High p_T Spectra and R_{AA}: What have we learned and where do we go next?

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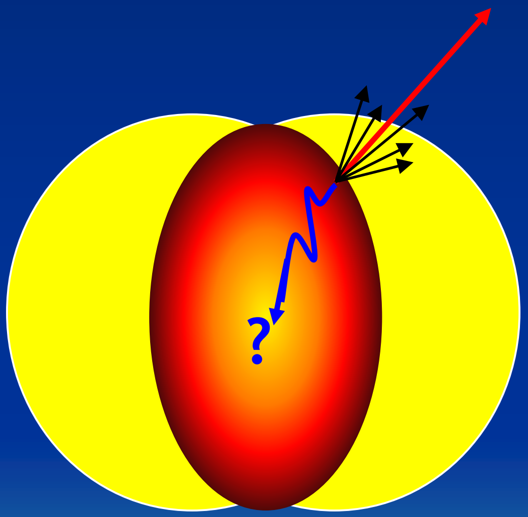
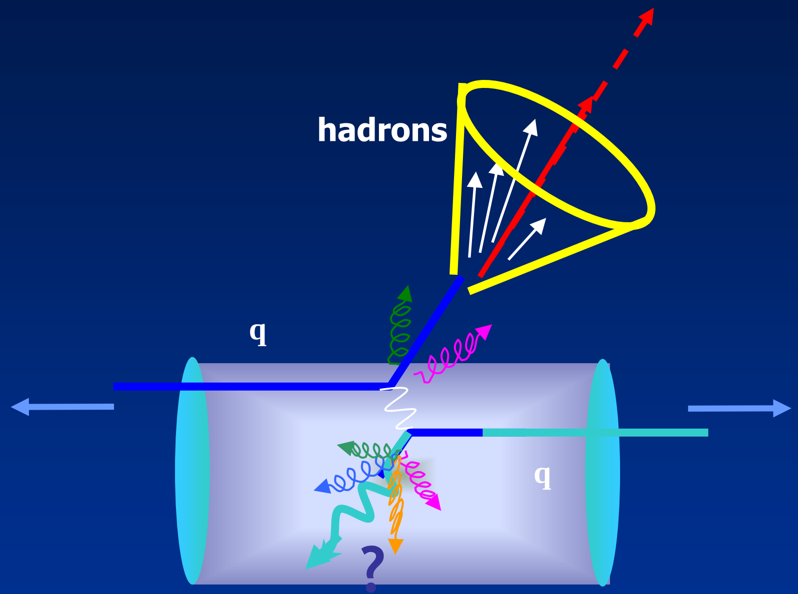
- High p_T Particle production in p+p/A+A
- Quantifying nuclear effects - R_{AA}/R_{CP}
- Initial vs final state nuclear effects
- Pseudorapidity/$\sqrt{s_{NN}}$ dependence
- What have we learned?/Summary



Fundamental Goal of High p_T Studies



To understand partonic interactions within a dense colored medium

Baier, Dokshitzer, Mueller, Schiff

$$\Delta E_{BDMS} = \frac{C_R \alpha_s}{4} \hat{q} L^2 \tilde{\nu}$$

$$\hat{q} = \frac{\mu^2_{Debye}}{\lambda_{glue}} \propto \alpha_S \rho_{glue}$$

Established theoretical framework connects partonic energy loss to fundamental properties of the medium -

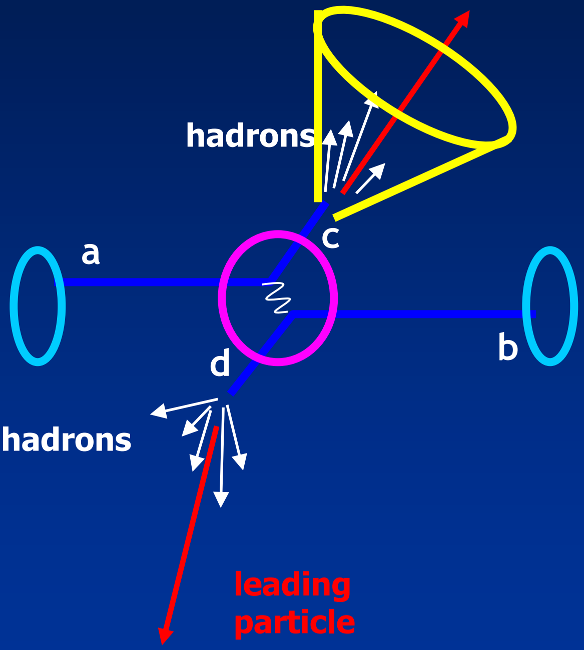
gluon density, system size

Gyulassy, Levai, Vitev

$$\Delta E_{GLV} = C_R \alpha_S^3 \int d\tau \, \tau \rho_{glue}(\tau, r(\tau)) Log\left(\frac{2E_{jet}}{\mu^2 L}\right)$$

High p_T Particle Production

Jet: A localized collection of hadrons which come from a fragmenting parton



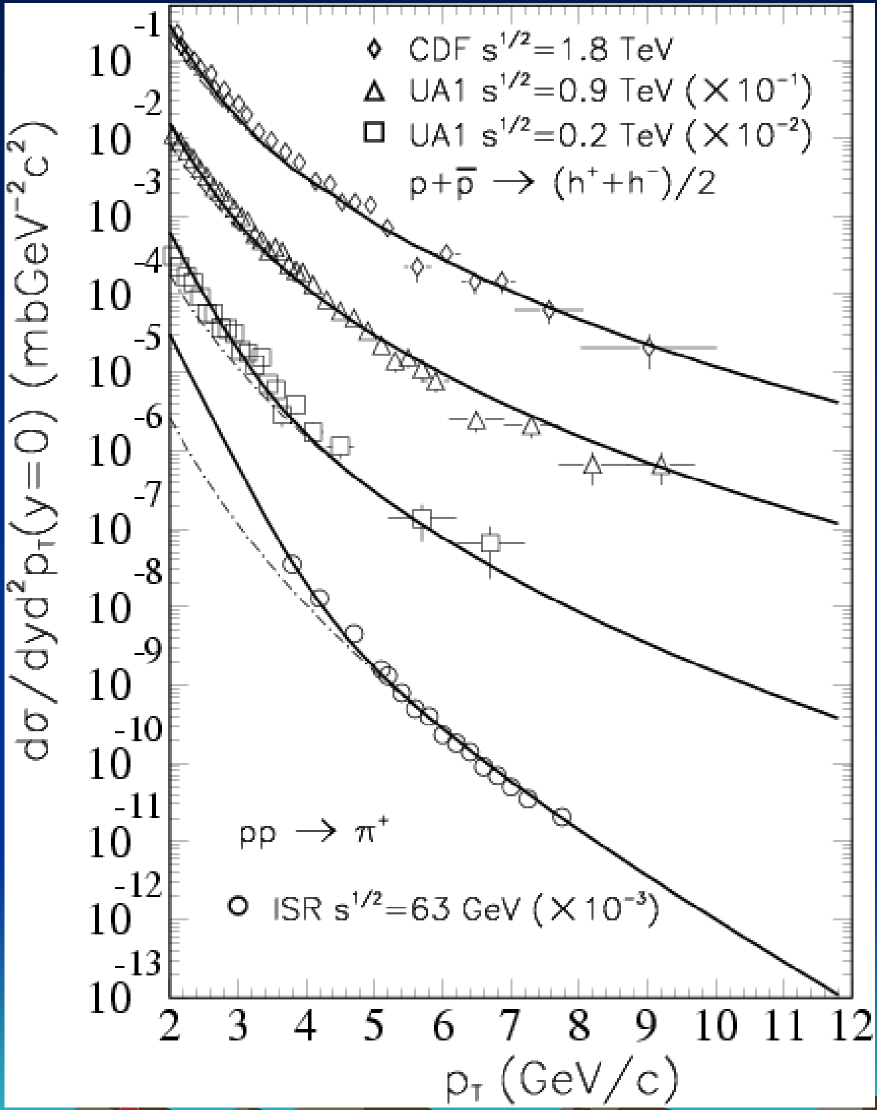
Parton Distribution Functions
Hard-scattering cross-section
Fragmentation Function

High p_T (≳ 2.0 GeV/c) hadron production in pp collisions for $\sqrt{s}$ > 60 Gev:

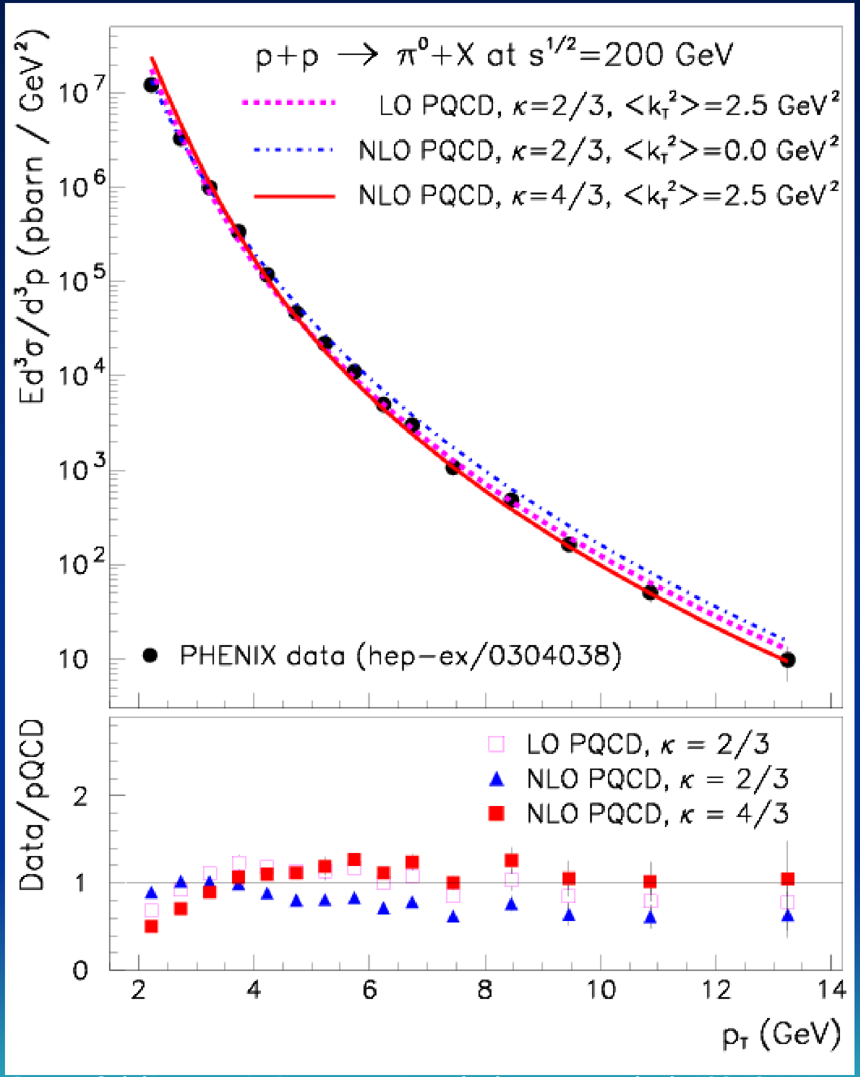
$$\frac{d\sigma_{pp}^{h}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a dx_b\, f_a(x_a,Q^2)\, f_b(x_b,Q^2)\,\frac{d\sigma}{d\hat{t}}(ab\to cd)\,\frac{D^0_{h/c}}{\pi z_c}$$

"Collinear factorization"

How do they do?



X.N. Wang, PRC 61 (2000) 064910



Barnafoldi, Levai, Papp, Fai and Zhang, nucl-th/0212111

High p_T Particle Production in A+A

(pQCD context…)

$$\frac{dN^h_{AB}}{dy d^2 p_T} = ABK \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

$\otimes f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2)$ — Parton Distribution Functions

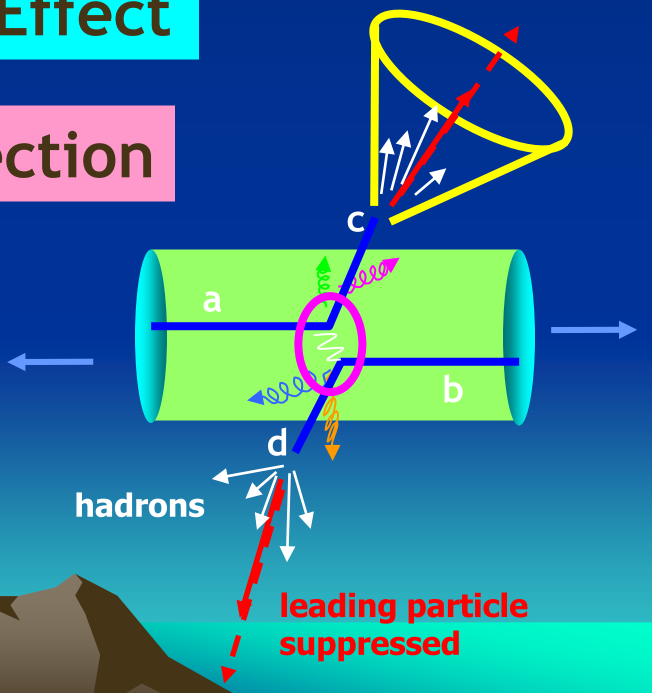
$\otimes g(\mathbf{k}_a) g(\mathbf{k}_b)$ — Intrinsic k_T , Cronin Effect

$\otimes S_A(x_a, Q_a^2) S_B(x_b, Q_b^2)$ — Shadowing, EMC Effect

$\otimes \frac{d\sigma}{d\hat{t}}(ab \to cd)$ — Hard-scattering cross-section

$\otimes \int_0^1 d\varepsilon P(\varepsilon) \frac{z_c^*}{z_c}$ — Partonic Energy Loss

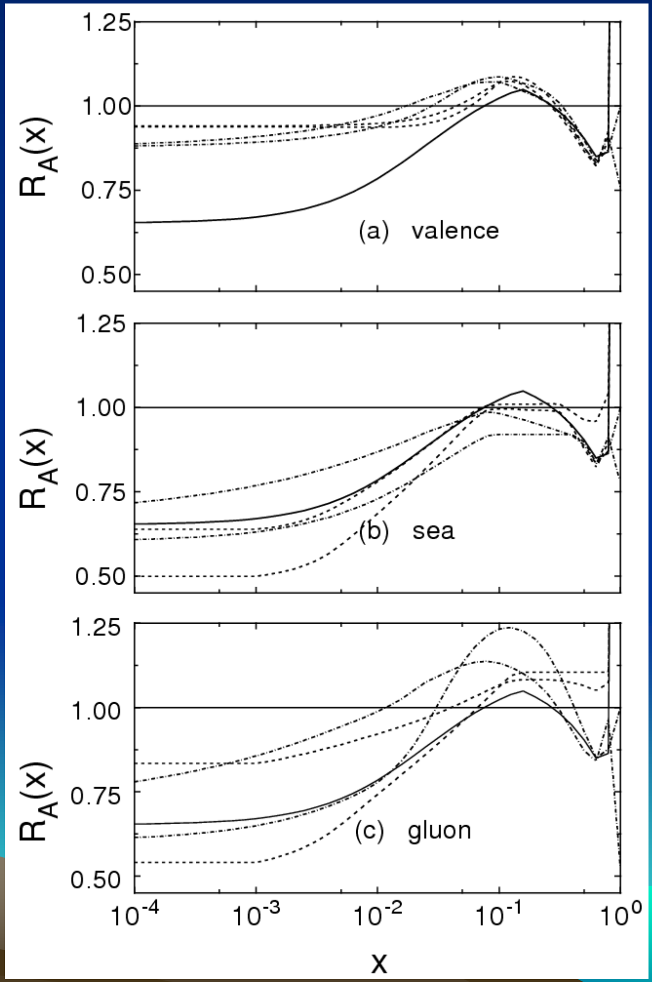
$\otimes \frac{D^0_{h/c}(z_c^*, Q_c^2)}{\pi z_c}$ — Fragmentation Function



Modified PDFs: "Shadowing"

Parton distributions in nuclei are different from those in nucleons (e.g., "EMC effect") ⇒ shadowing and anti-shadowing

Shadowing ~ suppression of the structure functions vs. x in nuclei compared to free nucleons



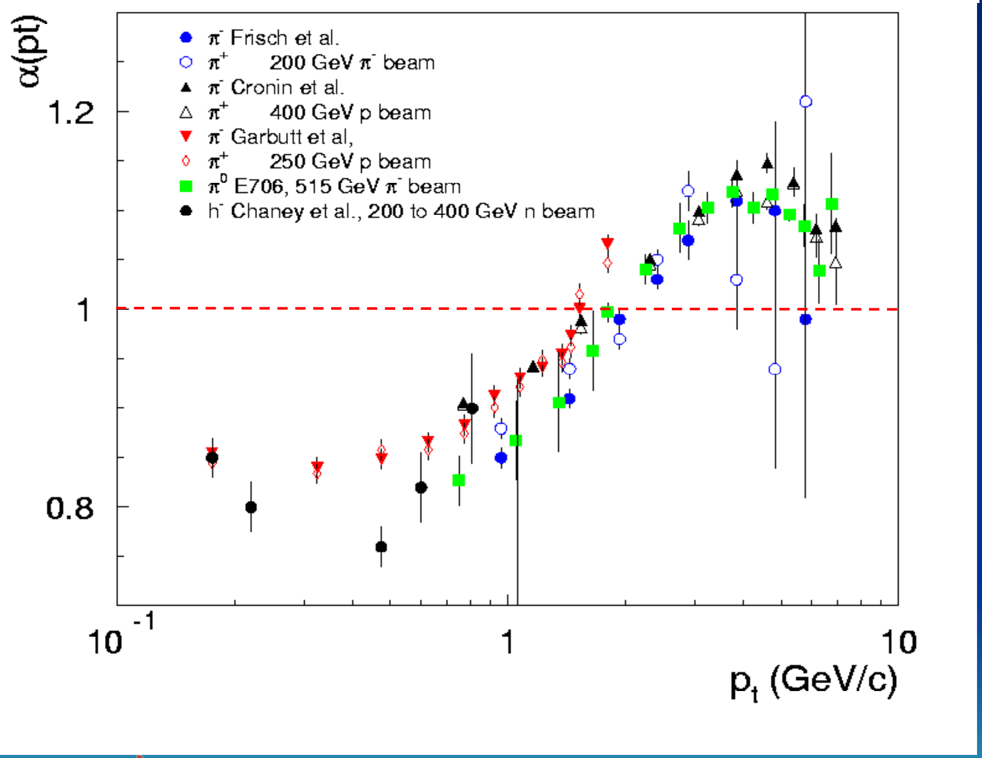
A=200

Emel'yanov, Khodinov, Klein, & Vogt, PRC 61 (2000) 044904

Initial State Multiple Scattering: "Cronin Effect"

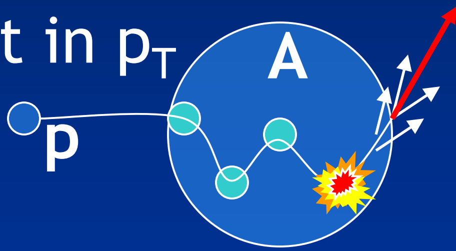
Experimental observation:

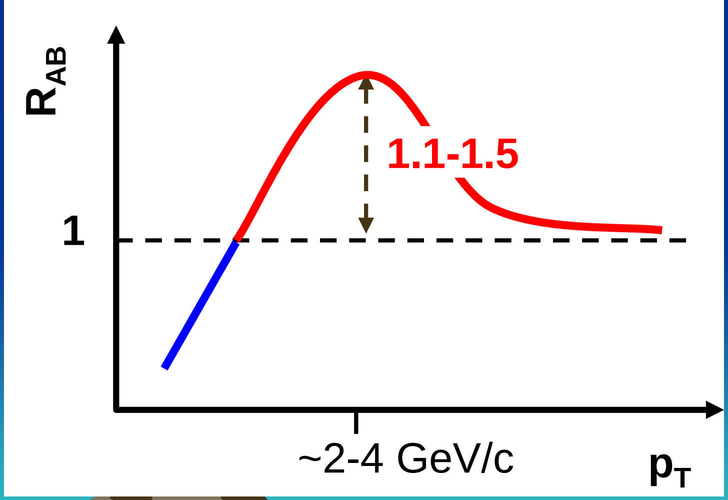
p+A collisions: $\sigma_{pA} = A^{\alpha(p_t)} \sigma_{pp}$



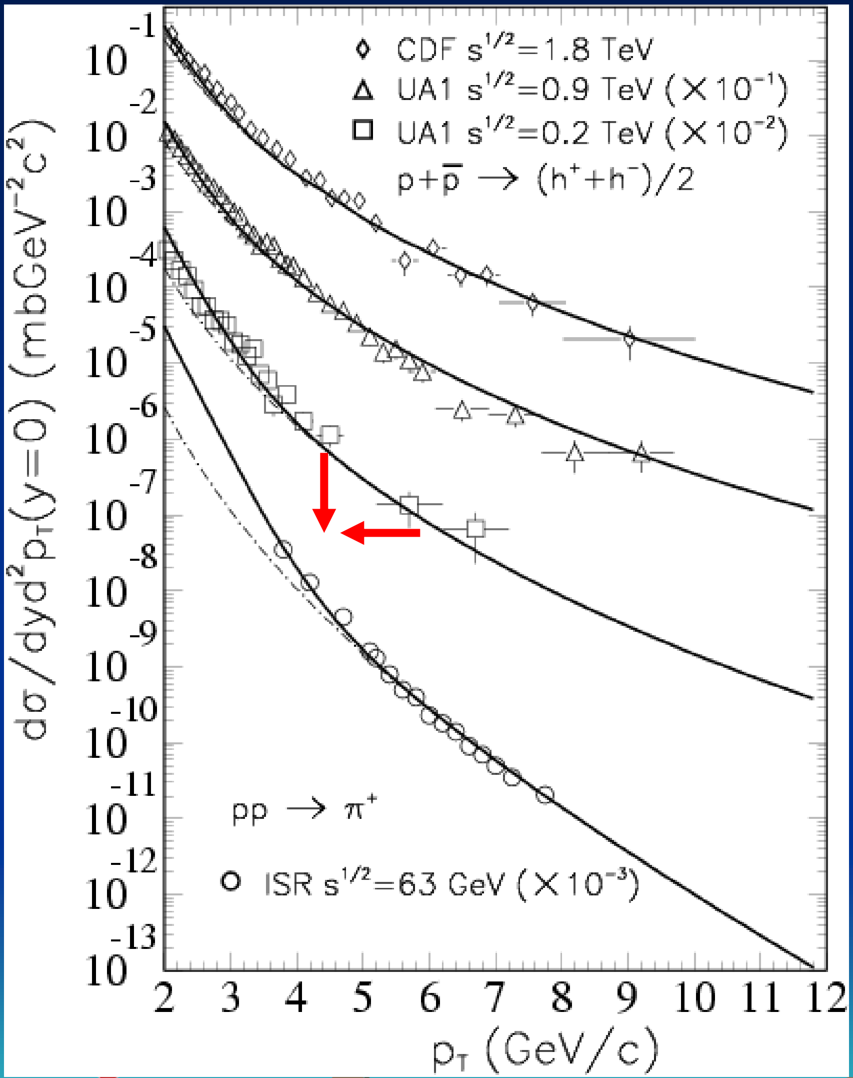
Theoretical explanation:

Partons can undergo soft scatters prior to the hard collision ⇒ spreads the spectrum out in p_T

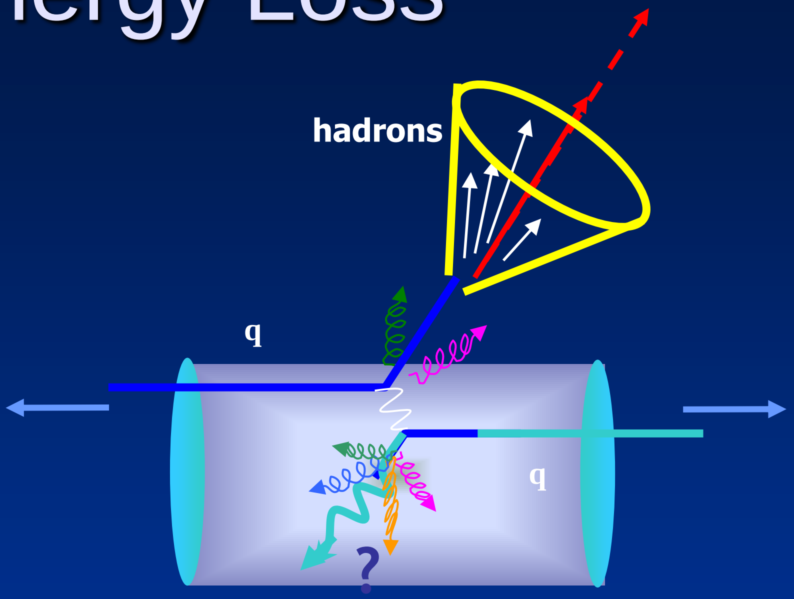




Partonic Energy Loss



X.N. Wang, PRC 61 (2000) 064910



Energy loss $\Rightarrow$
softening of fragmentation $\Rightarrow$
suppression of leading hadron yield

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Binary collision scaling

p+p reference

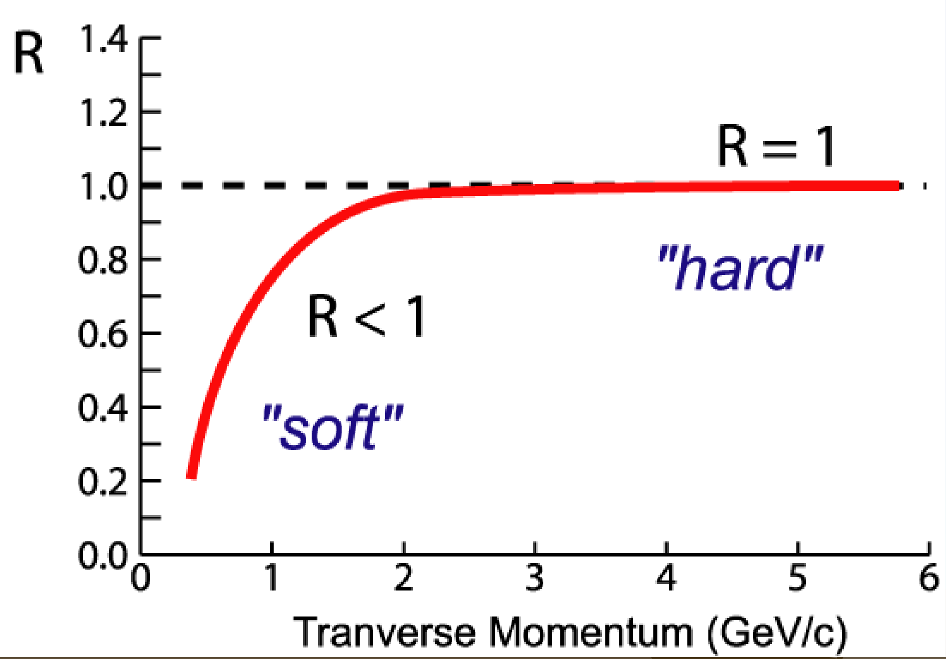
Nuclear Modification Factor R_{AA}/R_{CP}

Quantify deviations from expected behaviour in p+p collisions:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$$R_{CP}(p_T) = \frac{Yield_{central} / \langle N_{bin}^{central} \rangle}{Yield_{peripheral} / \langle N_{bin}^{peripheral} \rangle}$$

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$ ⟺ (Nuclear Geometry)



If no "effects":

- R < 1 in regime of soft physics
- R = 1 at high-p_T where hard scattering dominates

→ A+B = A*B(p+p)

High p_T Hadron Spectra at RHIC: The Raw Materials

Particle species… $h^{\pm}$, π^0, Λ, K^0_s, p,…

Multiple energies… 62.4, 130, 200 GeV

Multiple beams… p+p, d+Au, Au+Au

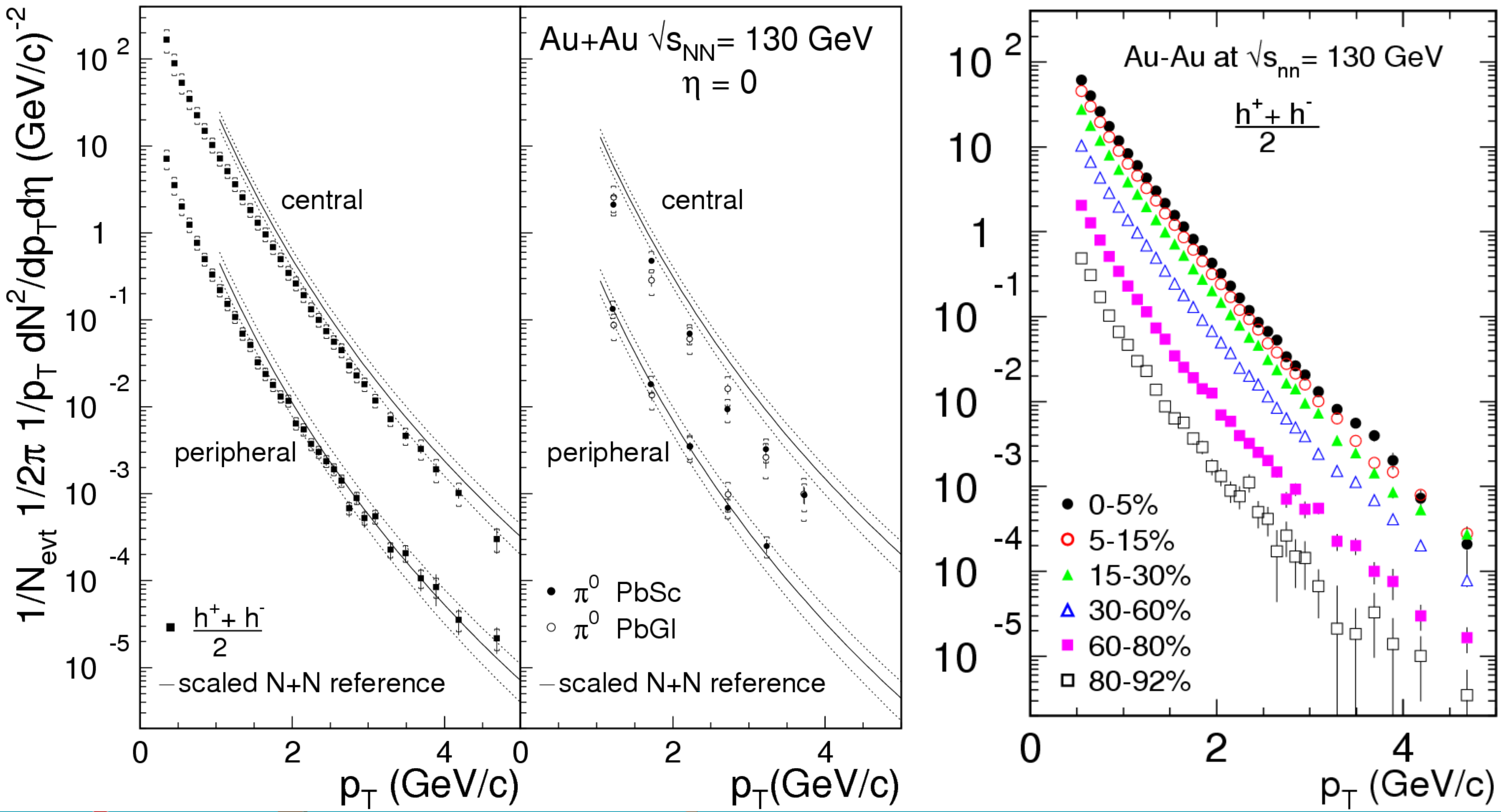
Large phase space coverage… Midrapidity/Forward

More to come… Cu+Cu/Si+Si, Higher Statistics…

PHENIX Au+Au 130 GeV

PRL 88 (2002) 022301

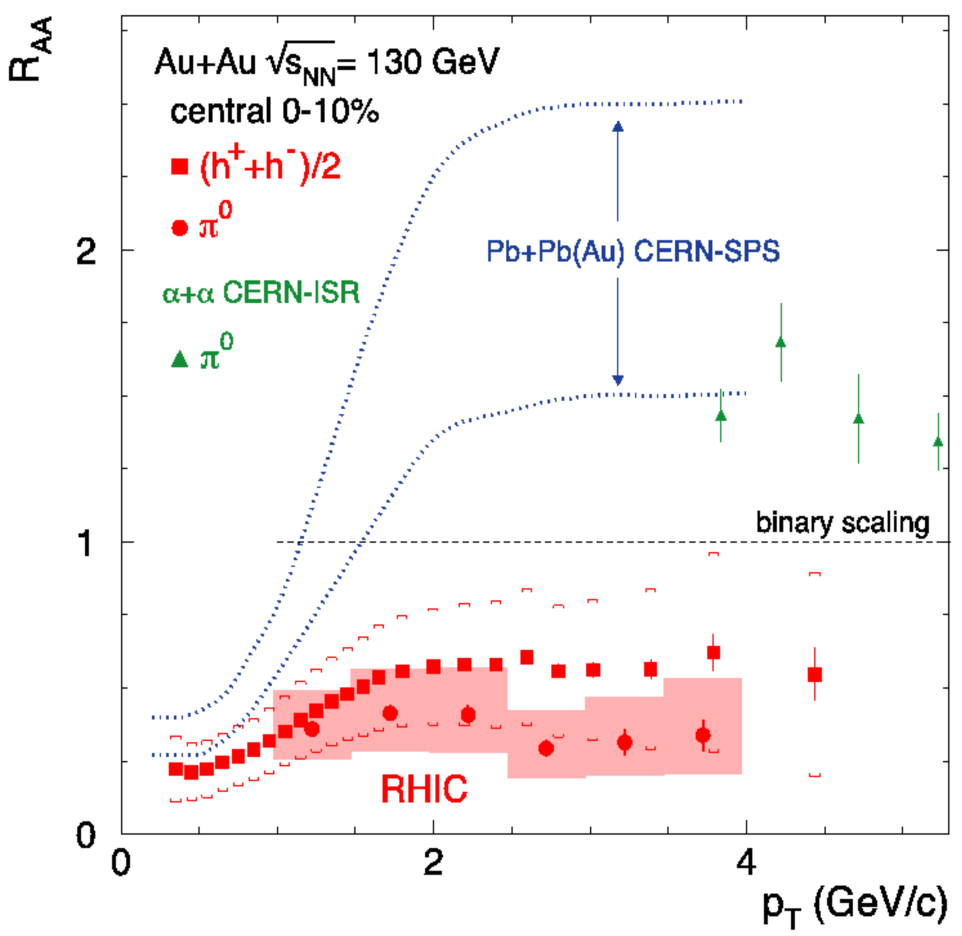
PLB 561 (2003) 82-92

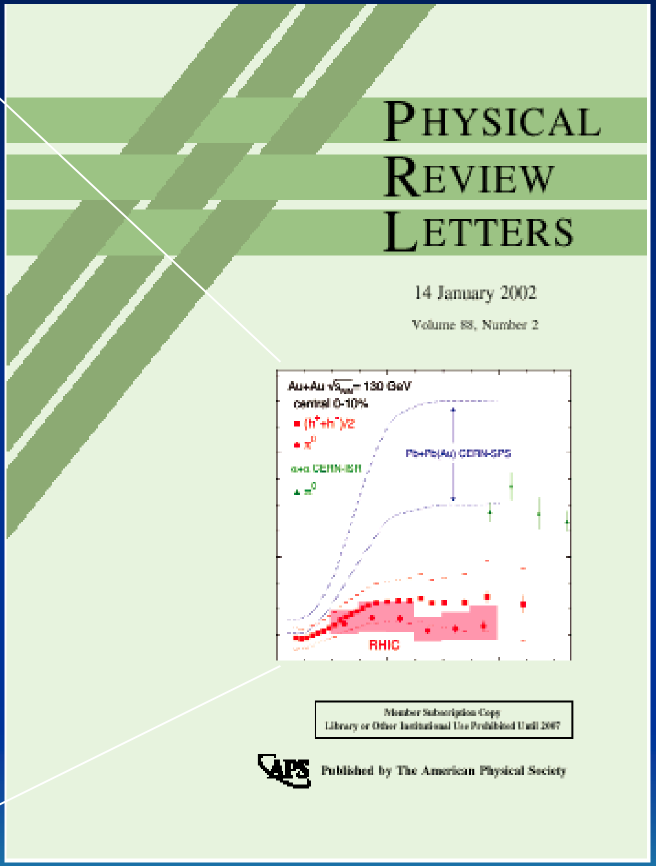


The First Big RHIC Result

Au+Au Collisions at 130 GeV

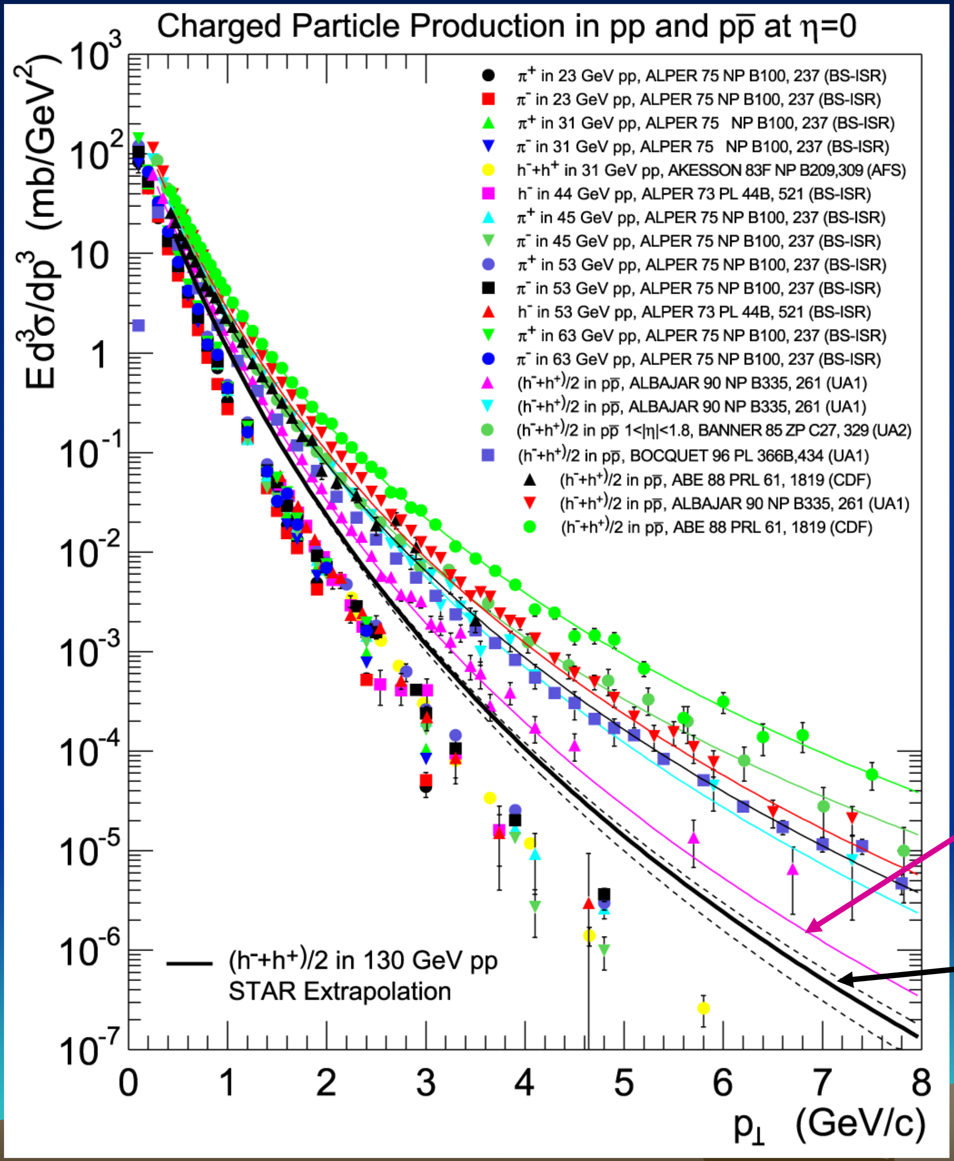
PHENIX, PRL **88**, 022301 (2001)





**Parameterized reference based on world's data (no p+p at 130 GeV)

Reference Spectrum for 130 GeV



UA1 Measured at 200 GeV for |η| < 2.5

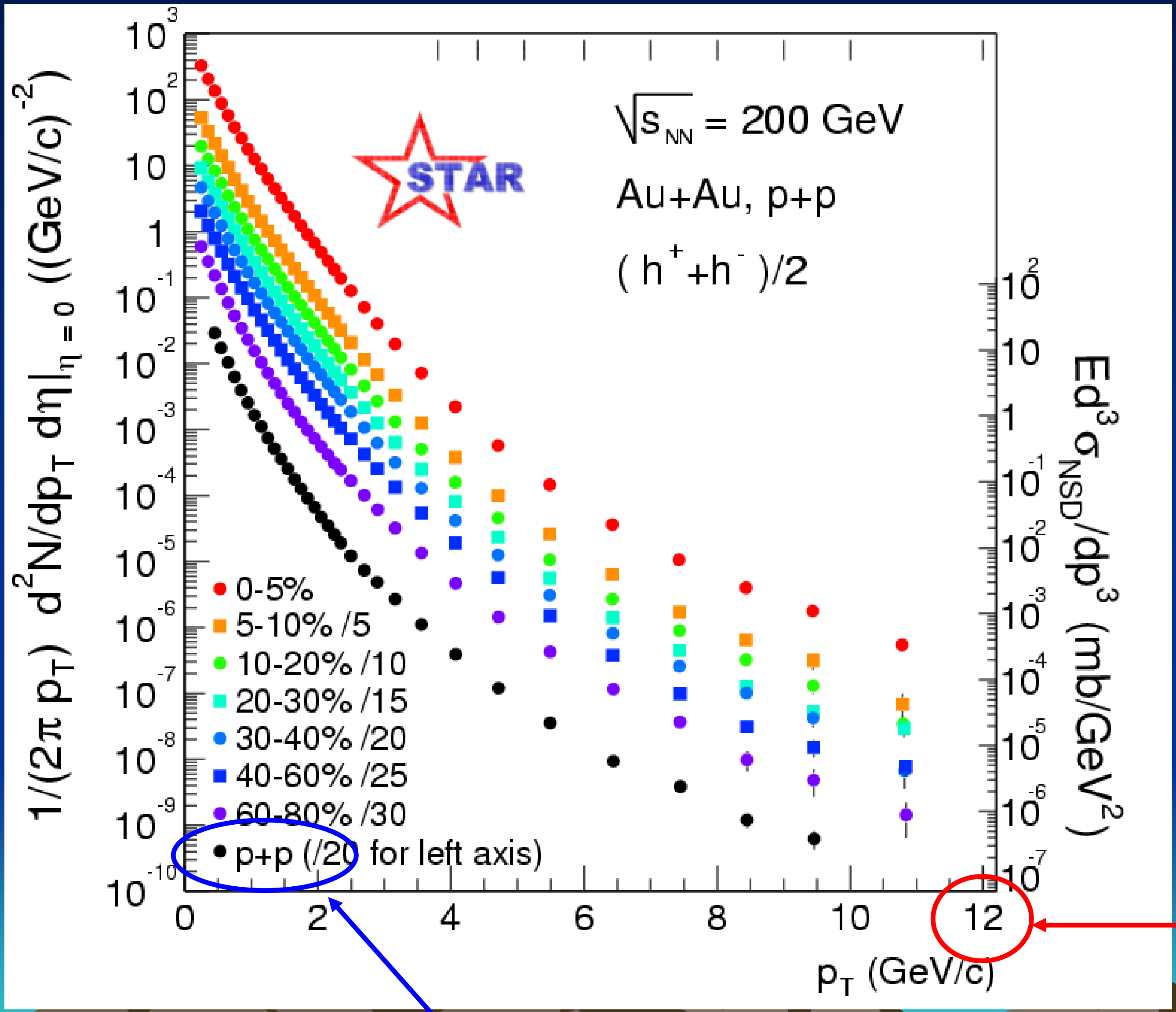
Reference spectrum at 130 GeV is an *interpolation* of many data sets over a wide range of √s

Power Law Parameters:

200 GeV A = 310±18, p_0 = 1.77±0.09, n = 12.08±0.37

130 GeV A =267±6, p_0 =1.90±0.09, n = 12.98±0.9

STAR p+p and Au+Au 200 GeV



PRL **91** (2003) 172302

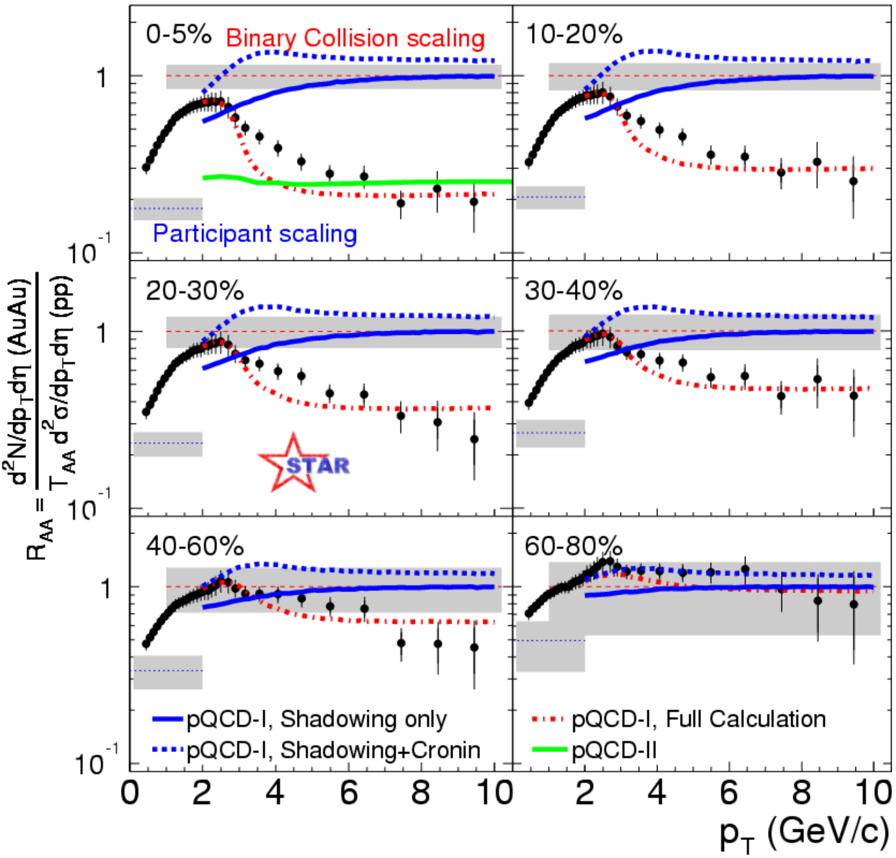
Eh, what's a few more GeV/c, give or take?

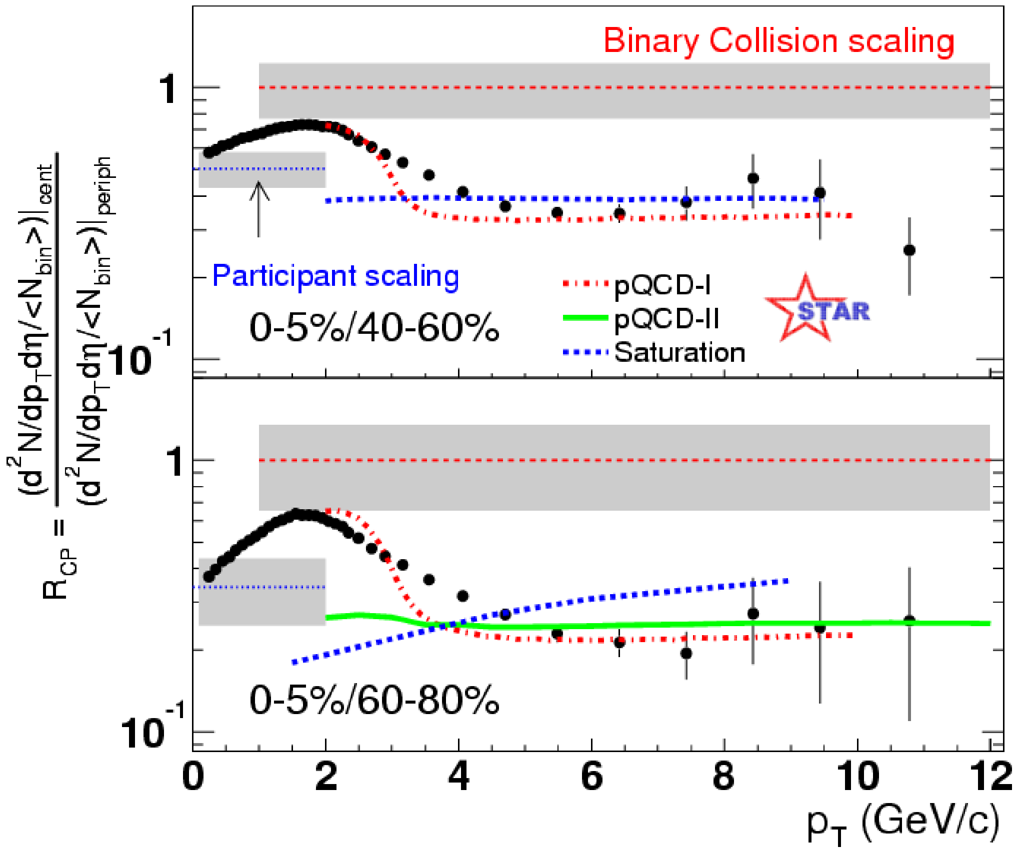
Much bigger data sample

Reference spectrum ***measured*** at RHIC

STAR R_{AA} and R_{CP} at 200 GeV

PRL **91** (2003) 172302



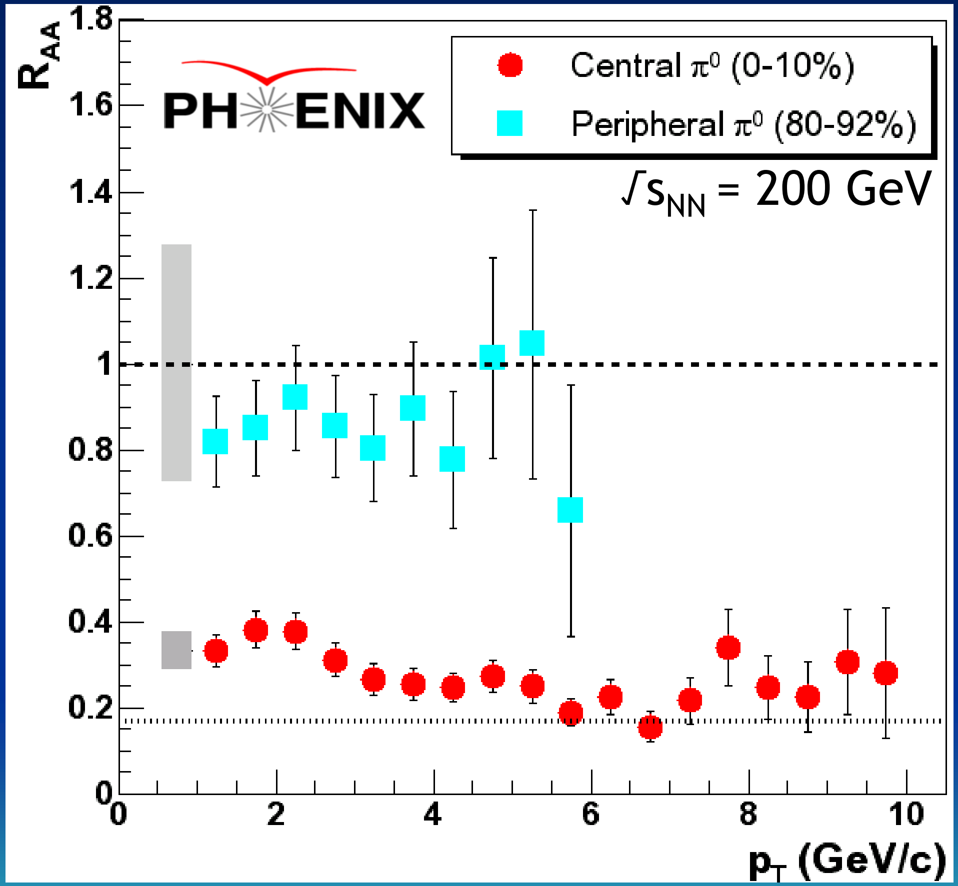


A few more GeV/c reveals a new feature for $h^{\pm}$:

R_{AA}/R_{CP} are ~flat for p_T > 6 GeV/c

PHENIX High p_T π^0 Suppression

PRL 91, 072301 (2003)



Binary scaling

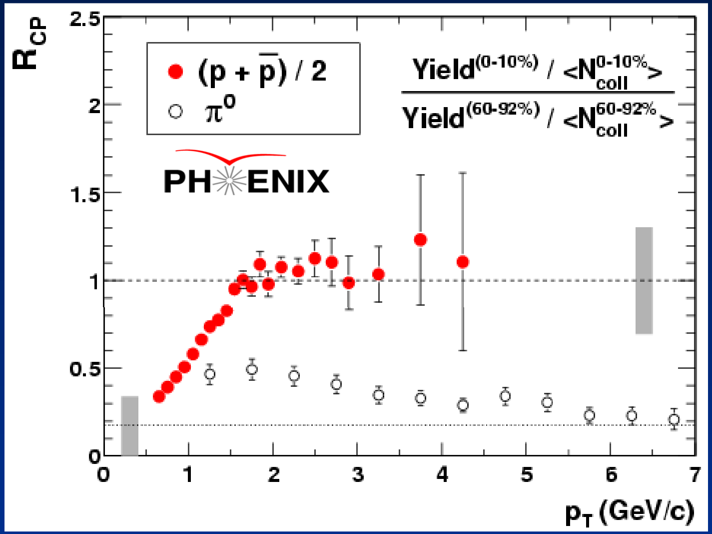
Participant scaling

π^0 are pretty much always flat →

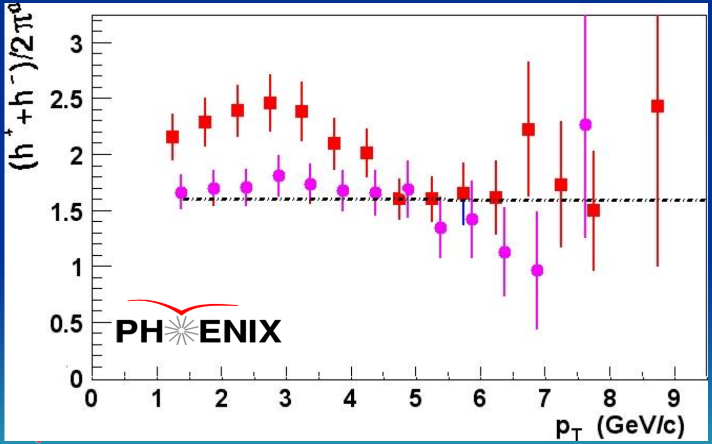
Particle dependence at intermediate p_T is INTERESTING!

Baryons vs. Mesons

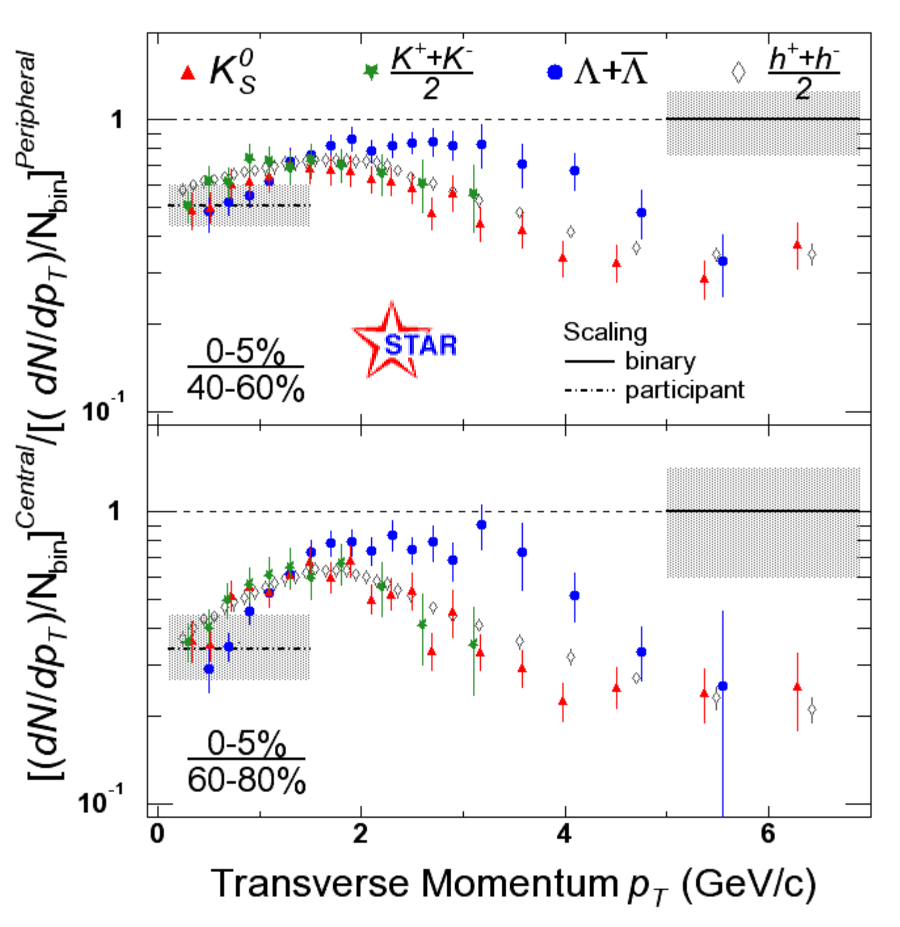
PRC 69, 034909 (2004)



PRC 69, 034910 (2004)



PRL **92** (2004) 052302

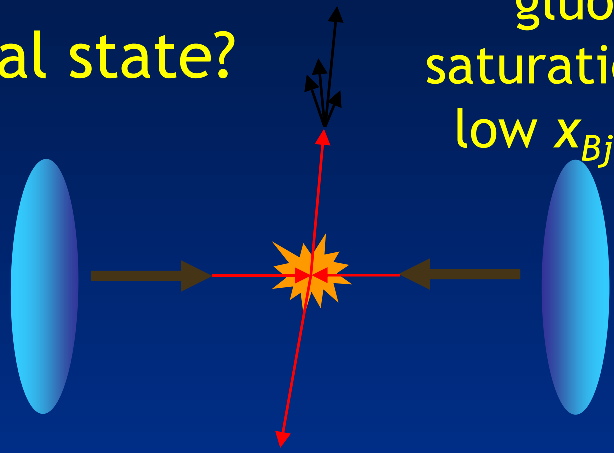


Significant proton-pion and lambda-kaon differences, but the "baryon enhancement" ends by p_T ~ 5-6 GeV/c

Establishing suppression as a final state effect

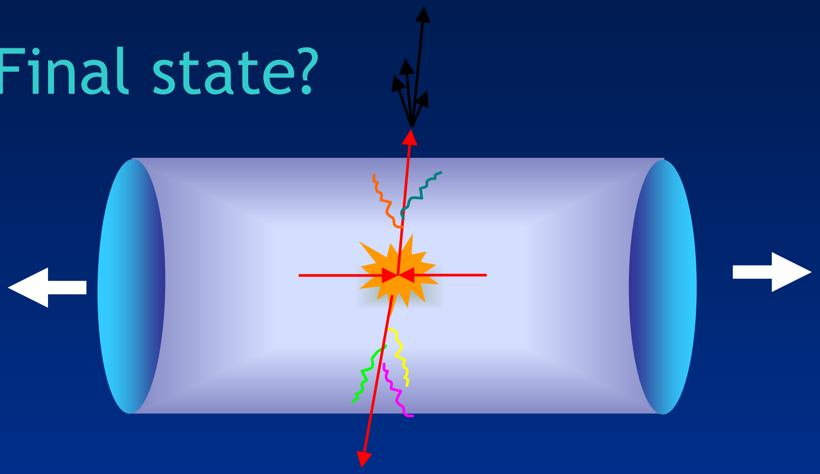
Initial state?

gluon saturation at low $x_{Bjorken}$



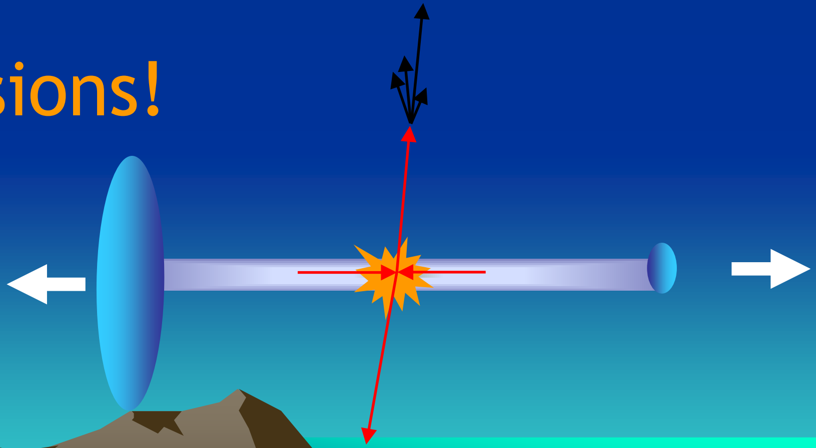
strong modification of Au wavefunction ⇒ initial jet production rates suppressed for heavy nuclei

Final state?



partonic energy loss in dense medium generated in collision

Turn off final state ⇒ d+Au collisions!



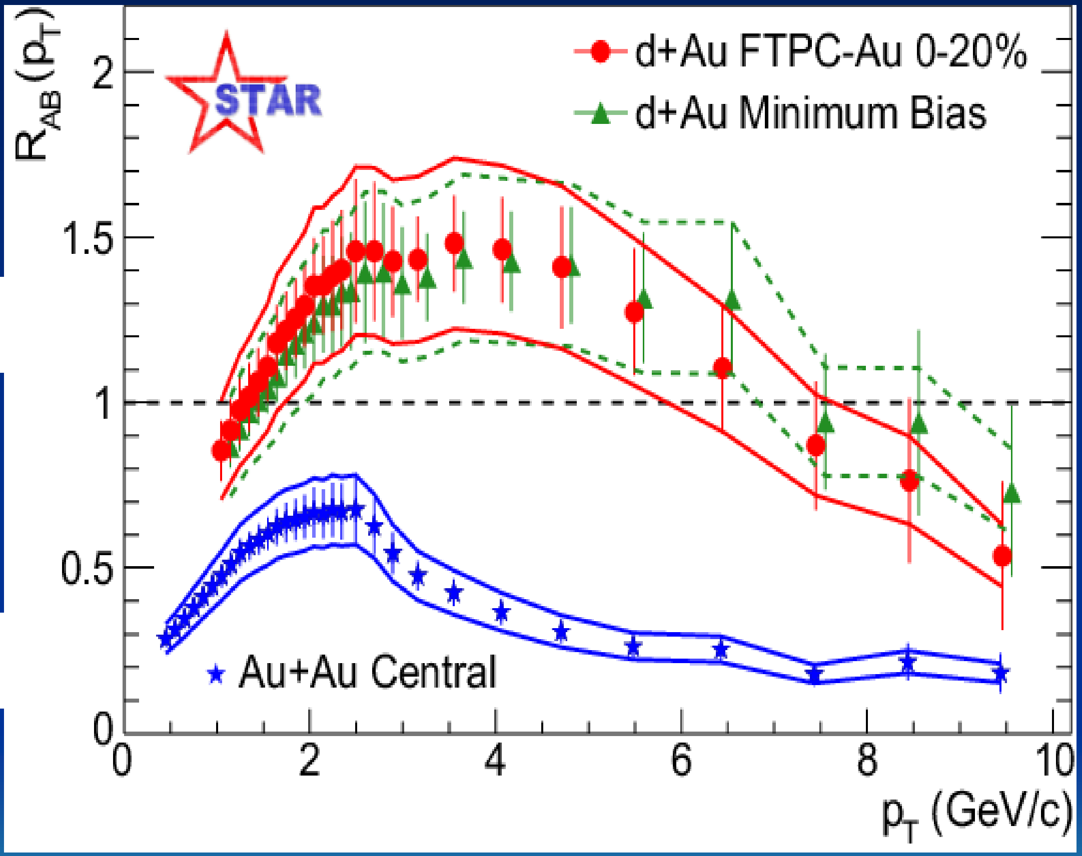
d+Au inclusive yields relative to binary-scaled p+p

PRL 91, 072304 (2004)

$$R_{AB} = \frac{dN^{AB} / dp_T d\eta}{T_{AB} d\sigma^{pp} / dp_T d\eta}$$

d+Au → Enhancement

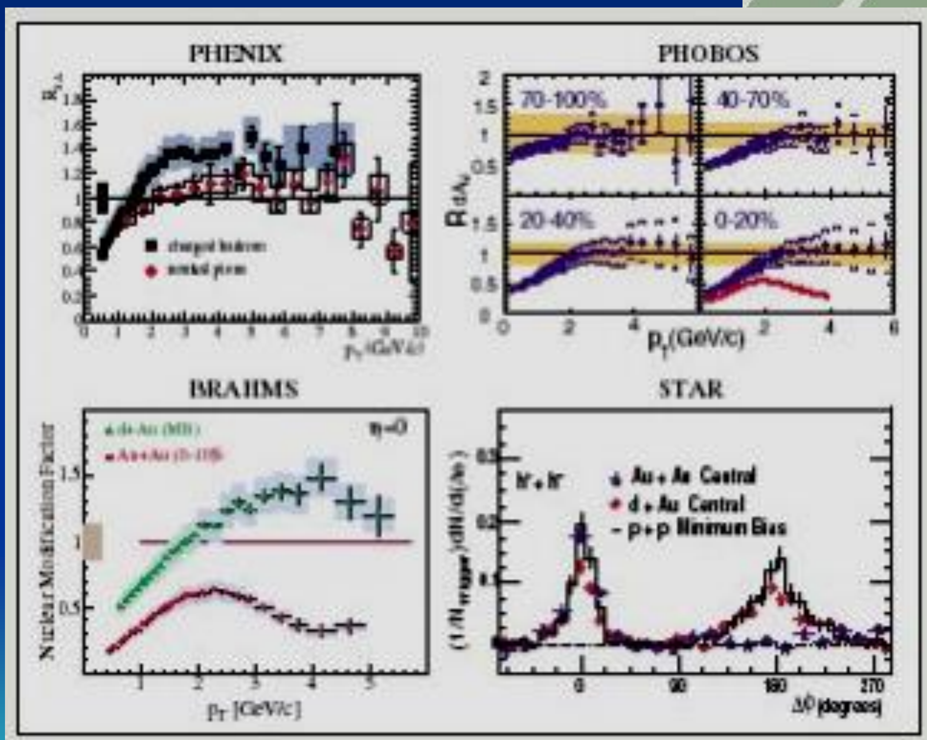
Au+Au → Suppression

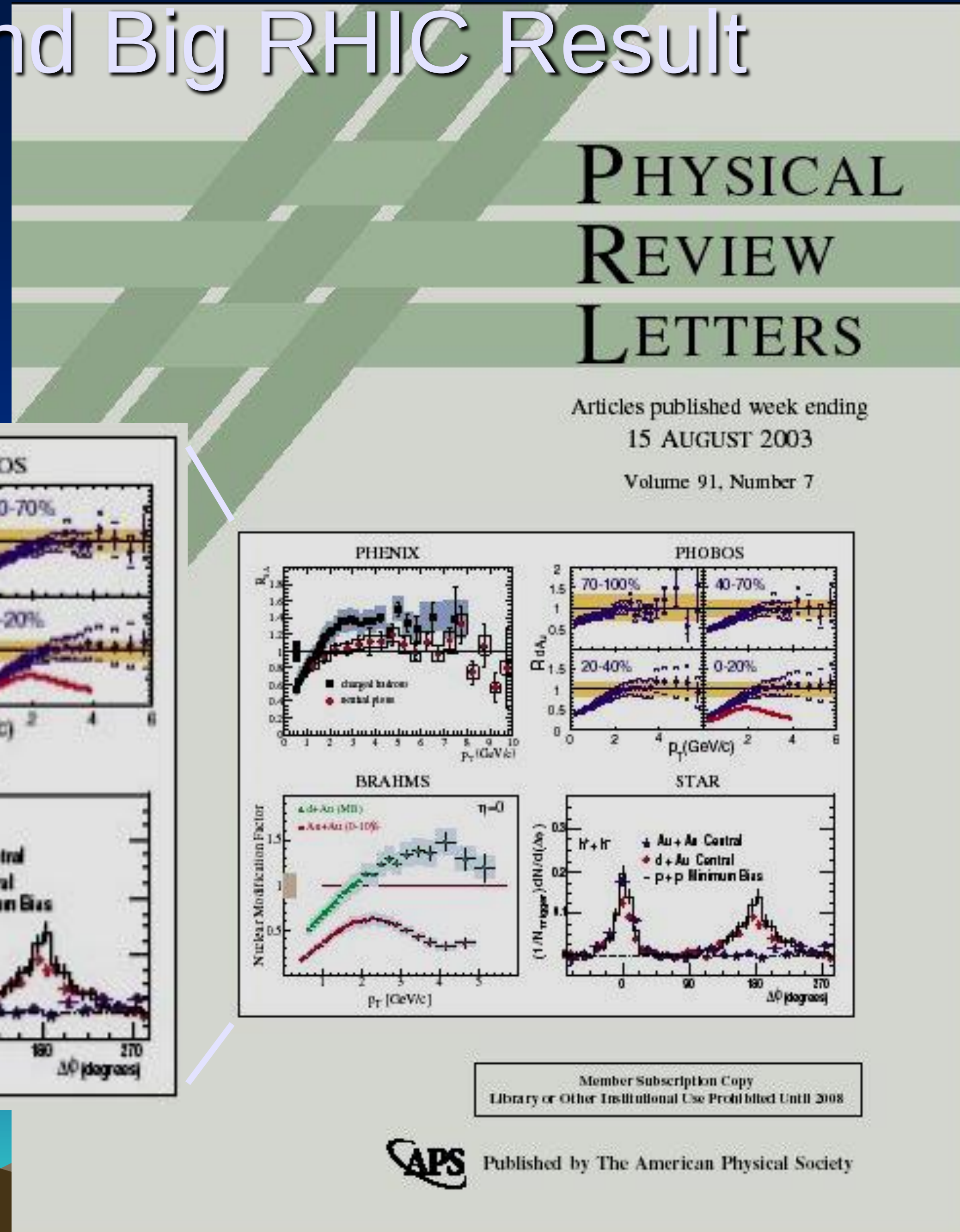


Suppression of the inclusive yield
in central Au+Au is a final-state effect

The Second Big RHIC Result

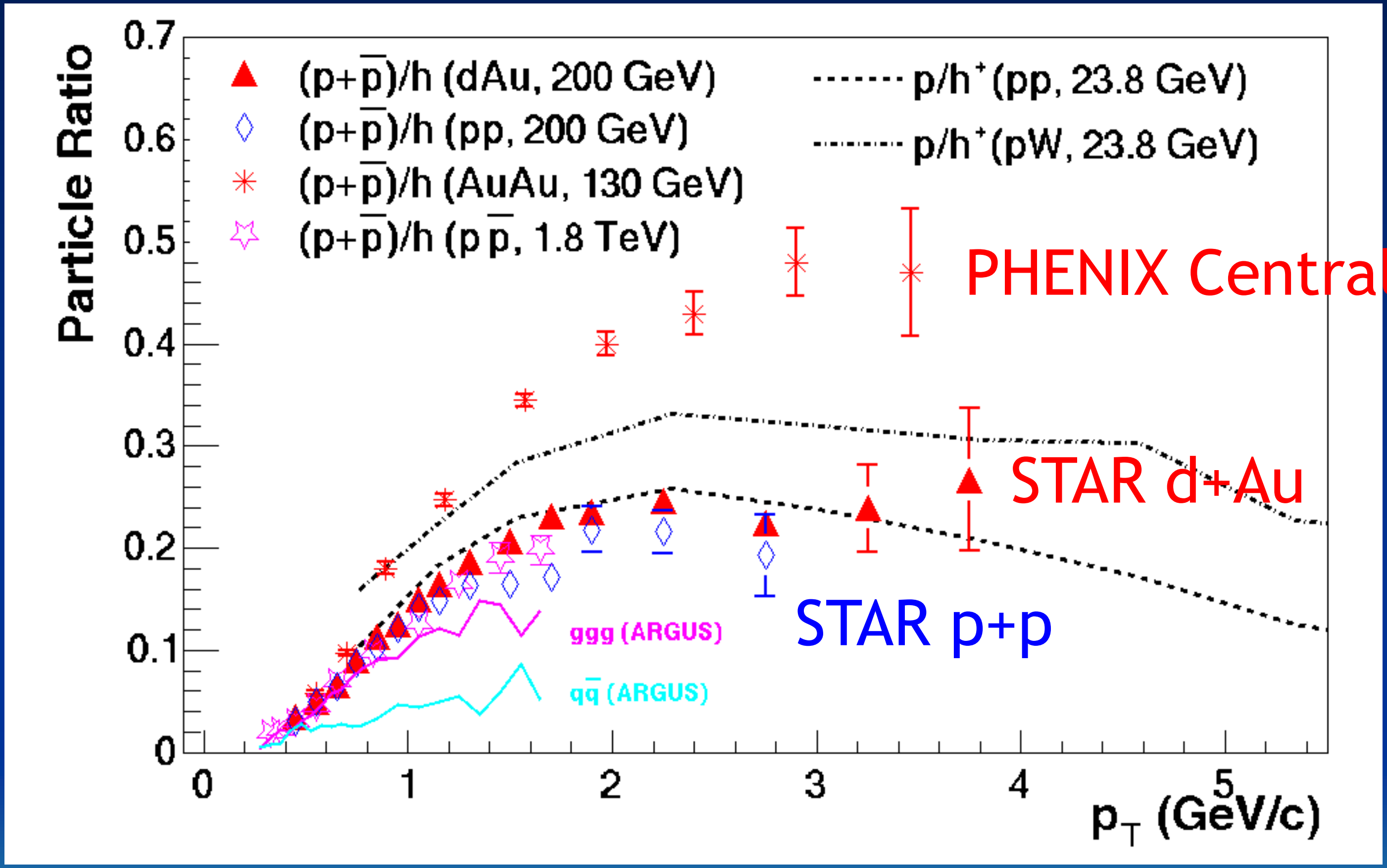
Phys Rev Lett 91, 072302/3/4/5





Baryon Enhancement a final state effect too!

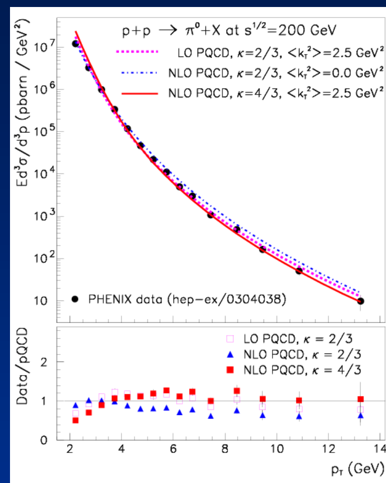
nucl-ex/0309012



- proton/charged hadron consistent in d+Au, p+p, e^+e^- (gluon jets)
- baryon enhancement in central Au+Au is final state effect

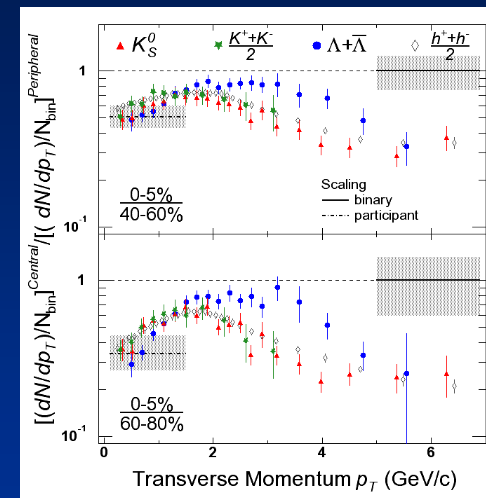
What have we learned so far?

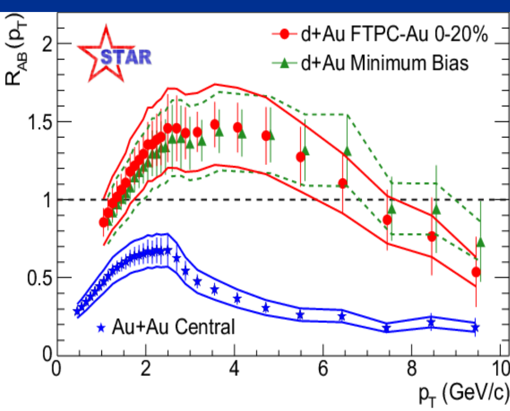
We understand our reference data**



**when we measure them

There's more going on at Intermediate p_T than we expected





We see significant suppression of yields at high p_T in Au+Au and enhancement in d+Au → final state effects

Is it partonic or hadronic?

What is the eta/√s_{NN} dependence?

Final state hadronic rescattering?

$t_F \approx 1 \ldots 1.2(E/GeV)\, fm/c$

For 5 < E_T < 12 GeV/c, <L/λ> decreases substantially

→ Cannot describe flat R_{AA}

Gallmeister, Greiner and Xu, PRC 67, 044905

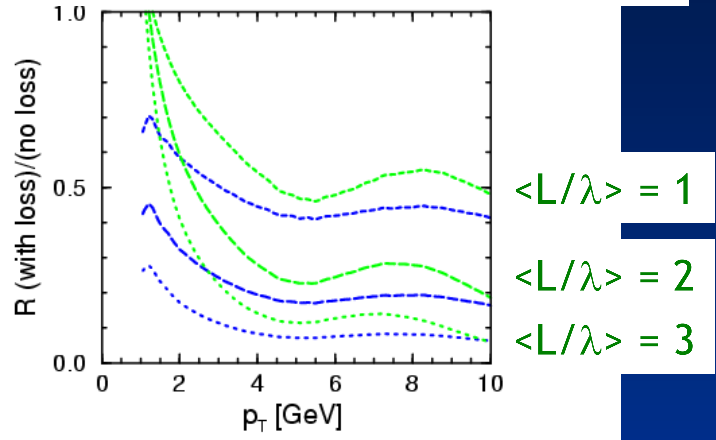
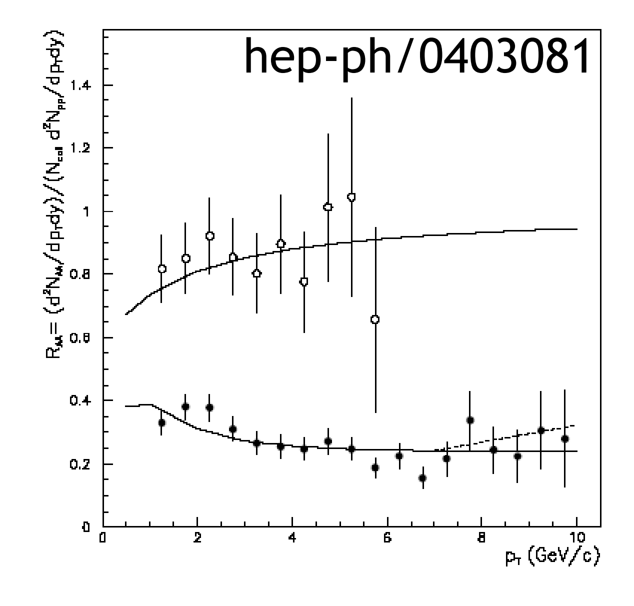


FIG. 9: The suppression factor $R(p_\perp)$ of charged hadrons at midrapidity for $\sqrt{s} = 200\,\text{GeV}$ for $\langle L/\lambda \rangle \equiv 1, 2, 3$ (top to bottom) collisions according (in)elastic scattering on a ρ (blue) or elastic scattering on a π (green).

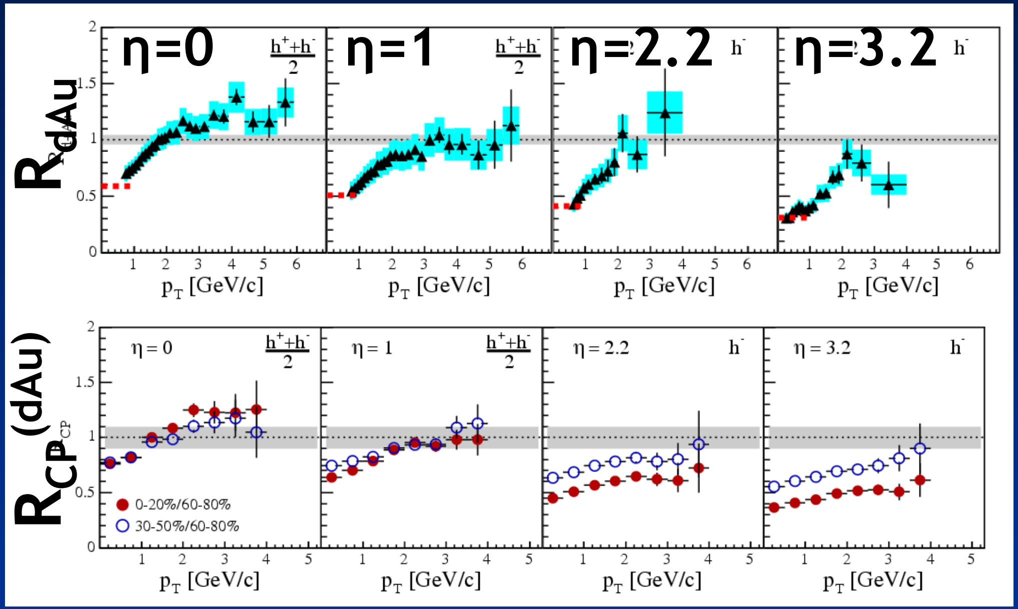


Ferreiro, Capella, Kaidalov, Sousa:
JetQuenching + JetAbsorption

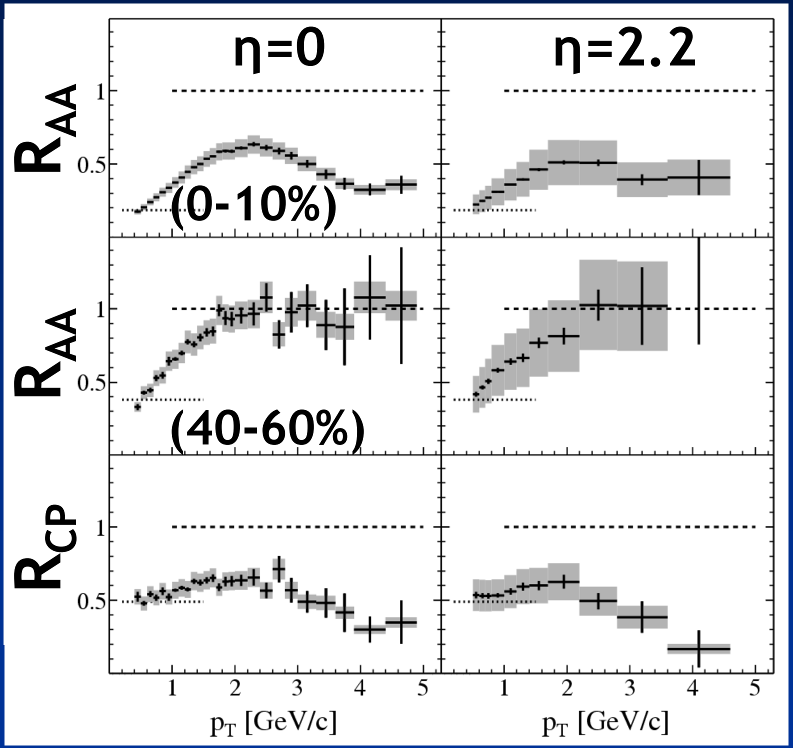
Can reproduce the shape, but requires ~75% of the energy loss in partonic phase with ~25% from "pre-hadron" re-scattering

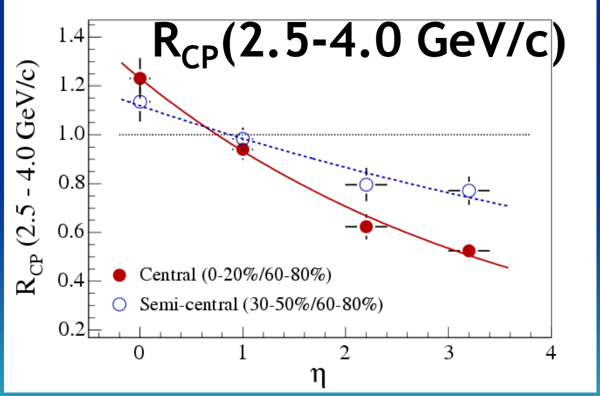
BRAHMS d+Au and Au+Au 200 GeV

d+Au: nucl-ex/0403005



Au+Au: PRL 91, 072305 (2003)



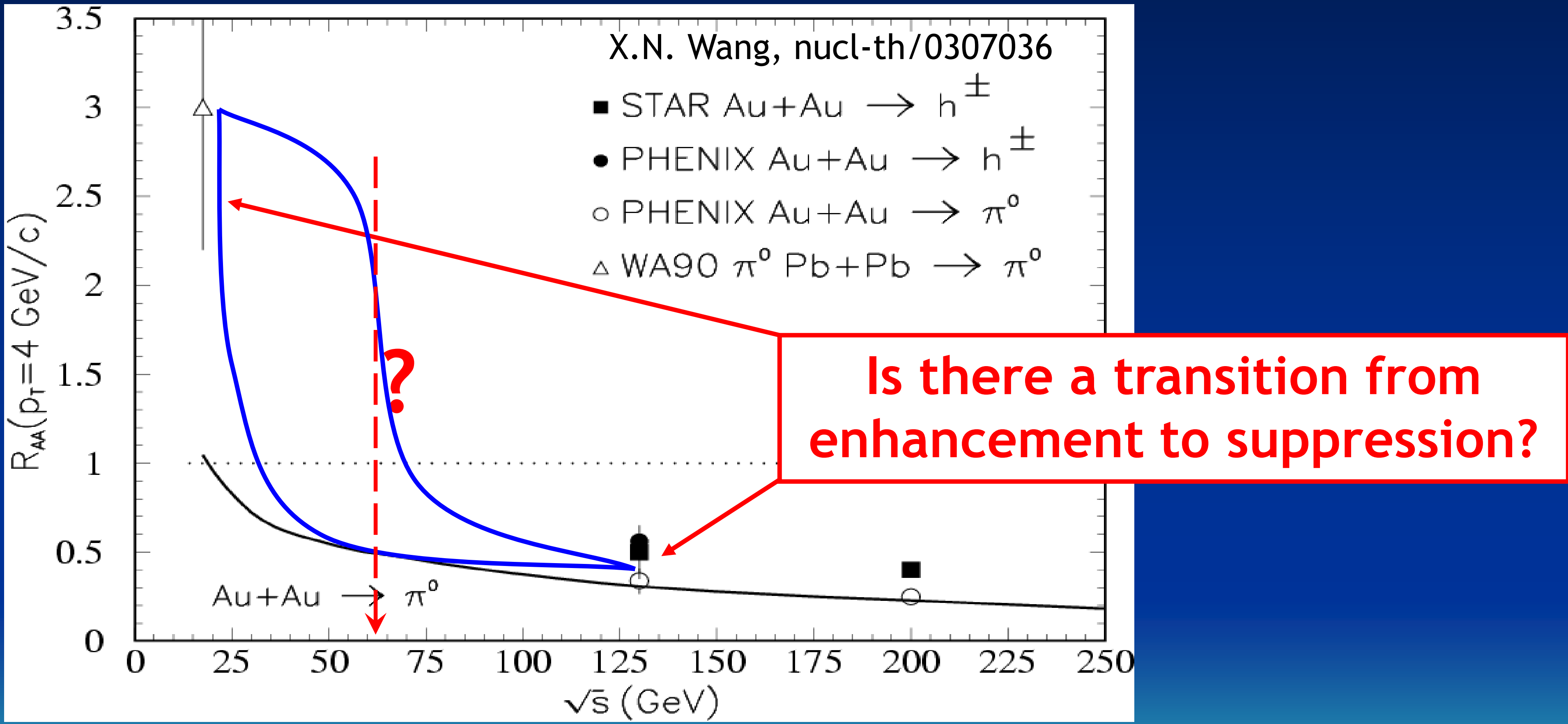


No strong eta dependence in Au+Au

Could CGC dynamics govern forward rapidity in d+Au?

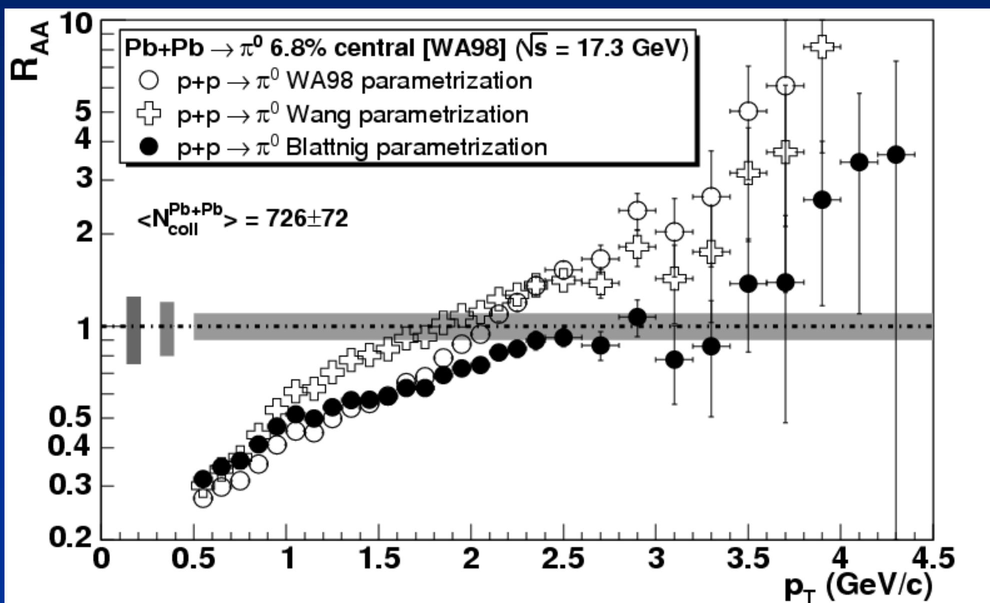
Where does suppression start?

Primary motivation for running Au+Au at 62.4 GeV

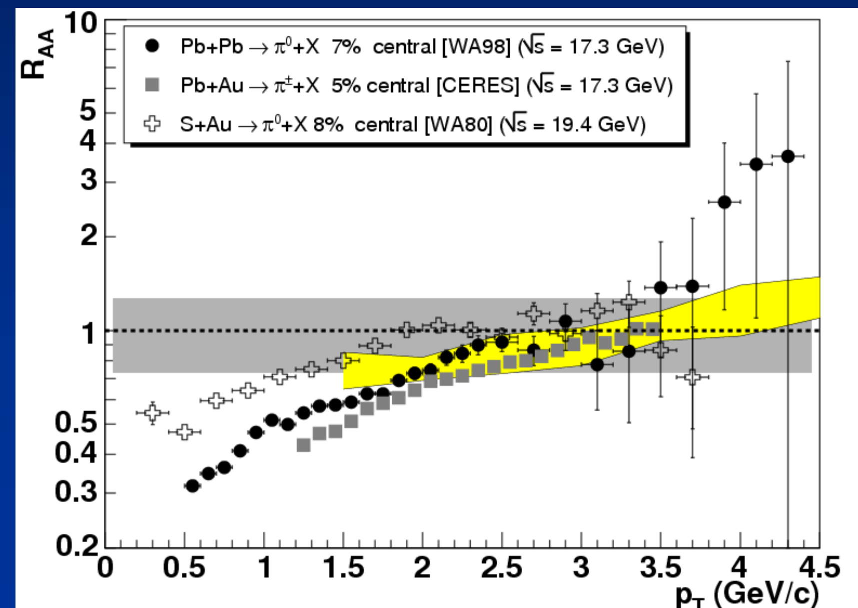


Important Aside: Reference Matters…

At the SPS (√s = 20 GeV) no good p+p->π^0/h reference…



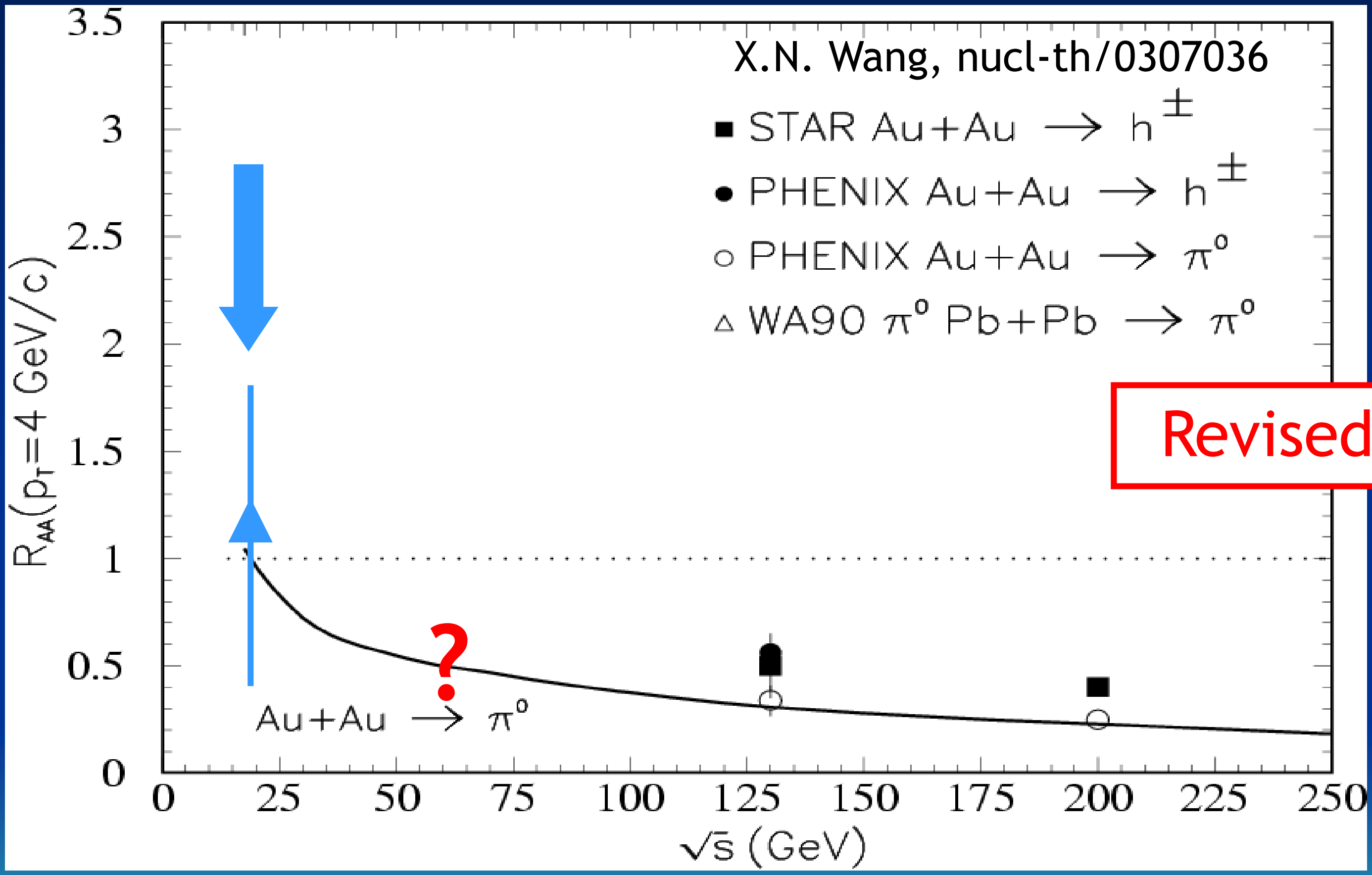
D. d'Enterria, nucl-ex/0403055



Vitev-Gyulassy Energy loss with dN^{glue}/dy = 400-600*

* Compared to dN^{glue}/dy = 200-300 in PRL **89** 252301 (2002)

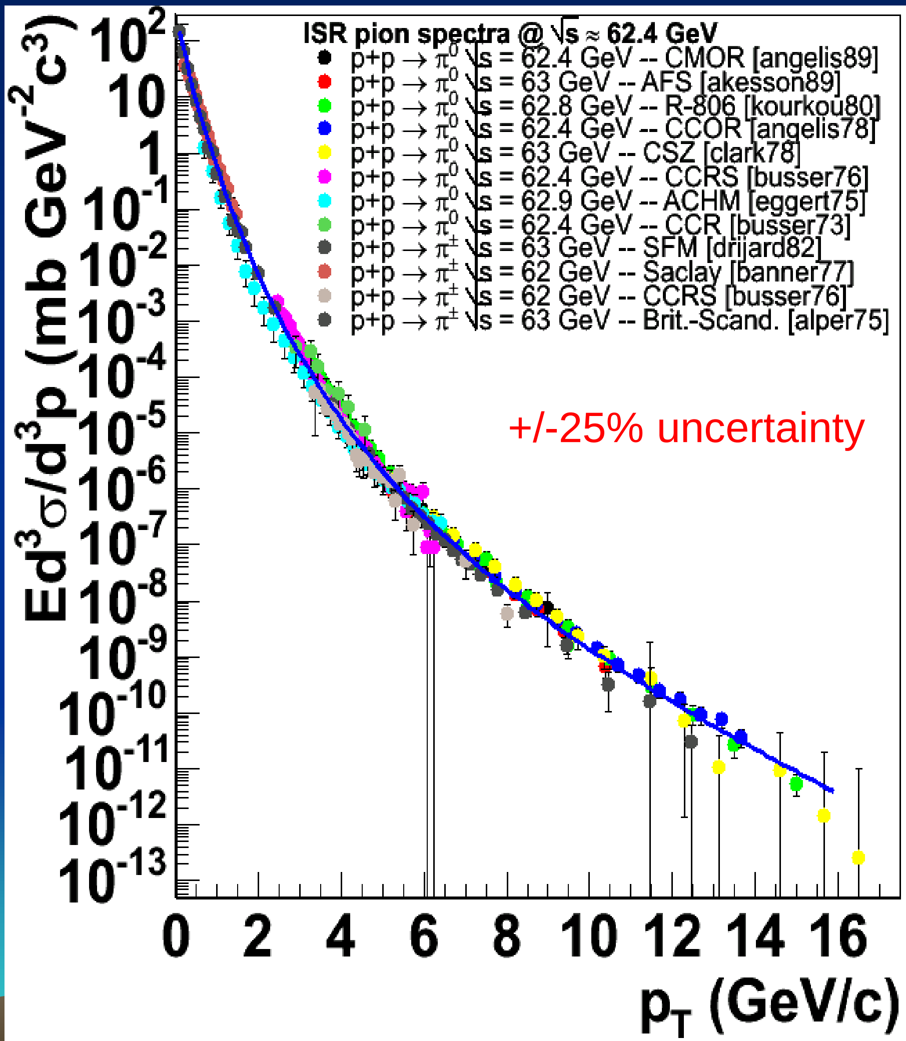
Where does suppression start?

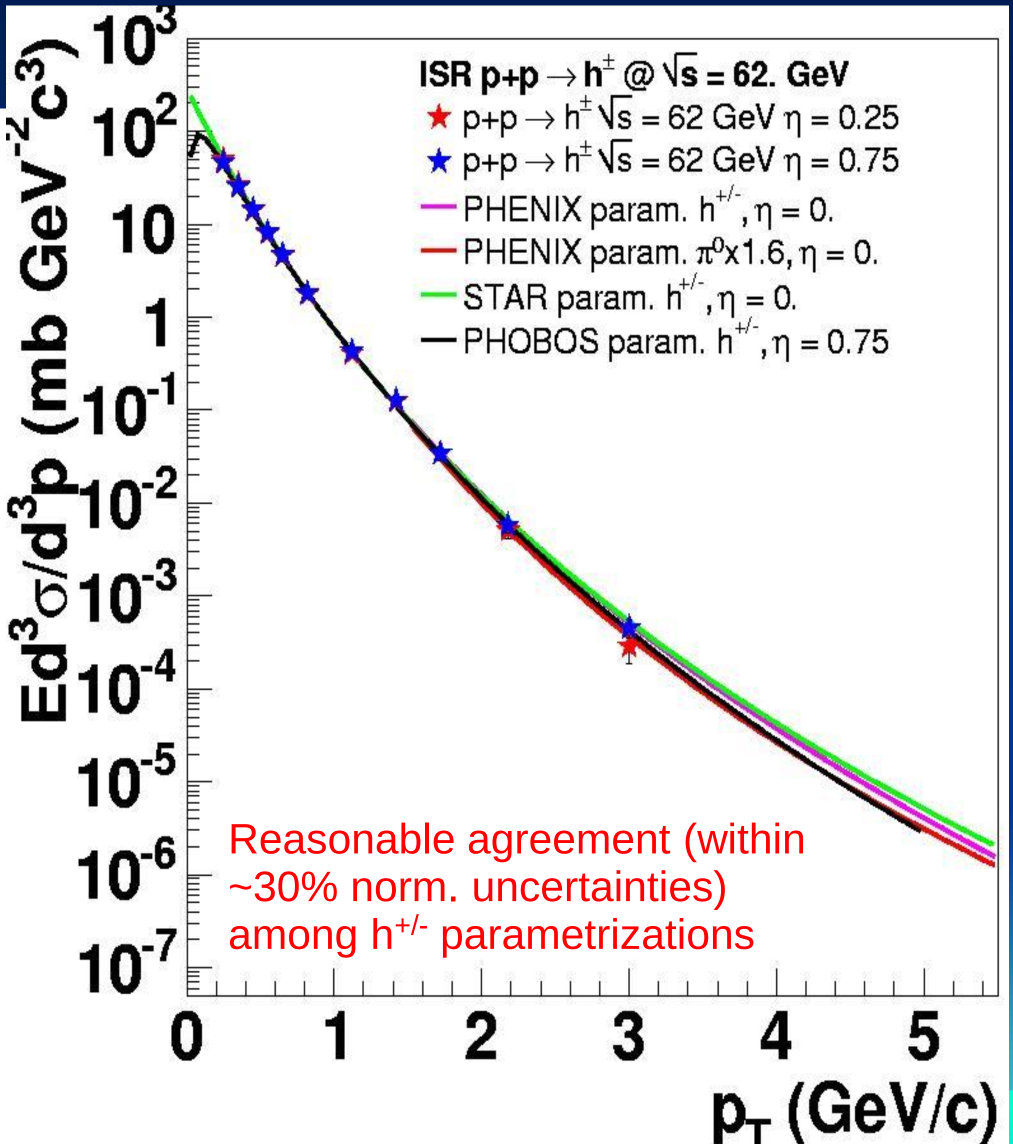


Revised expectations?

Reference Spectrum at 62.4 GeV: ISR Results

Compiled References: π^0, $h^\pm$

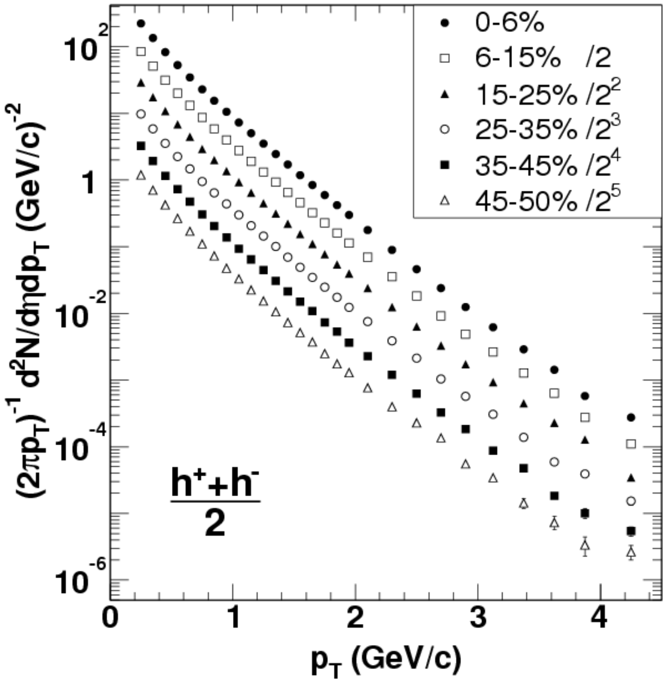


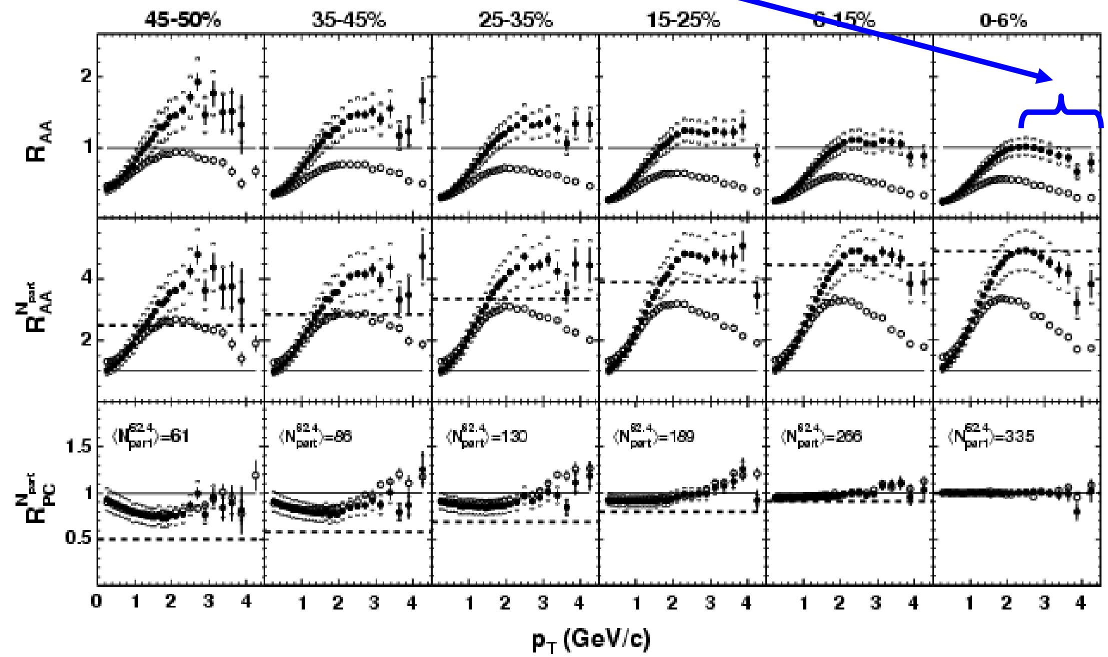


PHOBOS Au+Au 62.4 GeV

Once again, there is action at intermediate p_T

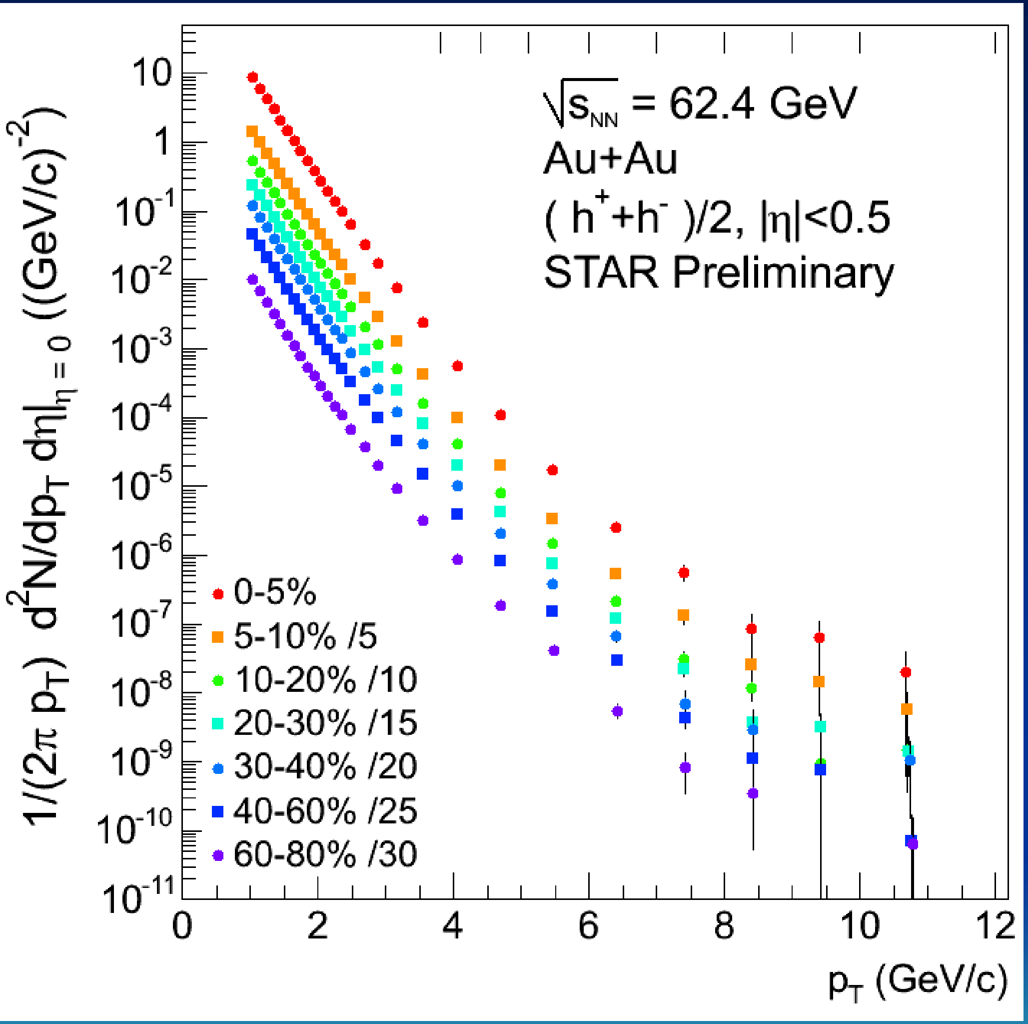
nucl-ex/0405003

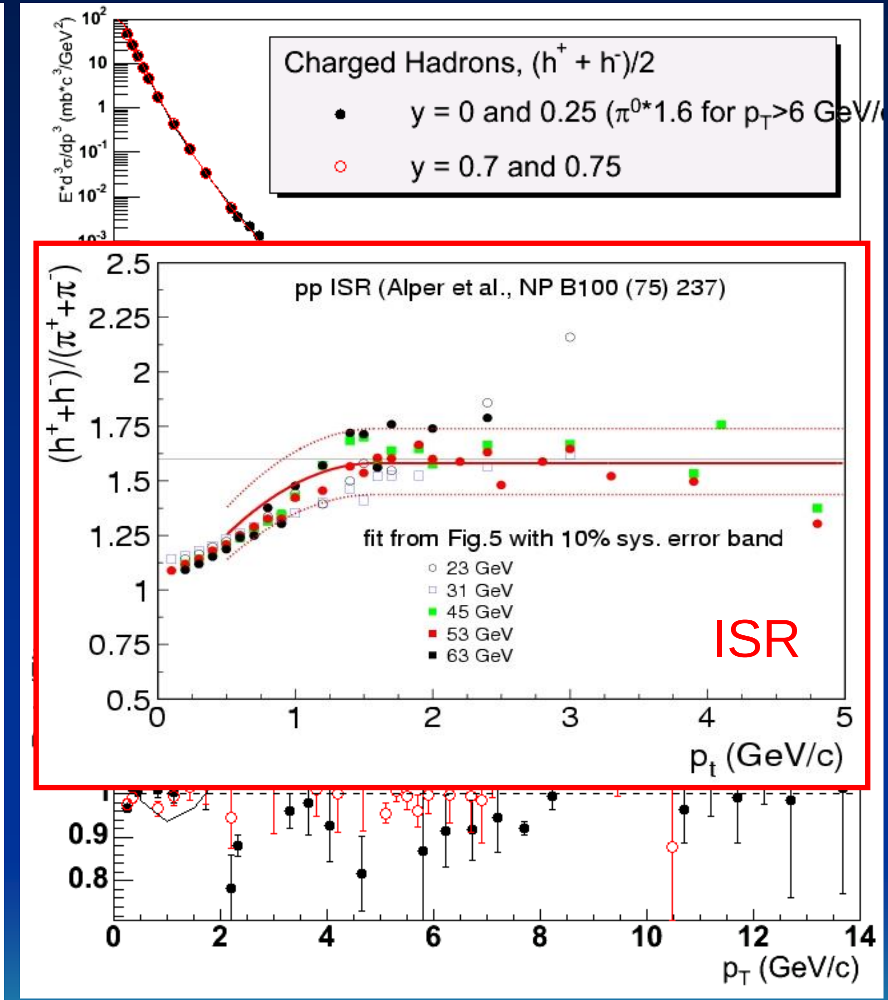




Exciting results (first to be submitted), but what about higher p_T?

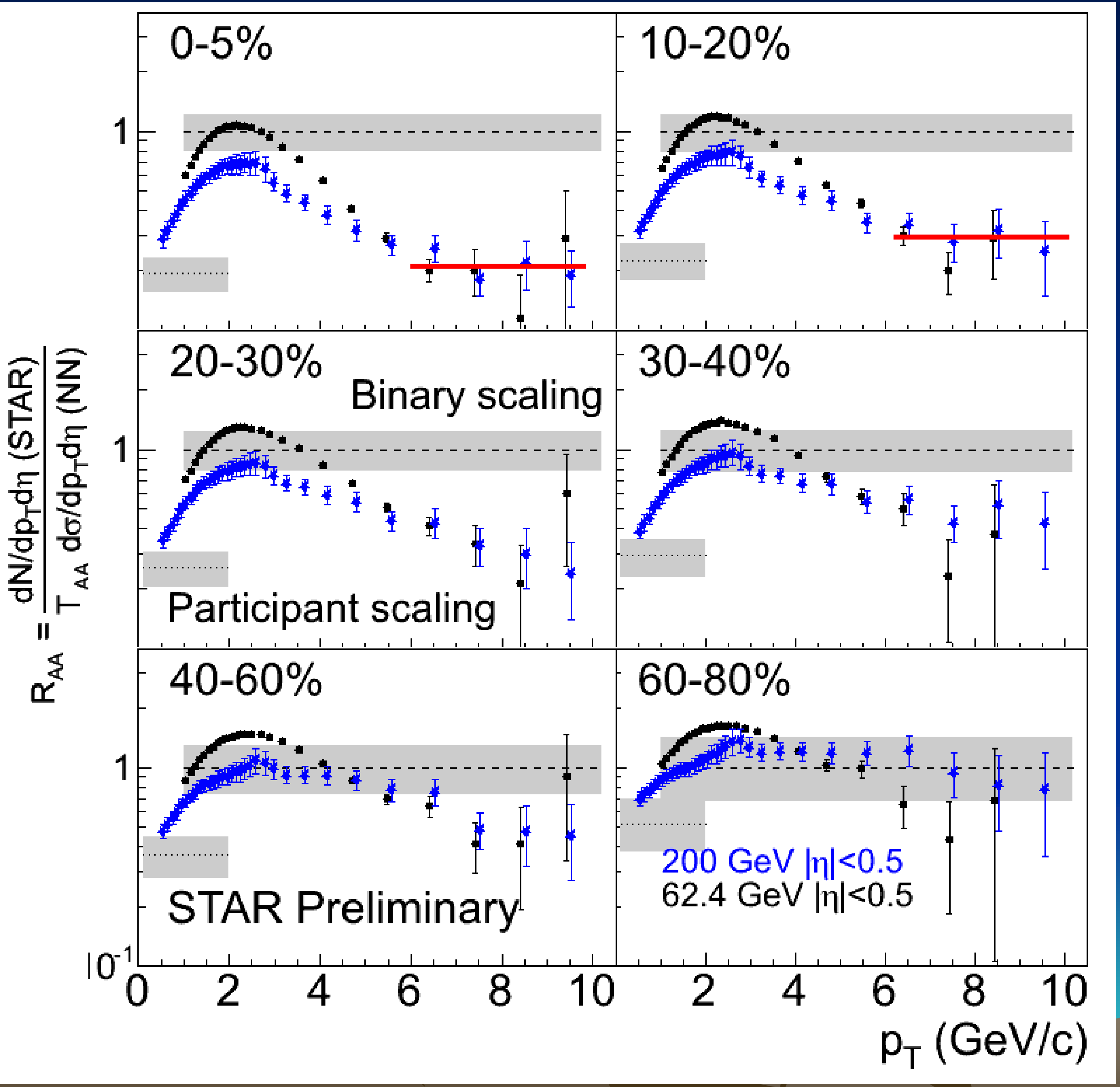
STAR Au+Au 62.4 GeV





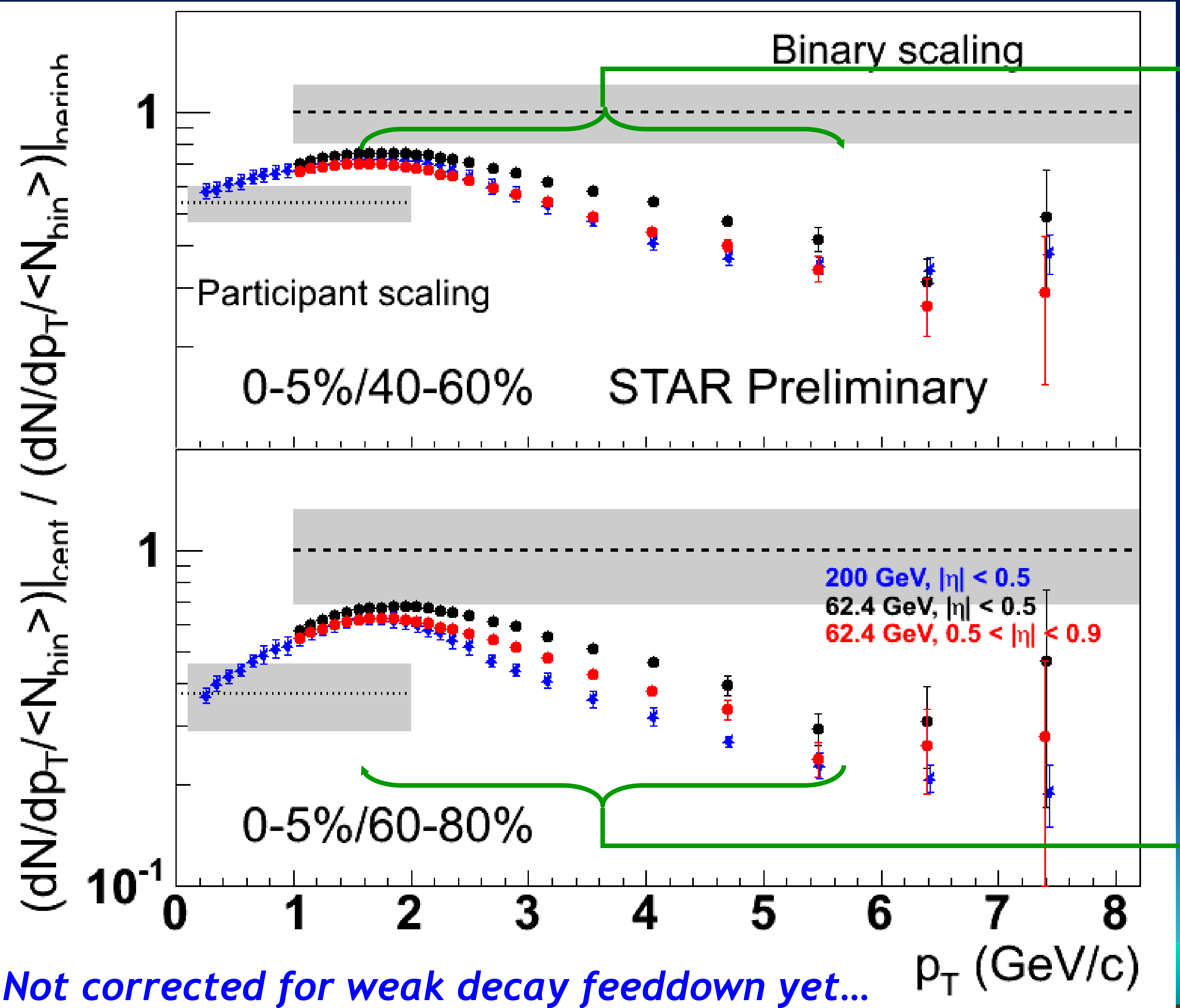
ISR Reference Compilation

STAR R_{AA} at 62 GeV



Splitting at intermediate p_T but ~convergence above ~6 GeV

STAR $R_{CP} \equiv$ Central/Peripheral



Moderate splitting at intermediate p_T but ~convergence above ~6 GeV

Not corrected for weak decay feeddown yet…

Summary I

We have a very comprehensive set of data from RHIC that will keep growing

From p+p:

- ✓ We have good agreement with NLO pQCD – an established baseline
- ✓ Good reference spectra are *essential* for understanding A+B collisions

From d+Au:

- ✓ Consistency with Cronin effects seen at lower energies (enhancement)
- ✓ Suggestions of possible CGC dynamics at forward rapidity (BRAHMS)
- ✓ No initial state suppression observed (No CGC at mid-rapidity high-pT at RHIC)

Summary II

From Au+Au:

✓ High p_T Suppression is large and due to final state effects

✓ Consistent with Jet Quenching via partonic energy loss with initial gluon densities of order $dN^g/dy \sim 1000$

✓ Interesting production mechanisms at work at intermediate $p_T \sim$ 2-6 GeV/c

✓Coalescence/recombination models are promising explanation

✓ Precision Identified particle measurements extremely important

✓ Energy independence of suppression for $\sqrt{s}$ = 62 – 200 GeV?

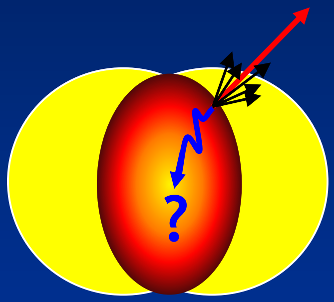
✓ Experiment ←→ Theory feedback driving exciting progress in the field

RHIC Physics IS exciting: 2 PRL Covers, (both featuring results on high p_T spectra)

What's on the horizon?

Short term (~1 year):

Si+Si/Cu+Cu



Smaller uncertainties in geometric scaling (central Si+Si/Cu+Cu vs. peripheral Au+Au)

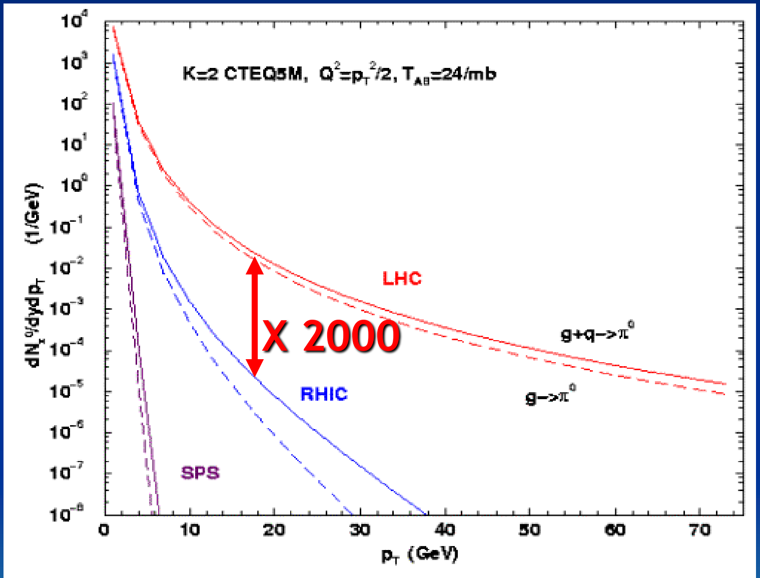
<u>High statistics Run IV Au+Au →</u>
PID'ed spectra PHENIX/STAR π^0:
p_T ~ 20 GeV/c…?

STAR Λ/K^0_s, STAR/PHENIX π/k/p:
p_T ~ 10 GeV/c…?

Longer term (~3-5 years):

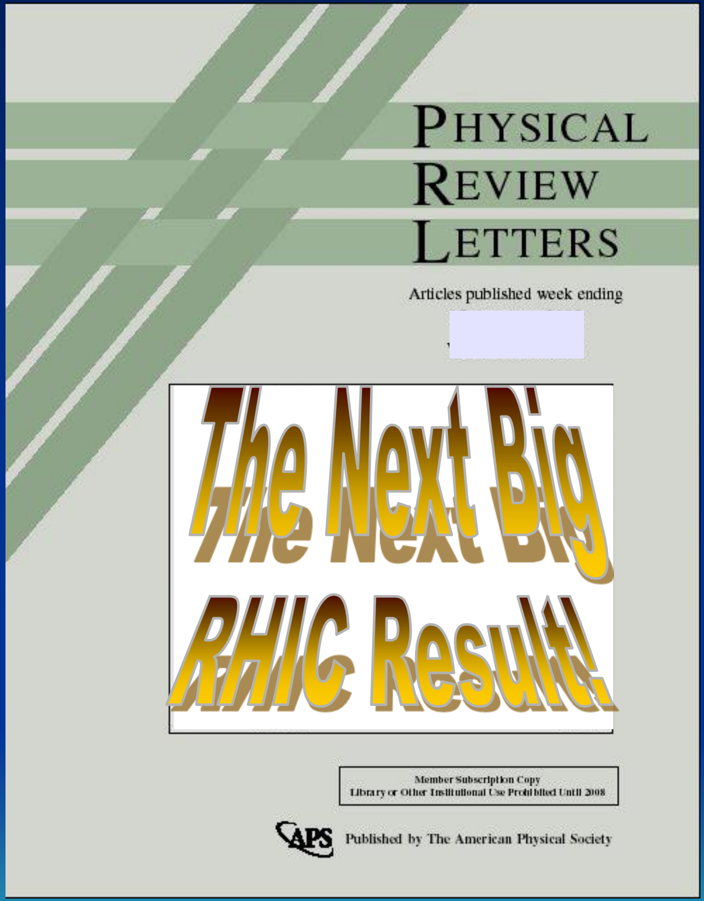
REALLY high p_T:

LHC



Well into the fragmentation regime…

Fin



PHYSICAL REVIEW LETTERS

Articles published week ending

The Next Big RHIC Result!

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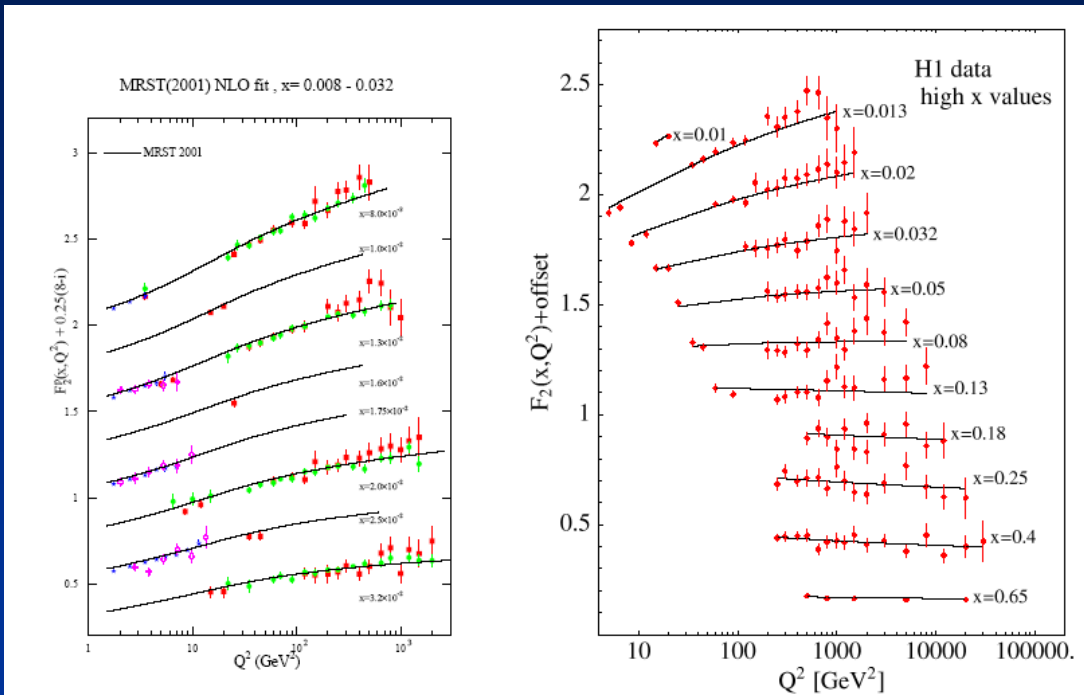
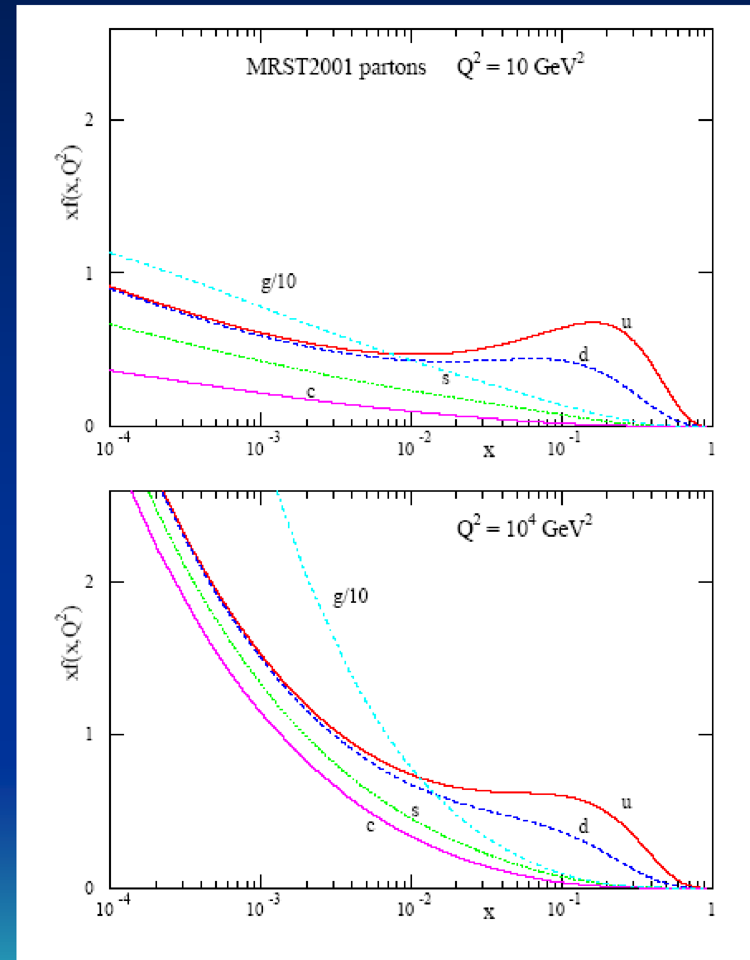
Parton distribution functions

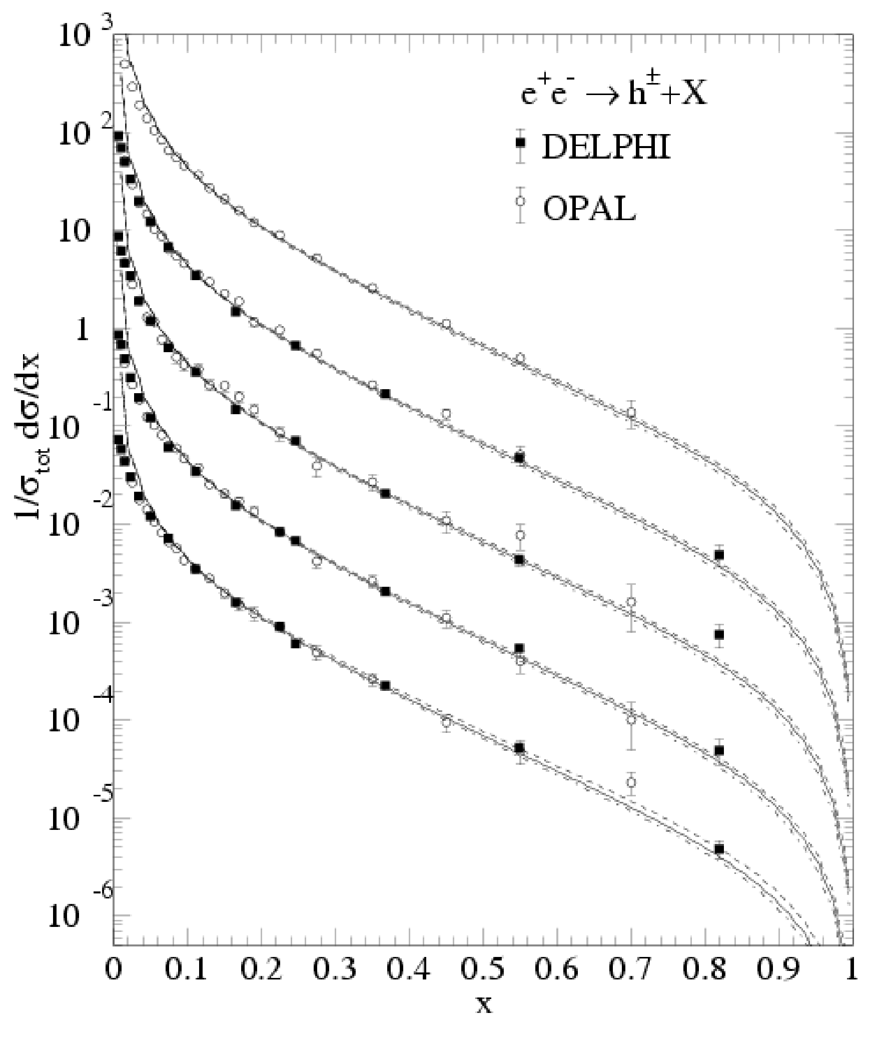
NLO Global fits to data



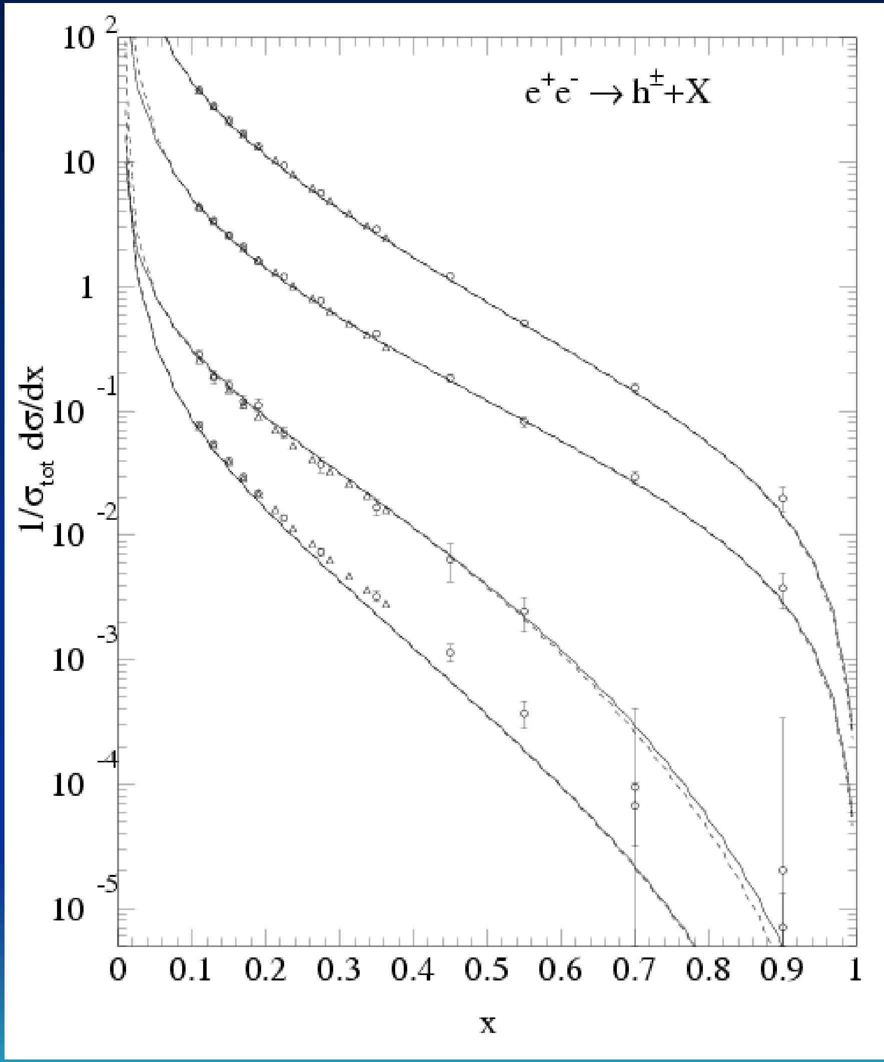


Many different flavors… MRST, GRV LO, CTEQ4M,5M,6 etc…

Fragmentation Functions

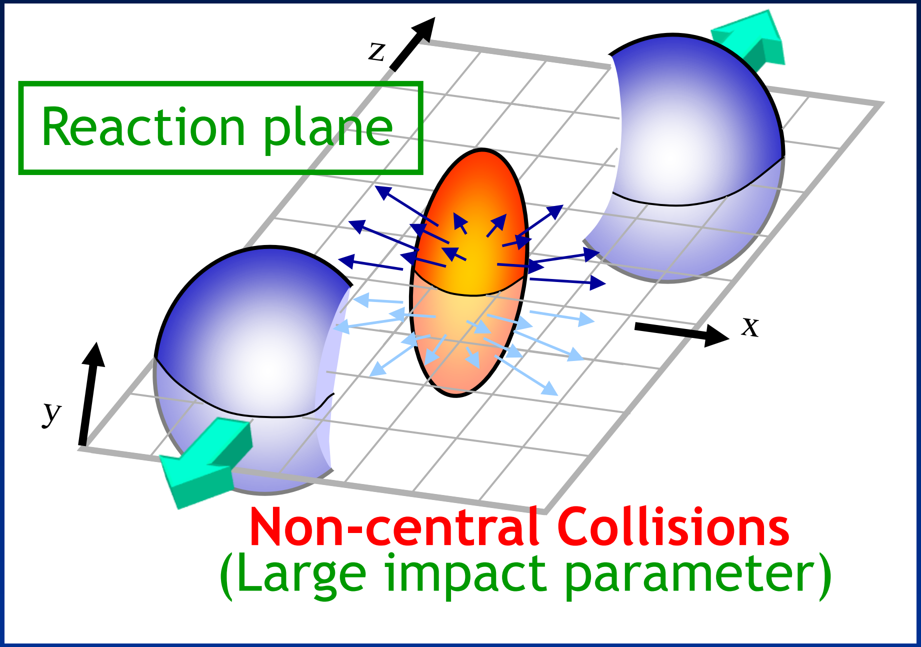


Kniehl, Kramer, Potter, Nucl. Phys. B 597, 337 (2001)

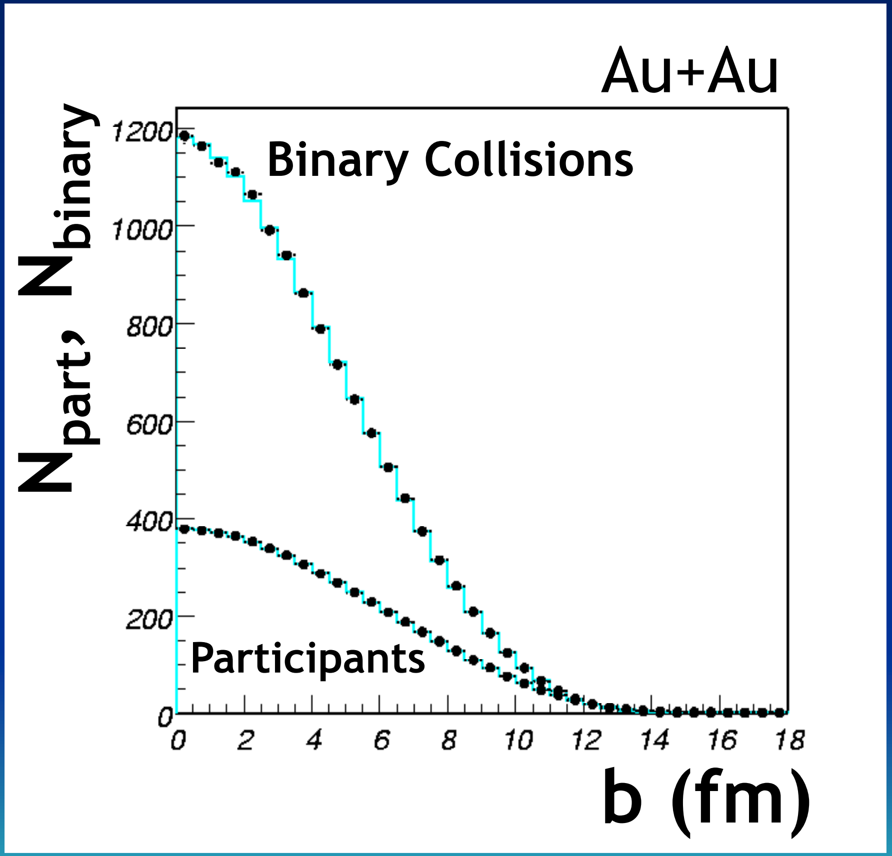


Kniehl, Kramer, Potter, Nucl. Phys. B 582, 514 (2000)

Nuclear Collision Geometry



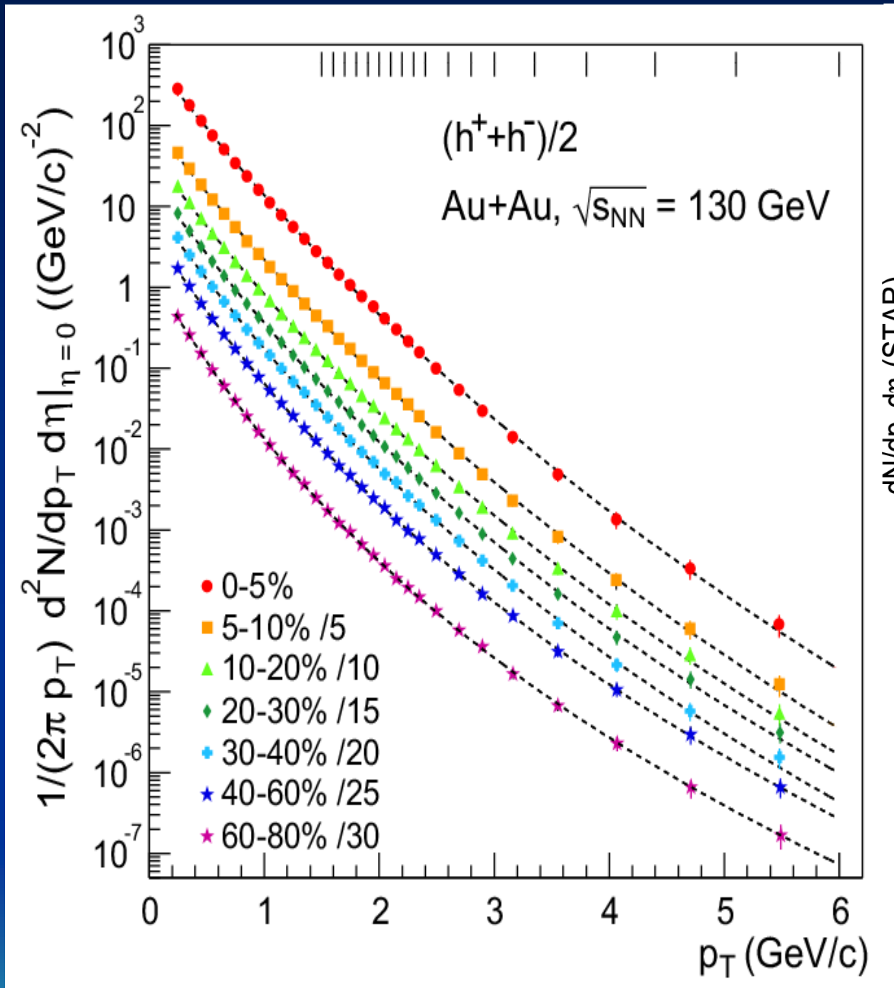
Glauber Model Calculation:

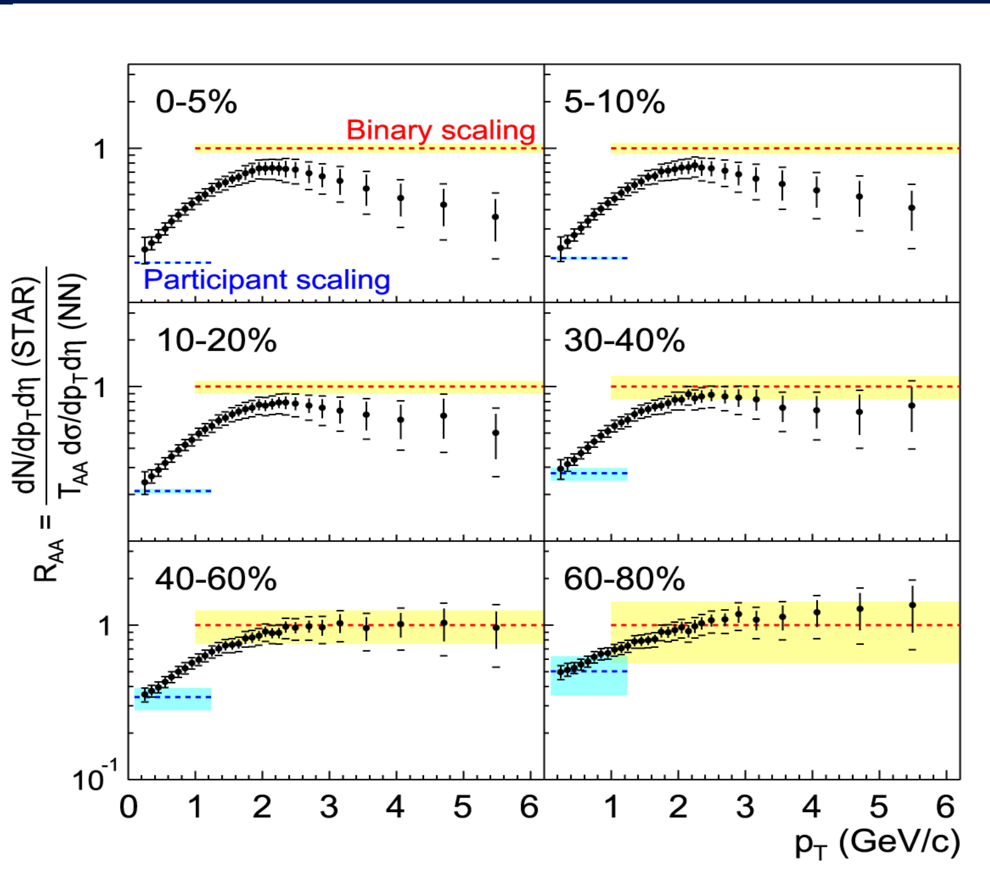


Number of participants: number of incoming nucleons (participants) in the overlap region

Number of binary collisions: number of inelastic nucleon-nucleon collisions

STAR Au+Au 130 GeV





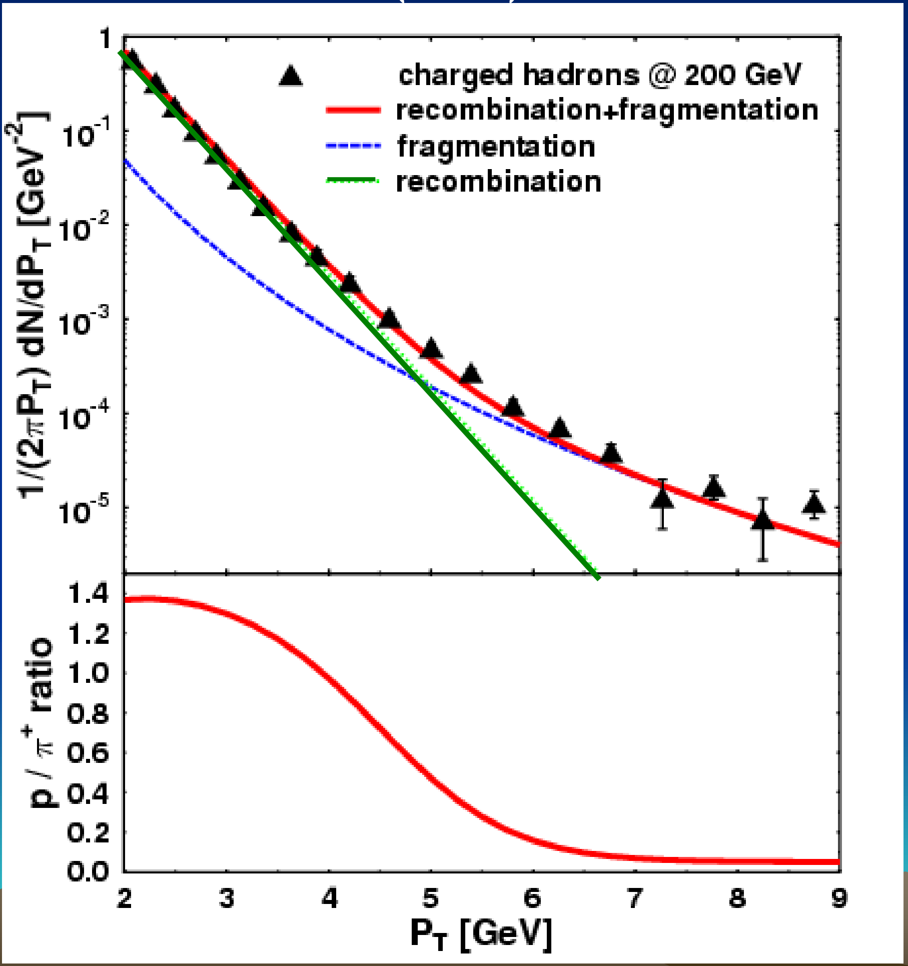
**Parameterized reference based on world's data (no p+p at 130 GeV)

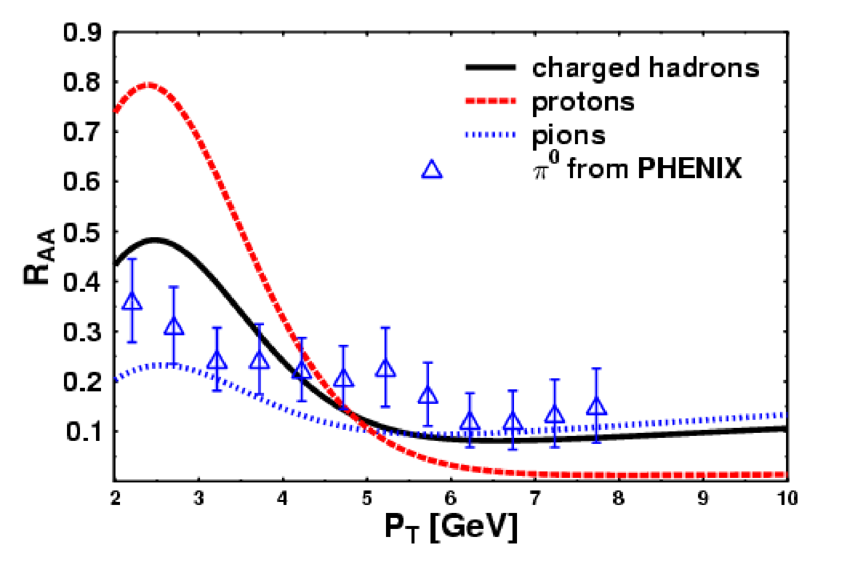
Recombination/Coalescence Models

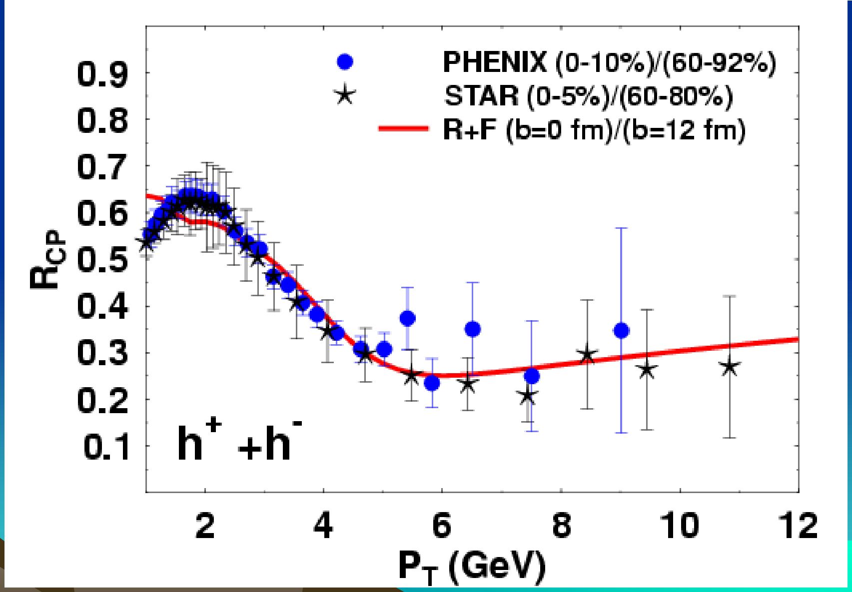
Recombination + Fragmentation:

Fries, Muller, Nonaka, Bass, PRC 68 (2003) 044902;

PRL 90 (2003) 202303





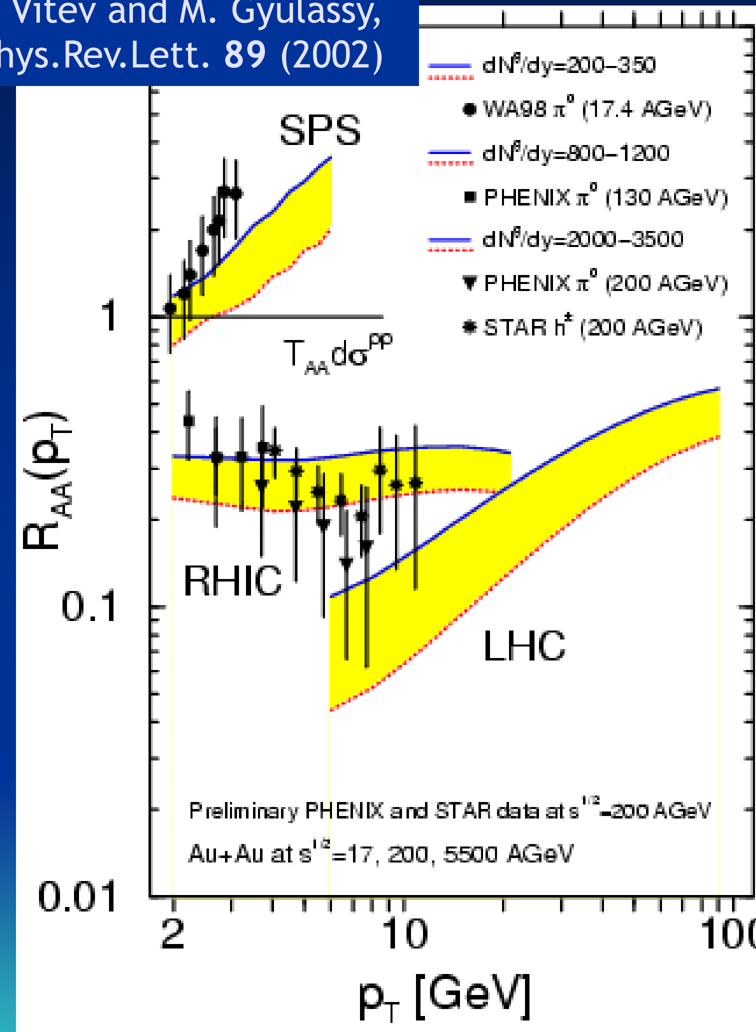


Energy dependence

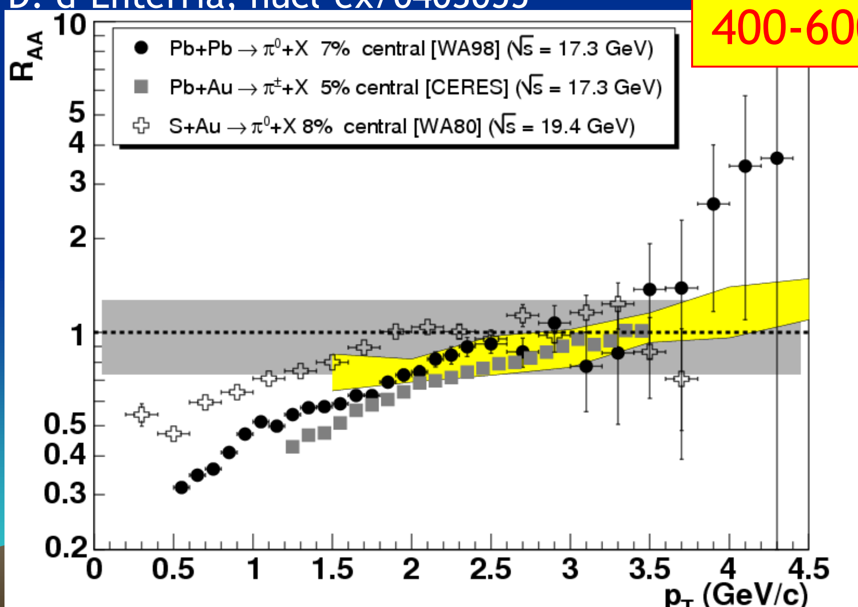
Steeper spectra at SPS → Larger impact of Cronin effect

Between SPS and RHIC:
Factor ~2 in ε_{Bj} and factor ~2 in dN^{glue}/dy

I. Vitev and M. Gyulassy, Phys.Rev.Lett. **89** (2002)

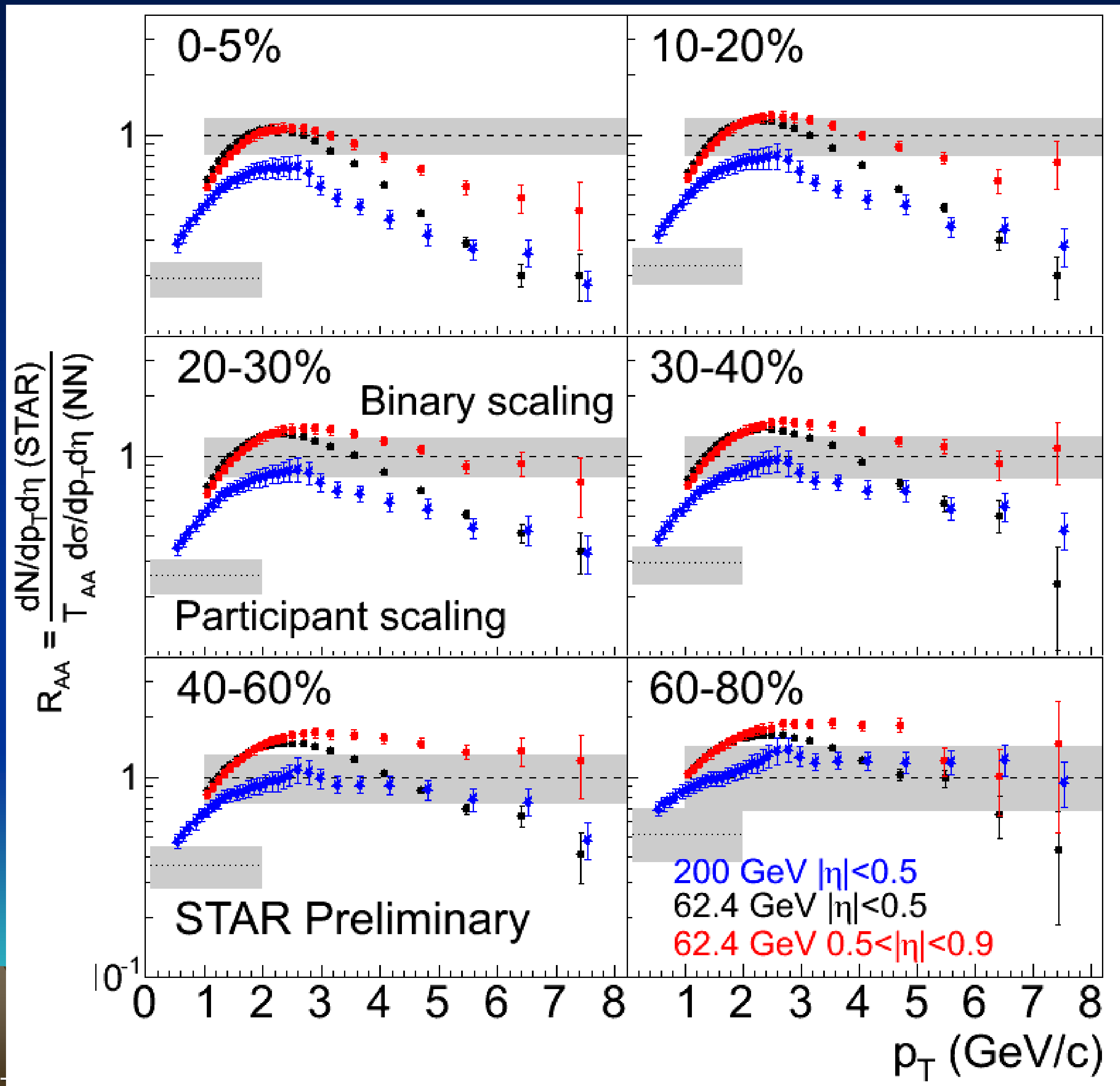


D. d'Enterria, nucl-ex/0403055



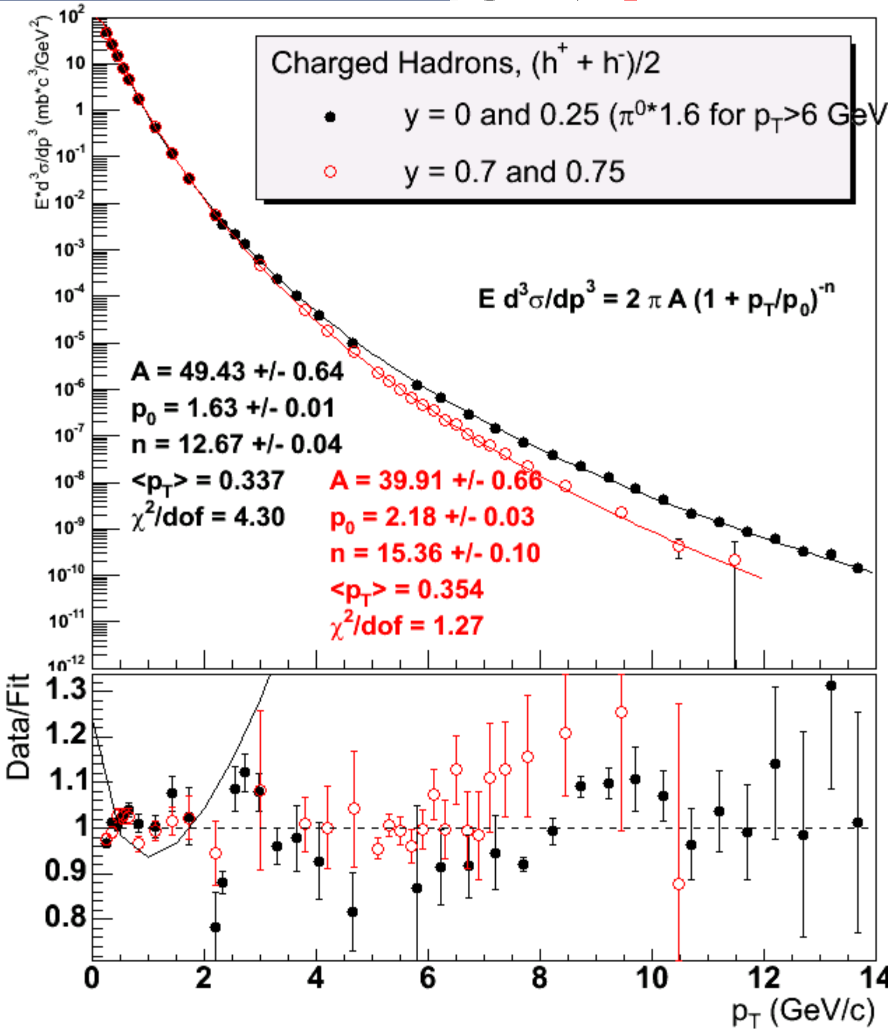
dN^{glue}/dy = 400-600

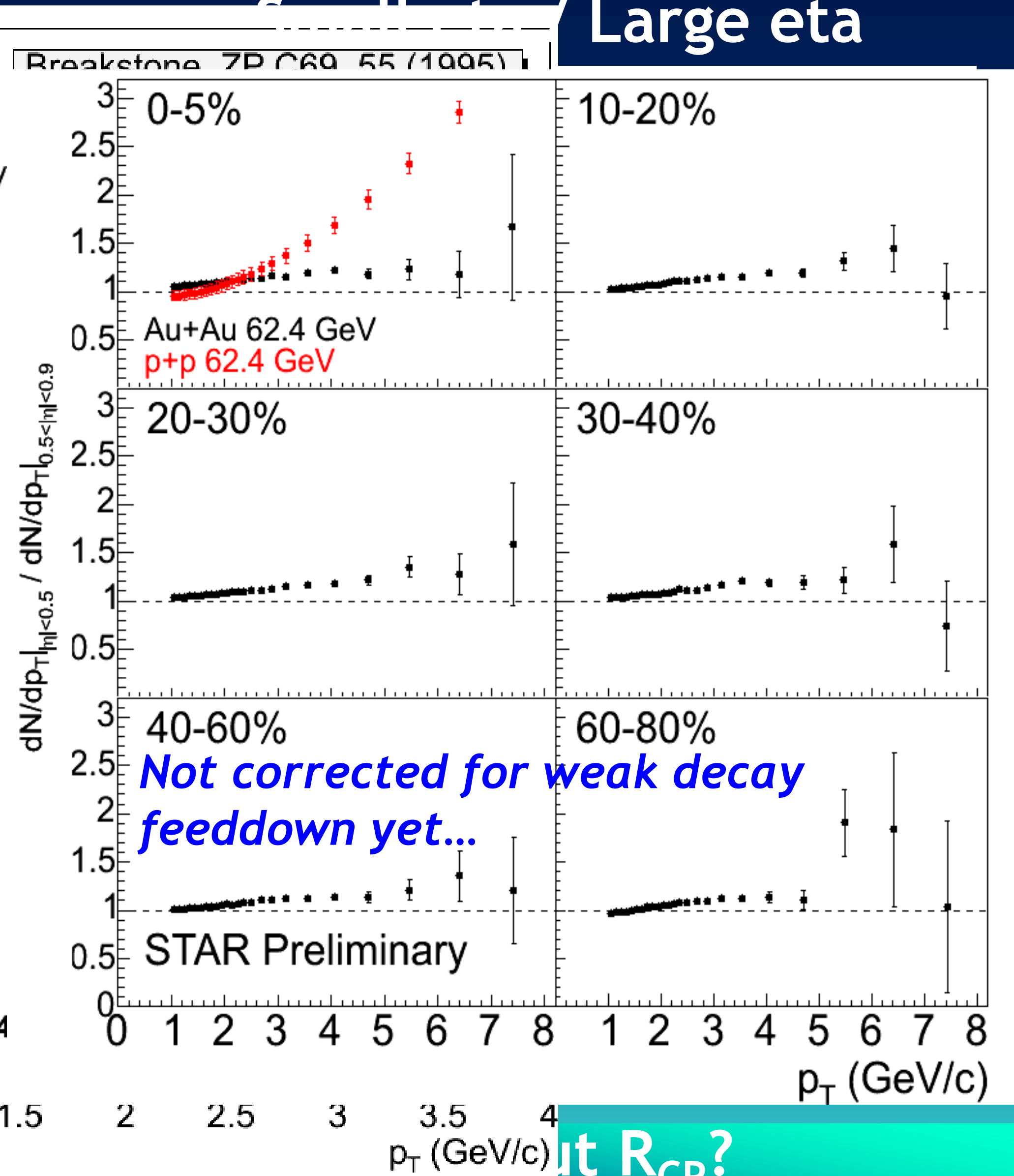
STAR R_{AA} at 62.4 GeV



Why the big eta difference?

/ Large eta





Doh! Th… …ut R_{CP}?