Recent Results from the Relativistic Heavy Ion Collider: a Perfect Liquid?

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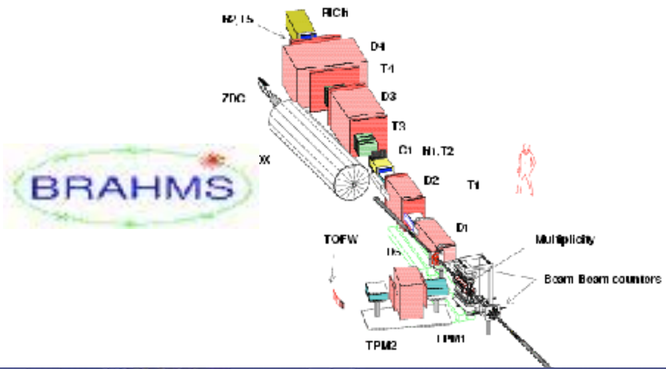
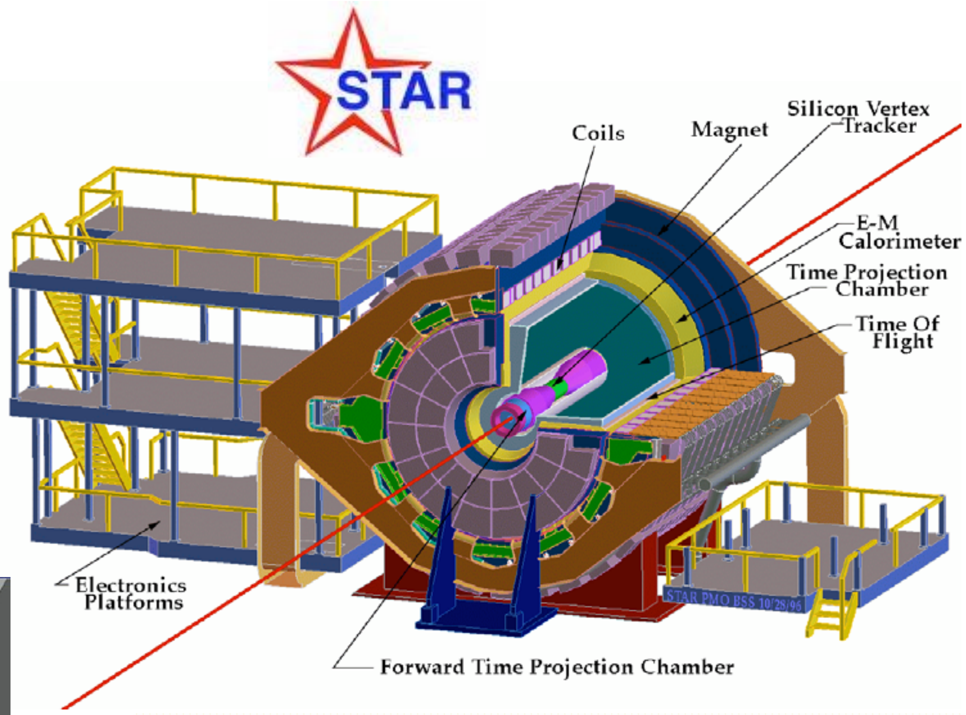
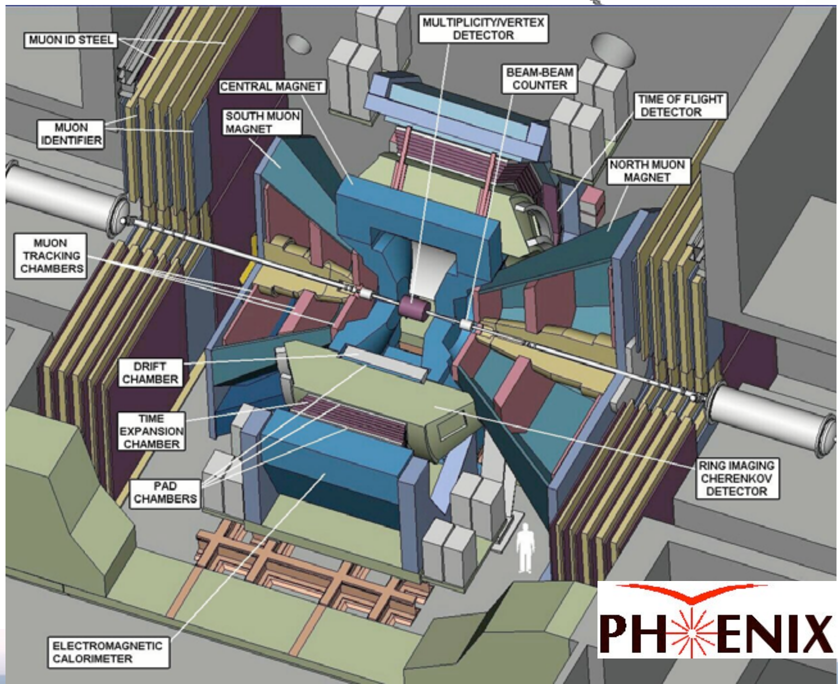
Introduction

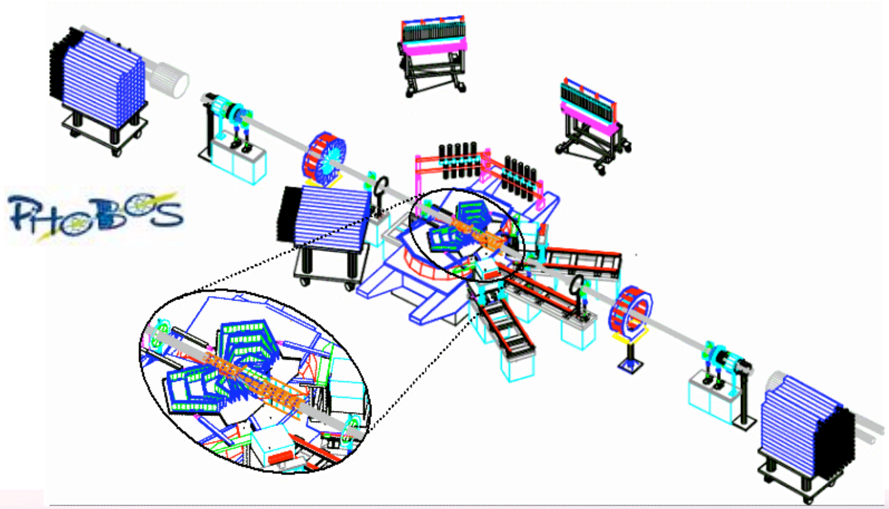
- RHIC experiments and programme
- Some useful concepts in HI studies
- Basic system properties
- The opaque medium
- Future directions

RHIC experiments









RHIC Programme - timeline

- 2000 started with $\sqrt{s}$ = 130 GeV Au+Au collisions
- 2001-2 first 200 GeV run with Au+Au & first p+p run
- 2003 d+Au at 200 GeV & p+p
- 2004 high statistics Au+Au 200 GeV run and 62 Gev Au+Au run
- 2005 Cu+Cu runs at 200 and 62 GeV & p+p
- 2006 p+p running
- 2007 Au+Au high luminosity run
- 2008 d+Au high luminosity and p+p
- 2009 first 500 GeV p+p run …

State of our current understanding from

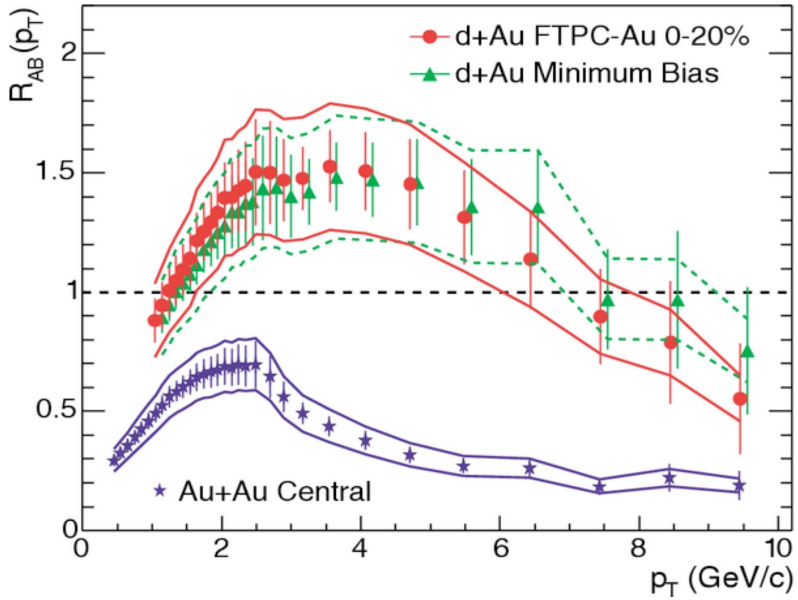
- I will present a selective snapshot
  - 600+ participants, 180+ talks
- All talks avaliable online
  - http://qm09.phys.utk.edu/indico/conferenceOtherViews.py?confId=1

Useful concepts

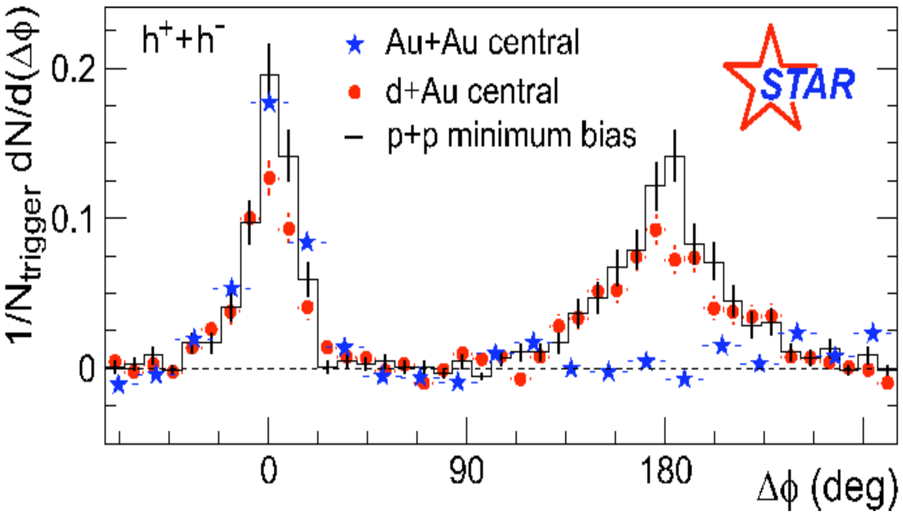
- (Pseudo)rapidity - longitudinal variable
- Transverse momentum p_T
  - Produced in collision (modulo initial k_T)
- Centrality - impact parameter in A+A
  - Experimentally based on observed multiplicity
  - Access to different eccentricities
- From centrality can calculate
  - the number of participant pairs N_{part}
  - The number of binary collisions N_{bin}
  - Eg central Au+Au: N_{part} ~ 350 but N_{bin} ~ 1000

High p_T and back-to-back suppression

Ratio to p+p



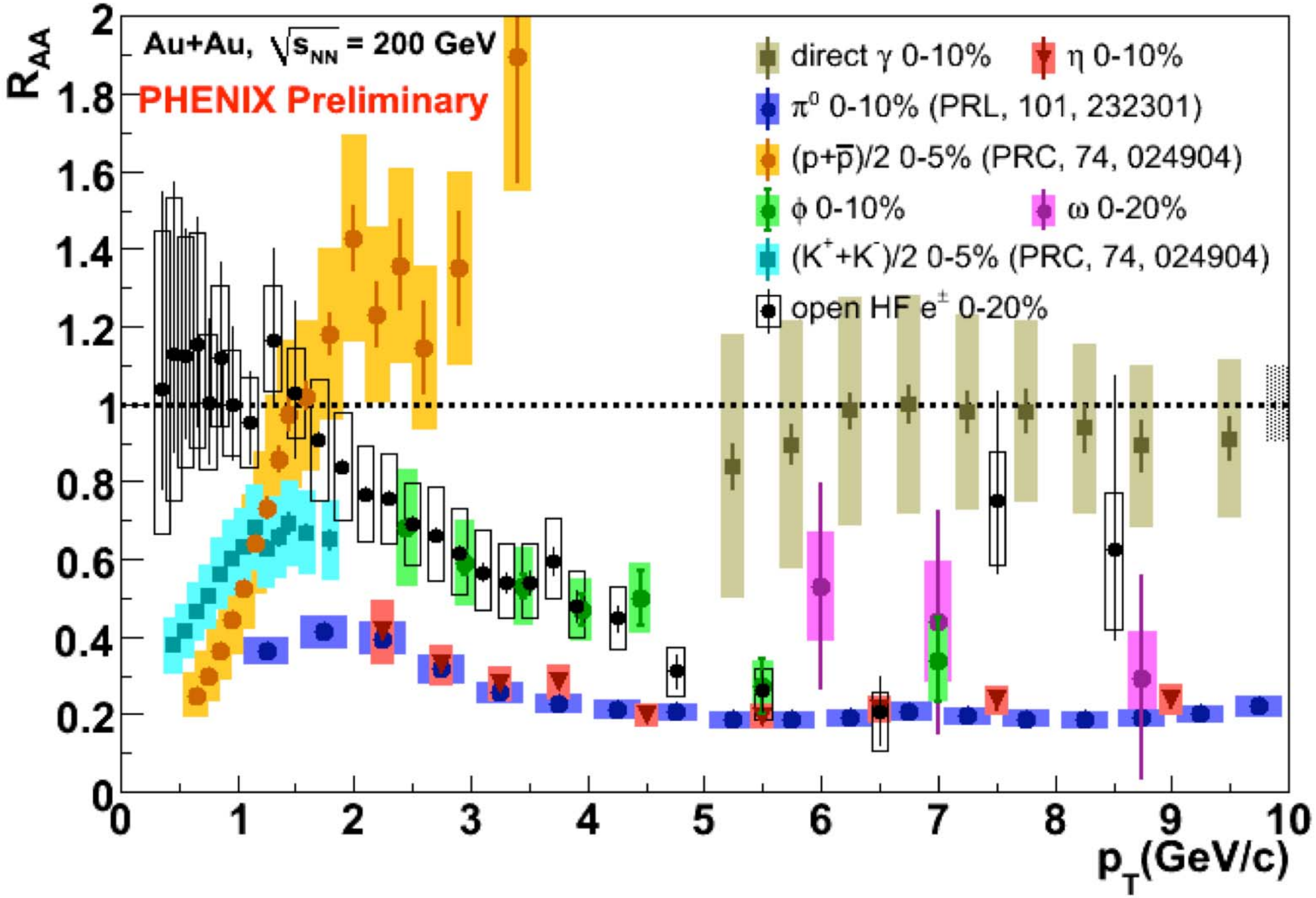
PRL **91** (2003) 072304



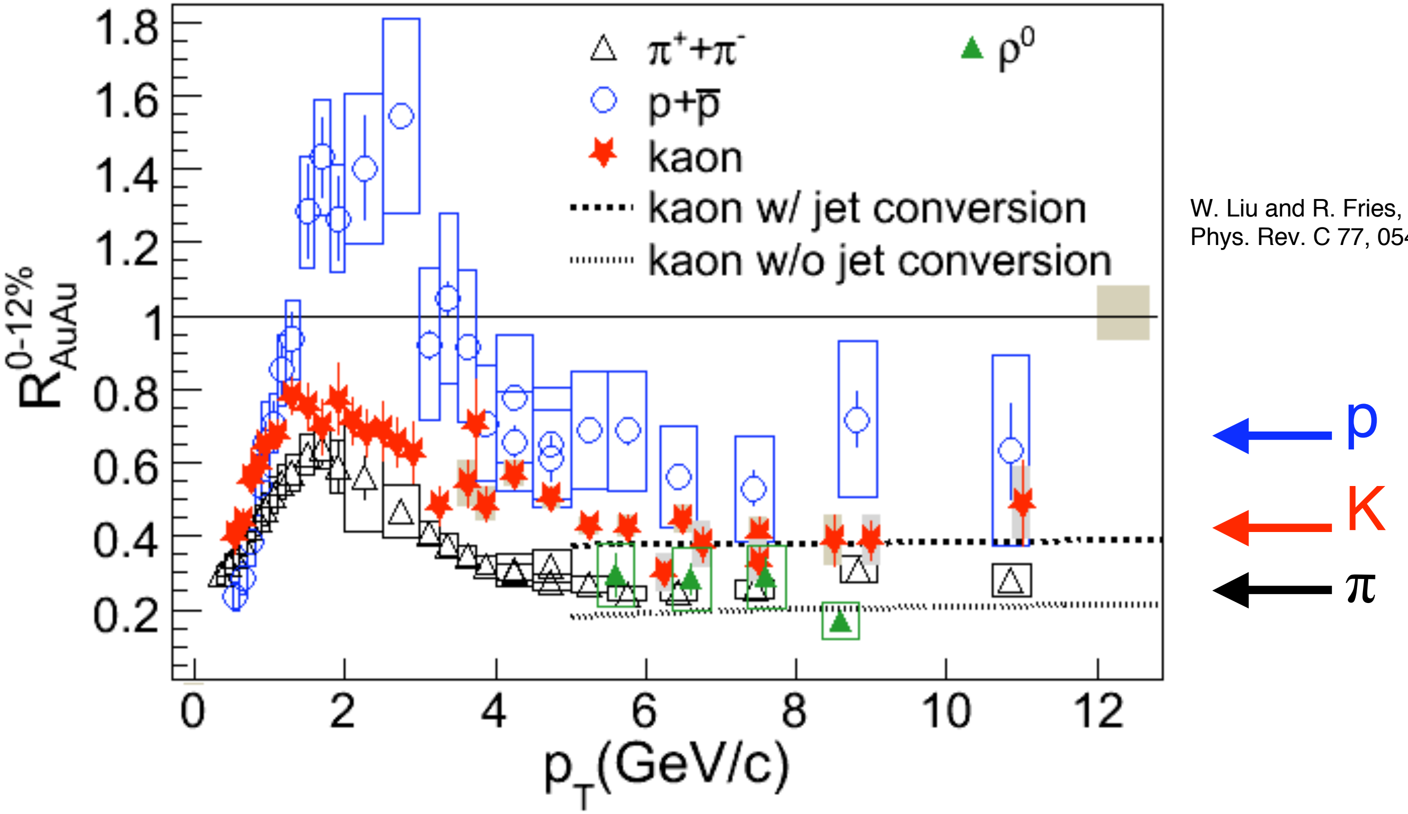
- Compare hadron spectra to p+p
  - d+Au and Au+Au scaled for system size
  - Central Au+Au factor 5 suppression at high p_T
- Absence of away side in back-to-back Δφ correlation

Sample of R_{AA} in PHENIX

$$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\mathrm{Yield}_{pp}}$$



Jet flavour conversion in Au+Au

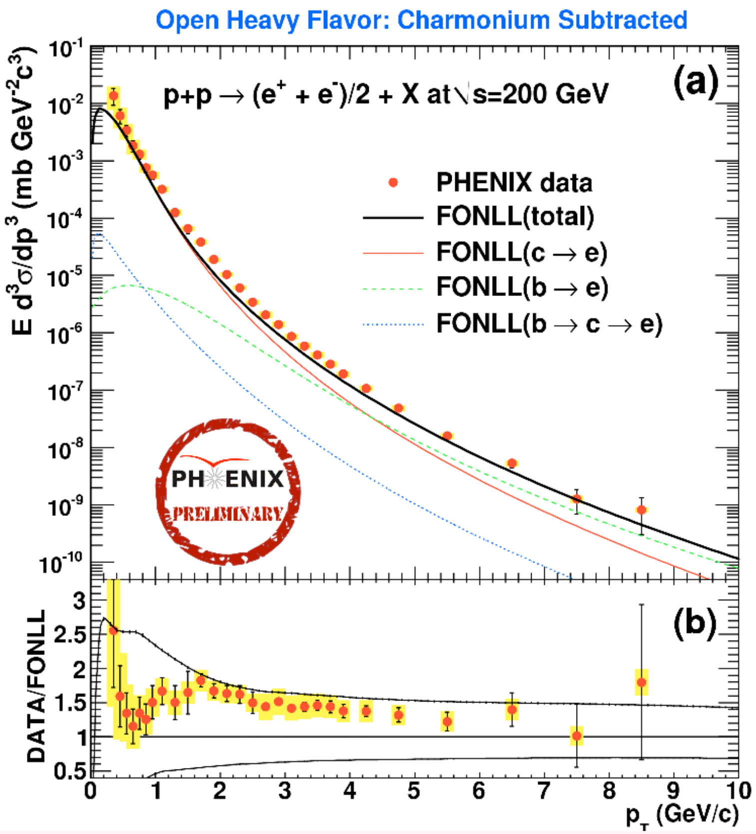


W. Liu and R. Fries, arXiv:0801.0453; Phys. Rev. C 77, 054902 (2008)

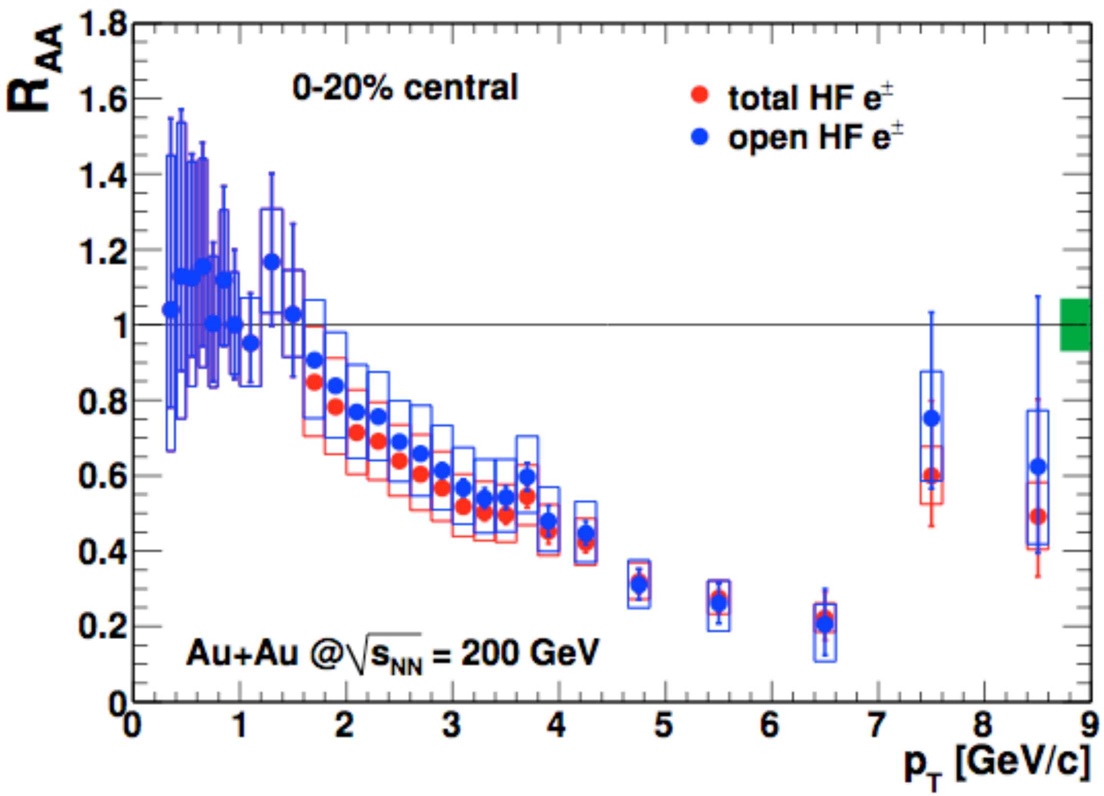
- Expectation from colour charge dependence of energy loss: pion R_{AA} > Proton and kaon R_{AA}
- We measure: Proton and kaon R_{AA} > pion R_{AA}
- Hint of *jet flavour conversion* due to parton interaction with the medium

Heavy flavor from single $e^{\pm}$

J/ψ→ $e^{\pm}$ contribution taken into account ⇒ more precise look into open c/b energy loss



R_{AA} essentially unchanged

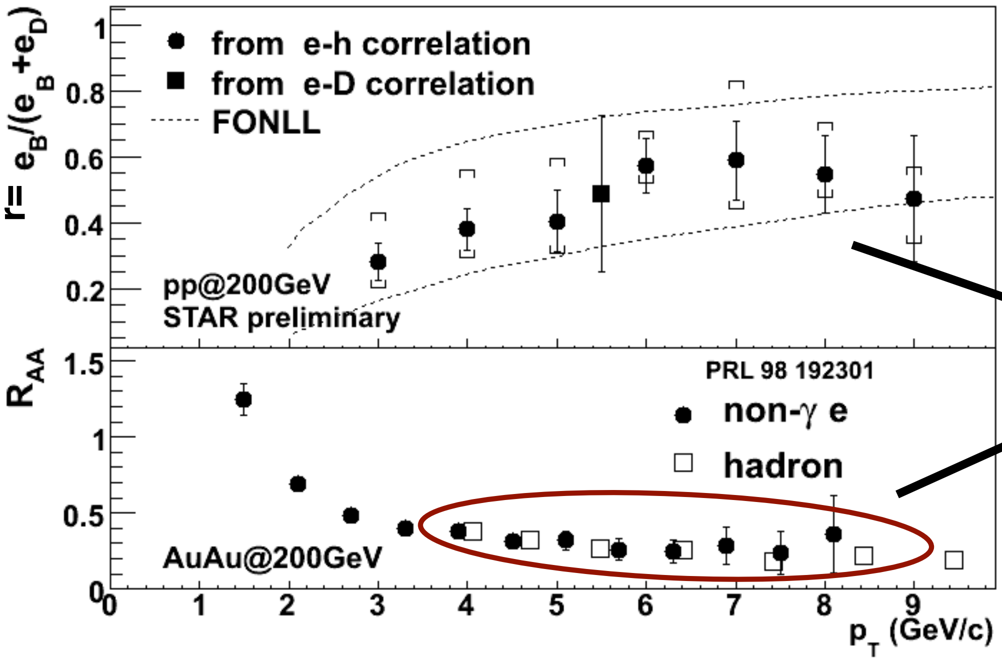


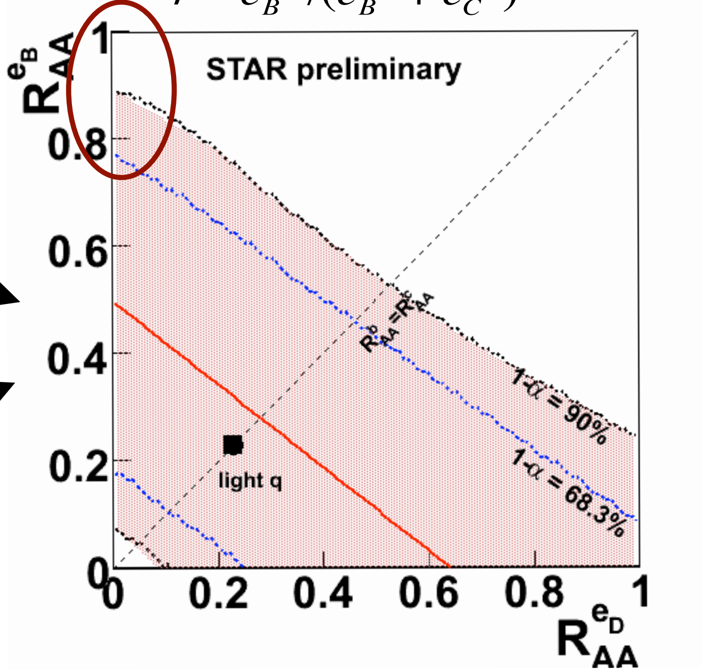
Next step: study for v_2

Non-photonic electron-hadron correlations

$$R_{AA} = rR_{AA}^{e_b} + (1-r)R_{AA}^{e_c}$$

$$r = e_B^{pp} / (e_B^{pp} + e_C^{pp})$$





- Measure $r=e_B/(e_B+e_C)$ via e-h correlations in p+p
- Combined with measured R_{AA} in Au+Au
  $\Rightarrow R_{AA}(B)<1$
- **B meson also suppressed in heavy ion collisions**

Disentangle c and b

• Different fragmentation of associated jets

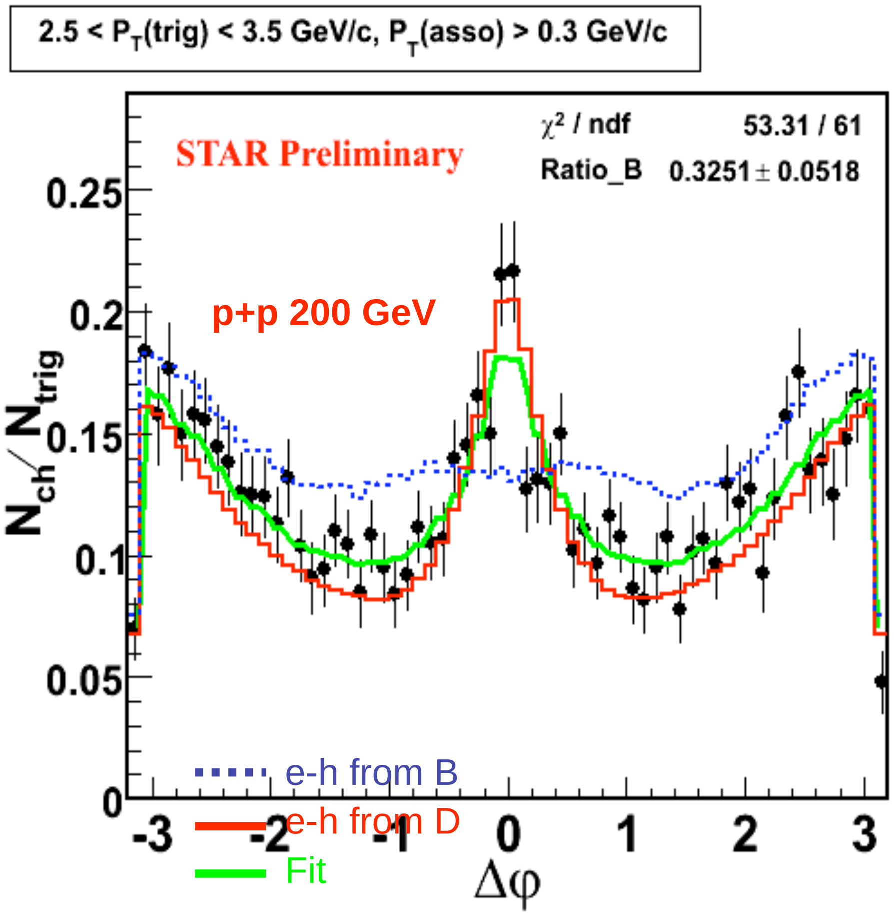
• Study non-photonic electron-hadron azimuthal correlations in p+p

• B much heavier than D mesons

→ sub-leading electrons get larger kick from B (decay kinematics)

→ near-side e-h correlation is broadened

• Extract relative bottom contribution using PYTHIA simulations:



$$\Delta\phi_{measured} = R \cdot \Delta\phi_B + (1 - R) \cdot \Delta\phi_D$$

Comparing to energy loss models 1

used to be just 4 schemes based on pQCD!

Jet weakly coupled to weakly coupled medium
A.M.Y

Jet weakly coupled to arbitrary medium
Higher Twist

Jet weakly coupled to strongly coupled medium
L.R.W, C-S.T

Jet strongly coupled to strongly coupled medium
Trailing String

W.H.D.G.

A.S.W.

Factorized approaches

G.L.V.

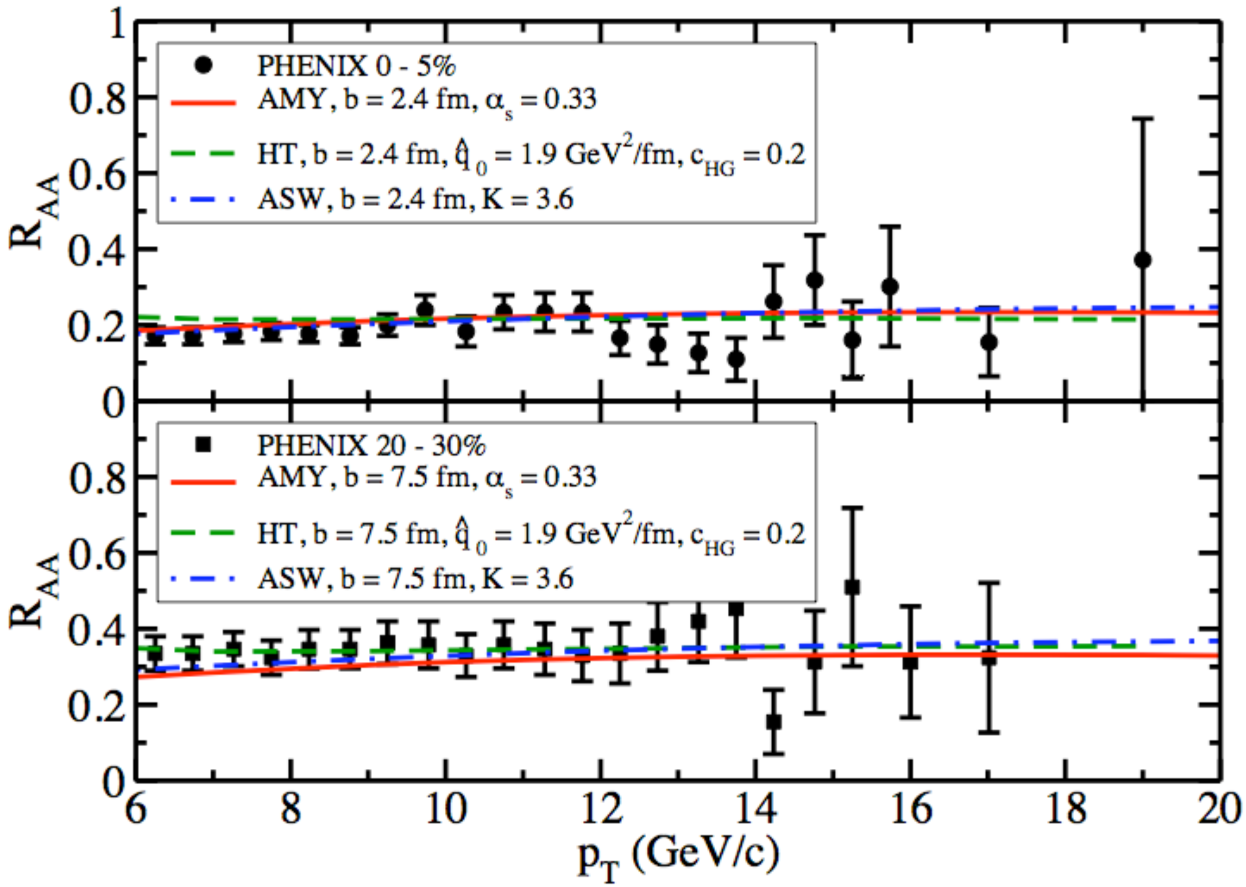
A.S.W.

$$\frac{d\sigma^h}{dy dp_T} \sim \int dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} \tilde{D}_q^h(z_1)$$

→ N-hadron data

Comparing to energy loss models 2

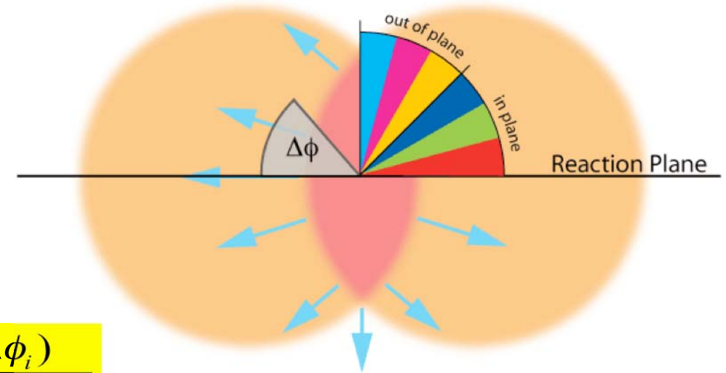
Look into models that describe $R_{AA}(p_T)$ well at high-p_T



Calculations by S.Bass *et al* in arXiv:0808.0908

Experiment Measurements

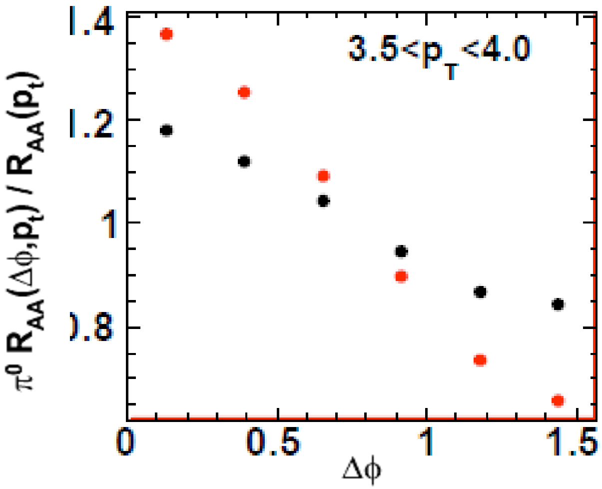
- Azimuthal anisotropy (v_2):
  - Particle yields w.r.t. the reaction plane
  - Corrected for R.P. resolution
  - π^0s in this analysis;



- $R_{AA}(\Delta\phi)$:

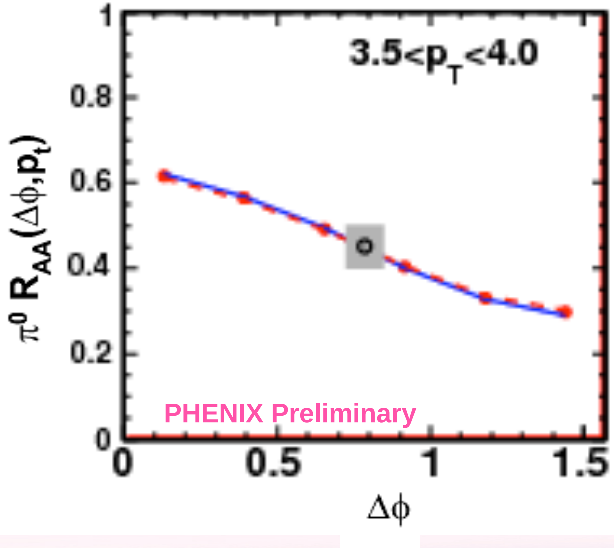
$$R_{AA}(p_T,\Delta\phi) \cong R_{AA}(p_T) \times \frac{N(p_T,\Delta\phi_i)}{\sum_{\phi_i} N(p_T,\Delta\phi_i)}$$

Relative yields corrected by R.P resolution

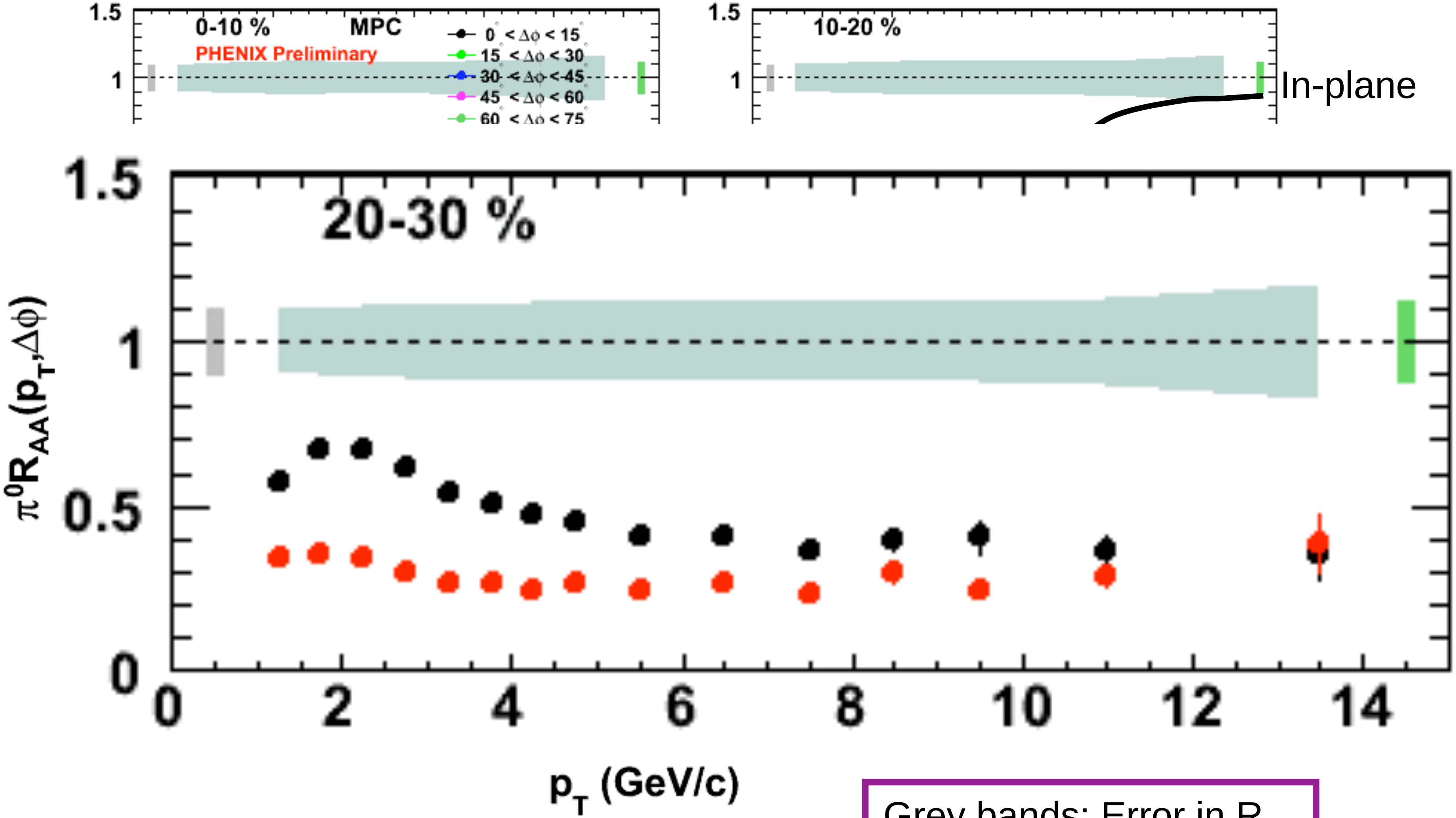


30-40%

Multiply By inclusive R_{AA}

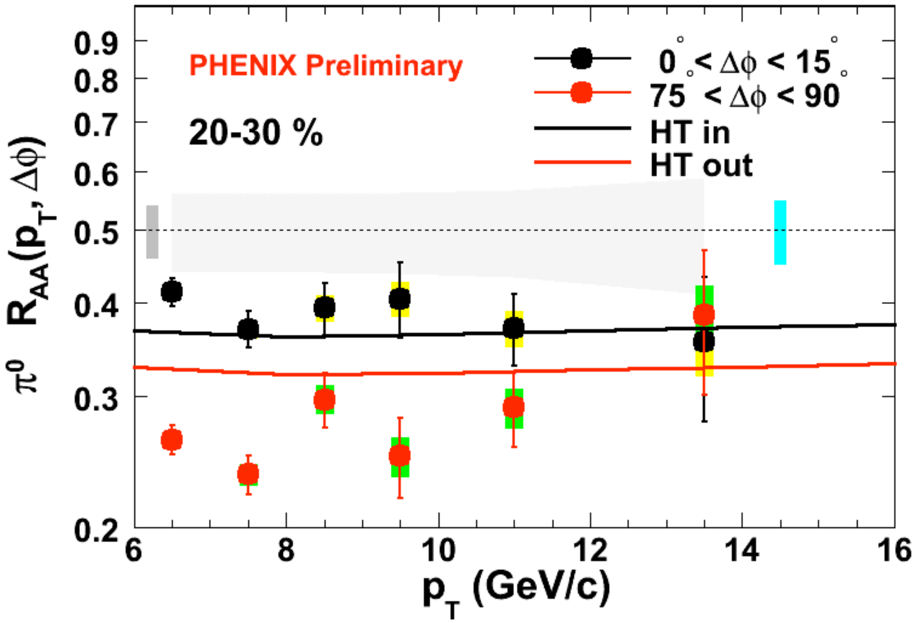


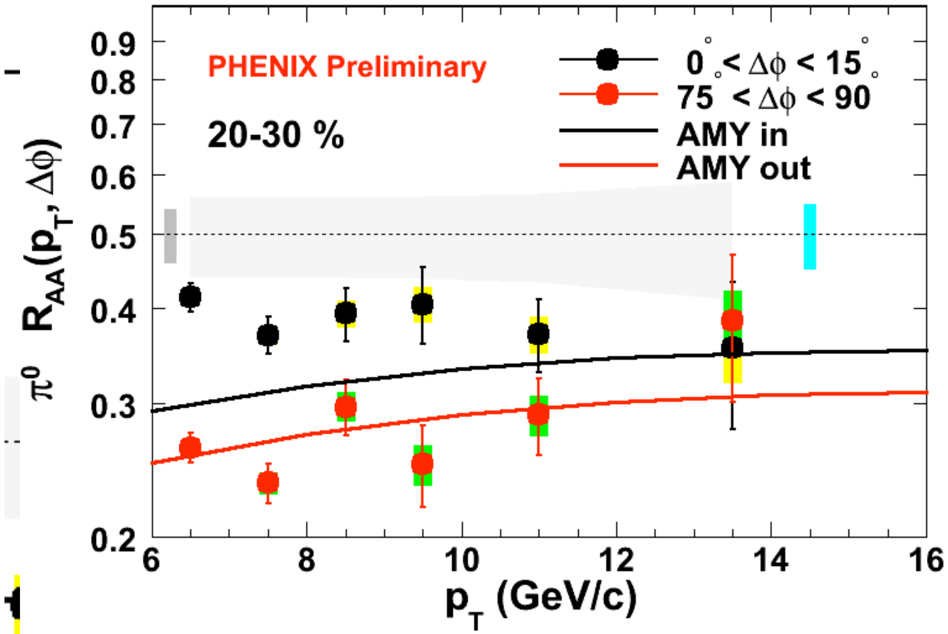
$R_{AA}(\Delta\phi, p_T)$ results

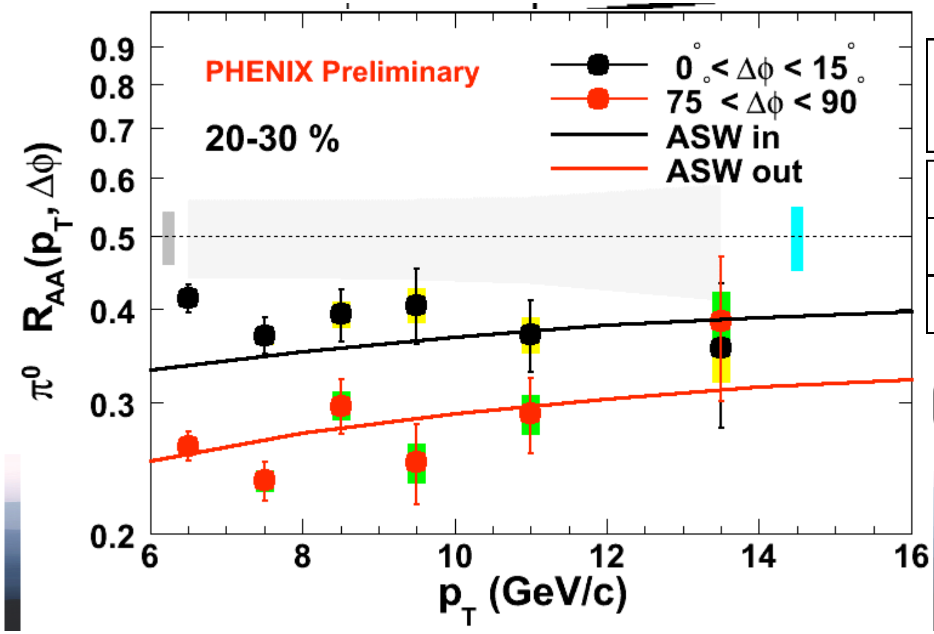


Grey bands: Error in R_{AA}

Comparisons to model calculations





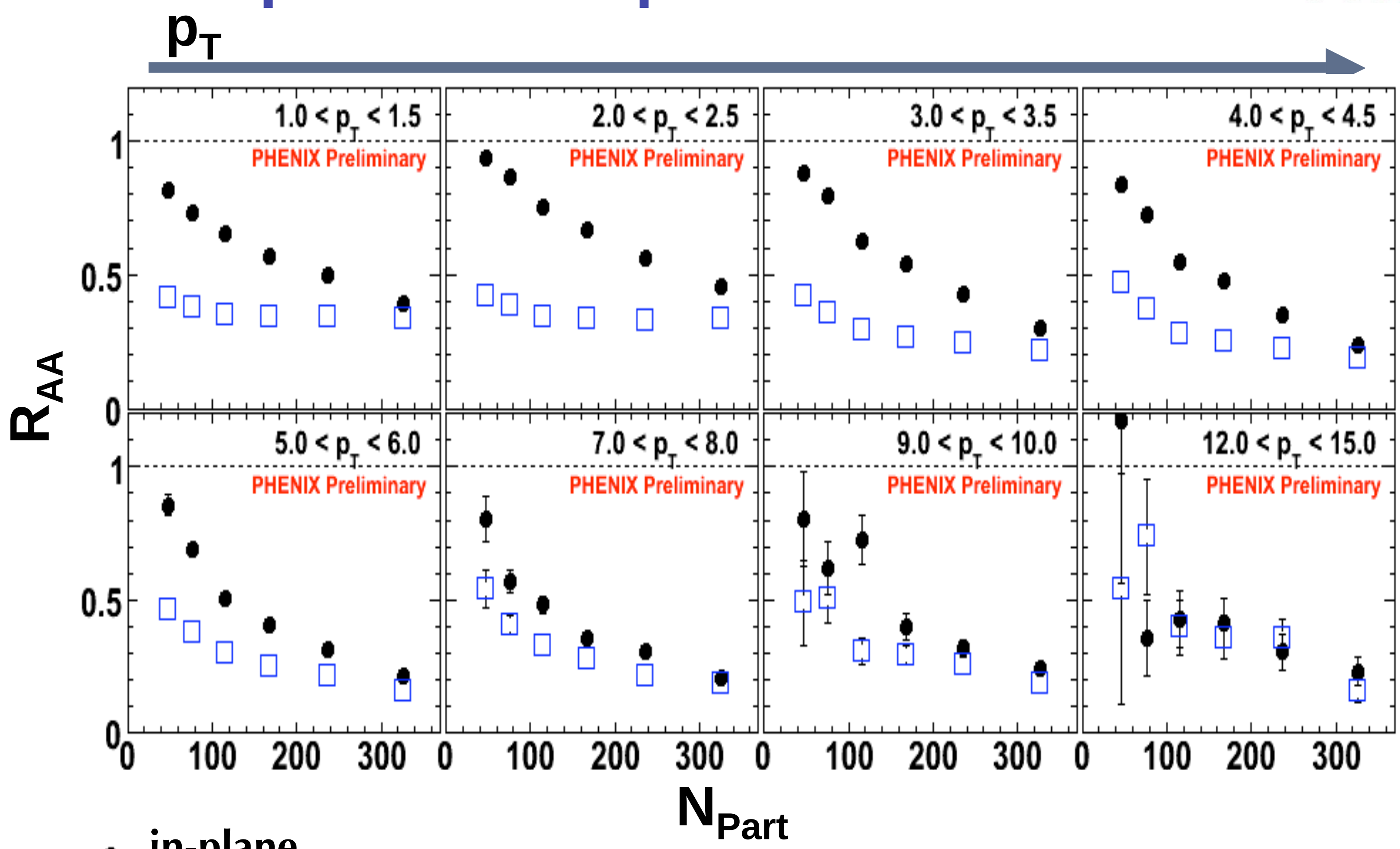


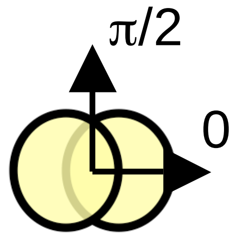
$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 $\mathrm{GeV}^2/\mathrm{fm}$	4.5 $\mathrm{GeV}^2/\mathrm{fm}$	
$s(\vec{r},\tau)$		4.3 $\mathrm{GeV}^2/\mathrm{fm}$	

Implication: large q-hat for the medium?

Calculation from S.Bass et al arXiv:0808.0908

Out-of-plane vs. in-plane



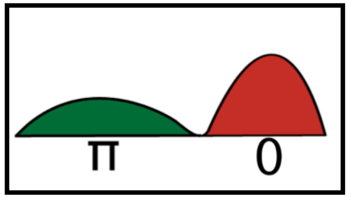


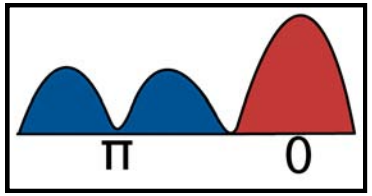
● in-plane

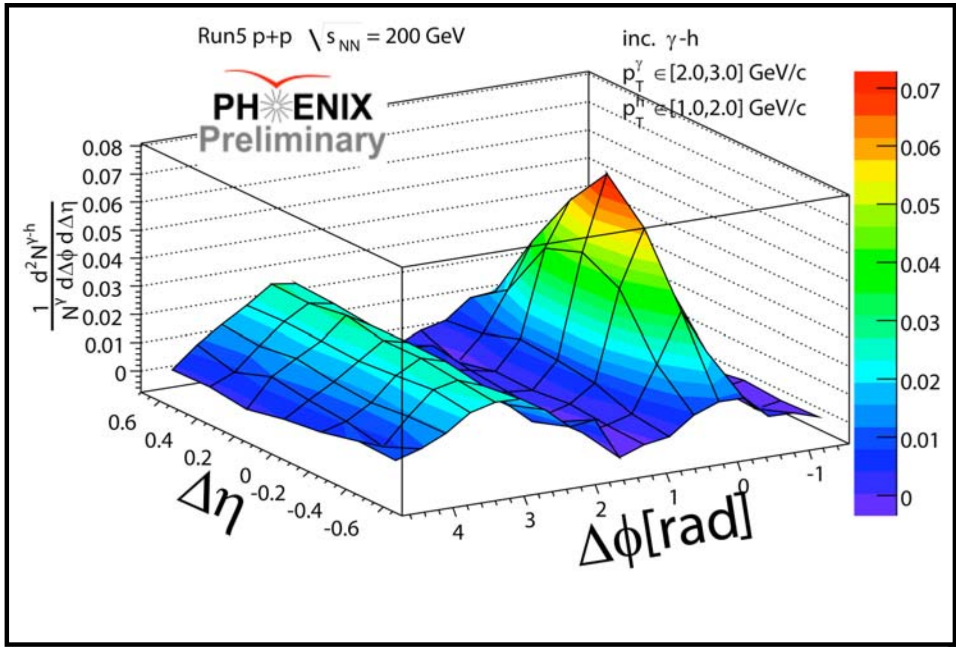
□ out-of-plane

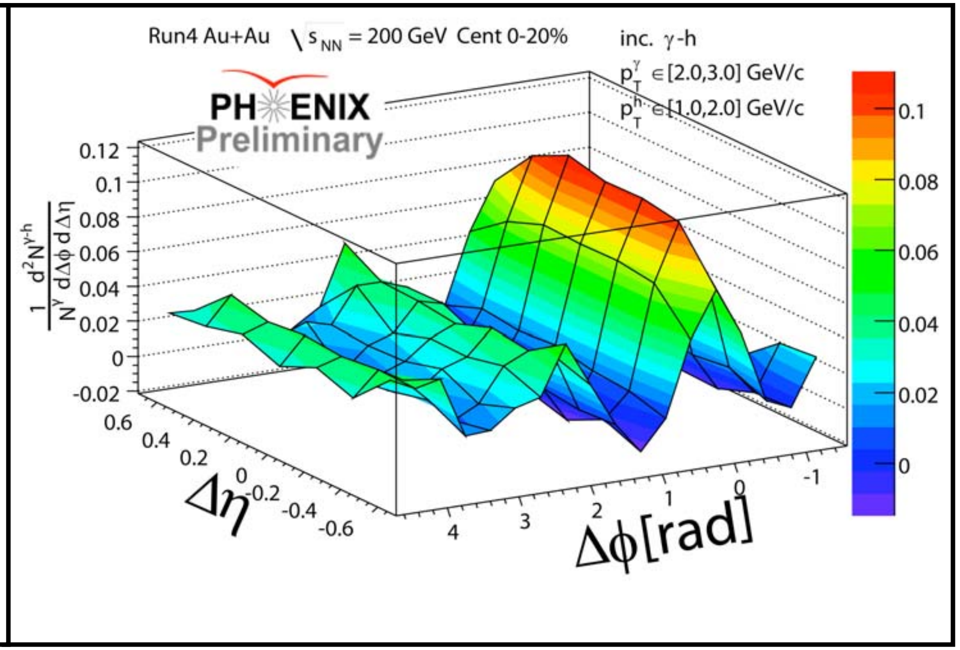
Low p_T: relatively flat at the out-of-plane direction; Geometric dependences are different for two orientations.

Defining the terminology









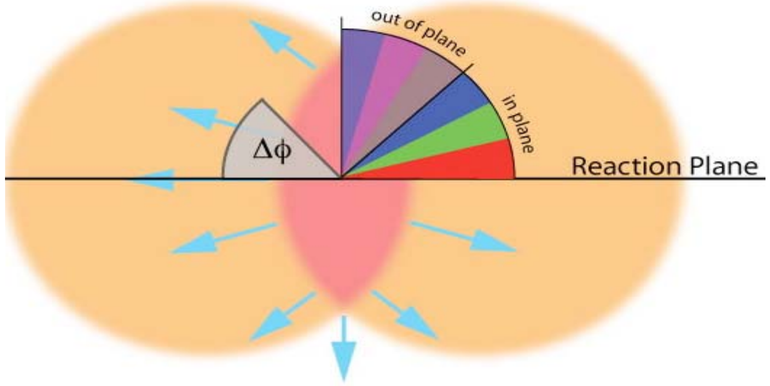
Near side: $\phi \sim 0$

Away side: $\phi \sim \pi$

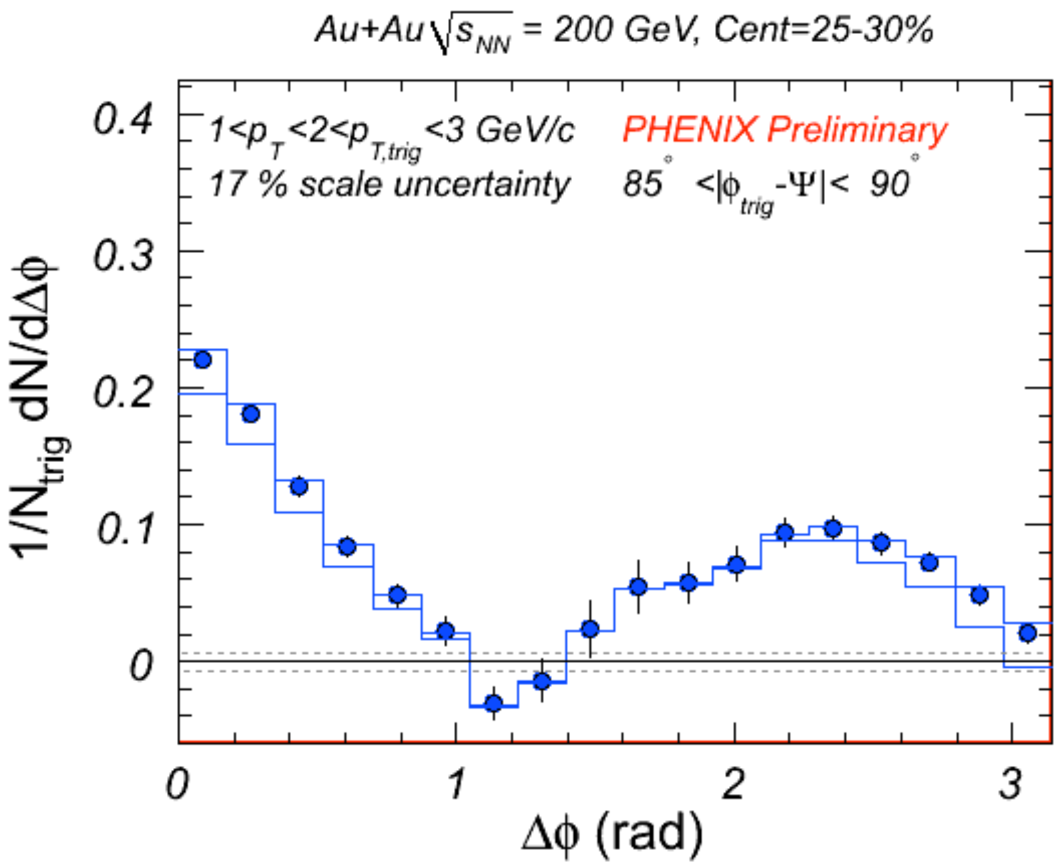
Near side features: Ridge ($\Delta\eta$)

Away side features: Head, Shoulder

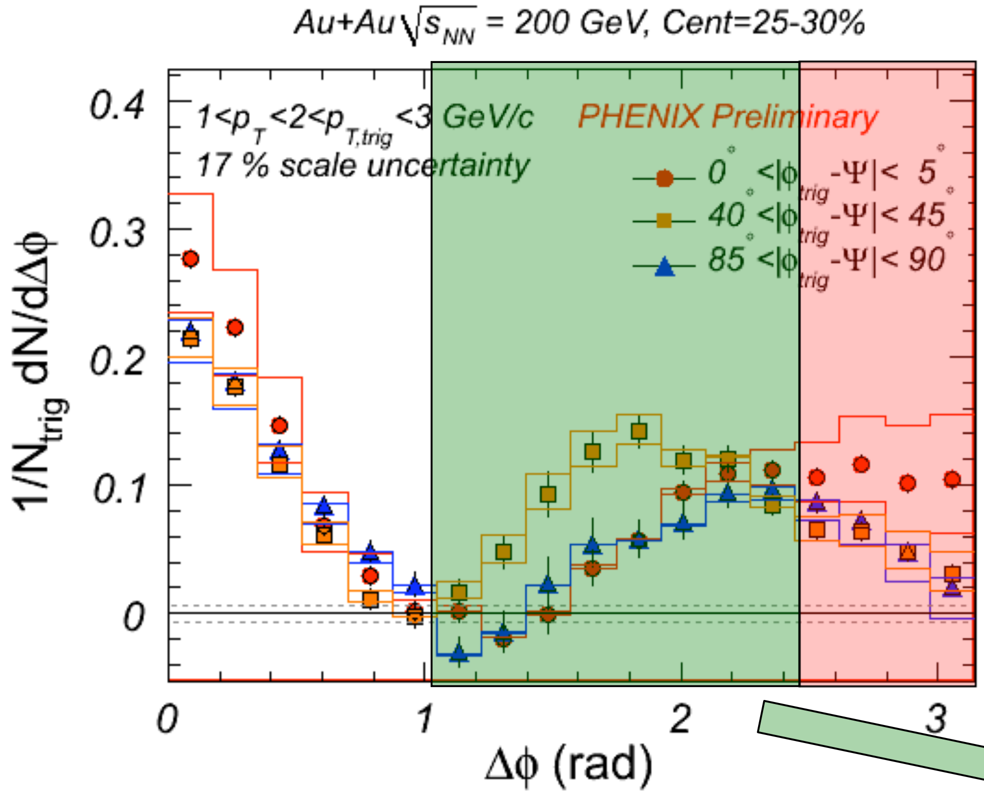
Reaction-Plane-dependent correlations

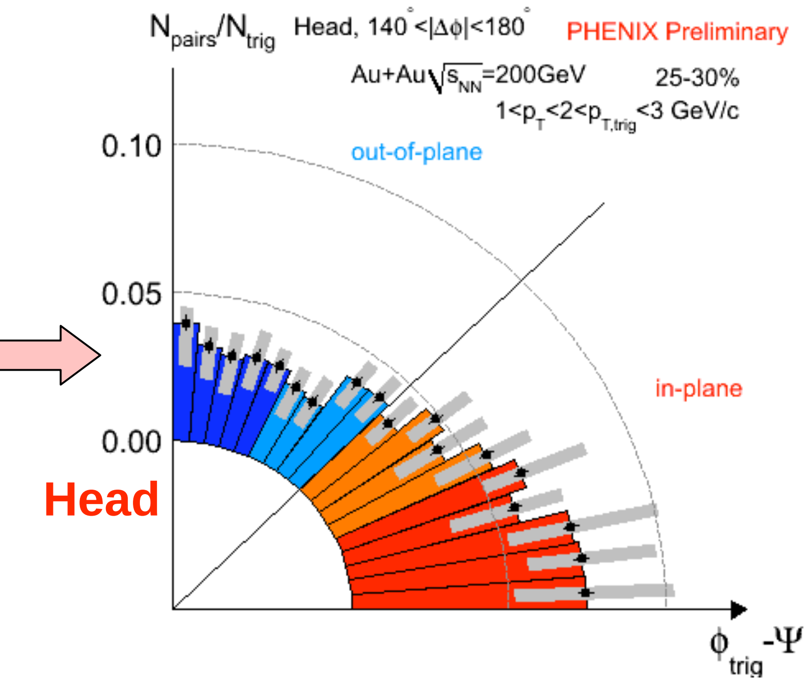


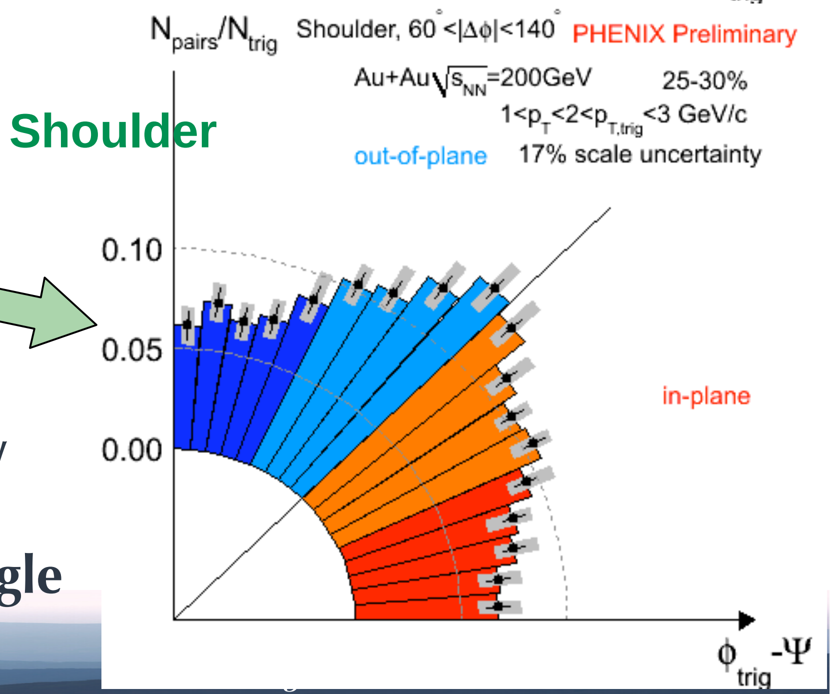
Measure in 18 $|\phi_{trig} - \psi|$ angle bins of 5 degrees folded into 0-90 degrees



In detail



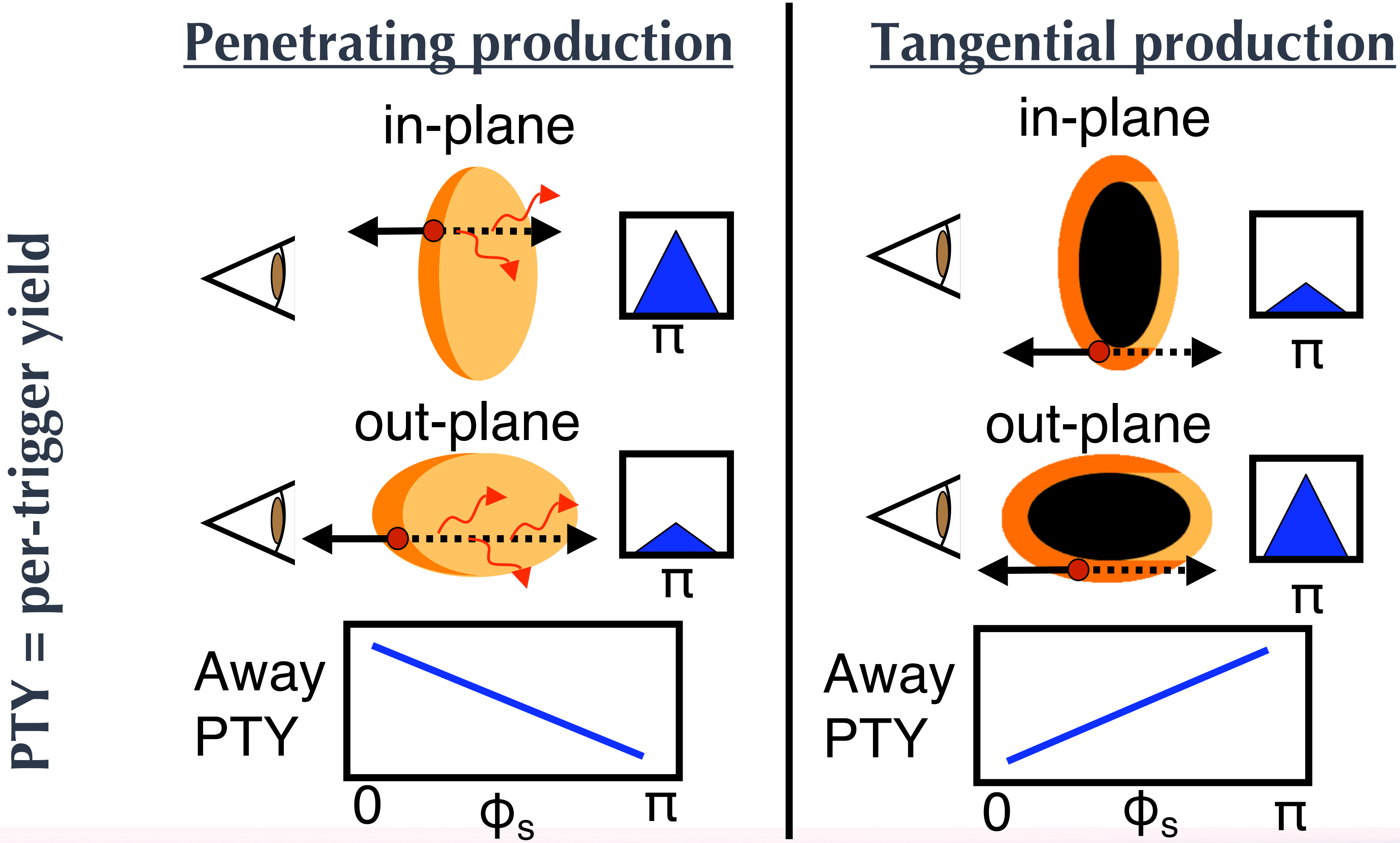




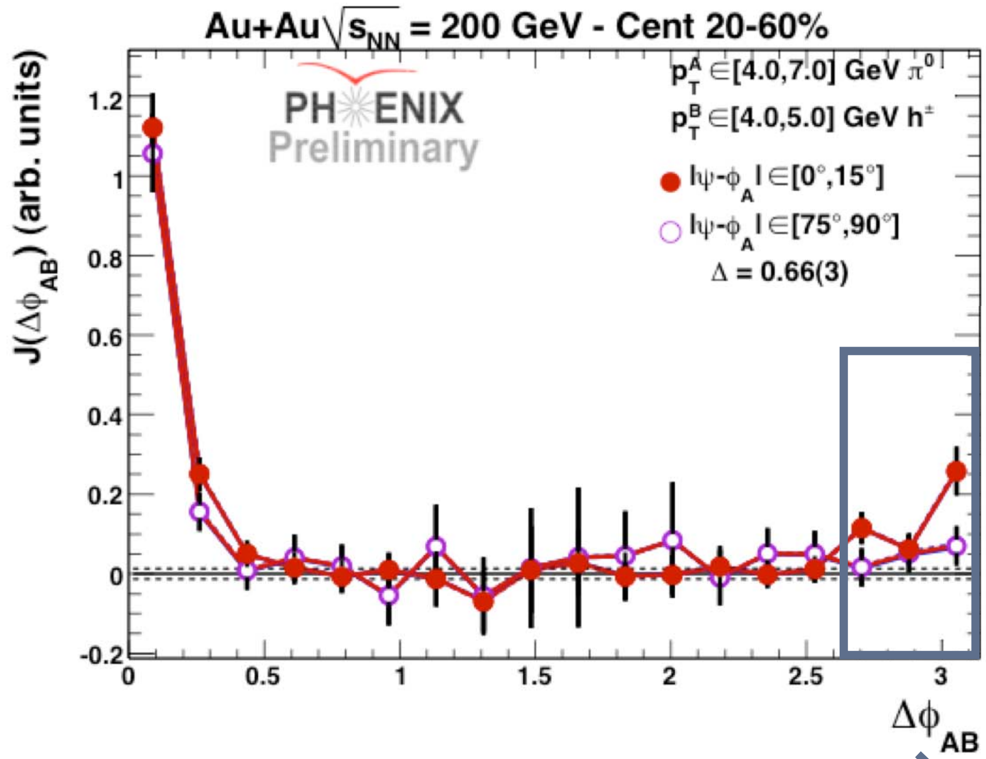
head: yield confirms simple picture of energy loss vs. path length; in- and out-of-plane show similar away-side width

shoulder: geometry effects harder to disentangle

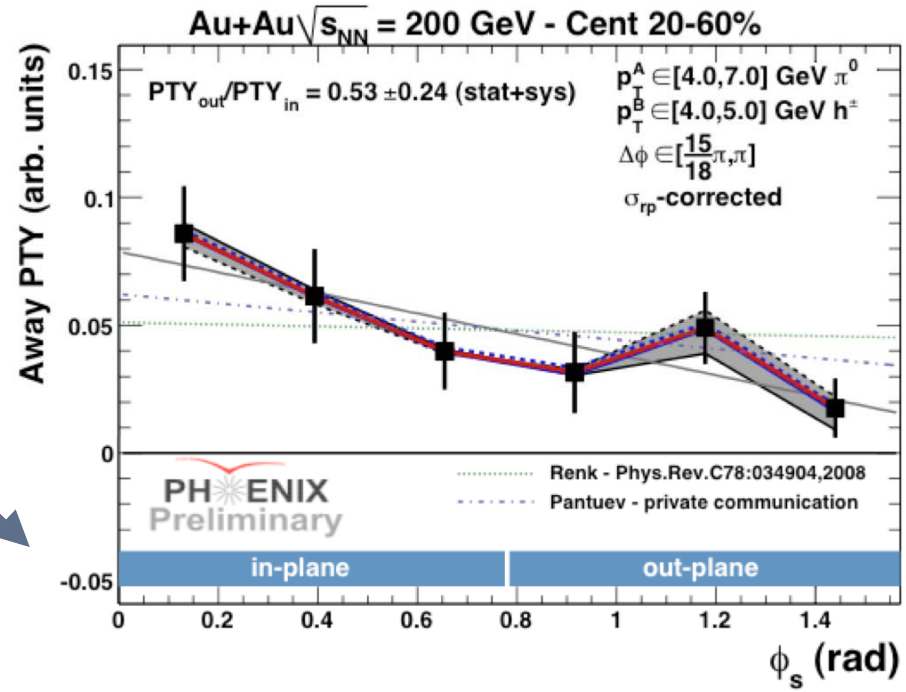
Away-side yield RP dependence at high-p_T



Away side yield



Away side yields drop from in-plane to out-of-plane: favor penetrating production picture



Reference: Charged ξ Jet Fragmentation in p+p

JP trigger
$|\eta_{jet}|<1\text{-}R$

Data not corrected for particle level

Increasing Jet Energy

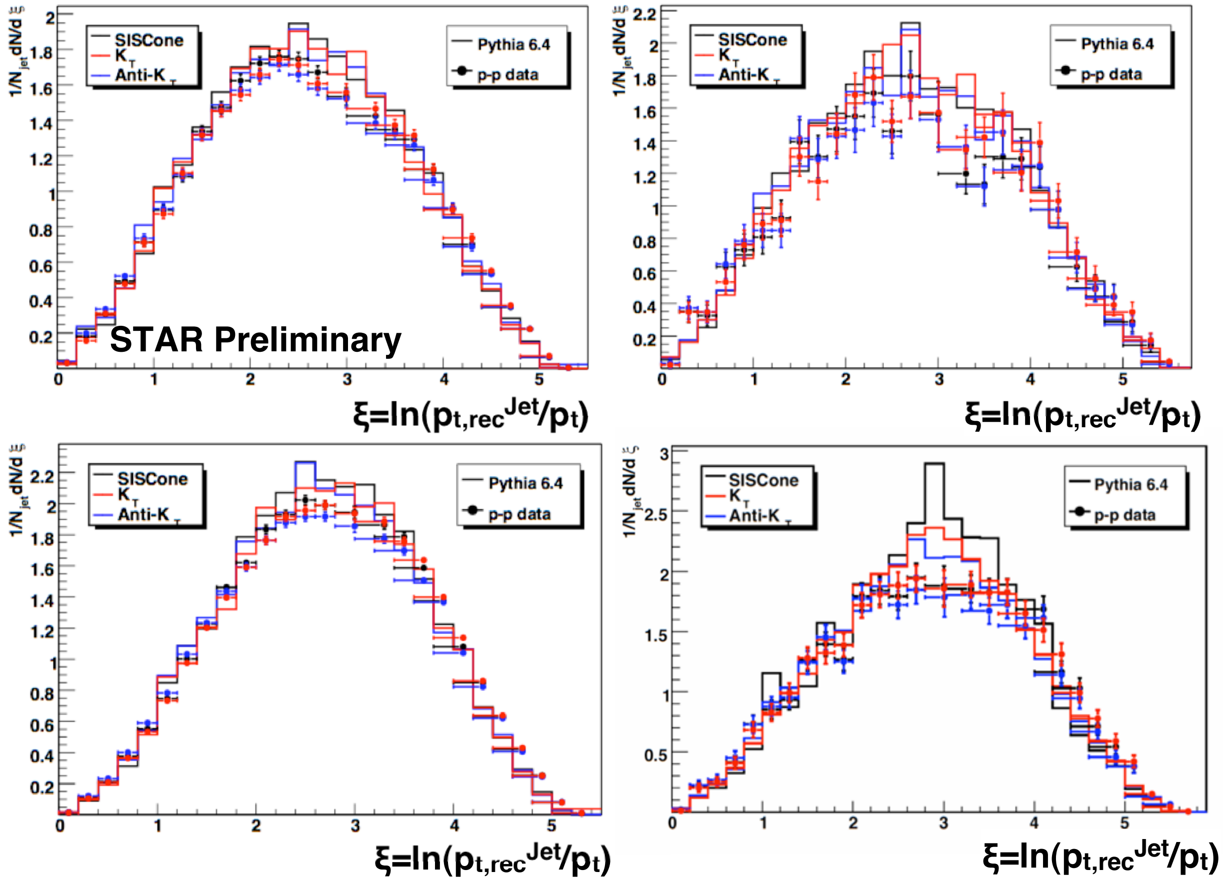
$20<E^{reco}<30$ GeV

$30<E^{reco}<40$ GeV

R<0.4

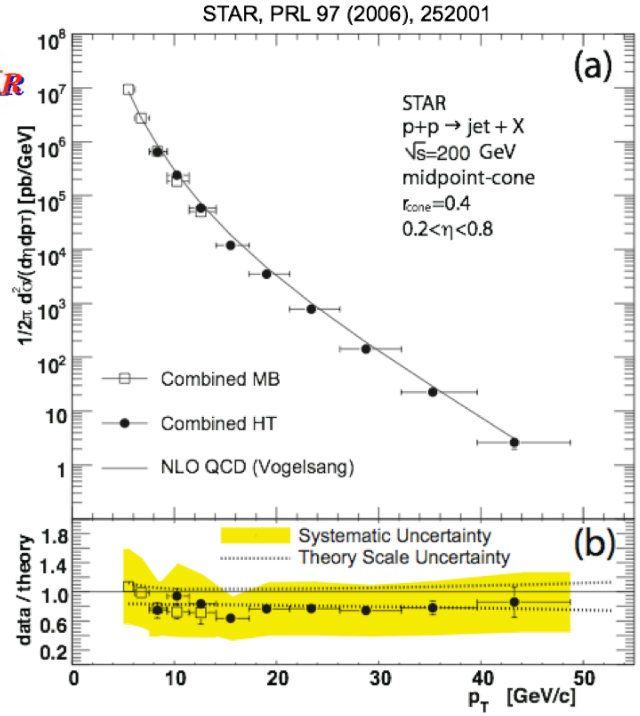
R<0.7

Increasing Cone R

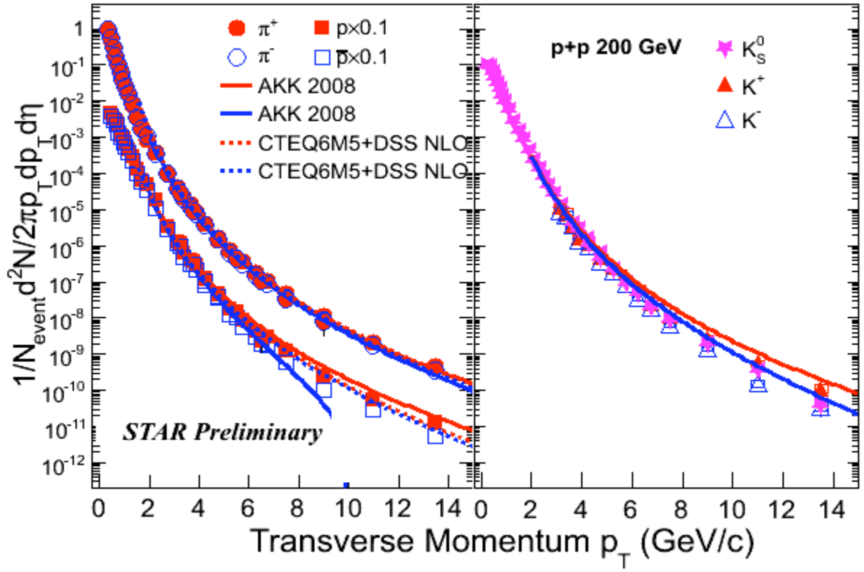


Reasonable agreement with Pythia+Geant simulations for different R and jet p_t

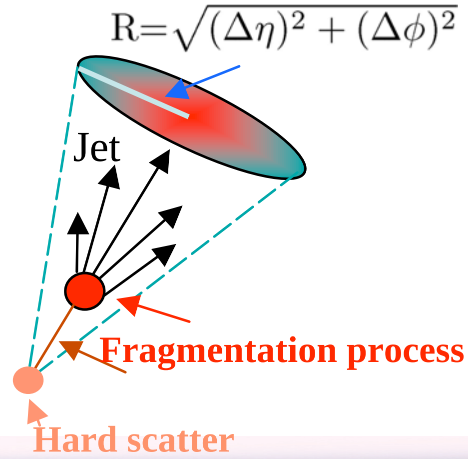
Reference: jet x-section in p+p collisions



New p+p data at 200 GeV



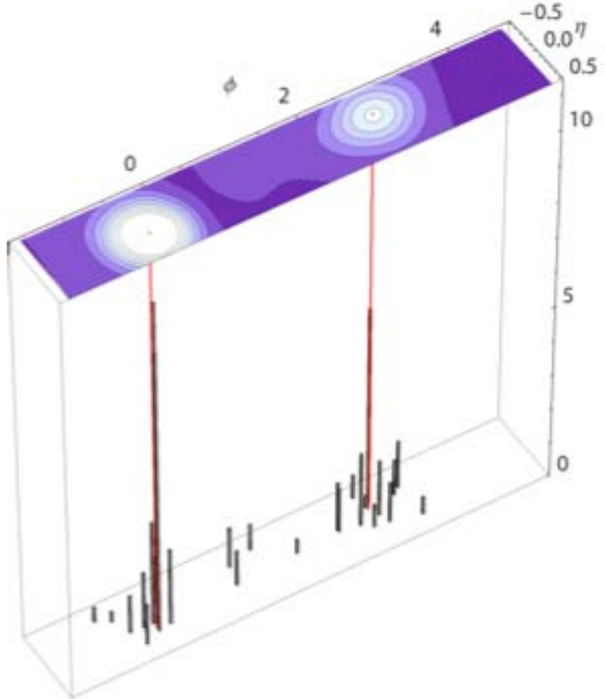
Jet cross-section and particle production in p+p is well described in pQCD framework over 7 orders of magnitude



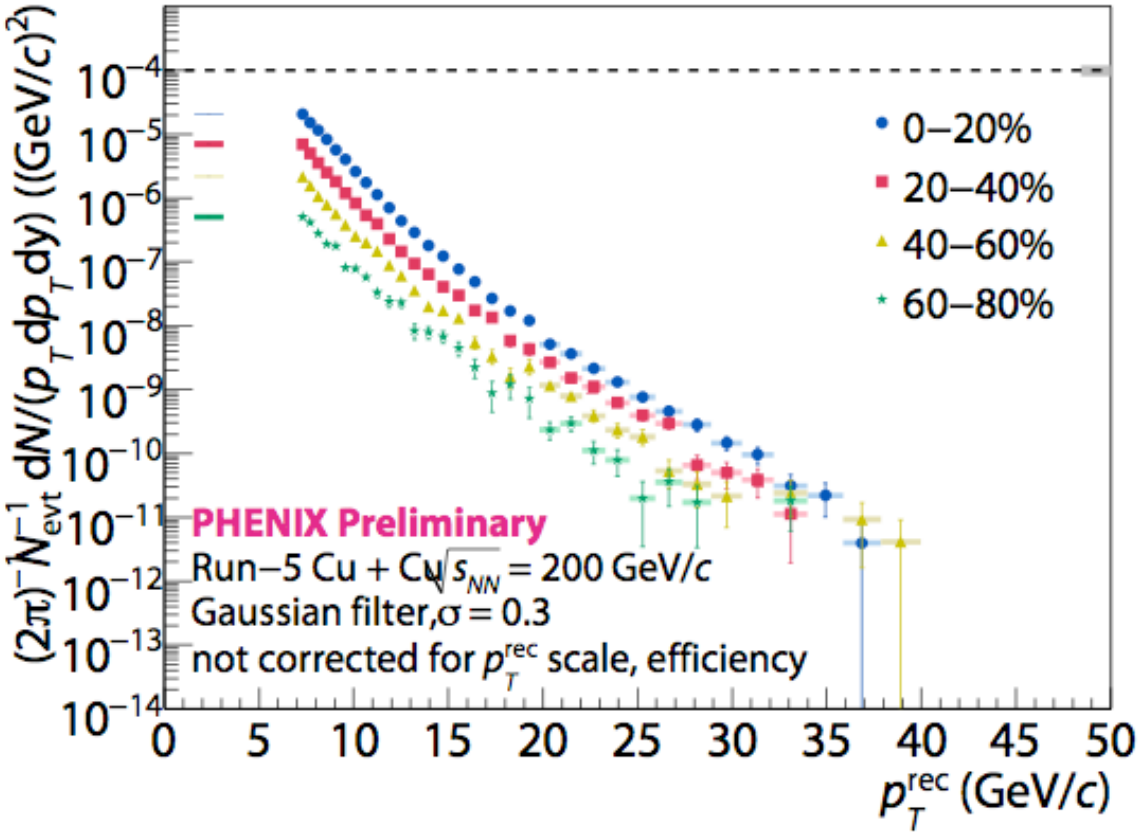
Look now at the <u>real</u> jet fragmentation function: $z=p_t/E_{jet}$ and $\xi=\ln(1/z)$

Jörn Putschke for the STAR Collaboration, QM09, Knoxville
Yichun Xu, 5A

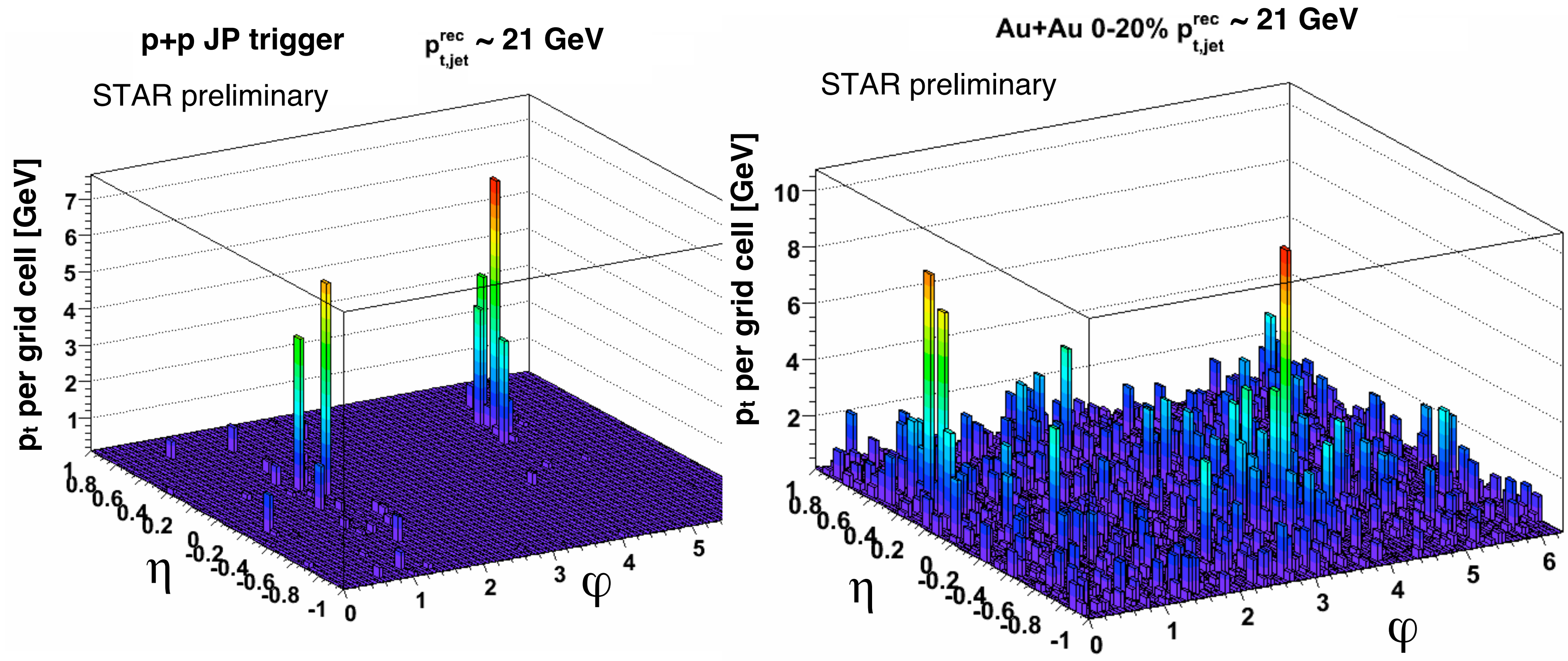
Full jet reconstruction in Cu+Cu



Run 150513, event 277518
19–20% centrality
24.3 GeV/c and 10.3 GeV/c dijet



Full-Jet reconstruction in HI collisions



- Full jet reconstruction in HI collisions is a challenge due to the underlying background
- $\langle p_t(bkg) \rangle$ ~ 45 GeV for a cone of R=0.4 in central Au+Au collisions

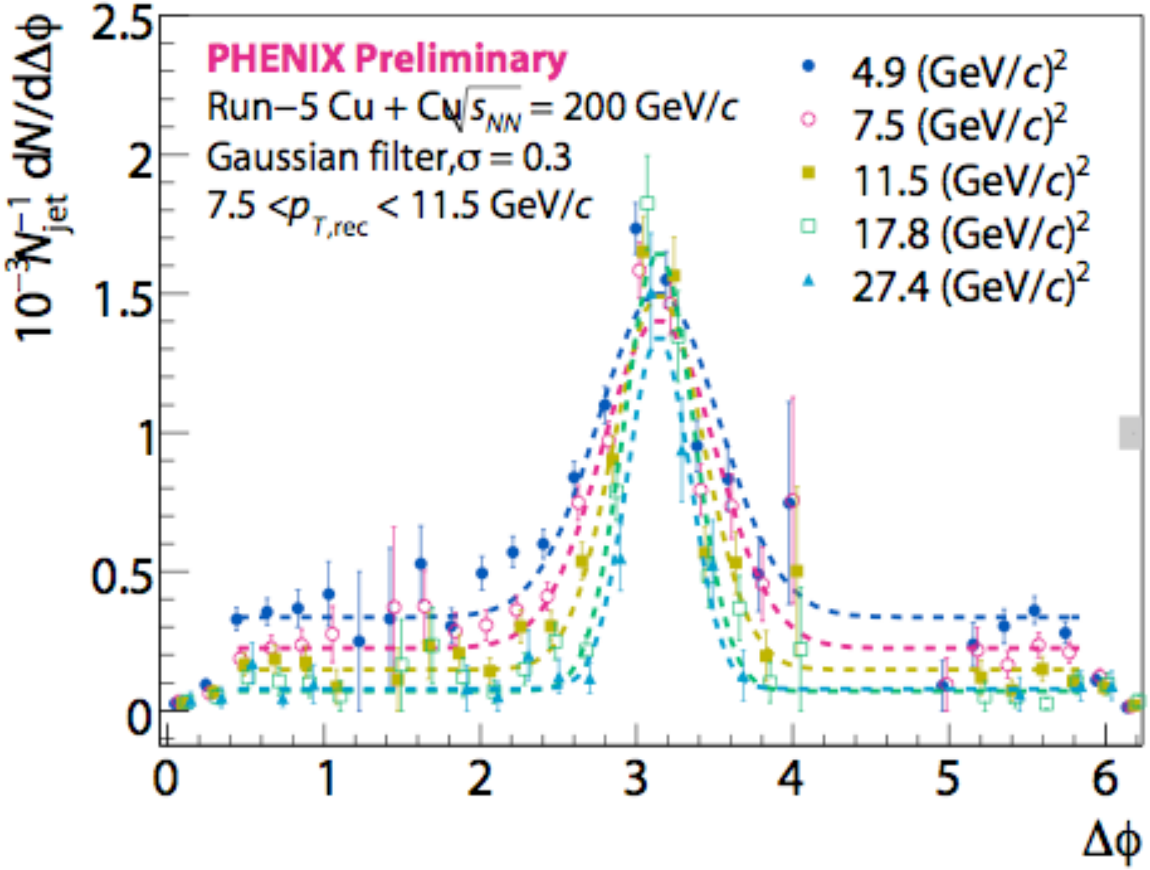
⇒ for a 20 GeV jet: S/B~0.5

- Region-to-region background fluctuations ~6-7 GeV for a cone of R=0.4

<u>But:</u> We have all the tools (FastJet jetfinder) and methods (unfolding) to correct for background and fluctuations in a data driven approach

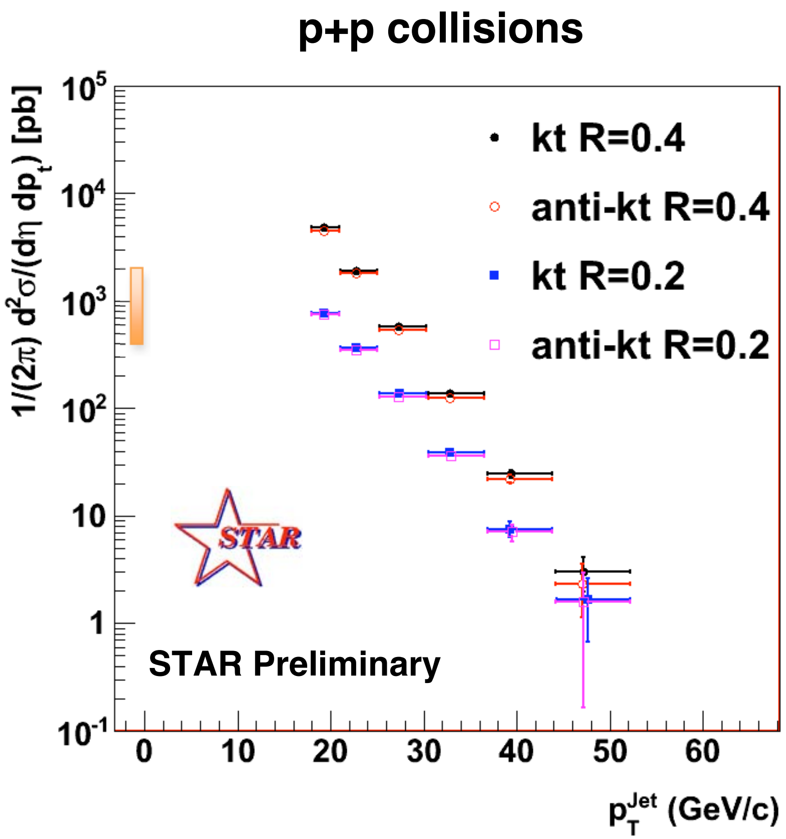
Matteo Cacciari, Gavin P. Salam and Gregory Soyez; arXiv: 0802.1188

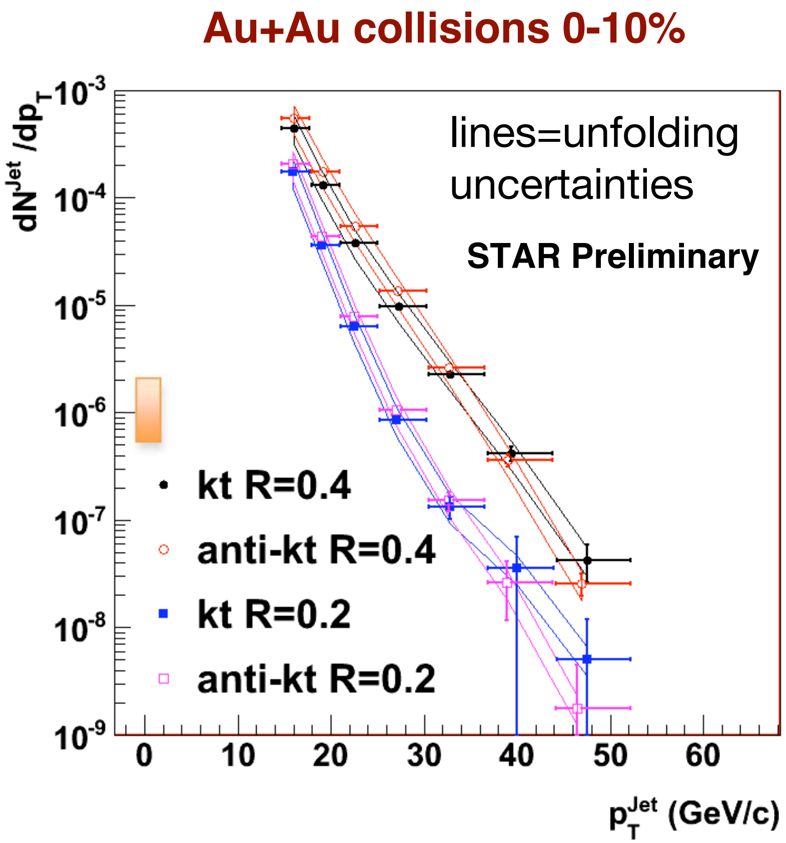
Fake jet rejection



- Fake jets are a natural consequence of HI background fluctuations
- We need to remove them from HI jet measurements
- By studying the azimuthal correlation, we can quantify the effect and optimize rejection

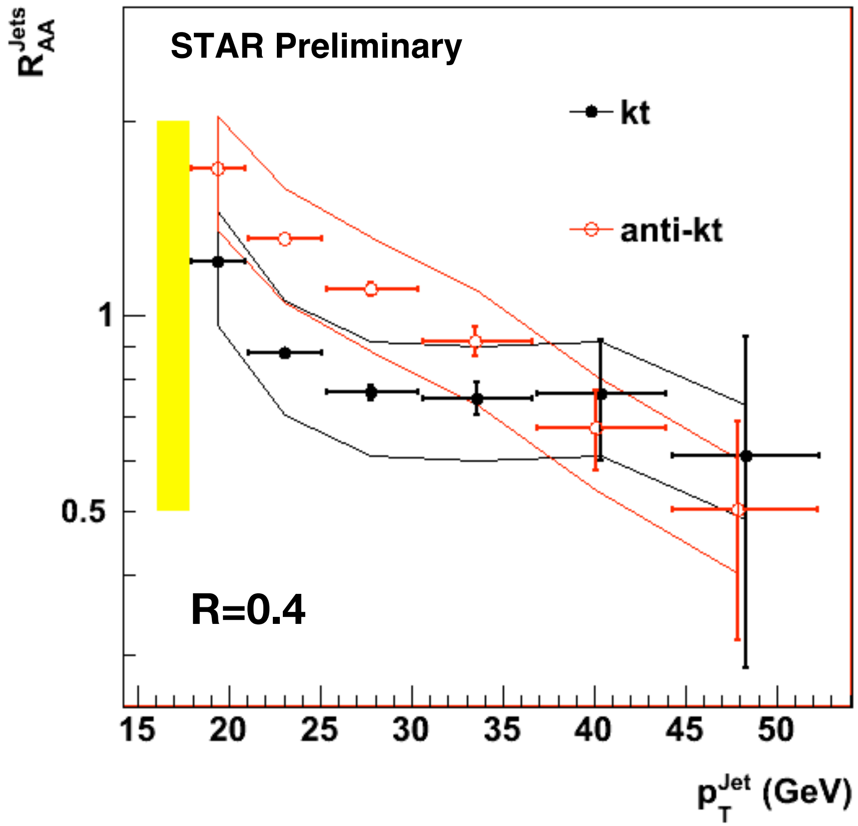
Inclusive jet x-section in central Au+Au





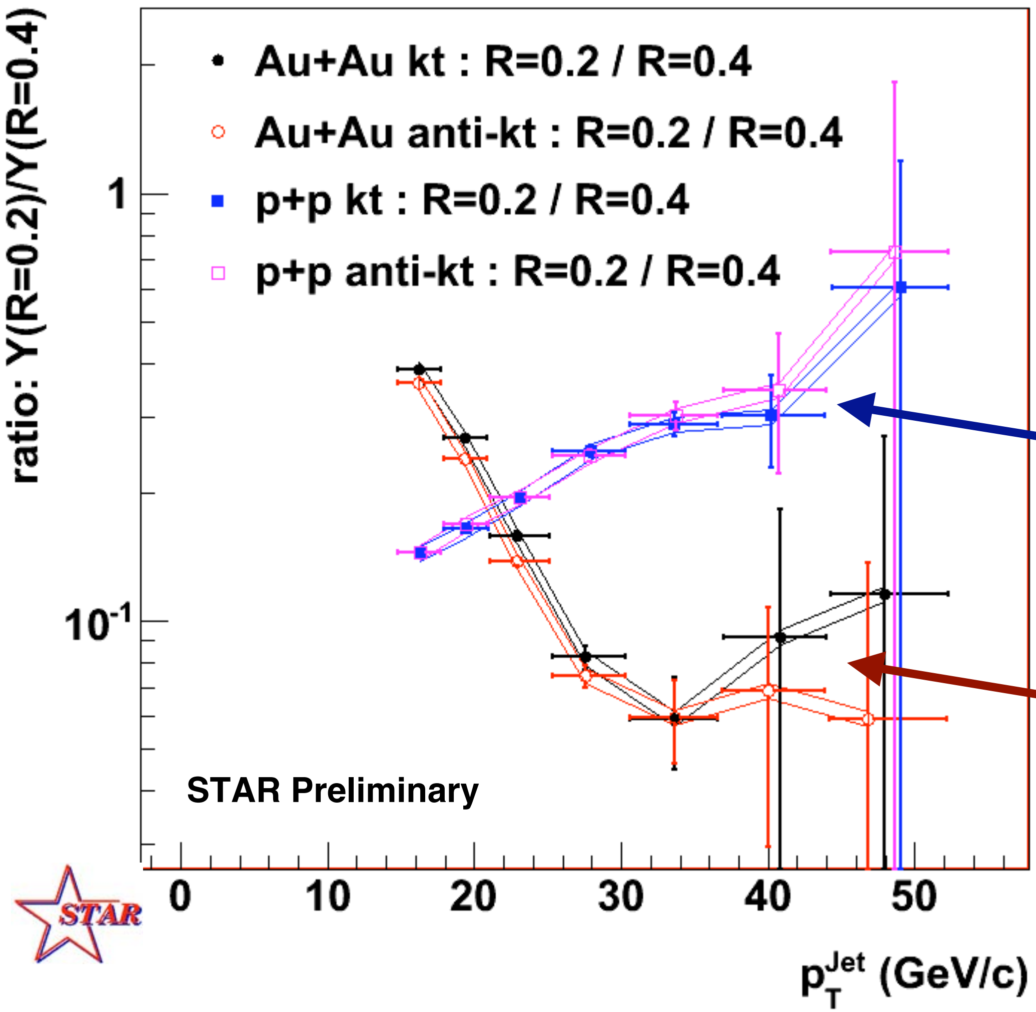
- **Inclusive Jet spectrum measured in central Au+Au collisions at RHIC**
- **Extended the kinematical reach to study jet quenching phenomena to jet energies > 40 GeV**

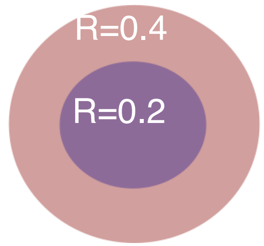
Jet R_{AA} in central Au+Au



- We see a substantial fraction of jets
  - in contrast to x5 suppression for light hadron R_{AA}
- k_T and Anti-k_T known to have different sensitivities to background

First look at the jet energy profile





p+p: “Narrowing” of the jet structure with increasing jet energy

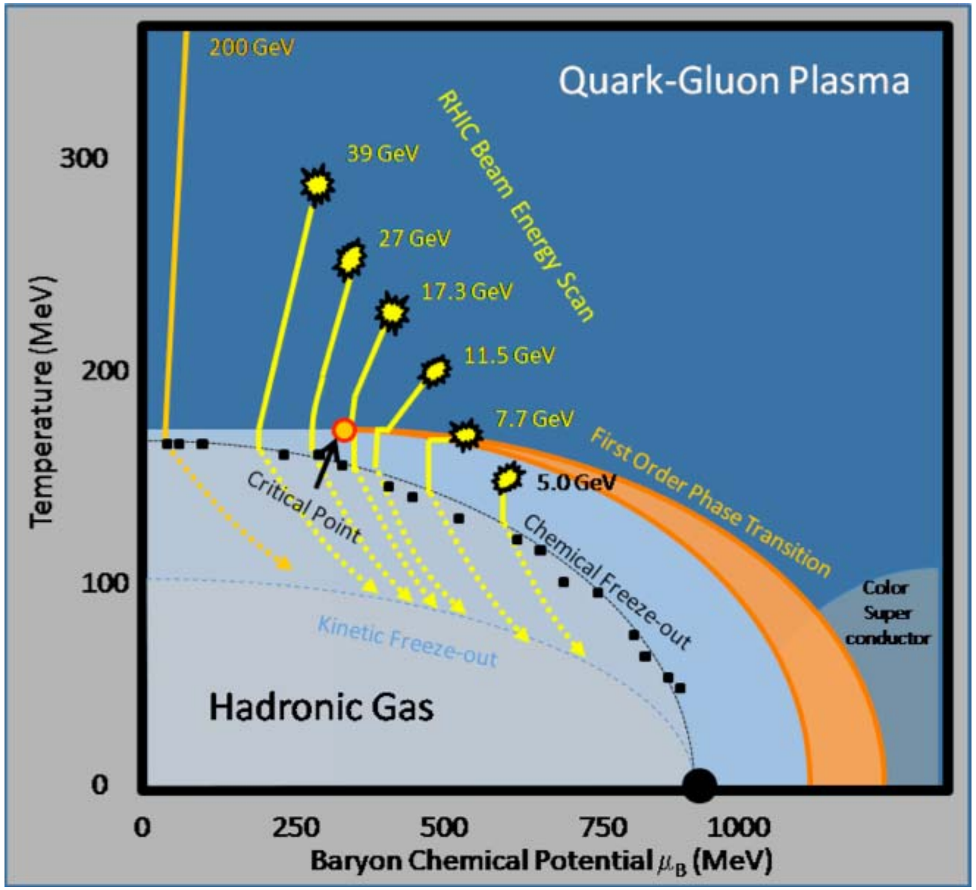
Au+Au: “Deficit” of jet energy of jets reconstructed with R=0.2

Strong evidence of broadening in the jet energy profile

Conclusions

- Hard Processes have important role in determining 'QGP' properties.
  - RHIC programme will continue with increasing luminosities
  - At LHC energies these probes will occur more frequently
- Current data support opaque matter interpretation
  - Detailed theoretical work still required

Search for QCD Critical point



1st-order Phase Tran. / Critical Point

Elliptic & directed flow

Azimuthally-sensitive HBT

Fluctuations & correlations

- Kurtosis analysis on net protons

Turn-off major sQGP signatures already established at top RHIC energies

- NCQ scaling
- Hadron suppression
- Pair correlations in $\Delta\varphi$&$\Delta\eta$
- Parity violation vs. $\sqrt{s_{NN}}$

Acknowledgements

- Quark Matter speakers and their collaborators, in particular
  - Carla Vale (PHENIX Collab.)
  - Jörn Putschke (STAR Collab.)