Heavy Flavor Tagged Jet Correlations @ RHIC

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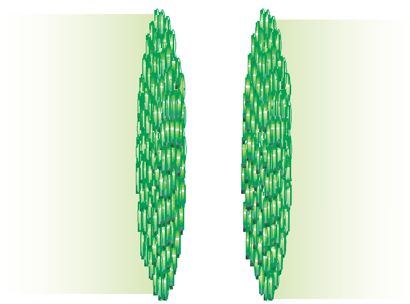
BROOKHAVEN NATIONAL LABORATORY

Heavy Ion Collision

illustration: S. Bass

Heavy Ion Collision



incoming
nuclei

illustration: S. Bass

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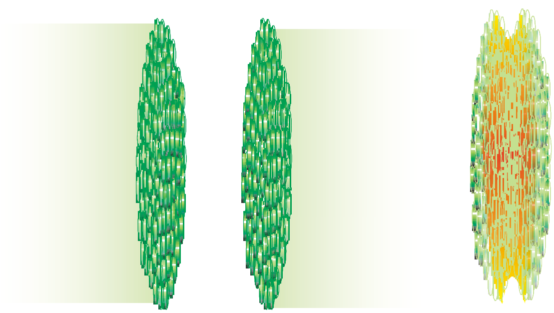

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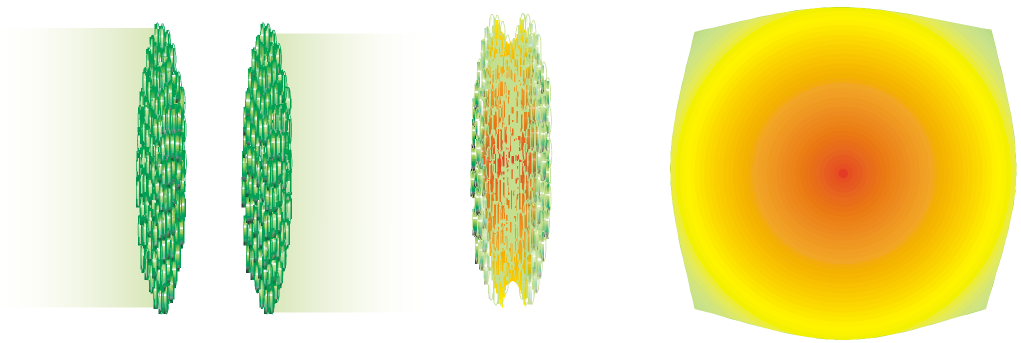
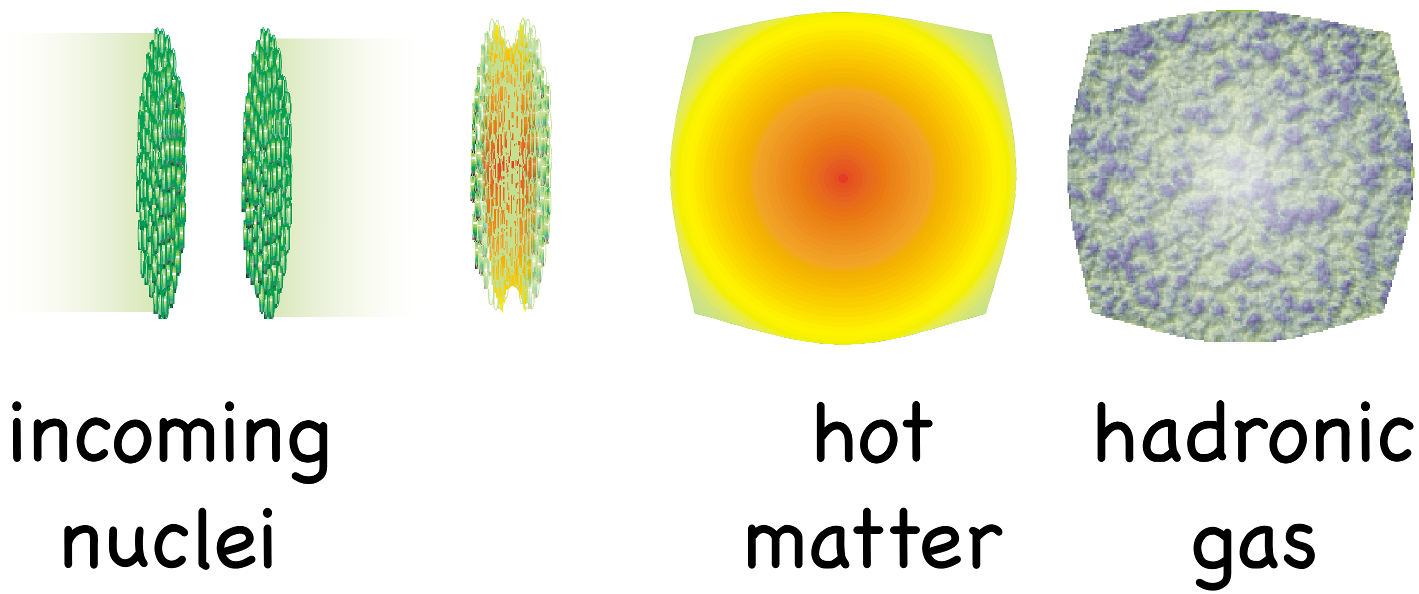


incoming nuclei

hot matter

illustration: S. Bass

Heavy Ion Collision



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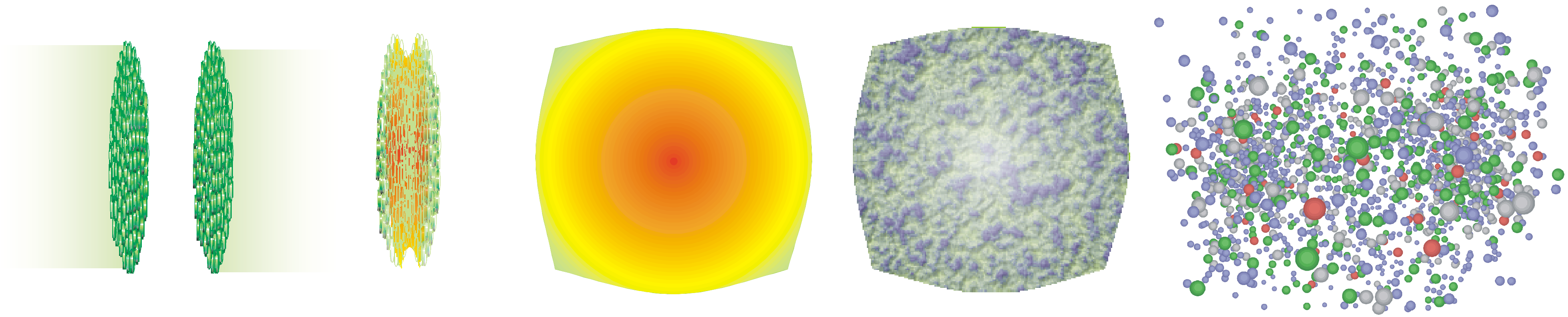


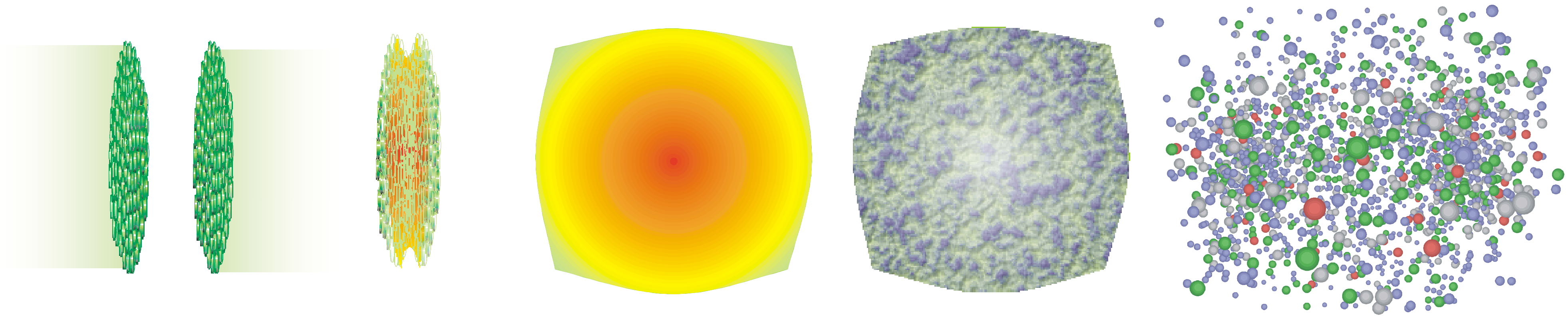
incoming nuclei

hot matter

hadronic gas

illustration: S. Bass

Heavy Ion Collision



incoming nuclei

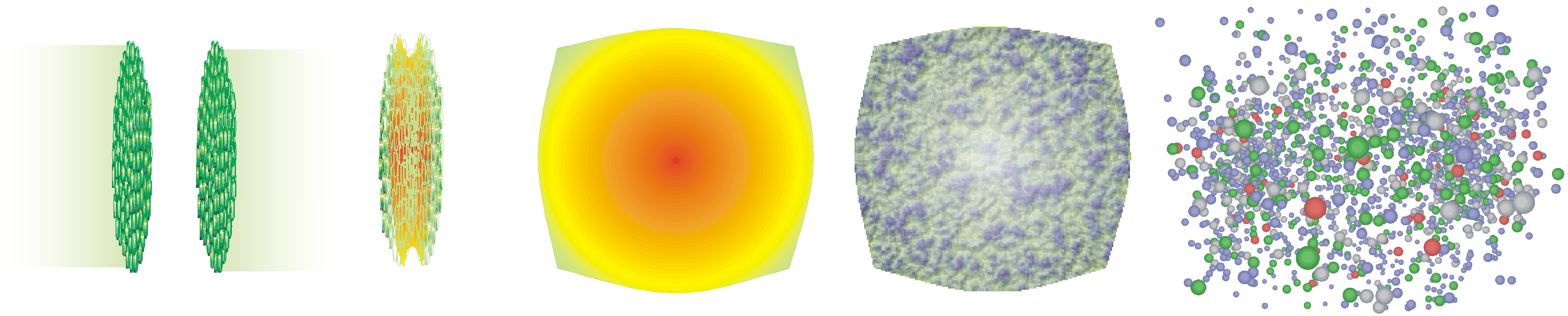
hot matter

hadronic gas

- RHIC: ion-ion collisions at up to $\sqrt{s_{NN}}$=200GeV

illustration: S. Bass

Heavy Ion Collision



incoming nuclei

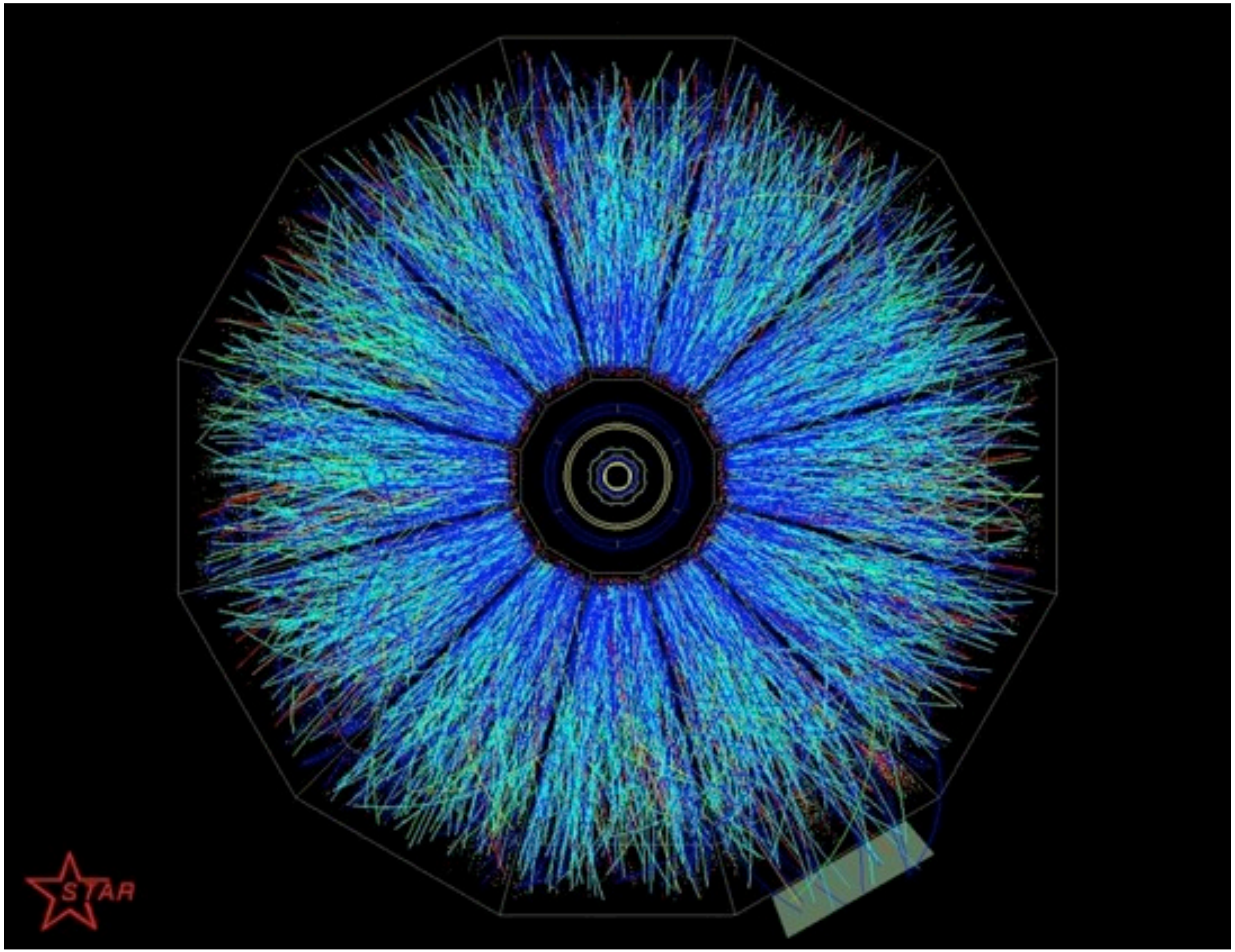
hot matter

hadronic gas

- RHIC: ion-ion collisions at up to $\sqrt{s_{NN}}$=200GeV
- also p+p collsions, crucial baseline

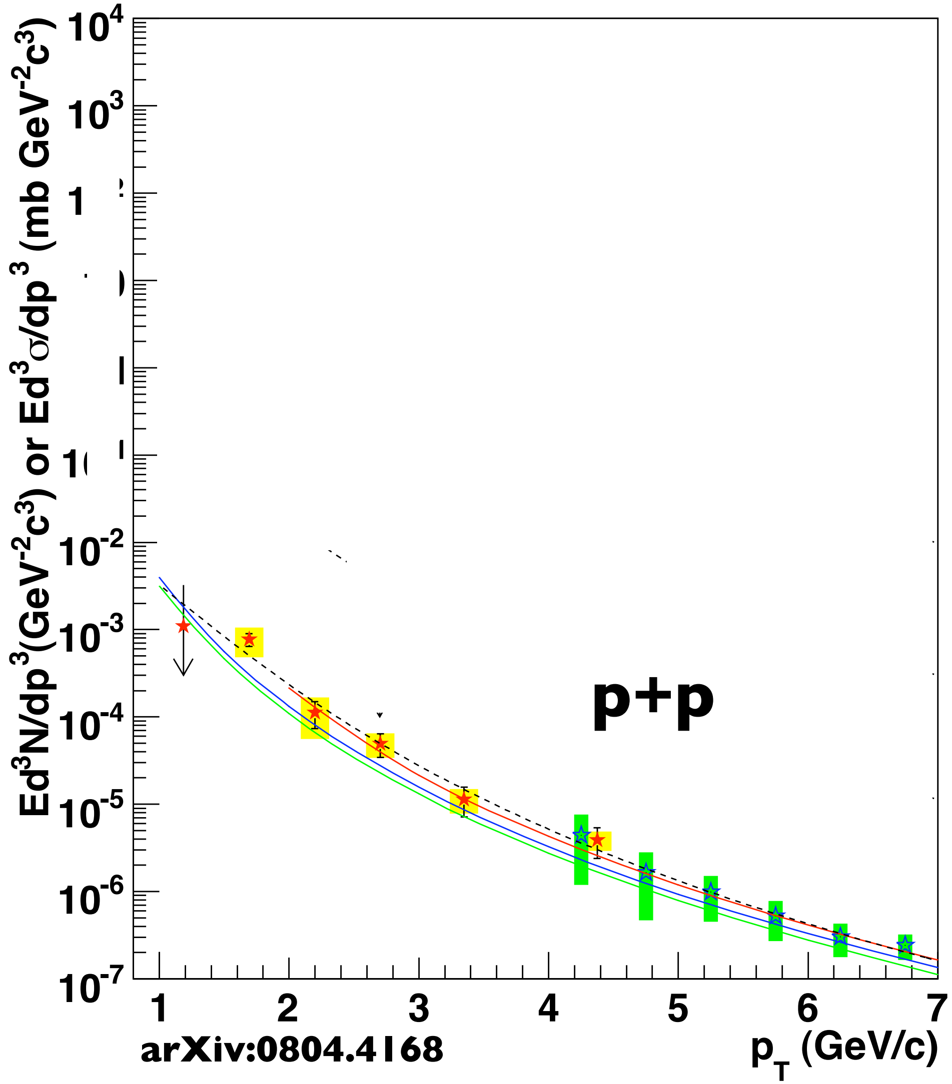
illustration: S. Bass

Au+Au collision



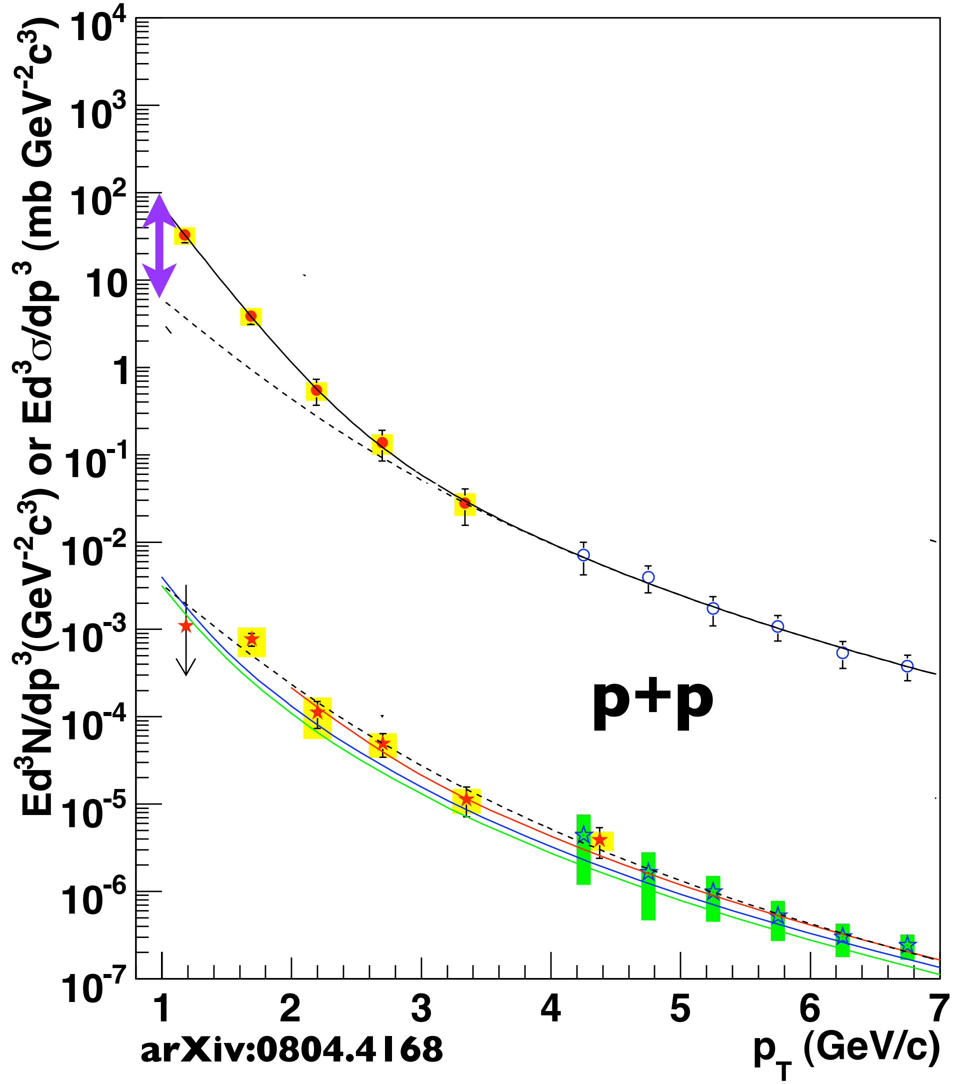
hot nuclear matter

Direct γ



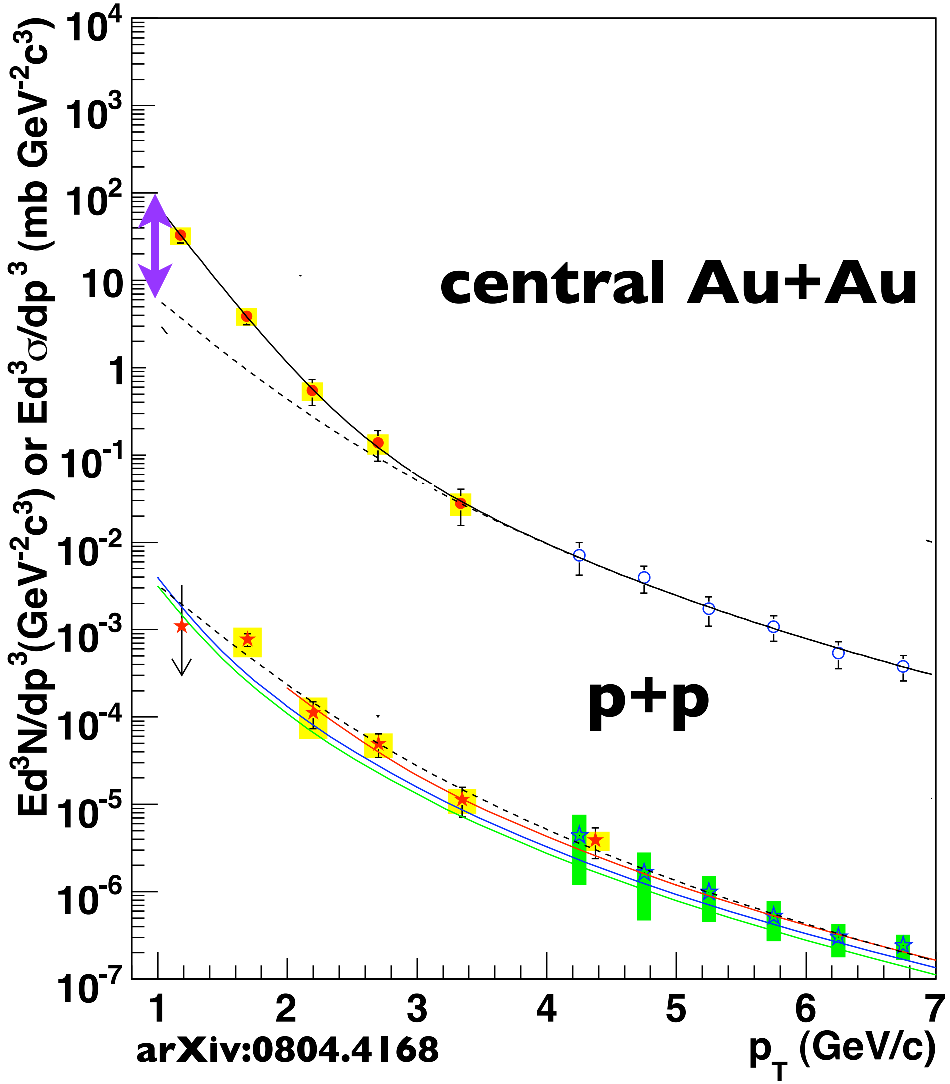
hot nuclear matter

Direct γ

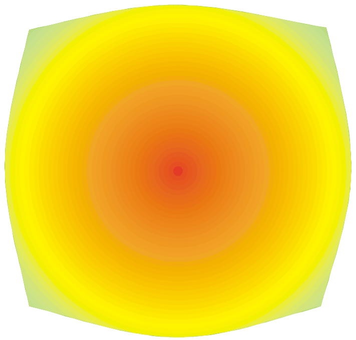


hot nuclear matter

Direct γ

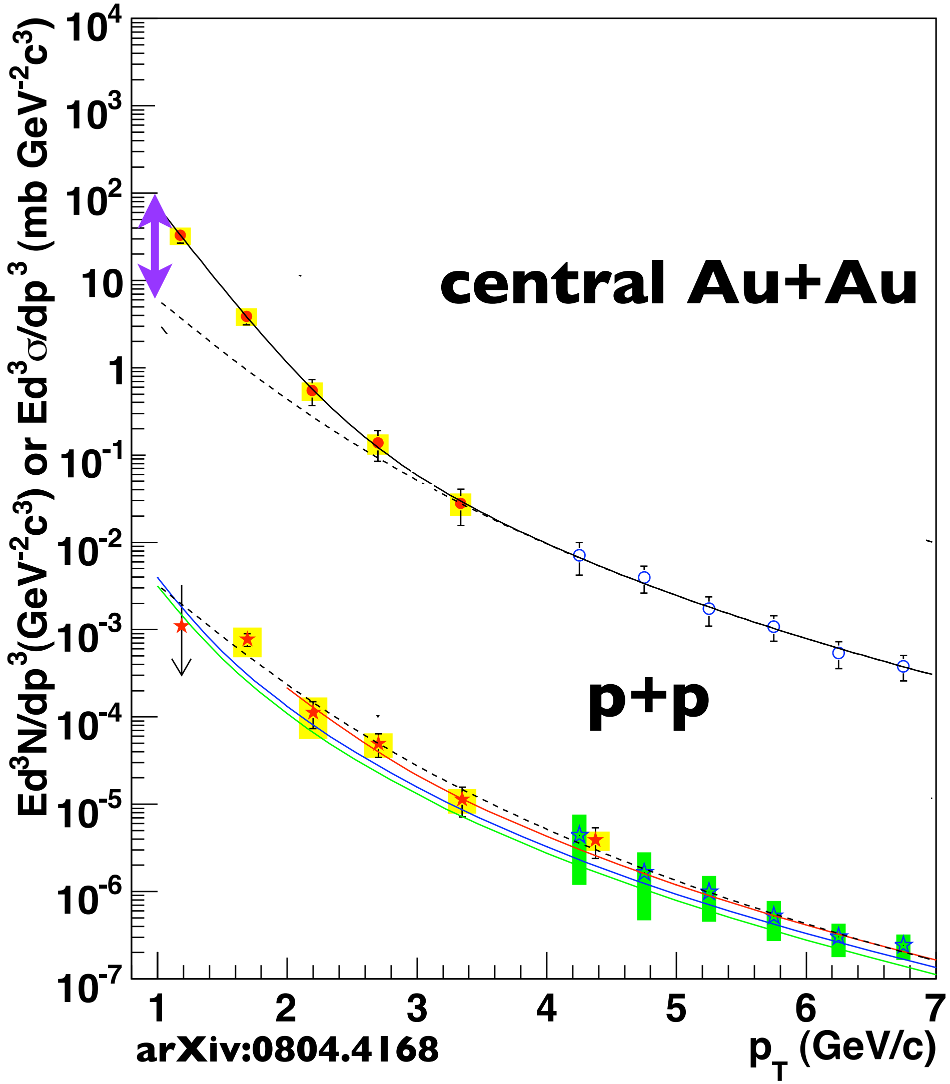


hot nuclear matter



central Au+Au:
large excess over
binary scaled p+p

Direct γ



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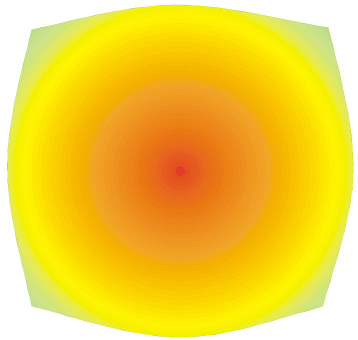
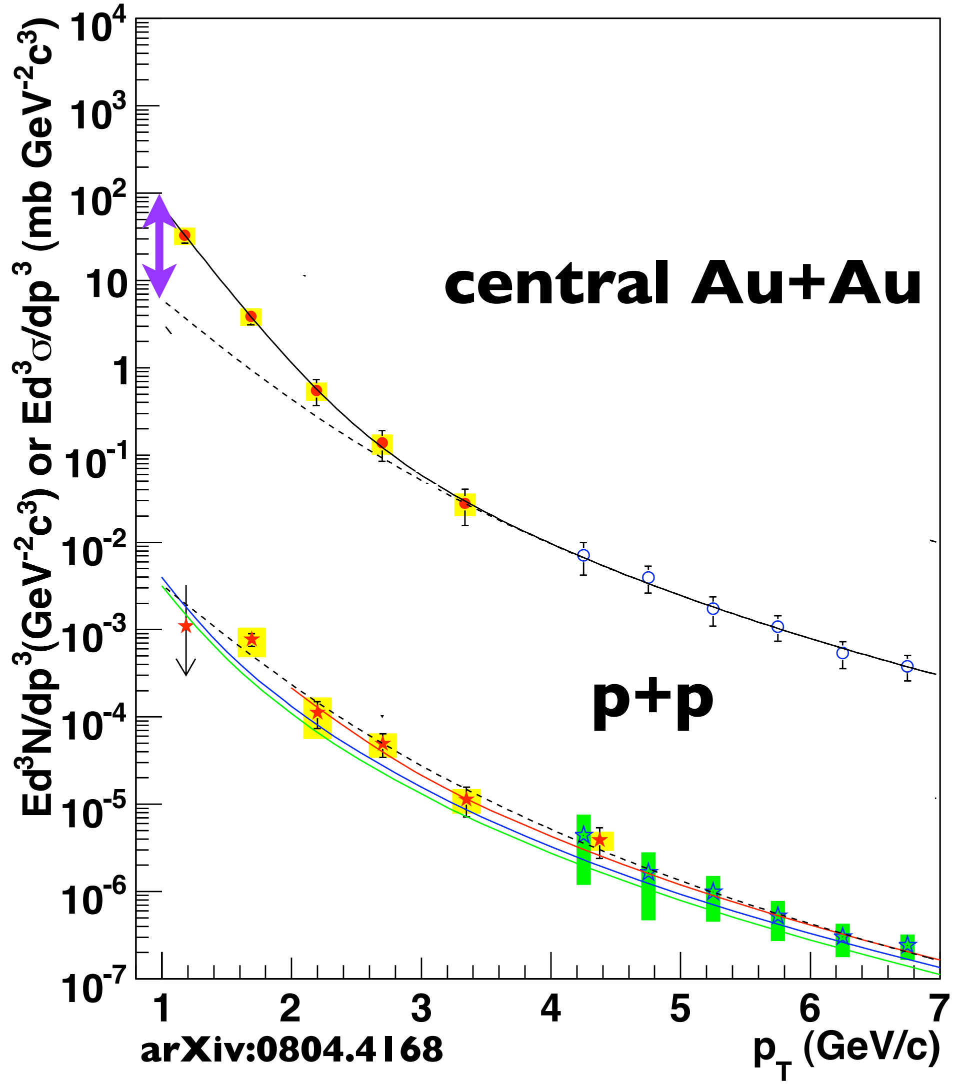


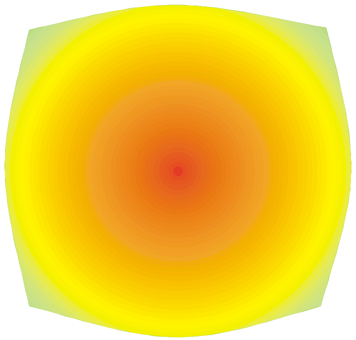
central Au+Au:
large excess over
binary scaled p+p

excess:
221±23±18MeV

Direct γ



hot nuclear matter

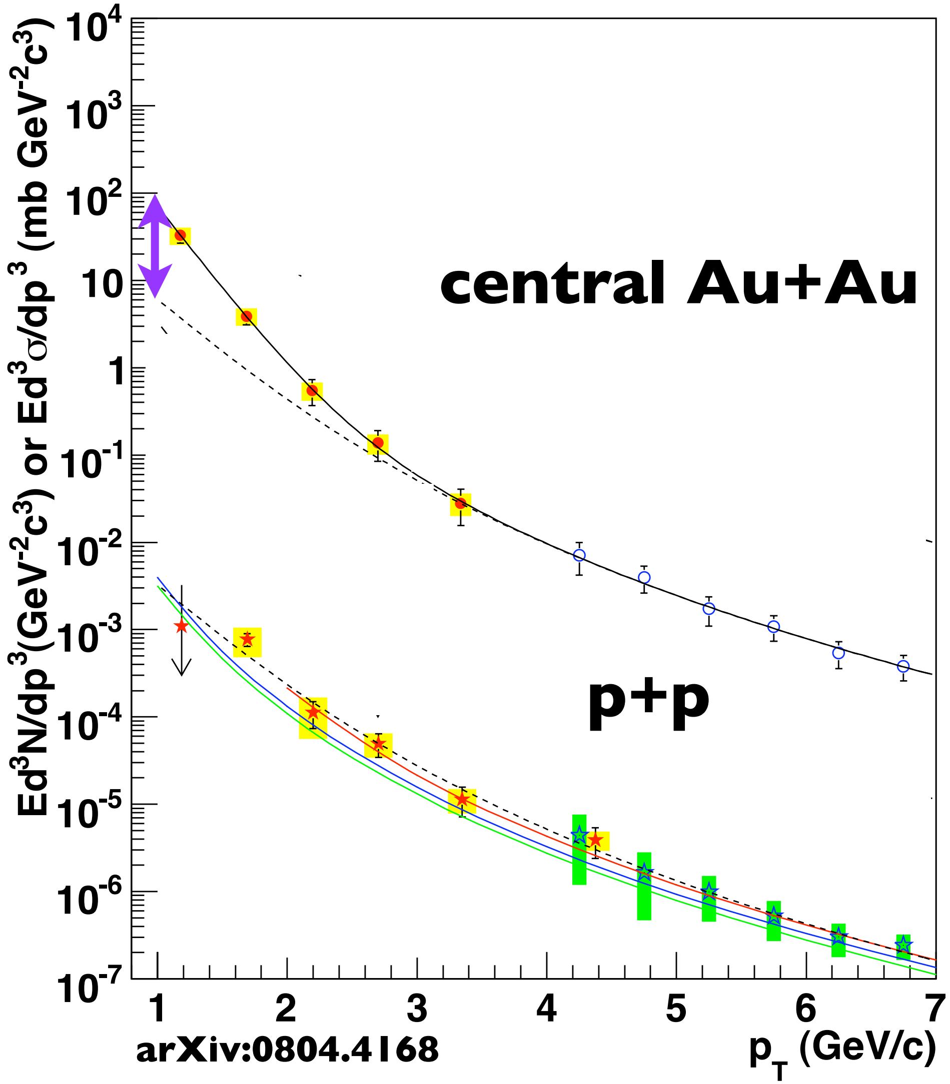


central Au+Au:
large excess over
binary scaled p+p

excess:
221±23±18MeV

consistent with initial
T ~ 300-600MeV

Direct γ



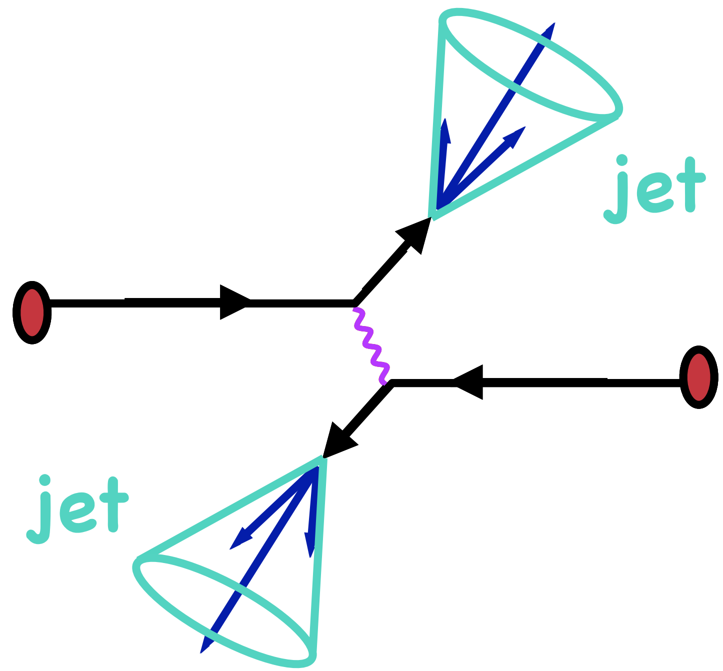
high p_T particle production

p+p collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

Hard Scattering Cross Section: Calculated with pQCD

Fragmentation into Hadrons: Measured in e+e- Collisions



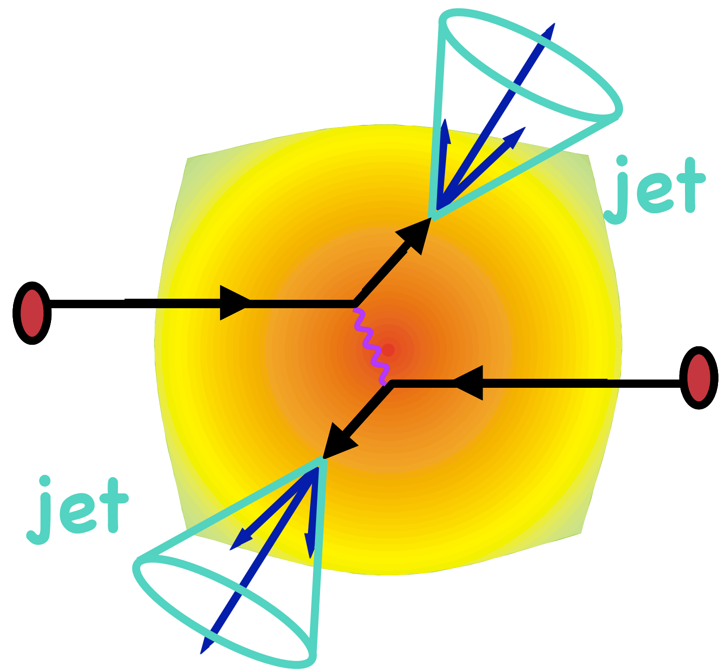
high p_T particle production

Au+Au collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

Hard Scattering Cross Section: Calculated with pQCD

Parton-Medium Interactions & Hadron Formation

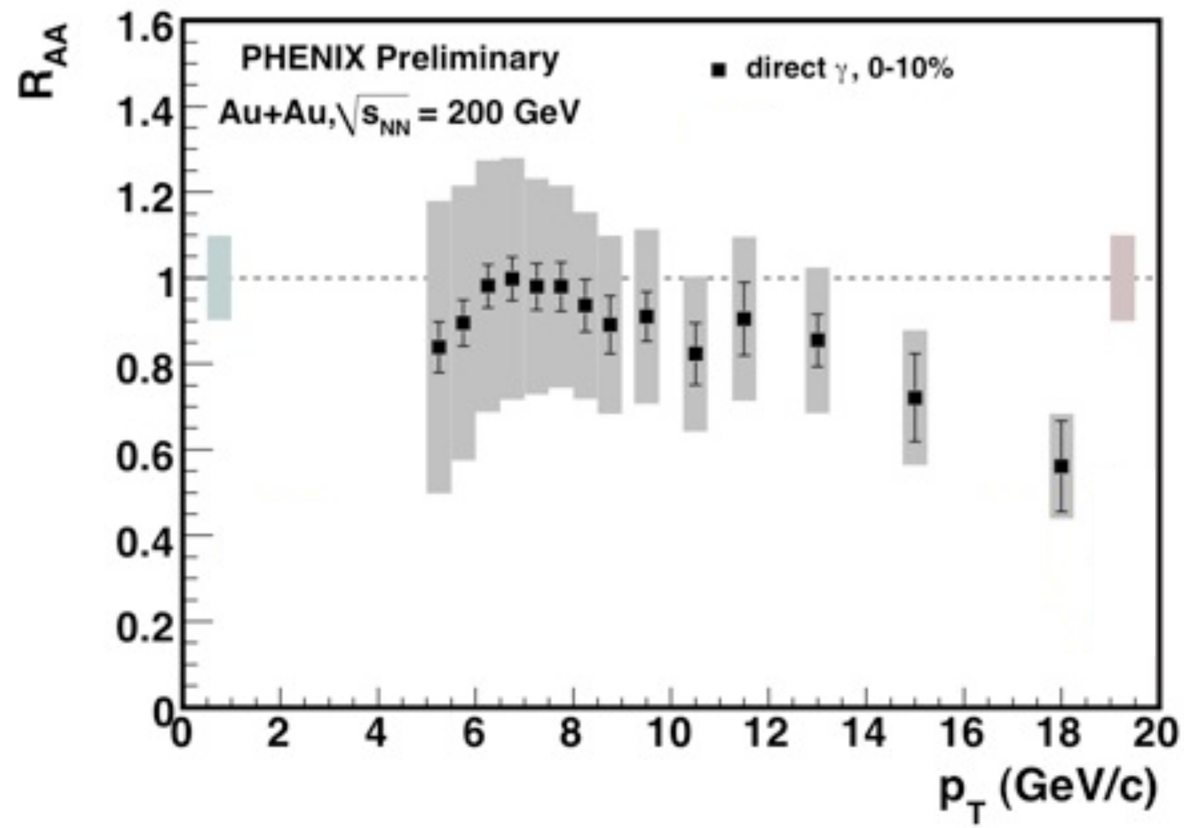


γ: control measurement

$$R_{AA} = \frac{yield_{AA}}{yield_{pp} * N_{coll}}$$

$R_{AA} = 1$

no nuclear effects



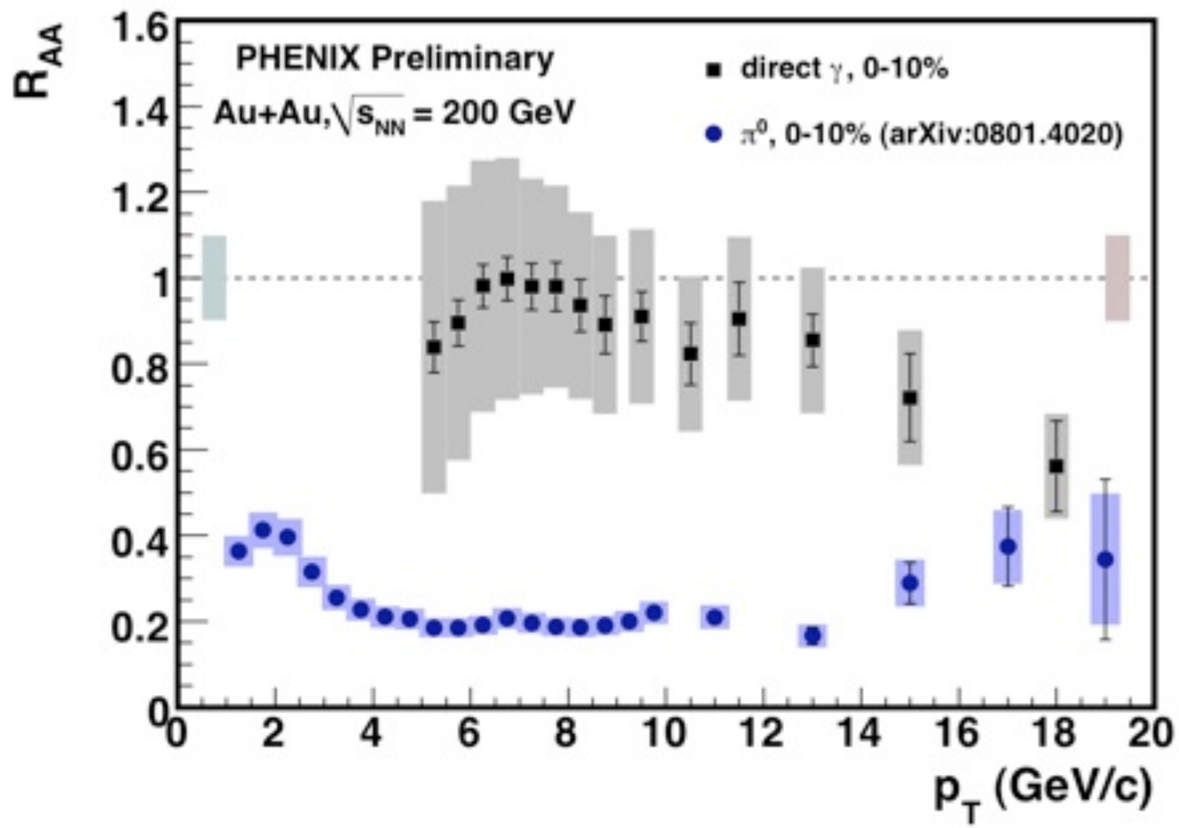
γ: no color charge → insensitive to produced matter
$R_{AA}(p_T$<14GeV/c) consistent with unity

π^0: light meson

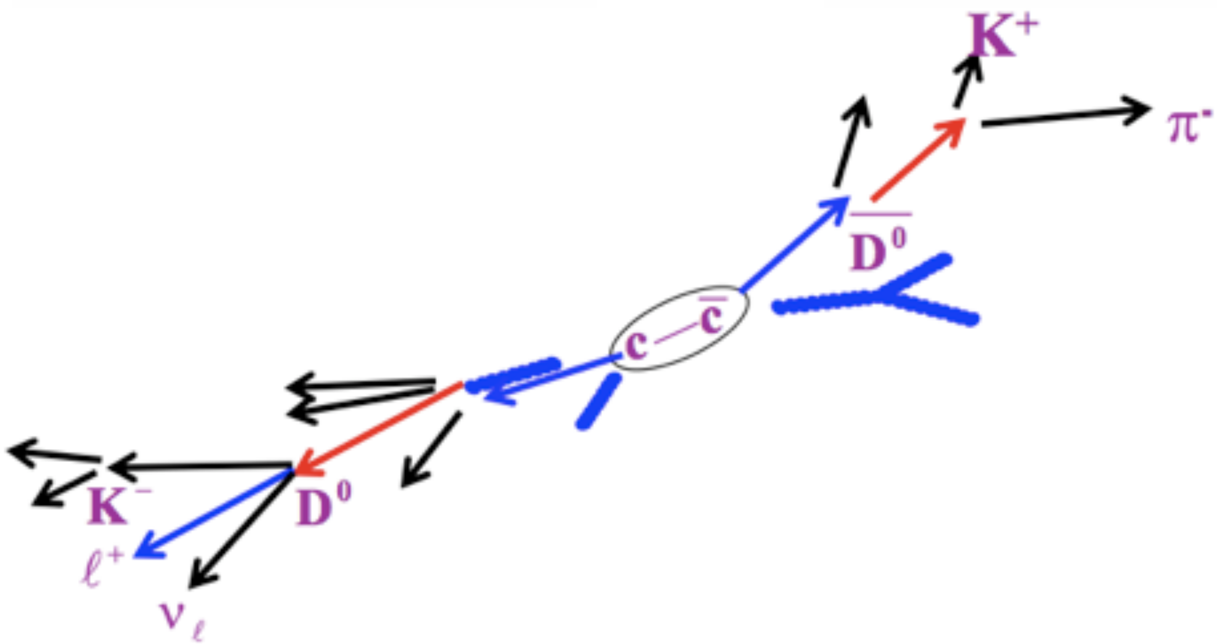
$$R_{AA} = \frac{yield_{AA}}{yield_{pp} * N_{coll}}$$

$R_{AA} << 1$

parton energy loss



Heavy Flavor via Semi-leptonic decays

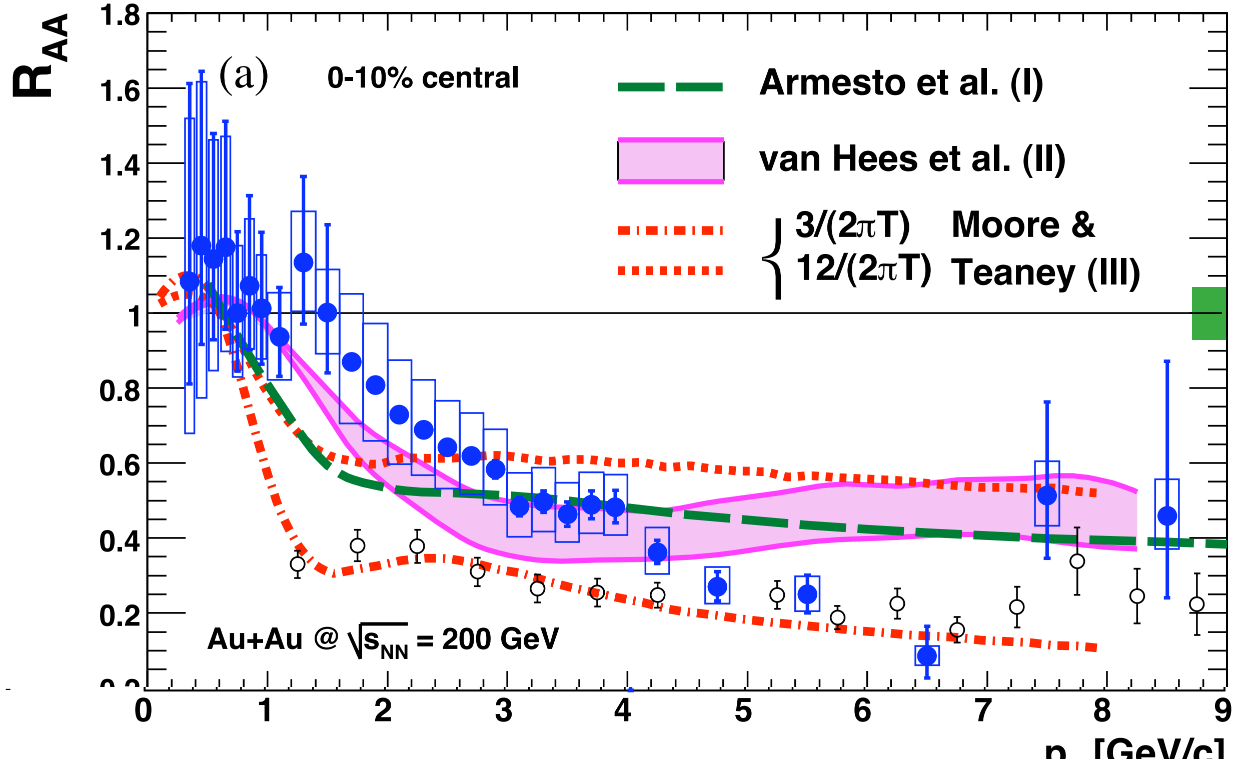


Decay	Branching Ratio
$D^{\pm} \rightarrow e+X$	16.0%
$D^{0} \rightarrow e+X$	6.5%

- single particles: measure $e^{\pm}$ from D, B decay
- hadronic decays: large backgrounds

problem: how do you know if $e^{\pm}$ came from charm or bottom?

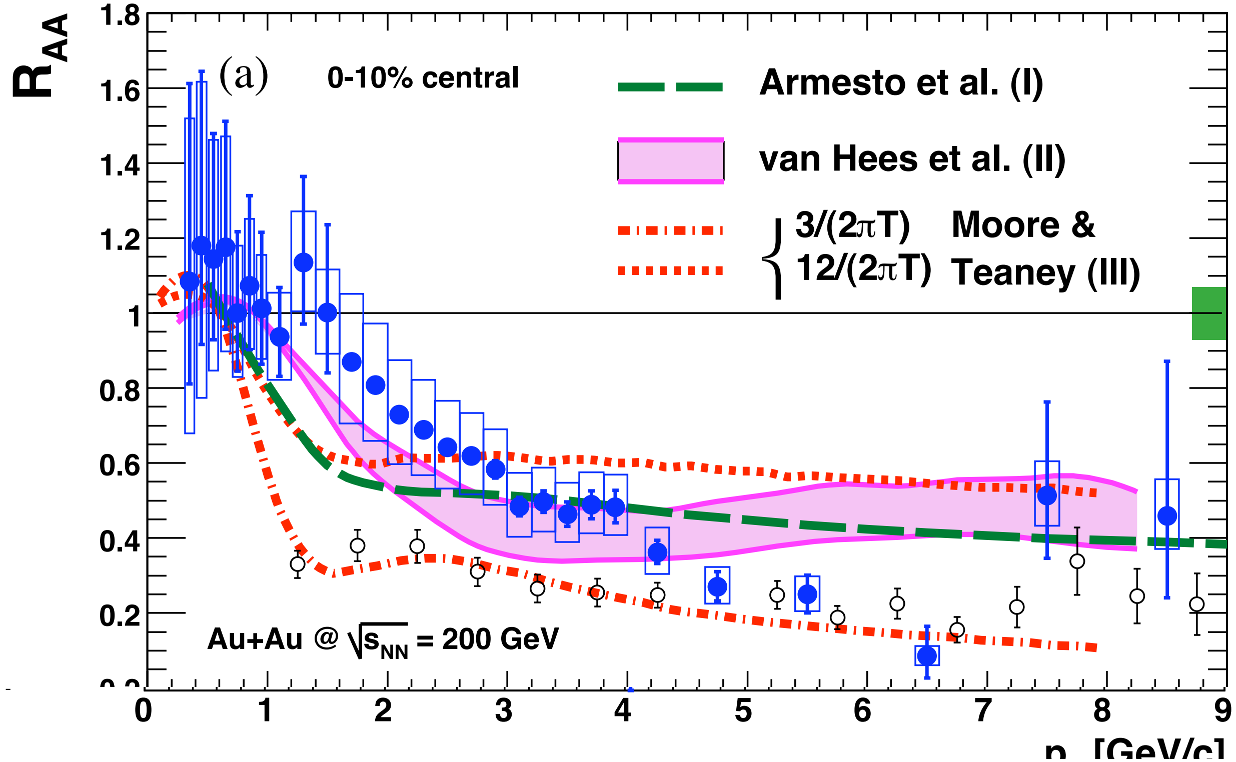
...and heavy quarks?



- electrons from decay of heavy mesons are modified by the matter in heavy ion collisions
  - yields are suppressed at nearly same level as π^0

PHENIX, PRL 98 172301 (2007)

...and heavy quarks?



- electrons from decay of heavy mesons are modified by the matter in heavy ion collisions
  - yields are suppressed at nearly same level as π^0

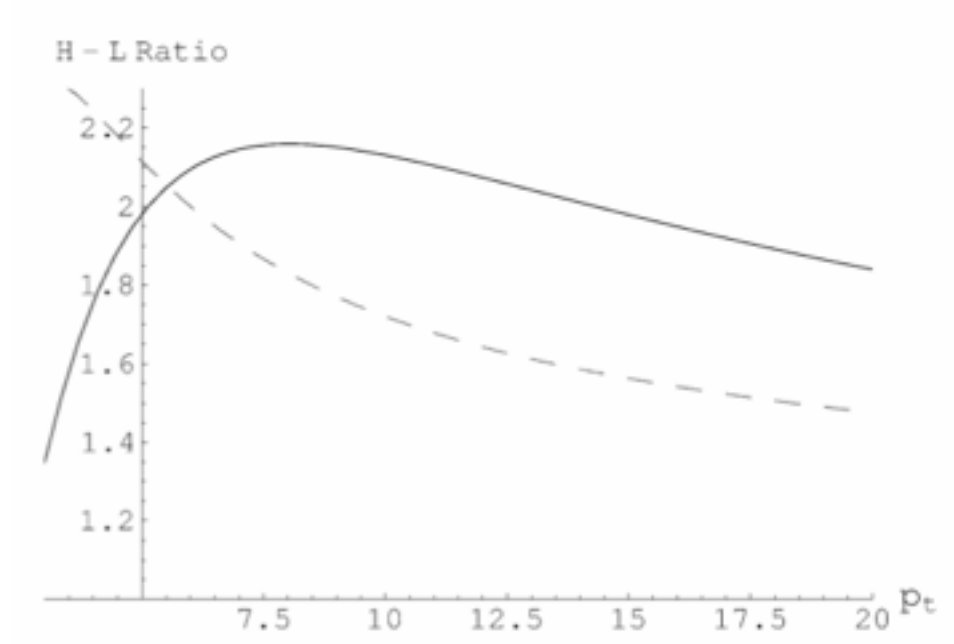
heavy quarks are a good probe of hot nuclear matter!

PHENIX, PRL 98 172301 (2007)

heavy quark energy loss

- radiative energy loss should be suppressed for heavy quarks: "dead cone effect" (Dokshitzer & Kharzeev)
- some calculations expect large collisional energy loss

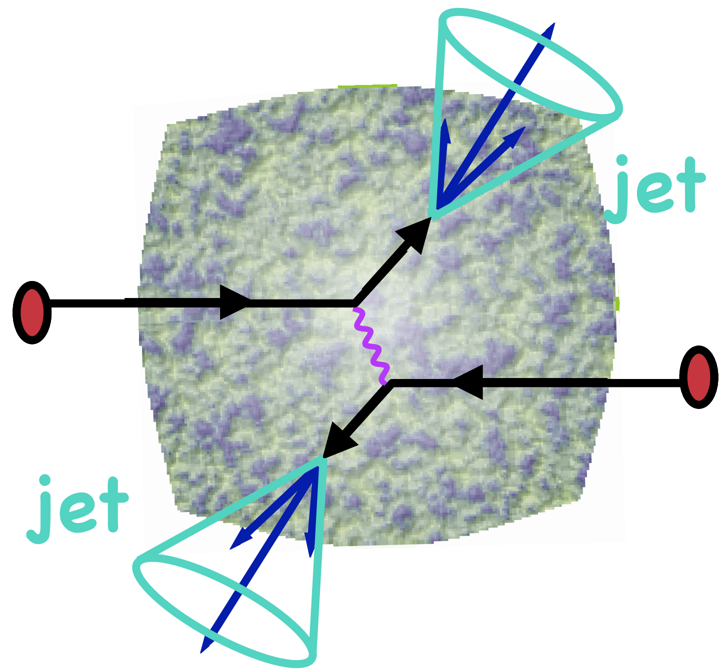
R_{AA}(charm)/R_{AA}(light quarks)



experimental question: how does the energy loss pattern of heavy quarks differ from light partons?

final state effects

- jets are produced before the matter, but the see the entire lifetime of the system
- final state effects could change which hadrons are formed



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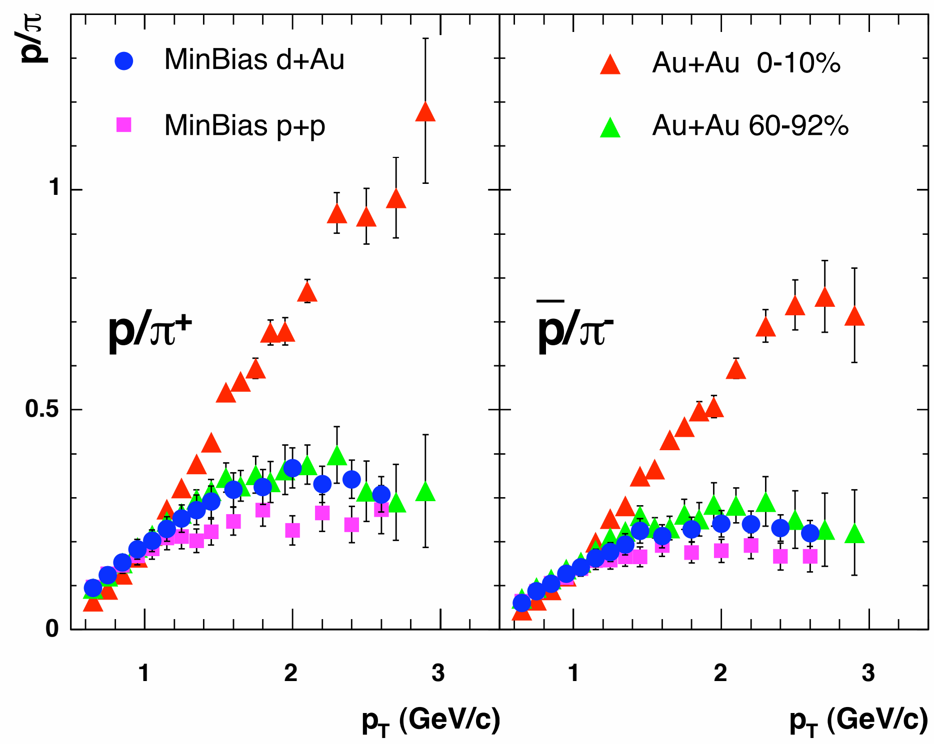

PHENIX PRC 74 024904 (2006)

recombination

basic idea: valence quarks coalesce to form final state hadrons

Fries et al., Hwa et al., Ko et al.

recombination

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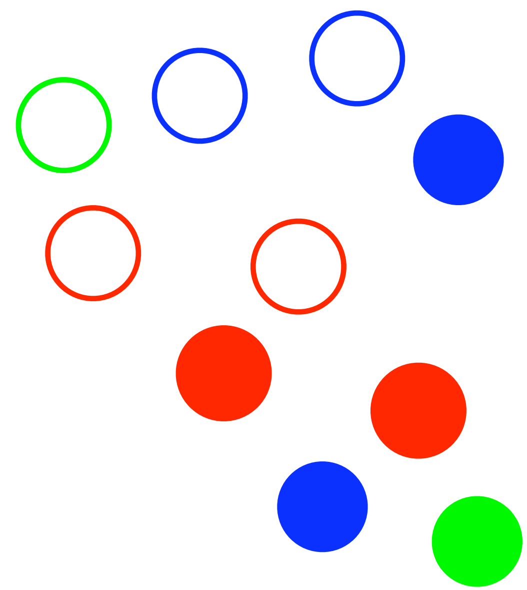

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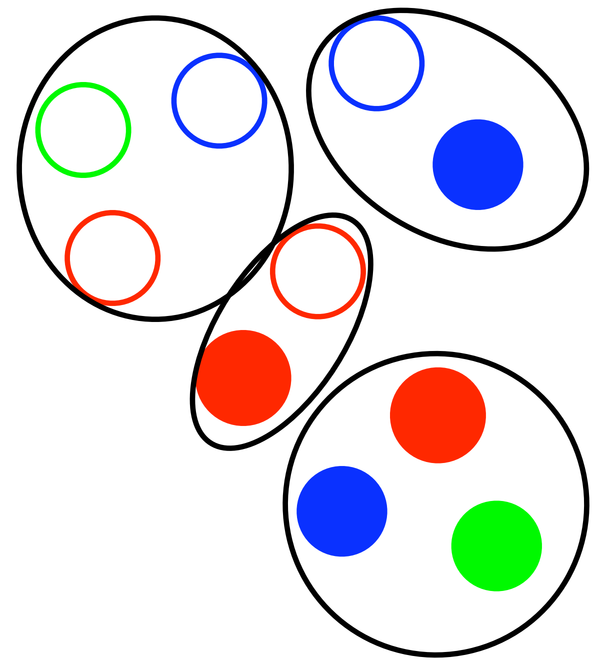

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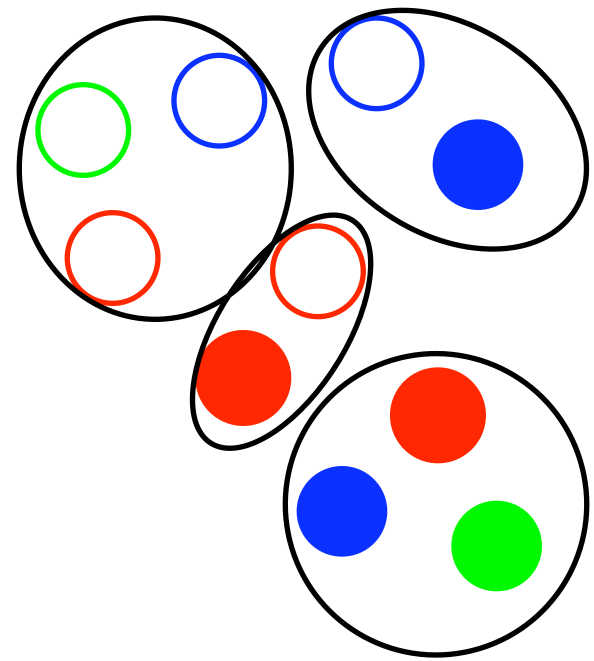

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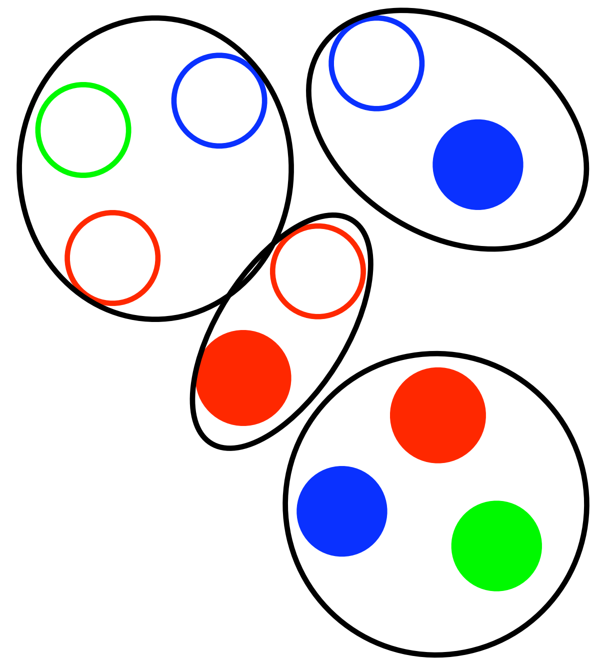
- quark momenta add:
  - p_T(hadron) > p_T(quark)
  - baryons get an extra boost→extra quark



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recombination

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- quark momenta add:
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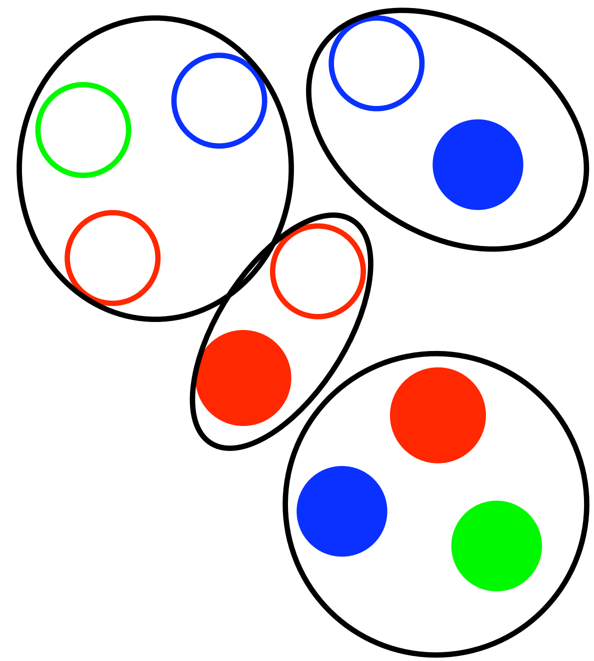
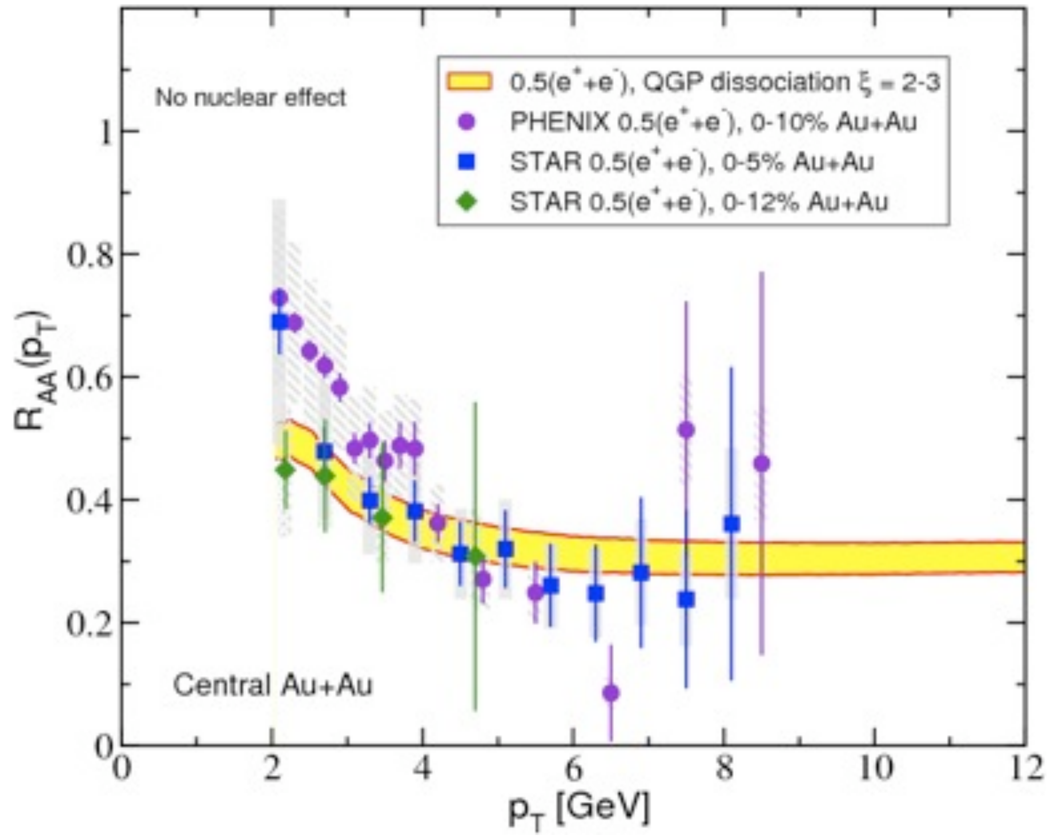
- if heavy quarks also recombine, it could lower their R_{AA}
  - heavy baryons don't decay into electrons as much as mesons



Fries et al., Hwa et al., Ko et al.

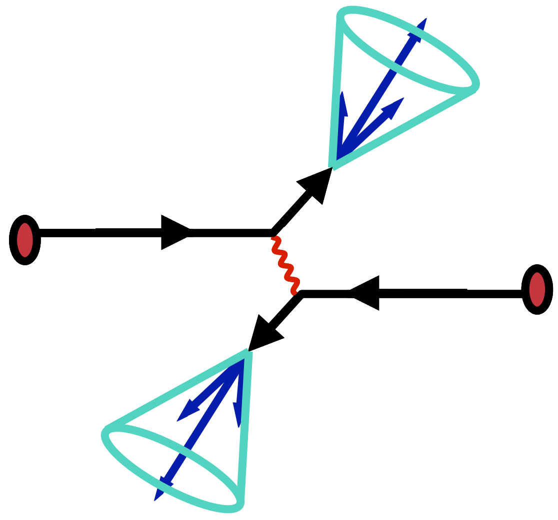
D/B in medium formation

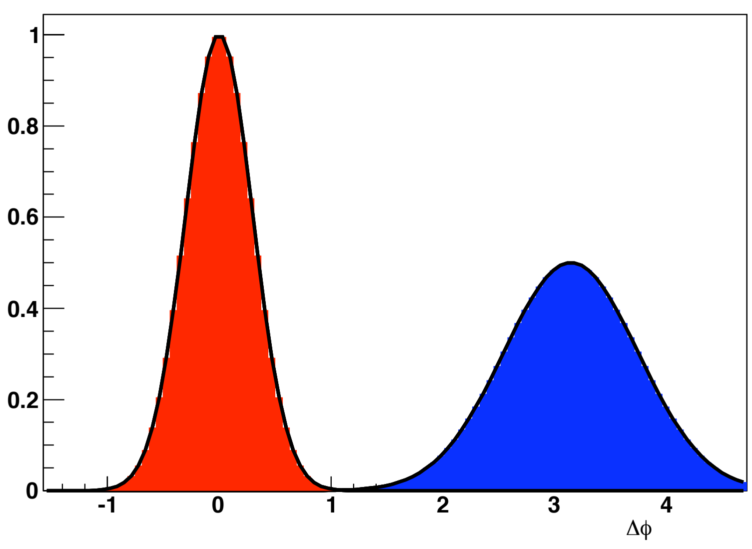
- D/B form & dissociate in the matter:
  - $\tau_{form} \propto p_T$
  - τ_{formD}(10GeV/c)=1.6fm/c
  - τ_{formB}(10GeV/c)=0.4fm/c
- expect to see extra hadrons on the near side from the D & B energy loss



Adil & Vitev PLB649 139 (2007)

2 particle correlations





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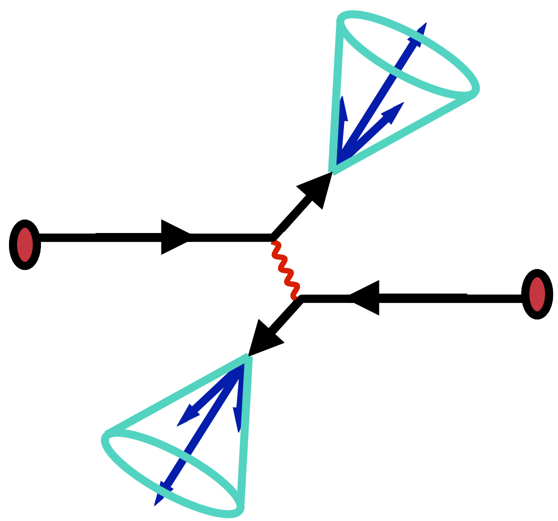
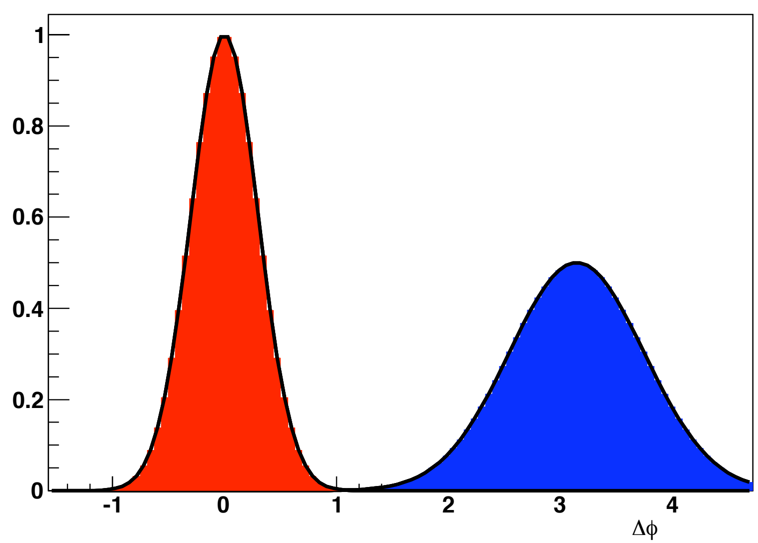
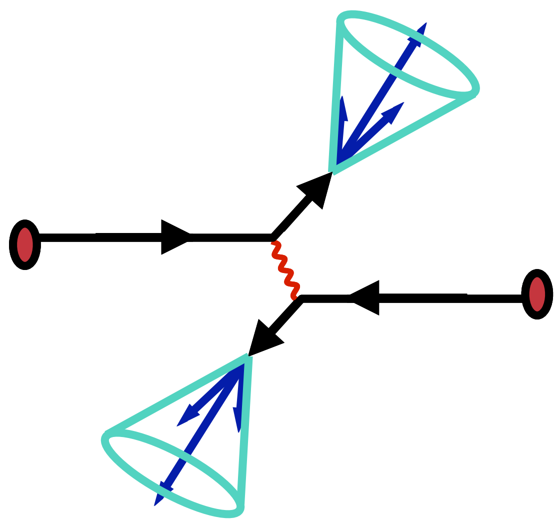


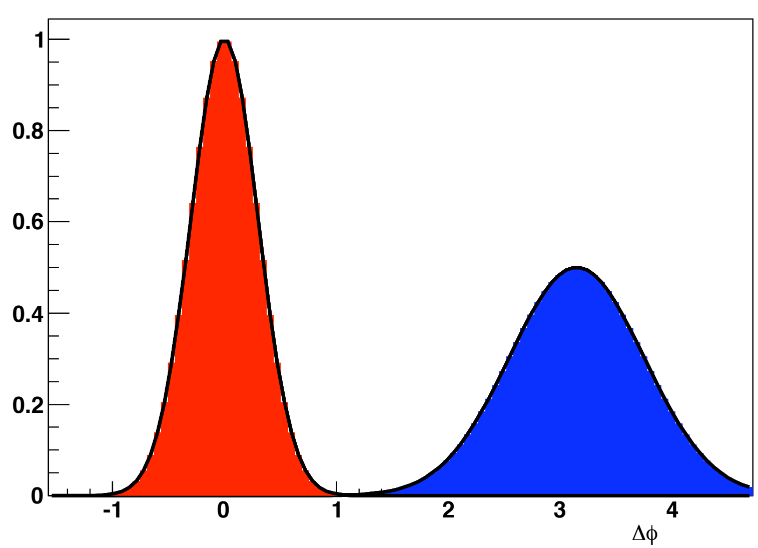


- complementary to single particle observables

2 particle correlations



- complementary to single particle observables
- different sensitivity to geometry



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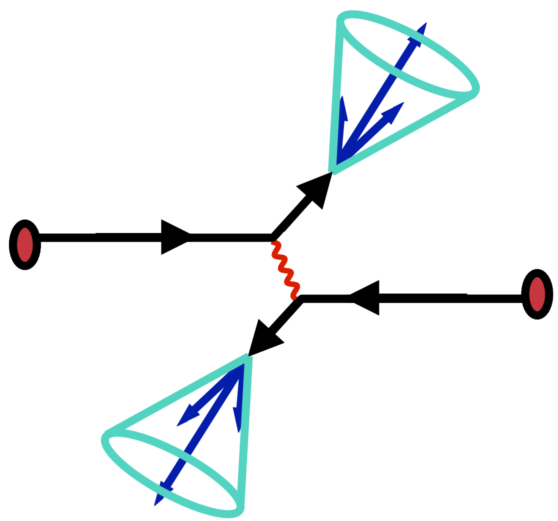
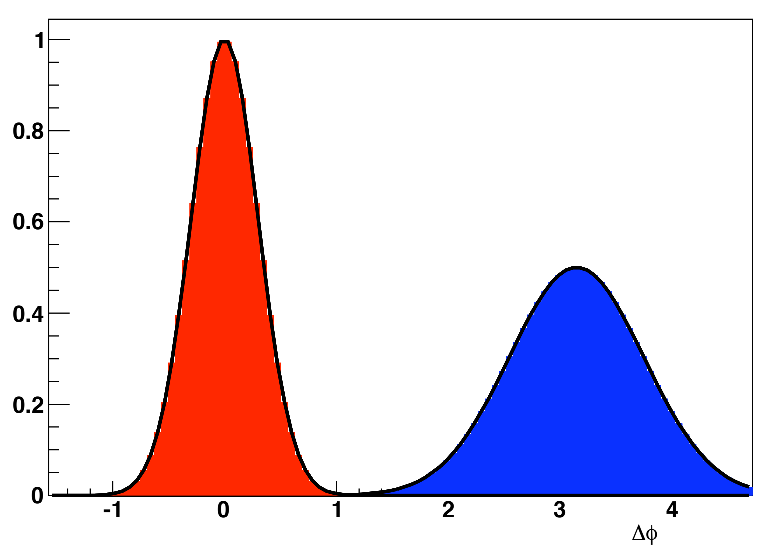
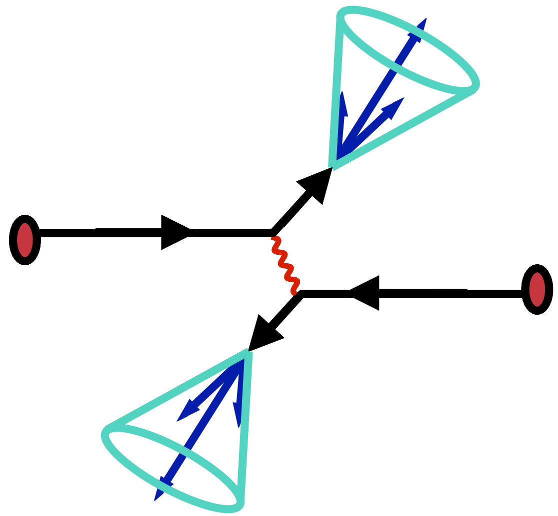




- complementary to single particle observables
- different sensitivity to geometry
- sensitive to energy flow

2 particle correlations



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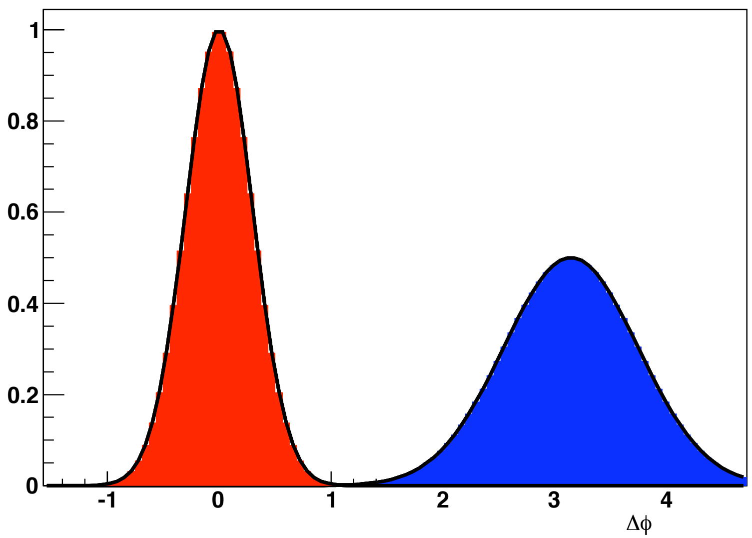
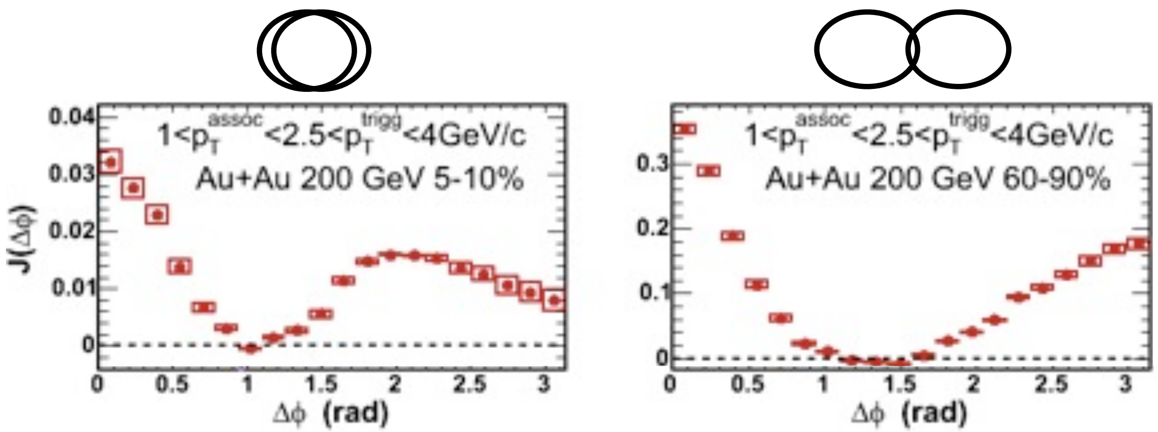


quantifcation

$$I_{AA} = \frac{\text{conditional yield in AuAu}}{\text{conditional yield in pp}}$$

Mach Cones?

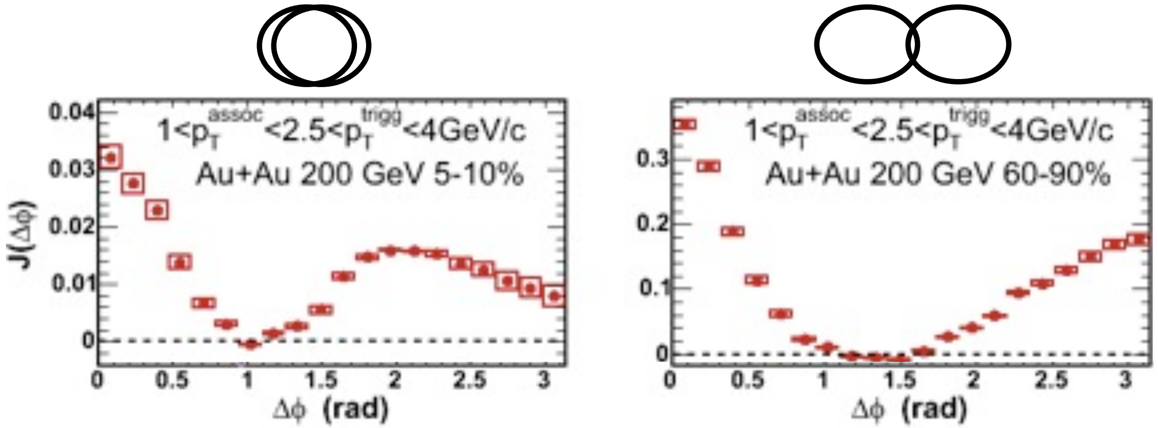
hadron correlations
Mach Cones?



PRL 98 232202 (2007)

Mach Cones?

hadron correlations
Mach Cones?

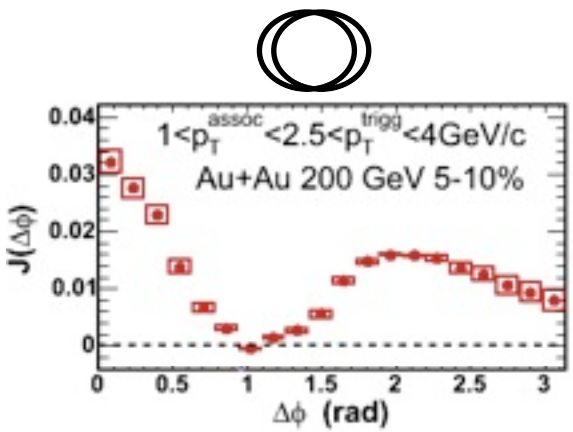


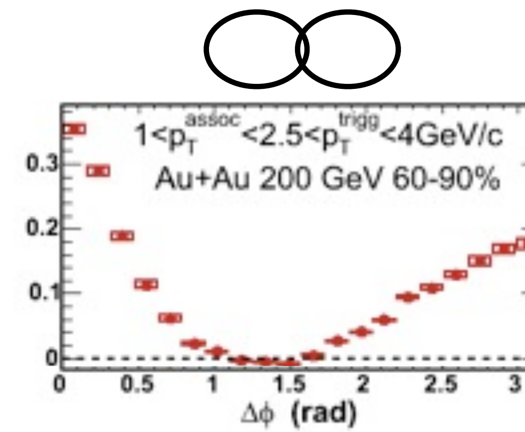
cone angle: $$cos\theta_M = \frac{\bar{c}_s}{v_{jet}}$$

PRL 98 232202 (2007)

Mach Cones?

hadron correlations
Mach Cones?





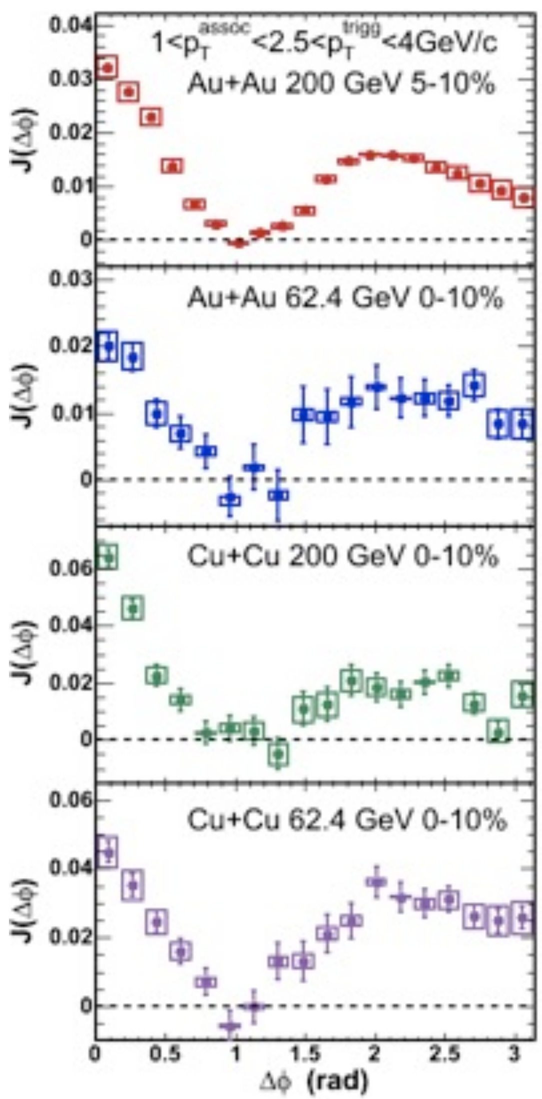
cone angle:

$$cos\theta_M = \frac{\bar{c}_s}{v_{jet}}$$

change θ_m by changing:
$<c_s>$ → $\sqrt{s}$NN
jet velocity → massive partons

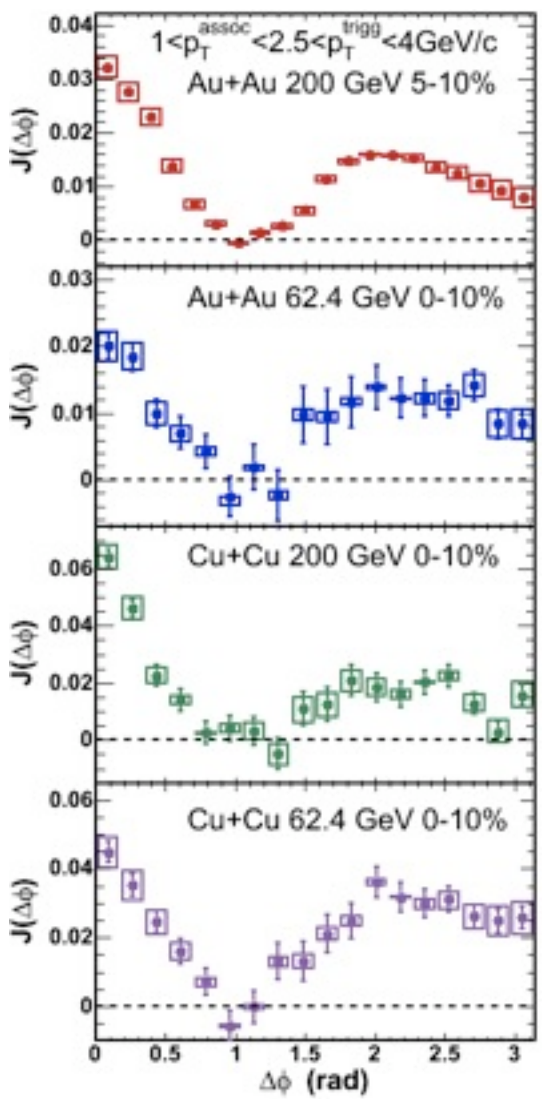
PRL 98 232202 (2007)

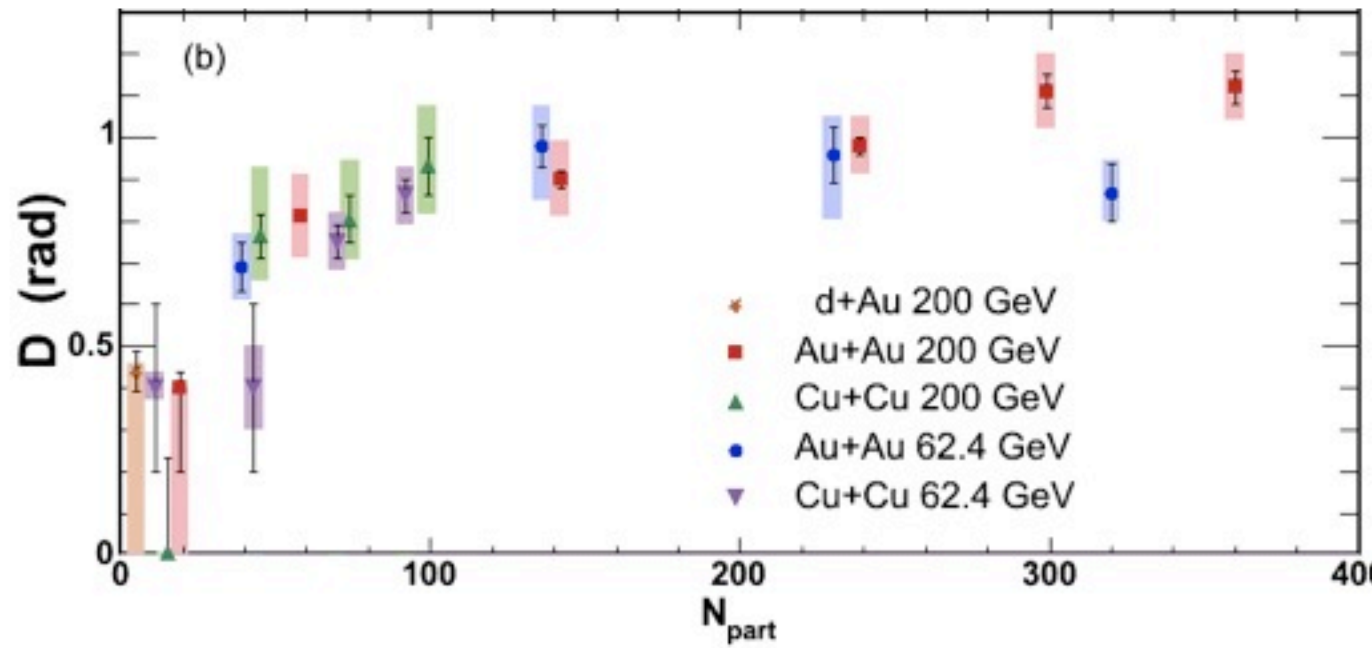
changing beam energy



PHENIX, PRL 98 232302 (2007)

changing beam energy





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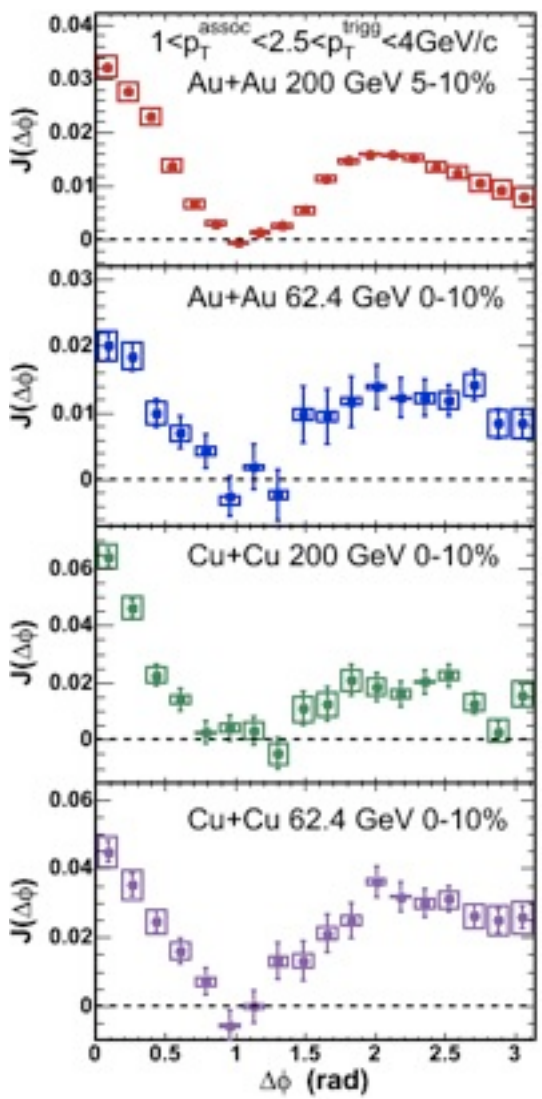
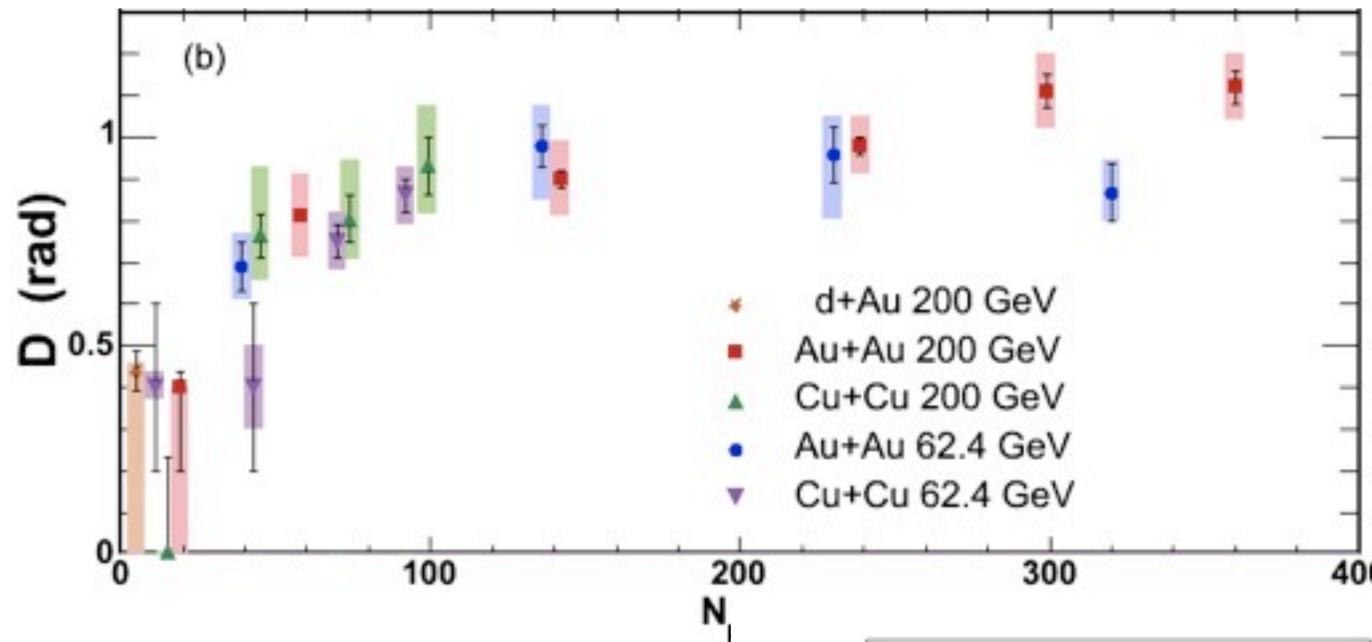
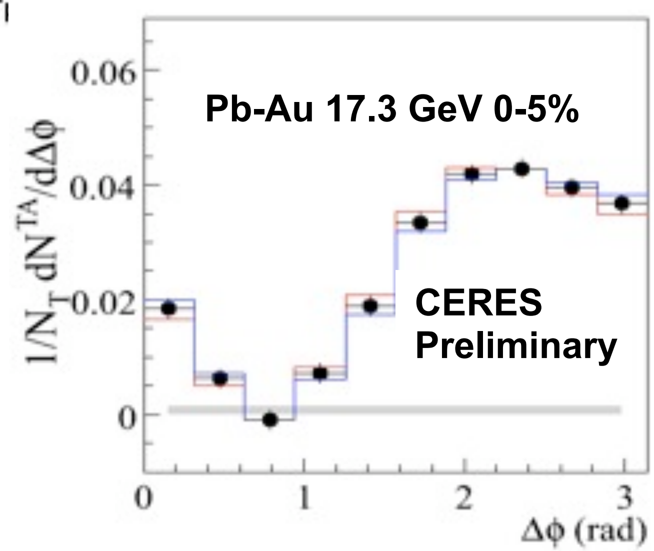
changing beam energy







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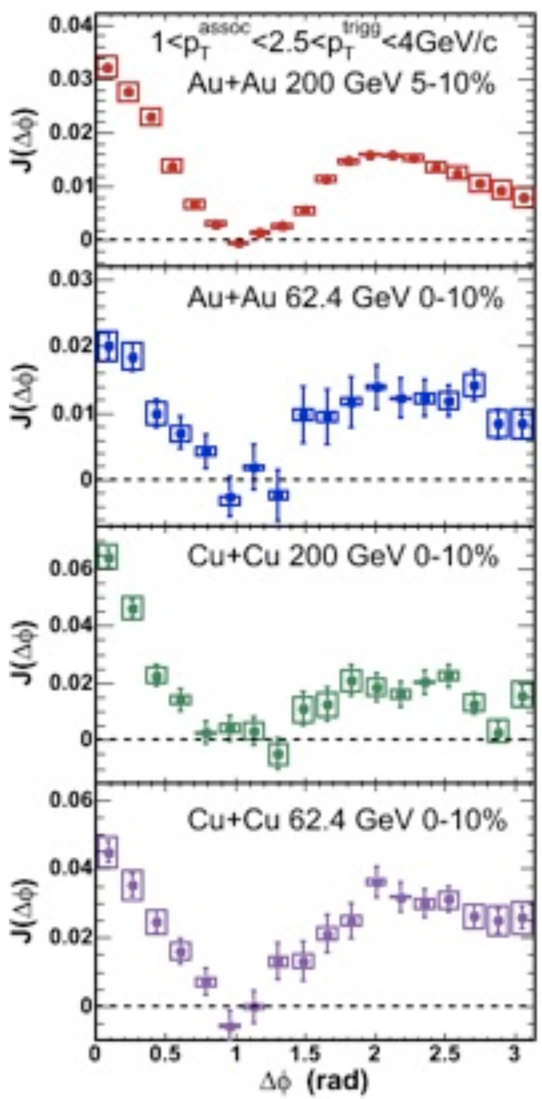
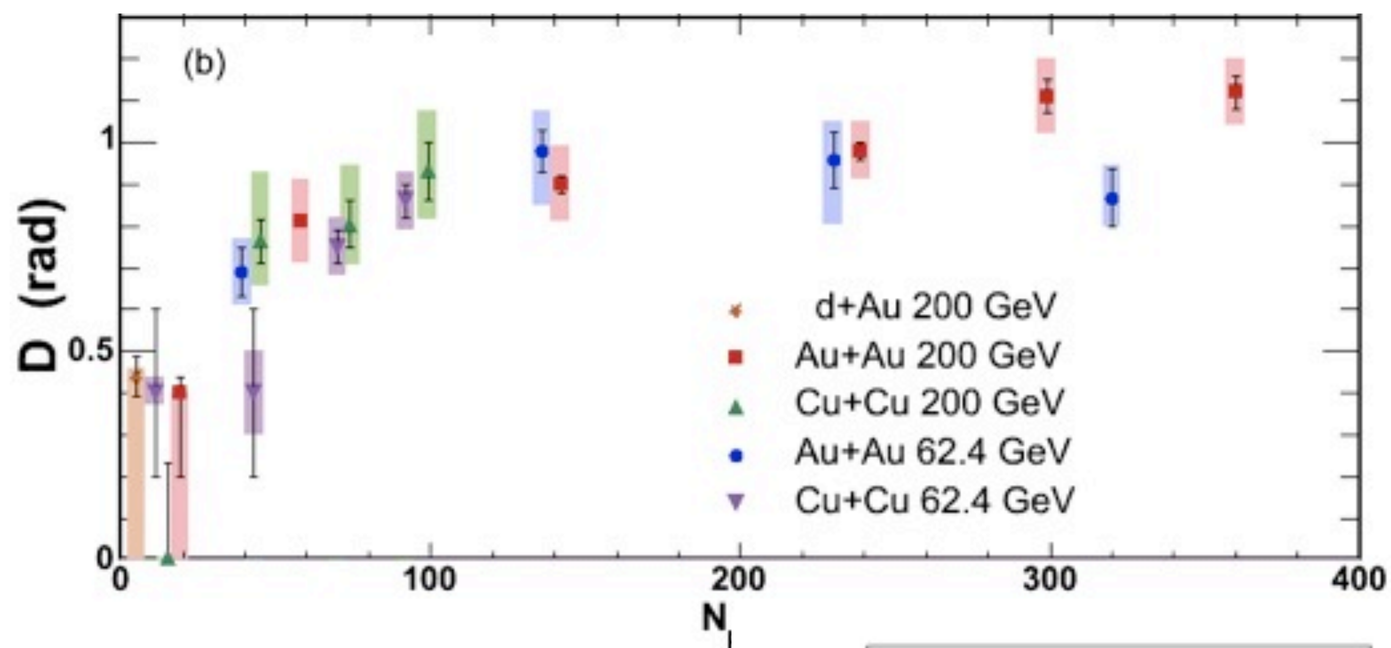
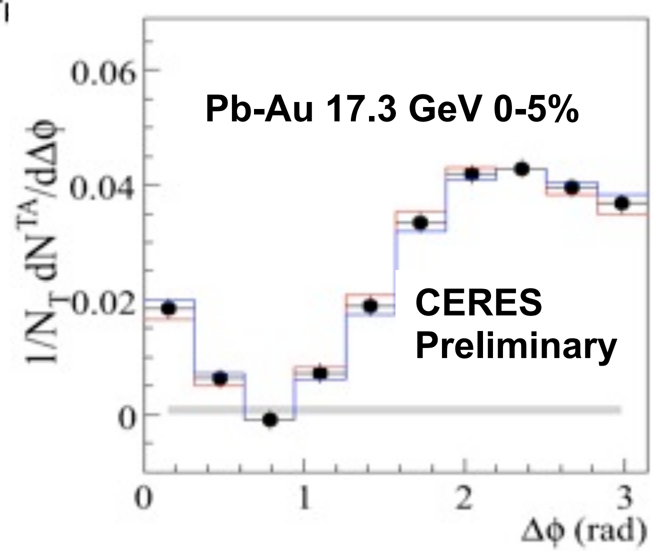




heavy quarks change the jet velocity!

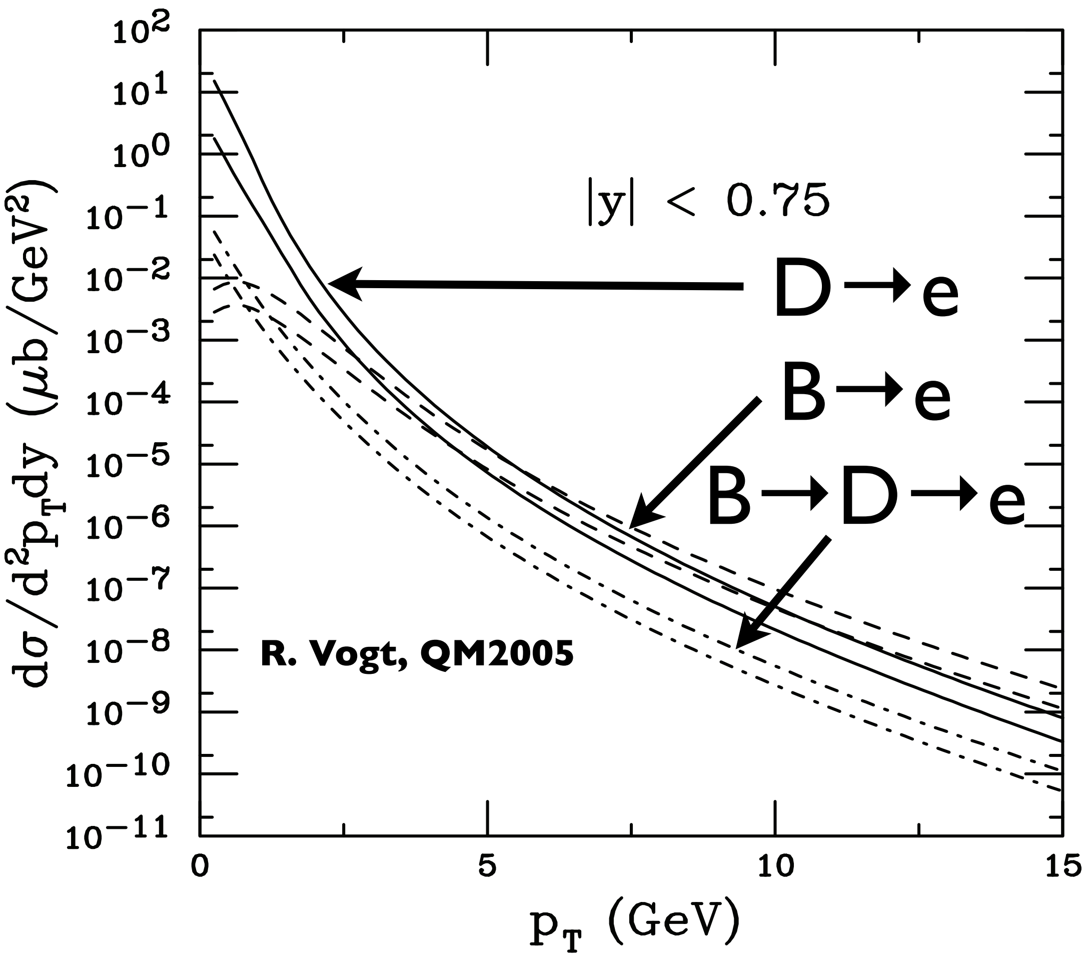


PHENIX, PRL 98 232302 (2007)

The Landscape: Heavy Flavor in p+p

charm & bottom: theory

Single electrons from heavy flavor



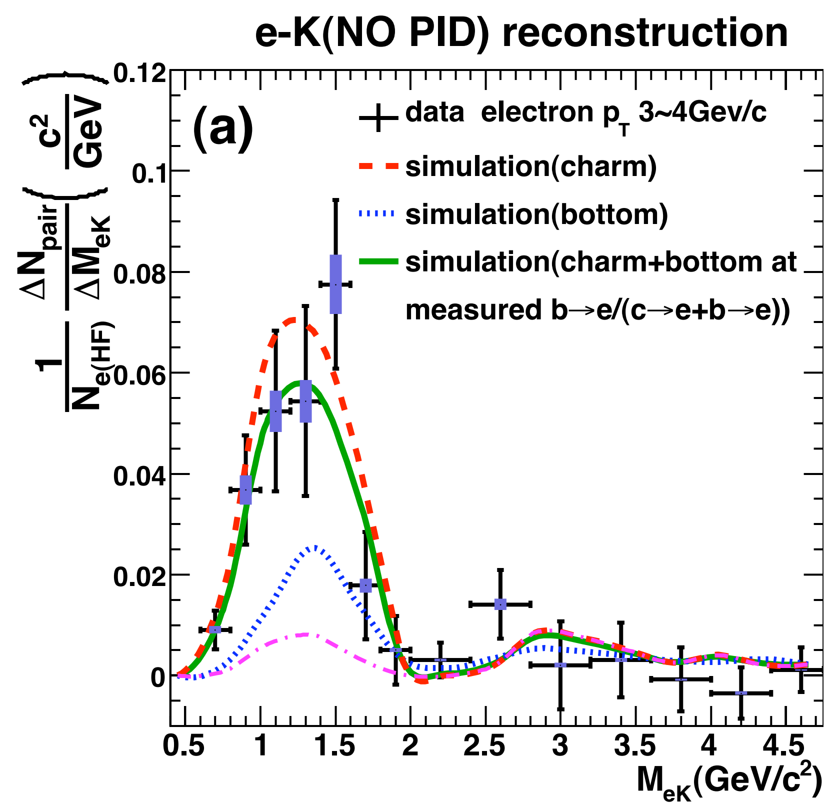
bands show theoretical uncertainty (FONLL) in components

knowledge of relative c/b contributions crucial for understanding HF modifications in Au+Au collisions

what can experiment say?

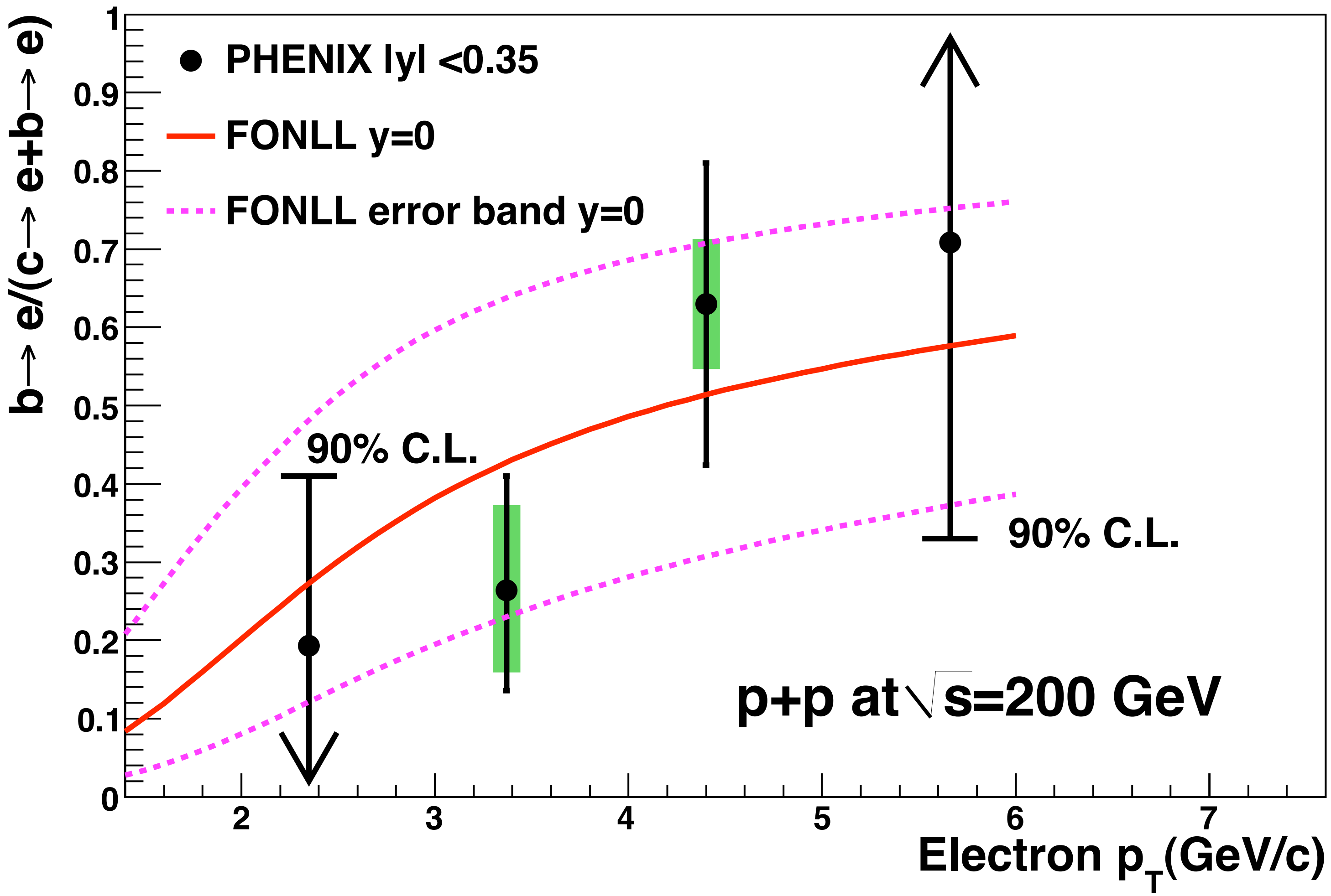
idea: D→eKν, reconstruct eK invariant mass

- heavy meson decay: e & K have opposite signs
  - like sign pairs approximate the background
- compare to simulations to get relative contributions from charm and bottom



arXiv:0903.4851[nucl-ex]

relative b→e contribution vs $p_{T,e}$

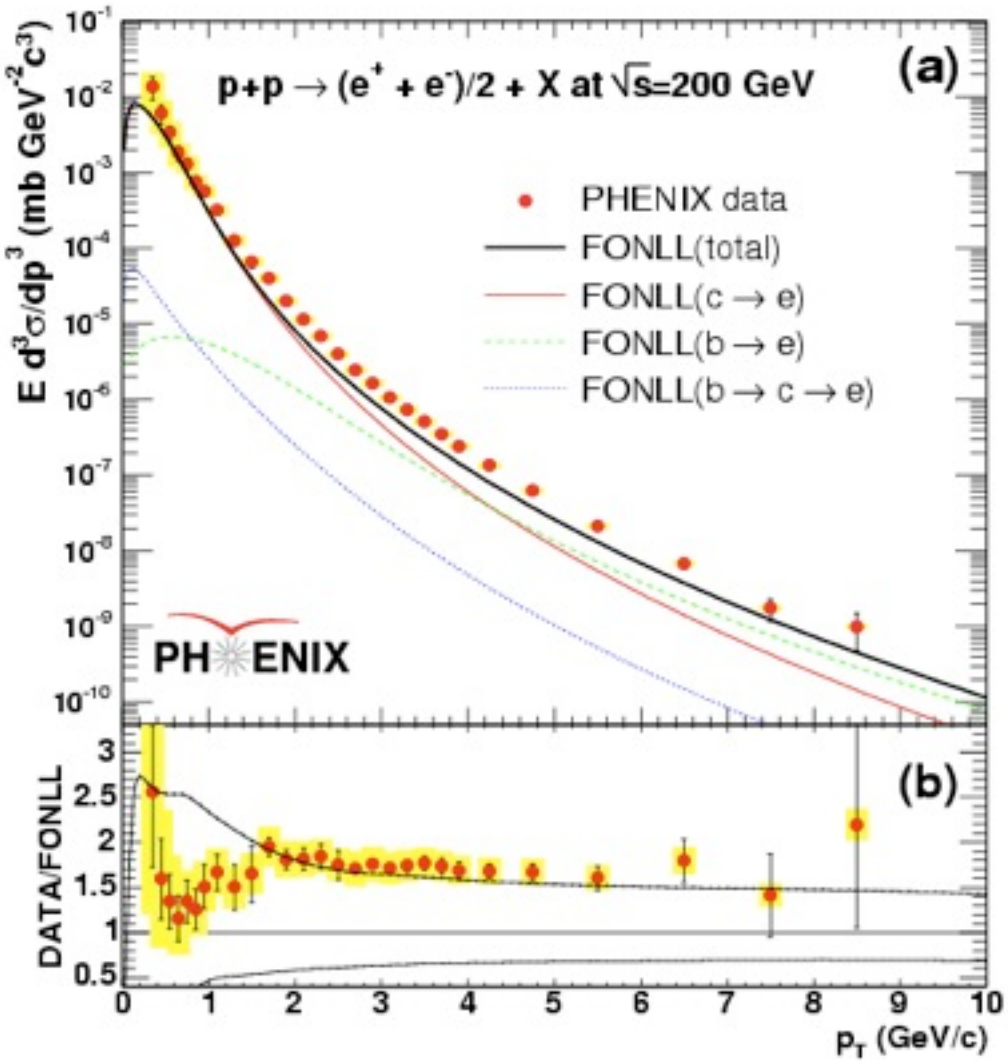


significant bottom contributions
good agreement with FONLL

arXiv:0903.4851[nucl-ex]

two types of electrons

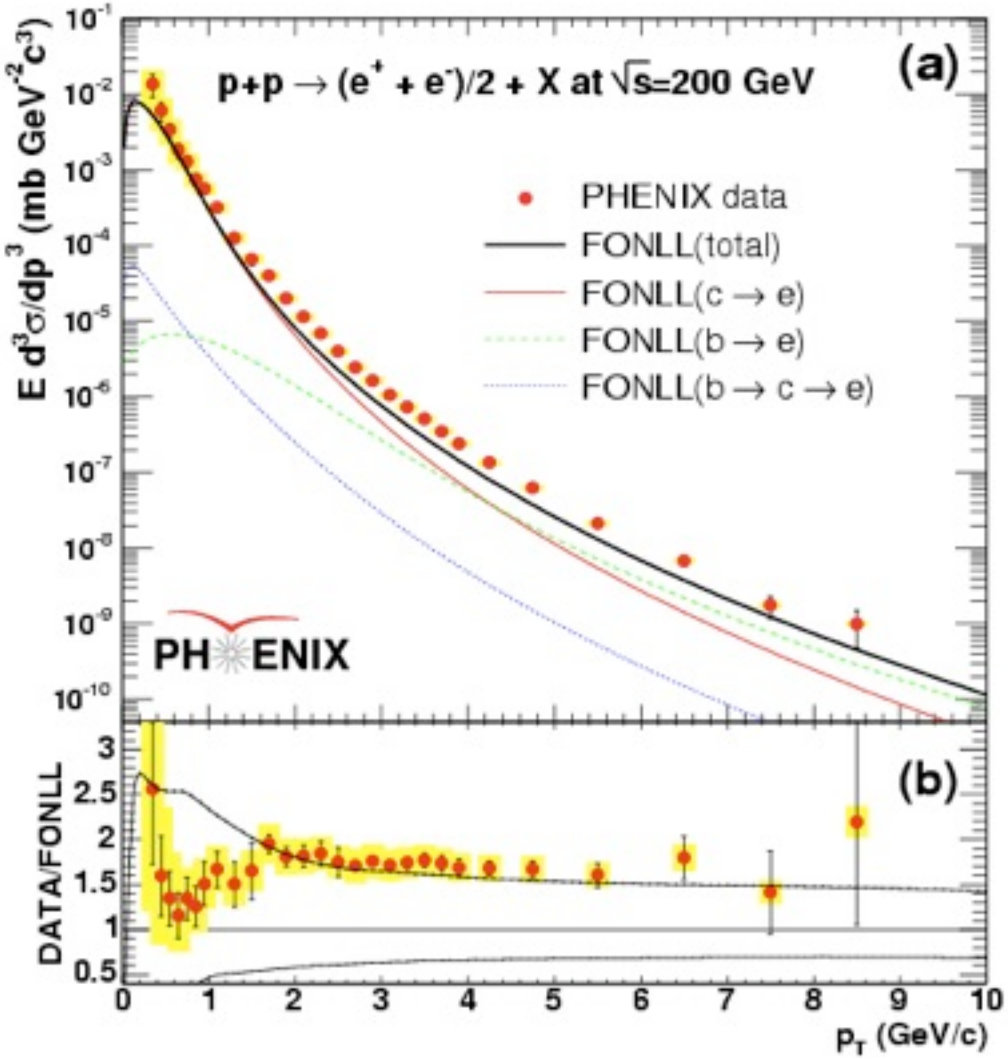
Heavy Flavor



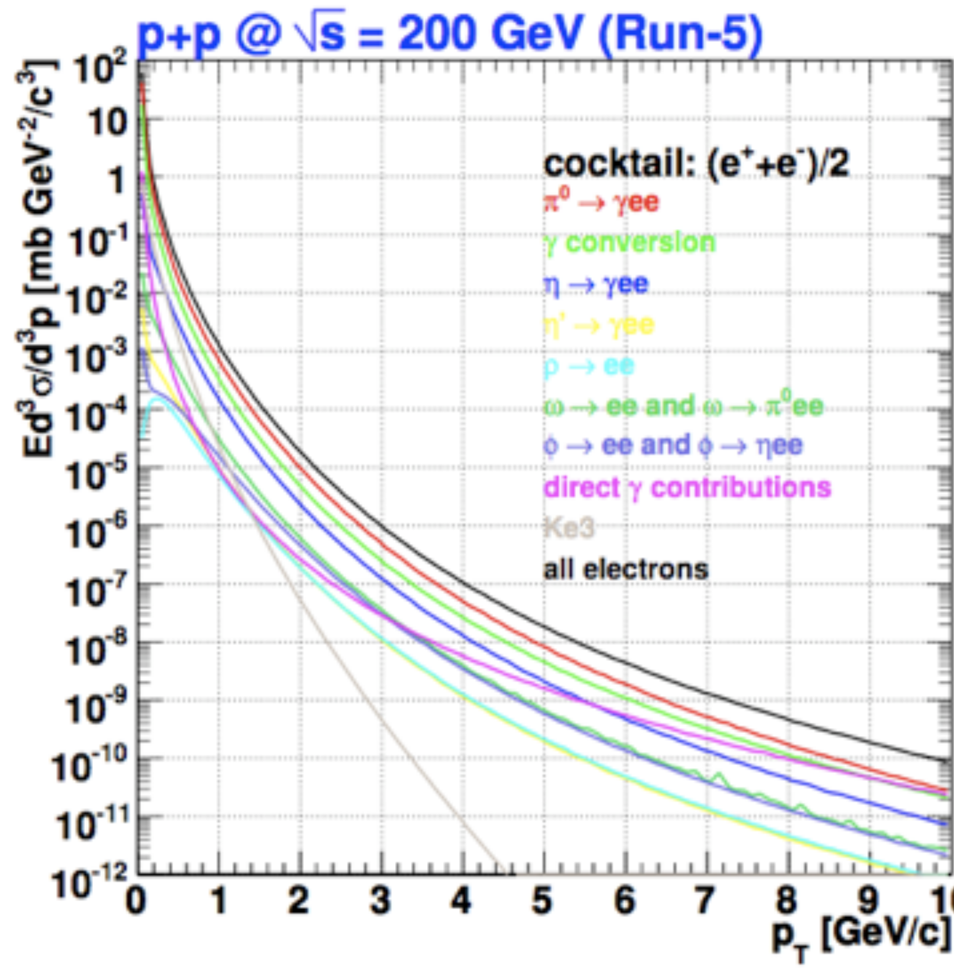
PHENIX, PRL 97 252002 (2006)

two types of electrons

Heavy Flavor



Photonic Electrons



PHENIX, PRL 97 252002 (2006)

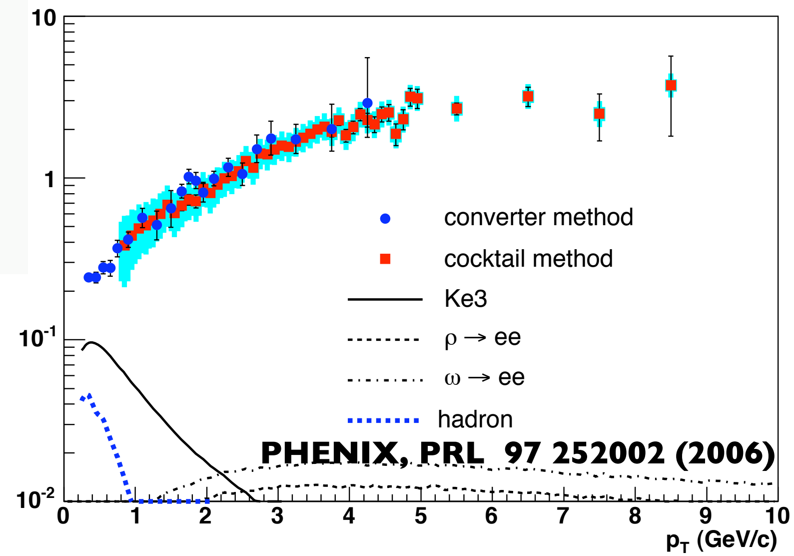
separating the correlations

$$Y_{e_{incl}-h} = \frac{N_{e_{HF}} Y_{e_{HF}-h} + N_{e_{phot}} Y_{e_{phot}-h}}{N_{e_{HF}} + N_{e_{phot}}}$$

separating the correlations

$$Y_{e_{incl}-h} = \frac{N_{e_{HF}} Y_{e_{HF}-h} + N_{e_{phot}} Y_{e_{phot}-h}}{N_{e_{HF}} + N_{e_{phot}}}$$

$$R_{HF} = \frac{N_{e_{HF}}}{N_{e_{phot}}}$$



separating the correlations

$$Y_{e_{incl}-h} = \frac{N_{e_{HF}} Y_{e_{HF}-h} + N_{e_{phot}} Y_{e_{phot}-h}}{N_{e_{HF}} + N_{e_{phot}}}$$

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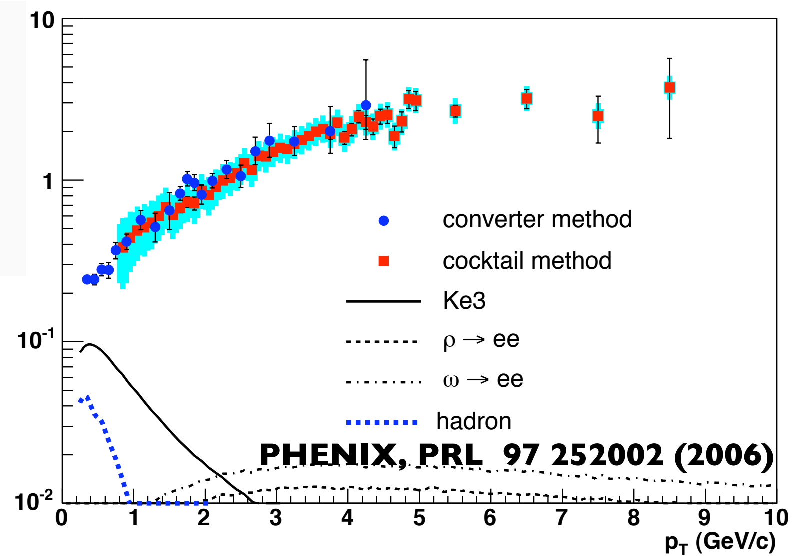
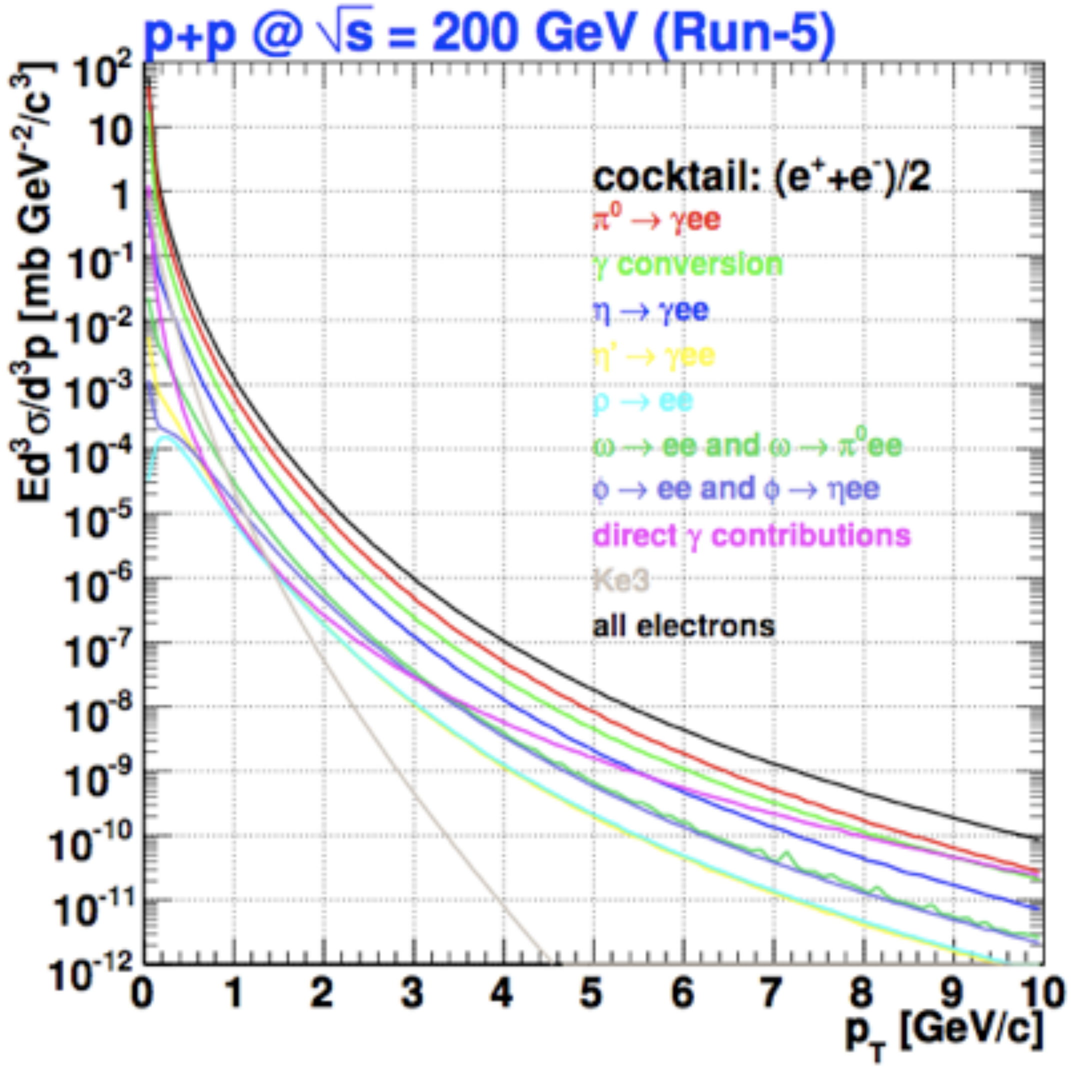


$$Y_{e_{HF}-h} = \frac{(R_{HF}+1) Y_{e_{incl}-h} - Y_{e_{phot}-h}}{R_{HF}}$$

e_{phot}-h correlations

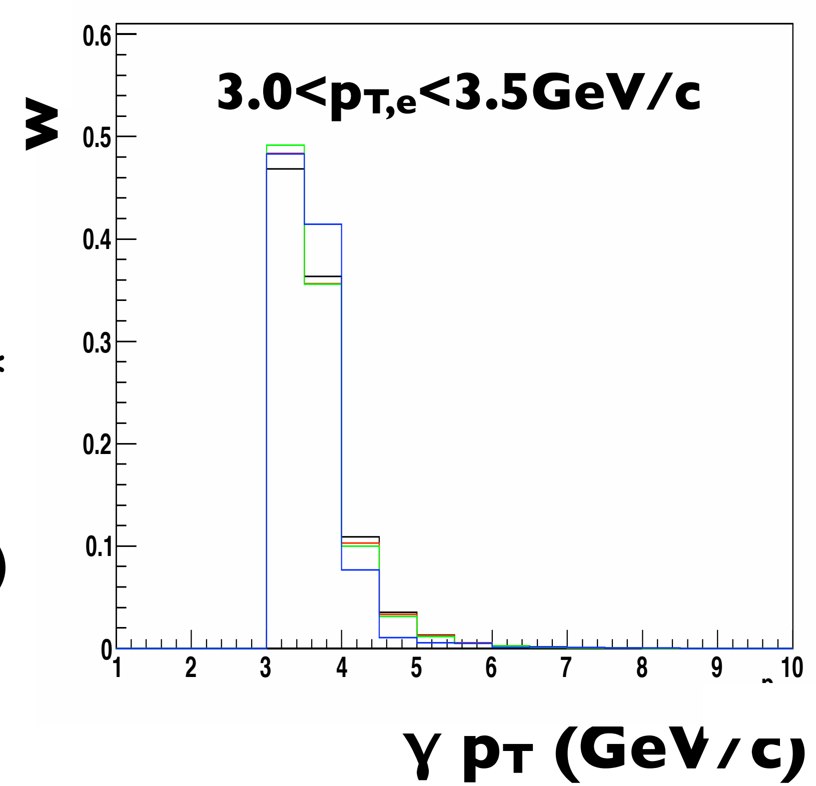
$$Y_{e_{HF}-h} = \frac{(R_{HF}+1)Y_{e_{incl}-h} - Y_{e_{phot}-h}}{R_{HF}}$$

- photonic electrons: Dalitz decays and γ conversions
  - dominantly from π^0s
- measure γ_{inc}-h correlations
  - also dominantly from π^0s
- use MC to map between $e_{phot}(p_T)$ & $\gamma_{inc}(p_T)$



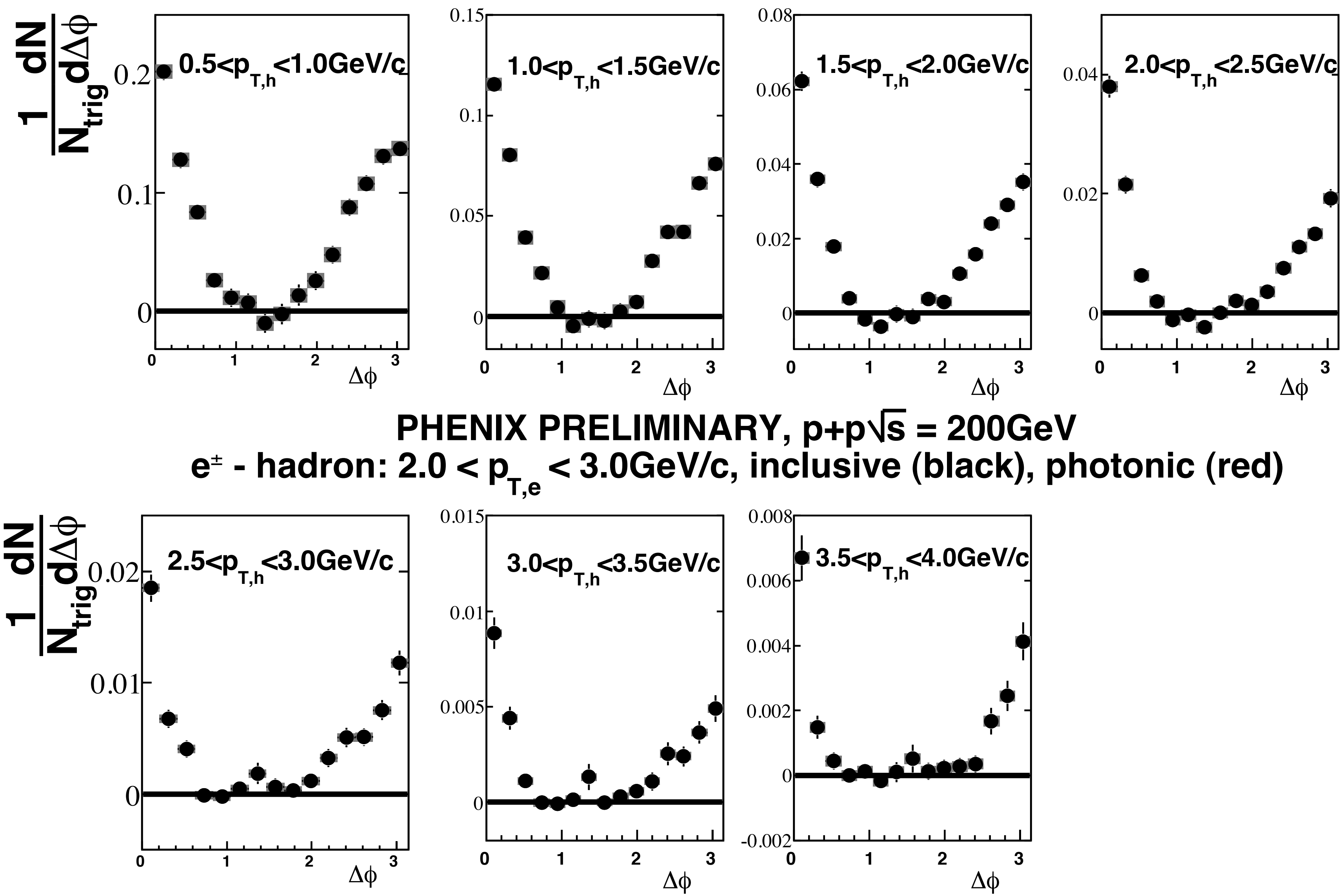
e_{phot}-h correlations (II)

- $\gamma_{inc}(p_T)$ ➡ $e_{phot}(p_T)$?
  - **conversions**: $\gamma inc(pT)$ + PHENIX GEANT + reco. eff.
  - **Dalitz decays**: $\pi^0(p_T) \rightarrow \gamma e^+e^-$ get γ^* from e^+e^-
- both methods: $e_{phot}(p_T) \sim \gamma_{inc}(p_T) \approx \pi^0(p_T)$
  - π^0 spectrum falls very steeply

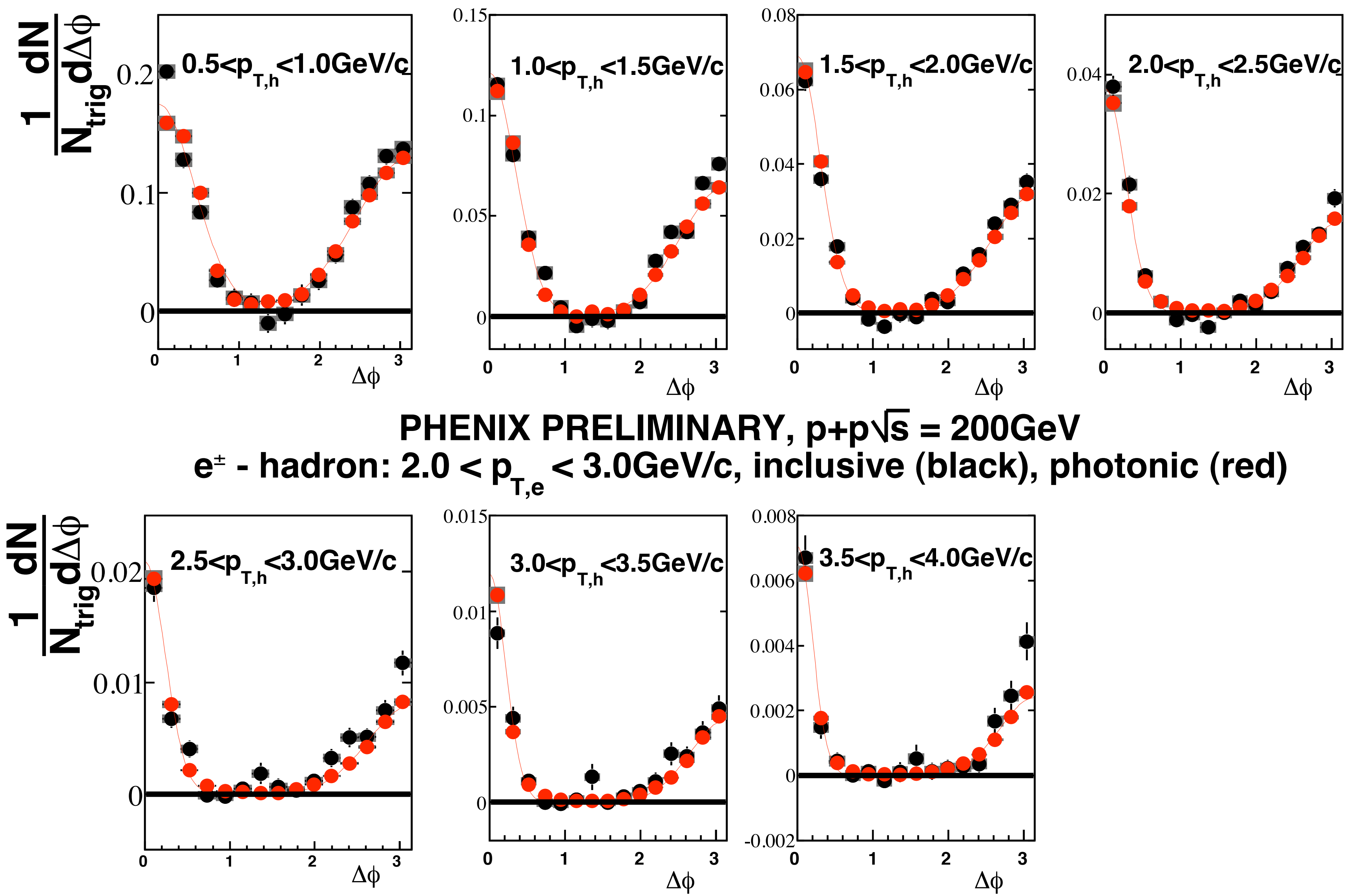


$$Y_{e_{phot}-h}(p_{T,i}) = \sum_j w_i(p_{T,j})\ Y_{\gamma-h}(p_{T,j})$$

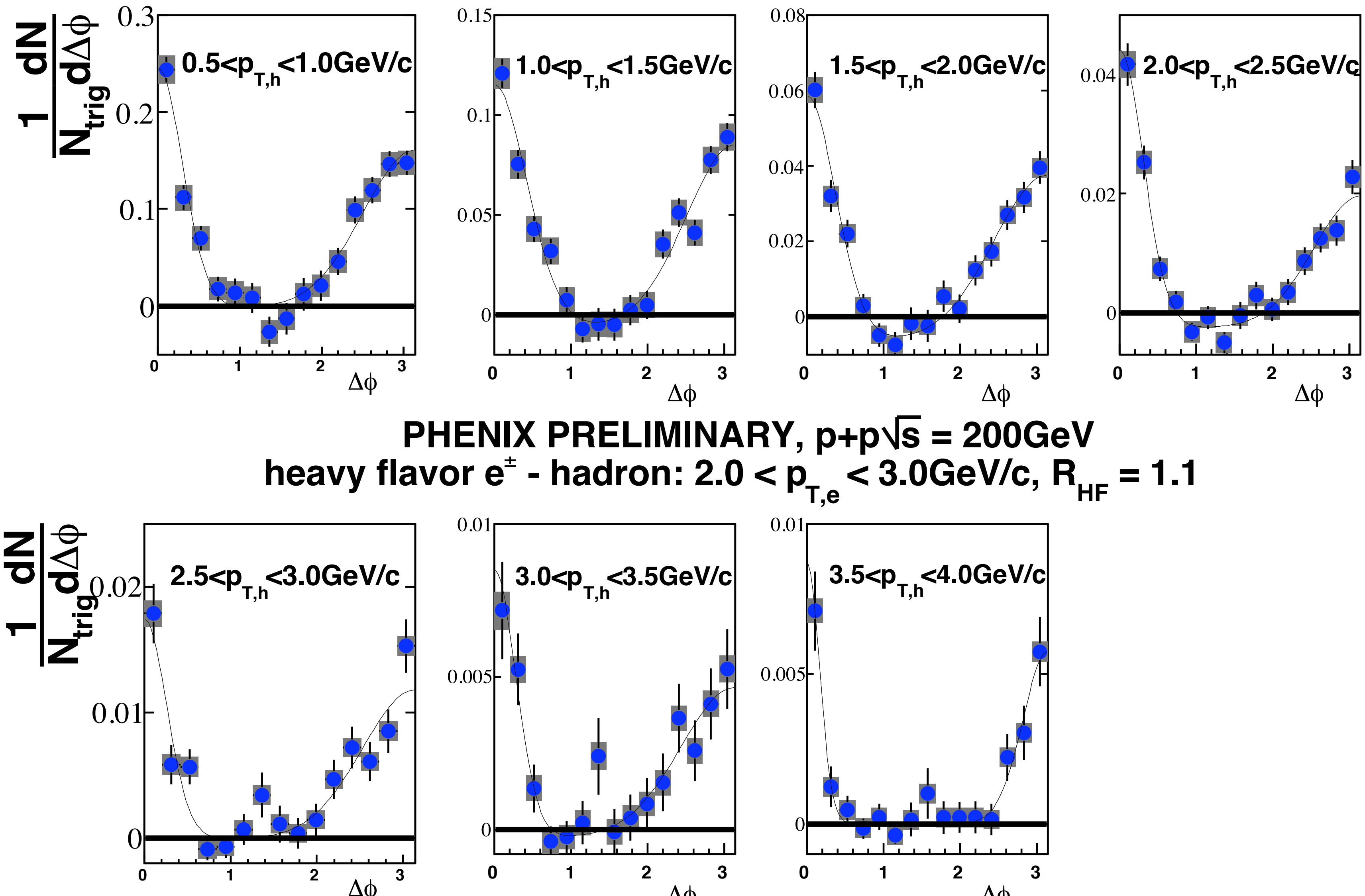
e_{inc}-h correlations



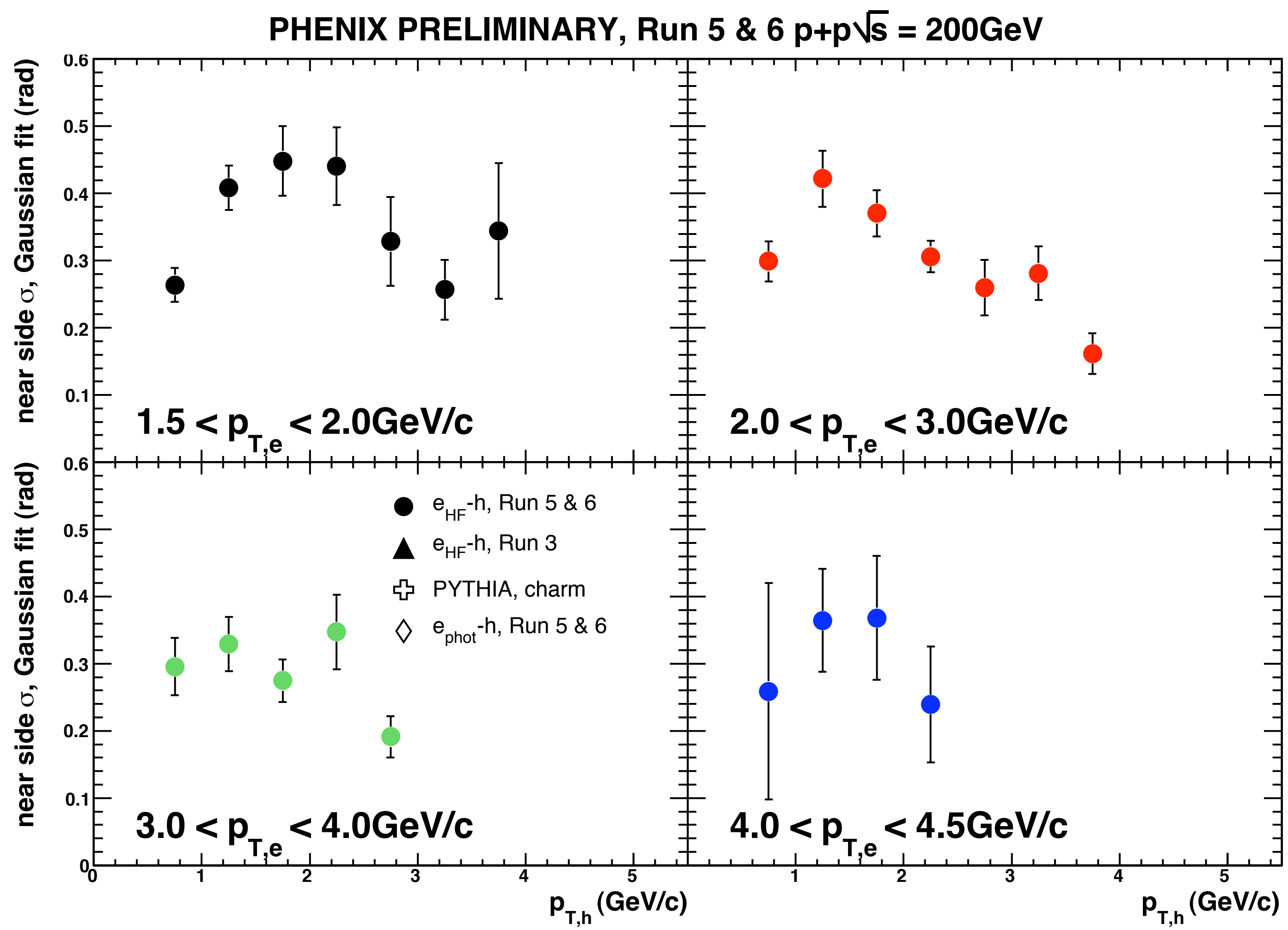
adding e_{phot}-h ...



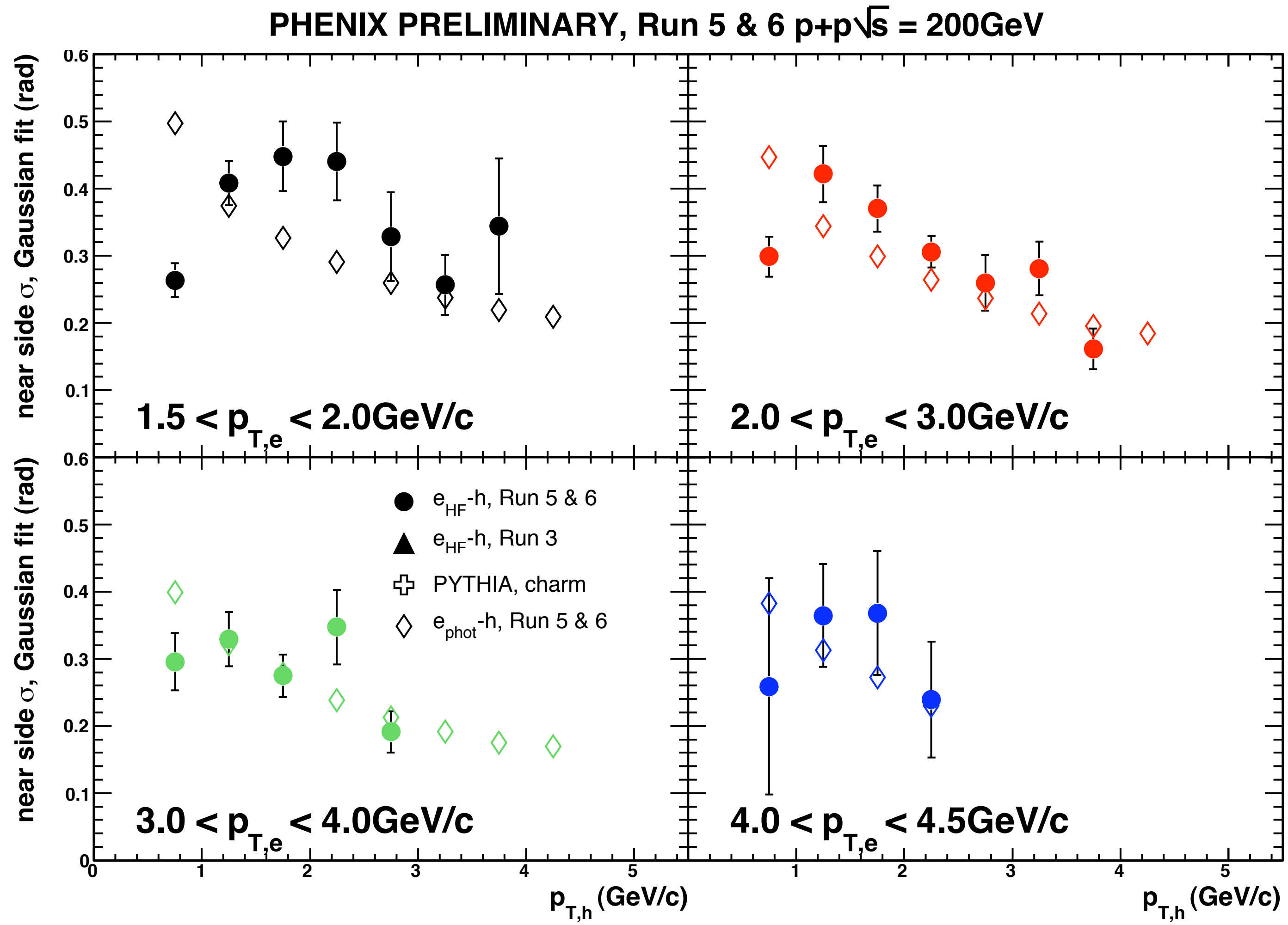
heavy flavor correlations



near side widths

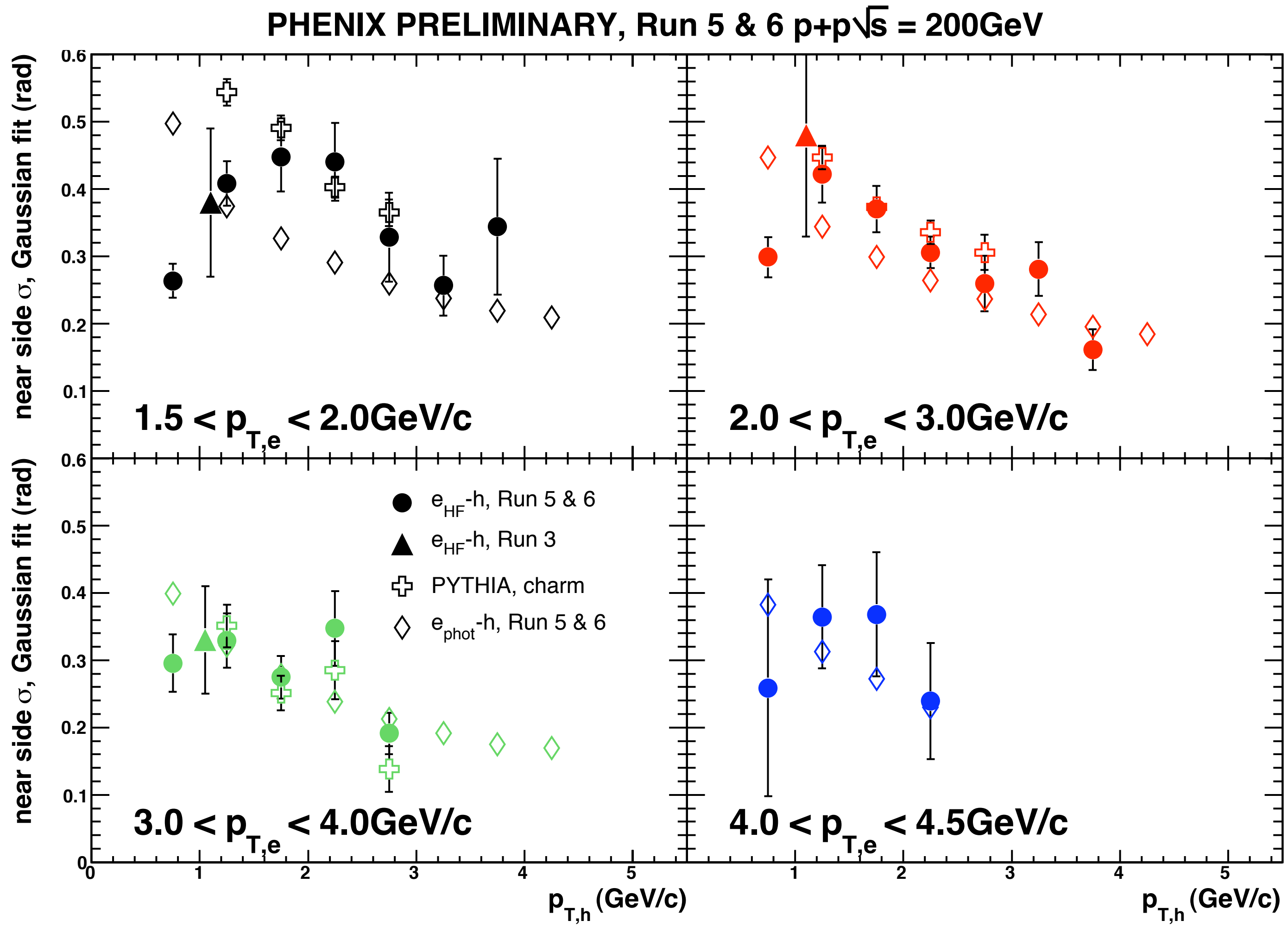


near side widths



$\sigma_{HF} > \sigma_{phot}$: D/B decay kinematics

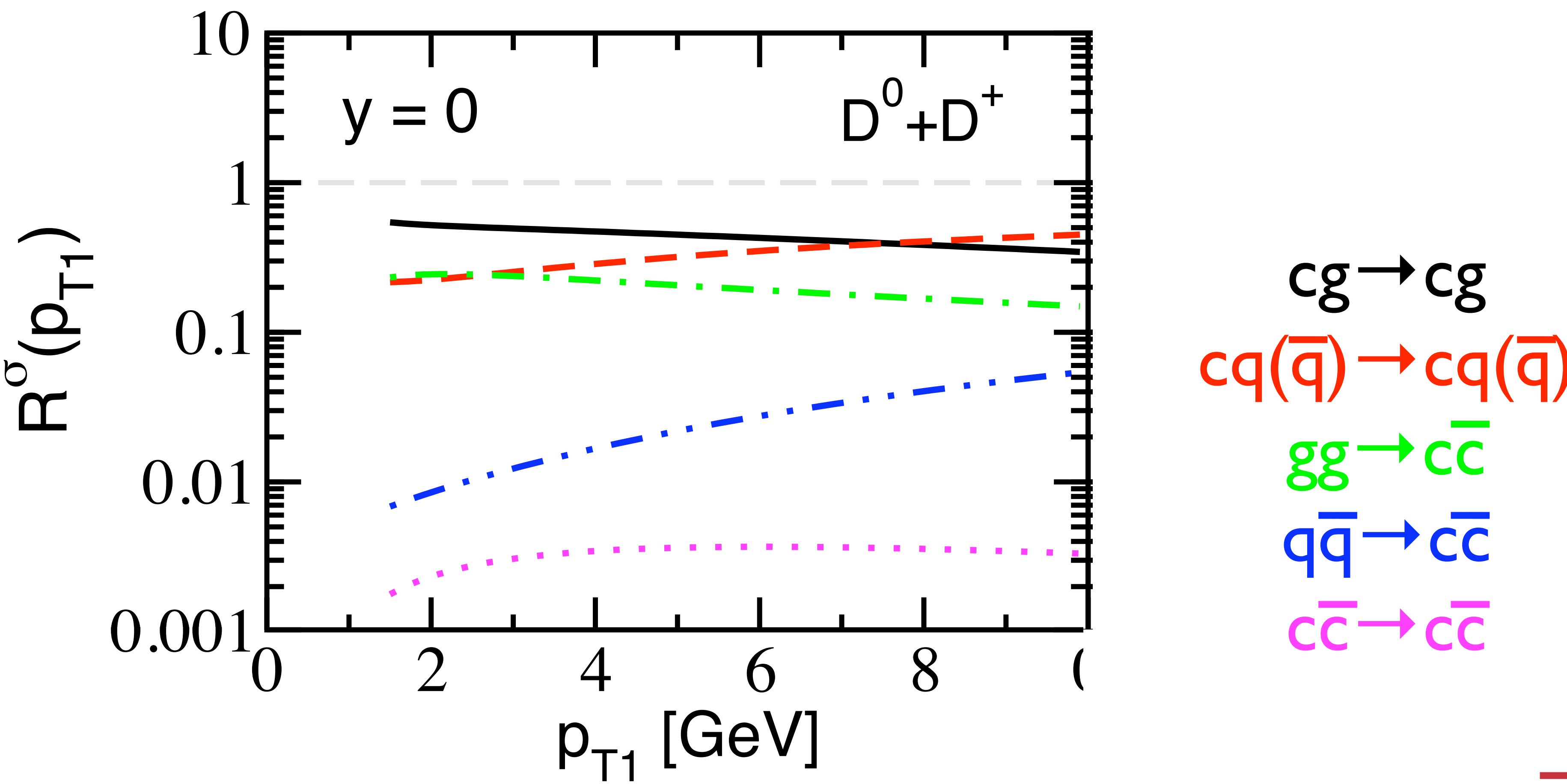
near side widths



$\sigma_{HF} > \sigma_{phot}$: D/B decay kinematics

good agreement with PYTHIA (charm production)

charm production subprocesses



most of the time a D is not balanced by a mid-rapidity $\bar{D}$
(caveat: LO calculation)

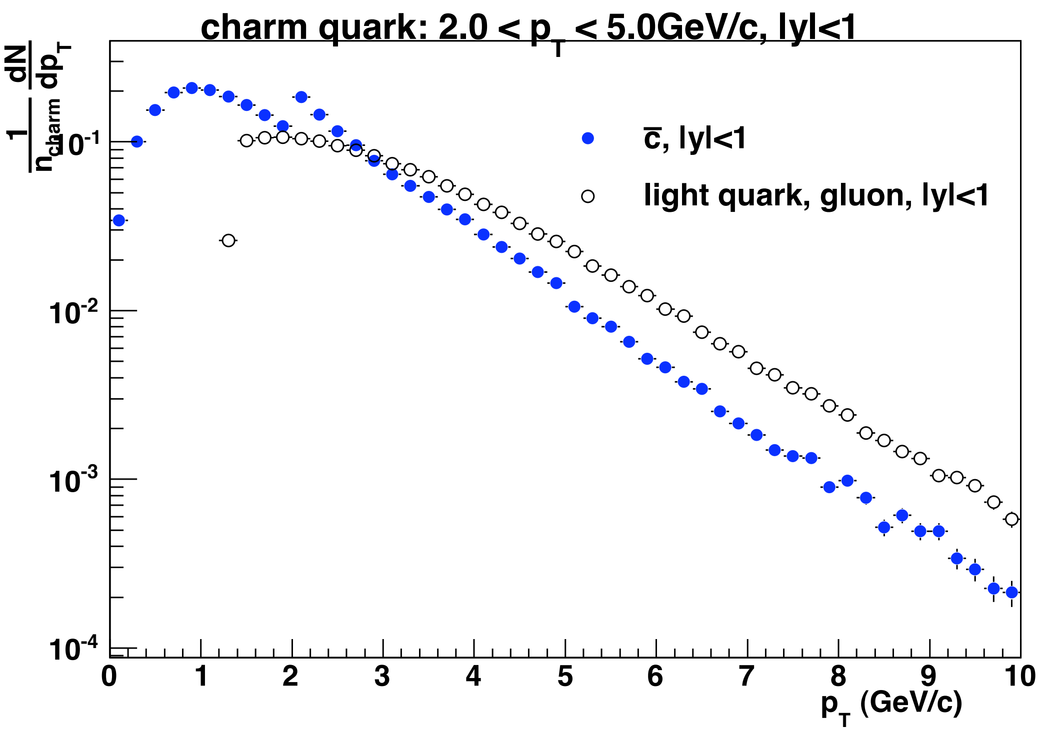
Vitev et al PRD 74 054010 (2006)

Next to Leading Order

- POWHEG NLO Monte Carlo: $2 \rightarrow 2$ & $2 \rightarrow 3$ processes

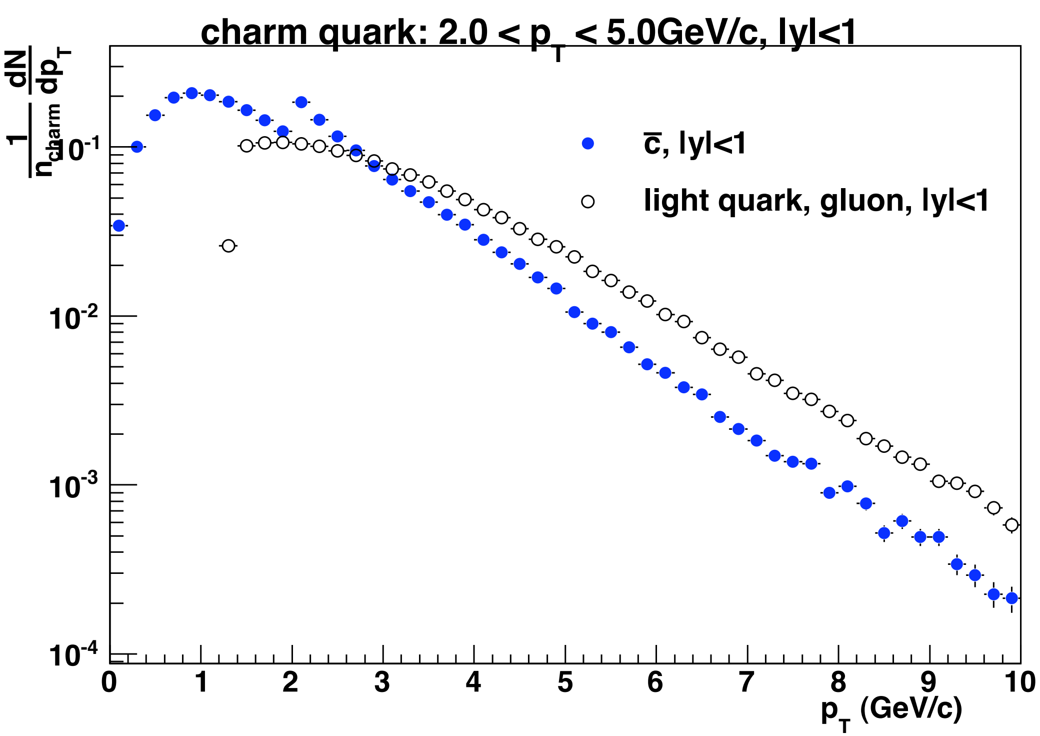
Next to Leading Order

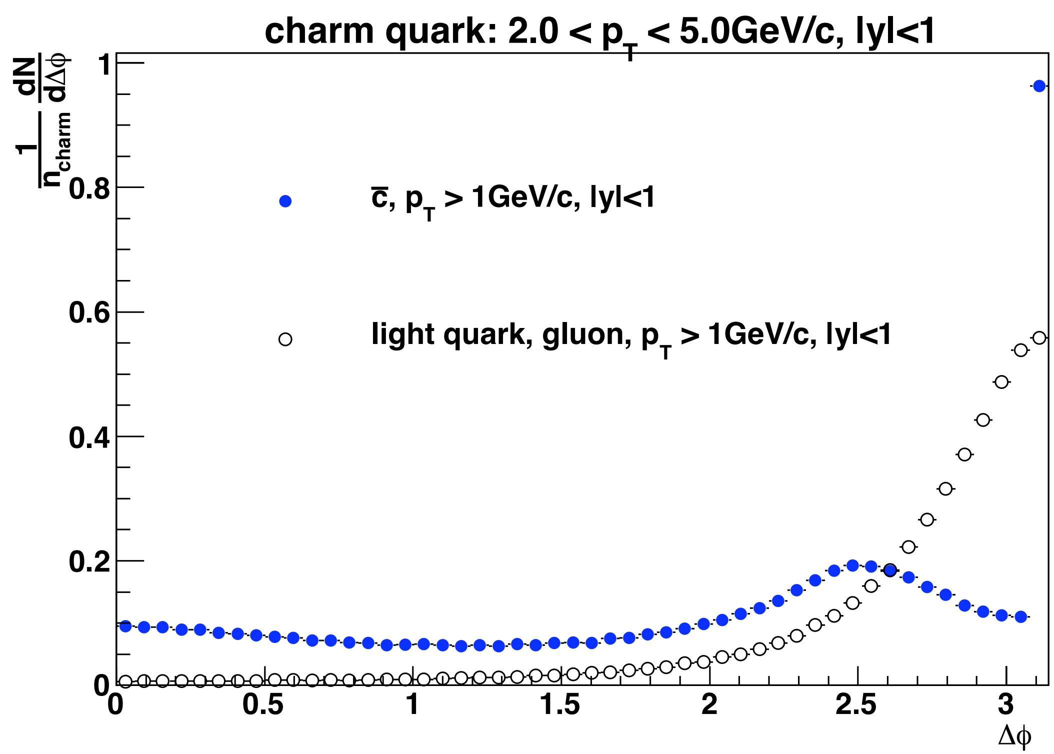
- POWHEG NLO Monte Carlo: 2→2 & 2→3 processes



Next to Leading Order

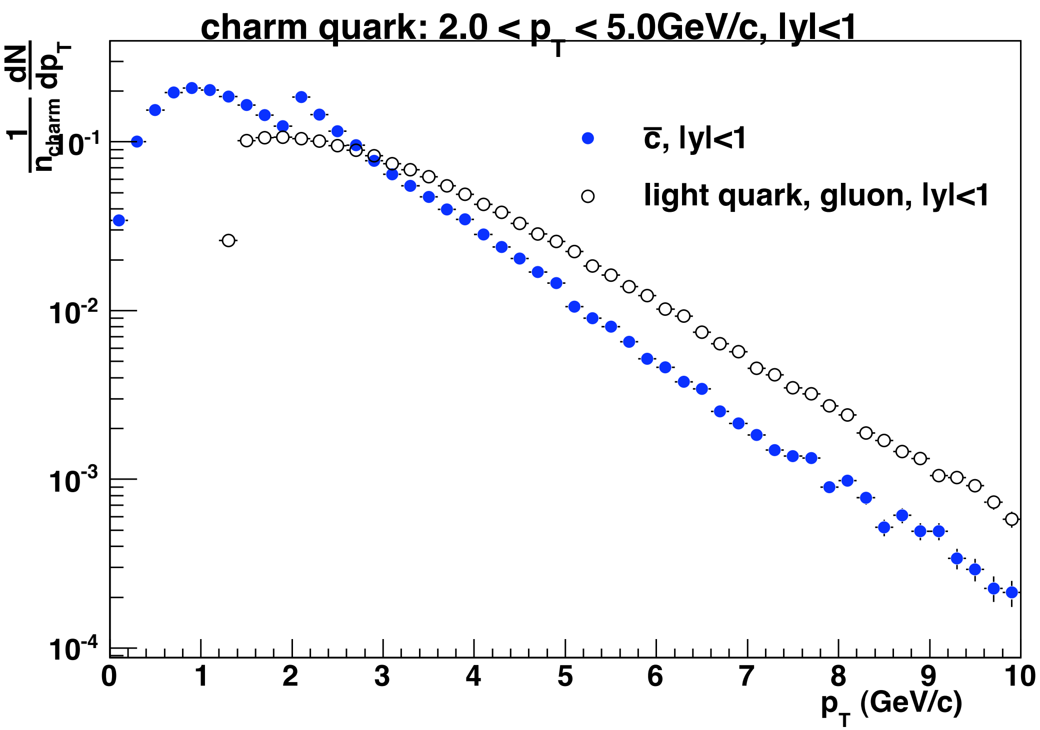
- POWHEG NLO Monte Carlo: 2→2 & 2→3 processes

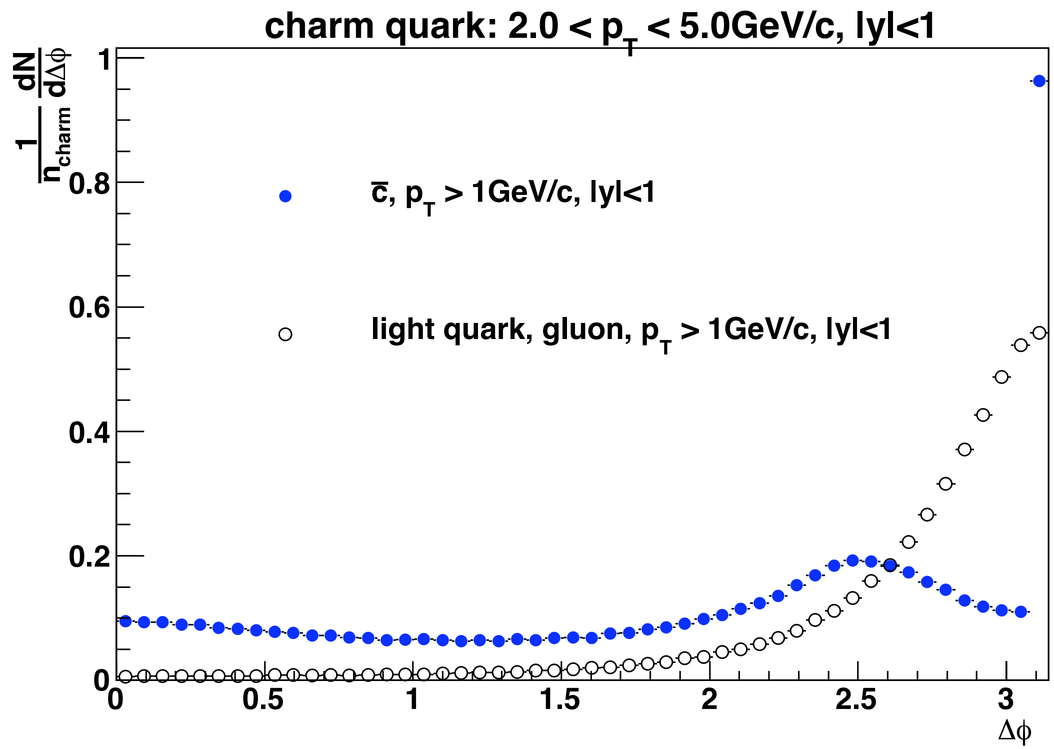




Next to Leading Order

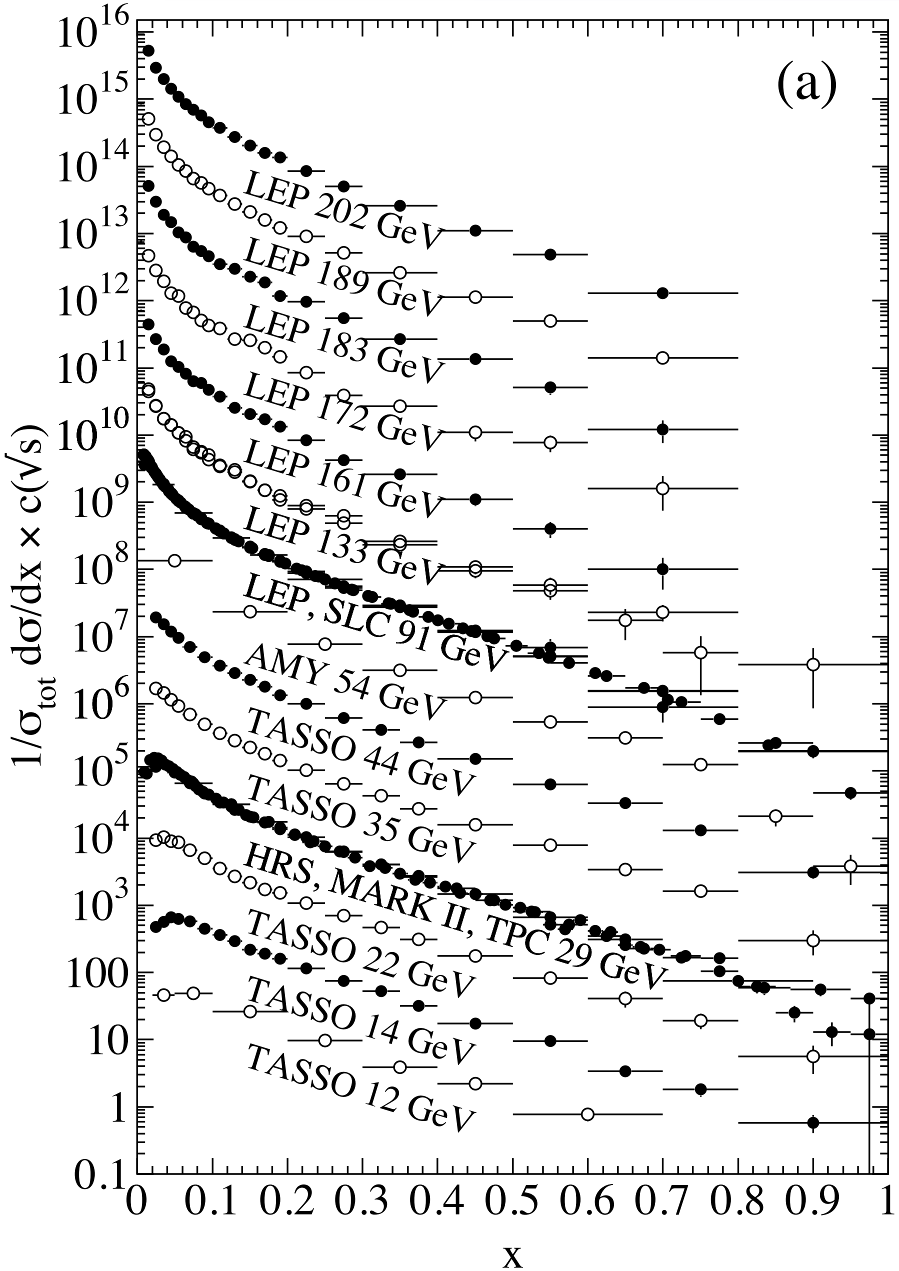
- POWHEG NLO Monte Carlo: 2→2 & 2→3 processes





light parton jets are a significant contribution to the away side correlations

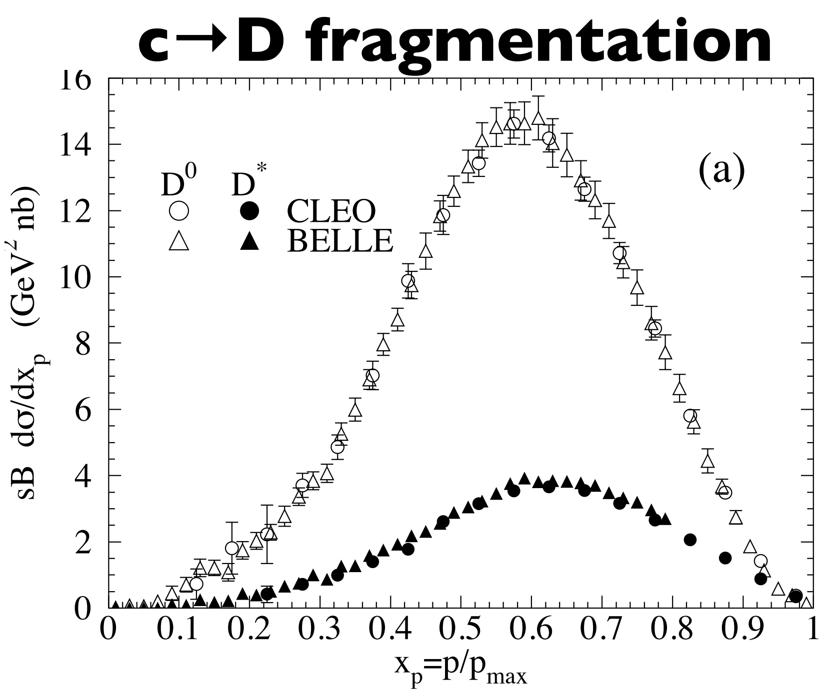
Light Quark Fragmentation

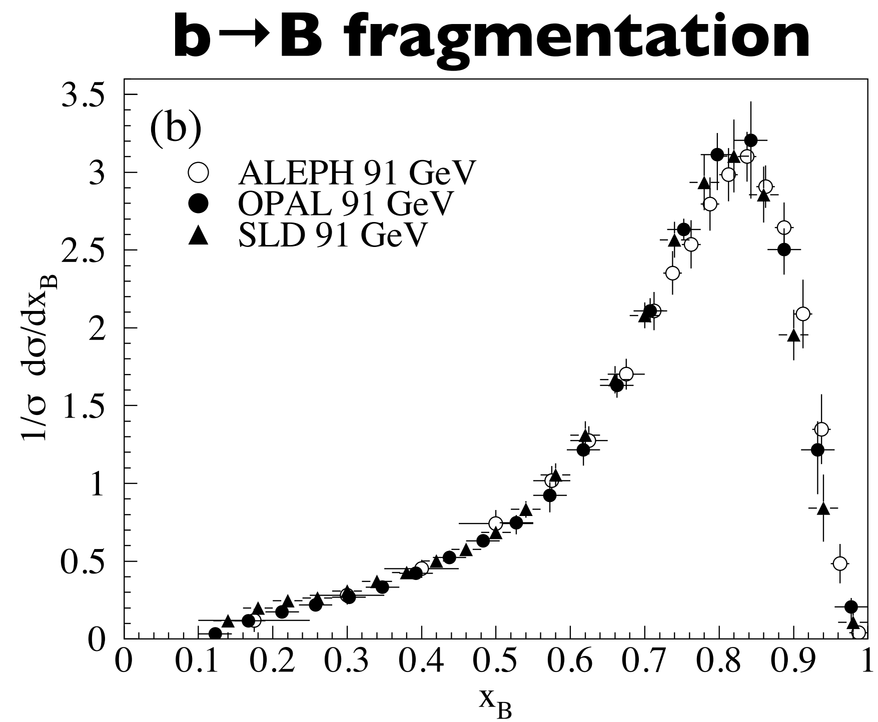


- fragmentation functions from e^+e^- collisions
- most particles carry small fraction of jet energy

Particle Data Book

what about heavy quark jets?

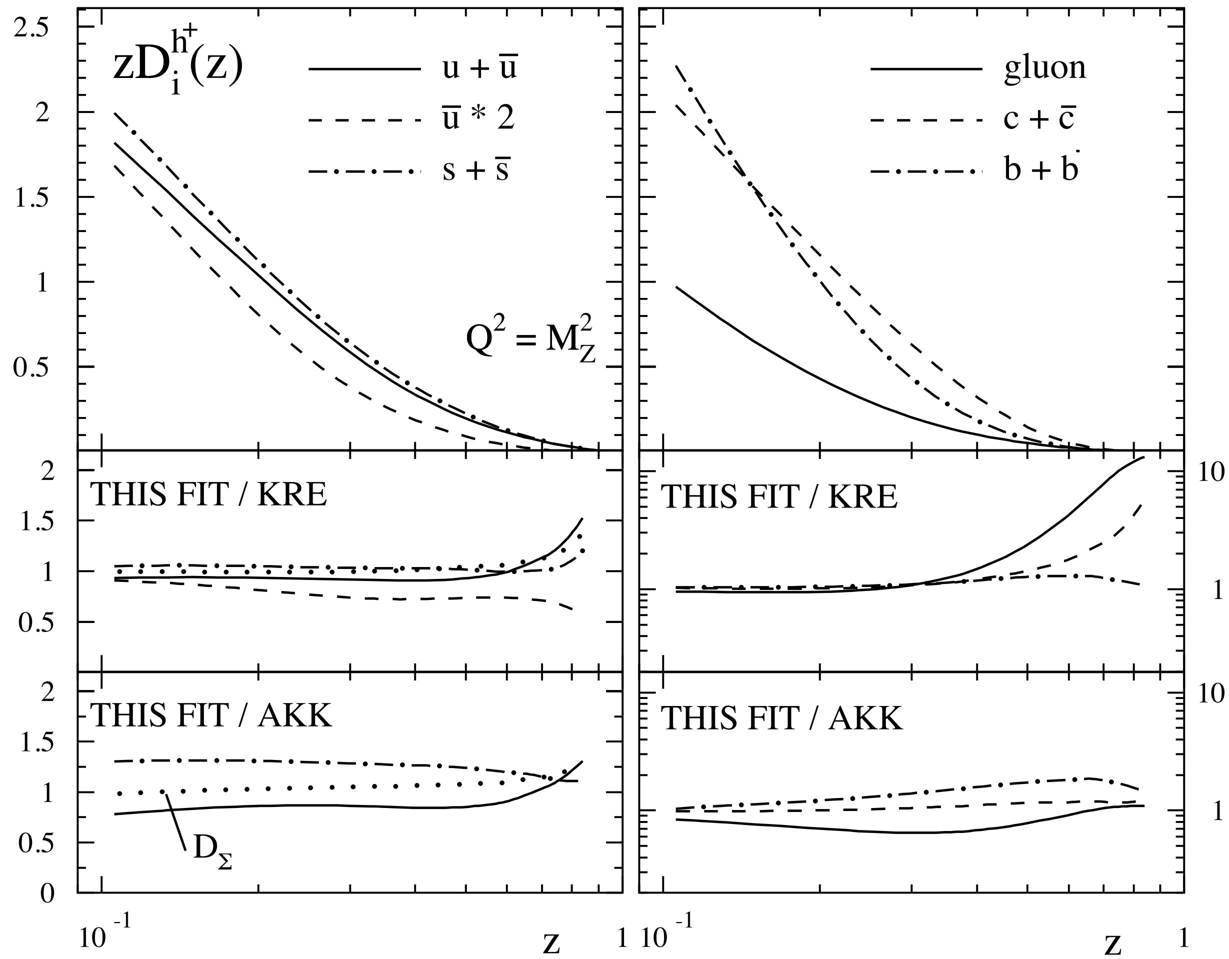




- c→D fragmentation hard
- b→B fragmentation harder

Particle Data Book

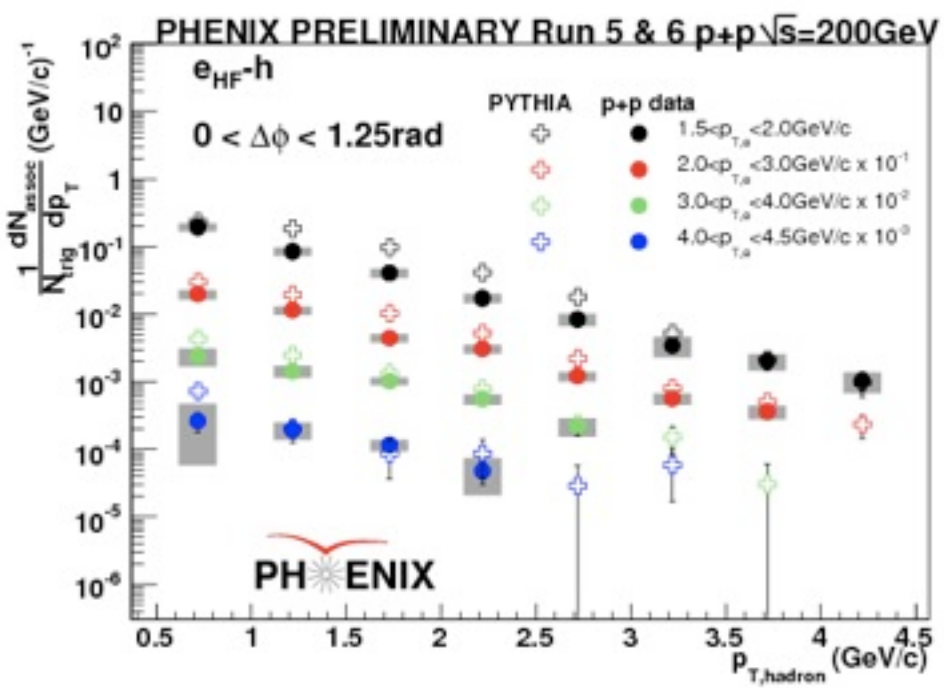
...and the rest of jet energy?

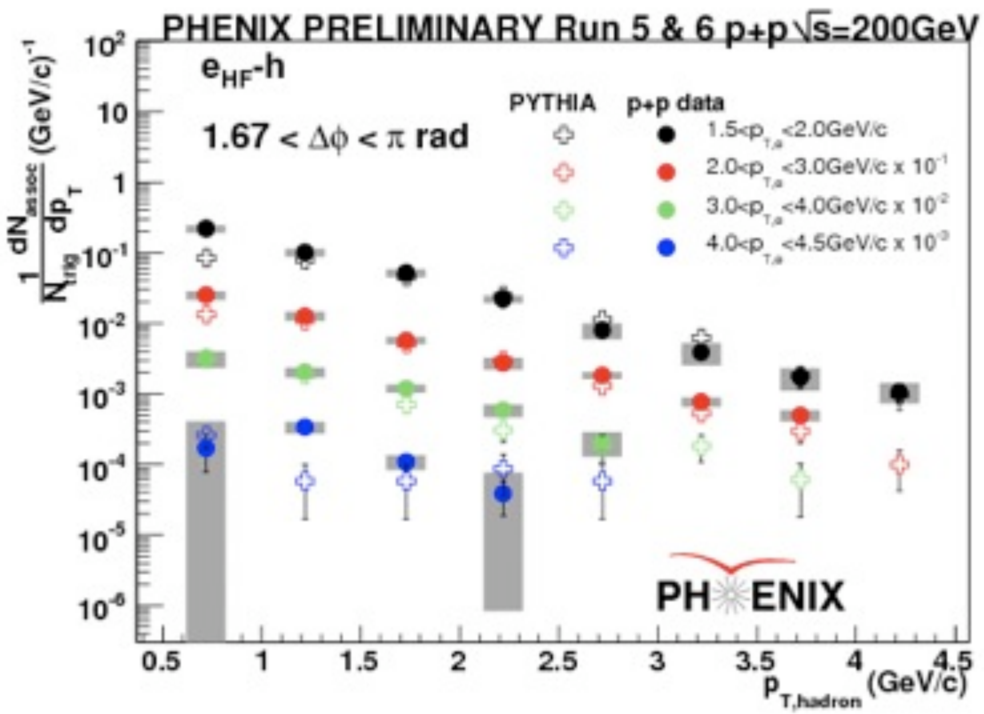


c,b → hadrons softer than q, g jets

de Florian et al PRD 76 074033 (2007)

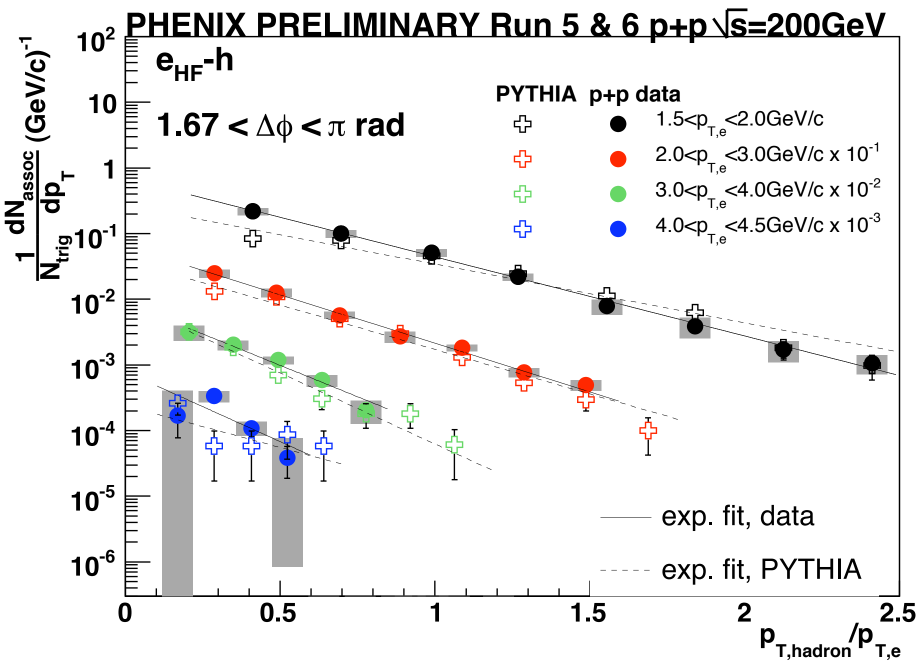
conditional yields

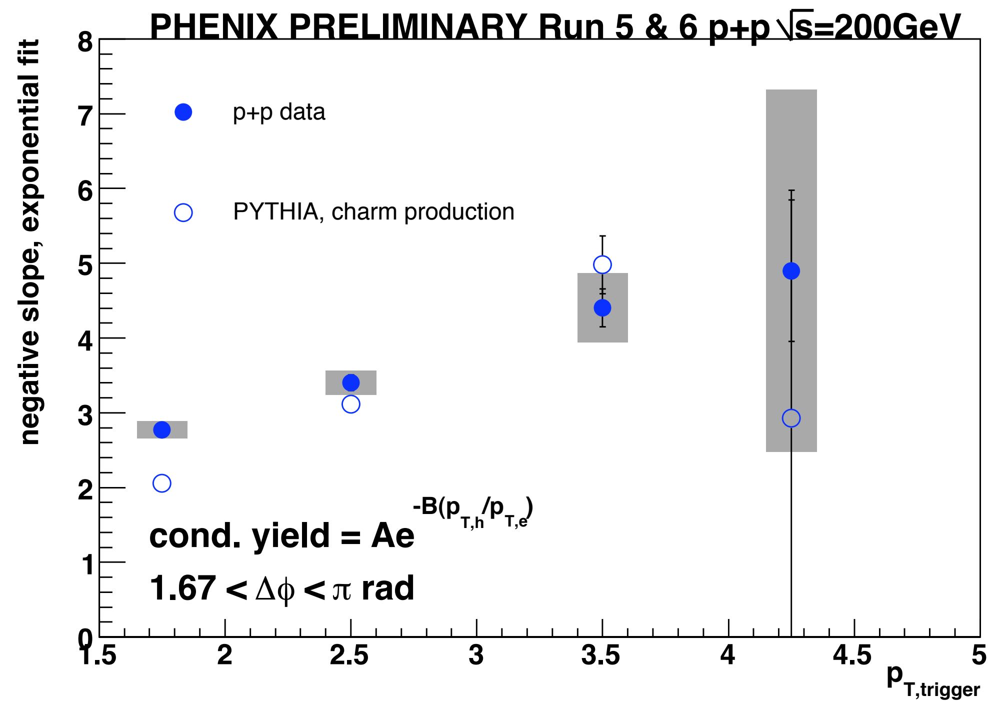




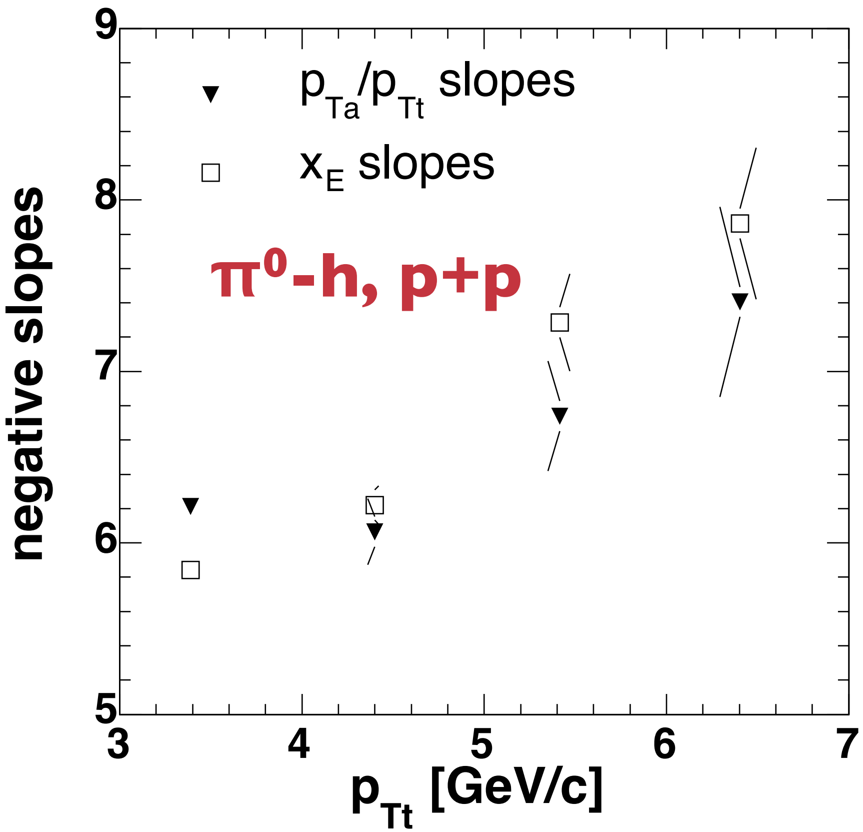
- near side: heavy quarks, dominated by decays
- away side: heavy & light partons, fragmentation and decays

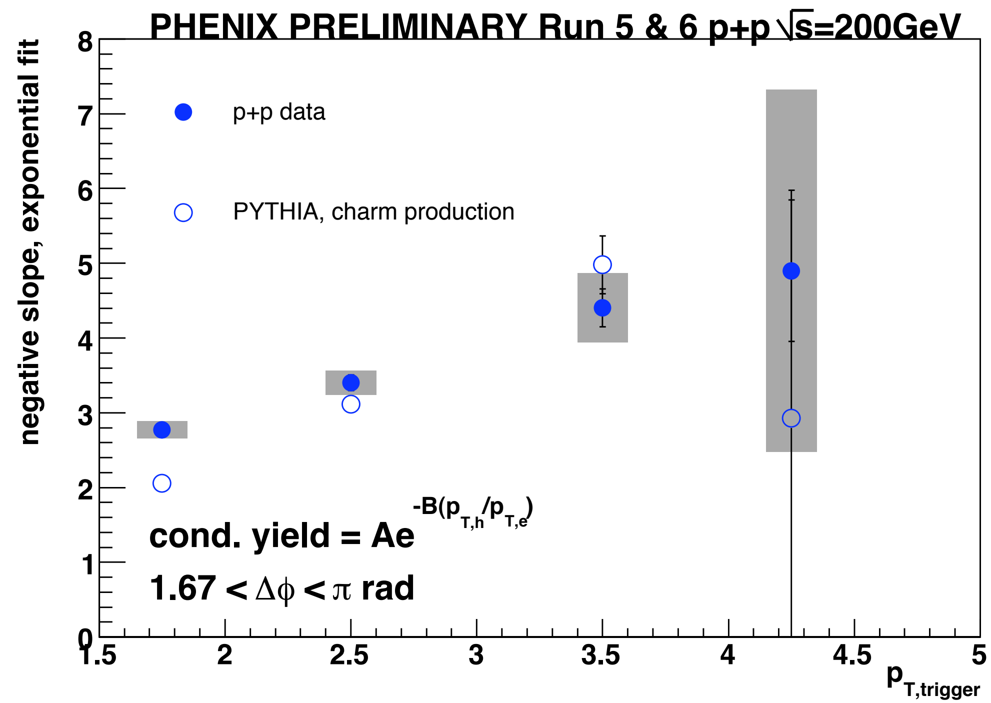
comparison to light jets





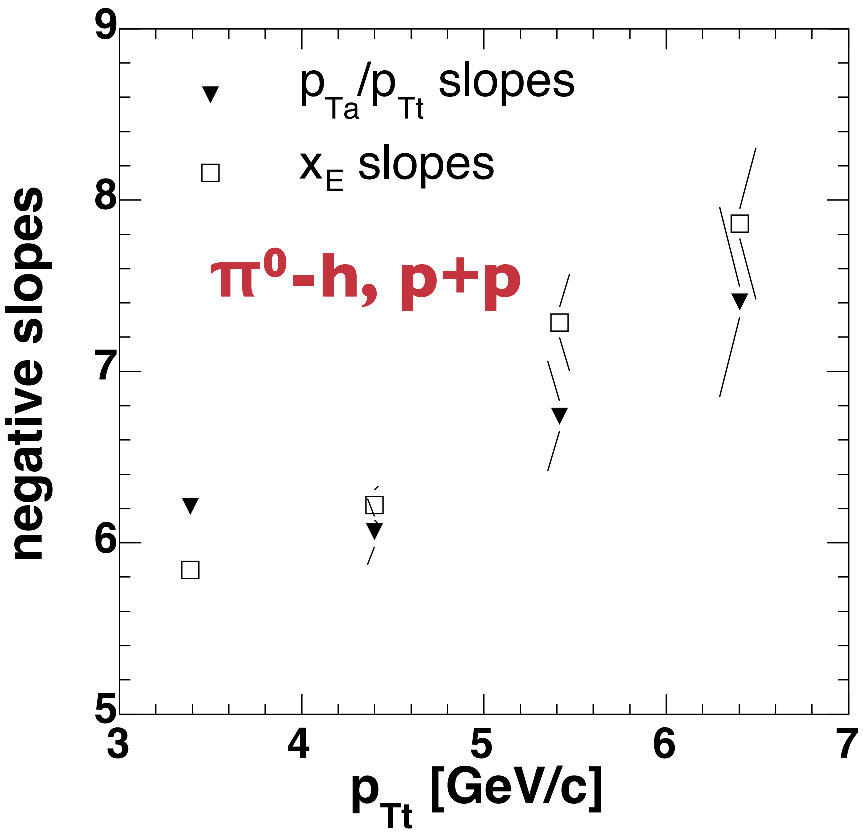
comparison to light jets

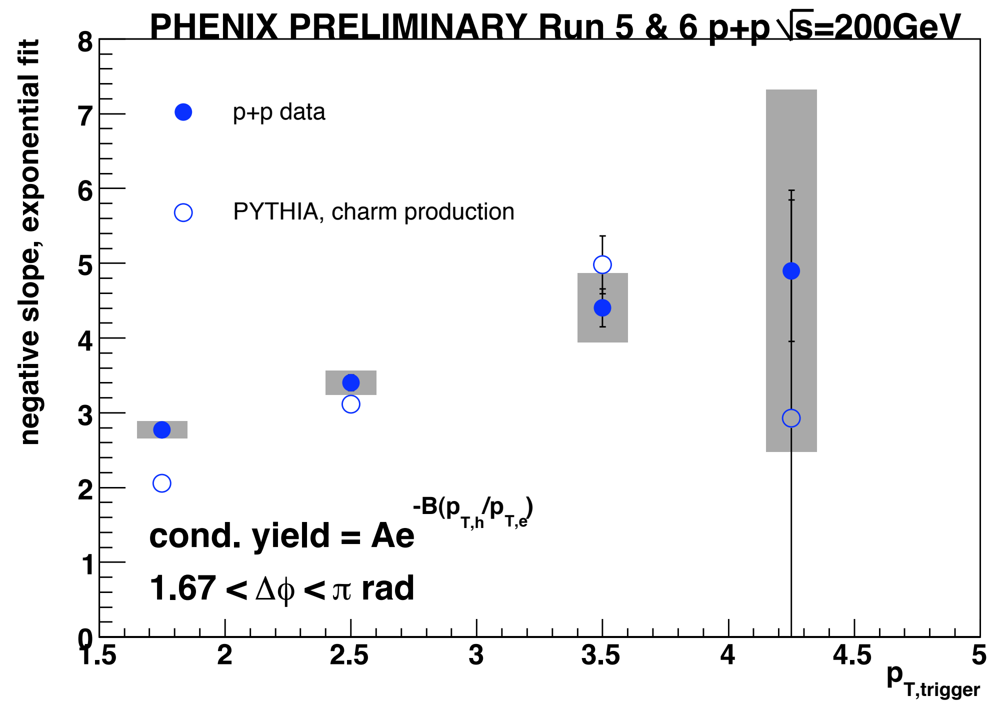




PHENIX PRD 74 072002 (2006)

comparison to light jets





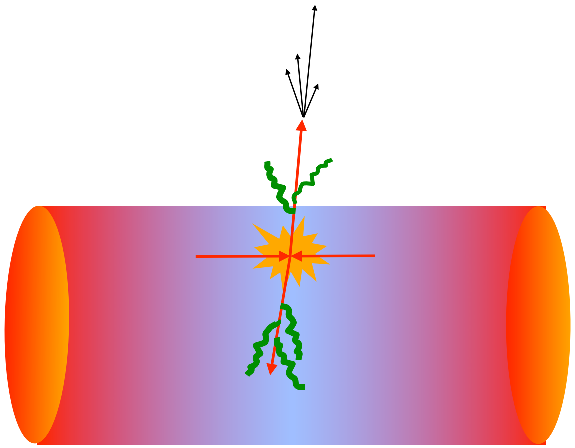
PHENIX PRD 74 072002 (2006)

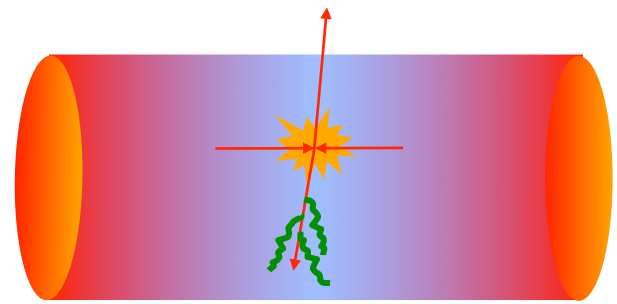
e_{HF}-h harder @ same $p_{T,trig}$ ($\neq p_{T,parton}$)

effects of the matter...

Au+Au

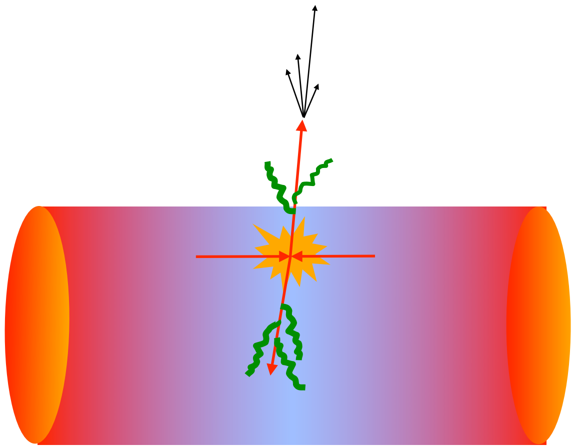
energy loss: π^0-h v γ_{direct}-h

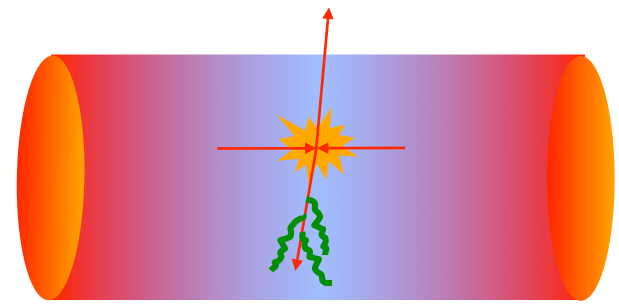




π^0-h	γ_{direct}-h
g,q interact strongly--energy loss	γ don't interact strongly

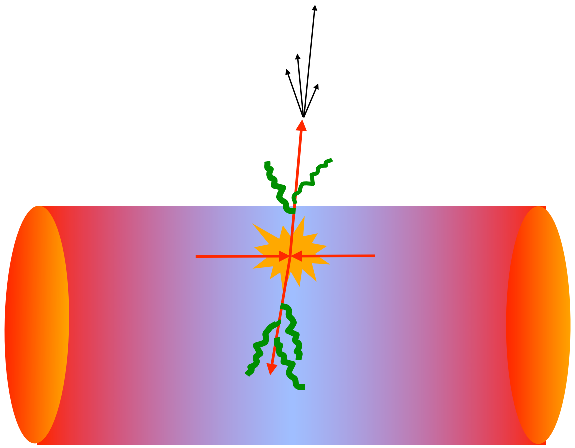
energy loss: π^0-h v γ_{direct}-h

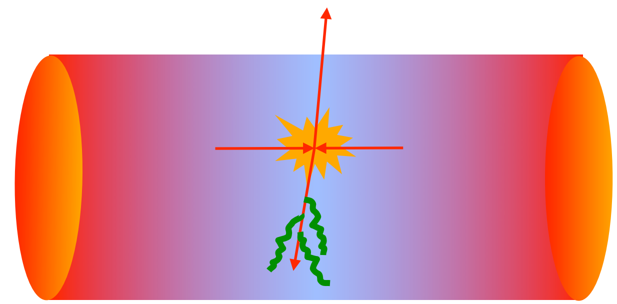




π^0-h	**γ_{direct}-h**
g,q interact strongly--energy loss	γ don't interact strongly
surface bias	no surface bias

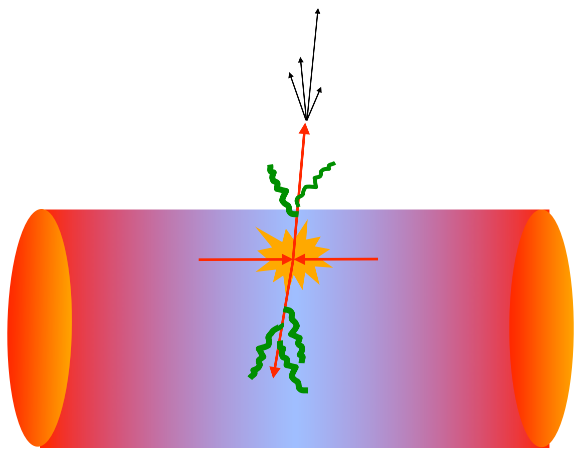
energy loss: π^0-h v γ_{direct}-h

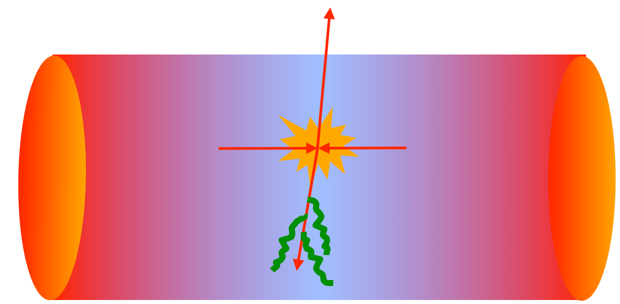




π^0-h	γ_{direct}-h
g,q interact strongly--energy loss	γ don't interact strongly
surface bias	no surface bias
$p_{T,\pi 0} < p_{T,jet}$	$p_{T,\gamma} \sim p_{T,jet}$

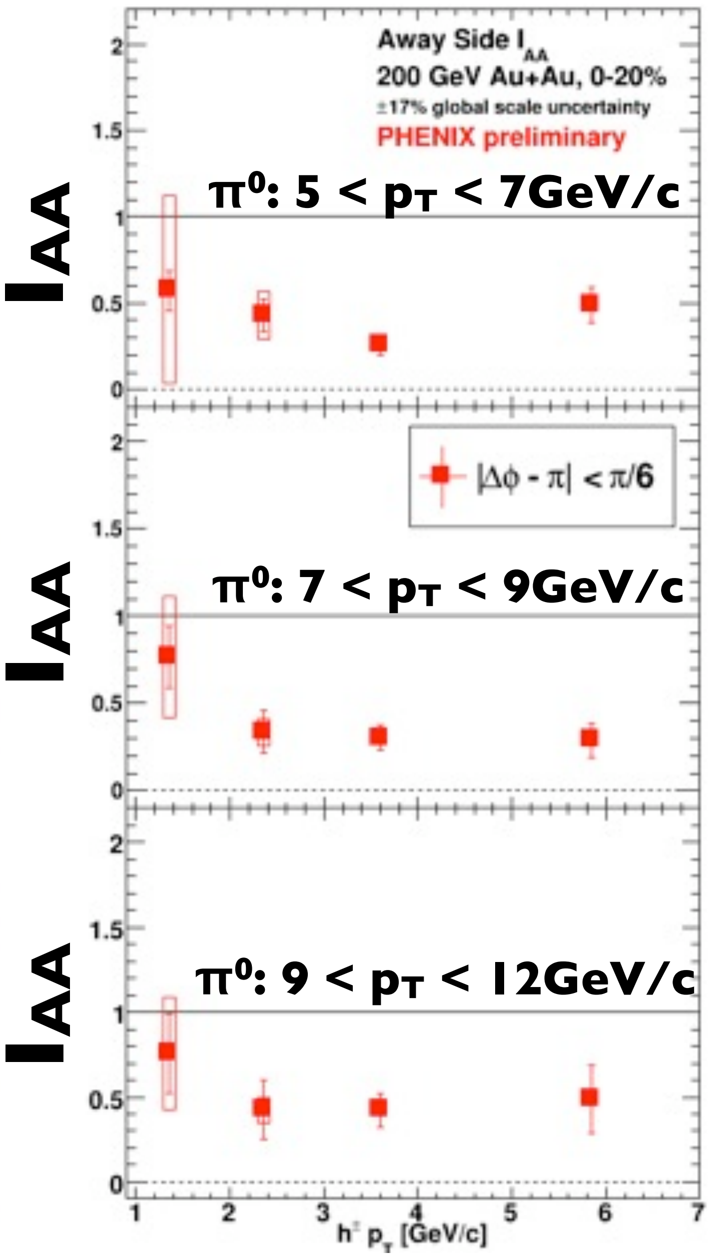
energy loss: π^0-h v γ_{direct}-h

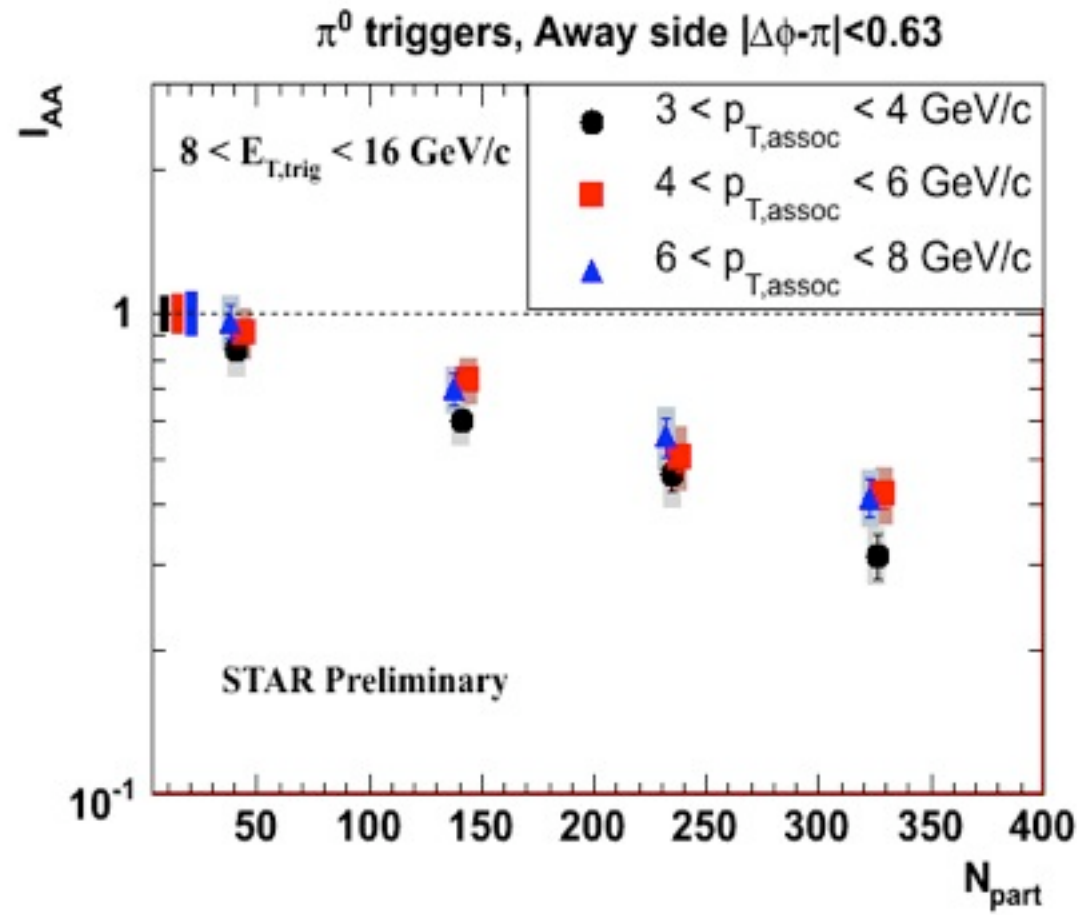


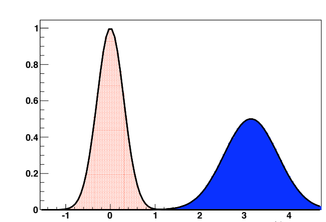


π^0-h	γ_{direct}-h
g,q interact strongly--energy loss	γ don't interact strongly
surface bias	no surface bias
$p_{T,\pi 0} < p_{T,jet}$	$p_{T,\gamma} \sim p_{T,jet}$
	away side more likely to be quark: $q + g \rightarrow q + \gamma$

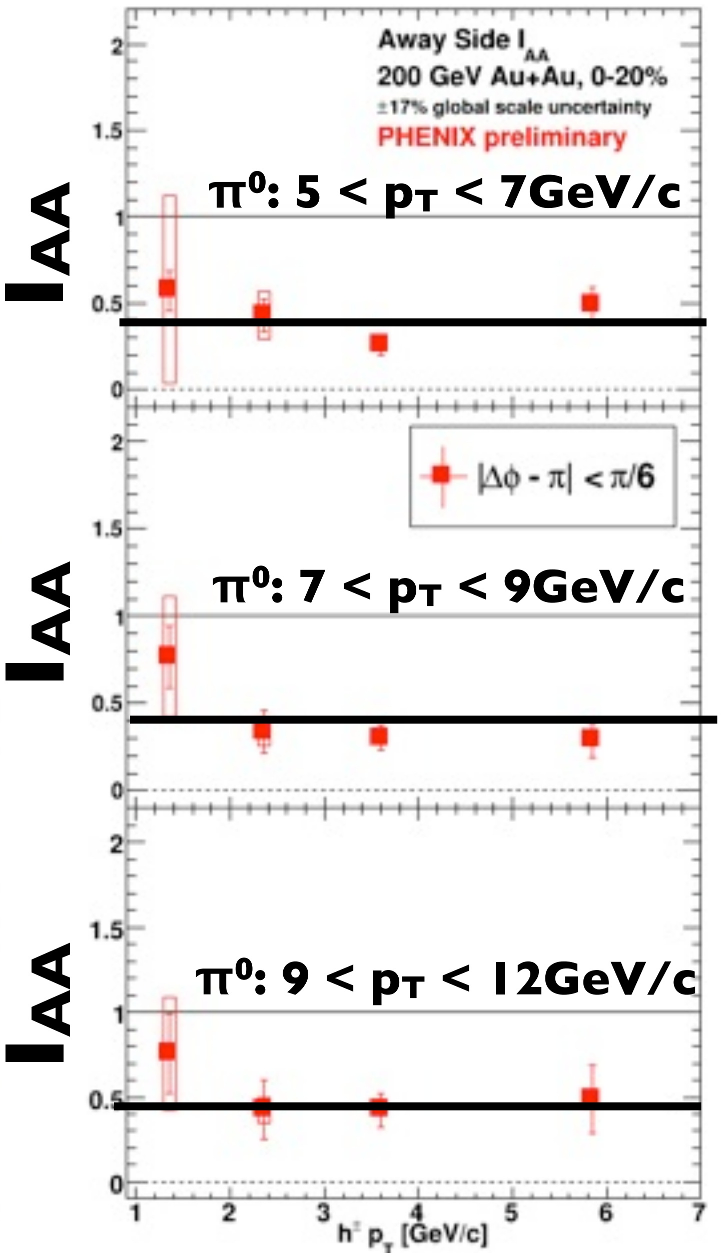
π^0-hadron: opacity

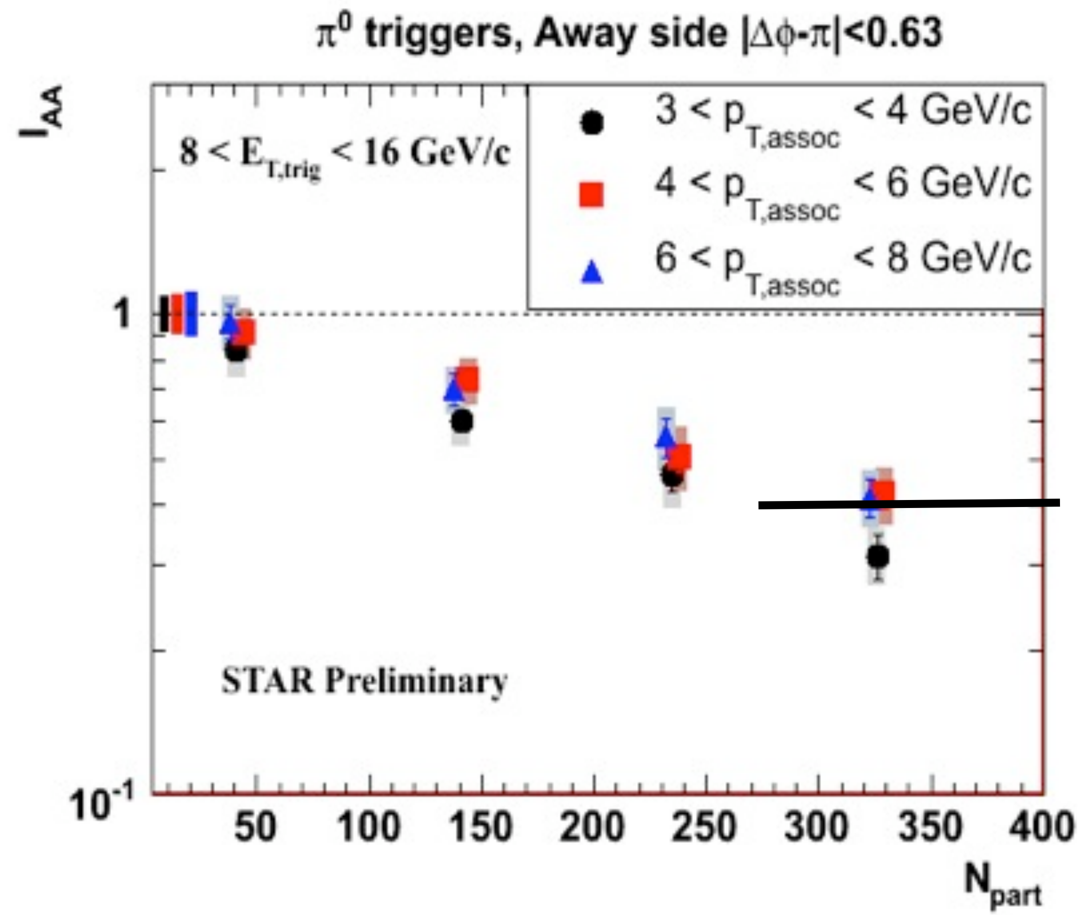




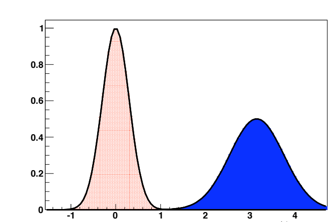


π^0-hadron: opacity

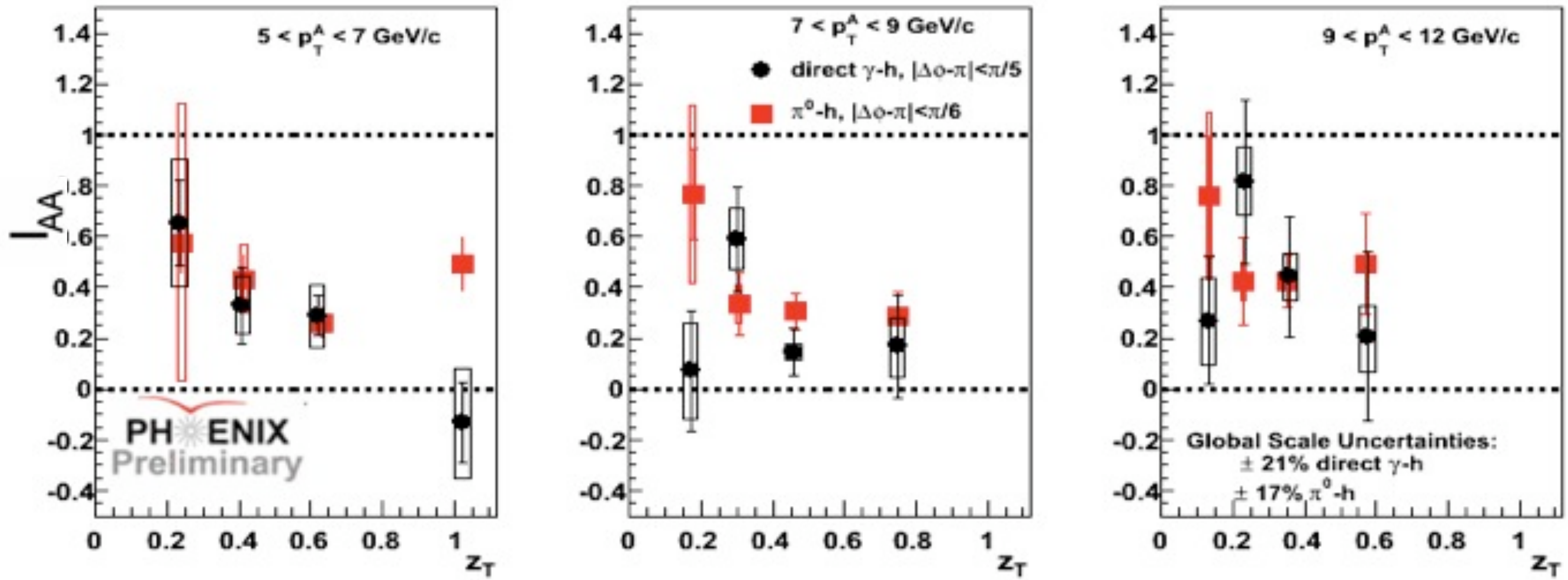


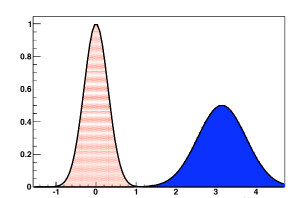


suppression nearly constant with $p_{T,trig}$ $p_{T,h}$

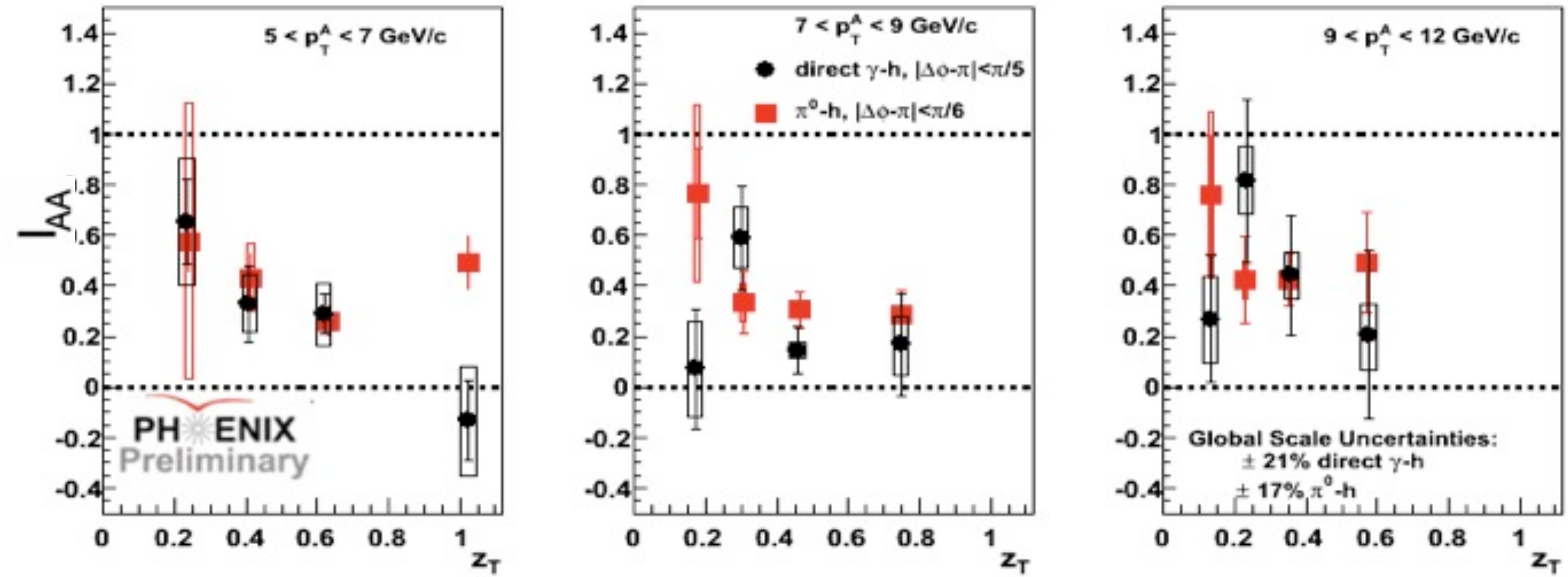


I_{AA}: π^0-h & γ_{direct}-h

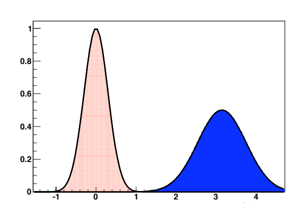




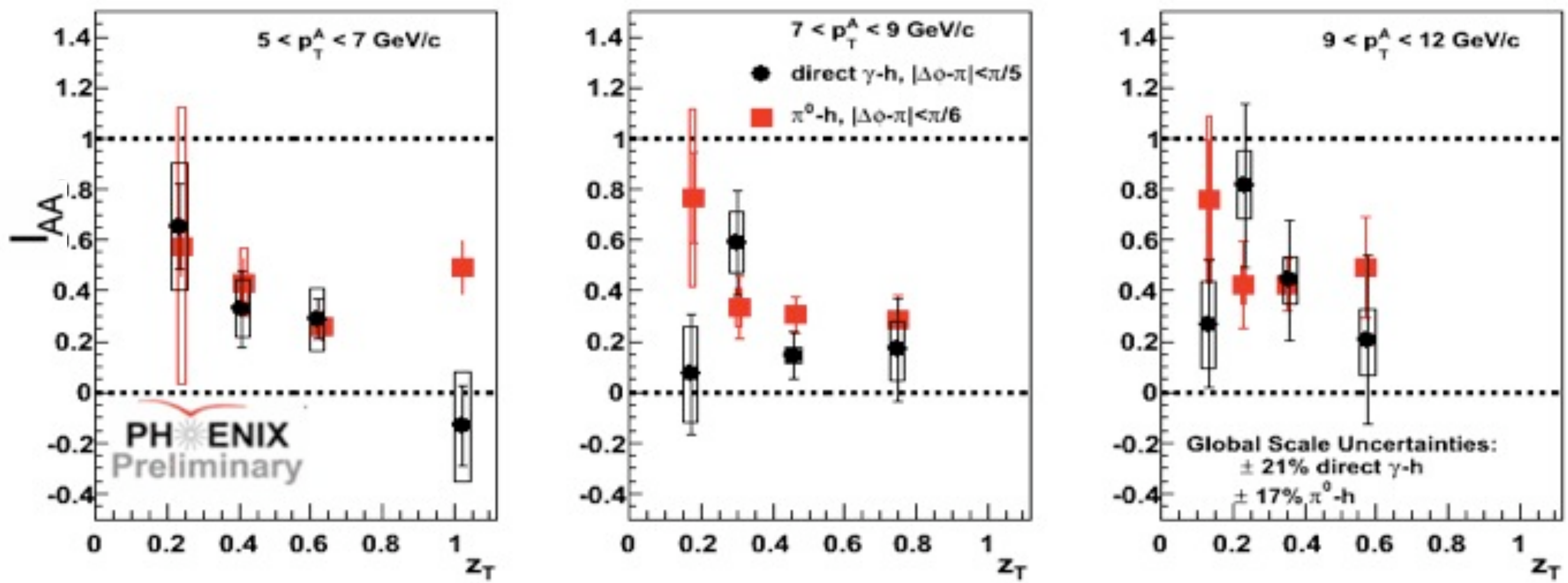
I_{AA}: π^0-h & γ_{direct}-h



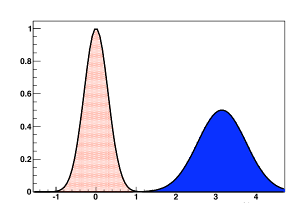
- no significant difference between π^0-h and γ_{dir}-h suppression



I_{AA}: π^0-h & γ_{direct}-h

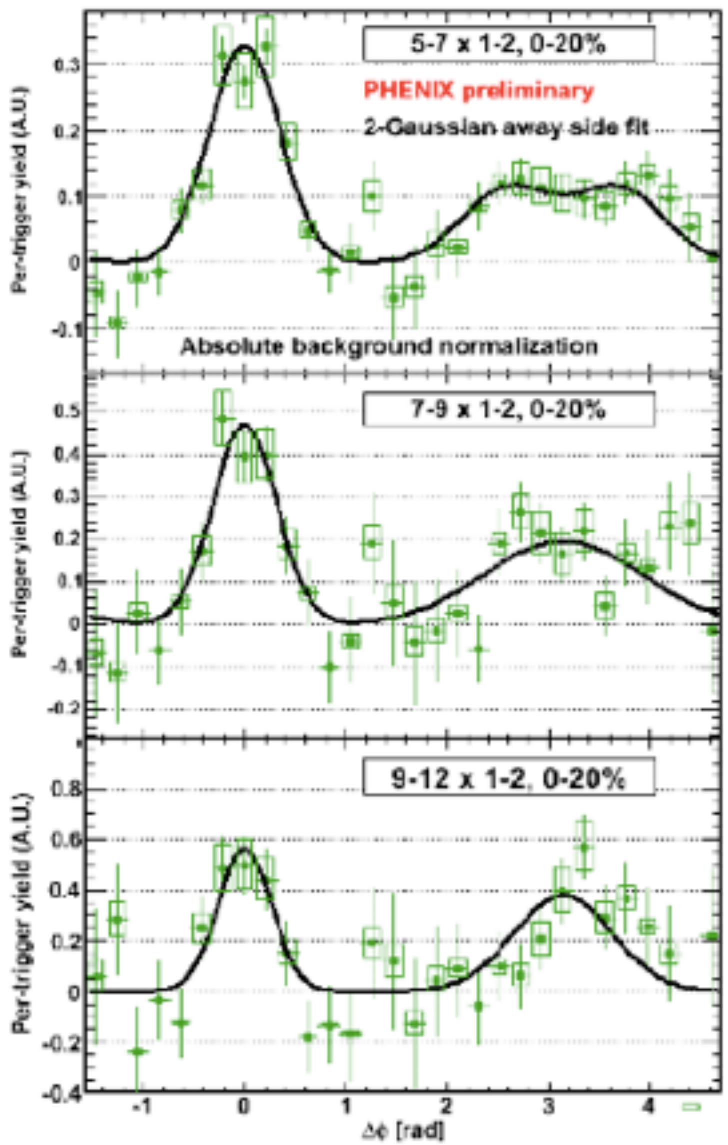


- no significant difference between π^0-h and γ_{dir}-h suppression
  - just how important is the π^0 surface bias?



π^0-h: away side shape

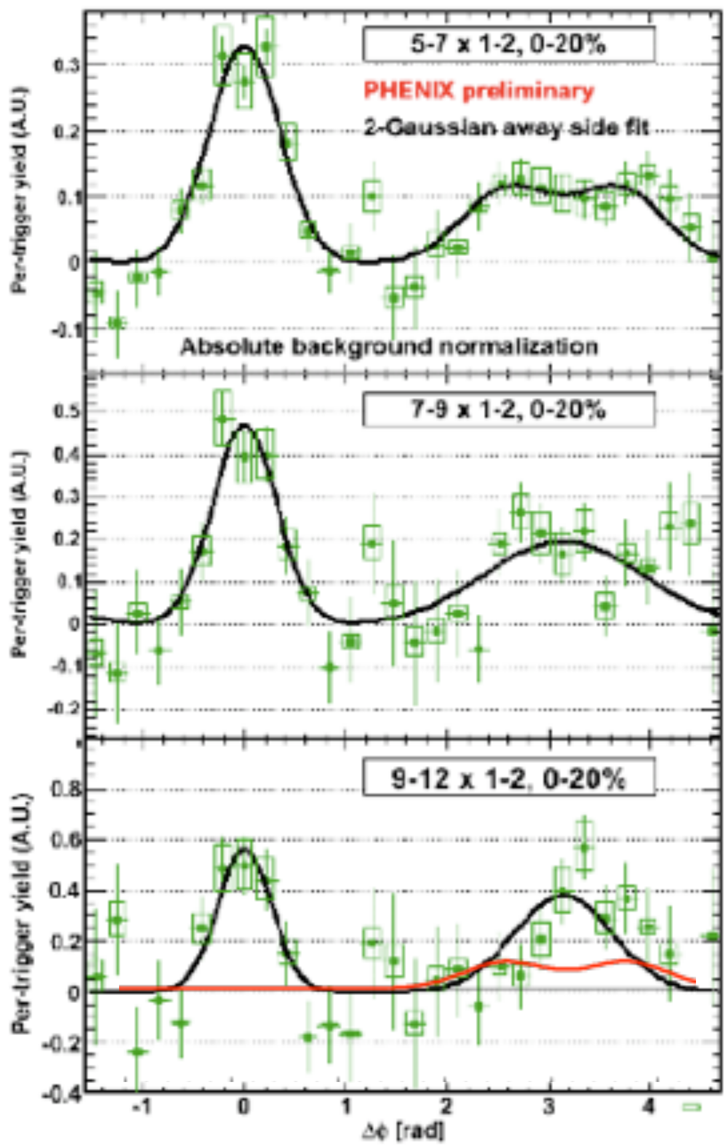
increasing π^0 p_T



no evidence for double peaks for very high p_T π^0

π^0-h: away side shape

increasing π^0 p_T

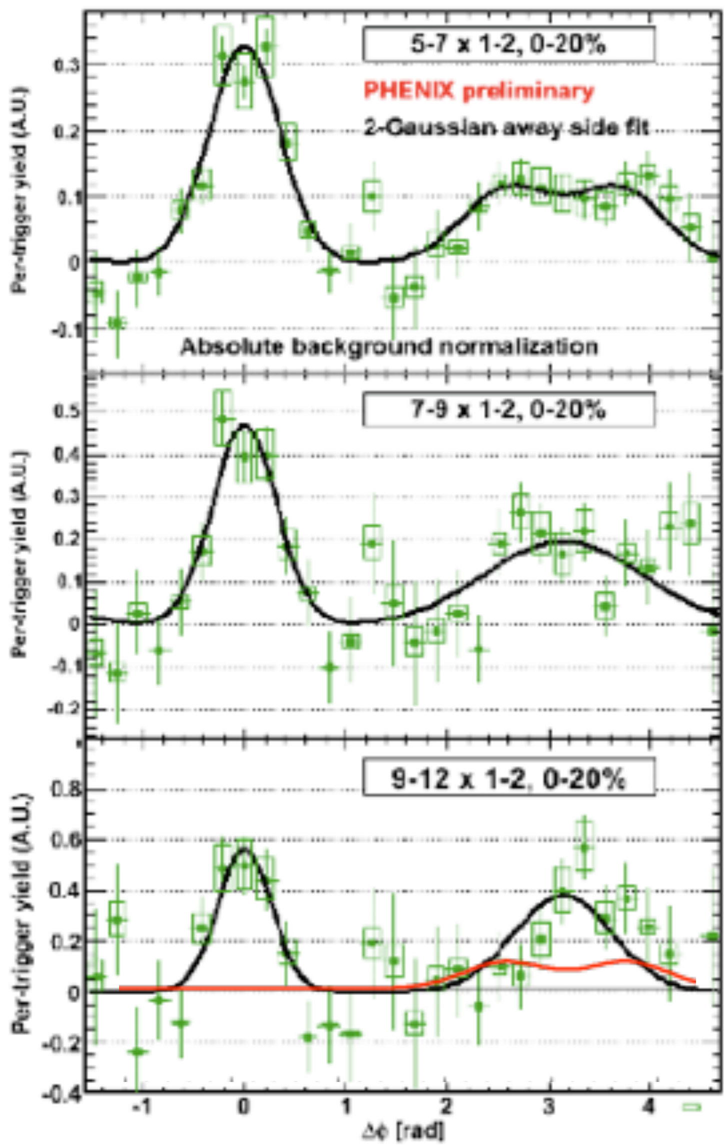


no evidence for double peaks for very high p_T π^0

don't have the statistical precision to exclude it

π^0-h: away side shape

increasing π^0 p_T

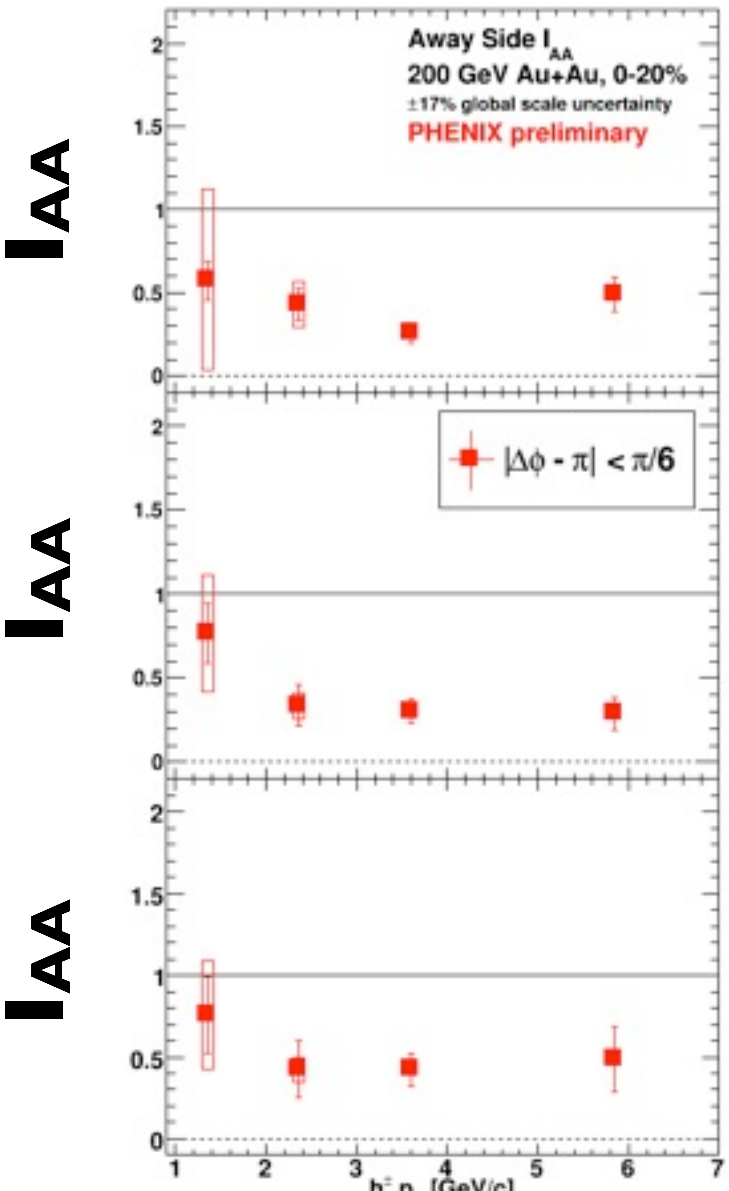


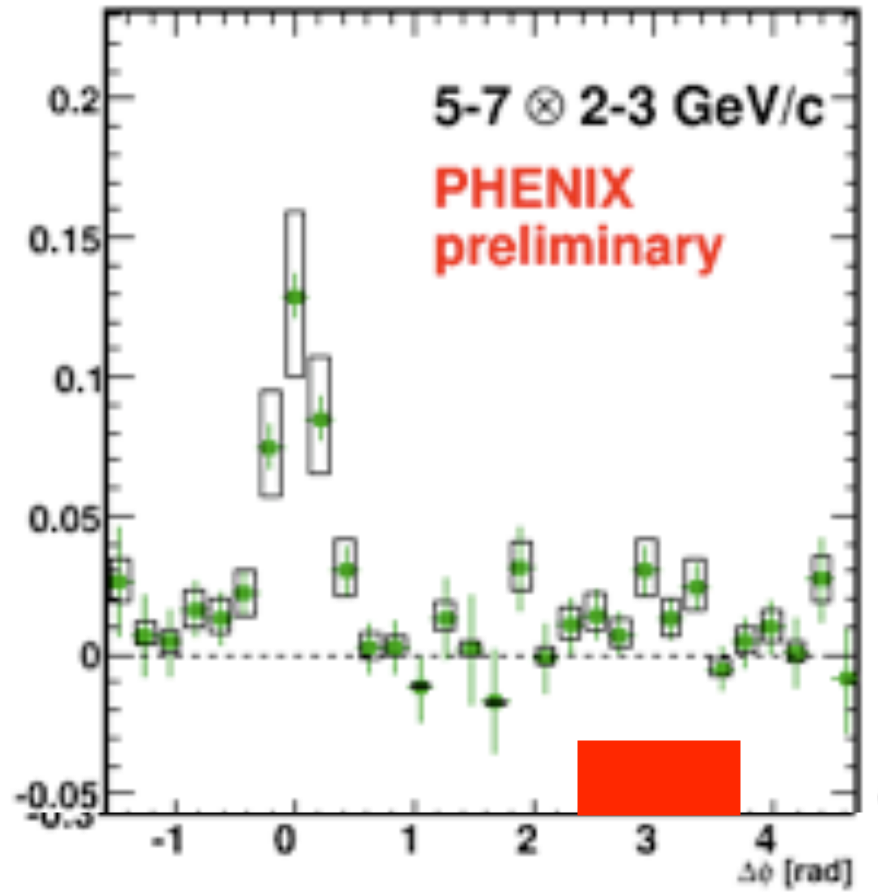
no evidence for double peaks for very high p_T π^0

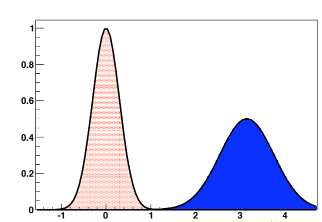
don't have the statistical precision to exclude it

→more data!

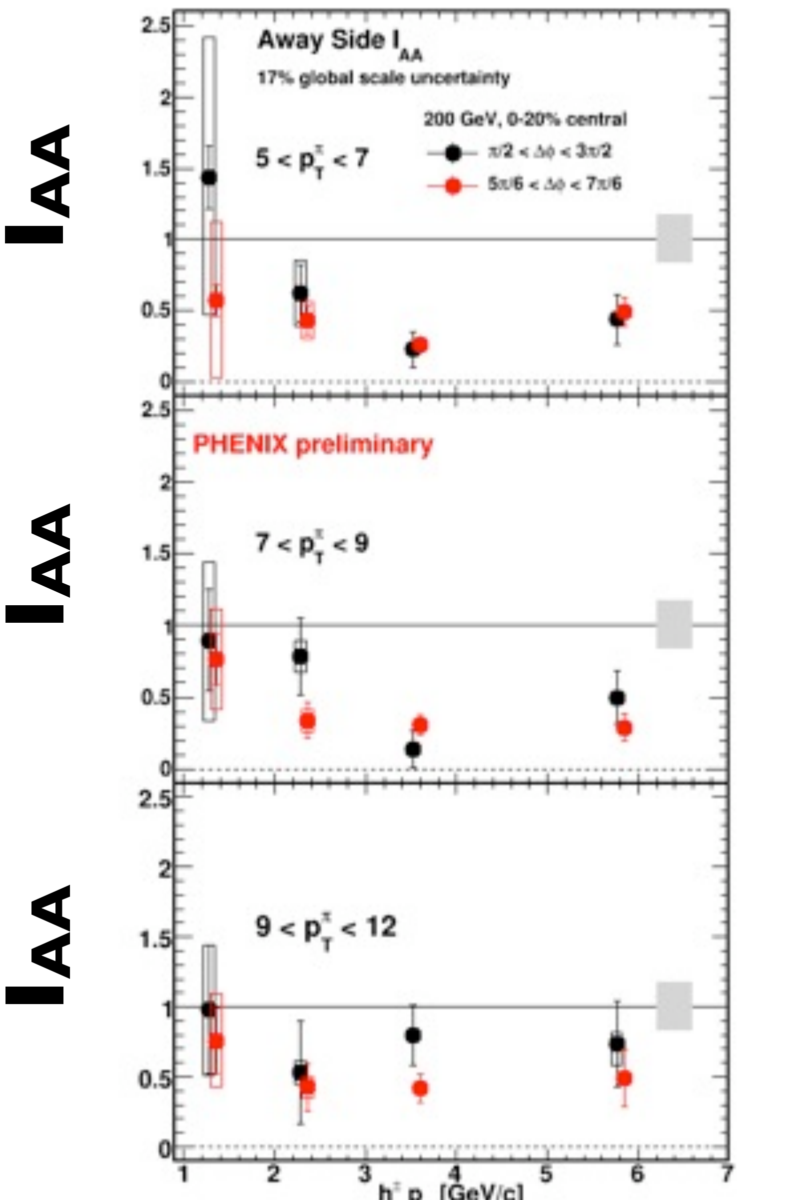
π^0-h: away side shape?

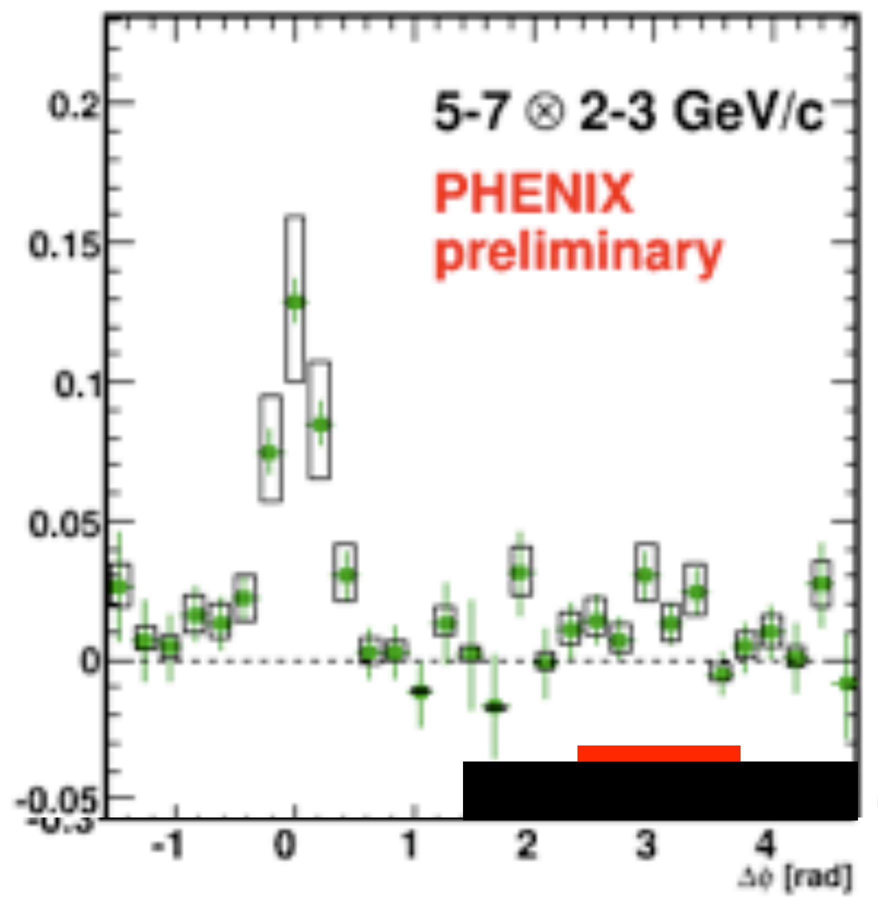


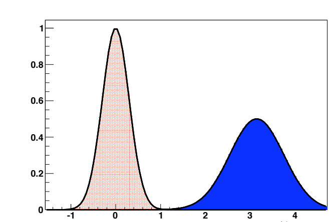




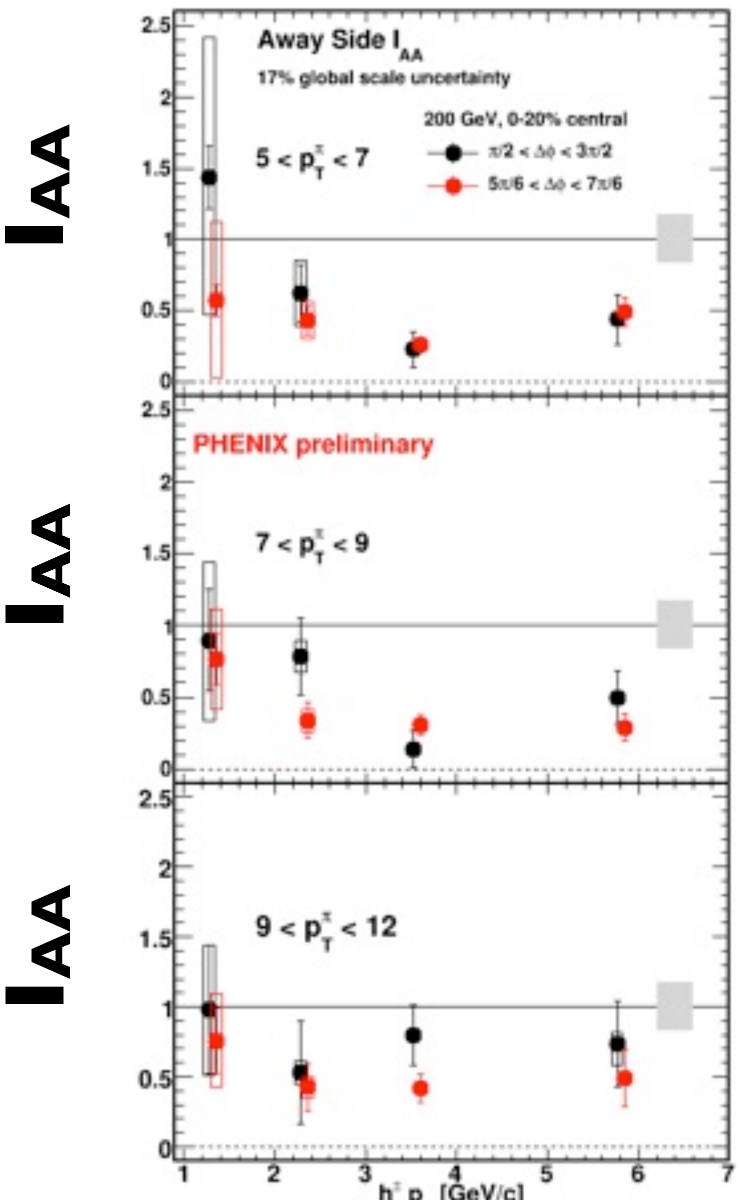
π^0-h: away side shape?

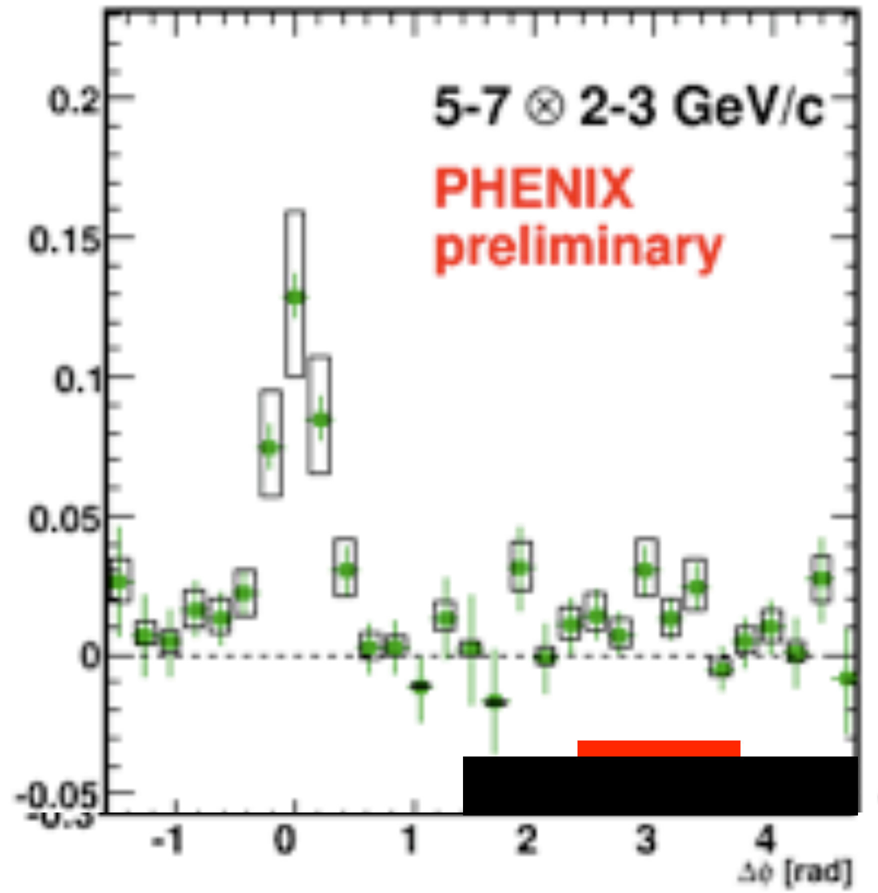




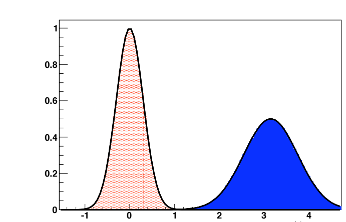


π^0-h: away side shape?

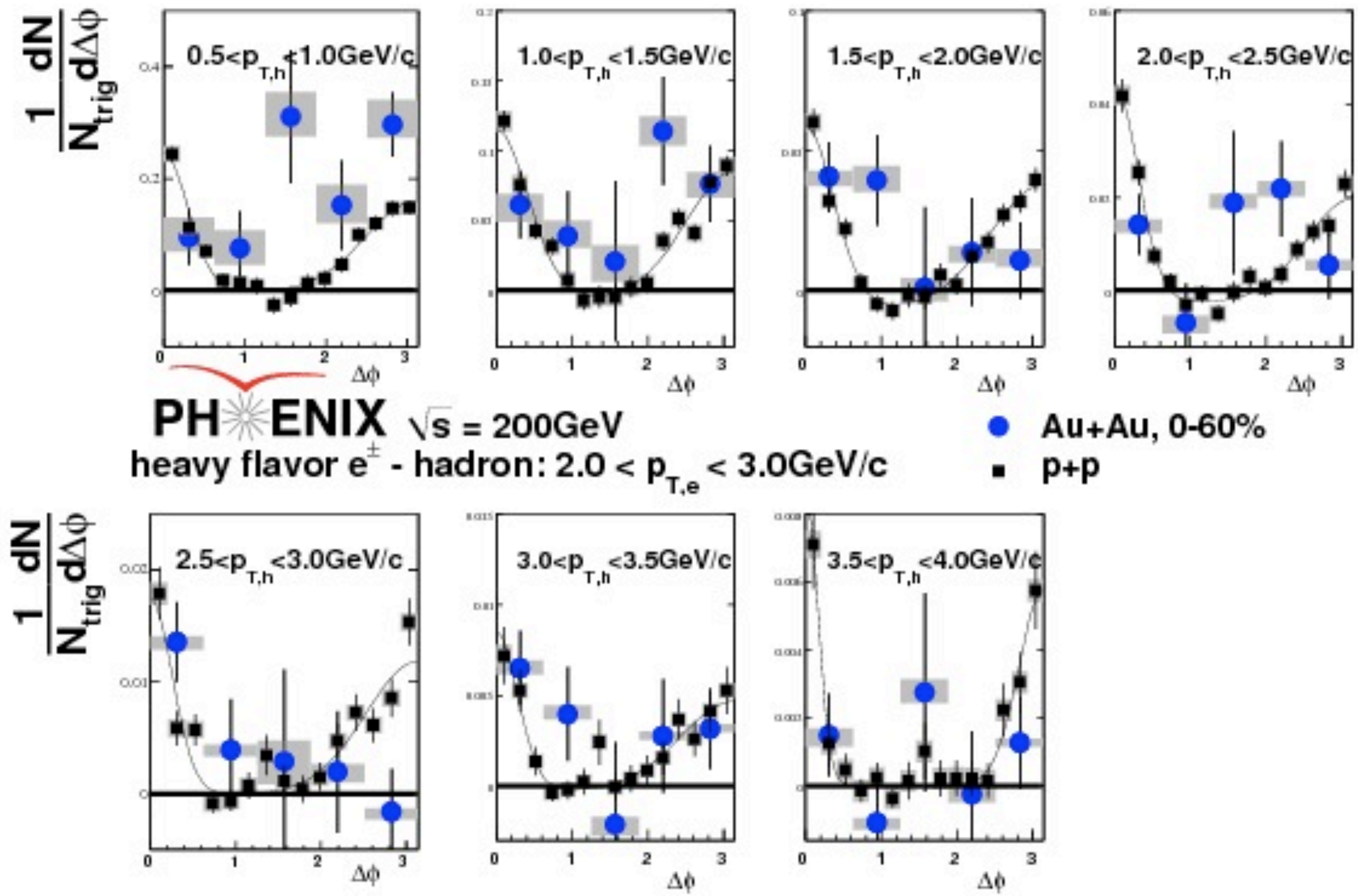




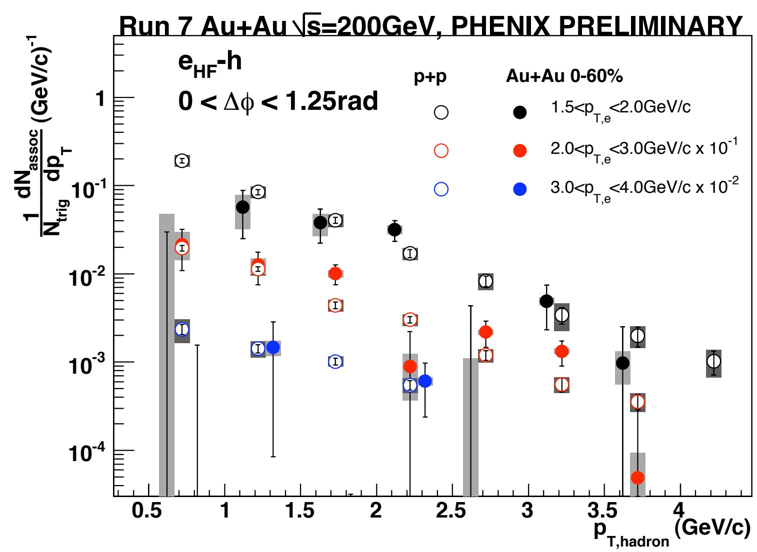
- dominated by punch through jets

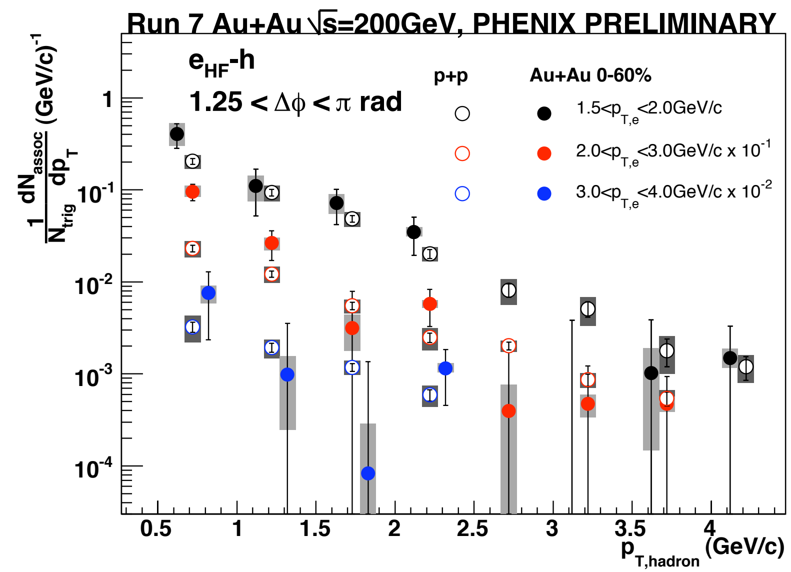


Heavy Flavor: Au+Au



Au+Au vs p+p


Run 7 Au+Au √s=200GeV, PHENIX PRELIMINARY
e_{HF}-h
$0 < \Delta\phi < 1.25$rad
p+p
Au+Au 0-60%
$1.5<p_{T,e}<2.0$GeV/c
$2.0<p_{T,e}<3.0$GeV/c x 10^{-1}
$3.0<p_{T,e}<4.0$GeV/c x 10^{-2}
$\frac{1}{N_{trig}}\frac{dN_{assoc}}{dp_T}$ (GeV/c)$^{-1}$
$p_{T,hadron}$ (GeV/c)


Run 7 Au+Au √s=200GeV, PHENIX PRELIMINARY
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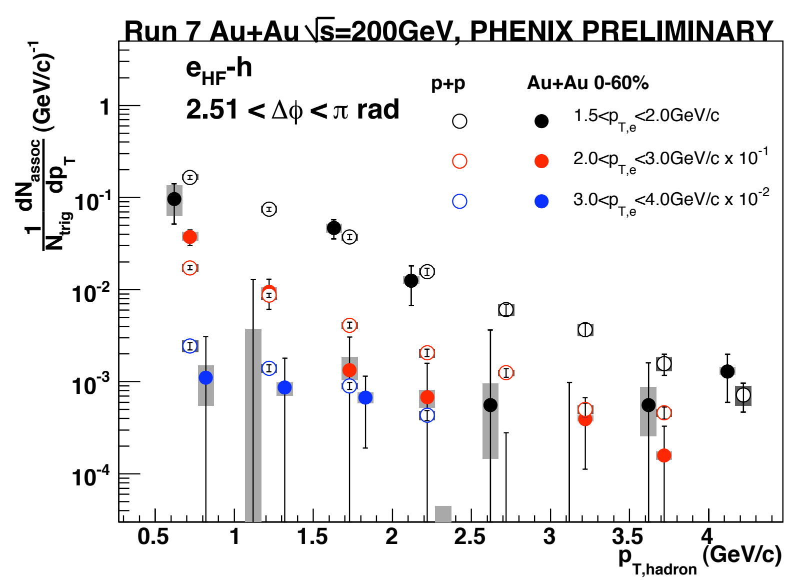
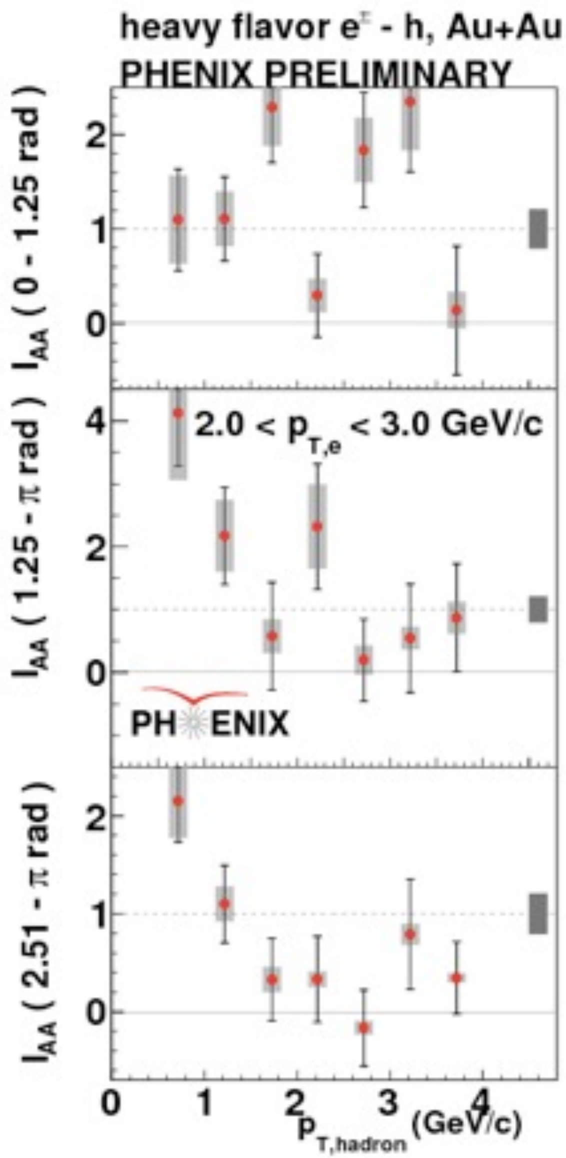

Run 7 Au+Au √s=200GeV, PHENIX PRELIMINARY
e_{HF}-h
$2.51 < \Delta\phi < \pi$ rad
p+p
Au+Au 0-60%
$1.5<p_{T,e}<2.0$GeV/c
$2.0<p_{T,e}<3.0$GeV/c x 10^{-1}
$3.0<p_{T,e}<4.0$GeV/c x 10^{-2}
$\frac{1}{N_{trig}}\frac{dN_{assoc}}{dp_T}$ (GeV/c)$^{-1}$
$p_{T,hadron}$ (GeV/c)

heavy flavor: I_{AA}



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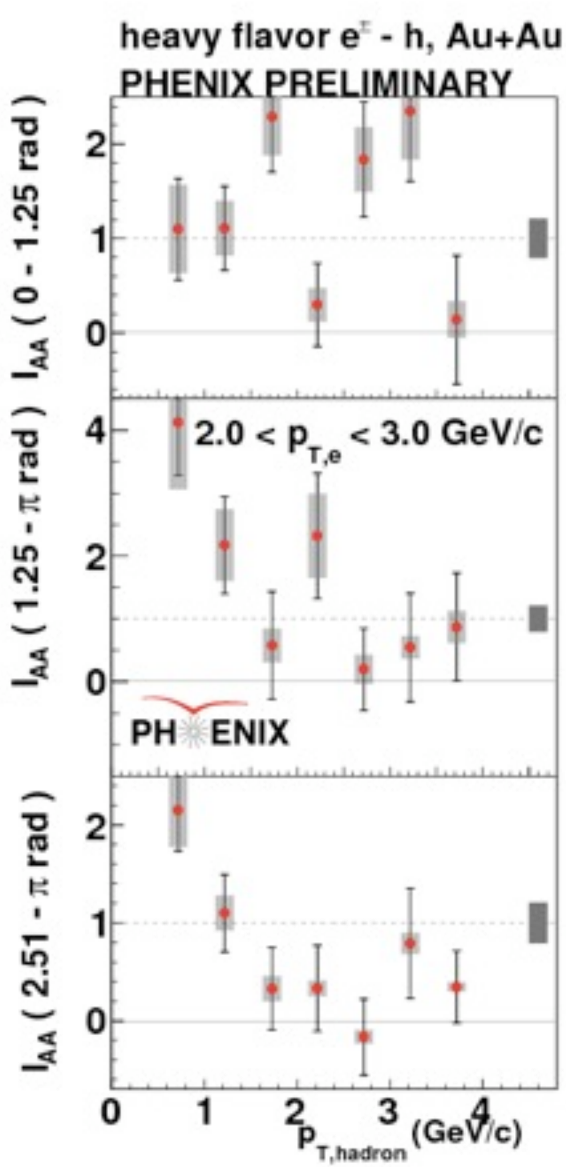
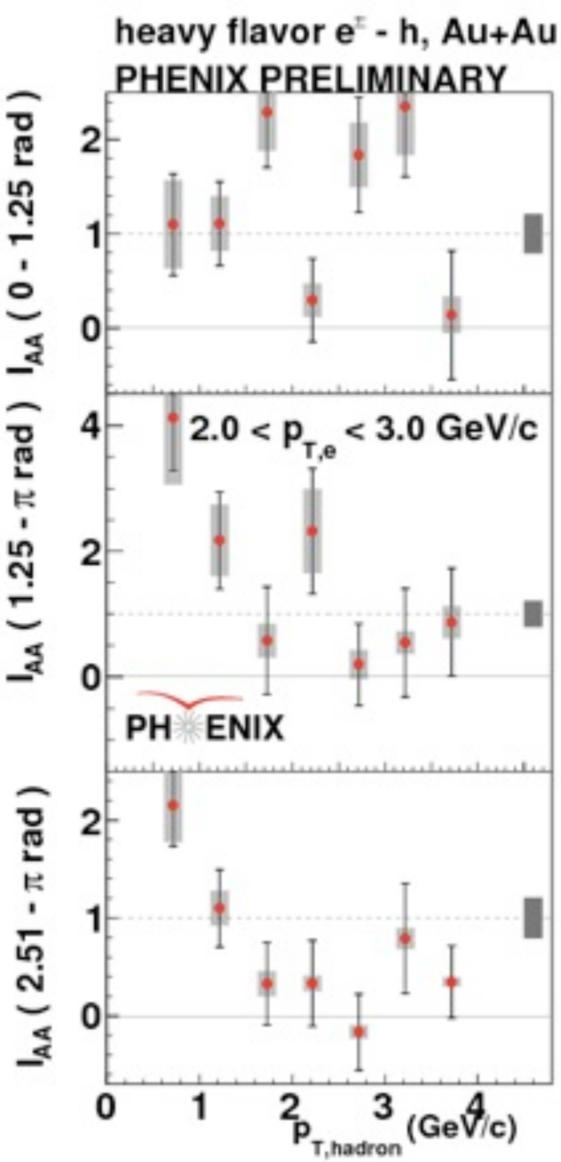


$\langle I_{AA} \rangle$

$\Delta\Phi$	$2.0<p_{Te}<3.0$GeV/c
0-1.25rad	1.17±0.21
1.25-πrad	1.43±0.31
2.51-πrad	0.67±0.16

heavy flavor: I_{AA}



$<I_{AA}>$

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- large errors

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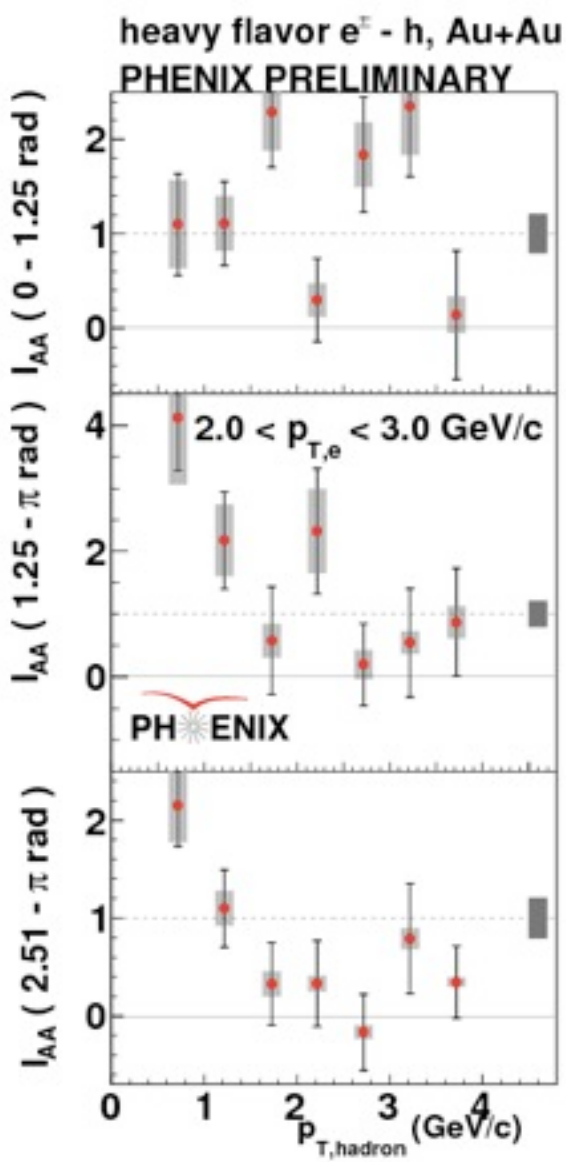

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1.25-πrad	1.43±0.31
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- large errors
- I_{AA}(near side) ~ 1
  - consistent with D decays

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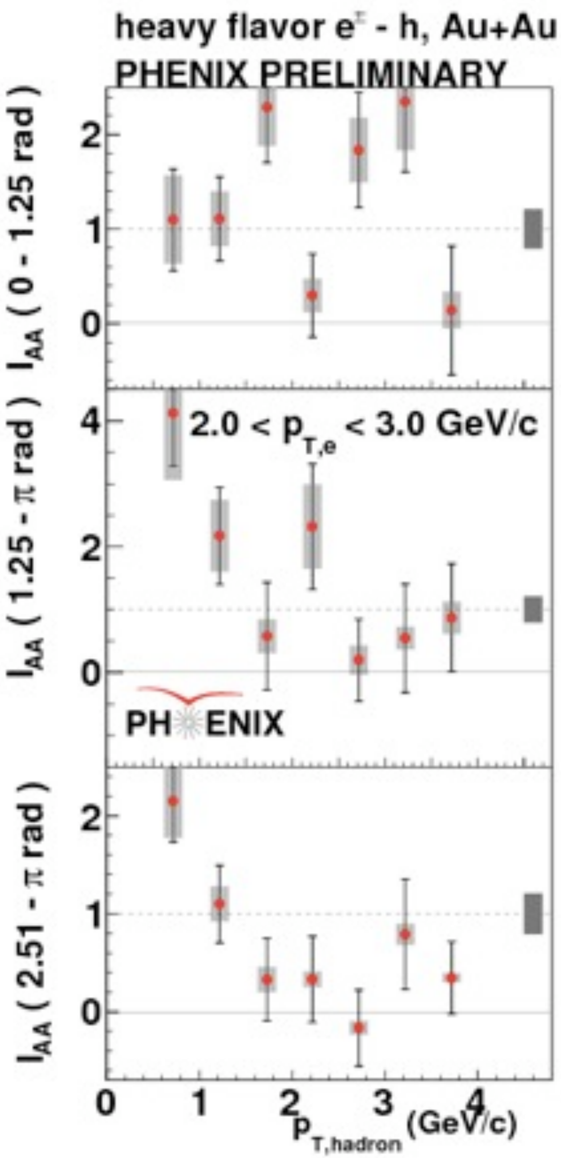

$\langle I_{AA} \rangle$

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1.25-πrad	1.43±0.31
2.51-πrad	0.67±0.16

- large errors
- I_{AA}(near side) ~ 1
  - consistent with D decays
- I_{AA}(1.25-π) > I_{AA}(2.51-π)
  - evidence for shoulder?

conclusions

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- open heavy flavor is an important frontier in jet physics

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- open heavy flavor is an important frontier in jet physics
  - complementary to γ-h & π^0-h measurements
  - it will be crucial for energy loss & hadronization models to describe all these observables
- however, it is harder to interpret, more statistics starved and a harder measurement than γ-h or π^0-h

a promising future

- p+p: jet properties & understanding parton subprocesses
- Run 10: 200 GeV Au+Au: 4-6x statistics for PHENIX e_{HF}-h
  - luminosity & acceptance increases
  - Hadron Blind Detector can reject some photonic electrons further improving the measurement
  - 2-3x statistics for π^0-h & γ_{dir}-h
- Run 11: Silicon Vertex Detector:
  - separation of charm and bottom

I_{AA} straight line fits

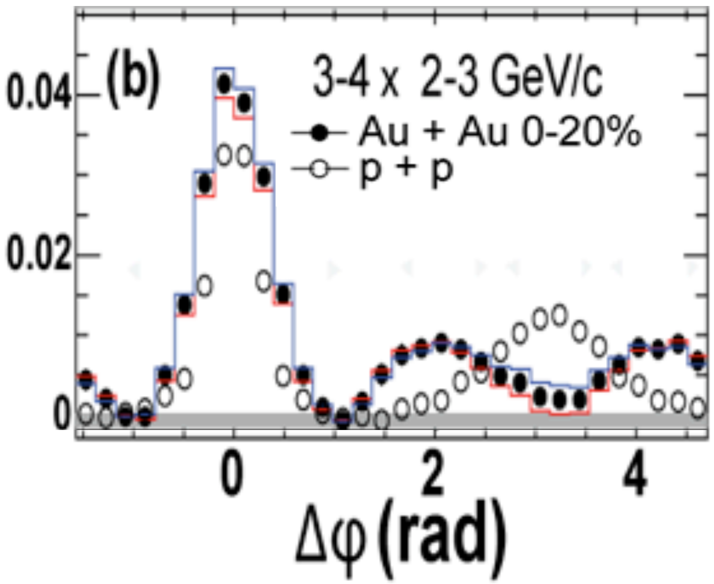
$\Delta\Phi$	$1.5<p_{Te}<2.0$GeV/c	$2.0<p_{Te}<3.0$GeV/c	$3.0<p_{Te}<4.0$GeV/c
0-1.25rad	0.53±0.17	1.17±0.21	0.29±0.40
1.25-πrad	1.18±0.28	1.43±0.31	1.05±0.63
2.51-πrad	0.52±0.13	0.67±0.16	0.47±0.31

conclusions & outlook

HF correlations provide a new tool to study passage of fast parton through matter

- c/b ratio in p+p consistent with FONLL
  - this ratio crucial to understanding e± results in Au+Au
- e_{HF}-h conditional yields in p+p measured
  - method established to extract HF correlations
  - useful for testing charm fragmentation into hadrons
  - baseline for Au+Au results, being analyzed now

Double Peak Structure



PHENIX, PRC 78 014901 (2008), Noronha et al. arXiv:0807.1038, Neufeld arXiv:0807.2996

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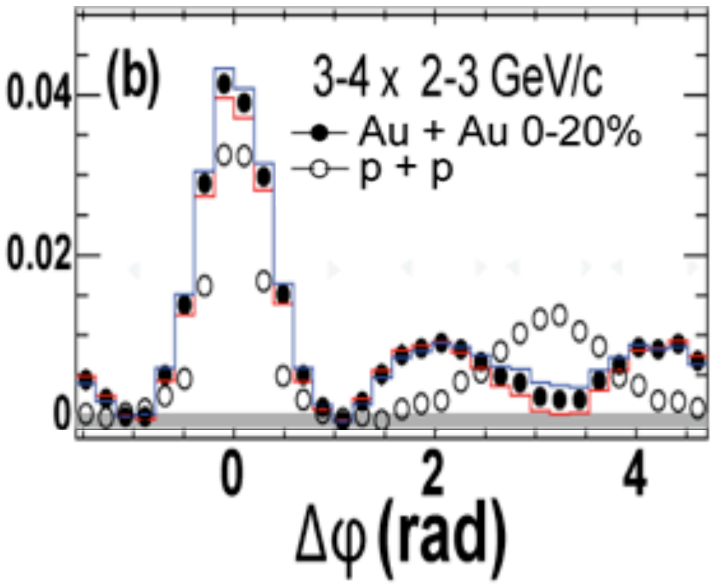

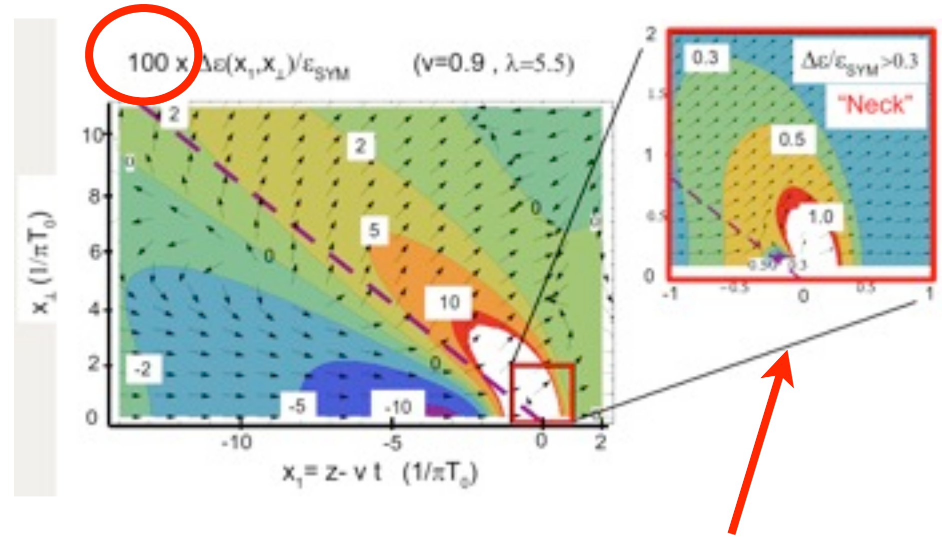

AdS/CFT: Correlations from Neck region

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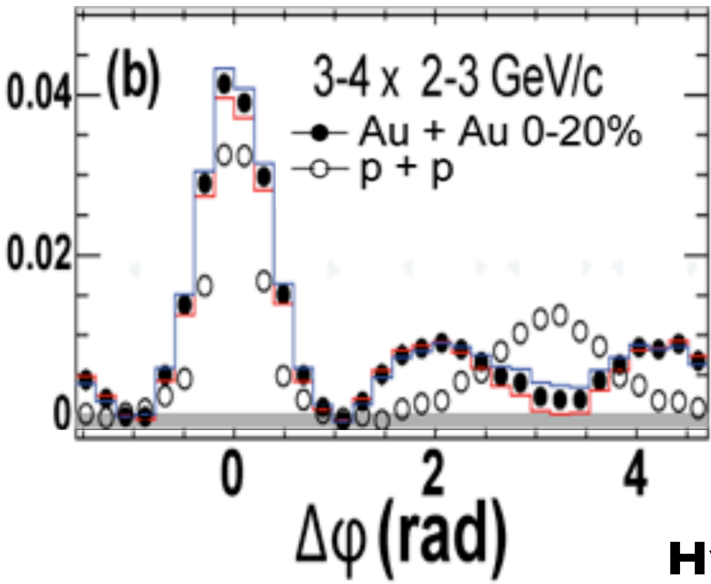
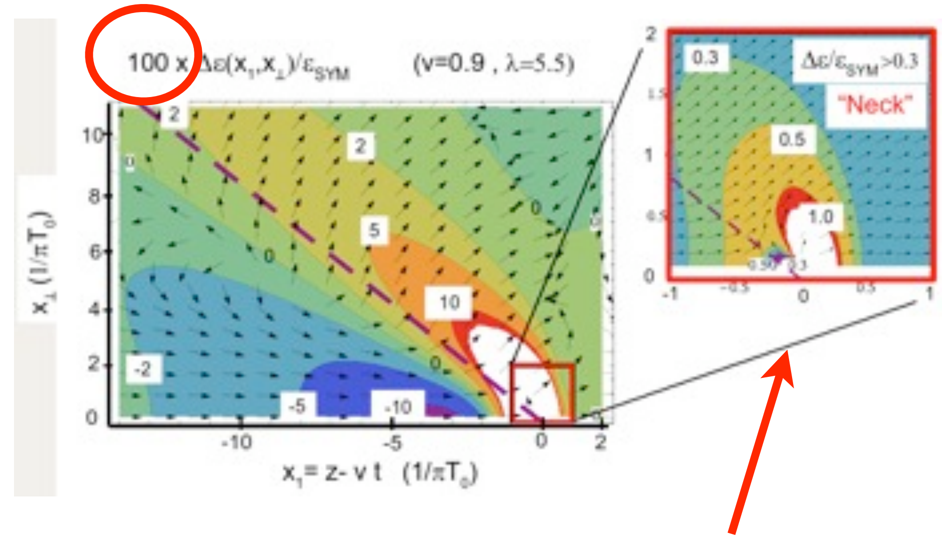
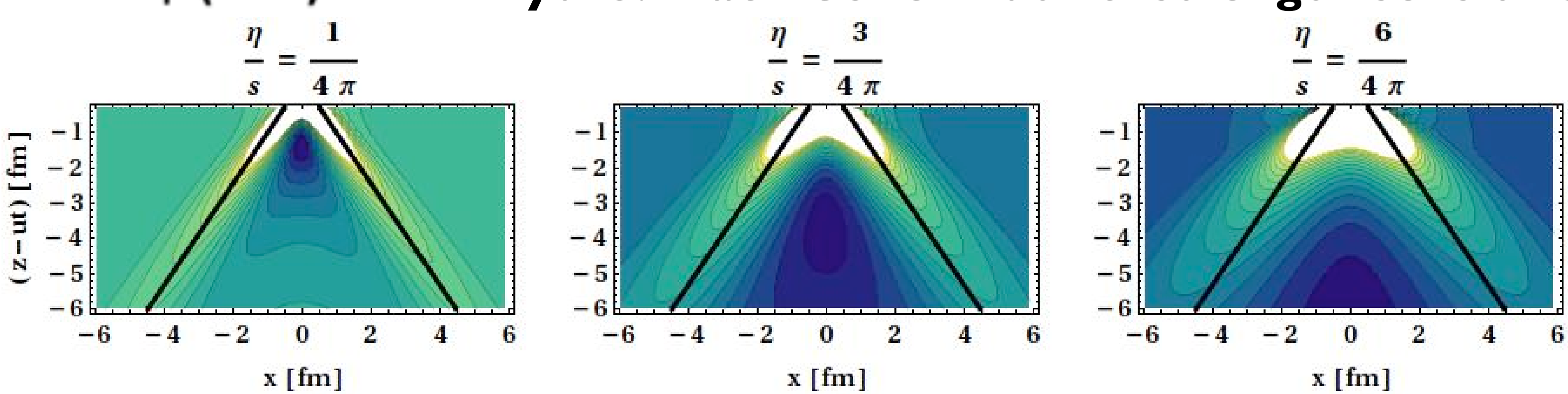
Double Peak Structure





AdS/CFT: Correlations from Neck region

Hydro: Mach Cone width & strength sensitive to η/s



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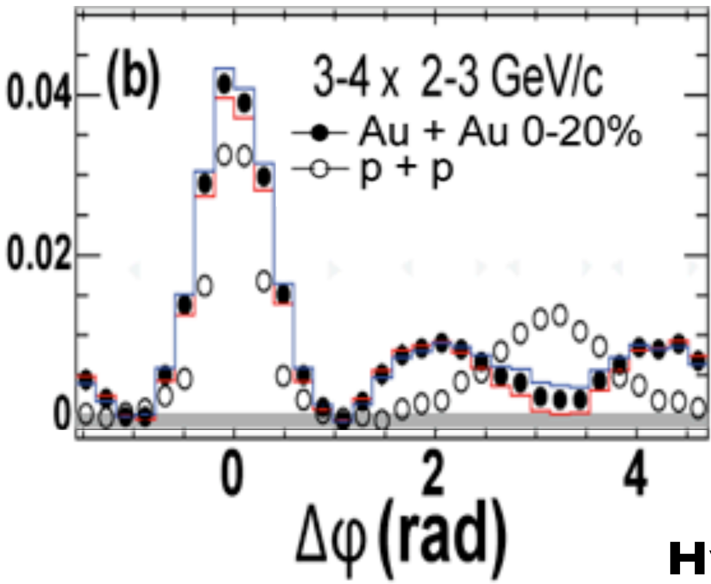

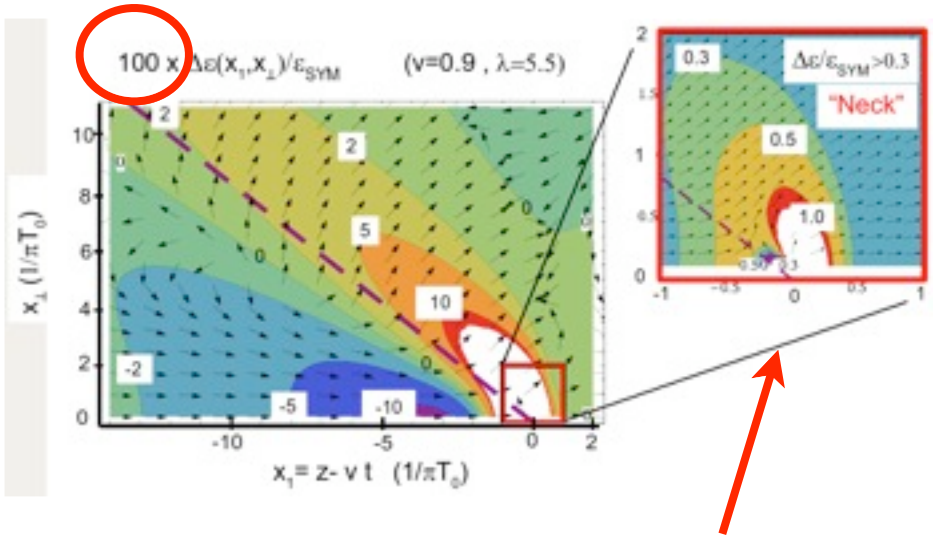

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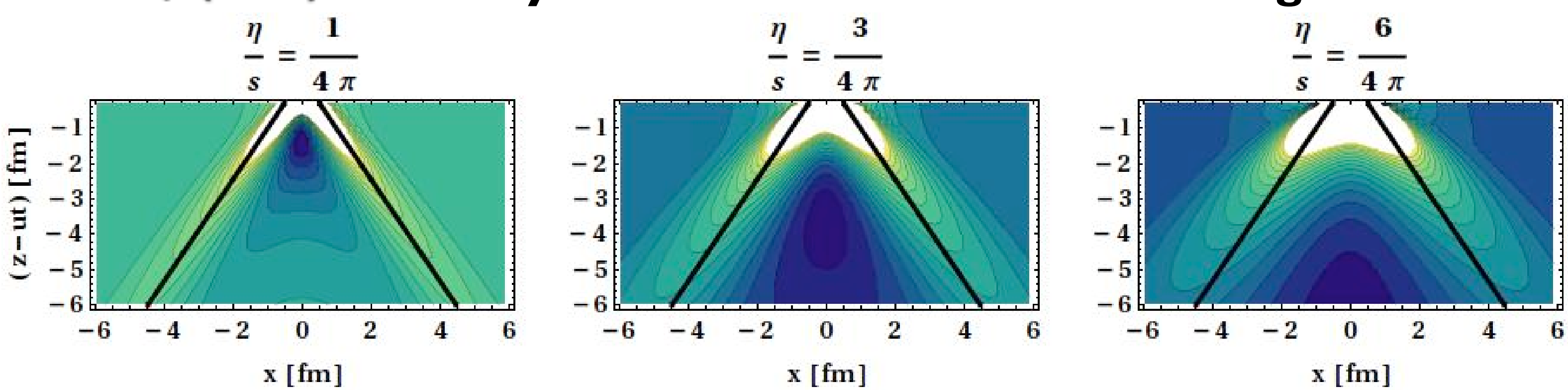
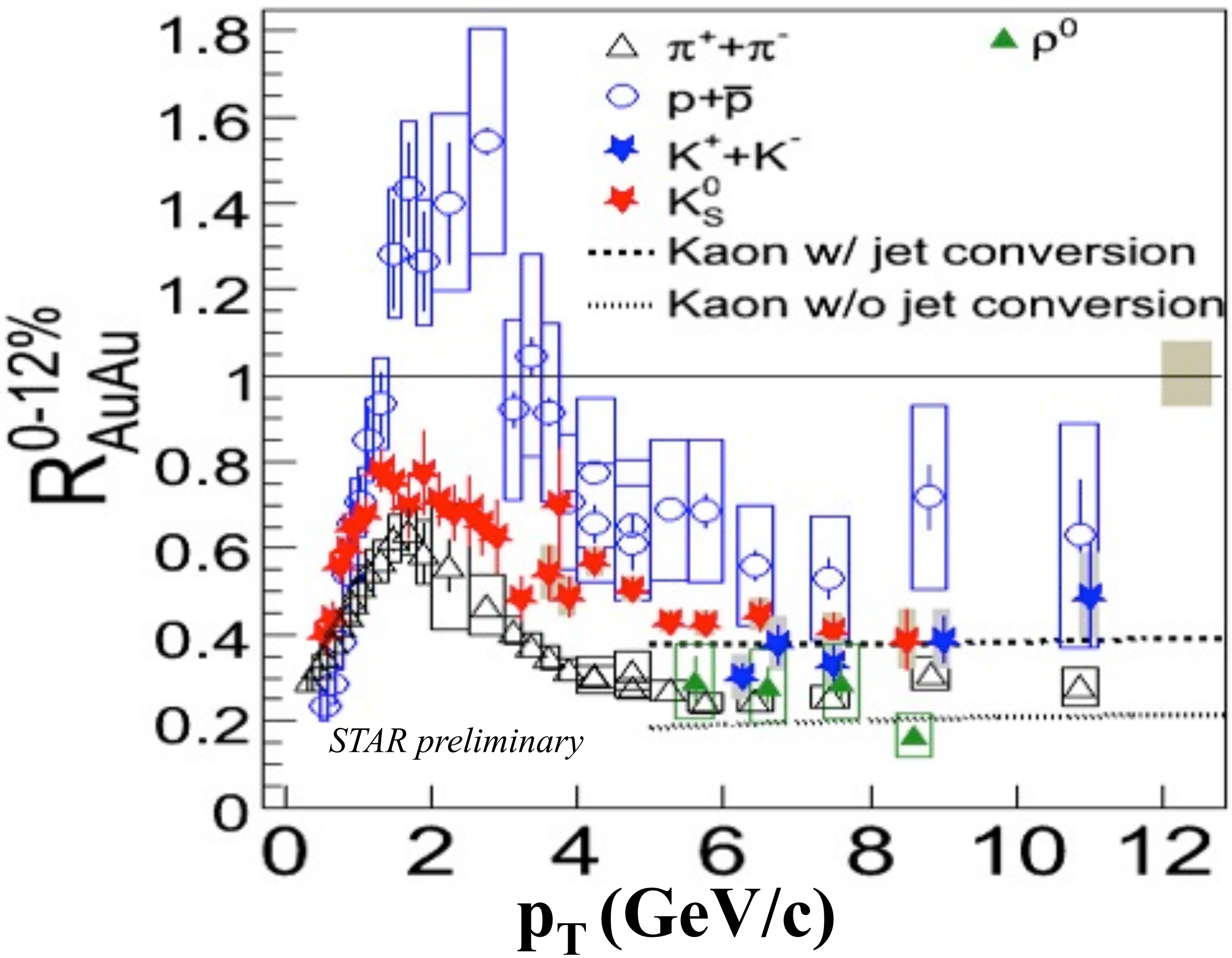


Heavy quark correlations should help discriminate!

PHENIX, PRC 78 014901 (2008), Noronha et al. arXiv:0807.1038, Neufeld arXiv:0807.2996

RAA of hadrons



and what about heavy quarks?

- 1.04 for a 4 GeV bottom quark
- 1.2 for a 3GeV charm quark
- work backward, if you wanted to see this number march in to 0.7 at RHIC you would need v= 0.45 which is a 2.3GeV bottom quark

are the measurements sensitive?

$$\cos\theta_M = \frac{\bar{c}_s}{v_{jet}}$$

phase	c_S	θ_M (rad)
QGP	$1/\sqrt{3} \sim 0.57$	0.95
hadron gas	$\sqrt{0.2} \sim 0.44$	1.1
mixed phase	0	1.57?
RHIC (time average)	0.33	1.2

numbers from: Casalderry-Solona, et al hep-ph/0411315