowing of structure with increasing energy

NLO: narrower jet profile ➔ hadronization effects?
What happens in HI collisions?
Jet-medium interaction

QED: Bremsstrahlung is dominant energy loss mechanism at high energy limit

QCD: High energy partons lose energy via gluon radiation (QCD bremsstrahlung)

Medium characterized by the transport coefficient $q_{\text{hat}}$:
- squared momentum transfer per unit length (mean free path)

Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED $\sim$ linear)
- to density of the medium
Factorization in HI collisions

Medium induced E-loss
Finding jets?

STAR TPC Event Display

xy plane

p+p Collision

Au+Au Collision

1/22/2010
Jet quenching via hadron suppression

\[ R_{AB} = \frac{d^2 N / dp_t d\eta}{T_{AB} d^2 \sigma^{pp} / dp_t d\eta} \]

\[ T_{AB} = \langle N_{bin} \rangle / \sigma_{inel}^{pp} \]

No “effect”: R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

Photon – color neutral probe => No suppression
Hadrons from color charged jets => Suppression
Jet quenching: recoil jet suppression via leading hadron azimuthal correlations

Azimuthal Correlation ~ 180 deg

Leading particle

4 < p_T^{trig} < 6 GeV/c
p_T^{assoc} > 2 GeV/c

Strong modification of the recoil-jet indicates substantial partonic interaction within the medium


Hirschegg 2010, MPloskon
High $p_T$ hadrons: quantitative analysis

Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

- Reasonably self-consistent fit of independent observables
- Main limitation is the accuracy of the theory
- So what is missing? ....
Towards the full jet reconstruction in HI collisions

Star: central Au+Au @ 200 GeV
Complete Jet Reconstruction in Heavy Ion Collisions: why bother?

Jet quenching is a *partonic* process
⇒ obscured by hadronization

High $p_T$ hadron triggers bias towards non-interacting jets
⇒ suppresses the jet population that interacts the most
⇒ no access to dynamics of energy loss

Soft hadron correlations ($p_T<$ few GeV/c) are difficult to interpret as QCD jets
⇒ requires strong analysis and modeling assumptions
⇒ no clear connection to theory

Goal of full jet reconstruction: integrate over hadronic degrees of freedom to measure medium-induced jet modifications at the *partonic* level ⇒ much more detailed connection to theory
HI Jet Reconstruction: strategy

What we have learned over the past two years:
“anti-quenching” biases lurk everywhere!

1. Detector level trigger (high-pT single particle)
2. Seeded reconstruction algorithms
3. Track and tower p_T cuts to suppress background

No shortcuts: we have to face the full event background and its fluctuations head-on
• complex interplay between event background and jet signal

Need multiple *independent* background correction schemes to assess systematics
• more is better than few, but must be independent
• no shortcuts: corrections depend on observable
HI Jet Reconstruction: observables

Primary observables (jets):
- Cross sections vs p+p
- Cross sections vs R: Energy redistribution (aka jet broadening)
- h+jet and jet+jet coincidences
- subjet distributions
- ....

Secondary observables (hadrons):
- Longitudinal momentum distributions (which are not “fragmentation functions”)
- Transverse momentum distributions ($j_T$)
- ....

Note: in HI collisions we should very little rely on kinematics since E is smeared. Counting is more robust!
Background characterization

Background: central Au+Au @ 200 GeV

\[ \rho = \text{Median background density} \ [\text{GeV/sr}] \]

\[ B_i = \frac{p_{T,i}}{A_i} - \rho \]

\[ p_{\text{jet}} = p_{\text{true}} \otimes \delta \rho \]

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Spectrum unfolding

Background non-uniformity (fluctuations) and energy resolution introduce pT-smearing

Correct via “unfolding”: inversion of full bin-migration matrix

Check numerical stability of procedure using jet spectrum shape from PYTHIA

Procedure must be numerically stable
Correction depends critically on background model
→ main systematic uncertainty for HI
Jet production cross-sections in HI Collisions at RHIC

STAR Preliminary

Au+Au at $\sqrt{s_{NN}}=200$ GeV/c
10% most central events

PHENIX Preliminary
Run-5 Cu + Cu $\sqrt{s_{NN}} = 200$ GeV/c
Gaussian filter, $\sigma = 0.3$
not corrected for $p_T^{rec}$ scale, efficiency

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Current result: jet $R_{AA}$

- $R_{AA} < 1$: full jet cross-section not recovered $\Rightarrow$ jet broadening
- But systematically difficult measurement

**STAR Preliminary**

- $R_{AA}$ of pions $\sim 0.2$

**PHENIX Preliminary**

- $0-20\%$
- $\pi^0$ $0-10\%$, $\langle z \rangle = 0.7$ (PRL 101, 162301)

**Graph:**
- Au+Au and p+p at $\sqrt{s_{NN}}=200$ GeV/c
- Au+Au: 10% most central
- $kt$ $R=0.4$
- anti-$kt$ $R=0.4$

$R_{AA}$ vs $p_T^{Jet}$ (GeV/c)

$R_{AA}$ vs $p_T^{rec-pp}$ (GeV/c)
Au+Au: cross-section ratio $R=0.2/R=0.4$

STAR Preliminary

Stronger broadening seen in measurement than NLO calculation...

⇒ strong hadronization effects? (that would be unfortunate)
Calculations and models of jet quenching and jet reconstruction
TECHQM: energy loss in a static “QGP Brick”

Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma “Brick”
(Outline Version II)

TEC-HQM Collaboration
The Earth, Solar System, Milky Way, Virgo Supercluster, Universe
(Dated: January 8, 2010)

This is the second draft of the outline of a report describing the comparison of various pQCD based formalisms treating the energy loss of hard partons in a thermal quark-gluon plasma for a simplified geometry. Specifically, we compare the predictions of the WHDG and ASW, and Higher Twist (HT) formalisms in the opacity expansion, and of the BDMPS–Z and AMY formalisms in the multiple soft scattering approximation.

• All analytical approaches represented:
  GLV/WHDG, ASW, HT, AMY
• Exercise has explored systematically the limitations of all approaches due to soft and collinear approximations (known previously but not via model-to-model comparisons)

Solutions:
  • NLO calculations
  • Monte Carlo codes (modifications of PYTHIA and HERWIG)
Jet quenching analytic approaches: theory uncertainties

Will Horowitz (TECHQM/CATHIE workshop Dec ‘09)

Same QGP brick for all models:
Systematic uncertainty on qhat due to soft and colinear approximations

• “Central” values disagree by a factor of several, but within realistic uncertainty band
• This clarifies the “qhat puzzle”
New theory development: Jet quenching Monte Carlos

- **HIJING (Heavy Ion Jet Interaction Generator)**

- **JEWEL (Jet Evolution With Energy Loss)**

- **MARTINI (Modular Algorithm for Relativistic Treatment of Heavy Ion Interactions)**

- **PQM (Parton Quenching Model)**

- **PYQUEN/HYDJET/HYDJET++ (HYDrodynamics plus JETs)**

- **Q-PYTHIA / Q-HERWIG**

- **YaJEM (Yet another Jet Energy-Loss Model)**

Modeling jet quenching by modified splitting function

JEWEL, YaJEM use Salgado/Wiedemann ansatz:

Fit to high $p_T$ pion suppression

$$P_{a\to bc}(z) = \frac{4}{3} \left( \frac{1 + z^2}{1 - z} \right) \rightarrow \frac{4}{3} \left( \frac{2(1 - f_{\text{med}})}{1 - z} - (1 + z) \right)$$

qPYTHIA, qHERWIG use ASW quenching weights

$$P_{\text{tot}}(z) = P_{\text{vac}}(z) + \Delta P,$$

$$\Delta P = \Delta P(z, t, \hat{q}, L, E) = \frac{2\pi k_T^2}{\alpha_s} \frac{dI_{\text{med}}}{dzdk_T^2}$$
Modeling jet quenching by modified splitting function

JEWEL, YaJEM use Salgado/Wiedemann ansatz:

Fit to high $p_T$ pion suppression

\[ P_{a\to bc}(z) = \frac{4}{3} \frac{1 + z^2}{1 - z} \rightarrow \frac{4}{3} \left( \frac{2(1 + f_{\text{med}}(z))}{1 - z} \right) \]

qPYTHIA, qHERWIG: quenching weights

Straight forward application of jet algorithms. Either on parton or particle level.

\[ P_{\text{tot}}(z) = P_{\text{vac}}(z) + \Delta P , \]

\[ \Delta P = \Delta P(z, t, \hat{q}, L, E) = \frac{2\pi k_T^2}{\alpha_s} \frac{dI_{\text{med}}}{dzdk_T^2} \]
NLO E-Loss calculations and jet finding

GLV medium induced radiation: number of scatterings, momentum transfers, color current propagators, coherence phases (LPM)...

Jet cross-sections:

\[
\frac{d\sigma_{\text{jet}}}{dE_T dy} = \frac{1}{2!} \int d\{E_T, y, \phi\}_2 \frac{d\sigma[2 \rightarrow 2]}{d\{E_T, y, \phi\}_2} S_2(\{E_T, y, \phi\}_2) \\
+ \frac{1}{3!} \int d\{E_T, y, \phi\}_3 \frac{d\sigma[2 \rightarrow 3]}{d\{E_T, y, \phi\}_3} S_3(\{E_T, y, \phi\}_3)
\]

$S_2$ and $S_3$ contain jet finding algorithm (phase space constraints identifying jet with its parent parton)

I. Vitev, B.-W. Zhang
and refs there
qPYTHIA is the only publically released code at present...
qPYTHIA vs RHIC data I

B. Fenton-Olsen, LBNL
qPYTHIA vs STAR data II

STAR Preliminary

qPYTHIA predicts more suppression (smaller $R_{AA}$) and less broadening that observed.

B. Fenton-Olsen, LBNL
High-pT hadron suppression at LHC

\[
\pi^0 \frac{R_{AA}}{p_{T}} \quad \text{Pb+Pb } \sqrt{s_{NN}} = 5.5 \text{ TeV} \\
0-10\% \text{ Central}
\]

\[
\frac{d\sigma}{dp_{T}}(\pi^0) \quad \text{at } s^{1/2} = 5.5 \text{ TeV}
\]

\[
\frac{d\sigma}{dp_{T}}(\pi^0) \quad \text{at } s^{1/2} = 200 \text{ GeV}
\]

\[
R_{AA}(p_{T})
\]

\[
\frac{d\sigma}{dp_{T}}(\pi^0) \quad \text{in central Pb+Pb, GLV E-loss } 0^{0}/d\eta/dy = 2000
\]

\[
\frac{d\sigma}{dp_{T}}(\pi^0) \quad \text{in central Pb+Pb, GLV E-loss } 0^{0}/d\eta/dy = 3000
\]

\[
\frac{d\sigma}{dp_{T}}(\pi^0) \quad \text{in central Pb+Pb, GLV E-loss } 0^{0}/d\eta/dy = 4000
\]

\[
\frac{d\sigma}{dp_{T}}(\pi^0) \quad \text{in } p+p \text{ at } s^{1/2} \]

1/22/2010

Hirschegg 2010, MPloskon
Jet quenching signals at LHC

Jet Broadening

\[ \frac{d\sigma(R=0.2)}{d\sigma(R=0.4)} \]

\[ \text{Pb+Pb} \ \sqrt{s_{\text{NN}}} = 5.5 \text{ TeV} \]

0-10\% Central 

Anti-\( k_T \), R=0.4

qPythia

LHC

\[ p_T^{\text{jet}} \text{ (GeV/c)} \]

\[ R_{AA}^{\text{jet}} \]

qPYTHIA

\[ q = 1 \]
\[ q = 6 \]
\[ q = 17 \]
\[ q = 61 \]

GLV

\[ R_{\text{max}}^{\text{jet}} \]

\[ E_T \text{ (GeV)} \]

Pb+Pb@5500 GeV

b = 3 fm

Hirschegg 2010, MPloskon

1/22/2010
Further jet measurements

Not possible w/o full jet reconstruction(!)
Jet shapes

\[ \psi(r, R) = \frac{d}{dr} \left\{ \sum_i E_{T_i} \theta(r - R_{i,\text{jet}}) \right\} \]

I. Vitev, B.-W. Zhang


LHC/ Tevatron

20 GeV

100 GeV

500 GeV

RHIC: 200 GeV

1/22/2010
Hadron+jet coincidence

- Trigger on hard, leading $\pi^0$ ($p_T > 6\text{ GeV/c}$)
  - 3x3 tower cluster in BEMC
  - Construct spectrum of recoil jets
    - normalized per di-hadron trigger

This event selection will **maximize** the recoil path length distribution in matter

STAR high $p_T$ dihadrons: bias towards non-interacting jet population

Conditional yield vs. $\Delta\phi$

- $p+p$
- $Au+Au$

Cond. yield ratio $I_{AA}^{Jet}$
Hadron+jet coincidence

1. Trigger on hard, leading $\pi^0$ ($p_T > 6$ GeV/c)
2. 3x3 tower cluster in BEMC
3. Construct spectrum of recoil jets
4. Normalized per di-hadron trigger

This event selection will maximize the recoil path length distribution in matter.

Au+Au: 10% most central events

Jet: anti-kt $R=0.4$
- Au+Au / p+p $p_T^A > 6.0$ $p_T^B > 6.0$
- Au+Au / p+p $p_T^A > 6.0$ $p_T^B > 4.0$
- Au+Au / p+p $p_T^A > 6.0$ $p_T^B > 2.0$

Conditional yield

Energy shift? 

Absorption?

$R=0.4$

$1/22/2010$
qPYTHIA: geometric bias of high $p_T$ hadron production

Distribution of vertices generating high $p_T$ pion trigger in $x$-direction

Pb+Pb 5.5 TeV
$q\hat{a}=50$ GeV$^2$/fm

Hiroki Yokoyama, Tsukuba

Comparison to STAR data in progress...
High-pT hadron bias (LHC: central PbPb @ 5.5 TeV; qhat=20)

Masato Sano
Tsukuba/LBNL

Jet/hadron direction

Hadron triggers

Jet triggers

5 GeV
15 GeV
30 GeV
40 GeV

60 GeV
100 GeV
160 GeV
200 GeV

Hirschegg 2010, MPloskon
Path lengths: high-pT hadron vs jet trigger

$\pi^0$-Jet: -> surface bias

Jet-Jet: complete exploration of path lengths
Future measurement: subjets

Count sub-jets when $y_{ij} > y_{cut}$:

$$y_{ij} = 2 \min(E_i^2, E_j^2)(1 - \cos \theta_{ij})/E_{cm}^2$$

Subjet distributions:

- Insensitive to hadronization
- Quenching signal with bg suppressing pt cut

- Suffer from energy irresolutions:

$$-\log_{10}(f_{corr}^2)$$

where

$$f_{corr} = \frac{E_{true}}{E_{measured}}$$

C. Zapp et al.
Properties of the Fragmentation Function

- Universal (independent of collision system)
- Scale dependence $\Rightarrow$ DGLAP evolution
- Dependence on partonic species ($g$ vs $q$ vs $Q$)
Fragmentation Functions in $e^+e^-$

Scaling violations

\[ z = \frac{p_{L|\text{jet}}}{p_{\text{Jet}}} \]

\[ \xi = \ln \left( \frac{E_{\text{Jet}}}{p_{\text{hadron}}} \right) \]

MLLA:

peak position $\xi_p \approx \frac{1}{4} \ln \left( \frac{s}{\Lambda^2} \right)$

Gaussian width $\sigma \propto \left[ \ln \left( \frac{s}{\Lambda^2} \right) \right]^{\frac{3}{4}}$
Tevatron circa 2000 A.D.

Note: these are not fragmentation functions – Rather: hadronic momentum distributions in jets

Why not FFs?
• No evidence that they are universal
• No unambiguous definition of scale $Q^2$
  ➔ What is evolution equation?
• Complex and unknown mixture of partonic species

Dijet events: $E_{jet} = M_y/2$, $Y = \ln\left(\frac{E_{jet}}{Q_{eff}}\right)$

$\zeta = \ln\left(\frac{E_{jet}}{P_{TkJ}}\right)$

$Q_{eff} \equiv Q_0 = \Lambda_{QCD}$

1/22/2010

Hirschegg 2010, MPloskon
Hadrons in jets @ RHIC

\[ \xi \cdot \xi_{\text{max}} \equiv \log(1/x_p)_{\text{max}} \]

Test?
Why to measure fragmentation patterns in HI collisions?

CERN LEP

Jet quenching

“hump-back plateau”

\[ \frac{dN^h}{d\xi}(\xi, \tau) \]

- OPAL, \( \sqrt{s} = 192 - 209 \text{ GeV} \)
  - in vacuum, \( E_{\text{jet}} = 100 \text{ GeV} \)
  - in medium, \( E_{\text{jet}} = 100 \text{ GeV} \)

\[ p_{\text{T, hadron}} = 2 \text{ GeV} \]

\[ \xi = \ln \left( \frac{E_{\text{Jet}}}{p_{\text{hadron}}} \right) \]
Outlook

Complete jet reconstruction promises qualitatively new insight into jet interactions in matter

- major focus of RHIC II and LHC HI programs
- has stimulated significant new theory activity

But significant technical issues for systematically well-controlled measurements

- main issue: HI background characterization
- high backgrounds expected also in high luminosity p+p at LHC
Hadronic collisions and pQCD

\[ E \frac{d^3 \sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}_{ab \rightarrow cd}}{dt} \otimes D_{h/c}(z_c, Q^2) \]

\( D(z, m_F) \) is the Fragmentation function

Perturbative x-section

Not Perturbative!

Proton Remnant

\( p \) (uud)