Experimental Perspectives on Hard Probes in Heavy Ion Collisions at RHIC

Anne Sickles

November 3, 2010

BROOKHAVEN NATIONAL LABORATORY

What is our goal?

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$\text{parton}_i(E)$

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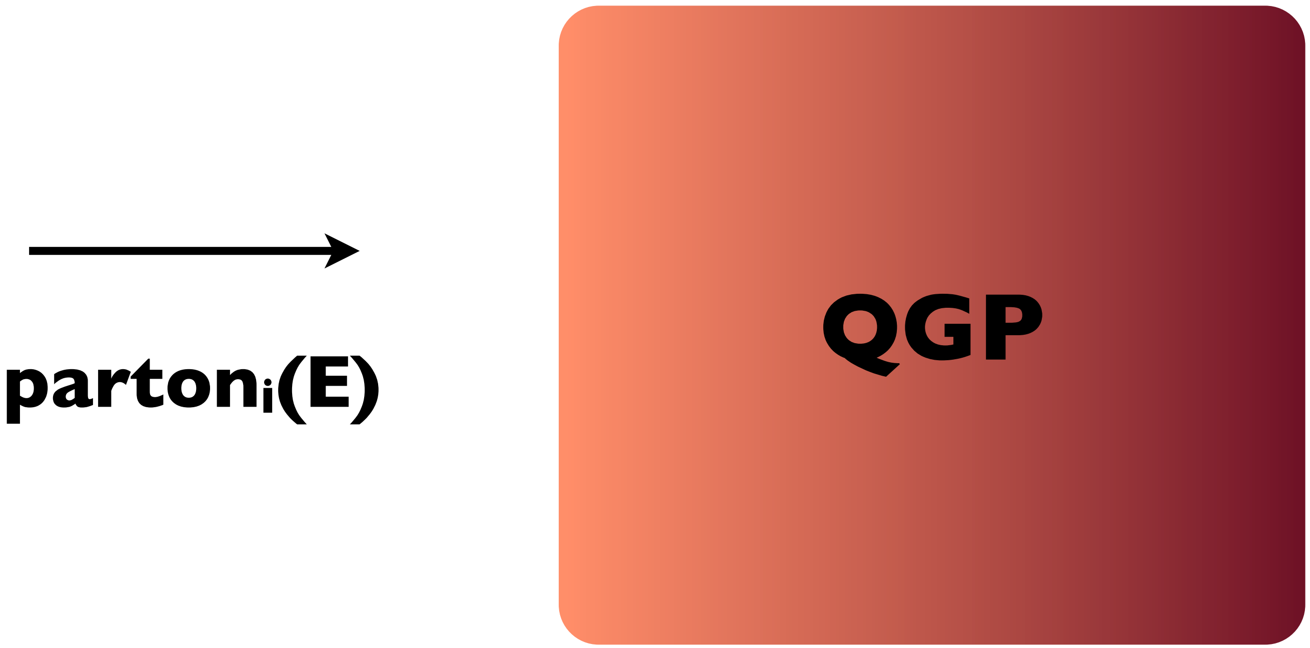

What is our goal?

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→determine the mechanism(s) of energy loss
pQCD radiative & collisional, AdS/CFT, something else?

→determine the strength of the interactions

reality more complicated

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geometry, intial state effects, time evolution, fragementation, flow of various kinds

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geometry, intial state effects, time evolution, fragementation, flow of various kinds

it's all important!, so how do we learn anything...

large energy loss

$$R_{AA} = \frac{\text{yield AuAu}}{N_{coll}\,\text{yield pp}}$$

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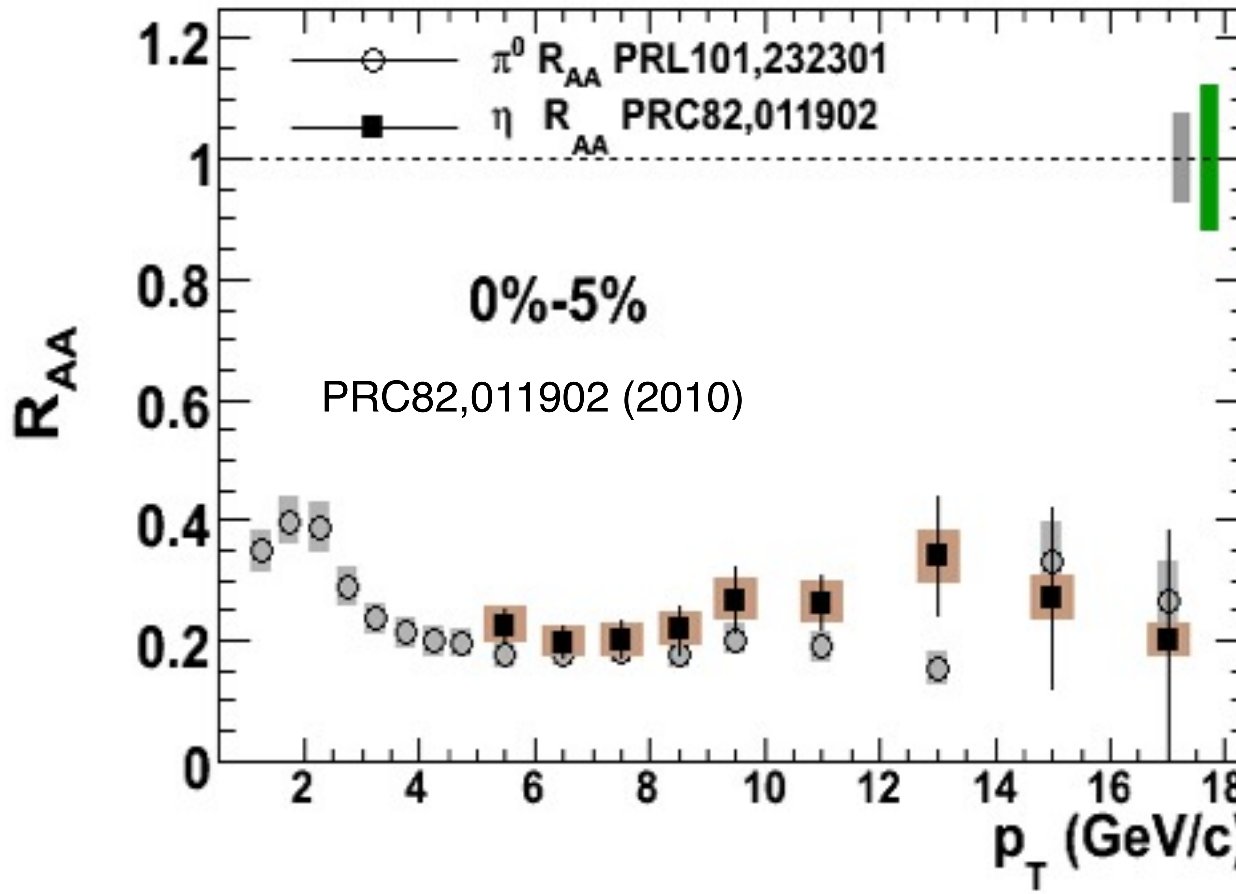

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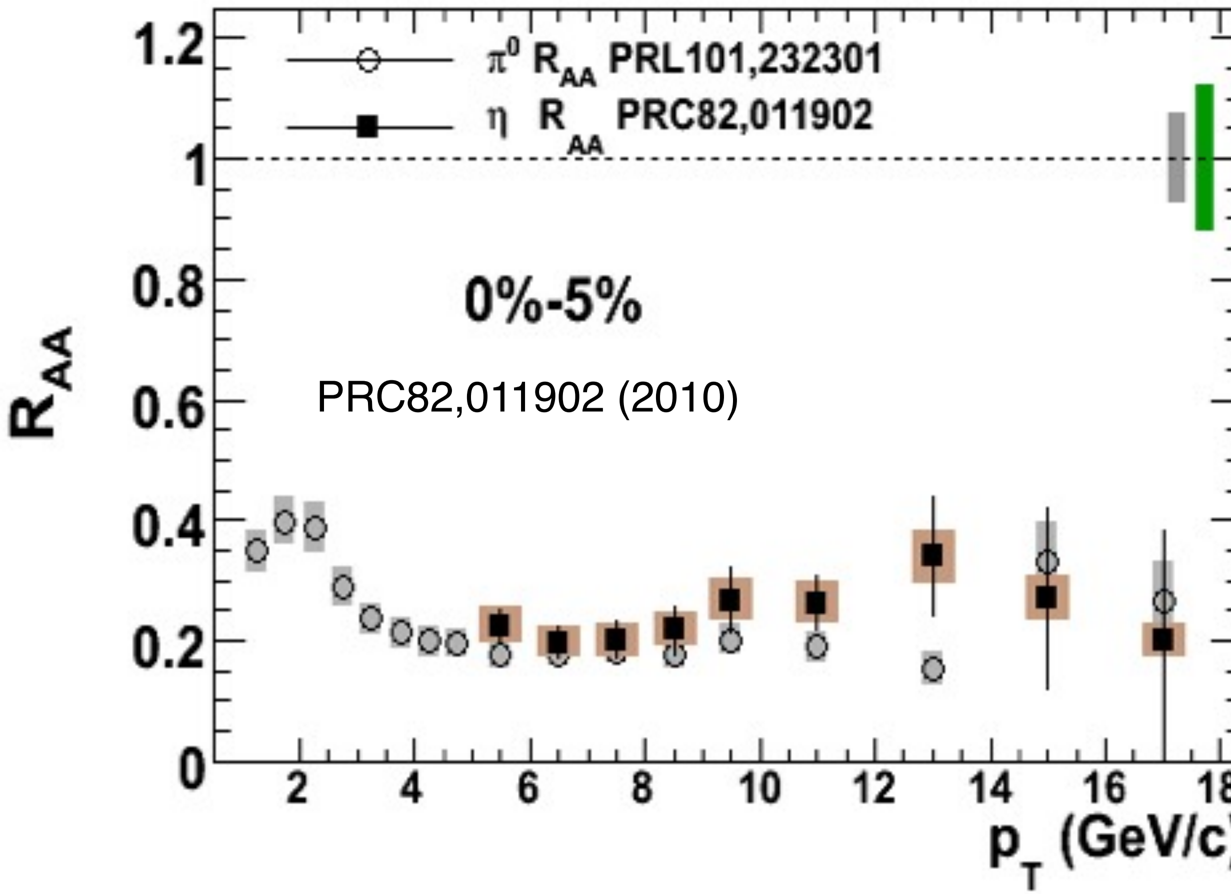
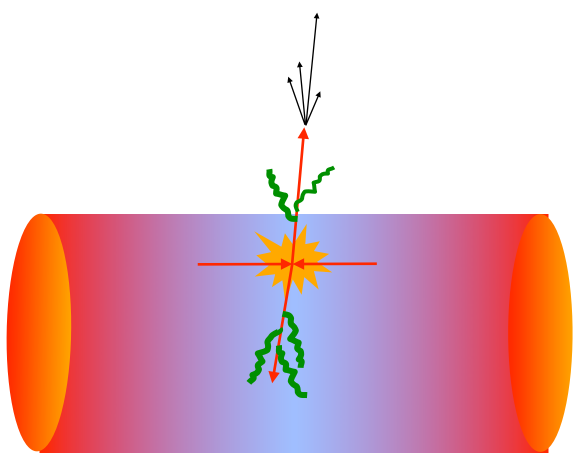
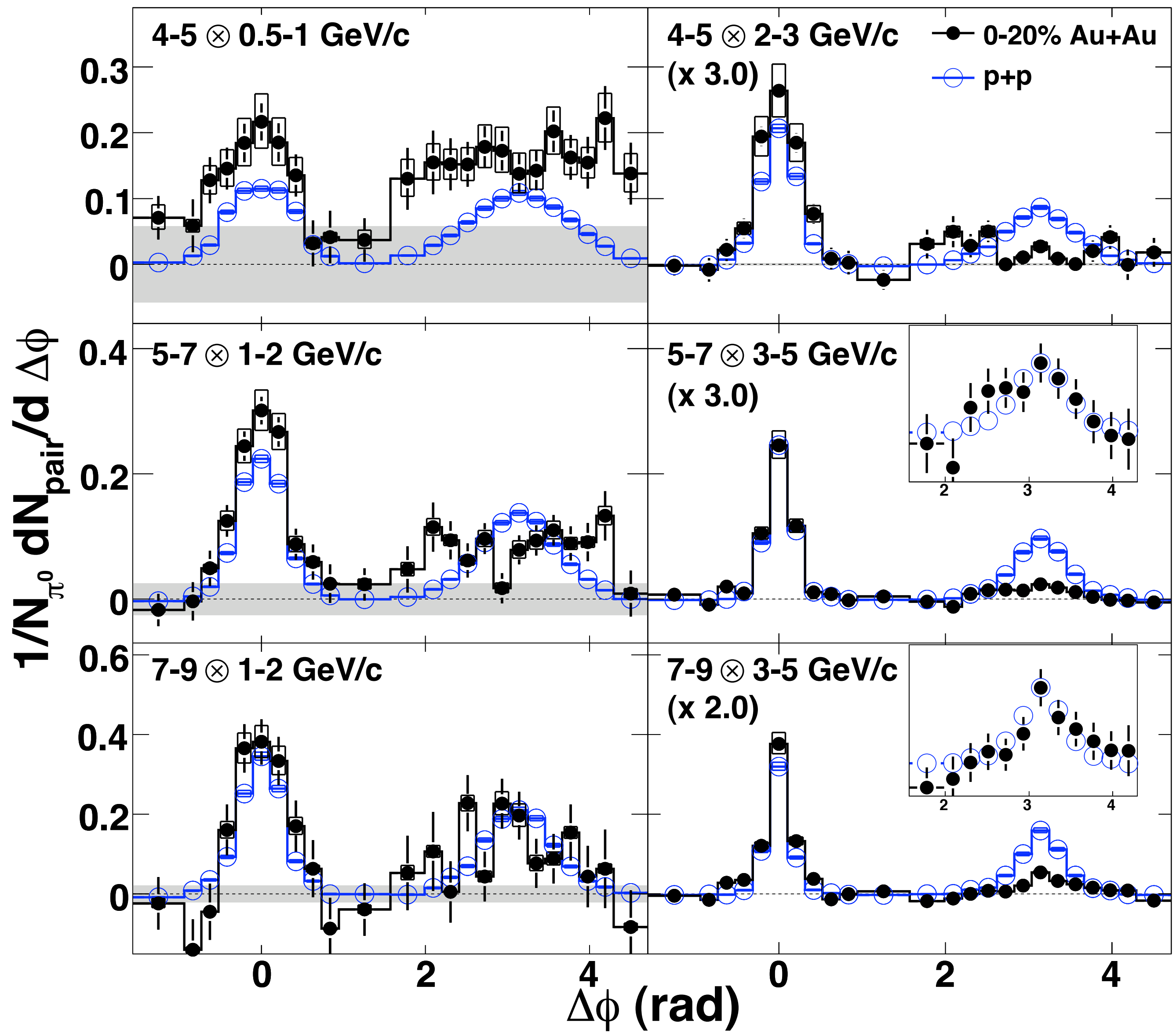


- both π^0 & η R_{AA} still flat out to 20GeV/c!

what's opposite these π^0s?





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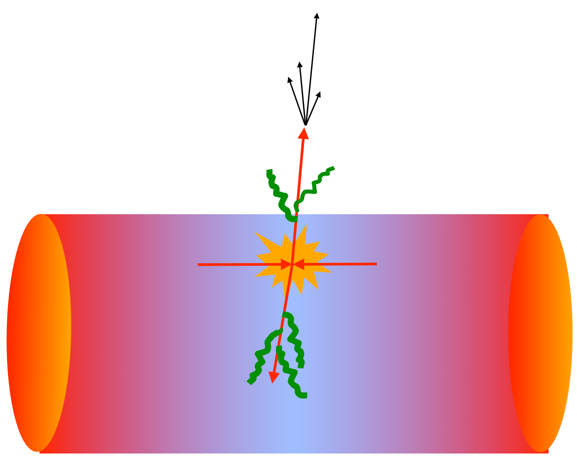

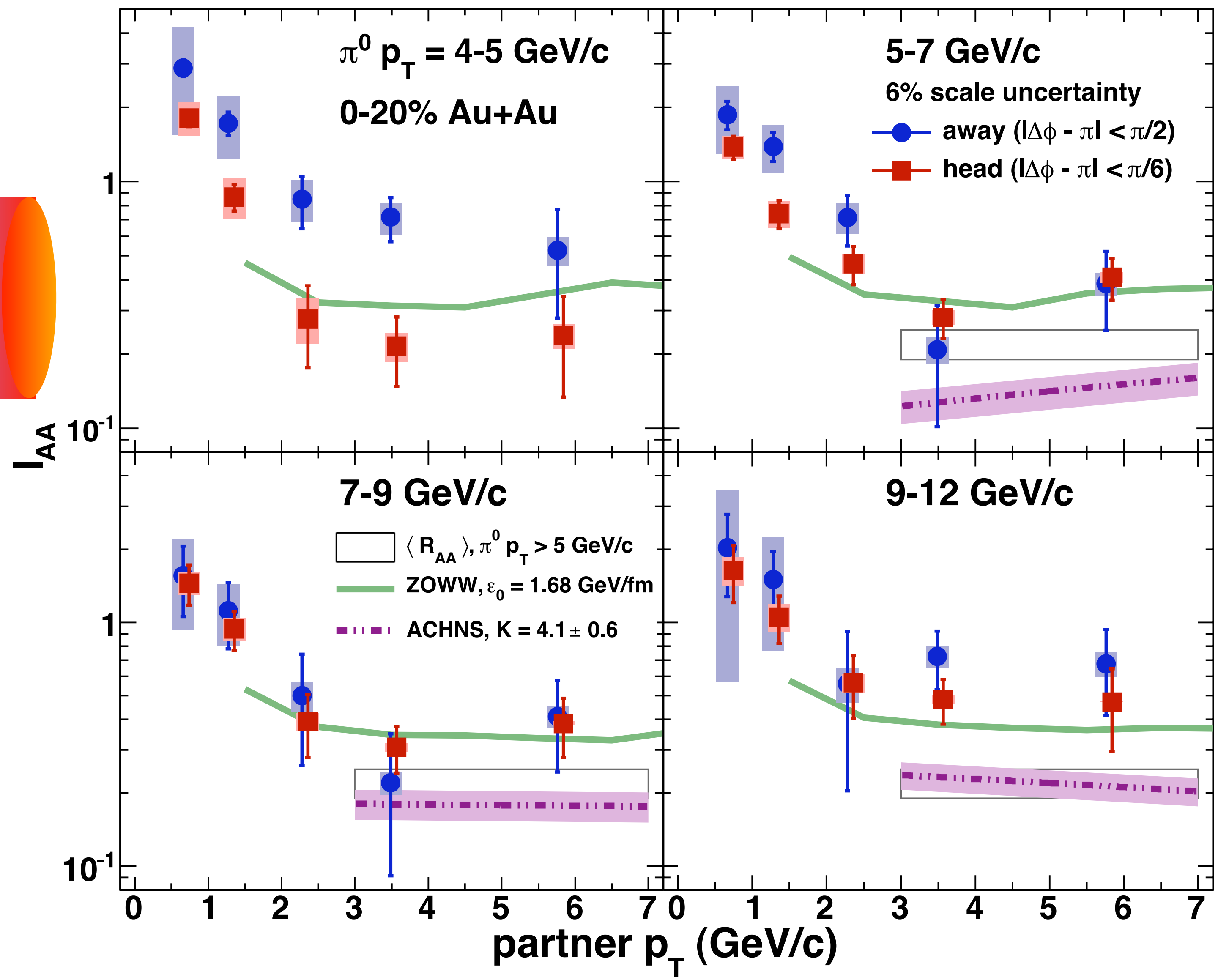

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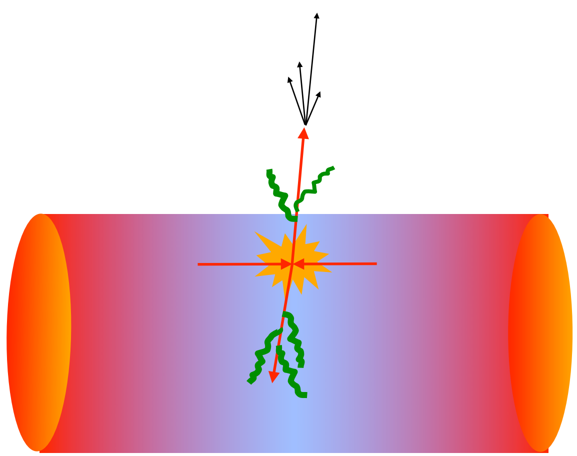

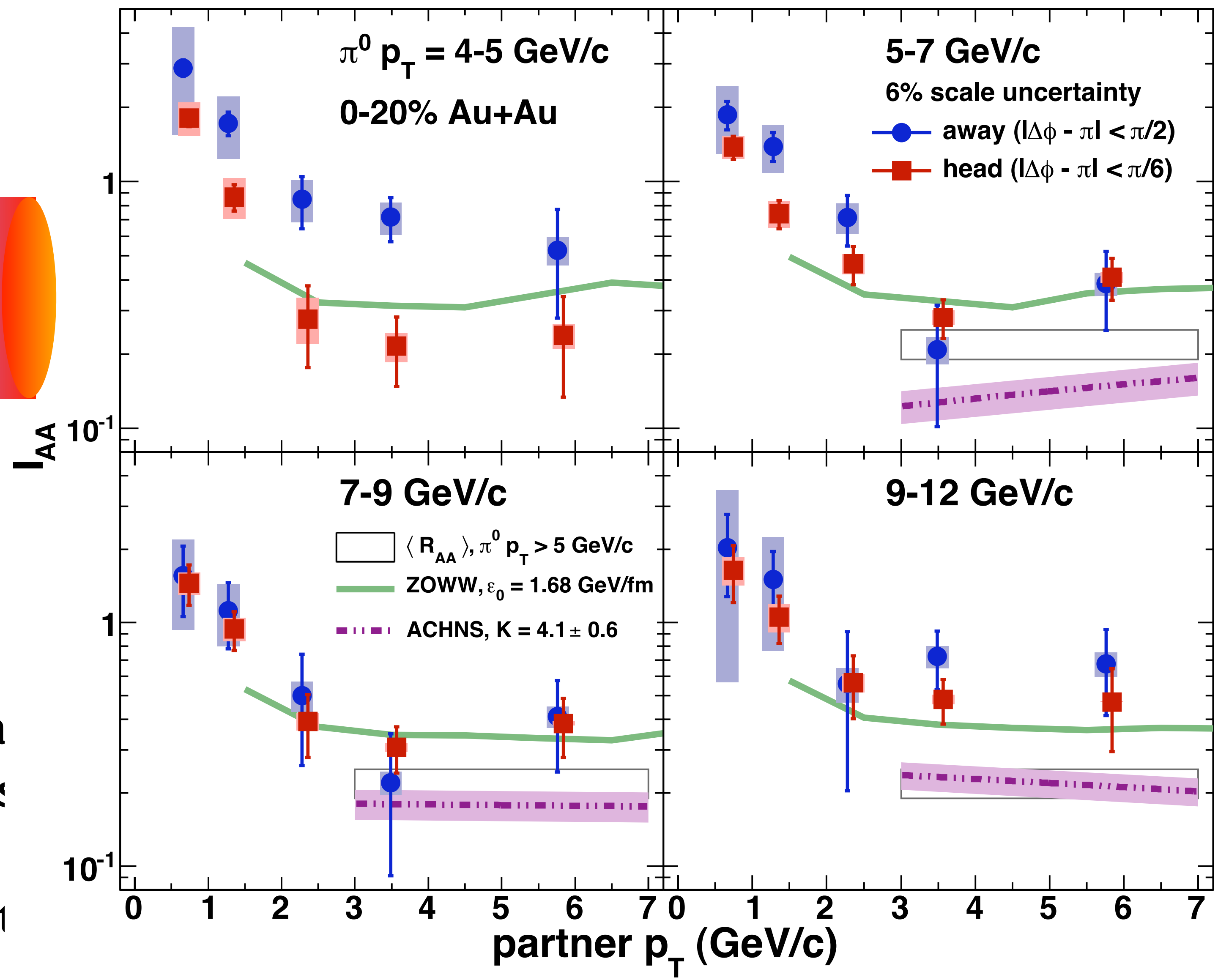

$I_{AA} > R_{AA}$

away side spectra harder than singles

same decrease results in different suppression

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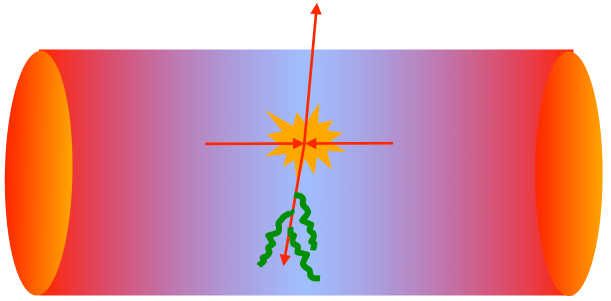
γ-jet correlations



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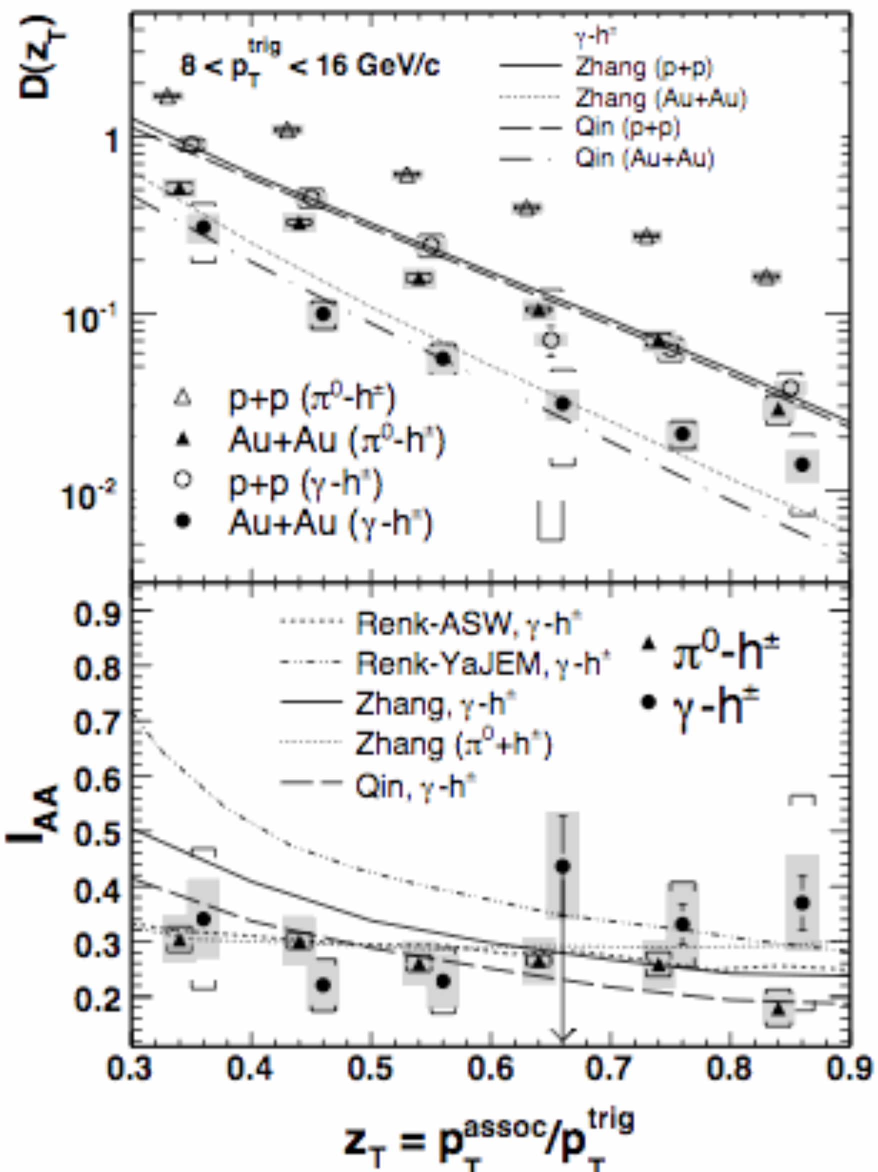
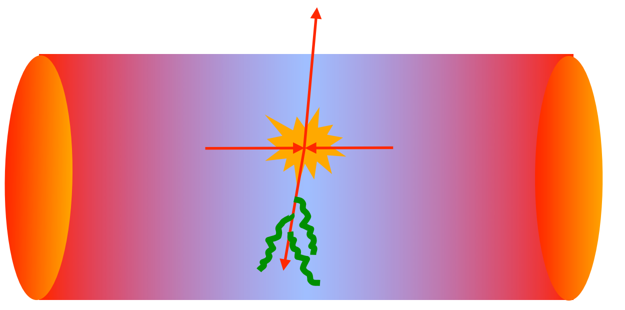


STAR arXiv:0912.1871



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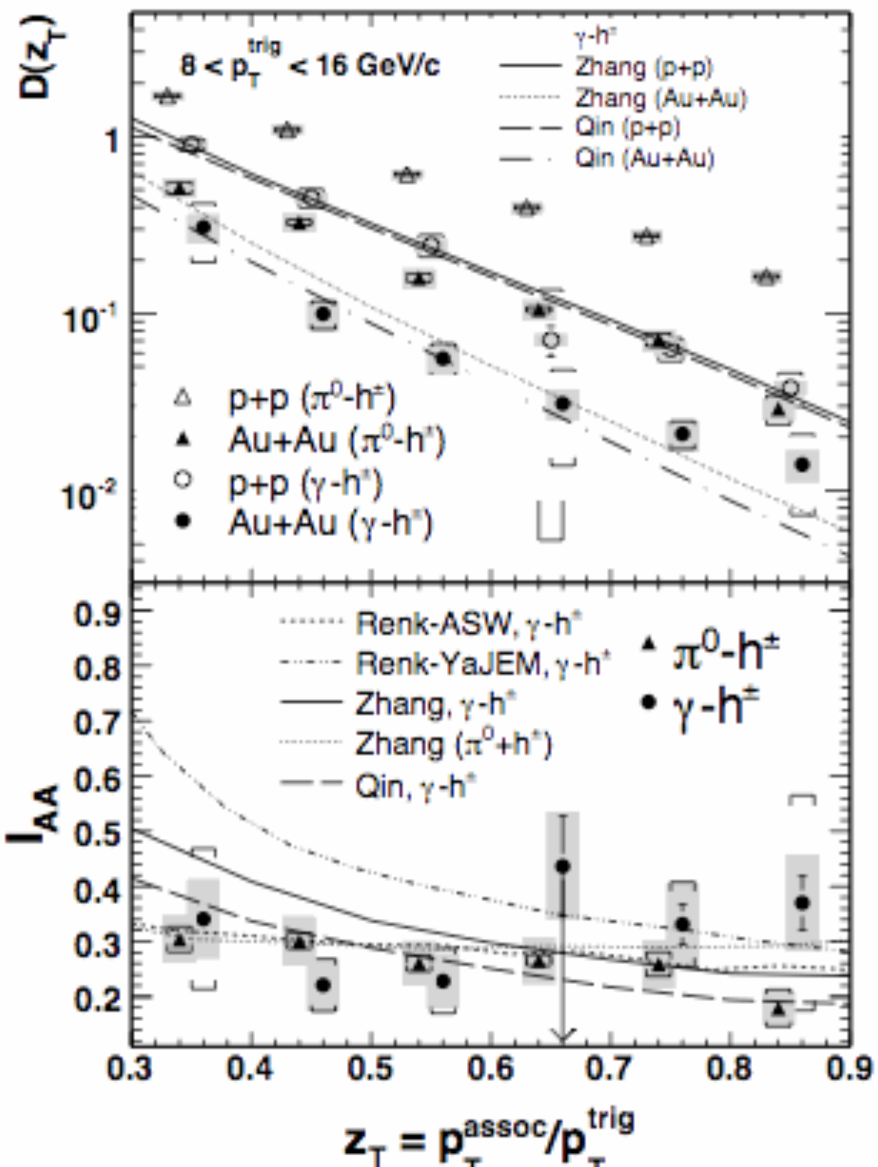

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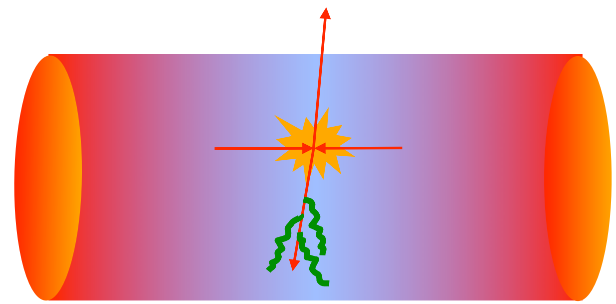
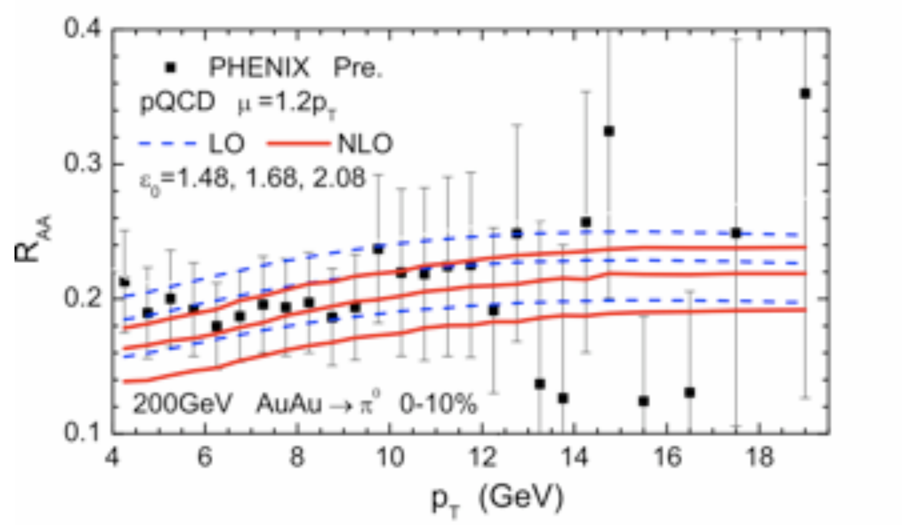


no significant difference between π^0 & γ triggered away sides

constraining energy loss

arXiv:0912.1871, arXiv:1002.1077, Zhang et al

constraining energy loss



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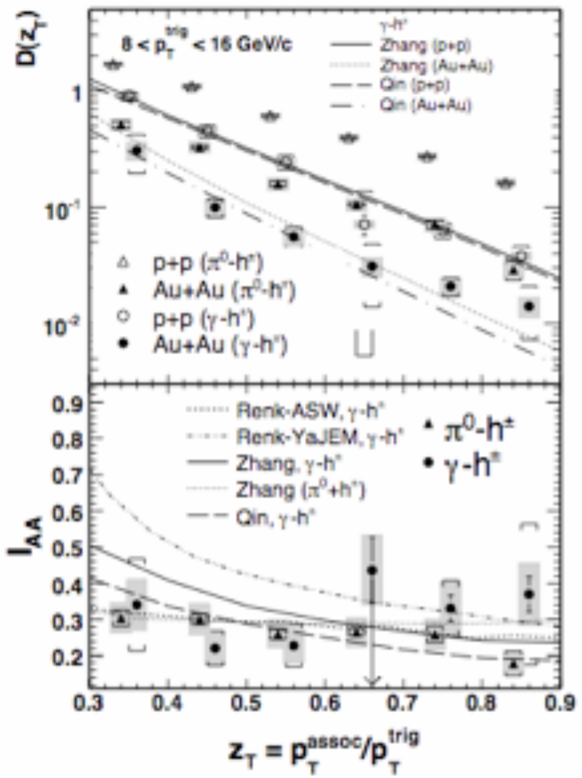

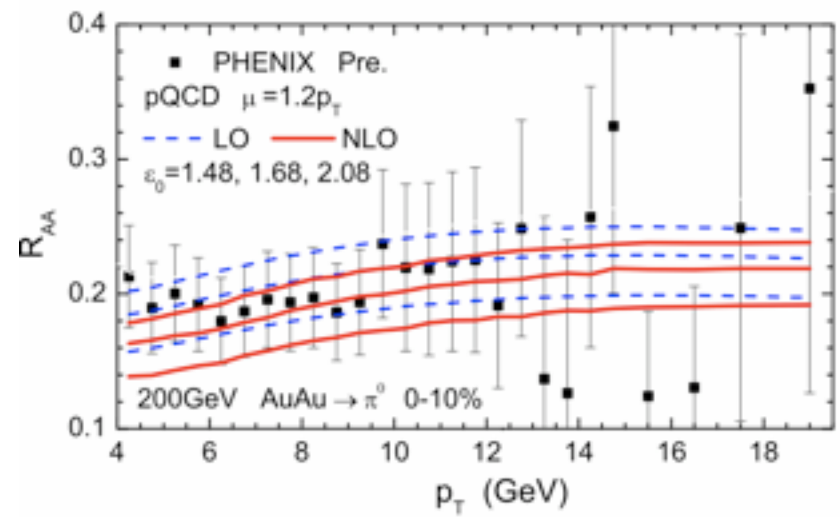

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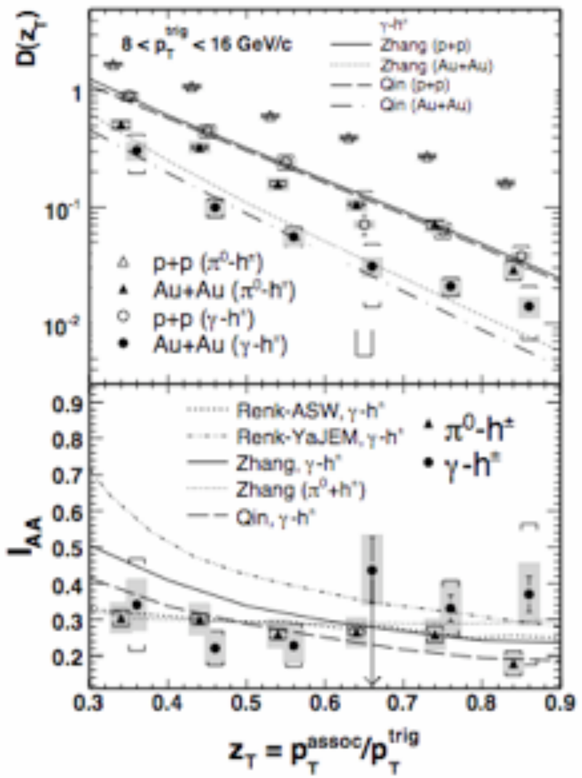

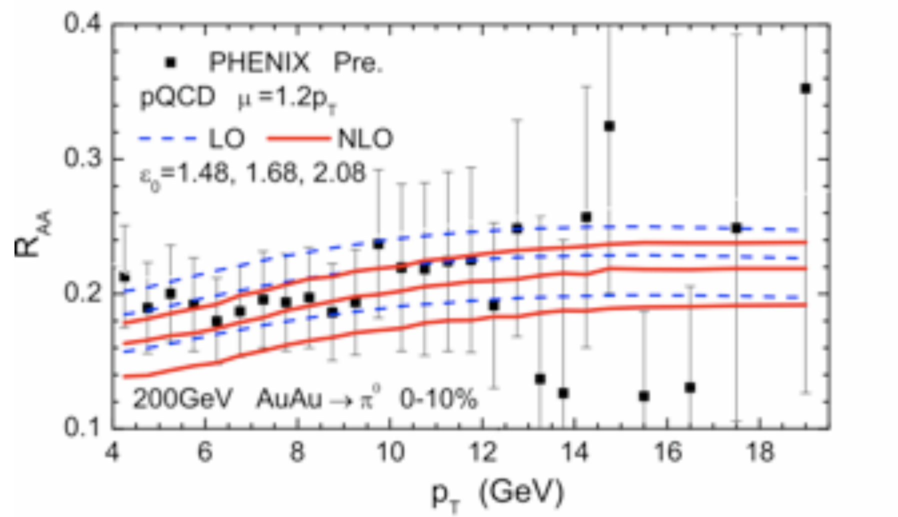

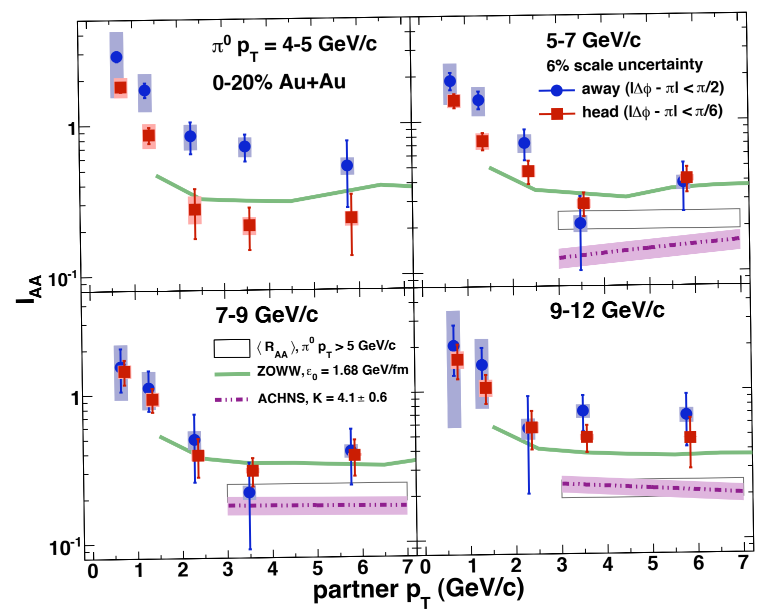

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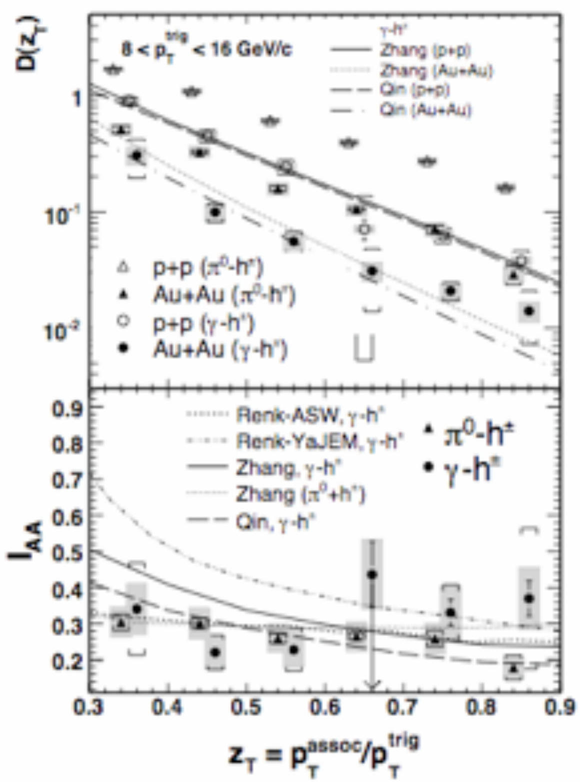

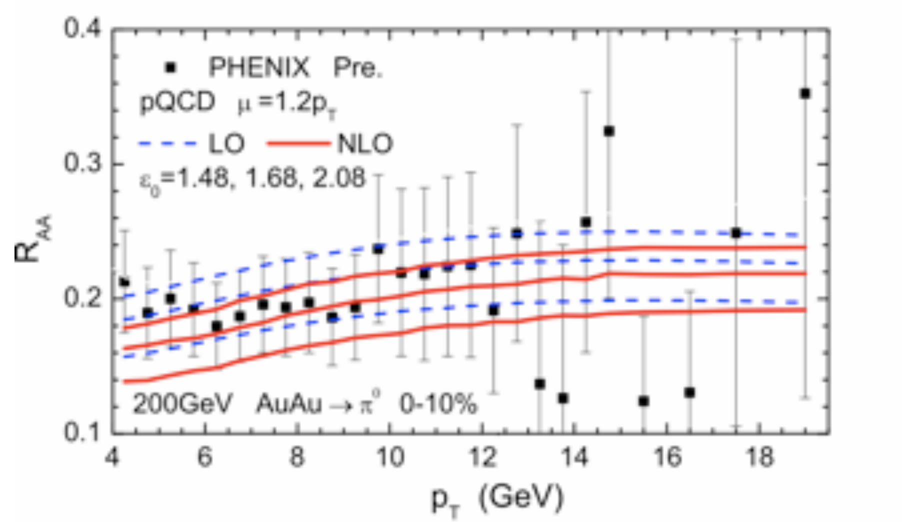

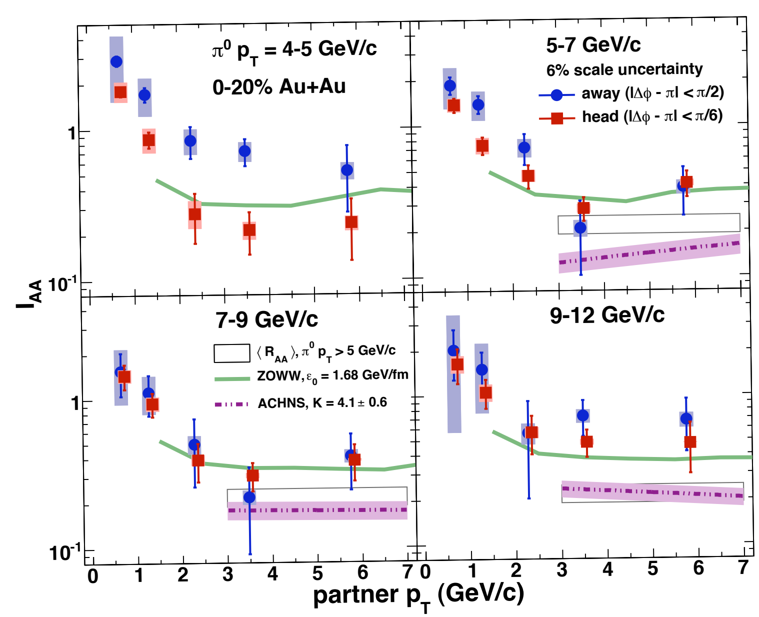

- ZOWW with ε_0=1.68

arXiv:0912.1871, arXiv:1002.1077, Zhang et al

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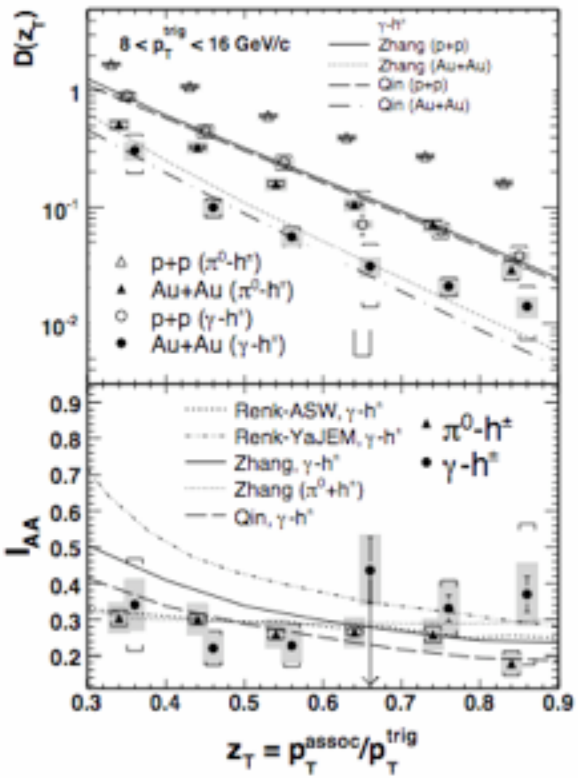
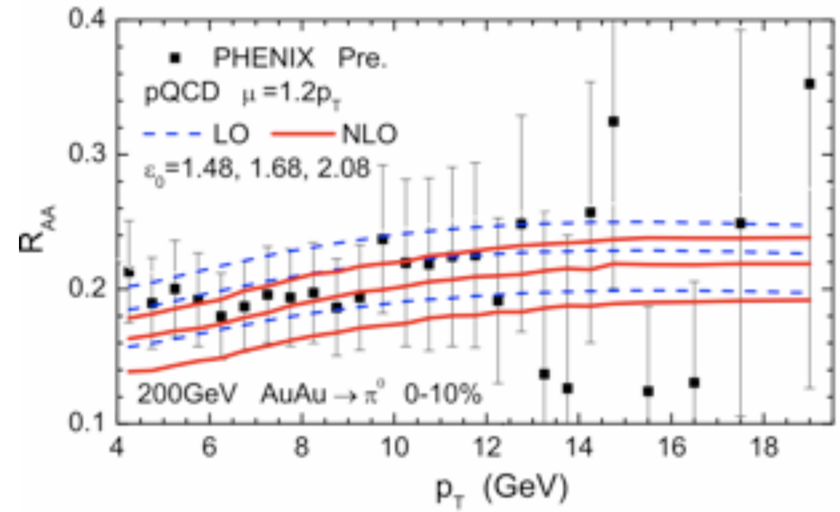
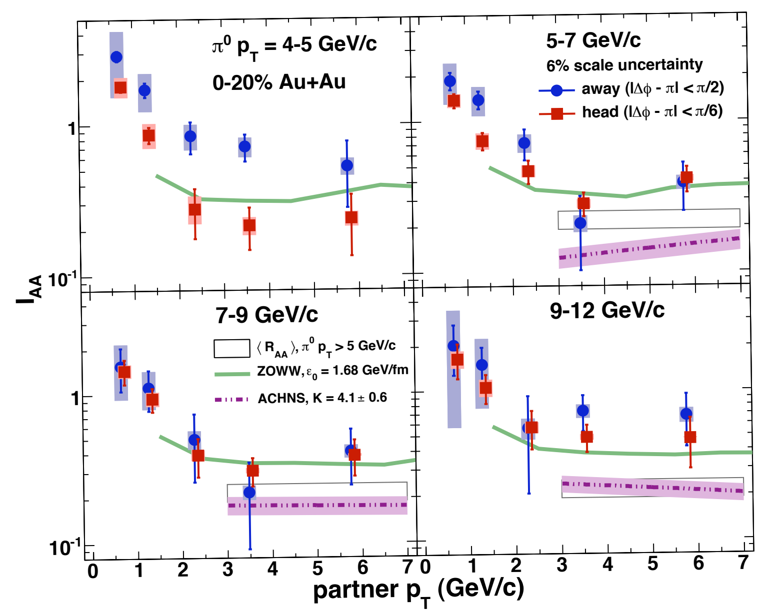




- ZOWW with ε_0=1.68

uses hard sphere geometry rather than hydro medium



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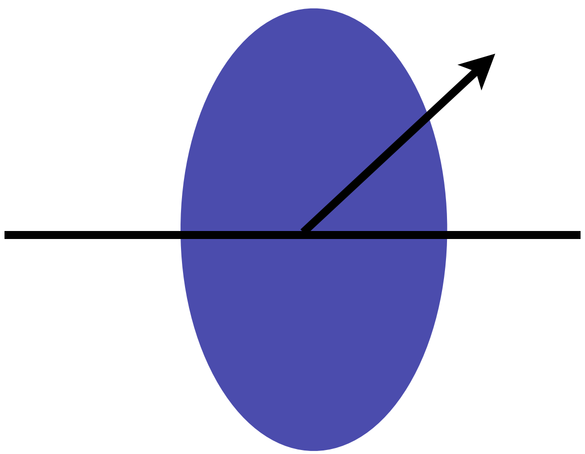
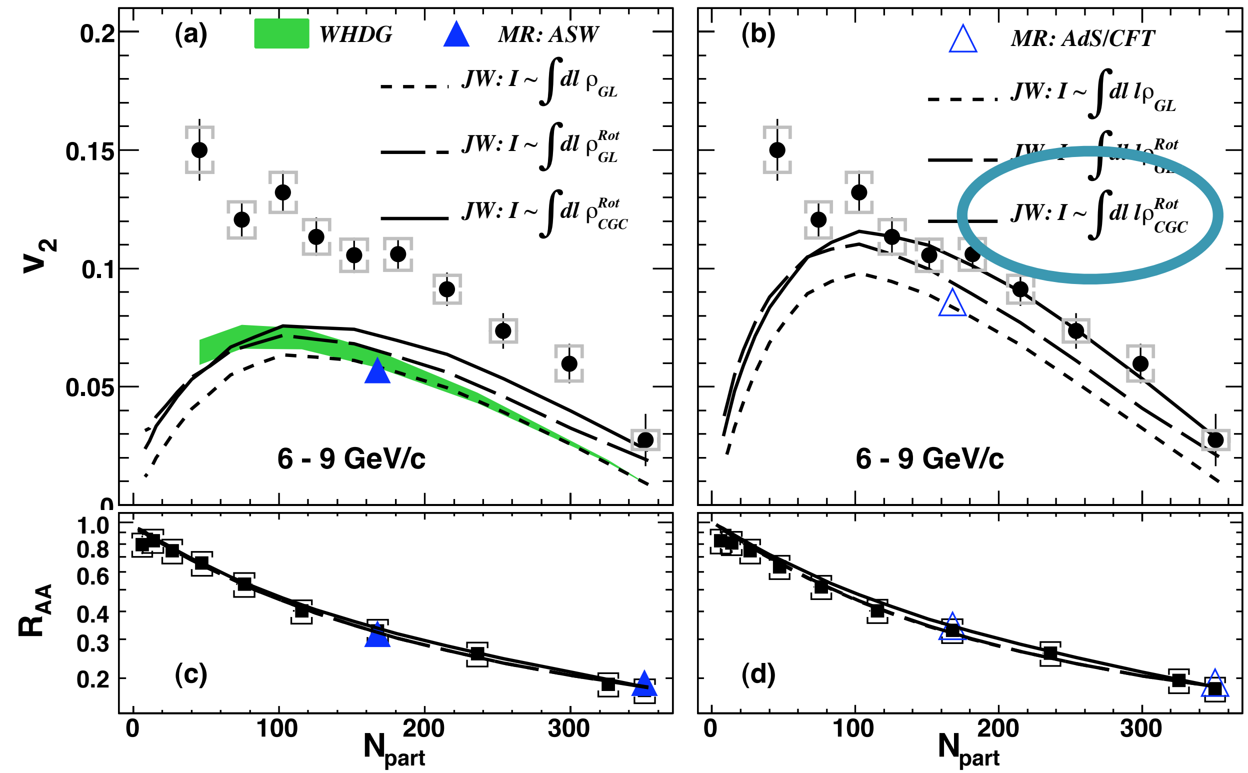
reaction plane: a closer look





points to very strong path length dependence

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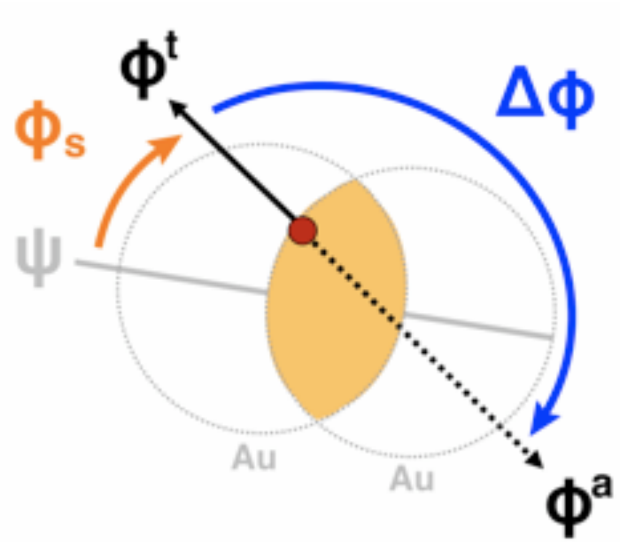
same message from I_{AA}



energy loss calculation from
Renk in 2 hydro codes (Nokana
& Bass and Eskola et al.)

PHENIX 1010.1521

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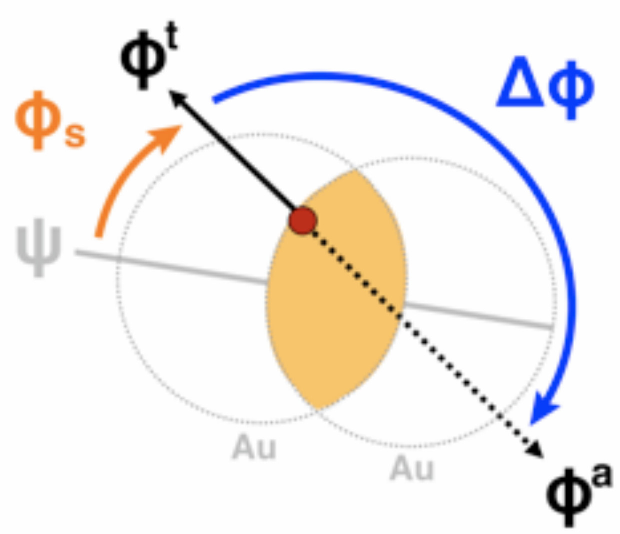

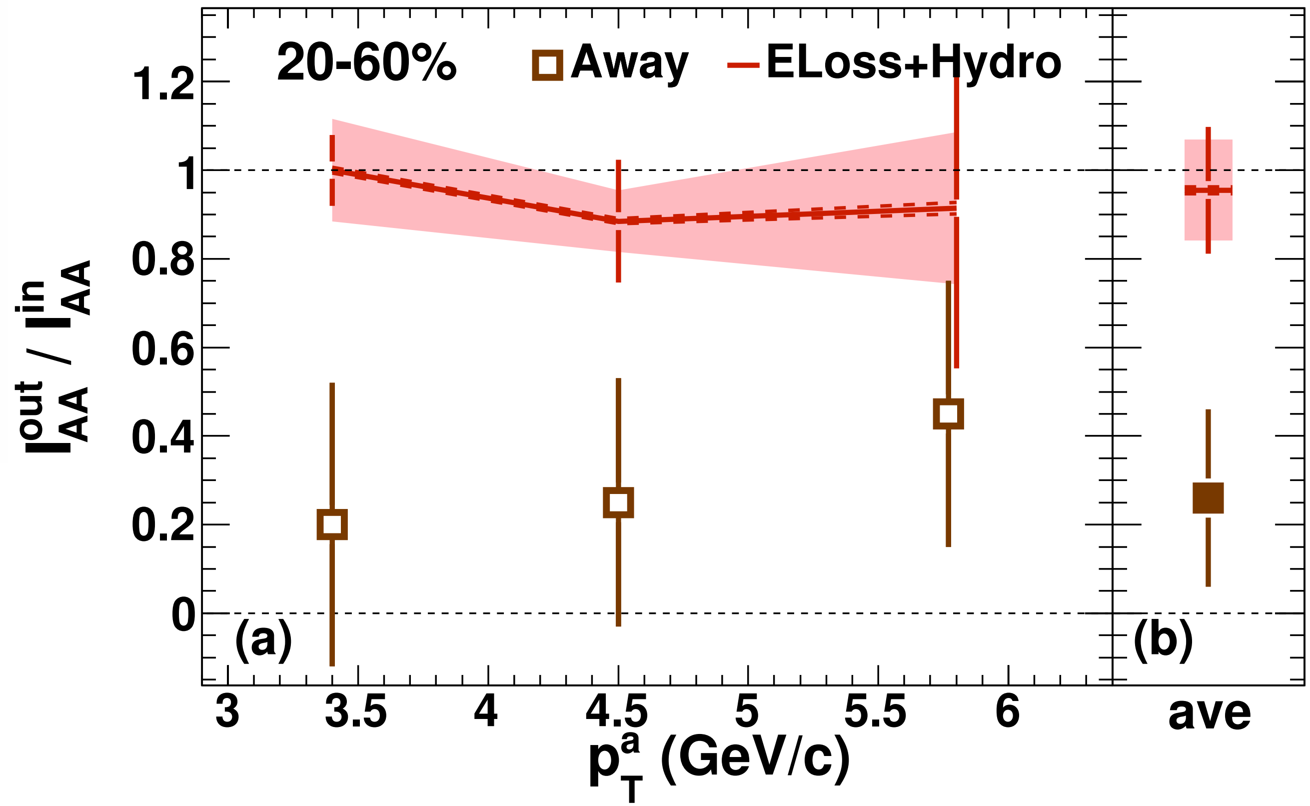

energy loss calculation from Renk in 2 hydro codes (Nokana & Bass and Eskola et al.)

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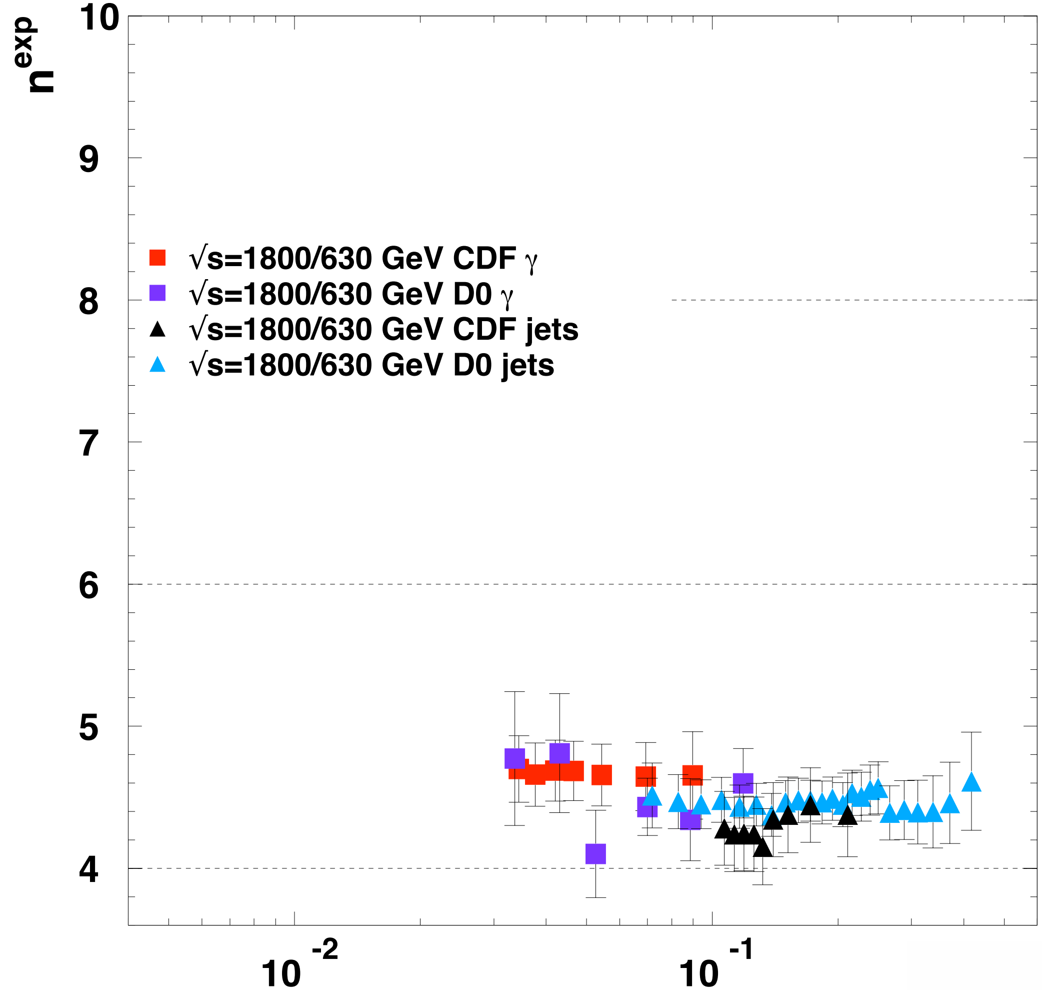
details matter!

- a model that successfully describes the π^0 results, including, reaction plane dependence hasn't been found yet
- reaction plane data has proven a challenge to models
- challenge to theorists
  - but also to experimentalists
    - what other observables can help point in the right direction?

direct hadron production?

$$n_{eff}(x_T) = \frac{log\left(yield\left(x_T, \sqrt{s_a}\right)/yield(x_T, \sqrt{s_b})\right)}{log\left(\sqrt{s_b}/\sqrt{s_a}\right)}$$



jets & γs

$$x_T = \frac{2p_T}{\sqrt{s}}$$

arXiv:0911.4604

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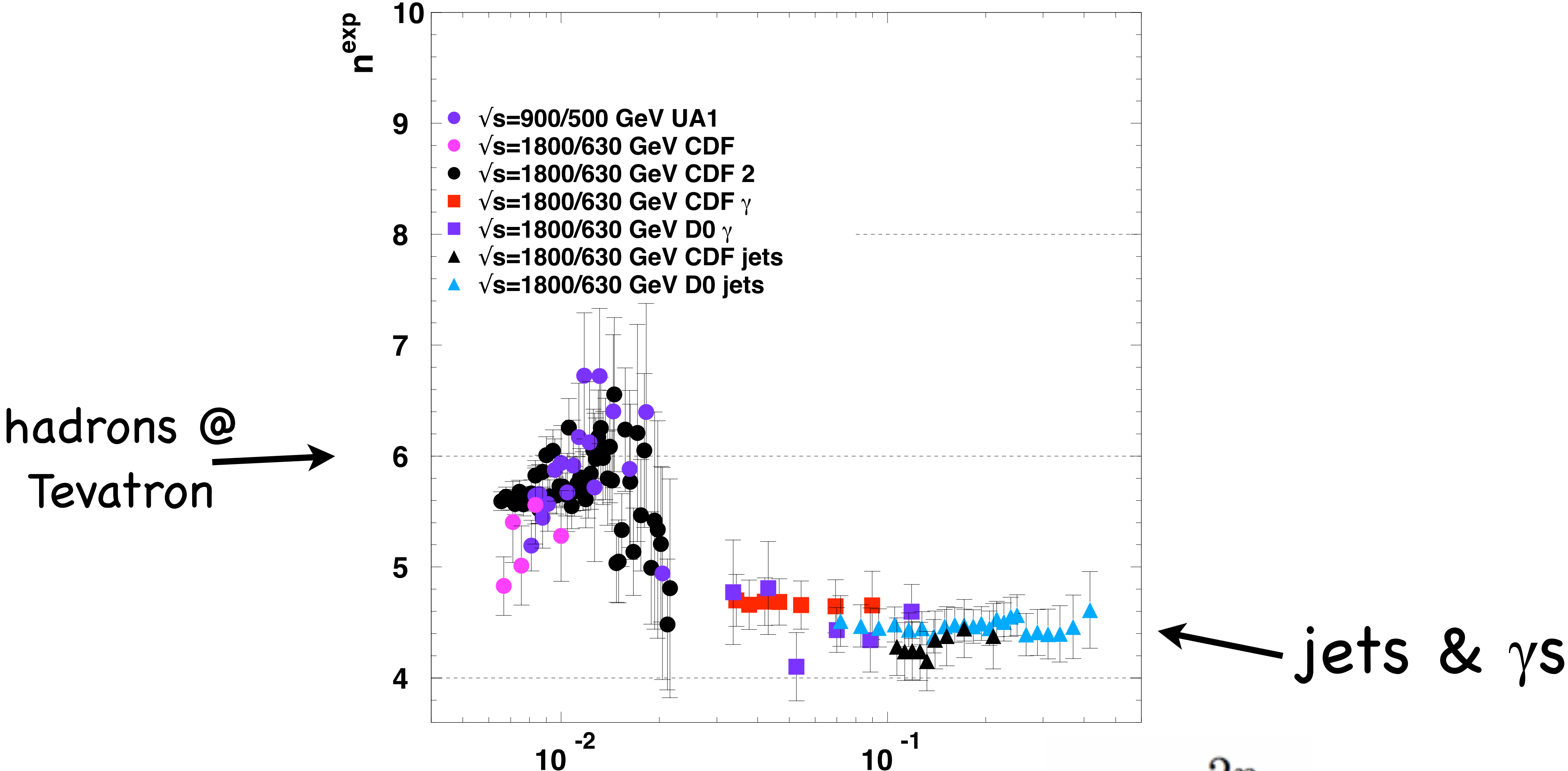

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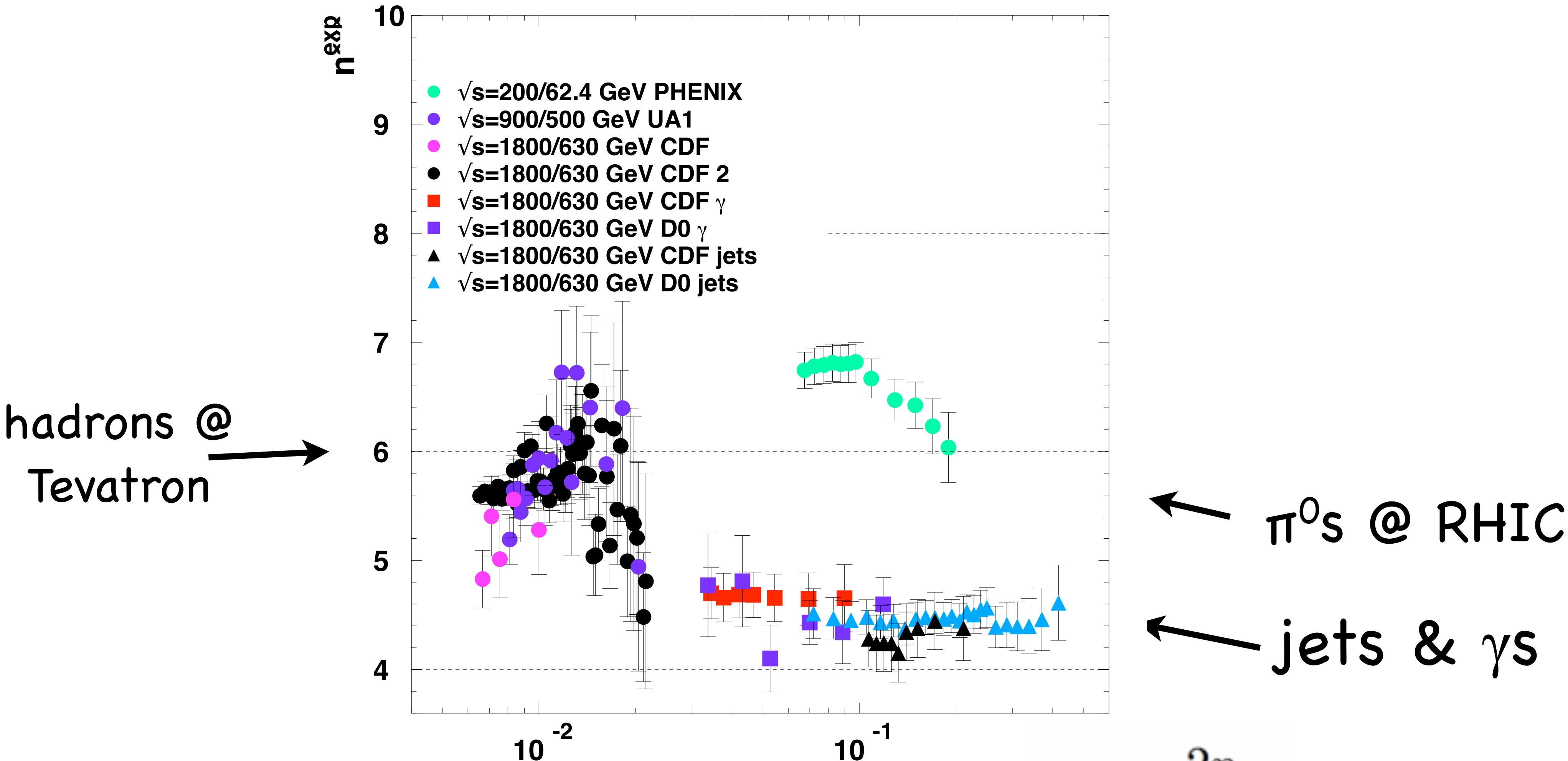

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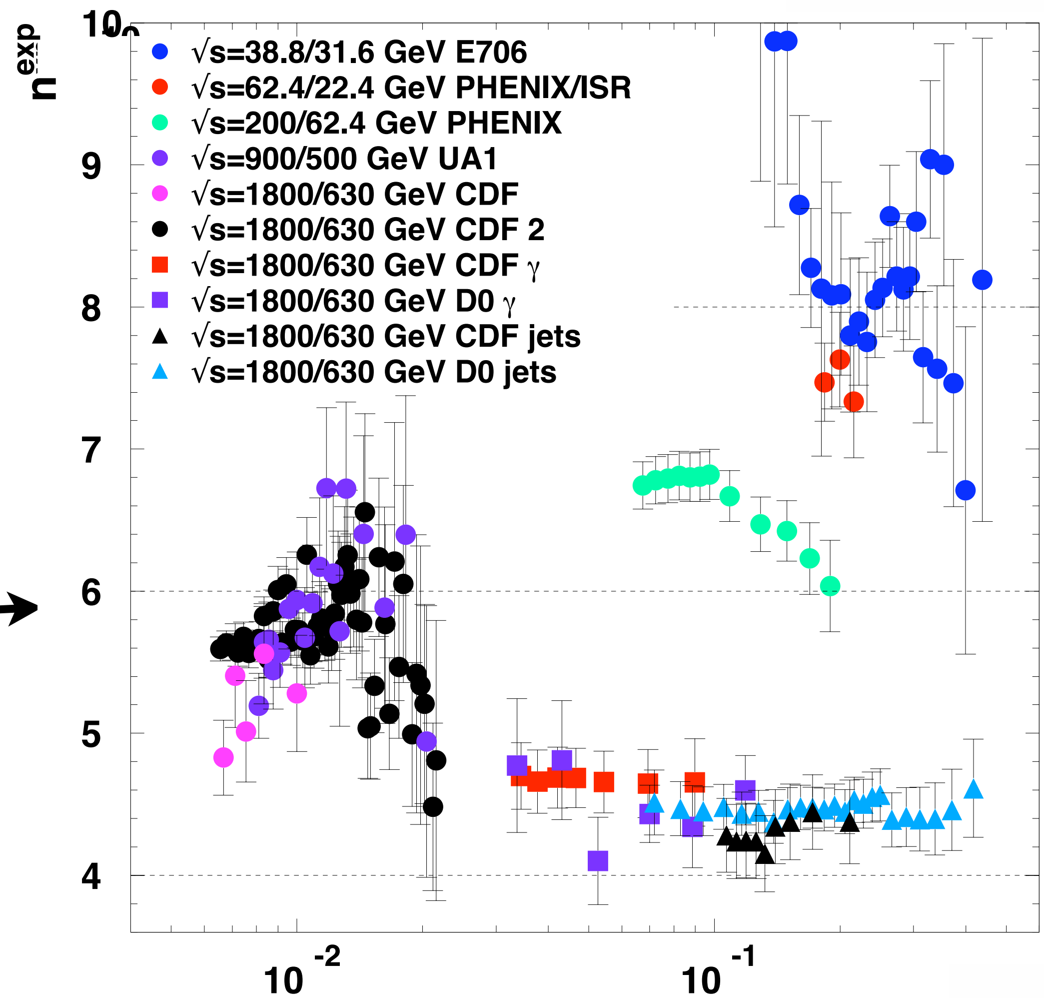
hadrons @ Tevatron



π^0s @ RHIC/E706

π^0s @ RHIC

jets & γs

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arXiv:0911.4604

well, what do you expect?

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$\Delta \equiv n^{exp} - n^{NLO}$

arXiv:0911.4604

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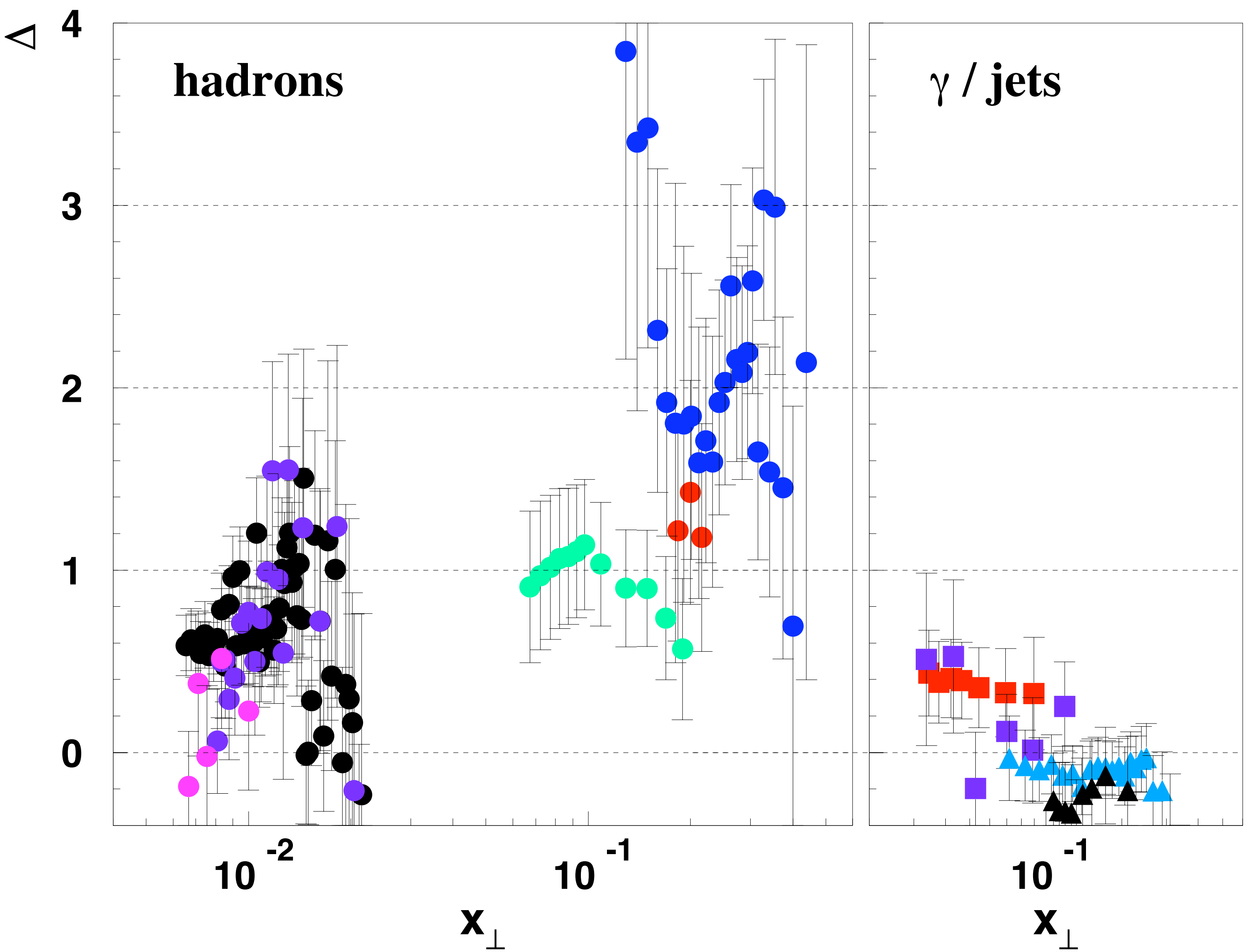

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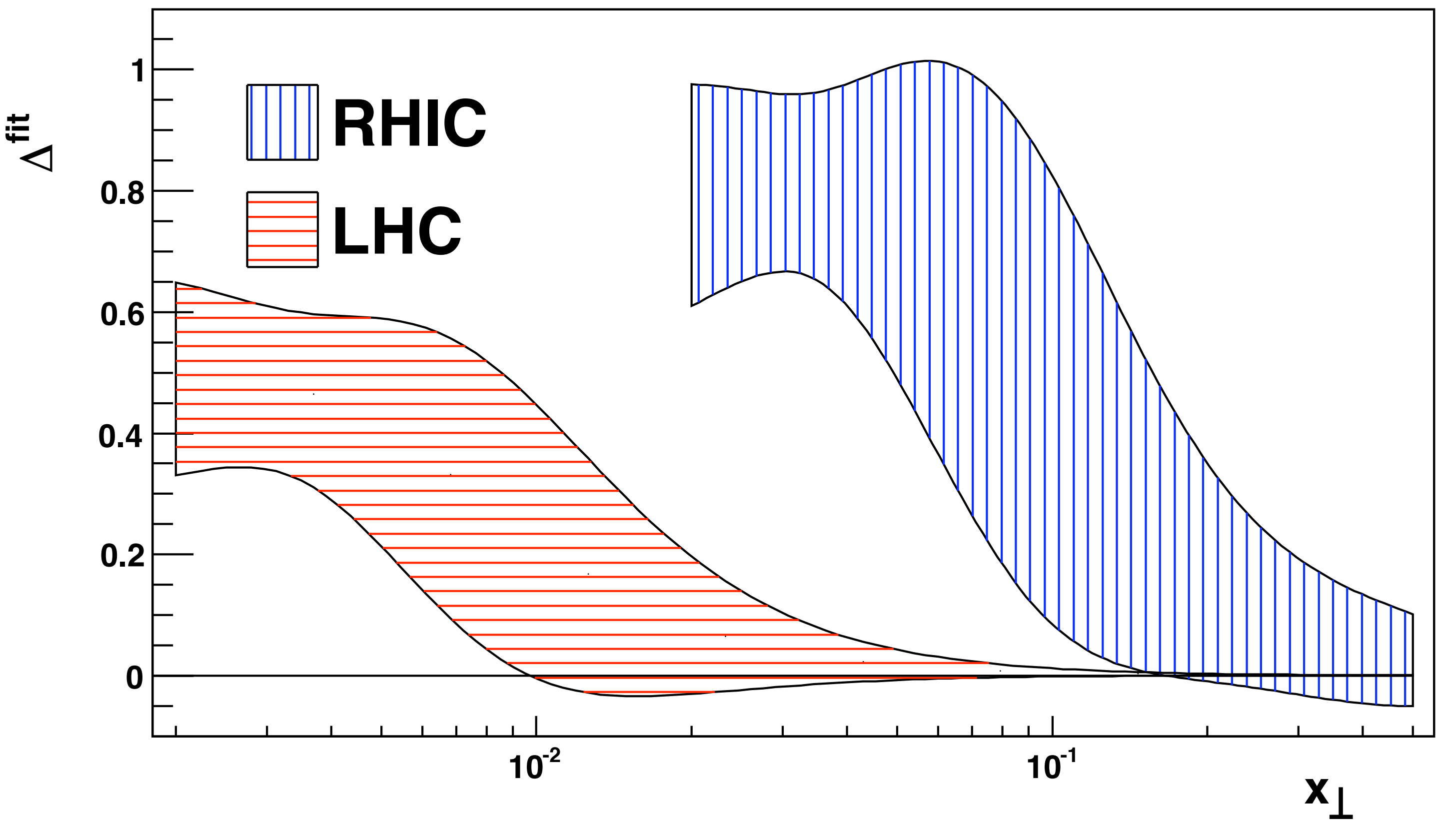
prediction for 500GeV p+p data



RHIC: 500GeV/200GeV
LHC: 7TeV/1.8TeV

Arleo, Brodsky, Hwang, AMS: PRL105 062002

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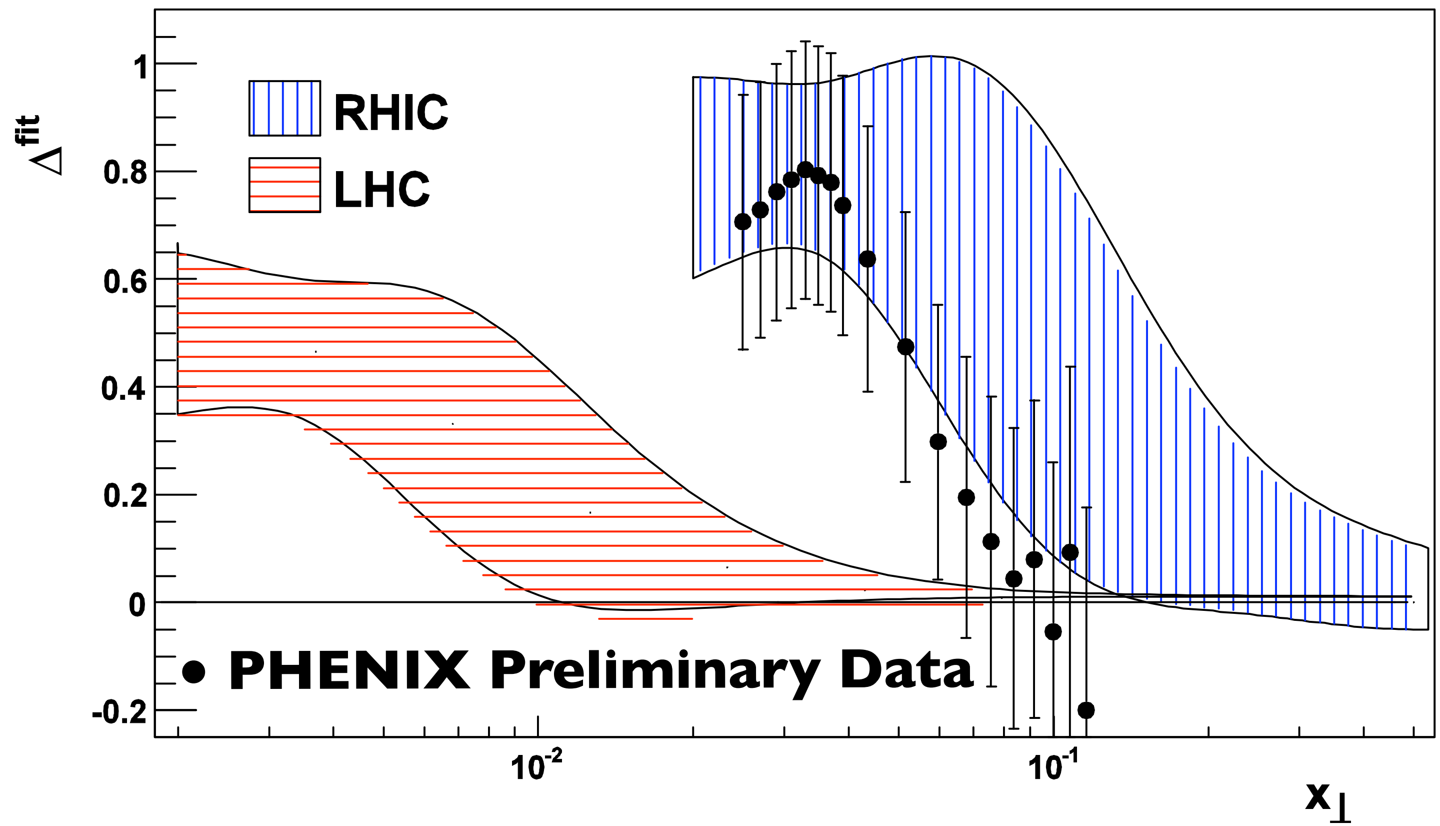

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momentum imbalance between photon & jet large
nuclear effects: small

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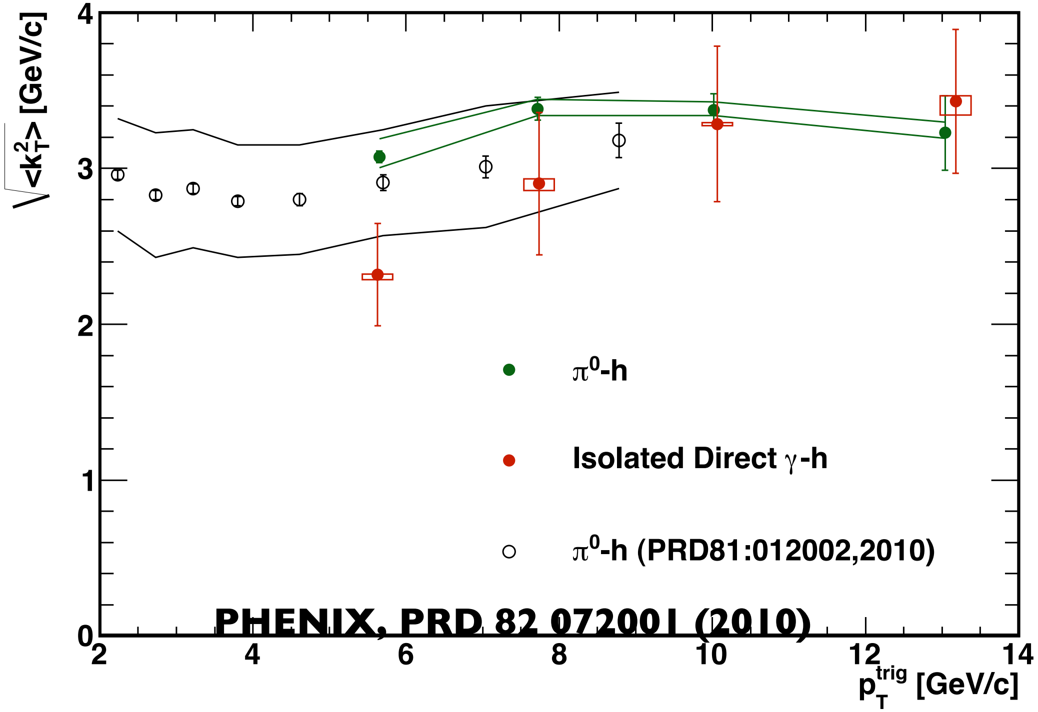

PHENIX, PRD 82 072001 (2010)

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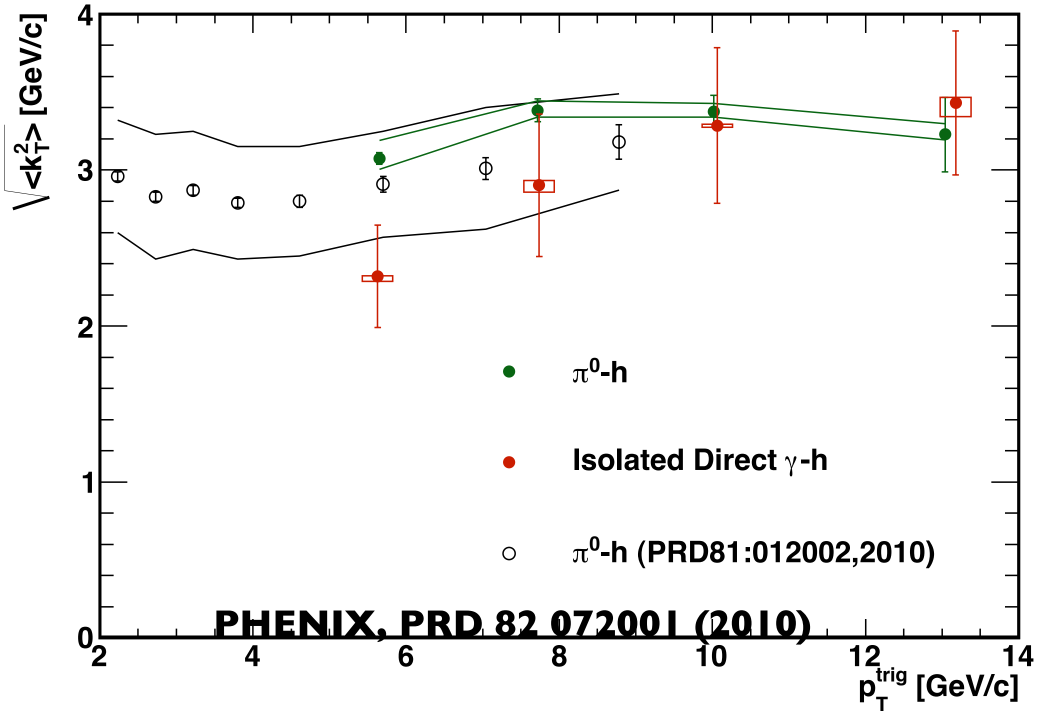

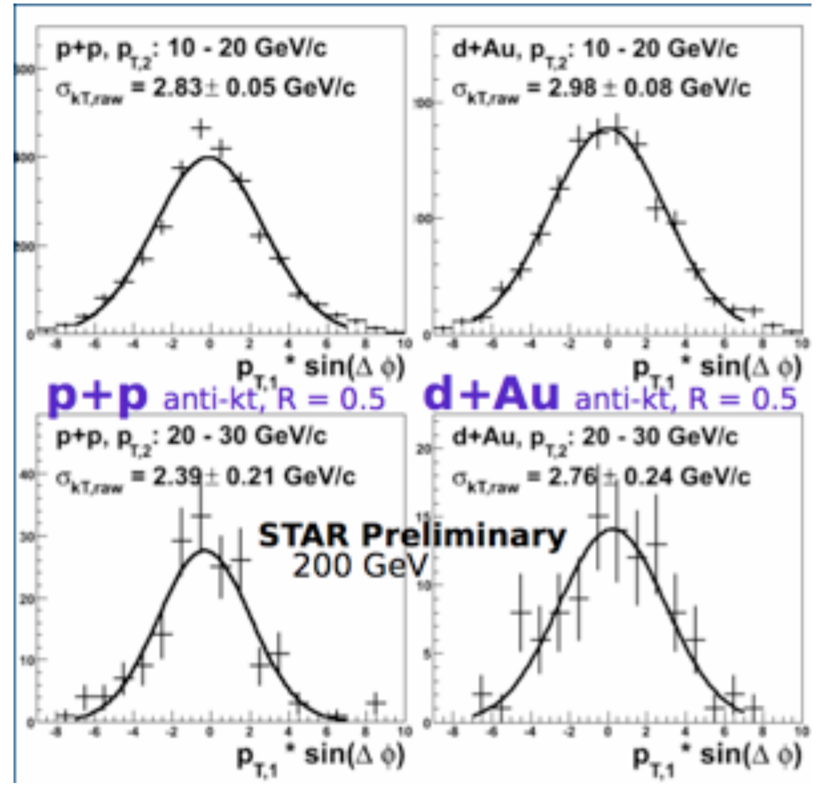

p+p: 2.8±0.1GeV/c
d+Au: 3.0±0.1GeV/c

J. Kapitan HP 2010

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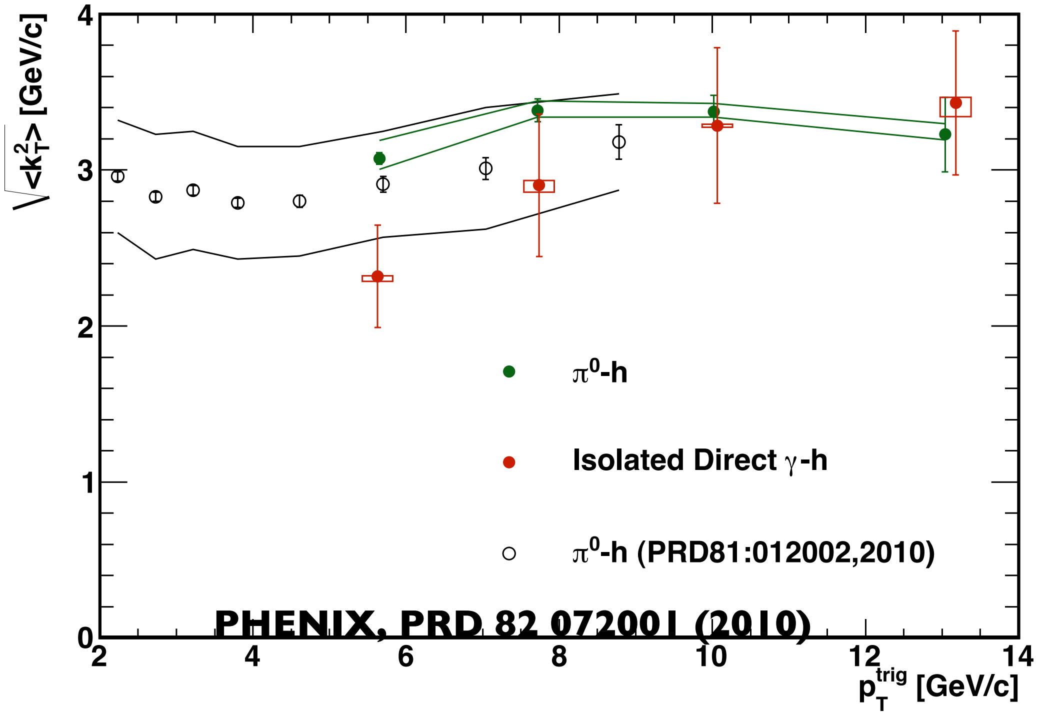

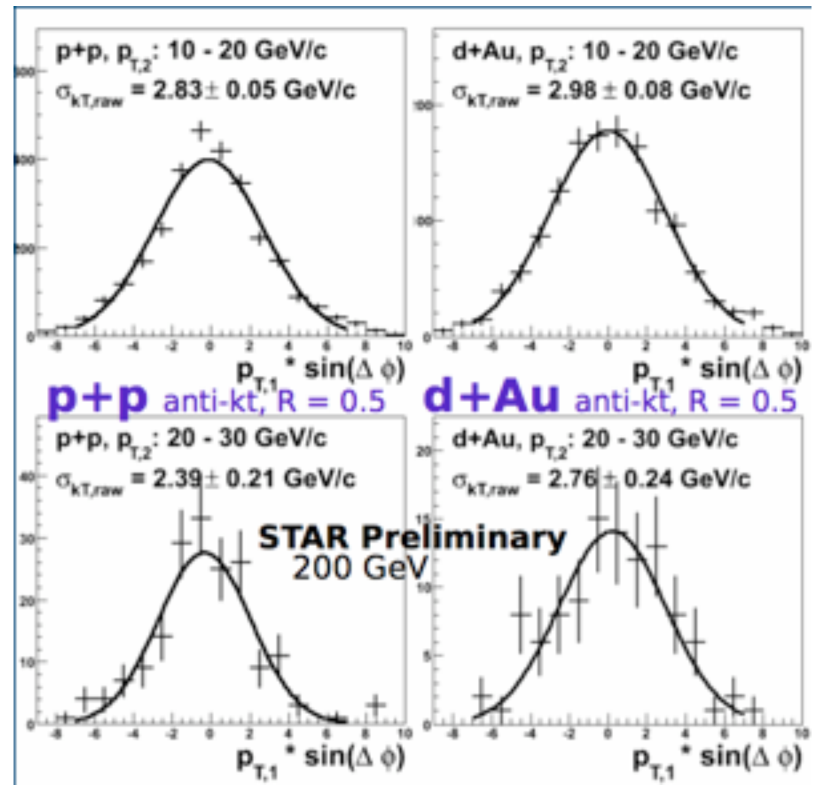

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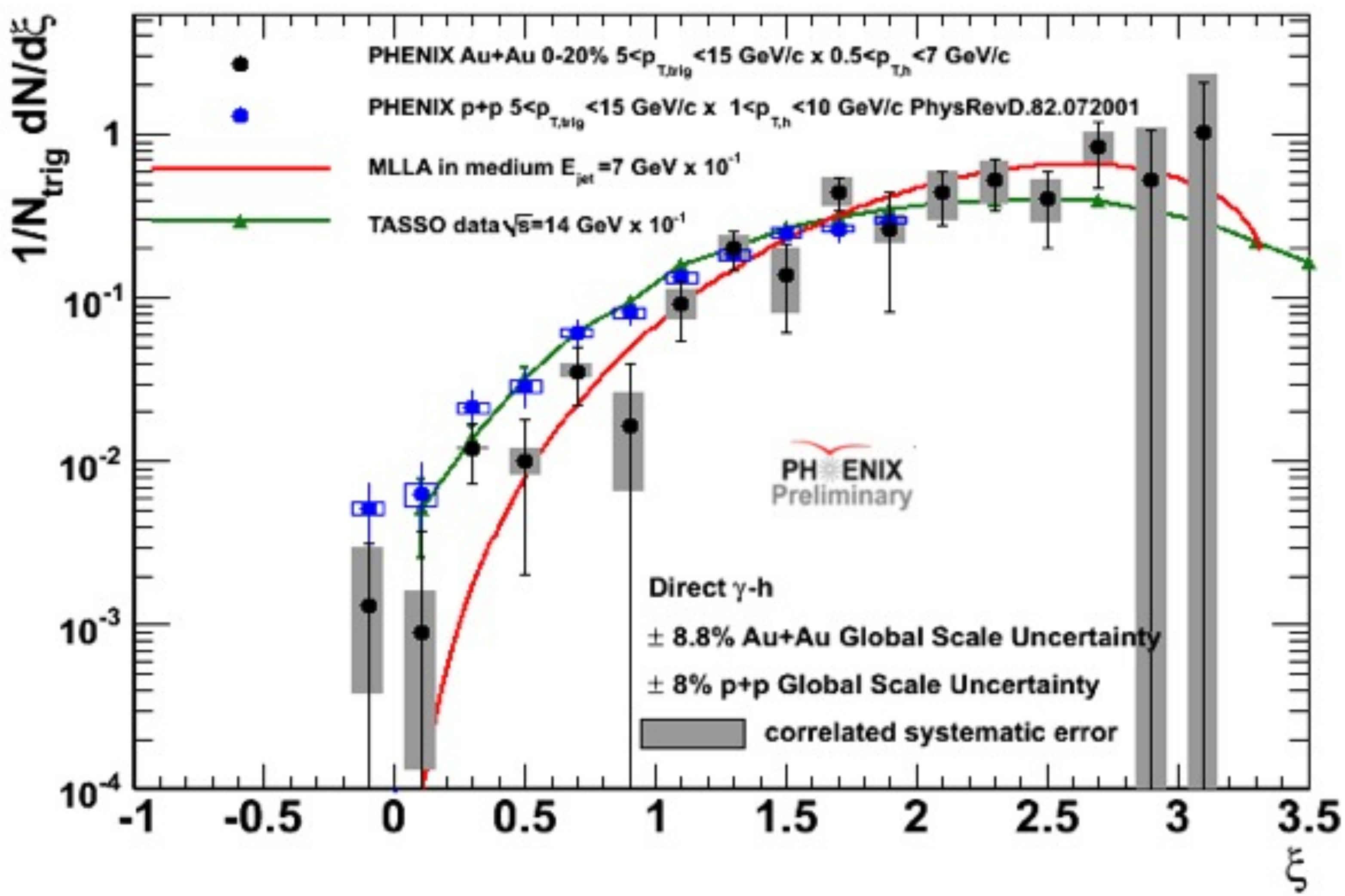
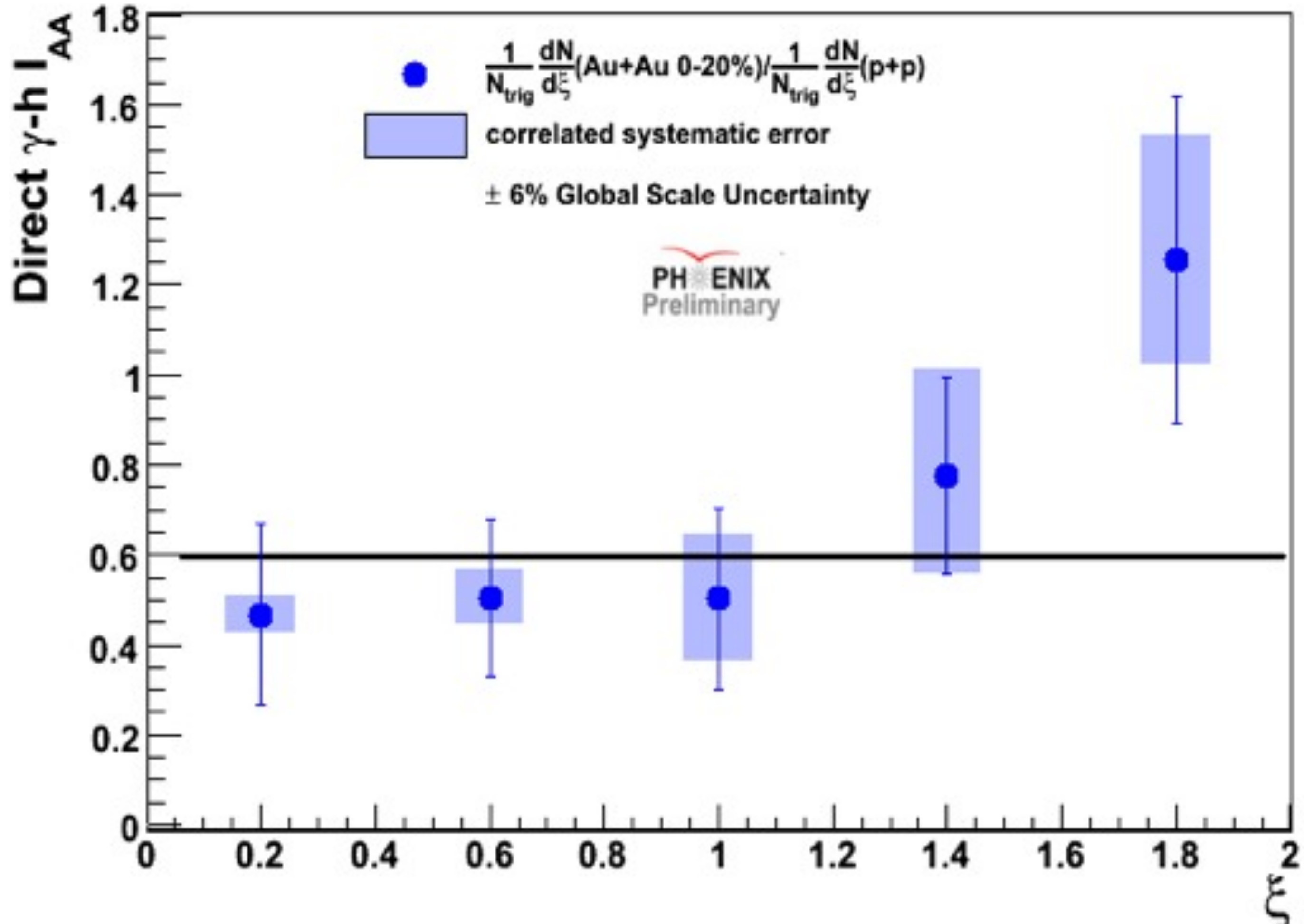
direct photon correlations



M. Connors HP10

modified fragmentation?



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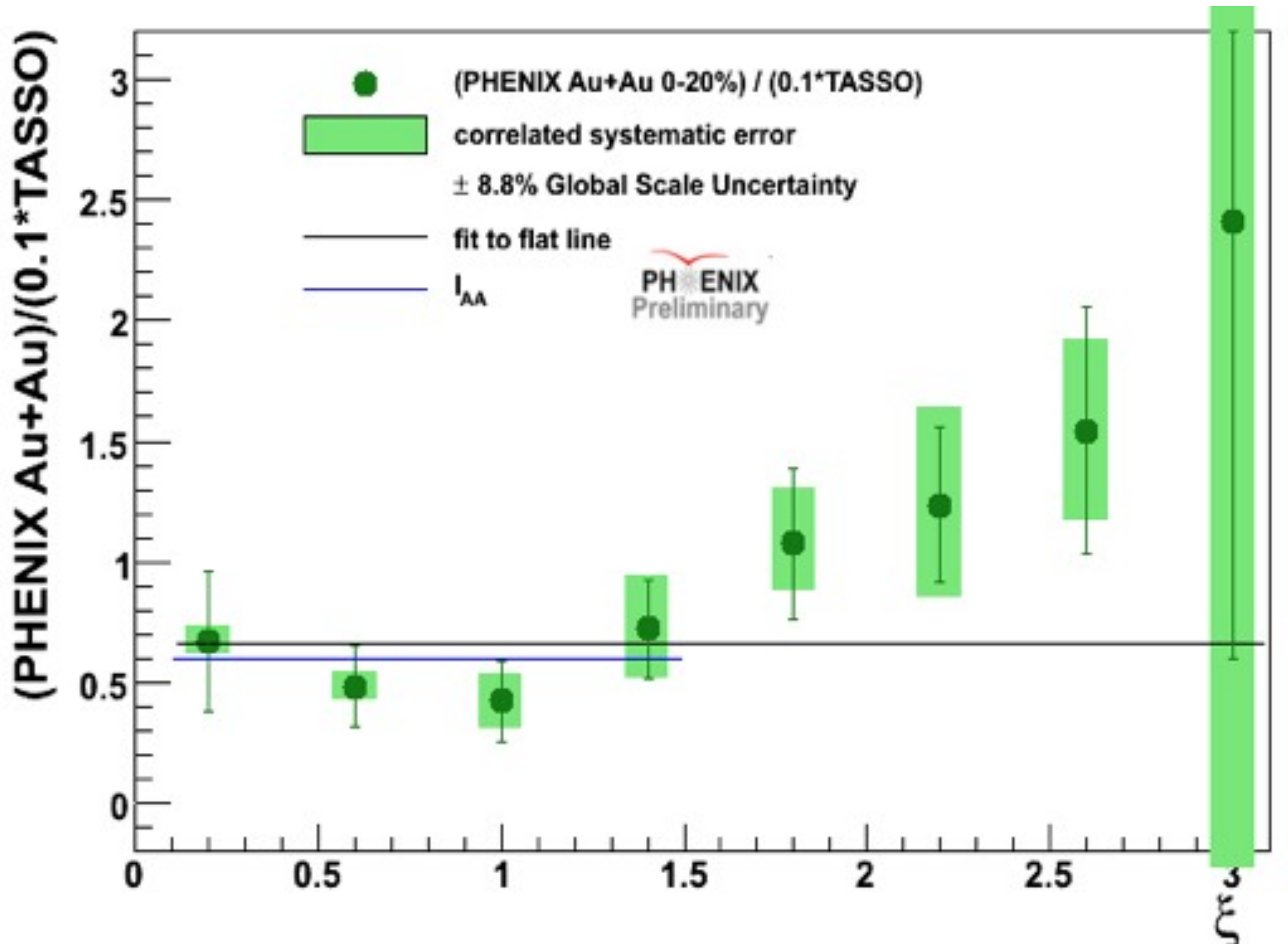
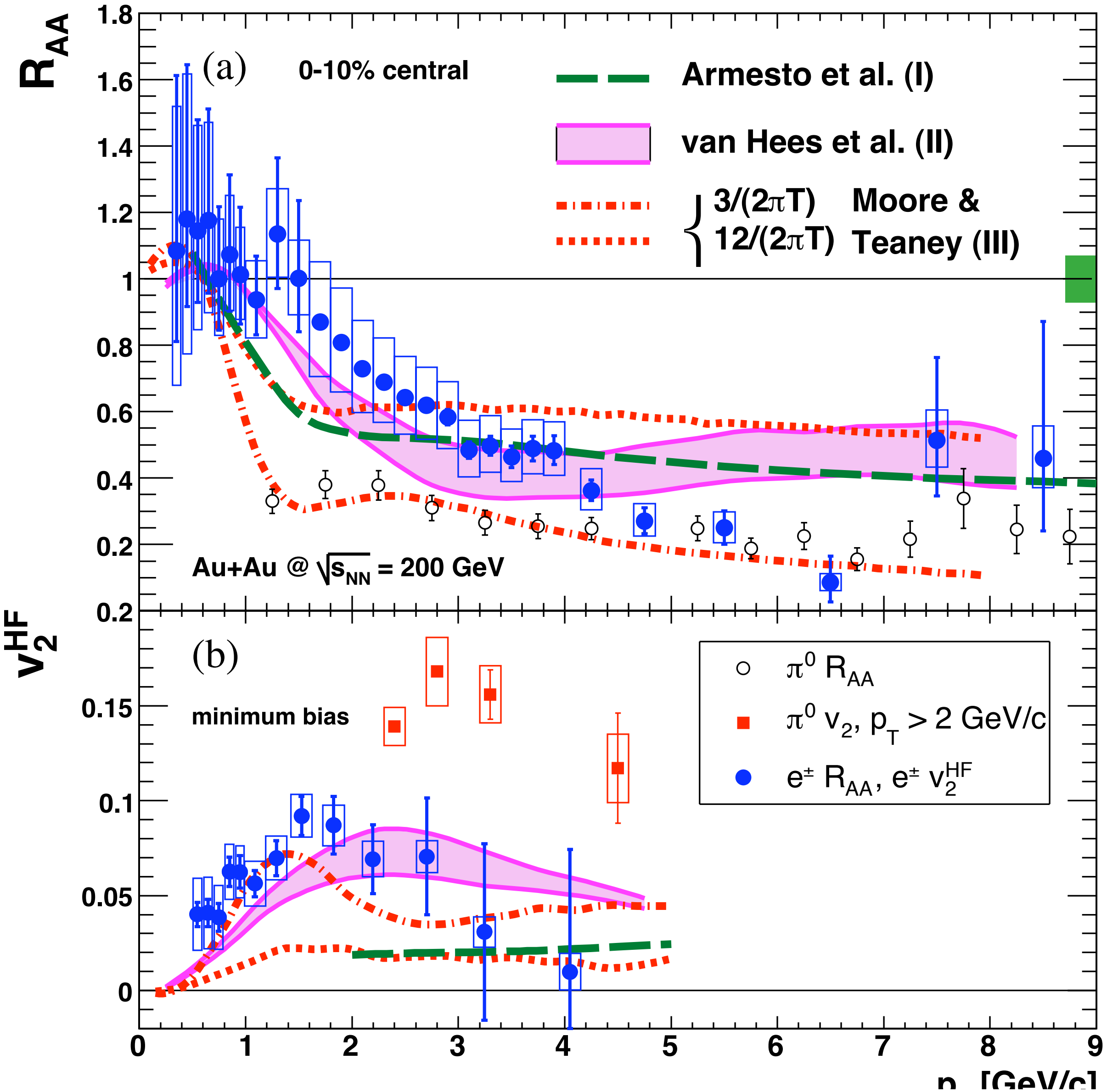


TASSO → higher ξ

heavy flavor

heavy flavor



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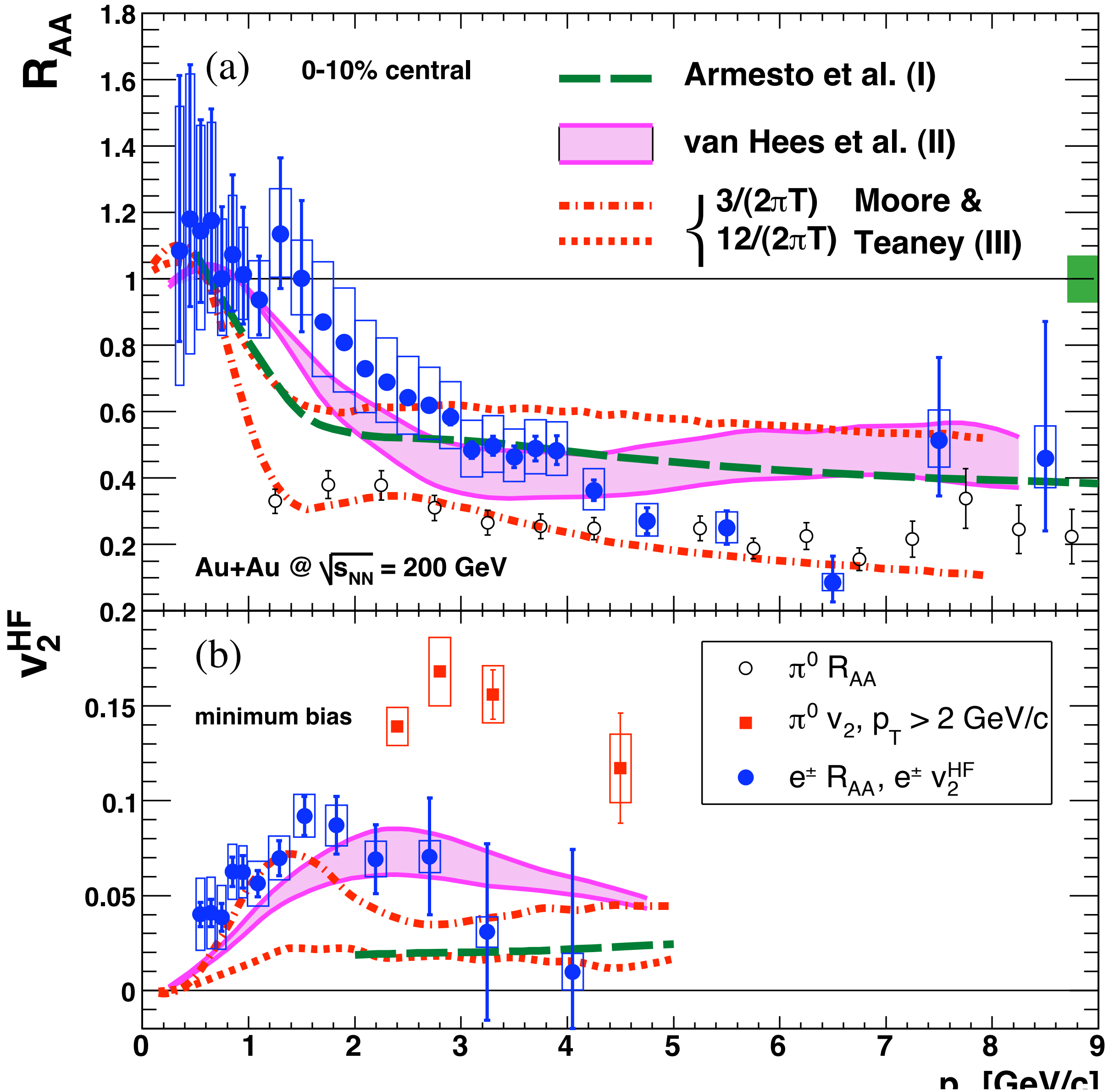

- collectivity and suppression
- not expected from radiative energy loss

charm vs. bottom

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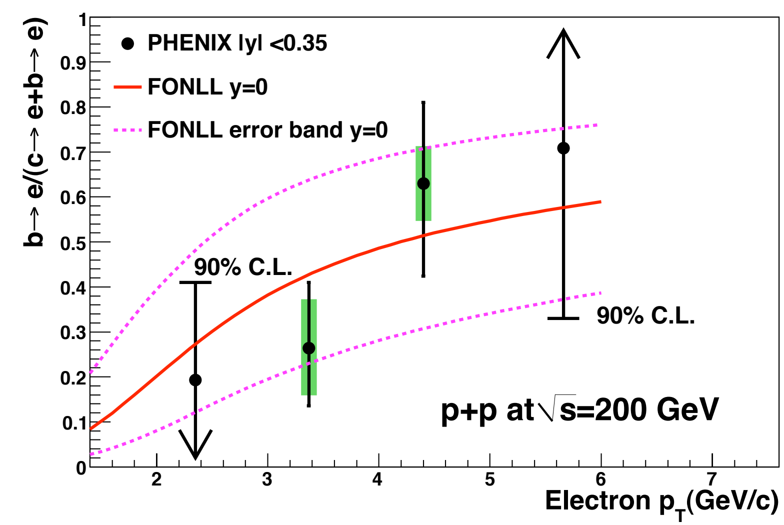
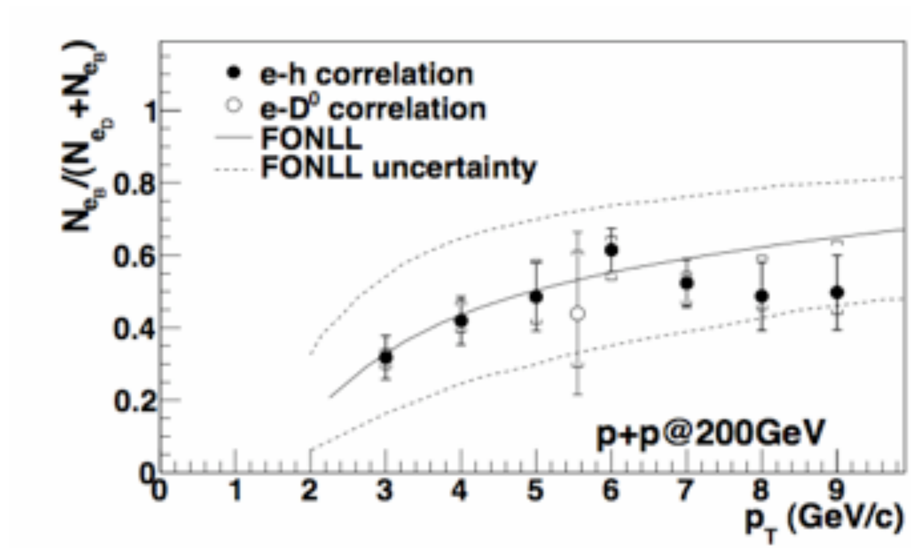
STAR: 1007.1200 [nucl-ex]

charm vs. bottom





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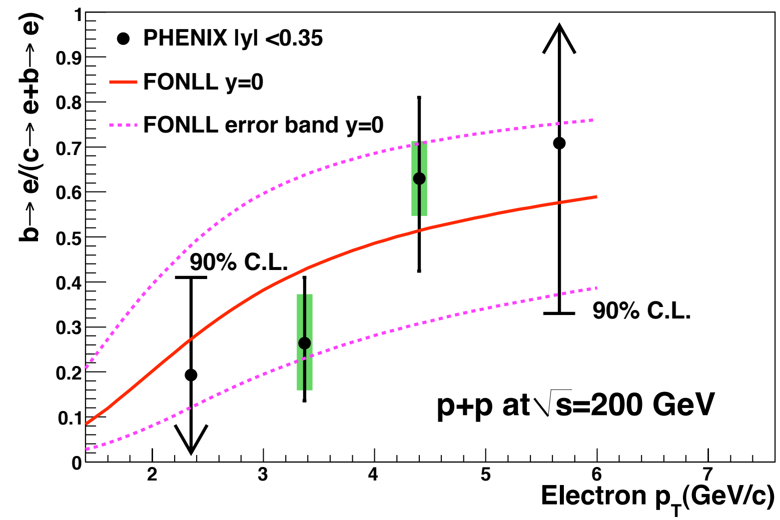
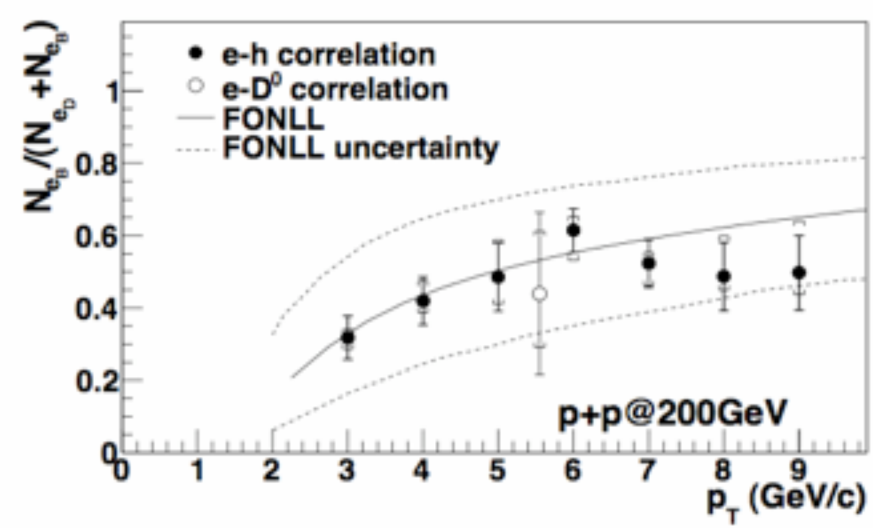
charm vs. bottom

- suppression large even as electrons become dominated by bottom at high p_T
  - well described by FONLL





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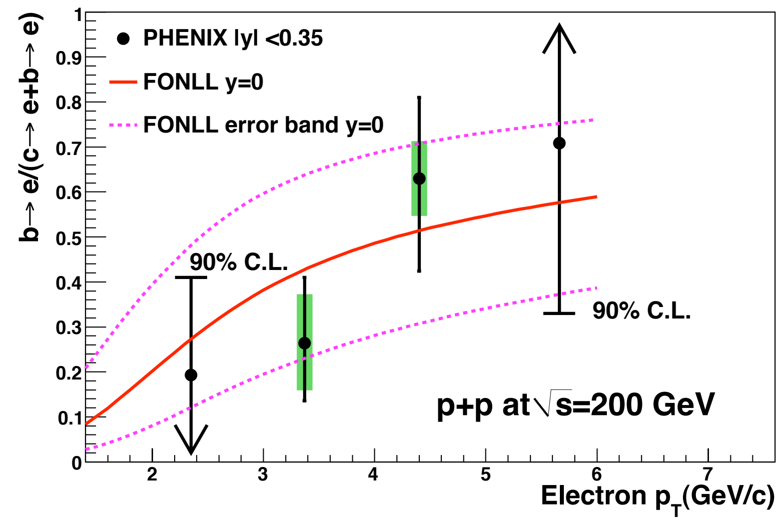
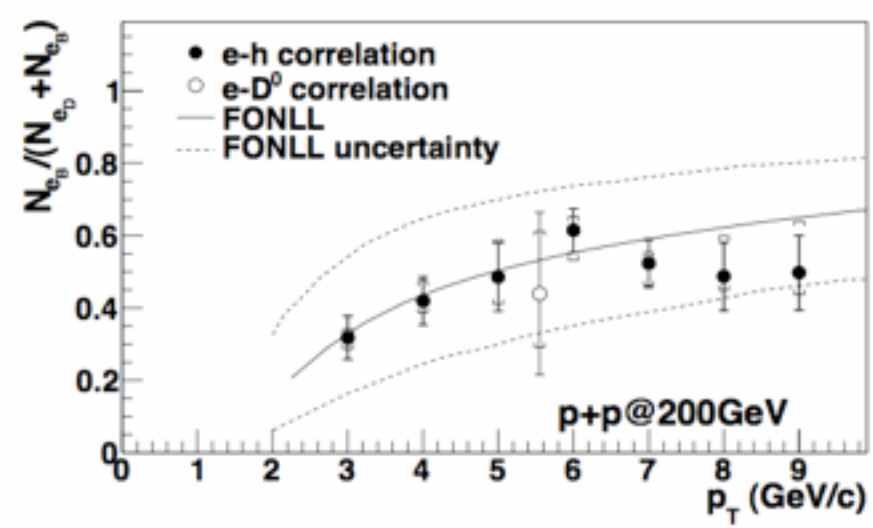
$$R_{AA}^{\rm HF} = (1-r_B)R_{AA}^{e_D} + r_B R_{AA}^{e_B}$$





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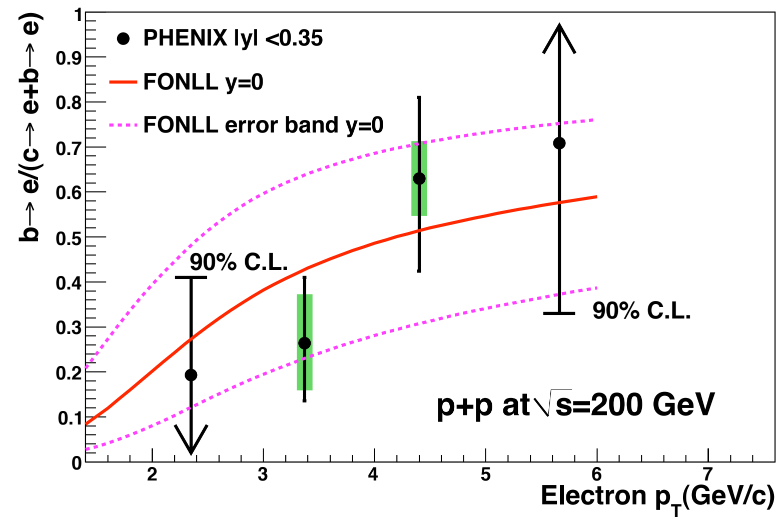

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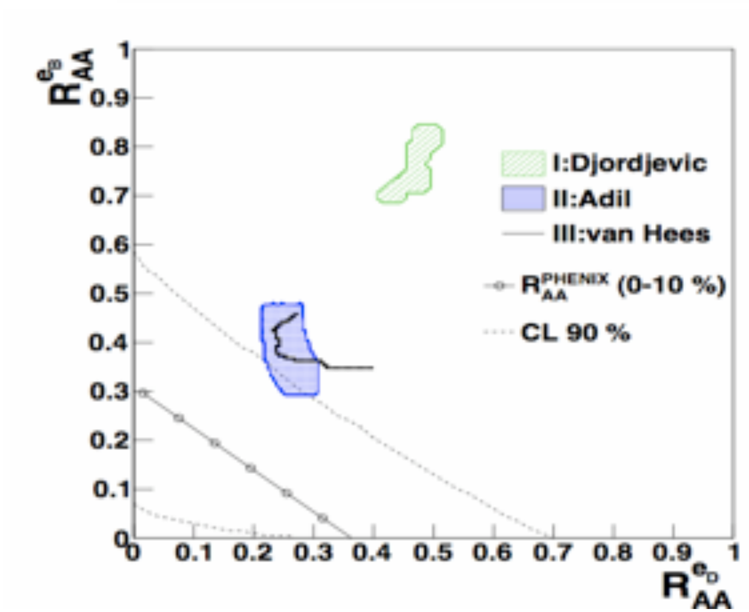

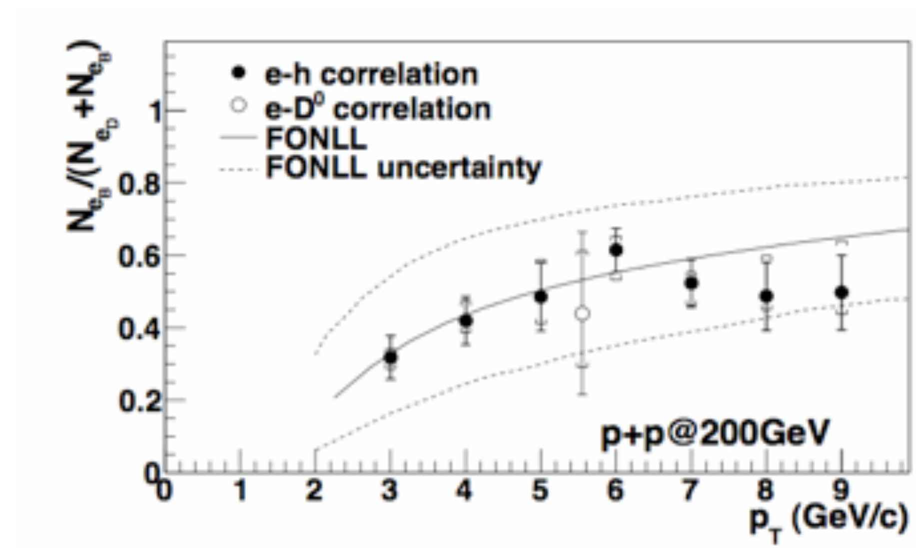

bottom is suppressed!

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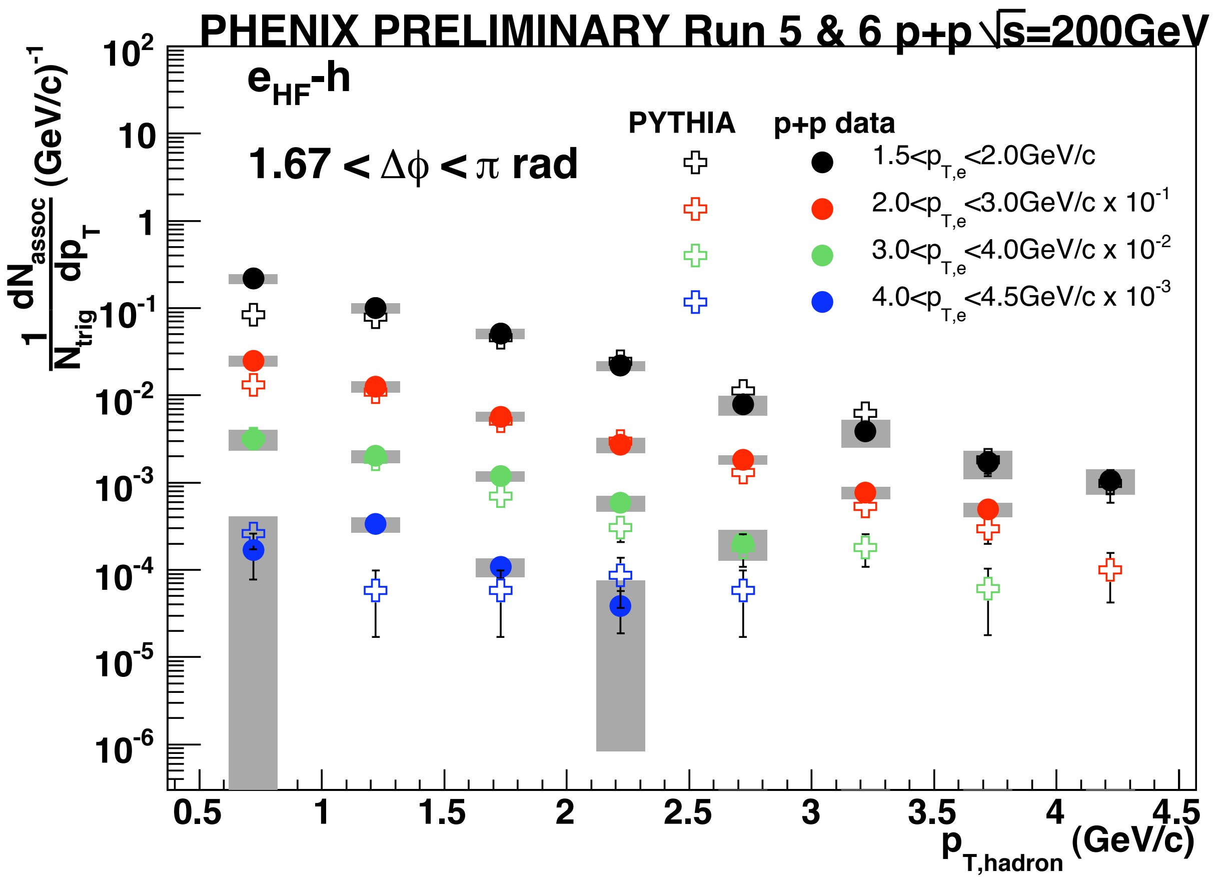
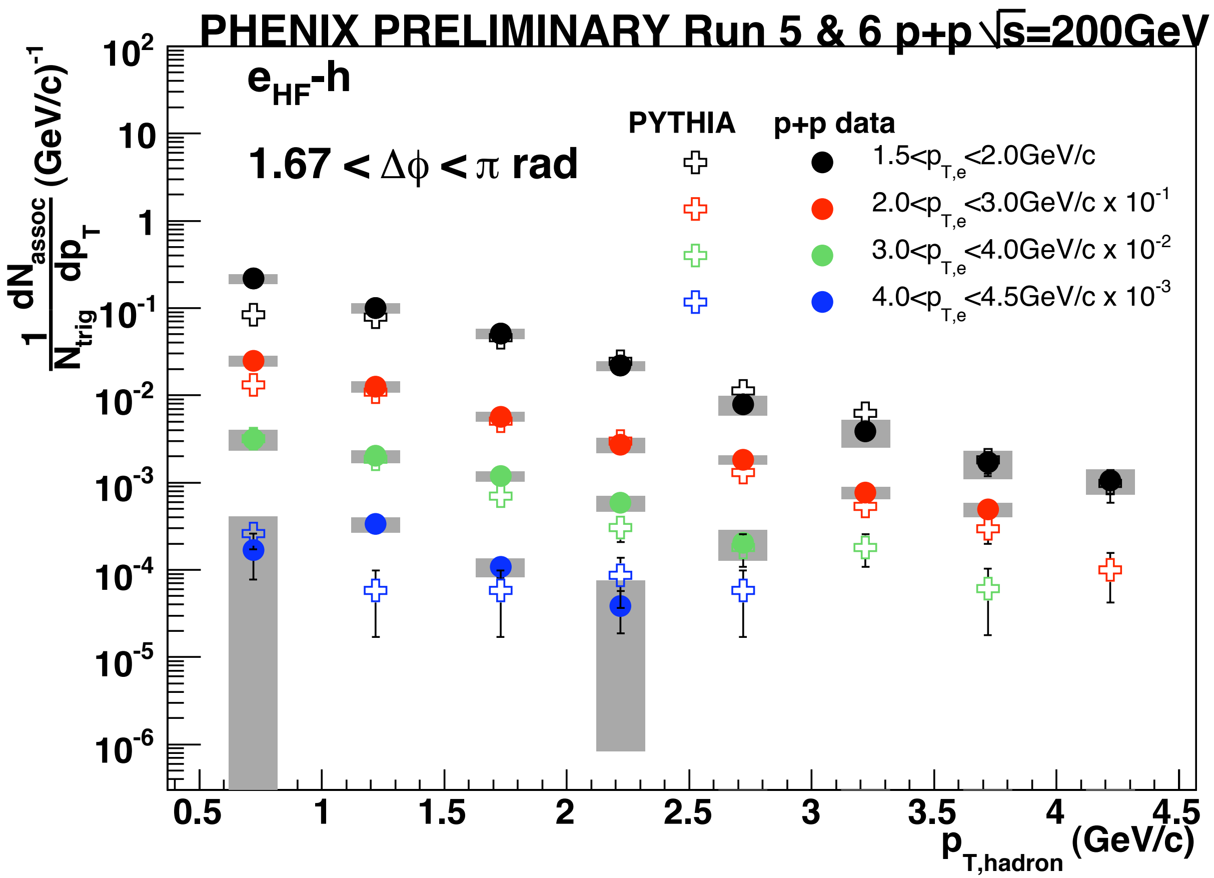
HF: e±-h± Correlations

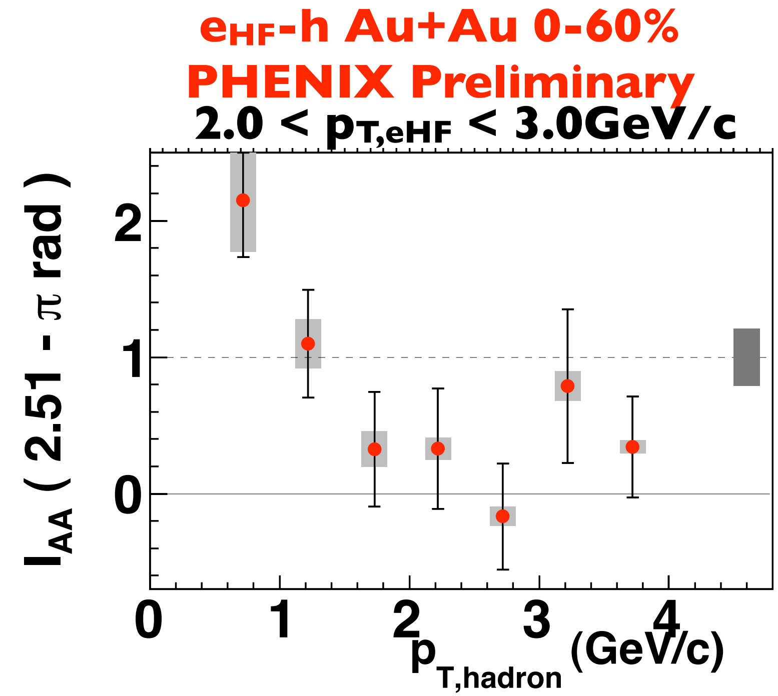
- the next step forward



HF: $e^{\pm}$-$h^{\pm}$ Correlations

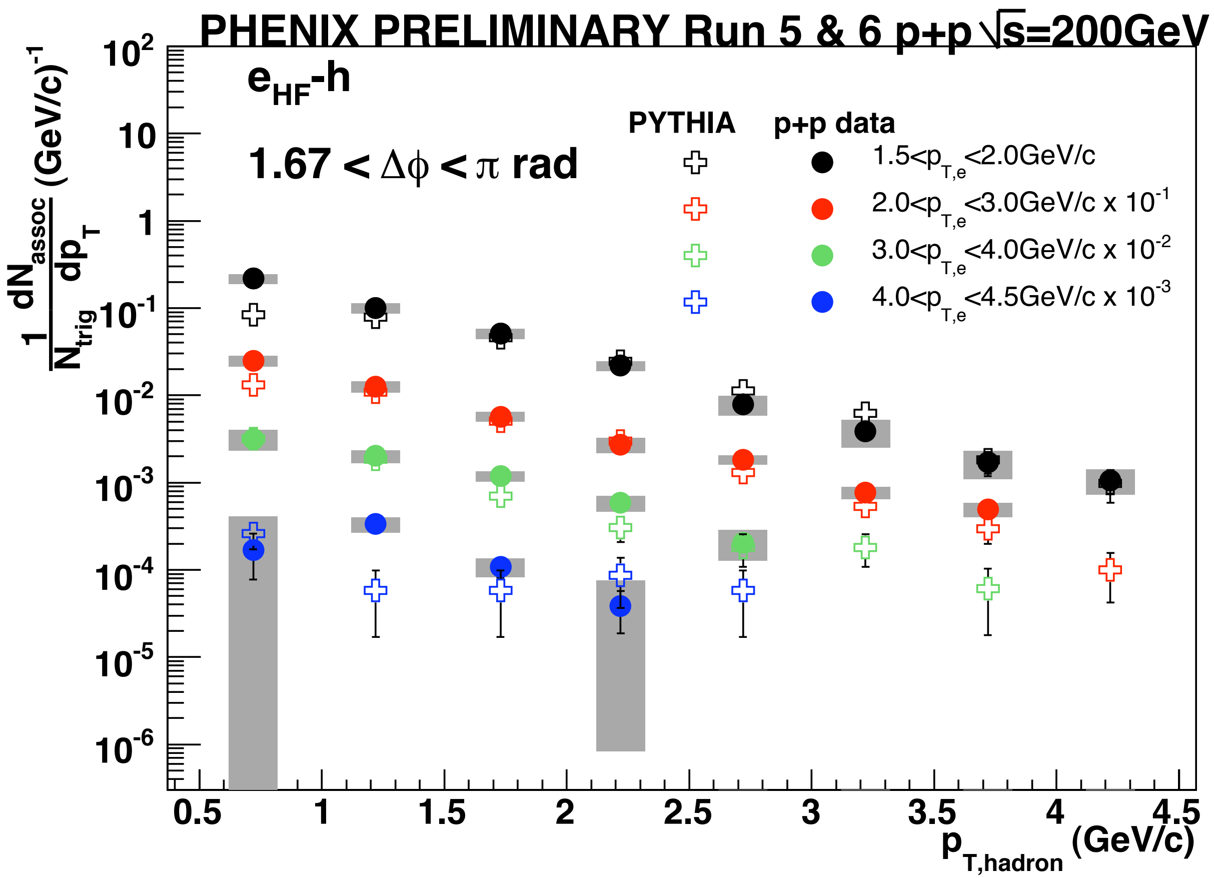
- the next step forward

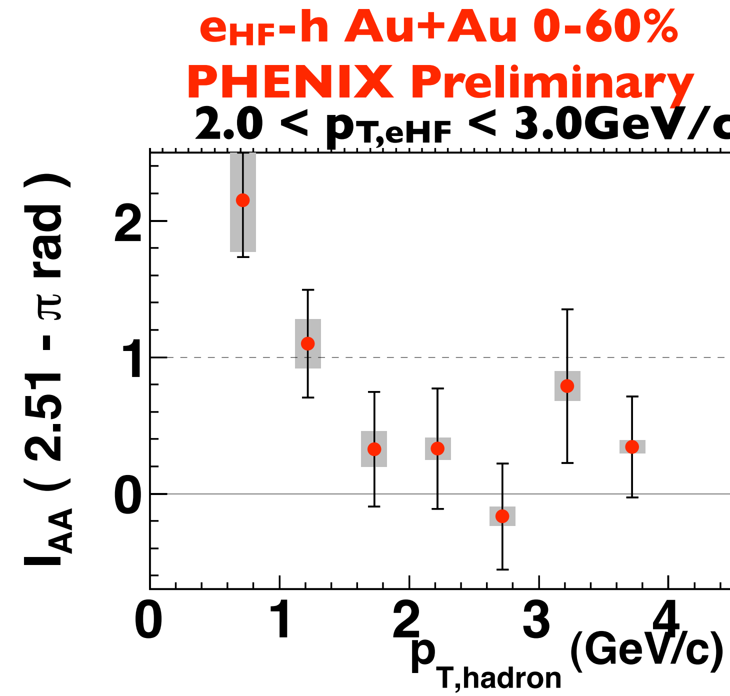


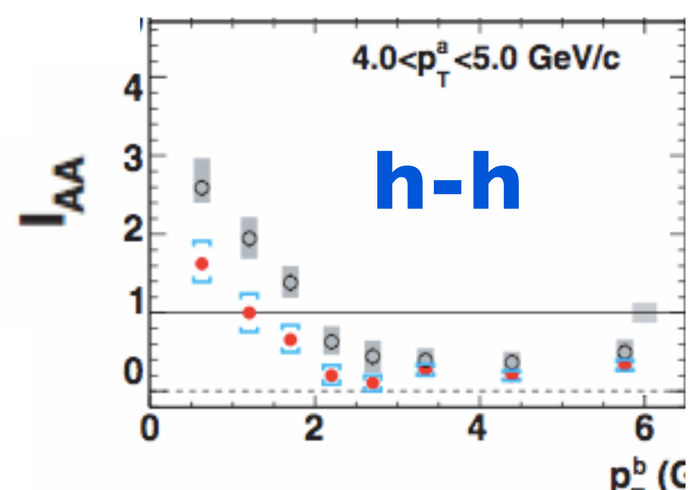


HF: e±-h± Correlations

- the next step forward

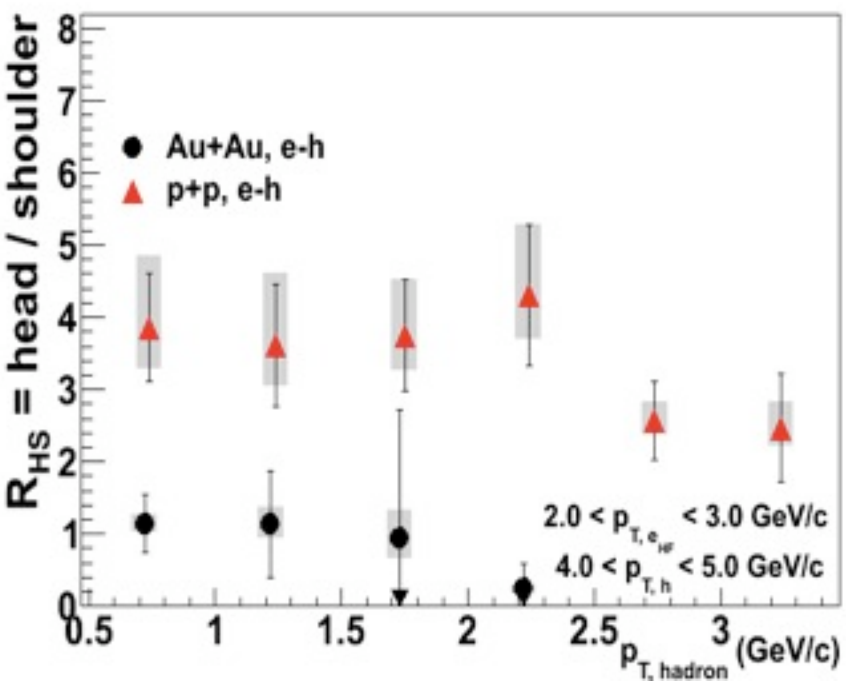


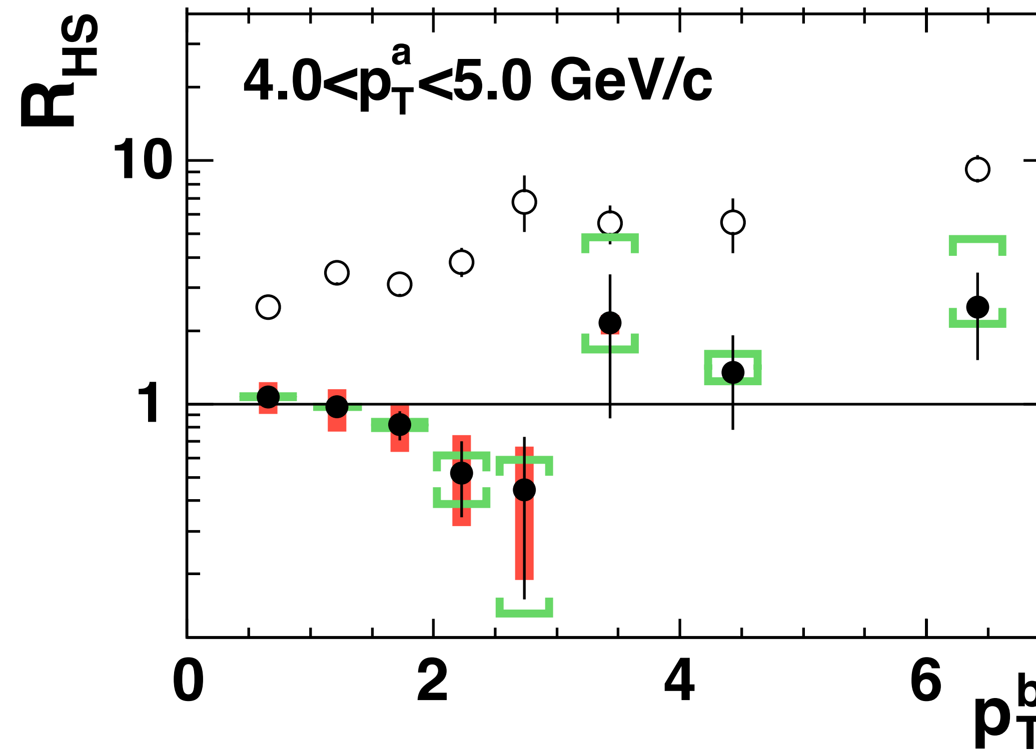




PHENIX PRC78 014901 (2008)

HF: away side shape

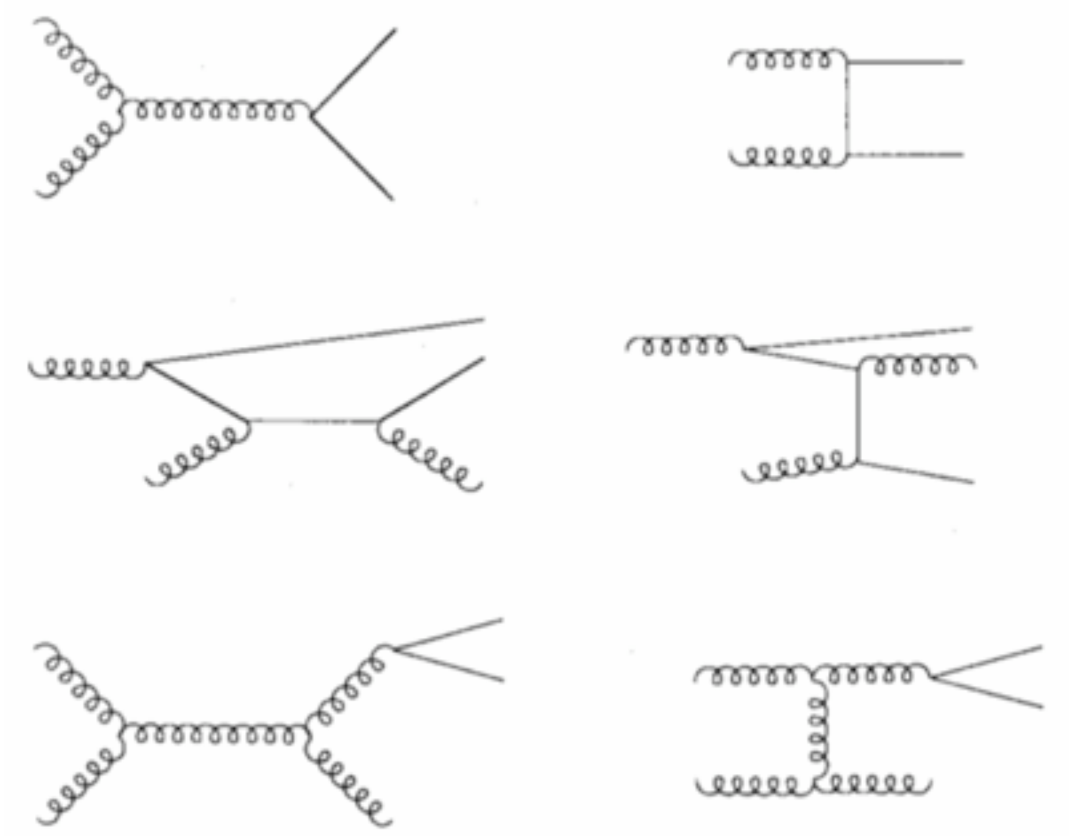




HF & light hadron triggered away side shapes both modified

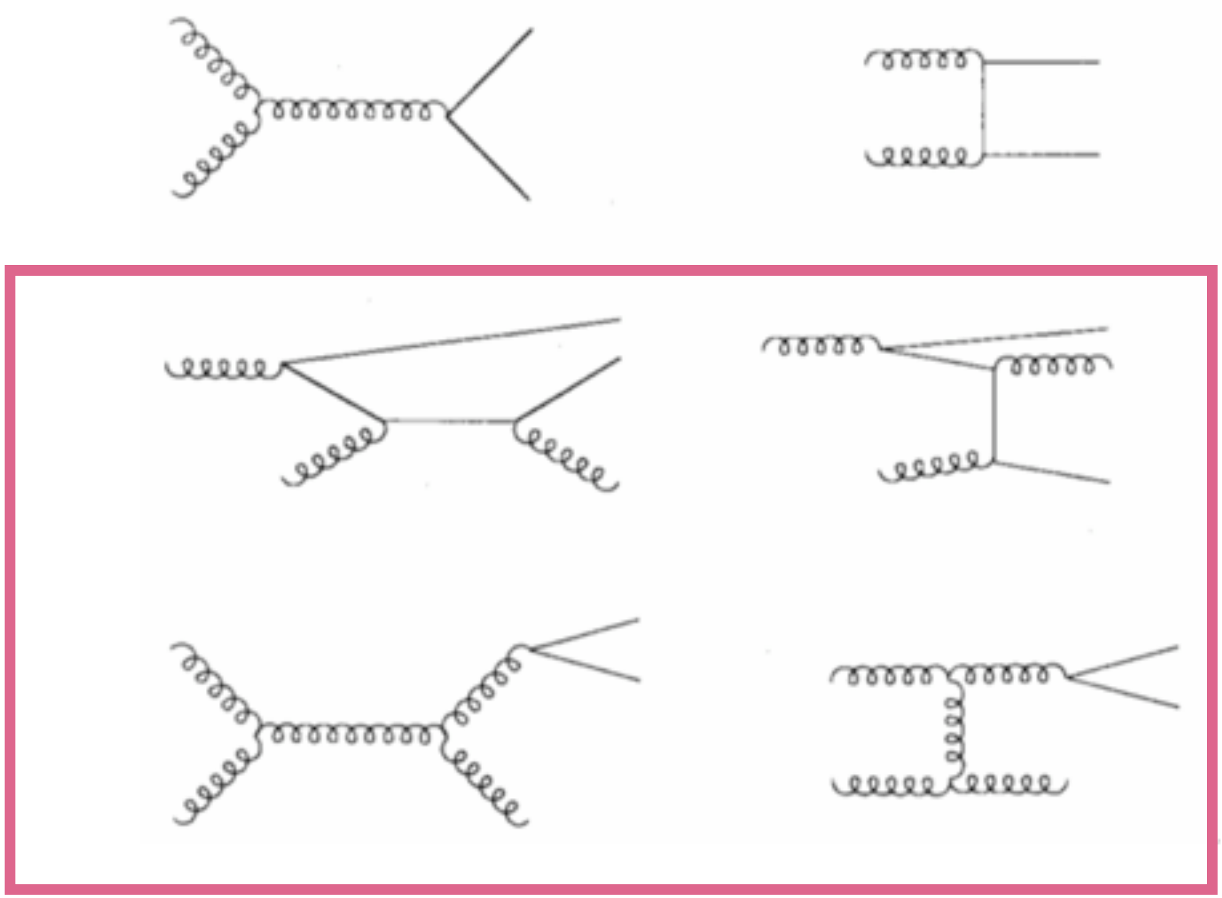
not unexpected

heavy quark production diagrams



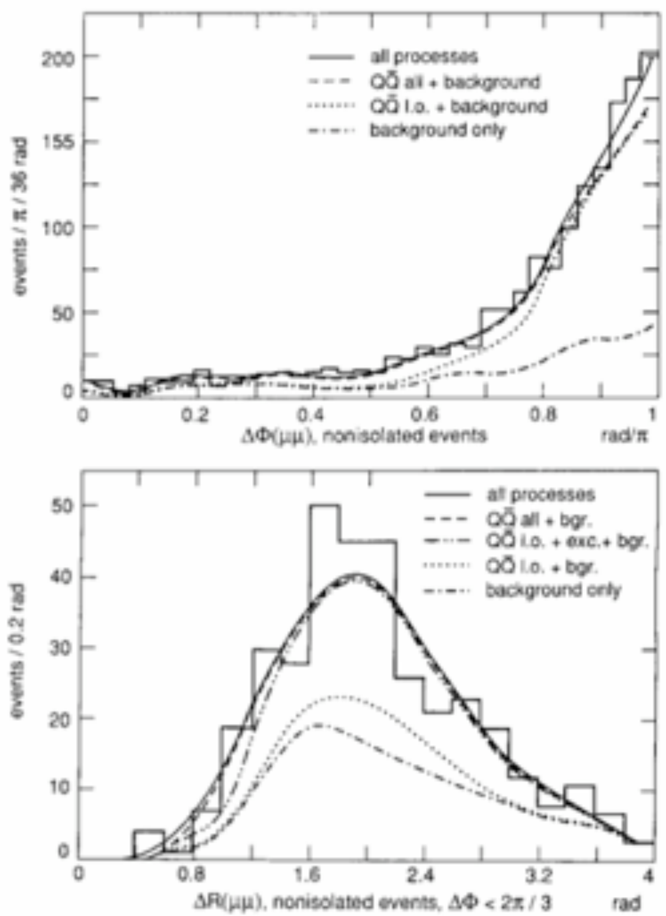
not unexpected

heavy quark production diagrams



sizable contributions from NLO effects

pp @ 630GeV



- UA1 μμ correlations
- fit with ISAJET
- 20-35% "higher order"

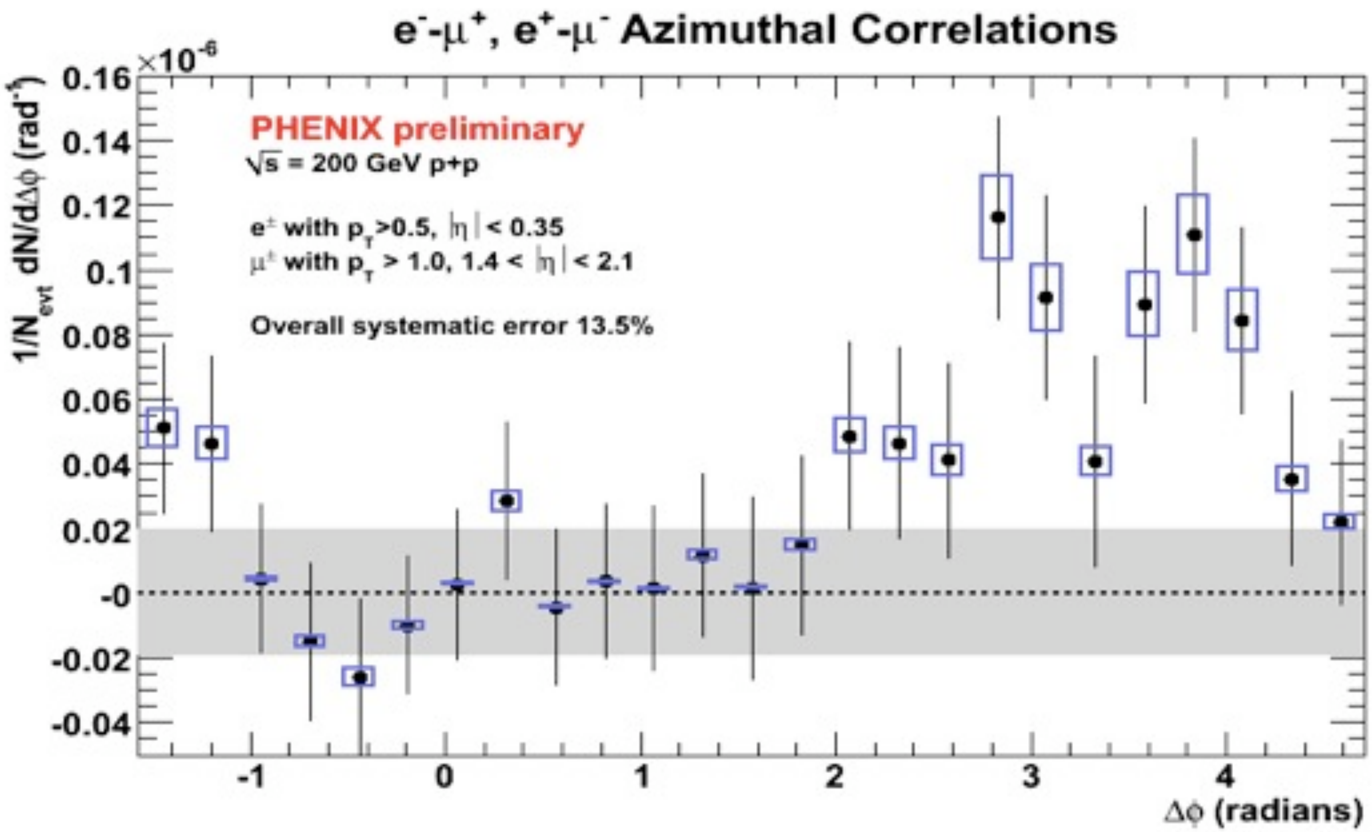
$p_{T\mu}^{high}$ range [GeV/c]	p_{Tb} range [GeV/c]	$b\bar{b}$ nonisol. $m_{\mu\mu} > 4$ GeV/c^2 [events]	'high.ord.' fraction [%]
All	$\gtrsim 6$	829 ± 58	26.2 ± 4.0
3–5	$\gtrsim 6$	402 ± 37	24.6 ± 8.5
5–7	$\gtrsim 8$	286 ± 23	31.2 ± 5.4
7–10	$\gtrsim 11$	103 ± 12	35.2 ± 5.1
10–20	$\gtrsim 15$	32 ± 6	21.3 ± 12.4

Z Phys C 61 41 1994

e-e correlations at RHIC needed to quantify this!

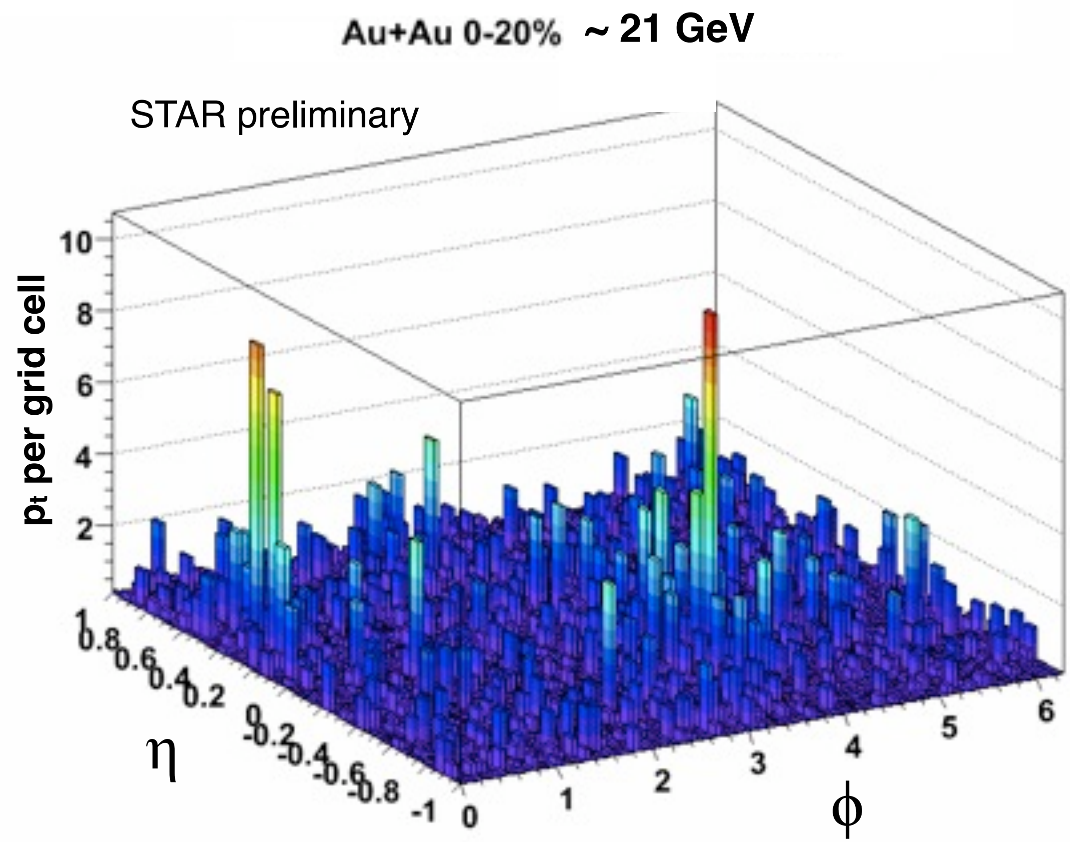
e-μ correlations

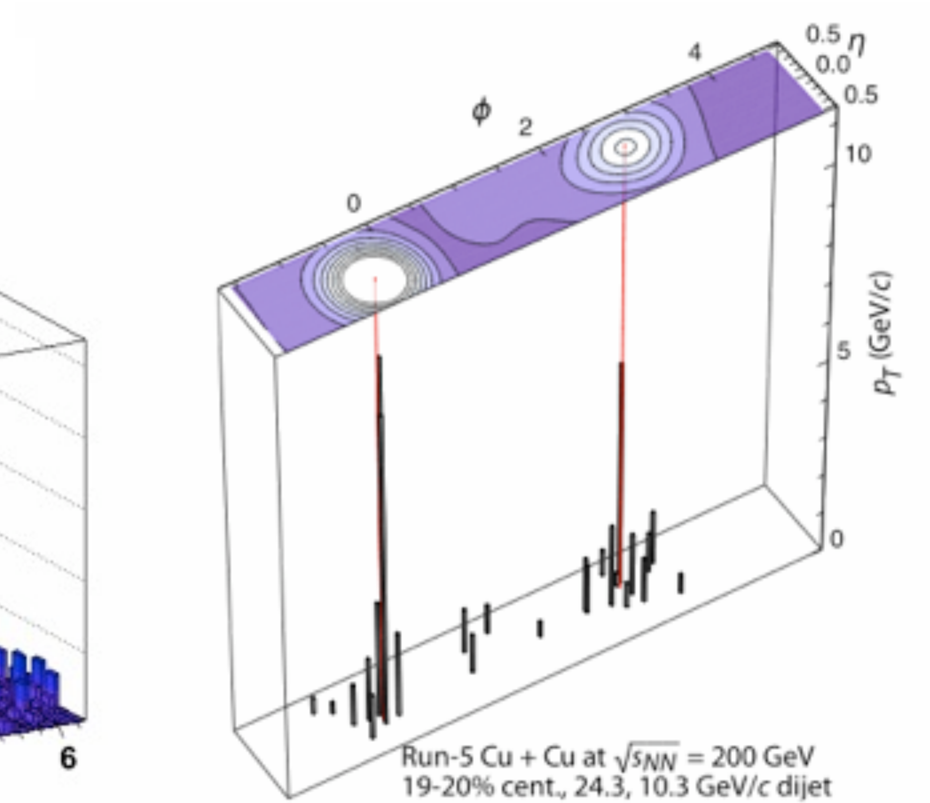
- sensitive to correlated charm, but at forward/mid-rapidity



T. Engelmore, QM09

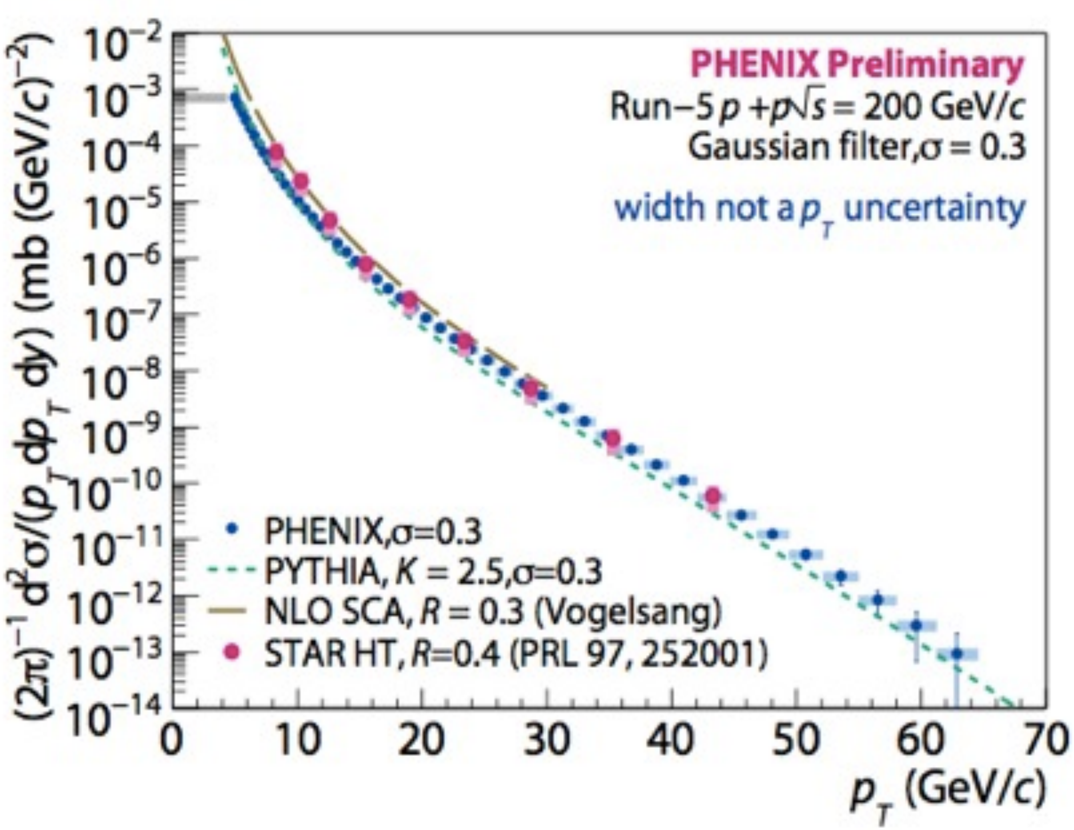
jets

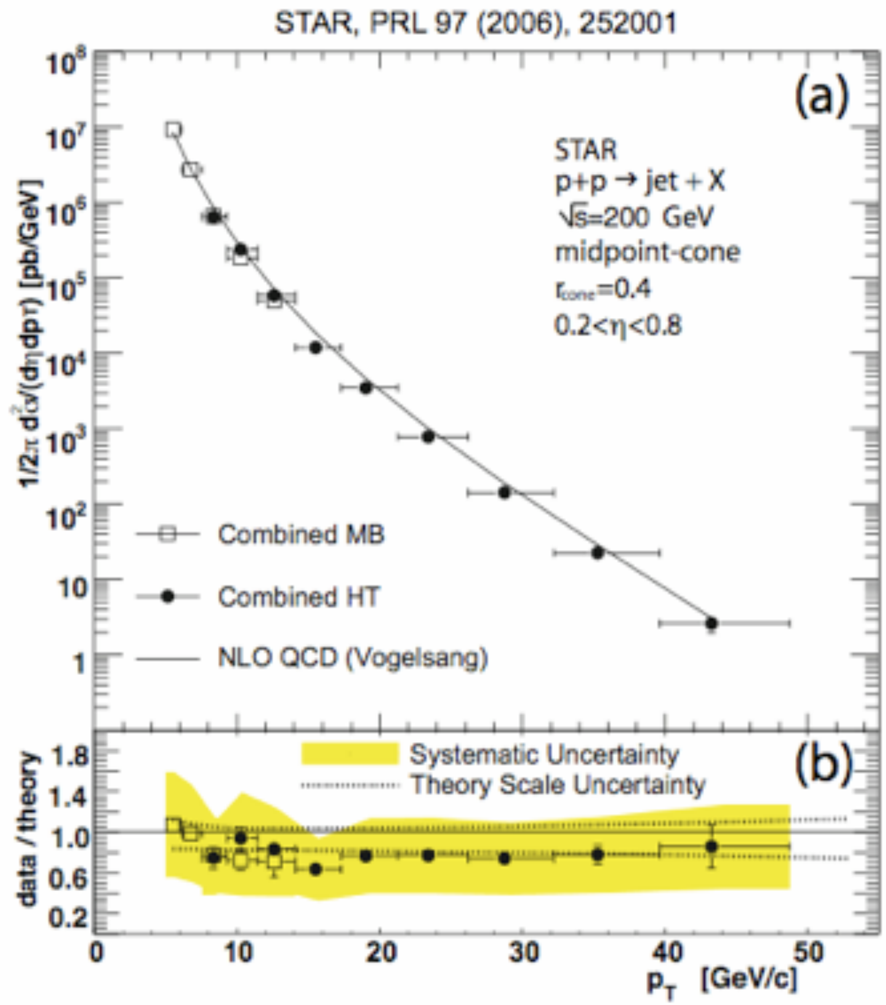




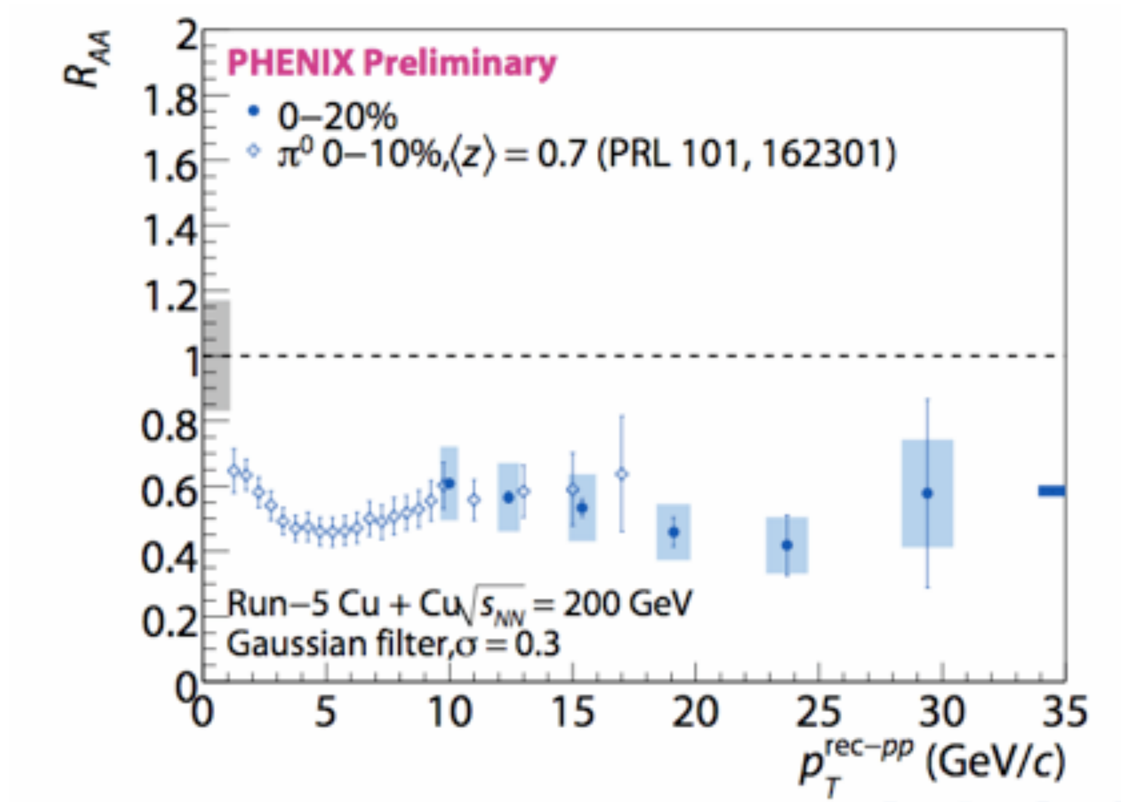
great recent progress!

p+p: well understood

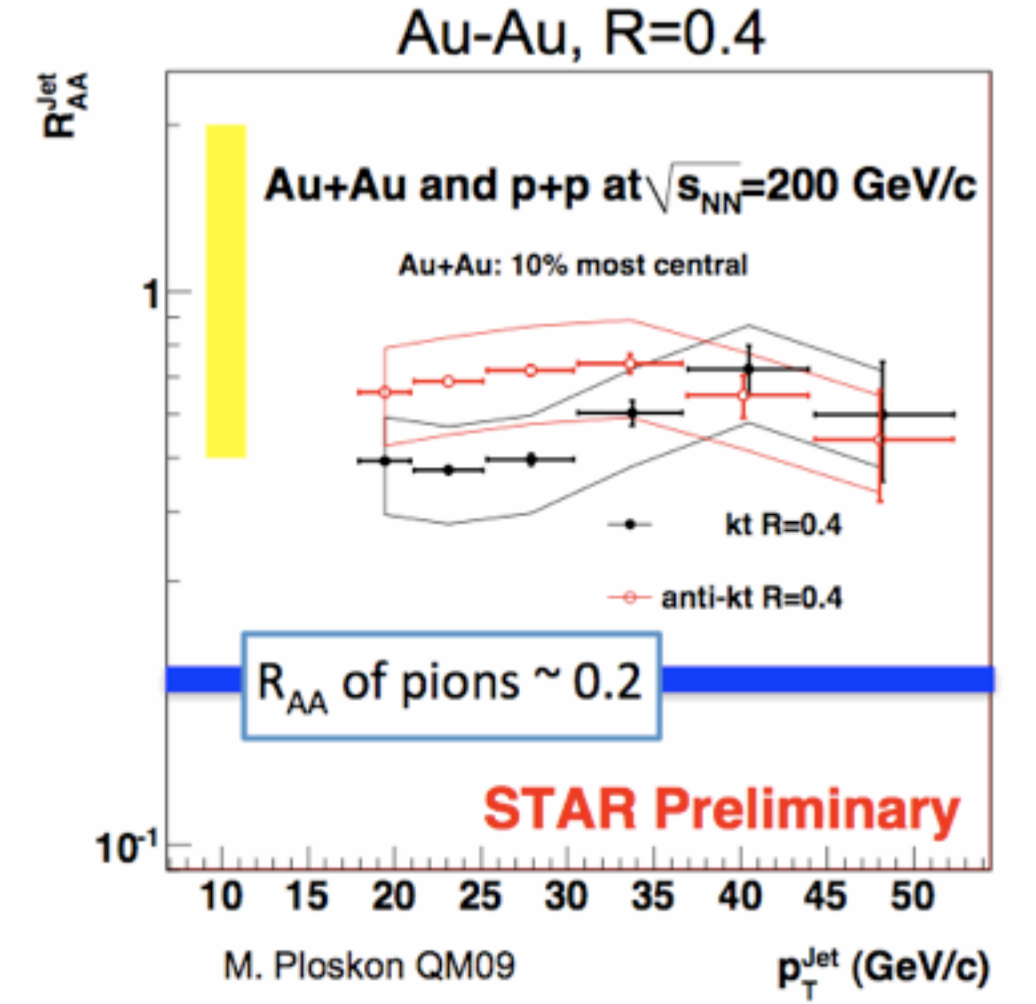


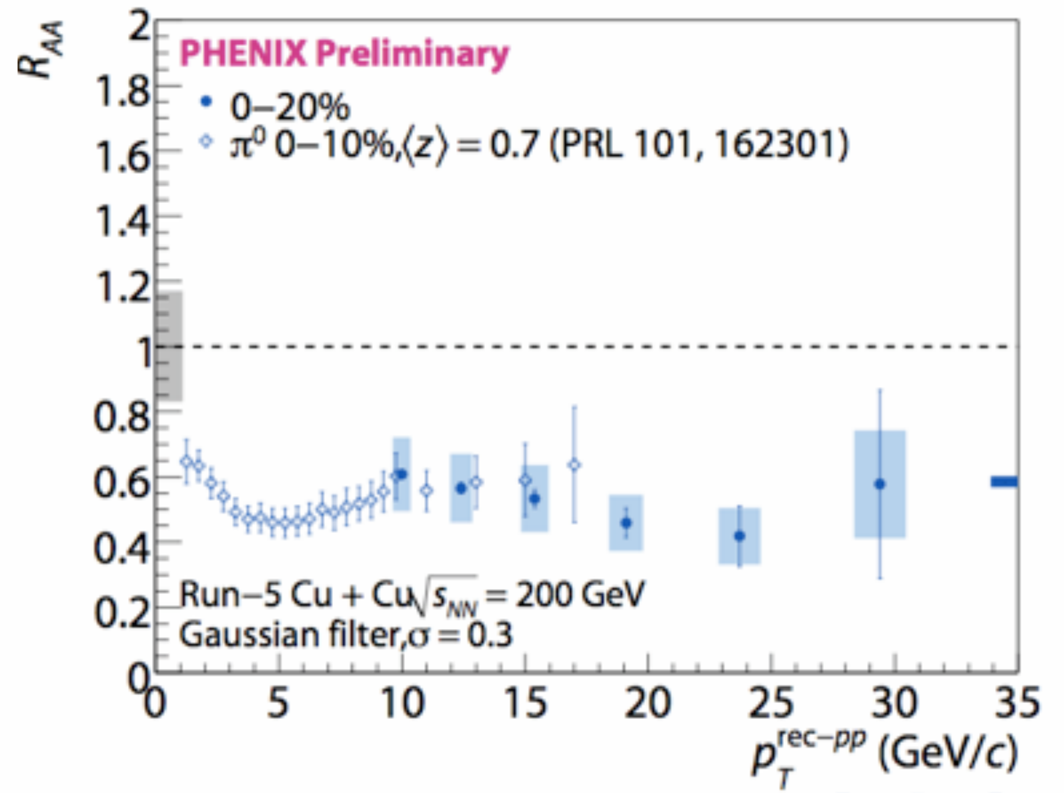


algorithm matters

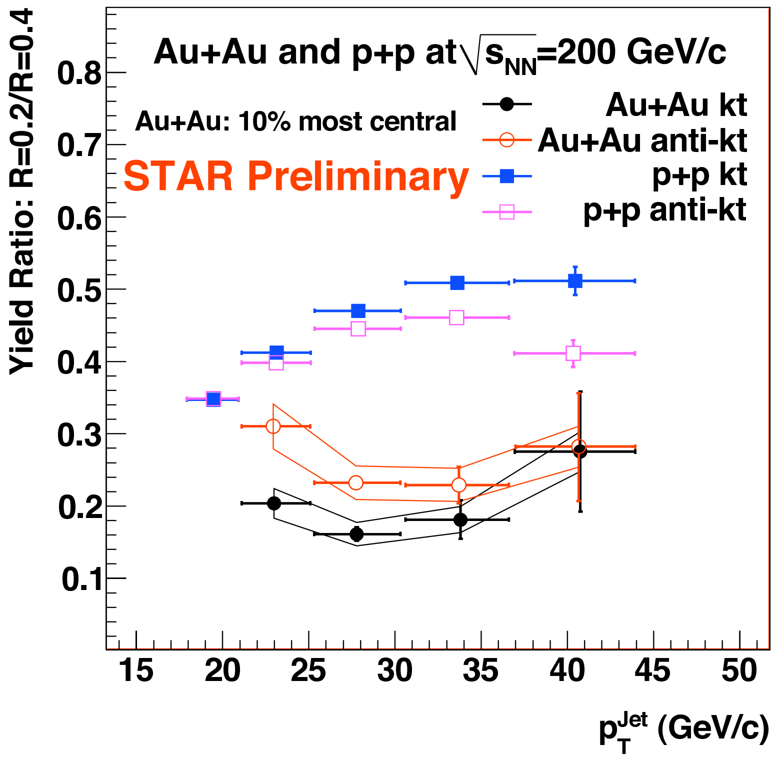


algorithm matters



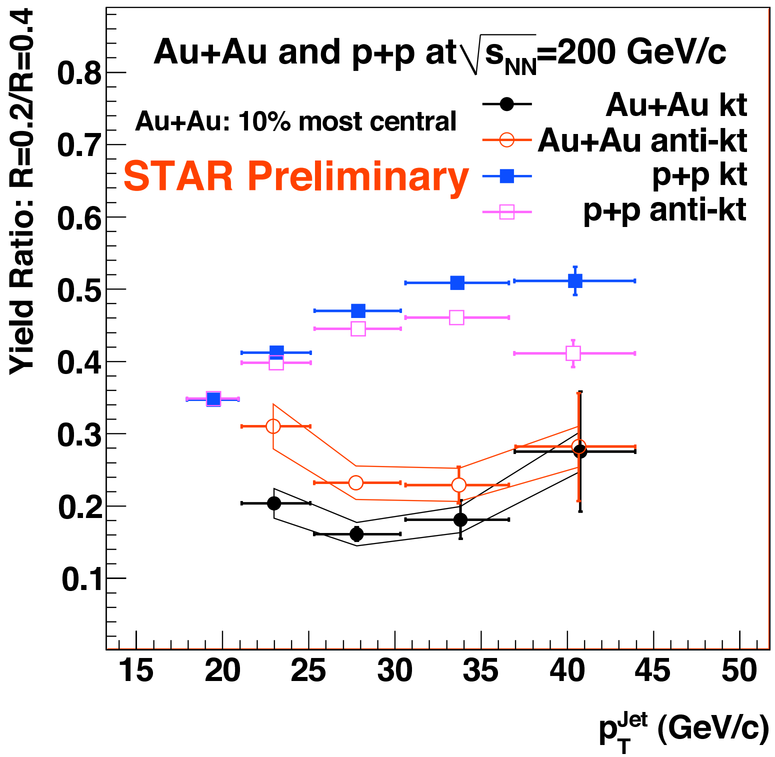


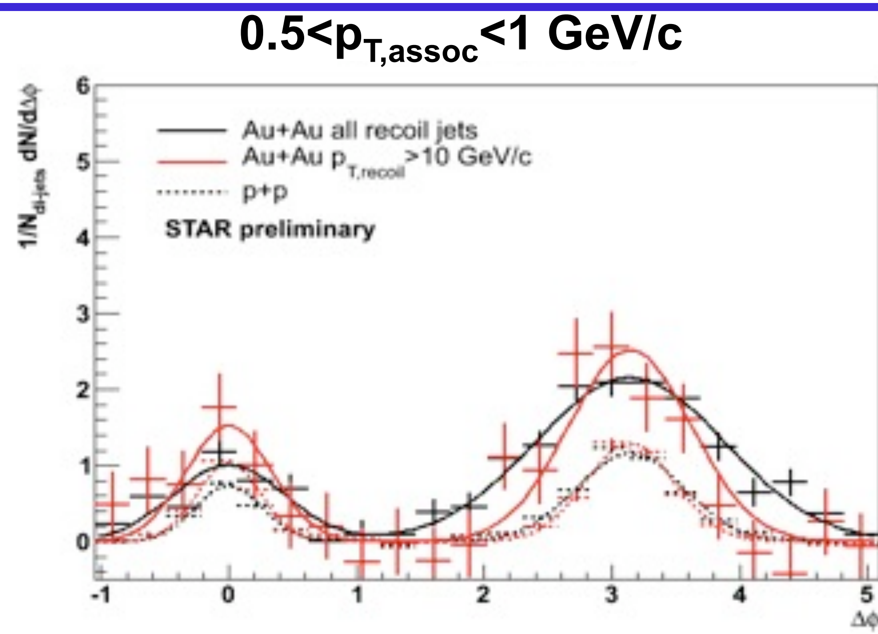
broadening



- qualitatively what you'd expect from both broadening and background

broadening



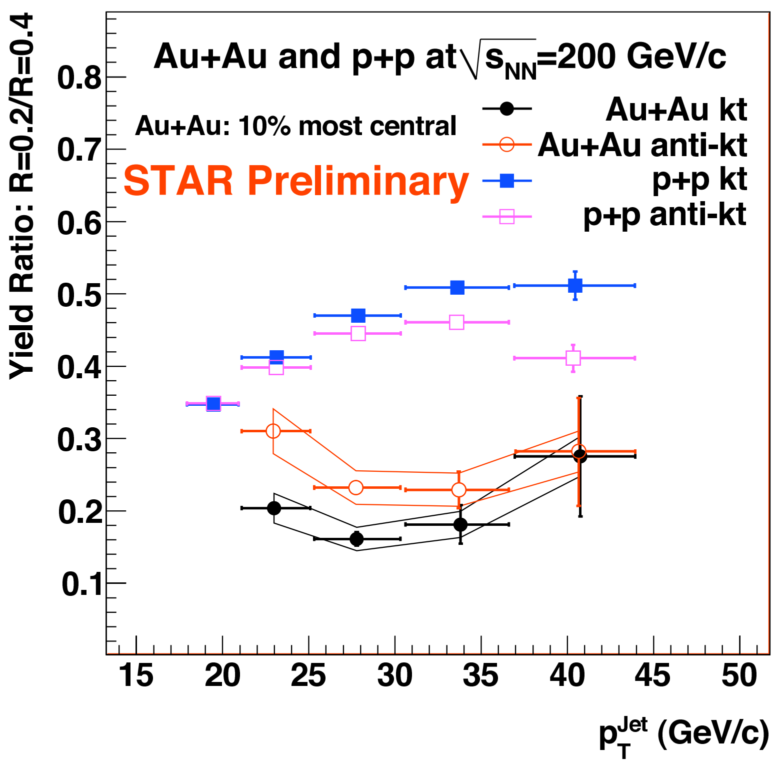


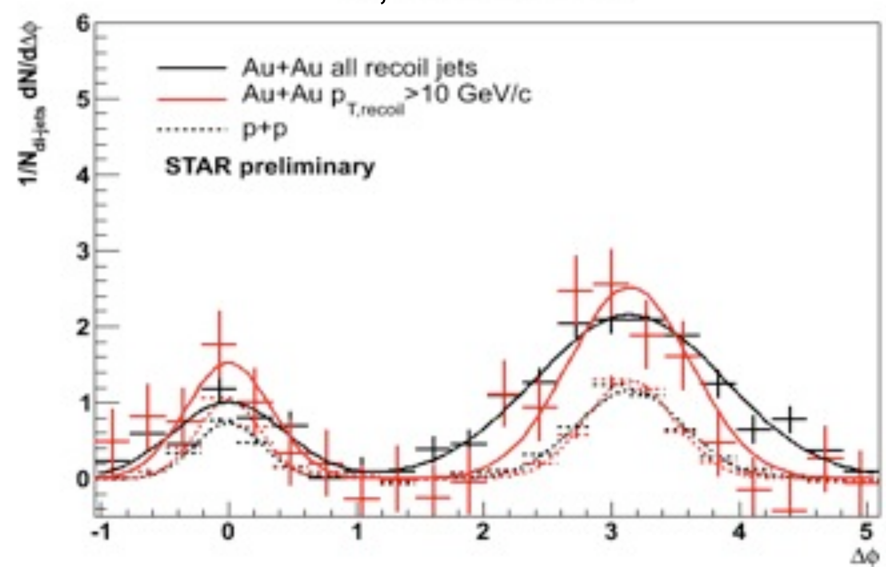
- qualitatively what you'd expect from both broadening and background

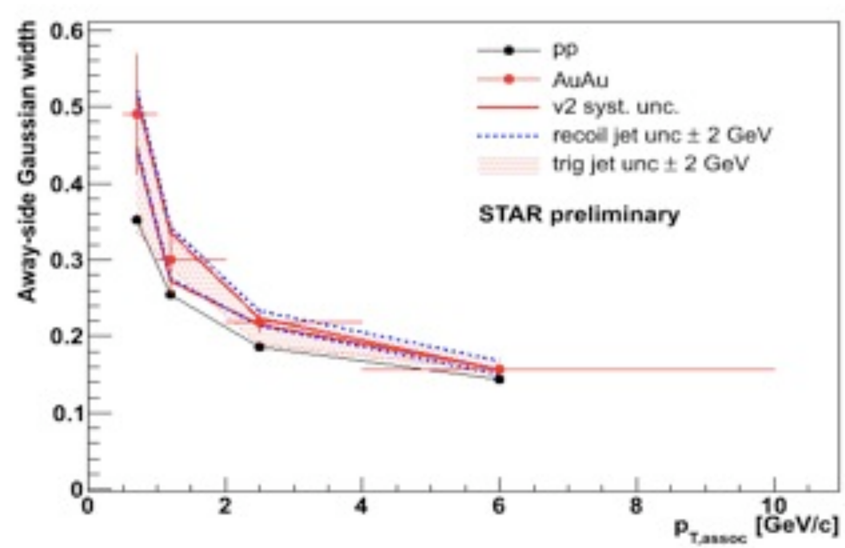
broadening on both near and away sides...

broadening

0.5<p$_{T,assoc}$<1 GeV/c



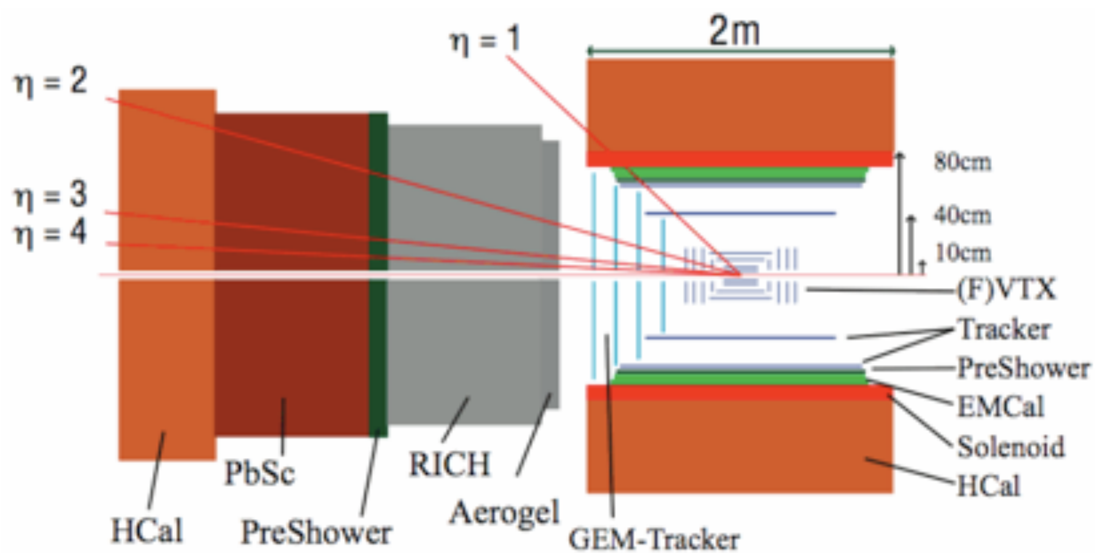




- qualitatively what you'd expect from both broadening and background

the future

- jets offer huge rate advantages and a reduction of biases from spectra & correlations
- however need a real jet detector for RHIC
  - high rate, hadronic calorimetry, heavy flavor tagging, large acceptance
  - complementary to LHC



PHENIX Decadal Plan, Jacak HP10

Conclusions

- theoretical understanding of π^0 results still elusive
  - strong path length dependence in the data
- reaction plane dependent and heavy quark results suggestive of AdS/CFT type scenarios
  - strong L dependence & strong HF energy loss
- softening and broadening of fragmentation observed
- challenges to both theory and experiment
  - theory: detailed modeling of medium & geometry
  - experiment: sensitive measurements ➔ reaction plane dependences, heavy flavor, jets

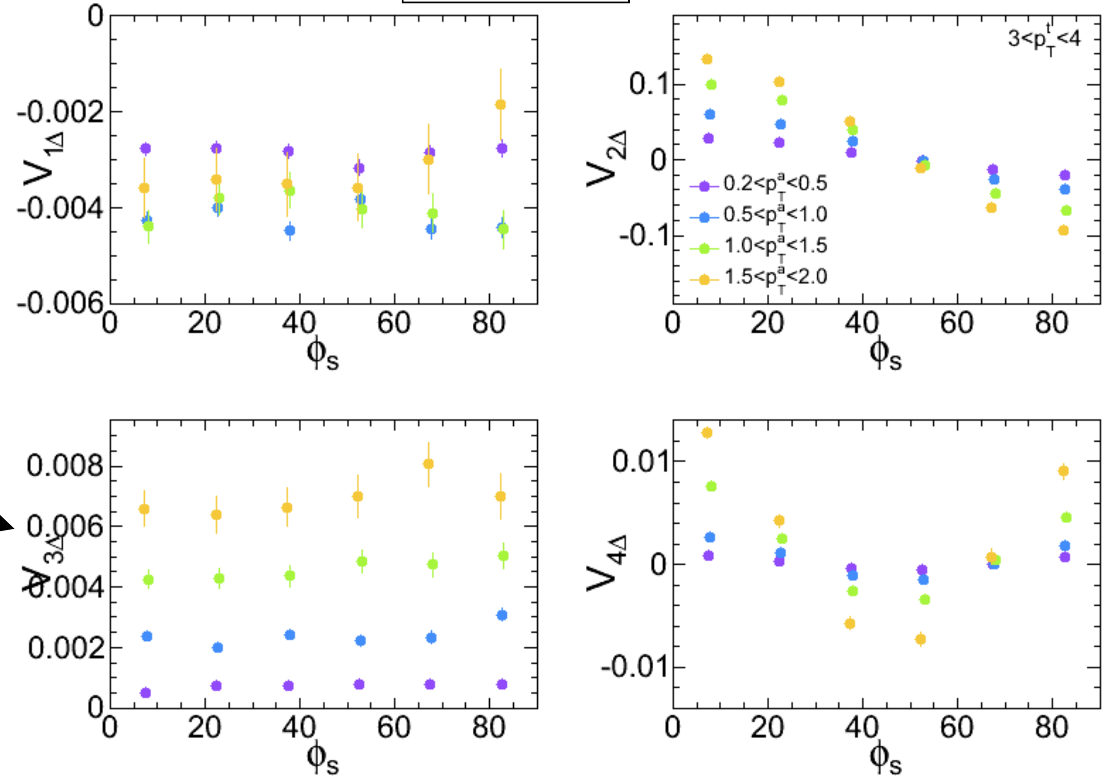
Fourier Components of STAR ϕ_s data

Burak Alver, private communication, **10/9/2010**

$|\Delta\eta| > 0.7$

Data from STAR
arXiv:1010.0690

v_3^2 is approximately constant vs ϕ_s



By definition, Fourier coefficients v_1, v_2, v_3, v_4
can be calculated for STAR data

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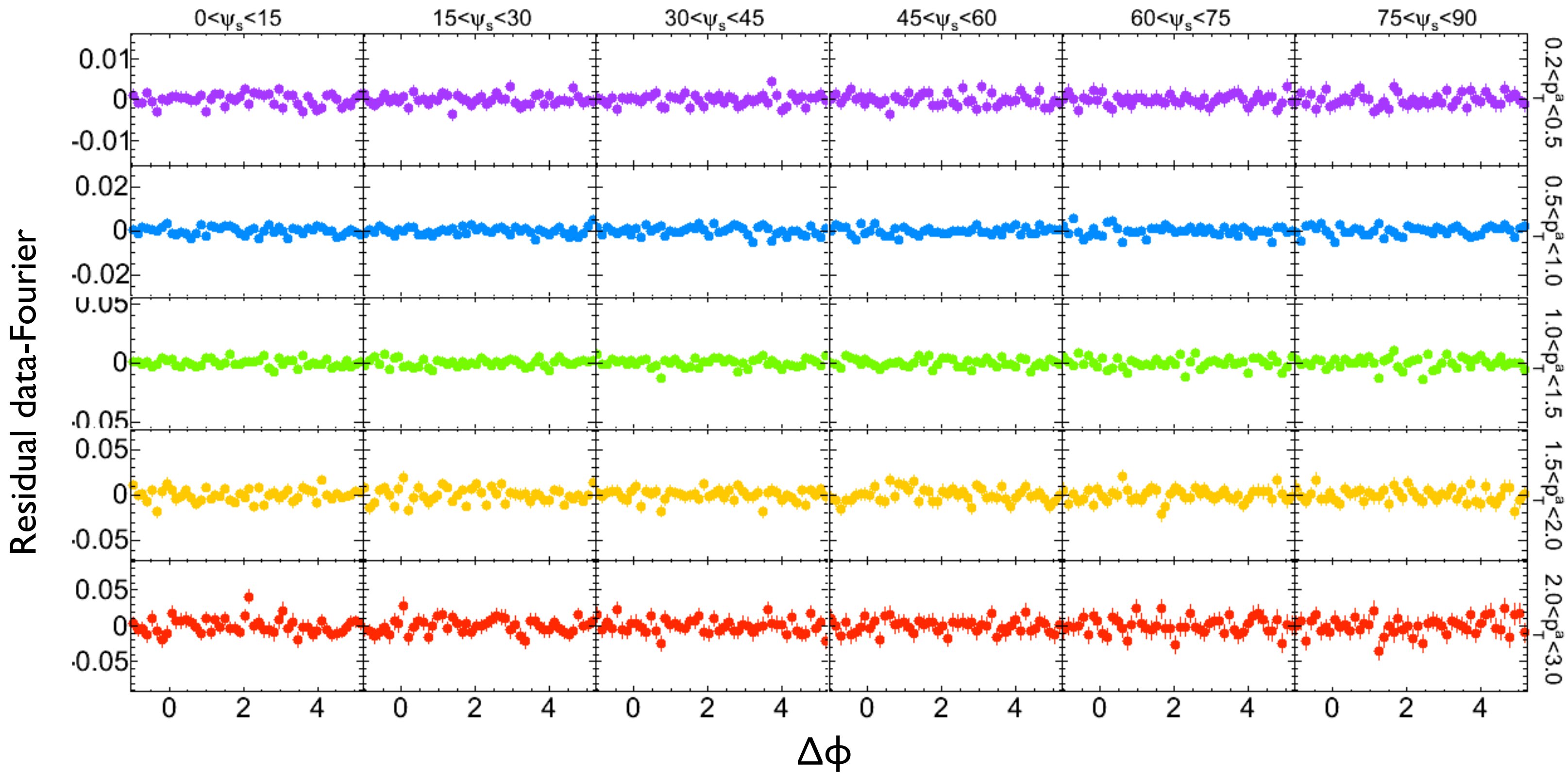
Fourier Components of STAR ϕ_s data

Data from STAR
arXiv:1010.0690

Residuals after subtraction of first 4 Fourier components

Burak Alver, private communication 10/10/2010



Fourier coefficients v_1, v_2, v_3, v_4 exhaust information content of C.F.'s vs ϕ_s

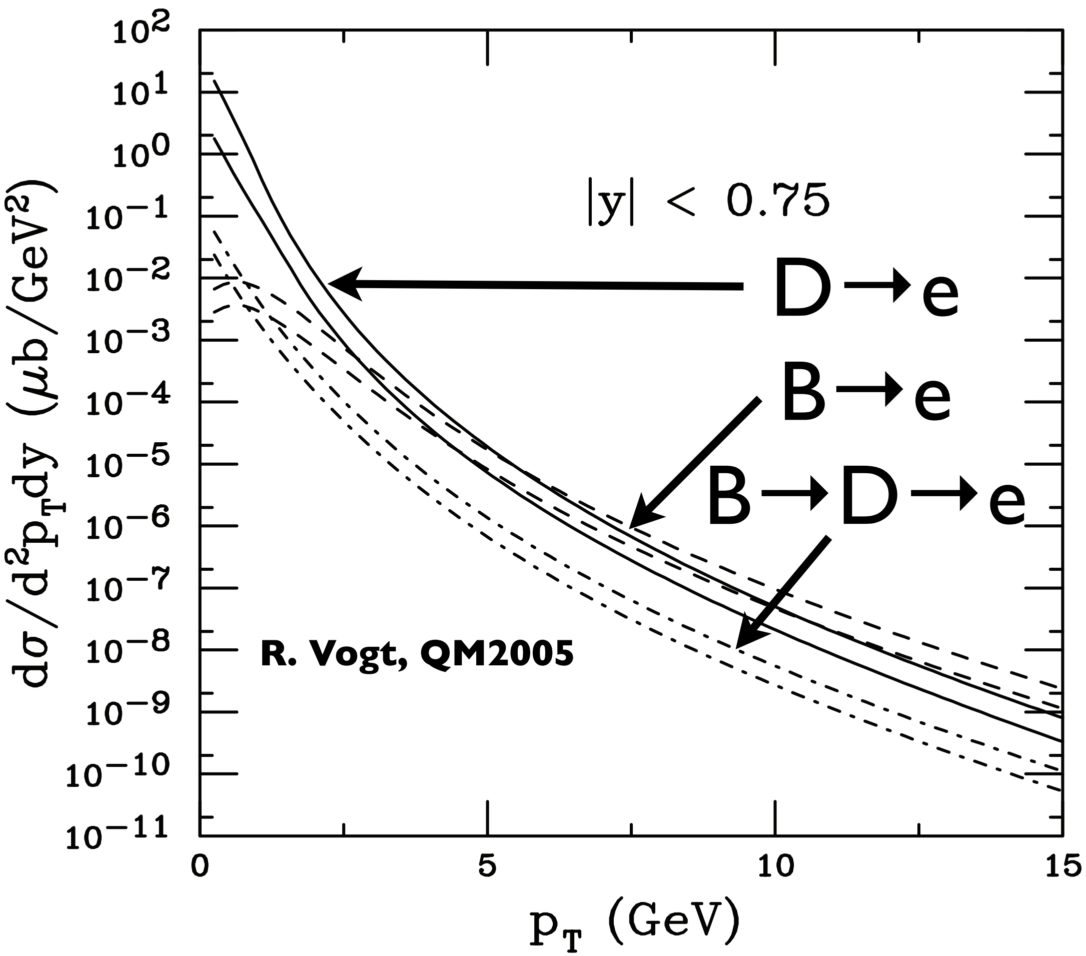
All four v_N components are result from hydro flow - magnitude?

What is the more natural basis to begin physics discussion?

20

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

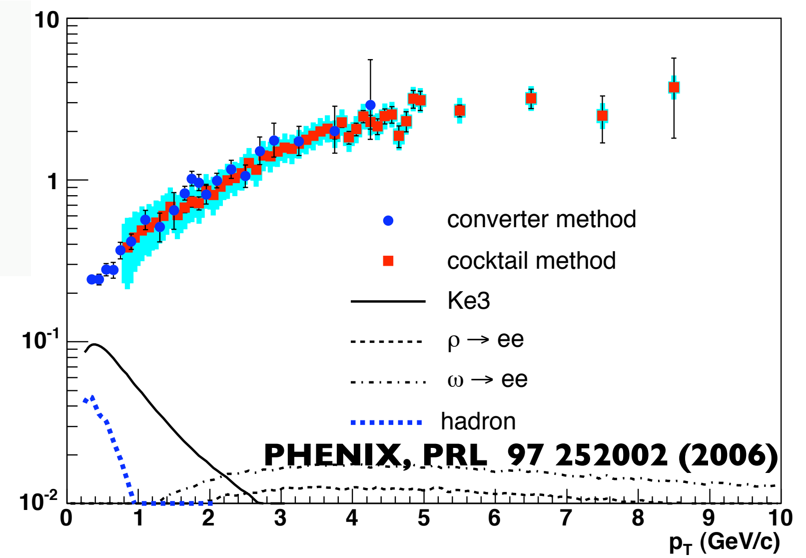
separating the correlations

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

separating the correlations

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

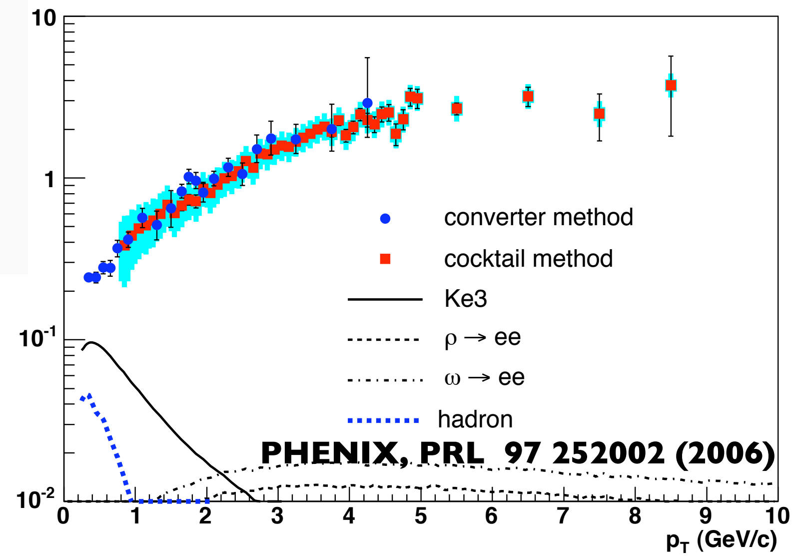
$$R_{HF} = \frac{N_{e_{HF}}}{N_{e_{phot}}}$$



separating the correlations

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

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

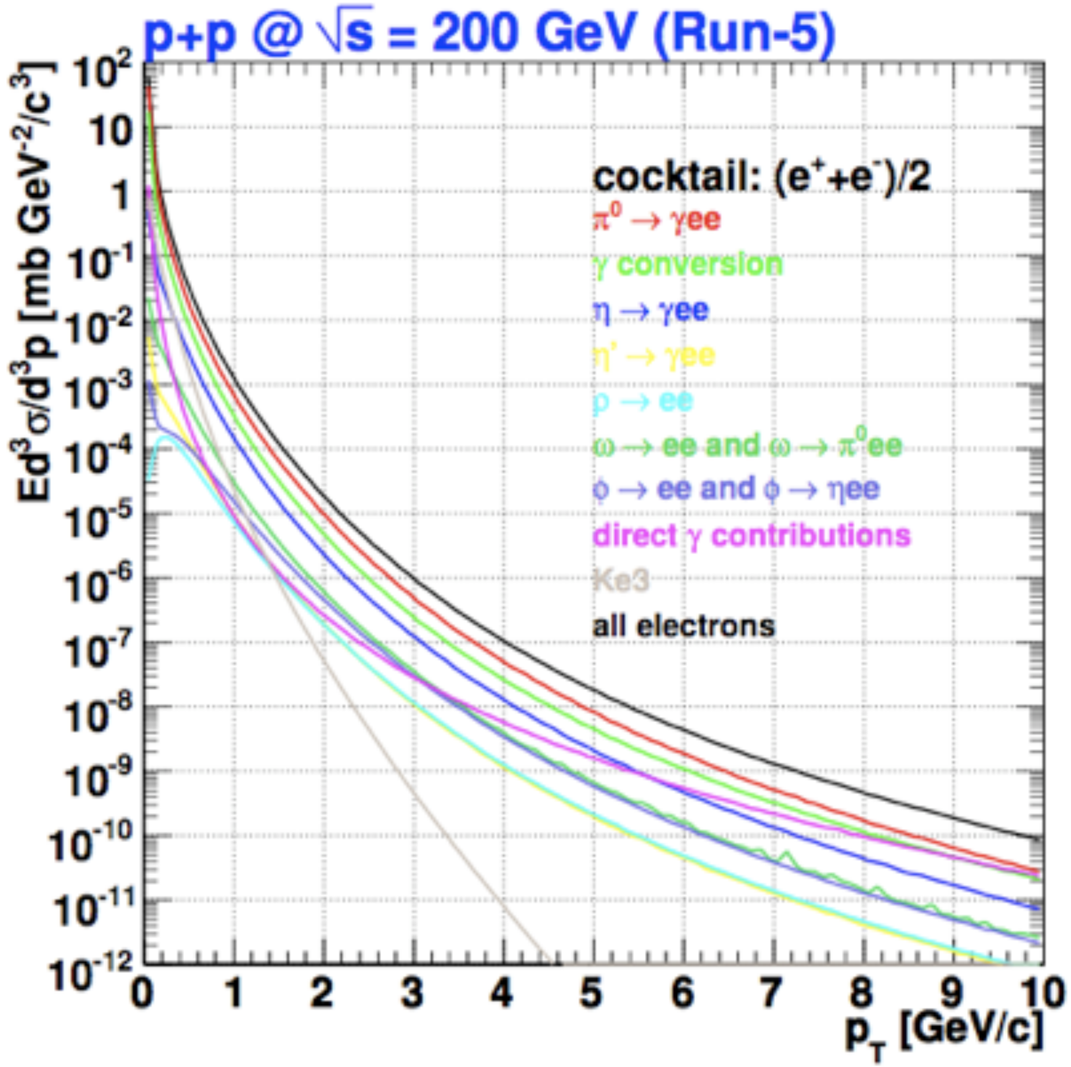


$$Y_{e_{HF}-h} = \frac{(R_{HF}+1) Y_{e_{incl}-h} - Y_{e_{phot}-h}}{R_{HF}}$$

e_{phot}-h correlations

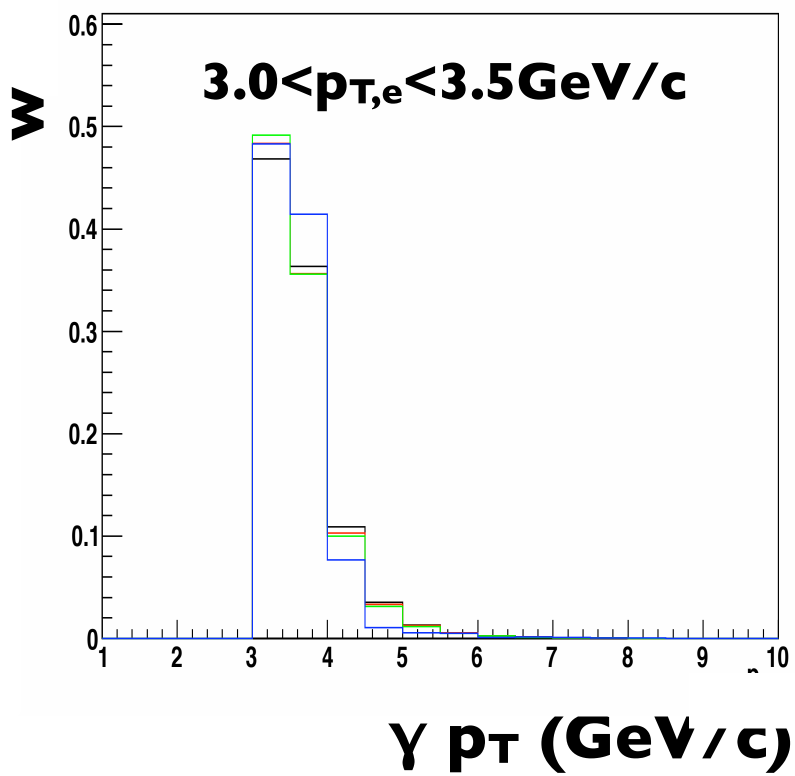
$$Y_{e_{HF}-h} = \frac{(R_{HF}+1)Y_{e_{incl}-h} - Y_{e_{phot}-h}}{R_{HF}}$$

- 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 $e_{phot}(p_T)$ & $\gamma_{inc}(p_T)$



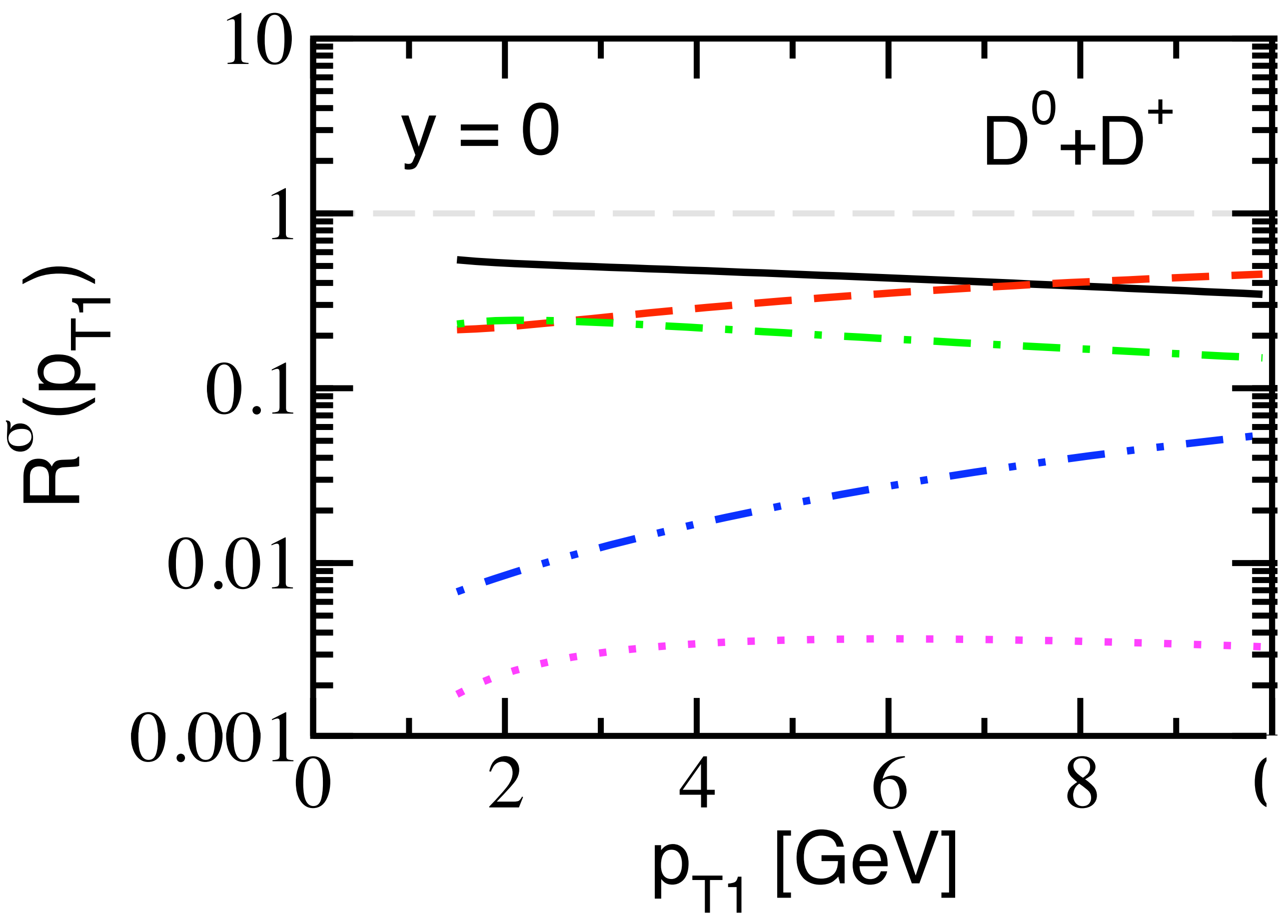
e_{phot}-h correlations (II)

- $\gamma_{inc}(p_T)$ ➡ $e_{phot}(p_T)$?
  - **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



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

charm production subprocesses



cg → cg

cq($\bar{q}$) → cq($\bar{q}$)

gg → c$\bar{c}$

q$\bar{q}$ → c$\bar{c}$

c$\bar{c}$ → c$\bar{c}$

most of the time a D is not balanced by a mid-rapidity $\bar{D}$

(caveat: LO calculation)

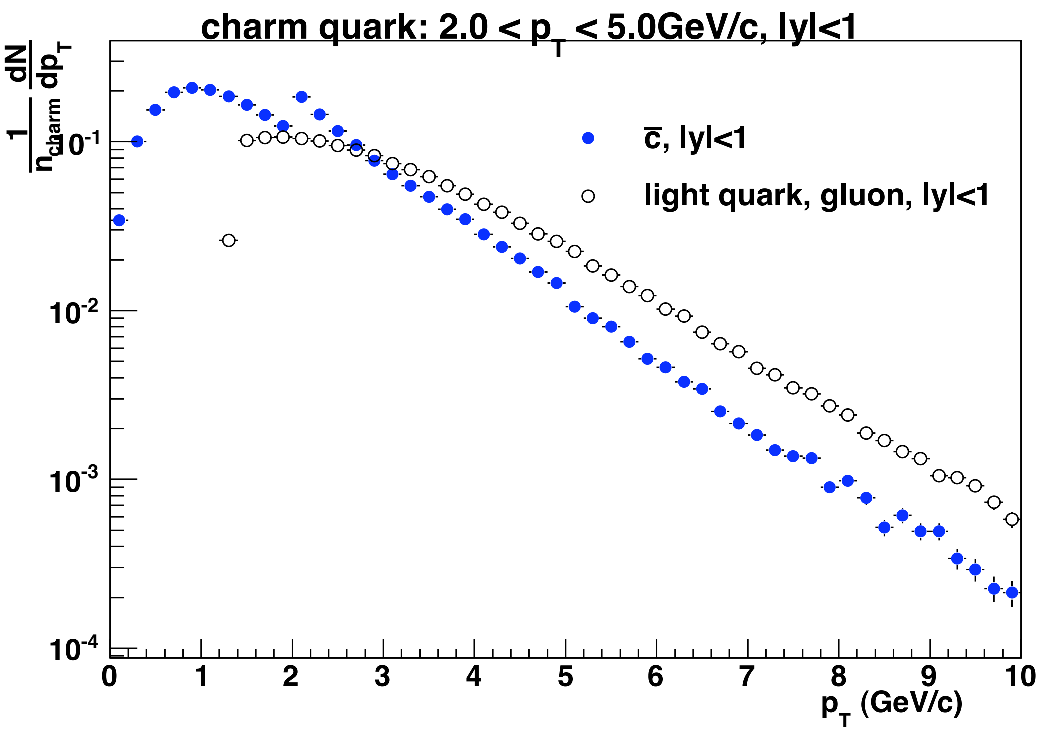
Vitev et al PRD 74 054010 (2006)

Next to Leading Order

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

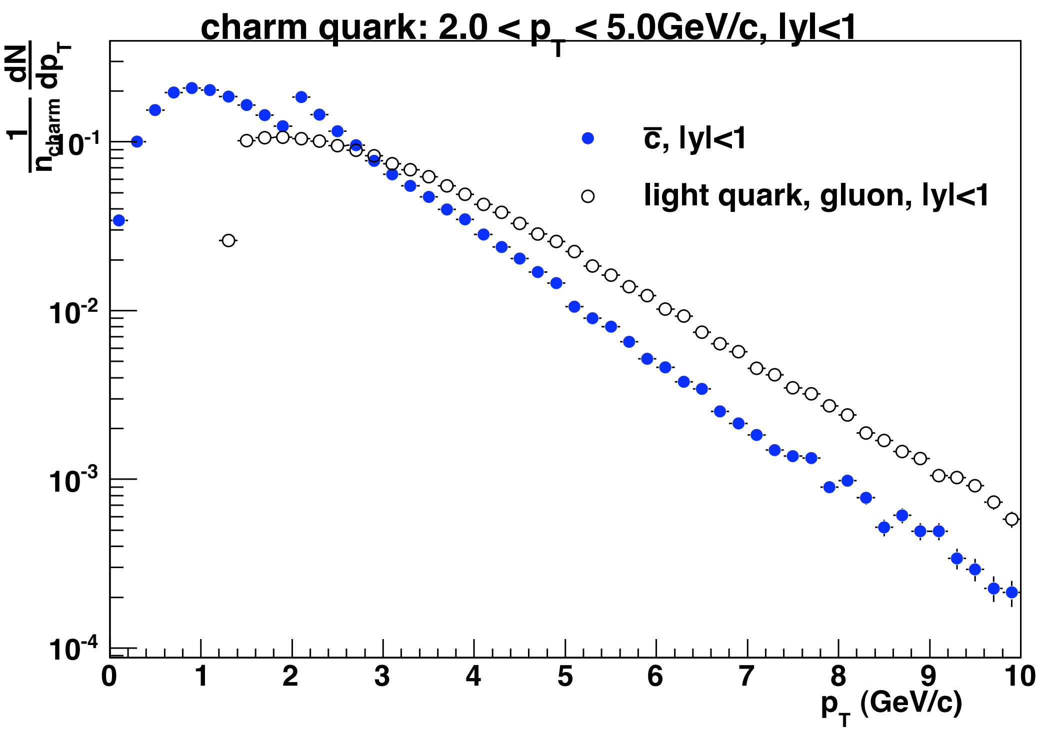
Next to Leading Order

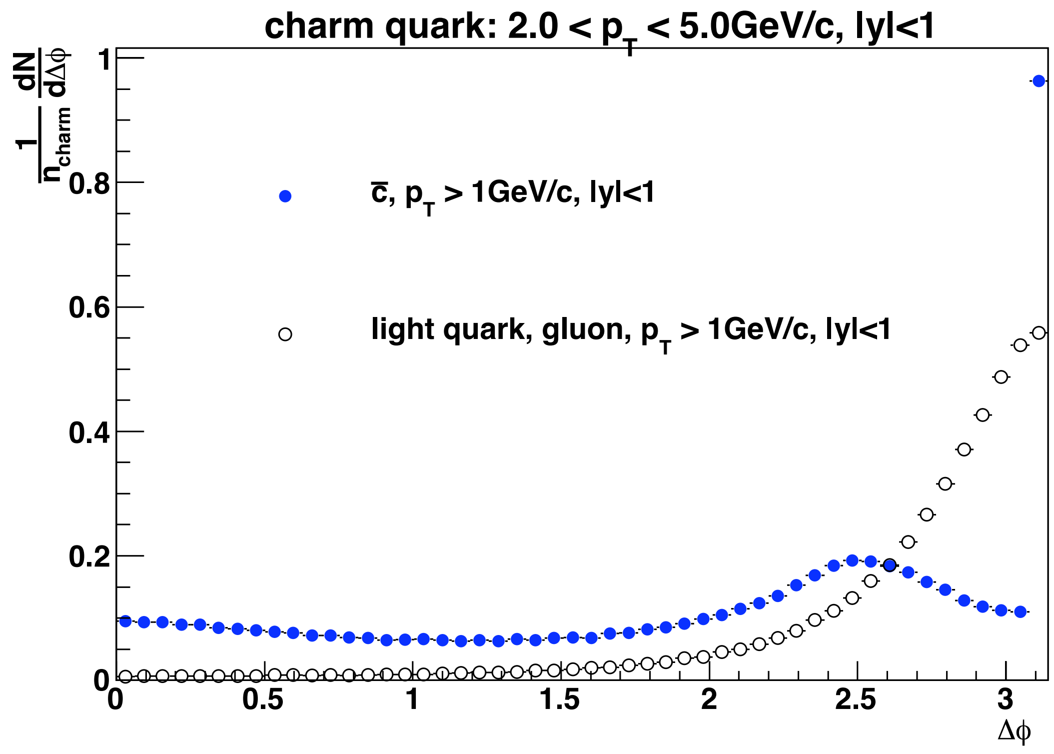
- POWHEG NLO Monte Carlo: 2→2 & 2→3 processes



Next to Leading Order

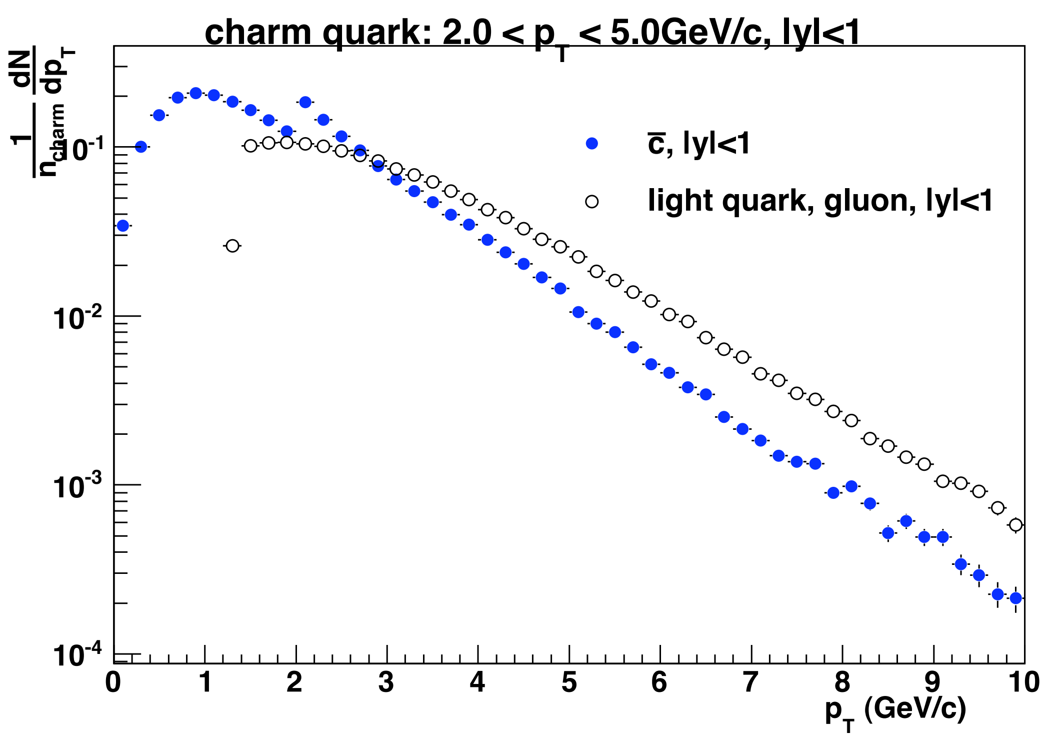
- POWHEG NLO Monte Carlo: 2→2 & 2→3 processes

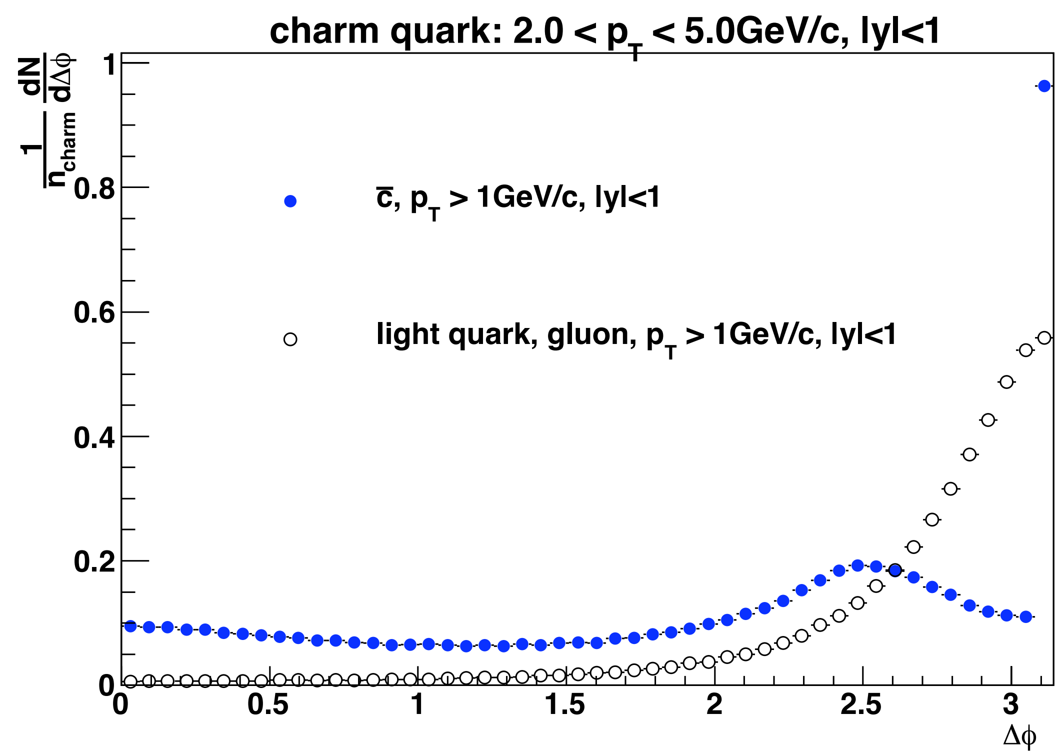




Next to Leading Order

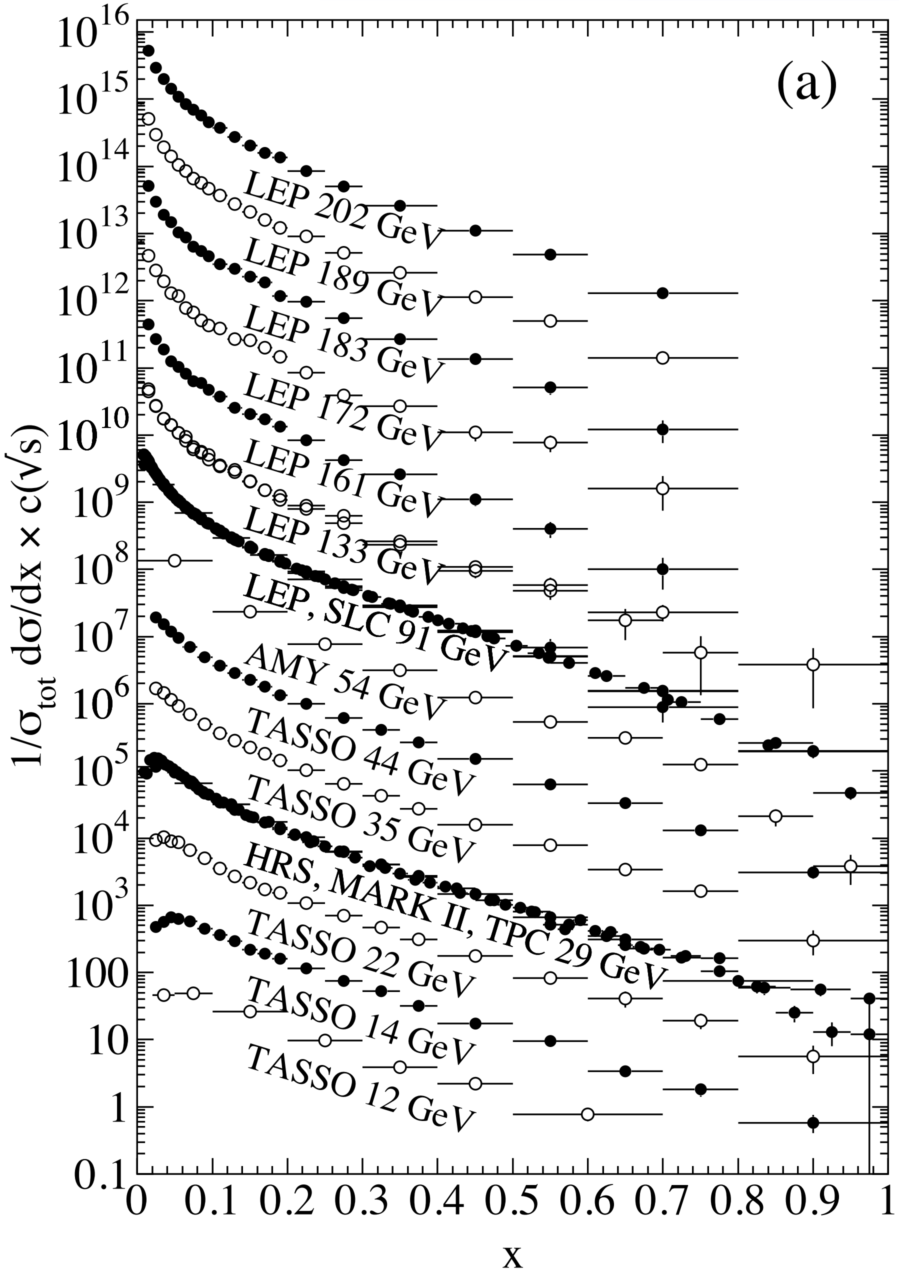
- POWHEG NLO Monte Carlo: 2→2 & 2→3 processes





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

Light Quark Fragmentation

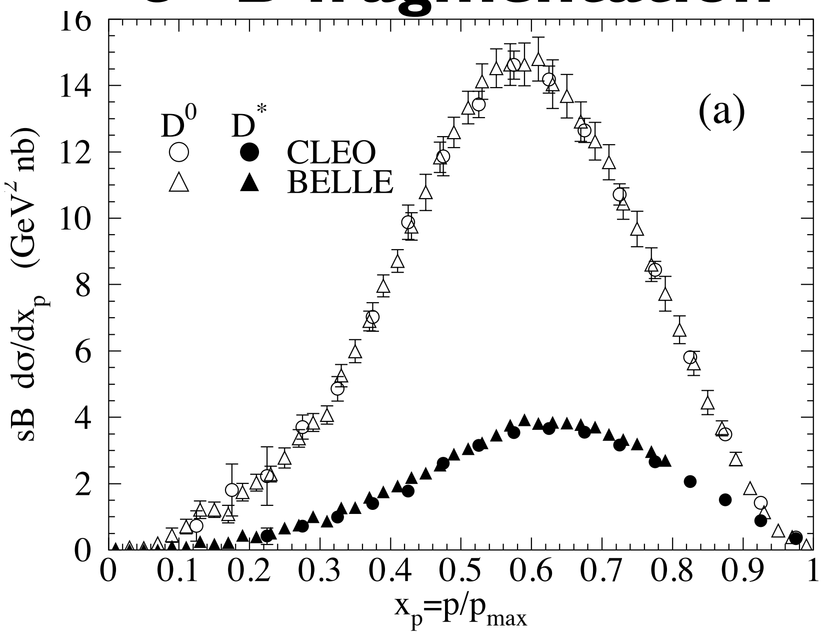


- fragmentation functions from e^+e^- collisions
- most particles carry small fraction of jet energy

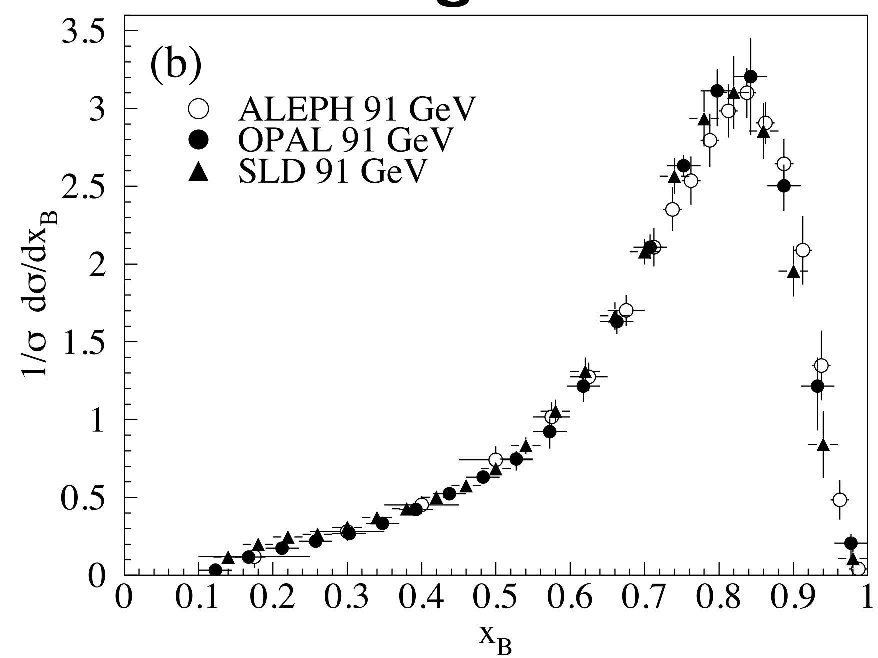
Particle Data Book

what about heavy quark jets?

c→D fragmentation



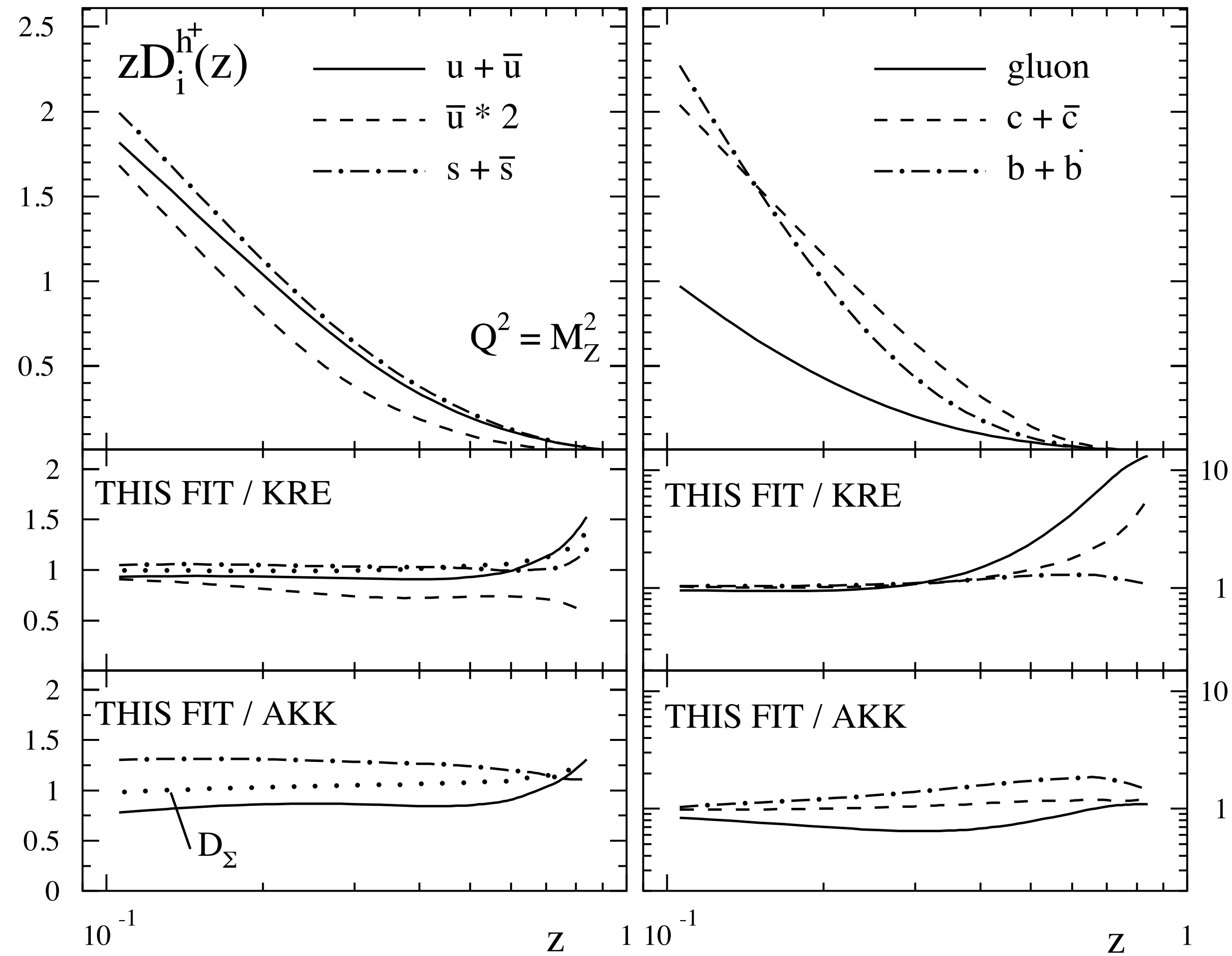
b→B fragmentation



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

Particle Data Book

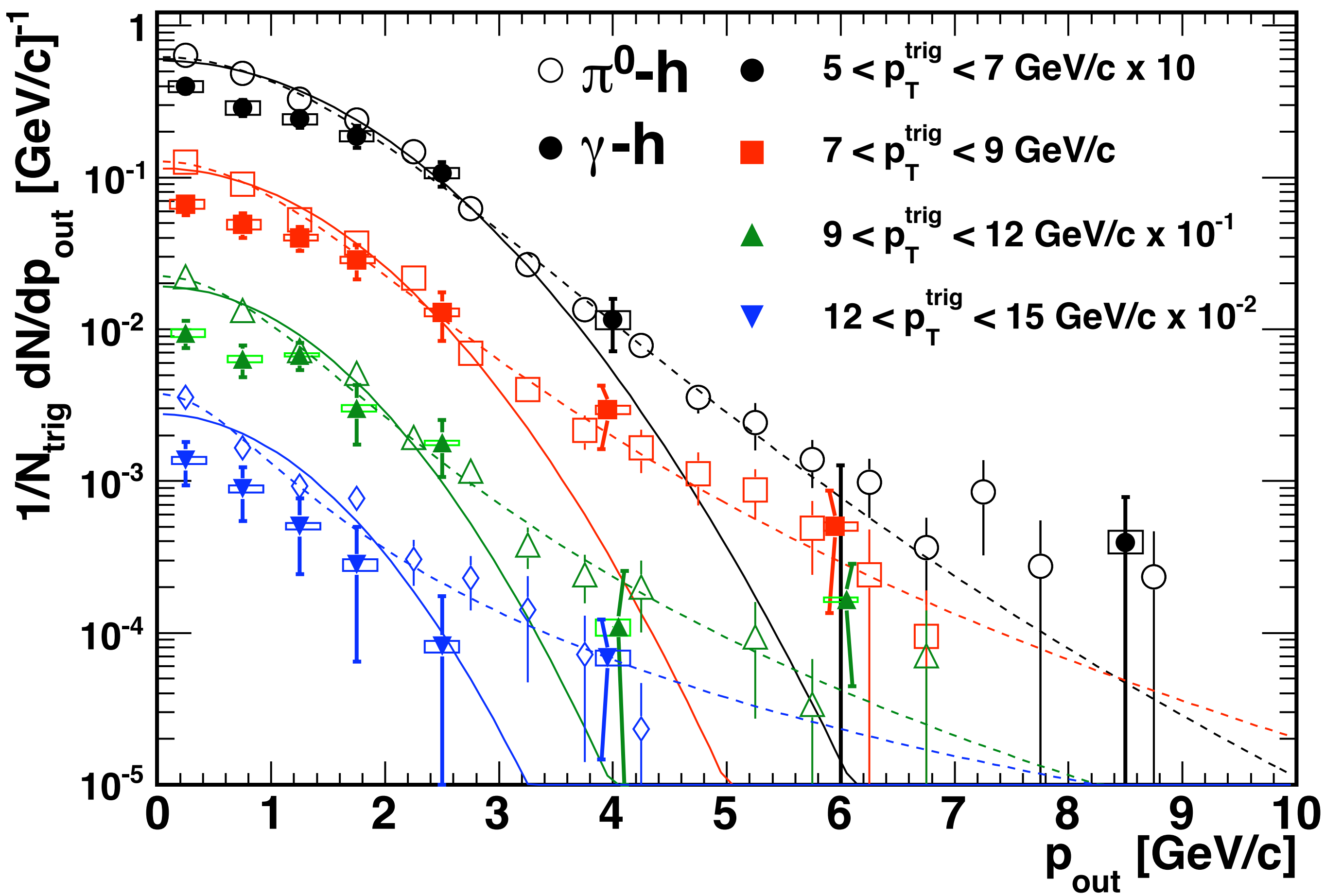
...and the rest of jet energy?



c,b → hadrons softer than q, g jets

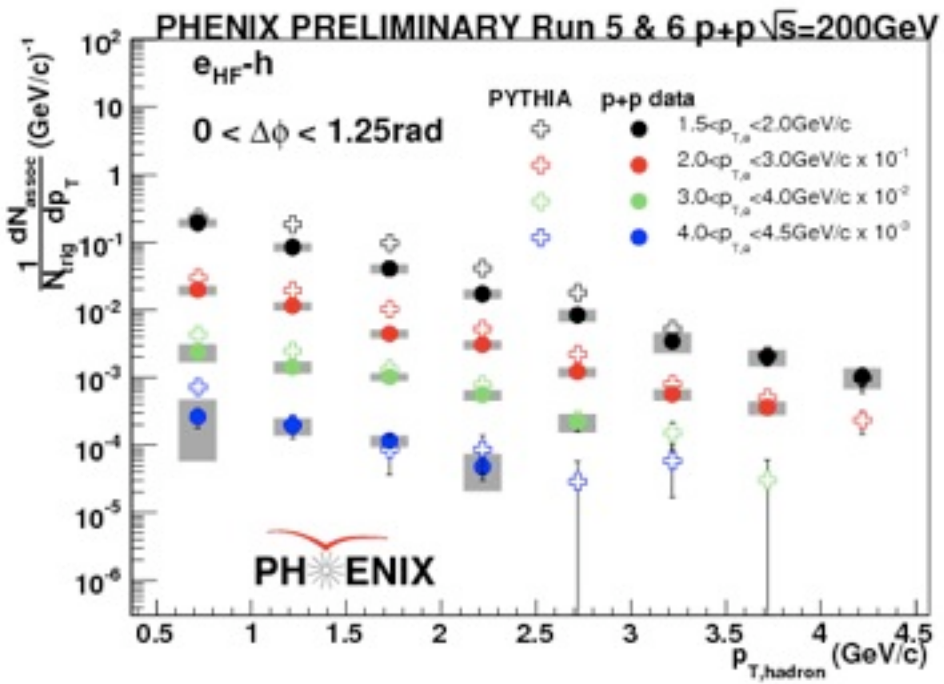
de Florian et al PRD 76 074033 (2007)

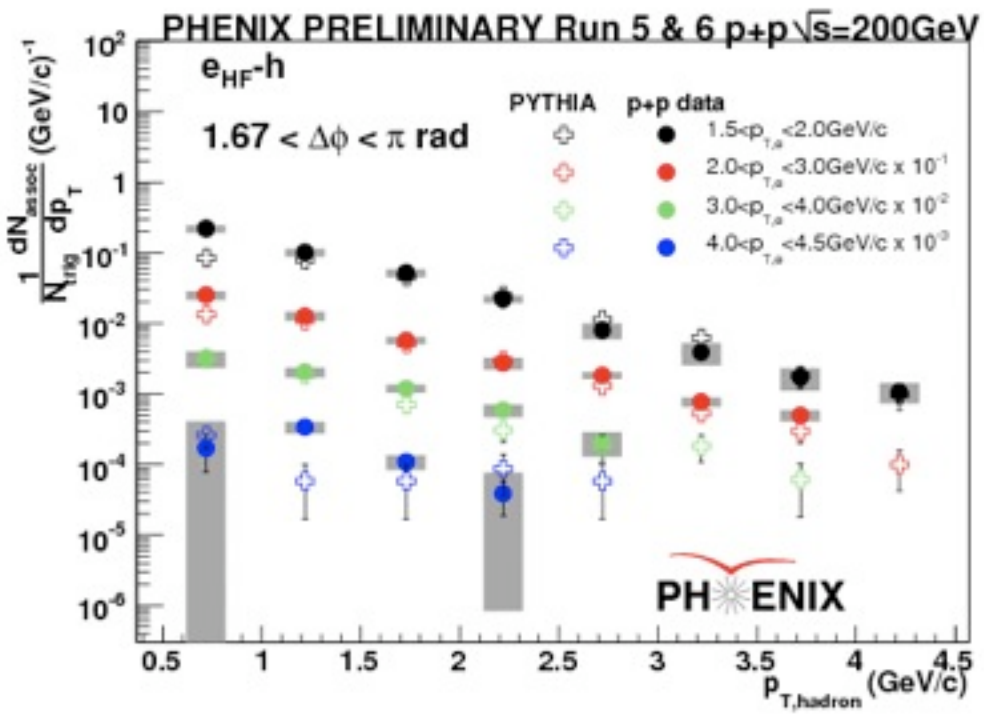
matt's results



PHENIX: 1006.1347

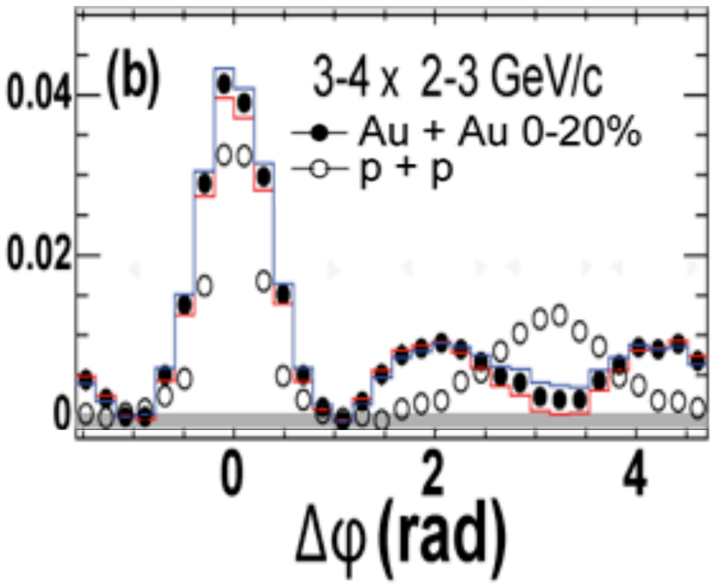
conditional yields





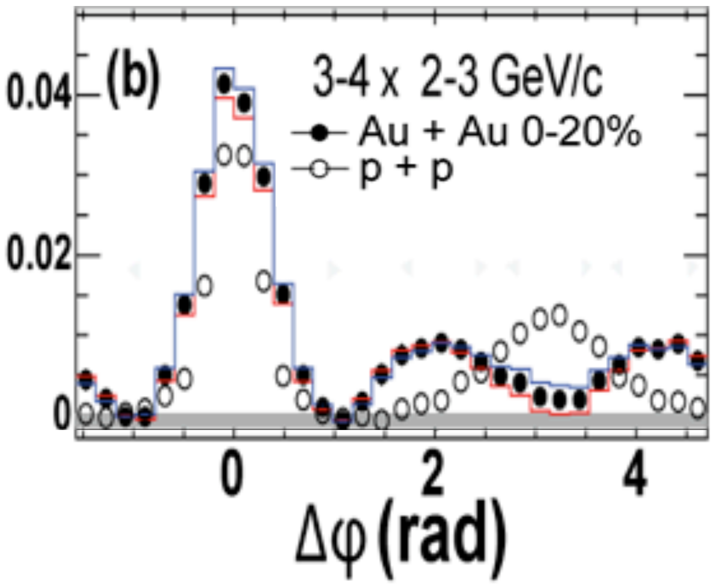
- near side: heavy quarks, dominated by decays
- away side: heavy & light partons, fragmentation and decays

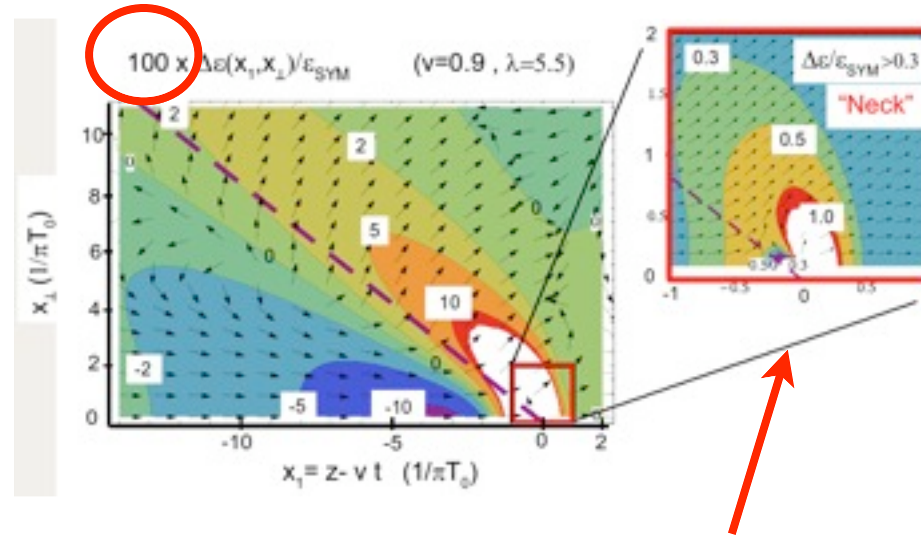
Double Peak Structure



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

Double Peak Structure

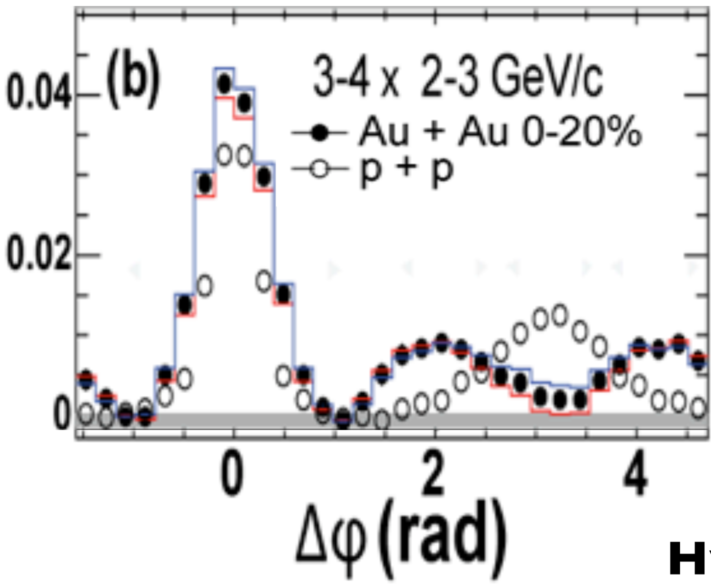


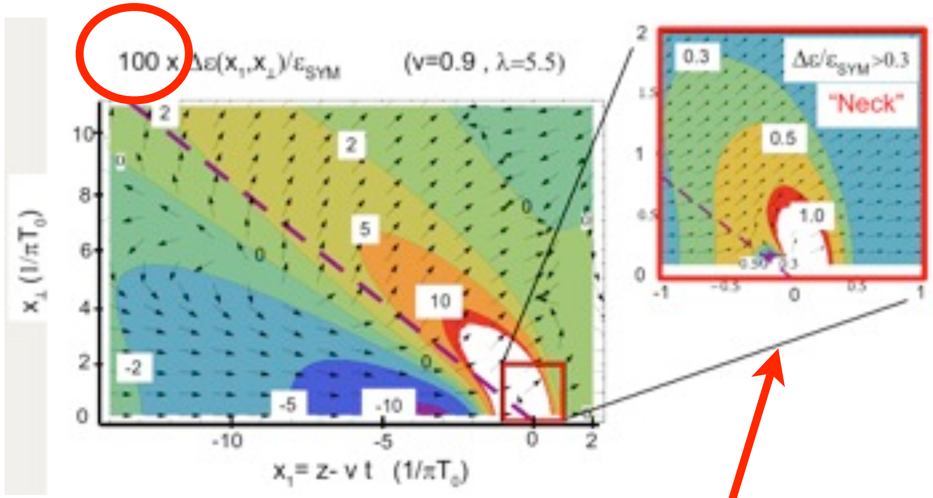


AdS/CFT: Correlations from Neck region

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

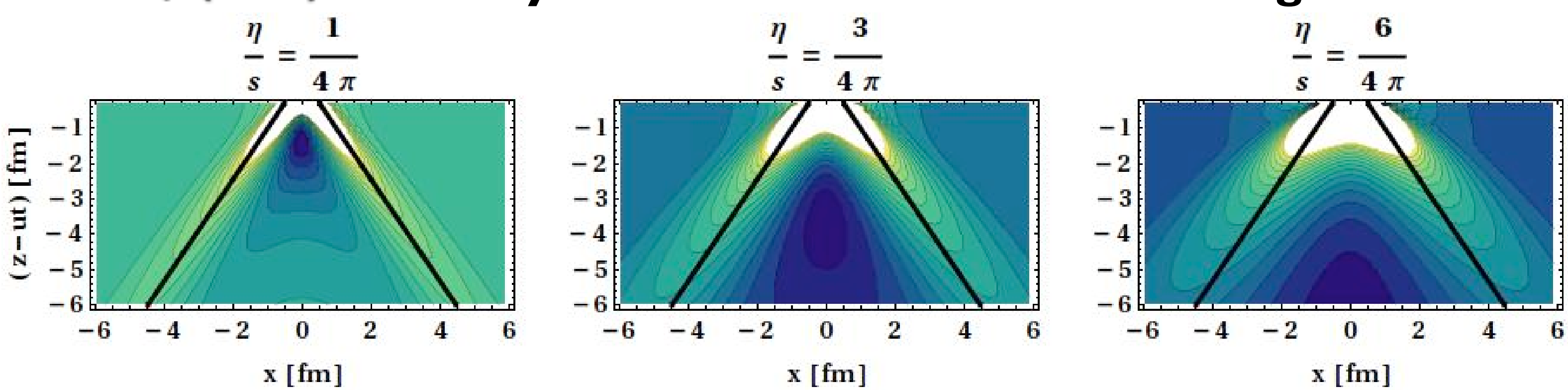
Double Peak Structure





AdS/CFT: Correlations from Neck region

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



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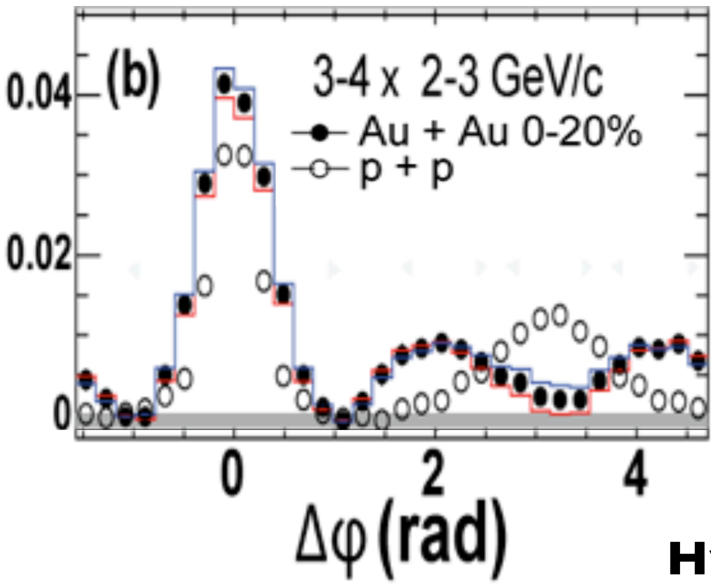

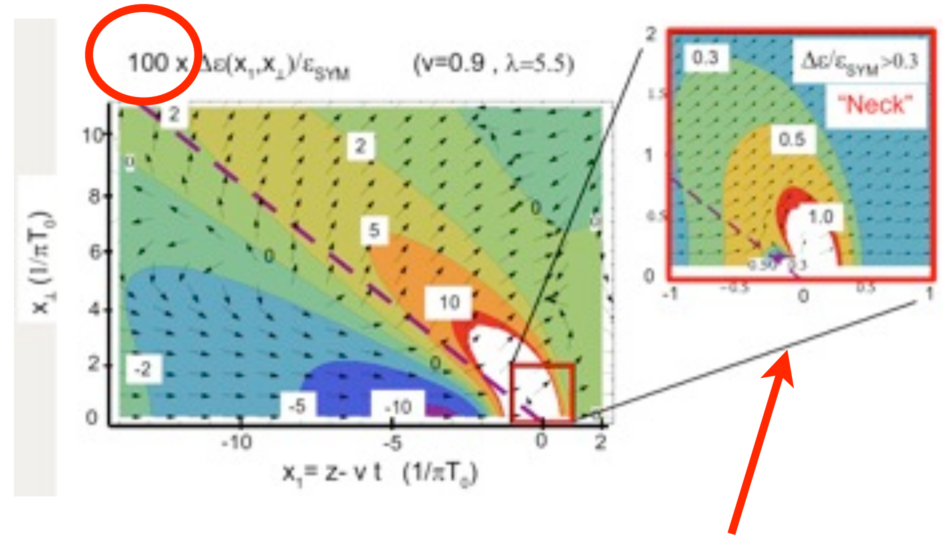

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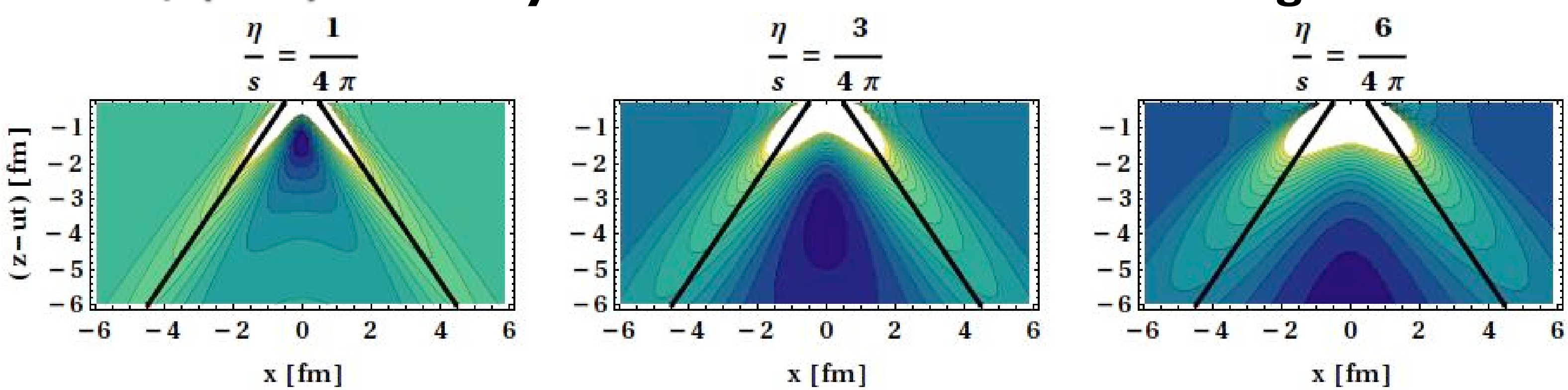

Heavy quark correlations should help discriminate!

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

RAA of hadrons