Positive Progress from Hard Scattering

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QGP

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these are worth understanding both for their own sake and for enabling us to disentangle parton-medium interactions

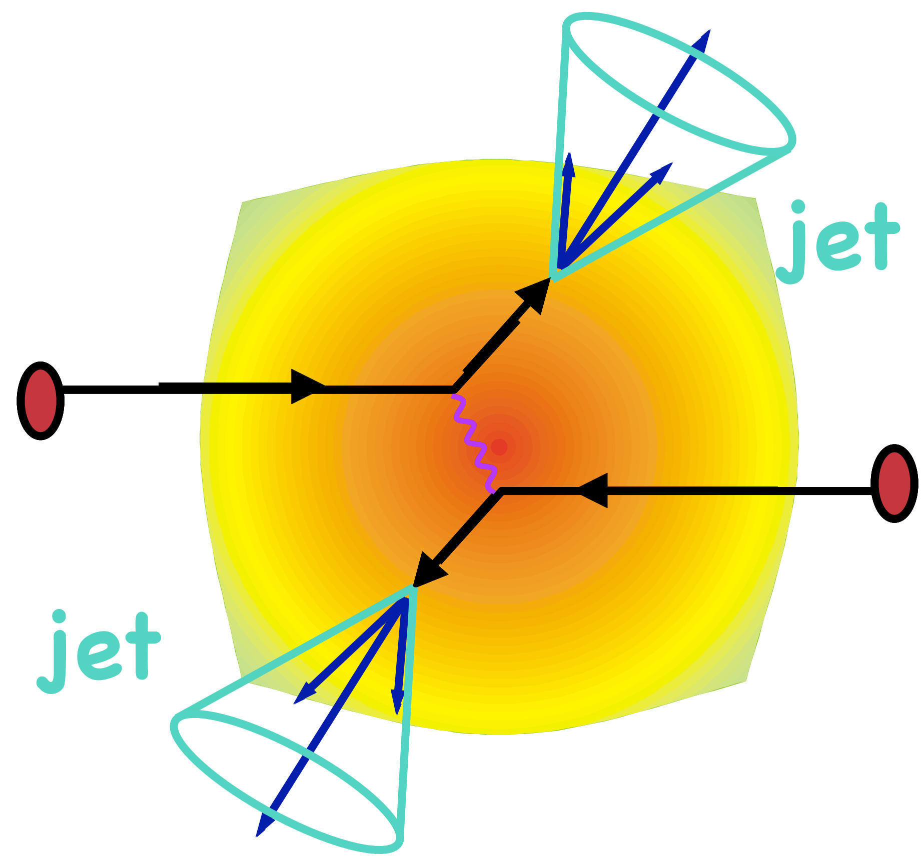
high p_T particle production

Au+Au collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

Hard Scattering Cross Section: Calculated with pQCD

Parton-Medium Interactions & Hadronization



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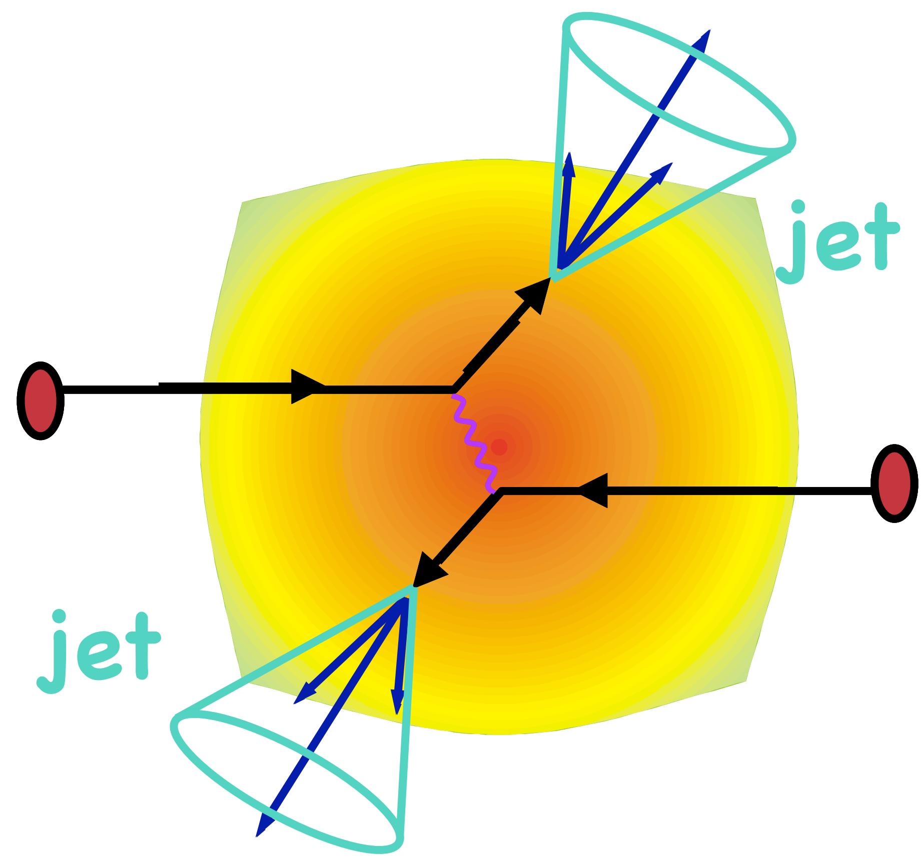

don't assume these are independent of each other!

Jets @ RHIC

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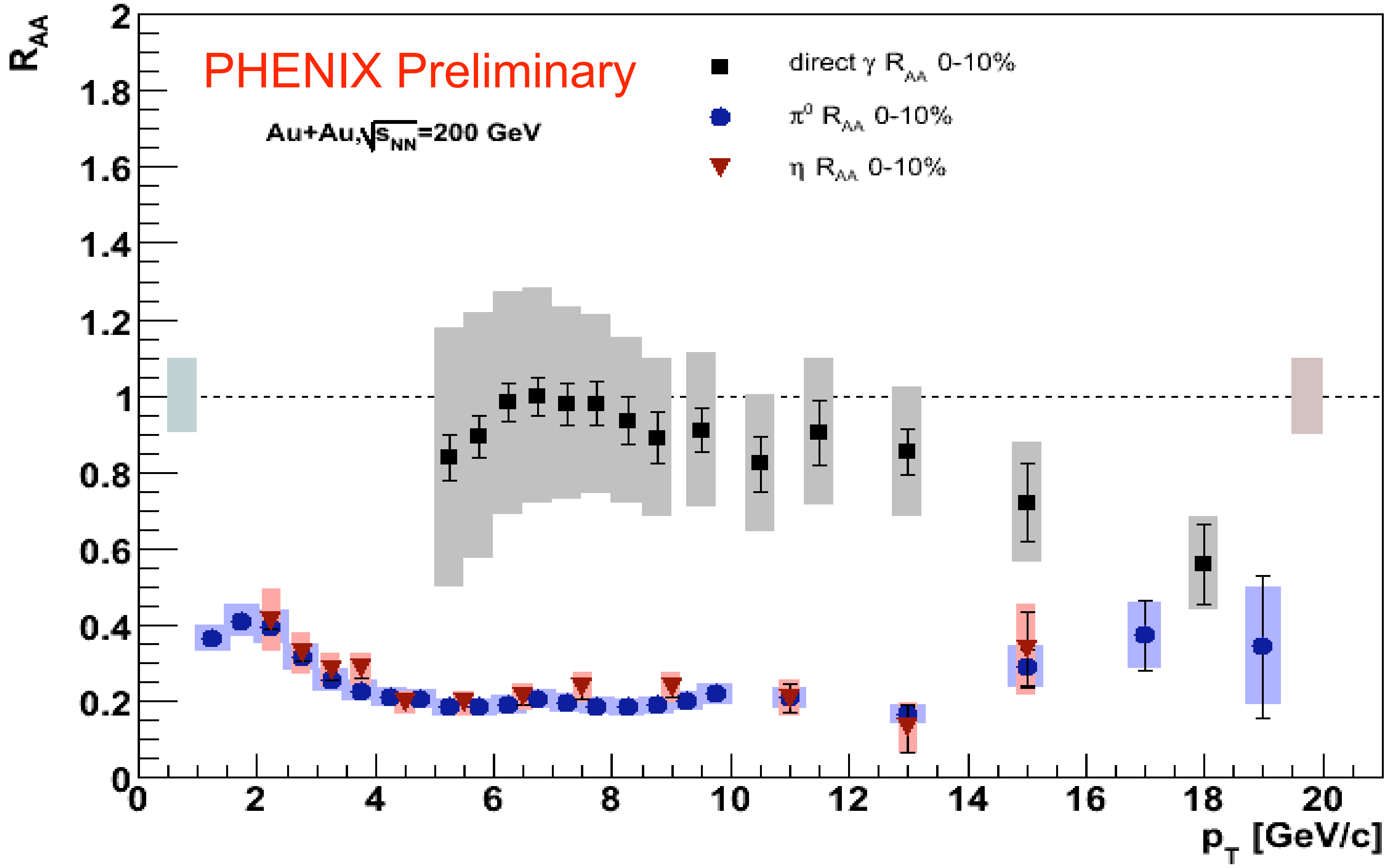
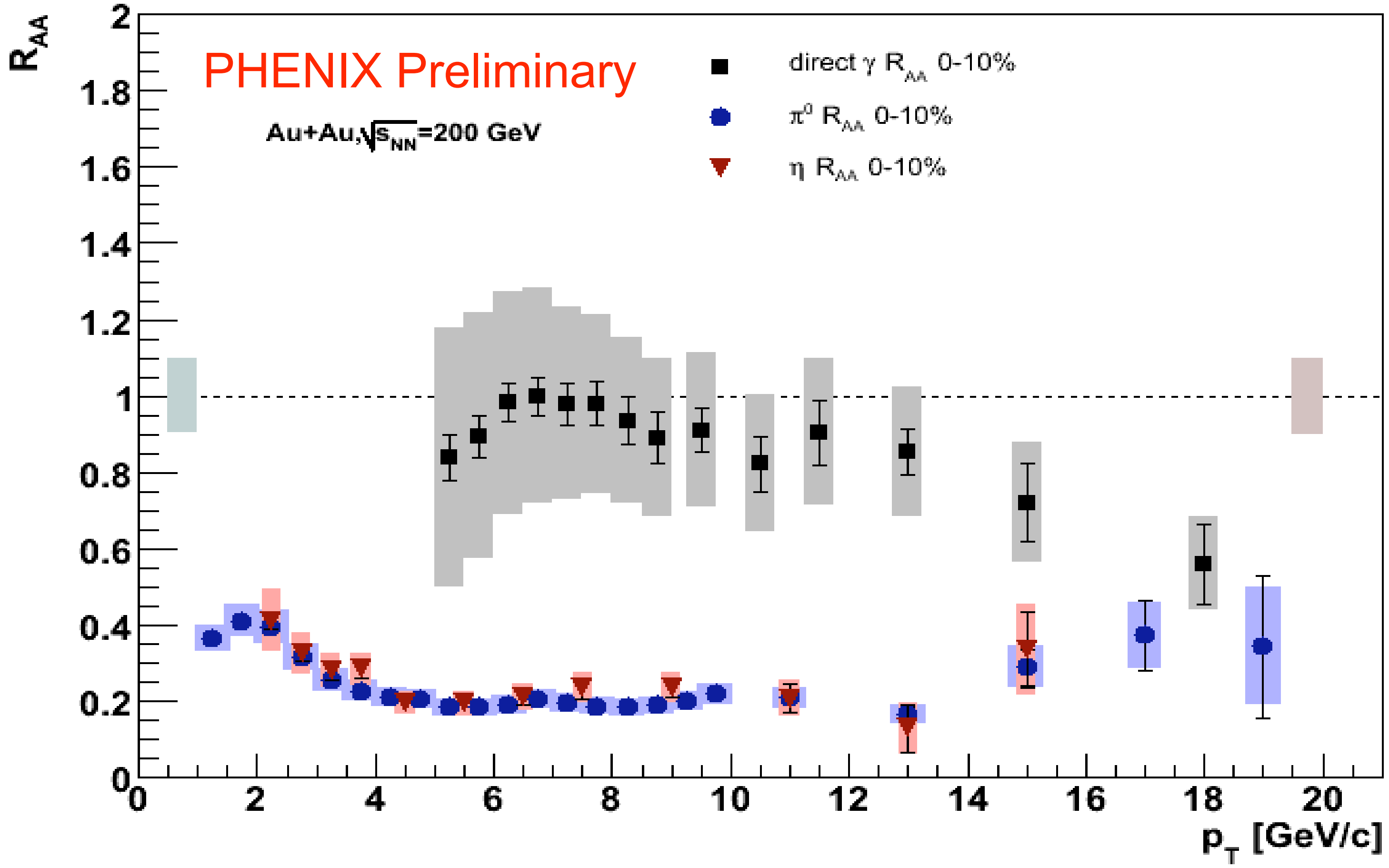


PHENIX Preliminary
Au+Au,$\sqrt{s_{NN}}$=200 GeV
direct γ R_{AA} 0-10%
π^0 R_{AA} 0-10%
η R_{AA} 0-10%
R_{AA}
p_T [GeV/c]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
20

Jets @ RHIC



- γ_{direct}: initial hard scattering

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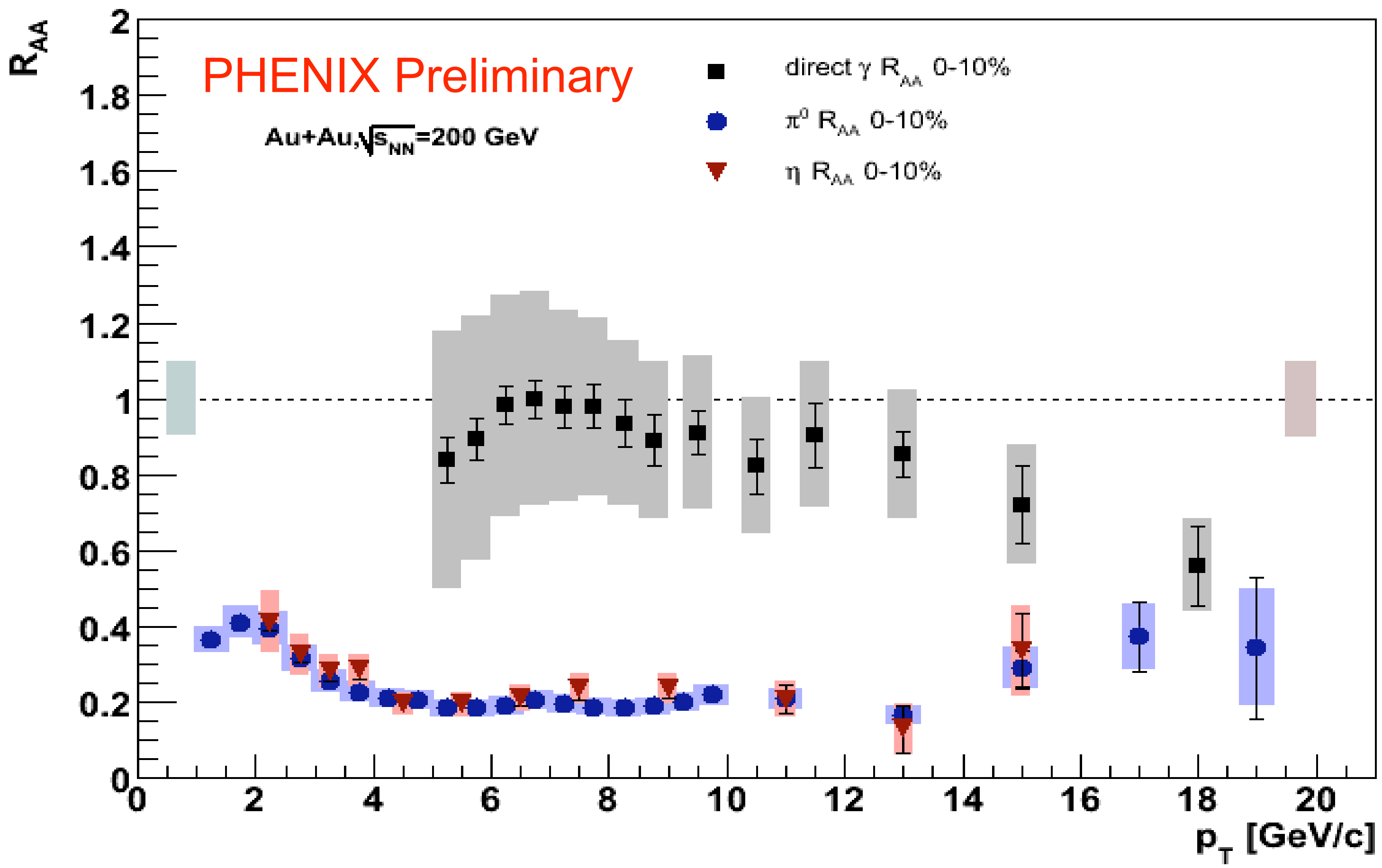

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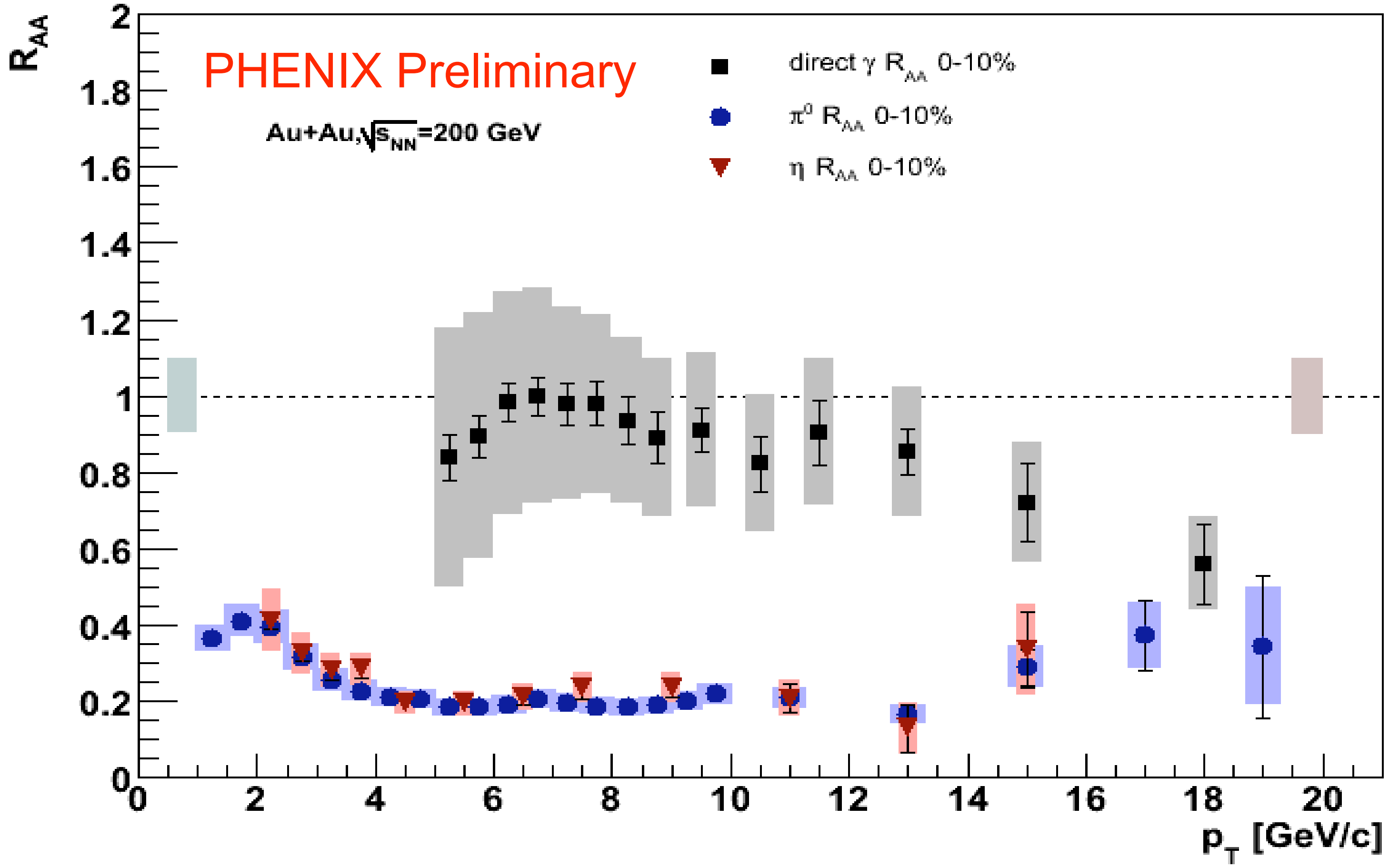

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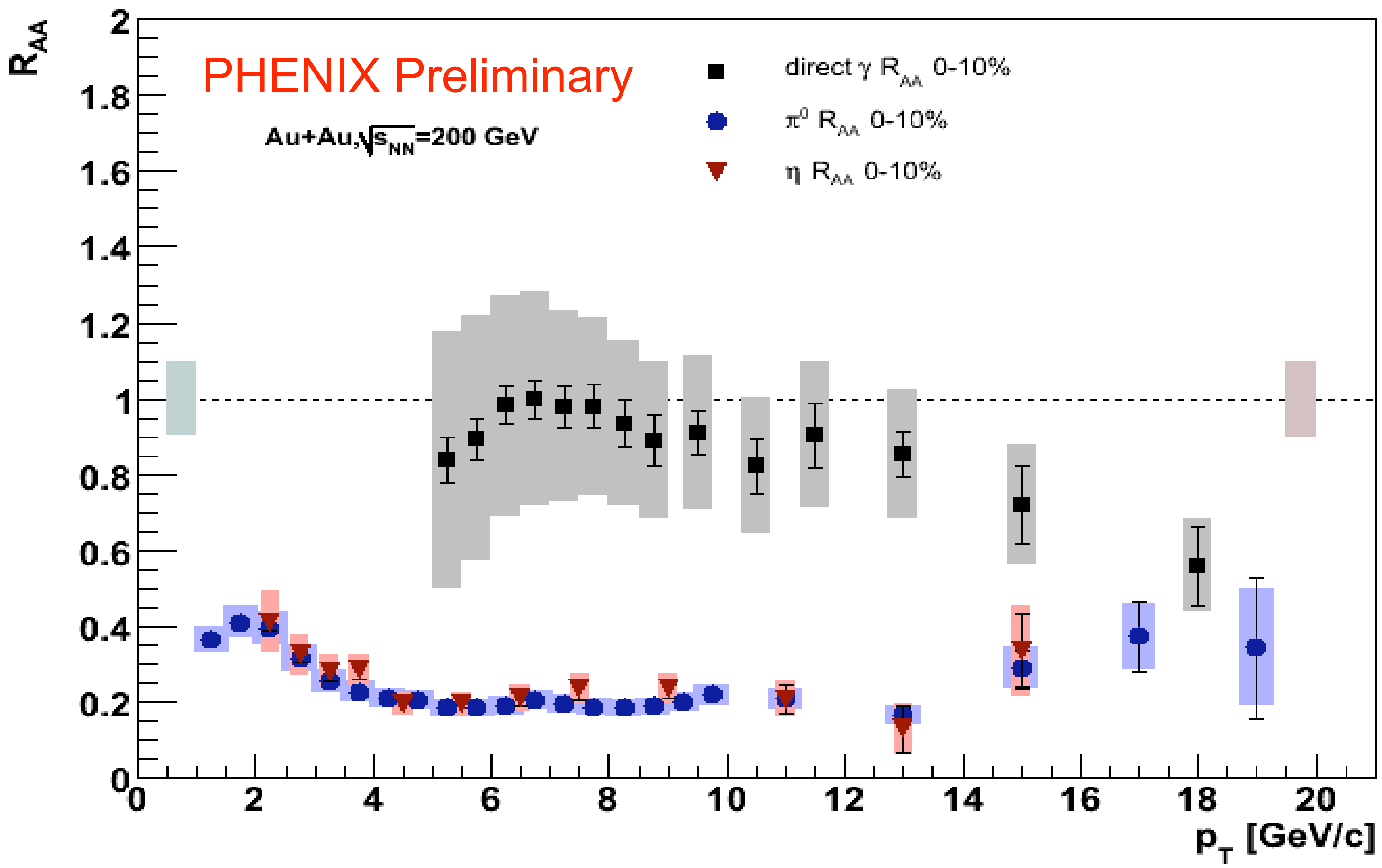

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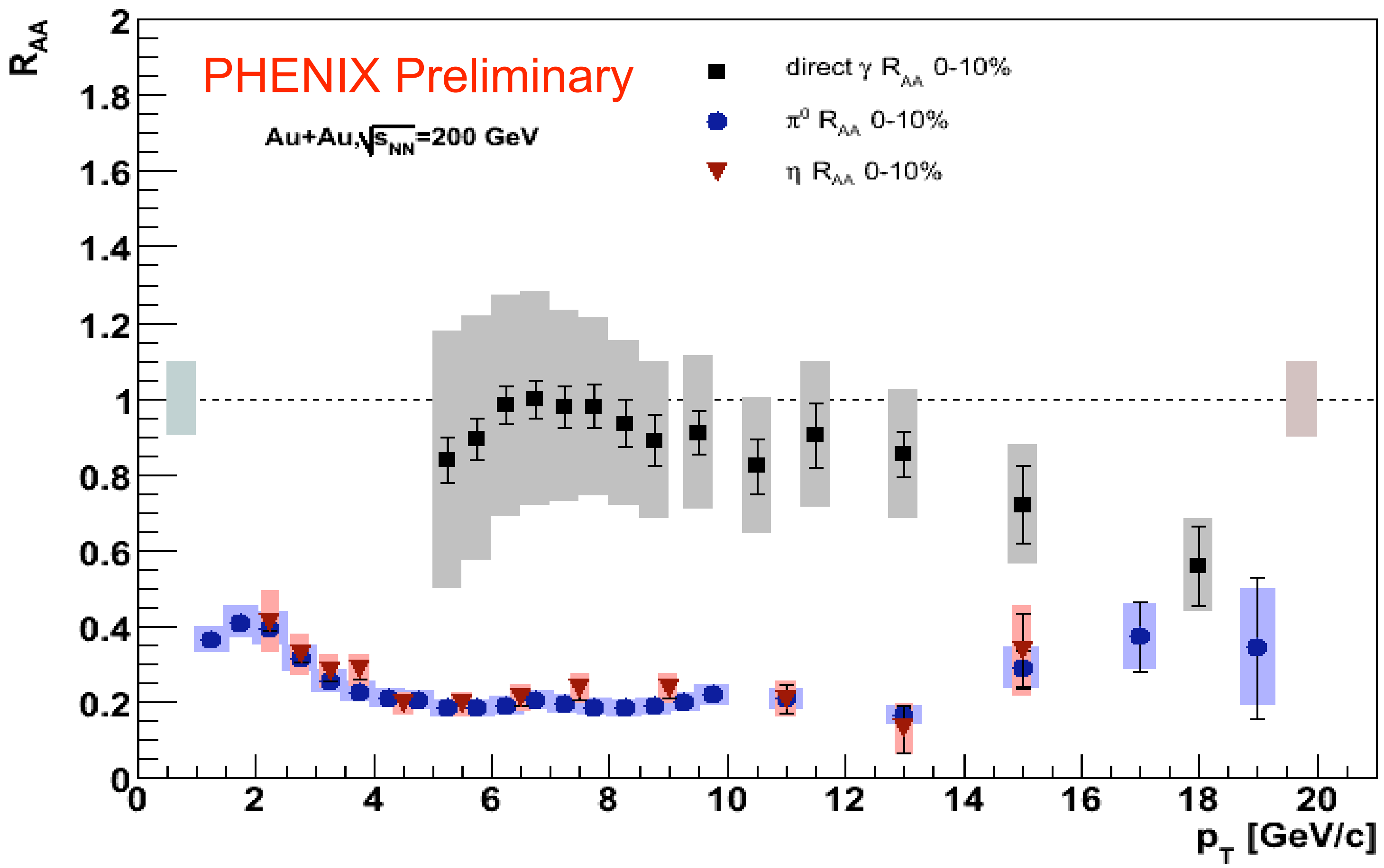

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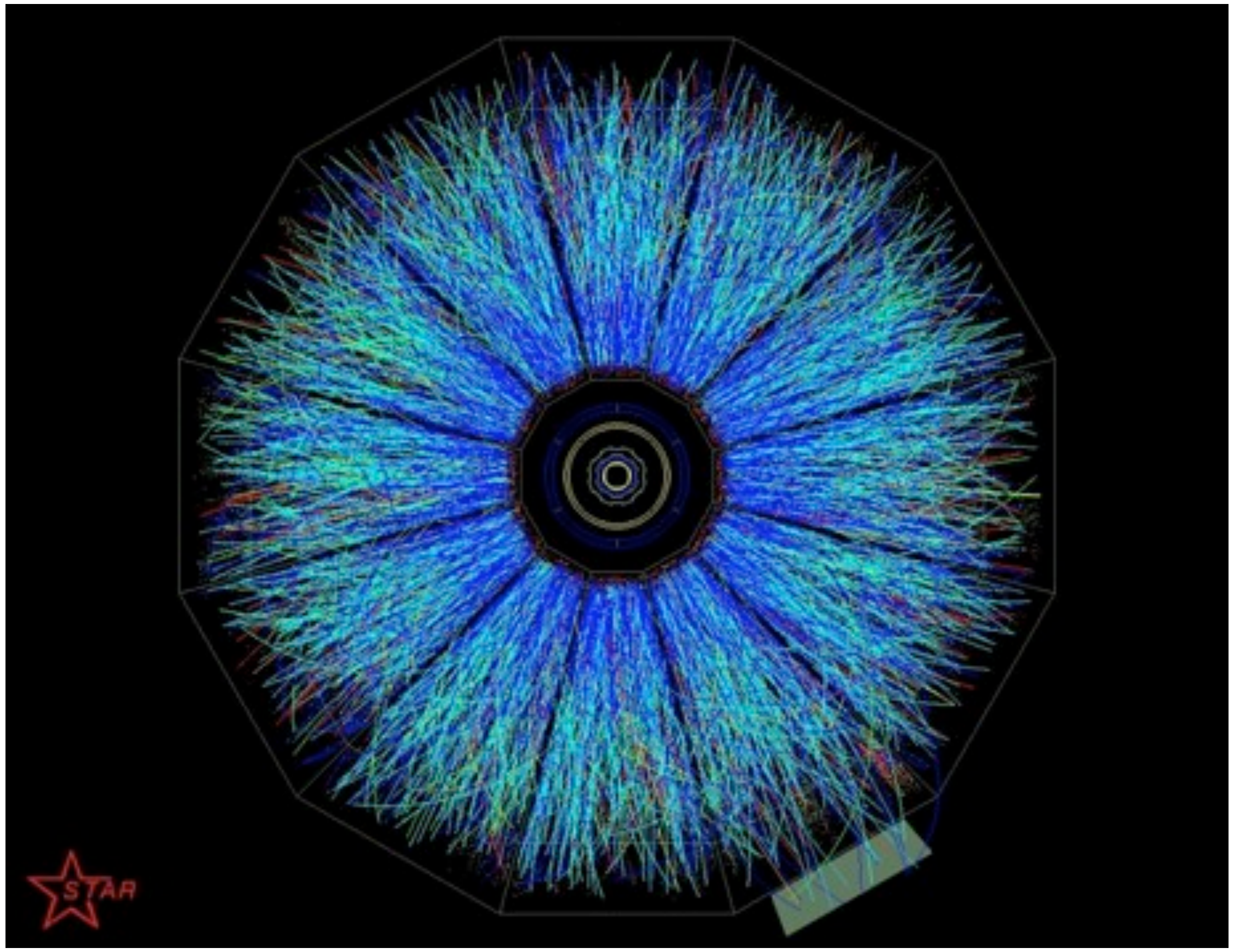
how are we addressing these questions with the data in hand?

Spectra & Correlations

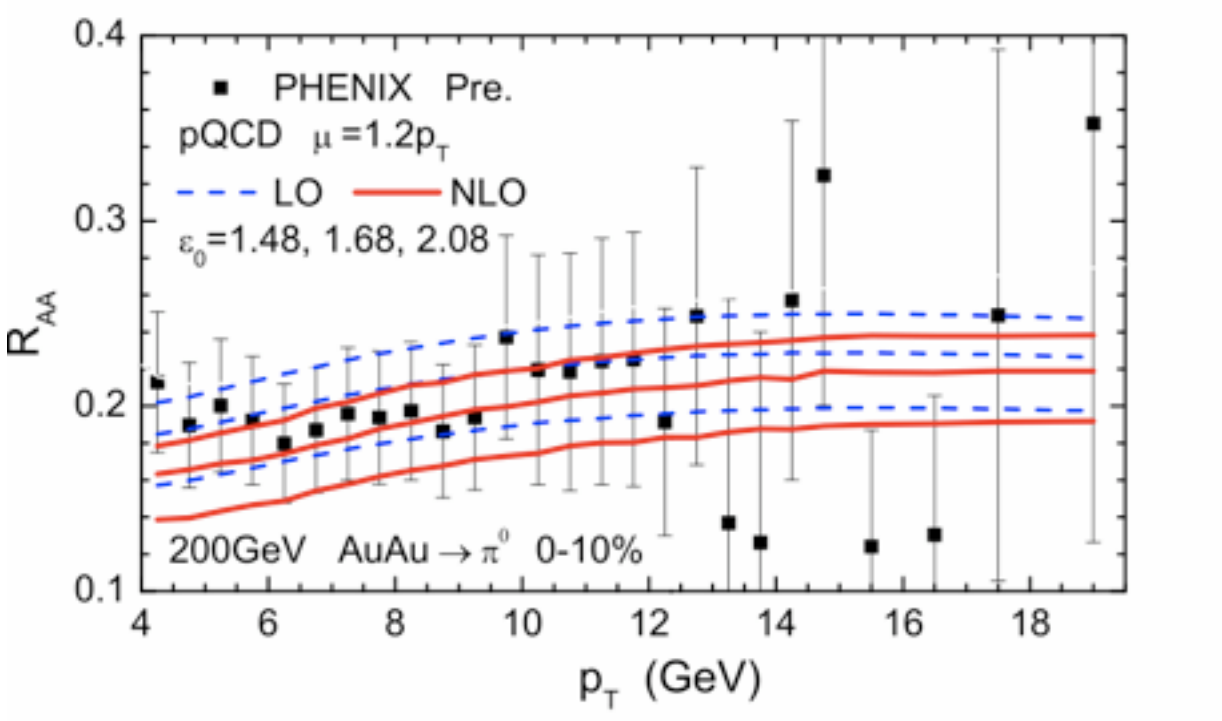
- one parton leads to many hadrons in the final state
- single and dihadron spectra are in some ways proxies for jets
  - introduce geometrical, energy loss and fragmentation biases
  - their power lies in their extreme simplicity



constraining energy loss

arXiv:0912.1871, arXiv:1002.1077, Zhang et al

constraining energy loss



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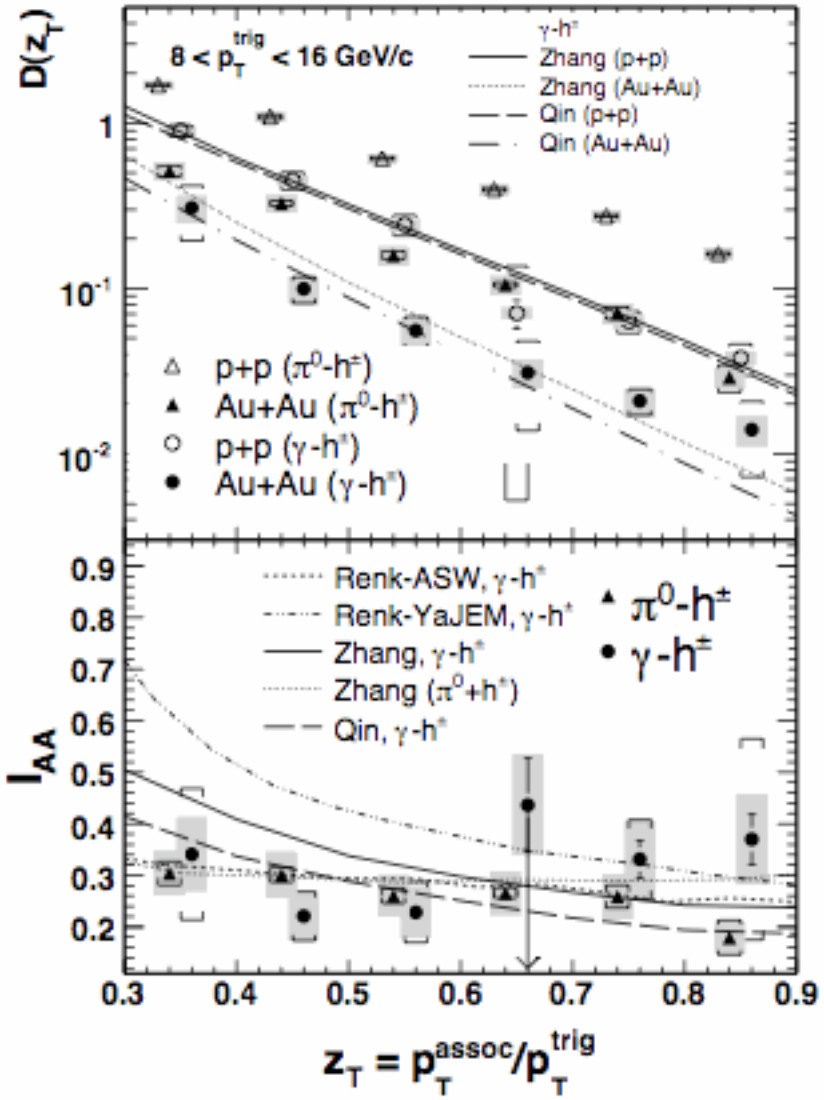

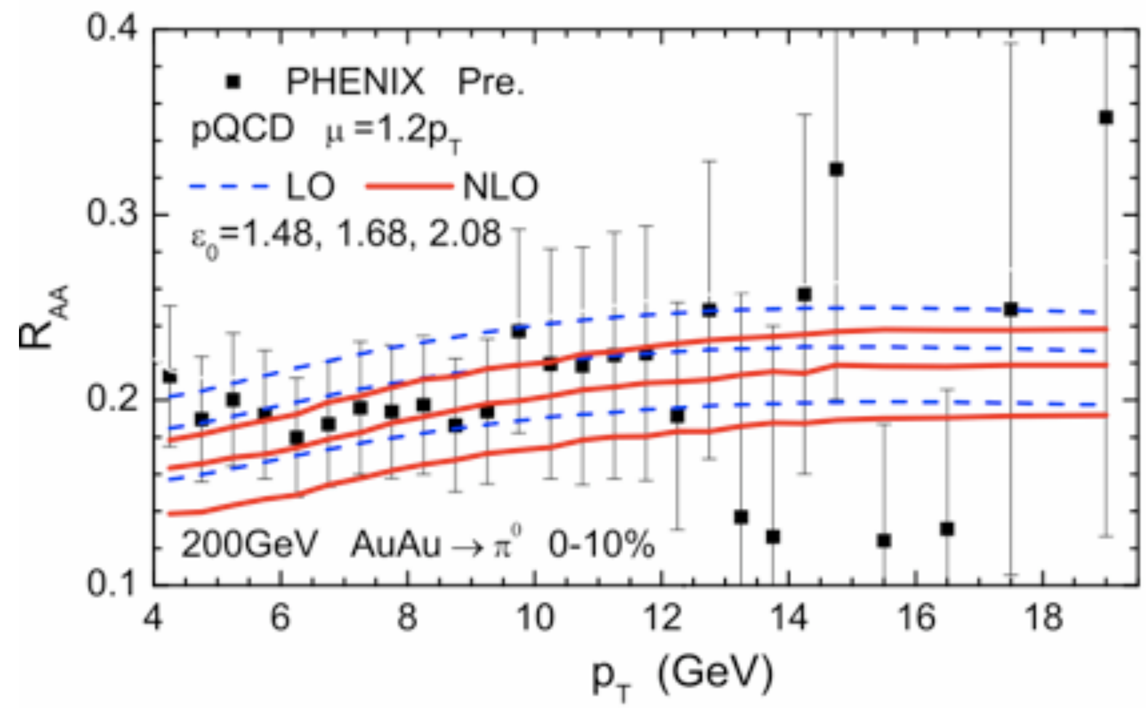

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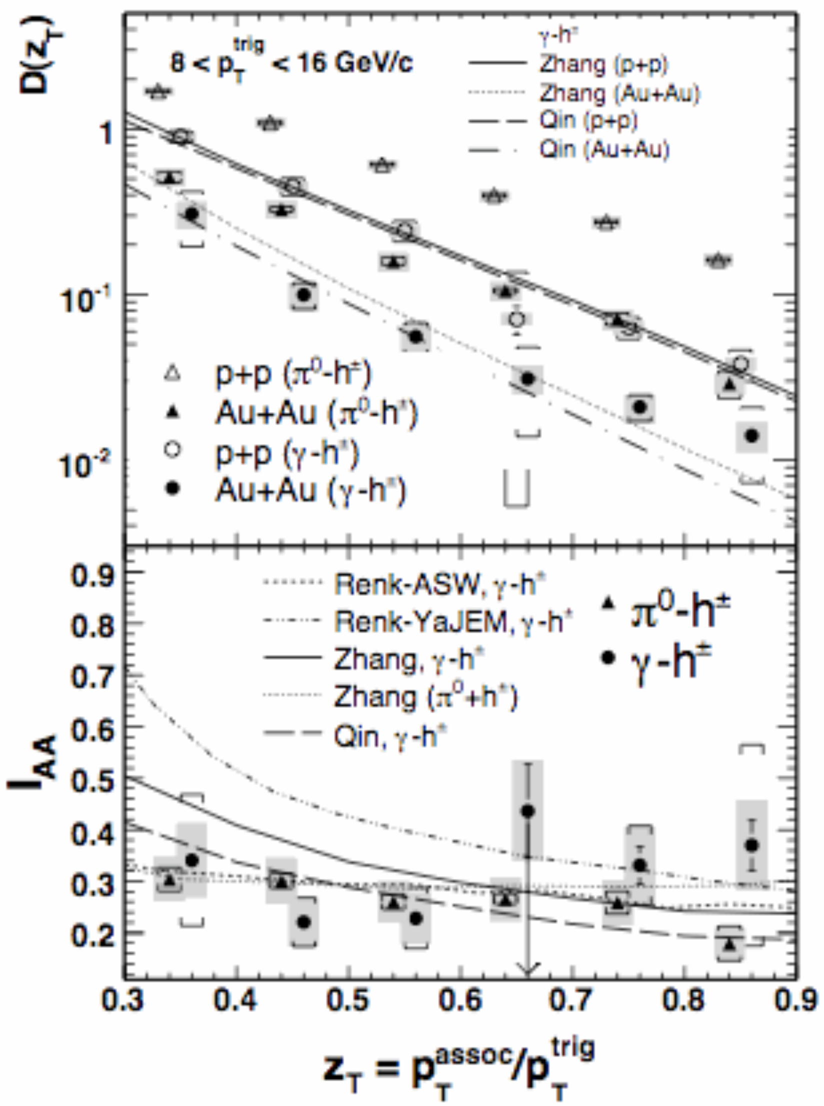

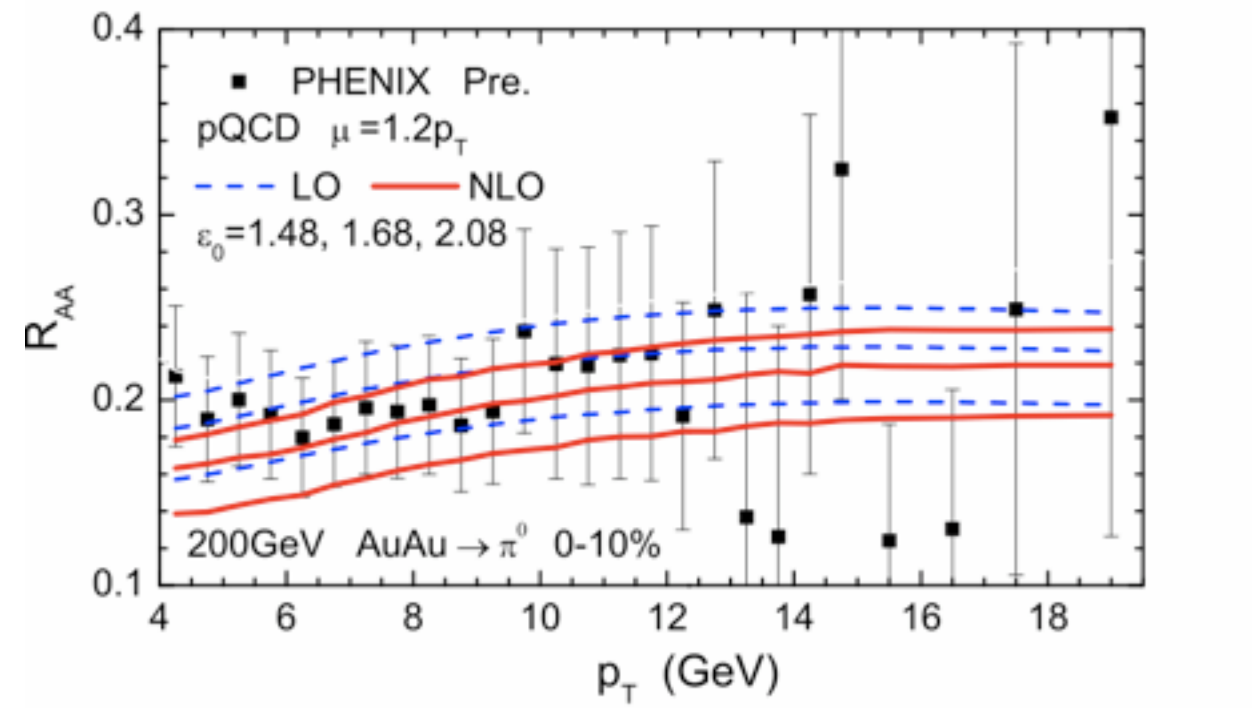

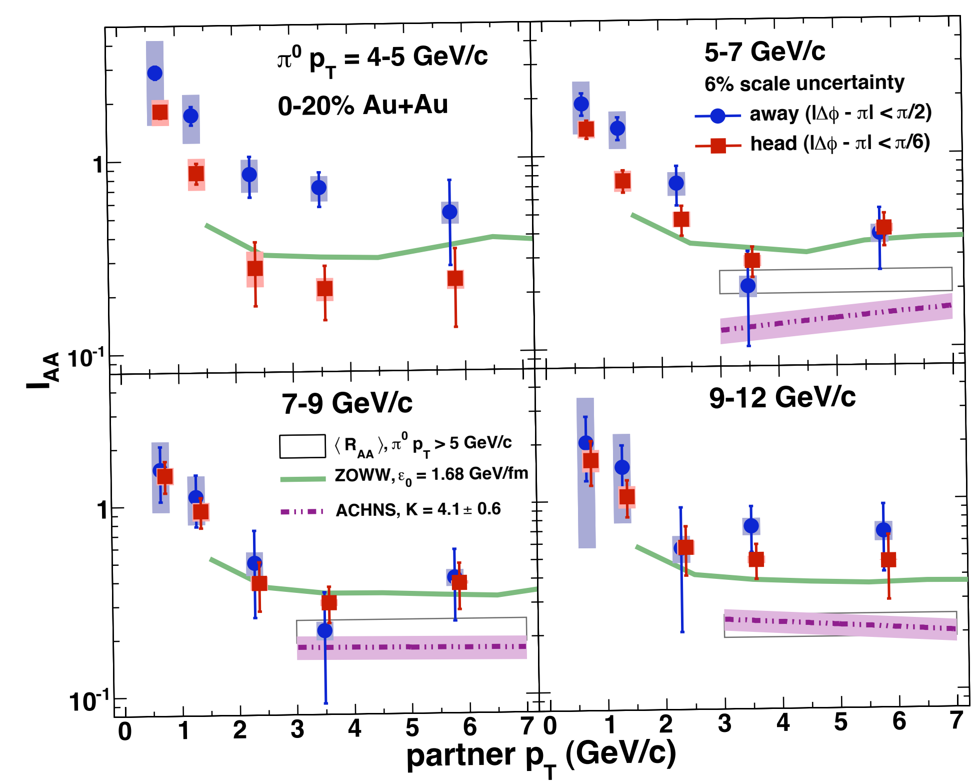

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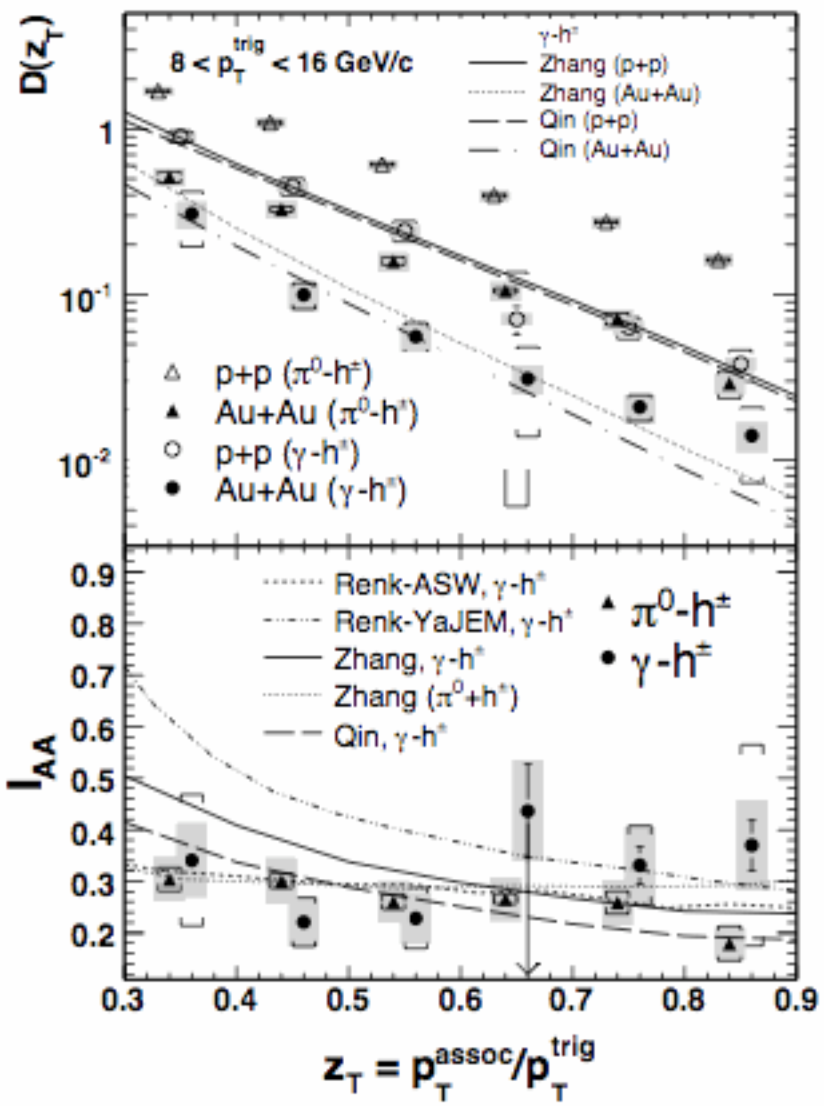

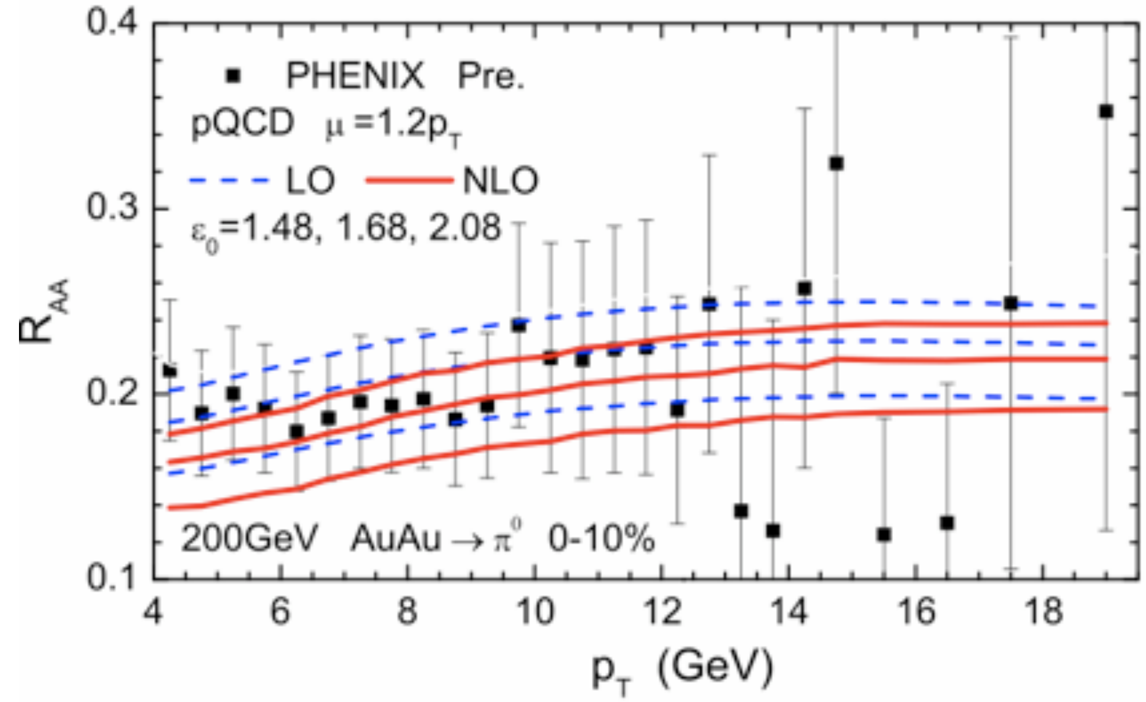

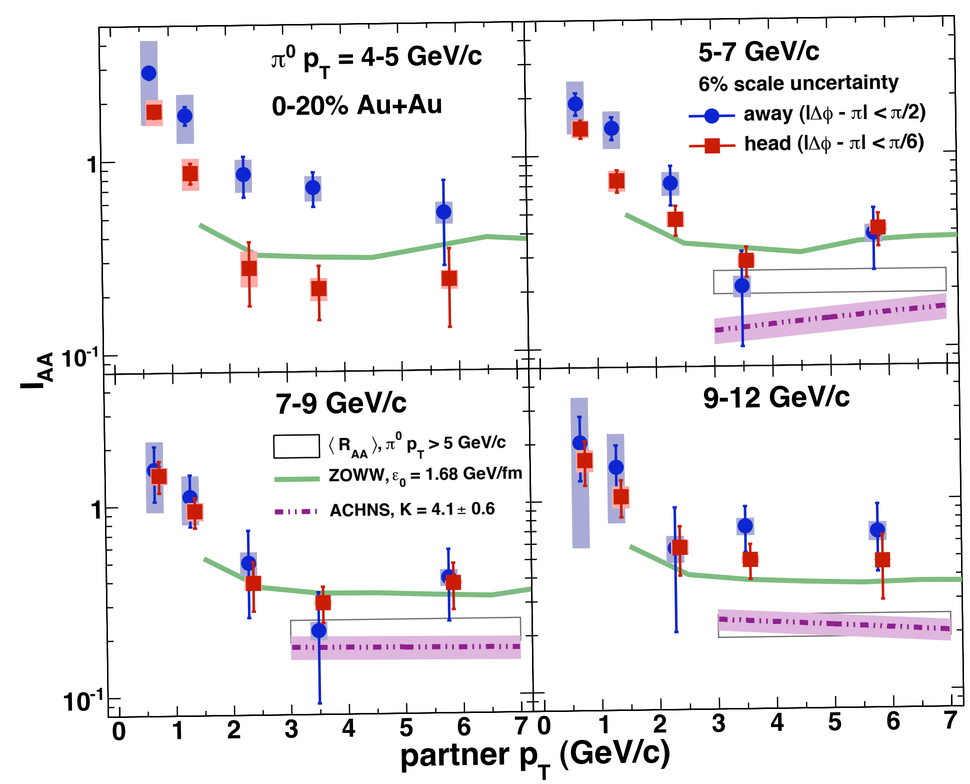

- ZOWW with ε_0=1.68

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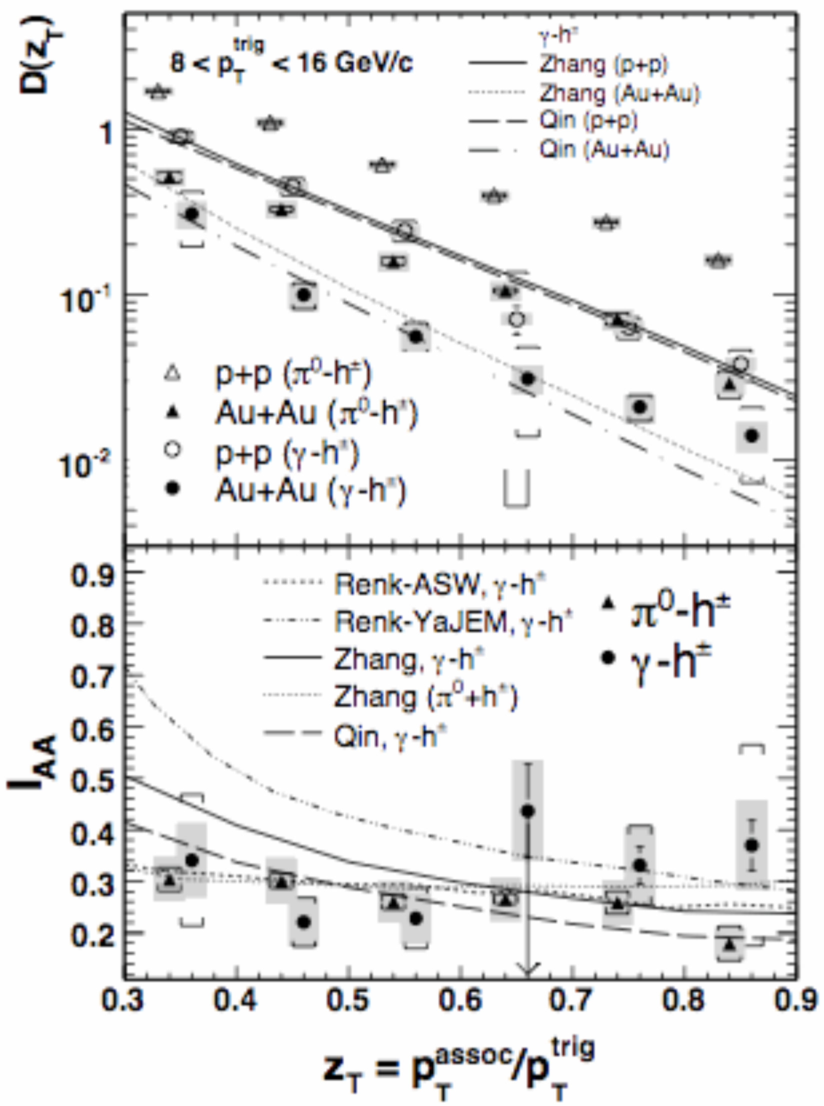

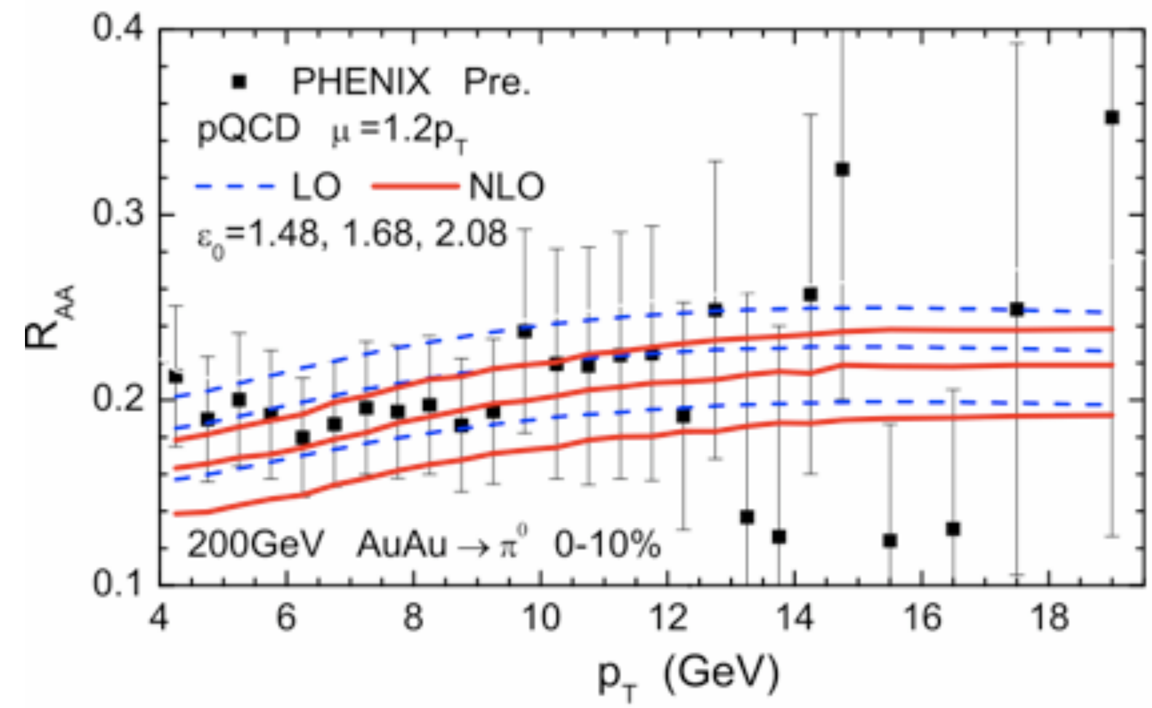

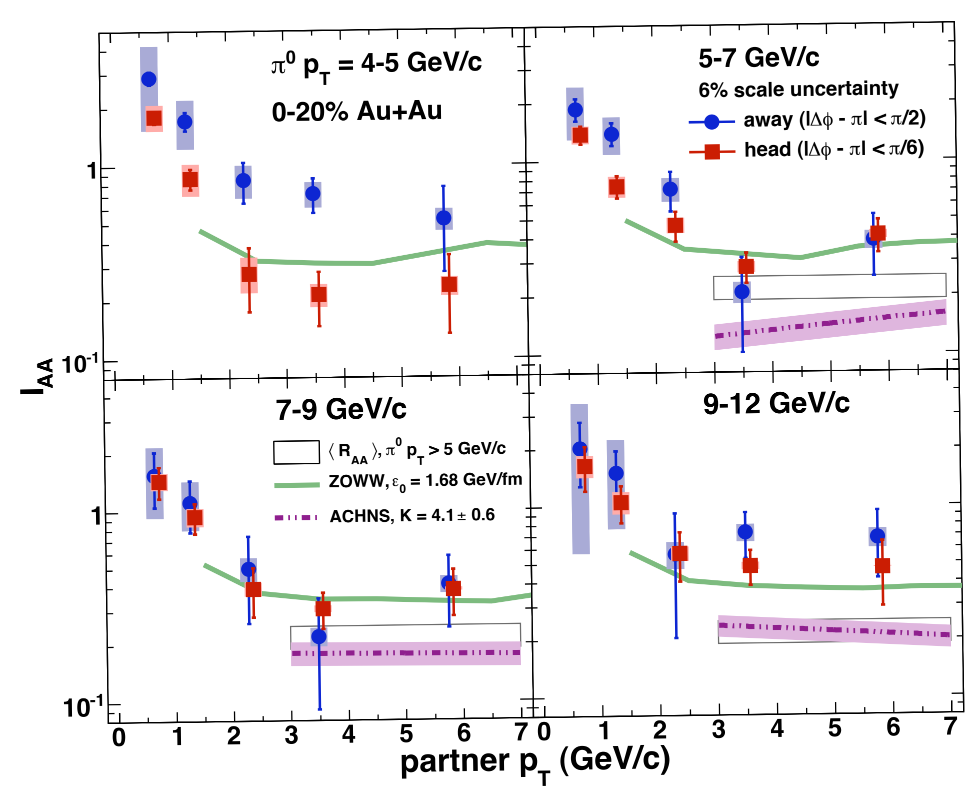

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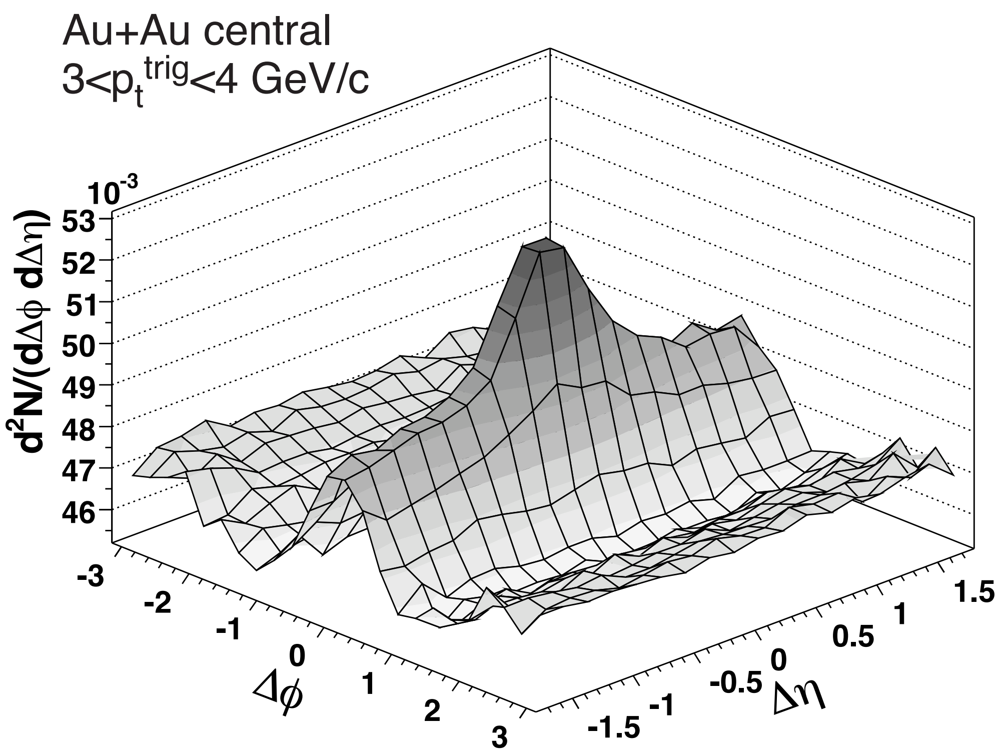
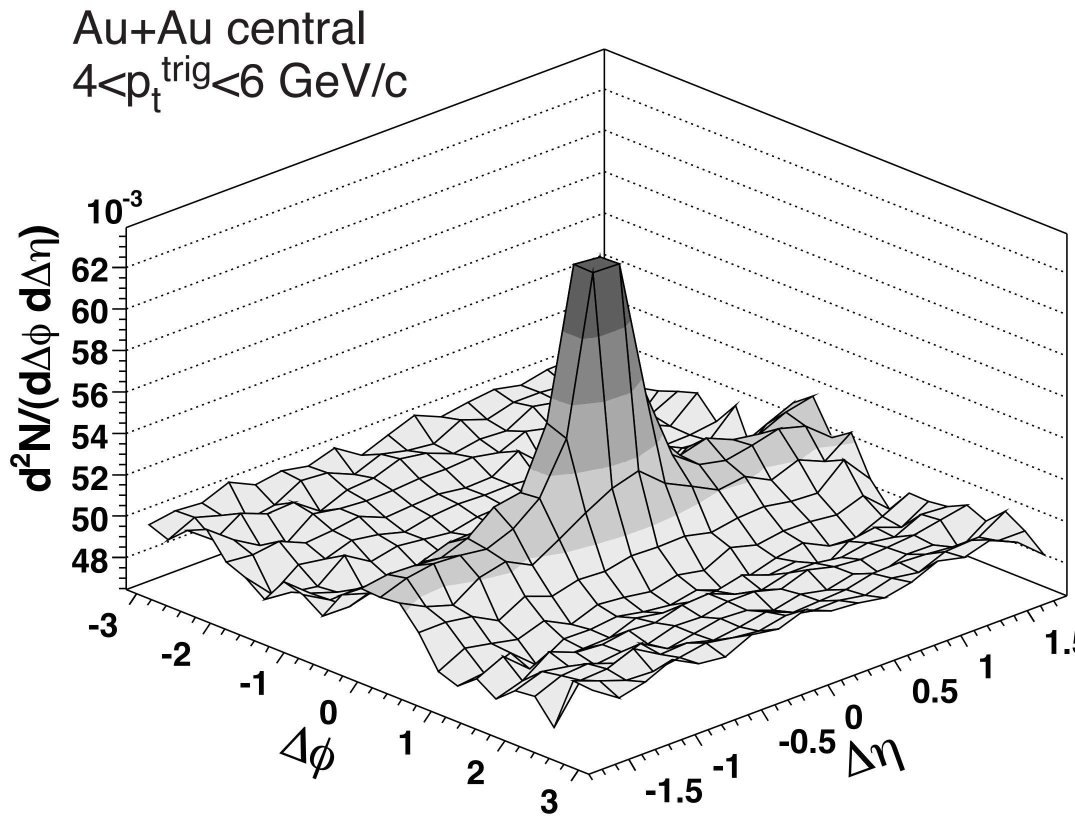
- ZOWW with ε_0=1.68
- n.b. RXNP plane dep. not done yet

Correlation Shapes

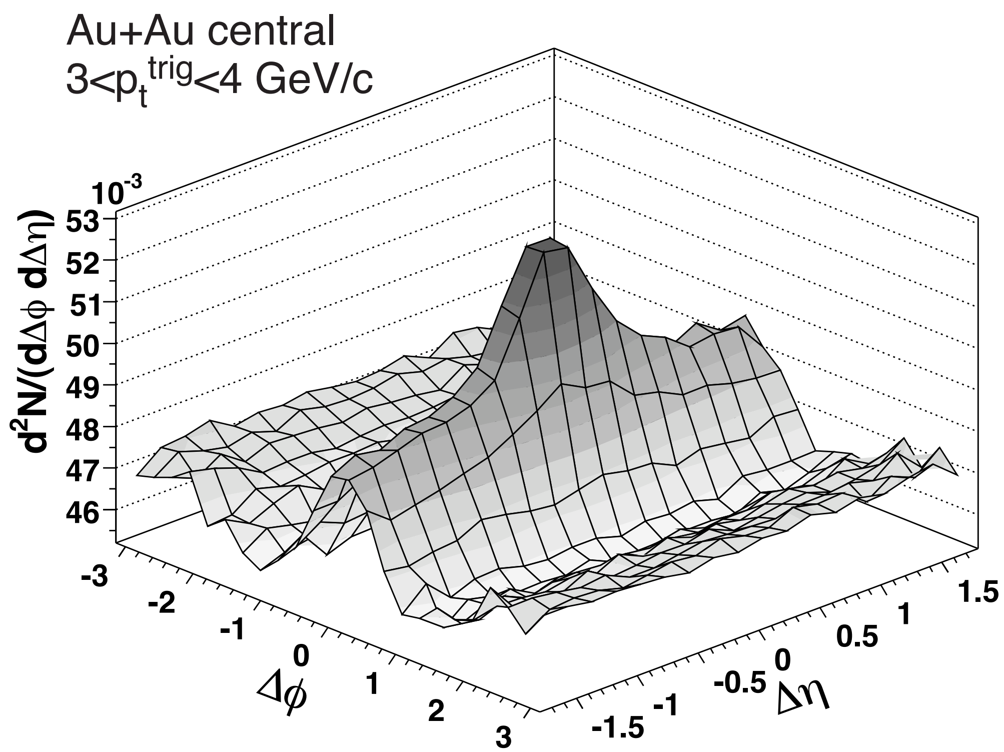
hard ridge

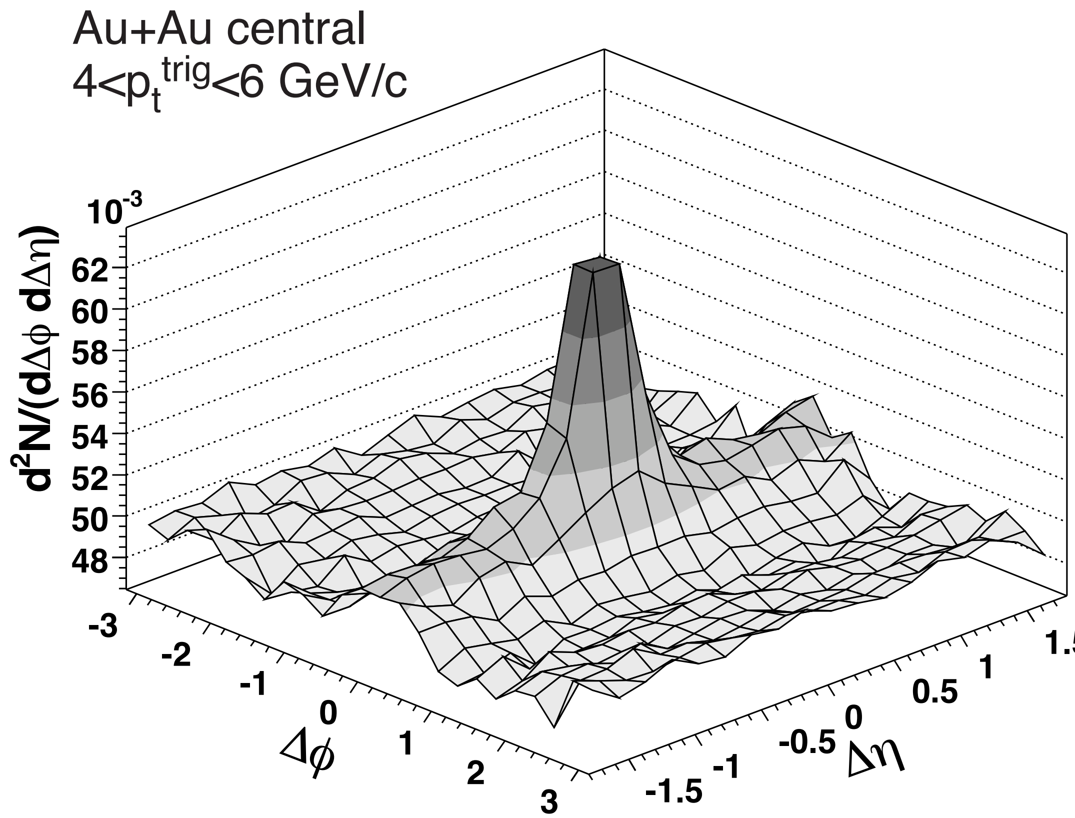




STAR PRC 064912 (2009)

hard ridge





- visible ridge persists out to >4GeV/c triggers

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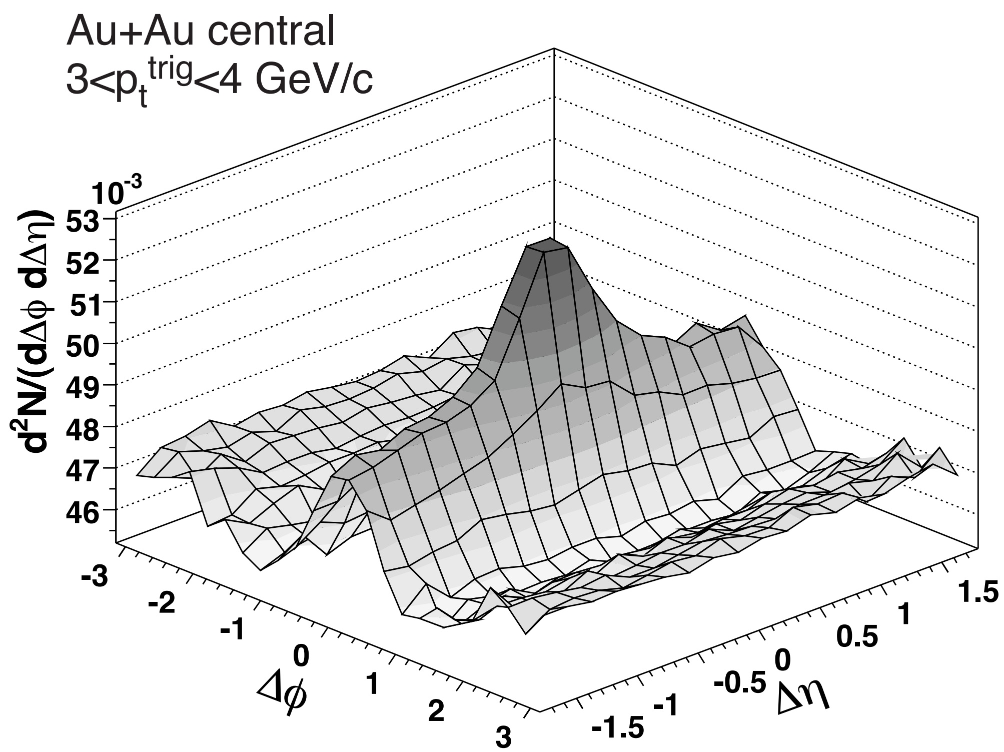

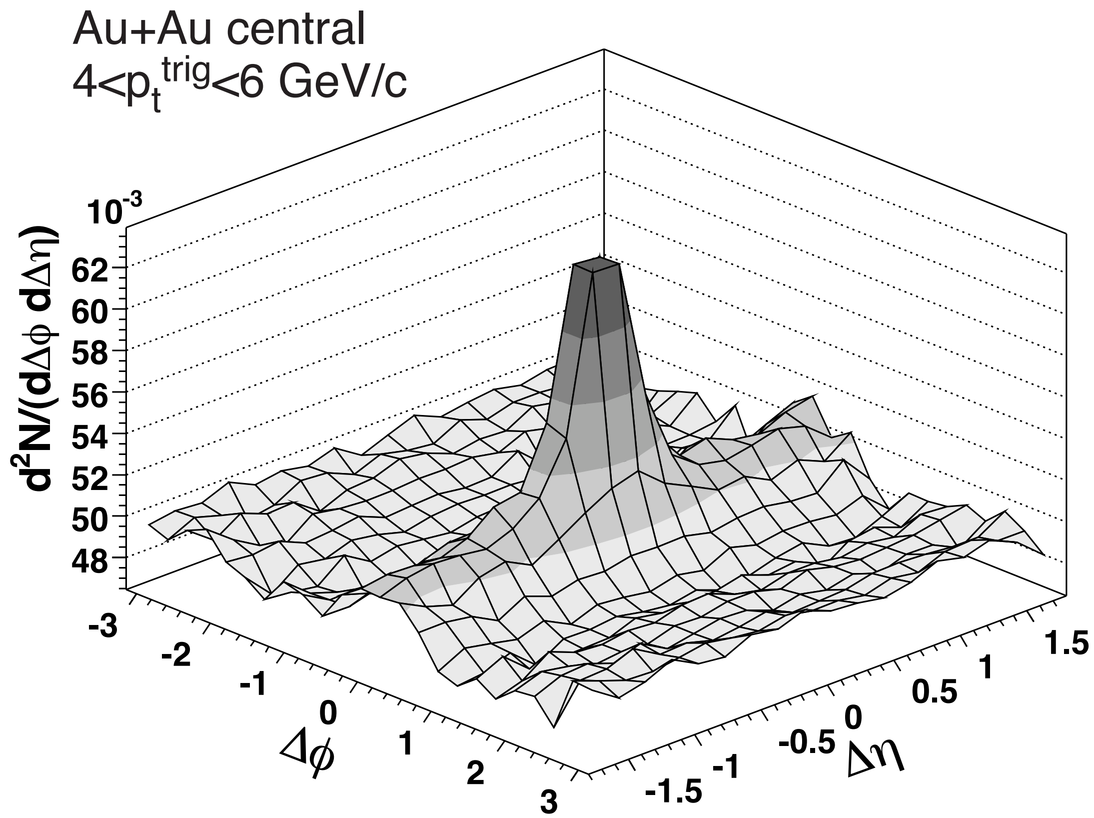

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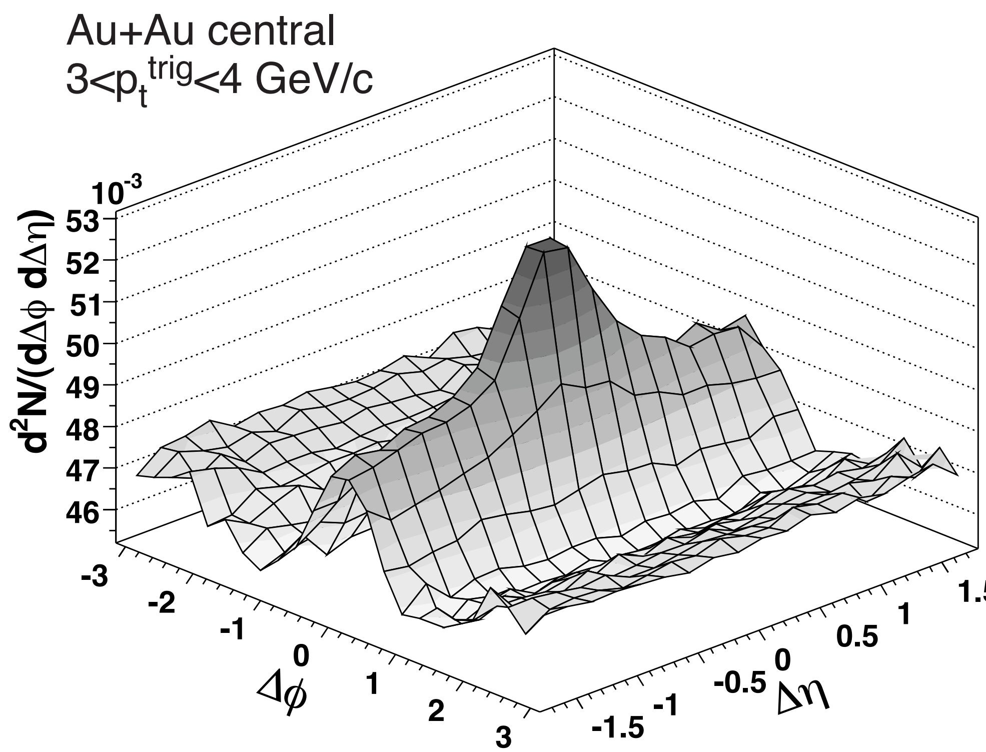

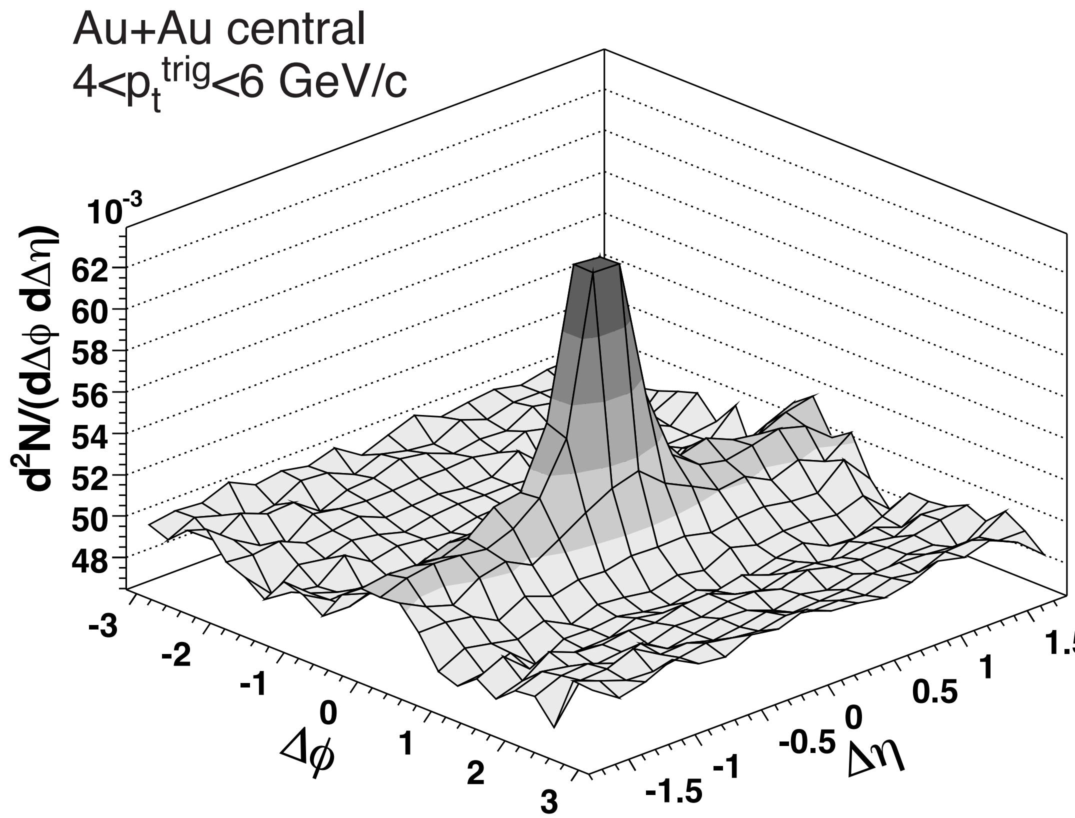

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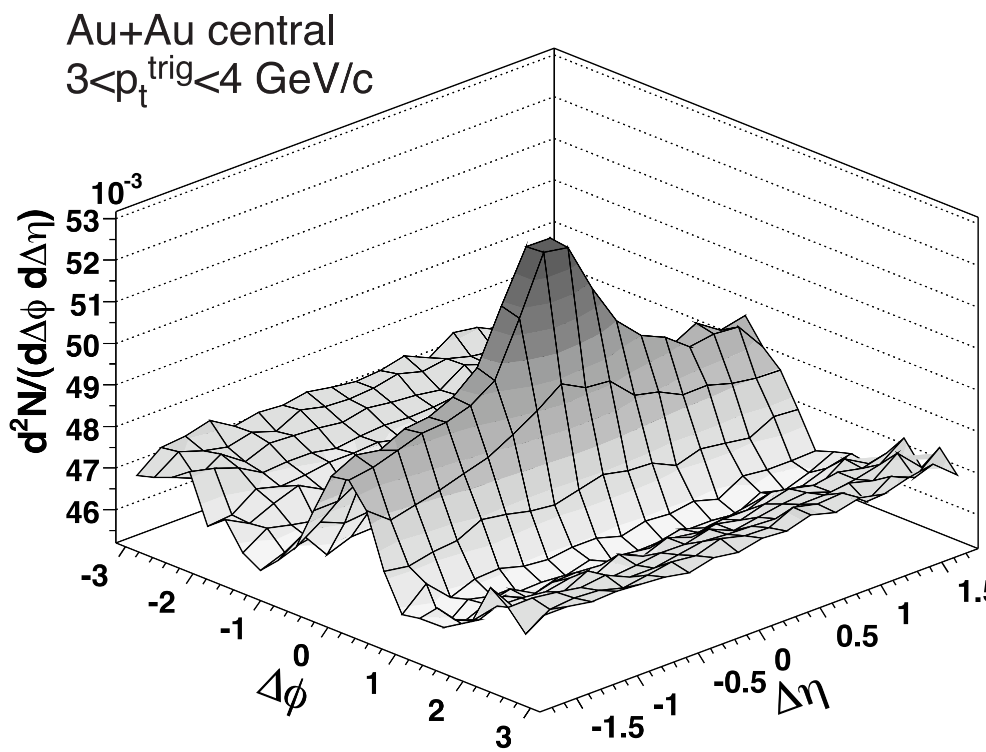

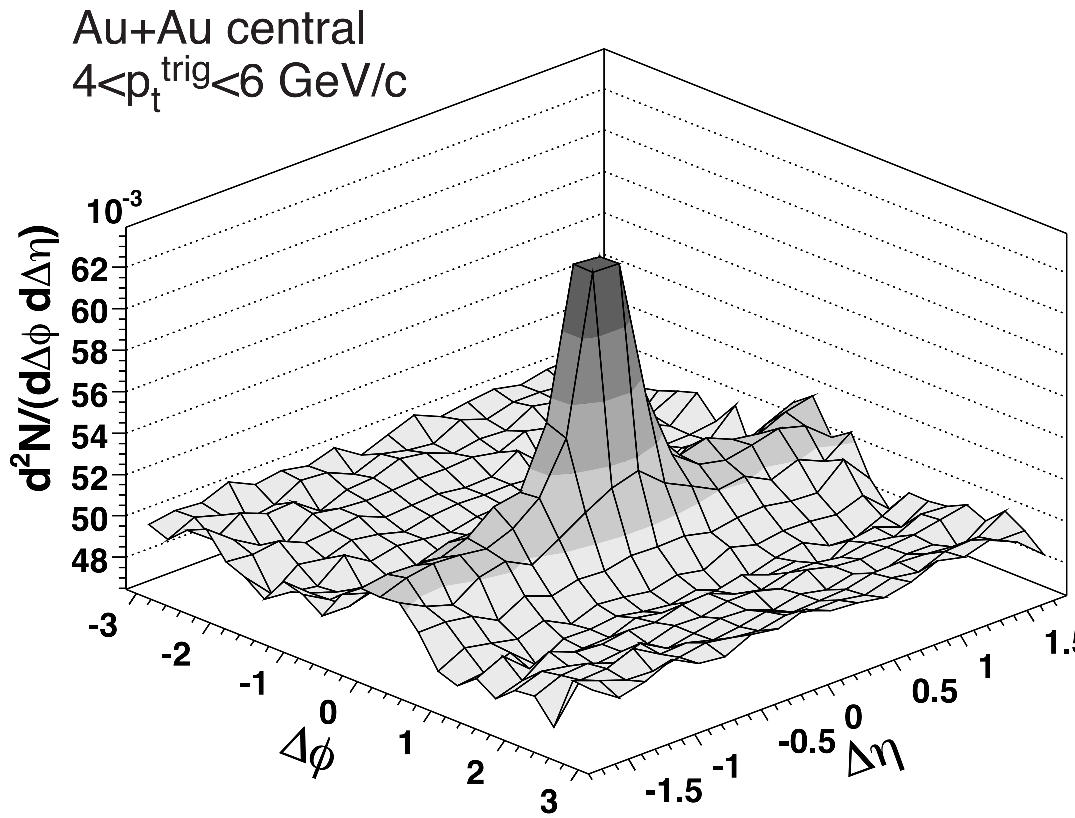

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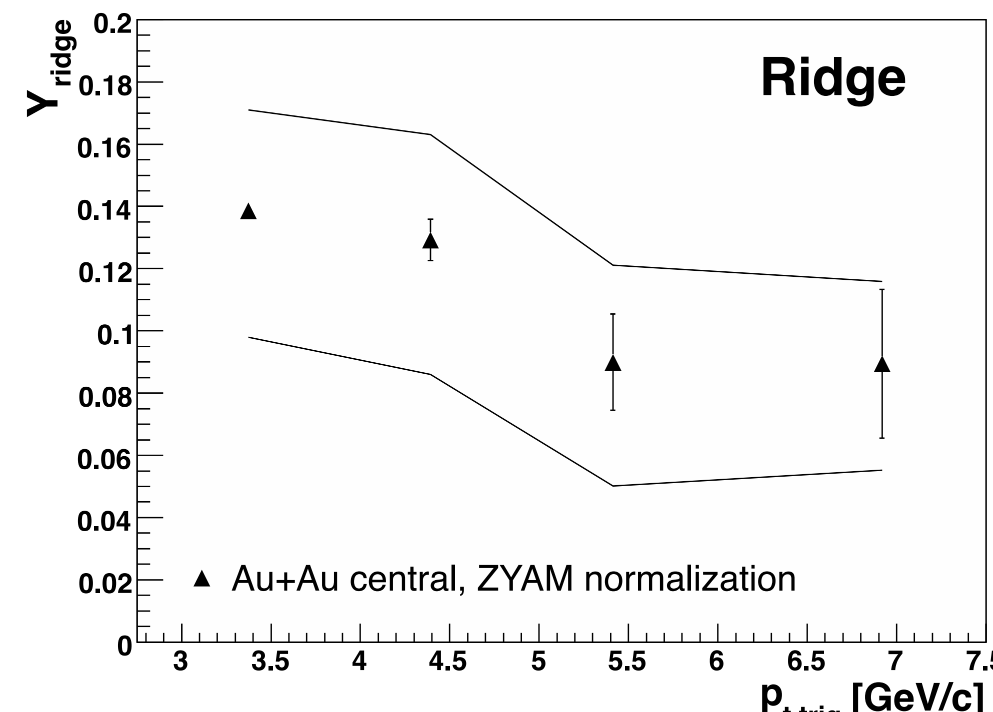

STAR PRC 064912 (2009)

ridge is WIDE

PHOBOS, PRL 104 062301 (2010)

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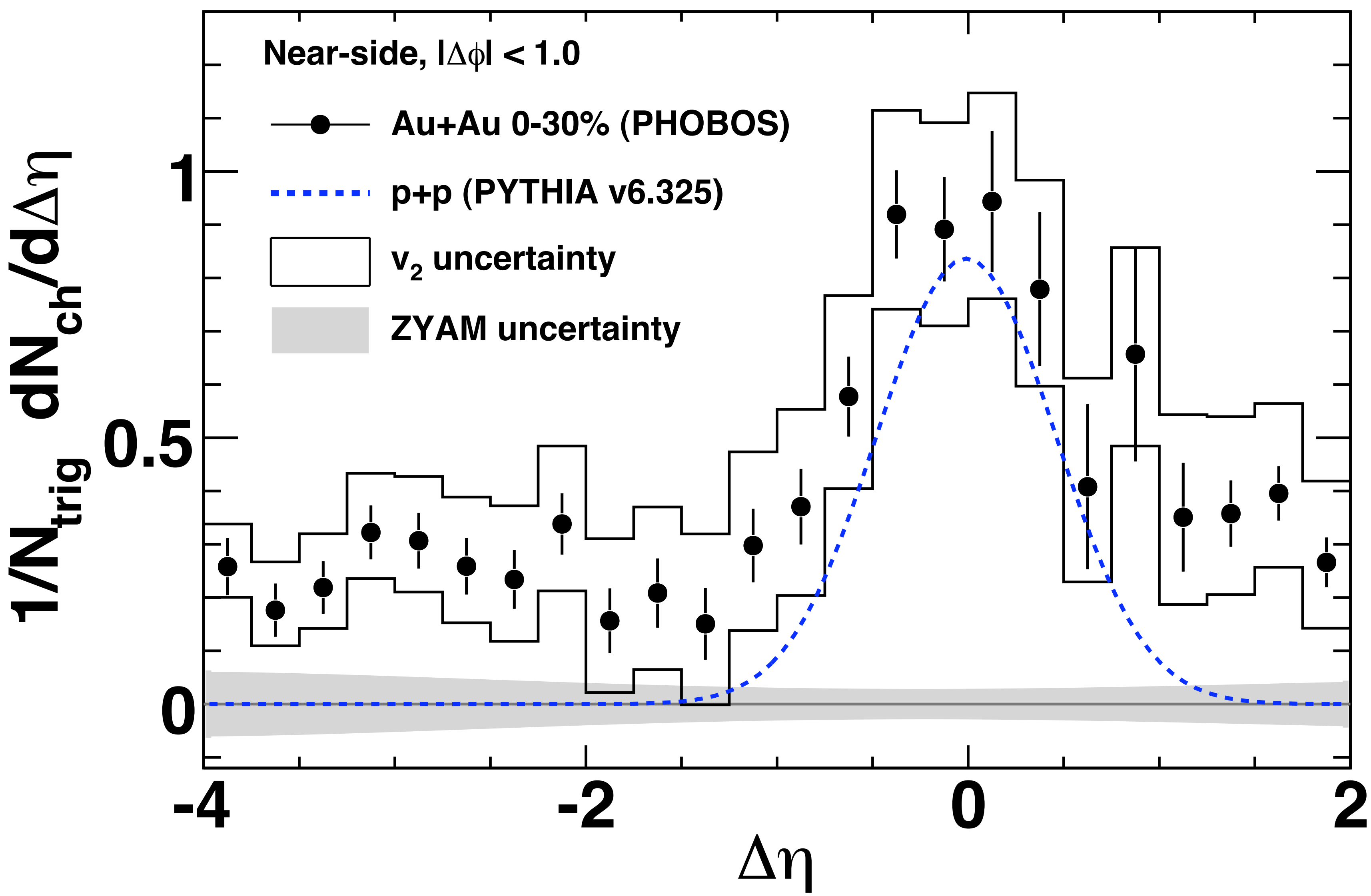

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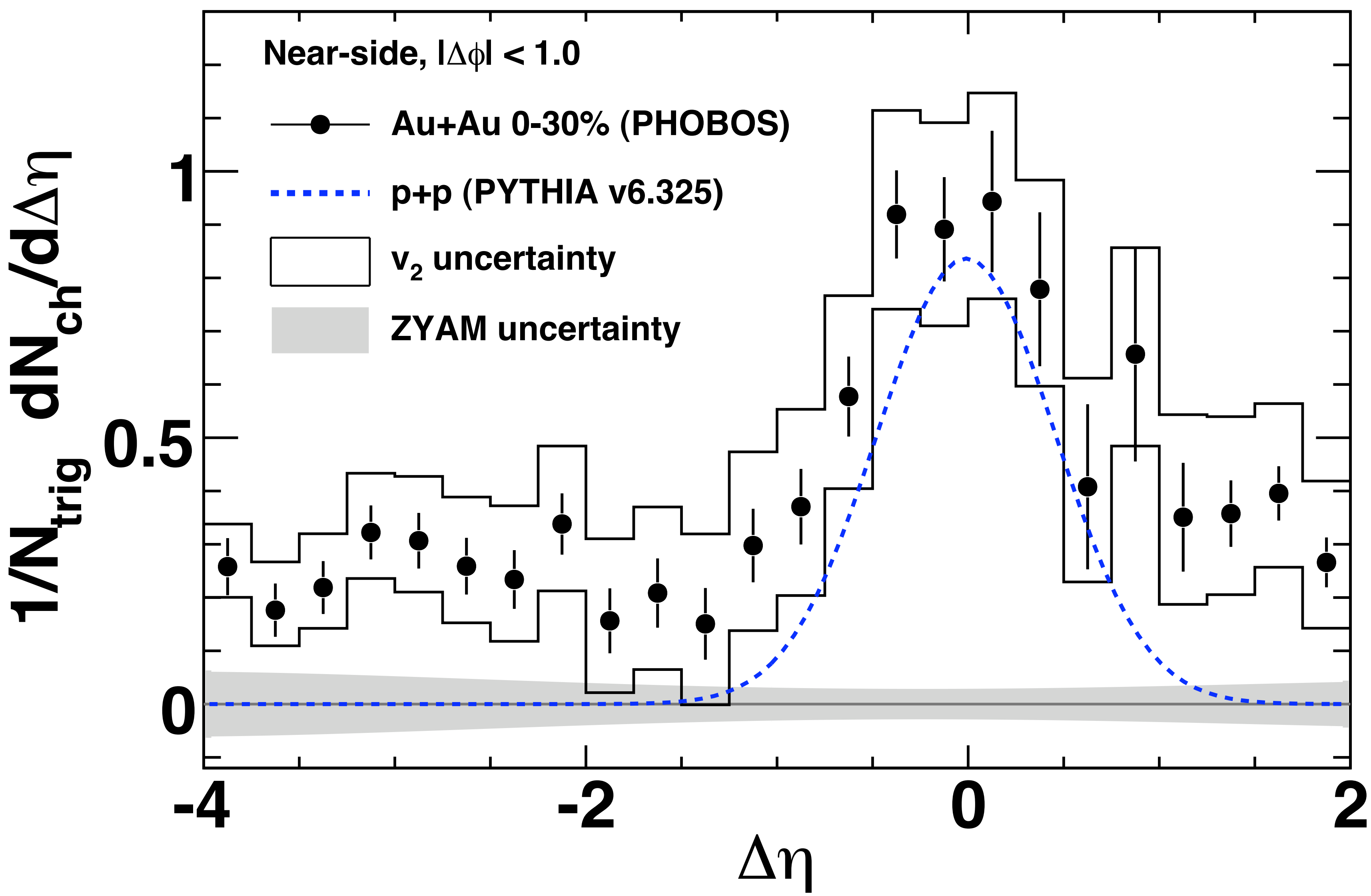

- suggests mechanisms in the initial state

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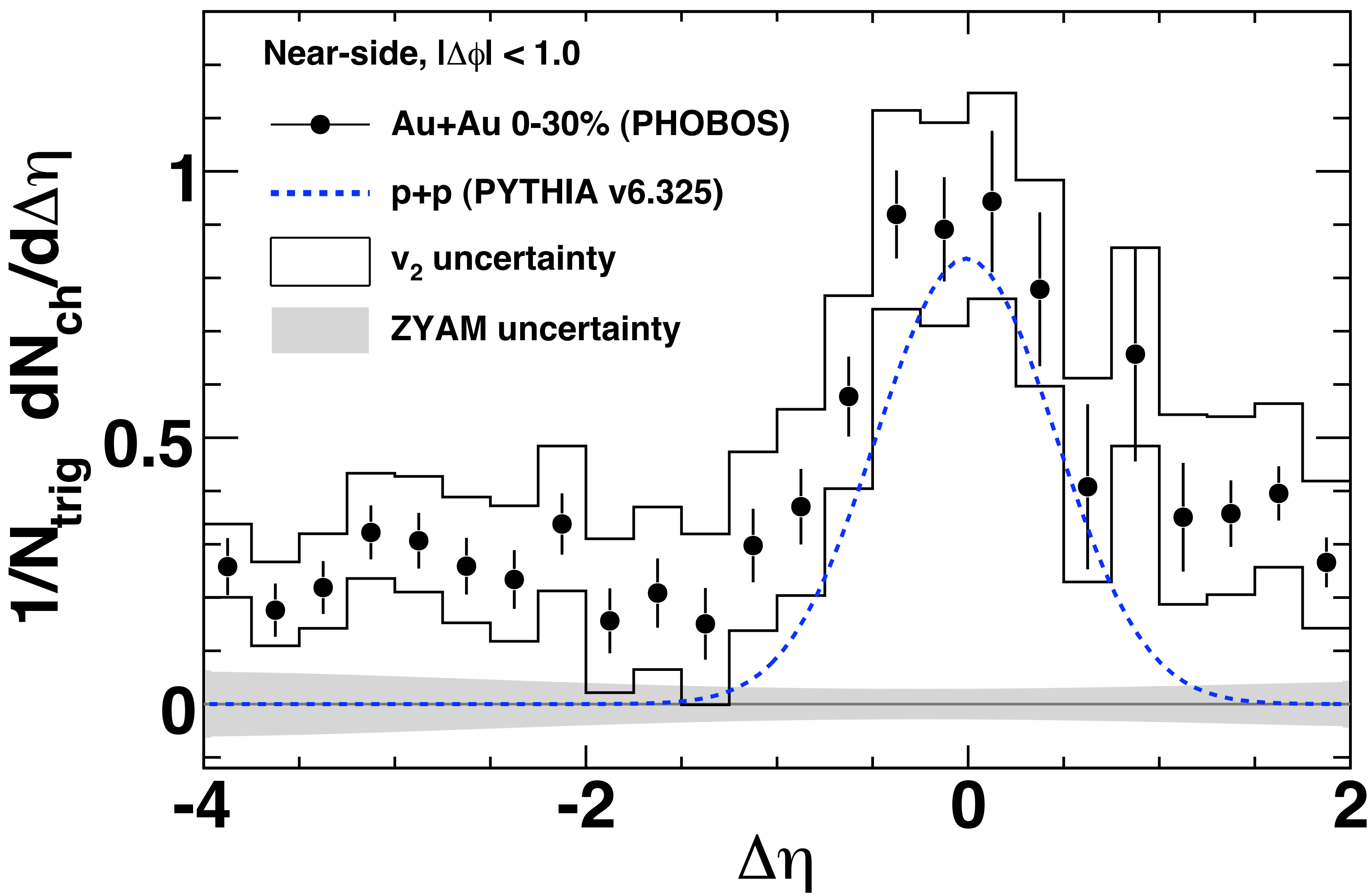
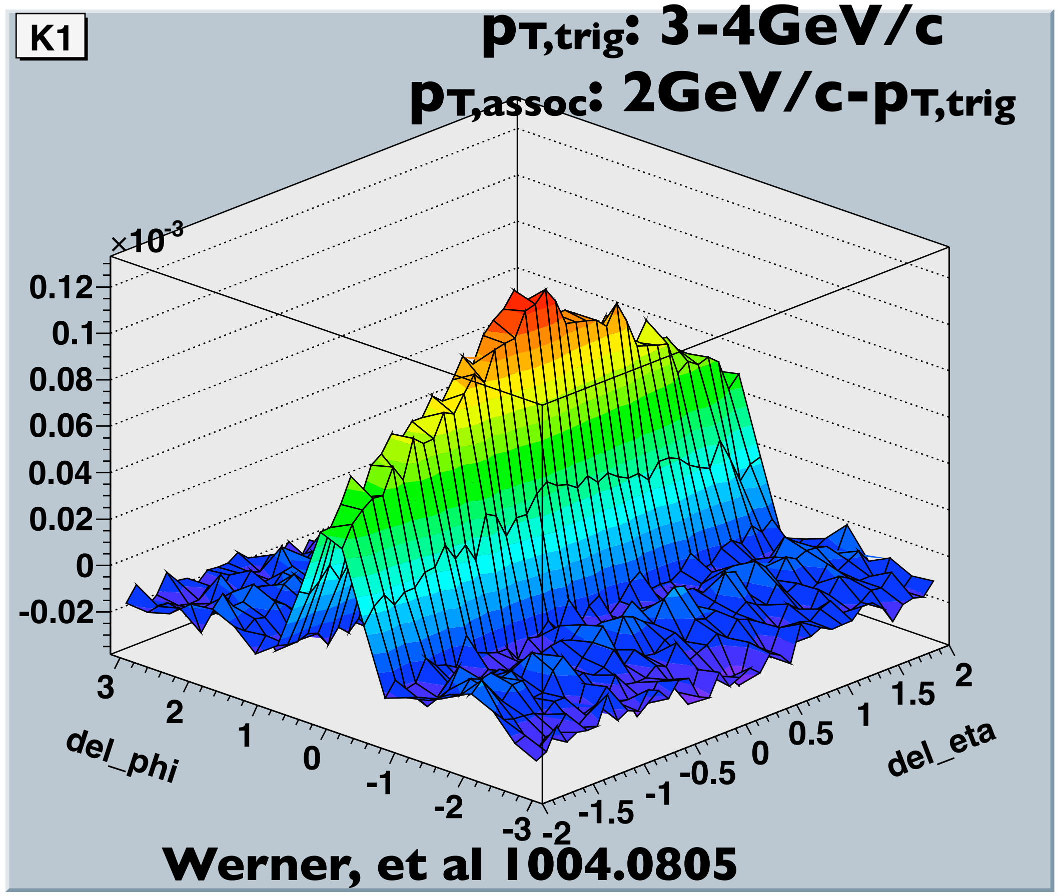


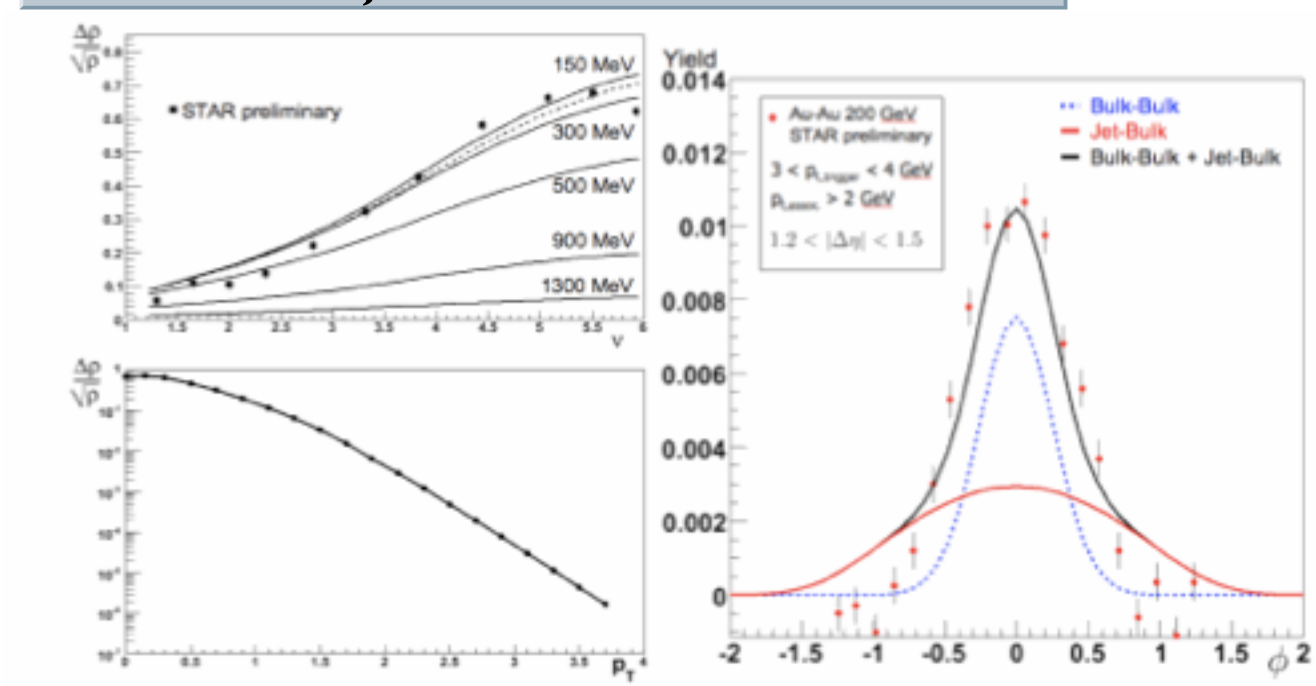
- suggests mechanisms in the initial state
- can it be directly related to the jet?

initial state related ridges



Werner, et al 1004.0805

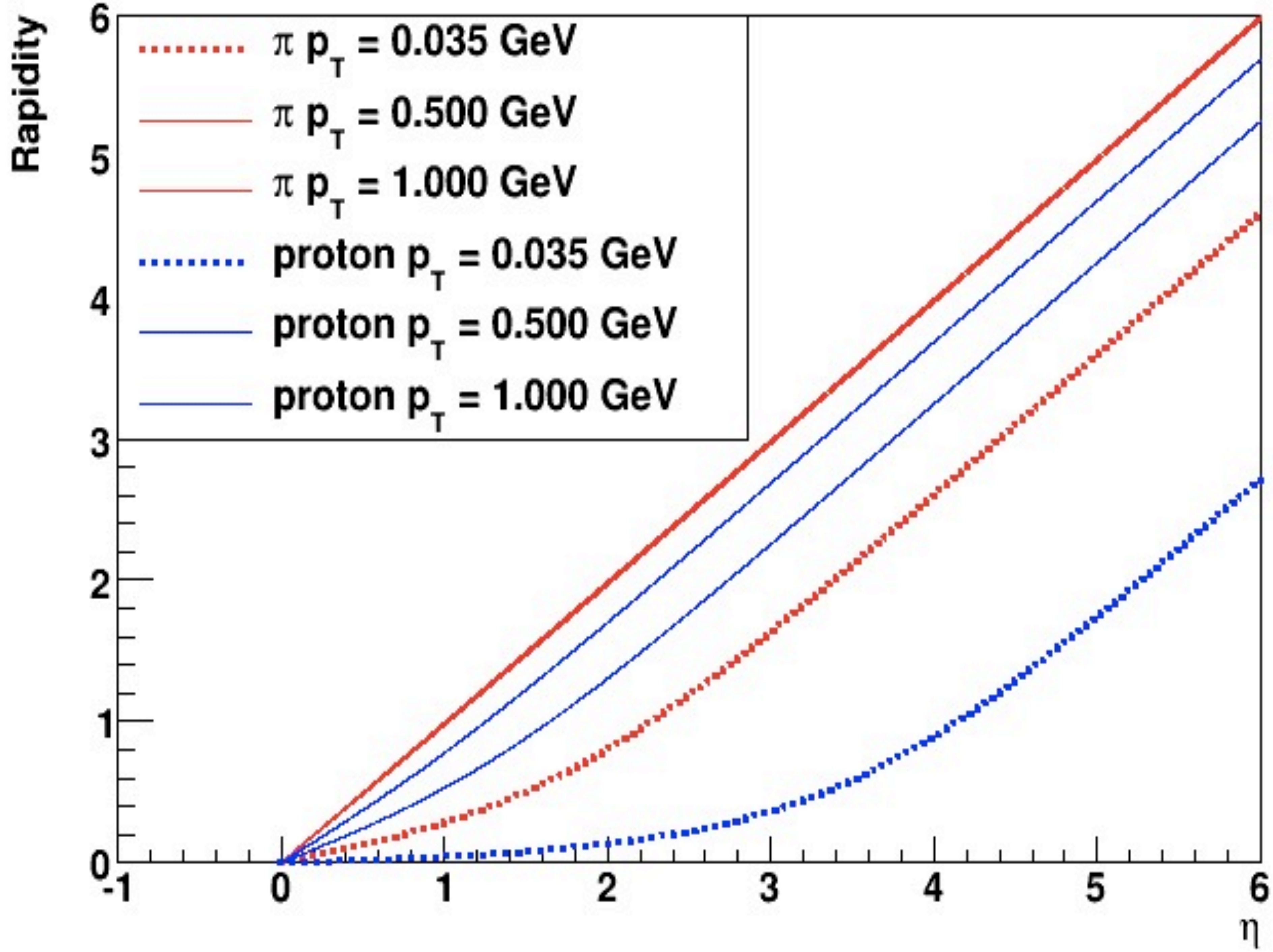
- ridge from EPOS flux tube initial conditions
- qualitatively similar to STAR measurements for hard ridge



Moschelli & Gavin NPA 830 623 (2009)

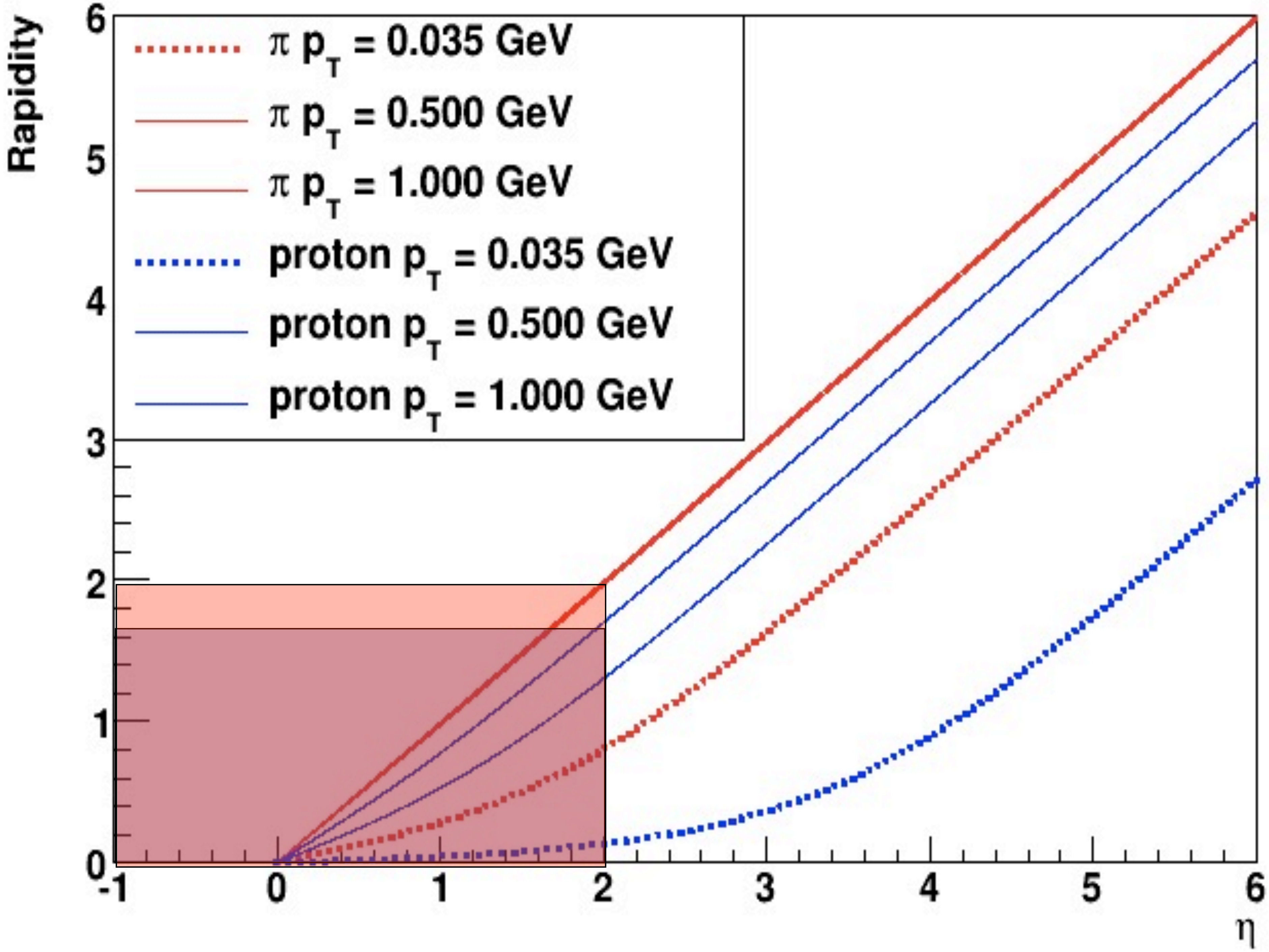
- CGC flux tubes
- reasonable agreement with hard and soft ridge

y vs. η



calculation from J. Nagle

y vs. η



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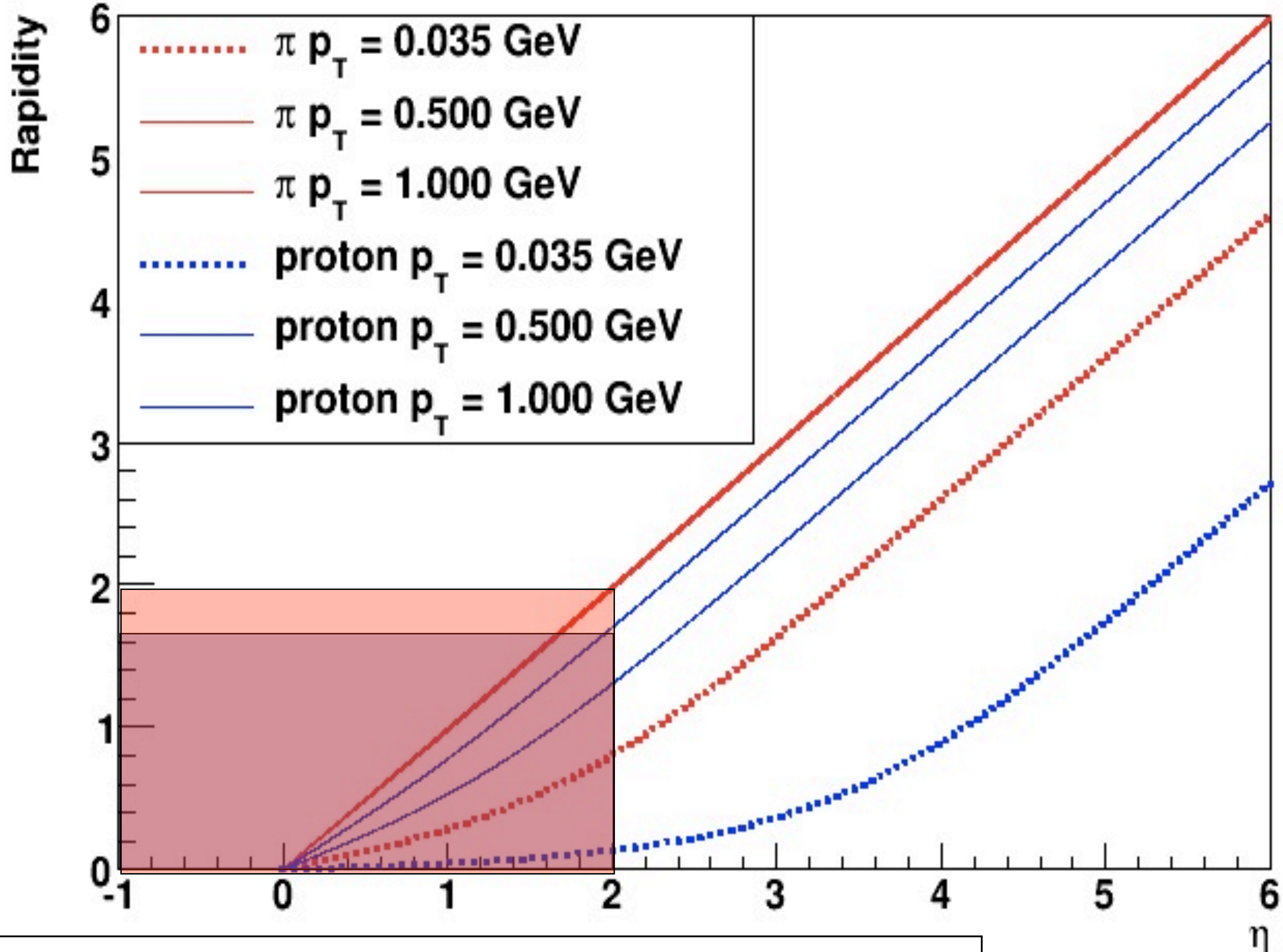
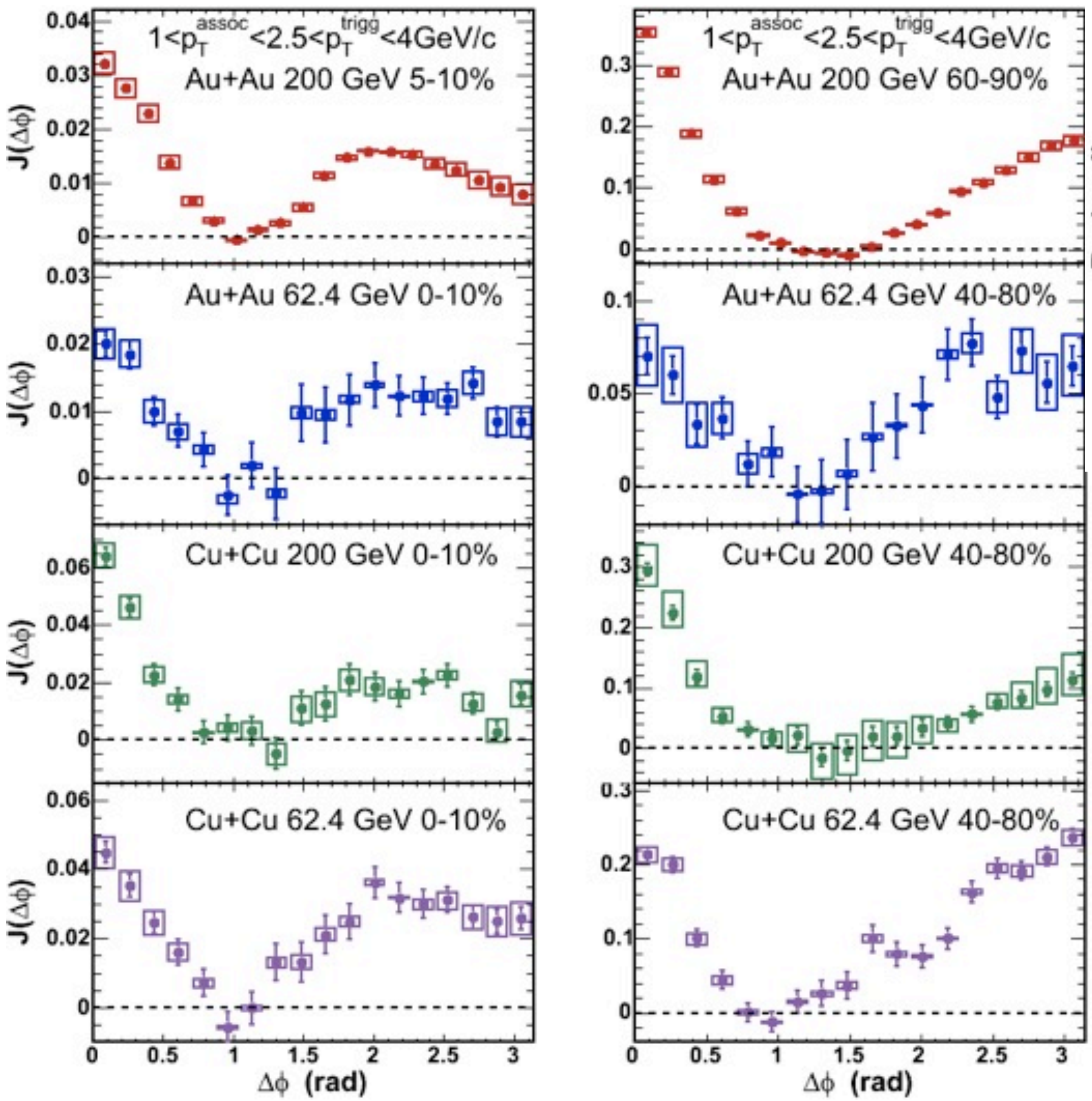
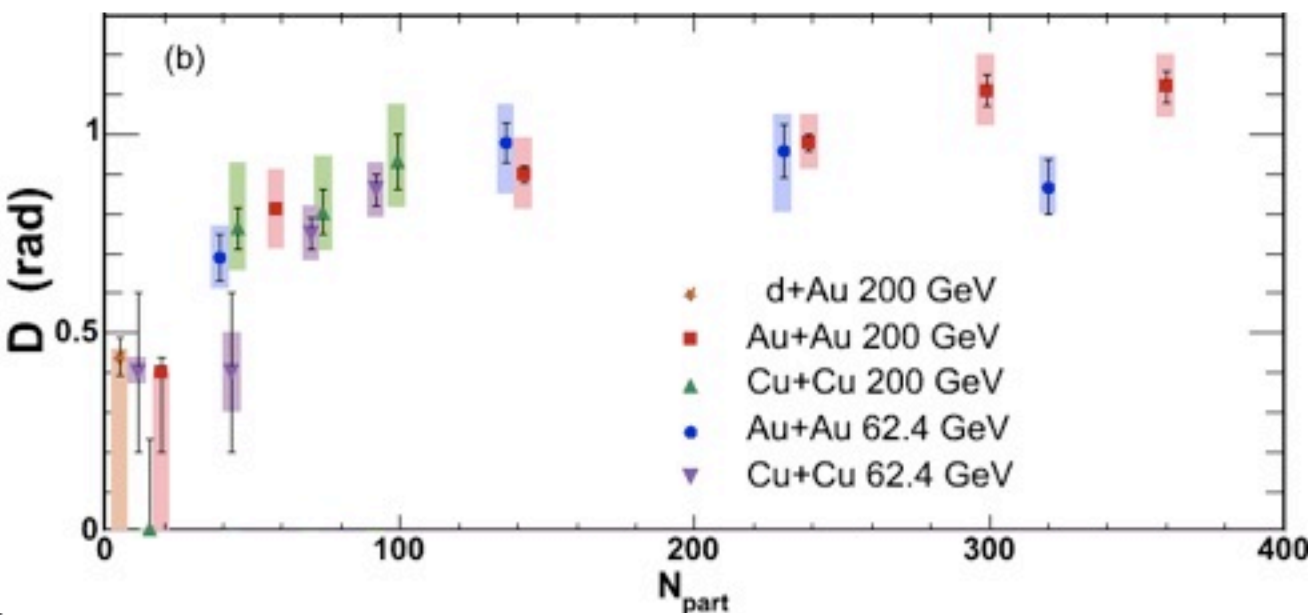


even for protons in STAR data y ~ η

calculation from J. Nagle

shoulder structure





PHENIX PRL 98 232302 (2007)

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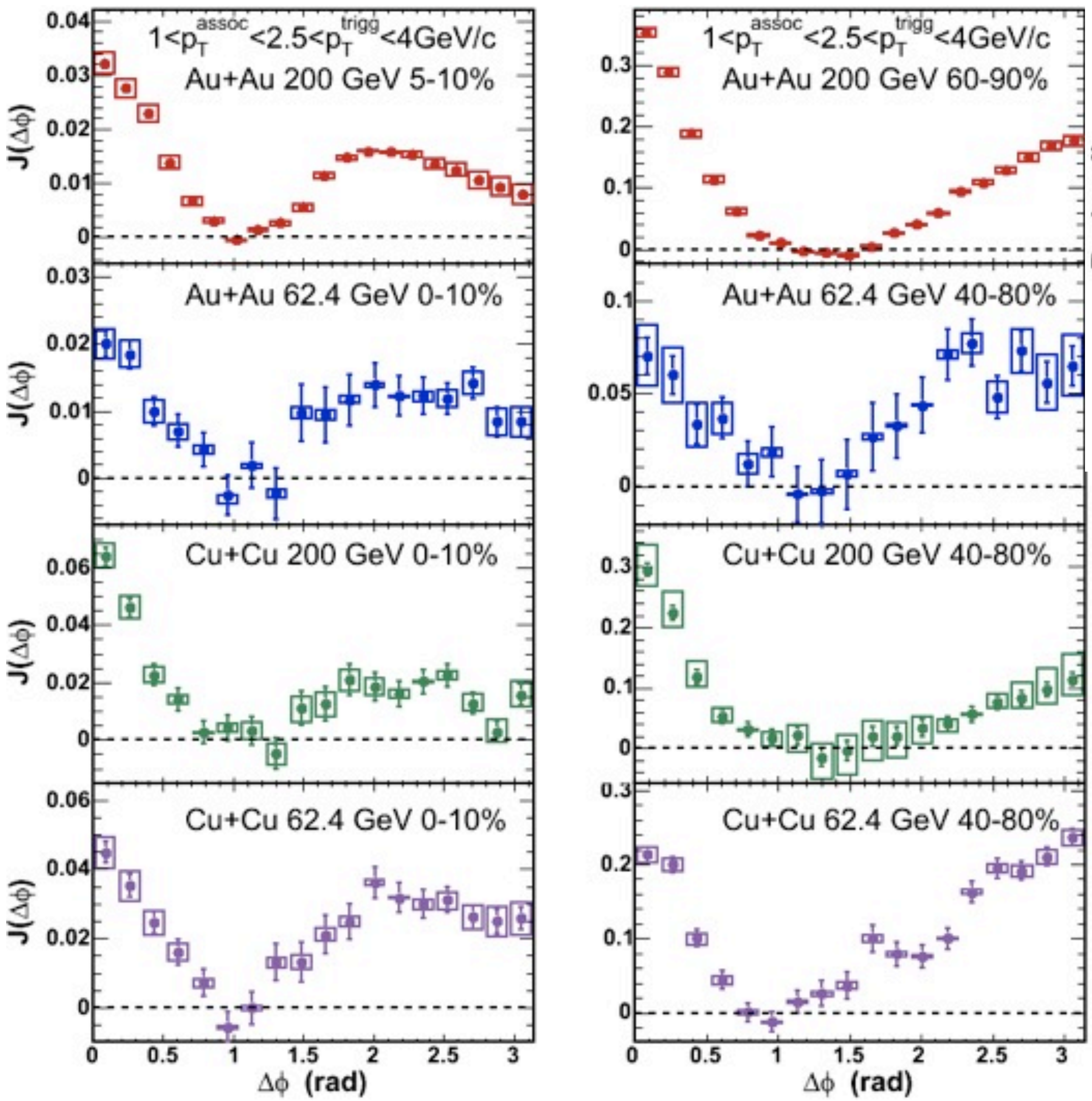

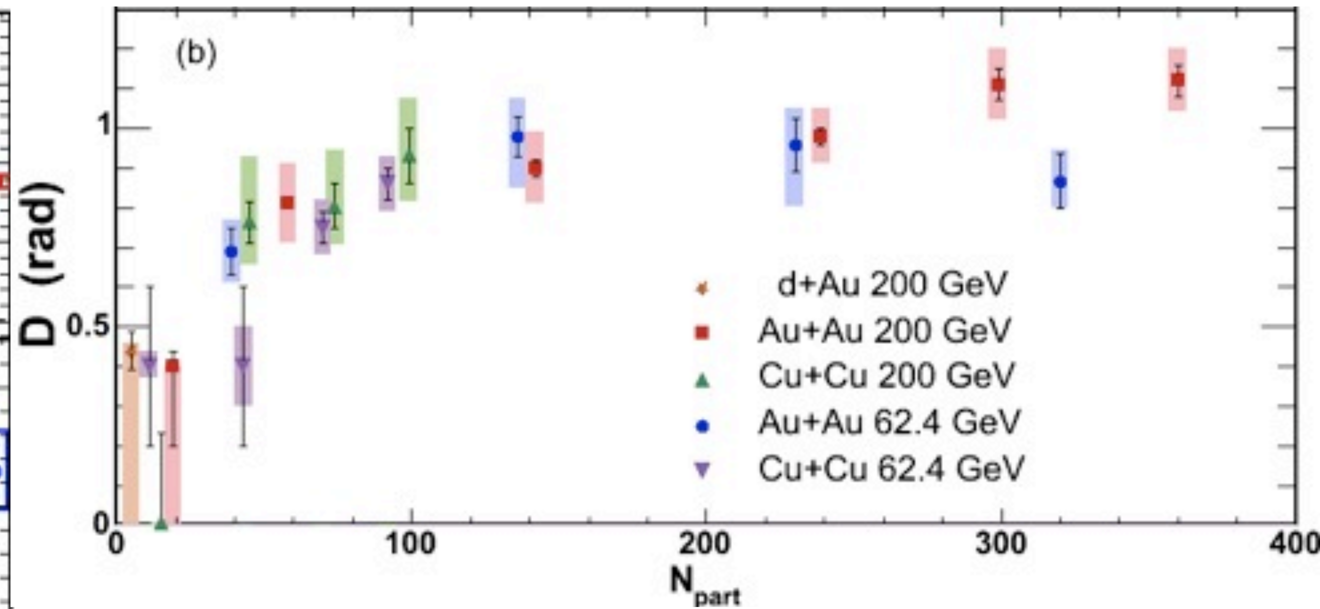

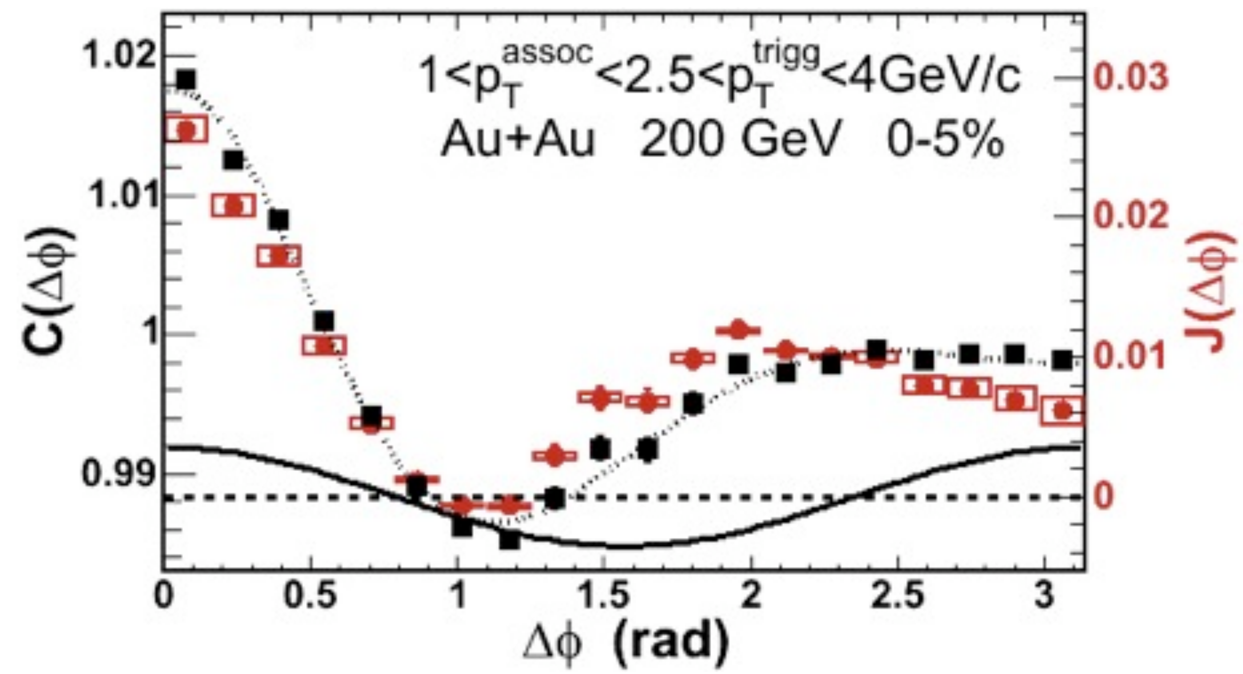

PHENIX PRL 98 232302 (2007)

mock-Mach Cones!

Pb-Au 17.3 GeV 0-5%

CERES Preliminary

Takahashi et al, PRL 103 242301 (2009)

Li et al, PRC 80 064913 (2009)

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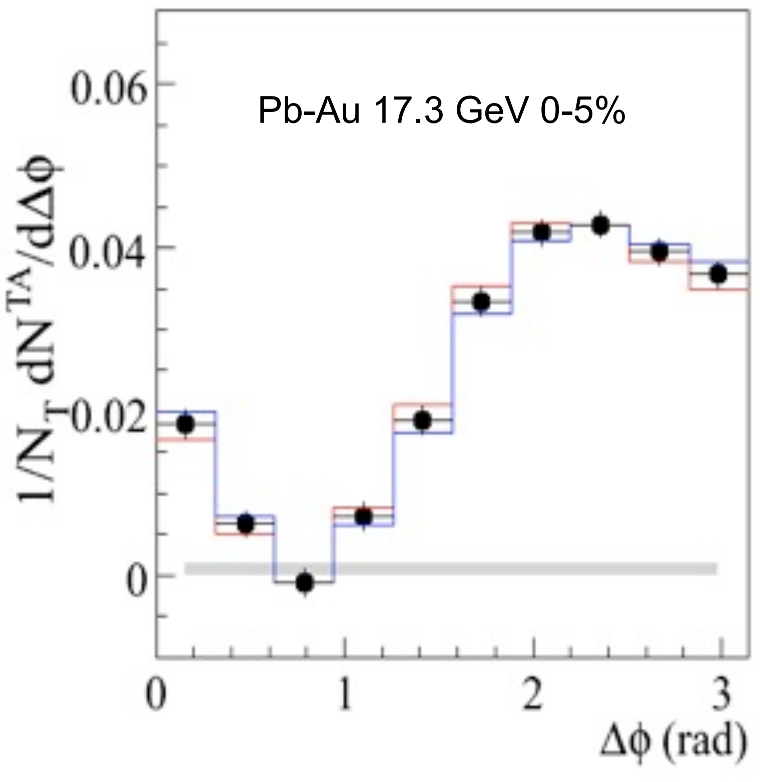

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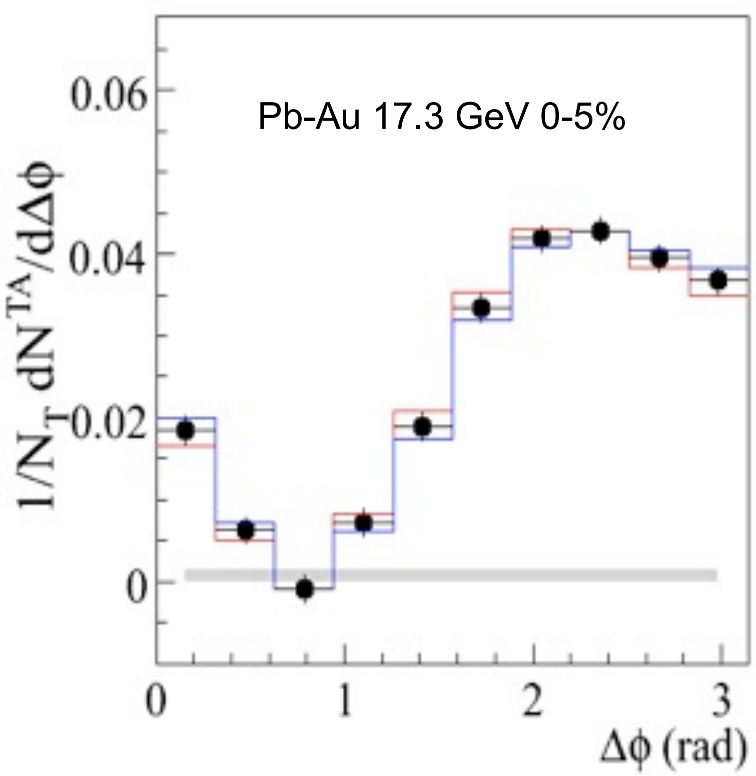

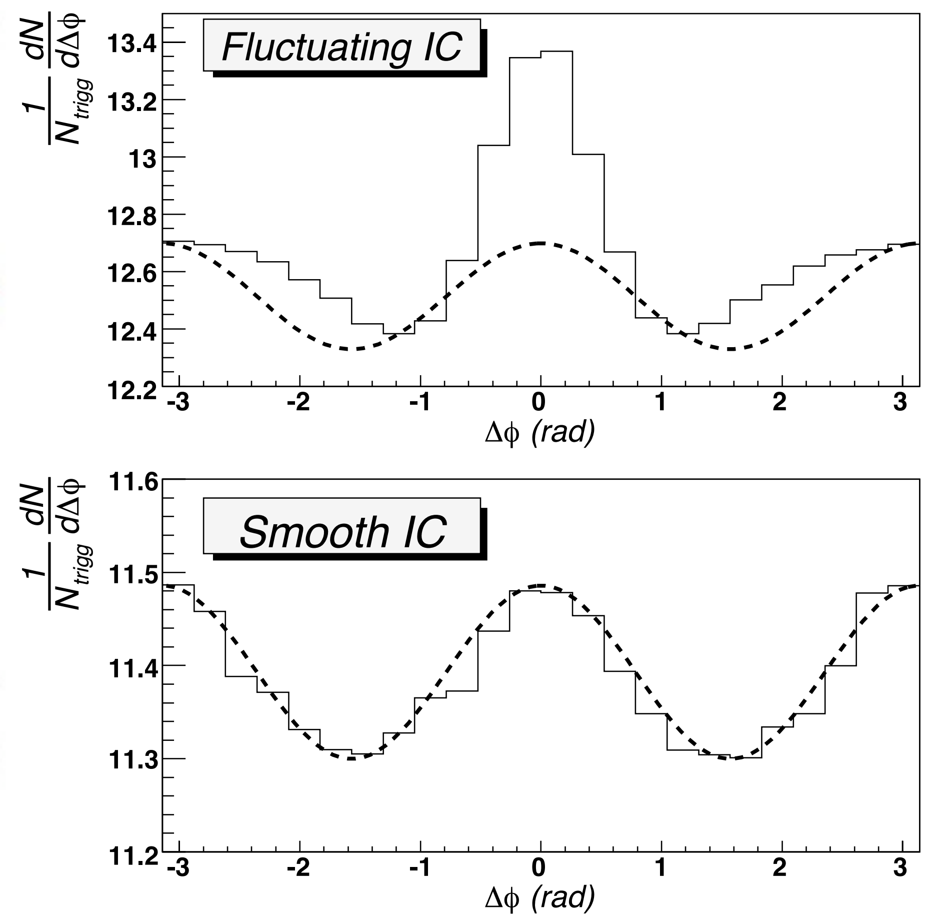

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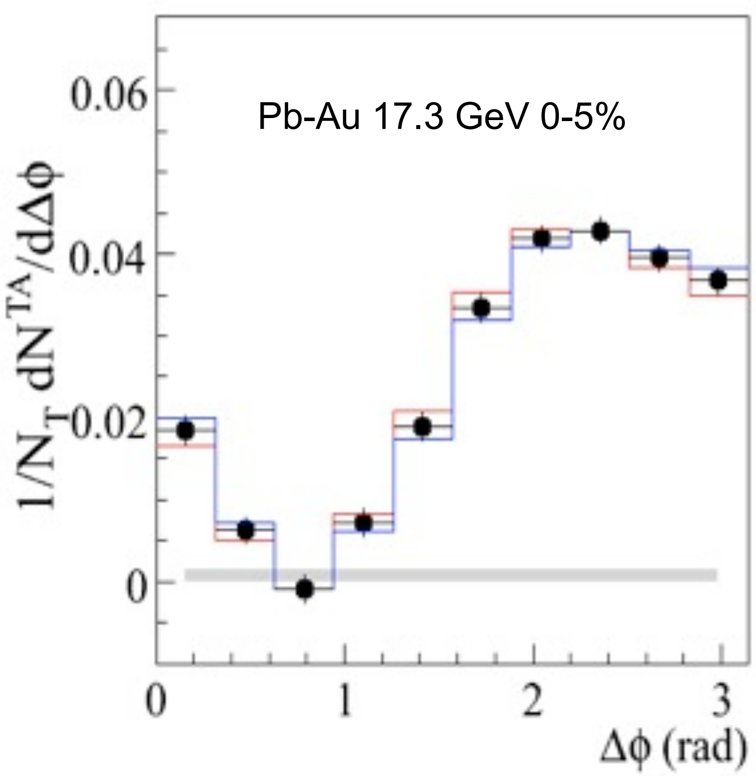
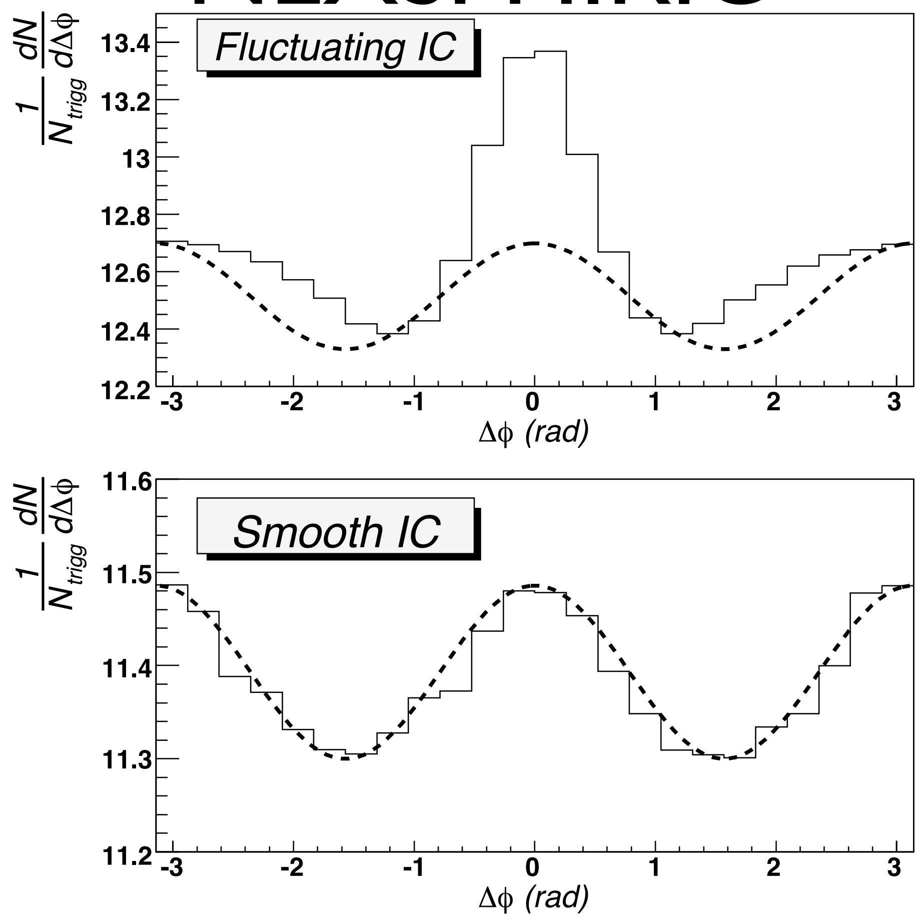


NEXSPHIRIO



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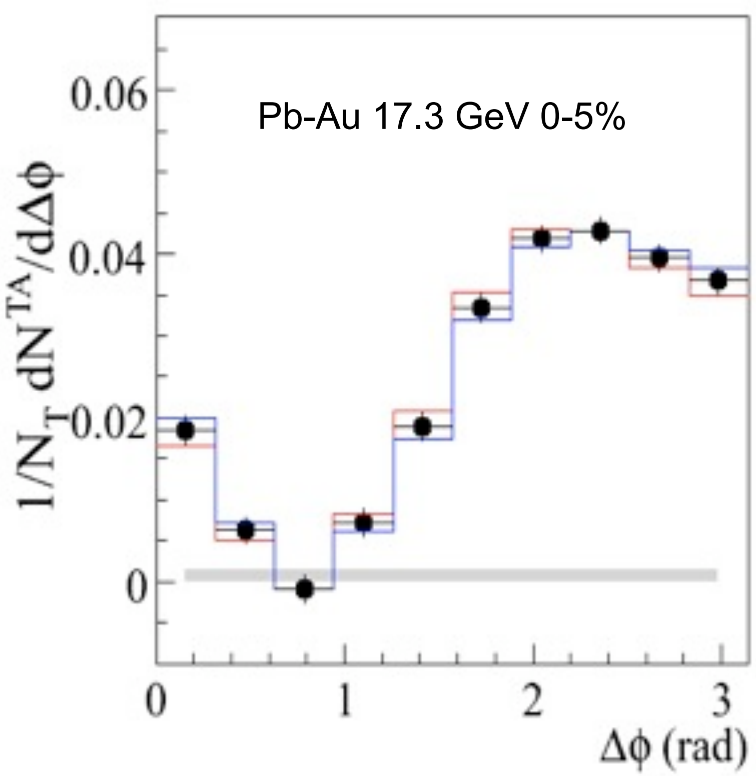

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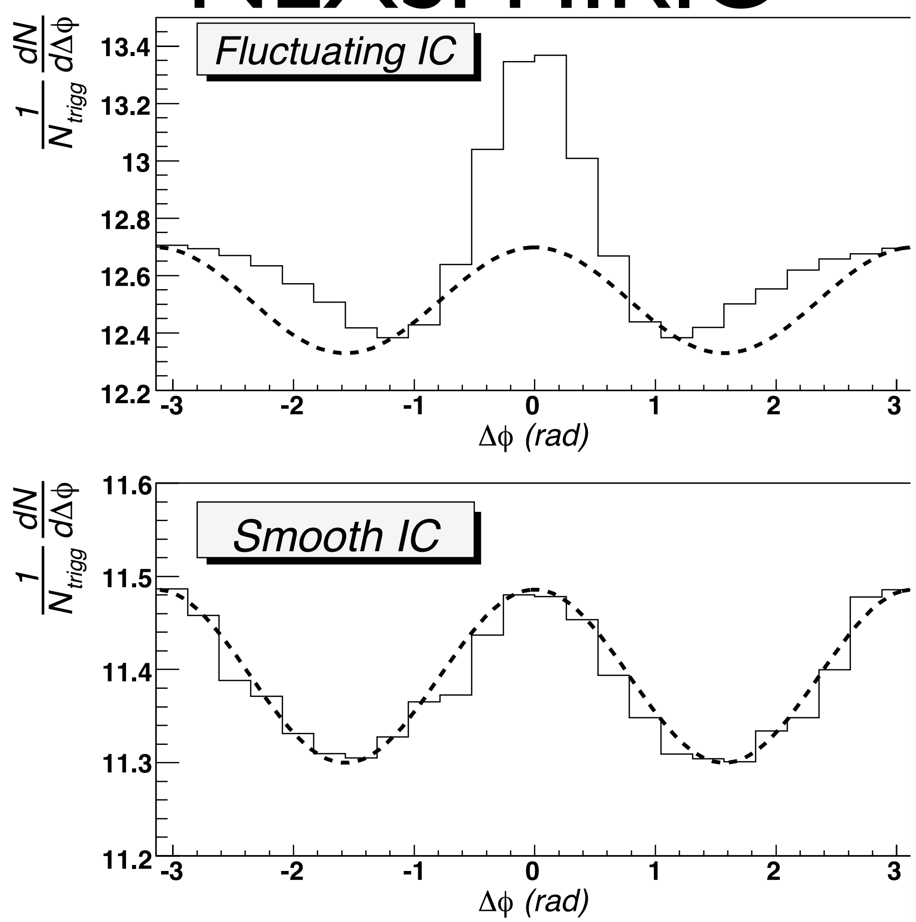
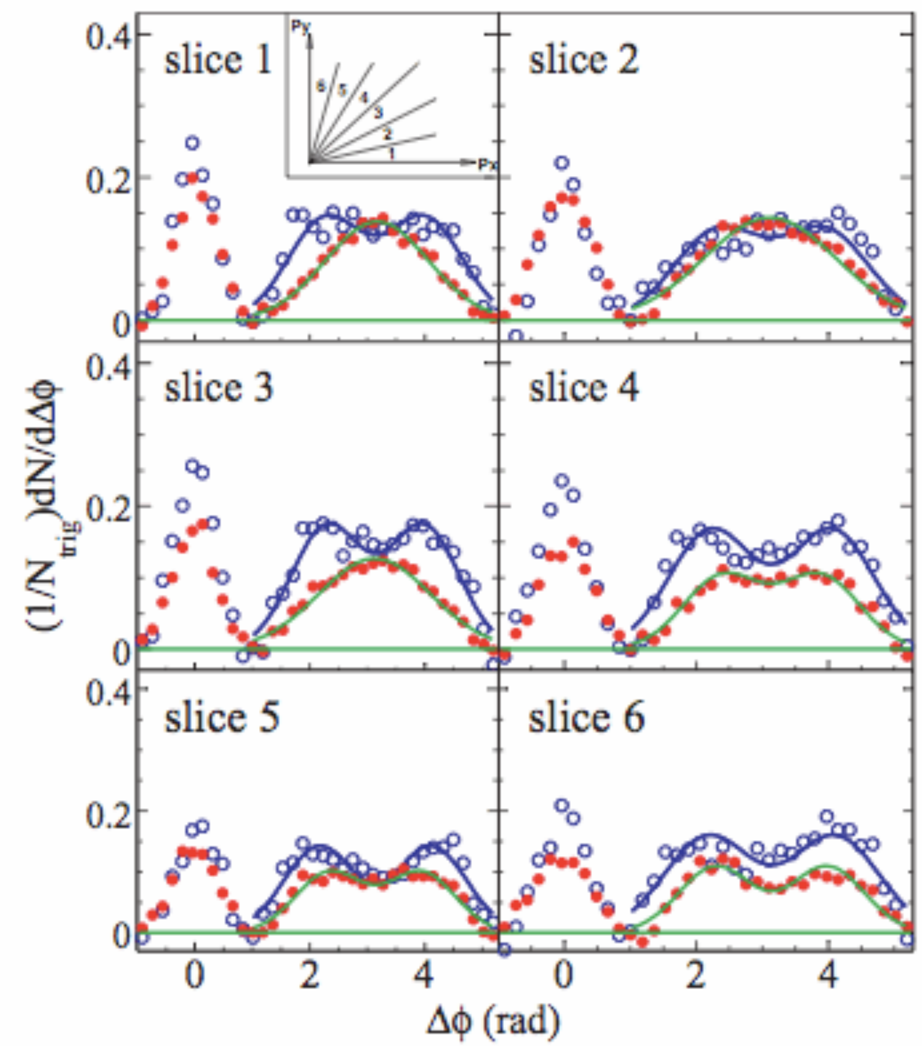


AMPT



0-10%
20-60%
p_{Ttrig}: 2.5-6GeV/c
$p_{T,assoc}$: 0.15-3GeV/c

CERES Preliminary

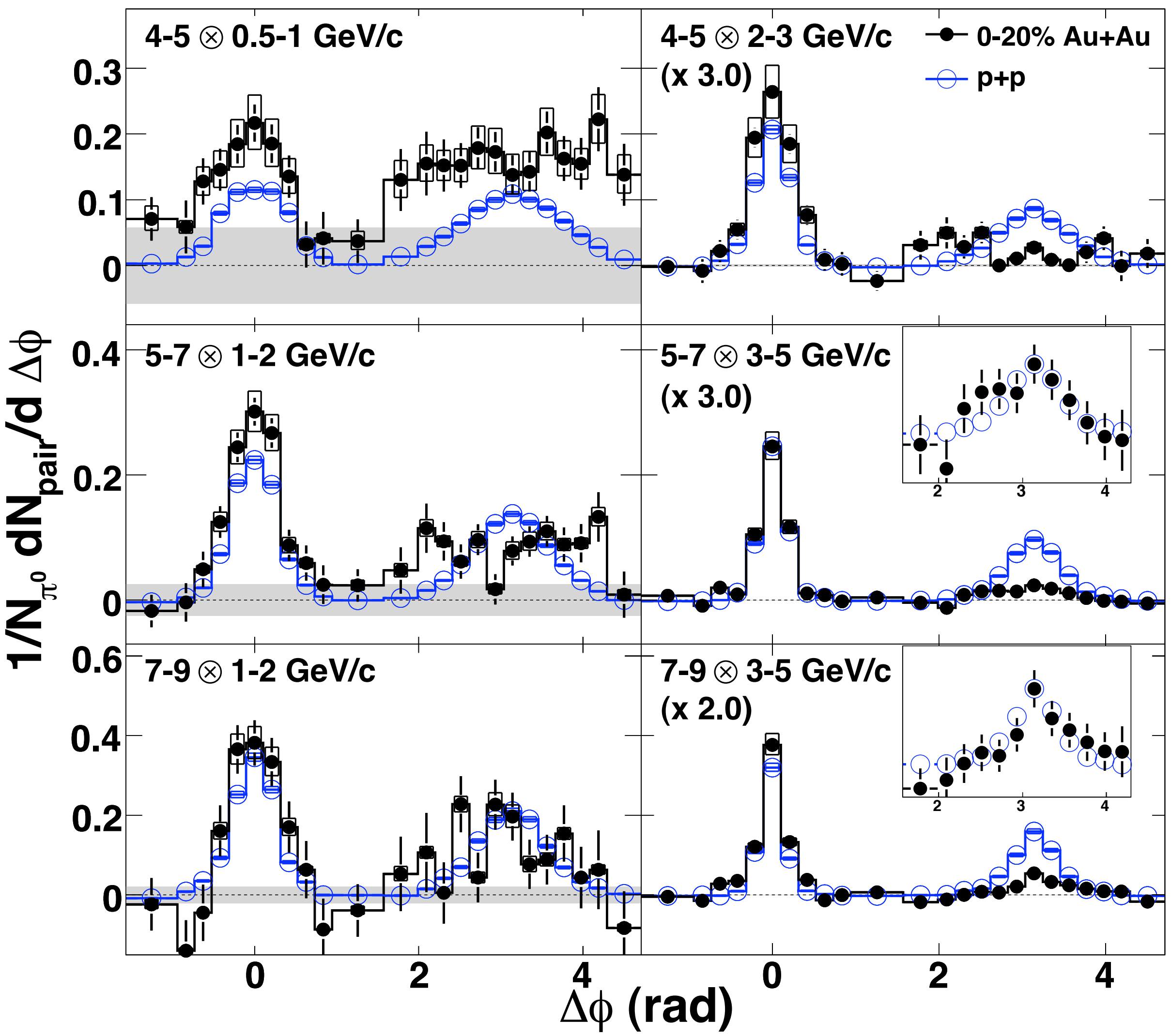
Takahashi et al, PRL 103 242301 (2009)

Li et al, PRC 80 064913 (2009)

diminishing

PHENIX arXiv:1002.1077

diminishing



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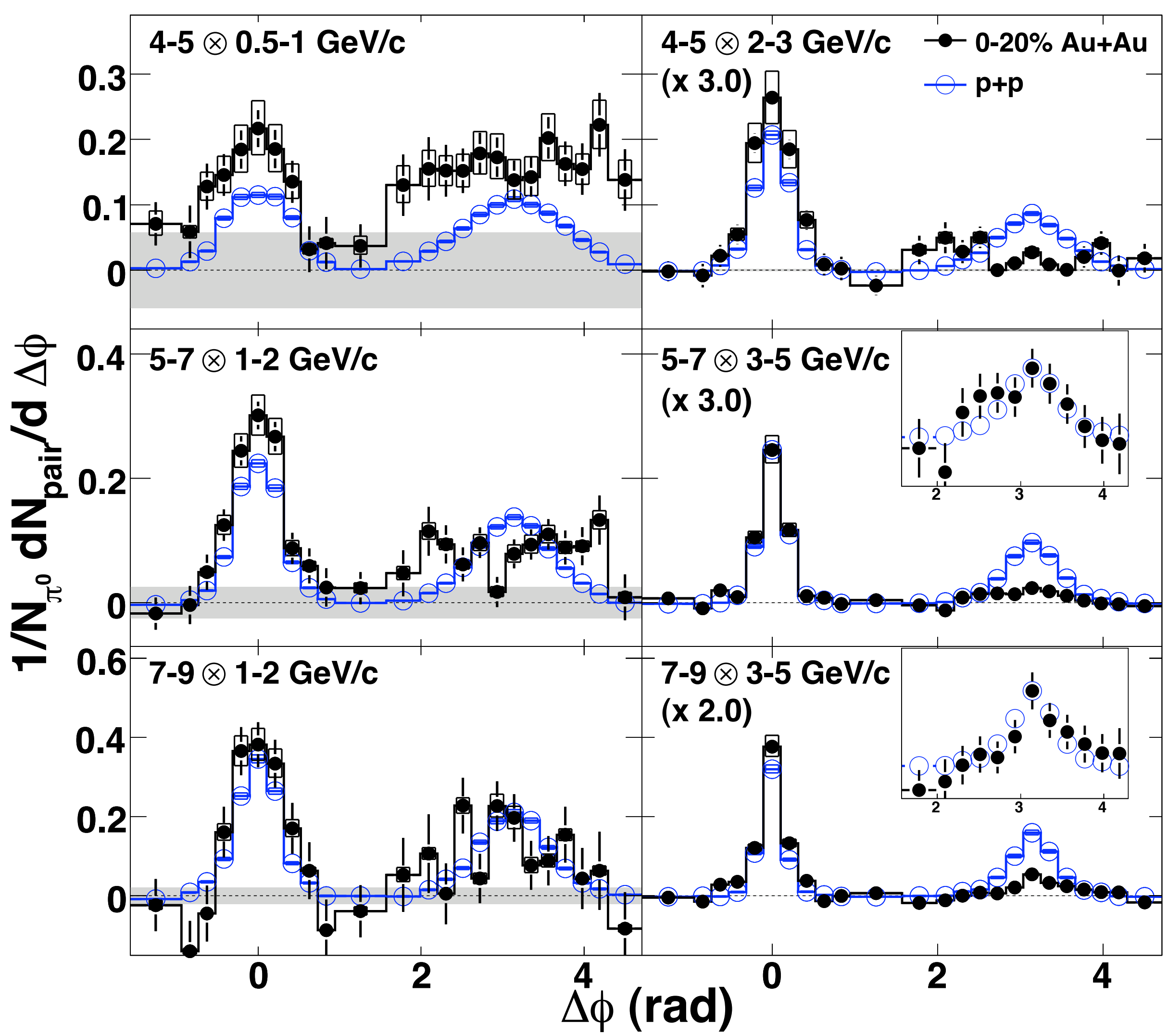

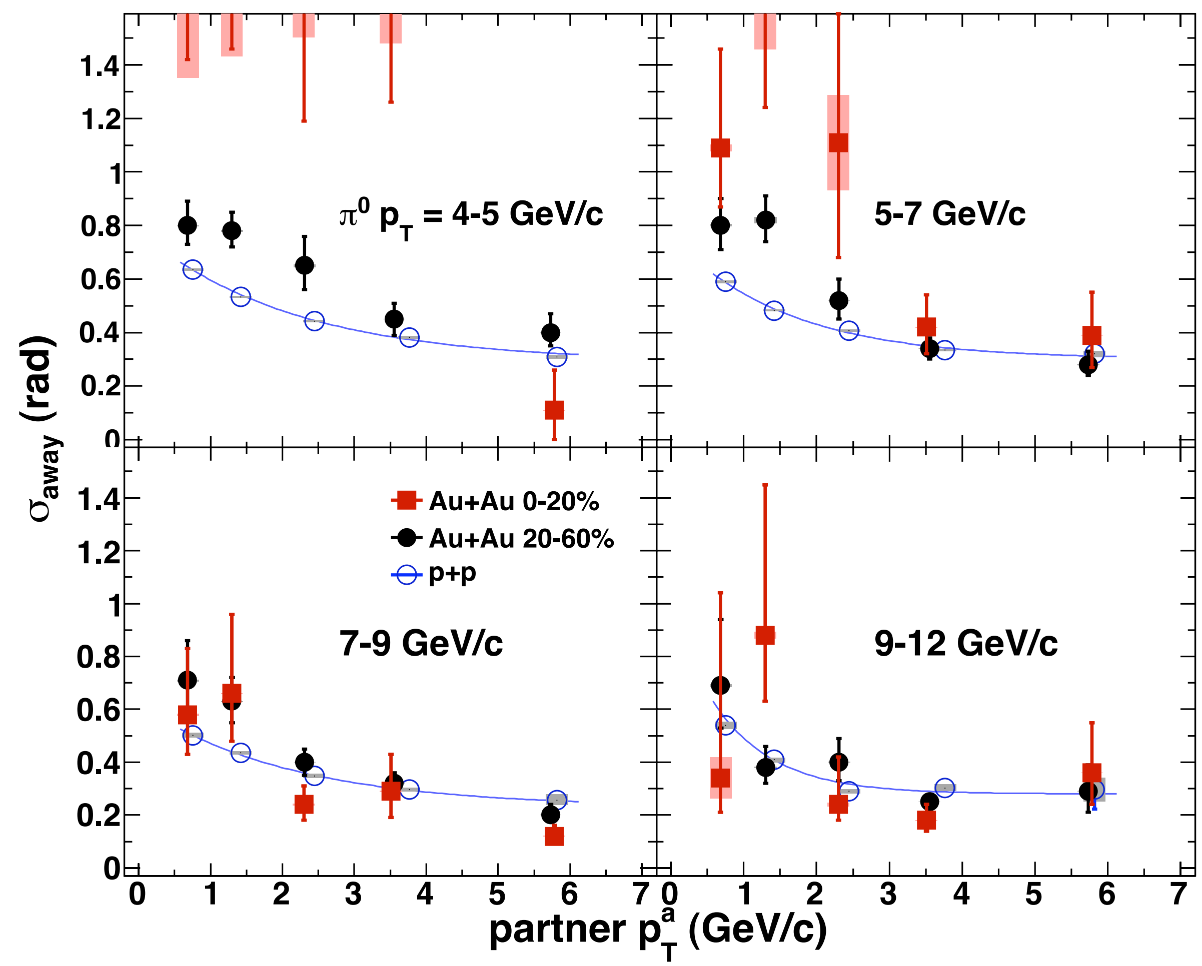

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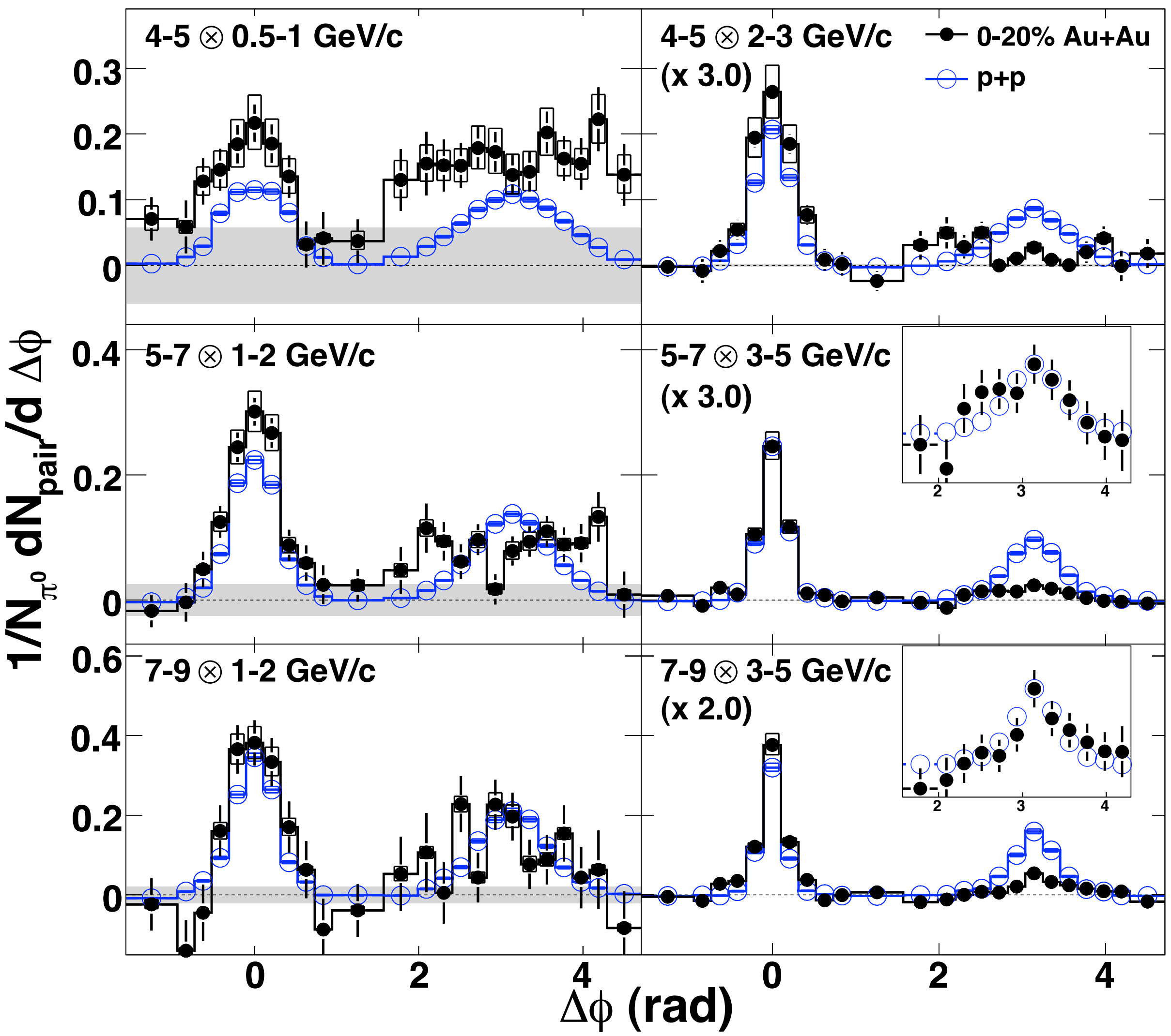
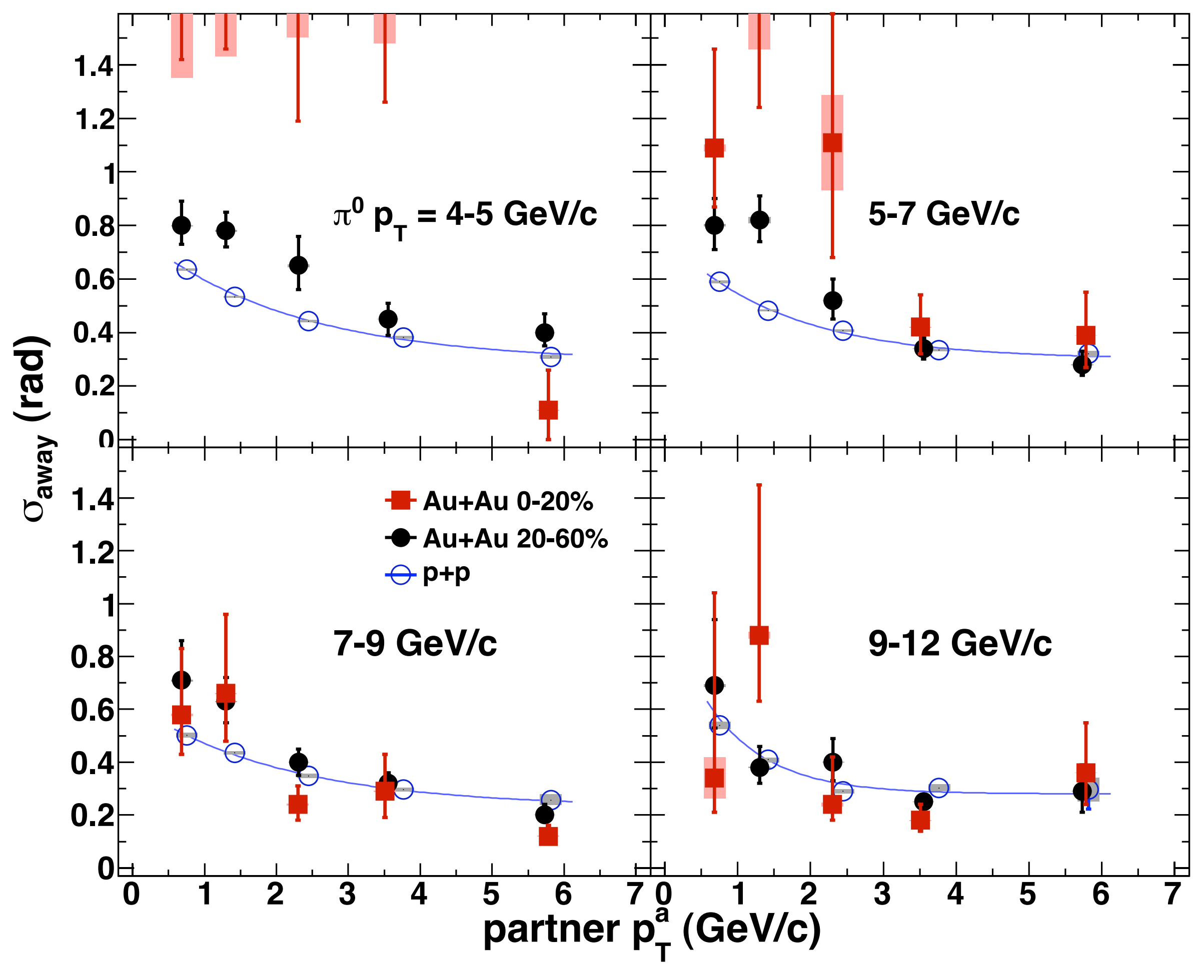
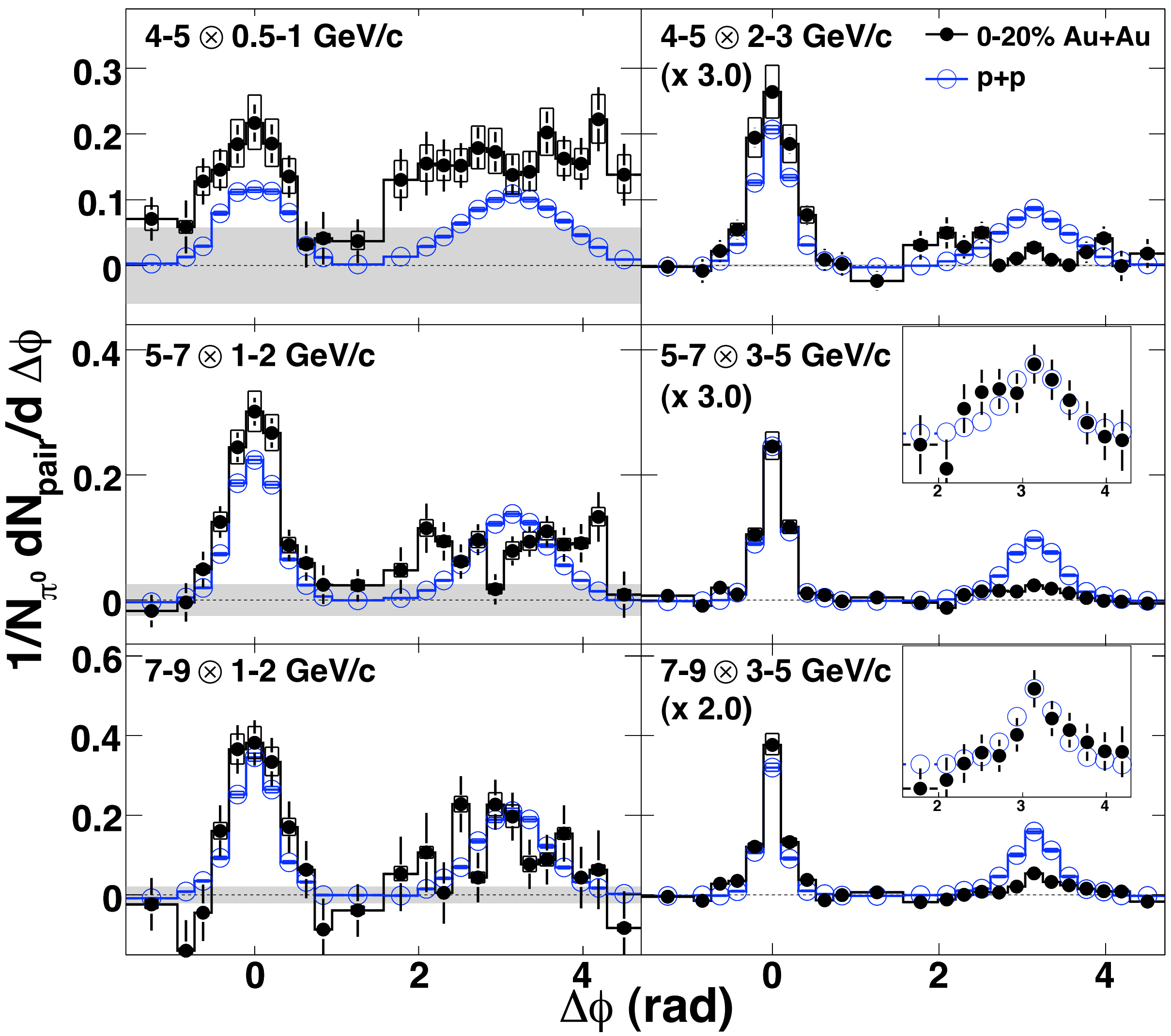


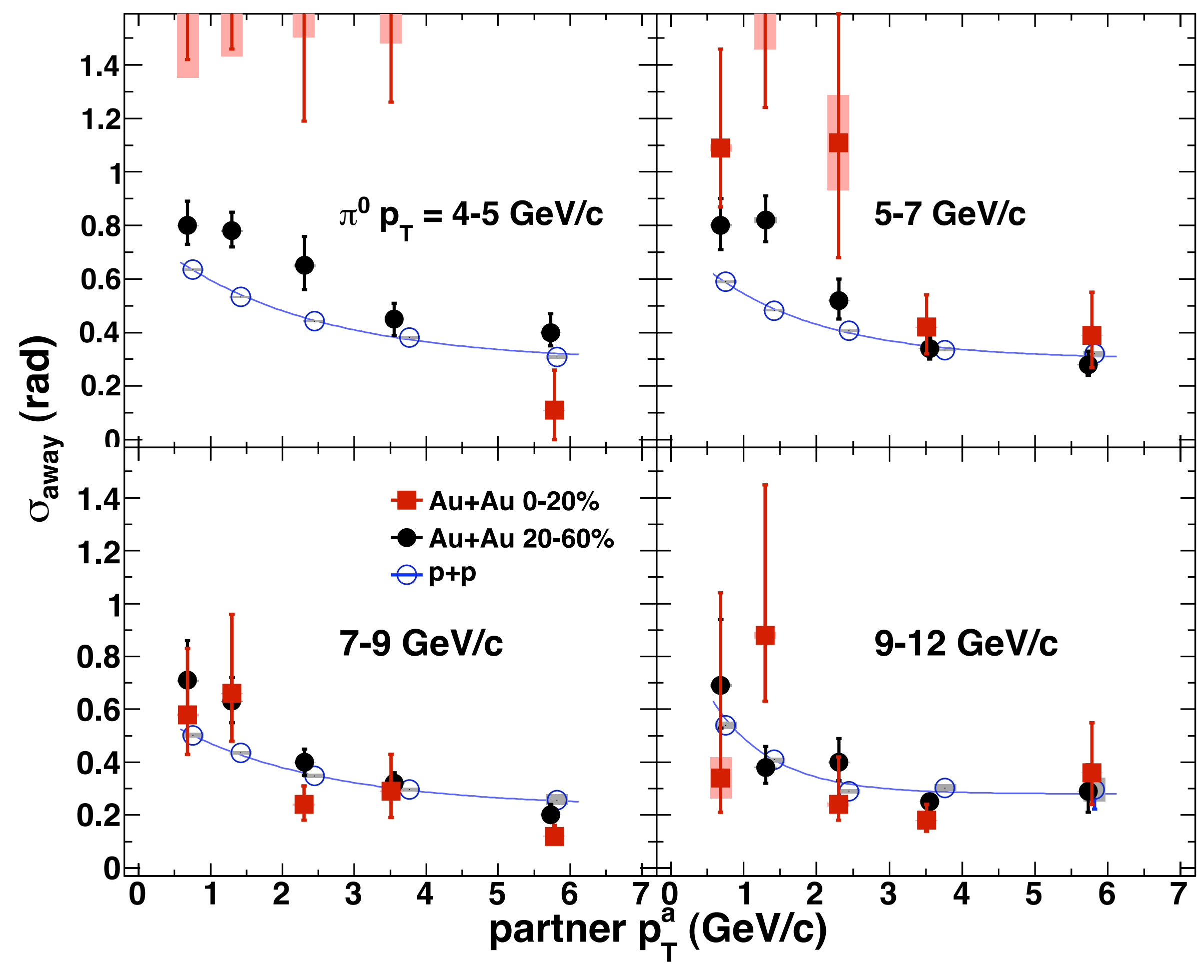


- no (visible) shoulder for high p_T dijets

PHENIX arXiv:1002.1077

diminishing

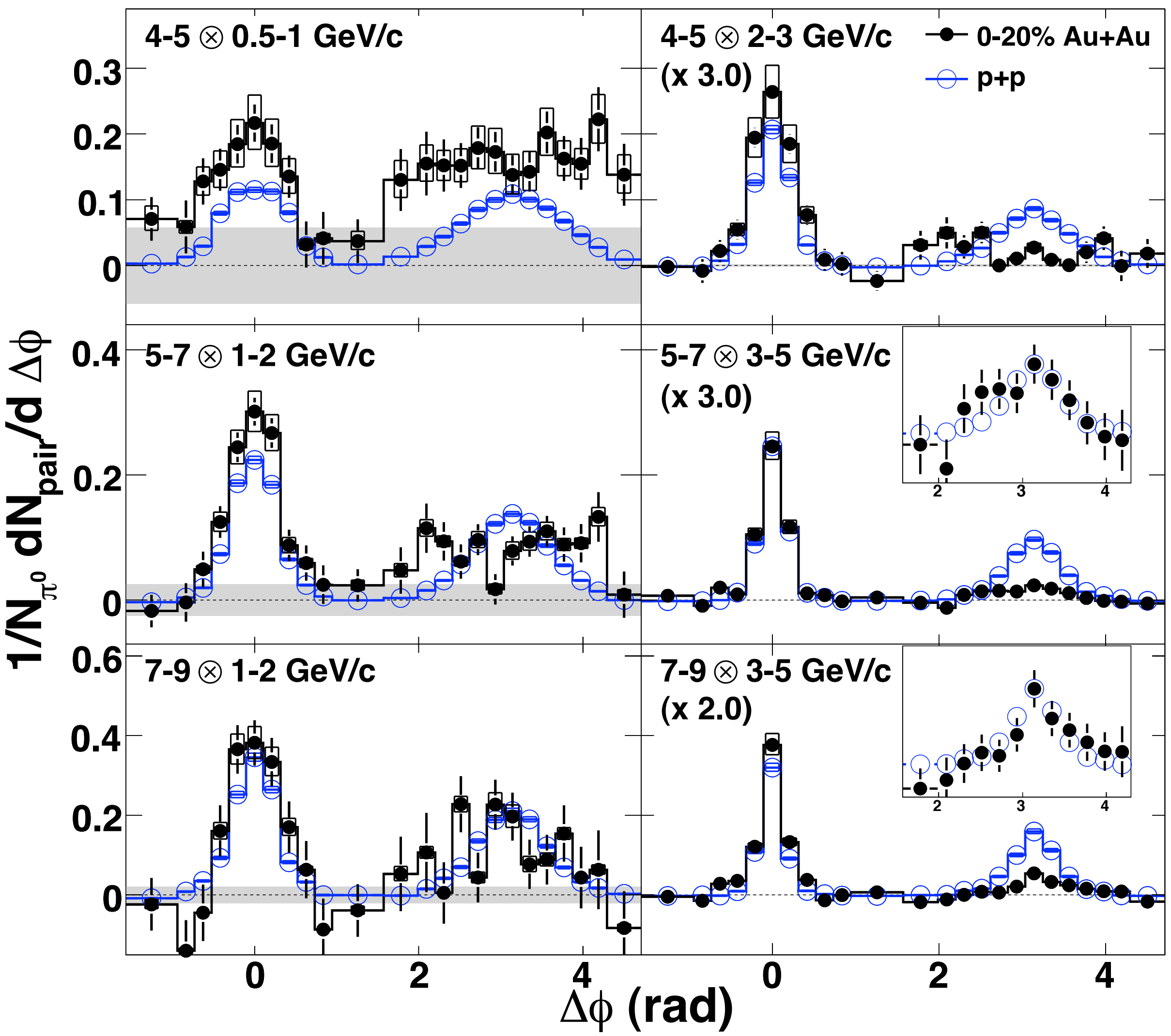


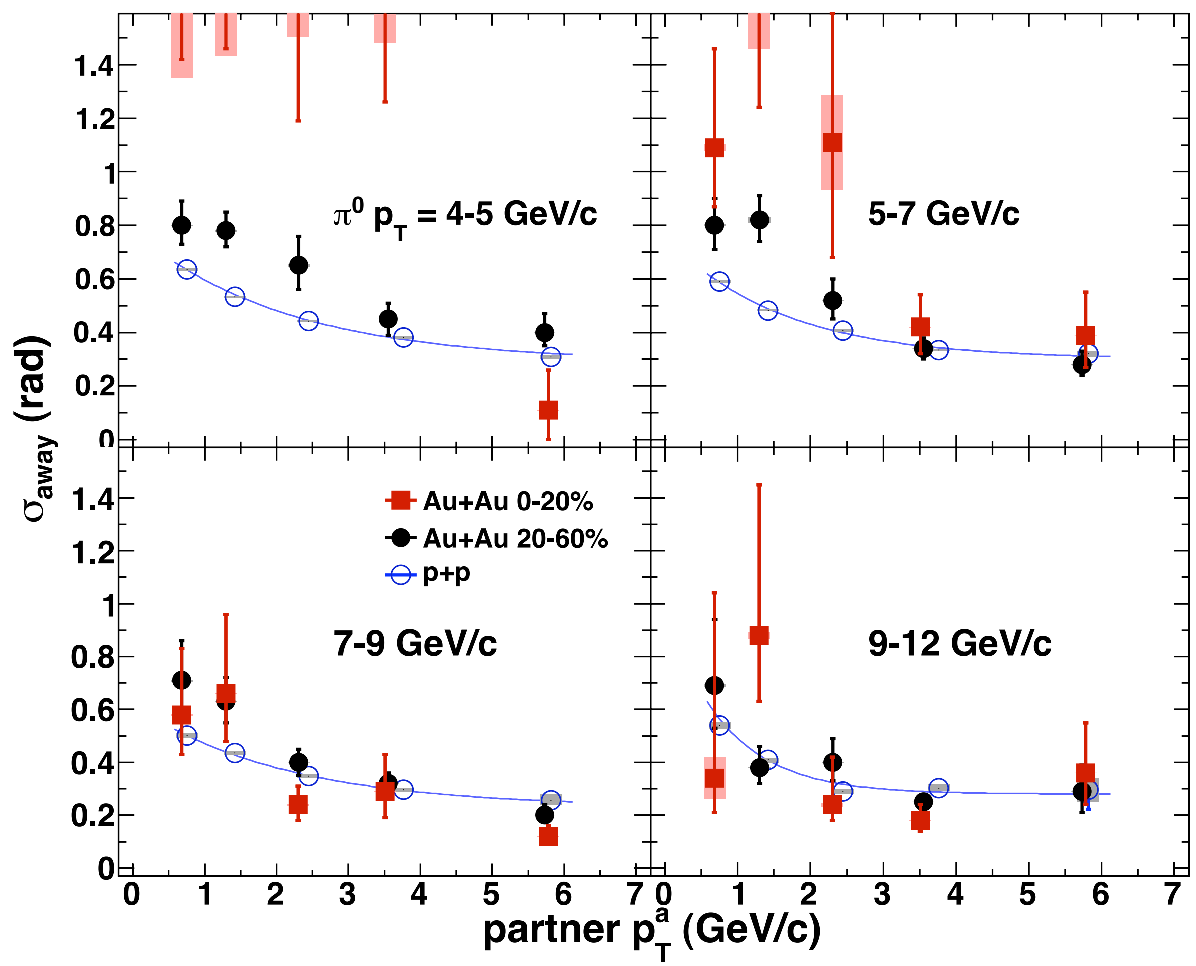


- no (visible) shoulder for high p_T dijets
  - if the shoulder is really related to the jet the shoulder should grow with it

PHENIX arXiv:1002.1077

diminishing

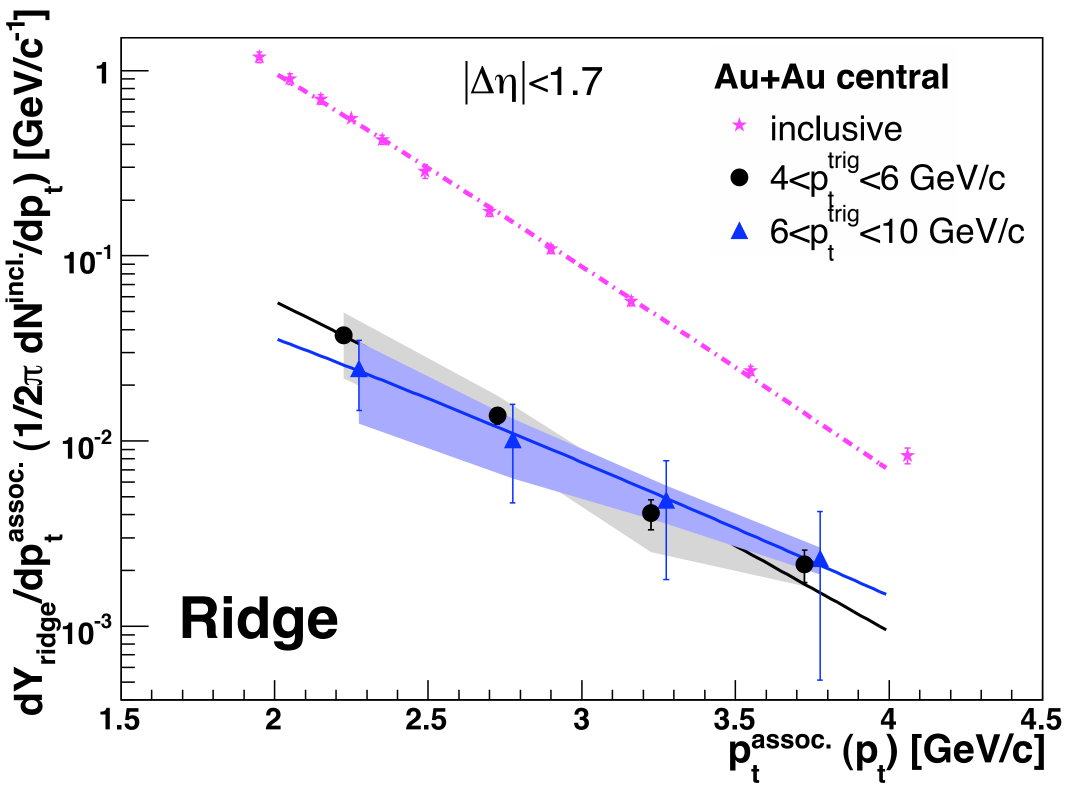




- no (visible) shoulder for high p_T dijets
  - if the shoulder is really related to the jet the shoulder should grow with it
  - ...unless we're just looking at jets that don't interact

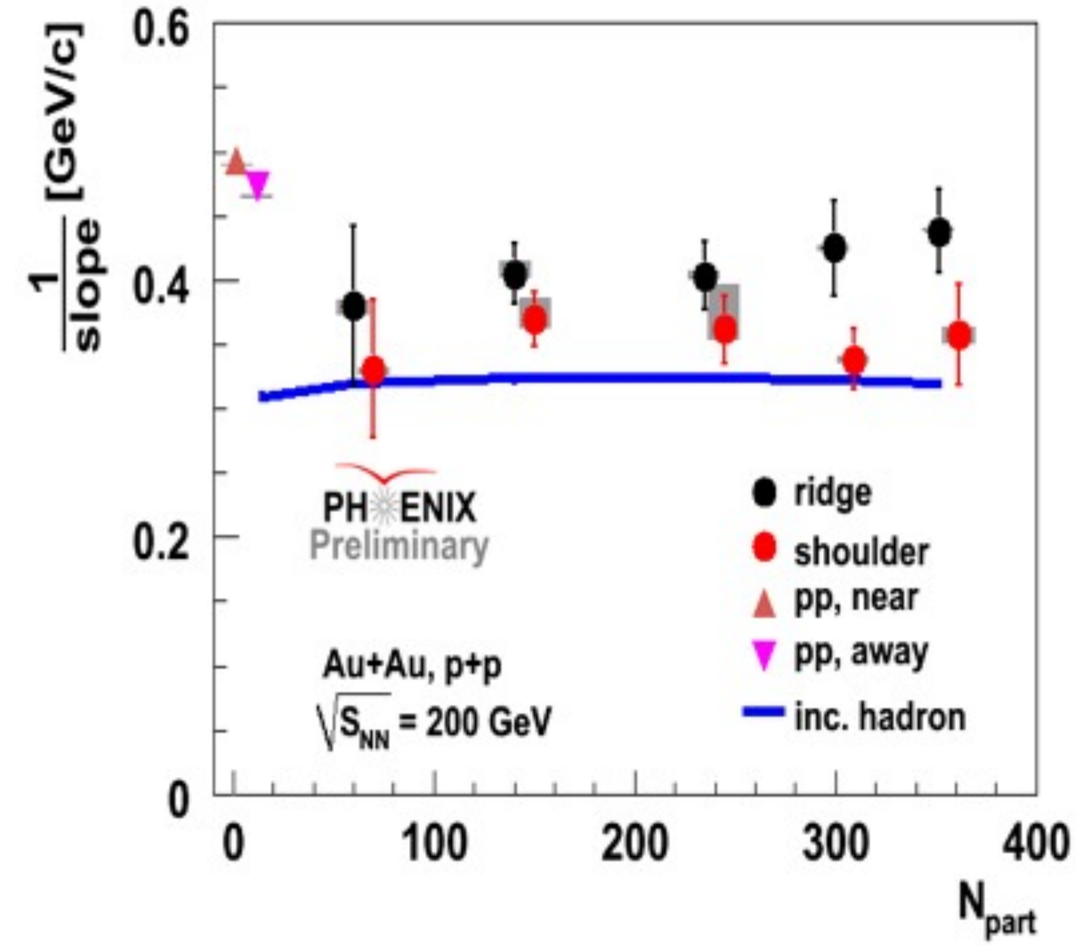
PHENIX arXiv:1002.1077

Ridge & Shoulder are similar...to the bulk



reference measurement (statistical error only). The slope of the inclusive spectrum is $T = 355 \pm 6$ MeV/c.

p_t^{trig} (GeV/c)	T_{ridge} (MeV/c)	T_{jet} (MeV/c)	T_{jet}^{dAu} (MeV/c)
4–6	416 ± 22	598 ± 21	647 ± 24
6–10	514 ± 148	702 ± 47	723 ± 86

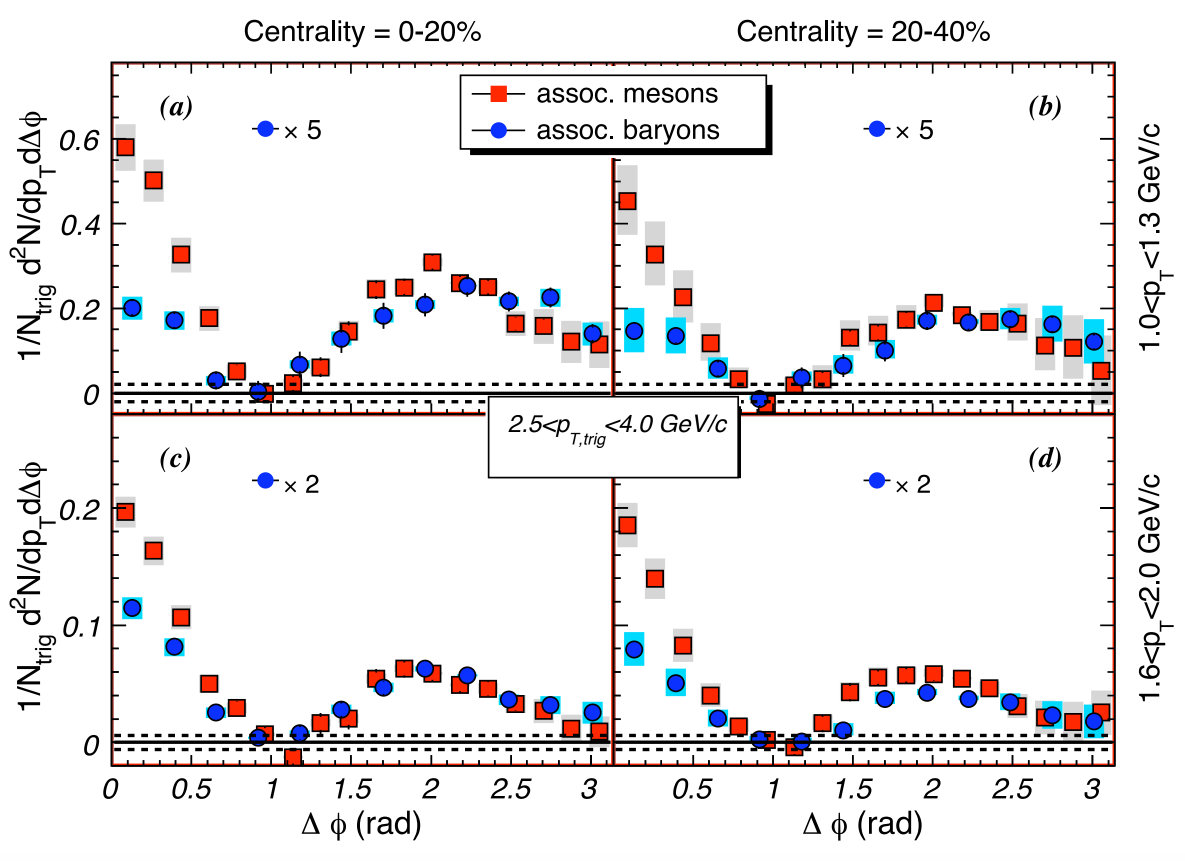


- ridge slightly harder than inclusive, but softer than jet part

STAR, PRC 80 064912 (2009), C.H. Chen QM09

particle composition

PHENIX PRL 101 082301 (2008)



C. Suarez, QM08

particle composition

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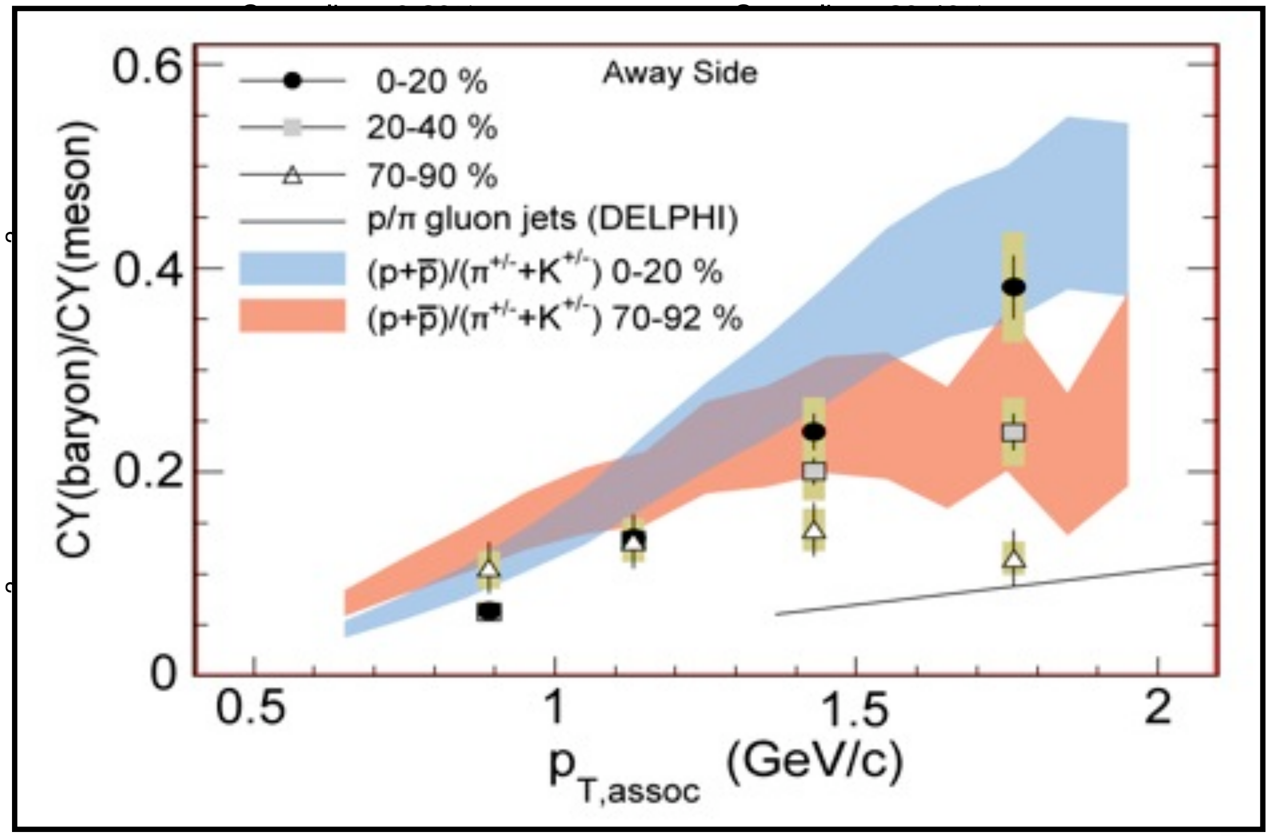

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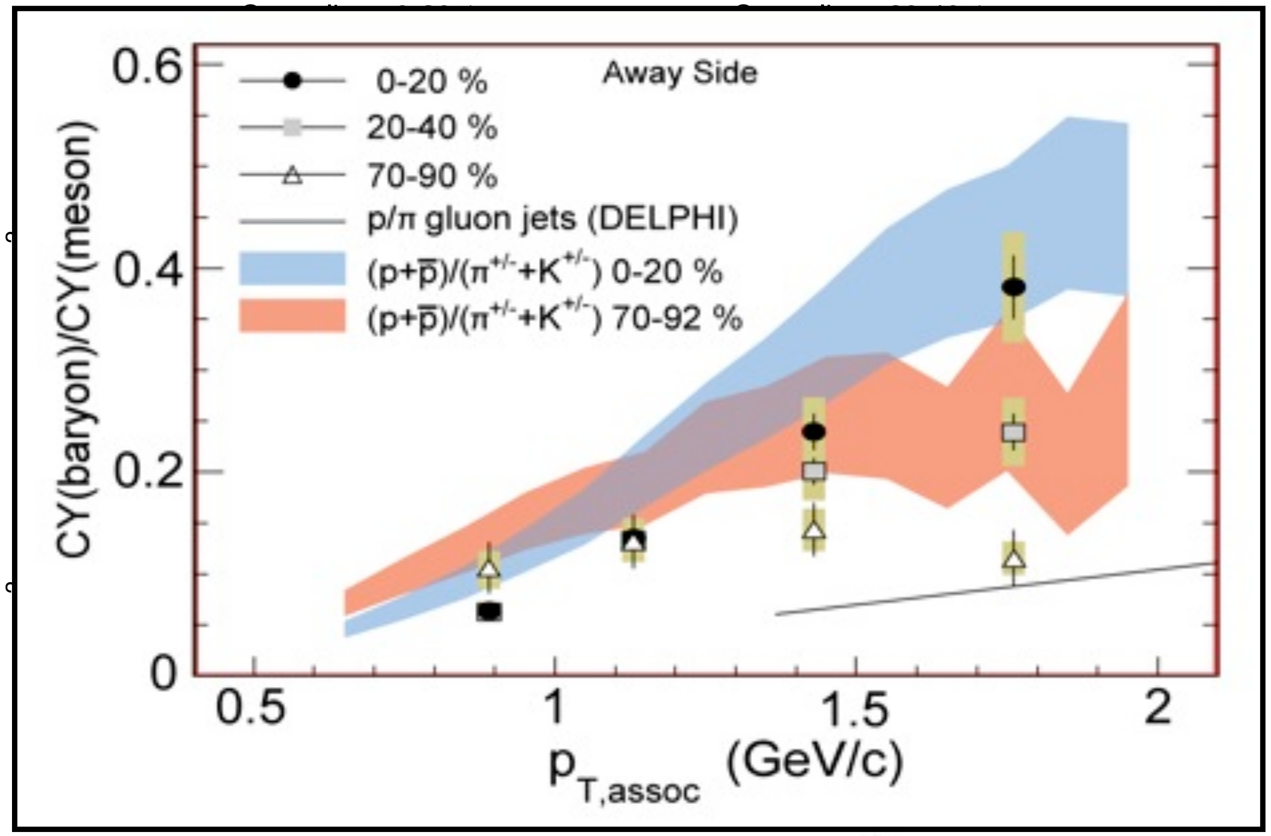

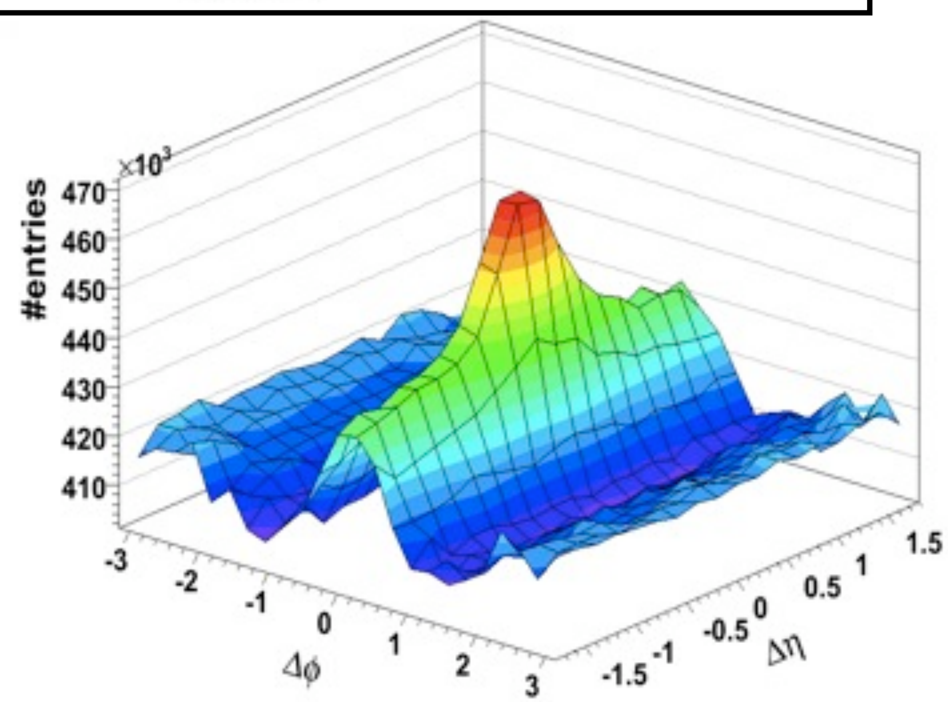

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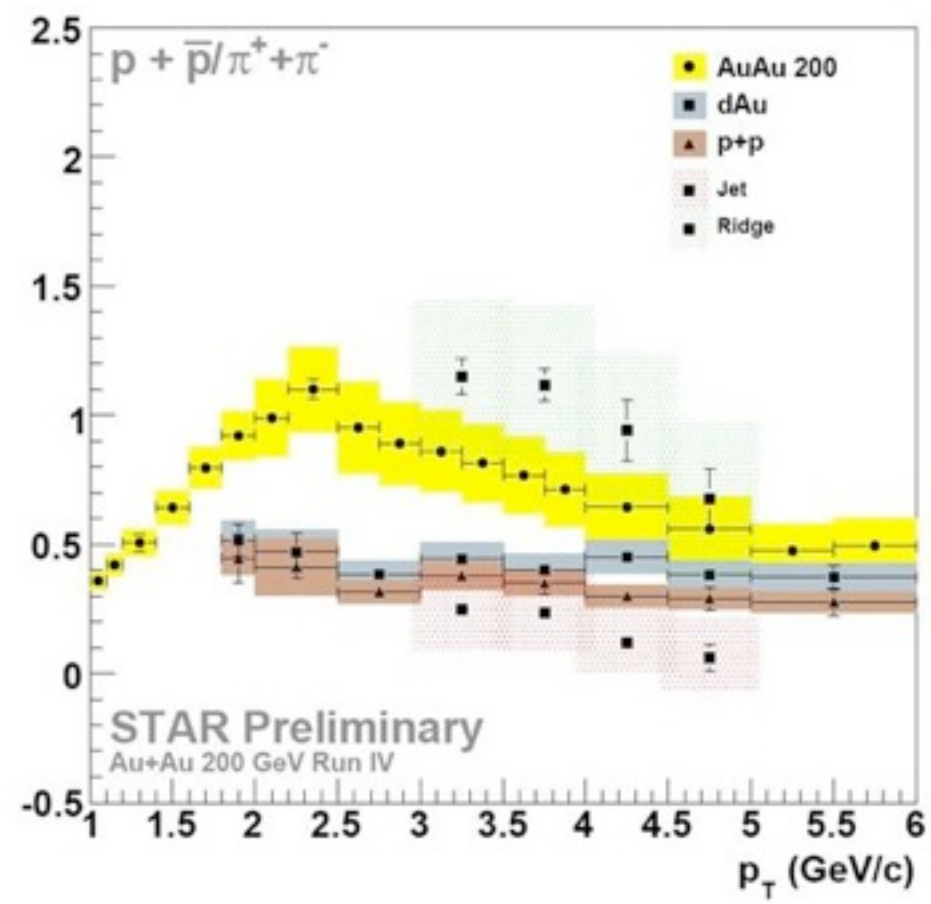

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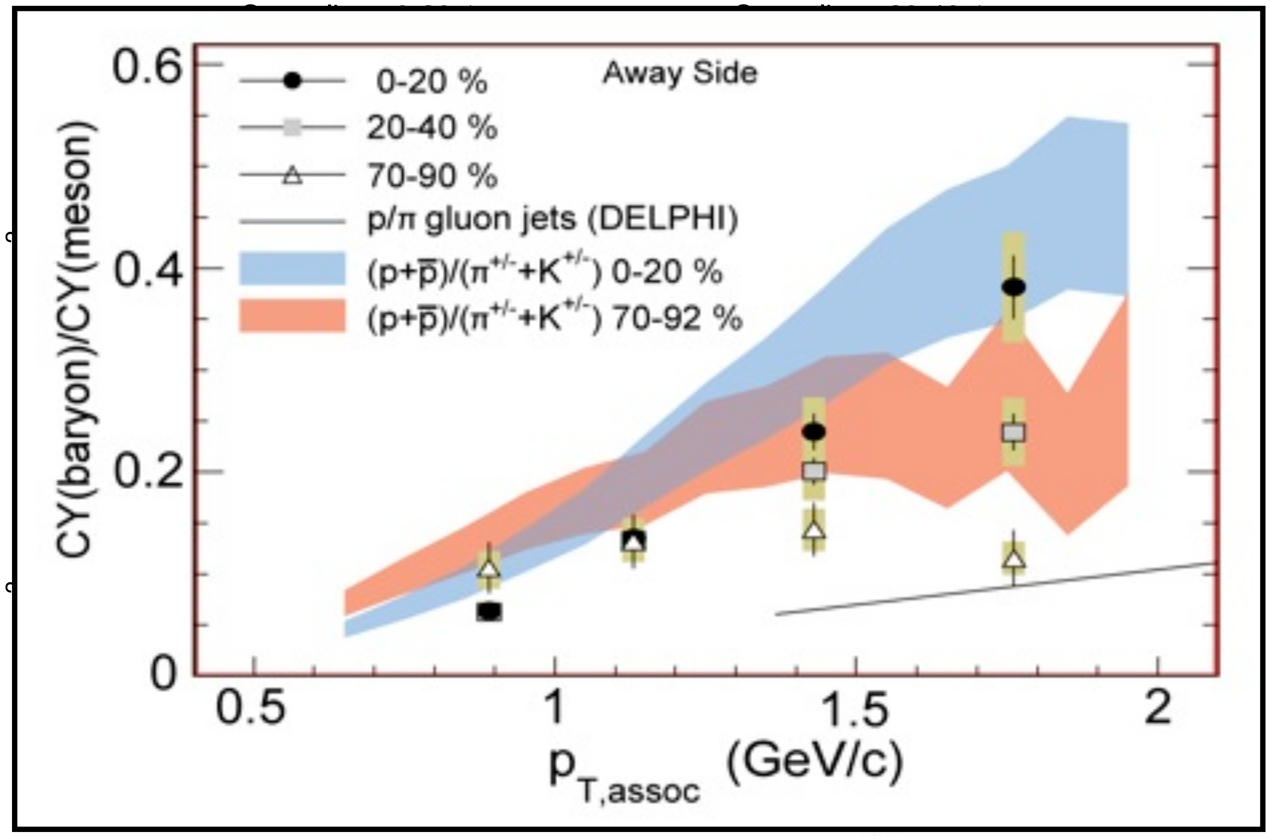
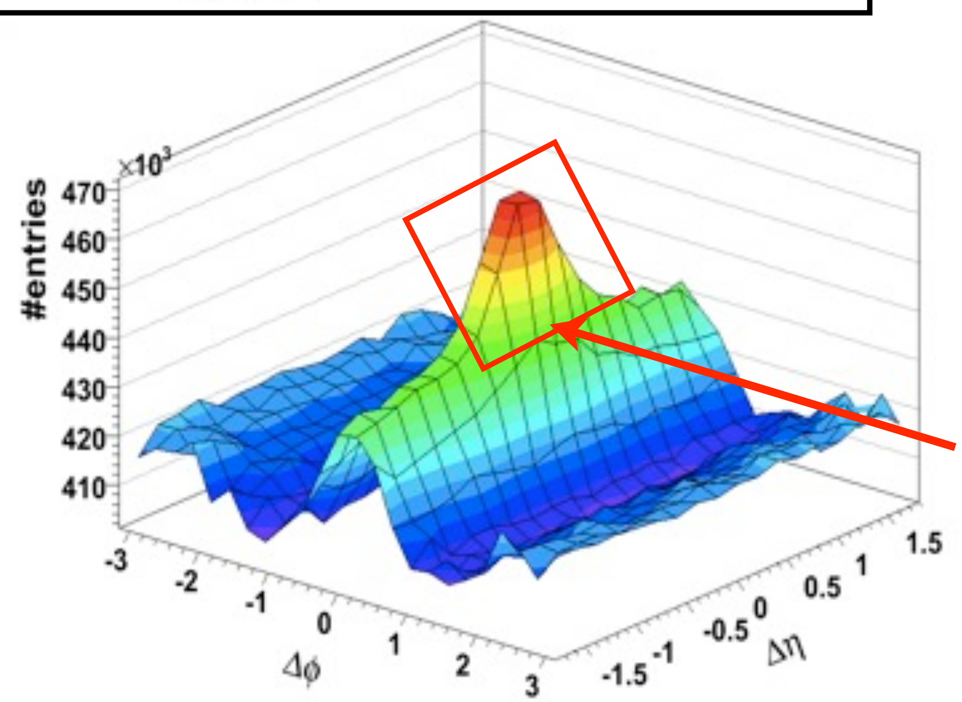
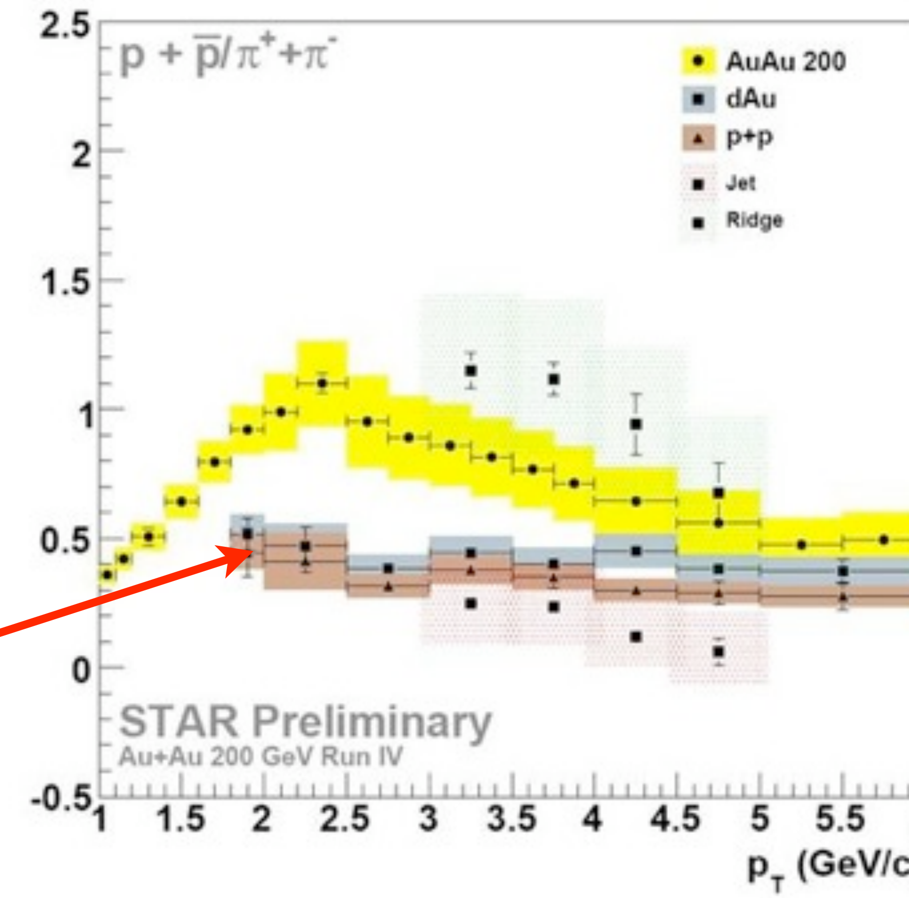




jet

C. Suarez, QM08



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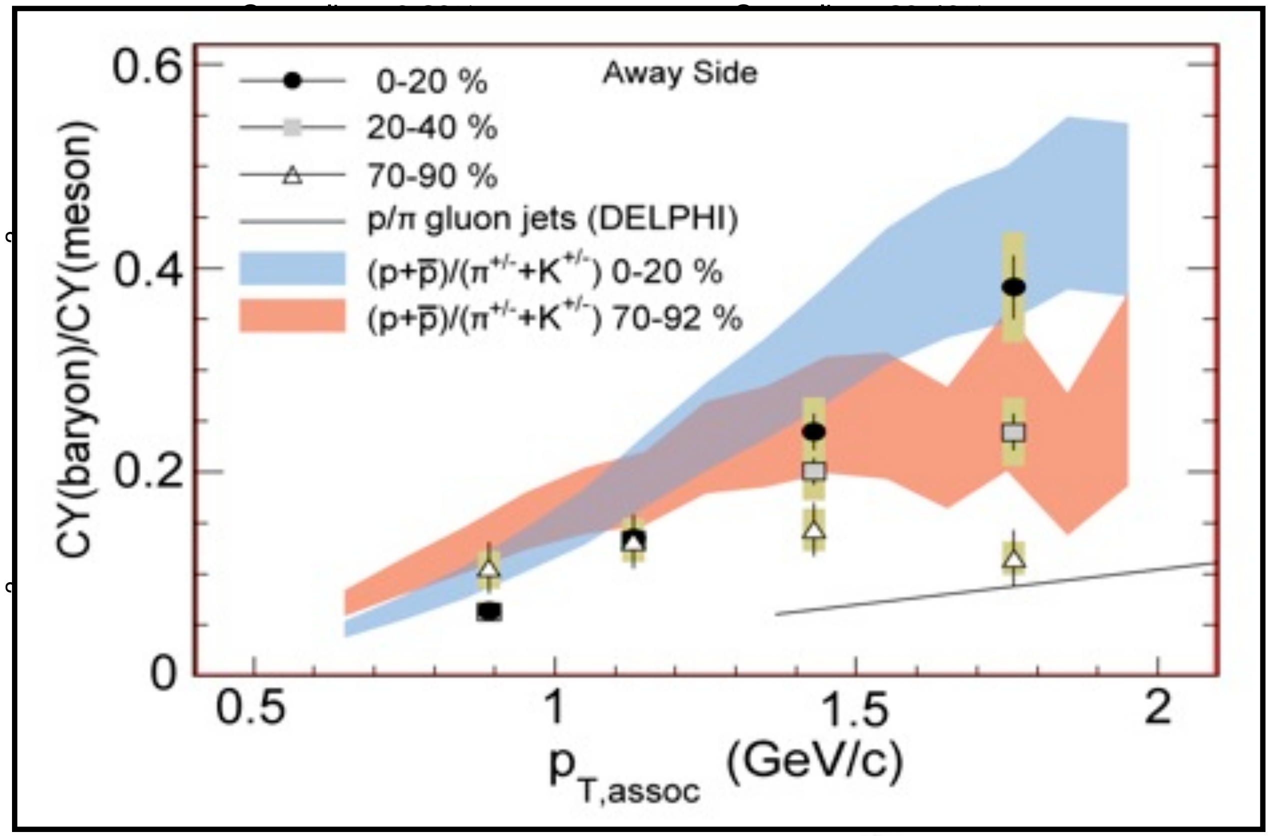

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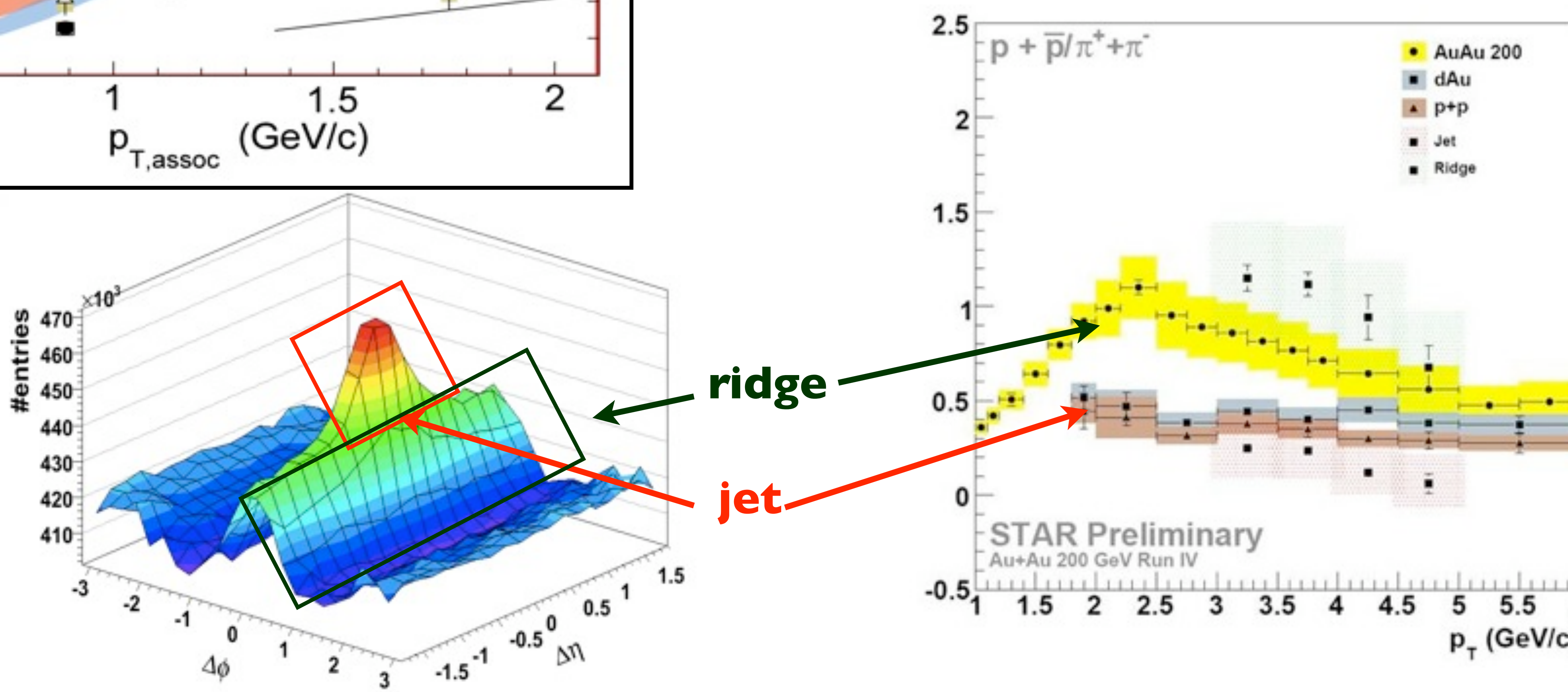
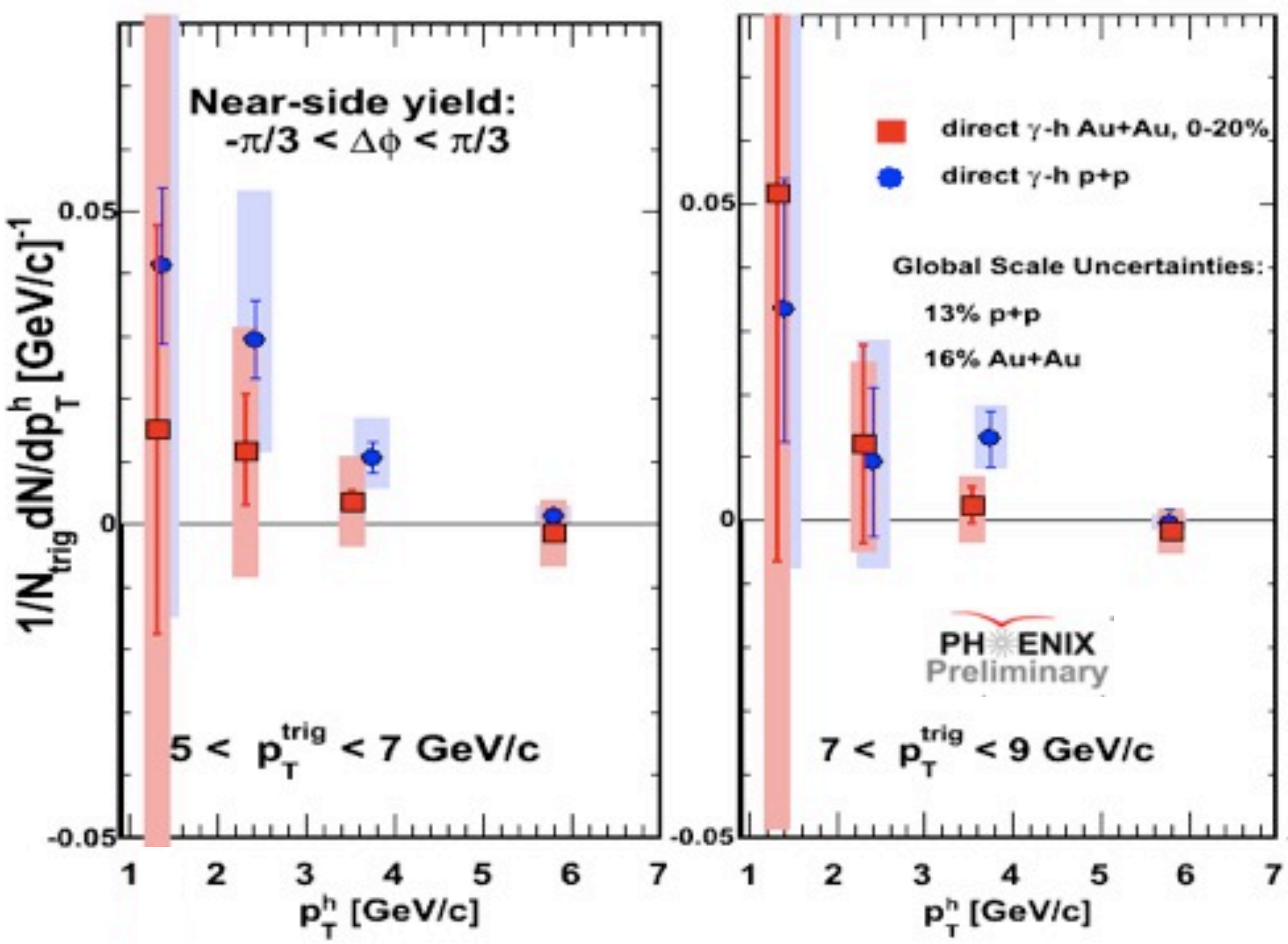


only in hadrons?



M. Connors QM09

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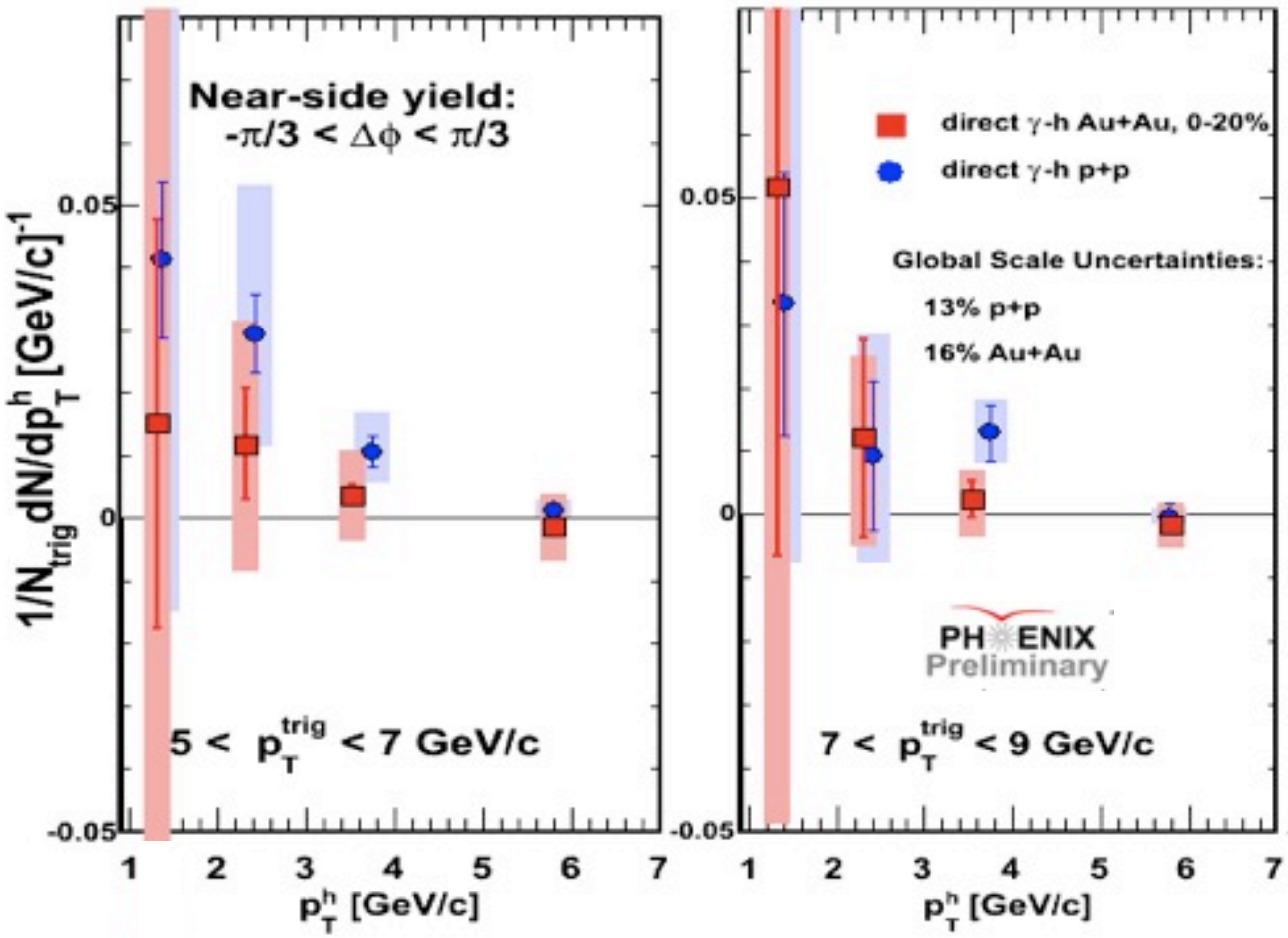
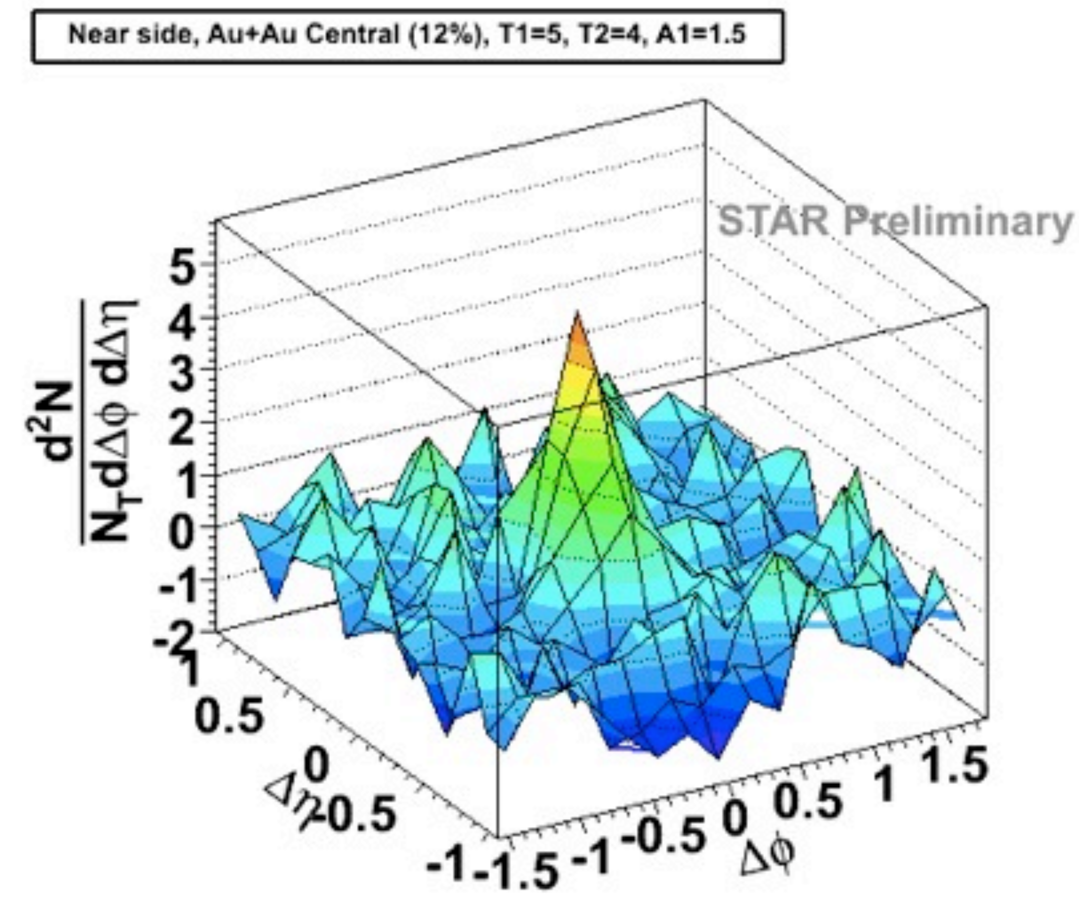


M. Connors QM09

Near side 2+1 Correlations



Kauder, QM09

only in hadrons?

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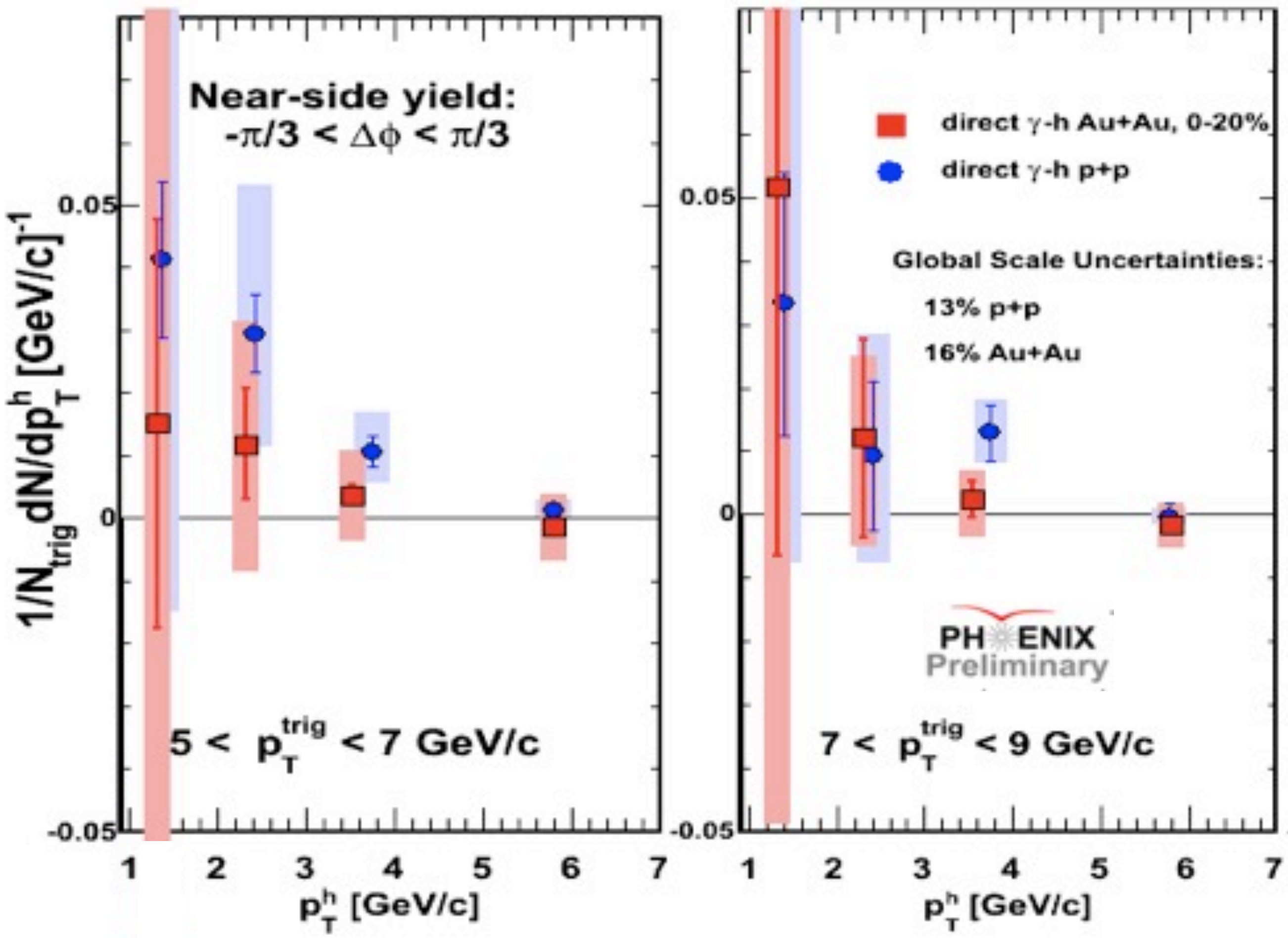

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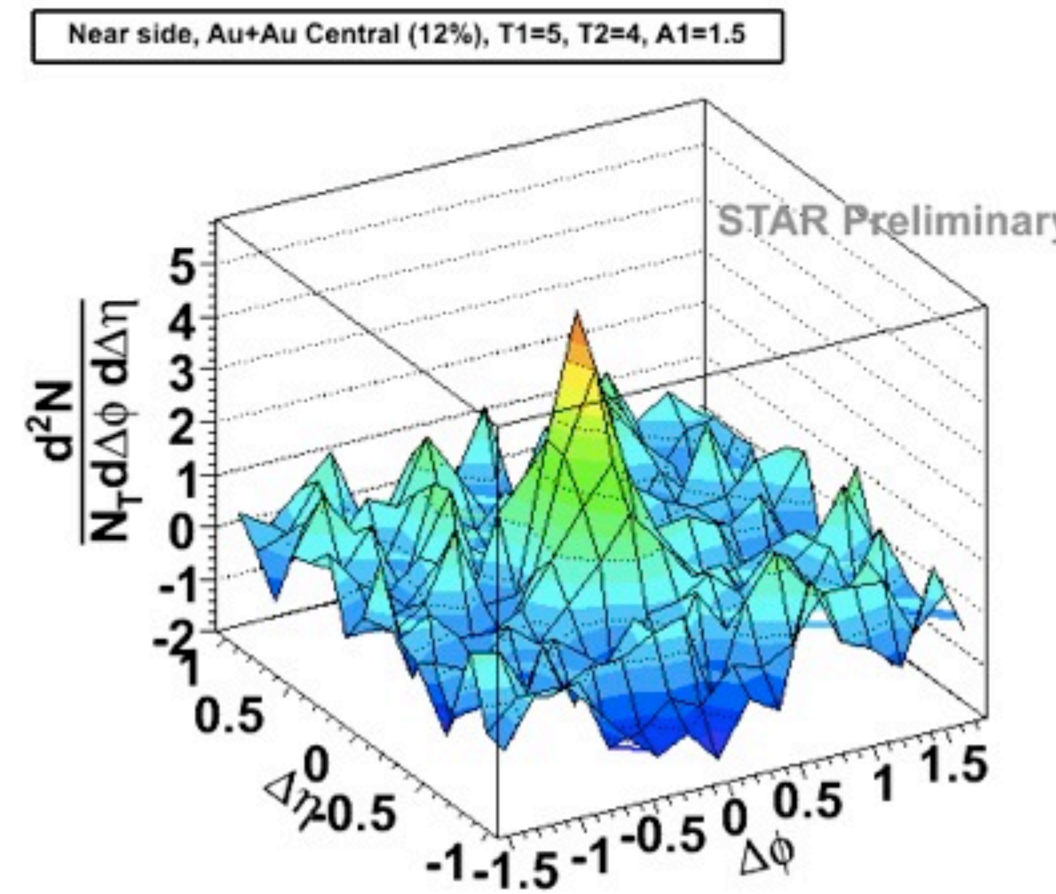

Kauder, QM09

- provide constraints on the ridge mechanism

only in hadrons?

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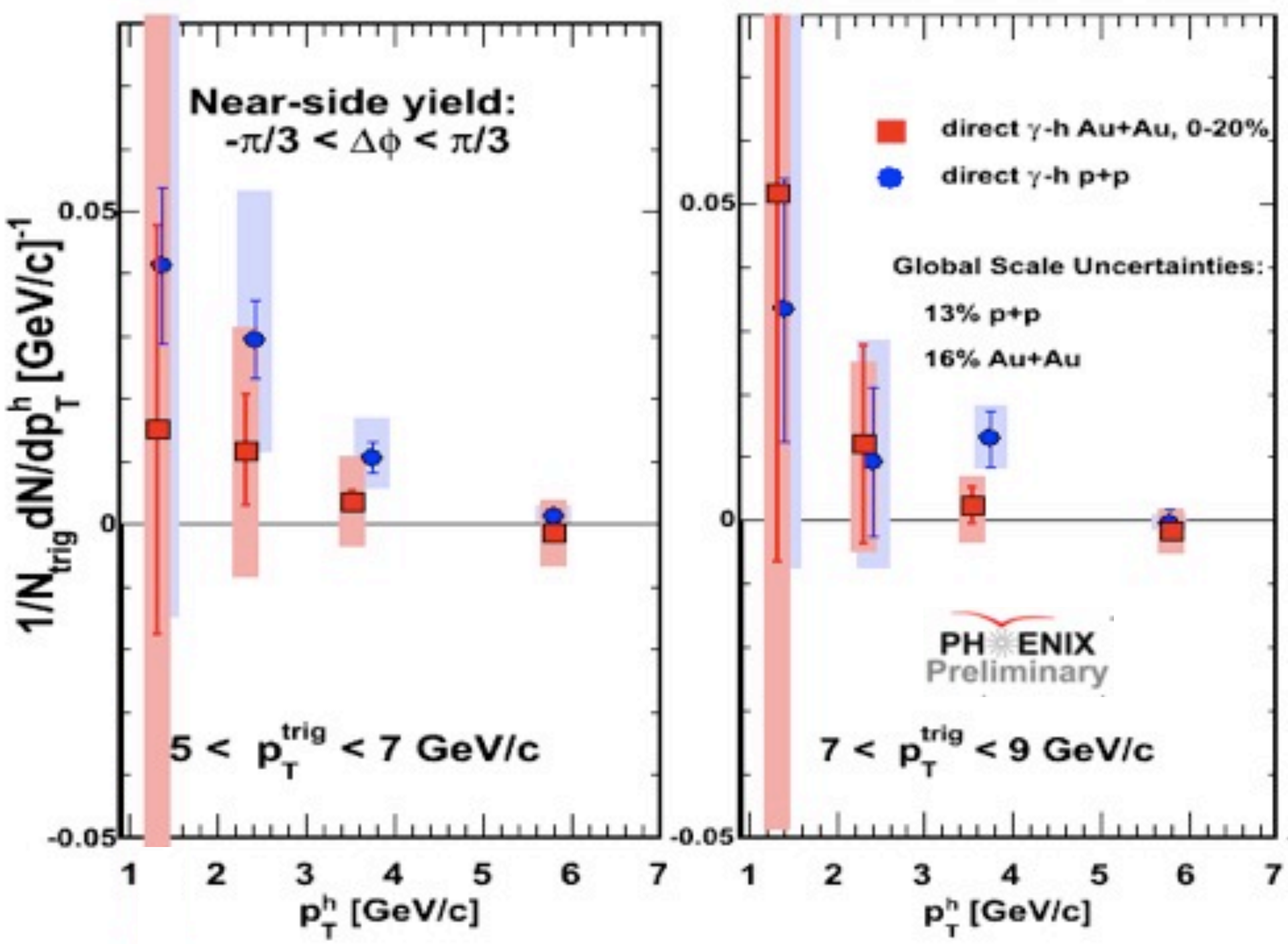
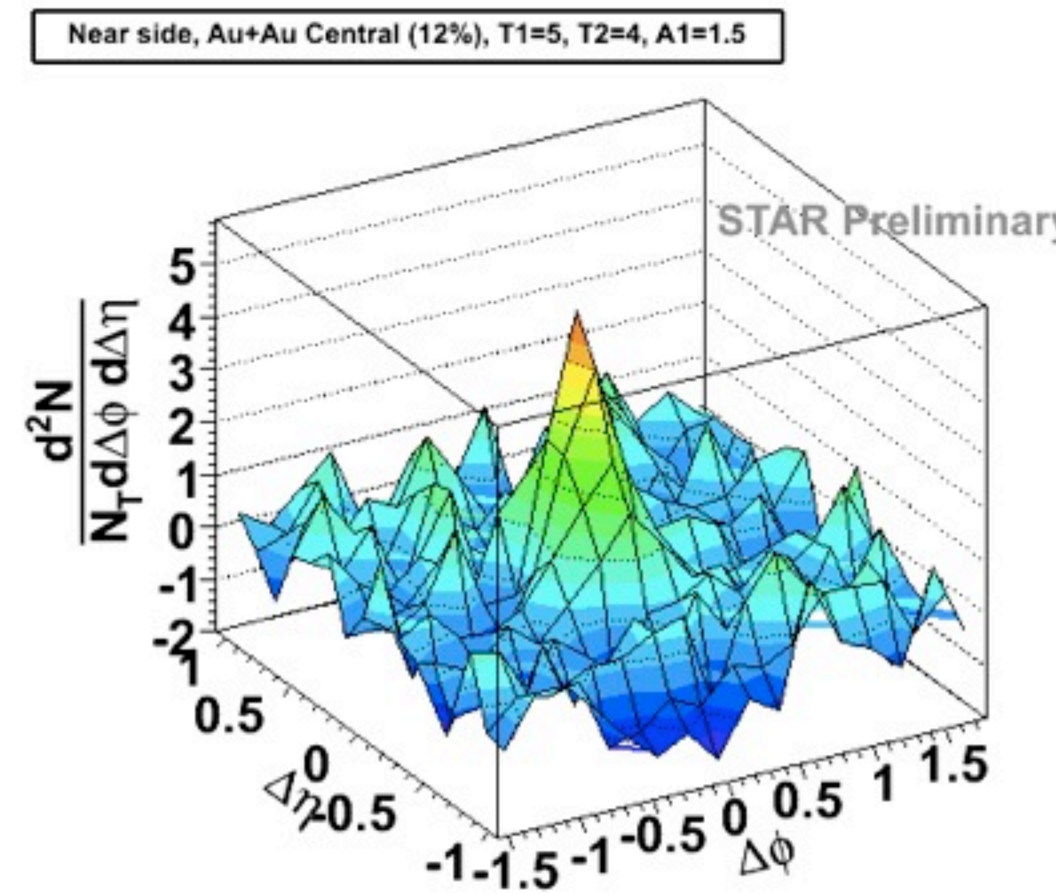


M. Connors QM09



Kauder, QM09

- provide constraints on the ridge mechanism
  - radial flow→ no gamma-h ridge

the ridge: a distraction?

- is studying the ridge like studying the underlying event in p+p?
  - important, but mostly so you know how to get rid of it?
  - useful for studying initial state?
- seems too wide to be energy lost by jet or coupling between jet and flow

types of partons

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  - parton speed → do we see Mach cones?
  - parton mass → collisional vs radiative energy loss?

light quarks vs gluons

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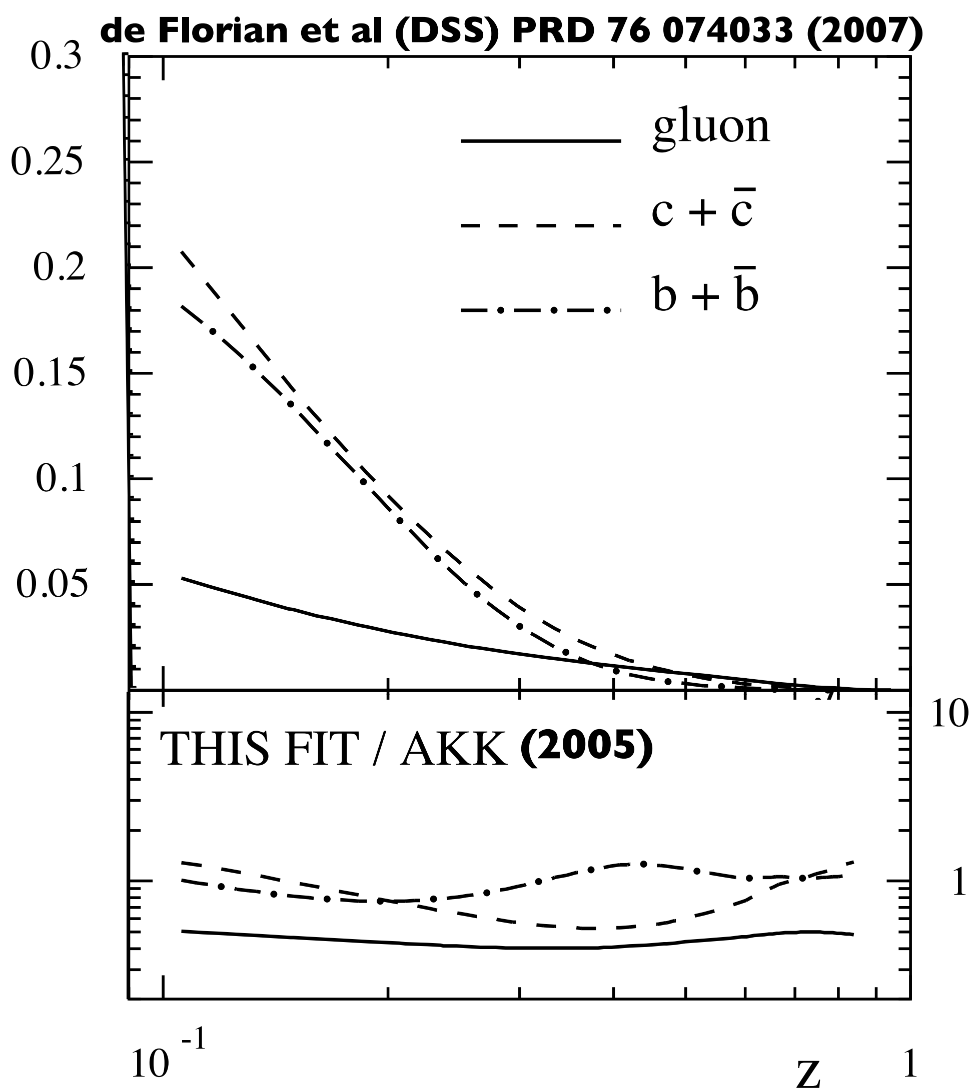

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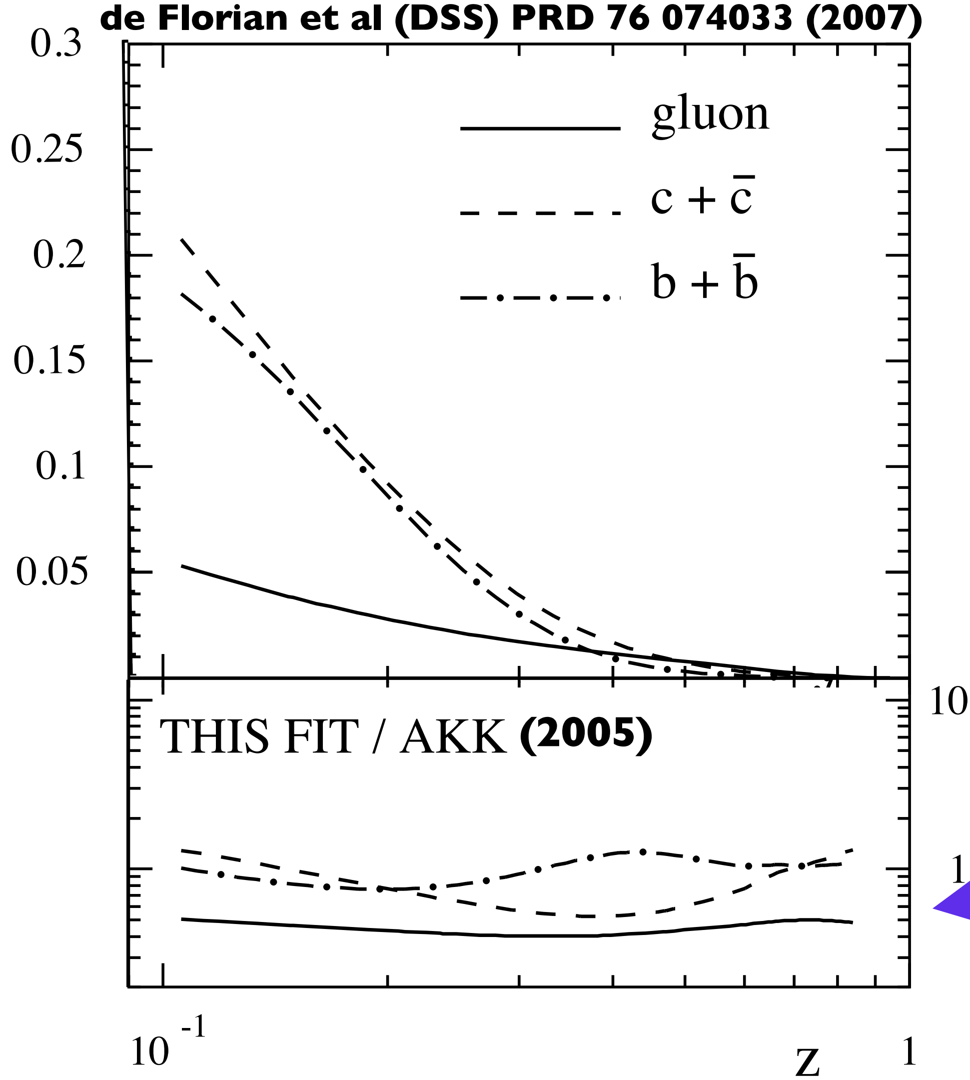
de Florian et al (DSS) PRD 76 074033 (2007)



$\frac{g \rightarrow p \text{ (DSS)}}{g \rightarrow p \text{ (AKK)}}$

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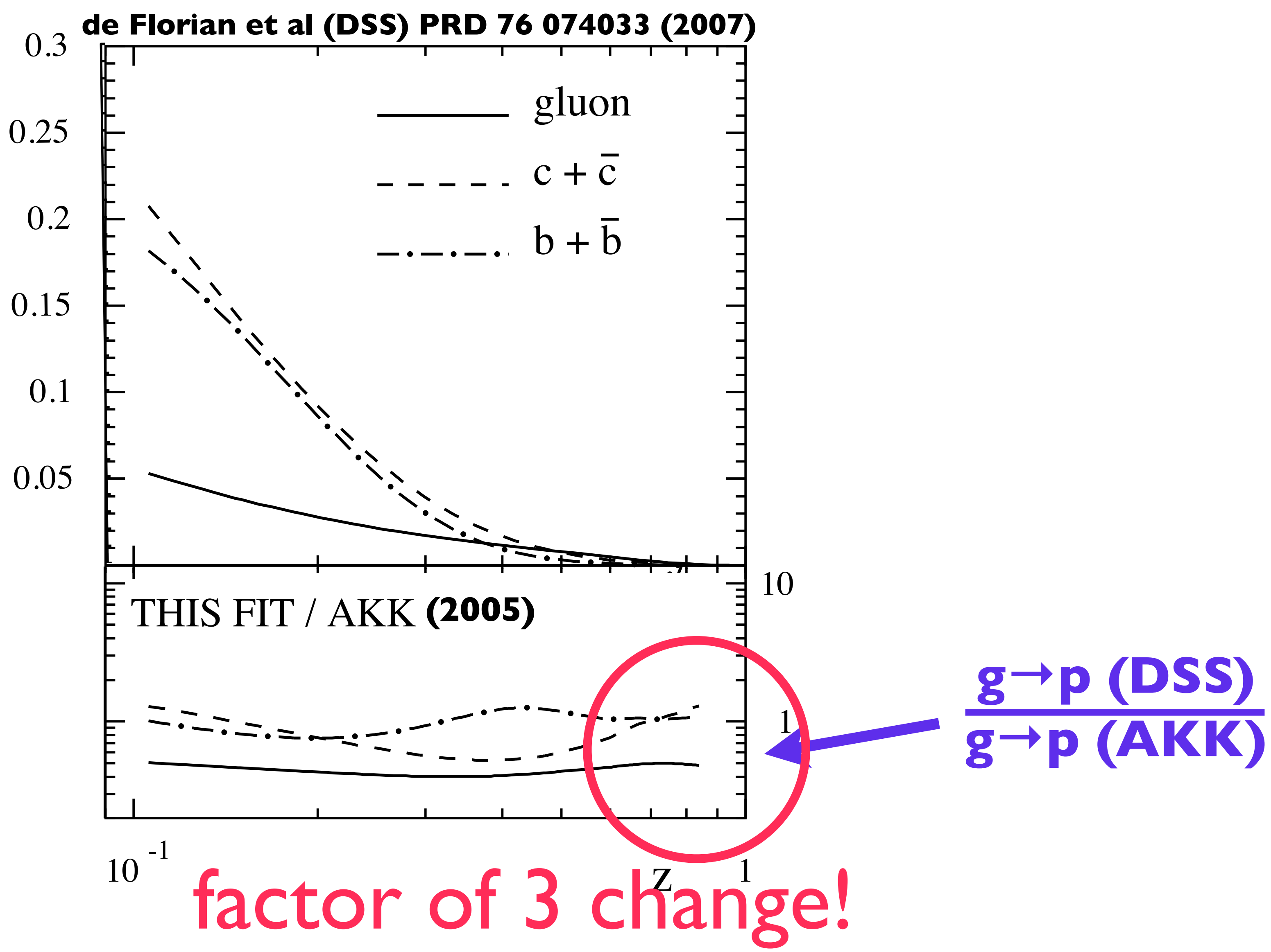

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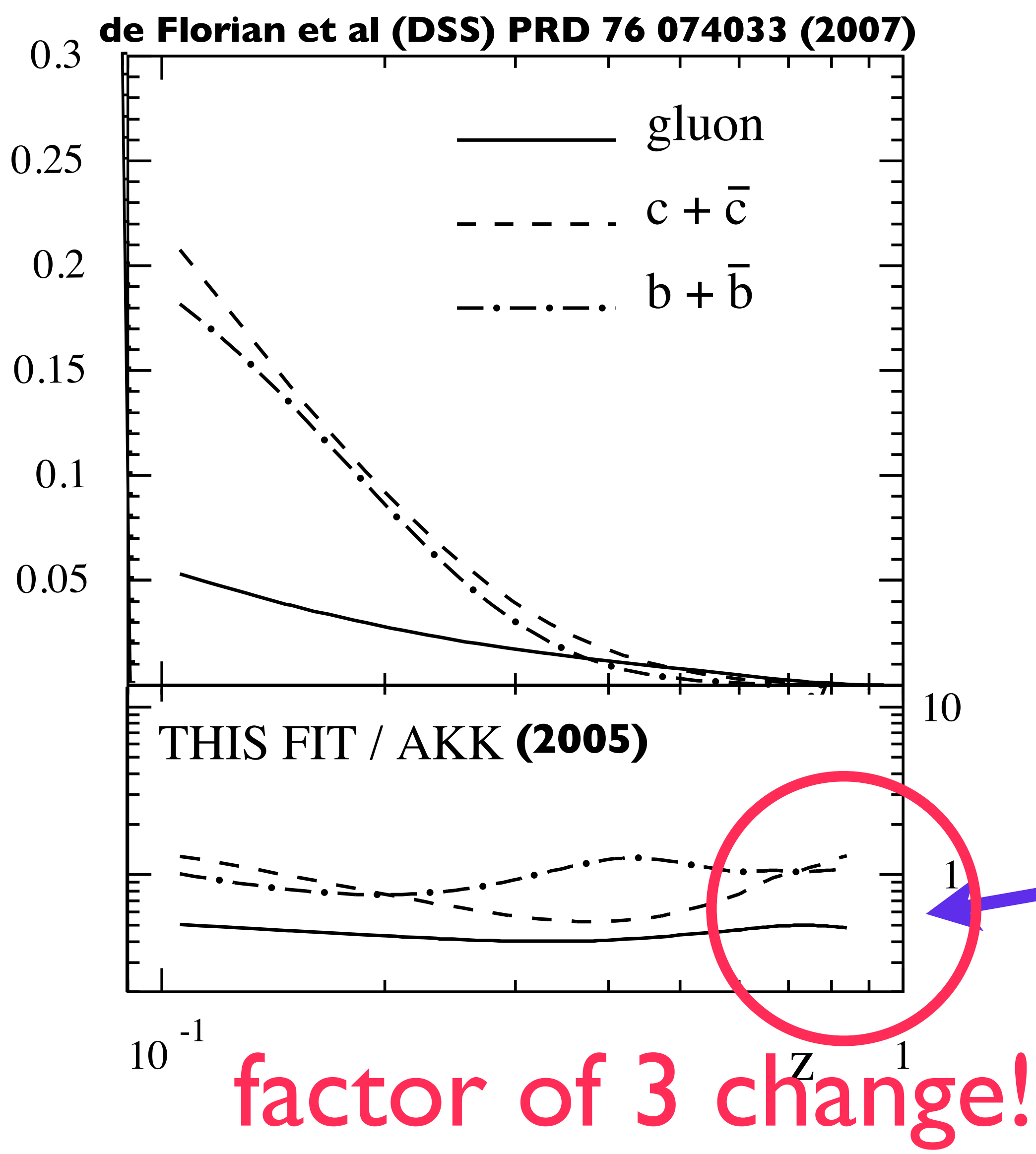

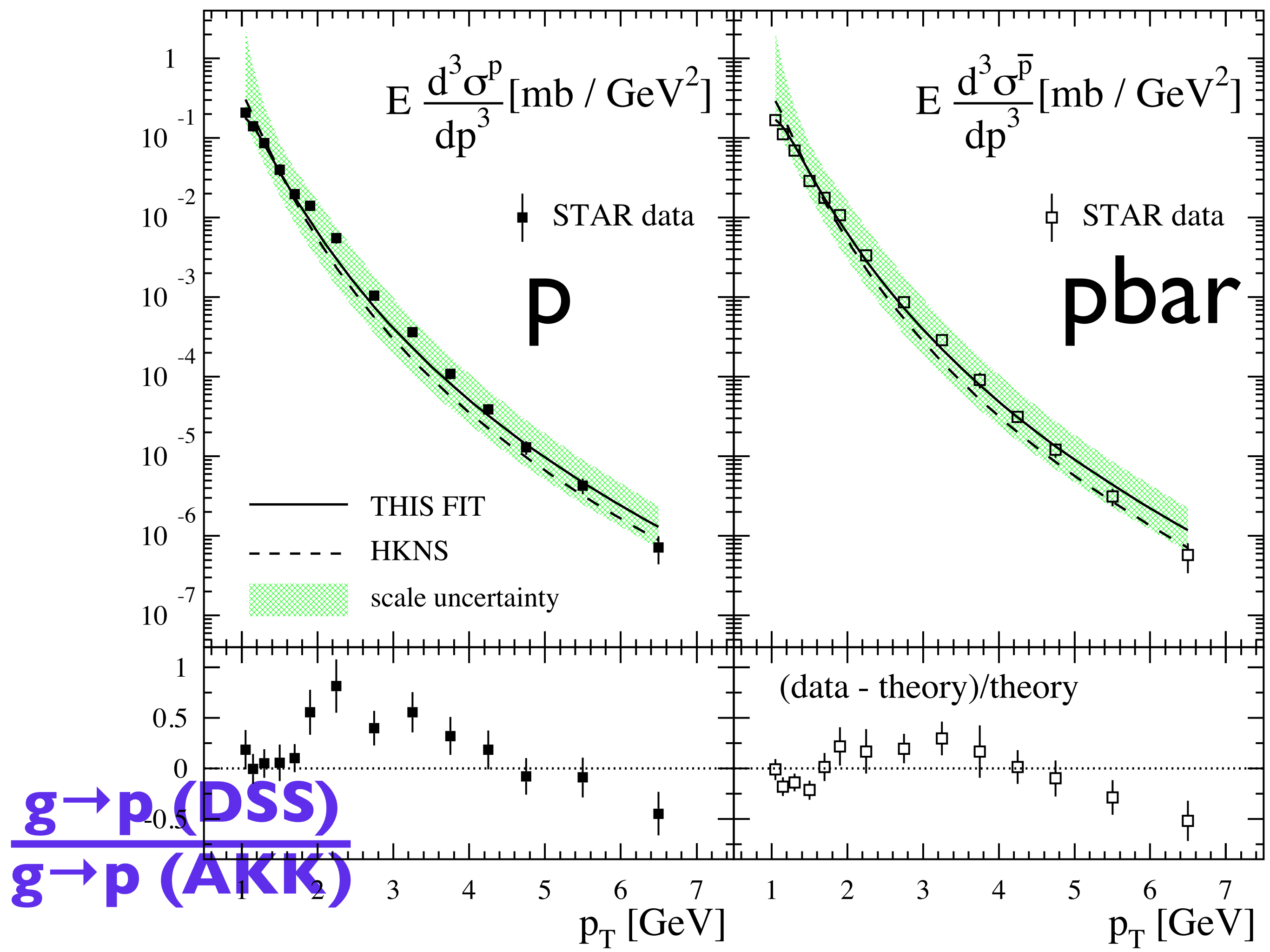

what about the protons?

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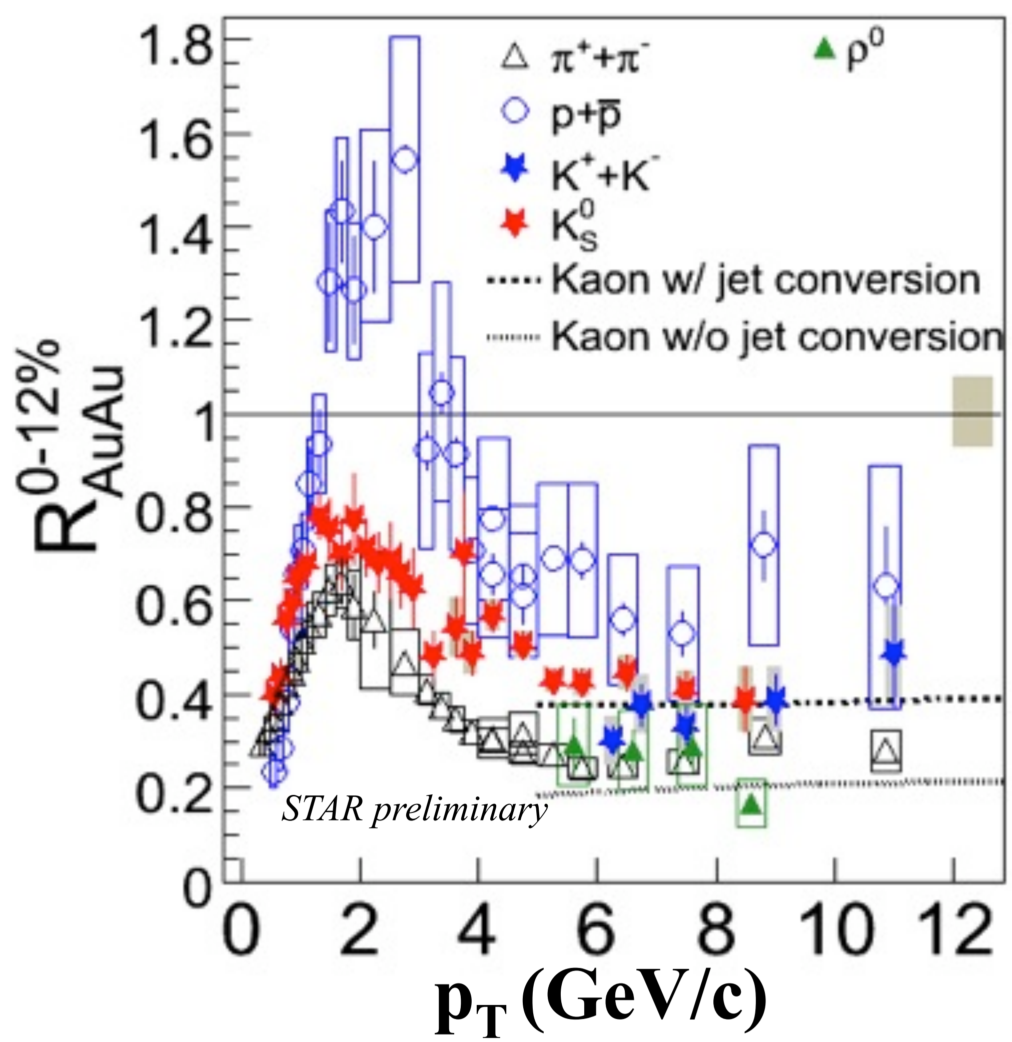

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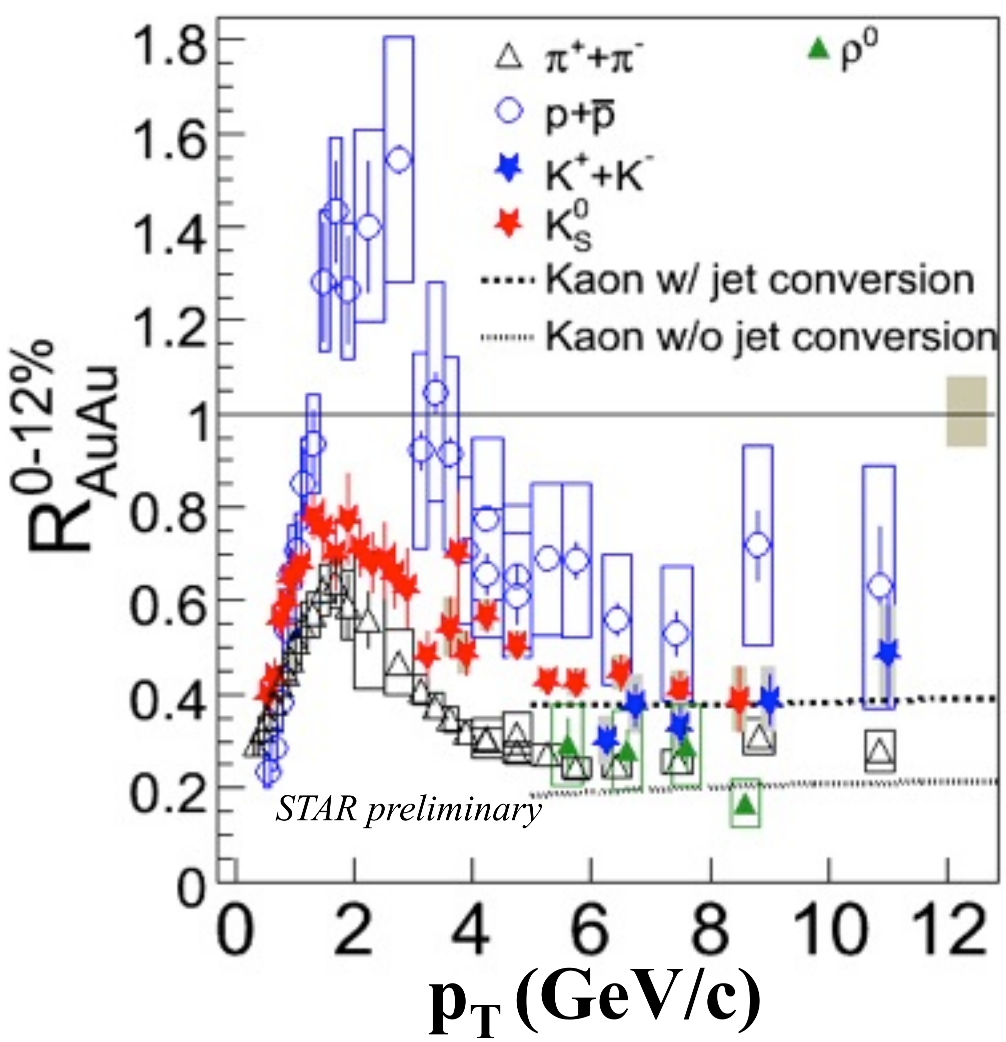

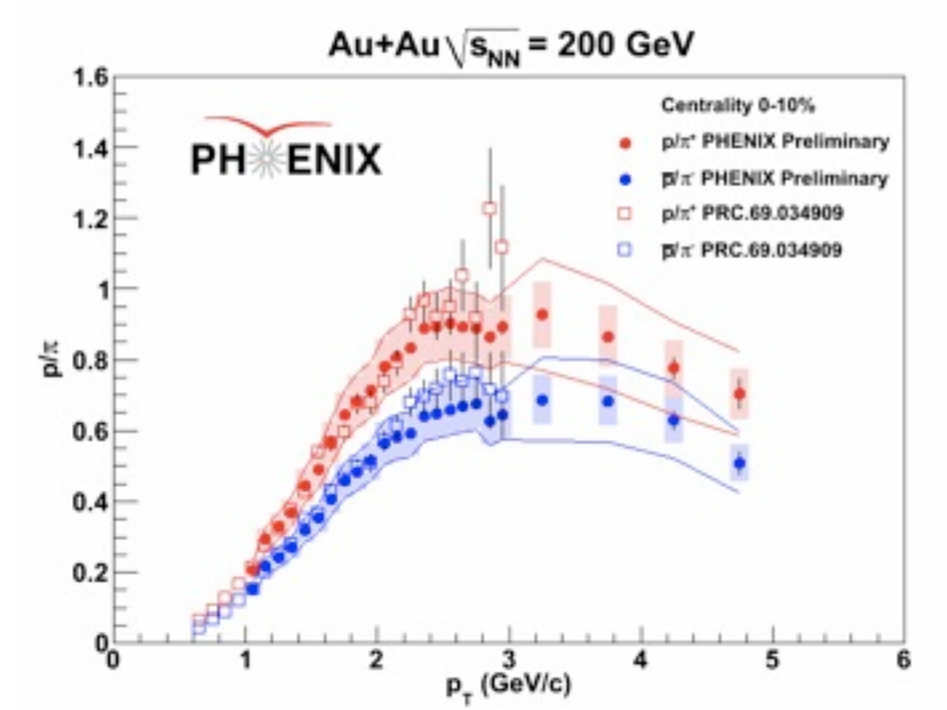

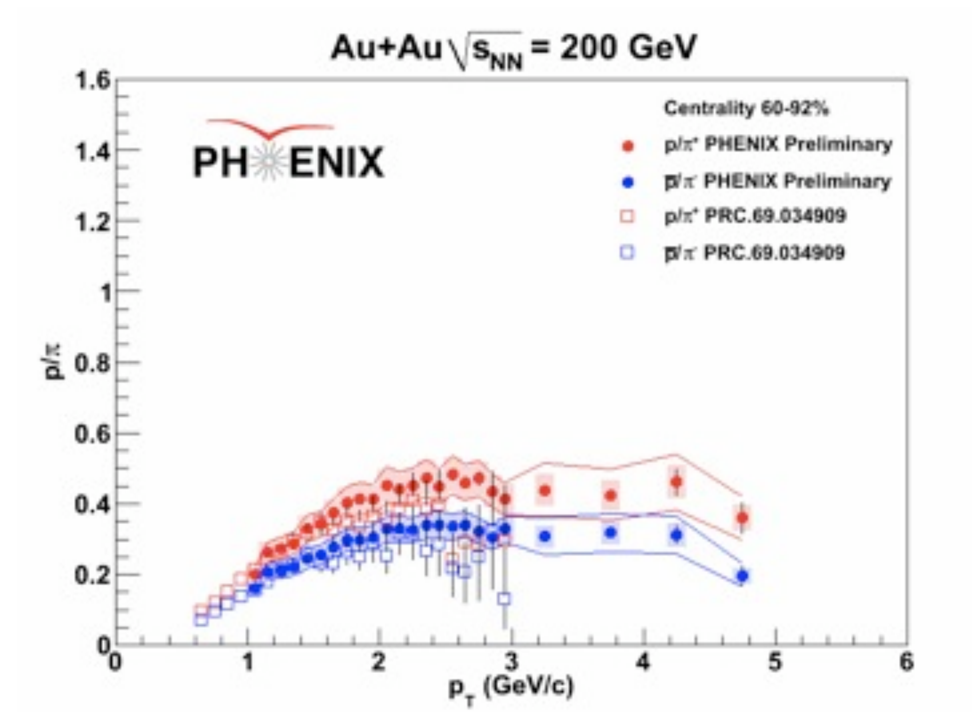

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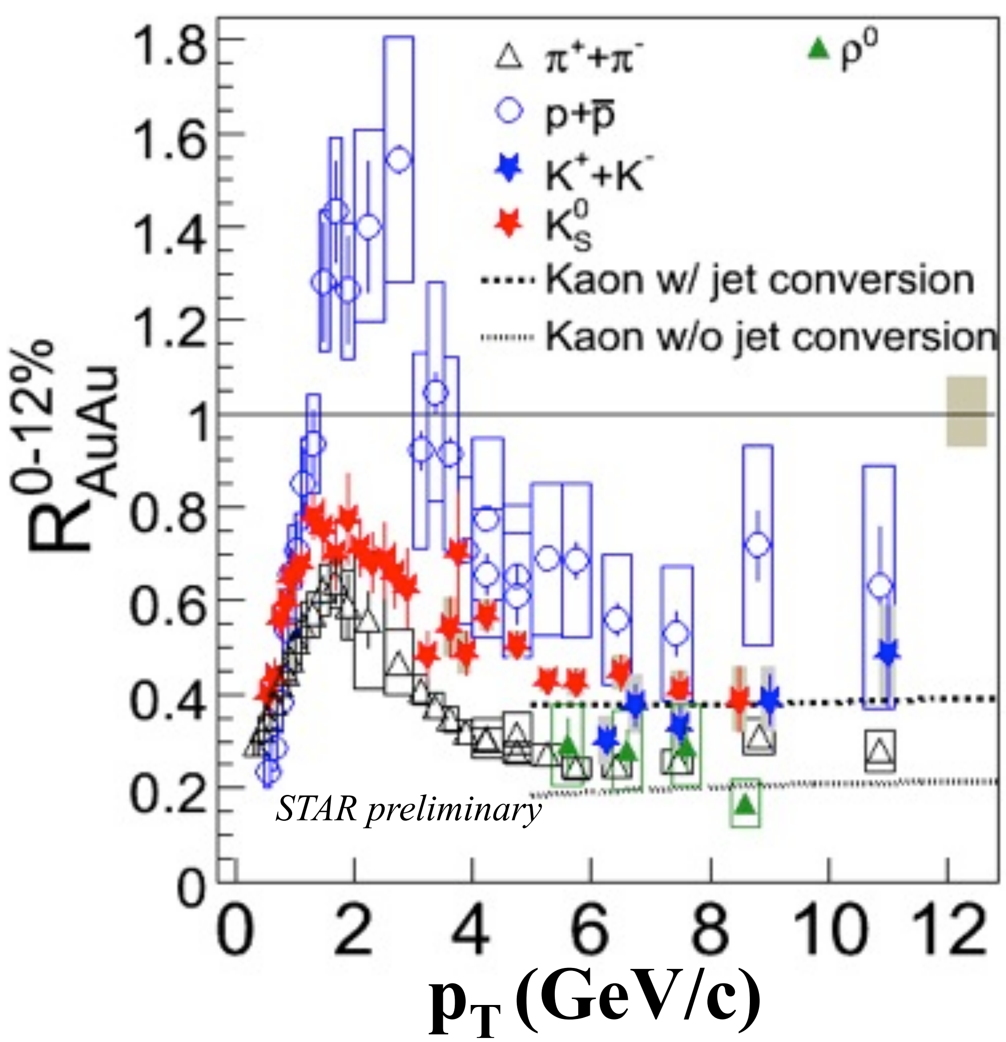

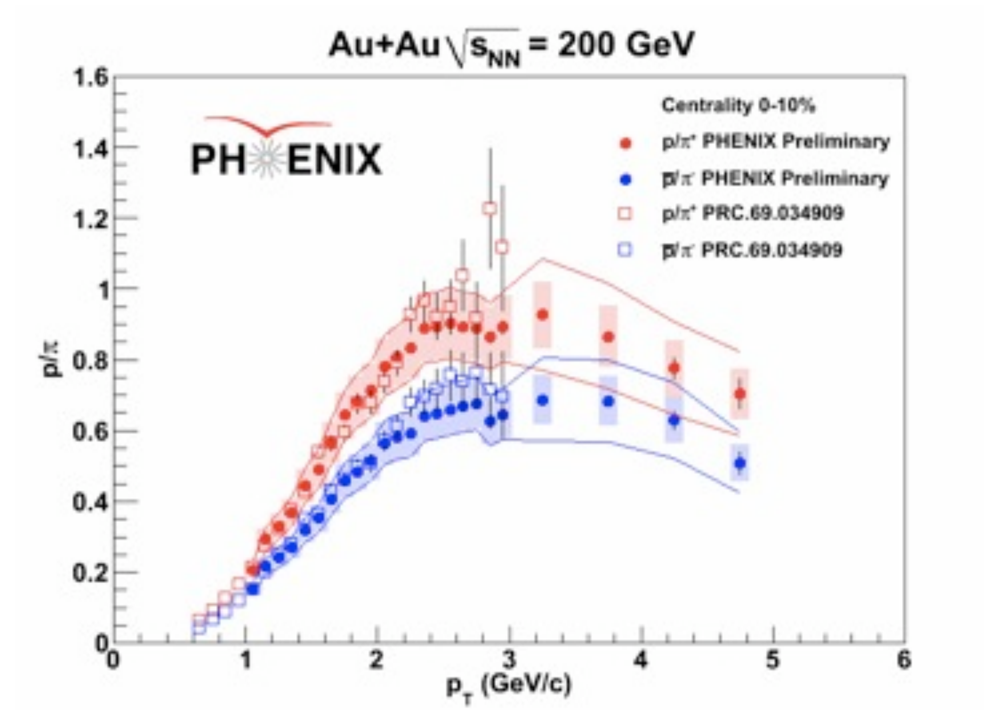

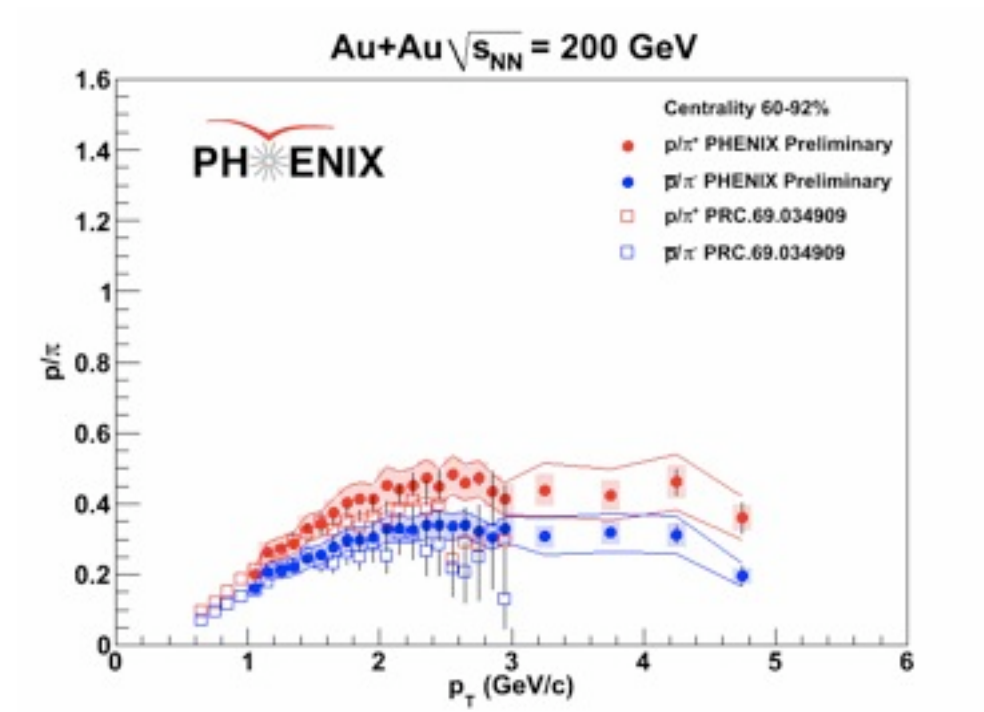

- this needs to be understood

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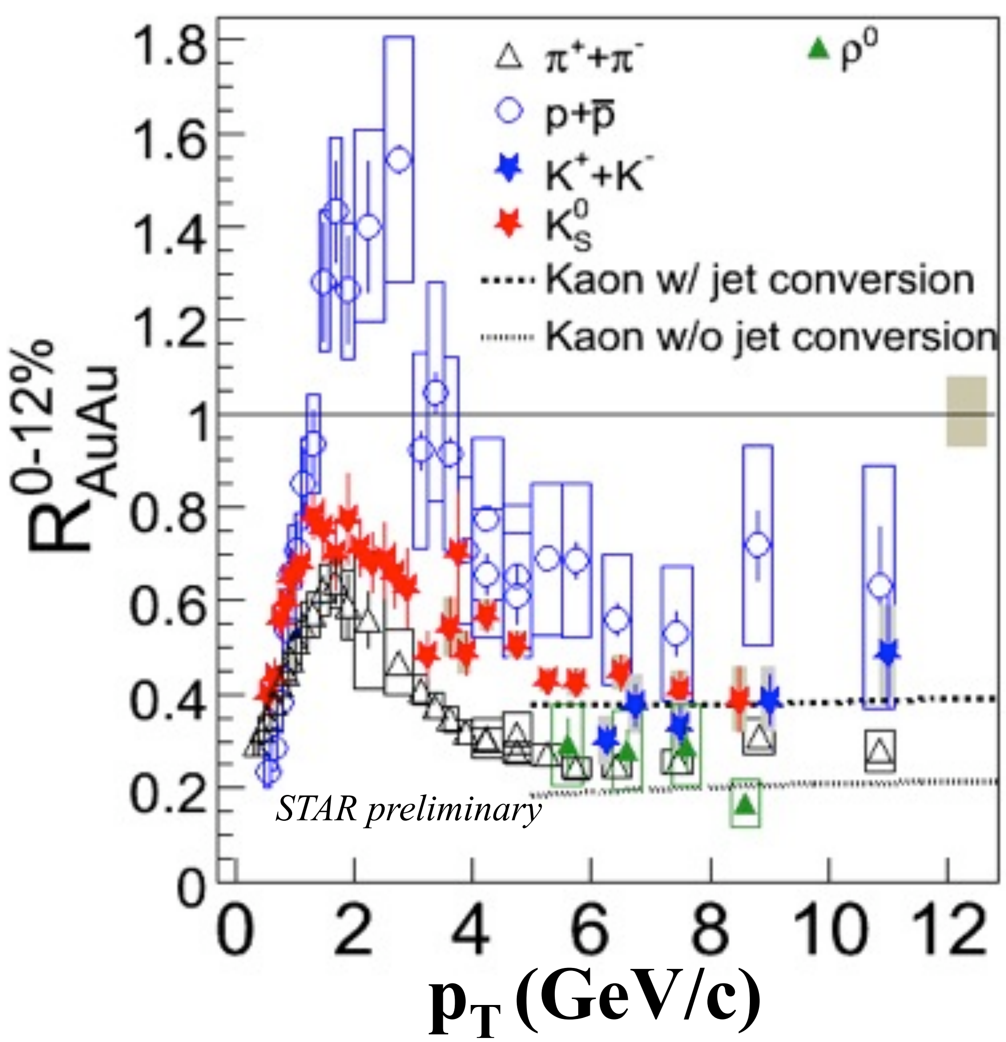

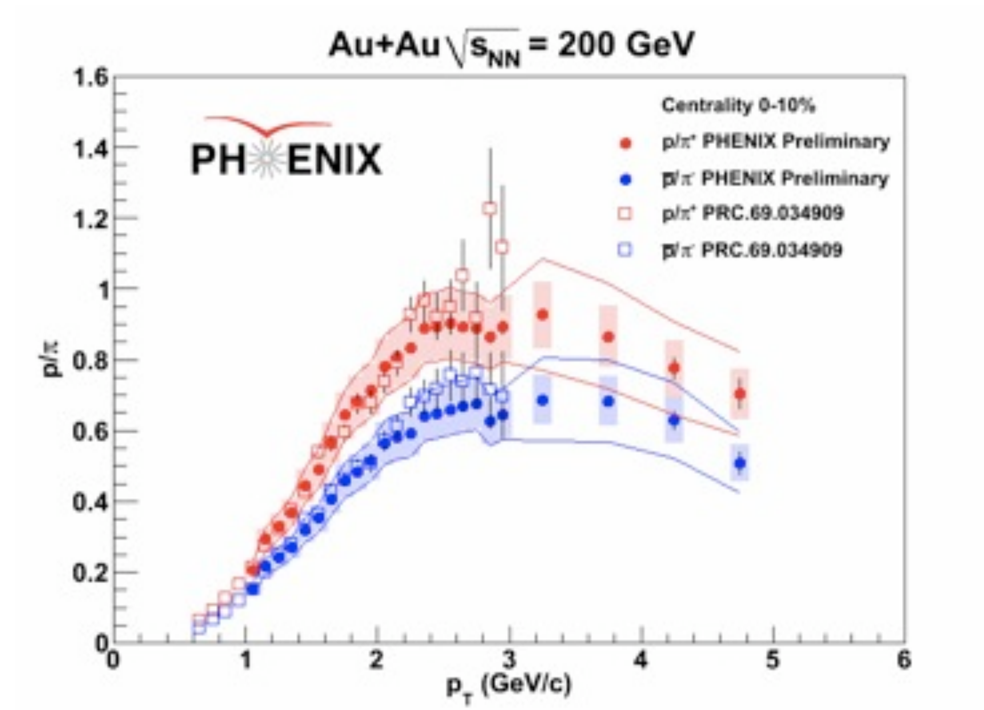

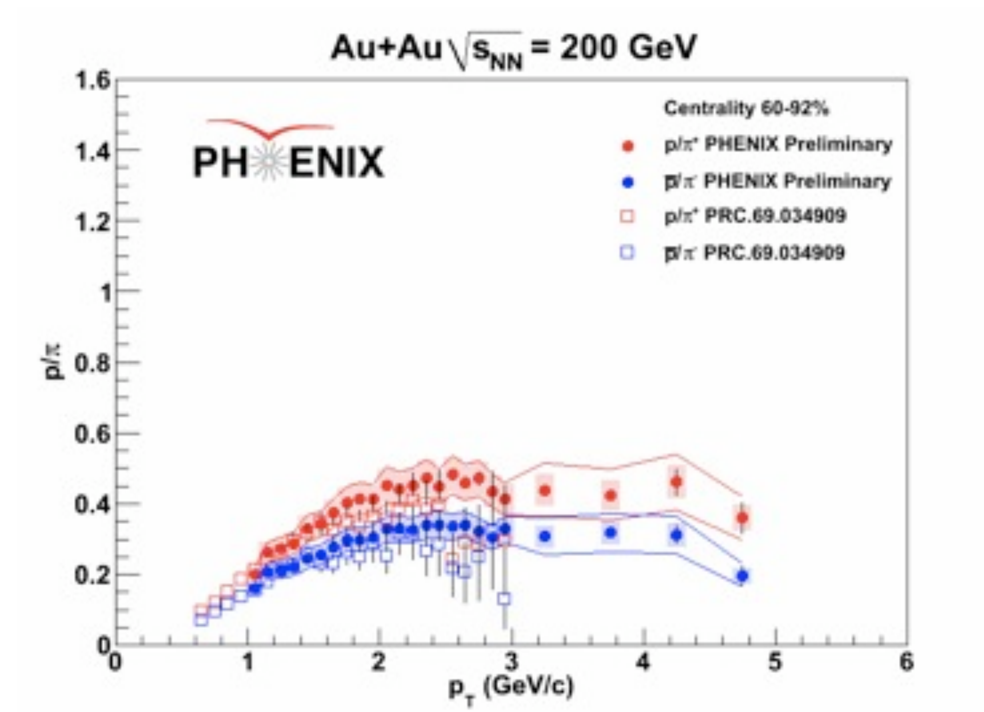

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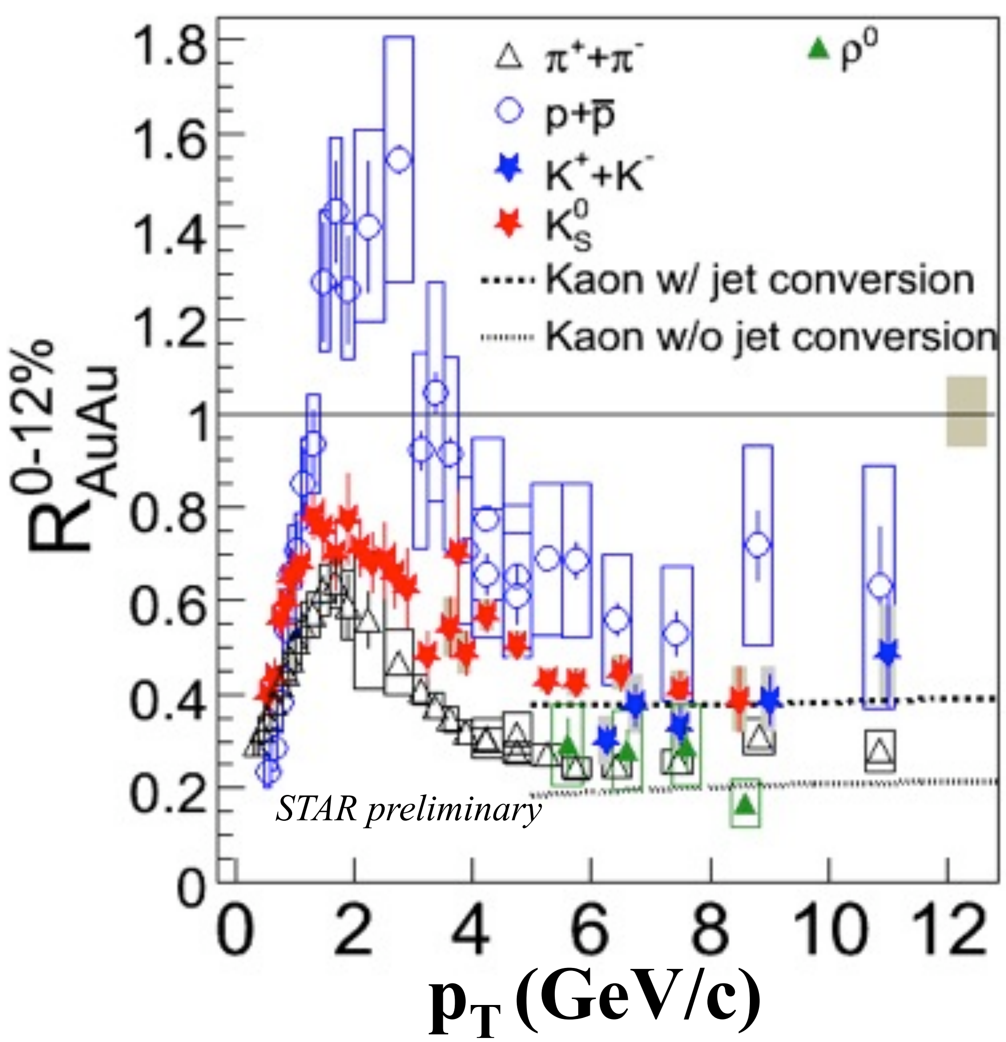
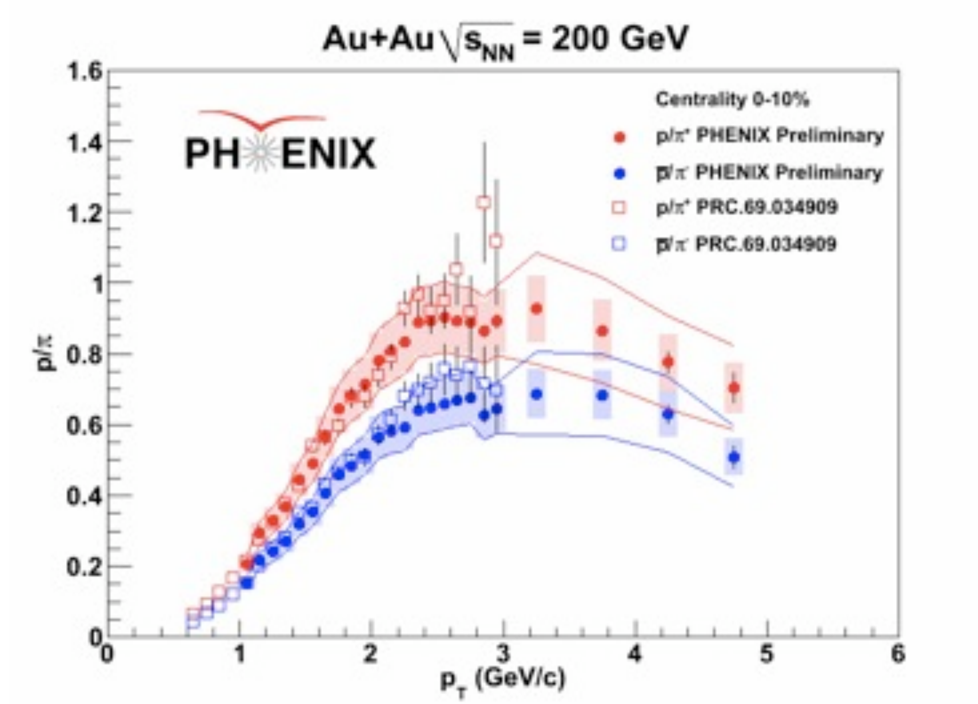
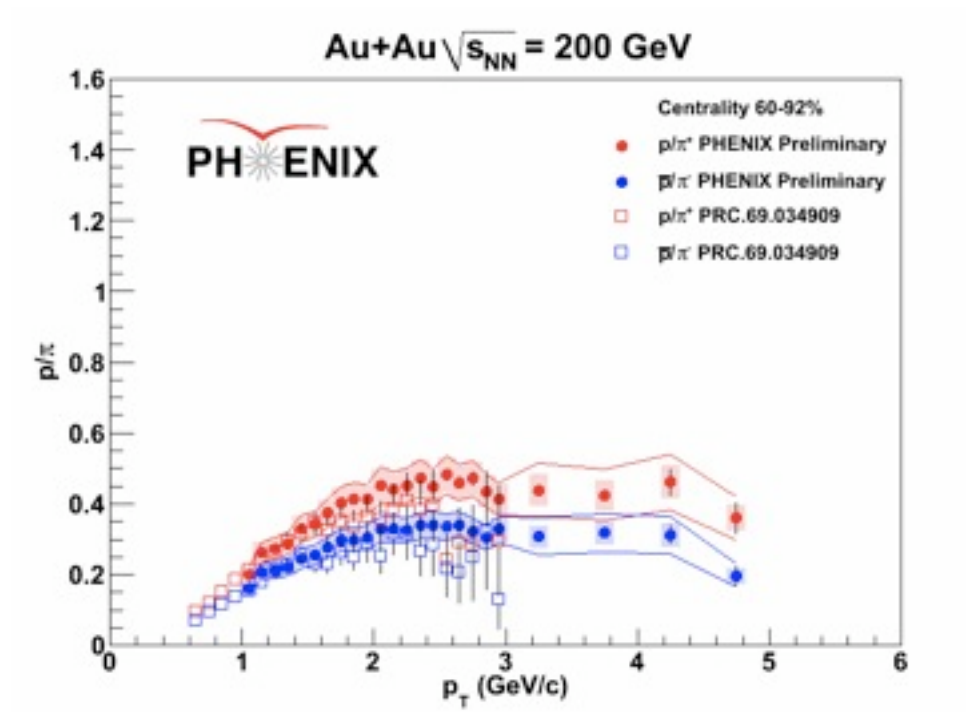
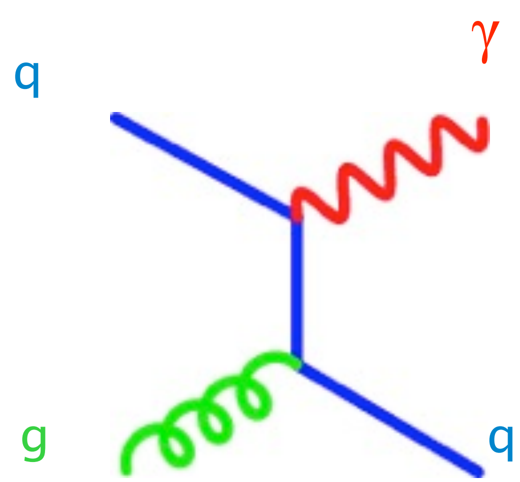






- this needs to be understood
  - high p_T flow?
- direct production, flavor conversions, etc

γ-h correlations



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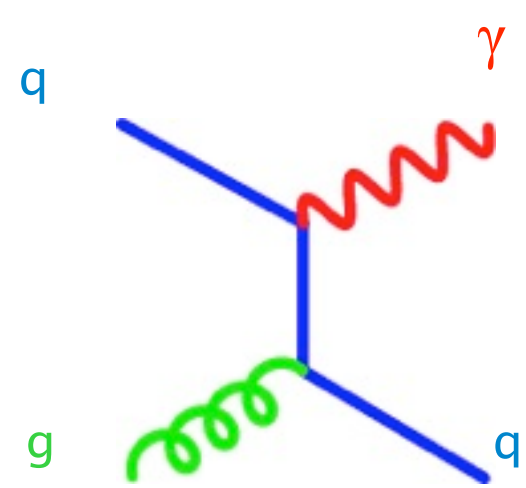

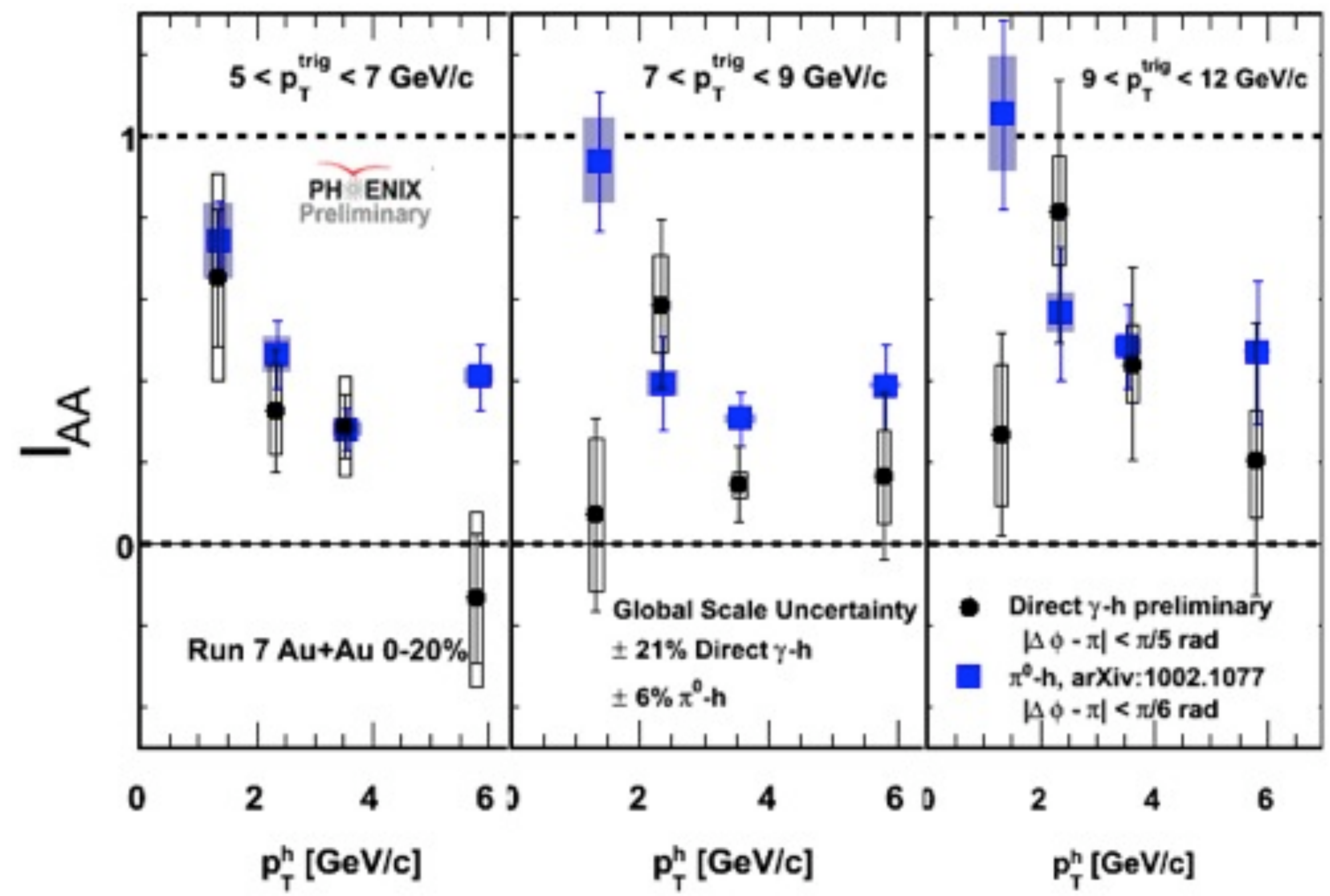

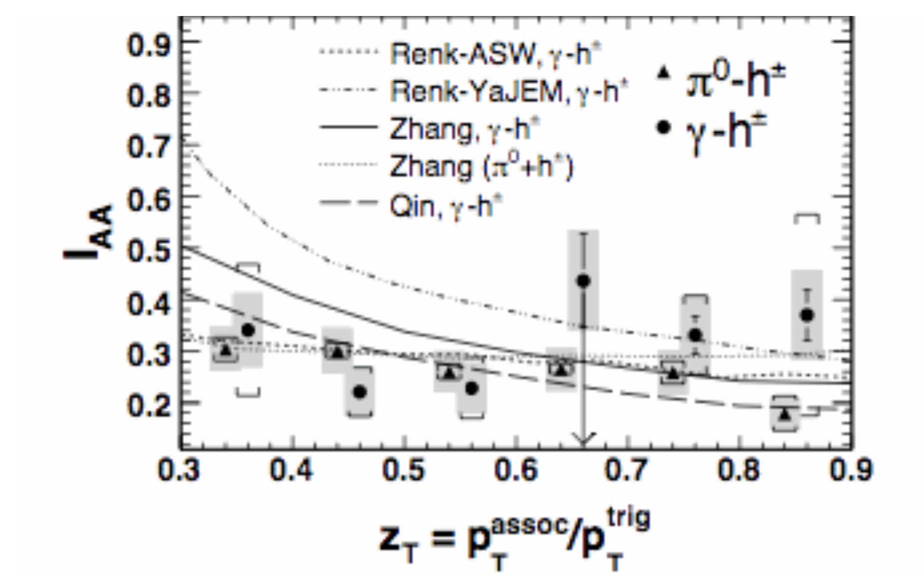

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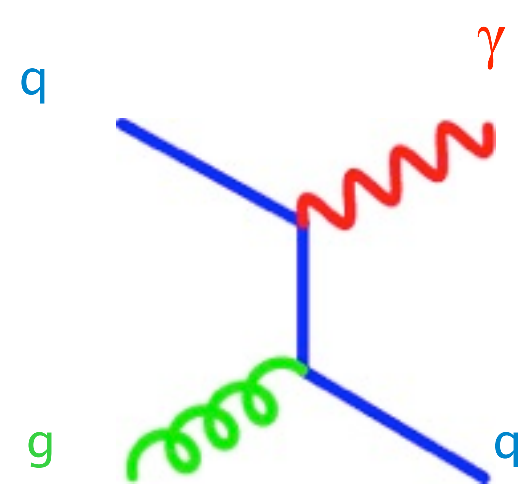
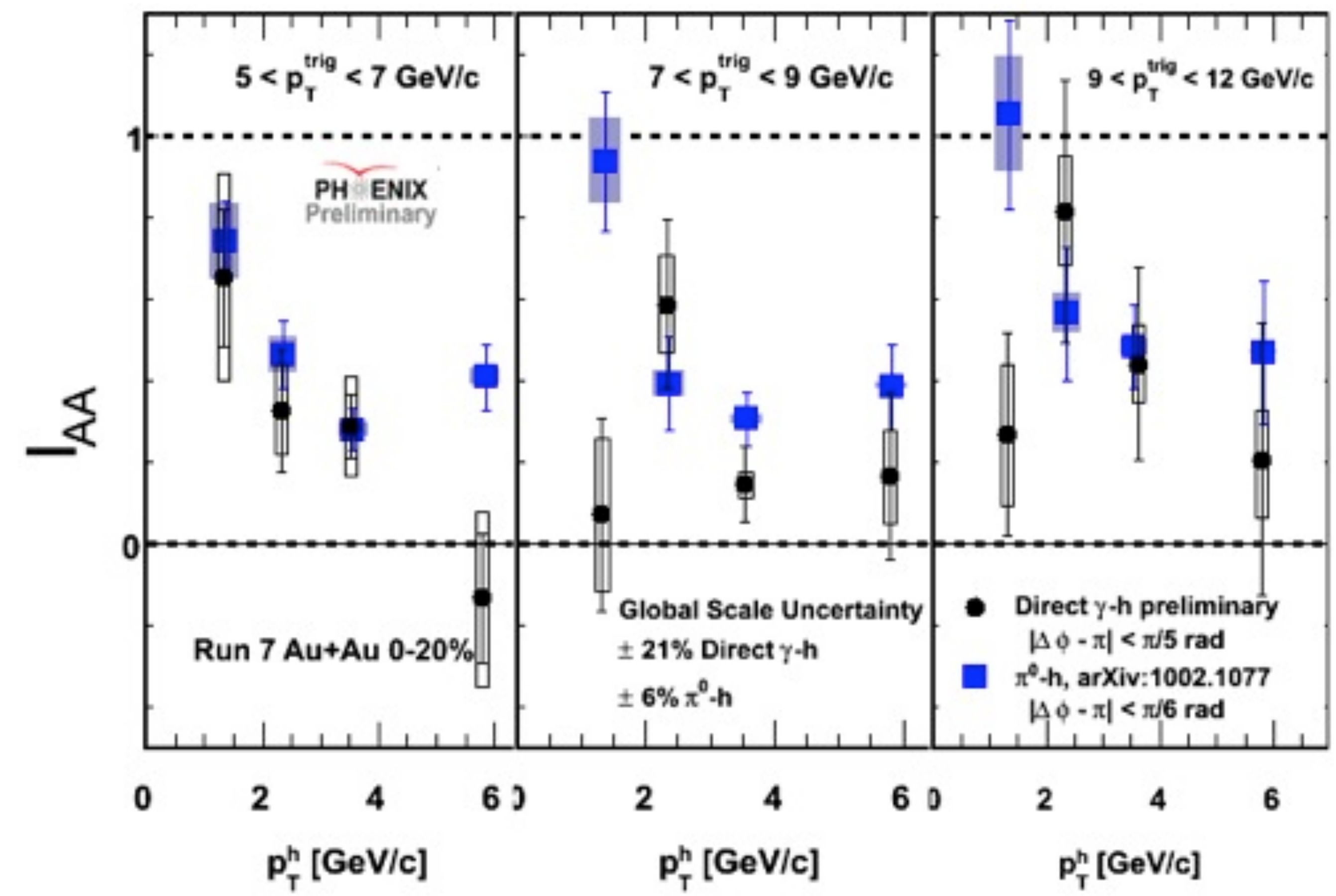
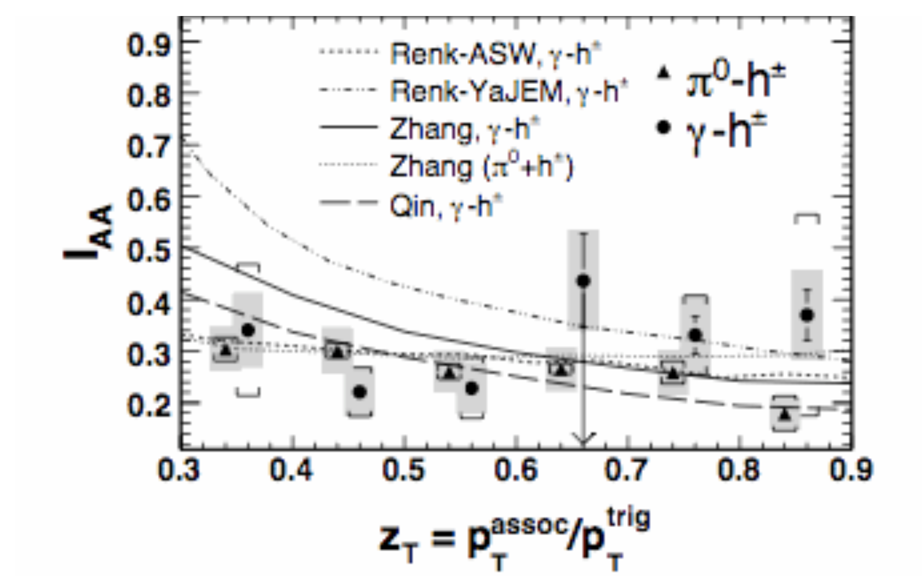




- much firmer ground!



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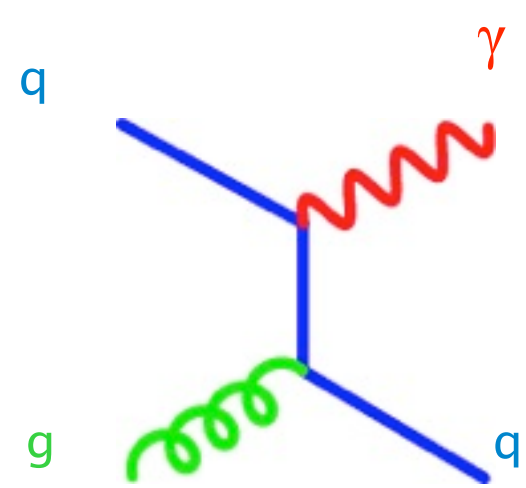

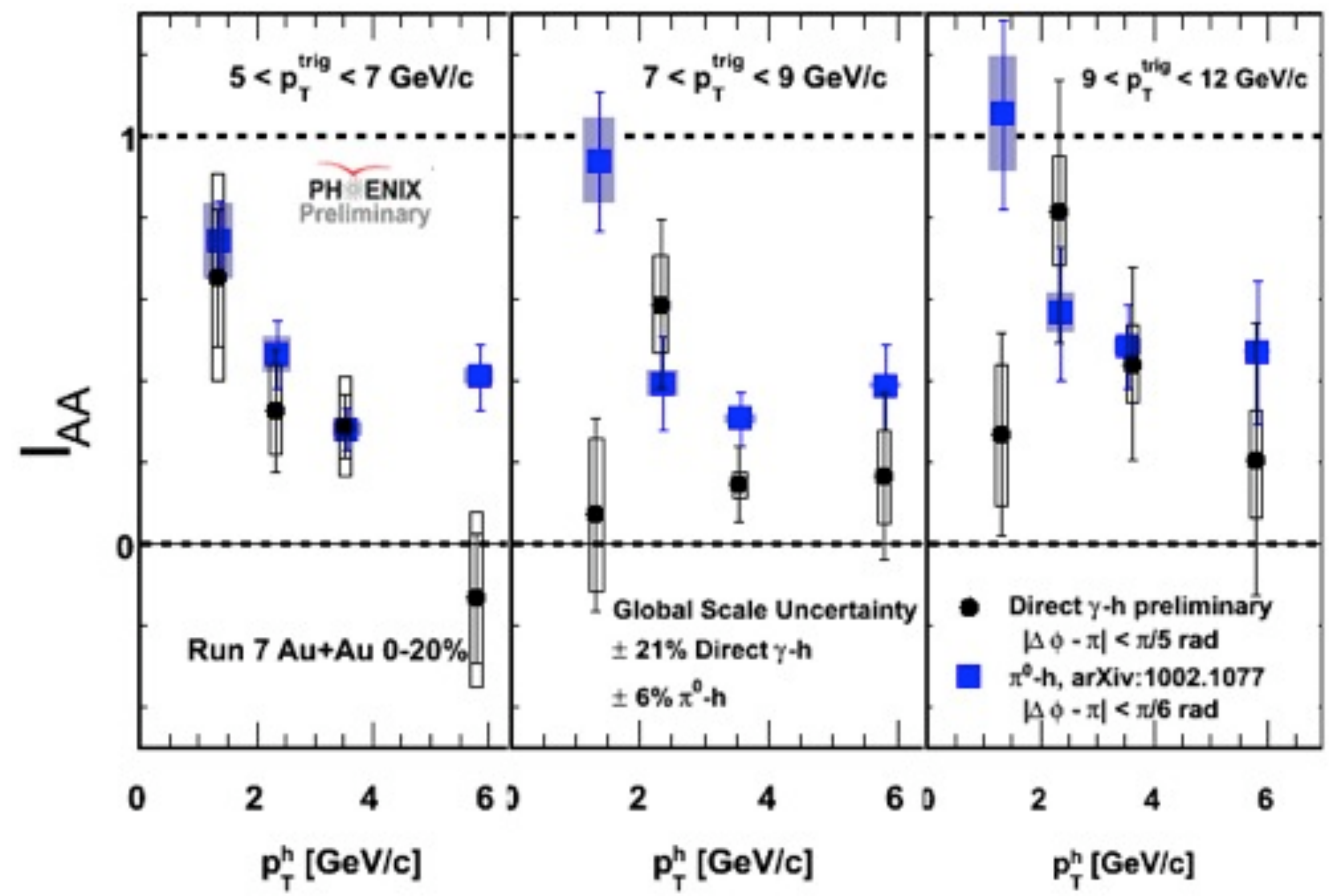

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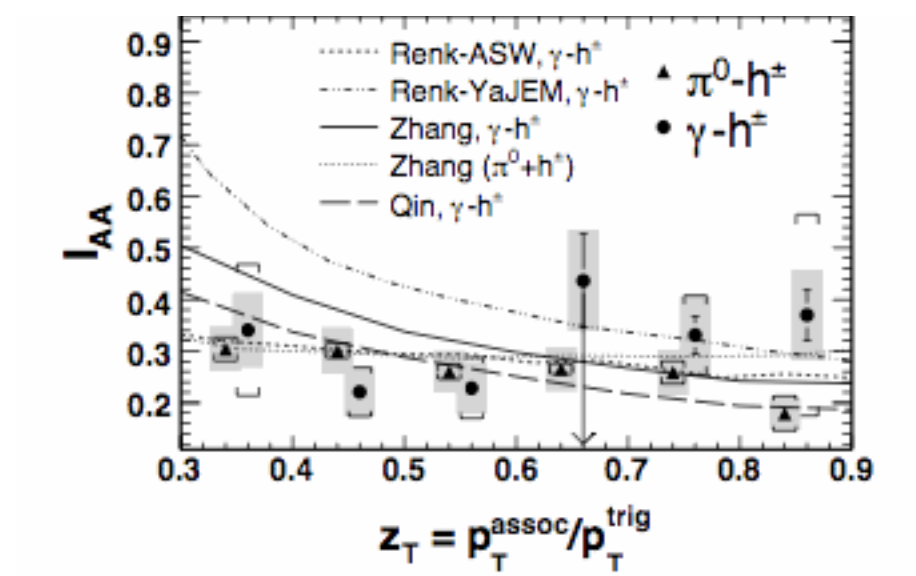

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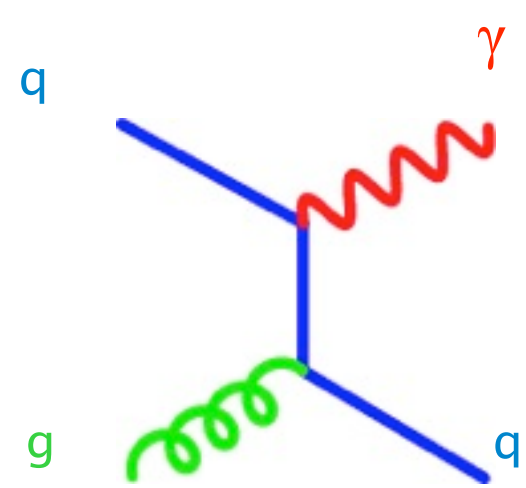

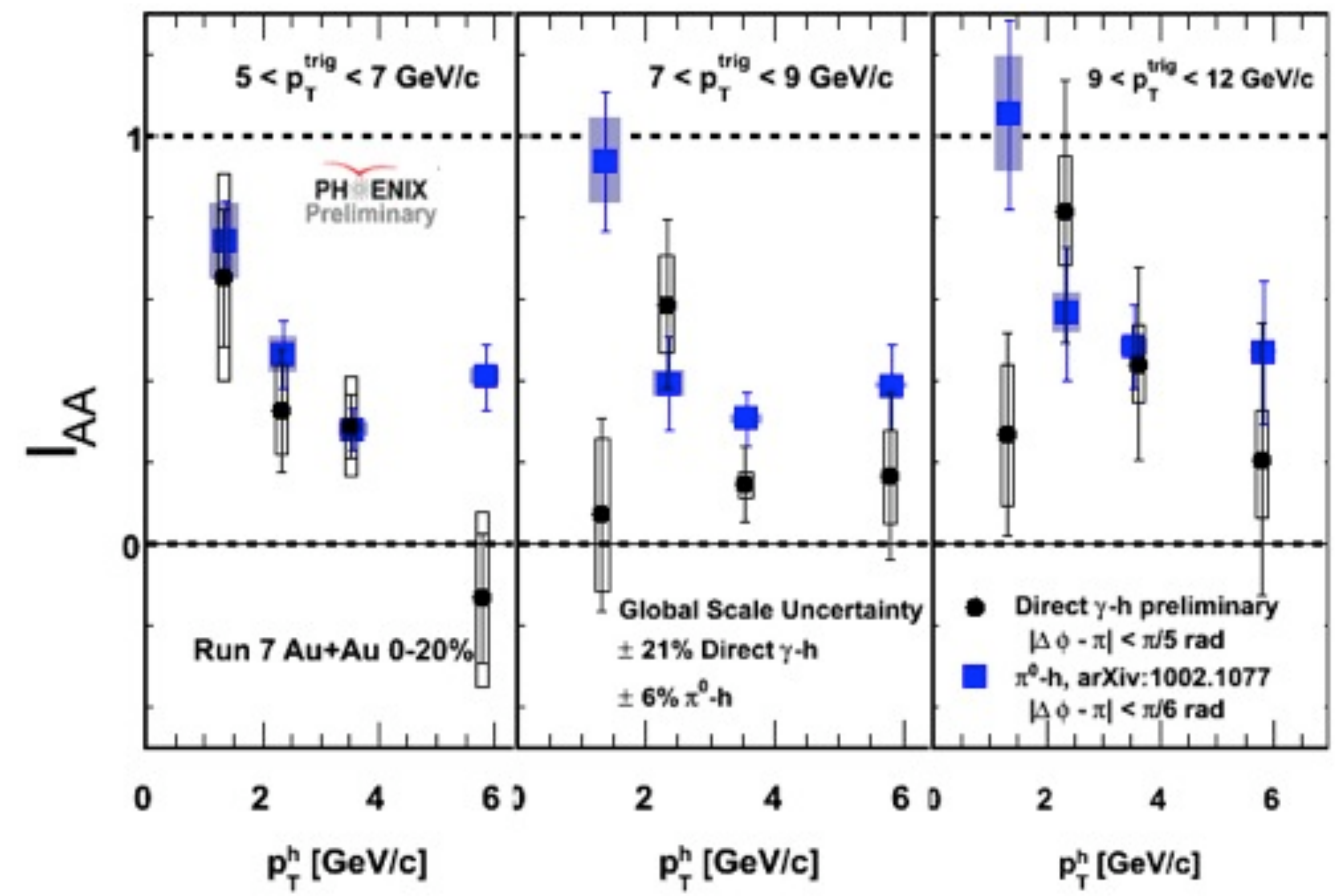

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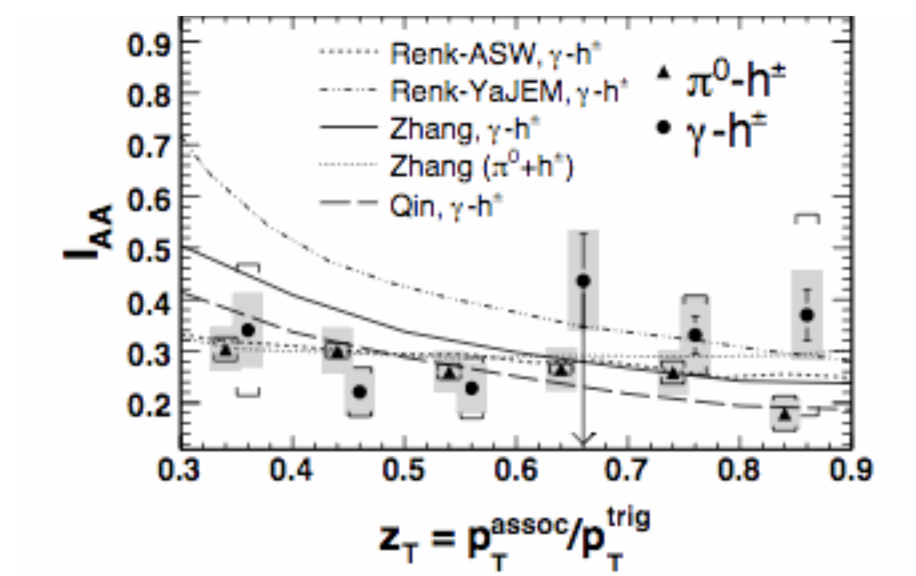

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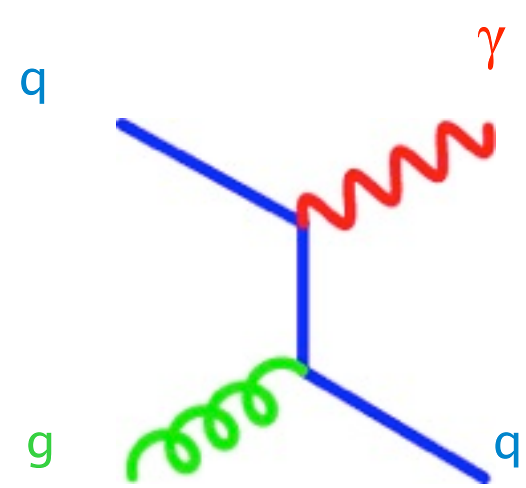

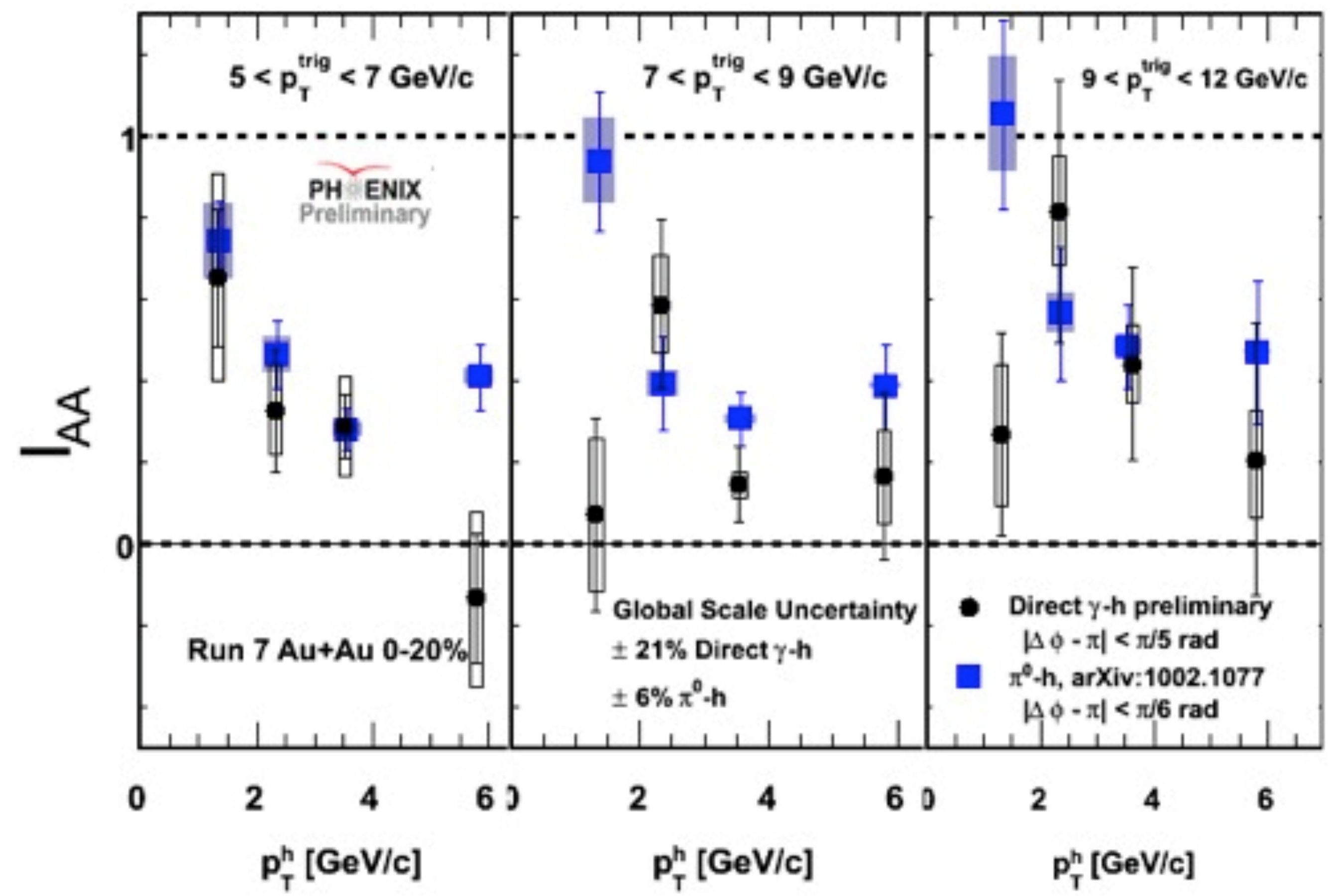

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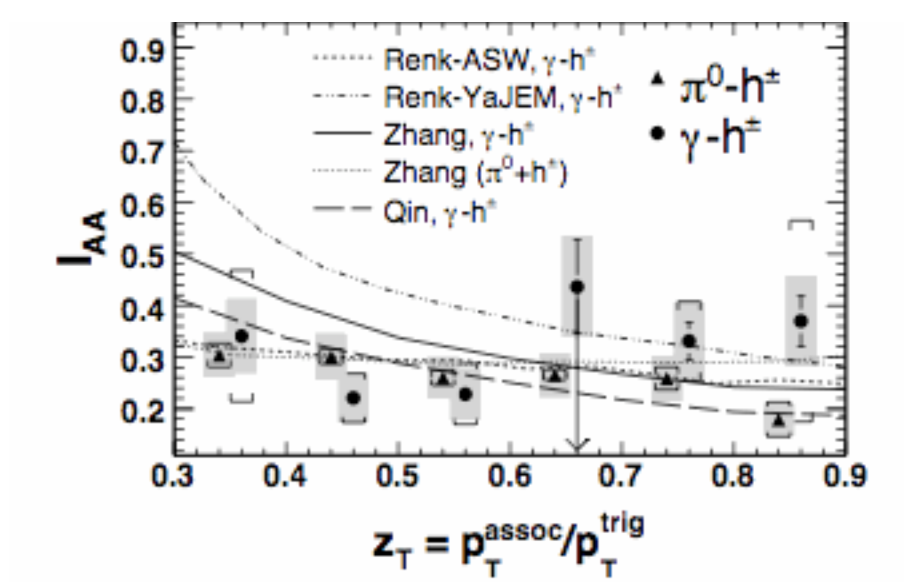

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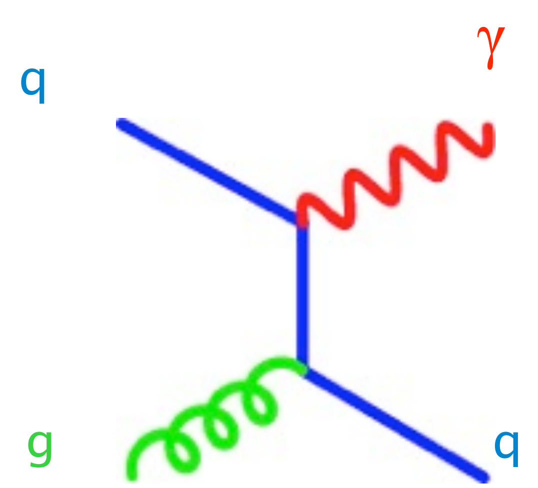
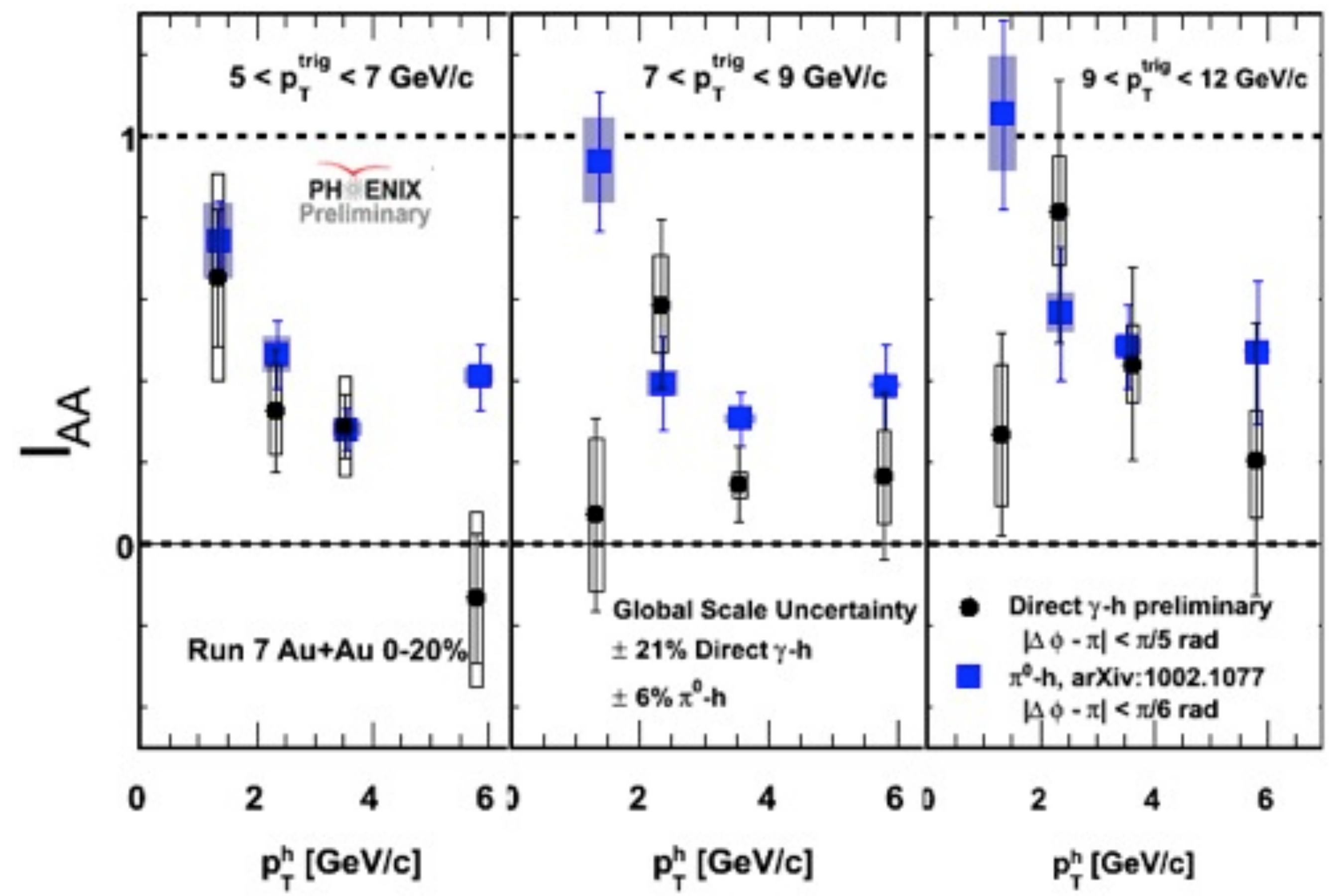
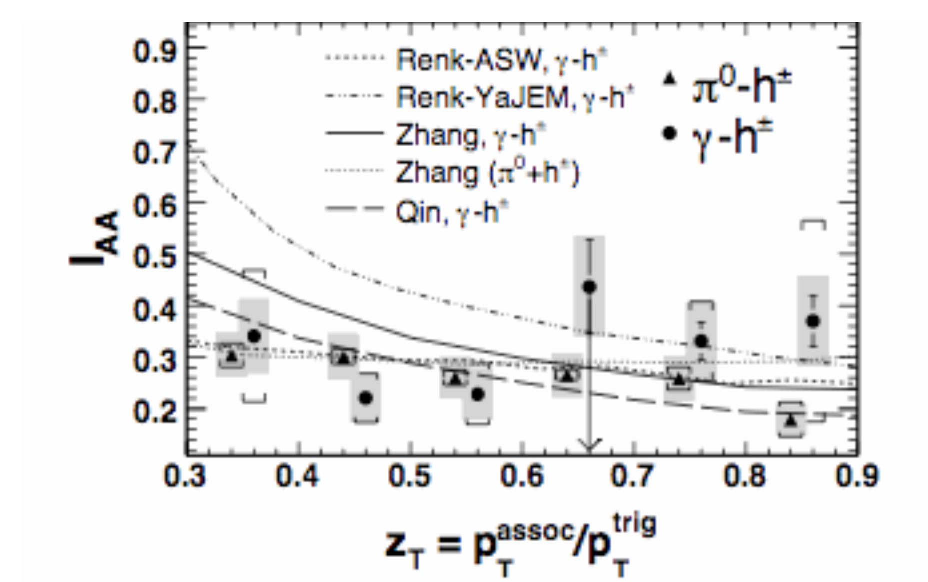




- much firmer ground!
- no evidence π^0-h vs γ-h differences
  - more data just taken
- also other factors play a role
  - surface bias, $\pi^0(p_T)$ < parton p_T



what about strange quarks?

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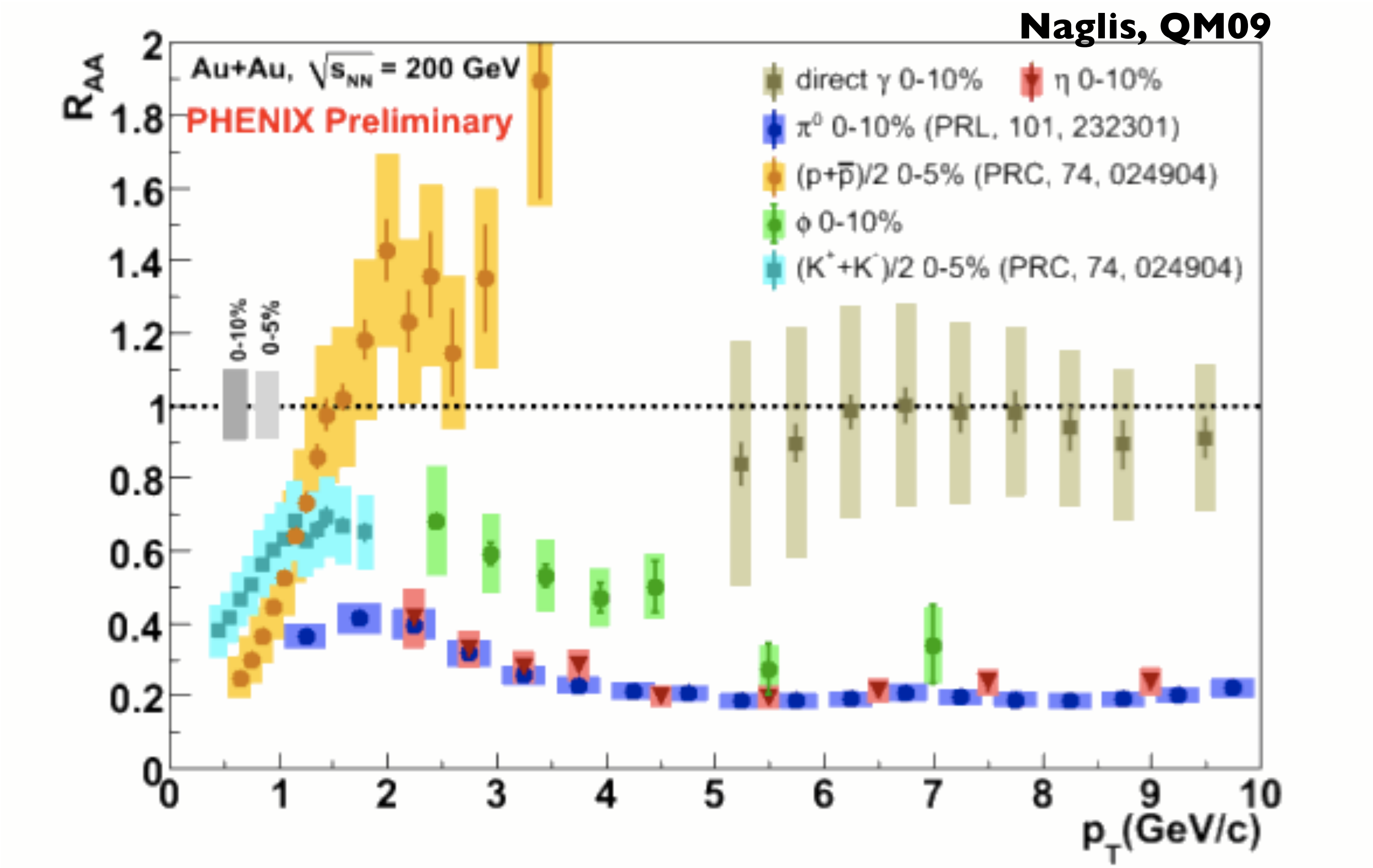

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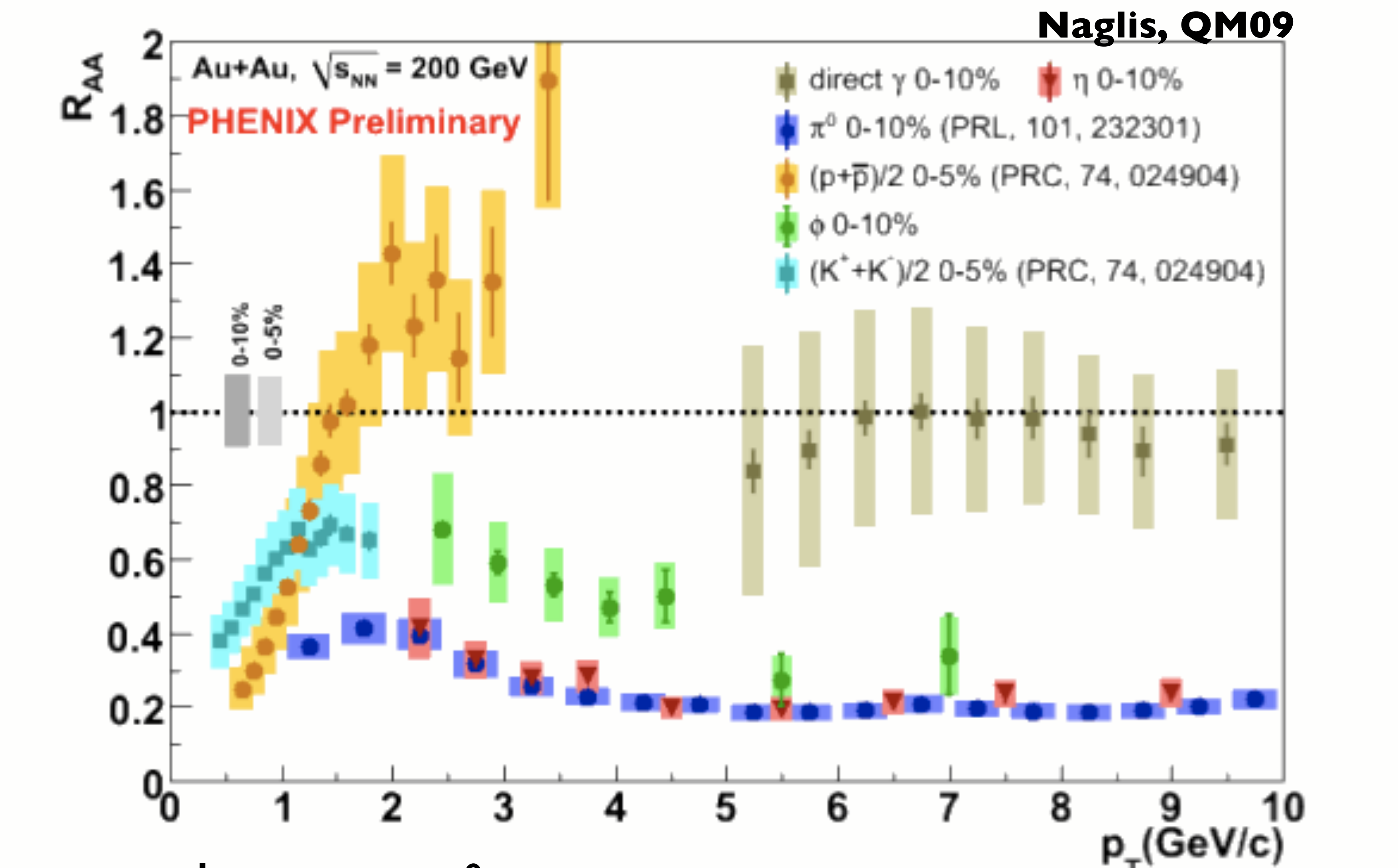

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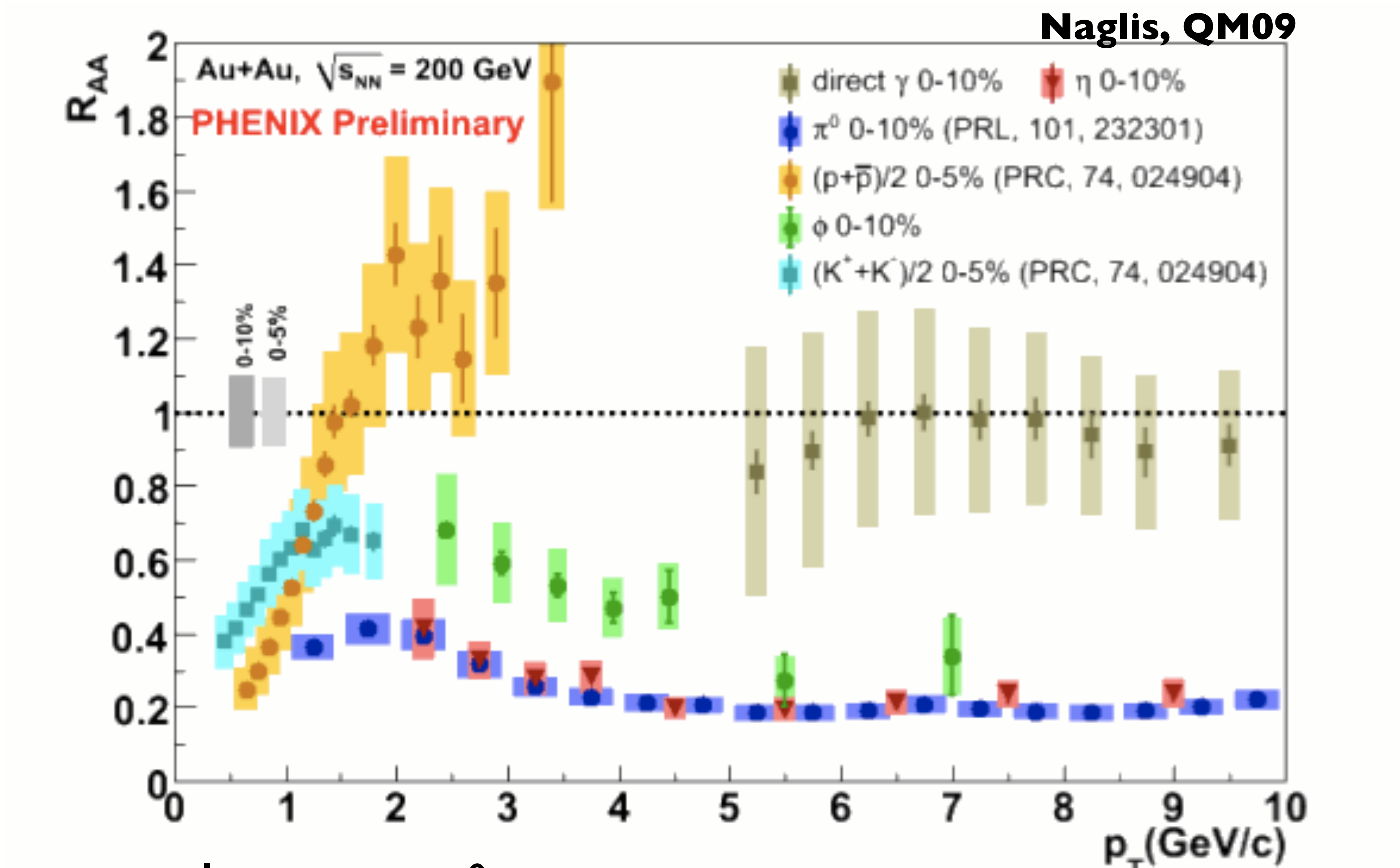

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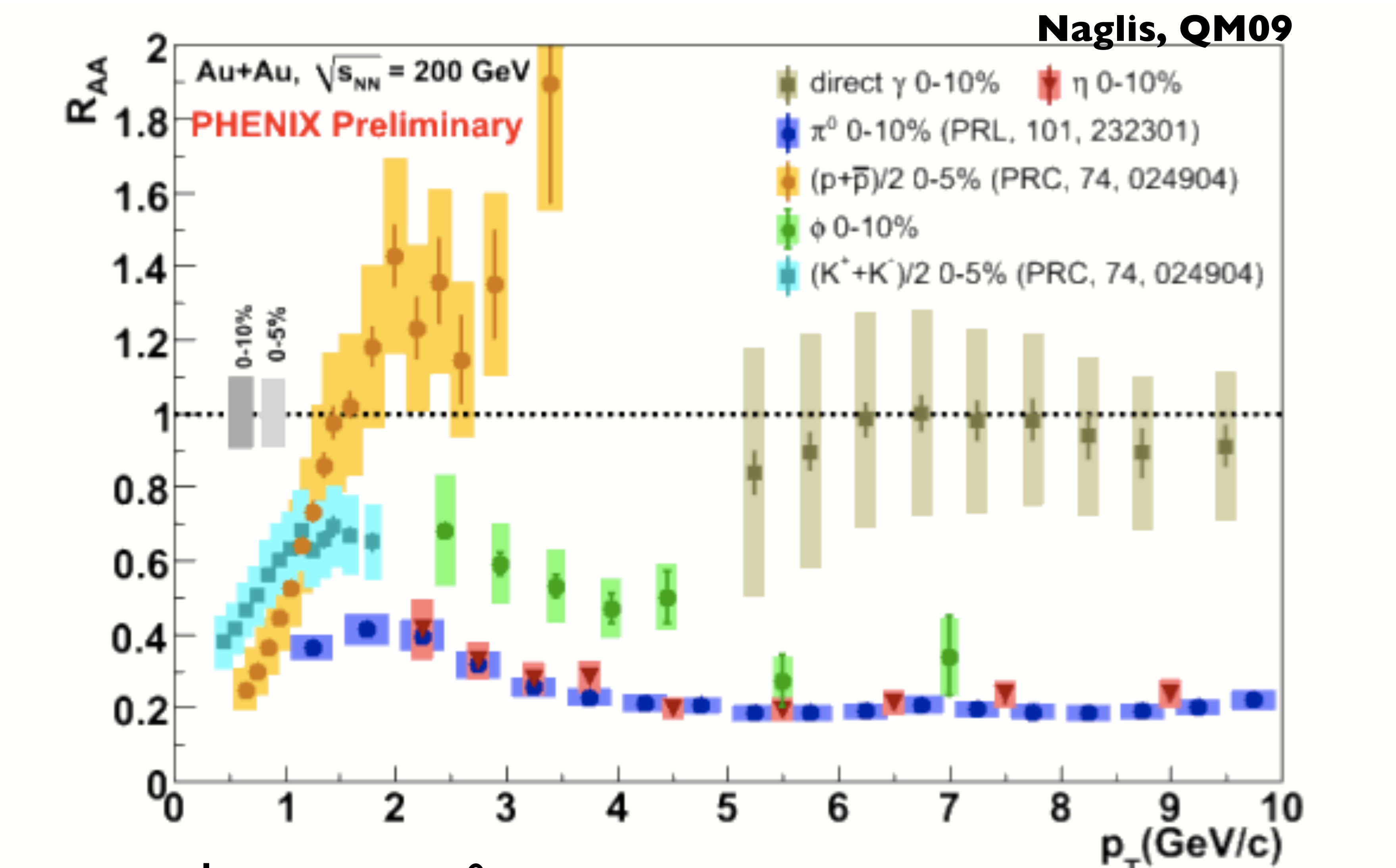

- K, ϕ R_{AA} > π^0, η R_{AA}
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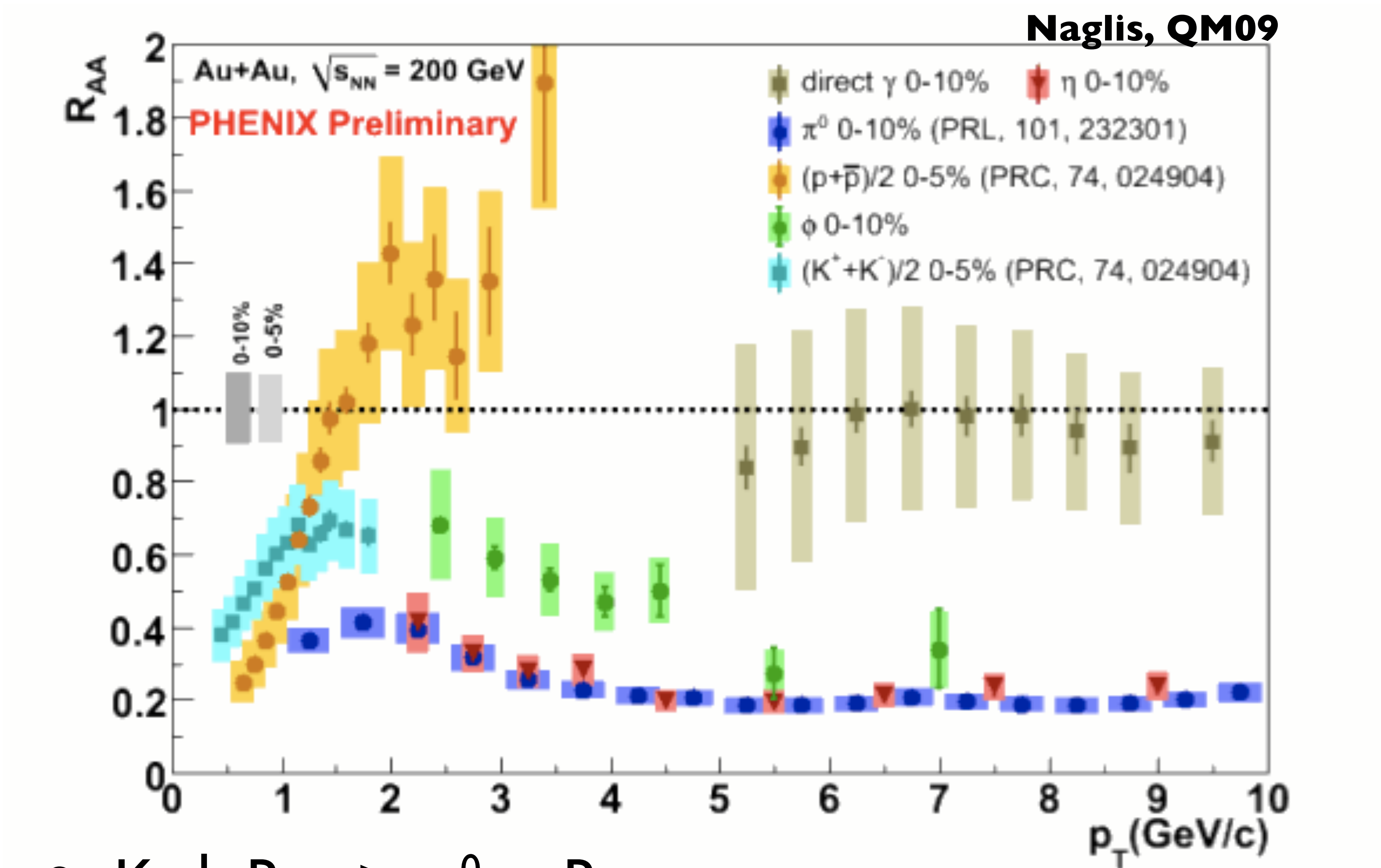
- not the strict baryon/meson separation seen in v_2

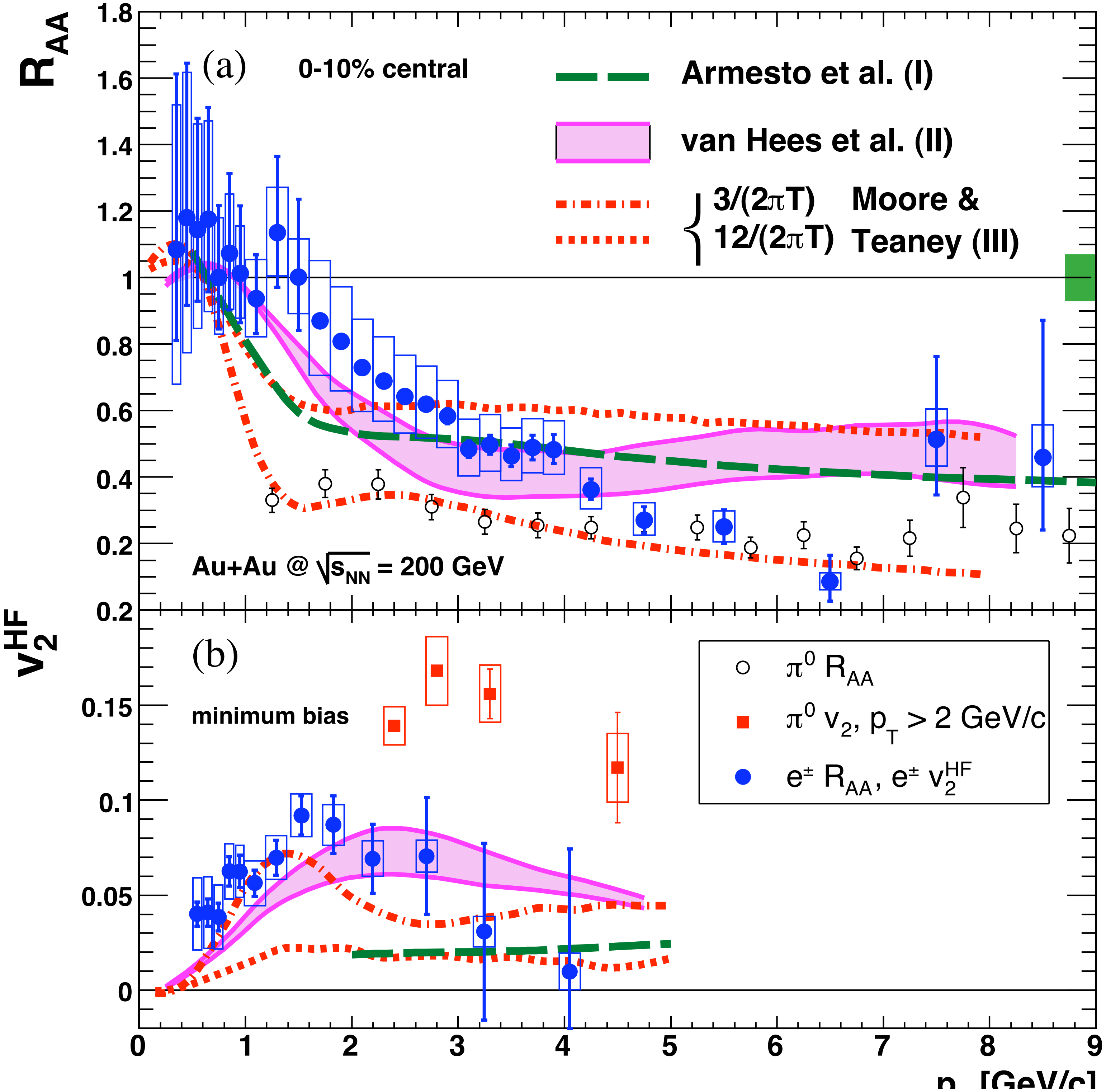
what about strange quarks?



- K, ϕ R_{AA} > π^0, η R_{AA}
  - $M_K < M_\phi$ $R_{AA}(K) \sim R_{AA}(\phi)$
- not the strict baryon/meson separation seen in v_2
- no significant effects of hidden strangeness in η

heavy flavor

heavy flavor



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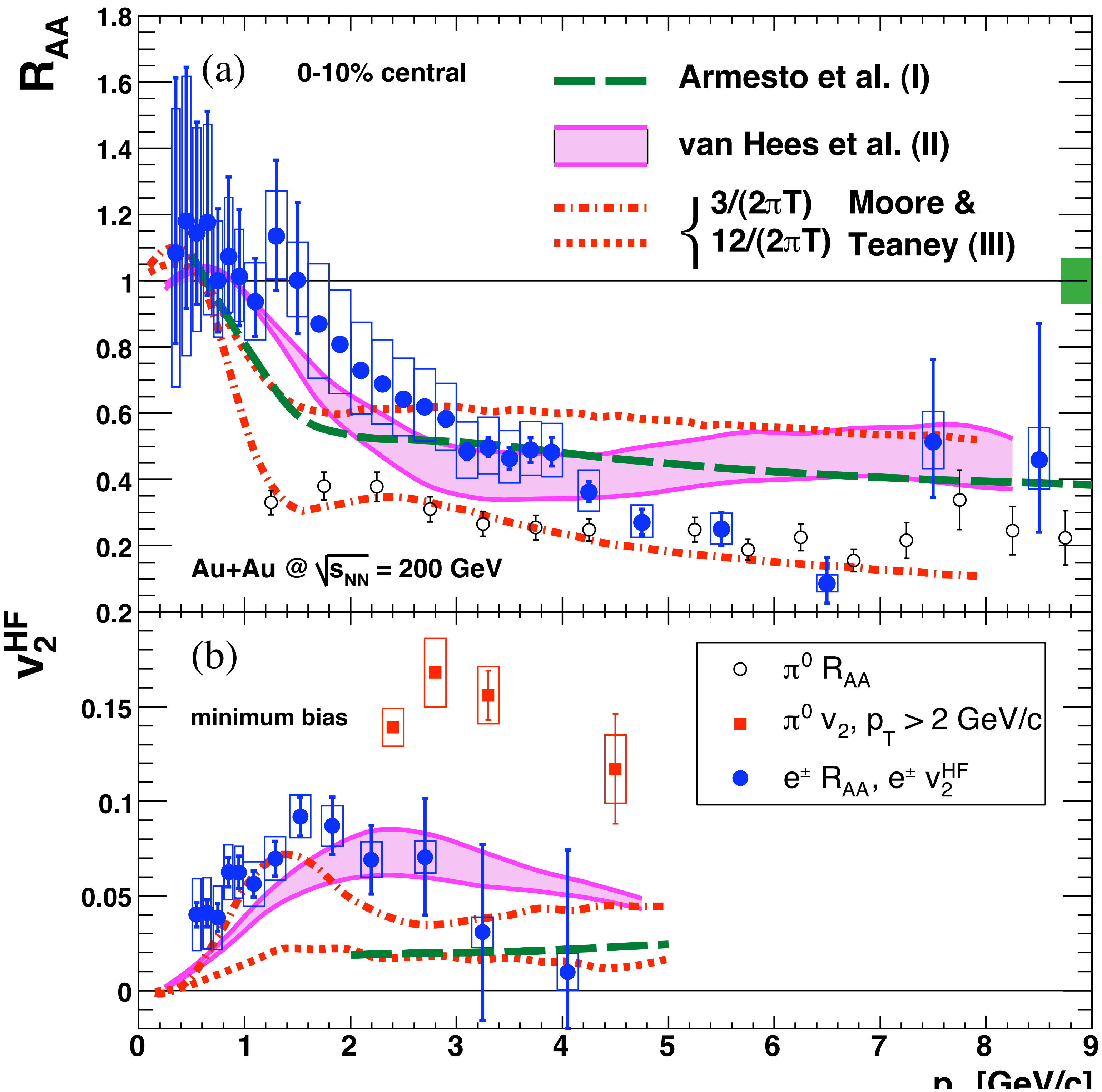

- collectivity and suppression
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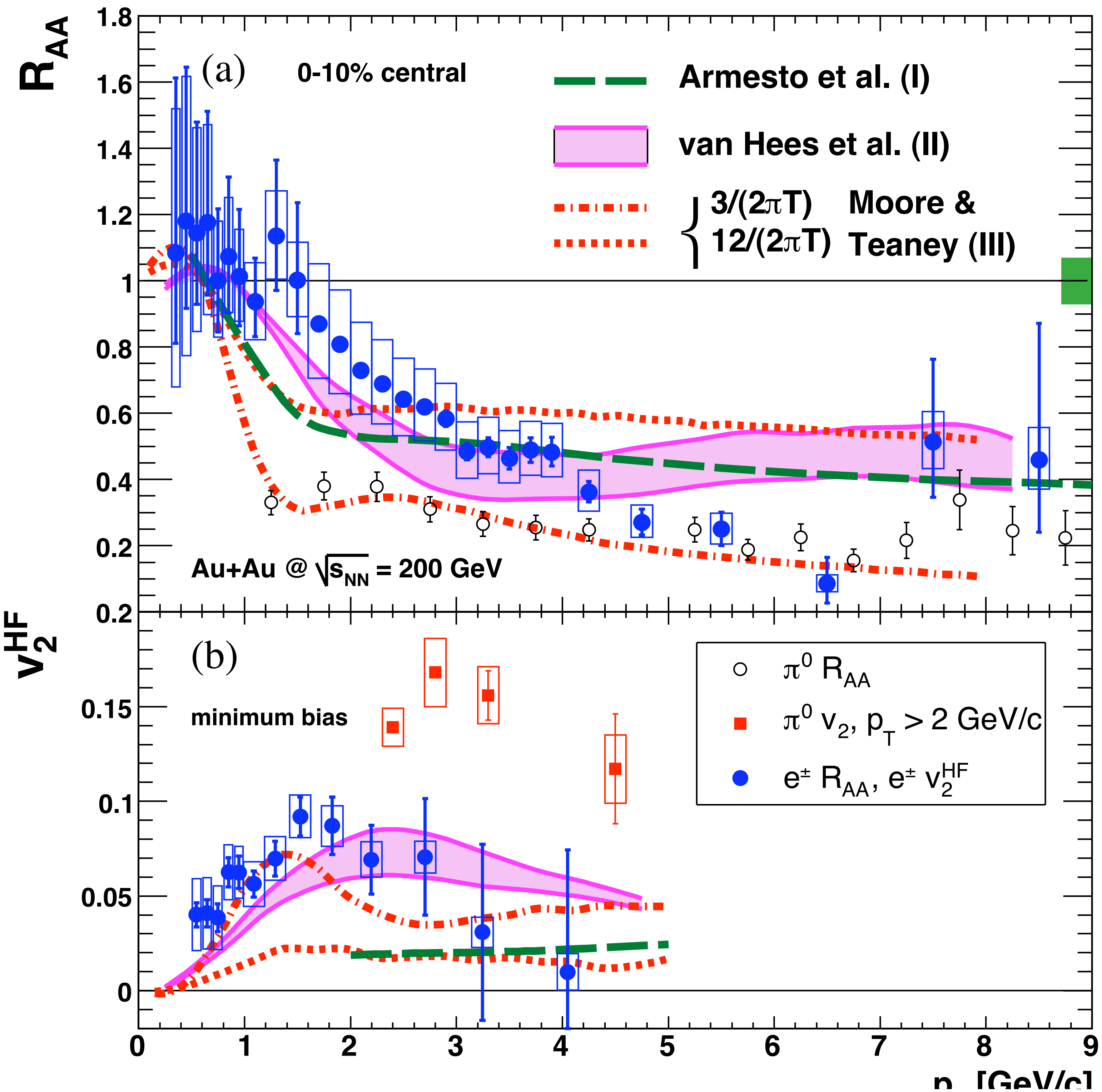

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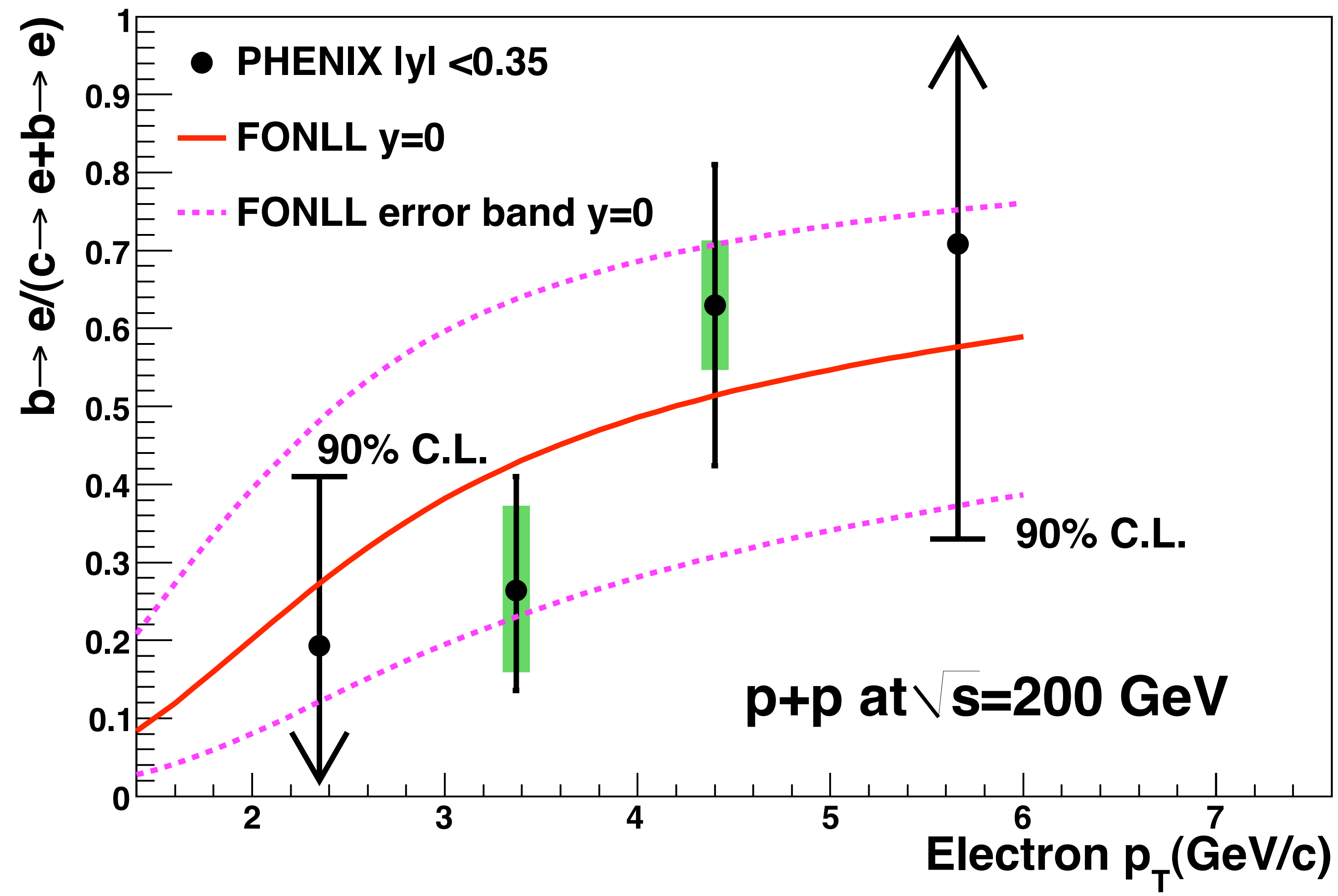
formation time for 10GeV hadron

pion	25fm
D	1.6fm
B	0.4fm

Adil & Vitev PLB 649 139 (2007)

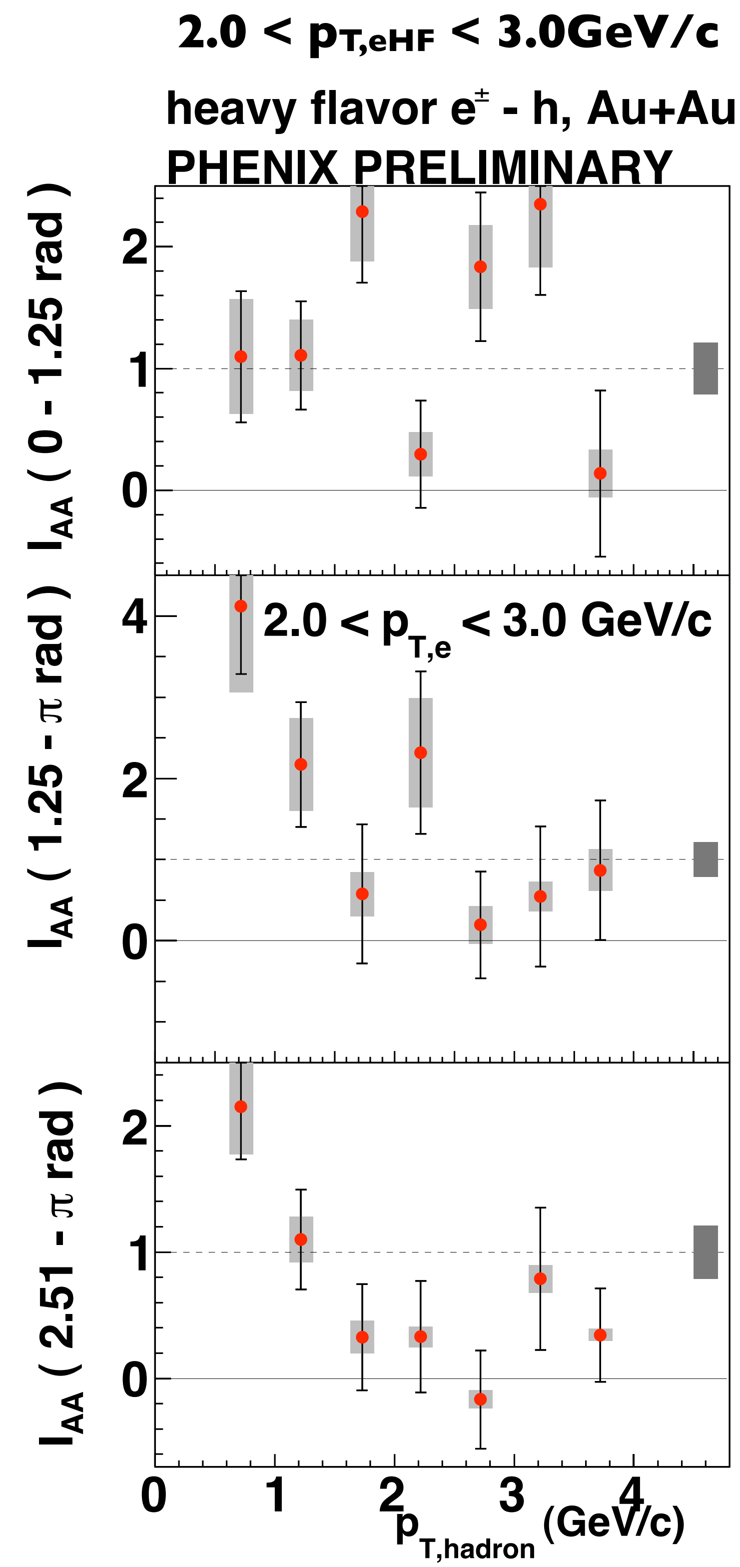
charm vs. bottom

- suppression large even as electrons become dominated by bottom at high pT
- possibility of novel suppression mechanisms
  - e.g. Adil & Vitev in medium formation/ dissocication



PHENIX PRL 103 082002 (2009)

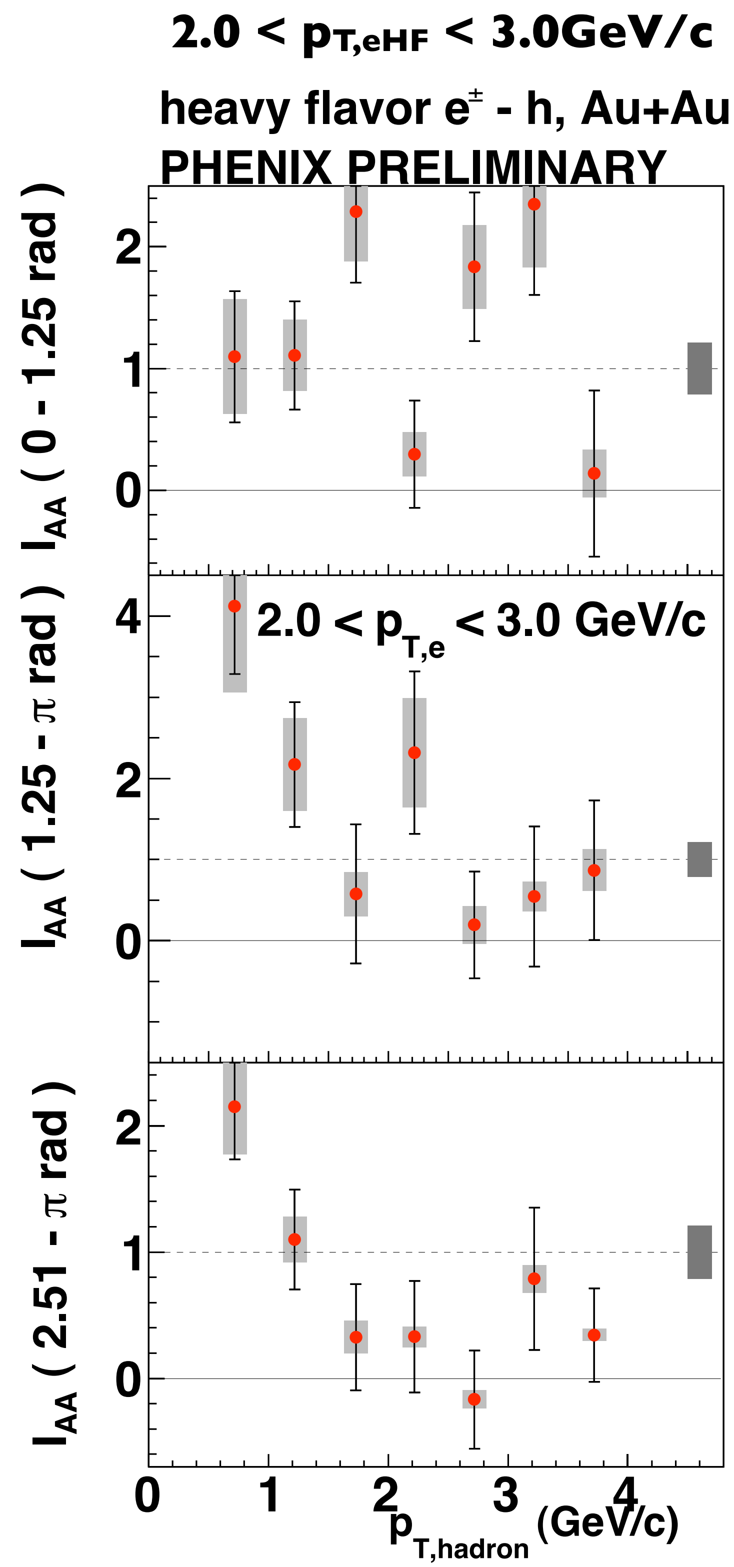
correlations: some insight



PRC 78 014901 (2008)

correlations: some insight

- near side: I_{AA}~1



PRC 78 014901 (2008)

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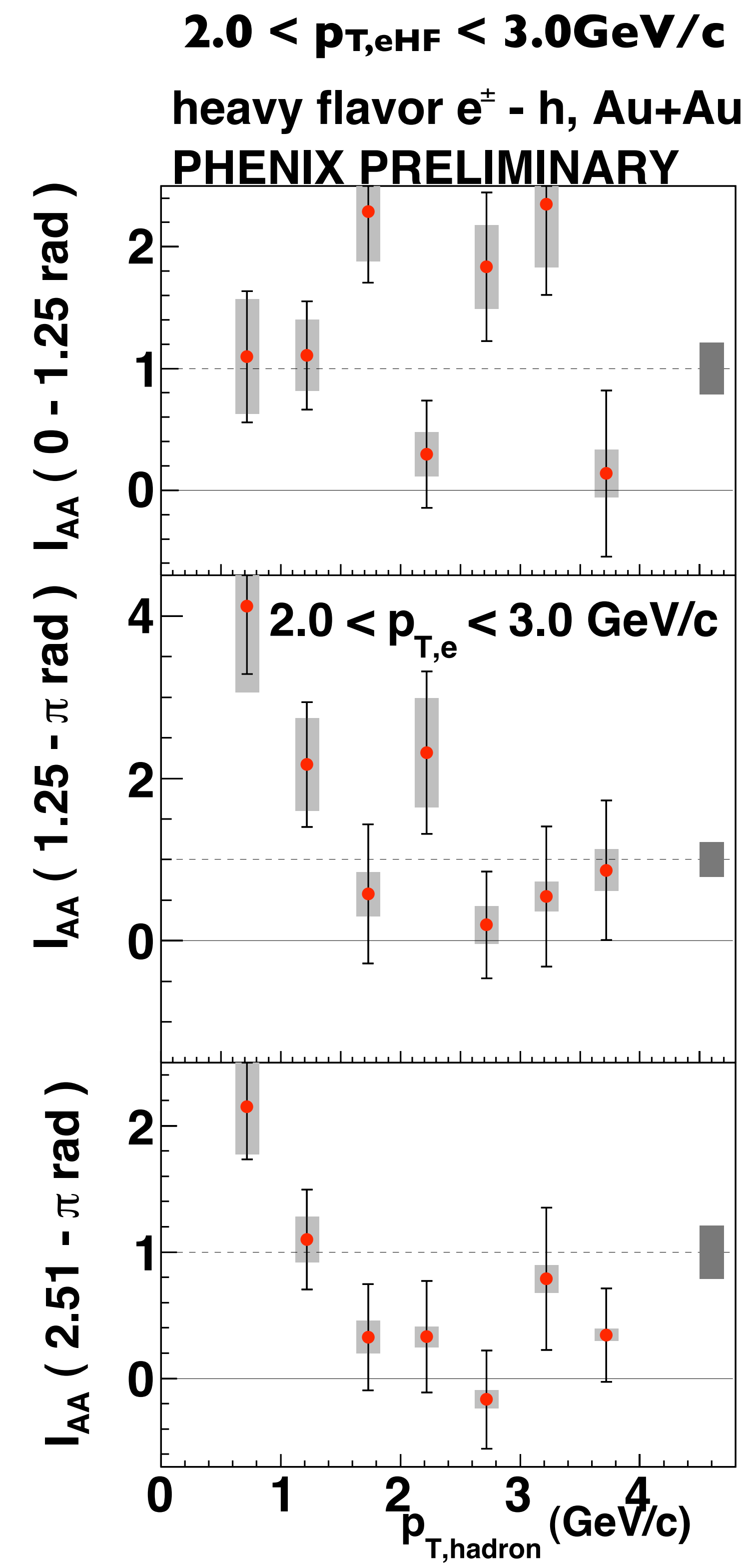

PRC 78 014901 (2008)

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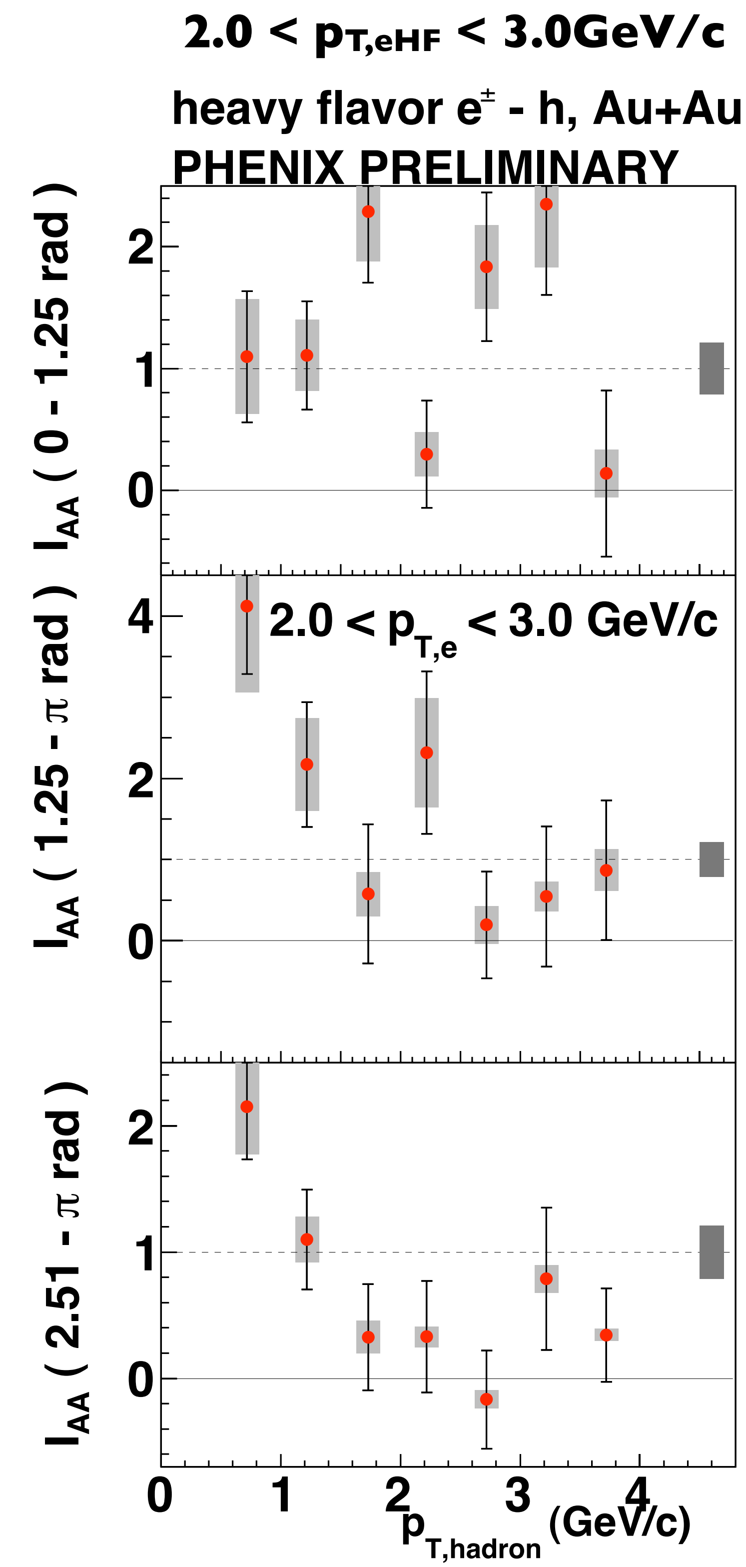

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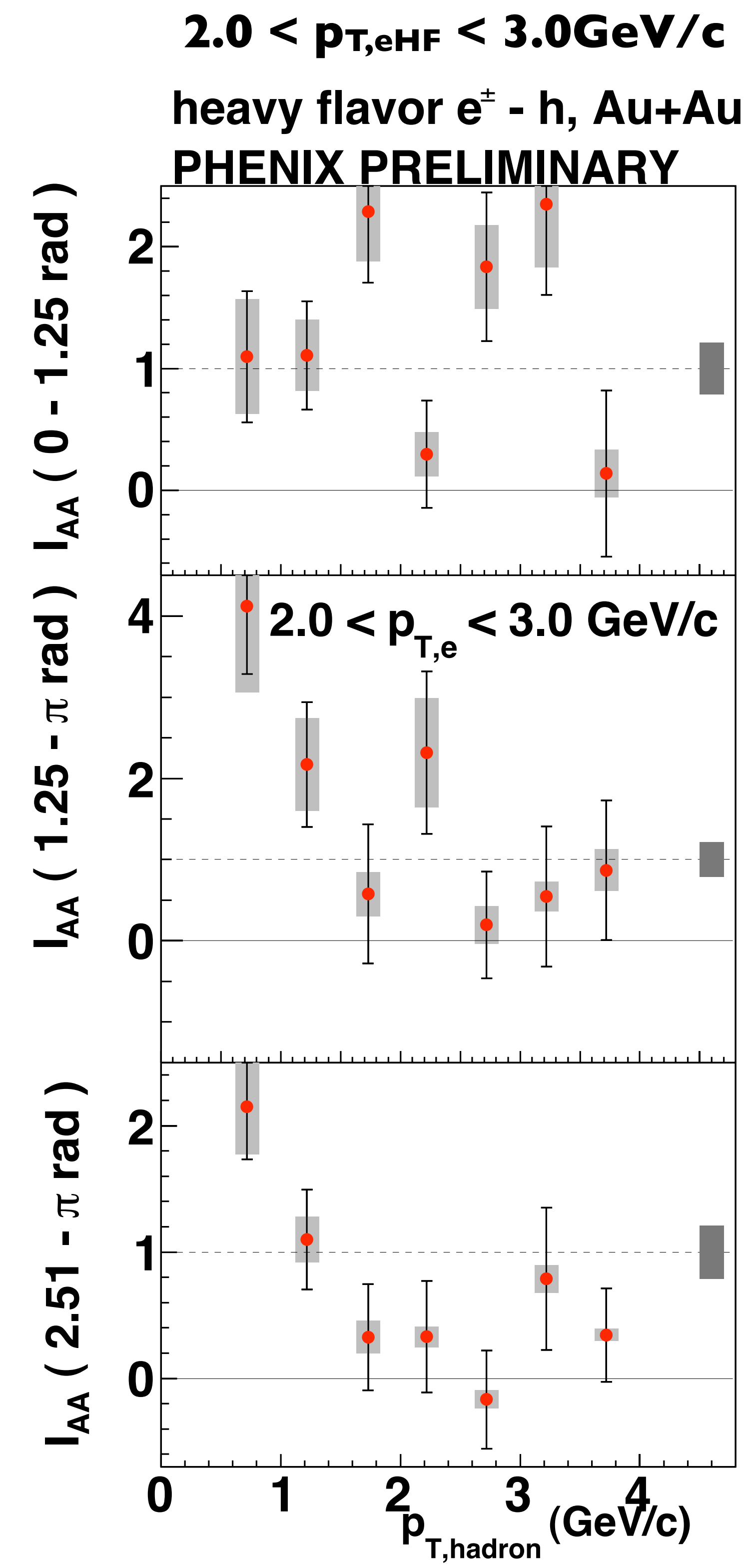

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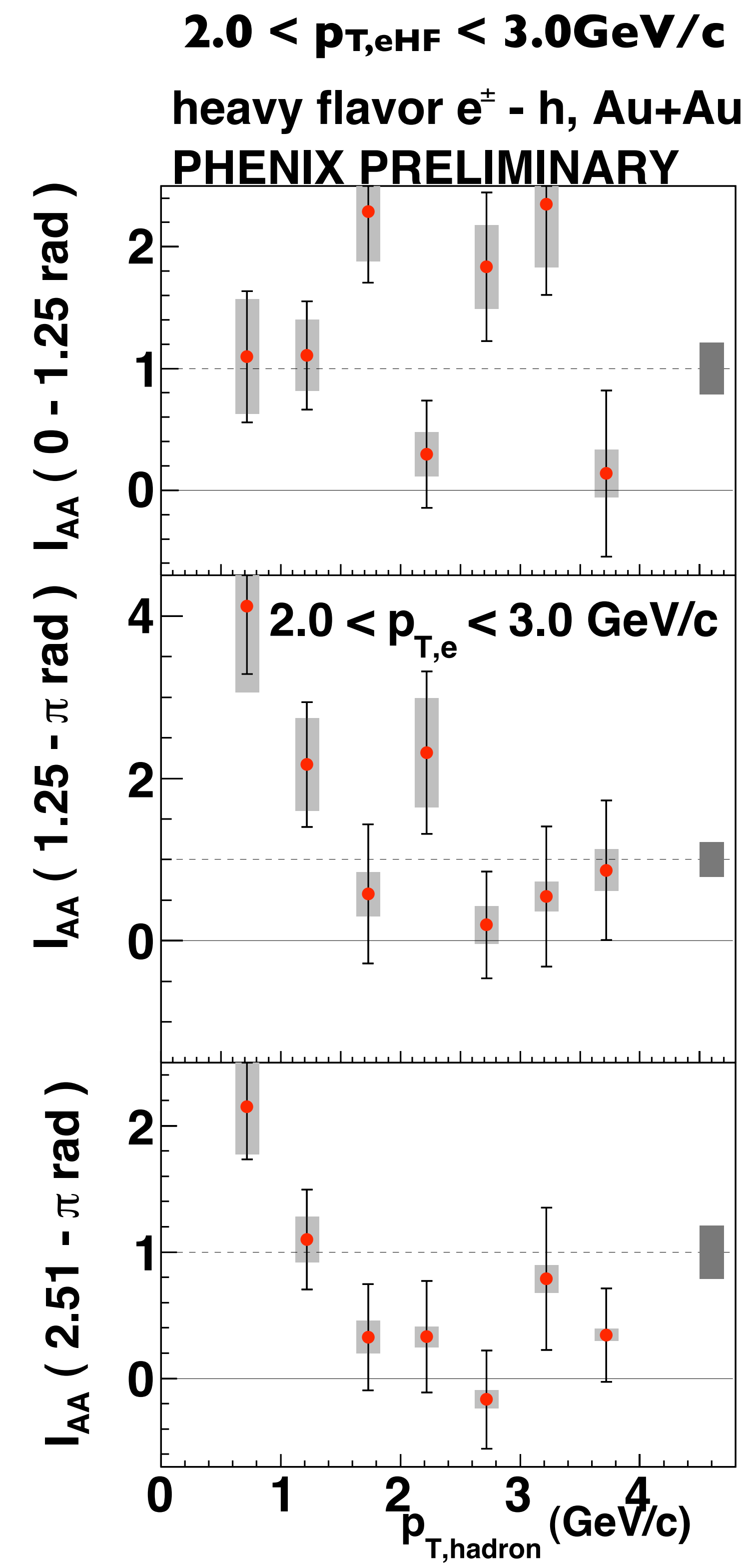

PRC 78 014901 (2008)

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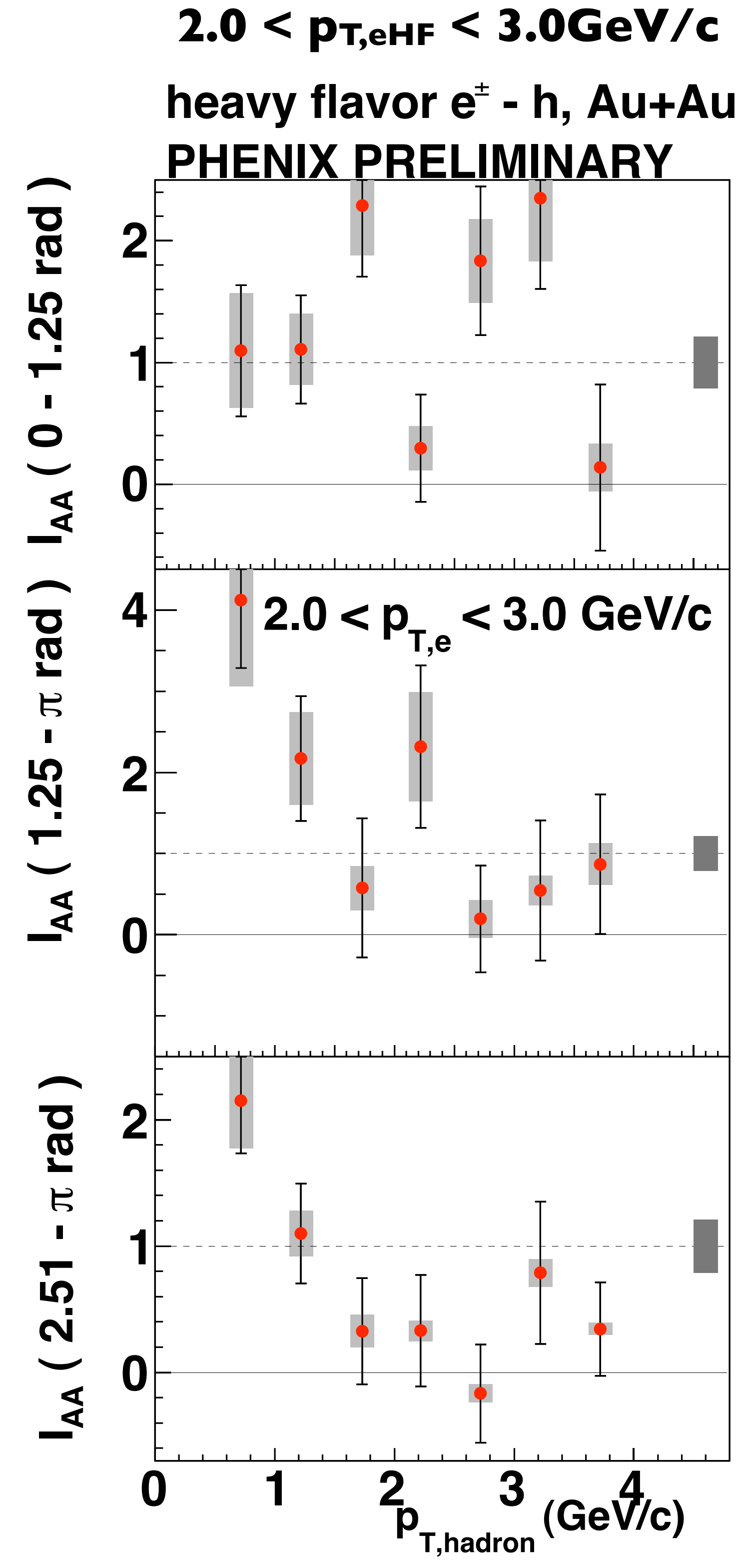

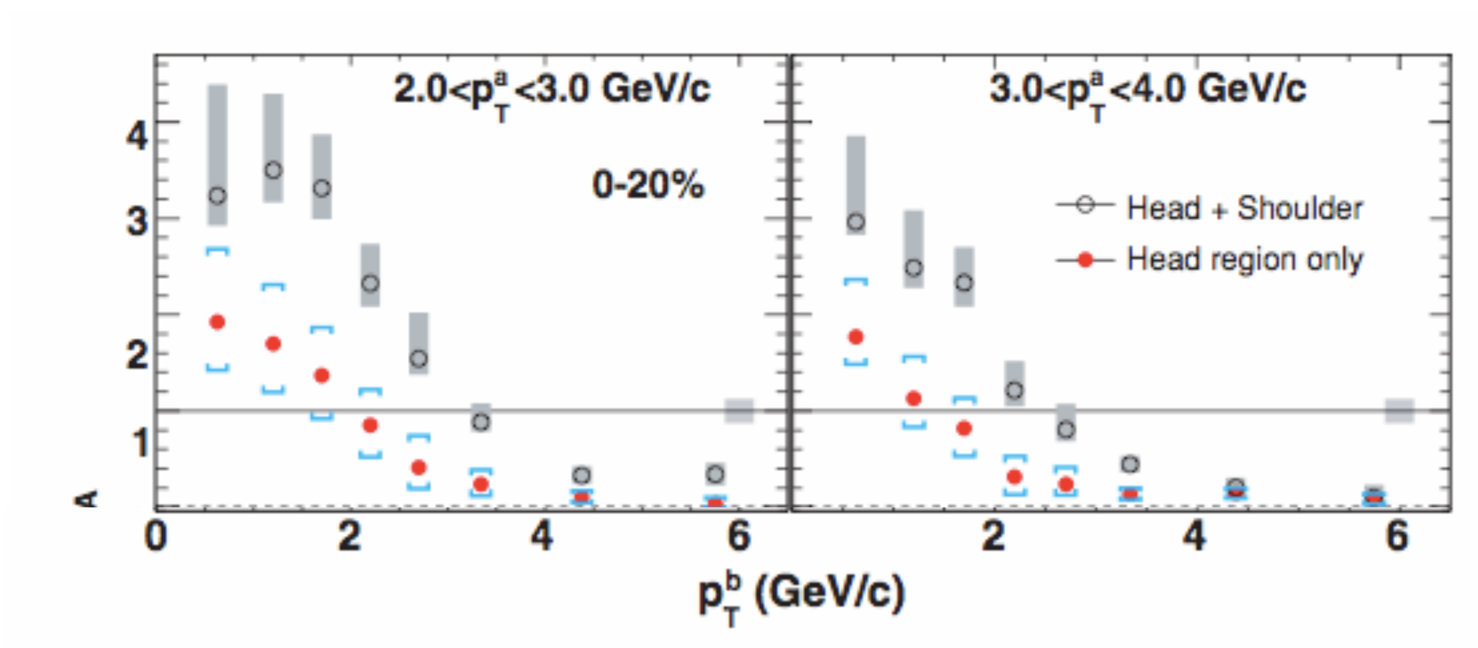

PRC 78 014901 (2008)

more questions than answers

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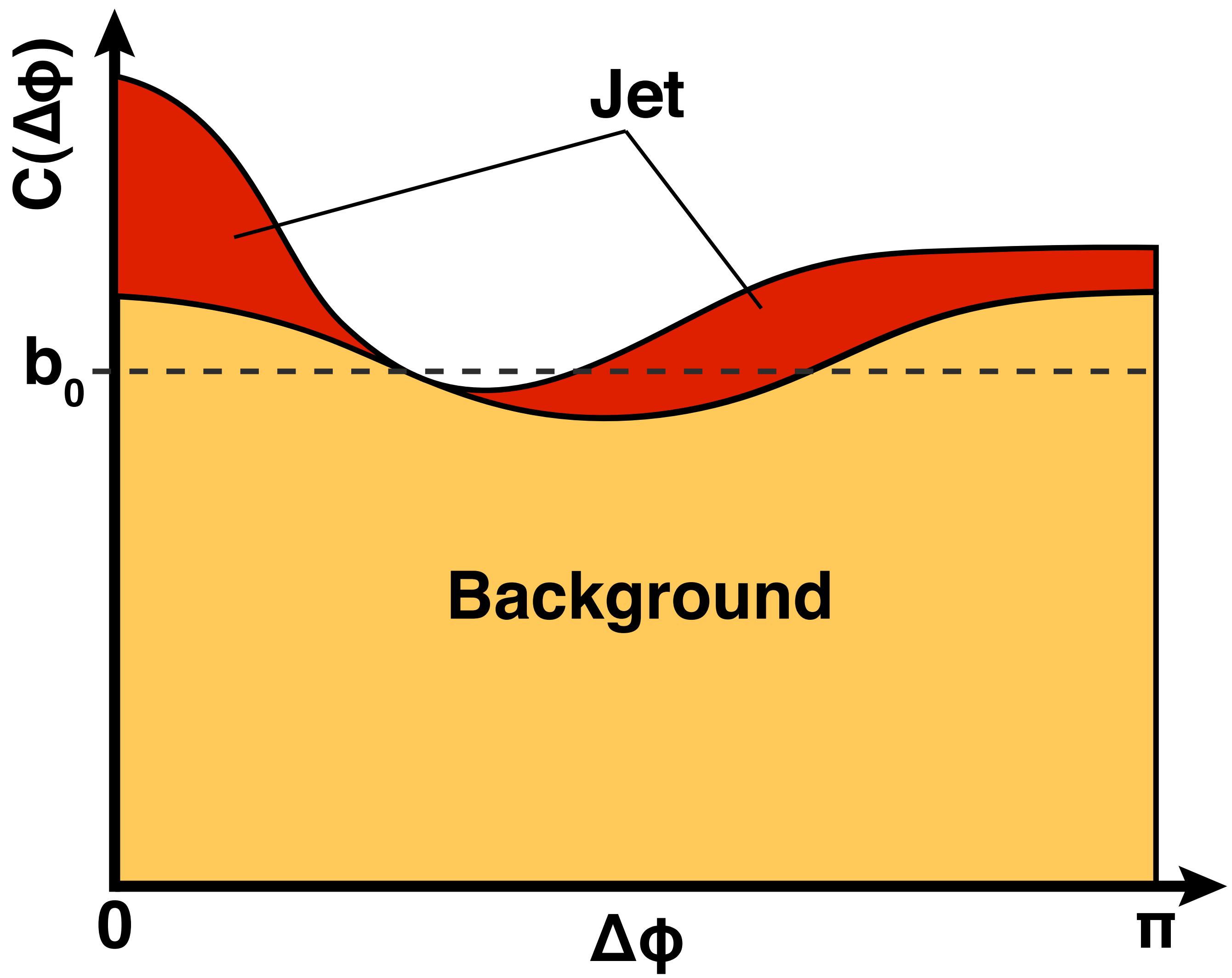
    - very difficult (impossible?) in central AuAu with current detectors
- electron is a poor estimate of D/B momentum
  - reconstuction of mesons via hadronic decays will help

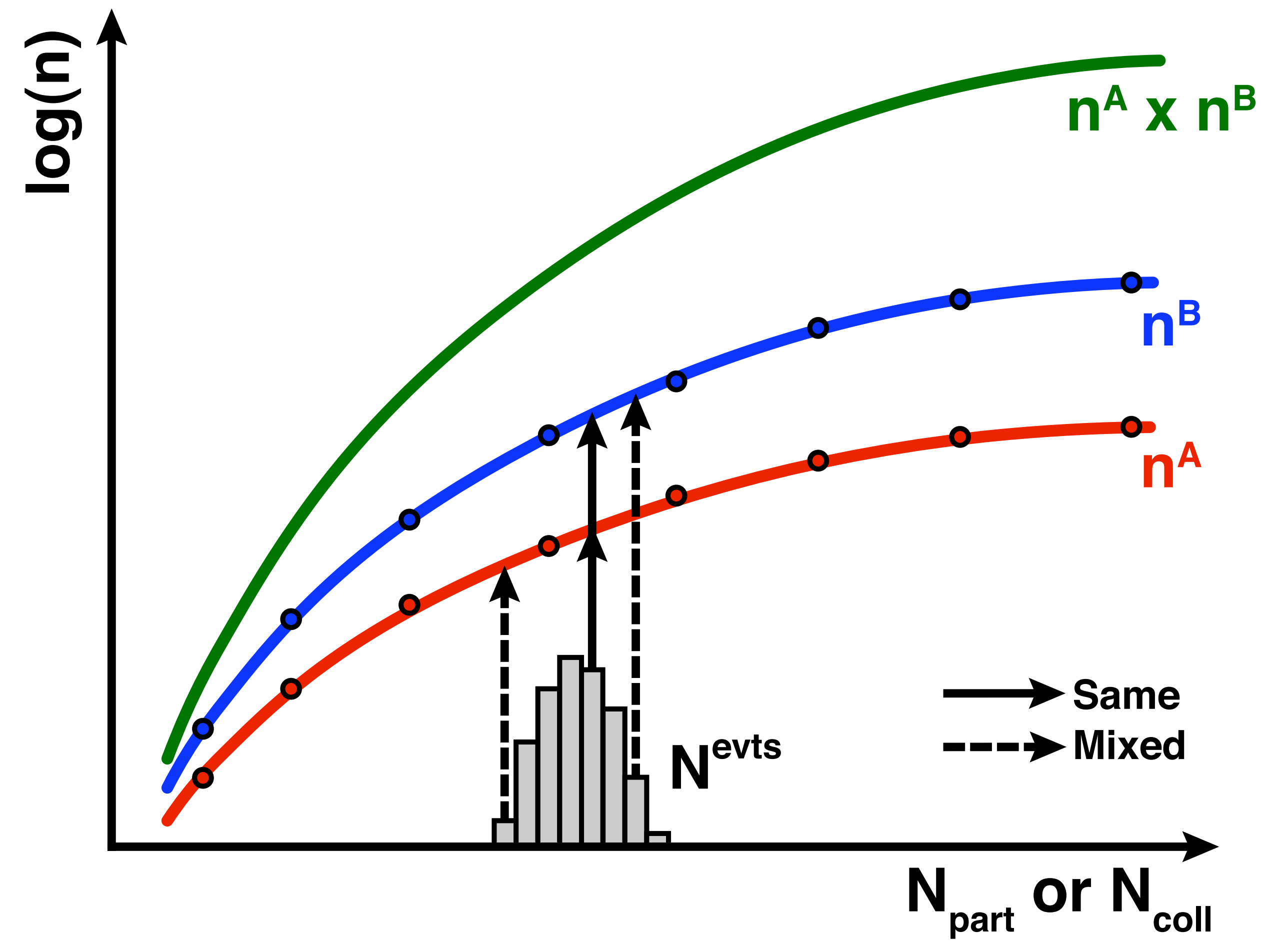
two-source model

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

- it's never been shown to be wrong
  - that doesn't mean it's right
- in principle $\langle v_{2A}v_{2B}\rangle \neq \langle v_{2A}\rangle\langle v_{2B}\rangle$
- B can be calculated in HI collisions (no fudge factors) from the data (Sickles, McCumber, Adare PRC 81 014908 (2010))
  - depends on the widths of the centrality bins
  - generally very close to ZYAM, however some significant advantages
    - wide jets
    - poor statistics

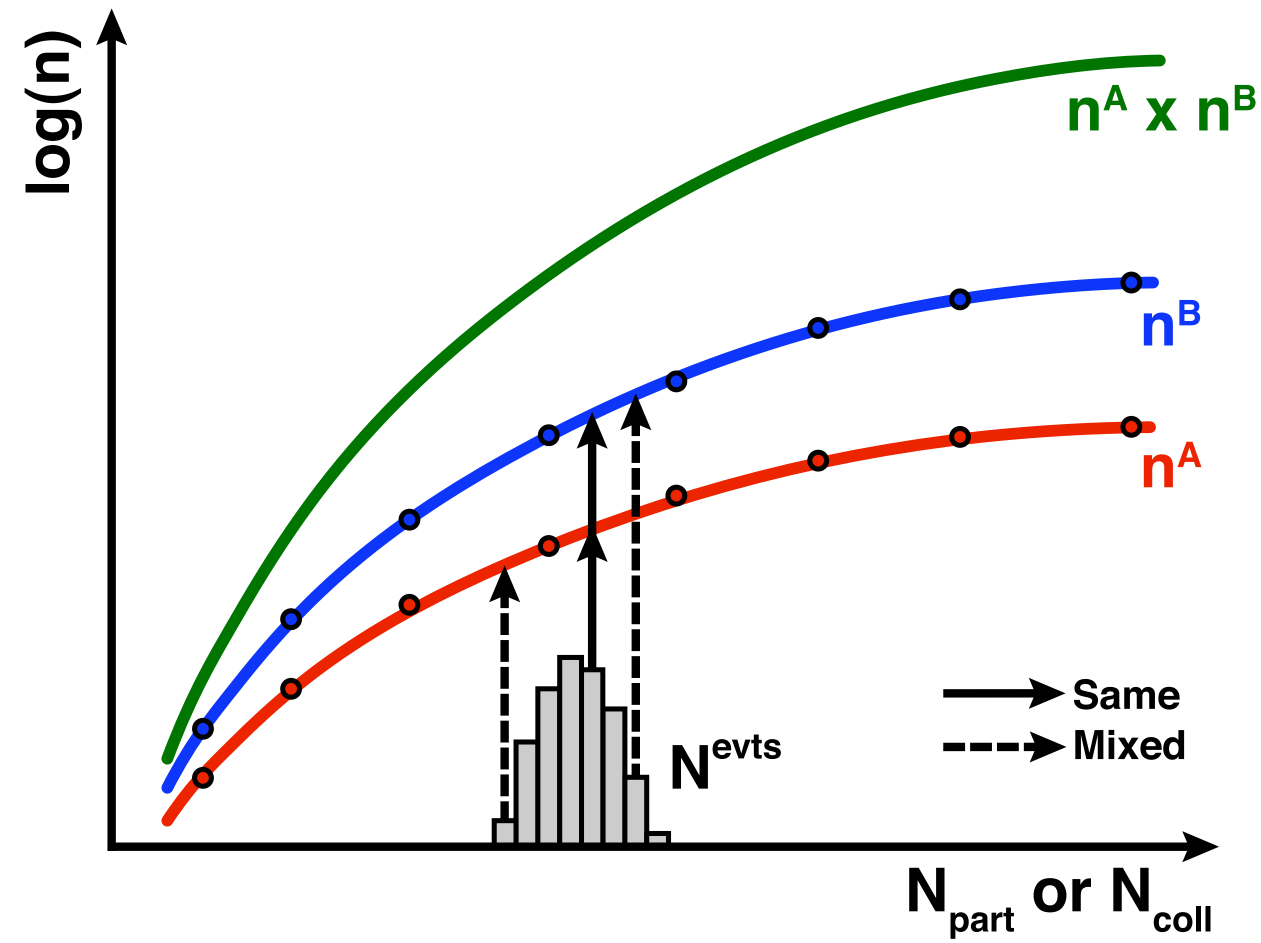


b_0 determination



b_0 determination

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



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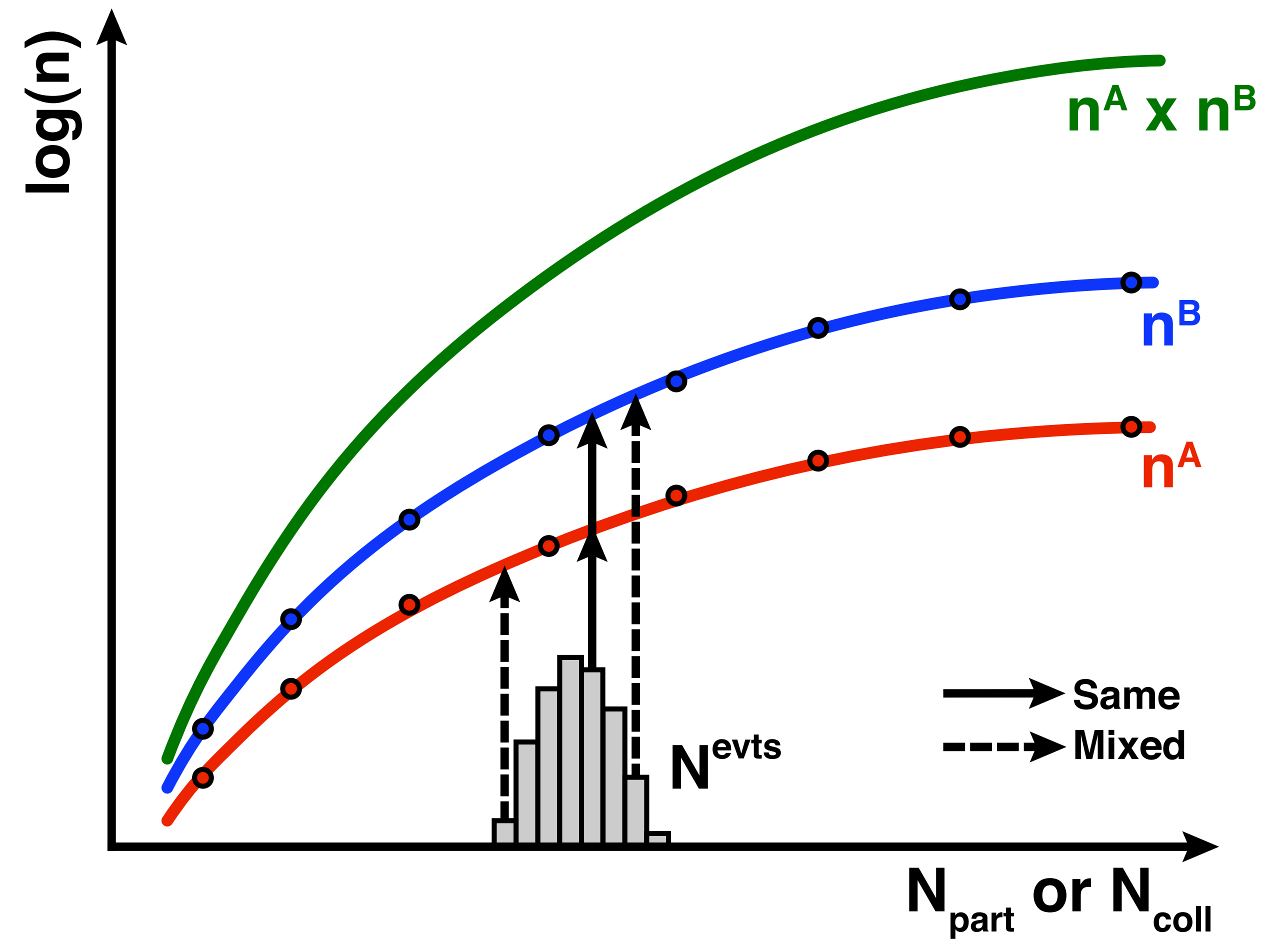

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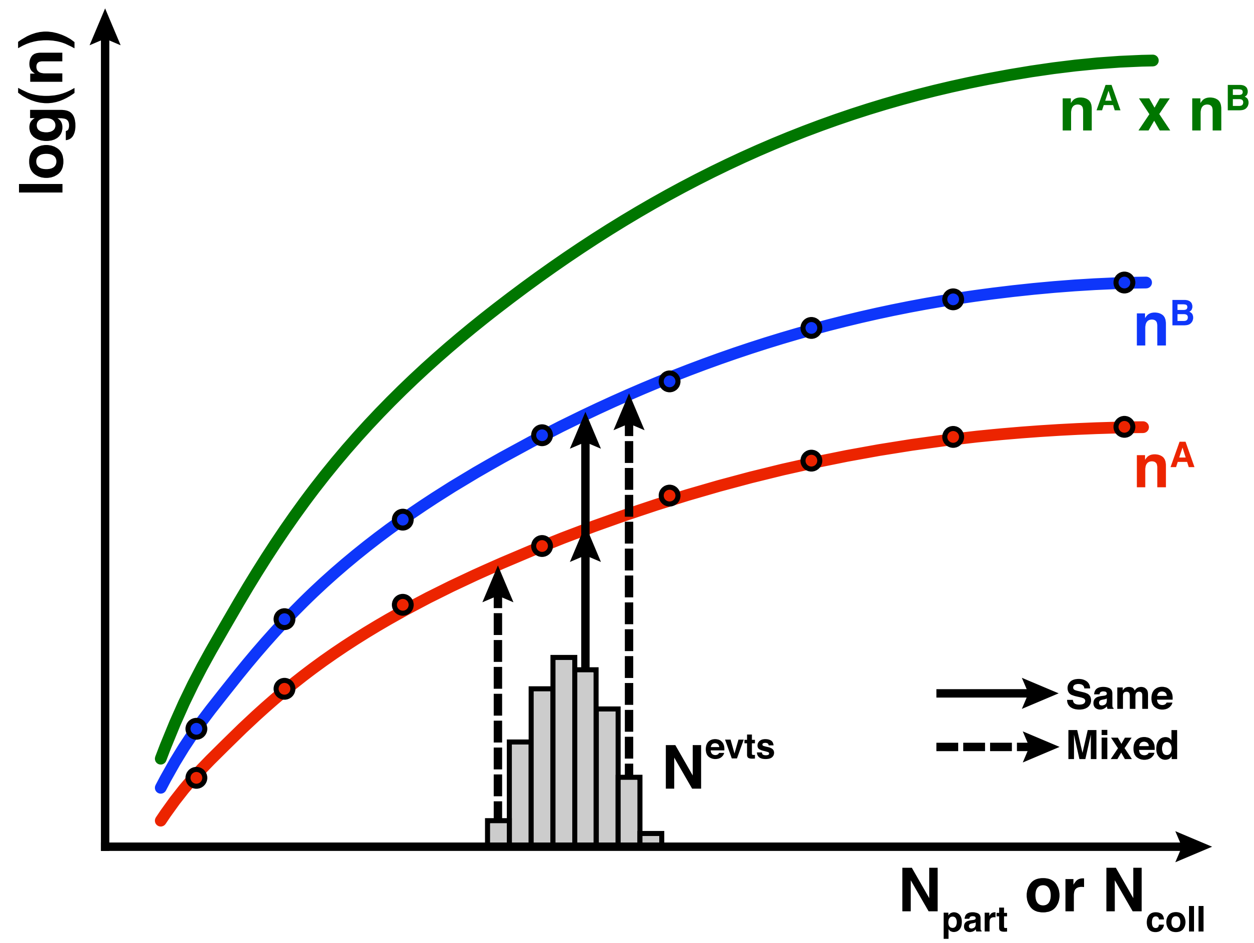

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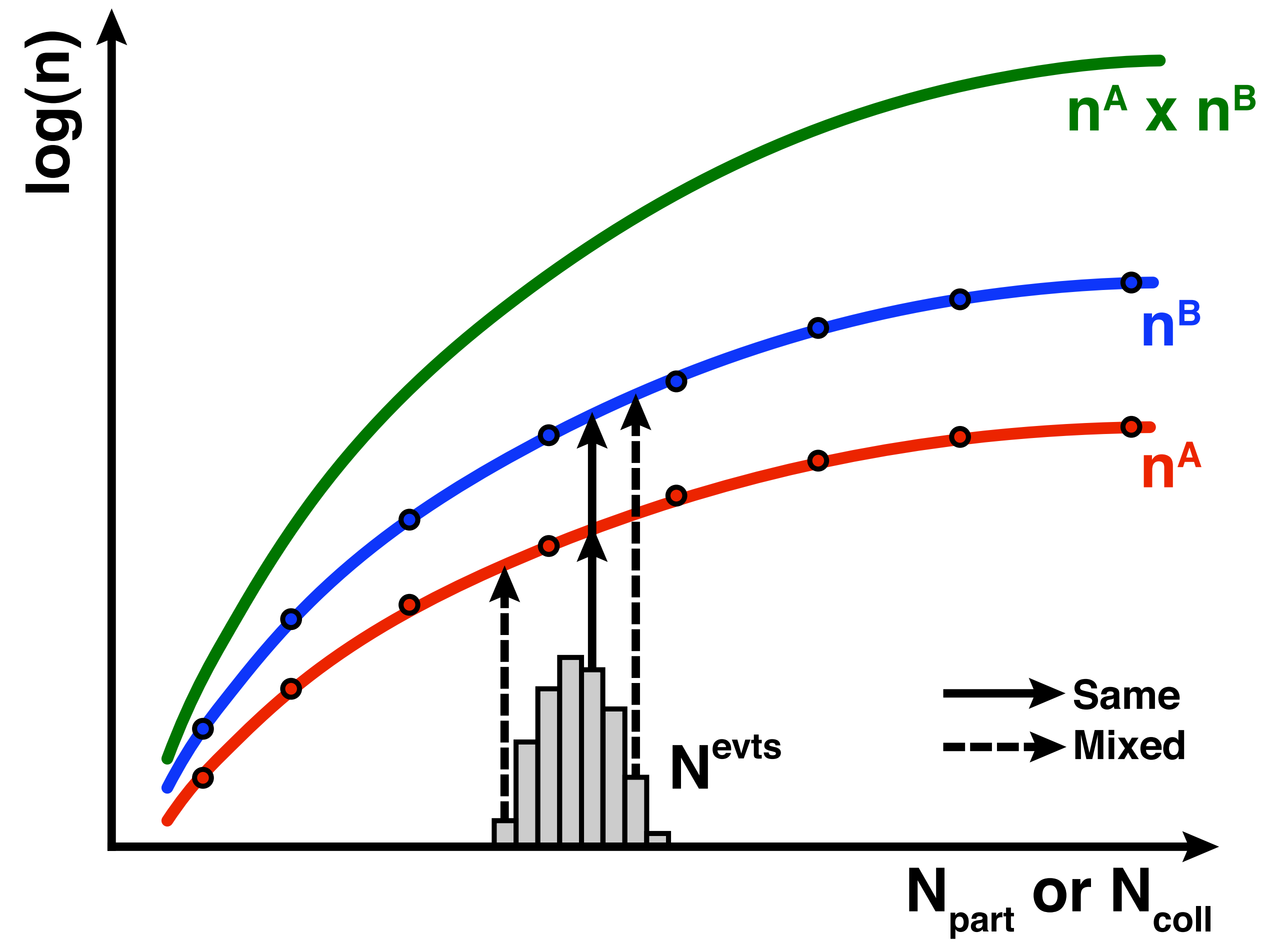

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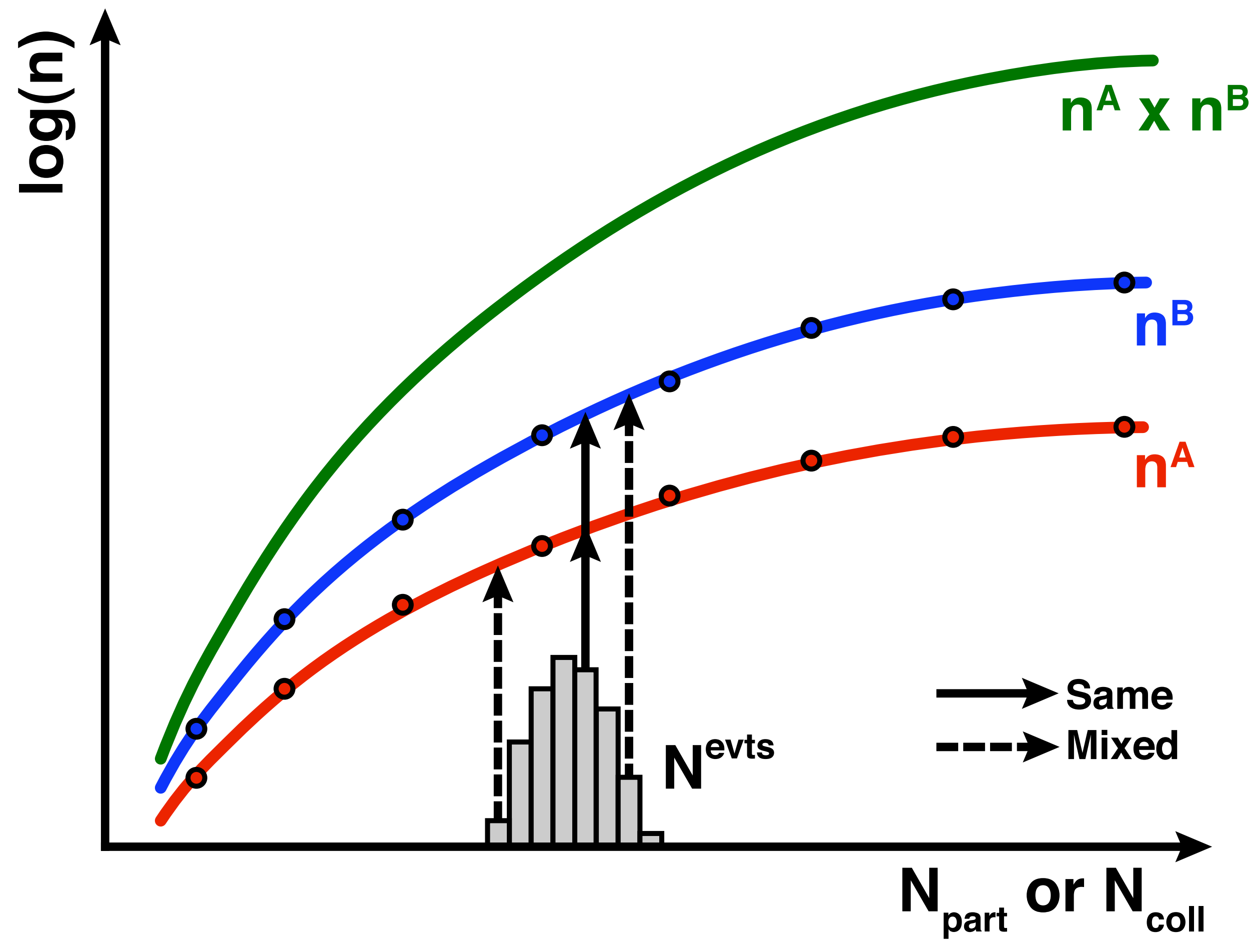

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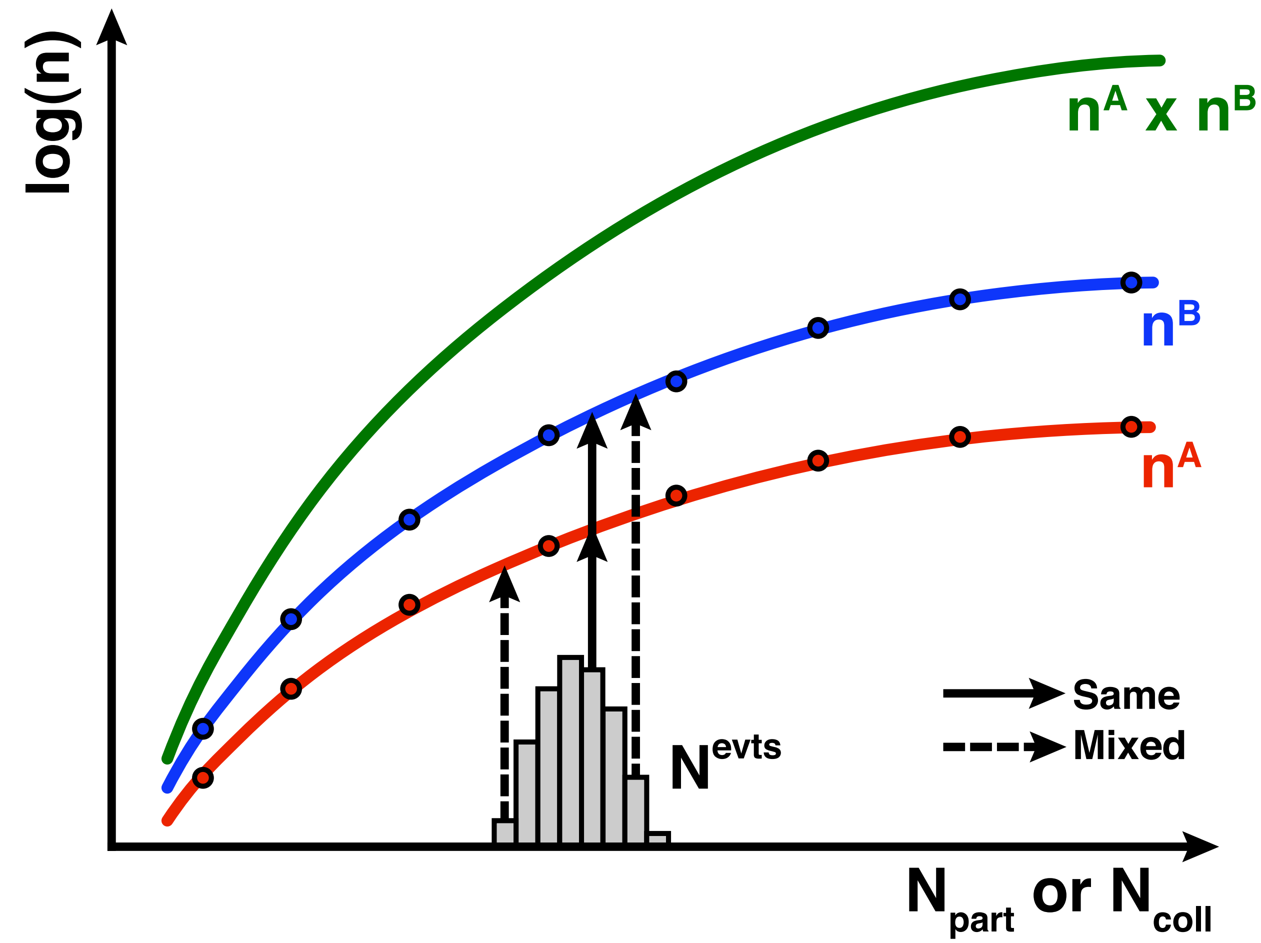

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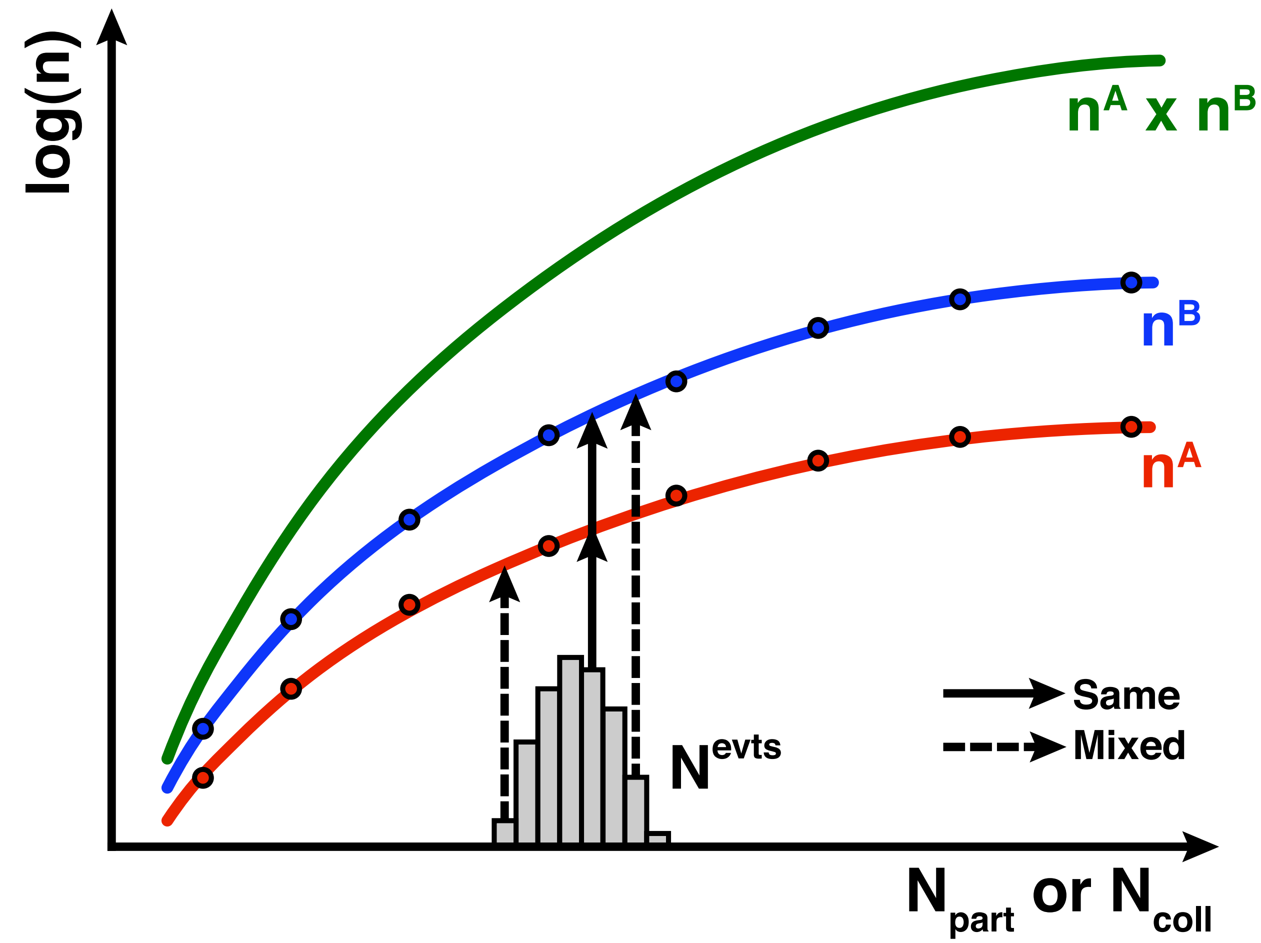

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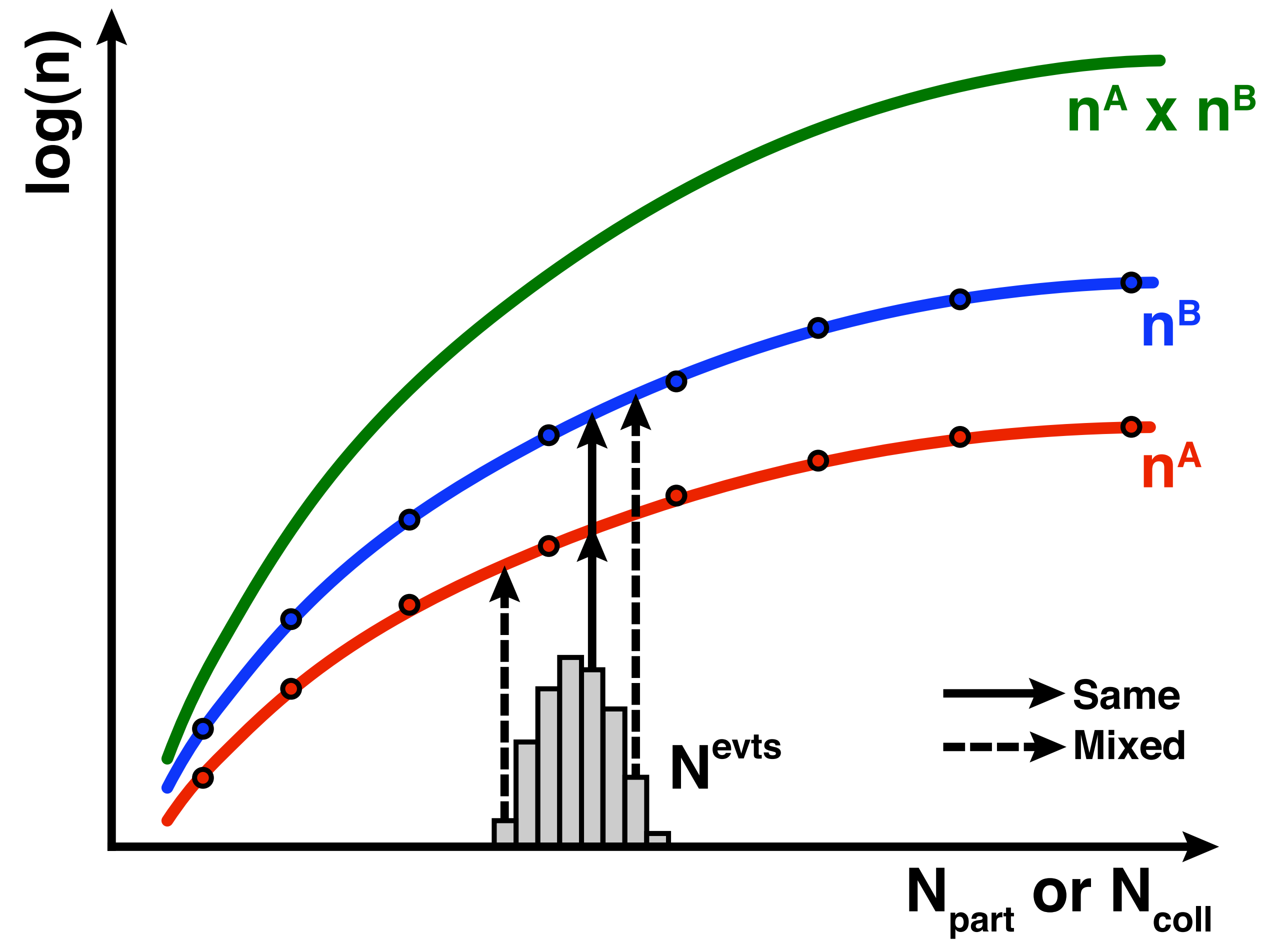

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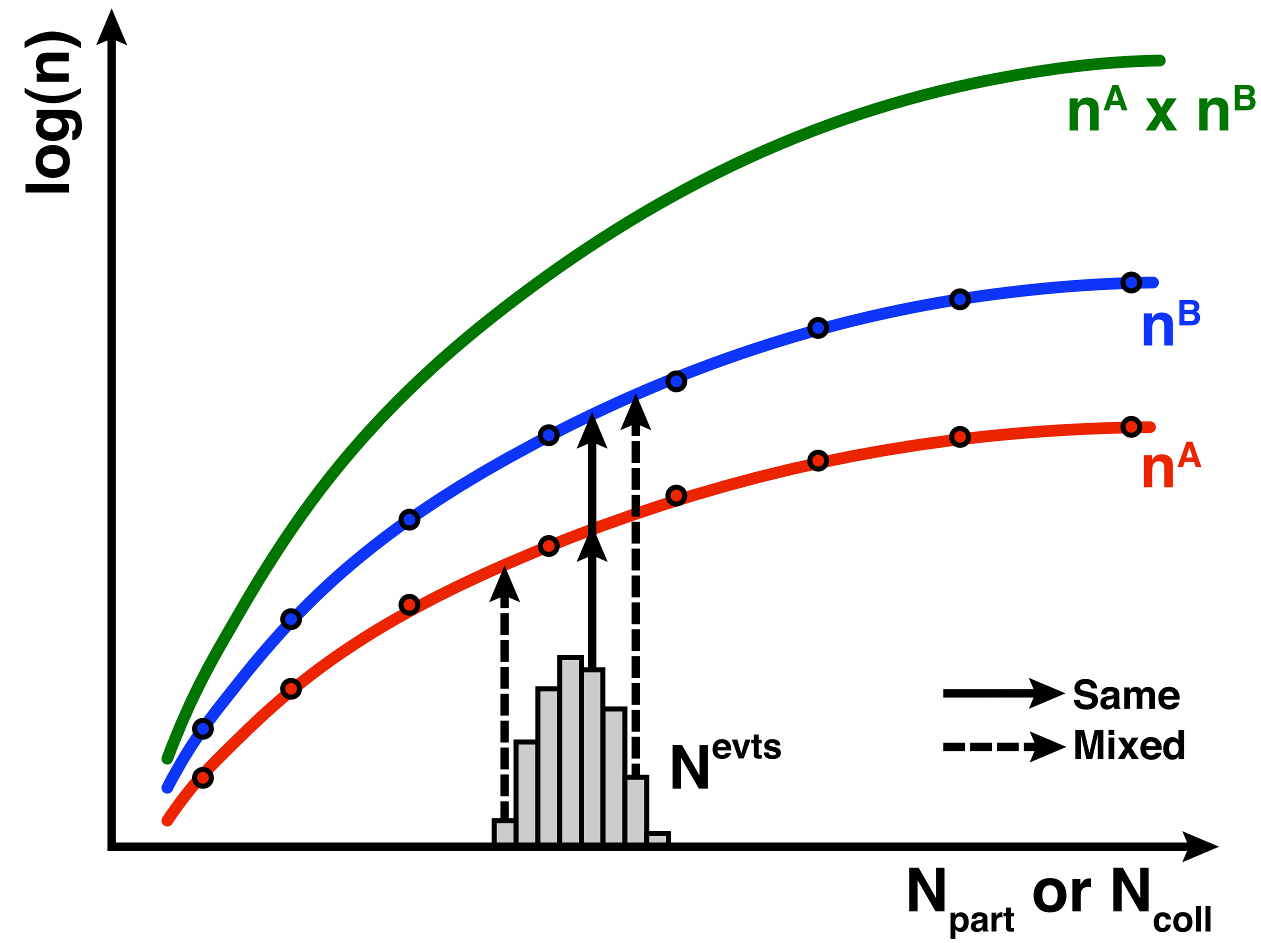

jets

- if jet energy is the parton energy then jet reconstruction followed by fragmentation function measurements provide exactly what's needed
- caveats:
  - energy transfer between parton and matter: e.g. collisional energy loss
  - missing energy--no hadronic calorimeters at RHIC
  - soft background will limit jet reconstruction in a very interesting pT range
  - we still have to understand the initial conditions!

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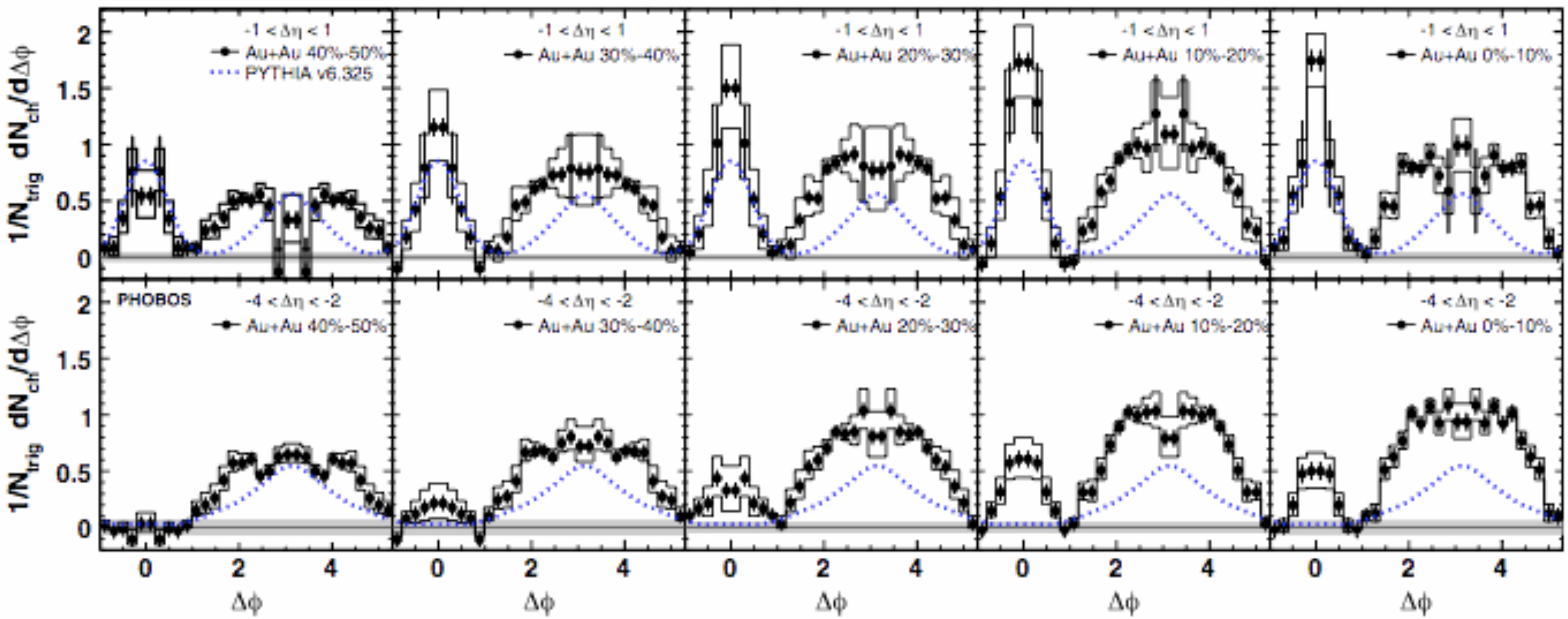
- changing the parton
- open questions: what is the role of formation time, geometry, other effects in interpreting results?


-1 < Δη < 1
Au+Au 40%-50%
PYTHIA v6.325
Au+Au 30%-40%
Au+Au 20%-30%
Au+Au 10%-20%
Au+Au 0%-10%
PHOBOS
-4 < Δη < -2
1/N_trig dN_ch/dΔφ
Δφ

jet conversions

idea: jet parton scatters on medium parton and changes flavor

$$q + \bar{q} \leftrightarrow g + g$$

$$q + g \leftrightarrow g + q$$

Ko et al. PRC 75 051901 (2007)
Liu & Fries PRC77 054902 (2008)

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parton R_{AA}

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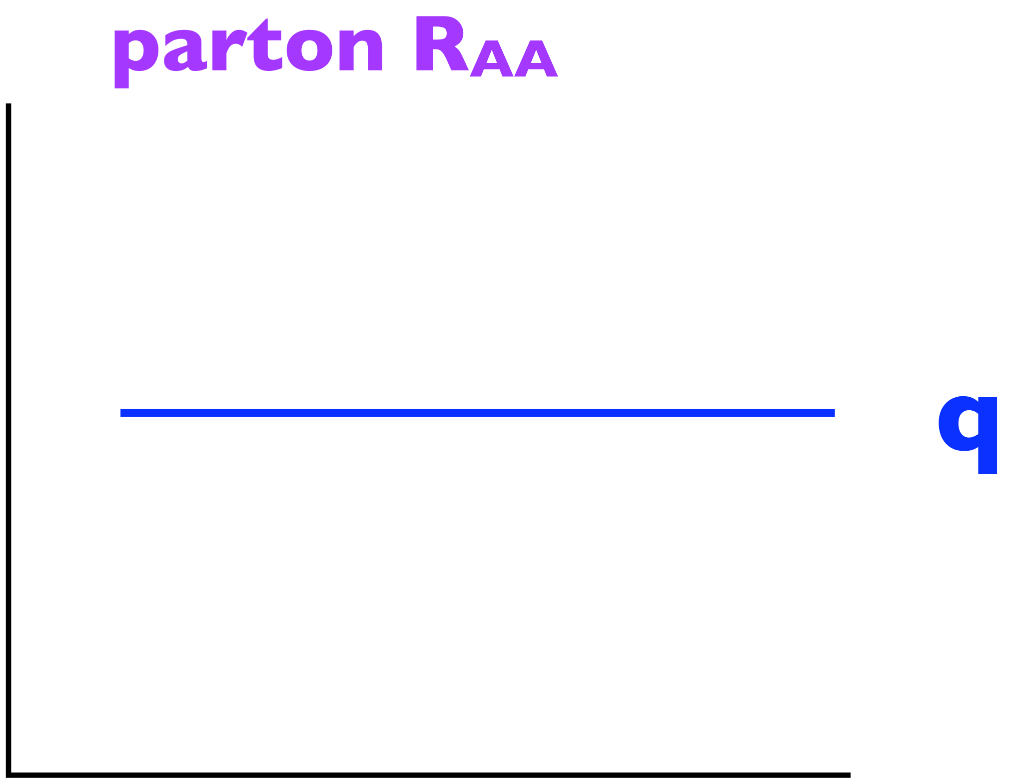

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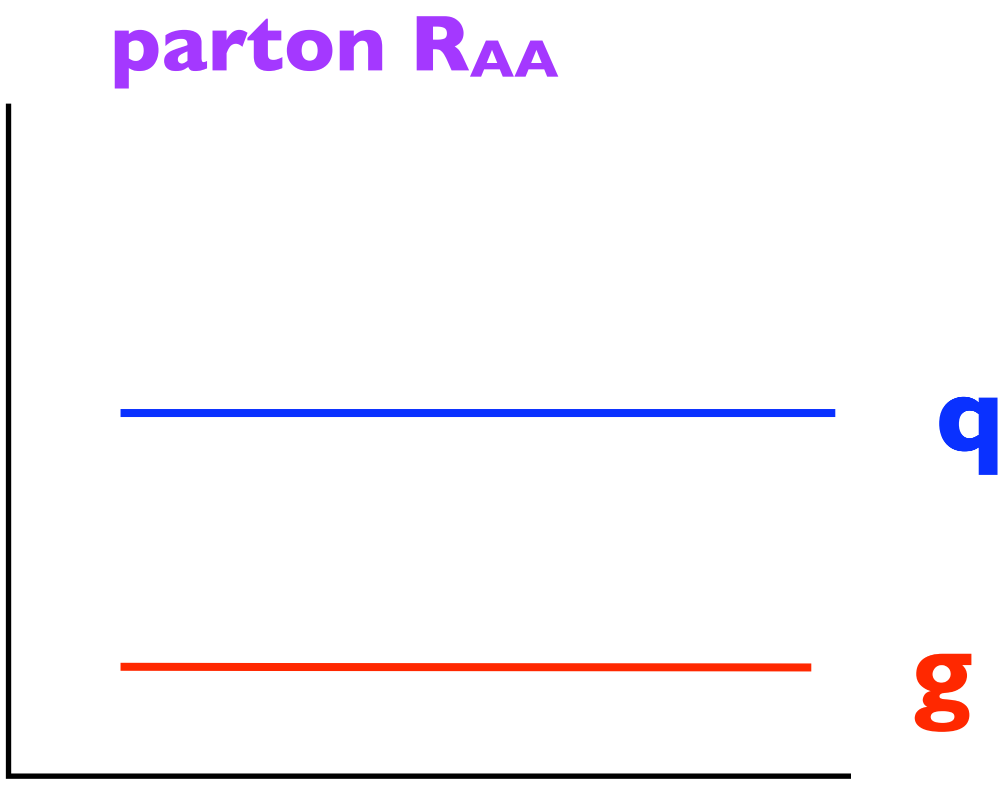

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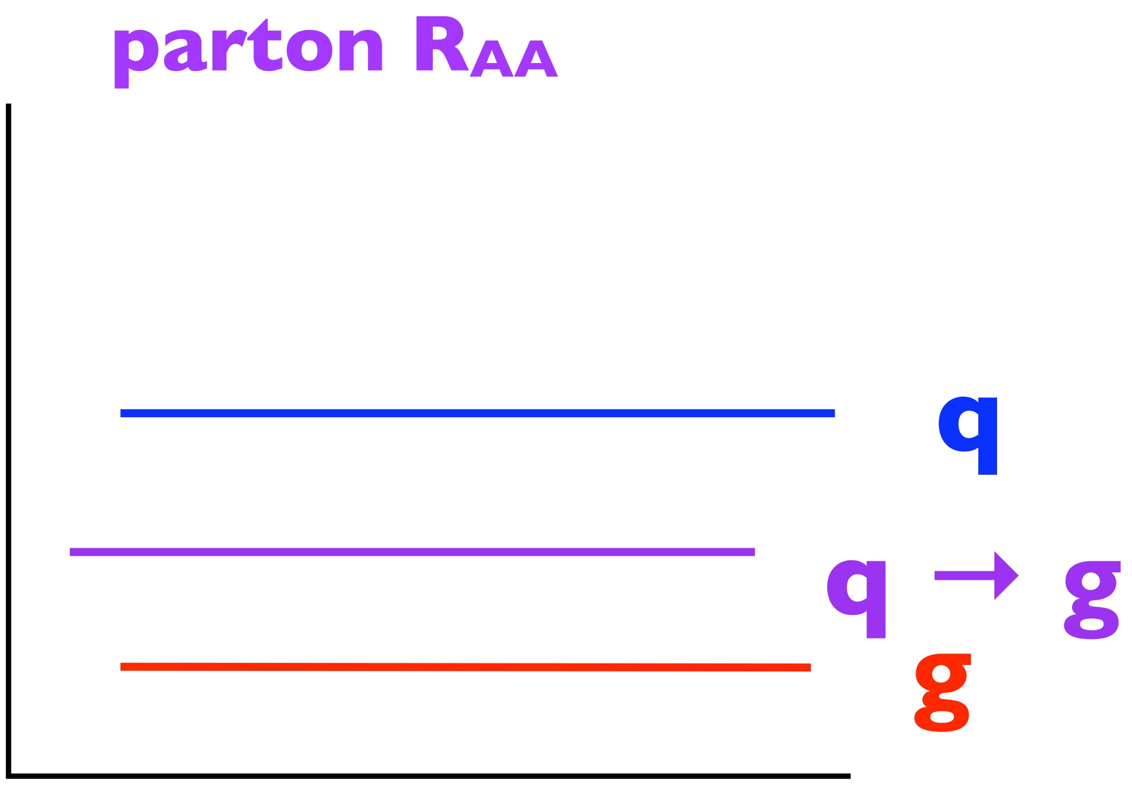

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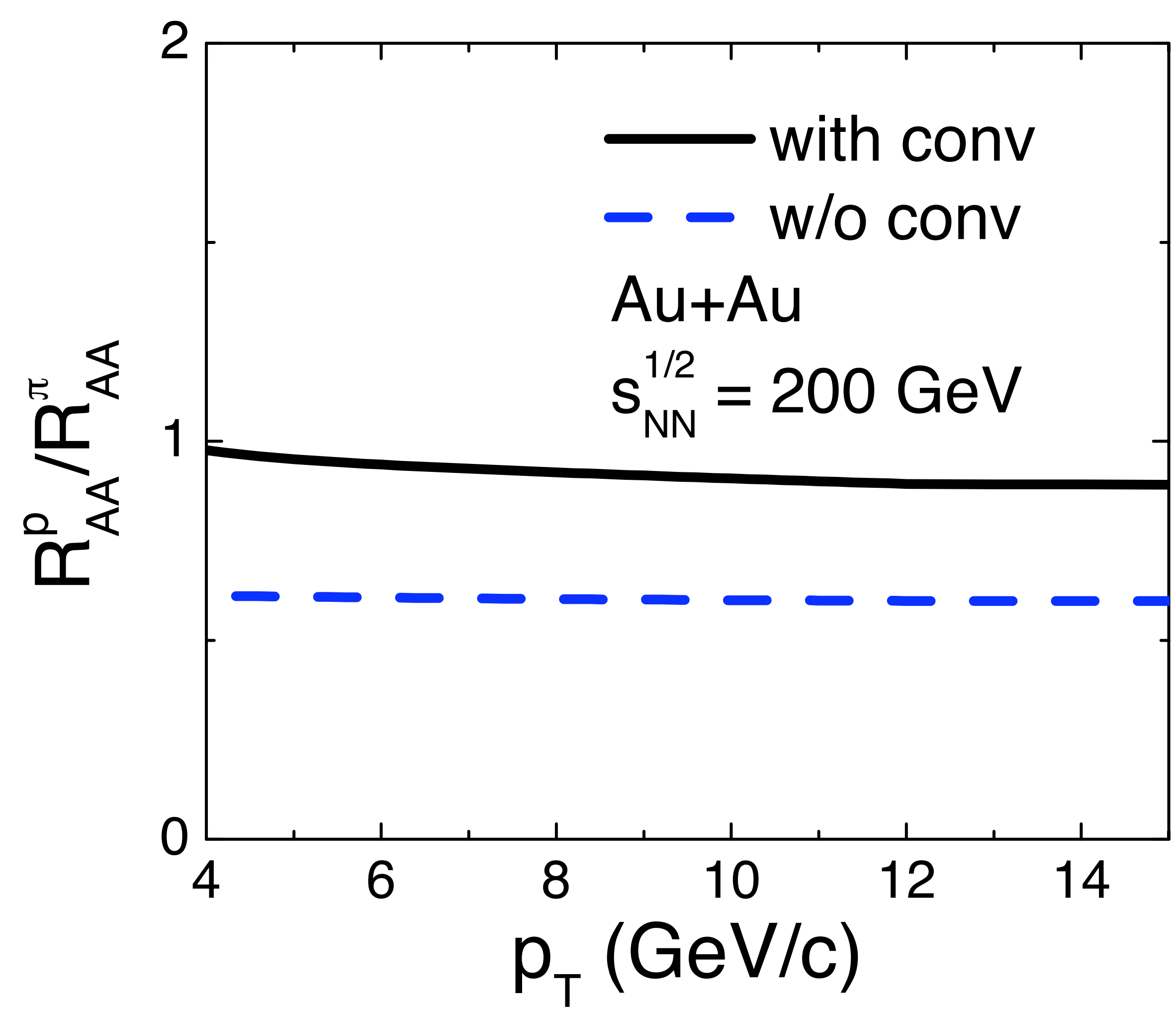

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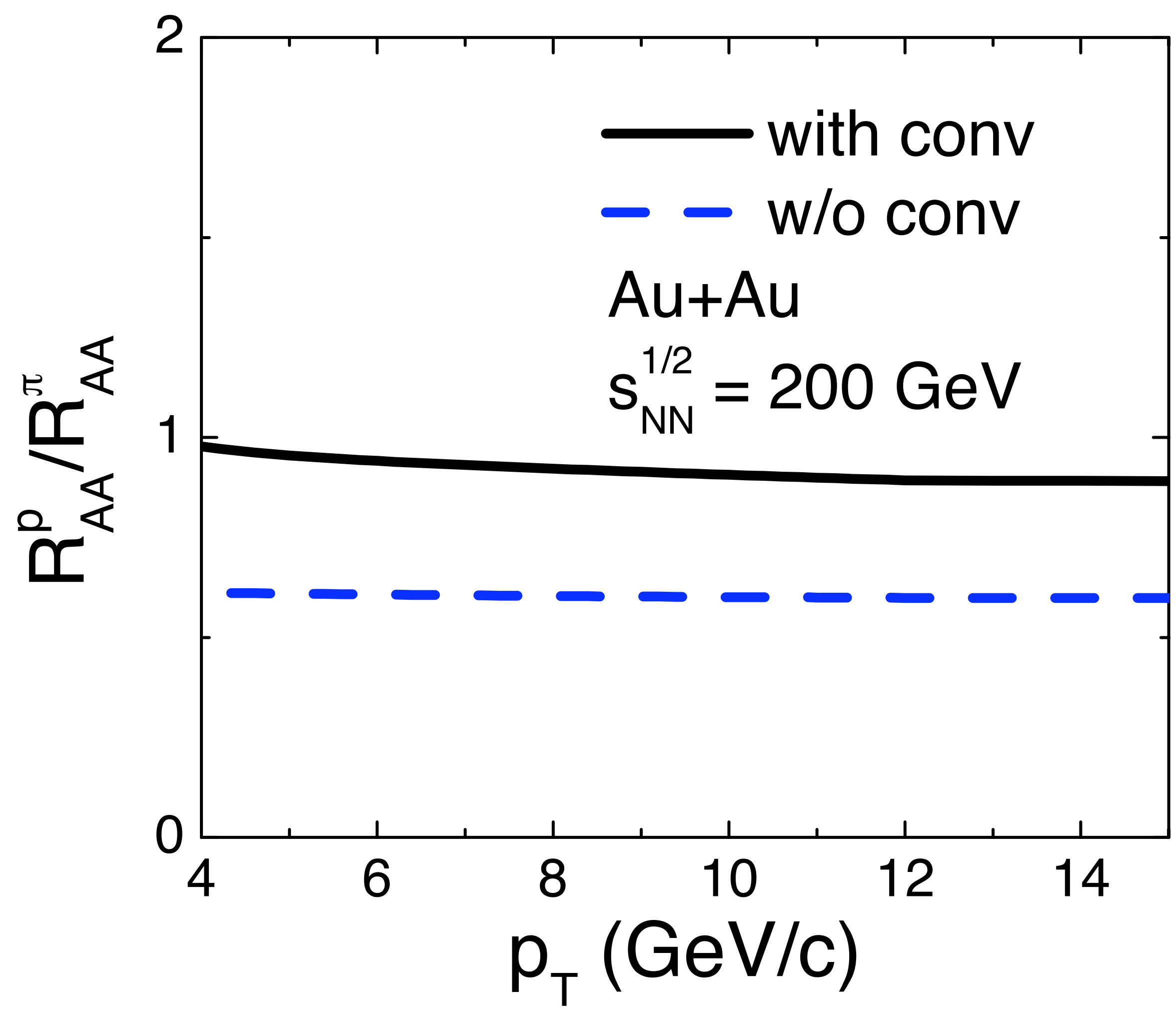

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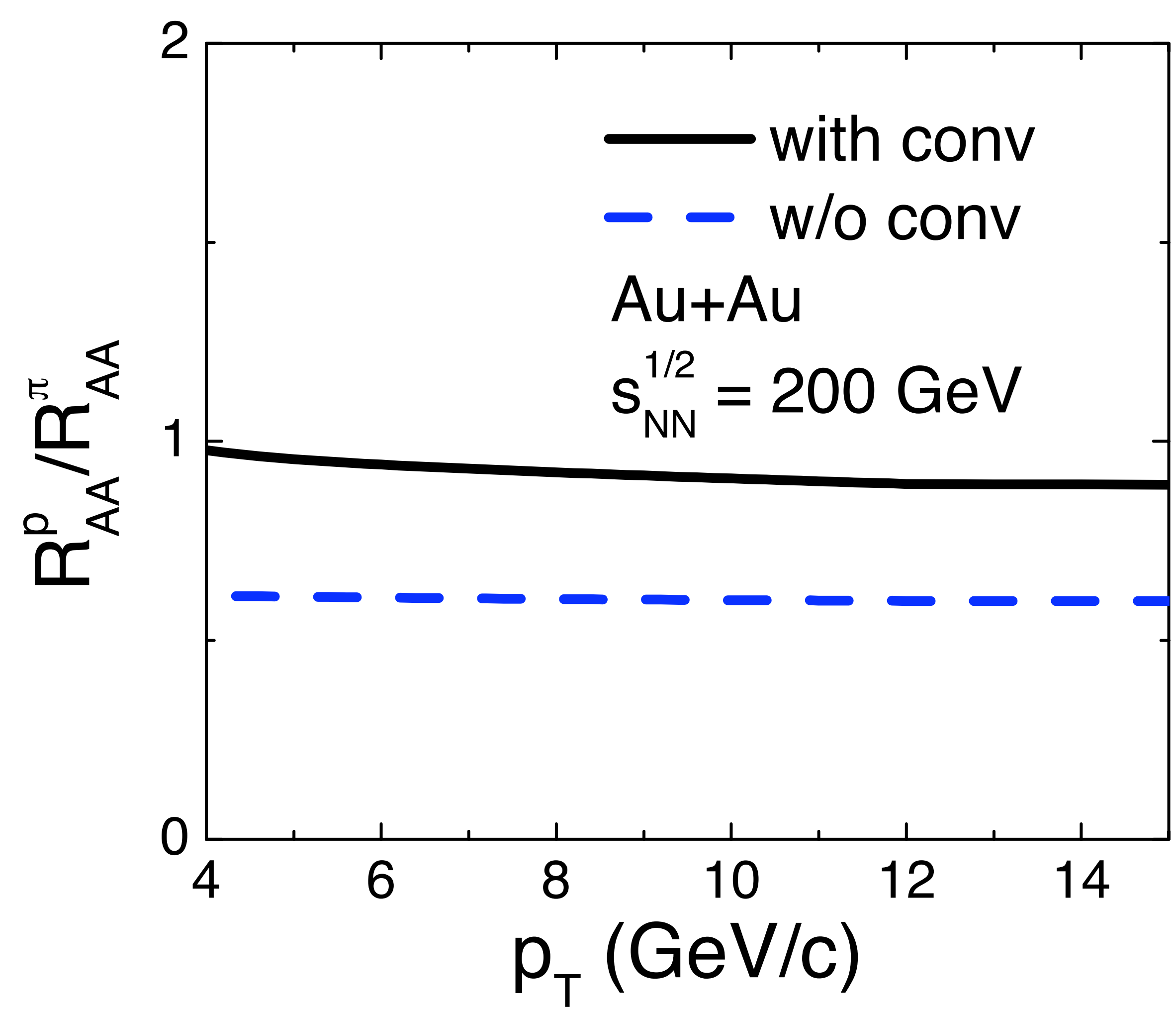

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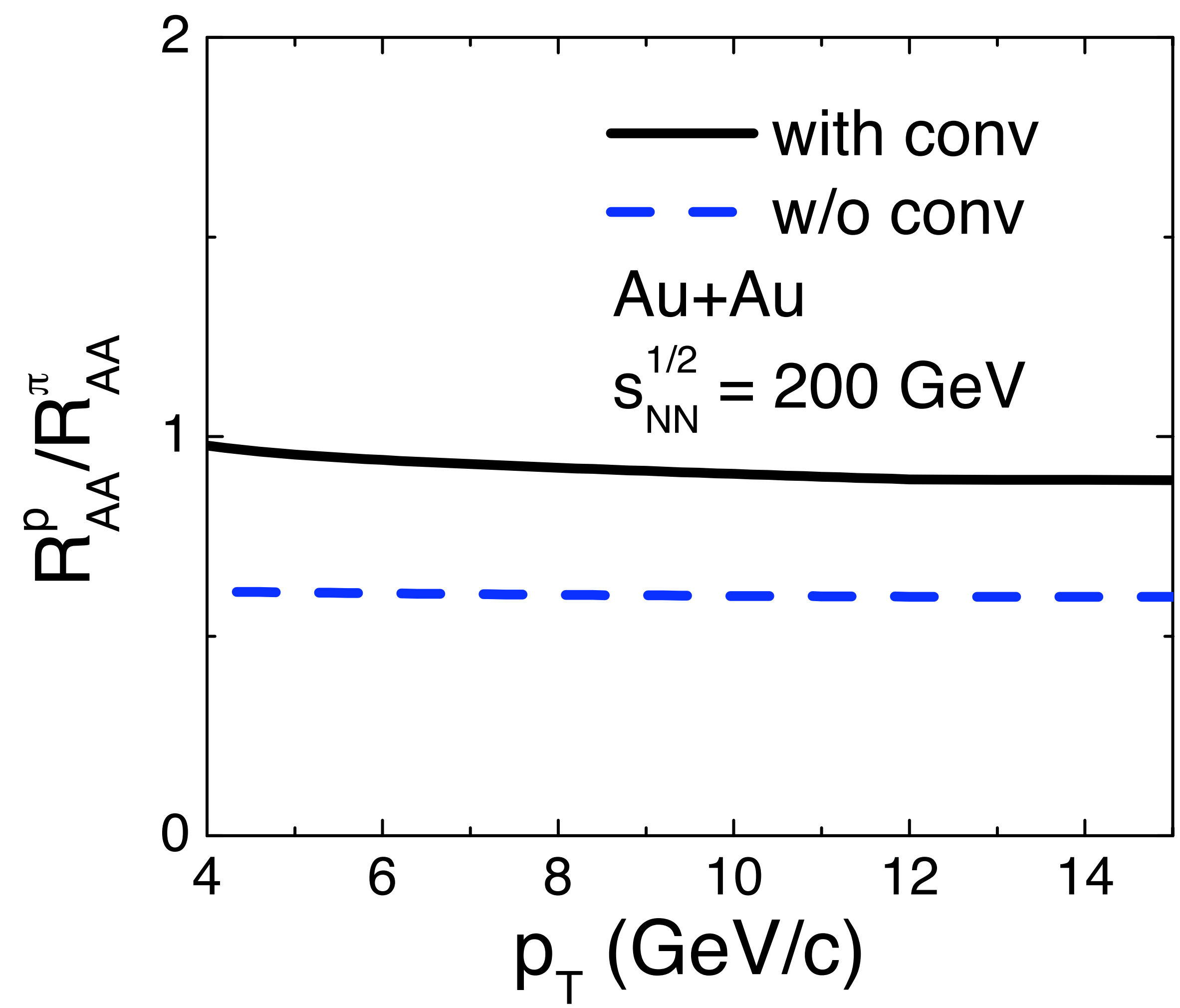

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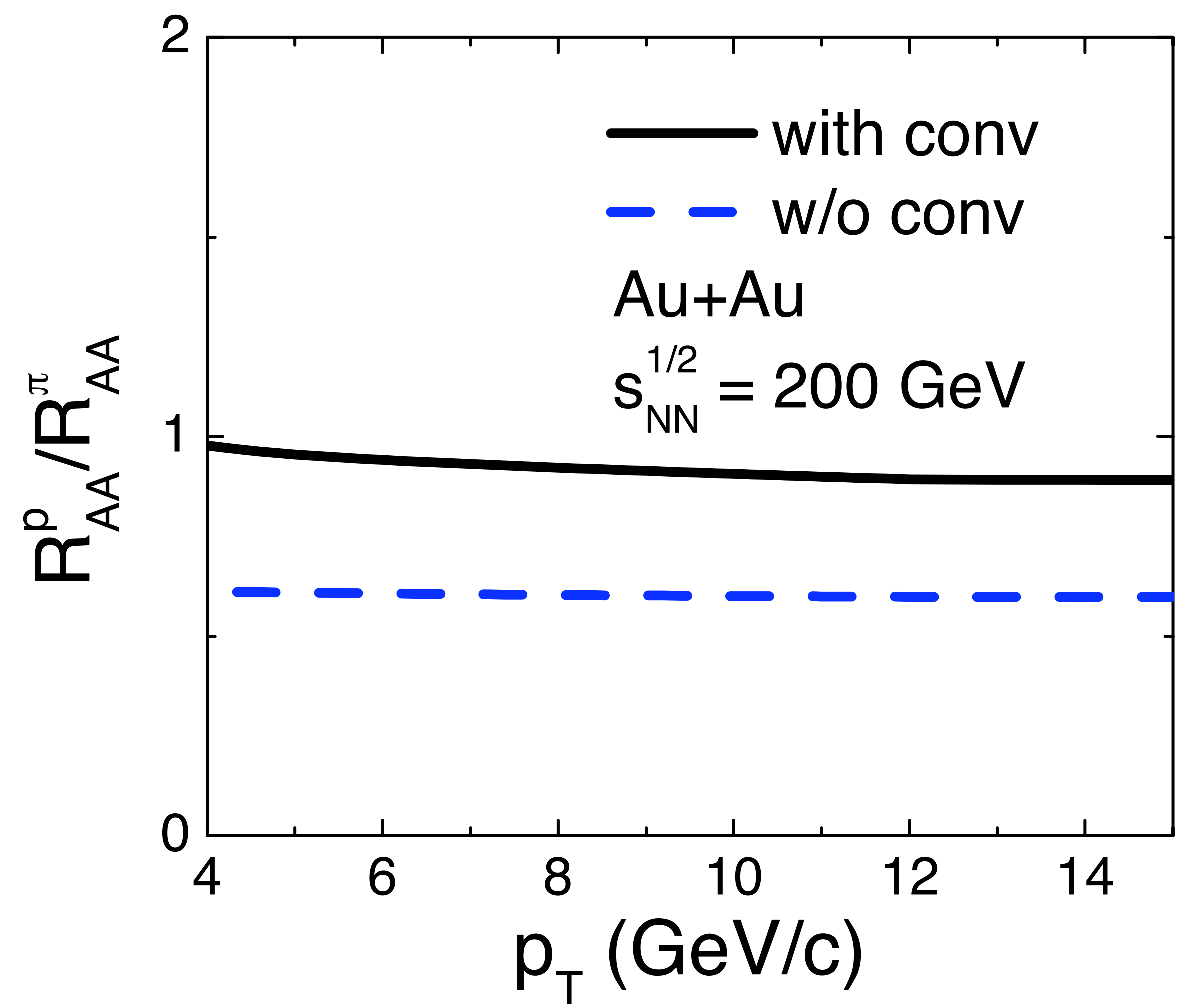

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Ko et al. PRC 75 051901 (2007)
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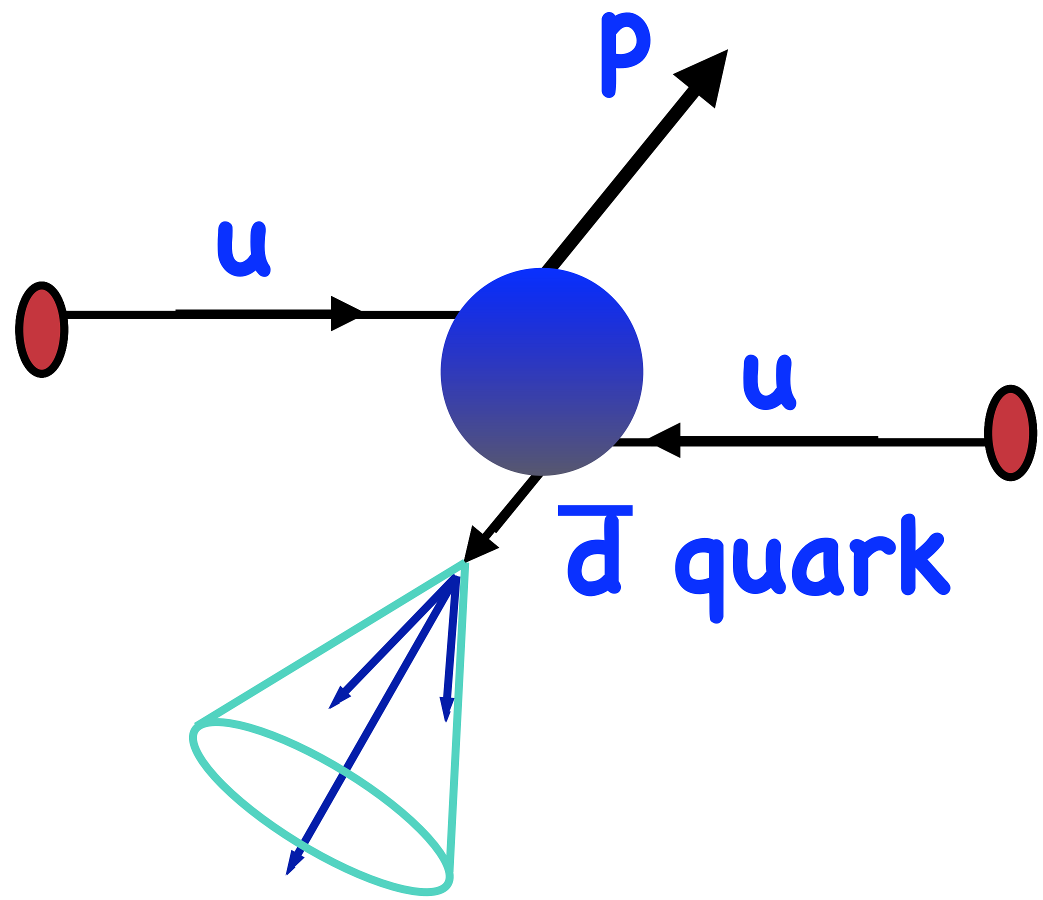
direct proton production?



$uu \rightarrow p\bar{d}$

Brodsky & AMS PLB 668 111 (2008)

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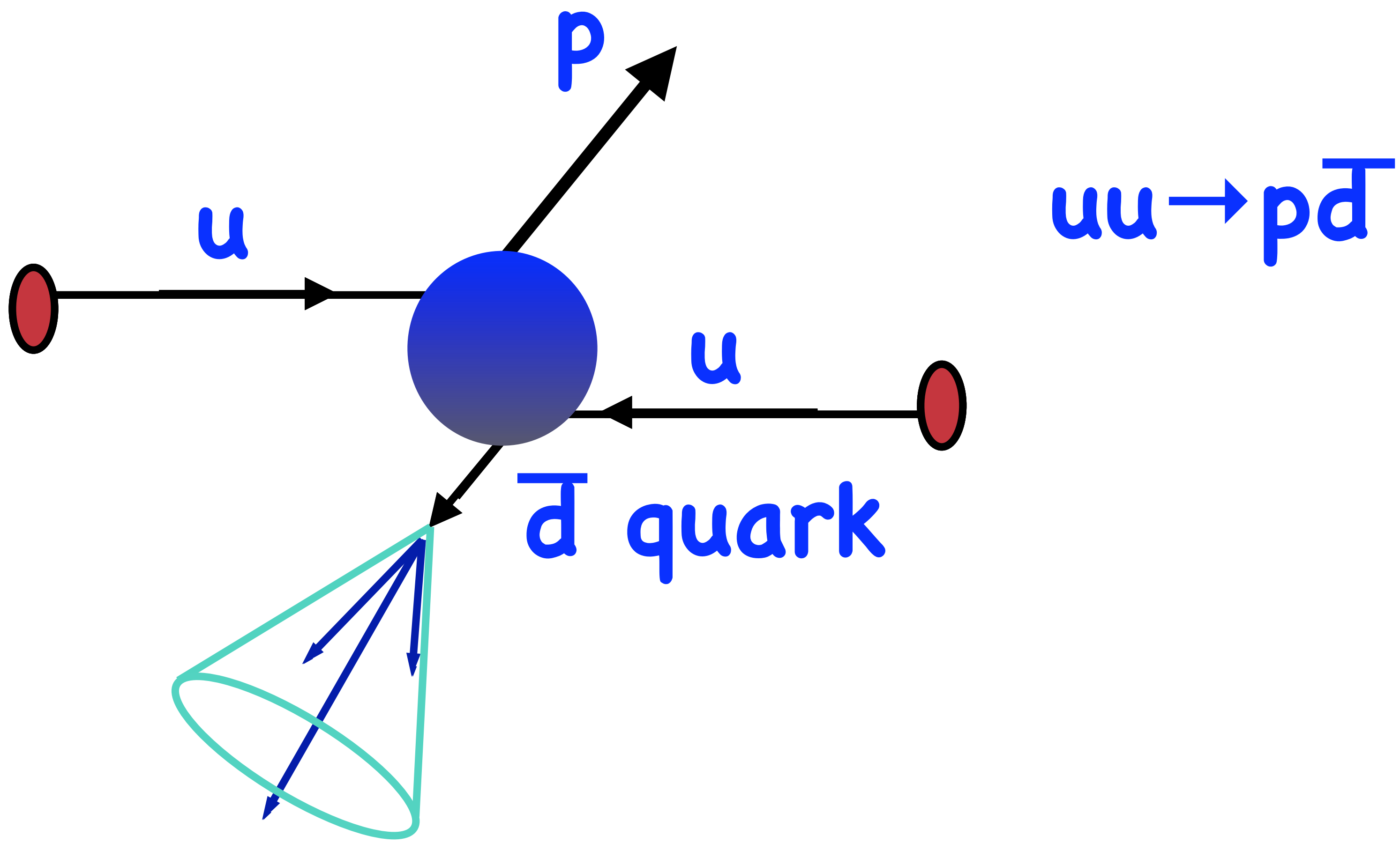

- color singlet proton directly produced within hard scattering

Brodsky & AMS PLB 668 111 (2008)

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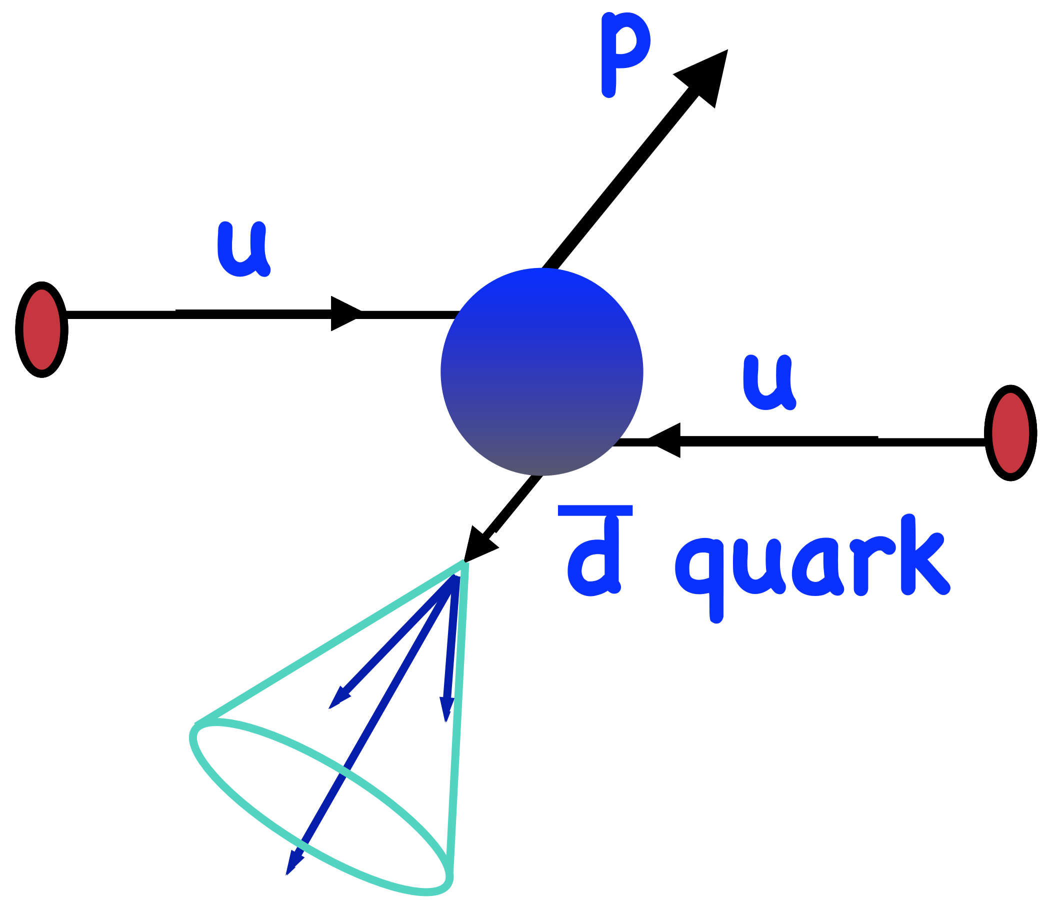

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- size of proton decreases with increasing p_T: color transparent

Brodsky & AMS PLB 668 111 (2008)

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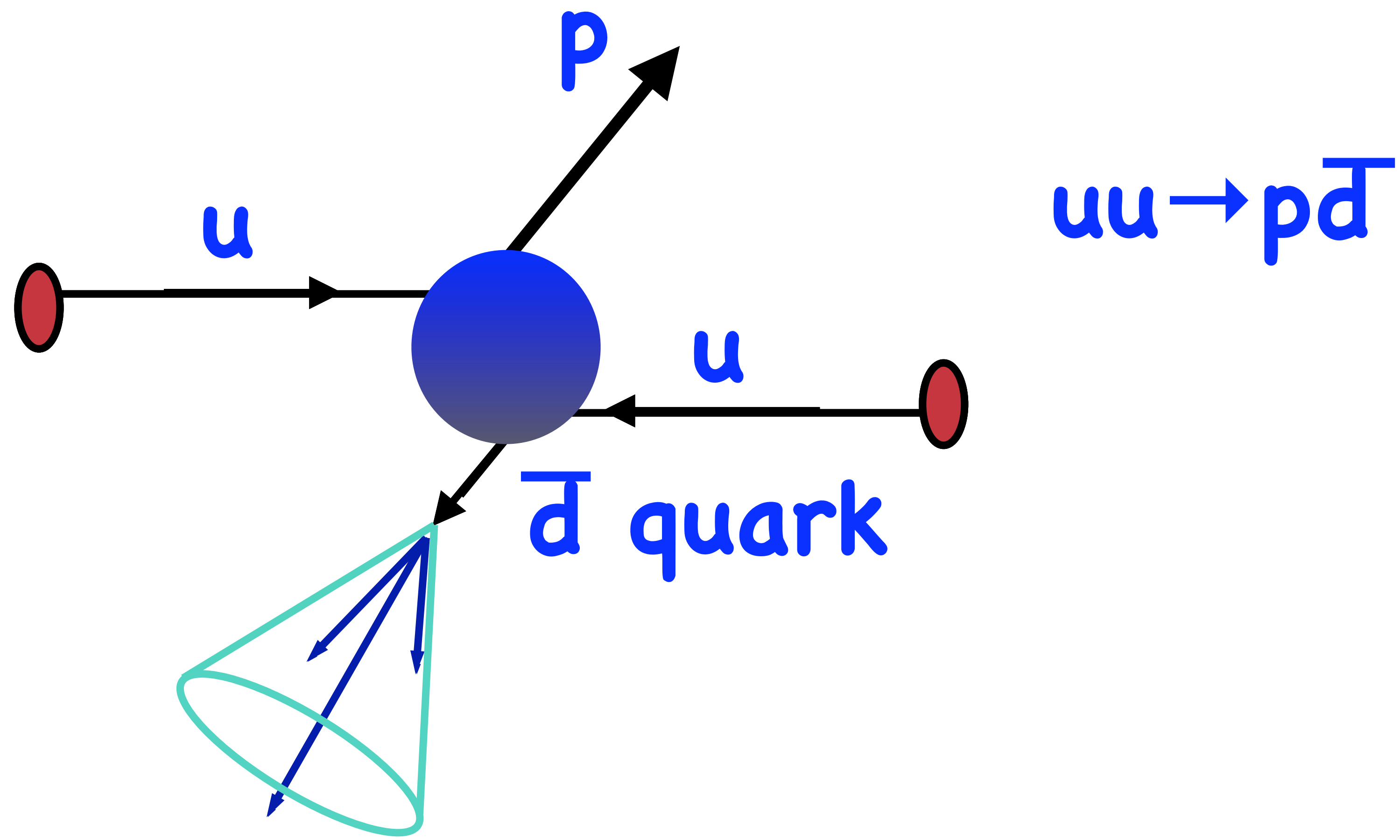

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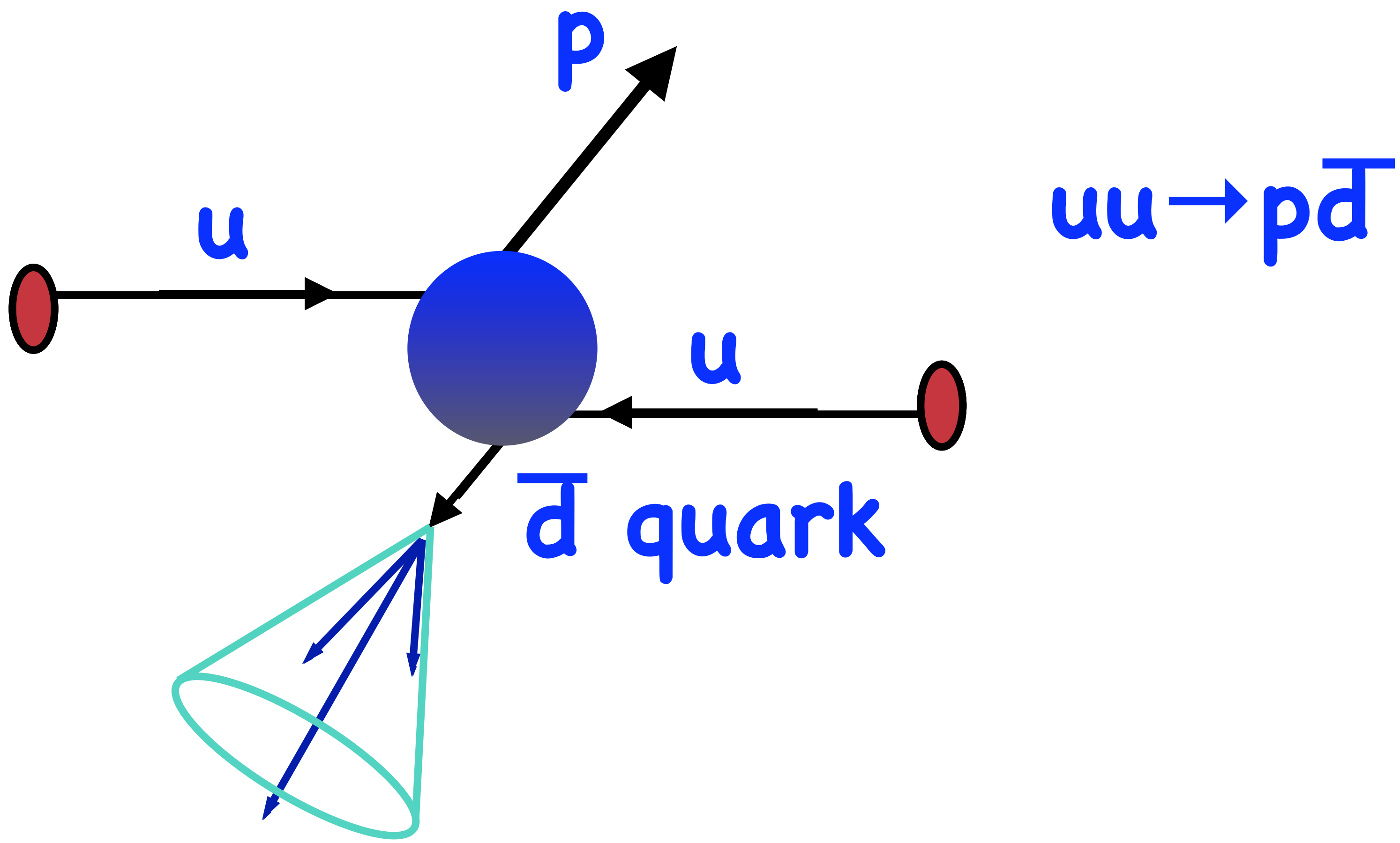

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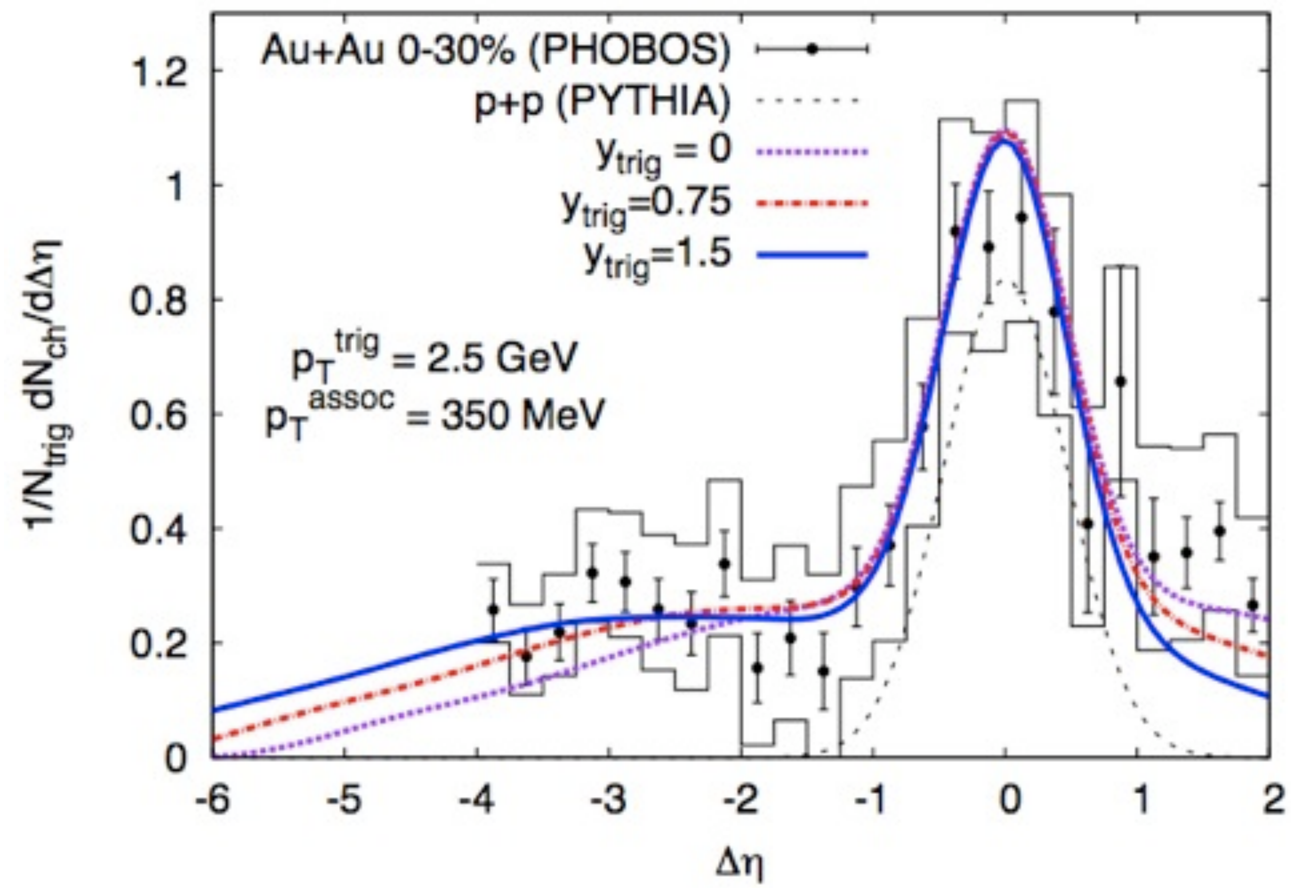
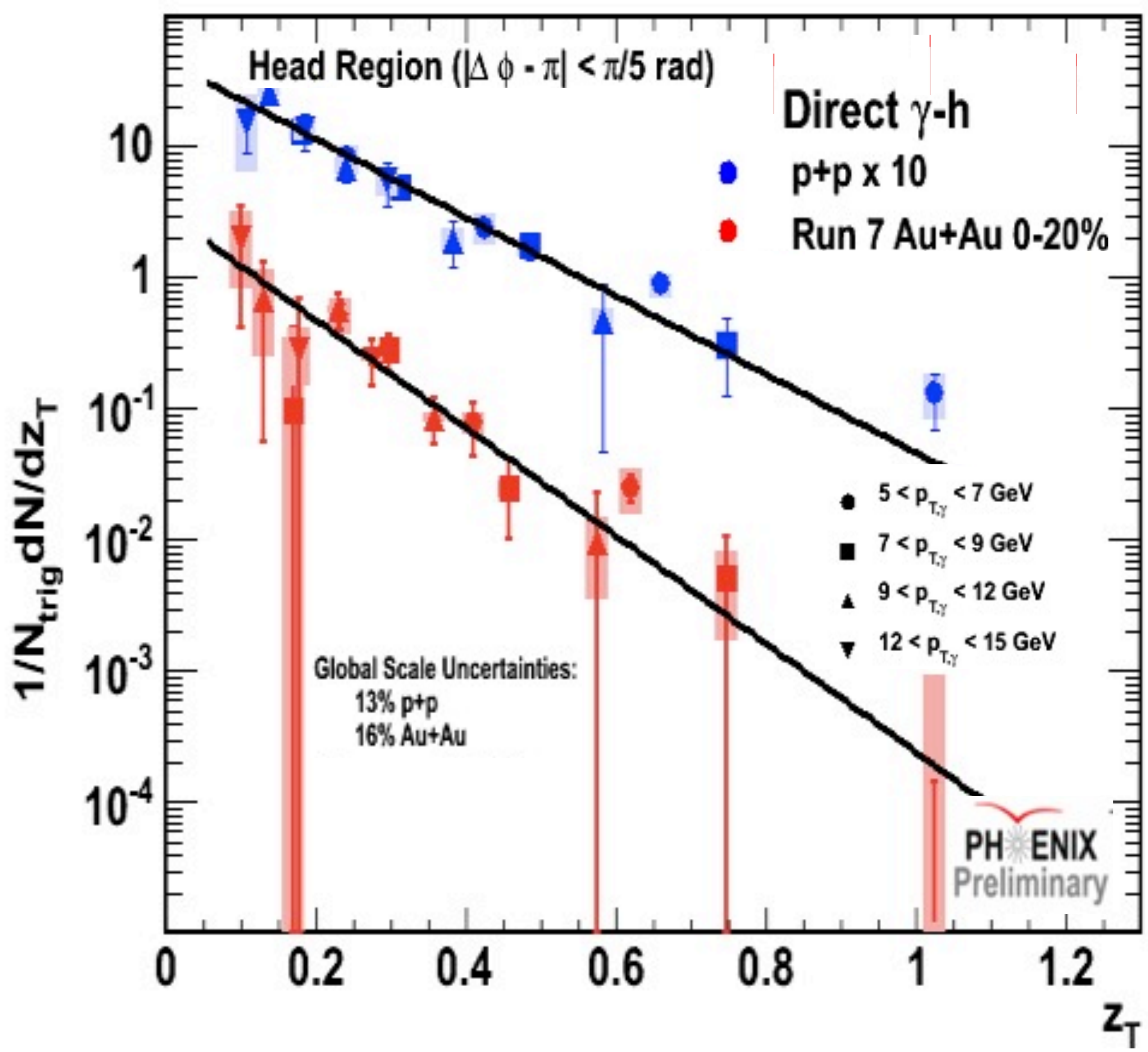
Brodsky & AMS PLB 668 111 (2008)

CGC + radial flow ridge



Dumitru, et al



$$\frac{dN}{dz_T} = Ne^{-bz_T}$$

- p+p: b= 6.89 ± 0.64
  - consistent with quark fragmentation (b=8)
- Au+Au: b = 9.49 ± 1.37