Highlights from PHENIX!

Andrew Adare
University of Colorado
for the
PHENIX Collaboration

Outline

I apologize in advance!

500 scientists + many TB data + yrs. of work >> 20 min. of material*

Today's selections:

- Temperature information from photons & quarkonia
- Leptons from heavy flavor
- Using the event plane: R_{AA} and dihadron correlations
- High p_T jets and energy loss: γ-hadron correlations
- Precision elliptic and hexadecapole flow

Tomorrow:

Jet Probes of Hot Dense QCD Matter (Brian Cole)

Recent Results on d+Au Collisions (Rich Seto)

*Don't bother with dimensional analysis. It doesn't work out.

Thermal photons and quarkonia

Taking the temperature of the QGP

The hadron mass spectrum

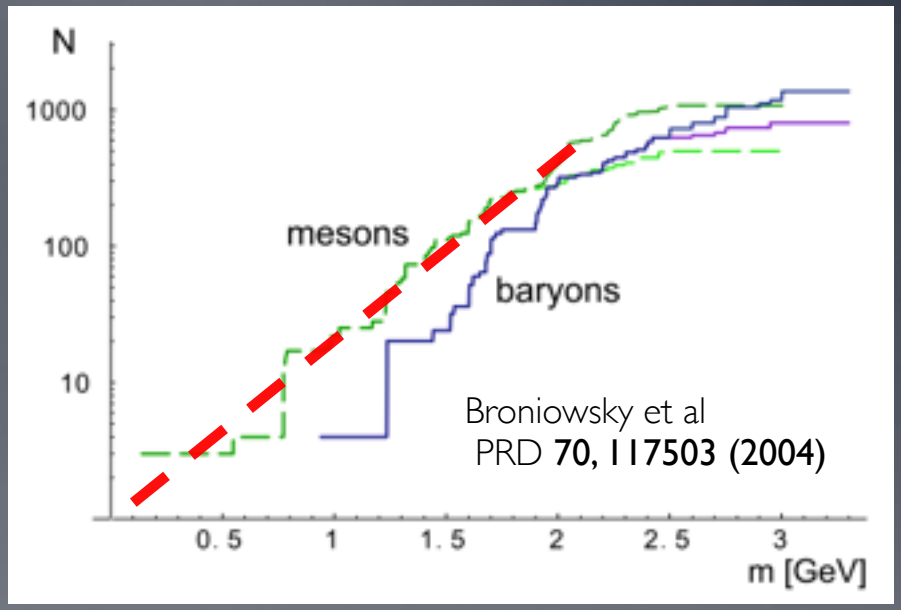
Hagedorn picture:

- If matter is purely hadronic, adding energy introduces more states.

$$\rho(m) = f(m)\exp(m/T_H)$$

f(m) "slowly varying".
T_H ~ 170 MeV

- Limiting temperature: energy diverges as $T \rightarrow T_H$ unless fundamental nDOFs change



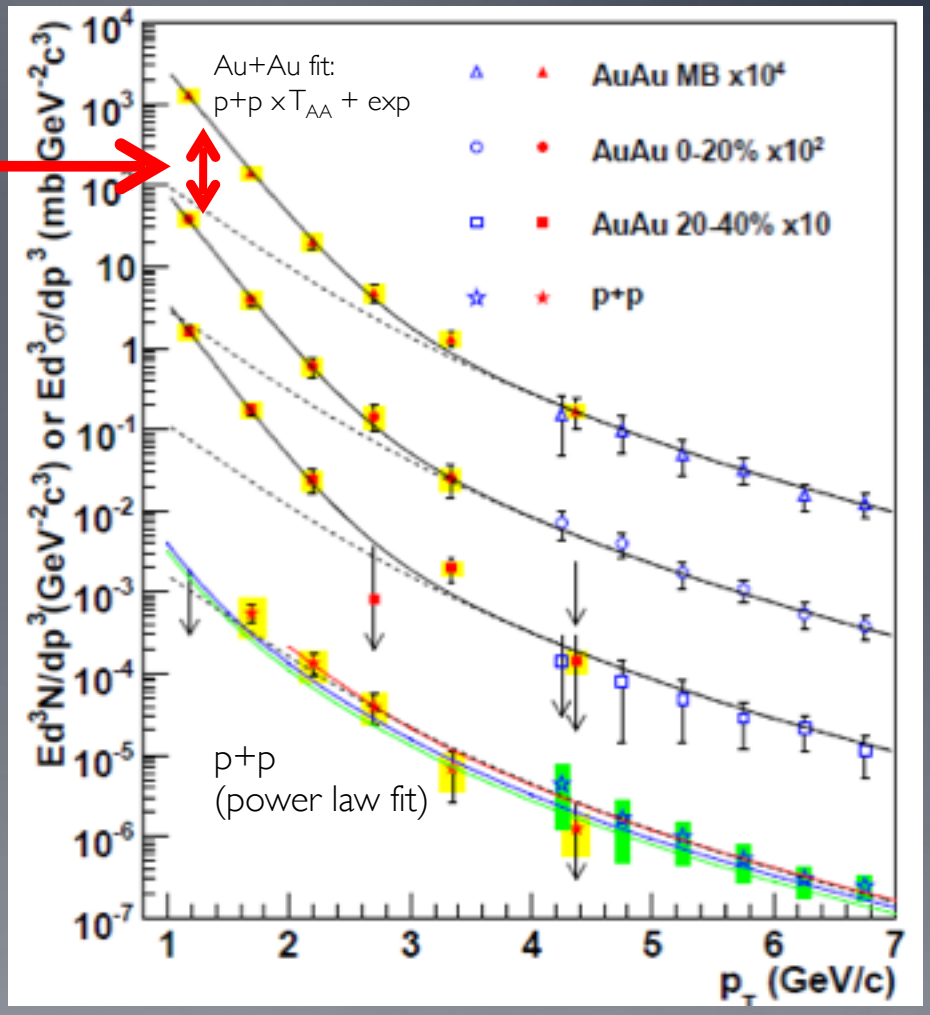
Exponential ρ(m) also predicted from first principles in large N_c QCD (hep-th/0901.0494v2) .

Lattice QCD also predicts phase transition at T~ 170 MeV.

Thermal photons in Au+Au

- At low p_T, Au+Au has large excess of photons above scaled p+p expectation.
- If slope $\propto$ 1/T, this is an experimental lower bound on the temperature of an evolving medium.
- Fits to low p_T component give $T = 221 \pm 23(stat) \pm 18(sys)$ MeV
- Data agrees with hydro models using T_i = 300-600 MeV
  Eur. Phys. J. C 46, 451-464 (2006)

The matter appears to be well above T_c!



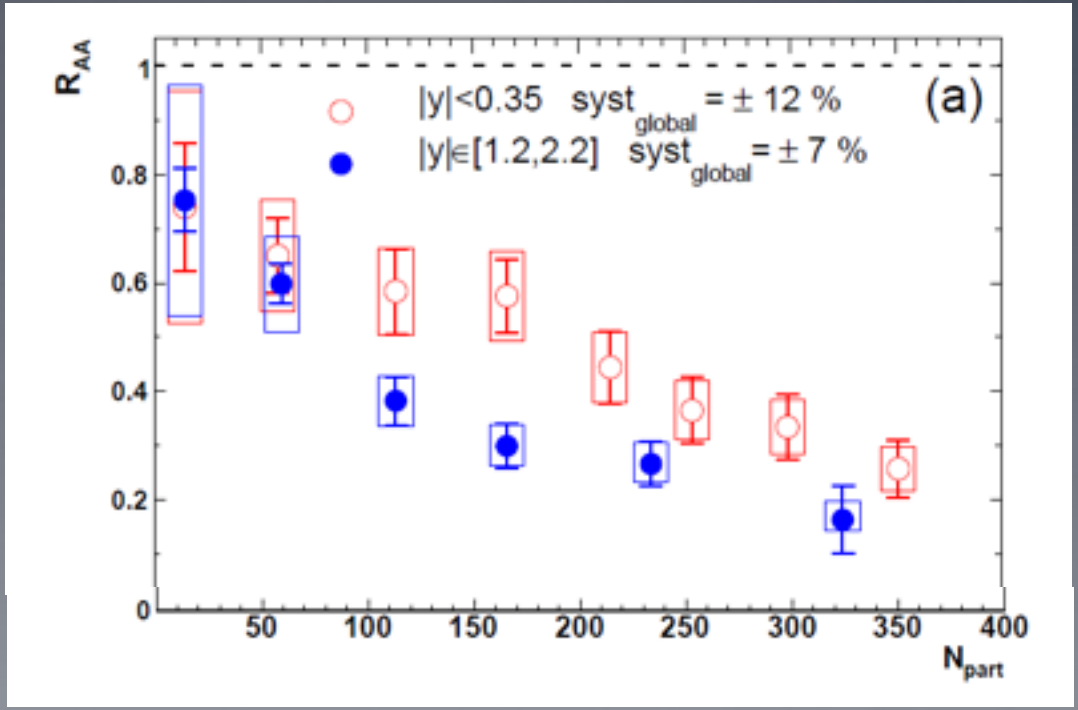
nucl-ex/0804.4168v1

The QGP and quarkonia

- Hot, deconfined matter should melt different quarkonia states at a variety of temperatures
- J/ψ suppression is well established in Au+Au w.r.t binary scaled p+p.
- Some of this suppression is from cold nuclear matter effects. We are improving our handle on this…

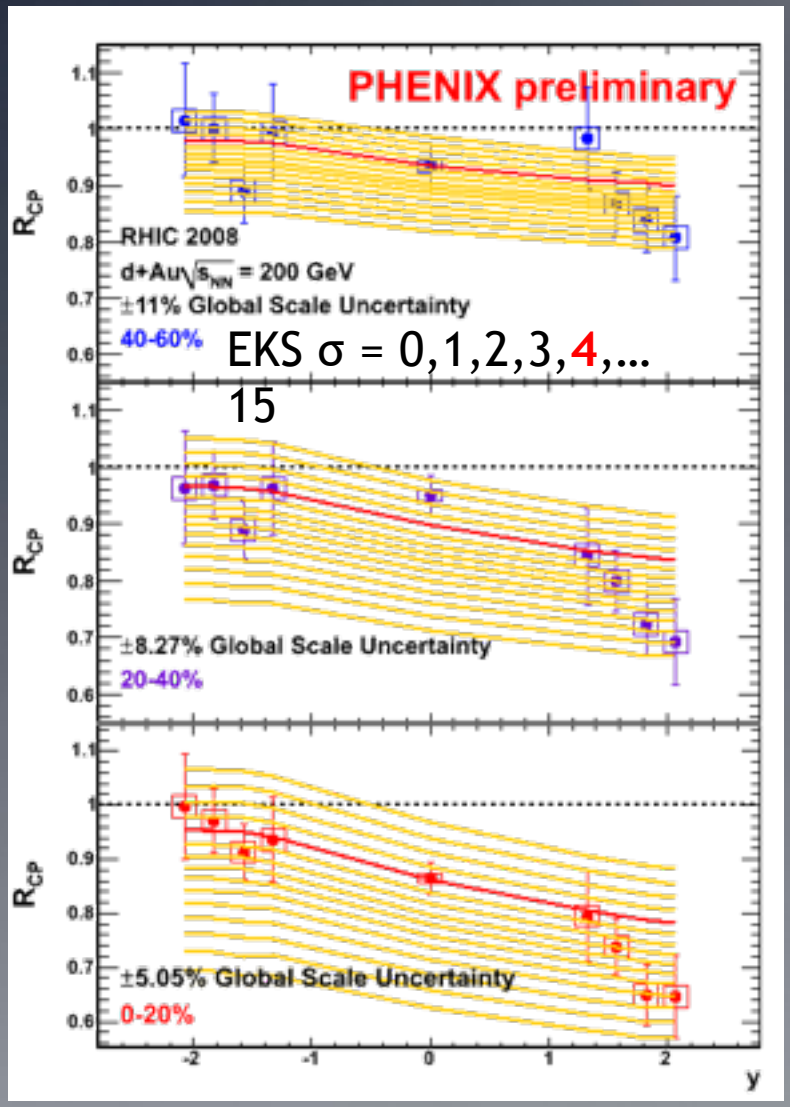
state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$<T_c$	$\leq T_c$	$1.2\,T_c$	$1.2\,T_c$	$1.3\,T_c$	$2\,T_c$

hep-ph/0706.2183v2



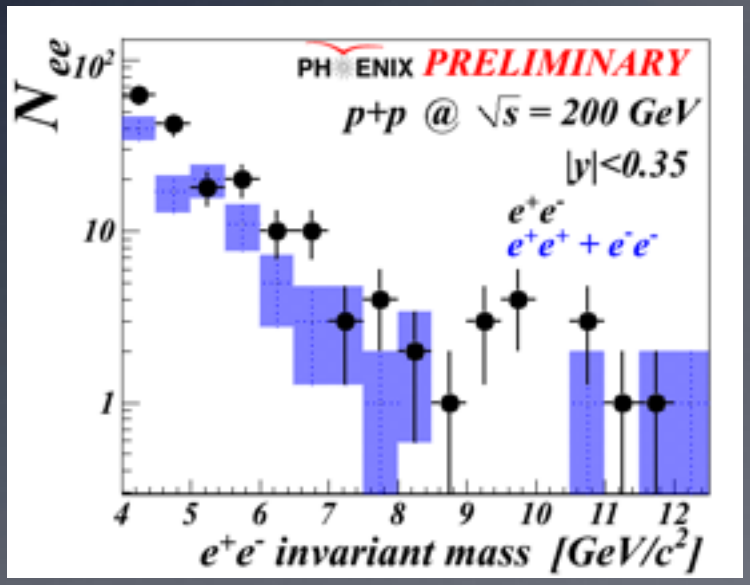
PRL 98 232301

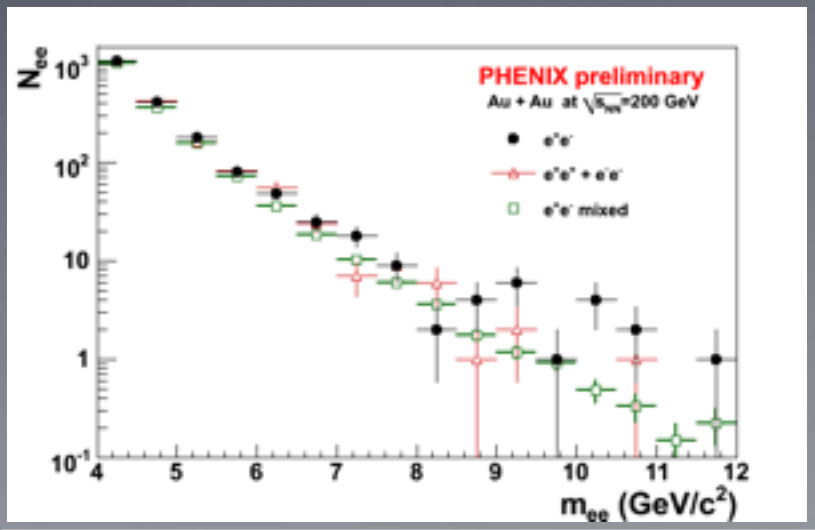
J/ψ R_{cp} in d+Au



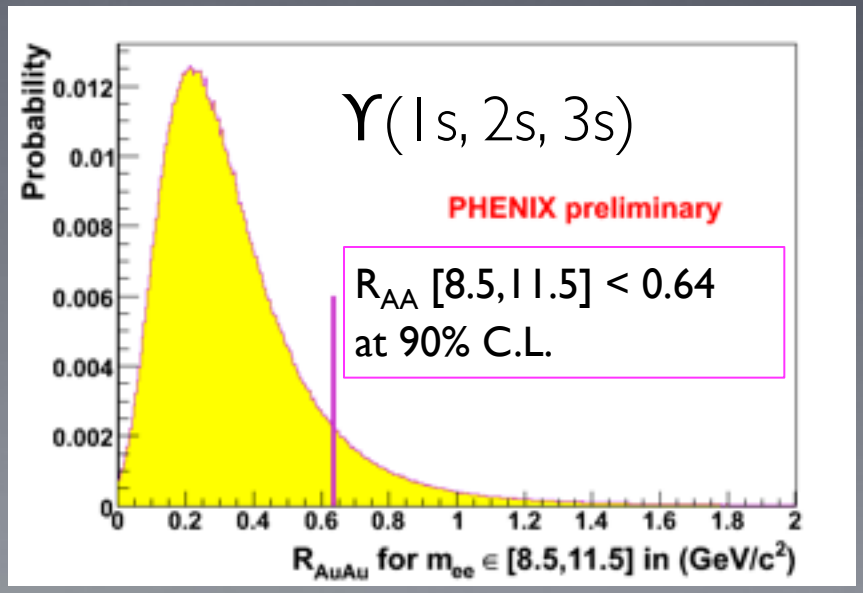
- Suppression vs. rapidity constrains shadowing models
- Run 8 results have improved precision from Run 3…final result is in progress
- See Rich Seto's talk tomorrow for more details

Upsilon suppression in Au+Au





- Combined poisson probablility analysis for p+p and Au+Au
- We can now constrain an upper limit on R_{AA} for Υs!



A few words on Υ suppression

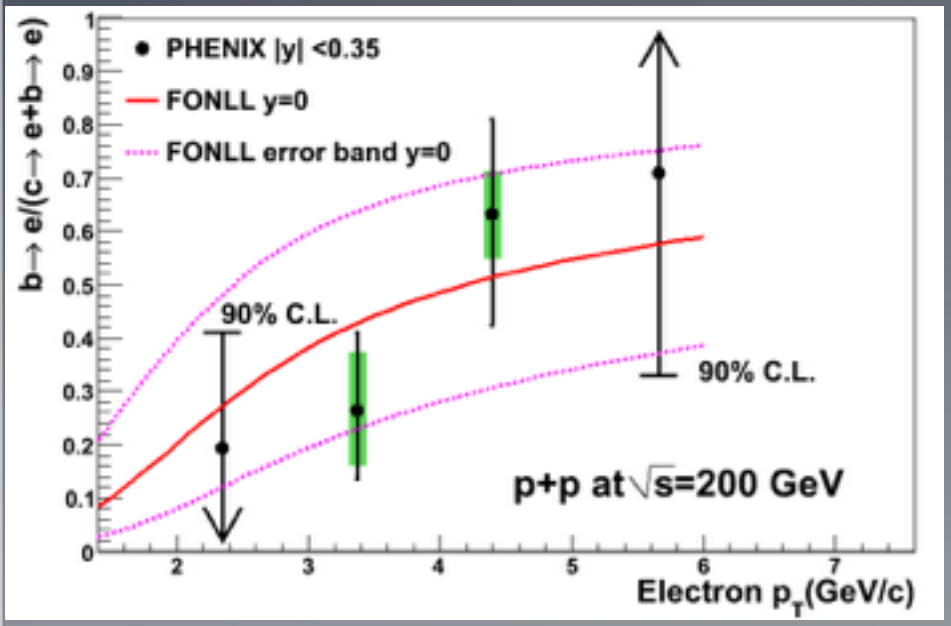
- Caveat from previous slide: $b\text{-}\bar{b}$ and Drell-Yan background contributions were not removed in quoted R_{AA} upper limit.
- However, they are expected to be small, and were measured to be < ~15% of background in p+p
- Absorbtion, (anti)shadowing, feed-down, and suppression of higher states all potentially contribute. More work required to generate quantitative prediction. I will leave this to the experts….

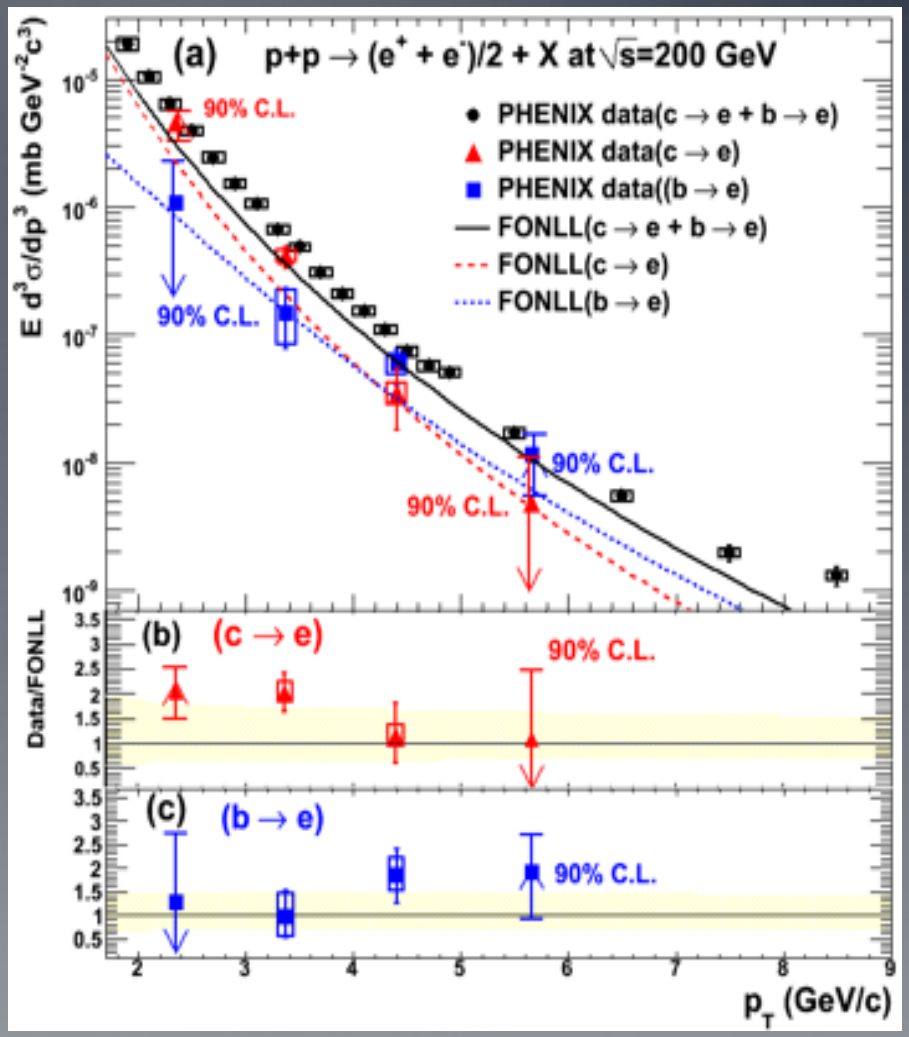
Charm, beauty, and energy loss

Do heavy quarks lose less energy than light ones?

Beauty contribution to $e^{\pm}$

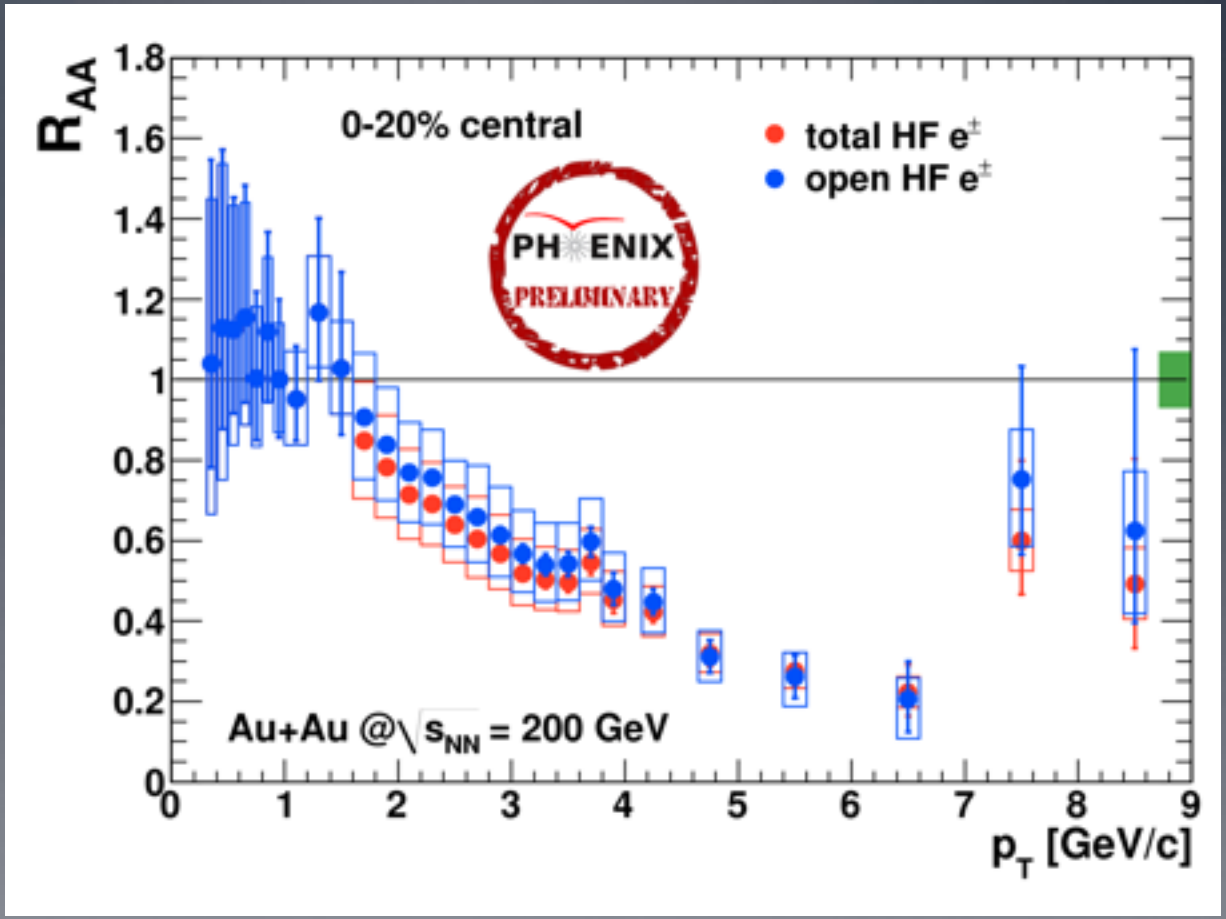
- b's contribute substantially to $e^{\pm}$ spectra at high p_T
- b and c cross sections agree well with p+p FONLL using these ratios





Nonphotonic electron R_{AA}

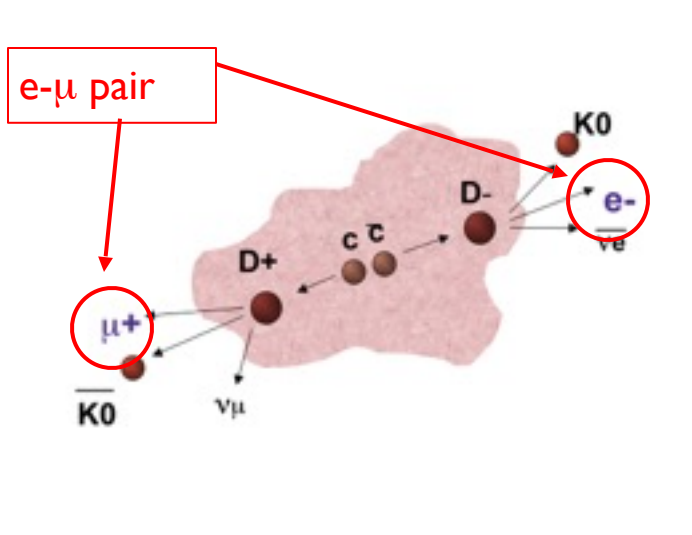
- Single NPE R_{AA} from charm and beauty. J/ψ, DY and Υ contributions removed for open HF points
- Surprisingly large suppression-- comparable to pion R_{AA}
- Even including collisions, suppression is underpredicted by many E loss models.

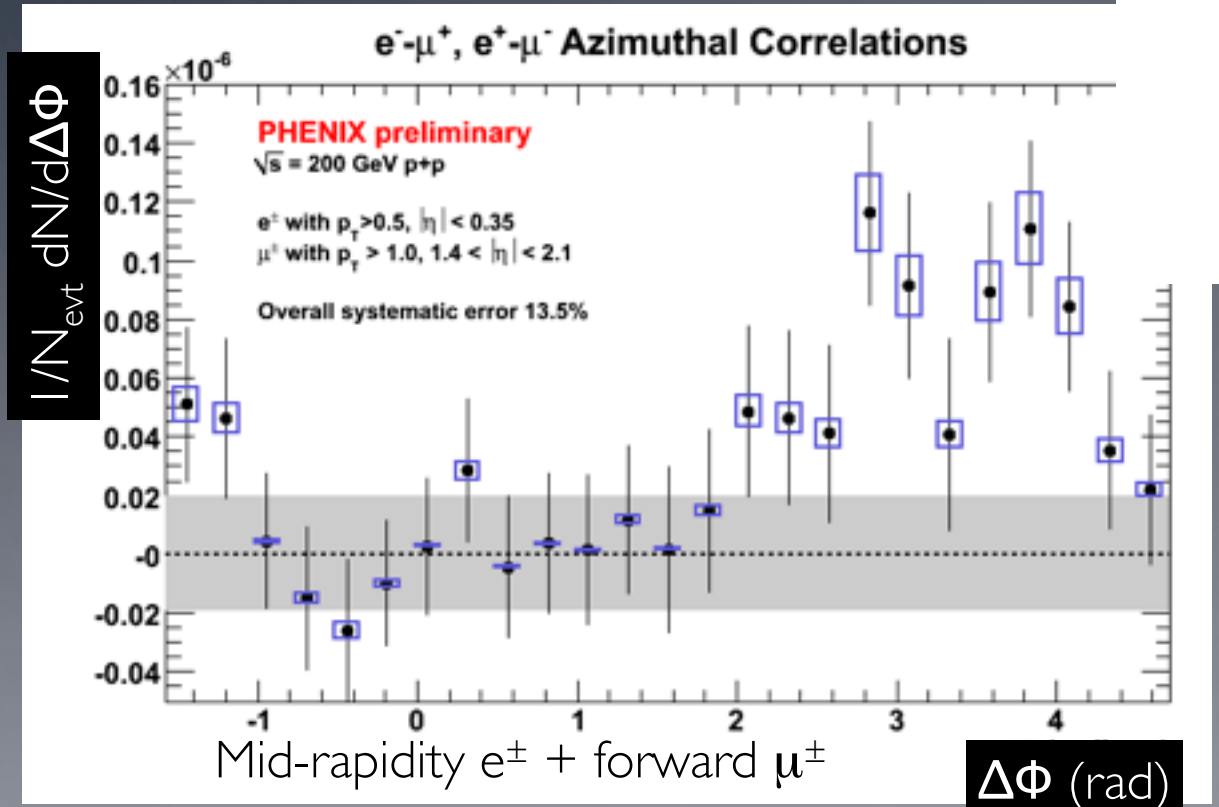


Explaining measured flow and such large suppression is a tough theoretical task.
What can be done to clarify the picture from the experimental side?

$e^{\pm}$-$\mu^{\pm}$ correlations

Probes back-to-back c-cbar production.
Low background, could use as proxy for charm-charm correlations to get k_T.

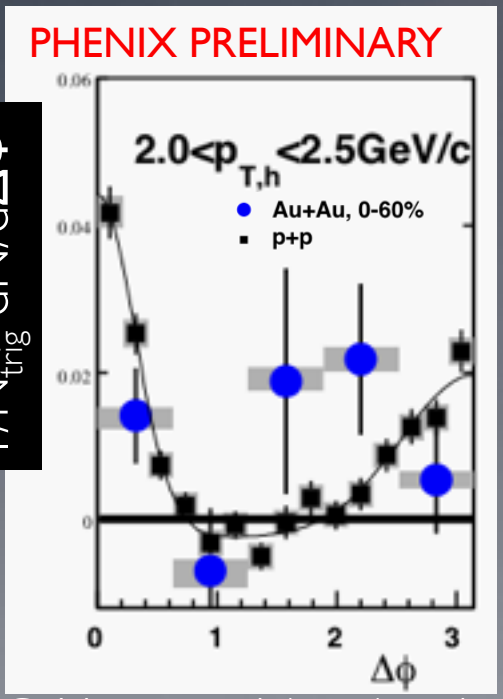




- Promising proof-of-principle measurement in p+p
- Could use to get charm cross section in future

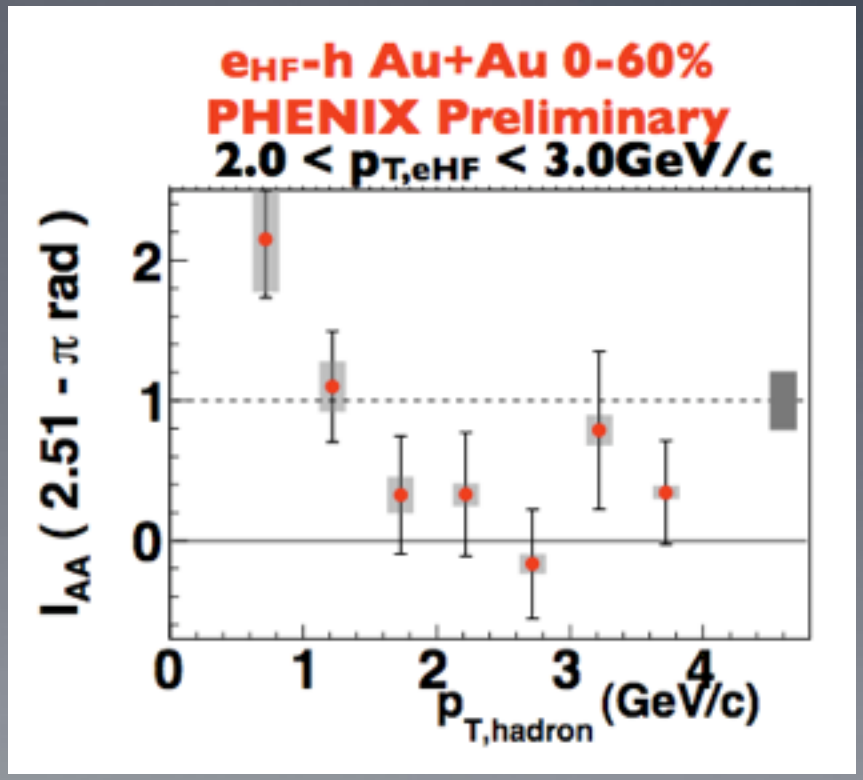
$e^{\pm}$-$h^{\pm}$ correlations

- Trigger particles are electrons from heavy flavor decay at midrapidity
- Obtained by subtracting photonic $e^{\pm}$ background from inclusive sample
- Studies HF decays on near side, HF jets on away side.



Au+Au currently limited by statistics, not systematics.

Optimistic for future runs.



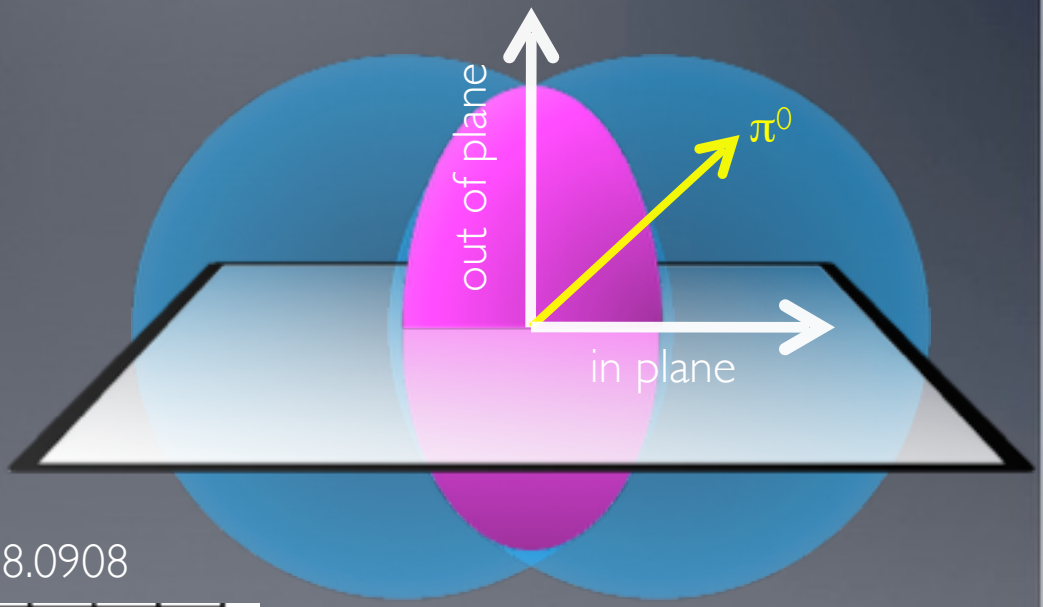
200 GeV p+p and Au+Au, electron p_T 2-3 GeV/c

Probing energy loss and collision geometry

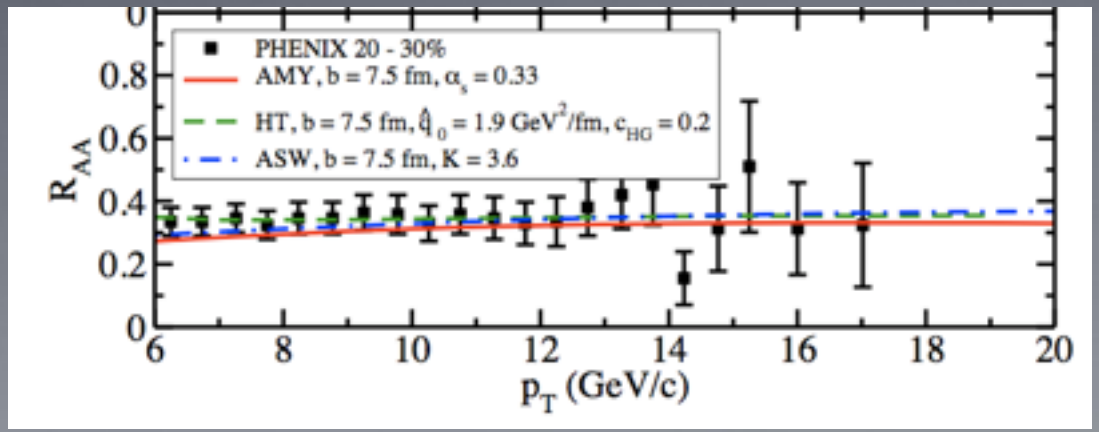
Reaction-plane dependent R_{AA} and dihadron correlations

Collision geometry

- Looking at suppression in-plane vs. out-of-plane probes different path lengths
- Several models match data for integrated geometry…



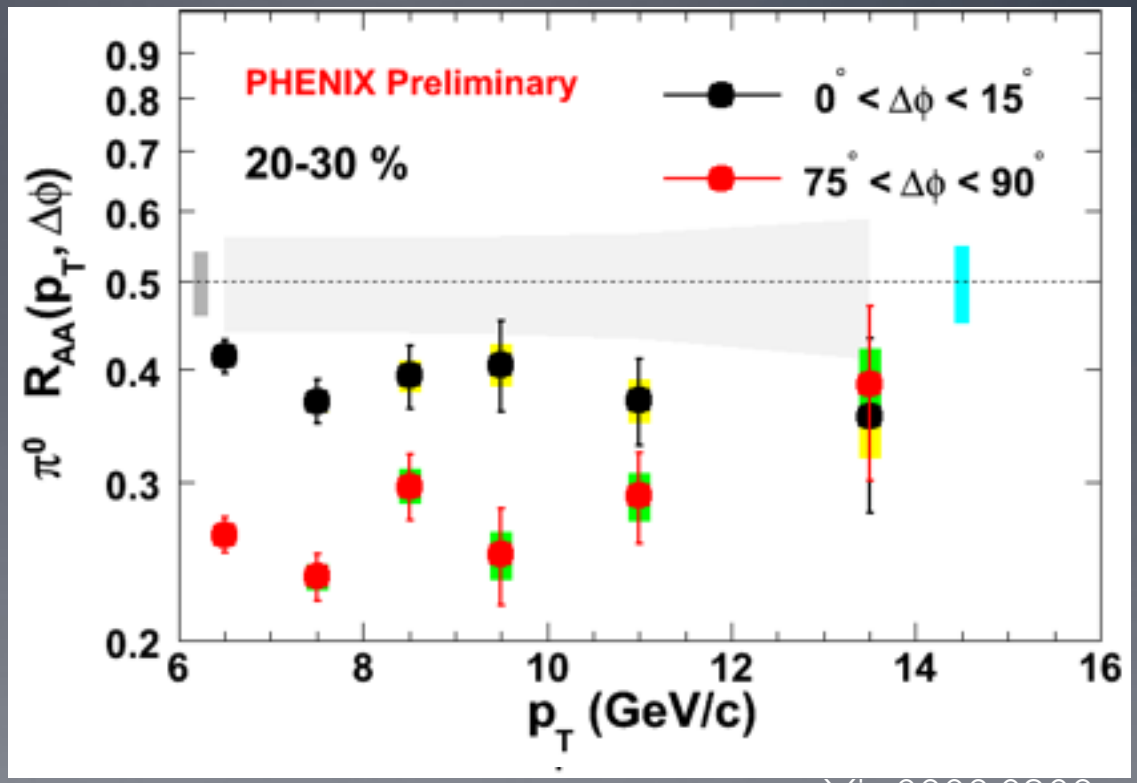
arXiv:0808.0908



…examining suppression w.r.t. the reaction plane adds an important constraint.

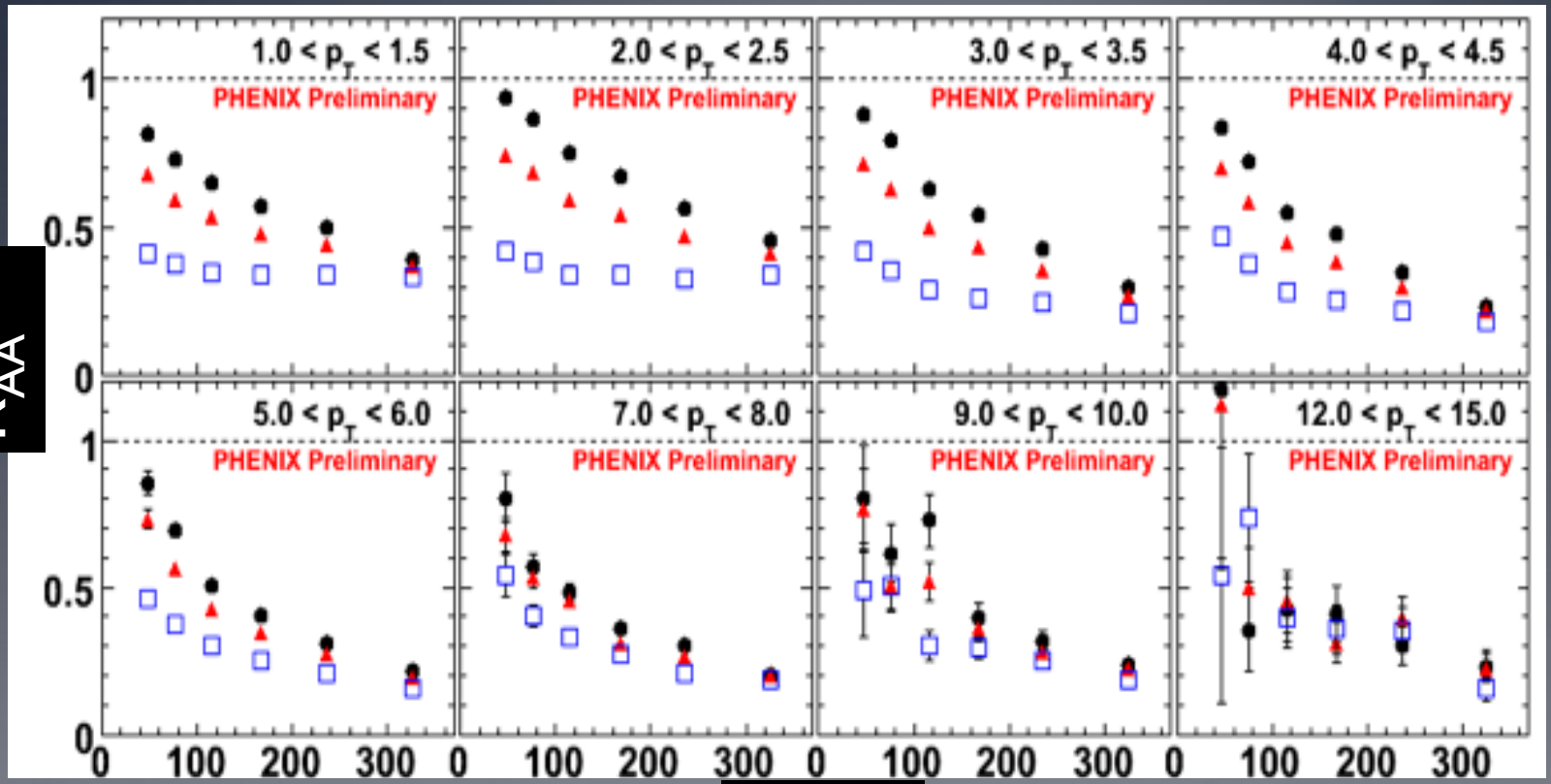
R_{AA} vs RP and p_T

- AMY (q = 4.1)
- HT (q = 2.3)
- ASW (q = 10)
- → R.P. dependence improves qhat discrimination over R_{AA}.



arXiv:0808.0908

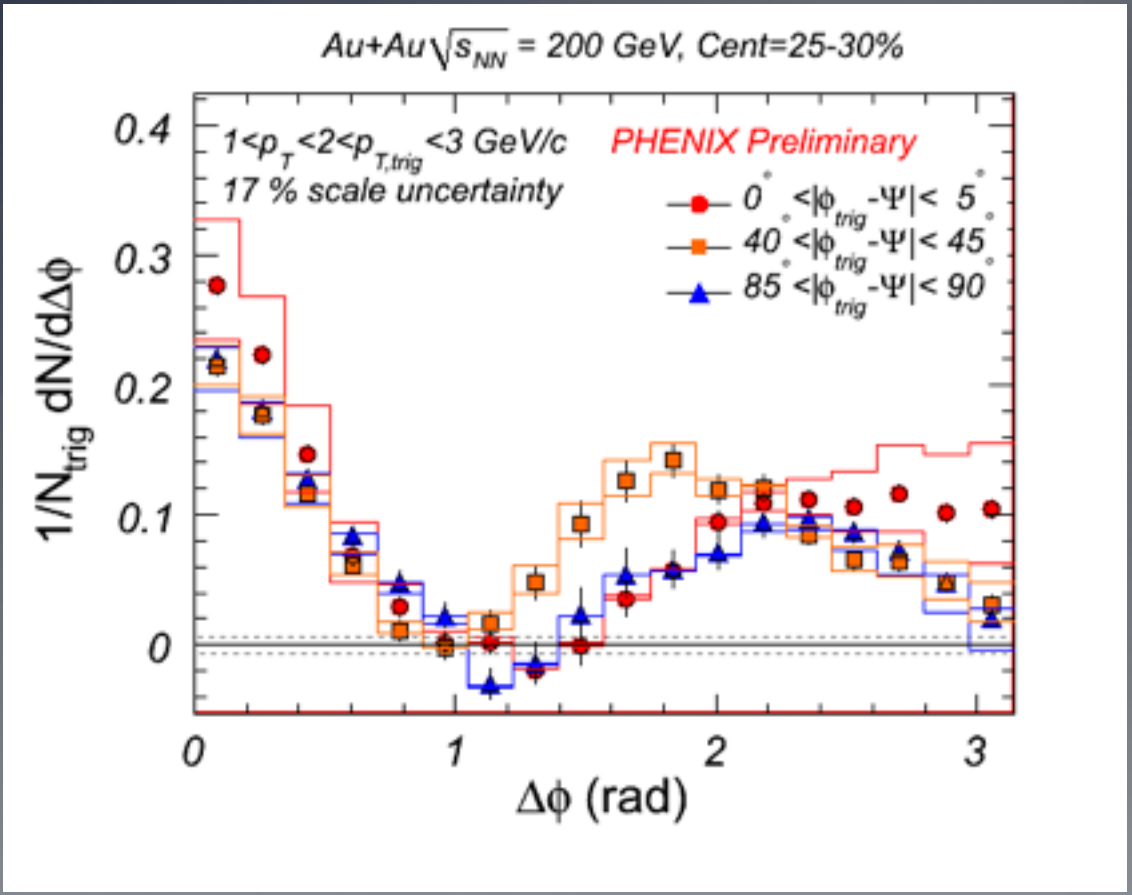
Another look: R_{AA} vs N_{part}



- Flatter out of plane
- Azimuthal dependence diminishes at high p_T

R.P. dihadron correlations

- Midcentral Au+Au: 2-3 GeV triggers, 1-2 GeV partners.



Trigger orientation:

In plane

Out of plane

Intermediate

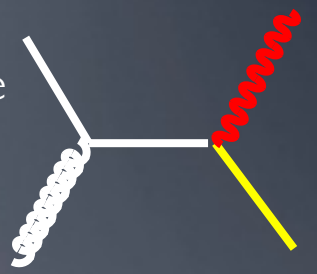
- Head region suppressed out of plane, shoulder region enhanced at intermediate angles.

Direct γ-h correlations

Probe E loss cleanly: correlate unsuppressed photons produced back to back with quenched partons.

No trigger surface bias!

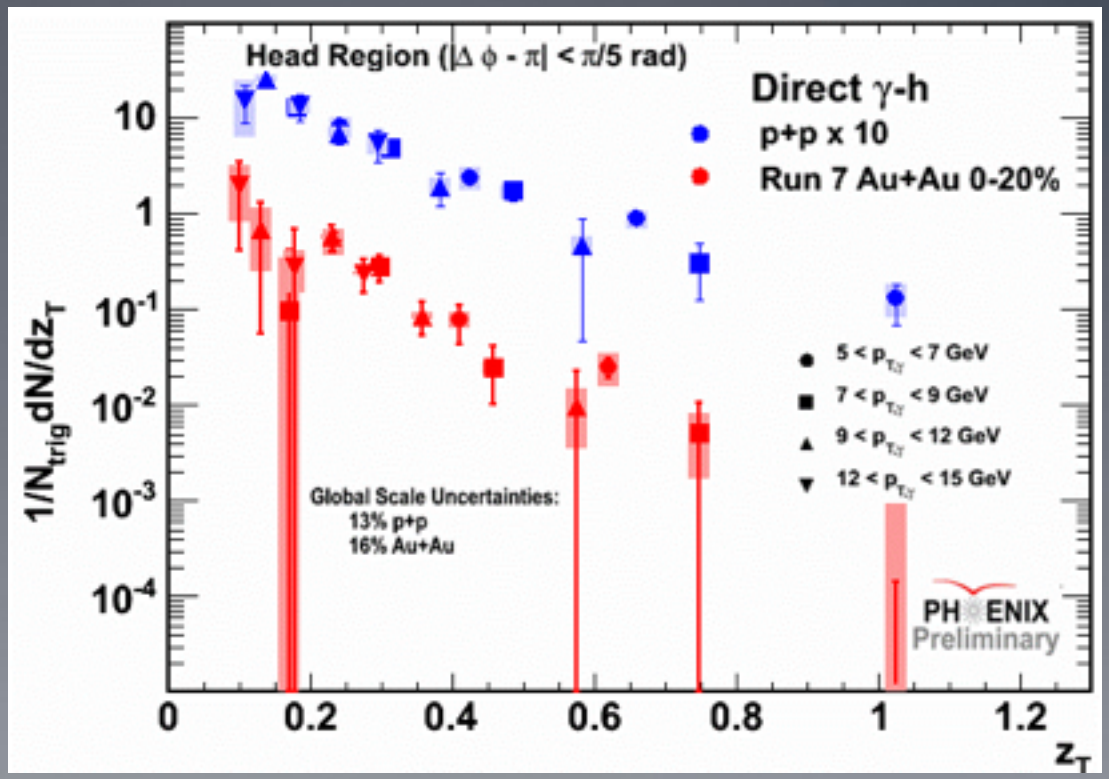
$E_\gamma = E_{parton}$



Softer D(z) in Au+Au than p+p: $\exp(-bz_T)$ fit gives

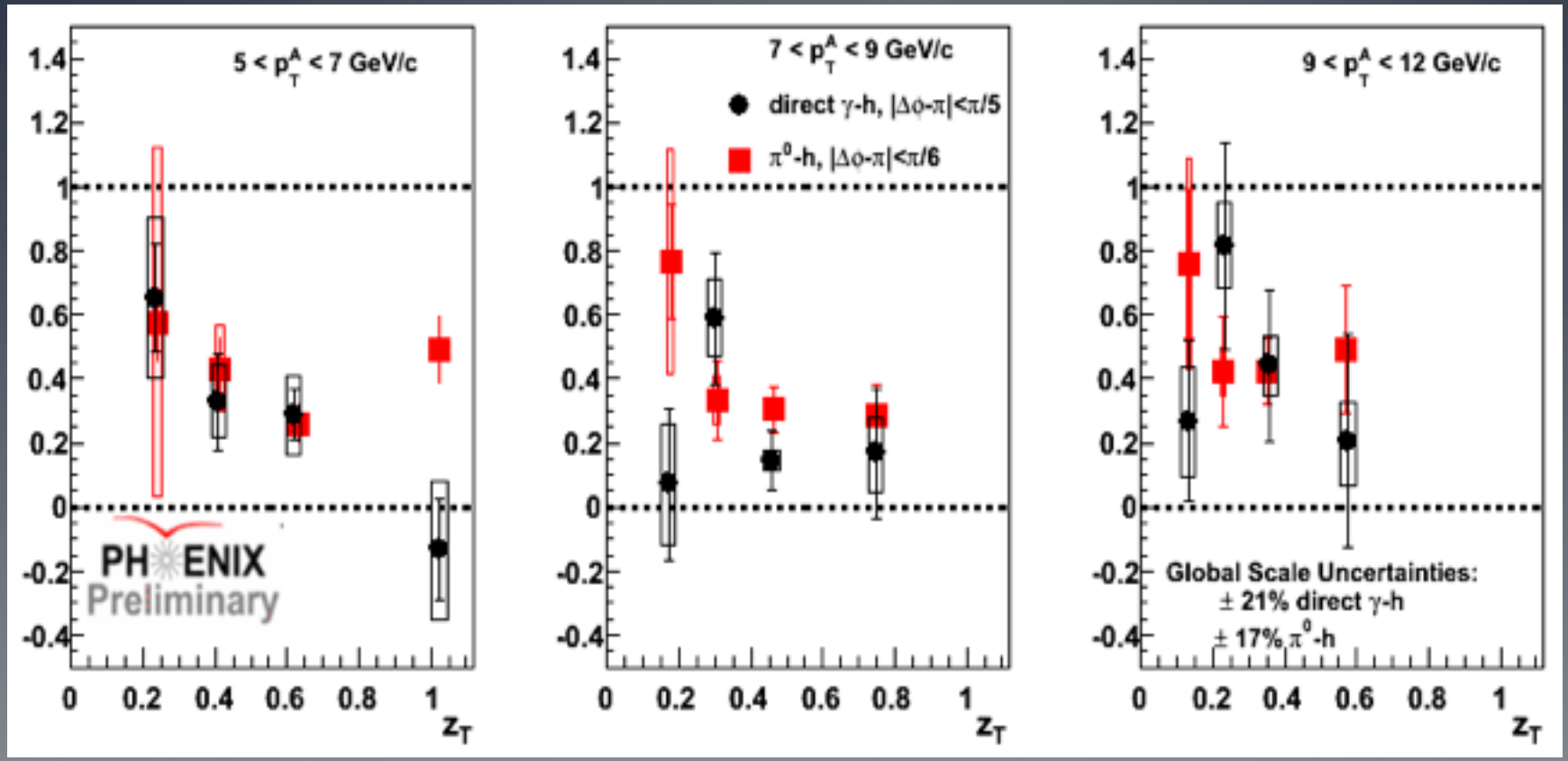
p+p slope = 6.89 ± 0.64

Au+Au slope = 9.49 ± 1.37



I_{AA} vs z_T for π^0-h and γ-h

- $z_T = p_T^h/p_T^\gamma$…note that $z \approx 1$ for γs, while $z < 1$ for π^0s.



- Comparable results except where $z_T \sim 1$. NLO component?

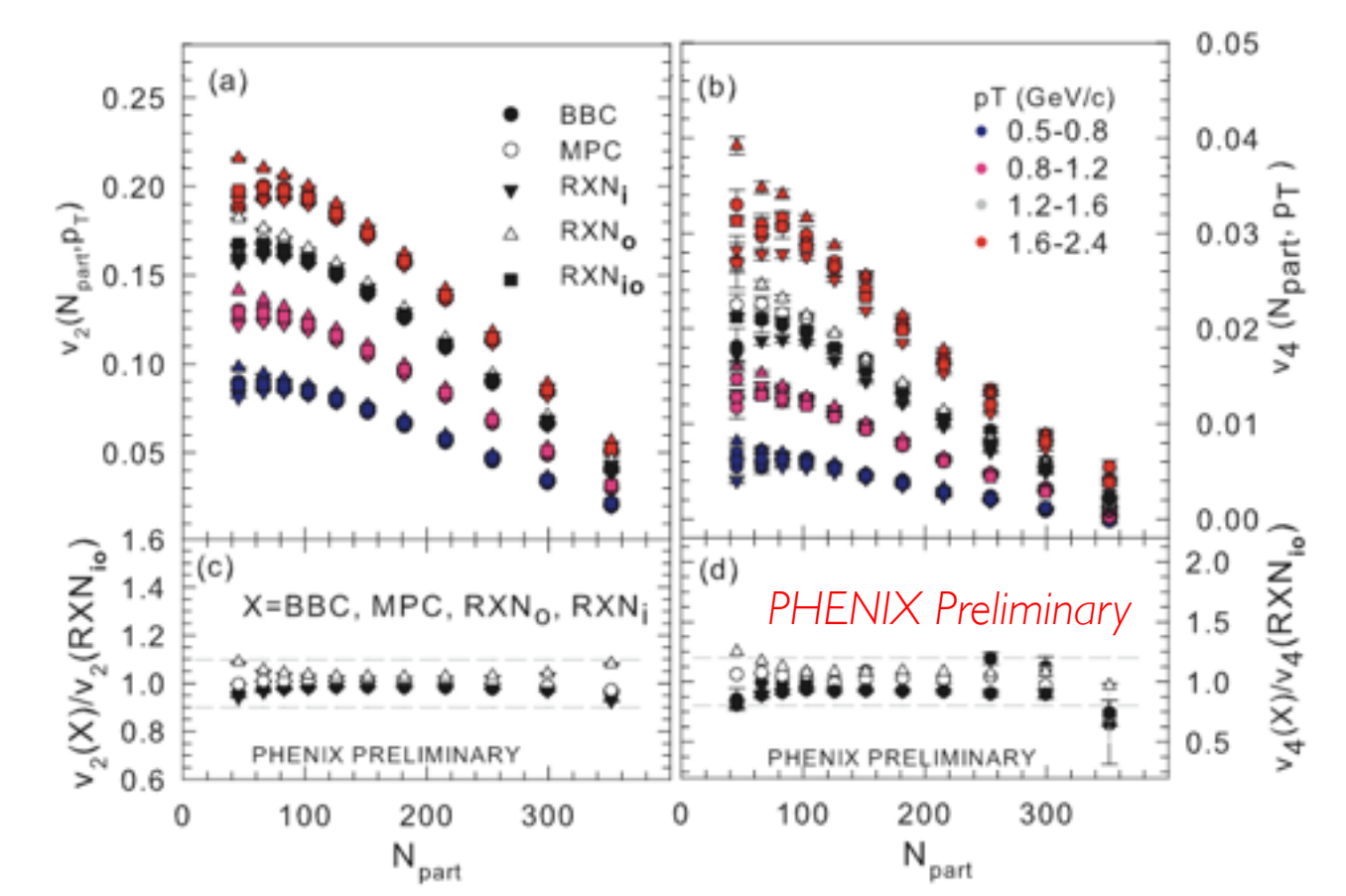
Global event characterization: azimuthal anisotropy

Precise v_2 and v_4 data

4 reaction plane detectors available in Run 7 give consistent results in wide η range.

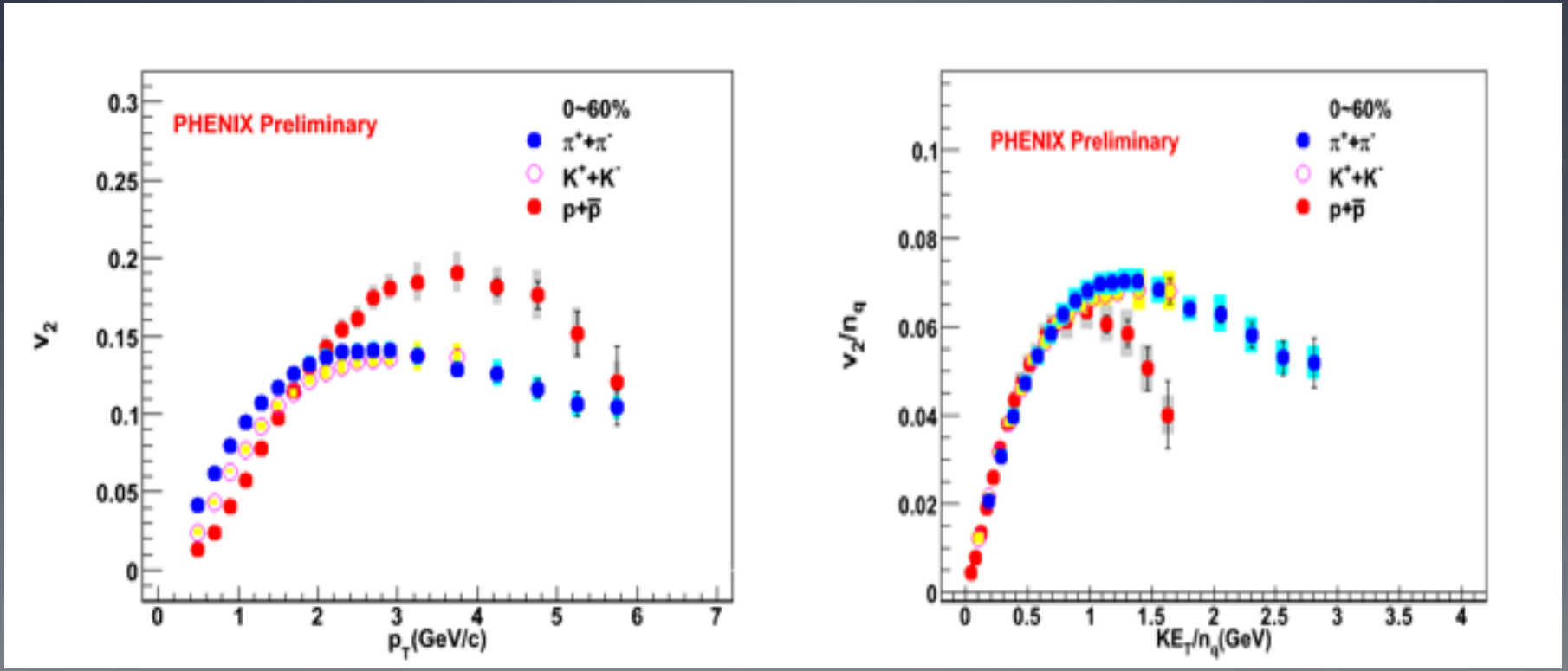
→ Strongly limits possibility of large η-dependent non-flow contributions.

- RXN_{in} ($1.5<|\eta|<2.8$)
- RXN_{out} ($1.0<|\eta|<1.5$)
- BBC ($3<|\eta|<4$)
- MPC ($3.1<|\eta|<3.9$)
- 5th RP value from RXN_{in+out}



Constituent quark scaling in v_2

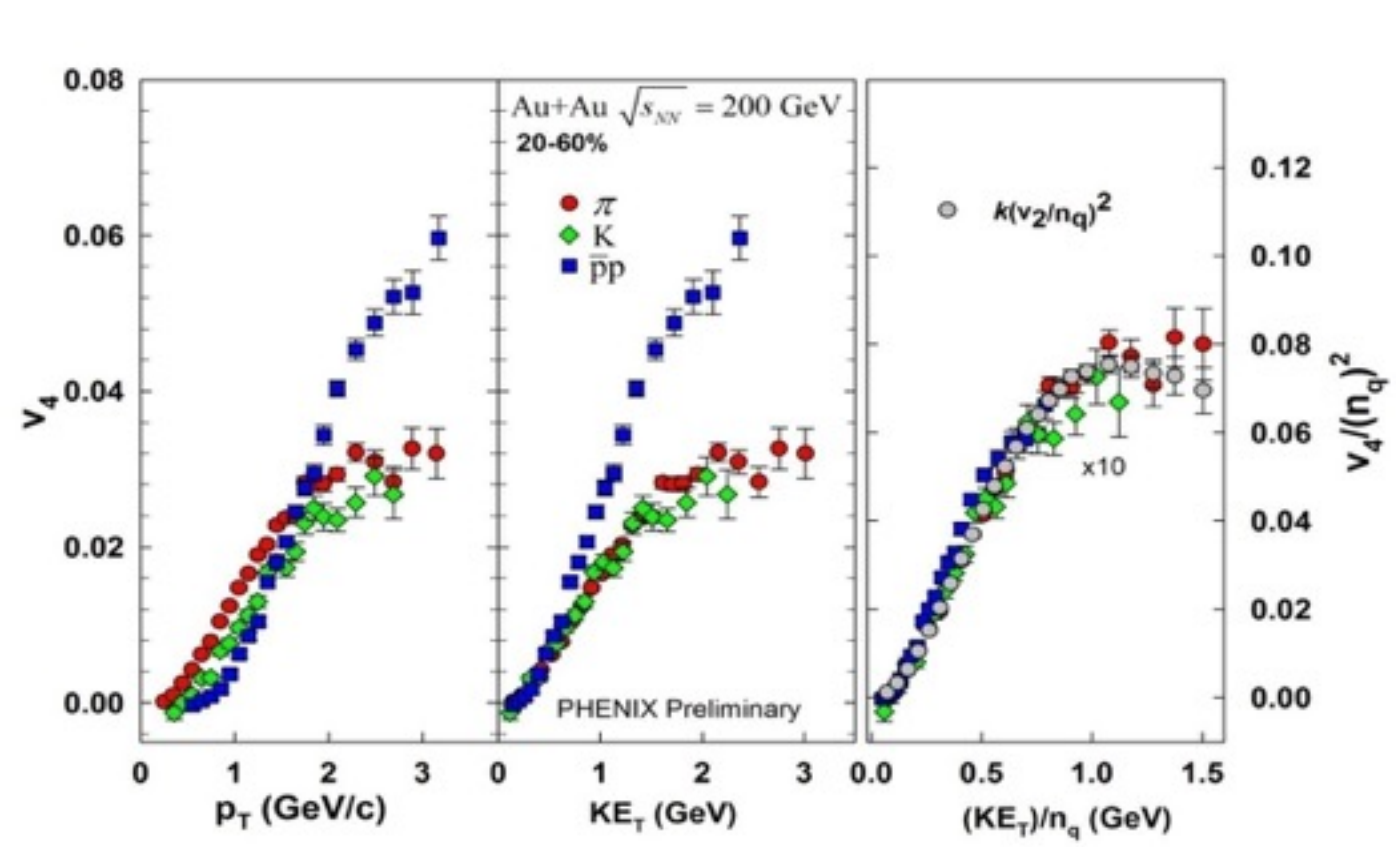
- CQN scaling observed up to $KE_T/n_q \sim 1$ GeV



- Mechanism for scale breaking not yet understood. Recombination?

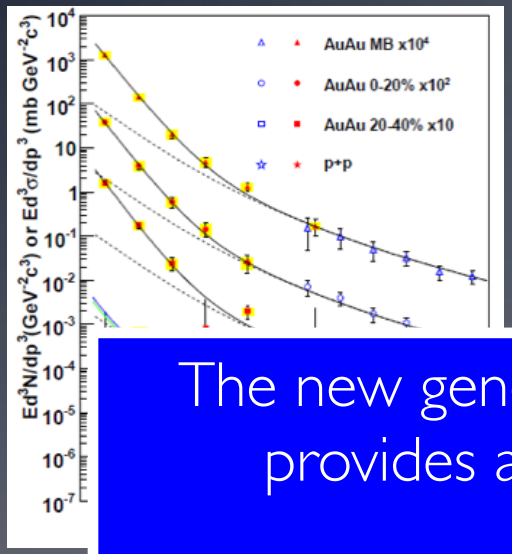
v_4 obeys CQN scaling too

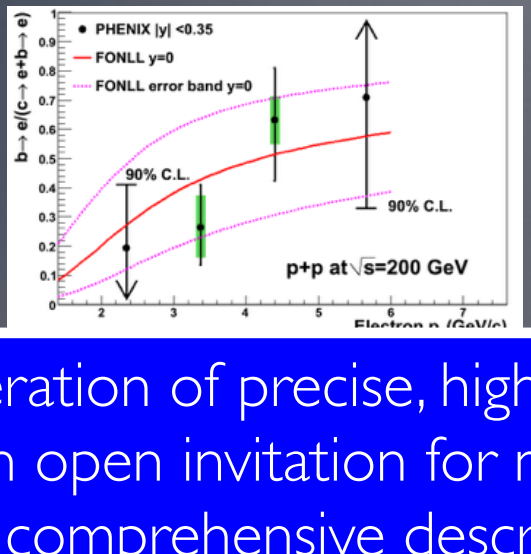
- New data provides precise target for viscous hydro, transport, and recombination models

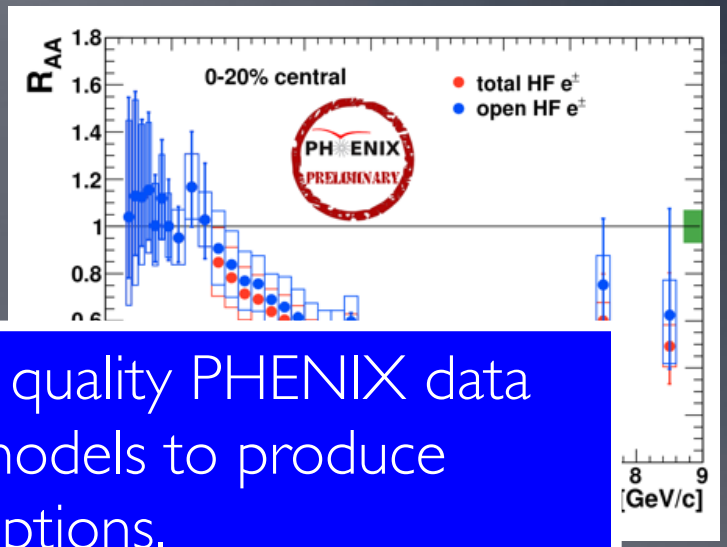


- Hybrid models parametrizing viscous corrections to hydrodynamics are under development (e.g. arXiv:0905.4368v2)

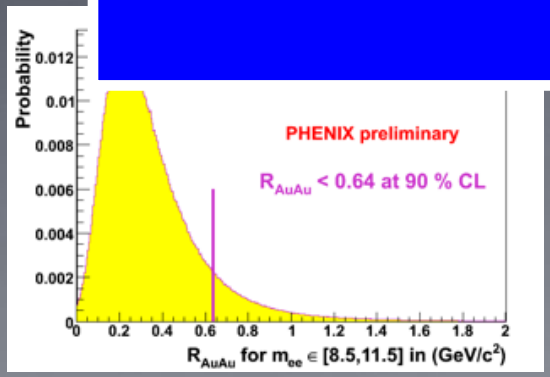
Strong evidence…the matter is

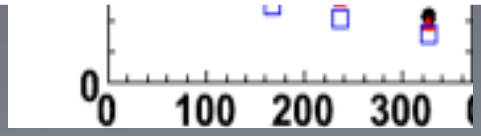


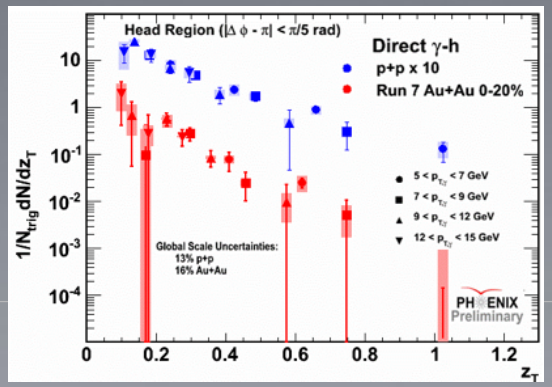


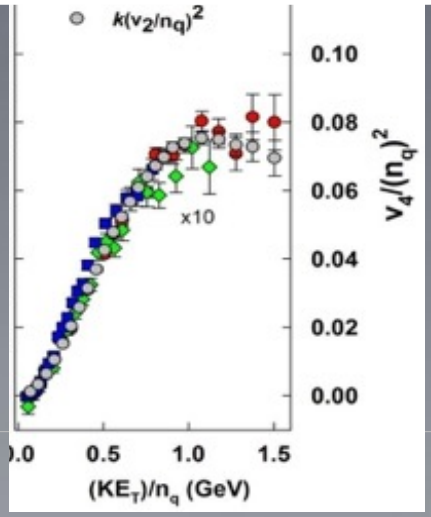


The new generation of precise, high quality PHENIX data provides an open invitation for models to produce comprehensive descriptions.
Good luck!









Hot

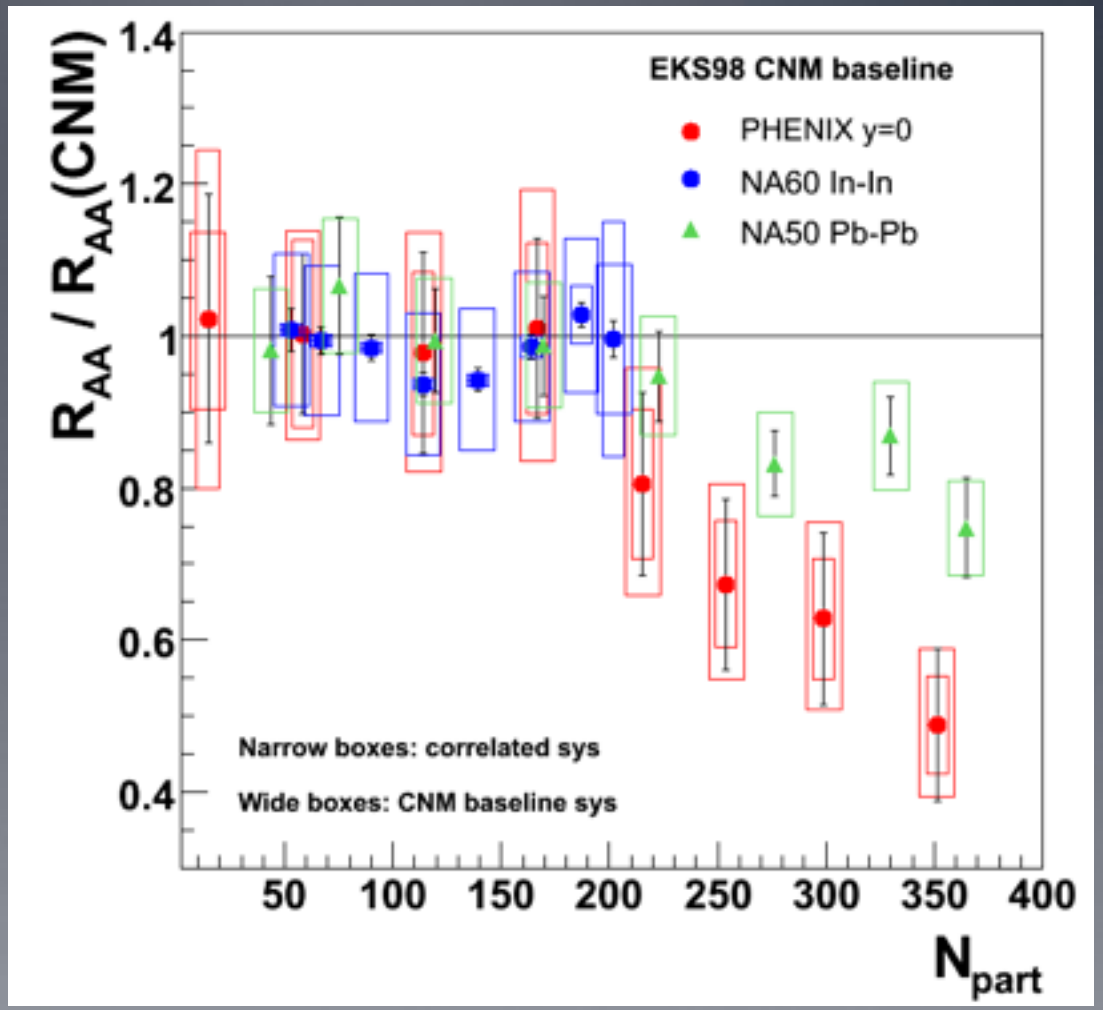
Strongly opague

Flowing at partonic level

Extras

J/ψ "survival probability"

- Attempt to isolate hot nuclear matter effects in Au+Au: divide by R_{AA}(CNM) (from d+Au R_{cp}, Glauber, and EKS98)
- Result: J/ψs appear more suppressed at RHIC than SPS in central collisions.
- What about states with higher dissociation temperatures?



Should Υ's be Suppressed? (Mike Leitch, QM09)

Υ's long touted as a standard candle for quarkonia melting
- but what should we really expect?

	$R_{AuAu}(y=0)$
J/Ψ	0.425 ± 0.025 ± 0.072
M_{e+e-}= [8.5,11.5 GeV]	< 0.64 at 90% C.L.

- σ_{abs} of Υ probably ~1/2 of that for J/Ψ – E772 *(PRL 64, 2479 (1990))*
  - E772 Υ nuclear dependence corresponds to R_{AuAu} = 0.81

- Lattice expectations in Au+Au - Υ_{2S+3S} suppressed: R_{AuAu} = 0.73

- **absorption x lattice ~ 0.73 x 0.81 ~ 0.60 ??? –** but need serious theory estimate instead of this naïve speculation!
  - e.g. Grandchamp et al. hep-ph/0507314

Other considerations:
- Υ in anti-shadowing region (for mid-rapidity)

- CDF: 50% of Υ from χ_b for p_T>8 GeV/c - but less (25%?) at our p_T
  - *PRL84 (2000) 2094, hep-ex/9910025*

Old summary

More justified than ever in claiming existence of a new state of matter. Picture is clarified every year and PHENIX has exciting progress to confirm and measure QGP properties

- Therm. phot: QGP above T_c → implies deconfinent
- deconfinement further confirmed by quarkonia suppression
- b quarks are a big contribution at high pT, even they lose energy
- gaining more precise info on L dep. of E loss

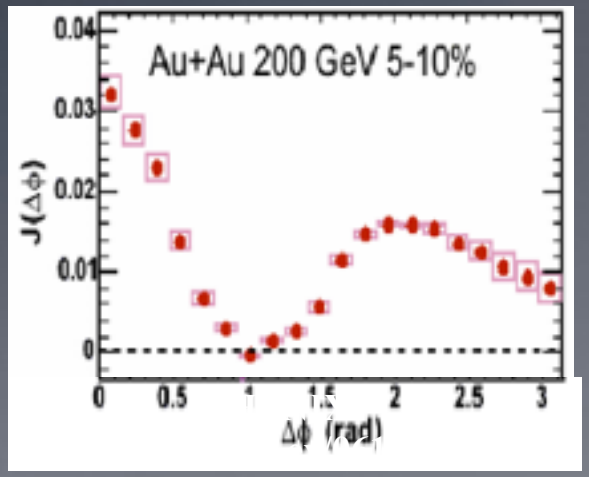
getting more detail on medium response

moving towards direct measurements of modified D(z) with gamma+jet

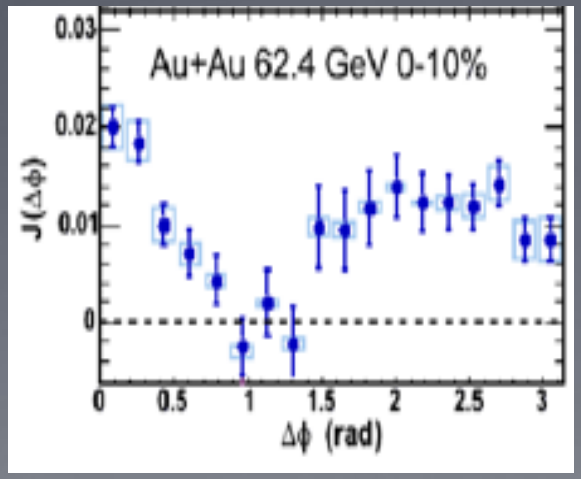
Where is the energy going?

- Shoulder structure in dihadron correlations persists to low beam energies – coherent medium response at $\sqrt{s}$ = 17 GeV??

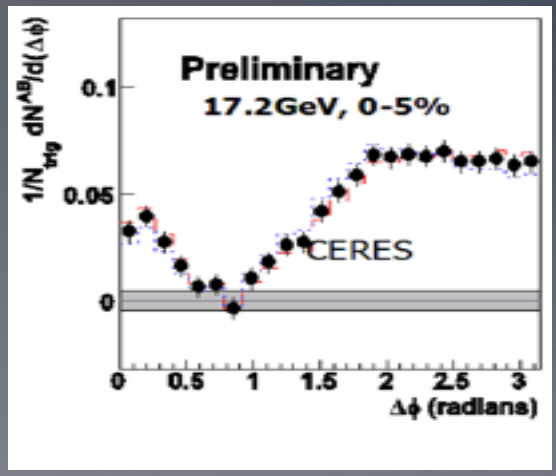
RHIC 200 GeV



RHIC 62 GeV



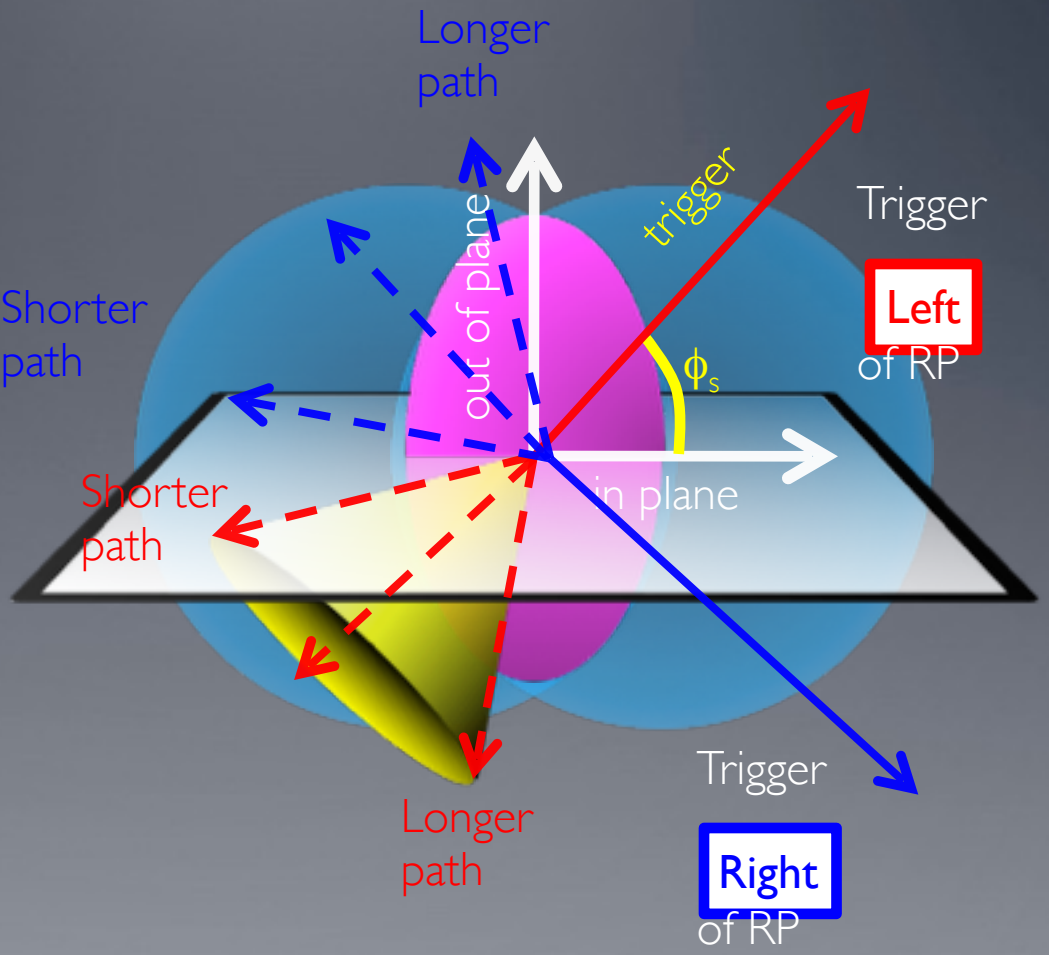
SPS 17 GeV



- Try looking at dihadron correlations vs reaction plane…

Left-right asymmetry

- In previous plot, ϕ_s was folded into [0, 90°]. But path length is asymmetric for particles in away-side cone
- Flipping $\phi_s \rightarrow -\phi_s$ reverses this asymmetry
- Provides direct info on path-length dependence of medium response



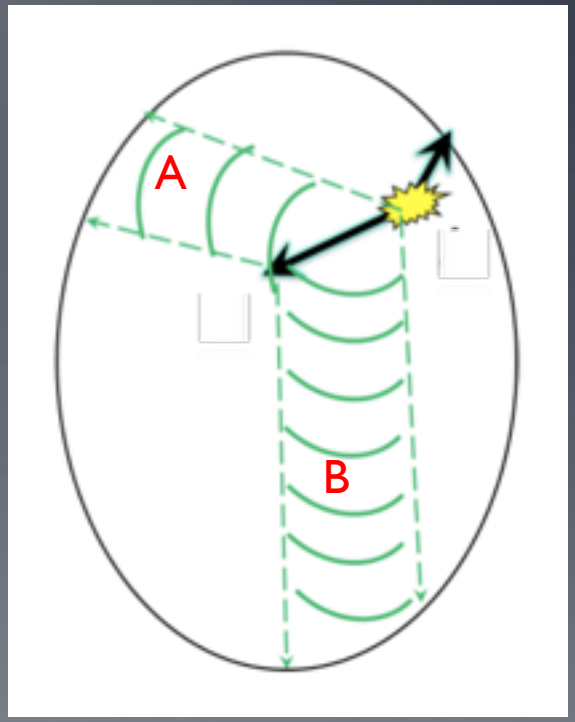
Expectations for conical ansatz

Two opposite scenarios for shoulder regions:

1. The medium attenuates radiated gluons, so B more suppressed than A
2. Medium pushed outward by radiated gluons, so B more enhanced than A

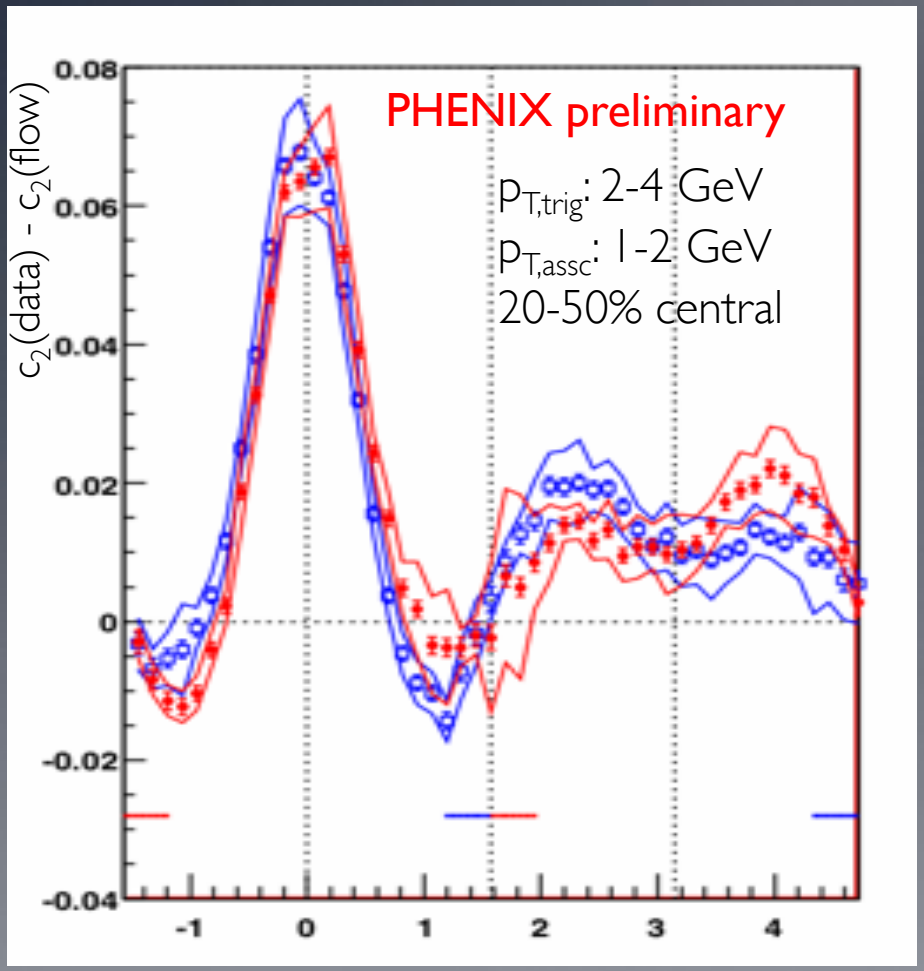
Also, note that fixing ϕ_s

- strengthens flow contribution (v_4 important now)
1. shifts phase of v_2 by $2\phi_s$

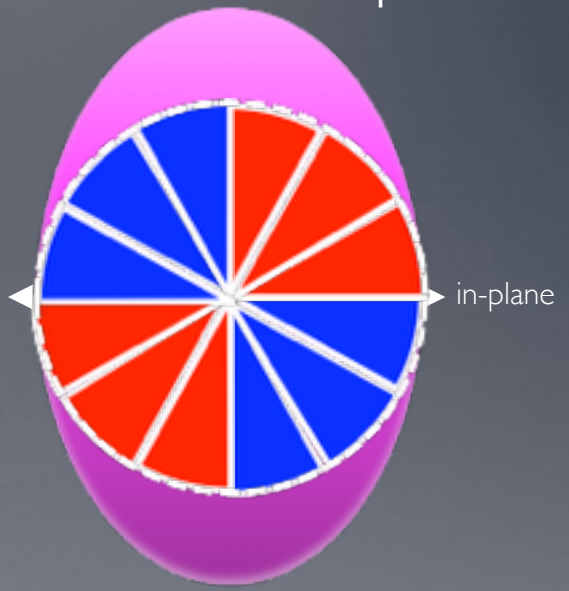


J. Jia et al, hep-ph/0903.3263

Au+Au $h^{\pm}$-$h^{\pm}$ L/R asymmetry



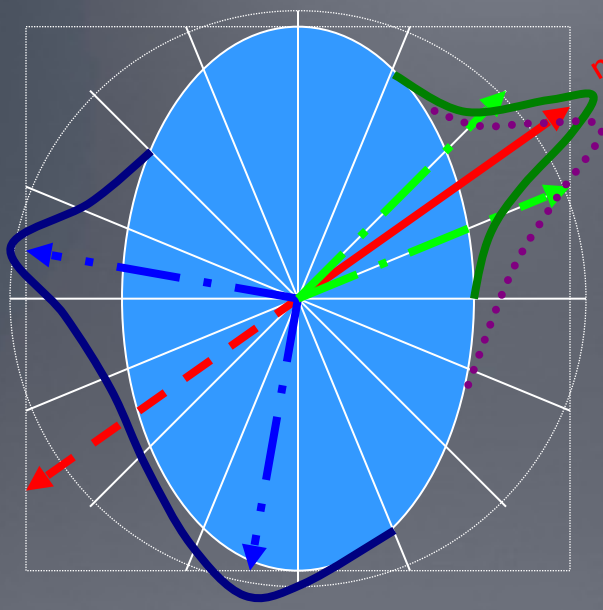
$\Delta\phi$ bin width = $\pi/8$



- Data support expectation #1 for in-plane triggers
- Out-of-plane interpretation less clear

thin side

mach-cone
(shoulder region)
$\phi_{ASSO}-\phi_{TRIG}>0$



near side
(trigger direction)

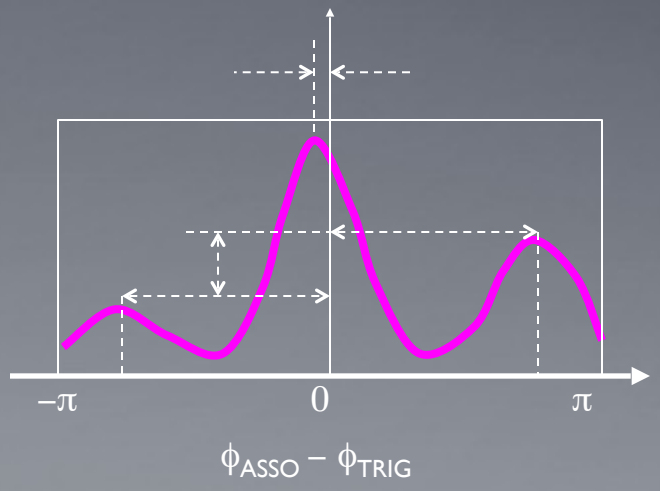
$\phi_{ASSO}-\phi_{TRIG}<0$

away side
(head region)

mach-cone
(shoulder region)
$\phi_{ASSO}-\phi_{TRIG}<0$

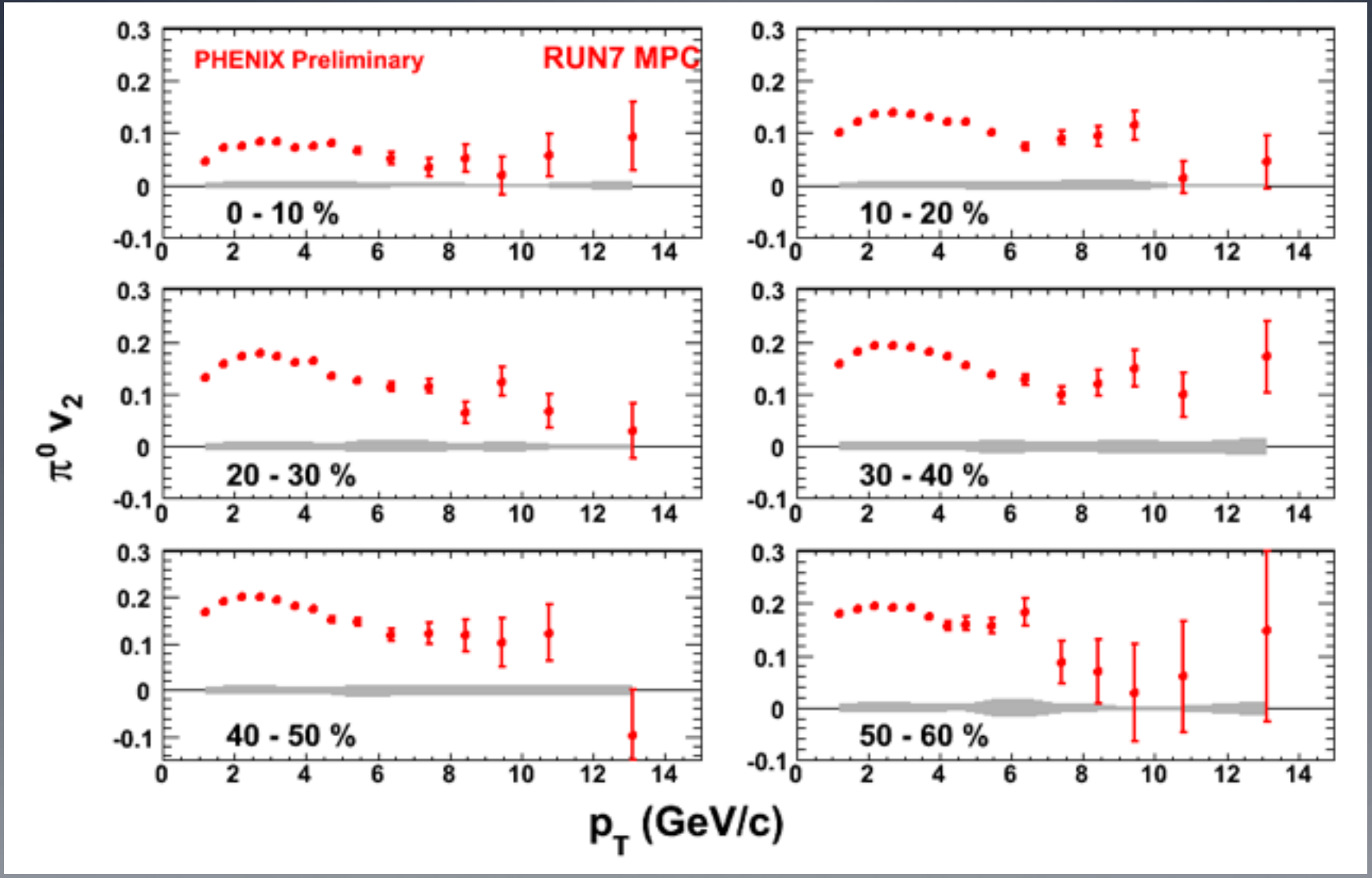
thick side

Trigger angle selected with respect to the **2nd moment event plane** $[-\pi/2,\pi/2]$ to probe the participant geometry



If trigger angle is fixed around $+/-(\pi/4)$, the associate particles emitted left or right w.r.t. trigger direction would feel the different thickness of the almond. It is because the almond shaped medium is asymmetric w.r.t. jet axis.

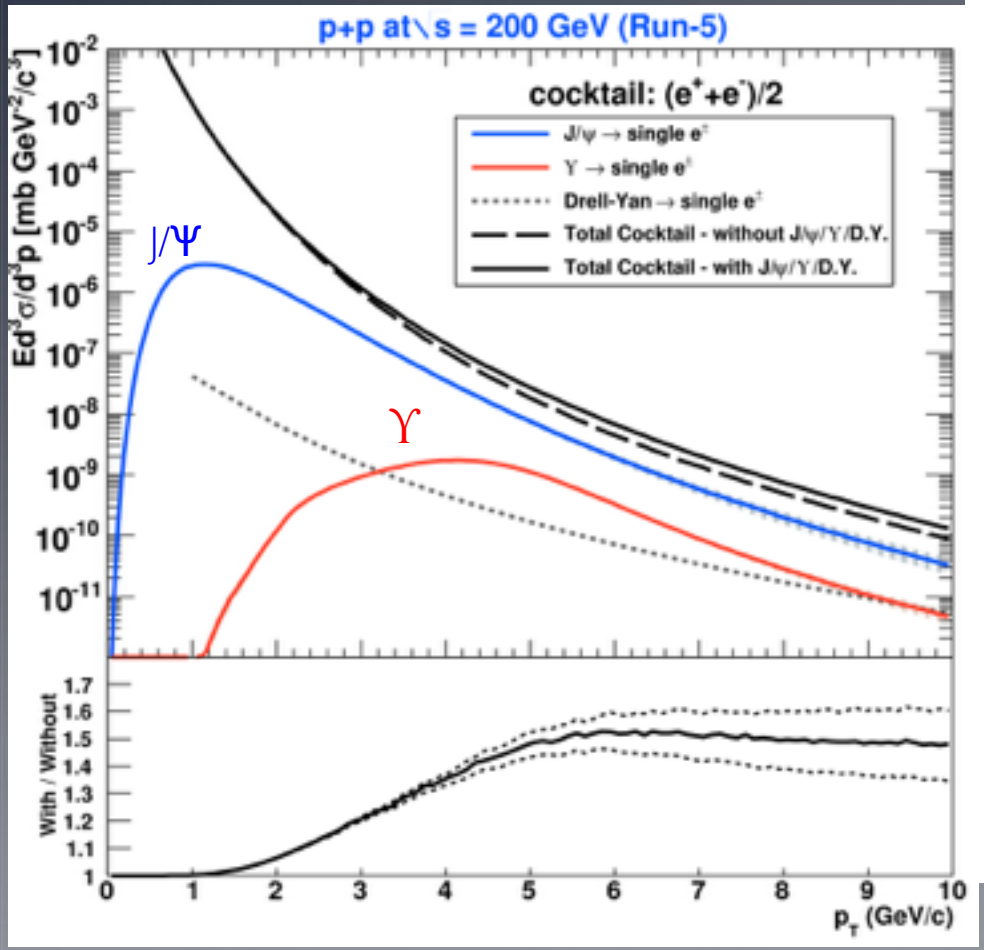
Neutral pion v2 from MPC

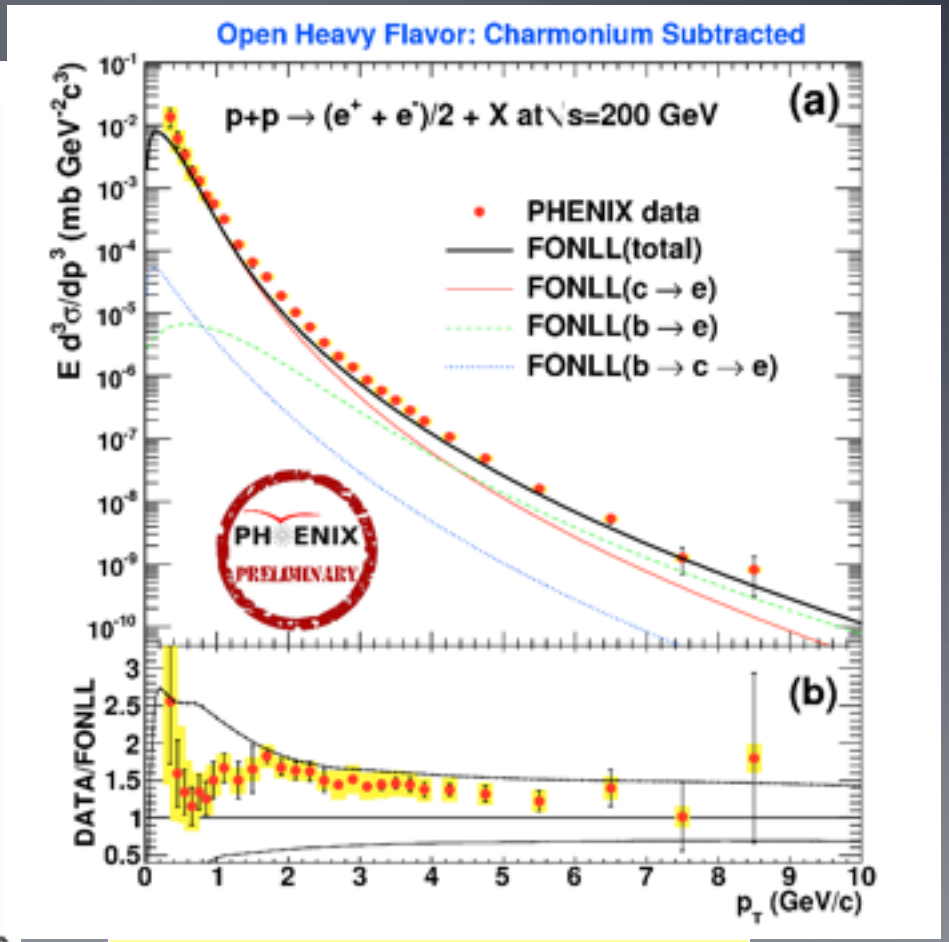


Quarkonia Contributions to high-p_T heavy-quark electrons in p+p!

p+p collisions:

- up to 16% decrease in open heavy for $p_T > 5$ GeV/c
- similar story for Au+Au & R_{AuAu} not significantly changed





Talk: A. Dion (5D, Fri)

Cocktail correction

- Prior to QM09, cocktail was underestimated due to neglect of J/psi and upsilon DY contributions.
- Accounting for these increased the cocktail by 50%.
- This does NOT imply that the signal went down by 50%!

Rapidity-separated dihadron correlations

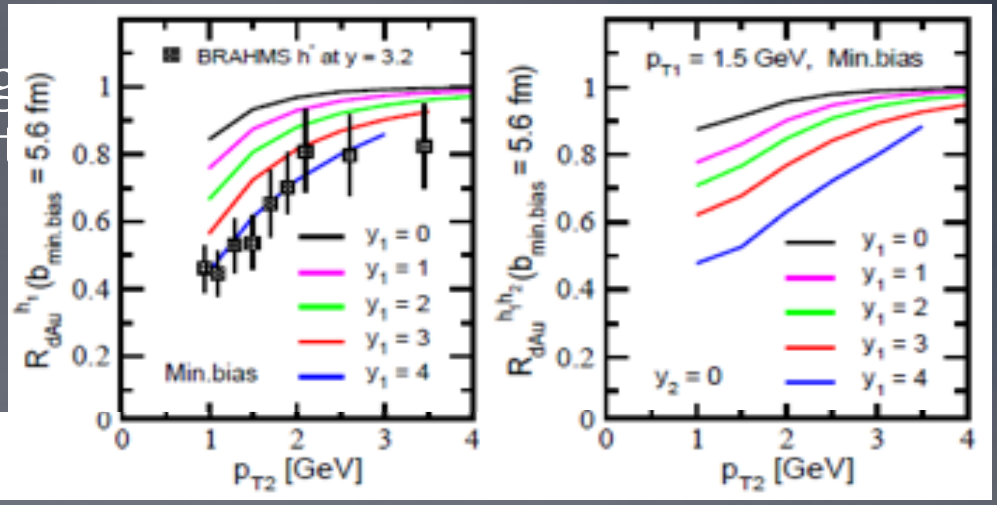
Forward jet pair modification

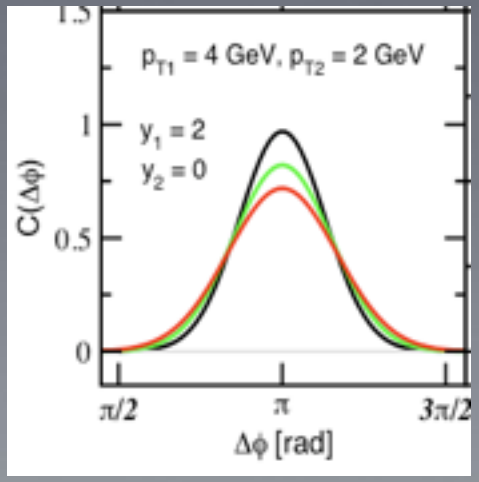
Qiu, Vitev:

- coherent multiple scattering leads to suppression for bot singles and pairs—at comparable levels
- →Implies IdAu ~ 1 (however ML did not seem to agree in an email)
- broadening predicted [what level? be quantitative]

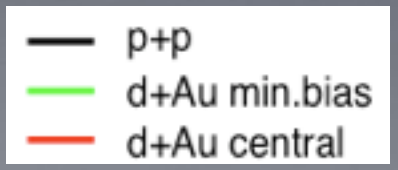
Single hadron RdAu

Dihadron RdAu





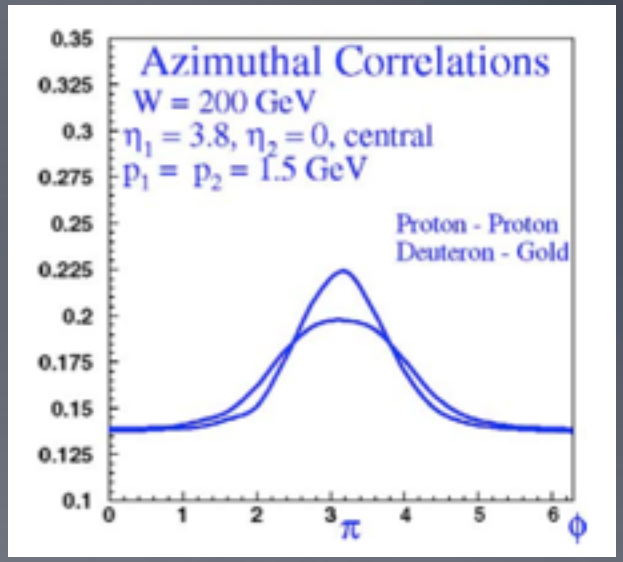
hep-ph/0405068



Forward jet pair modification

CGC picture:

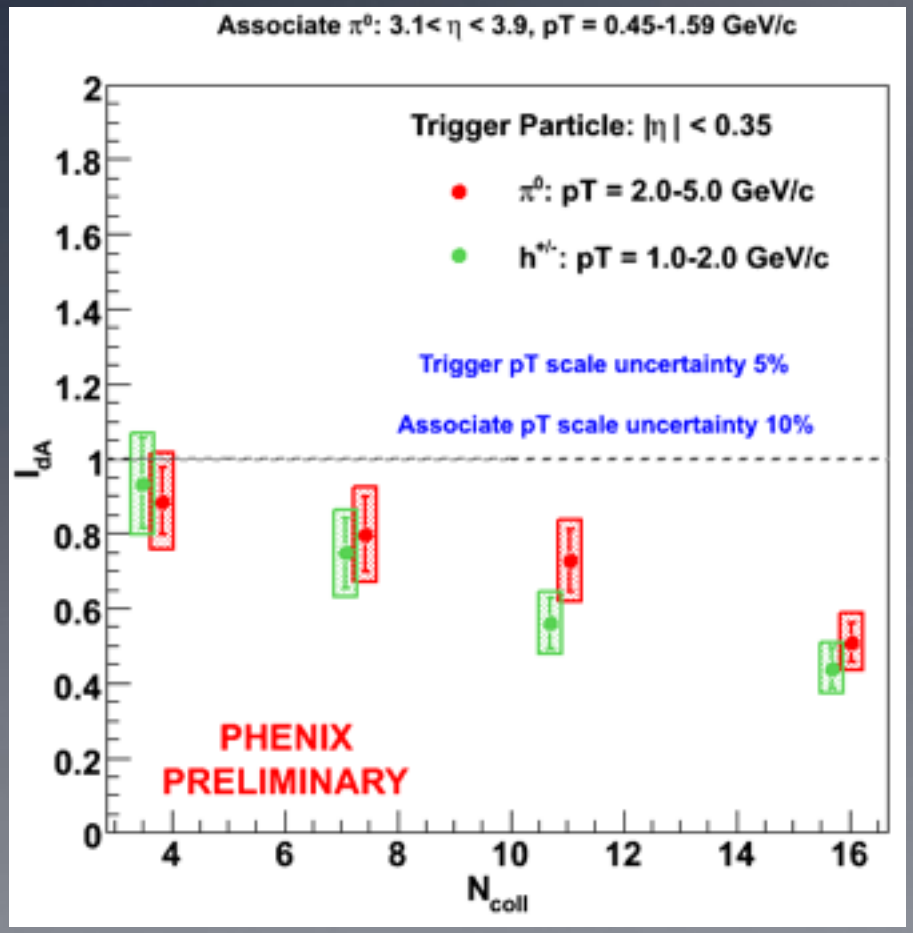
- recoil jet absorbed by many gluons
- predicts strong pair suppression (small ldAu)
- Again, only very small width enhancement



Get this ref from ML, or some ref that shows IAA in CGC framework

Levin, Kharzeev, McClerran
Nuc. Phys A 748, 627 (2005)

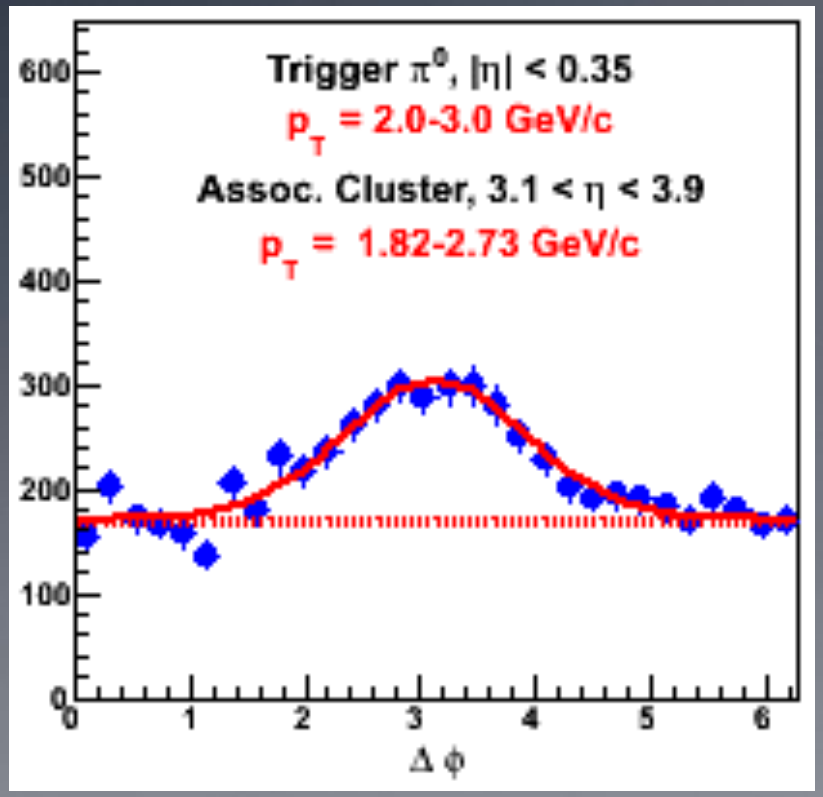
Suppression in d+Au

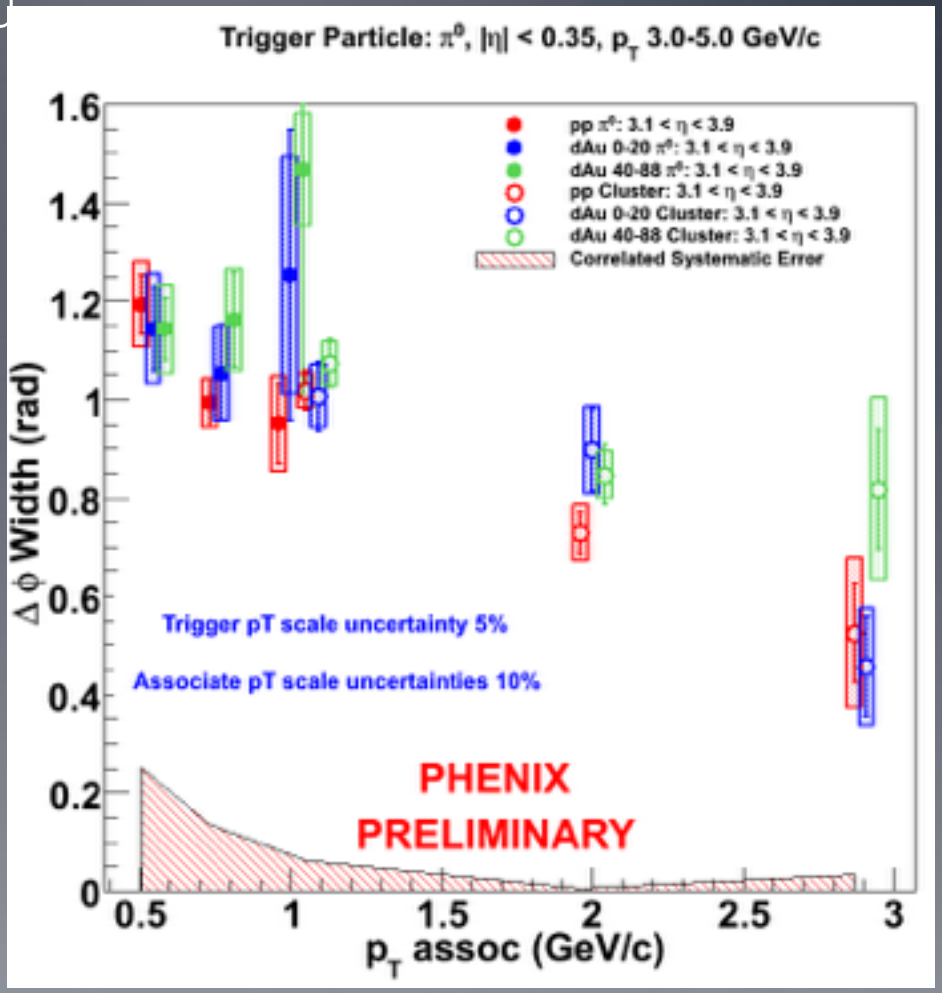


- larger than vitev predicts

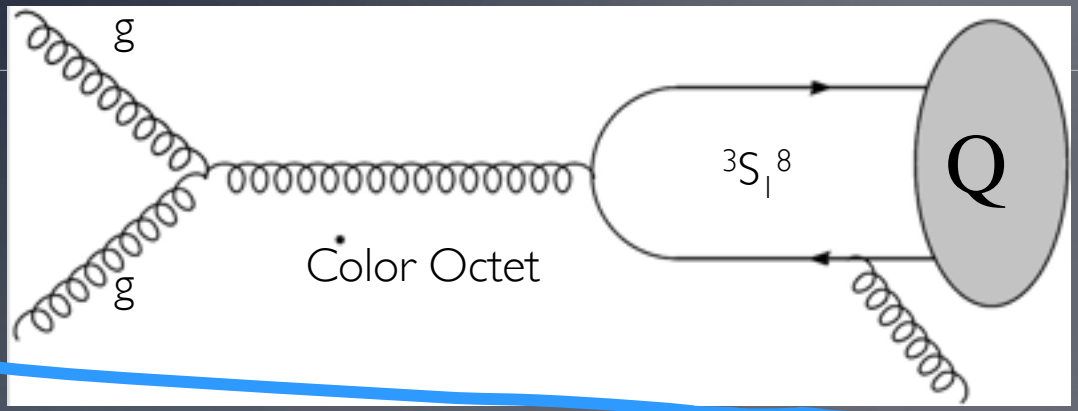
Jet widths in d+Au

No broadening in central d+Au vs. p+p at 1 sigma

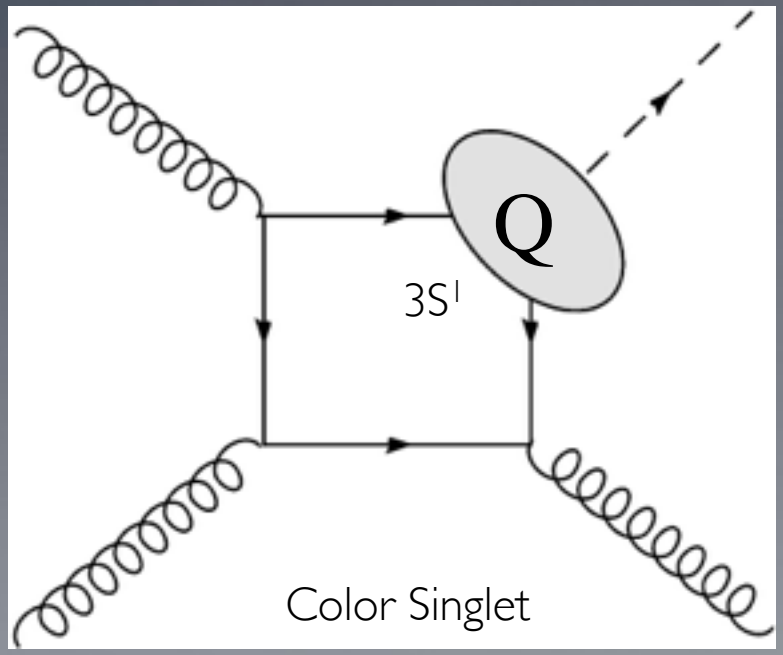




Understanding polarization (from Alex)

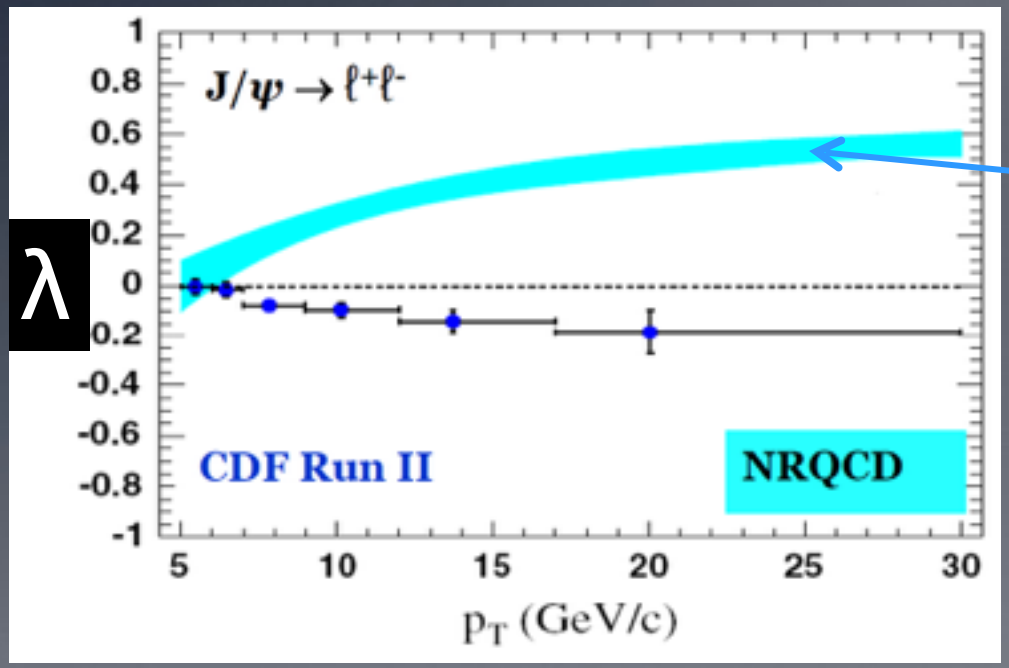


- High p_T gluon nearly on mass shell → transverse polarization.
- Octet quarkonia inherits transverse polarization of gluon.
- Spin symmetry of non-relativistic heavy quarks implies suppression of spin flip.

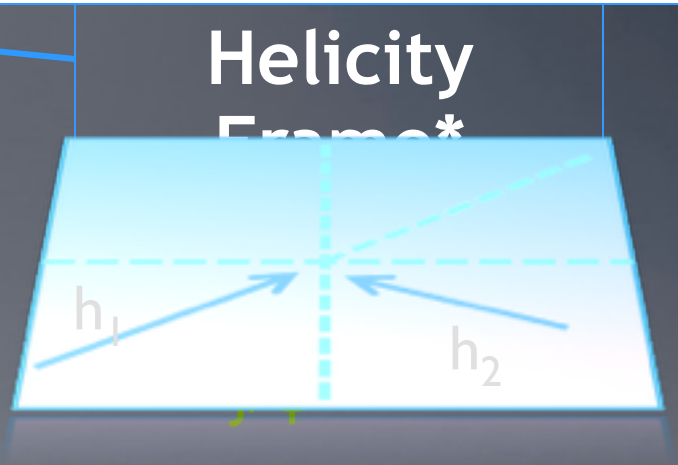


- No strong correlation between initial gluon polarization and final state.
- Washed out by hard gluon emission in final state.

Measuring Polarization (from Alex)



$$\frac{dN}{d\cos\theta} = A(1+\lambda\cos^2\theta)$$



Q Rest Frame

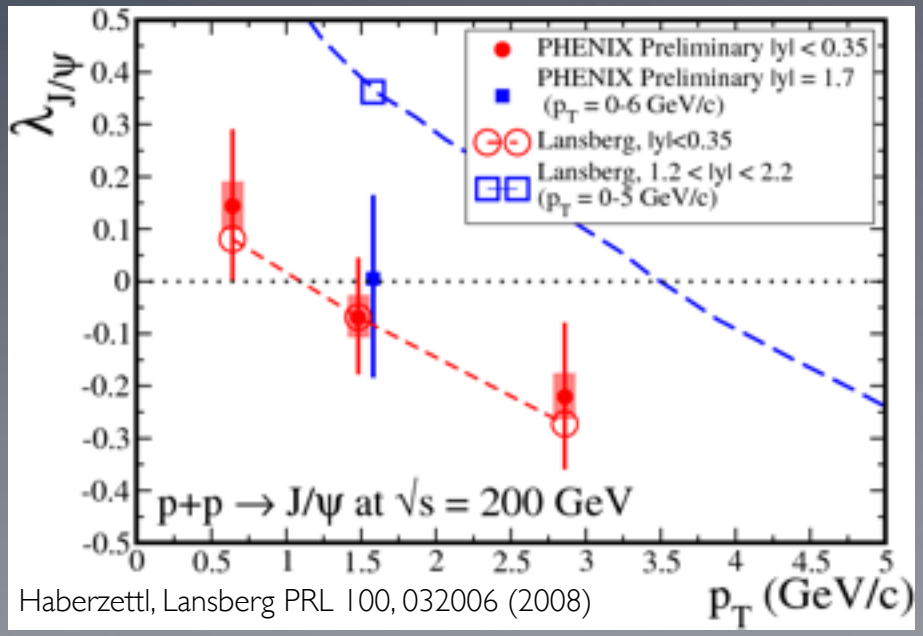
COM LO disagrees with CDF data!(PRL 99, 132001)

Addition handle on production.

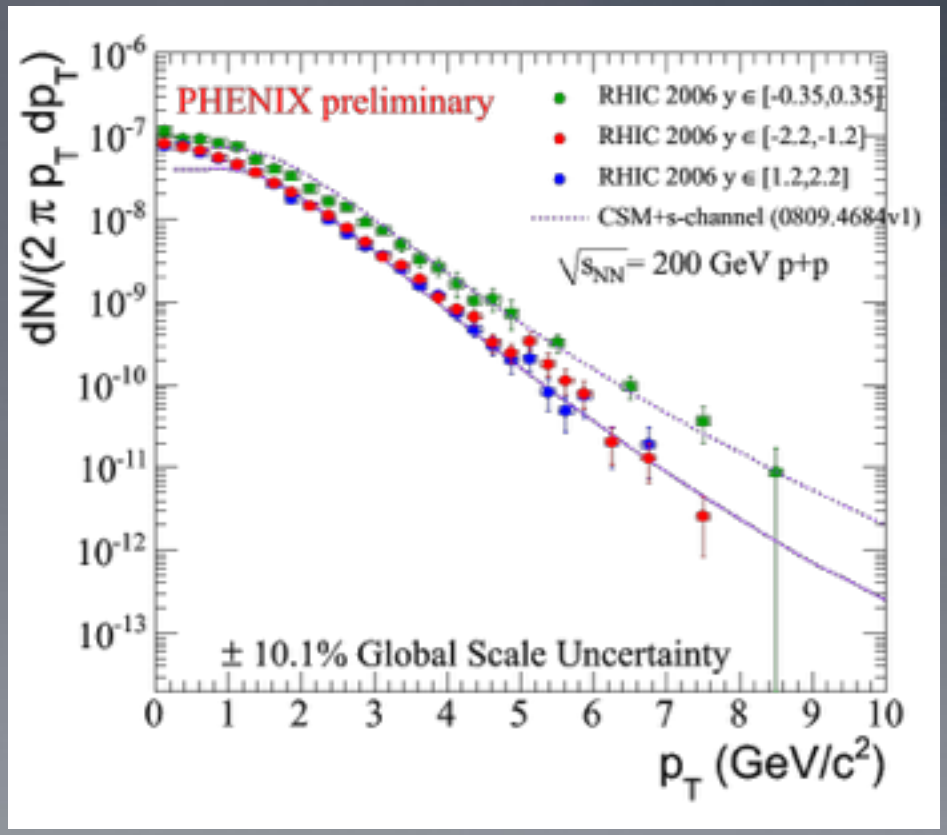
* see arXiv:0902.4462 for discussion of reference frames

Testing the CSM in p+p

- Improved s channel modified CSM agrees w/ p_T spectra and polarization at y=0, but disagrees (at 2-3 σ level) at forward rapidity



Haberzettl, Lansberg PRL 100, 032006 (2008)

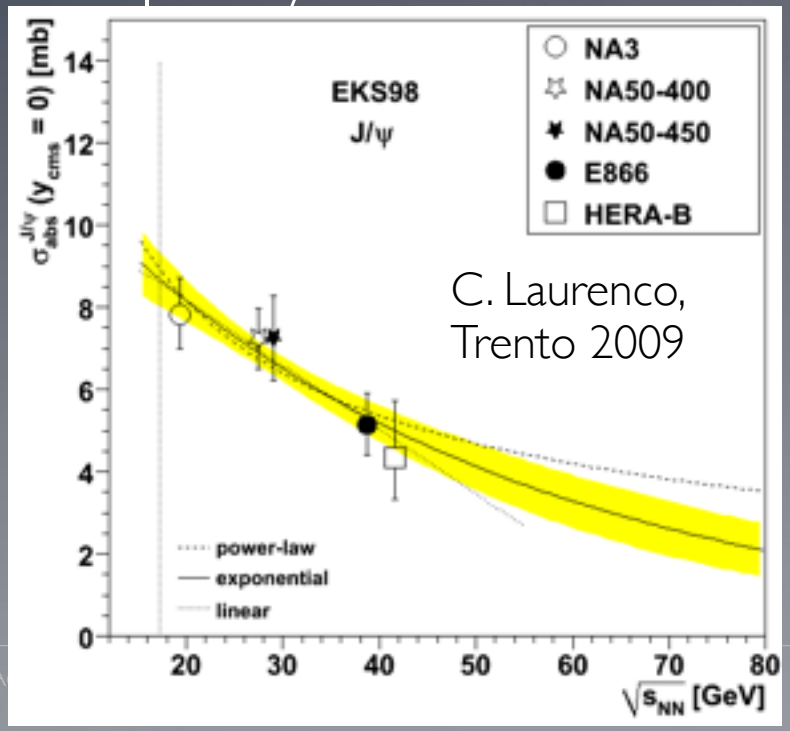


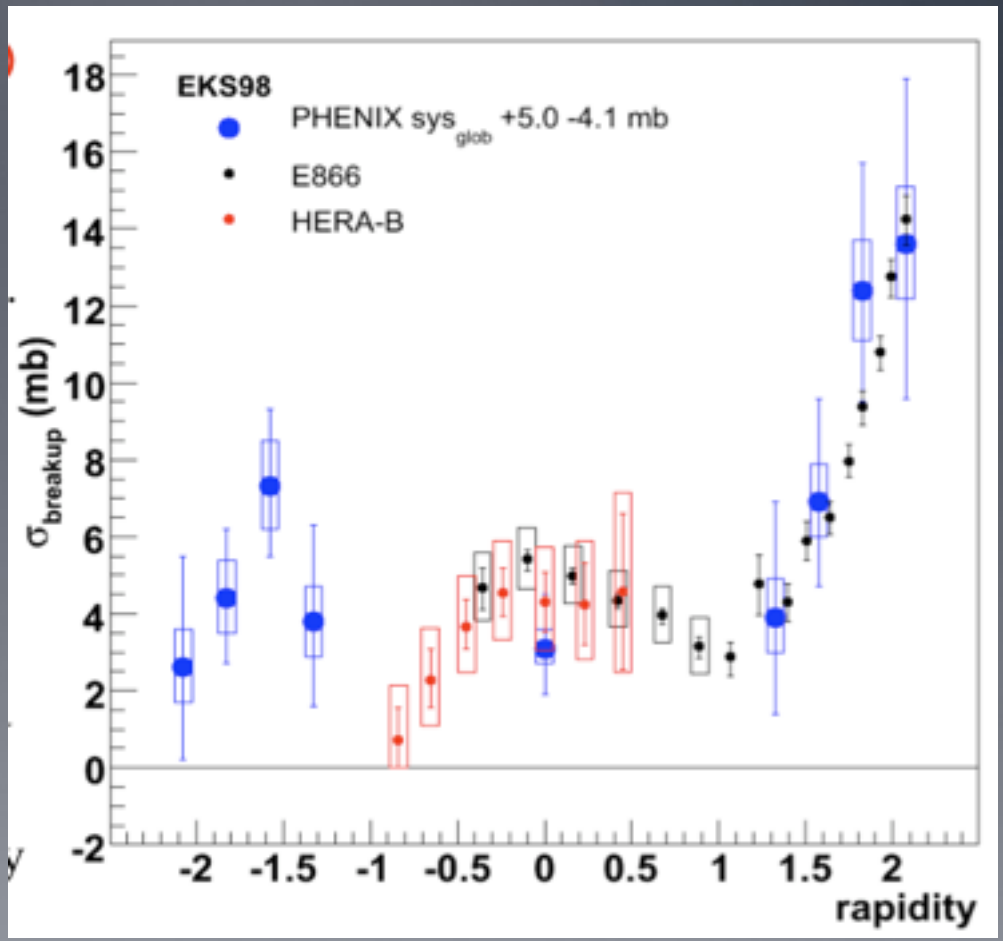
Constraining cold nuclear matter effects

This section is a candidate for removal if time is short.
Rich will cover d+Au in detail on Friday.

$\sigma_{breakup}$ independent of $\sqrt{s}$?

- 200 GeV breakup x-section agrees closely with E866 $\sqrt{s} \approx 39$ GeV)
- Seems to break trend at





J/psi survival probability