Jets, high-pt results from PHENIX

Craig Ogilvie, on behalf of the PHENIX Collaboration
Iowa State University

Goals of talk

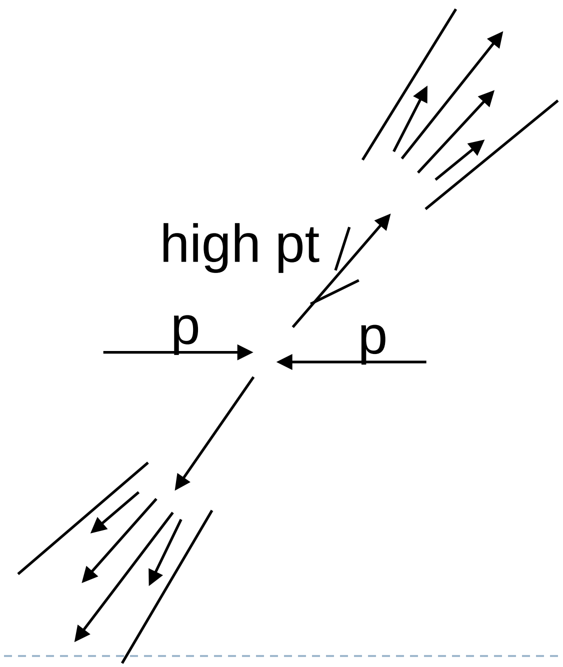
1. PHENIX results on how jets interact with the QGP
    a. Connect with LHC + STAR
2. Use other PHENIX results to provide more detailed view
    a. Fragmentation functions, R_{AA}, v_2, …
3. Critical next measurements

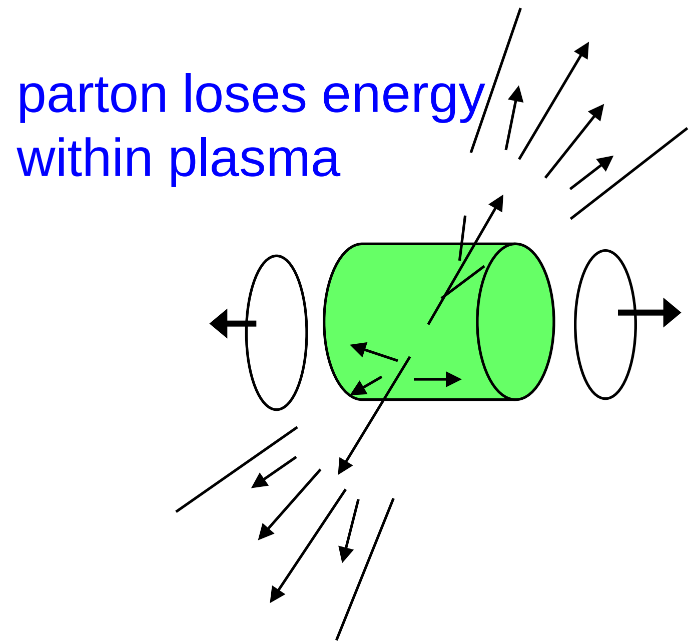
Intro to jets (I of III): in-situ probe

hard-scattered parton p+p:
baseline measurements

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

jet of hadrons



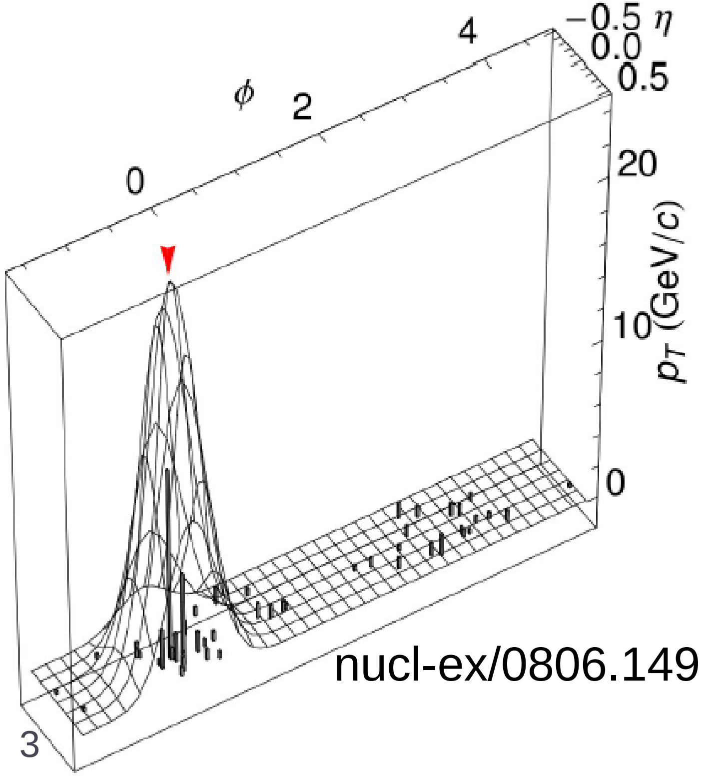


Intro to jets (II of III): Jet Finding

Jet is a weighted combination of measured momenta.

Gaussian filter used in Cu+Cu

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



nucl-ex/0806.1499

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.

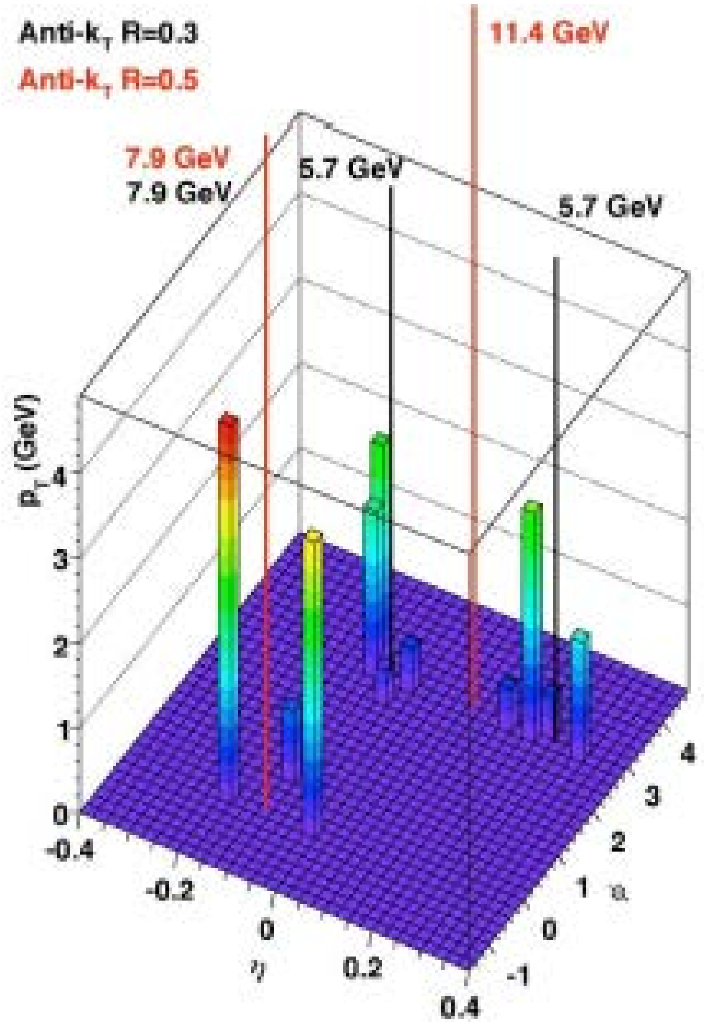
Intro to jets (III of III): Jet Finding

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

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

$$d_{i,j} = \min\left(\frac{1}{p_{Ti}{}^2}, \frac{1}{p_{Tj}{}^2}\right)\Delta R_{ij}{}^2/R^2$$

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



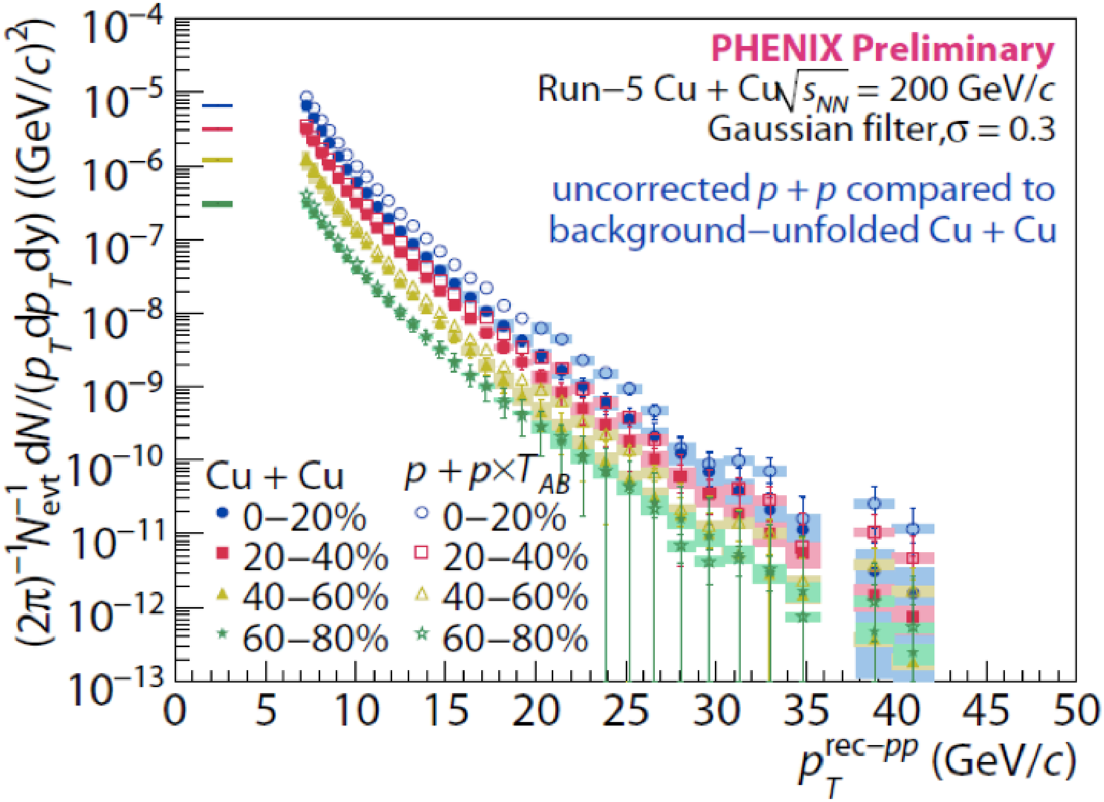
Goal 1:

- 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

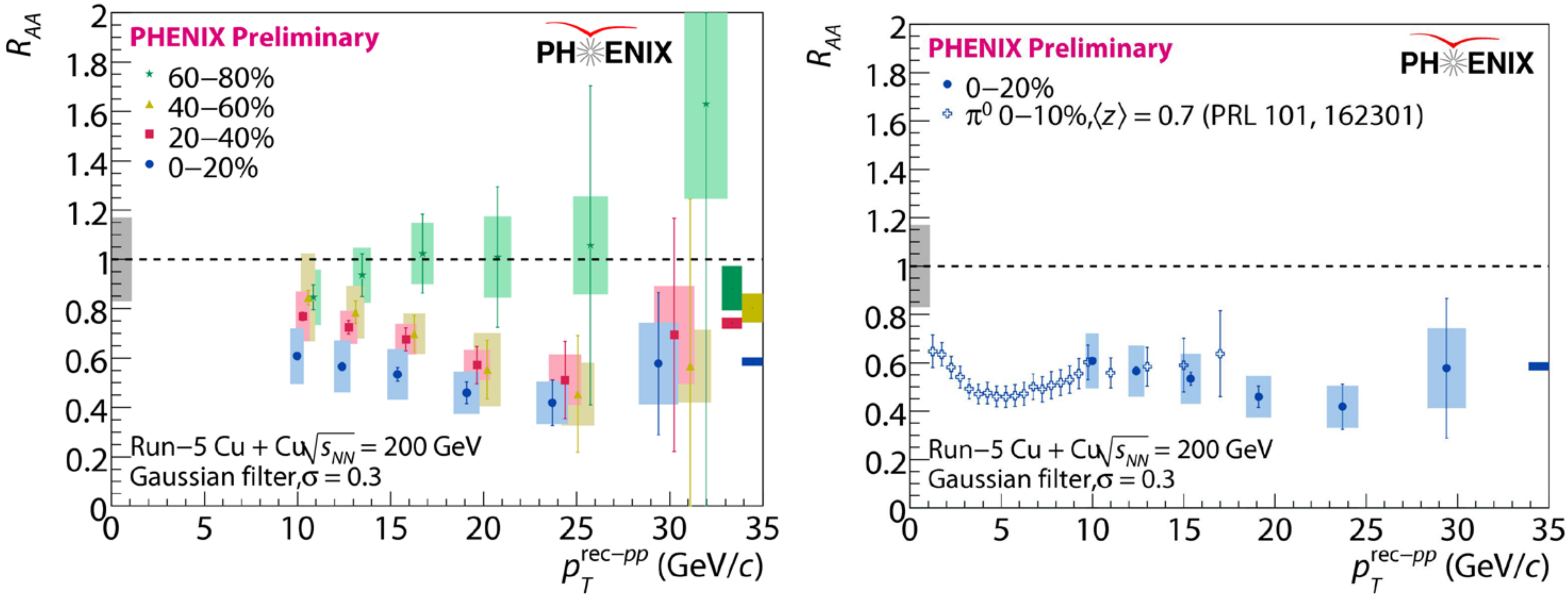
Jet Spectra in Cu+Cu



- 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

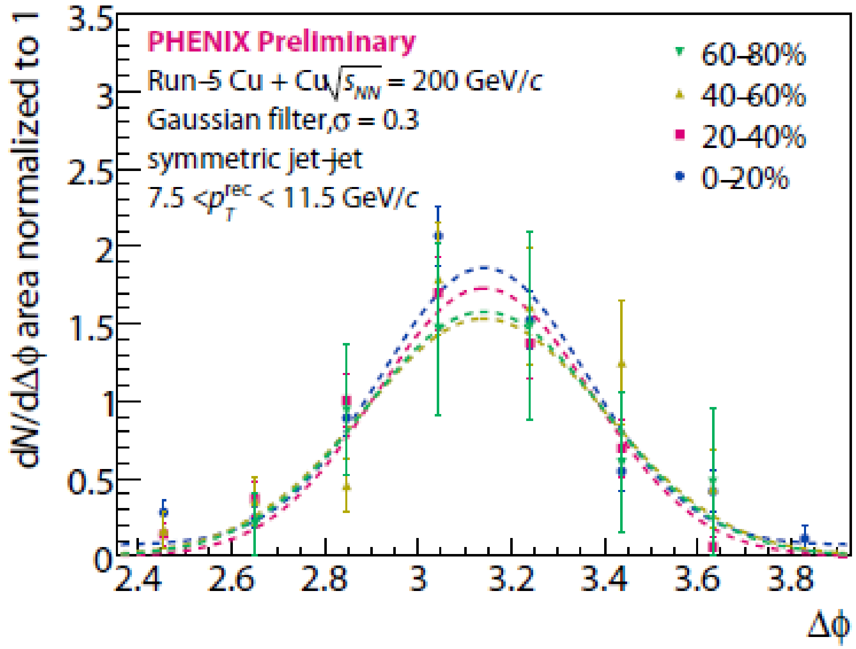
$$R_{AA} = \frac{1}{< ncoll >} \frac{dN_{AA}/dpT}{dN_{pp}/dpT}$$



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

Transverse scattering? Back-to-back jets

- Expectation
  - Radiative + collisional energy-loss, builds up random walk
  - Expected to increase width of Δϕ distribution



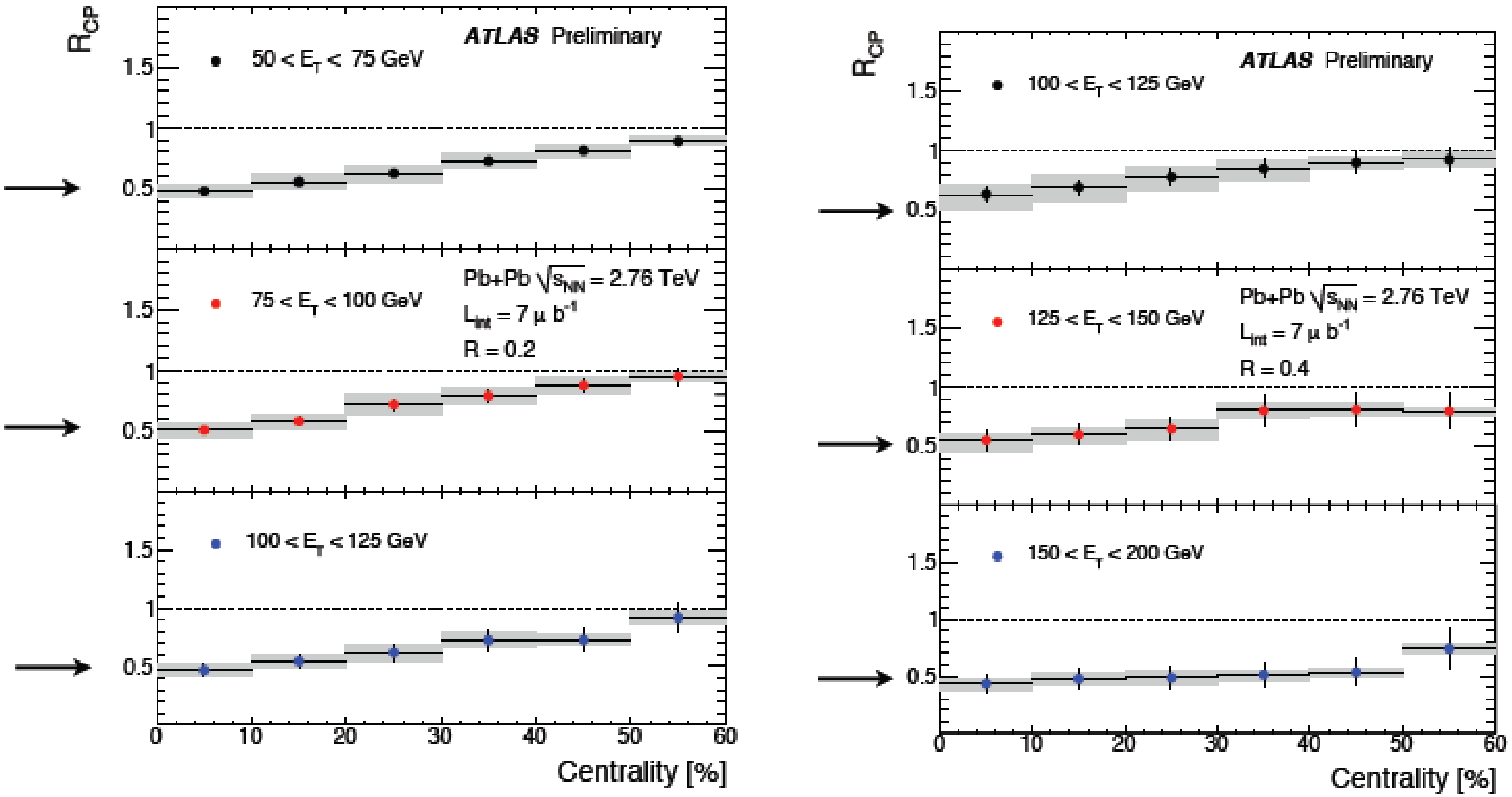
Centrality	$\Delta\varphi \approx \pi$ width σ
0–20%	0.223 ± 0.017
20–40%	0.231 ± 0.016
40–60%	0.260 ± 0.059
60–80%	0.253 ± 0.055

- Angular distribution does not strongly depend on centrality

Similar behavior observed at LHC

- ATLAS, jets lose energy

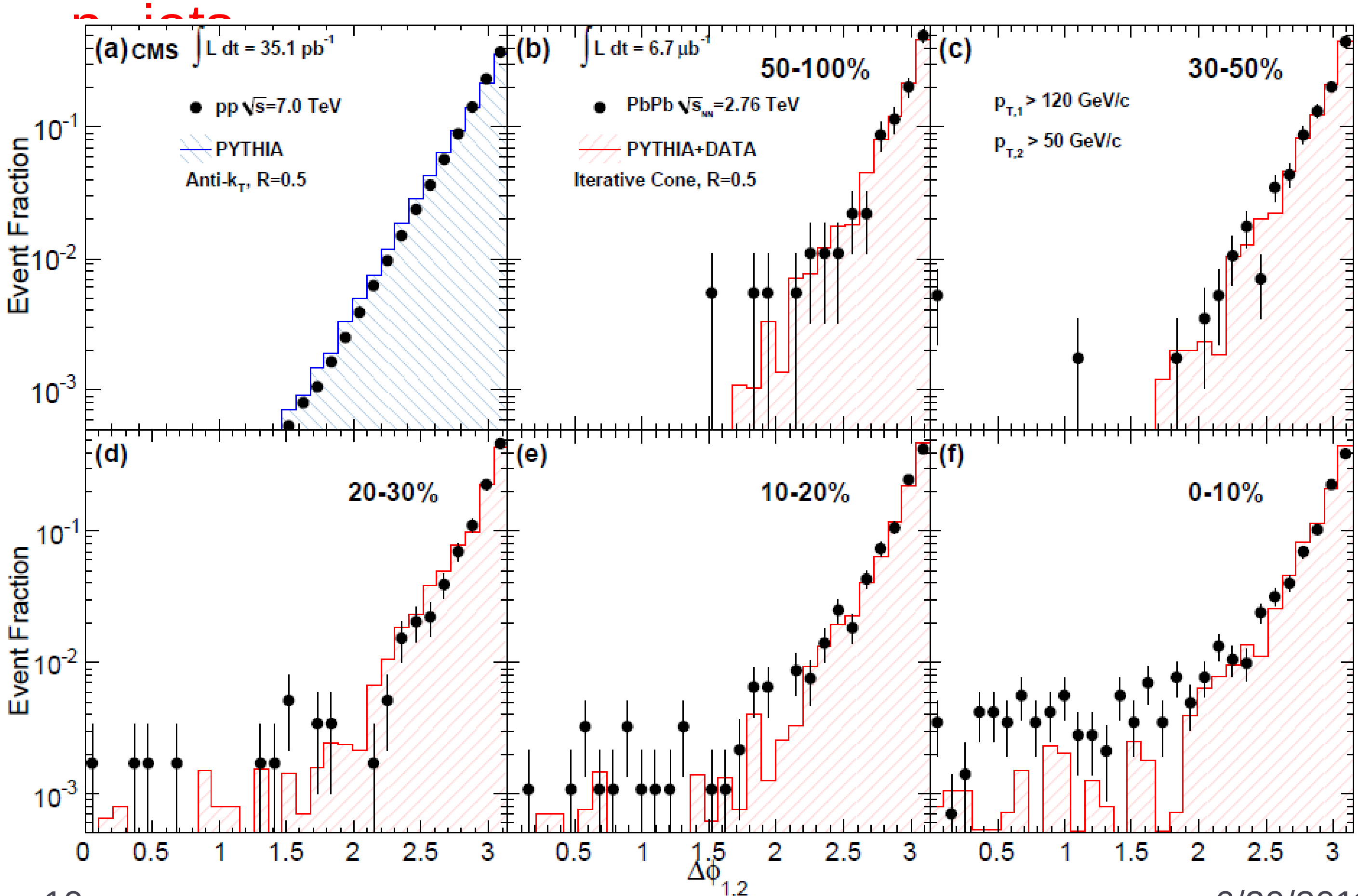
$$R_{CP} = \frac{<ncoll>_{periph}}{<ncoll>_{central}} \frac{Njet_{central}}{Njet_{periph}}$$

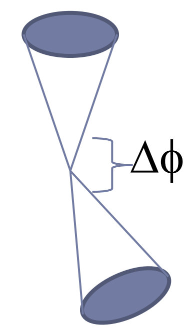


R_{CP} decreases to 0.5

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



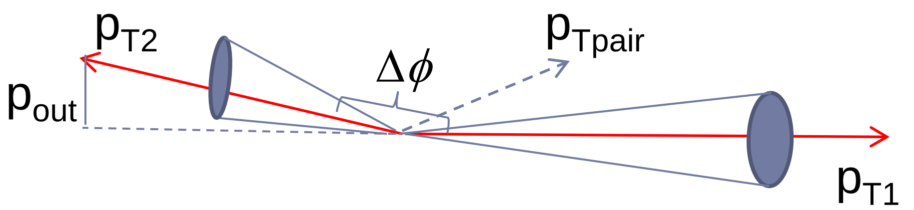


Common observable to compare results

PHENIX, STAR, CMS, ATLAS all report $\Delta\phi$ distributions

But widths depend on p_T ranges of jets

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



$$p_{out} = p_{T\,pair\,y} \qquad < k_T{}^2 > = \frac{< p_T{}^2 >_{pair}}{2}$$

$$< k_{T\,y}{}^2 > = \frac{< p_{out}{}^2 >}{2}$$

$$< k_T{}^2 > = < p_{out}{}^2 >$$

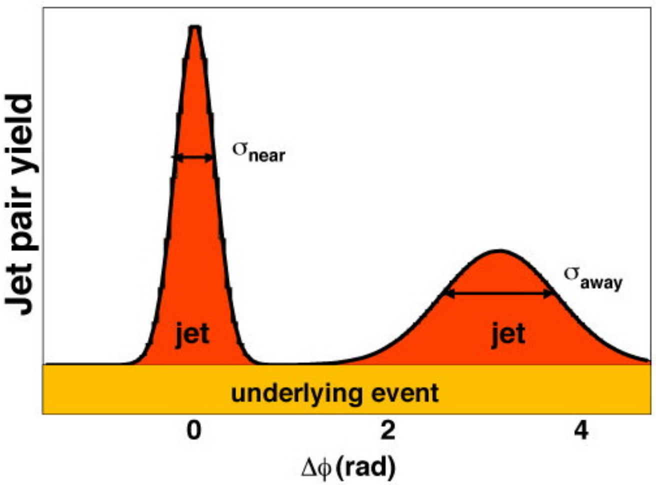
Extract k_T as rms of p_{out} distribution

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

Pitch: 1) all experiments report k_T

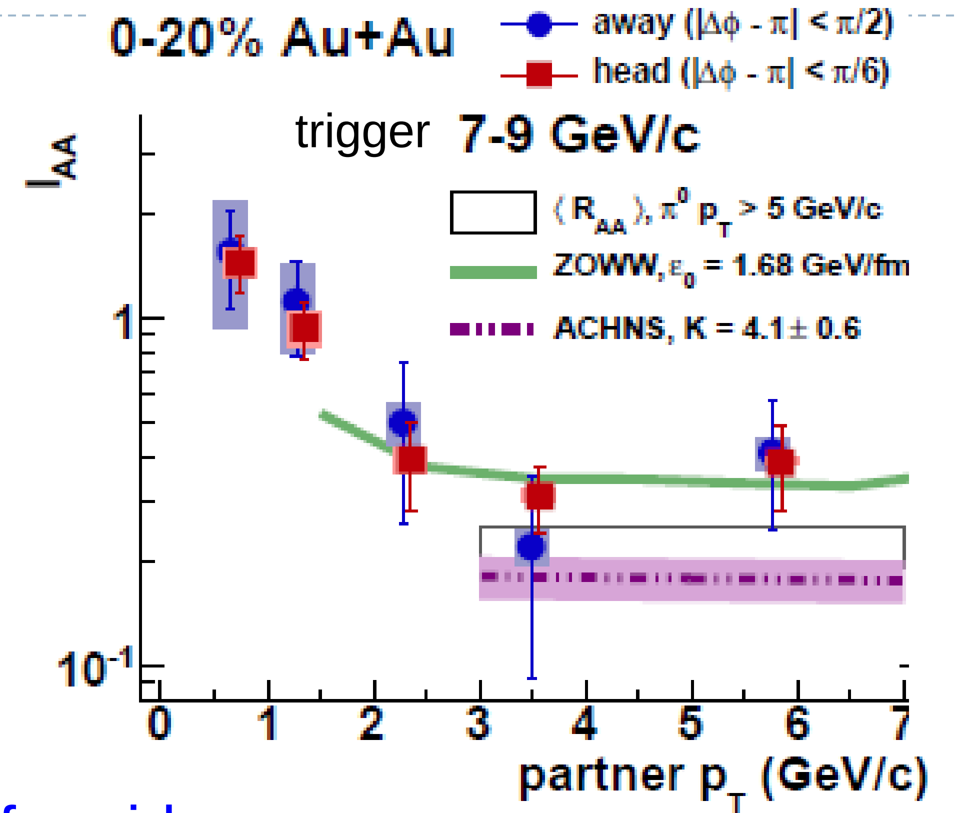
2) Plot k_T vs $\sqrt{s}$, centrality

What happens to energy that is lost?



Away-side π^0-h correlations

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



High-p_T associate: $I_{AA} < 1$, far-side suppressed

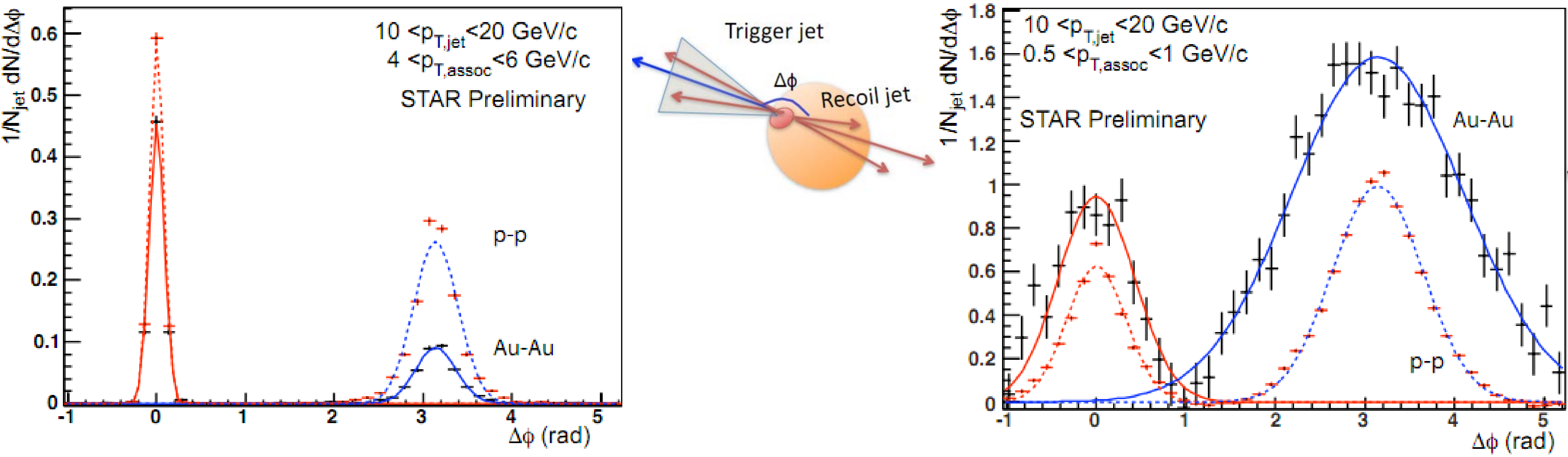
Low-p_T associate: $I_{AA} > 1$

→ additional low-p_T hadrons, correlated in ϕ with initial hard-scatter

→ to be done, subtract v_3

Phys. Rev. Lett. 104, 252301 (2010)

Consistent picture with STAR

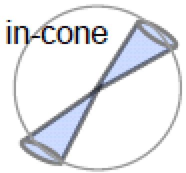


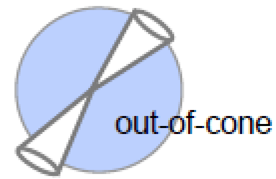
- High p_T assoc
  - Au-Au away-side yield suppressed, width ~same → little deflection
- Low p_T assoc
  - Au-Au away-side higher, broader
- RHIC consensus
  - Energy that is lost → extra hadrons, well correlated with parton

LHC: where does energy loss go?

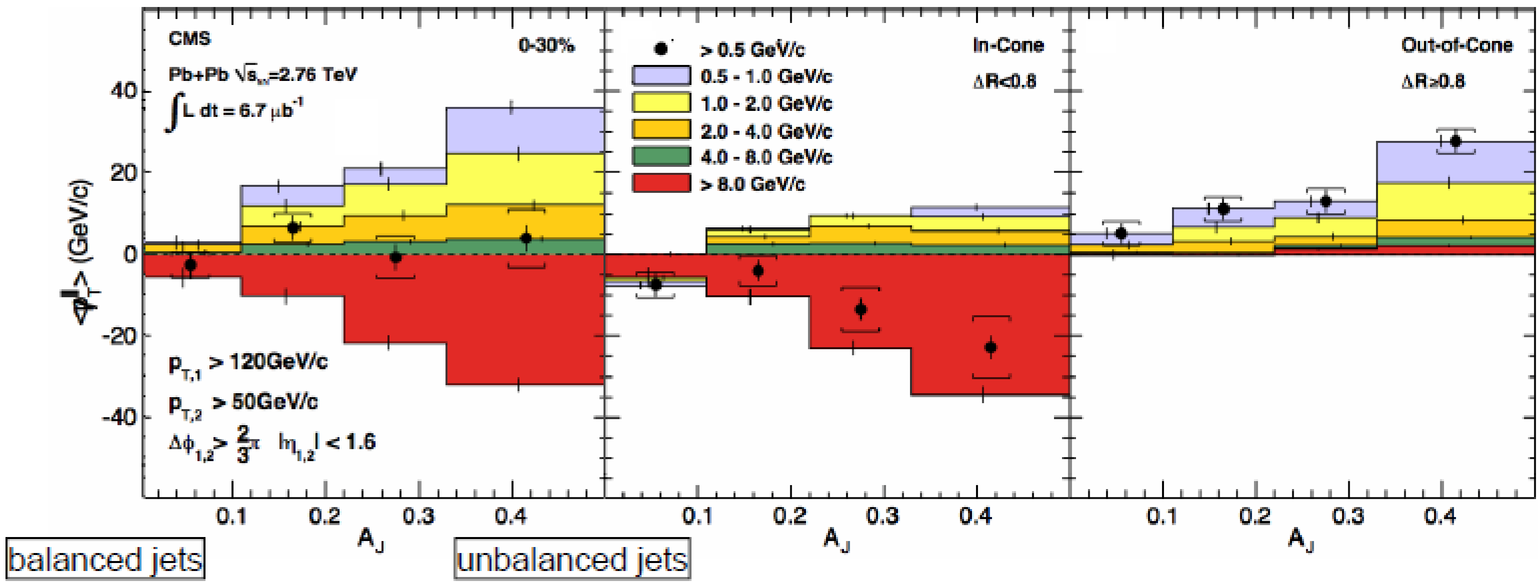
$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb



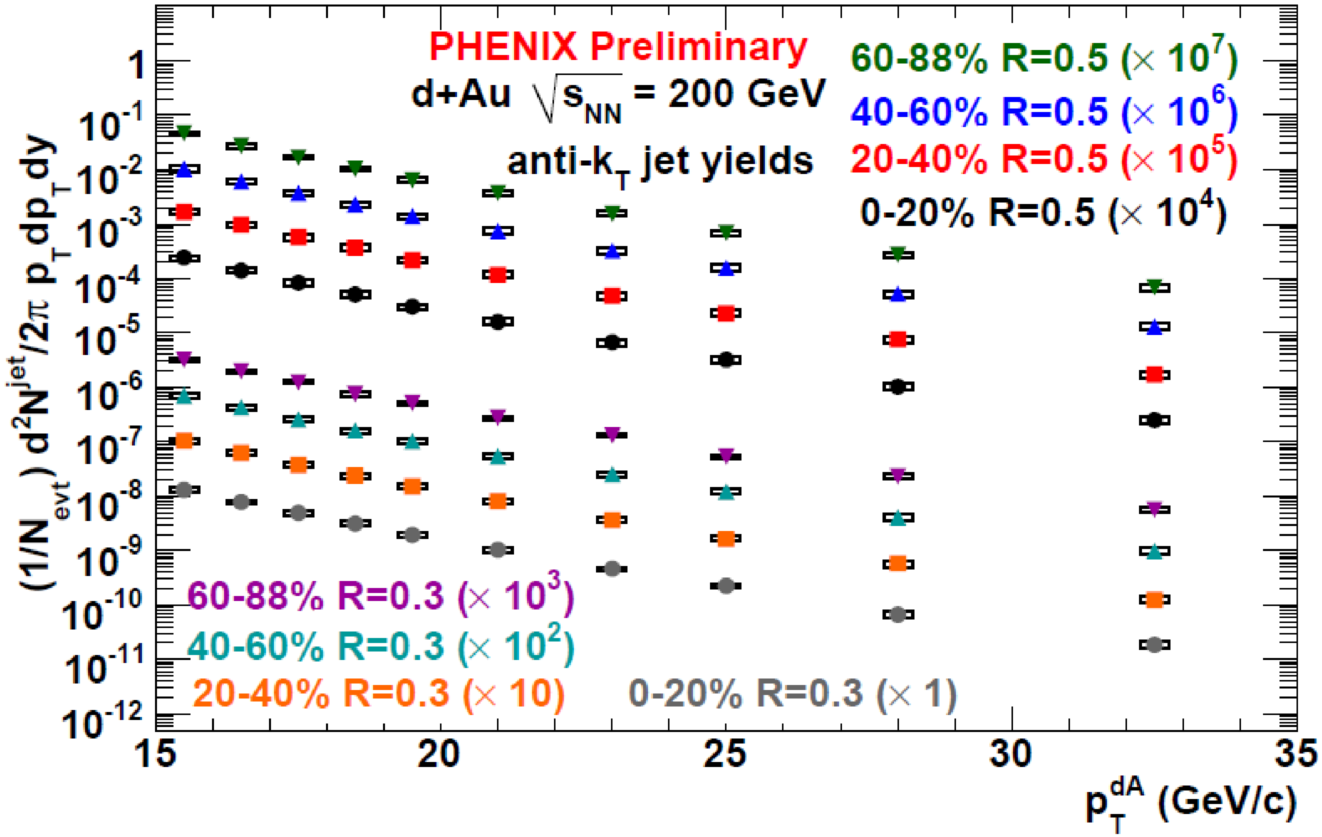


arXiv 1102.1957

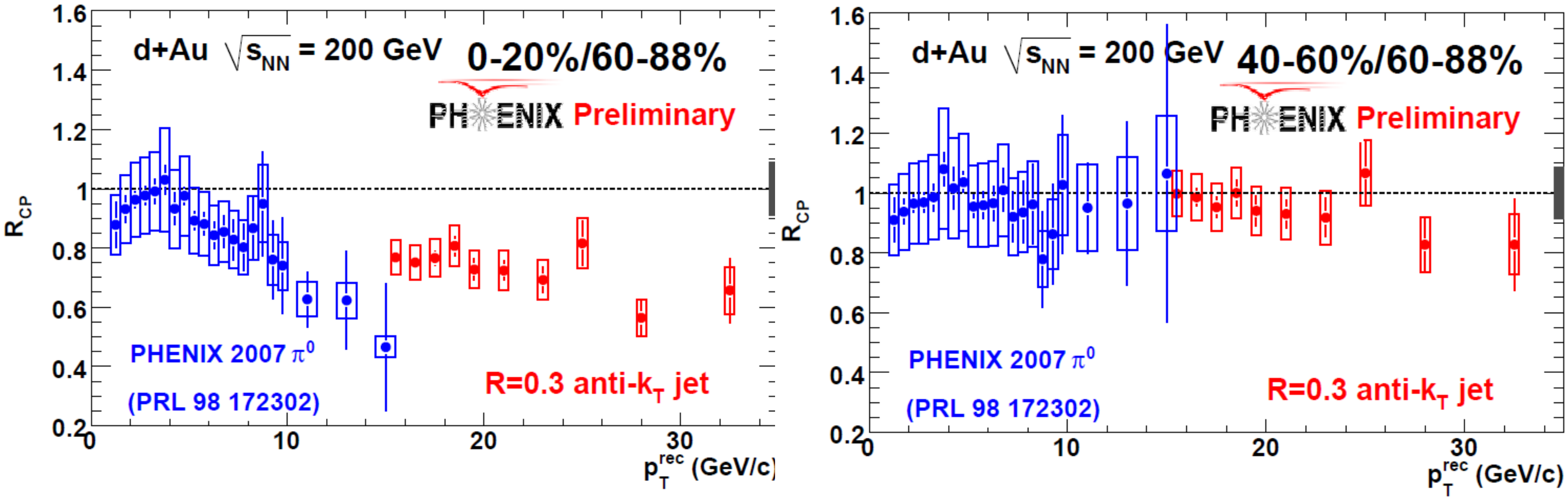


- high p_T : $<p_T^{\parallel}>$ less than 0 → fewer particles on far-side
- low p_T : $<p_T^{\parallel}>$ greater than 0 → more particles on far-side
  - inside and outside cone, but still correlated with far-side jet → broader

Cold Nuclear Matter effects: baseline d+Au



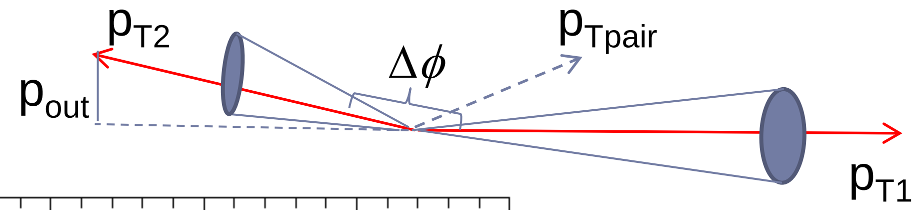
Cold Nuclear Matter effects: baseline d+Au

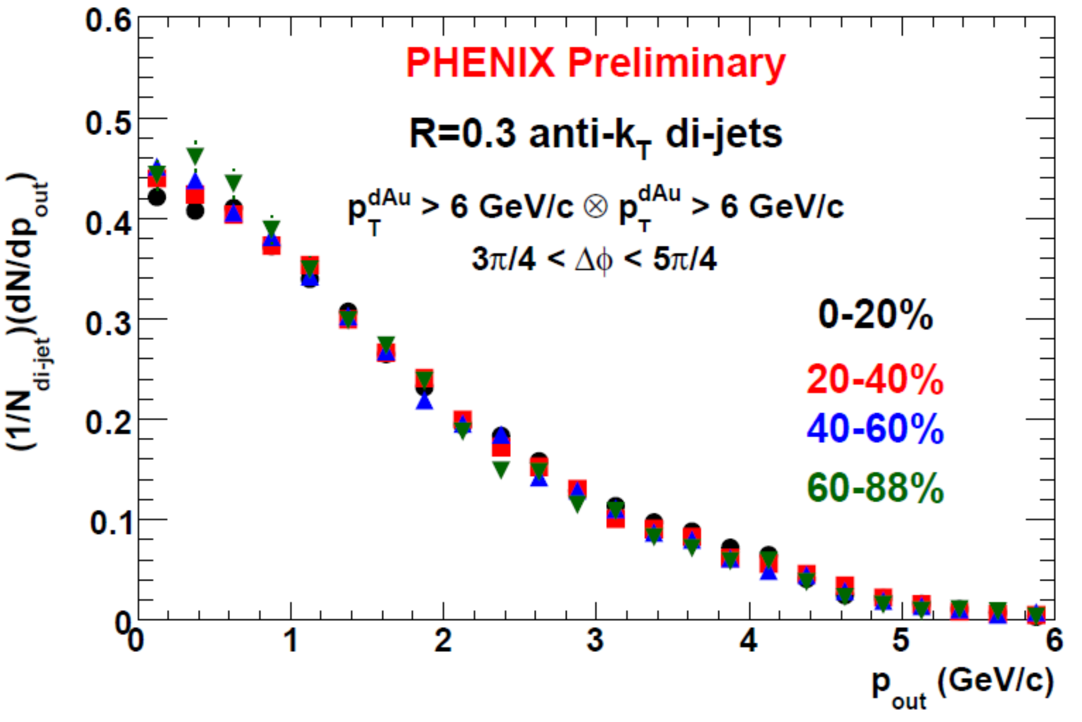


- Both π^0 and jets suppressed (R_{CP})
  - Energy-loss in CNM?
  - Initial-state effects?
- Calculations should reproduce this before use in A+A

Cold Nuclear Matter effects: baseline d+Au

$$< k_T{}^2 > = < p_{out}{}^2 >$$





- No indication of transverse broadening of di-jets

Goal 2:

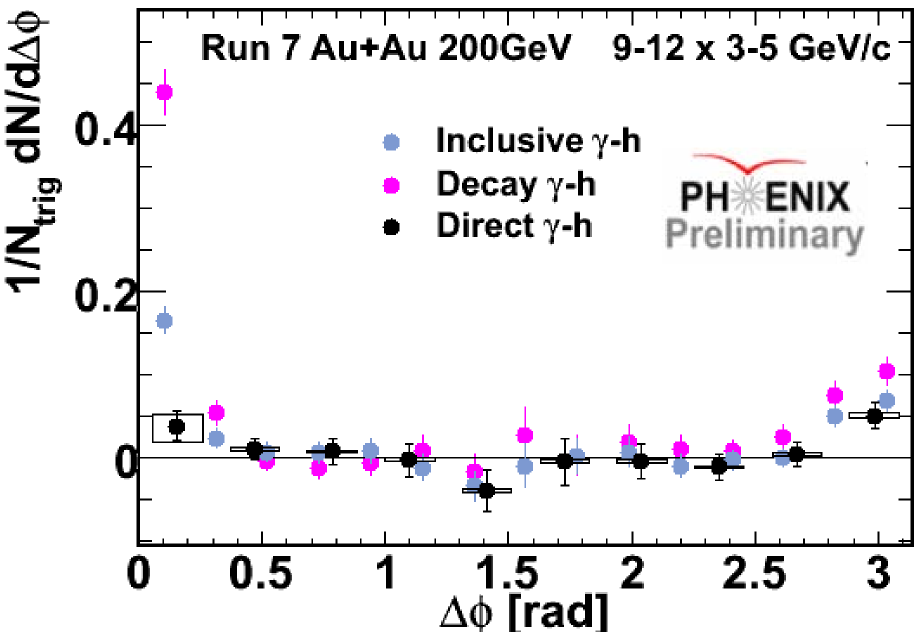
Use other results to provide more detailed view

- Fragmentation
- Single – particle R_{AA}, v_2 at high-p_T
- ……

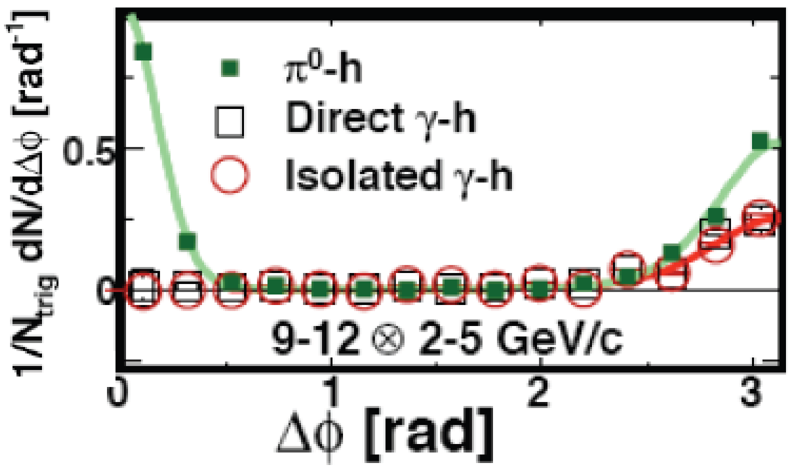
γ-h: Golden probe of energy-loss

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

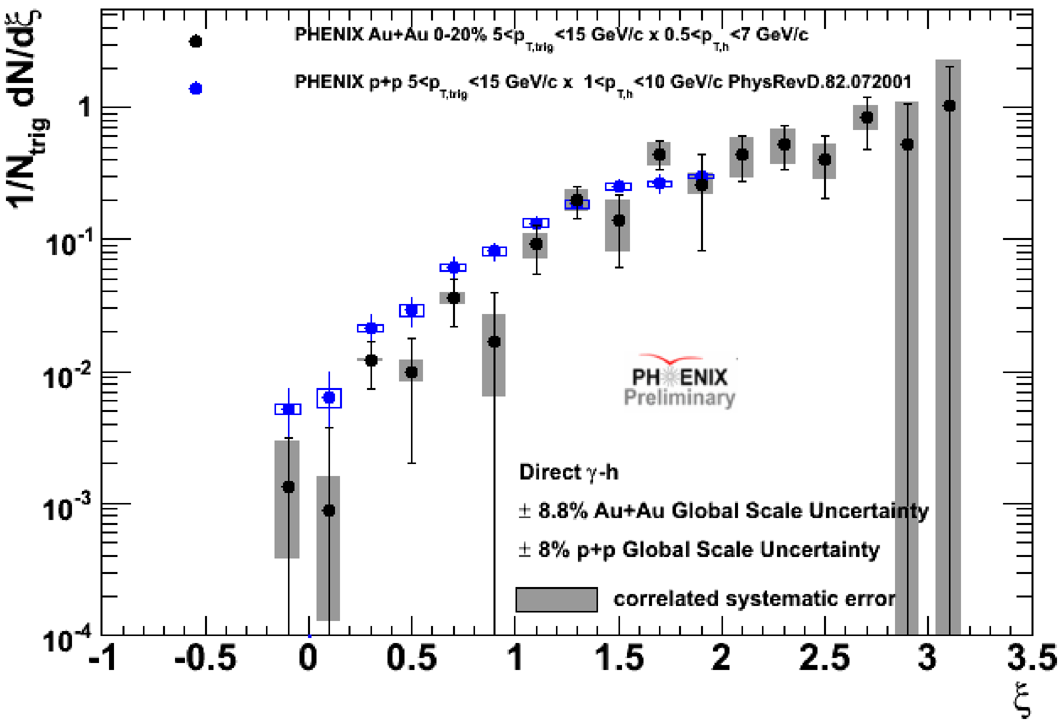
Statistical subtraction



Isolation(p+p) **PRD 82** 072001



γ-h → Fragmentation Functions

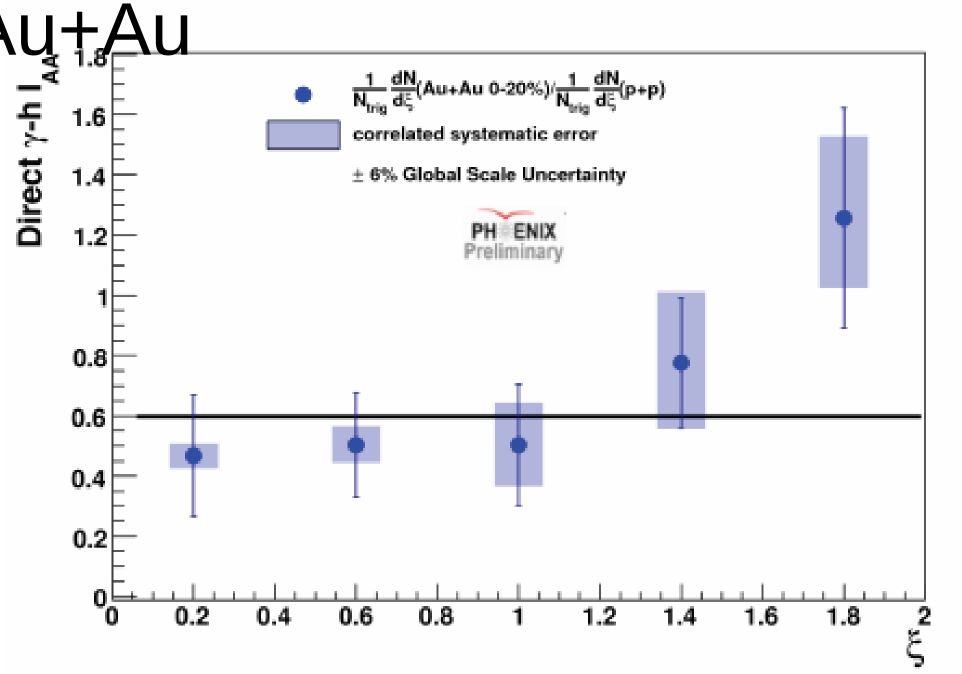


$$\xi = -\ln\left(\frac{p_T^h \cos(\Delta\phi)}{p_T^\gamma}\right)$$

- Au+Au compared with p+p
  - Smaller yield at high-z, low ξ

γ-h → Fragmentation Functions

The ratio of fragmentation functions in p+p and Au+Au

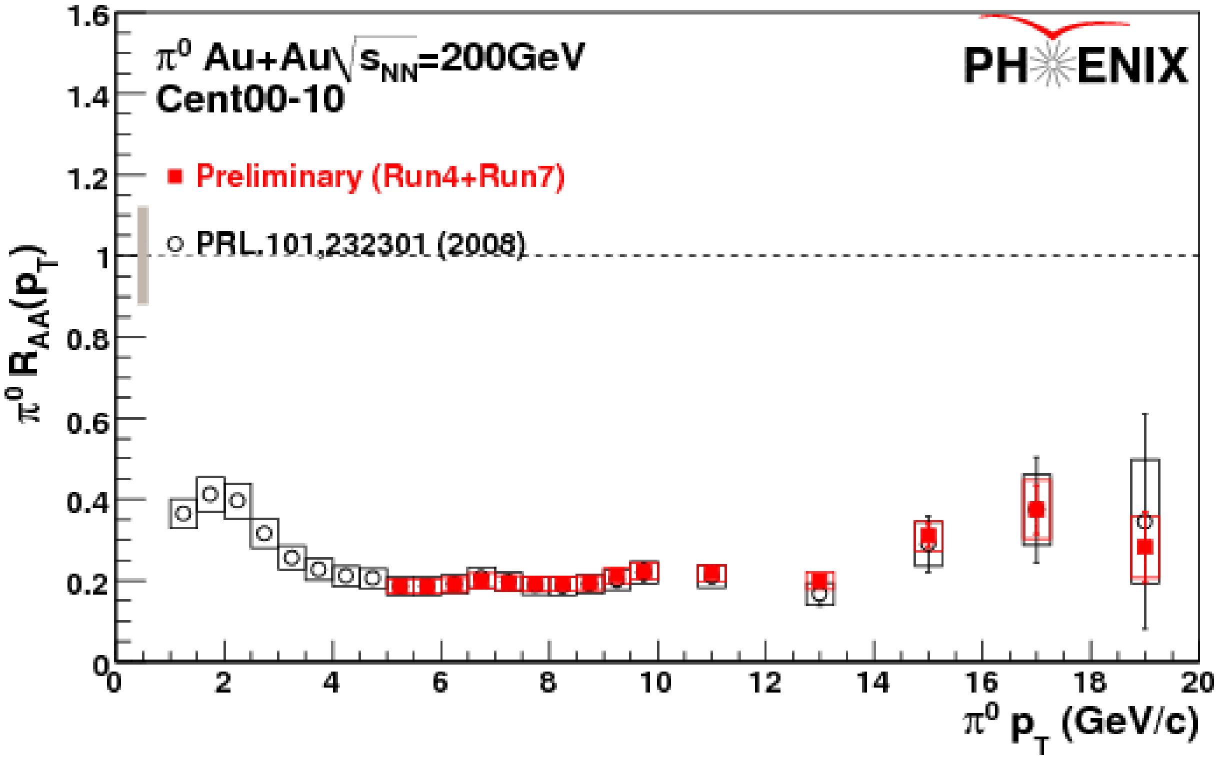


$$\xi = -\ln\left(\frac{p_T^h \cos(\Delta\phi)}{p_T^\gamma}\right)$$

$$\langle I_{AA} \rangle = 0.598 \pm 0.095$$

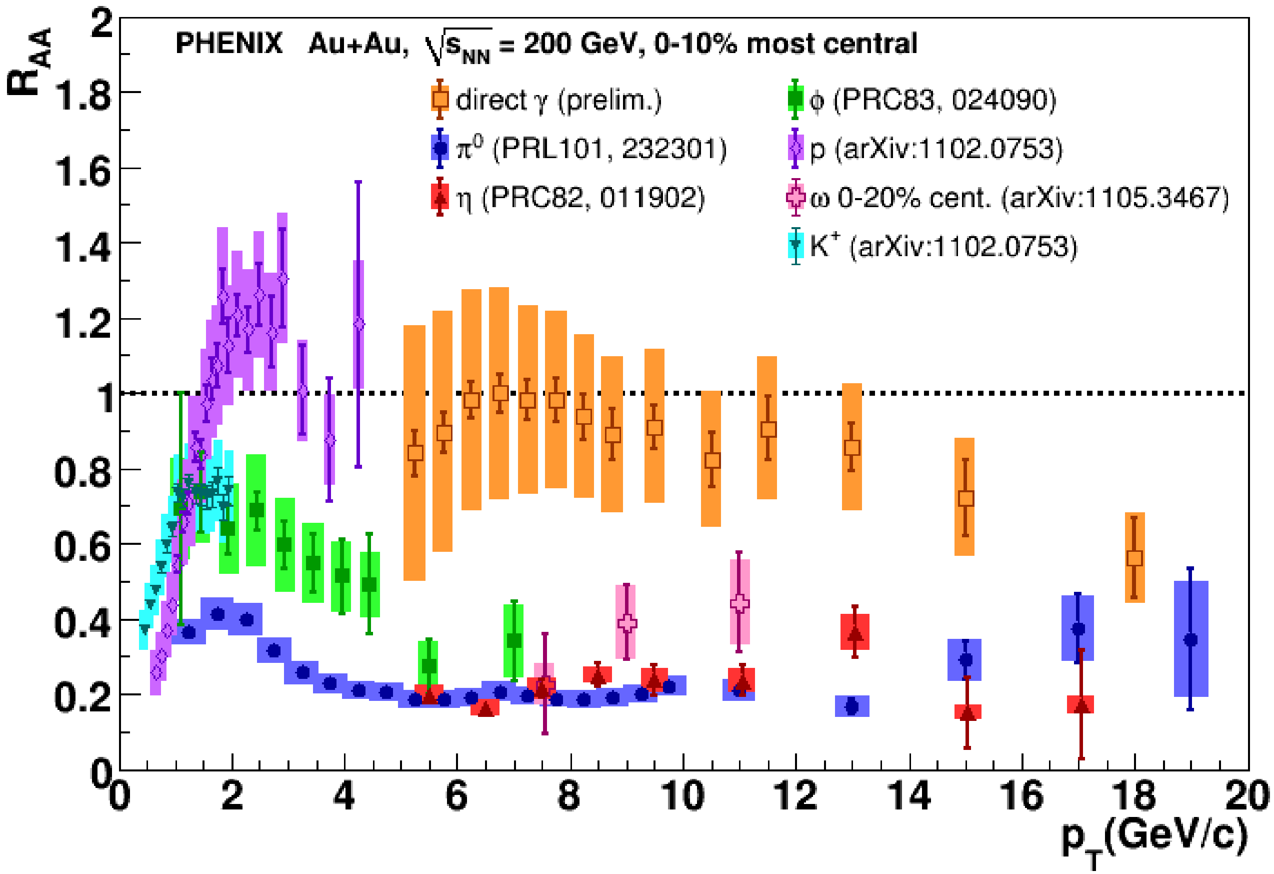
R_{AA} of single particles

- Jet energy-loss + fragmentation + medium response
  - Precise data, unambiguous observable
  - Constraint on models



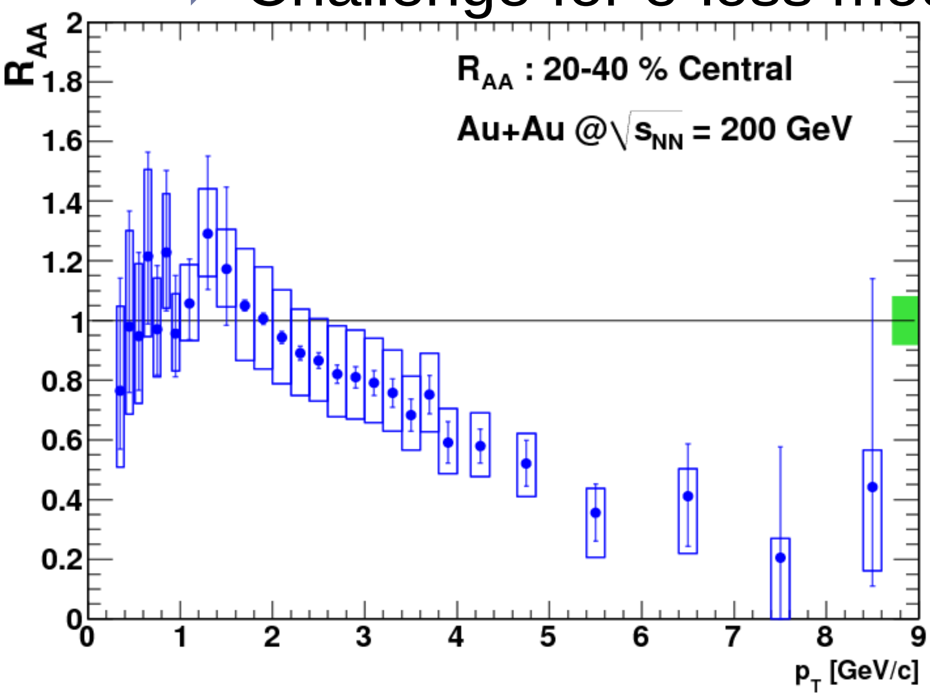
Particle species: R_{AA}

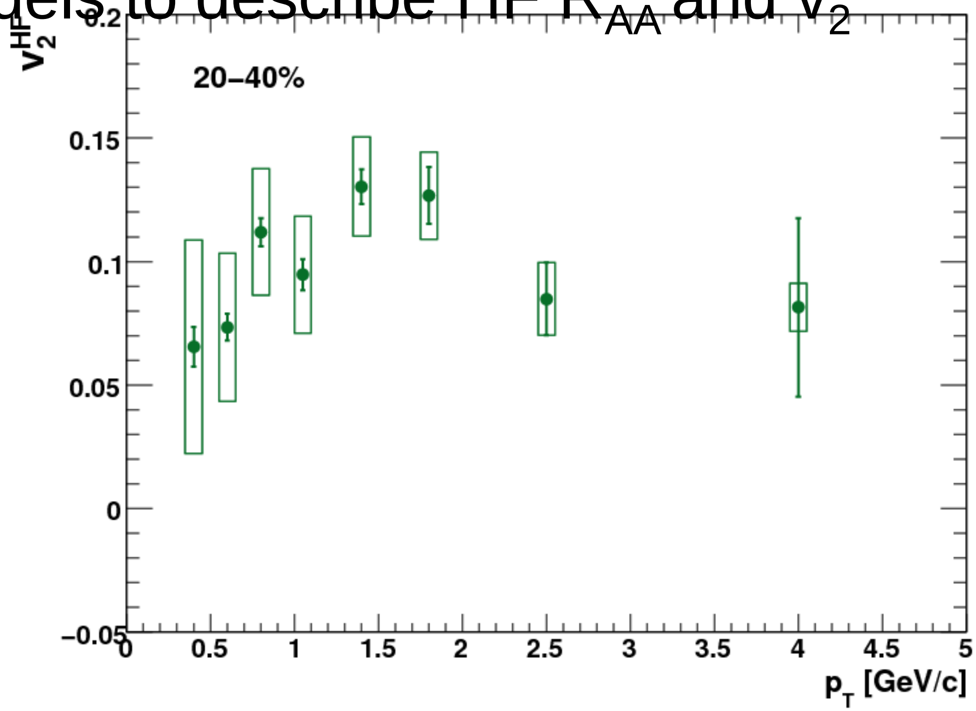
- Multiple insights, tests ofs models



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

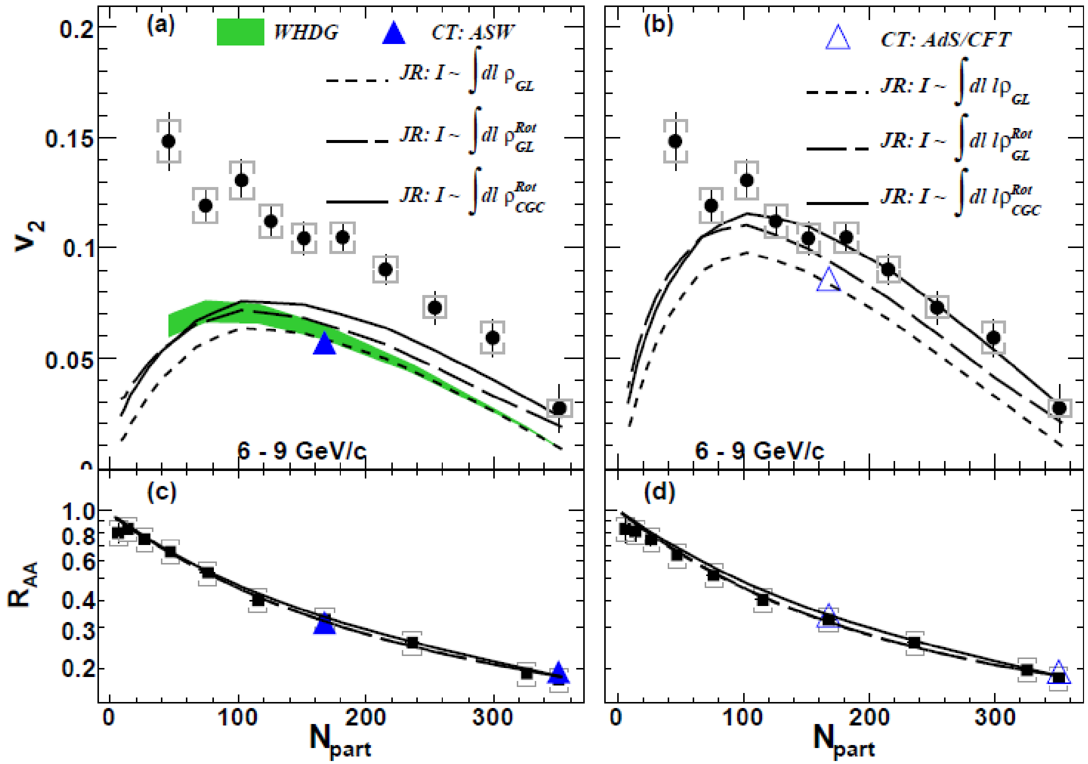




arXiv:1005.1627

Elliptic flow of π^0 at high-pt:

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

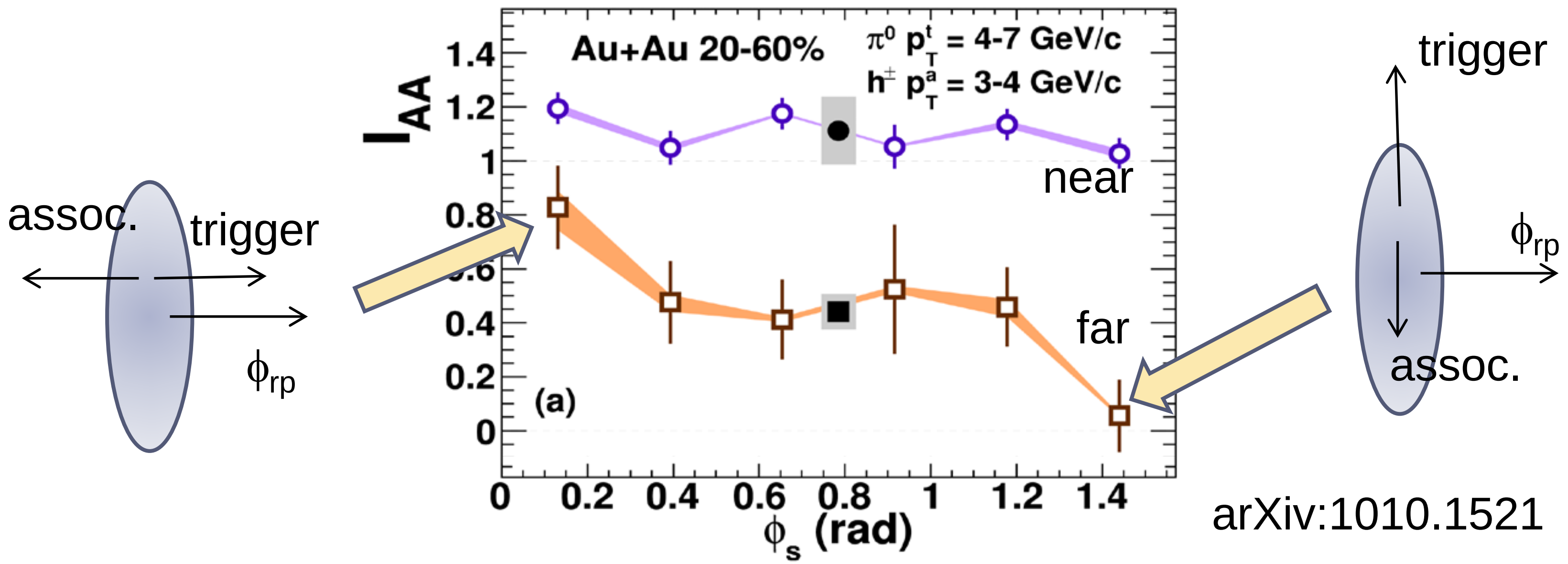


PRL105,142301

- $\Delta E \sim (\text{path length})^3$ favored
- Need v_2 of jets

Further control of path-length

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



arXiv:1010.1521

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

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 $\leftarrow$ excitation function (Jeff Mitchell talk)
    - RHIC sweet spot 10-50 GeV/c jets
    - sPHENIX
- Jet measurements: pp, dA, AA
  - $\langle k_T^2 \rangle$ as well as E-loss
  - v_2 of jets
- Increase precision of γ-h measurements $\rightarrow$

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
  - $\langle k_T^2 \rangle$ can quantify this and enable comparisons across $\sqrt{(s)}$
- γ-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