Exploring the Underlying Event and Hadronization Using Di-jets at STAR

Brian Page
for the STAR Collaboration
MPI 2015 - Trieste
Outline

• Overview of RHIC and STAR

• Jet / Di-jet Reconstruction at STAR

• PYTHIA studies of di-jet sensitivity to underlying event and hadronization effects
RHIC: First Polarized pp Collider
The STAR Detector

Time Projection Chamber (TPC)
Charged Particle Tracking $|\eta|<1.3$

Barrel Electromagnetic Calorimeter (BEMC):
$|\eta|<1$

Endcap Electromagnetic Calorimeter:
$1<\eta<2$

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Latest $A_{LL}$ results from RHIC (inclusive jets from STAR & inclusive $\pi^0$ from PHENIX) have been included in global fits by DSSV and NNPDF groups and give evidence of first non-zero values of gluon polarization in $x$ range above 0.05.
Jet Reconstruction

Jet Levels:
- Jets reconstructed at 3 levels – Detector, Particle, and Parton
- Detector jets constructed from charged particle tracks (assumed to have pion mass) and EMC tower energy deposits (assumed to have zero mass)
- Particle jets constructed from all final state particles (particles have correct mass)
- Parton jets constructed from partons originating with hard interaction and ISR / FSR

Anti-kT Algorithm:
- Radius = 0.6
- E-Scheme recombination
- Less sensitive to underlying event and pile-up effects
- Implemented using FastJet
- Used in both data and simulation

MC Jets

GEANT

PYTHIA

Particle:
- e, ν, γ
- π, p, etc

Parton:
- q, g
Beyond Inclusive Measures: Di-jets

- Correlation measurements such as di-jets capture more information from the hard scattering – di-jet $A_{LL}$ may place better constraints on the functional form of $\Delta g(x, Q^2)$

- Agreement between measured di-jet cross section and theoretical calculation gives confidence that observable is understood at STAR

- Realized that it may be possible to use the di-jet cross section to probe underlying event and hadronization effects due to the dependence of the di-jet mass on individual jet masses
Di-jet Cross Section

- Raw data yields corrected to particle level using the SVD unfolding method as implemented in RooUnfold

- Theory values from the NLO code of de Florian et al using the CTEQ6m PDF set

- Theory has been corrected for underlying event and hadronization effects
UEH Correction

- Di-jet cross section extracted to the particle level
- Theoretical calculations are at parton level, do not account for underlying event or hadronization (UEH)
- Need to apply UEH correction to theory so that comparison to data can be made
- UEH correction is the ratio of particle over parton level di-jet yield from PYTHIA
- UEH effects should be at lower mass, surprise that the ratio does not reach unity at highest masses
Jet $p_T$ Spectra: Particle vs Parton

- Is discrepancy between particle and parton level di-jet mass caused by transverse momentum of jets?
- Look at $p_T$ of the jets which make up the di-jet
- Very good agreement seen between jet $p_T$ at particle and parton level
- Could jet masses be driving the discrepancy?
Di-jet Mass Formula

\[
P = \begin{bmatrix} m_T \ Cosh(y) \\ p_T \ Cos(\varphi) \\ p_T \ Sin(\varphi) \\ m_T \ Sinh(y) \end{bmatrix}
\]

\[
M^2 = [P_1 + P_2]^2
\]

- Di-jet mass constructed from the 4-vectors of both jets
- Full mass formula contains terms which depend on the individual jet masses
- Disregarding individual jet masses gives di-jet mass which depends only on transverse momenta and geometric orientation of both jets

\[
M = \sqrt{m_1^2 + m_2^2 + 2 \cdot \sqrt{m_1^2 + p_{T1}^2} \cdot \sqrt{m_2^2 + p_{T2}^2} \cdot Cosh(\Delta y) - 2 \cdot p_{T1} \cdot p_{T2} \cdot Cos(\Delta \varphi)}
\]

- Full Formula

\[
M = \sqrt{2 \cdot p_{T1} \cdot p_{T2} \cdot [Cosh(\Delta \eta) - Cos(\Delta \varphi)]}
\]

- Massless Formula
Particle and parton level di-jet yields match very well when jet masses are excluded.

In Perugia0 tune (using L.O. CTEQ 5L PDFs) particle/parton discrepancy largely caused by jet mass terms arising from the hadronization of partons into massive final state particles.

Is behavior different for other tunes or PDFs?
See that the inclusion/exclusion of the jet mass terms in di-jet mass formula has much bigger effect at particle level than parton level

This is expected as final state particles have greater mass than partons

Behavior is statistically consistent between the three tunes / PDFs investigated
Jet $p_T$ Spectra: Tune/PDF Dependence

Particle Level
Parton Level
Di-jet Mass: TuneA

- Look at TuneA using L.O. CTEQ 5L PDF set
- As with Perugia0 tune, we see alignment of the spectra, however there is now an excess of events at parton level at low mass
Di-jet Mass: Perugia0 (CTEQ6)

- Behavior seen when using Perugia0 tune parameters with CTEQ 6m PDF set very similar to TuneA
Jet Mass Spectra: Data / Simulation

Data (Preliminary)
Simulation

Di-jet Mass:
19 - 40

Di-jet Mass:
40 - 70

Di-jet Mass:
70 - 120

Data: 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6
Simulation: 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6

Jet Mass Spectrum (Dijet mass 19-40): Blue=Data Red=Simu

Jet Mass Spectrum (Dijet mass 40-70): Blue=Data Red=Simu

Jet Mass Spectrum (Dijet mass 70-120): Blue=Data Red=Simu

Jet Mass Data/Simu Ratio

Lo Dijet Mass
Mid Dijet Mass
Hi Dijet Mass

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**Dijet ΔM Vs M: Data / Simulation**

- **Data (Preliminary)**
  - Difference between di-jet mass with and without jet mass terms as a function of full di-jet mass
  - Error bars on 2-D plots show RMS while error bars on bottom plot show error on the mean of the distribution

- **Simulation**

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Dijet $\Delta M$ Vs $M$: Particle Level
• Theory di-jet cross section needs to be corrected to account for underlying event and hadronization effects before comparison to data can be made.

• These UEH corrections (particle/parton level di-jet yield ratio) persist to highest measured masses – found to be due to jet mass terms in di-jet mass formula.

• UEH corrections vary substantially when including/excluding jet mass terms and when using different PDF sets and PYTHIA tunes.

• Effect of the jet mass terms on individual particle and parton level spectra is independent of tune or PDF set studied.
Backup
Di-jet Mass: TuneA

- Look at TuneA using L.O. CTEQ 5L PDF set
- As with the Perugia0 tune, the effect of including/excluding the jet mass is much more pronounced at particle level
- Particle and parton level ratios are consistent with Perugia0 results
Di-jet Mass: Perugia0 (CTEQ6)

- The inclusion/exclusion of the jet mass has the same effect on the particle and parton spectra regardless of tune or PDF set.

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$\sqrt{s}$ Dependence: Jet Levels W/ Mass

$\sqrt{s} = 500 \text{ GeV}$

Particle Level
Parton Level

$\sqrt{s} = 200 \text{ GeV}$

Jet Mass Included
dependence: jet levels w/o mass

\( \sqrt{s} = 500 \text{ GeV} \)

\( \sqrt{s} = 200 \text{ GeV} \)

jet mass not included

particle level

parton level
$\sqrt{s}$ Dependence: Jet Masses Particle

Jet Mass
No Jet Mass

$\sqrt{s} = 500 \text{ GeV}$

$\sqrt{s} = 200 \text{ GeV}$
$\sqrt{s}$ Dependence: Jet Masses Parton Level

$\sqrt{s} = 500$ GeV

$\sqrt{s} = 200$ GeV

Jet Mass
No Jet Mass

Parton Level