Understanding the Role of jet and Underlying Event in p+p and d+Au collisions at RHIC

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- Introduction/Motivation
- Underlying event in p+p and d+Au
- Jet correlation from p+p to d+Au

Focus on <10 GeV/c region
Strong interest for underlying event from HEP community: one of the main sources of uncertainty for QCD/jet physics and Higgs searches.

- Studied from $630 < \sqrt{s} < 1900$ GeV.
- RHIC results can fill the low energy end.
p+A: cold nuclear matter effects

- PDF (saturation/CGC)
- Multiple scattering, increased multiparton interaction (MPI), cold nuclear e-loss, isospin etc
  - The UE level will increase.
  \[ \propto N_{\text{part}}, N_{\text{coll}} \]
  - But not the jet shape?

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p+A: cold nuclear matter effects

- Strong modification on single yield exist (esp. below 5 GeV/c) without final state plasma.
- Jet and UE should be modified as well?

Cronin enhancement due to multiple scattering, recombination

Shadowing / saturation, energy loss, EMC
**Au+Au: final state interaction in QGP**

- More multi-parton interaction (MPI)
- ISR/FSR different from pp?
- Strong interaction between jet and Underlying event (final state plasma)

*Modified jet + flowing medium (UE)*
Final state interaction between jet and medium

- Suppression of high pT yield and surface bias
- Response of the flowing medium to energy deposition

High $p_T (>5$ GeV/c)
Jet quenching

Low $p_T (<5$ GeV/c)
Medium response

medium response mechanisms?

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- Jet and UE intrinsically coupled. Need to study them together.
  - p+p: ISR/FSR + Color connection between Jet and UE
  - d+Au: plus multiple-scattering and eloss, power correction etc
  - Au+Au: plus strong final state interaction.

- Baseline measurements in p+p and p+A collisions are necessary to understand the medium response mechanisms

- This talk covers two topics.
  - Jets: Cold nuclear modifications from p+p $\rightarrow$ d+Au ($\rightarrow$ Au+Au)
  - UE: The scaling behavior from p+p $\rightarrow$ d+Au ($\rightarrow$ Au+Au).
Relative importance of jet and UE in p+p

- Jet fraction >> the few % level seen in Au+Au.
- A significant fraction come from soft processes, not all trigger from hard-scattering (jet)?
Comparing the average "transverse" charge particle density with the average "Min-Bias" charge particle density ($|\eta|<1, p_T>0.5$ GeV). Shows how the "transverse" charge particle density and the Min-Bias charge particle density is distributed in $p_T$.

$$\zeta = \frac{\text{Assoc. Pedestal Yield Per-trig}}{\text{Min. Bias yield Per-event}}$$

From Rick Field
UE yield in p+p

- Procedure is different from CDF: Dihadron correlation, instead of jet reconstruction, not $p_{\text{max}}$.
  - Full jet reconstruction is questionable at $p_T<10$ GeV/c.
  - Same method used for p+p, p+A and A+A collisions.
- Charge particle density of UE integrated from 0.6-5 GeV/c.
  - Saturation behavior is similar to CDF results.

![Graph showing UE yield in p+p](image)

"Transverse" Charged Particle Density: $dN/d\eta d\phi$

- CDF Run 1 data uncorrected
UE yield in p+p

- Low assoc pT: UE saturated with trigger pT, multiple-parton interactions or centrality bias.
- High assoc pT: UE increase with trigger pT, contribution from ISR.

\[ \zeta = \frac{\text{Assoc. Pedestal Yield Per-trig}}{\text{Min. Bias yield Per-event}} \]

- For p+p 0.4 < p_T < 0.6 GeV/c
- For p+p 3.0 < p_T < 4.0 GeV/c

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Compare with PYTHIA 6.419

- Tried three tunes:
  - TUNE A (100) -- Parameter set tuned to CDF data by Rick Field.
  - TUNE S0A (303) -- New UE/MI framework introduced since Pythia 6.3
  - TUNE A with independent fragmentation (default string fragmentation).
    - Results depend on fragmentation scheme since we don’t reconstruct jet

- Under-predicts the pT dependence of UE yield
  - Tune 100 seems ok for integrated yield.
  - Either the ISR and/or MPI need additional tuning at RHIC?
Underlying event in d+Au

- The scaling from p+p to d+Au have different sensitivity to MPI and ISR
  - Should have only one hard-scattering.
  - MPI increase, however less centrality bias.
Test with a simple model

- Assuming one d+Au collision contains one hard-scattering n-n collision + $N_{coll} - 1$ minimum bias n-n collisions (with nuclear effects).

$$\left(UE\right)_{dAu} = \left(UE\right)_{pp} + R_{dAu} \left(N_{coll} - 1\right) \text{ m.b. p+p Yield}$$

- The $\zeta$ values in dAu and pp should be connected via ($\epsilon_{mb}$ is the p+p trigger efficiency)

$$\zeta_{dAu} R_{dAu} N_{coll} = \zeta_{pp} / \epsilon_{mb} + R_{dAu} \left(N_{coll} - 1\right)$$
Does it work?

- However this seems not working,
  - eg. Under-predicts the UE level by factor of 2 in 60-88% bin
- Require more activities for ambient n-n collisions.
  - More radiation or ISR of hard-scattering re-interact with the Au nuclei?
d+Au jet correlation at high pT

- No modification is seen when triggering at high pT


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**d+Au jet correlation at low pT**

- **Enhancement in central d+Au to p+p at low pT**
  - Enhance by same factor on both near and away-side
  - Very little change in shape.
- **Modifications disappear at high pT**

\[
\text{per-trig yield} = \frac{\text{Pair Yield}}{\text{Trig Yield}}
\]
**d+Au jet correlation at low pT**

Single particle yield is modified in the same pT region.

$\text{per-trig yield} = \frac{\text{Pair Yield}}{\text{Trig Yield}}$

- **RHIC-AGS meeting 2009**
- **PHENIX Preliminary**
What is the correct observables?

Enhancements due to modification of trigger yield?

Three quantities for medium modifications

Modification of single particle yield: \[ R_{dA} = \frac{(\text{Trig Yield})_{dA}}{N_{coll} \times (\text{Trig Yield})_{pp}} \]

Modification of per-trigger yield: \[ I_{dA} = \frac{\text{per-trig yield}_{dA}}{\text{per-trig yield}_{pp}} \]

Modification of correlated pair yield: \[ J_{dA} = \frac{(\text{Pair Yield})_{dA}}{N_{coll} \times (\text{Pair Yield})_{pp}} \]

Only two variables are independent!

\[ J_{dA} (p_T^a, p_T^b) = I_{dA} (p_T^a, p_T^b) R_{dA} (p_T^a) = I_{dA} (p_T^b, p_T^a) R_{dA} (p_T^b) \]

If \( R_{dA} \) varies with \( pT \), then \( I_{dA} \) will vary with \( pT \) even if jet is unmodified.
Modification on Pair yield: $J_{dAu}$

- Pair yield scales with pair energy: $|p_T^a| + |p_T^b|$ (hard-scattering scale)
- Pair yield enhanced relative to $N_{coll}$ scaled $p+p$ to 5-8 GeV/c
- Cronin like peaks at $\sim$4 GeV/c in pair energy
Modification on Pair yield: $J_{dAu}$

- Similar trend at the away-side (similar amplitude)
- No such effects in peripheral $d+Au$

$$J_{dAu} = \frac{(Pair\ Yield)_{dAu}}{N_{coll} \times (Pair\ Yield)_{pp}} \times R_{dAu}(p_T)$$

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Mechanisms for modifications at low pT?

- **Shadowing effect.**
  - Believed to cause suppression of single yield at low pT. But hard-scattering process not suppressed in pair momentum?

- **Power correction.**
  - Factorization theorem breaks down at low $Q^2$ (we start at 1-2 GeV/c$^2$)?

- **Initial state multiple scattering**
  - Since near-side jet shape not modified, so should happen on parton level?

- **Increased radiation or re-interaction of ISR with remaining nuclei**
  - Increased multiple parton interactions, may break kT-factorization.

- **Cold nuclear matter energy loss**
  - Can increase low pT jet yields, but should suppressed high pT yield (not seen).

- **Isospin and EMC effects**
  - Such effects should be small, since we are dominated by gluon jets
Implications for Au+Au measurements

- **Strong medium response at similar pT in Au+Au (<5 GeV/c).**
  - Strong modification of single particle yield, elliptic flow, and di-hadron correlation.

- **Part of that should be attributed to cold nuclear effects (non-perturbative?).**
  - Not enough to account for the yield change and can’t explain the shape modification.

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![Graphs showing particle yields and correlations for Au+Au collisions](image_url)
Conclusion

- Studied the jet and underlying event in p+p and d+Au collisions

- Underlying event in p+p and d+Au
  - p+p: similar pT dependence as Tevtron, but under-predicted by several PYTHIA tunes.
  - d+Au: more than a simple hard-scattering plus several minimum bias p+p

- Jet modifications in d+Au
  - High pT: no modifications.
  - Low pT: Jet shape unchanged, but jet pair yields are enhanced (no suppression), a Cronin-like peak seen in pair energy.

  The role of non-perturbative processes?

- Jet modification happens in same pT range where the both single and dihadron correlation is modified in Au+Au collisions.
  - dAu/pp help to better understand the Jet quenching and medium response.

- Need to study the scaling behavior of UE in Au+Au.
Backup
Comparison to single yield

- Tune 303 agrees better
Comparing the jet yield

- **Near-side Jet yield:**
  - Indep. frag. gives better description
  - Tune 303 is better than tune 100

- **Away side jet yield:**
  - Tune 303 is better than tune 100,
  - For tune 100, indep. frag. is better

**Near-side yield:**
![Near-side yield graph](image)

**Away-side yield:**
![Away-side yield graph](image)
Quantify UE in di-hadron correlation

- Correlation function is defined as ratio of pairs from same event to that of mixed events

\[ C'(\Delta \phi) = \frac{N_{fg}(\Delta \phi)}{N_{mix}(\Delta \phi)} = \frac{\text{Jet}_{\text{pairs}} + \text{UE}_{\text{pairs}}}{\langle n_a \rangle \langle n_b \rangle} \]

- Measure the UE in same event relative to mixed event
  - Advantage: tracking efficiency cancels in the ratio

\[ \zeta = \frac{\text{UE}_{\text{pairs}}}{\langle n_a \rangle} = \frac{\text{Assoc. Pedestal Yield Per-trig}}{\text{Min. Bias yield Per-event}} \]

Level defined by ZYAM

In CDF method, less UE since jet is reconstructed.
Run5 p+p

- $1.0 < p_T^a < 1.5$ GeV/c
- $2.0 < p_T^a < 3.0$ GeV/c
- $3.0 < p_T^a < 5.0$ GeV/c
- $5.0 < p_T^a < 10.0$ GeV/c

$\zeta = \frac{\text{Jet Pedestal Yield}}{\text{Min.Bias Event Yield}}$

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dAu single particle modification: $R_{dA}$
\begin{align*}
&\text{p+p} \\
&\text{2-3} \otimes \text{2-3 GeV/c} \\
&\text{C}(\Delta\phi) \\
&\Delta\phi(\text{rad})
\end{align*}

\begin{align*}
&\text{0-20\% dAu} \\
&\Delta\phi(\text{rad})
\end{align*}