First Hints for Jet Quenching at RHIC

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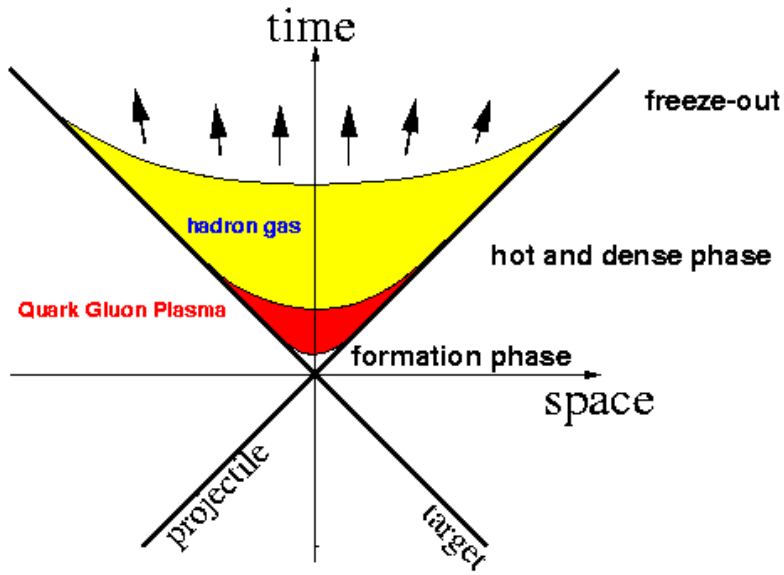
QM2001, Stony Brook, January 20, 2001

An Experimental Summary

- Introduction
- Knowledge from p-p and p-A collisions
- Mini-review of CERN results
- First data from RHIC
- Summary

Hard Probes In Heavy Ion Collisions



a) formation phase
parton scattering

b) hot and dense phase
Quark Gluon Plasma
Hadron Gas

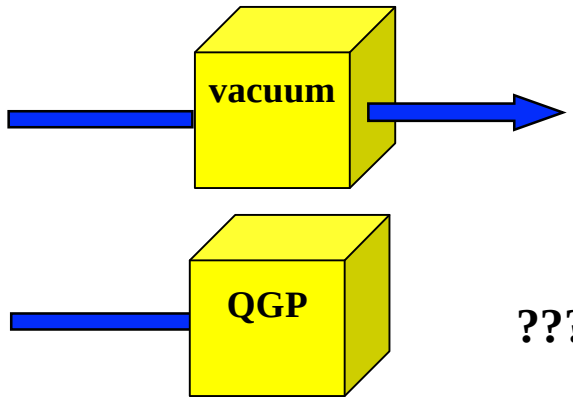
c) freeze-out
emission of hadrons

- **"hard" probes** **$c\,\bar{c}$, $b\,\bar{b}$ and jets**

  during formation phase parton scattering processes with large Q^2
  create high mass or high momentum objects
  penetrate hot and dense matter
  sensitive to state of hot and dense matter

matter box

beams of hard probes: jets, J/ψ ….

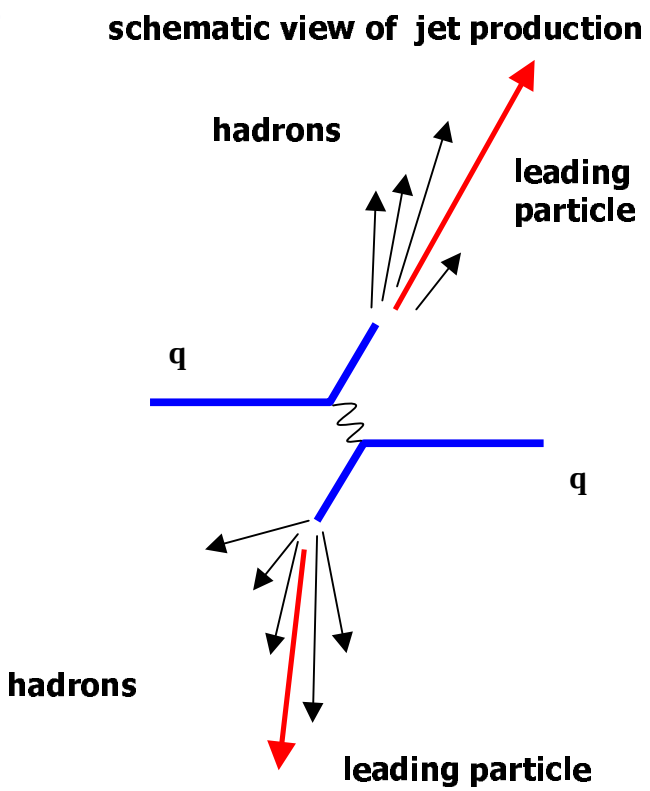


????

- **color screening** in partonic phase ⇒ **J/ψ suppression**
- **dE/dx** by strong interaction ⇒ **jet quenching**

Jet in Heavy Ion Collisions

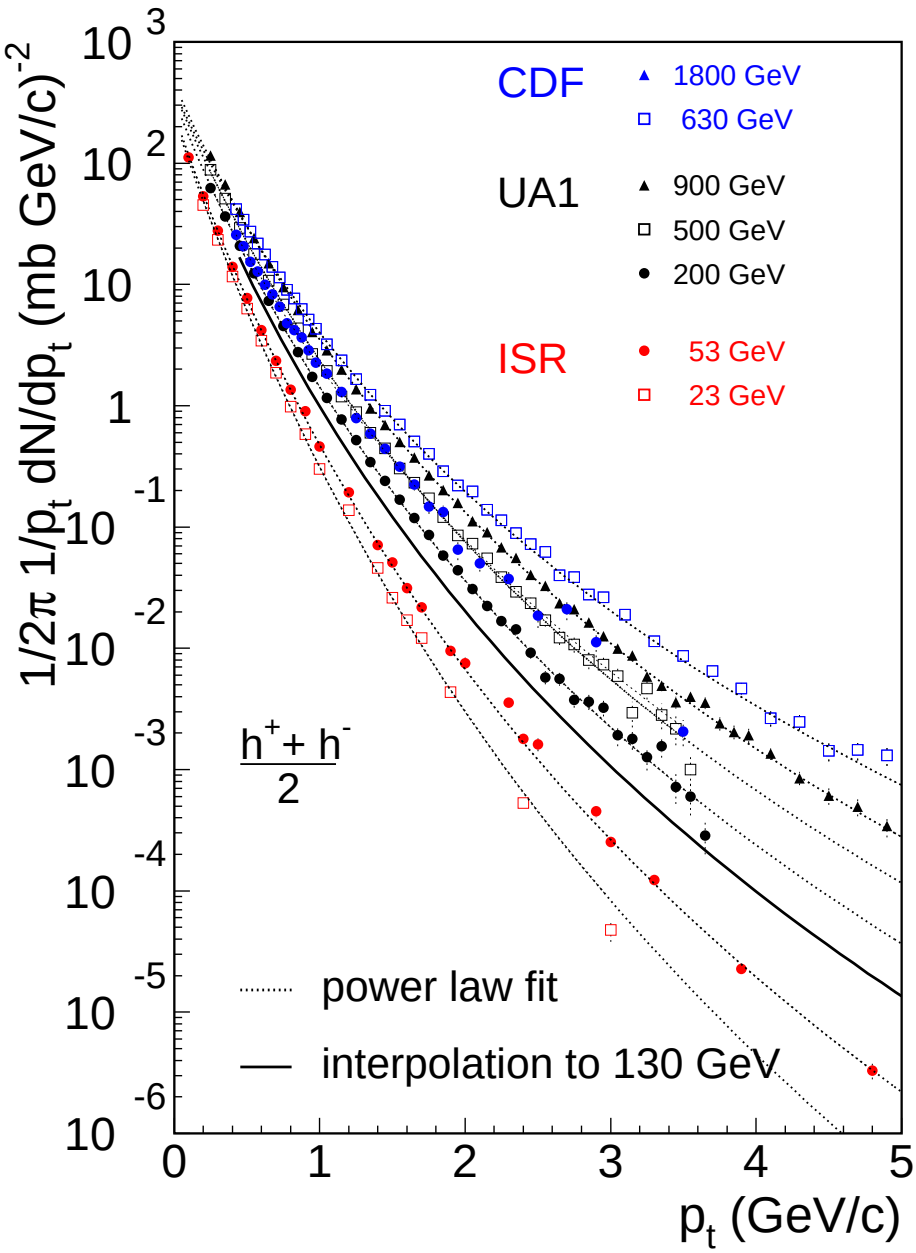
- jets and mini-jets contribute ~30% of particle production at RHIC energies
- observable in A-A collisions by
  - high p_t leading particles
  - azimuthal correlation



- scattered quarks radiate energy (~ GeV/fm) in colored medium
  - suppression of high p_t particles "jet quenching"
  - suppression of angular correlation

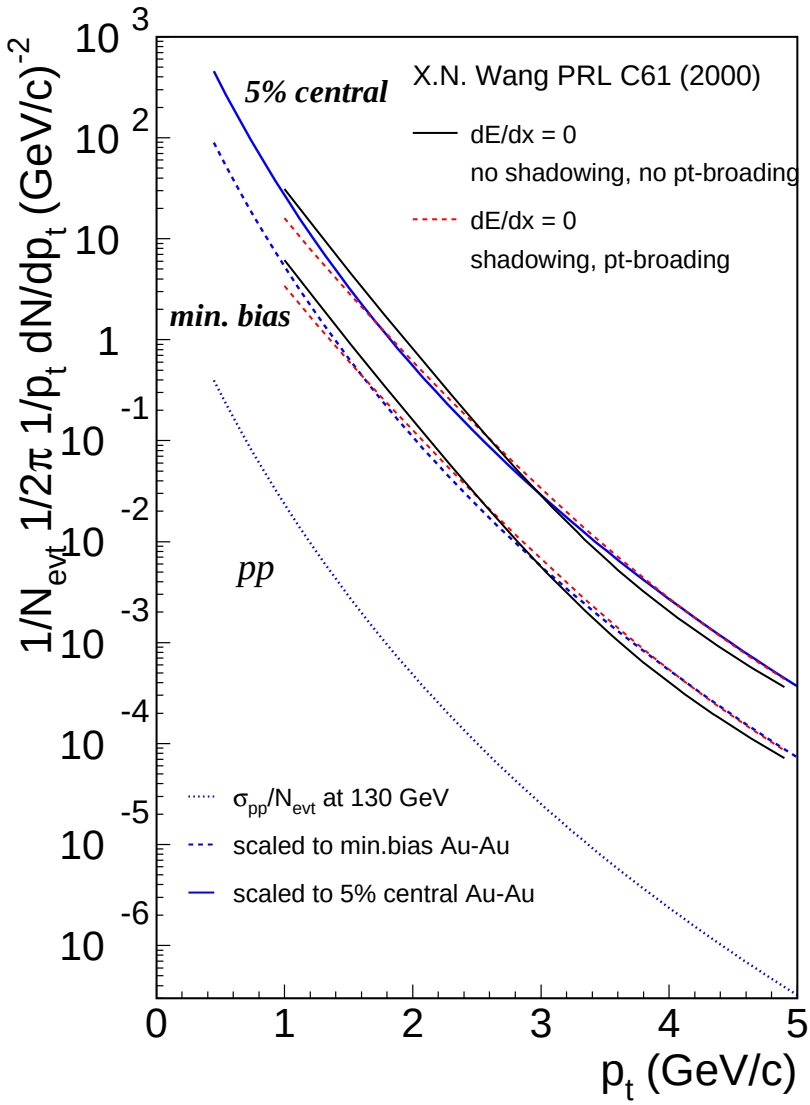
Inclusive p_t-Distribution in p-p

- **Data available over wide range of $\sqrt{s}$, but not for 130 GeV**



- **power law: $\sigma_{pp} = d^2N/dp_t^2 = A\,(p_0+p_t)^{-n}$**
- **interpolate A, p_0, n to 130 GeV**

Extrapolating from pp to AA



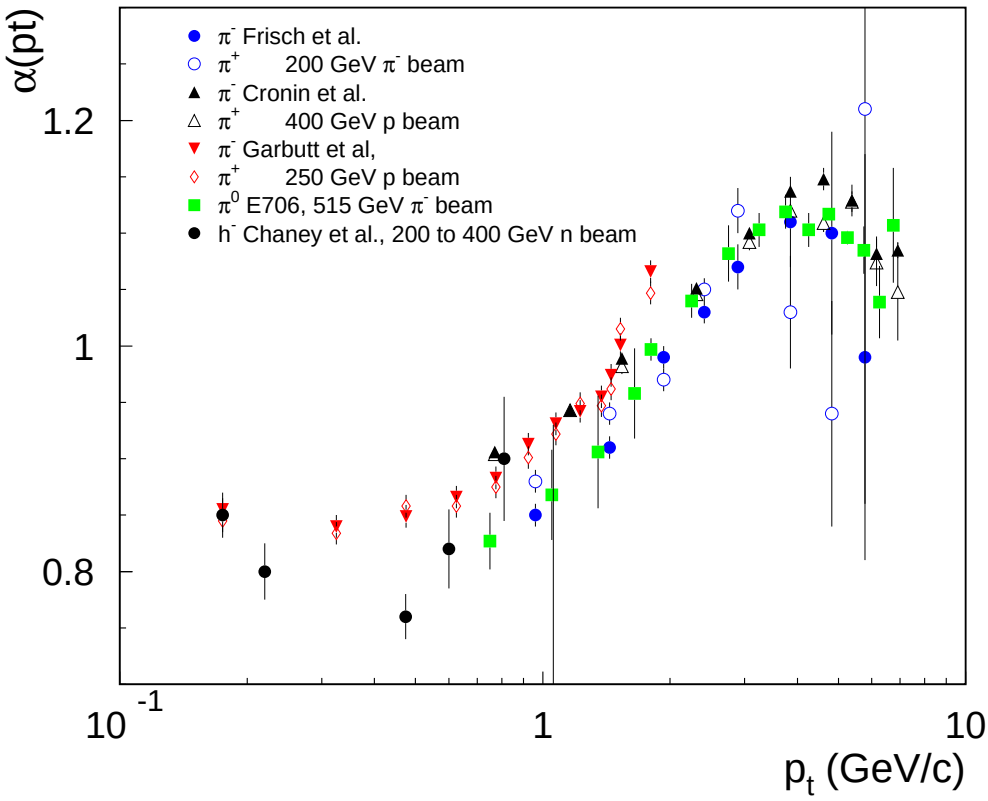
- **hard scattering processes scale with binary collisions:**
  - **scale to min. bias Au-Au:** $\sigma_{AA} = A^2 \sigma_{pp}$
  - **scaling to central collisions:** $\sigma_{AA}(b_c) = \sigma_{pp} \int_0^{b_c} db^2 T_{AA}$

systematic errors ~20-30% at 5 GeV

The Cronin Effect

- **modification of p_t spectrum in p-A collisions:**

$$\sigma_{pp} = A^{\alpha(p_t)}\,\sigma_{pA}$$

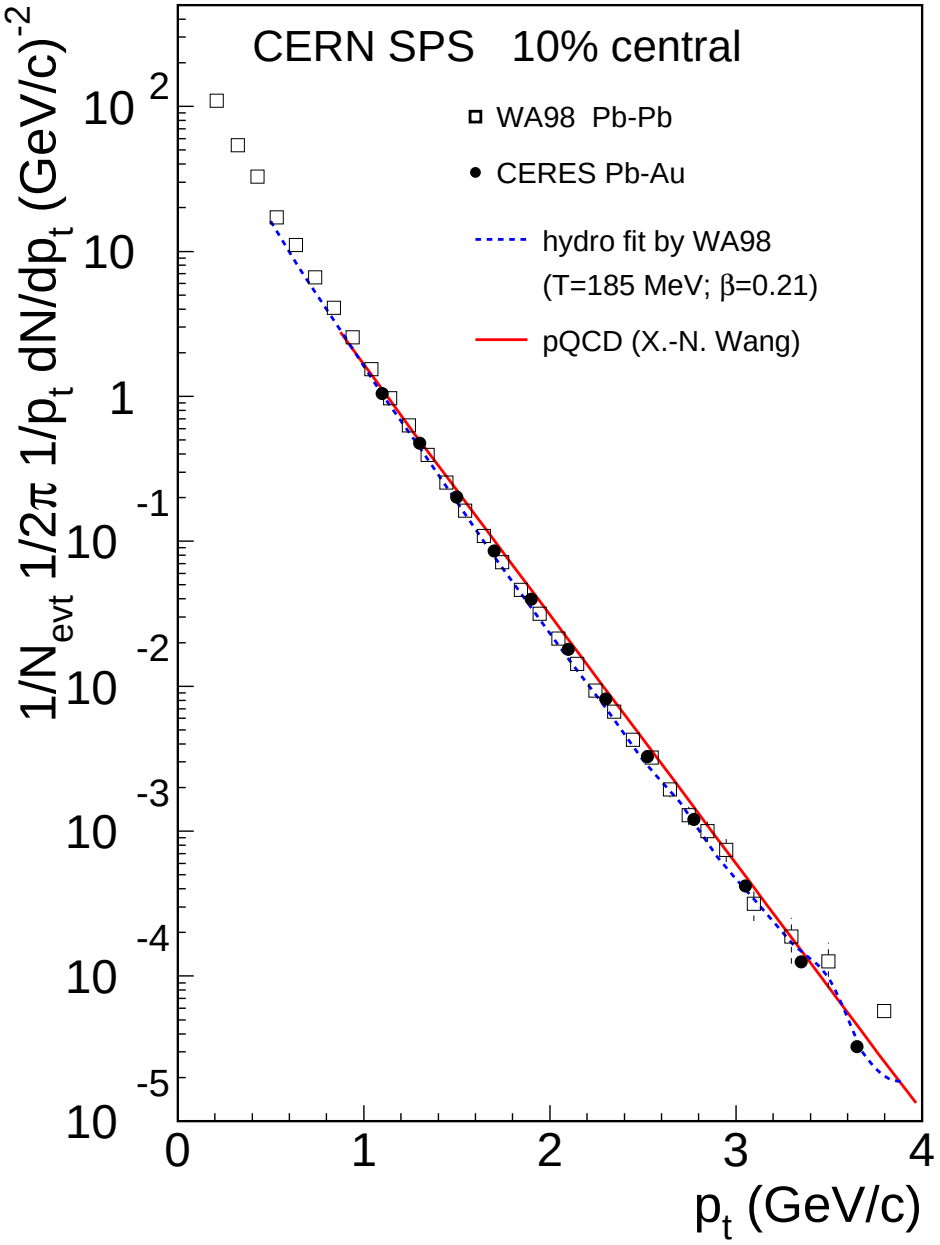


- **ratio analysis:**

$$R_{pA} = \frac{1}{A}\left(\frac{d^2\sigma_{pA}}{dp_t^2}\right)\Big/\left(\frac{d^2\sigma_{pp}}{dp_t^2}\right)$$

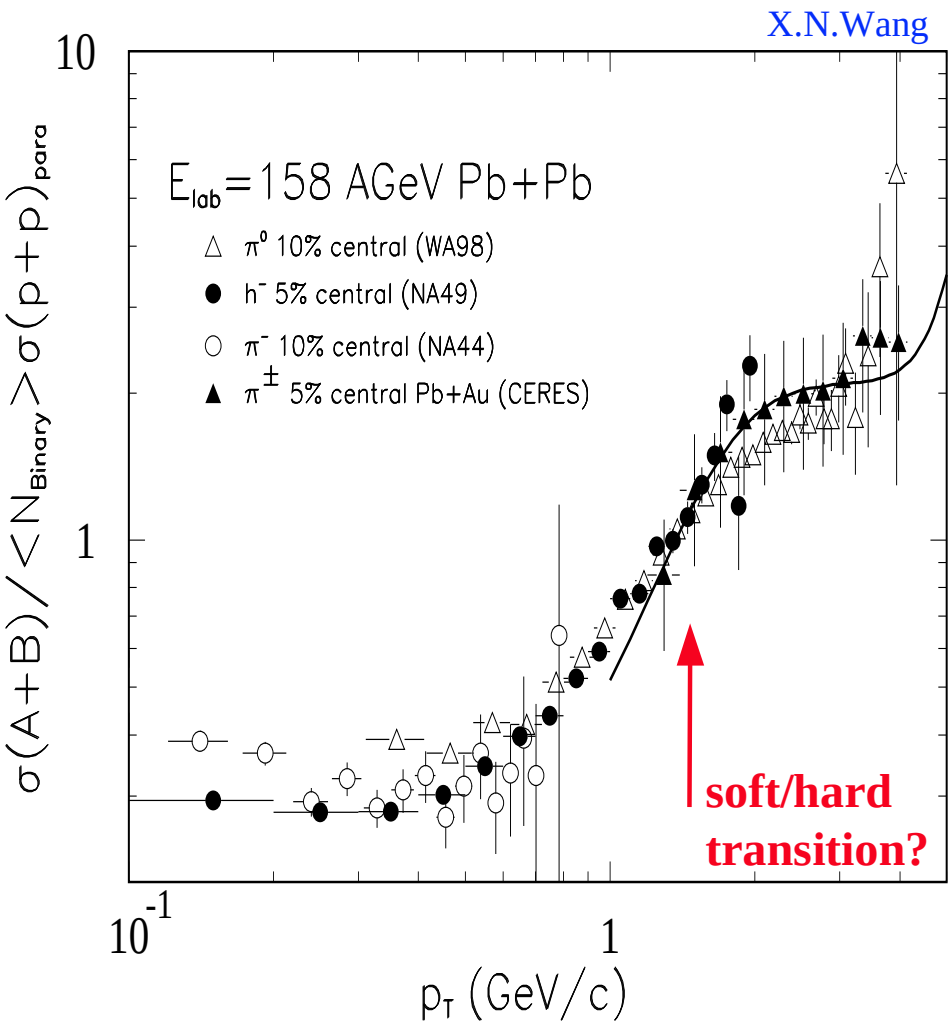
- **for p-Au collisions:**
  - **increases above 1 at ~2 GeV**
  - **saturates at ~2 GeV**
  - **eventually decreases to 1 at high p_t**

Results from the SPS



- **data well described by pQCD**
- **data equally well described by hydrodynamic fit**

Comparing CERN-SPS Pb-Pb to p-p



- **R_{AA} exhibits typical "Cronin effect" behavior**

$$\sigma_{pp} = A^{2\alpha(p_t)}\,\sigma_{AA}$$

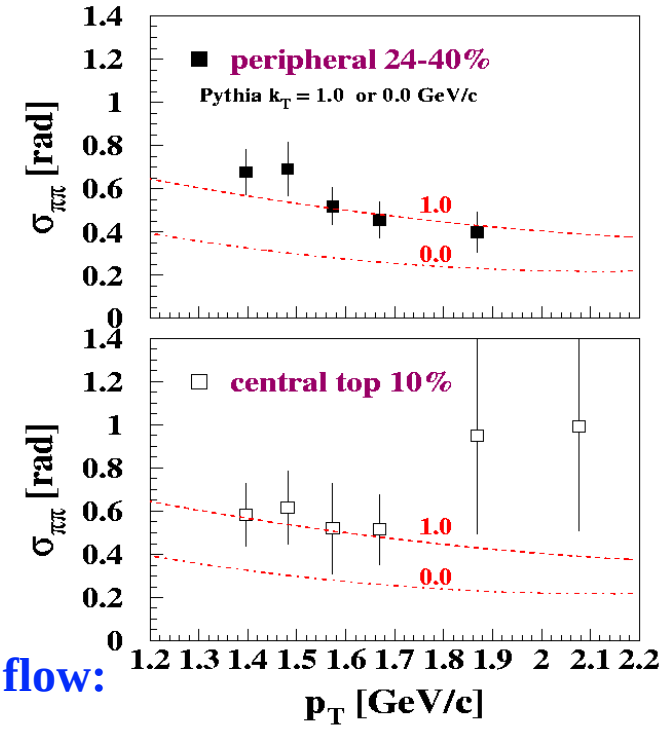
- **at SPS energy high p_t spectra evolve systematically from pp → pA → AA**

no need to invoke energy loss

Evidence for hard scattering at SPS?

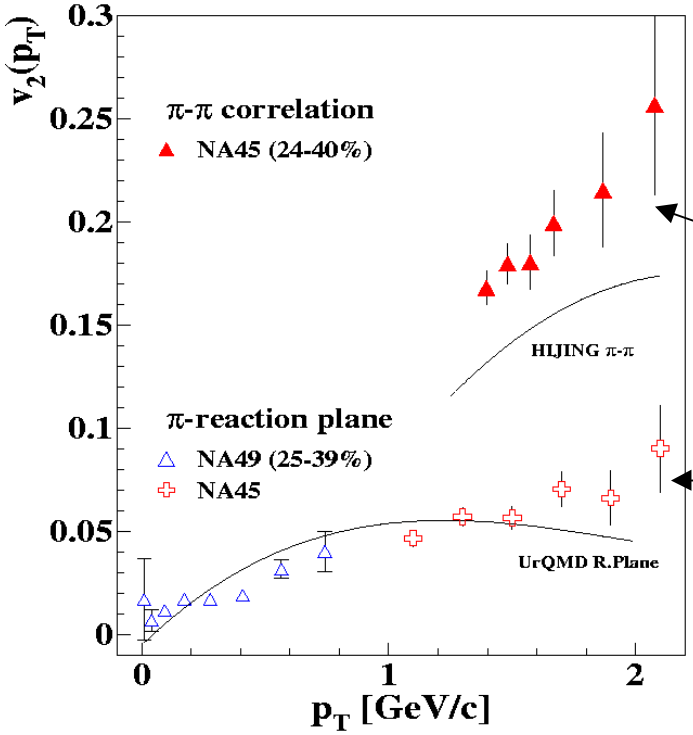
J.Rak, CERES
H.Büsching, WA98

- **back-to-back azimuthal angular correlation for pions with p_t >1.2 GeV (or photons not shown)**



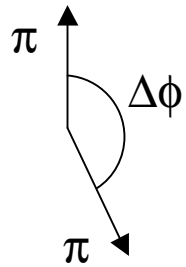
- **angular correlation at 180° width of drops with p_t:**

- **correlation stronger than expected from elliptic flow:**



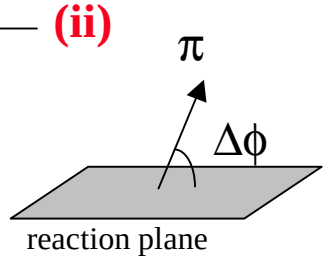
measure v_2 from $dN/d\Delta\phi$:

(i)



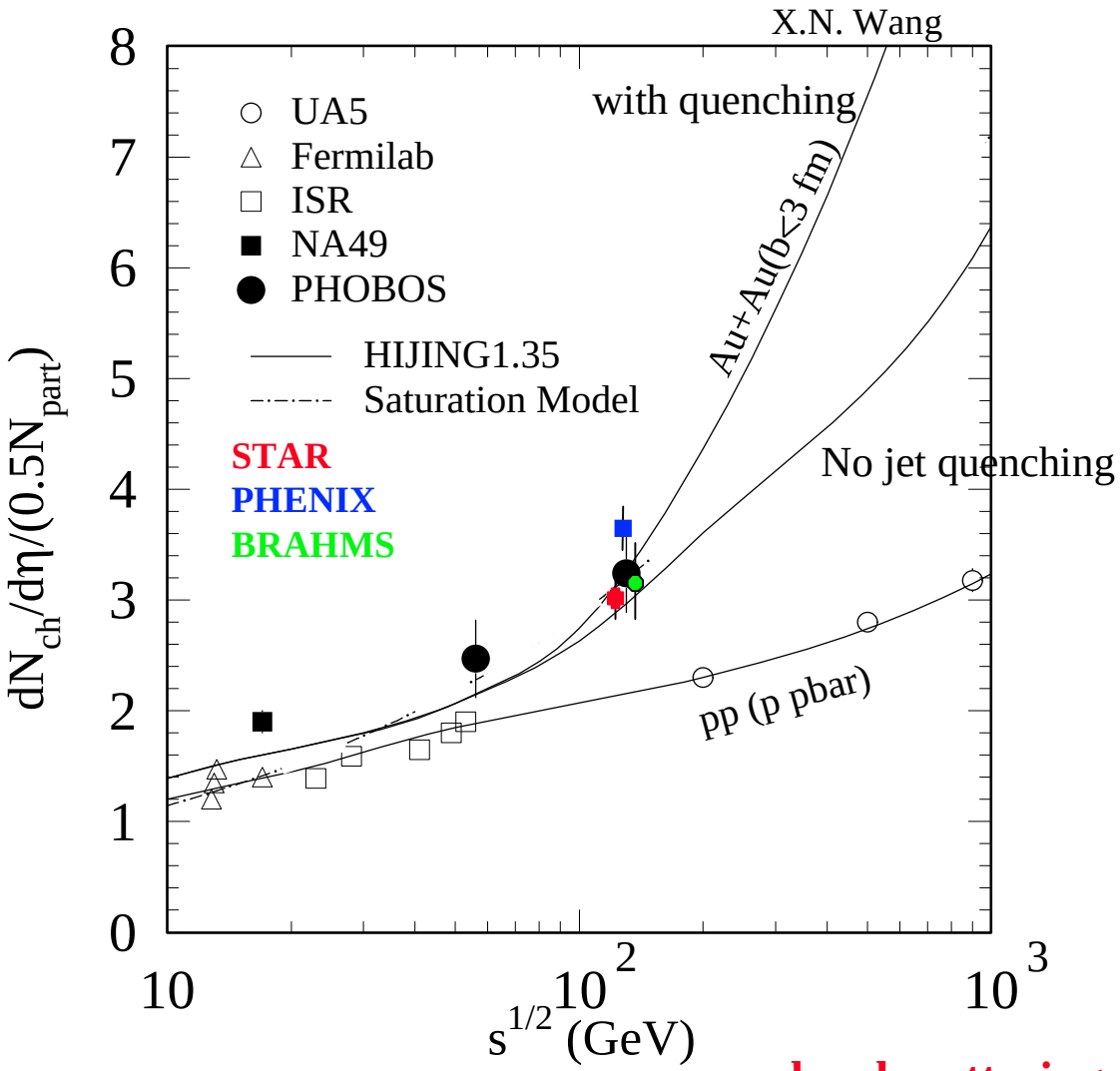
sensitive to jet like correlation and elliptic flow

(ii)



mostly sensitive to elliptic flow

First Hints from dN/dη at RHIC



soft physics **hard scattering**

$$\frac{2}{\langle N_{part}\rangle}\frac{dN_{ch}^{AA}}{d\eta} = \langle n\rangle_{soft} + \frac{2\langle N_{Binary}\rangle}{\langle N_{part}\rangle}\langle n\rangle_{hard}\frac{\sigma_{jet}^{pp}}{\sigma_{in}^{pp}}$$

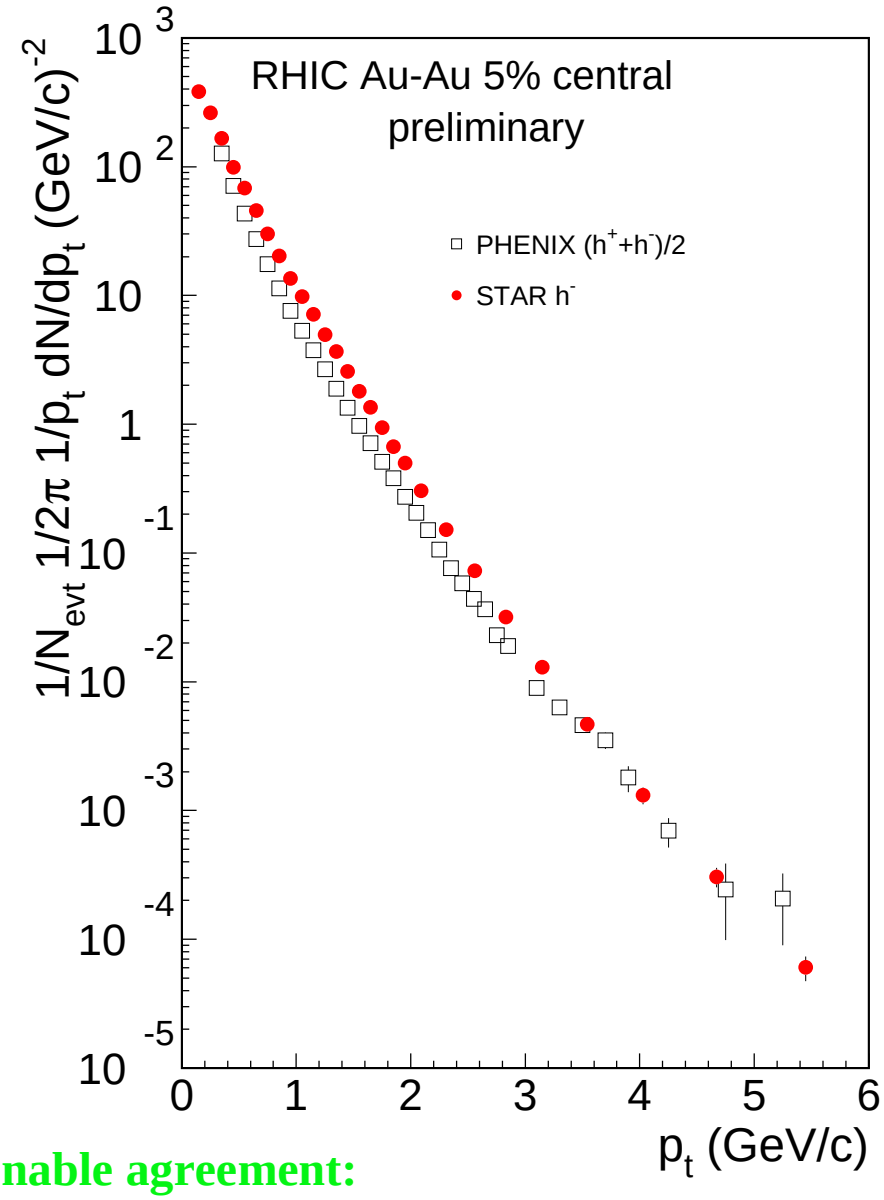
scales like number of participating nucleons

scales like number of binary collisions

Inclusive p_t Spectra of charged Particles

J.C. Dunlop, STAR
F. Messer, PHENIX

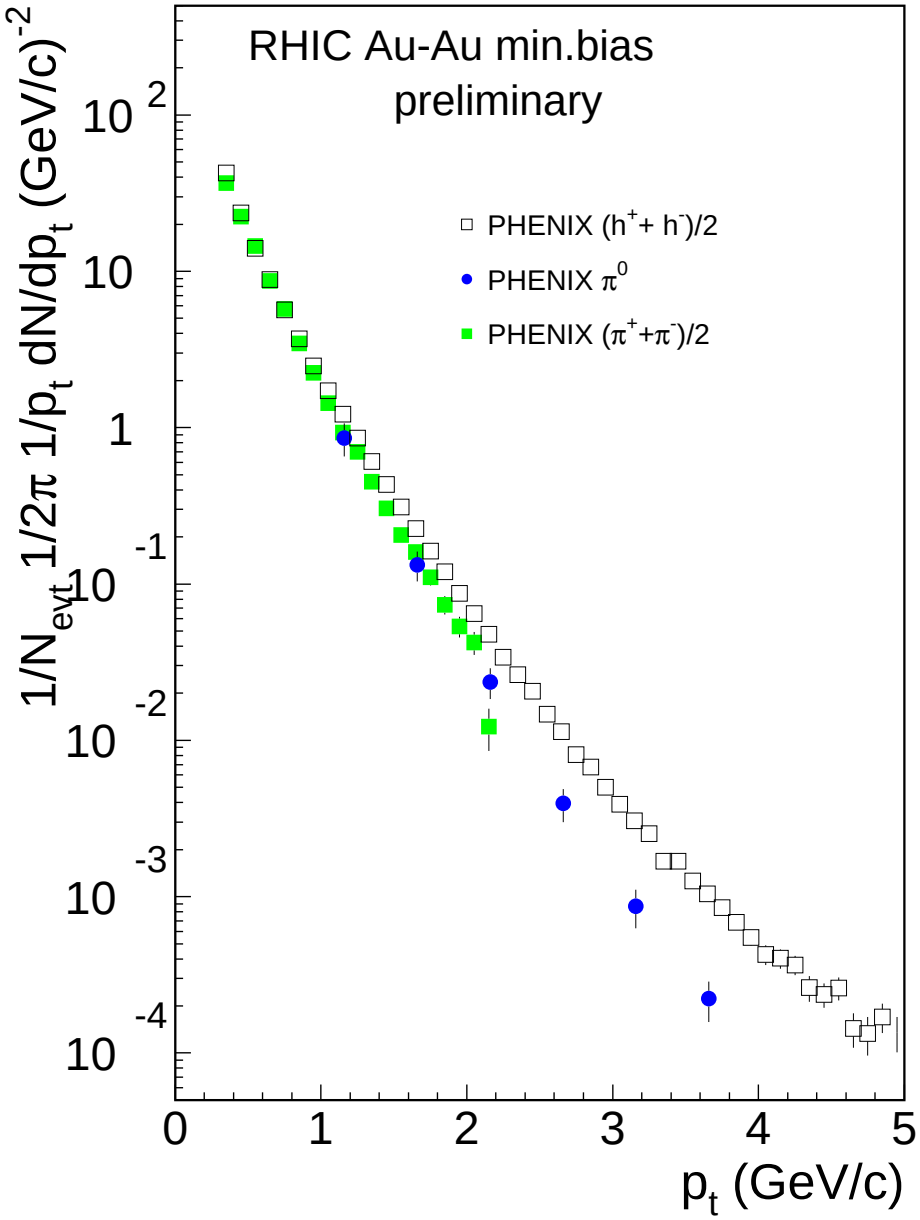
- **first high p_t data from RHIC:**
  - **p_t range to 6 GeV, covering >6 orders of magnitude**
  - **well above what was reached at the SPS**



- **reasonable agreement:**
  - **small differences in shape and yield**
  - **centrality selection …**

Inclusive p_t Spectra of Pions

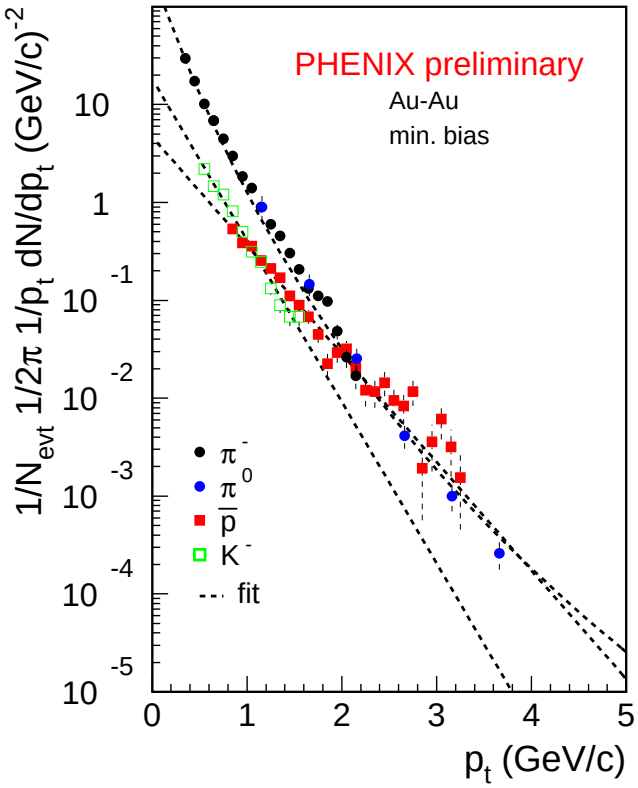
G. David, PHENIX
F. Messer, PHENIX
J.Velkovska, PHENIX

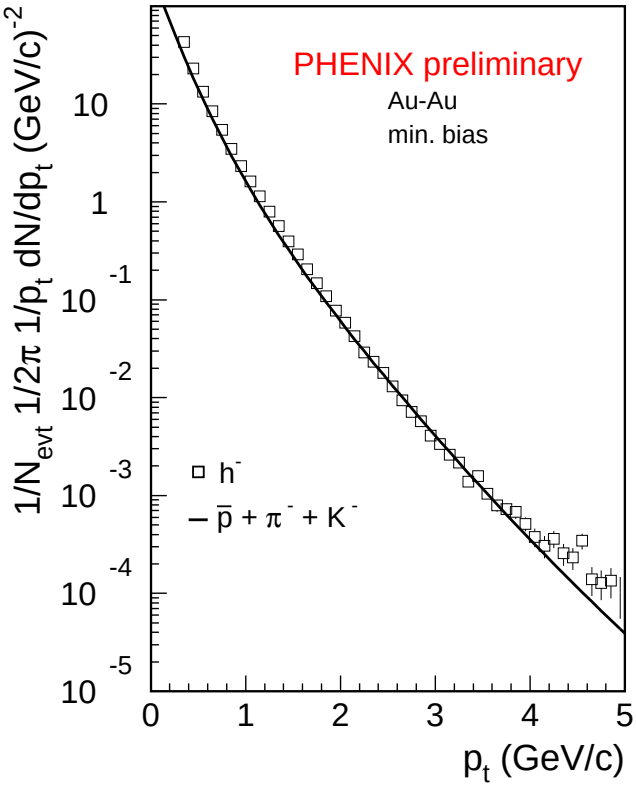


- π^0 from 1 to 4 GeV
- good agreement with h^- below 2 GeV
- agreement in shape with $\pi^\pm$ from 0.3 to 2.2 GeV

Remarks on charged particle spectra

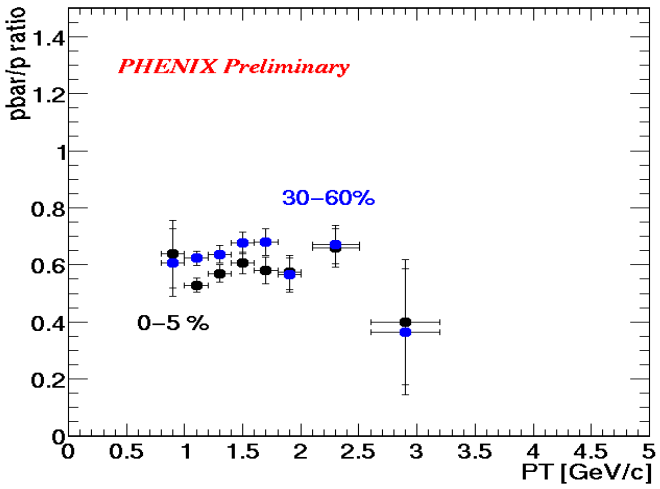
F. Messer, PHENIX
J.Velkovska, PHENIX





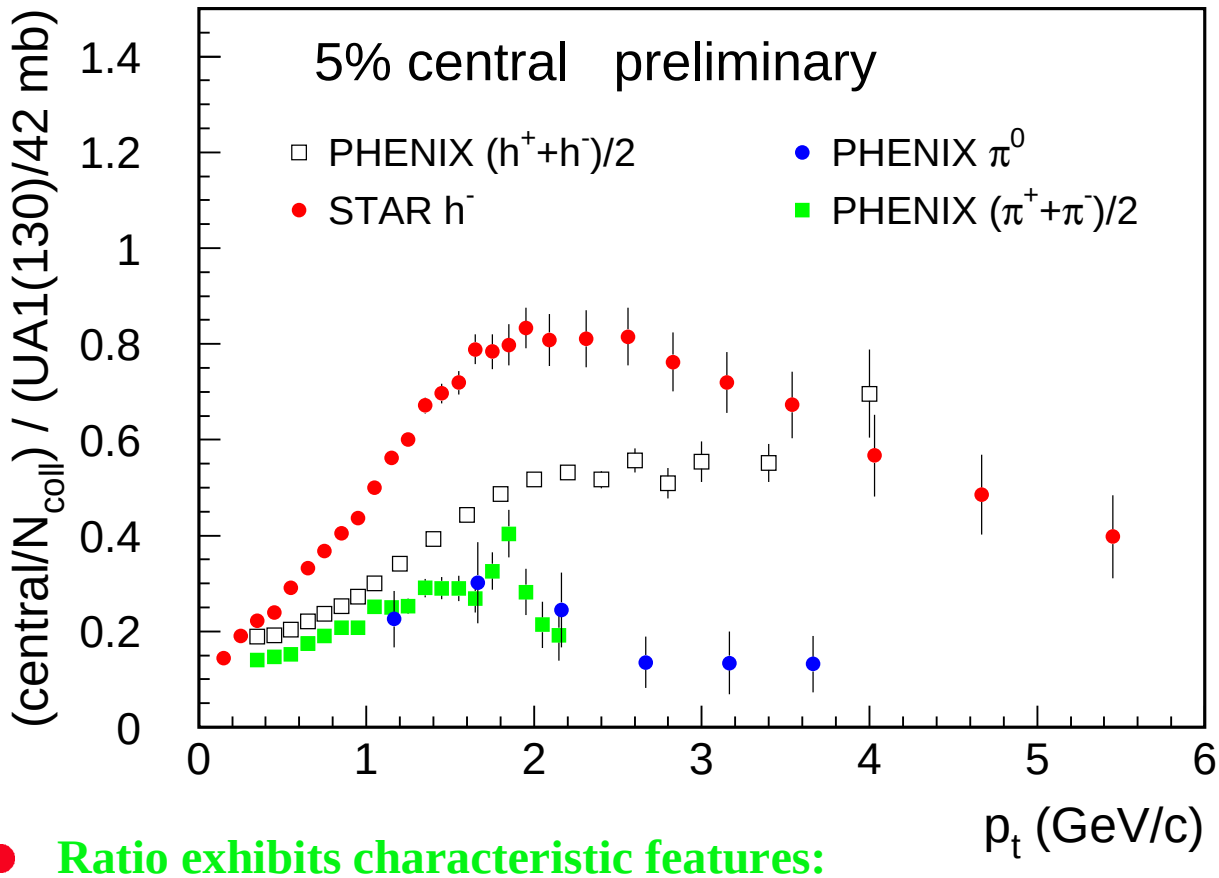
- $h^- = \bar{p} + \pi^- + K^-$
- $\bar{p}$ yield $= \pi^-$ yield at 2-2.5 GeV
- $\bar{p}/p \sim 0.6$ at all p_t
- p yield $= \pi^+$ yield at ~ 2 GeV

H.Ohnishi, PHENIX



Comparison to central Au-Au to p-p

- **Use identical p-p parameterization for all data sets**
  - **normalize data to number of binary collisions**
  - **divide by p-p parameterization UA1(130)/42 mb**

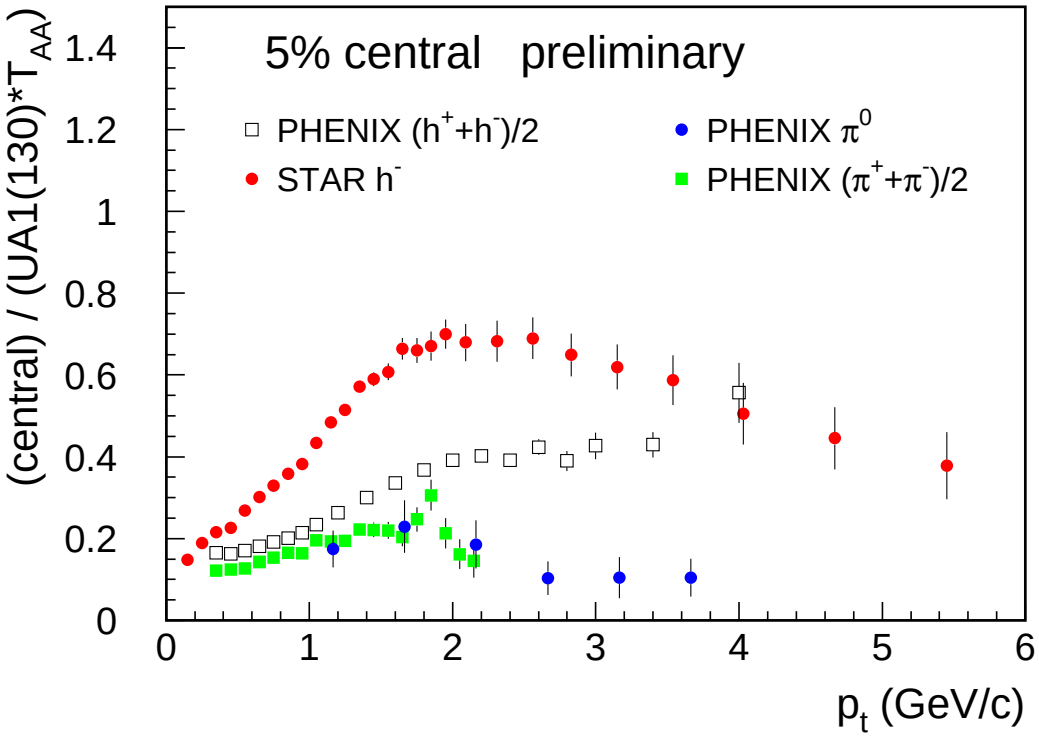


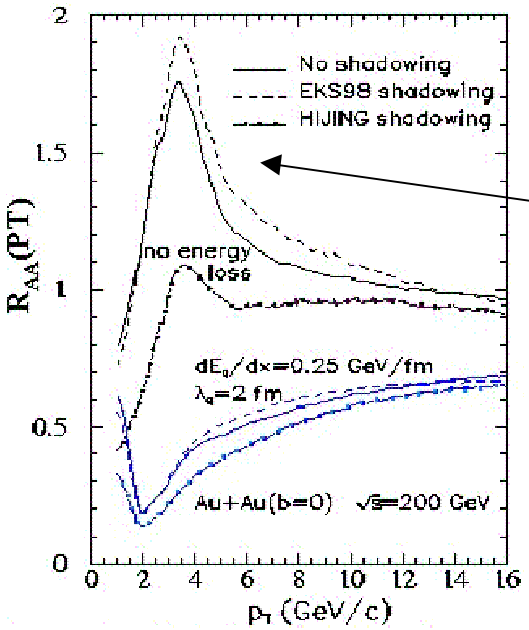
- **Ratio exhibits characteristic features:**
  - **increases up to ~ 2 GeV**
  - **saturates at $R_{AA} < 1$**
  - **decrease at high p_t**

- **Issues: large systematic error ~ 30%**
  - **data: normalization, differences in shape, centrality selection, p/ p contribution ..**
  - **systematic uncertainty of p-p parameterization**

Comparison to Central Au-Au to p-p

- **systematic check: use different p-p parameterization**
  - **divide by p-p parameterization UA1(130) scaled to T_{AA}**





within systematic errors:

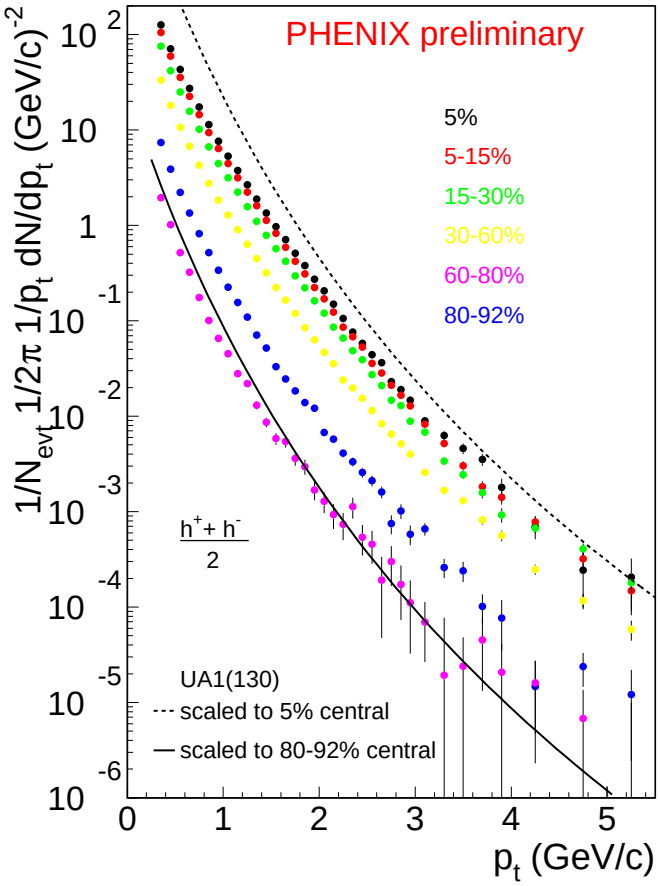
$R_{AA} < 1$

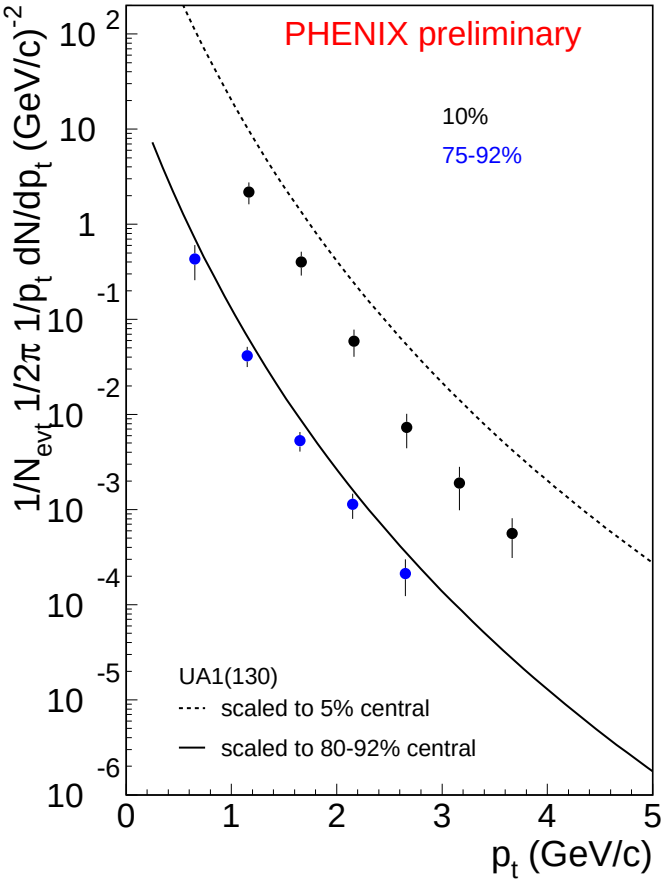
- **R_{AA} very different form expectation:**
  - **increase at low p_t**
  - **exceeds 1 at ~2 GeV "Cronin effect"**
  - **approaches 1 at high p_t**
- **very different from SPS:**
  - **follows expectation**

Centrality Dependence of pt Spectra

F. Messer, PHENIX

G.David, PHENIX



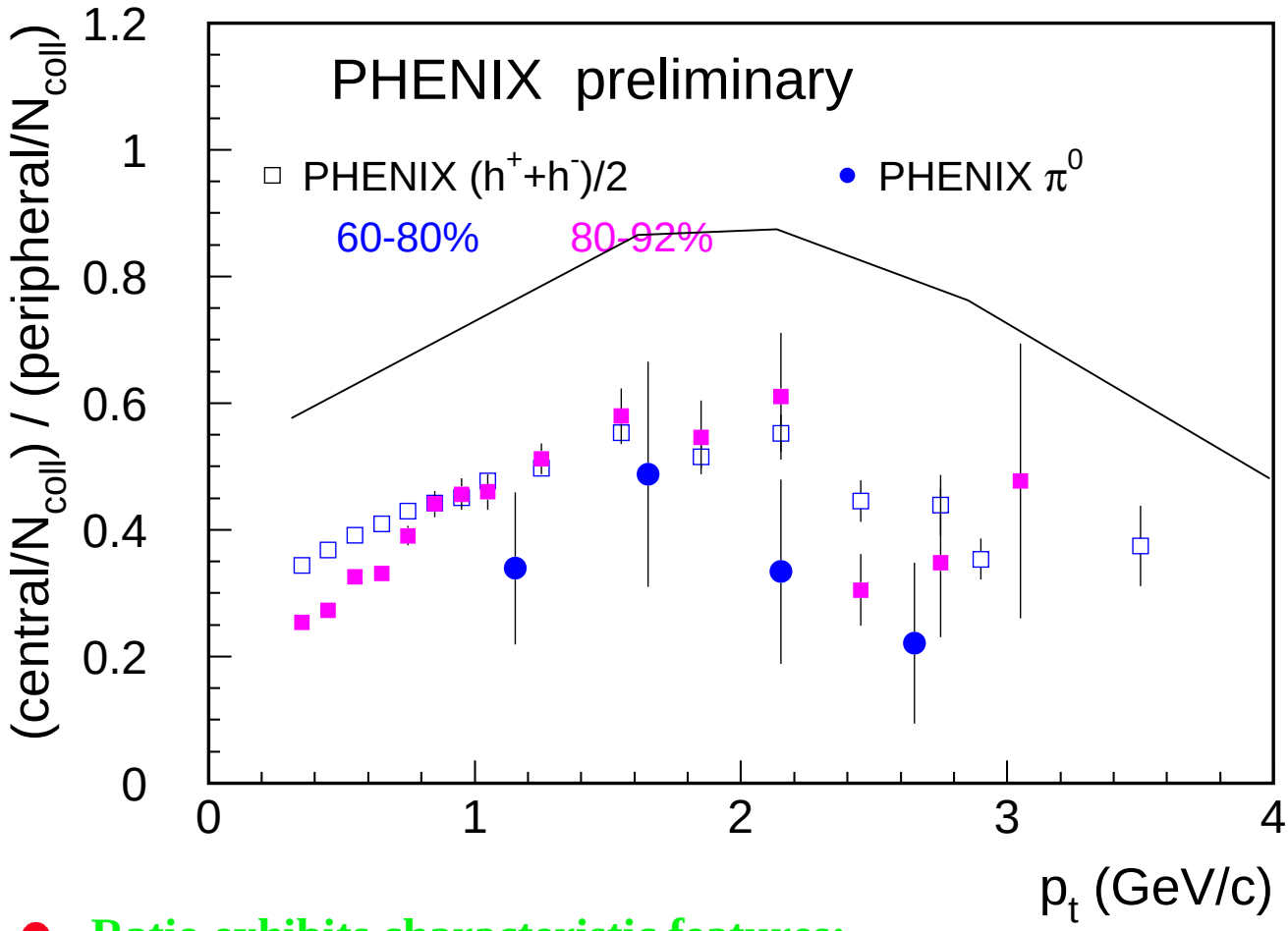


- **Centrality dependence:**
  - **complete systematic for charged**
  - **central and peripheral for π^0**

- **Comparison to p-p**
  - **central below p-p extrapolation**
  - **peripheral agree reasonably with p-p extrapolation (note systematic uncertainty ~60% due to N_{coll})**

Ratio Central/Peripheral

- normalize central and peripheral to number of collisions
- different systematic errors:
  - many experimental errors cancel
  - systematic uncertainty ~60% on N_{coll}



- Ratio exhibits characteristic features:
  - increases up to ~ 2 GeV
  - saturates at $R_{AA} < 1$
  - decrease at high p_t

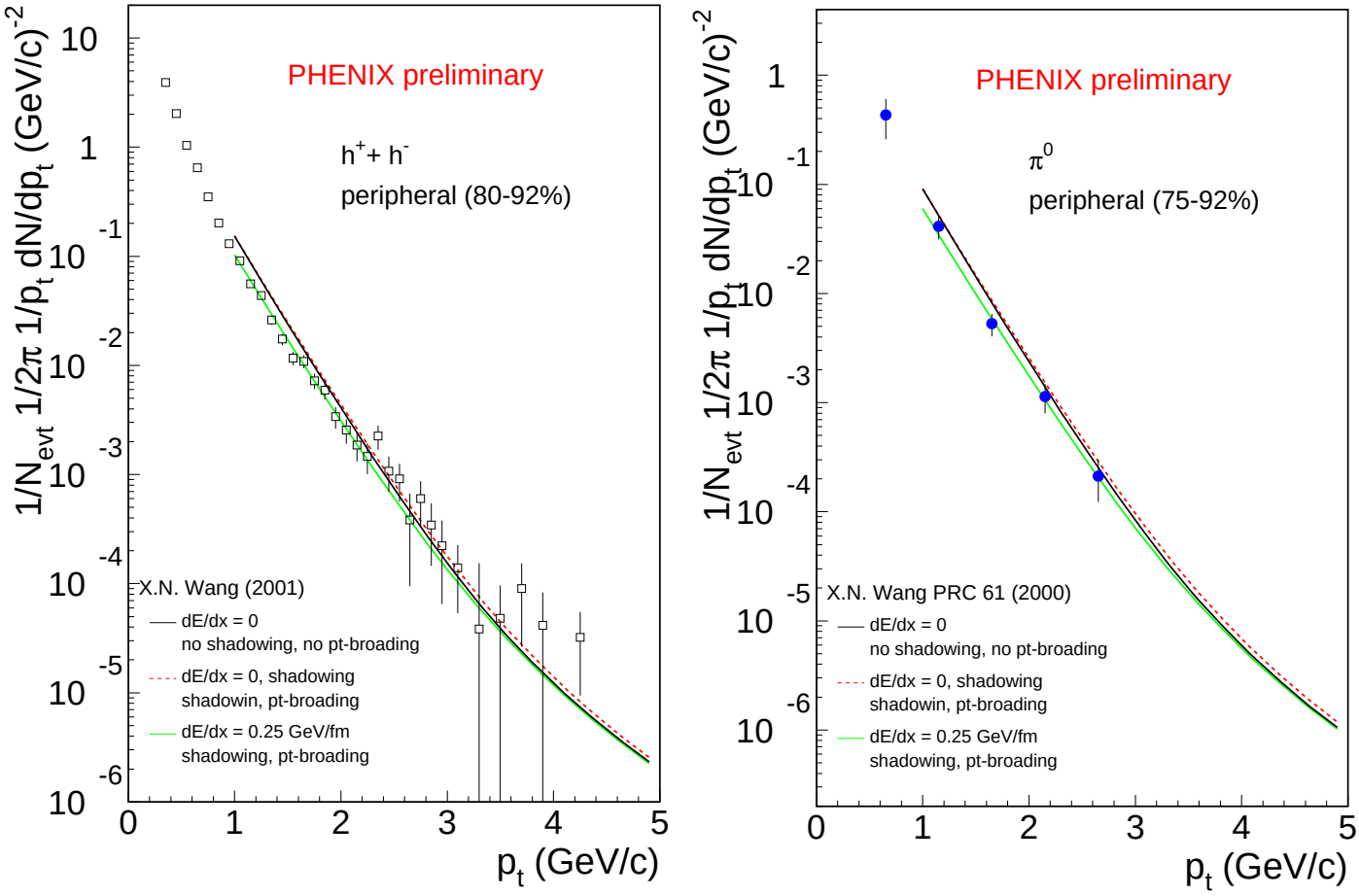
within systematic errors:

$R_{AA} < 1$

Comparison with QCD calculations I

thanks to X.N. Wang for providing calculations

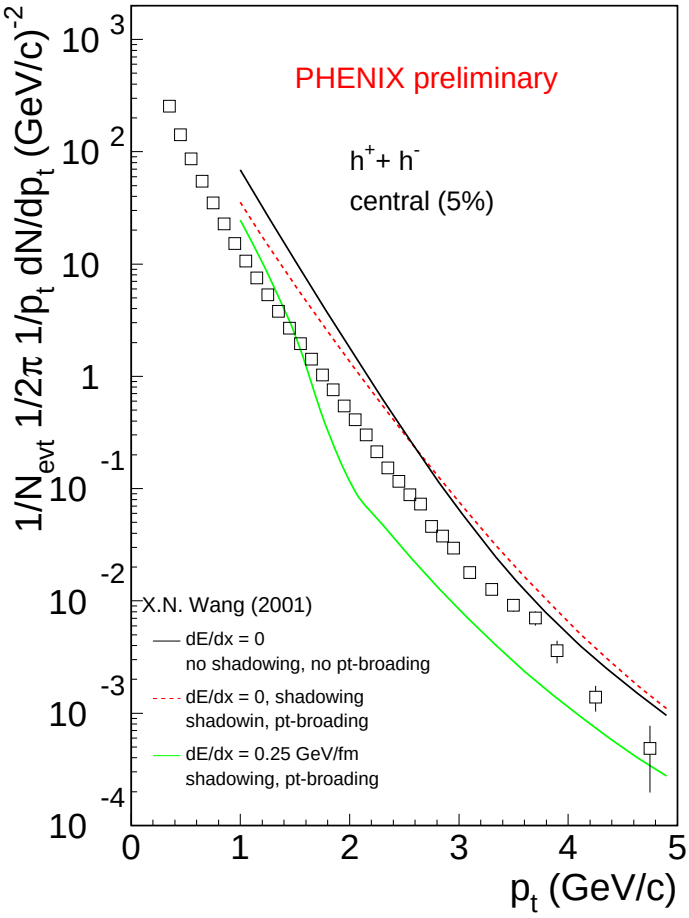
Peripheral Au-Au collisions

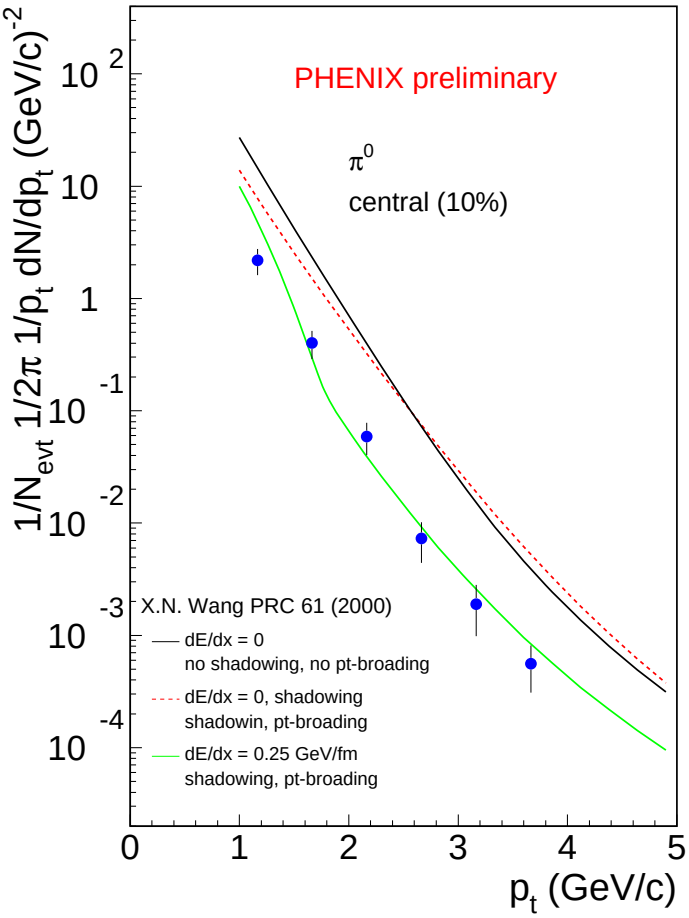


- **excellent agreement with 'simple' pQCD calculation**
- **for charged particles and for identified π^0**

Comparison with QCD Calculations II

central Au-Au collisions





- **p-QCD over estimates the cross-section**
  - **for π^0 at least a factor of 5**
  - **for charged factor of 2**
    (calculation does not describe p & $\bar{p}$ contribution)
- **shadowing and p_t-broadening seem insufficient**
- **calculation including constant energy loss**
  - **consistent with π^0**
  - **for charged magnitude & shape different in detail**

Double-Differential Yields

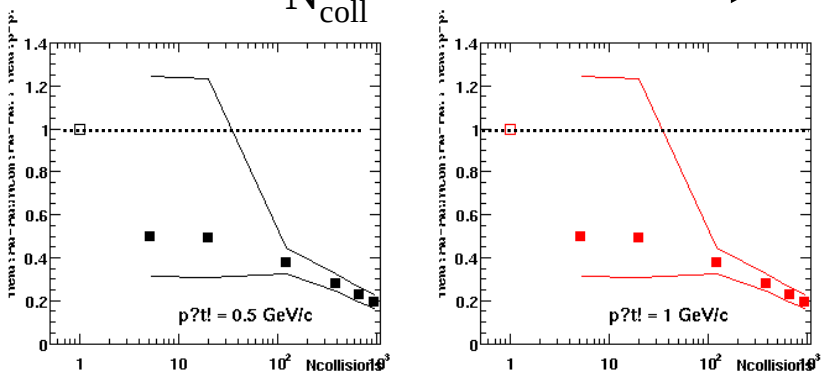
F. Messer, PHENIX

$$\left(\frac{d^2\sigma_{AA}}{dp_t^2} \Big/ N_{coll} \right) \Big/ \frac{d^2\sigma_{pp}}{dp_t^2}$$ as function of p_t and N_{coll}

N_{coll} →

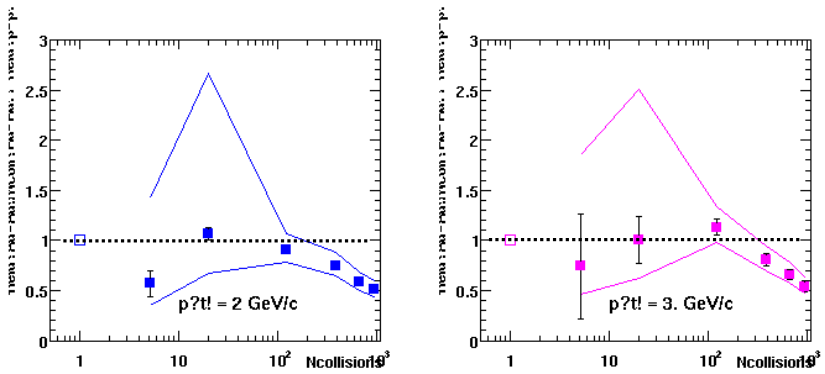
low p_t

<1 GeV



soft physics

does not scale with N_{coll}

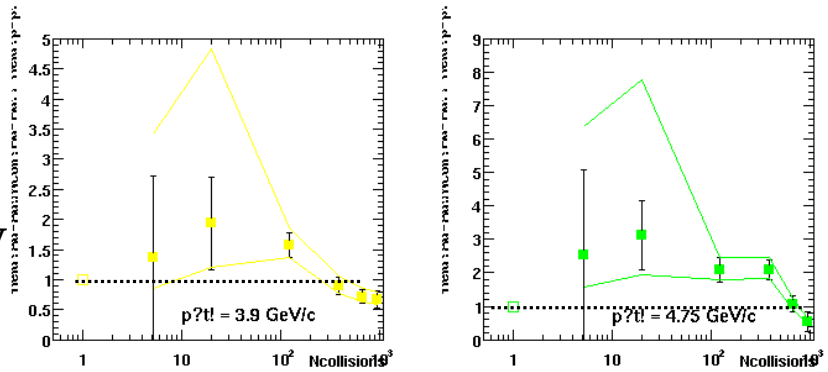


hard physics in per. collisions

decrease for central collisions

high p_t

4 -5 GeV

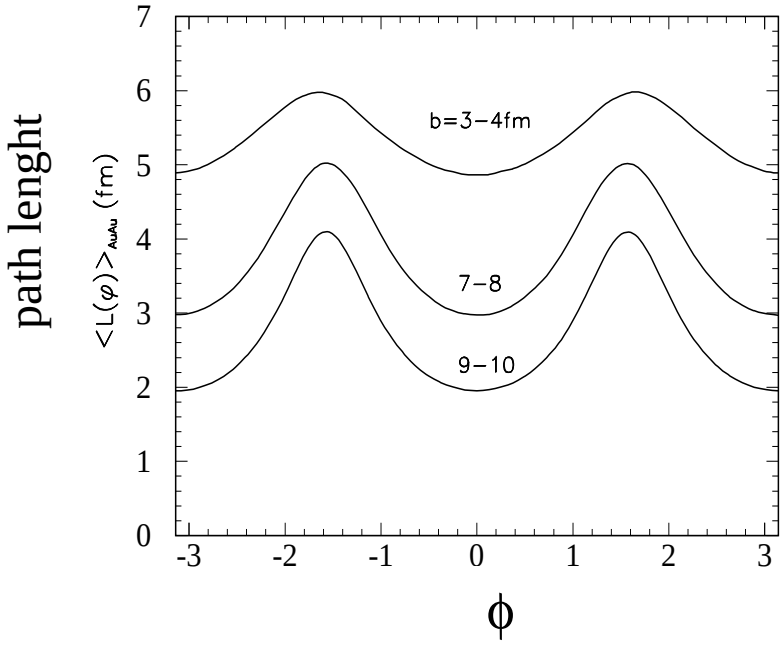


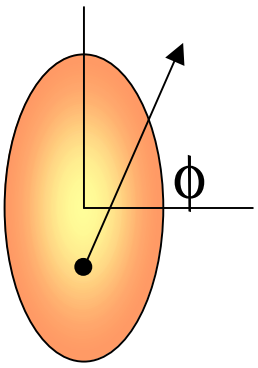
double differential yields exhibit interesting structure

Azimuthal Anisotropy

X.Y. Wang

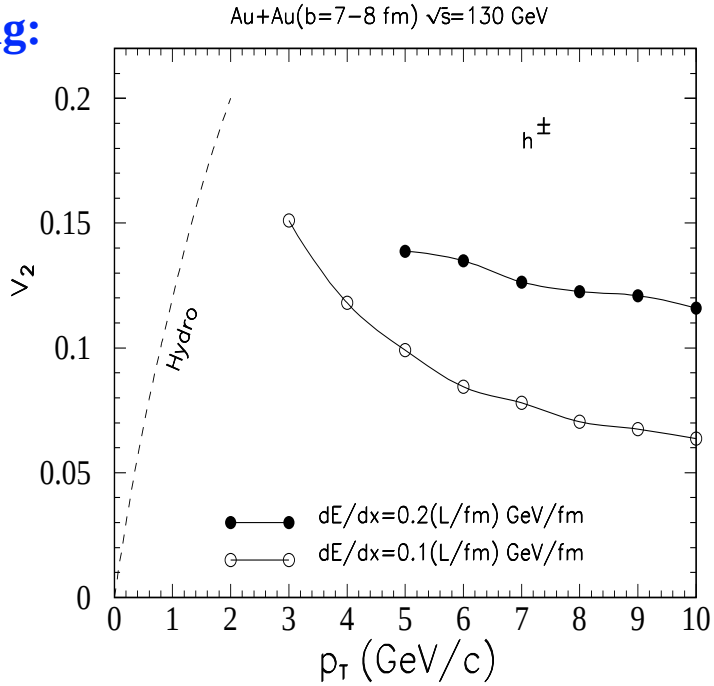
- **Anisotropy in geometry:**





nucl-th/0009019

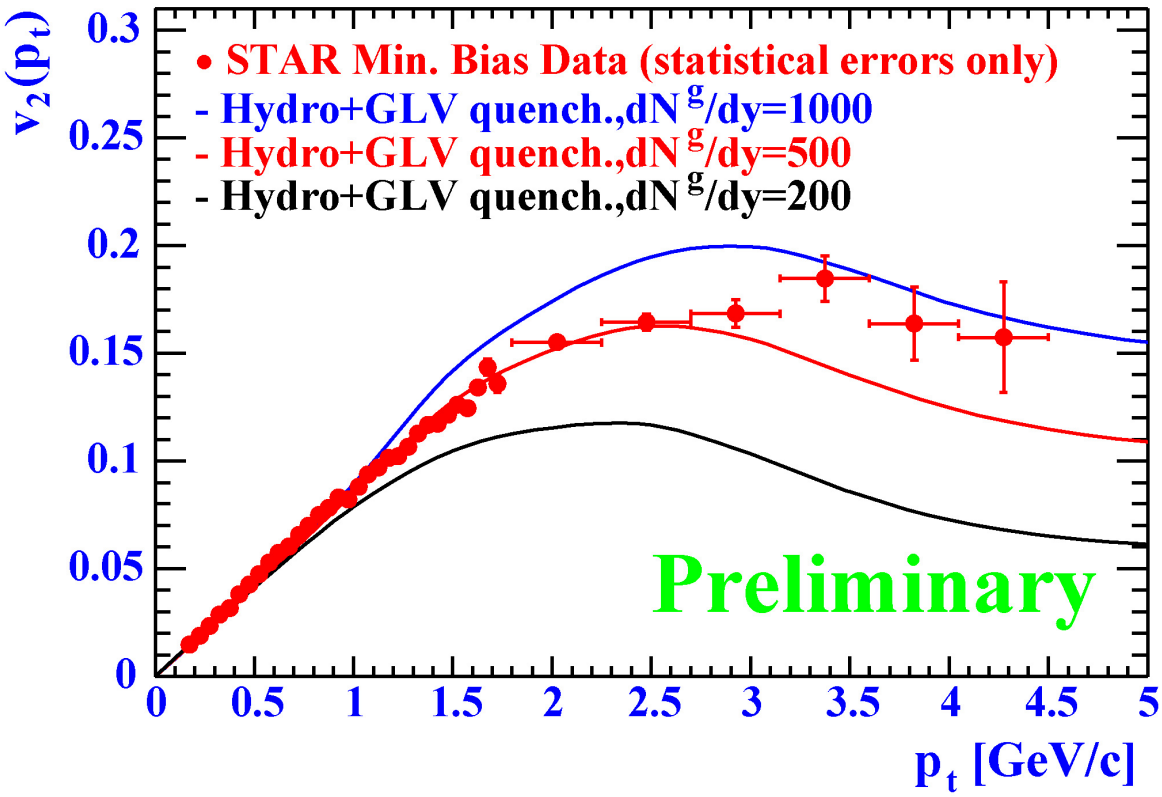
- **Anisotropy in jet quenching:**
  - **hydro valid up to some p_t**
  - **without dE/dx**
    $v_2 \rightarrow 0$
  - **with finite dE/dx**
    anisotropy in geometry
    $\rightarrow$ $v_2 > 0$



Charged particle anisotropy
$0 < p_t < 4.5$ GeV/c

Raimond Snellings, STAR

- **STAR data: only statistical errors plotted. Systematic error 10% - 20% for p_t = 2 – 4.5 GeV/c**
- **Hydro+GLV: M. Gyulassy, I. Vitev and X.N. Wang, nucl-th/00012092**

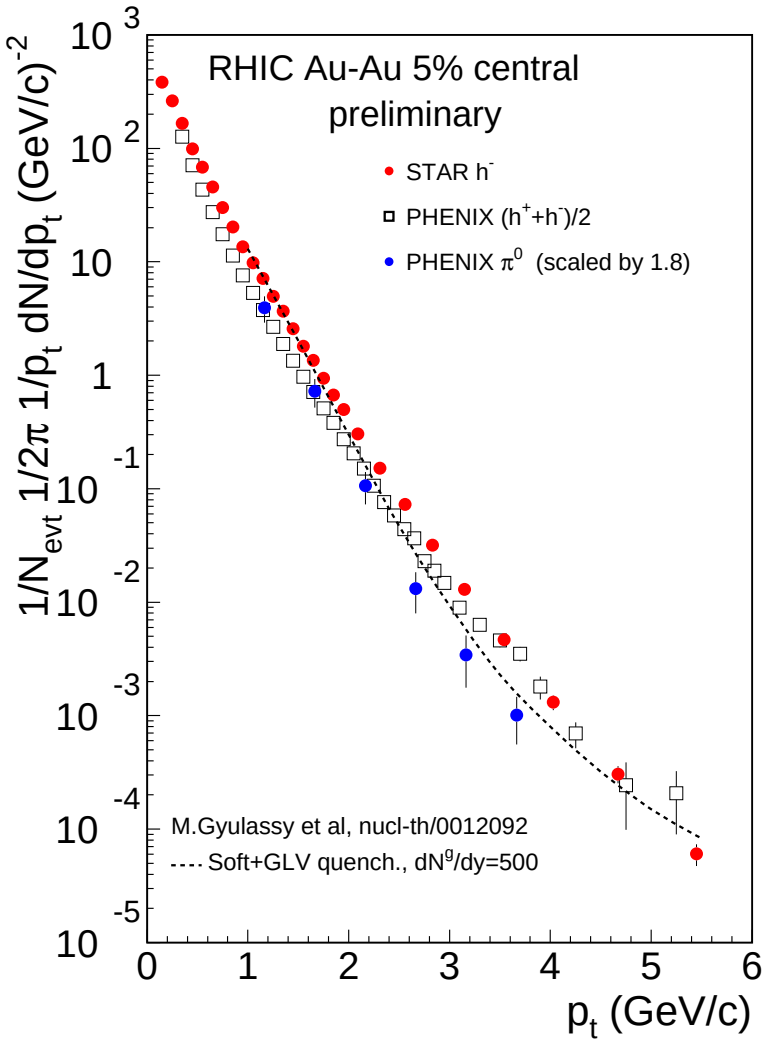


- **azimuthal angular correlation measured by v_2:**
  - **hydrodynamic behavior up to ~1.5 GeV**
  - **followed by saturation**

- **comparison to a recent theoretical calculation**
  - **compatible with jet quenching scenario**
  - **sensitivity to initial conditions**

Comparison with p_t distribution

Hydro+GLV: M. Gyulassy, I. Vitev and X.N. Wang, nucl-th/00012092



- **calculation compatible with**
  - **anisotropy measurement**
  - **and p_t - spectra**

Summary

- **only 4 months after the first run at RHIC we saw very interesting high-p_t data from PHENIX and STAR**
  - **charged and identified particles p_t spectra to 4 - 6 GeV**
  - **azimuthal angular correlation out to 4.5 GeV**

amount an variety of RHIC data exceeds all expectations

- **p_t spectra from peripheral collisions seem well reproduced by extrapolations from p-p**
- **p_t spectra from central collisions show clear deviation from p-p extrapolation**

high-p_t data are consistent with "jet quenching" scenarios

- **premature to draw definite or quantitative conclusions**
  - **high p_t-physics has proven to be a useful new penetrating probe**
  - **complementary to charmoniuum production**

- **RHIC run 2001:** **more complete experimental setups**
  higher statistics $\rightarrow$ higher p_t
  accurate p-p reference data