Correlations of Heavy Flavor Electrons in Au+Au & p+p Collisions in PHENIX

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January 25, 2011

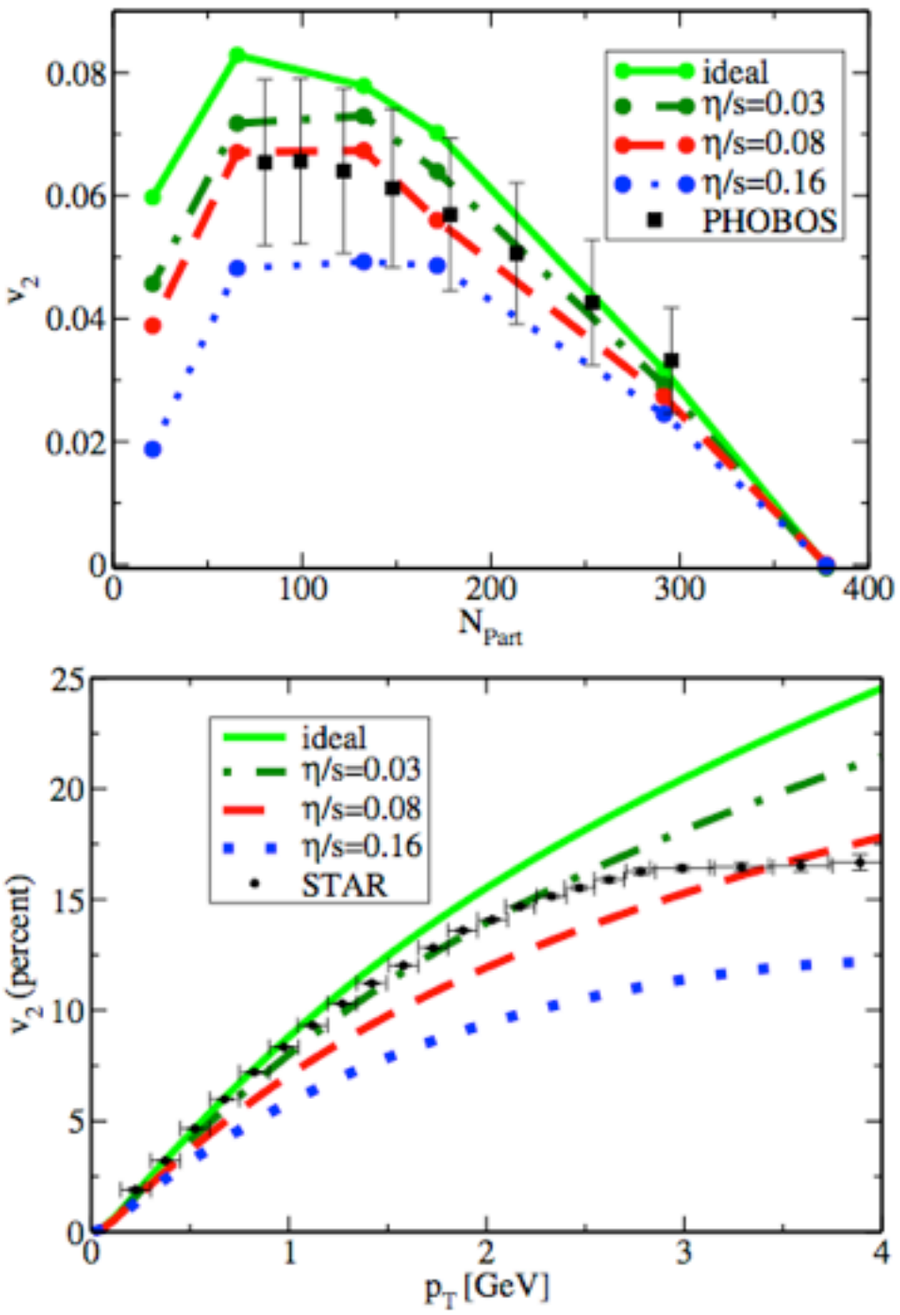
PHENIX arXiv:1011.1477

BROOKHAVEN
NATIONAL LABORATORY

why heavy ion collisions?

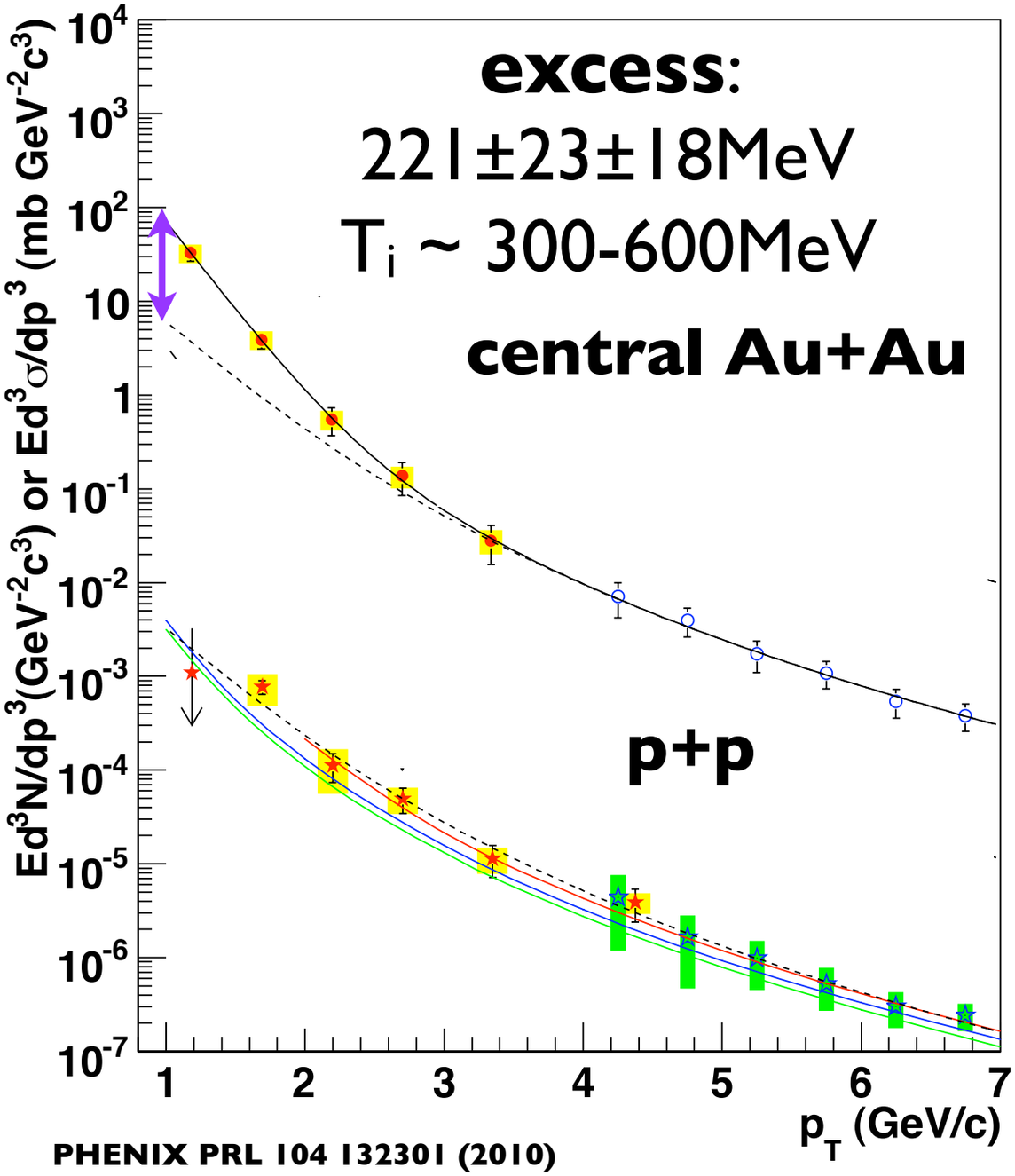
- what happens to dense QCD matter at extremely high temperature?

hot nuclear matter



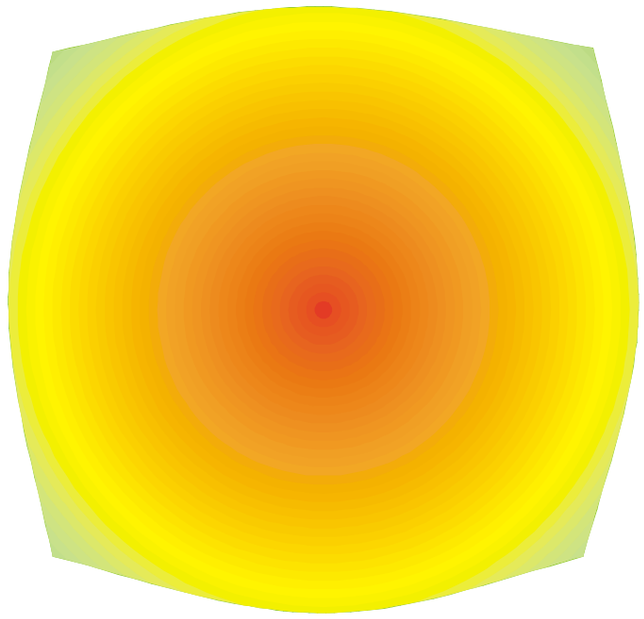
Romatschke & Romatschke PRL 99 172301 (2007)

Direct γ* (via e^+e^-)



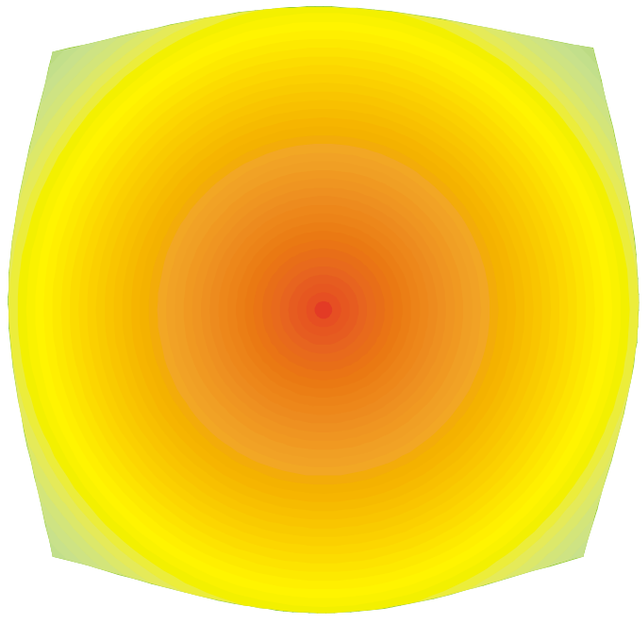
PHENIX PRL 104 132301 (2010)

What is our goal?



What is our goal?

parton$_i$(E)



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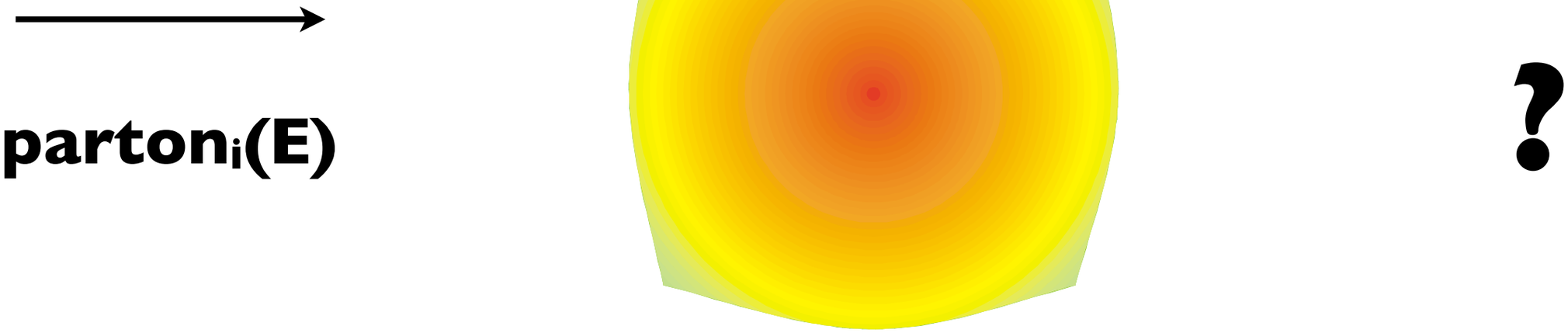

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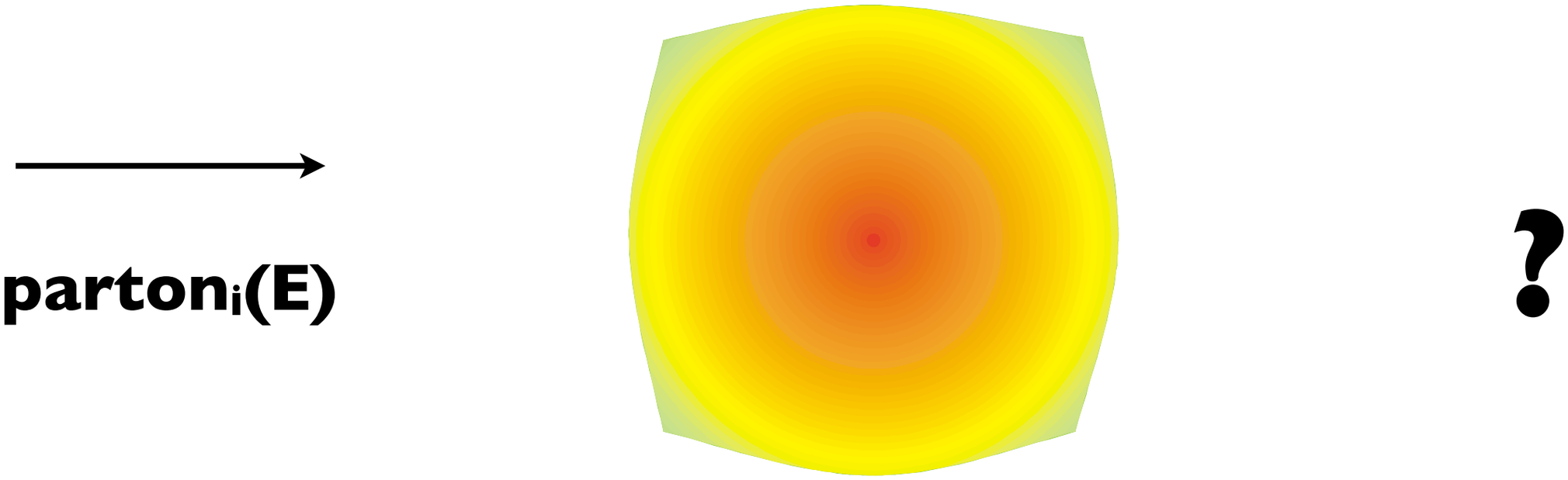

→determine the mechanism(s) of energy loss

→determine the strength of the interactions

reality more complicated

reality more complicated

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

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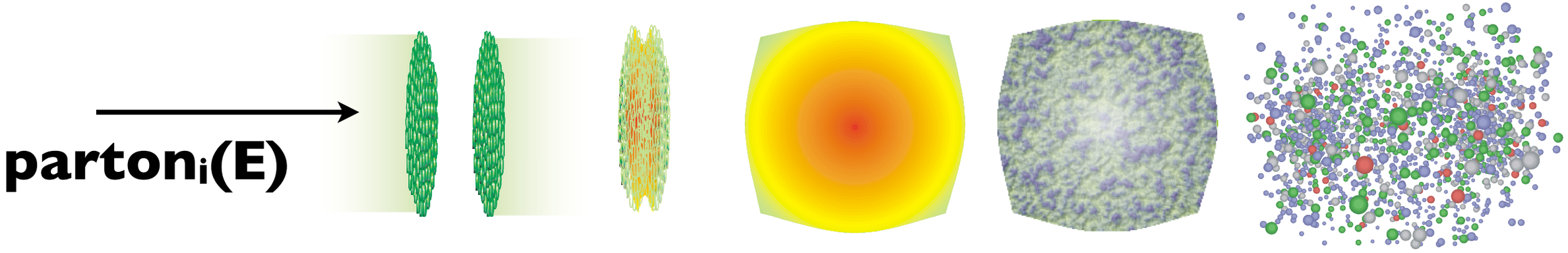

reality more complicated

geometry, intial state effects, time evolution,
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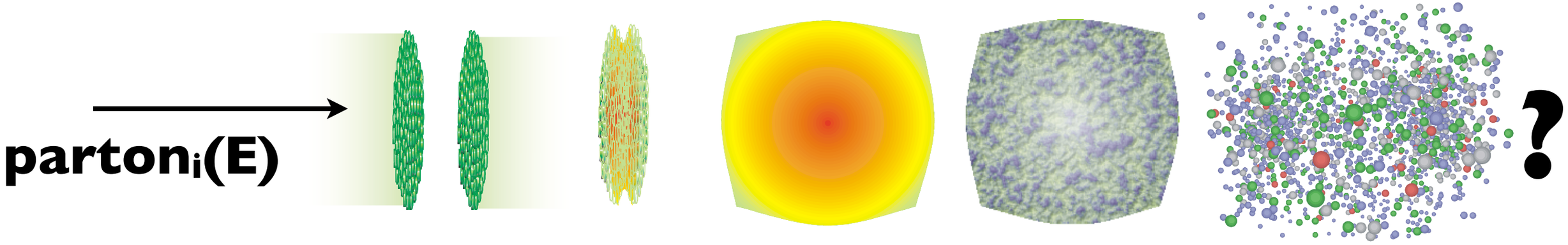
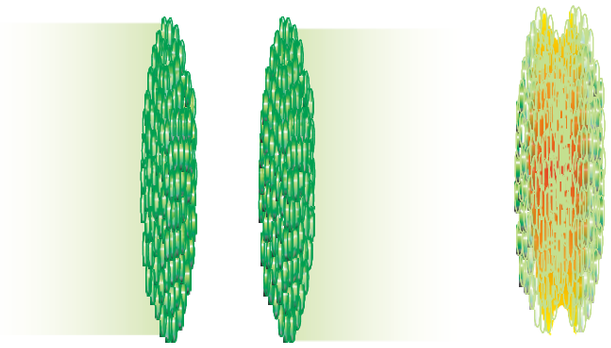


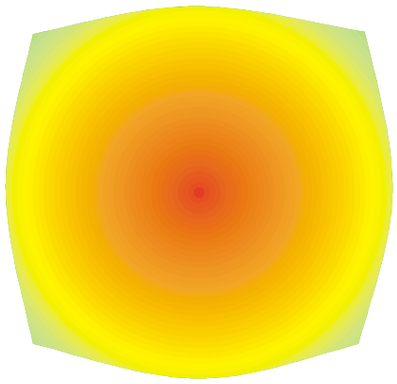
approaching realistic models

initial conditions
Glauber
CGC

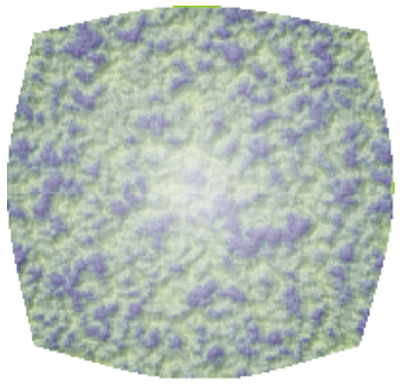


pre-equilibrium

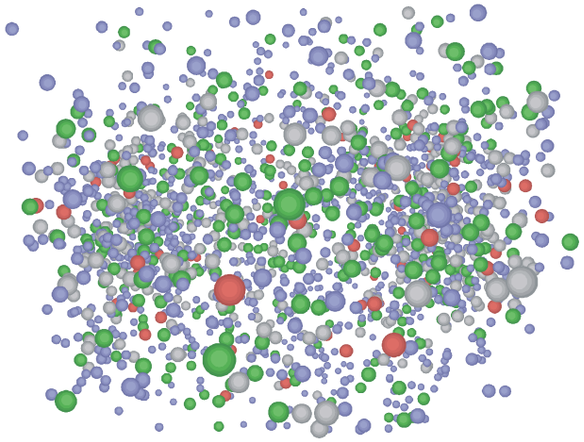
sQGP



hadronization



freeeze out

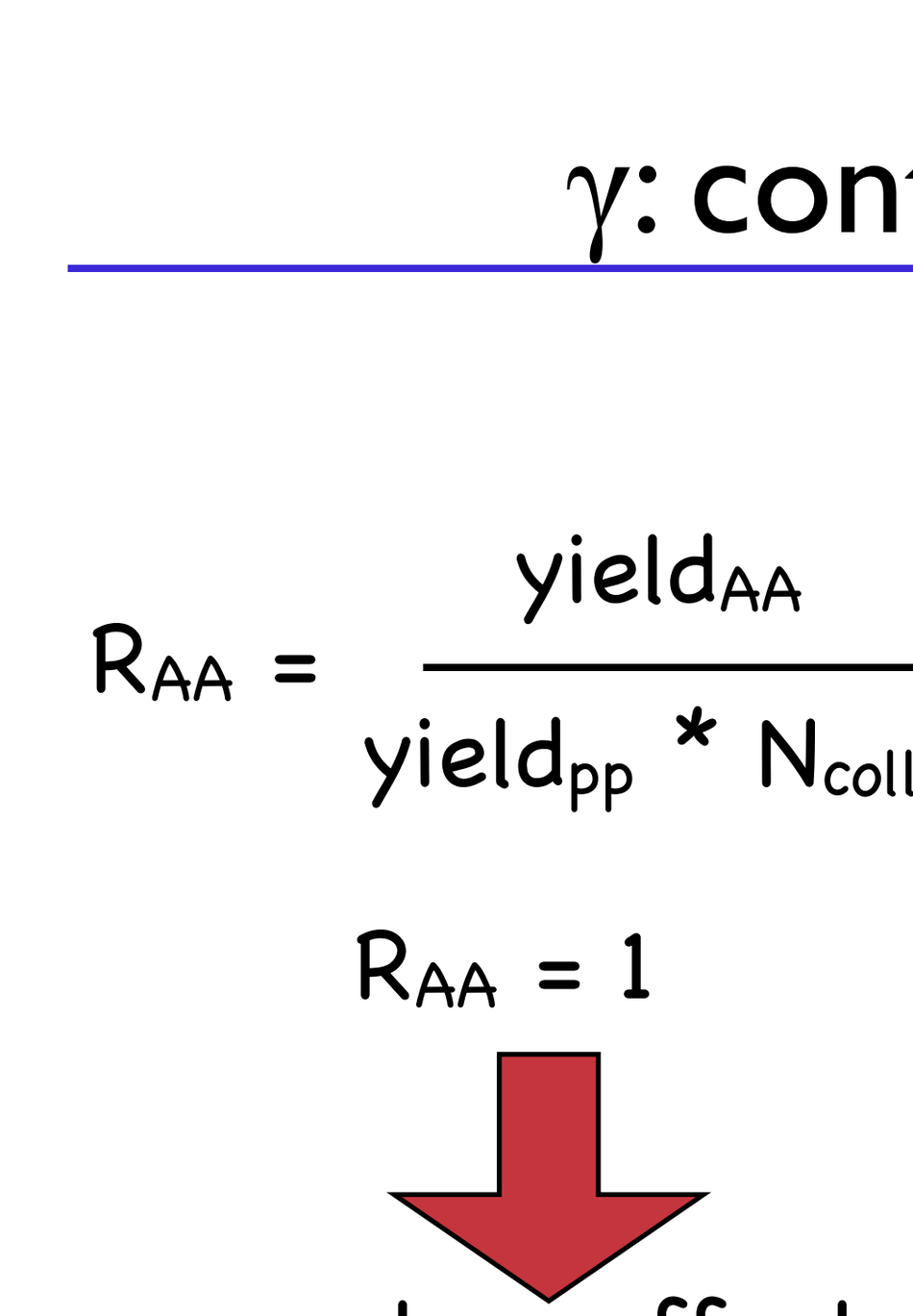


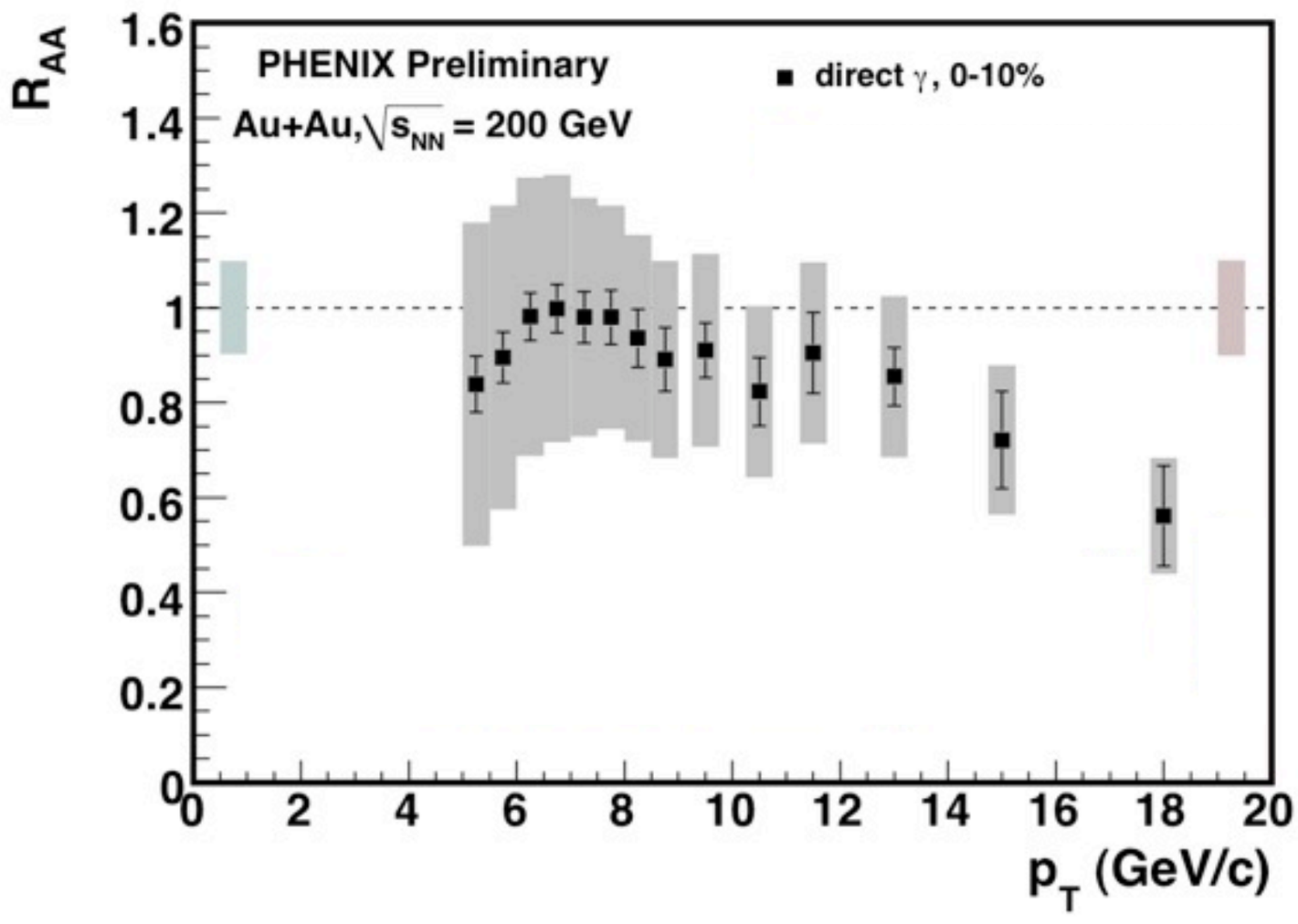
any colored probe interacts in all phases of the collision!

γ: control measurement

$$R_{AA} = \frac{\text{yield}_{AA}}{\text{yield}_{pp} * N_{coll}}$$

$R_{AA} = 1$



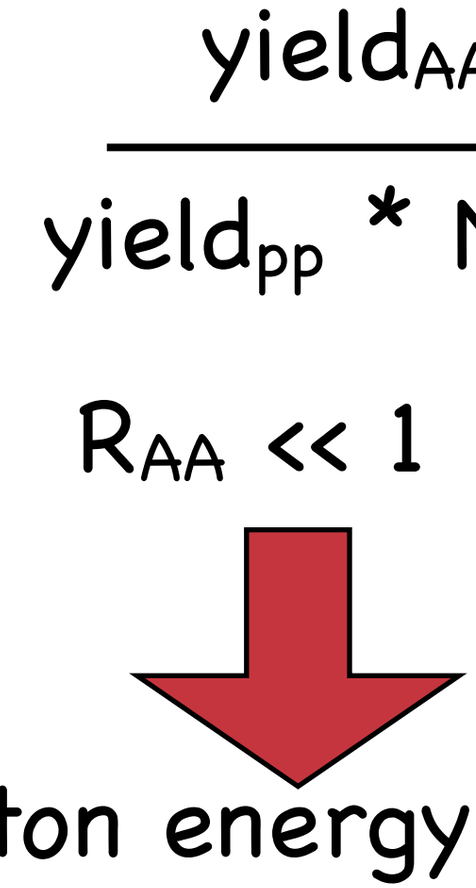


γ: no color charge → insensitive to produced matter
$R_{AA}(p_T<14\text{GeV/c})$ consistent with unity

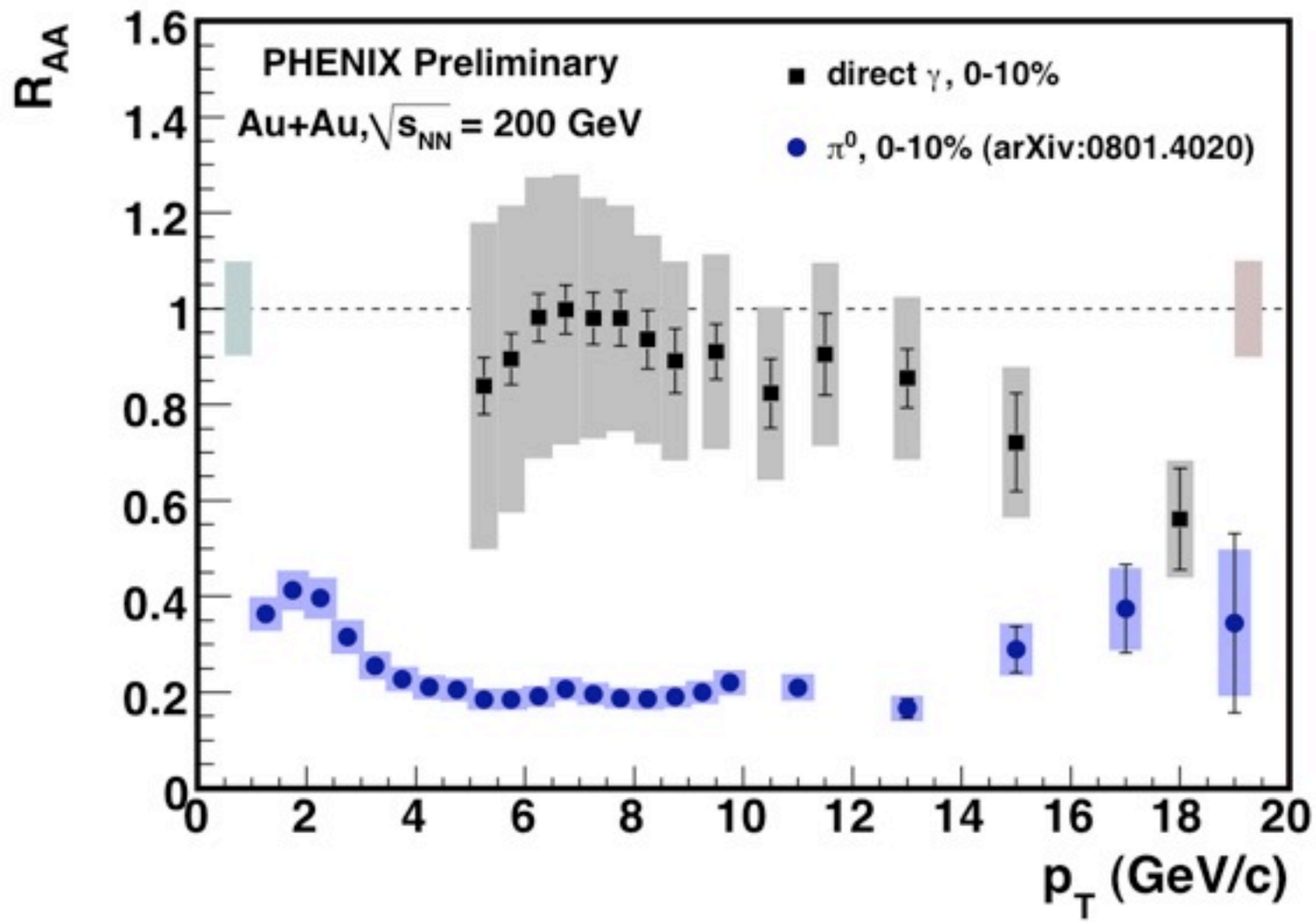
π^0 R_{AA}

$$R_{AA} = \frac{\text{yield}_{AA}}{\text{yield}_{pp} * N_{coll}}$$

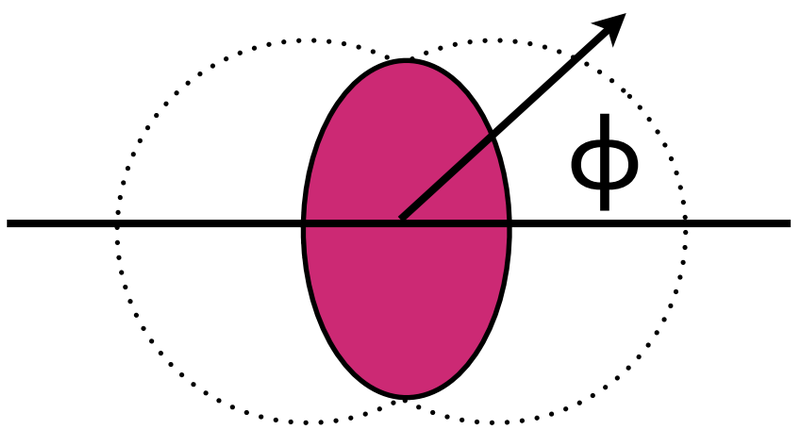
$R_{AA} << 1$

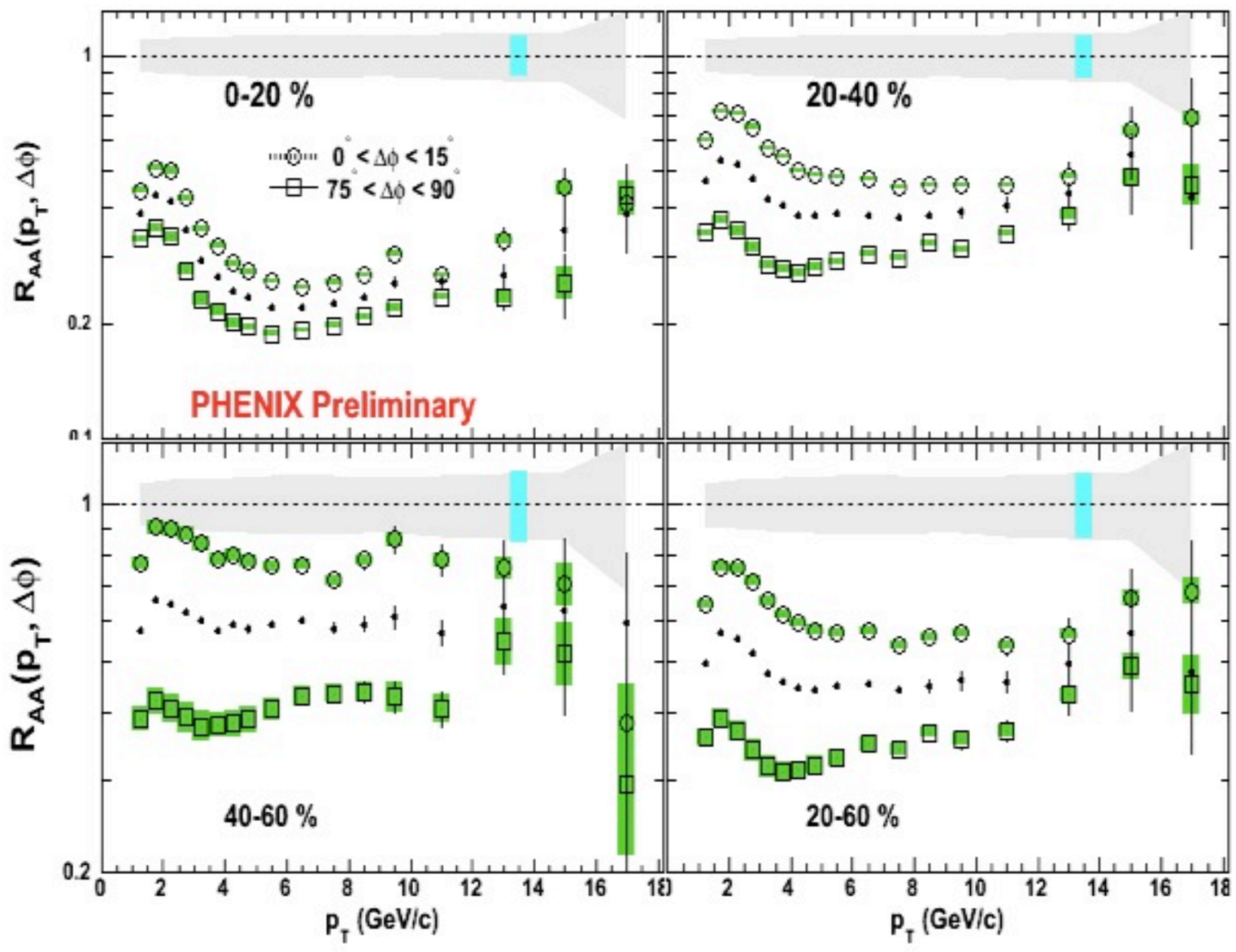


parton energy loss

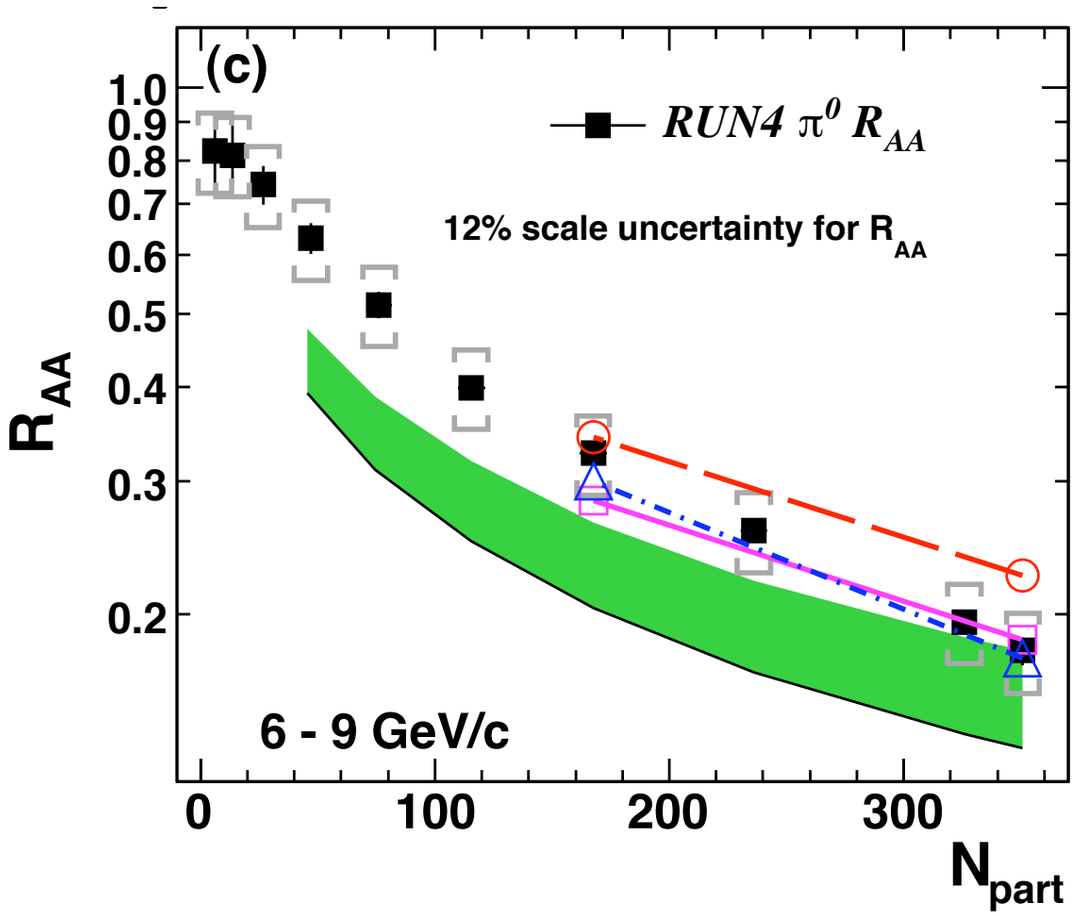


path length dependence to R_{AA}





models which get R_{AA} right...



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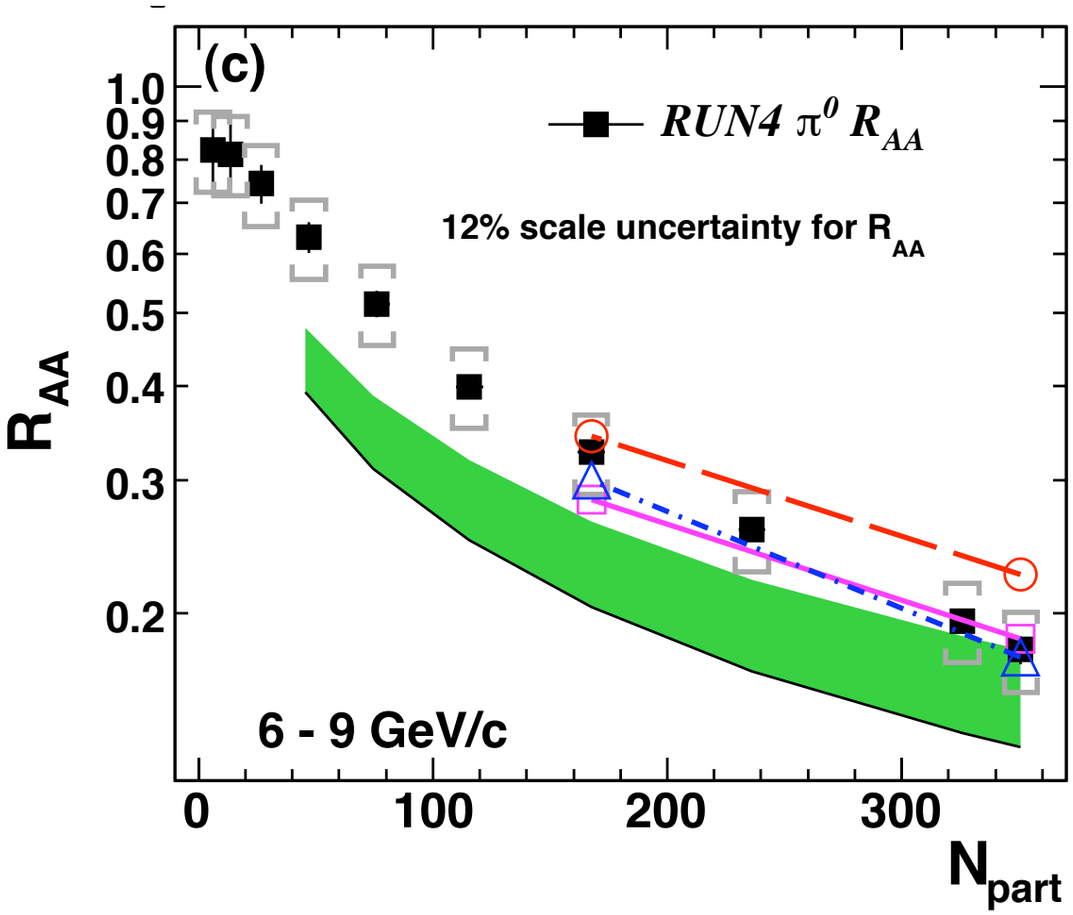

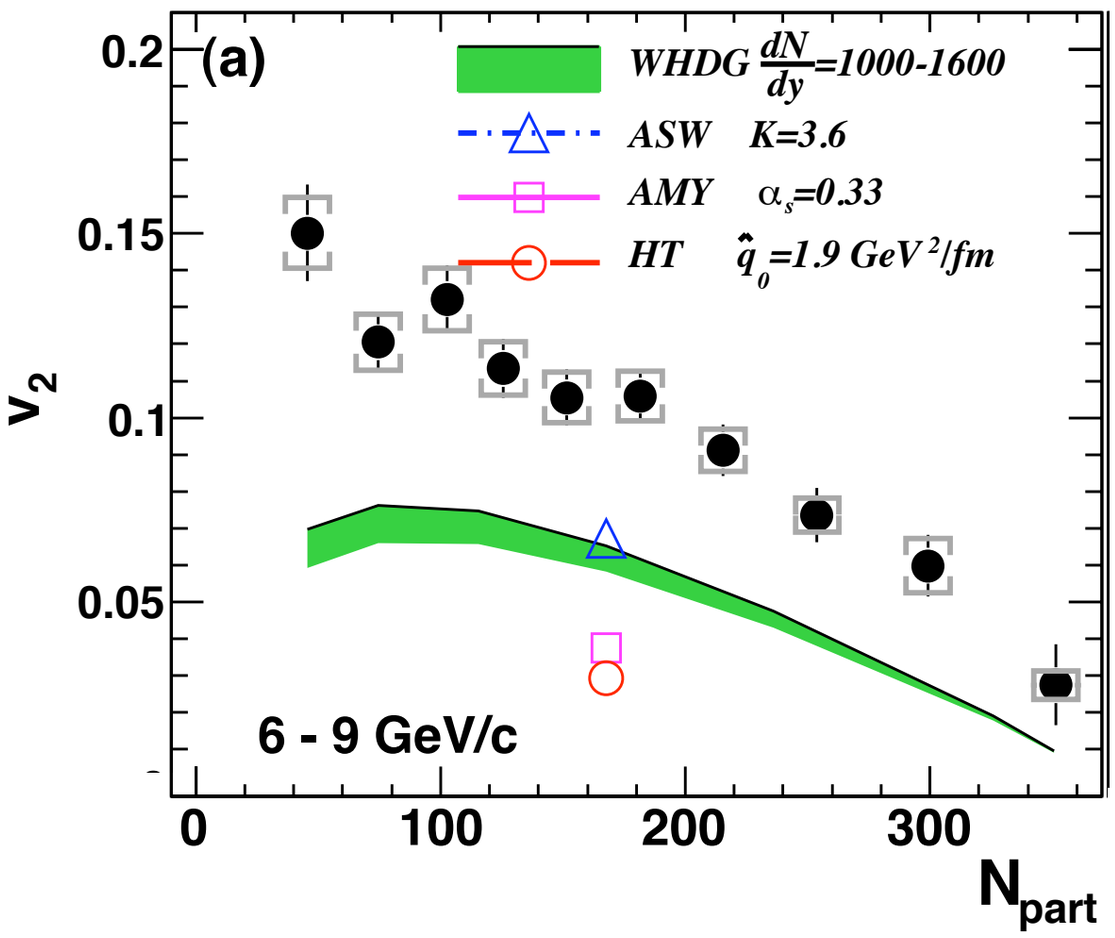

...under predict v_2

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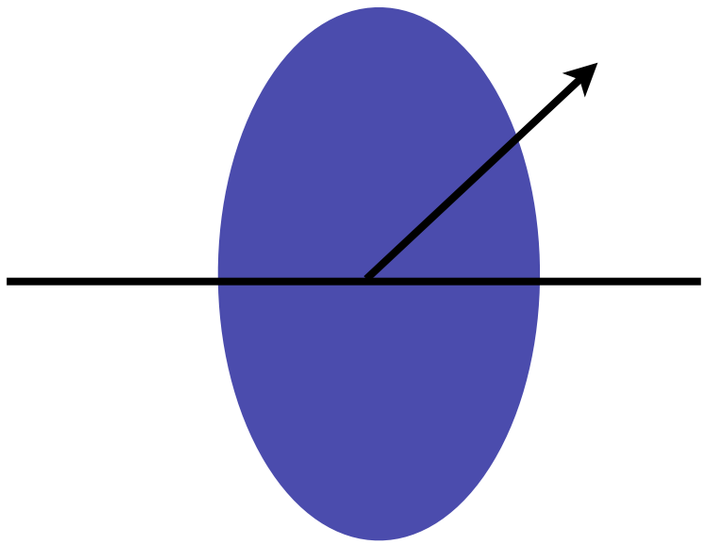
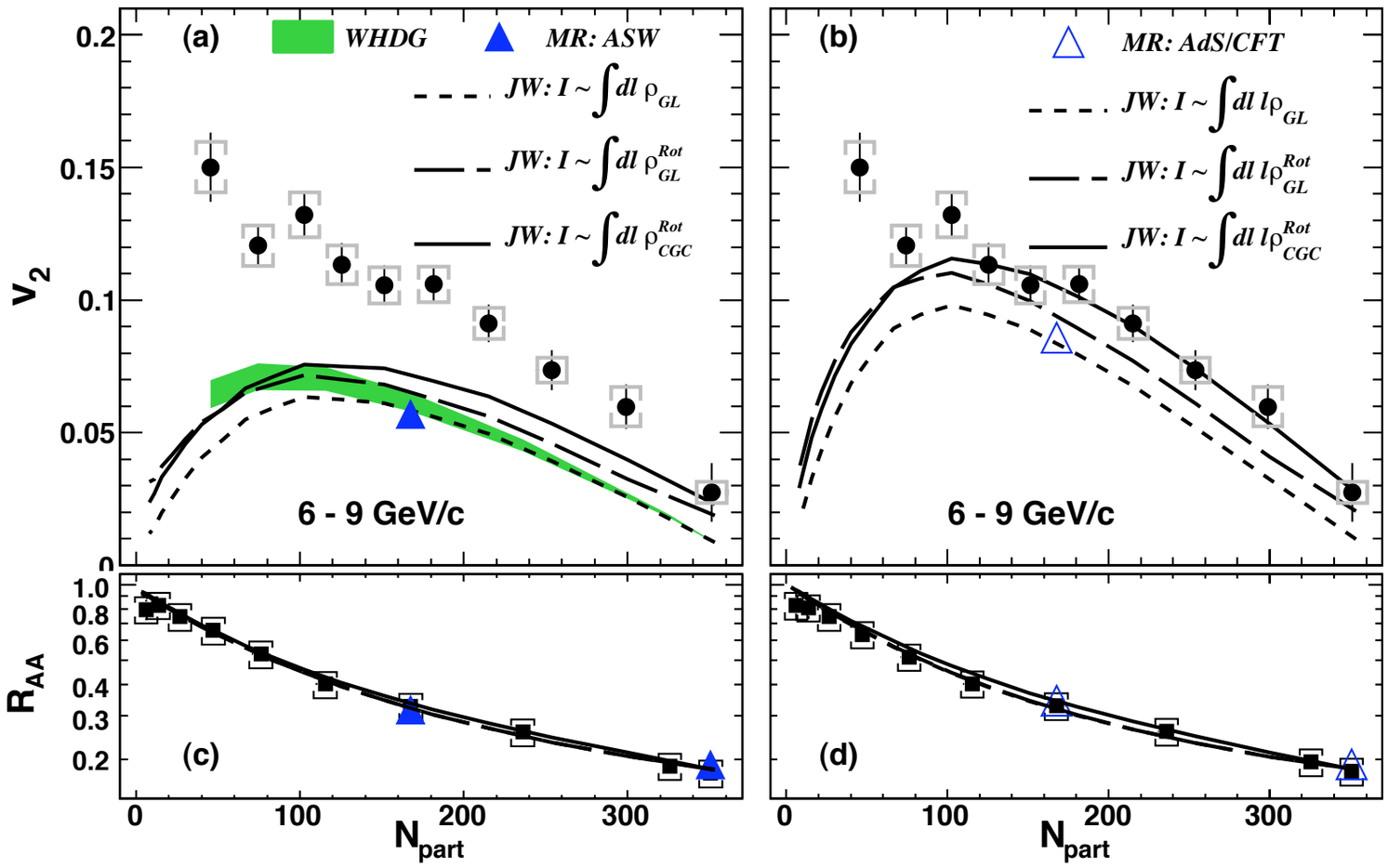
reaction plane: a closer look





points to very strong path length dependence

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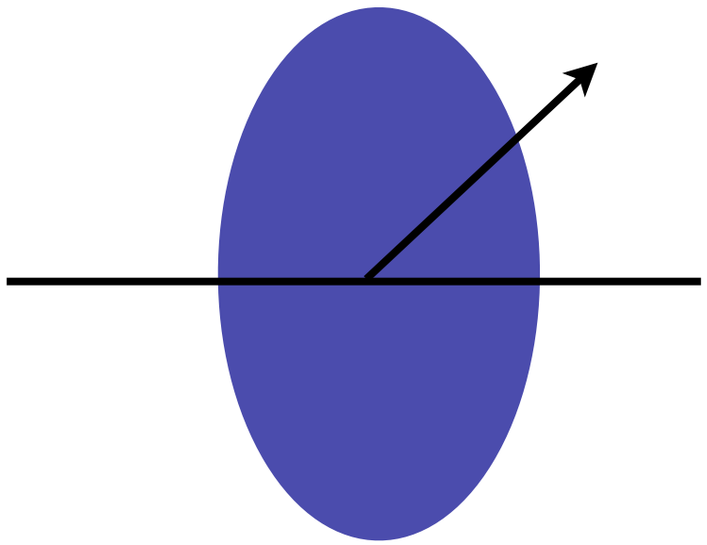

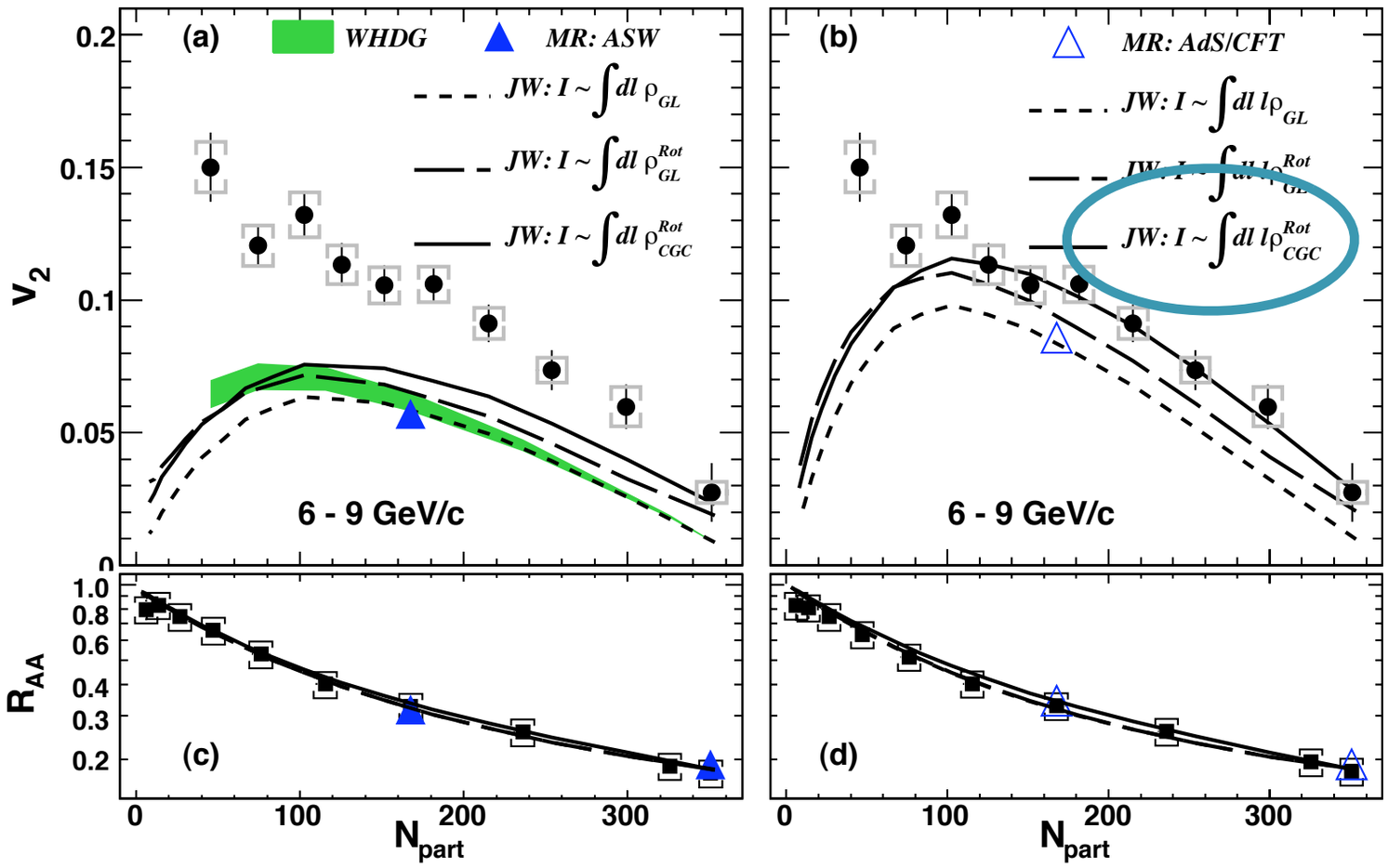

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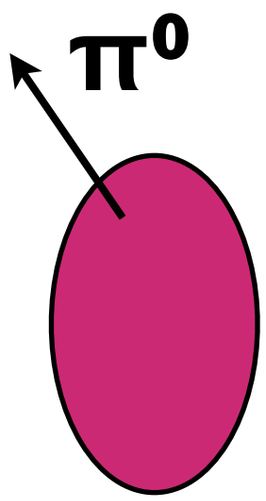
I_{AA}: di-jet suppression



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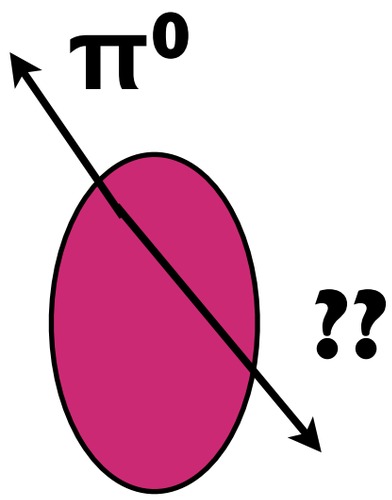

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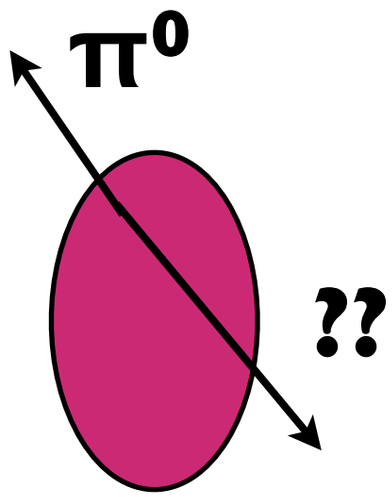

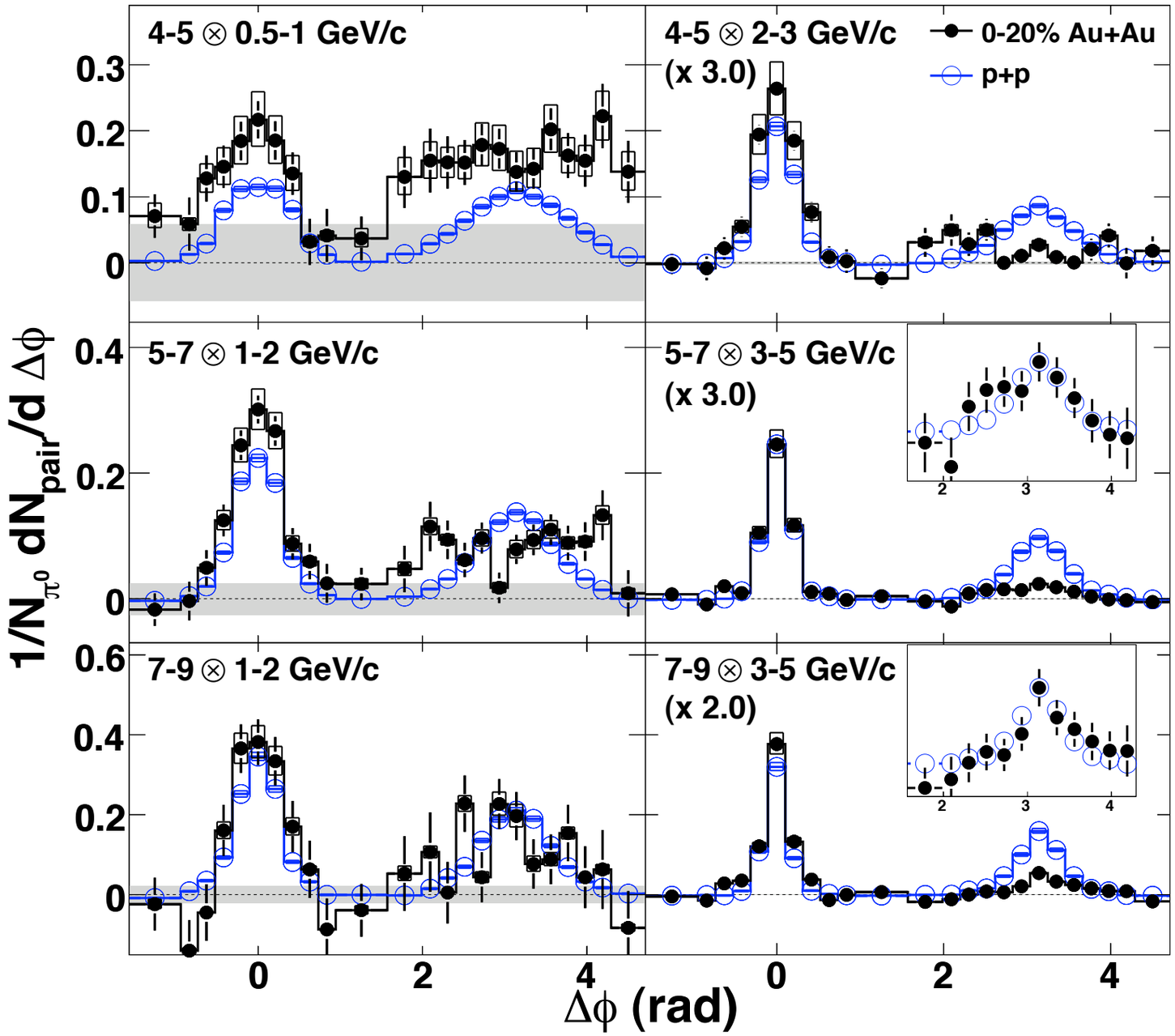

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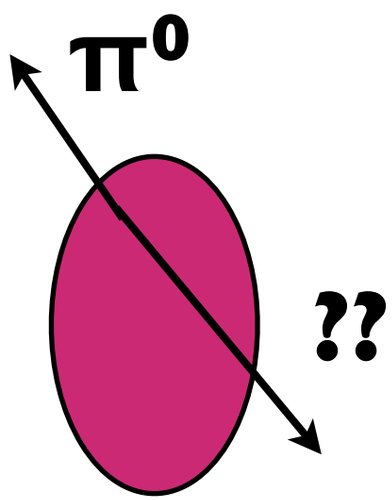
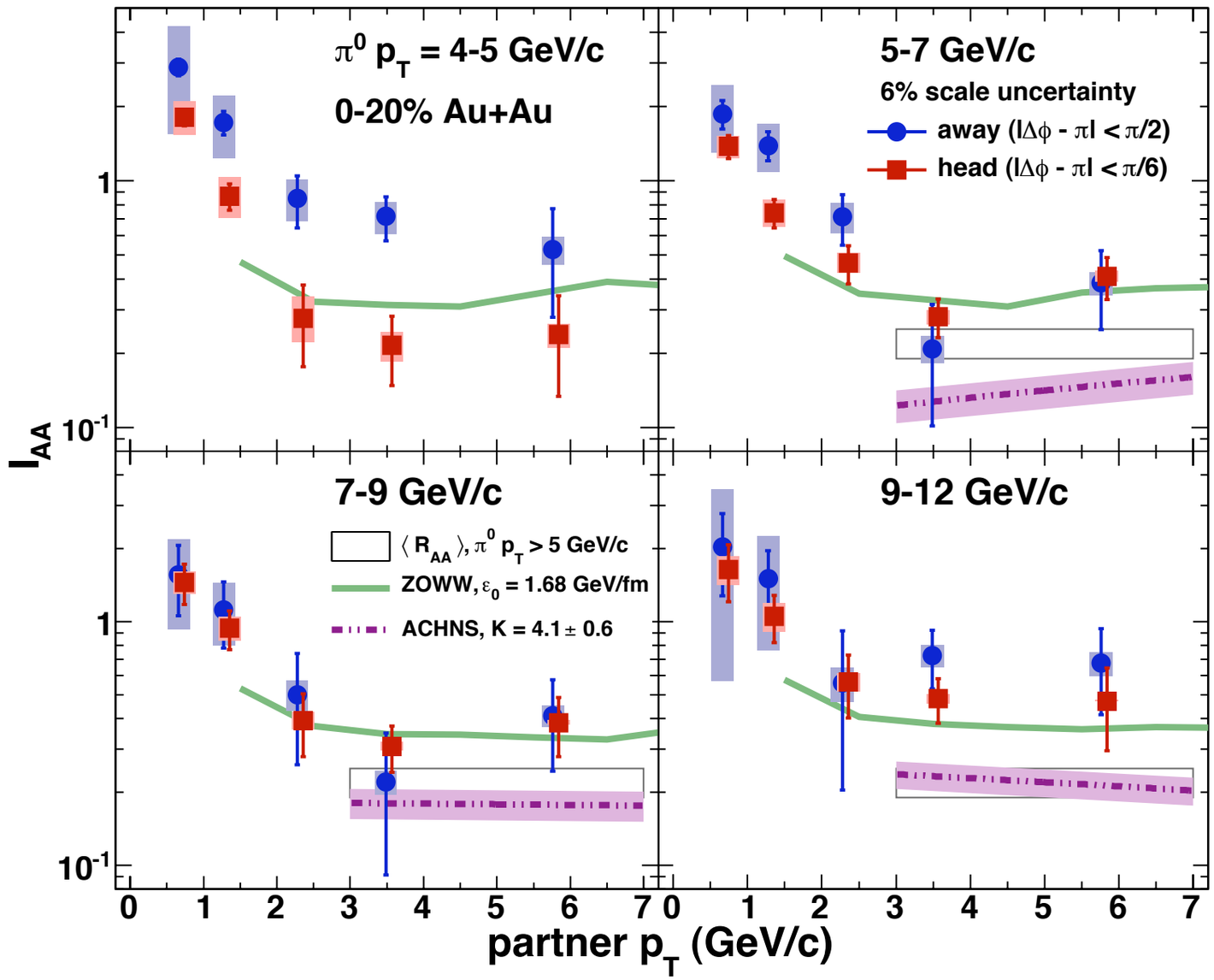
IAA





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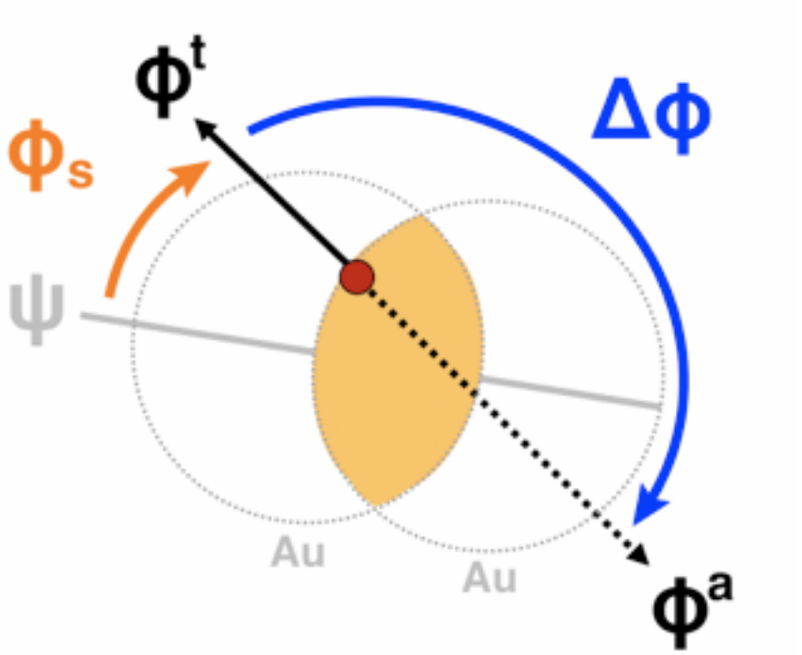
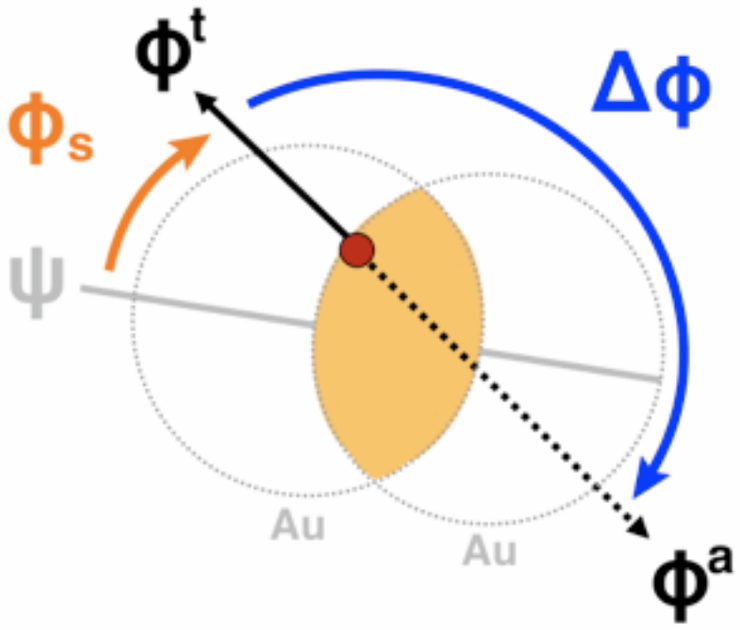
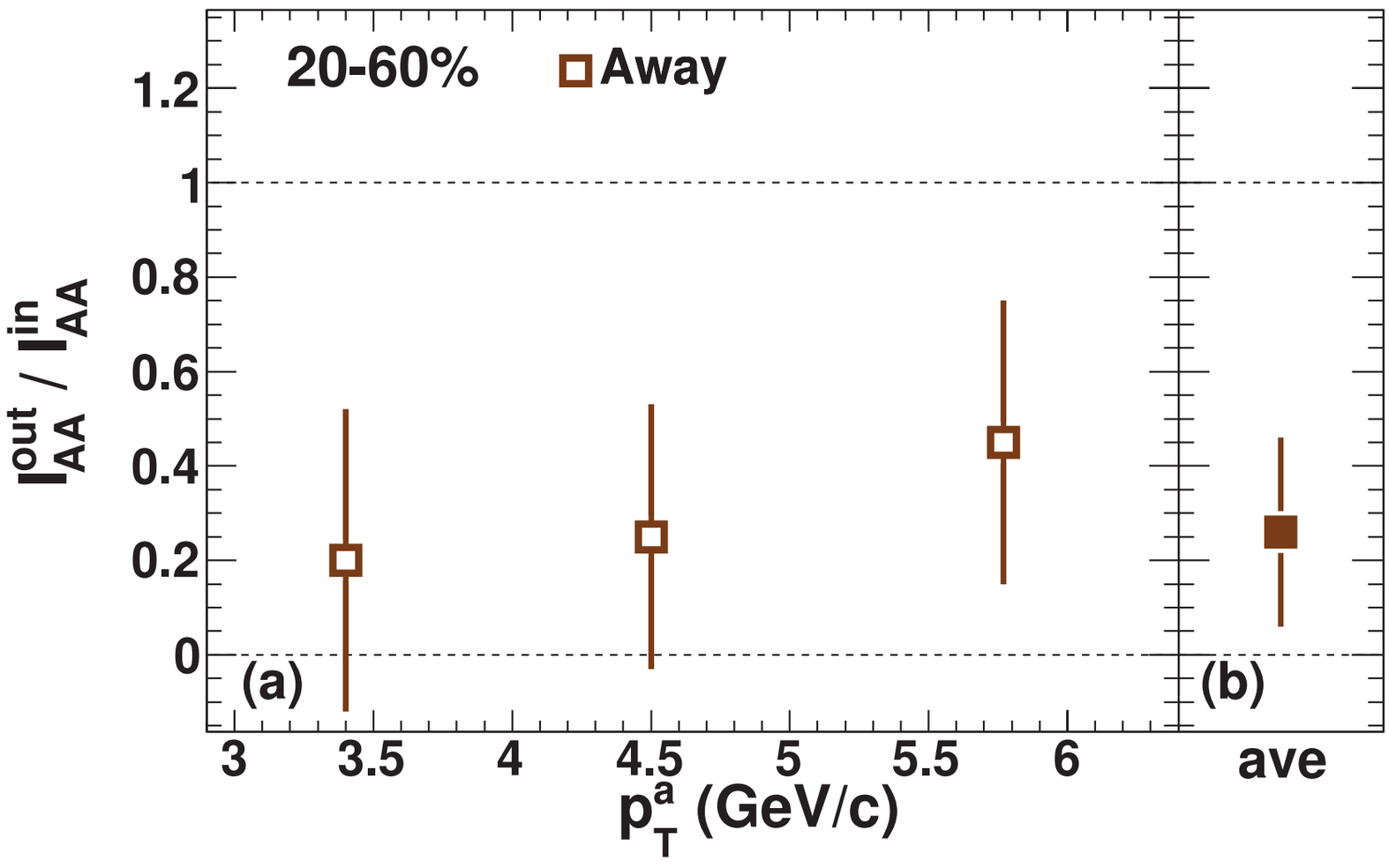
same message from I_{AA}



PHENIX 1010.1521

same message from I_{AA}





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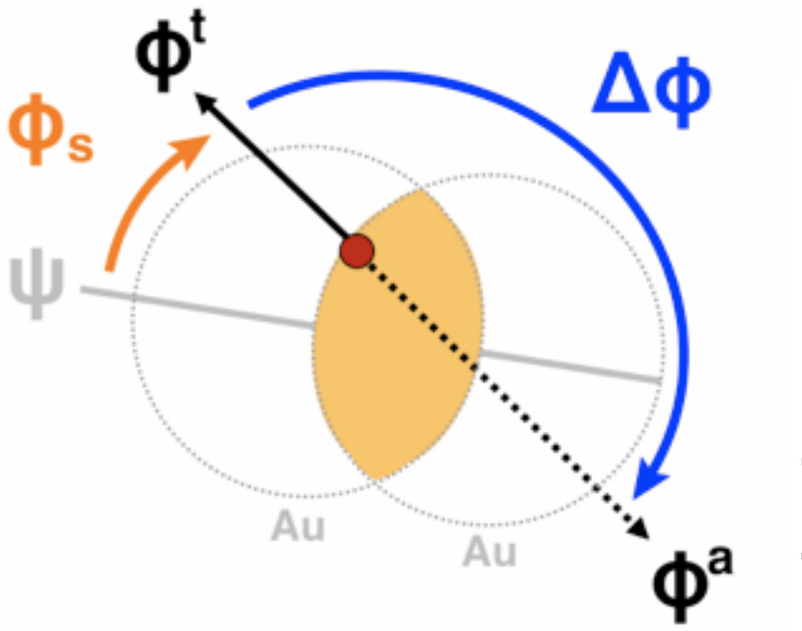
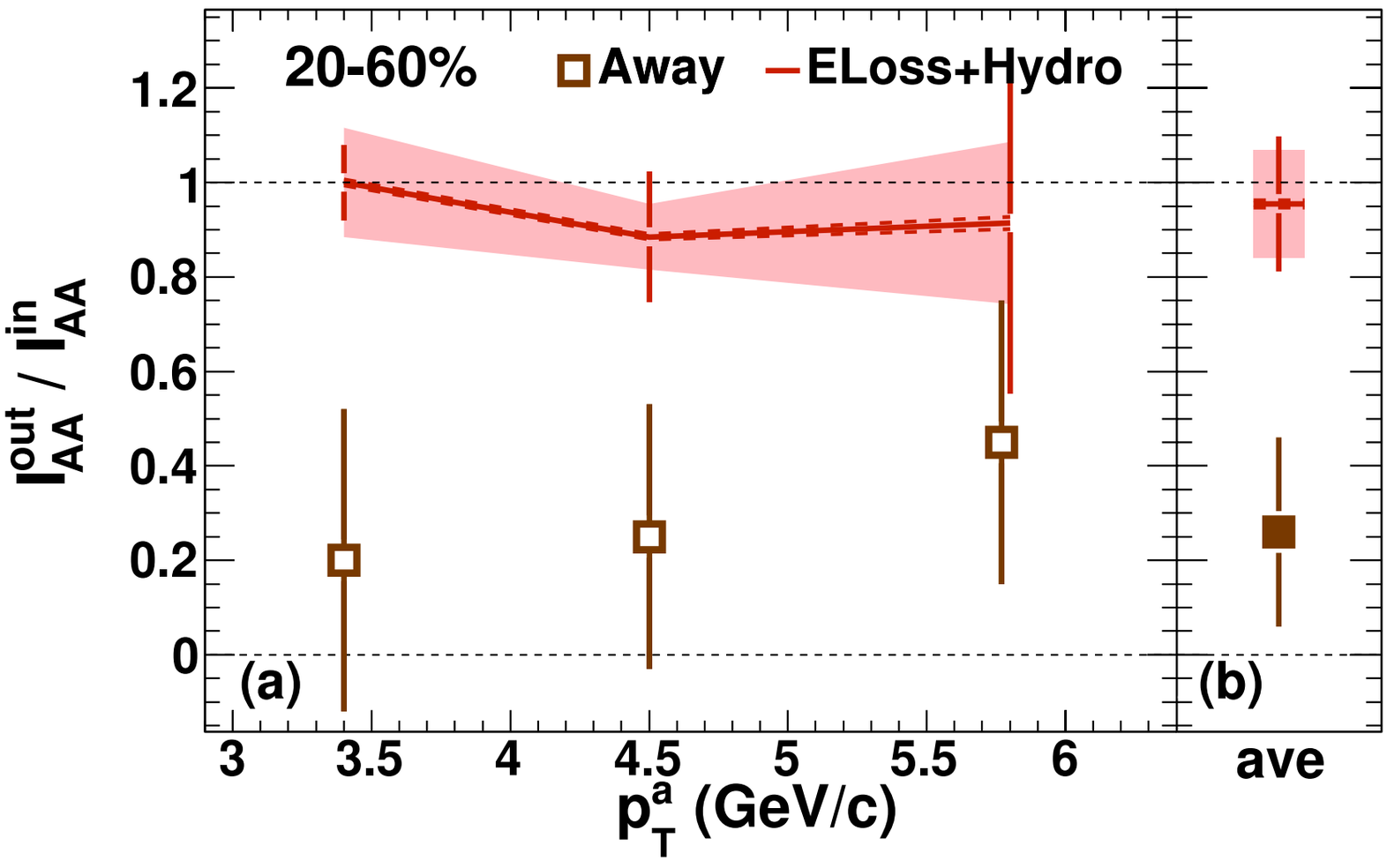




energy loss calculation from Renk in 2 hydro codes
(Nokana & Bass and Eskola et al.)

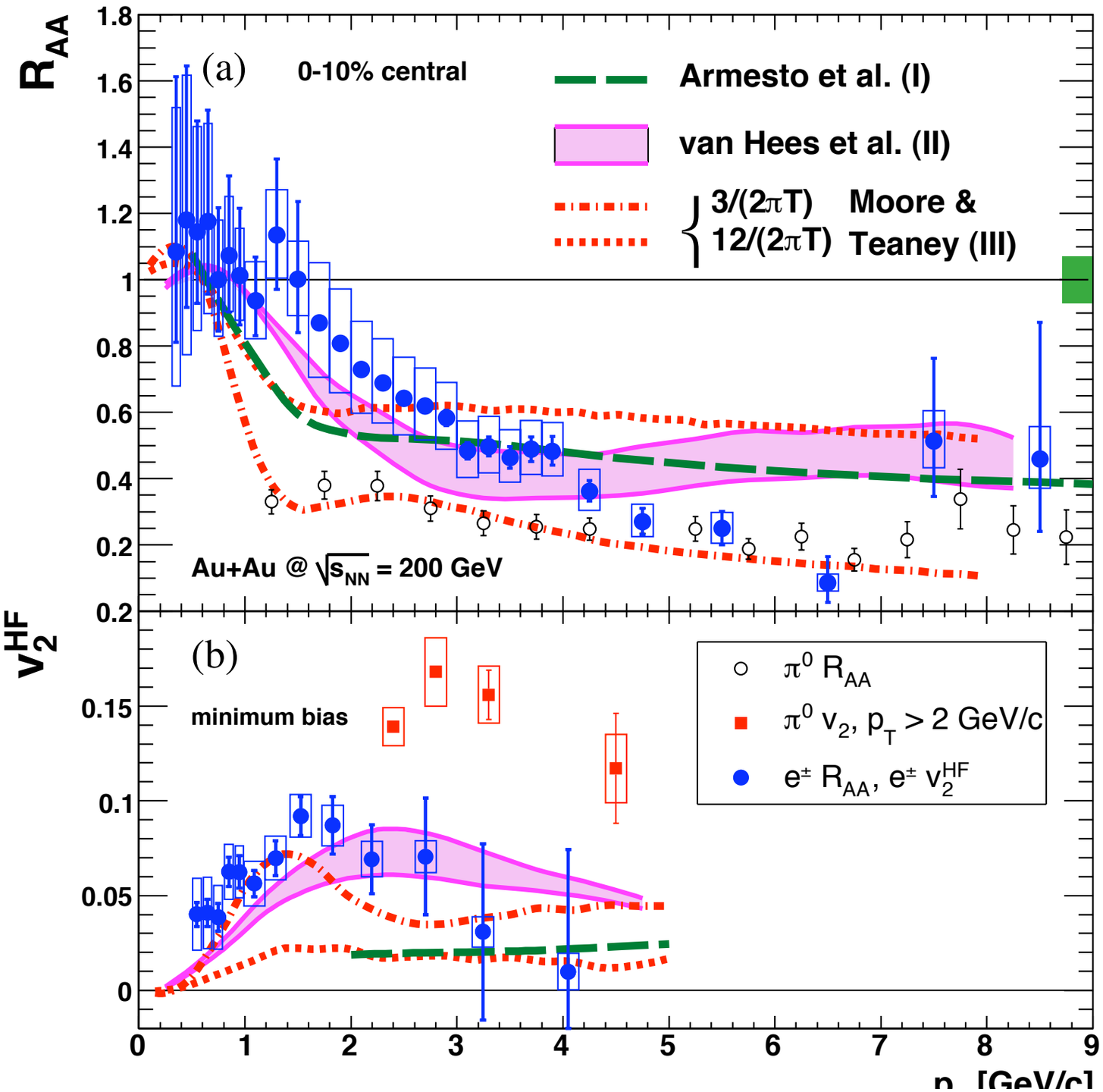
PHENIX 1010.1521

heavy flavor

- collectivity and suppression
- not expected from radiative energy loss
- raises lots of questions:
  - c/b mixture in $e^{\pm}$
  - correlations
  - new theoretical ideas?

PRL 98 172301 2007

heavy flavor



PRL 98 172301 2007

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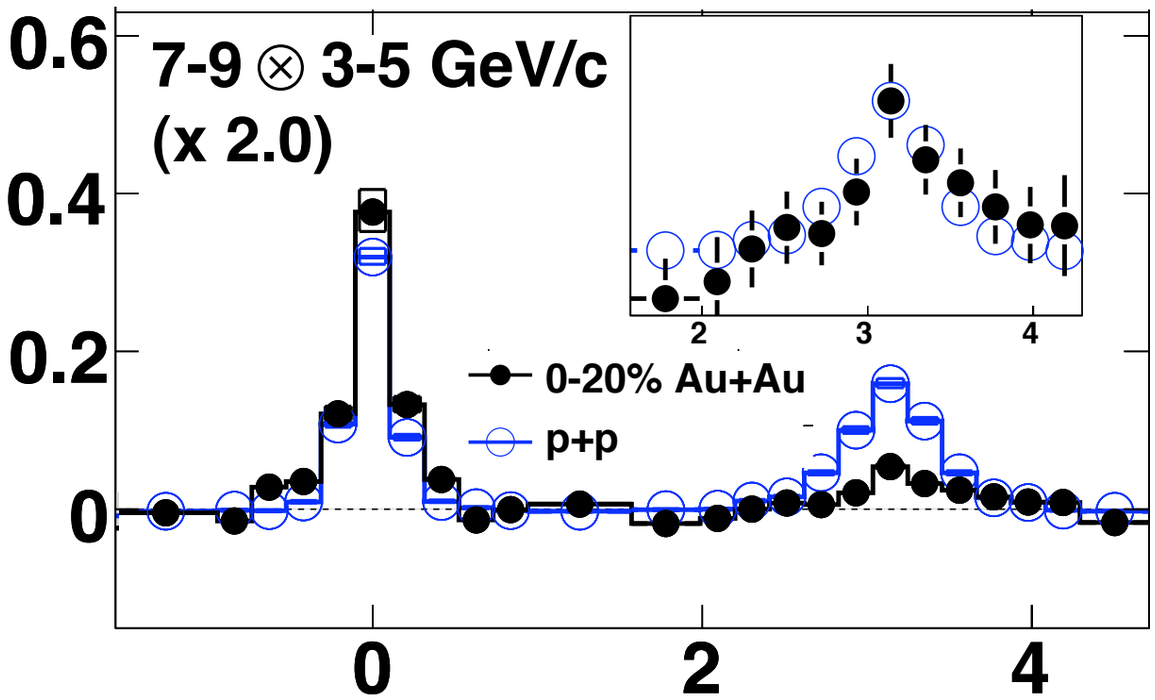
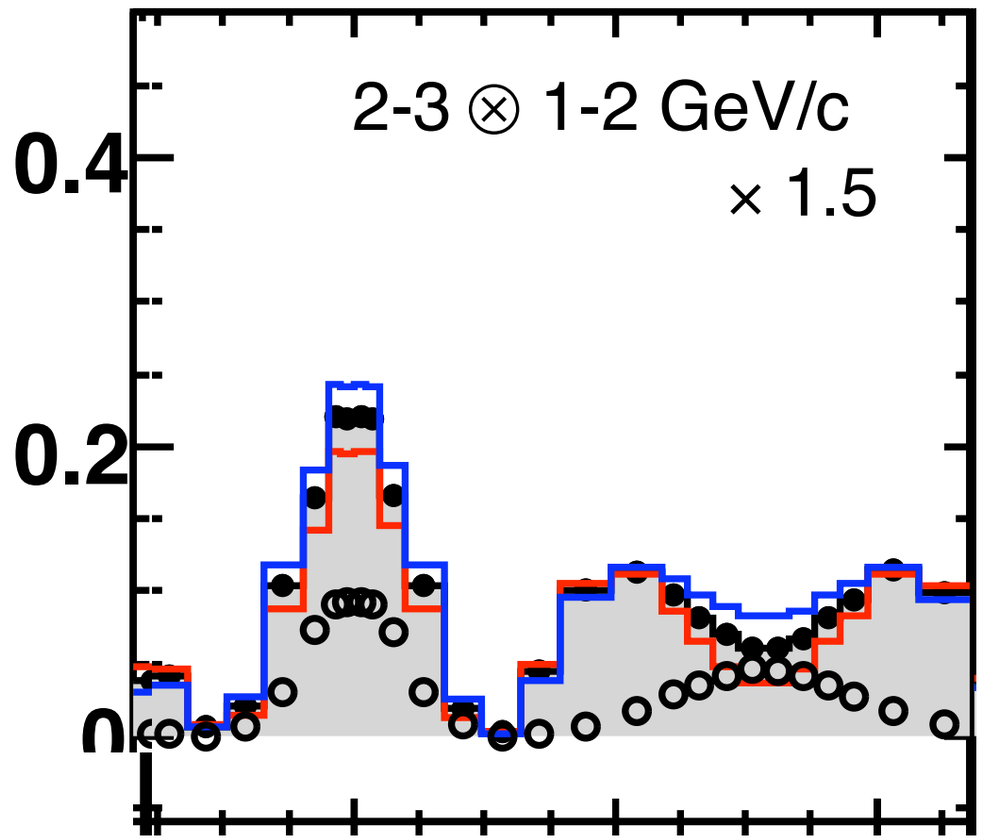
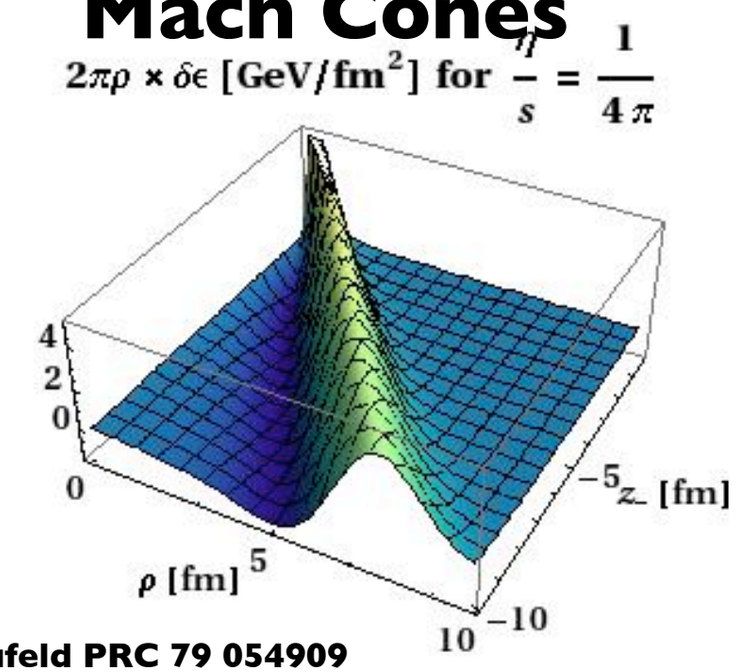
double peak structure





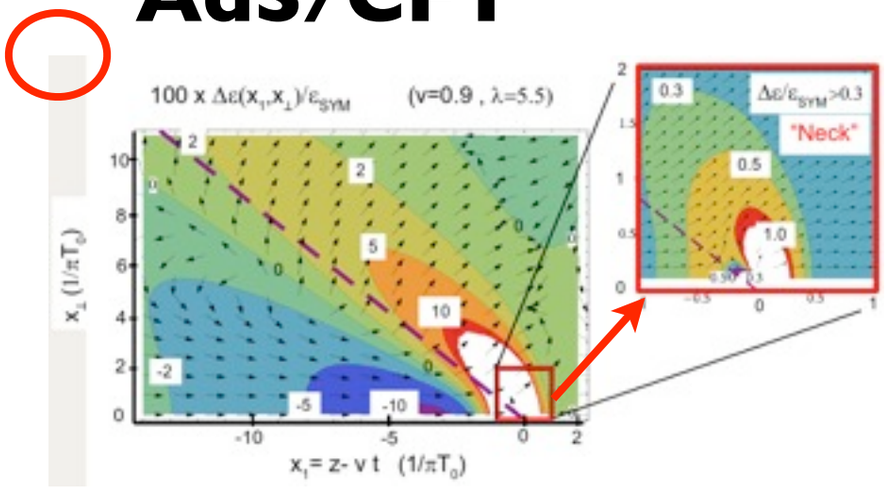
double peaks

Mach Cones



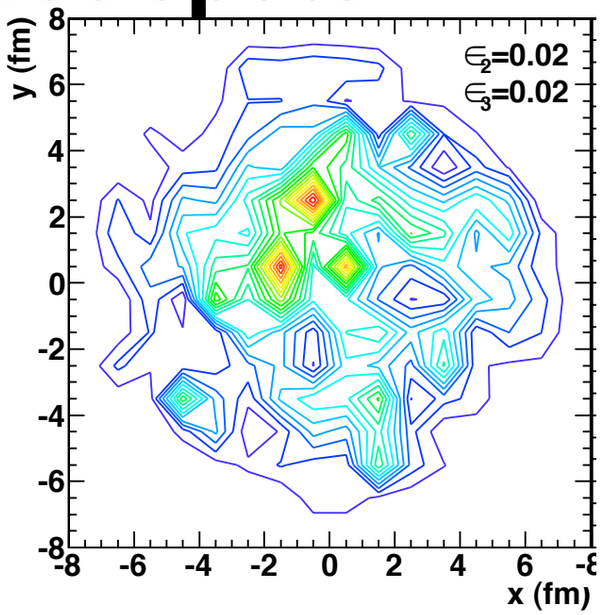
Neufeld PRC 79 054909

AdS/CFT



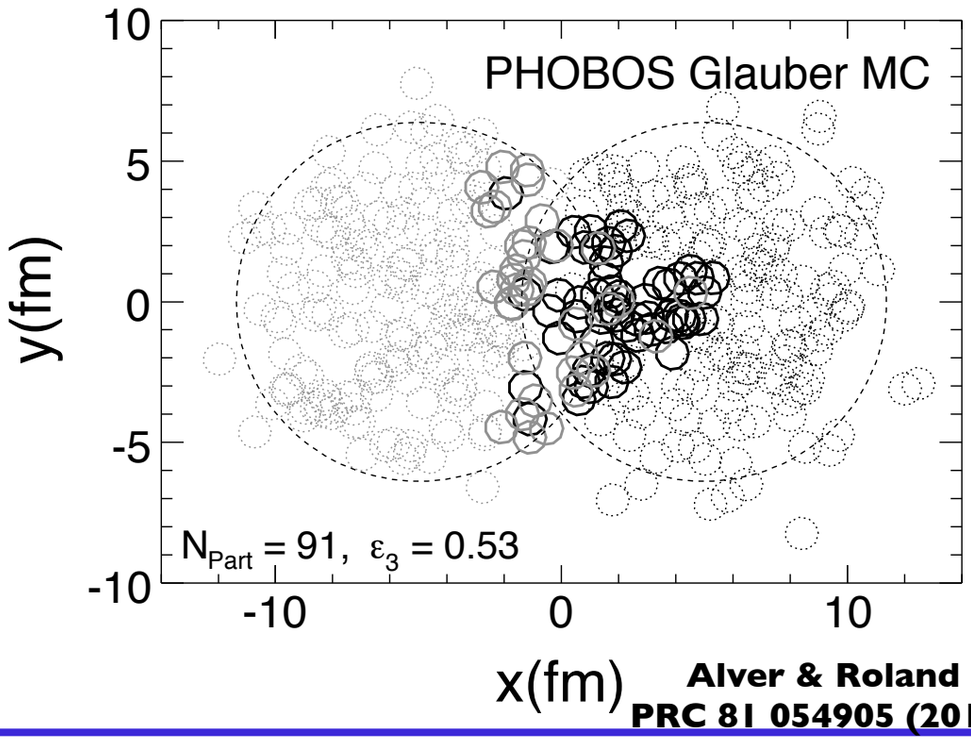
Noronha et al, PRL 102 102301 (2009)

Hot Spots



Ma & Wang 1011.5249

Initial State Fluct.

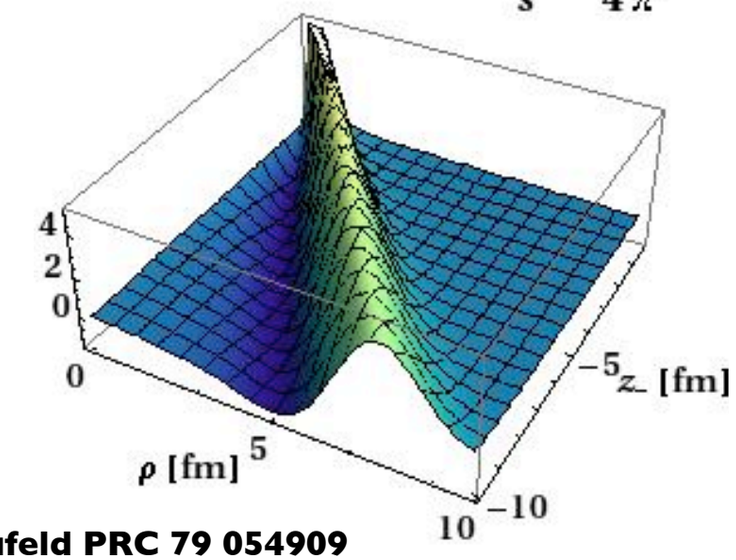


Alver & Roland PRC 81 054905 (2010)

double peaks

Mach Cones

$2\pi\rho \times \delta\epsilon\ [\mathrm{GeV/fm^2}]$ for $\frac{\eta}{s} = \frac{1}{4\pi}$

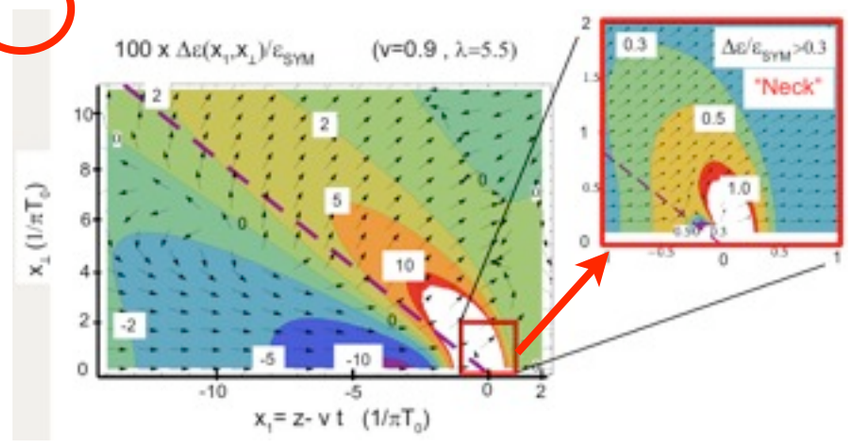


Neufeld PRC 79 054909

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

b-b correlations can determine if correlations follow Mach's Law

AdS/CFT



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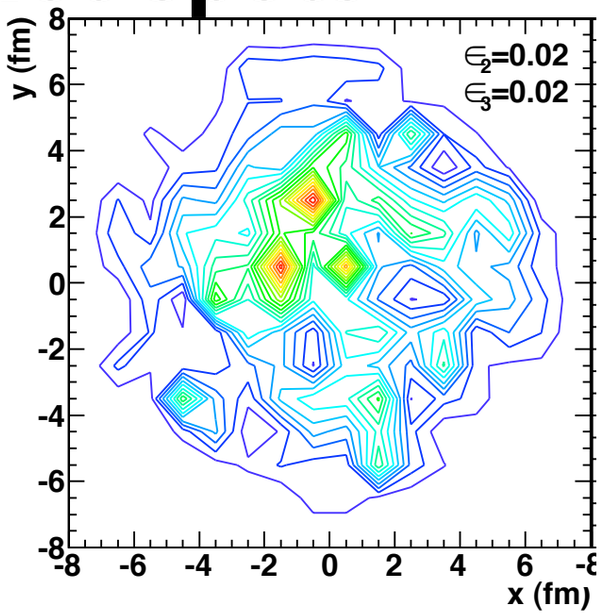

Ma & Wang 1011.5249

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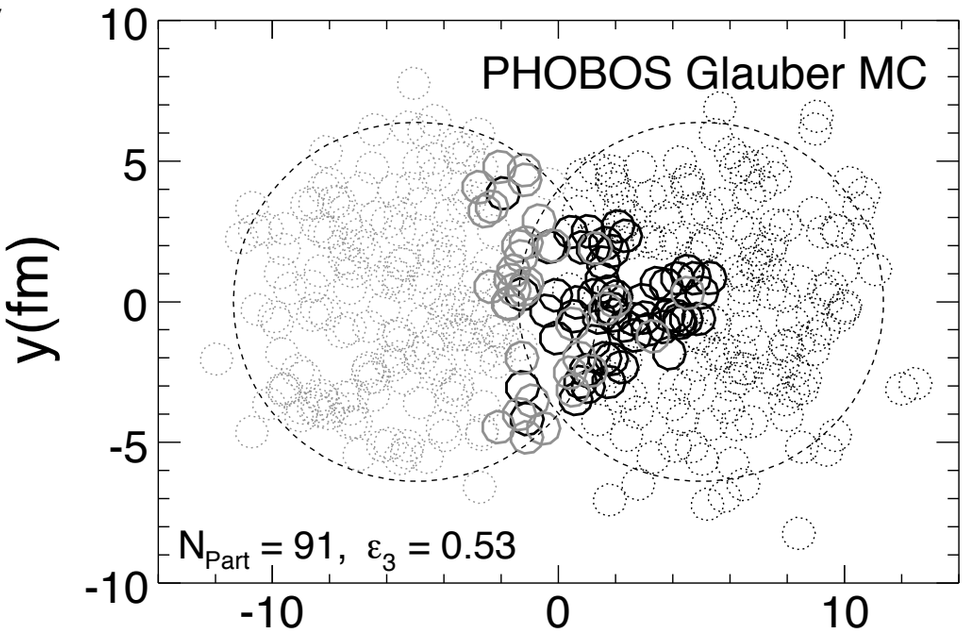
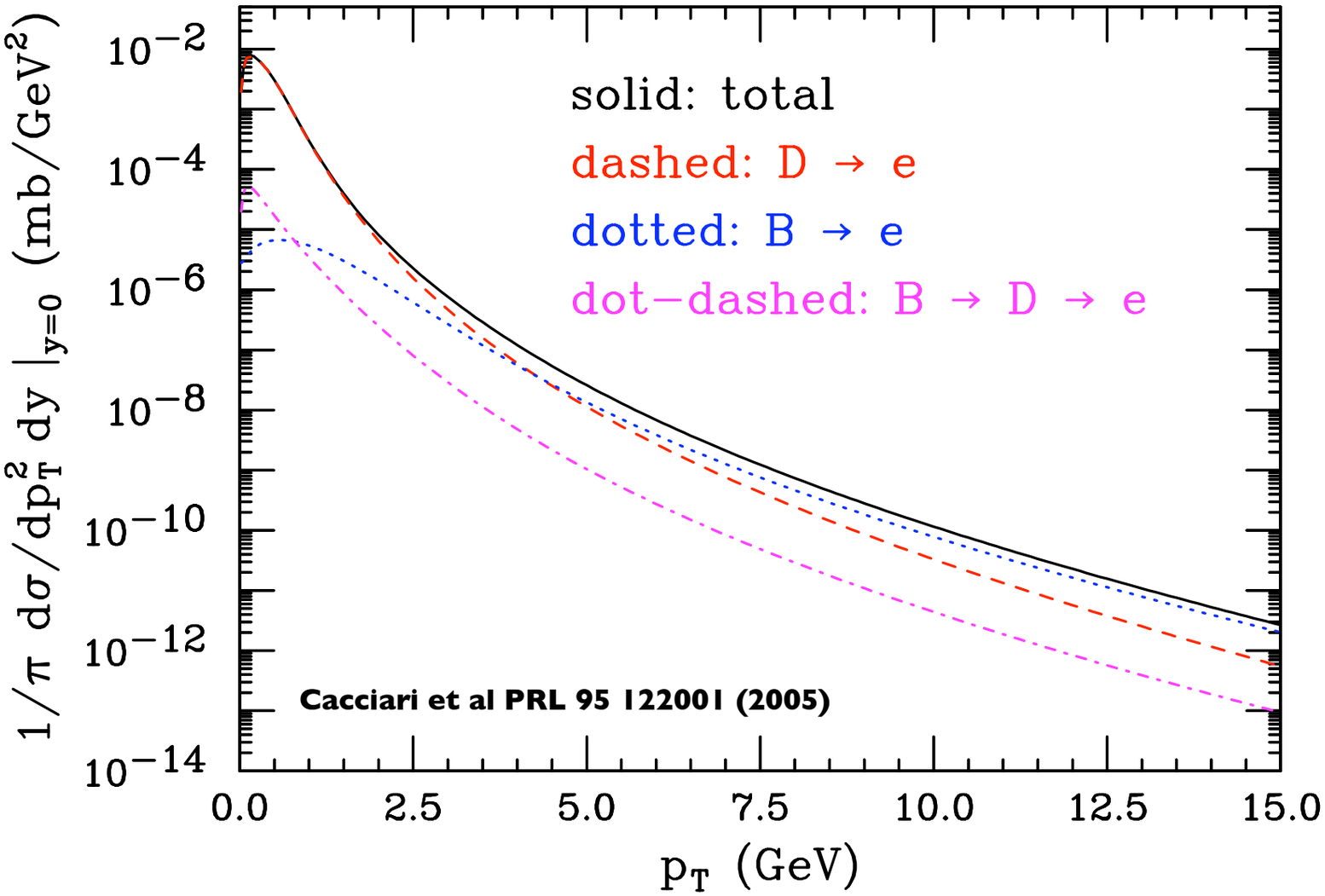


Alver & Roland PRC 81 054905 (2010)

charm & bottom: theory

$e^{\pm}$ from c & b p+p $\sqrt{s}$=200 GeV

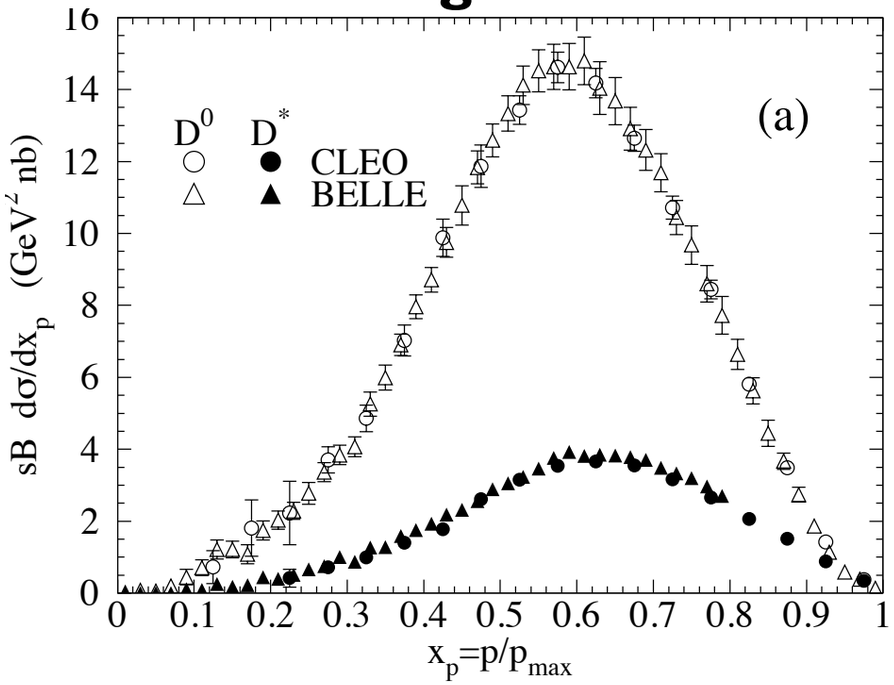


knowledge of relative c/b contributions crucial for understanding energy loss in Au+Au collisions

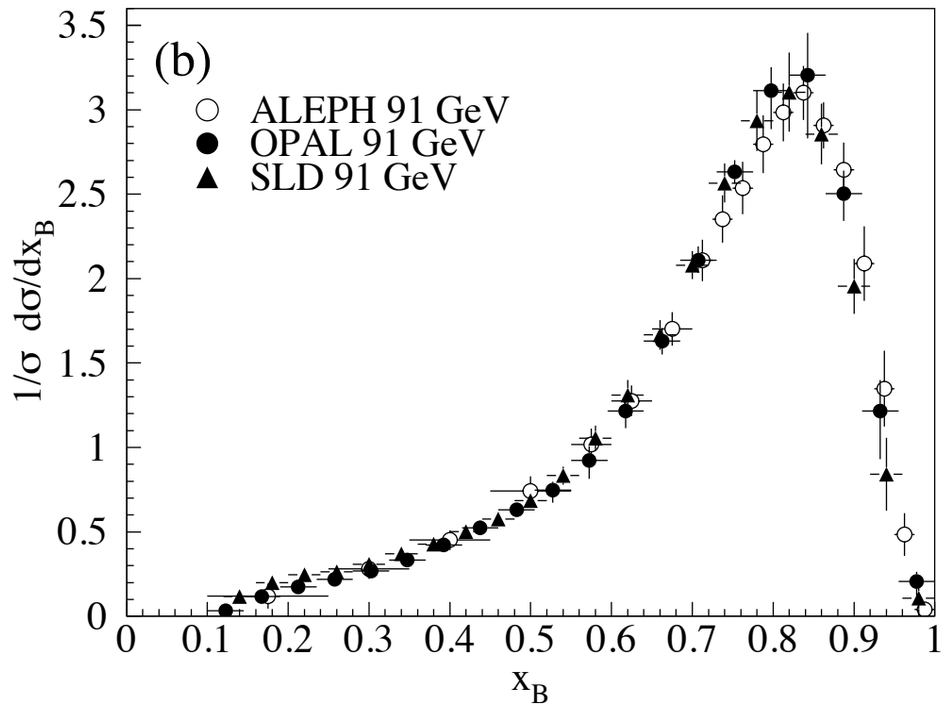
quarks to electrons

quarks to electrons

c→D fragmentation



b→B fragmentation



quarks to electrons

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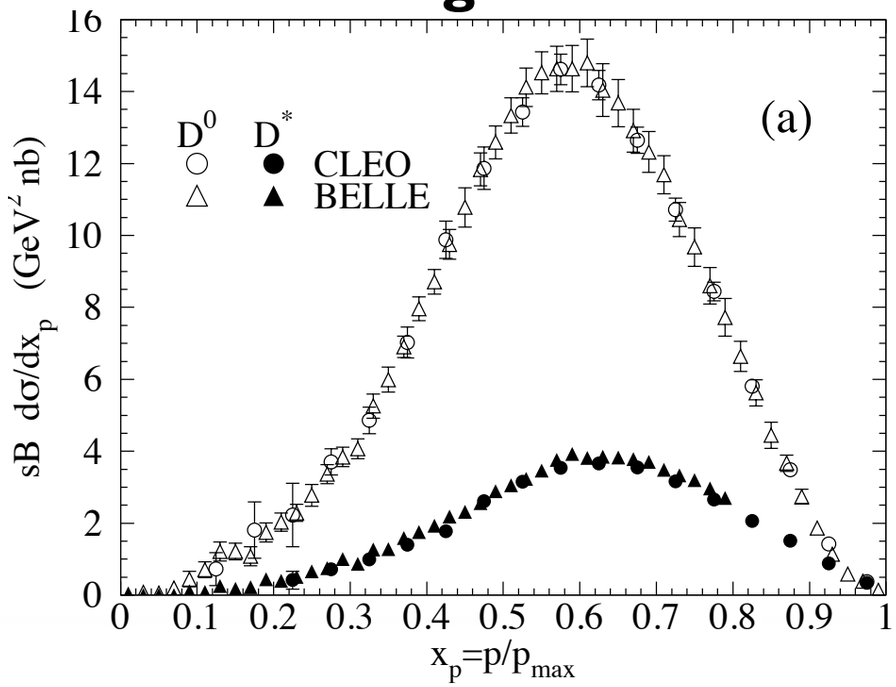

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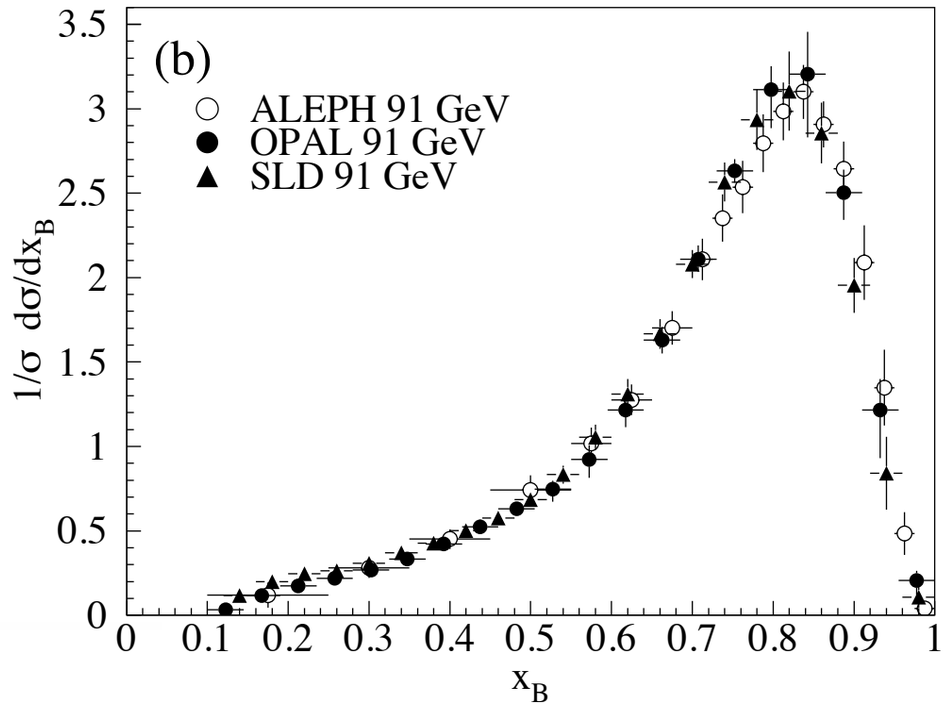

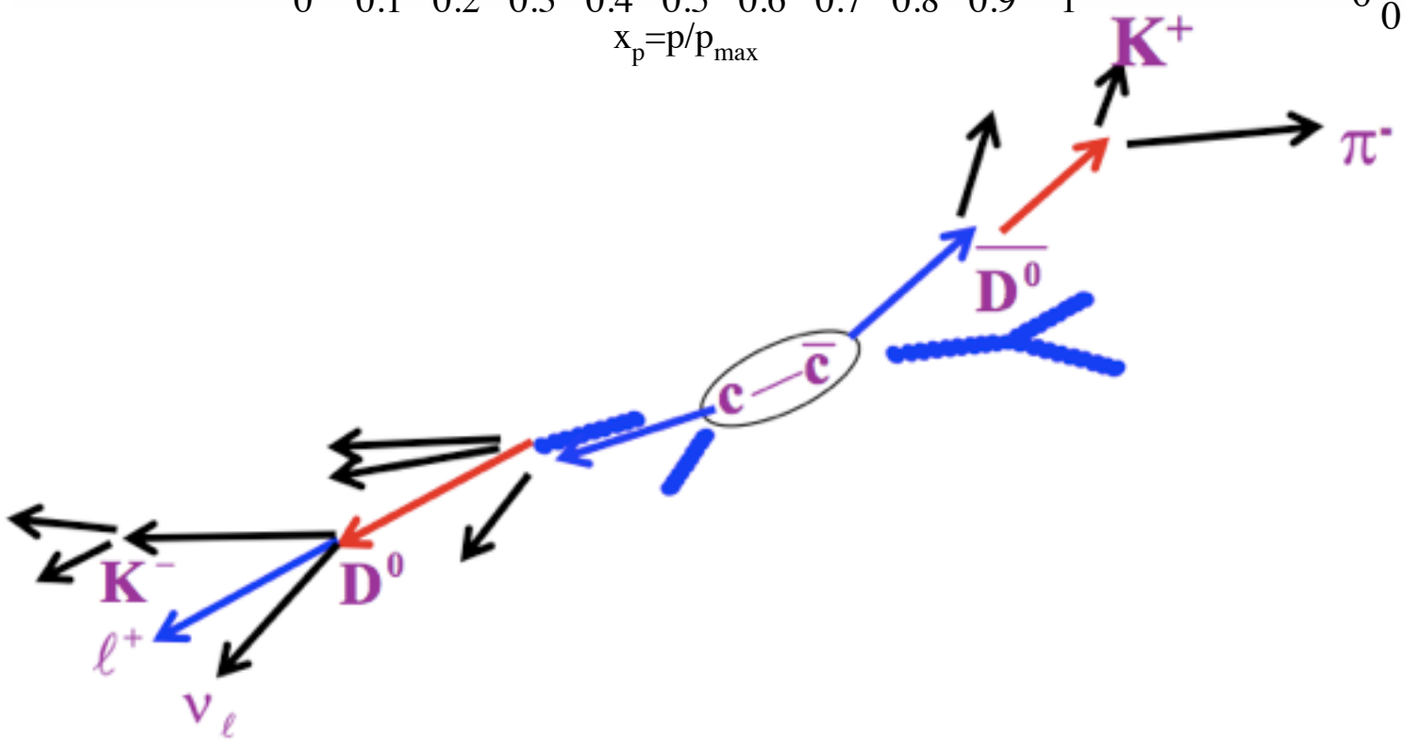

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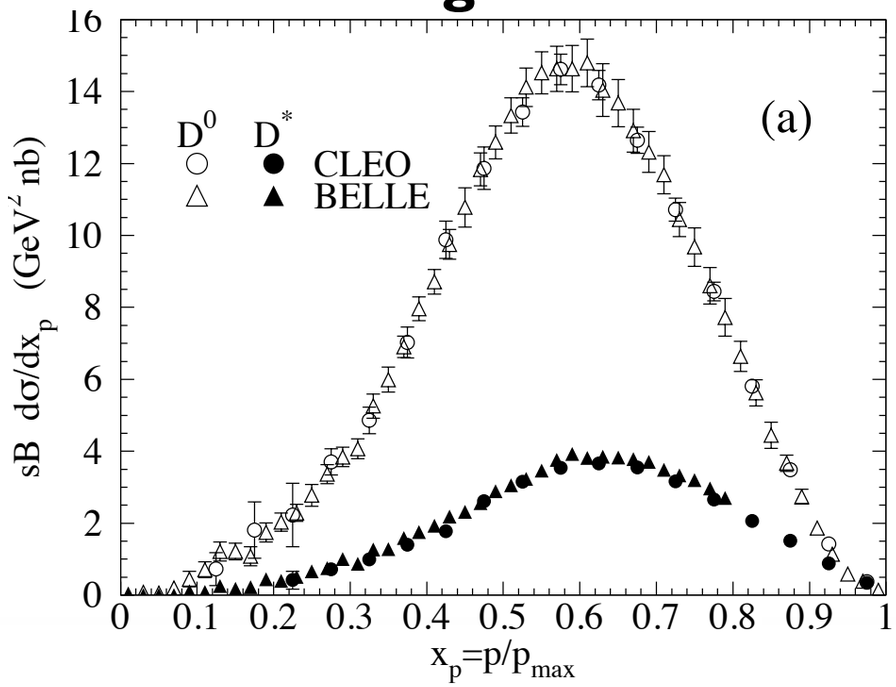
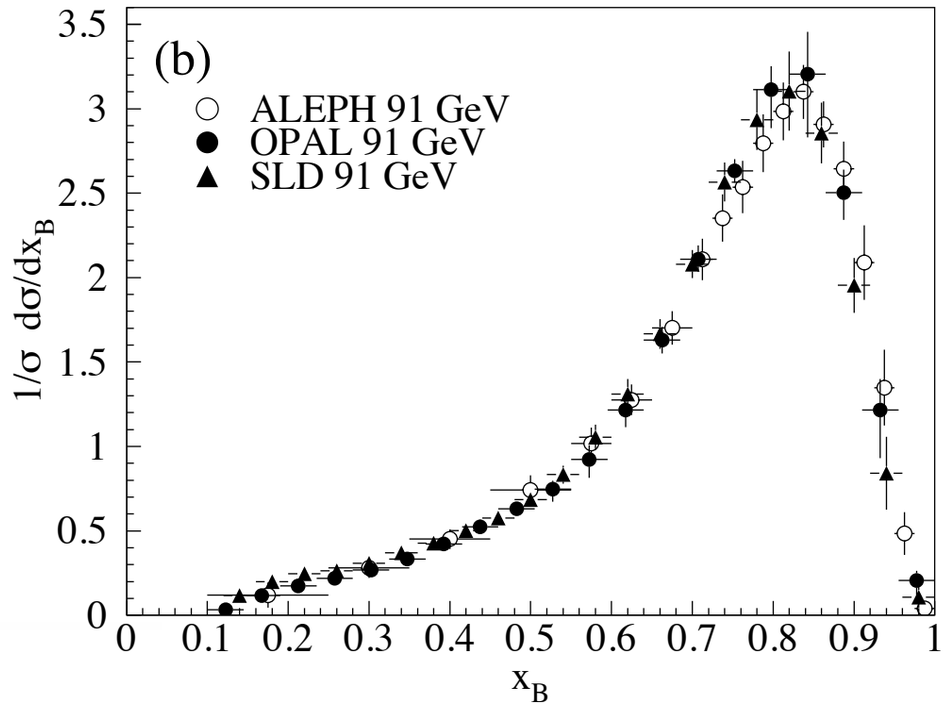
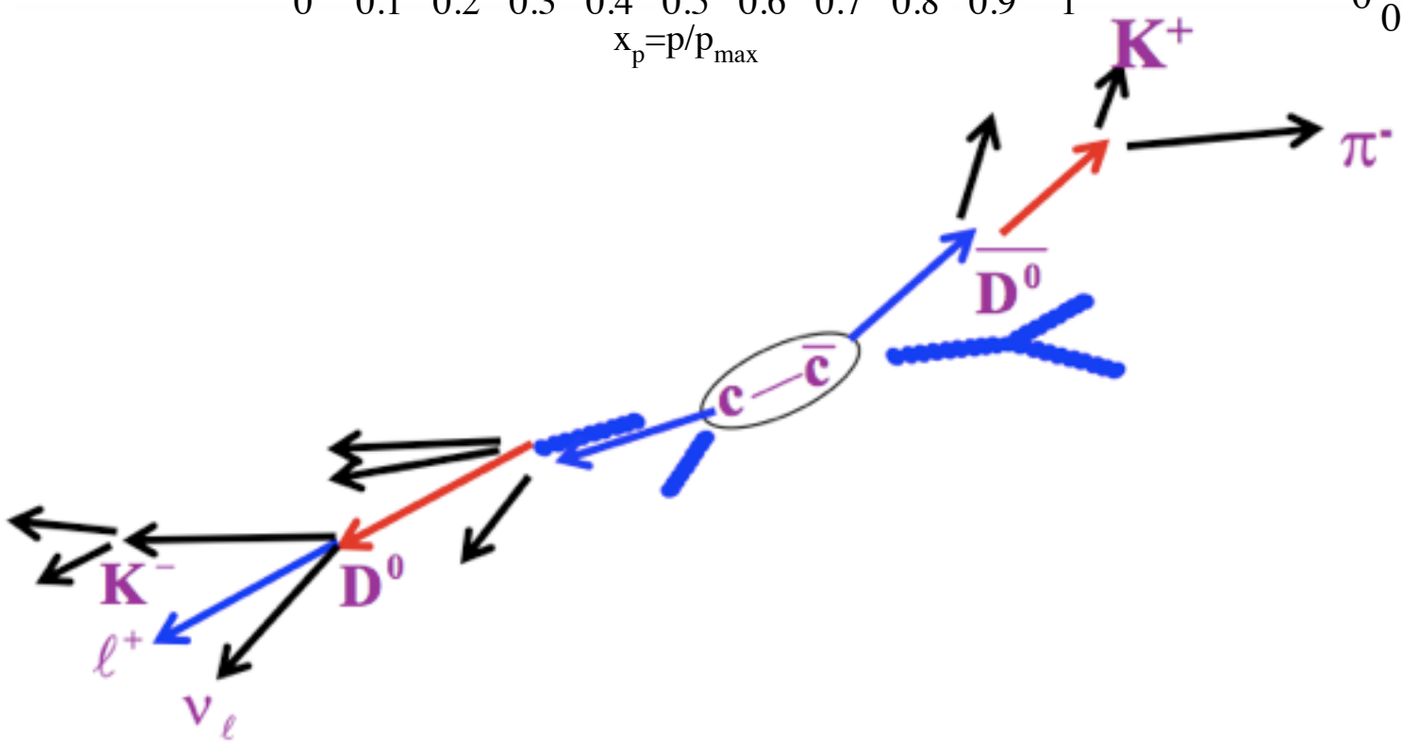
c→D fragmentation



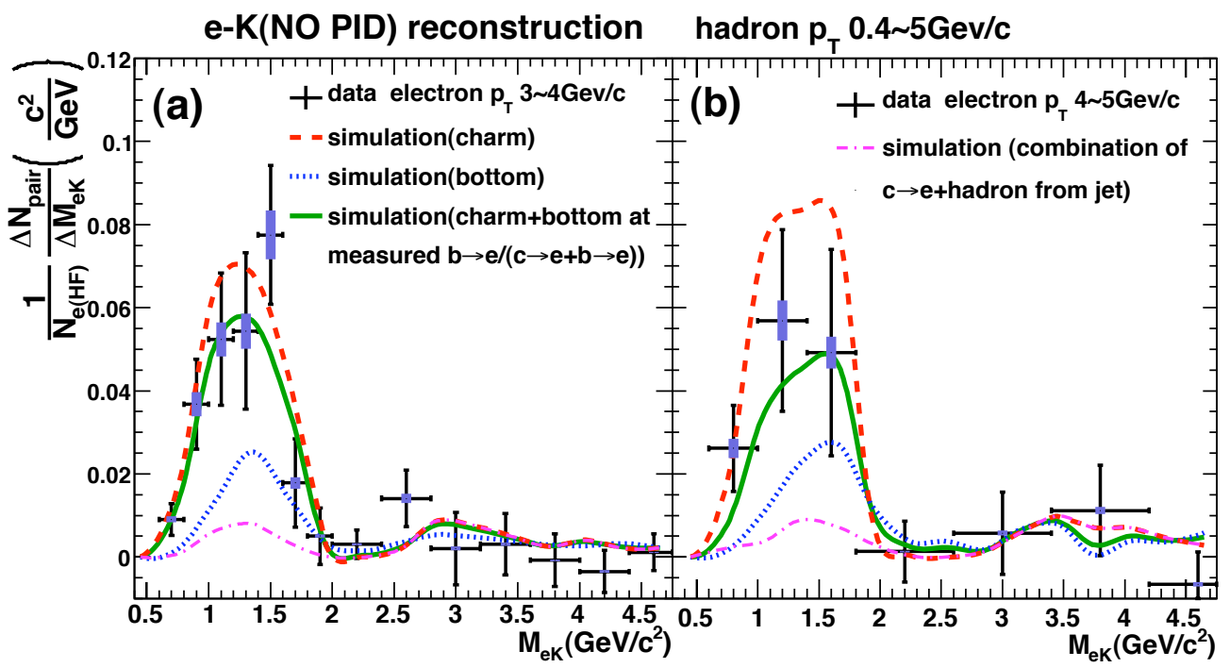
b→B fragmentation

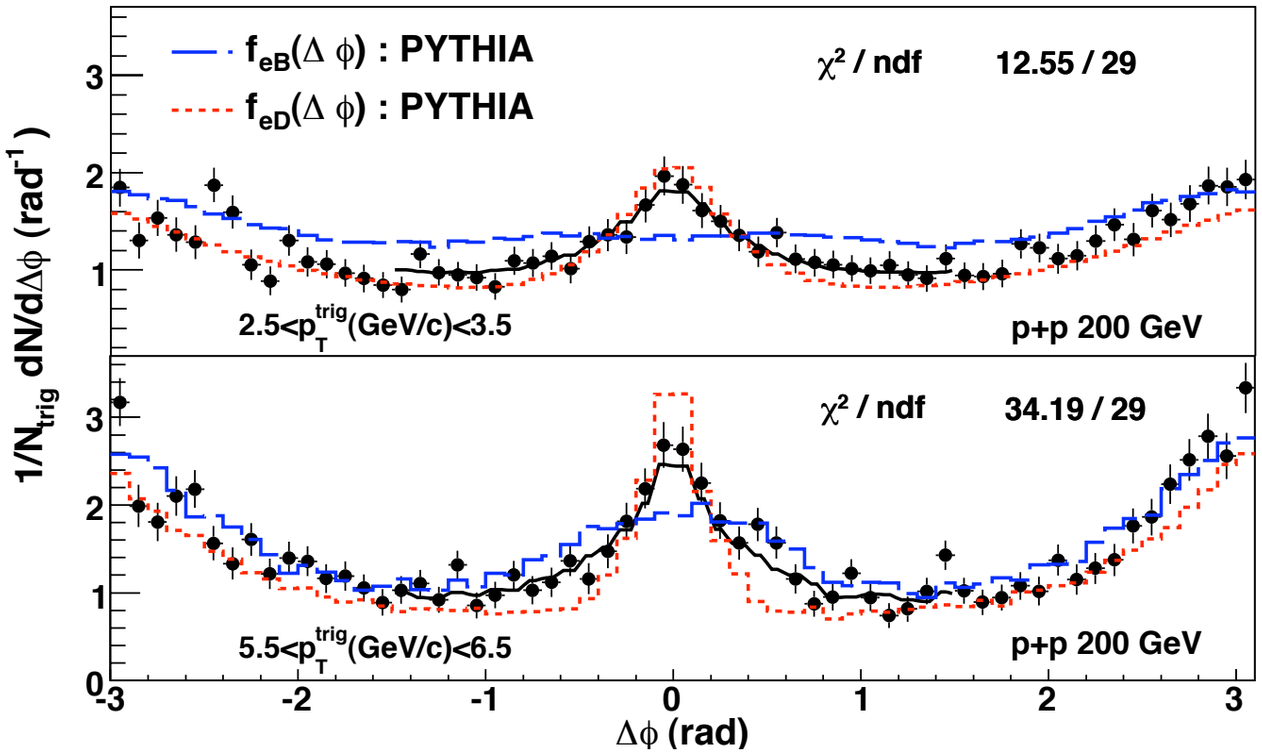




- small angle e-h correlations dominated by D & B decay products

model the near side





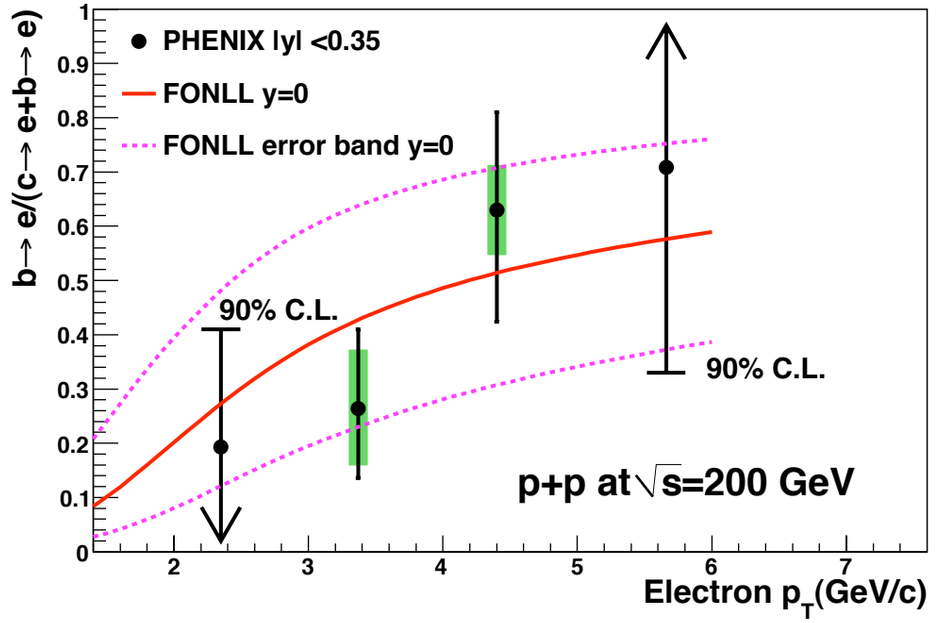
- introduces a dependence on MC for decays and particle mix
  - PYTHIA to handle decays

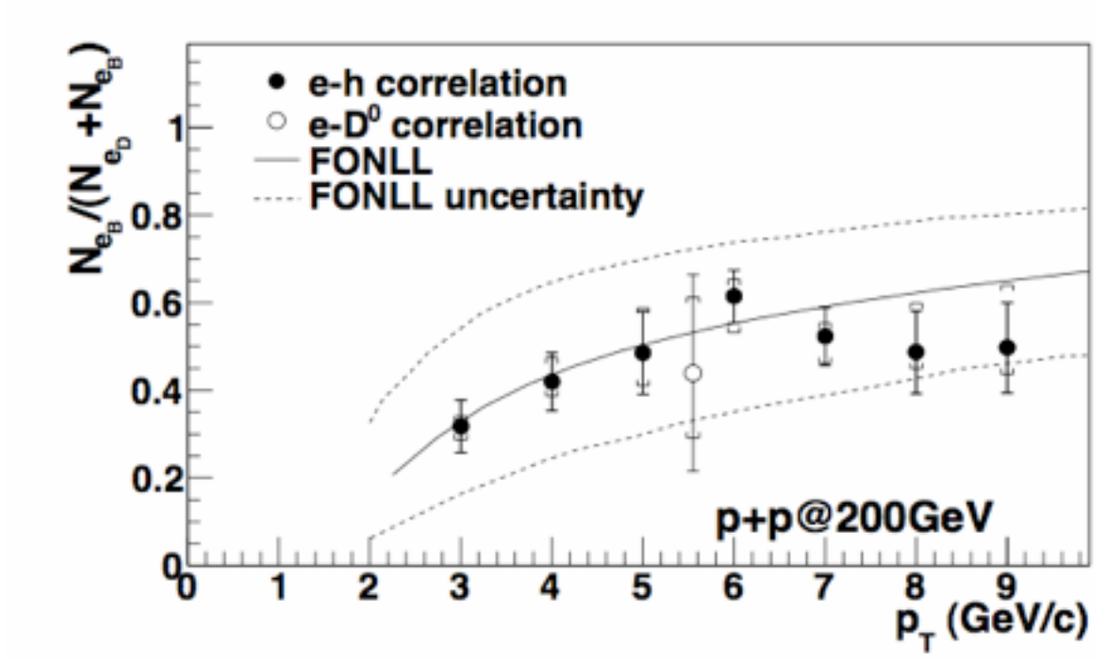
PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

charm vs. bottom: experiment

PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

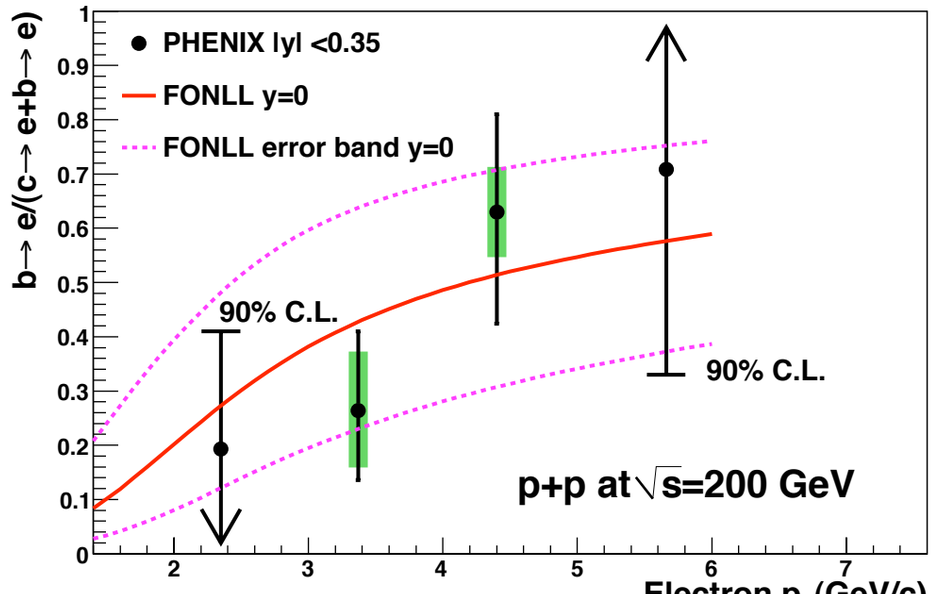
charm vs. bottom: experiment

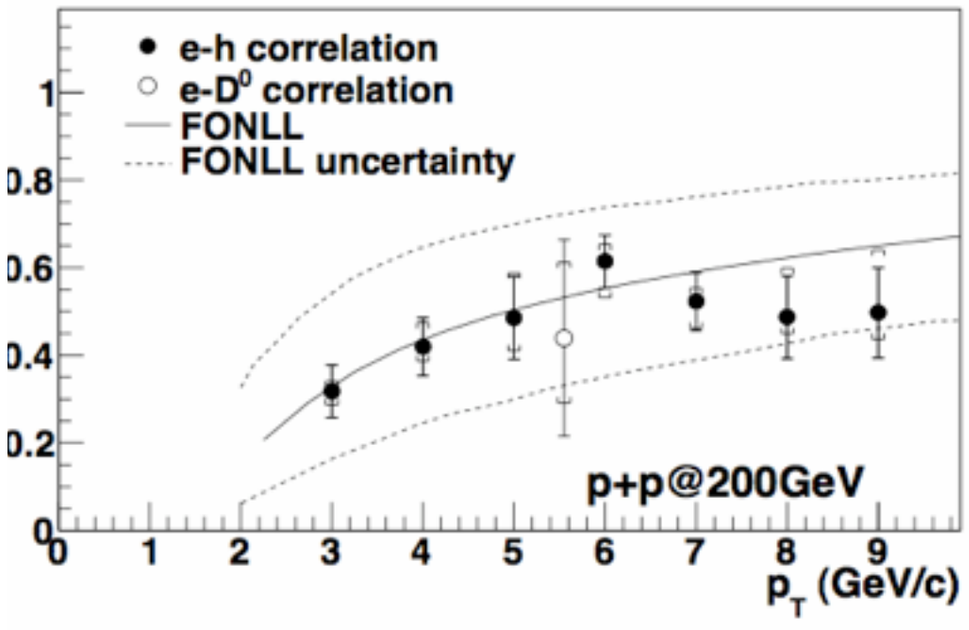


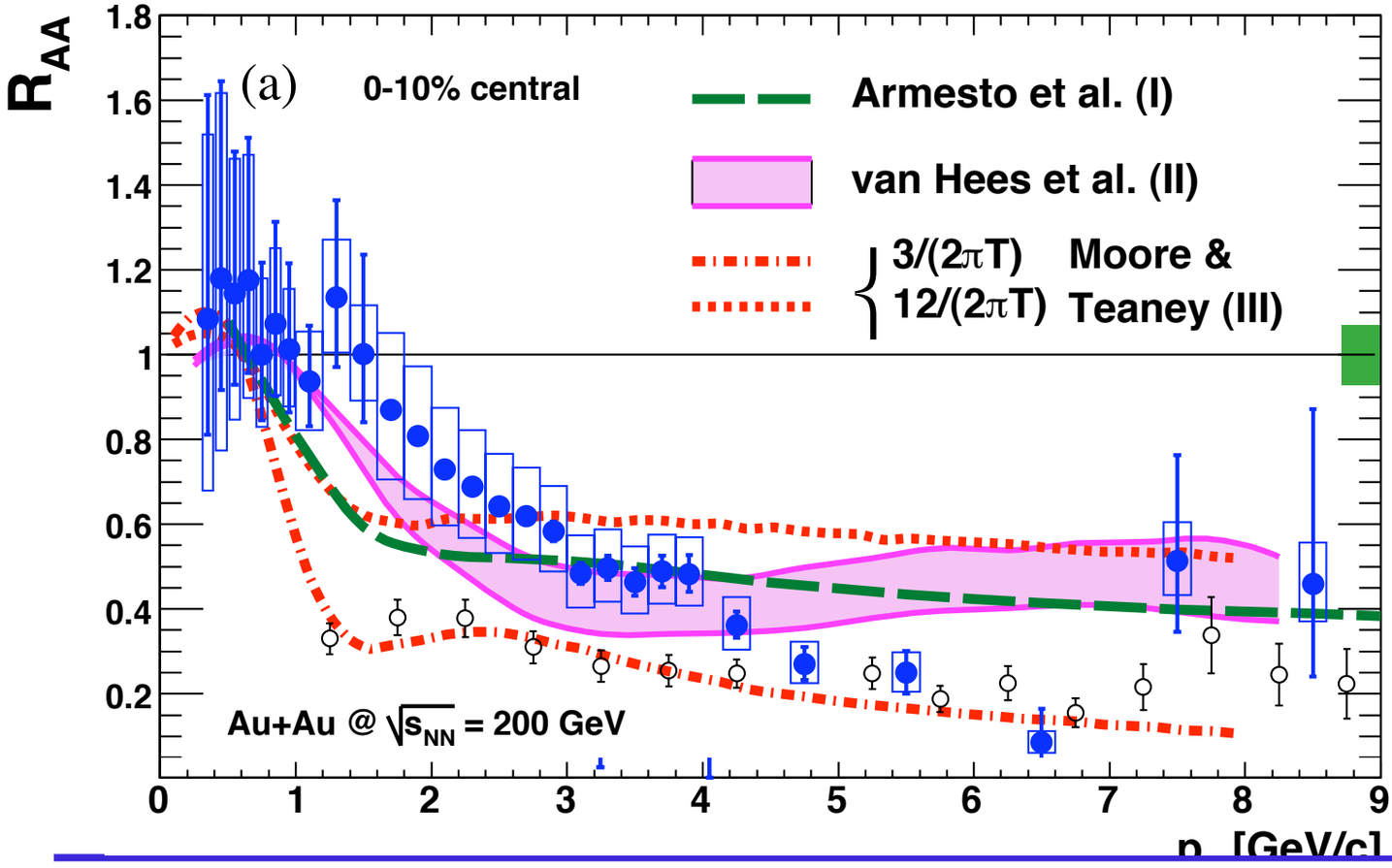


PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

charm vs. bottom: experiment



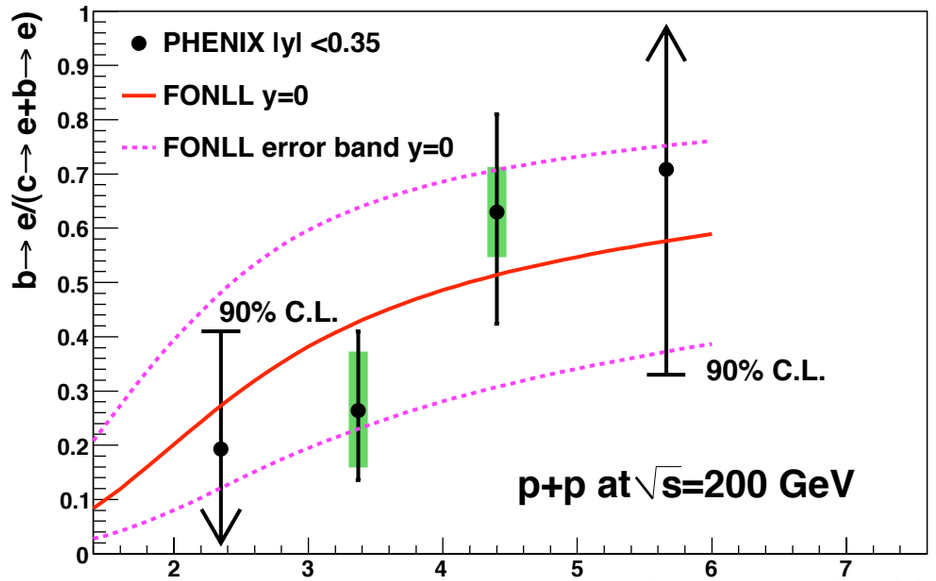


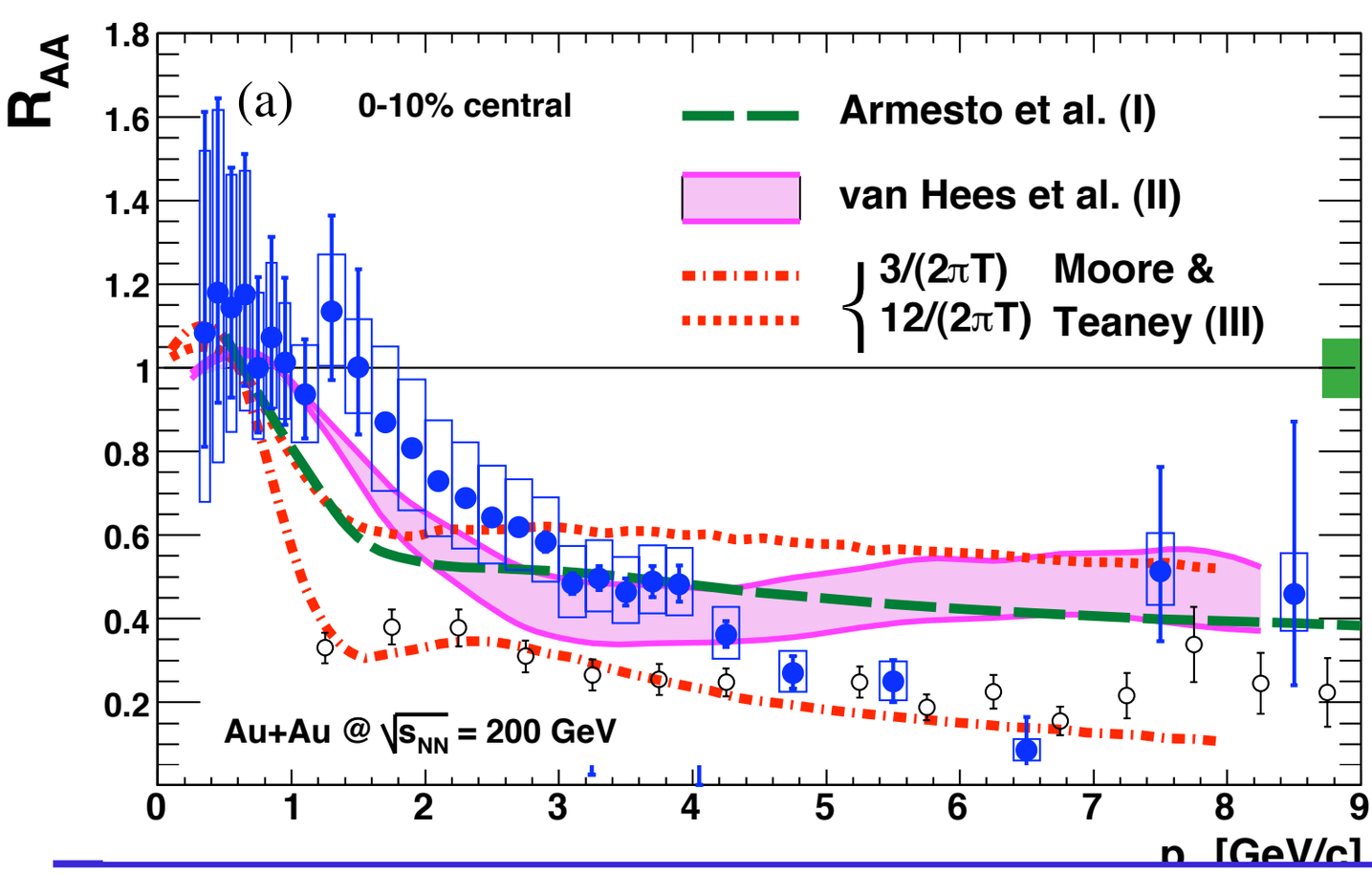


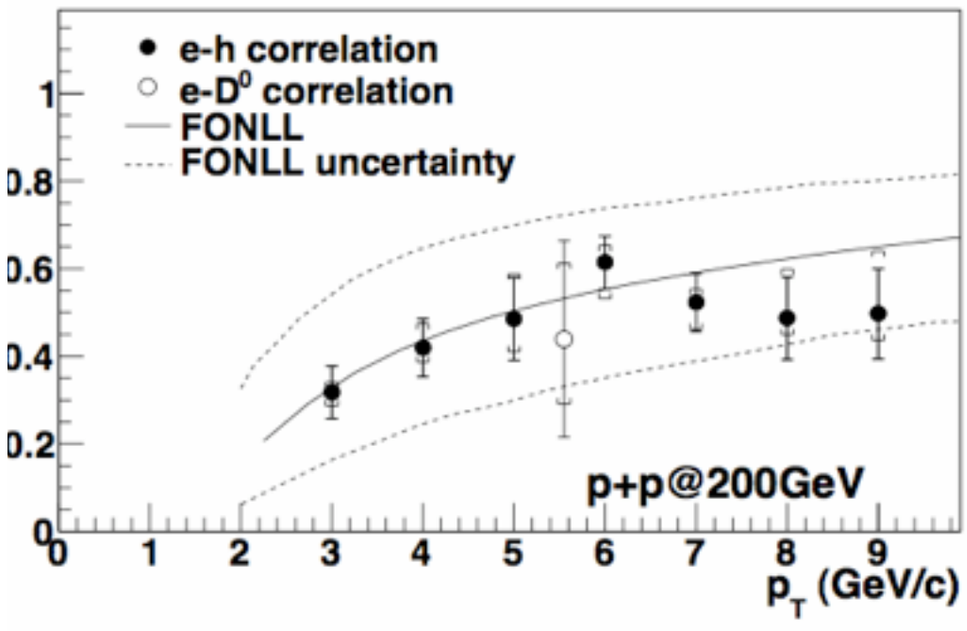
PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

charm vs. bottom: experiment

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







PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

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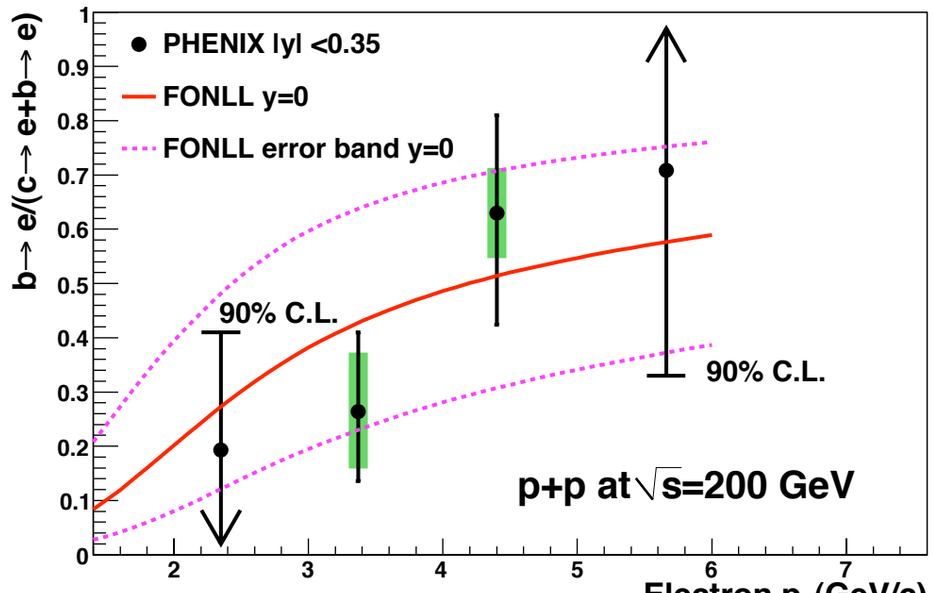
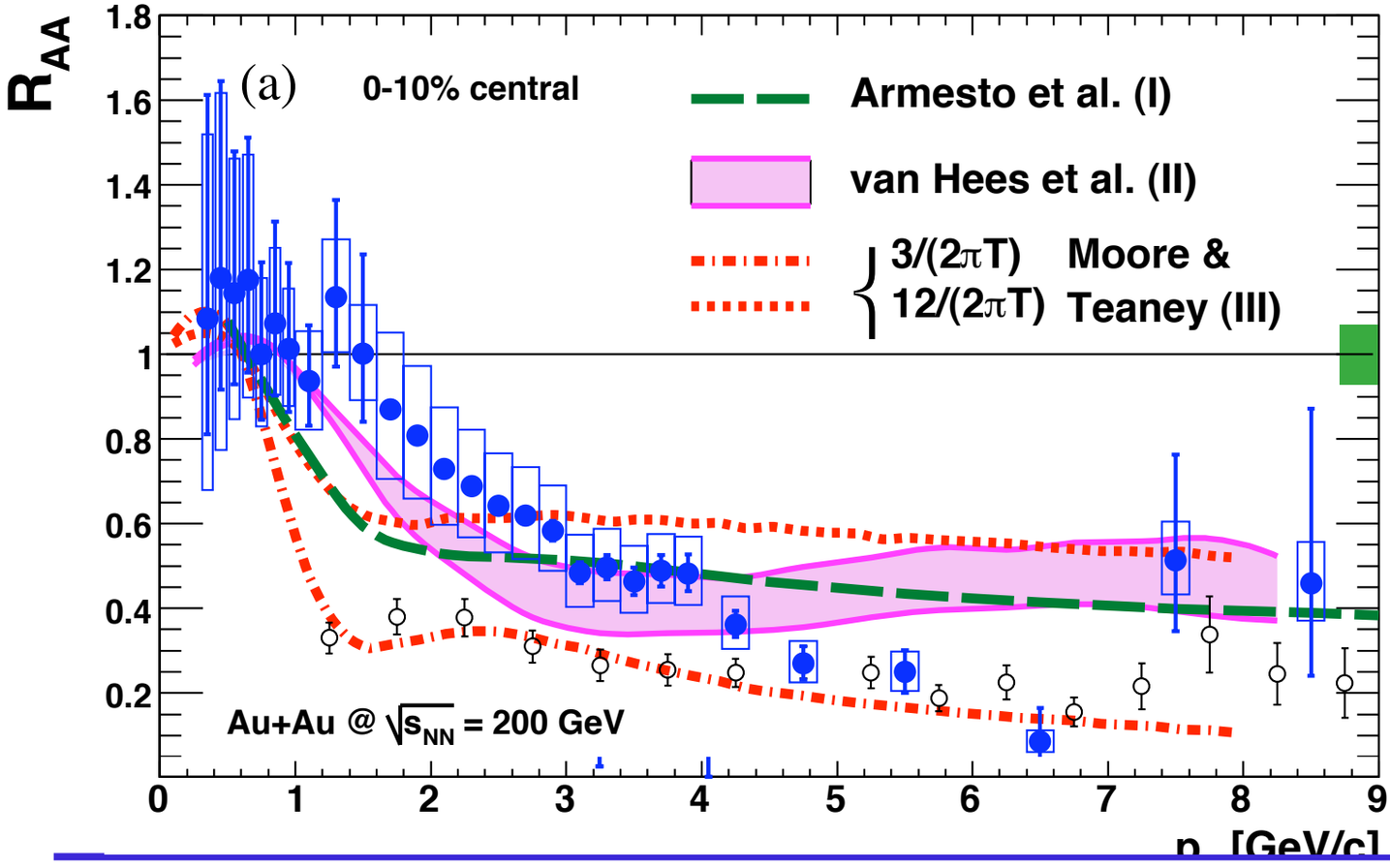
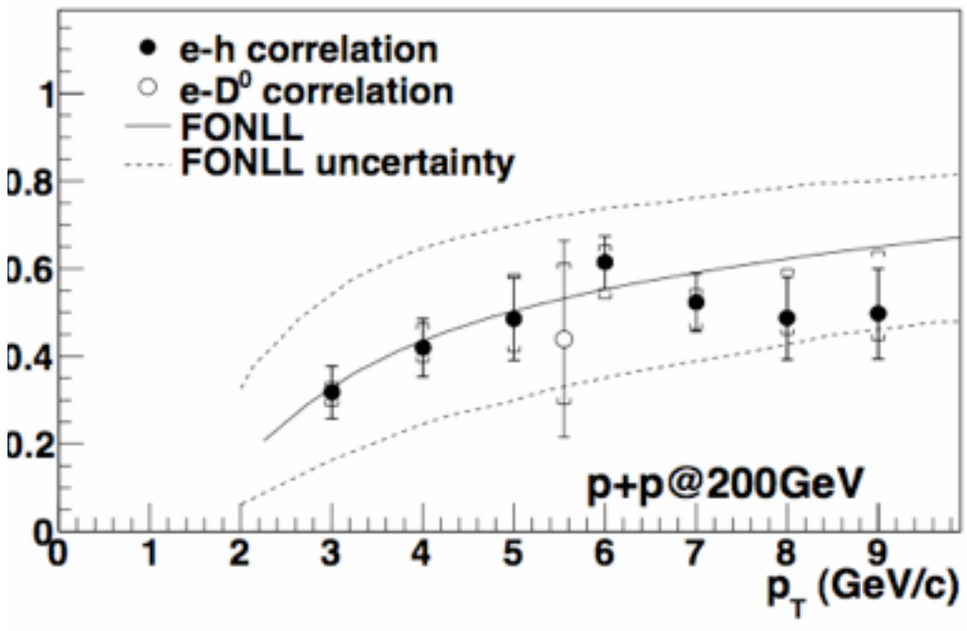
$$R_{AA}^{\mathrm{HF}} = (1 - r_B) R_{AA}^{e_D} + r_B R_{AA}^{e_B}$$







PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

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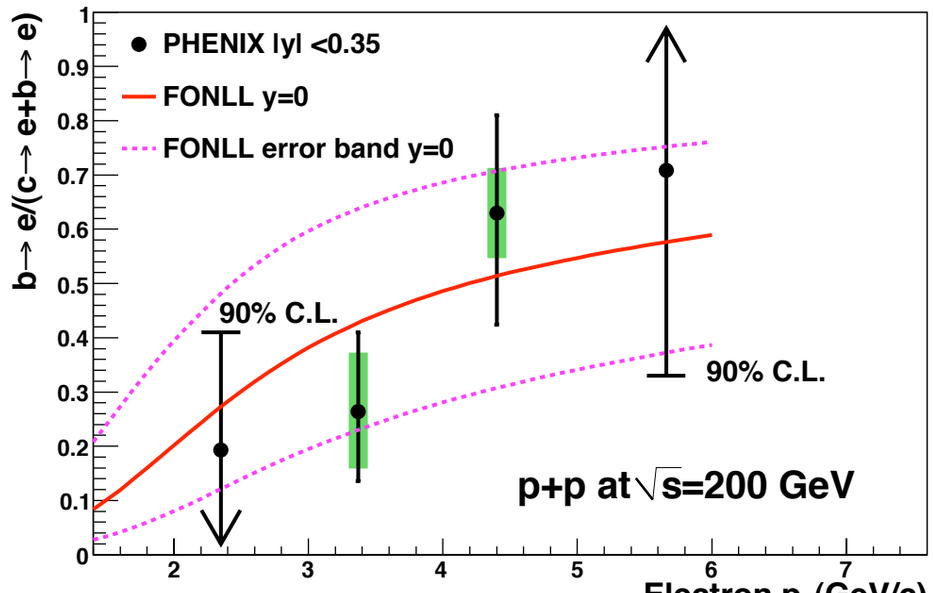

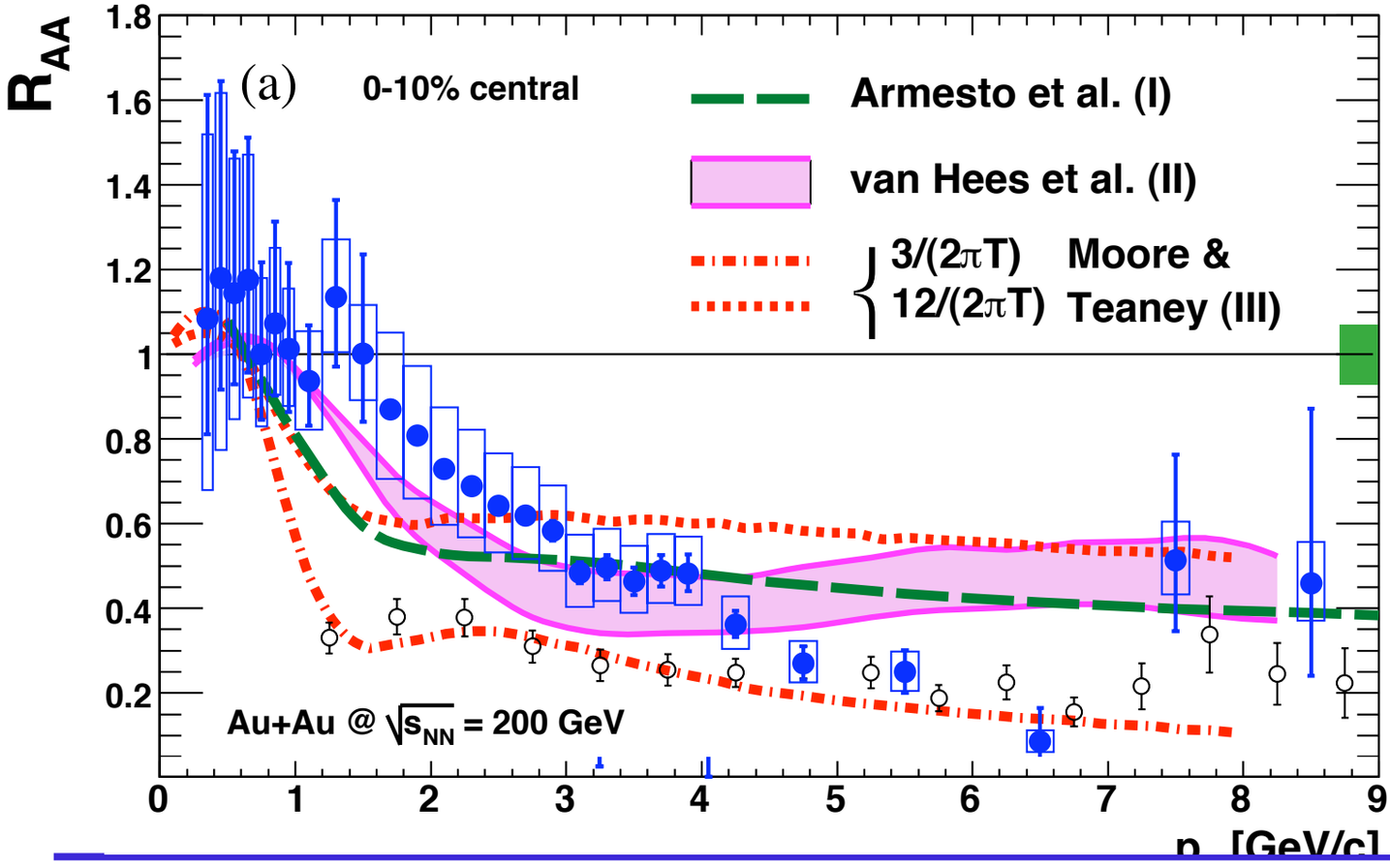

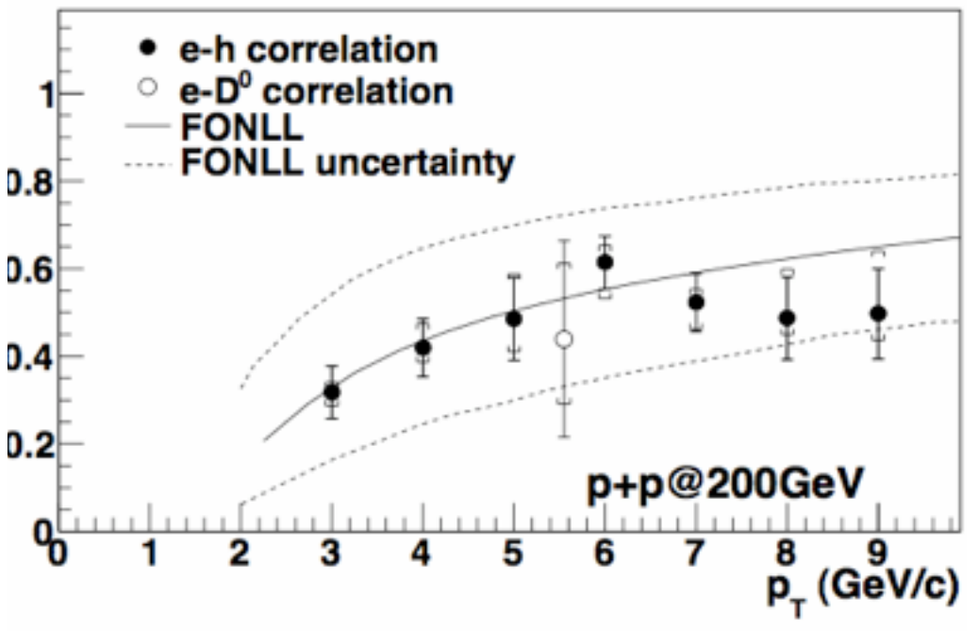

PHENIX PRL 103 082002 (2009)
STAR: PRL 105 202301 (2010)

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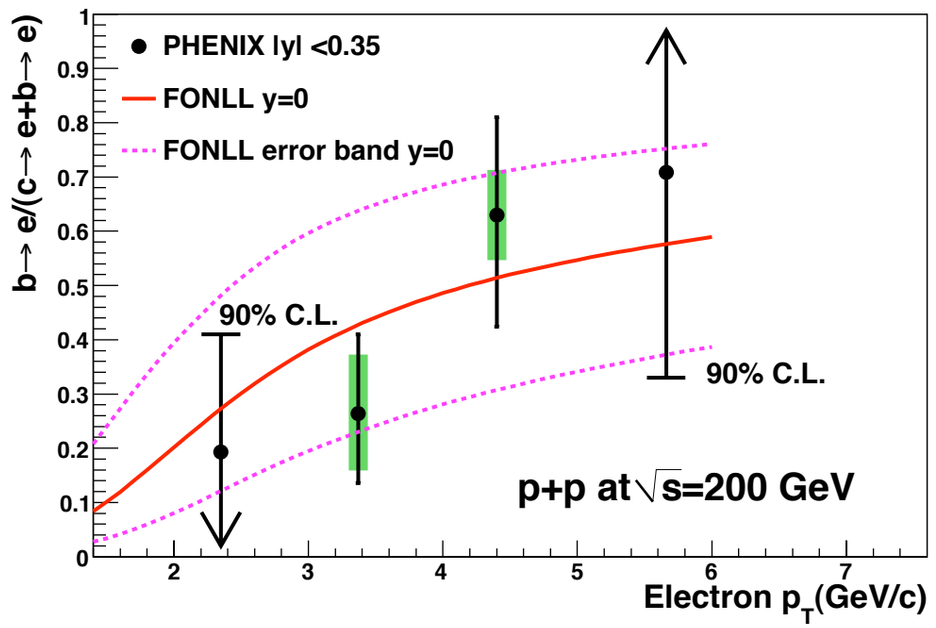

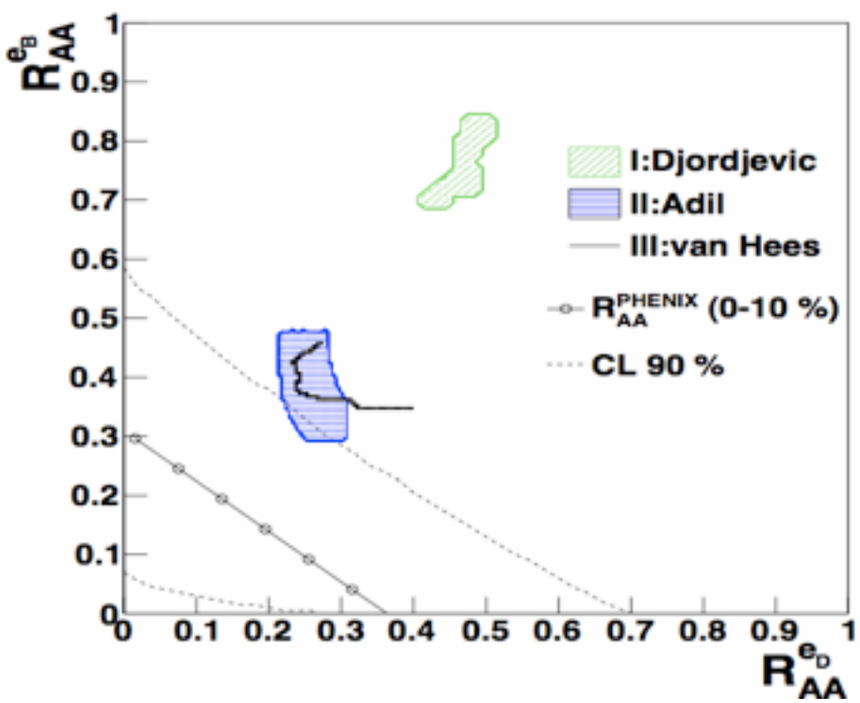

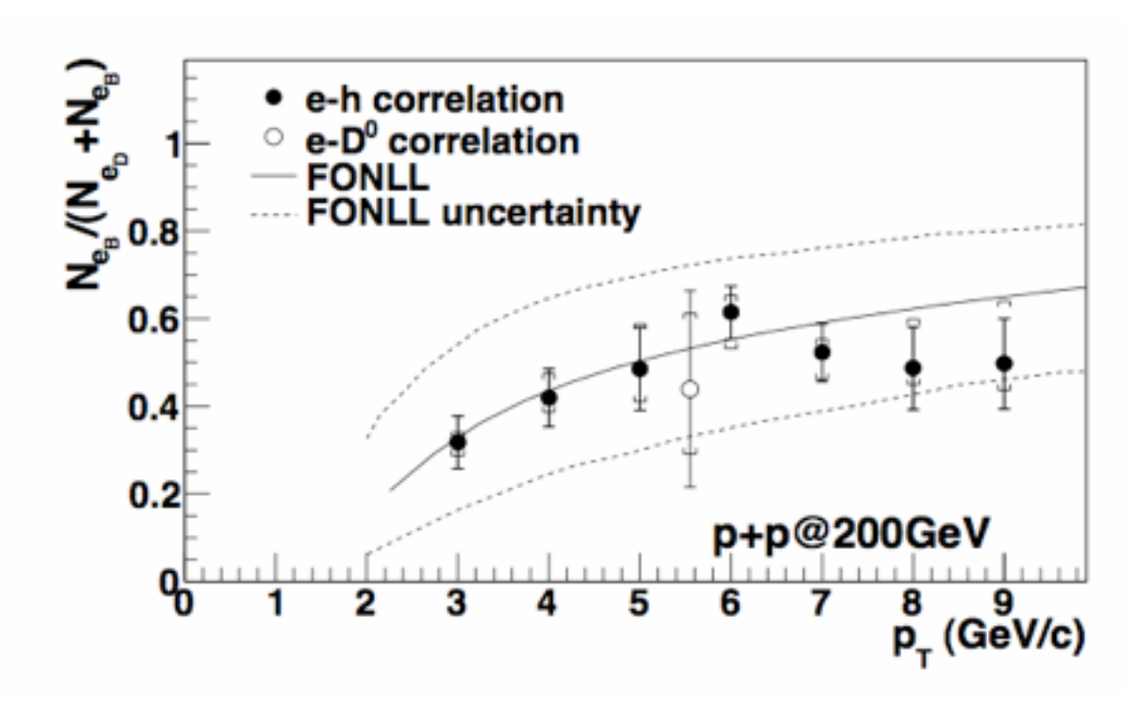

bottom is suppressed!

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STAR: PRL 105 202301 (2010)

A Roadmap for Hard Probes

A Roadmap for Hard Probes

π^0 R_{AA}
π^0 I_{AA}

A Roadmap for Hard Probes

π^0 R_{AA}
π^0 I_{AA}

control geometry

π^0 R_{AA} (ϕ)
π^0 I_{AA} (ϕ)

A Roadmap for Hard Probes

π^0 R_{AA}
π^0 I_{AA}

→ *control geometry*

π^0 R_{AA} (ϕ)
π^0 I_{AA} (ϕ)

↓ *control parton*

$e^{\pm}$ R_{AA}
$e^{\pm}$ I_{AA}

A Roadmap for Hard Probes

π^0 R_{AA}
π^0 I_{AA}

→ ***control geometry***

π^0 R_{AA} (ϕ)
π^0 I_{AA} (ϕ)

↓ ***control parton***

$e^{\pm}$ R_{AA}
$e^{\pm}$ I_{AA}

→ **jets & di-jets**

A Roadmap for Hard Probes

π^0 R_{AA}
π^0 I_{AA}

→ *control geometry*

π^0 R_{AA} (ϕ)
π^0 I_{AA} (ϕ)

↓ *control parton*

$e^{\pm}$ R_{AA}
$e^{\pm}$ I_{AA}

A Roadmap for Hard Probes

π^0 R_{AA}
π^0 I_{AA}

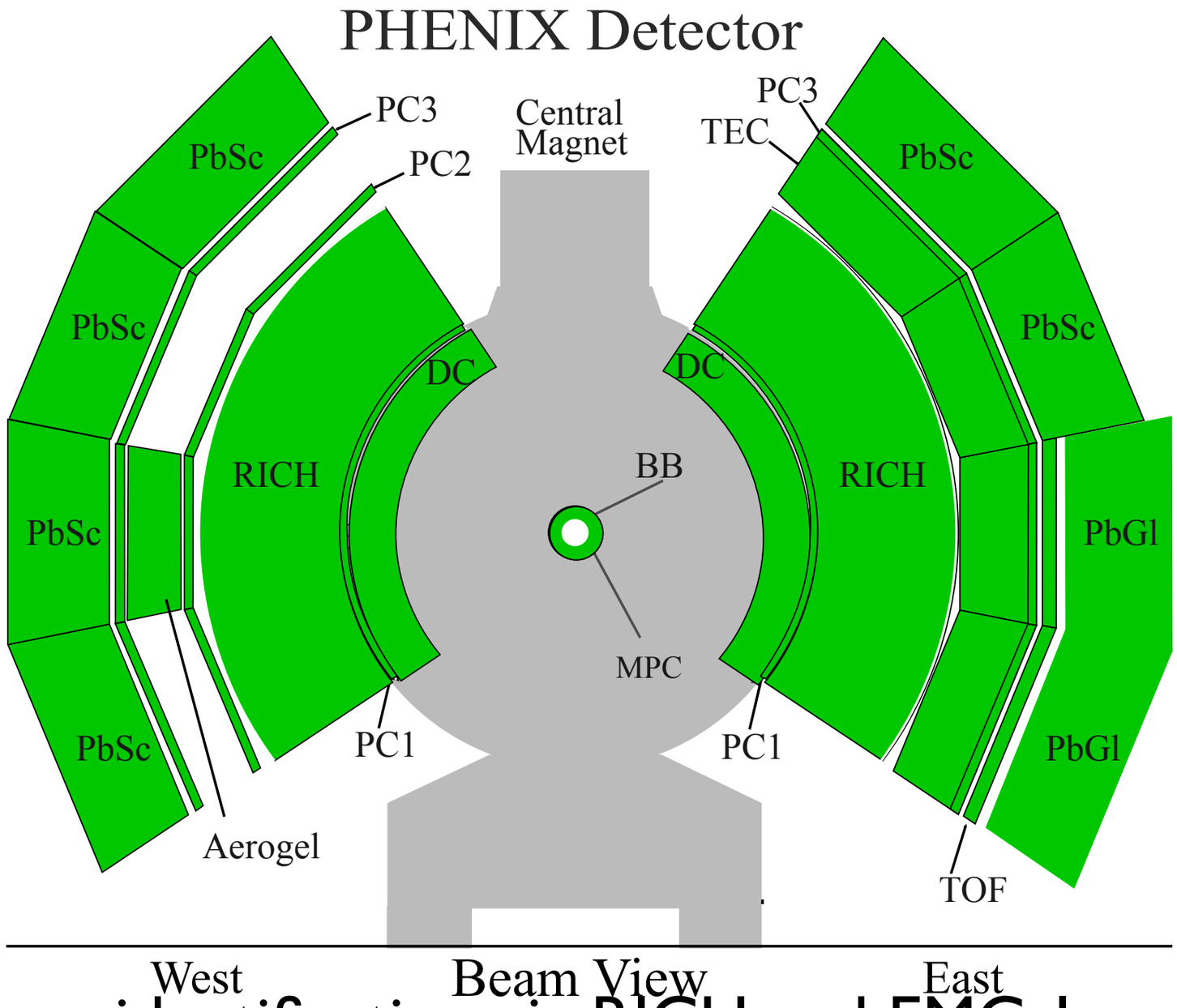
→ *control geometry*

π^0 R_{AA} (ϕ)
π^0 I_{AA} (ϕ)

↓ *control parton*

$e^{\pm}$ R_{AA}
$e^{\pm}$ I_{AA}

Electron Measurement



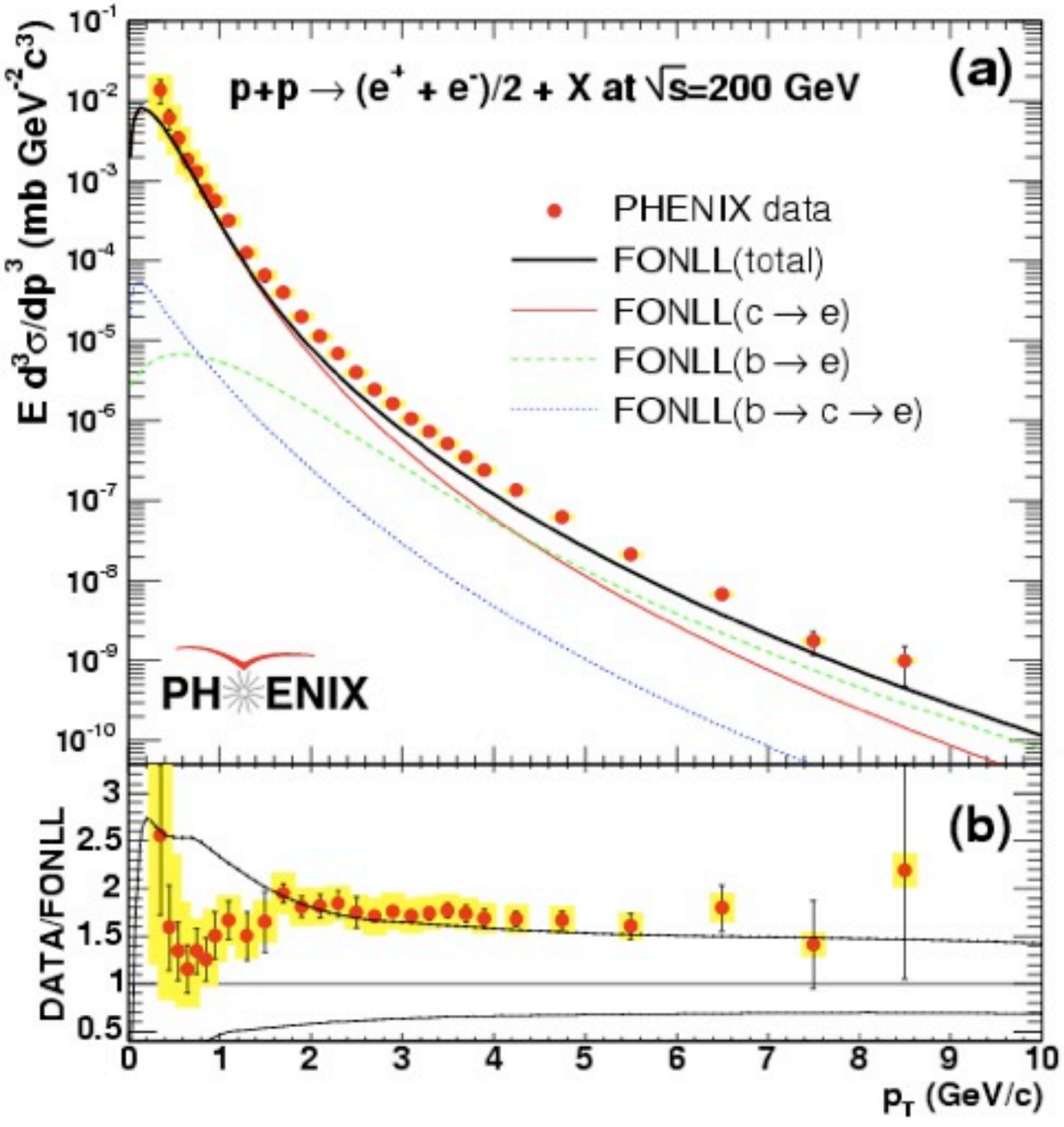
- electron identification via RICH and EMCal
- residual hadron contamination: <1% p+p, <3% Au+Au

two types of electrons

PHENIX, PRL 97 252002 (2006)

two types of electrons

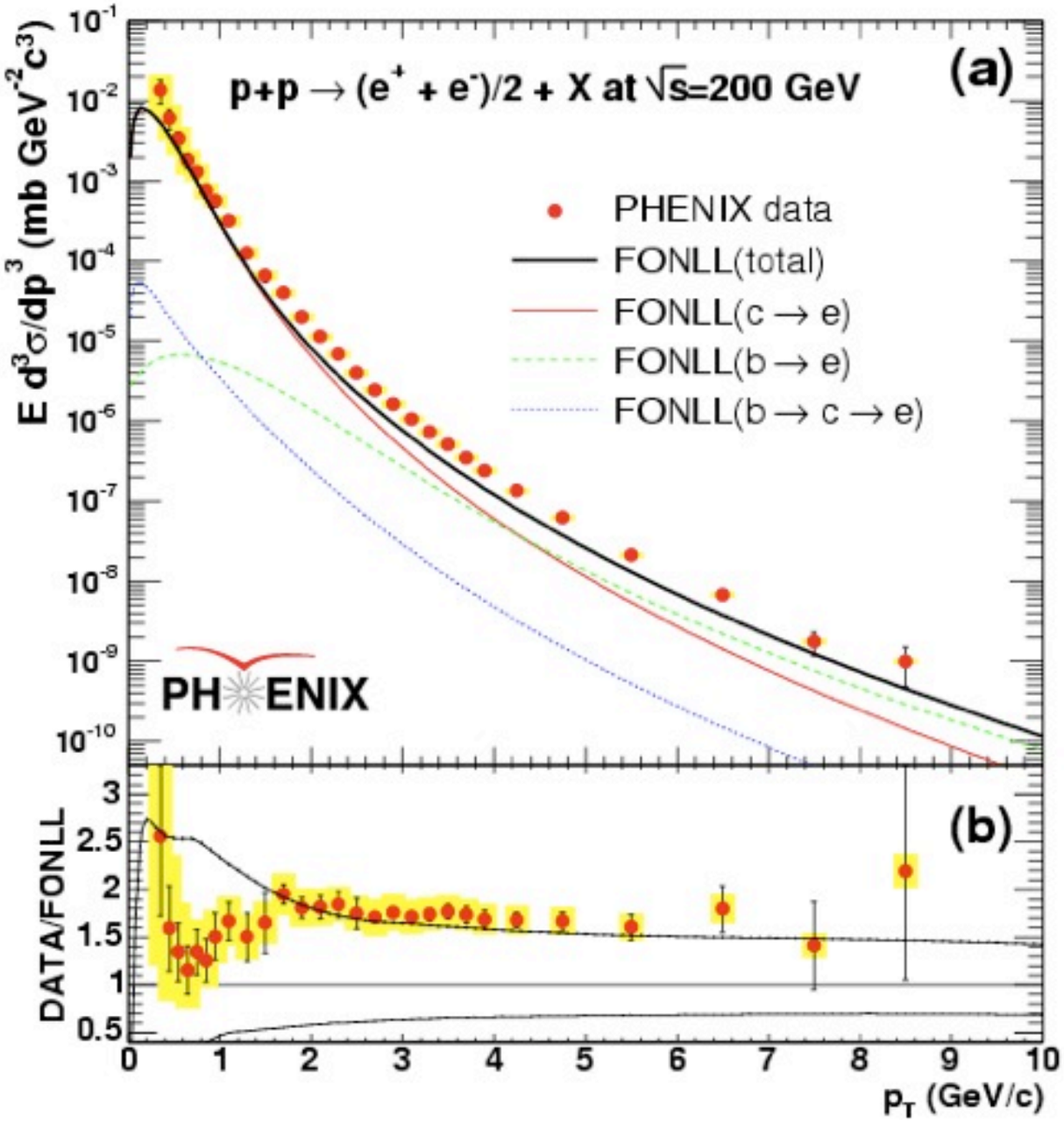
Heavy Flavor



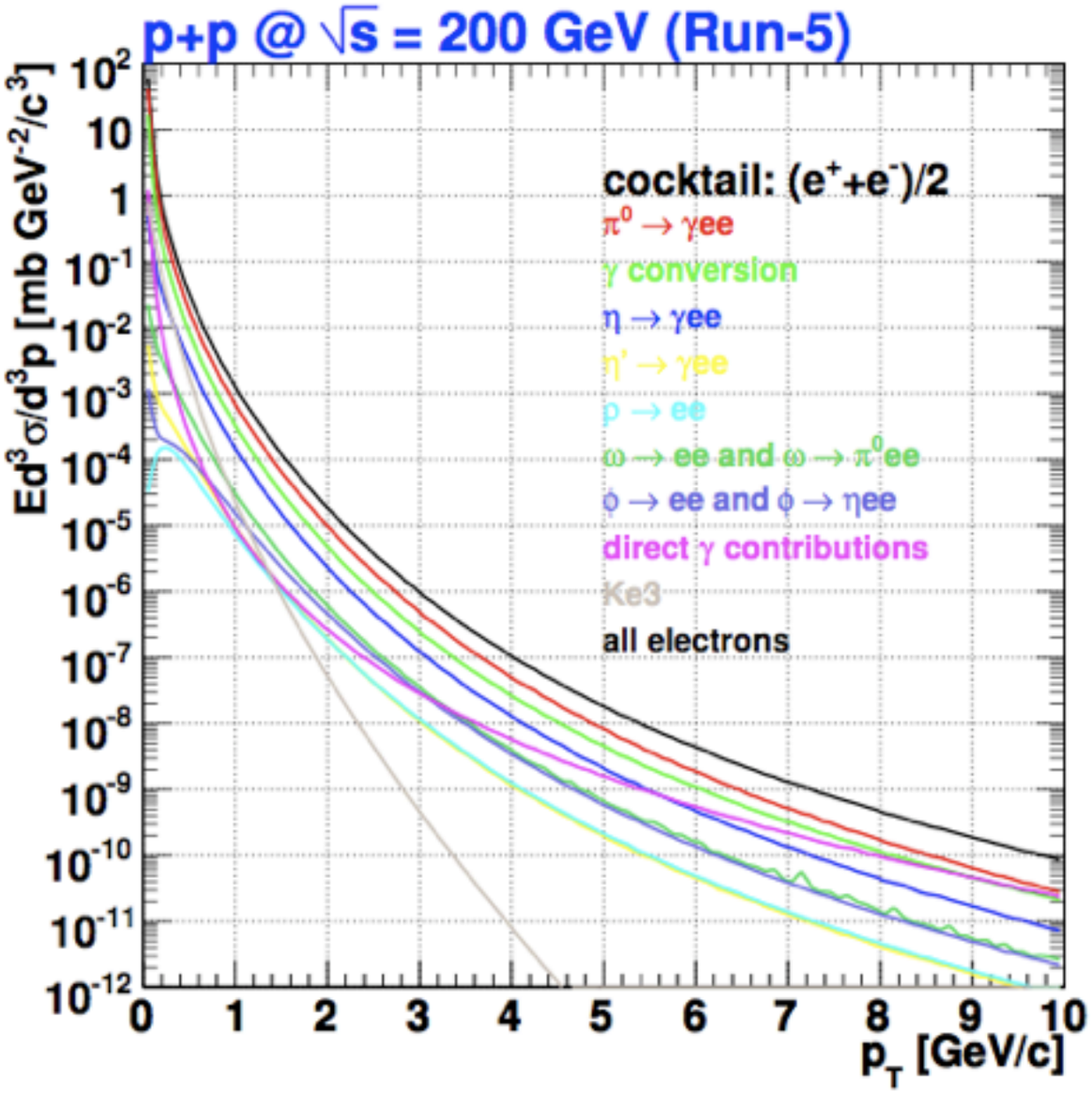
PHENIX, PRL 97 252002 (2006)

two types of electrons

Heavy Flavor



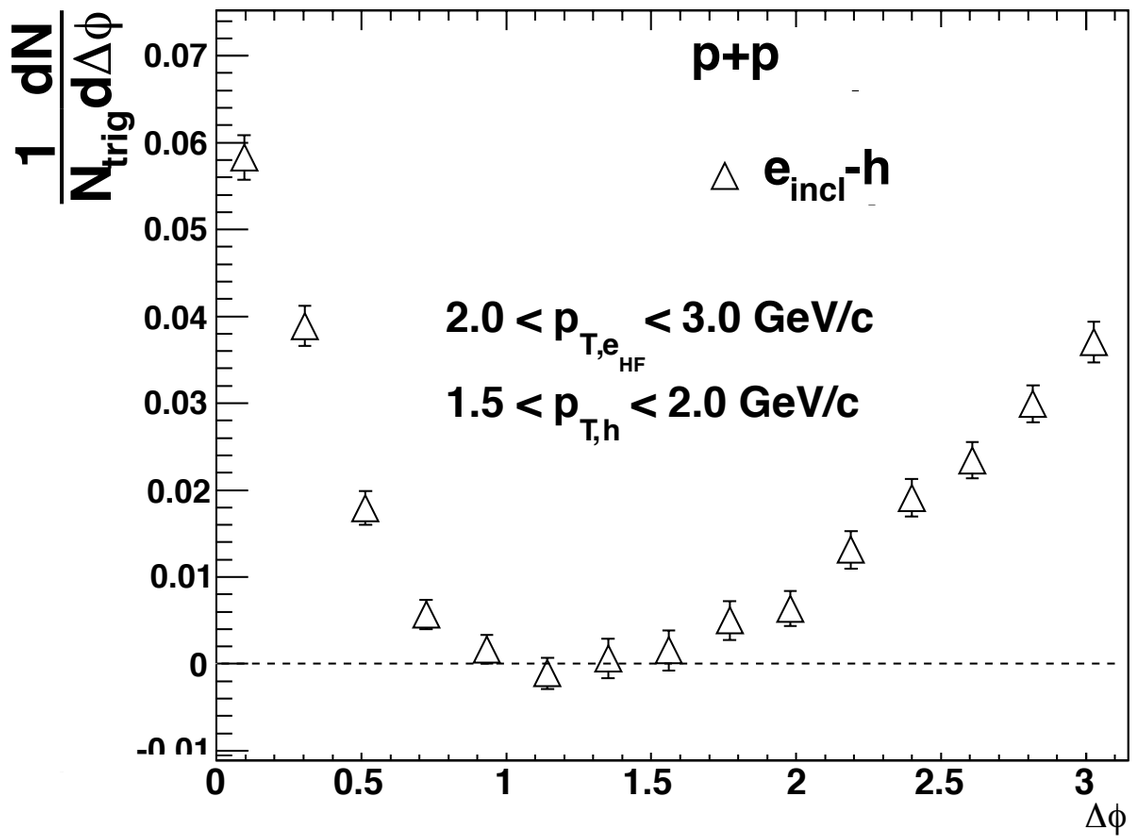
Photonic Electrons



PHENIX, PRL 97 252002 (2006)

inclusive electron correlations

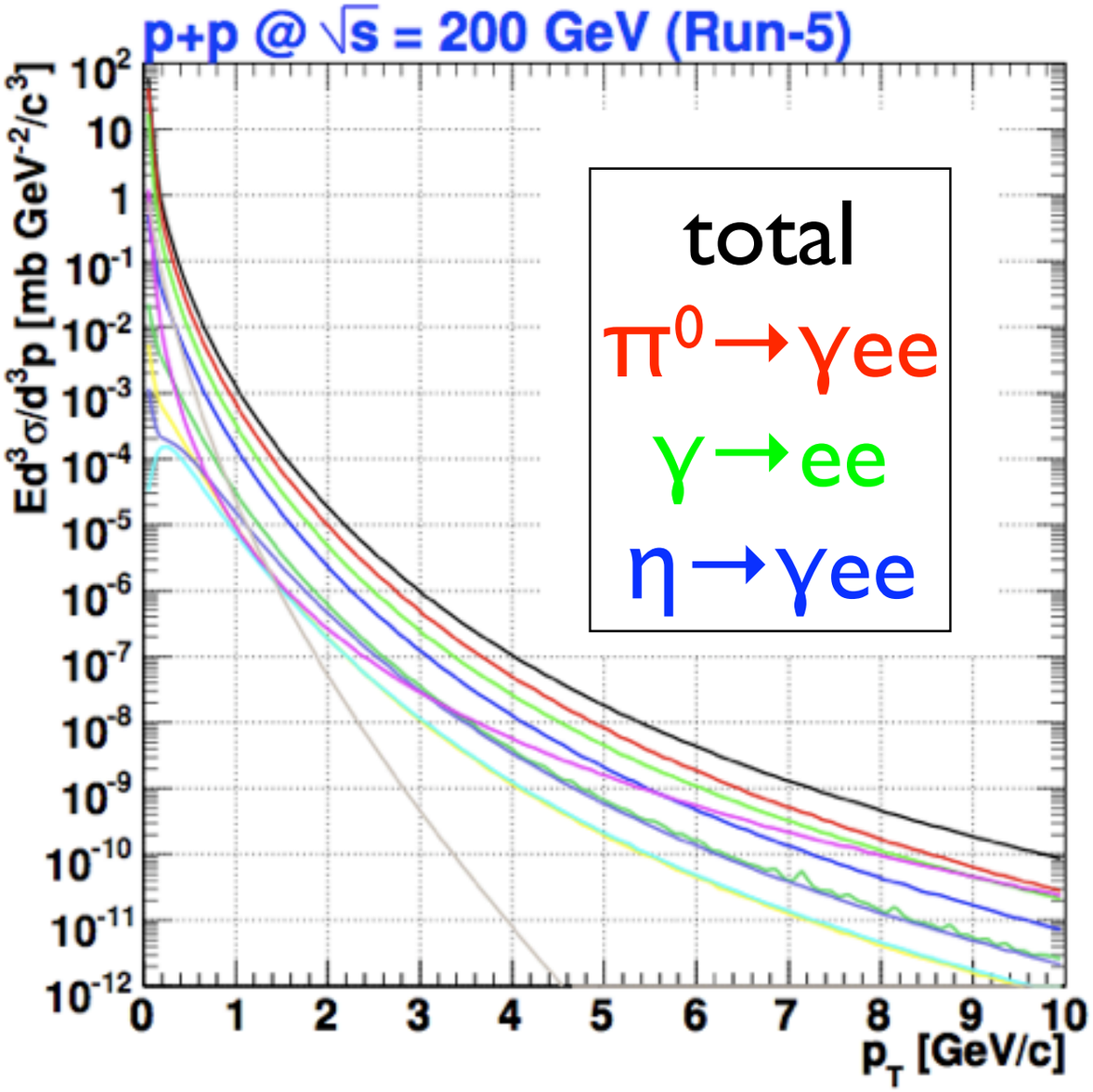
$$Y_{e_{incl}-h}$$



arXiv:1011.1477

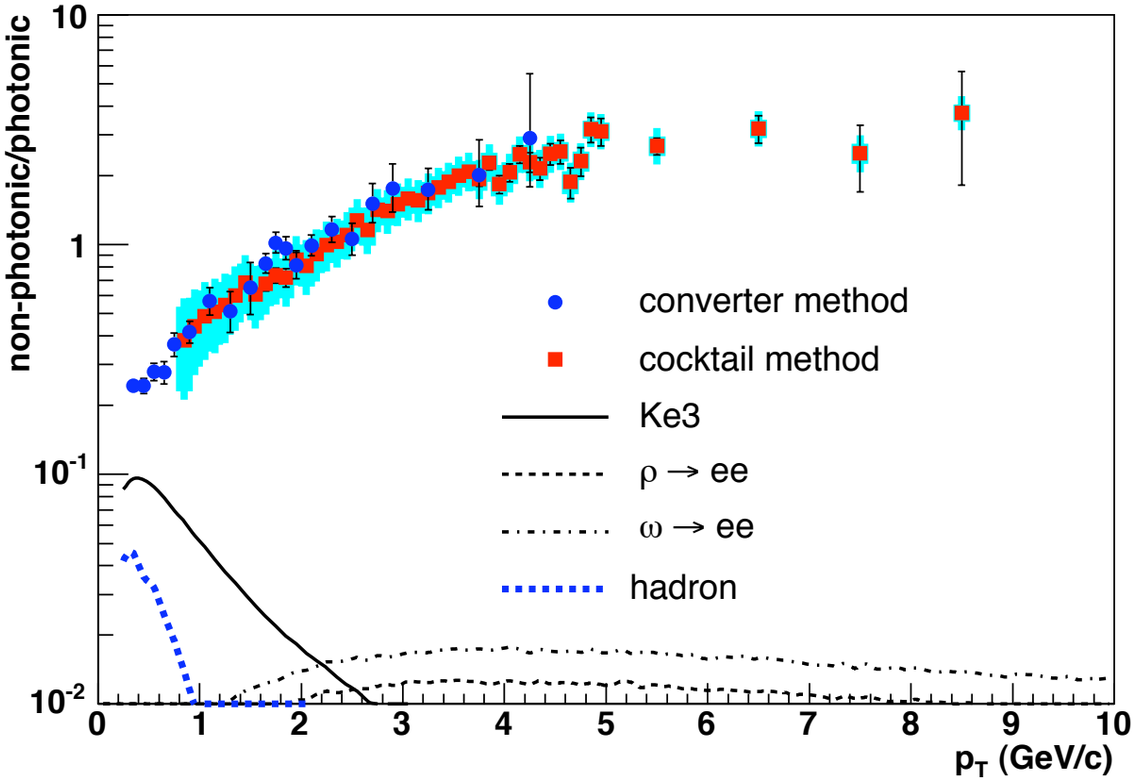
photonic electrons

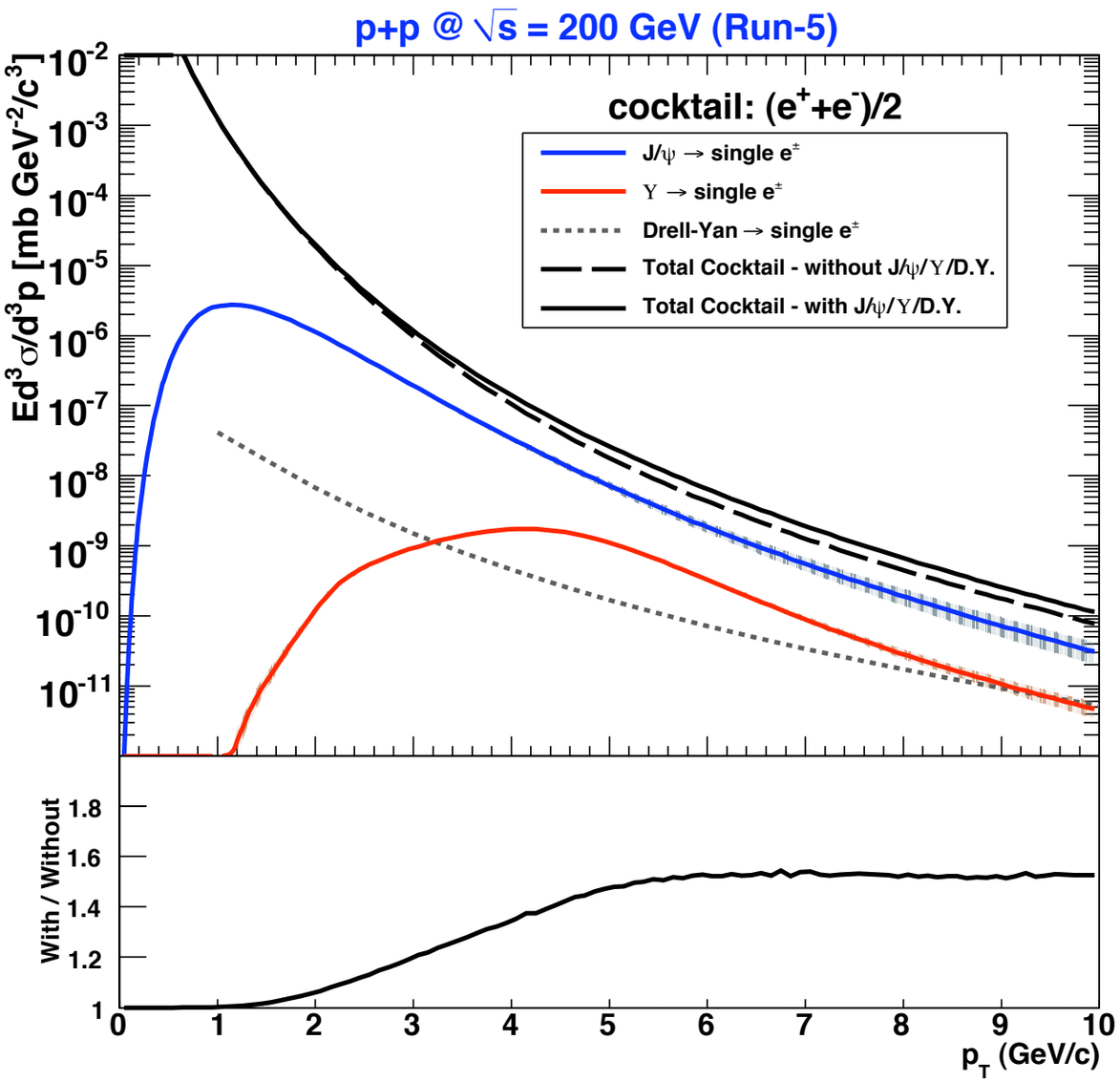
- p_T < 5GeV/c:
  - →dominantly from π^0s
- measure *photon*-h correlations
  - also dominantly from π^0s
- use MC to map between $e_{phot}(p_T)$ & $\gamma_{inc}(p_T)$



$$\gamma_{e_{phot}-h}$$

relative contributions



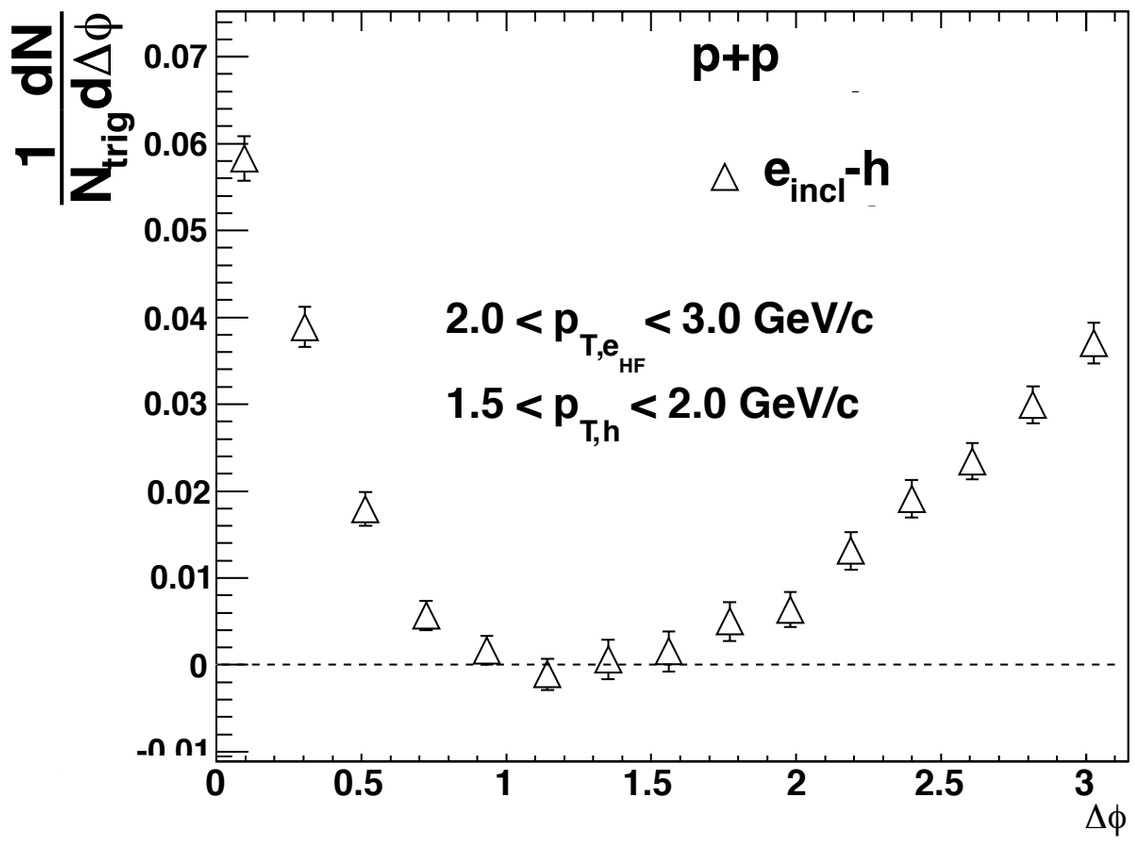


- S/B ~ 1 in the p_T range of interest
- J/ψ contributions also significant toward high p_T

PHENIX PRL 97 252002 (2006)
1005.1627[nucl-ex]

inclusive electron correlations

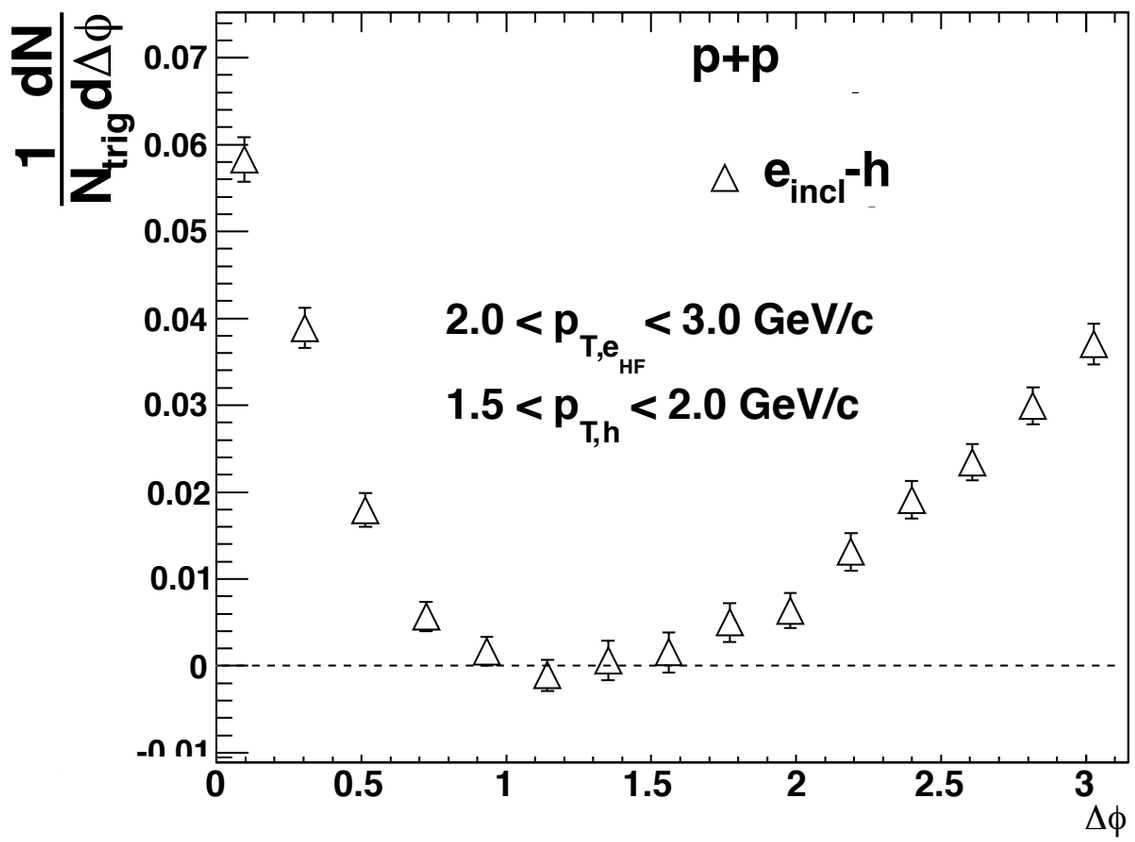
$$Y_{e_{incl}-h}$$



arXiv:1011.1477

inclusive electron correlations

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



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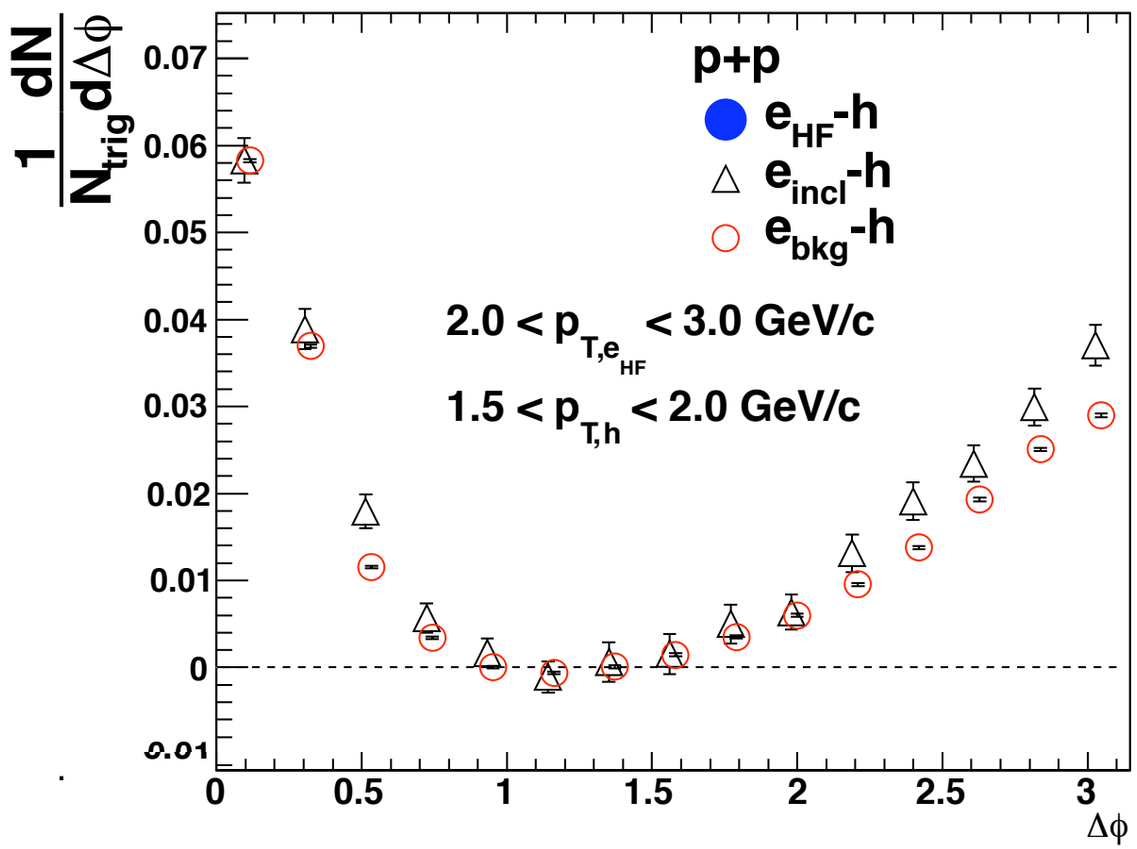

arXiv:1011.1477

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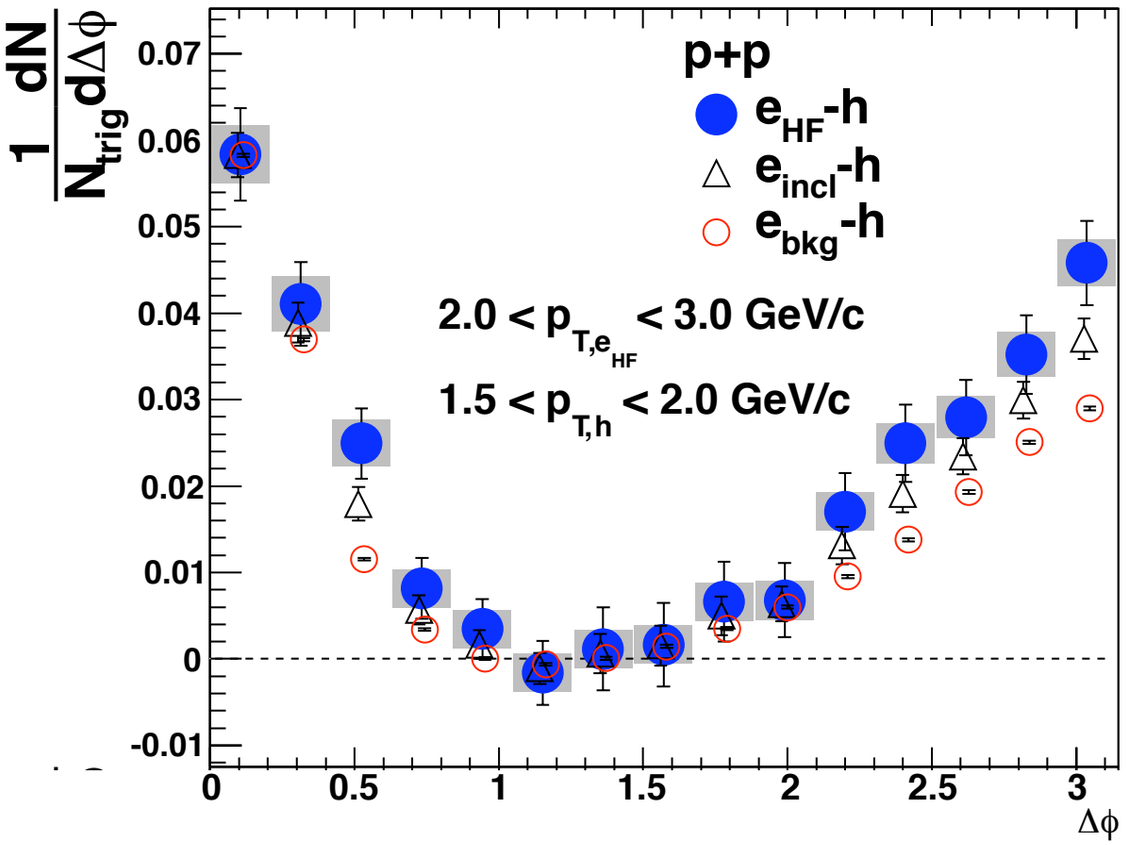
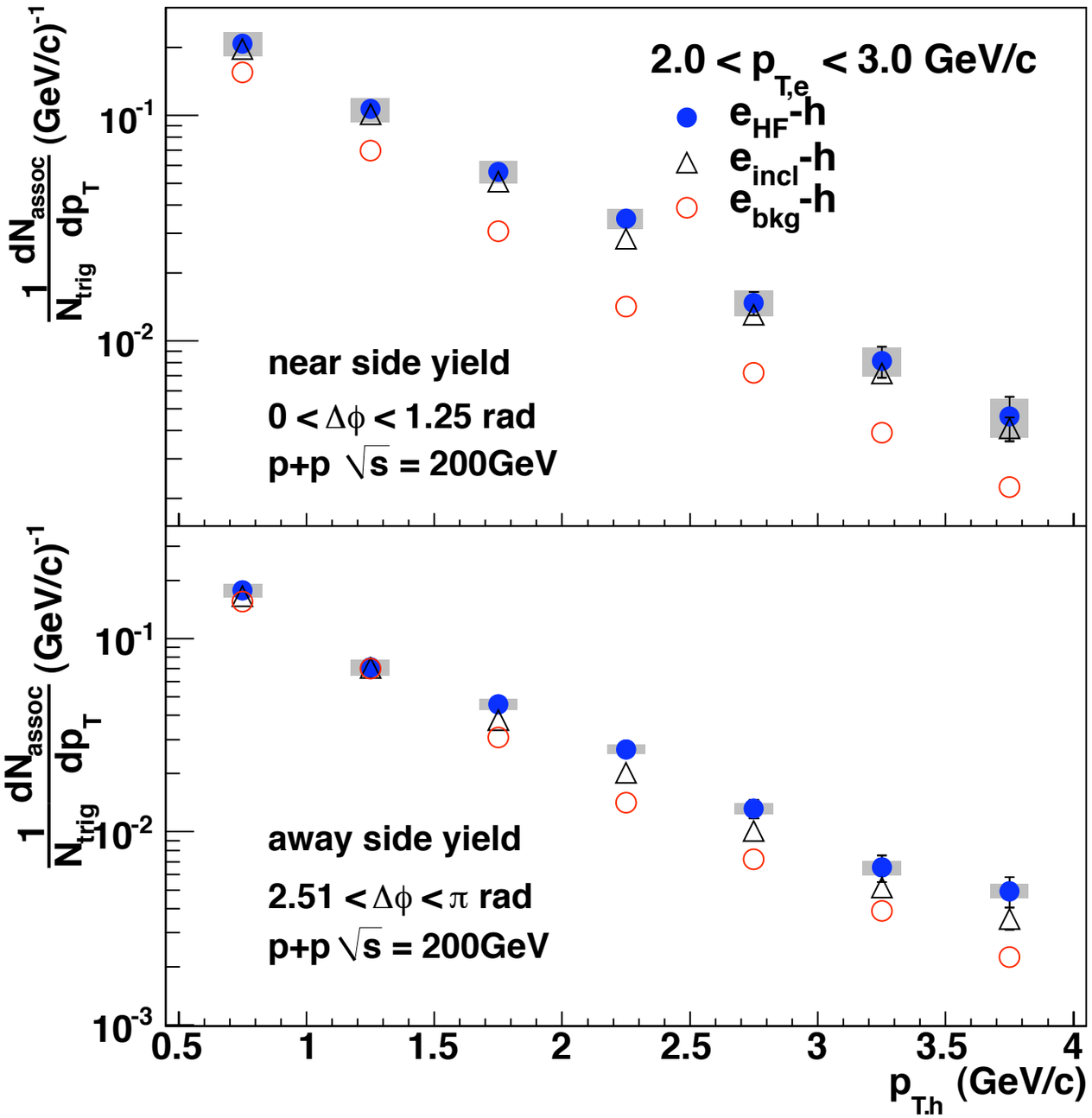


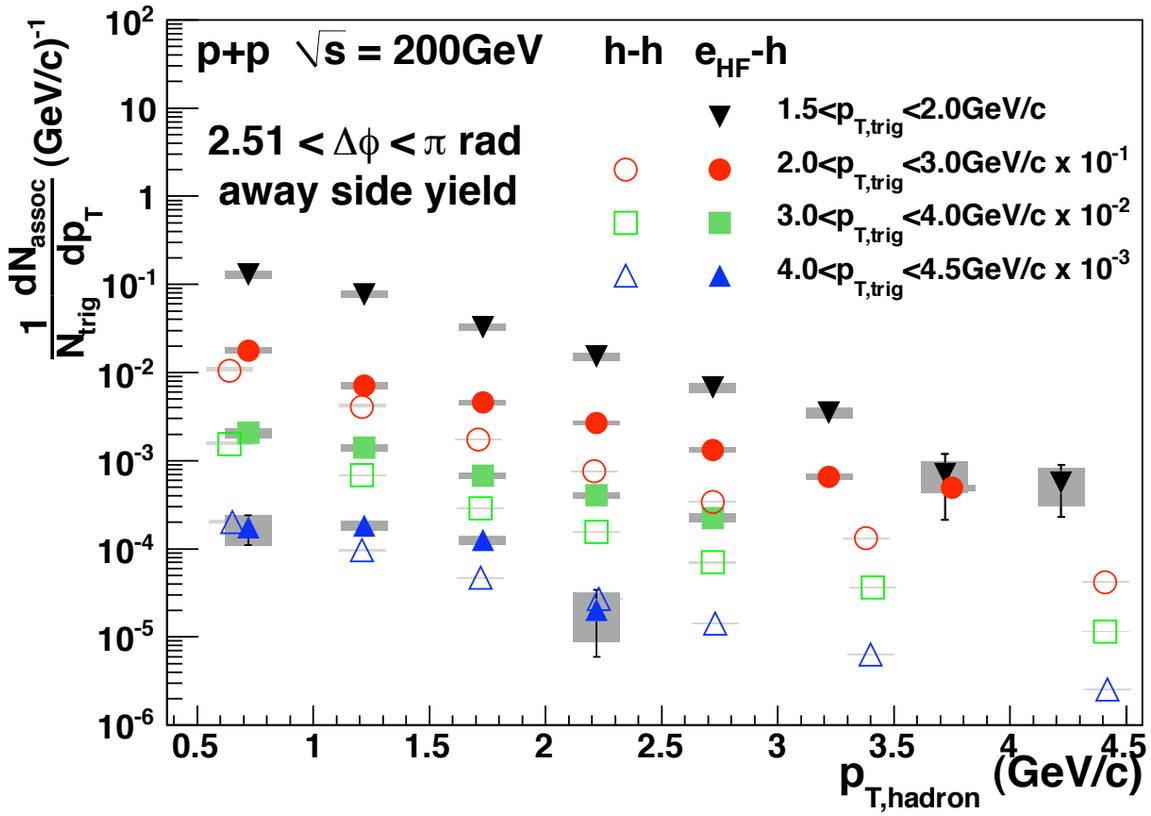
arXiv:1011.1477

jet-like correlations

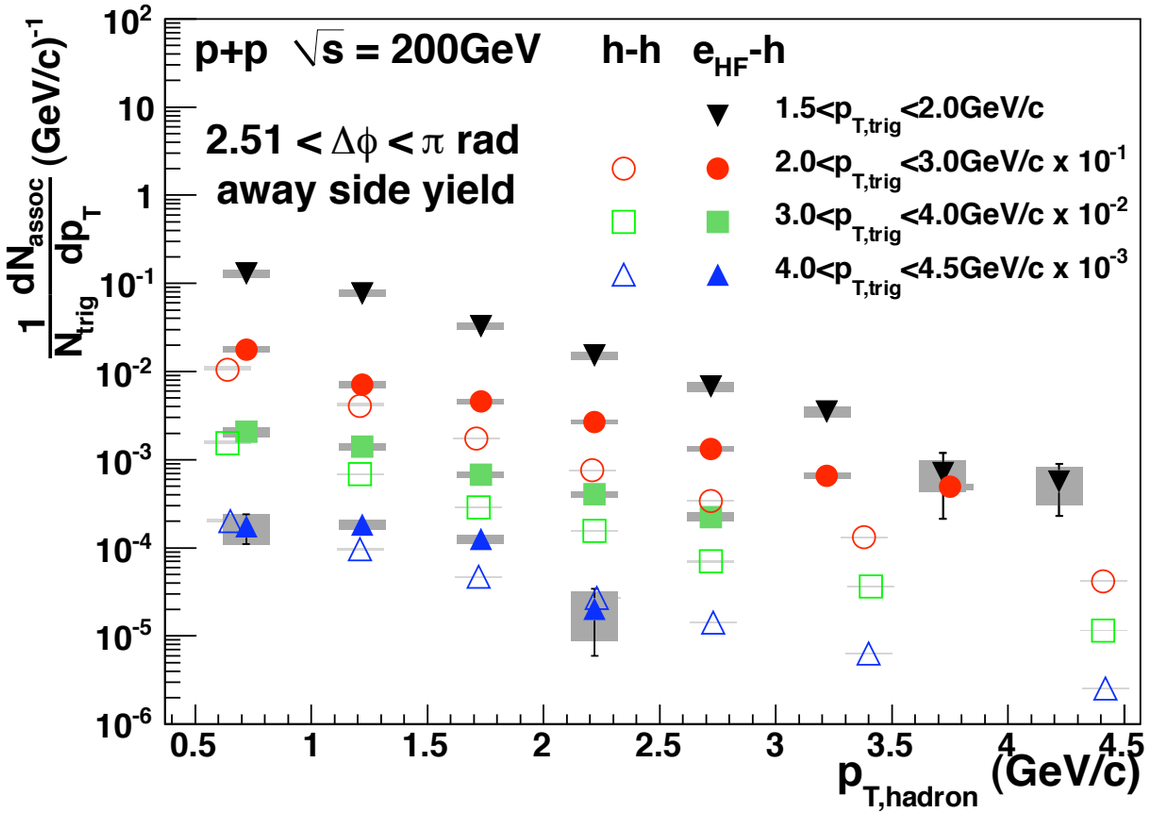


PHENIX: 1011.1477

p+p alone...


p+p $\sqrt{s}$ = 200GeV
h-h
e_{HF}-h
2.51 < Δφ < π rad
away side yield
1.5<$p_{T,trig}$<2.0GeV/c
2.0<$p_{T,trig}$<3.0GeV/c x 10^{-1}
3.0<$p_{T,trig}$<4.0GeV/c x 10^{-2}
4.0<$p_{T,trig}$<4.5GeV/c x 10^{-3}
$\frac{1}{N_{trig}}\frac{dN_{assoc}}{dp_T}$ (GeV/c)$^{-1}$
$p_{T,hadron}$ (GeV/c)

p+p alone...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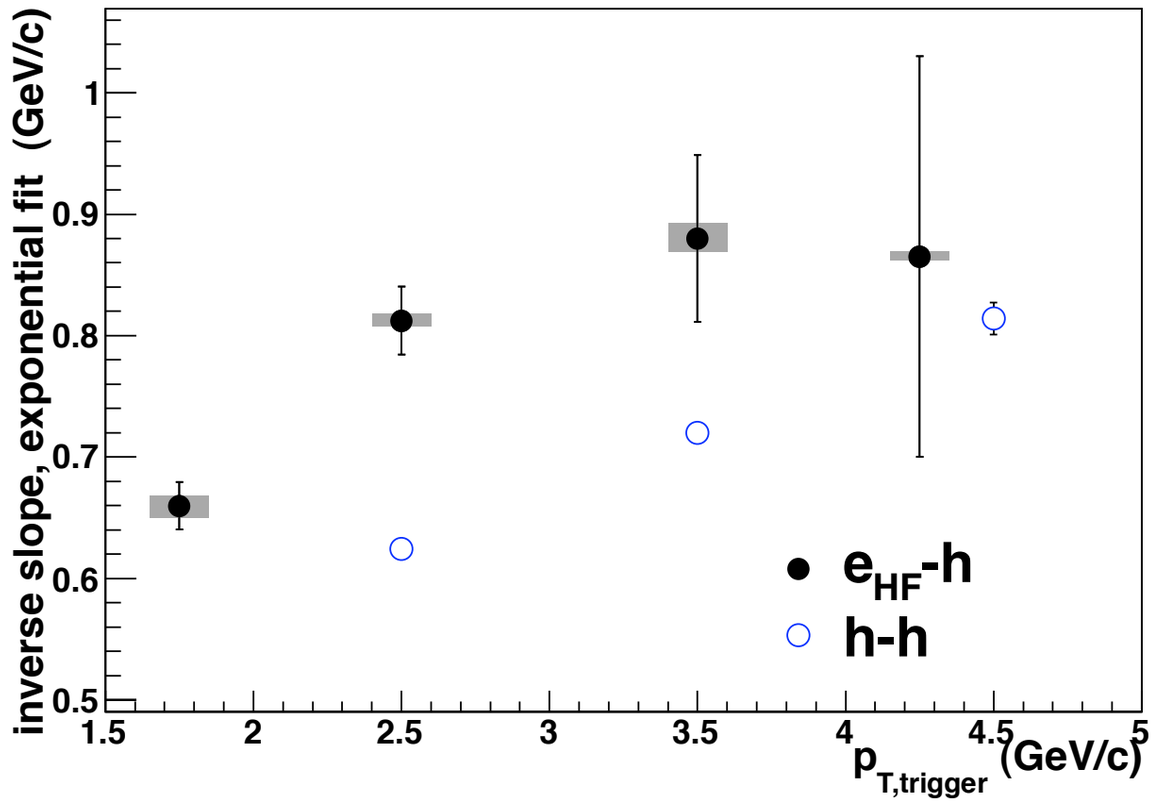
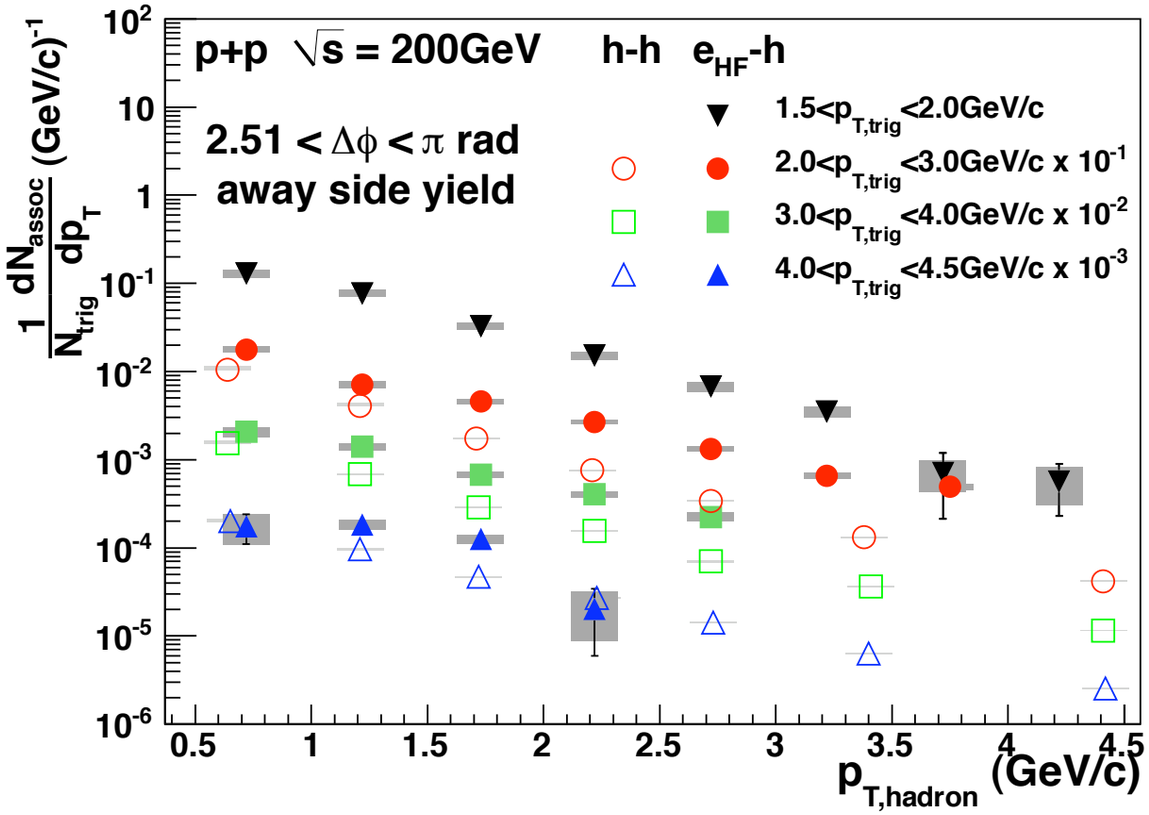

inverse slope, exponential fit (GeV/c)
e_{HF}-h
h-h
$p_{T,trigger}$ (GeV/c)

p+p alone...



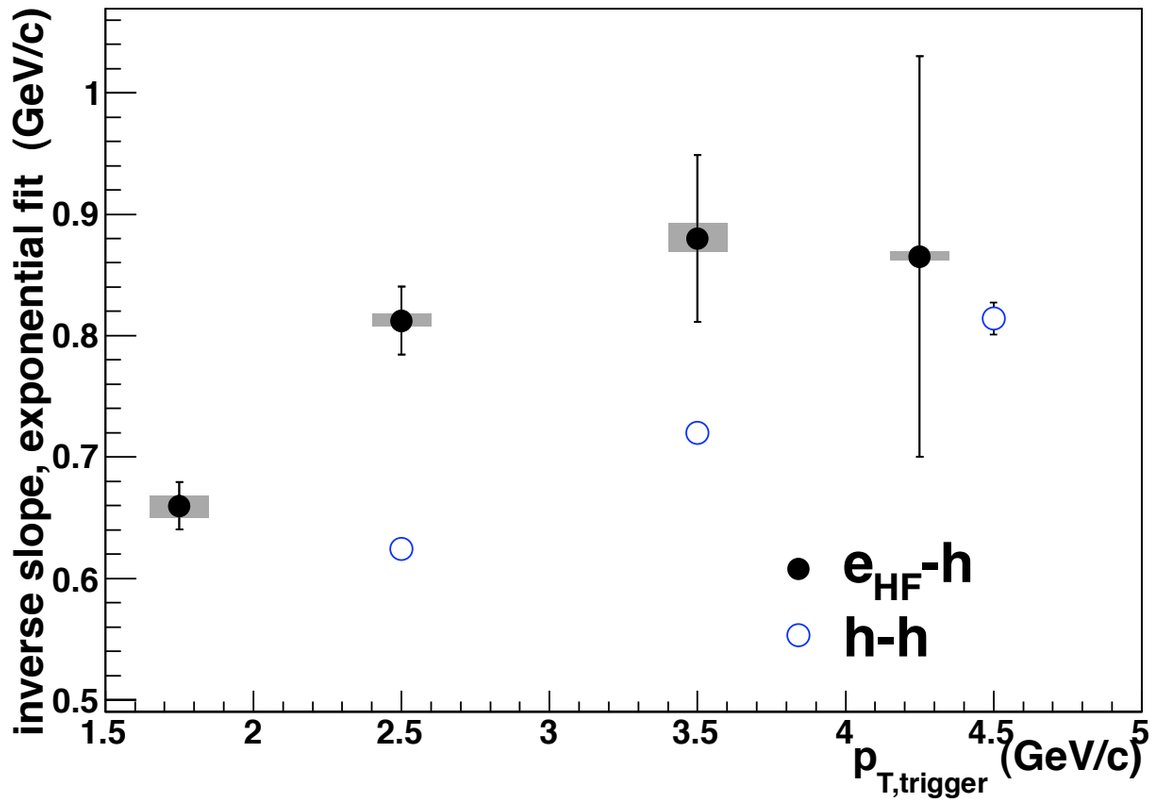
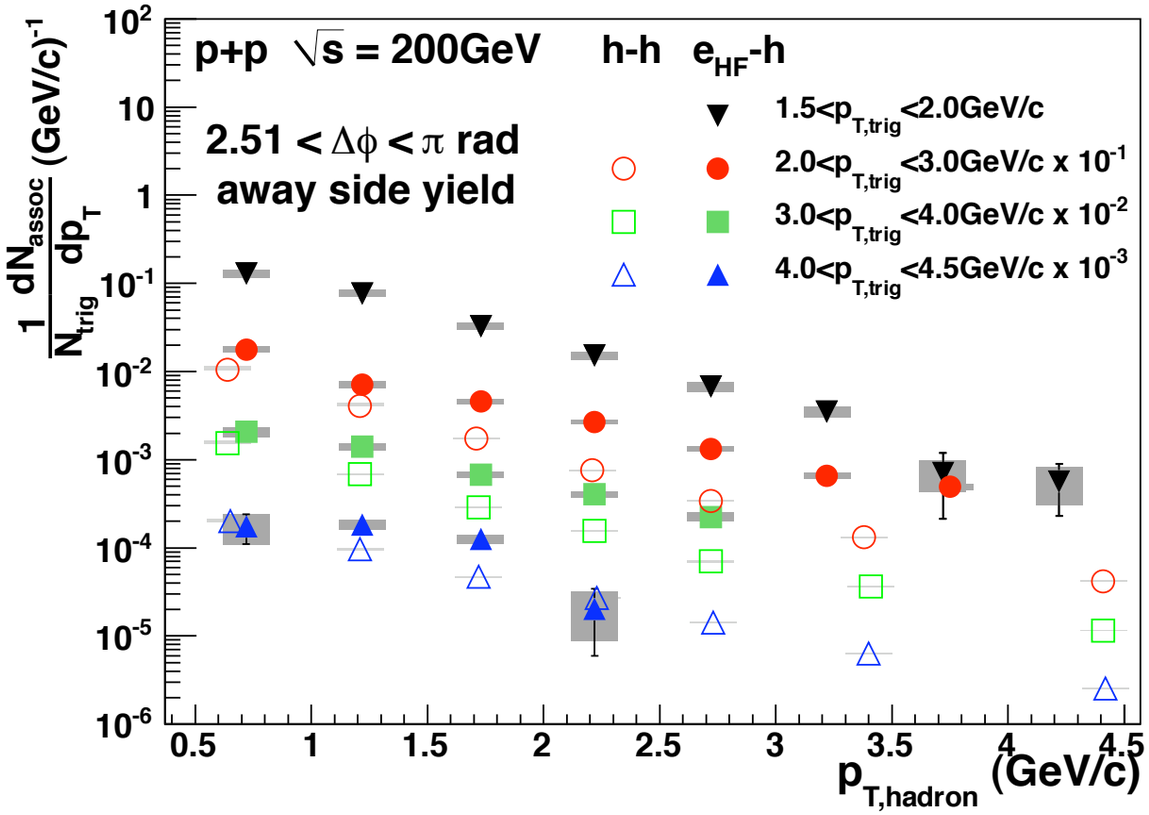
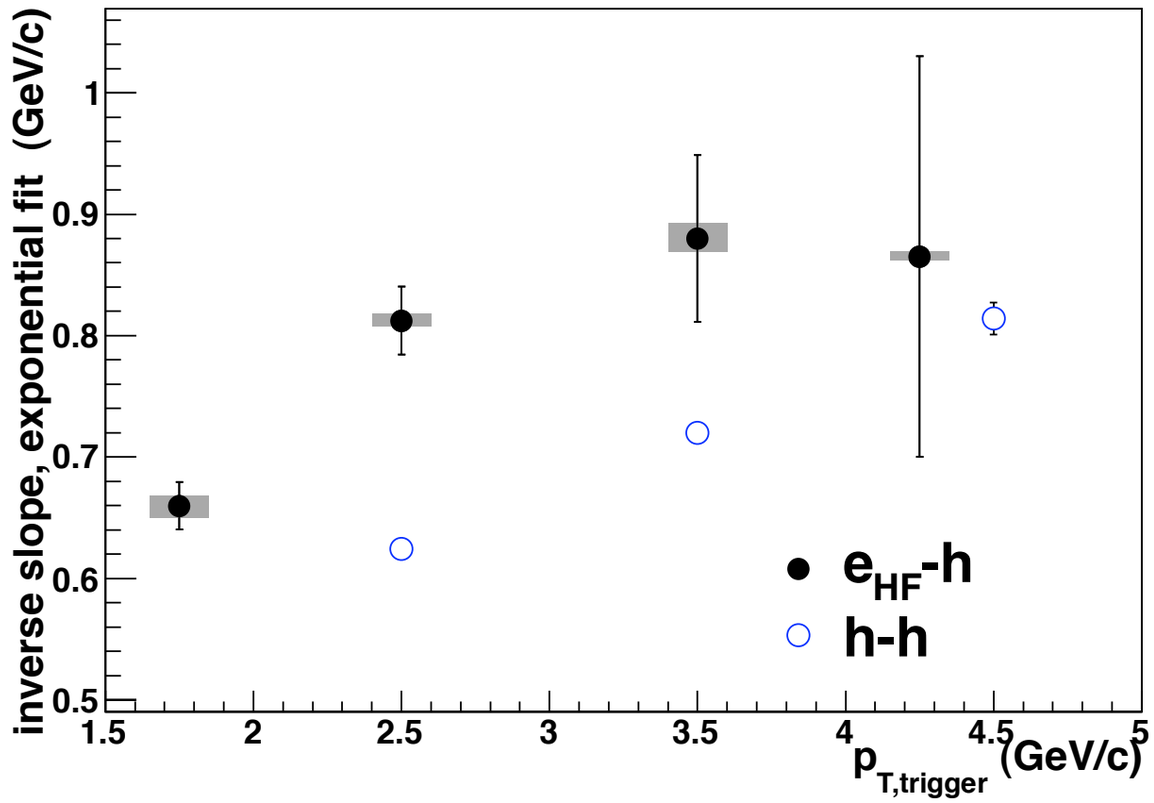


TABLE III: Mean transverse momentum of the parent D and B mesons contributing to the heavy-flavor electron p_T bins used here. They are combined according to the fraction of heavy-flavor electrons from b quarks, $\frac{b\to e}{(c\to e+b\to e)}$ according to the FONLL calculations [31] (as shown in Ref. [29]) to determine the mean heavy meson transverse momentum.

$p_{T,e}$ (GeV/c)	$\langle p_T\rangle_D$ (GeV/c)	$\langle p_T\rangle_B$ (GeV/c)	$\frac{b\to e}{(c\to e+b\to e)}$	$\langle p_T\rangle_{meson}$ (GeV/c)
1.5-2.0	3.4	4.4	0.15	3.6
2.0-3.0	4.1	4.7	0.26	4.3
3.0-4.0	5.6	5.6	0.42	5.6

p+p alone...





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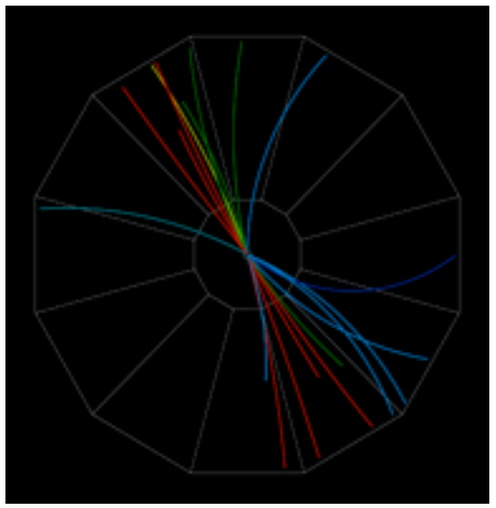
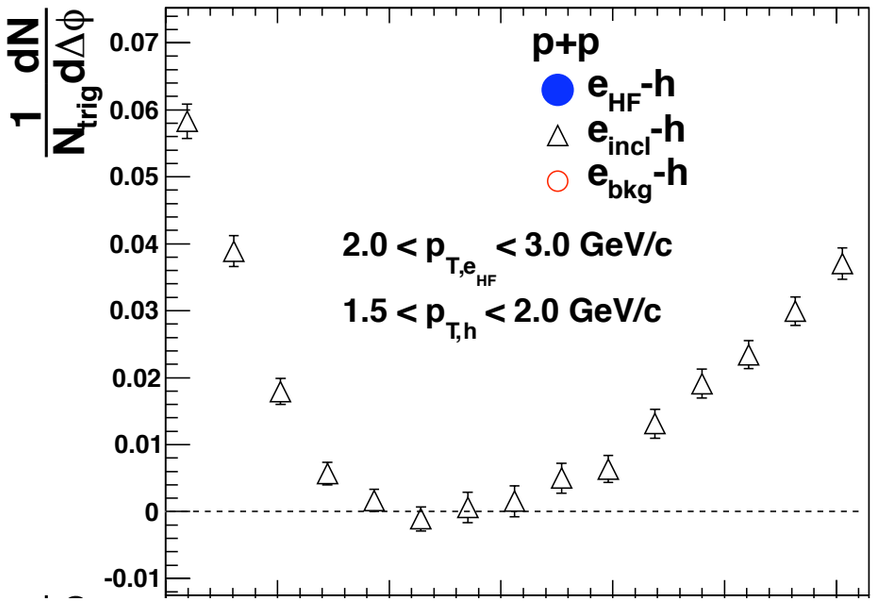
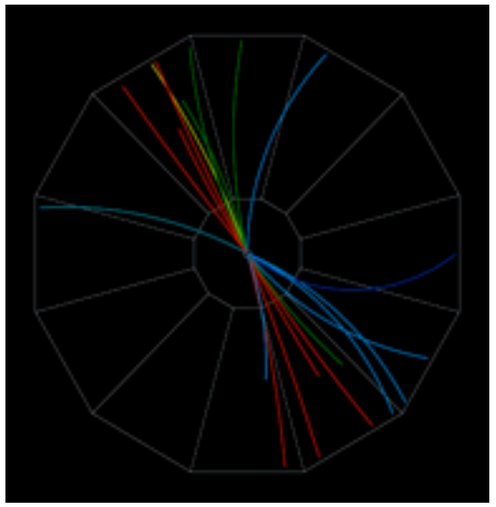
combinatoric background

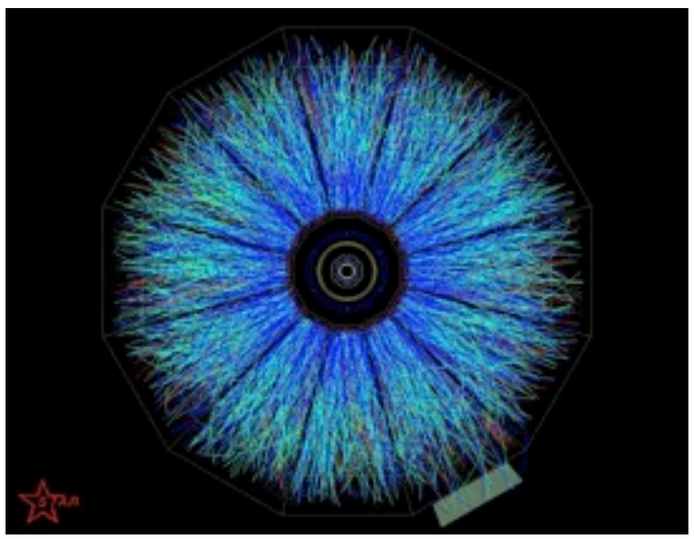


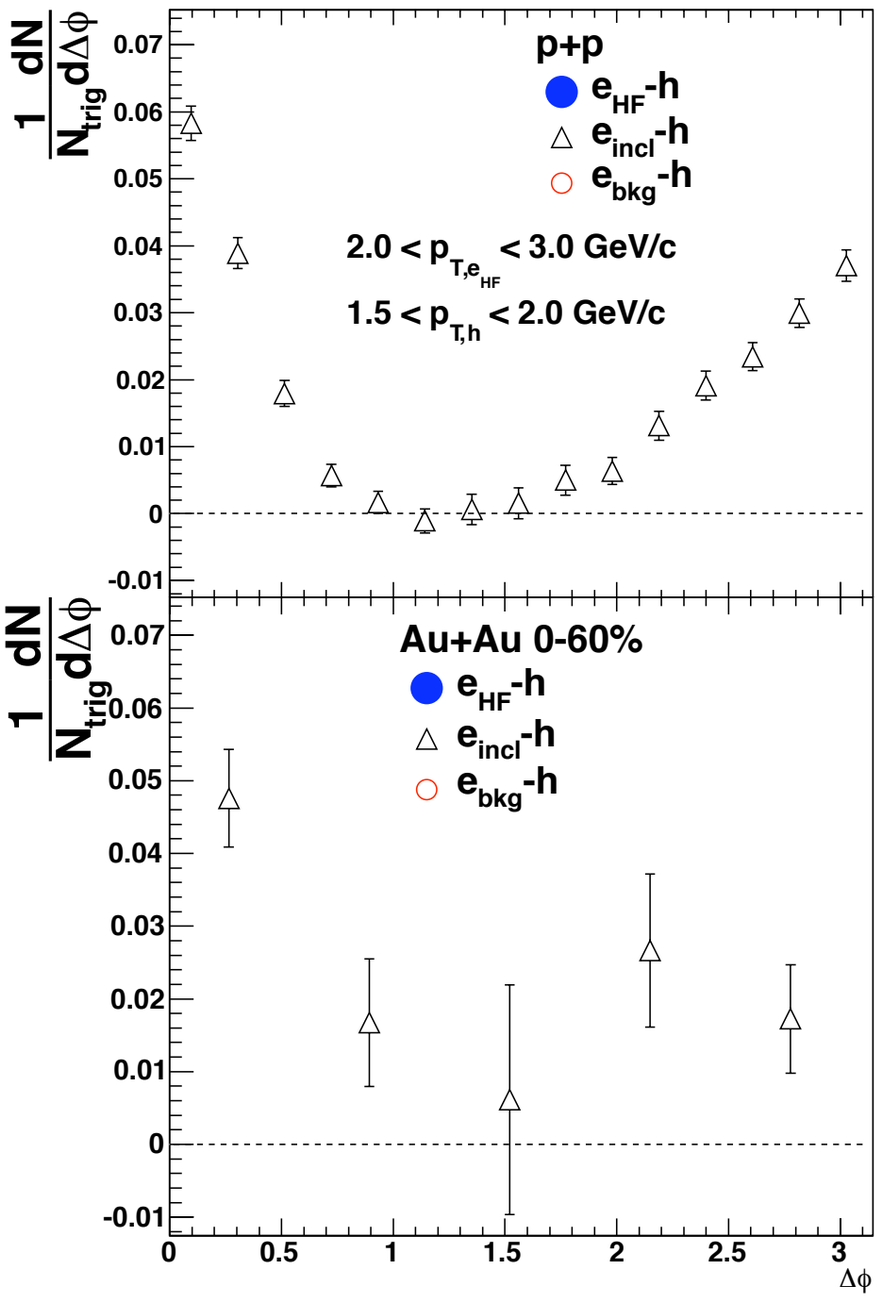


jet S/B > 1

combinatoric background







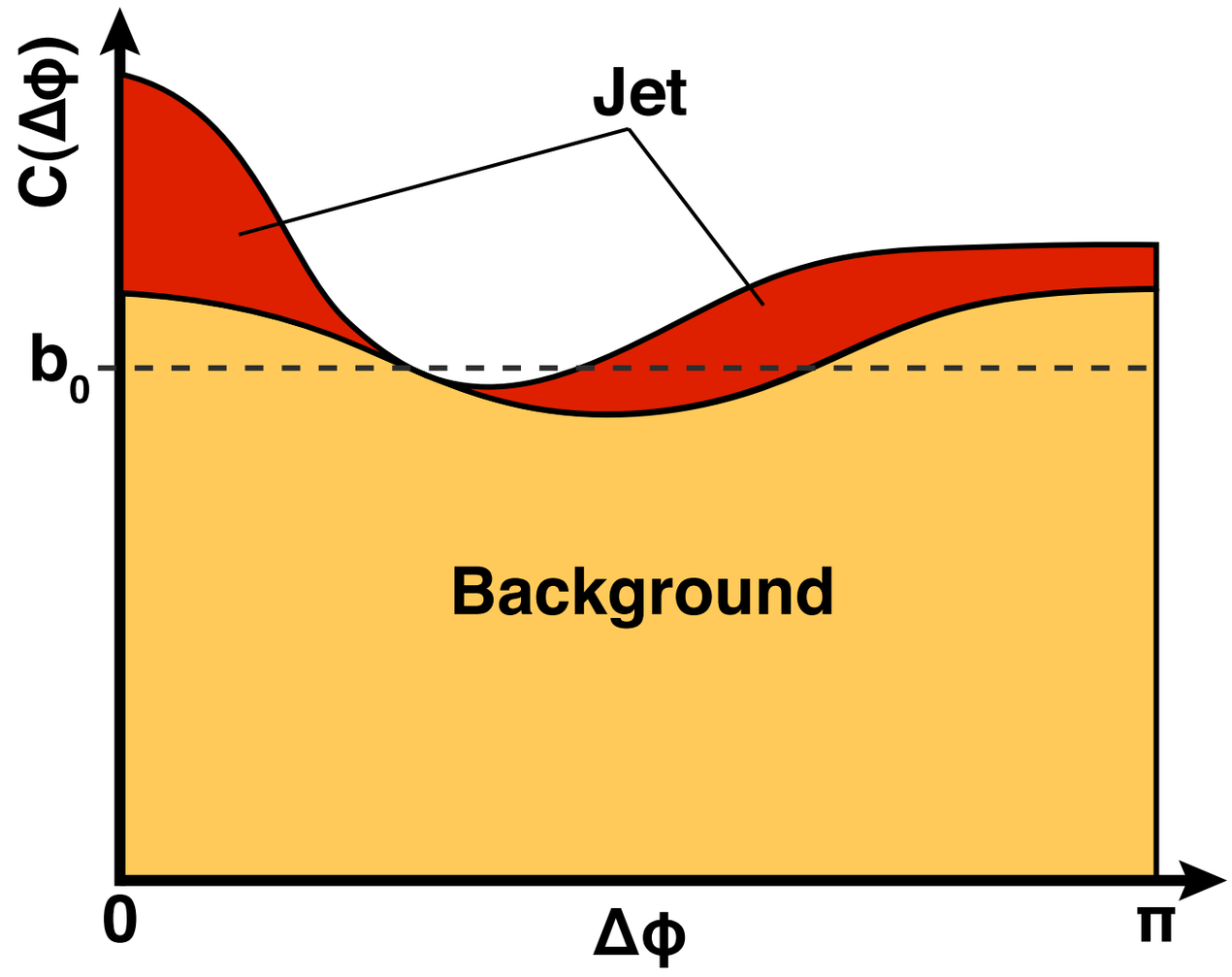
jet S/B > 1

jet S/B ~ 1%

absolute background subtraction

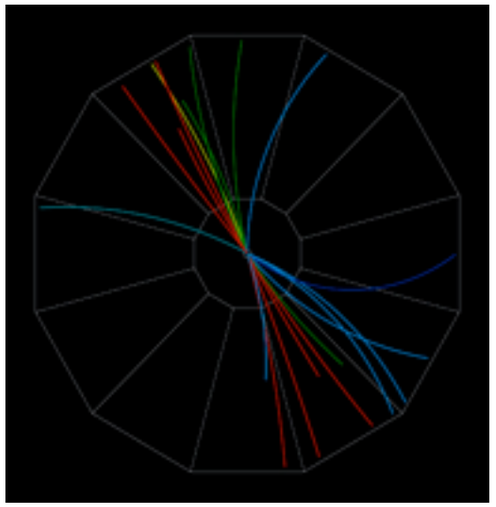
combinatoric background = $b_0(1+2v_{2A}v_{2B}\cos(2\Delta\phi))$

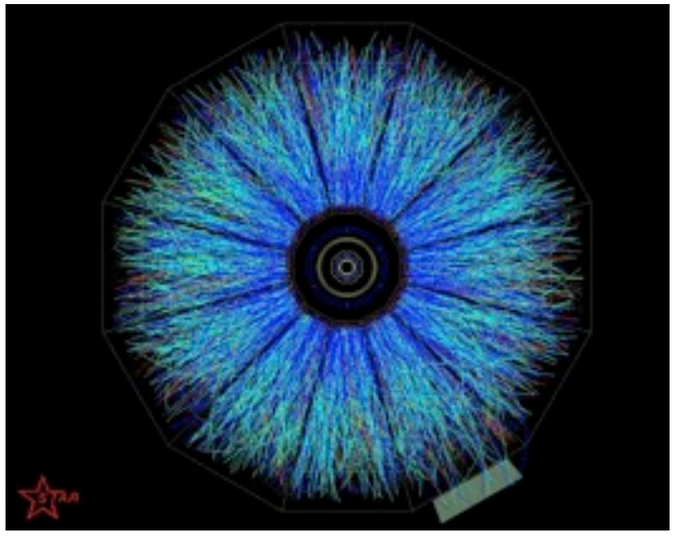
- b_0 can be calculated in HI collisions (no fudge factors) w/ negligible statistical errors
  - depends on the centrality fluctuations
- generally very close to ZYAM, however some significant advantages
  - wide jets
  - poor statistics

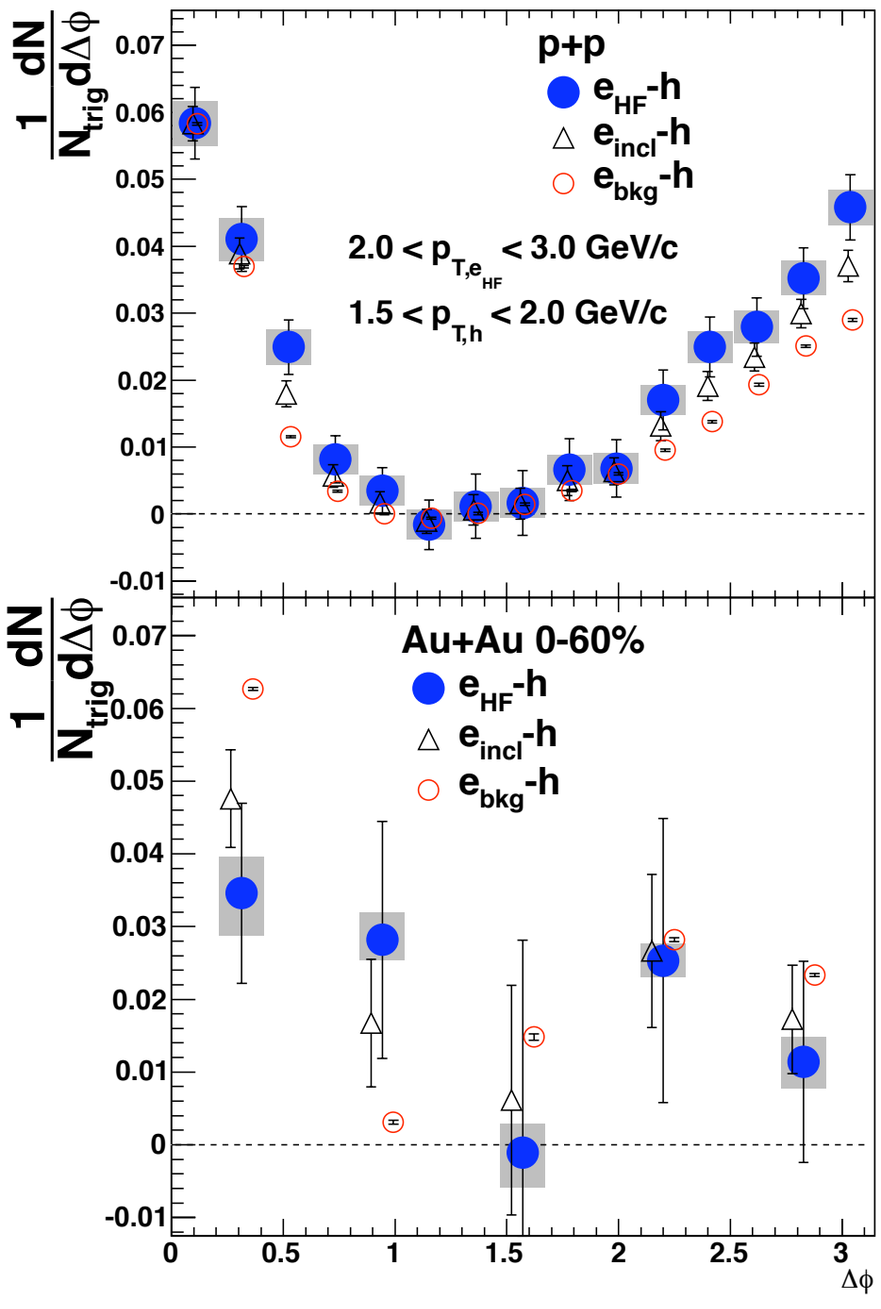


AMS, McCumber, Adare PRC 81 014908 (2010)

combinatoric background



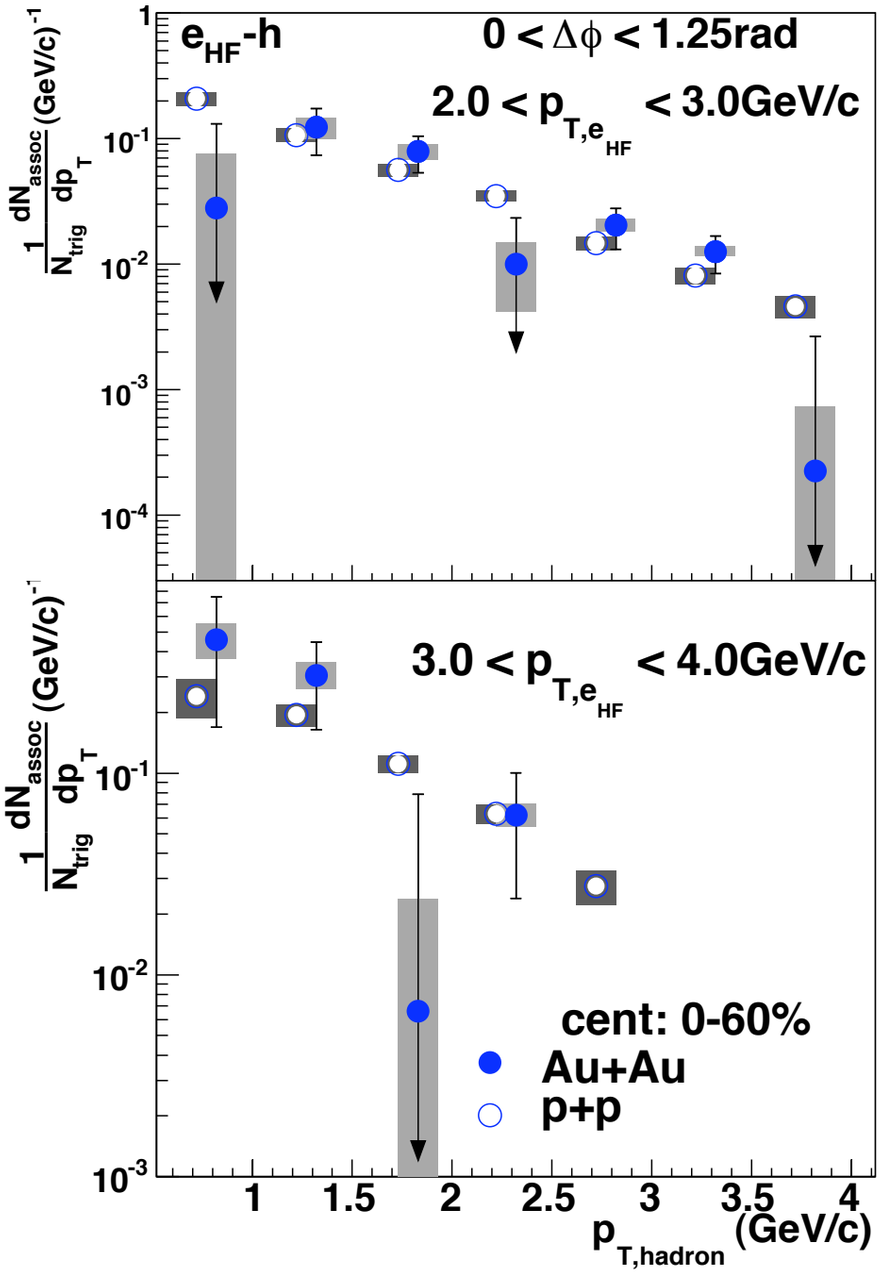




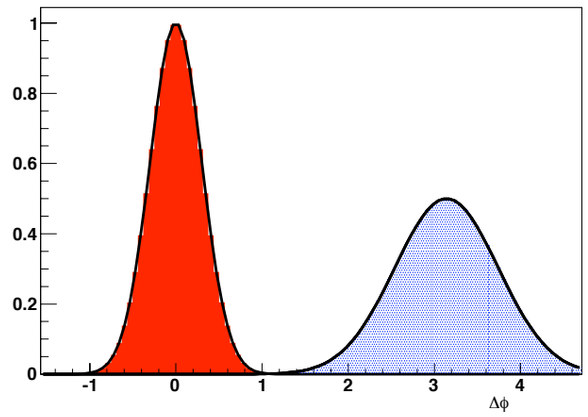
jet S/B > 1

jet S/B ~ 1%

e-h: same side correlations

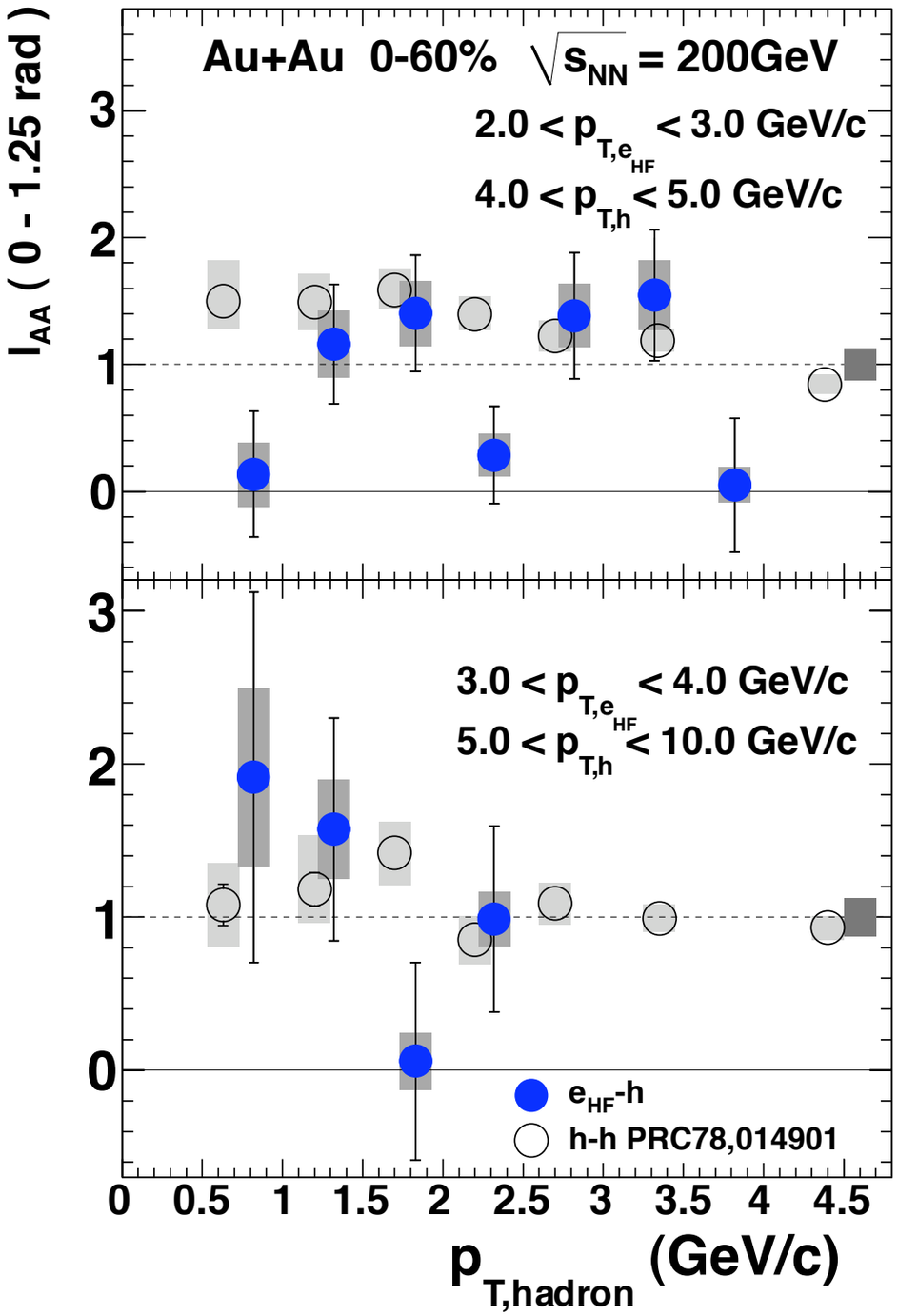


- no evidence for any modification
- consistent with hadron triggered



PHENIX: 1011.1477

e-h: same side correlations



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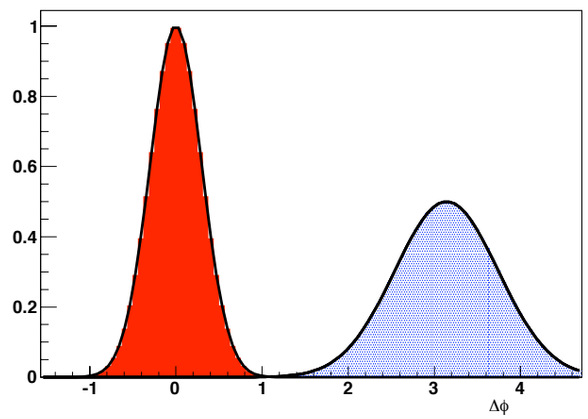
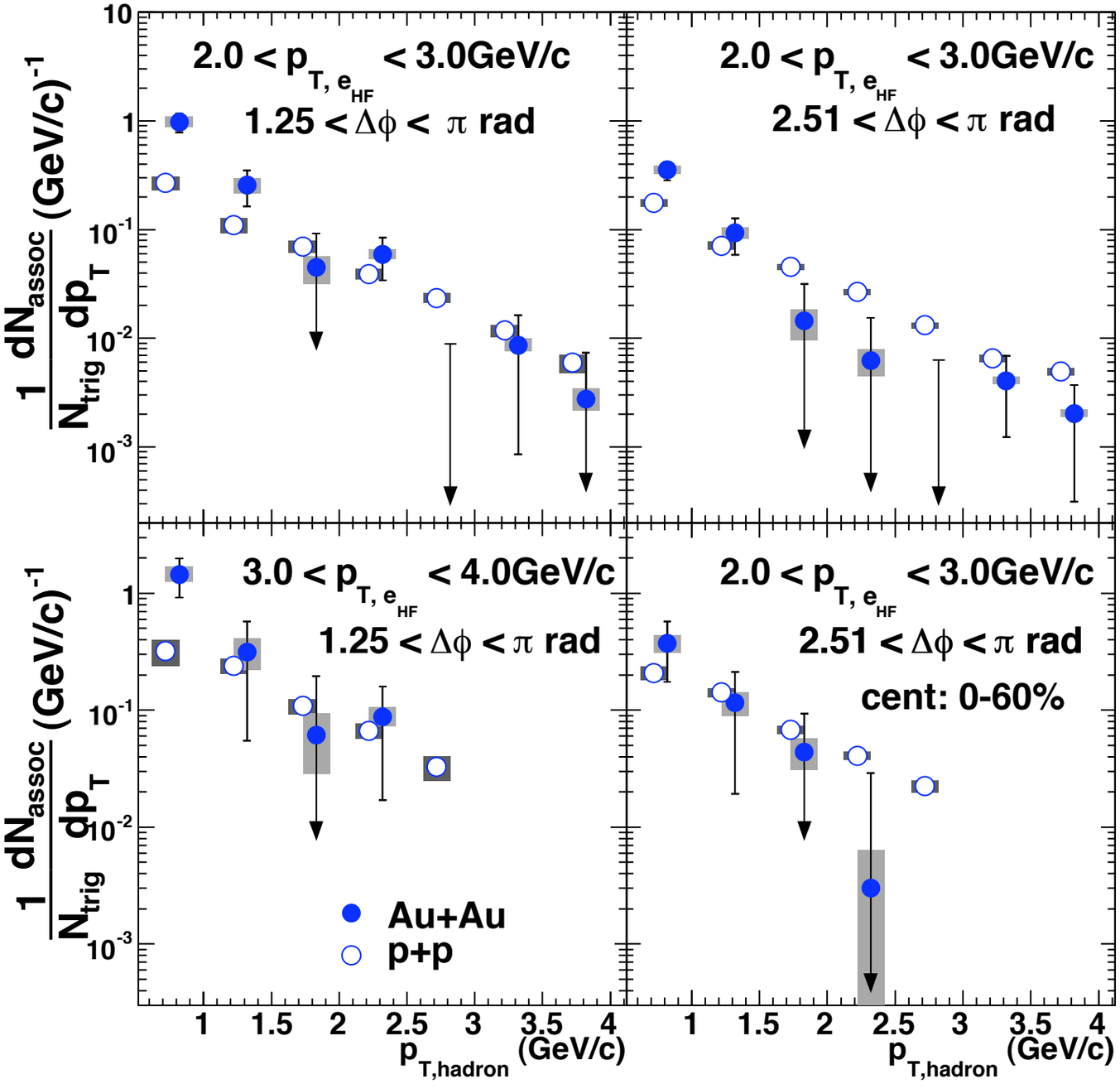


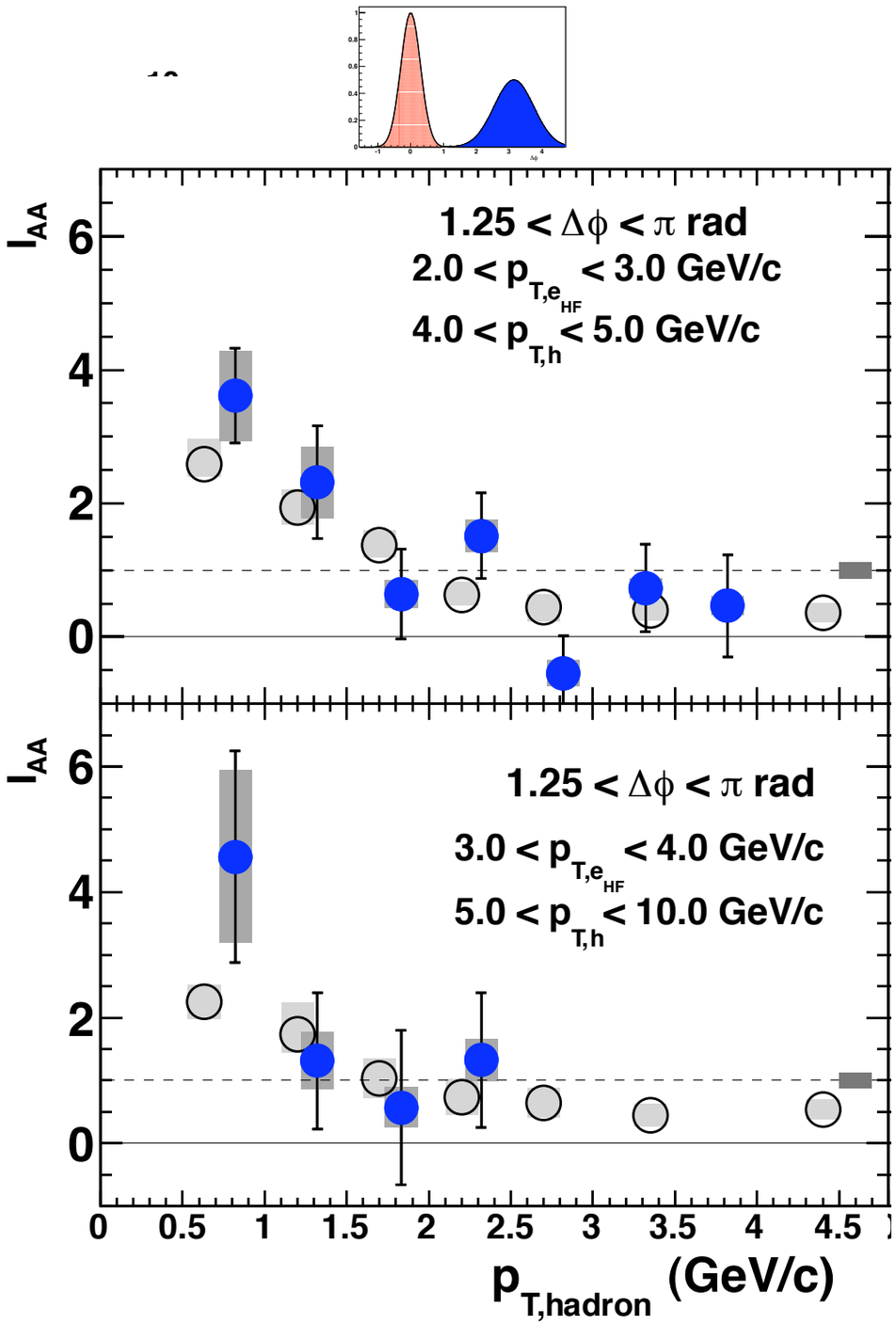
PHENIX: 1011.1477

e-h: opposite side correlations



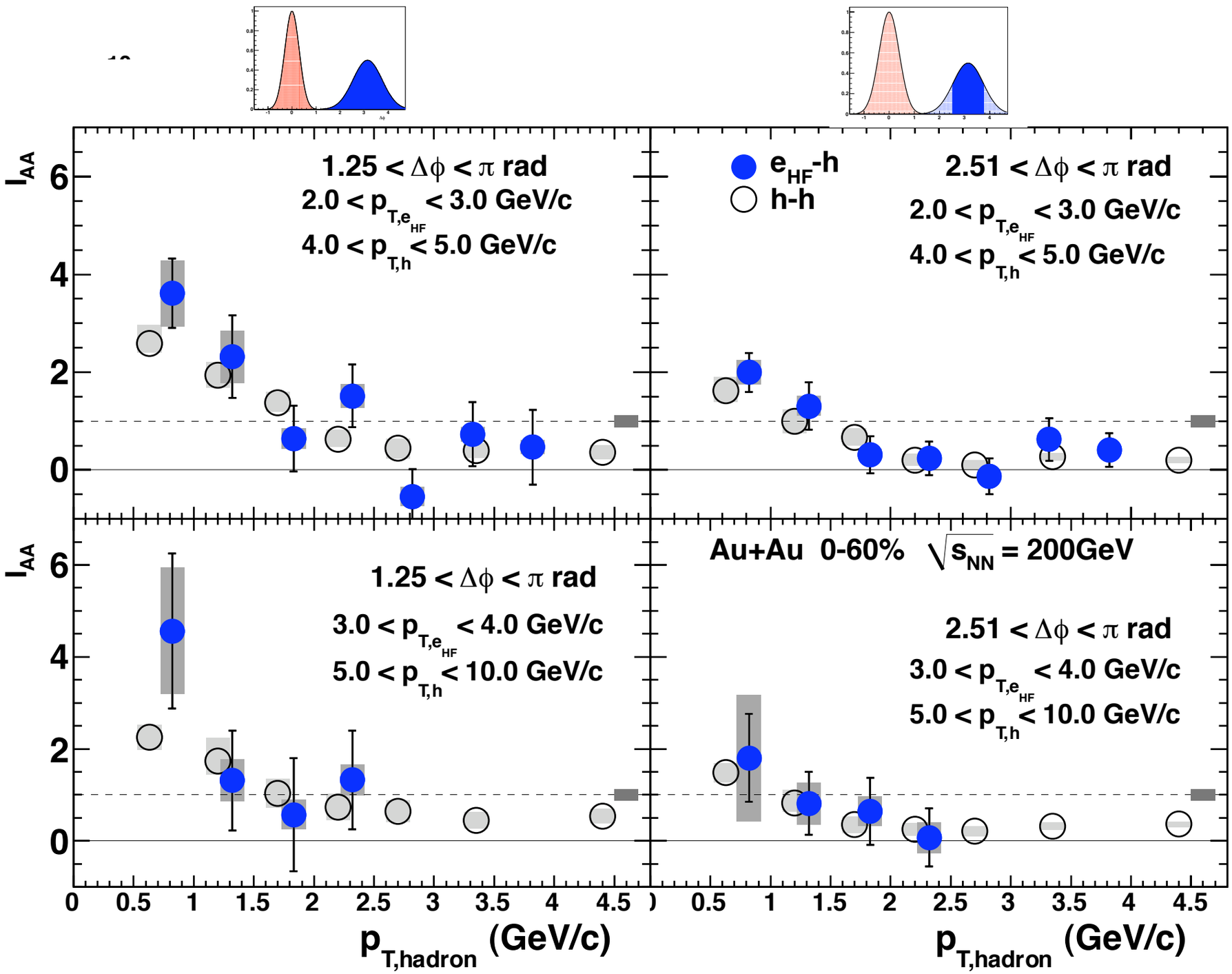
PHENIX: 1011.1477

e-h: opposite side correlations



PHENIX: 1011.1477

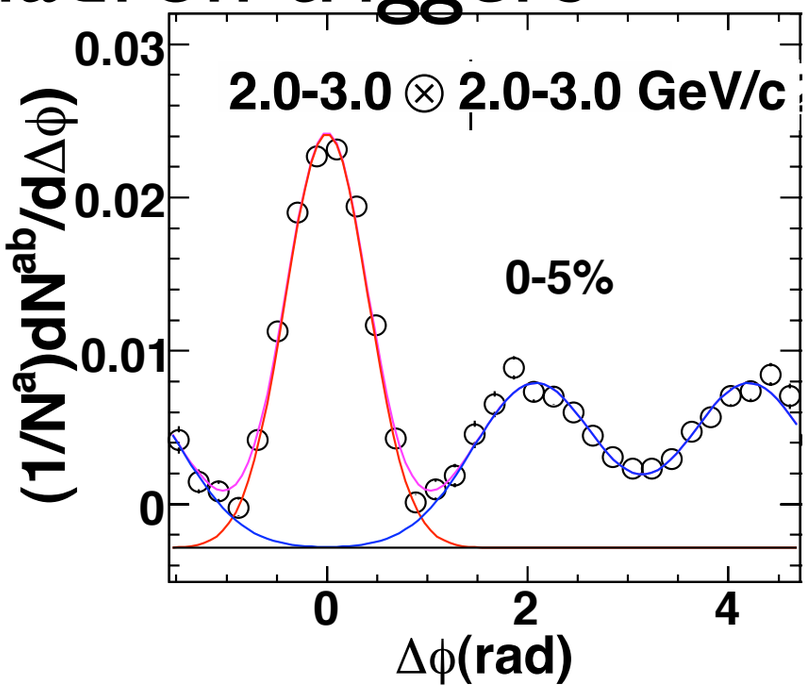
e-h: opposite side correlations



PHENIX: 1011.1477

shape modifications

hadron triggers

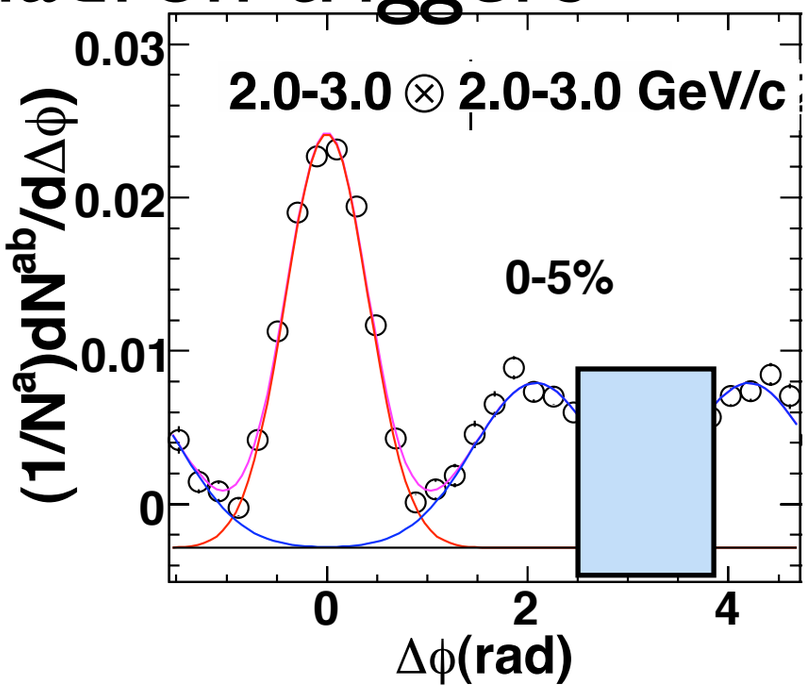


n.b. not exactly comparable
(head, shoulder definitions
slightly different)

PRC 78 014901
1011.1477[nucl-ex]

shape modifications

hadron triggers



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PRC 78 014901
1011.1477[nucl-ex]

shape modifications

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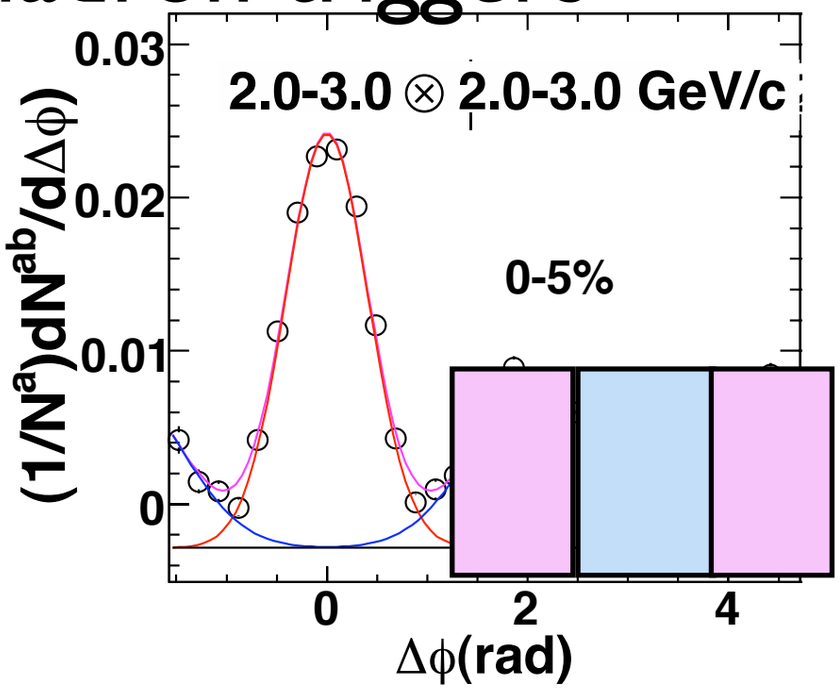

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PRC 78 014901
1011.1477[nucl-ex]

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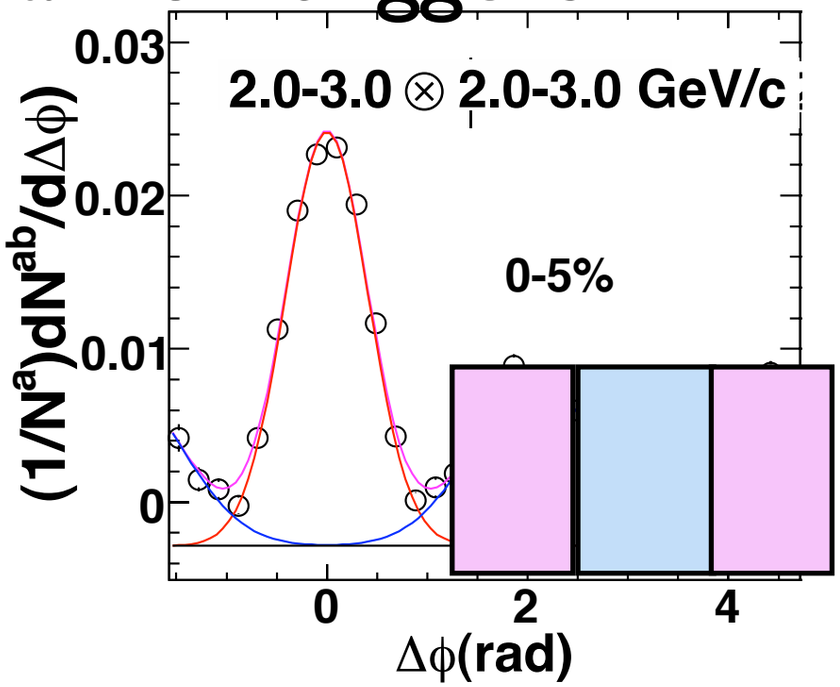

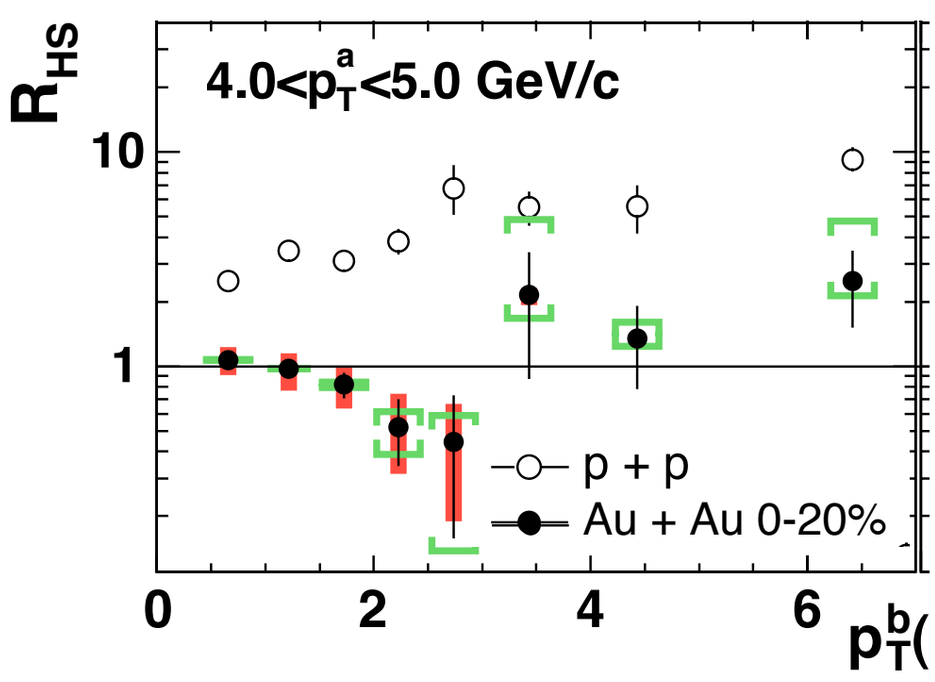

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PRC 78 014901
1011.1477[nucl-ex]

shape modifications

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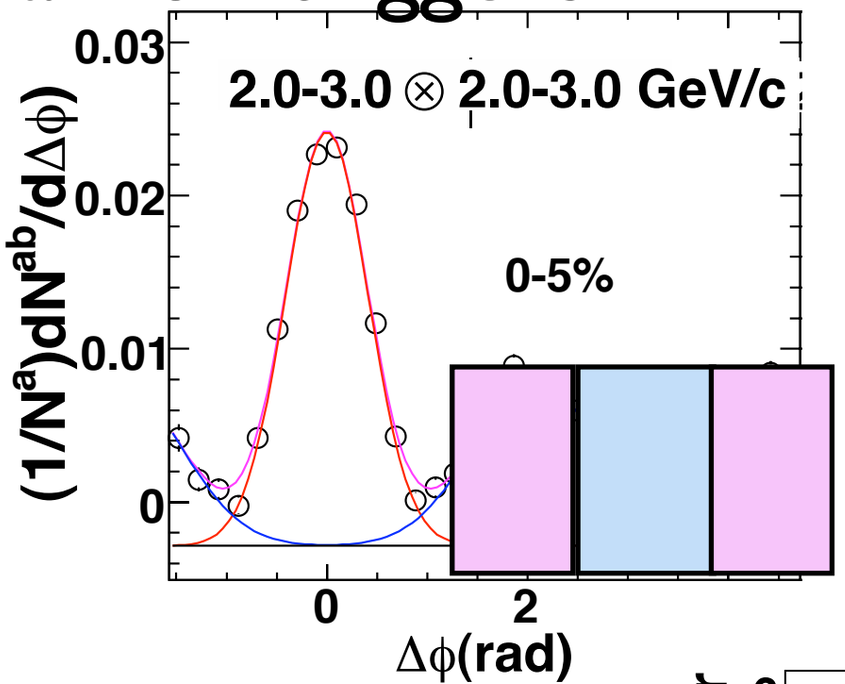
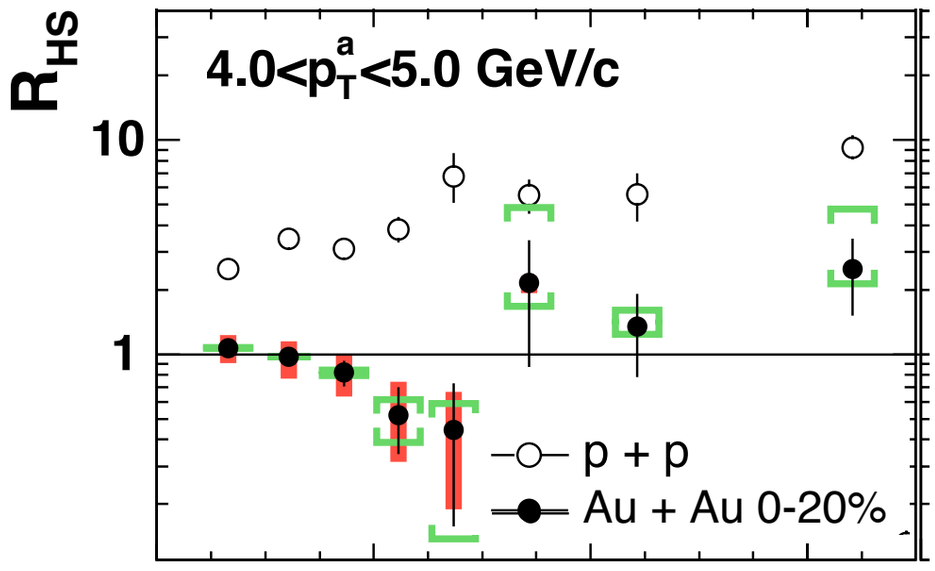
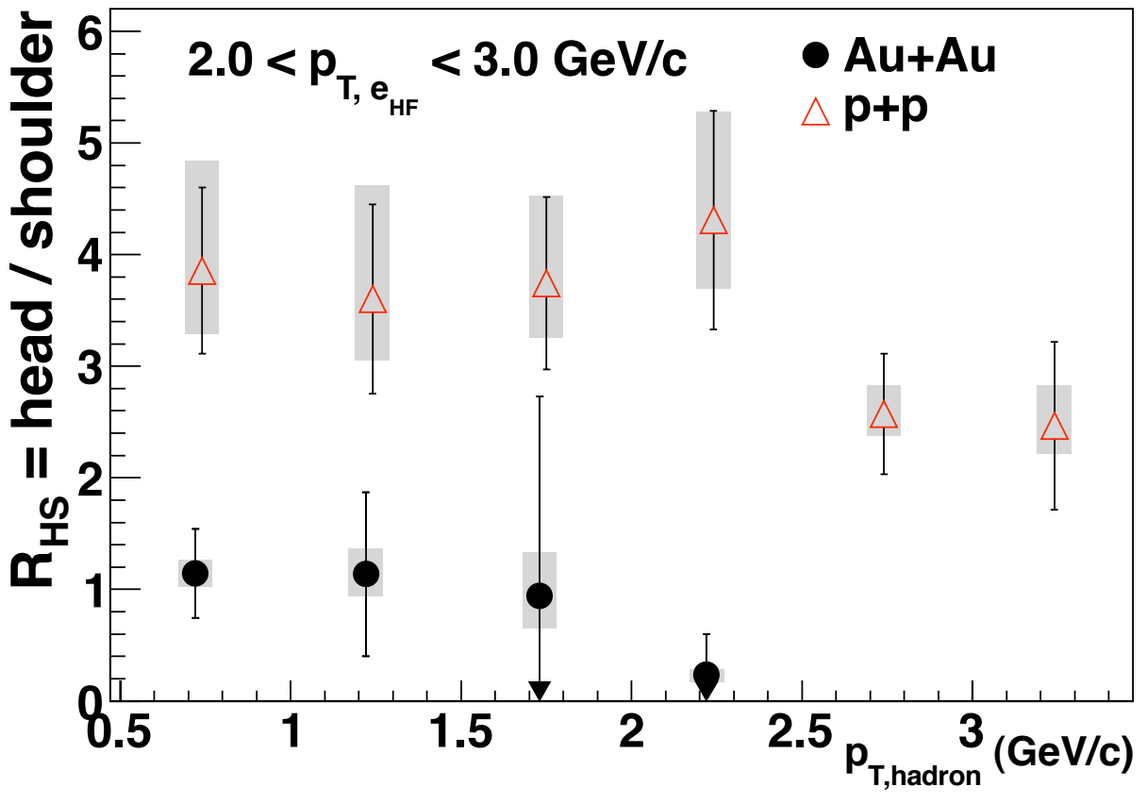




electron triggers

n.b. not exactly comparable (head, shoulder definitions slightly different)



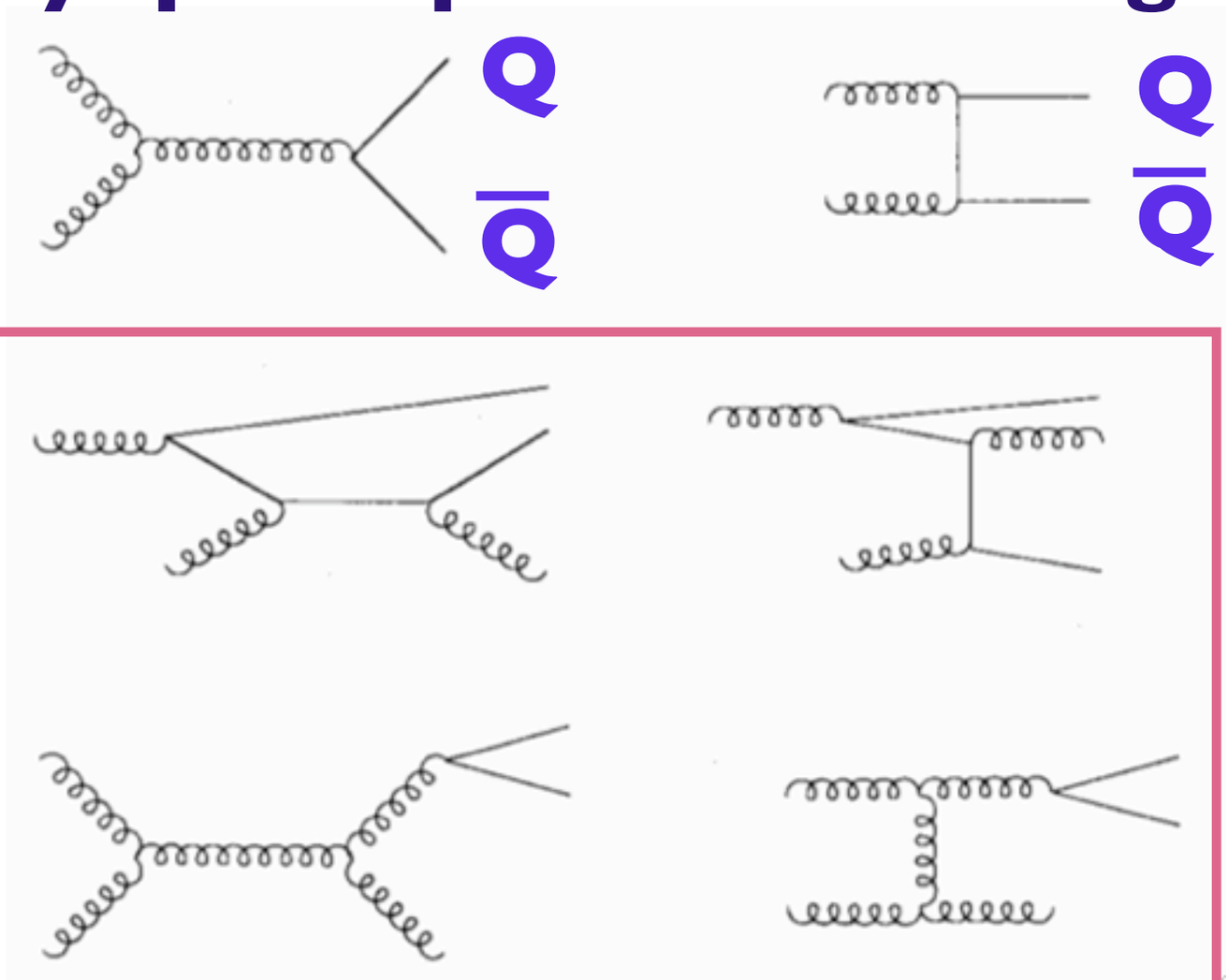
PRC 78 014901
1011.1477[nucl-ex]

not unexpected

heavy quark production diagrams

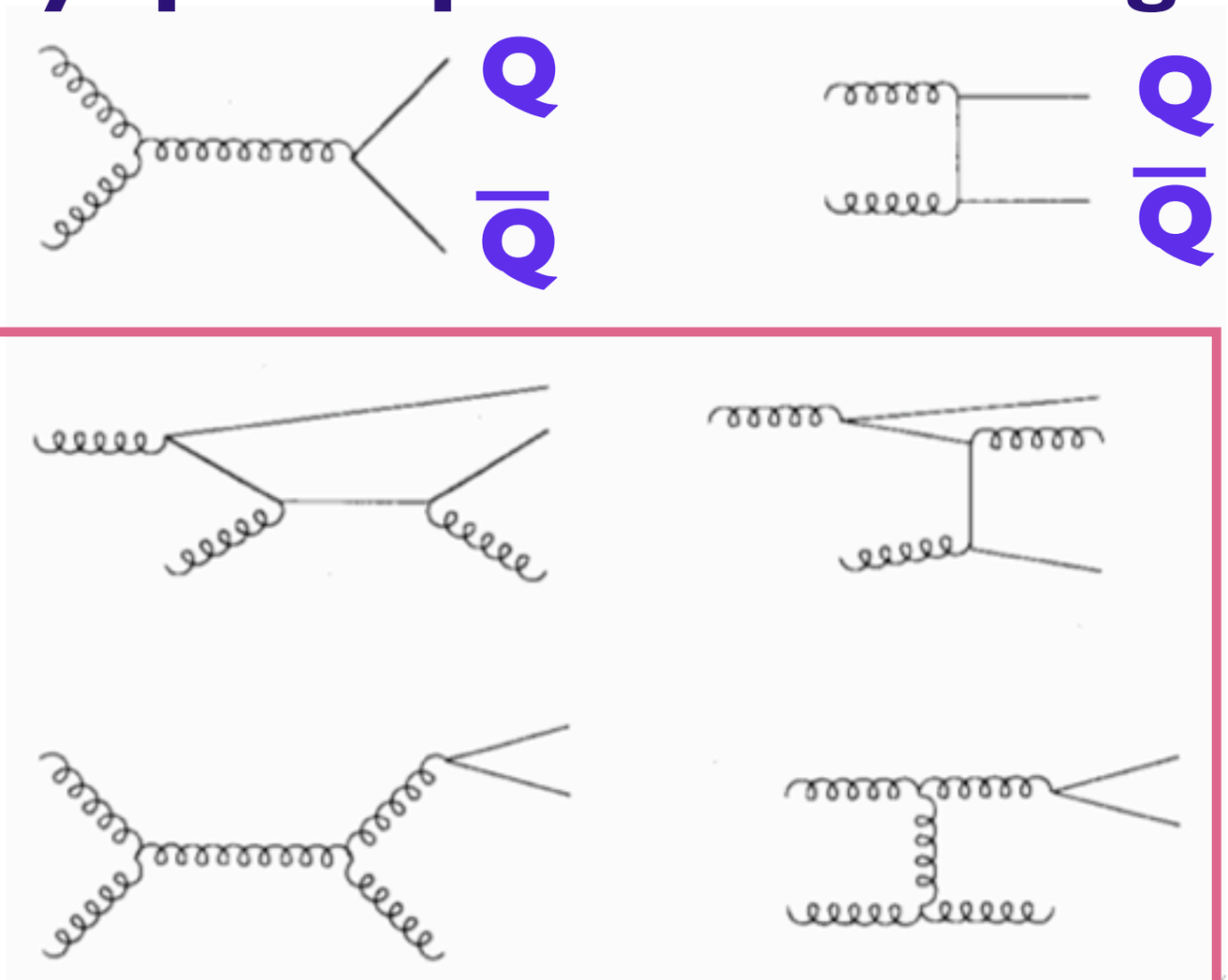
not unexpected

heavy quark production diagrams



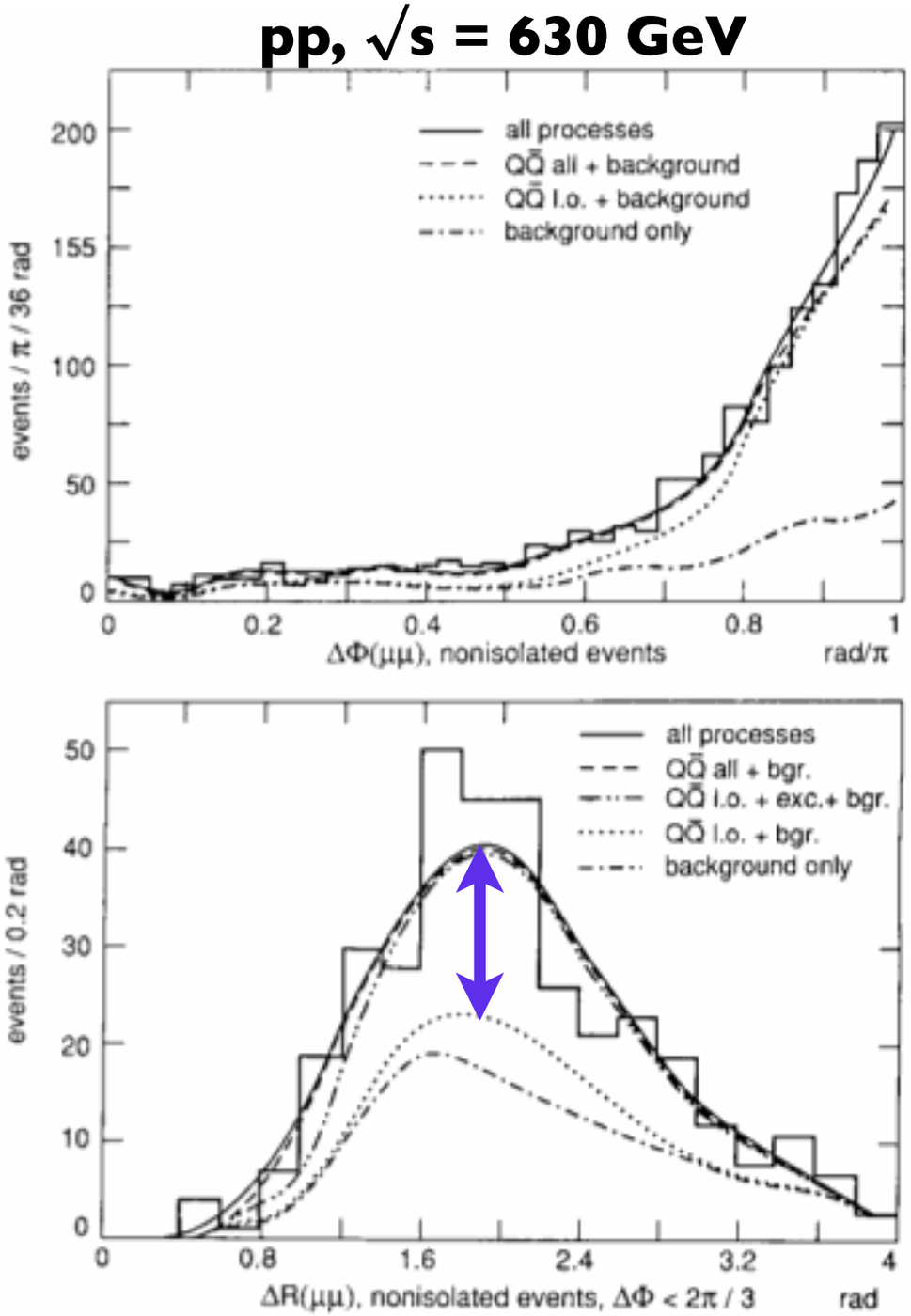
not unexpected

heavy quark production diagrams



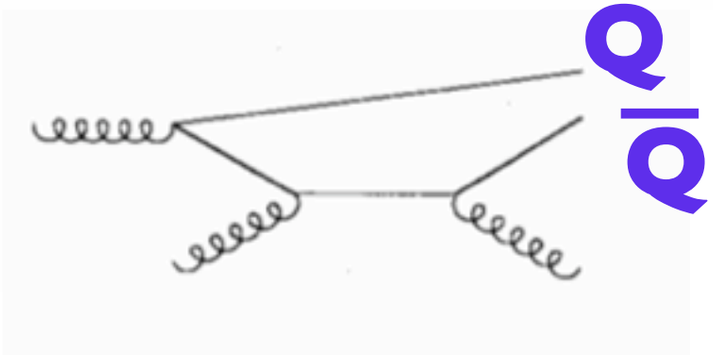
sizable contributions from NLO effects

μμ Correlations @ ISR



- fit with ISAJET
- 20-35% "higher order"
- similar sorts of measurements @ Tevatron

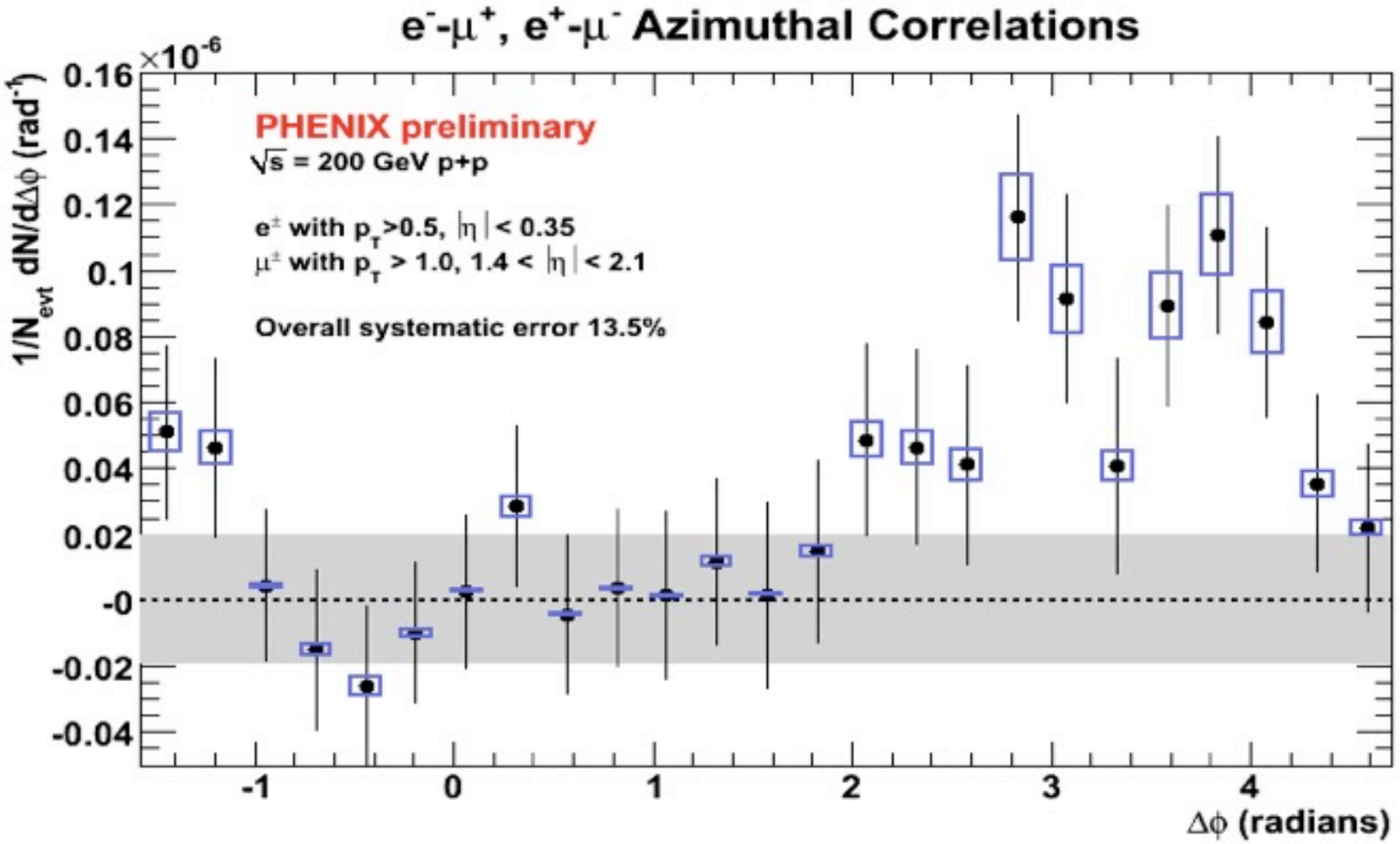
$p_{T\mu}^{high}$ range [GeV/c]	p_{Tb} range [GeV/c]	$b\bar{b}$ nonisol. $m_{\mu\mu} > 4$ GeV/c^2 [events]	'high.ord.' fraction [%]
All	$\gtrsim 6$	829 ± 58	26.2 ± 4.0
3–5	$\gtrsim 6$	402 ± 37	24.6 ± 8.5
5–7	$\gtrsim 8$	286 ± 23	31.2 ± 5.4
7–10	$\gtrsim 11$	103 ± 12	35.2 ± 5.1
10–20	$\gtrsim 15$	32 ±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



UA1, Z Phys C 61 41 1994

e-μ correlations

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



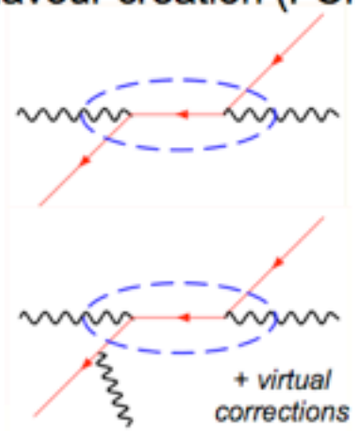
T. Engelmore, QM09

RHIC vs. LHC

- also different production mix

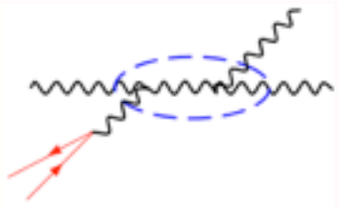
Production processes in p-p

Flavour creation (FCR)

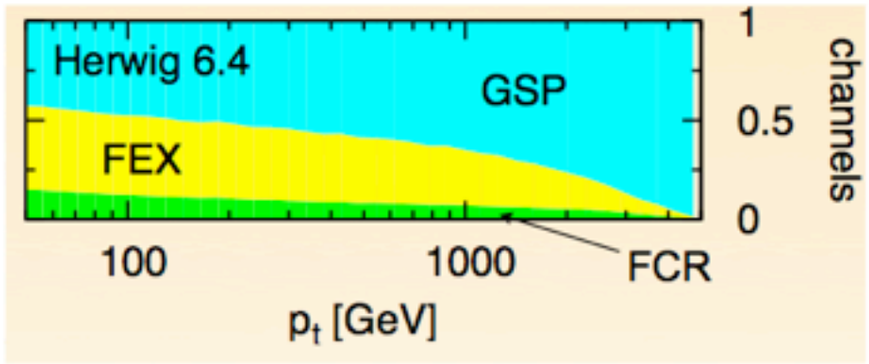


Flavour excitation (FEX)

Gluon splitting (GSP)



- 2→2 processes:
  - Flavour creation: gluon fusion and qq annihilation
- 2→3 processes:
  - *Flavour Excitation*: bb from the proton sea, only one b participates to the hard scatter, asymmetric transverse momentum for the two b-quarks
  - *Gluon splitting*: g→ bb in initial or final state, b at low pT and close in the azimuthal angle (Δφ)
  - Real and virtual corrections to Flavour creation



2 to 3 processes dominant at the LHC!

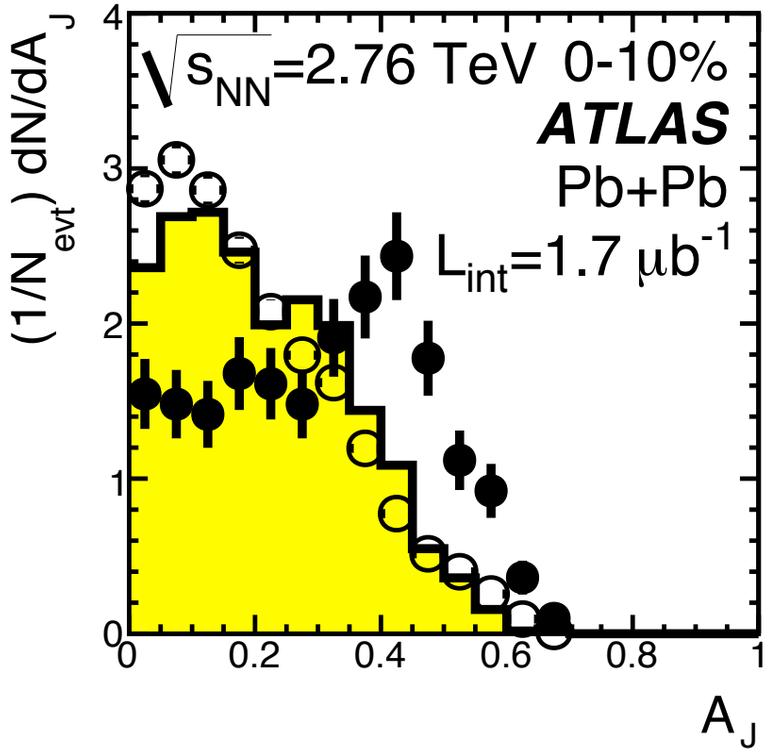
V. Chiochia (Uni. Zürich) – Measurement of inclusive b production at CMS - HP2010, Eilat - 14/10/2010 3

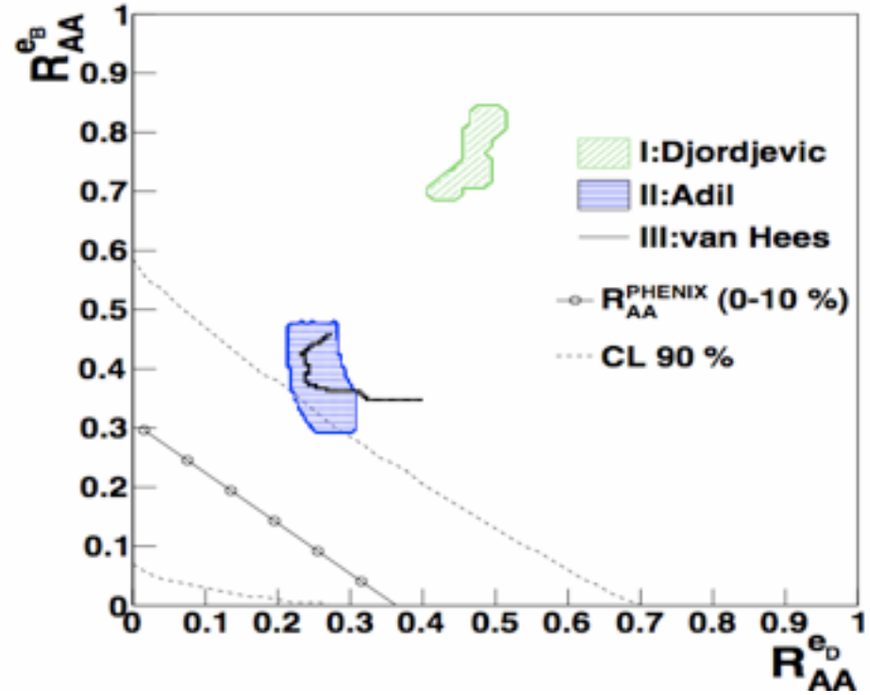
Near Term Future

- Silicon Vertex Detector
  - e-h and e-e correlations to understand HF production
    - here 500 GeV p+p data provides a good opportunity
      - increased HF cross sections and different collision energy
        ➔ useful input for understanding HI data at 200 GeV

heavy flavor and the LHC

- ATLAS di-jet results and bottom suppression at RHIC both point to the strong quenching ability of the matter





heavy flavor and the LHC

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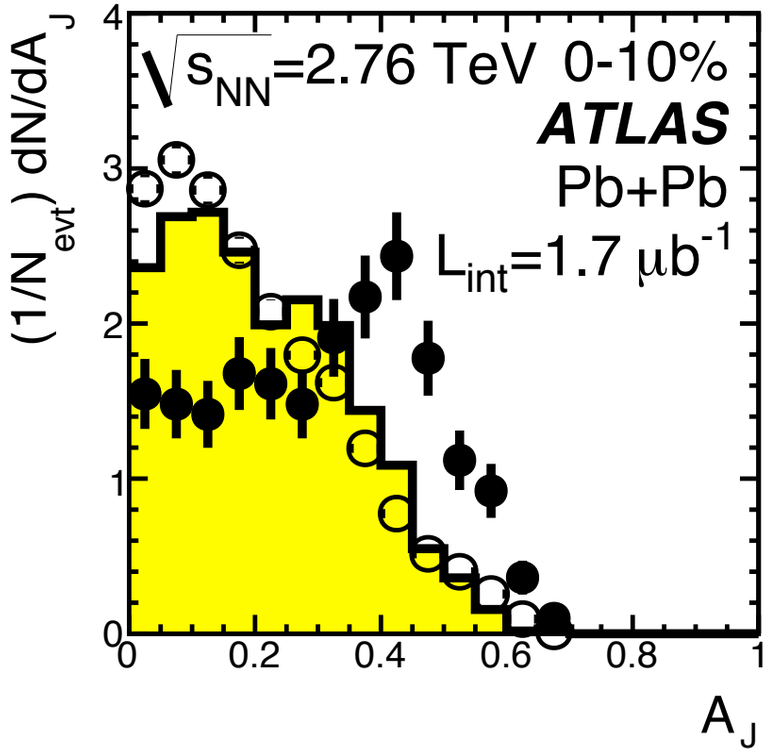
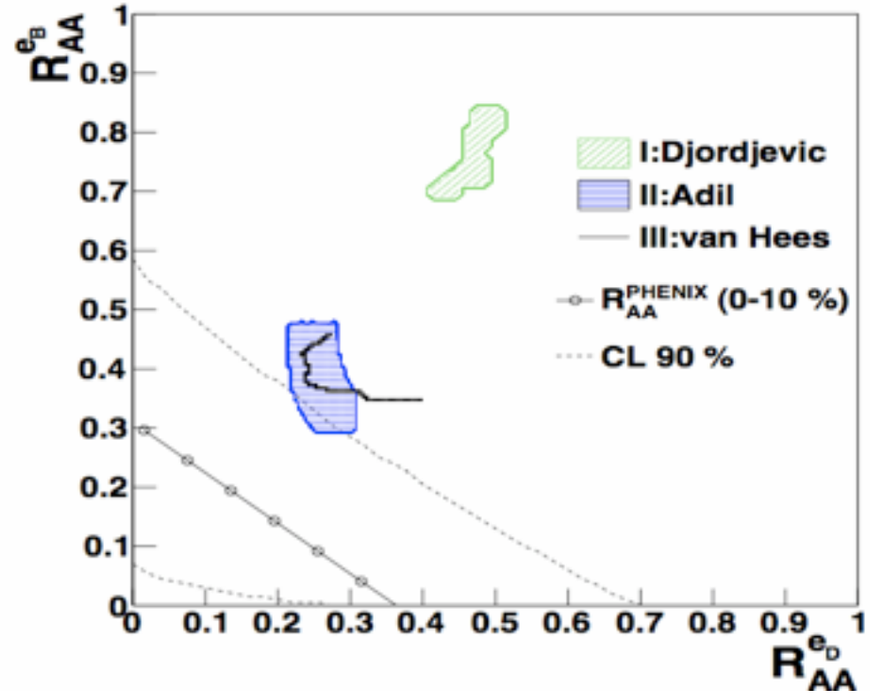
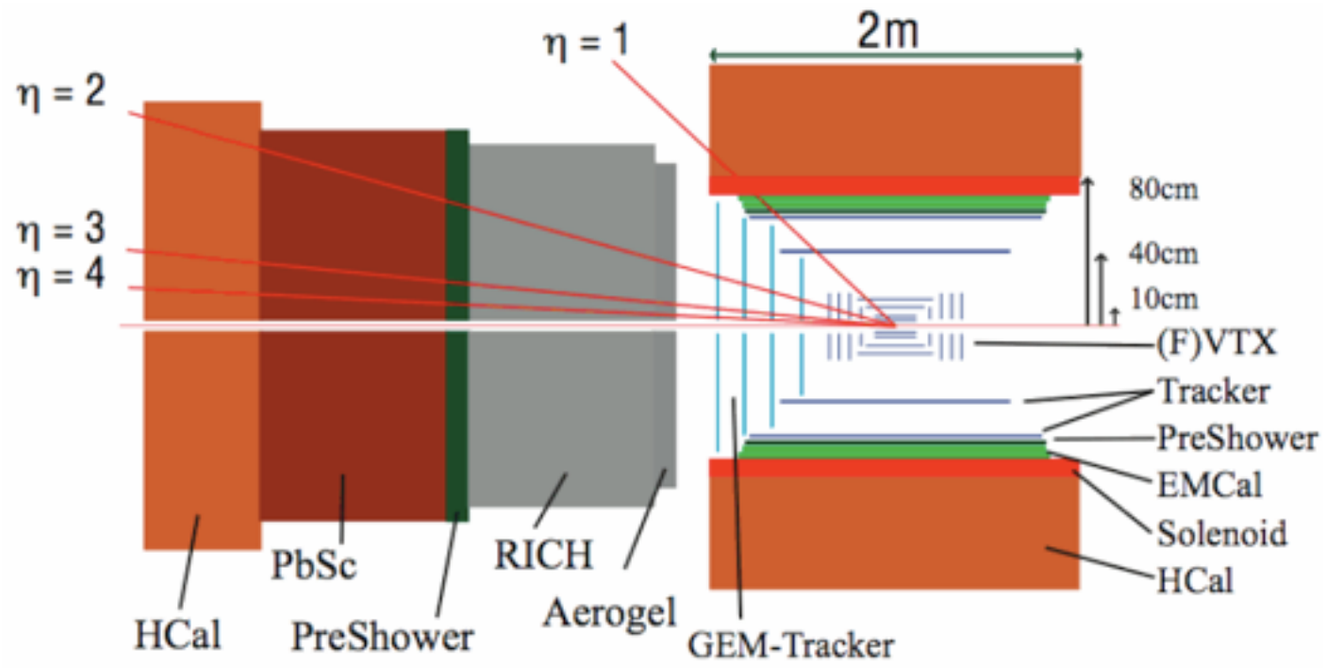




what will *b*-jets look like at the LHC?

sPHENIX

- 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
  - suited to systematic studies (system size, energy, etc)



PHENIX Decadal Plan, Jacak HP10

outlook

outlook

- heavy flavor is one of the best tools to understand how partons interact with the QGP

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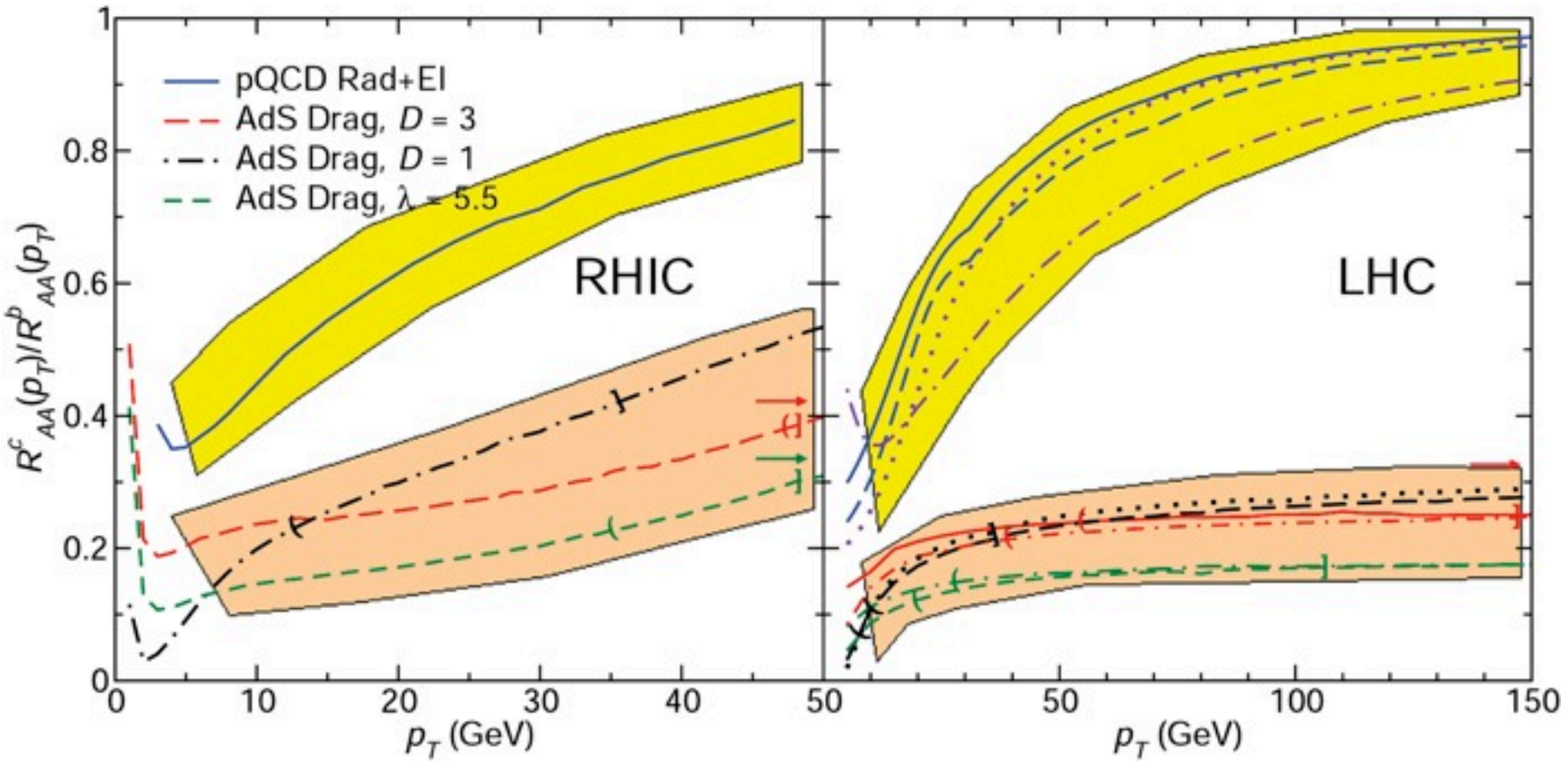
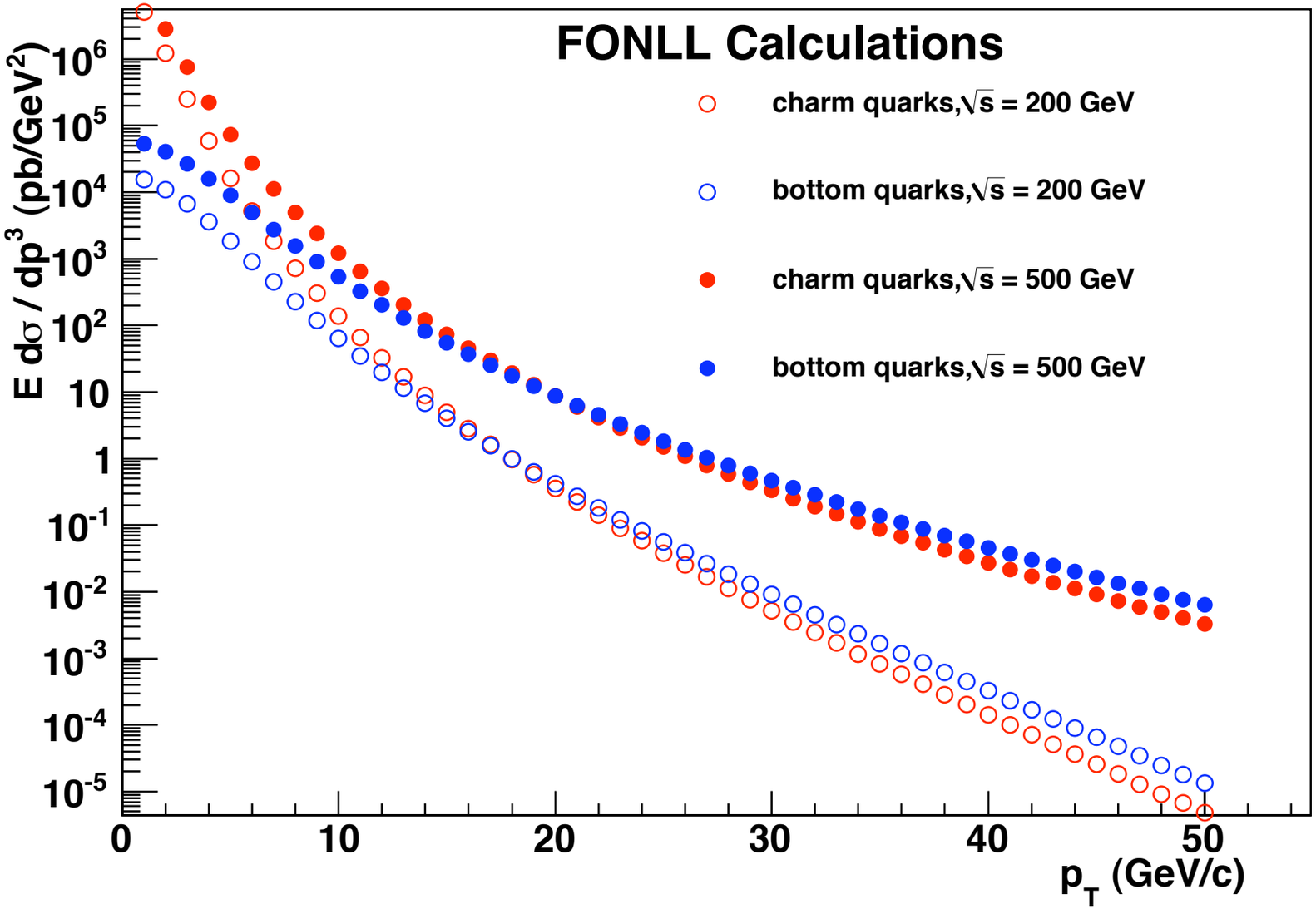
- experimentally very challenging
  - rate
  - charm & bottom mixture
  - different production configurations
  - measurement via single electrons

outlook

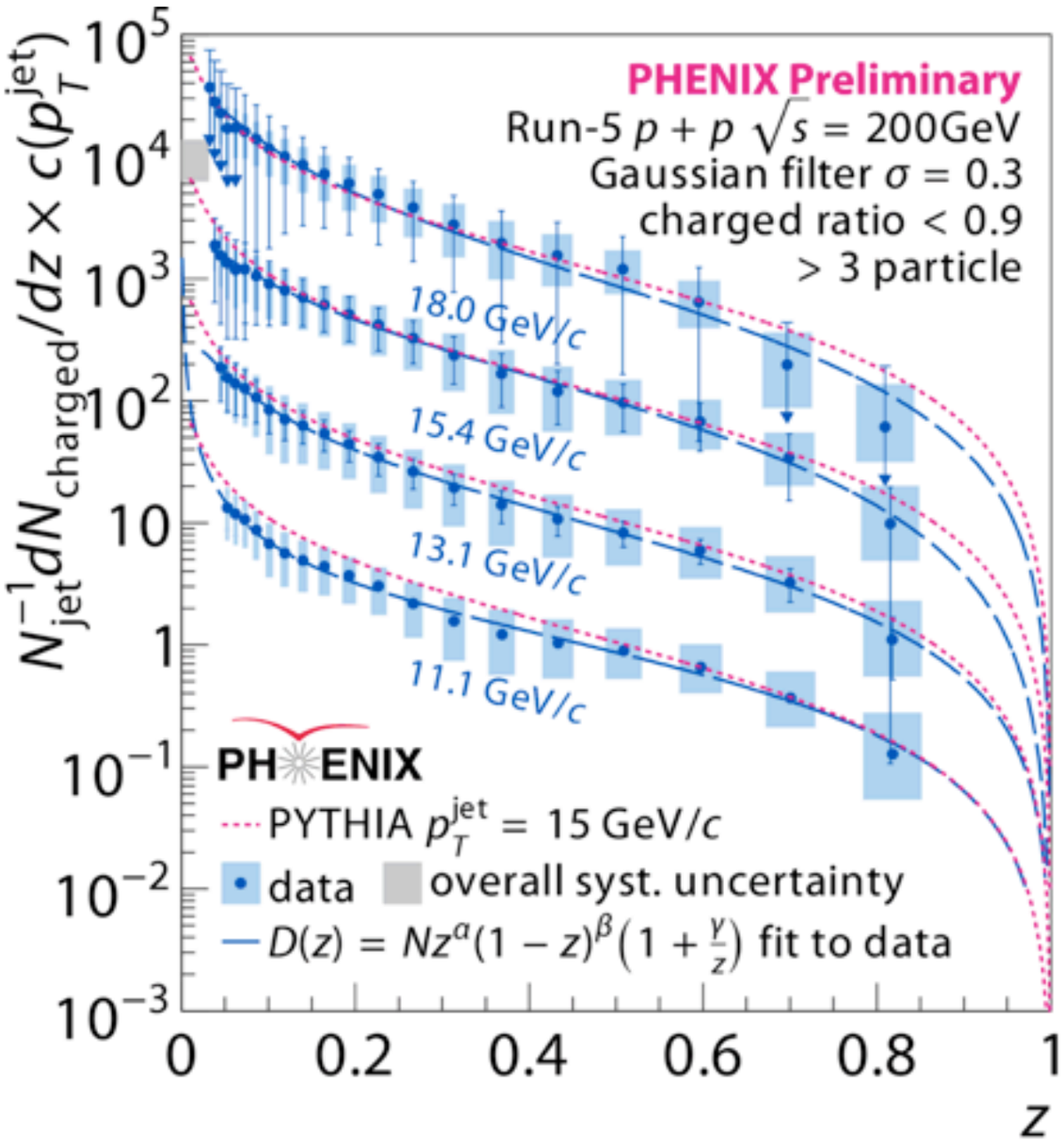
- heavy flavor is one of the best tools to understand how partons interact with the QGP
- experimentally very challenging
  - rate
  - charm & bottom mixture
  - different production configurations
  - measurement via single electrons
- investigations are still in their early stages
  - vertex upgrades at RHIC & LHC provide big improvements!
  - correlations will be key

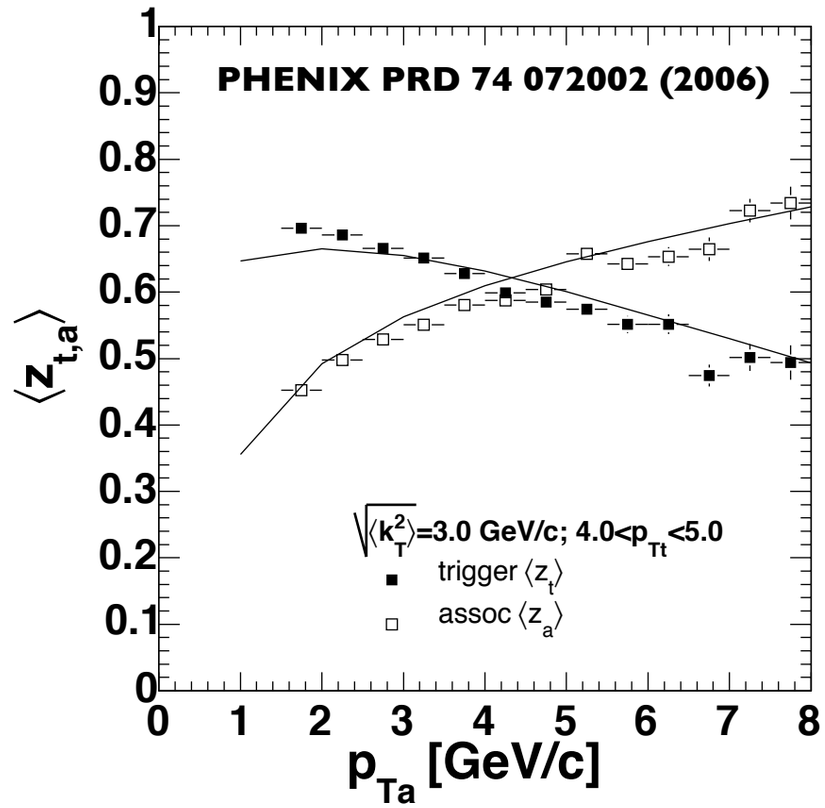

pQCD Rad+El
AdS Drag, D = 3
AdS Drag, D = 1
AdS Drag, λ = 5.5
RHIC
LHC
$R^c_{AA}(p_T)/R^b_{AA}(p_T)$
p_T (GeV)
p_T (GeV)
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40
50
50
100
150



private communication, M Cacciari

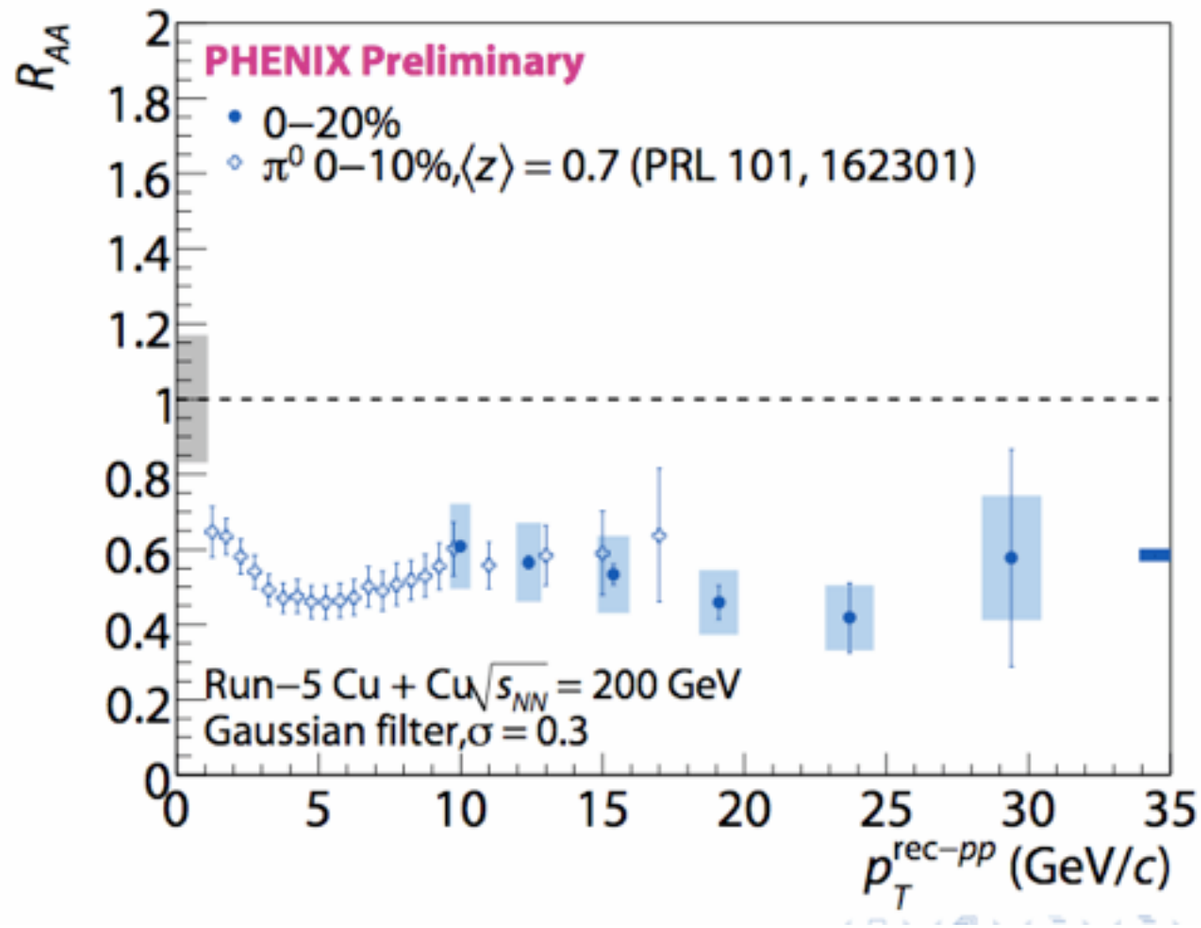
tool for the future: jets





- leading particles sample high z part of the fragmentation function
  - little sensitivity to modification patterns...that's where the energy loss physics is→radiated gluons, broadened jet profile...

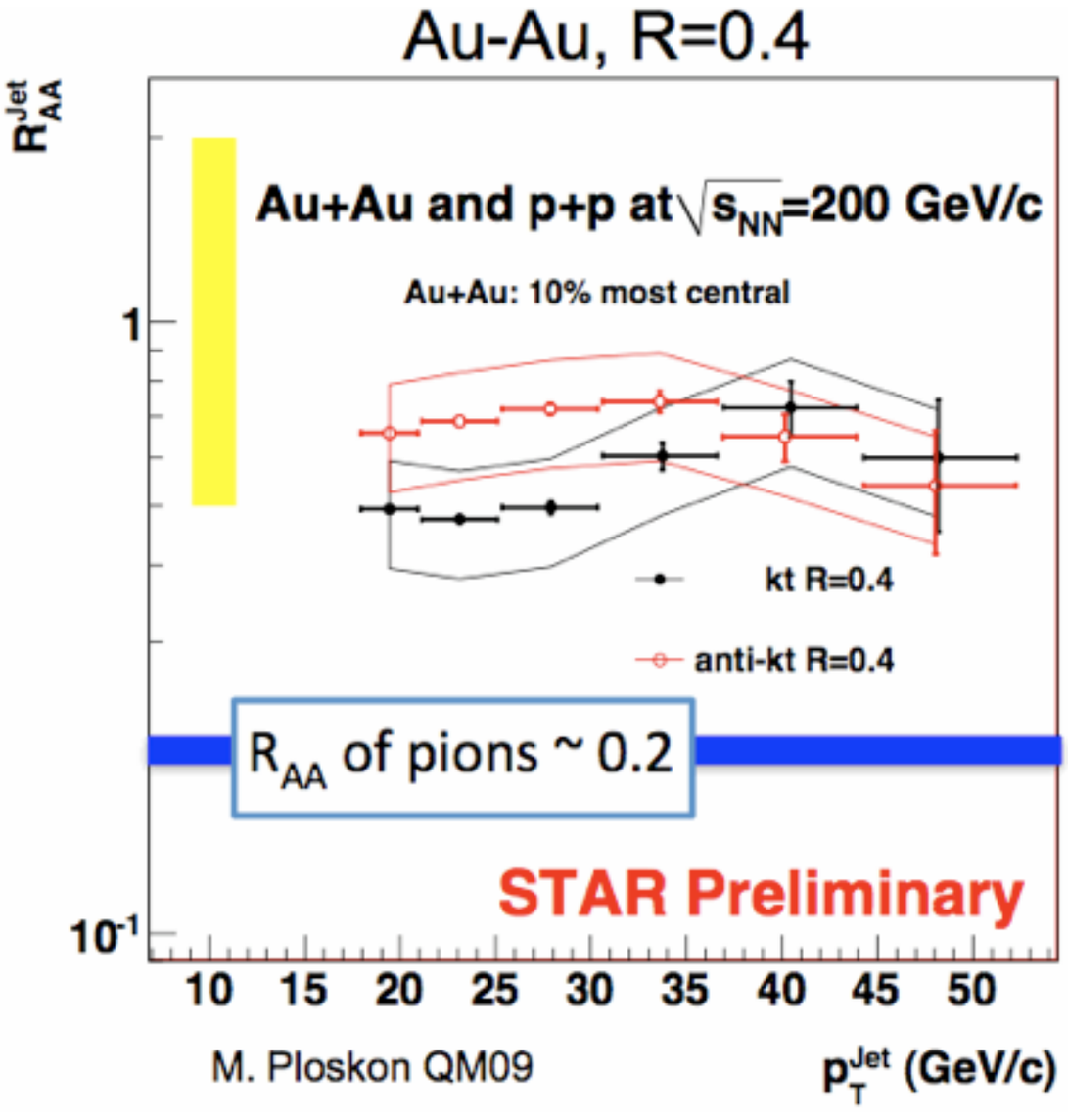
jets: algorithm matters!

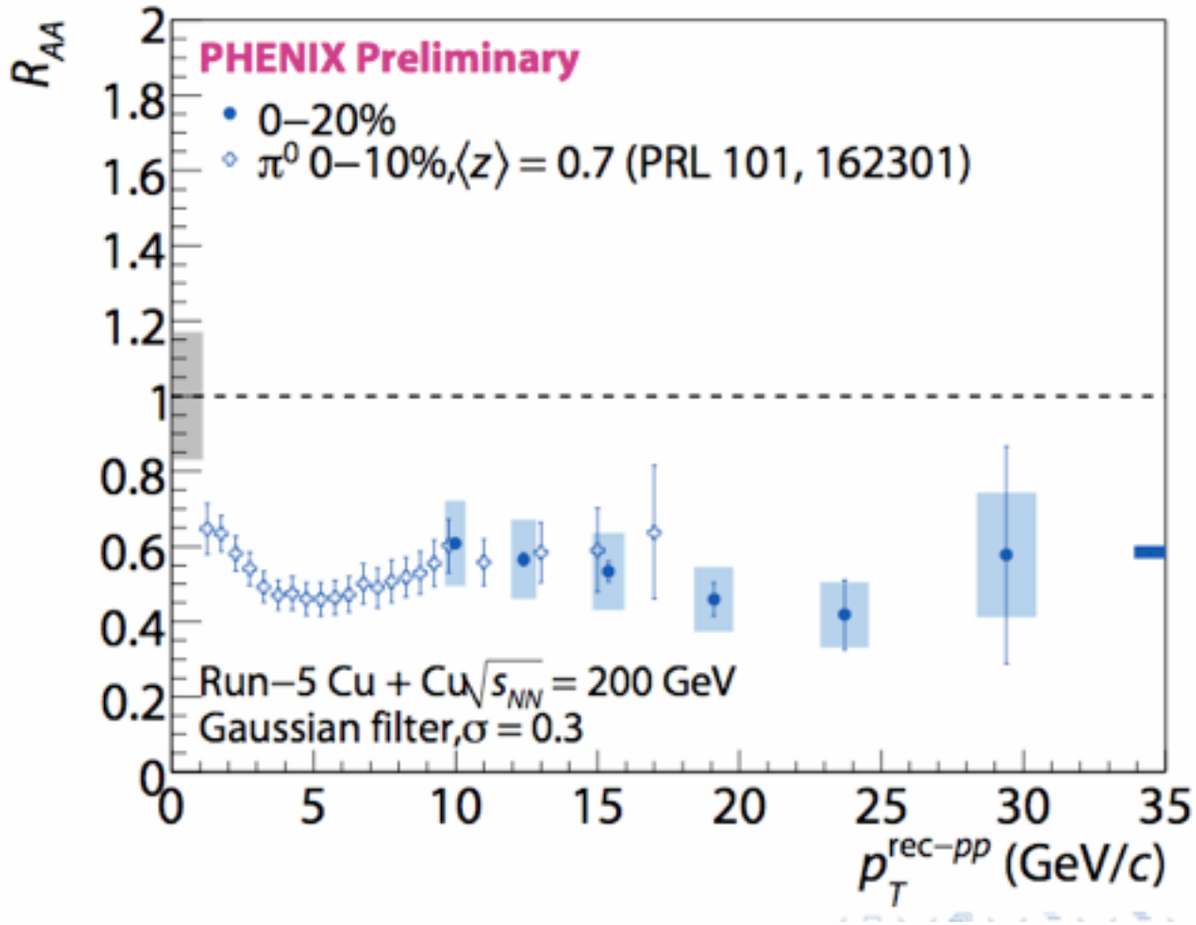


STAR: R_{AA}(jet) ≠ R_{AA}(π^0)
large uncertainties

PHENIX: R_{AA}(jet) = R_{AA}(π^0)
small uncertainties

jets: algorithm matters!

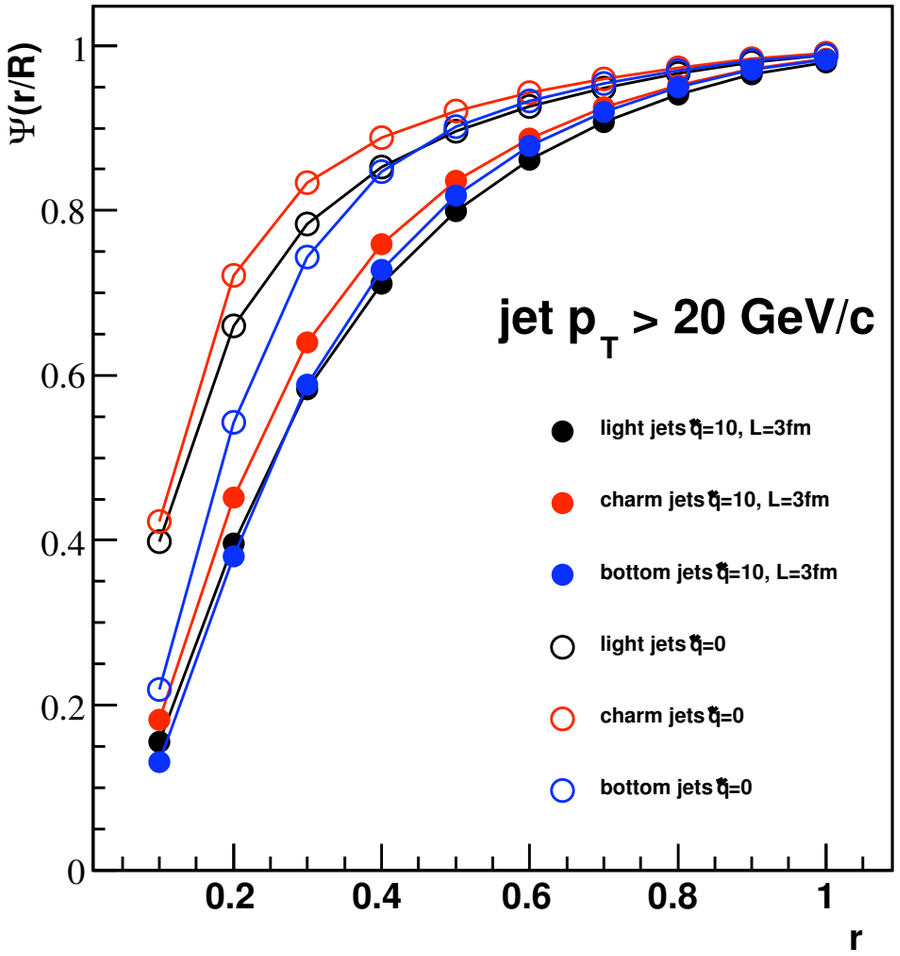


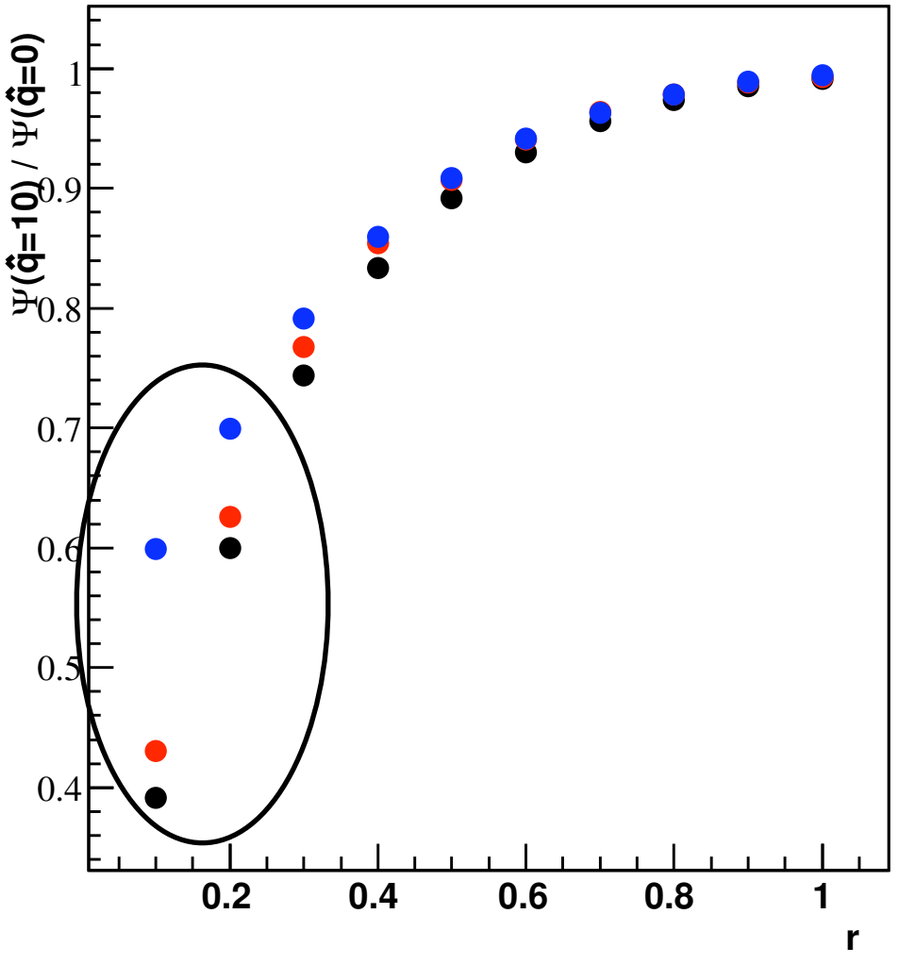


STAR: R_{AA}(jet) ≠ R_{AA}(π^0)
large uncertainties

PHENIX: R_{AA}(jet) = R_{AA}(π^0)
small uncertainties

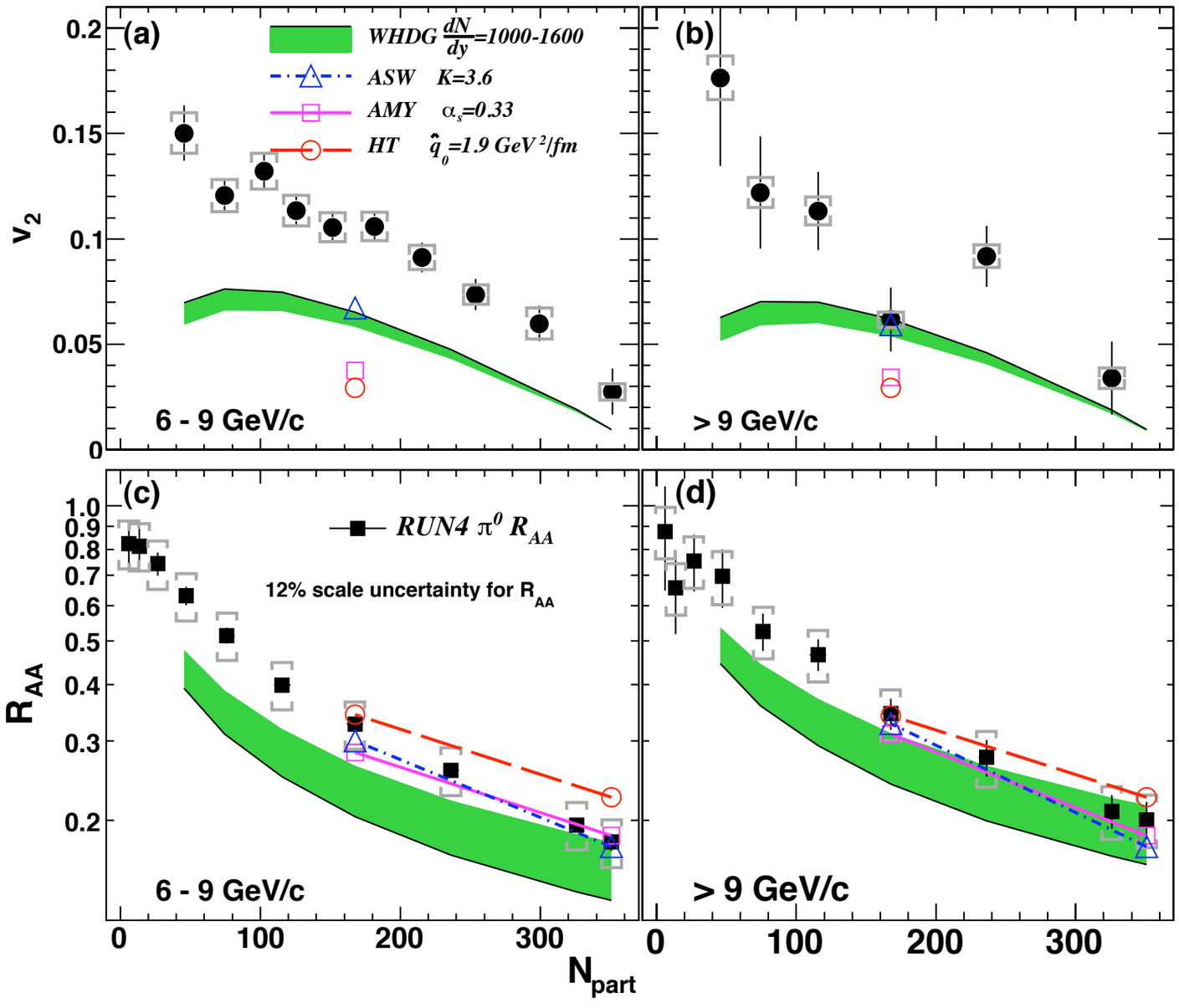
jet shape studies





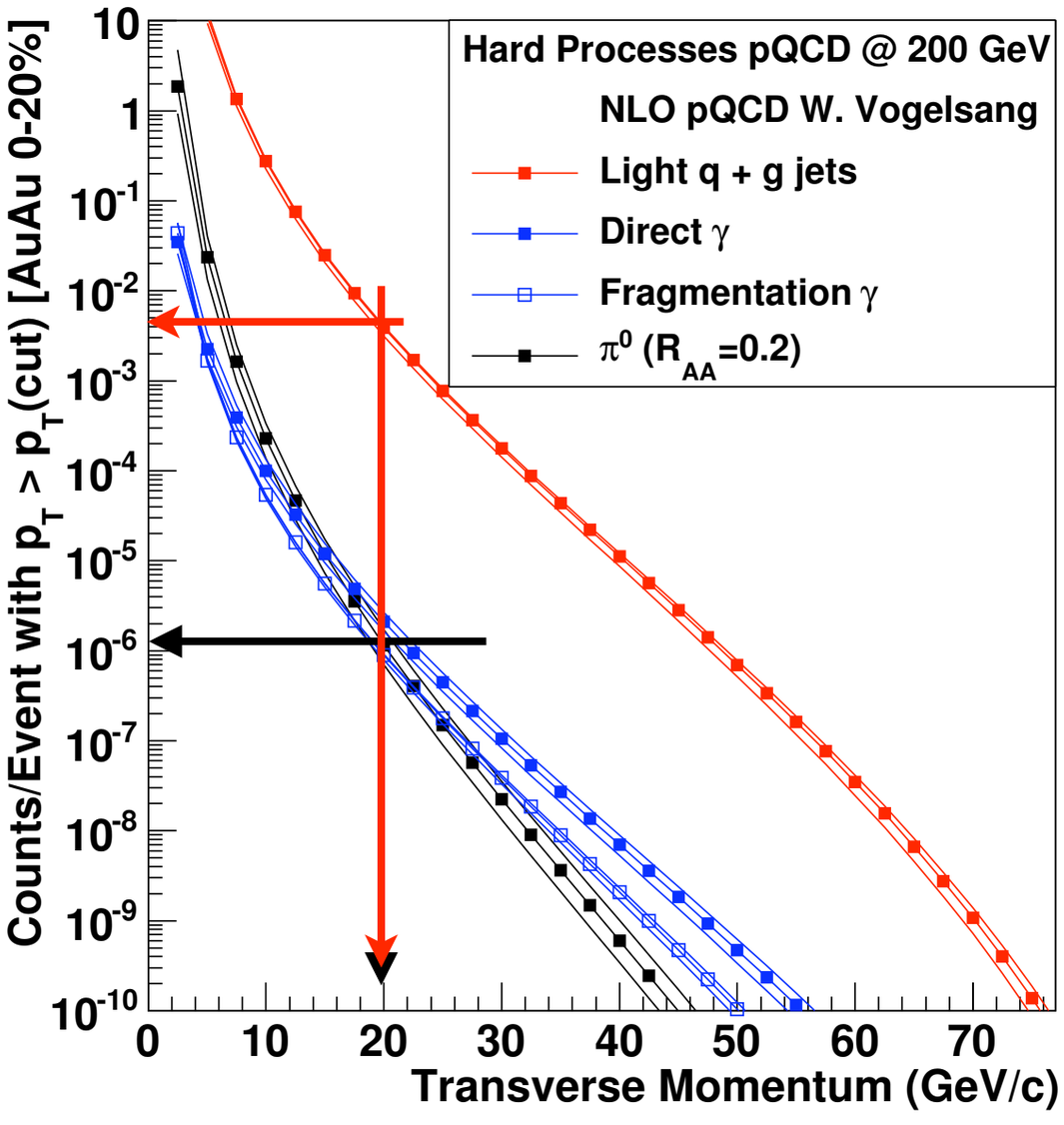
broadening

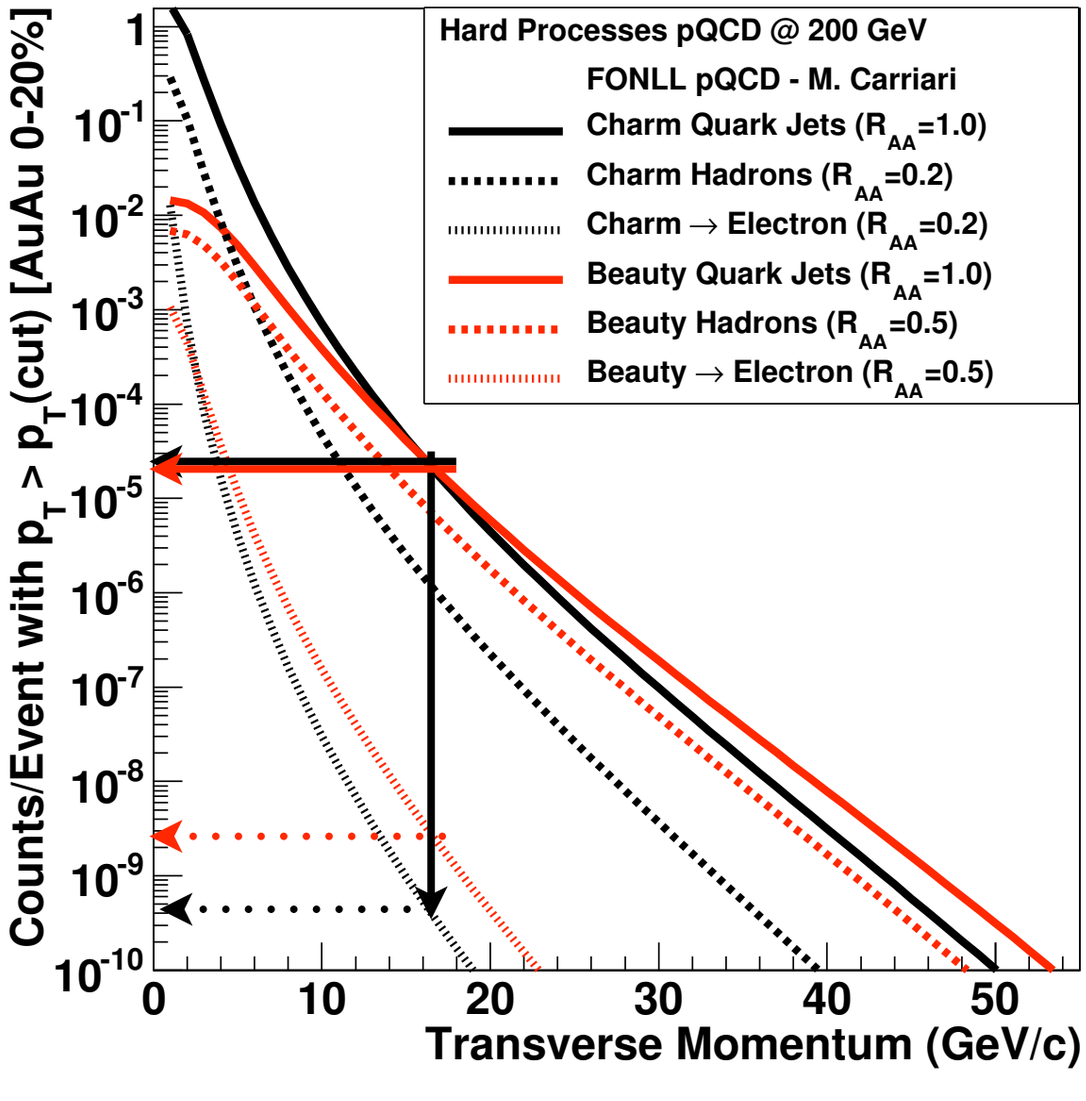
high pt


(a)
WHDG dN/dy=1000-1600
ASW K=3.6
AMY α_s=0.33
HT q̂_0=1.9 GeV²/fm
6 - 9 GeV/c
(b)
> 9 GeV/c
v2
(c)
RUN4 π⁰ R_AA
12% scale uncertainty for R_AA
6 - 9 GeV/c
(d)
> 9 GeV/c
R_AA
N_part

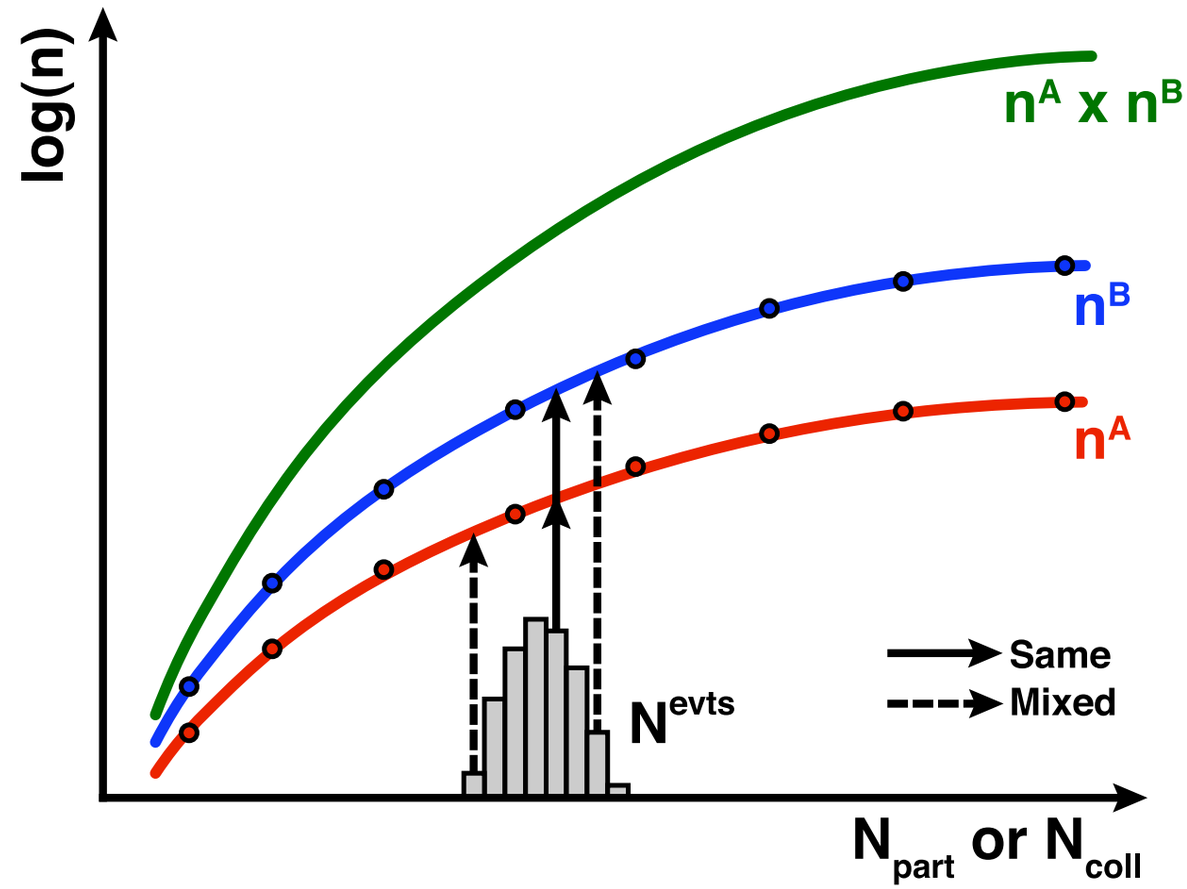
rate!

all hard physics at RHIC is statistics limited!





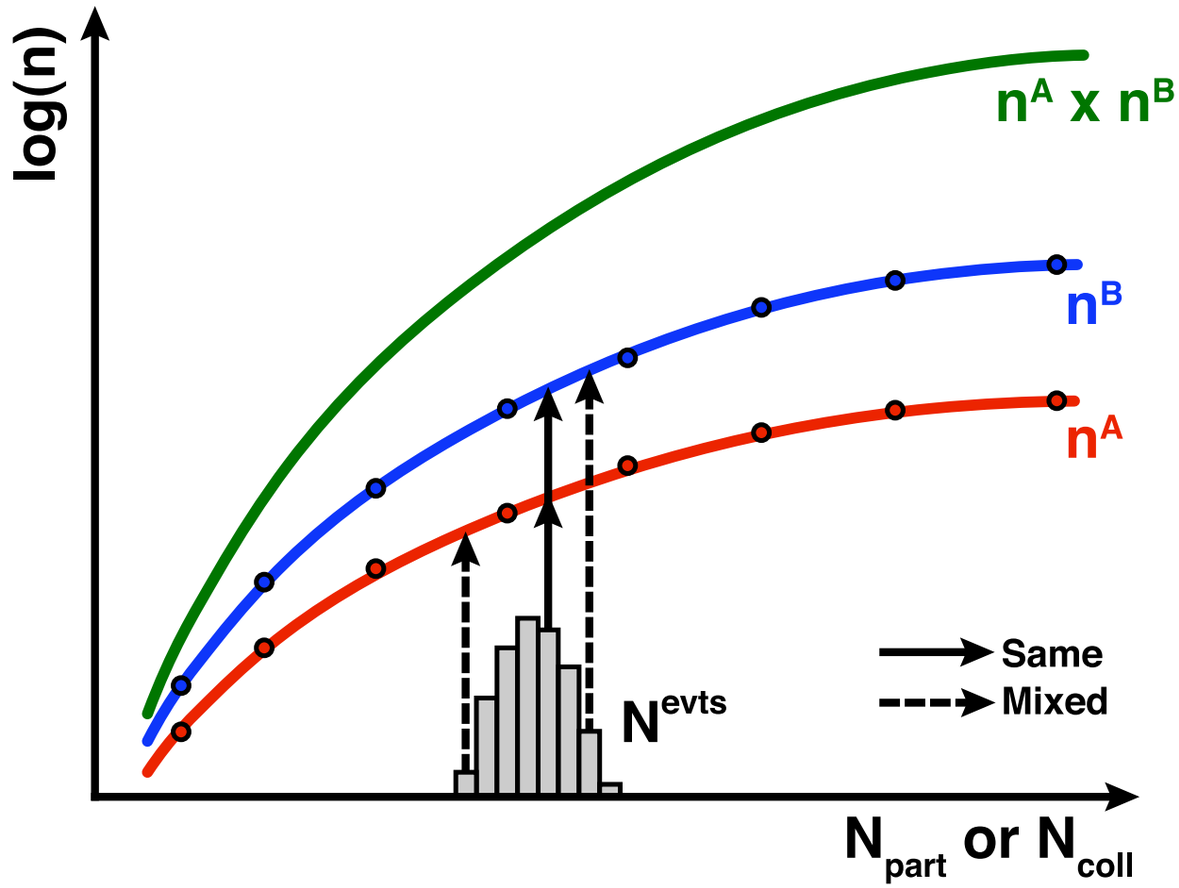
b_0 determination



AMS, McCumber, Adare PRC 81 014908 (2010)

b_0 determination

- in general $b_0 \sim \langle n_{trig} \rangle \langle n_{assoc} \rangle$



AMS, McCumber, Adare PRC 81 014908 (2010)

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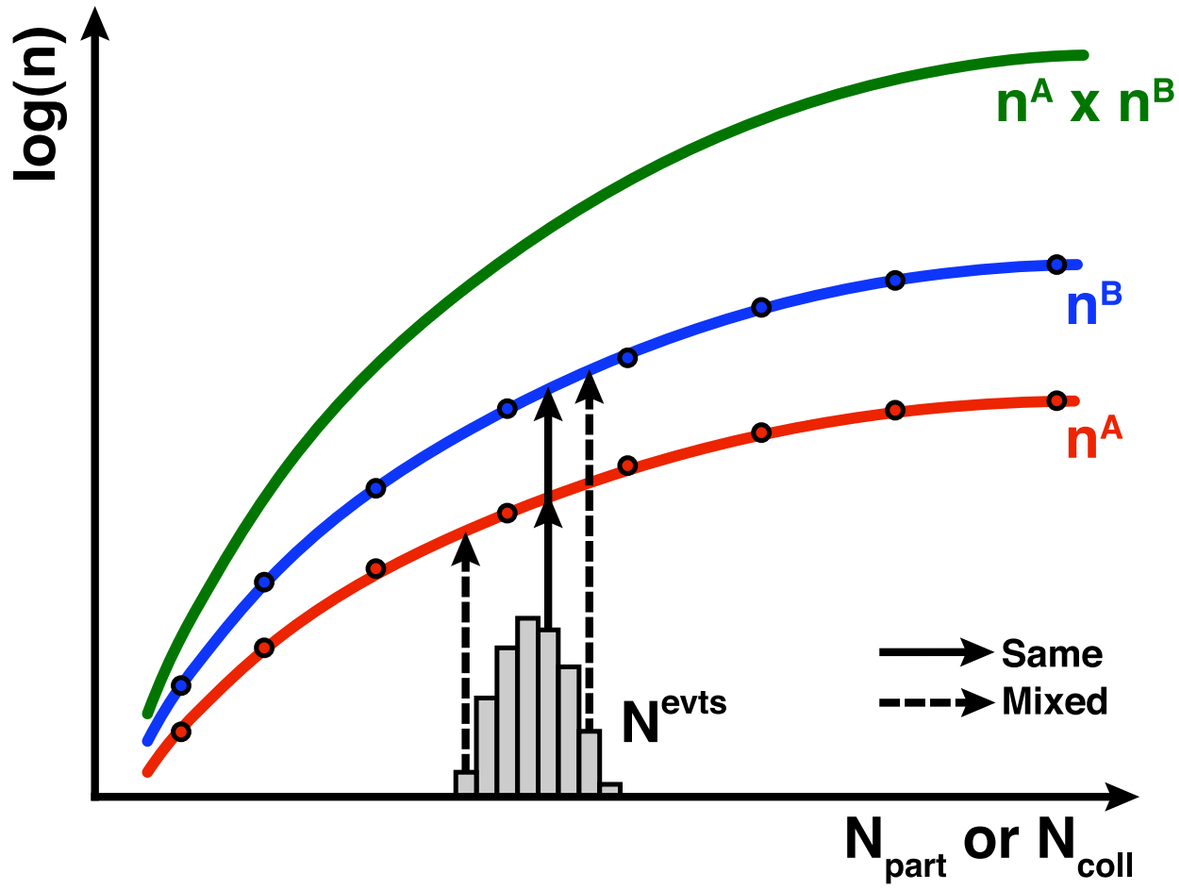
- additional centrality dependent factor, ξ



AMS, McCumber, Adare PRC 81 014908 (2010)

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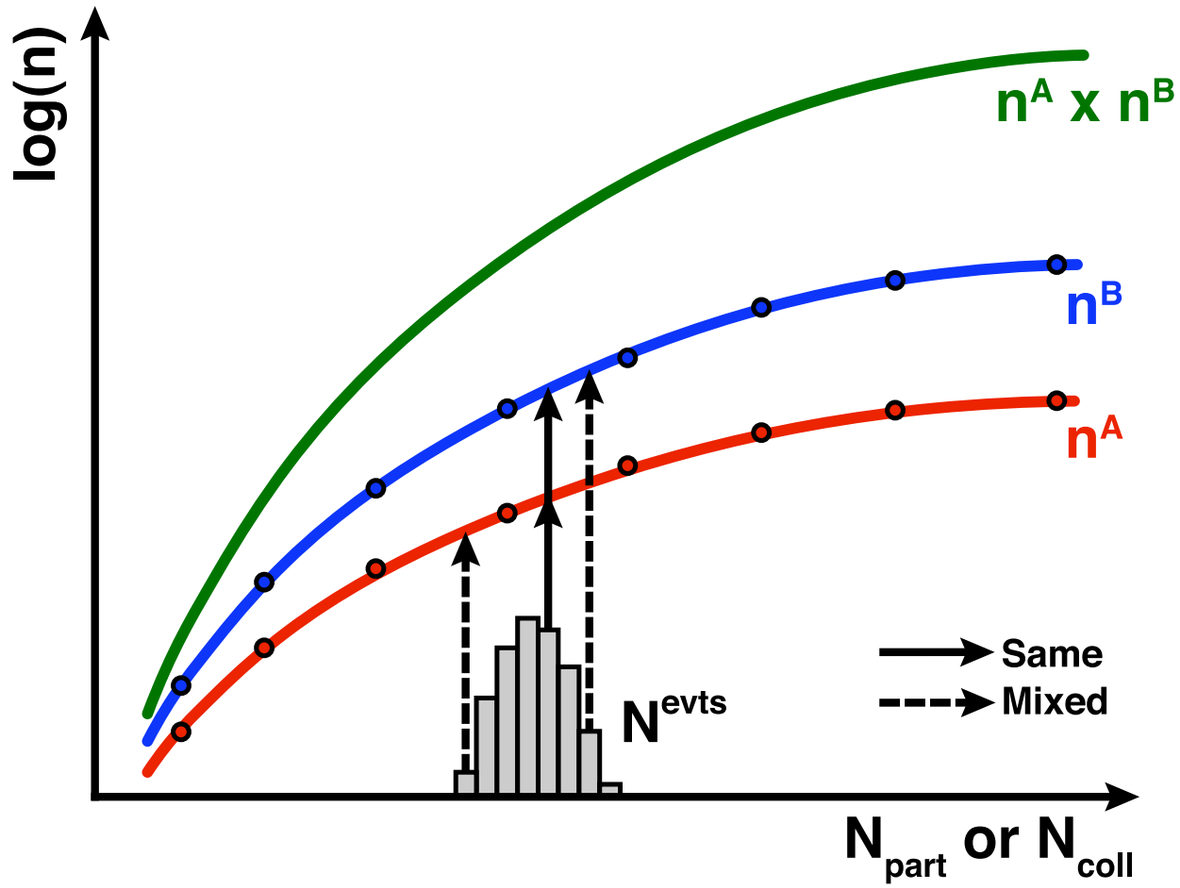

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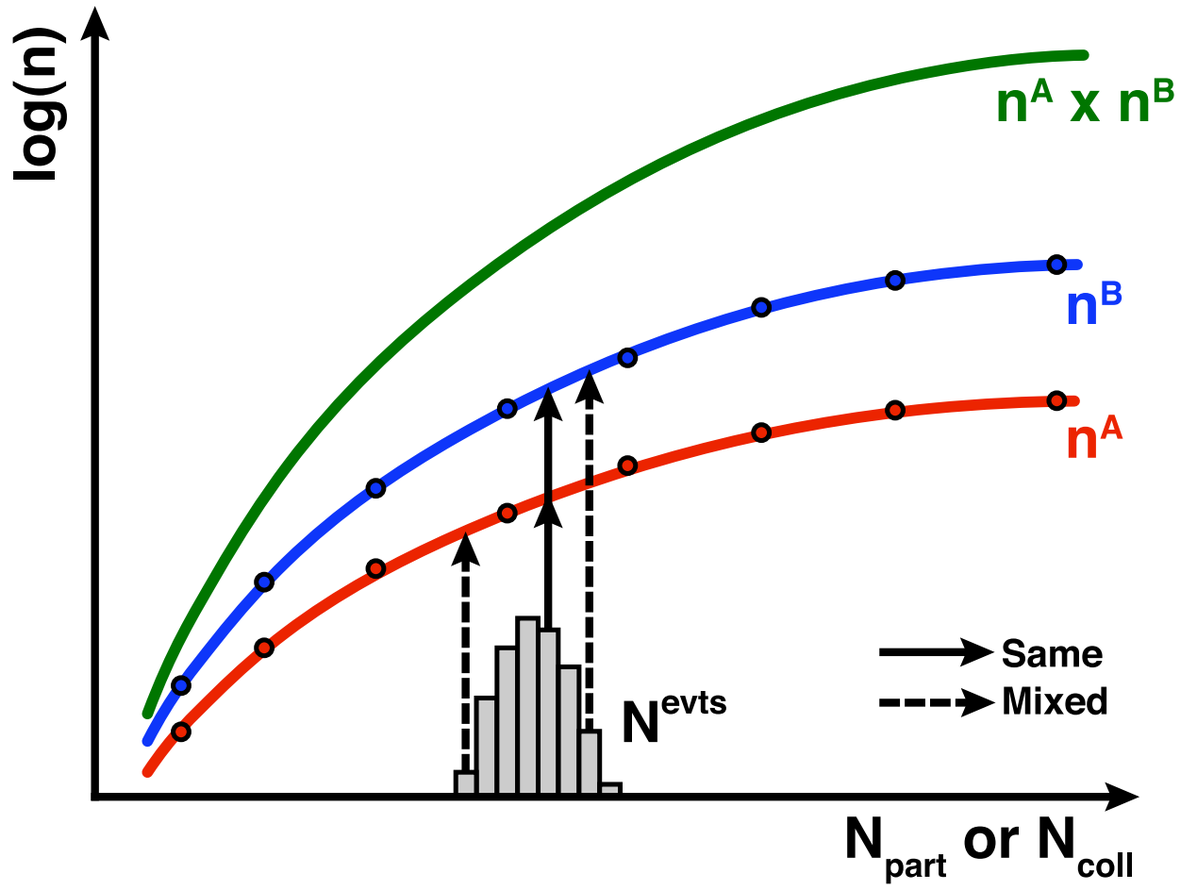

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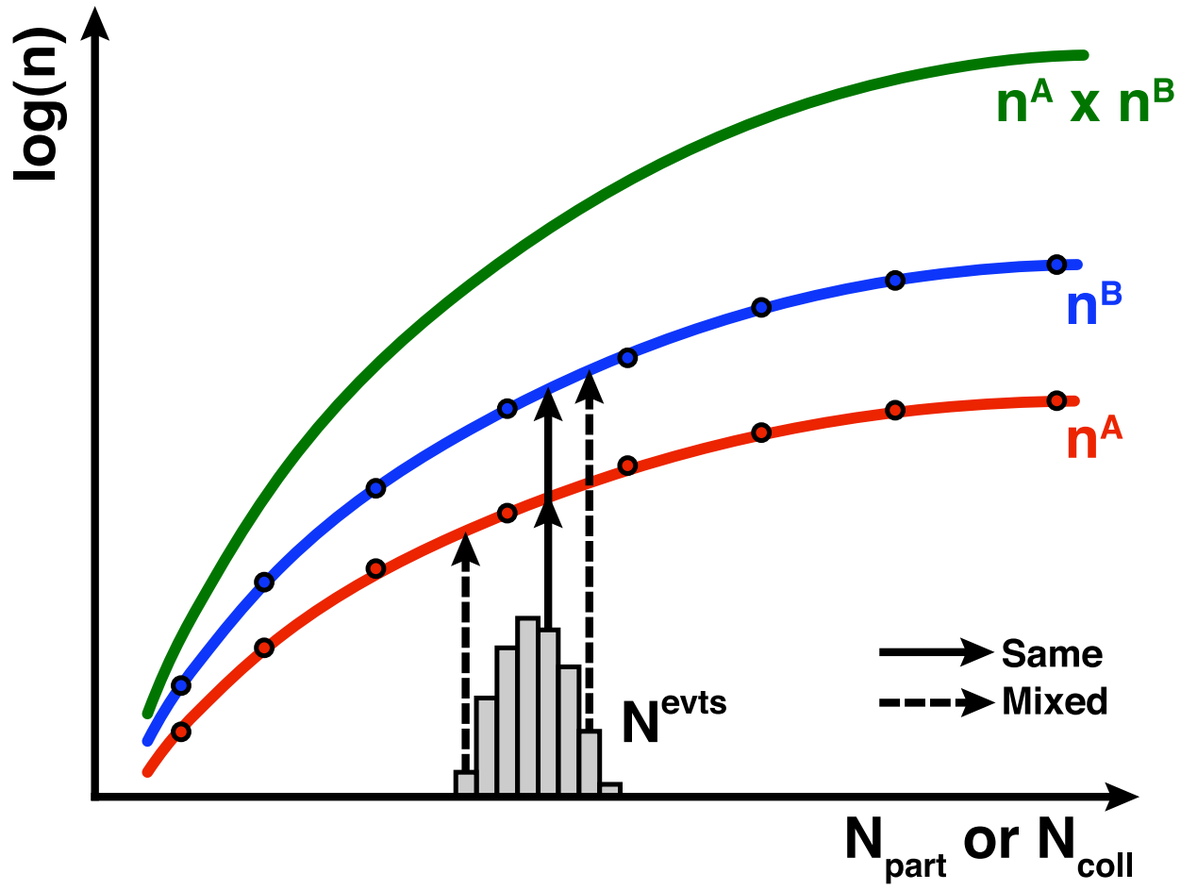

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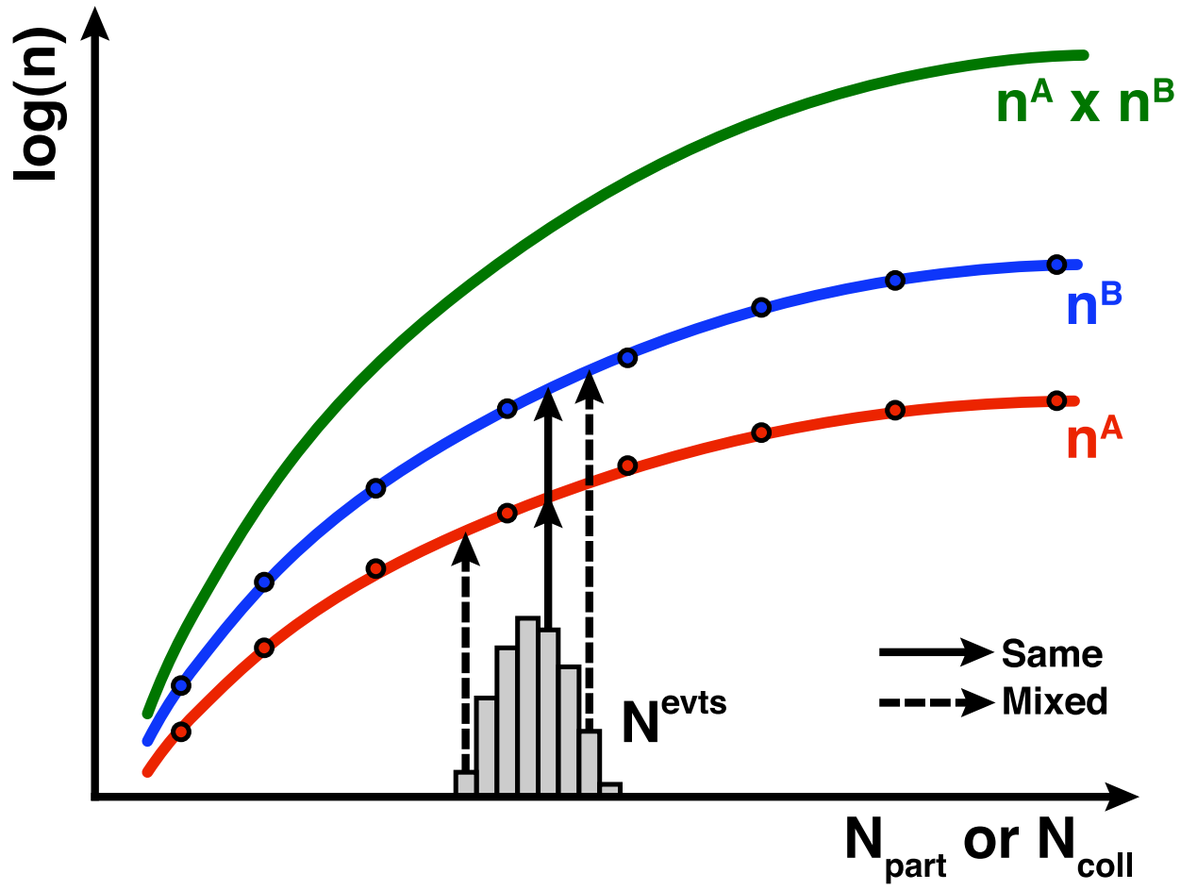
  - PHENIX PRL 98 232302



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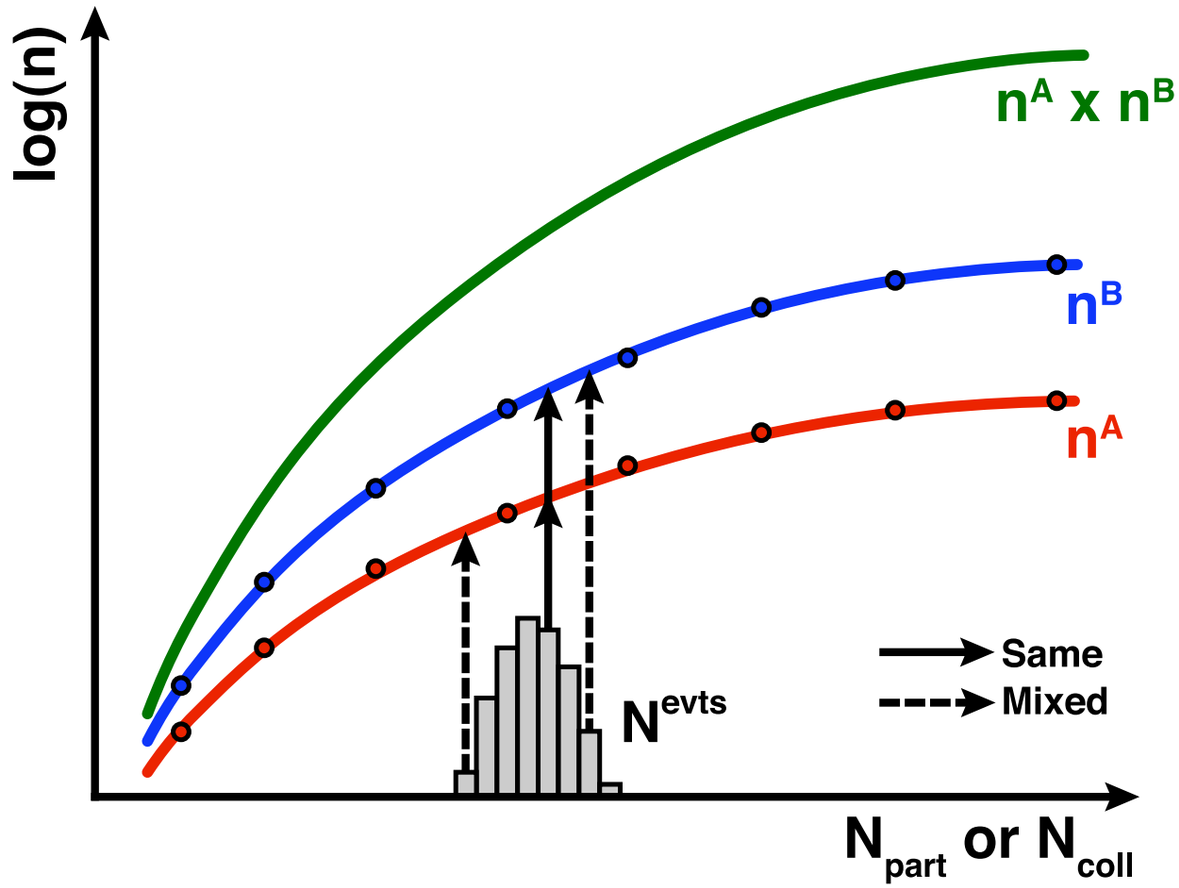
  - PLB 649 359 (2007)



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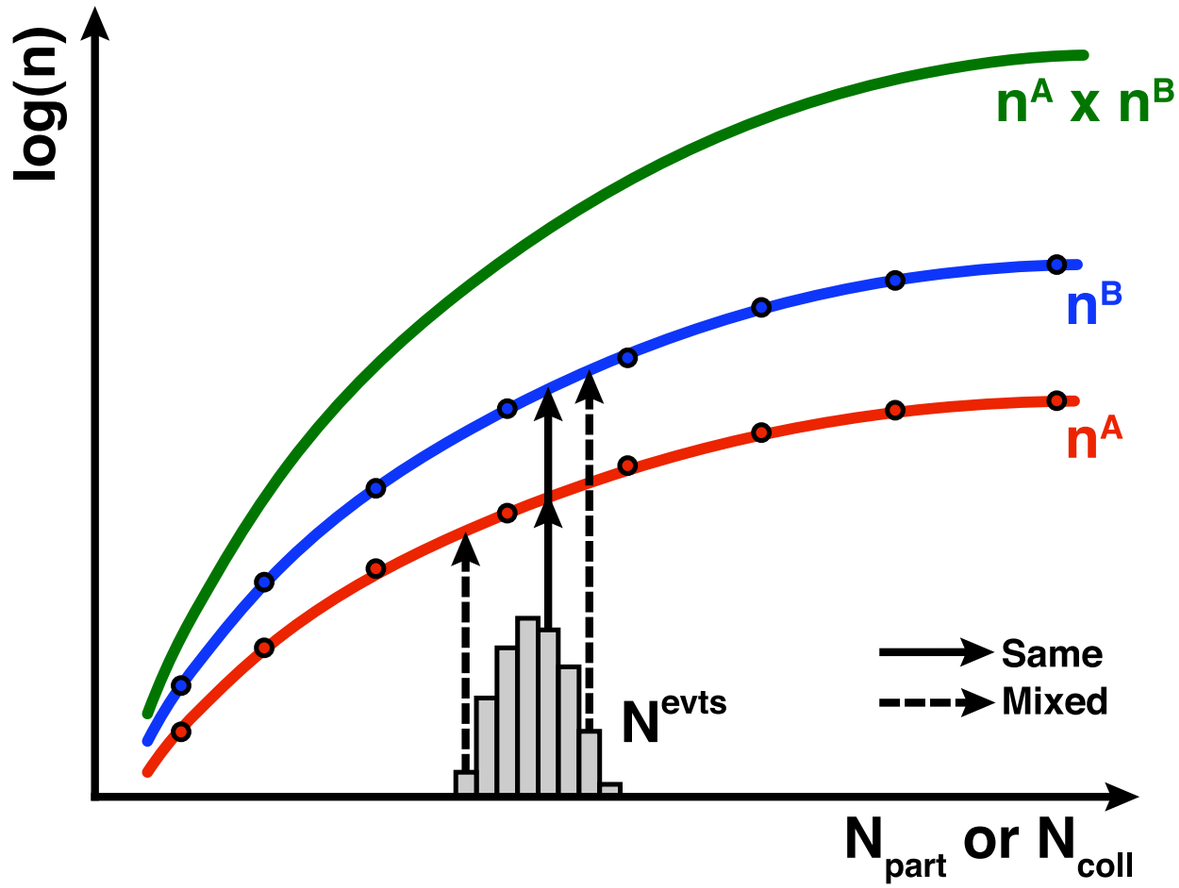

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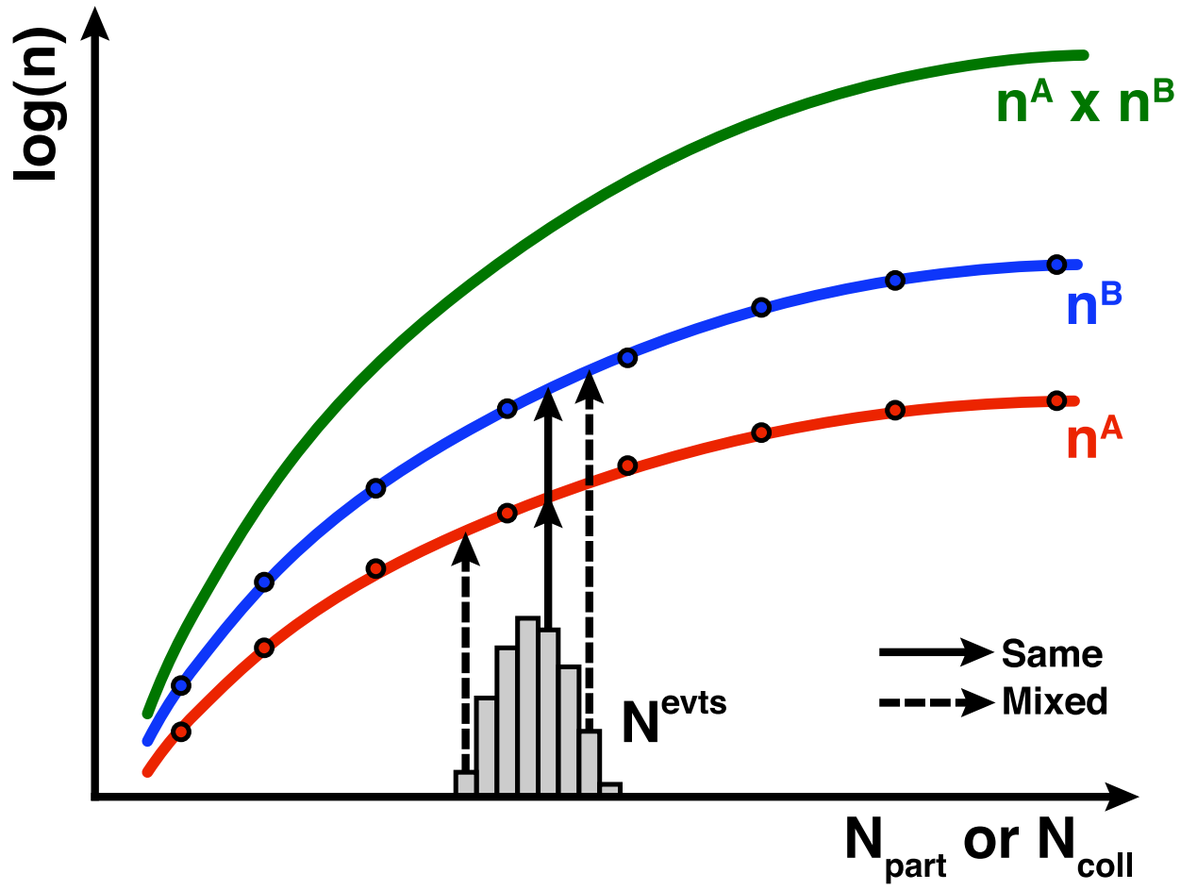
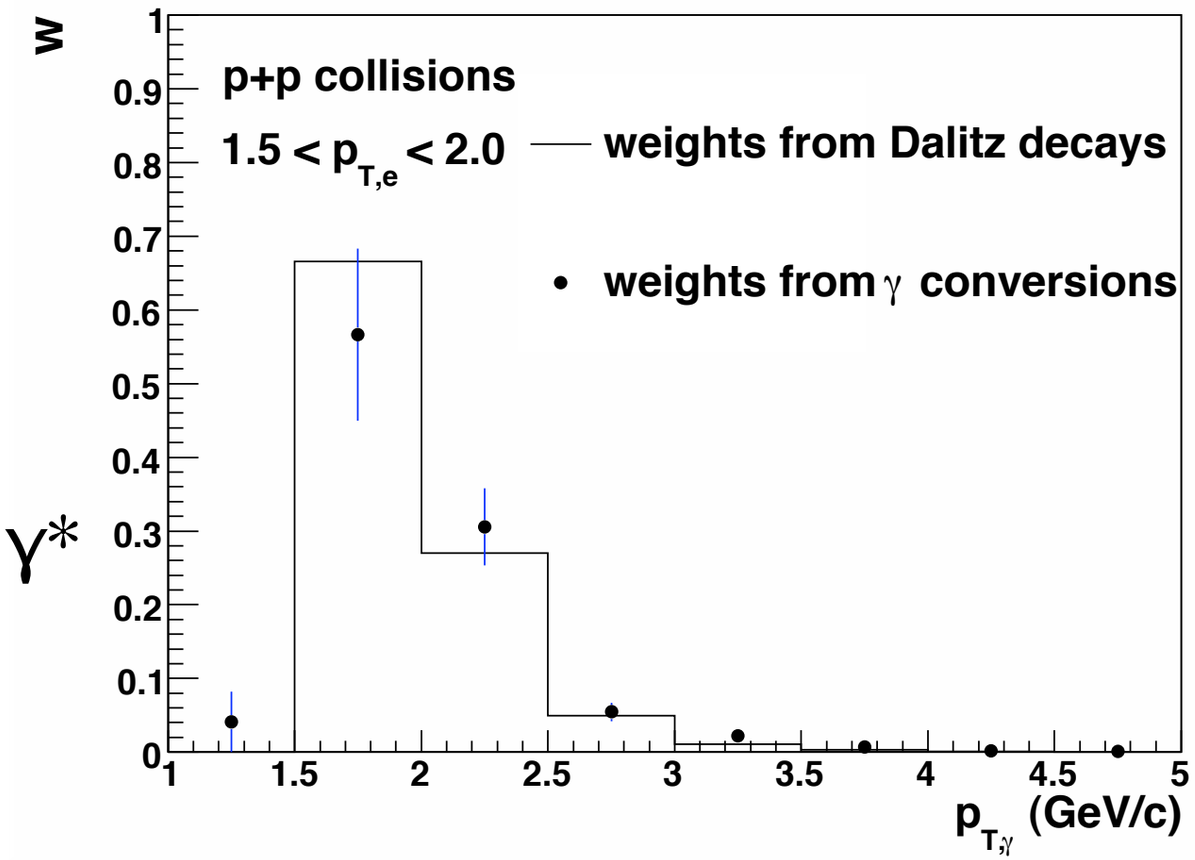
  - PHENIX arXiv:1002.1077



AMS, McCumber, Adare PRC 81 014908 (2010)

e_{phot}-h correlations (II)

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



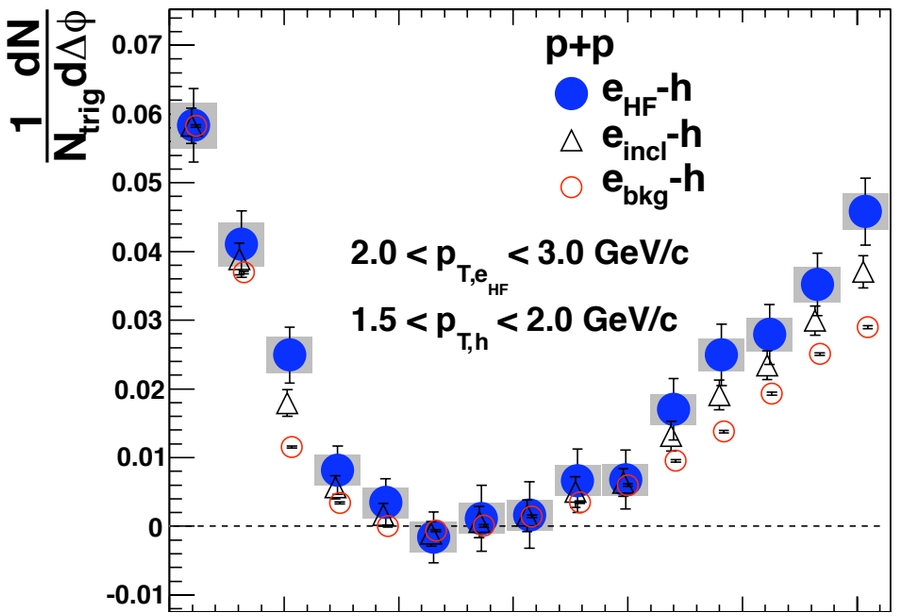
$$Y_{e_{phot}-h}(p_{T,i}) = \sum_j w_i(p_{T,j})\ Y_{\gamma-h}(p_{T,j})$$

why heavy flavor?

- mc & mb large compared to Λ_{QCD} and T_i
  - these quarks provide a partonic variation of the quark probing the matter
    - --fundamental handle
  - clean, production only in initial stages of the collision, before the matter is formed

moving to Au+Au collisions

moving to Au+Au collisions



moving to Au+Au collisions