High $p_T$ Physics at RHIC

Outline:
1) High pt (spectra)
2) 2-$p$ / Gamma-jet results
3) sPHENIX

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RHIC/AGS Users Meeting
June 26, 2013
Exploit RHIC’s **Flexibility** to study different systems, small and large

Geometry: Exotics CuCu, CuAu, UU, dAu, He\(^3\)Au?

The BES : Phase Transition Physics

**High p\(_T\) / For jet quenching studies:** exploit the large collision energy difference within RHIC and between RHIC and LHC to understand the physics of quenching

Robustness of theory and more! (sPHENIX goal): understand the emergence of interactions by varying time spent near T\(_C\).

Understand **Geometrical** and **Initial State Effects In Quenching**!
Part 1
High $p_T$ Spectra Results from Energy and Geometry Scans

http://w.000finance.com/
New Results Exploiting RHIC’s Flexibility in $s$

- Another T-shirt Plot?
Understanding Cronin?

- Presumably there is still quenching below \( \sim 30 \text{ GeV} \)
- Cronin Effect blows up at low \( \sqrt{s} \) \( \Rightarrow (k_T(\sqrt{s})) \)
  - But note, not necessarily in p+A! See WA 98 next slide
- Quote from April Workshop:
  “It’s time we understand the Cronin Effect”...
  - G. Barnafoldi

(Tangram paradoxes)

wikipedia.org
Useful New Context for WA98

- WA98 LEDA: A RHIC Detector Too!
  - (Now PHENIX PbGl – JF/ Ohio U Manage Pbgl Operations ;> !)
- $\sqrt{s}$ 17.4 Cronin Blowup starts only above $N_{\text{part}} > \sim 50$

WA98 0708.2630  PRL 100 (2008) 242301
$R_{CP}$ vs $R_{AA}$: References!

- Draw back for $R_{CP} \rightarrow$ Peripheral spectra might be the hardest to get right theoretically; preferably use $R_{AA}$
  - Note PHENIX Data below using Fermilab E706
- These A+A studies need references! $p+p$ and ...

PHENIX 1204.1526
PRL 109, 152301 (2012)
High $p_T$ pp/pA Energy “Scan”? 

- Significant critical mass of theorists interested in CNM developing? April Workshop very successful!
- RHIC should continue to lead this effort!
- Short term “Scan”?: Get p+p and p+A ~one point above and below ~30 GeV ?
- Longer term sPHENIX can contribute with full Jet studies → a key observable?

![Graph showing Cronin Dominated and Suppression Dominated regions with STAR $R_{CP}$, PHENIX $R_{AA}$, and ALICE data points.](6/27/2013 Justin Frantz RHIC Users Mtg 2013 8)
Expanding the Geometry Dimension...

Comprehensive 2005 Cu+Cu Results from PHENIX

- New HI Geometries Cu+Au, U+U: p+Si, C, Au,
- Whole workshop this morning right now – Organizers Hui Wang, Shengli Huang
Part 2: 2-particle Measurements and Jets

http://w.000finance.com/
Di-hadrons are undergoing surgery

- RHIC continues to explore di-hadron correlations but currently there is some noise that needs (and is being) resolved (related to Jet-Medium coupling—see next talk) before we can apply to quenching constraints.
A Different Complimentarity?

- Jet-h and $\gamma$-h 2-p Correlations Can be used and should!
- **My Opinion:**
  - Jet Reconstruction is crucial for final understandings of Jet Quenching $\rightarrow$ Modifications to Showering Process
    - sPHENIX!
  - In the short term **DANGER**: Don’t let jet quenching studies (RHIC/LHC) become too Jet Reco- biased!
  - We first need to learn what quenched jets look like!
    - May need completely new jet finding techniques to study quenched jets
- Complimentarity: Jet Finding + Angular Correlation (Jet-h and $\gamma$-h) Measurements
  - We can study when modification is mostly NOT there with jet finding: e.g. Energy Asymm
  - Don’t ignore modification just because it not seen w/ jet finding observables

Justin Frantz RHIC Users Mtg 2013
**Example: “Jet” Finding + Correlations**

- **Event by Event** CHOOSE jets with quenching $A_j / x_j$
- The Ultimate Tool? Identify perturbative quenching regions, vary the quenching fraction?
- Look for shape of quenched jets in regions of di-jet asymmetry. Direct $\gamma$-jet/di-jet different systematics.
  - Di-jet $A_j$, Gamma-jet $x_j$ cut
- Need to do it with and without quench reco axis!

**Di-jet Asymmetry Distribution**


**$\gamma$-jet Asymmetry Distribution**

![$\gamma$-jet Asymmetry Distribution](CMS PLB 718 (2013) 773)
“Jet” Finding + Correlations

- Wait... what about current measurements
- LHC FF Modification Correlates with Large $A_J$? No?
- Bias of found jets
  - Look outside jet cone!
  - Look below jet finding cutoff

\[
\frac{\text{d}N}{\text{d}A_J}
\]

\[
\text{Ratio FF Pb+Pb / p+p} = 1 \rightarrow \text{No mod?}
\]
• Photon Hadron FragFn Modification!
• Low $z$ Enhancement
• Very Similar to LHC Jet-reco
  o LHC FF=1 \(\sim\) Jet RAA
• \(~\)Consistent with STAR Jet-hadron
  o RHIC-RHIC Consistency!
• These analyses are important!
• \(\text{Reco jets} \neq \text{All Jet Suppression} \text{ (?)}\)
There’s more information

- Modified FF isn’t the whole story (don’t stop there!)
- Correlations: angular shape

![Graph showing correlation data]

PHENIX
1212.3323
PRL Accepted
Angular distributions

So much broadening too “weird”? -There’s a lot of interesting stuff at $R > 0.8$!
Also Keep in Mind

- Results dominated by $<p_T>\sim 6$ GeV Jets with an RMS $O(2\text{GeV})$ due to $k_T$
  - $< 2 \times$ Lower Than STAR Jet-$h$
  - $<<$ than LHC Results
- No Isolation Cut applied: other photons sources: e.g. more fragmentation photons (Iso coming soon)

PHENIX 1212.3323
PRL Accepted
Correlations + “Jet”(γ) 2: Quark Tagging

• In γ-h Compton scattering means quark jet tag

• Charge asymmetry of cross section and valence u vs d quark should be reflect in final state charged hadrons

SEEN IN p+p 2-p @ PHENIX
Allow q vs g Eloss study in AuAu

PHENIX PRD 82, 072001 (2010)

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Charge Asymmetry

- Applying Iso Cut allows selection of Compton--u, d quark counting should govern expected scale of asymmetry
  - $d\sigma \sim Z_q^2$ u:d $\Rightarrow$ 8:1 p+p, A+A, d+Au: 4.7-6.2
- Assoc p vs n similar - independent

- How do these go together (d+A $\Rightarrow$ p+A)?
Part 3 sPHENIX

- How PHENIX can access jet finding tools...

http://w.000finance.com/

→ Coincidence?
sPHENIX

- Upgrade optimized around jet/di-jet/photon/HF measurements
- **Compact**: High rate, large **uniform** acceptance over $|\eta| < 1$
- Submitted by BNL to DOE for MIE CD-0 review in ~Feb
- Opportunity for detector building experience:
- Prototyping is already underway! Join us!

Inner Radius 70 cm
B = 2 T

Fe-Scint Hcal Unique Design

Prototyping underway
(Previous Design Beam Tested Dec 2012)

W-Sc EMCal – Accordion Design
sPHENIX MIE Proposal

- CD-0 DOE MIE Proposal: 60/120 pages: Generic RHIC Physics Discussion!
  - (A good read! link to mie pdf)
- The crucial physics offered by an LHC-like detector at RHIC using LHC-like Jet Reconstruction Methods

**Bkg Subtraction**

- Run jet reco algorithm on 0.1x0.1 calorimeter cells
- Determine set of R=0.2 seed jets
  - 1st pass: towers in jet satisfy $p_T > 3$
  - 2nd pass: jet $E_T > 20$
- Determine $v_2$ for event
  - exclude towers within $\Delta\eta < 0.4$ of seed jet
- Determine background $E_1$ in $\eta$ strips
  - demodulate by $v_2$
  - exclude towers within $\Delta R < 0.4$ of seed jet
- Subtract background from jets tower-by-tower
  - first remodulate background by $v_2$
- Subtract background from event tower-by-tower
  - first remodulate background by $v_2$
- Run jet reco algorithm
- Output: background subtracted reco jets of various R values

**Unfolding**
Possible “in Principle”?  

- Too many Fake Jets?  **NOPE!** Even at $\sqrt{s} = 100$ GeV

- vs LHC: Lower underlying event wins over steeper production spectra for $E > \sim 18$ GeV

- Lower $E$ limited by stats not fake jets? (& stats good down to 100!)
Larger Cone Sizes?

- Yes: baseline for 0.4: $E_{\text{min from bkg}} = 35 \rightarrow$ fake rejection should lower this
- LHC Interesting stuff at these cones, sPHENIX energies
Event By Event Opportunities

- Dijet $A_J: 0-10 \%$ HIJING Embedding—Unfolding procedure works well
- Good separation in raw distributions
**γ-Jet in SPHENIX**

- Access high stats...
- Clear Modification signal, comparable to current LHC Results
- Separation in raw distributions at large $x_{\gamma}$
Back to Di-Hadron?

• The status of di-hadron correlations:
2-Particle Correlations

- Hadron-Hadron @ RHIC:
- Currently taking time off from jet quenching studies to understand medium and jet Medium
- Strategy: understand Jet Coupling to the Medium...
  - Short of that: systematics thereof?
- This effort continues at RHIC

- Example: 2-p vs Reaction Plane
- Quenching Shape vs RXNP! (Pretty important constraint on $E_{\text{loss}}$ models—at least qualitative agreement is needed)
2-p vs Reaction Planes

- Initial Measurements WITH FULL $v_n$ subtractions need finalized? (Modulo experimental Q’s)
- Theory still addressing fundamental q’s about
- Headed for good convergence of Theory and Experiment in a few years? (Understand Init. State Fluctuations/Volume $\rightarrow$ Apply to quenching models)
2-p vs n=3 Rxn Plane

- Initial Measurements WITH FULL vn subtractions need finalized?
- Headed for good convergence of Theory and Experiment in Few Years?
Conclusions

- Jet Quenching Studies at RHIC are and should exploit RHIC’s Flexibility
- Spectra:
  - Both STAR and PHENIX have nice comprehensive spectral data that can be a nice starting point for finally understanding Cronin Effect
    - With sufficient theoretical interest!
  - RHIC spans the key energy range to do this uniquely!
- Two particle Correlations
  - Di-hadrons at intermediate $p_T$ are focused on understanding medium/jet medium systematics, not so much quenching itself
  - Could this be largely resolved within a few years?
  - Direct $\gamma$-hadron and Jet-h and ARE important to quenching considerations NOW and shouldn’t be disregarded because of bias in field towards pure jet reconstruction
- sPHENIX!
  - A powerful new detector to understand robust physics of jet quenching across 2 orders of magnitude in $\sqrt{s}$ at RHIC and the LHC
sPHENIX @ $\sqrt{s}$ 100 GeV?

- fake-jet dominance subsides at $\sim$same E
- Lower UE wins again!
- Stats > 20 GeV $\sim$1/50 compared to 200
- Still $10^5$-$10^6$ Jets > 20
- Even Lower E limited by stats not fake jets?
- How would this addt’l factor of 2 in $\sqrt{s}$ leverage for theory?
sPHENIX: u & d-jet “tagger”

<table>
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<th>Energy (GeV)</th>
<th>Au+Au (central 20%)</th>
<th>p+p</th>
<th>d+Au</th>
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<td>$10^7$ jets</td>
<td>$10^6$ jets</td>
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<td>&gt;50</td>
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<td>$10^4$ jets</td>
</tr>
</tbody>
</table>

Rates based on full stochastic cooling, but no additional accelerator upgrades.
Cronin Mass Effect Strangeness?

- I will almost certainly
Cronin Mass Effect Strangeness
How do the models compare?

- Models get some qualitative features right but are all over the map—affected a lot by hadronization
- Use other hard observables (e.g. open HF) at higher $\sqrt{s}$’s (talks yesterday p+A pre-workshop)
Cronin Mass Effect

Strangeness?

- I will almost certainly skip combine with next p+p reference!
Don’t forget Geometry Axis!!!

- Geometries Cu+Au U+U
- See Talks by Aneta, Jeff
What’s on the ~2-yr horizon for PHENIX \(\gamma\)-jet

- Run 11/14 VTX installed: 10 x stats (acceptance) for \(\gamma\)-jet associated hadron acceptance ~
- And ~3 x Integrated Lumi Run 7/10 Current Result

- Isolation cut in Au+Au analysis well underway
  - Should improve precision in peripheral collisions \(\rightarrow\) towards centrality dependence of enhancement