Baryon Production in Relativistic Heavy Ion Collisions

Anne Sickles

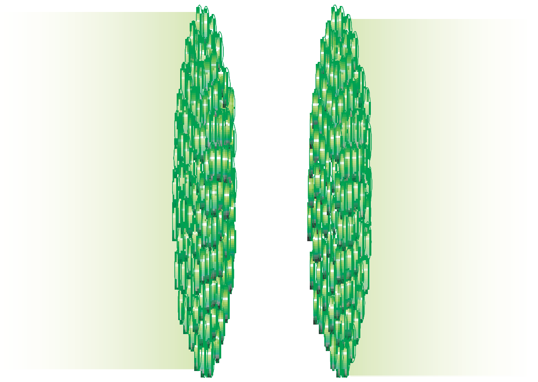
April 29, 2009

BROOKHAVEN
NATIONAL LABORATORY

Heavy Ion Collision

illustration: S. Bass

Heavy Ion Collision



incoming
nuclei

illustration: S. Bass

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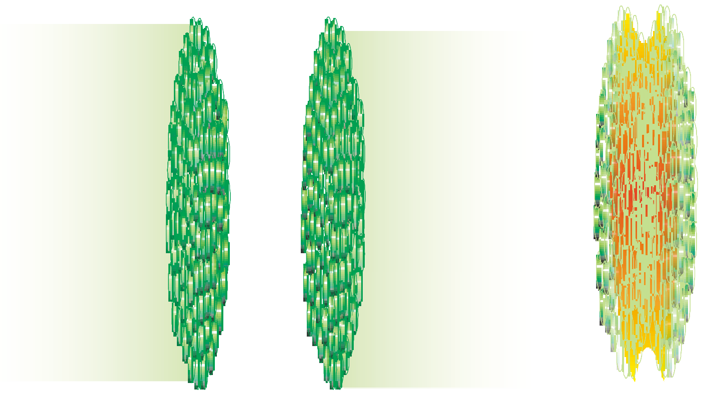

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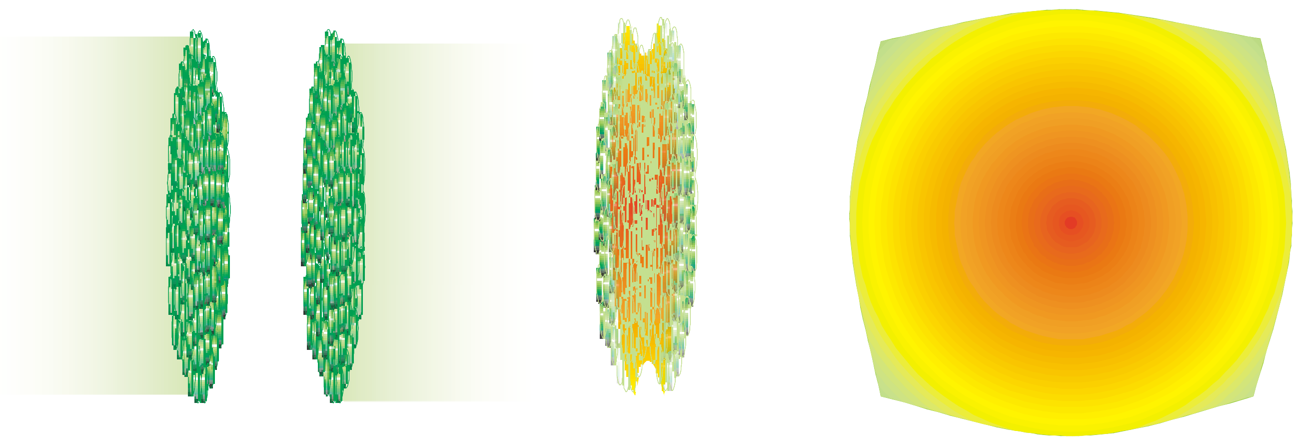
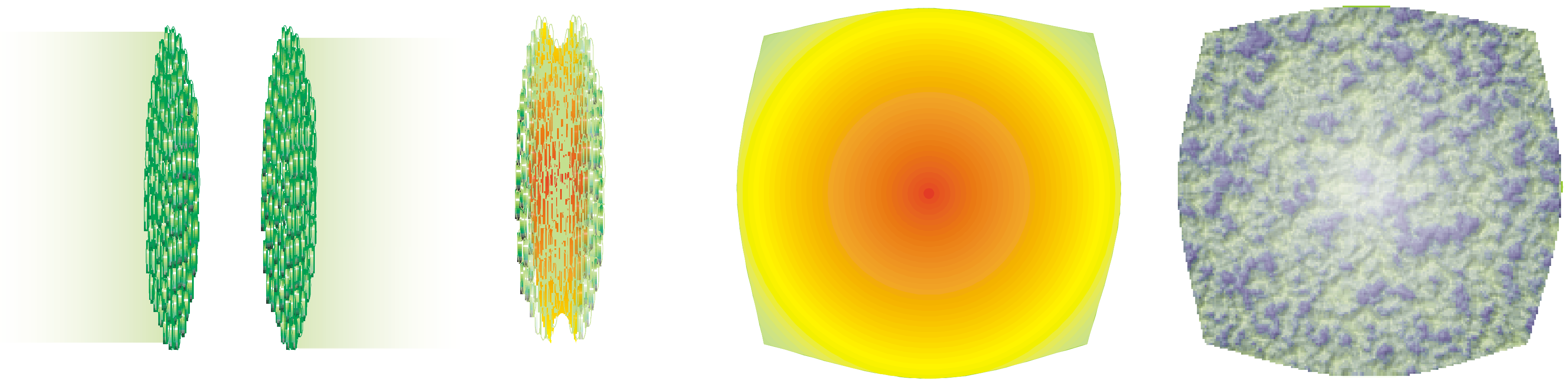


incoming nuclei

hot matter

illustration: S. Bass

Heavy Ion Collision



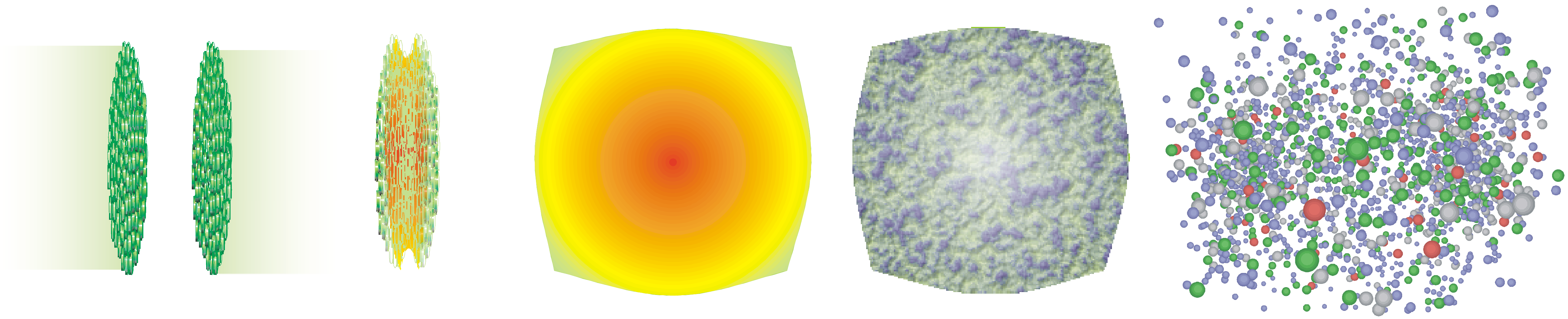
incoming nuclei

hot matter

hadronic gas

illustration: S. Bass

Heavy Ion Collision



incoming nuclei

hot matter

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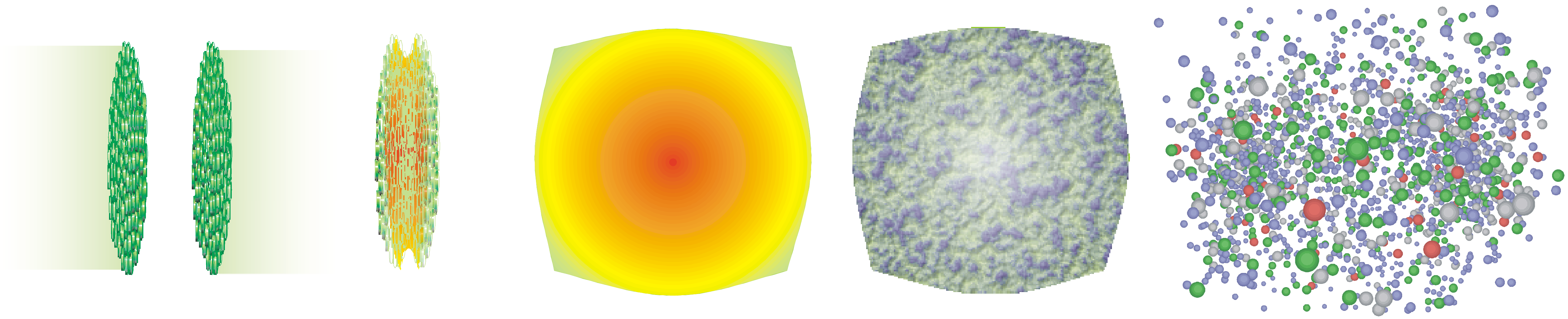
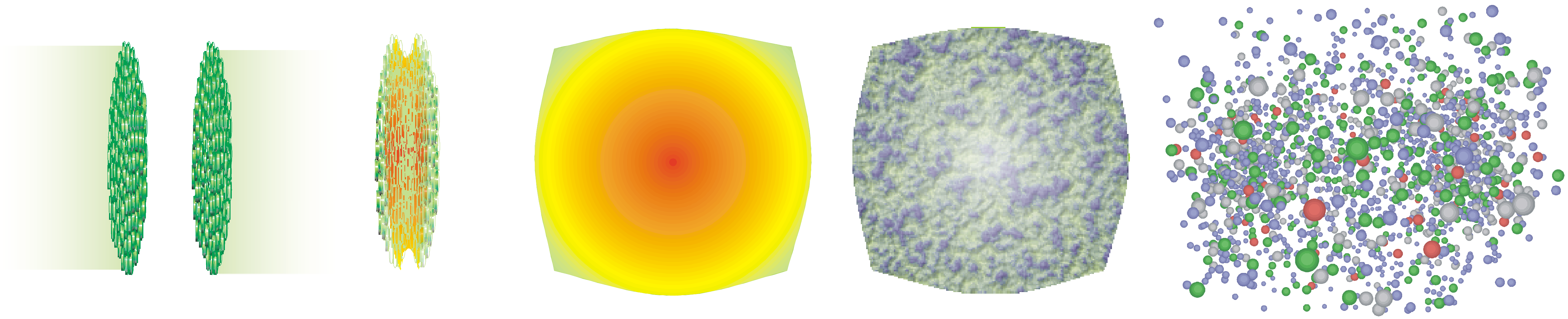
Heavy Ion Collision



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

Heavy Ion Collision

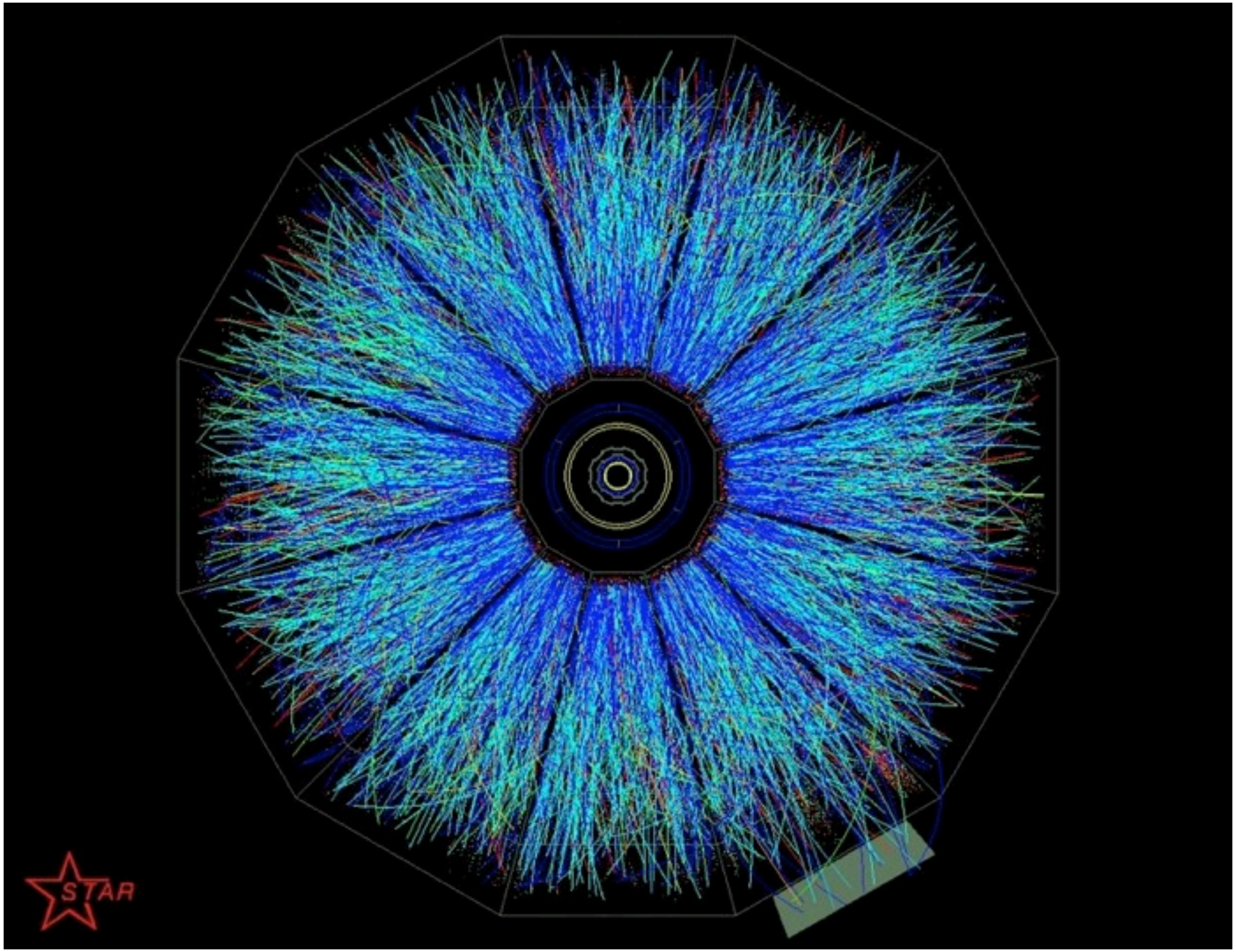


incoming nuclei | hot matter | hadronic gas

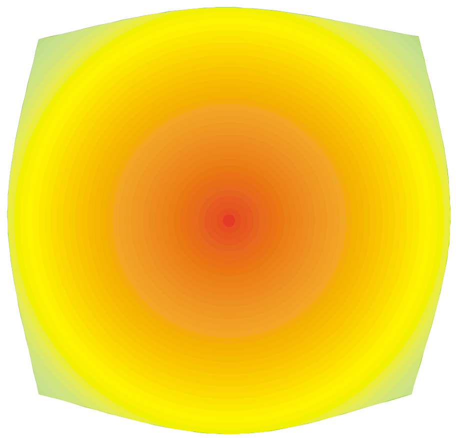
- RHIC: ion-ion collisions at up to $\sqrt{s_{NN}}$=200GeV
- also p+p collsions, crucial baseline

illustration: S. Bass

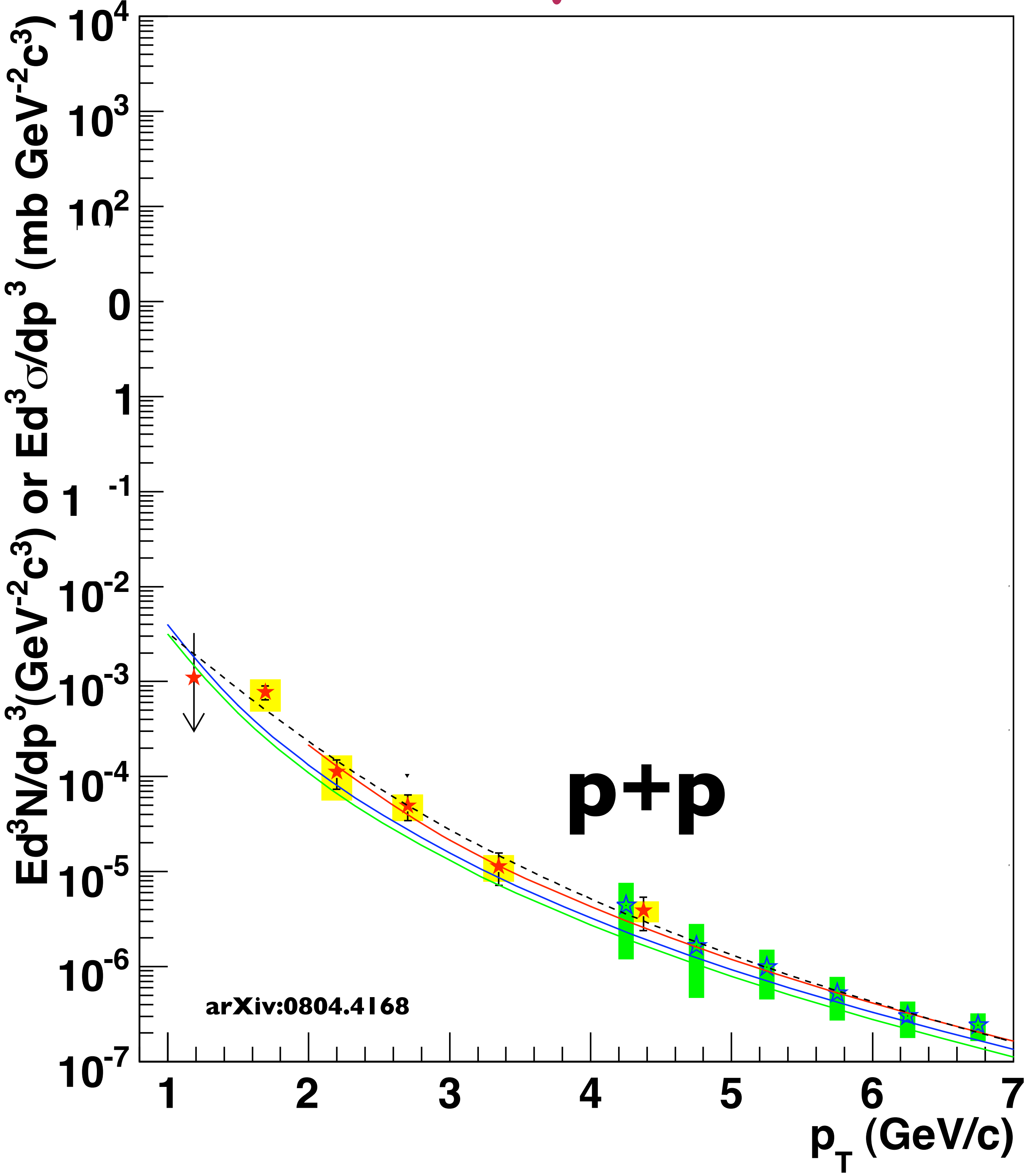
Au+Au collision



hot nuclear matter



Direct γ



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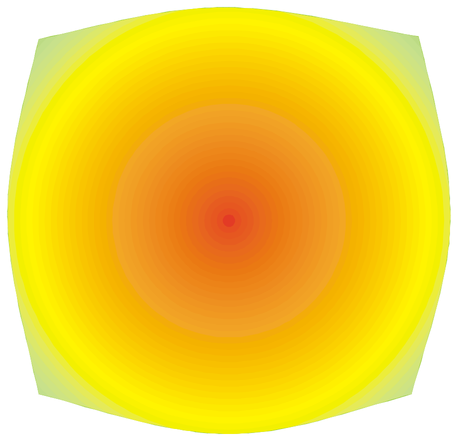

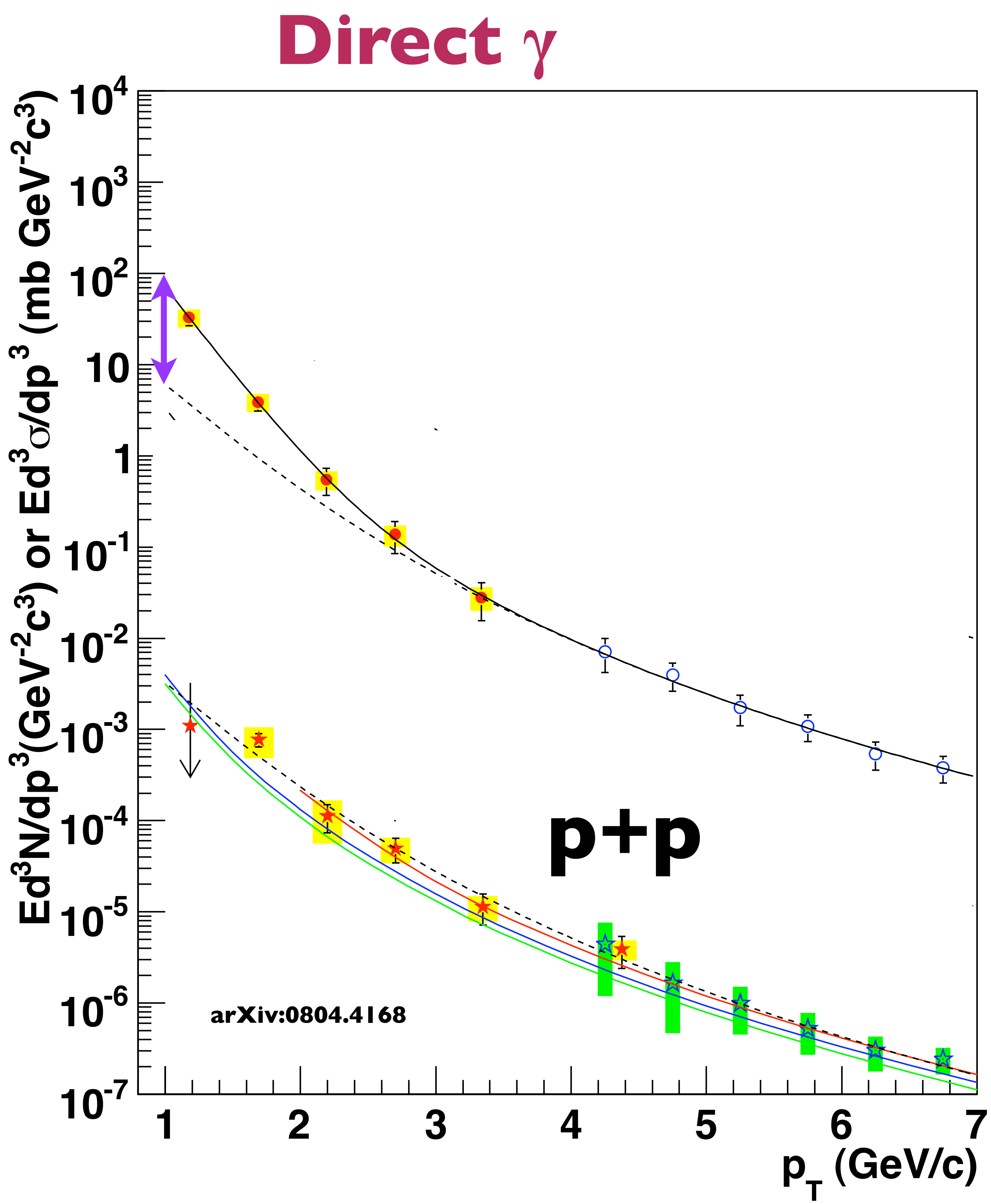

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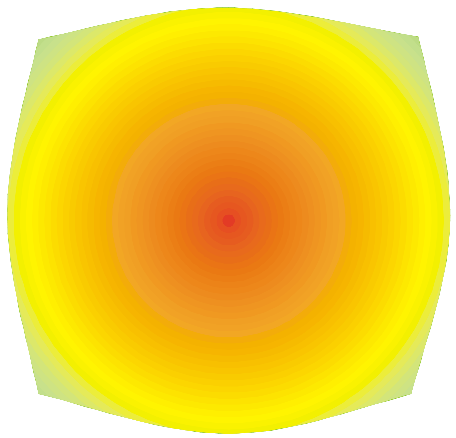

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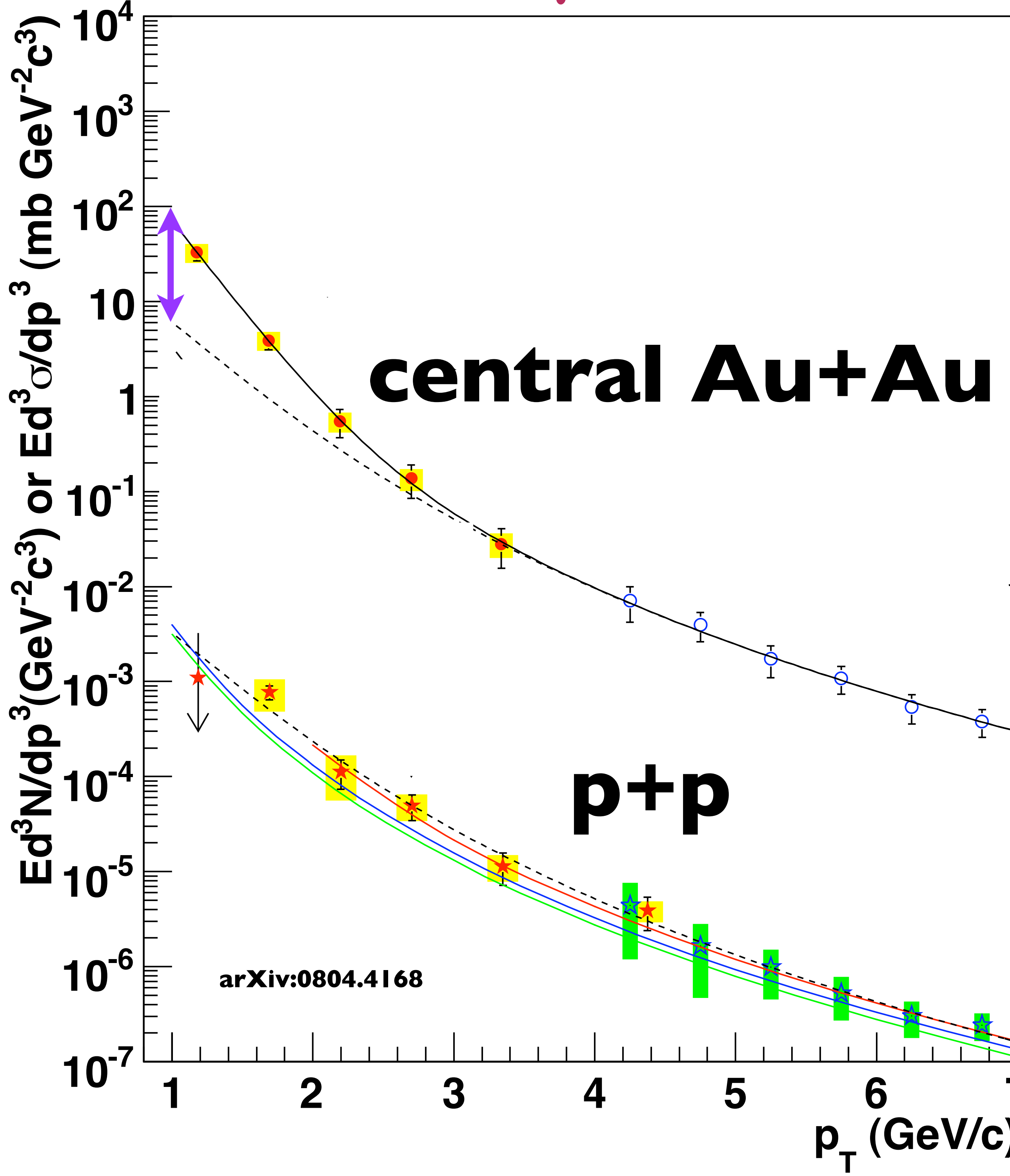

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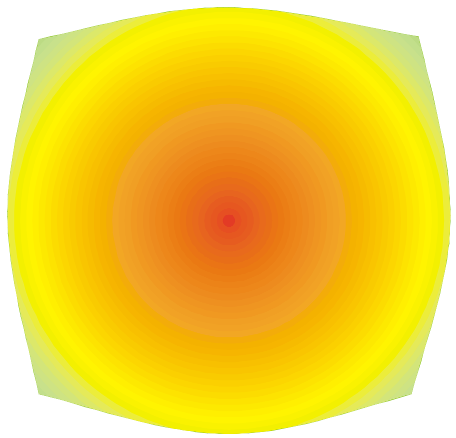
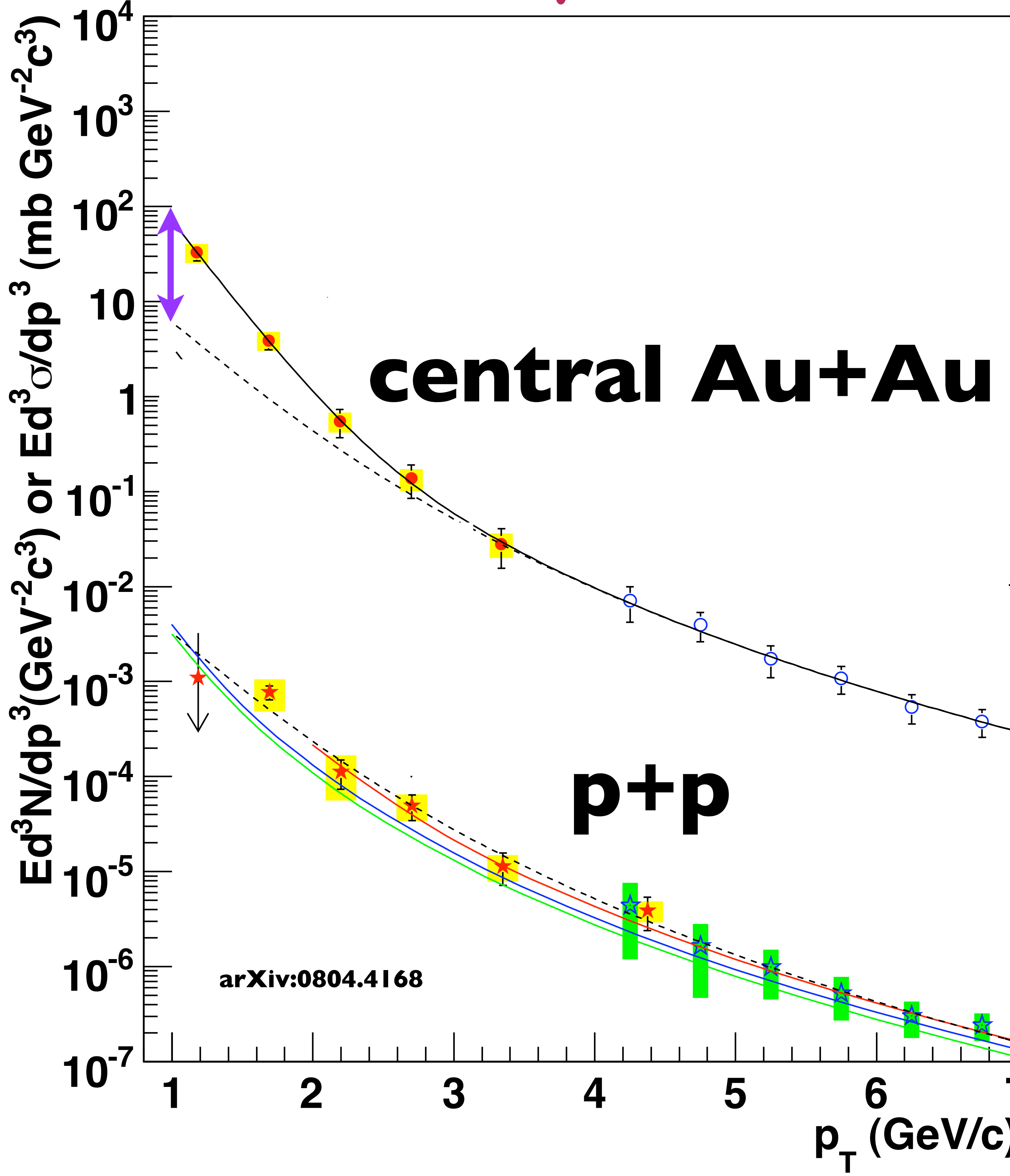


central Au+Au:
large excess over
binary scaled p+p

Direct γ



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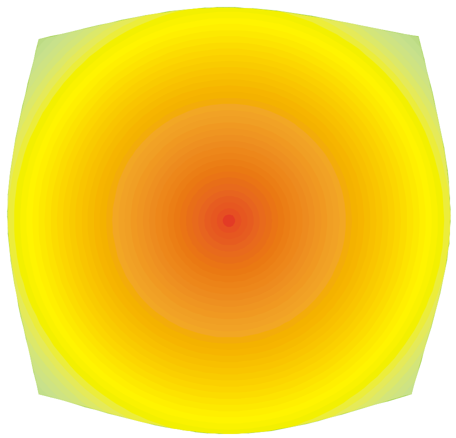
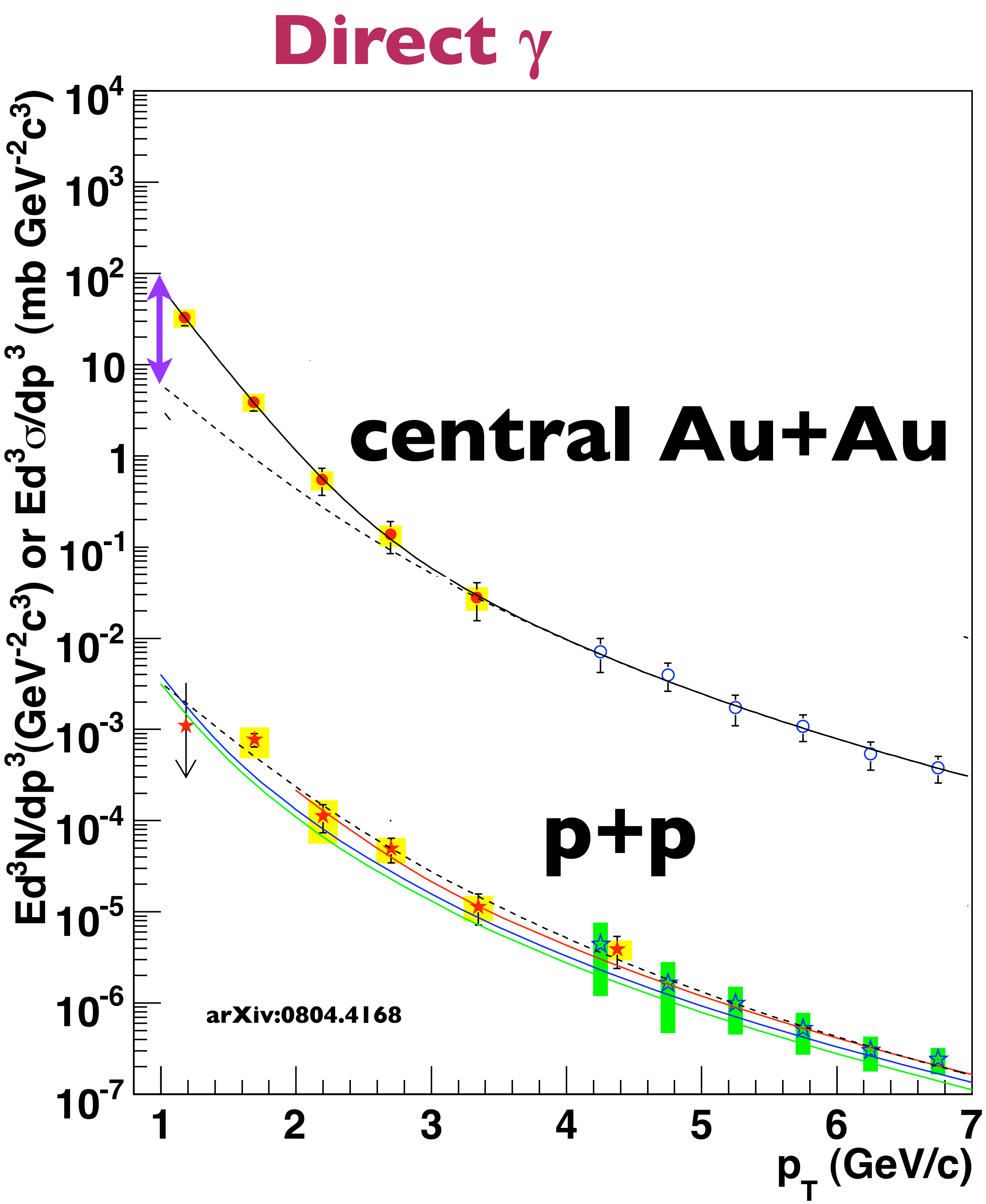
hot nuclear matter



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

excess:
221±23±18MeV



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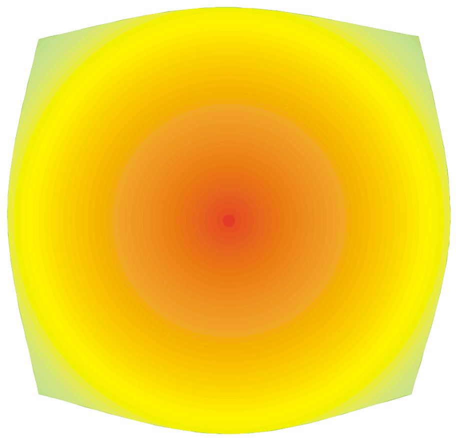
hot nuclear matter

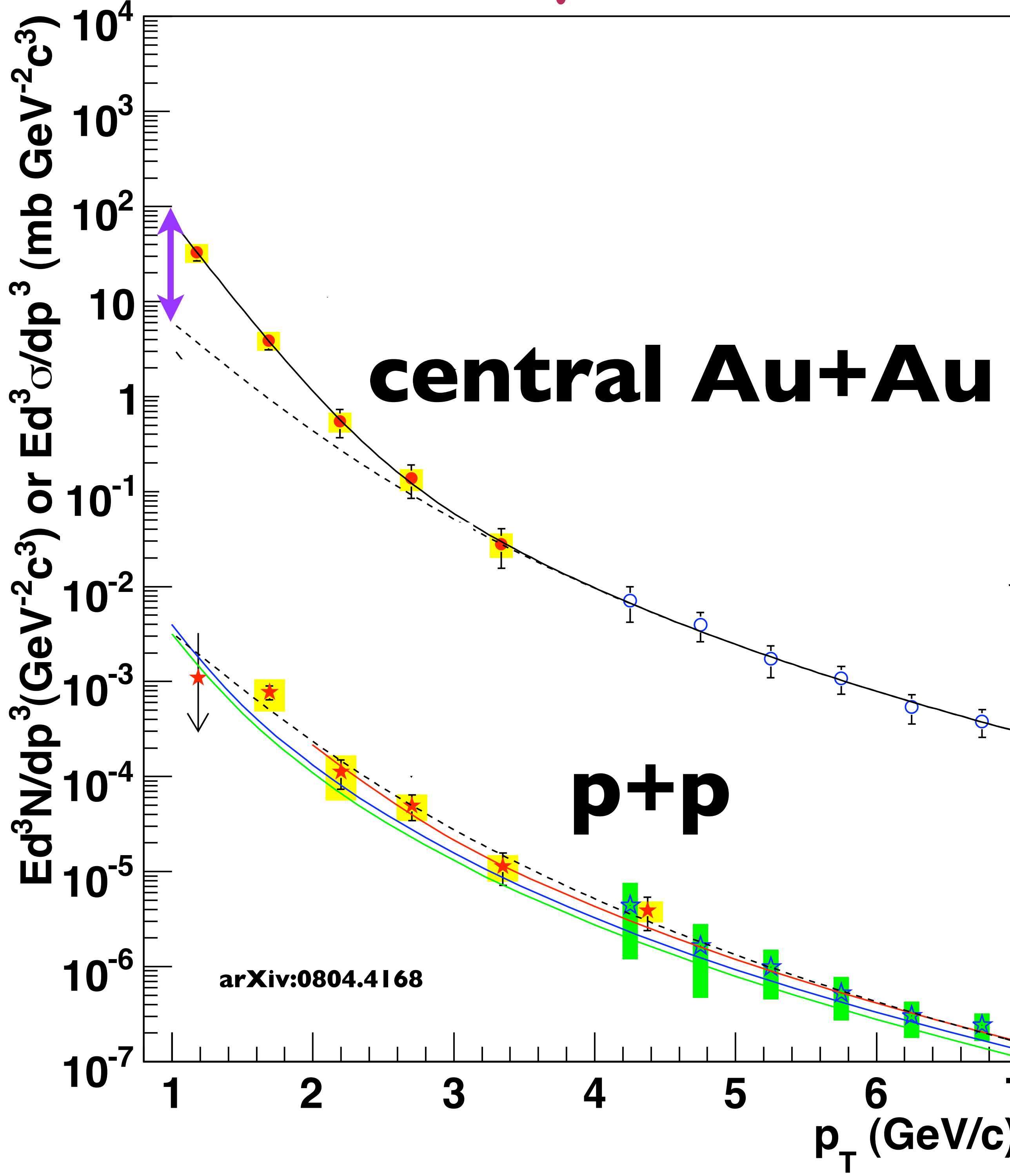


central Au+Au:
large excess over
binary scaled p+p

excess:
221±23±18MeV

consistent with initial
T ~ 300-600MeV

Direct γ



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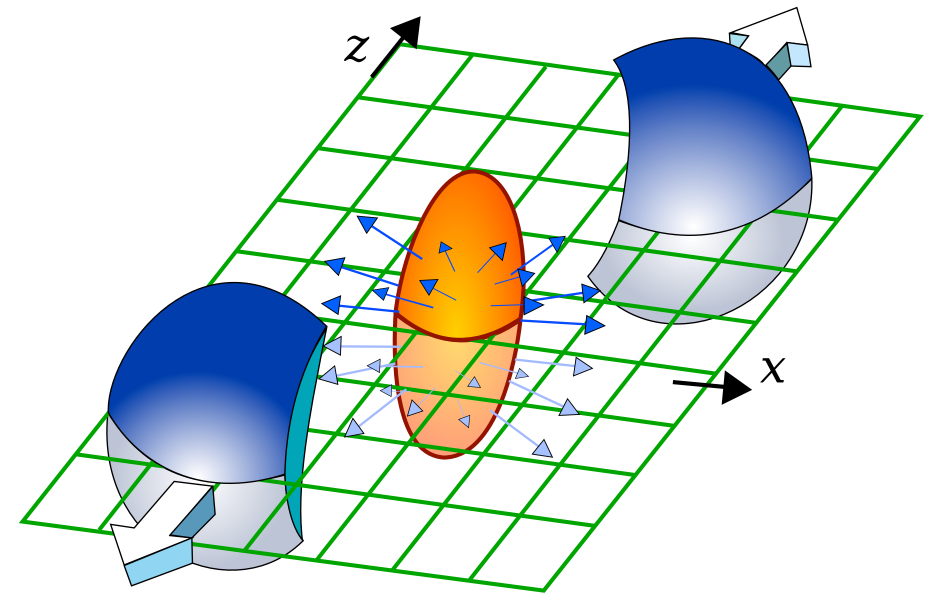
the matter flows

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



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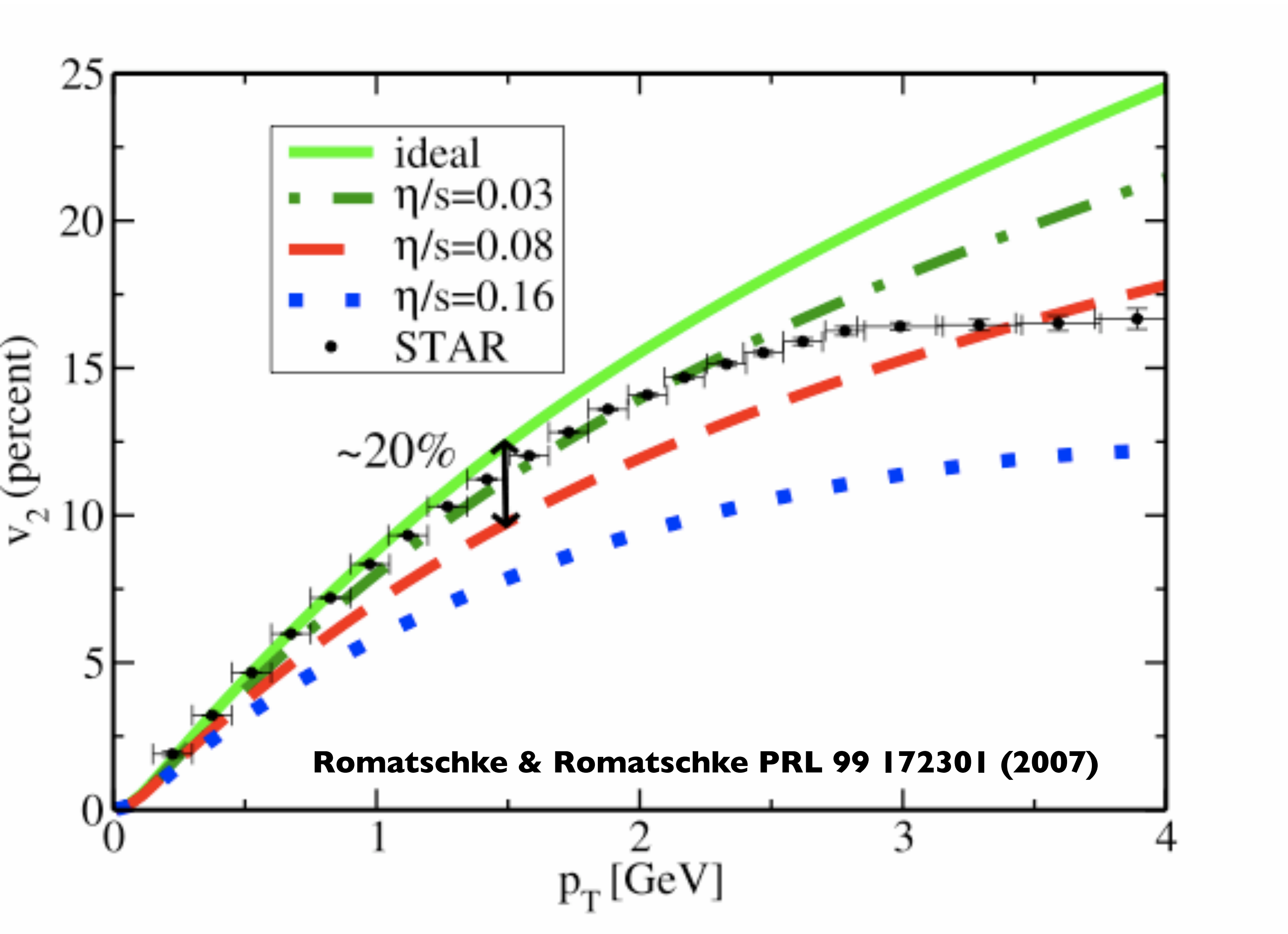

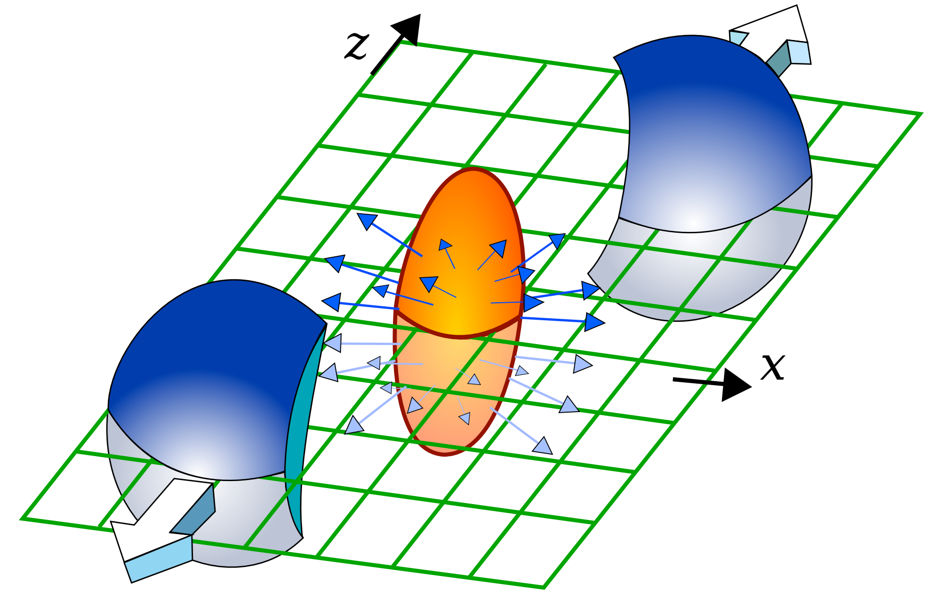

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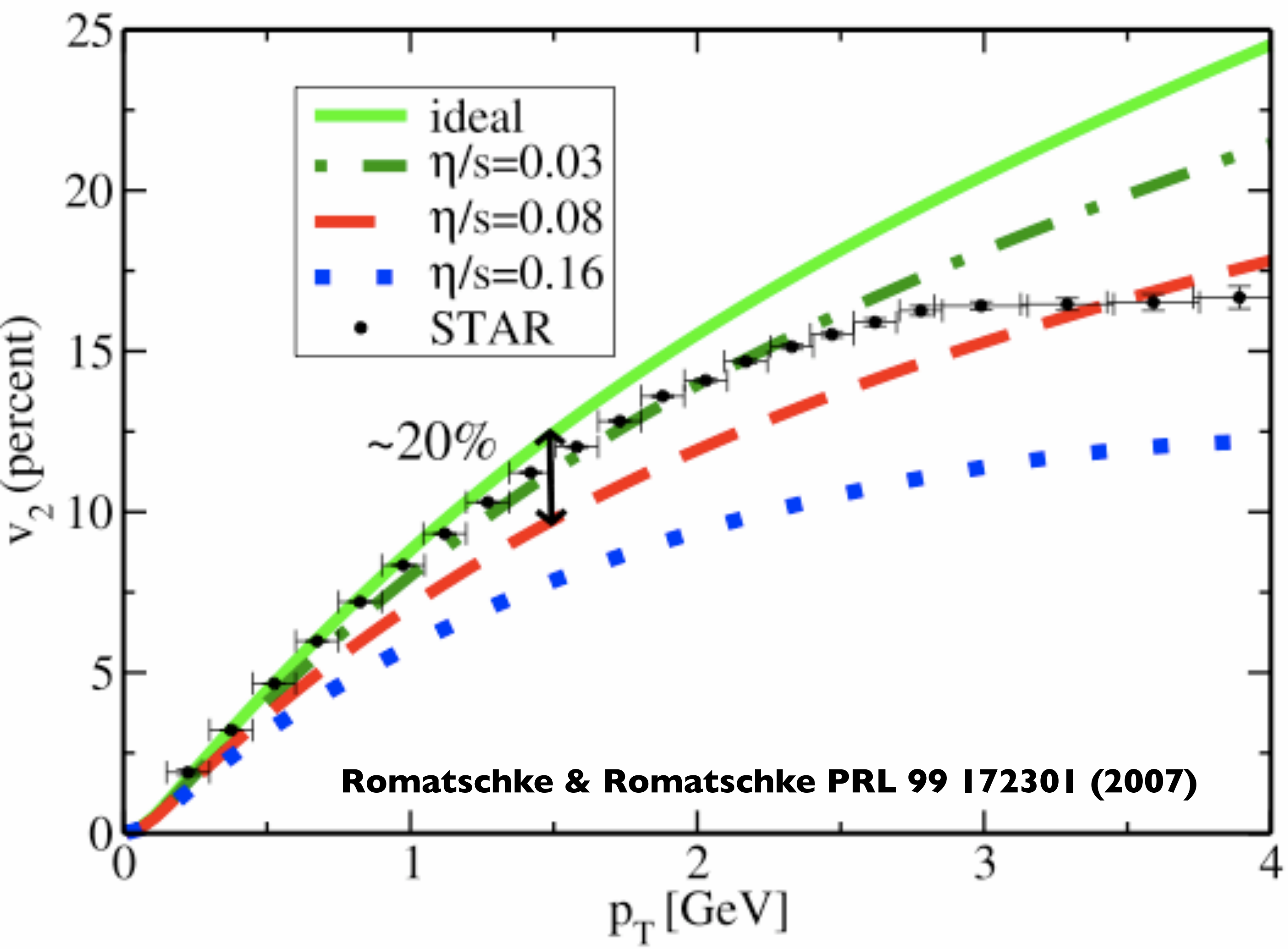
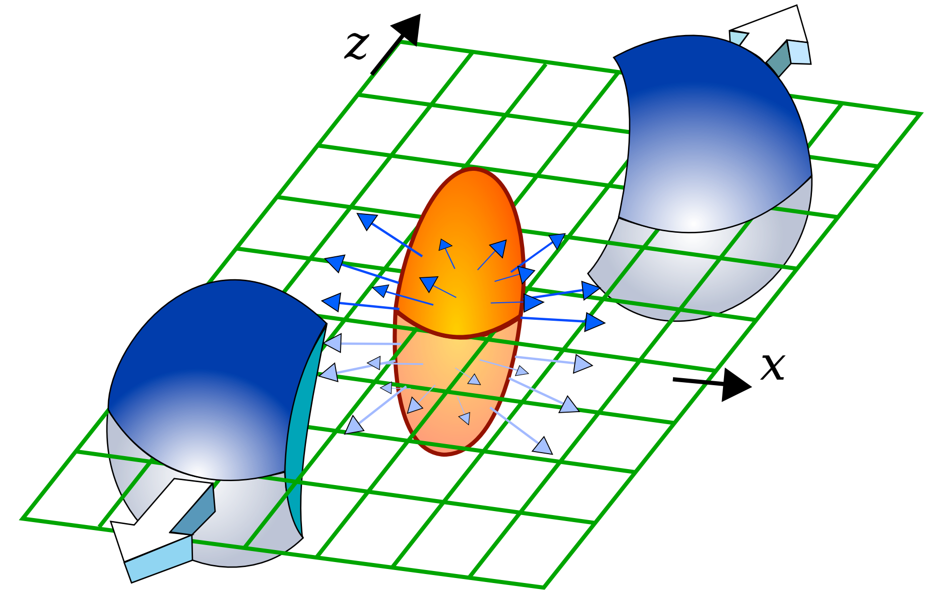
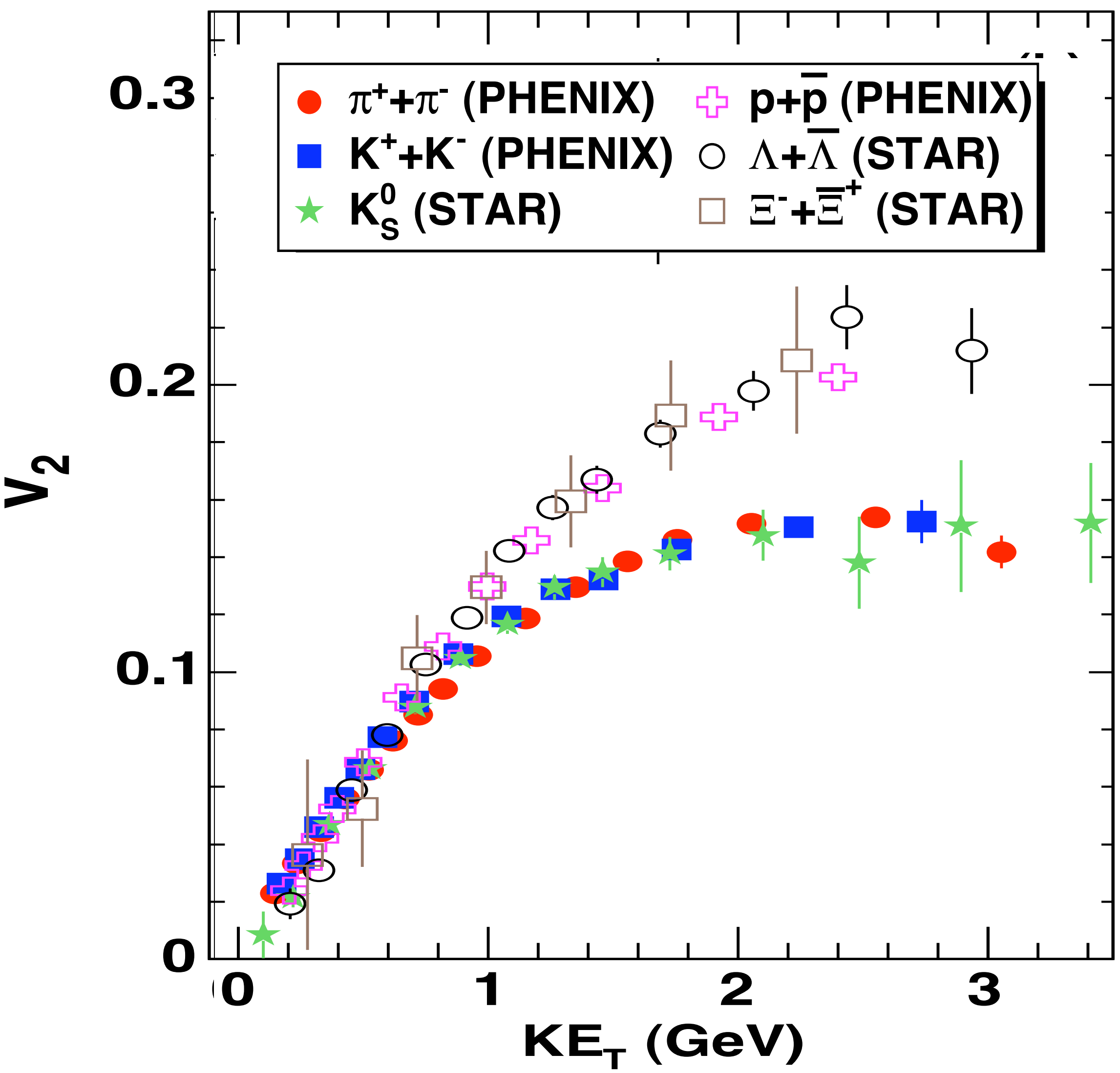




well described by hydrodynamics with small viscosity

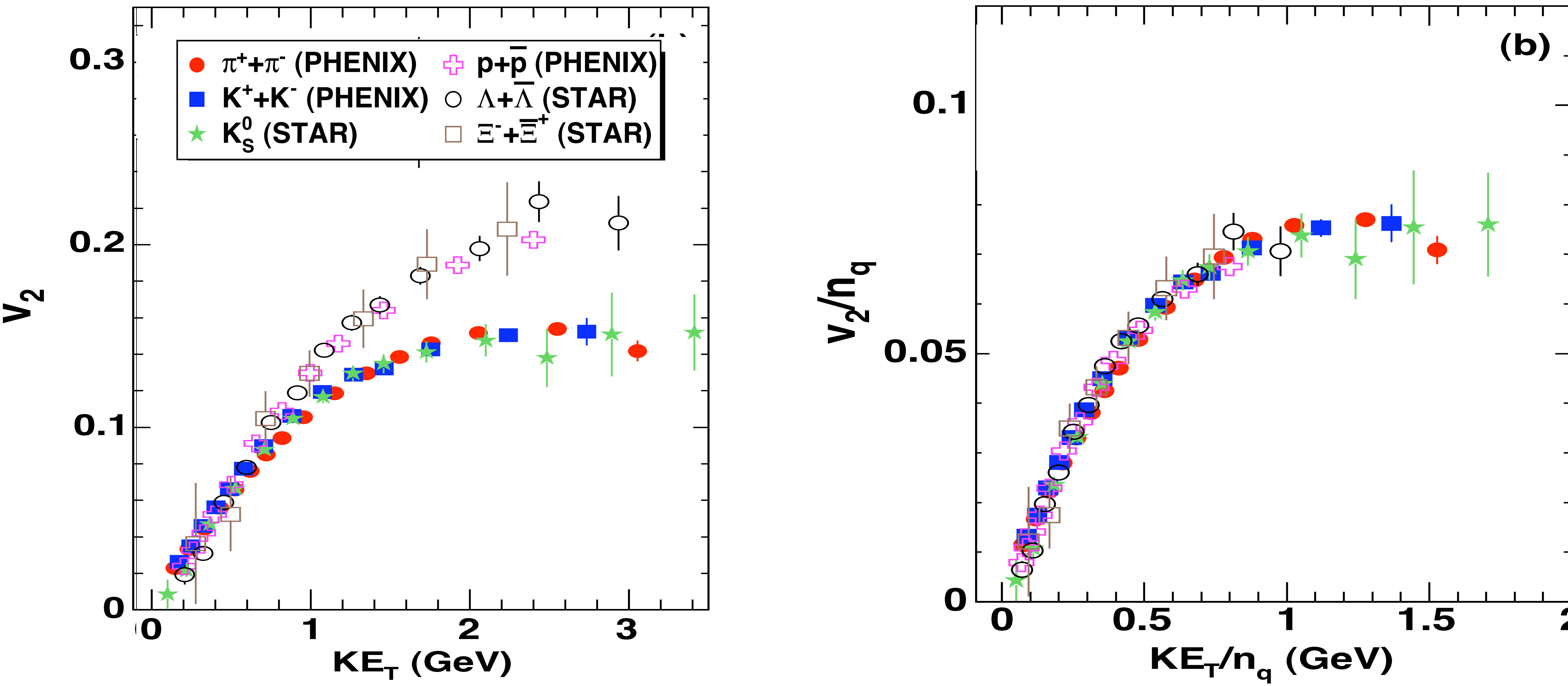
the partons flow



$$KE_T = m_T - m$$

PHENIX, PRL 98 162301 2007

the partons flow



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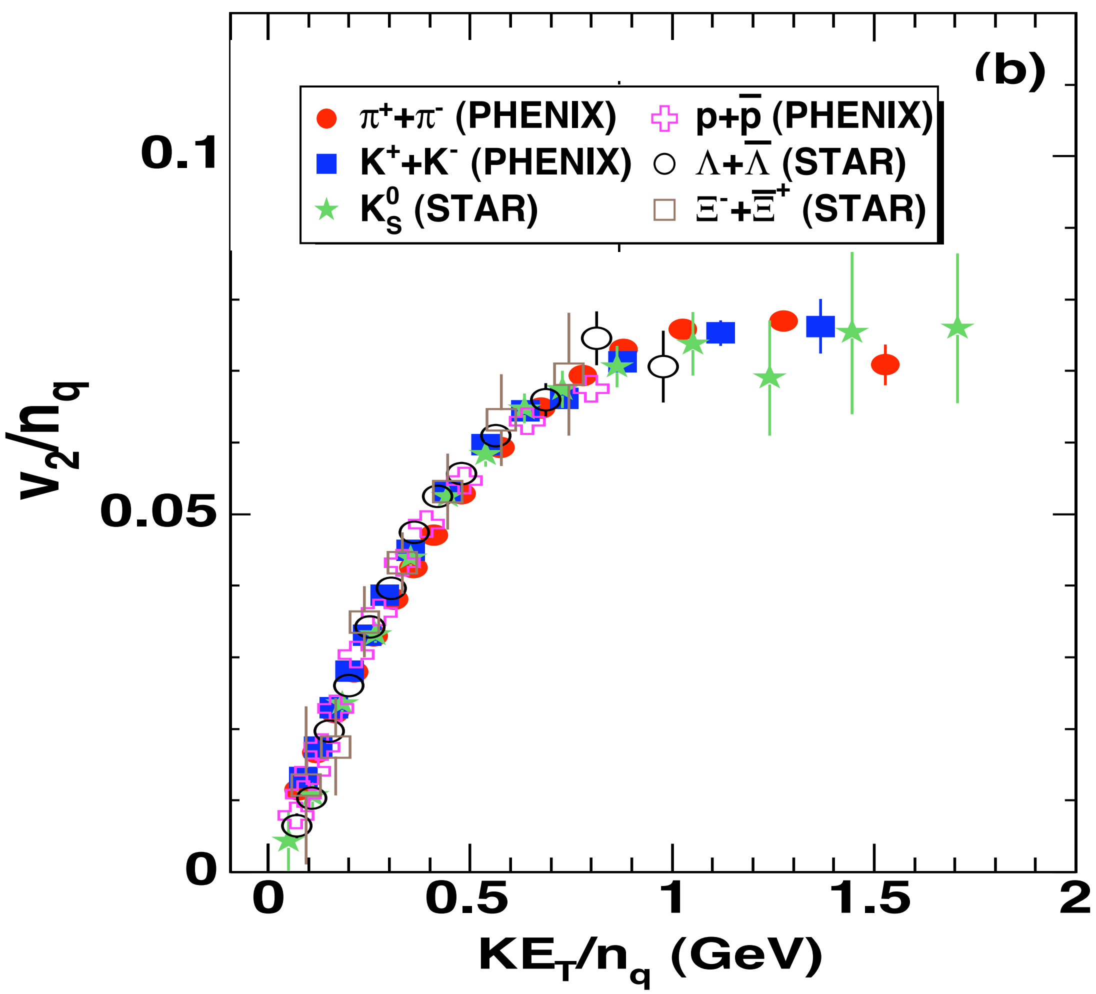
anomalous (anti)baryons



valence quark flow

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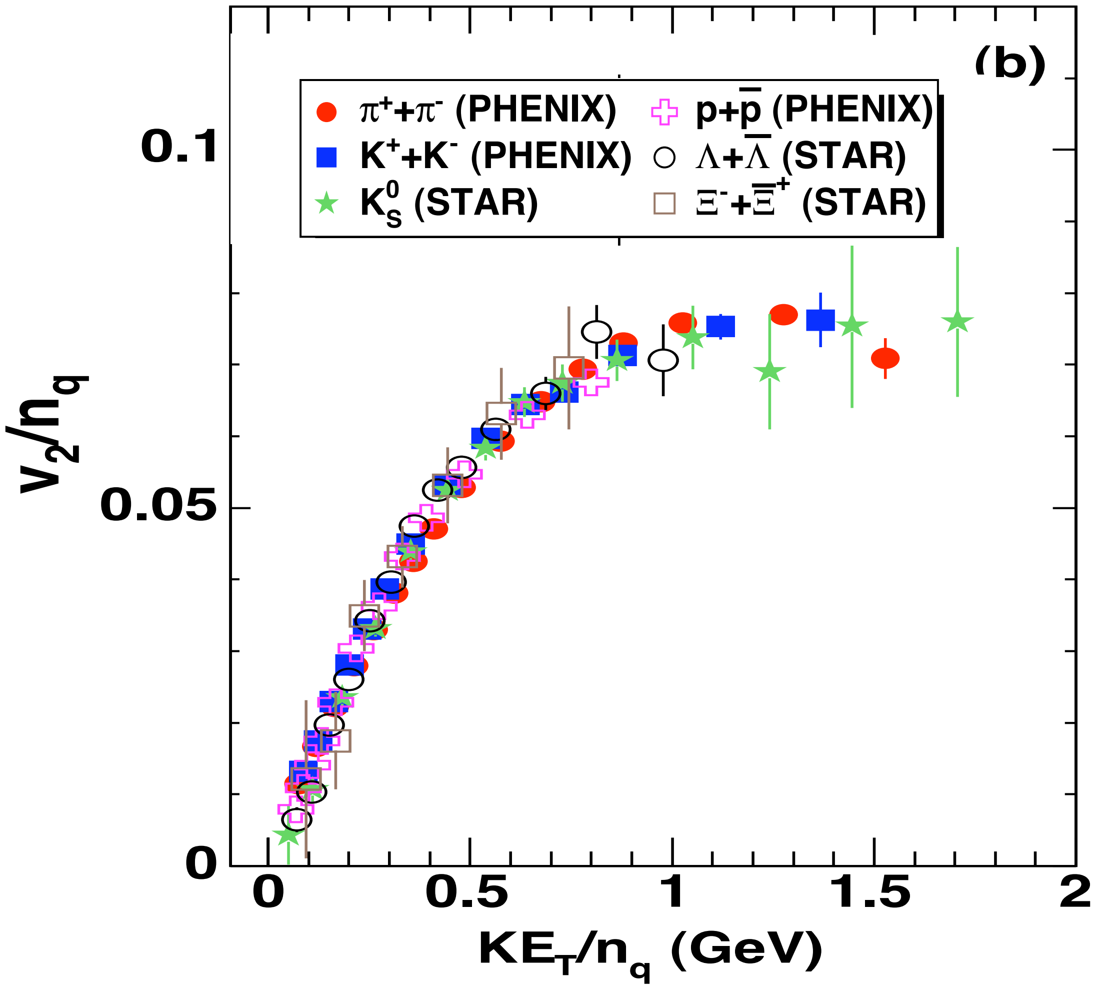
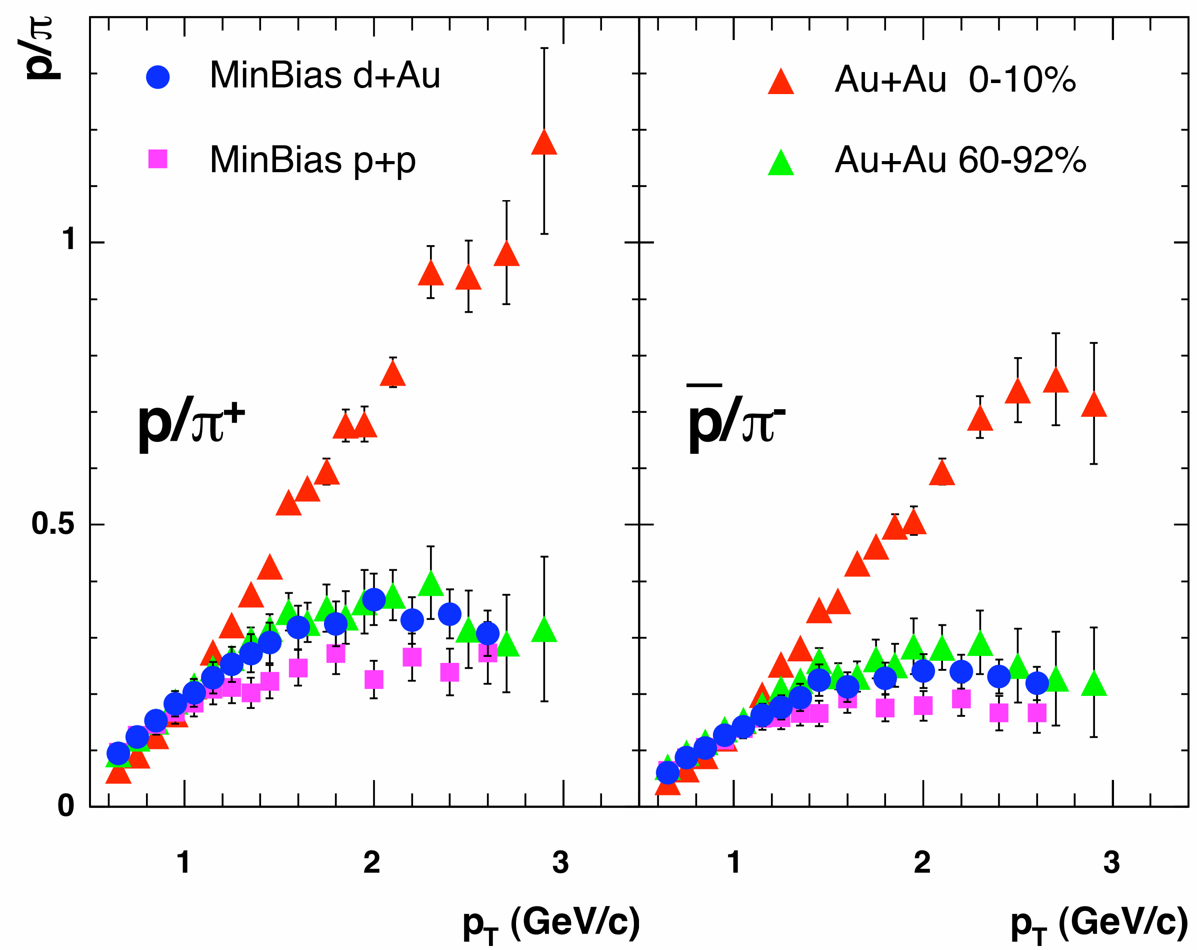
anomalous (anti)baryons





valence quark flow

excess baryons

PHENIX PRL 98 162301 (2007)

PHENIX PRC 74 024904 (2006)

recombination

basic idea: valence quarks coalesce to form final state hadrons

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

recombination

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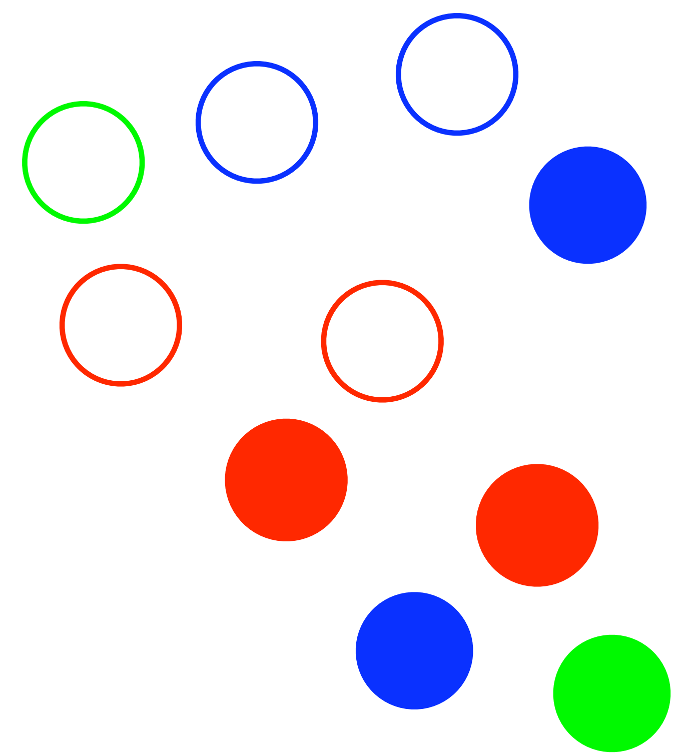

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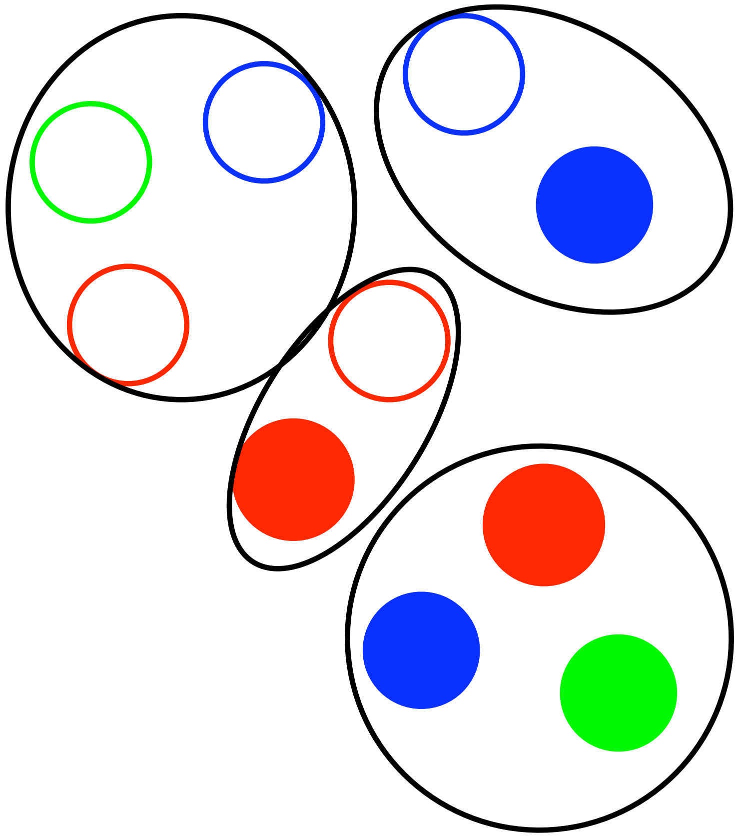

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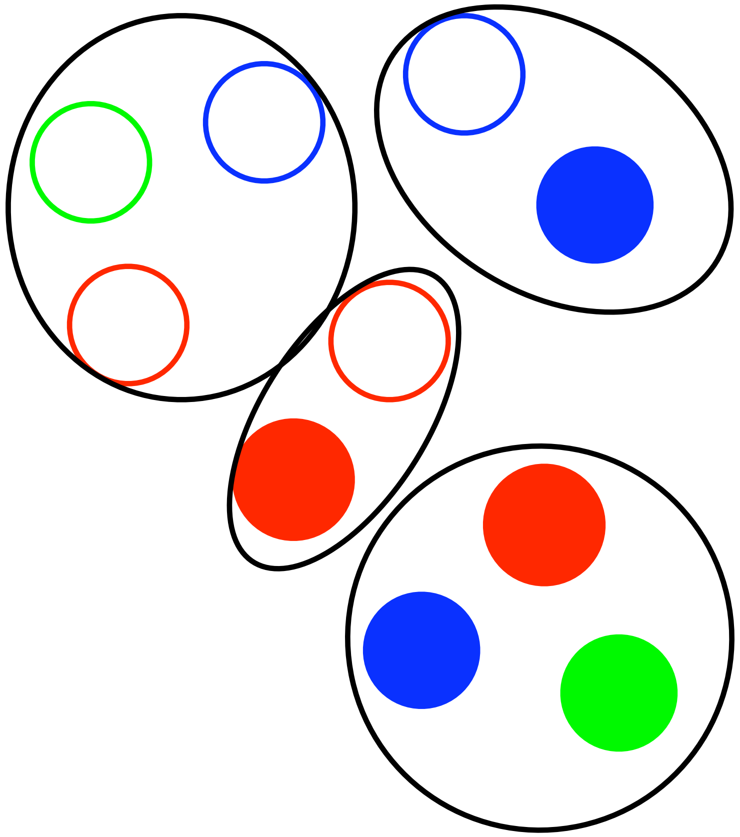

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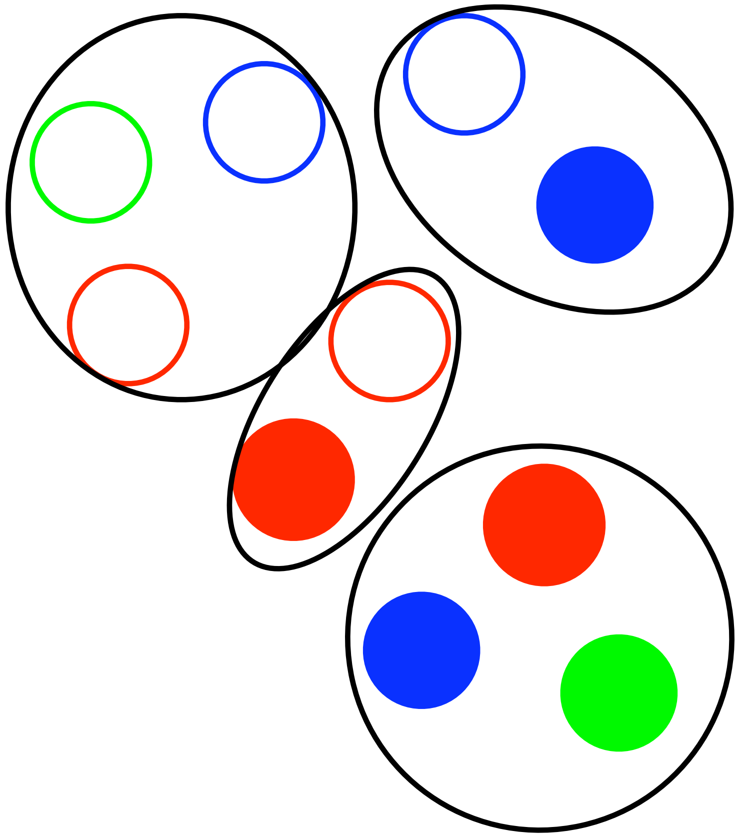
- quark momenta add:
  - p_T(hadron) > p_T(quark)
  - baryons get an extra boost→extra quark



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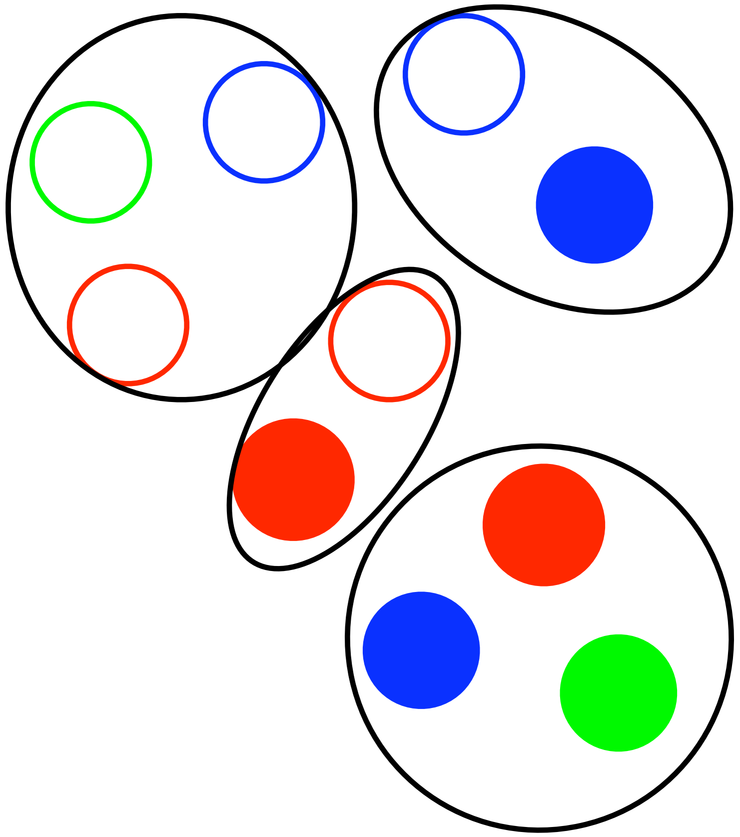

- quark momenta add:
  - p_T(hadron) > p_T(quark)
  - baryons get an extra boost→extra quark
- quark correlations amplified in hadrons:
  - e.g. flow

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

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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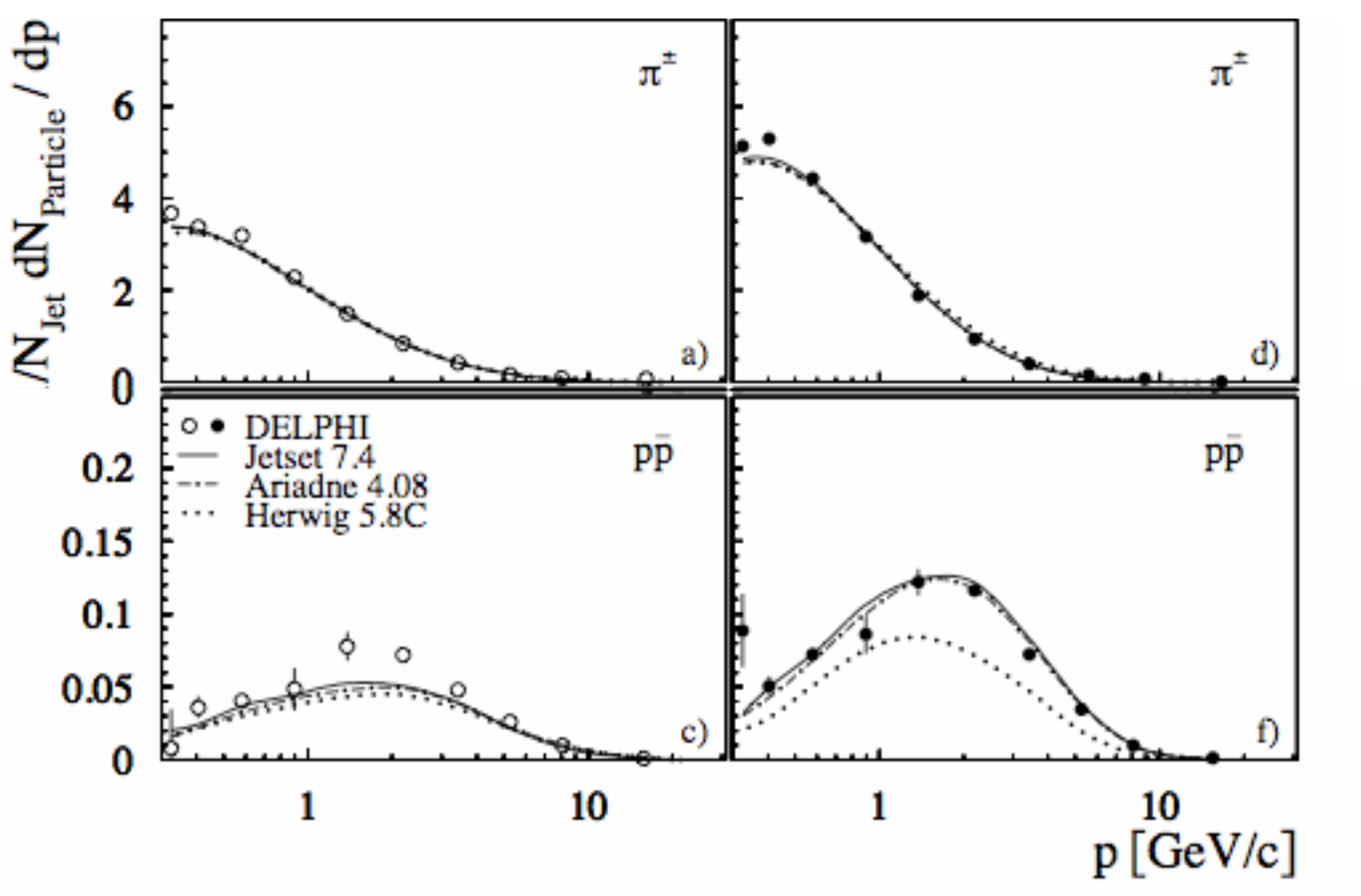
DELPHI e^+e^-

quark jets **gluon jets**



EPJ 17 207 (2000)

baryons via fragmentation

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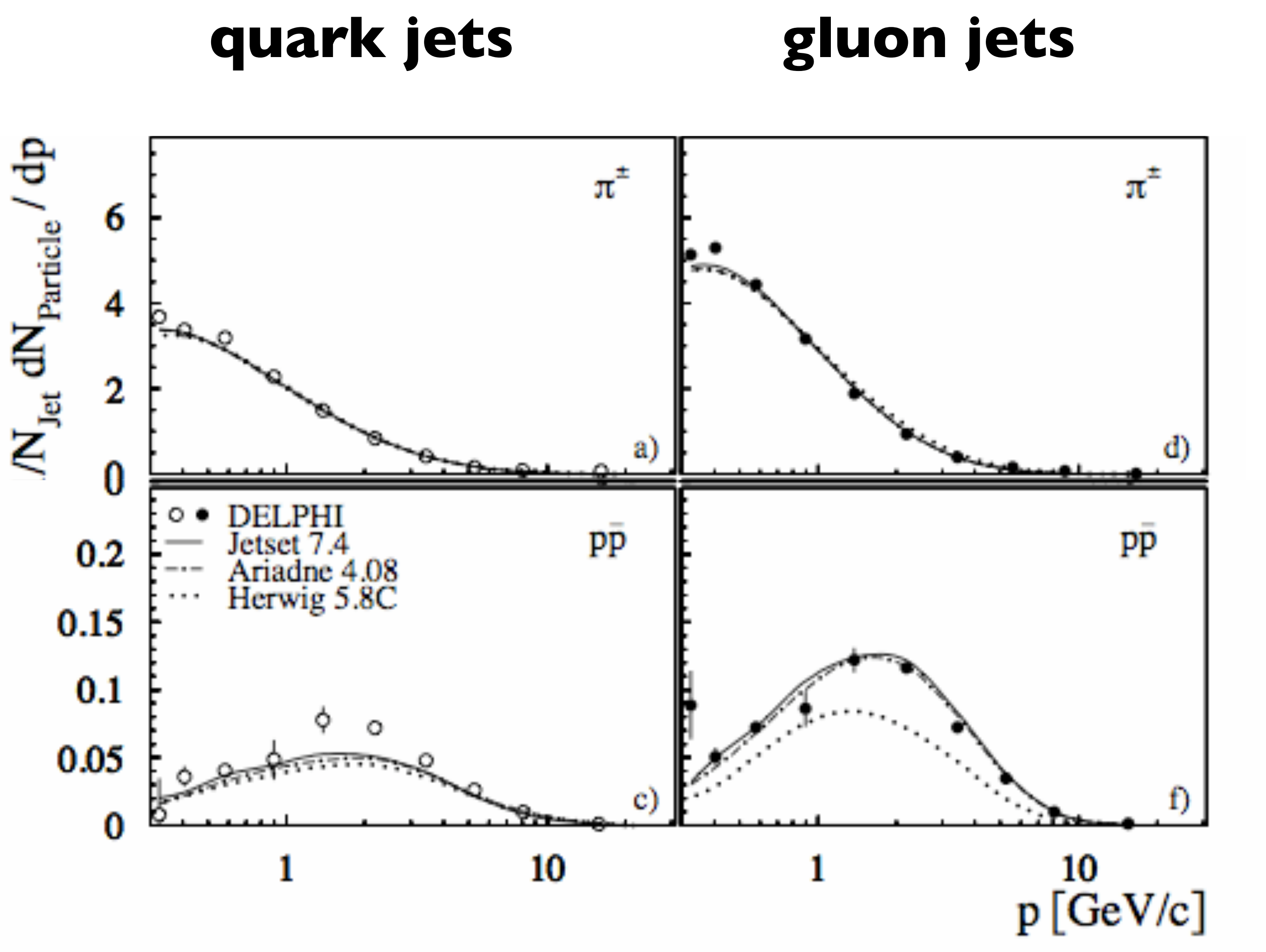

EPJ 17 207 (2000)

- baryon production difficult in fragmentation

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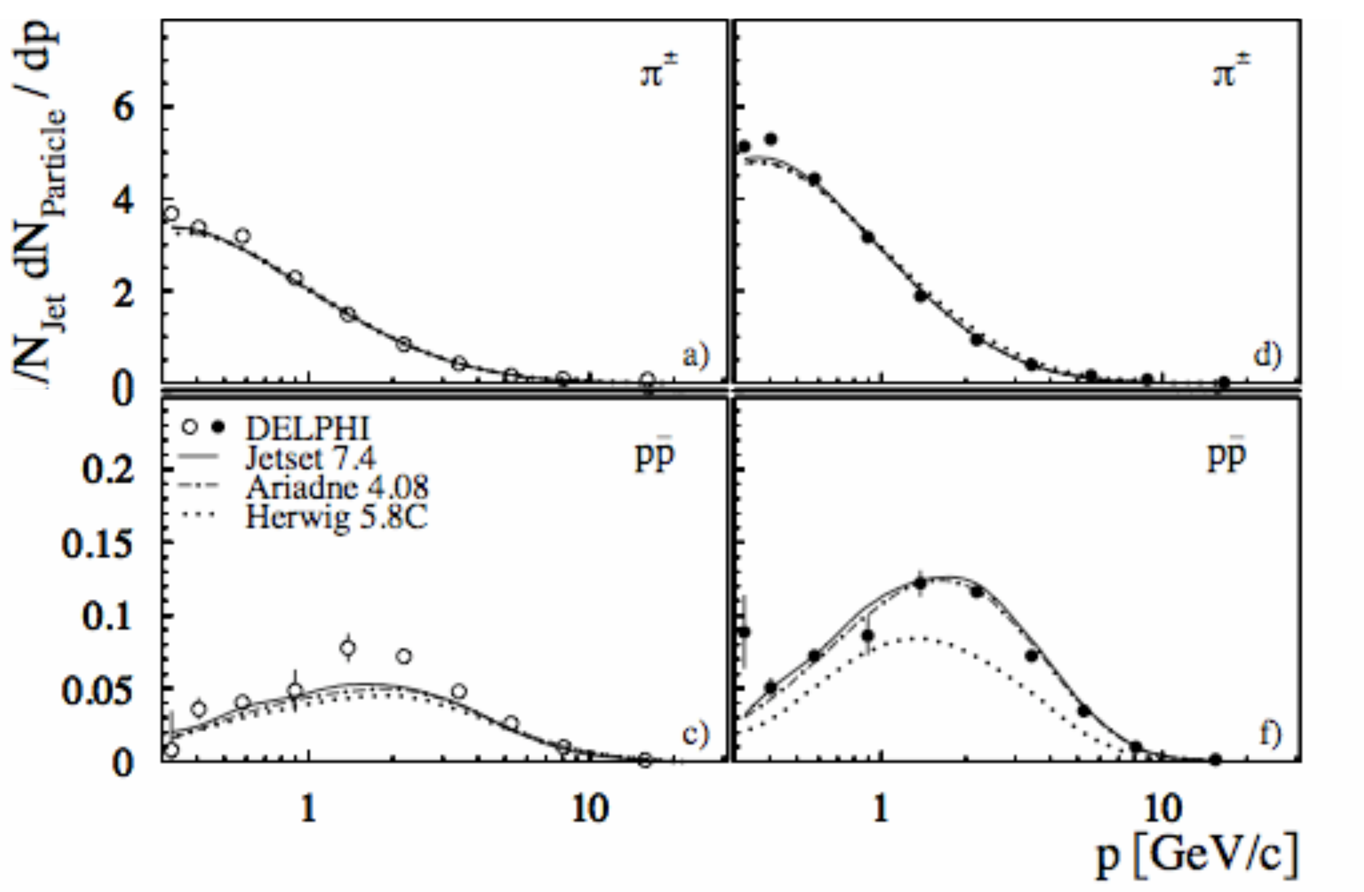


EPJ 17 207 (2000)

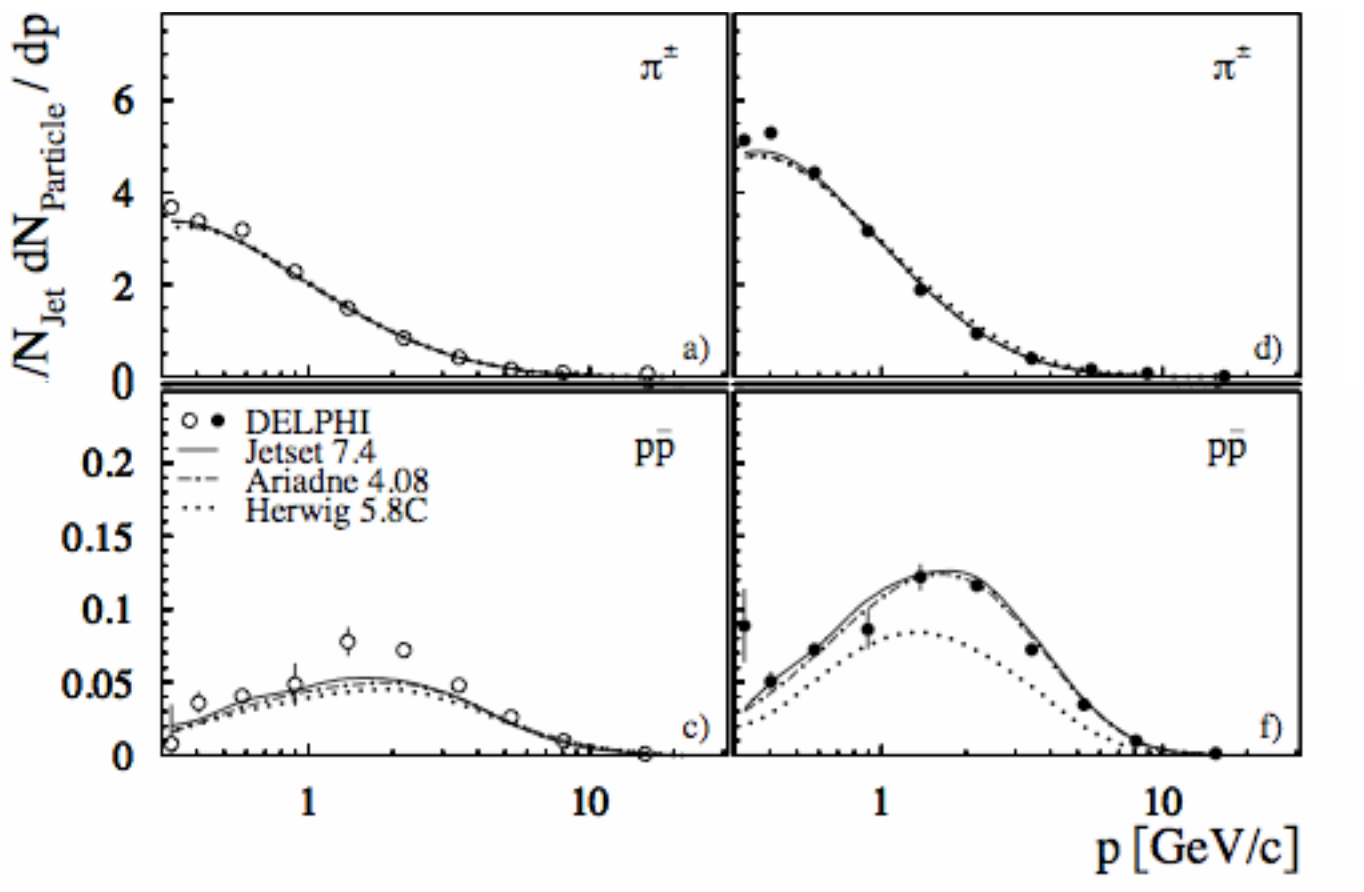
- baryon production difficult in fragmentation
    - need 3 quarks together

baryons via fragmentation

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

DELPHI e^+e^-

quark jets **gluon jets**



EPJ 17 207 (2000)

- baryon production difficult in fragmentation
    - need 3 quarks together
- makes baryons a good place to look for novel effects

recombination: when?

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- high phase space density
  - large system, low p_T

recombination: when?

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

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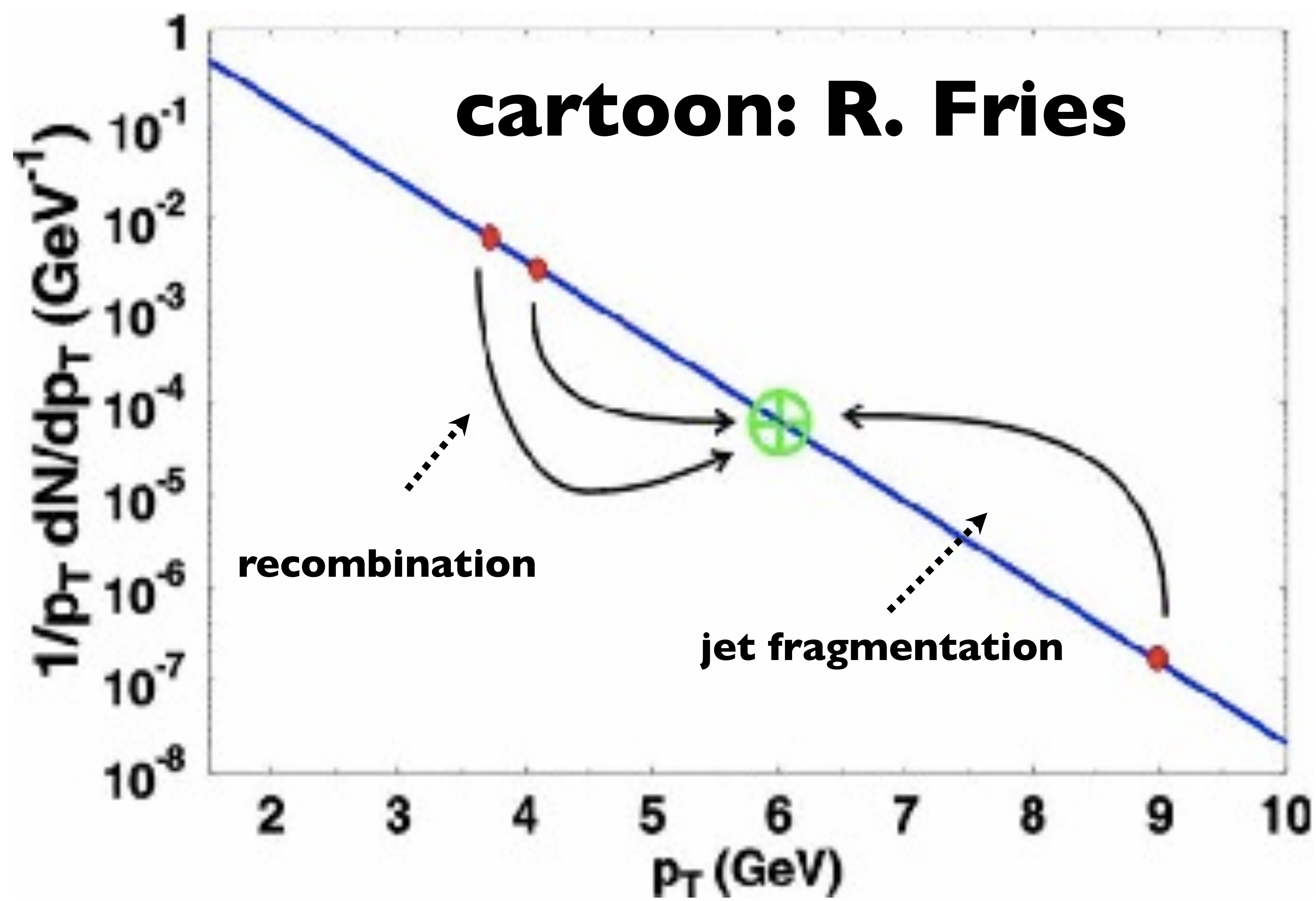
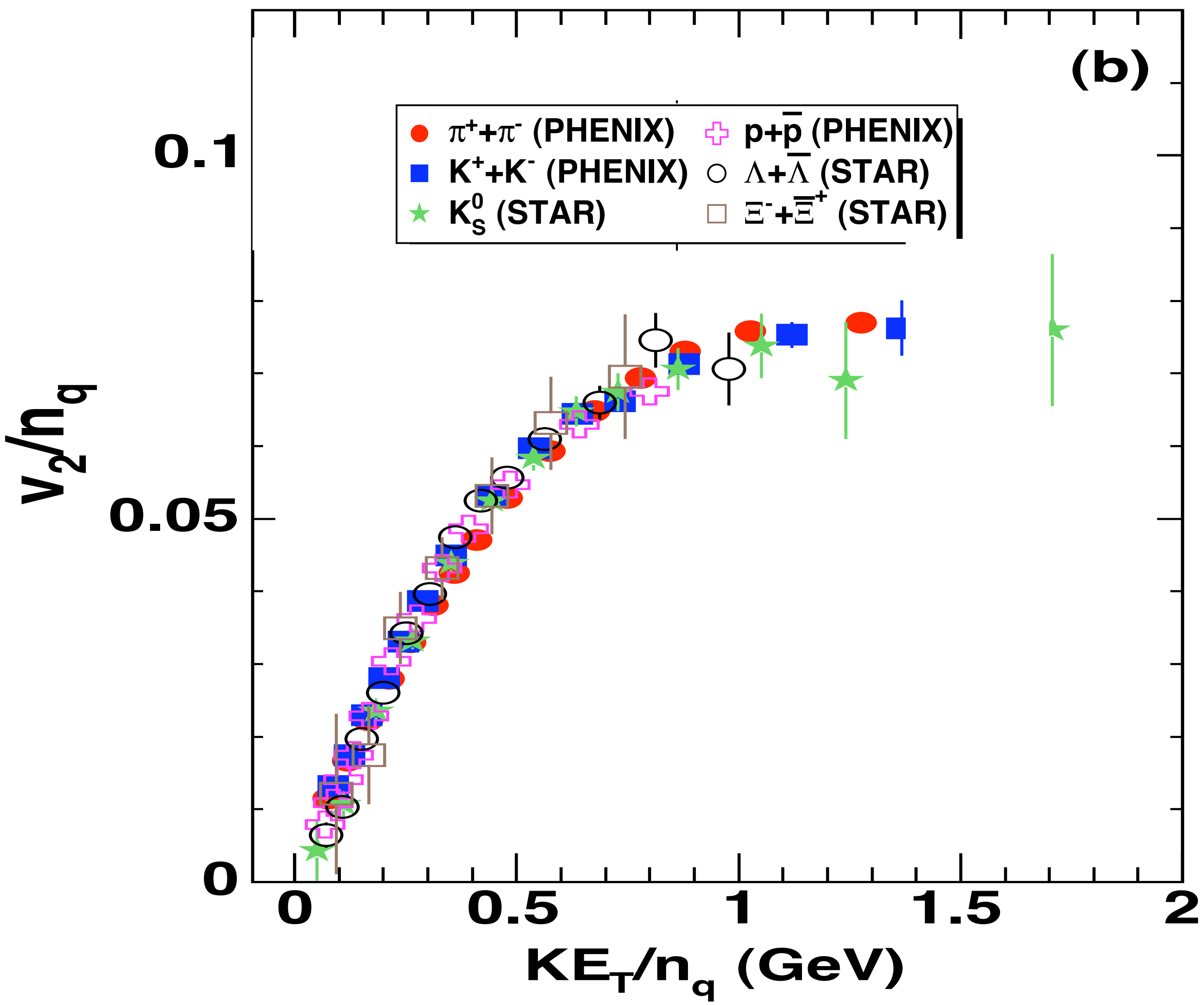


beyond recombination



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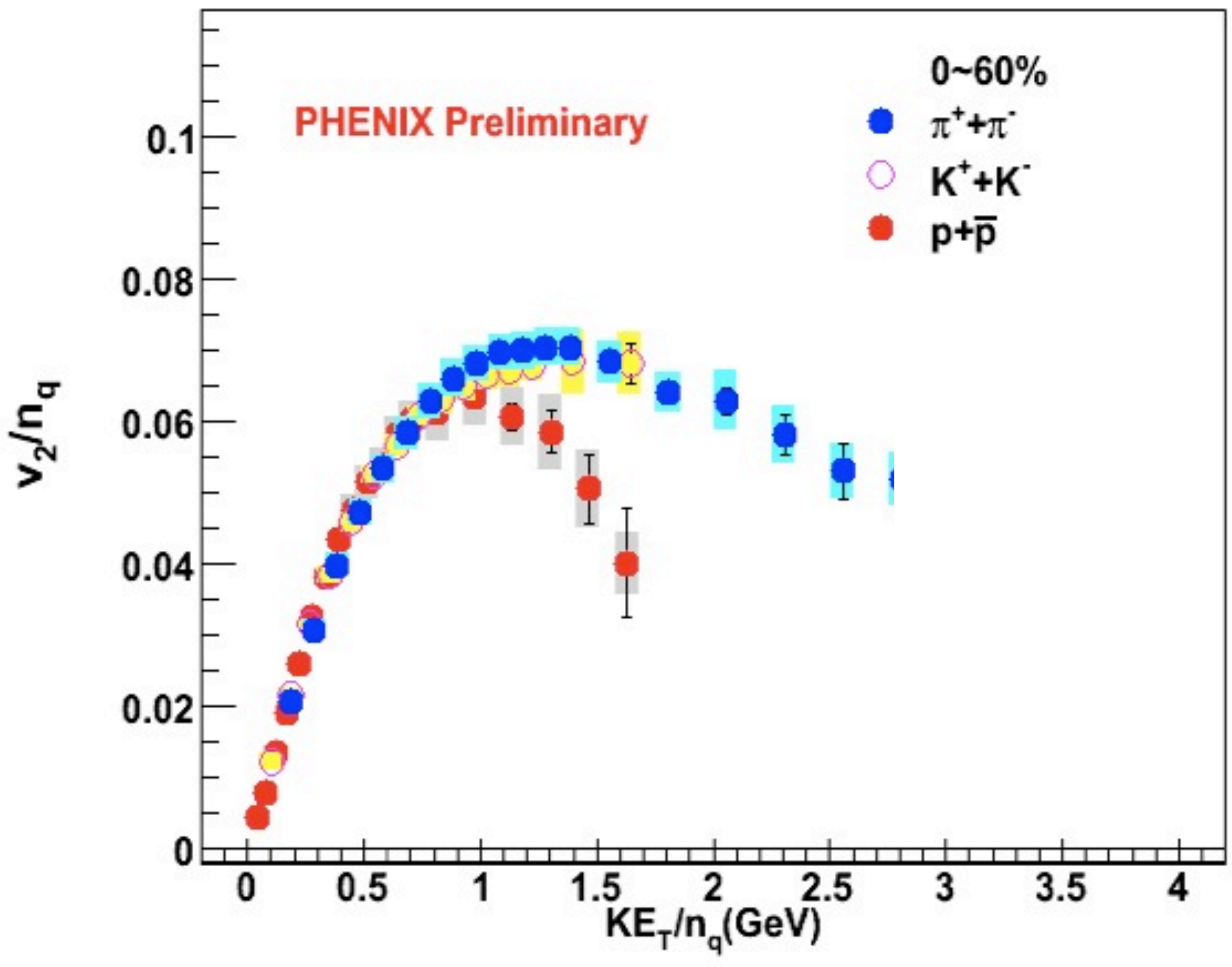

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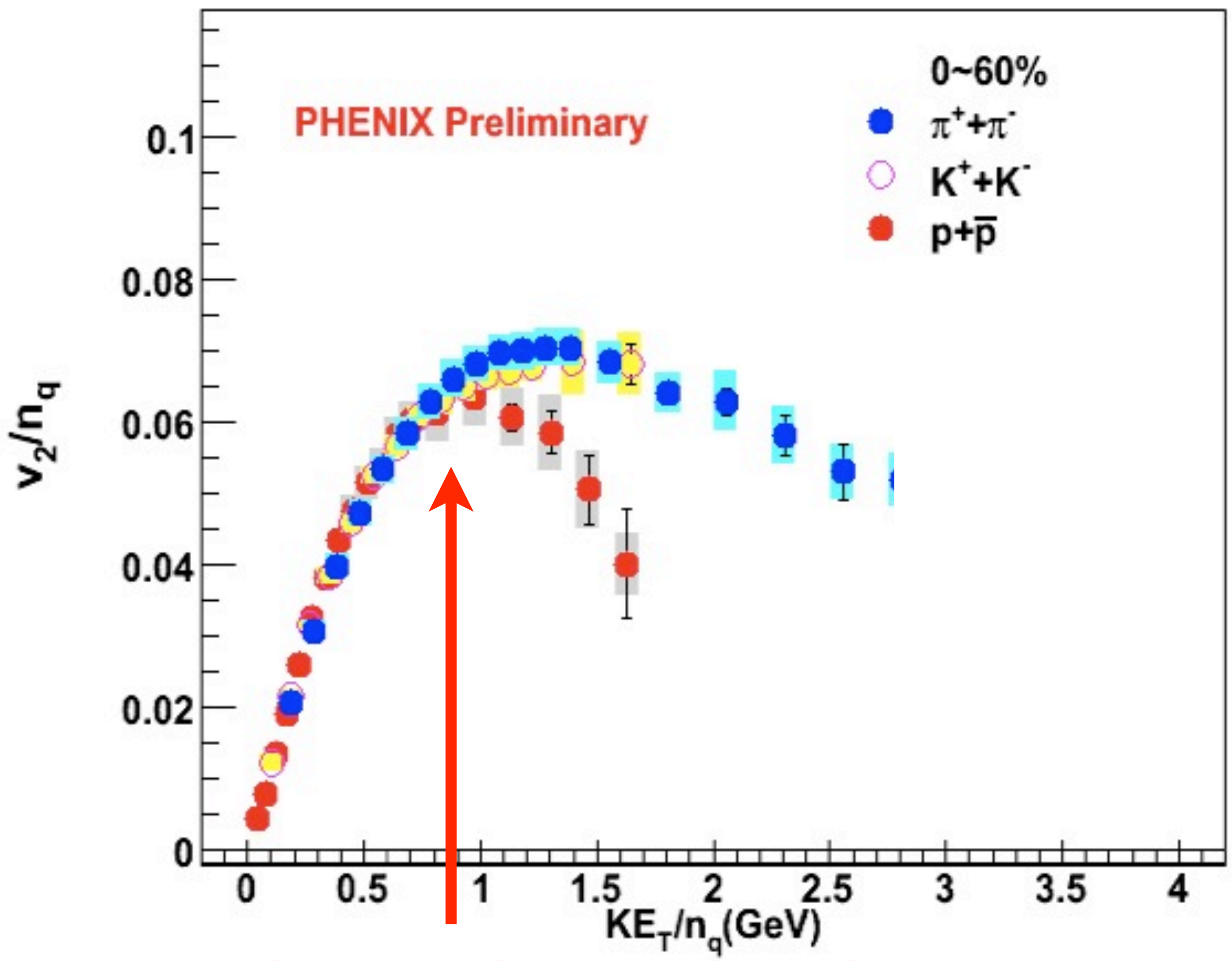
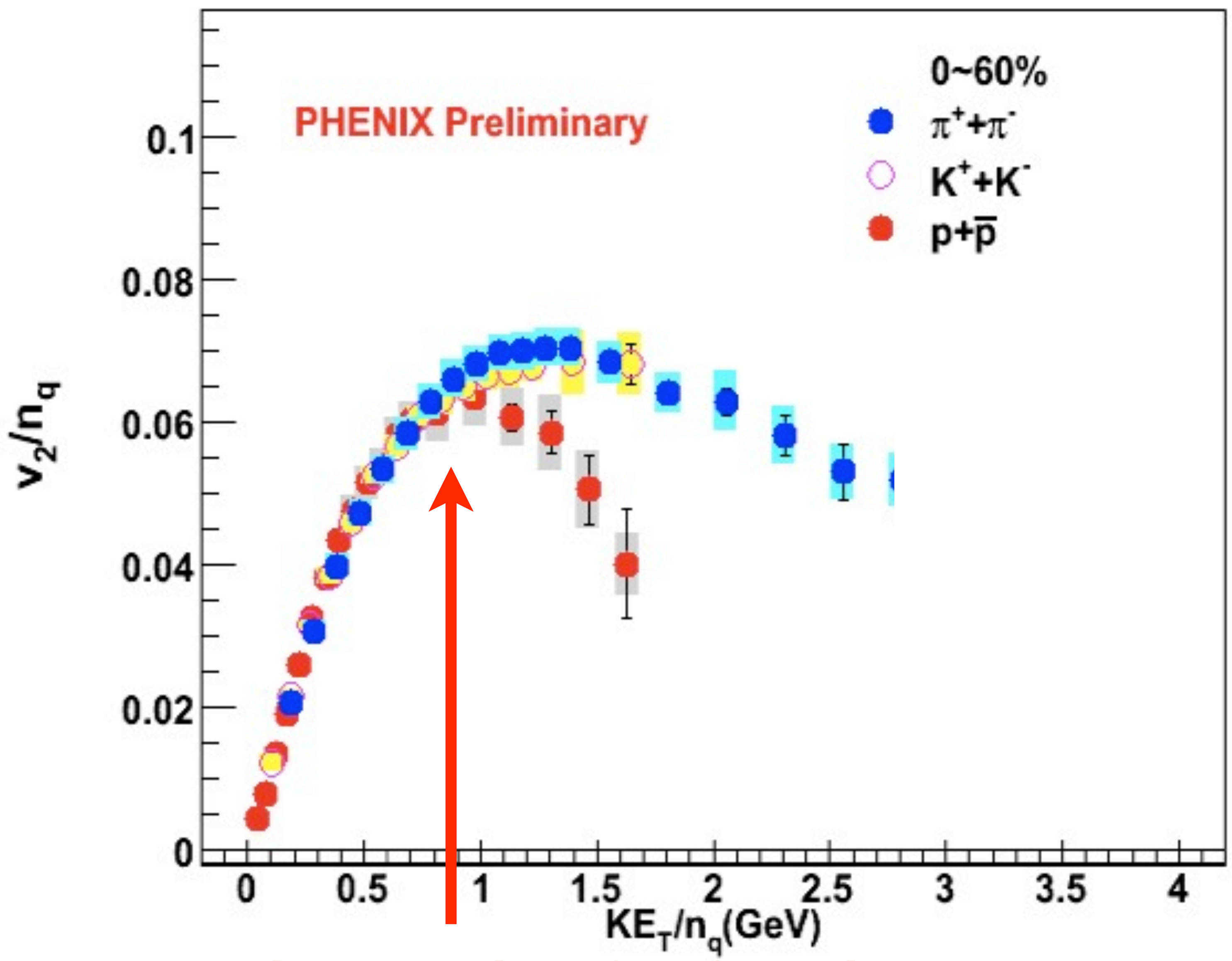


p_T(proton) ~ 3.5GeV/c

beyond recombination

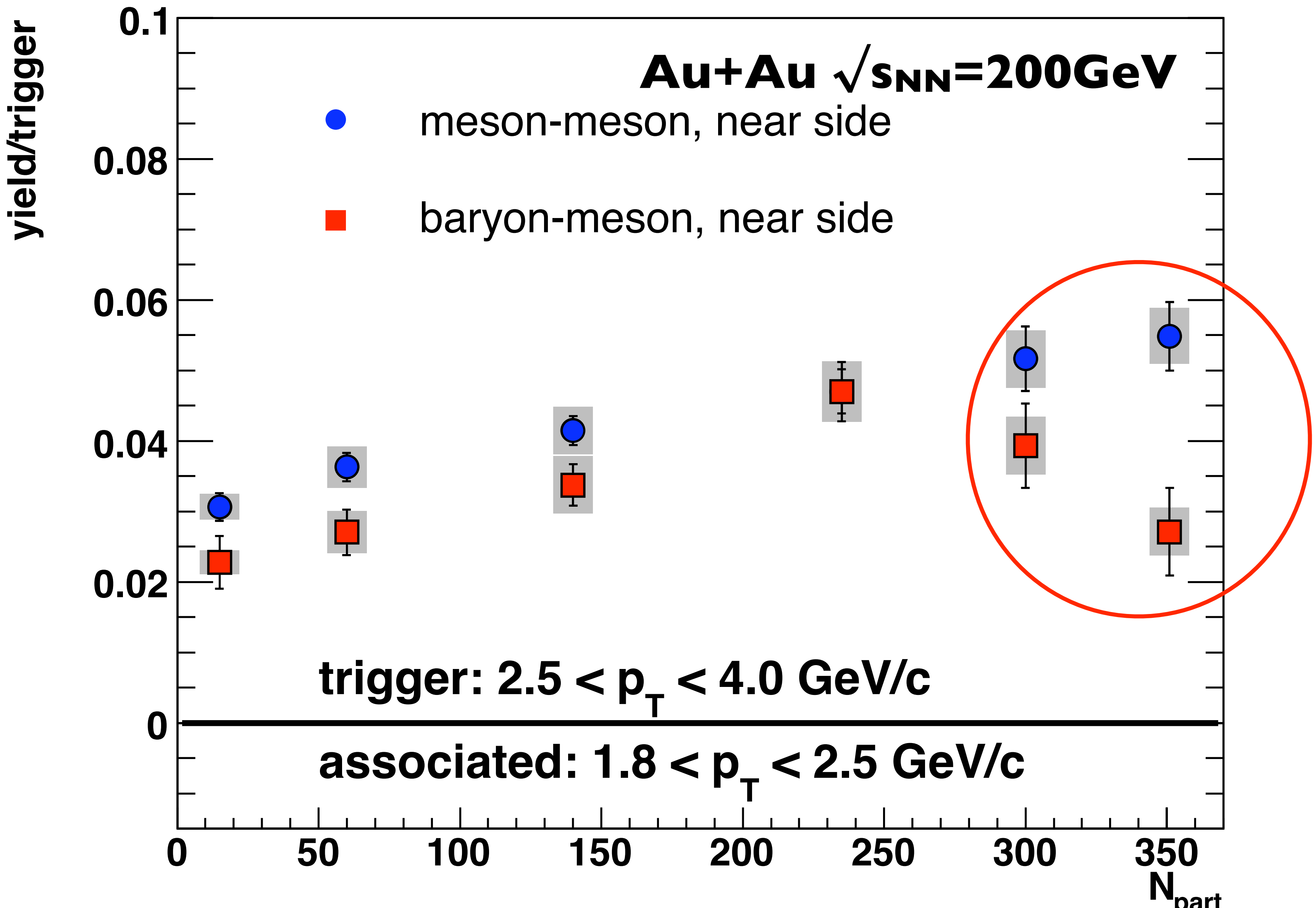


p_T(proton) ~ 3.5GeV/c

- scaling deviations: p_T ~ 3-4GeV/c

correlated baryons?

pairs from jet-like correlations



baryons: less same side correlations in the most central collisions

PHENIX, PLB 649 359 2007

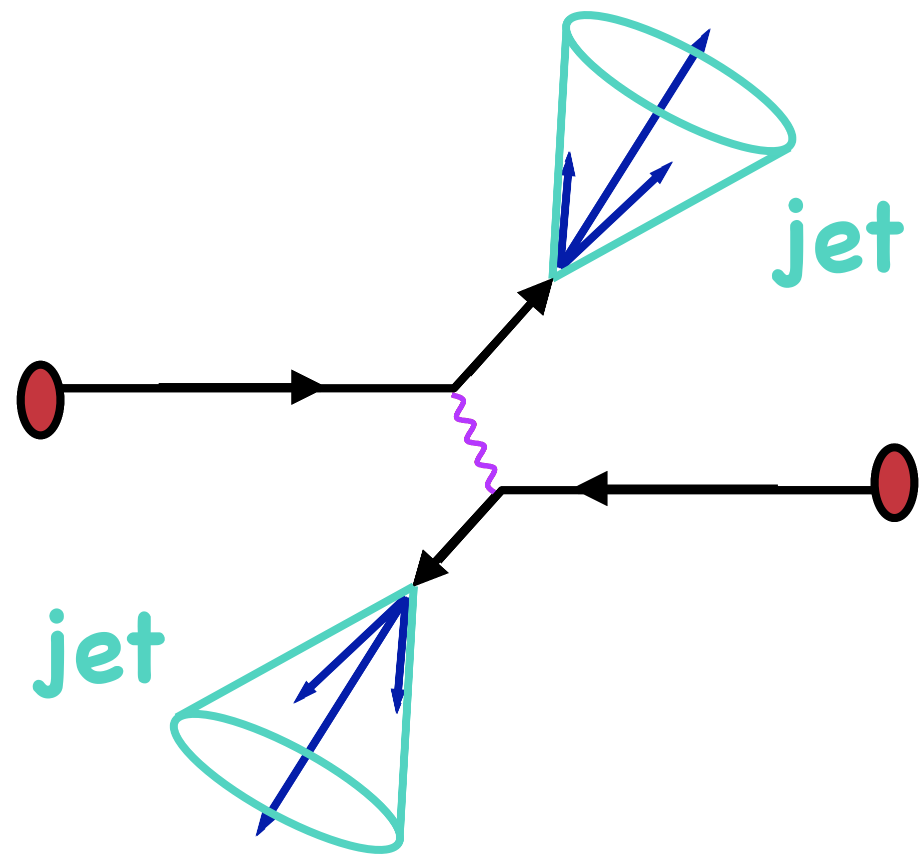
high p_T particle production

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

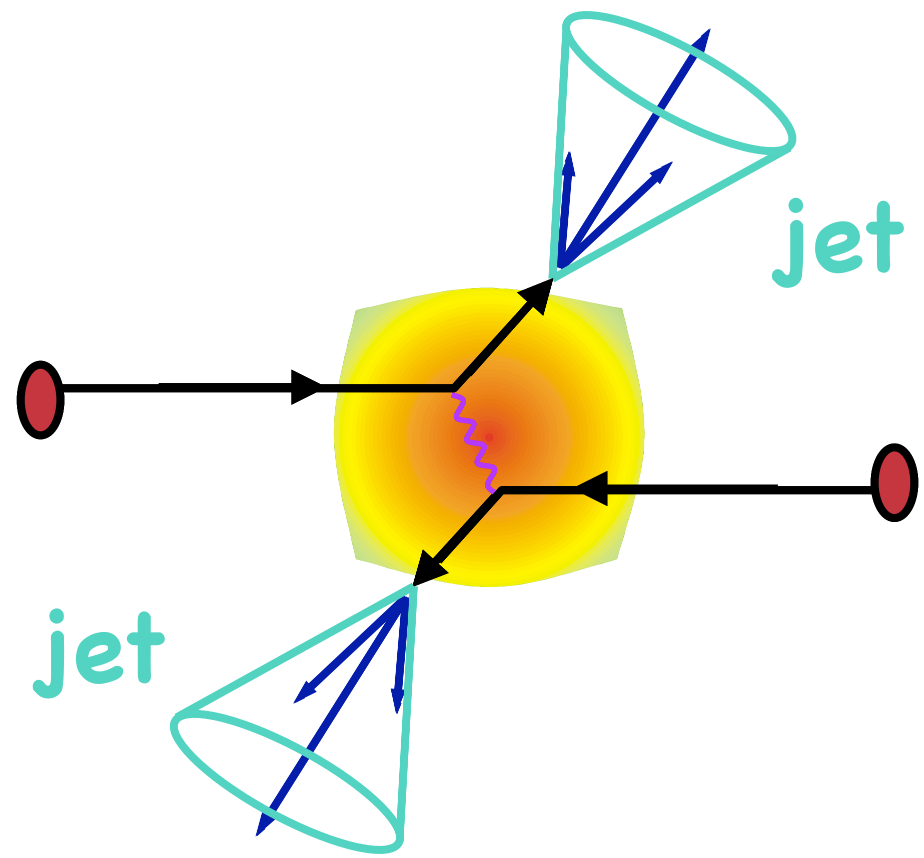
Au+Au collisions

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

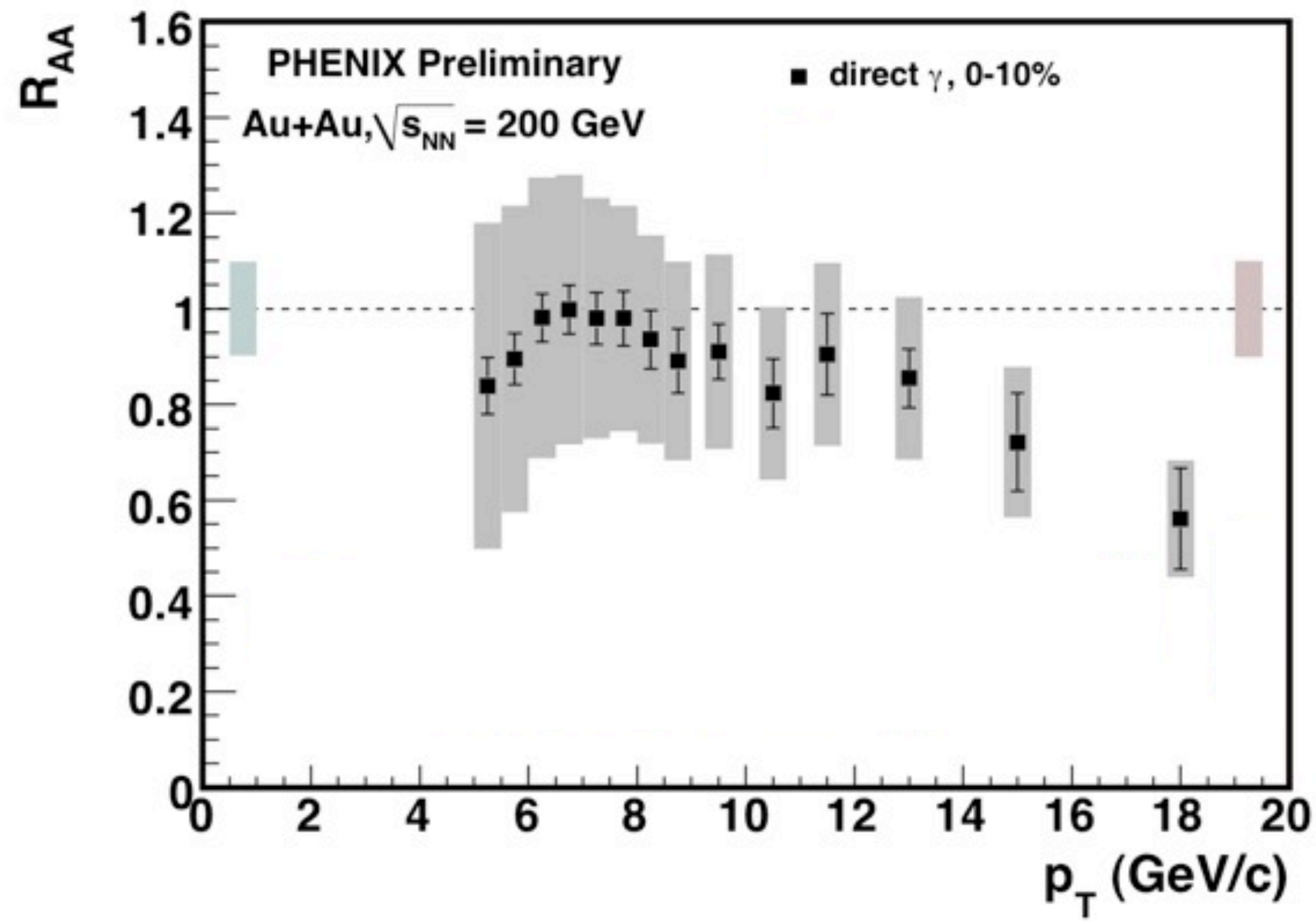


γ: control measurement

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

$R_{AA} = 1$

no nuclear effects



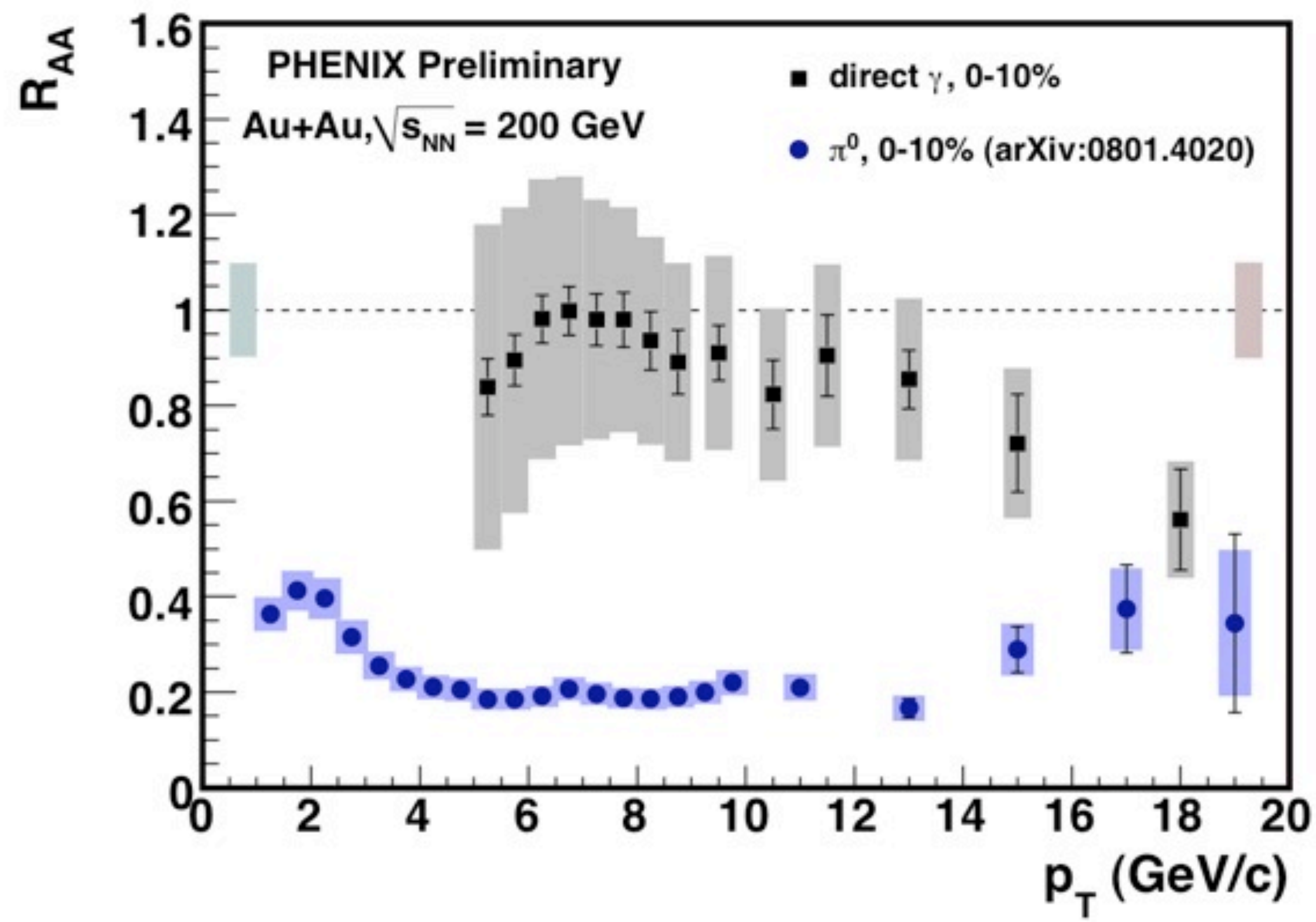
γ: no color charge → insensitive to produced matter
$R_{AA}(p_T<14 GeV/c)$ consistent with unity

π^0: light meson

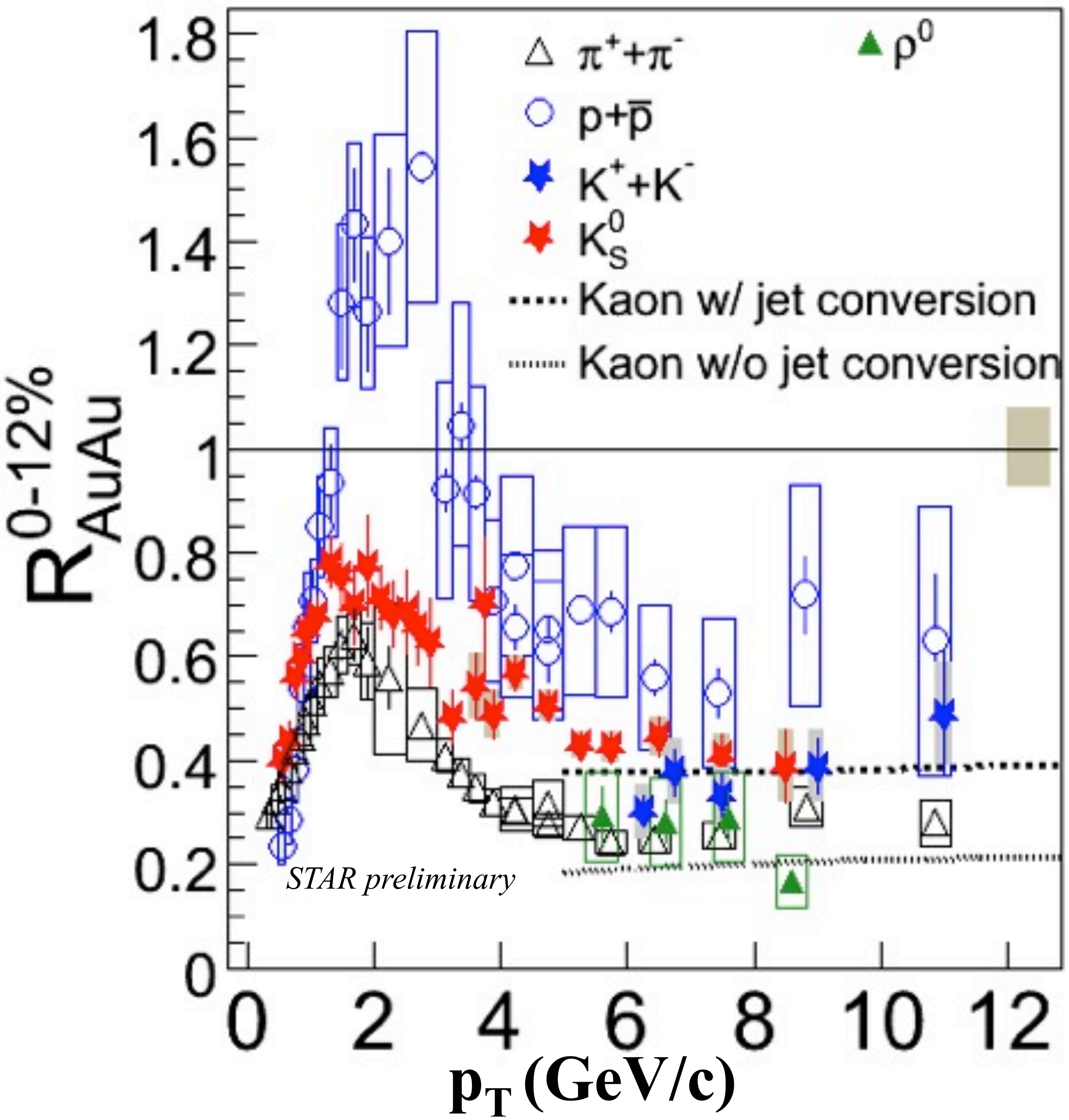
$$R_{AA} = \frac{yield_{AA}}{yield_{pp} * N_{coll}}$$

$R_{AA} << 1$

parton energy loss



and protons...



- R_{AA}(p,pbar) > $R_{AA}(\pi)$
- even @ high p_T, baryon/meson differences persist!
- inconsistent with parton energy loss & vacuum fragmentation

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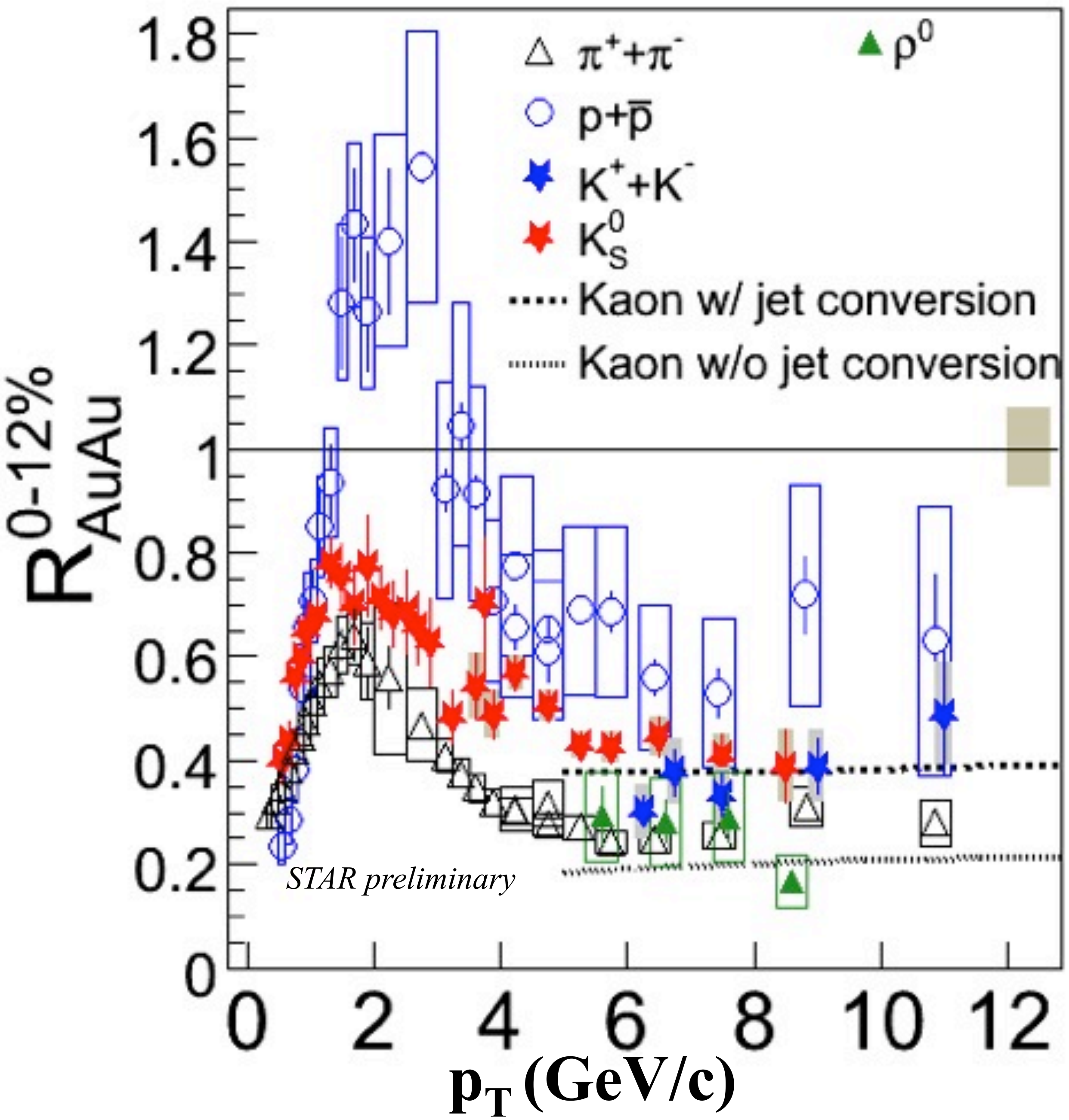

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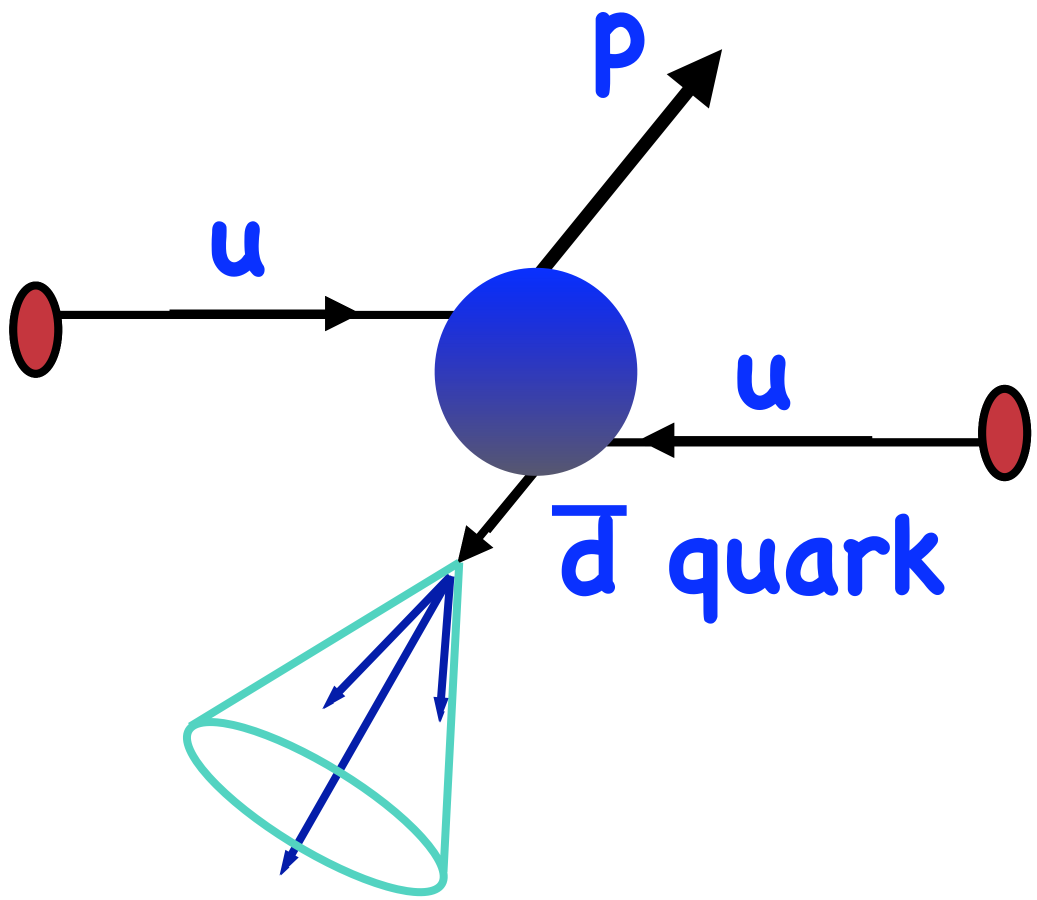
are baryons coming from somewhere else?

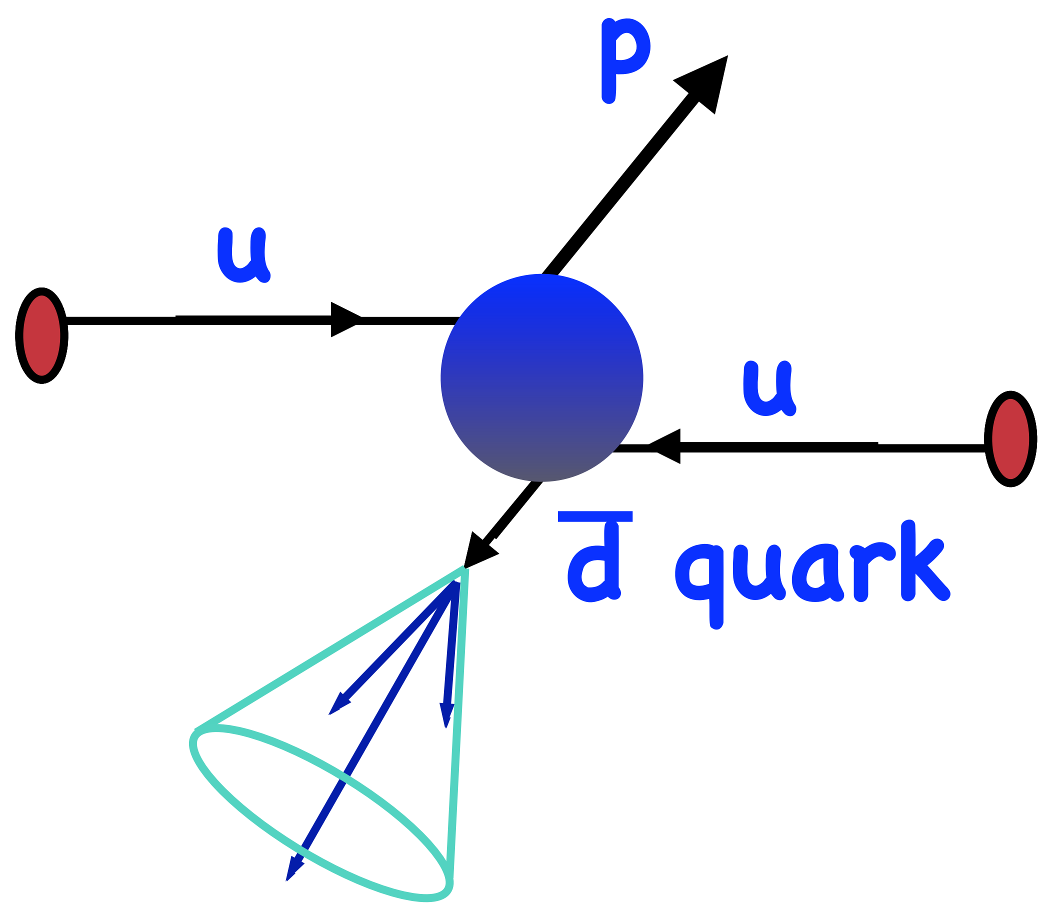
direct proton production?



$uu \rightarrow p\bar{d}$

Brodsky & AMS PLB 668 111 (2008)

direct proton production?

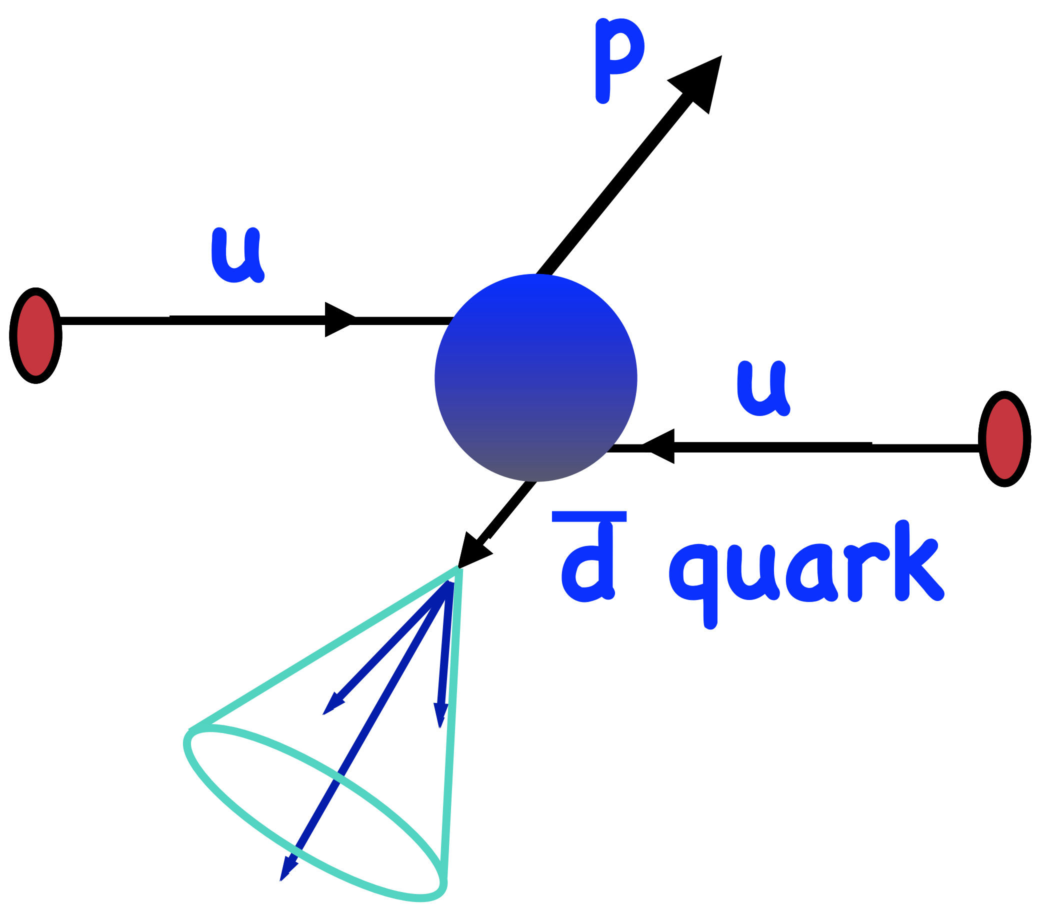


$uu \rightarrow p\bar{d}$

- color singlet proton directly produced within hard scattering

Brodsky & AMS PLB 668 111 (2008)

direct proton production?

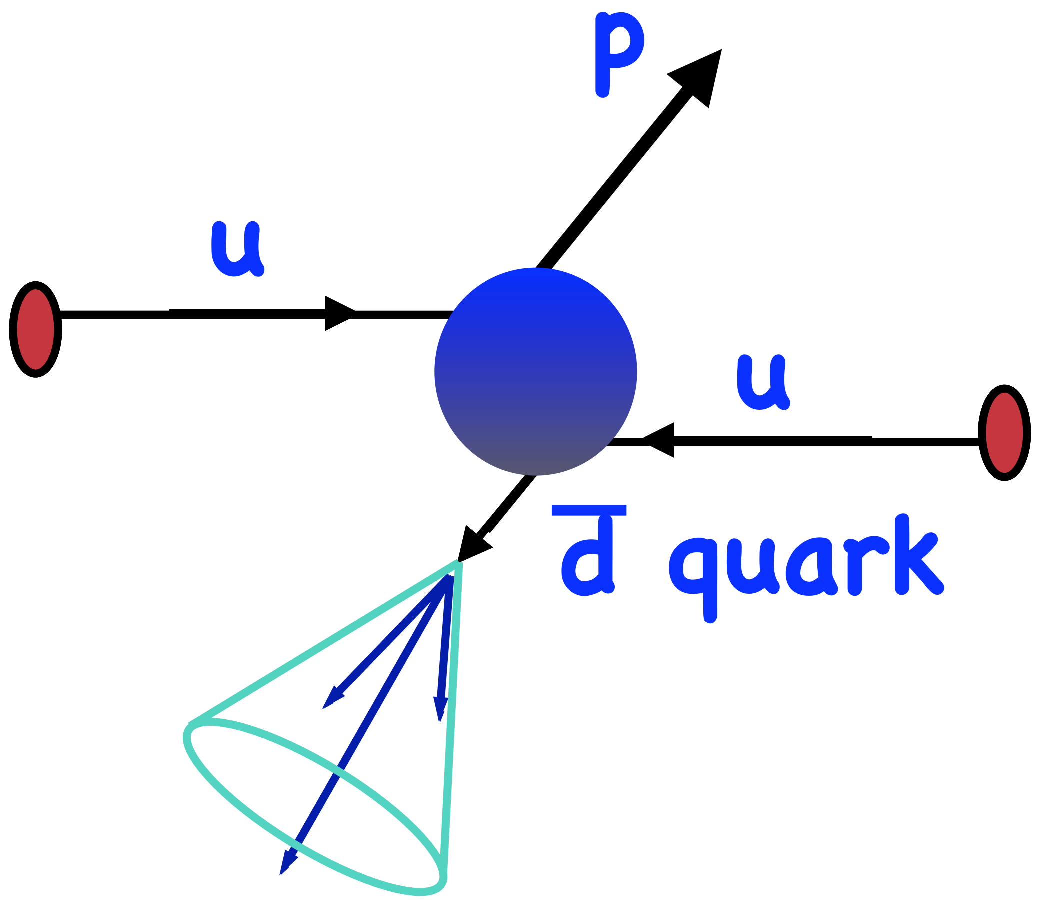


$uu \to p\bar{d}$

- color singlet proton directly produced within hard scattering
- small color neutral protons: color transparent

Brodsky & AMS PLB 668 111 (2008)

direct proton production?



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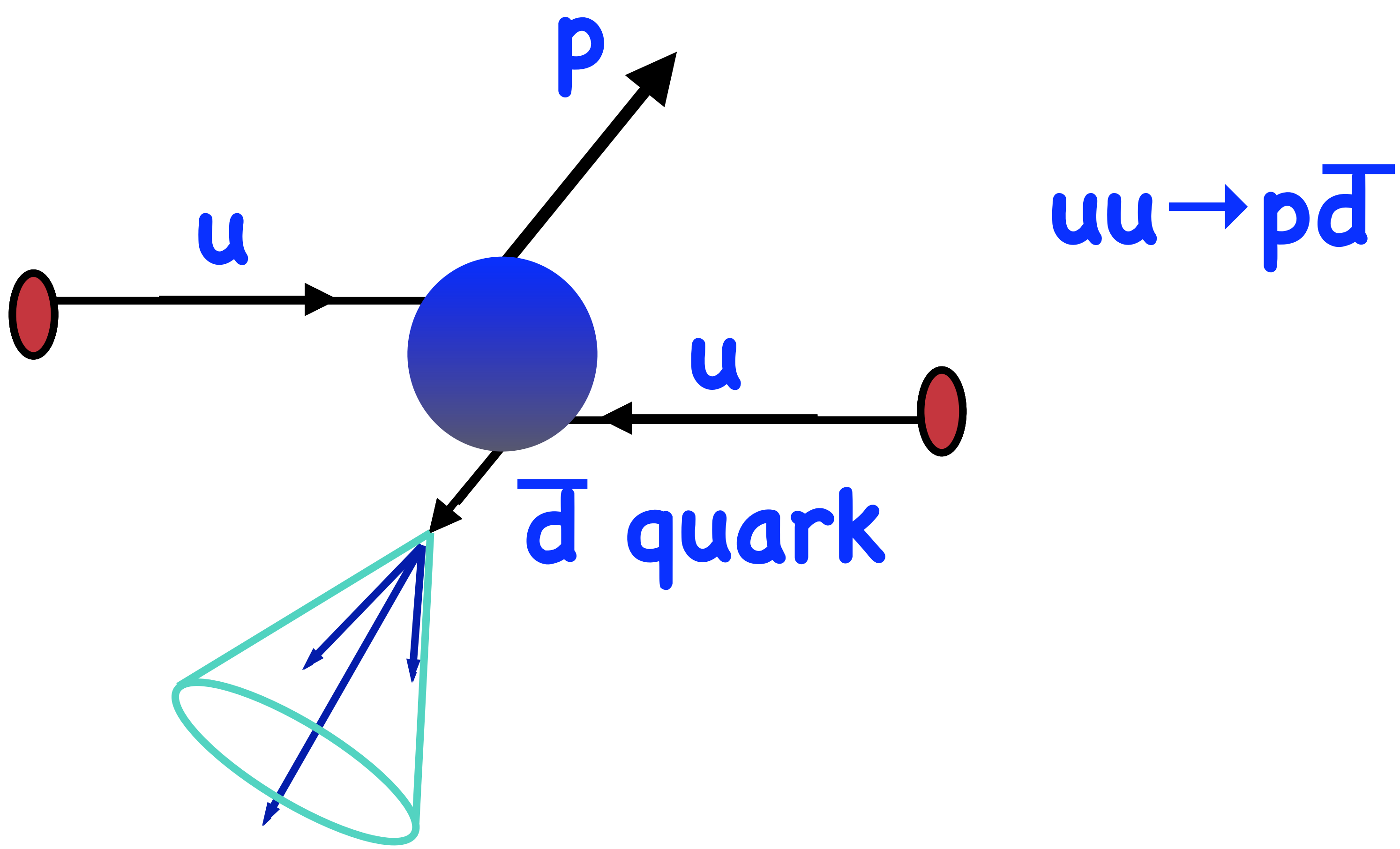

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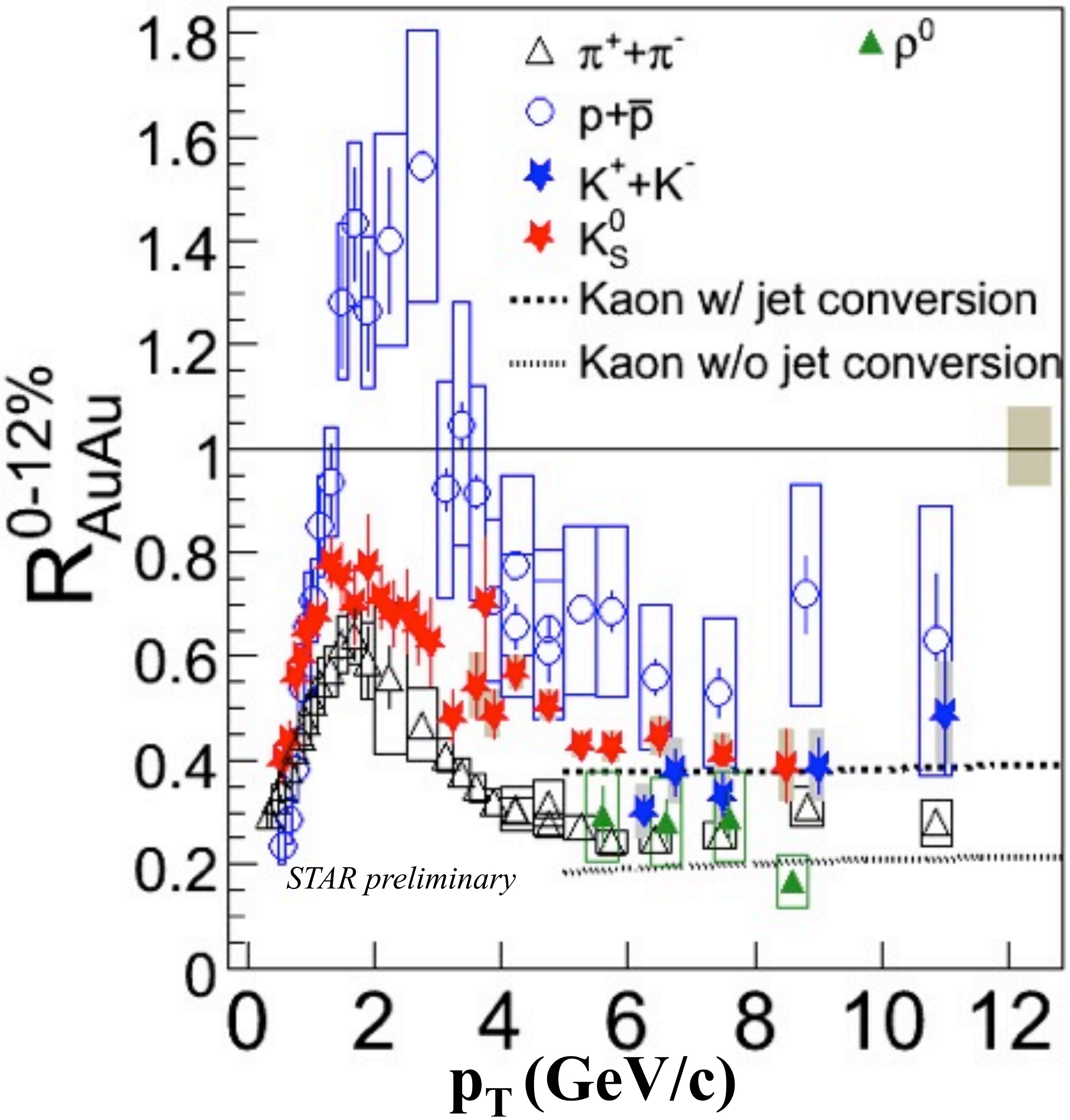
Brodsky & AMS PLB 668 111 (2008)

filter: hot nuclear matter



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

x_T scaling

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

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

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

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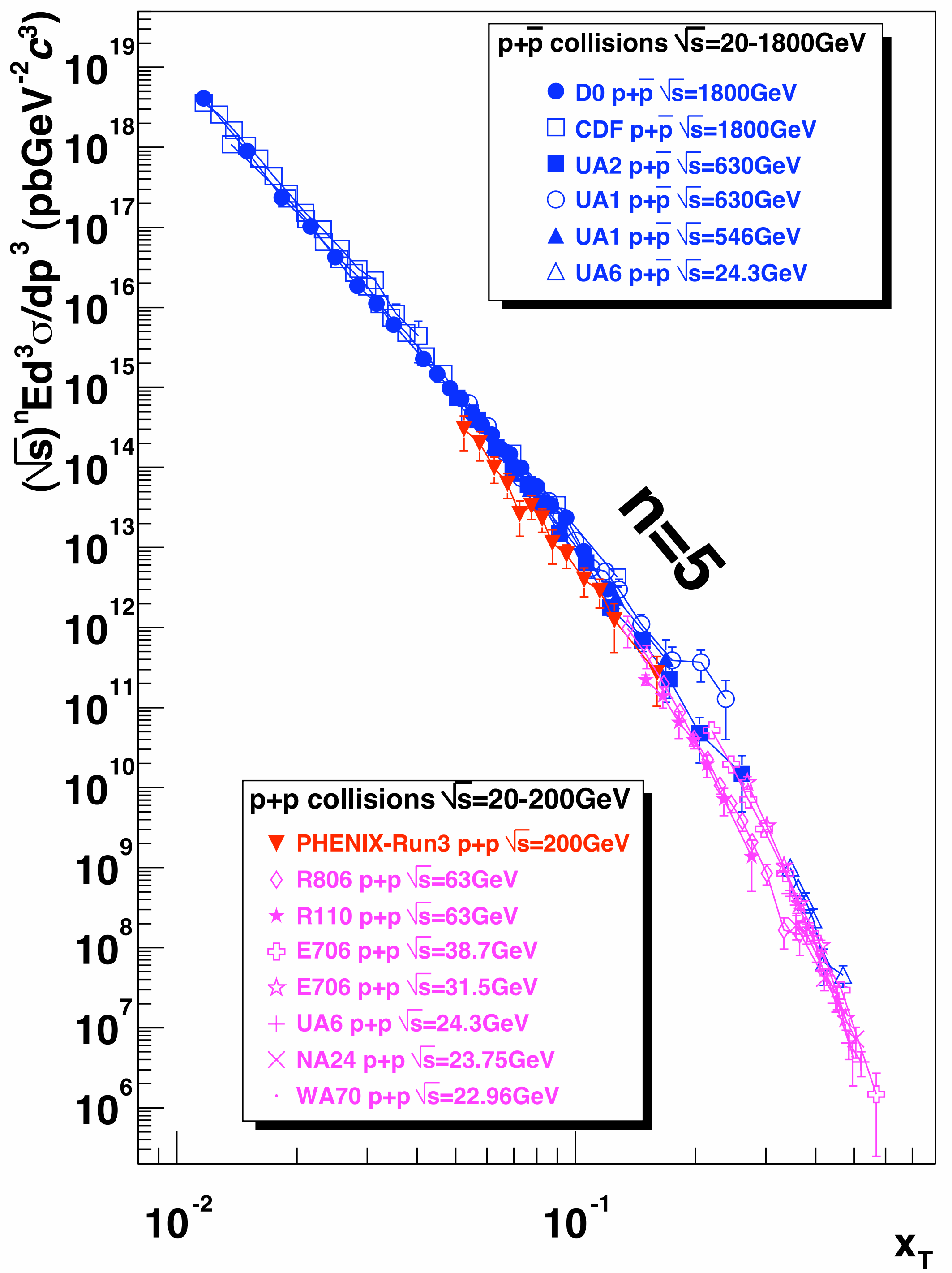
- n related to "twist", number of participants, of the hard scattering
- leading twist: g+g→g+g, n=4
- higher twist: qq→p+qbar, n=8
- n increased slightly
  - running coupling, evolution of PDFs & FFs

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

x_T scaling: photons

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

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

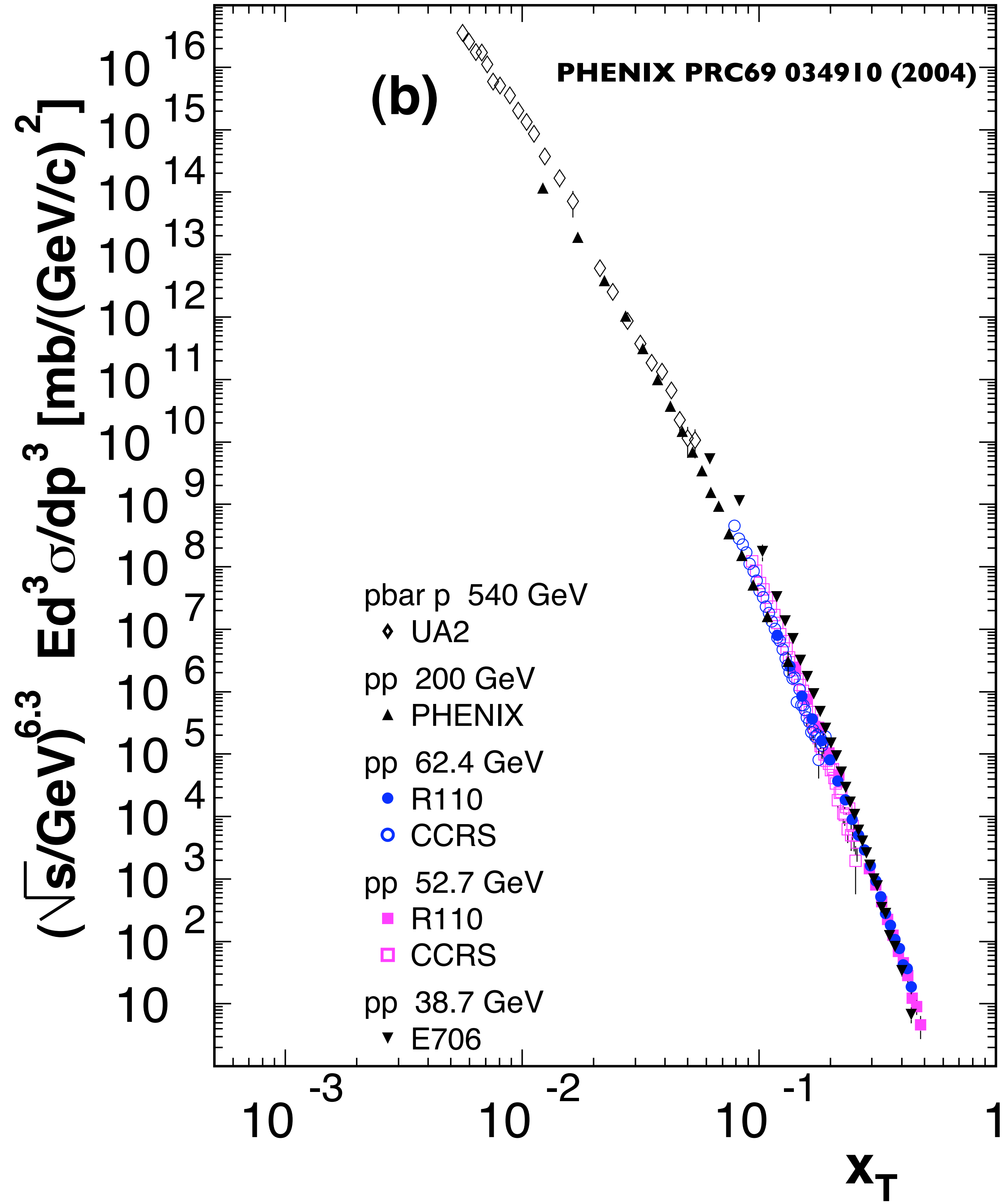


nucl-ex/0611008

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

x_T scaling: pions

- good scaling over a wide range of xT
- higher exponent than the photons n=6.3



Anne M. Sickles, April 29, 2009

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

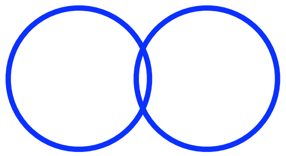
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}} G(x_T)$$

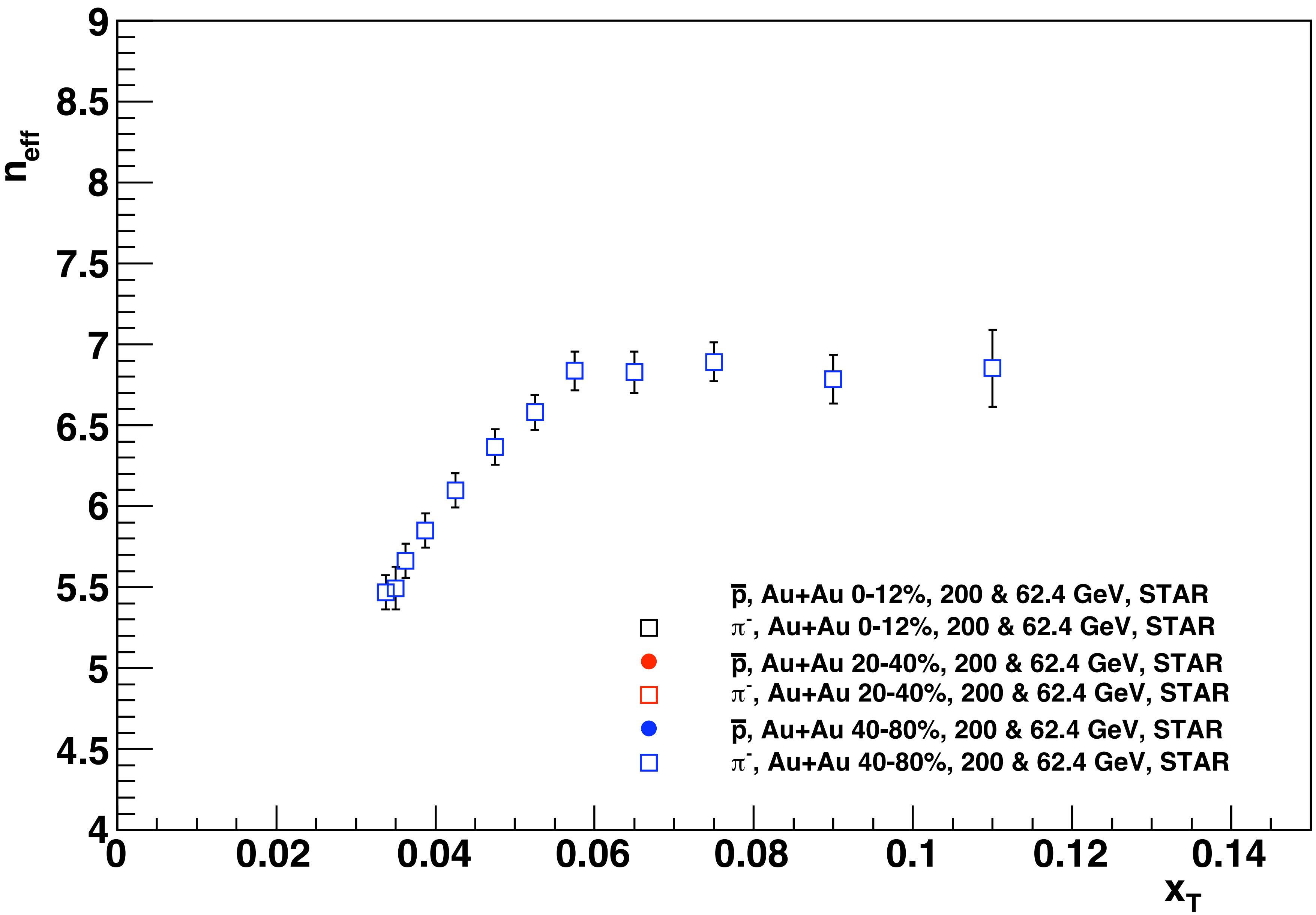
Cahalan et al PRD 11 1199 (1975)

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

- use measurements at two collision energies to extract the effective exponent

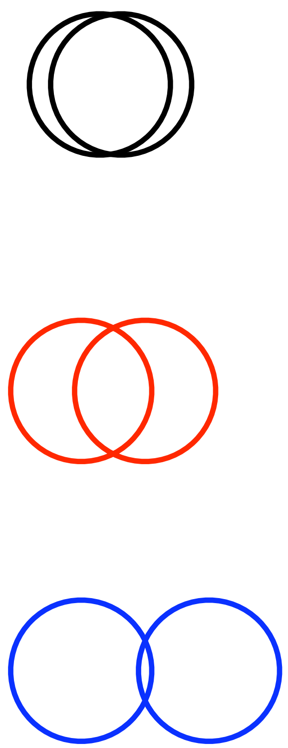
pions: heavy ion collisions

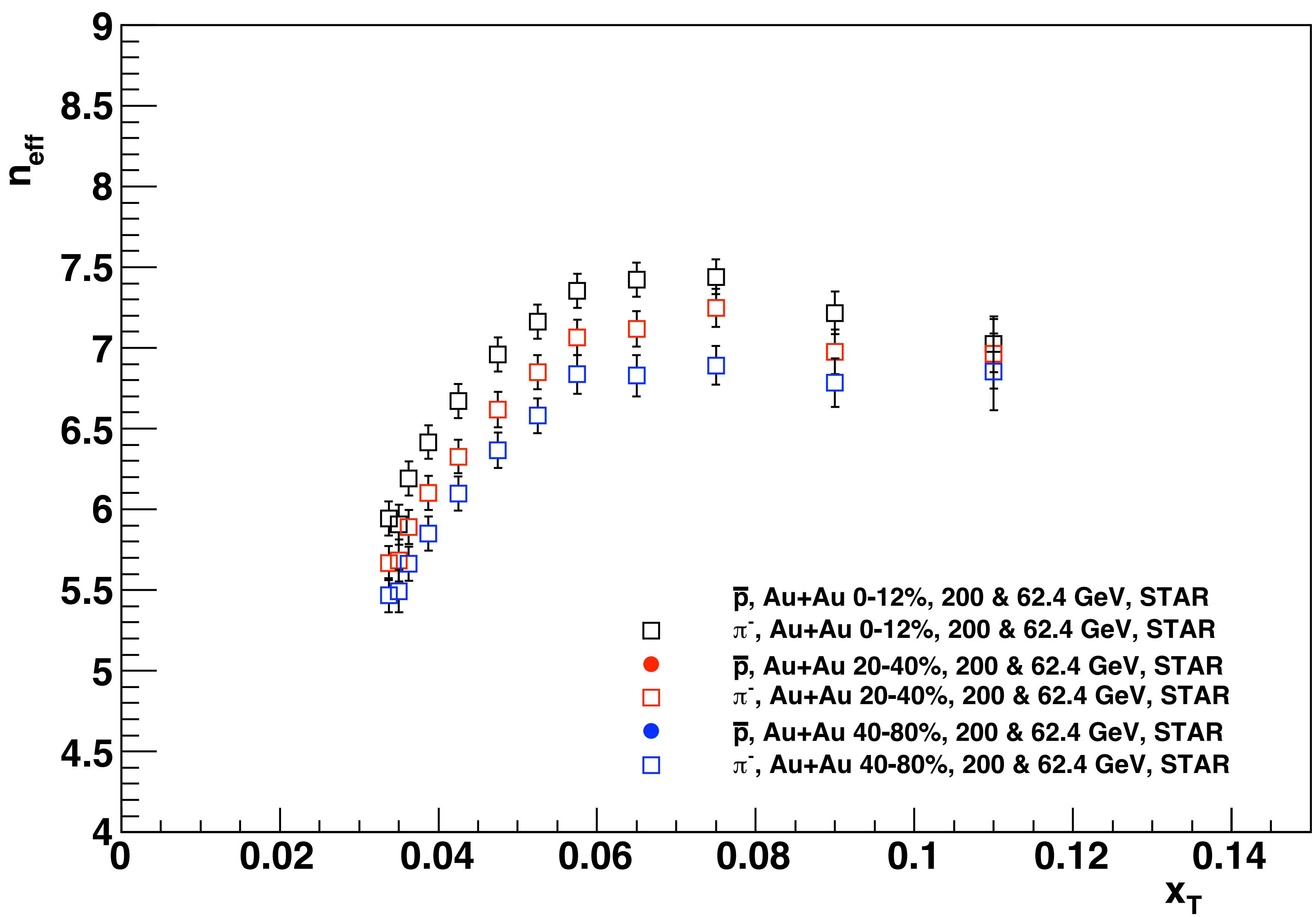




data from: STAR PLB 655 104 (2007)

pions: heavy ion collisions





data from: STAR PLB 655 104 (2007)

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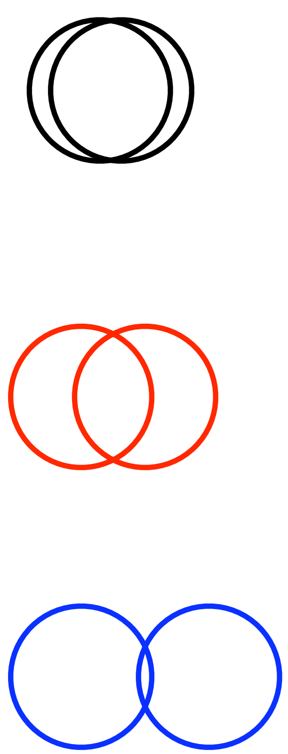
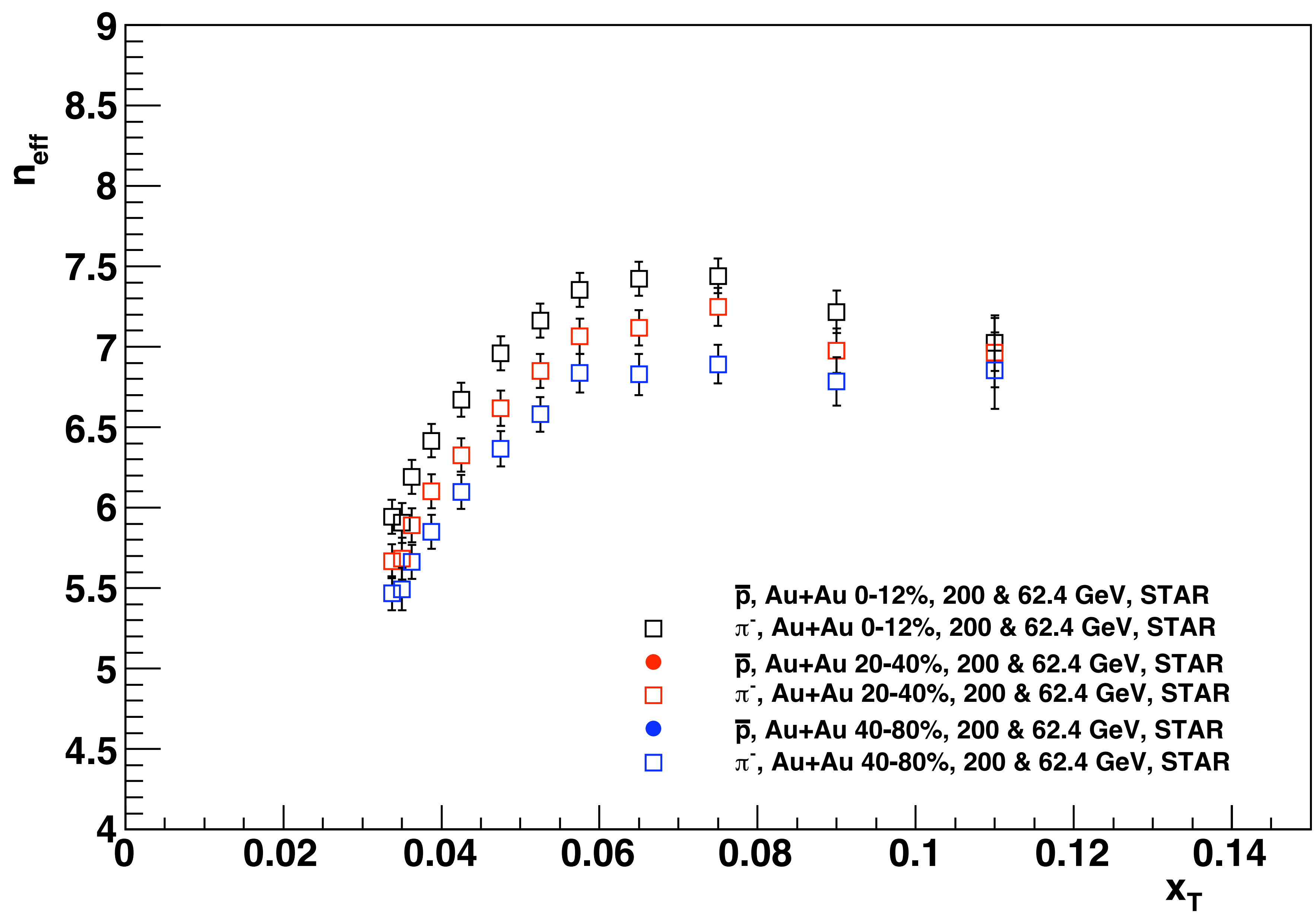
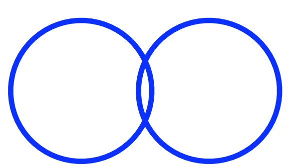


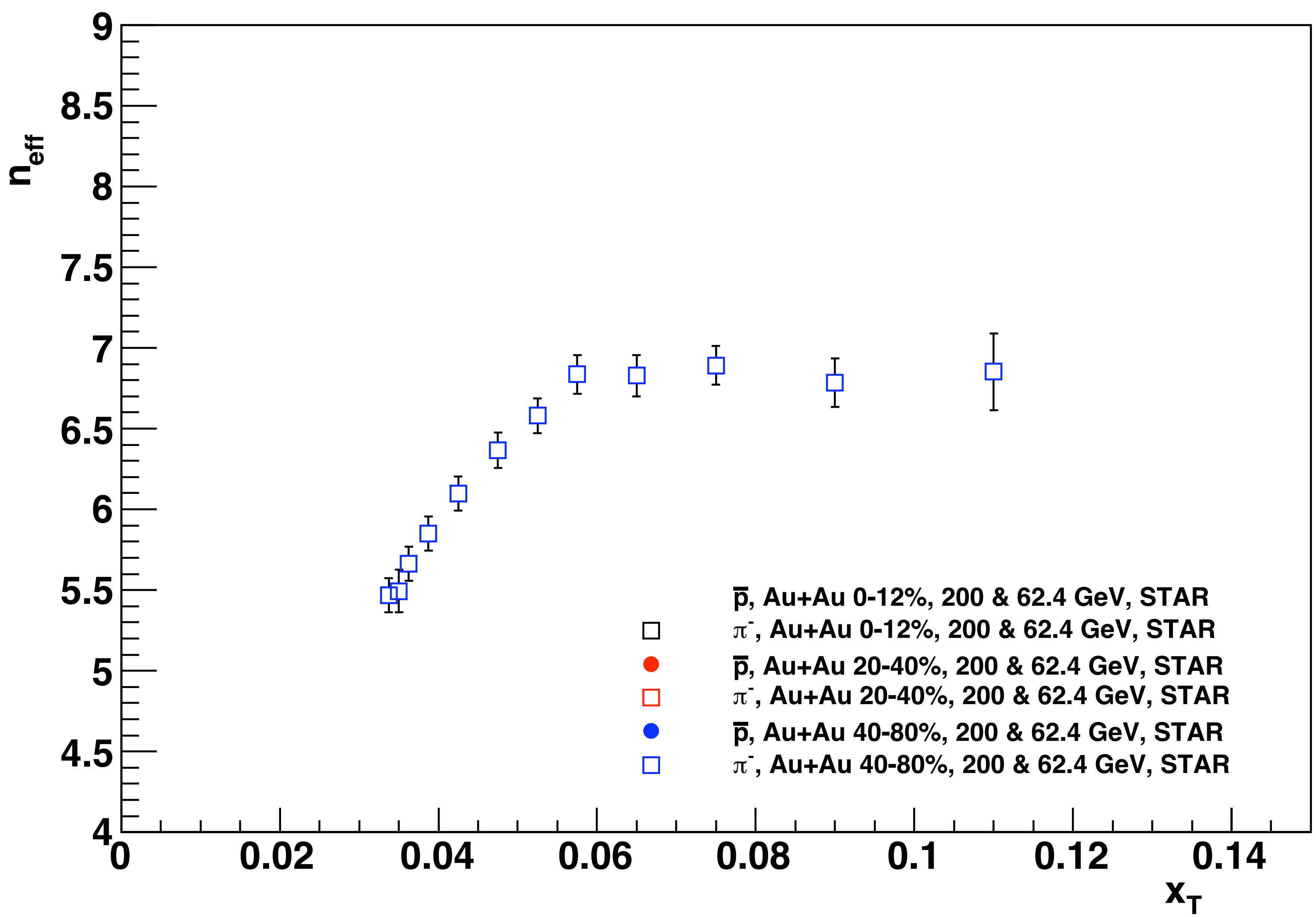


data from: STAR PLB 655 104 (2007)

- n_{eff}(pions) increases with centrality

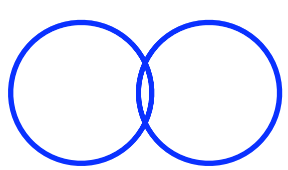
anti-protons: heavy ion collisions

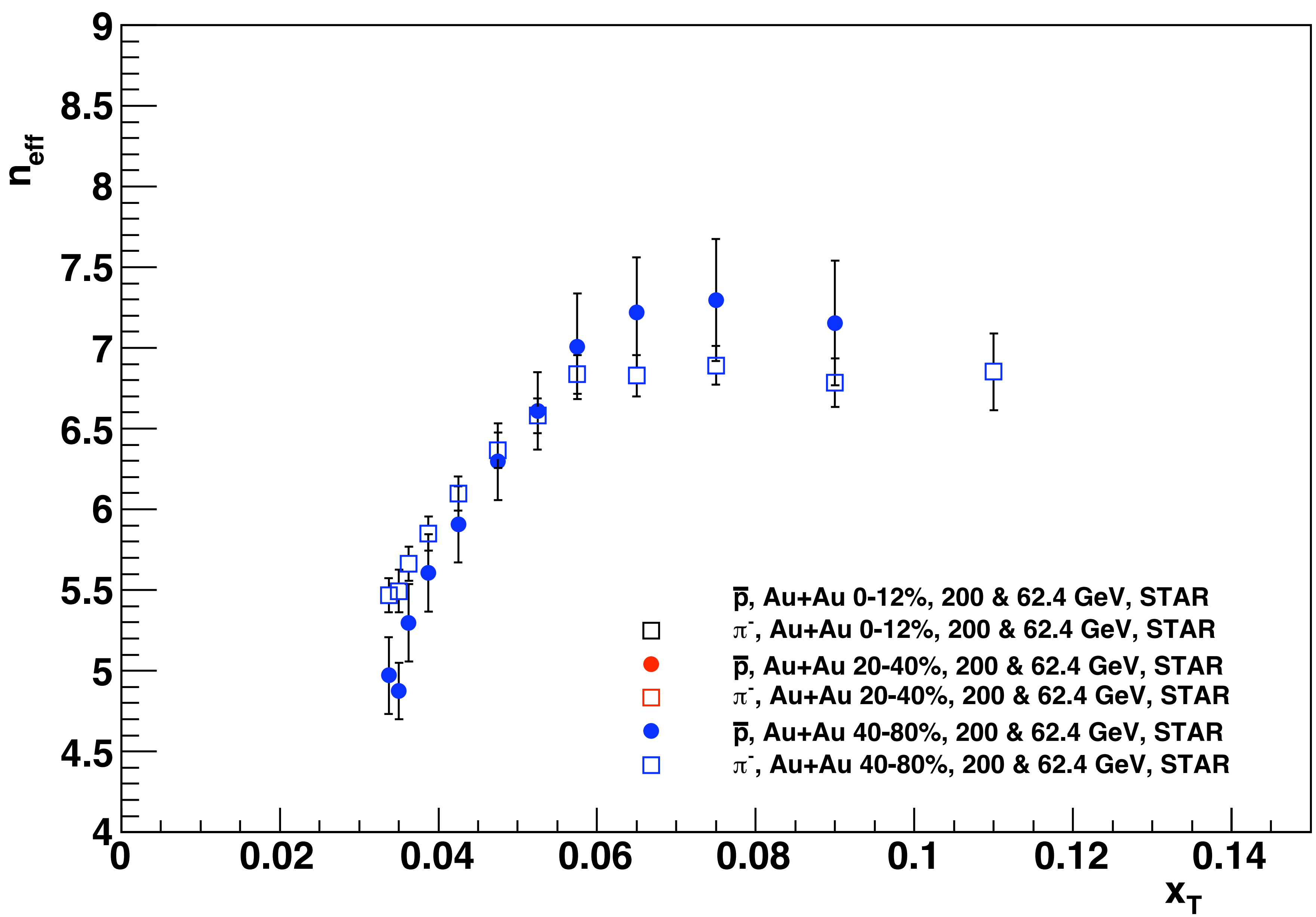




data from: STAR PLB 655 104 (2007)

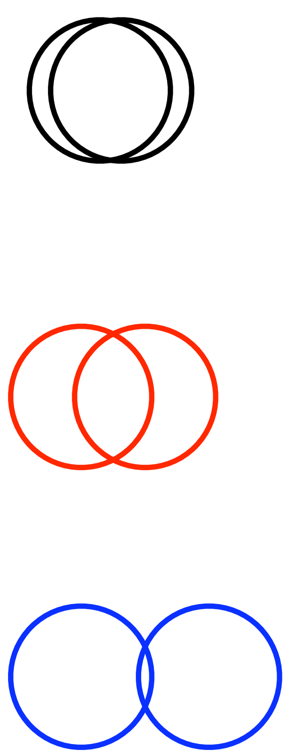
anti-protons: heavy ion collisions

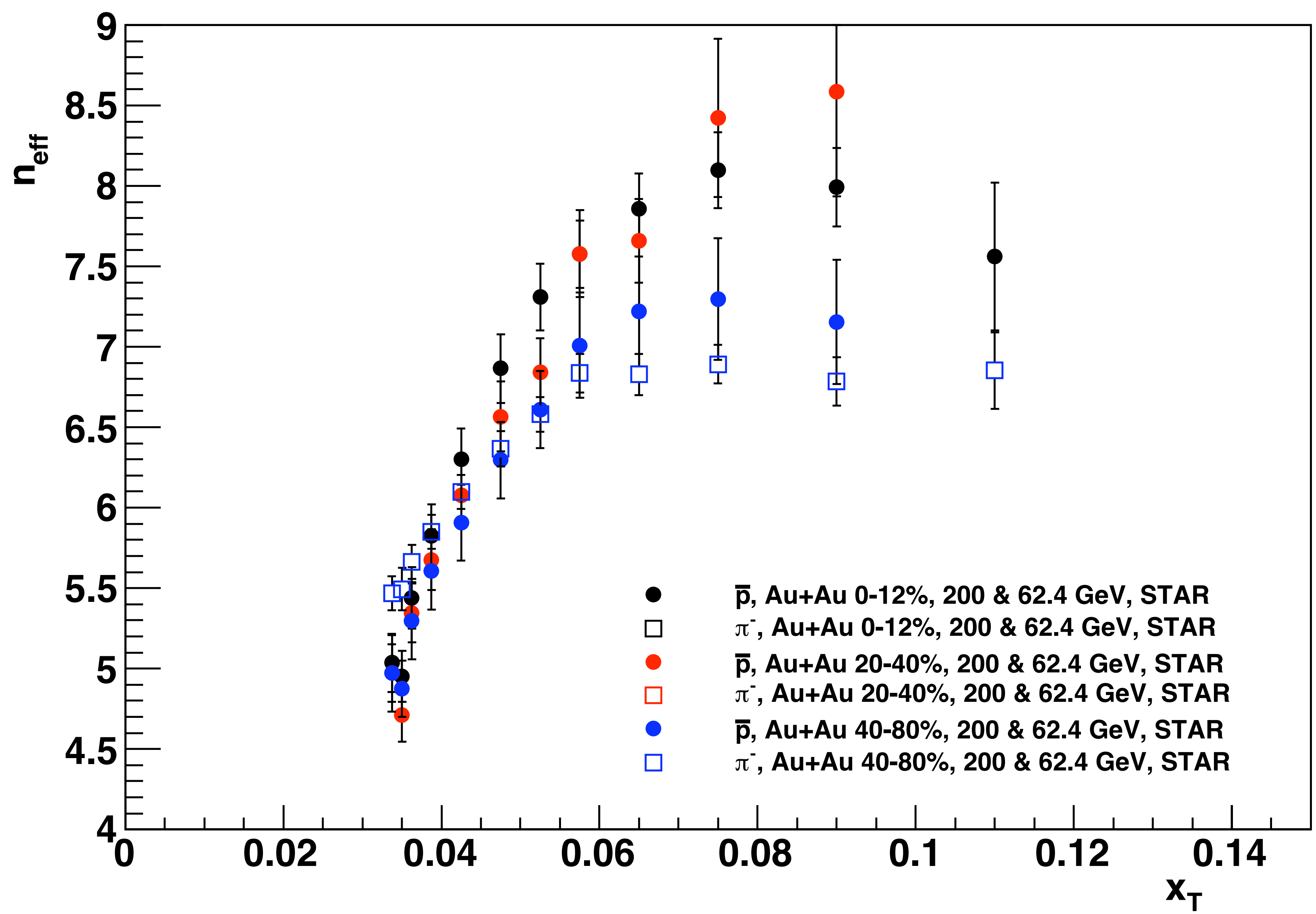




data from: STAR PLB 655 104 (2007)

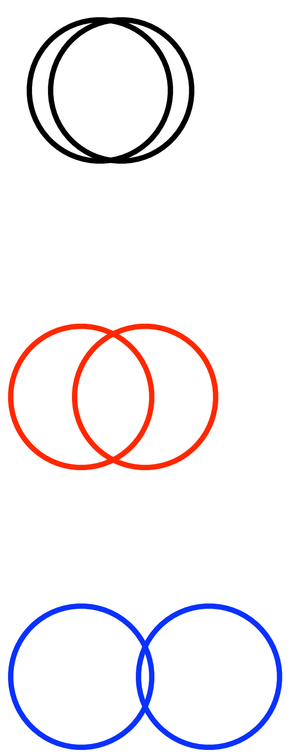
anti-protons: heavy ion collisions

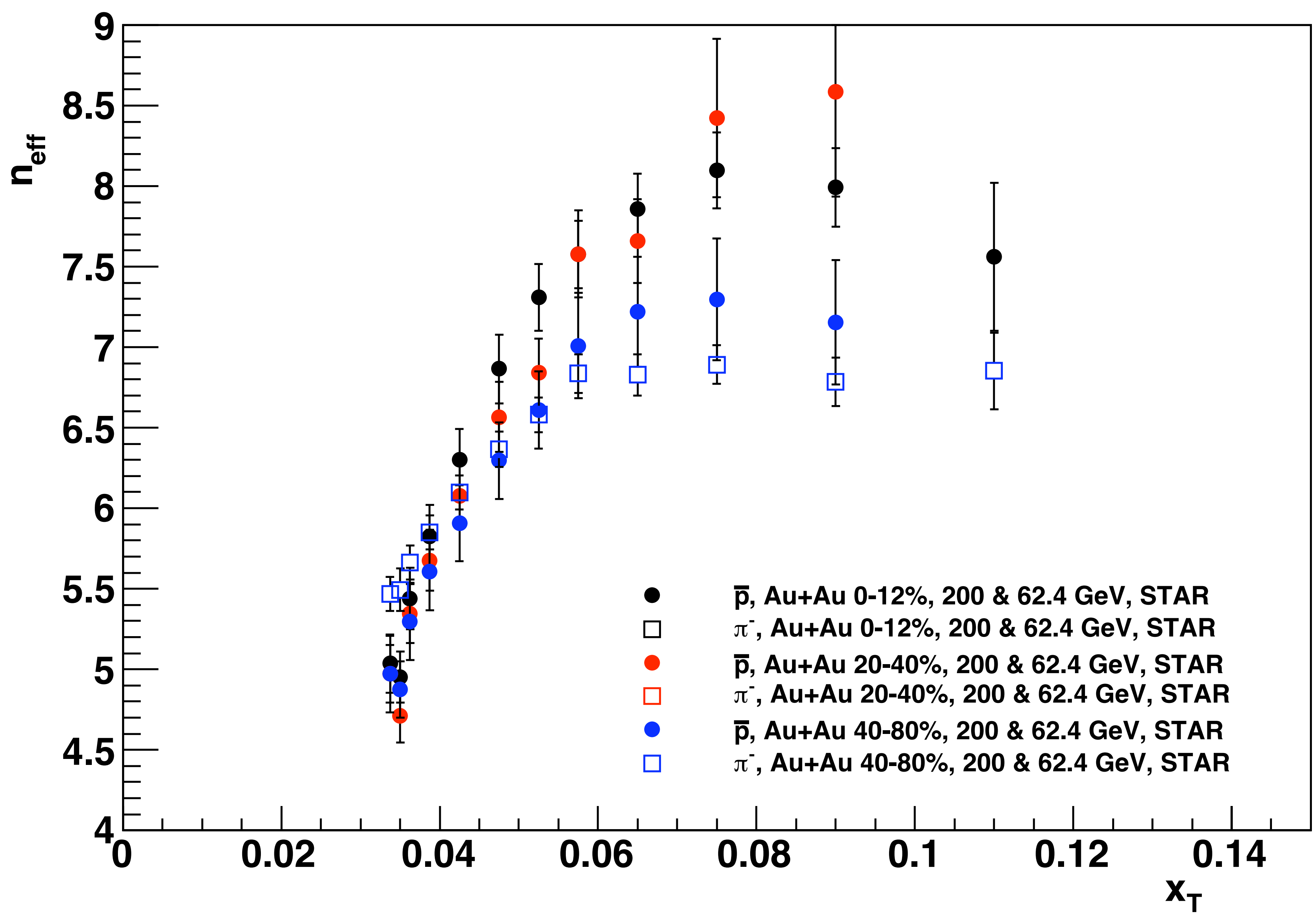




data from: STAR PLB 655 104 (2007)

anti-protons: heavy ion collisions

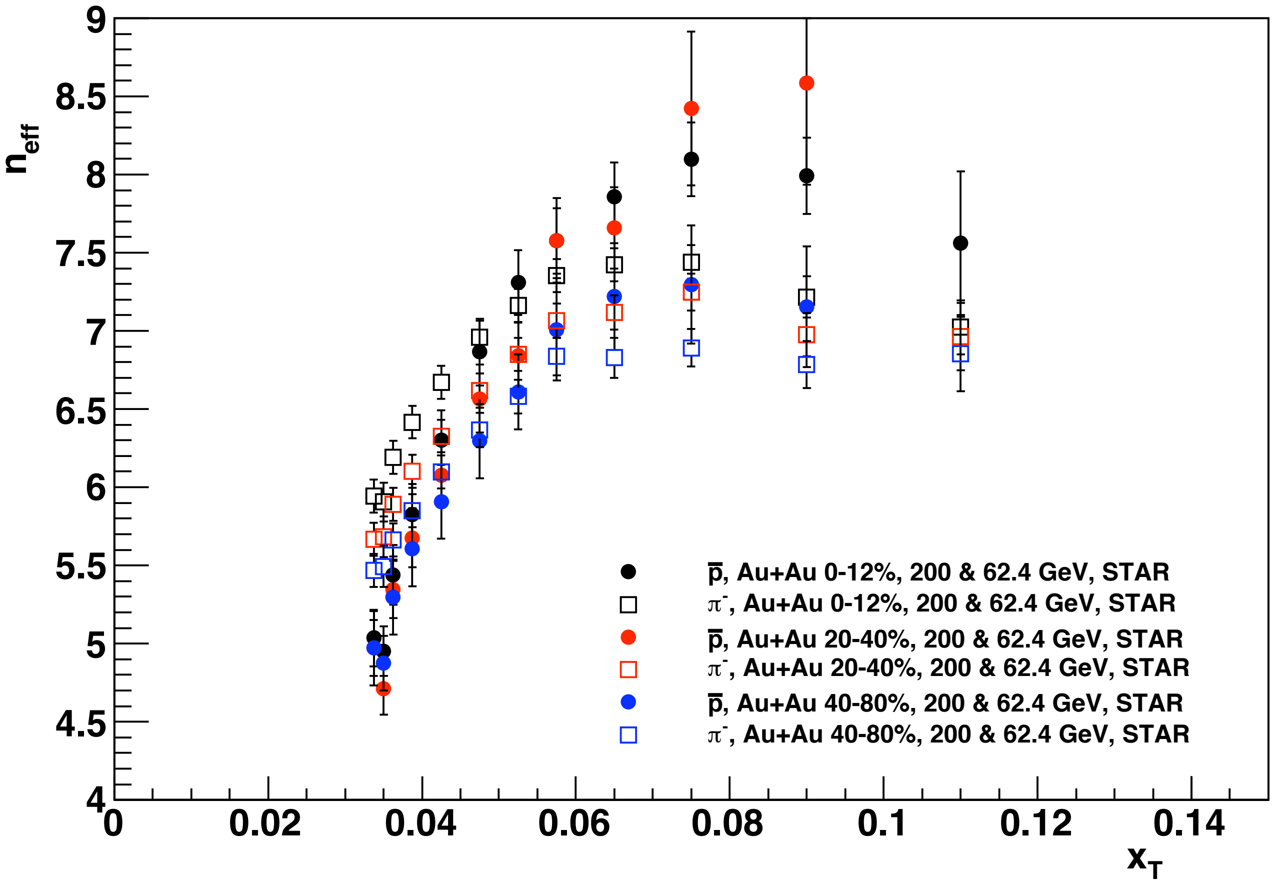


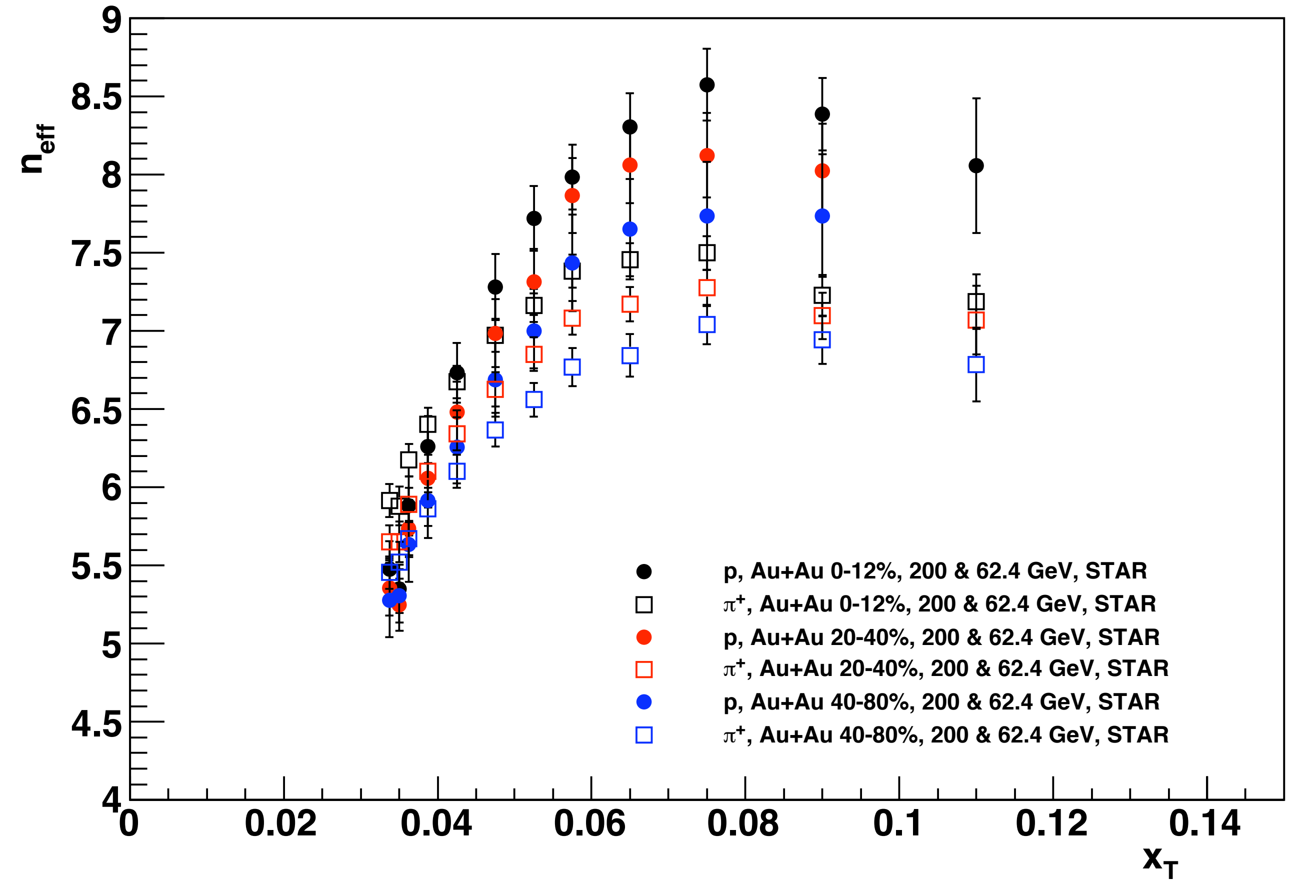


- power increased for protons, increases w/ centrality

data from: STAR PLB 655 104 (2007)

p and pbar



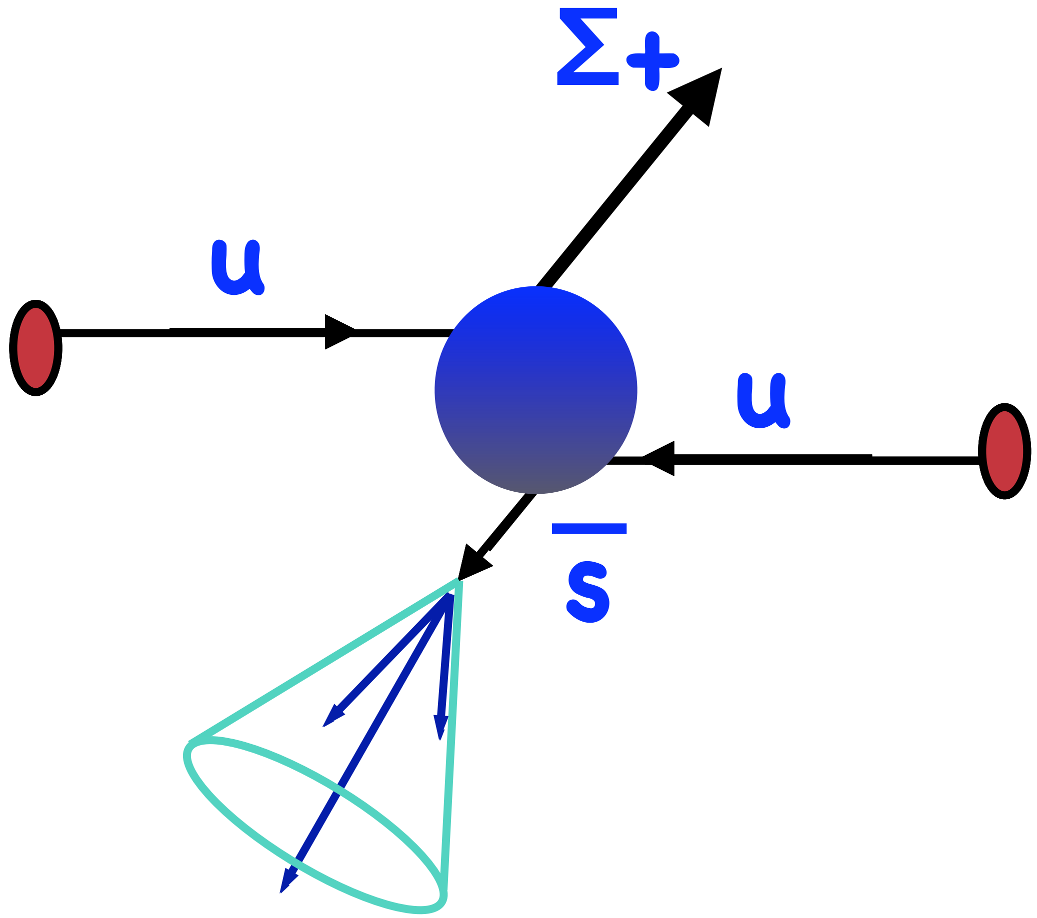


- n higher for p and pbar than pions
- n increases with centrality
- both charges show the same trend

data from: STAR PLB 655 104 (2007)

how would you test this?

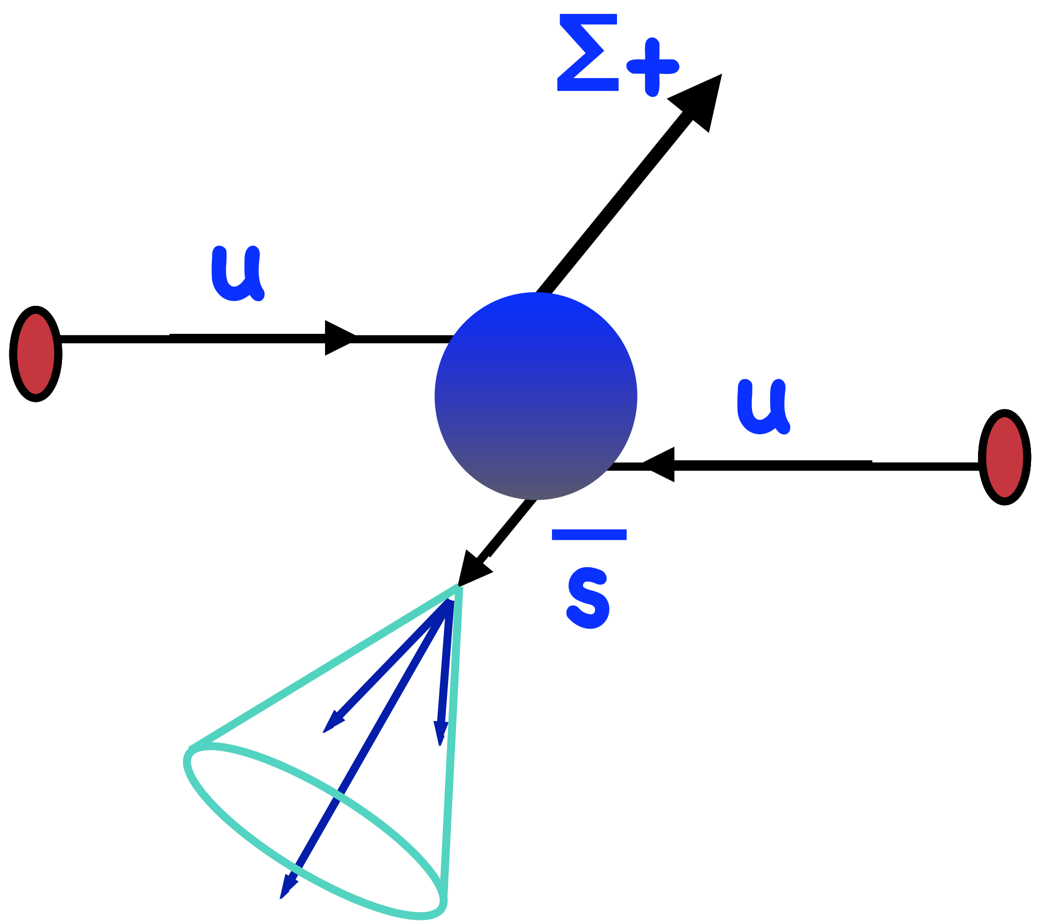
how would you test this?



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

Brodsky, AMS
PLB 668 111 (2008)

how would you test this?



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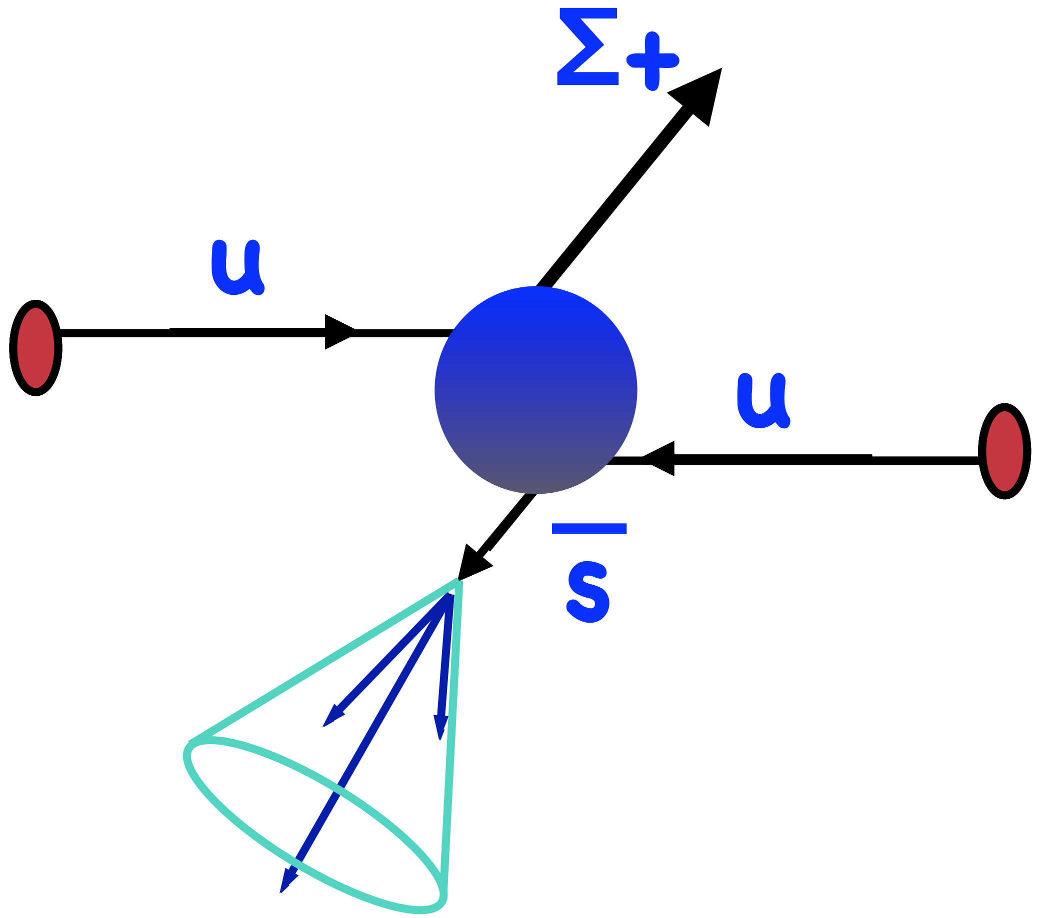
Brodsky, AMS
PLB 668 111 (2008)

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

how would you test this?



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

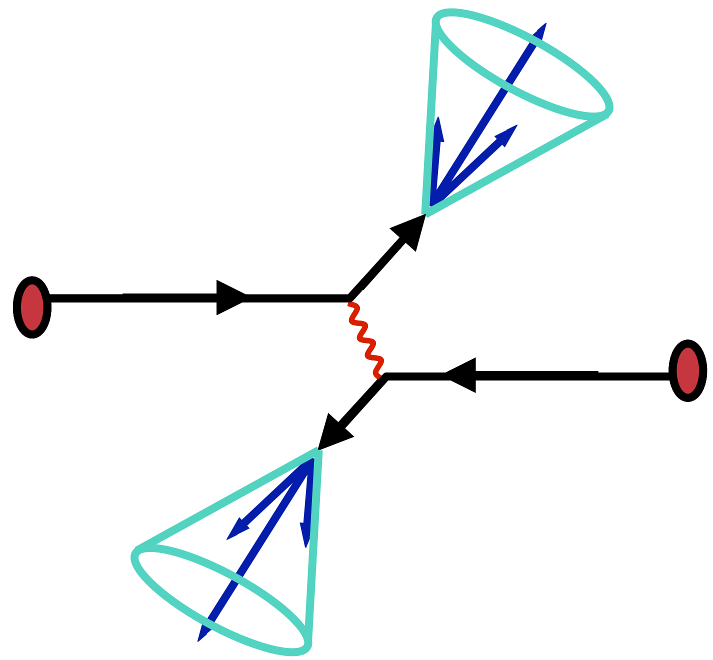
Brodsky, AMS
PLB 668 111 (2008)

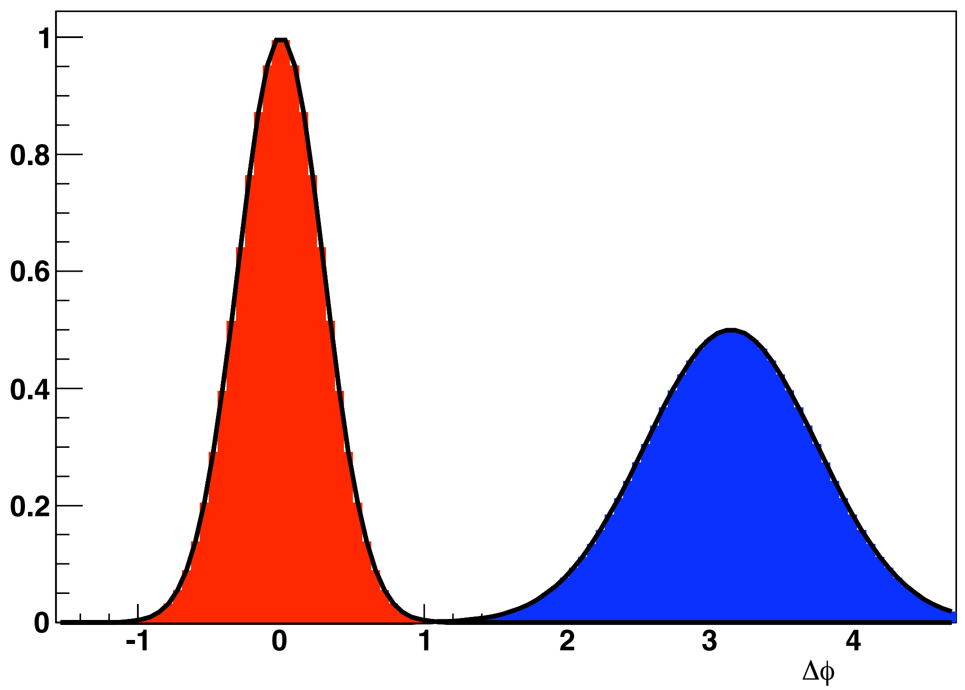
- can also make strange baryons: signature balancing strangeness will be on in recoil jet
- in contrast, in hard fragmentation picture: balancing strangeness will be close, in same jet

baryon “anomaly”

- low p_T: recombination
- intermediate & high p_T: higher twist
  - hot nuclear matter → study rare QCD processes!
  - identified particle measurements in a range of systems and energies provide a great way to study higher twist QCD processes and hot nuclear matter
  - strong motivation for RHIC energy scan at moderate center of mass (40-200GeV) p+p & heavy ions

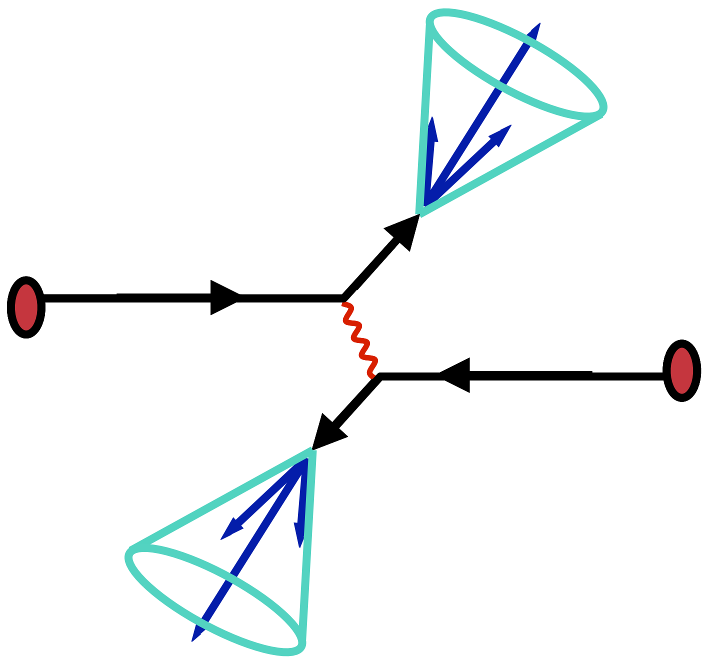
2 particle correlations





- complementary to single particle observables
- different sensitivity to geometry

2 particle correlations



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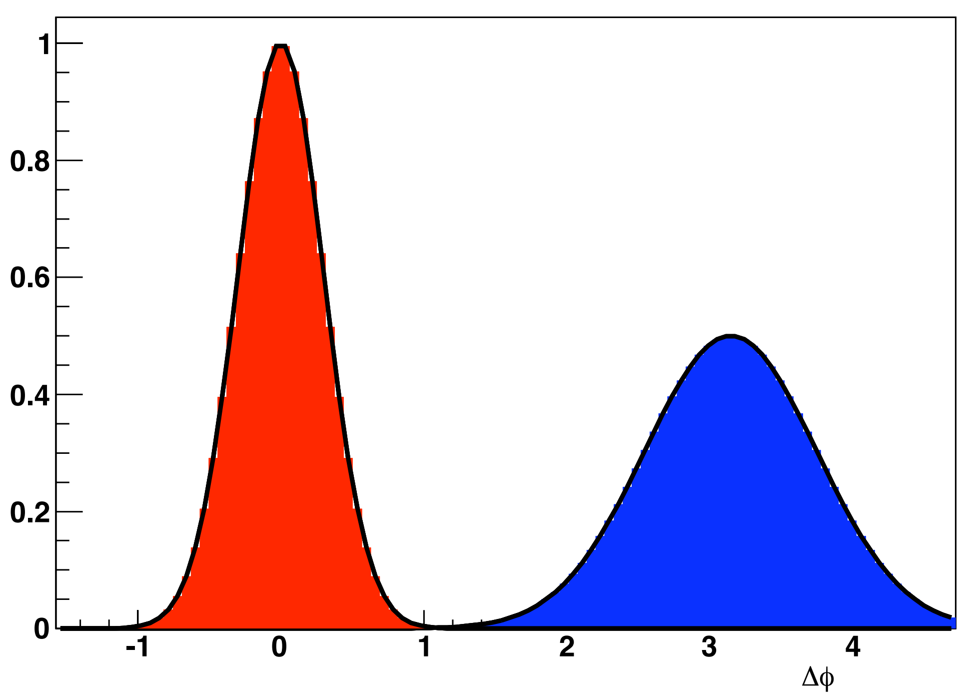
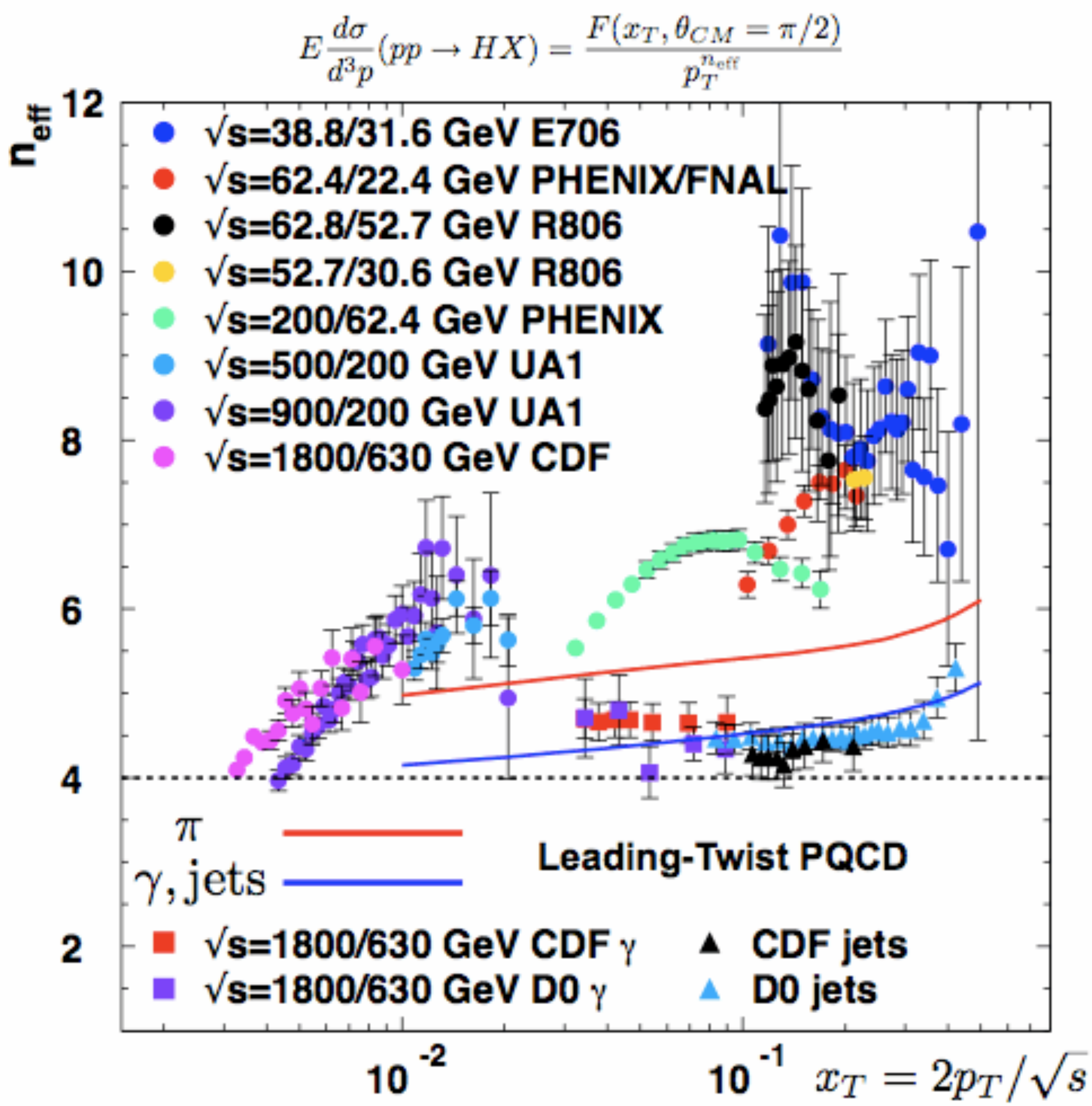
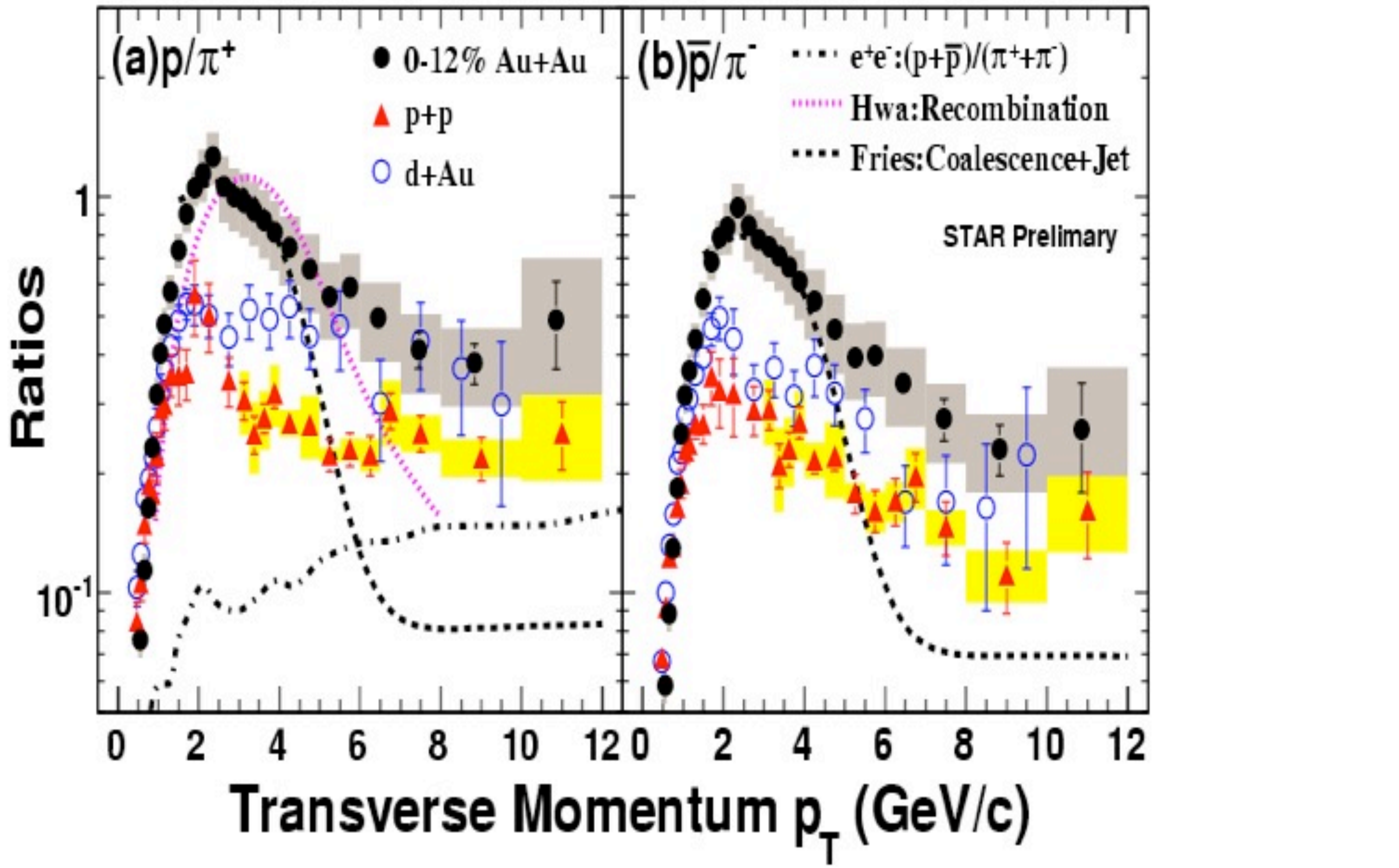


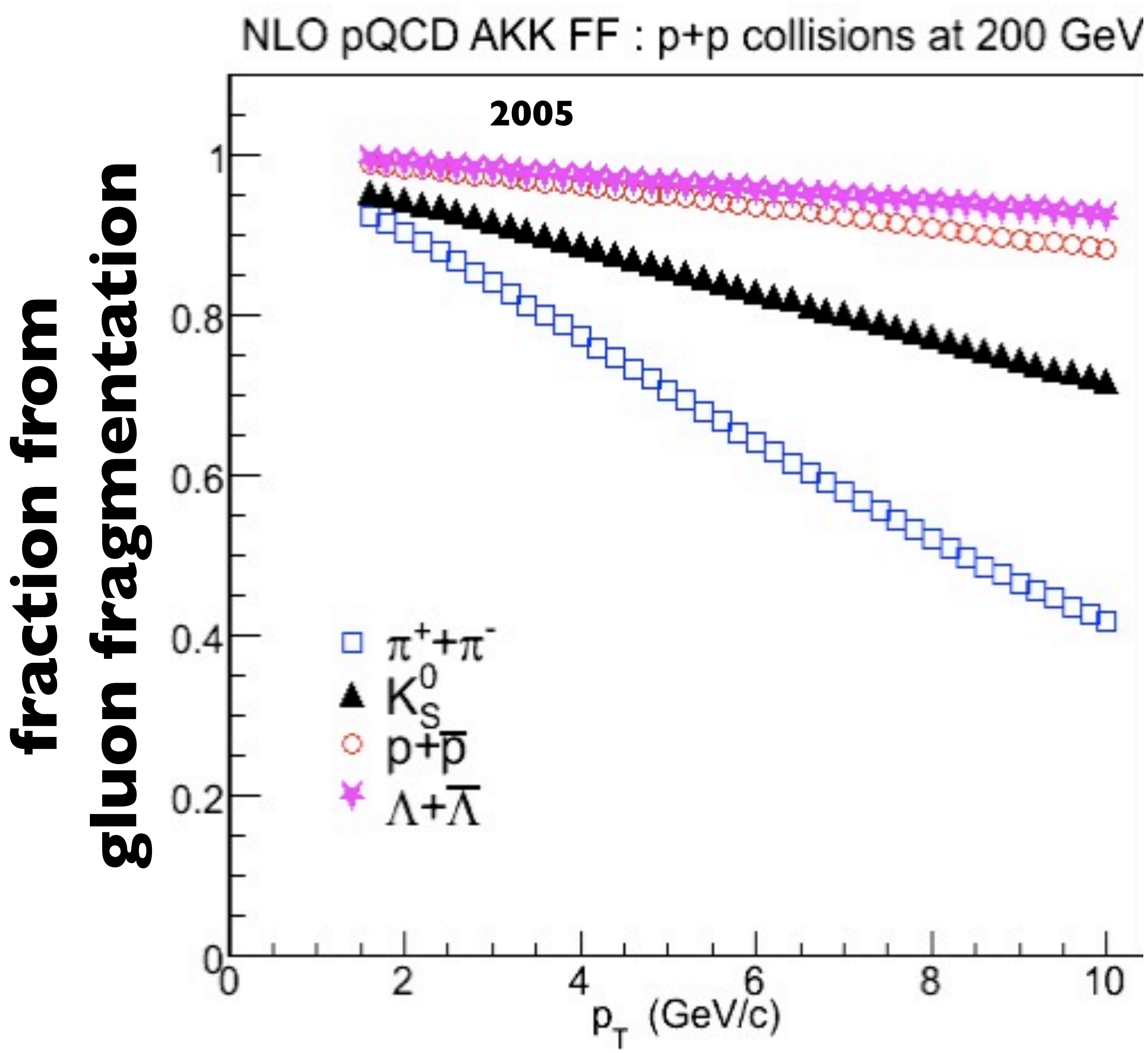
$$I_{AA} = \frac{\text{conditional yield in AuAu}}{\text{conditional yield in pp}}$$



Arleo, Aurenche, Brodsky, Hwang, & Sickles: in preparation
Brodsky: arXiv:0904.3037


(a)p/π+
0-12% Au+Au
p+p
d+Au
(b)p̄/π-
e+e-:(p+p̄)/(π++π-)
Hwa:Recombination
Fries:Coalescence+Jet
STAR Prelimary
Ratios
1
10-1
0 2 4 6 8 10 12
Transverse Momentum pT (GeV/c)

uncertainties in proton FF



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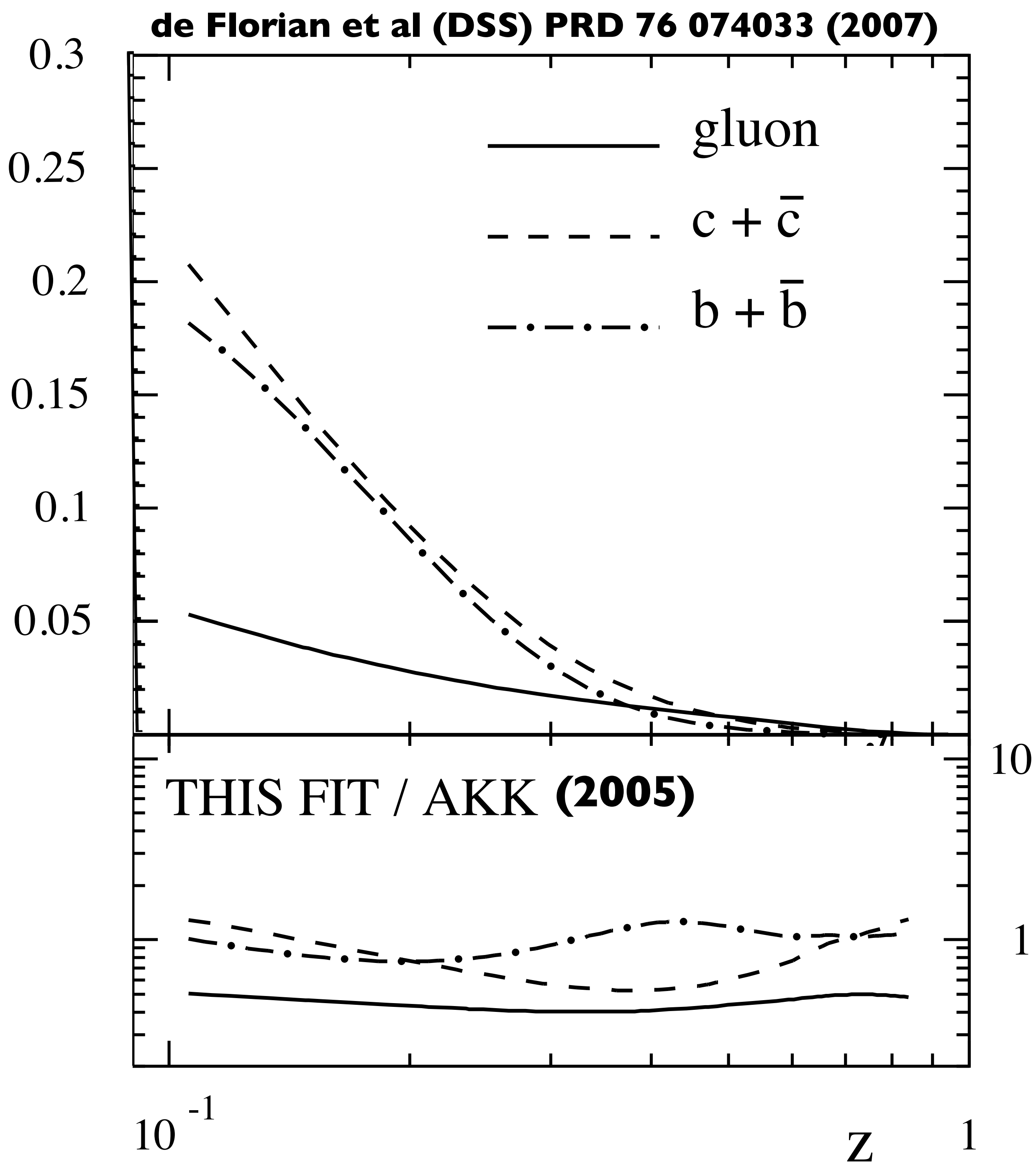
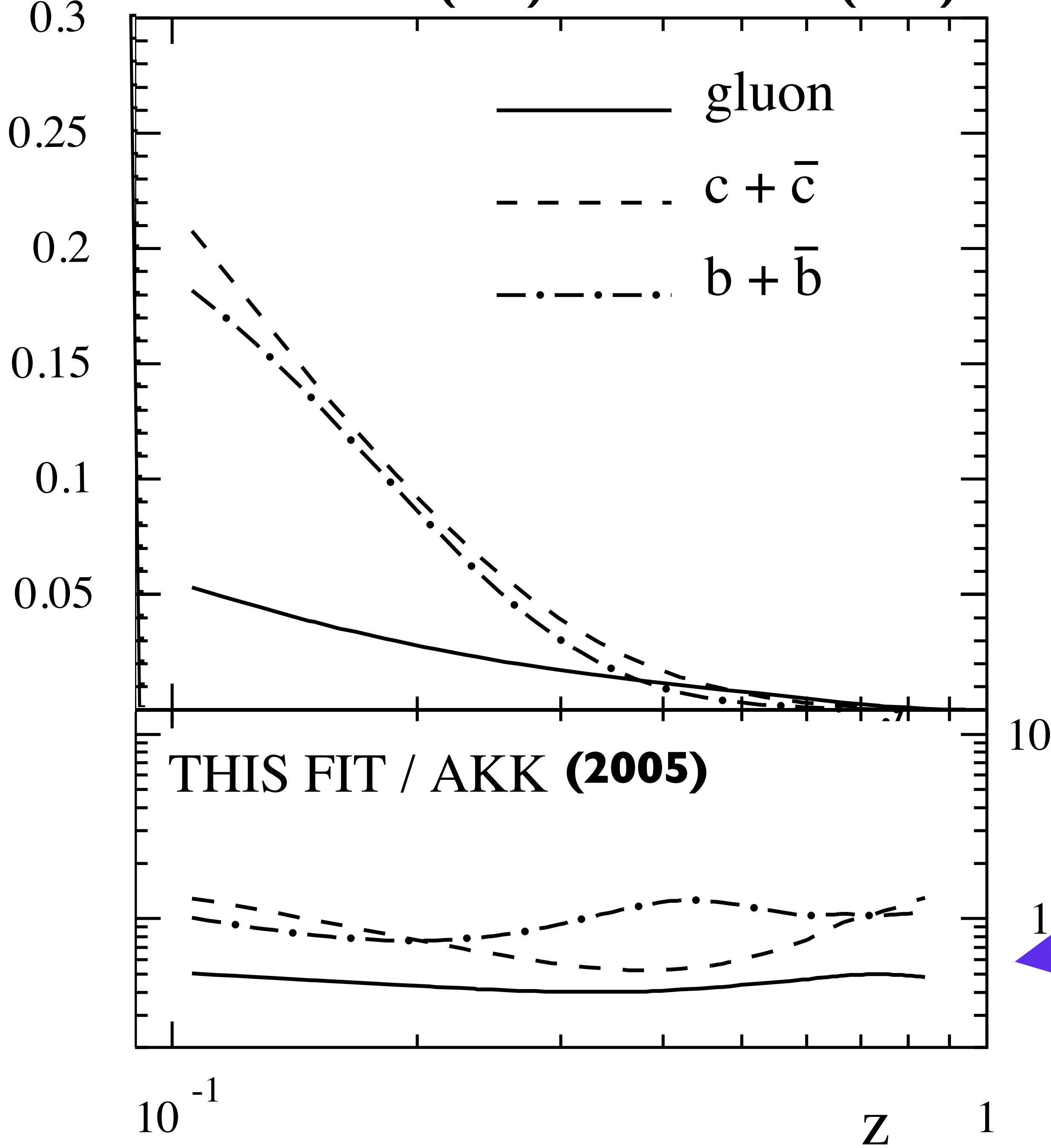


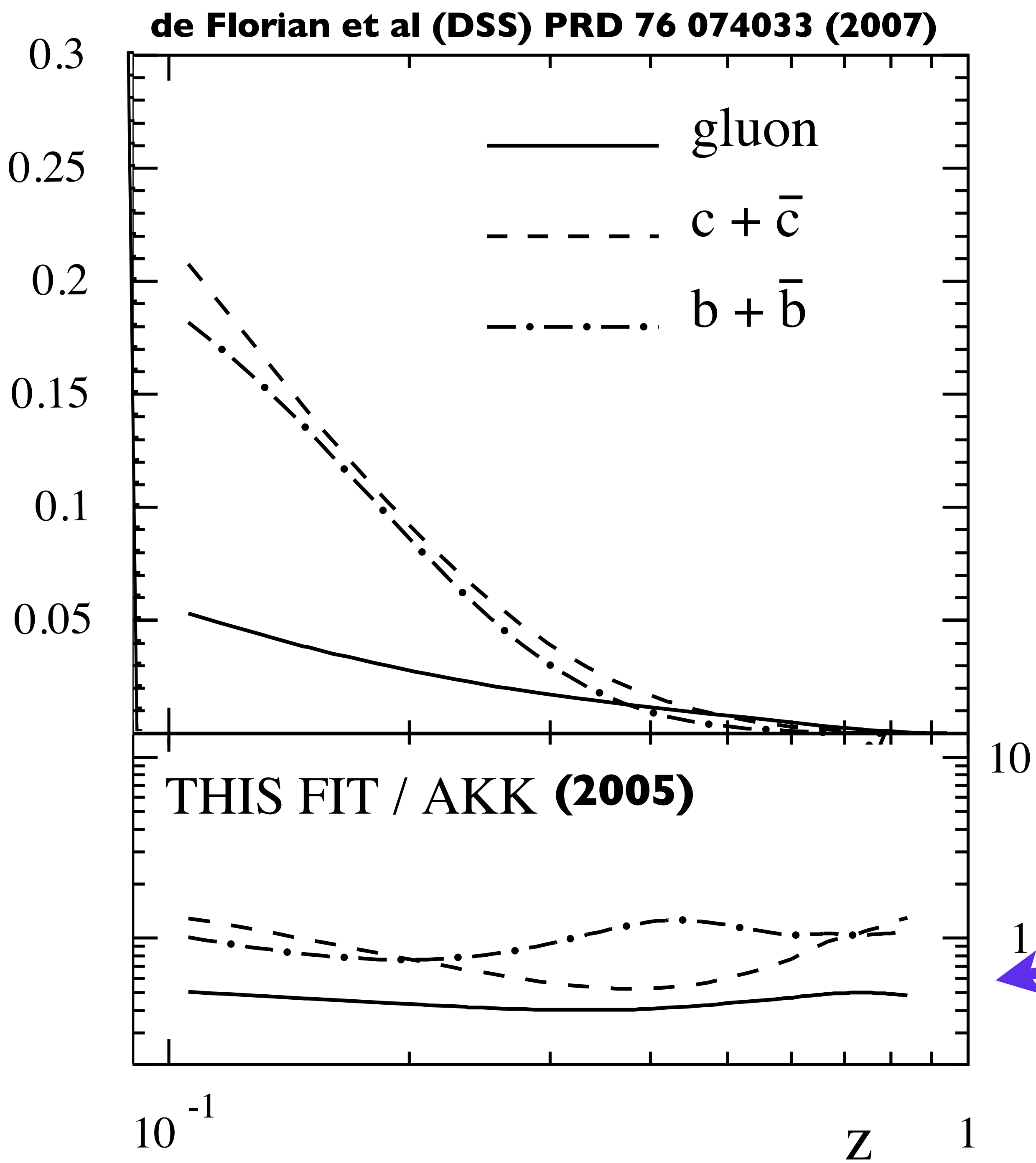
uncertainties in proton FF

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



g→p (DSS) / g→p (AKK)

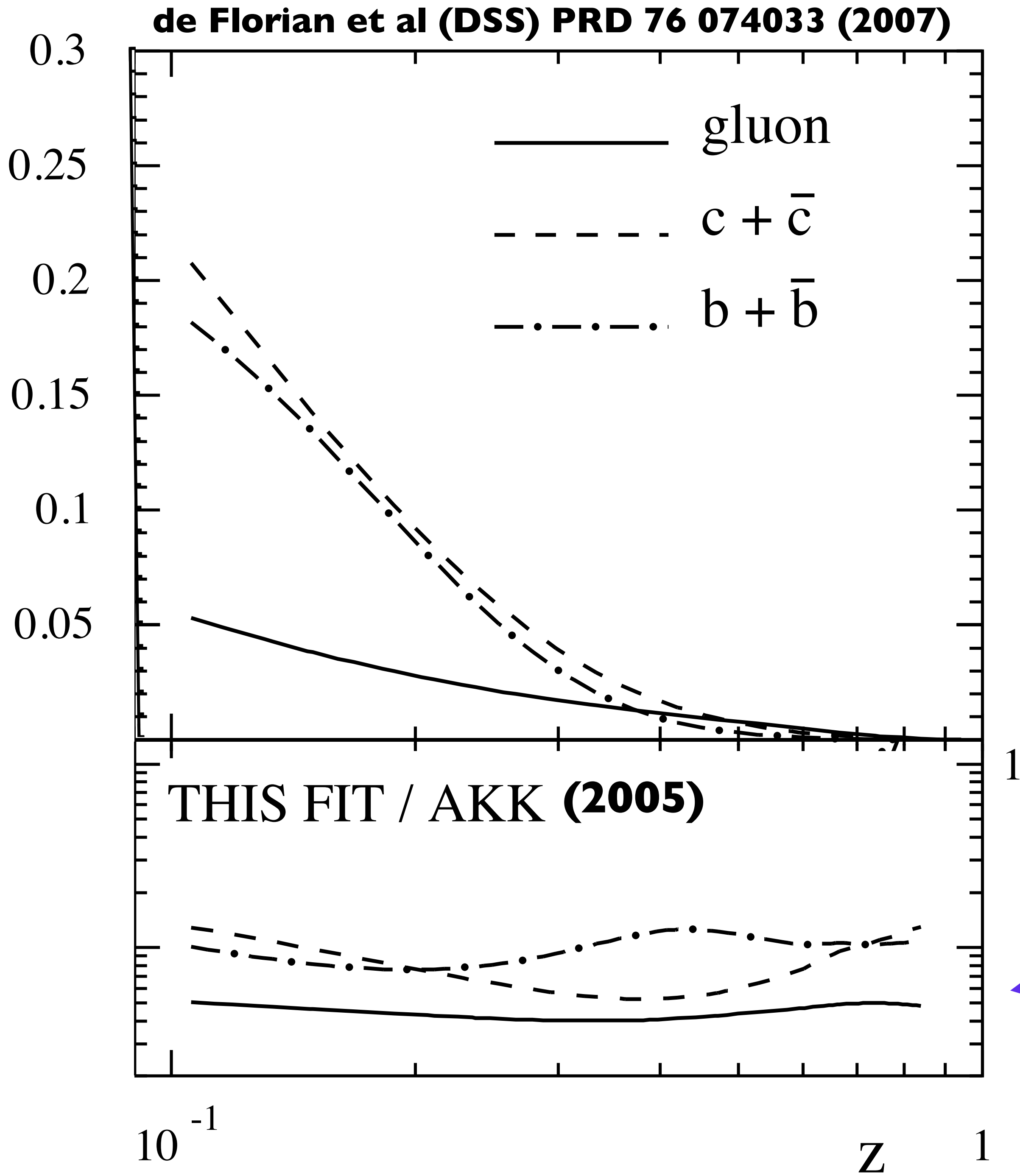
uncertainties in proton FF



- **factor of three** differences in gluon → proton FF!
- DSS fragmentation functions reproduce STAR p+p results (they were used in the constraint)

g→p (DSS) / g→p (AKK)

uncertainties in proton FF



- factor of three differences in gluon → proton FF!
- DSS fragmentation functions reproduce STAR p+p results (they were used in the constraint)

g→p (DSS) / g→p (AKK)

still unclear why $R_{AA}(p) > R_{AA}(\pi)$

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)

jet conversions

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parton R_{AA}

Ko et al. PRC 75 051901 (2007)
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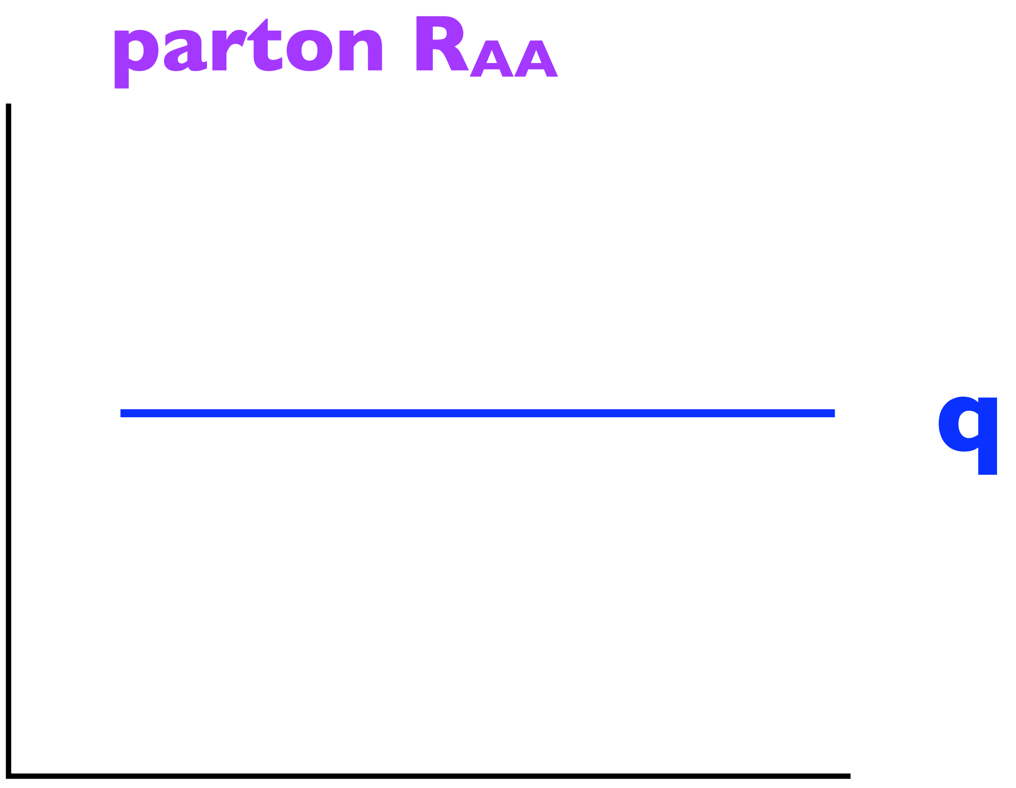

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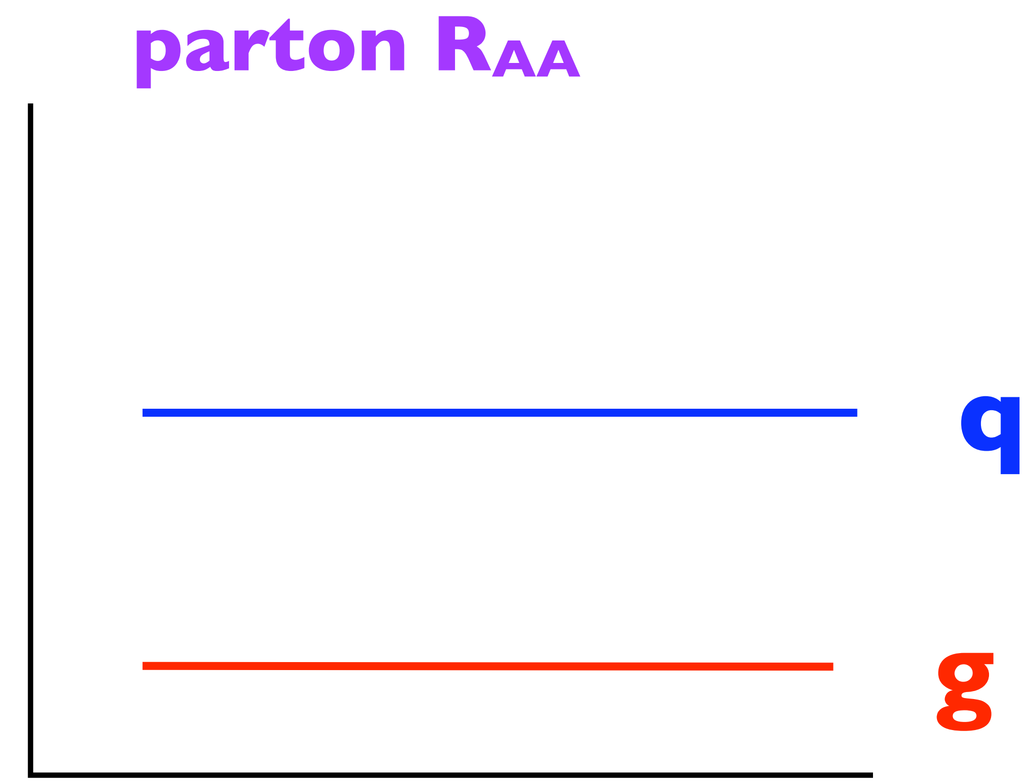

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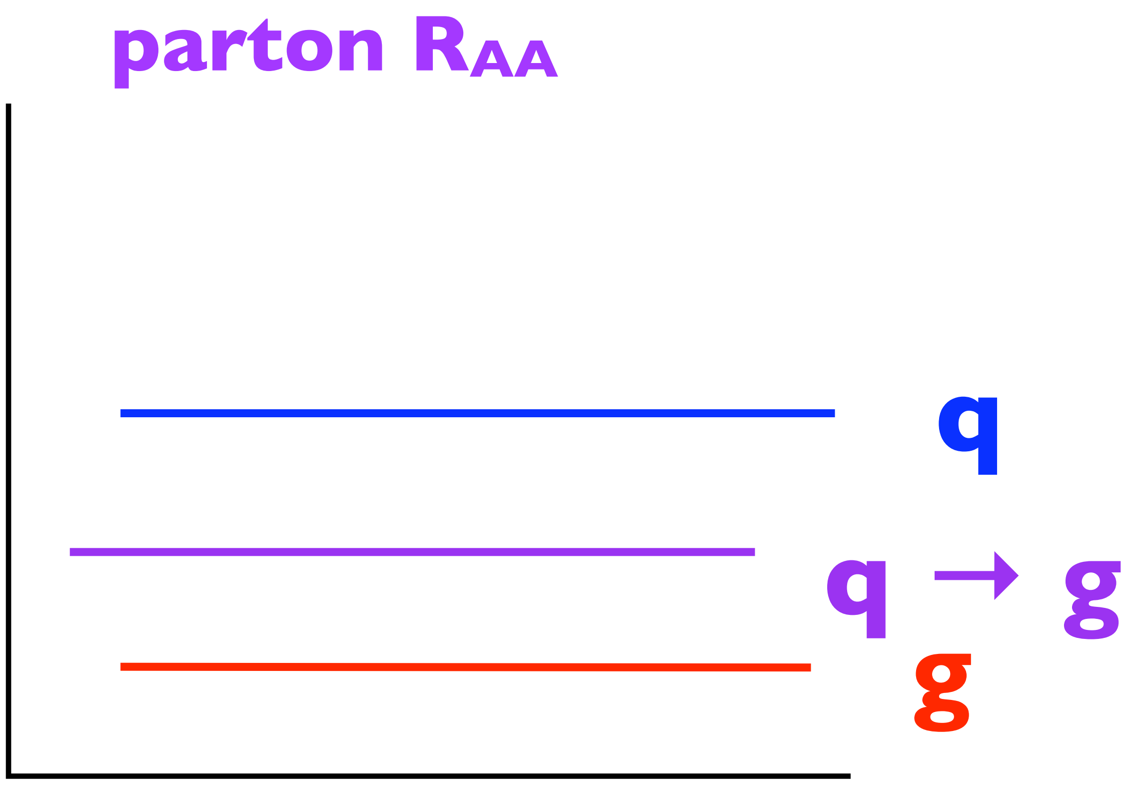

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Anne M. Sickles, April 29, 2009

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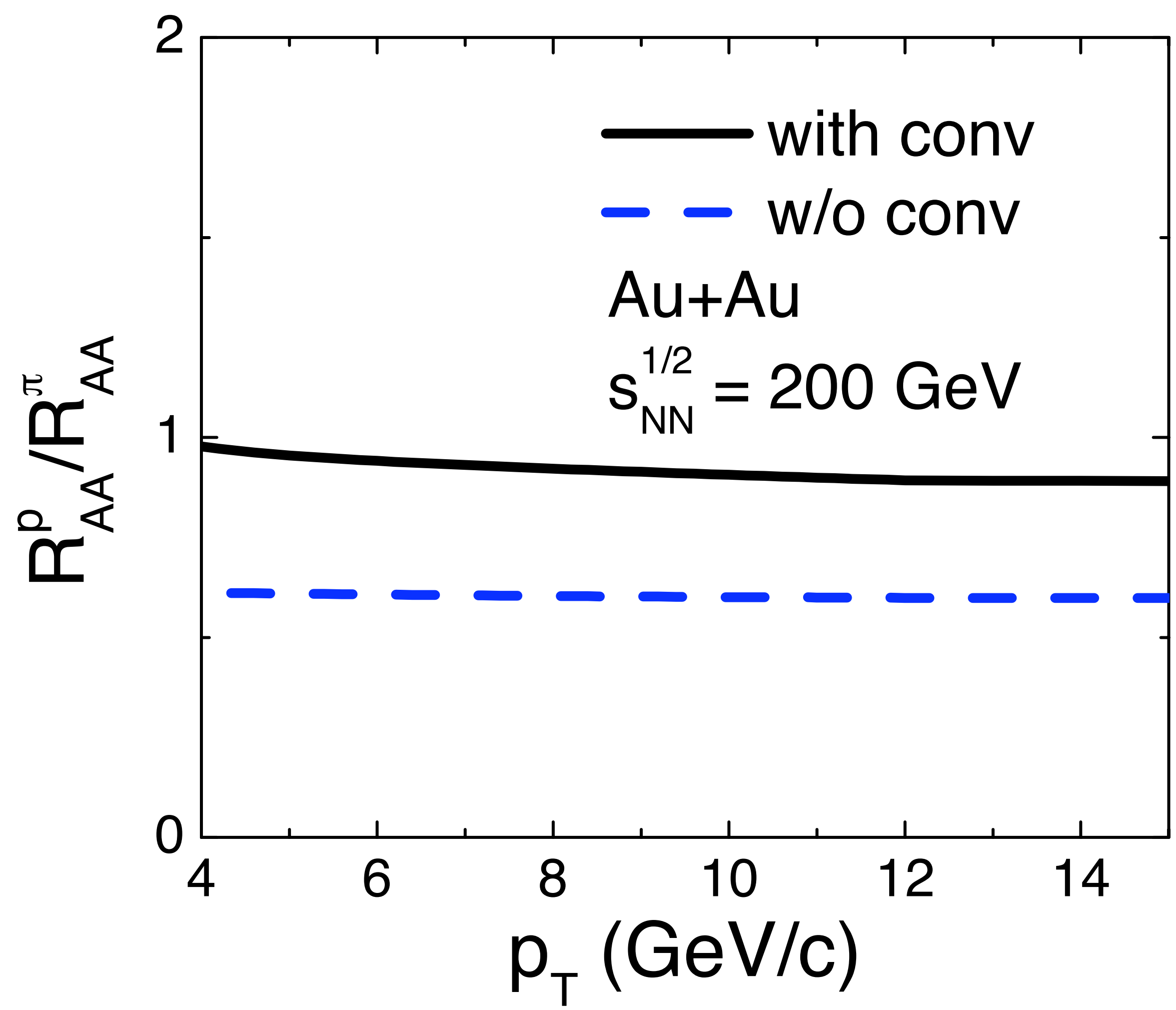

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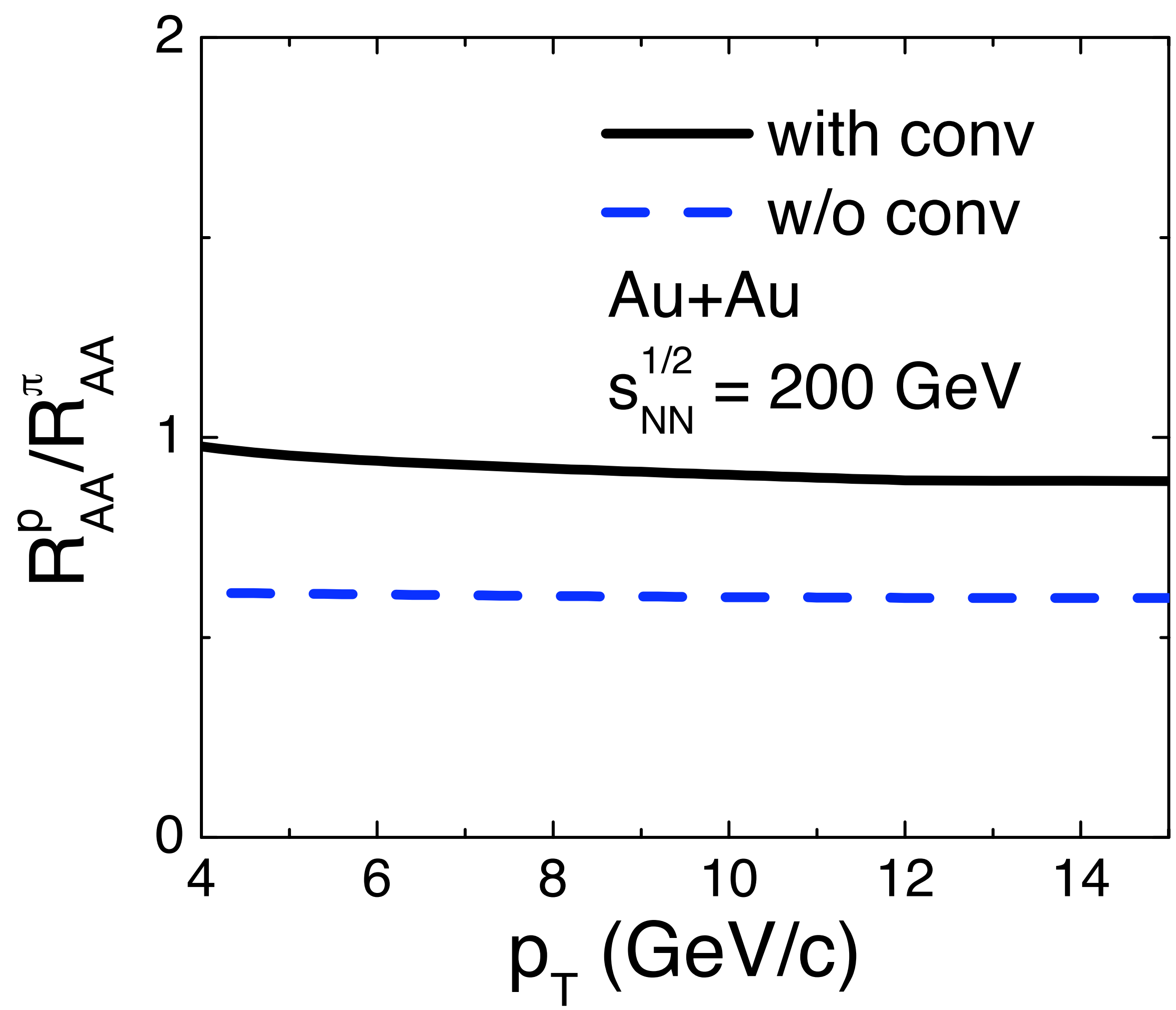

- could increase R_{AA}(protons)/R_{AA}(π), but not beyond 1

Ko et al. PRC 75 051901 (2007)
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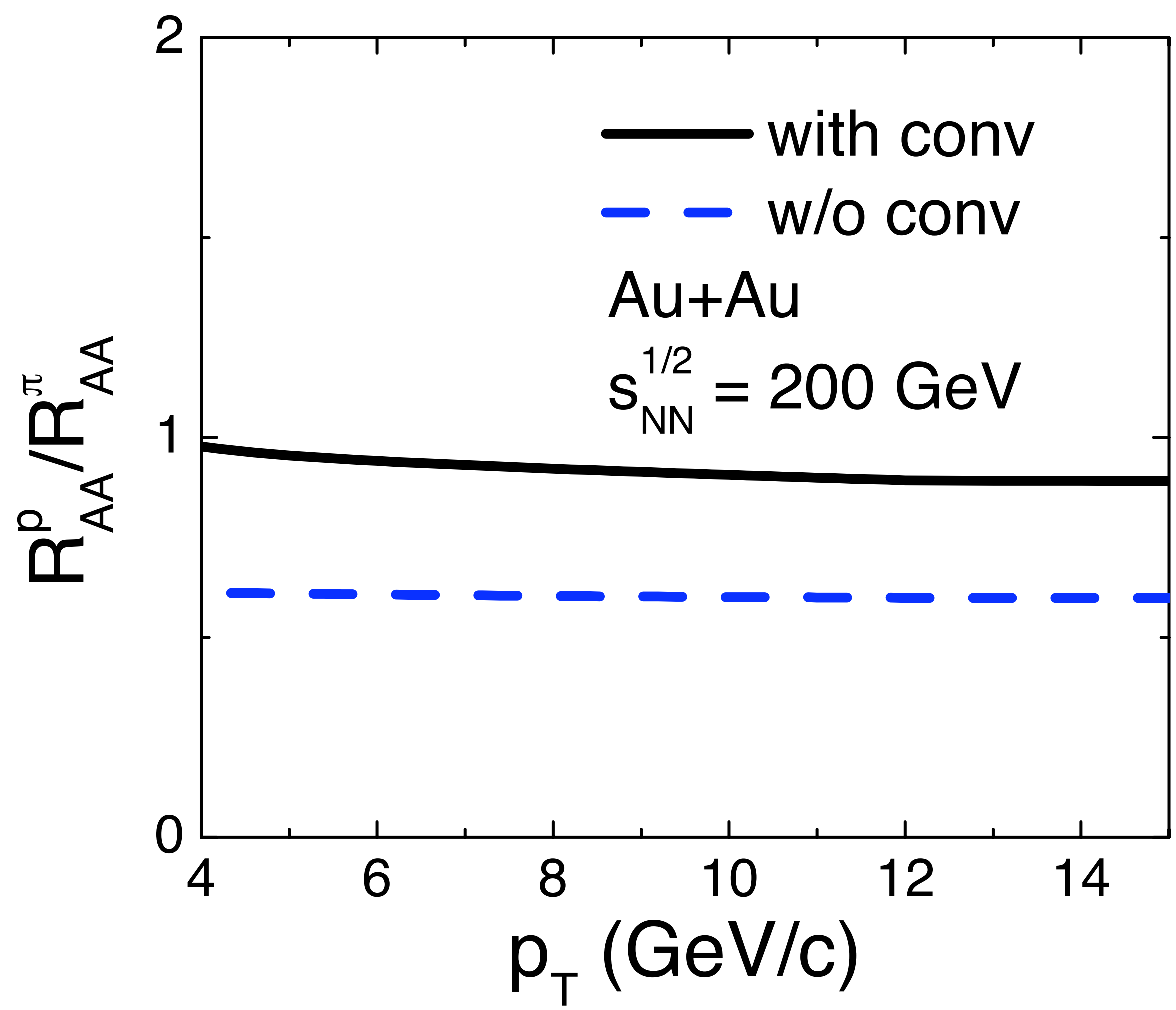

- could increase R_{AA}(protons)/R_{AA}(π), but not beyond 1
  - recombination at high p_T?

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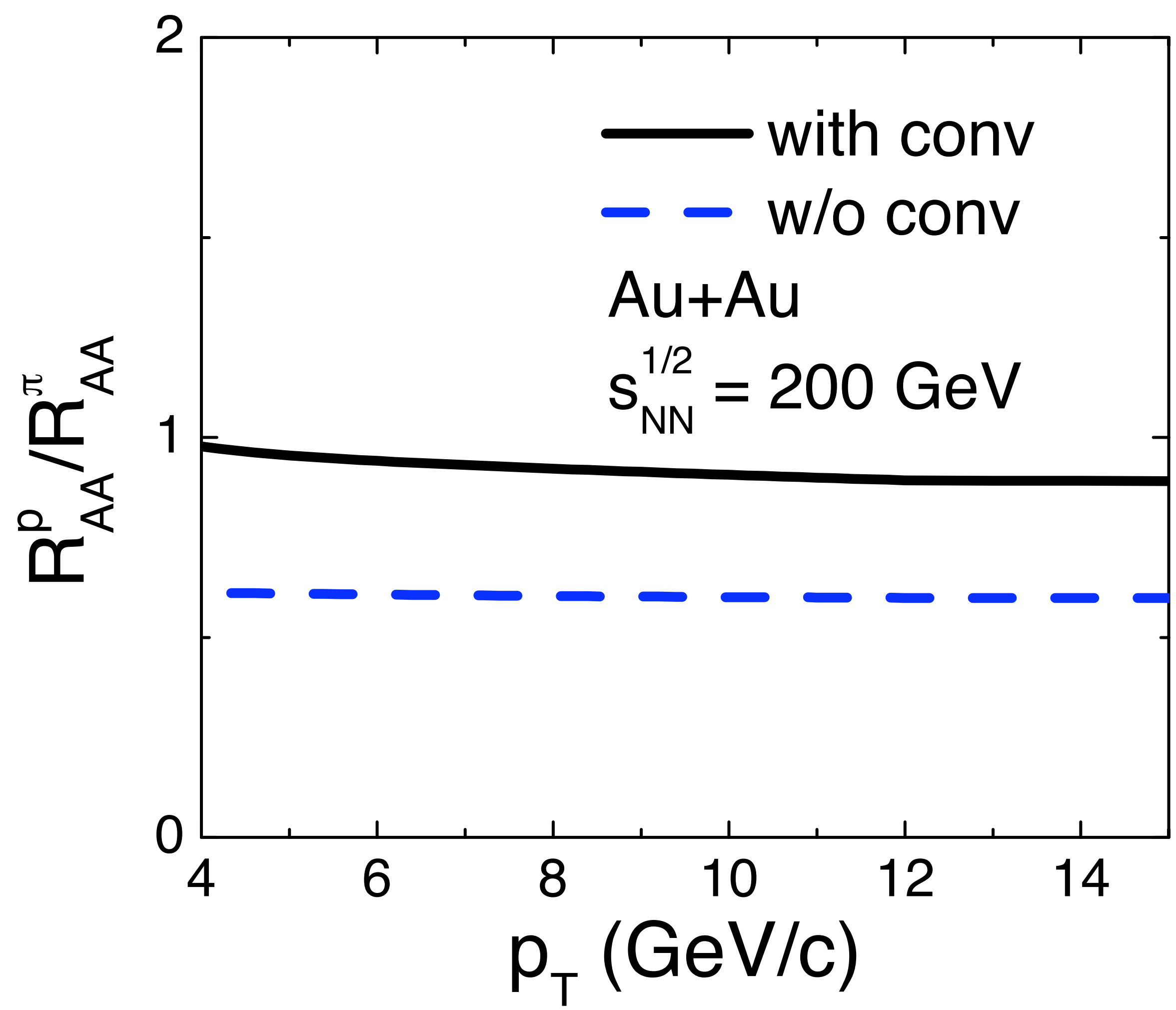
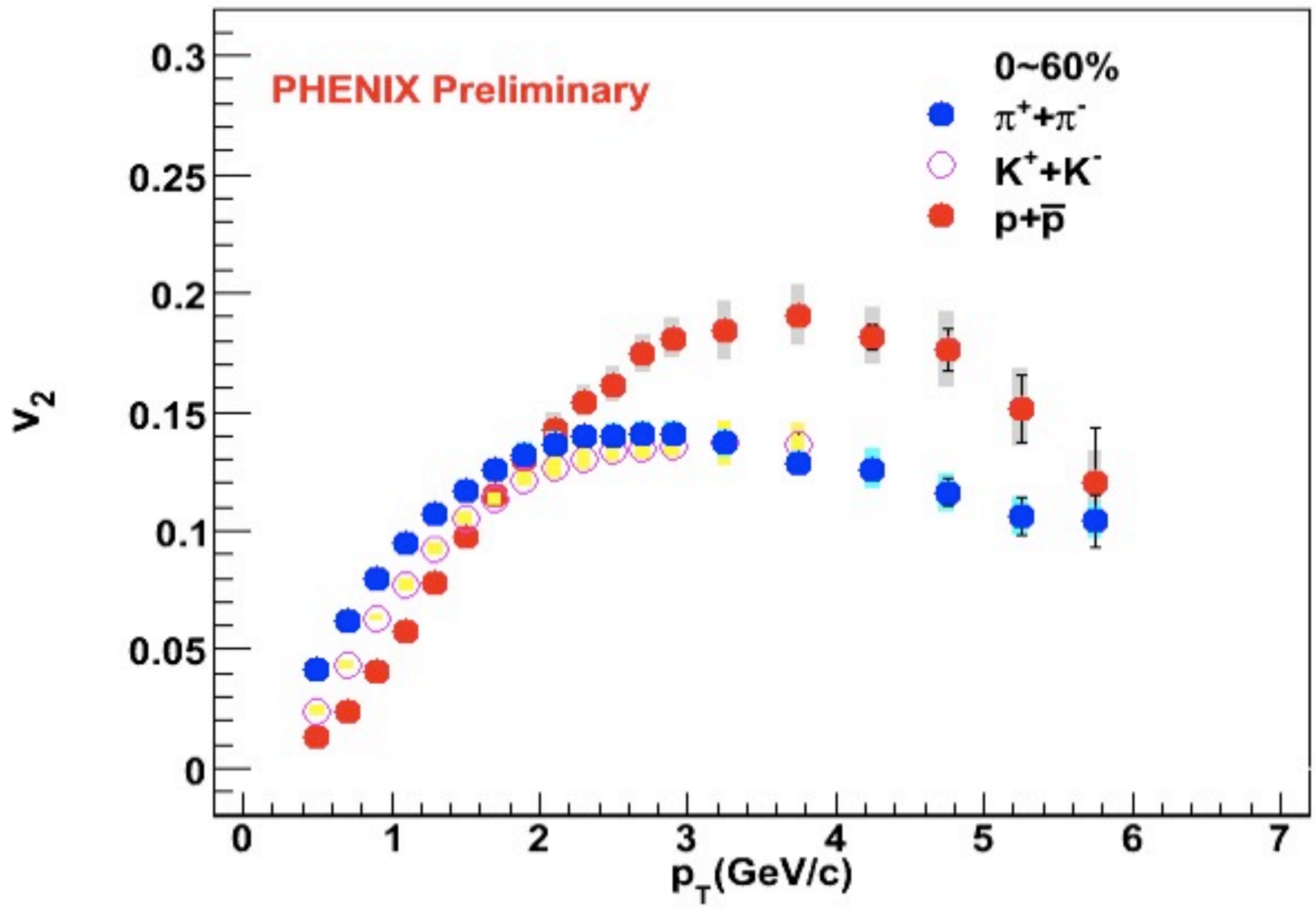


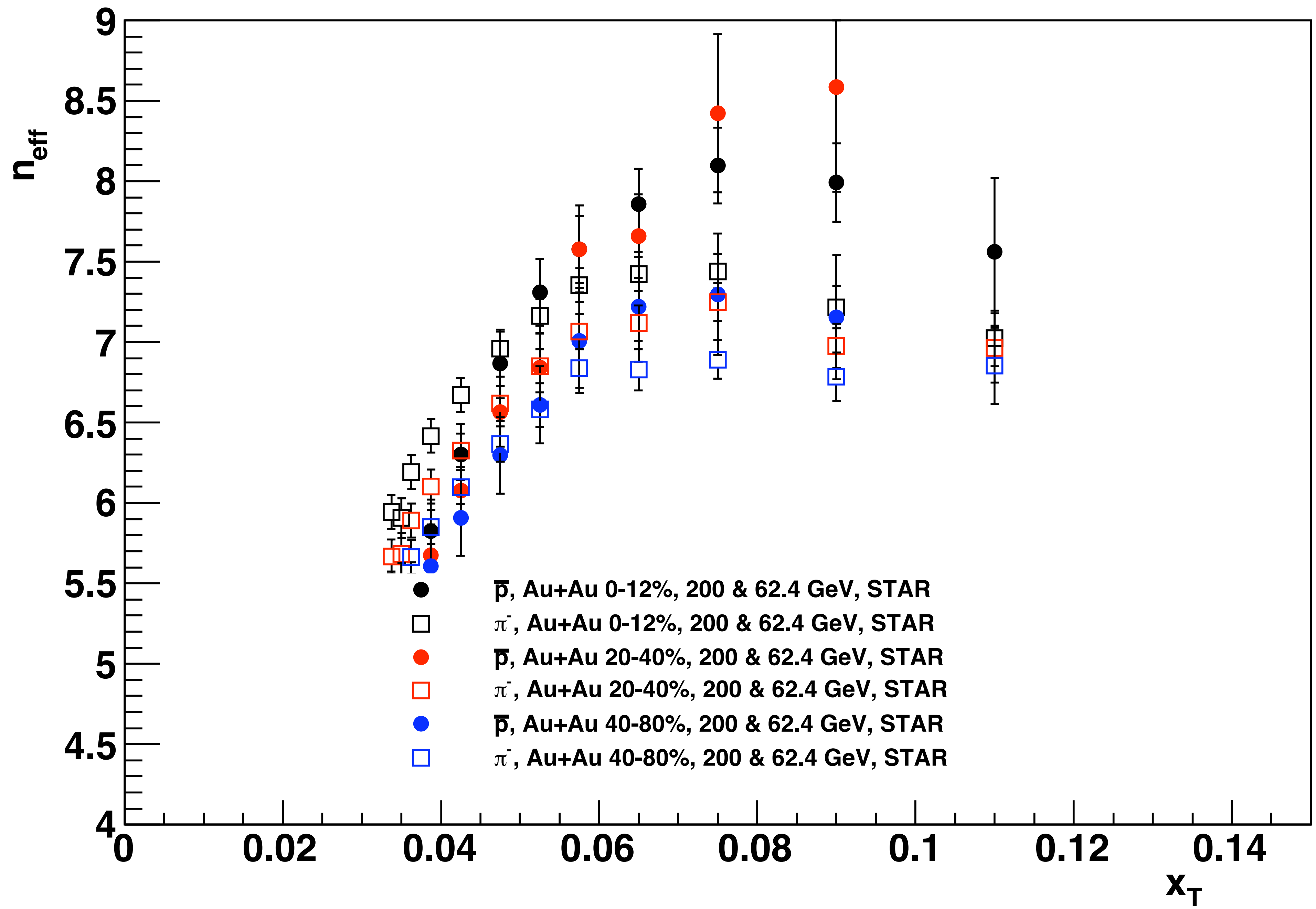
- could increase R_{AA}(protons)/R_{AA}(π), but not beyond 1
  - recombination at high p_T?
- potentially extremely interesting: sensitive to mean free path

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

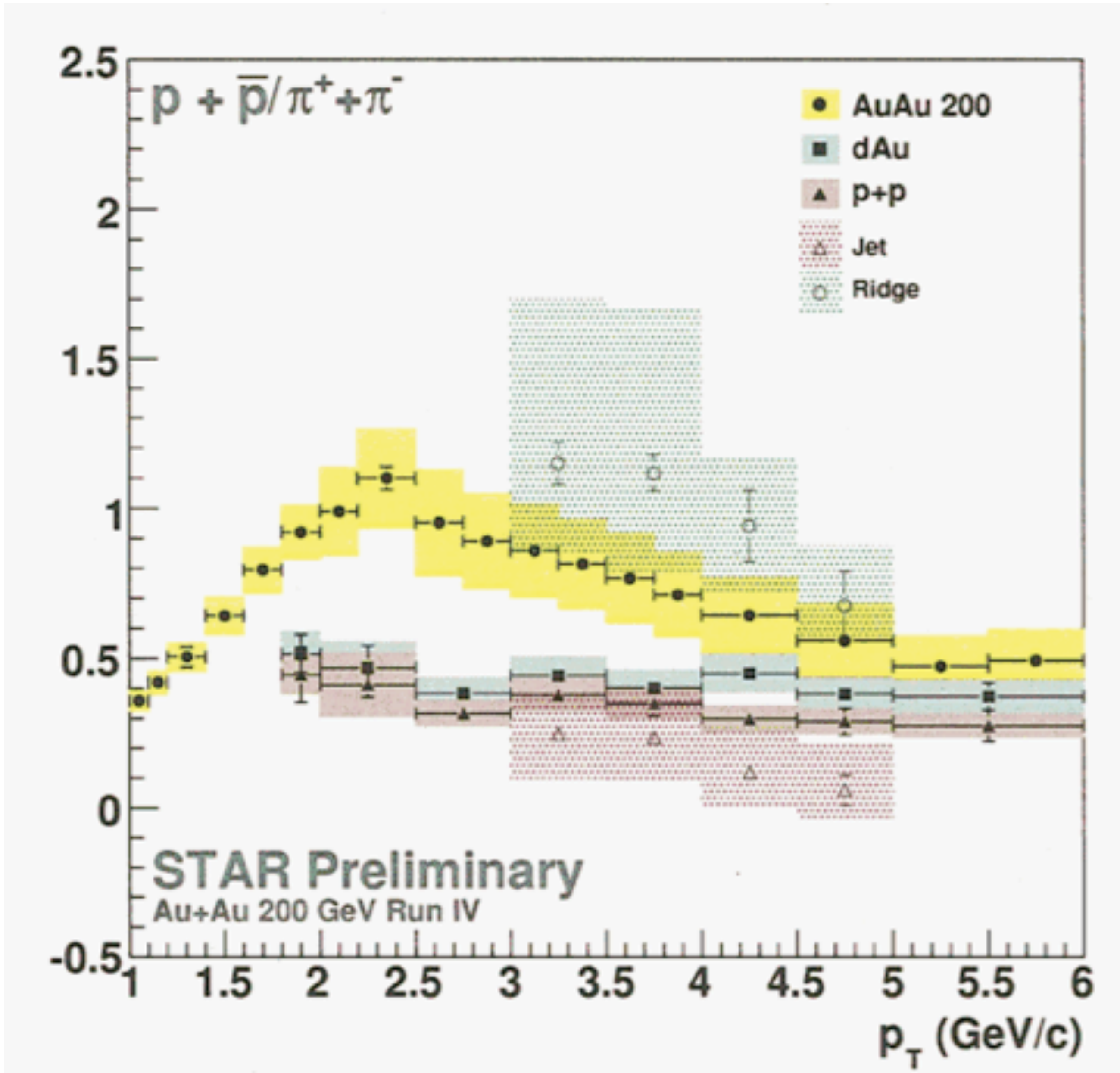


- decreasing proton v2? increasing direct component?

xT scaling

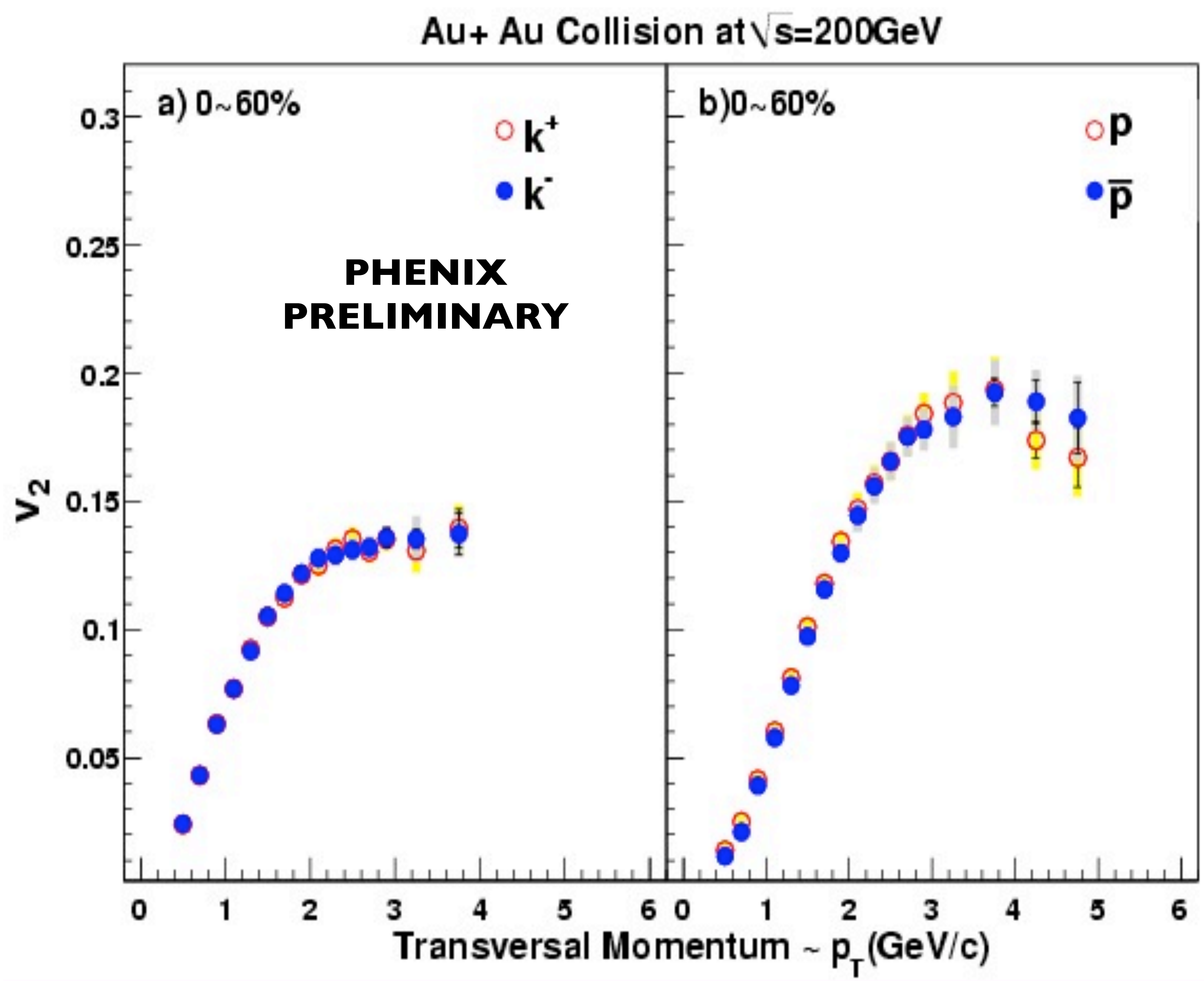


data from STAR PLB 655 104 (2007)



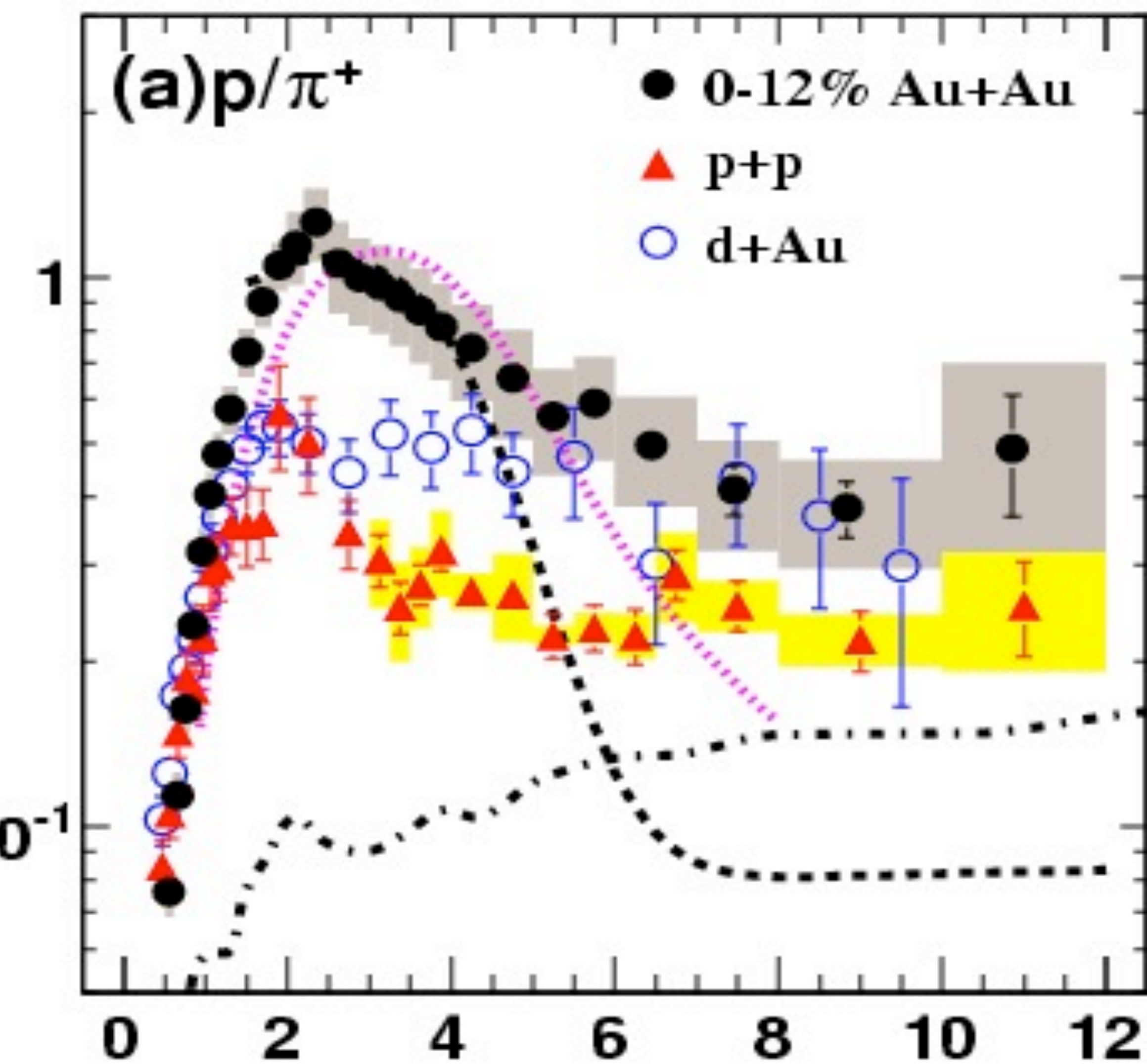
$p + \bar{p}/\pi^{+}+\pi^{-}$
AuAu 200
dAu
p+p
Jet
Ridge
STAR Preliminary
Au+Au 200 GeV Run IV
2.5
2
1.5
1
0.5
0
-0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
p_T (GeV/c)

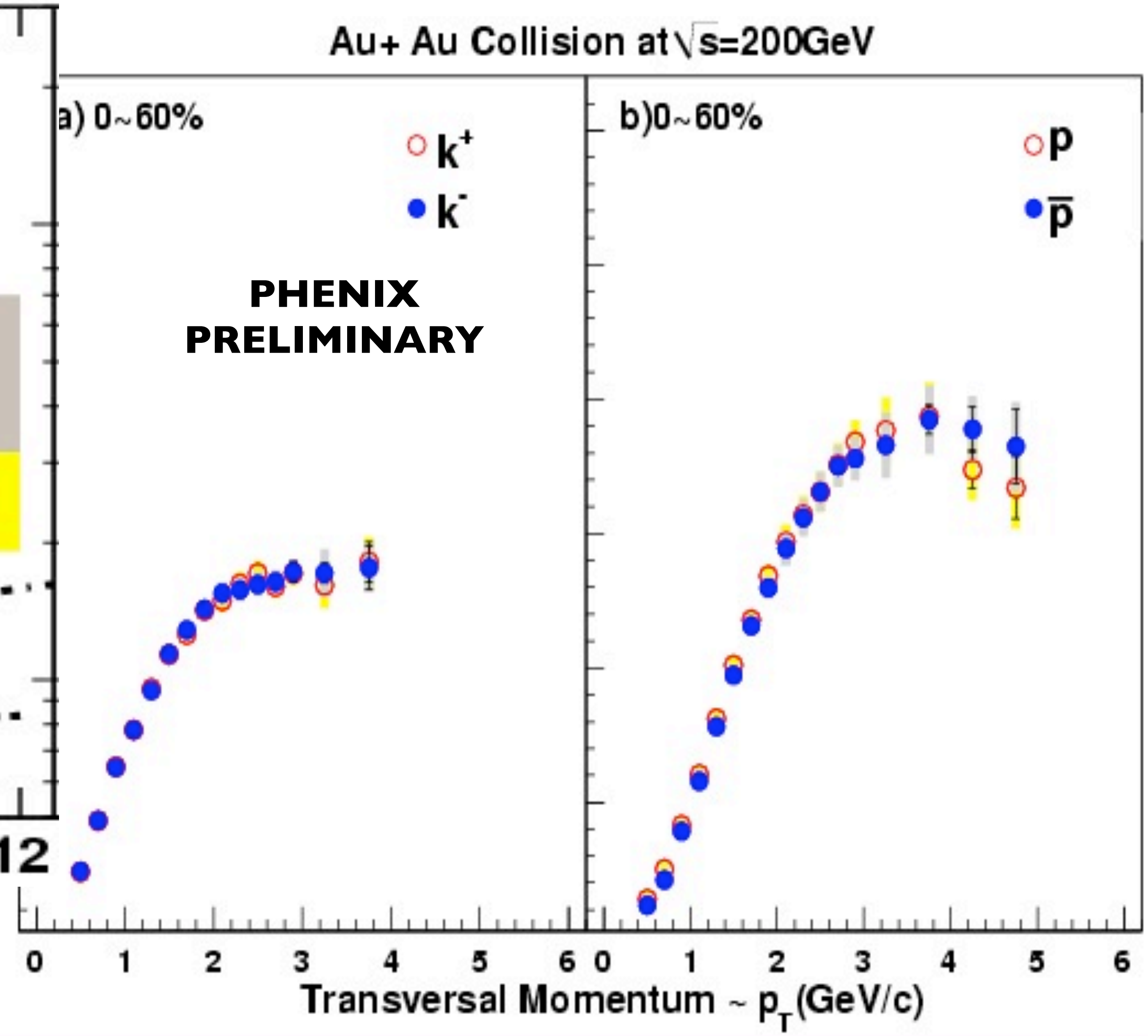
baryon/anti-baryon ratio



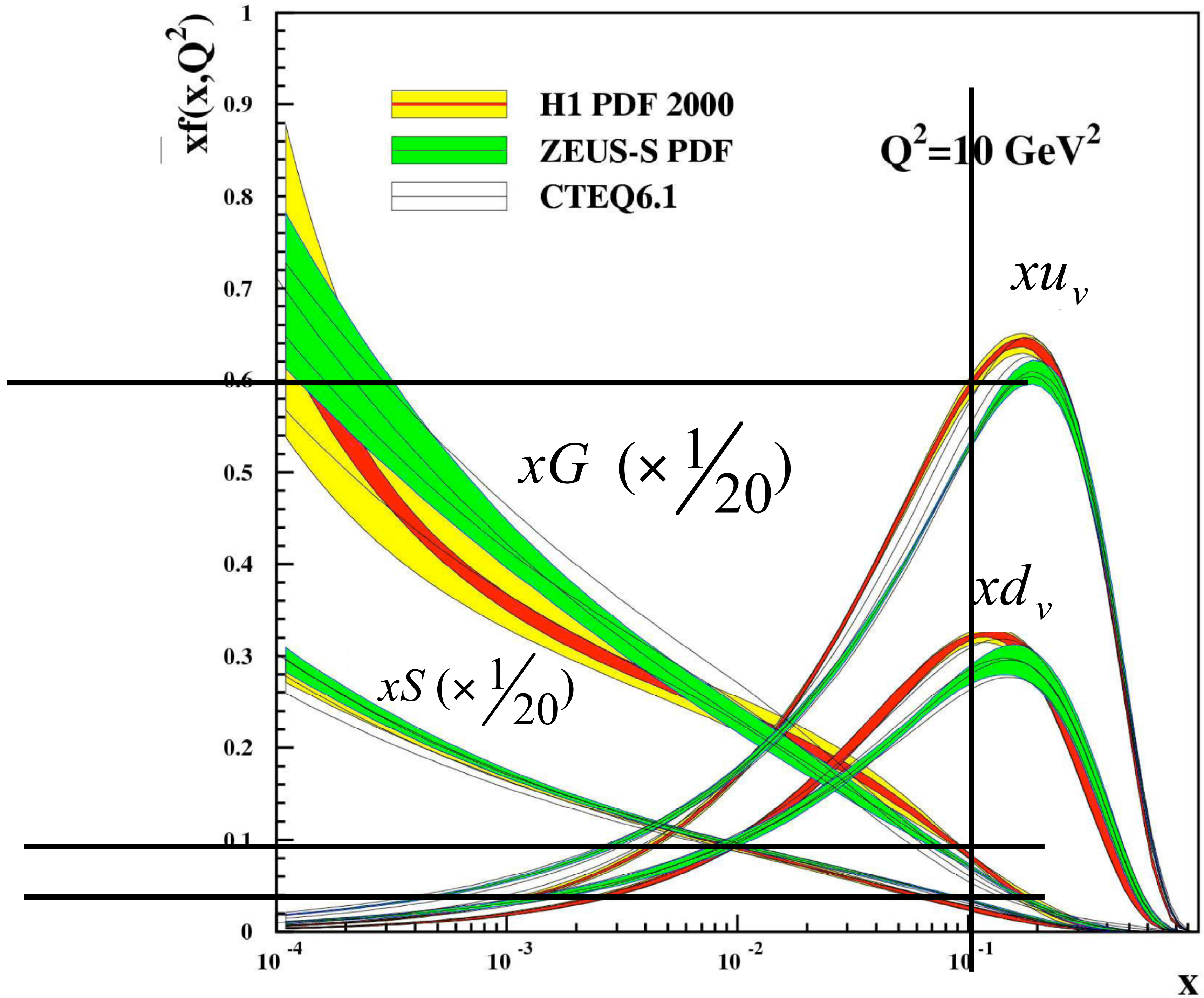
Anne M. Sickles, April 29, 2009

baryon/anti-baryon ratio





valance up: 0.6



gluon: 0.09x20=1.8

sea: 0.04x20=0.8

x_T scaling

$$\frac{d\sigma}{d^3p/E}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^n} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

- n related to "twist", number of participants, of the hard scattering
- $n(x_T)$ = 4: leading twist 2→2 scattering
  - increased slightly: running coupling, evolution of PDFs

$$E\frac{d\sigma}{d^3p}(AB \to CX) \propto \frac{(1-x_T)^{2n_{spectator}-1}}{p_T{}^{2n_{active}-4}}$$

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