

QCD Rencontres de Moriond
Session



Jet Energy Loss at RHIC

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for the PHENIX Collaboration



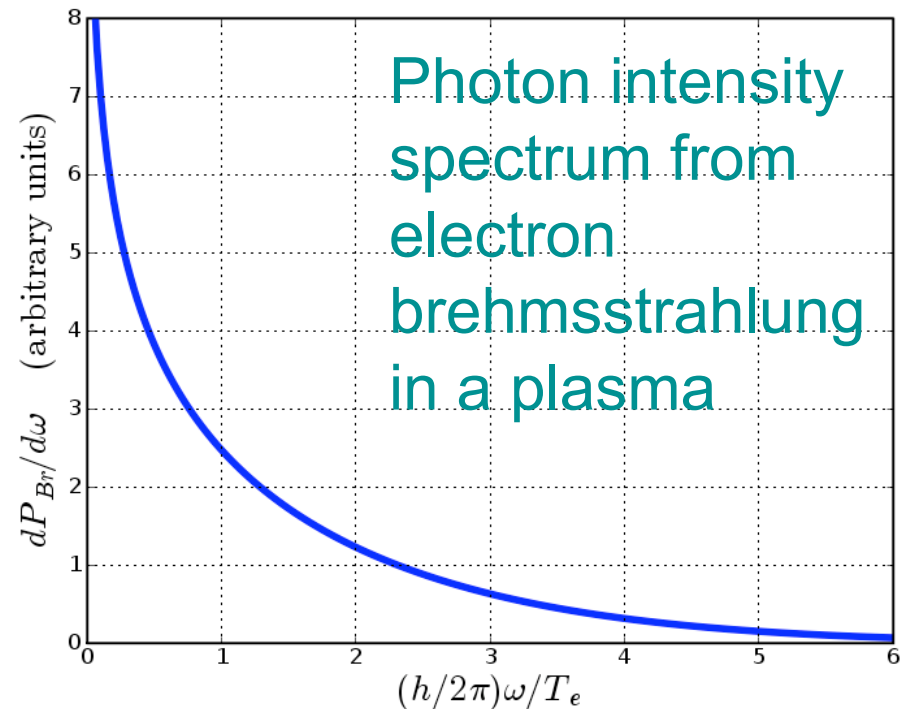
Fundamental Question in QED

- An early study in QED: charged particles losing energy in matter

Bethe Formula

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right) \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

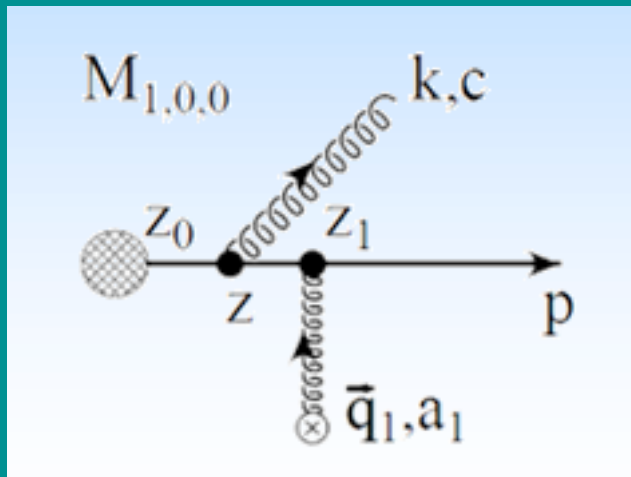
dE/dx independent of x



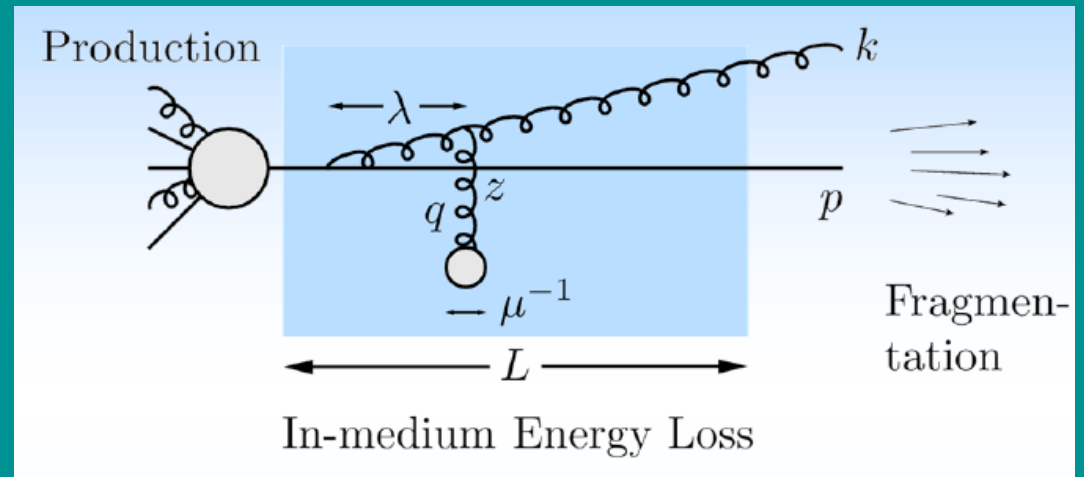
Fundamental Question in QCD

- Study the passage of a color-charged parton passing through a colored medium.
- Important difference: QCD is non-Abelian
 - $dE/dx \sim x$

Same diagram as QED

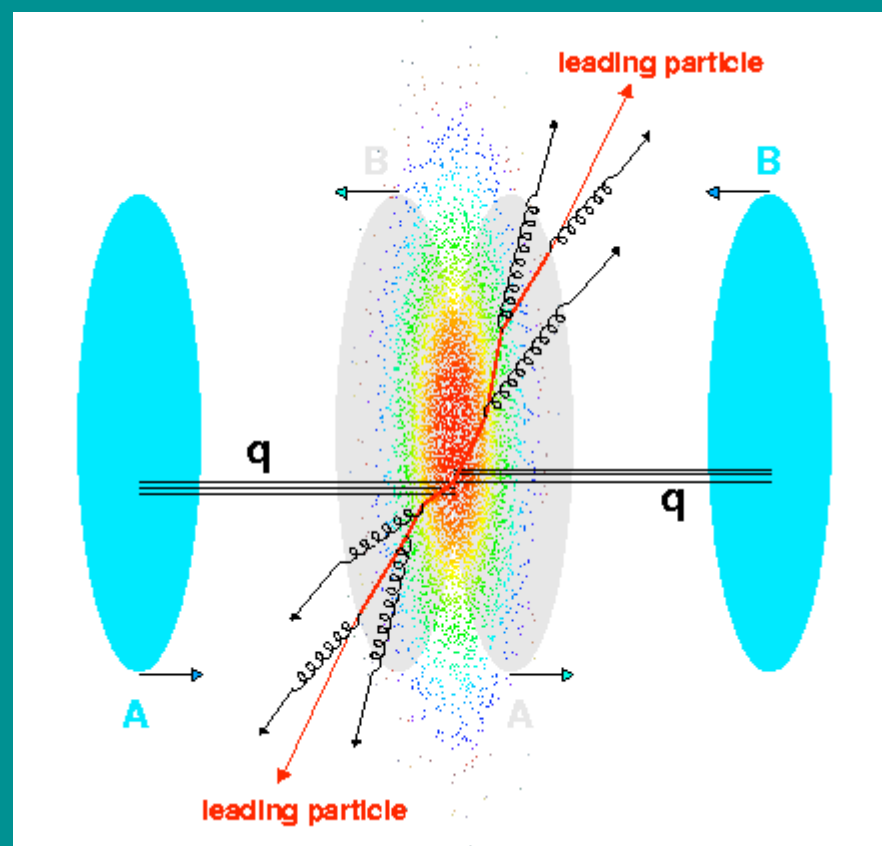


+ Additional diagram



Jets and Heavy Ion Collisions

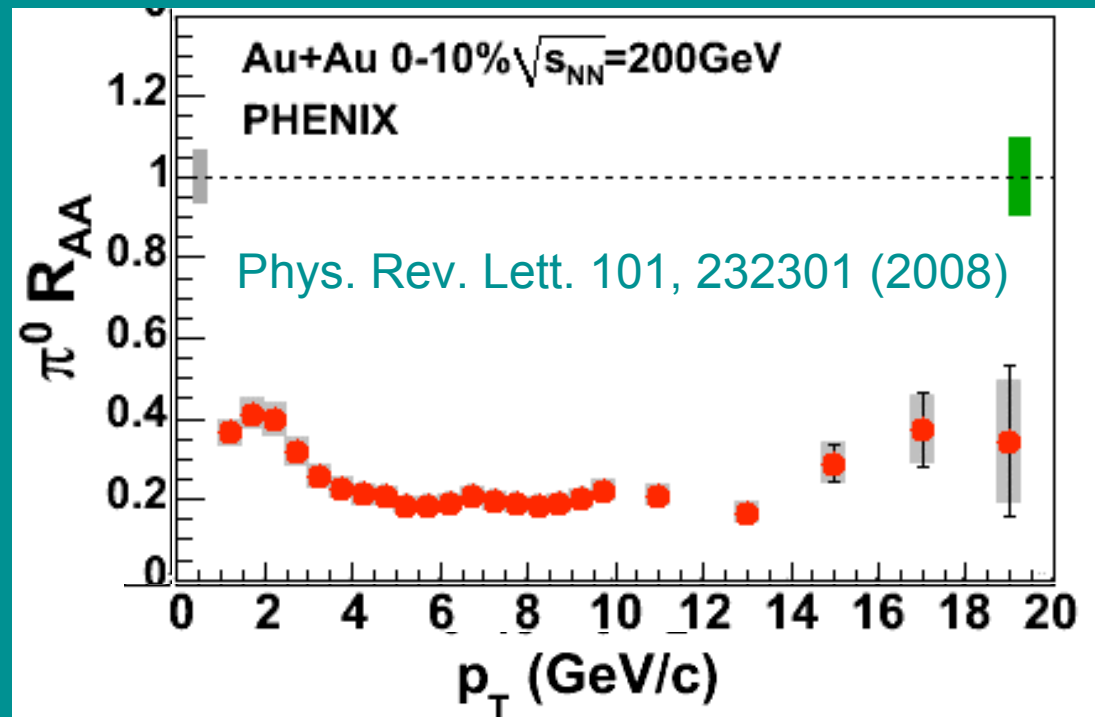
- Need a colored medium
 - Create a quark-gluon plasma
- Need a colored probe
 - Use partons that fragment to jets



Measuring Energy Loss: Singles

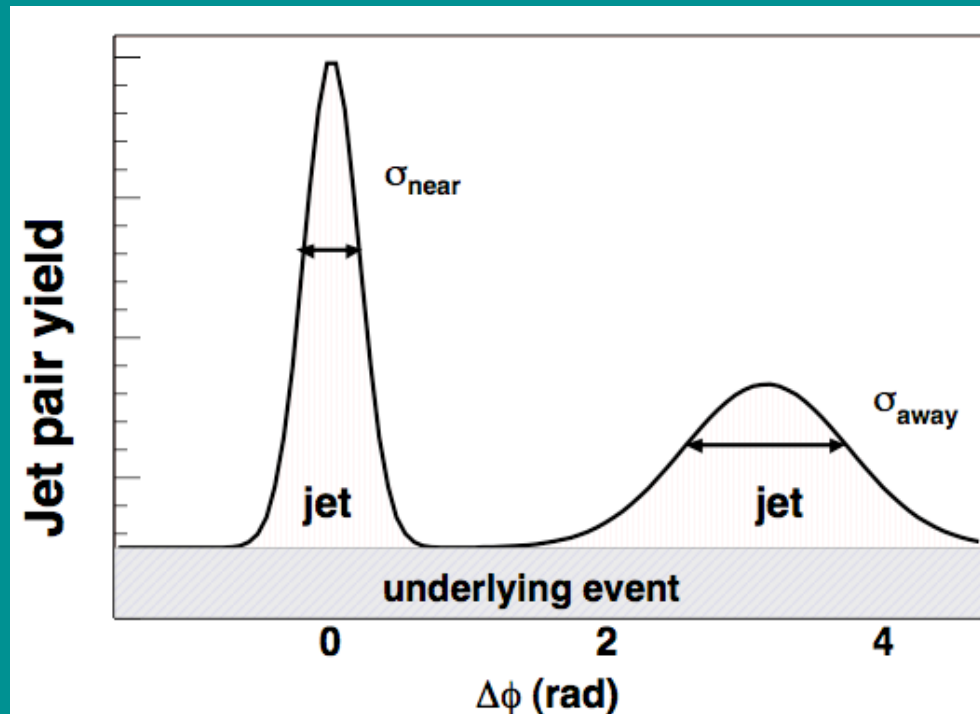
- First measurement: single high- p_T particle spectra
 - Leading fragments of a jet
- Quantify the difference between p+p and A+A with R_{AA}
 - How the rate scales with the number of binary collision
- $R_{AA} \sim 0.2$ in most central (head on) Au+Au collisions.

$$R_{AA} = \frac{1/N_{evt} dN^{AA \rightarrow \pi^0 X} / dp_T}{\langle N_{bin} \rangle 1/N_{evt} dN^{pp \rightarrow \pi^0 X} / dp_T}$$



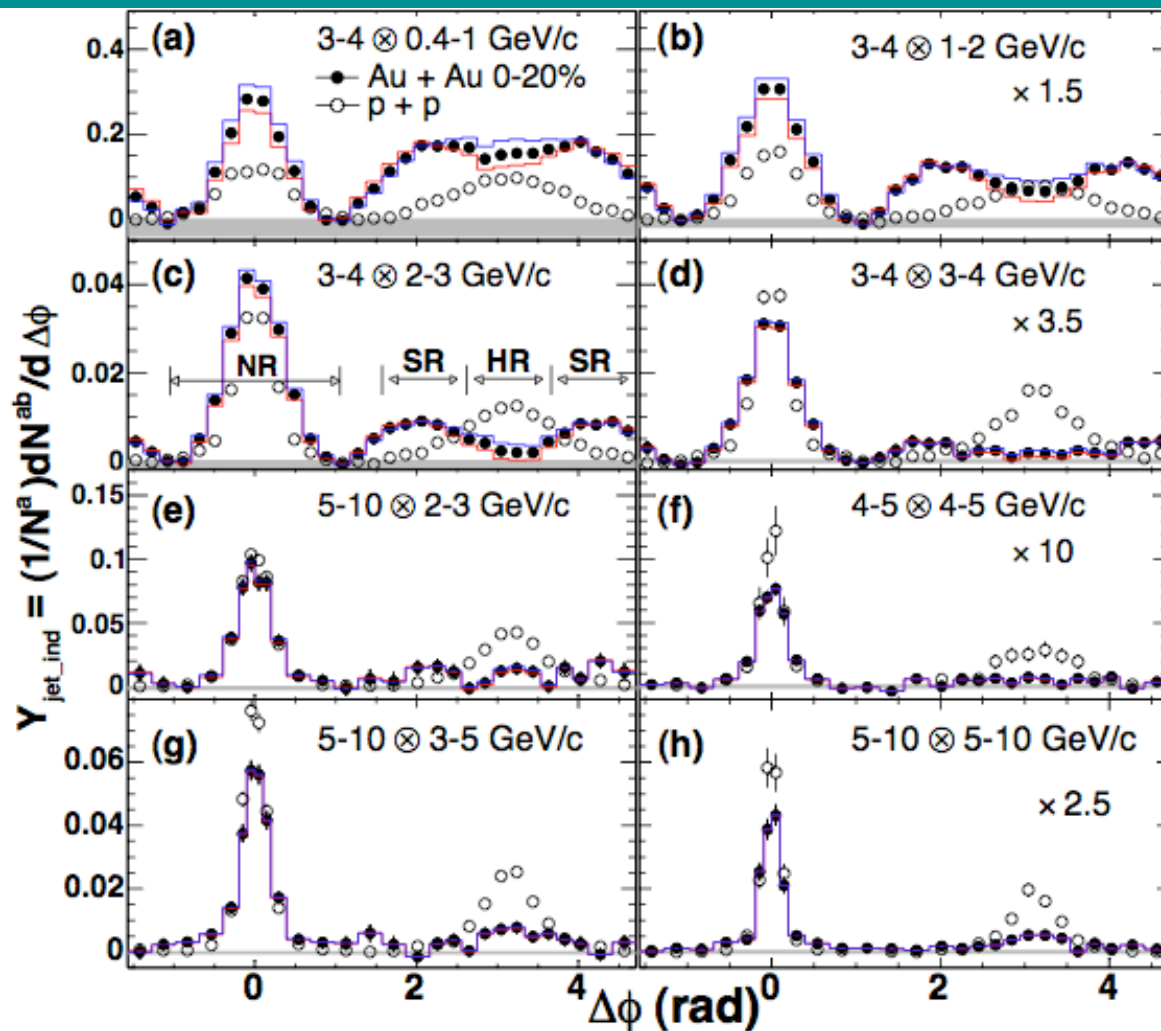
Two-Particle Correlations

- Statistically average pair rates over many events
- Pairs of particles near $\Delta\phi \sim 0$ fragment from a single jet
- Pairs of particles near $\Delta\phi \sim \pi$ fragments from opposing jets



Cartoon for azimuthal correlations from jets and di-jets

Measuring Energy Loss: Pairs



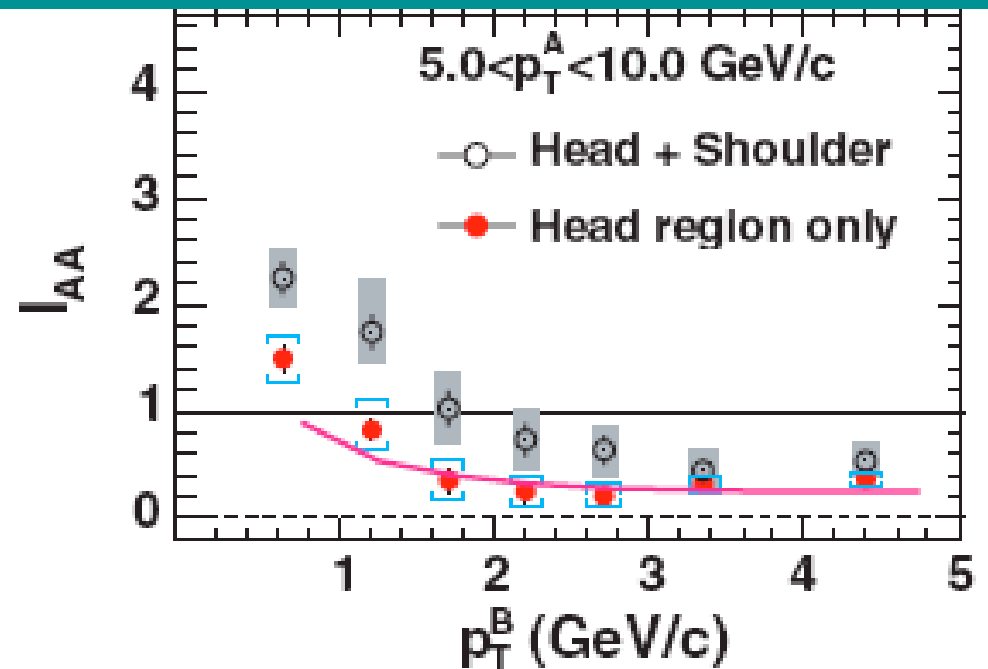
- Open points: p+p
- Closed points: Au+Au
- Shapes are jet-like in p+p
- In Au+Au
 - Shape modification at low p_T
 - Yield reduction at high- p_T

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Measuring Energy Loss: Pairs

- Look at hadron pairs with $\Delta\phi \sim \pi$, i.e. di-jet fragments
- Pair-per-trigger yield suppressed in Au+Au relative to p+p
- Jets that travel through the medium lose energy.

$$I_{AA} = \frac{1/N^{AuAu \rightarrow AX} dN^{AuAu \rightarrow ABX} / dp_T}{1/N^{pp \rightarrow AX} dN^{pp \rightarrow ABX} / dp_T}$$



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Open Questions

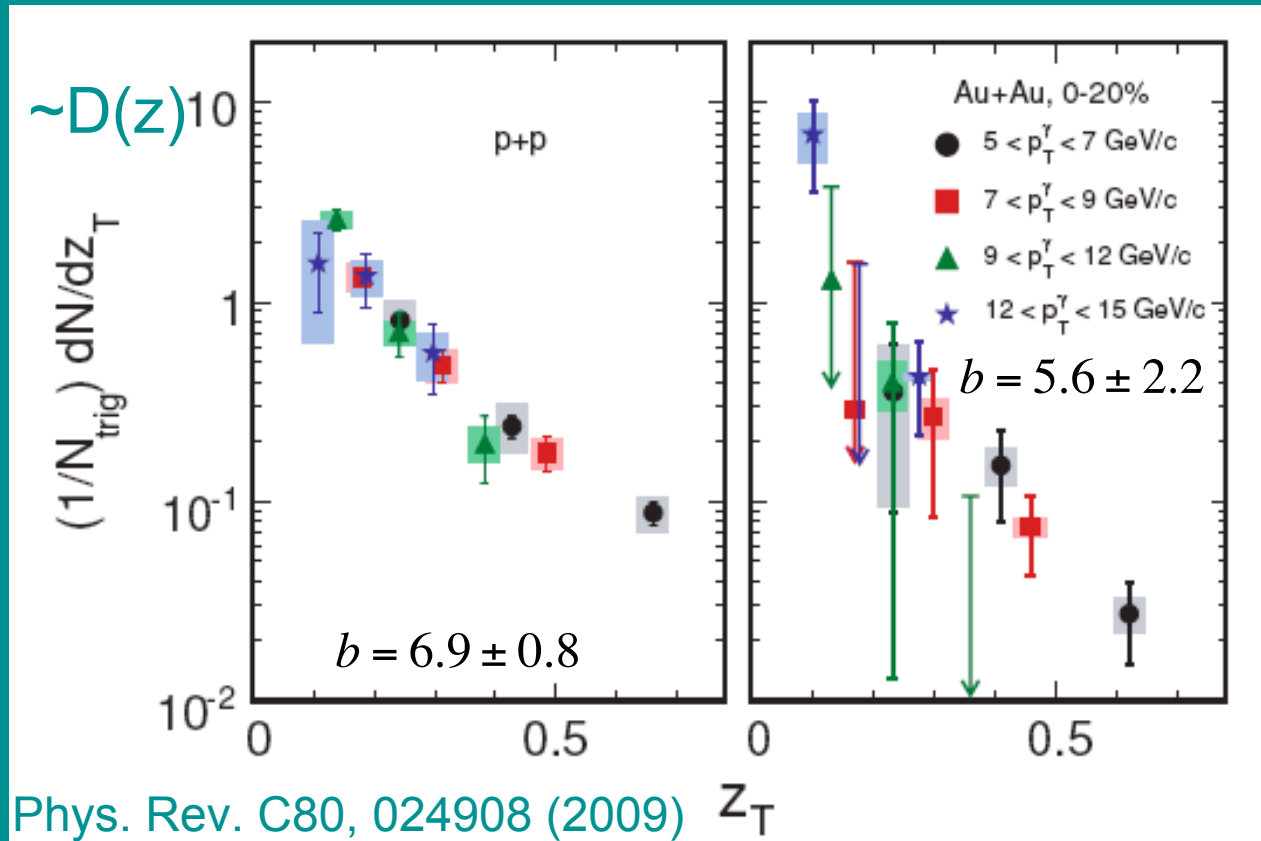
- There are still fundamental, quantitative open questions
- Data on jets from singles and pairs are integrated over path length, jet energy, etc.
- $dE/dx \sim x^n$
 - $n=1$, weak jet-medium coupling (perturbative)
 - $n>1$, strong jet-medium coupling (AdS/CFT)
- What is the angular distribution of gluon radiation?

Fixing the Jet Energy: Direct γ

- Direct γ -hadron correlations
- At LO $E_{\text{jet}} = E_{\gamma}$
- Look at hadrons at $\Delta\phi \sim \pi$ from γ
- Evidence $D(z)$ softer in Au+Au

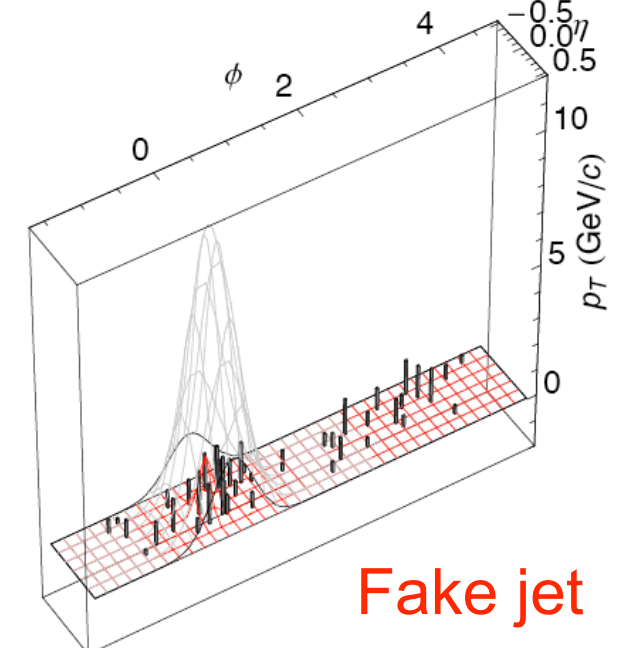
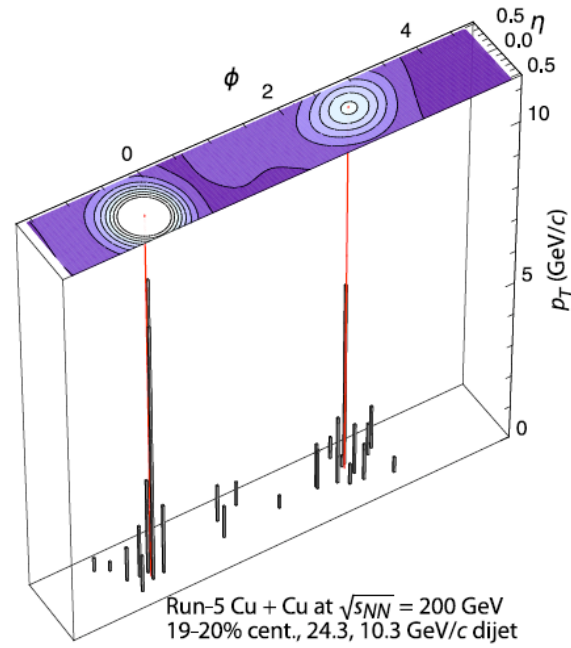
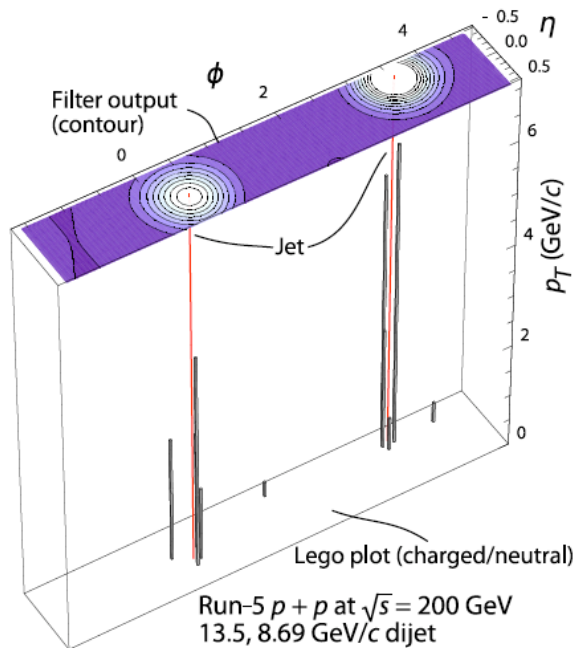
$$z_T = p_T^h / p_T^{\gamma} \approx z$$

$$D(z) \sim e^{-bz}$$



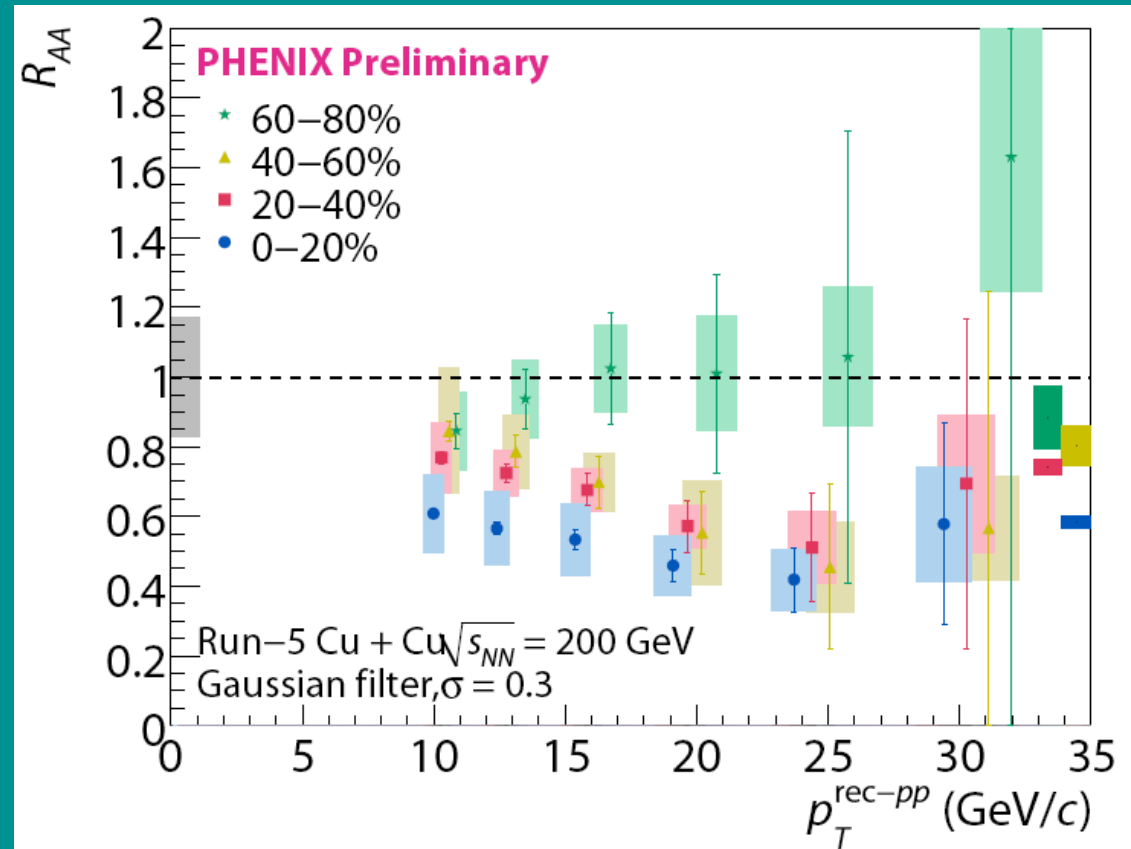
Fixing the Jet Energy: Jets

- Gaussian Filter algorithm (arXiv:0806.1499[nucl-ex])
 - Generalized seedless cone algorithm where Gaussian weighting applied to particles within the cone.
- Reconstruct jets with photons and charged tracks.



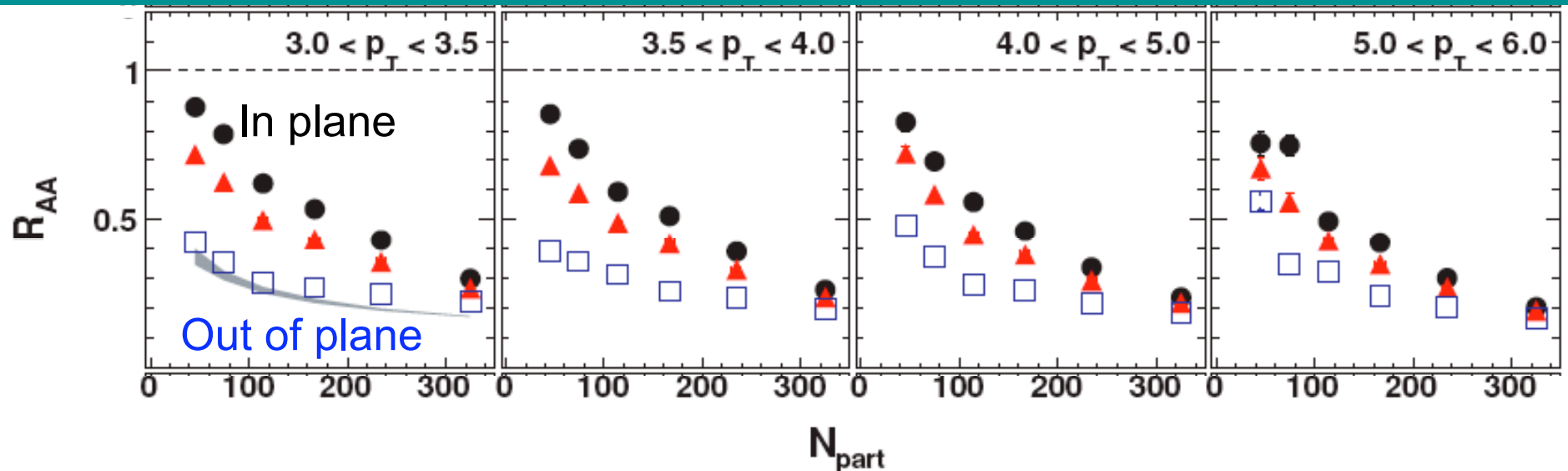
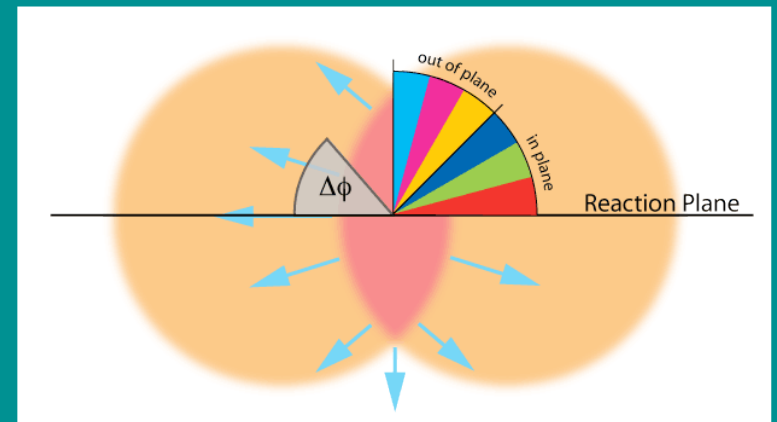
Fixing the Jet Energy: Jets

- Fake jet rejection removes very broad (possibly modified?) jets
- $R_{AA} \sim 0.5$ related to the fraction of jets that look p+p-like
- In the future relax the fake jet rejection cut to study jet modification.



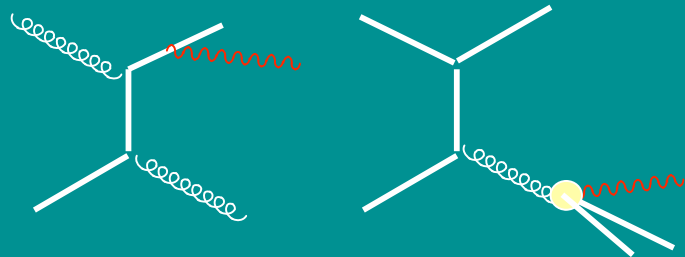
Accessing Path Length: R_{AA} vs Φ_{RP}

- Less energy loss when particle is emitted along the reaction plane

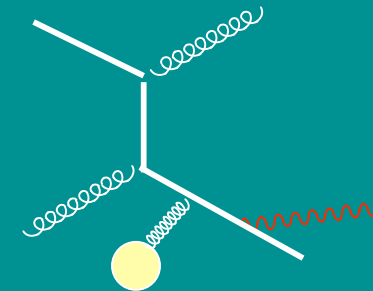


Accessing Gluon Spectrum

Next to leading order (NLO) - photon radiation and photon fragmentation:

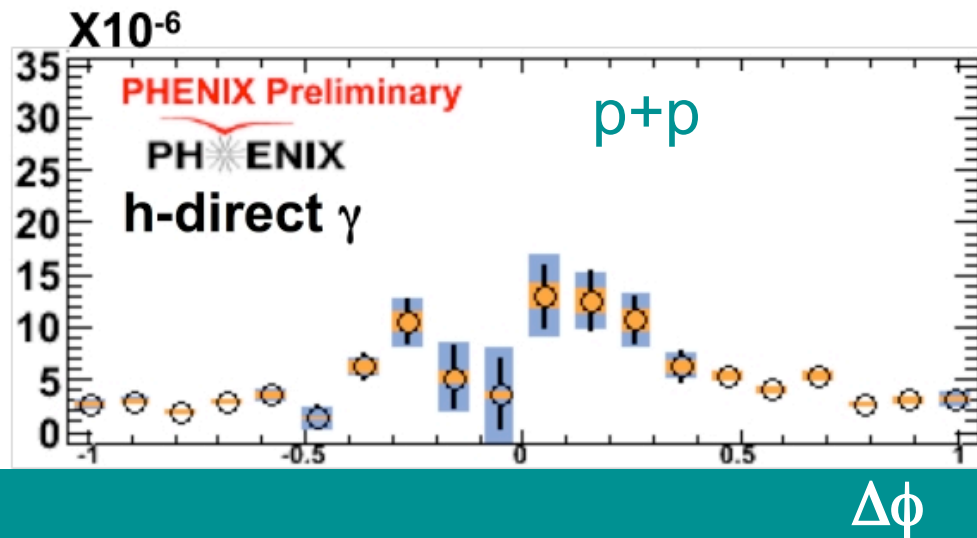


Medium induced modifications:



medium

- Occurs at NLO - modifies the fragmentation component of direct photon spectrum only
- Direct measure of the radiation spectrum!



Evidence of fragmentation photons in p+p

Energy Loss at the LHC

- At the LHC, the increase in center-of-mass energy over RHIC will produce a different medium.
 - It will be hotter.
 - It will be longer lived.
 - Net time the parton spends in the colored medium is longer.
- Comparison of RHIC and LHC will yield valuable insights about fundamental problems in QCD.

Summary

- Energy loss of a color-charged parton traversing a colored medium has been measured.
- There are still questions that we need to understand and precision measurements that we can begin to make in the future.
- The advent of the LHC heavy ion program will offer the opportunity to study energy loss in a different medium.

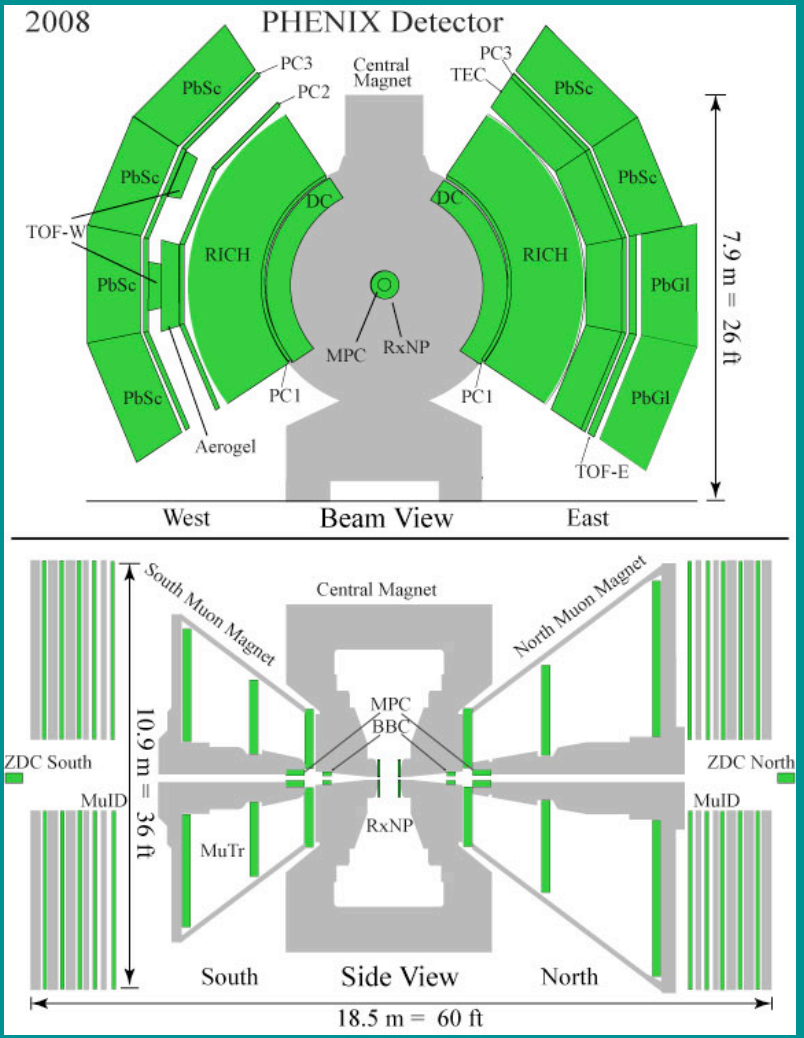
Backup

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Rencontres de Moriond

Jet Energy Loss at RHIC
 16-03-2010

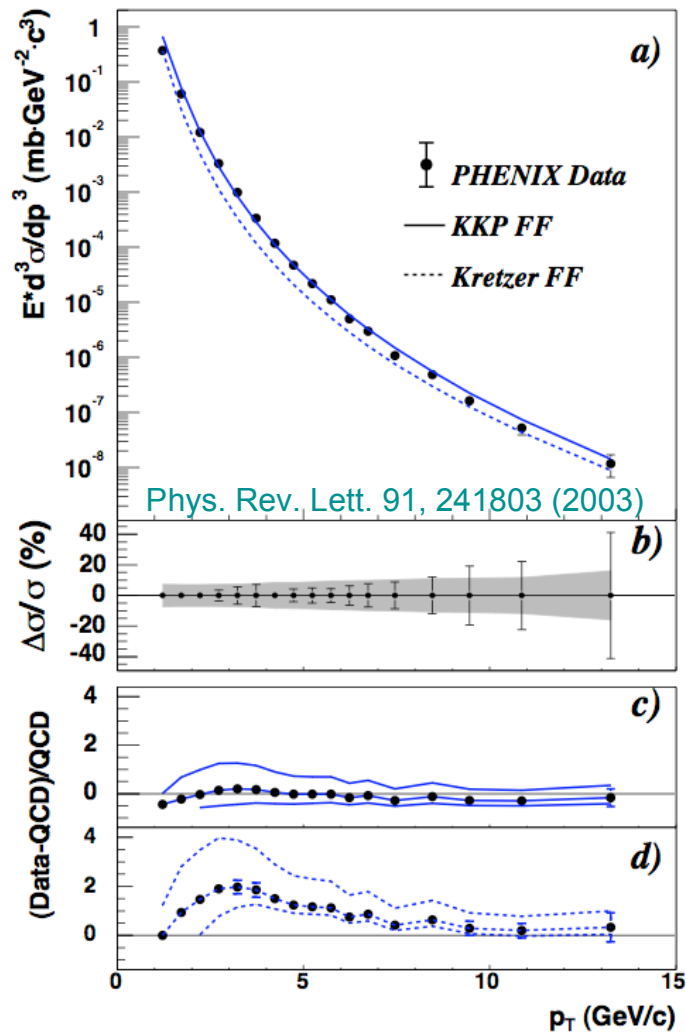


Initial Theoretical Analysis

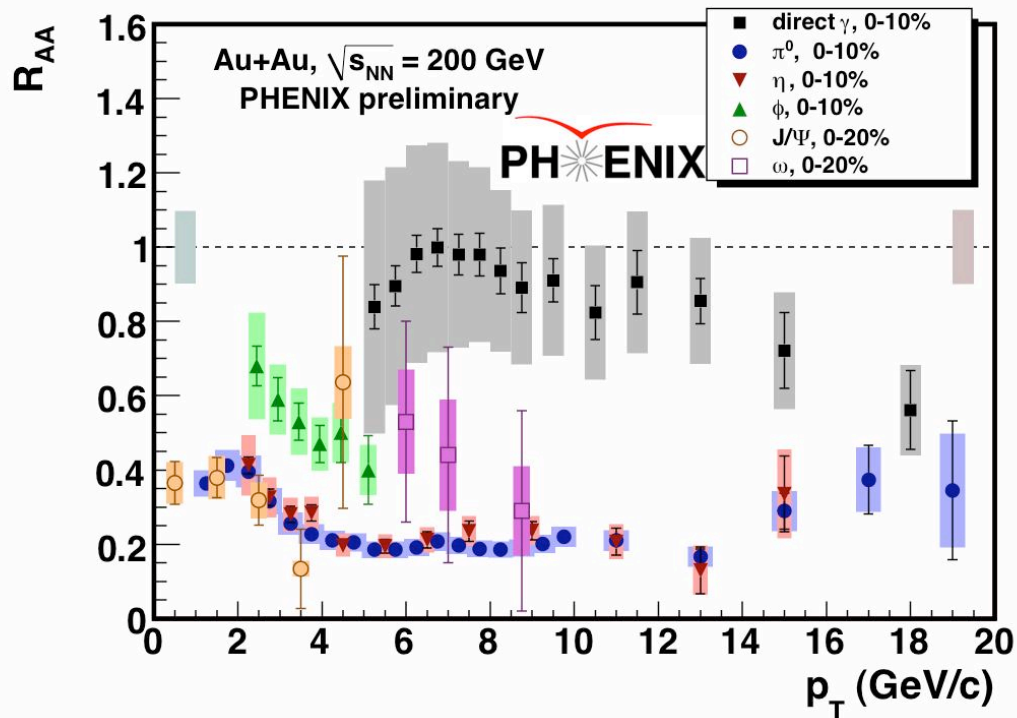
- BDMPS
 - Modeled the medium as static sources of color
 - $dE/dx \sim L$
 - Radiated gluons dI/dw
 - k_T broadening from multiple scattering
- q -hat related to the coupling to the medium
- $D(z)$ modification

pQCD description of singles

- Single particle production in p+p well described by pQCD.

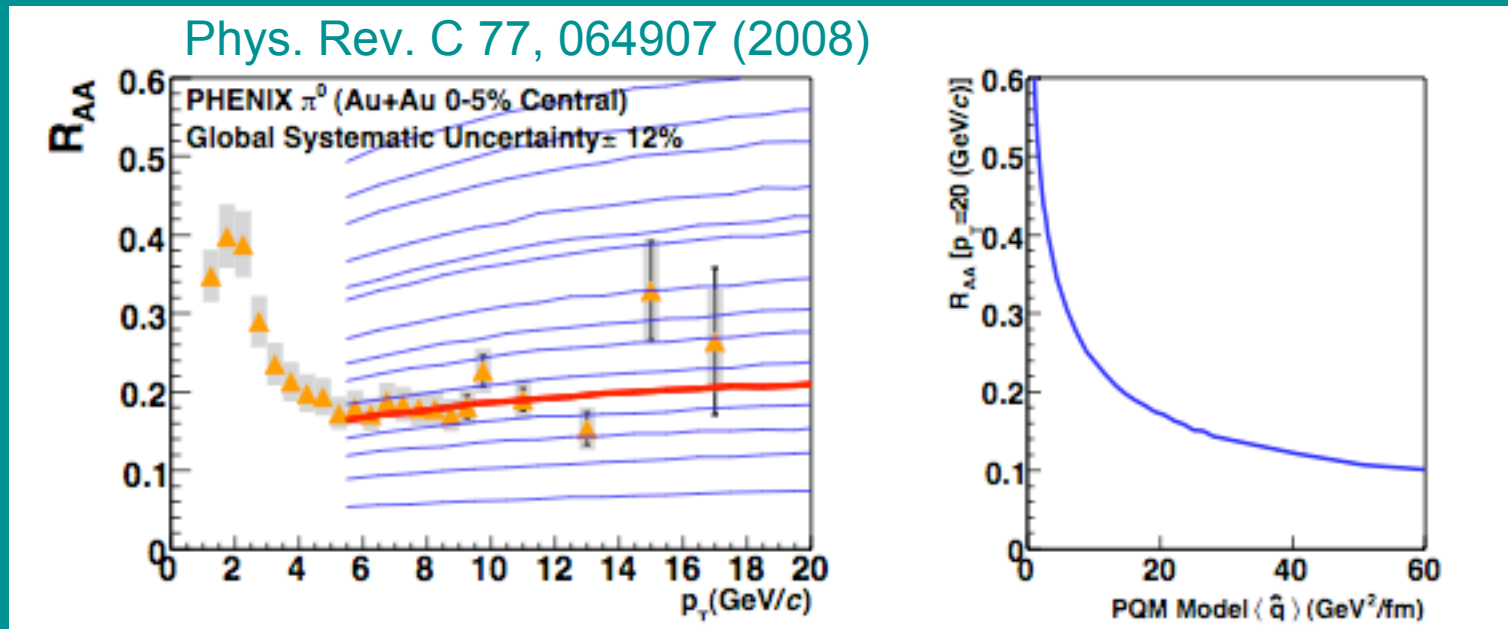


Photon R_{AA}



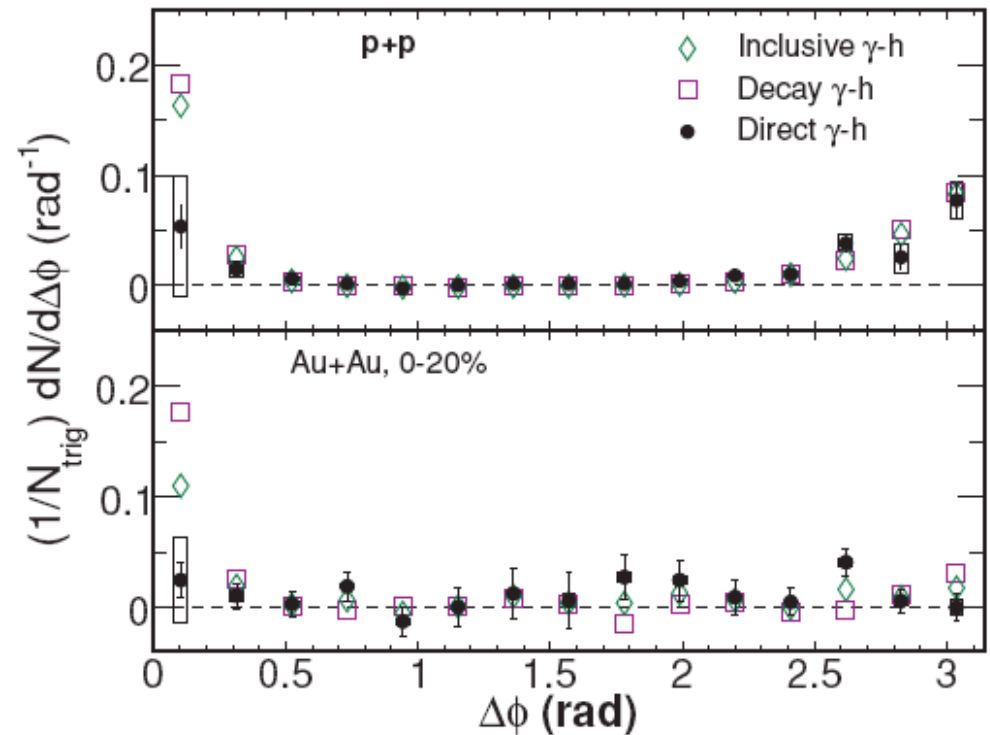
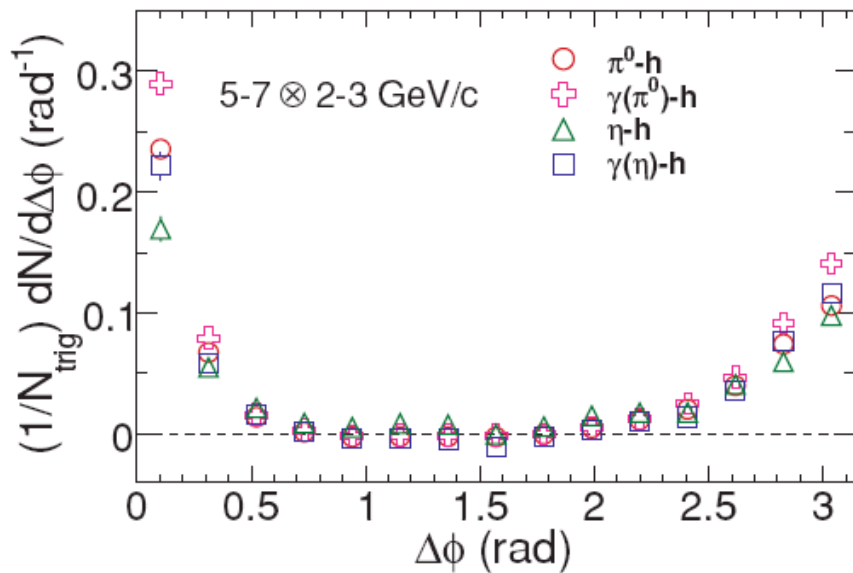
- All hadron species are suppressed
- Photon $R_{AA} < 1$ above ~ 13 GeV
 - Possibly due to isospin effects.

Quantitative Analysis



- Data is good enough to constrain a given model parameter to within $\sim 25\%$: $\langle \hat{q} \rangle = 13.2^{+2.1}_{-3.2} \text{ GeV}/\text{fm}^2$
- But there are large uncertainties between the models!

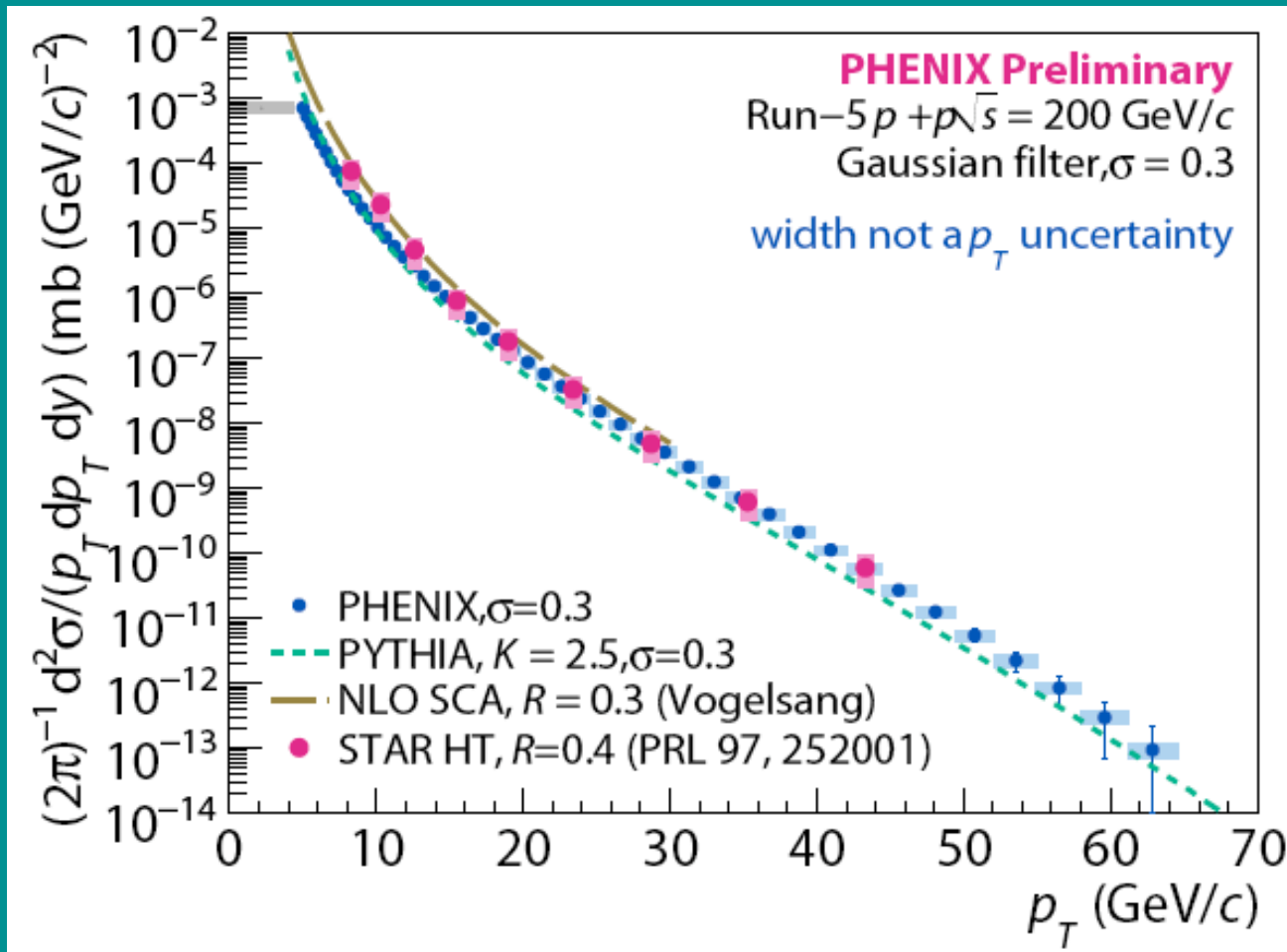
Direct Photon Correlations



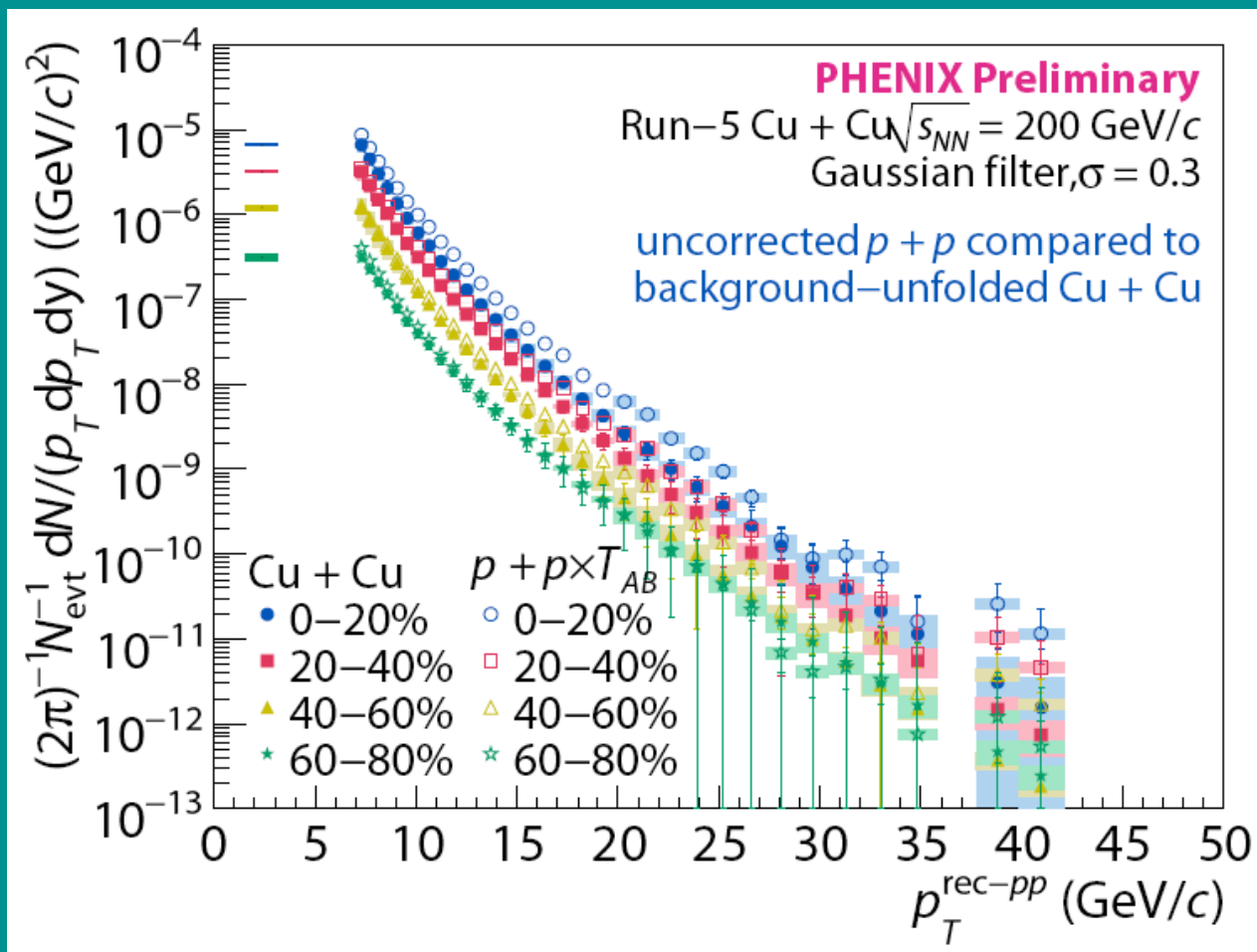
- Obtain decay-photon-triggered correlators by tagging photons from π^0 (and η in p+p)

- Statistically measure direct photon-triggered correlations.

Jet Spectrum in p+p

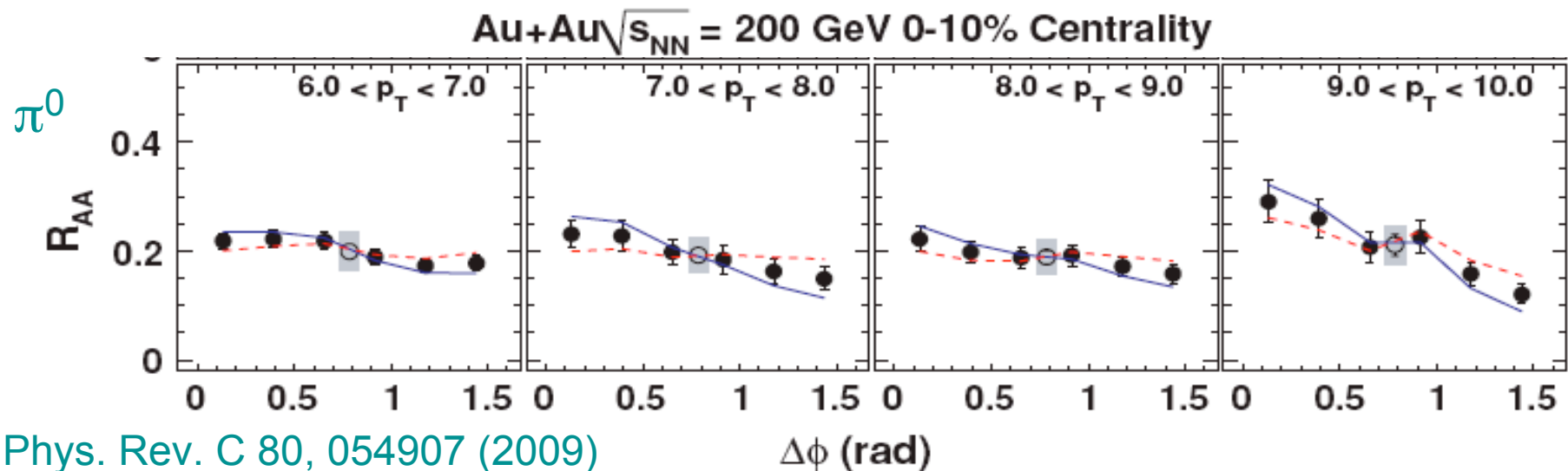
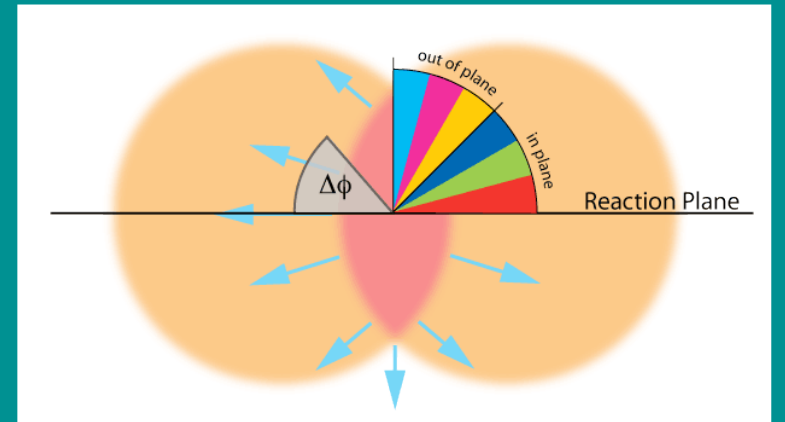


Jet Spectrum in Cu+Cu



Accessing Path Length: R_{AA} vs Φ_{RP}

- Less energy loss when particle is emitted along the reaction plane



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