Goals of talk

1. PHENIX results on how jets interact with the QGP
   a. Connect with LHC + STAR
2. Use other PHENIX results to provide more detailed view
   a. Fragmentation functions, $R_{AA}$, $v_2$, ...
3. Critical next measurements
Intro to jets (I of III): in-situ probe

hard-scattered parton $p+p$: baseline measurements

jet of hadrons

hard-scattered parton $Au+Au$:
1) Interaction parton + plasma
2) Information on the plasma

parton loses energy within plasma
Jet is a weighted combination of measured momenta.

Gaussian filter used in Cu+Cu

\[ p_T^{jet}(\eta, \phi) \equiv \max \left\{ \int \int d\eta' d\phi'[p_T(\eta', \phi') - p_T^{ave}(\eta', \phi')]e^{-(\Delta \eta^2 + \Delta \phi^2)/2\sigma^2} \right\} \]

Infrared-safe: lower-weight given to particles away from axis, stable against additional low-pt particles.

Collinear-safe: similar results if fragmentation splits into multiple nearby high-pt tracks or is dominated by single high-pt track.

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Intro to jets (III of III): Jet Finding

Anti-kt algorithm used in d+Au (hep-ph/0802.1189)

Successively recombine particles if they are close (inverse pt-weighted)

\[ d_{i,j} = \min\left( \frac{1}{p_{T_i}^2}, \frac{1}{p_{T_j}^2} \right) \Delta R_{ij}^2 / R^2 \]

Two values for R: 0.3, 0.5 → systematics and insight from using different areas, e.g. underlying event.
Goal 1:

- PHENIX results on how jets interact with the QGP
  - connect with LHC + STAR
1. Suppression, deflection of jets in A+A
2. Baseline of cold-nuclear matter effects, d+A

- Technical issues in backup-slides
  - Fake jet rejection
  - Influence of background high-pt tracks
  - Unfolding to obtain energy-scale
  - Efficiency, acceptance corrections
Jet Spectra in Cu+Cu

- Extends to 30 - 40 GeV/c (at pp reconstructed scale)
- Cu+Cu suppressed compared with p+p
  - Jet $R_{AA}$
Jet $R_{AA}$ in Cu+Cu

Jet $R_{AA}$ reaches 0.4~0.5
- Lost energy not within this tight jet area
- Extends $p_T$ reach of $\pi^0$ $R_{AA}$

$$R_{AA} = \frac{1}{\langle n_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- Run-5 Cu $+$ Cu at $\sqrt{s_{NN}} = 200$ GeV
- Gaussian filter $\sigma = 0.3$

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Transverse scattering? Back-to-back jets

- Expectation
  - Radiative + collisional energy-loss, builds up random walk
  - Expected to increase width of $\Delta \phi$ distribution

Angular distribution does not strongly depend on centrality
Similar behavior observed at LHC

- **ATLAS, jets lose energy**

\[
R_{CP} = \frac{< n_{coll} >_{periph}}{< n_{coll} >_{central}} \frac{N_{jet_{central}}}{N_{jet_{periph}}}
\]

\(R_{CP}\) decreases to 0.5
Little transverse broadening at LHC

- No large increased deflection due to energy-loss
- Increased transverse motion may not be observable for large $p_T$ jets
Common observable to compare results

PHENIX, STAR, CMS, ATLAS all report $\Delta \phi$ distributions
But widths depend on $p_T$ ranges of jets

\[ p_{out} = p_{T2} \sin(\Delta \phi) \]

Extract $k_T$ as rms of $p_{out}$ distribution

$k_T$ quantifies any transverse scattering of back-to-back partons

Pitch: 1) all experiments report $k_T$
        2) Plot $k_T$ vs $\sqrt{s}$, centrality

\[ < k_T^2 > = \frac{< p_T^2 >_{pair}}{2} \]
\[ < k_T^2 > = \frac{< p_{out}^2 >}{2} \]
\[ < k_T^2 > = < p_{out}^2 > \]
What happens to energy that is lost?

Away-side $\pi^0$-h correlations

$$I_{AA} = \frac{\int d\phi \frac{1}{N_{trig}} dN/d\phi[Au+Au]}{\int d\phi \frac{1}{N_{trig}} dN/d\phi[p+p]}$$

High-$p_T$ associate: $I_{AA} < 1$, far-side suppressed
Low-$p_T$ associate: $I_{AA} > 1$
→ additional low-$p_T$ hadrons, correlated in $\phi$ with initial hard-scatter


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Consistent picture with STAR

- **High $p_T$ assoc**
  - Au-Au away-side yield suppressed, width $\sim$same $\rightarrow$ little deflection

- **Low $p_T$ assoc**
  - Au-Au away-side higher, broader

- **RHIC consensus**
  - Energy that is lost $\rightarrow$ extra hadrons, well correlated with parton
LHC: where does energy loss go?

- high $p_T$: $<p_T^\parallel>$ less than 0 → fewer particles on far-side
- low $p_T$: $<p_T^\parallel>$ greater than 0 → more particles on far-side
  - inside and outside cone, but still correlated with far-side jet → broader
Cold Nuclear Matter effects: baseline d+Au

PHENIX Preliminary
\( d+Au \sqrt{s_{NN}} = 200 \text{ GeV} \)

- 60-88% \( R=0.5 \times 10^7 \)
- 40-60% \( R=0.5 \times 10^6 \)
- 20-40% \( R=0.5 \times 10^5 \)
- 0-20% \( R=0.5 \times 10^4 \)

anti-\( k_T \) jet yields

\( (1/N_{\text{evt}}) \frac{d^2N_{\text{jet}}^T}{d\eta dp_T} \)

- 60-88% \( R=0.3 \times 10^3 \)
- 40-60% \( R=0.3 \times 10^2 \)
- 20-40% \( R=0.3 \times 10 \)
- 0-20% \( R=0.3 \times 1 \)

\( p_T^{dA} \) (GeV/c)
Cold Nuclear Matter effects: baseline d+Au

- Both $\pi^0$ and jets suppressed ($R_{CP}$)
  - Energy-loss in CNM?
  - Initial-state effects?
- Calculations should reproduce this before use in A+A
Cold Nuclear Matter effects: baseline d+Au

\[ \langle k_T^2 \rangle = \langle p_{out}^2 \rangle \]

No indication of transverse broadening of di-jets
Goal 2:

Use other results to provide more detailed view

- Fragmentation
- Single – particle $R_{AA}$, $v_2$ at high-$p_T$
- ......
**γ-h: Golden probe of energy-loss**

- Di-jets can only ever measure relative energy-loss
- Direct γ provides the initial energy-scale

Statistical subtraction

*Run 7 Au+Au 200GeV 9-12 x 3-5 GeV/c*

*Isolation(p+p) PRD 82 072001*
\(\gamma - h \rightarrow \text{Fragmentation Functions}\)

\[\xi = -\ln\left(\frac{p_T^h \cos(\Delta \phi)}{p_T^\gamma}\right)\]

- Au+Au compared with p+p
- Smaller yield at high-z, low \(\xi\)
The ratio of fragmentation functions in p+p and Au+Au.

\[ \xi = -\ln\left( \frac{p_T^h \cos(\Delta \phi)}{p_T^\gamma} \right) \]

\[ \langle I_{AA} \rangle = 0.598 \pm 0.095 \]
$R_{AA}$ of single particles

- Jet energy-loss + fragmentation + medium response
  - Precise data, unambiguous observable
  - Constraint on models
Particle species: $R_{AA}$

- Multiple insights, tests of models
Energy-loss of heavy-flavor quarks

- Heavy quarks lose energy at comparable amounts as light-quarks
- Strongly couple to QGP: how, why?
- Challenge for e-loss models to describe HF $R_{AA}$ and $v_2$

arXiv:1005.1627
Elliptic flow of \( \pi^0 \) at high-\( pt \):

- Path-length dependence of E-loss, talk by Paul Sta

- \( \Delta E \sim (\text{path length})^3 \) favored

- Need \( v_2 \) of jets

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Further control of path-length

- Di-hadron yields \( \text{(Au+Au) / (p+p)} \)
  - relative angle between trigger particle and reaction plane, \( \phi_s = \phi_{\text{trig}} - \phi_{\text{rp}} \)

- Factor of 4 stronger suppression in yield, trigger is out-of-plane
  - Due to longer average path-length

\[ \text{arXiv:1010.1521} \]
Goal 3: Critical next measurements

- Change coupling
  - Separate measurements of charm and beauty (Mike Leitch Tue talk)
    - VTX upgrade in place and taking data
  - Vary $Q^2$ of hard-scattering
    - Are quarks strongly coupled to the QGP at all scales?
    - Are there quasiparticles at any scale?
    - Change medium ← excitation function (Jeff Mitchell talk)
  - RHIC sweet spot 10-50 GeV/c jets
  - sPHENIX

- Jet measurements: pp, dA, AA
  - $<k_T^2>$ as well as E-loss
  - $v_2$ of jets

- Increase precision of $\gamma$-h measurements → fundamental
Conclusions

- Energy-loss of high-\(p_T\) parton leads to suppression of jets
  - Lost energy produces extra hadrons
  - At both RHIC and LHC, these hadrons still correlated with jet
- Back-to-back angular distributions of jets are not strongly modified
  - \(<k_T^2>\) can quantify this and enable comparisons across \(\sqrt{s}\)
- \(\gamma\)-h results in Au+Au: reduction in high-z fragmentation
- Path-length dependence of energy-loss, consistent with \(L^3\)
- Use broad range of observables to
  - Obtain maximum insight into energy-loss mechanisms and properties of QGP