Experimental Results from RHIC: QGP or what?

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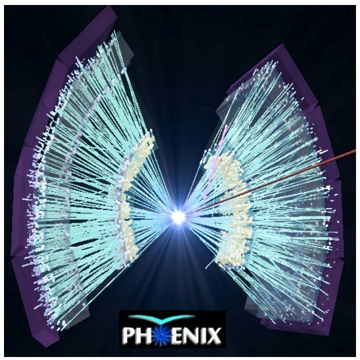
See Nuclear Physics A757 (2005)
PHENIX pp 184-283
BRAHMS pp 1-27
PHOBOS pp 28-101
STAR pp 102-183



Seminar
Clermont-Ferrand, Sept 9, 2005

Warning
Beware of Theory Curves on Experimental Data

Original observation of Drell-Yan pairs: "massive muon pairs in hadron collisions"

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

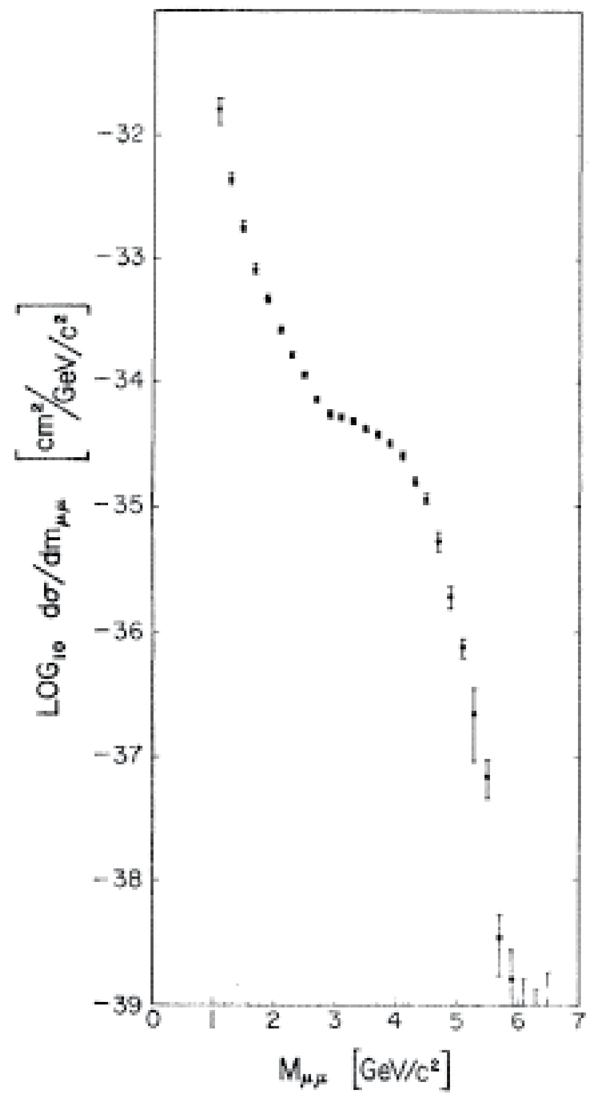
and

E. Zavattini
CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}{}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

The Measurement



Theorists at Work

VOLUME 26, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JANUARY 1971

Light-Cone Analysis of Massive μ-Pair Production*

Guido Altarelli,† Richard A. Brandt,‡ and Giuliano Preparata†
Rockefeller University, New York, New York 10021
(Received 9 September 1970)

An operator representation for the behavior of the product of two electromagnetic currents near the light cone is used to discuss massive μ-pair production in hadron-hadron interactions. Restrictions from the Stanford Linear Accelerator Center electroproduction experiments and from Regge theory are incorporated. Our predictions are in agreement with the recent Columbia–Brookhaven National Laboratory experiment.

The Measurement with "theory" curve

VIEW LETTERS 4 JANUARY 1971

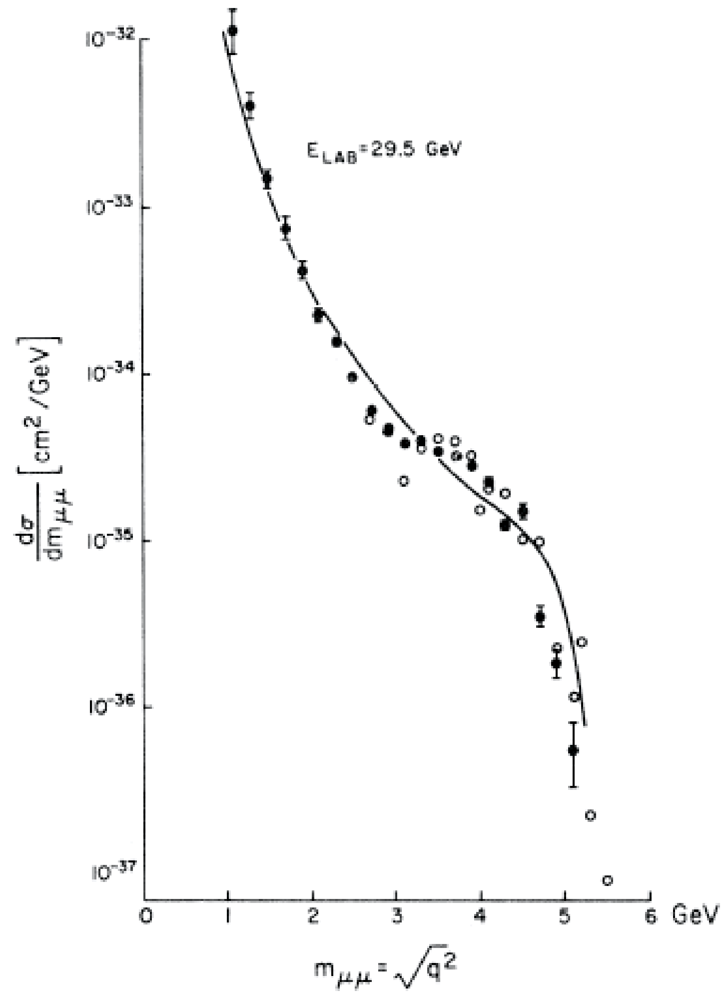
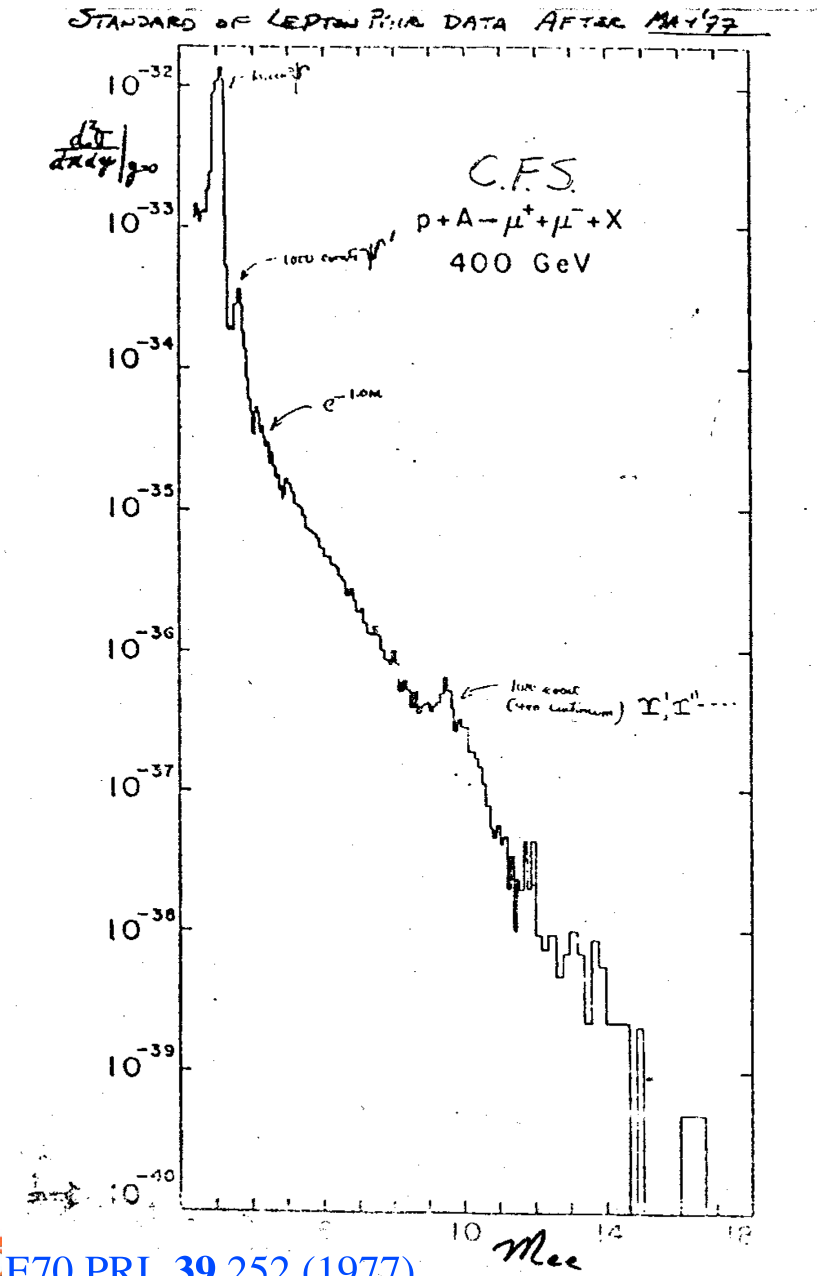
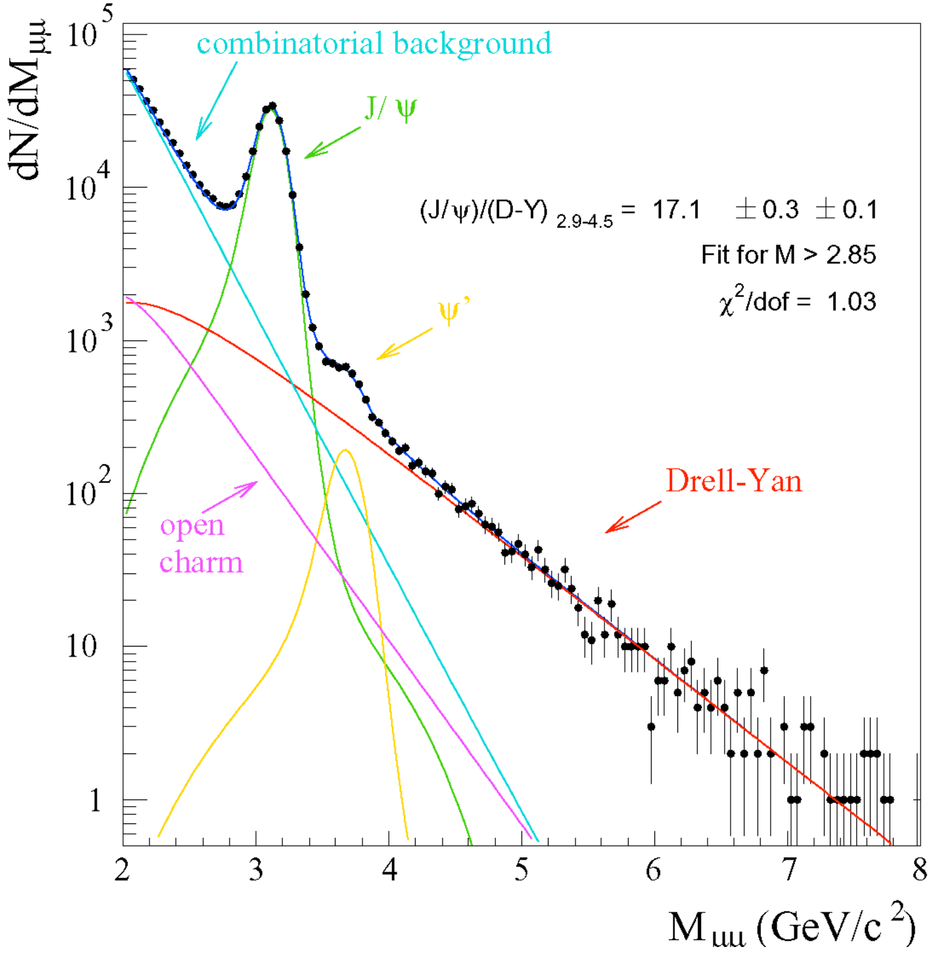


FIG. 2. Experimental cross section of Christenson *et al.*, Ref. 8.

La Verite



E70 PRL **39** 252 (1977)



NA50 PLB **477**, 28 (2000)

Invariance d'echelle

CFS, PRL **41**, 684 (1978)

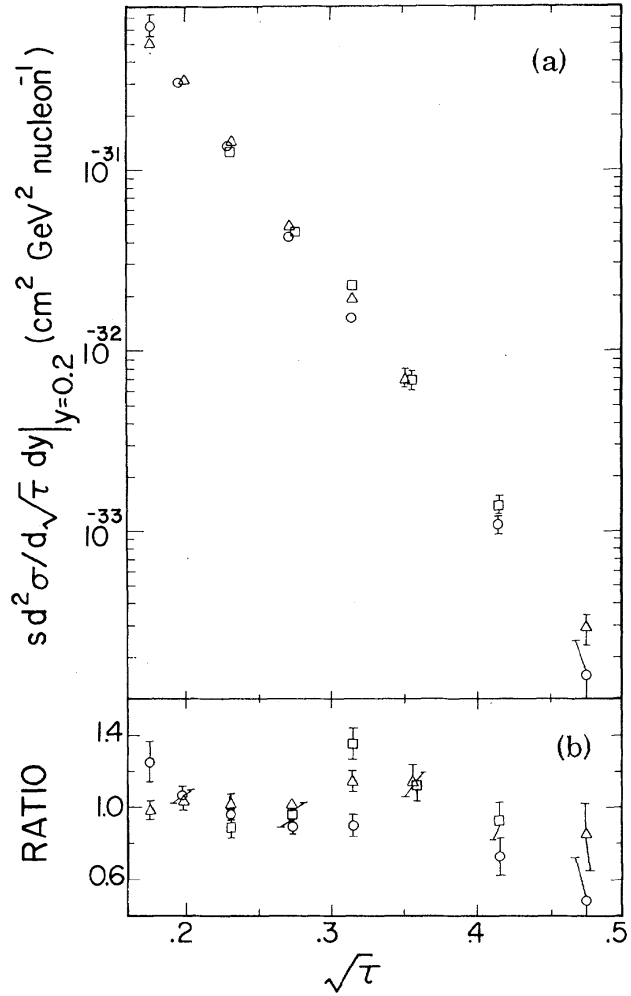
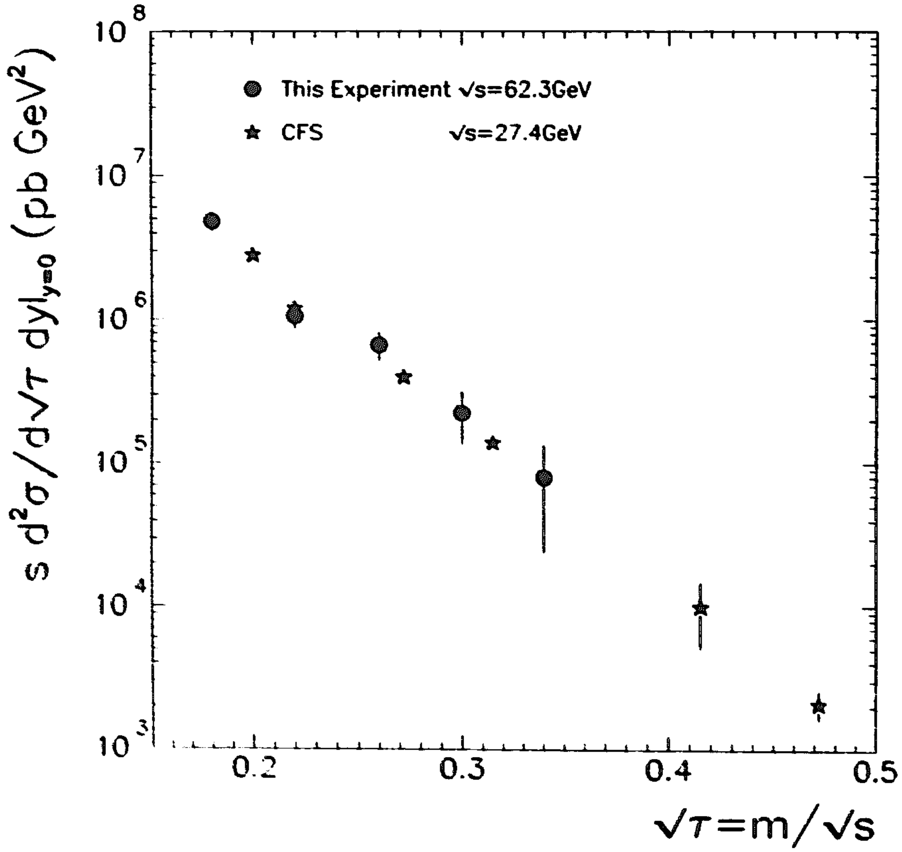


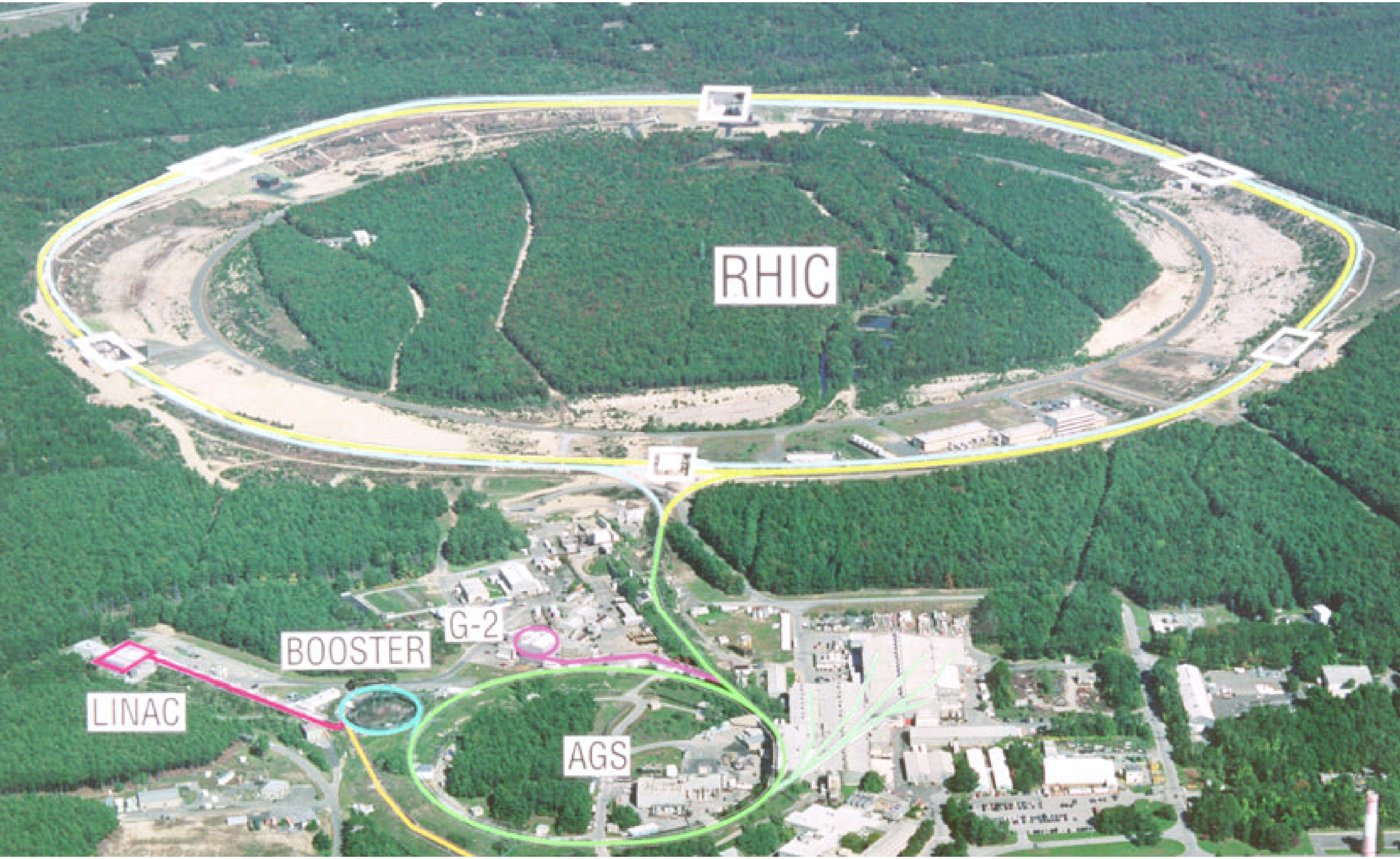
FIG. 3. (a) $s\, d^2\sigma/d\sqrt{\tau} dy|_{y=0.2}$ vs $\sqrt{\tau}$. Circles, triangles, and squares correspond to 400-, 300-, and 200-GeV beam energy, respectively. (b) Above data divided by the overall fit $Ae^{-b\sqrt{\tau}}$.



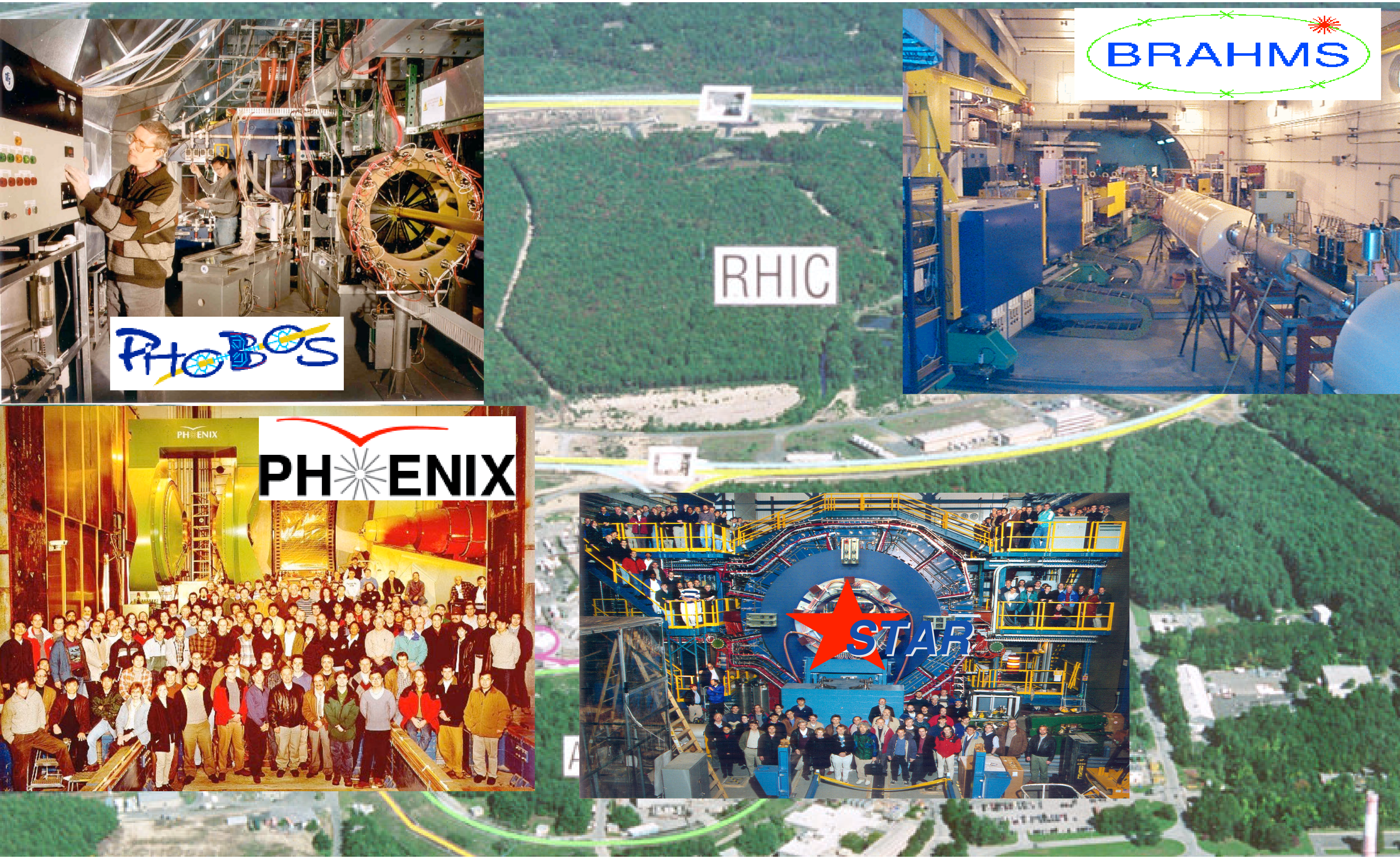
CMOR, NPB **348**, 1 (1991)

$$\sqrt{s}^3 d^2\sigma/dmdy|_{y=0} = f(m/\sqrt{s}) \sim e^{-27.4m/\sqrt{s}}$$

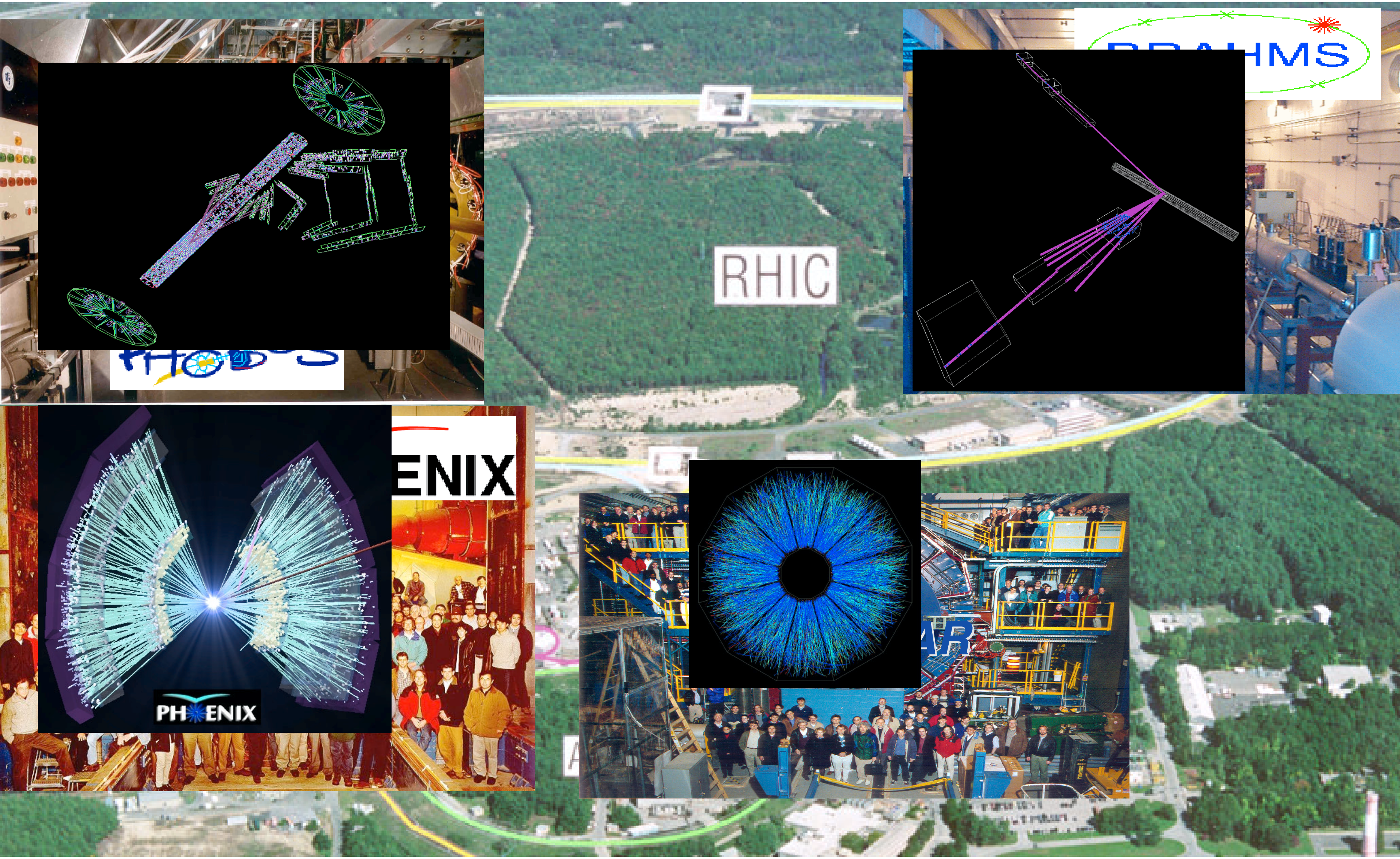
RHIC: Experiments



RHIC: Experiments



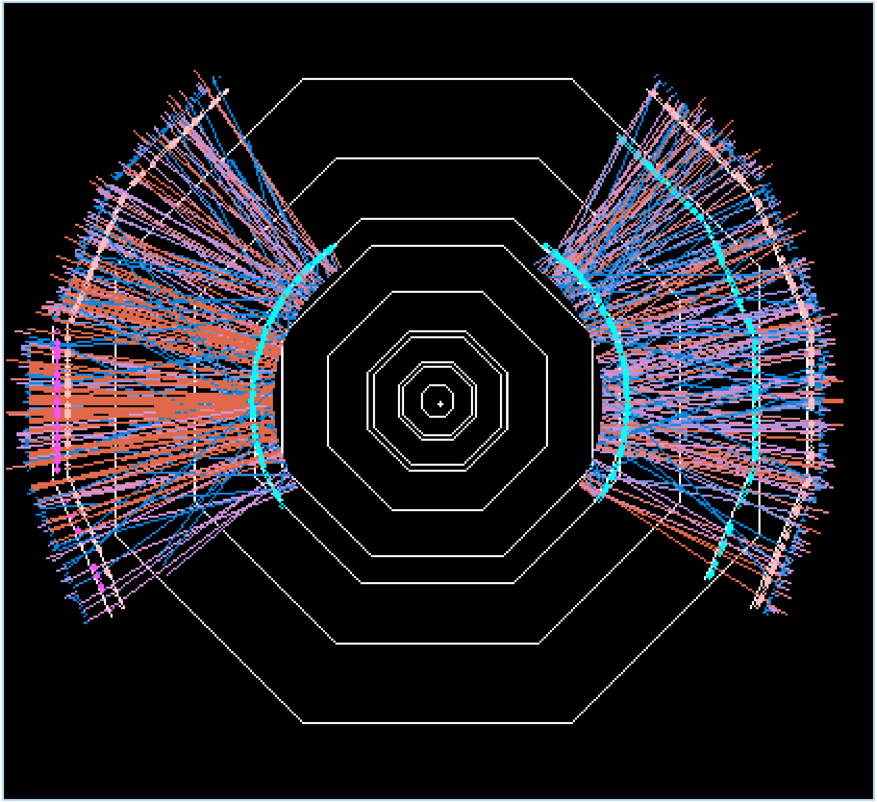
RHIC: Experiments

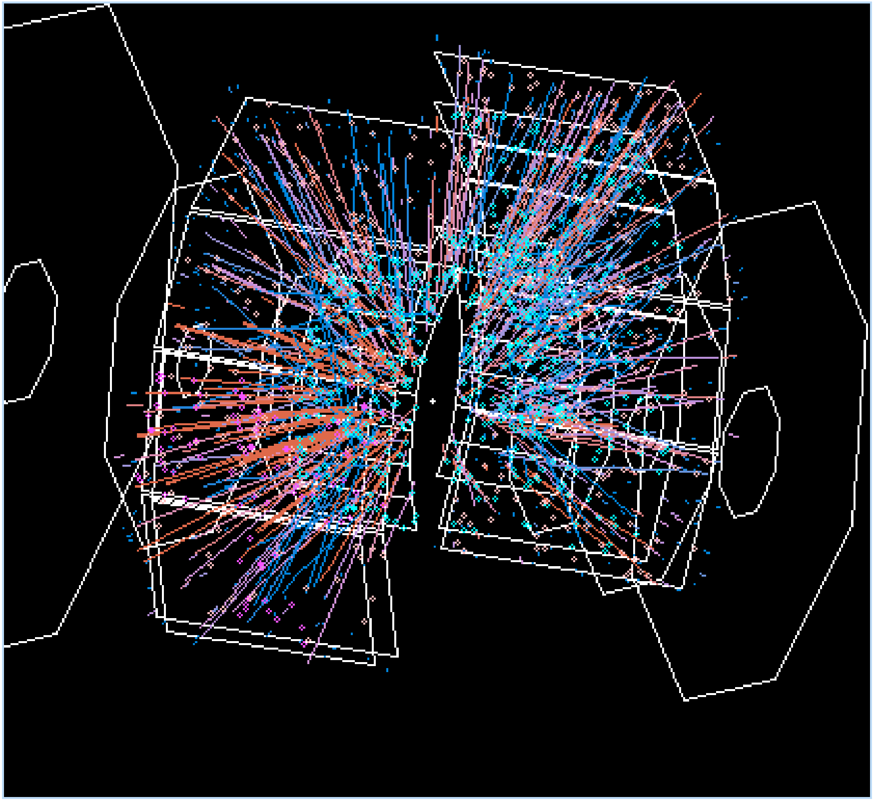


Example of a central Au+Au event at $\sqrt{s_{nn}}$ =200 GeV

$dn_{ch}/d\eta|_{\eta=0}$ =700 for central Au+Au collisions

cf. 2.5 for p-p collisions



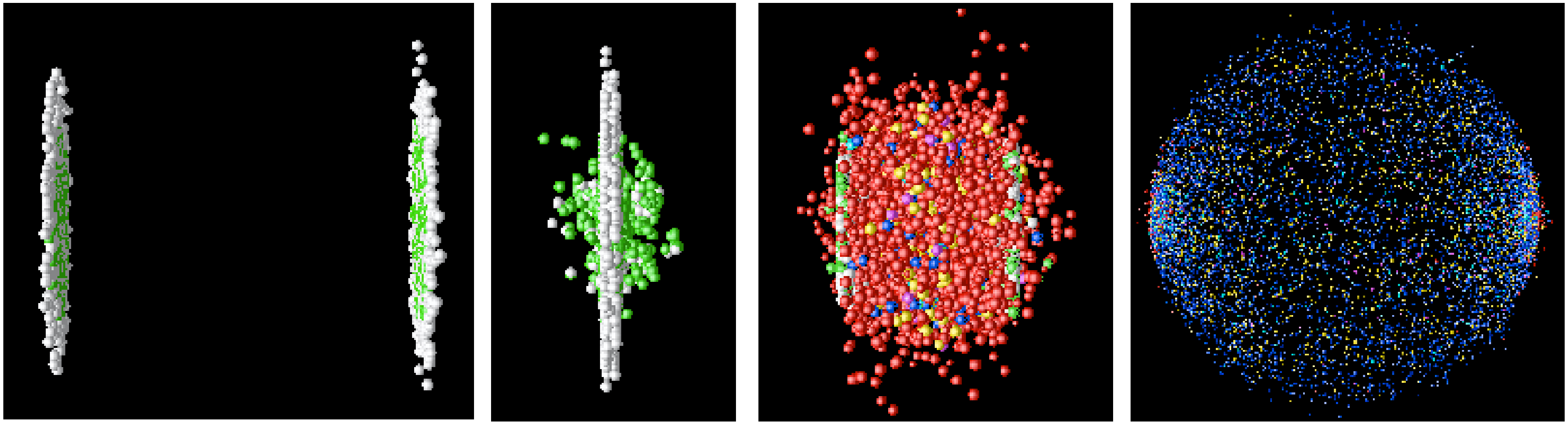


Run-1 to Run-5 Capsule History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3.06 nb^{-1}	8.6G	11.9 pb^{-1}	173TB
		Cu+Cu	62	185 μb^{-1}	413M	0.76 pb^{-1}	48TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1TB
		p+p	200	3.8 pb^{-1}	85G	3.8 pb^{-1}	262TB
		p+p	405	test pb^{-1}	164M	pb^{-1}	

Energy Density

Spacetime evolution is important



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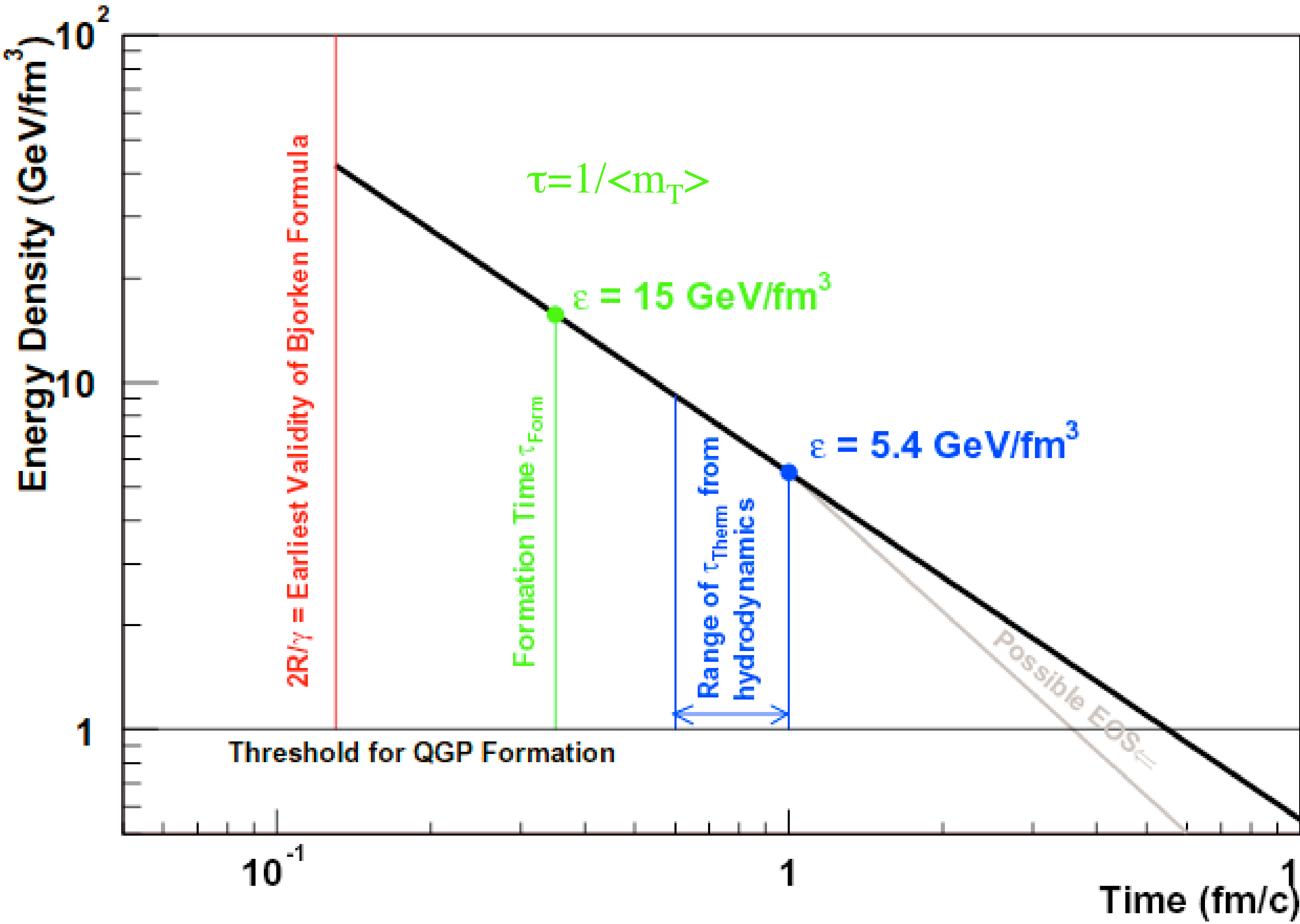
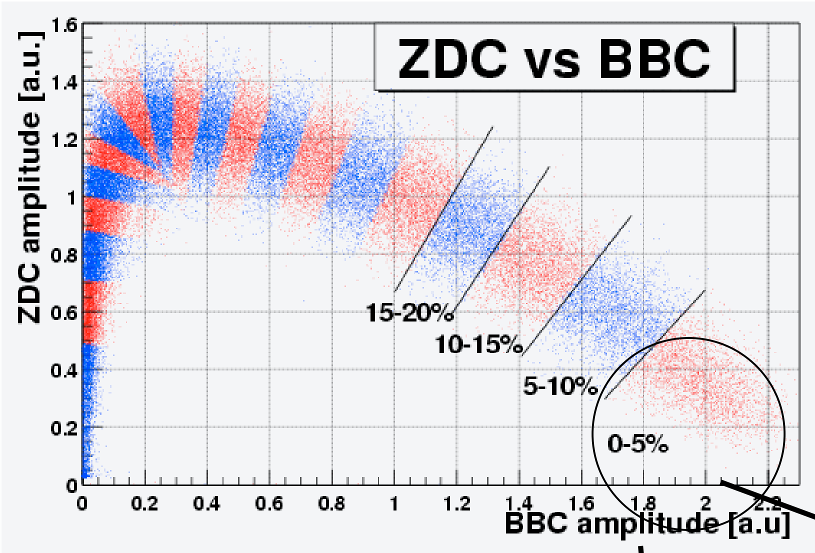
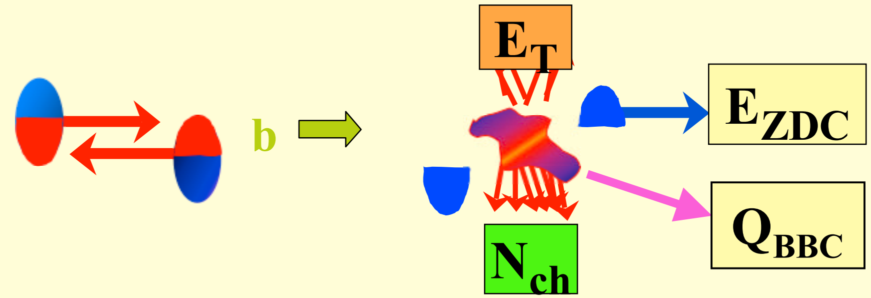


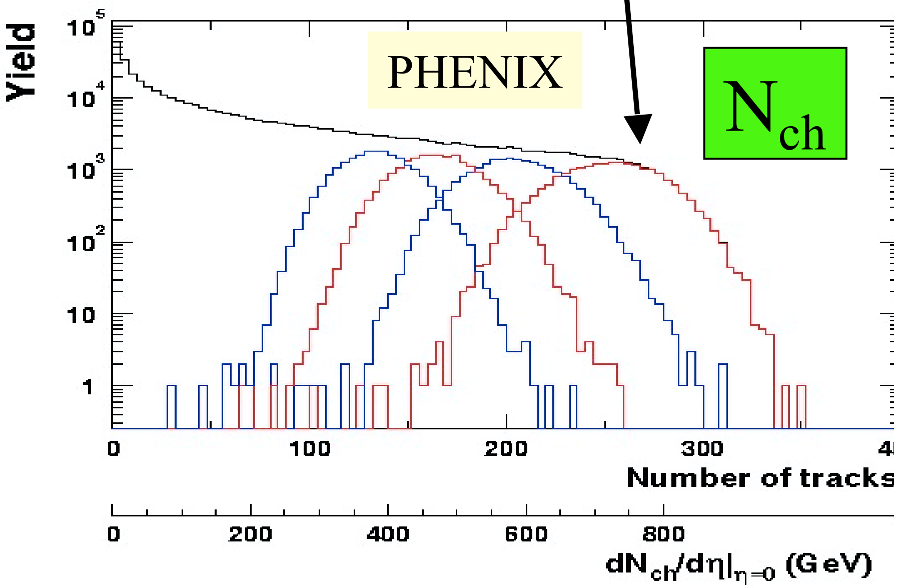
$N_{charged}$, E_T exhibit(&could determine) the Nuclear Geometry

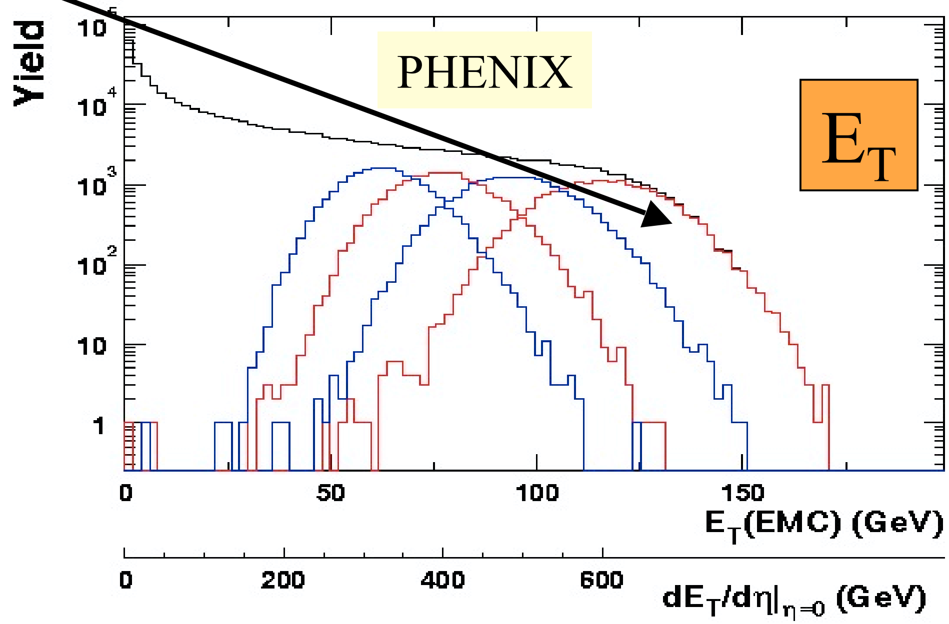


Define centrality classes: ZDC vs BBC



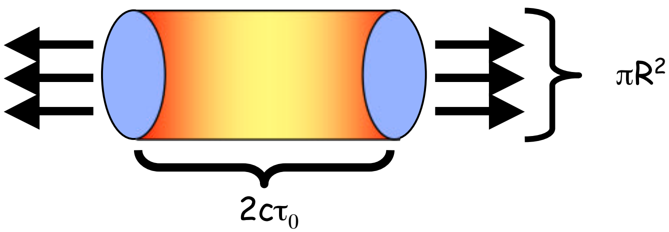
Extract N participants: Glauber model





Is the energy density high enough?

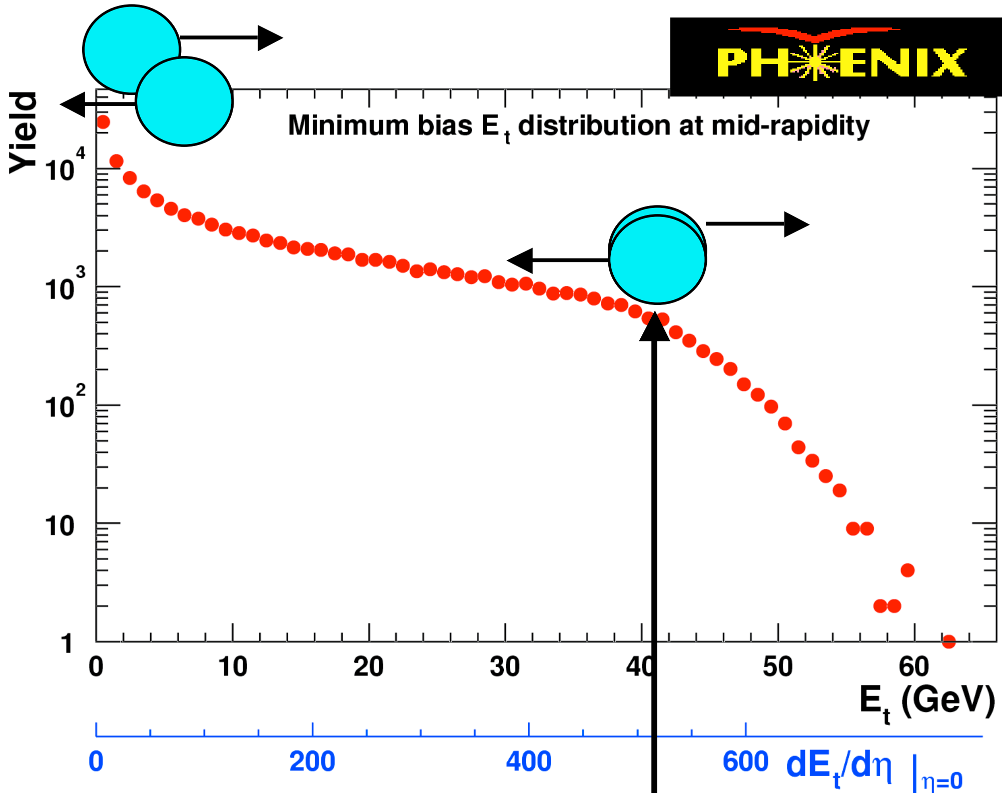
Colliding system expands:



Energy ⊥ to beam direction

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau_0}\left(2\frac{dE_T}{dy}\right)$$

per unit velocity || to beam



PRL87, 052301 (2001)

→ε ≥ *4.6 GeV/fm³* (130 GeV Au+Au)

***5.5 GeV/fm³* (200 GeV Au+Au)**

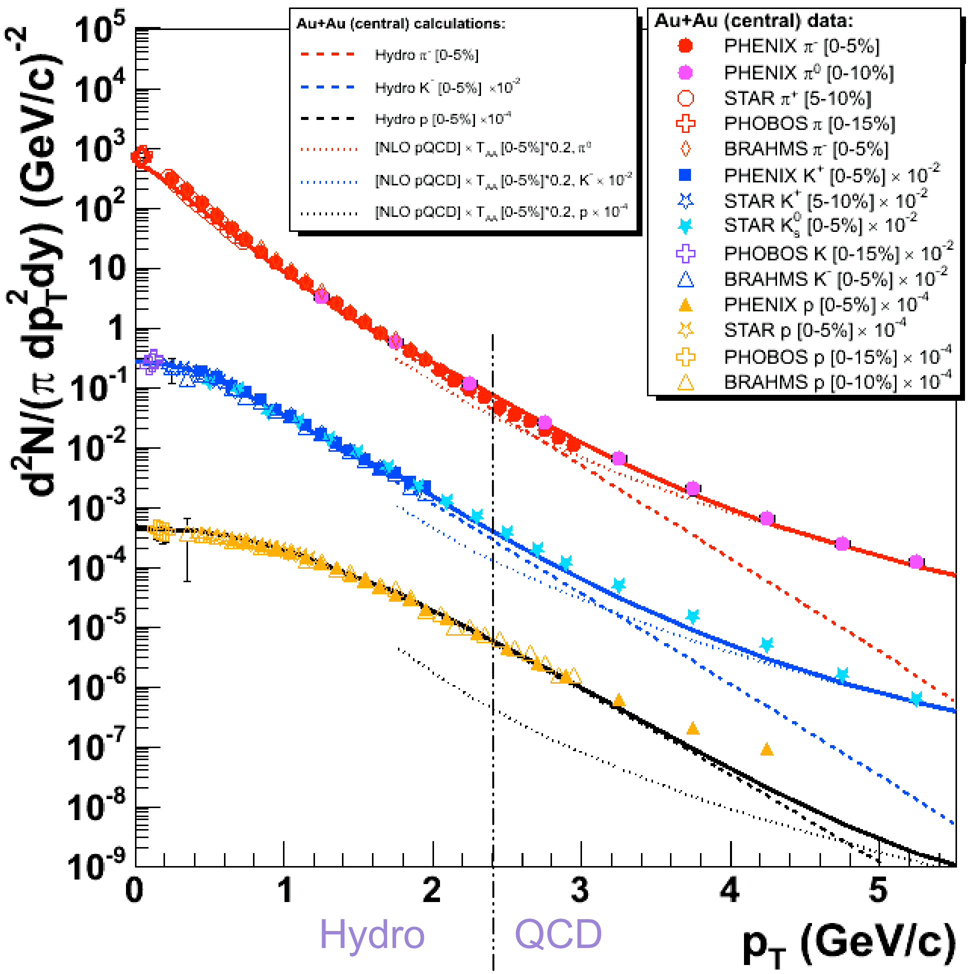
well above predicted transition!

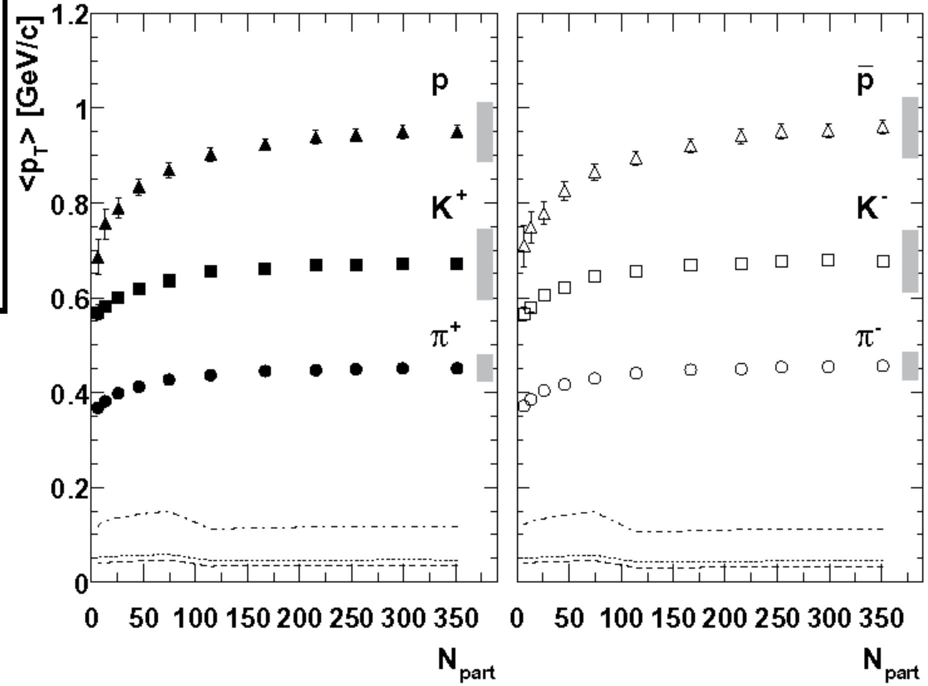
EMCal measures ε_{Bj}

Particle Production

Semi-Inclusive soft particle spectra

Au+Au central (b < 2.6 fm)

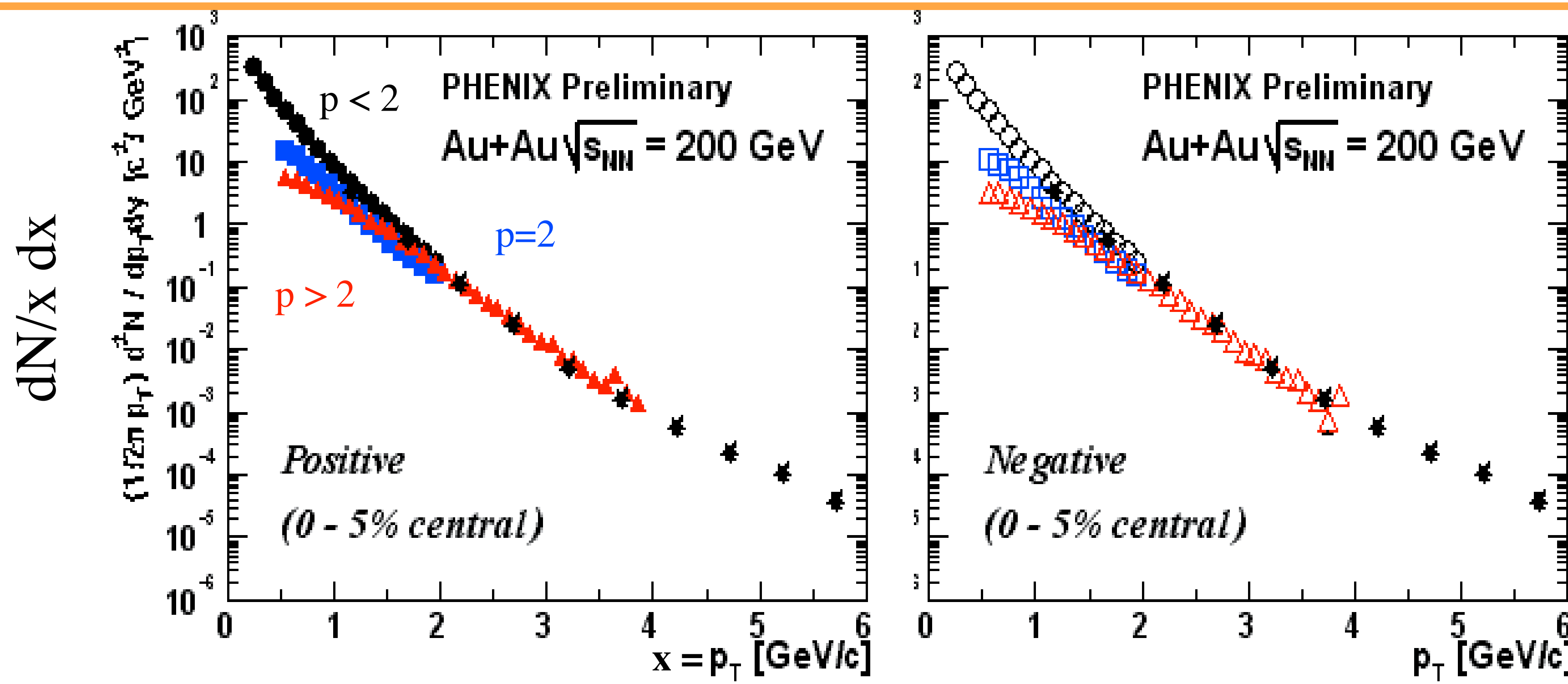




- $\langle pT \rangle$: $\pi < K < p$
- 25% (π) to 40% (p) increase from peripheral to central

D.d'Enterria &D. Peressounko
nucl-th/0503054

Inclusive p_T spectra are Gamma Distributions



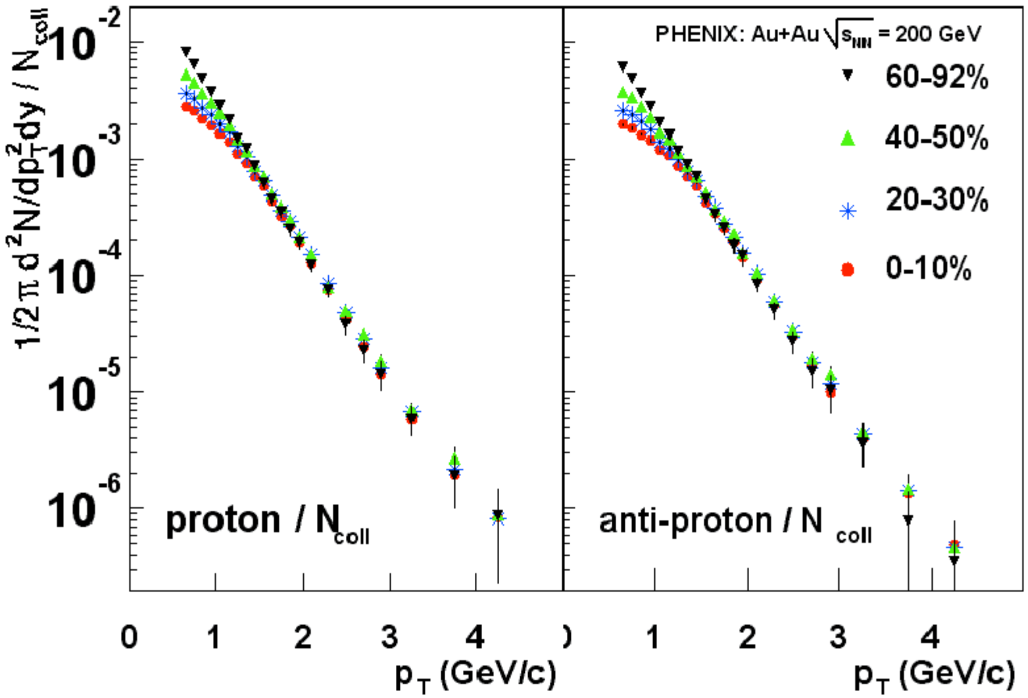
$$\frac{dN}{dx} = f_\Gamma(x,p,b) = \frac{b}{\Gamma(p)}(bx)^{p-1}e^{-bx}$$

$$\langle x \rangle = \frac{p}{b} \equiv \mu \qquad \sigma_x^2 = \frac{p}{b^2} \qquad \frac{\sigma^2}{\mu^2} = \frac{1}{p} \qquad \frac{\sigma^2}{\mu} = \frac{1}{b}$$

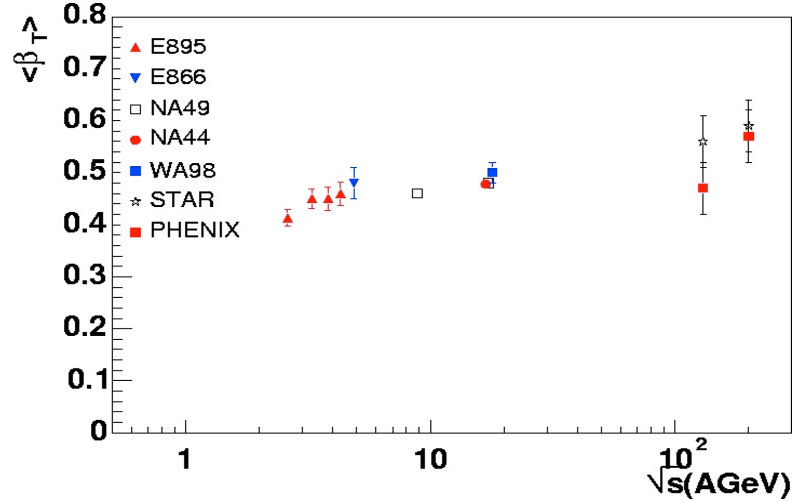
$$p \sim 2 \quad b \sim 6\ (\mathrm{GeV/c})^{-1}$$

Increase of $<p_T>$ with centrality--radial flow

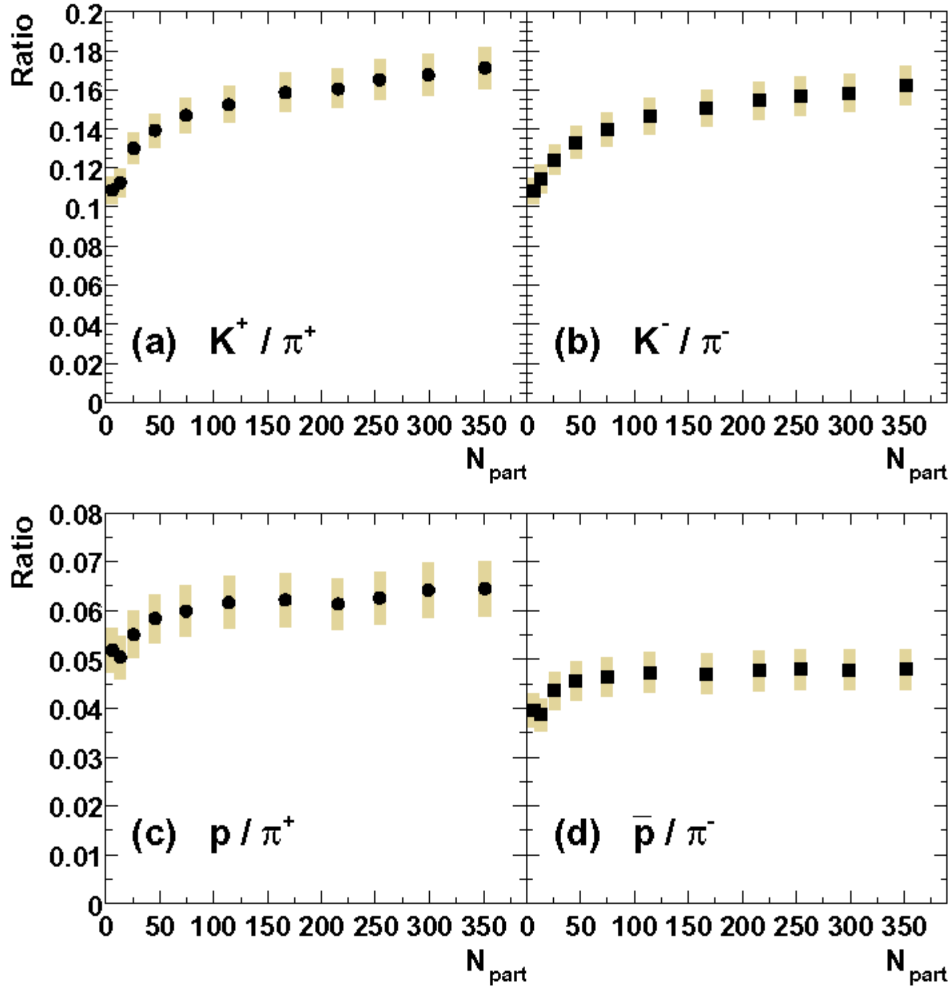
- $p_T \sim \gamma_T \beta_T m$ $$m_T = \sqrt{p_T^2 + m^2} = \gamma_T m$$



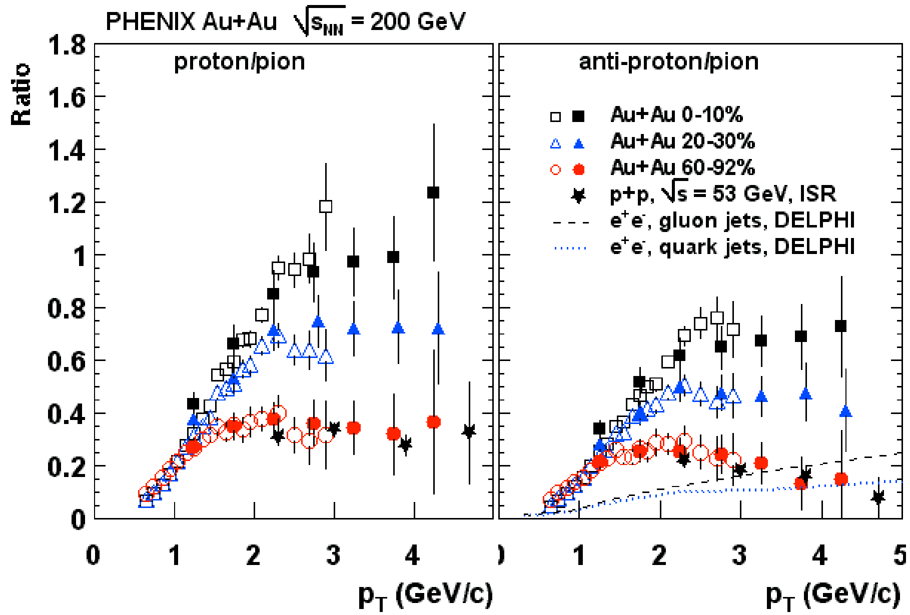
Strong radial collective flow built-up at freeze-out: $<\beta_T> \approx 0.6$



Particle ratios---inclusive and at high p_T



Au+Au $\sqrt{s_{NN}}$=200 GeV



dramatic with centrality vs p_T

inclusive vs centrality-nothing much

Low p_T (inclusive) ratios consistent with ``Thermal''--but so are pp and $e^+ e^-$

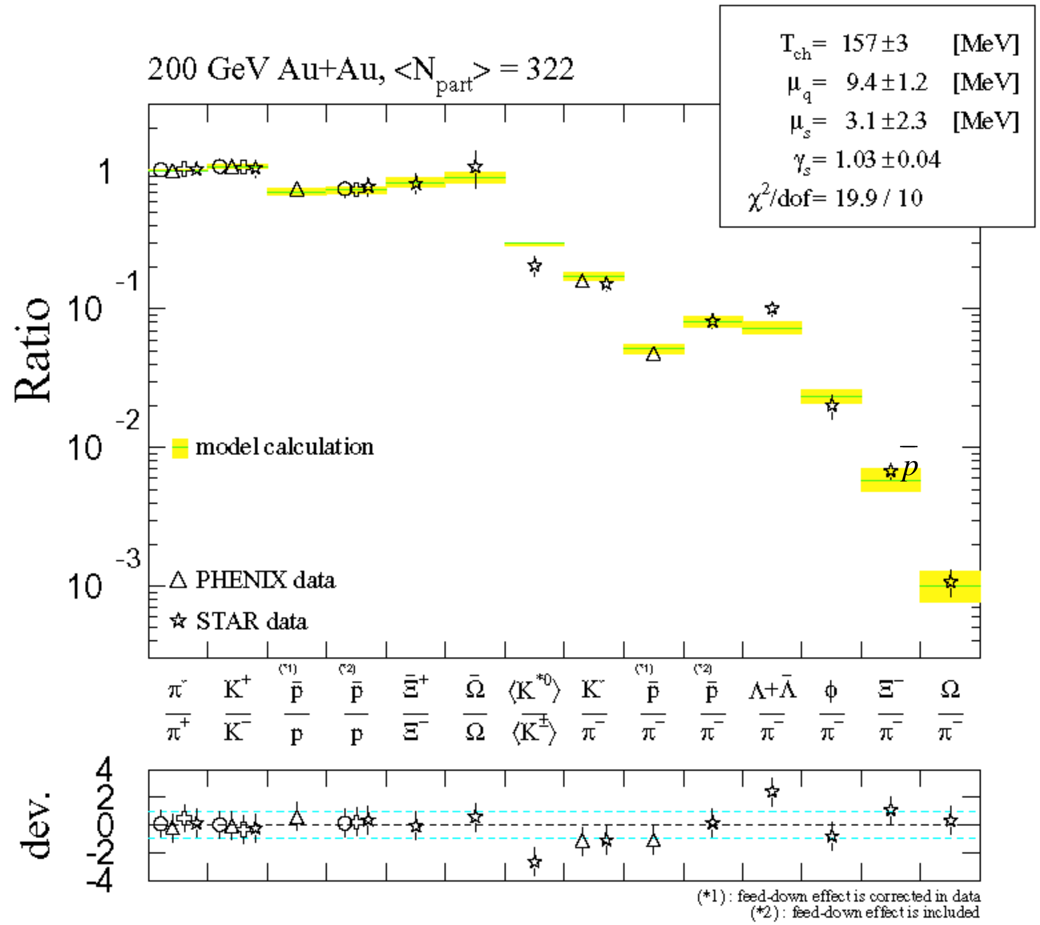


Fig. 10. Comparison of PHENIX (triangles), STAR (stars), BRAHMS (circles), and PHOBOS (crosses) particle ratios from central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity. The thermal model descriptions from Kaneta [78] are also shown as lines. See Kaneta [78] for the experimental references.

- Assume all distrib. described by one T and one μ:

$$dN \sim e^{-(E-\mu)/T}\, d^3p$$

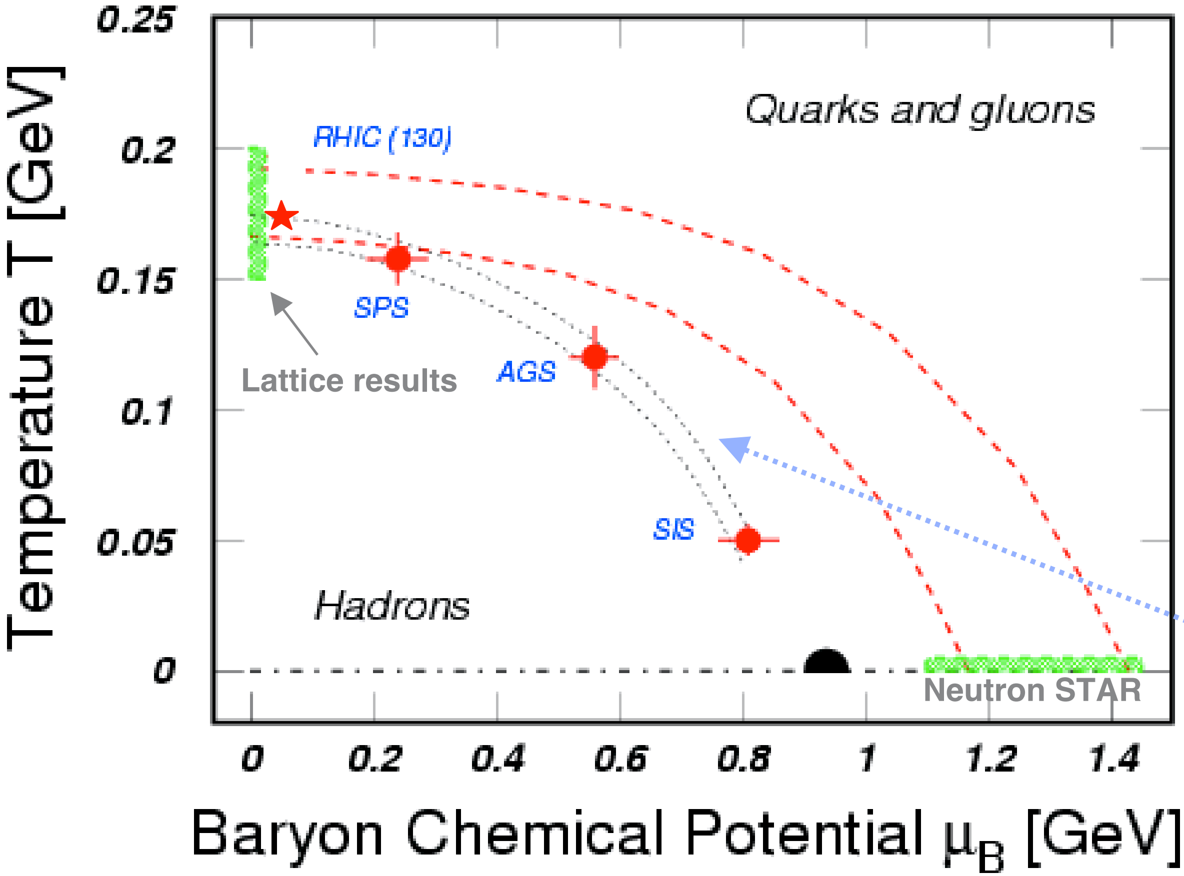
- 1 ratio (e.g. $\underline{p}$/p) determines μ/T

$$\underline{p}/p \sim e^{-(E+\mu)/T} / e^{-(E-\mu)/T} = e^{-2\mu/T}$$

- 2nd ratio (e.g. K/pi) provides T,μ.

- Then predict all other hadronic yields and ratios
- n.b strangeness not suppressed γ_s=1

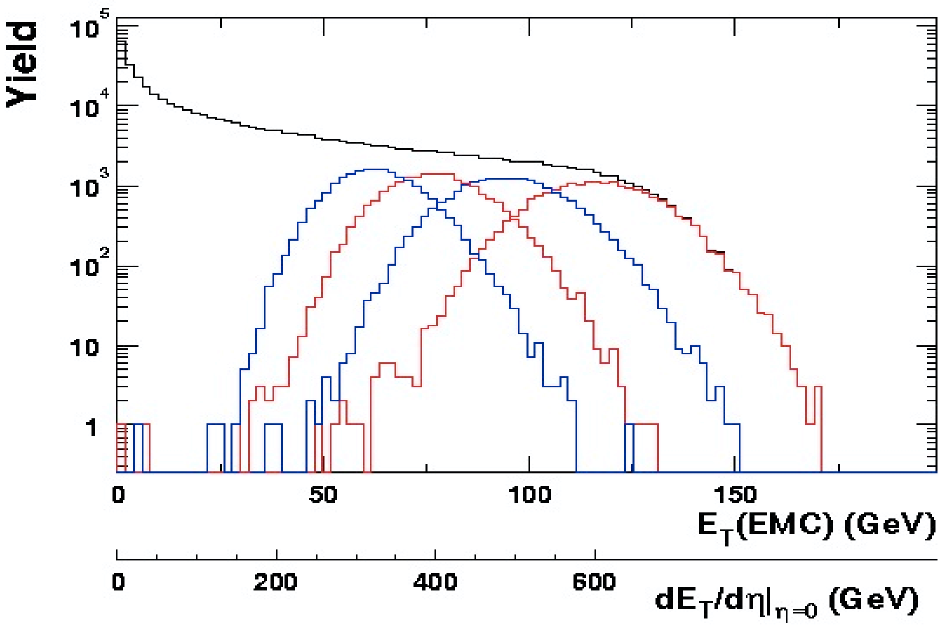
Phase Diagram from Thermal Fit of particle ratios---``chemical''

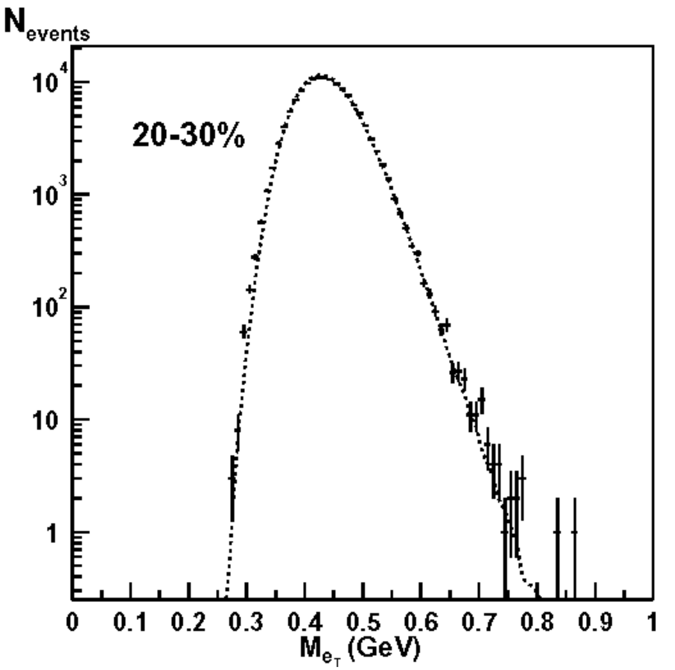


- **Final-state analysis suggests RHIC reaches the phase boundary**
- **Hadron resonance ideal gas** **(M. Kaneta and N. Xu, nucl-ex/0104021 & QM02)**
  - **T_{CH} = 175 ± 10 MeV**
  - **μ_B = 40 ± 10 MeV**
- **<E>/N ~ 1 GeV** **(J. Cleymans and K. Redlich, Phys.Rev.C, 60, 054908, 1999)**

- Where is the QGP critical point?

Are there fluctuations beyond random?





- Event-by-event average p_T (M_{pT}) is closely related to E_T

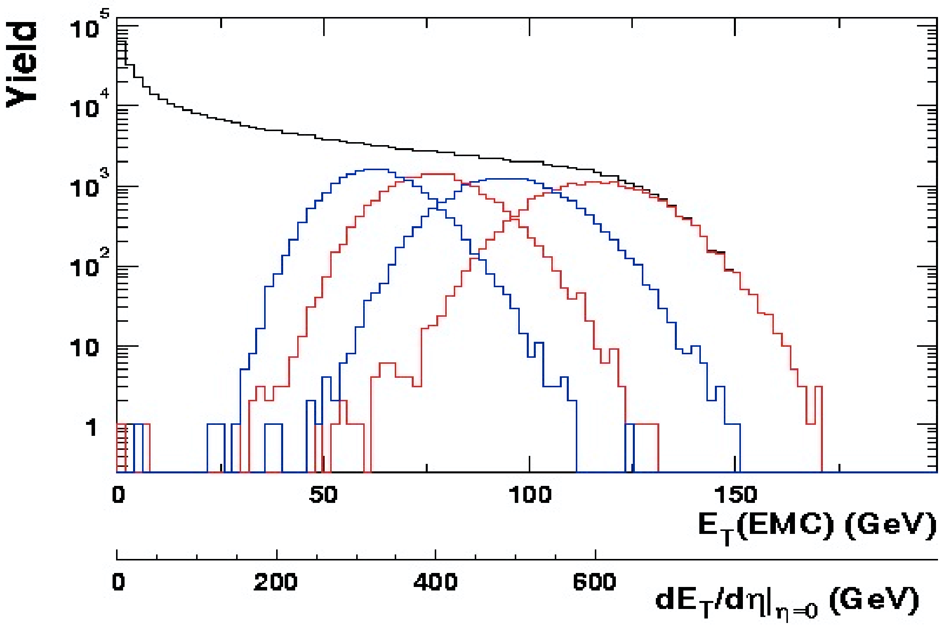
$$M_{p_T} = \overline{p_T}_{(n)} = \frac{1}{n}\sum_{i=1}^{n} p_{T_i} = \frac{1}{n}E_{Tc}$$

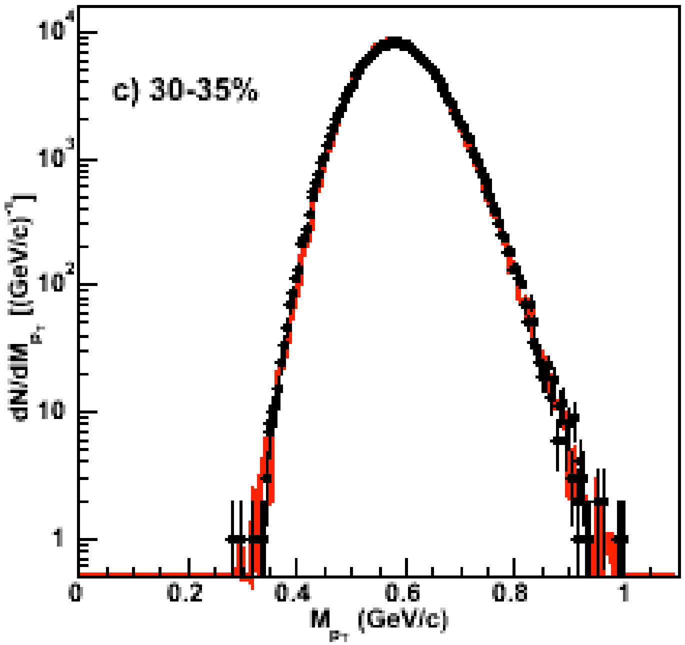
- compare Data to Mixed events for random.
- deviation expressed as:

$Fp_T = \sigma_{MpTdata} / \sigma_{MpTmixed} - 1 \;\sim$ few %

- due to jets see PRL **93**, 092301(04)

Are there fluctuations beyond random?





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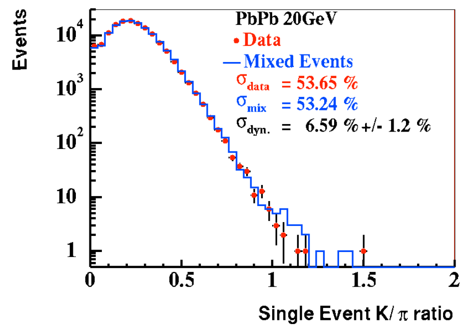
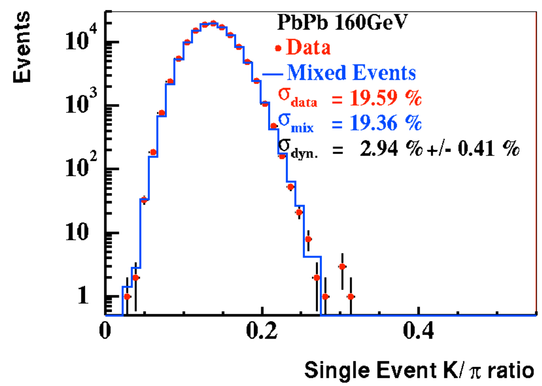
What e-by-e tells you that you don't learn from the inclusive average

- e-by-e averages separate classes of events with different average properties, for instance 17% of events could be all kaons, and 83% all pions---see C. Roland QM2004, e-by-e K/π consistent with random.





- A nice example I like is by R. Korus, et al, PRC **64**, 054908 (2004): The temperature T~1/b varies event by event with ⟨T⟩ and σ_T.

$$\frac{\sigma^2_{M_{p_T}}}{\mu^2} - \frac{1}{n}\frac{\sigma^2_{p_T}}{\mu^2} = \left(1-\frac{1}{n}\right)\frac{\sigma^2_T}{\langle T\rangle^2} \quad = \Sigma^2_{p_T} \qquad \text{CERES}$$

Assuming all fluctuations are from $\sigma_T/\langle T\rangle$
Very small and relatively constant with $\sqrt{s_{NN}}$

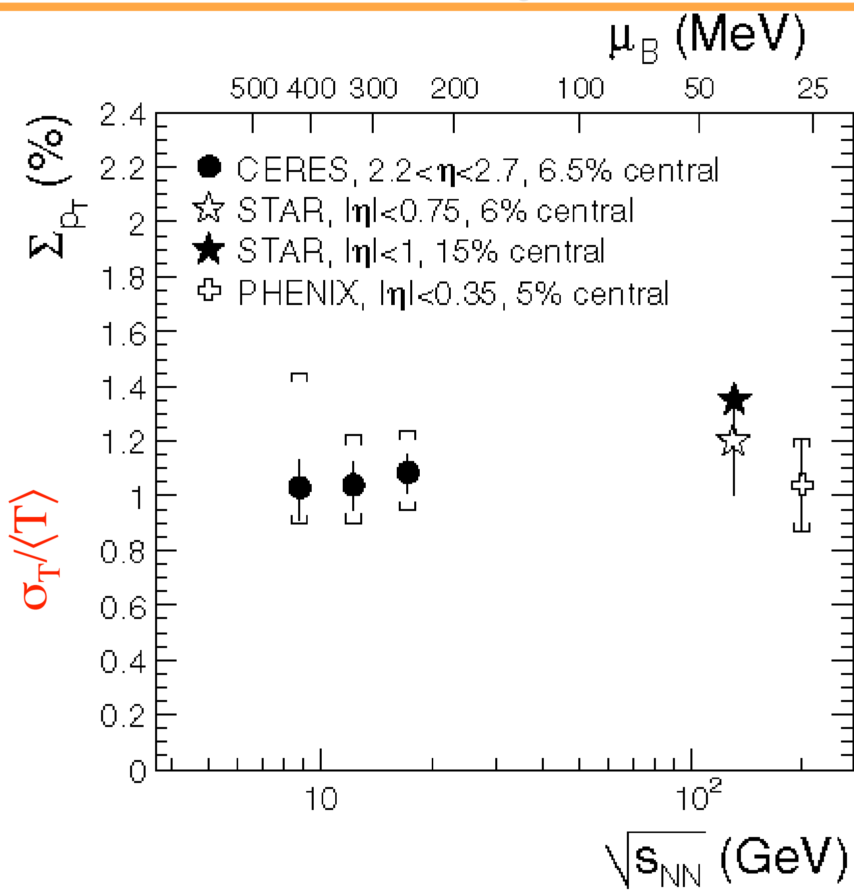


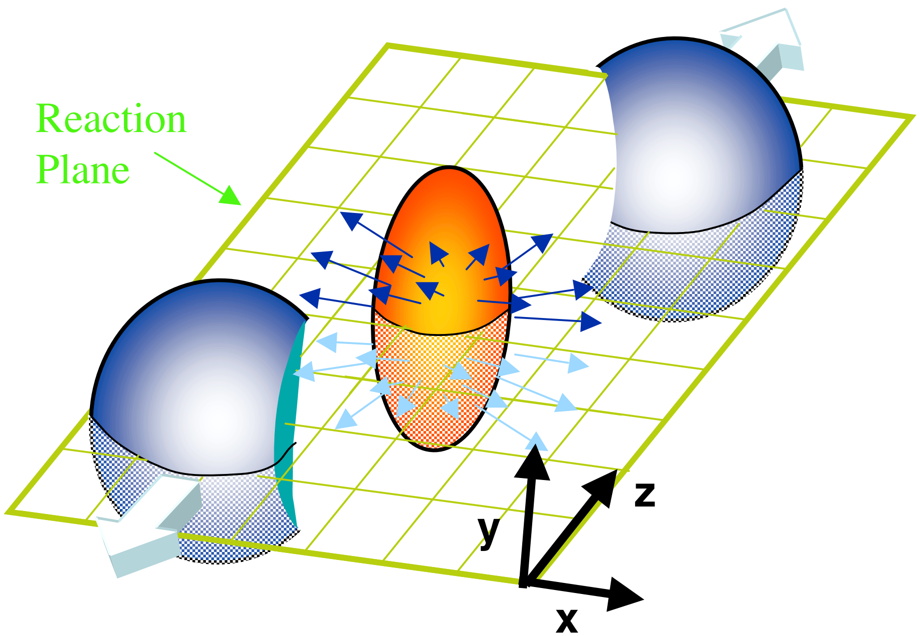
Figure 2. Σ_{p_T} as a function of $\sqrt{s_{NN}}$ in central events.

$$\Sigma^2_{p_T} = \frac{\sigma^2_{p_T,dyn}}{\mu^2} = \frac{\sigma^2_{M_{p_T}}}{\mu^2} - \frac{1}{\langle n\rangle}\frac{\sigma^2_{p_T}}{\mu^2} = \frac{\sigma^2_T}{\langle T\rangle^2}$$

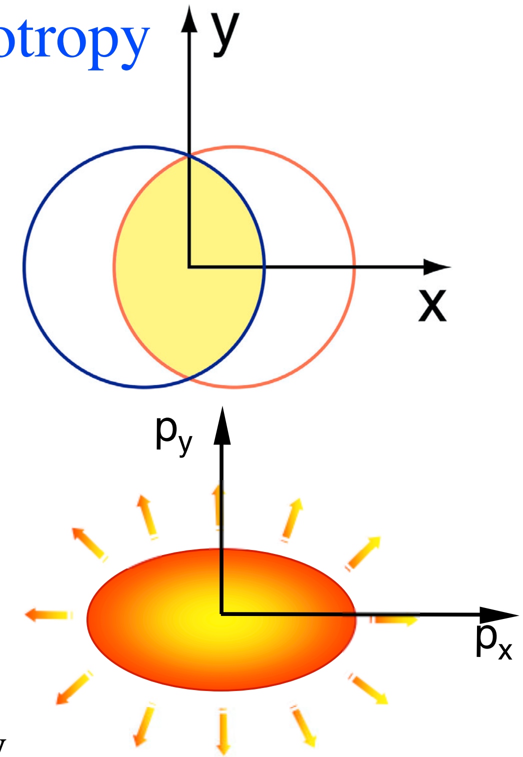
CERES tabulation H.Sako, et al, JPG 30, S1371 (04)

Where is the critical point?

Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions



- spatial anisotropy⇒ momentum anisotropy

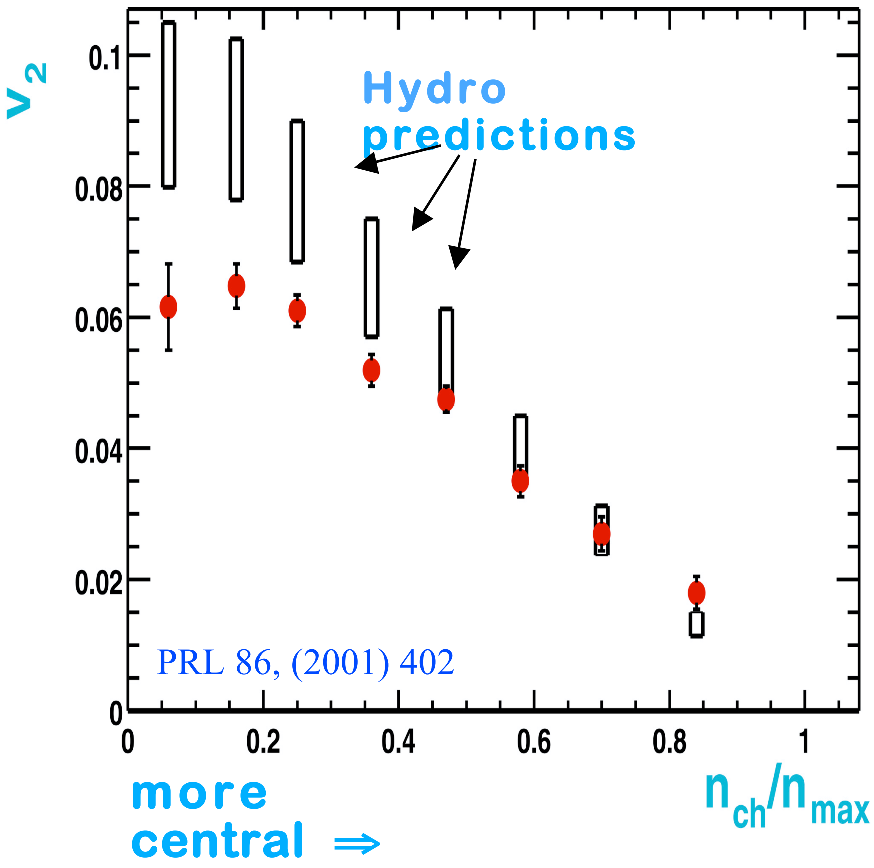


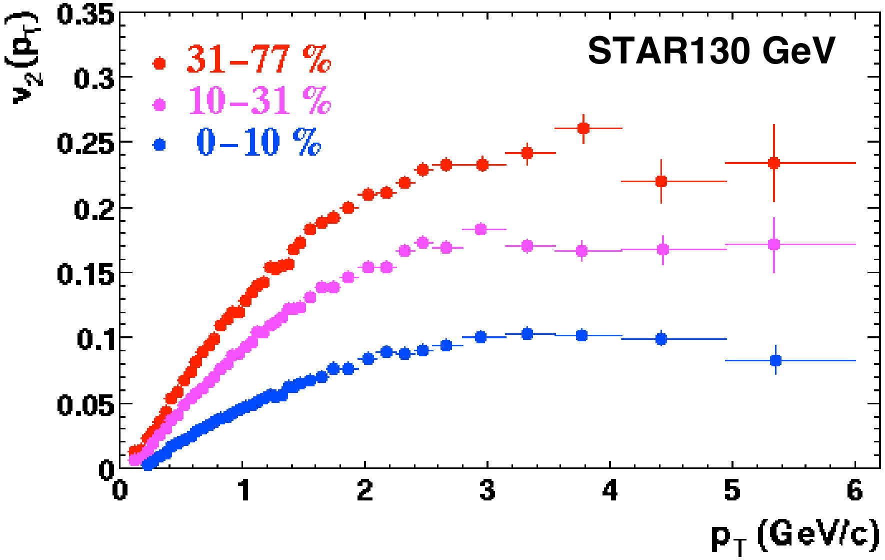
- Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane
  - ✓ v_2 is the 2nd harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane

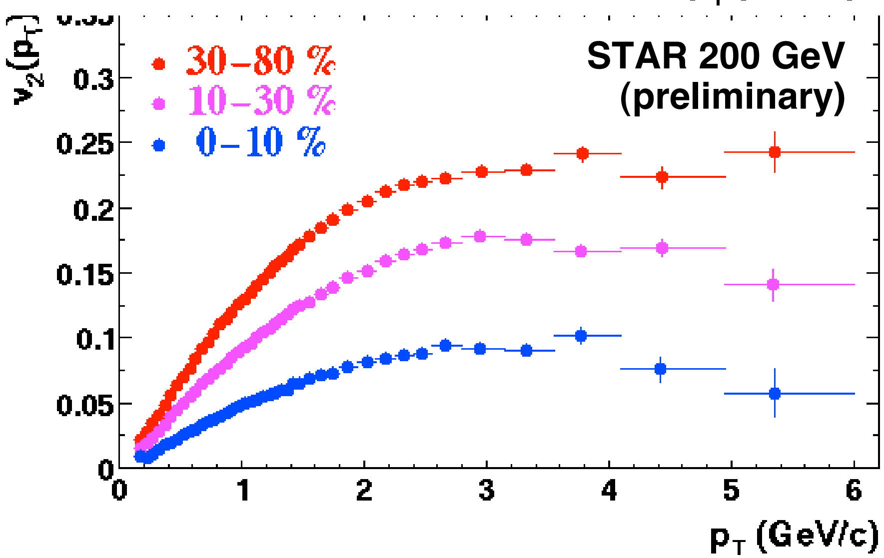
$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \operatorname{atan}\frac{p_y}{p_x}$$

Centrality and p_T dependence of v_2

unidentified charged hadrons

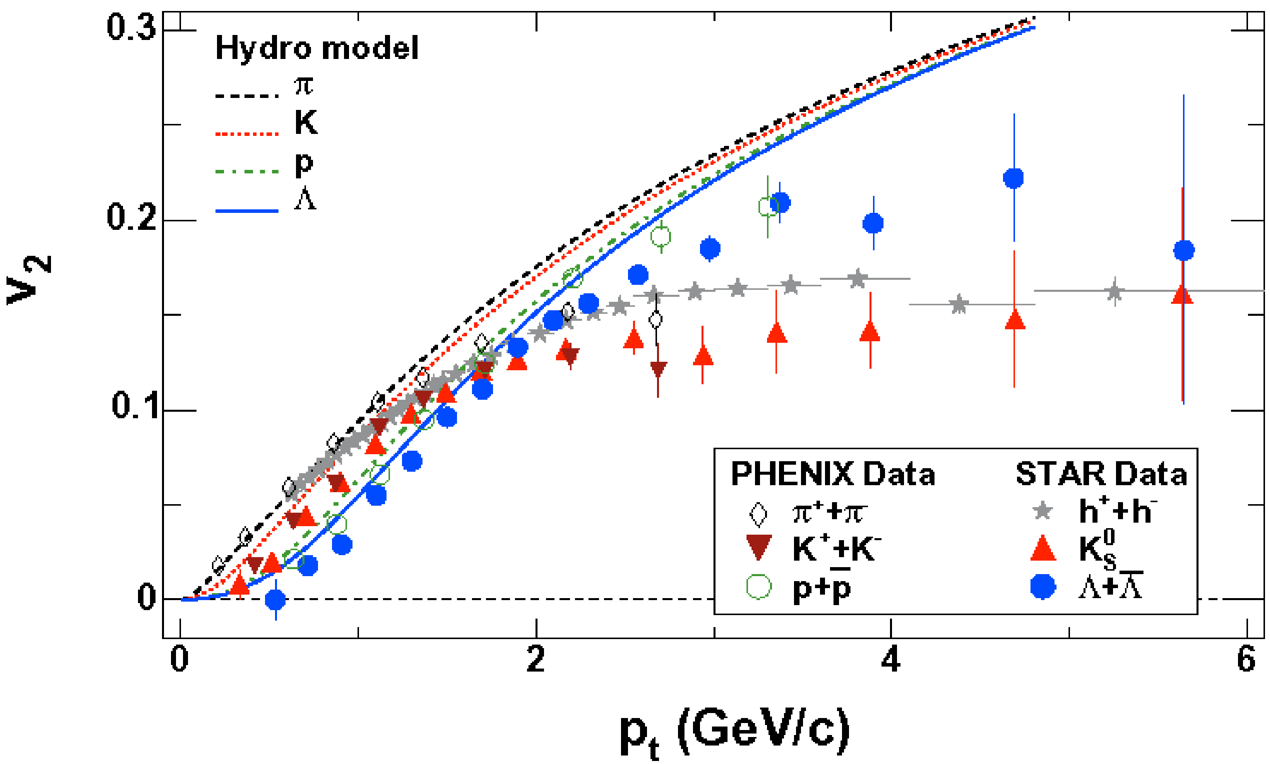


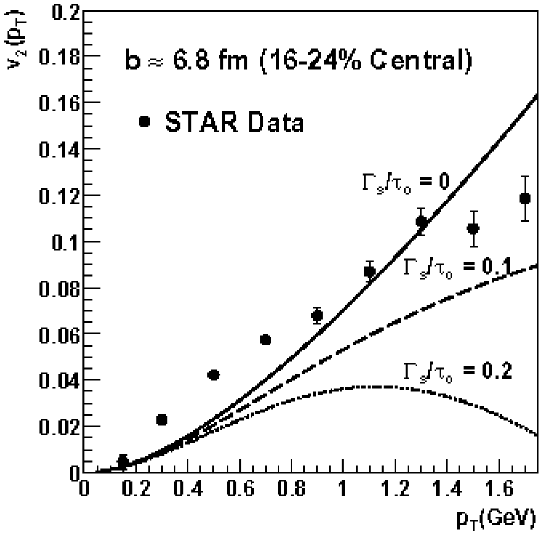




- follows eccentricity of almond
- saturates for pT >2 GeV/c

Detailed comparison to hydrodynamics with identified particles--The perfect fluid (?)



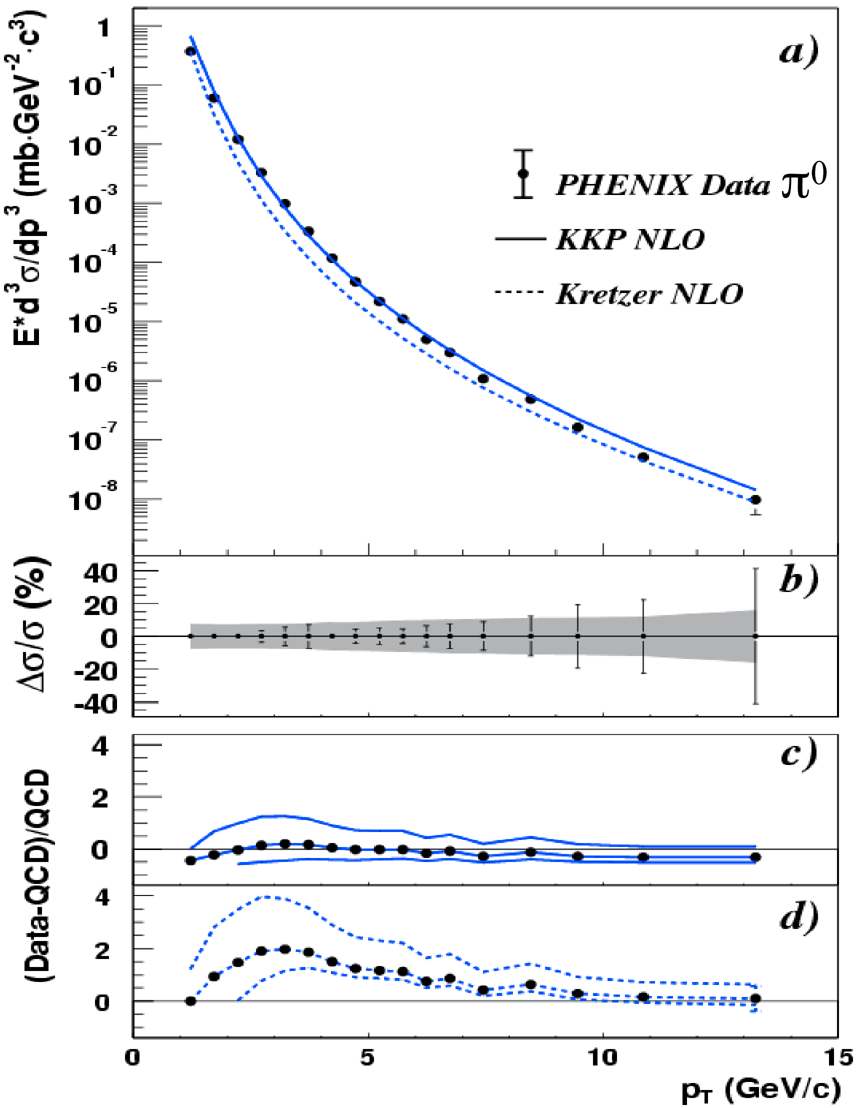


D.Teaney, PRC**68**, 034913 (2003)

STAR-PRC-nucl-ex/0409033

Hard-Scattering: Jet (π^0) Suppression

RHIC pp spectra √s=200 GeV nicely illustrate hard scattering phenomenology



- Good agreement with NLO pQCD
  - ✓ this is no surprise for `old timers' (like me) since single particle inclusive spectra were what proved QCD in the late 1970's before jets.
- **Reference for A+A and p+A spectra**
  - ✓ π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

PHENIX (p+p) PRL 91, 241803 (2003)

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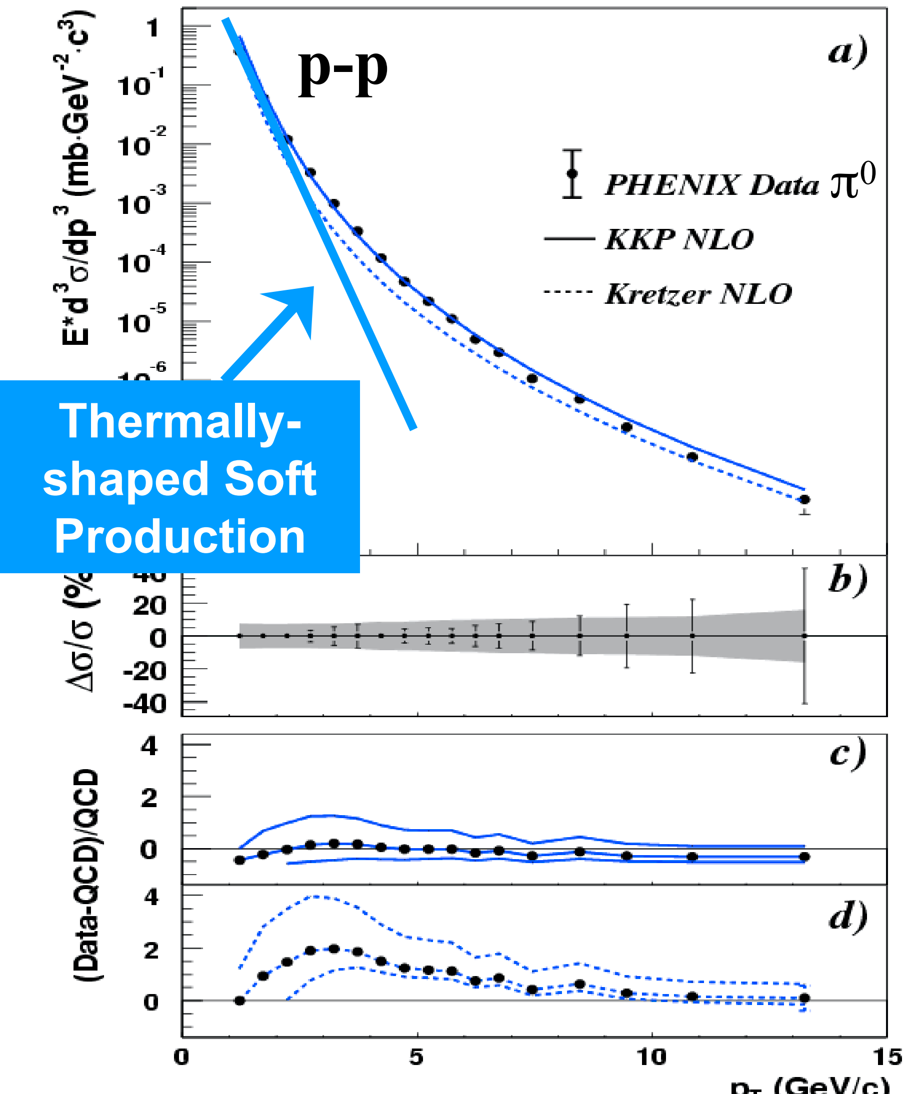

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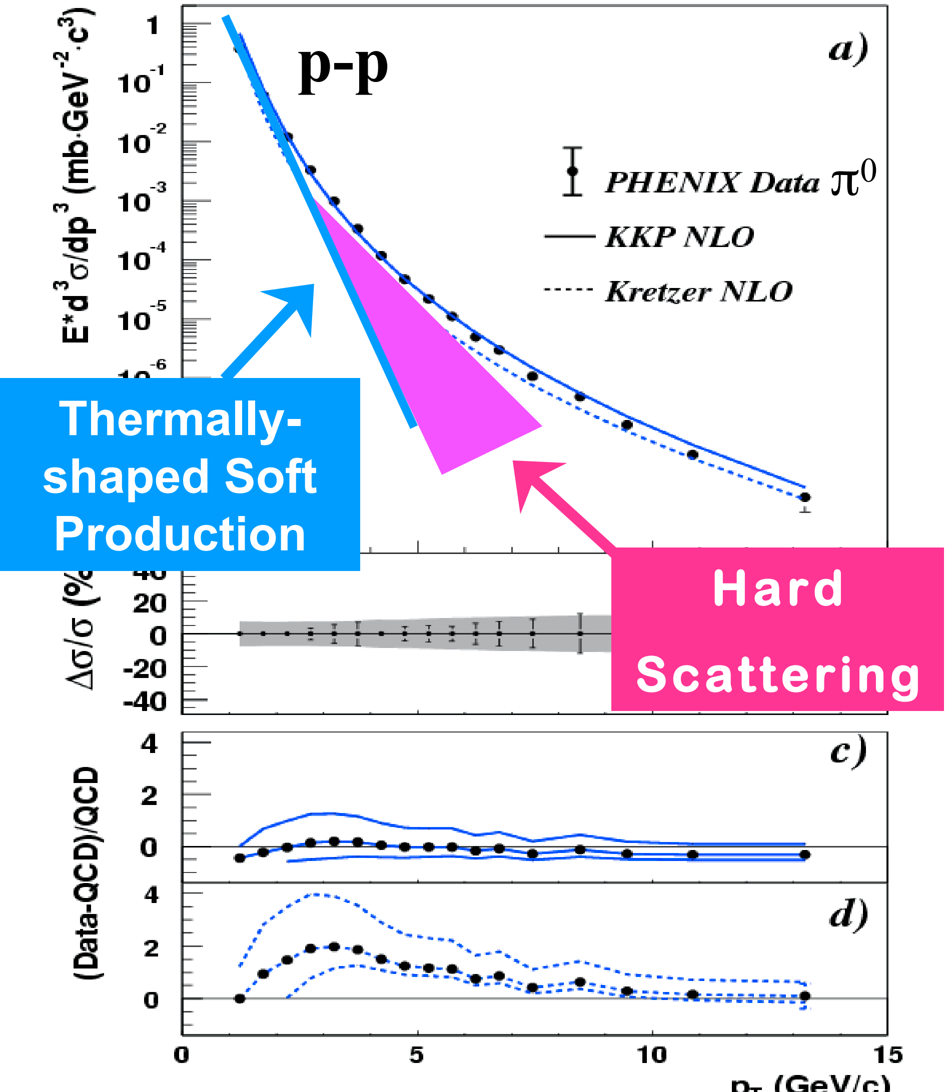
  - ✓ π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

PHENIX (p+p) PRL 91, 241803 (2003)

RHIC pp spectra √s=200 GeV nicely illustrate hard scattering phenomenology



- Good agreement with NLO pQCD
  - ✓ this is no surprise for `old timers' (like me) since single particle inclusive spectra were what proved QCD in the late 1970's before jets.
- **Reference for A+A and p+A spectra**
  - ✓ π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

PHENIX (p+p) PRL 91, 241803 (2003)

μ-A DIS at AGS (1973)--Hard-Scattering is pointlike

E. Gabathuler, Total cross-section

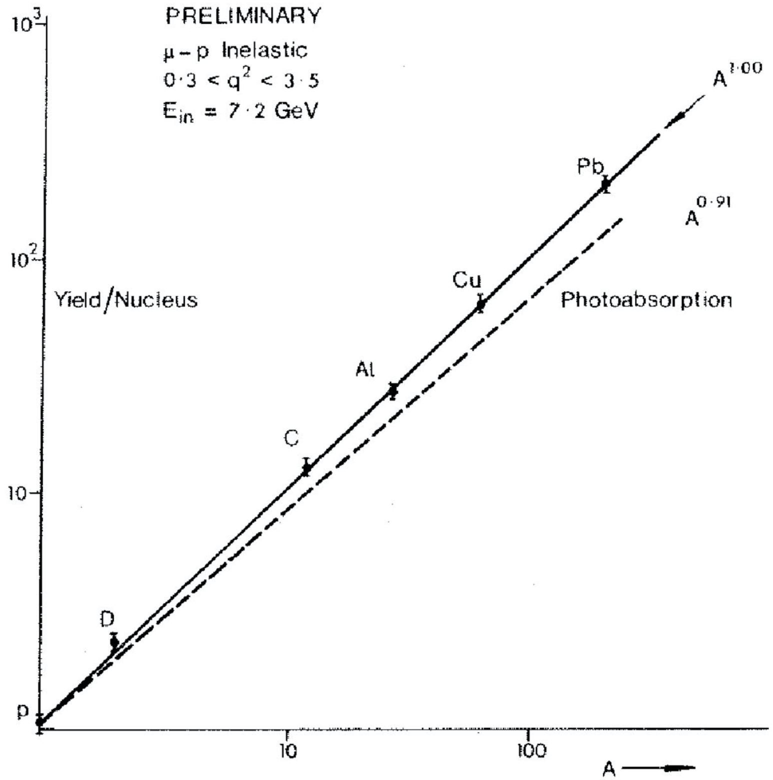
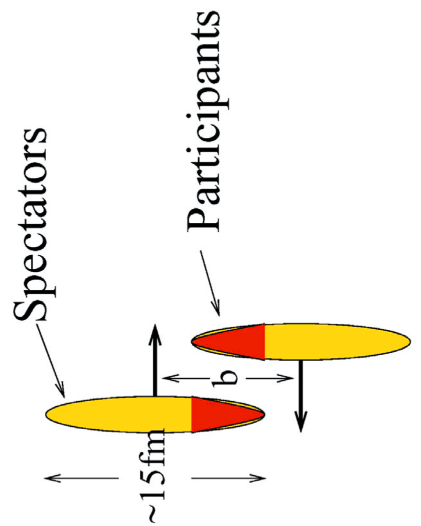


Fig. 14. The *A* dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

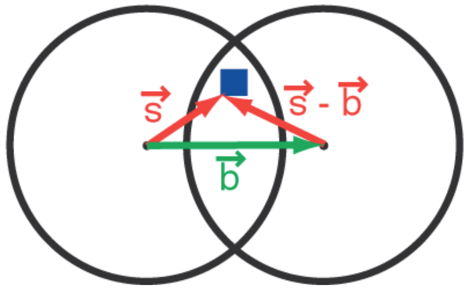
AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

- ♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.
- ♡ Photoproduction is shadowed—$A^{0.91}$

High p_T in A+B collisions---T_{AB} Scaling



looking down



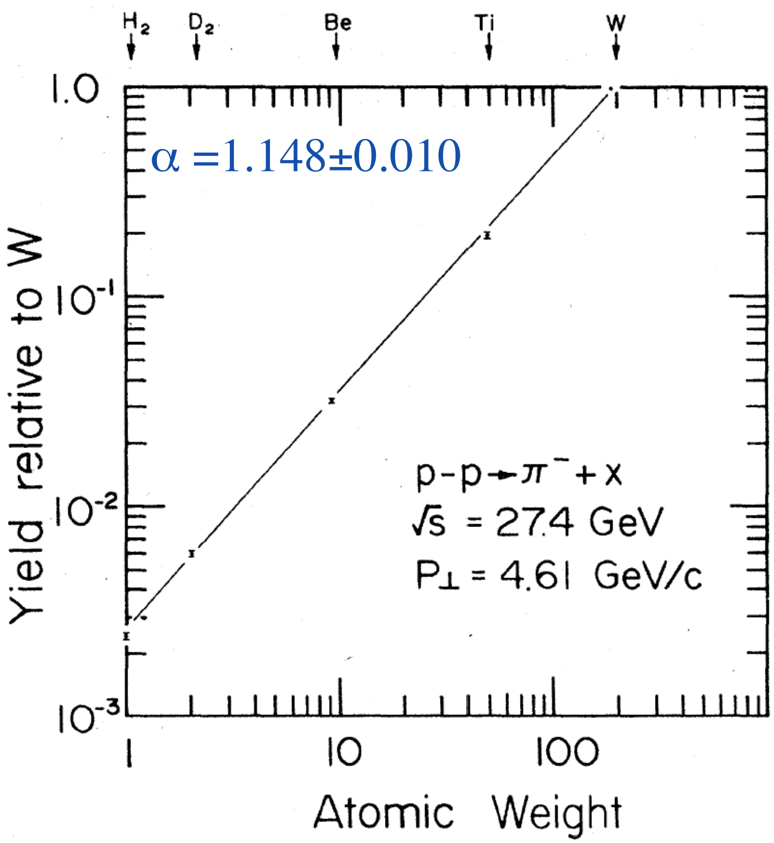
view along beam axis

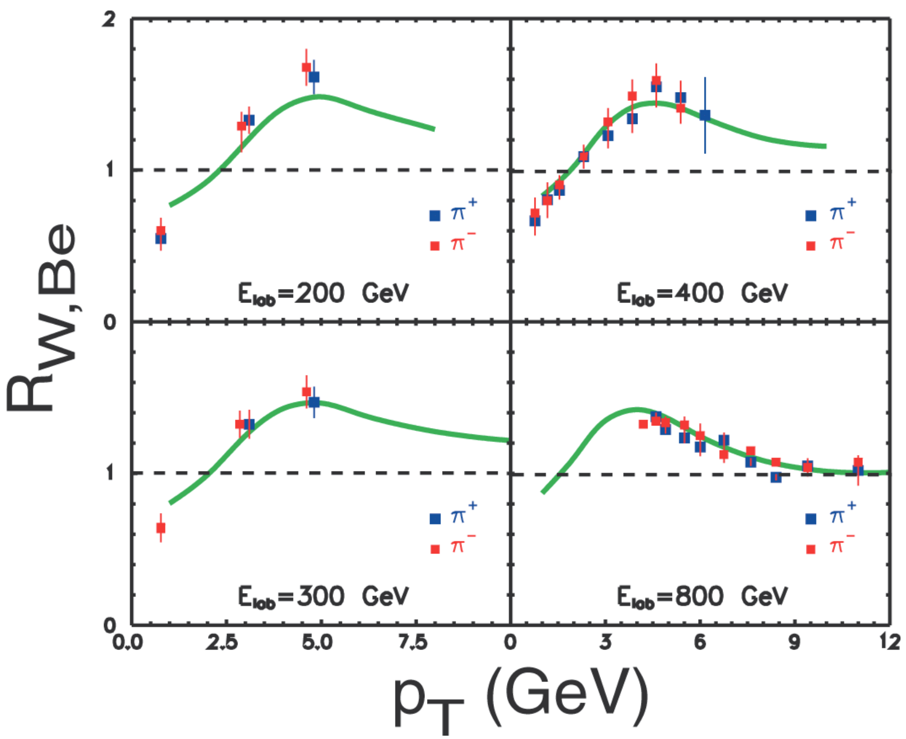
- For point-like processes, the cross section in p+A or A+B collisions compared to p-p is simply proportional to the relative number of possible pointlike encounters
  - ✓ A for p+A, AB for A+B for the total rate
  - ✓ T_{AB} the overlap integral of the nuclear profile functions, as a function of impact parameter b

What really Happens for p+A: $R_A > 1$!

The anomalous nuclear enhancement a.k.a. the Cronin effect--
due to multiple scattering of initial nucleons (or constituents)

- Known since 1975 that yields increase as A^{α}, $\alpha > 1$



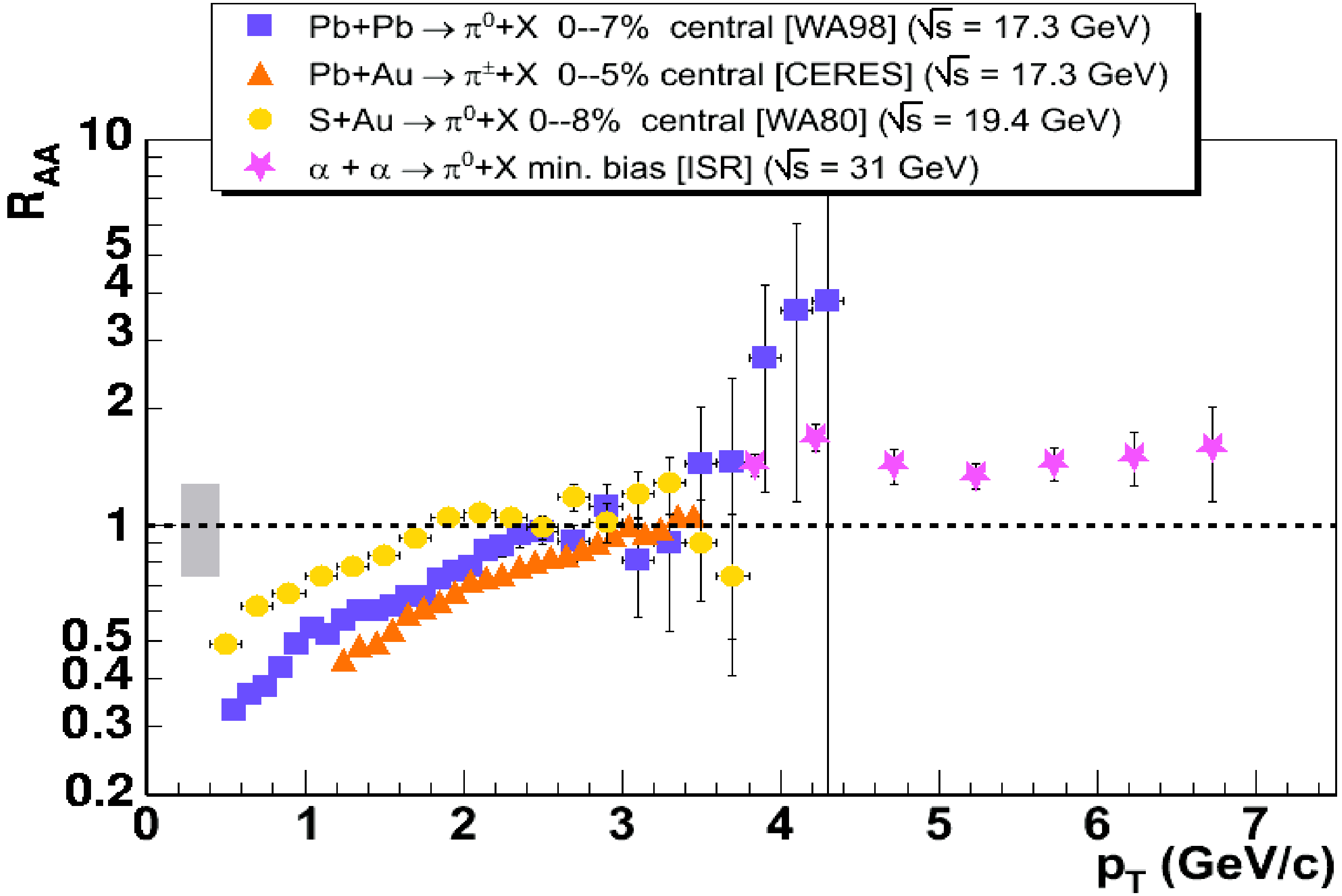


- J.W. Cronin et al., Phys. Rev. **D11**, 3105 (1975)
- D. Antreasyan et al., Phys. Rev. **D19**, 764 (1979)

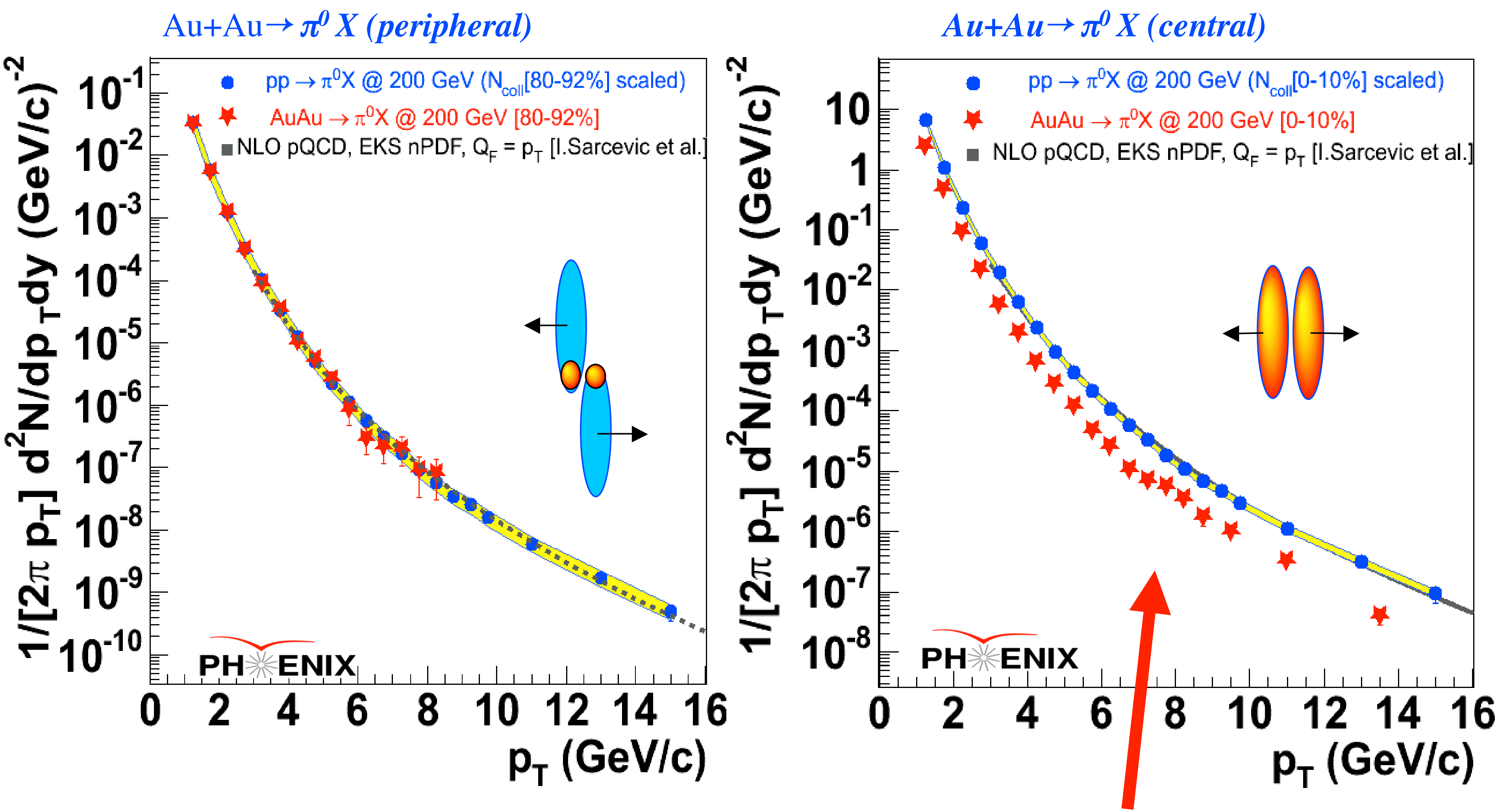
Same for A+A at $\sqrt{s_{NN}}$= 17, 31 GeV

Nuclear Modification Factor:

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



For Au+Au at RHIC--strong suppression !



Peripheral data agree well with p+p (data & pQCD) scaled by T_{AB} (N_{coll}-)

Strong suppression in central Au+Au collisions

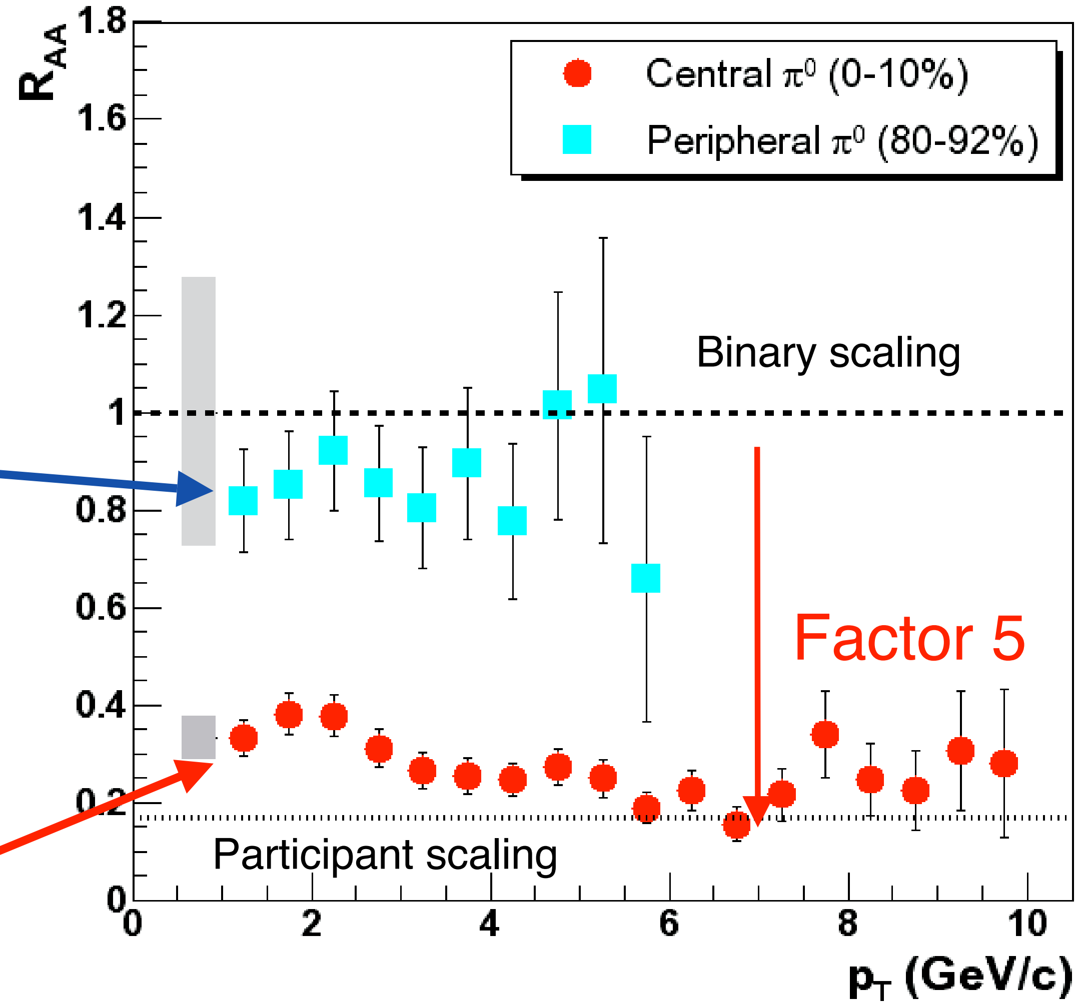
R_{AA} (π^0) AuAu:pp 200GeV

High p_T Suppression flat from 3 to 10 GeV/c !

$$R_{AA} = \frac{\mathrm{Yield}_{AuAu}(p_T)}{\langle T_{AB}\rangle_{AuAu} \times \sigma_{pp}(p_T)}$$

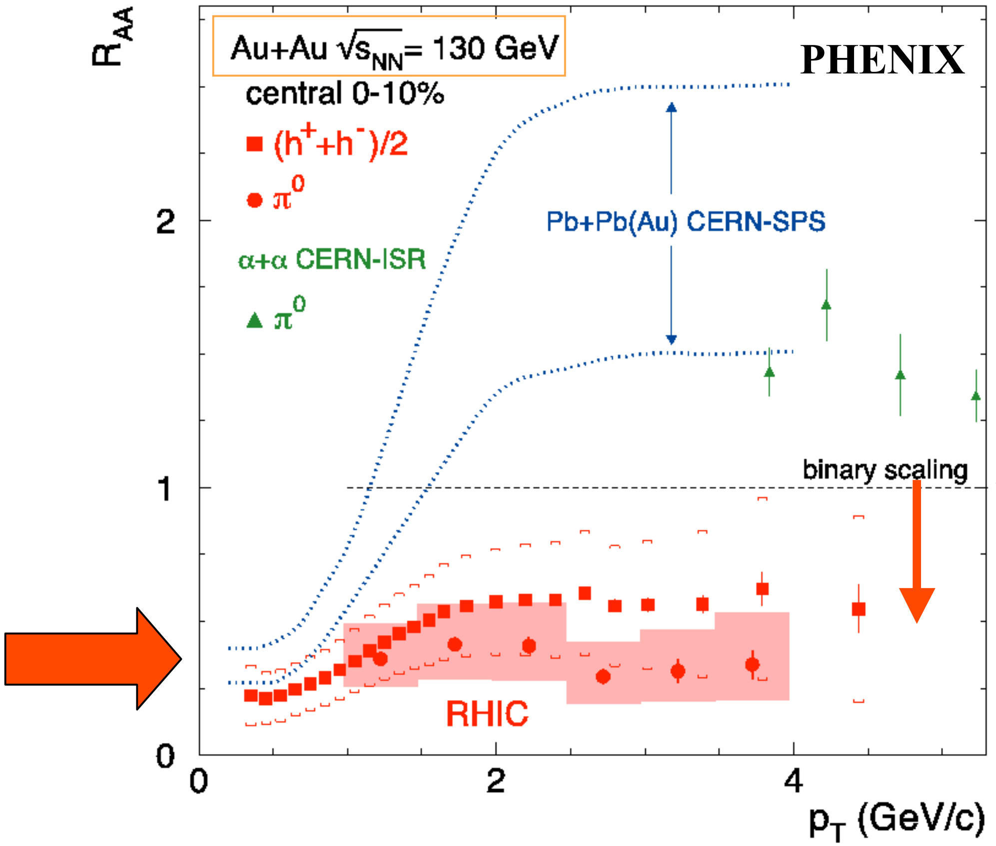
Peripheral AuAu - consistent with N_{coll} scaling (large systematic error)

Large suppression in central AuAu - close to participant scaling at high P_T



PRL 91, 072301 (2003)

Run-1: RHIC Headline News … January 2002
THE major discovery at RHIC (so far)



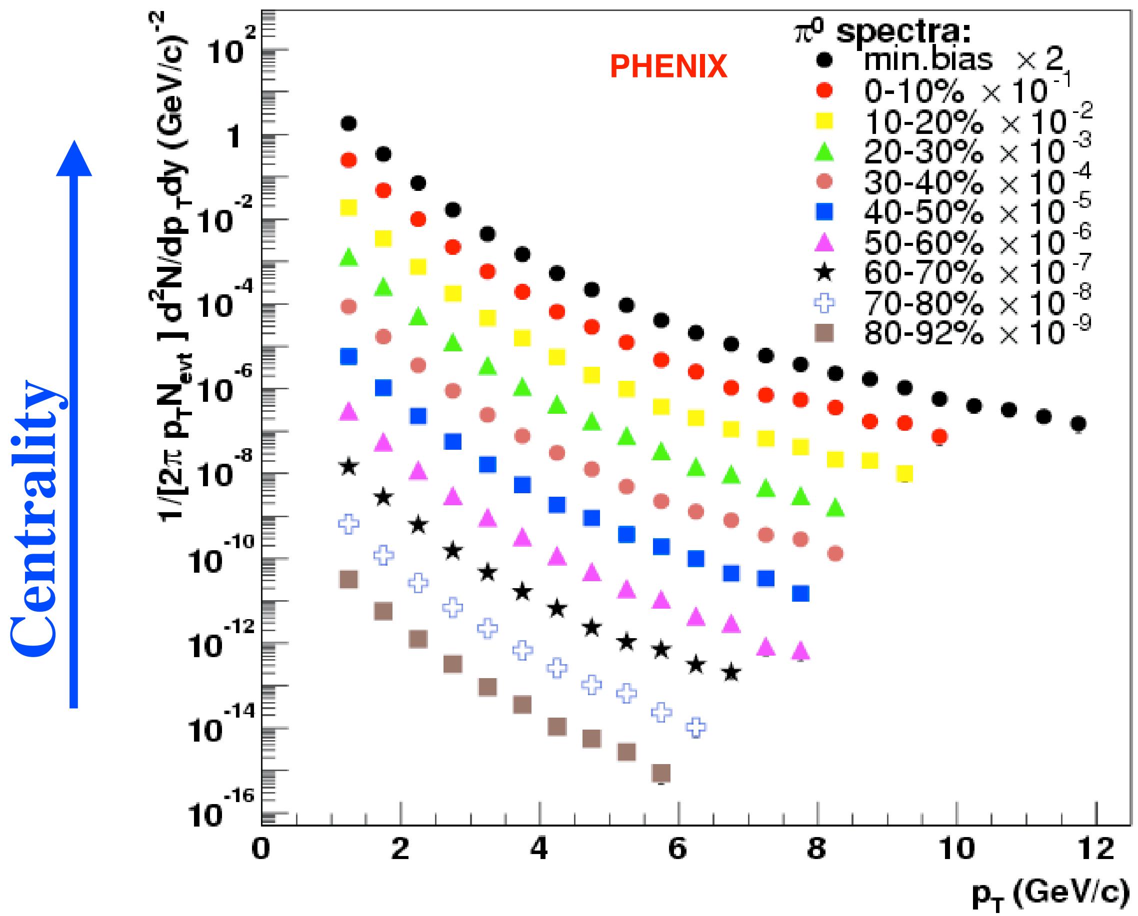
PHENIX PRL 88, 022301 (2002)

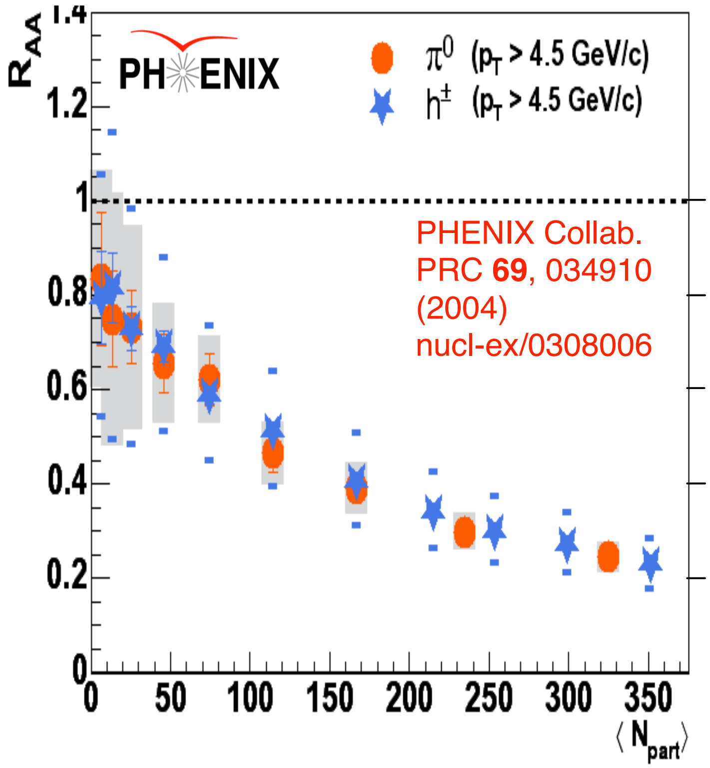
First observation of *large* suppression of high p_T hadron yields

"Jet Quenching"? == Quark Gluon Plasma?

RHIC Run 2 $\sqrt{s}$=200 GeV: Comprehensive π^0 data vs centrality in Au+Au + π^0 reference in p-p

Au-Au nucl-ex/0304022 Phys. Rev. Letters **91**, 072301 (2003)

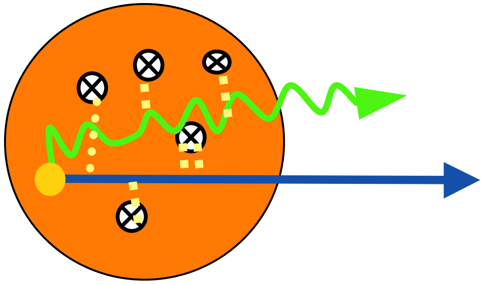




Suppression: Final State Effect?

- **Hadronic absorption of fragments:**
  - ✓ Gallmeister, et al. PRC67,044905(2003)
  - ✓ Fragments formed inside hadronic medium
- **Parton recombination (up to moderate p_T)**
  - ✓ Fries, Muller, Nonaka, Bass nucl-th/0301078
  - ✓ Lin & Ko, PRL89,202302(2002)
- **Energy loss of partons in dense matter**
  - ✓ Gyulassy, Wang, Vitev, Baier, Wiedemann…

  See nucl-th/0302077 for a review.



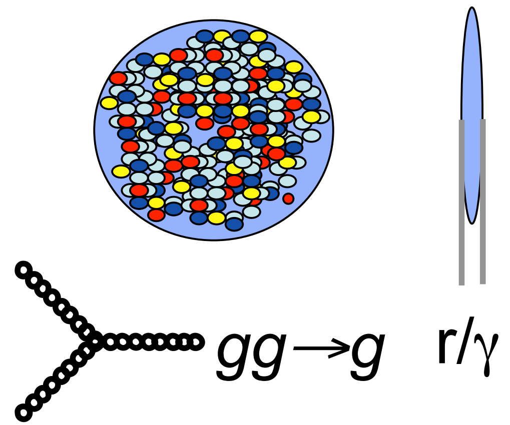
Alternative: Initial Effects

- **Gluon Saturation**
  - ✓ **(color glass condensate: CGC)**

Wave function of low x gluons overlap; the self-coupling gluons fuse, saturating the density of gluons in the initial state.

(gets N_{ch} right!)

hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi



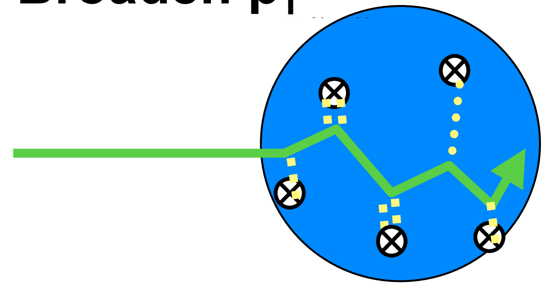
D.Kharzeev et al., PLB 561 (2003) 93

- **Multiple elastic scatterings**

(Cronin effect)

Wang, Kopeliovich, Levai, Accardi

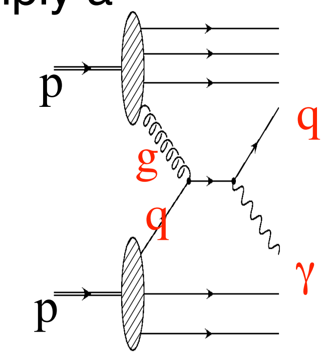
Broaden p_T

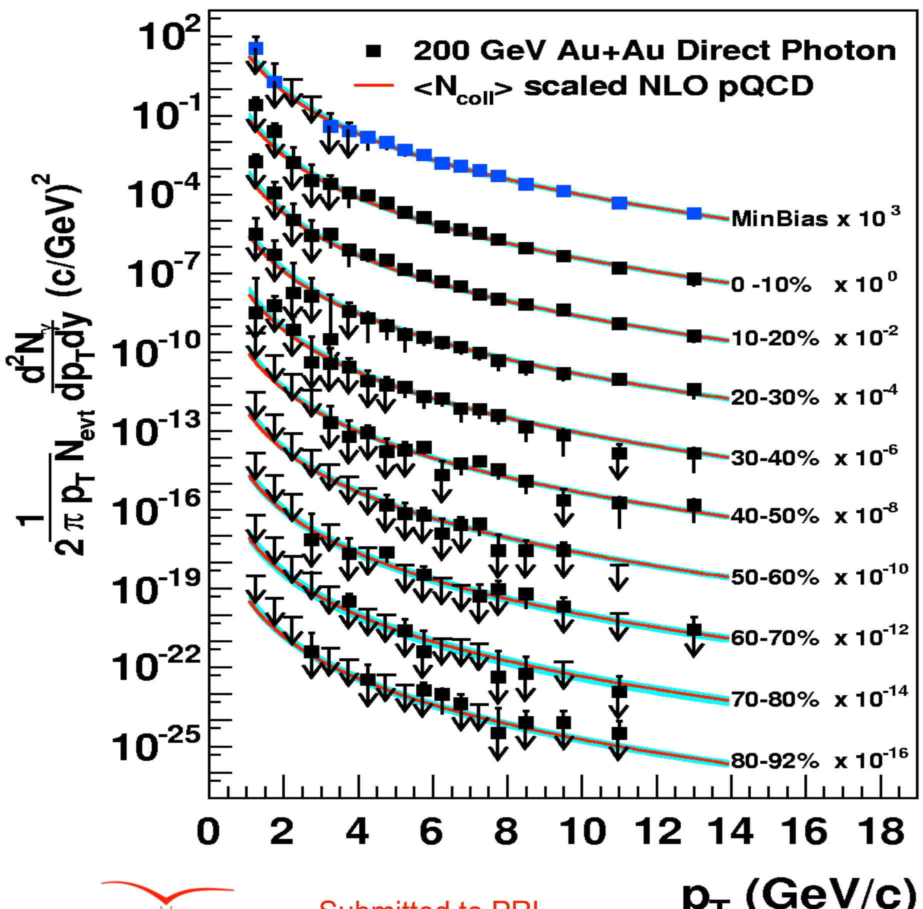


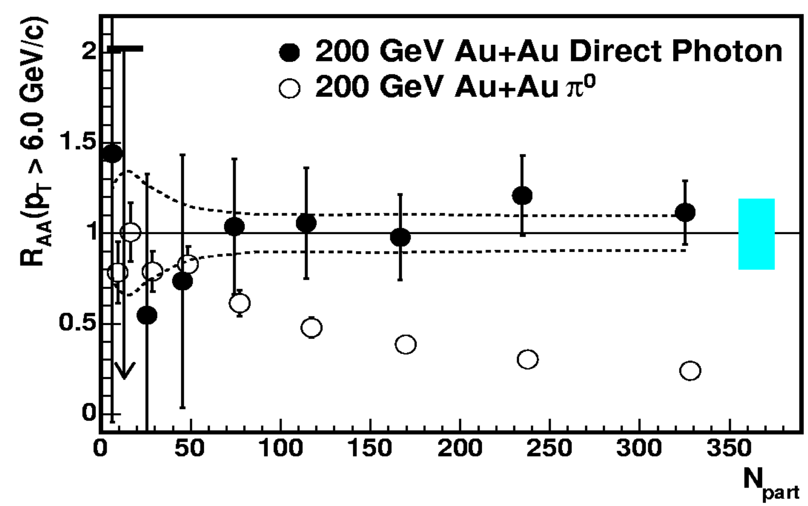
- **Nuclear shadowing**

2004--Direct Photons in Au+Au 200 GeV: follow T_{AB} scaling from p-p for all centralities-no suppression

- Direct photon production in Au+Au (all centralities) consistent w/ "T_{AB}-scaled" pQCD. Proves that initial state Au structure function is simply a superposition of p-p structure functions including g(x).





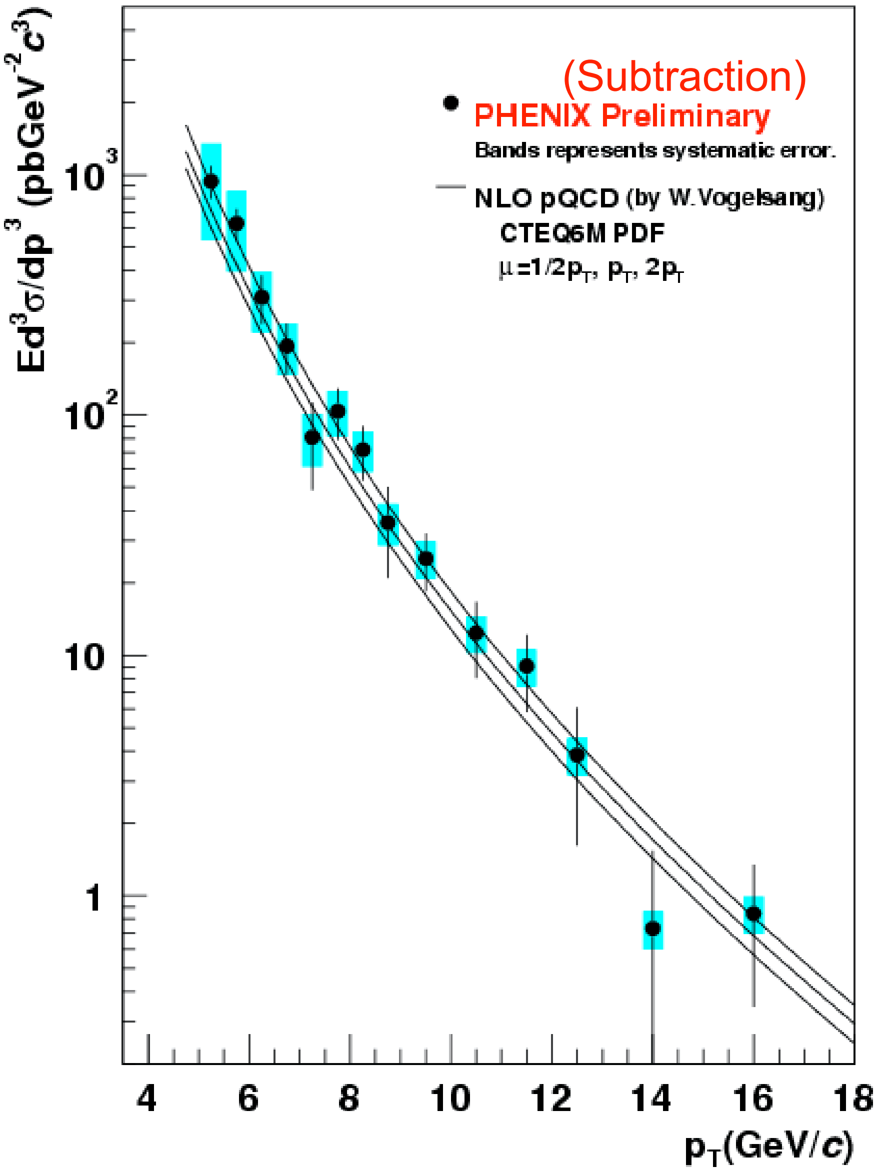


PHENIX

Submitted to PRL nucl-ex/0503003

- outgoing Direct photons unaffected by QCD medium in Au+Au → π^0 **suppression is medium effect**

Direct-γ measurement in $\sqrt{s}$=200 GeV p-p

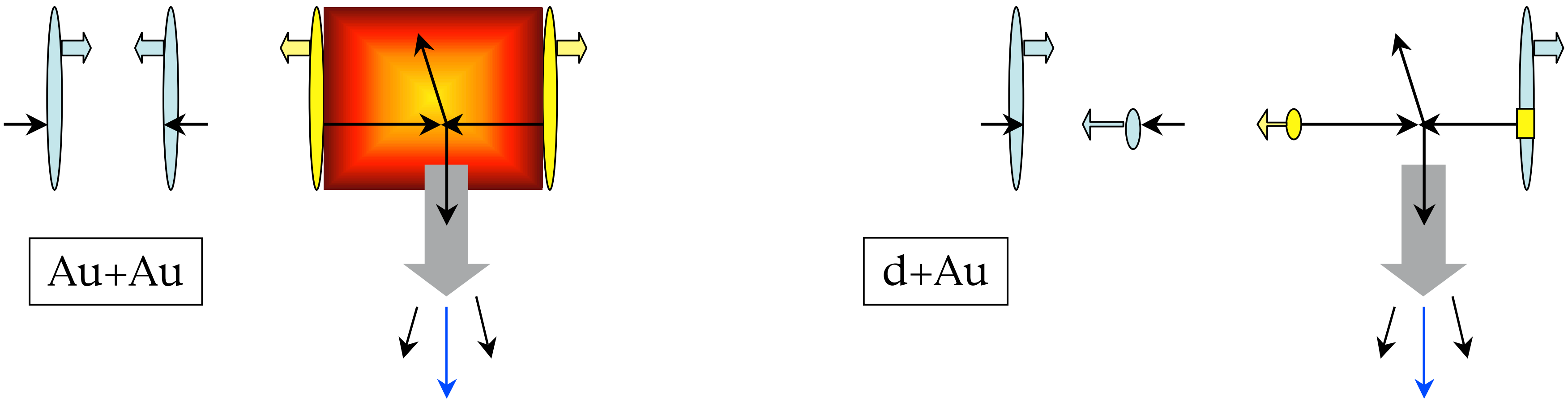


- NLO-pQCD calculation
  - ✓ Private communication with W.Vogelsang
  - ✓ CTEQ6M PDF.
  - ✓ direct photon + fragmentation photon
  - ✓ Set Renormalization scale

    and factorization scale pT/2,pT,2pT

- The theory calculation shows a good agreement with our result
- Confirms use of theoretical result as Au+Au comparison
- Opens the way for measurement of gluon spin structure function from A_{LL}

d+Au: Control Experiment to prove the Au+Au discovery



= hot and dense medium

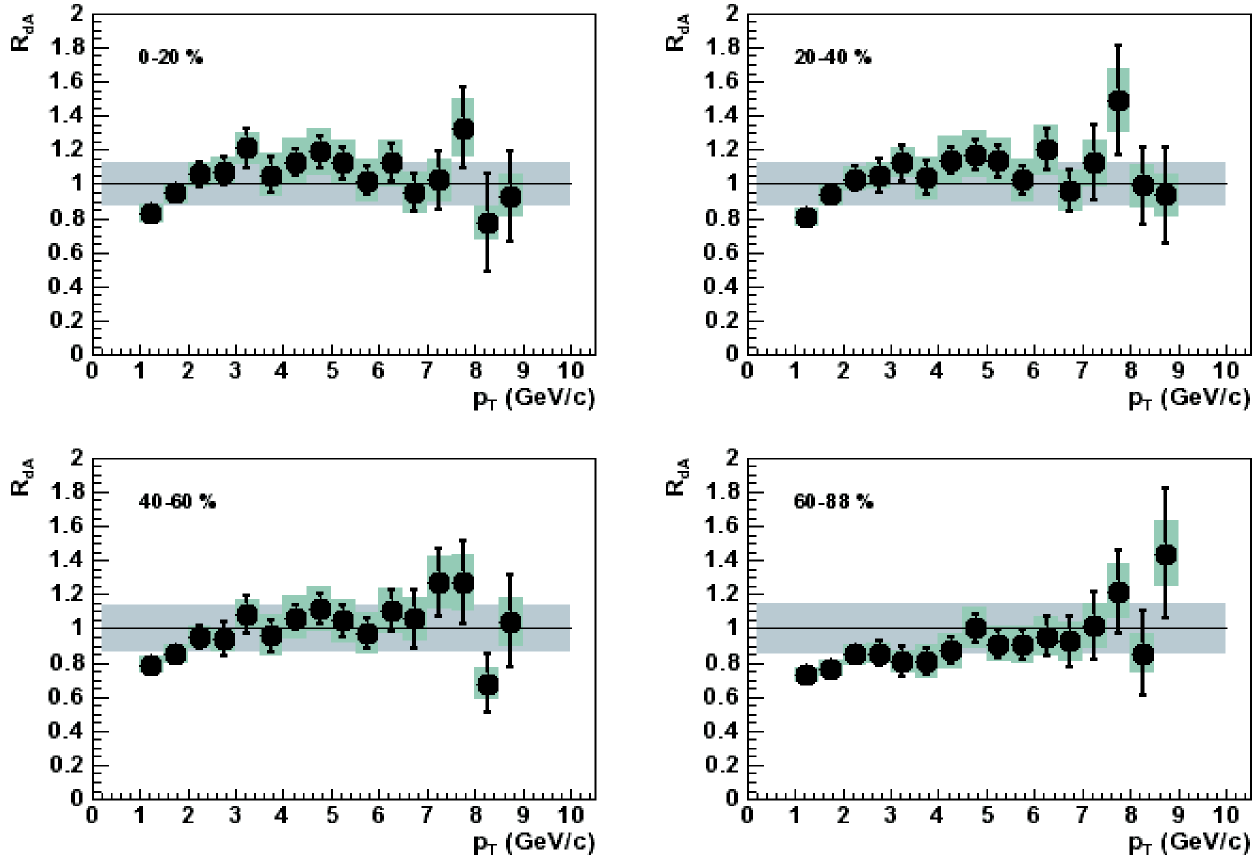
Initial + Final State Effects

= cold medium

Initial State Effects Only

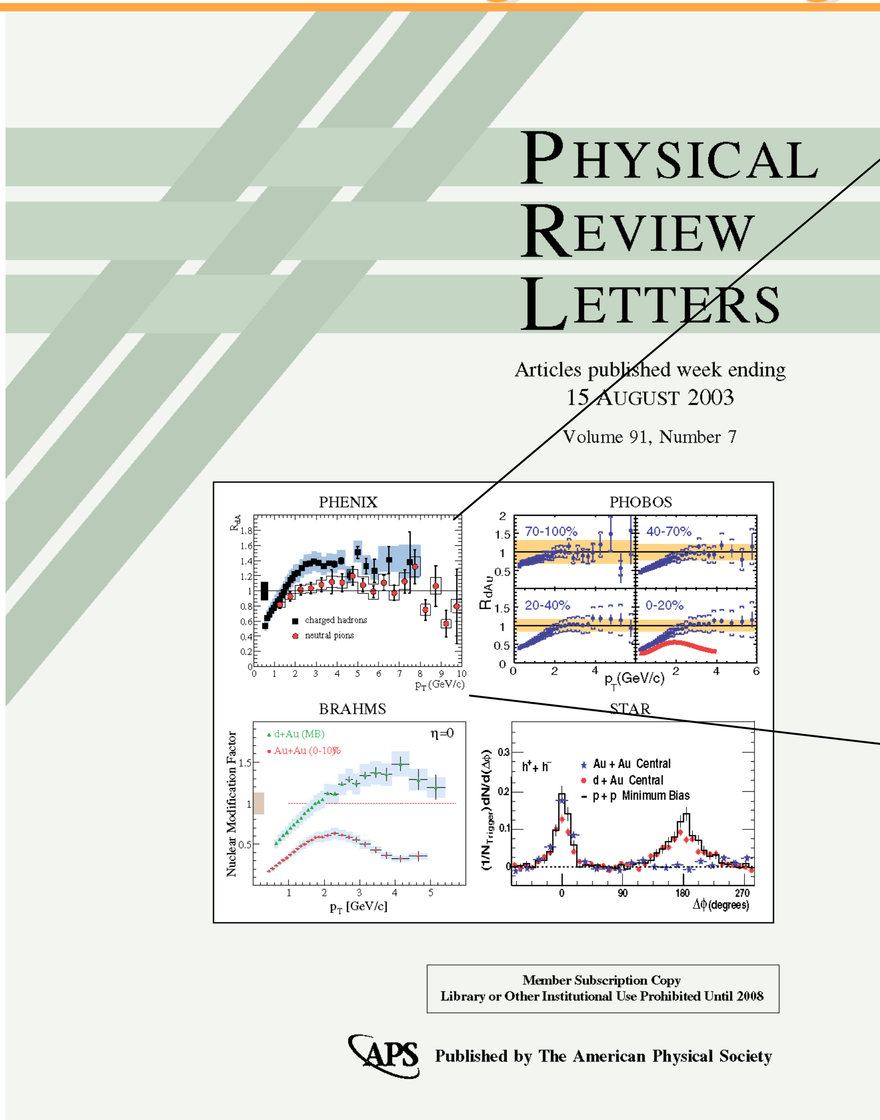
- The "Color Glass Condensate" model predicts the suppression in **both Au+Au and d+Au** (due to the initial state effect).
- **The d+Au experiment tells us that the observed hadron suppression at high p_T central Au+A is a final state effect.**
- This diagram also explains why we can't measure jets directly in Au+Au central collisions: all nucleons participate so charged multiplicity is ~200 times larger than a p-p collision→ 300 GeV in standard jet cone.

Cronin effect observed in d+Au at RHIC $\sqrt{s_{NN}}$=200 GeV, confirms x is a good variable



PHENIX preliminary π^0 d+Au vs centrality for DNP2003

This leads to our second PRL cover, our first being the original Au+Au discovery



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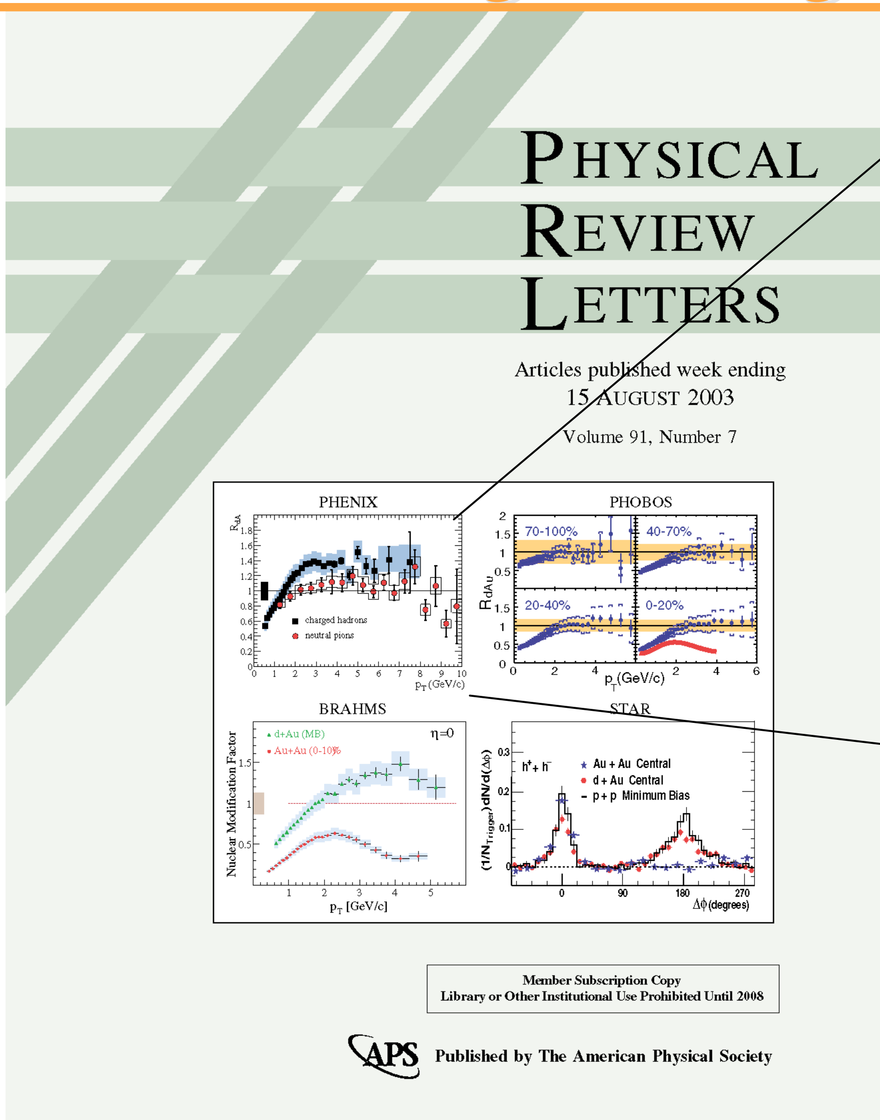
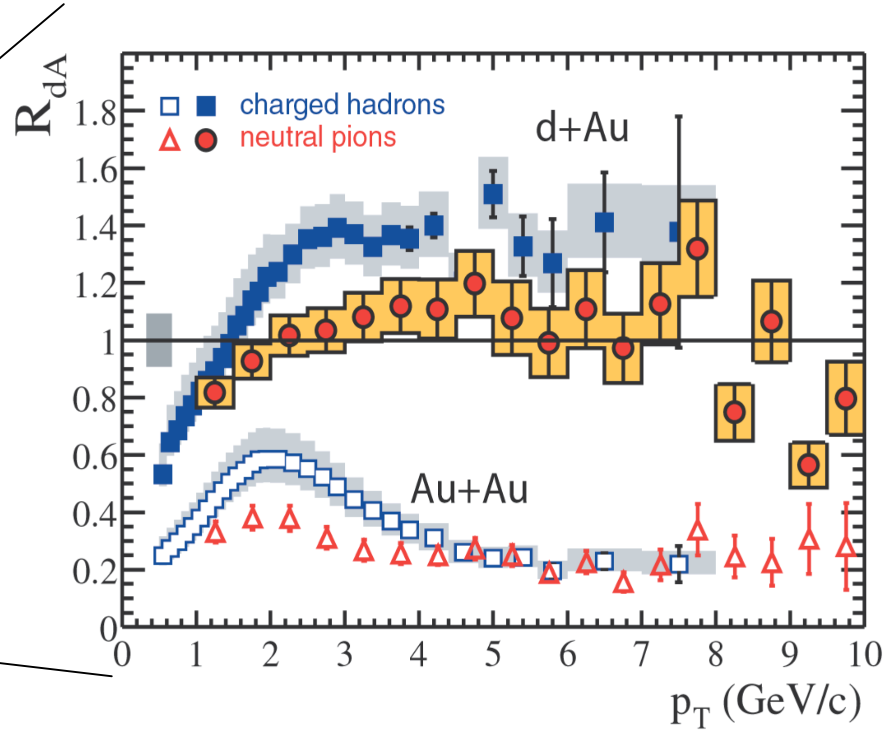




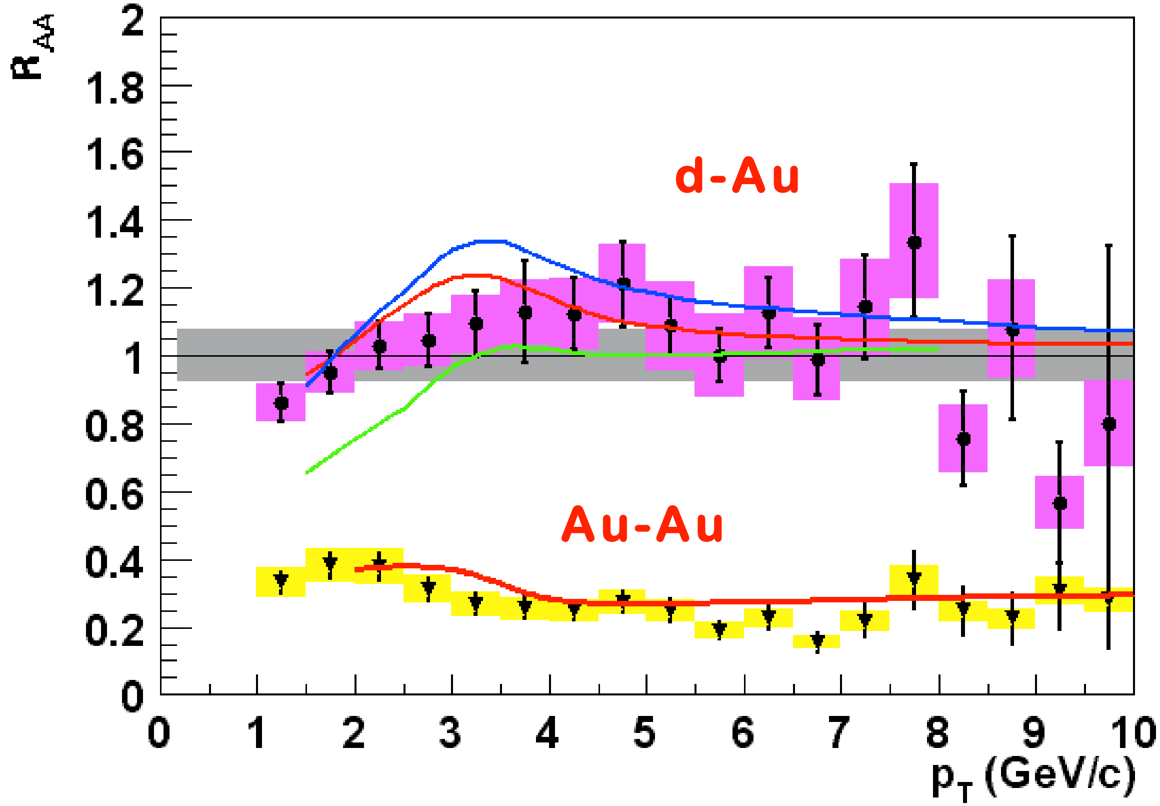
Theoretical Understanding?

Both

- ✓ Au-Au suppression (**I. Vitev and M. Gyulassy, hep-ph/0208108**)
- ✓ d-Au enhancement (**I. Vitev, nucl-th/0302002**)

understood in an approach that combines multiple scattering with absorption in *a dense partonic medium* See nucl-th/0302077 for a review.

➡ Our high p_T probes have been calibrated and are now being used to explore the precise properties of the medium

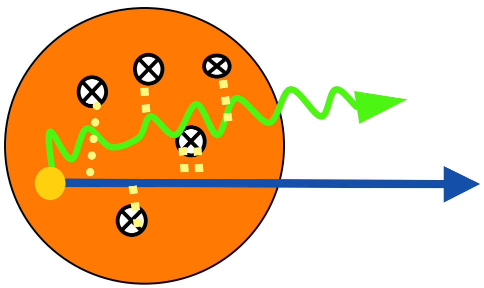


Suppression is a Final State Medium Effect

- **Energy loss of partons in dense matter--A medium effect predicted in QCD---Energy loss by colored parton in medium composed of unscreened color charges by gluon bremsstrahlung--LPM radiation**
  - ✓ Gyulassy, Wang, Vitev, Baier, Wiedemann…

    See nucl-th/0302077 for a review.
  - ✓ Baier, Dokshitzer, Mueller, Peigne, Shiff, NPB483, 291(1997), PLB345, 277(1995), Baier hep-ph/0209038,
- From Vitev nucl-th/0404052:

$$\frac{\langle \Delta E \rangle}{E} \approx \frac{9 C_R \pi \alpha_s^3}{4} \frac{1}{A_\perp} \frac{dN^g}{dy} L \, \frac{1}{E} \ln \frac{2E}{\mu^2 L} + \cdots$$



$\varepsilon_{Bj} \Rightarrow \varepsilon$=15 GeV/fm^3=10 x larger unscreened color charge density than in a nucleon

Baier, et al: Screened Coulomb potential MJT: μ^2 plays role of t_{min}

Secondly, an averaging over momentum transfers $q_{\perp\ell}$ should be performed with the distribution corresponding to the screened Coulomb potential scattering:

$$\prod_{\ell=1}^{n+2} dV(\boldsymbol{q}_\ell)\;; \quad dV(\boldsymbol{q}_\ell) = \frac{\mu^2\, d^2 q_\ell}{\pi(q_\ell^2 + \mu^2)^2}\;;$$

...

Straightforward algebra leads to

$$\frac{\omega\, dI}{d\omega\, dz} = \frac{N_c \alpha_s}{\pi\, \lambda} \int_0^\infty \frac{\mu^4\, dk_\perp^2}{k_\perp^2 (k_\perp^2 + \mu^2)^2} \left[1 + \left(\frac{N_c}{2C_F} \frac{\tau}{\lambda} \right)^2 \right]^{-1}$$

μ= 0.5 GeV/c=1/0.4 fm

One Big Grape-but size of a nucleon

H Satz Rep. Prog. Phys. **63** (2000) 1511

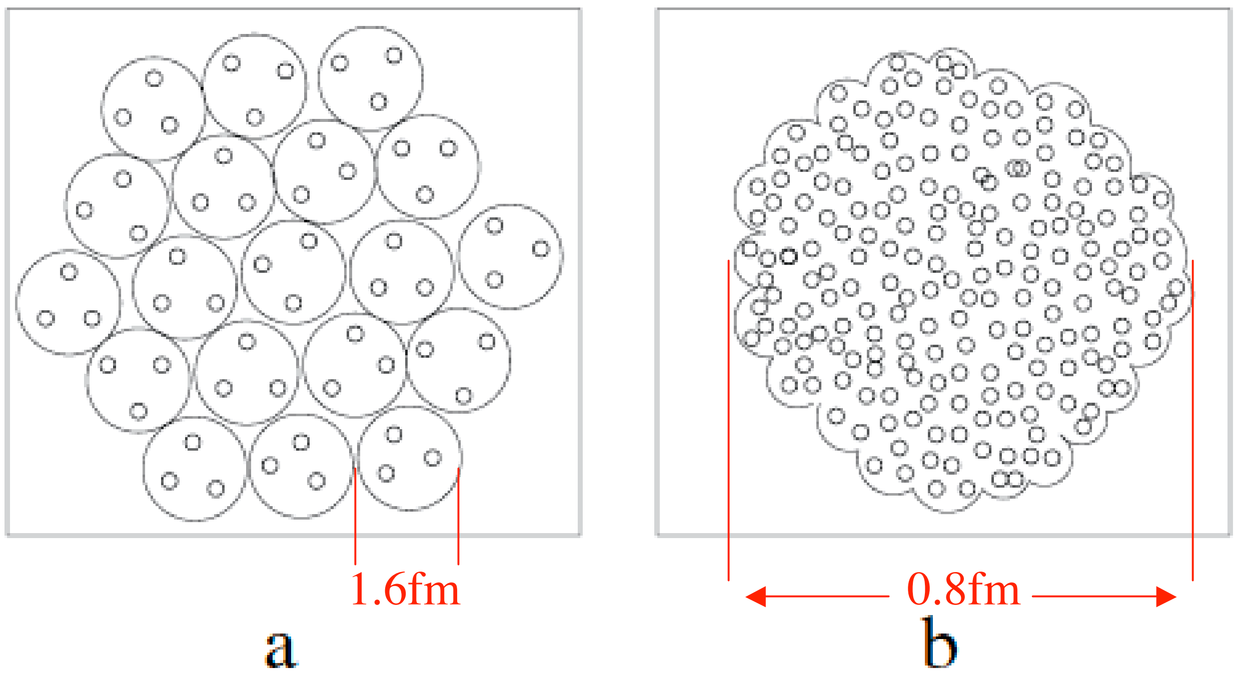
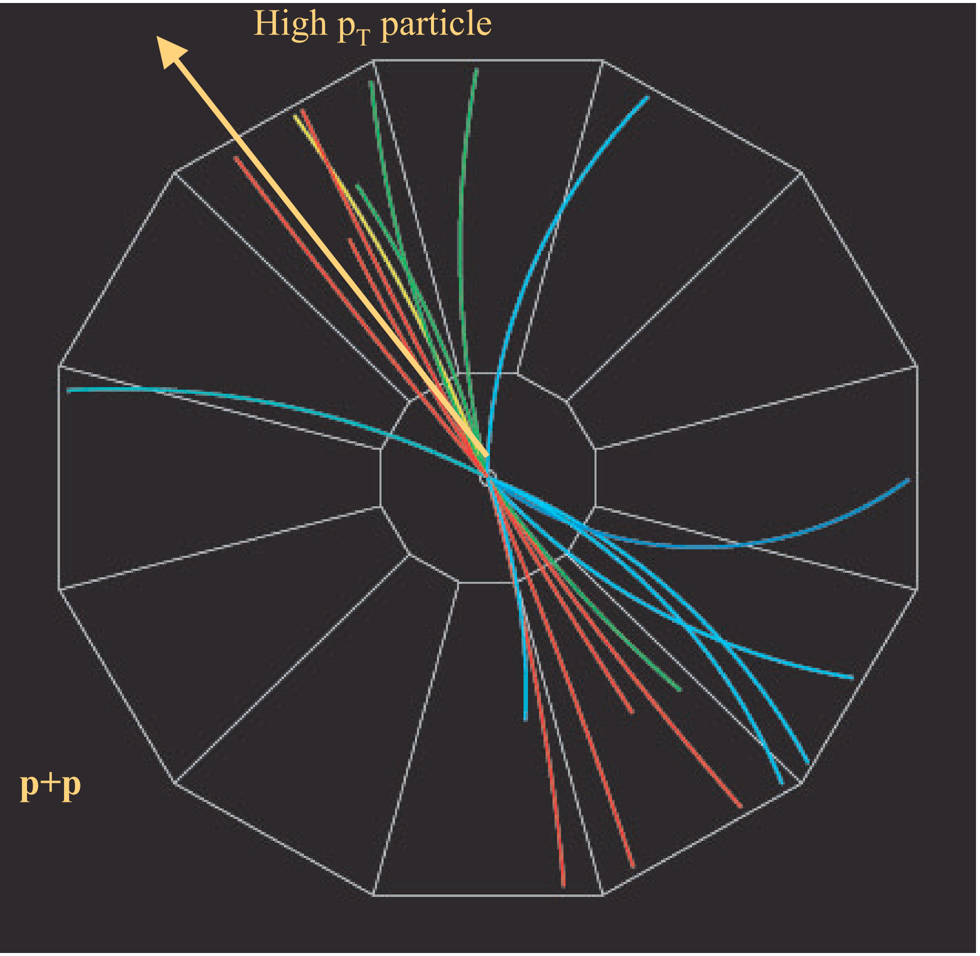


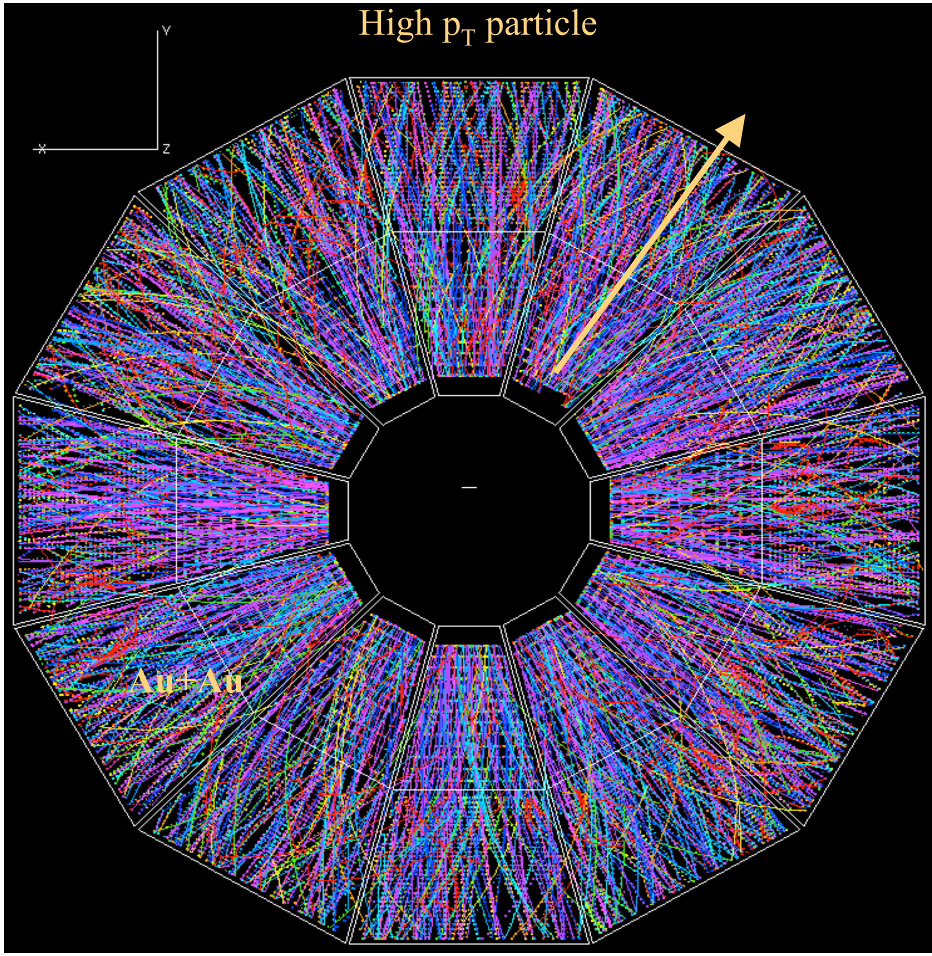
Figure 1. Strongly interacting matter as nuclear matter at a density of closely packed nucleons (a) and as quark matter at much higher density (b).

Jet Physics …jets in AuAu "difficult"--but

STAR-Jet event in pp collision

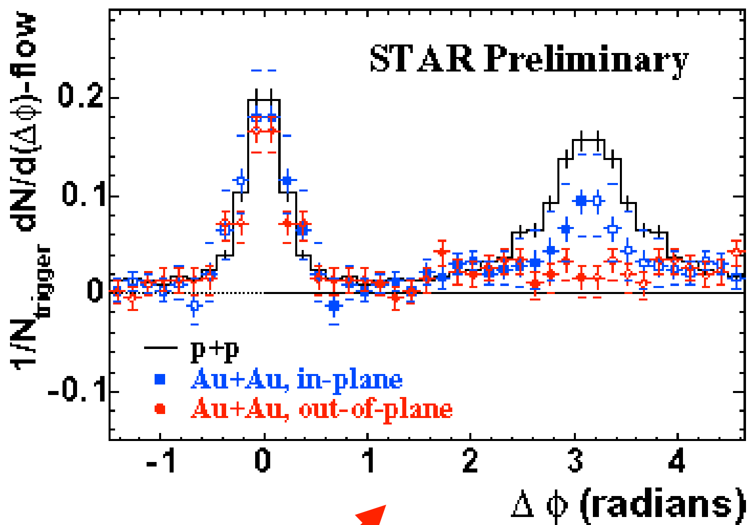
STAR Au+Au collision

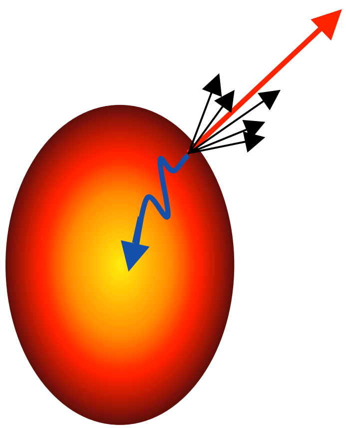


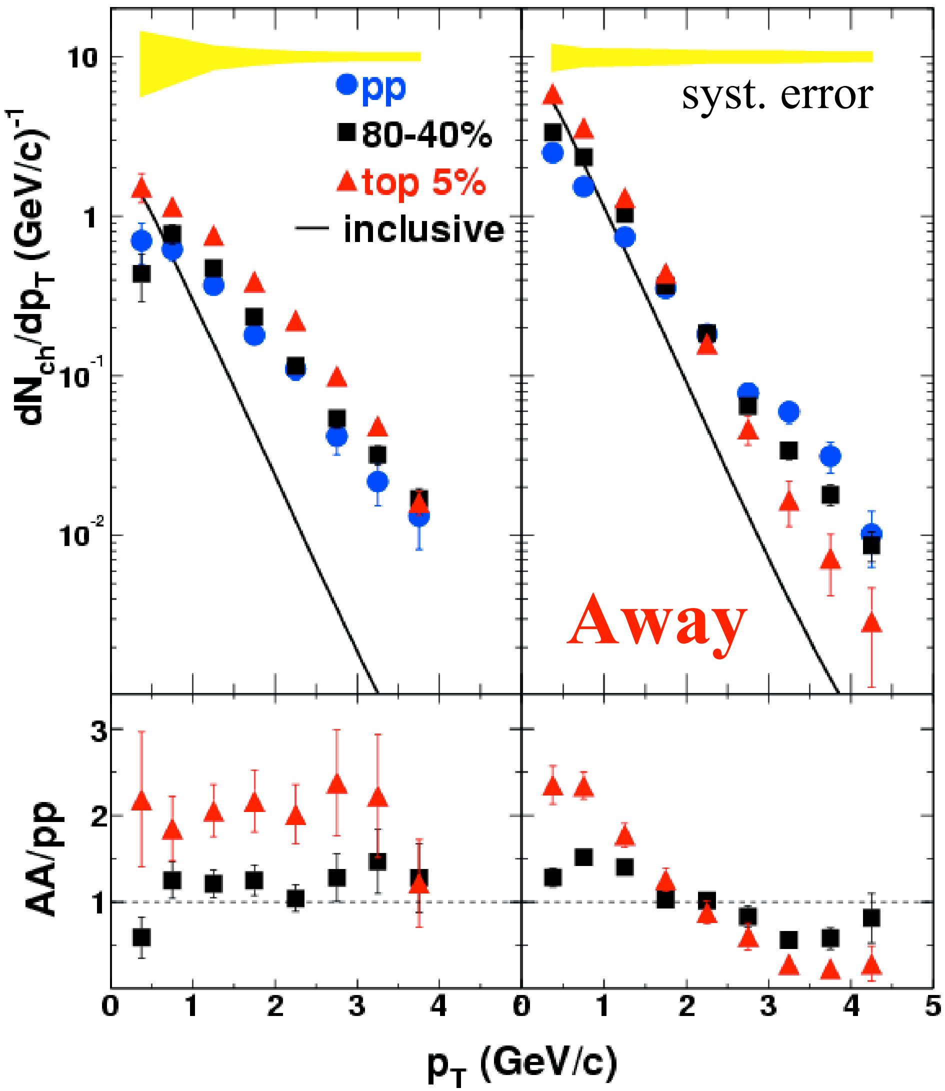


STAR--Away jet is suppressed-- consistent with energy loss

- Select a ``trigger'' particle $4<p_T<6$ GeV/c
  $2< p_T^{assoc} < 4$ GeV/c







nucl-ex-0501009
nucl-ex/0501016

STAR--Away jet is suppressed-- consistent with energy loss

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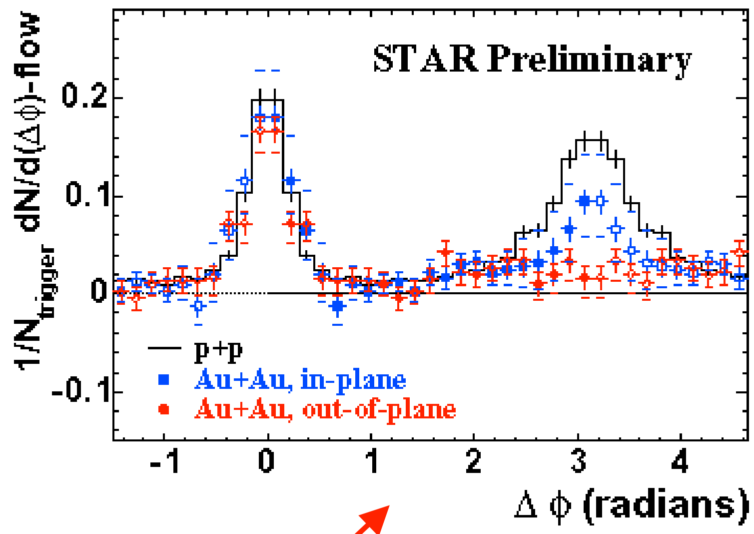

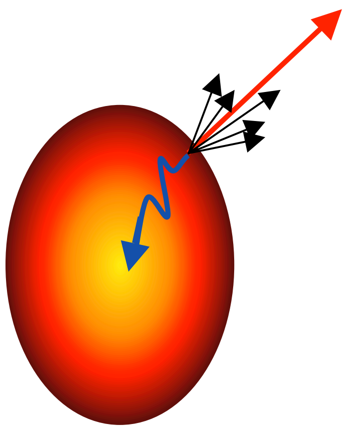

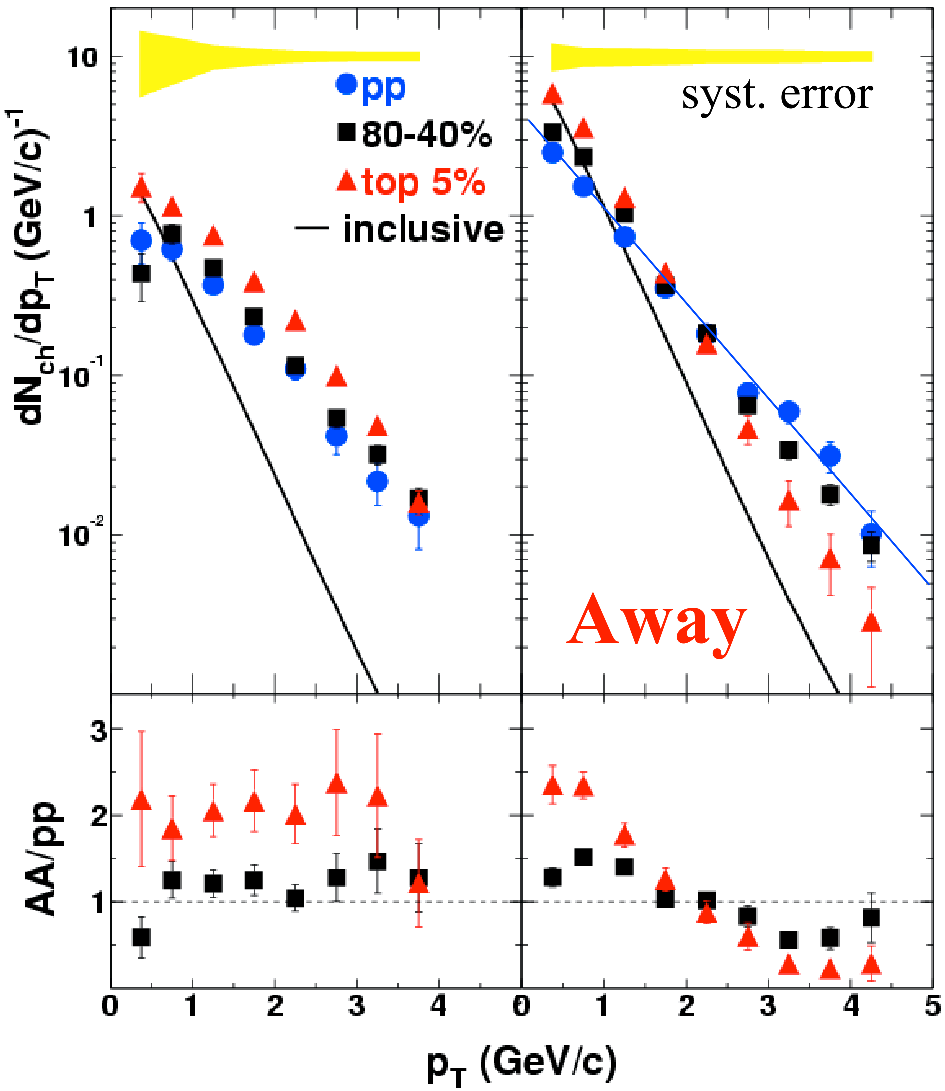

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nucl-ex/0501016

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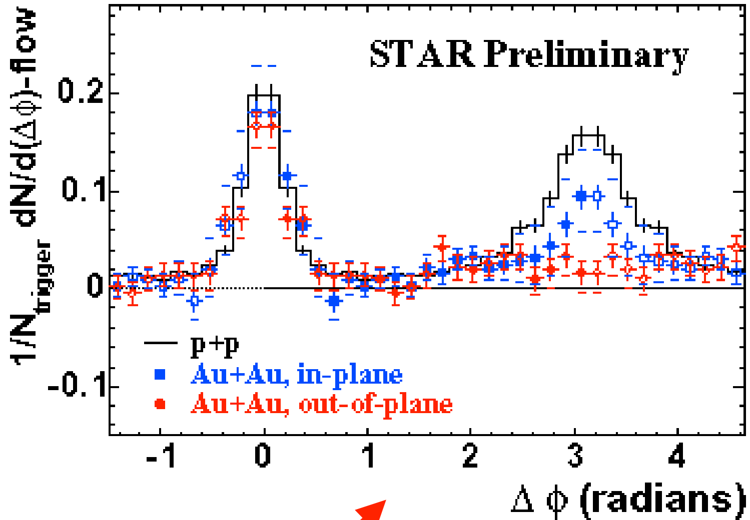

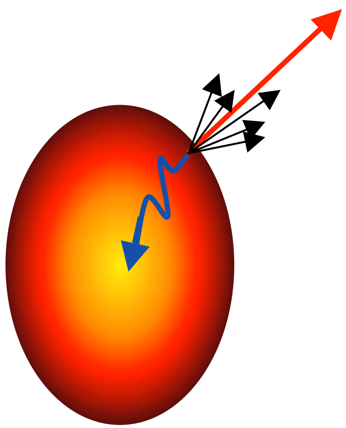

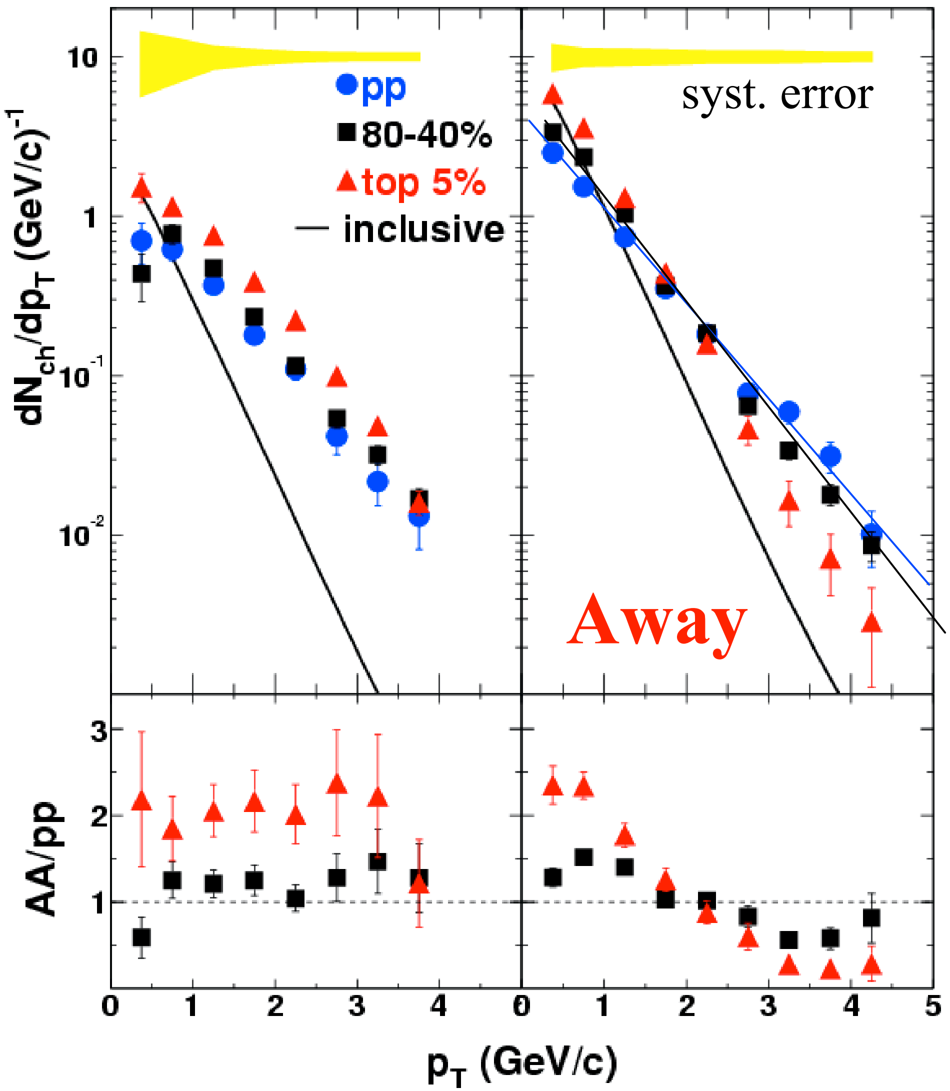

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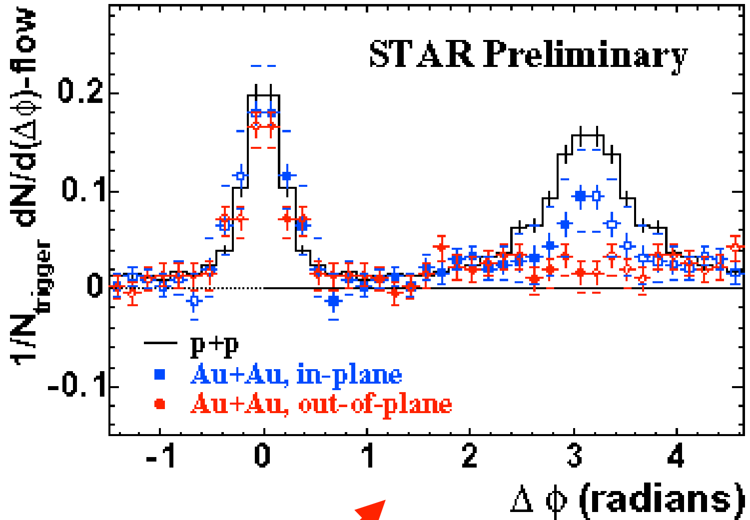
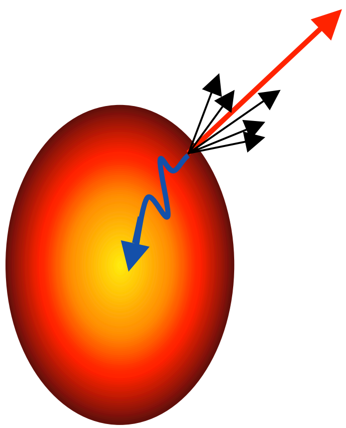
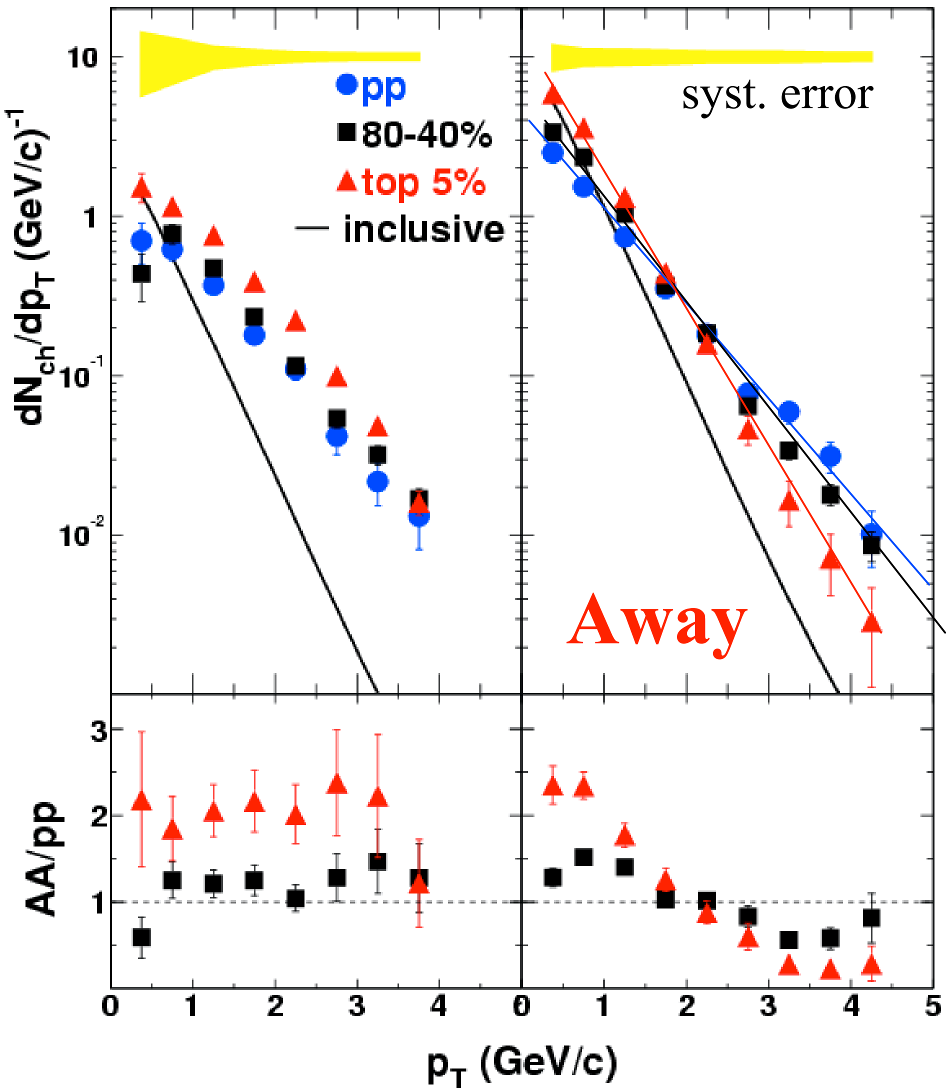
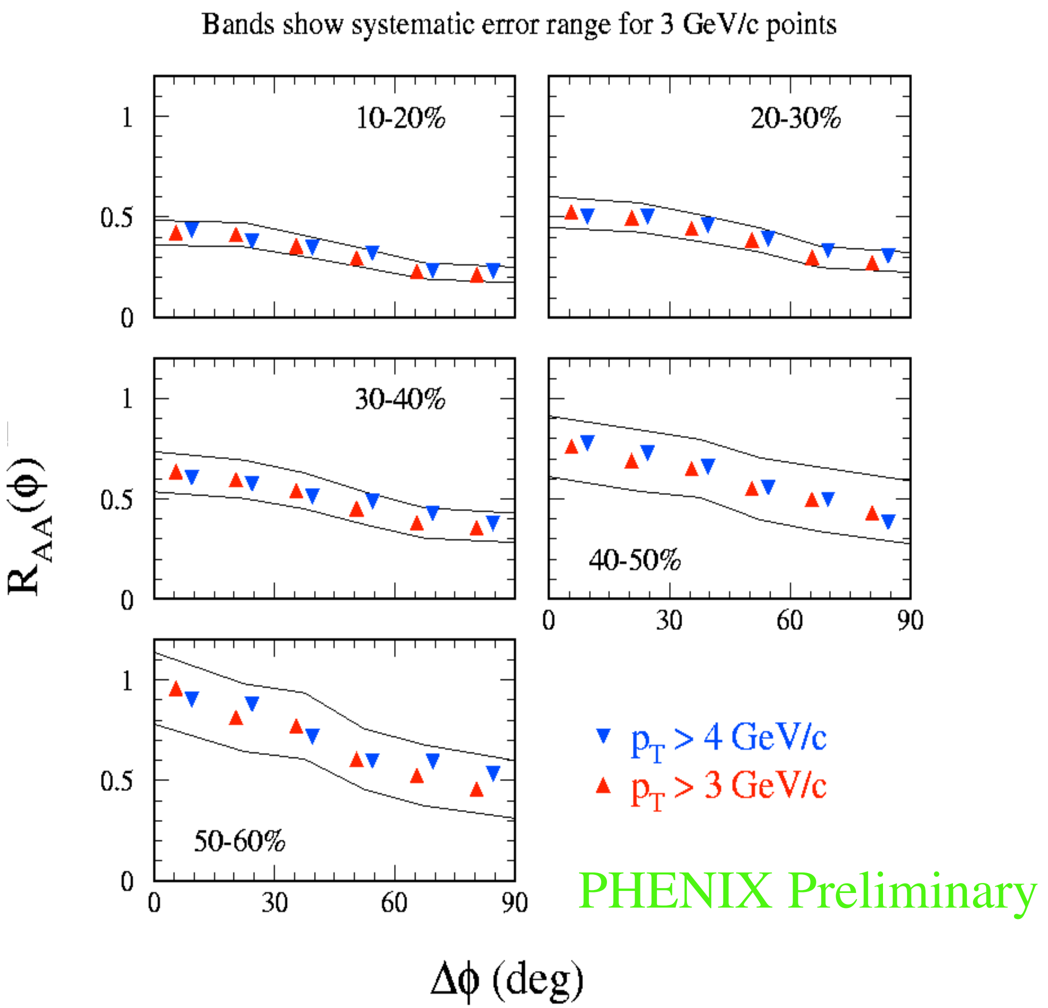


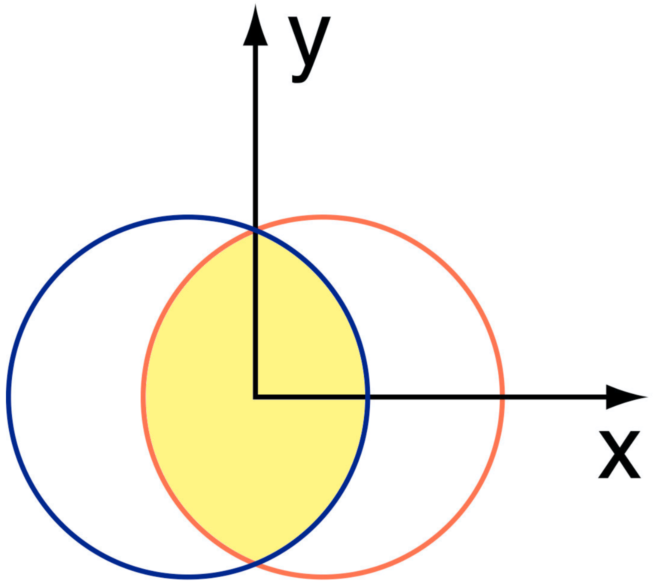




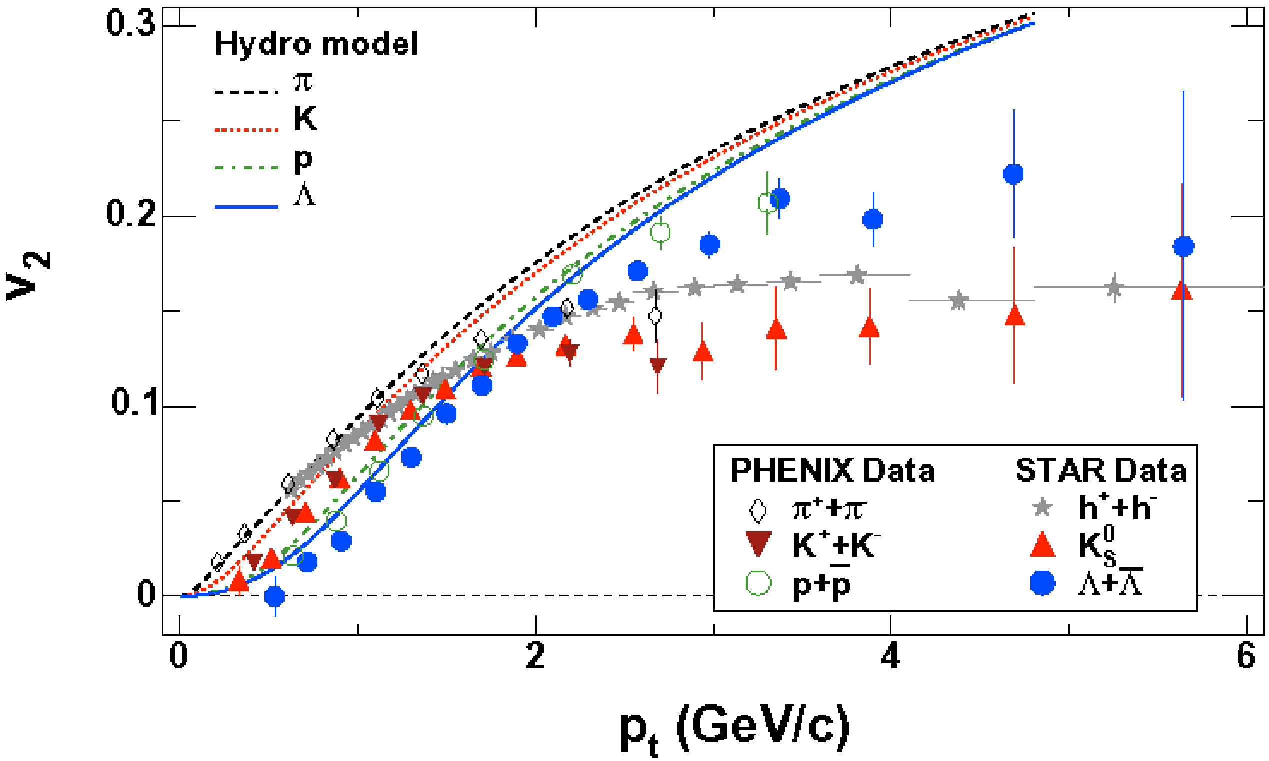
nucl-ex-0501009
nucl-ex/0501016

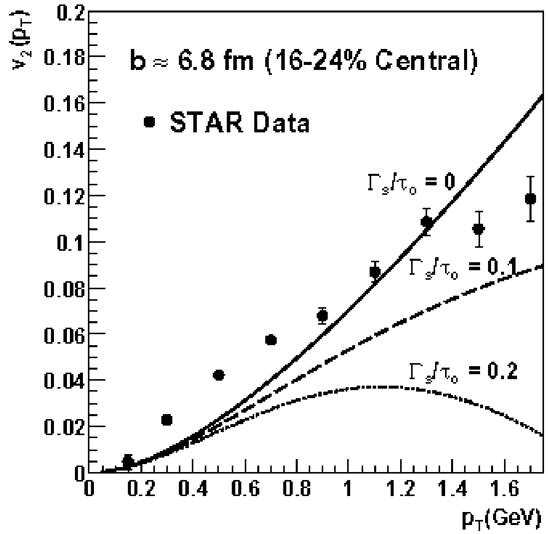
Implies that v_2 p_T> 2 GeV/c is due to anisotropic energy loss





Nobody believes that v_2 p_T>2 GeV/c is entirely due to hydro pressure--perfect fluid (?)





D.Teaney,
PRC**68**, 034913 (2003)

STAR-PRC-nucl-ex/0409033

Conclusions

- the nuclear matter produced in central Au+Au collisions at RHIC appears to be a nearly perfect quark-gluon "liquid" instead of behaving like a gas of free quarks and gluons.

- No signs of a rapid phase transition have been seen---consistent with latest ideas that transition is a cross-over at RHIC energies.

- The medium at RHIC is characterized by very high energy densities, density of unscreened color charges ten times that of a nucleon, large cross sections for the interaction between strongly interacting particles, strong collective flow which implies early thermalization.

- This state of matter is not describable in terms of ordinary color-neutral hadrons, because there is no known self-consistent theory of matter composed of ordinary hadrons at the measured densities.

But there is more

- Hydro totally fails for Bose-Einstein (Hanbury-Brown Twiss)(GGLP) correlations.

- In the range $2 < p_T < 4.5$ GeV/c protons are not suppressed. This has spawned a whole new idea called Recombination.

- J/Psi measurements in p-p collisions are consistent with total cross section measurements at lower $\sqrt{s}$, but Au+Au measurements are inconclusive so far--new results at Quark Matter 2005 in August.

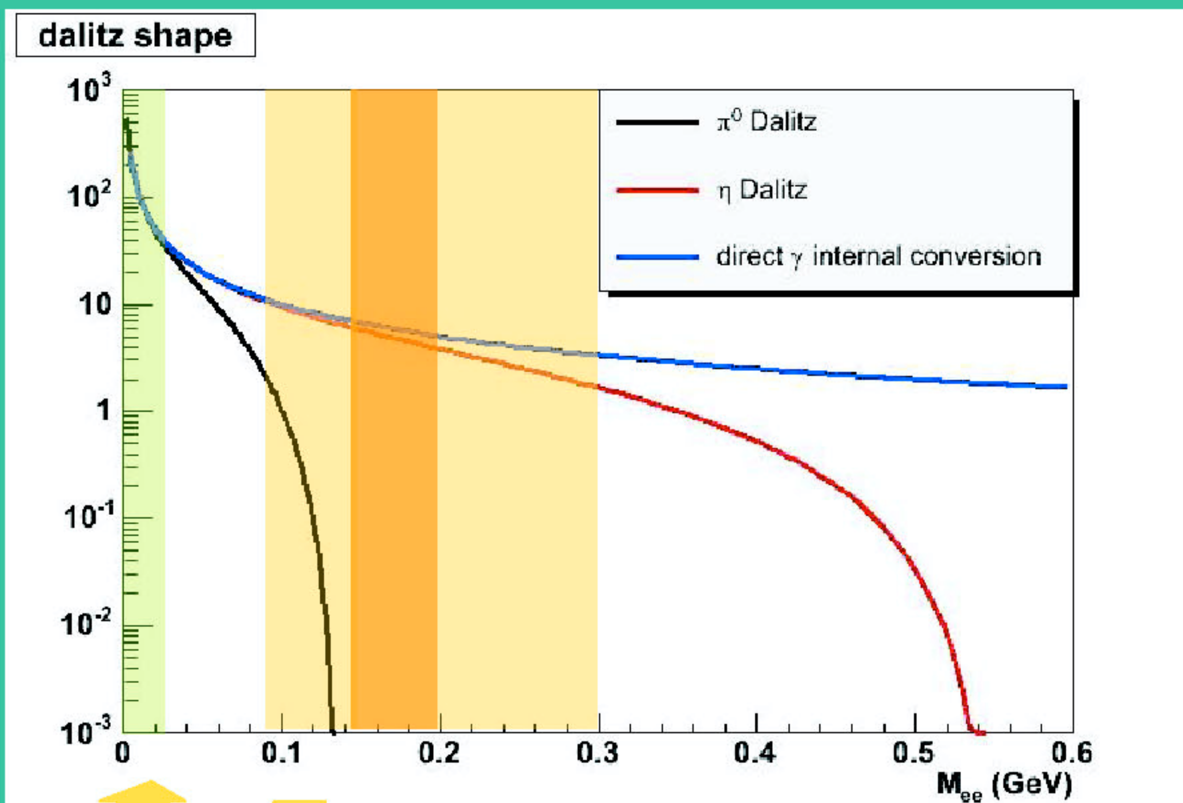
- Test whether the LPM energy loss formalism is correct in detail? If so, can measure properties of medium

- Do charm quarks flow?

RESULTS
from
Quark Matter
2005

Inv. Mass Distribution of Dalitz Pairs

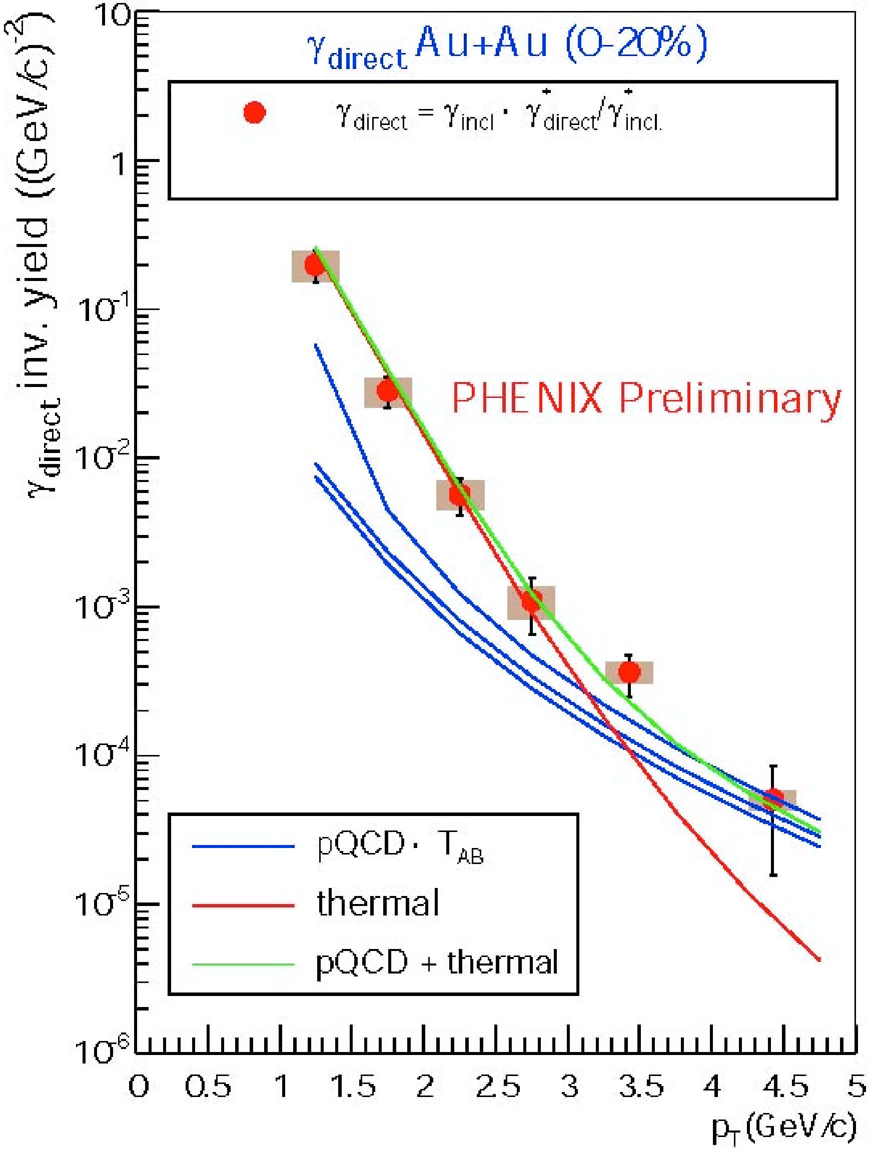
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}\left|F(m_{ee}^2)\right|^2\left(1-\frac{m_{ee}^2}{M^2}\right)^3$$



phase space factor $\longrightarrow$ *1 for high p_T γ*

- Ratios of M_{inv} bins to lowest one
- If no direct photons: ratios can be calculated from Dalitz decays
- If excess: direct photons

The Spectrum--Thermal???



Compare to NLO pQCD

- L.E.Gordon and W. Vogelsang
- Phys. Rev. D48, 3136 (1993)
- excess above pQCD

Compare to thermal model

- D. d'Enterria, D. Perresounko
- nucl-th/0503054

2+1 hydro

T_0^{ave}=360 MeV(T_0^{max}=570 MeV)

τ_0=0.15 fm/c

- data above thermal at high p_T

Compare to thermal + pQCD

- data consistent with thermal + pQCD

For comparison Drell Yan for p_T --> 0

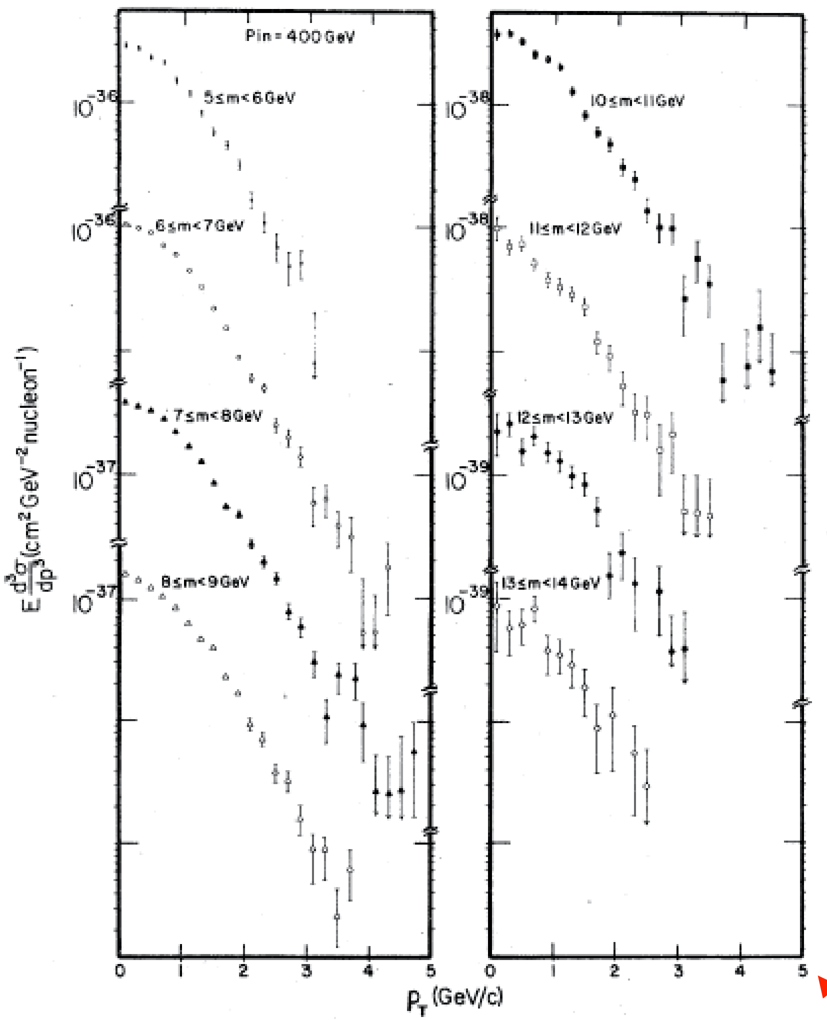
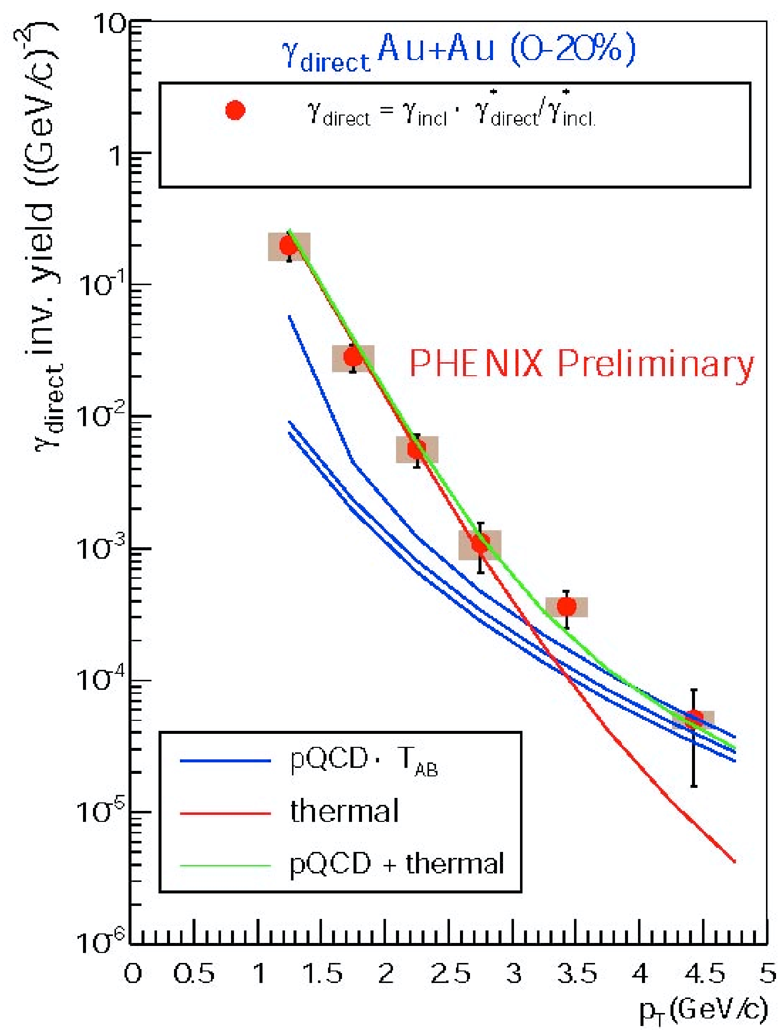


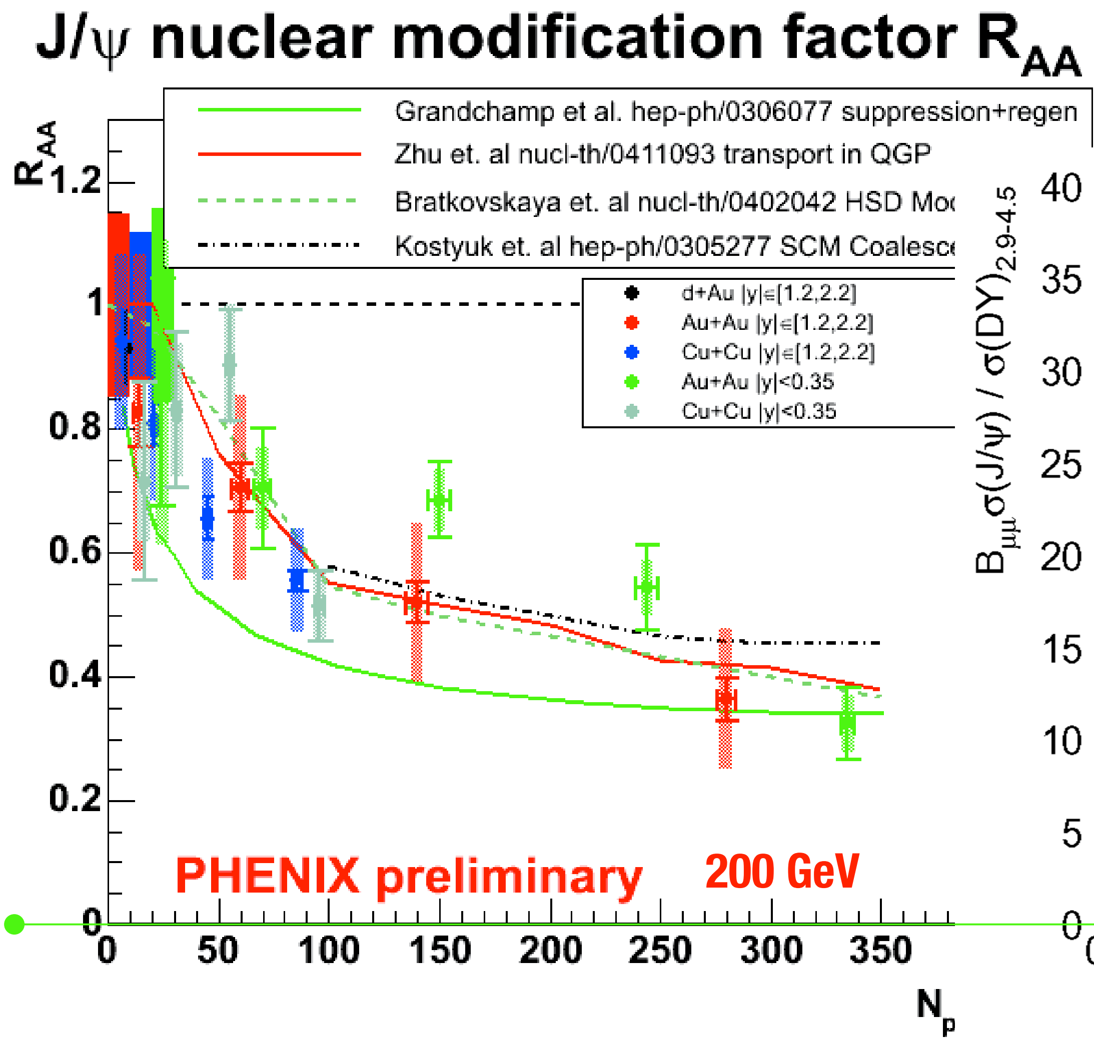
FIG. 12. Invariant yield of dimuons as a function of the transverse momentum p_T of the muon pair for 400 GeV incident protons.

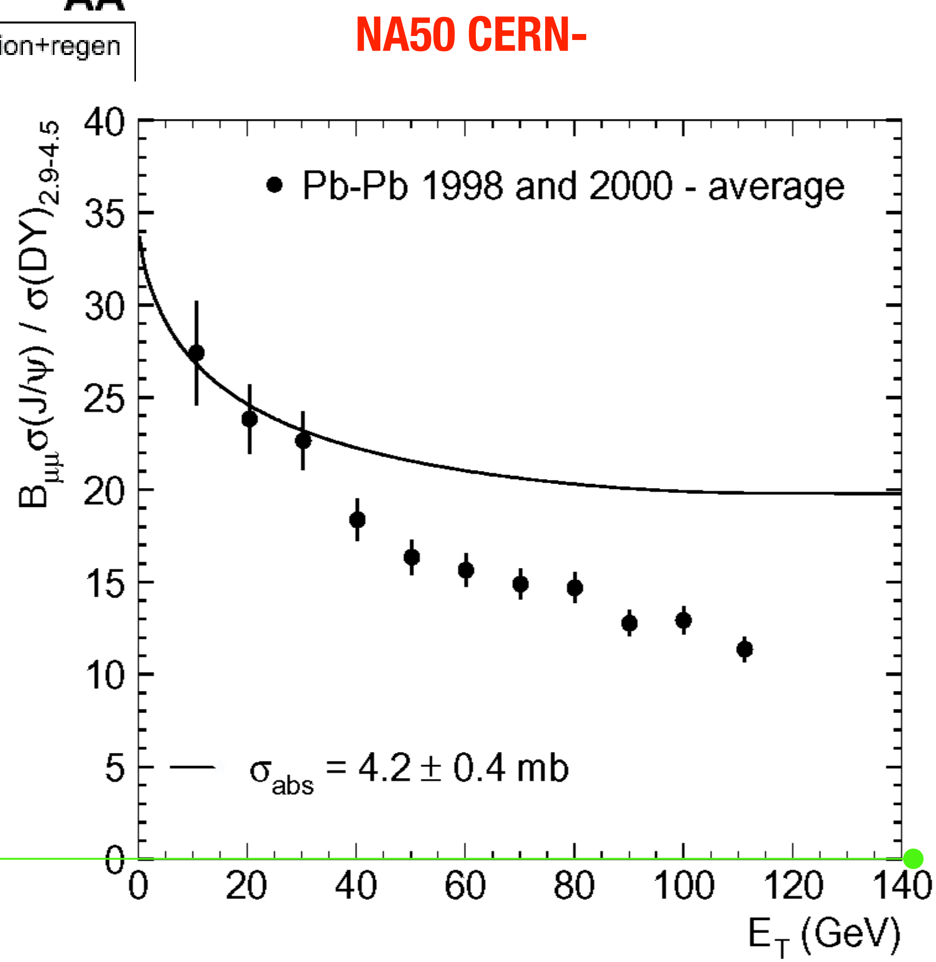
A.S.Ito, et al, PRD23,604 (1981)



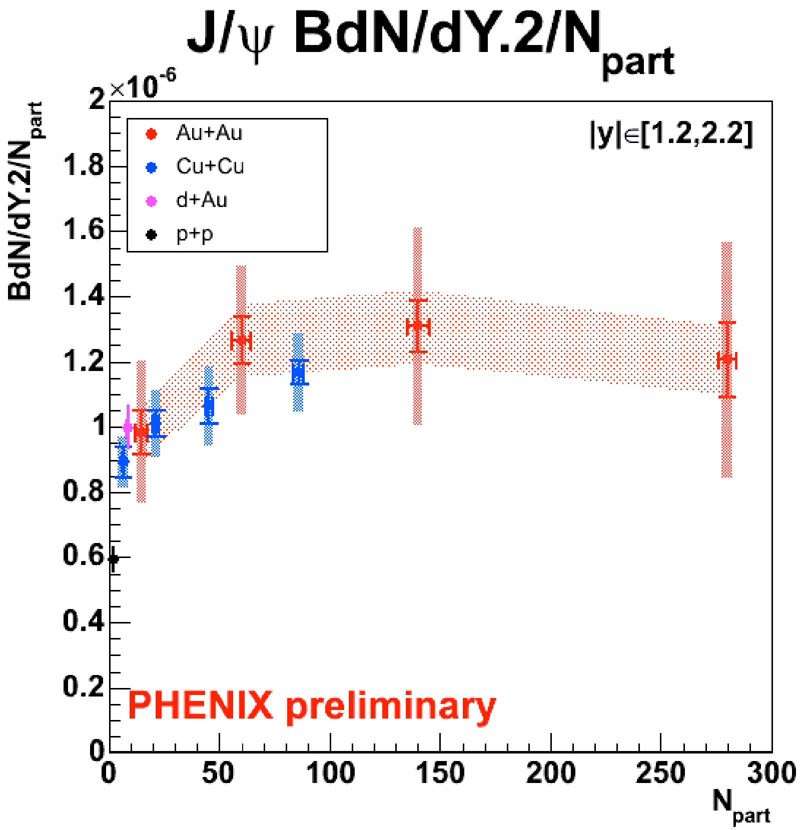
Note Gaussian shape, no power-law tail!

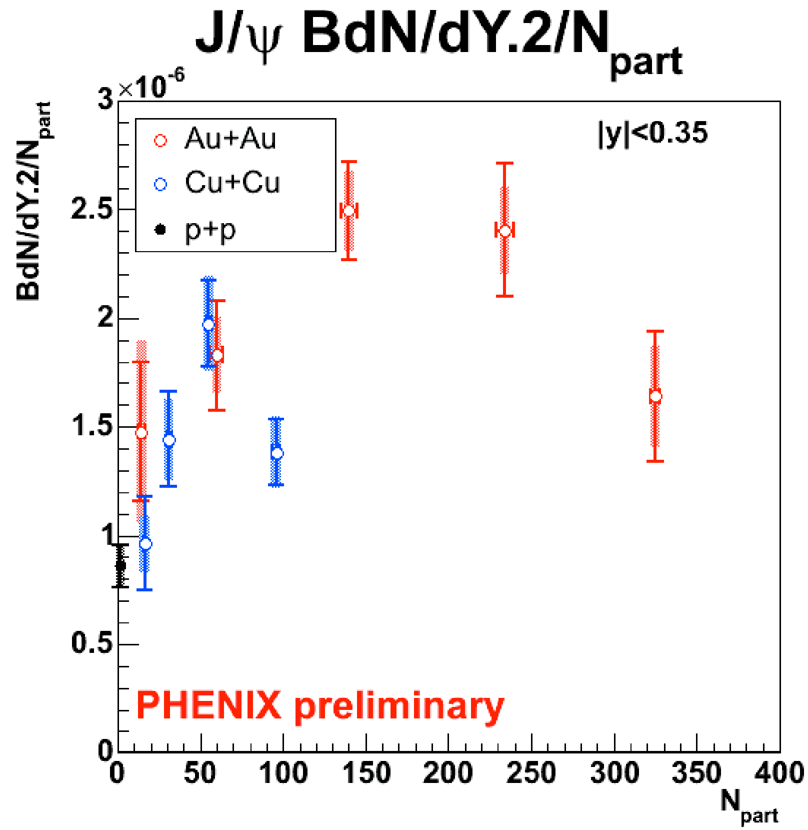
J/Ψ---My Nightmare Scenario





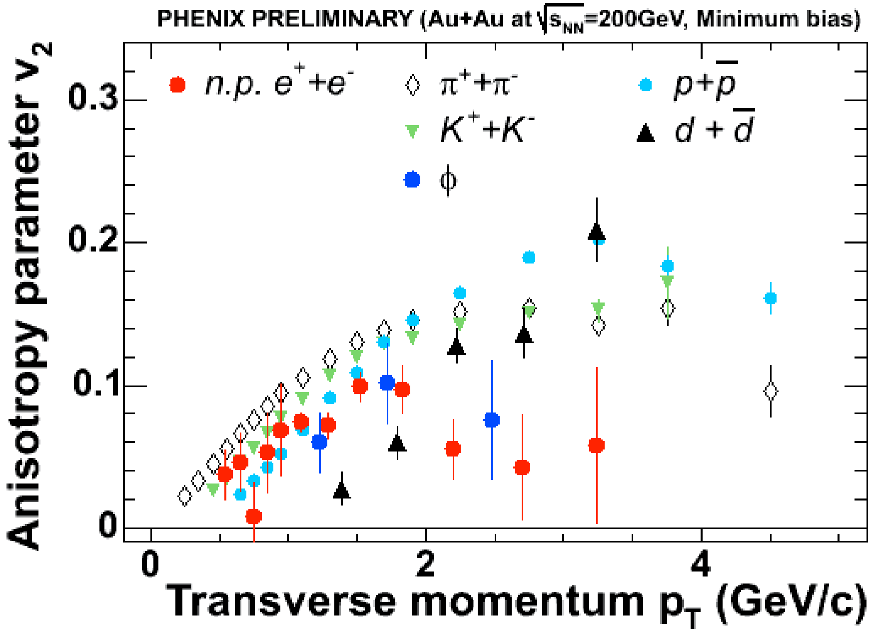
Test of N_{part} scaling



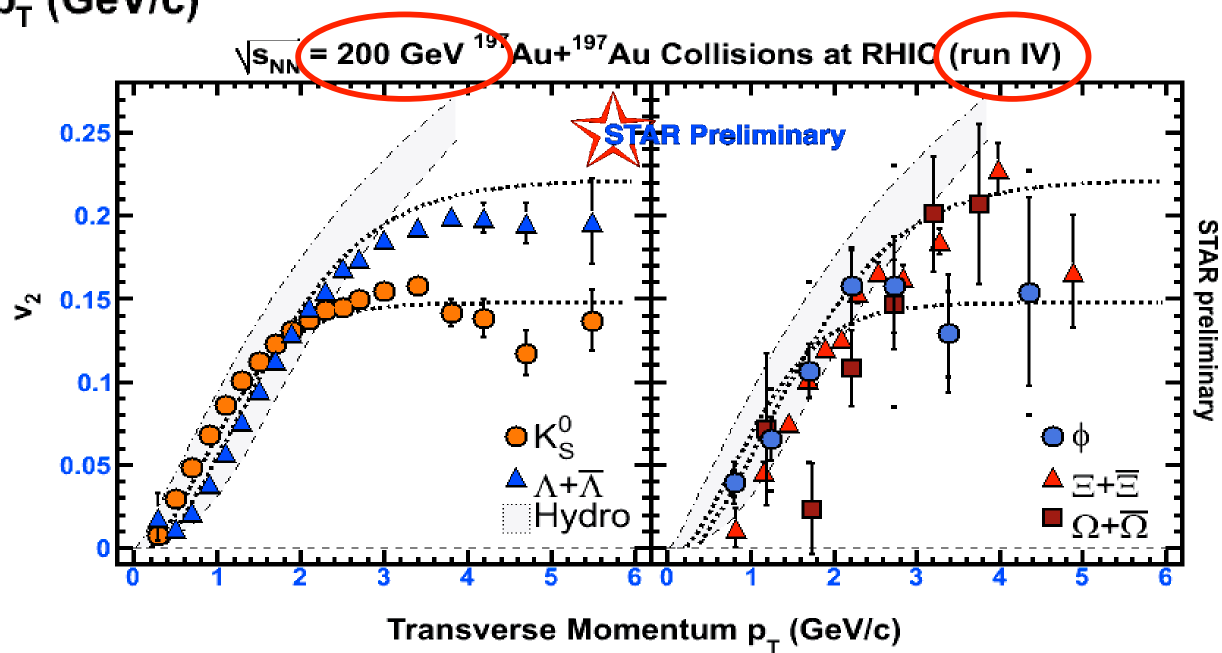


Is the J/Ψ just another hadron?

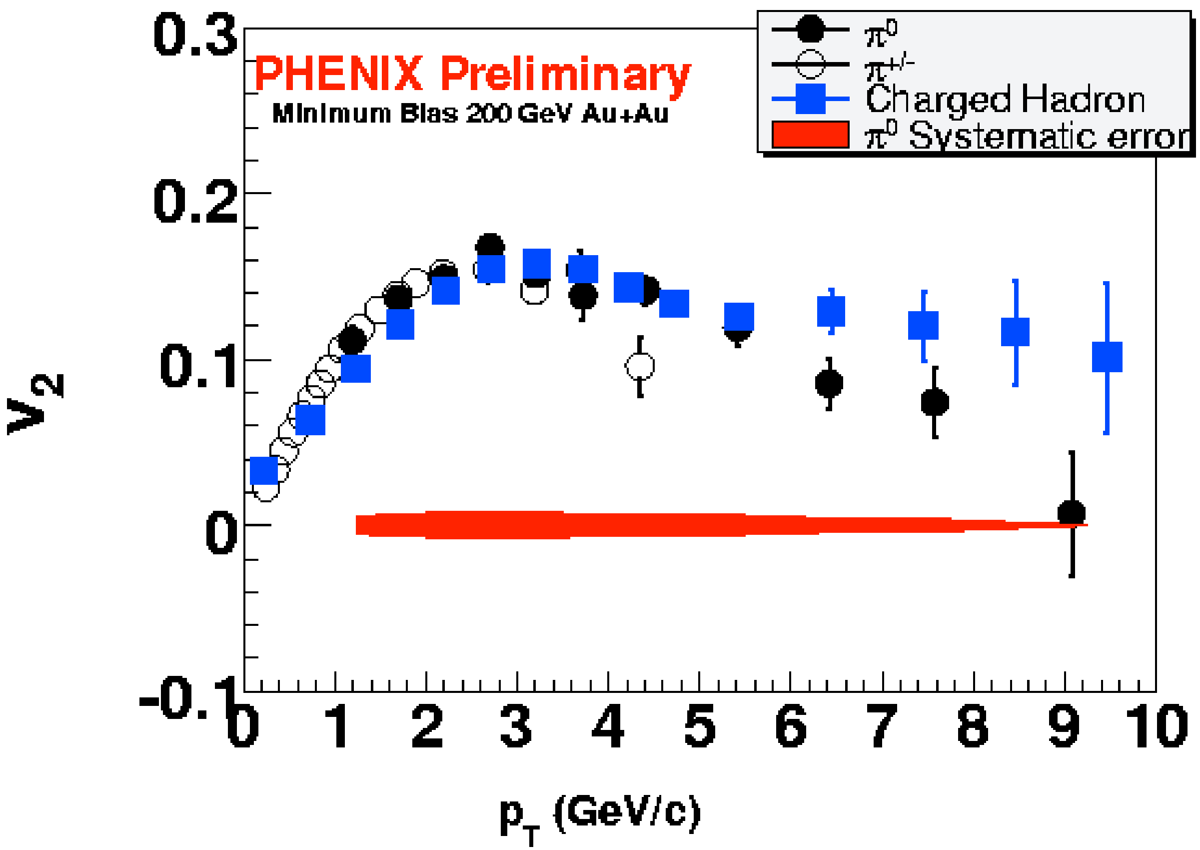
φ, Ξ, Ω, d `charm' flow



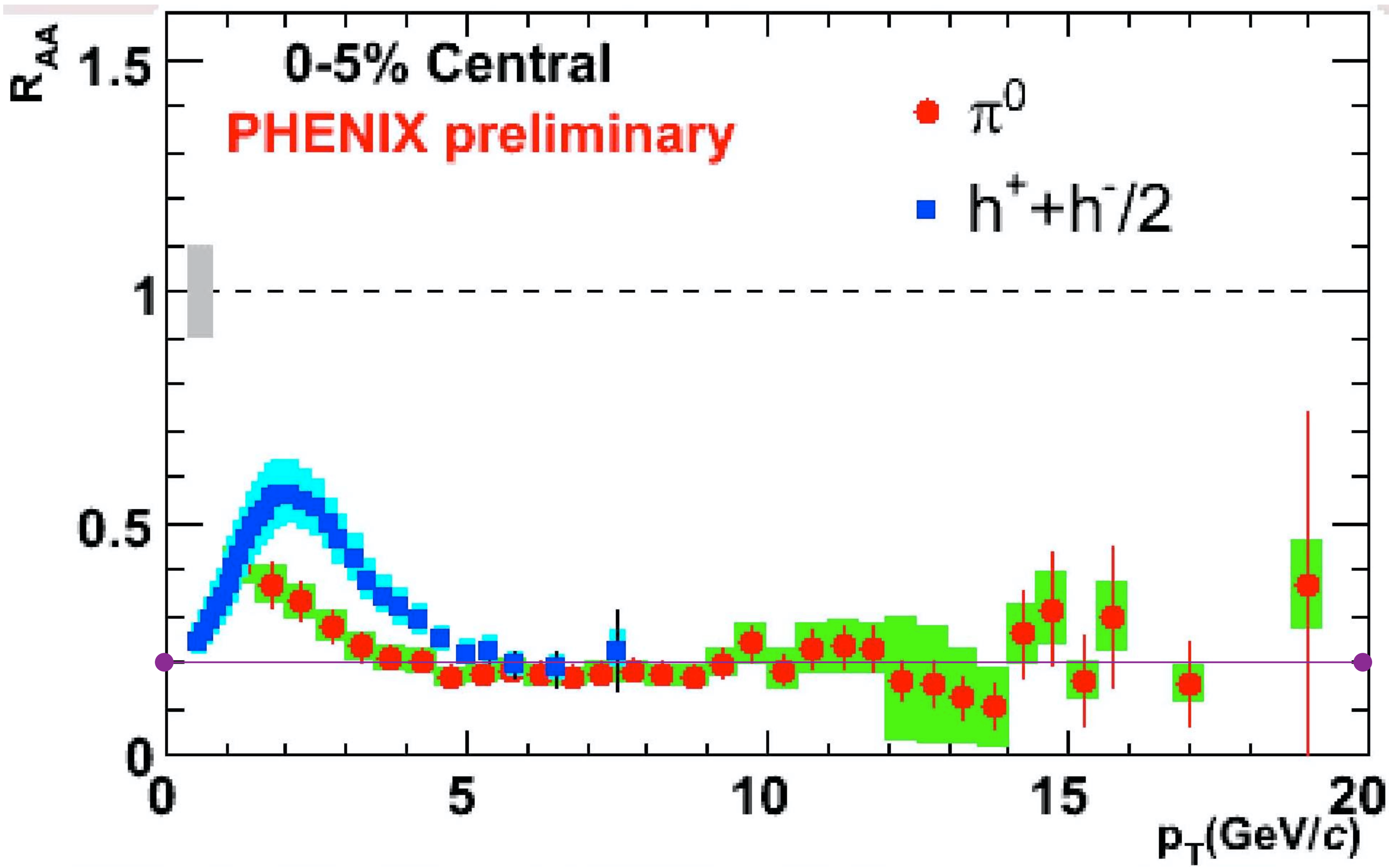
- φ flows ⇒ flow not hadronic



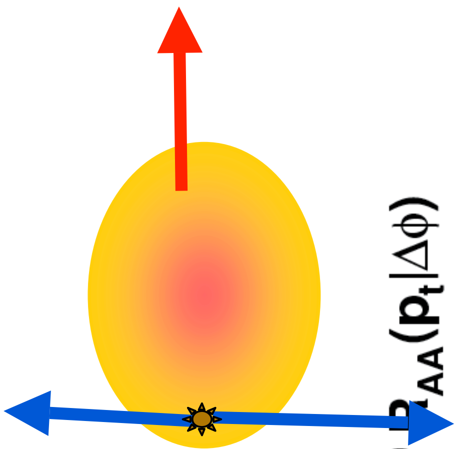
v_2 persists to high p_T

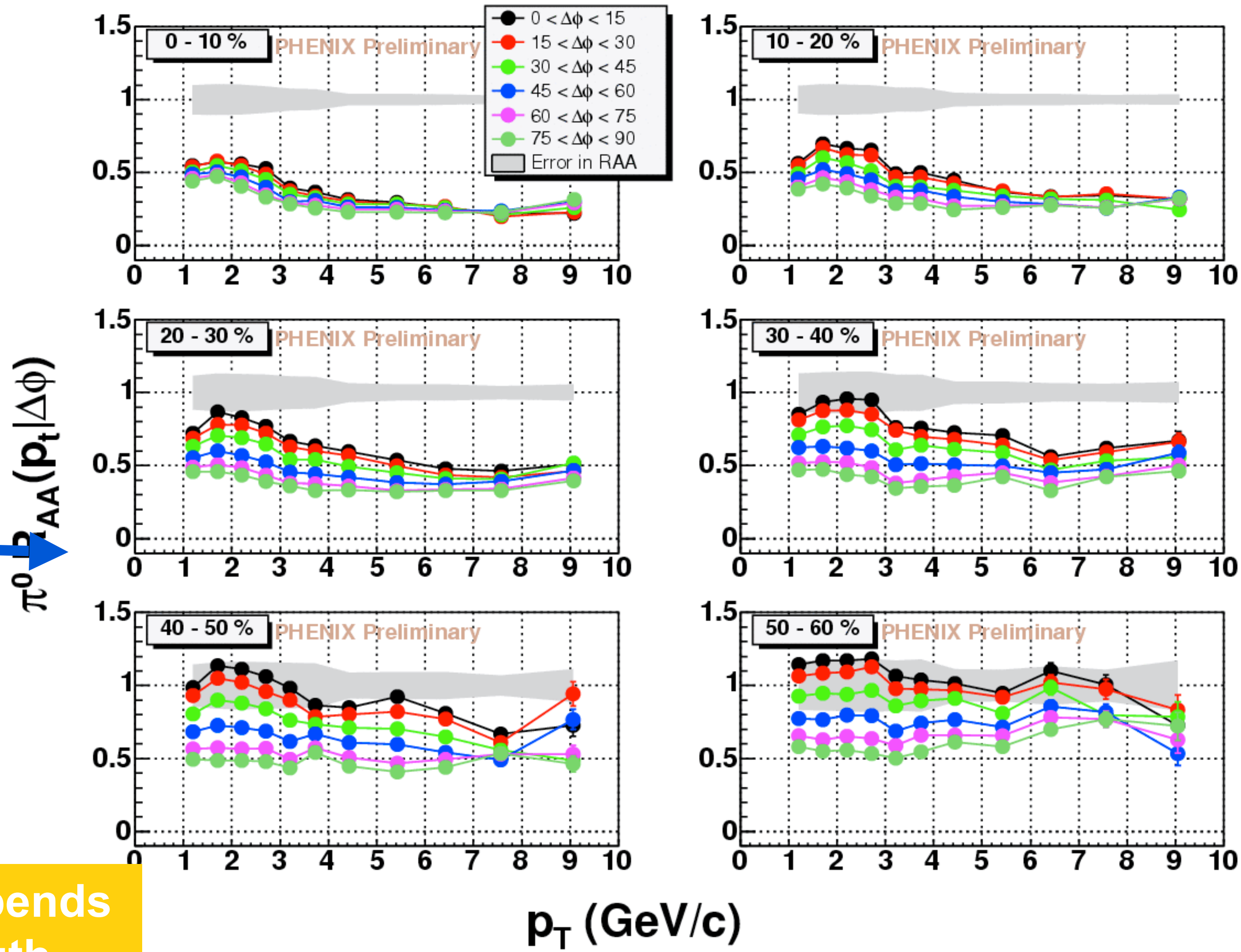


R_{AA} --π^0's still rule!



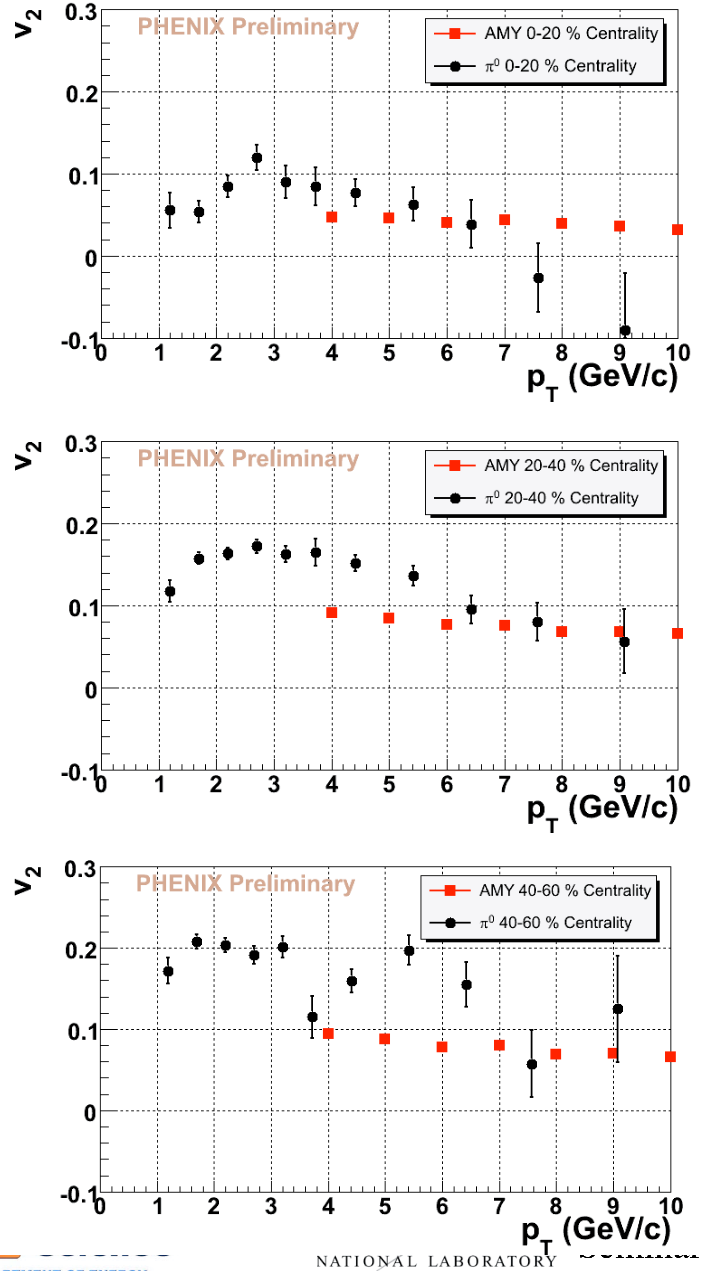
R_{AA} wrt reaction plane





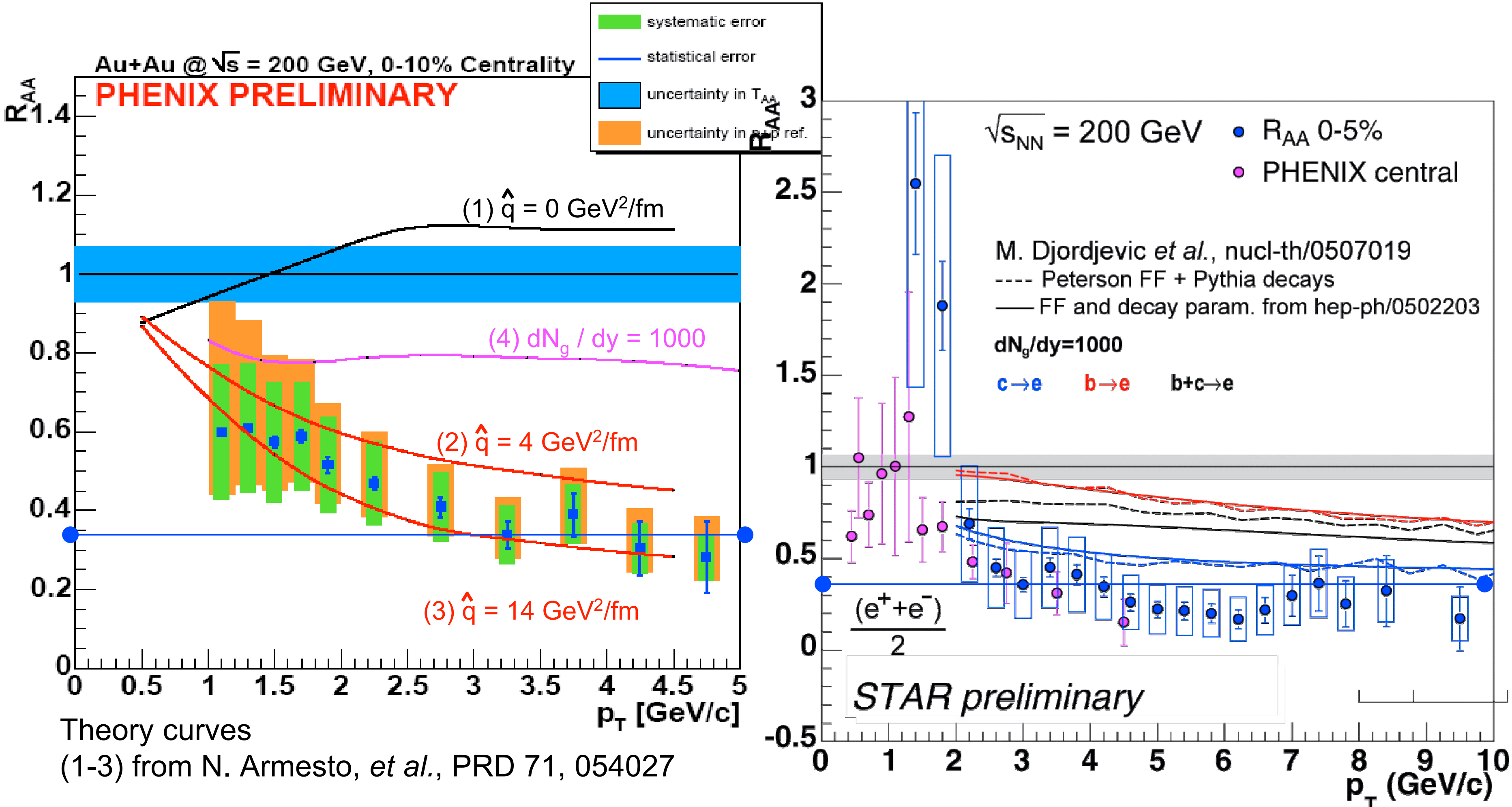
Energy loss depends on the path-length

π^0 v_2 Theory Comparison: AMY (Turbide et al.)



- Calculations based on Arnold, Moore, Yaffe (AMY) formalism
  - ✓ JHEP 0305:51 2003
- Energy loss only (BDMS++)
- High-p_T
  - ✓ v_2 appears to decrease to energy loss calculation
- Low(er)-p_T
  - ✓ Something additional going on…
- While the data appear to approach the energy loss limit at high p_T, there is something extra going on in 3-6 GeV/c region

Is PHENIX or STAR more charming?



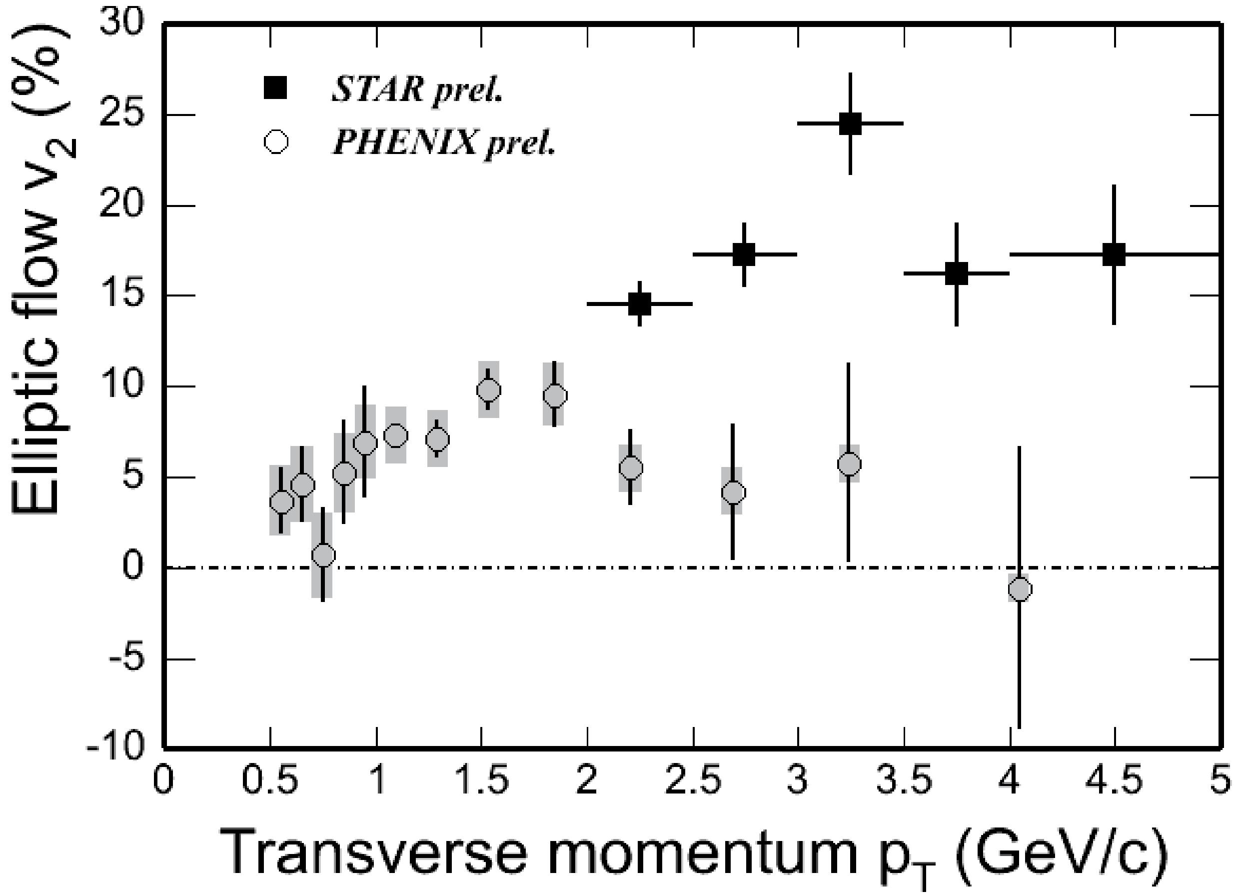
Theory curves

(1-3) from N. Armesto, *et al.*, PRD 71, 054027

(4) from M. Djordjevic, M. Gyullasy, S.Wicks, PRL 94, 112301

Non-photonic electron v_2

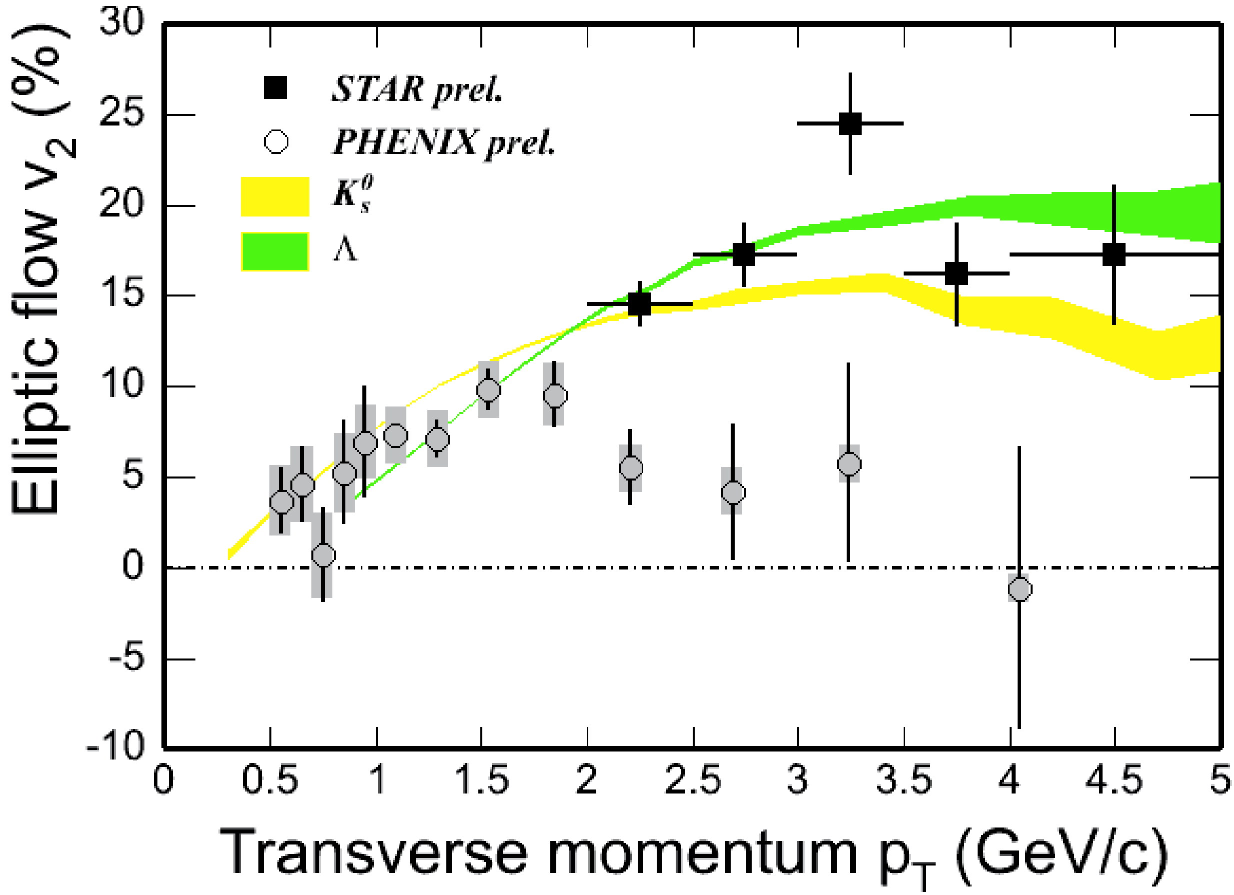
Schweda-ISMD'05 Kromeriz



$c\ (b) \rightarrow e + X$

Non-photonic electron v_2

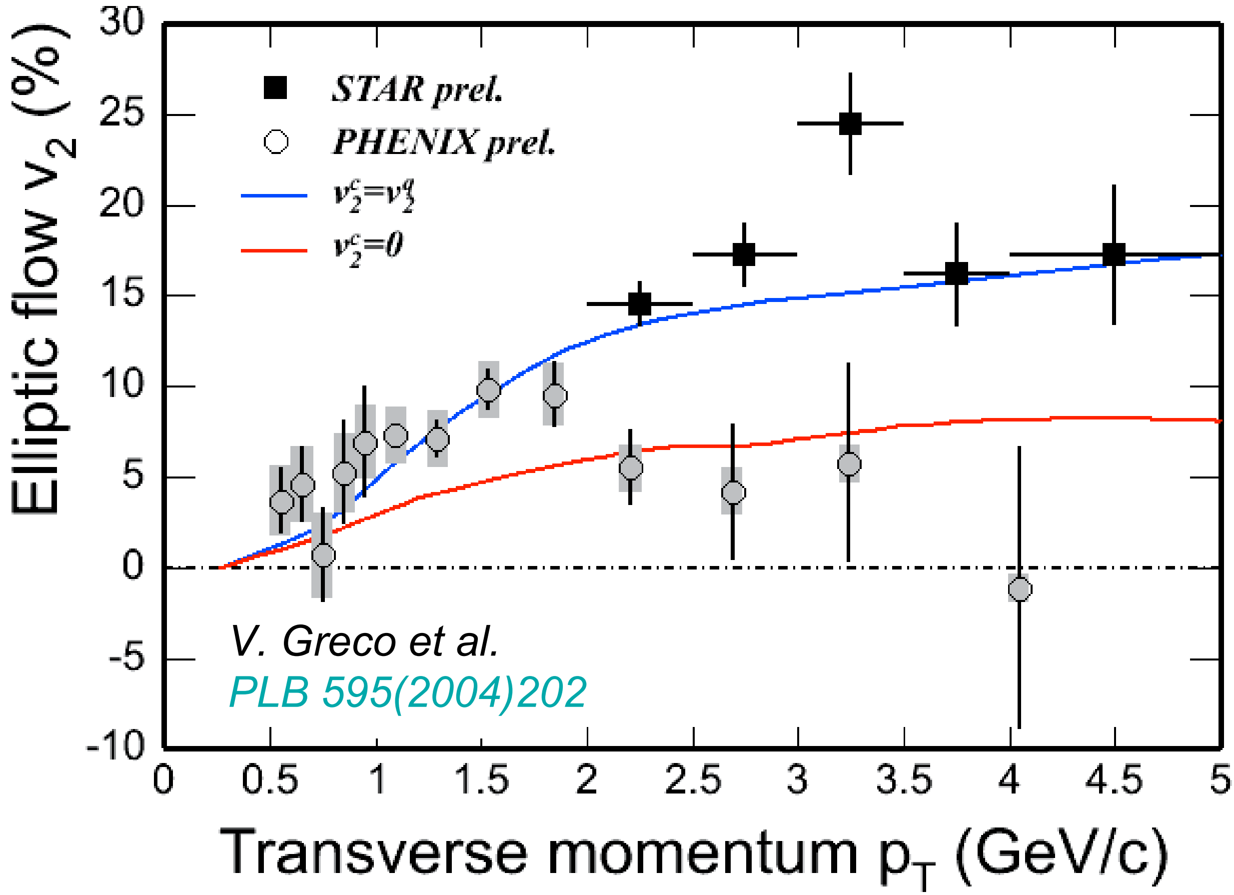
Schweda-ISMD'05 Kromeriz



$c\ (b) \rightarrow e + X$

Non-photonic electron v_2

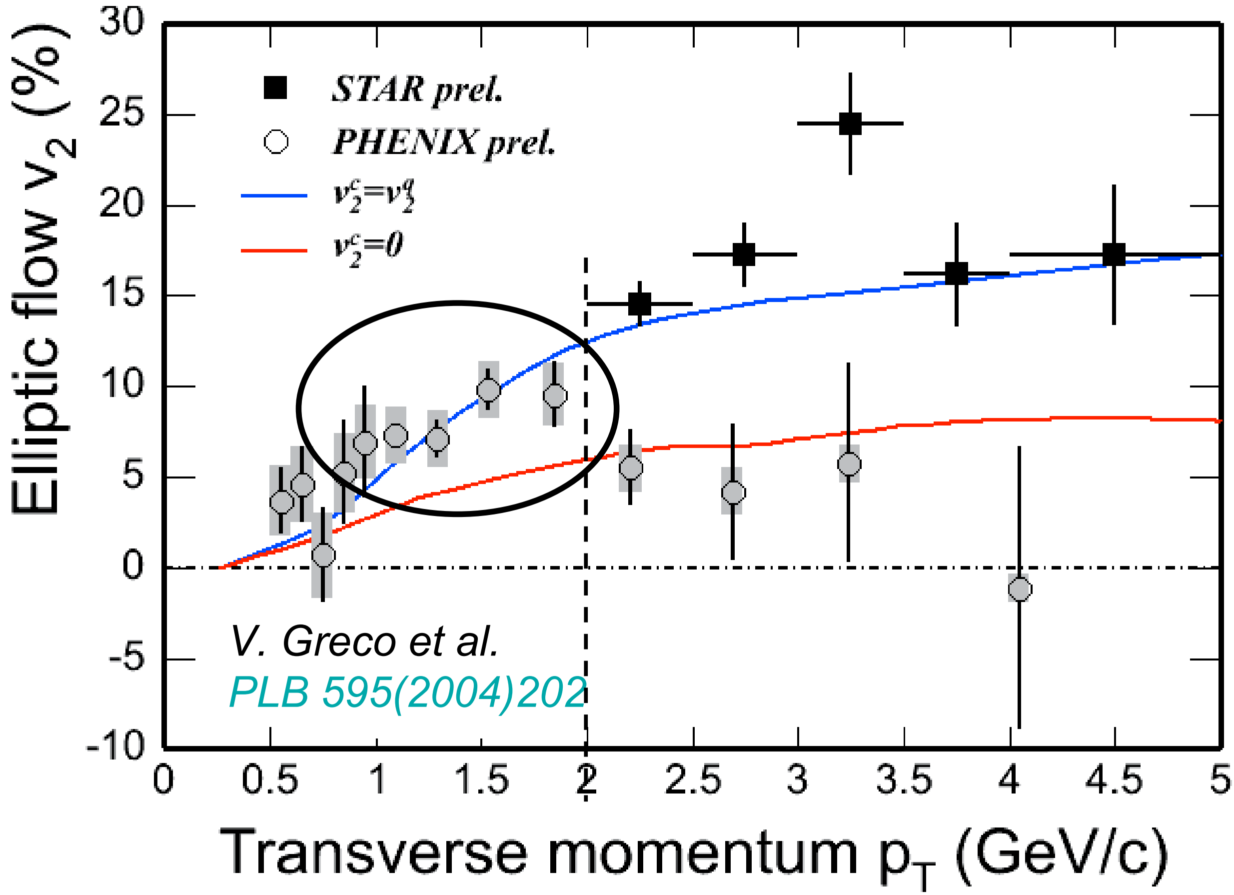
Schweda-ISMD'05 Kromeriz



c (b) → e + X

Non-photonic electron v_2

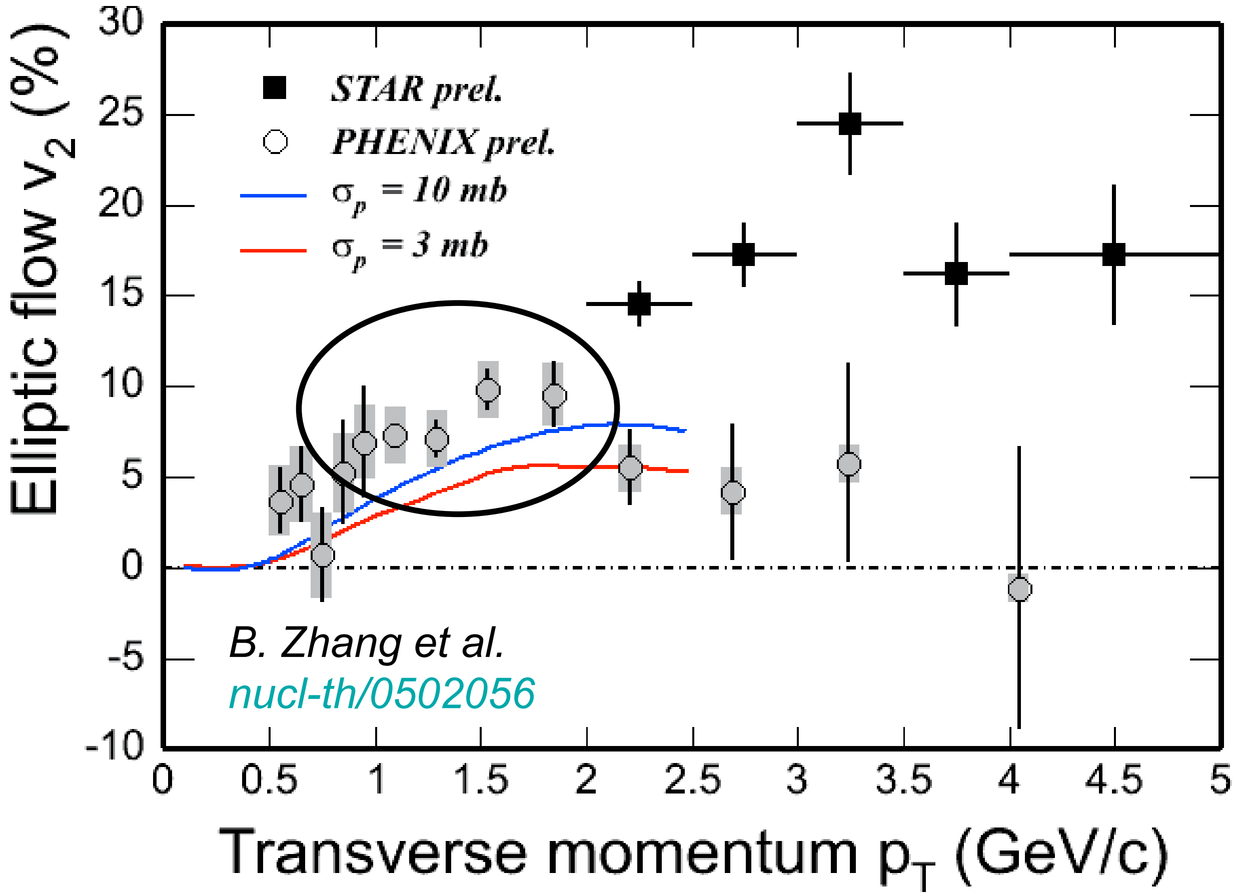
Schweda-ISMD'05 Kromeriz



c (b) → *e + X*

Non-photonic electron v_2

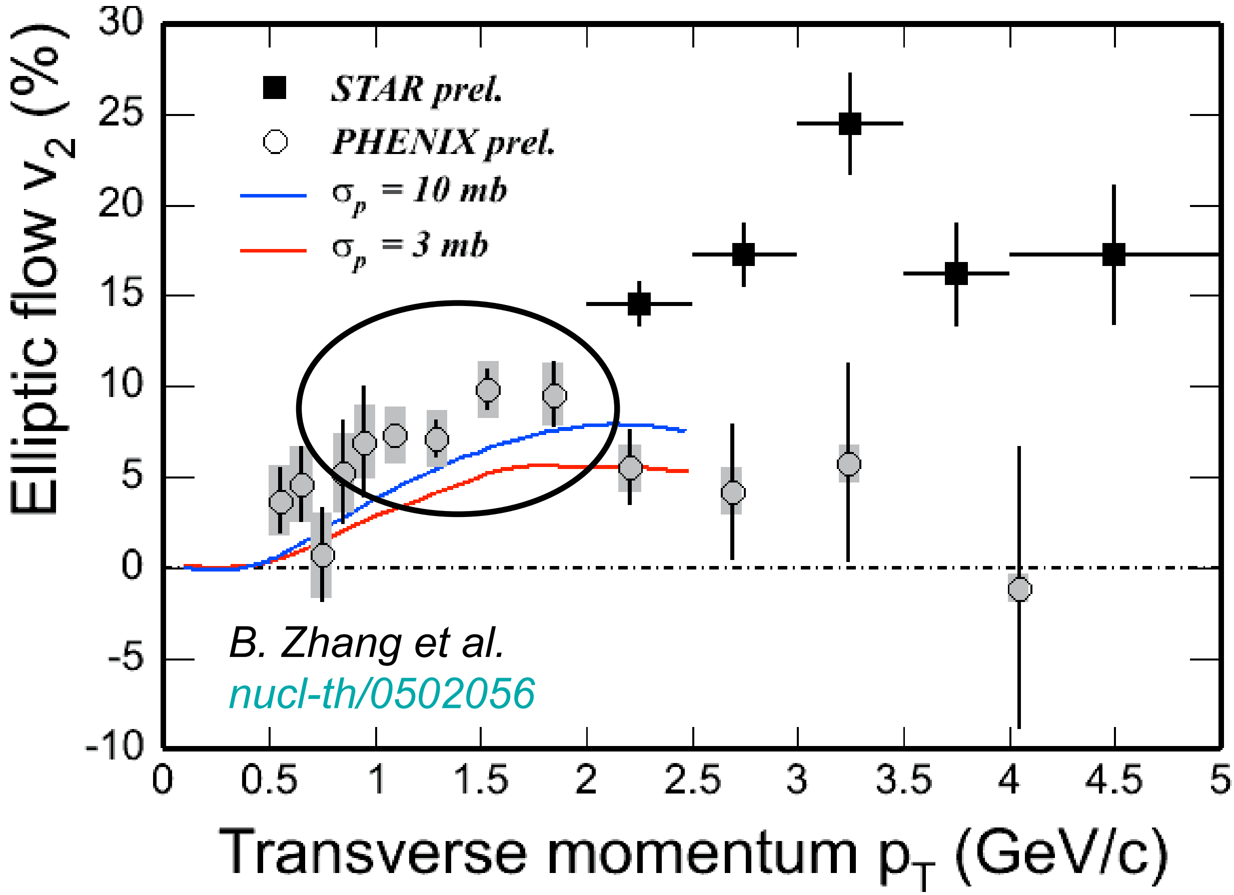
Schweda-ISMD'05 Kromeriz



c (b) → e + X

Non-photonic electron v_2

Schweda-ISMD'05 Kromeriz



c (b) → e + X

- ***Experimental data do not agree at $2<p_T(e)<5$ GeV/c!***
- ***$v_2(e)$ favors non-zero $v_2(c)$ at $p_T(e)<2$ GeV/c.***

PHENIX
NP Electron to Pion ratio p+p-MinBias