Baryons & Evidence for Direct Production in Relativistic Heavy Ion Collisions

Anne M. Sickles
February 14, 2010

BROOKHAVEN
NATIONAL LABORATORY

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some of this work in collaboration with:
Stan Brodsky, Francois Arleo and D.S. Hwang
Phys. Lett. B668 111 (2008) & arXiv: 0911.4604

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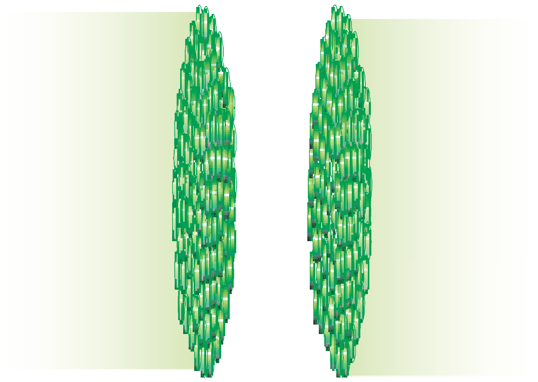
Heavy Ion Collision

illustration: S. Bass

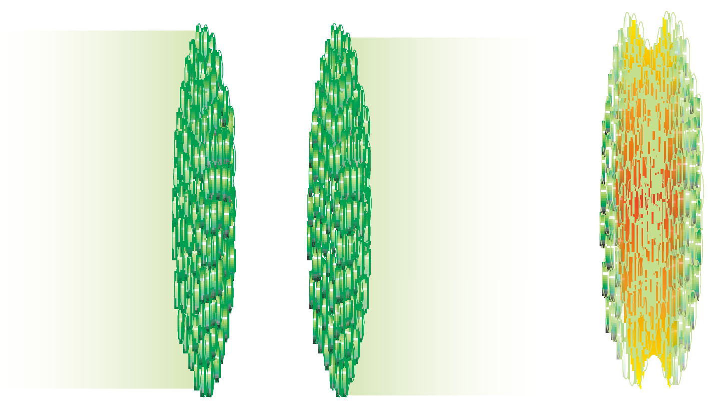
Heavy Ion Collision



incoming
nuclei

illustration: S. Bass

Heavy Ion Collision



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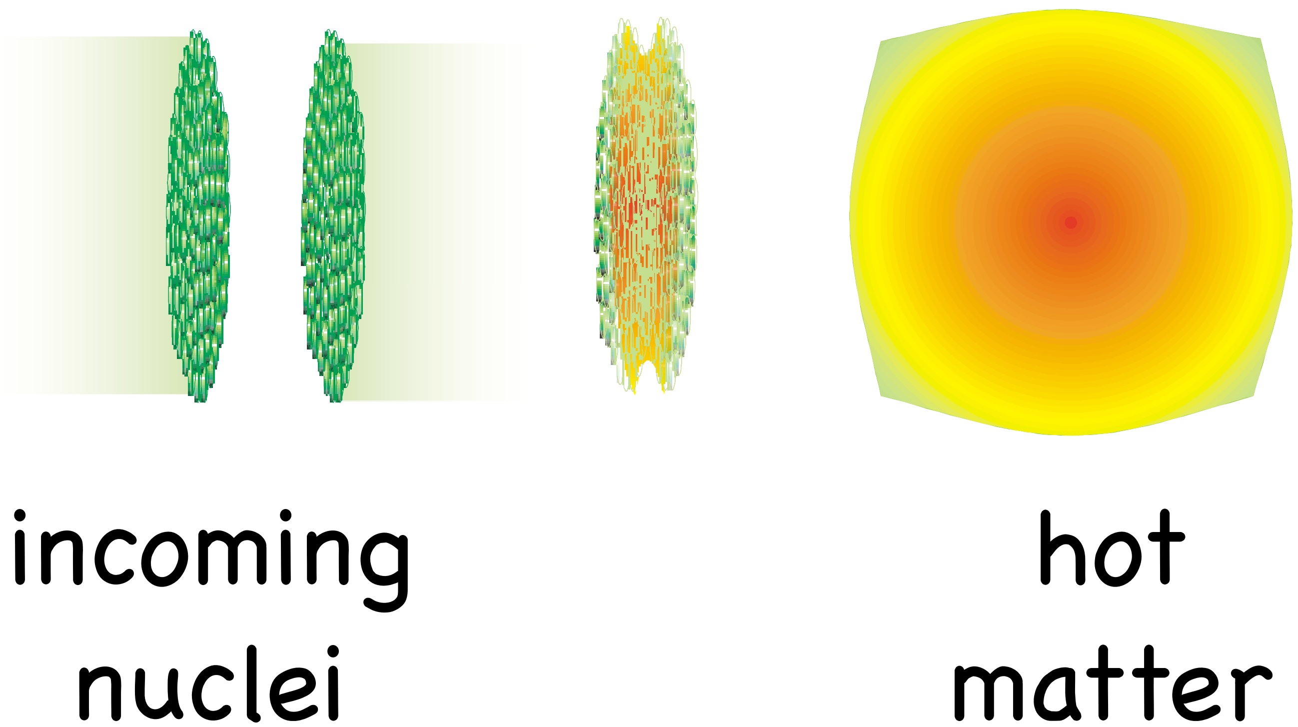
Heavy Ion Collision



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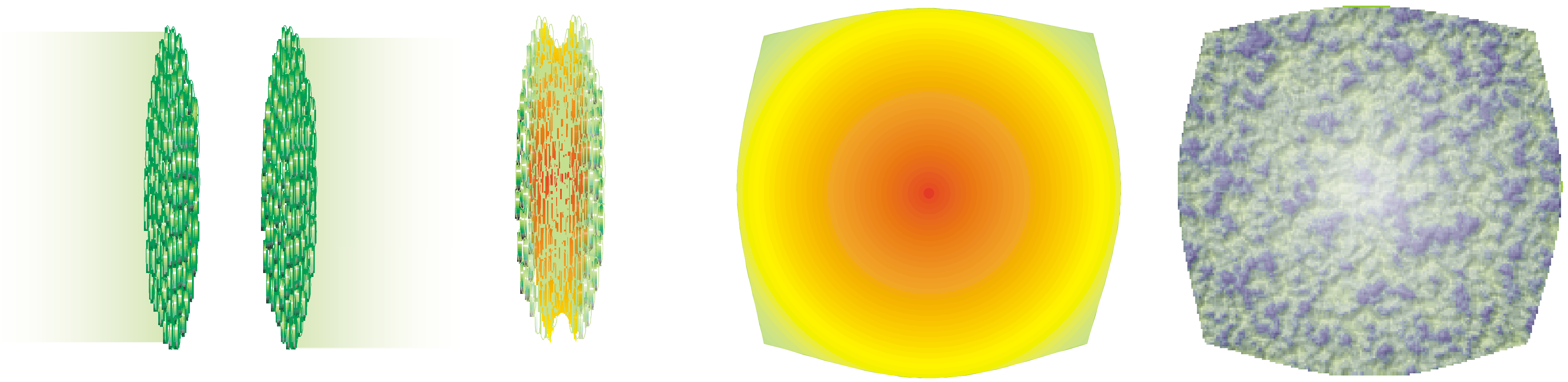
Heavy Ion Collision



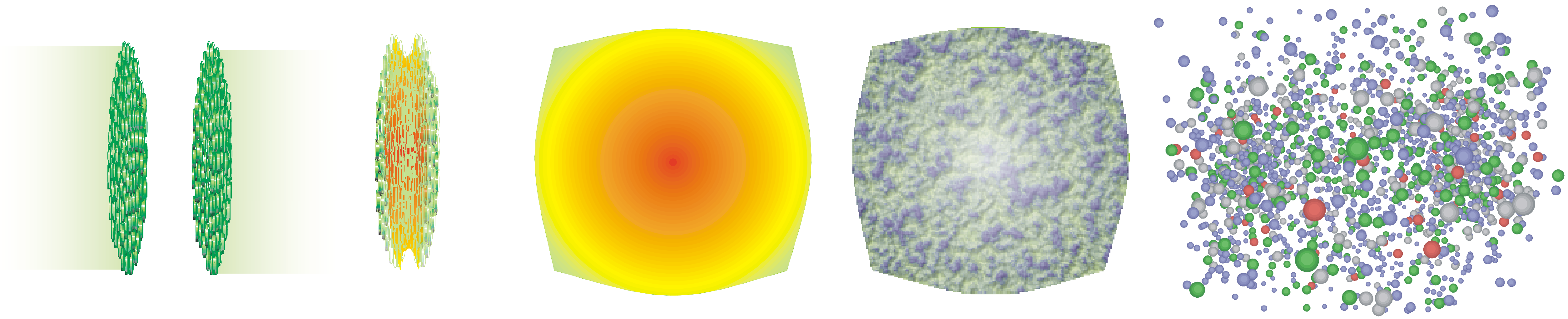
incoming nuclei

hot matter

hadronic gas

illustration: S. Bass

Heavy Ion Collision



incoming nuclei

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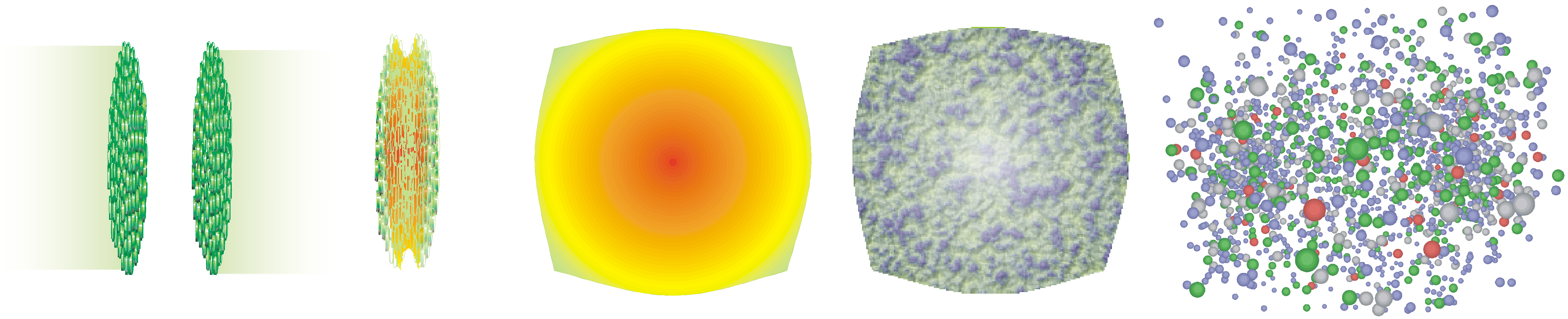
Heavy Ion Collision



incoming nuclei

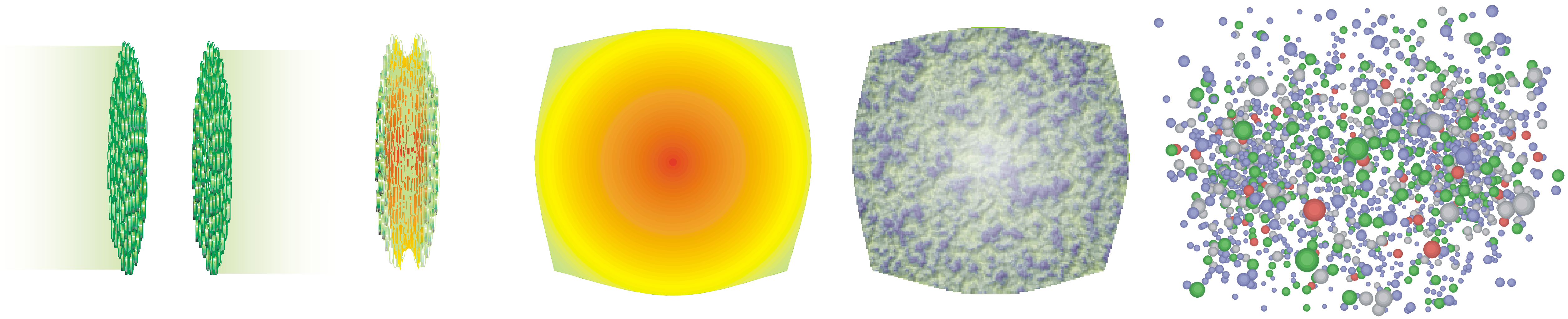
hot matter

hadronic gas

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

illustration: S. Bass

Heavy Ion Collision



incoming nuclei

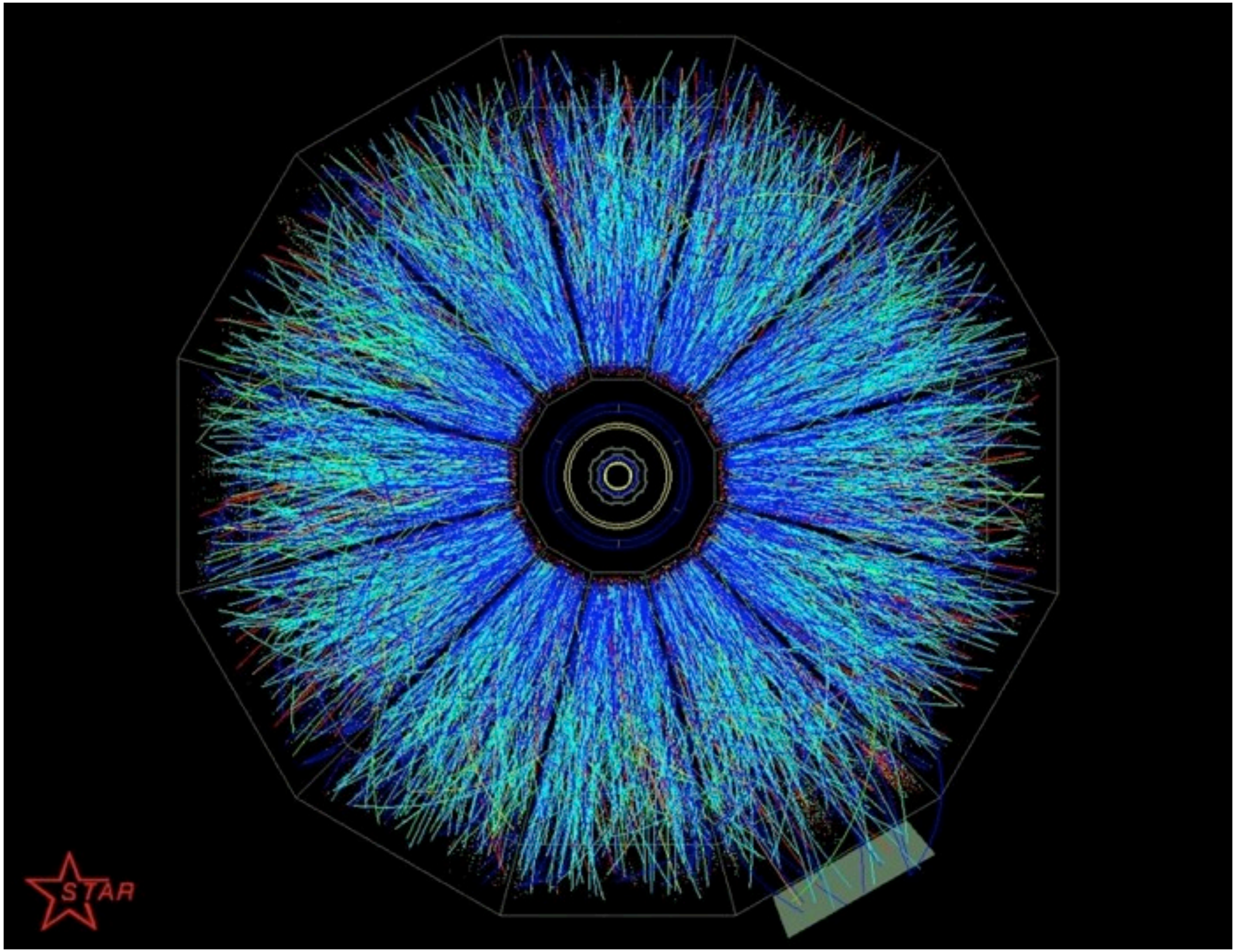
hot matter

hadronic gas

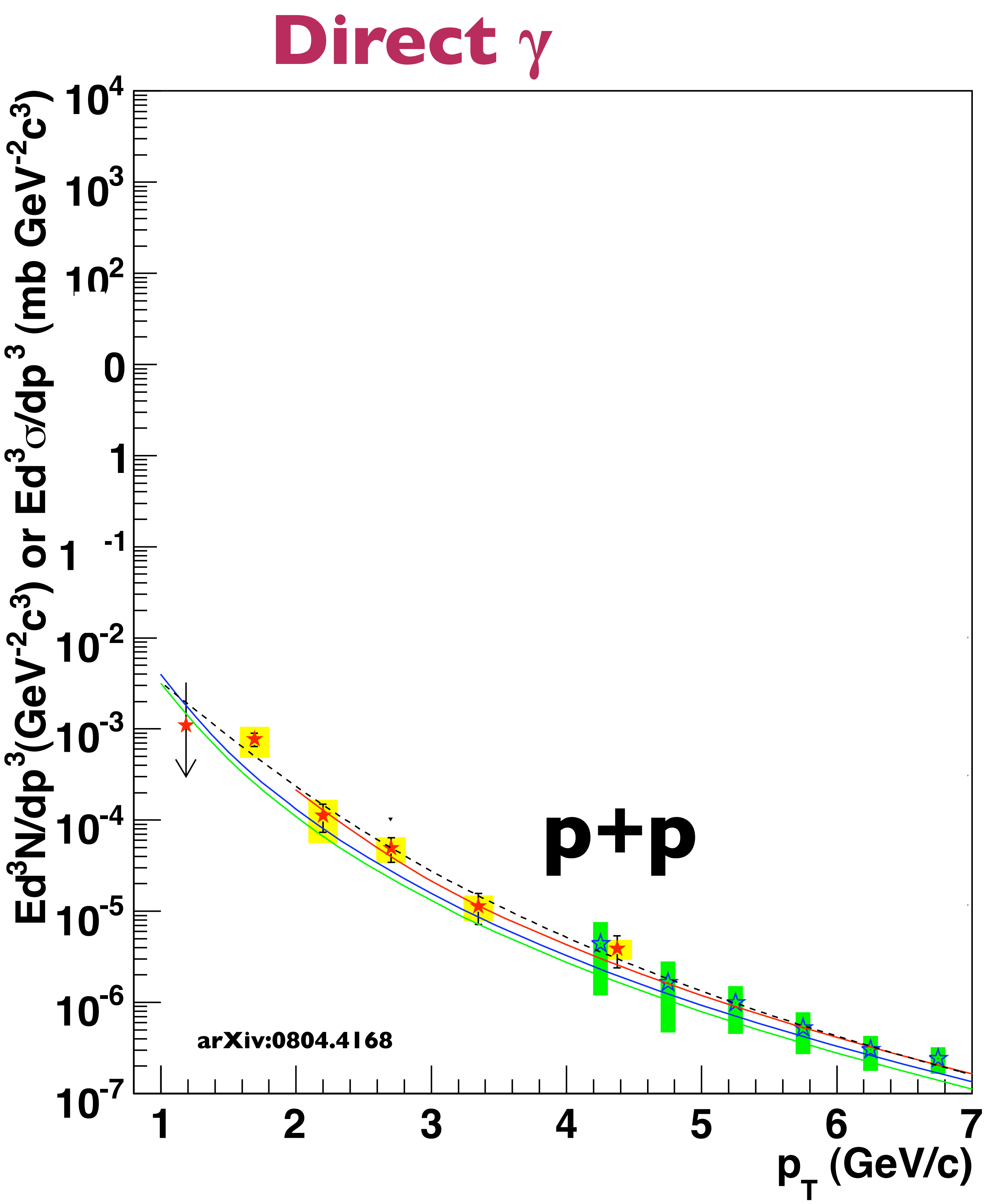
- RHIC: ion-ion collisions at up to $\sqrt{s_{NN}}$=200GeV
- also p+p collsions, crucial baseline

illustration: S. Bass

Au+Au collision



hot nuclear matter



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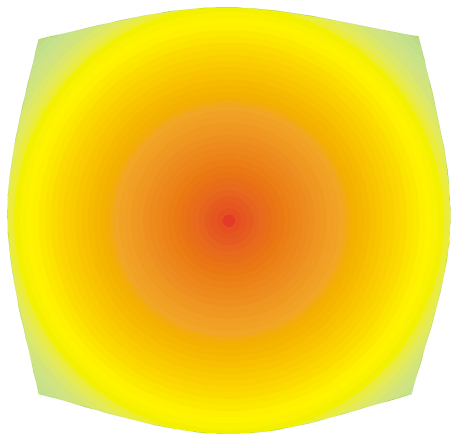

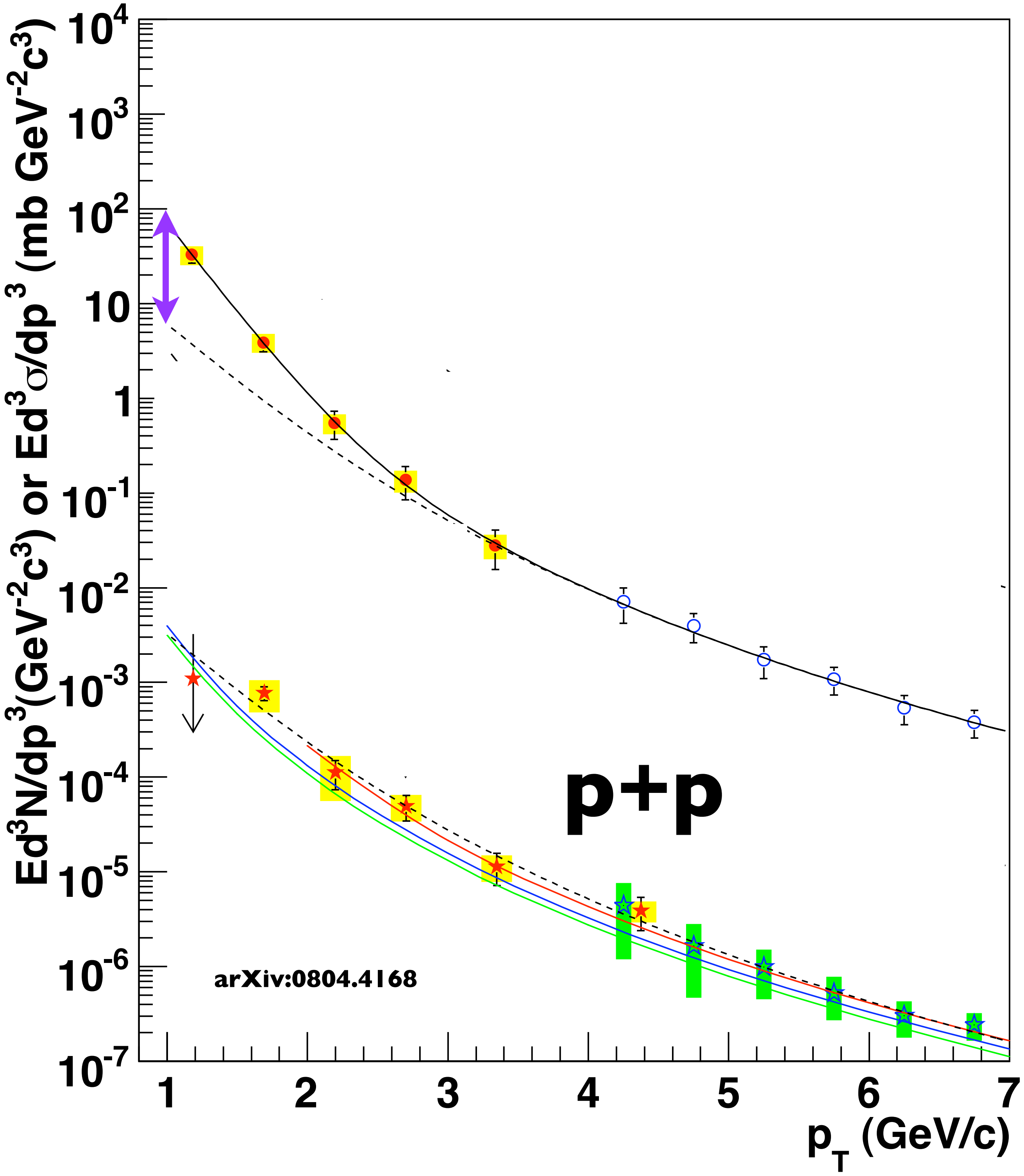

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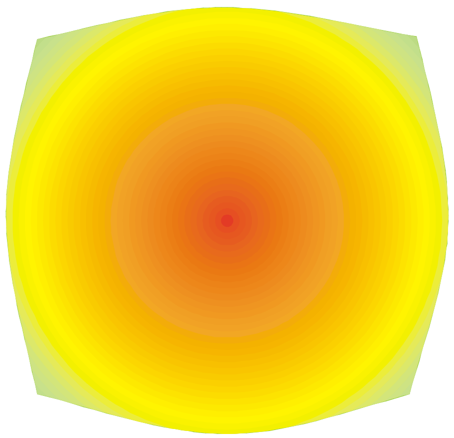
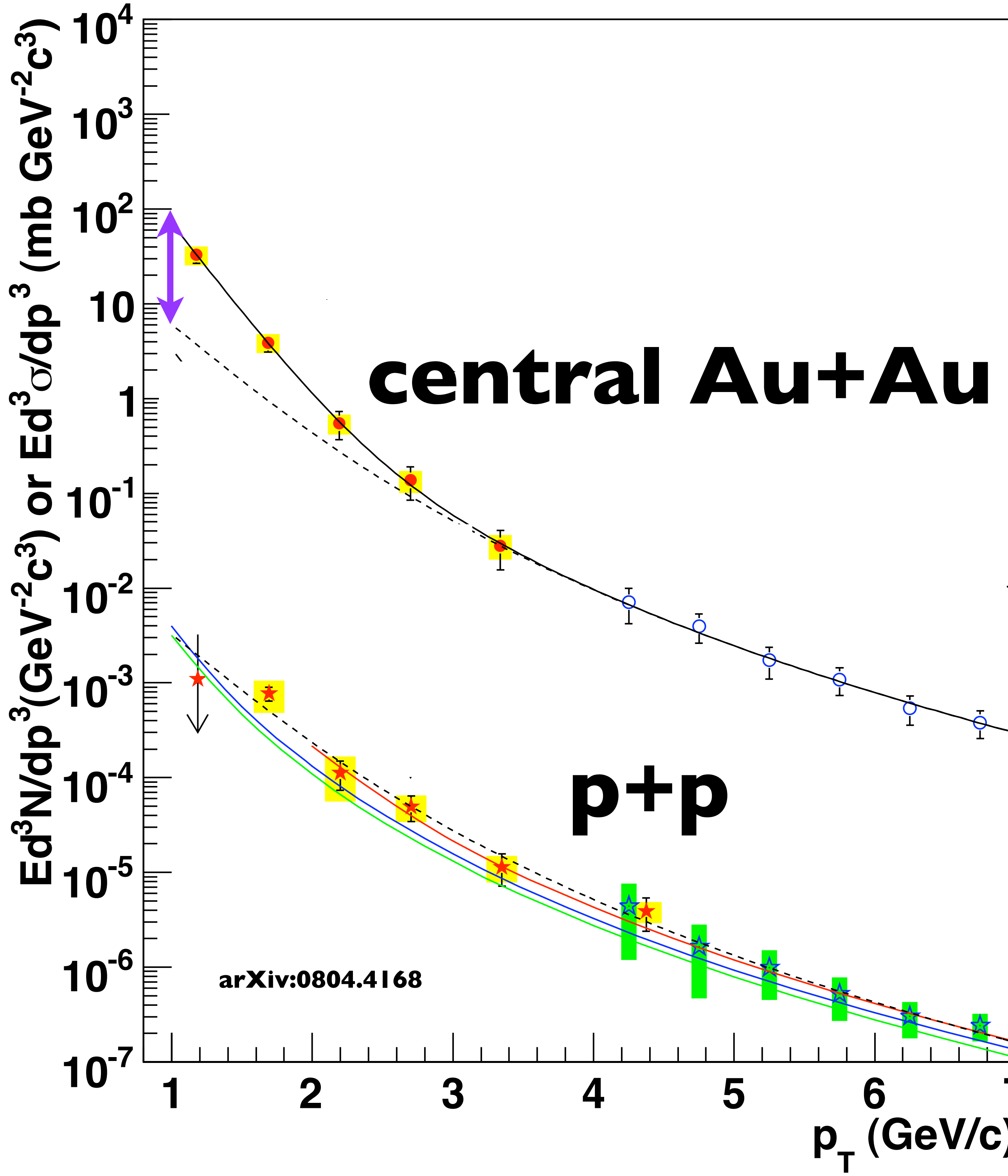
hot nuclear matter





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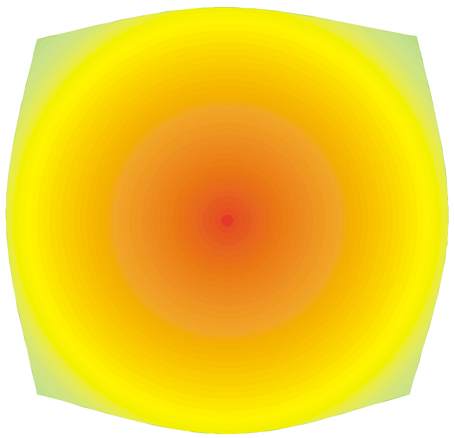
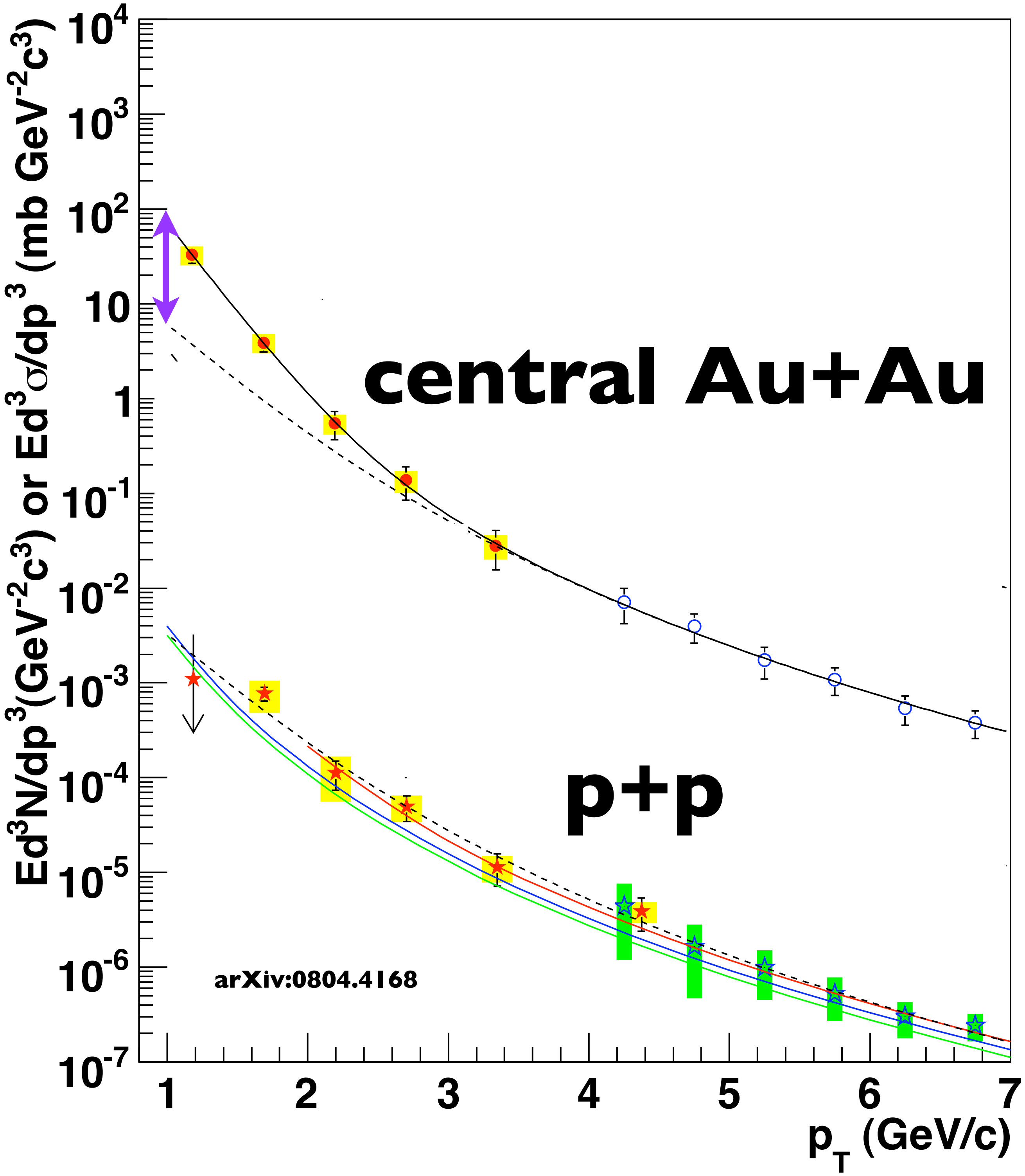
hot nuclear matter



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



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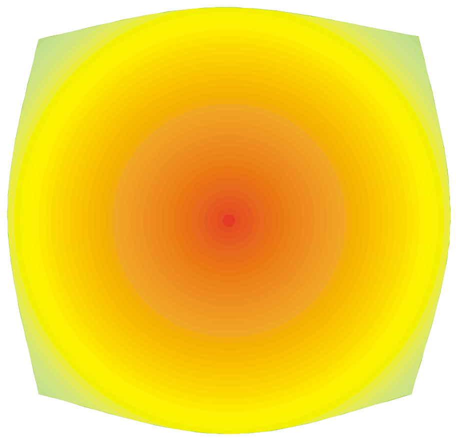
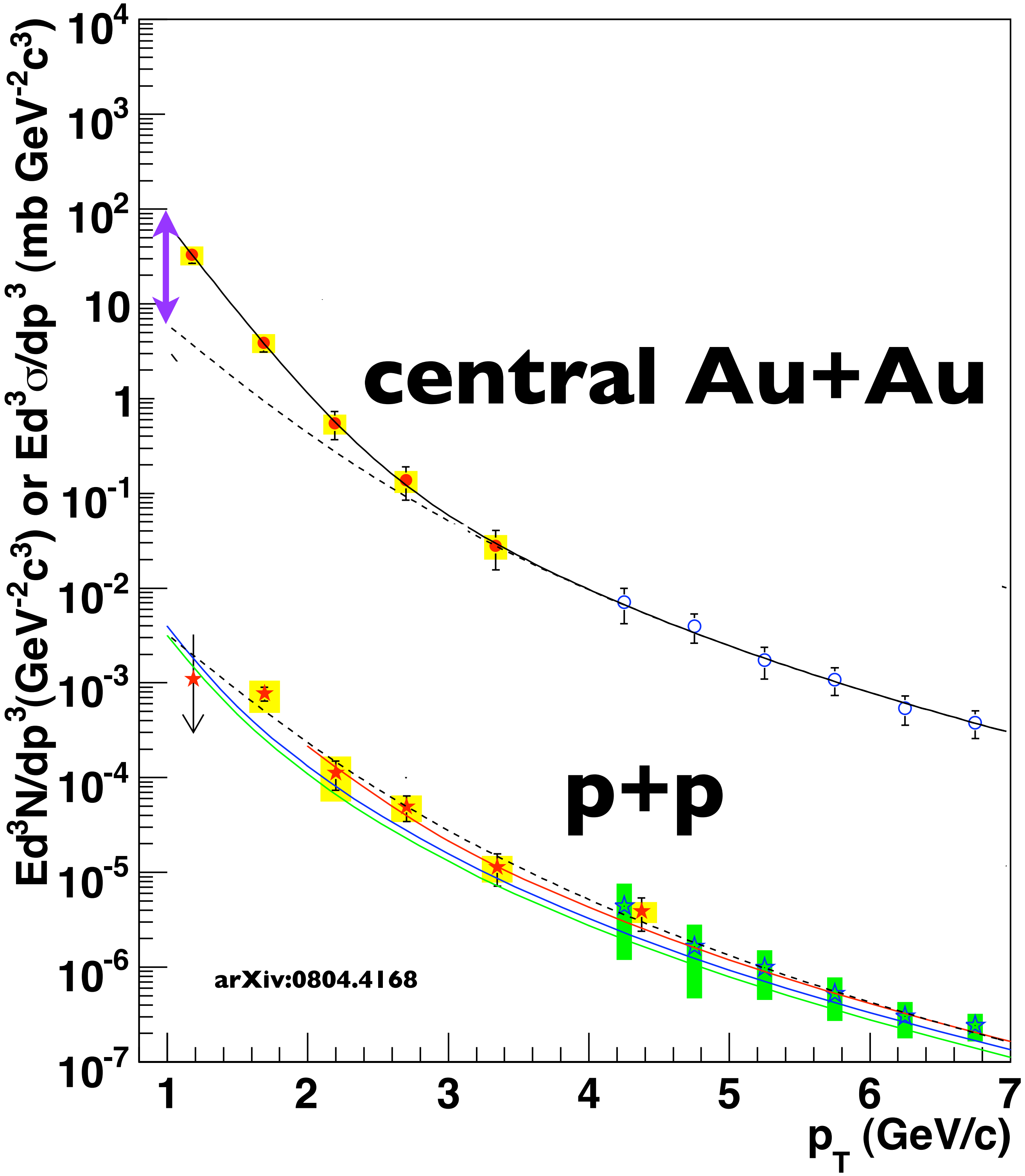


central Au+Au:
large excess over
binary scaled p+p

excess:
221±23±18MeV



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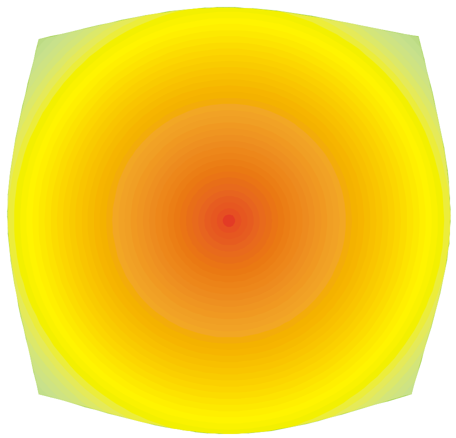
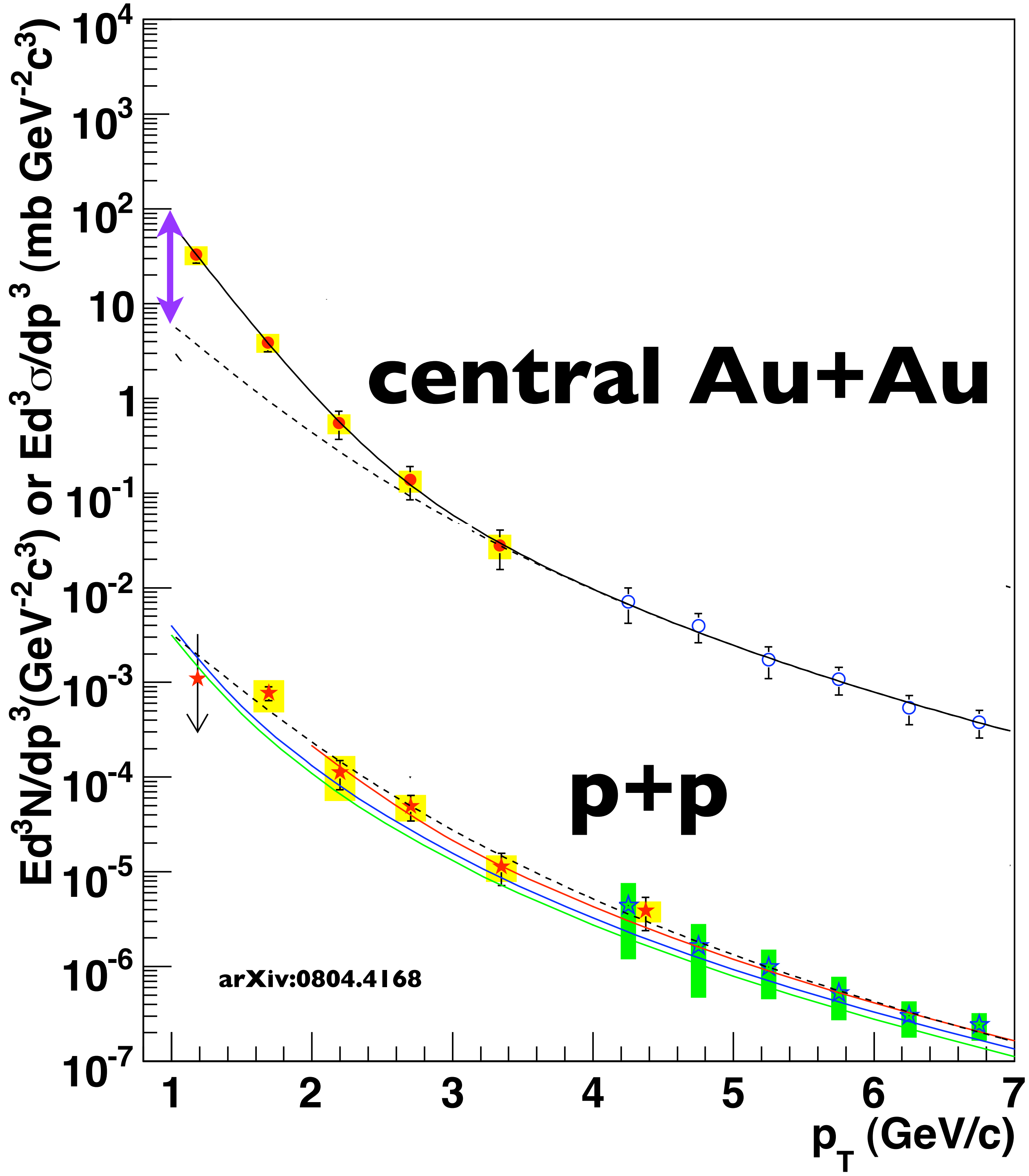


central Au+Au:
large excess over
binary scaled p+p

excess:
221±23±18MeV

consistent with initial
T ~ 300-600MeV



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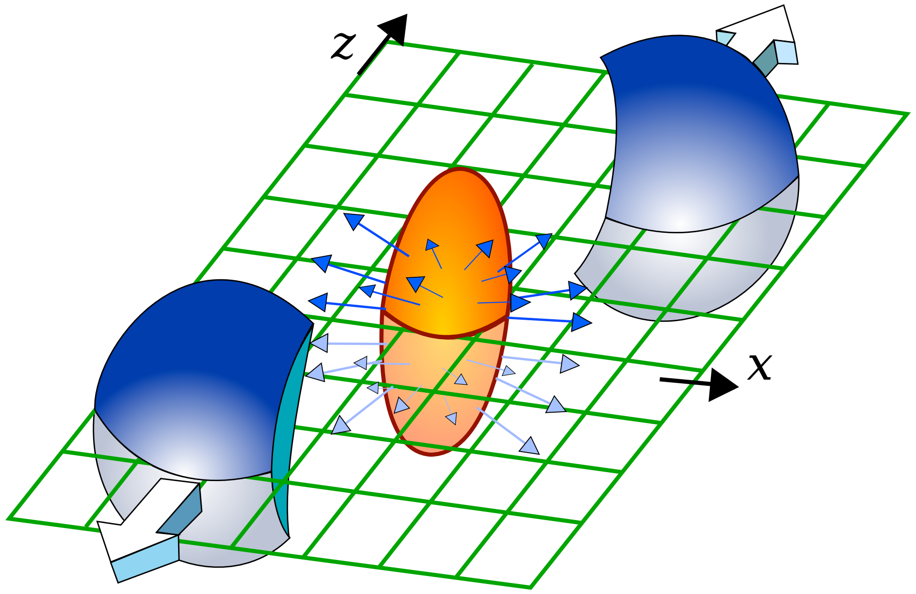
the matter flows

$$\frac{dN}{d(\Psi - \phi)} \propto 1 + 2v_2 \cos(\Psi - \phi) + \ldots$$



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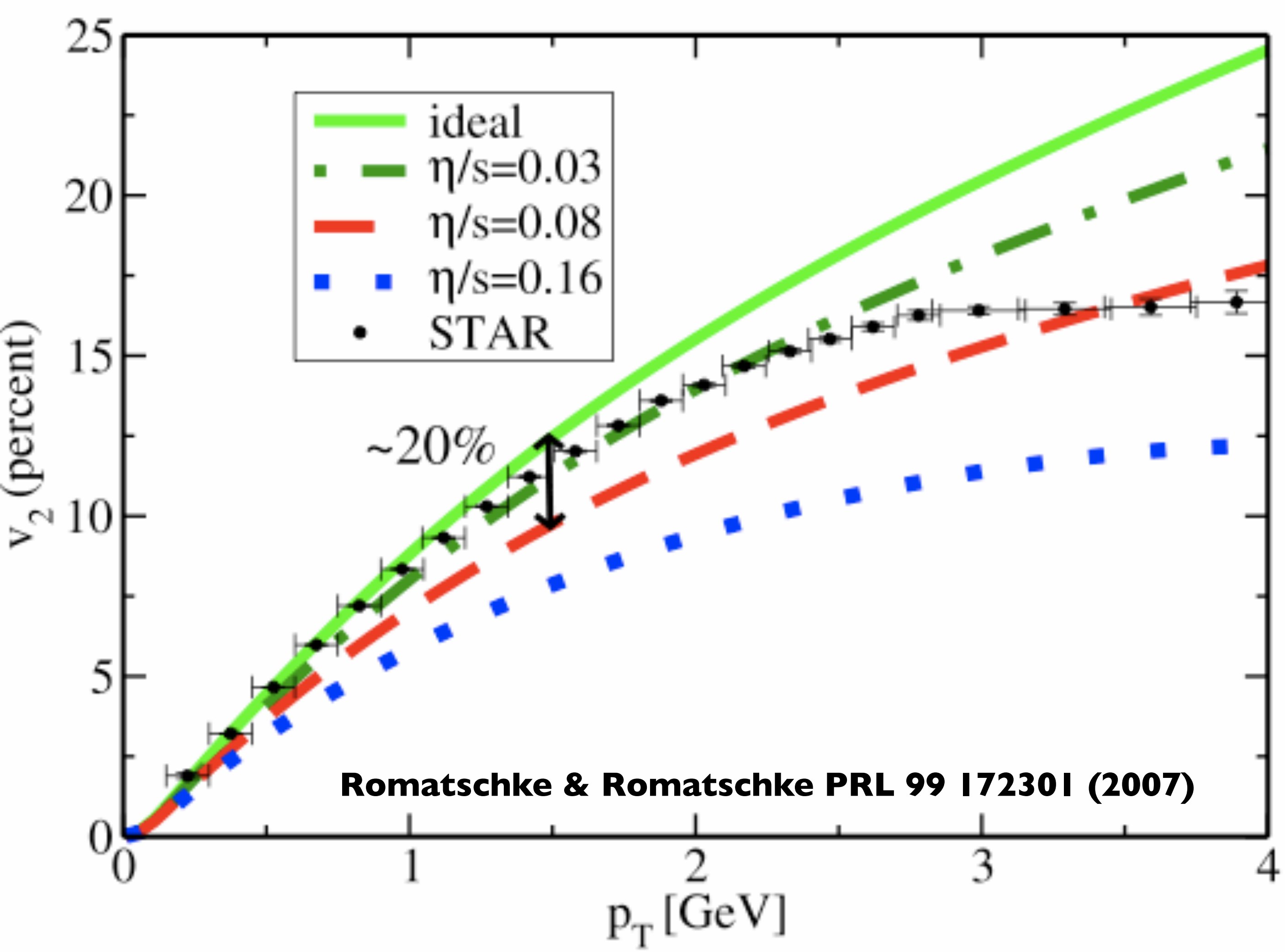

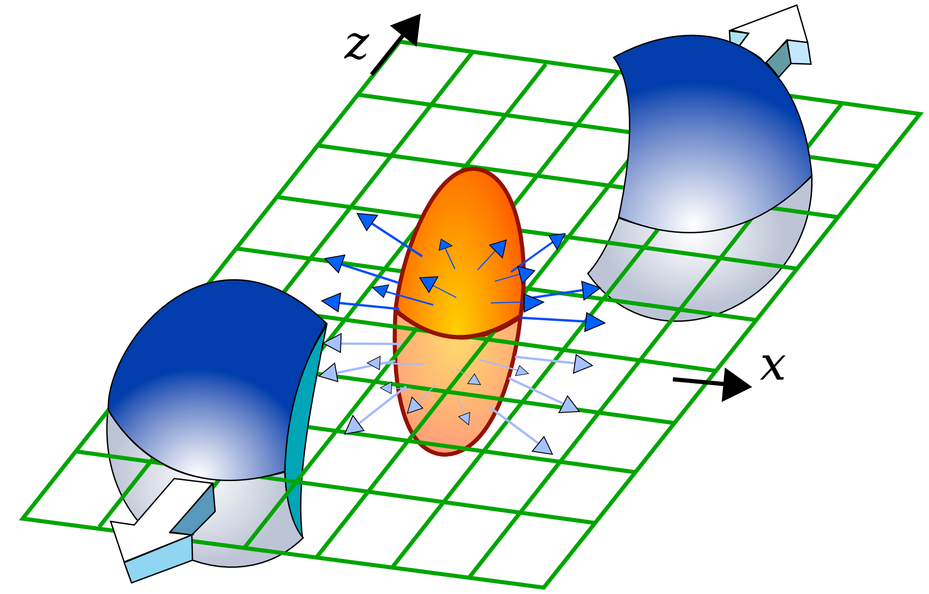

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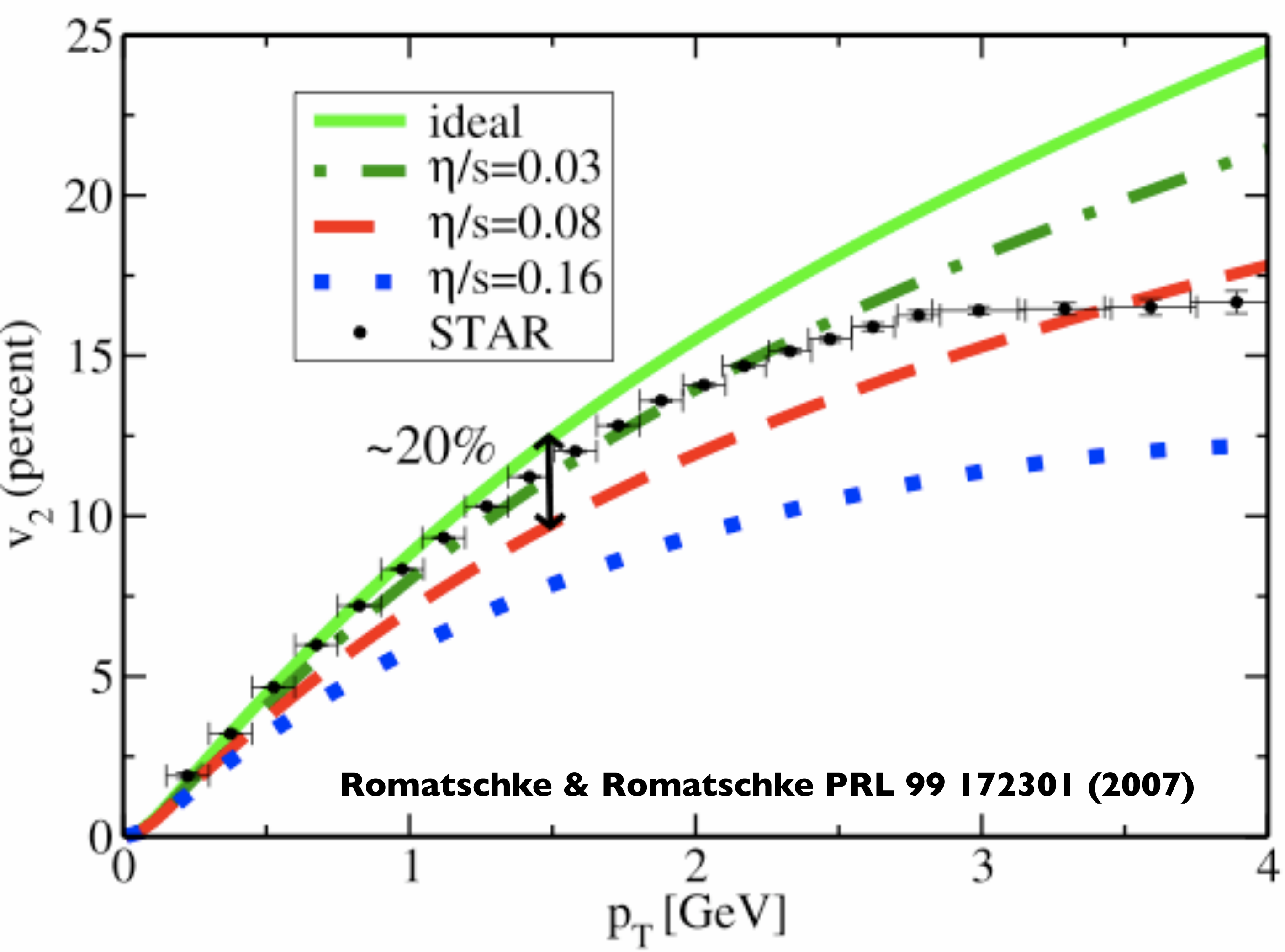
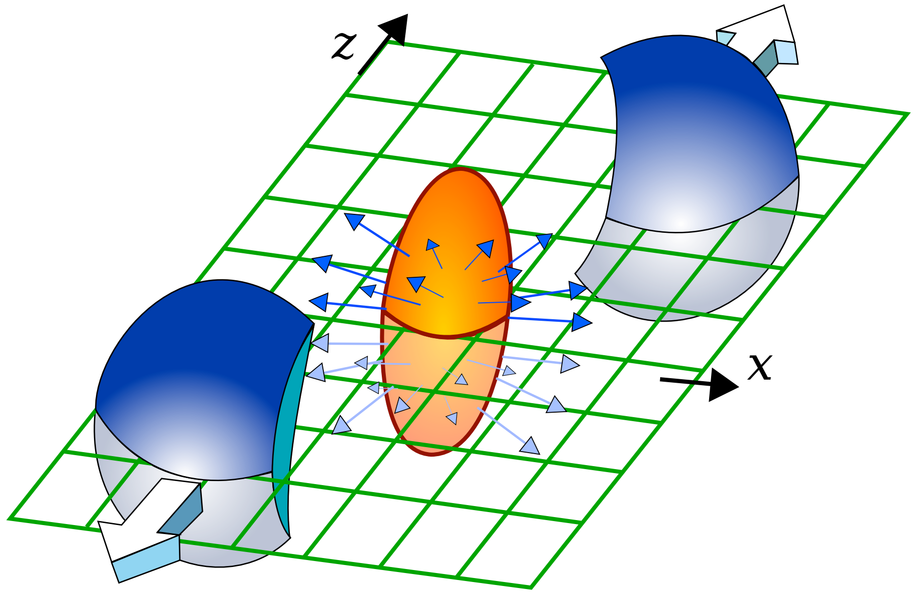
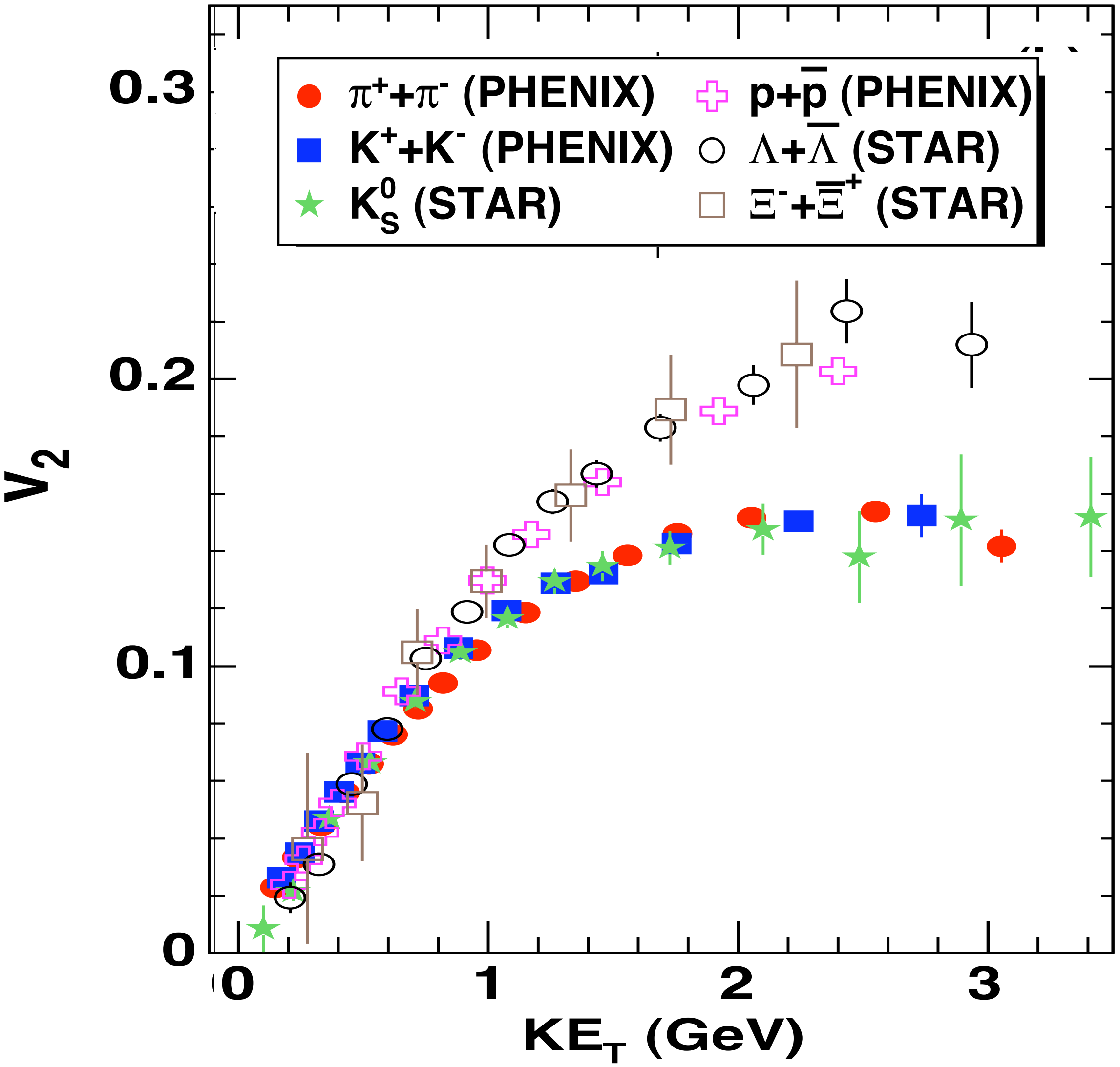




well described by hydrodynamics with small viscosity

the partons flow



$$KE_T = m_T - m$$

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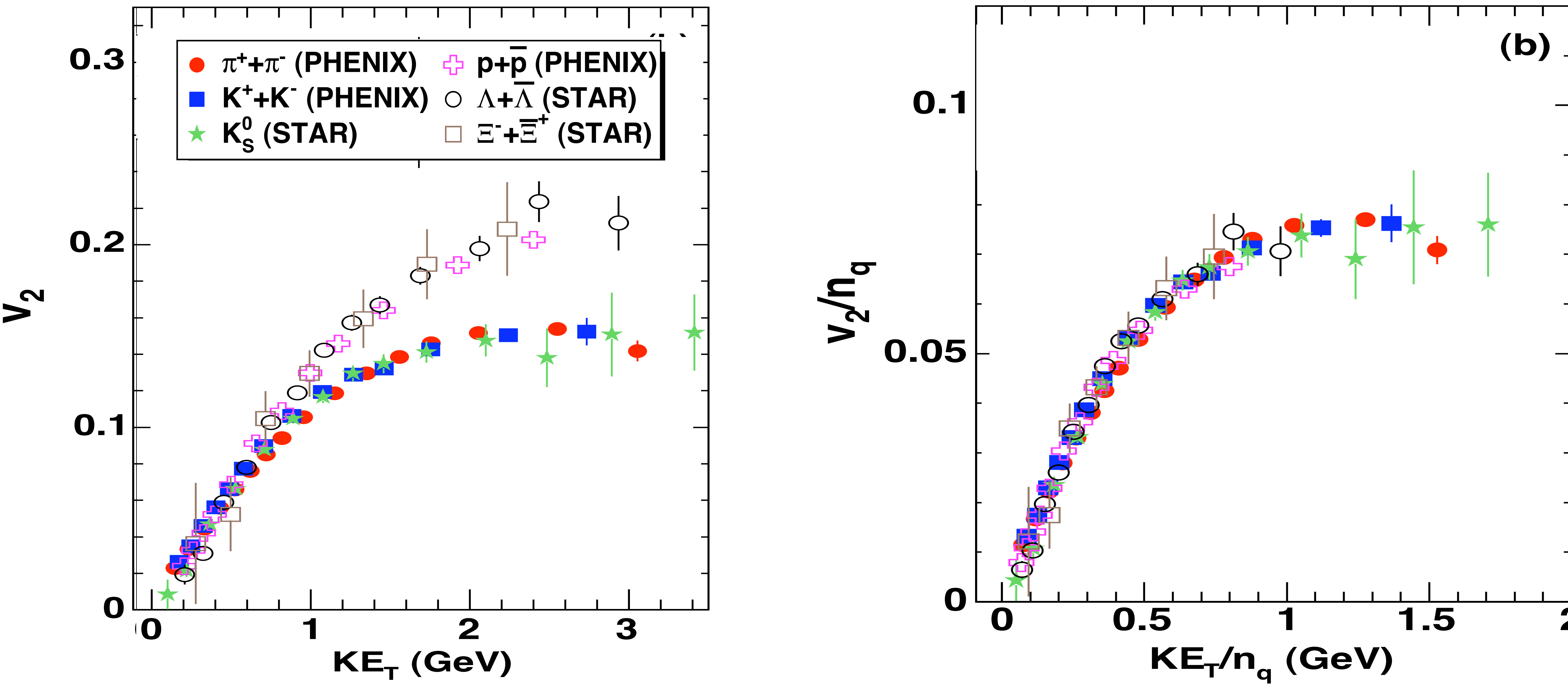
the partons flow



$$KE_T = m_T - m$$

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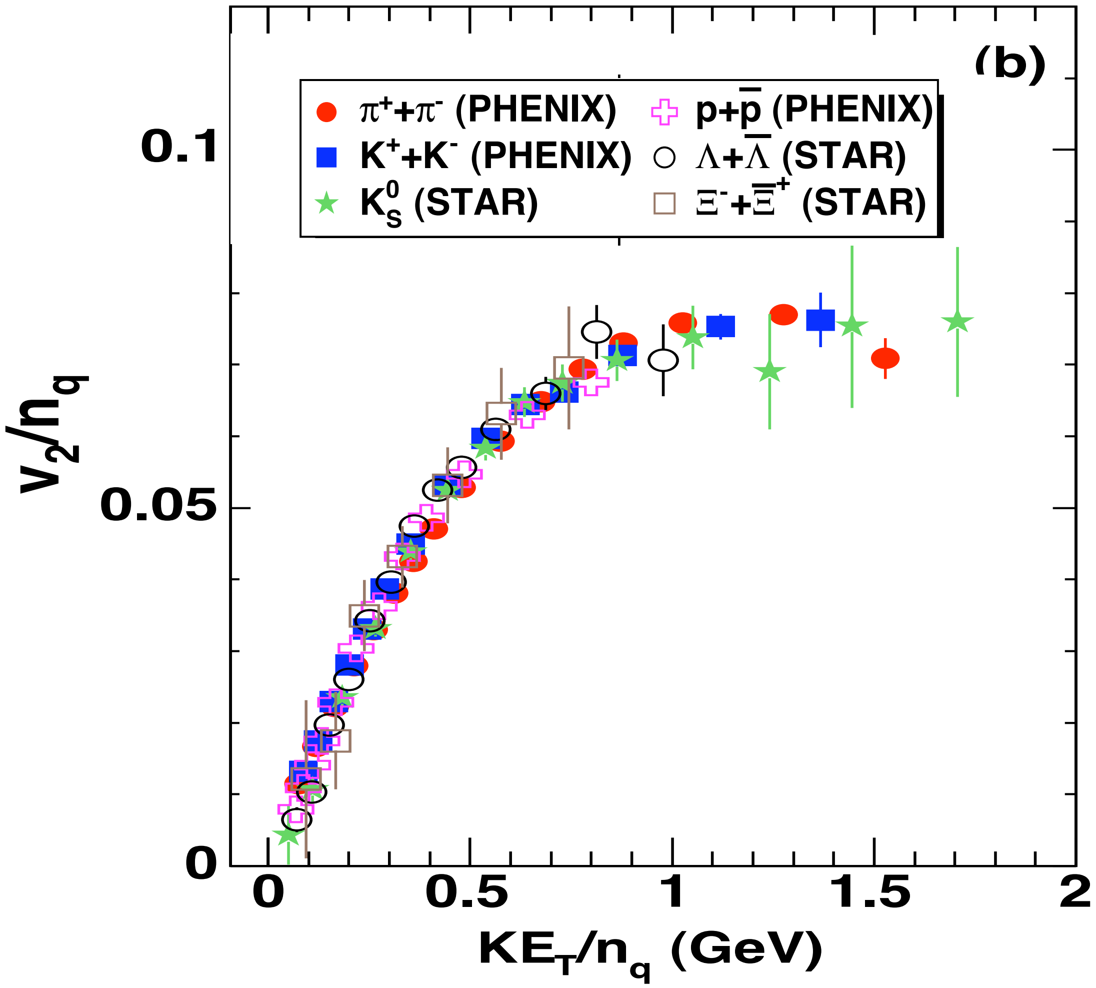
anomalous (anti)baryons



valence quark flow

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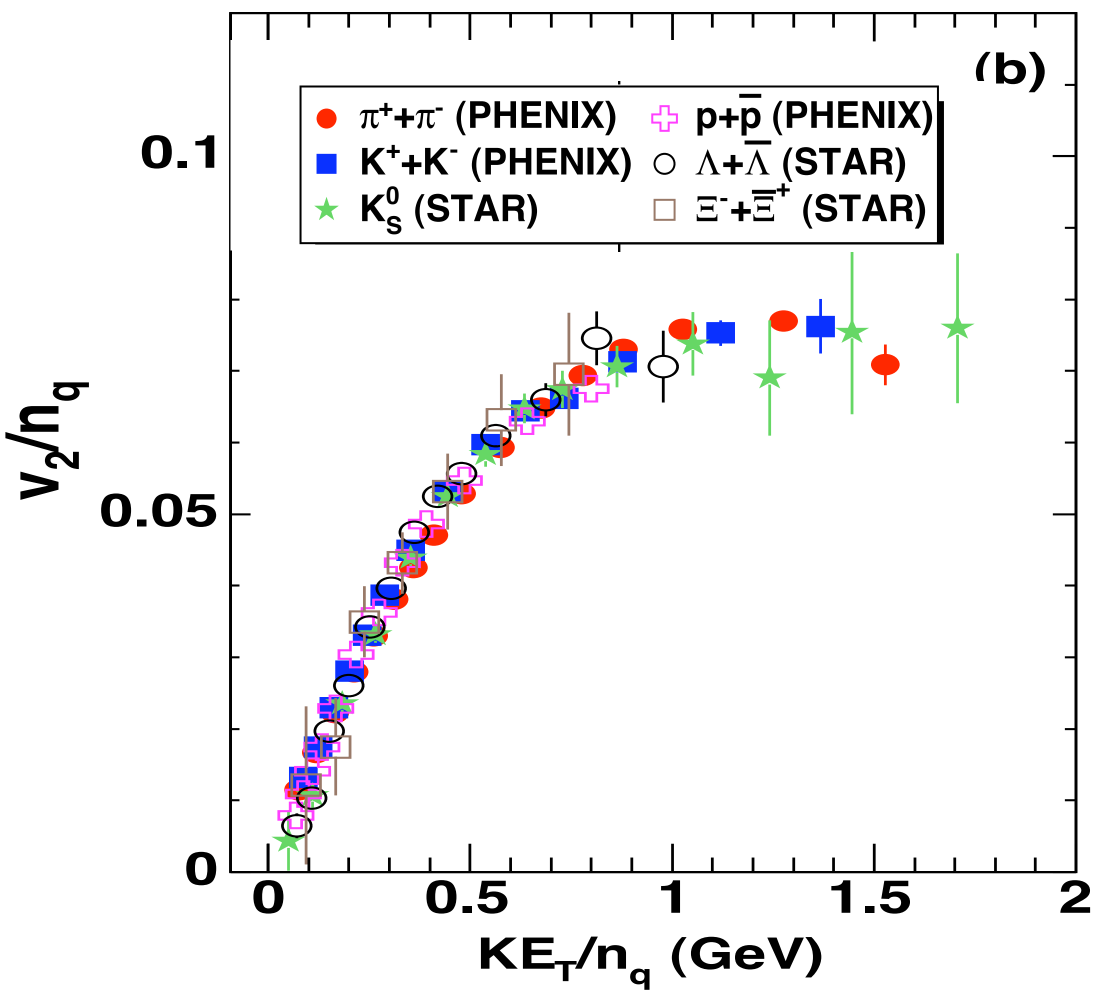
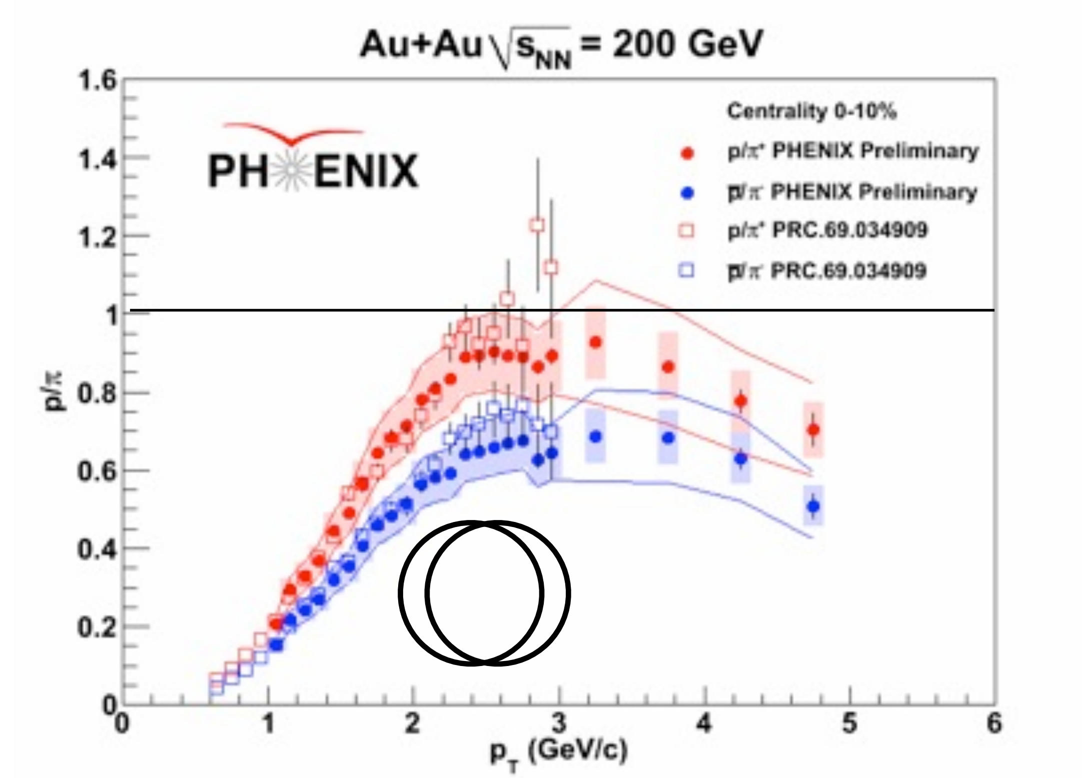
anomalous (anti)baryons





valence quark flow

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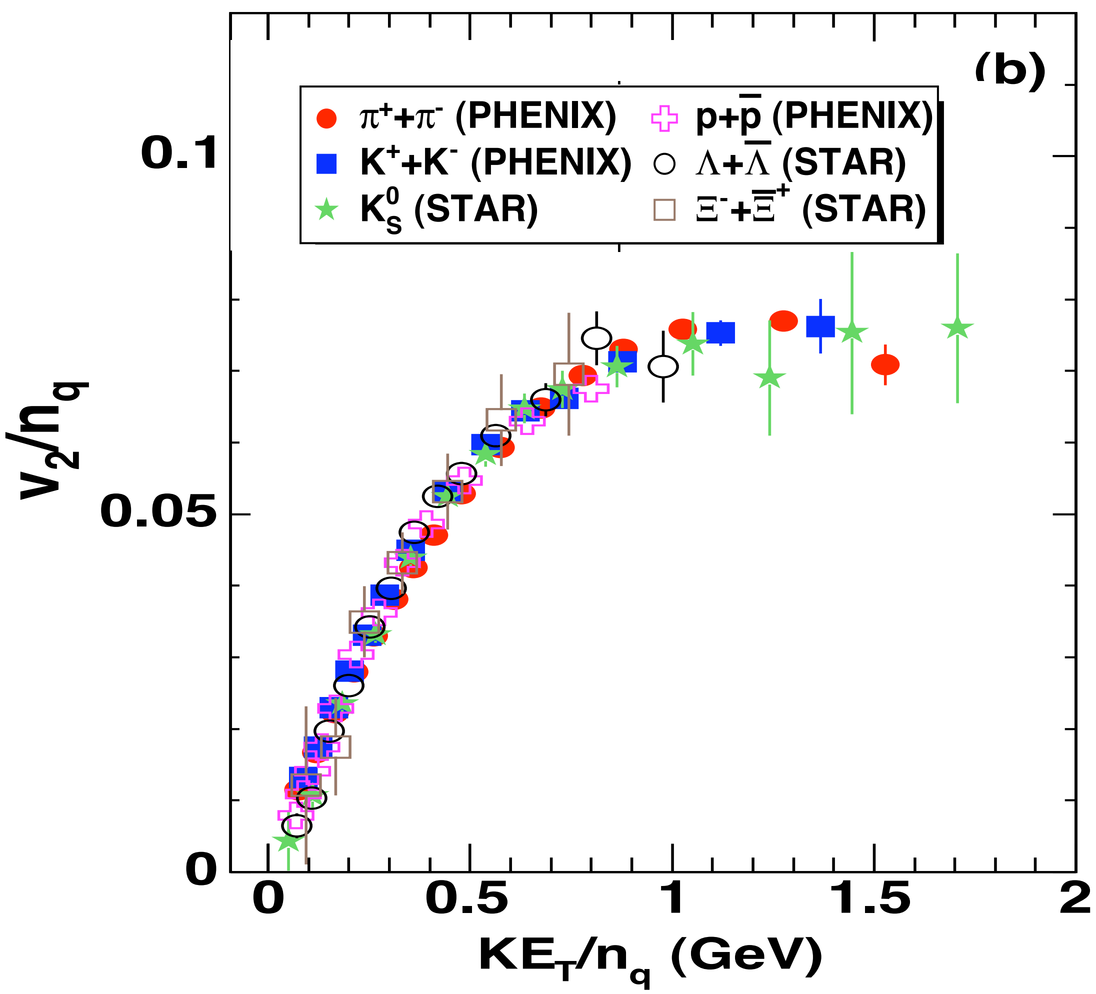
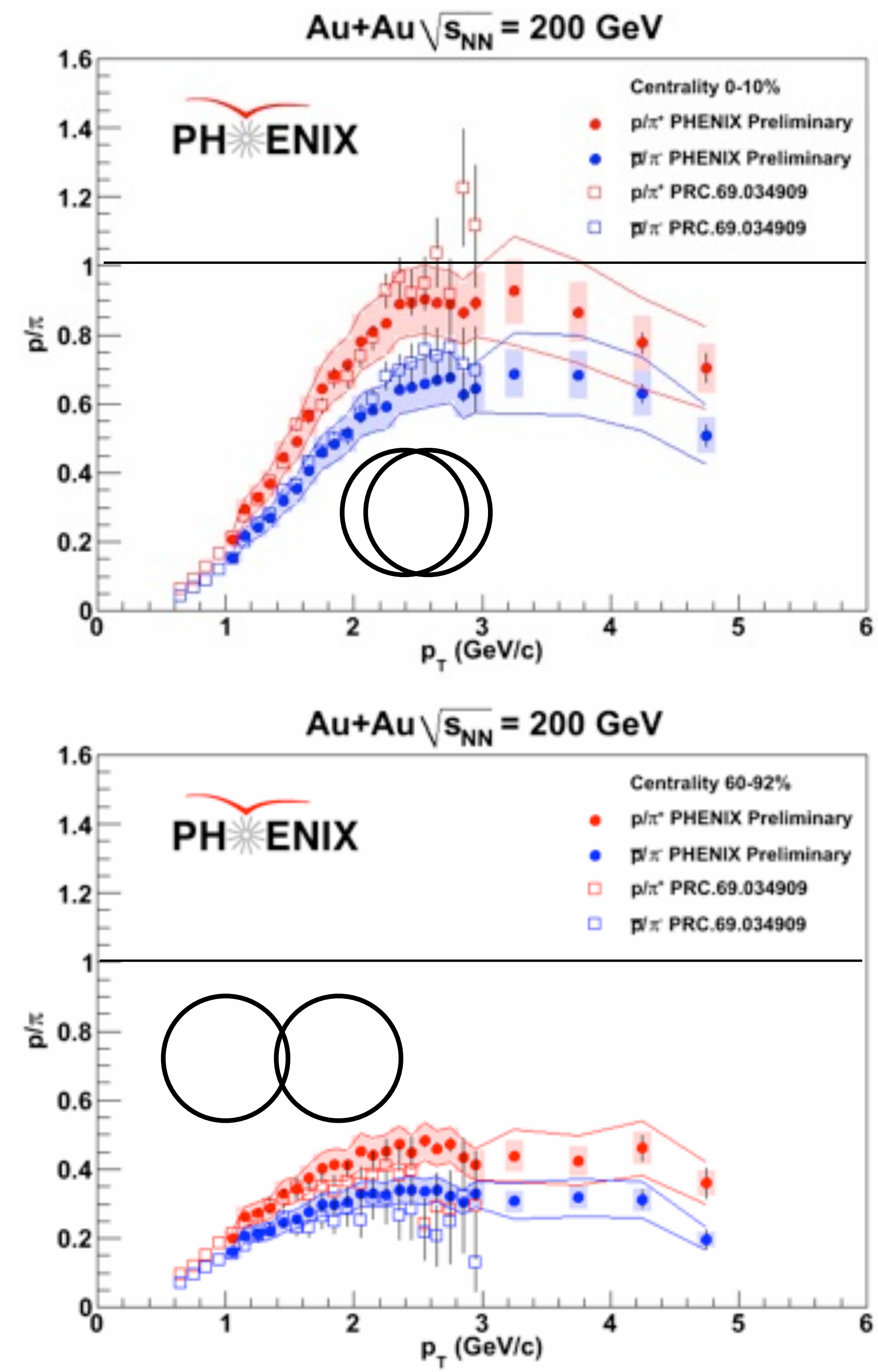
anomalous (anti)baryons





valence quark flow

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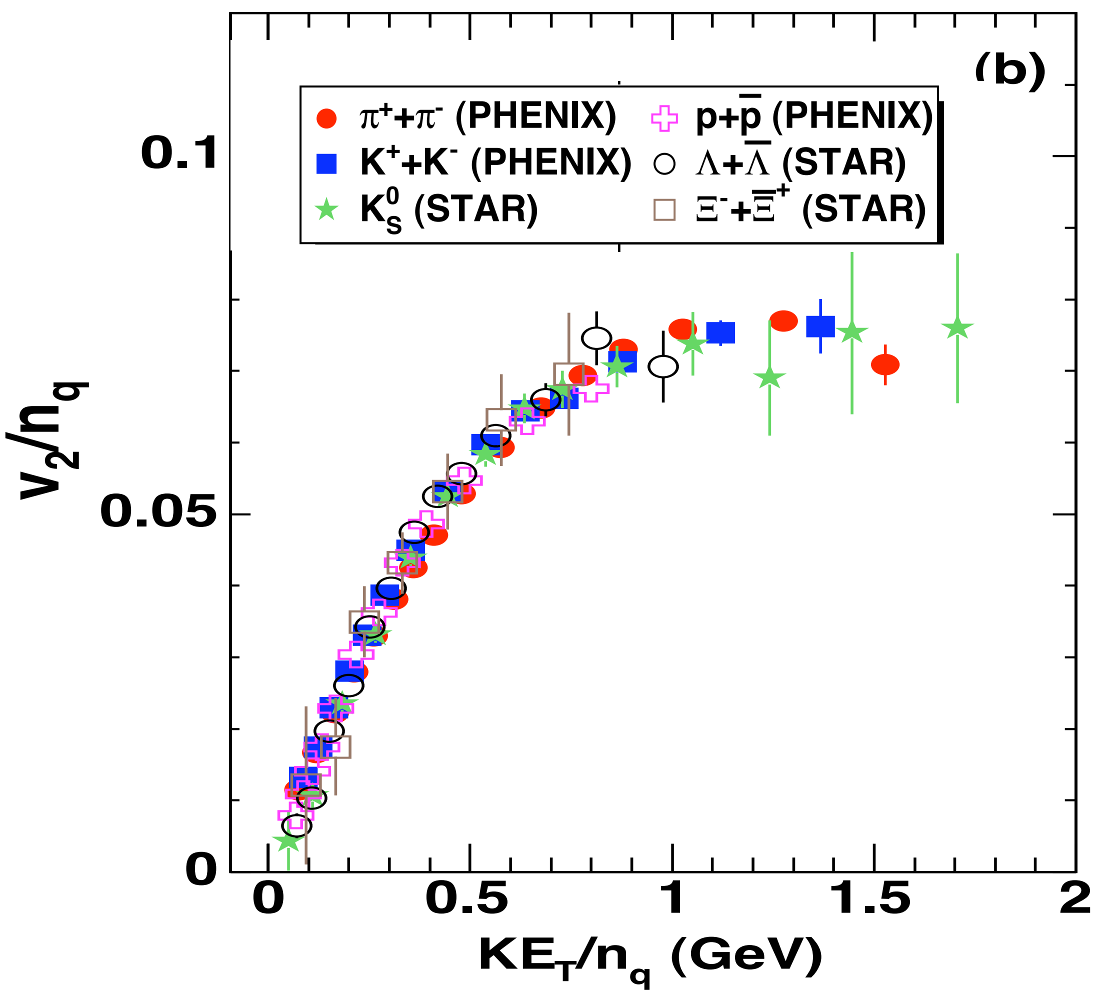
anomalous (anti)baryons



valence quark flow

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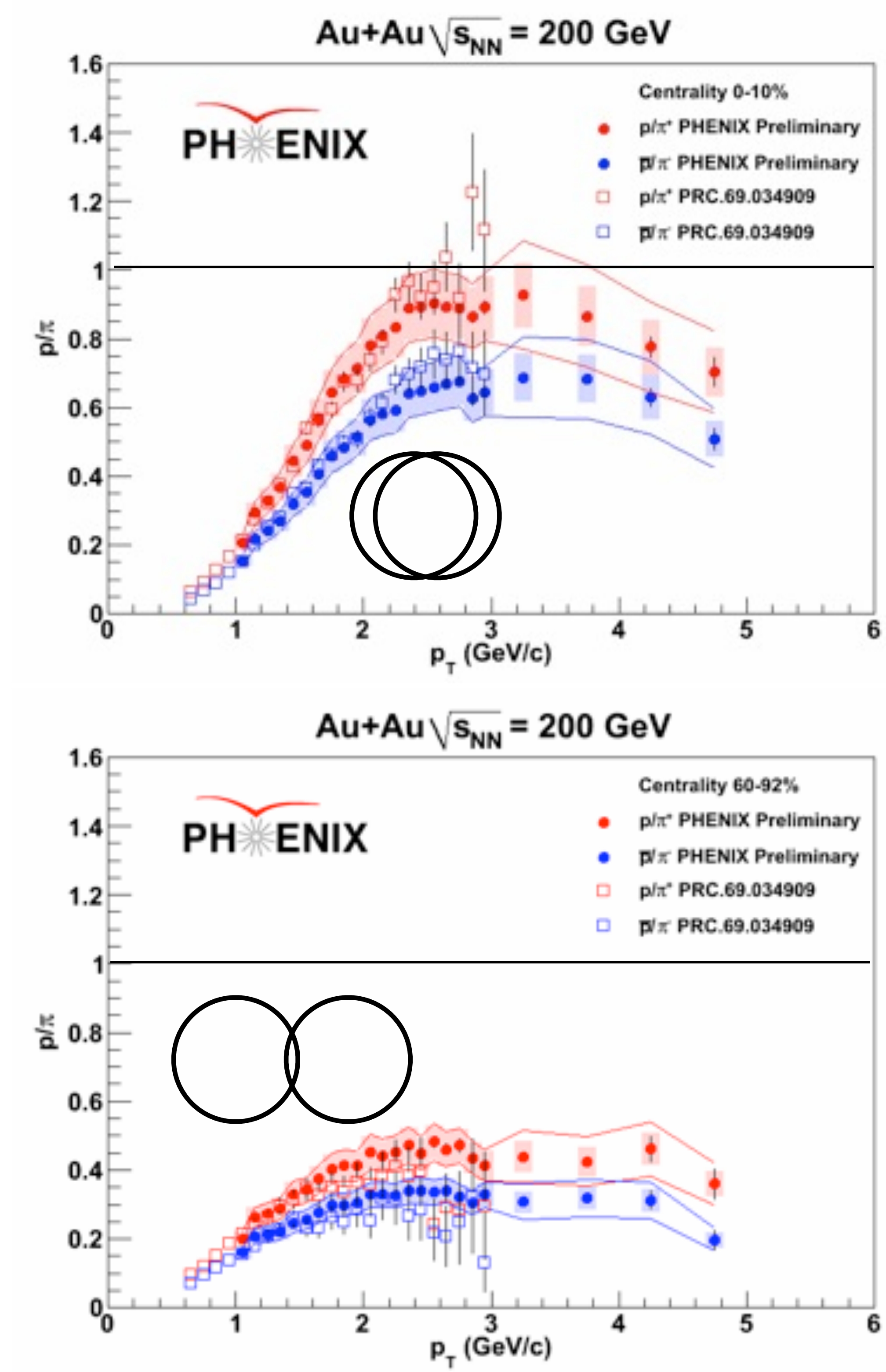


excess baryons

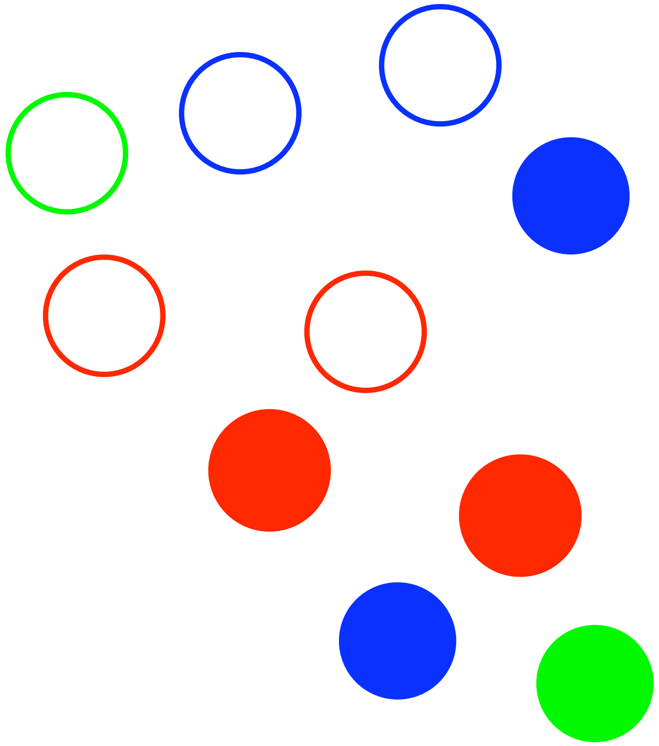
recombination

basic idea: valence quarks coalesce to form final state hadrons

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

recombination

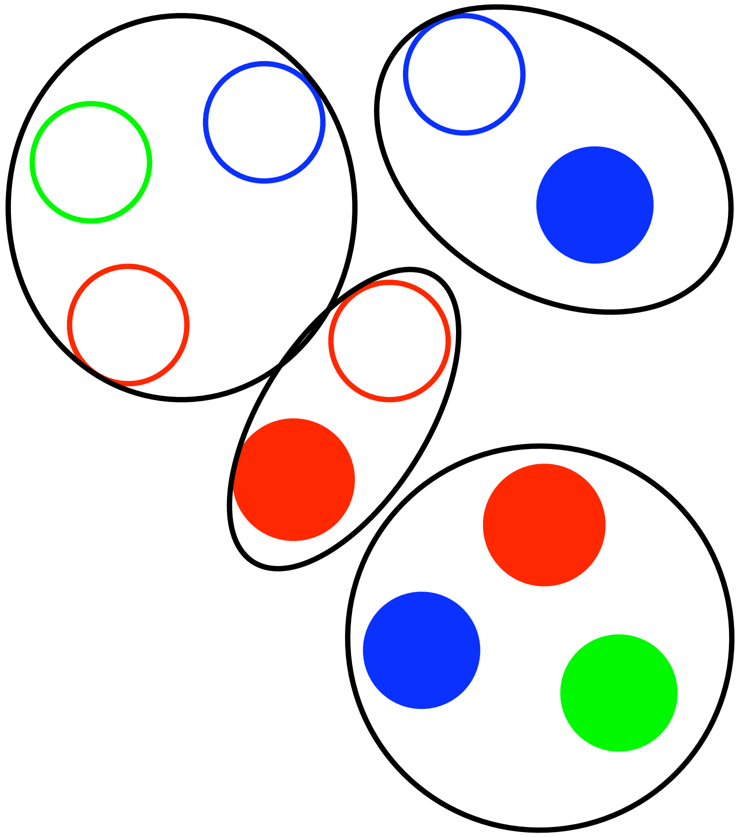
basic idea: valence quarks coalesce to form final state hadrons



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

recombination

basic idea: valence quarks coalesce to form final state hadrons



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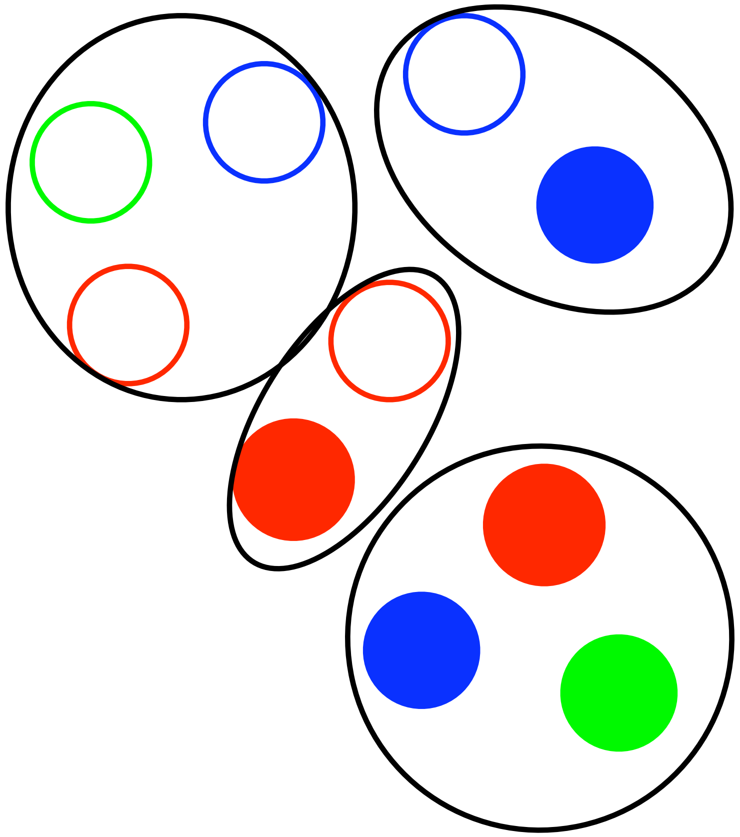
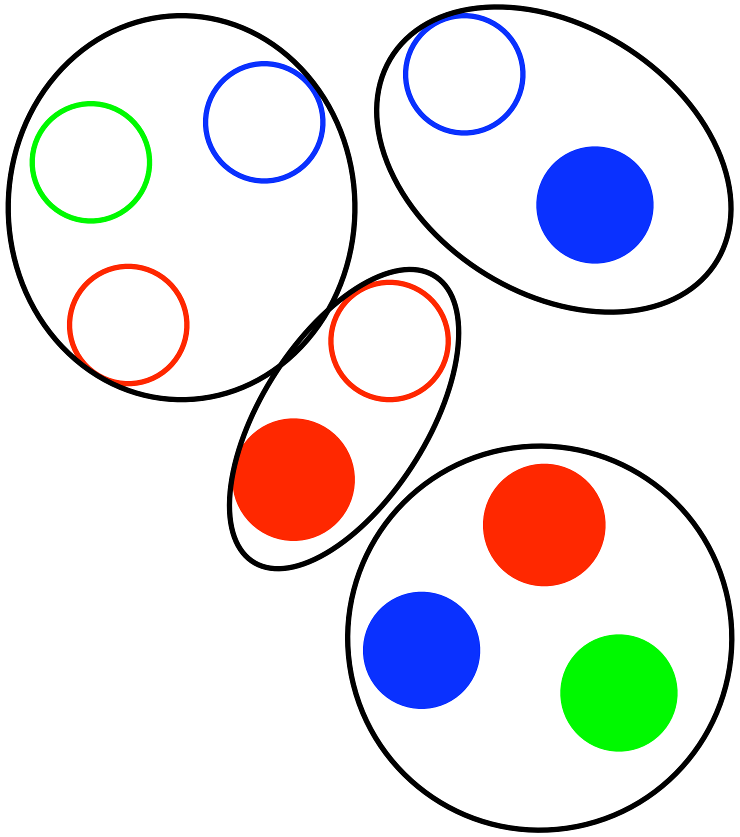


Fries et al., Hwa et al., Ko et al.

recombination

basic idea: valence quarks coalesce to form final state hadrons

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



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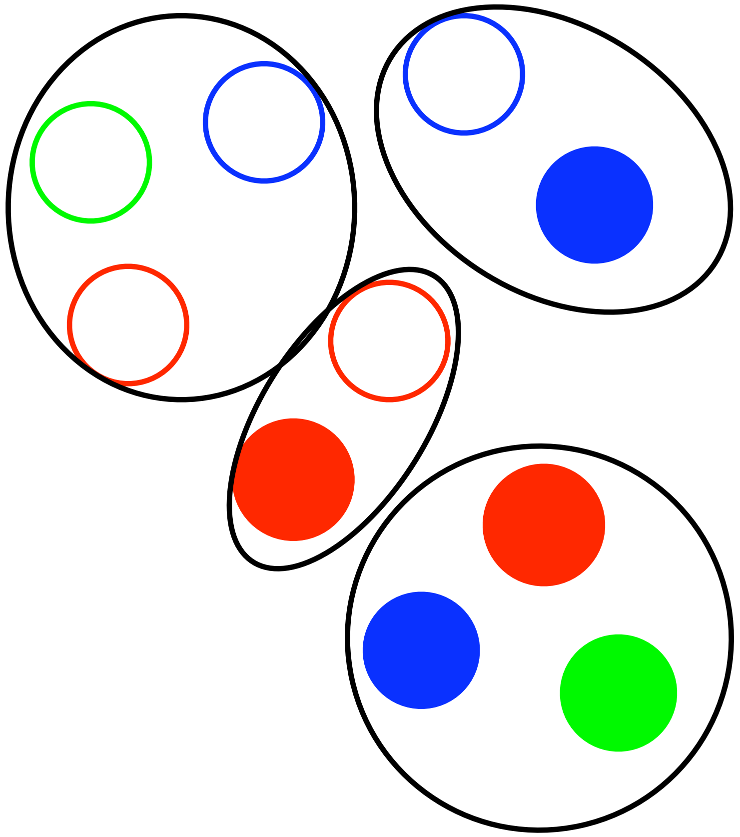
recombination

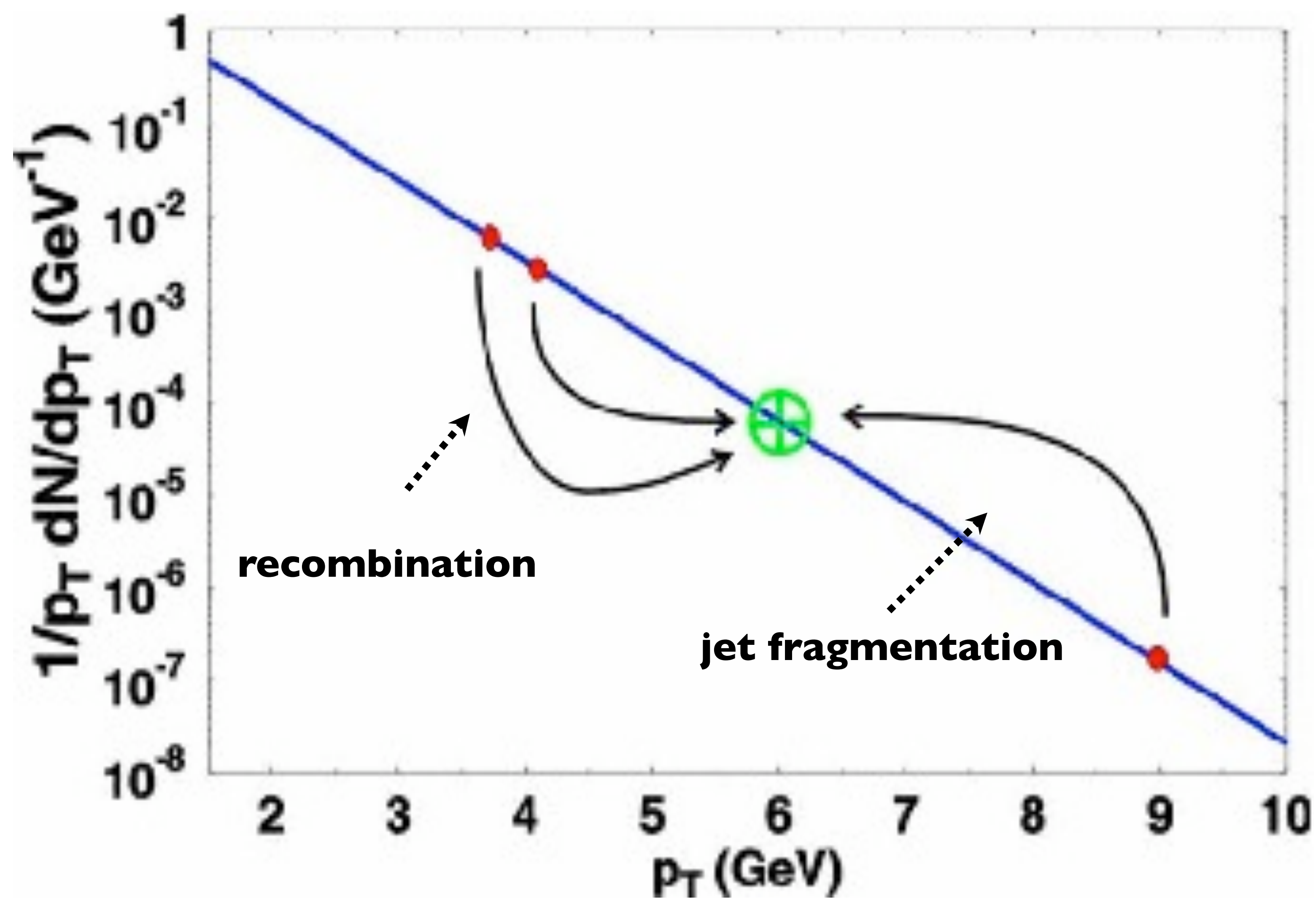
basic idea: valence quarks coalesce to form final state hadrons

- quark momenta add:
  - p_T(hadron) > p_T(quark)
  - baryons get an extra boost→extra quark
- quark correlations amplified in hadrons:
  - e.g. flow



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

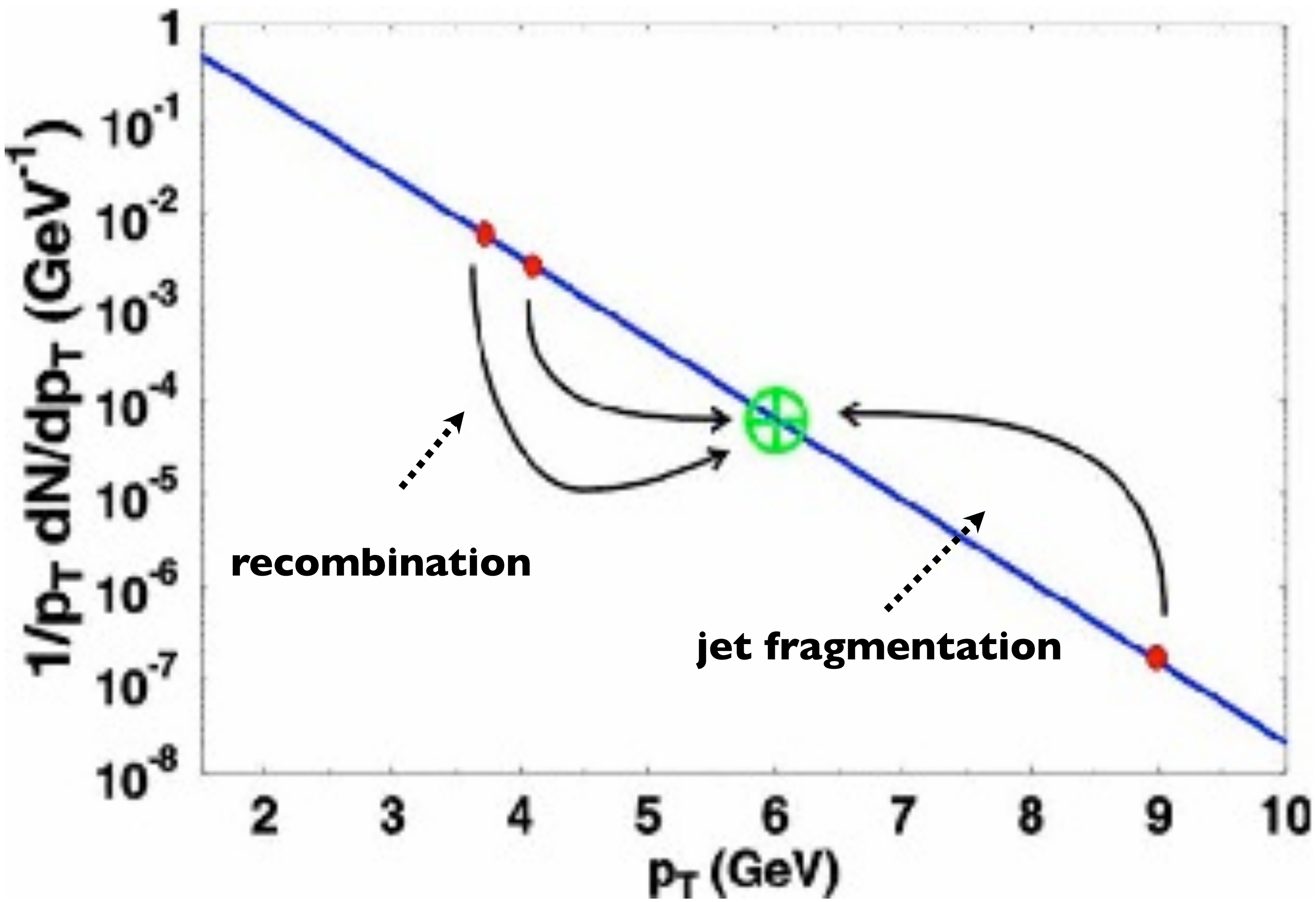
recombination: when?



cartoon: R. Fries

recombination: when?

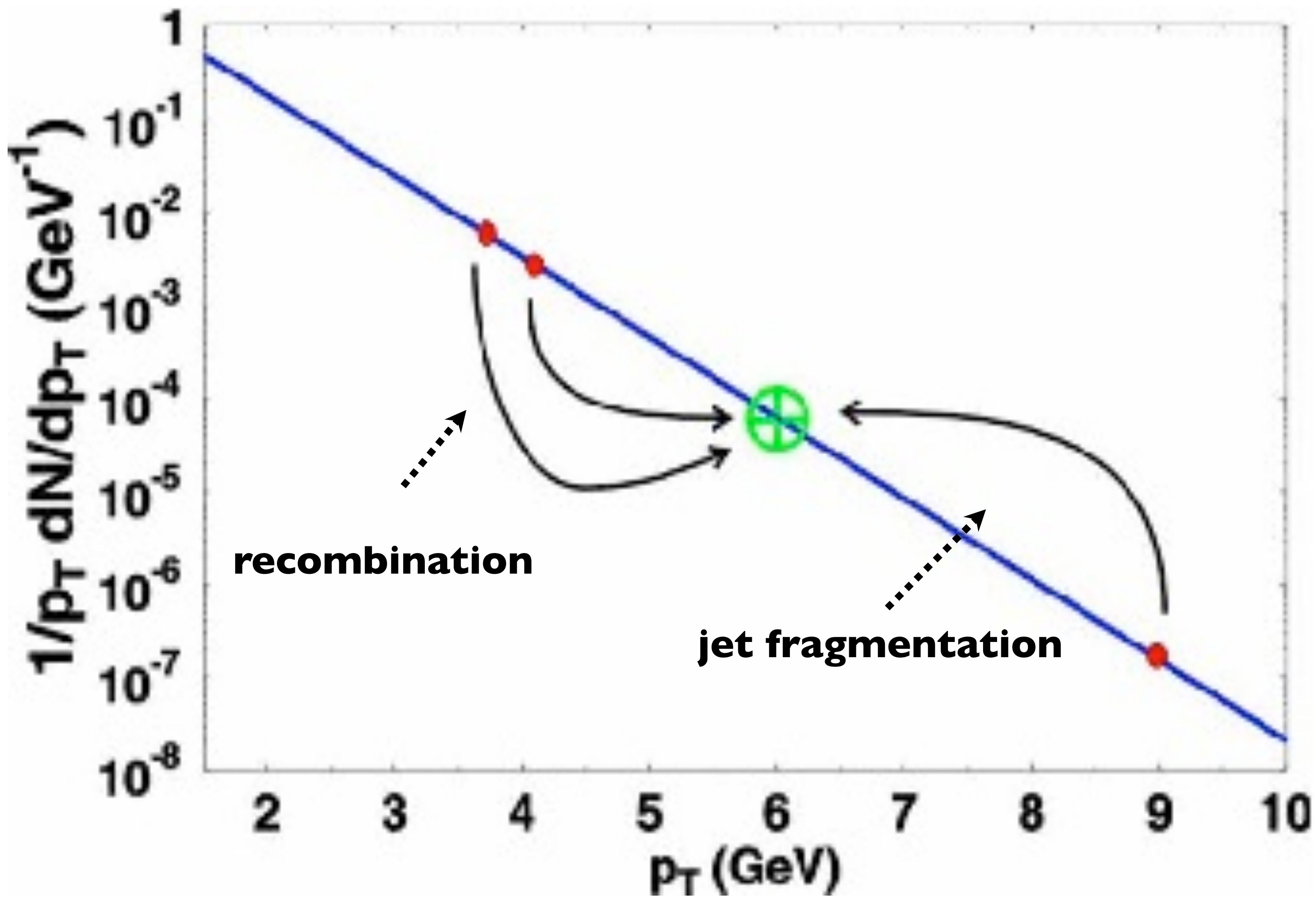
- high phase space density
  - large system, low p_T



cartoon: R. Fries

recombination: when?

- high phase space density
  - large system, low p_T
- exponential quark p_T spectrum disfavors fragmentation
  - high p_T hard power law distribution disfavors recombination



cartoon: R. Fries

baryons via fragmentation

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fragmentation: parton A→N hadrons
for each hadron: $p_{T,N} < p_{T,A}$

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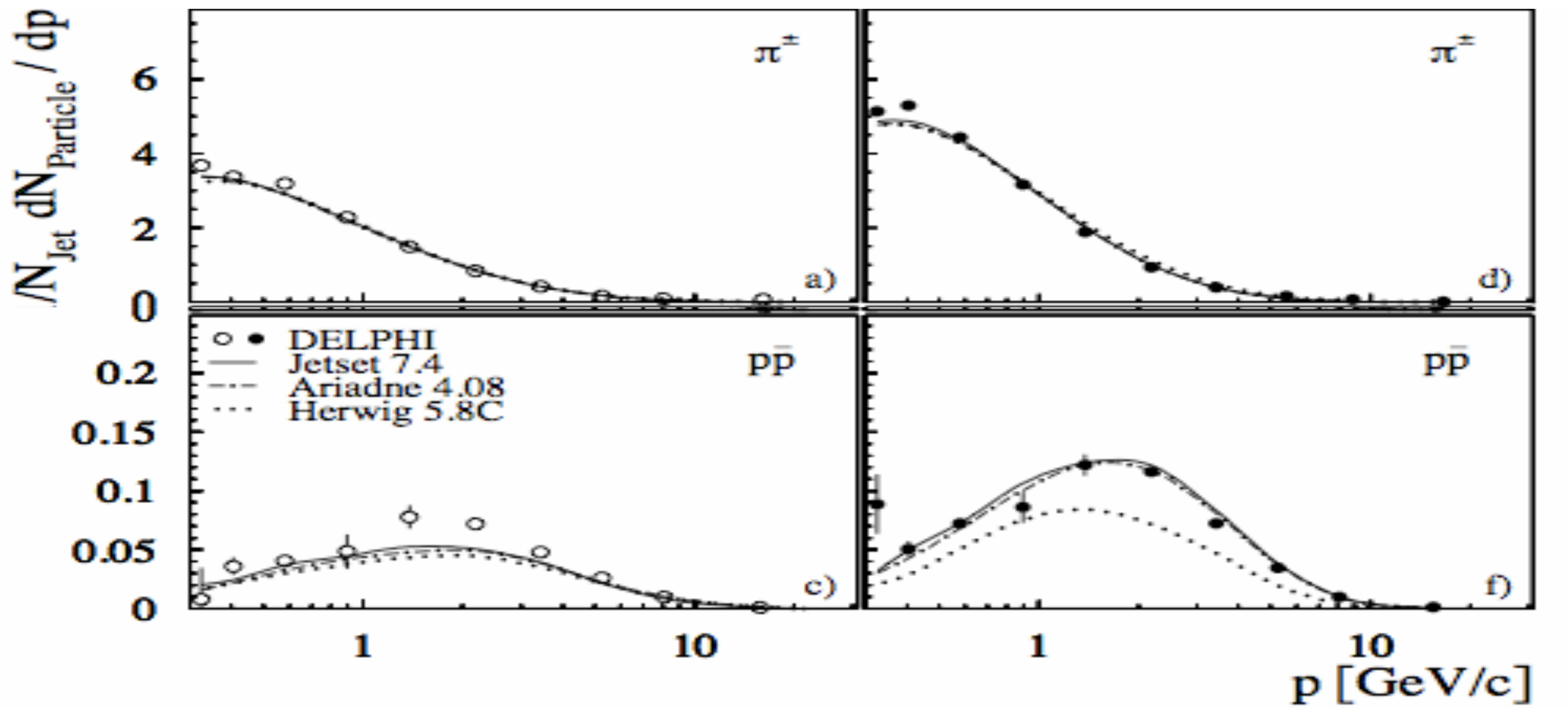
DELPHI e^+e^-

quark jets **gluon jets**

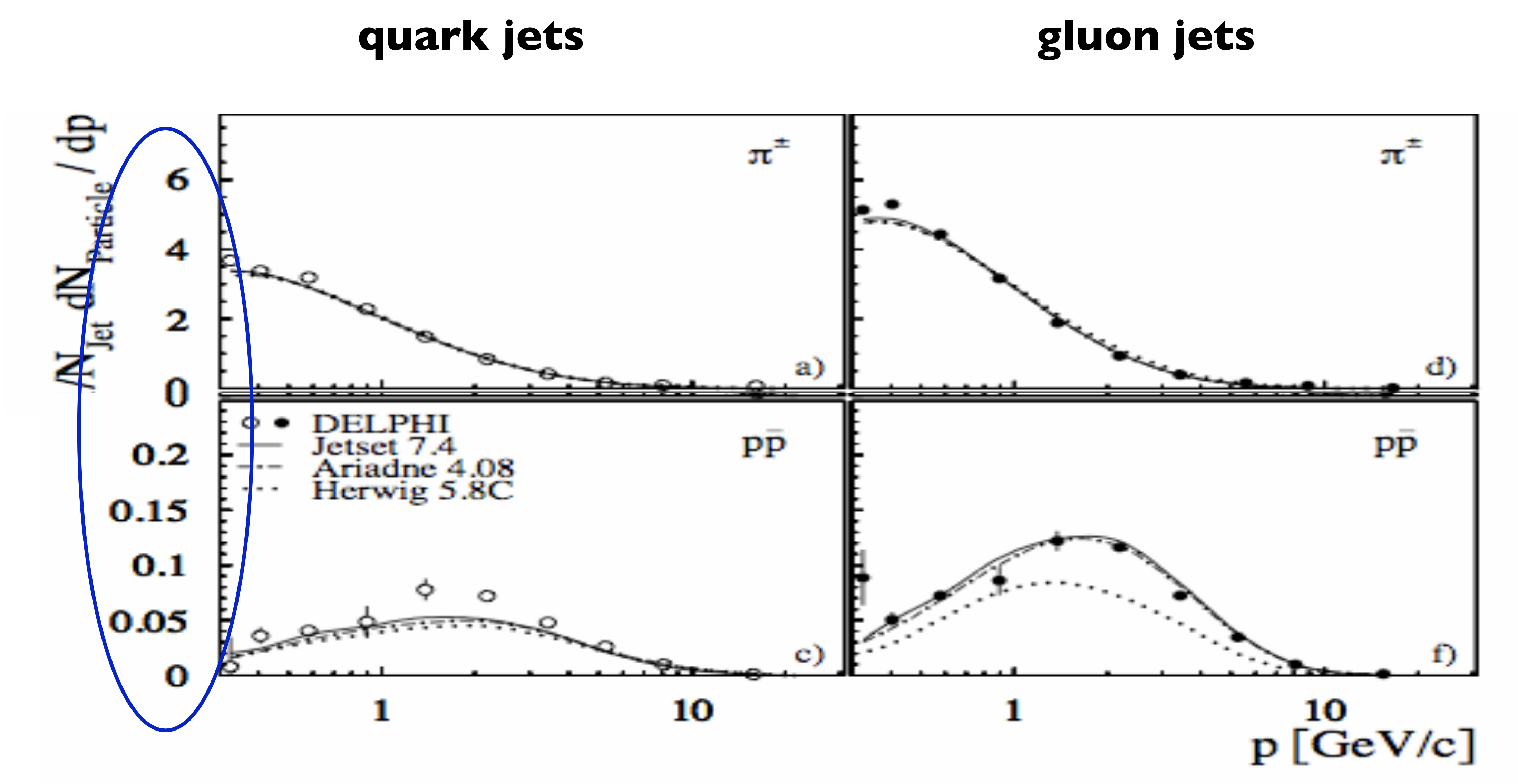


EPJ 17 207 (2000)

baryons via fragmentation

fragmentation: parton A→N hadrons
for each hadron: $p_{T,N} < p_{T,A}$

DELPHI e^+e^-



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baryons via fragmentation

fragmentation: parton A→N hadrons
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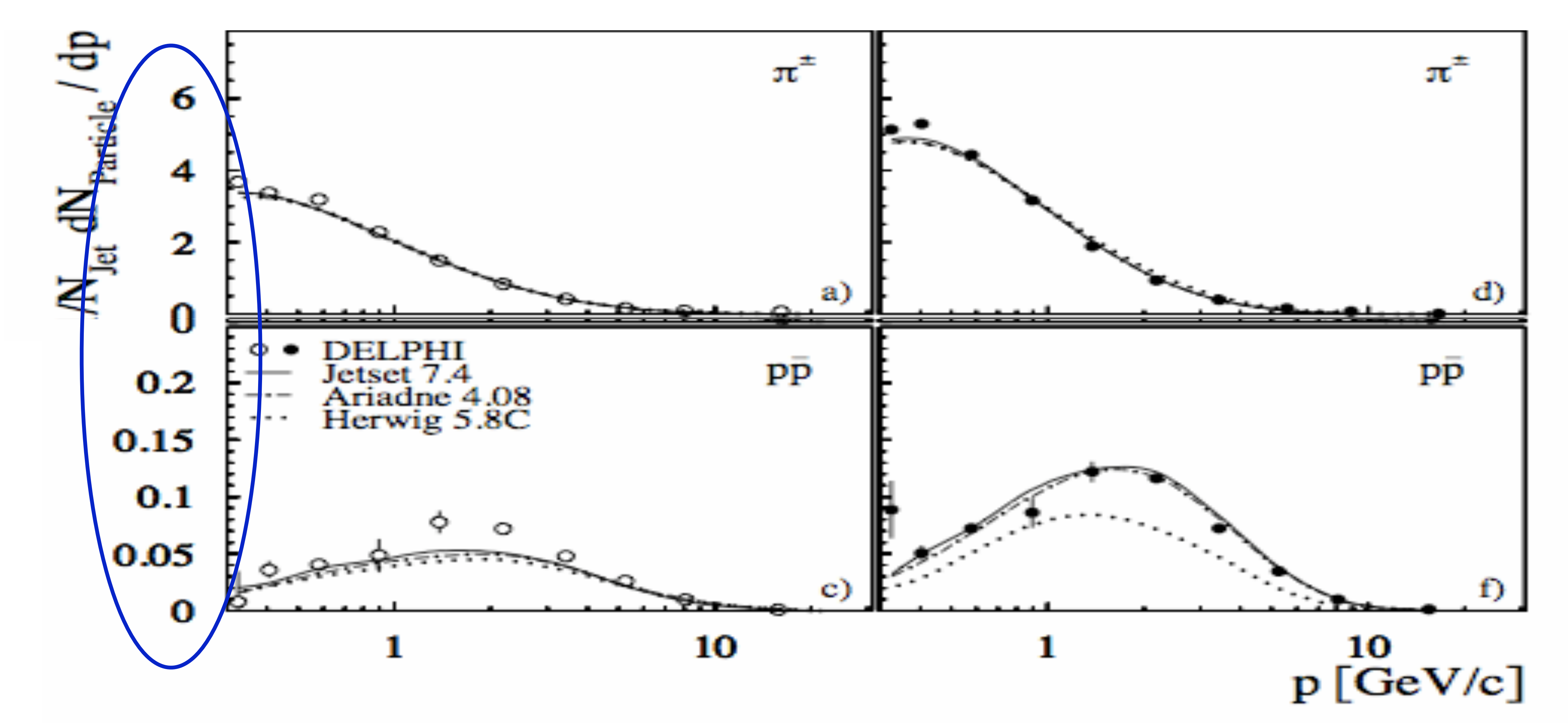
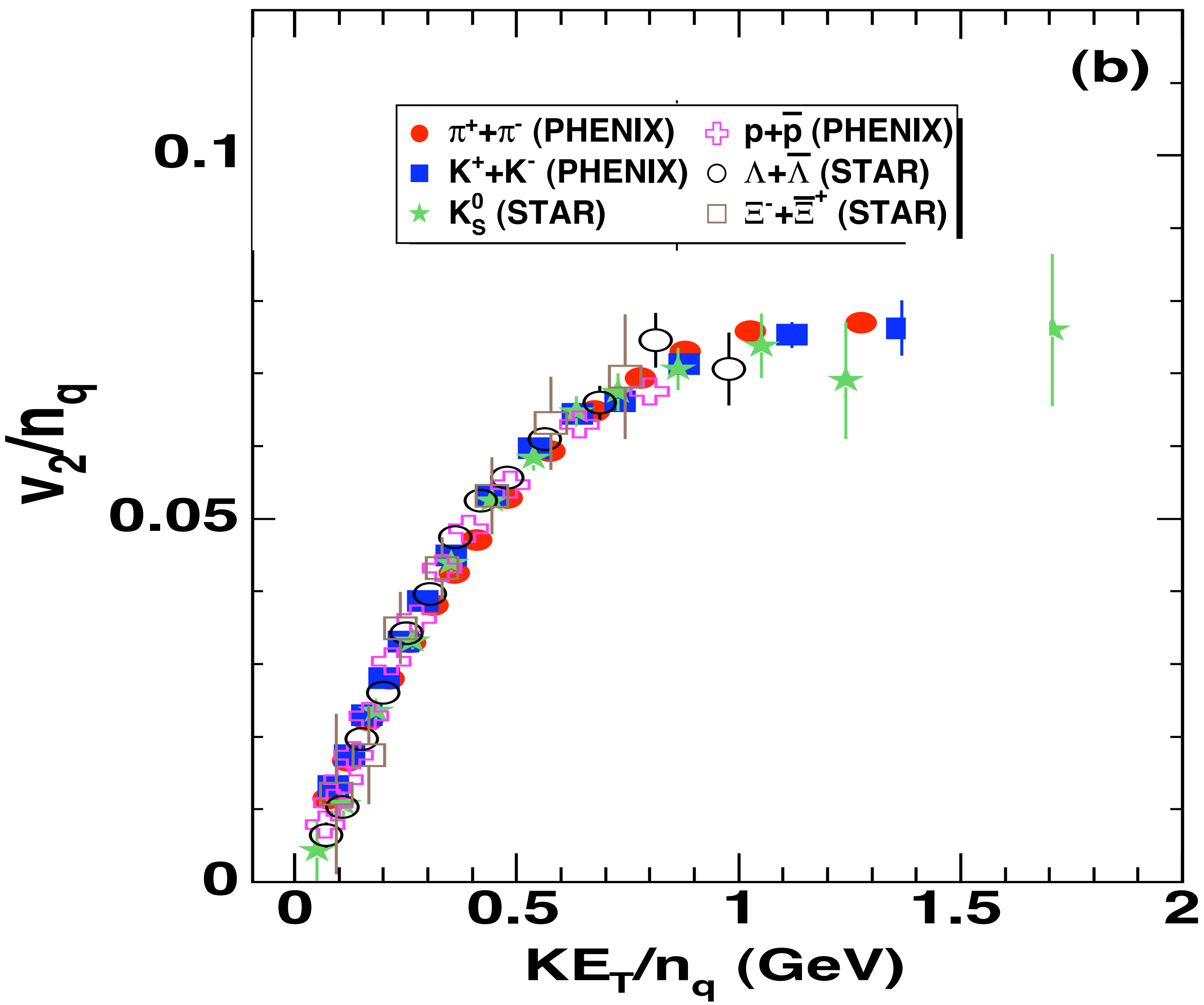
quark jets **gluon jets**



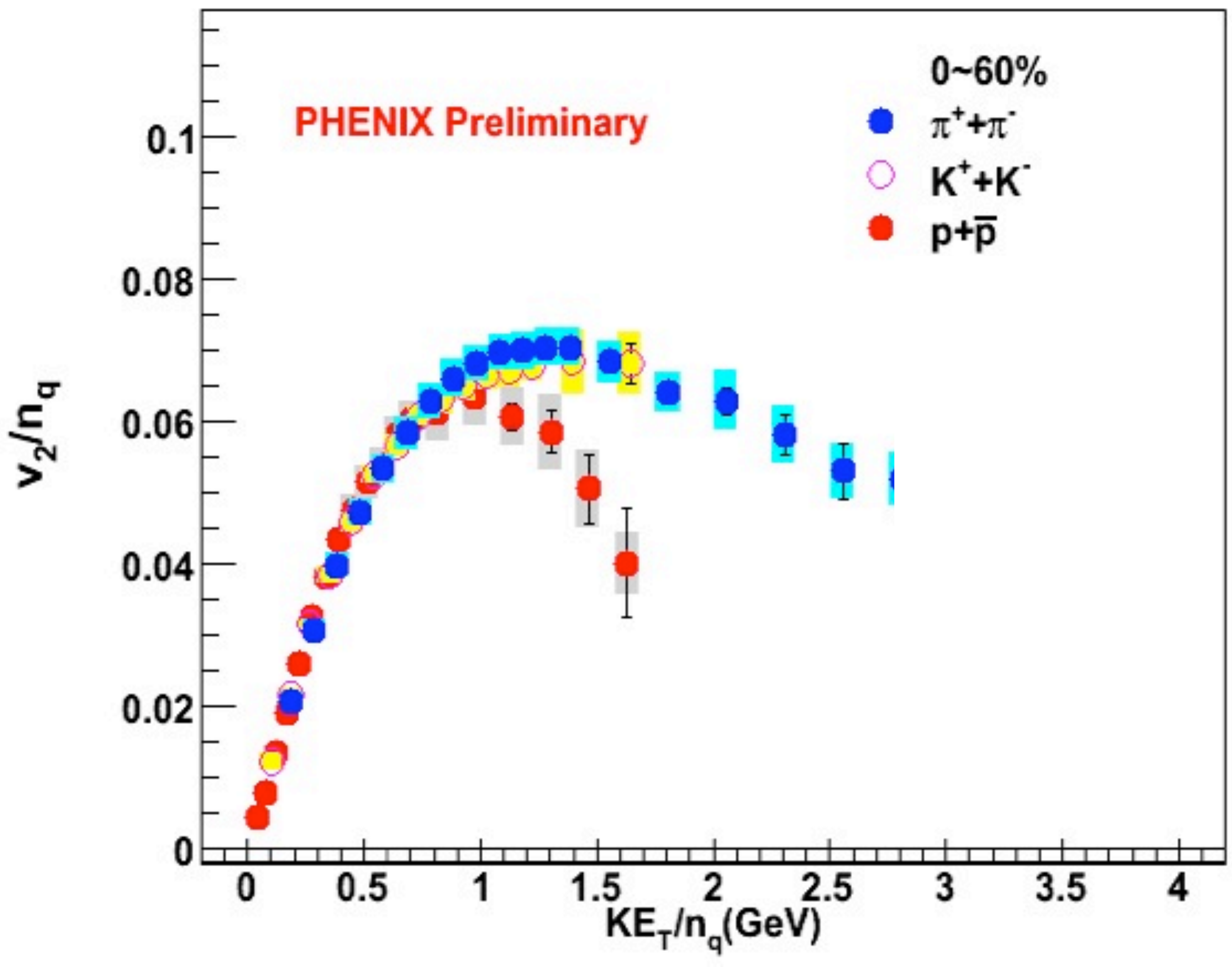
EPJ 17 207 (2000)

- baryon production difficult in fragmentation

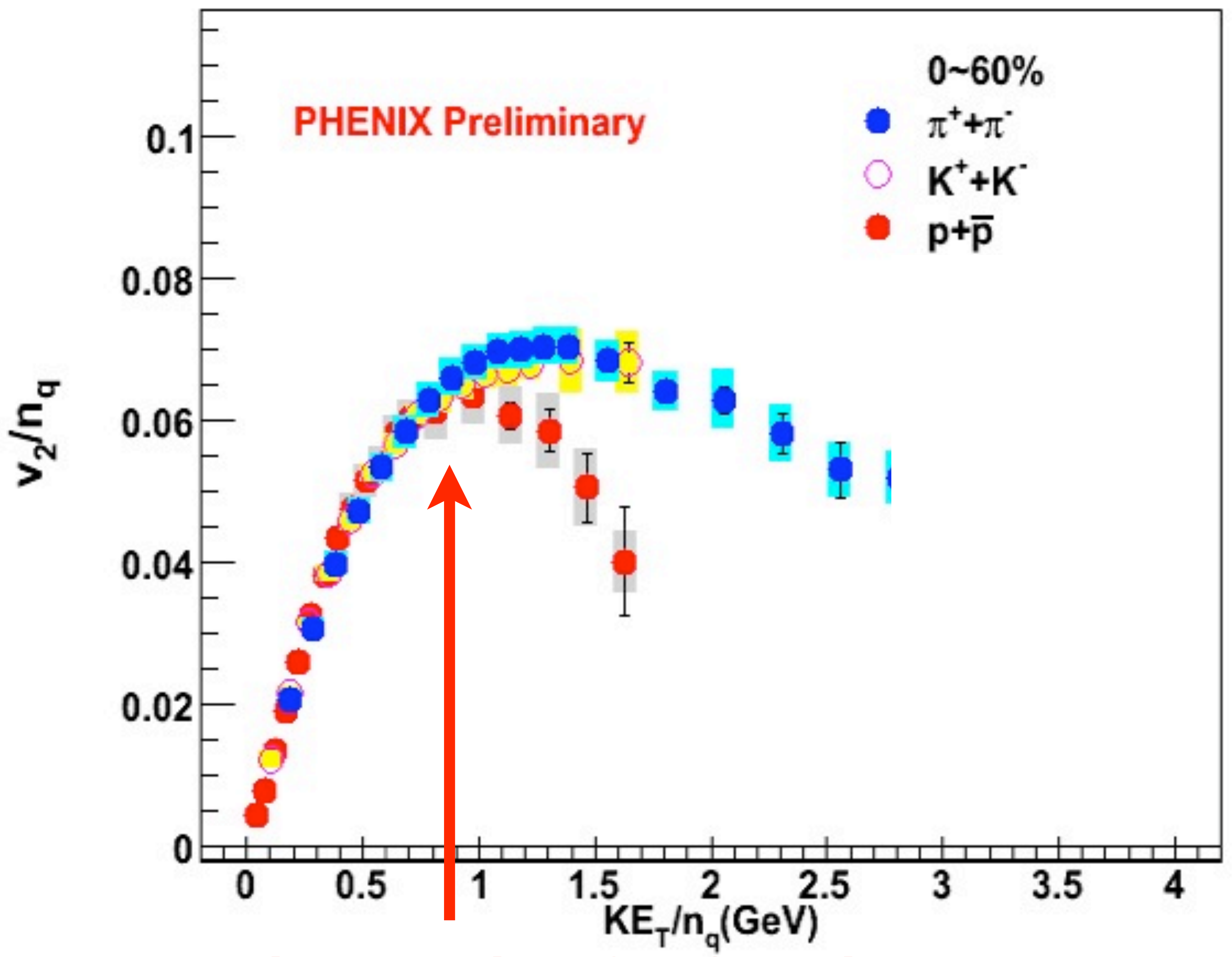
beyond recombination



beyond recombination



beyond recombination



p_T(proton) ~ 3.5GeV/c

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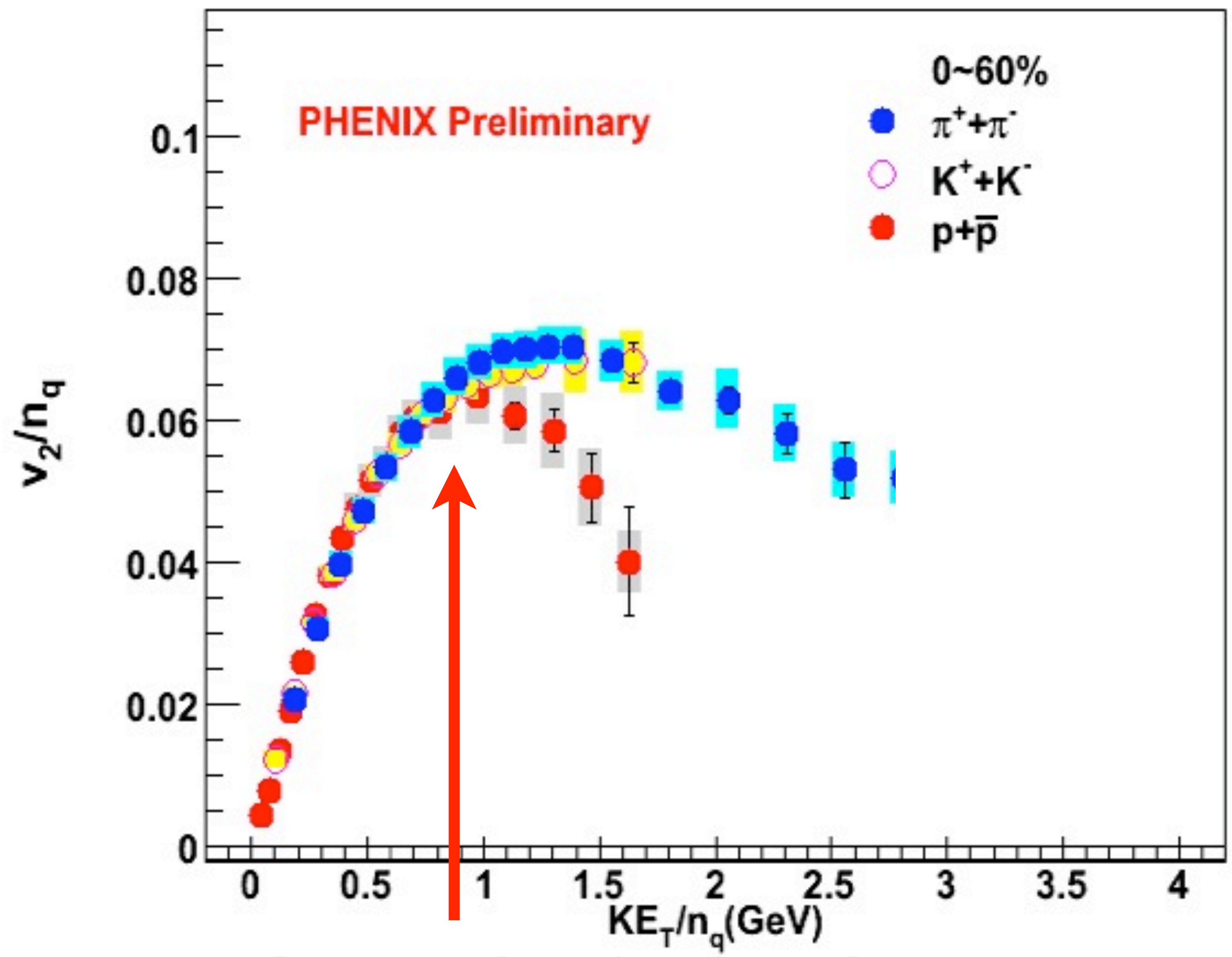
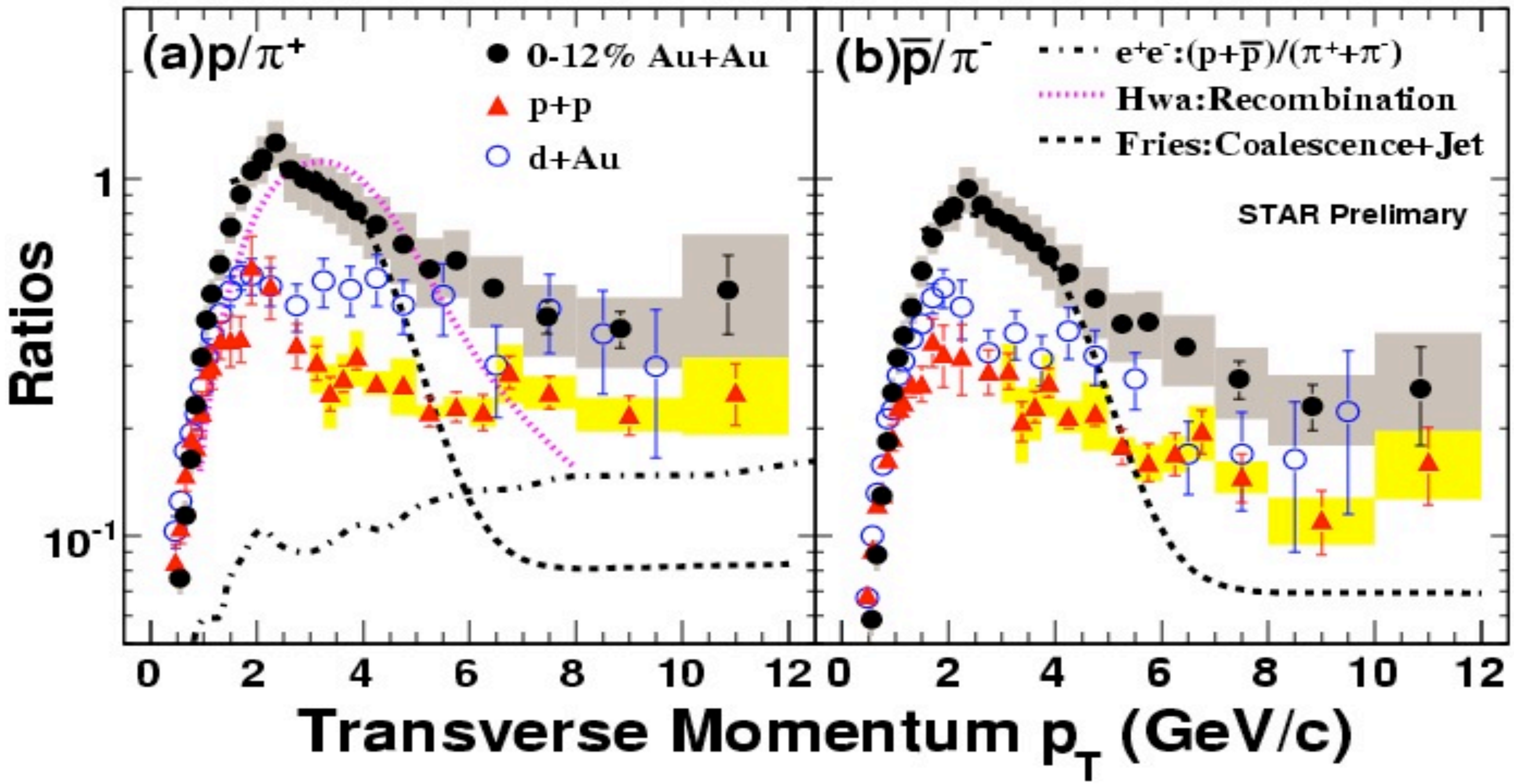
beyond recombination



p_T(proton) ~ 3.5GeV/c

- scaling deviations: p_T ~ 3-4GeV/c
  - →end recombination dominance

some p/pbar excess remains to high p_T



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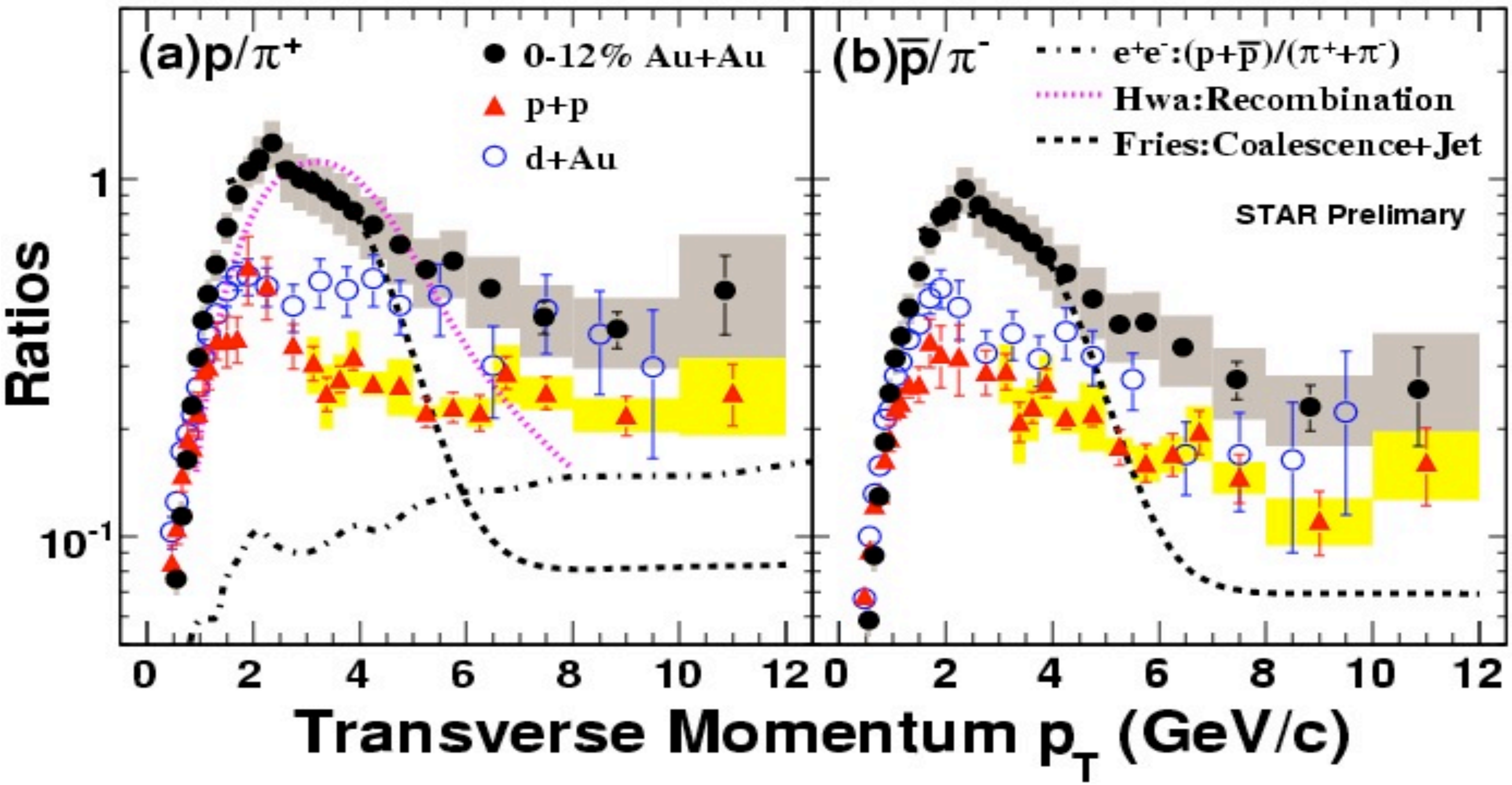
some p/pbar excess remains to high p_T



is there hard source of excess baryons?

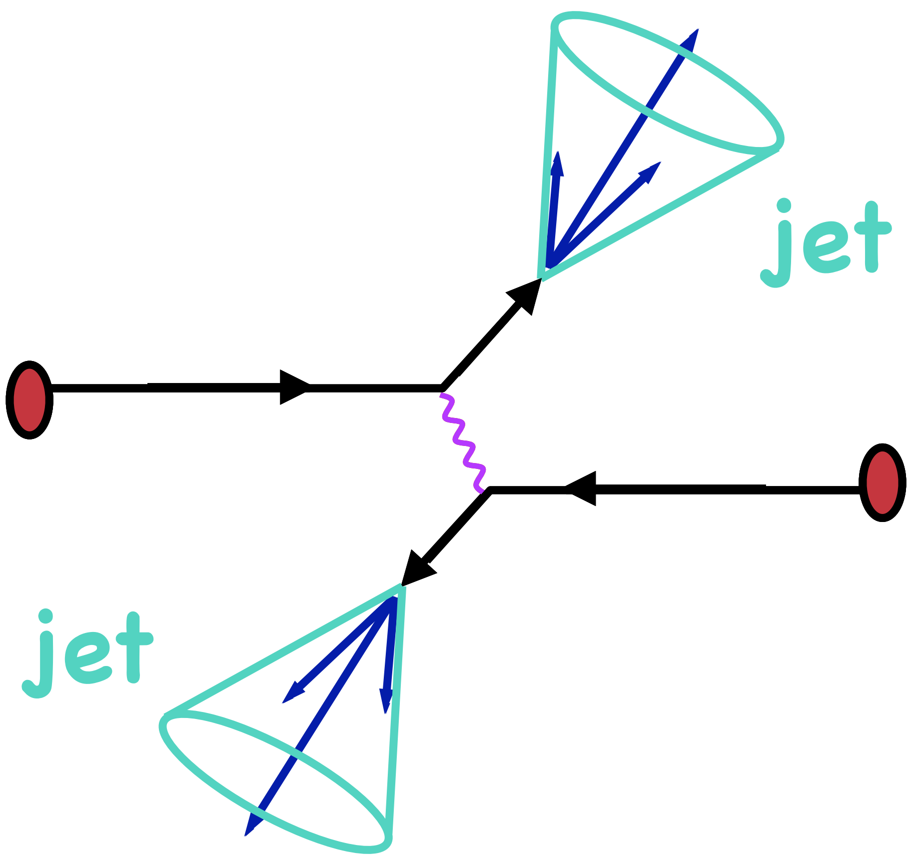
high p_T particle production

p+p collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

Hard Scattering Cross Section: Calculated with pQCD

Fragmentation into Hadrons: Measured in e+e- Collisions



high p_T particle production

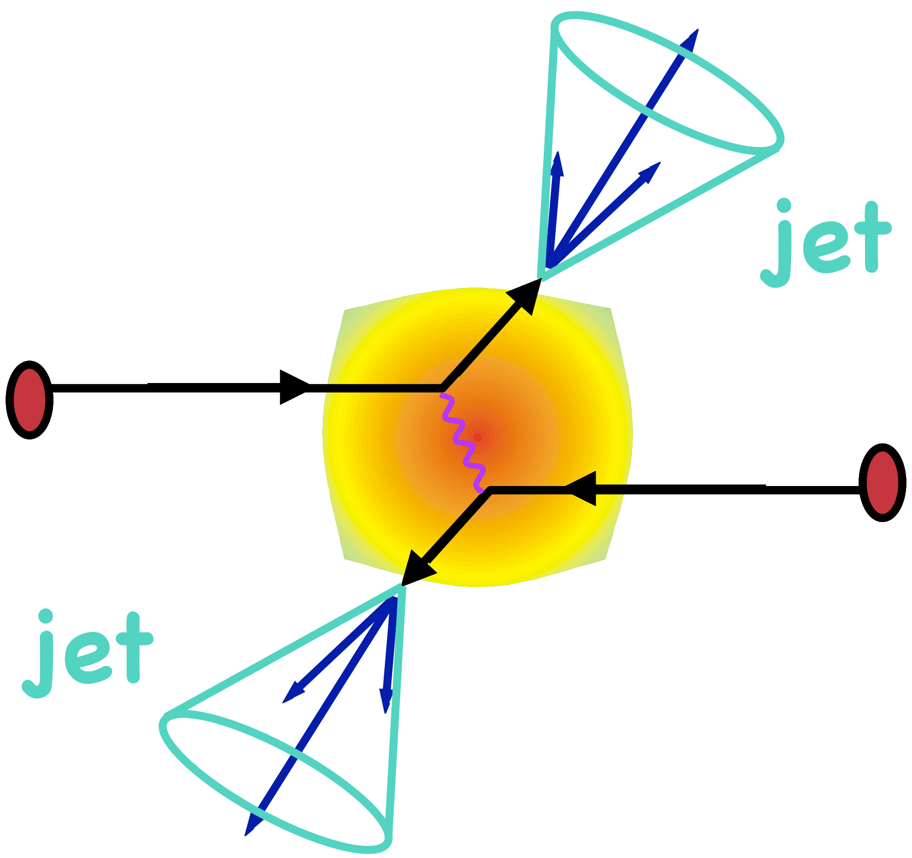
Au+Au collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

Hard Scattering Cross Section: Calculated with pQCD

Parton Medium Interactions

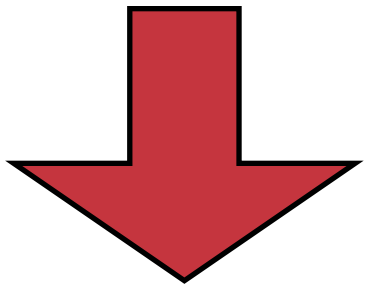
Fragmentation into Hadrons: Measured in e+e- Collisions



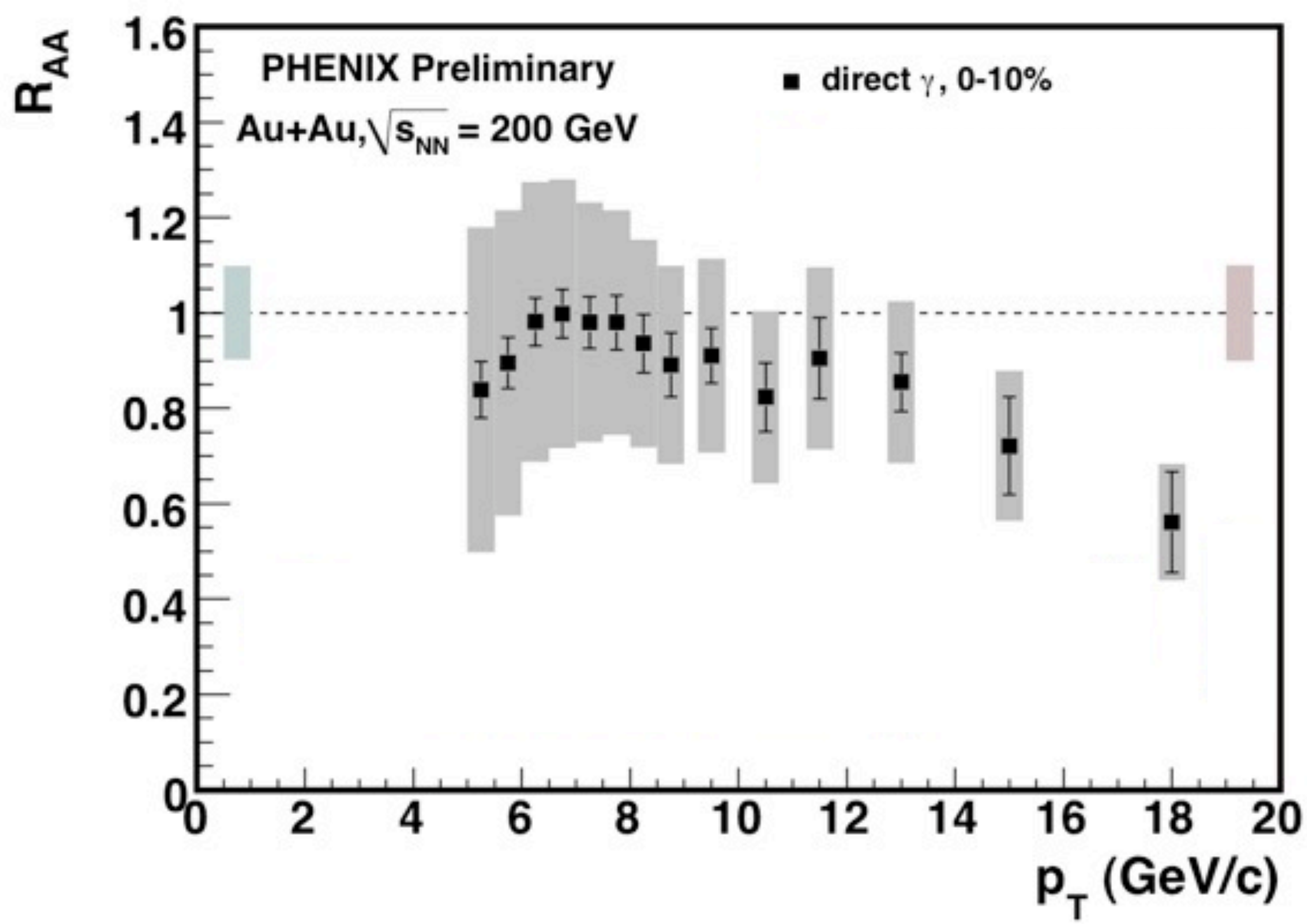
γ: control measurement

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

$R_{AA} = 1$



no nuclear effects



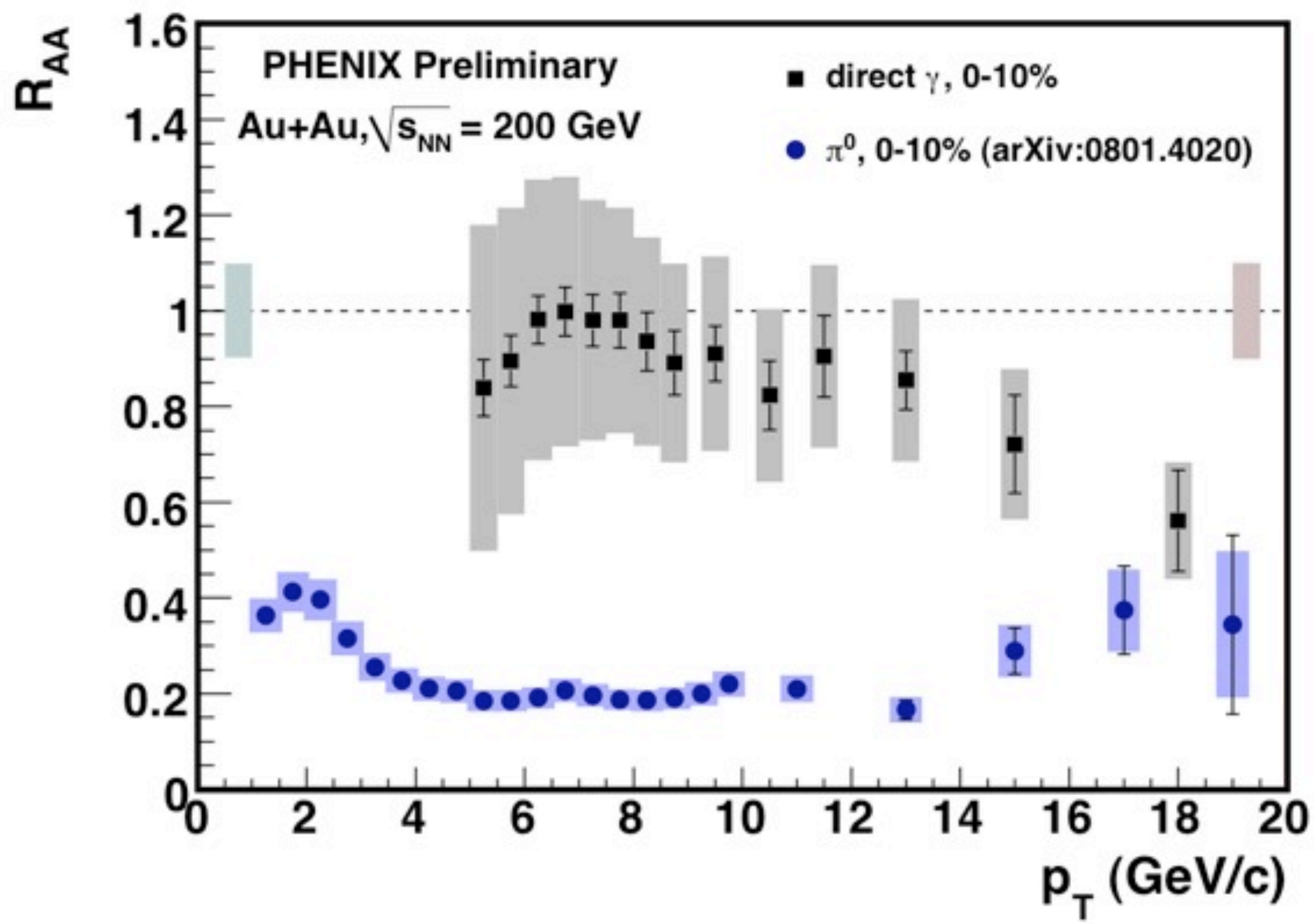
γ: no color charge → insensitive to produced matter
$R_{AA}(p_T<14 GeV/c)$ consistent with unity

π^0: light meson

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

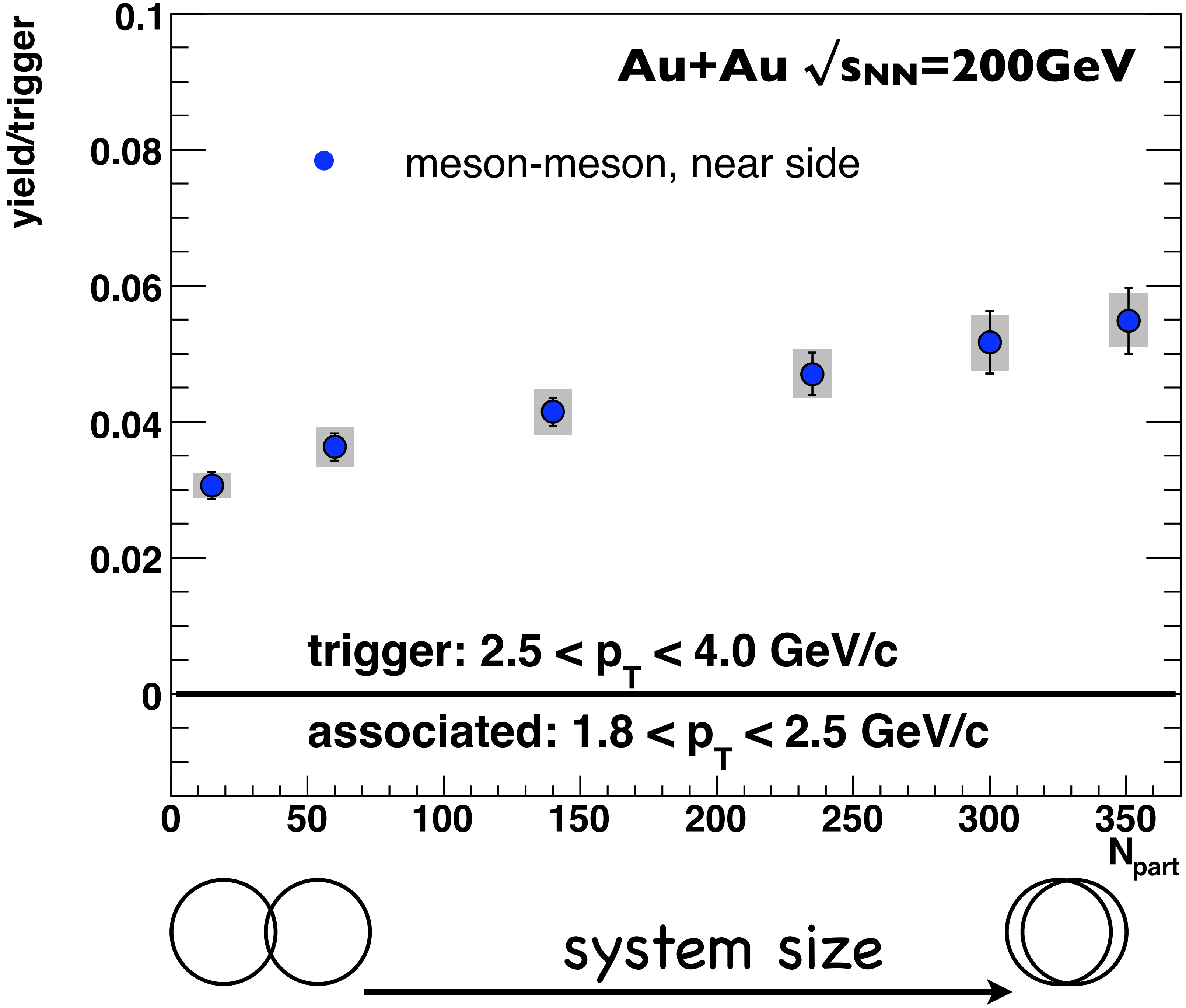
$R_{AA} << 1$

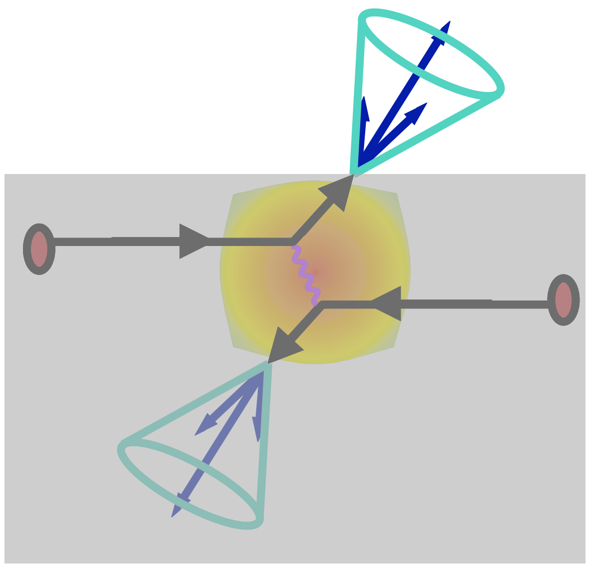
partonic energy loss



correlated baryons?

pairs from jet-like correlations





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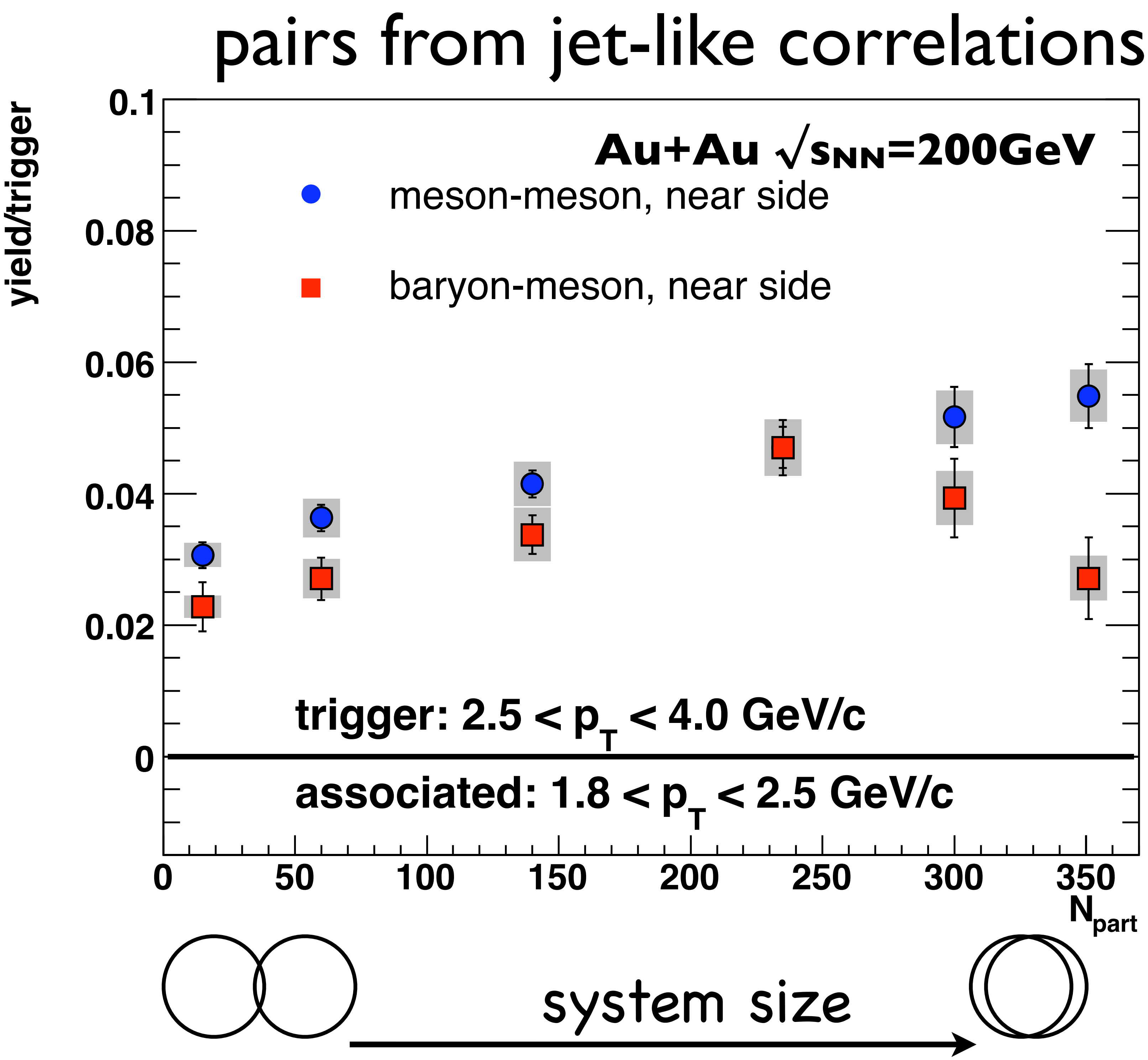
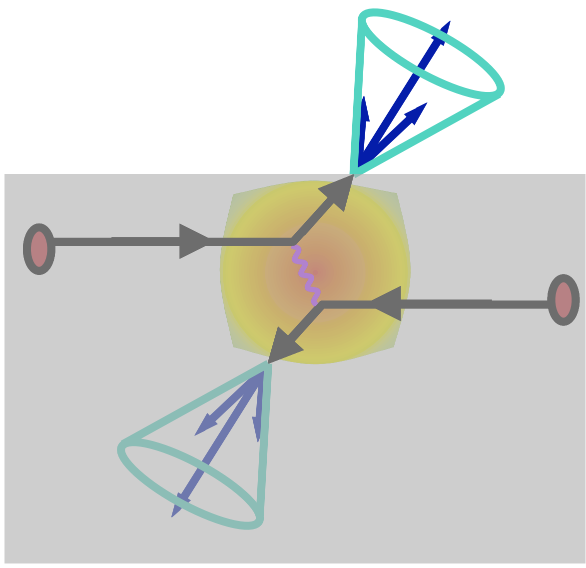
correlated baryons?





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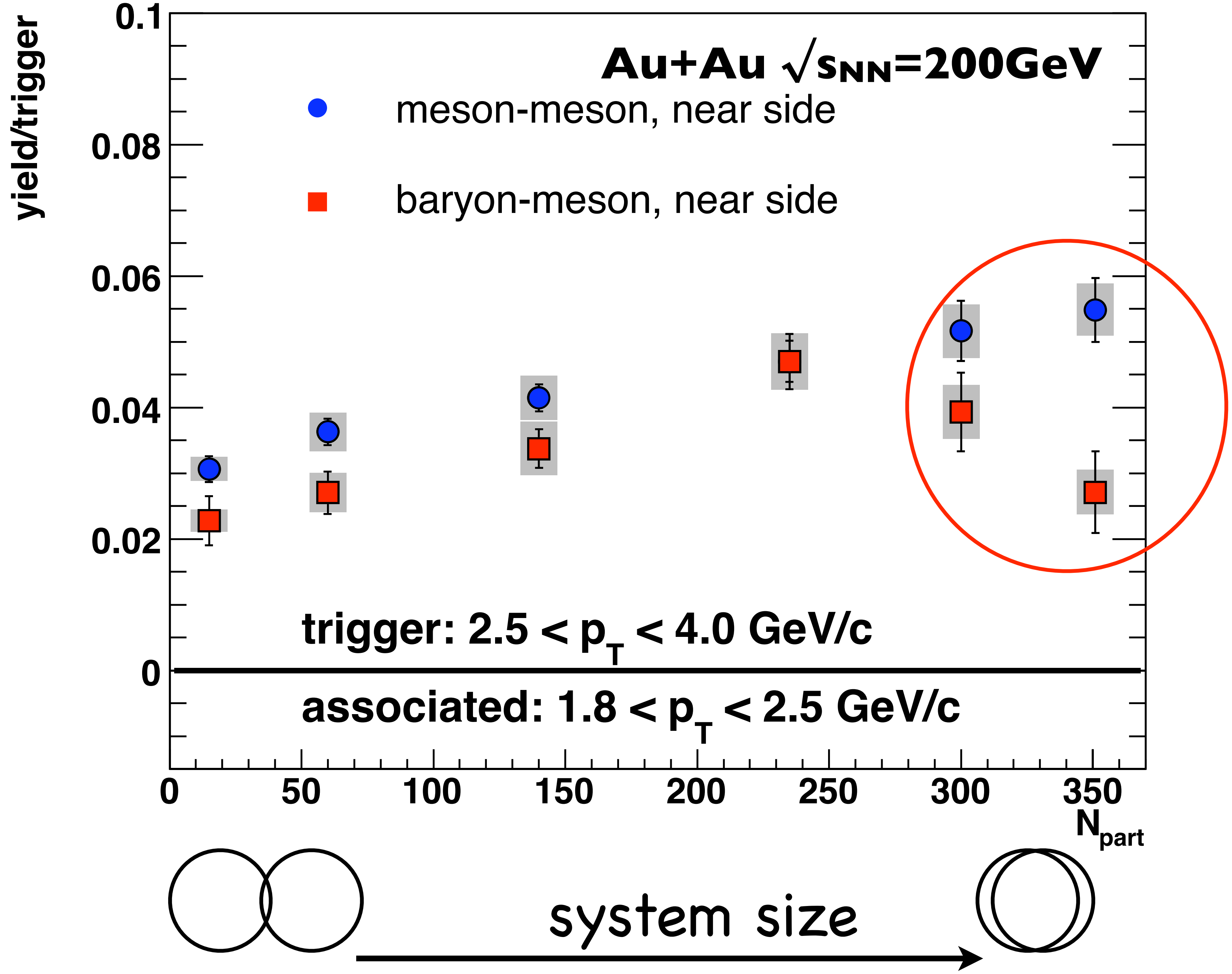
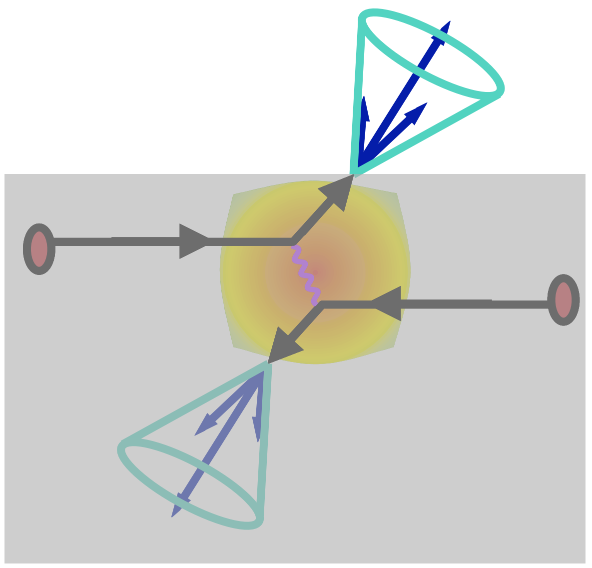
correlated baryons?

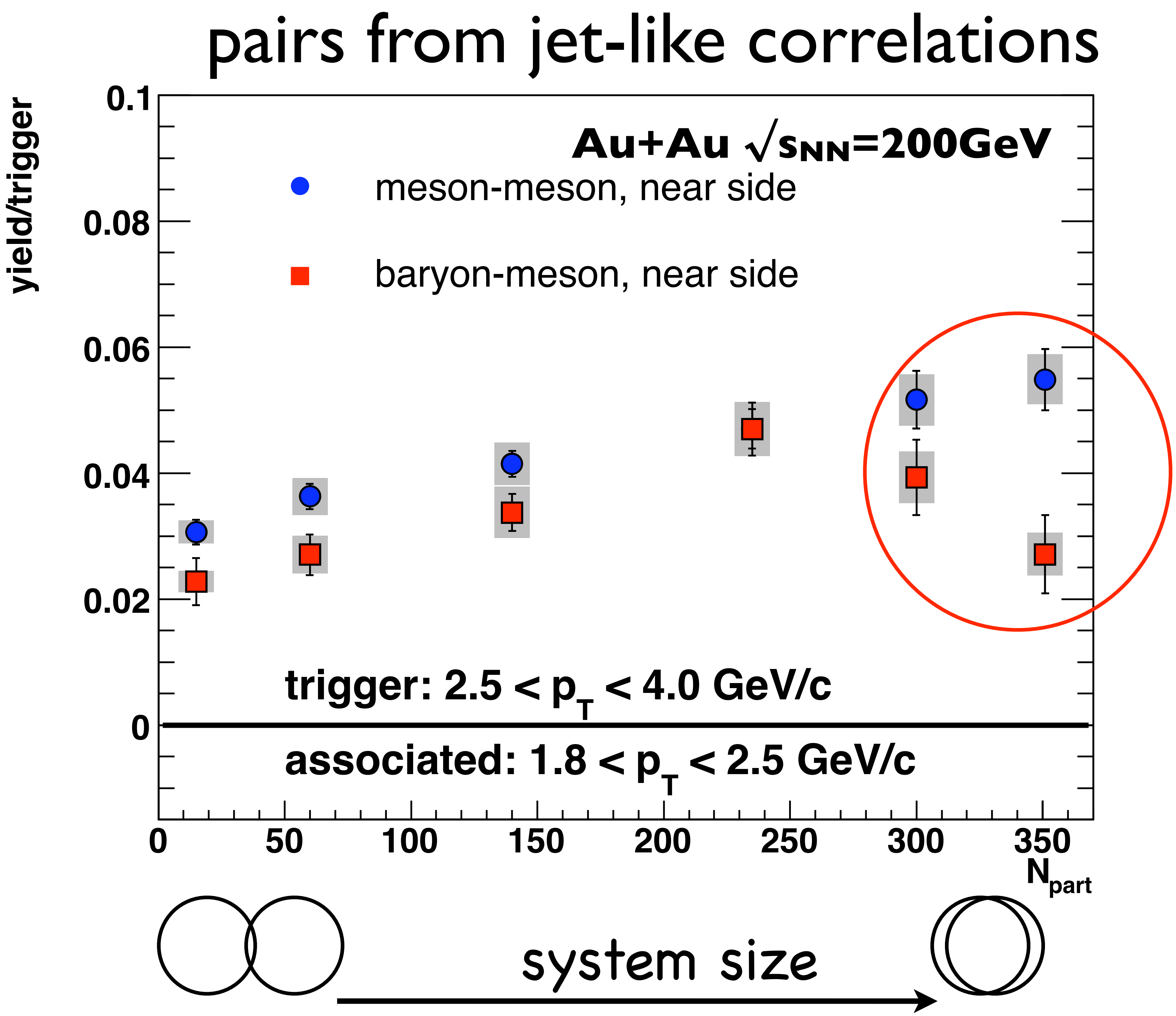
pairs from jet-like correlations

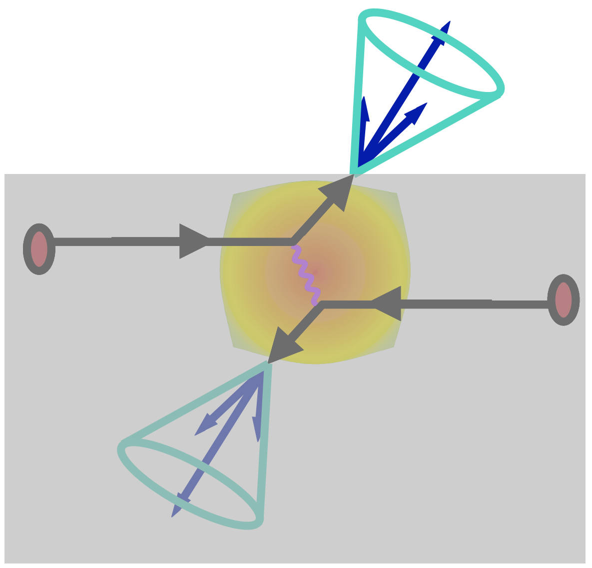




PHENIX, PLB 649 359 2007

correlated baryons?





baryons: less same side correlations in the most central collisions

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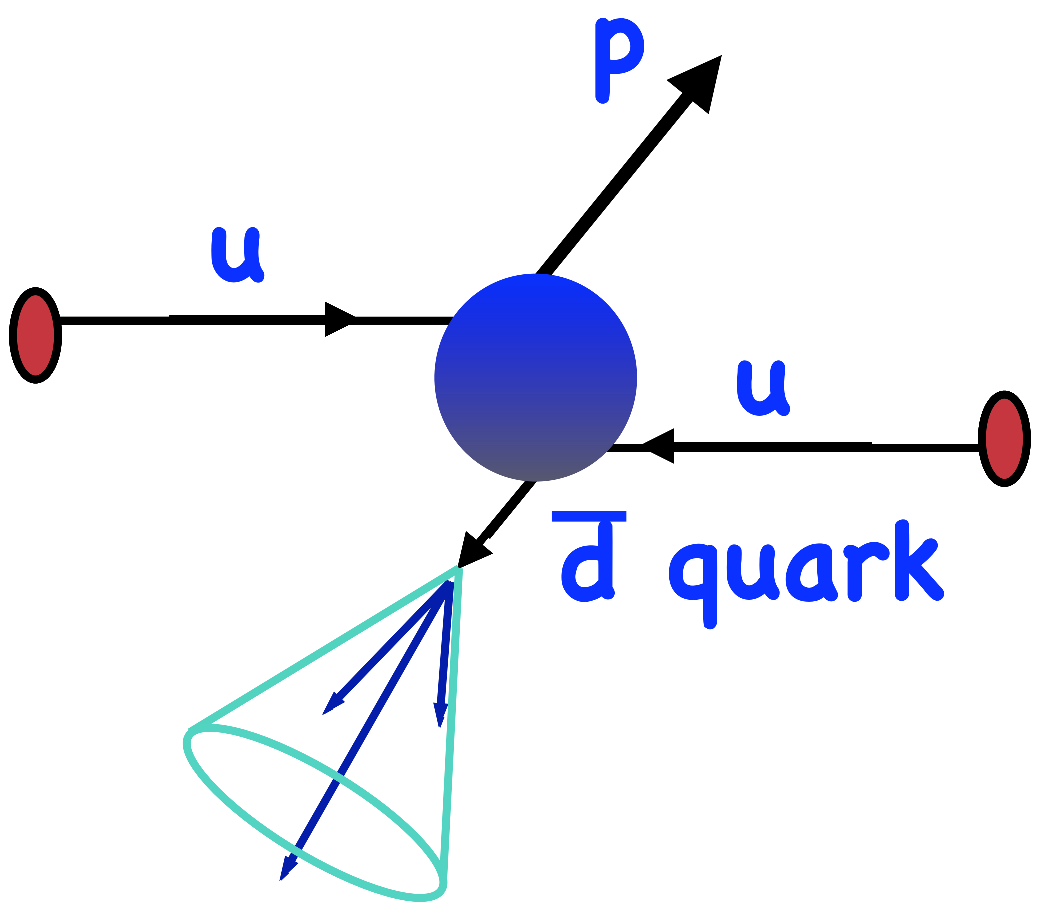
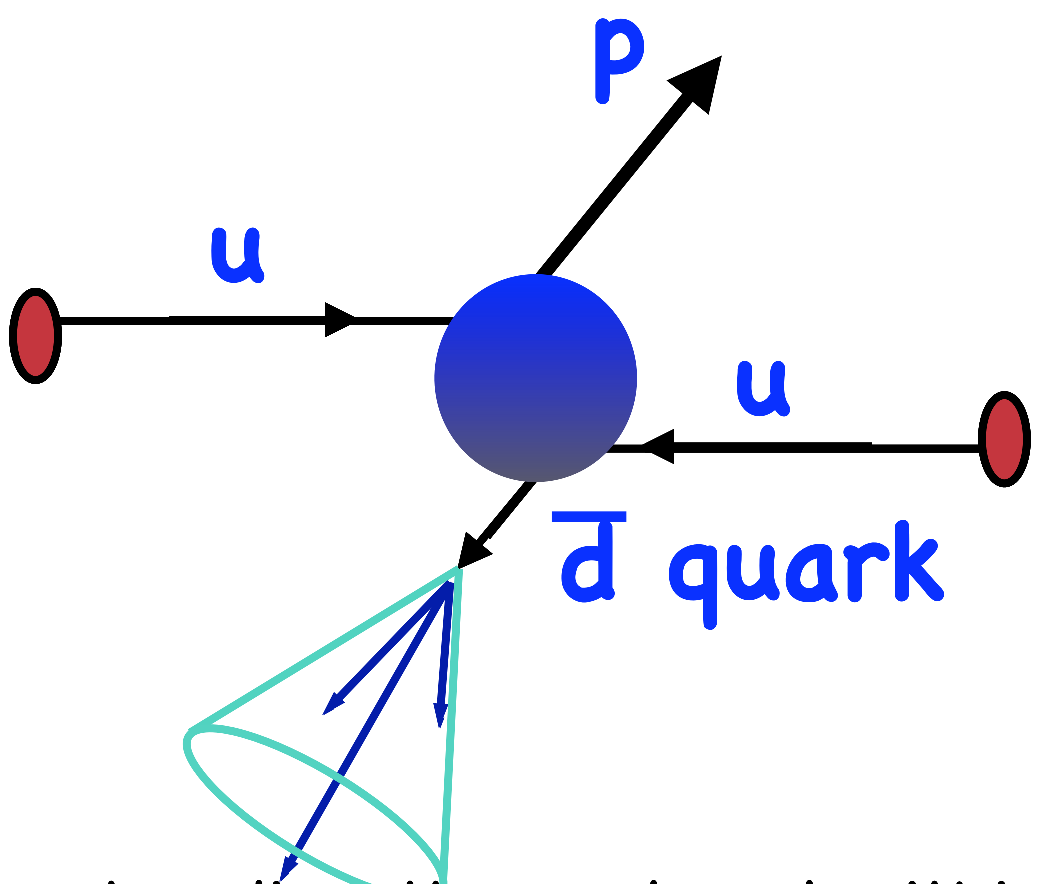
direct proton production?



$uu \rightarrow p\bar{d}$

Brodsky & AMS PLB 668 111 (2008)

direct proton production?



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- color singlet proton directly produced within hard scattering

Brodsky & AMS PLB 668 111 (2008)

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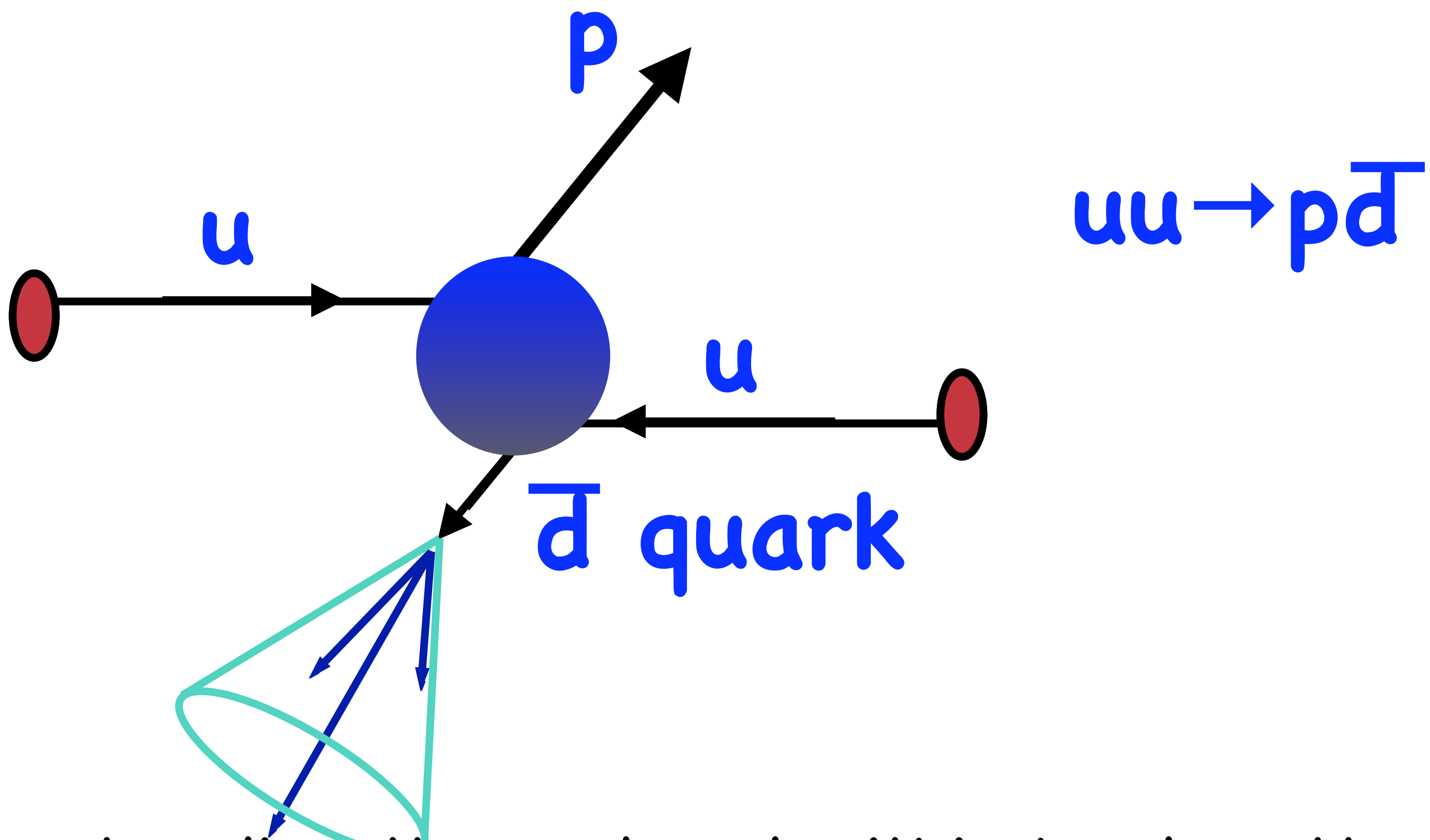

- color singlet proton directly produced within hard scattering
- no energy wasted in fragmentation

Brodsky & AMS PLB 668 111 (2008)

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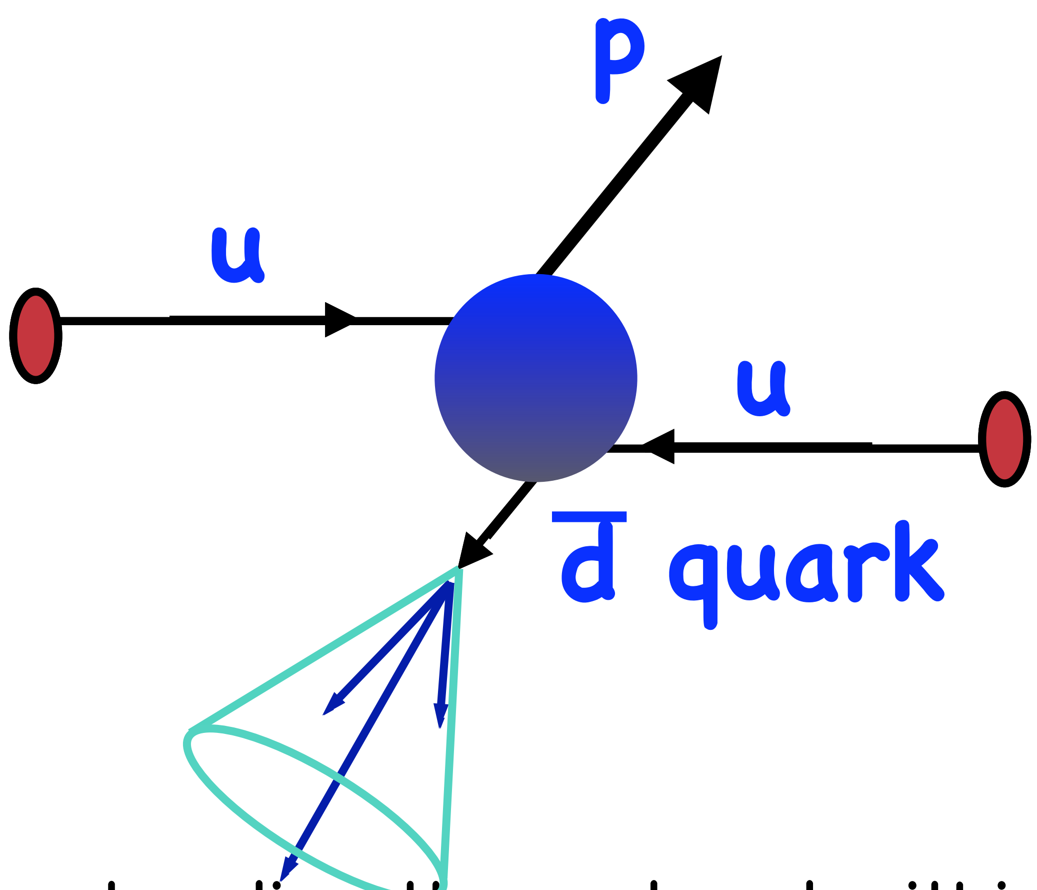

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- small color neutral protons: color transparent

Brodsky & AMS PLB 668 111 (2008)

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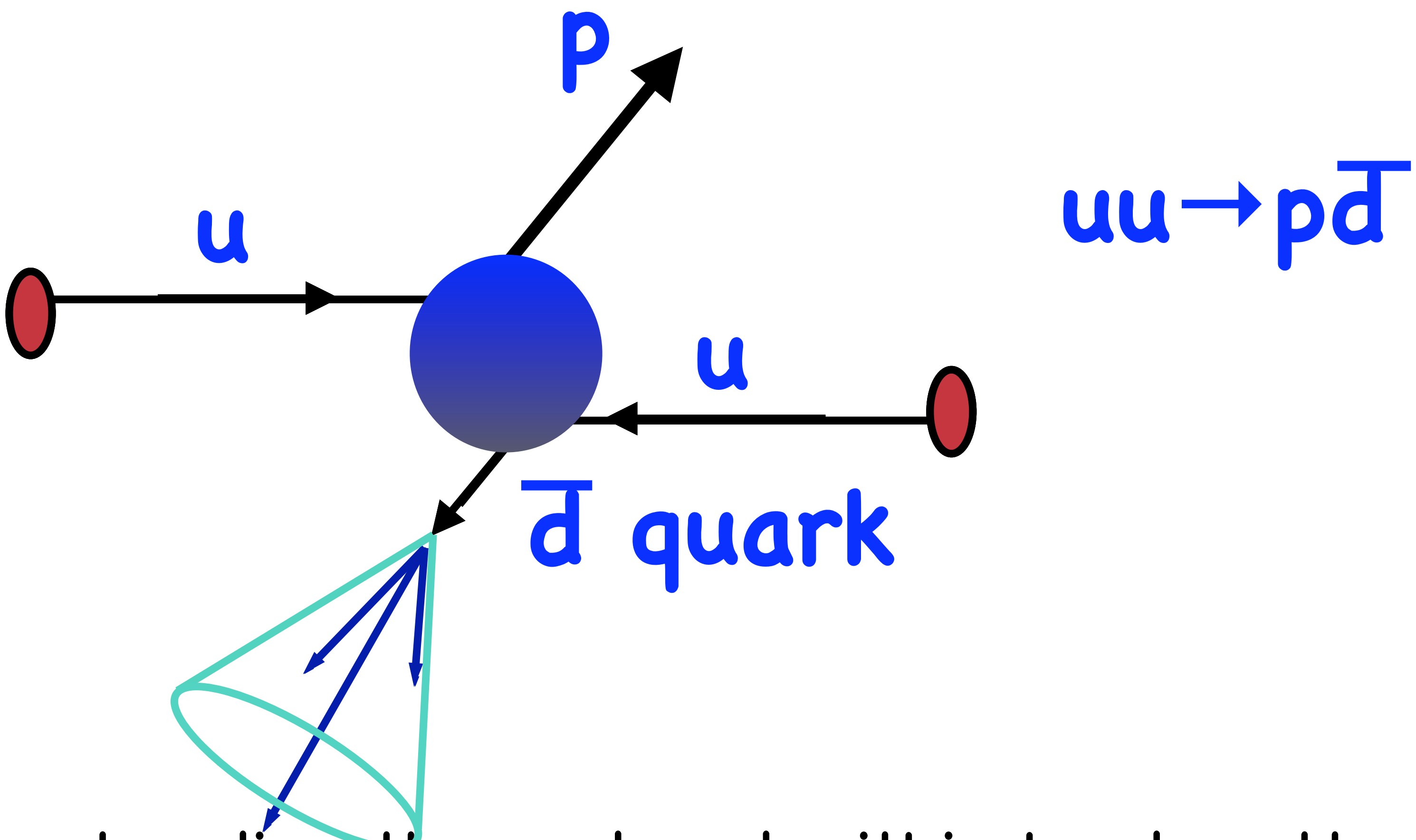

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Brodsky & AMS PLB 668 111 (2008)

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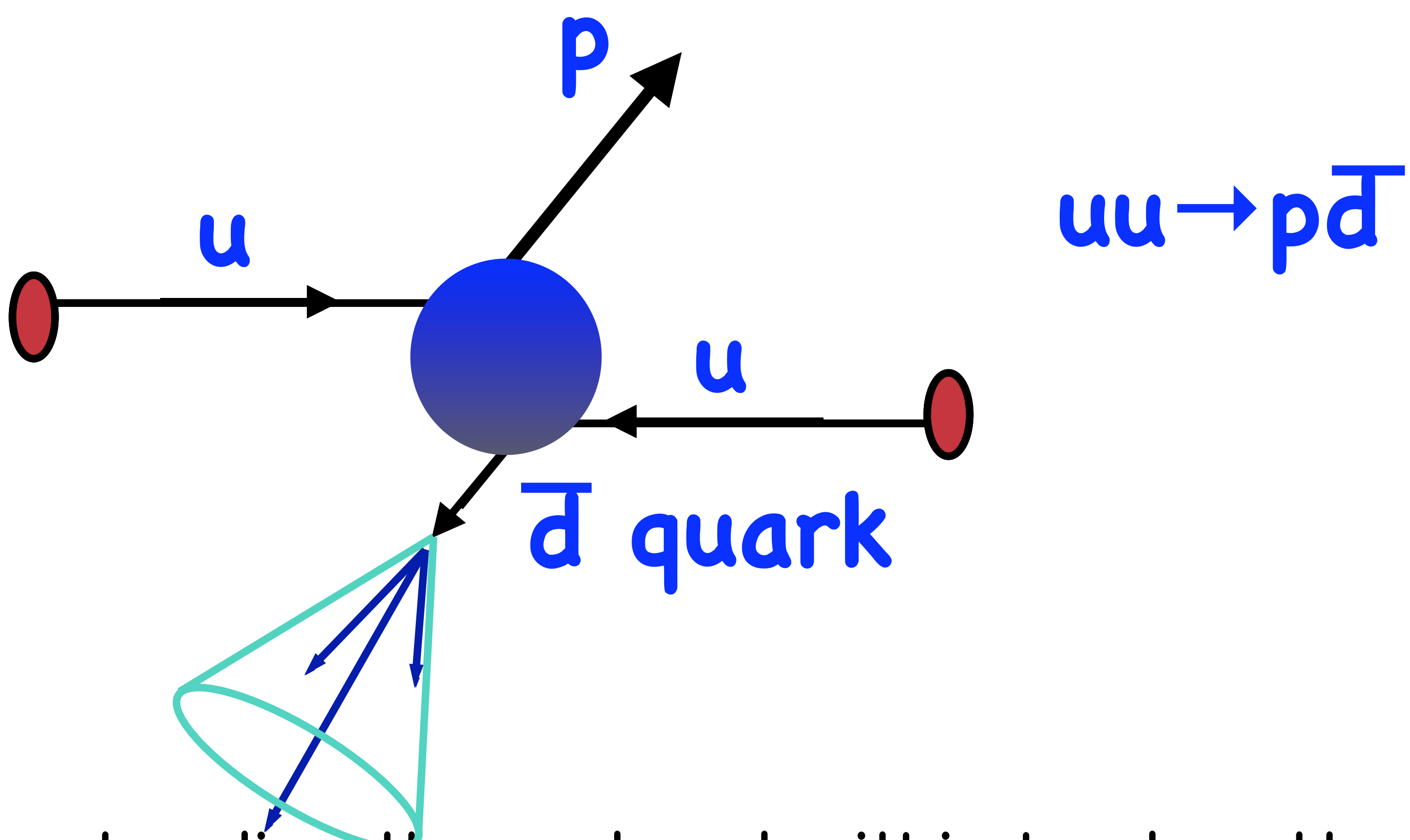
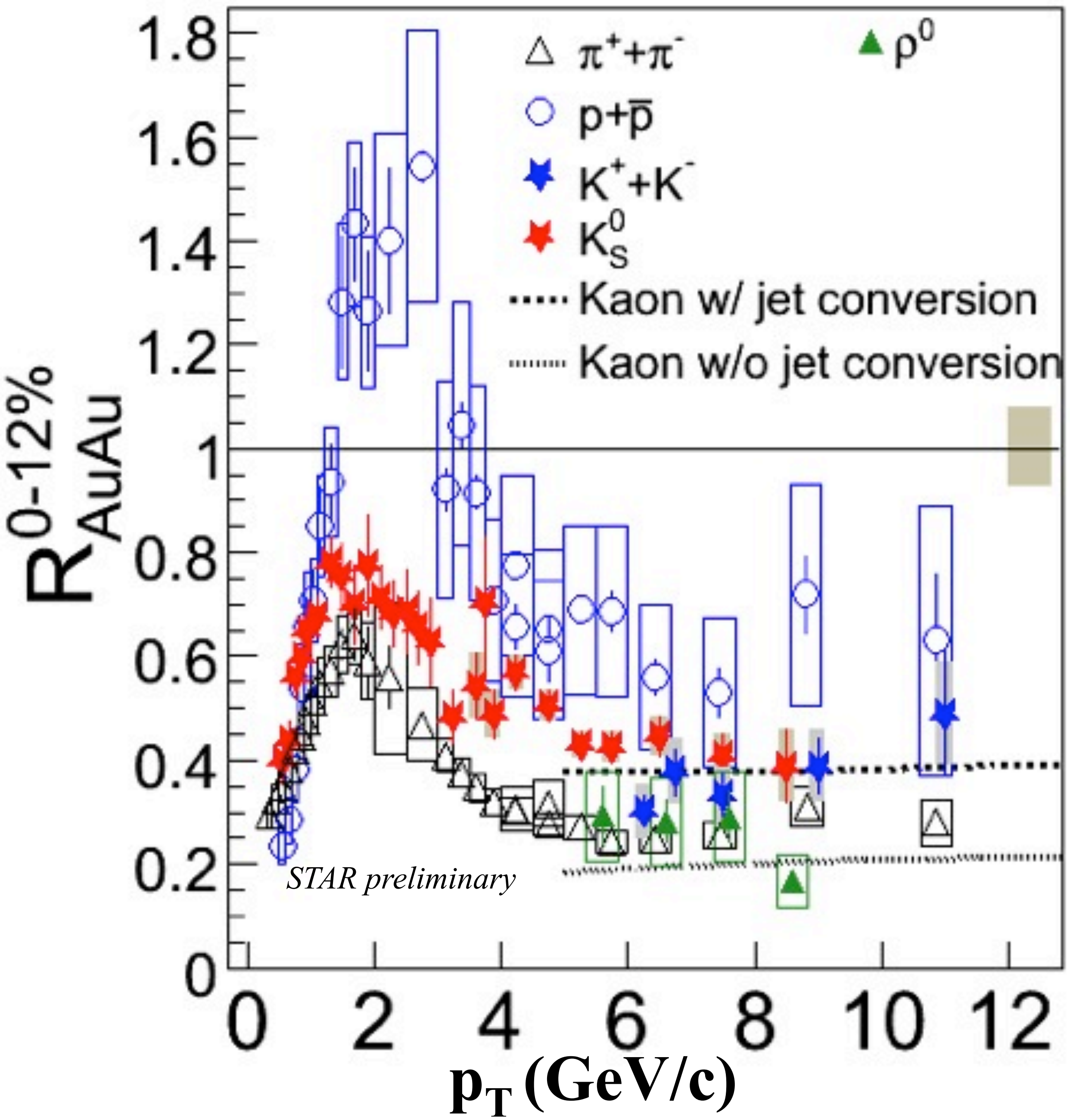


- color singlet proton directly produced within hard scattering
- no energy wasted in fragmentation
- small color neutral protons: color transparent
  - proton exits collision region without interacting, like a direct γ
  - R_{AA}(proton) > $R_{AA}(\pi)$

Brodsky & AMS PLB 668 111 (2008)

filter: hot nuclear matter



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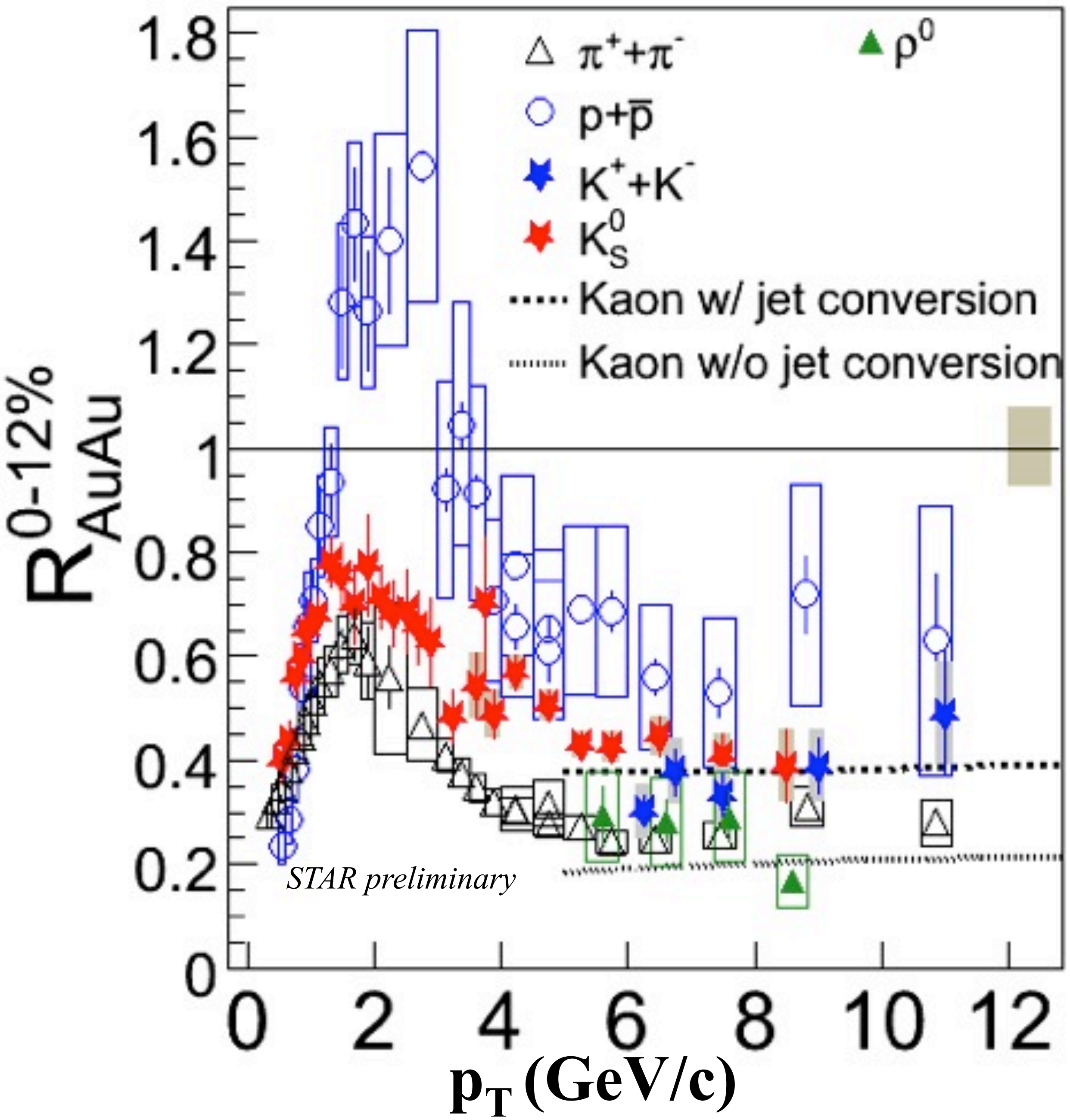

- colored partons lose a lot of energy

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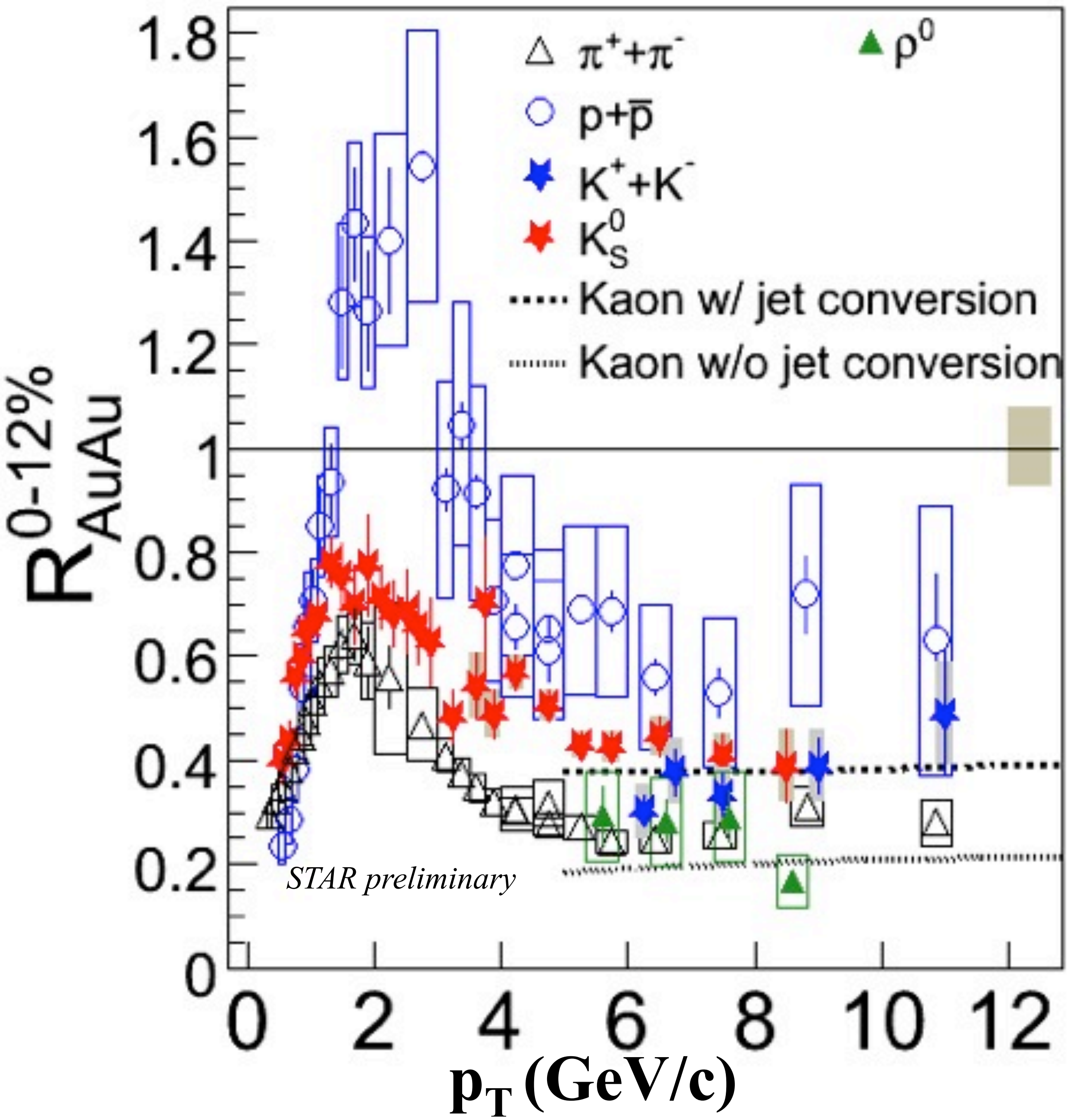

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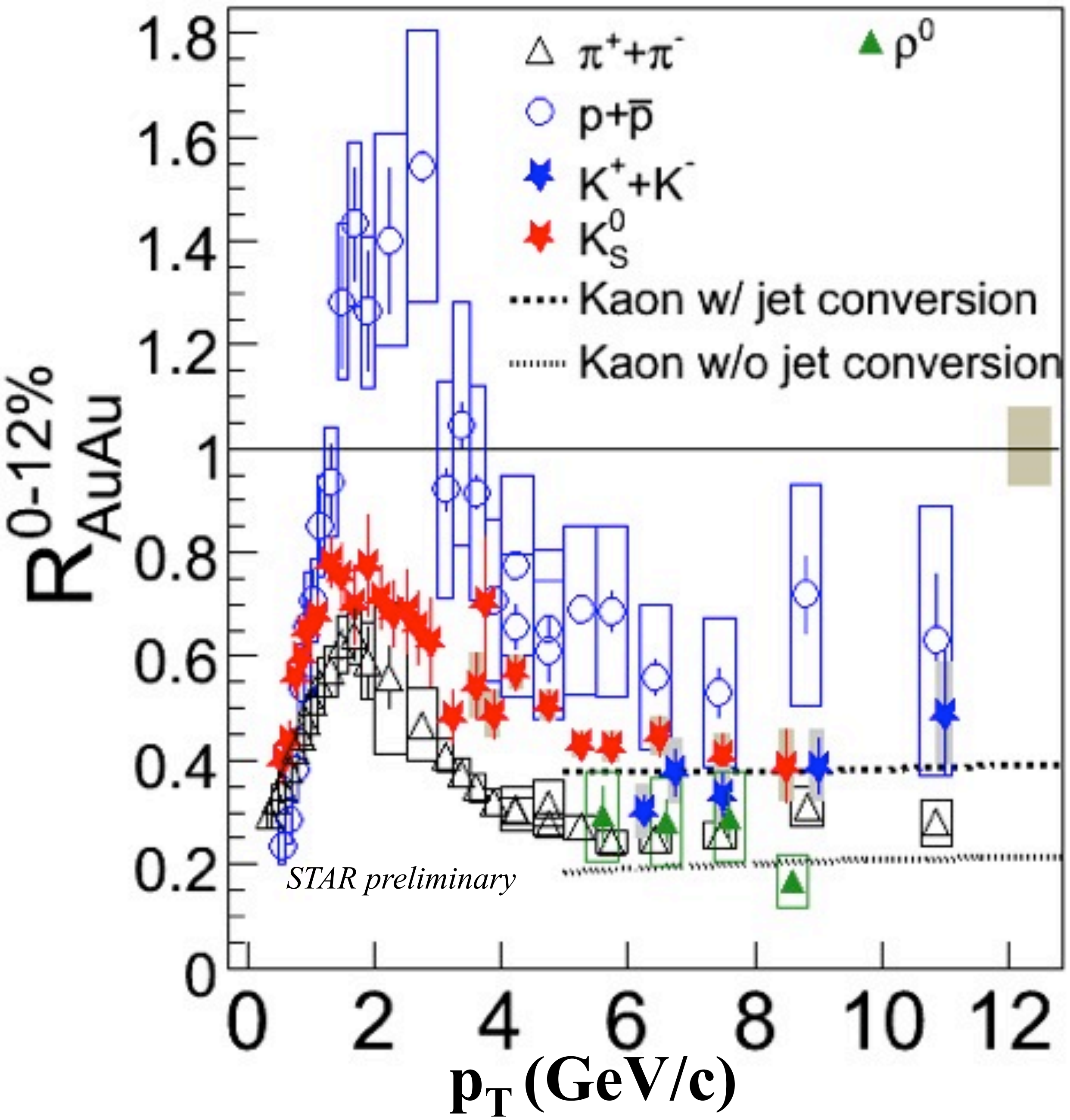

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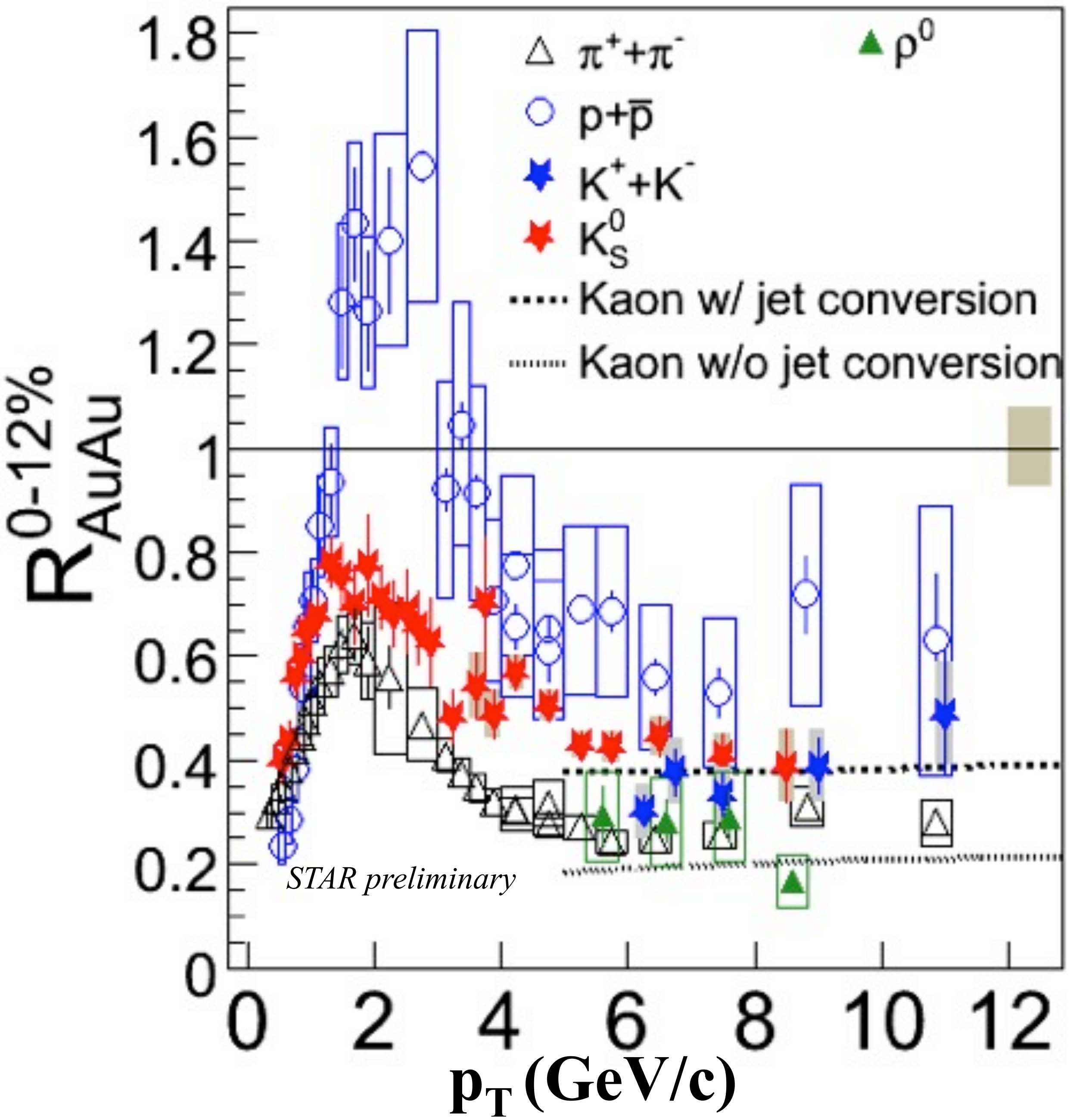

- colored partons lose a lot of energy
- suppresses baryons from fragmentation
- direct processes unsuppressed
  - relative contributions enhanced

x_T scaling

$$\frac{d\sigma}{d^3p/E}(pp \rightarrow HX) = \frac{F(x_T, \theta_{cm})}{p_T^n}$$

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

Brodsky, et al NPB441 197 (1995), Brodsky et al PLB637 58 (2006)

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- n related to "twist", number of participants, of the hard scattering
- leading twist: g+g→g+g, n=4
- higher twist: qq→p+qbar, n=8
- n increased somewhat, running coupling, evolution of PDFs & FFs

Brodsky, et al NPB441 197 (1995), Brodsky et al PLB637 58 (2006)

more quantitative: $n_{eff}(x_T)$

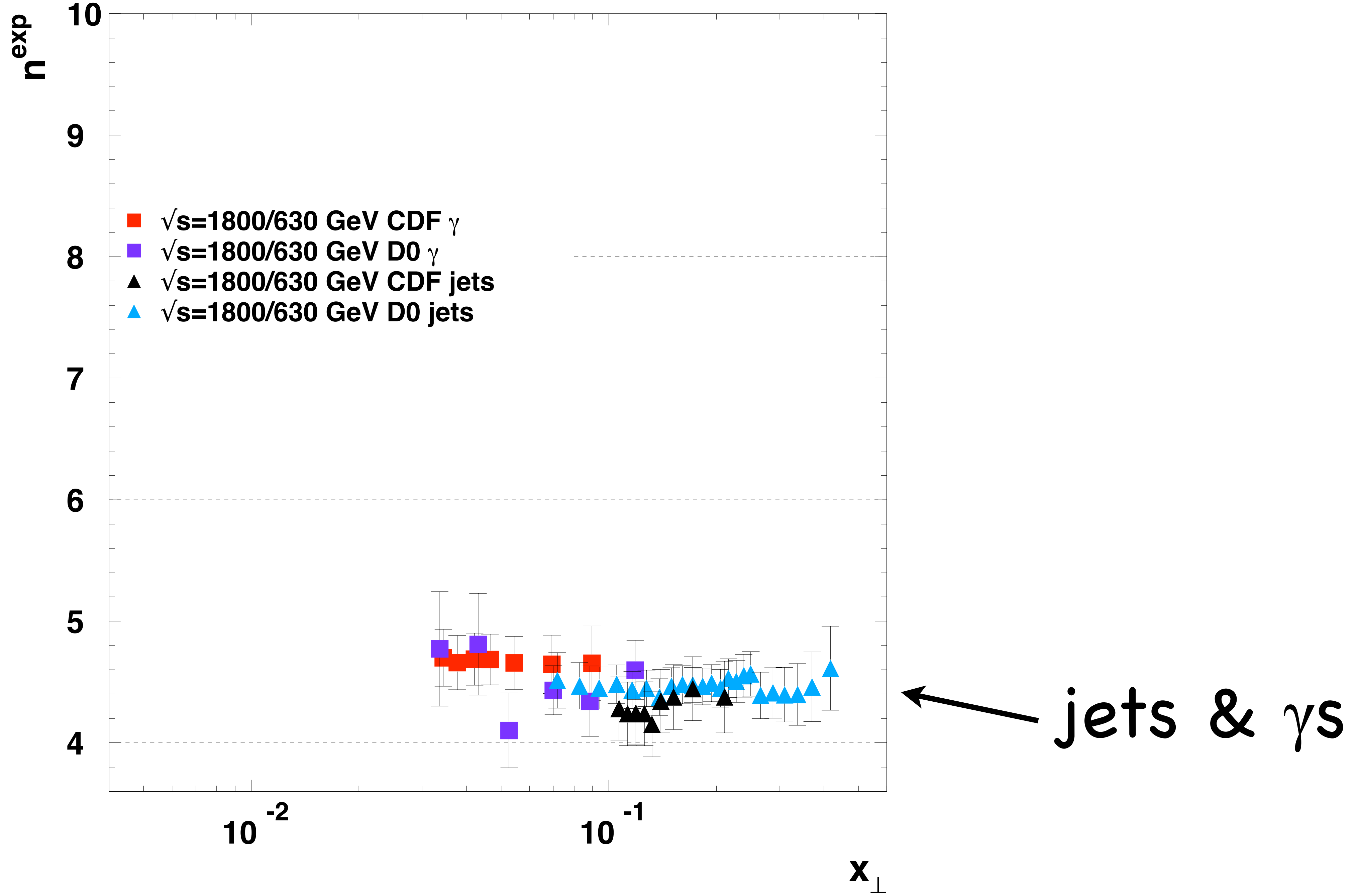
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}}\, G(x_T)$$

Cahalan et al PRD 11 1199 (1975)

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

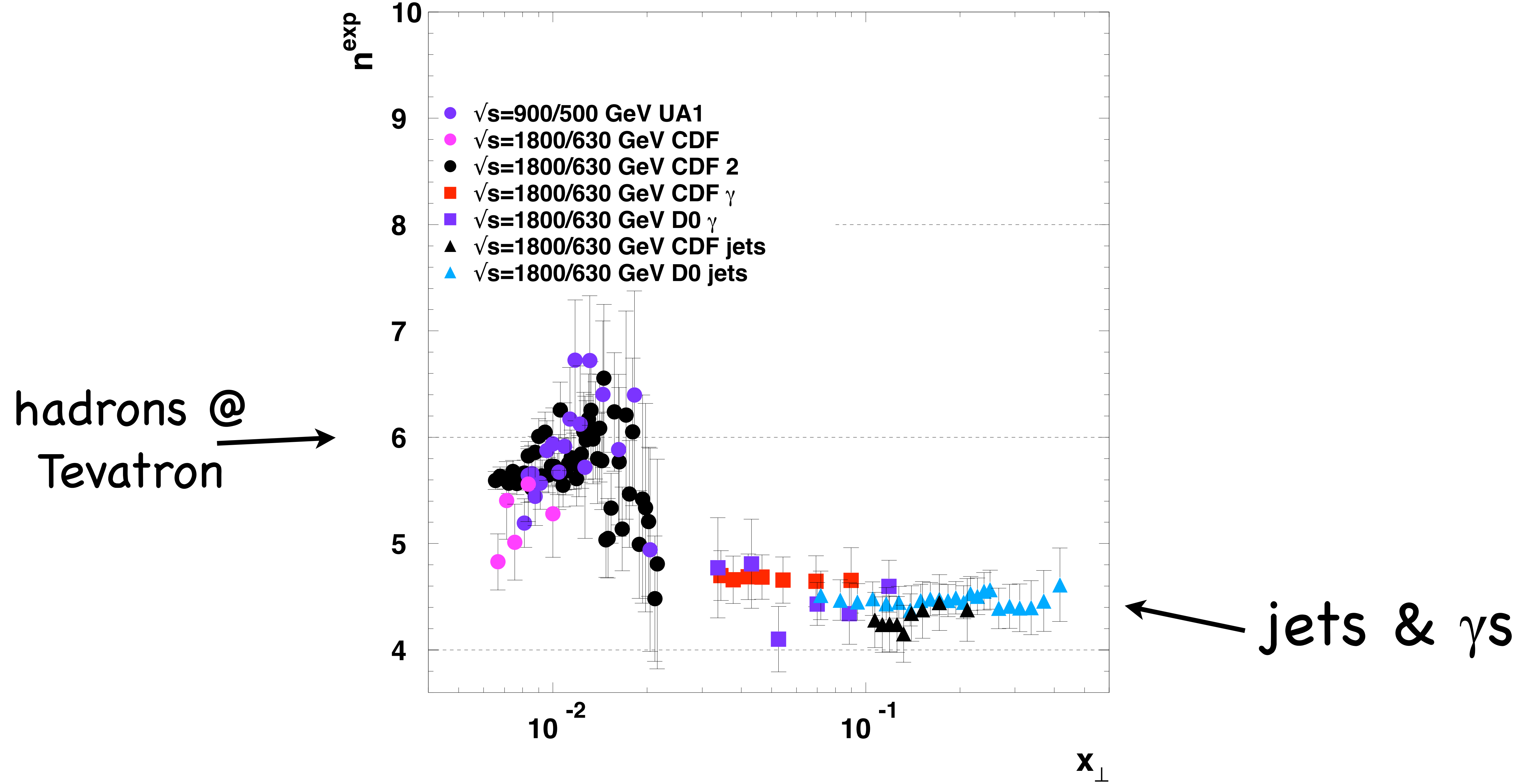
- physically motivated way to compare cross sections across collision energies

n: from p+p(bar) collisions



arXiv:0911.4604

n: from p+p(bar) collisions



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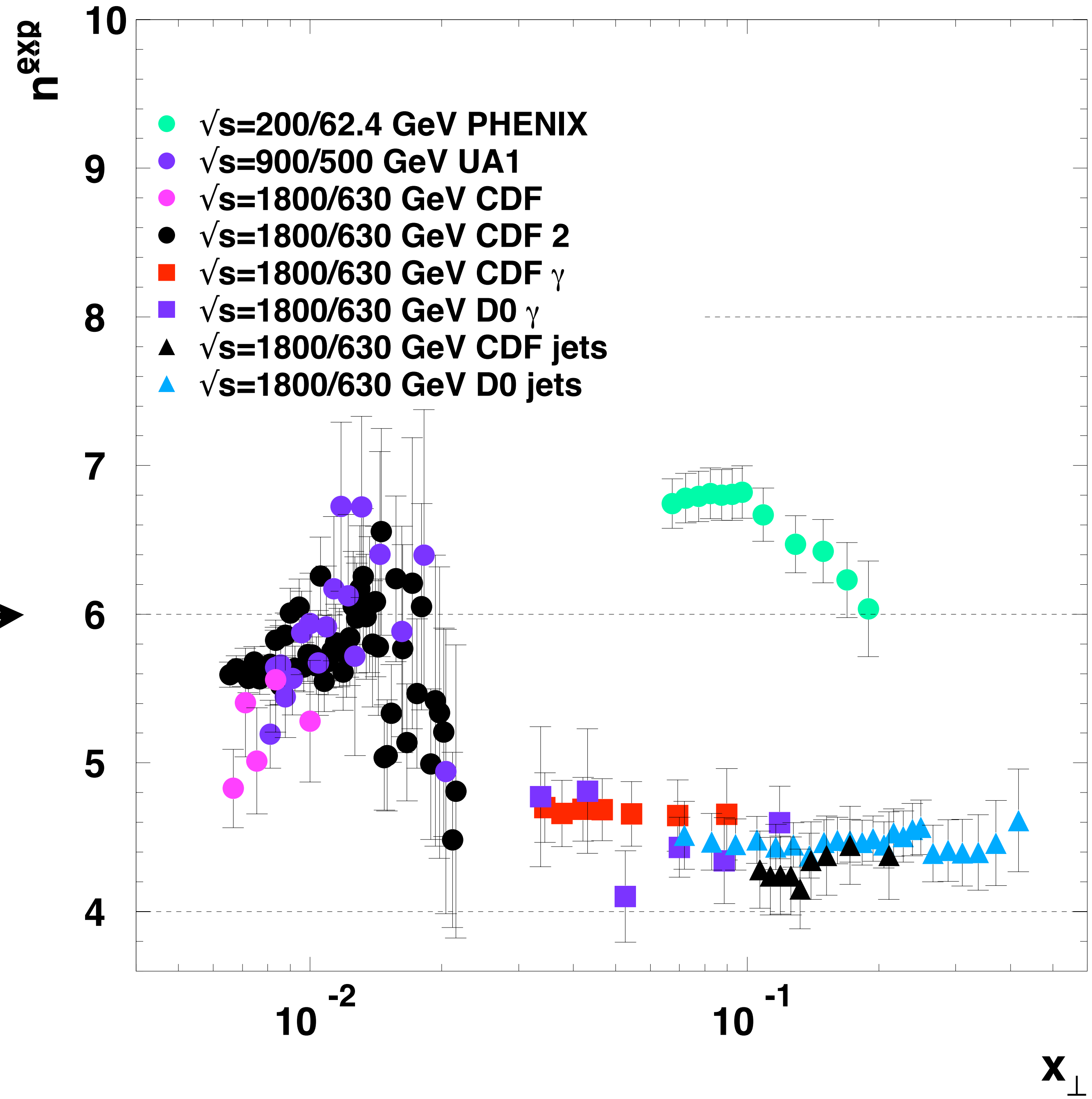
hadrons @ Tevatron

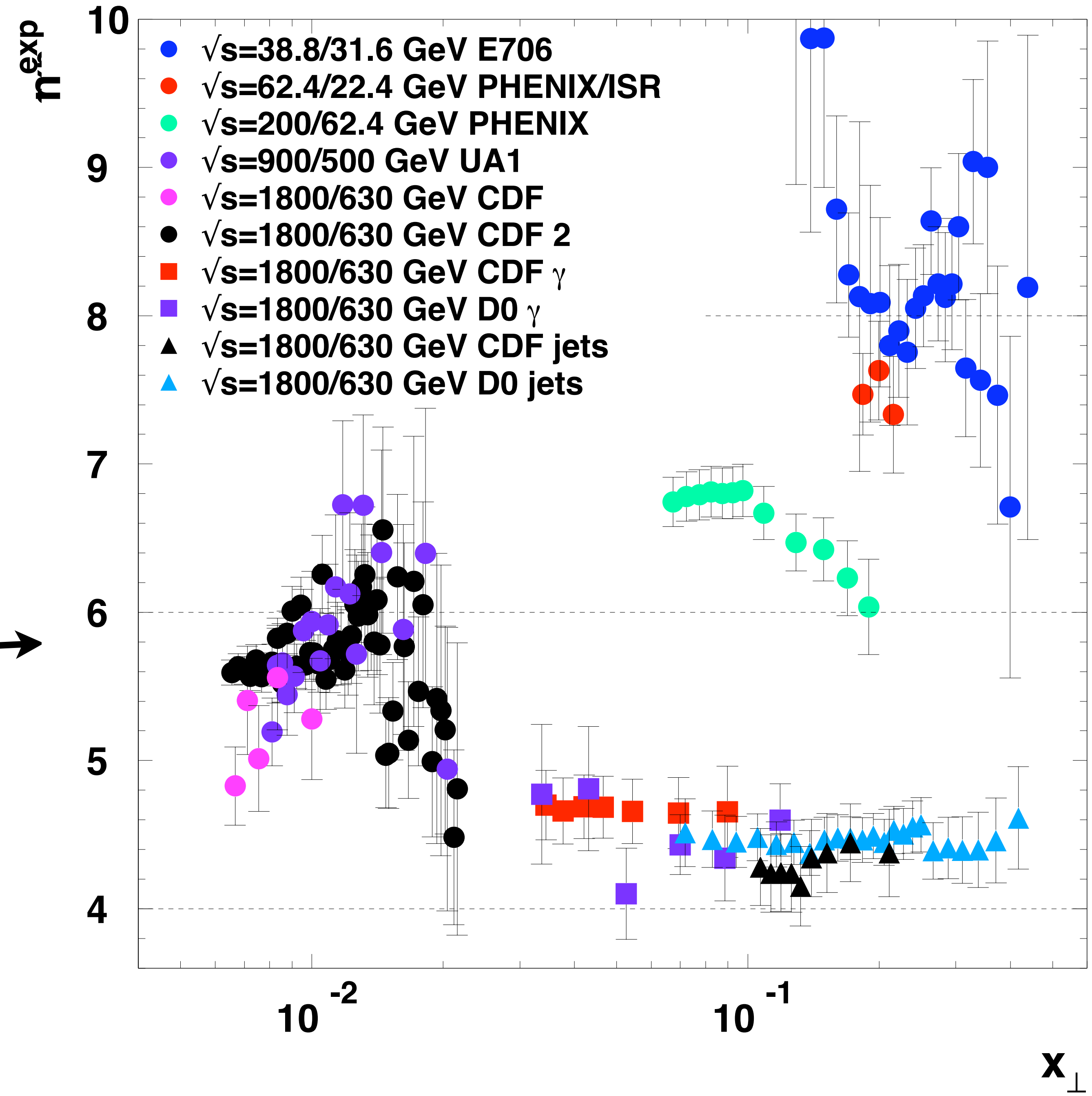


π^0s @ RHIC

jets & γs

arXiv:0911.4604

n: from p+p(bar) collisions



hadrons @ Tevatron

π^0s @ RHIC/E706

π^0s @ RHIC

jets & γs

arXiv:0911.4604

well, what do you expect?

arXiv:0911.4604

well, what do you expect?

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

arXiv:0911.4604

Anne M. Sickles, February 14, 2010

well, what do you expect?

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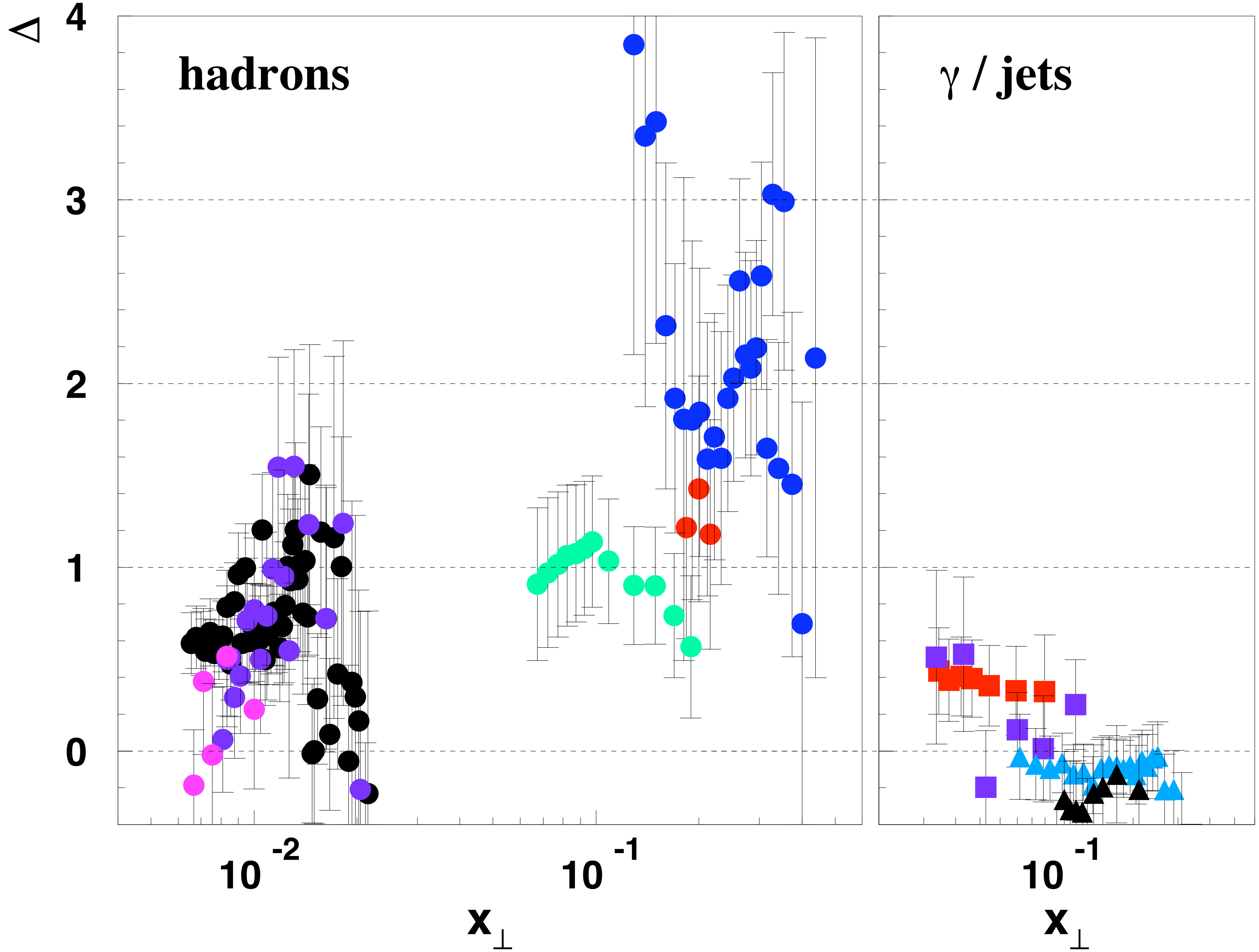

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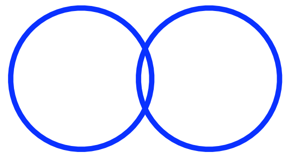
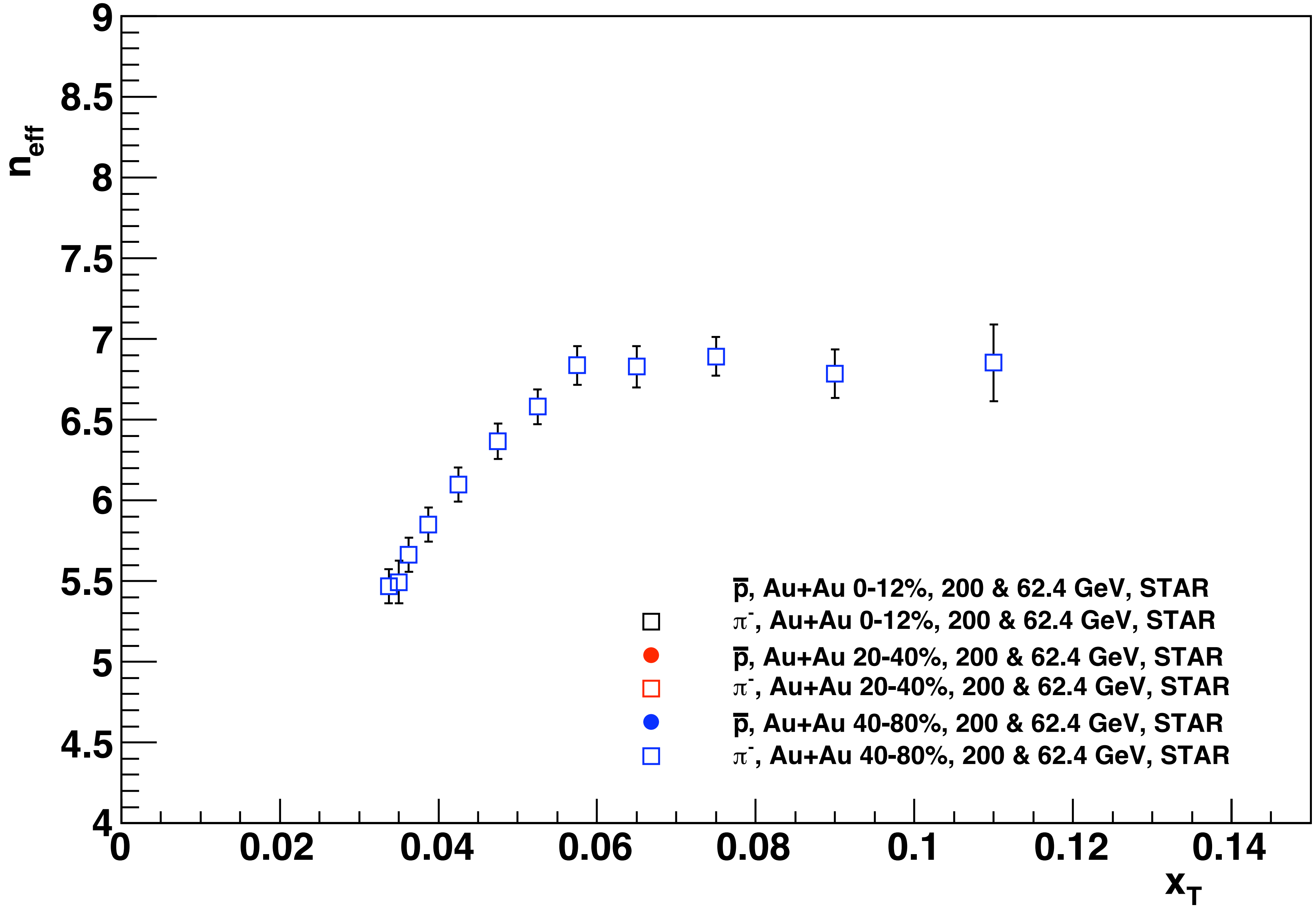
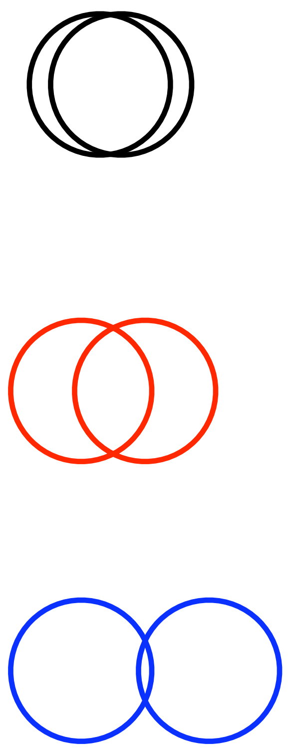
heavy ion collisions, $\pi^{\pm}$

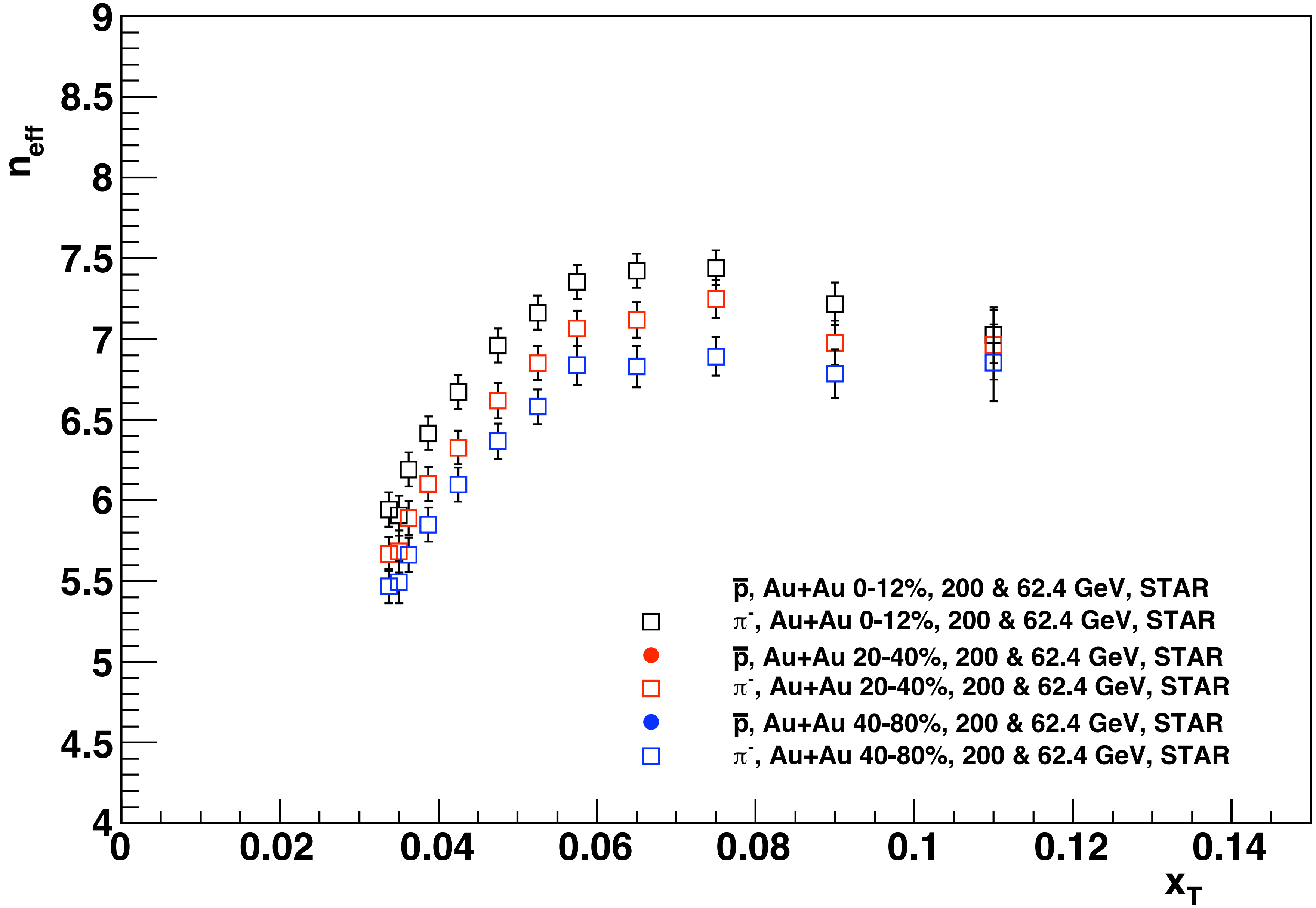




data from: STAR PLB 655 104 (2007)

heavy ion collisions, $\pi^{\pm}$





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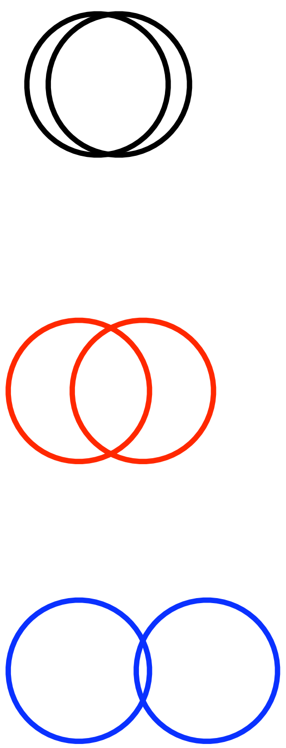
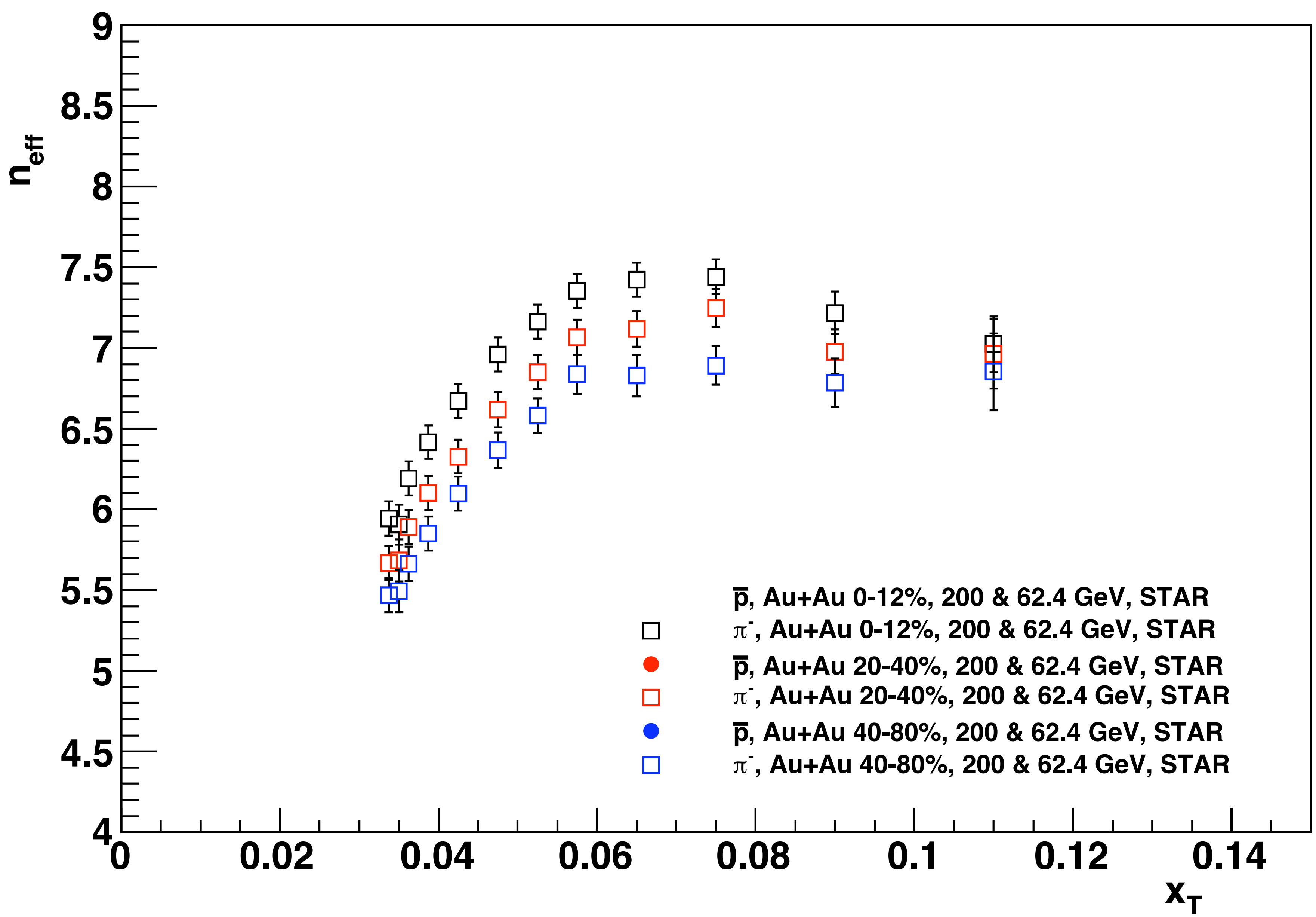
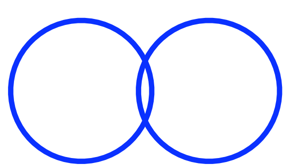


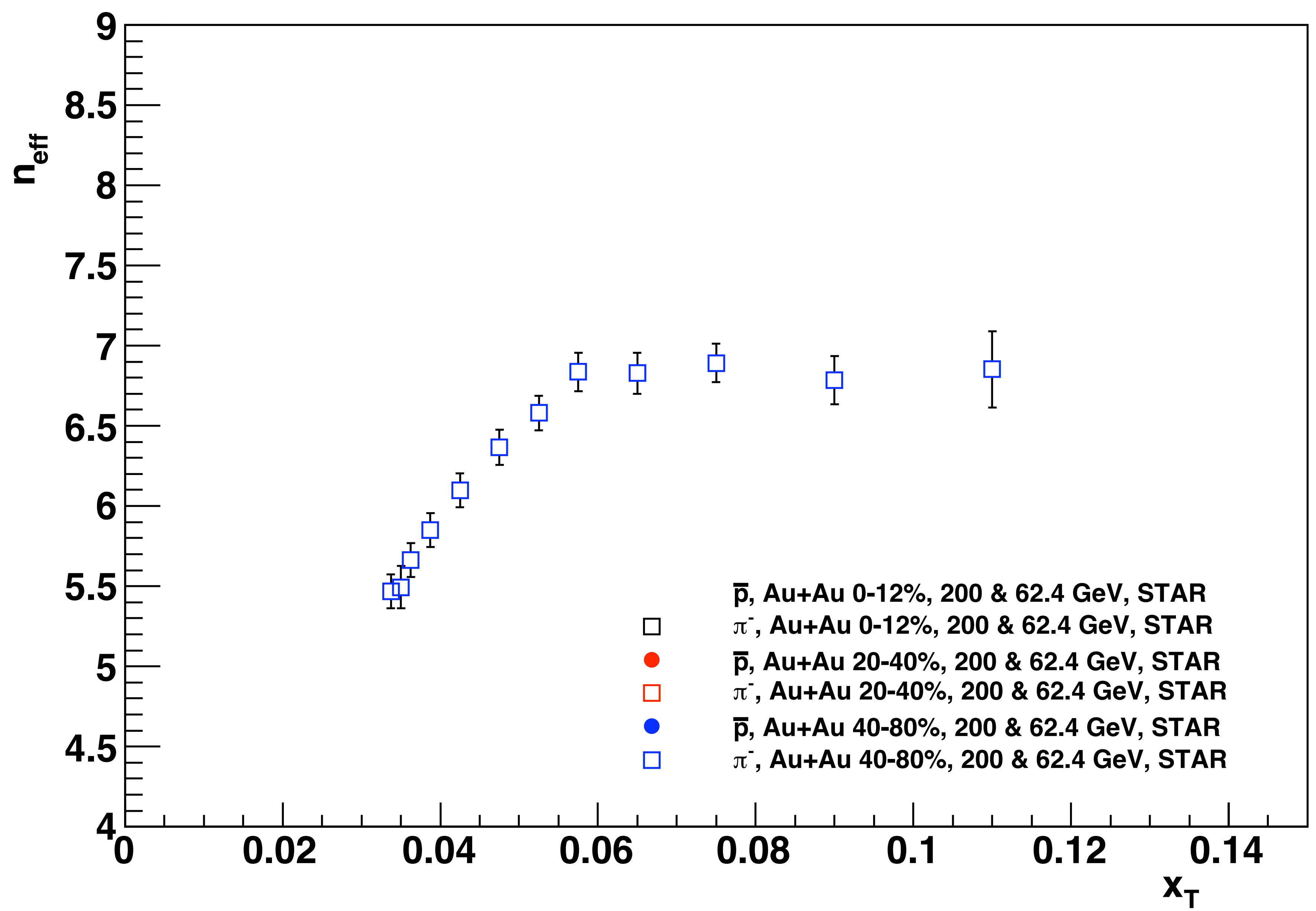


data from: STAR PLB 655 104 (2007)

- n_{eff}(pions) increases slightly with centrality

anti-protons: heavy ion collisions





data from: STAR PLB 655 104 (2007)

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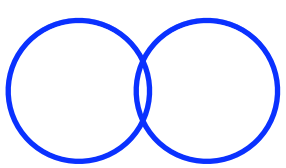

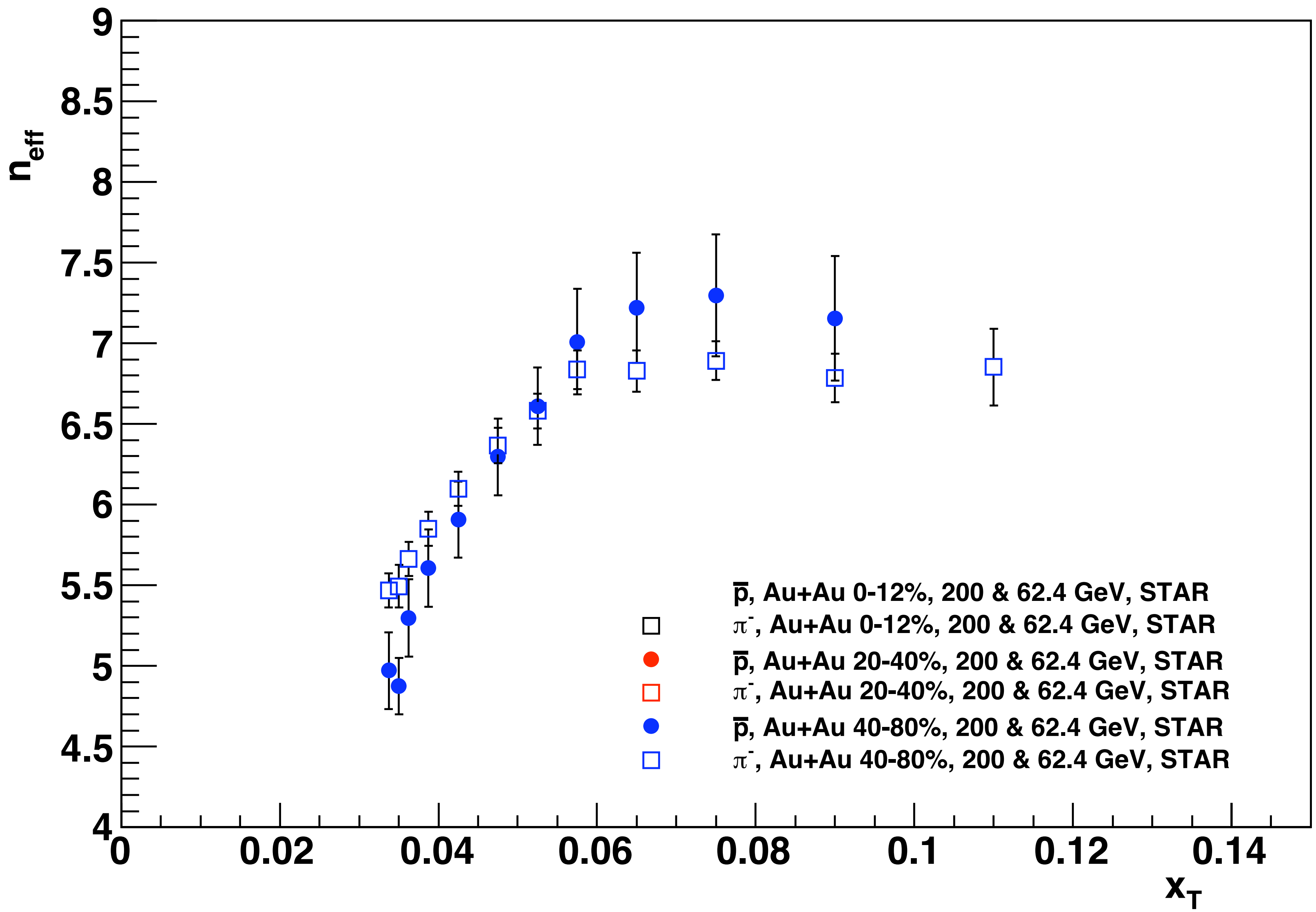

data from: STAR PLB 655 104 (2007)

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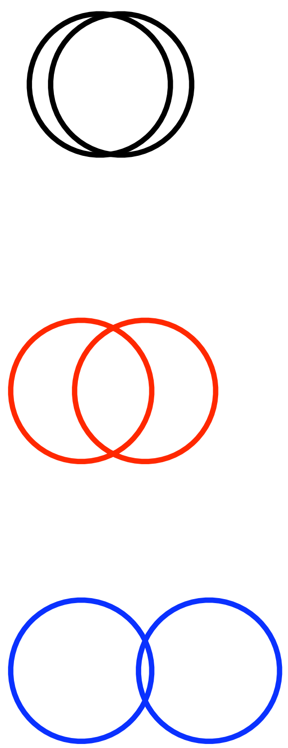

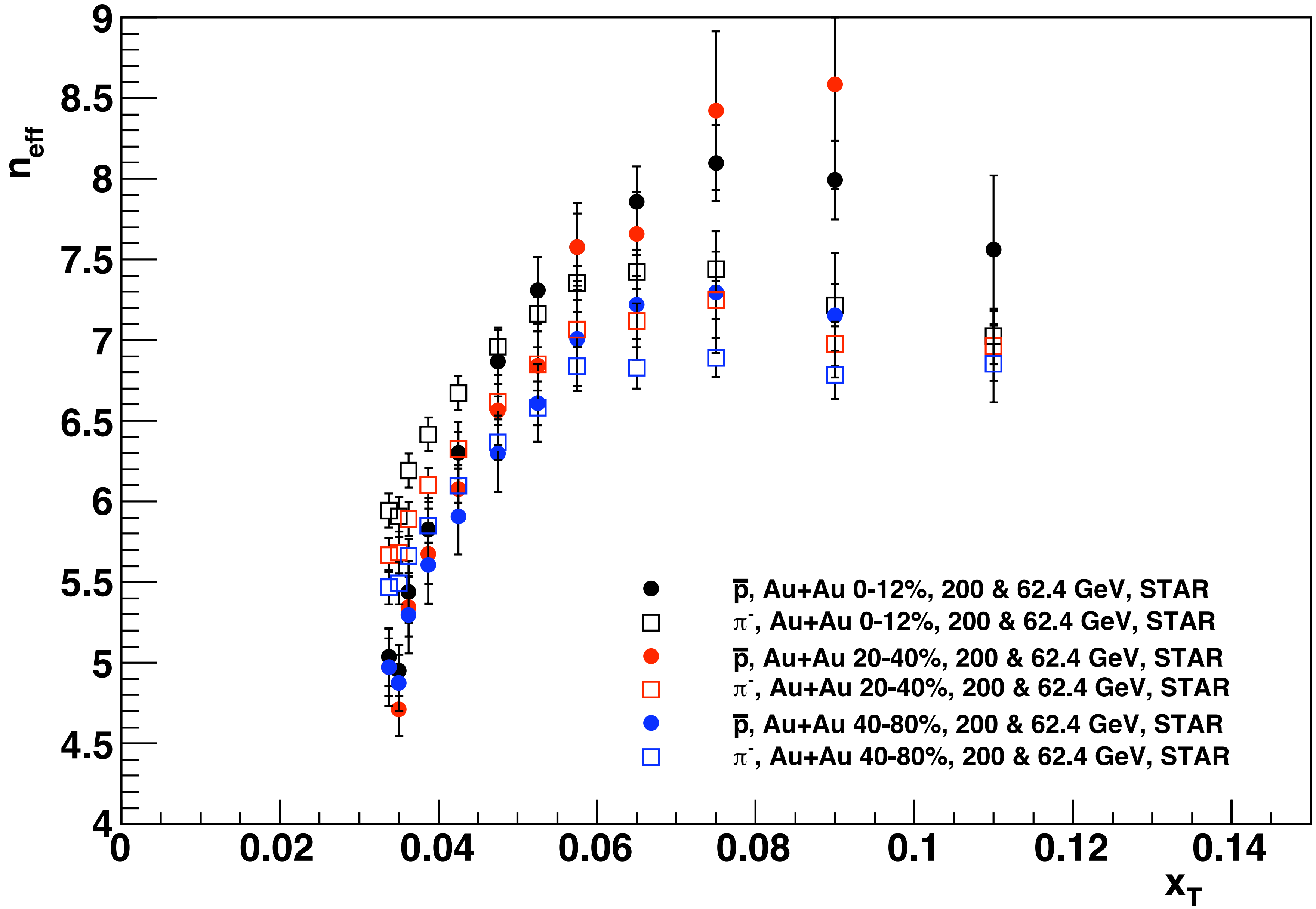

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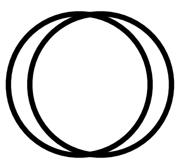
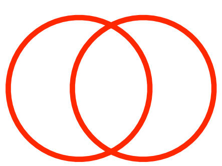
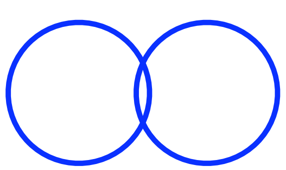
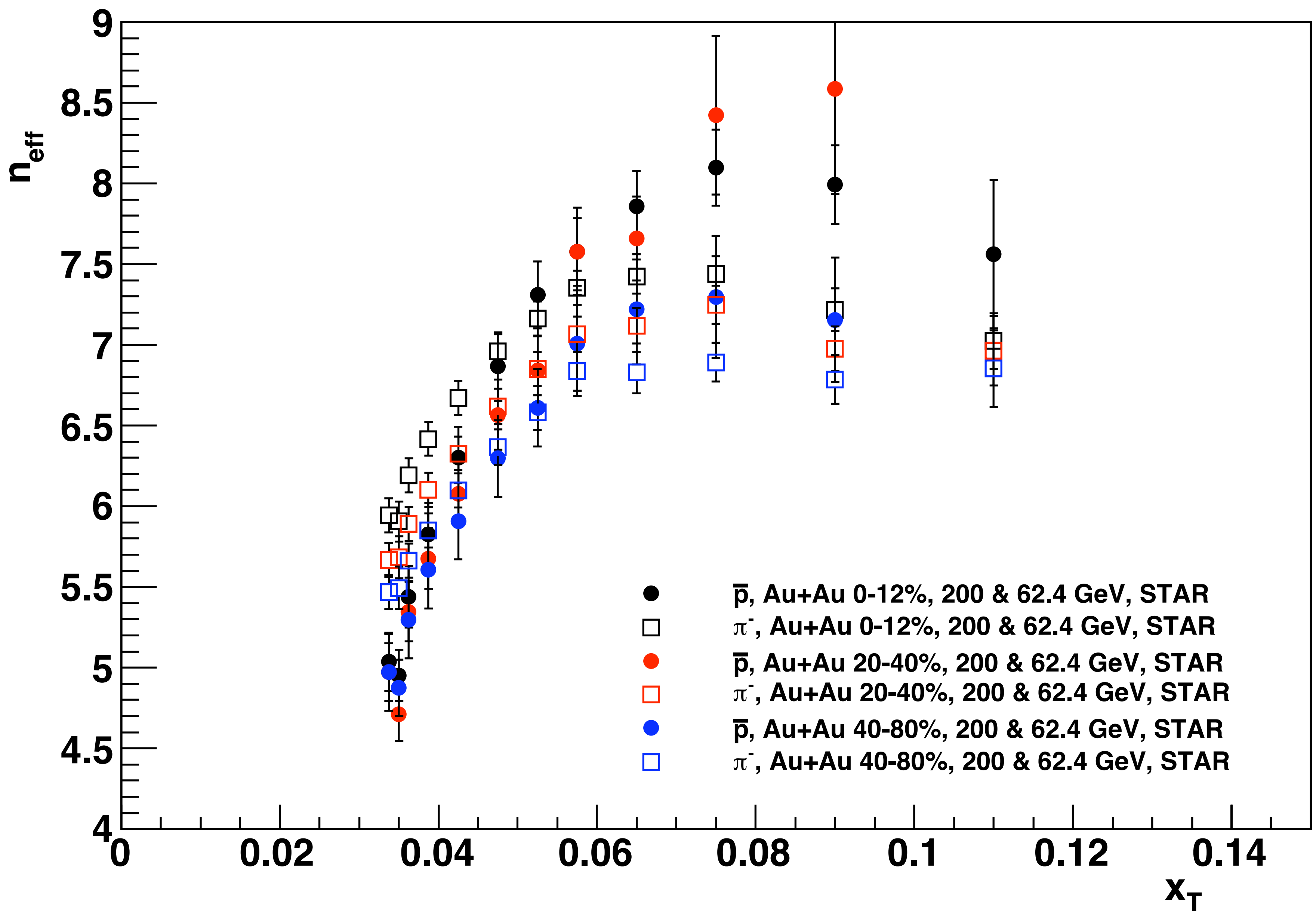
anti-protons: heavy ion collisions





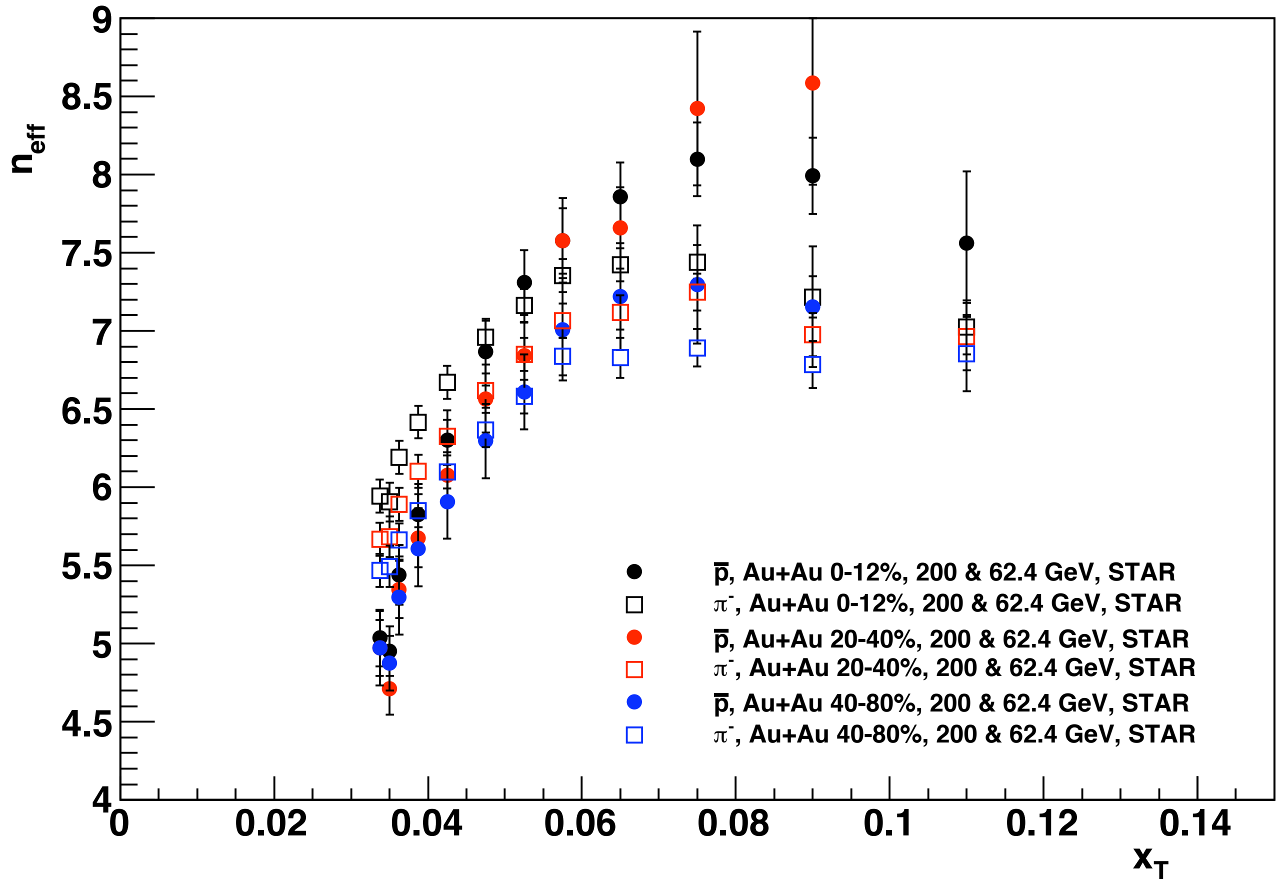


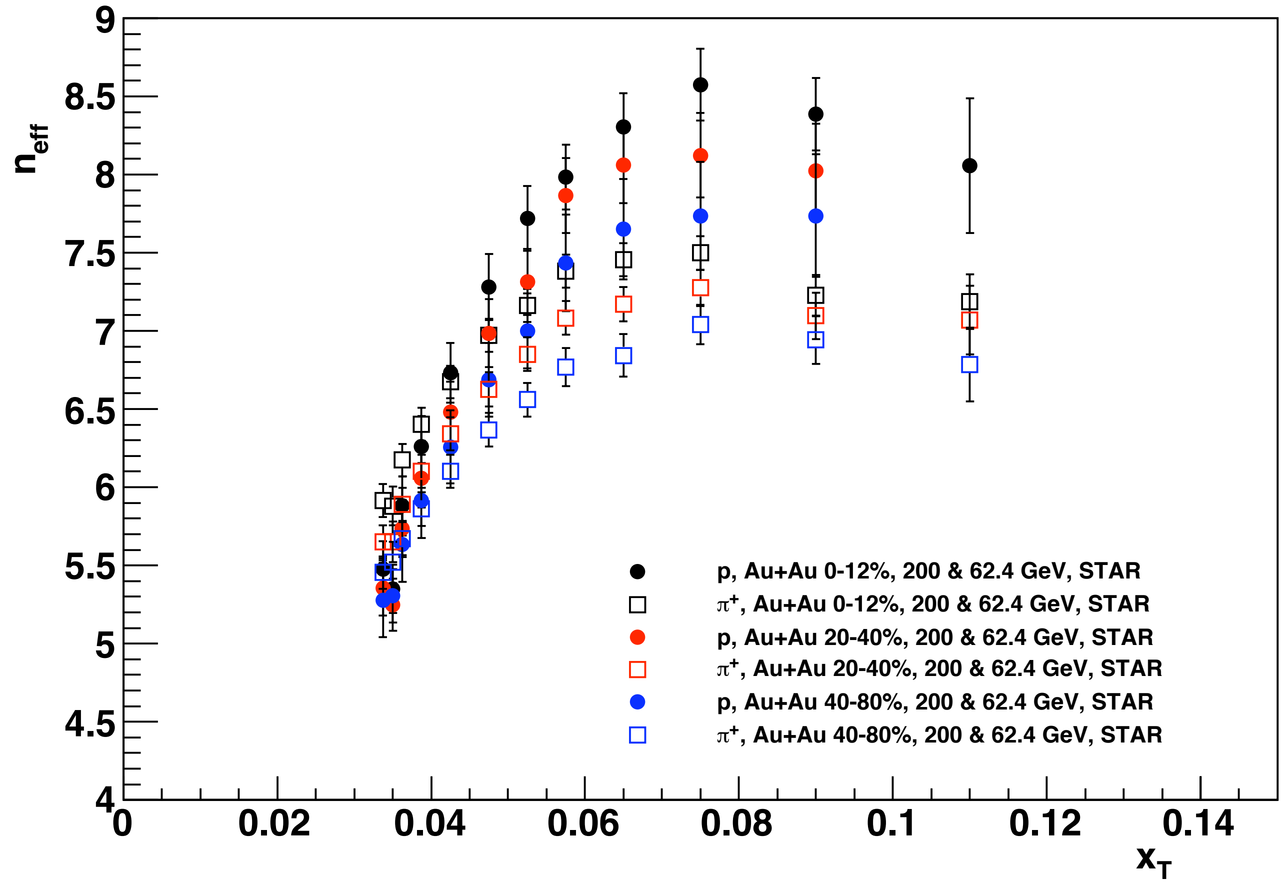


- power increased for protons, increases w/ centrality

data from: STAR PLB 655 104 (2007)

p and pbar





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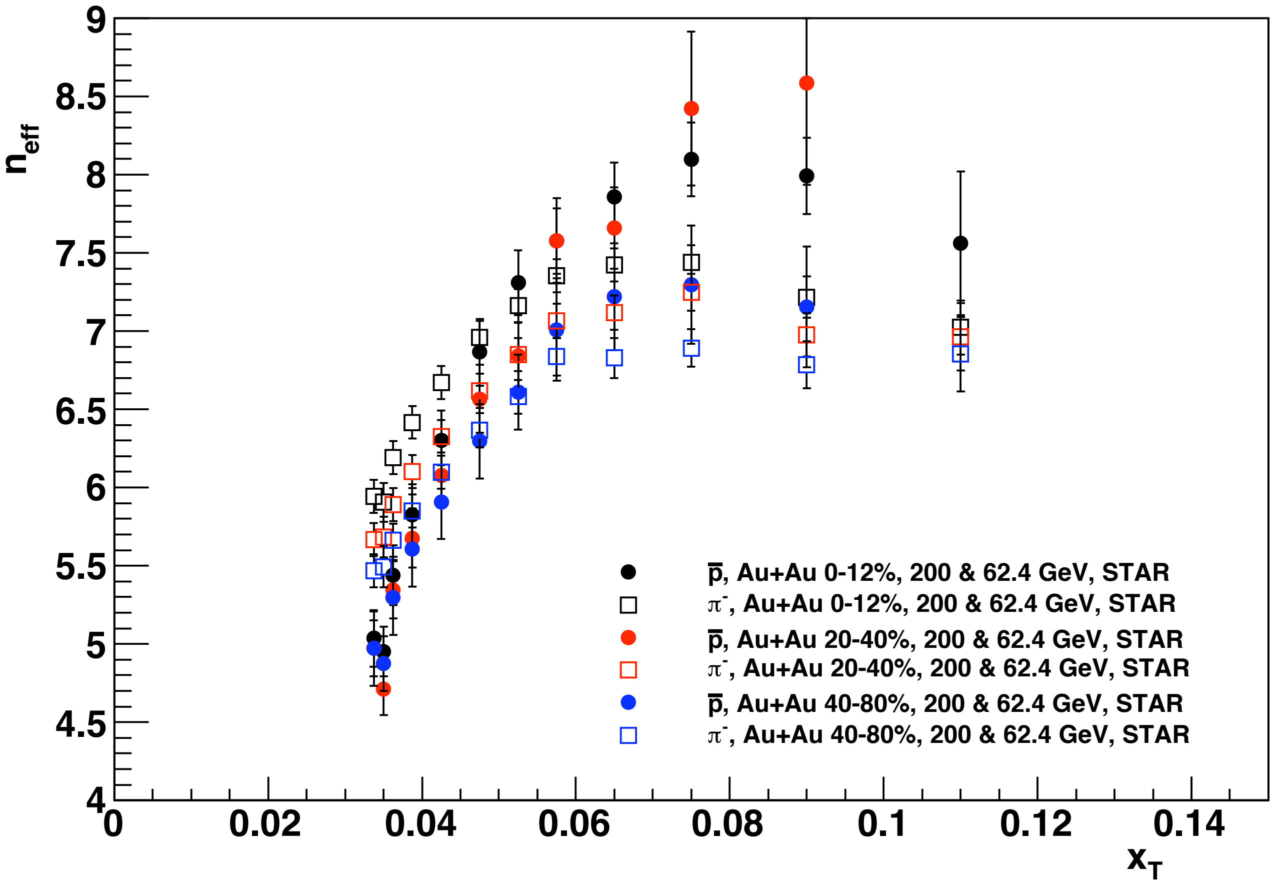
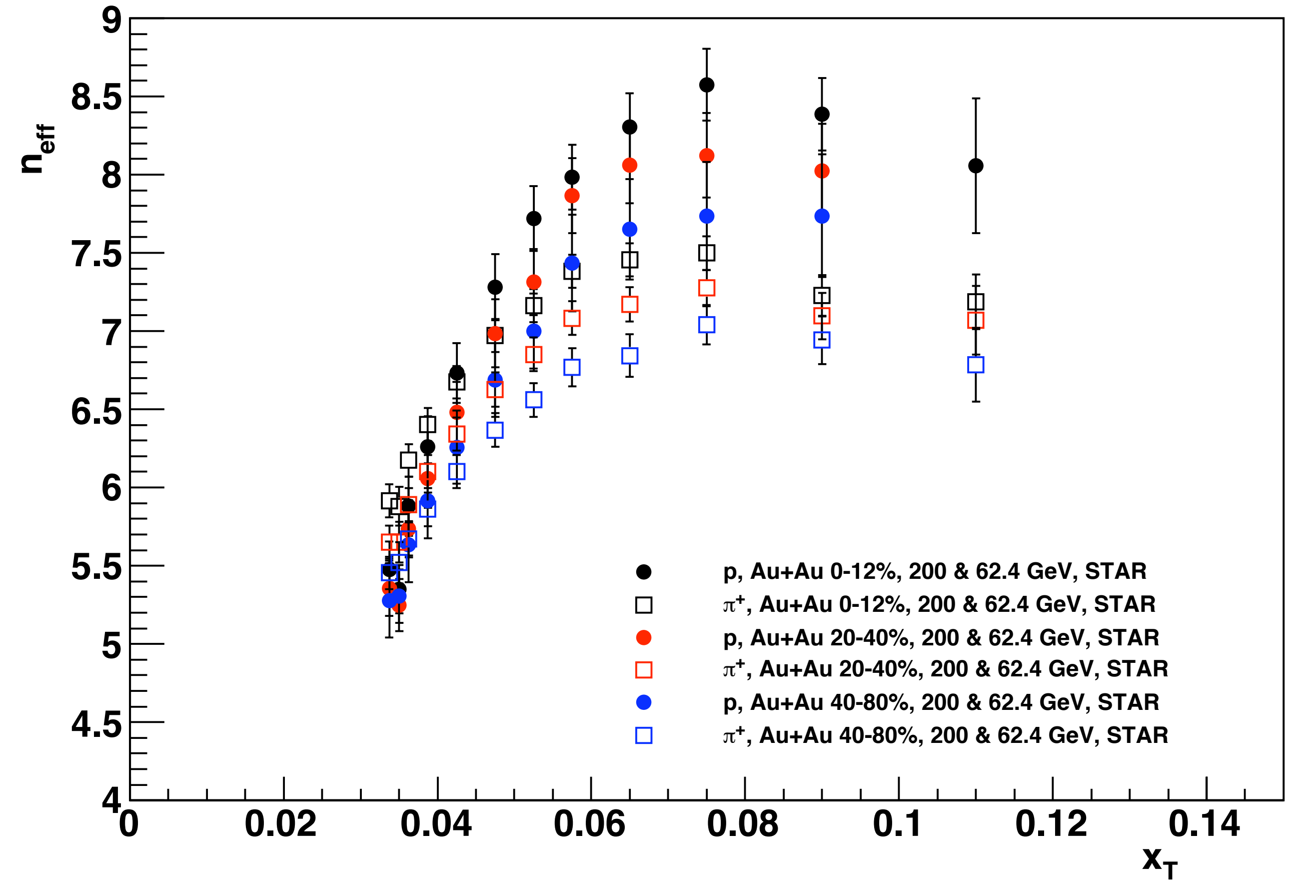
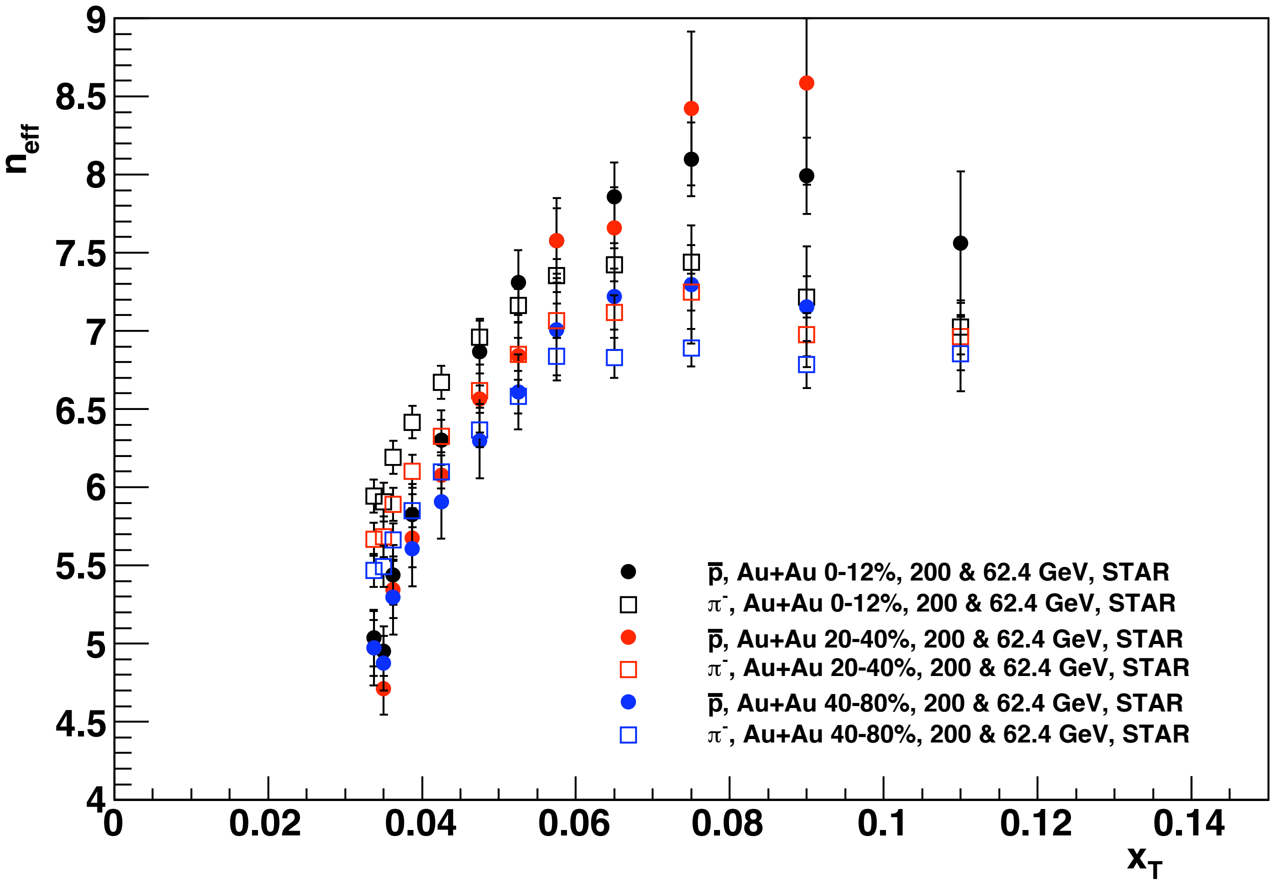


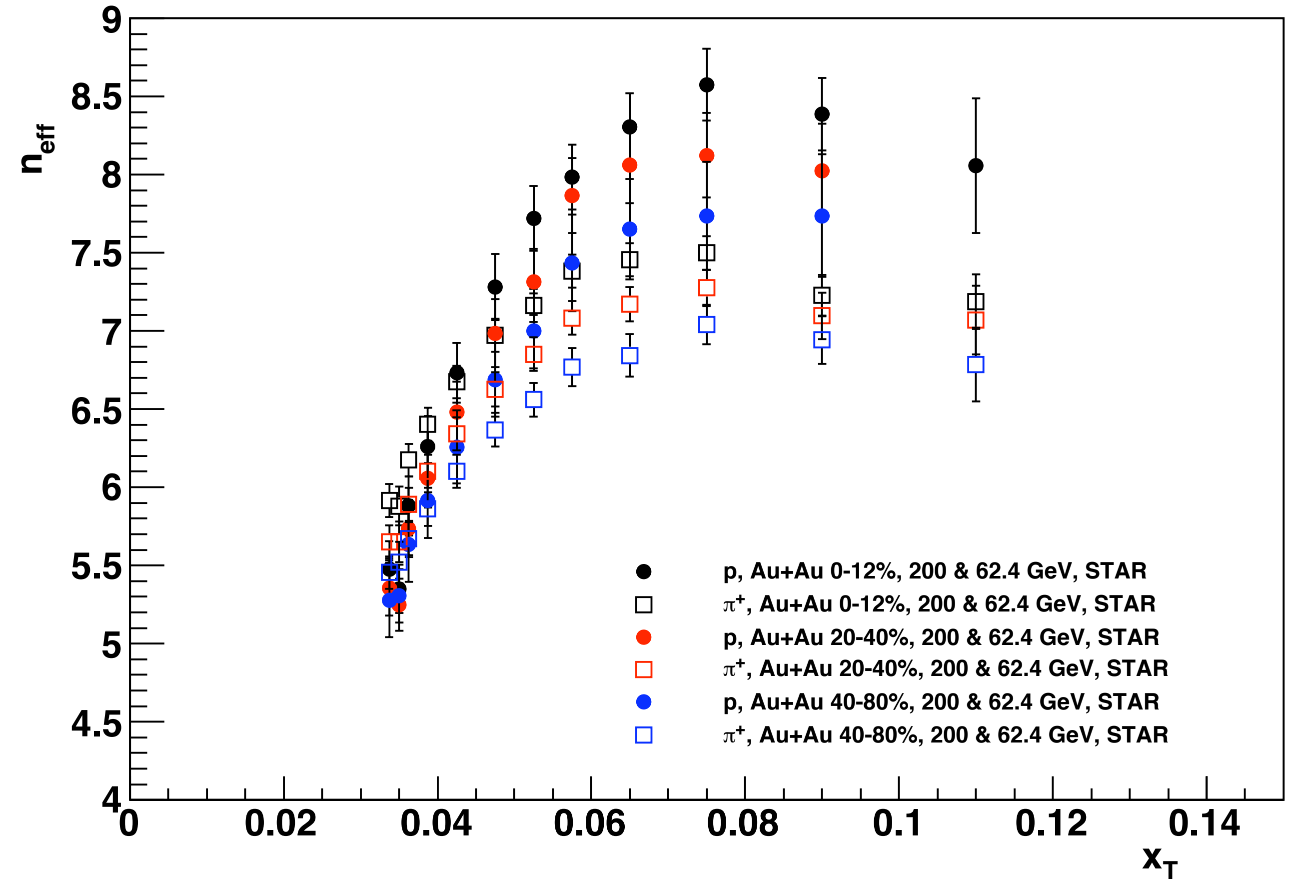


- n higher for p and pbar than pions

data from: STAR PLB 655 104 (2007)

p and pbar

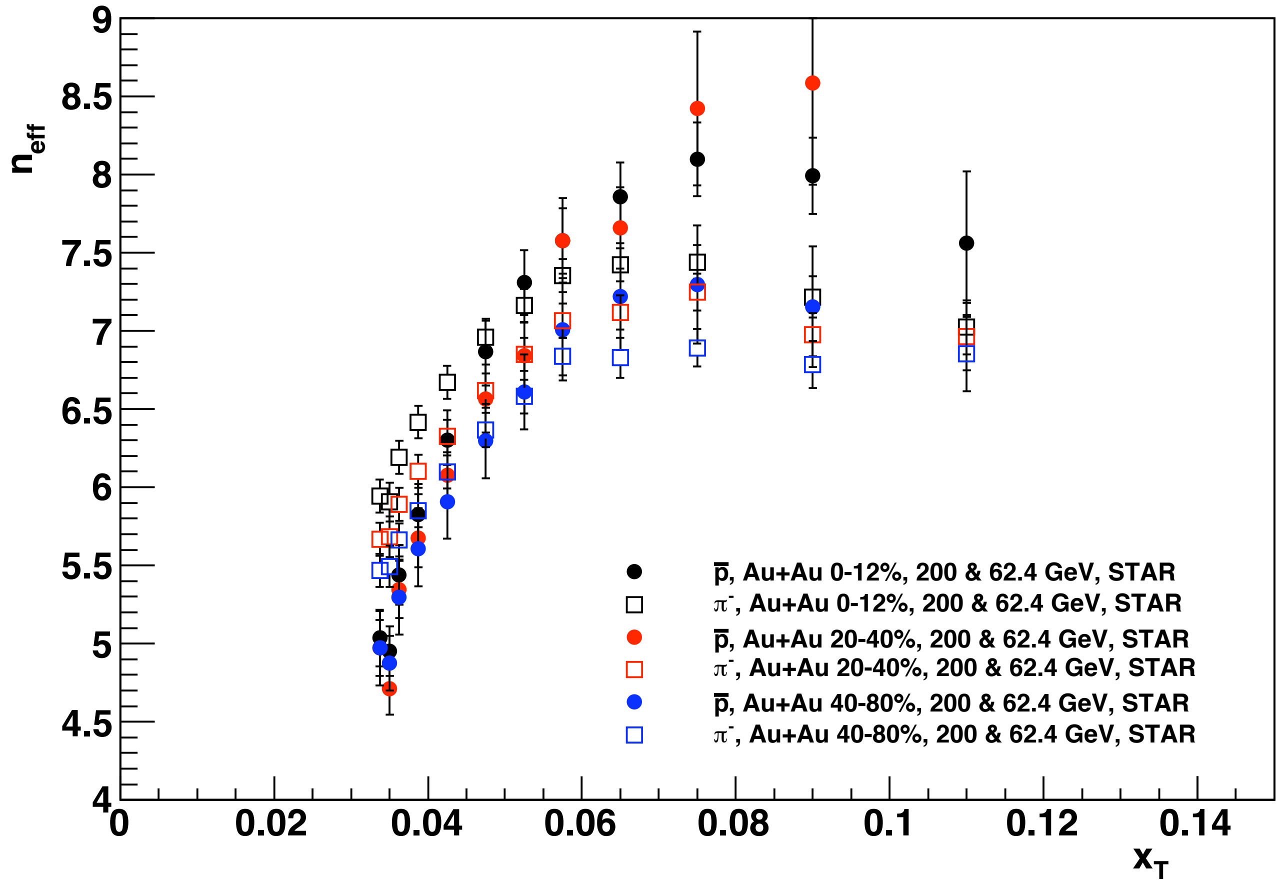


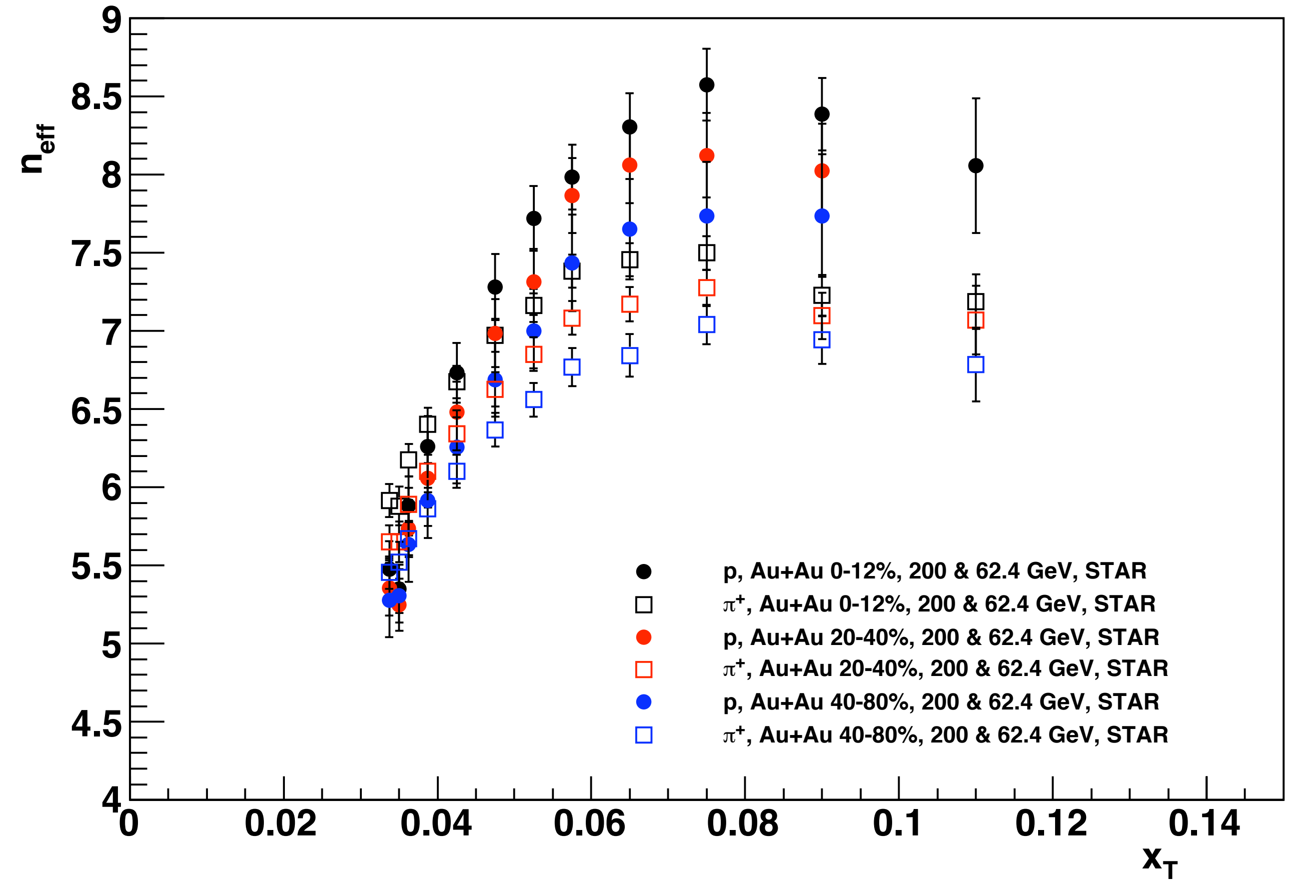


- n higher for p and pbar than pions
- n increases with centrality

data from: STAR PLB 655 104 (2007)

p and pbar





- n higher for p and pbar than pions
- n increases with centrality
- independent of charge

data from: STAR PLB 655 104 (2007)

tests: strangeness

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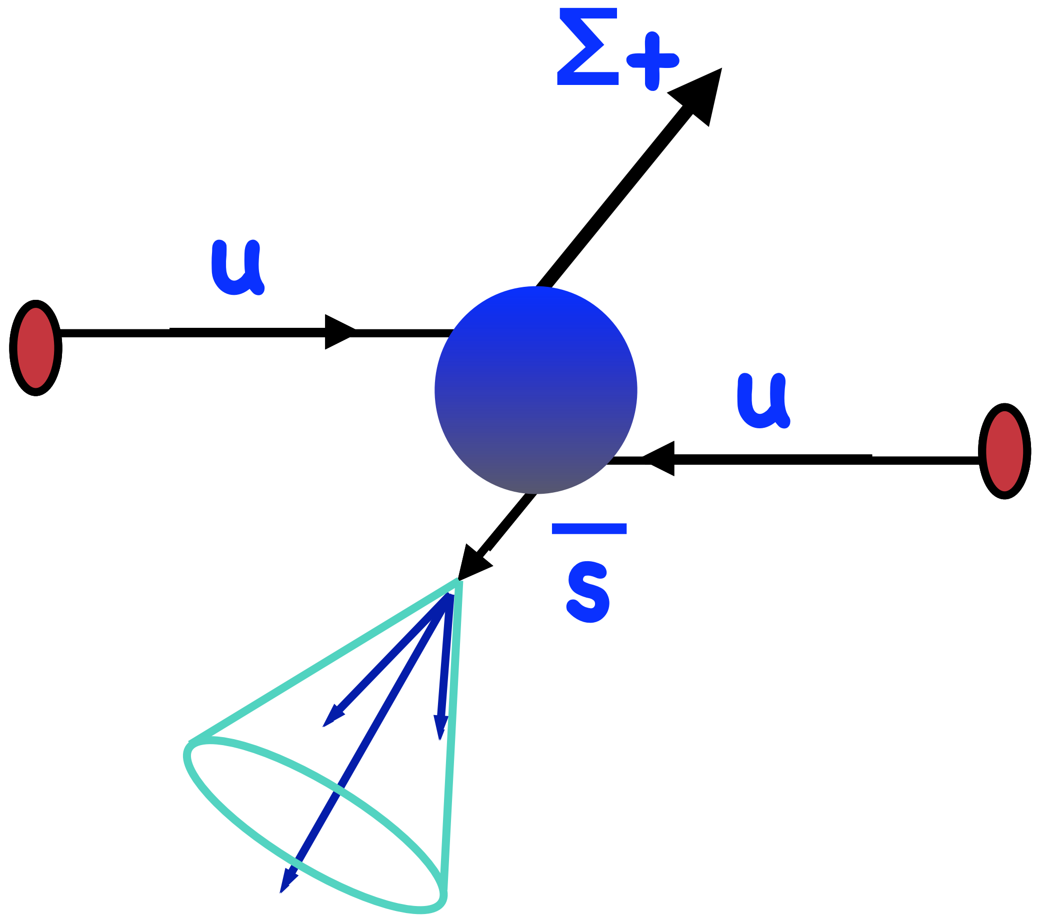
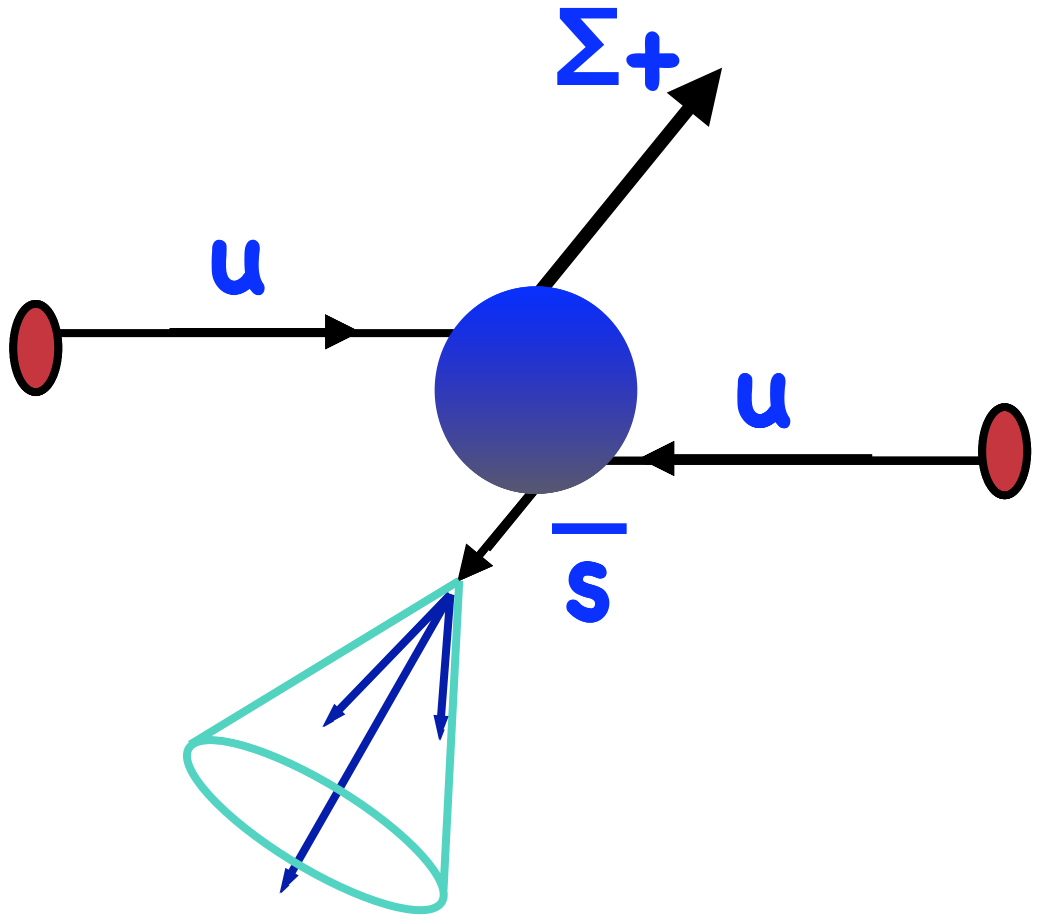


$uu \rightarrow \Sigma^{+}\bar{s}$

Brodsky, AMS
PLB 668 111 (2008)

tests: strangeness



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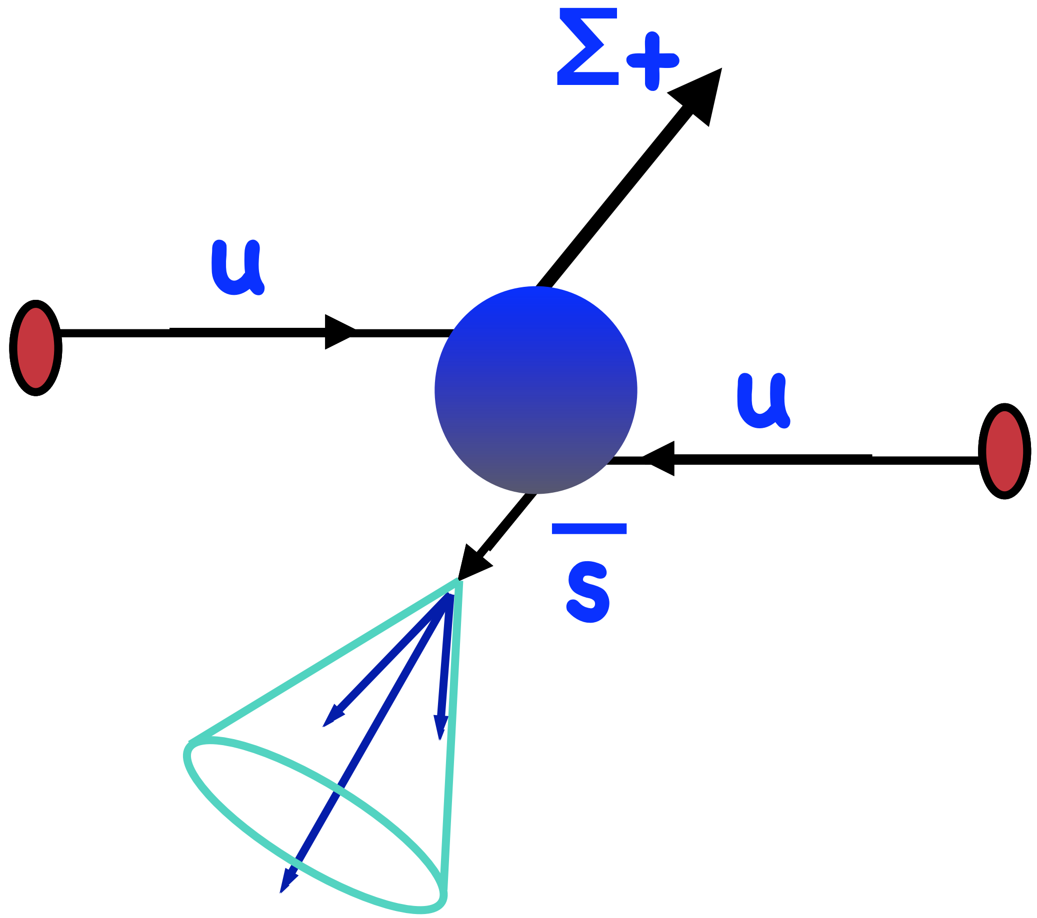
Brodsky, AMS
PLB 668 111 (2008)

- can also make strange baryons: signature balancing strangeness will be on in recoil jet

tests: strangeness



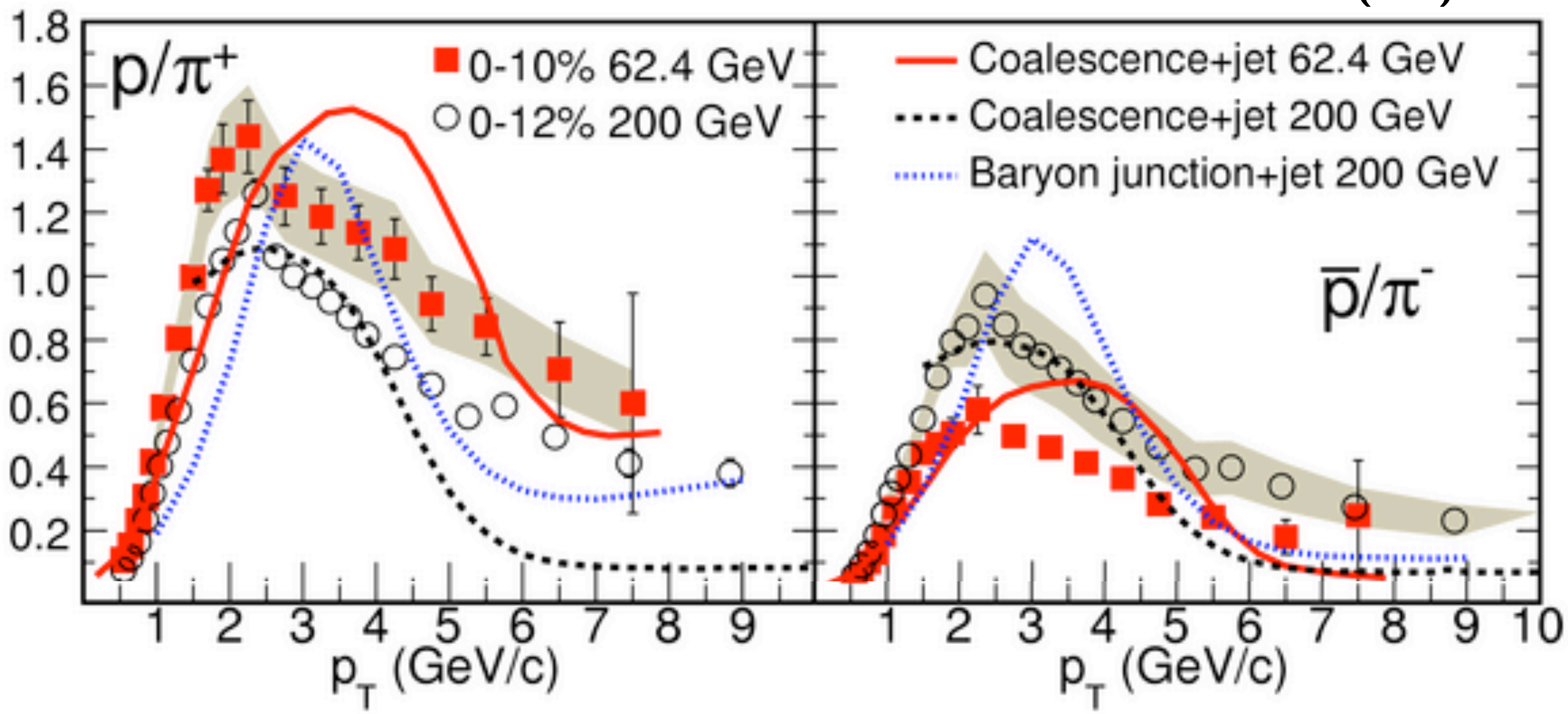
$uu \rightarrow \Sigma^{+}\bar{s}$

Brodsky, AMS
PLB 668 111 (2008)

- can also make strange baryons: signature balancing strangeness will be on in recoil jet
- in contrast, in hard fragmentation picture: balancing strangeness will be close, in same jet

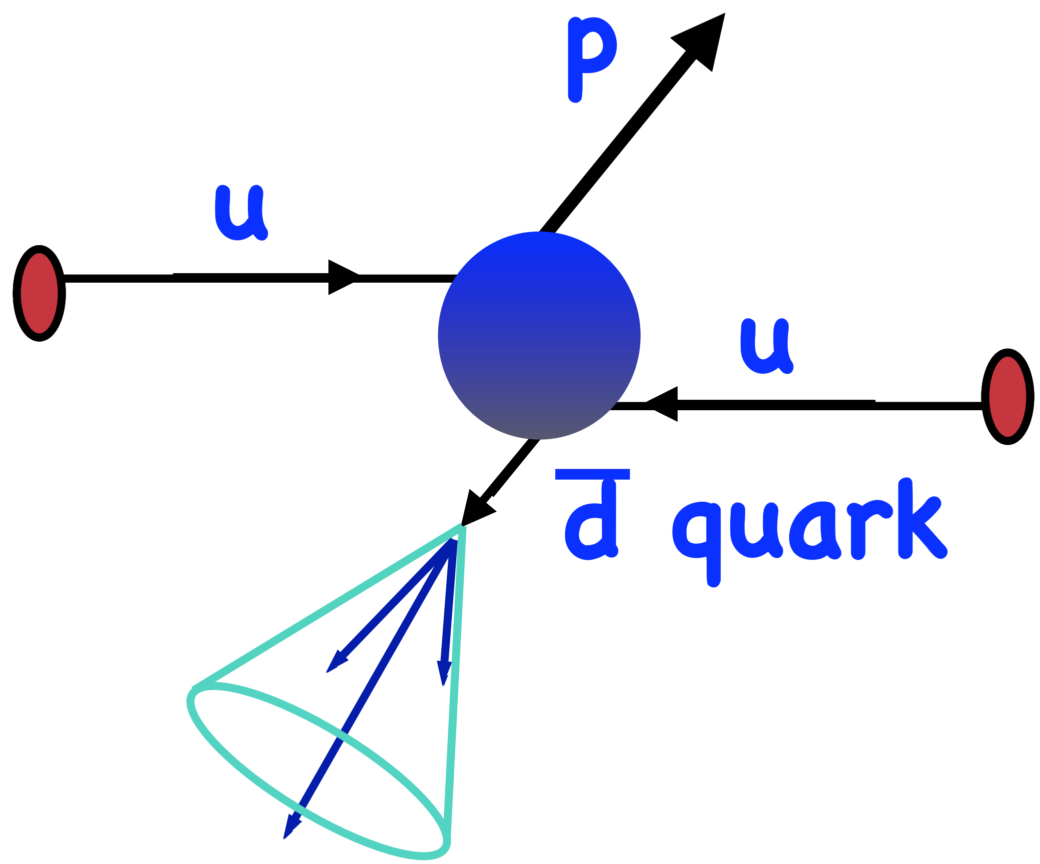
tests: energy dependence

STAR PLB 655 104 (2007)

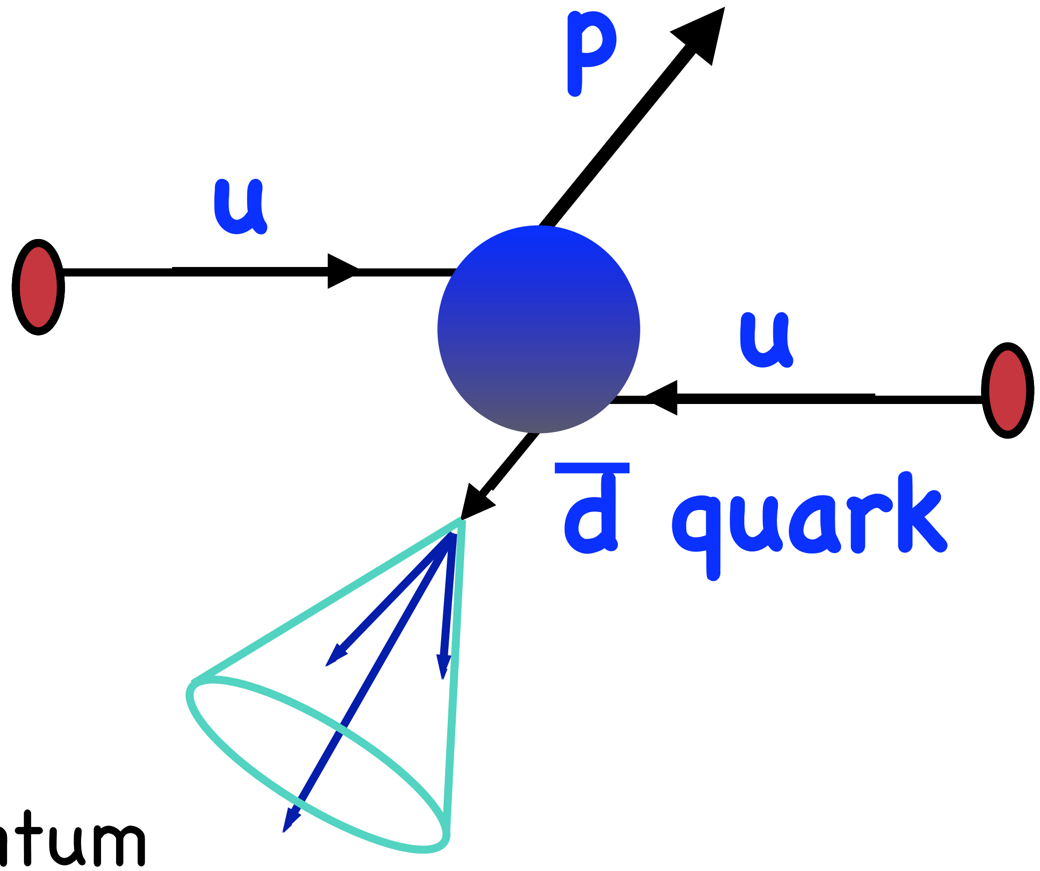


- p/pbar differences increase with decreasing √s
- p/pbar triggered correlations (separately) can help determine direct component if incoming nucleus probed in valence region

tests: jet-proton correlations

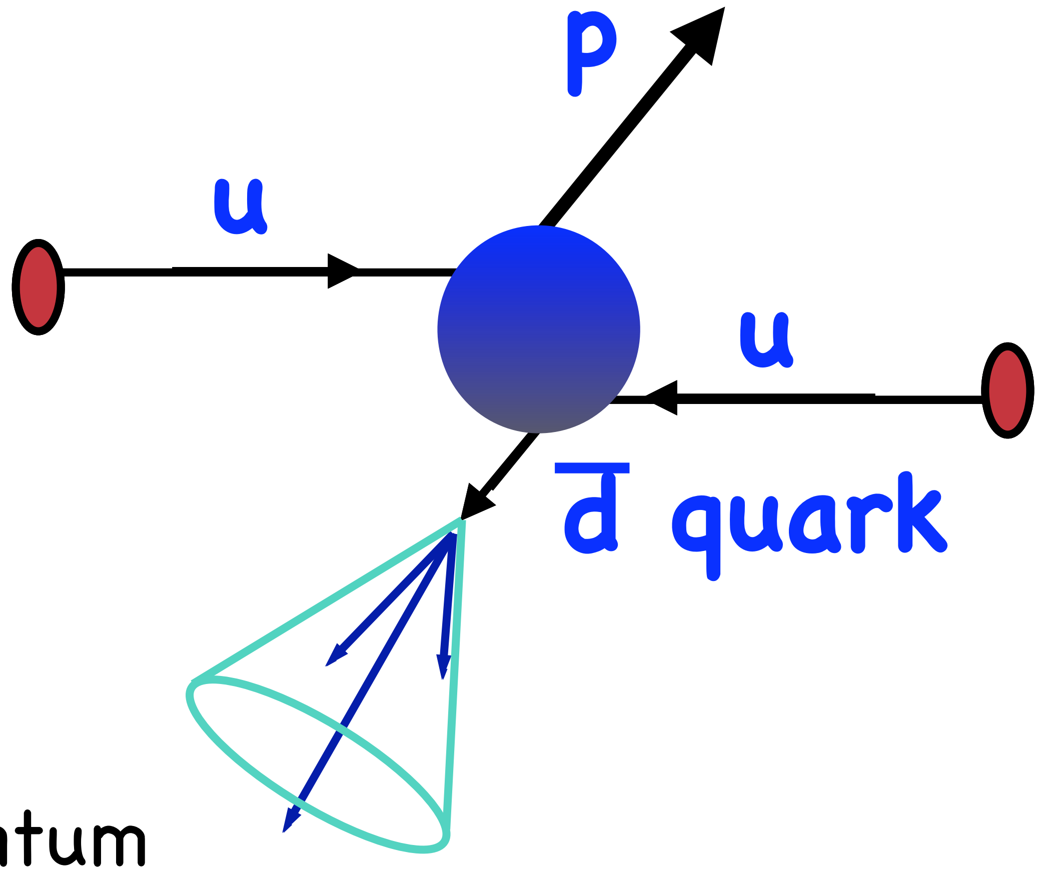


tests: jet-proton correlations



- jet balances proton momentum

tests: jet-proton correlations



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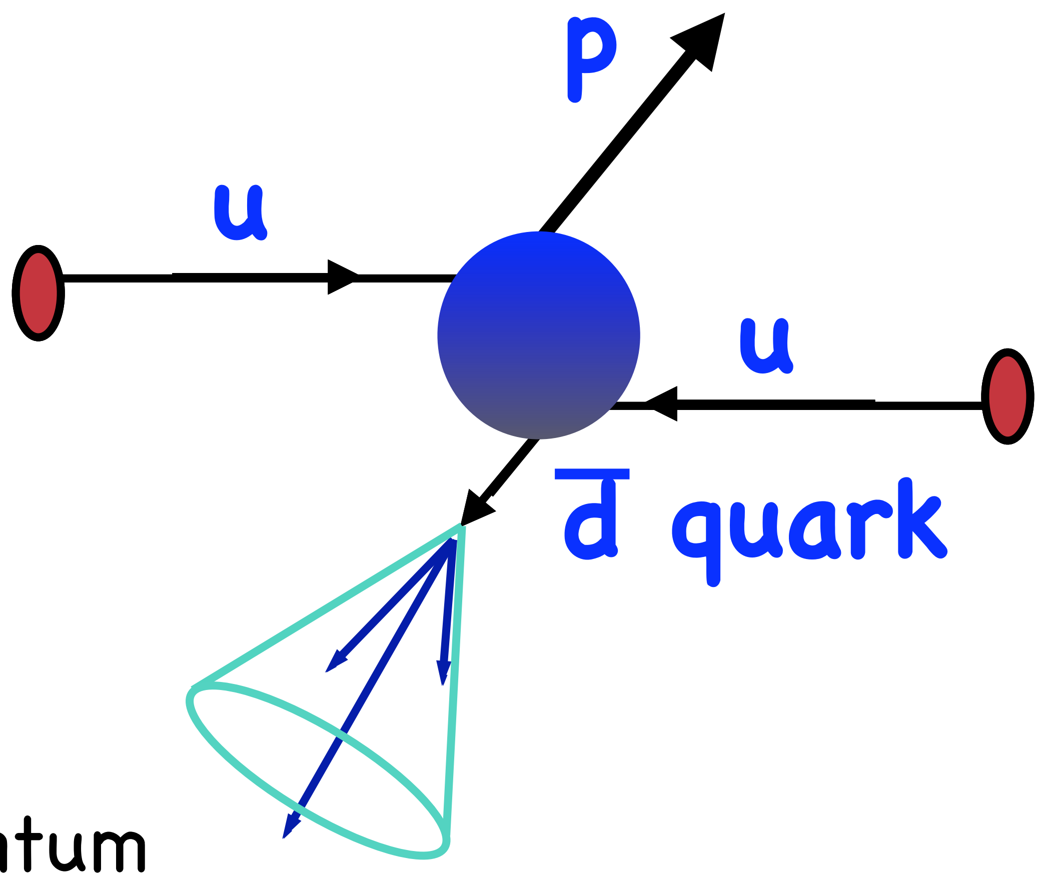
tests: jet-proton correlations



- jet balances proton momentum
- measure $z = p_{T,proton}/p_{T,jet}$
  - expect excess high z protons in heavy ion collisions compared to p+p

higher twist in π production

- this mechanism can also occur for meson production:
  - e.g. ug->πu
- proton production via higher twist expected to be more important because of the suppression of baryon production in fragmentation
- suppressed with large p_T and $\sqrt{s}$

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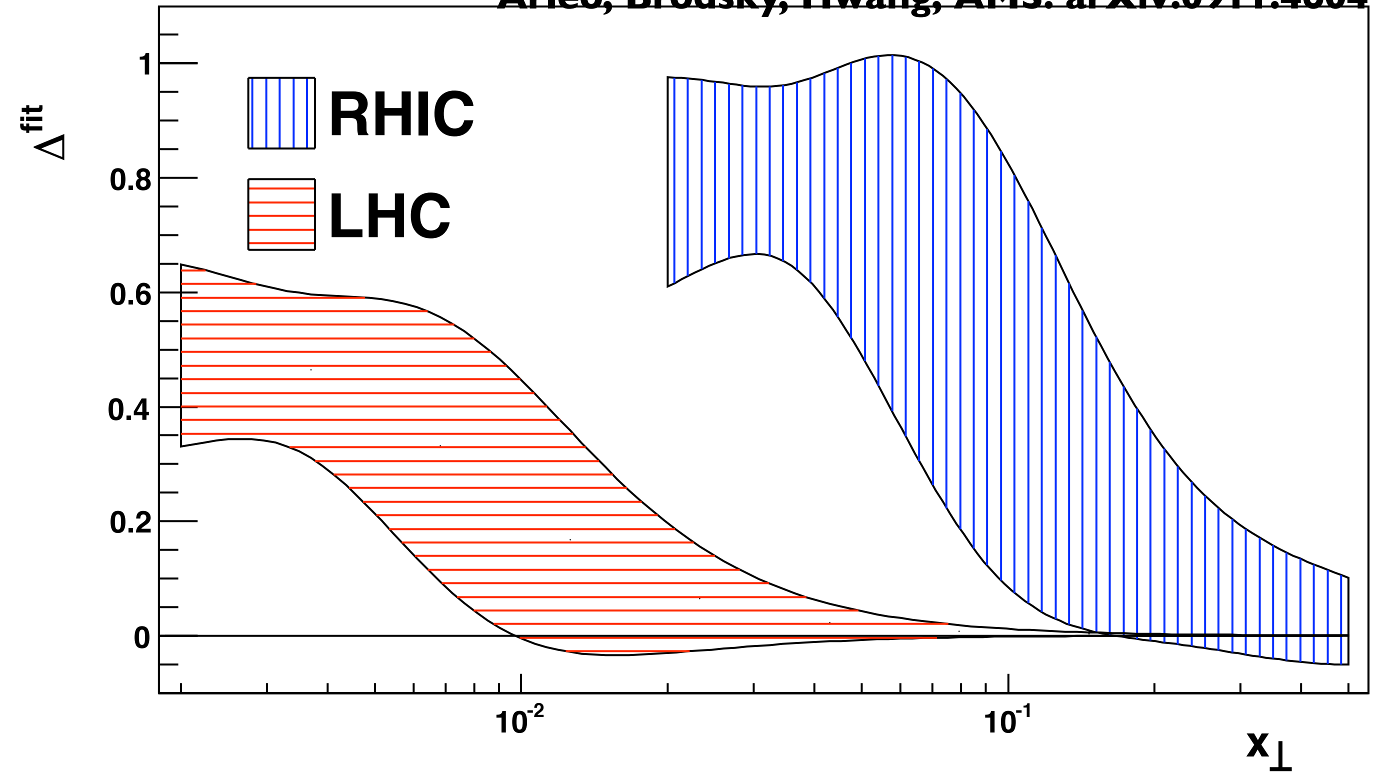
RHIC: 500GeV/200GeV
LHC: 7TeV/1.8TeV

Arleo, Brodsky, Hwang, AMS: arXiv:0911.4604



Anne M. Sickles, February 14, 2010

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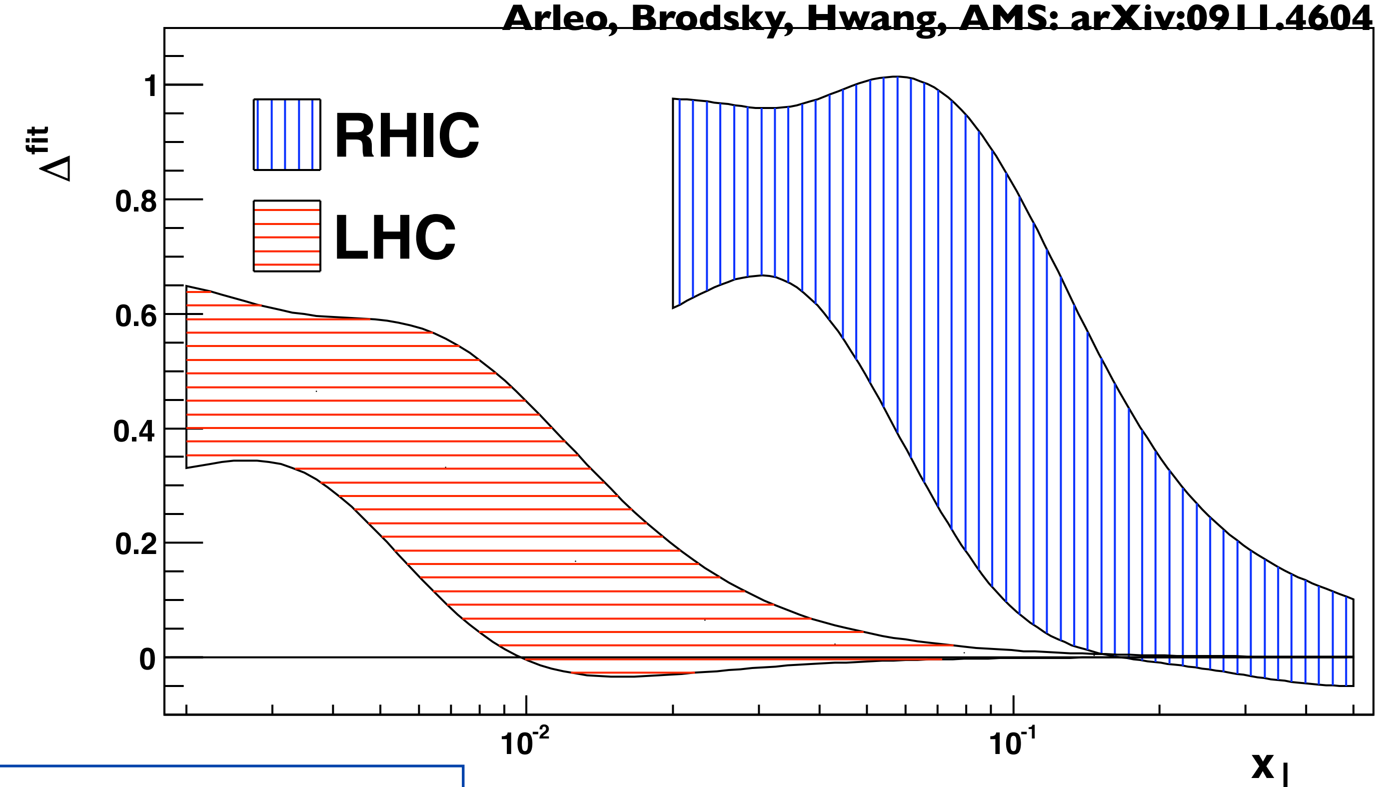

RHIC data exist: see A. Bazilevsky Sesson X11

baryons at RHIC

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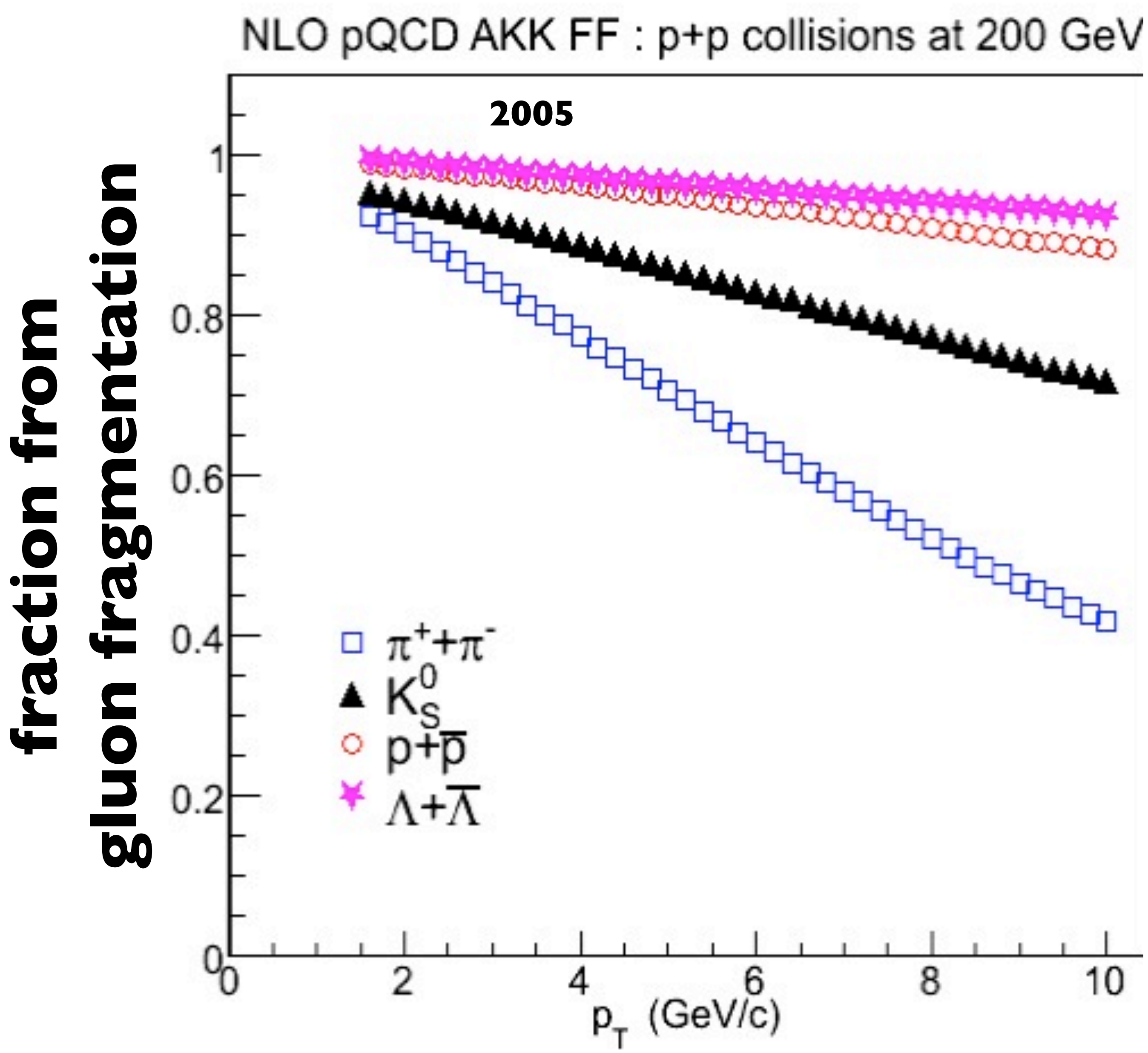
  - strong motivation for RHIC energy scan at moderate center of mass (40-200GeV) p+p & heavy ions
    - higher twist effects should grow at lower collision energies

Anne M. Sickles, February 14, 2010

uncertainties in proton FF



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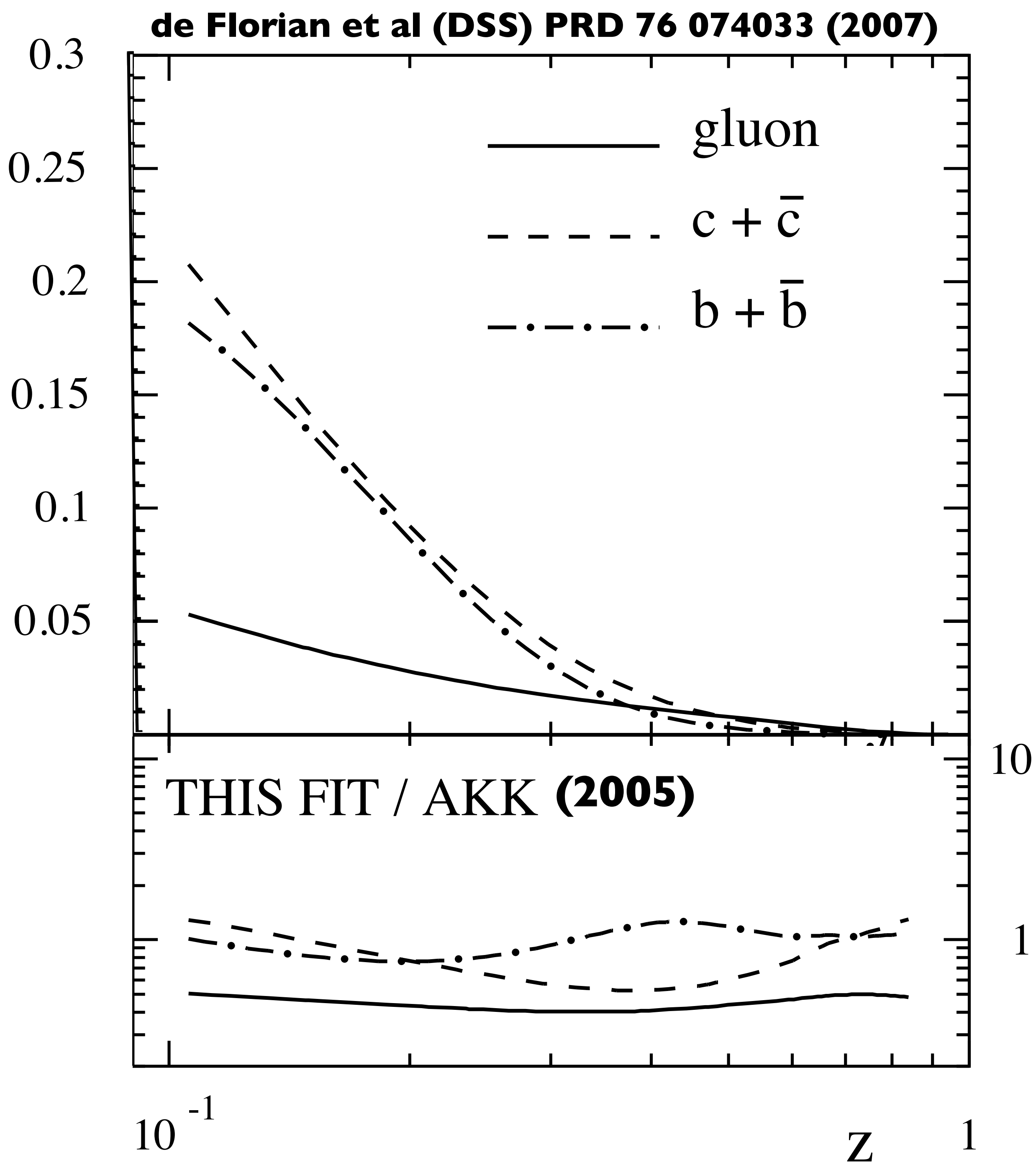

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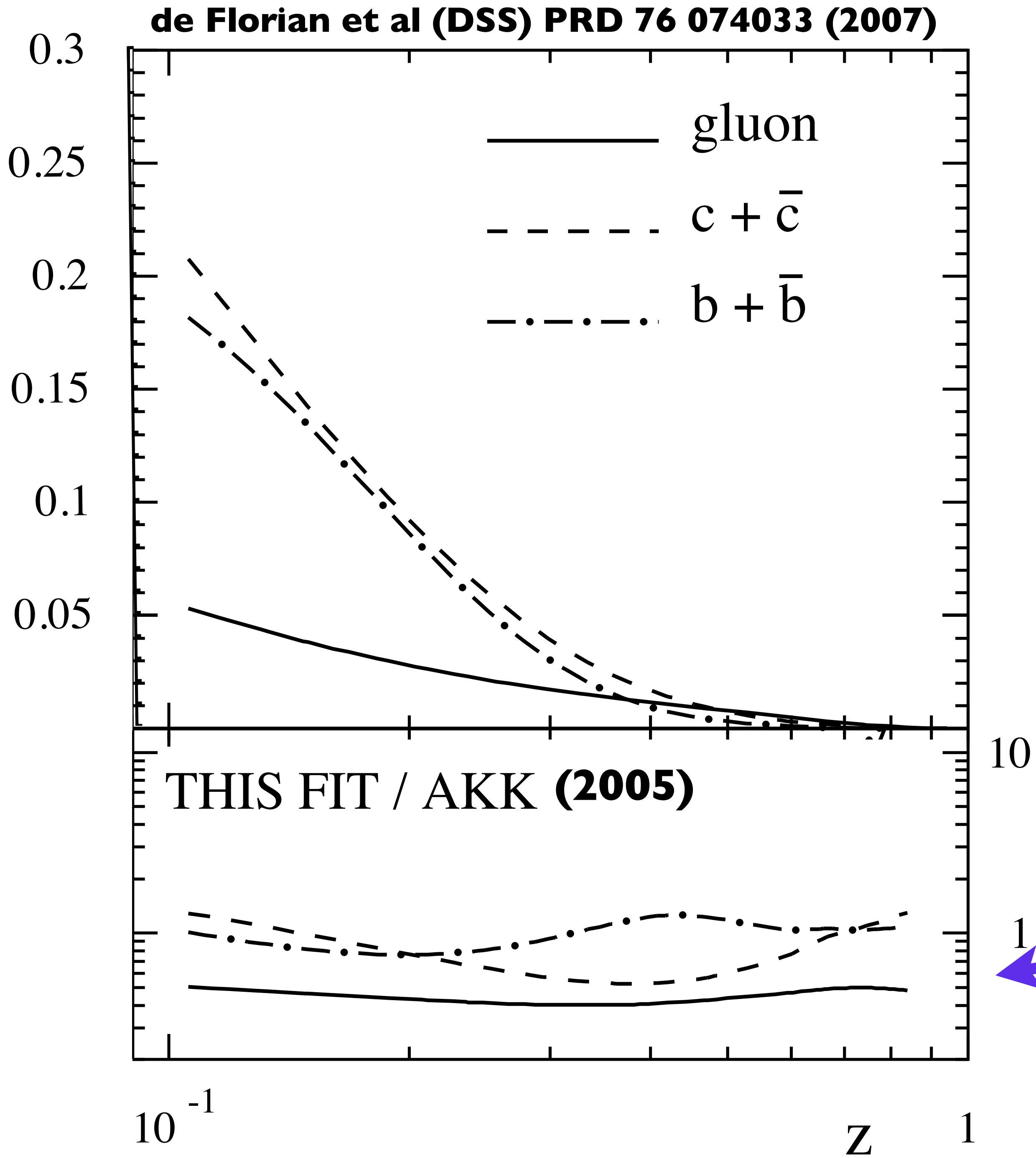

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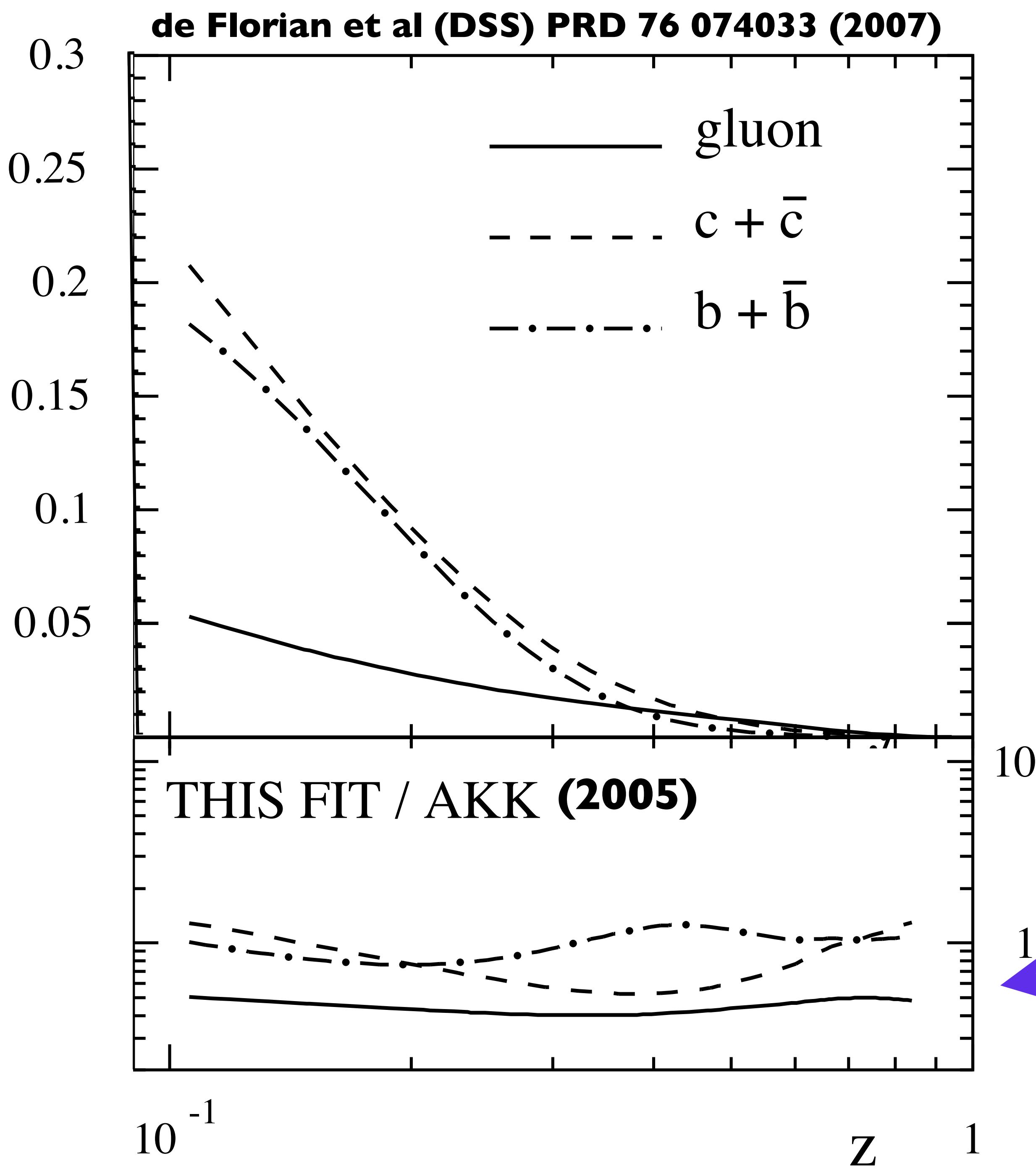

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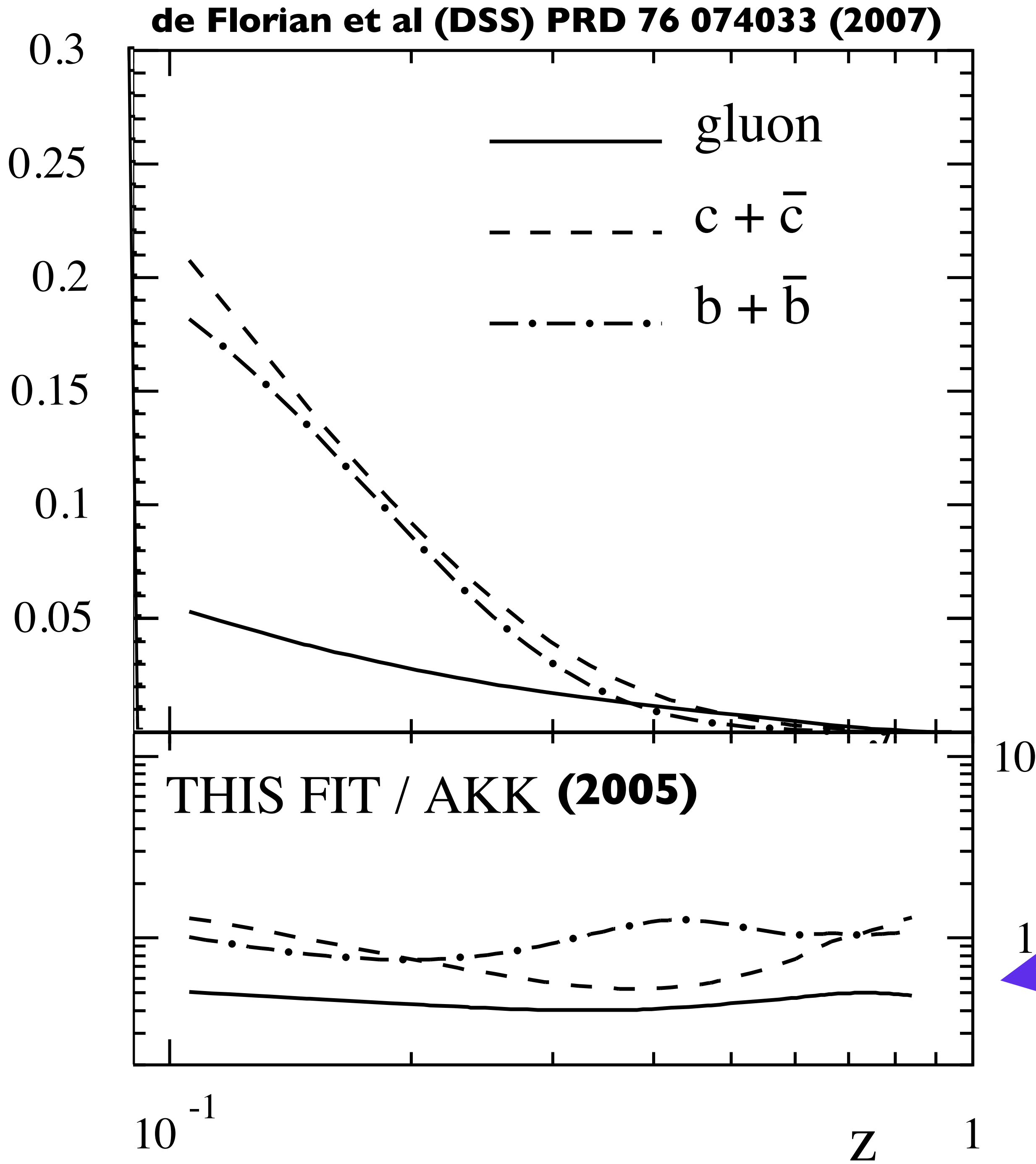

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jet conversions

idea: jet parton scatters on medium parton and changes flavor

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

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Ko et al. PRC 75 051901 (2007)
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parton R_{AA}

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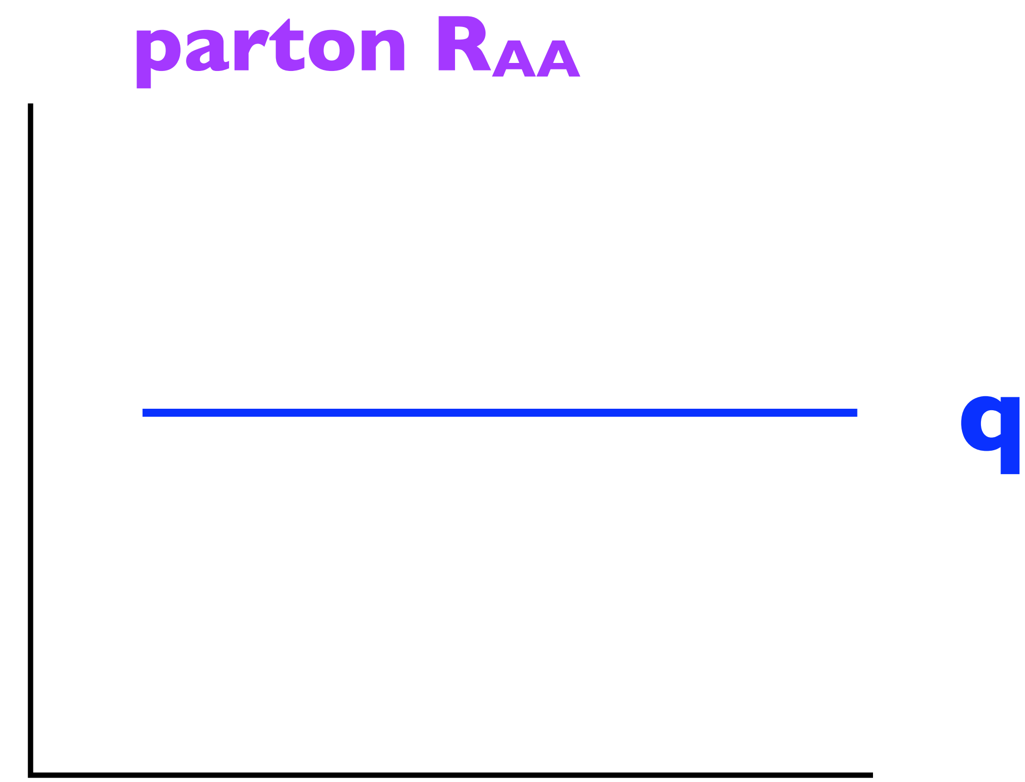

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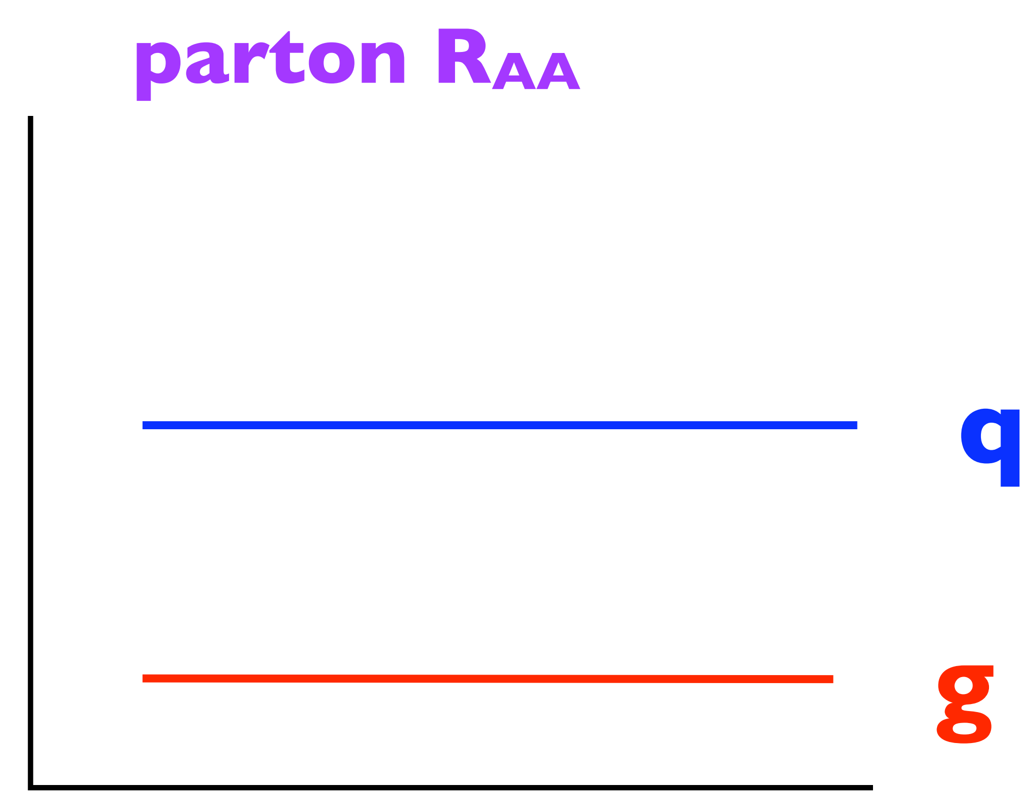

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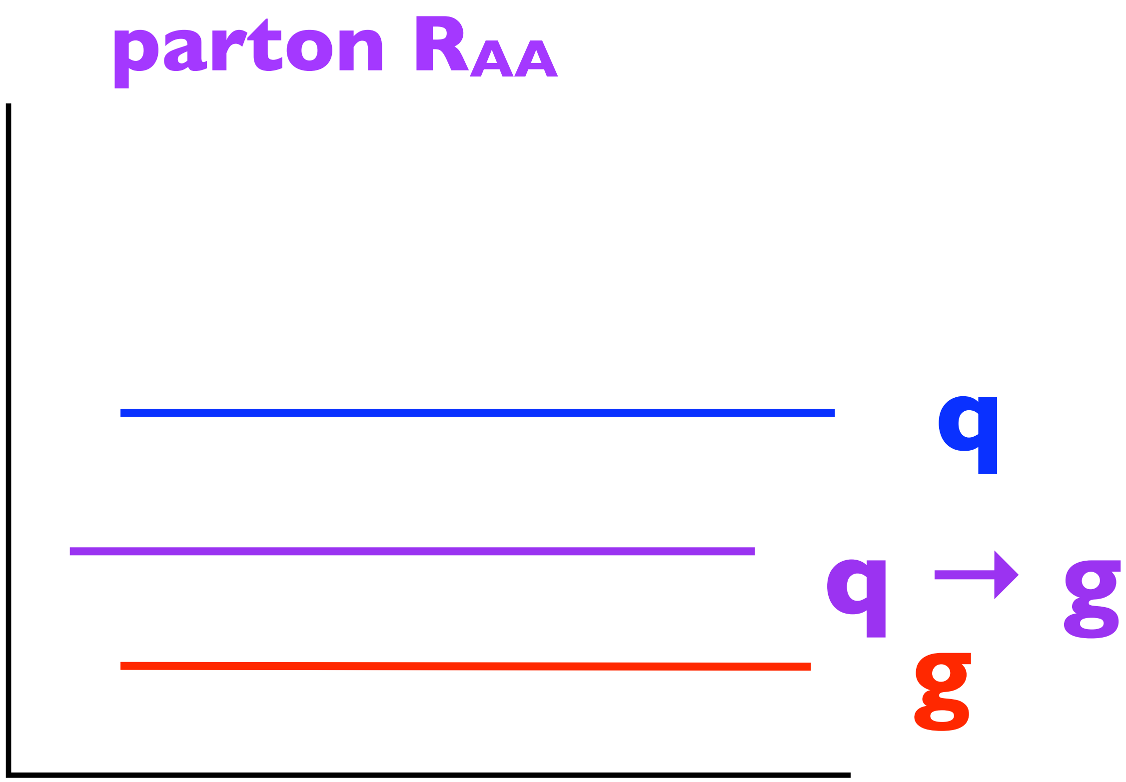

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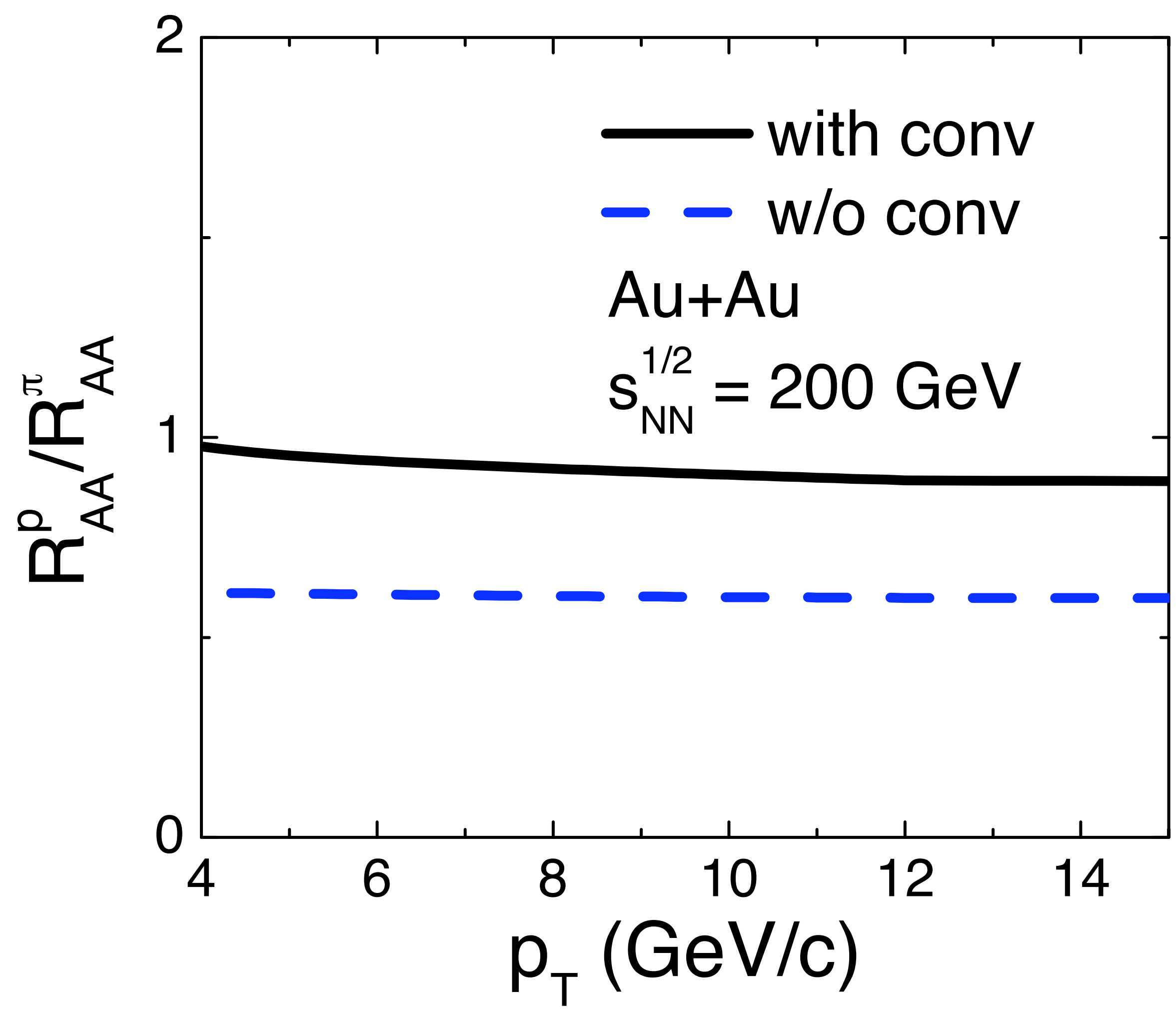

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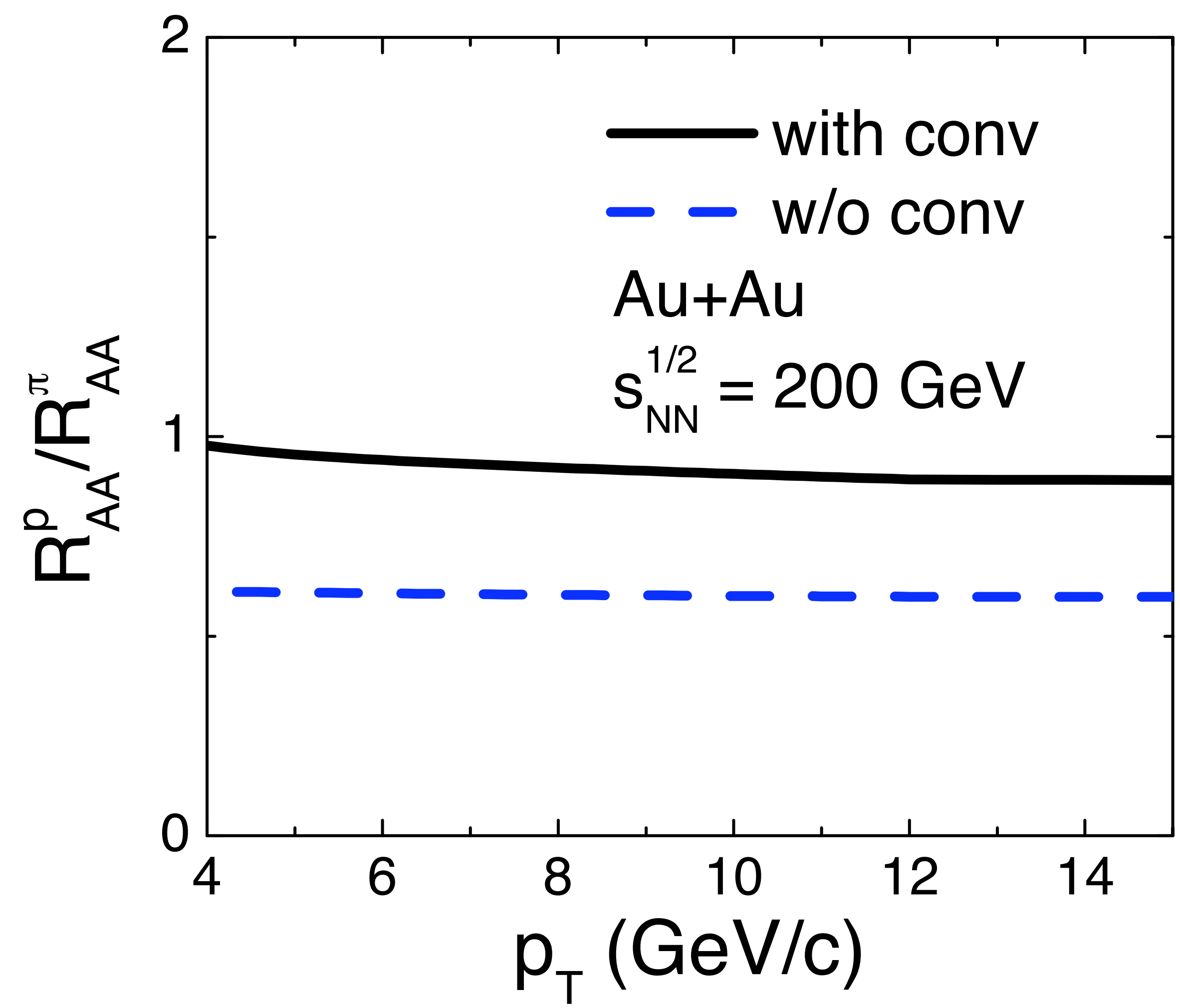

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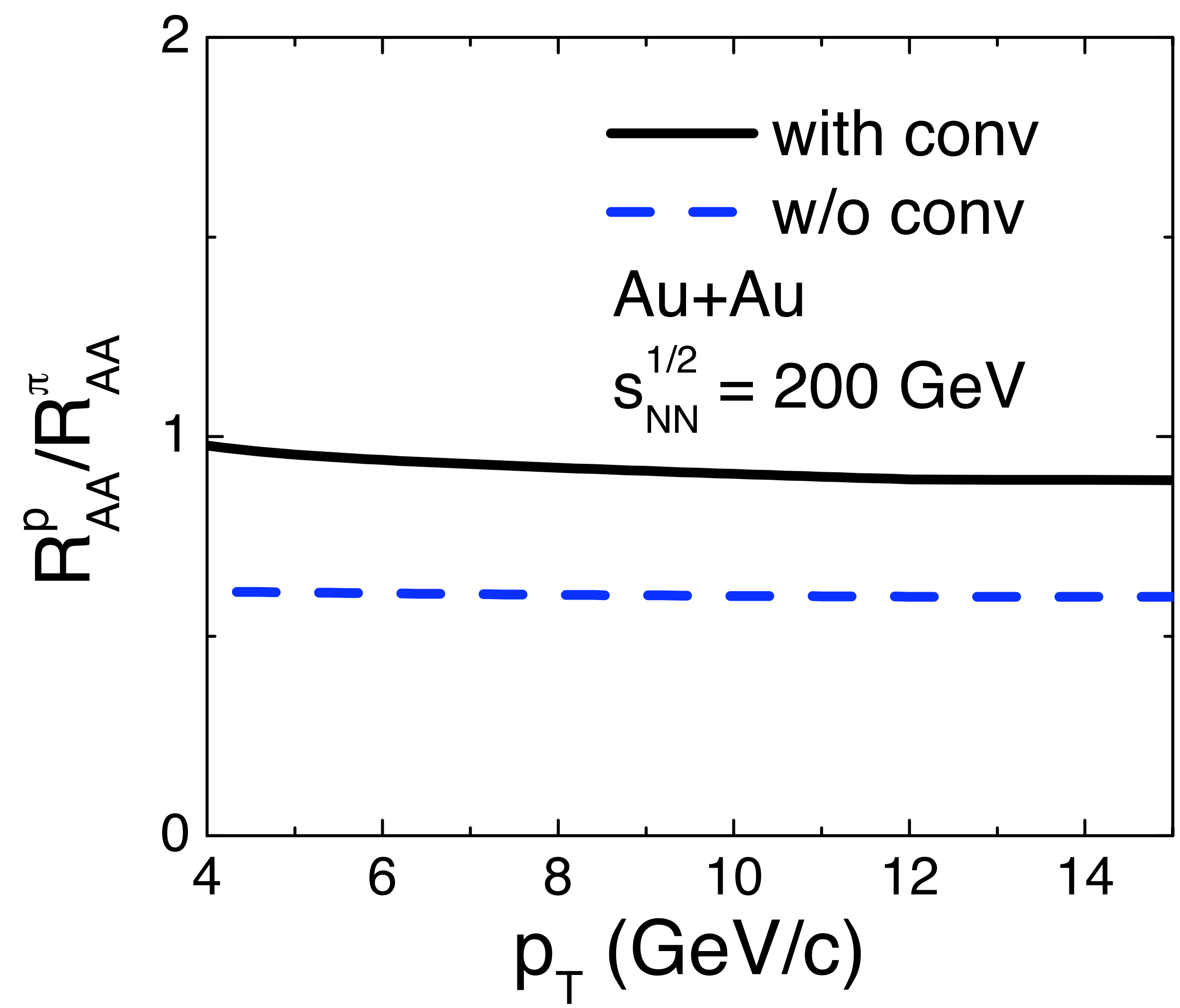

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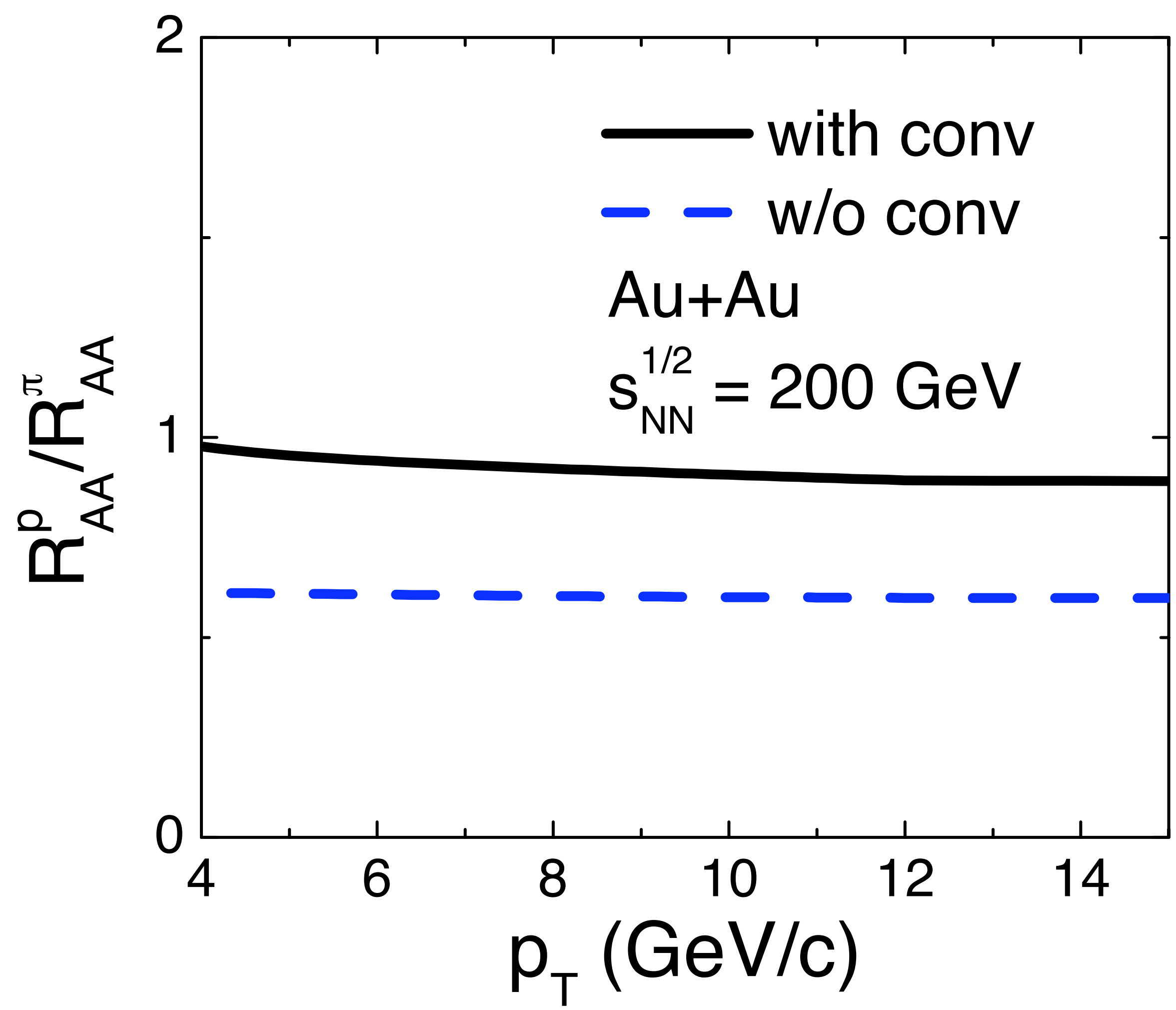

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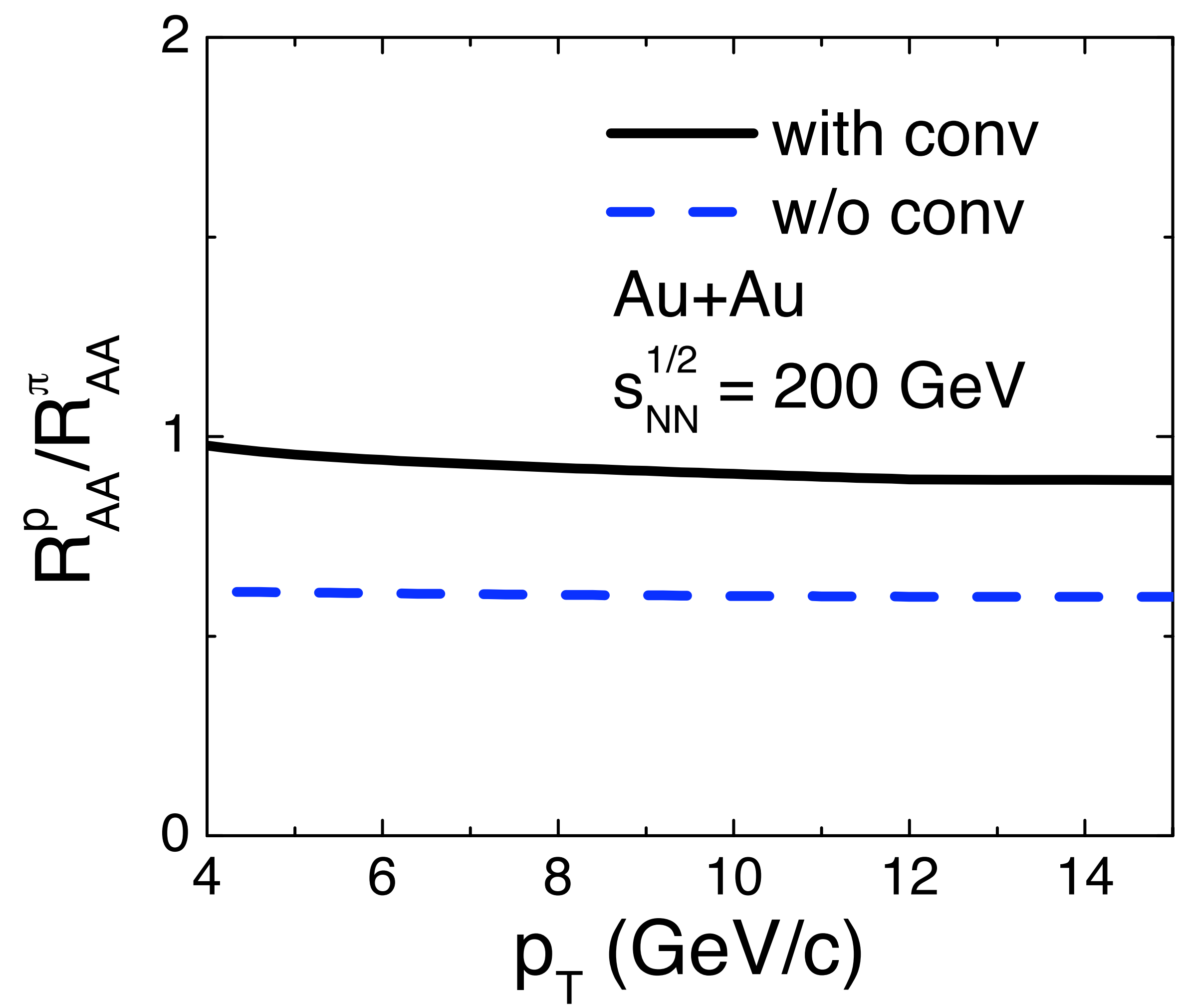

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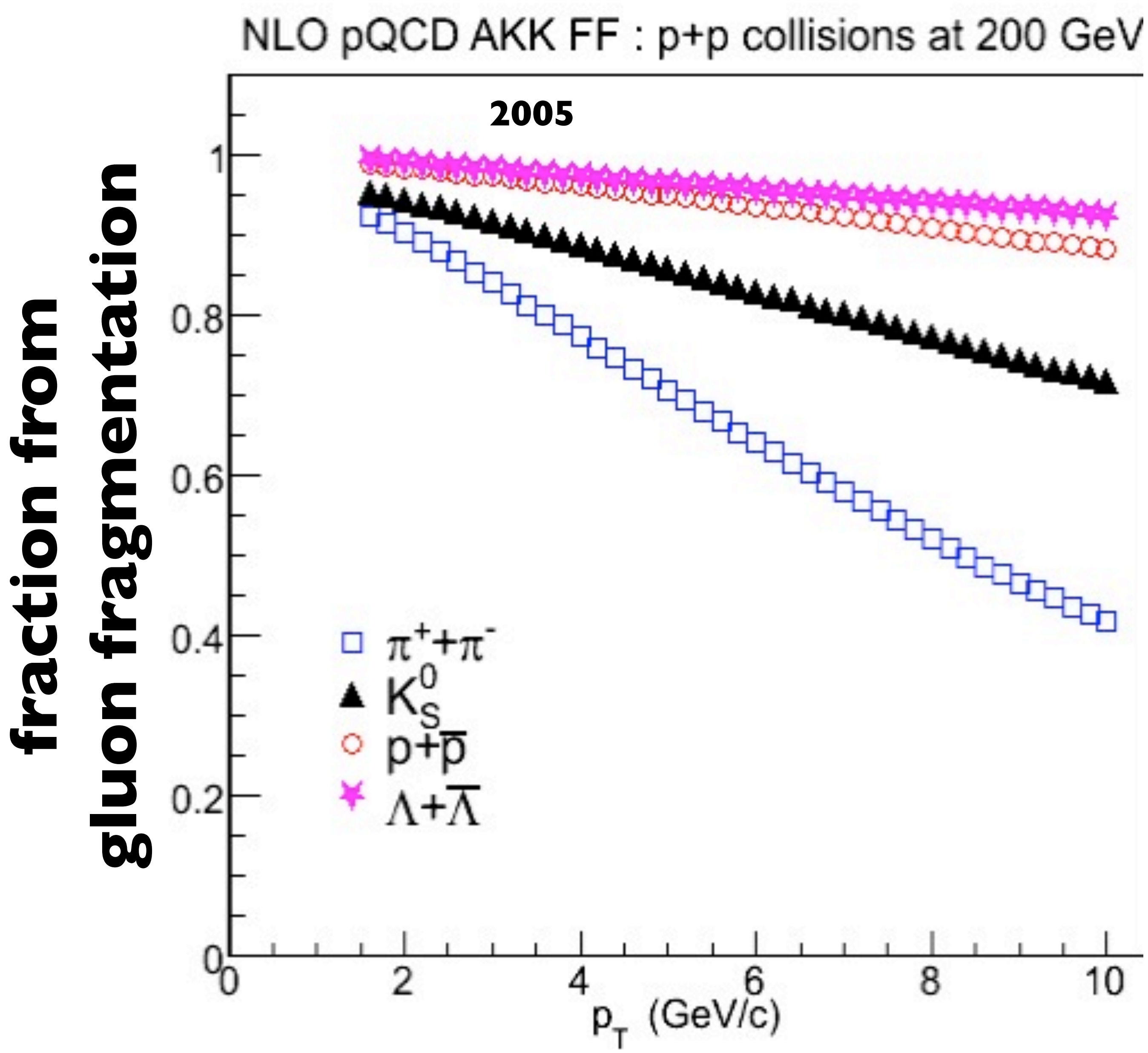

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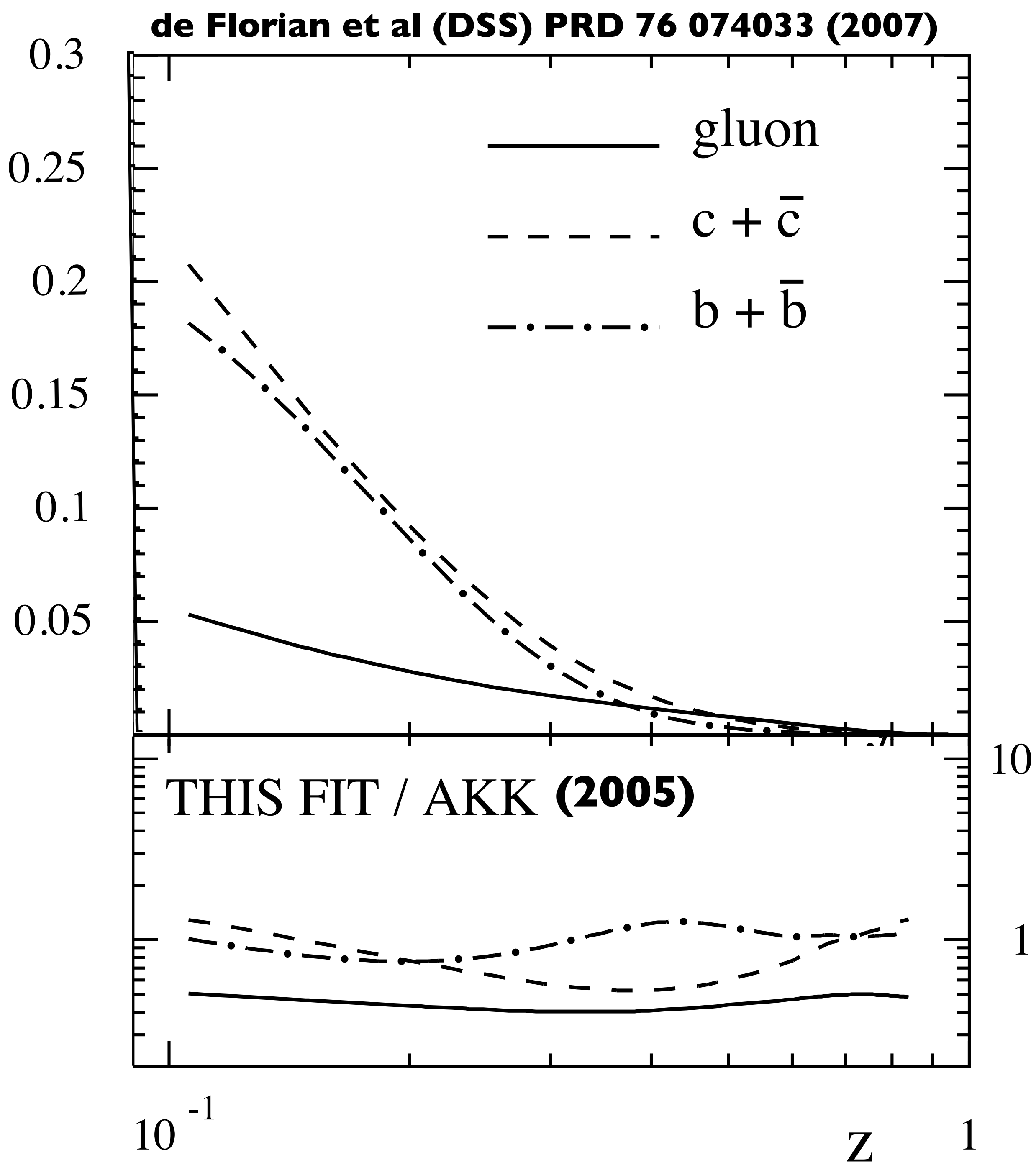

Anne M. Sickles, February 14, 2010

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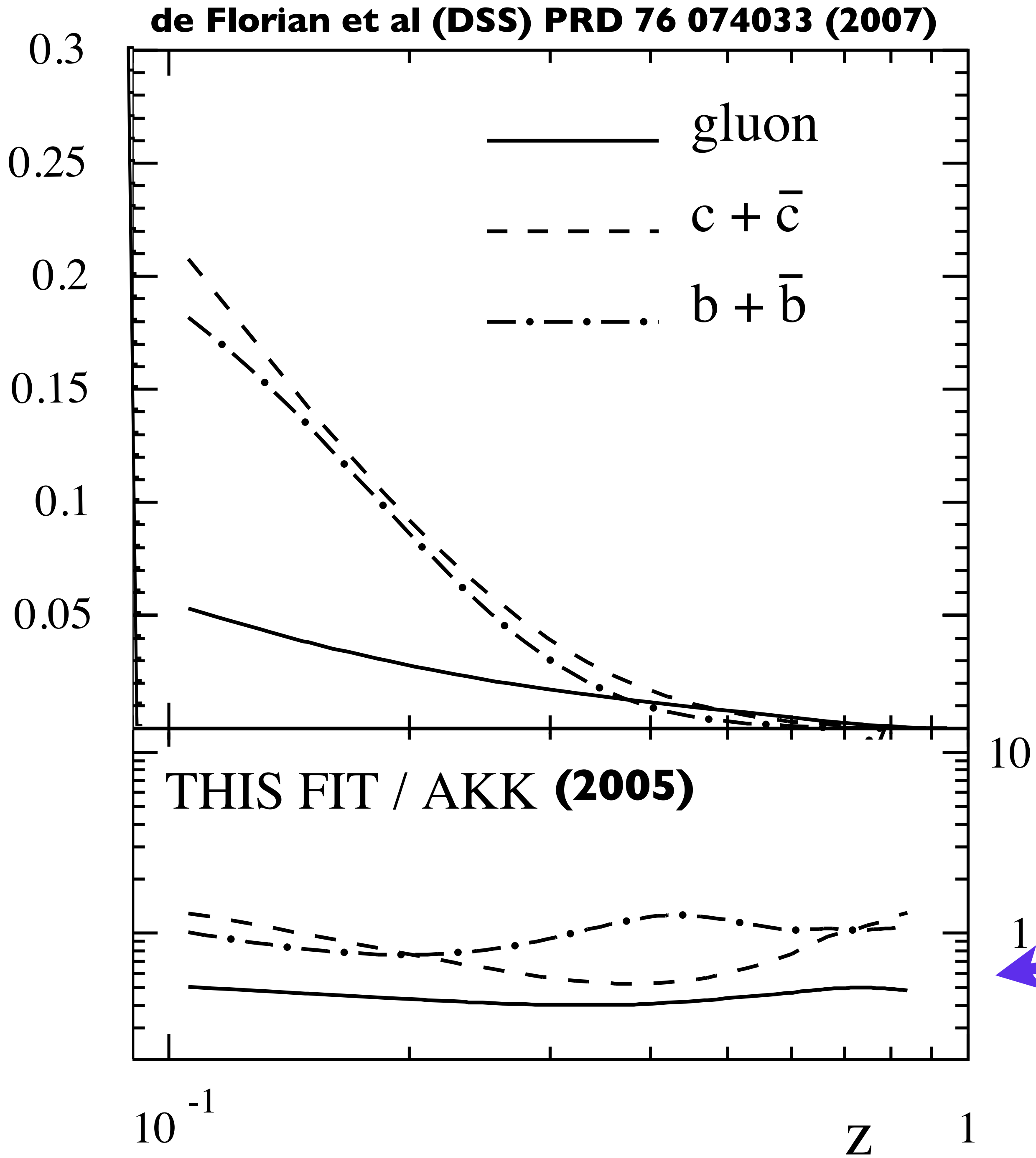

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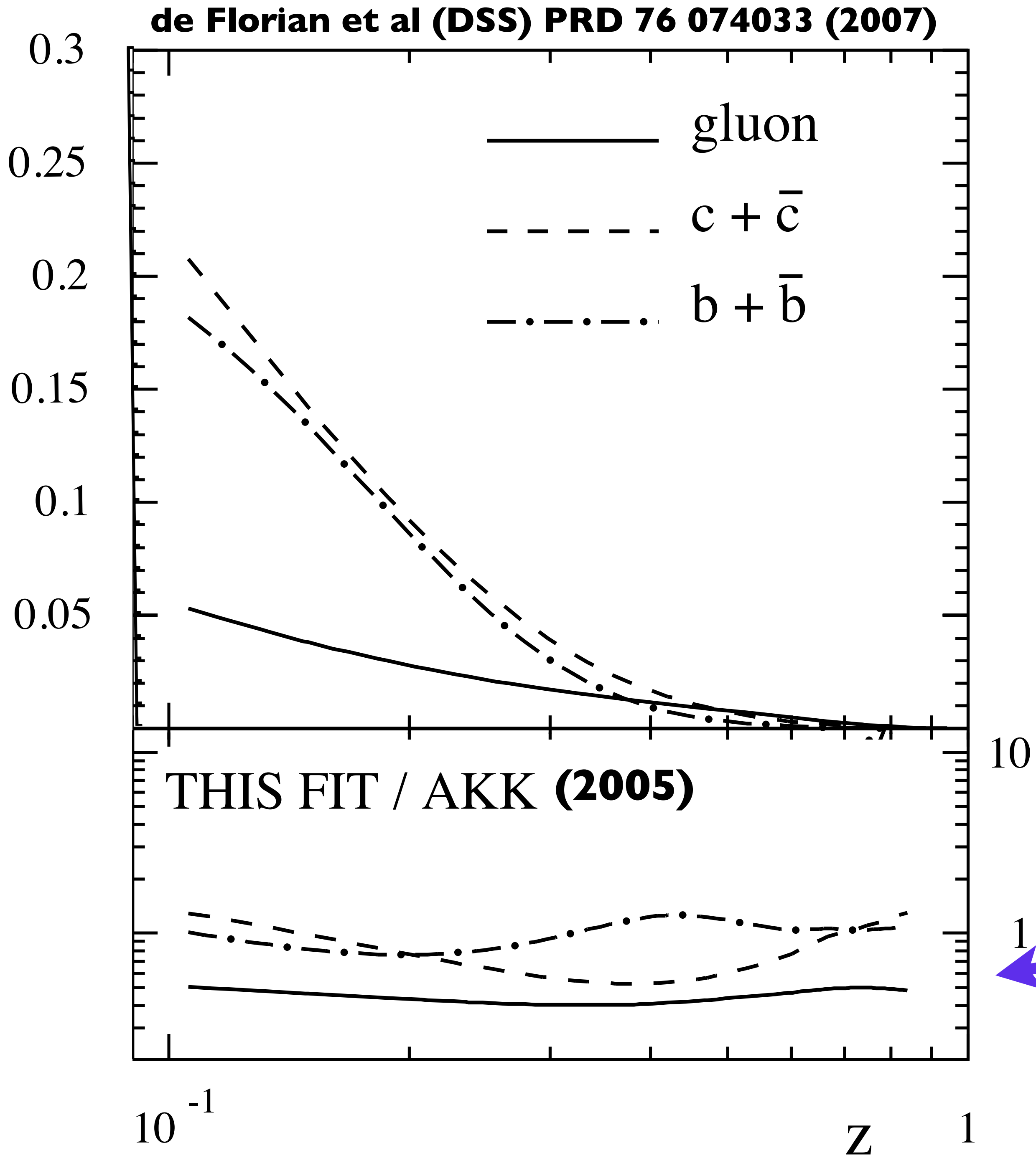

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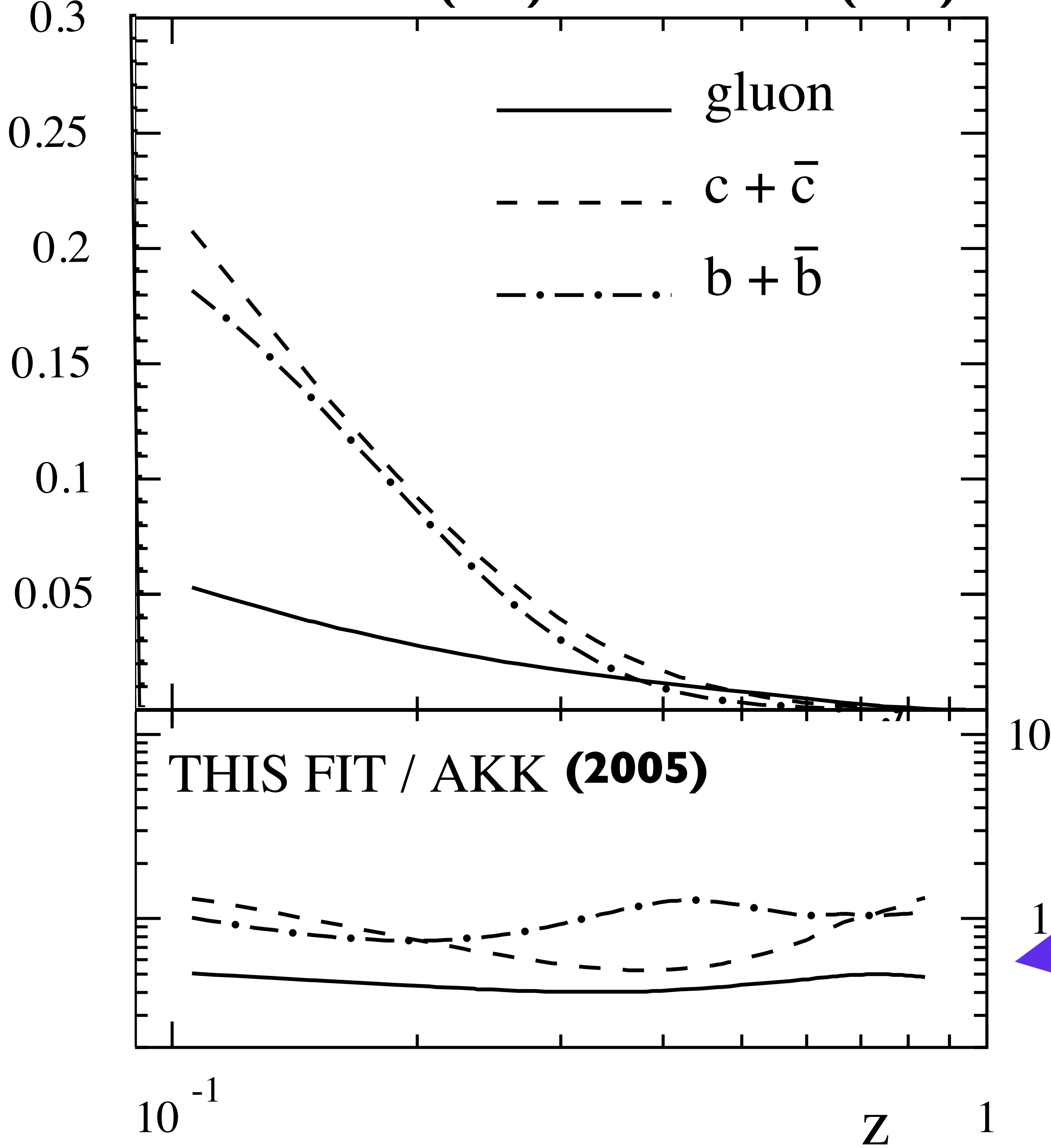
de Florian et al (DSS) PRD 76 074033 (2007)



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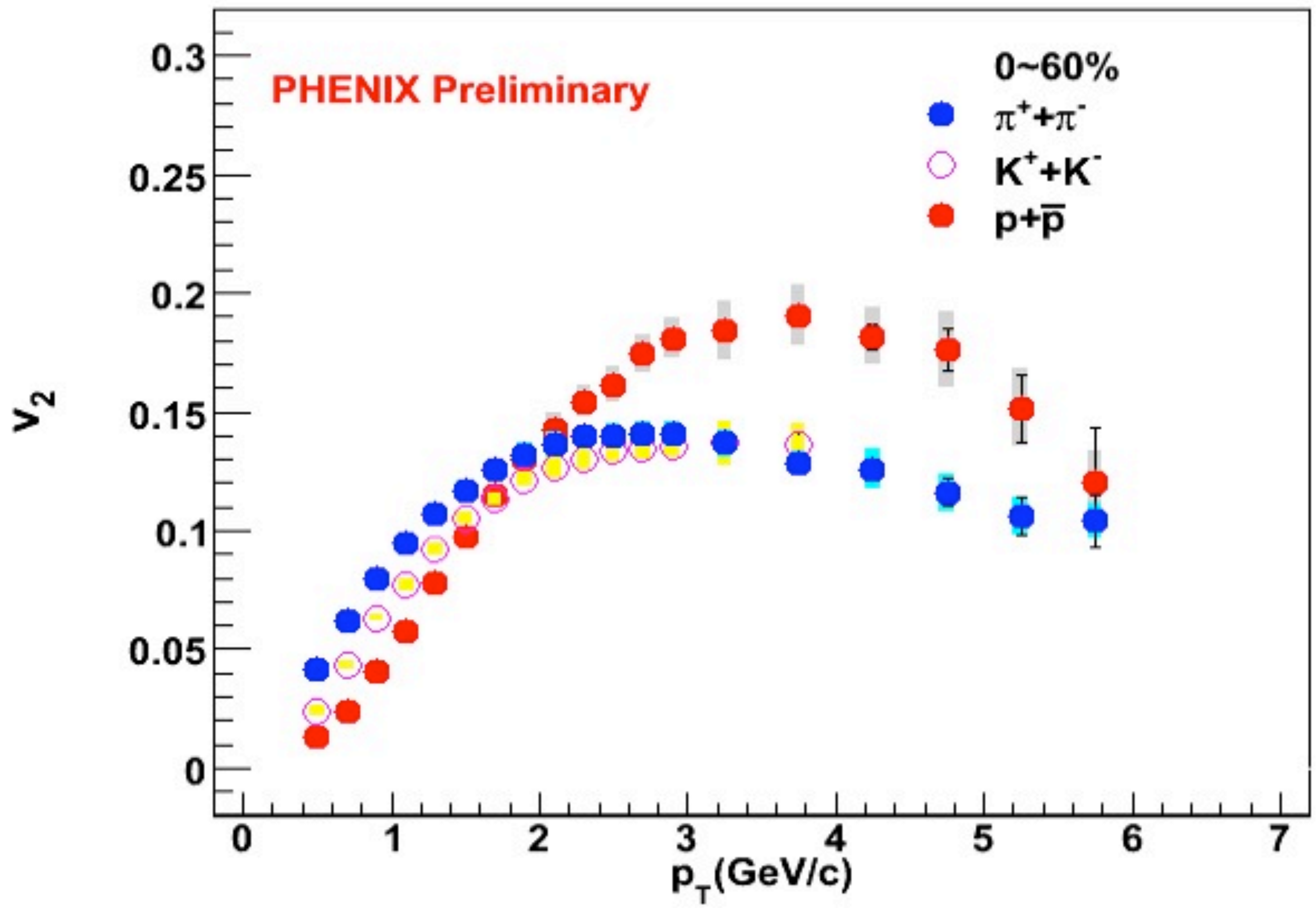
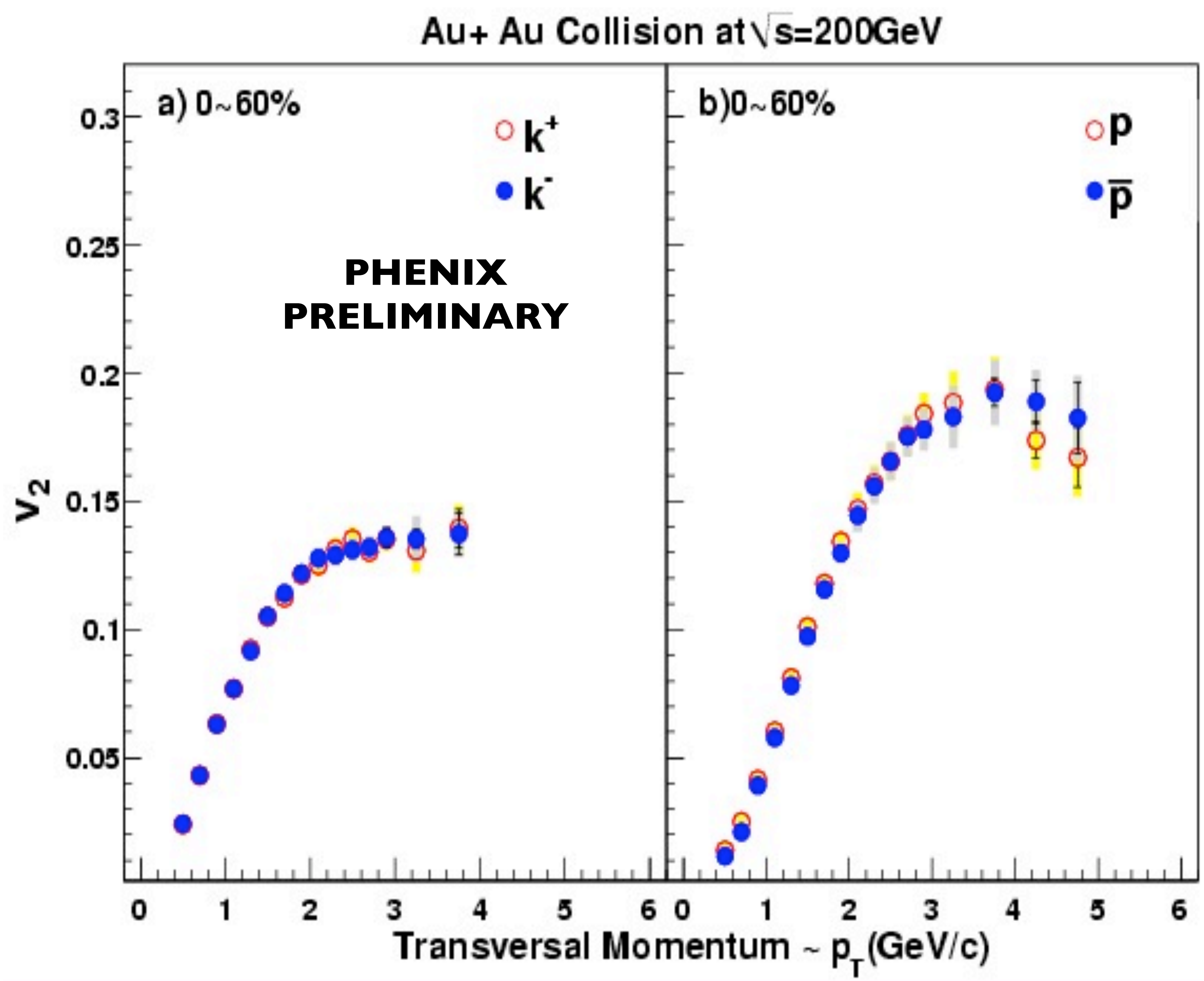


- decreasing proton v2? increasing direct component?

baryon/anti-baryon ratio



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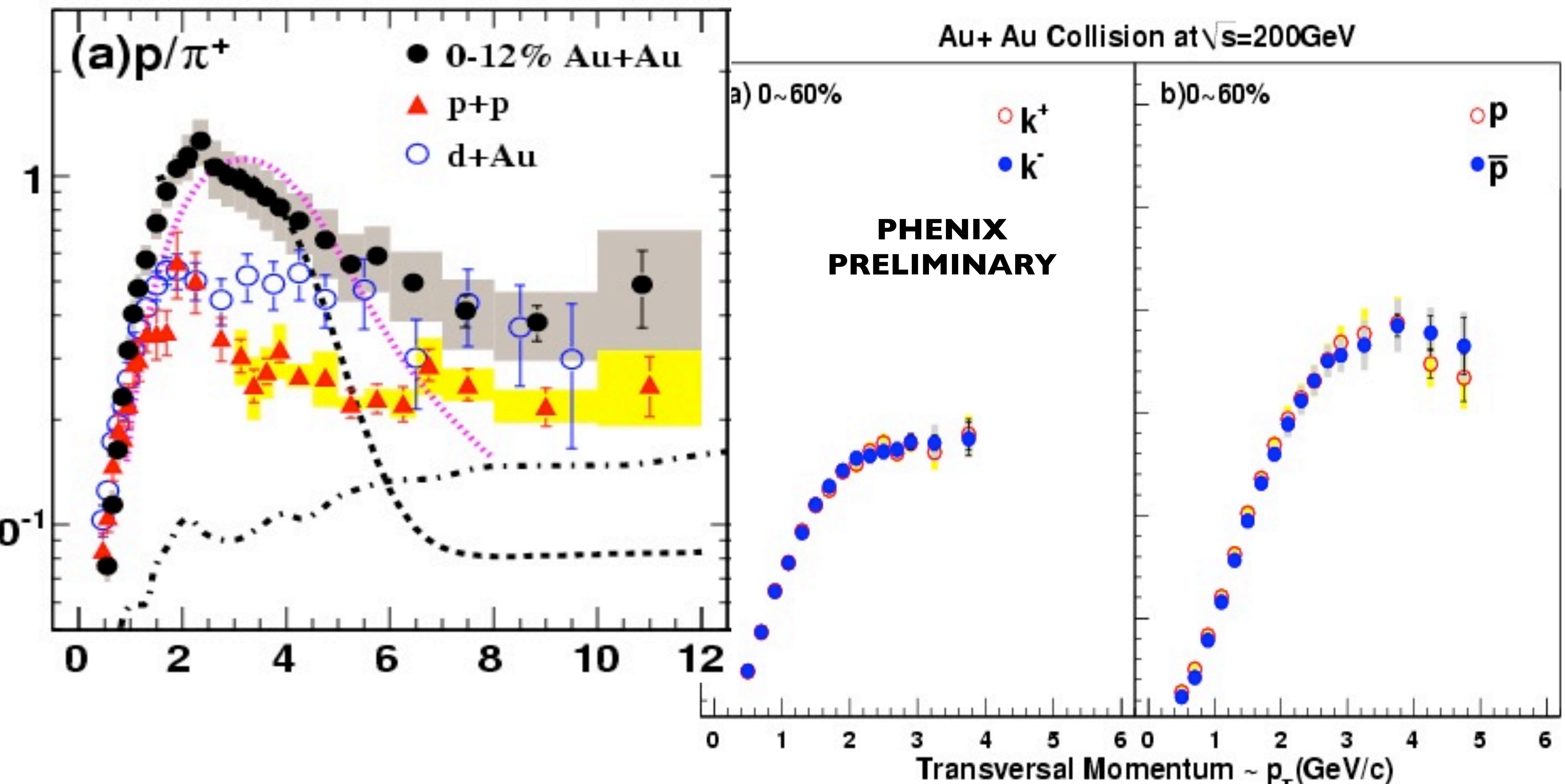
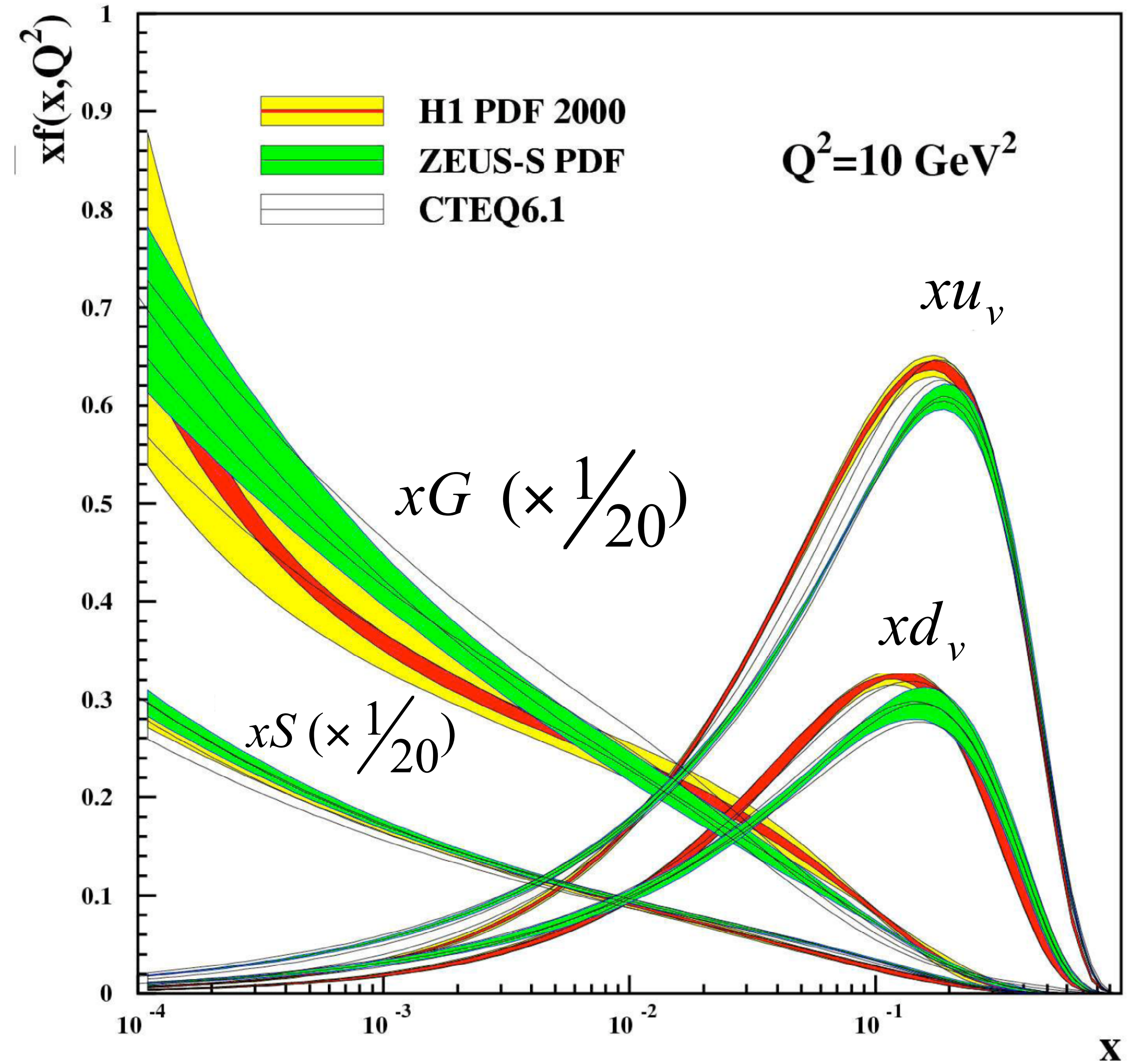
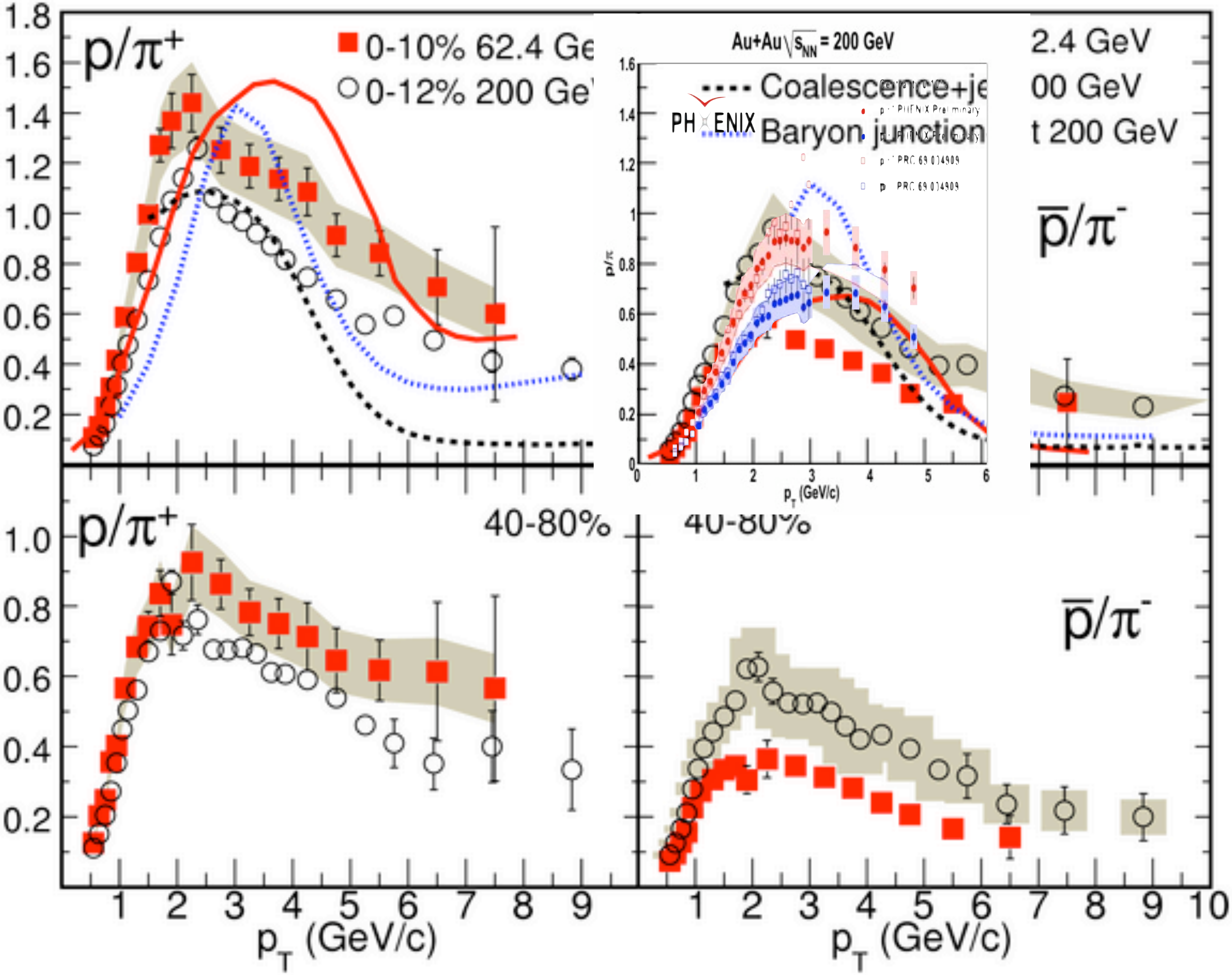



xf(x,Q²)
H1 PDF 2000
ZEUS-S PDF
CTEQ6.1
Q²=10 GeV²
xu_v
xG (×1/20)
xd_v
xS (×1/20)
x


p/π+
0-10% 62.4 Ge
0-12% 200 Ge
2.4 GeV
00 GeV
t 200 GeV
Au+Au √sNN = 200 GeV
Coalescence+je
Baryon junction
PHENIX
p̄/π-
40-80%
40-80%
p/π+
p̄/π-
pT (GeV/c)
pT (GeV/c)
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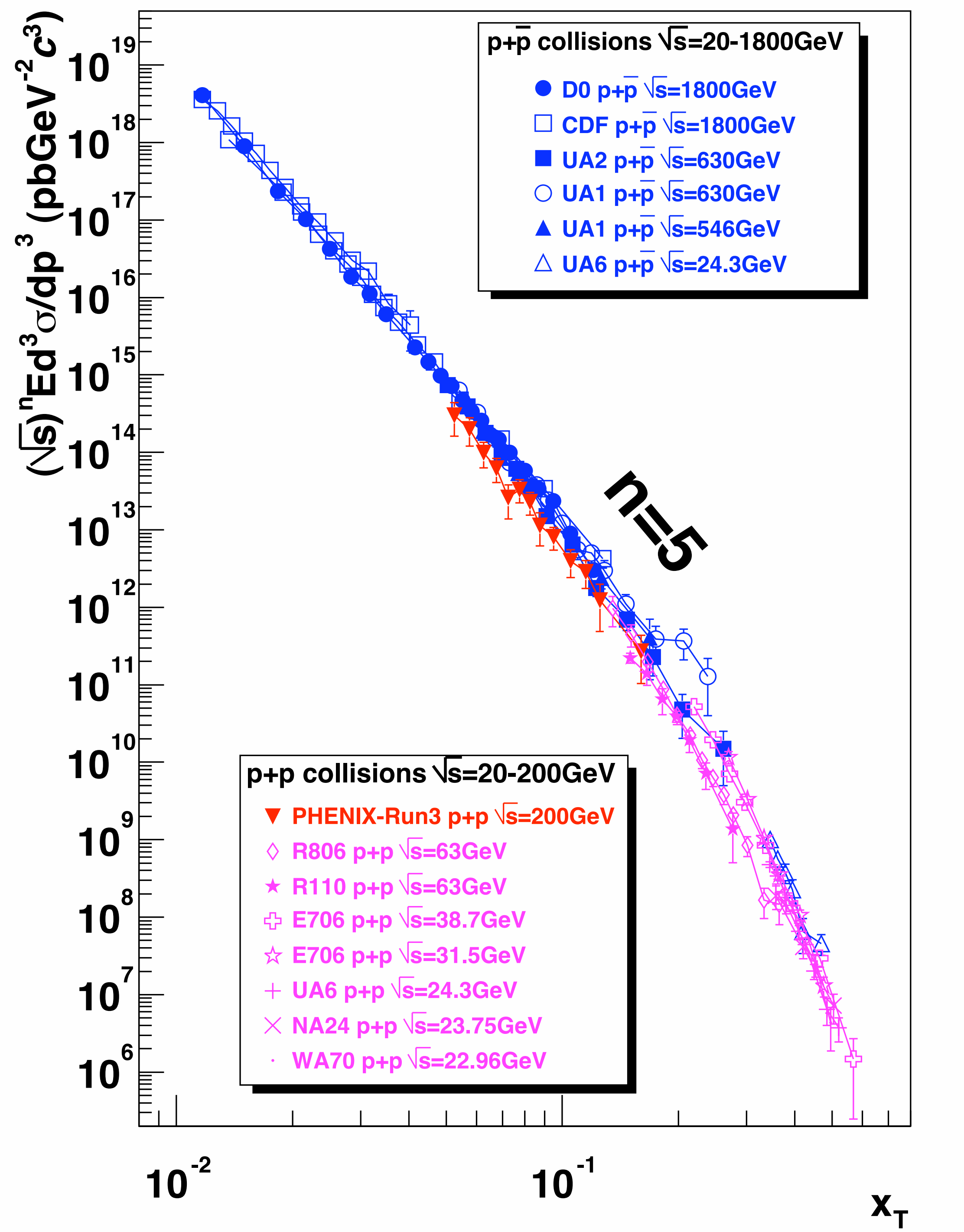
x_T scaling: photons

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}}\,G(x_T)$$

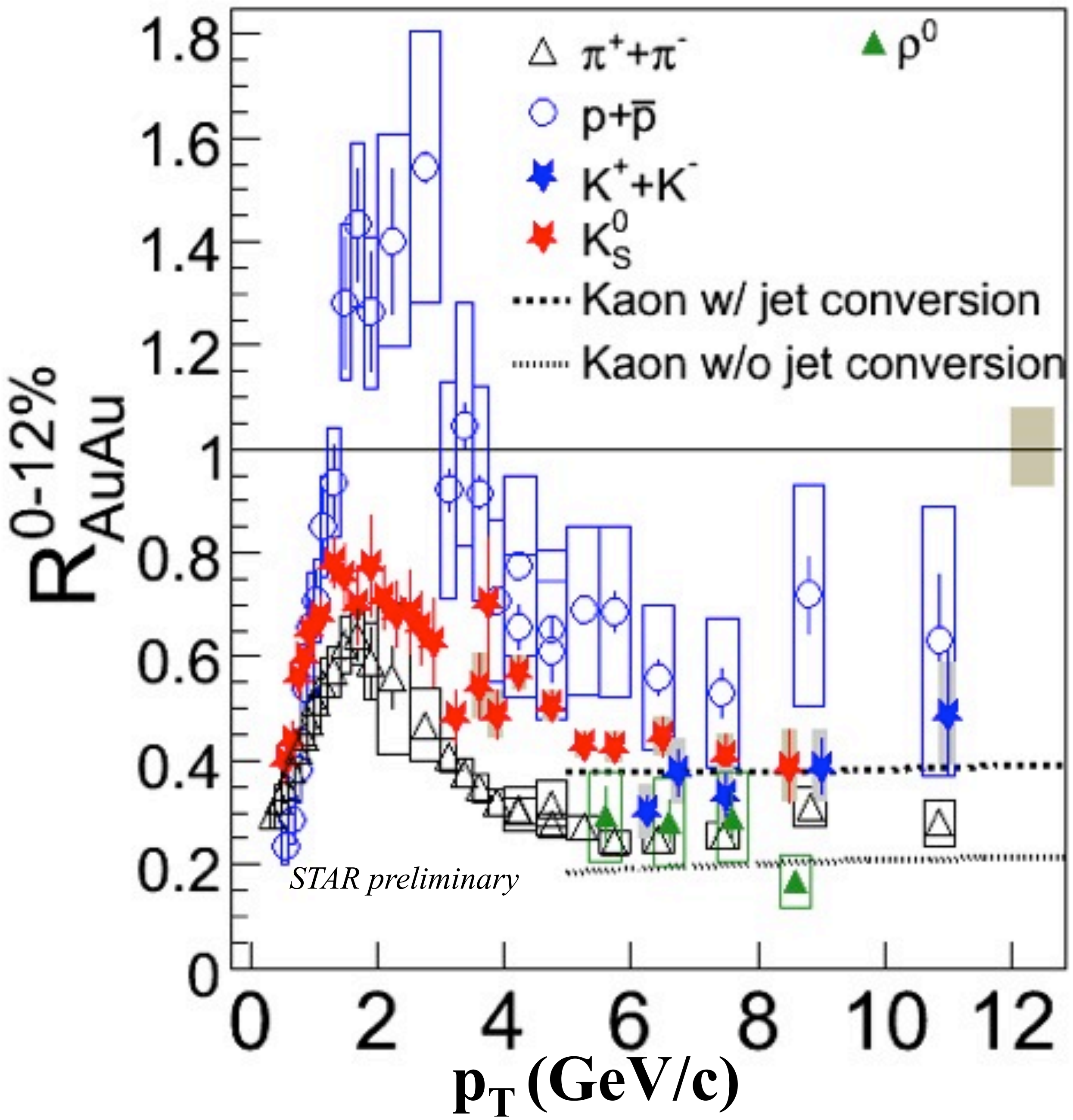
$$G(x_T) = E\frac{d^3\sigma}{dp^3}\sqrt{s}^n$$



nucl-ex/0611008

- good scaling over a wide range of x_T with n=5
  - $23 < \sqrt{s} < 1800$ GeV

and protons...



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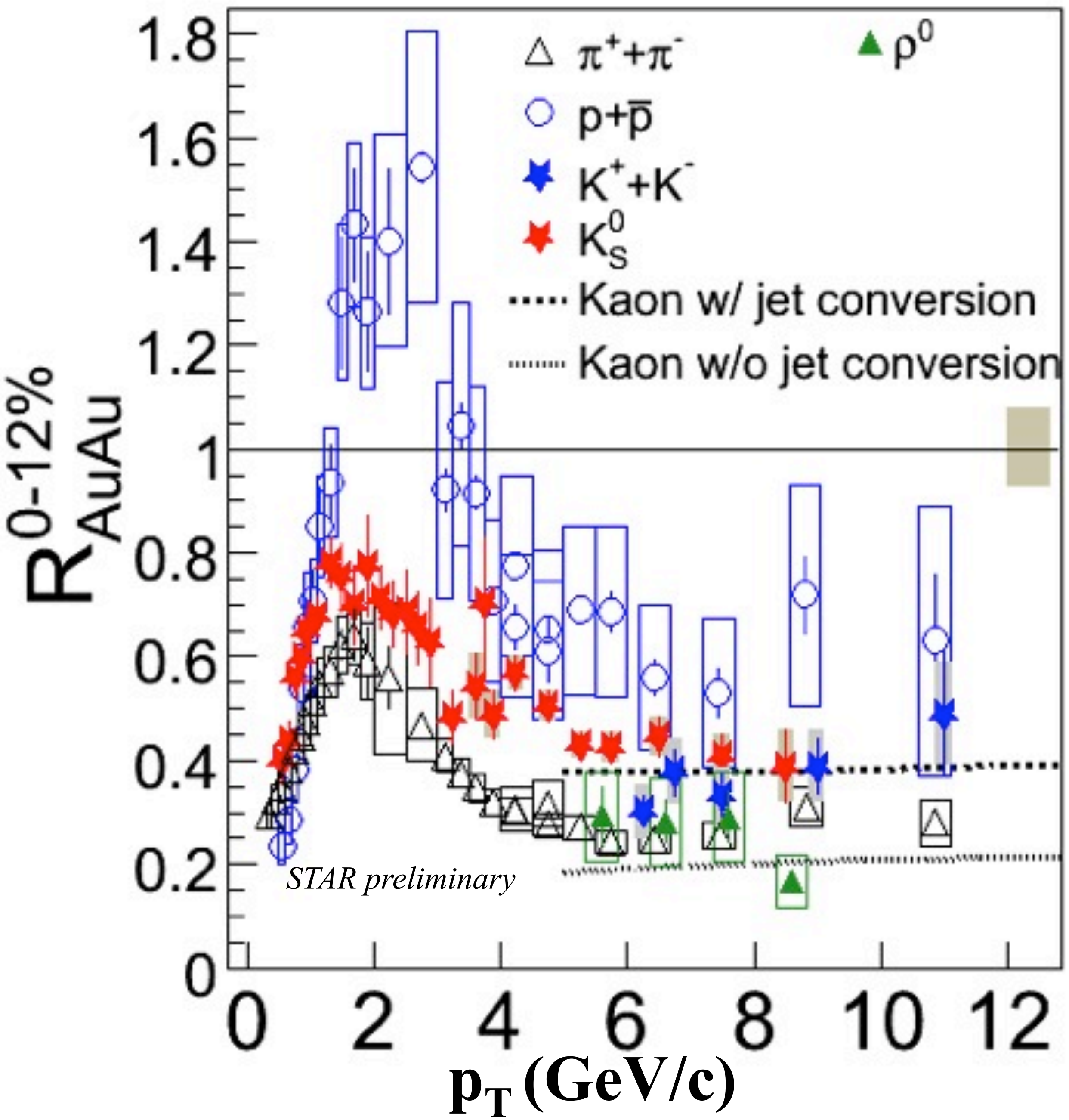

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are baryons coming from somewhere else?

QGP as filter