$\sqrt{s}$ Dependence of Pion Distributions

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for the PHENIX Collaboration

Overview

(I picked material that hasn't been presented here before)

- Quick overview of the PHENIX apparatus

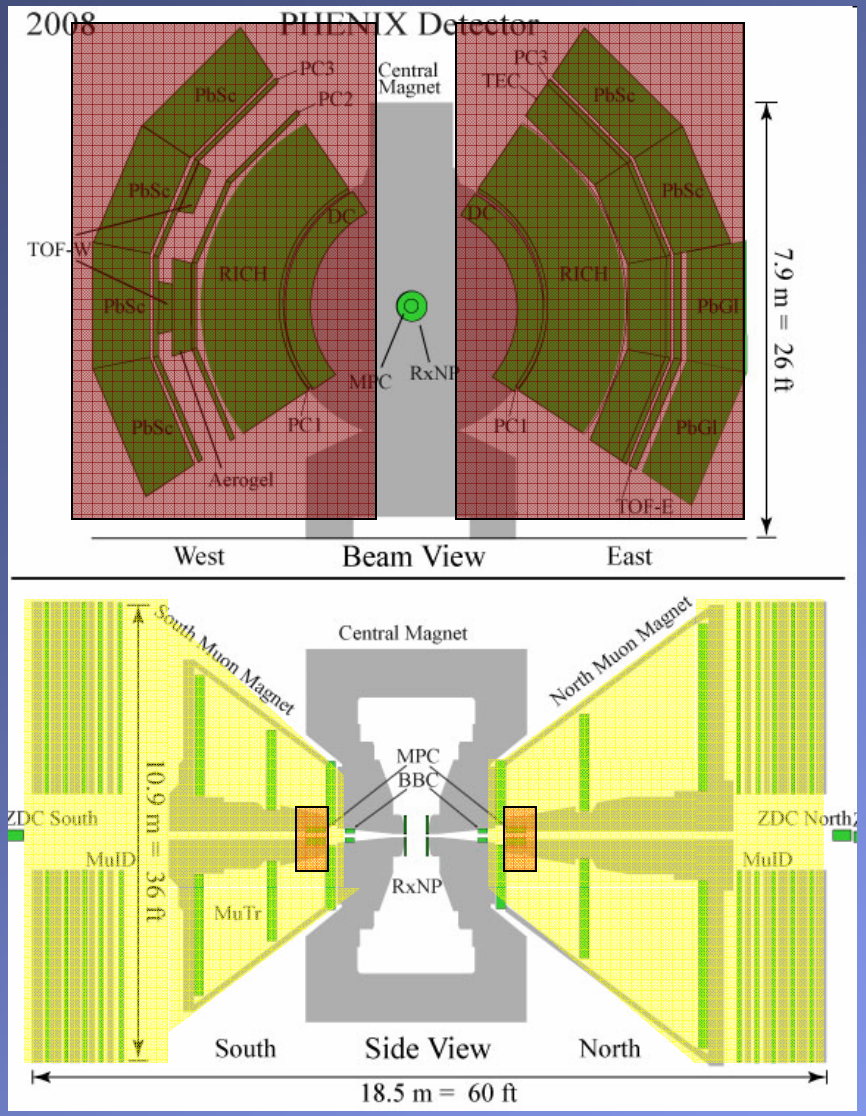
- p+p data at 62.4, 200 GeV
- New results from 500GeV
- x_T scaling

p + p

- Heavy Ion: R_{AA} at different sqrt (s)
- 22.4, 62.4, and 200 GeV data

Heavy Ion

The PHENIX Detector at RHIC

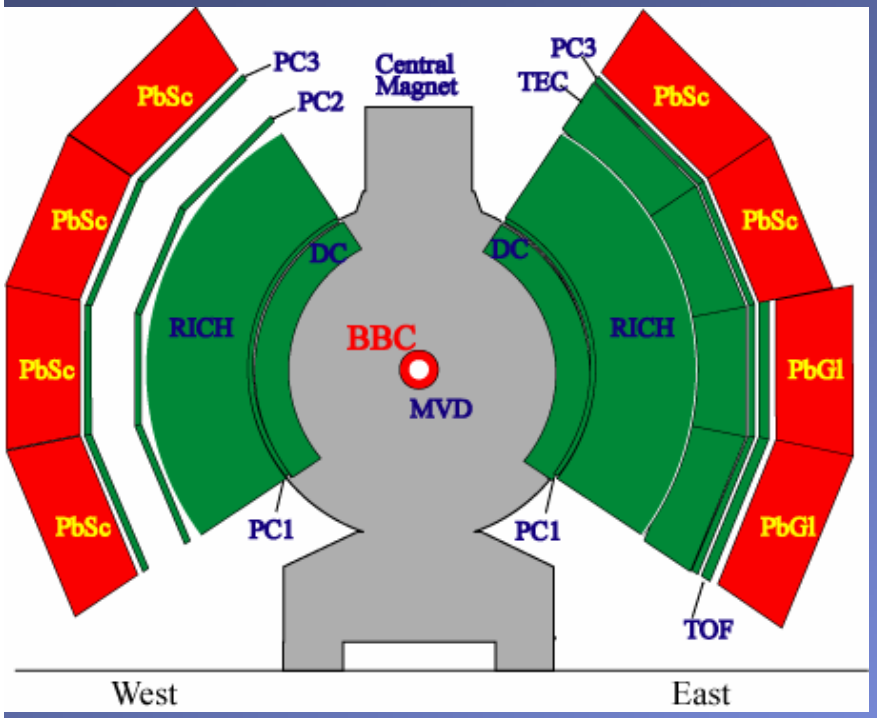


Central Arms $|\eta| < 0.35$
- Identified charged hadrons
- π^0, η
- Direct Photon
- J/Ψ
- Heavy Flavor

Muon Arms $1.2 < |\eta| < 2.4$
- J/Ψ
- Unidentified charged hadrons
- Heavy Flavor

MPC $3.1 < |\eta| < 3.9$
- π^0, η

π^0 in PHENIX



6 PbSc sectors (15,552 channels)

η=±0.35 $\Delta\varphi$=135^0

Granularity: $\Delta\eta\times\Delta\varphi$=0.011×0.011

2 PbGl sectors (9,216 channels)

η=±0.35 $\Delta\varphi$=45^0

Granularity: $\Delta\eta\times\Delta\varphi$=0.008×0.008

PbSc vs PbGl: important systematic cross check

Different granularity ⇒ Different $\pi^0\rightarrow\gamma\gamma$ merging

Different response to hadrons ⇒ Different background conditions

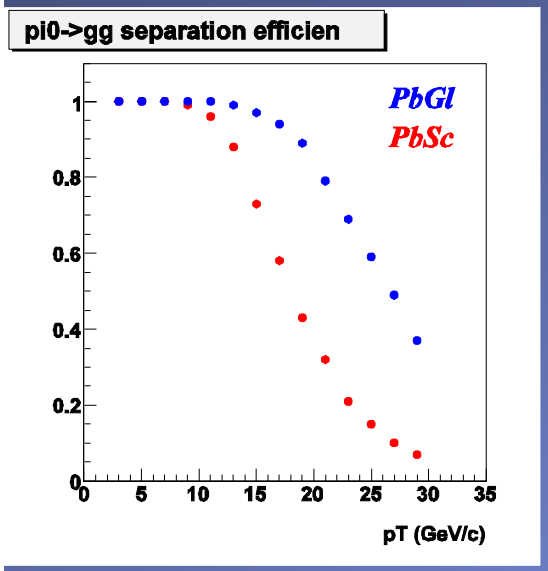
BBC: provide "Minimum Bias" (MB) trigger

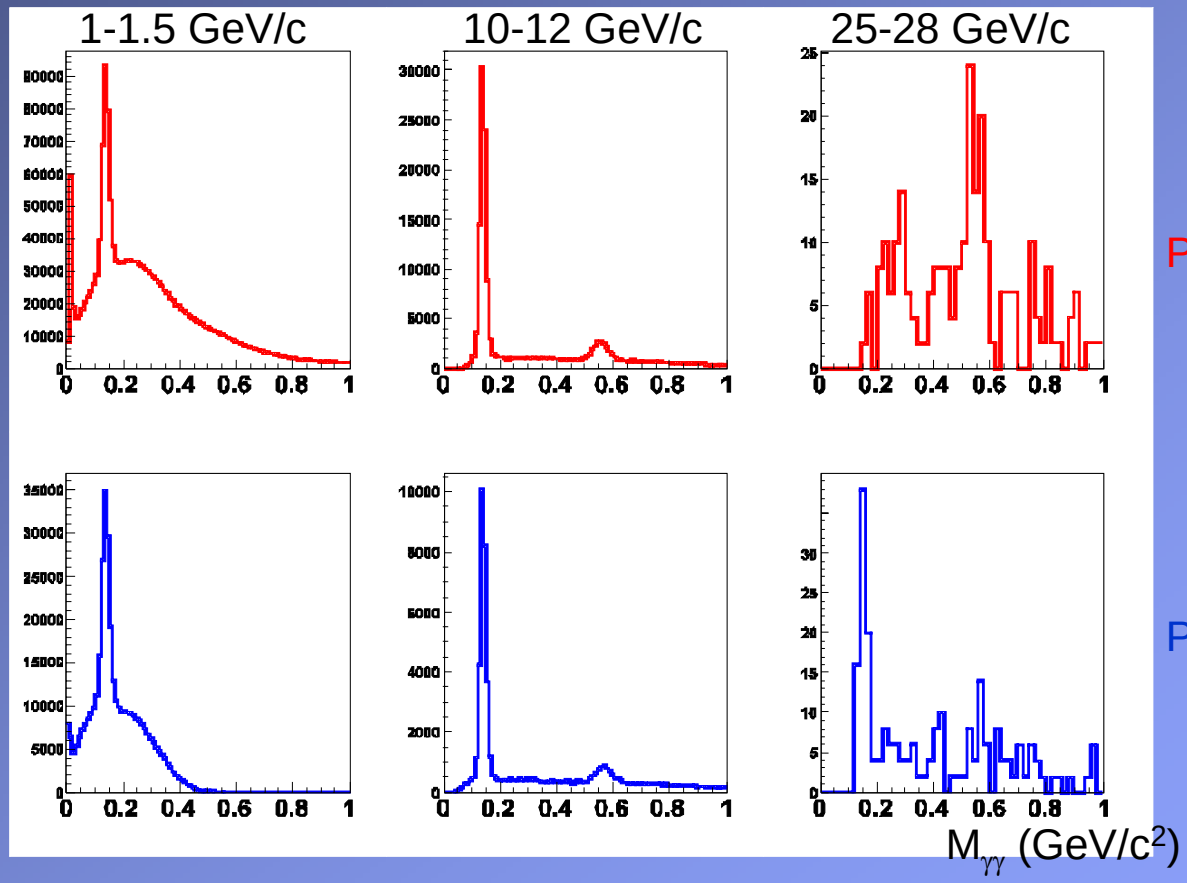
η=±(3.0-3.9) $\Delta\varphi$=360^0

Also provides z-vertex position

Triggers: ~40% of σ^{inel}_{pp} at $\sqrt{s}$=62 GeV
~60% of σ^{inel}_{pp} at $\sqrt{s}$=200 GeV
~70% of σ^{inel}_{pp} at $\sqrt{s}$=500 GeV

π^0 reconstruction from inv. mass





$\pi^0 \rightarrow \gamma\gamma$ at pT~25 GeV/c:

~90% are merged in PbSc

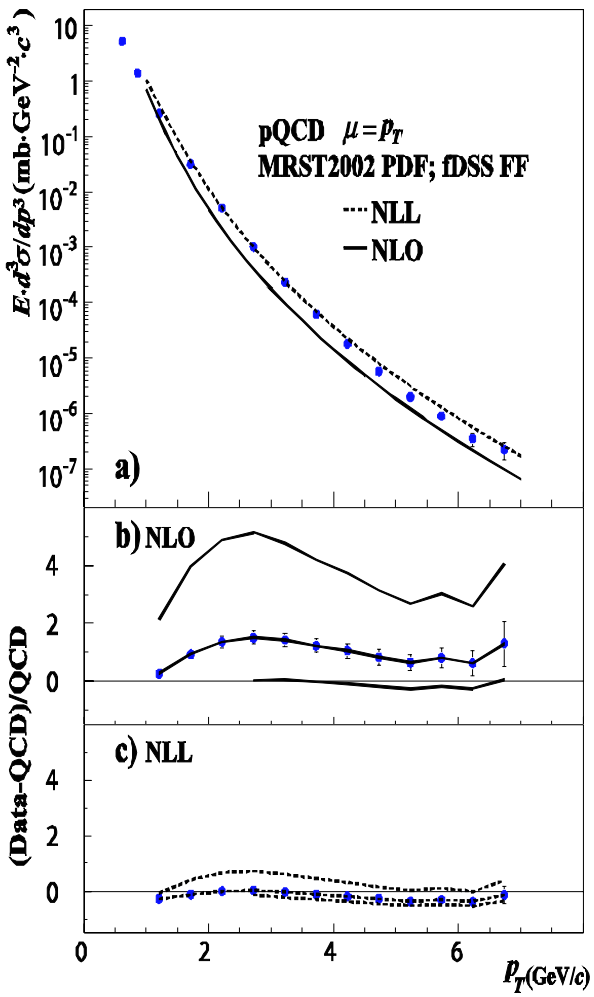
~50% are merged in PbGl

Challenges at p_T > 20GeV/c

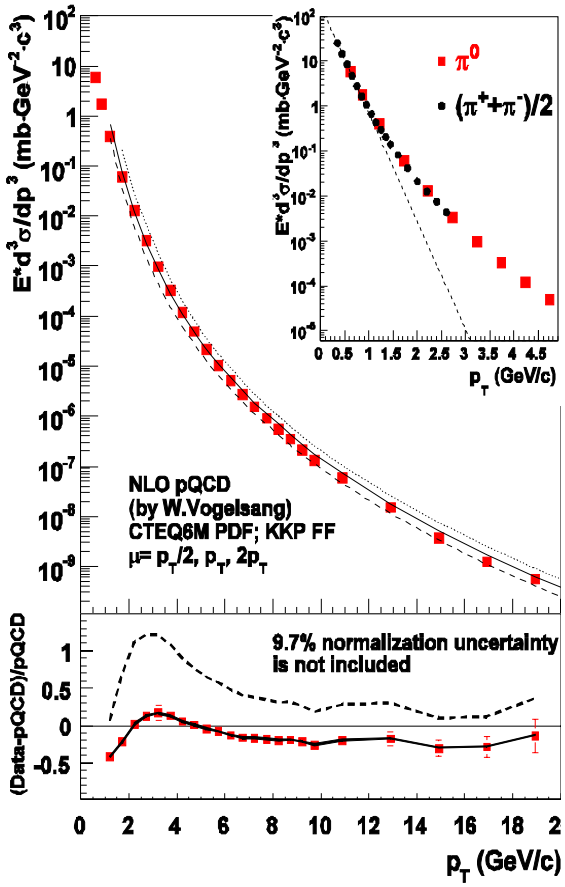
- Spacial separation of photons smaller than shower footprint → cluster merging, more severe in PbSc
- Different systematics of PbSc and PbGl offers an “idiot check”
- Small contamination from charged particles (< 6%)
- 2-4% contribution from other decay photons and, yes, direct photons

π^0 spectrum and NLO: $\sqrt{s}$=62, 200 and 500 GeV

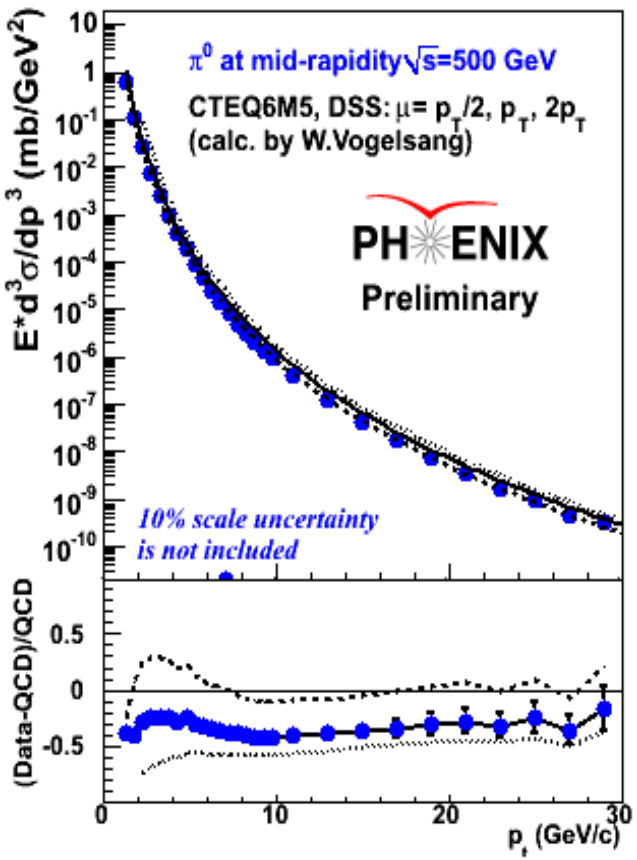
$\sqrt{s}$=62 GeV (PRD79, 012003)



$\sqrt{s}$=200 GeV (PRD76, 051106)



$\sqrt{s}$=500 GeV (Preliminary)

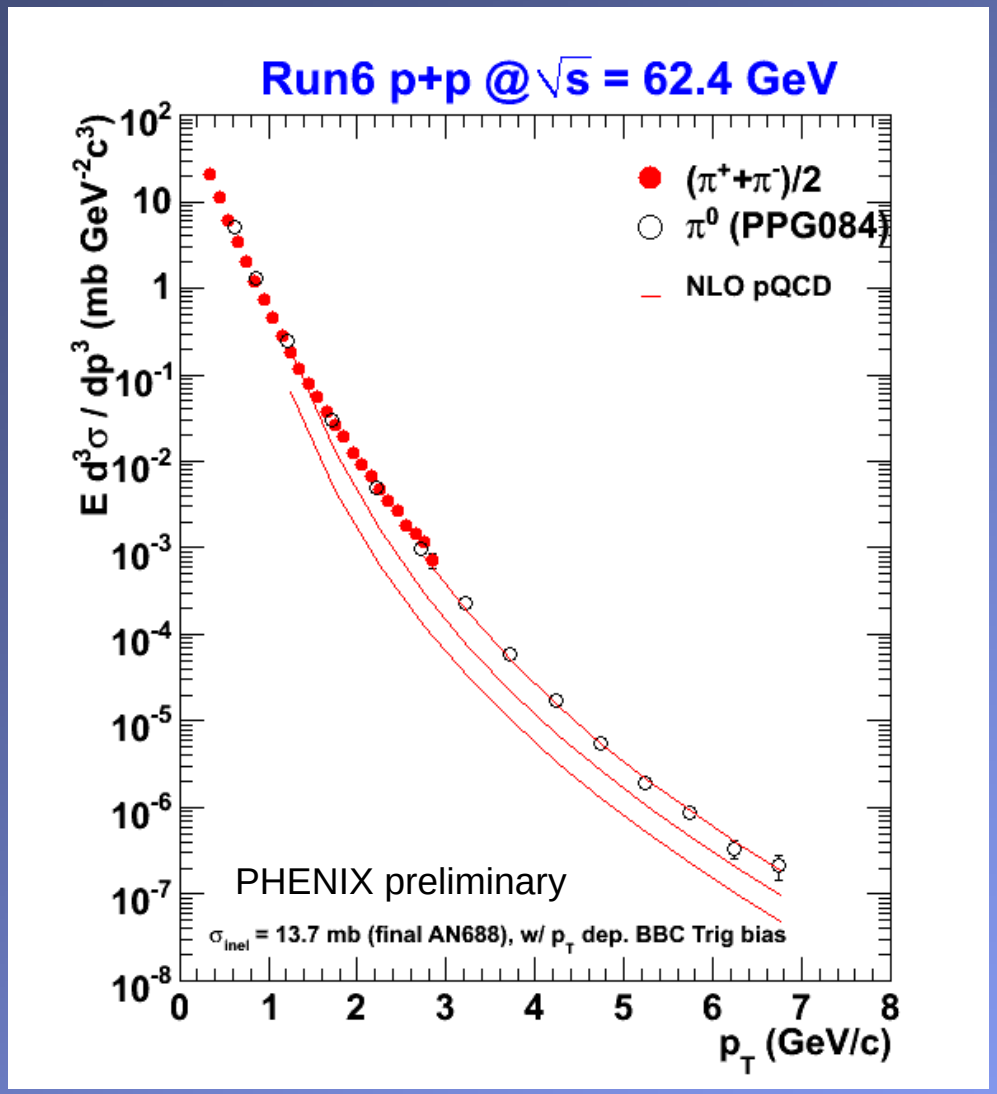


Data below NLO at $\mu=p_T$ by (25±15)%

Data below NLO at $\mu=p_T$ by (30±15)%

May need inclusion of NLL to NLO

Comparison of π^0 with π^{+-}



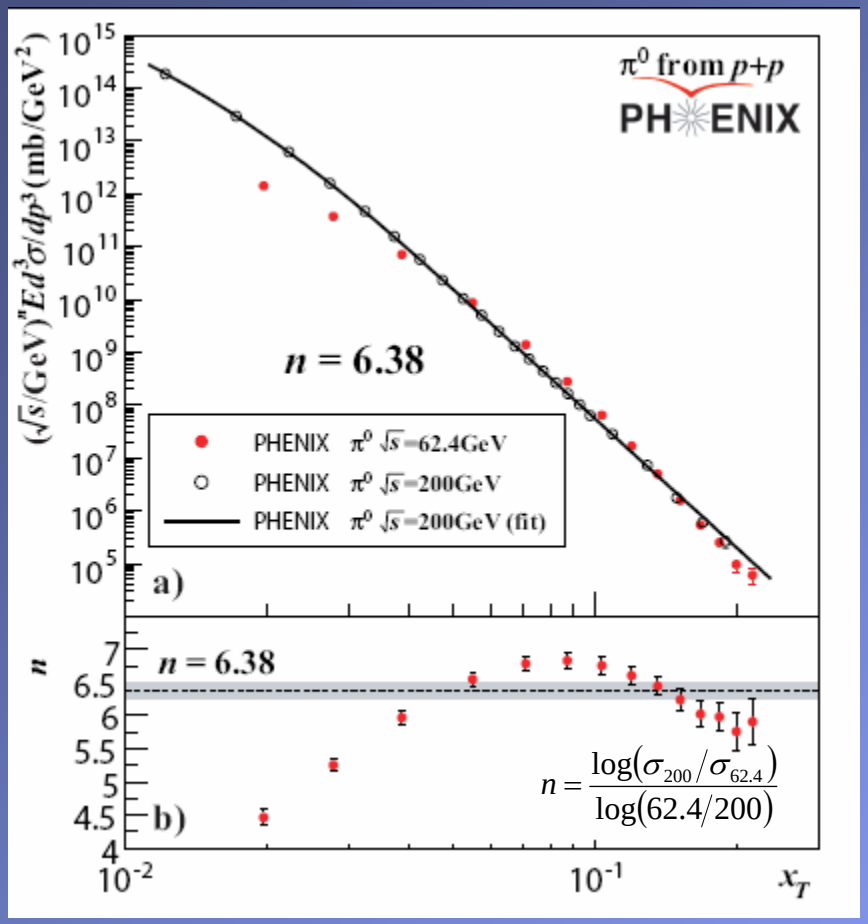
π^0: PRD 79, 012003 (2009), PHENIX

$\pi^{\pm}$: PHENIX preliminary

Good agreement between charged pions and neutral, ~10%.

x_T scaling

From comparison of √s=62 and 200 GeV



x_T scaling:

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

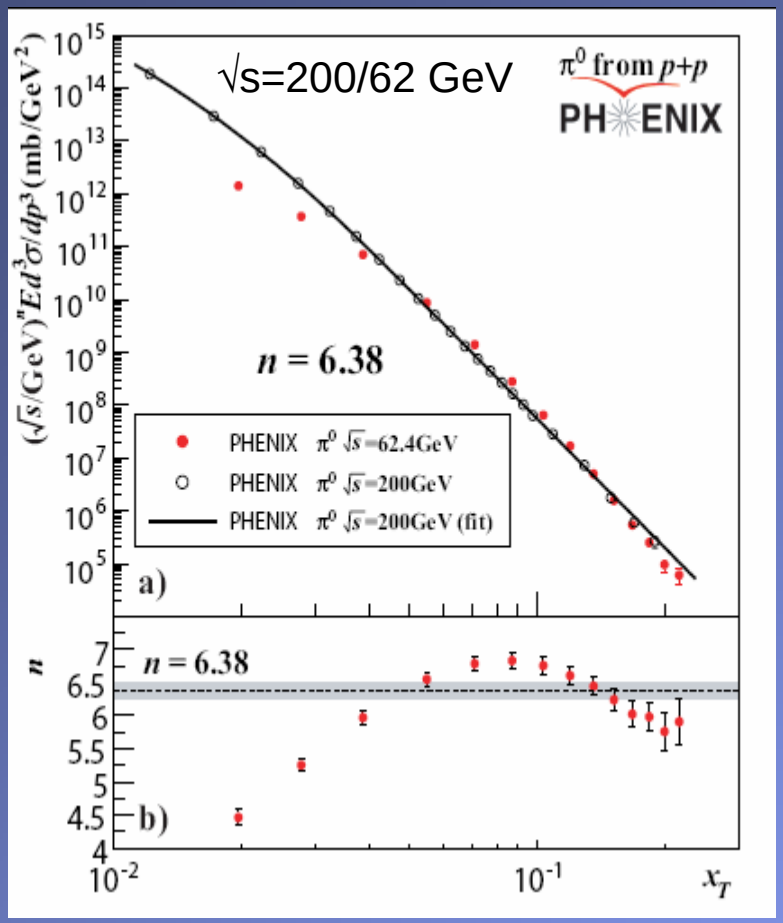
Note this *n* here

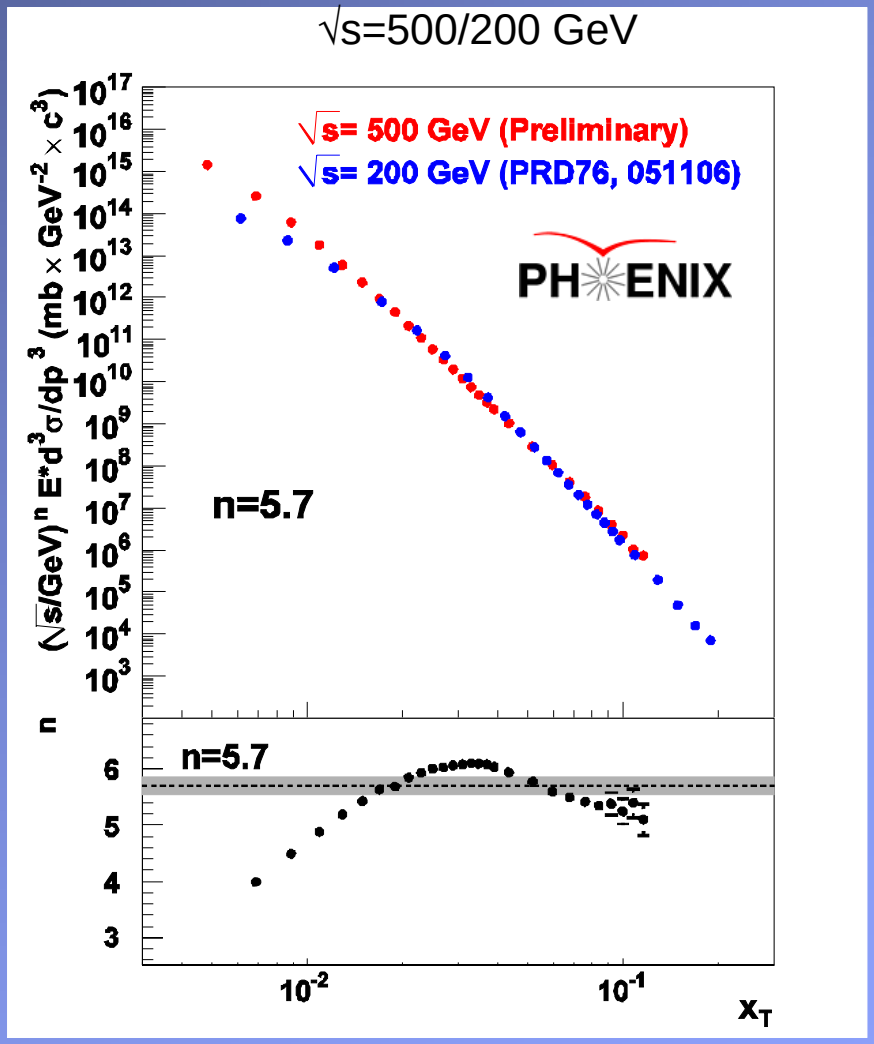
Soft region: $n(x_T)$ increase with x_T

Hard region: $n(x_T)$ decrease with x_T

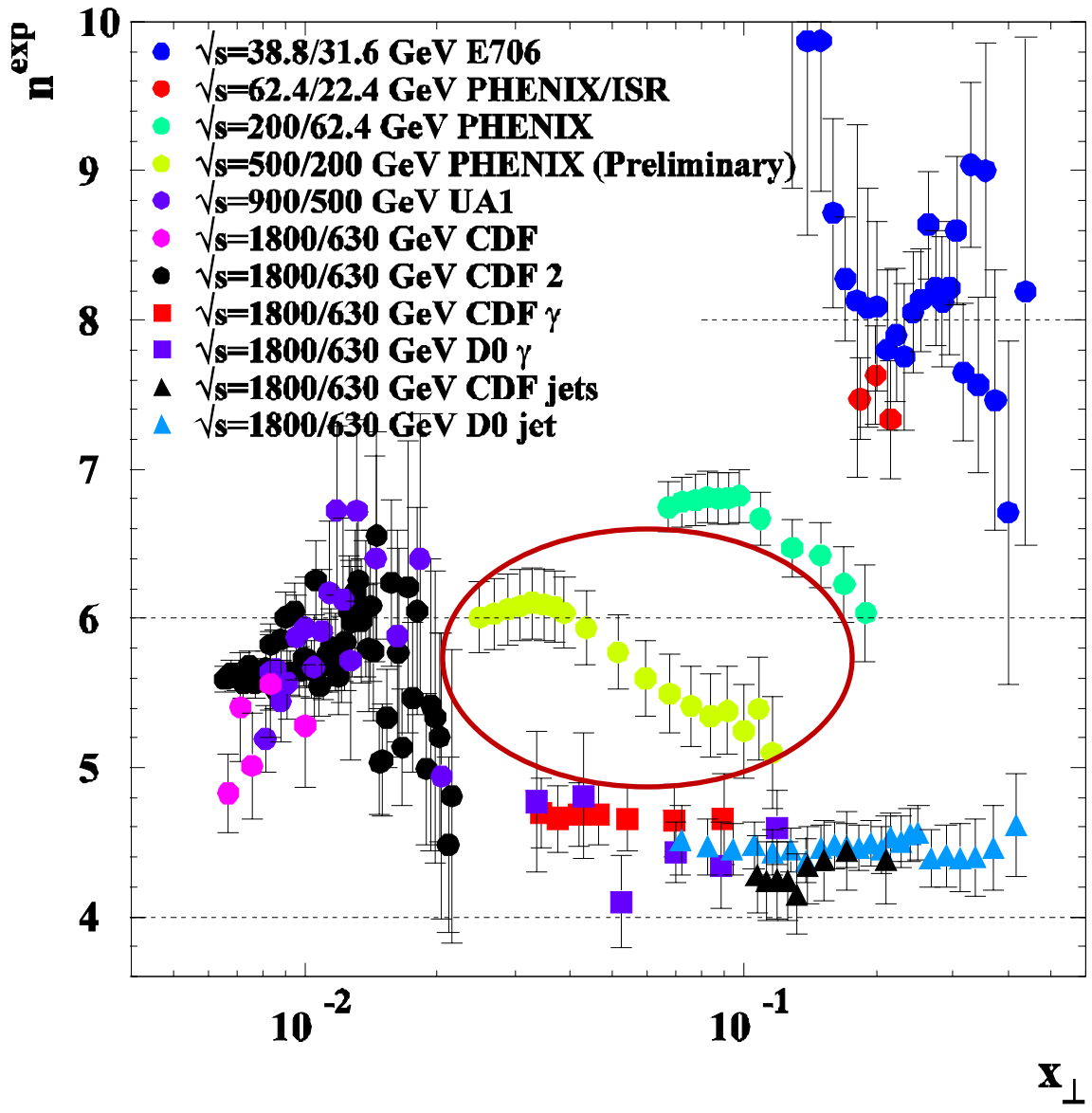
pT~2-3 GeV/c – transition from soft to hard scale; comparison of √s=200 and 500 GeV gives the same transition point

x_T scaling 62, 200, 500 GeV





x_T scaling



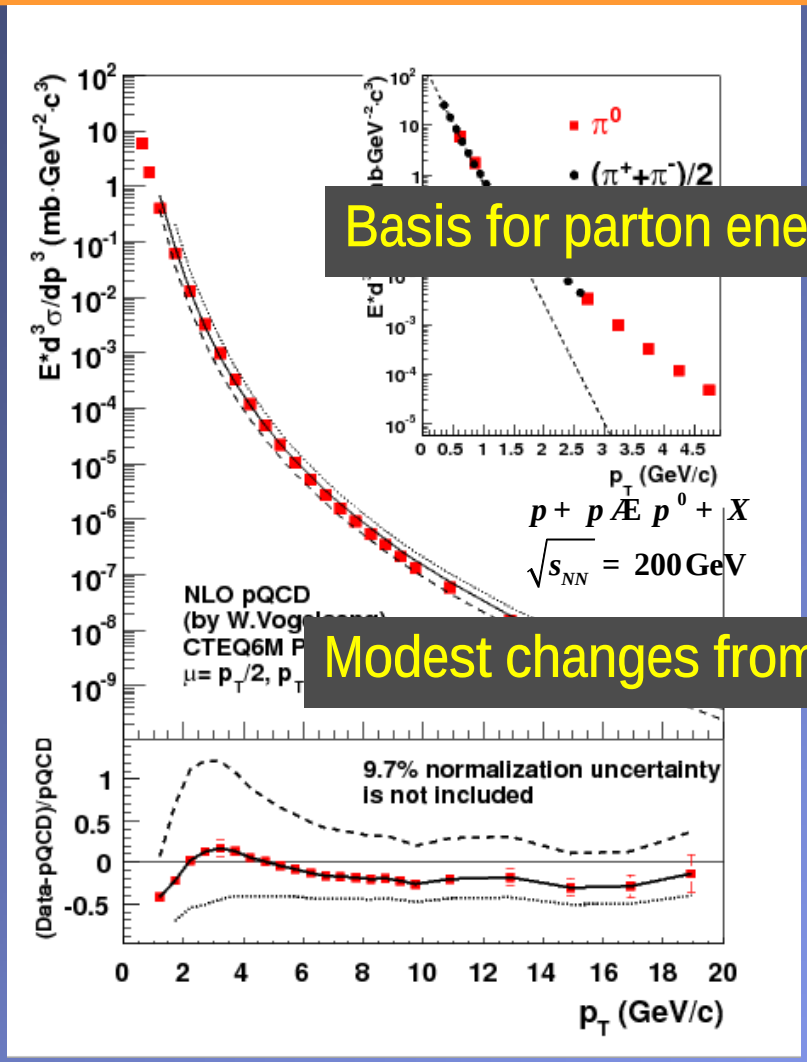
New PHENIX data ($\sqrt{s}$=500/200 GeV) added

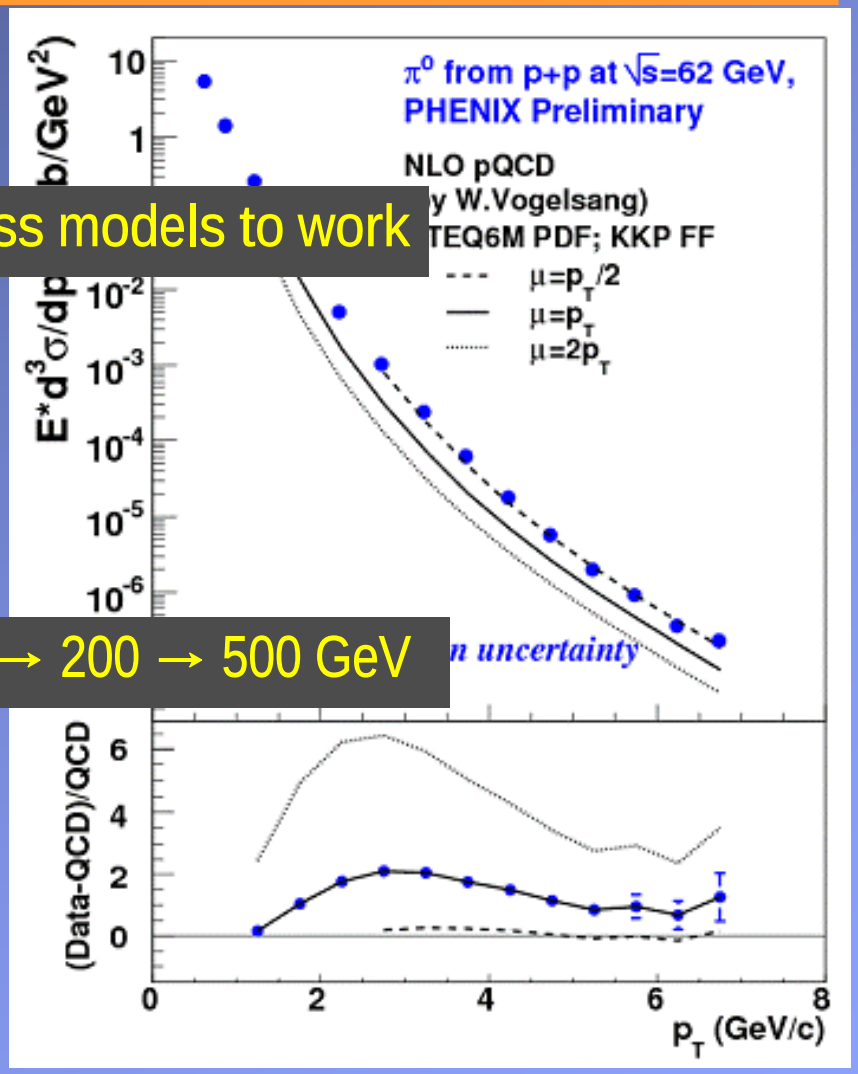
Helps to establish and evaluate Higher Twist (HT) contributions in high pT particle production

PHENIX new data follow the global trend

F.Arleo, S.Brodsky, DS Hwang and A.Sickles: arXiv:0911.4604

π^0 Spectra in p+p Agree with pQCD



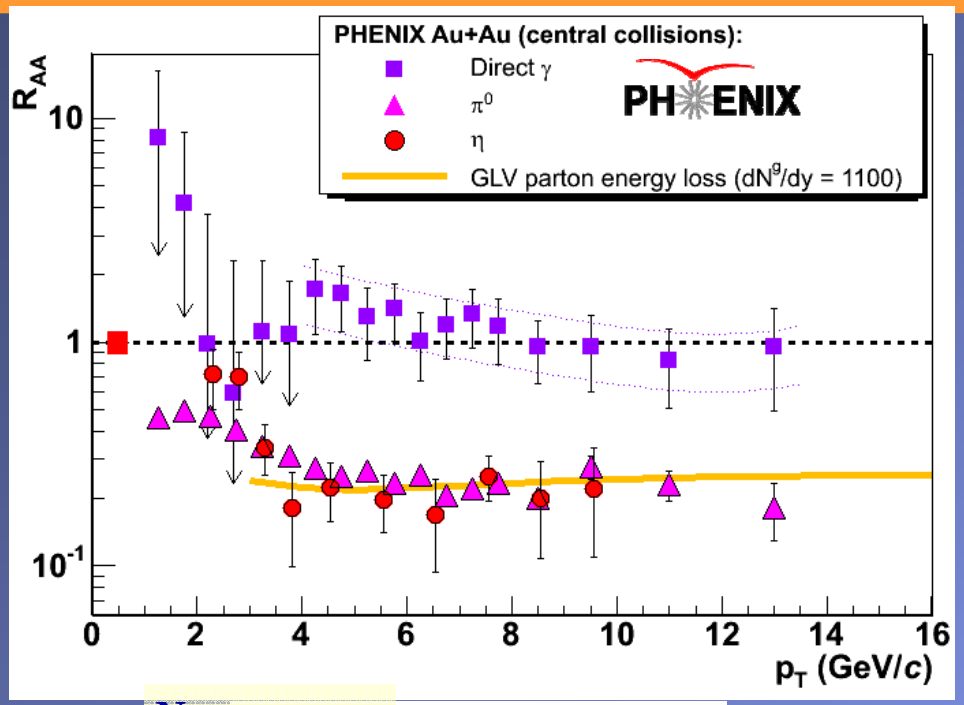


Basis for parton energy loss models to work

Modest changes from 62.4 → 200 → 500 GeV

Agreement with pQCD is a prerequisite for jet quenching models

Not-so-modest changes in Heavy Ions



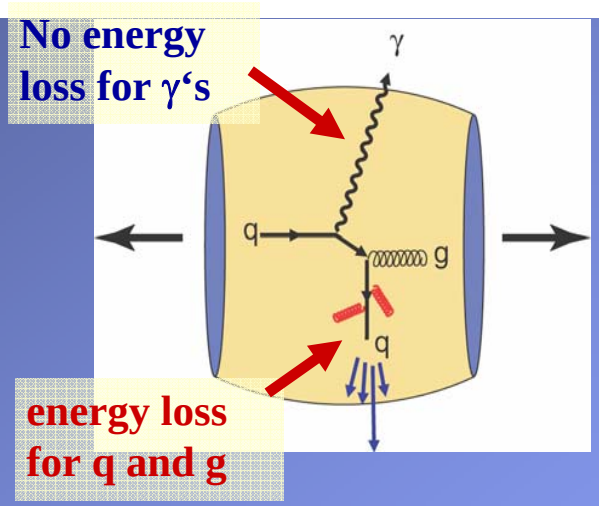
$$R_{AB} = \frac{dN/dp_T\big|_{A+B}}{\langle T_{AB}\rangle' \; ds_{inv}/dp_T\big|_{p+p}},$$

$$\text{where } \langle T_{AB}\rangle = \langle N_{coll}\rangle / s_{inel}^{NN}$$

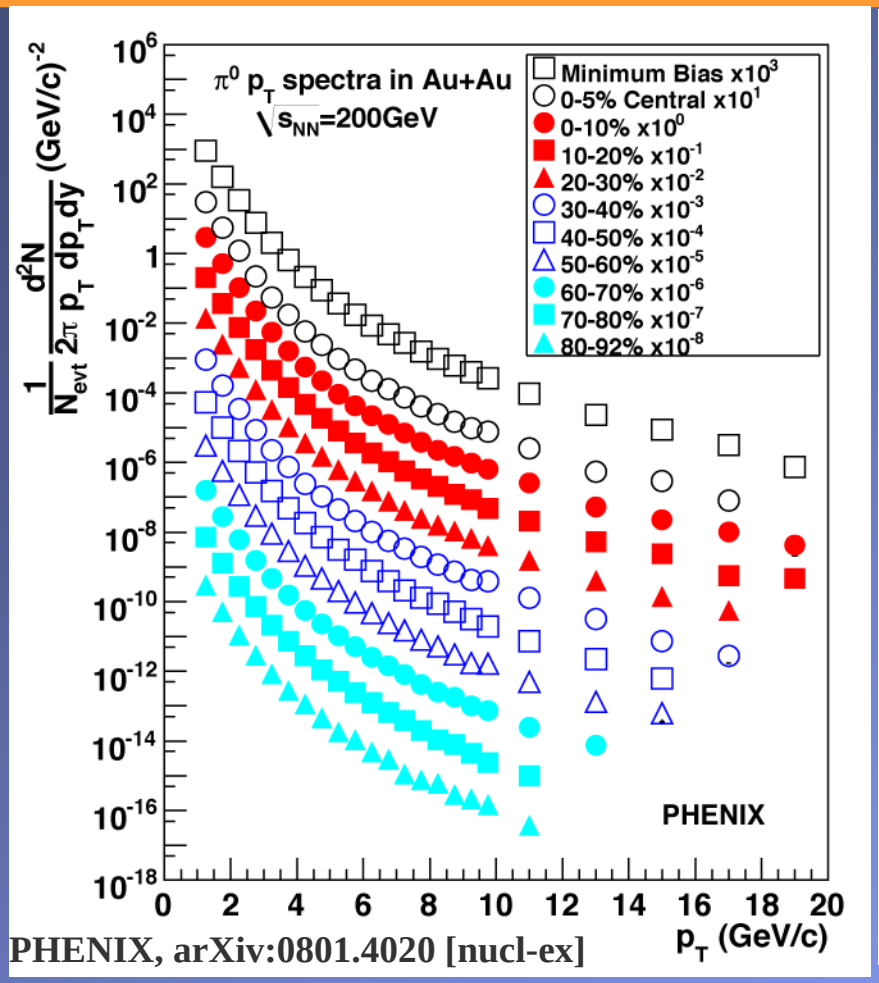
$$R_{AA}(p_T) = \frac{yield(AuAu)/N_{coll}}{yield(pp)}$$

- Early insights: Hadrons are suppressed, photons are not
- No initial-state effect: Absence of suppression in d+Au
- Evidence for parton energy loss

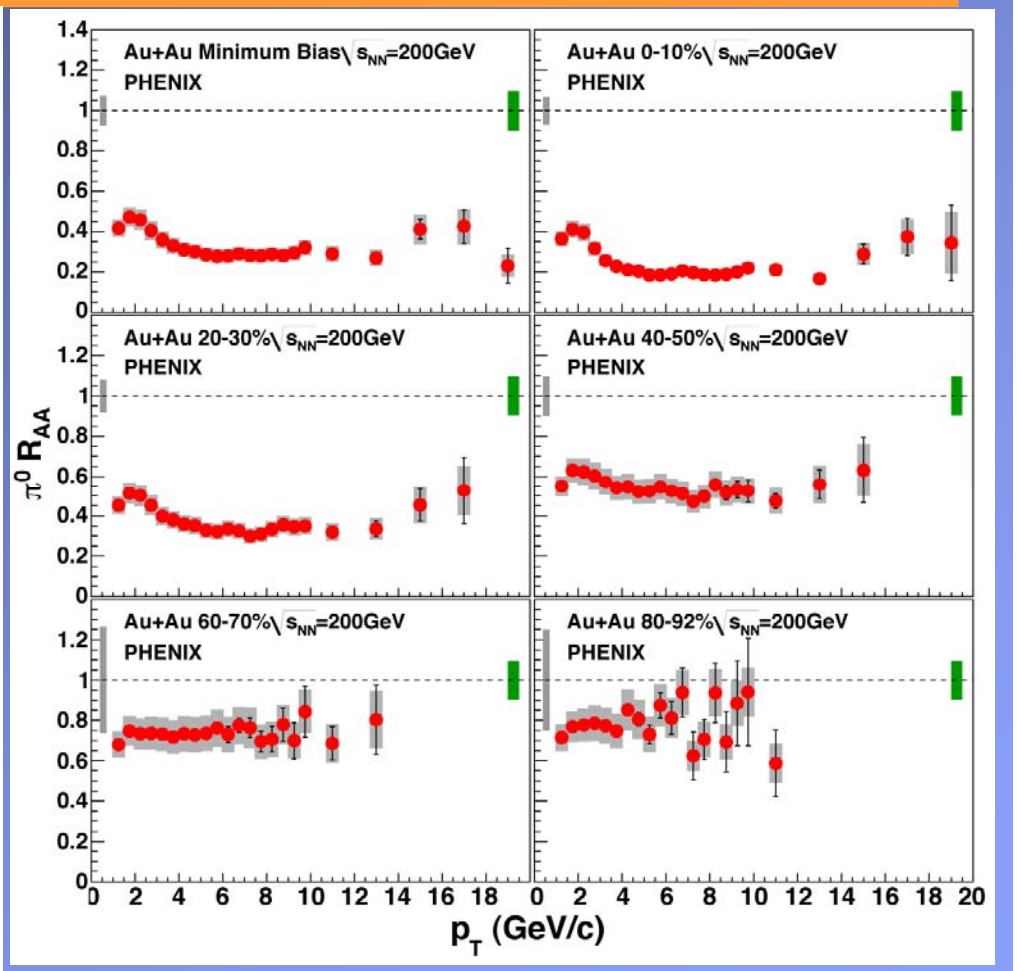
R_{AA} is a useful tool to constrain the medium's properties



Example: π^0 Spectra in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

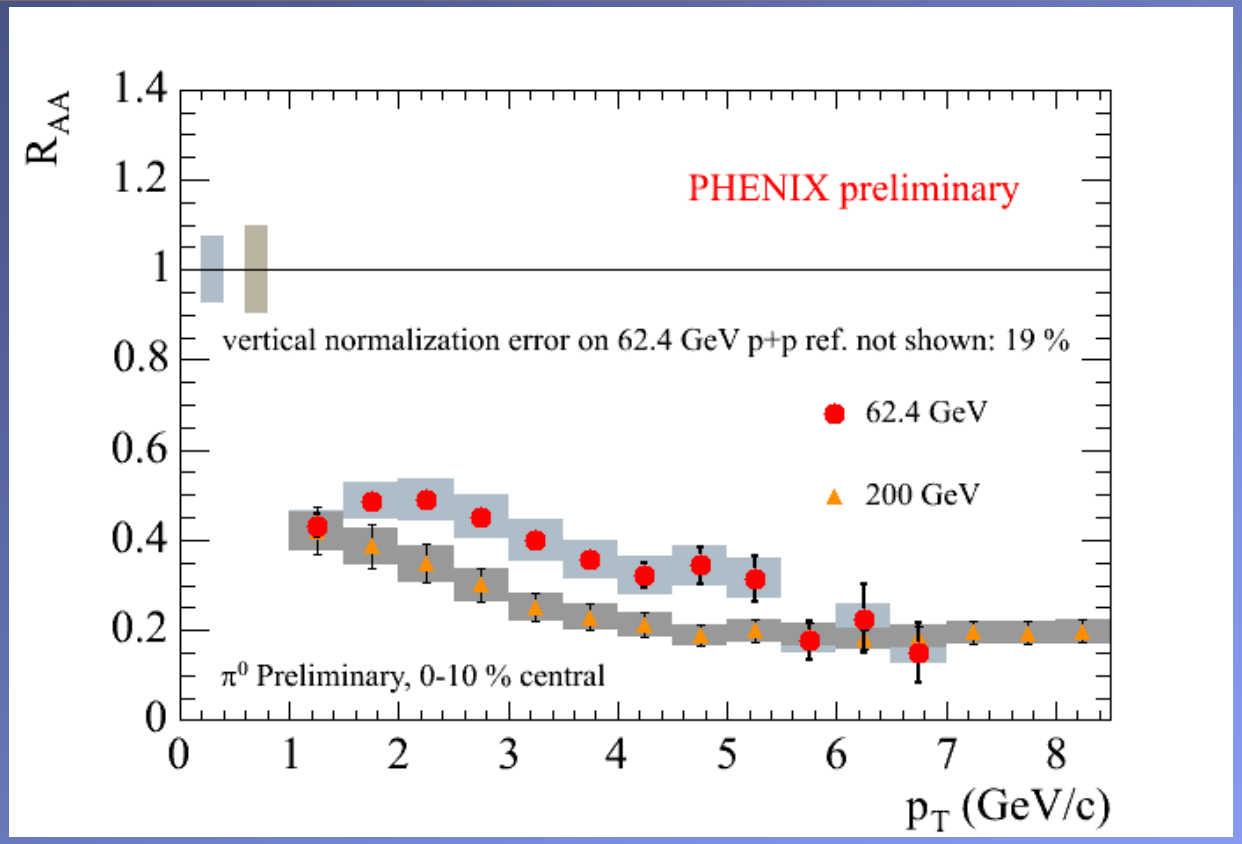


PHENIX, arXiv:0801.4020 [nucl-ex]



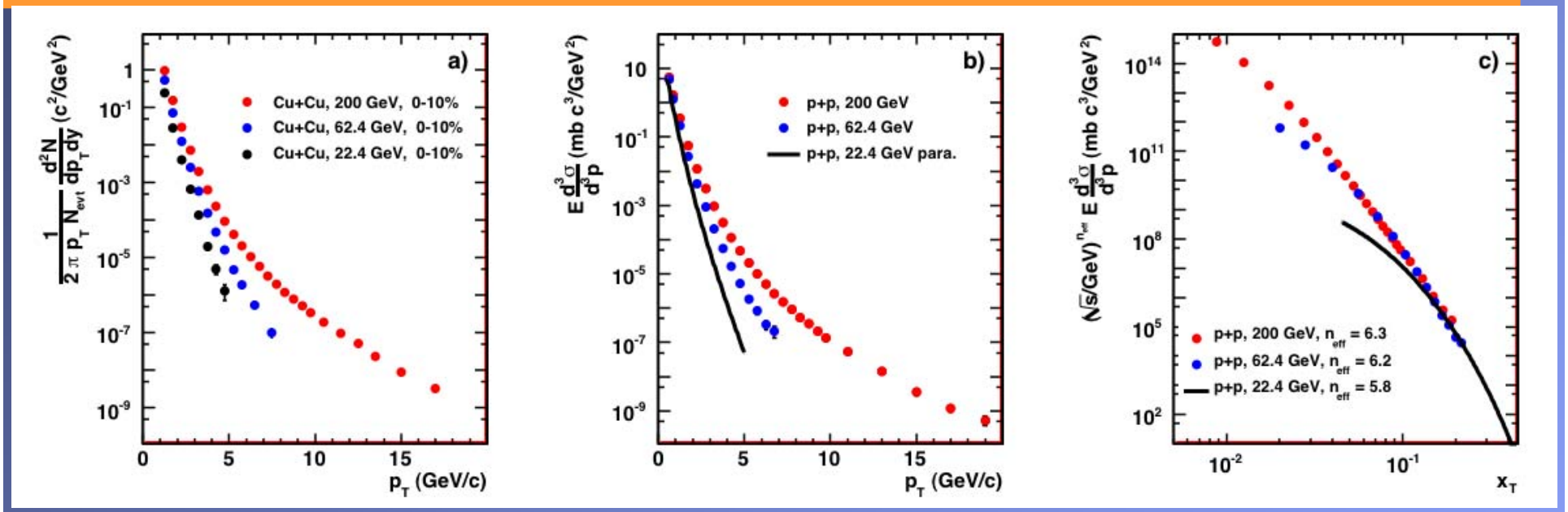
- π^0 R_{AA} measured up to p_T = 20 GeV/c (central Au+Au)
- Constant $R_{AA} \approx 0.2$ in central Au+Au up to highest p_T ($5 < p_T < 20$ GeV/c)

π^0 R_{AA} in Au+Au at 200, 62 GeV



- Central Au+Au:
  Similar R_{AA} at 62.4 and 200 GeV (for p_T > 6 GeV/c),
- Reminiscent of the smooth transition with centrality before

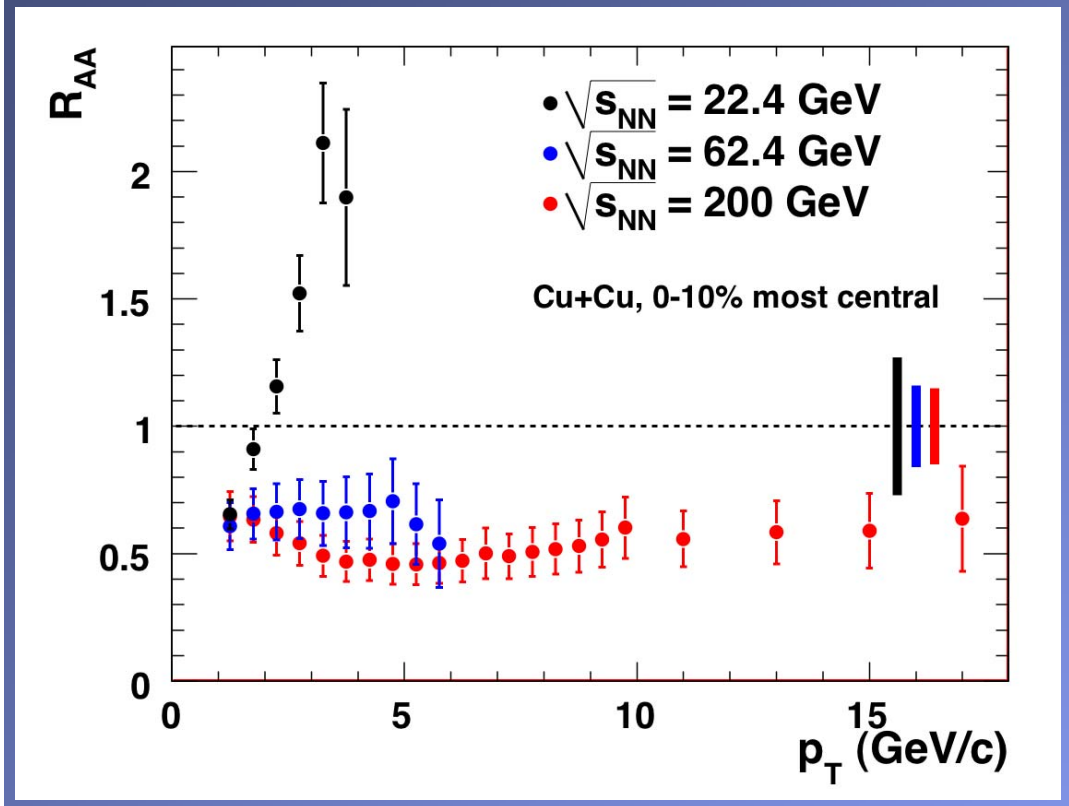
Adding the 22.4 GeV data point (Cu+Cu)



PHENIX, arXiv:0801.4555 [nucl-ex]

- p+p reference measured at 62.4 GeV and 200 GeV by PHENIX
- p+p reference at 22.4 GeV
  - World data for $21.7 < \sqrt{s_{NN}} < 23.8$ GeV rescaled to 22.4 GeV
  - Fit describes data within 25%
- Scaling in $x_T = 2\, p_T/\sqrt{s}$: Pion production dominated by hard scattering for $p_T > 2$ GeV/*c* at all three energies

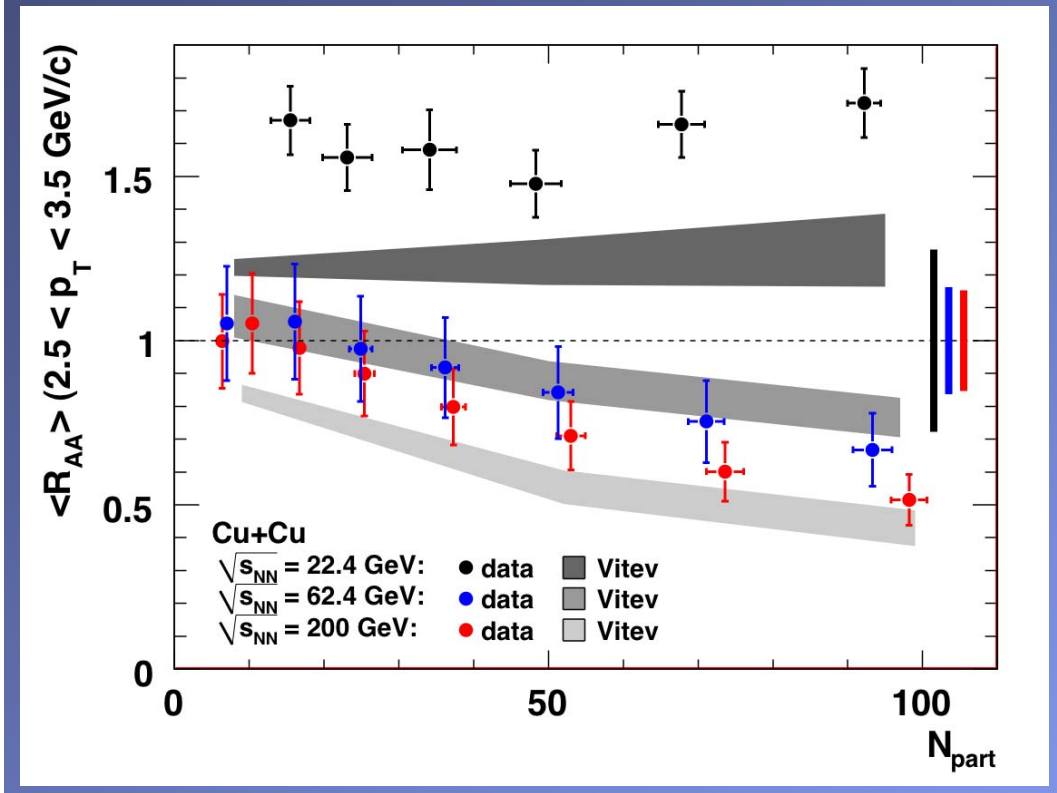
p_T Dependence of π^0 R_{AA} in Cu+Cu



PHENIX, arXiv:0801.4555 [nucl-ex]

- 62.4, 200 GeV:
  - Suppression consistent with parton energy loss for p_T > 3 GeV/*c*
- 22.4 GeV:
  - No suppression
  - Enhancement consistent with calculation that describes Cronin enhancement in p+A
- Parton energy loss starts to compensate Cronin enhancement between 22.4 and 62.4 GeV

Centrality Dependence of π^0 $\langle R_{AA} \rangle$ in Cu+Cu



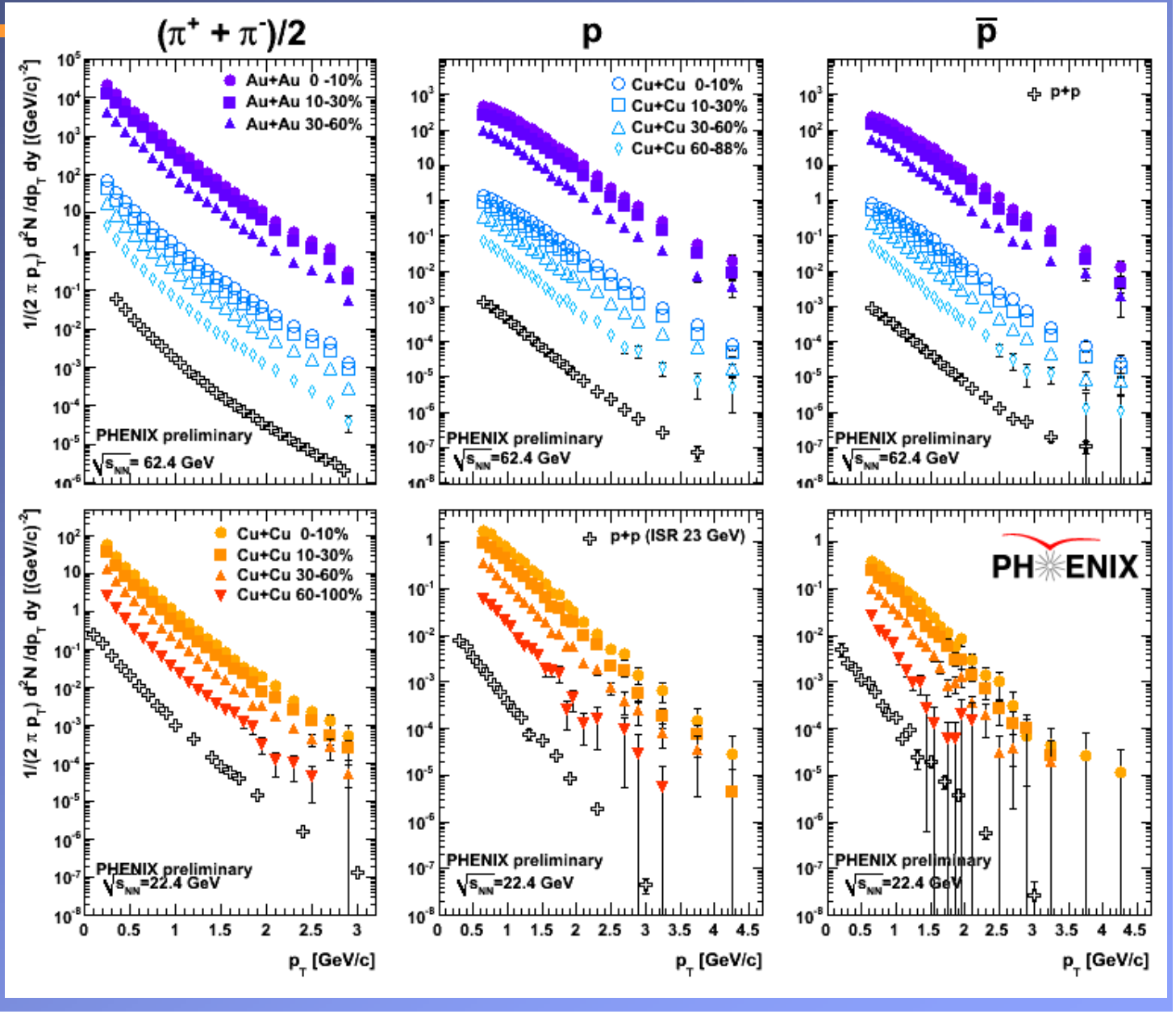
PHENIX, arXiv:0801.4555 [nucl-ex]

- 62.4, 200 GeV:
  - N_{part} Dependence of R_{AA} consistent with parton energy loss
- 22.4 GeV
  - Enhancement independent of centrality
  - Possible explanations
    - Weak centrality dependence of Cronin enhancement
    - Cronin enhancement offset by parton energy loss

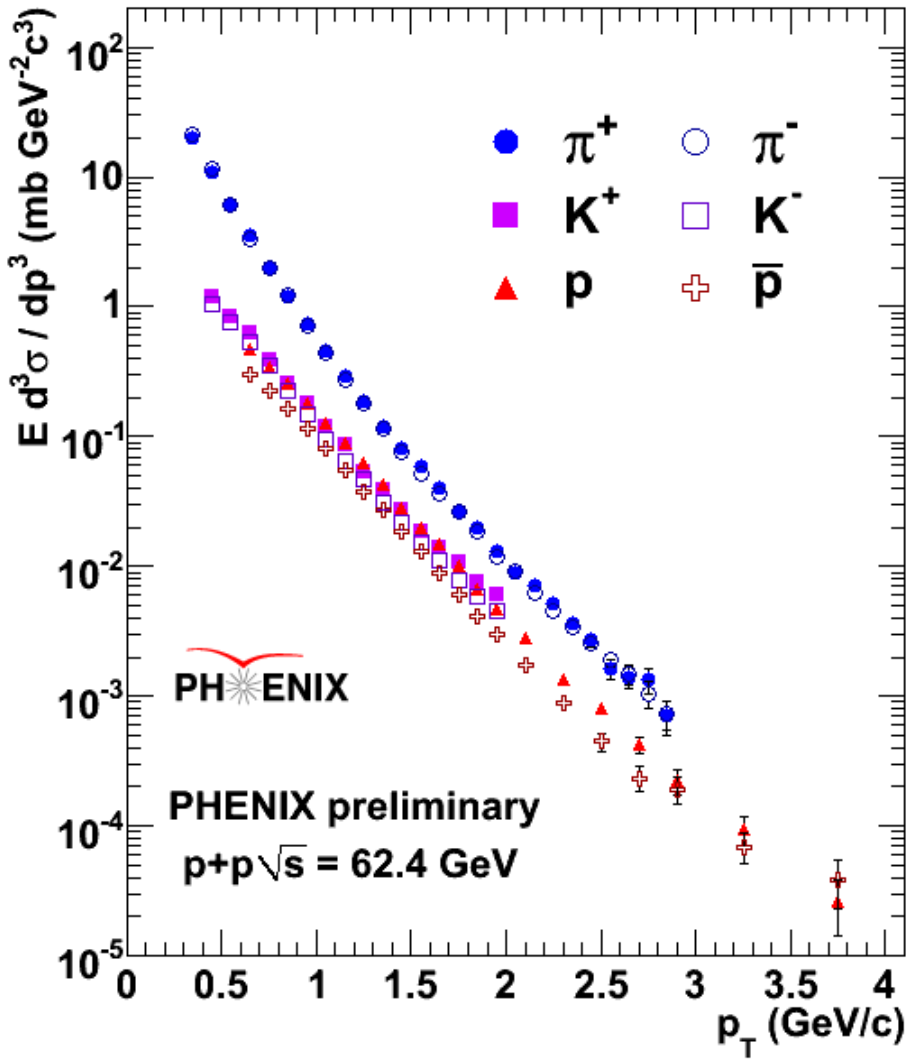
Charged p_T spectra

Au+Au,
Cu+Cu,
p+p
@ 62.4 GeV

Cu+Cu,
p+p (ISR)
@ 22.4 GeV



Charged Particle Cross Sections @ 62 GeV



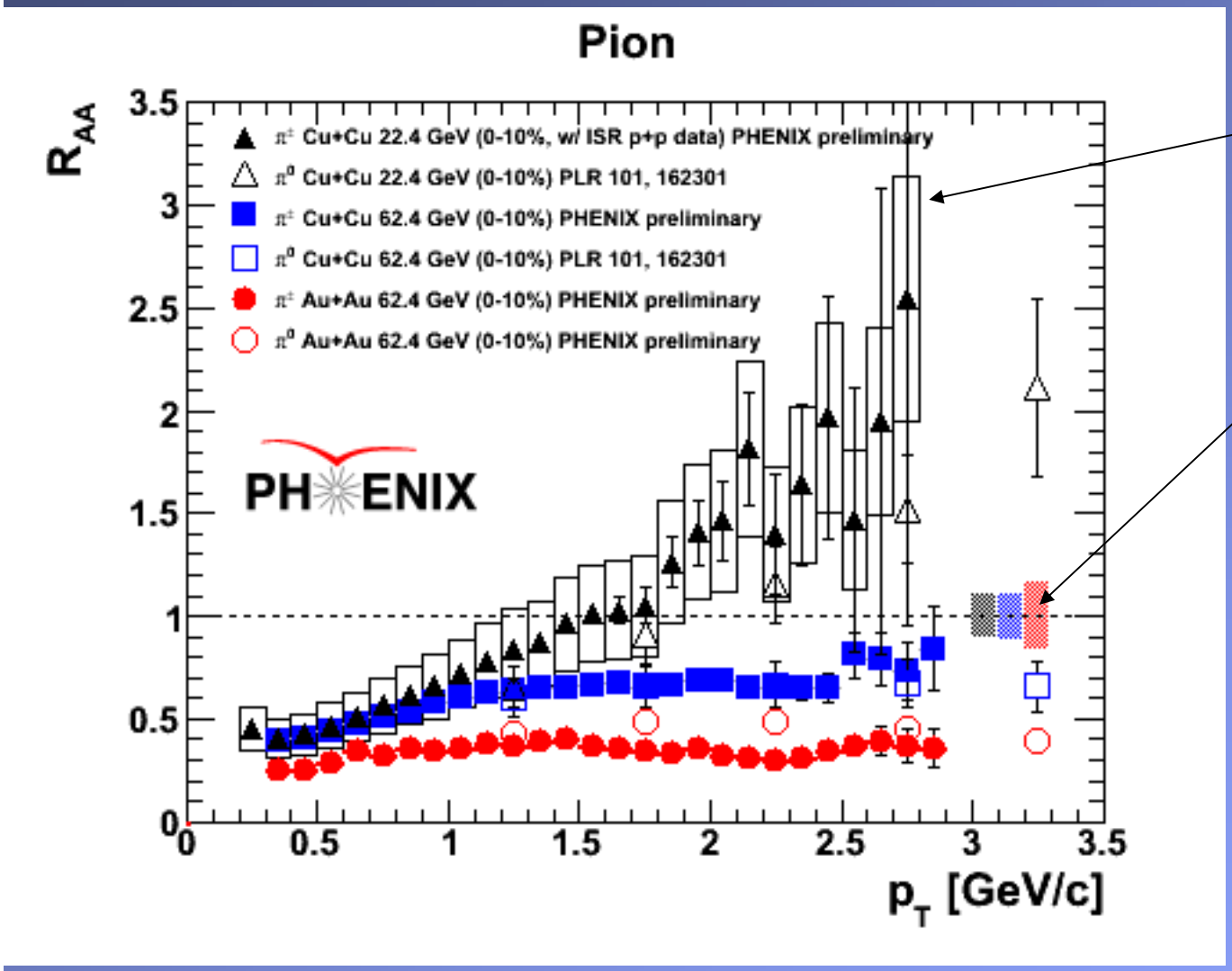
Systematic errors:

Overall normalization error: 11%.

p_T independent error: 6-9%.

p_T dependent error : <5% (only p_T > 2 GeV/*c*).

Neutral and charged pion R_{AA} in Cu+Cu

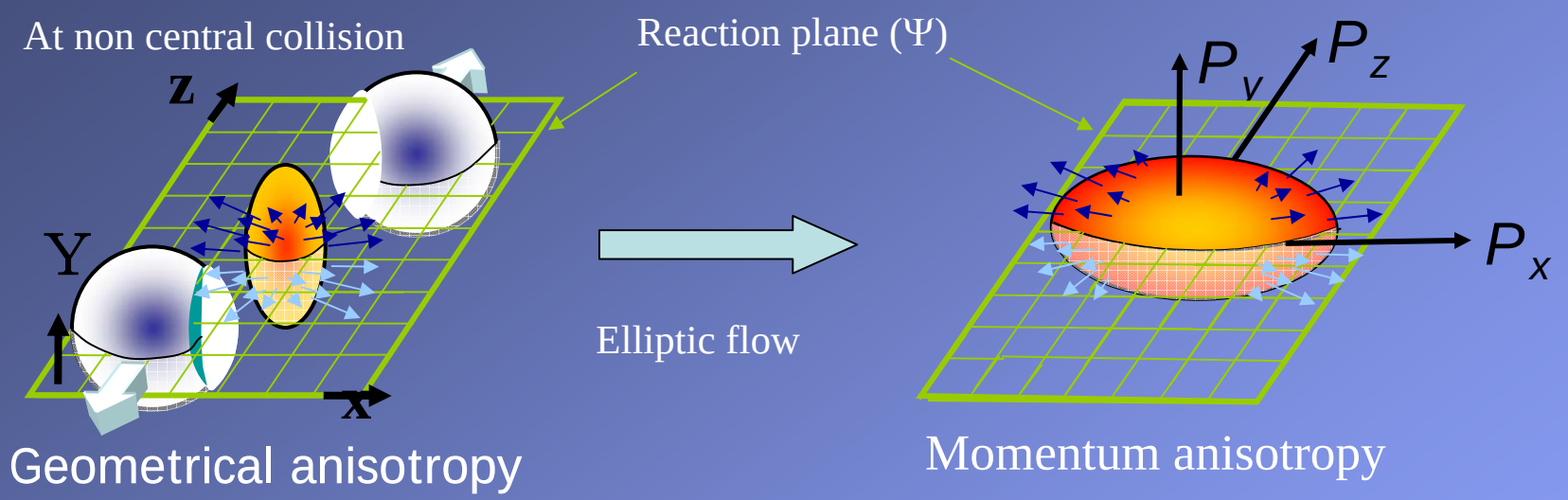


Cu+Cu 22.4 GeV:
(box) ISR p+p sys. error

Ncoll sys. error
- Cu+Cu 22.4 GeV (0-10%): black
- Cu+Cu 62.4 GeV (0-10%): blue
- Au+Au 62.4 GeV (0-10%): red

Normalization error for p+p 62.4 GeV (11%) is not shown here.

Azimuthal Anisotropy, Elliptic Flow (v_2)



Fourier expansion of the distribution of produced particle angle (ϕ) to reaction plane (Ψ)

$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi) + 2v_2\cos[2(\phi - \Psi)] + \ldots\}$$

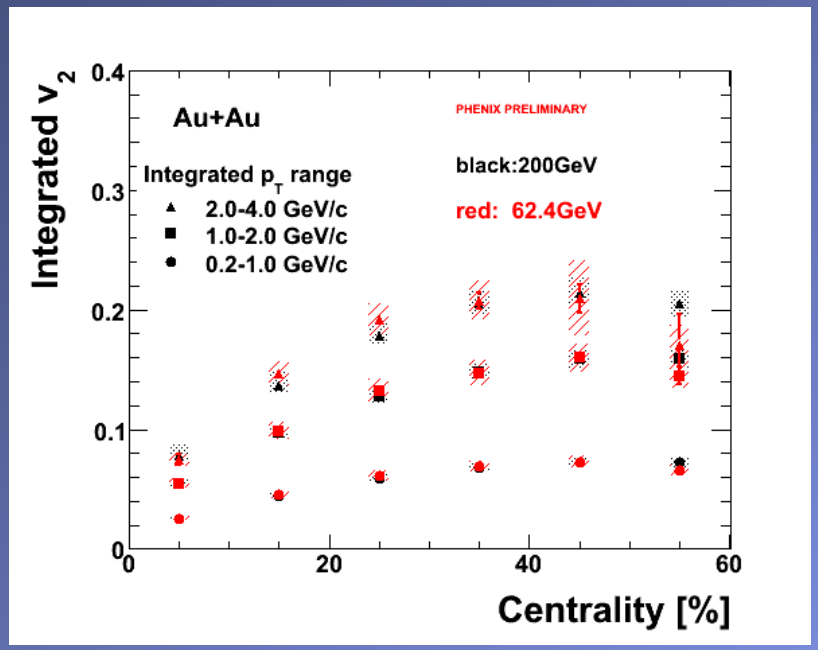
$$v_n = \langle\cos[n(\phi - \Psi)]\rangle$$

v_2 is the coefficient of the second term → indicates ellipticity

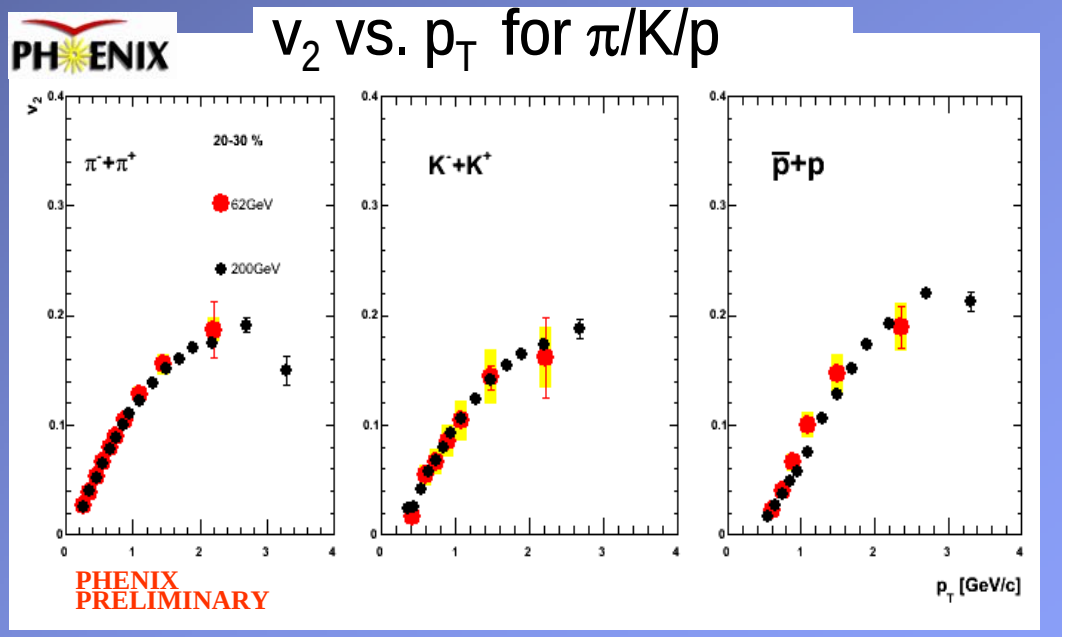
A v_2 measurement is a powerful tool to study the properties of the hot dense matter, and Is yet another "collective" effect

v_2 Studies at 200 and 62.4 GeV

Centrality dependence



Identified particles



No significant difference between 200 and 62.4 GeV

Summary

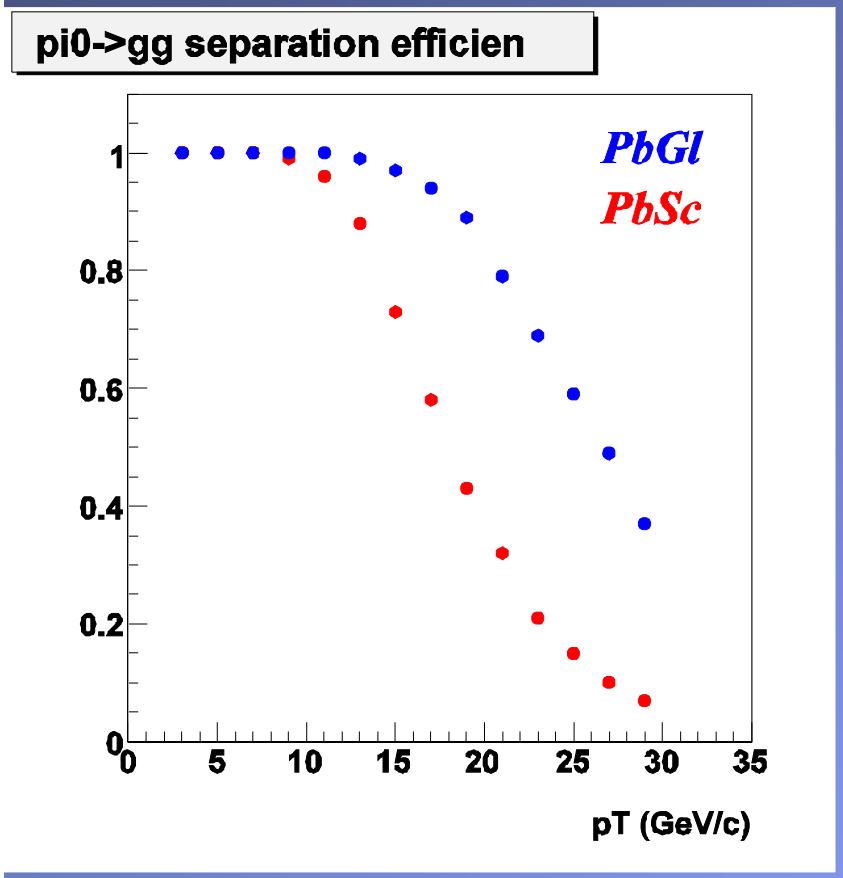
- p+p yields agree with NLO (+ NLL at 62.4 GeV)
- 500GeV p+p results
- NLO slightly overpredicts data at 200GeV, more pronounced at 500GeV, at the 30% level
- x_T scaling at 500GeV follows global trend
- Hadron suppression in Heavy Ion across the board at “standard” RHIC energies (62.4, 200GeV)
- Suppression consistent with parton energy loss
- 22.4 data points look more like what we have seen at the SPS
- Something is happening between 22.4 and 62GeV, transition from Cronin enhancement to suppression
- Looking forward to the low-energy run that has started yesterday

$\pi 0$ reconstruction: from $\pi^0 \rightarrow \gamma\gamma$ merged

Instead of correcting for $\pi^0 \rightarrow \gamma\gamma$ merging probability, identify "merged" π^0 and sum them up with "separated" π^0 (reconstructed from $M_{\gamma\gamma}$)

Identify "merged" π^0 as non-single-photon using shower profile

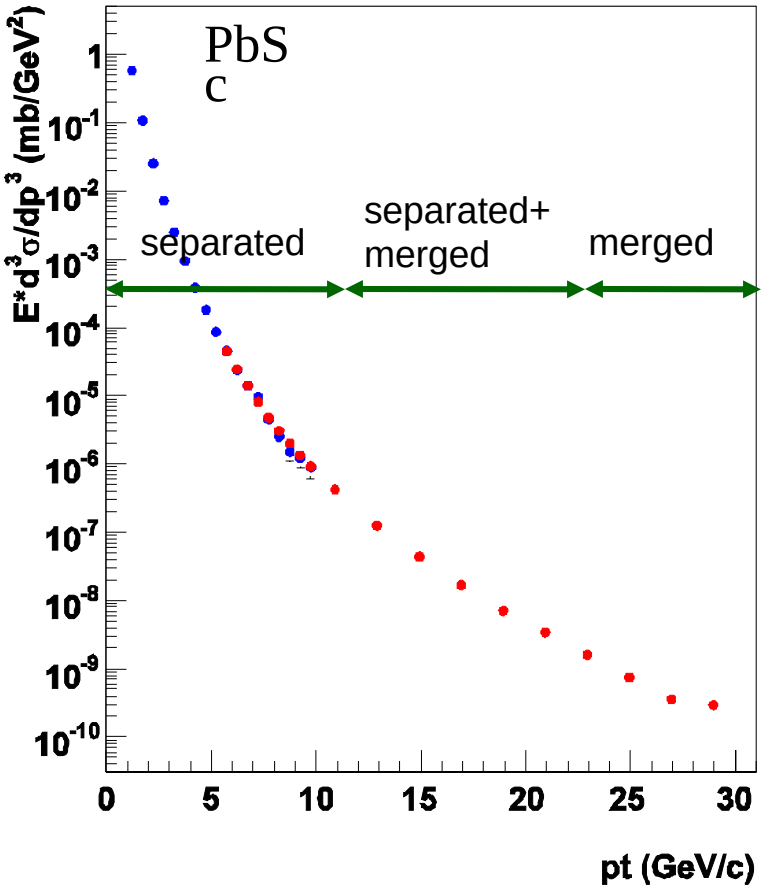
(works effectively at least <30 GeV/c in PbSc and <40 GeV/c in PbGl)

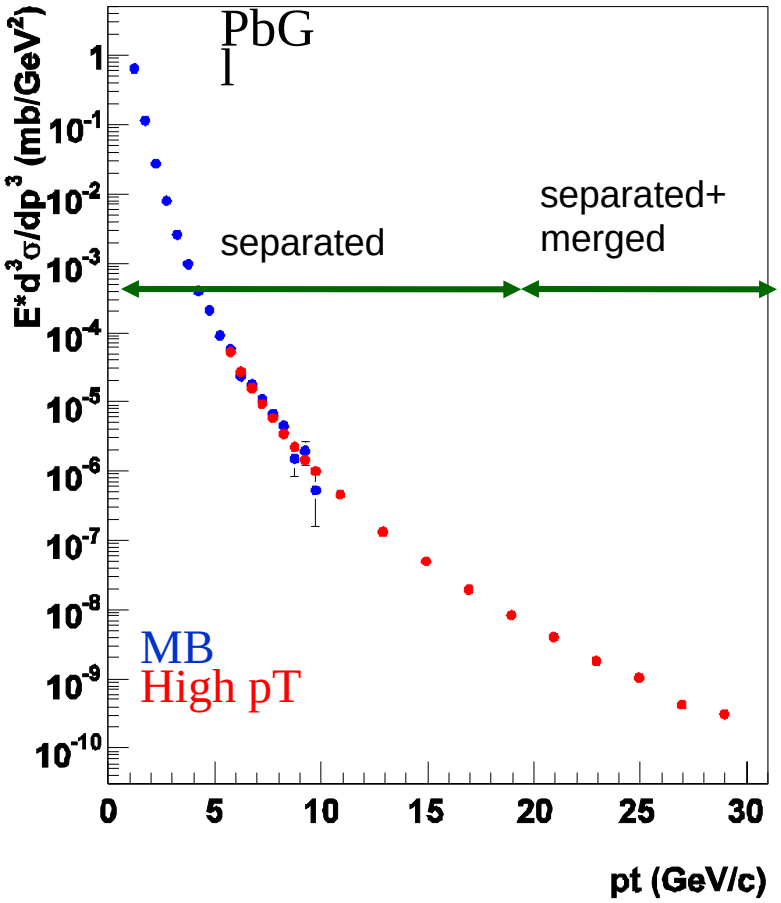


Background:

- $\pi\pm$ suppressed in the EMCal by x30-100 $\Rightarrow$ contribution is <6%
- Decay photons and direct photons are suppressed compared to pi0s and only 2-4% of them fake "merged" π^0
- Cosmic background: well identified and subtracted with Time-of-Flight (as randomly distributed)

π0 spectrum: PbSc vs PbGl



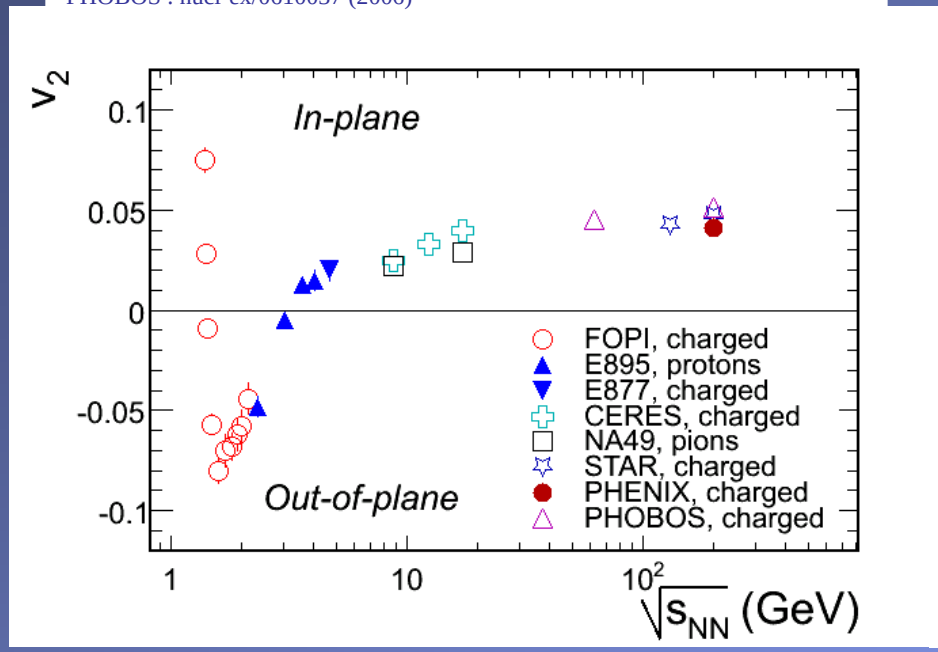


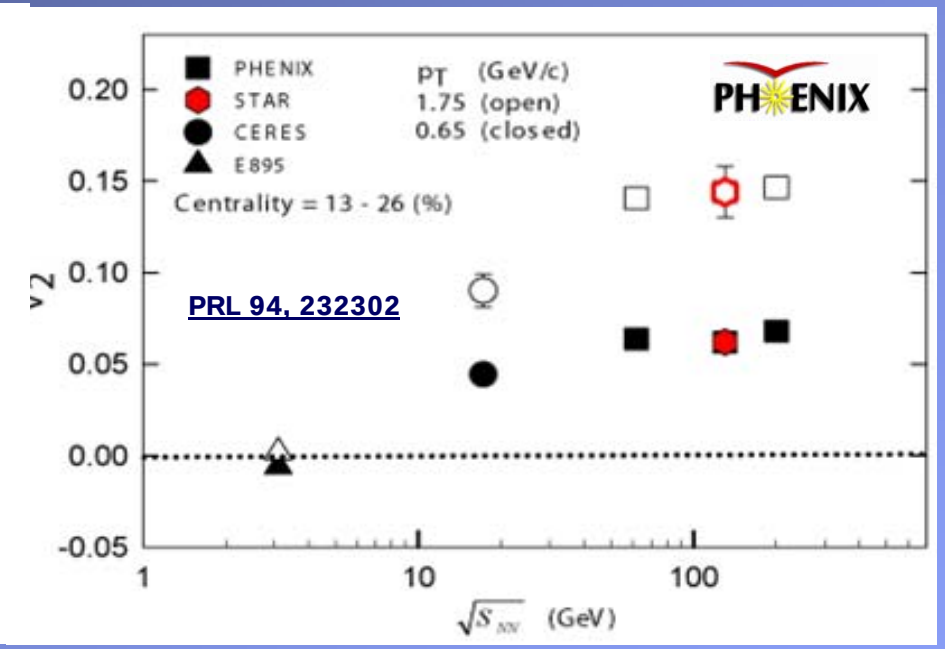
MB and "High pT" data samples are consistent in overlapping pT range

PbSc and PbGl are consistent within stat⊕syst uncertainties

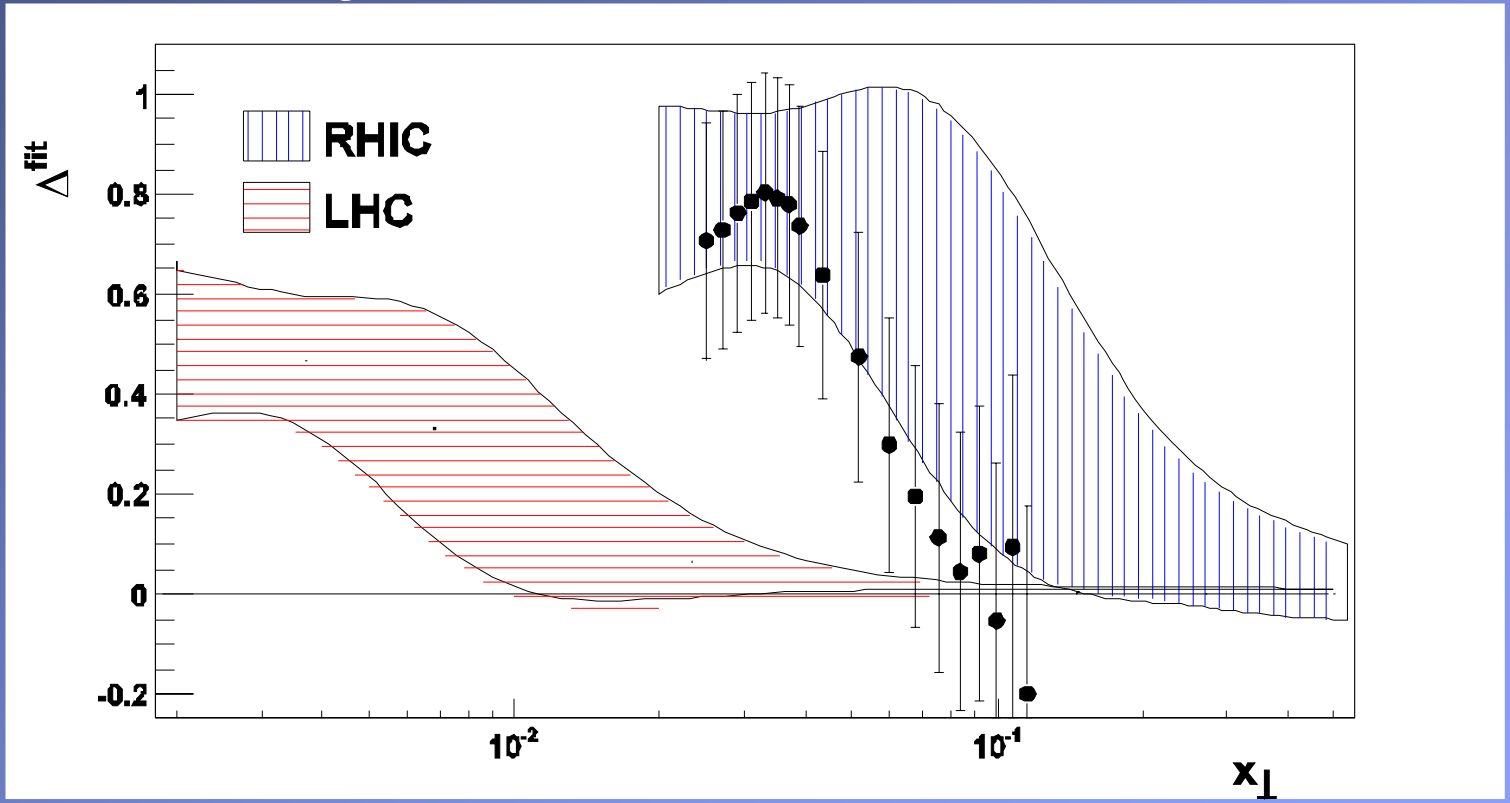
Below RHIC Energies

FOPI : Phys. Lett. B612, 713 (2005). E895 : Phys. Rev. Lett. 83, 1295 (1999)
CERES : Nucl. Phys. A698, 253c (2002). NA49 : Phys. Rev. C68, 034903 (2003)
STAR : Nucl. Phys. A715, 45c, (2003). PHENIX : Preliminary.
PHOBOS : nucl-ex/0610037 (2006)





Most of the change seems to happen below "standard" RHIC energies.

Consistent with picture from R_{AA}

Prediction from F.Arleo, S.Brodsky, DS Hwang and A.Sickles: arXiv:0911.4604
And PHENIX@RHIC data from 500/200 GeV