RHIC Experimental Results

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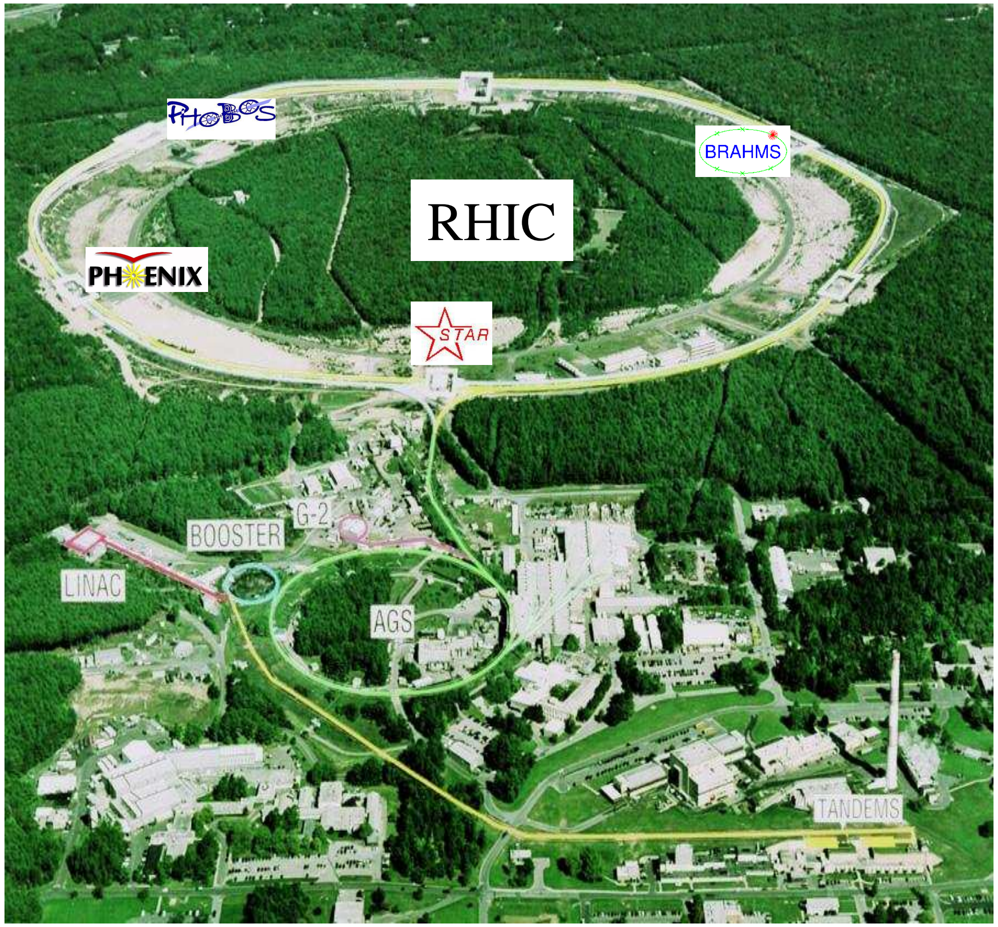
BNL

VI Workshop on Non-Perturbative QCD
American University of Paris
8 June 2001

A summary of measurements from the first year's run at RHIC will be presented. The second year's run at RHIC is presently underway with Au+Au (300 μb^{-1}) and p-p (3.5 pb^{-1}) collisions planned at $\sqrt{s_{NN}} = 200$ GeV.

The Relativistic Heavy Ion Collider at BNL

- Two independent rings 3.83 k in circumference
  - 120 bunches/ring
  - 106 ns crossing time
- Maximum Energy
  - $s^{1/2}$ = 500 GeV p-p
  - $s^{1/2}$ = 200 GeV Au-Au per N-N collision
- Design Luminosity
  - Au-Au 2×10^{26} $cm^{-2}s^{-1}$
  - p - p 2×10^{32} $cm^{-2}s^{-1}$ (polarized)
- Capable of colliding any nuclear species on any other nuclear species



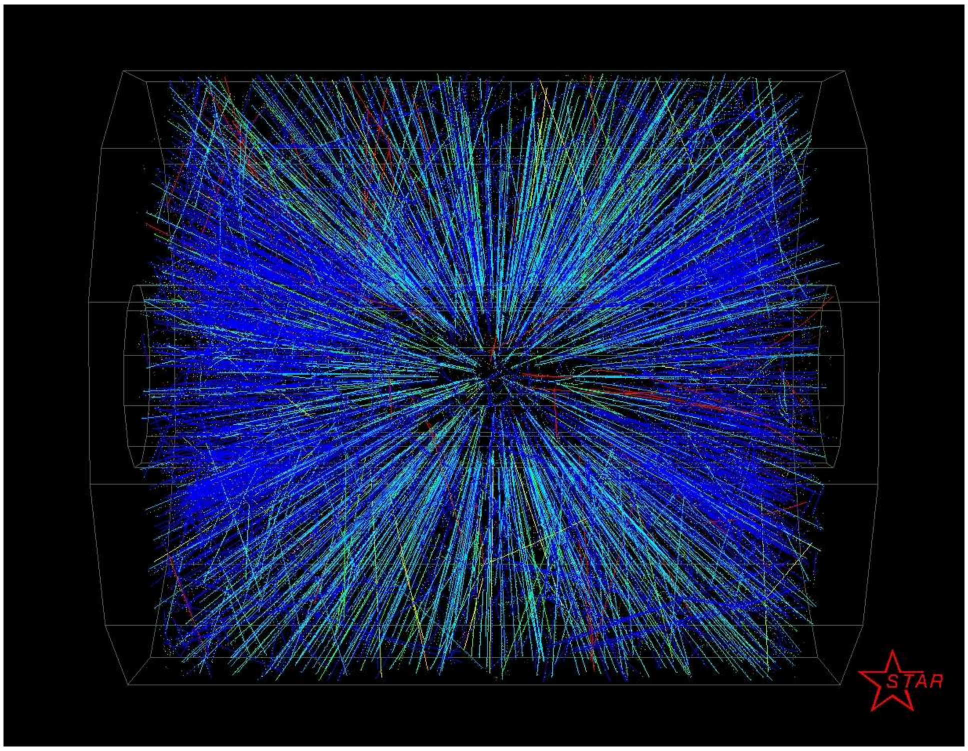
March 12, 2000

RHIC Experiments at a Glance

- **PHENIX**
  - High Granularity, High Resolution Central Spectrometer for electrons, photons and charged hadrons, $|\eta| < 0.35$, $\Delta\Phi = \pi$
  - Electron ID at the trigger level with RICH, EMCal, tracking
  - high segmentation $\gamma - \pi^0$ separation for $p_T \leq 25$ GeV/c
  - Two Endcap Di-Muon Spectrometers $1.1 \leq |y| \leq 2.5$
  - study of J/Ψ Ψ' via e^+e^-, $\mu^+\mu^-$
- **STAR**
  - large acceptance TPC tracking detector
  - good PID for $p_T \leq$ 1GeV/c
  - central TPC full tracking in $\Delta\Phi = 2\pi$ $|\eta| < 1$
  - endcap TPC extends tracking to $|\eta| \leq 2$
  - upgrade to Barrel/Endcap EMCalorimeter $|\eta| \leq 1 - 2$
  - Silicon Vertex Detector for short lived hyperons
- **PHOBOS**
  - large area silicon tracking ($dN_{ch}/d\eta$ over 4π)
  - momentum and particle ID at midrapidity $p^\pm$, $K^\pm$, $\pi^\pm$
  - interested in long lived sources, HBT at very low p_T
- **BRAHMS**
  - moveable 2-arm spectrometer
  - small solid angles, excellent PID
  - $p^\pm$, $K^\pm$, $\pi^\pm$ over wide kinematic and rapidity range

Our First Event, June 12, 2000

Au+Au $\sqrt{s_{NN}} = 56$ GeV



STAR—l'Étoile

Schematic Nuclear Collision Geometry

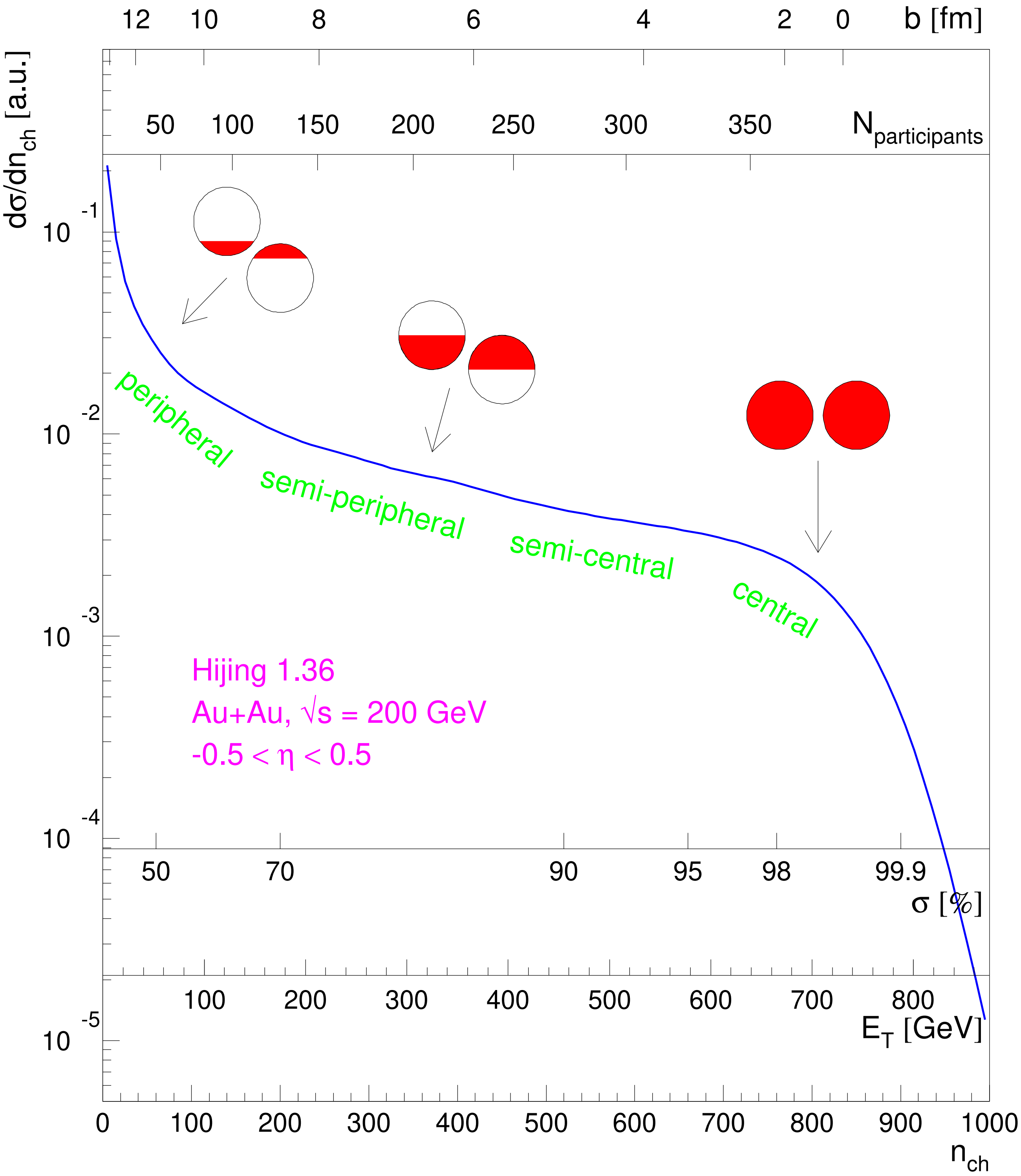
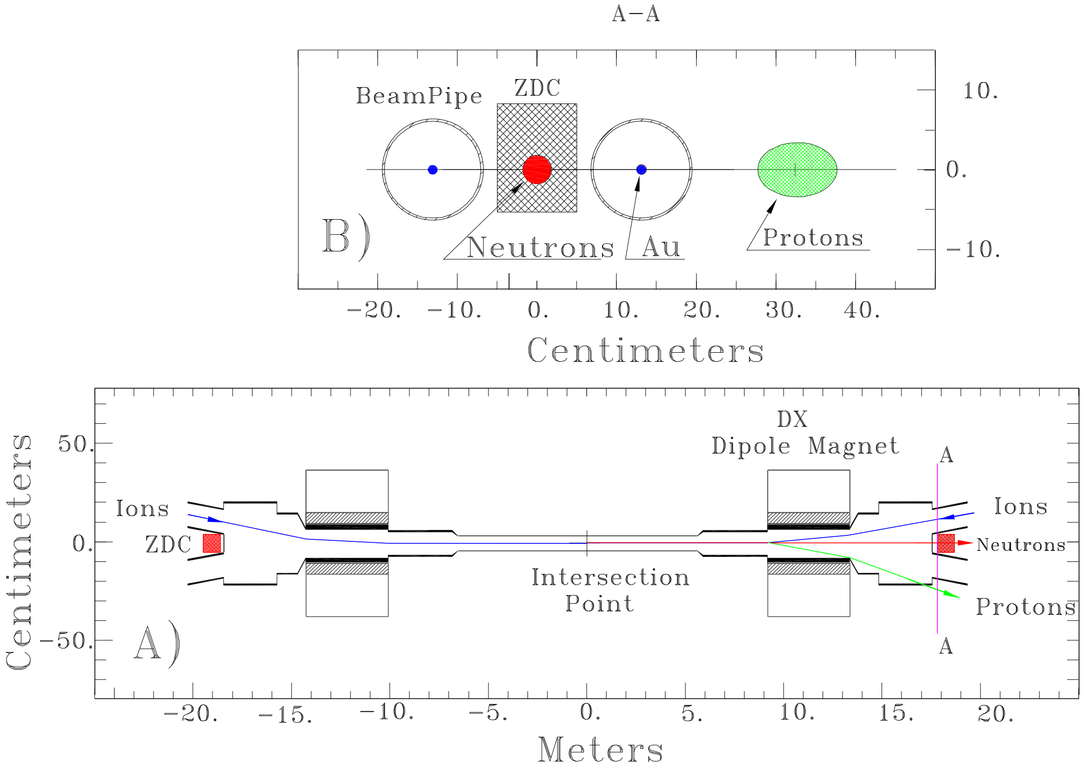


Figure 1: Schematic Nuclear Collision Geometry from Star-Yale

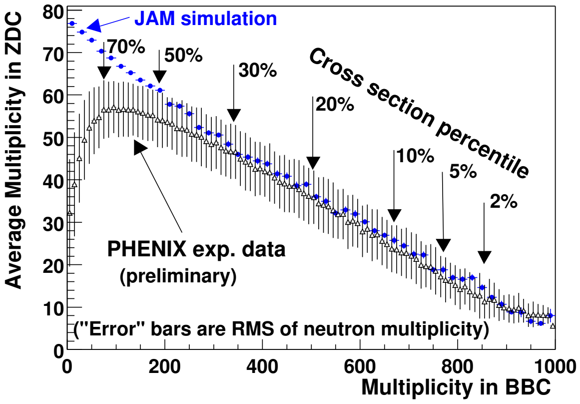
Nuclear Geometry Definition—Experiment

Identical Zero Degree Calorimeter all Expts

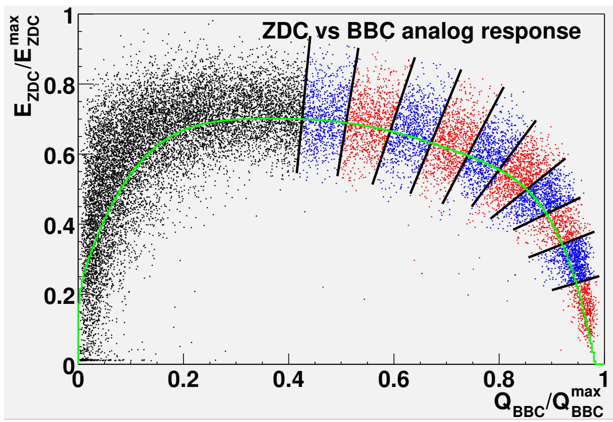


Plus/or BeamBeam/Paddle Counters $3 \leq |\eta| \leq\sim 4$

Phenix Ideal

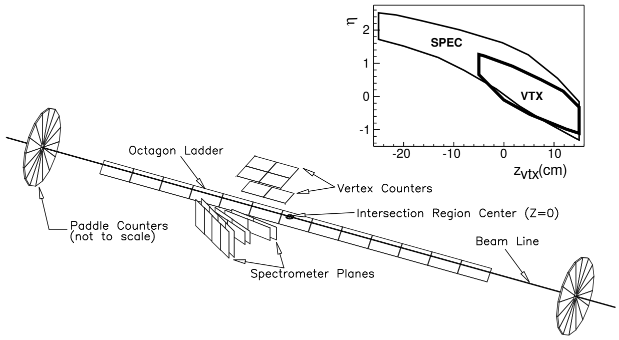


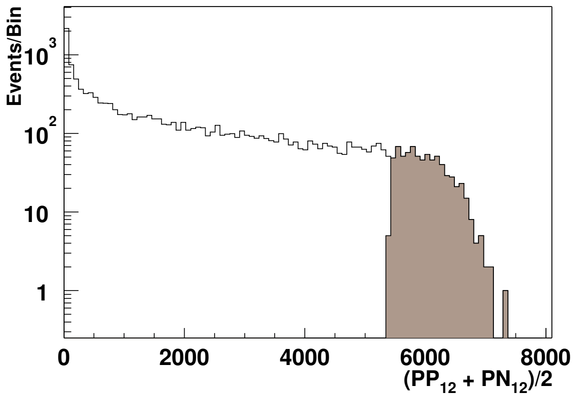
Phenix Real



First Rhic Publication 19 July 2000

Phobos $dN_{ch}/d\eta|_{|\eta|<1}$
Phys. Rev. Lett. 85, 3100 (2000)





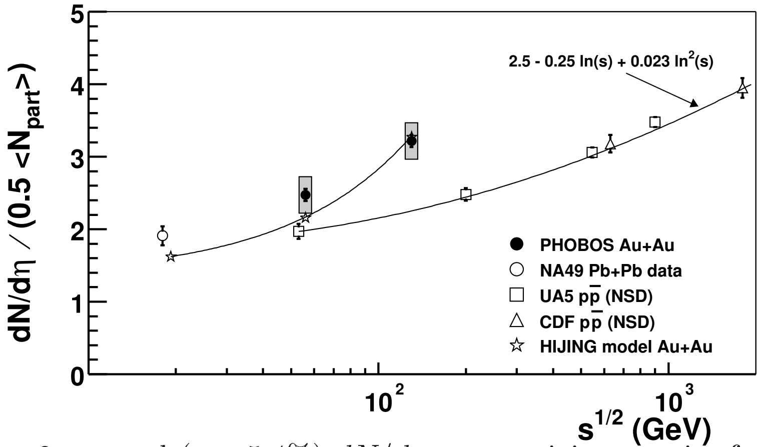


Figure 2: central (top 5.4%) $dN/d\eta$ per participant pair cf p-p

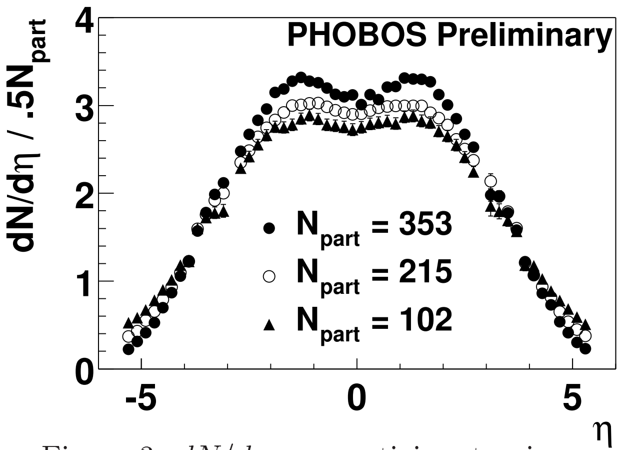


Figure 3: $dN/d\eta$ per participant pair vs η

PHENIX $dN_{ch}/d\eta|_{\eta=0}$ $dE_T/d\eta|_{\eta=0}$

Phys. Rev. Lett. **86**, 3500 (2001), nucl-ex/0104015

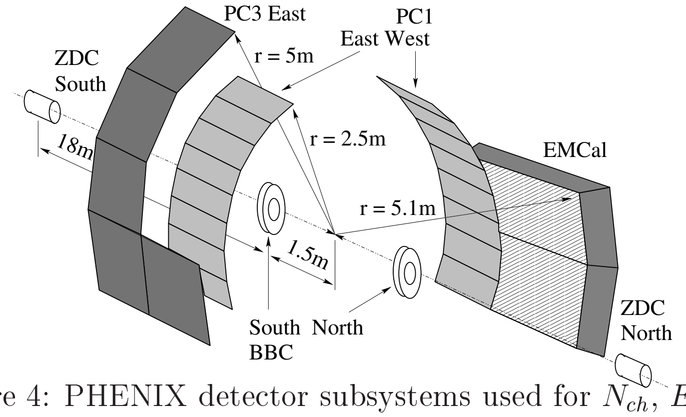
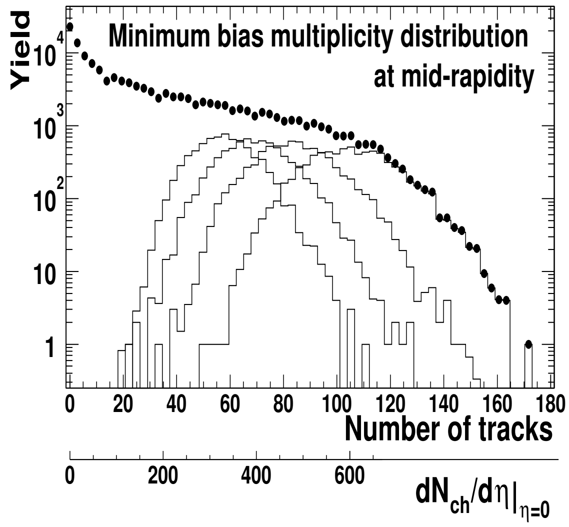
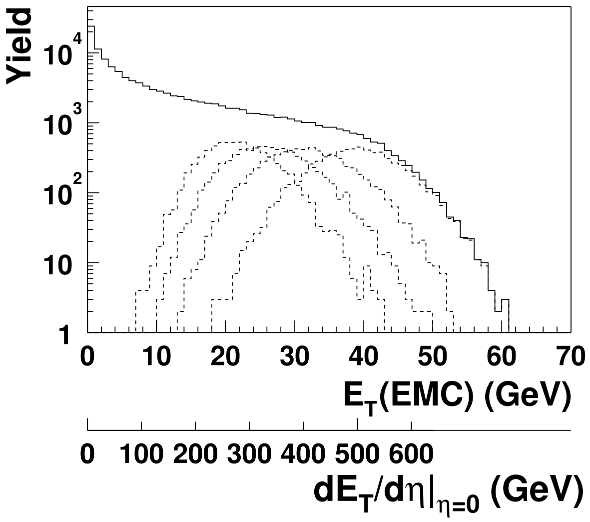
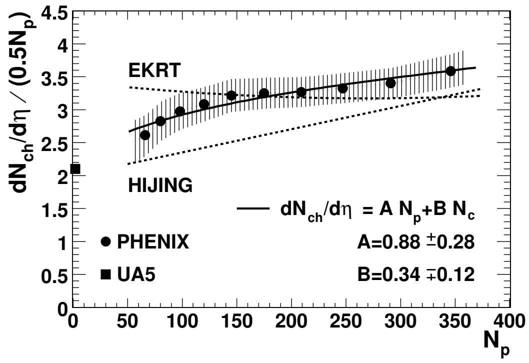
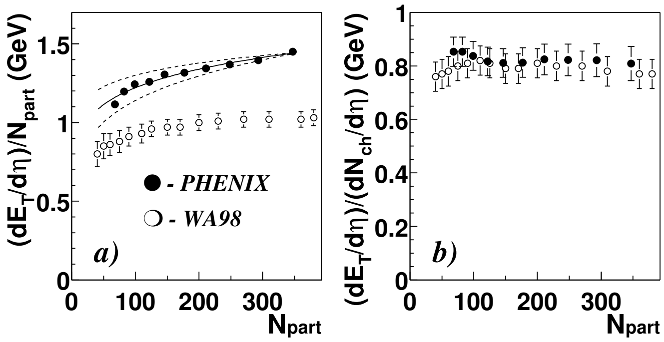


Figure 4: PHENIX detector subsystems used for N_{ch}, E_T, π^0







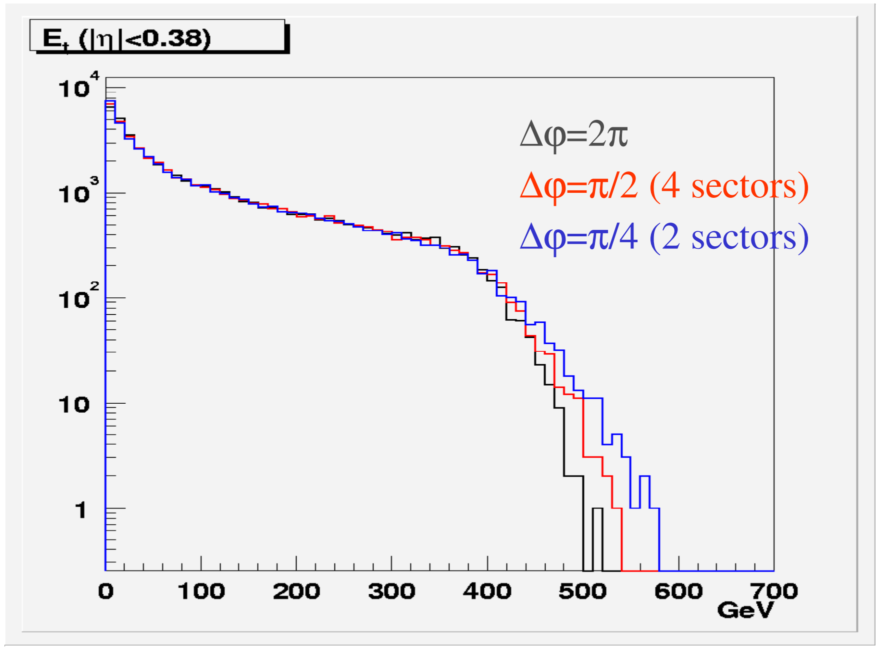


WNM fails, term $\propto N_{coll}$ indicated

$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\pi R^2} \rightarrow 4.6$ **GeV/fm^3 at RHIC (top 2%) cf 2.9 CERN**

due to increase in multiplicity $\langle E_T\rangle/\langle N_{ch}\rangle$ stays constant

Acceptance cut in E_t measurements



Limited EMCal acceptance changes *Et* distribution tail due to fluctuations of the number of particles in acceptance

Shape of Upper Edge is Acceptance Dependent

Identified $\pi^{\pm}$, $K^{\pm}$ $p^{\pm}$

PHENIX—QM2001 Proceedings

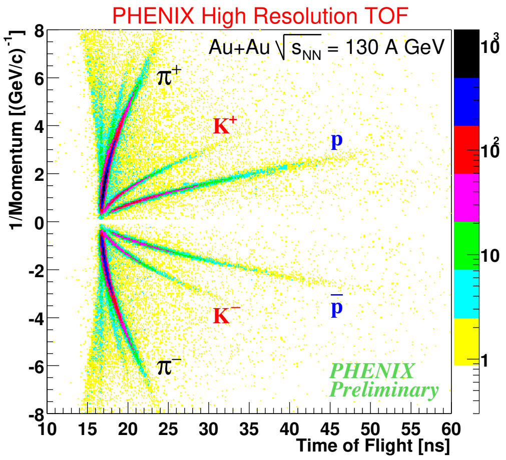


Figure 5: PHENIX PID in Time of Flight $|\eta| \leq 0.35$ $\Delta\Phi = \pi/8$

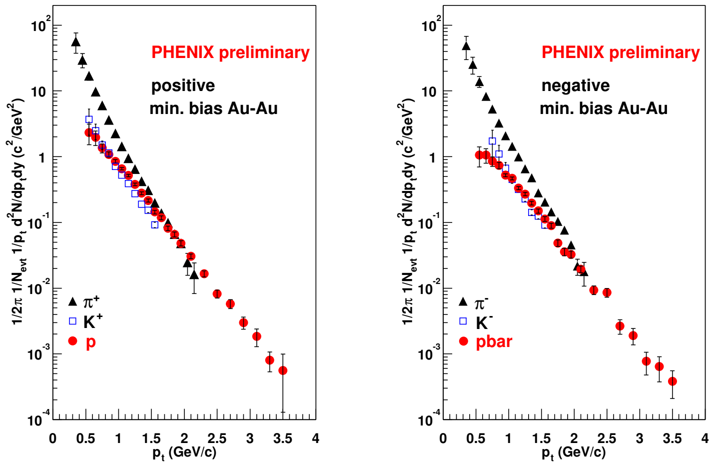


Figure 6: Semi-Inclusive Invariant Yield for Min-Bias Au+Au

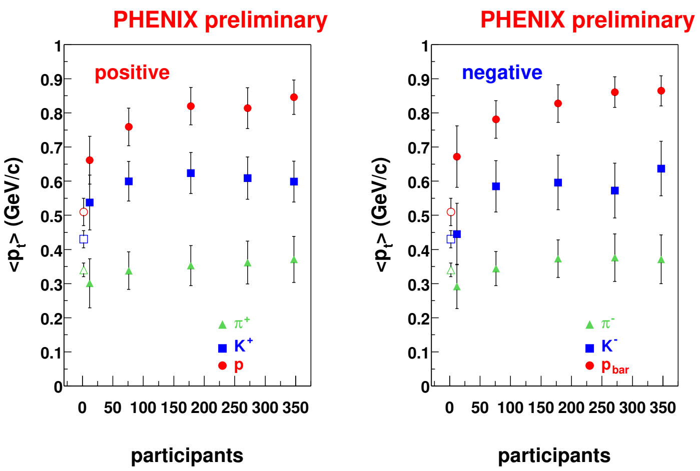
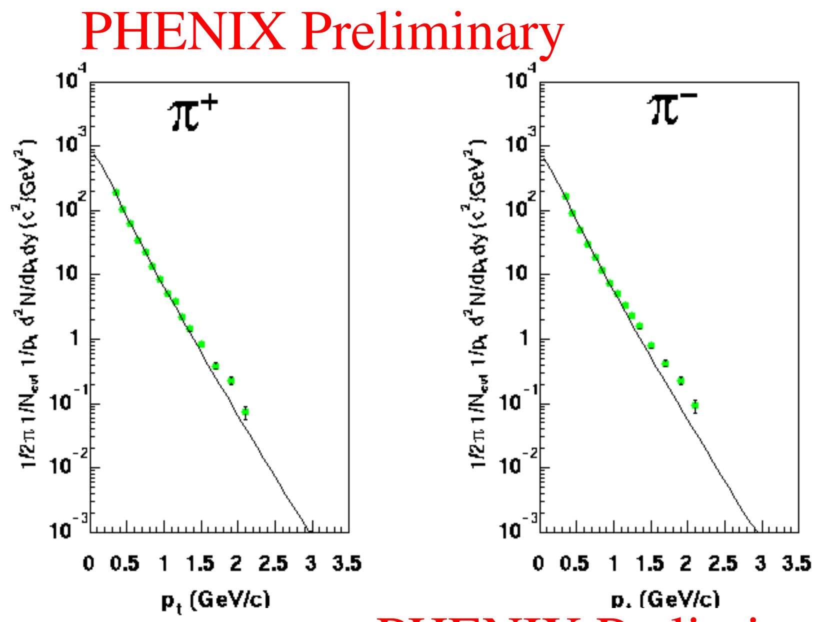
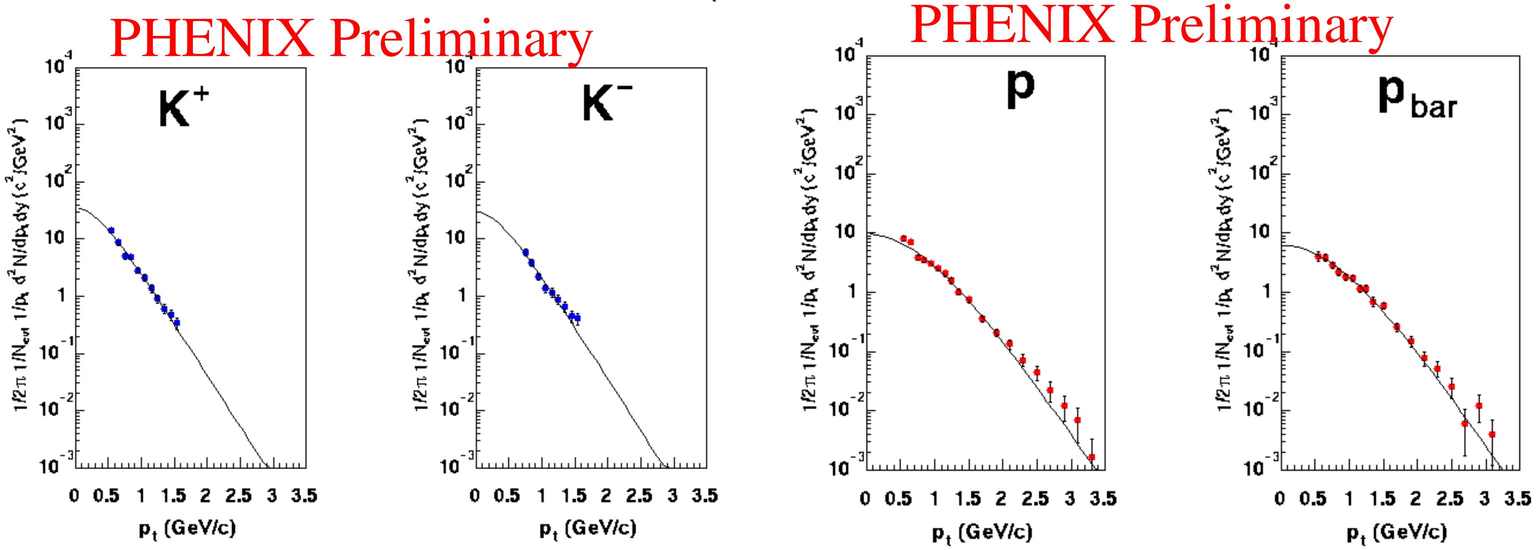


Figure 7: $\langle p_T \rangle$ vs N_{part} (dn/dy). Where is VanHove Signature?

HYDRO Fits—Theorists Get to Work

An example of a 1σ χ^2/NDF fit to 5% central data





J. Burward-Hoy

$\bar{p}/p$, K^-/K^+, π^-/π^+

All 4 Experiments Agree

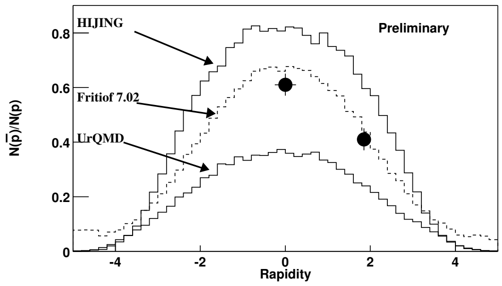
Little or No dependence on centrality or p_T

		$\bar{p}/p$	MidRapidity
STAR (PRL **86**)	MinBias	$0.65 \pm 0.01 \pm 0.07$	$0.4 \leq p_T \leq 1.0$ GeV/c
PHENIX	MinBias	$0.64 \pm 0.01 \pm 0.07$	$0.8 \leq p_T \leq 3.0$ GeV/c
PHOBOS	top 11%	$0.60 \pm 0.04 \pm 0.06$	$0.1 \leq p_T \leq 1.0$ GeV/c
BRAHMS	top 40%	$0.62 \pm 0.04 \pm 0.05$	$0.4 \leq p_T \leq 1.9$ GeV/c

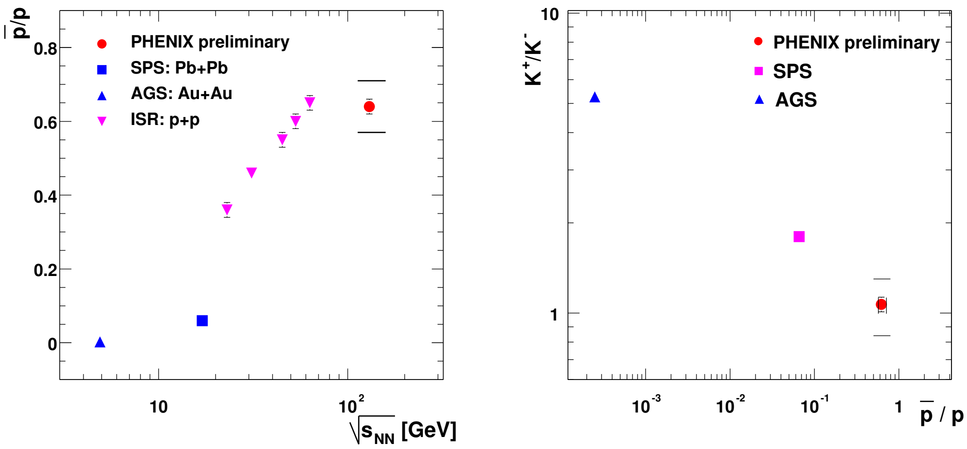
		K^-/K^+	MidRapidity
PHENIX	MinBias	$0.92 \pm 0.03 \pm 0.22$	$0.8 \leq p_T \leq 1.6$ GeV/c
PHOBOS	top 11%	$0.91 \pm 0.07 \pm 0.06$	$0.1 \leq p_T \leq 0.7$ GeV/c
BRAHMS	top 40%	$0.89 \pm 0.07 \pm 0.05$	$0.3 \leq p_T \leq 1.7$ GeV/c

		π^-/π^+	MidRapidity
PHOBOS	top 11%	$1.00 \pm 0.01 \pm 0.02$	$0.2 \leq p_T \leq 0.6$ GeV/c
BRAHMS	top 40%	$0.95 \pm 0.03 \pm 0.05$	$0.3 \leq p_T \leq 1.7$ GeV/c

Brahms—y dependence of $\bar{p}/p$



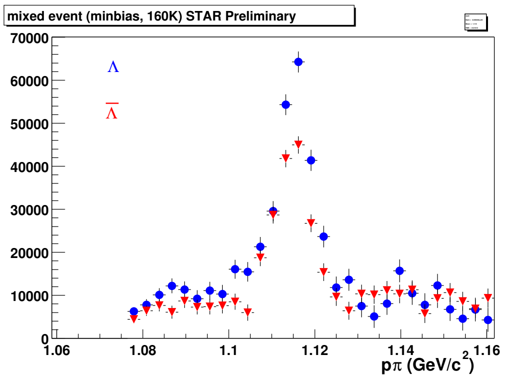
$\sqrt{s_{NN}}$ Dependence



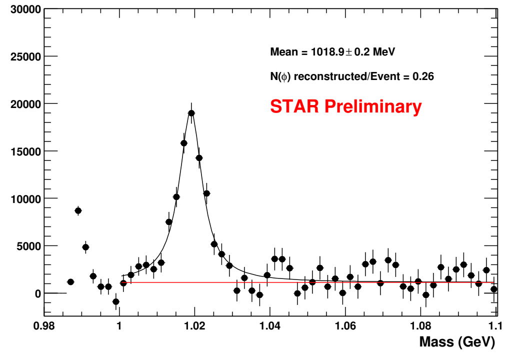
STAR Resonances, Hyperons, Antinucleons

nucl-ex/0104001, nucl-ex/0104007

$\Lambda\ \bar{\Lambda}$

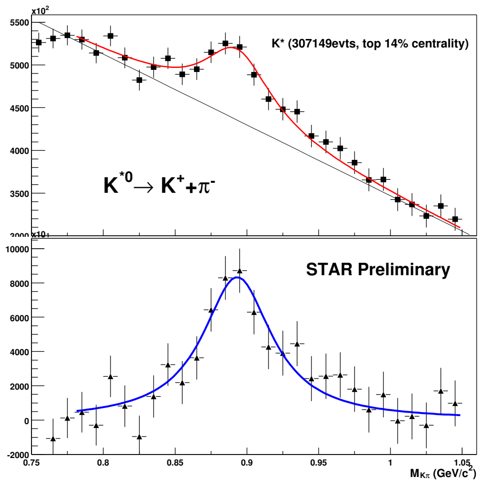


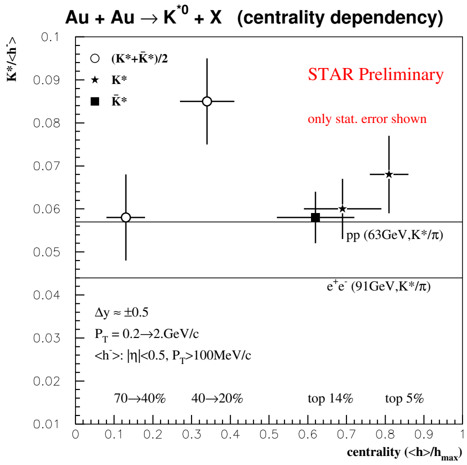
$\phi \to K^+K^-$



$\bar{\Lambda}/\Lambda = 0.73 \pm 0.03\ p_T < 2$ GeV/c

$K^{*0} \to K^+ + \pi^-$

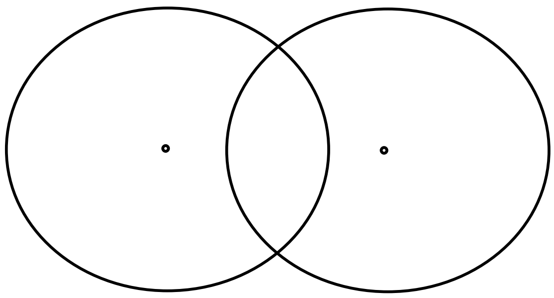




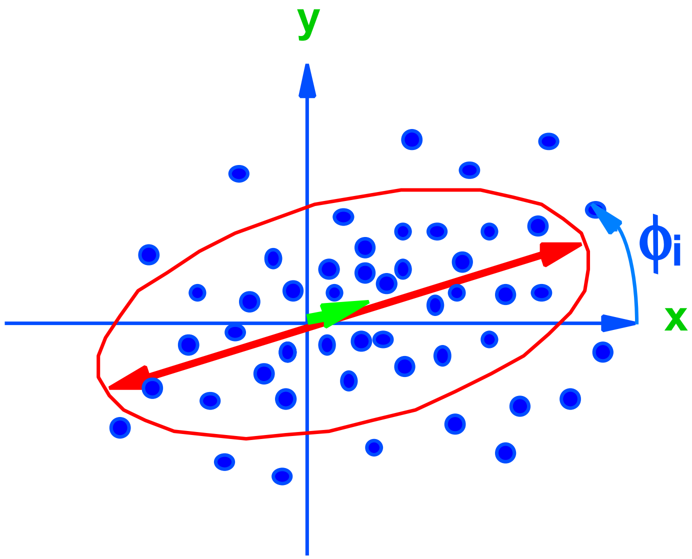
$K^{*0}/h^- \approx 0.07\ K^{*0}/K \approx 0.4 \sim 25\%$ systematic errors

Factor of 50 increase of $\bar{d}$ cf CERN SPS

Elliptic Flow

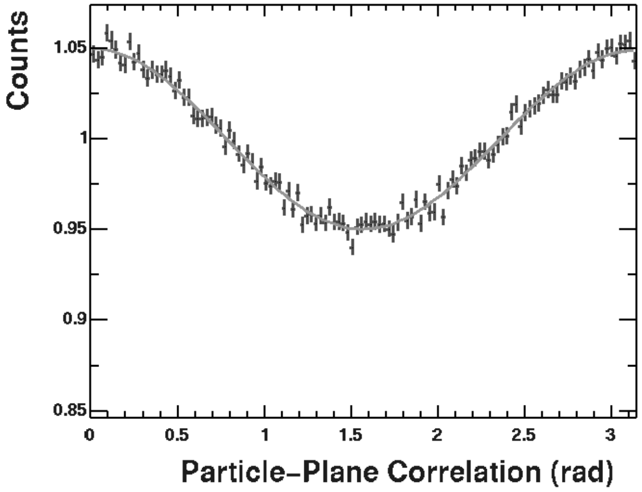


Azimuthal Anisotropy



- **Find event plane**

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{\sum_i w_i \cdot \sin(2\,\phi_i)}{\sum_i w_i \cdot \cos(2\,\phi_i)}\right)$$



- **Correlate particles to event plane**

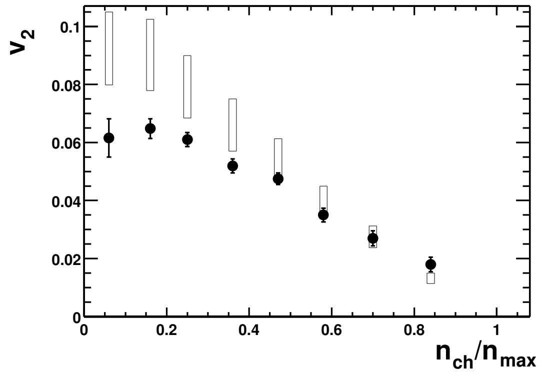
$$v_2 = \langle \cos(2[\phi - \Psi_2]) \rangle$$

•**PRL 86:402, 2001**

Elliptic Flow—Star

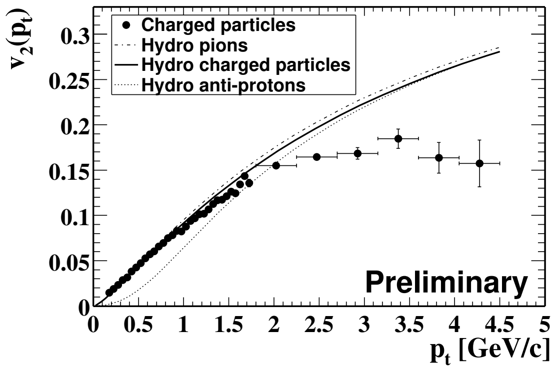
Phys. Rev. Lett. **86**, 402 (2001), nucl-ex/0104006

v_2 vs Centrality



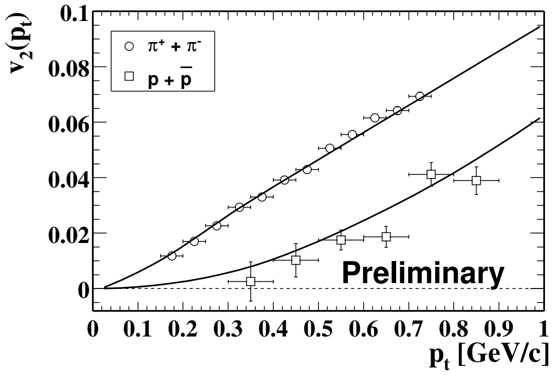
Elliptic Flow vs Almond ϵ

v_2 vs p_T

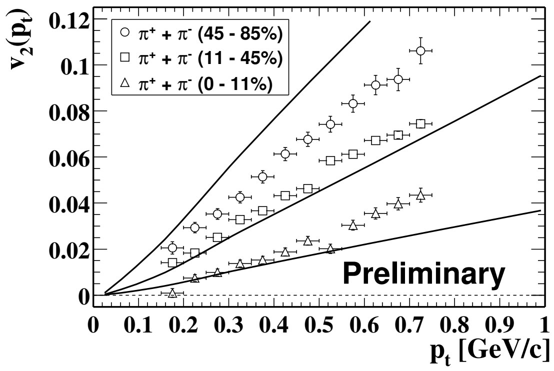


MinBias, all charged particles

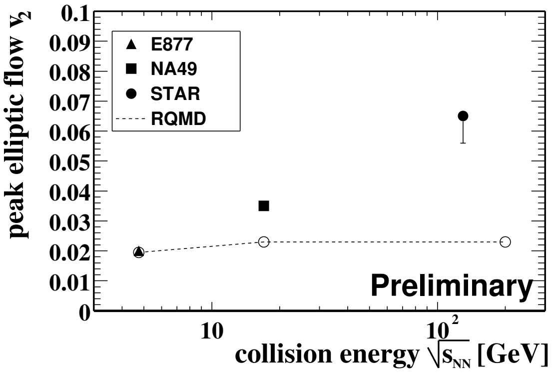
$p^{\pm}$ and $\pi^{\pm}$



$\pi^{\pm}$ vs Centrality

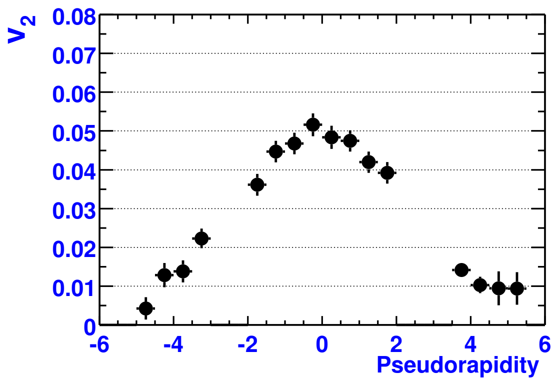


peak v_2 vs $\sqrt{s_{NN}}$



peak v_2 from AGS to RHIC

PHOBOS nucl-ex/0105015



PHOBOS v_2 vs η MinBias

Elliptic Flow—PHENIX

Uses 2-particle Azimuthal Correlations nucl-ex/0105003

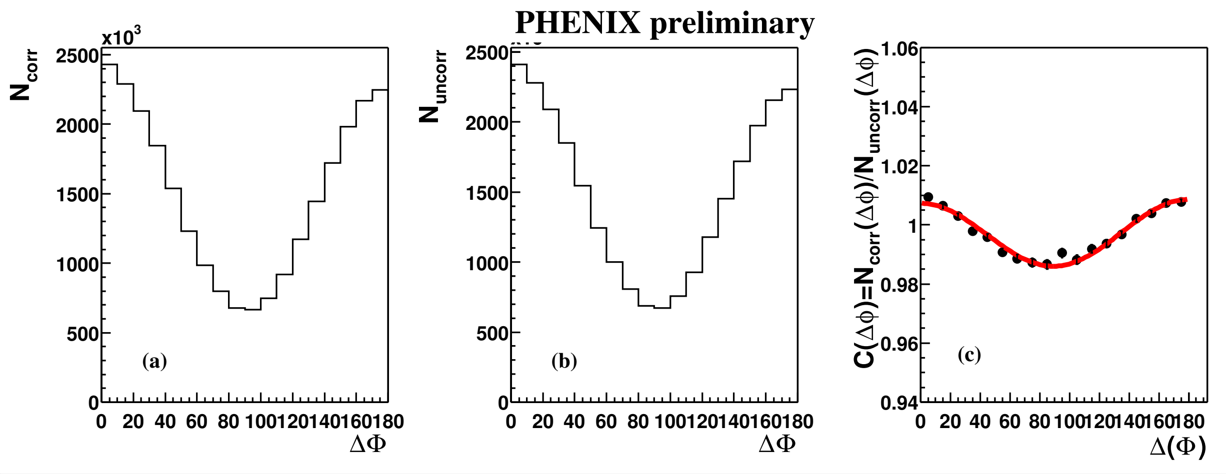
Uses standard 2-particle Correlation Function

$$C(\Delta\phi) = \frac{F_{cor}(\Delta\phi)}{B_{uncor}(\Delta\phi)}$$

$$C(\Delta\phi) \propto [1 + 2\lambda_1 \cos(\Delta\phi) + 2\lambda_2 \cos(2\Delta\phi)]$$

$$v_2 = \sqrt{\lambda_2}$$

$F_{cor}(\Delta\phi)$ $B_{uncor}(\Delta\phi)$ $C(\Delta\phi) = F/B$



New Elegant Theoretical Analysis
N. Borghini, P. M. Dinh, J.-Y. Ollitrault, nucl-th/0105040

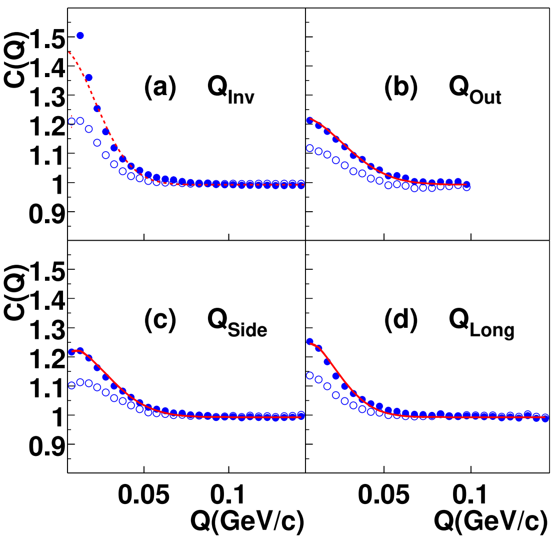
Pion Interferometry—2-Particle Correlations

STAR π^- pairs $|\eta| < 0.5$, subm PRL May 2001
PHENIX, nucl-ex/0104020 (agrees with STAR, not shown)

$$C(q_1, q_2) = 1 + \lambda \exp(-Q_{inv}^2 R_{inv}^2)$$

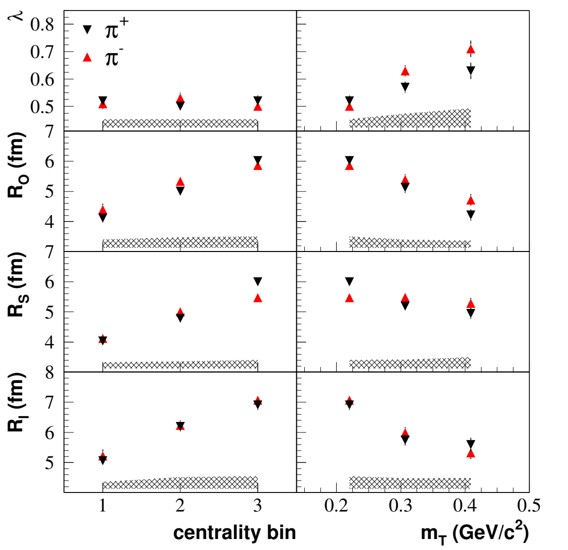
$$C(q_1, q_2) = 1 + \lambda \exp(-R_o^2 q_{out}^2 - R_s^2 q_{side}^2 - R_l^2 q_{long}^2)$$

$C(Q)$ w/wo Coulomb



Central 12%. $0.125 < p_T < 0.225$ GeV/c

Centrality & m_T



Bin 3 central 12%, bin 2 32%-12%, bin 1 62%-32% ($0.125 < p_T < 0.225$)

m_T for central

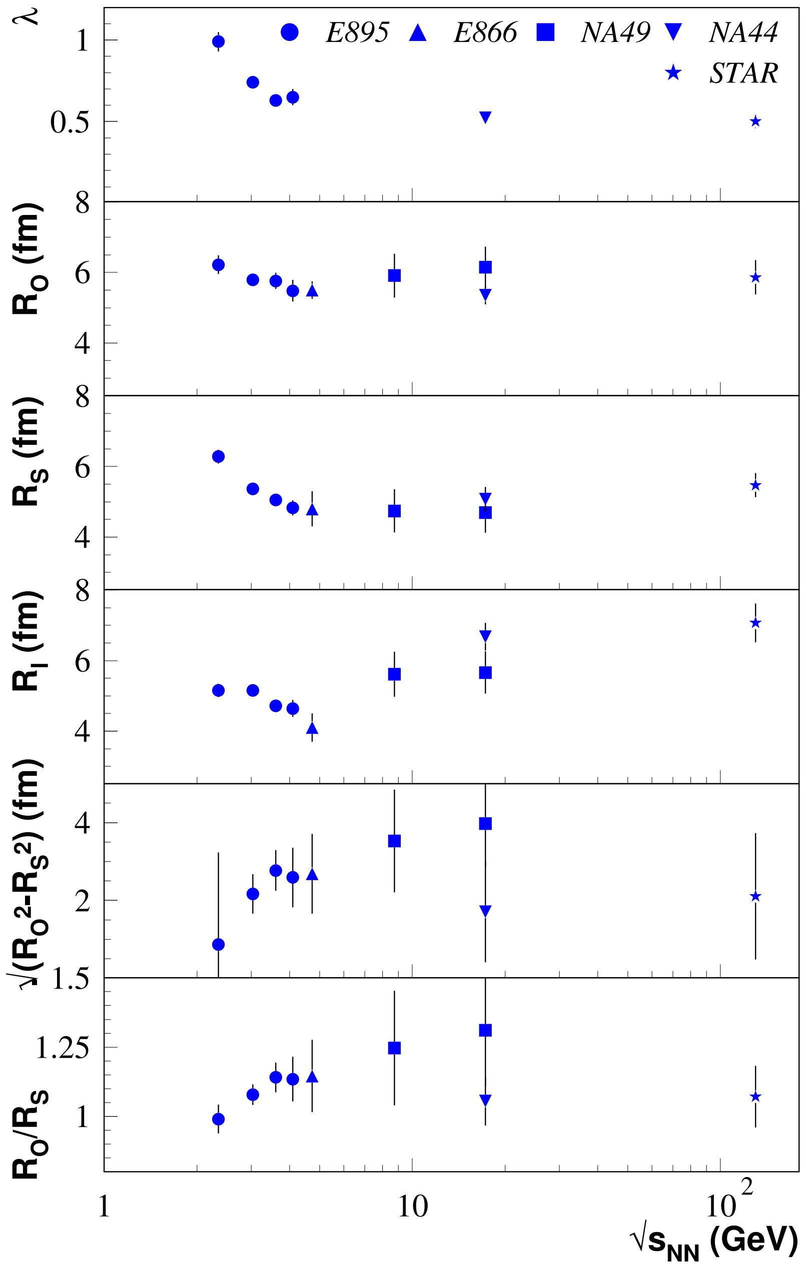
n.b. at $m_T = 0.4$ **GeV/c²** $R_o < R_s$

but conventionally the freezout duration $\tau = \sqrt{R_o^2 - R_s^2}/\langle\beta_T\rangle$?

THEORISTS start thinking

Midrapidity HBT Radii

$\sqrt{s_{NN}}$ dependence



π^- HBT radii central Au+Au, Pb+Pb

Smooth continuation from lower energies, no anomalous sizes

Event by Event Physics

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

Analytical formula for statistically independent emission

For statistical independent emission an analytical formula for the distribution in M_{p_T} can be obtained. It depends on the 4 semi-inclusive parameters $\langle n \rangle$, $1/k$, b and p which are derived from the quoted means and standard deviations of the semi-inclusive p_T and multiplicity distributions for central Pb+Pb collisions for NA49. The result is in excellent agreement with the NA49 measurement.

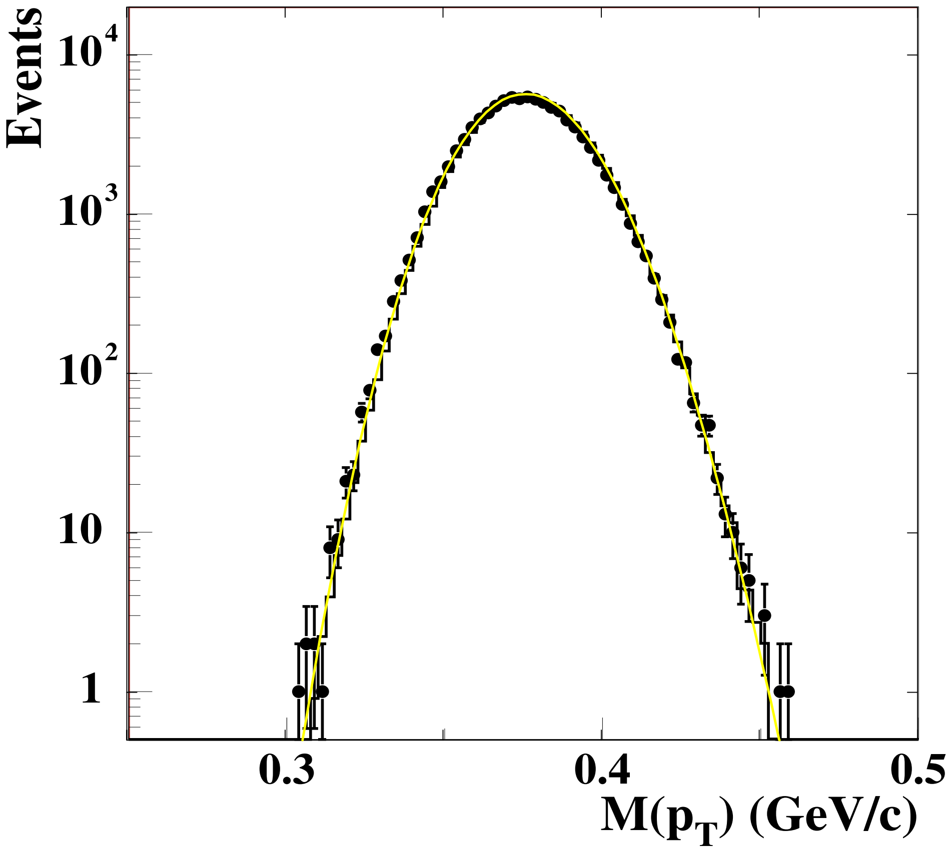


Figure 8: Full distribution in M_{p_T} (light line) compared to NA49 measurement (filled points) and mixed event distribution (histogram).

Hint, it's a Gamma Distribution

see M. J. Tannenbaum, Phys. Lett. B498, 29 (2001)

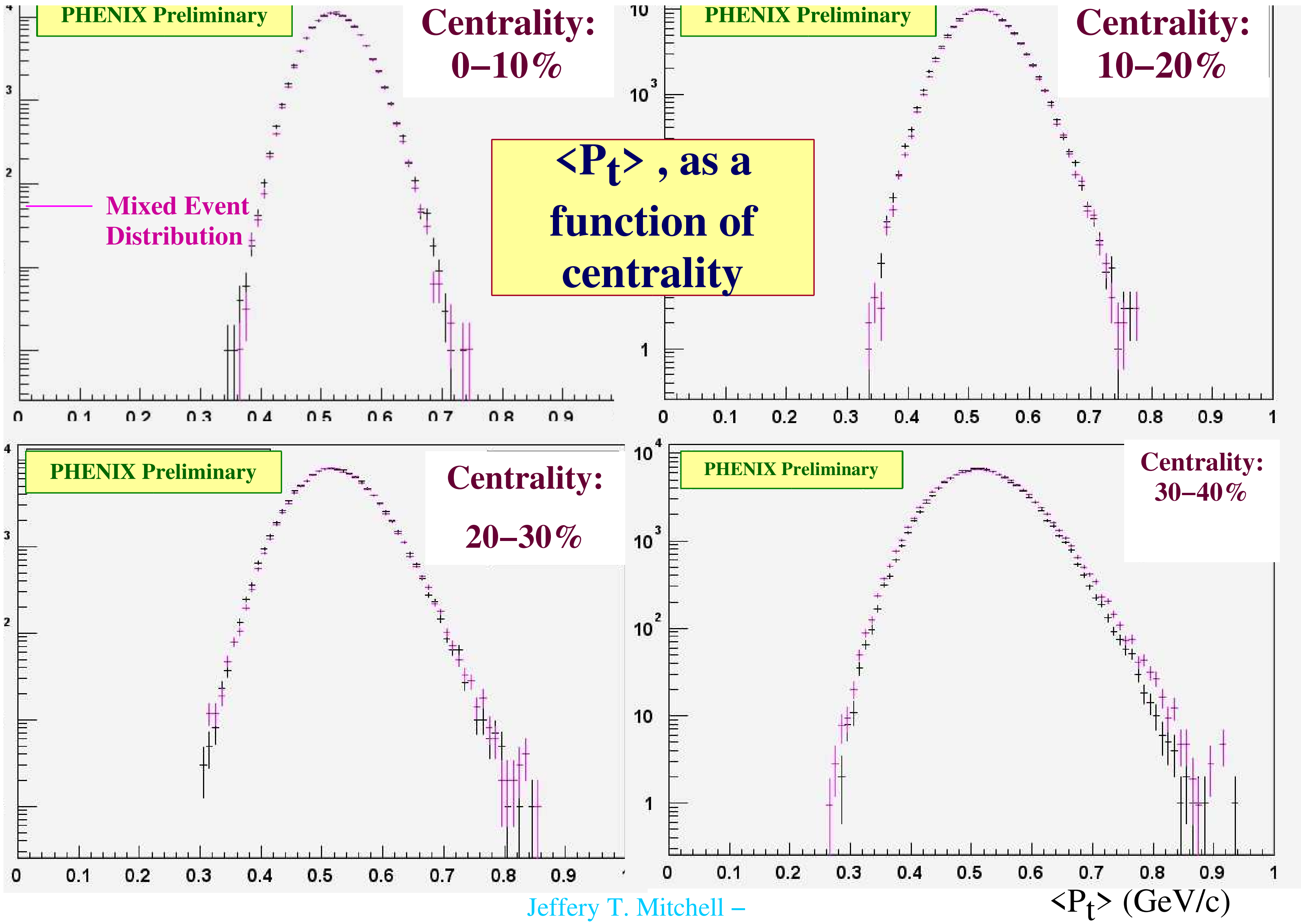
Event by Event Physics—RHIC results

STAR showed M_{p_T} at Quark Matter but

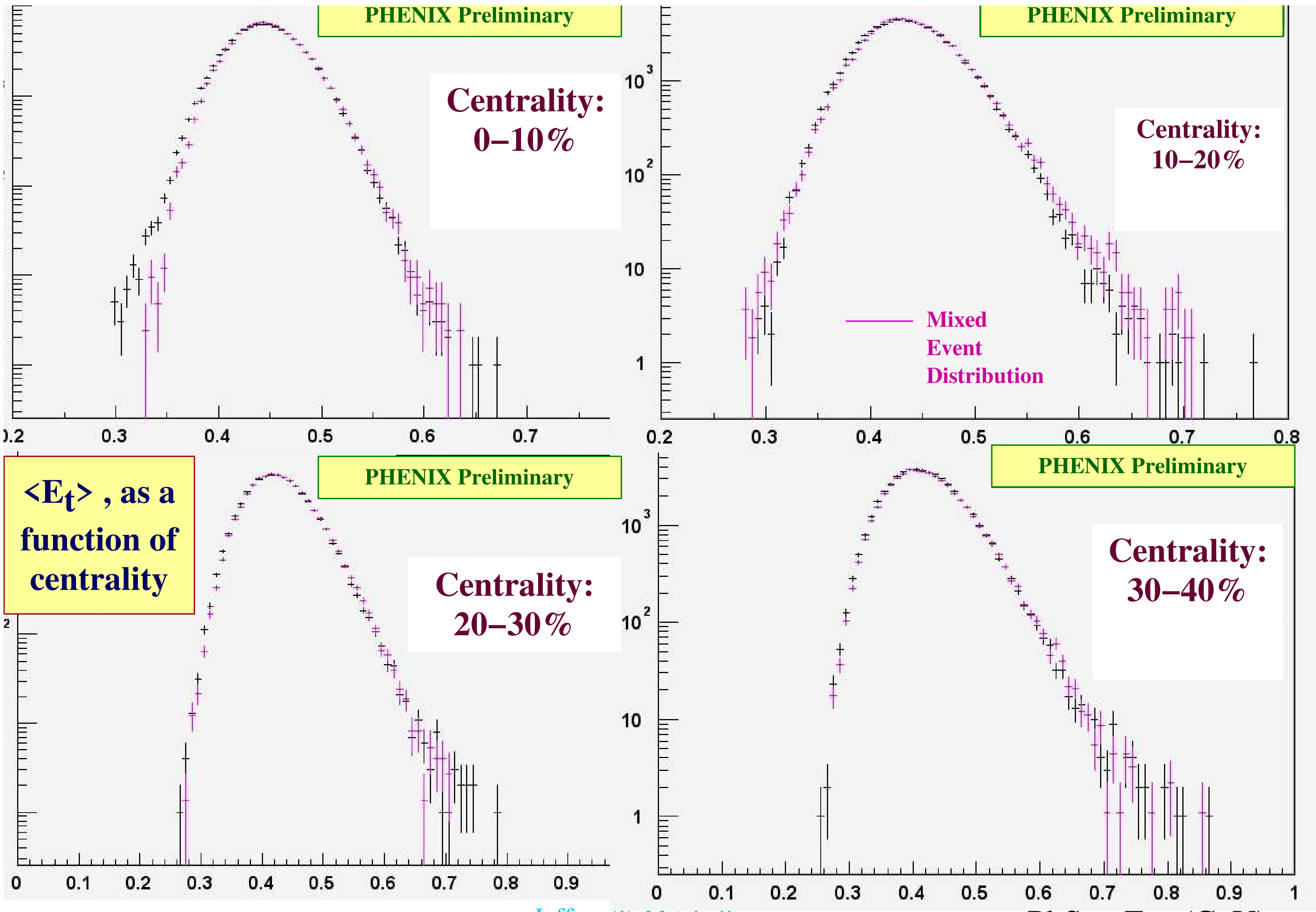
PHENIX Jeff Mitchell, APS Meeting April 2001

M_{p_T} and M_{E_T} vs Centrality
Anything beyond Statistical Independent Emission is Small $\sim$%

Charge Fluctuations Soon



Jeffery T. Mitchell –
APS/Washington DC – 4/30/01

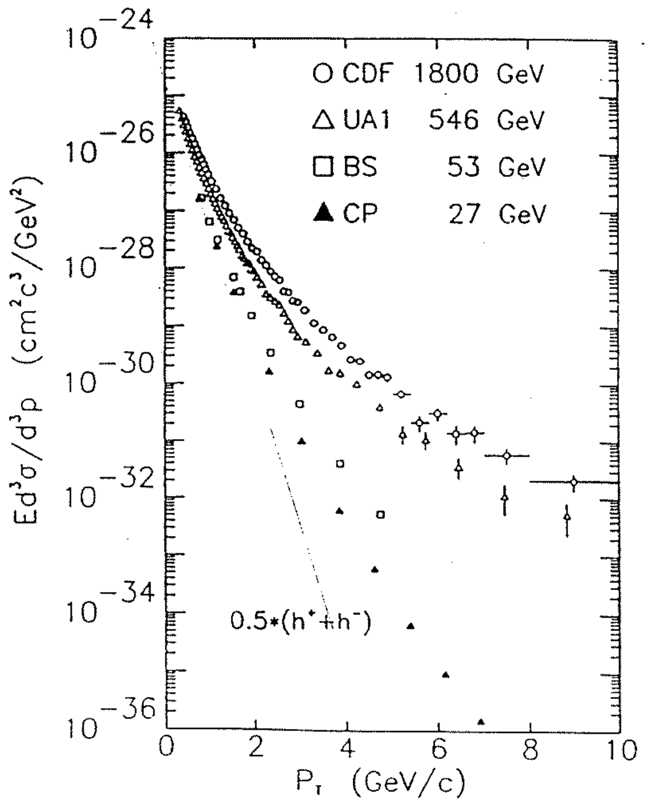


Jeffery T. Mitchell – APS/Washington DC – 4/30/01

High p_T Physics

From my talk in 1998

My Best Bet on Discovering QGP
Utilizes semi-Inclusive π^0 or $\pi^\pm$ production



Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T tablulated by CDF for a range of C.M. energies $\sqrt{s}$. There is an exponential tail (e^{-6p_T}) at low p_T, which depends very little on $\sqrt{s}$. This is the soft physics region, where the hadrons are fragments of 'beam jets'. At higher p_T there is a power-law tail which depends very strongly on $\sqrt{s}$. This is the hard-scattering region, where the hadrons are fragments of the high p_T QCD jets from constituent-scattering. **My hope is that the QGP causes the high p_T quarks to lose all their energy and stop, so that the high p_T tail will 'vanish' for central Au+Au collisions**

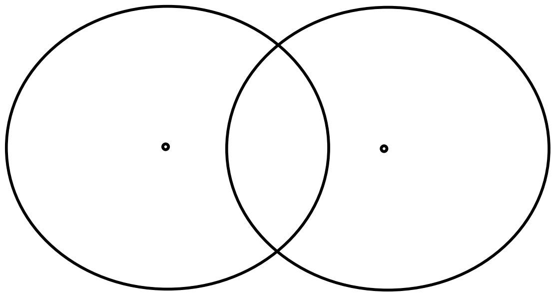
In RHI central collisions, leading particles are the only way to find jets because in one unit of Δr there is $\pi \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 375$ GeV !!!.

High p_T—RHIC results

Charged non-identified STAR h^-, PHENIX $h^+ + h^-(/2)$
STAR J. Dunlop, Quark Matter 2001
PHENIX F. Messer, Quark Matter 2001
Summary A. Drees, QM2001 nucl-ex/0105019
First a touch of 'theory'—'point-like scaling'

Hard-scattering is a point-like process, with excellent PQCD predictions $\sim$ 10% for $p-p$ and $\bar{p}-p$ collisions. For p+A or A+A collisions the cross sections should scale by the number of point sources, A for p+A or A^2 for A+A.

As a function of impact parameter, the profile function for a nucleus A



$$T_A(\vec{s}) = \int dz \rho_A(z, \vec{s})$$

is the number of nucleons per unit area along a direction z at a point from the center of the nucleus represented by a 2-d vector $\vec{s}$, where z is perpendicular to $\vec{s}$. For an interaction of nucleus A with nucleus B at impact parameter $\vec{b}$, the nuclear overlap integral $T_{AB}(\vec{b})$ is defined:

$$T_{AB}(\vec{b}) = \int d^2 s T_A(\vec{s}) T_B(\vec{b} - \vec{s}) \quad ,$$

where $d^2s = 2\pi s ds$ is the 2-dimensional area element. Simply:

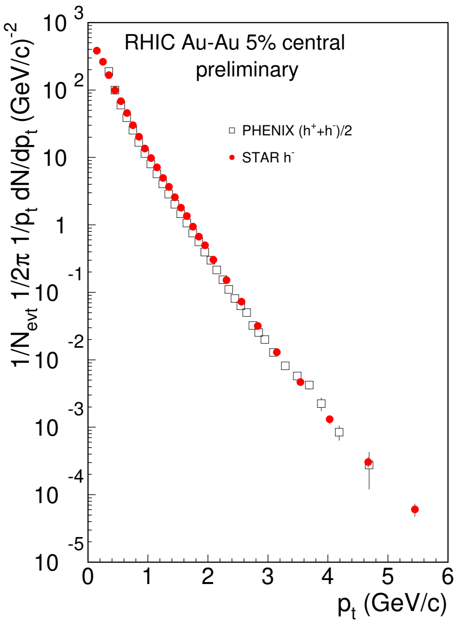
$$T_{AB}(\vec{b}) = N_{coll}(\vec{b}, \sigma)/\sigma$$

More precisely, for a certain fraction f of the nuclear interaction cross section for A+A collisions, the semi-inclusive yield is related to the $p-p$ inclusive cross section:

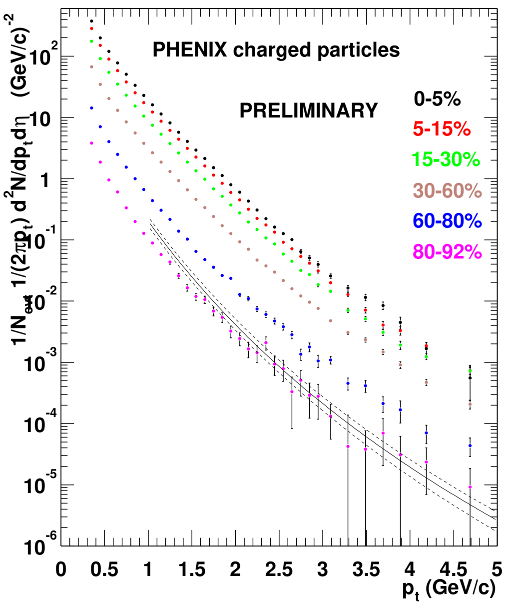
$$\frac{1}{N_f} \frac{d^3 N_f^{A+A}}{p_T dp_T dy d\phi} = \frac{d^3 \sigma^{p-p}}{p_T dp_T dy d\phi} \times \langle T_{AB} \rangle_f \cong \frac{d^3 \sigma^{p-p}}{p_T dp_T dy d\phi} \times \frac{\langle N_{coll}(\sigma_{nn}) \rangle_f}{\sigma_{nn}}$$

High p_T Charged

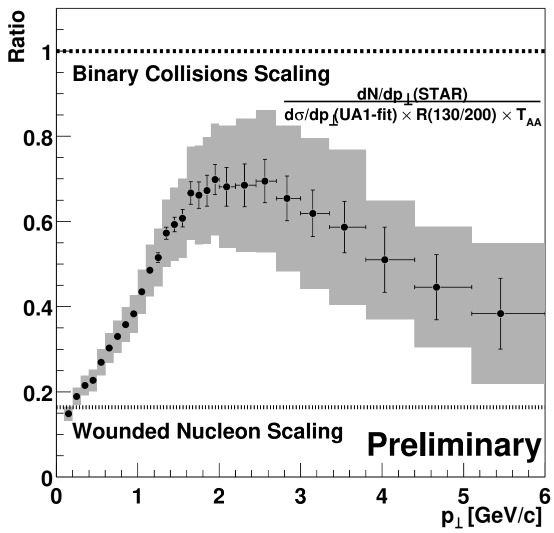
STAR h^-, PHENIX $(h^+ + h^-)/2$



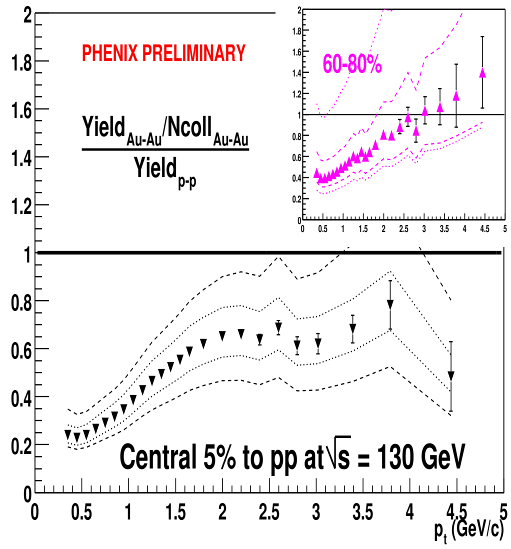
PHENIX h^- vs Centrality



STAR central cf. pointlike

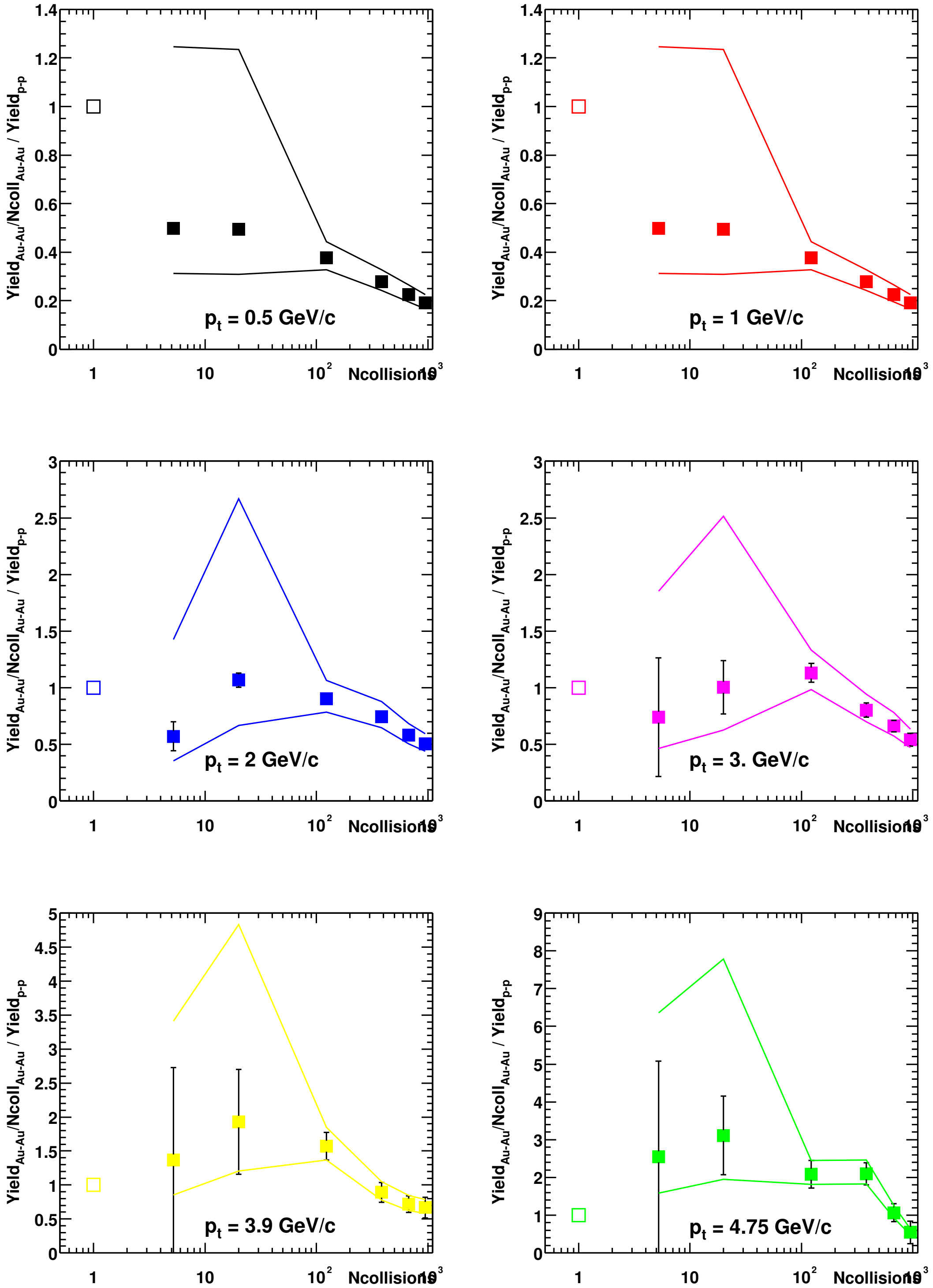


PHENIX cf. pointlike



Central Collisions show a deficit compared to pointlike scaling. This has never been seen before in p+A or A+A collisions. At lower energies the yield is enhanced over pointlike scaling, known as 'the Cronin effect'

Where does the effect turn on—PHENIX



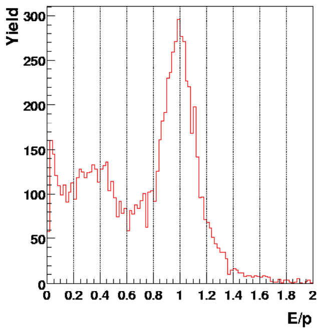
Inconlusive, this round—Wait till next year!

High $p_T \pi^0$—PHENIX

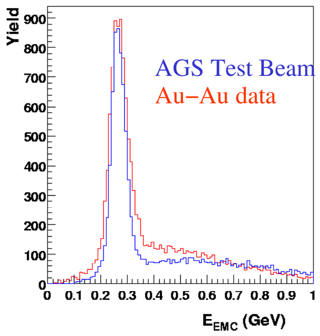
PHENIX qm01, G. David, nucl-ex/0105014

Energy Scale, Energy Scale, Energy Scale

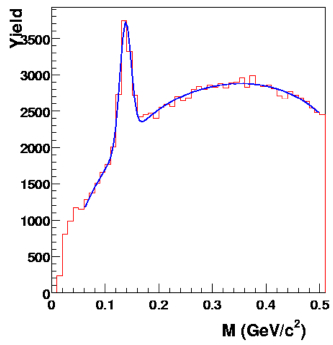
EMCal global energy calibration



E/p matching
for electron enriched sample (with RICH): p>0.5 GeV/c



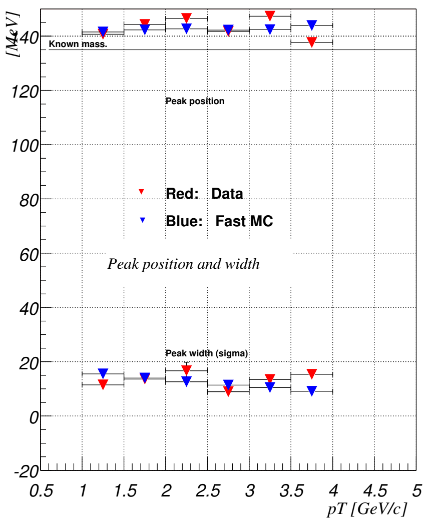
MIP peak position
for 1 GeV/c charged tracks (mostly pions):
Within 2% from Test Beam results



π0's
p_t>2 GeV, asym<0.8
m=136.7±0.3 MeV/c^2

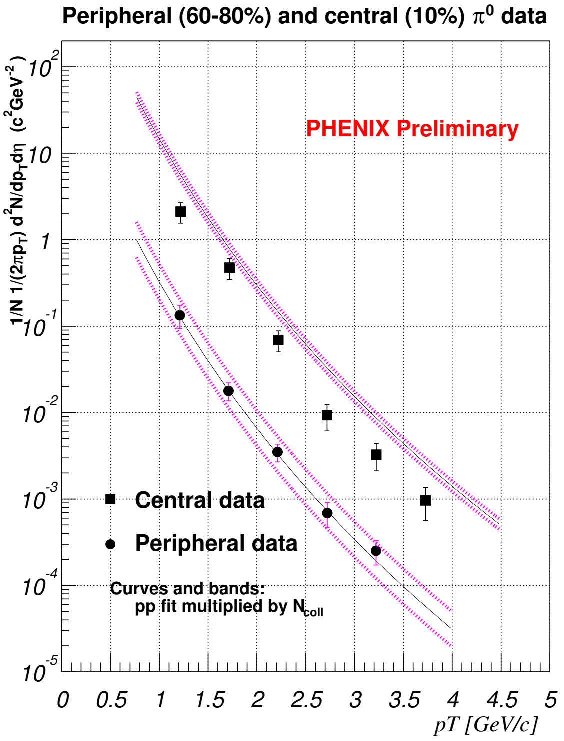
EMCal calibration is consistent within 2%

Slight change of π^0 mass with Centrality is Corrected

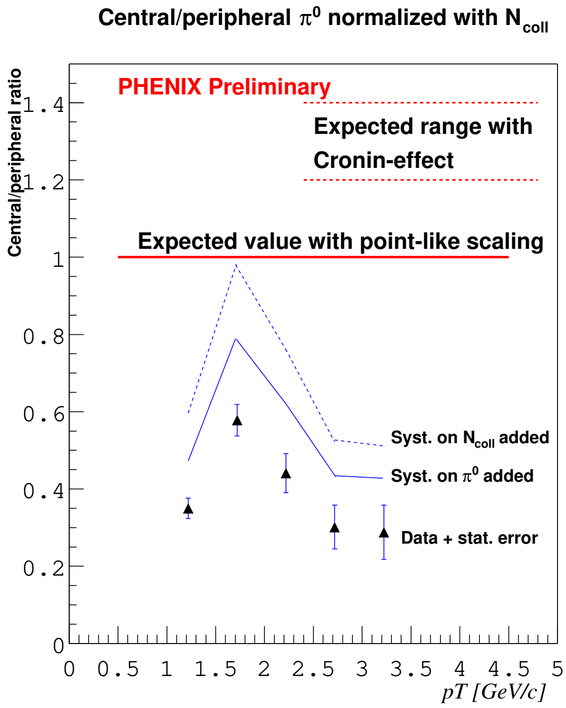


High $p_T \pi^0$—PHENIX

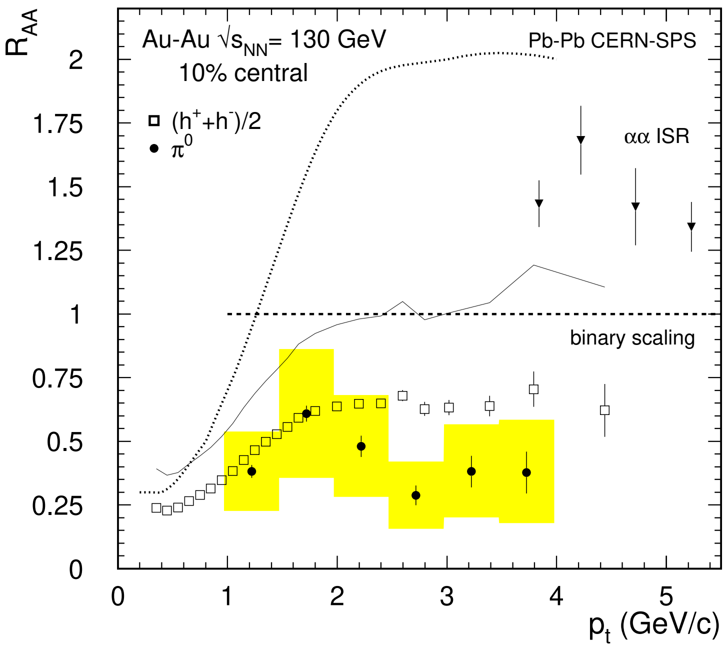
π^0 Cent. and Periph.



Cent/Perip. Norm by N_{coll}



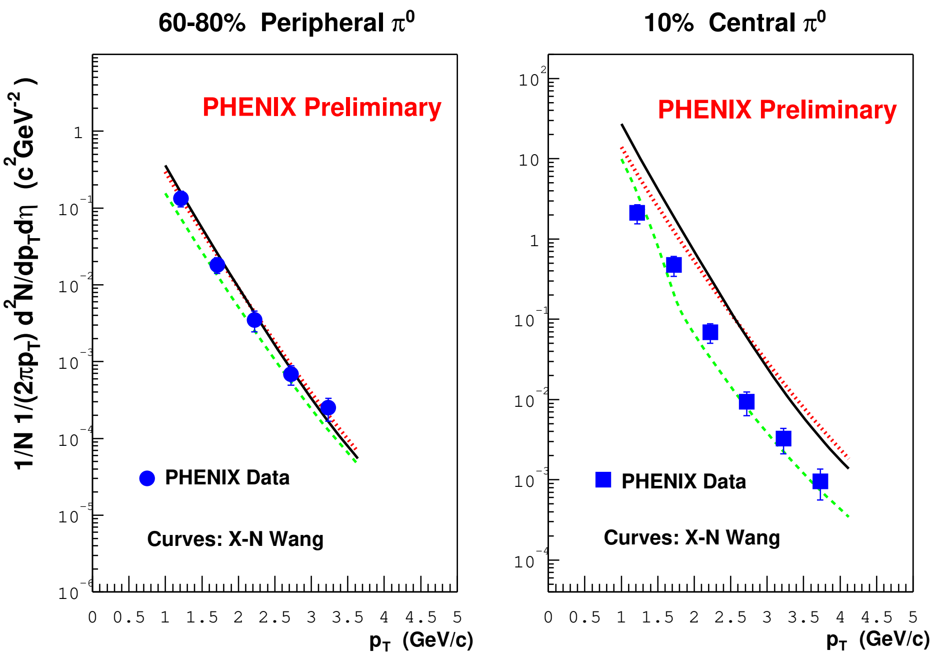
PHENIX π^0 and $(h^+ + h^-)/2$ Central cf. UA1 fit



Is this Jet Quenching—Theorists, Experimentalists, keep working!

Theorists already at work

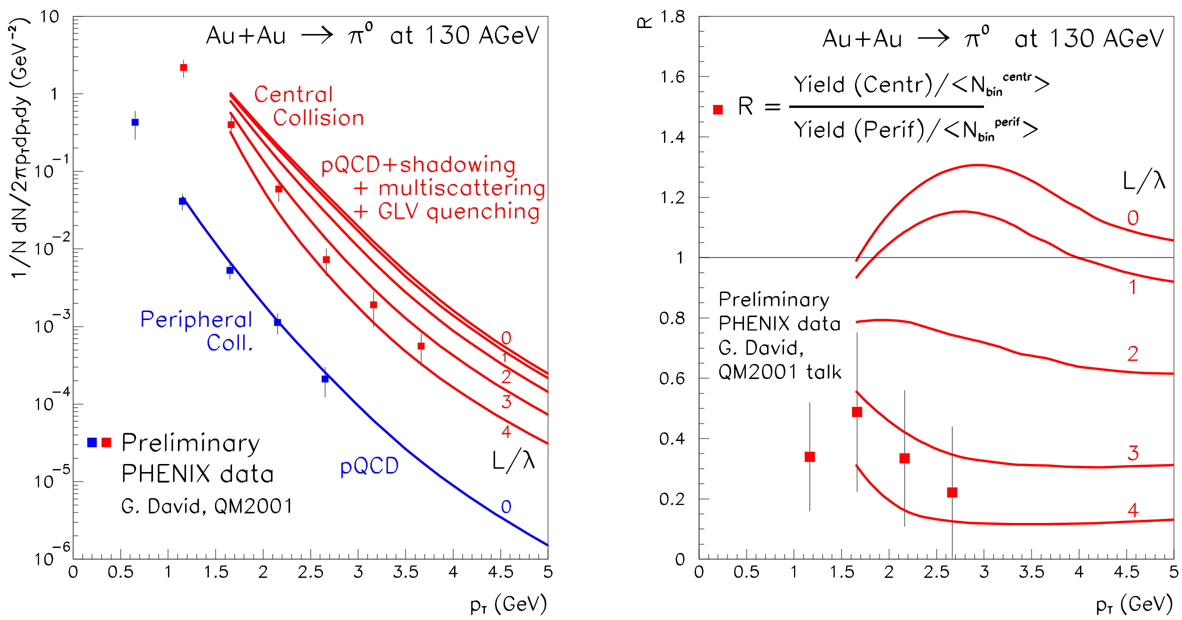
PHENIX π^0 c.f. X. N. Wang's Prediction



X. N. Wang, Phys. Rev. C**61**, 064910 (2000), Phys. Rev. C**63**, 054902 (2001) also `http://www.-hpc.lbl.gov/`

PHENIX qm01π^0 c.f. P. Levai, M. Gyulassy et al.

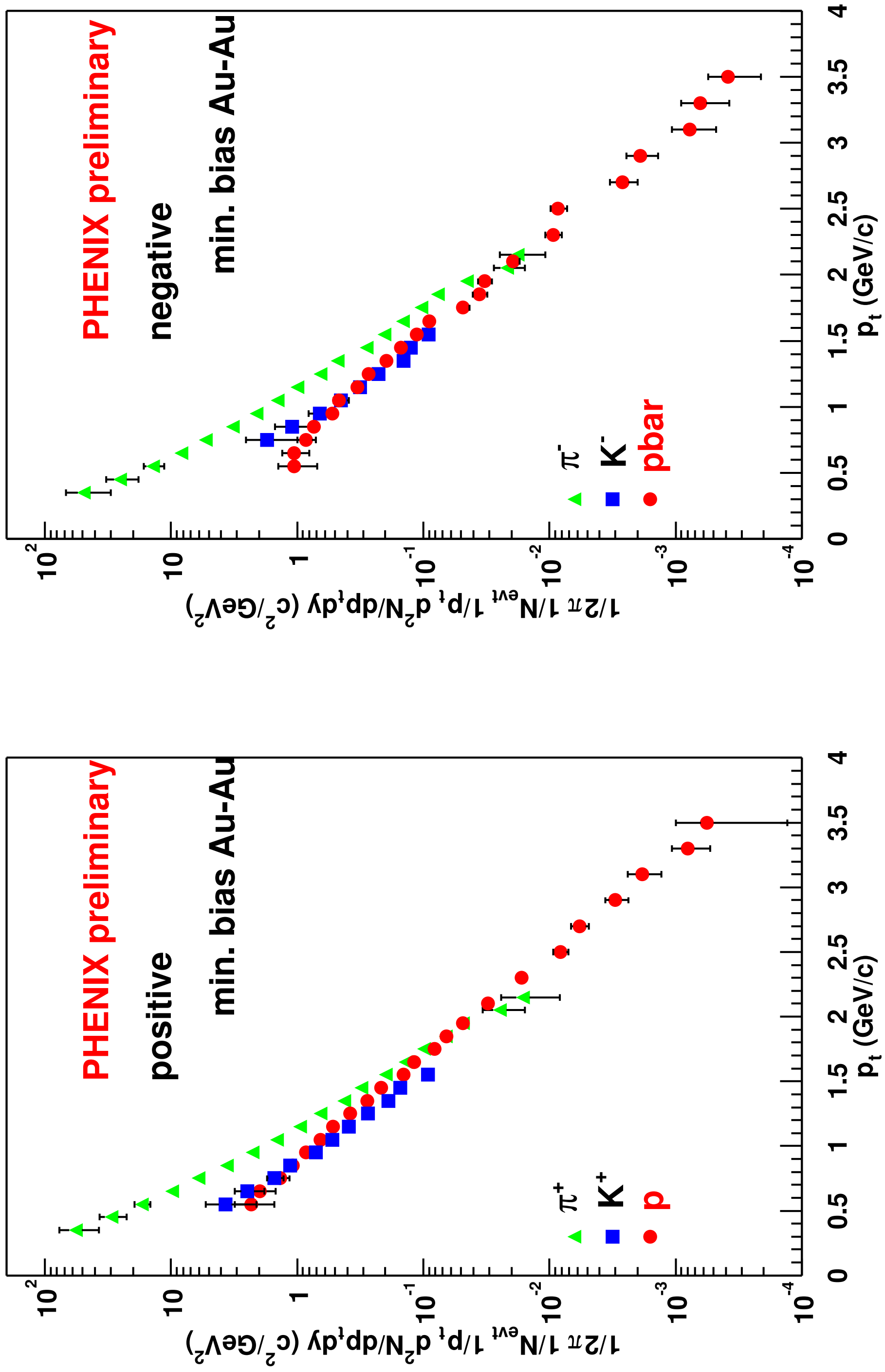
π^0 Cent. and Periph. Cent/Perip. Norm by N_{coll}



P. Levai, G. Papp, G. Fai, M. Gyulassy, G. G. Barnafoldi, I. Vitev, Y. Zhang, qm01, nucl-th/0104035

N.B. π^0 and $h^+ + h^-$ are different!

It's a real effect—different from $p-p$: Flow?



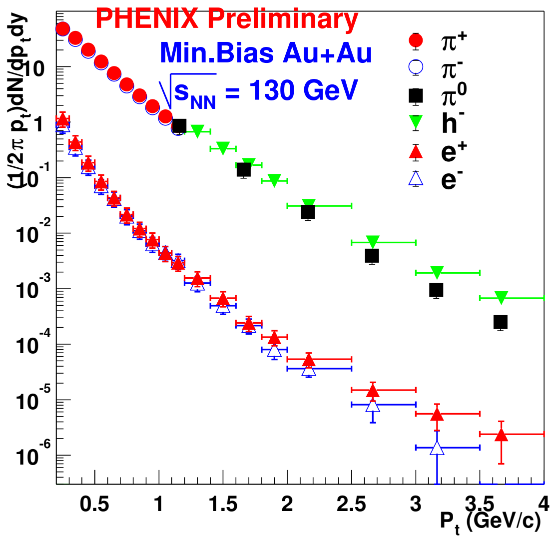
protons dominate pions for $p_T \geq 2$ GeV/c !!!

Single $e^{\pm}$, e^+e^- pairs—PHENIX

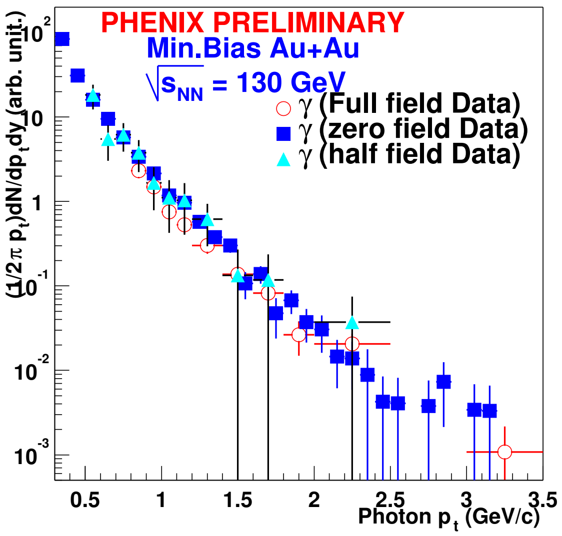
PHENIX qm01, Y. Akiba,

`http://www.phenix/bnl.gov/phenix/WWW/publish/akiba/QM2001/proceeding/`

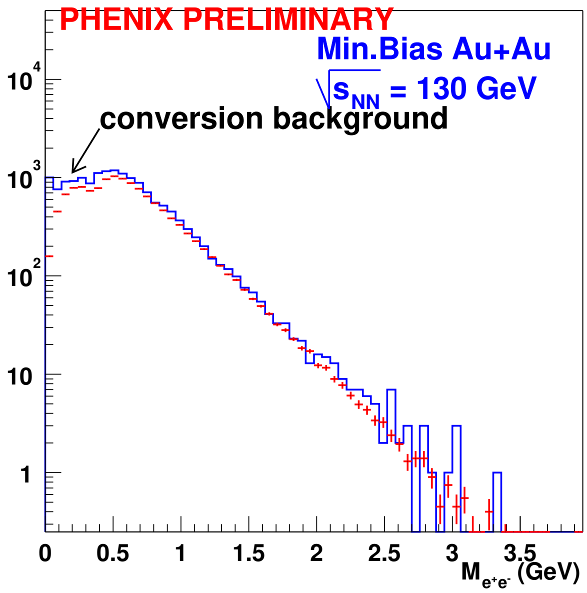
$\pi^{\pm}$, π^0, h^-, $e^{\pm}$



Photons from conversions



e^+e^- **Pairs (3** J/Ψ **??)**



Signal (blue) c.f. mixed events (red)

Nothing Dramatic with single e **or photon**

Next year $\sim 10000\ J/\Psi \to \mu^+\mu^-$, $\sim 2000\ e^+e^-$