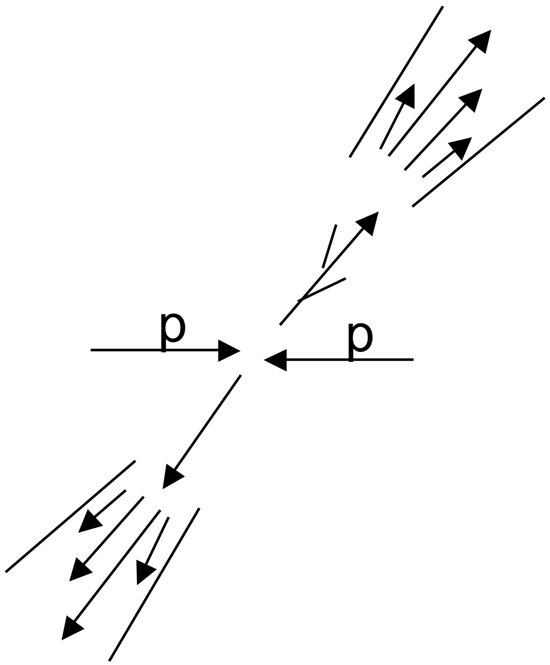
高運動量粒子生成
と
Jet Quenching

Physics Target (I) -Jet quenching-

Jet will loose its energy via gluon radiation in hot dense medium, and the energy distribution of Jet will be modified

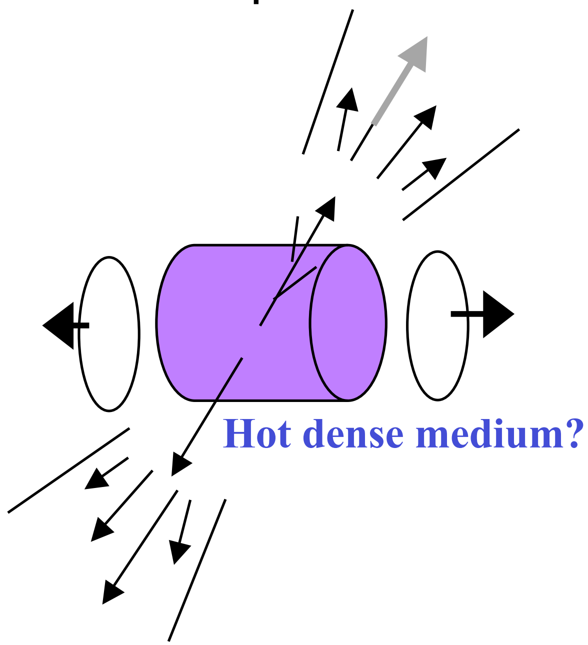
<u>hard-scattered parton from e.g. p+p</u>

cone of hadrons "jet"

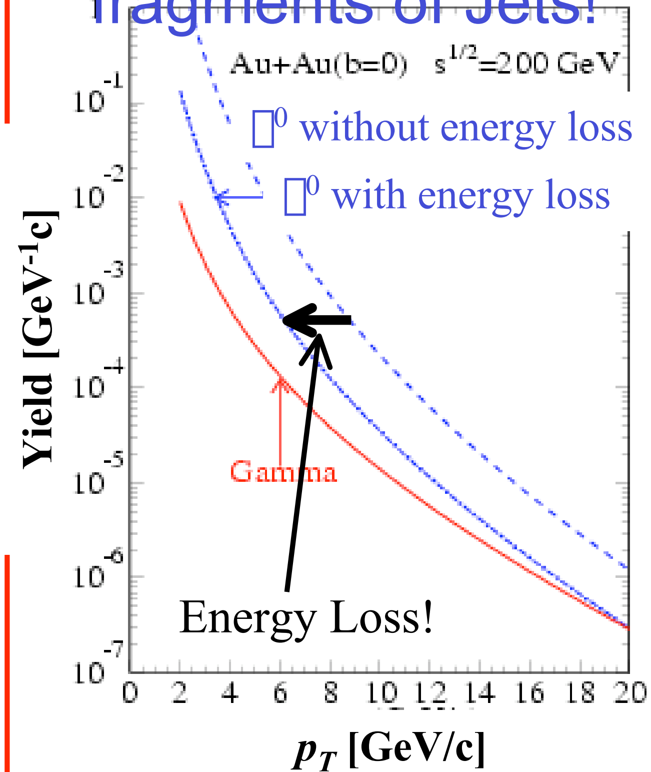


<u>hard-scattered parton during Au+Au</u>

increased gluon-radiation within plasma?



High p_T hadrons are fragments of Jets!



X.-N., Wang, PRC **58** (1998)2321

Expectations in nuclear collisions

- In the absence of nuclear effects, expect point-like scaling:

$$\frac{\text{ó}_{AA}}{\text{ó}_{pp}} \quad \text{the ratio of number of point-like sources} = A^2$$

$$\frac{N_{AA}(b)}{N_{pp}} = N_{coll}\text{; number of binary collisions for a certain } b$$

  - N_{coll} ← calculated using Glauber model
- Previously observed effects:
  - Nuclear Shadowing
  - k_T broadening (“Cronin effect”)

What to compare

- We measure yield per collision for certain centrality bins

$$\mathrm{Yield}(p_T, b) = \frac{1}{N_{event}(b)} \frac{d^2\sigma}{2\pi\, p_T dp_T dy}$$

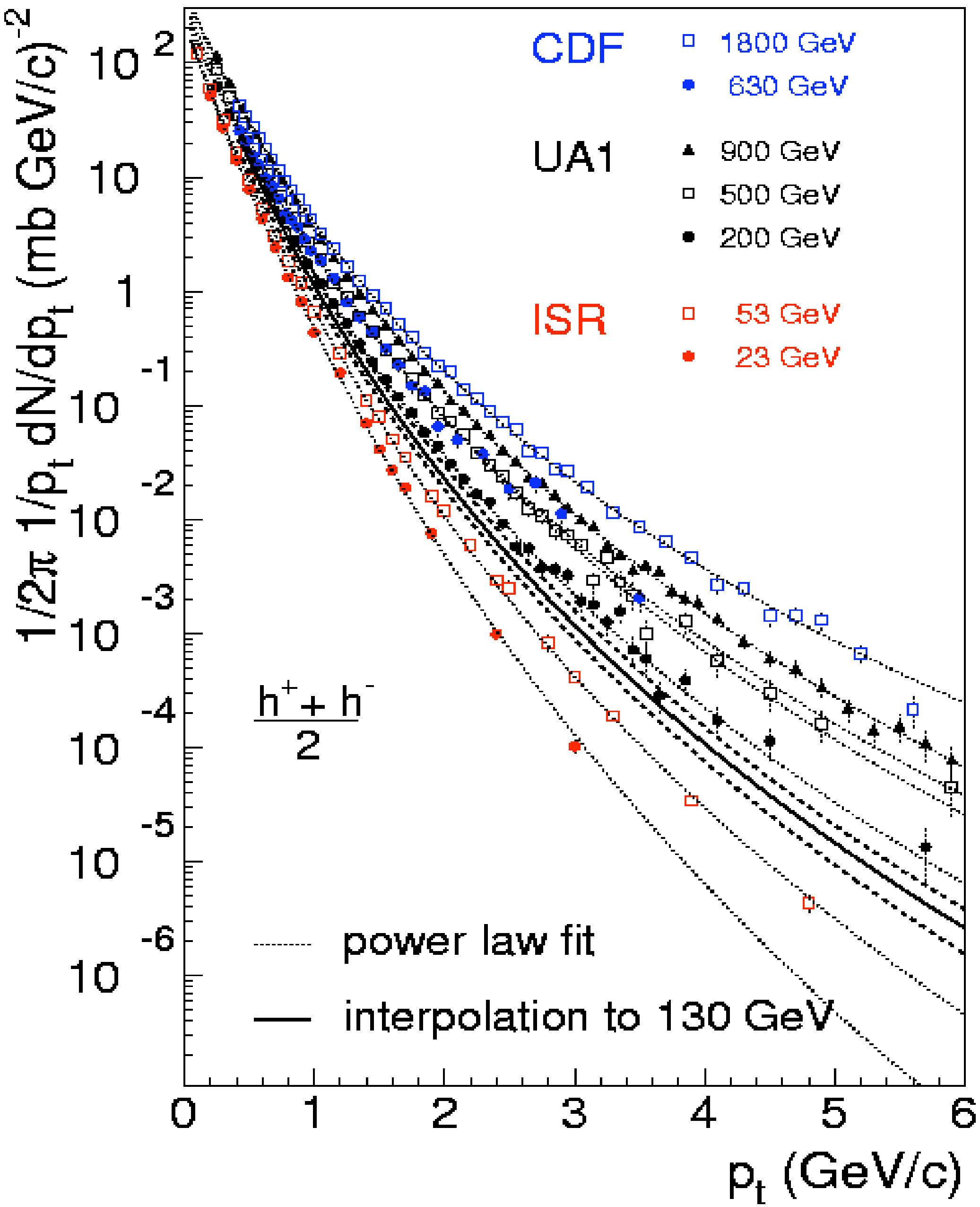
- Ratios of interest:

$$\frac{\mathbf{Yield}_{central} / \langle N_{coll} \rangle_{central}}{\mathbf{Yield}_{pp}} \qquad \frac{\mathbf{Yield}_{central} / \langle N_{coll} \rangle_{central}}{\mathbf{Yield}_{peripheral} / \langle N_{coll} \rangle_{peripheral}}$$

$p + p(\bar{p})$ Data as Reference

- Data available of large range of s, but not for 130 GeV
- Power law fit to: $A(p_0 + p_T)^{-n}$
- Interpolate p_T to s=130 GeV

→ reference p+p spectrum at our s

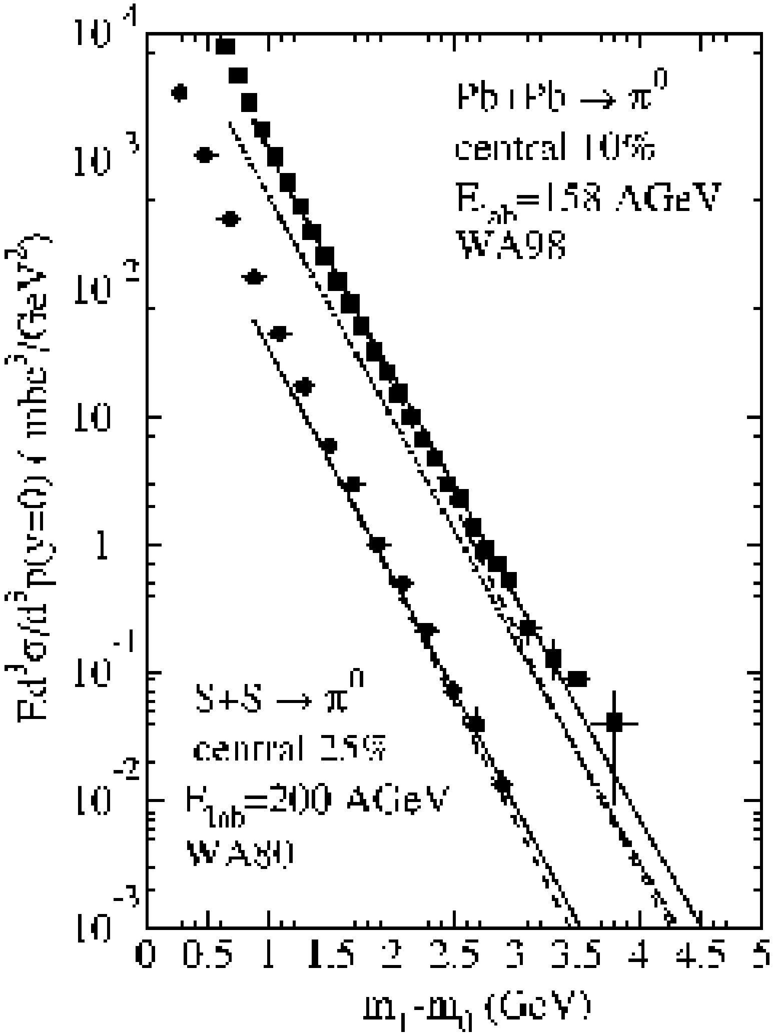


CERN SPS での測定

- データ □^{0} のスペクトル
  - 200 AGeV S+S (WA80)
  - 158 AGeV Pb+Pb (WA98)

- pQCD 計算との比較
  - k_T broadening を考慮すると良い一致が得られる

  - パートンのエネルギーロスは無い？

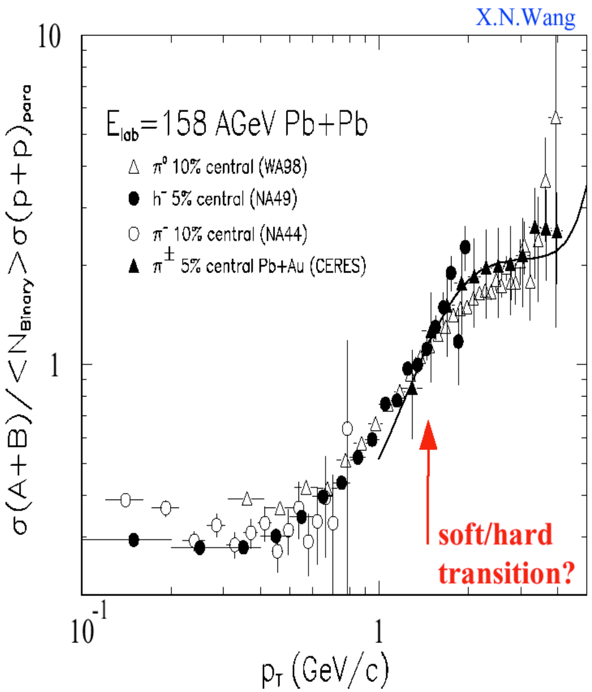


Cronin 効果

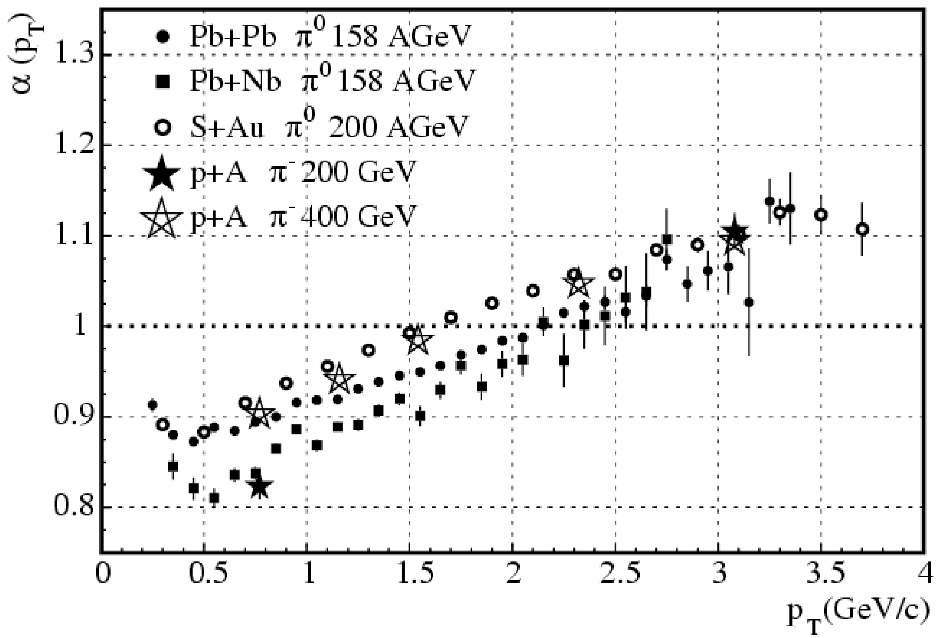
- pA 衝突での生成断面積のターゲット依存性

$$\square_{pA}(p_T) = \square_{pp}(p_T)\ A^{\square(p_T)}$$

  – High p_T 領域で、□ $(p_T) > 1$



Cronin Effect at SPS Energies (Min. Bias)



- 重イオン衝突でも同様な現象
- パートンの多重衝突

  → k_T broadening

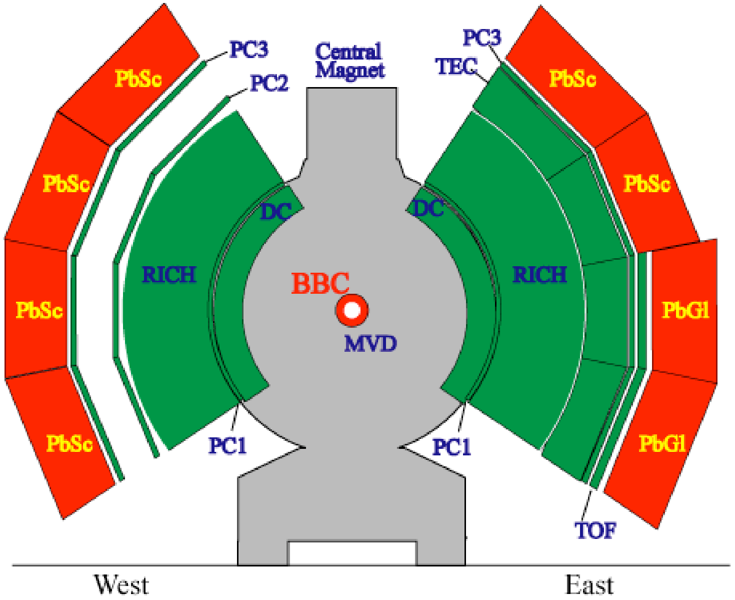
The device: PHENIX EMCal

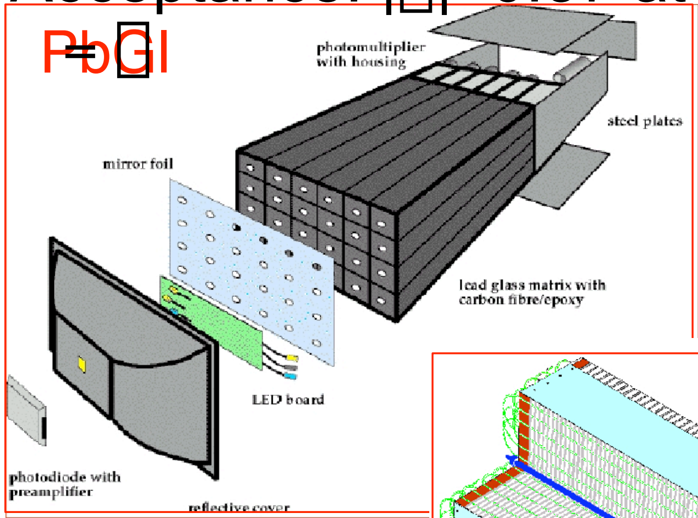
6 lead- scintillator (PbSc) sectors (15500 towers)

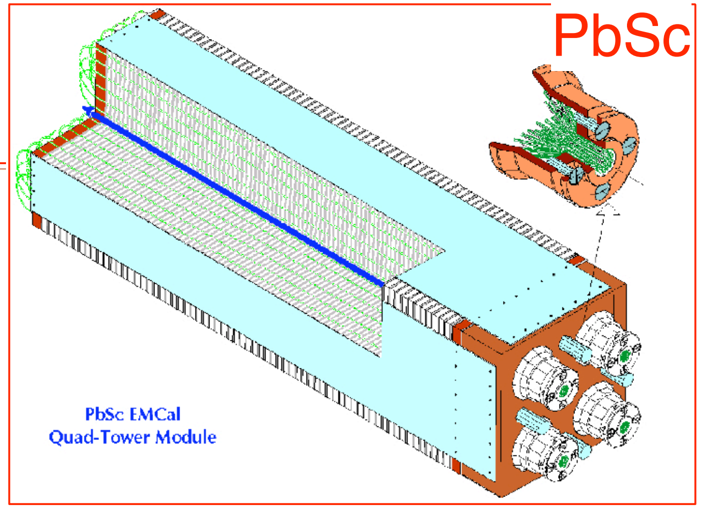
&

2 lead- glass (PbGl) sectors (9200 towers)

Acceptance: |□|<0.37 at midrapidity, □ = □

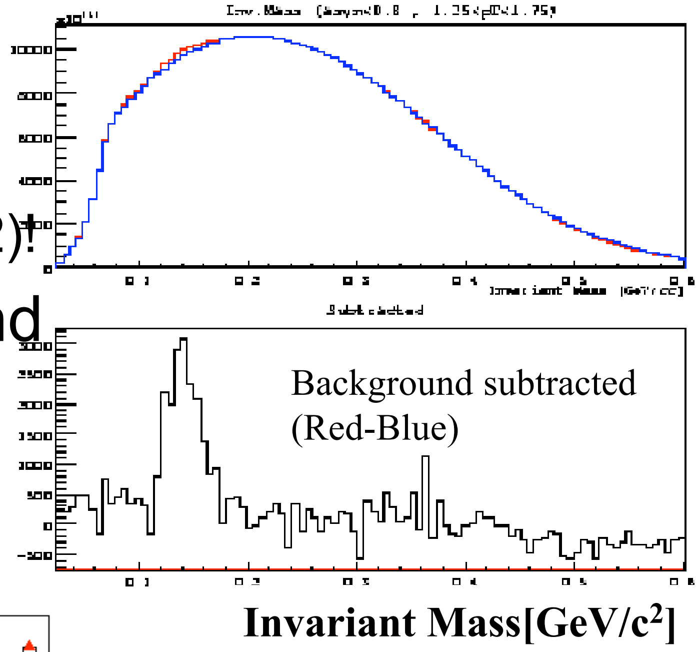




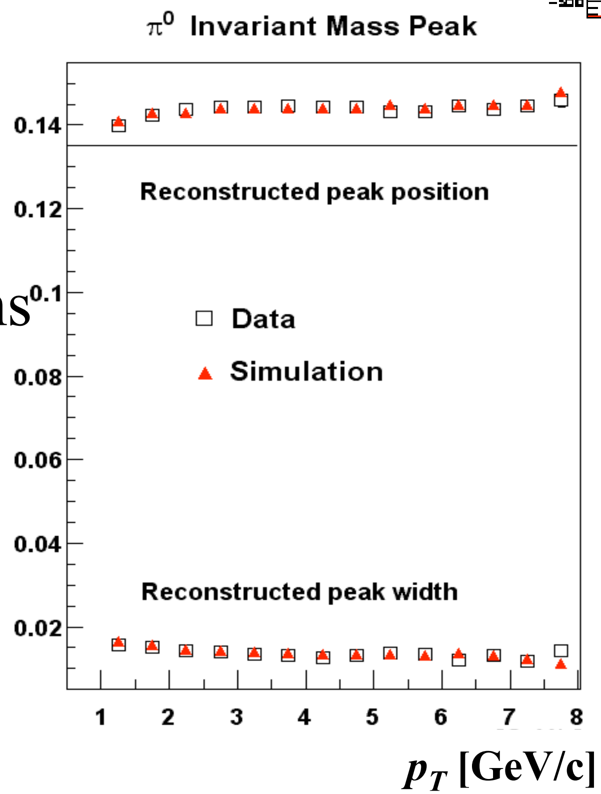


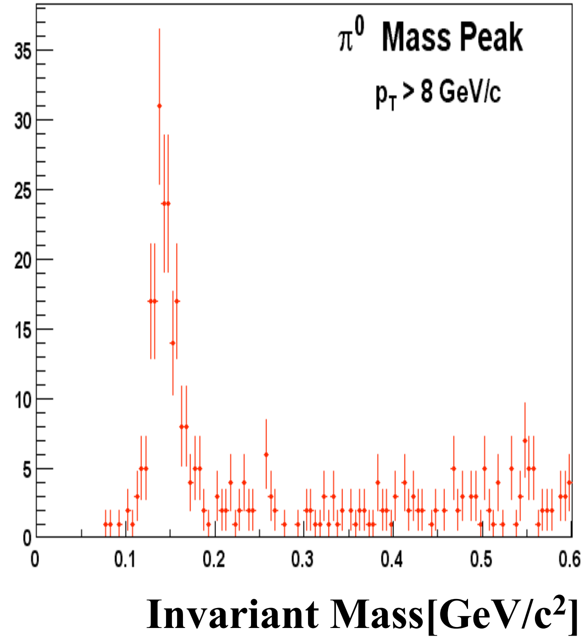
Analysis (Neutral Pion)

- Using Electro-magnetic Calorimeter
  - 1GeV/c<p_T<5(10)GeV/c for π^0 in Year-1(2)!
- Calculate γγ invariant mass spectra and subtract combinatorial background



- Excellent Energy scale accuracy and resolution
- Efficiency and acceptance corrections
  - Embedding single π^0 into real event
- Systematic Error:
  - p_T independent- 9%
  - Overall- 20-30%

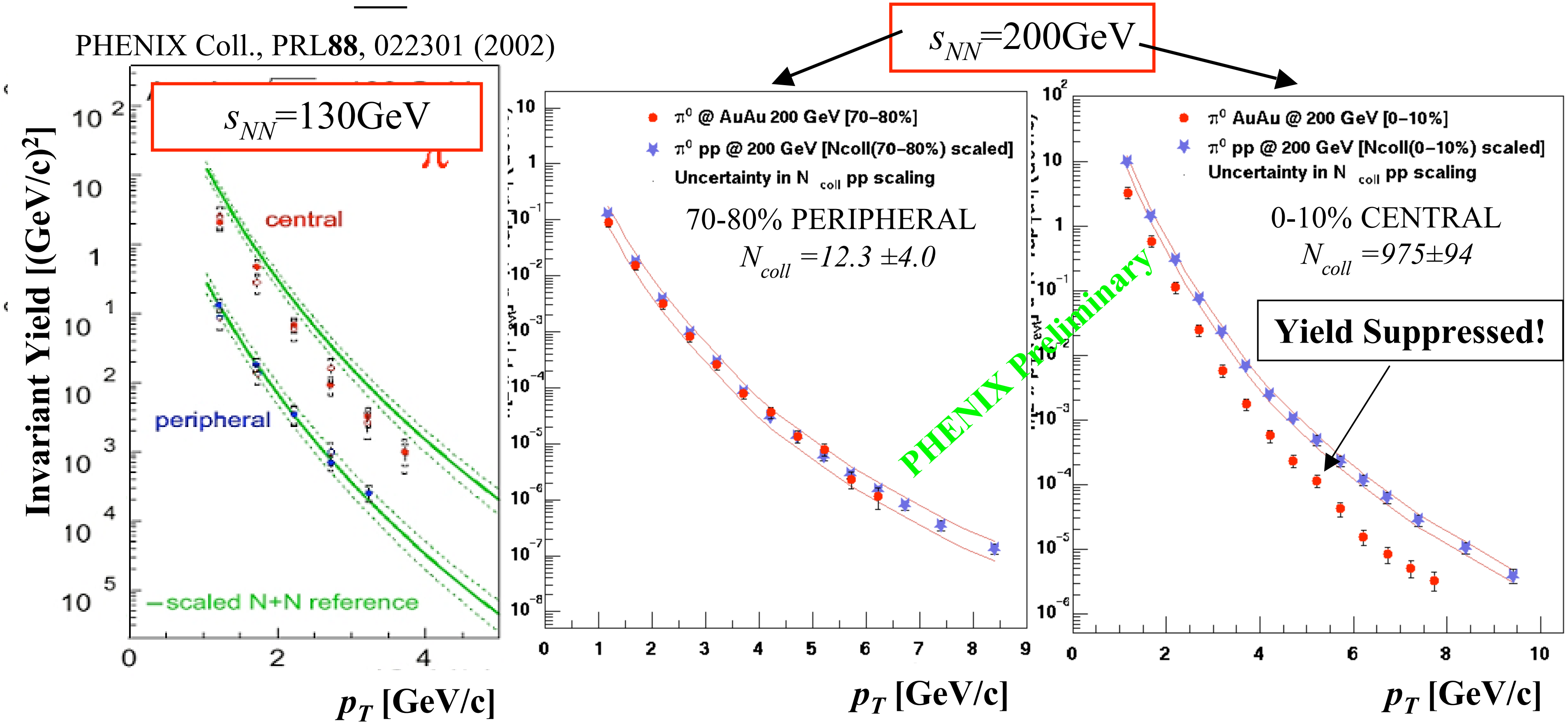




Neutral Pion p_T spectra

- Suppression is quantified relative to p+p “baseline” scaled by Number of binary collisions (N_{coll})
- s_{NN}=130 GeV and 200GeV Au+Au data are shown
- Central collisions data are inconsistent with p+p “baseline” scaled by N_{coll}, while peripheral data are consistent

PHENIX Coll., PRL**88**, 022301 (2002)



Nuclear Modification factor

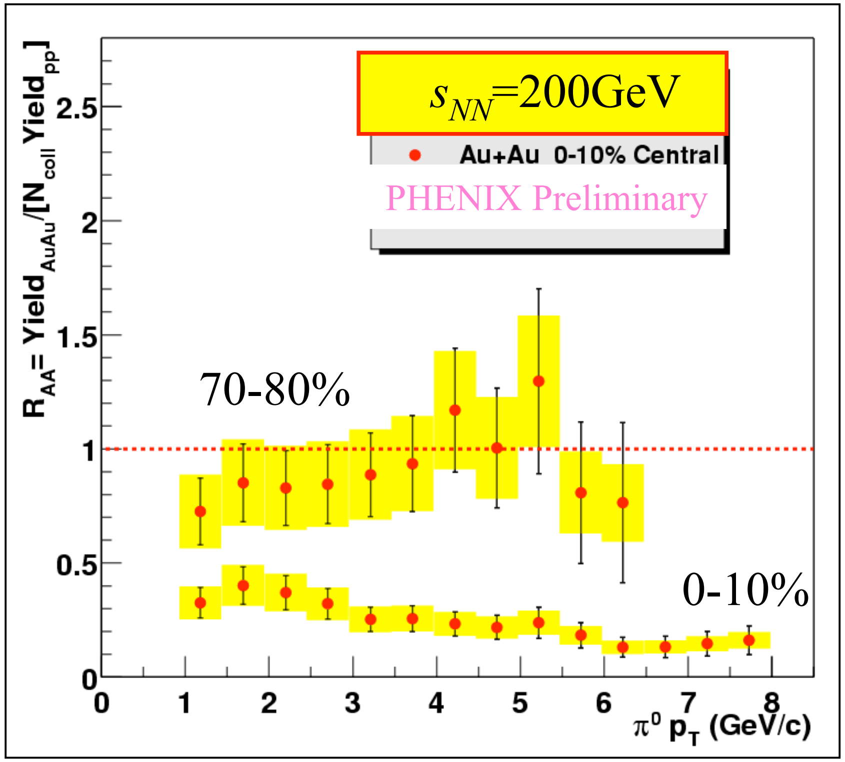
$$R_{AA}(p_T) = \frac{1/N_{events}\ d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma_{pp}/dp_T d\eta/\sigma^{pp}_{inelastic})} = \frac{Yield_{central}/\langle N_{binary}\rangle_{central}}{Yield_{pp}}$$

← Ratio of "Yield per collision"

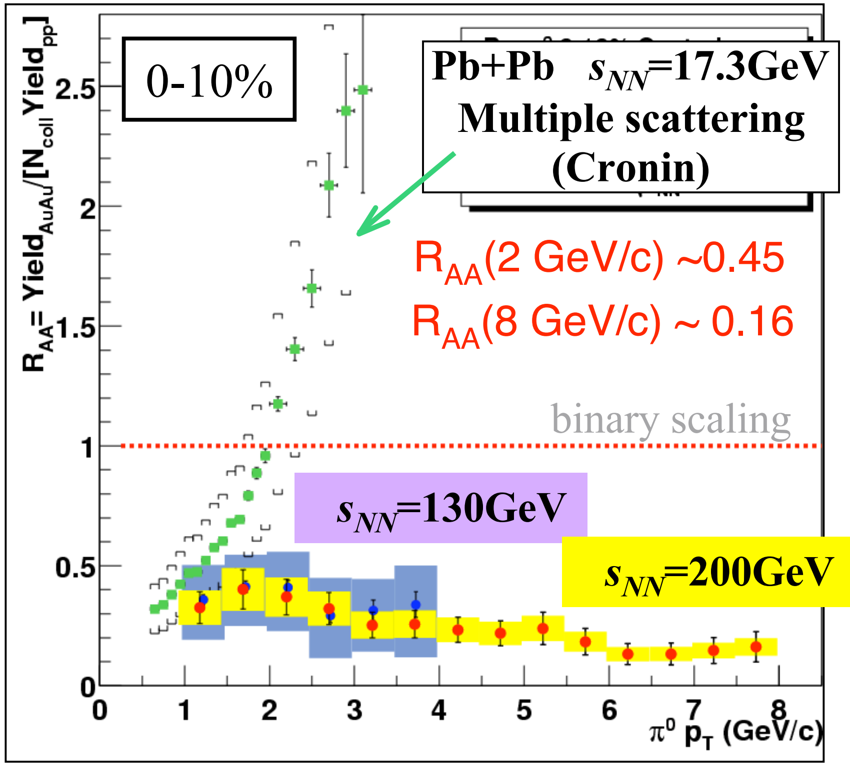
Nuclear Effects can be explored: multiple scattering energy loss, etc.

If there is NO nuclear effect, ratio = 1 (basic hard process)

Centrality Dependence



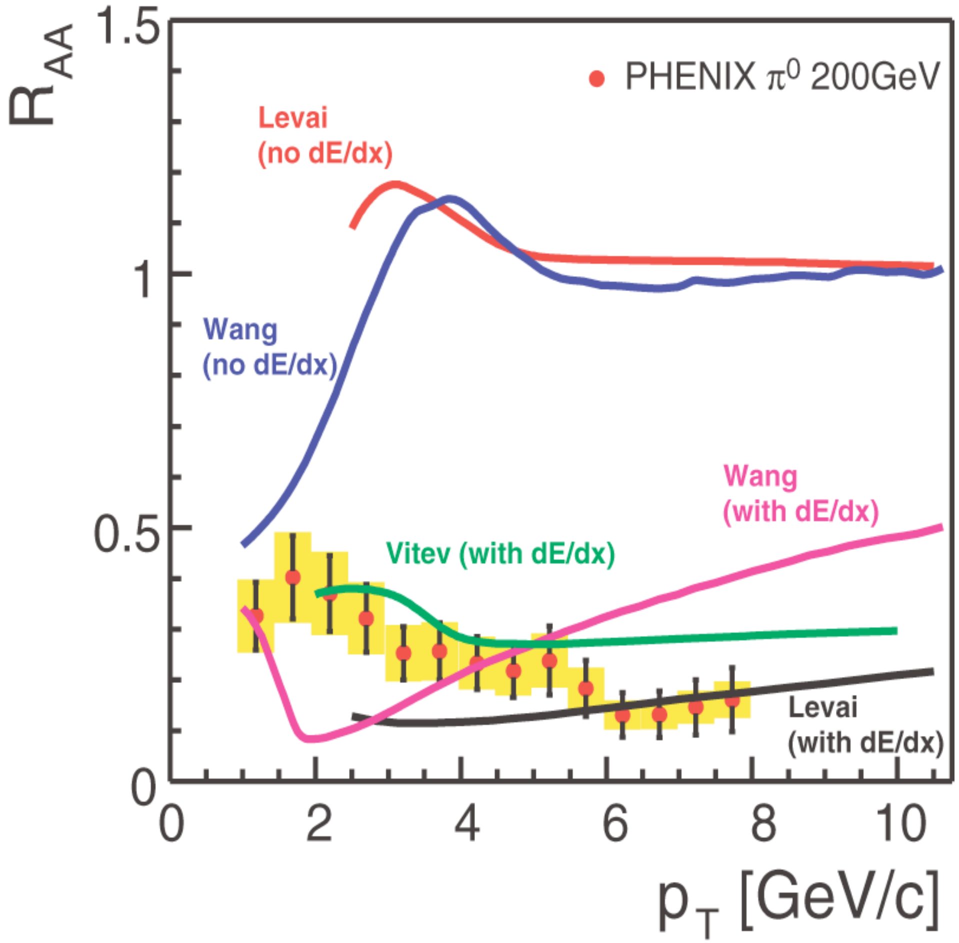
Beam Energy Dependence



Suppression at higher p_T and higher centrality (Energy loss?)

High p_T Neutral Pion Suppression – Comparison To Theory

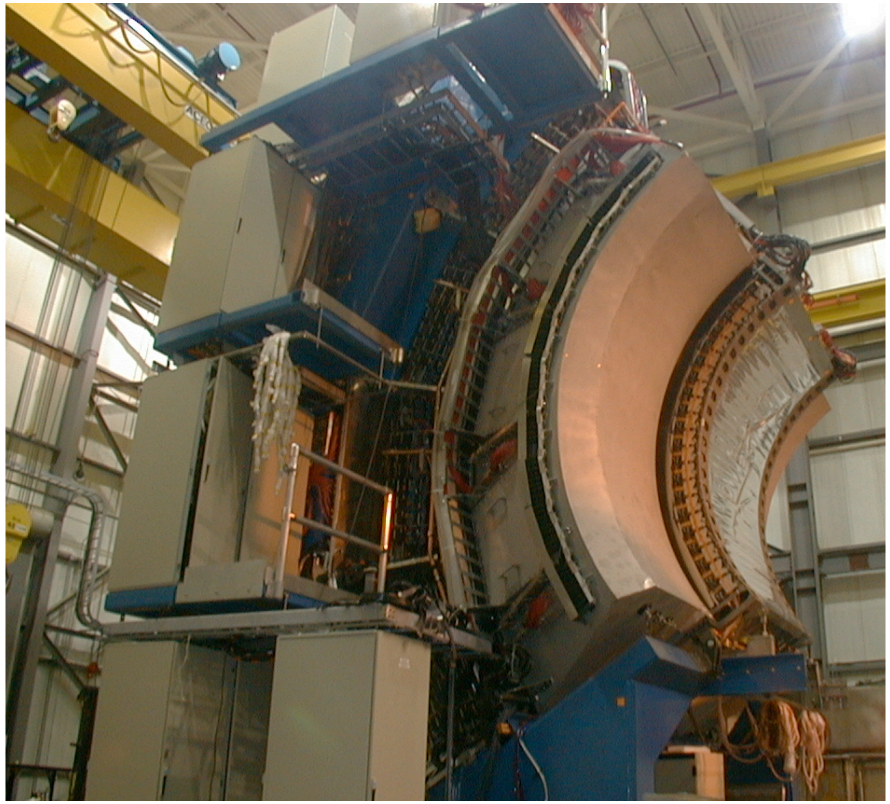
- pQCD calculations:
  - P. Levai, Nucl.Phys.A698 (2002) 631
  - X.N. Wang, Phys.Rev.C61 (200) 064910
  - I. Vitev, talk at QM2002
- so far suppression not described by theories
  - calculations without energy loss completely off
  - energy loss calculations show different p_T dependence



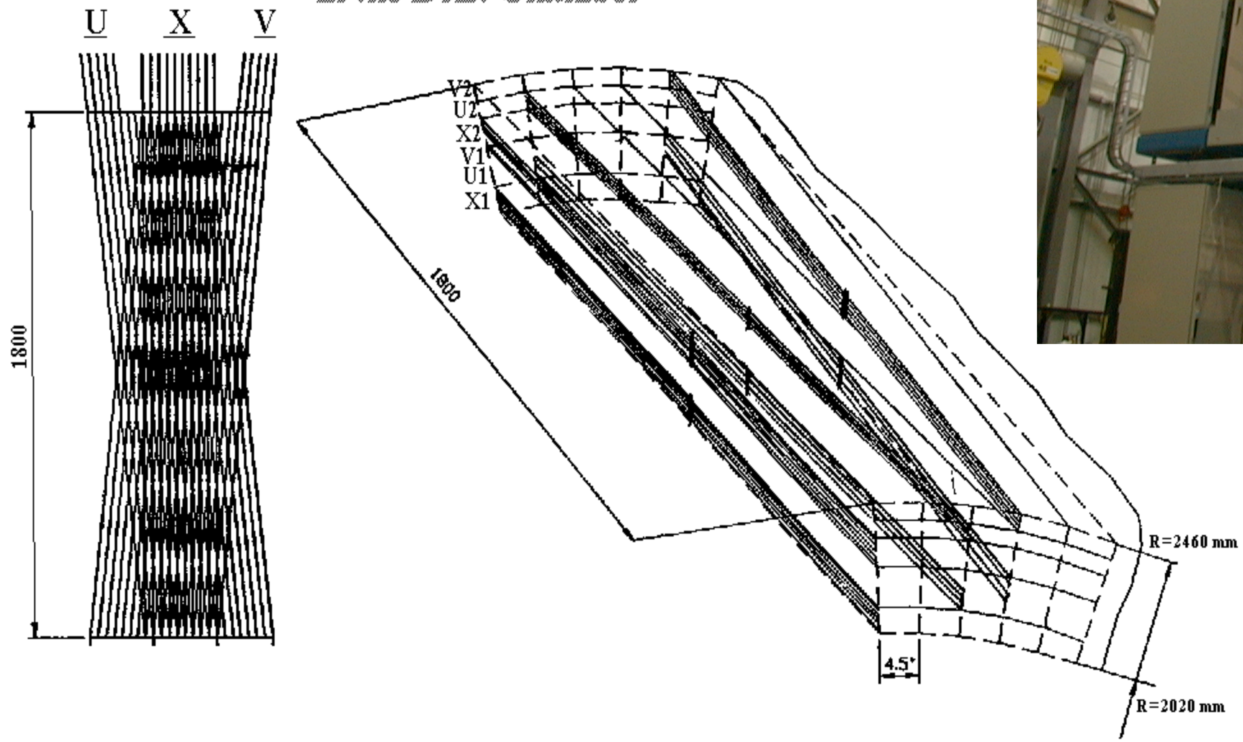
The Drift Chamber

Coverage:

□□ = 90° □□ = 0.7



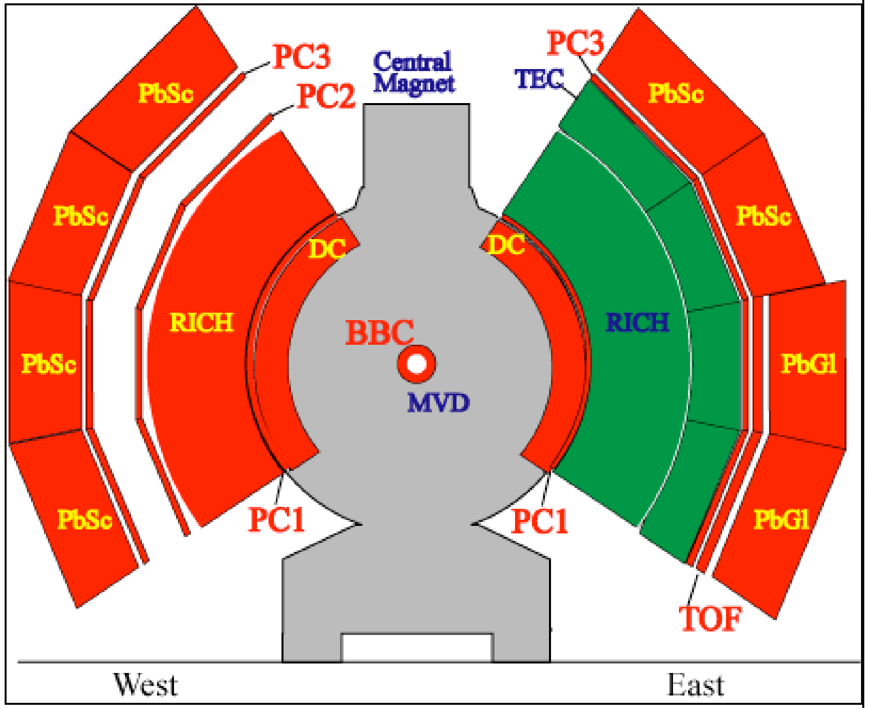
Schematic Drawing of X, U, V - planes wires location in the Drift Chamber

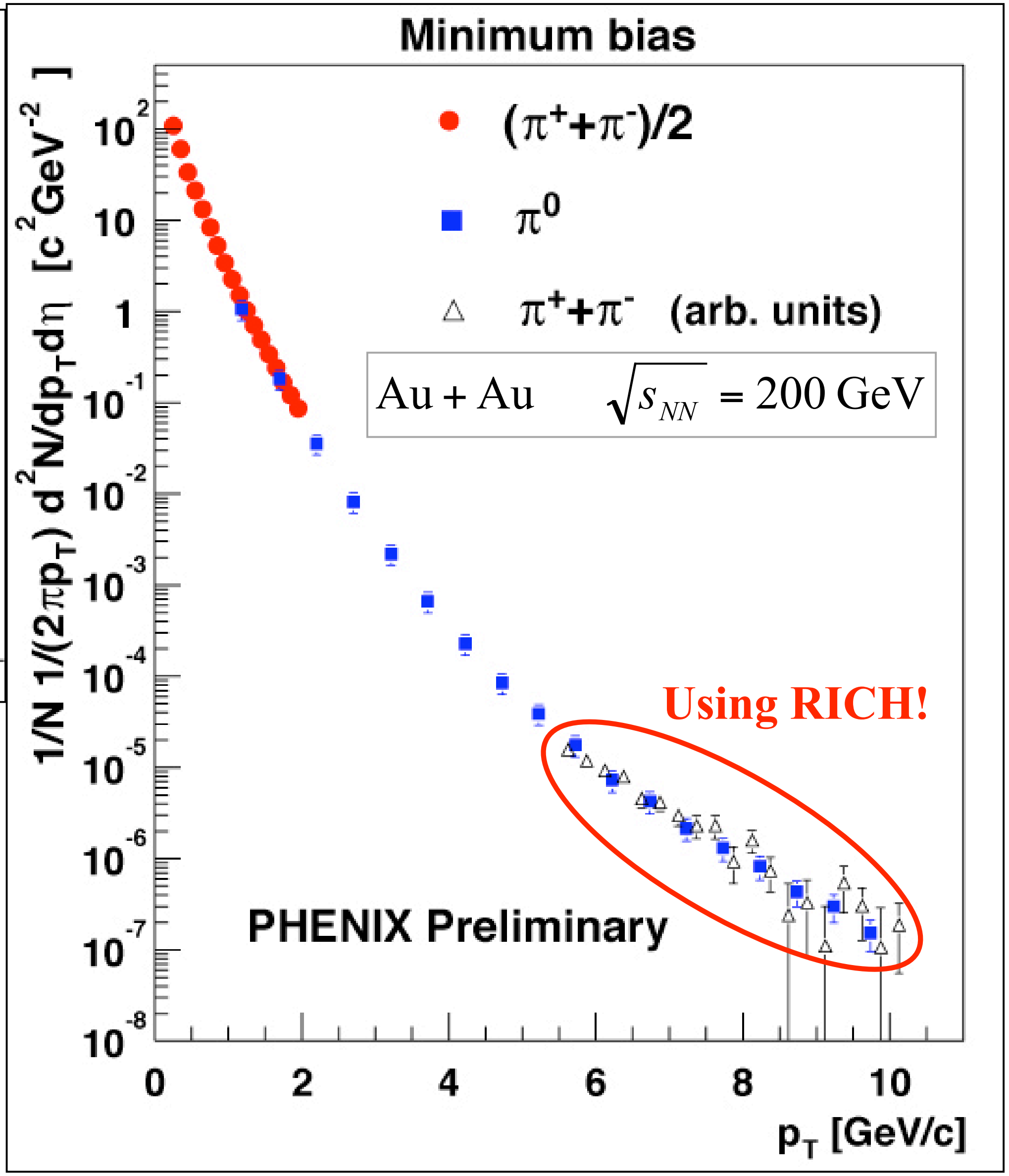


6 module types:

X1,U1,V1,X2,U2,V2

Wide range measurement of □'s



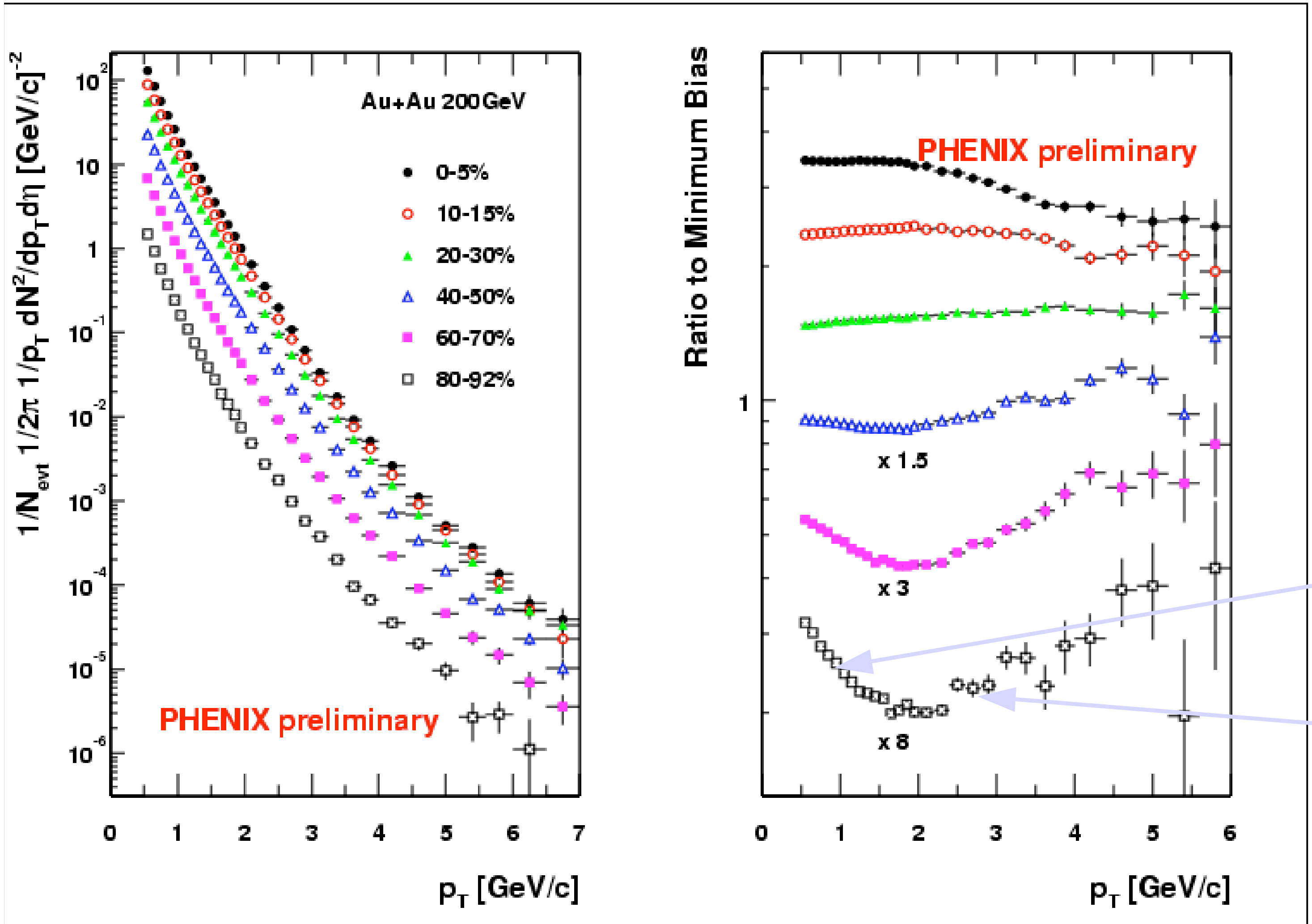


- Most of central arms used to measure the pion spectrum
- Powerful cross-checks of results

Charged Hadron spectra

- Strong shape change with centrality
- Same tendency as □⁰ is seen

s_{NN}=200GeV



Ratios to minimum bias spectrum

Most Peripheral:

p_T<2 GeV/c :

absence of flow

p_T>2 GeV/c :

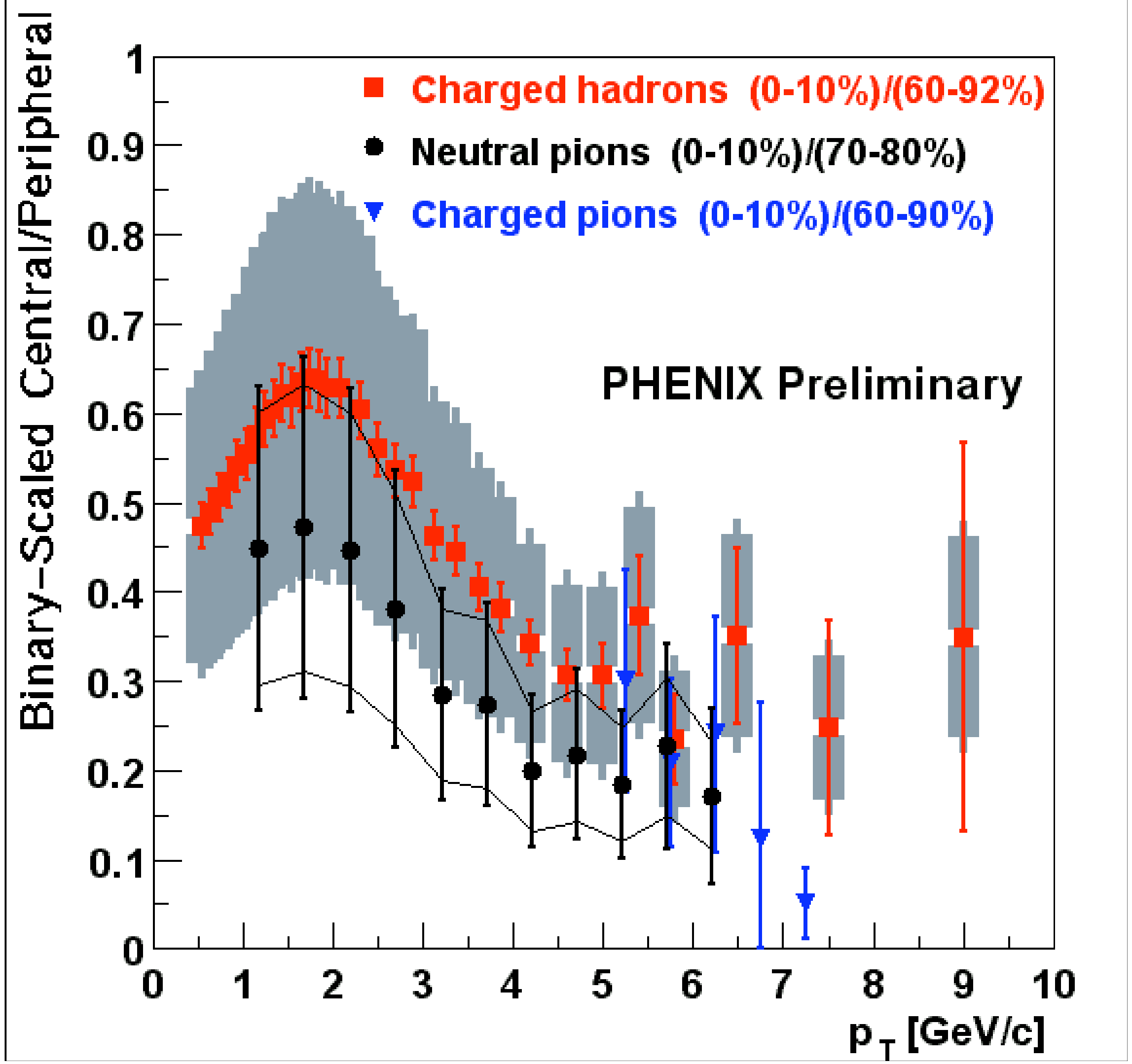
absence of suppression

Central to Peripheral Ratio

(A variation on R_{AA})

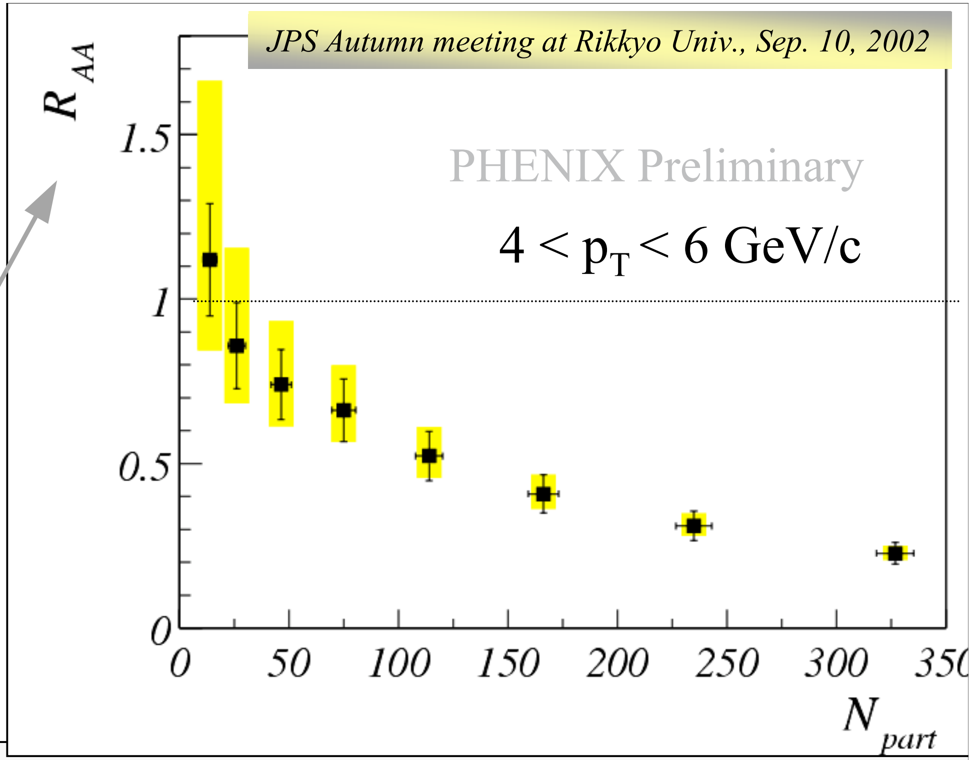
$$\frac{Yield_{central} / \langle N_{binary} \rangle_{central}}{Yield_{peripheral} / \langle N_{binary} \rangle_{peripheral}}$$

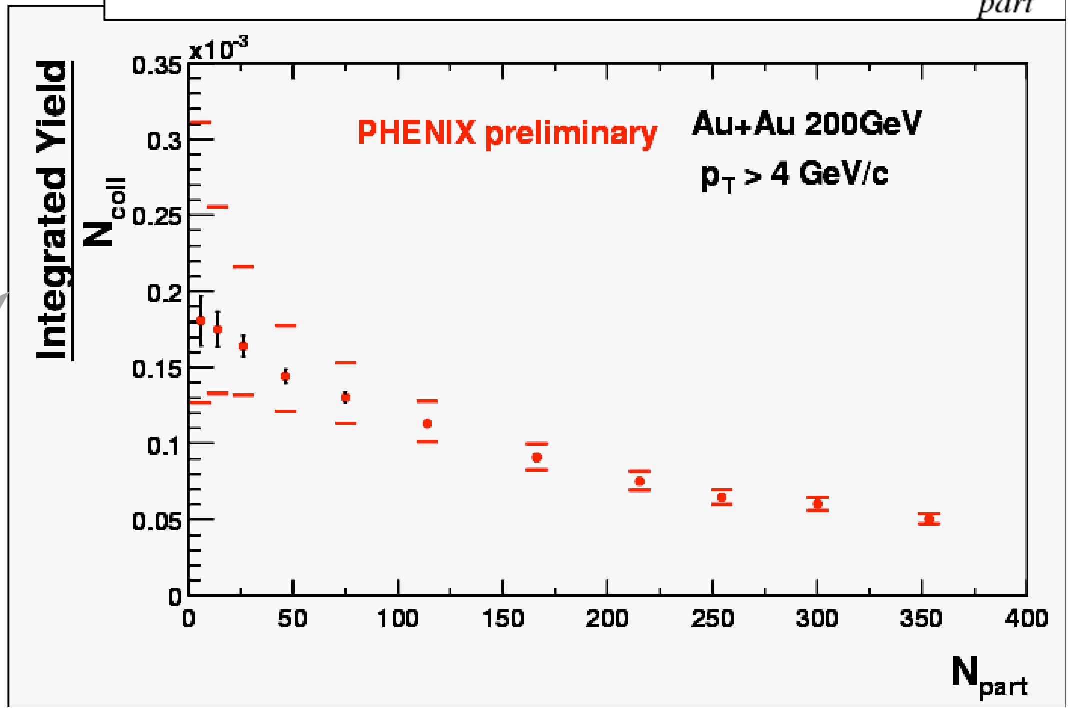
- Should be 1 if there is NO nuclear effect
- Suppression seen in three independent measurements



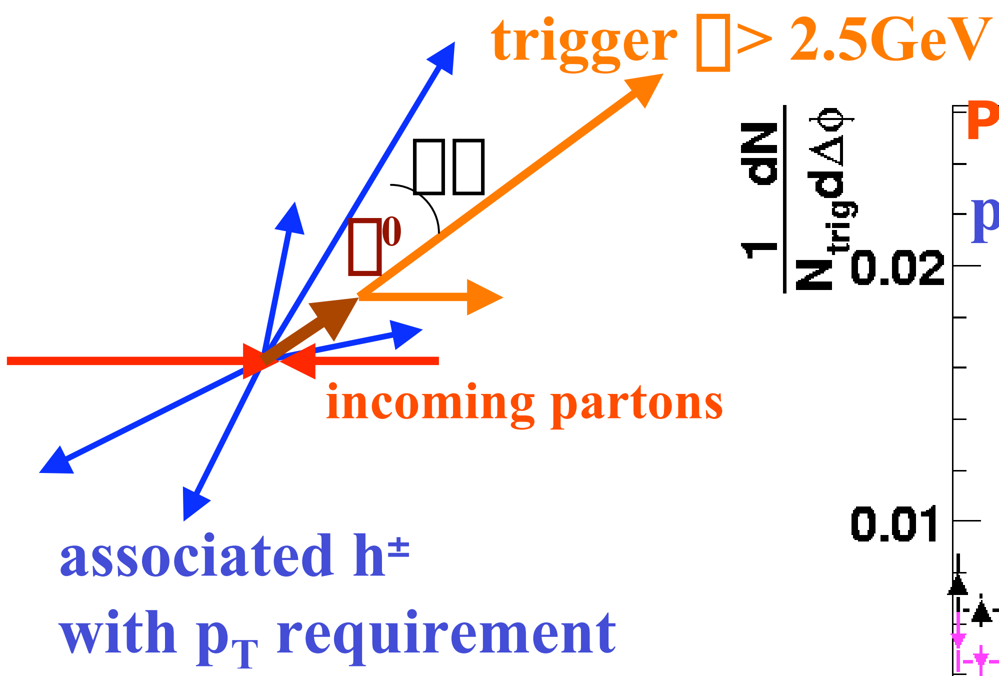
Centrality Dependence of Suppression

- Nuclear Modification Factor as a function of N_{part}
  π^0
- Binary-scaled yield as a function of N_{part}
  $h^{\pm}$

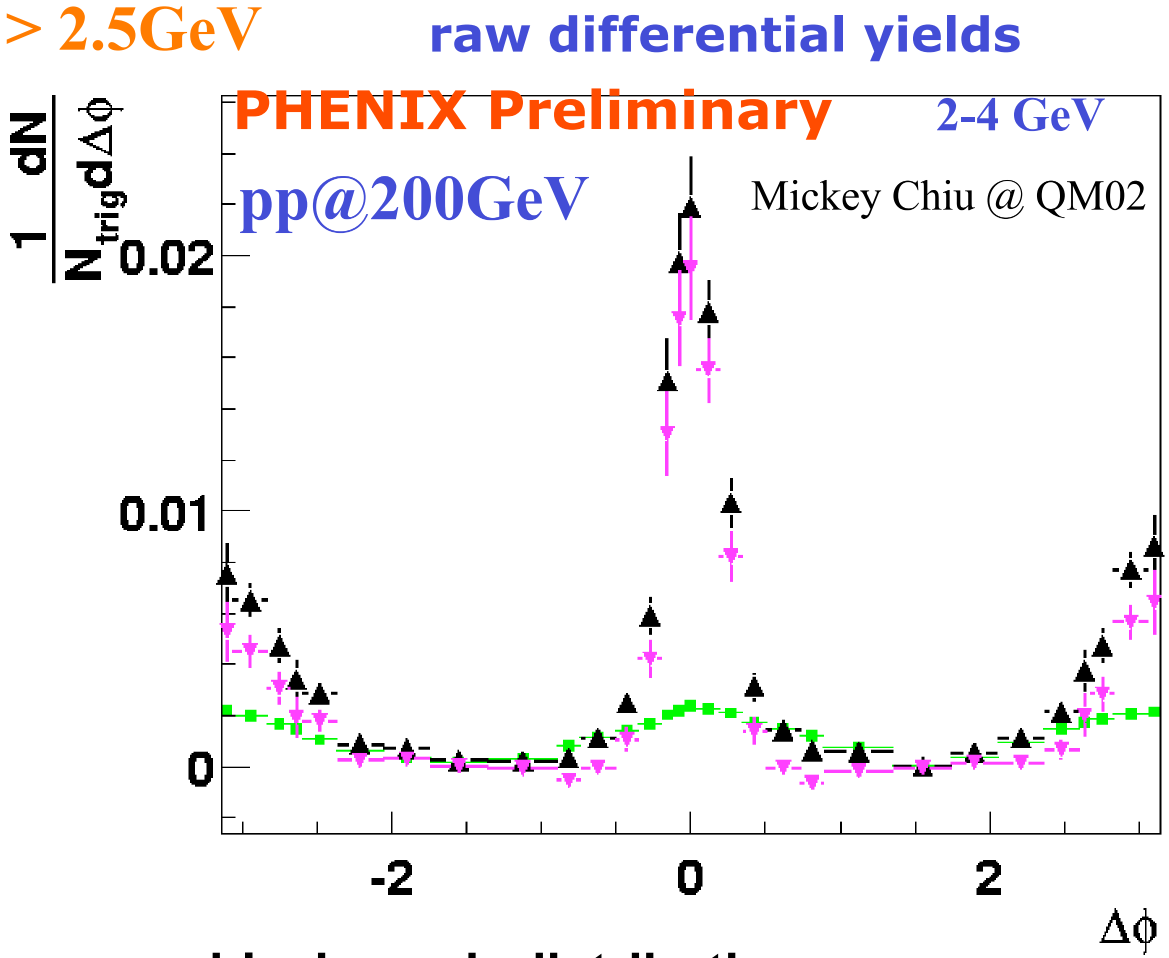




Jets in p+p



- Jet structure was observed in azimuthal correlation in pp at $\mathrm{sqrt}(S_{pp})$=200GeV.



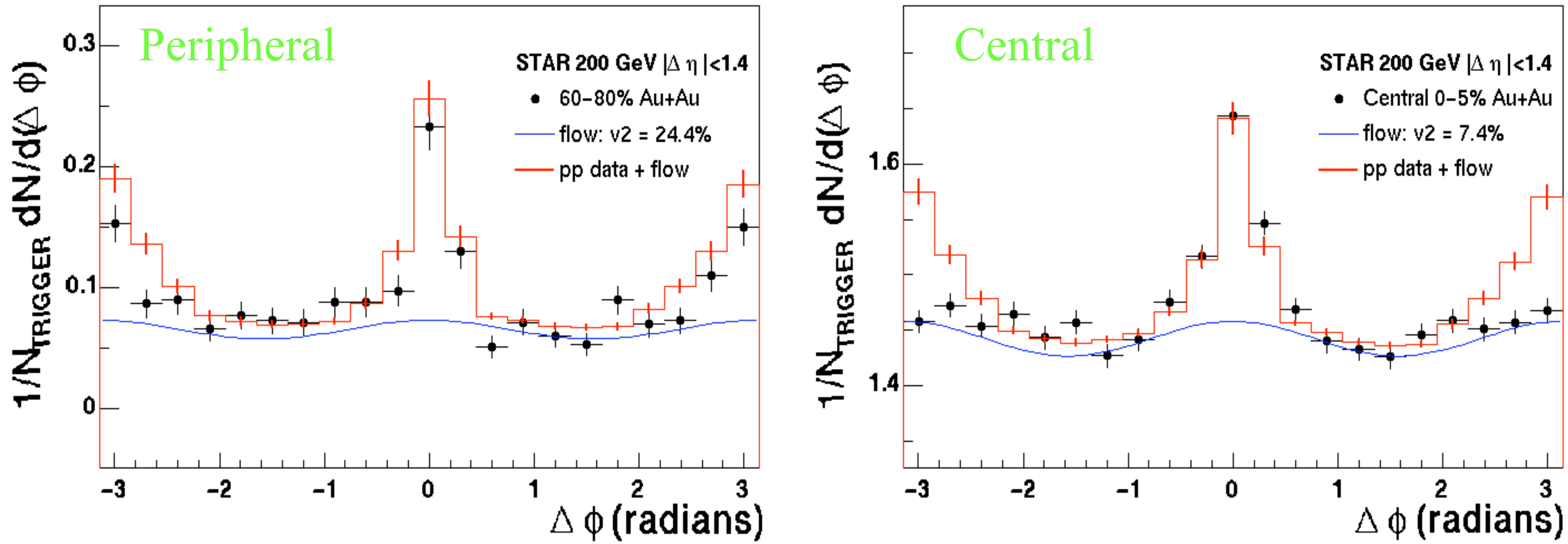
•black = pair distribution
•green = mixed event pair distribution
•purple = bkg subtracted distribution

Evidence for jets in Au+Au

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

Ansatz: high p_T triggered Au+Au event is superposition of high p_T triggered p+p event and elliptic flow:

- v_2 from reaction plane analysis
- A fit in non-jet region ($0.75<|\Delta\phi|<2.24$)

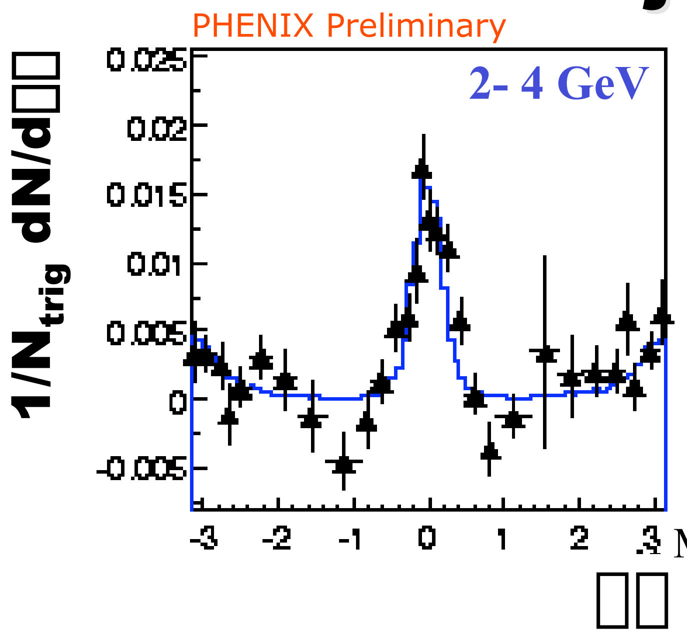


D. Hardtke, STAR plenary talk QM02

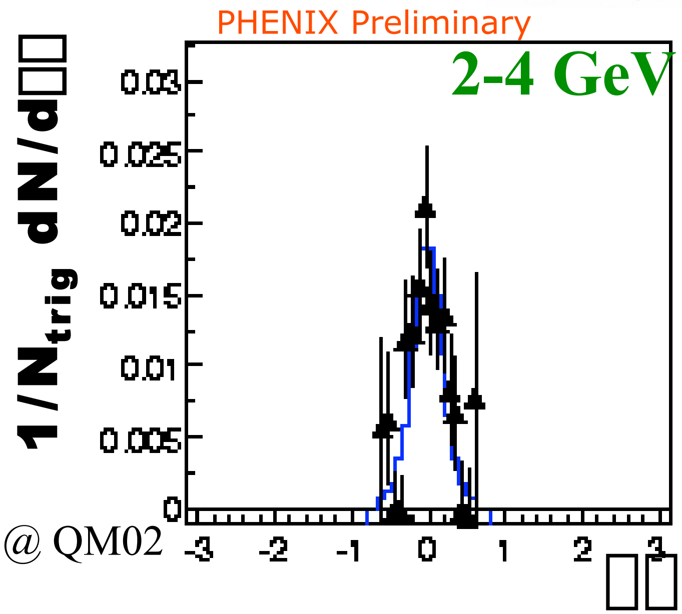
Back-to-back jet structure seen

Near side jets still exist
Away side jets disappear

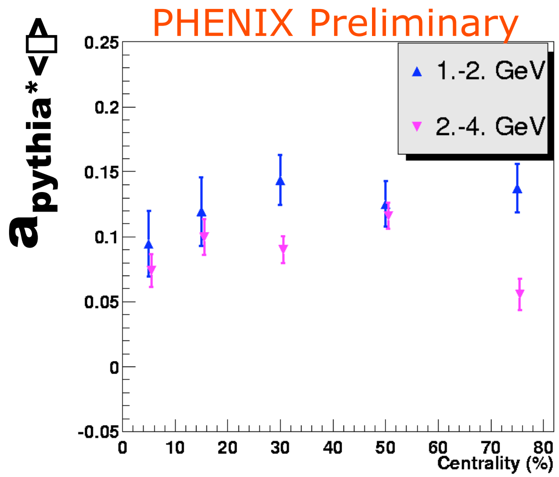
Evidence for jets in Au+Au



Mickey Chiu @ QM02

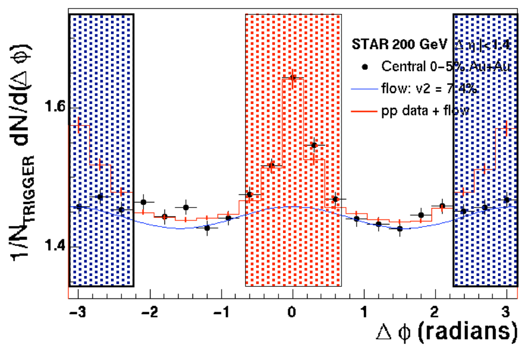


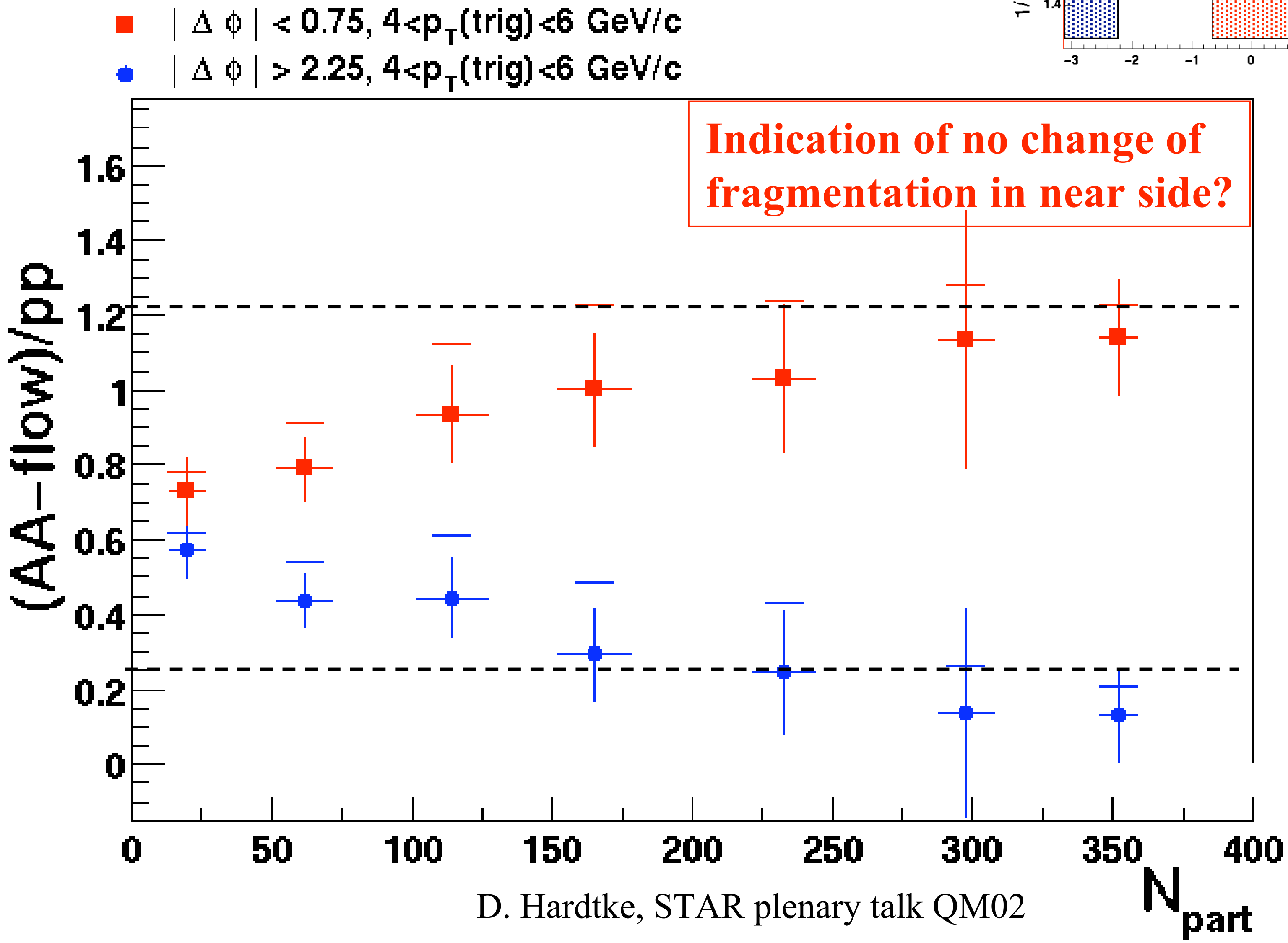
- Use p-p analysis as a reference for Au-Au jet signal
- Correlation seen simultaneously in □□ and □□ (Jet Cone)



- **In p_T 2-4 GeV/c, Jet-Like Signal dominates over elliptic flow component.**
- **This Jet-Like Signal approx. flat with centrality (no systematic**

$$Ratio = \frac{\int d(\Delta\phi)[C_2(Au+Au) - A^*(1+2v_2^2\cos(2\Delta\phi))]}{\int d(\Delta\phi)[C_2(p+p)]}$$

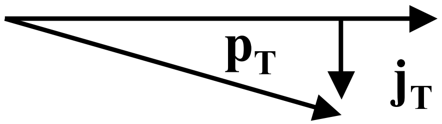




D. Hardtke, STAR plenary talk QM02

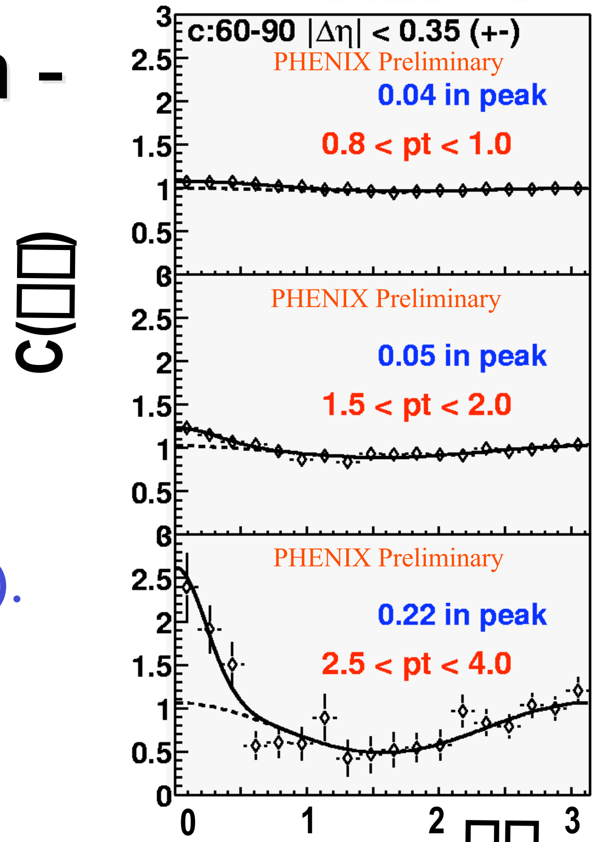
More evidence for jets
- Charged-Charged Correlation -

- Correlation fcn for charged hadrons.
- Observe large asymmetry
- Fit to gaussian + cos2□.
- Width of gaussian peak vs. pt.
- For a jet, the transverse momenta $<j_T> \sim 400$ MeV, independent of pt (dashed curve below).

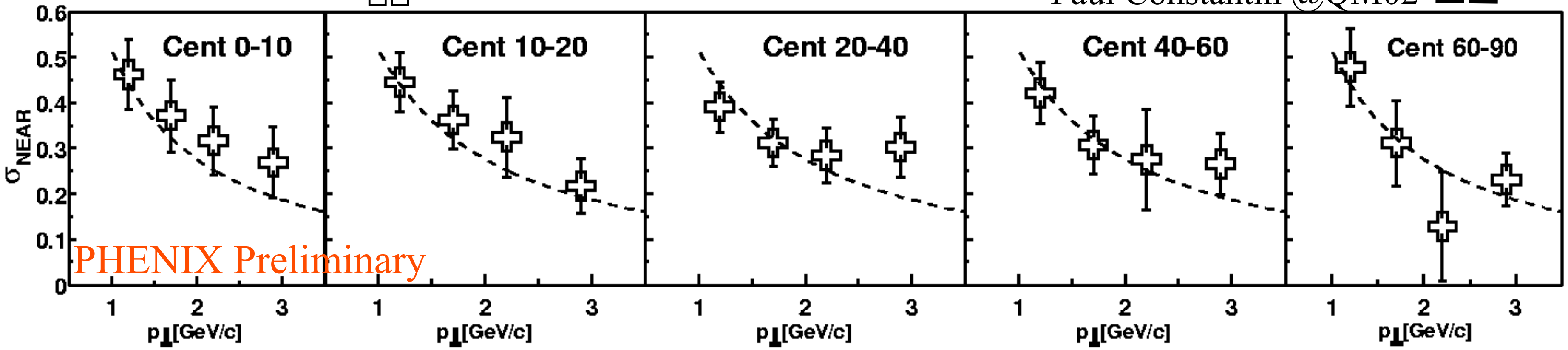


Correlation width µ j_T/p_T

Another hint of no change of fragmentation in near side?

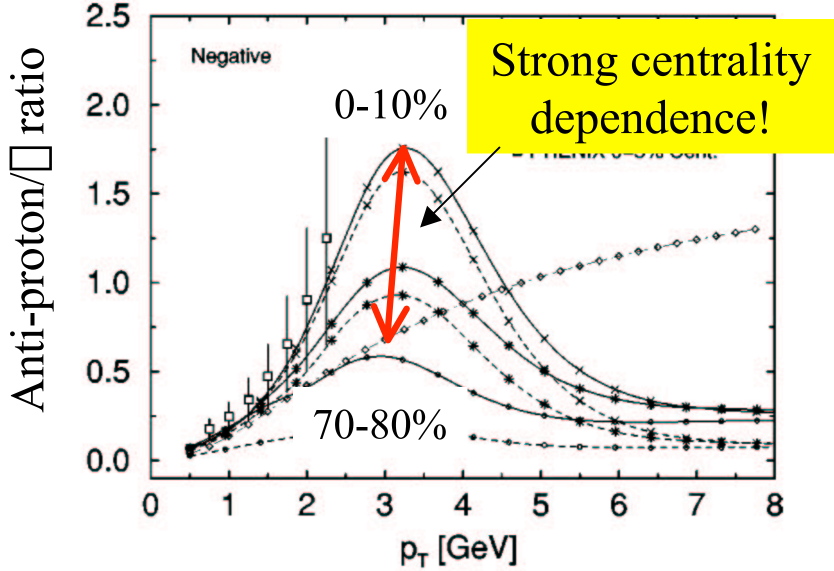


Paul Constantin @QM02



Physics Target (II) -Interplay of soft and hard processes-

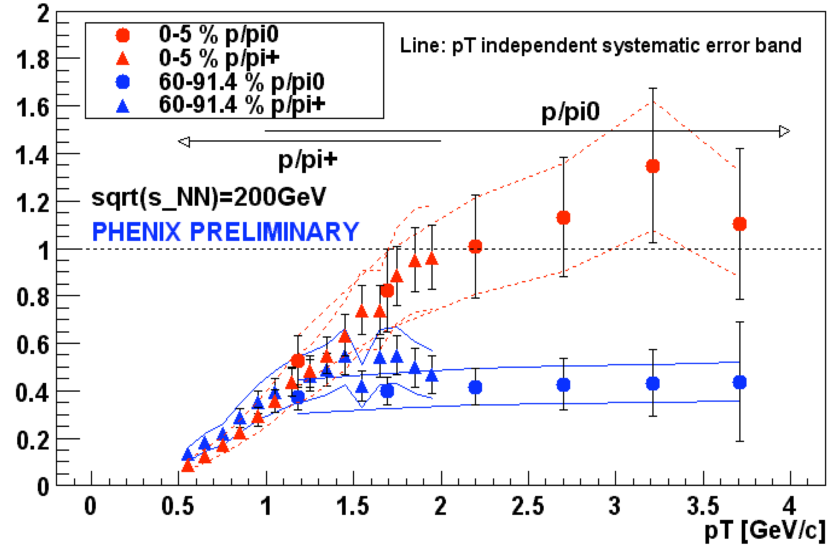
- Baryon number will be transported via gluon junction to mid-rapidity region (Soft process)
  - Effective string tension for baryons produced gets larger than mesons
  - Another p_T kick is given to baryons
- Baryon/meson ratio will do!
  - Jet quenching (hard) enhances baryon number transport (soft) at moderate hight p_T region
  - π^+, π^- and π^0 suppress, pbar and p enhance

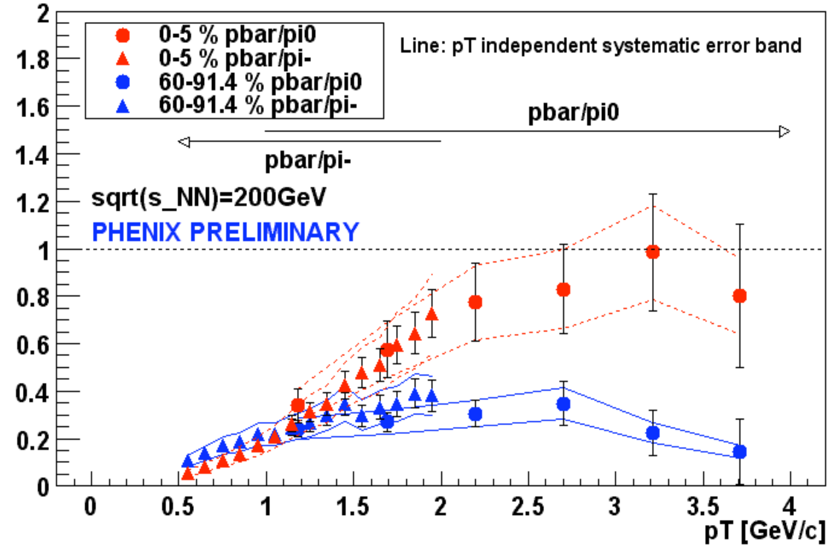


I. Vitev and M. Gyulassy, PRC65(2002)041902

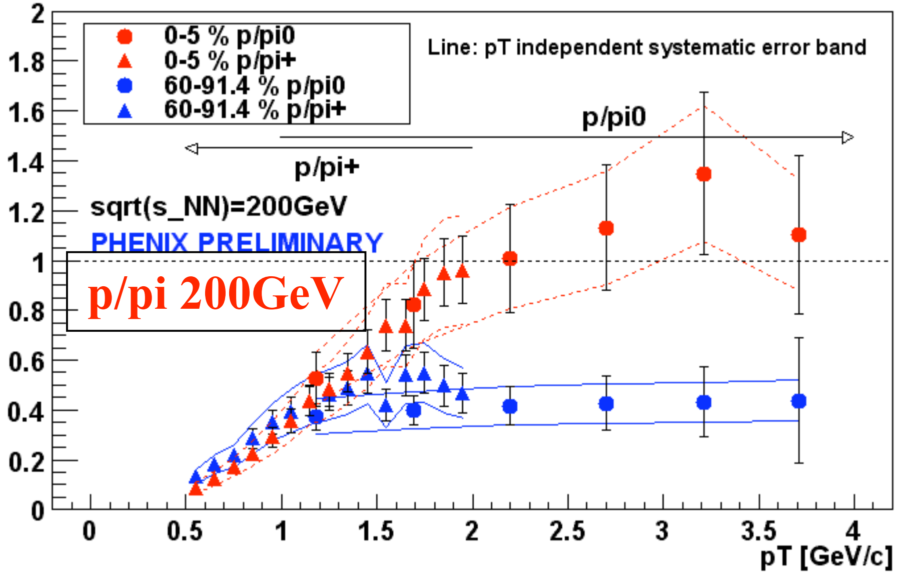
Puzzle: Baryons at high pt

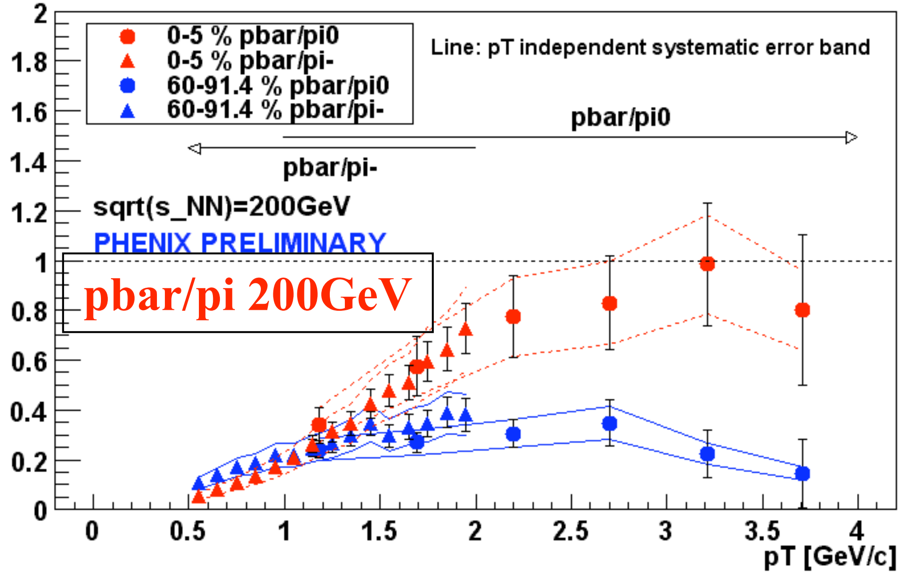
- A puzzle in high pt data:
  p/pbar yield is comparable or higher than pion in 3-4 GeV/c for central collision.
- If pbars are from jet fragments, pbar/ ratio should be small at high pt.
  - Peripheral collision agree with this expectation.
- How those high pt baryons are produce?
  - Very strong radial flow?
  - Gluon junction model?





hep-ex/0209030



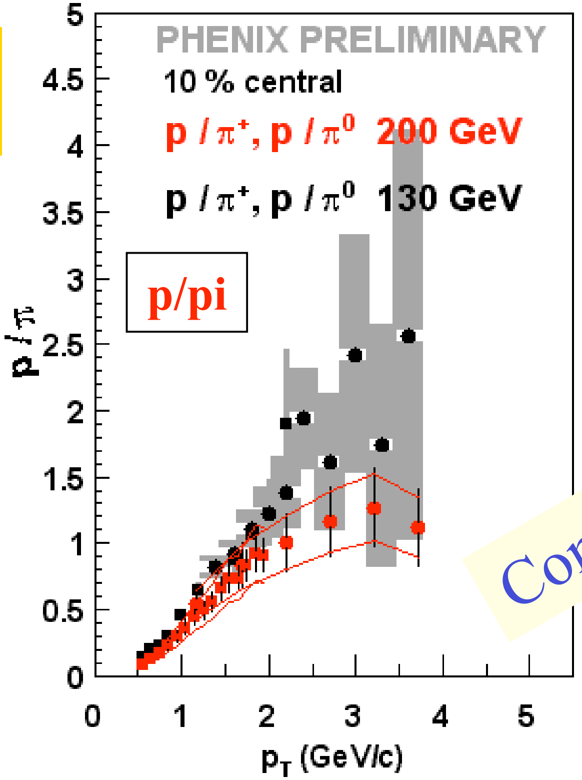


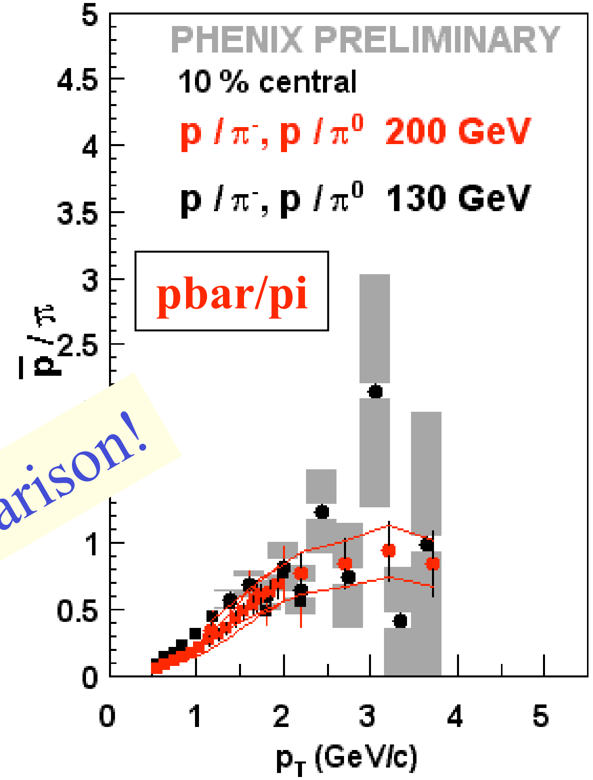
pbar/□ and p/□

Ratios strongly depend on centrality, and less depend on beam energies

↓

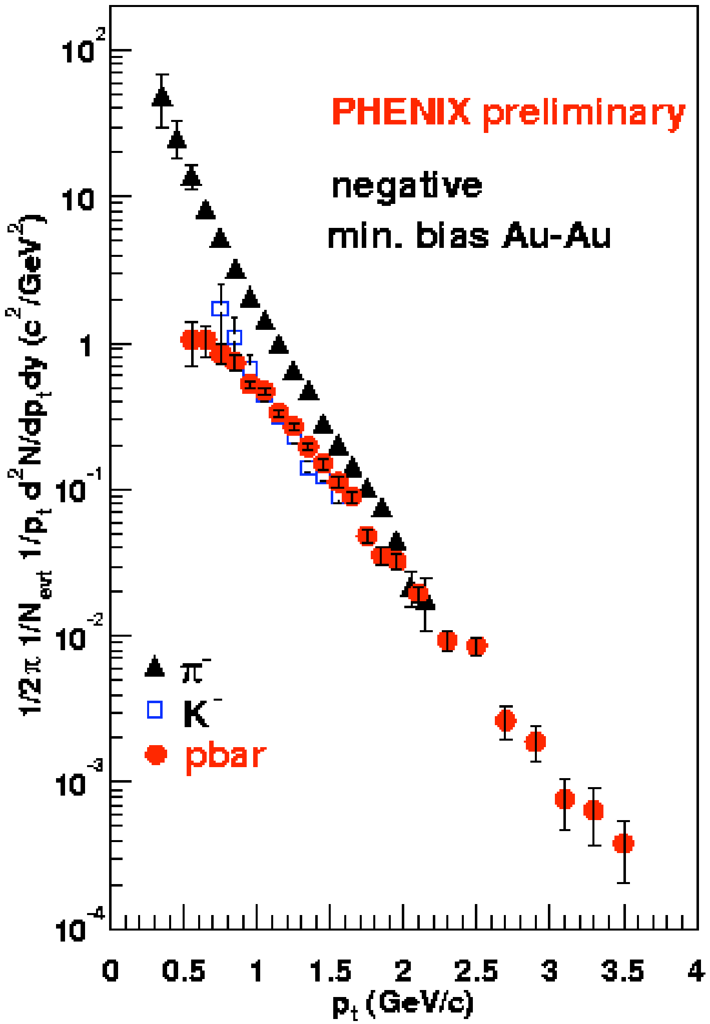
Interplay of soft and hard is well seen!





Comparison!

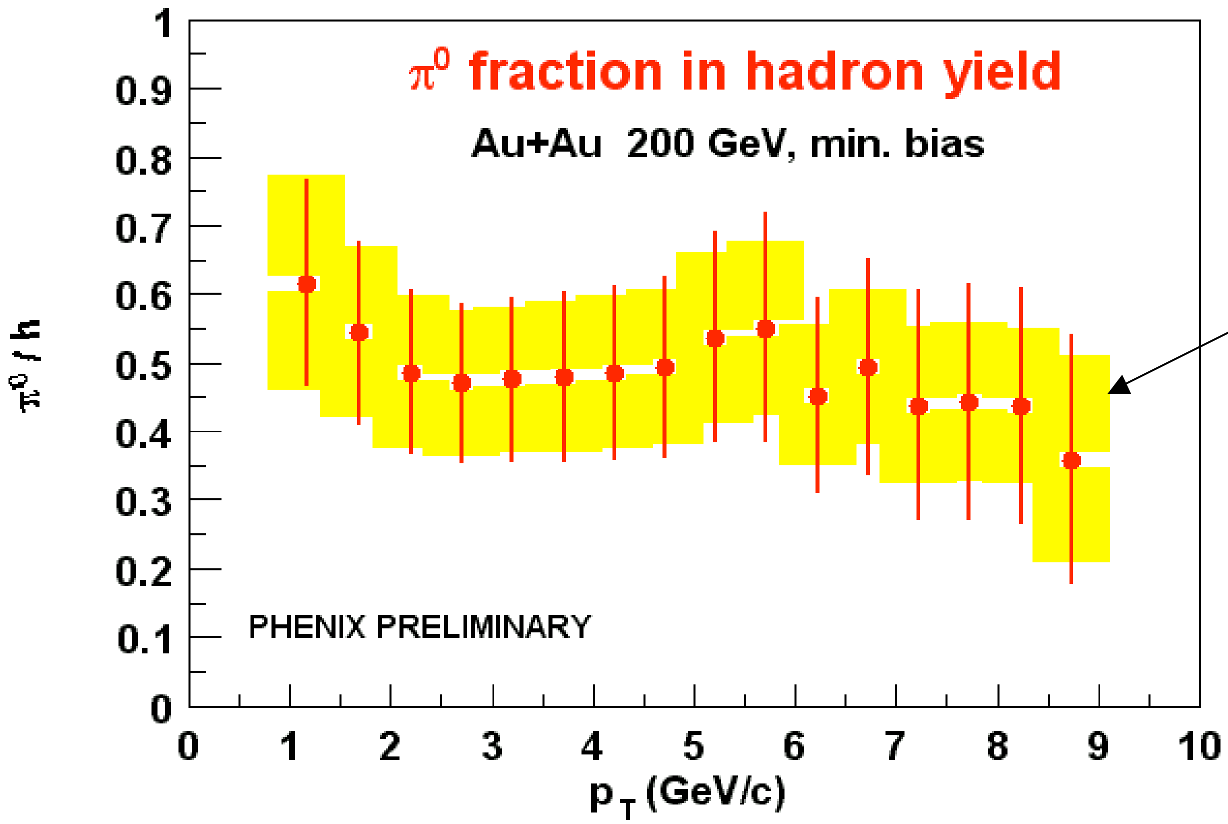
$(h^+ + h^-)/2$ と □^{0}



- $(h^+ + h^-)/2$ と □^{0} は同じではない
  - パイオンの収量が支配的であれば正しい
  - High p_T 領域では反陽子収量が □^{0} 収量と同程度

More puzzle in pT >4 GeV/c

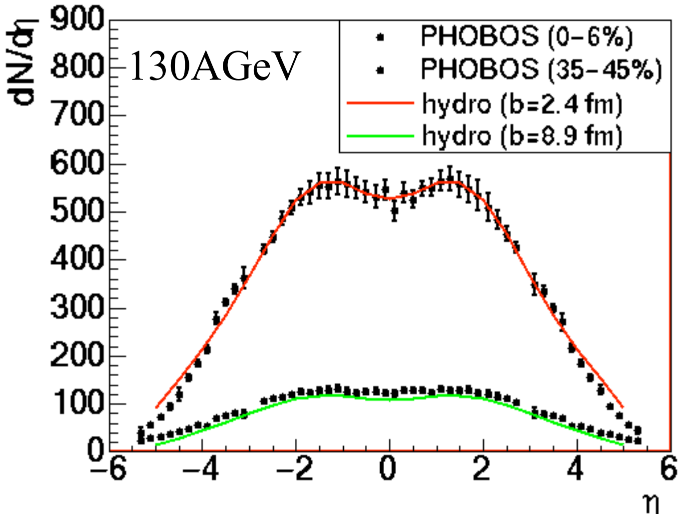
Proton identification not available.
Use pi0 and non-identified hadrons



Are the protons
_ of the hadron yield
up to 9 GeV/c ?

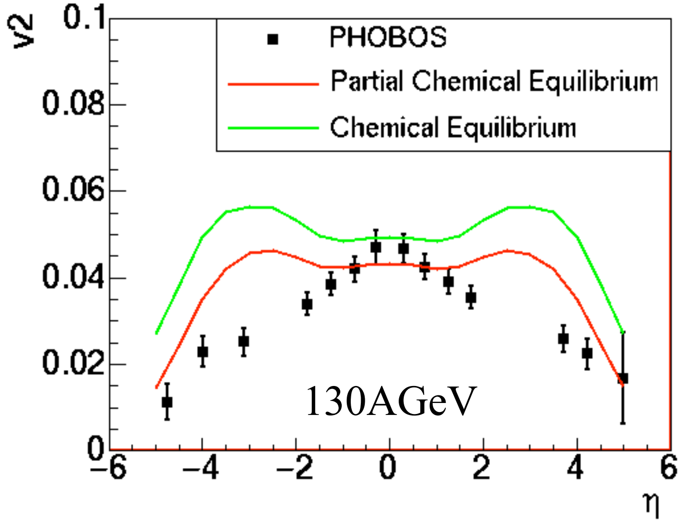
3D Hydro

Brief Summary of Our Hydro Results



- Full 3D hydro!
  - ✧ No Bjorken scaling ansatz
  - ✧ No cylindrical symmetry
  - ✧ ($\square$, $\square_s$, x, y) coordinate

T.Hirano, Phys.Rev.C65(2002)011901.

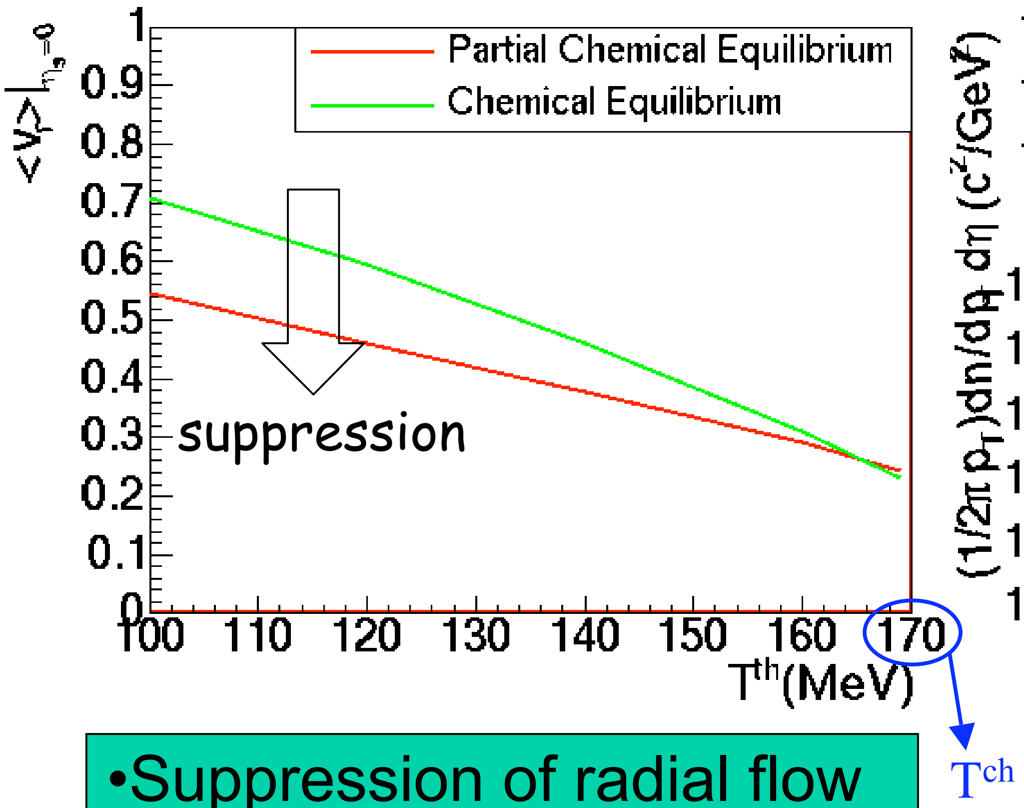


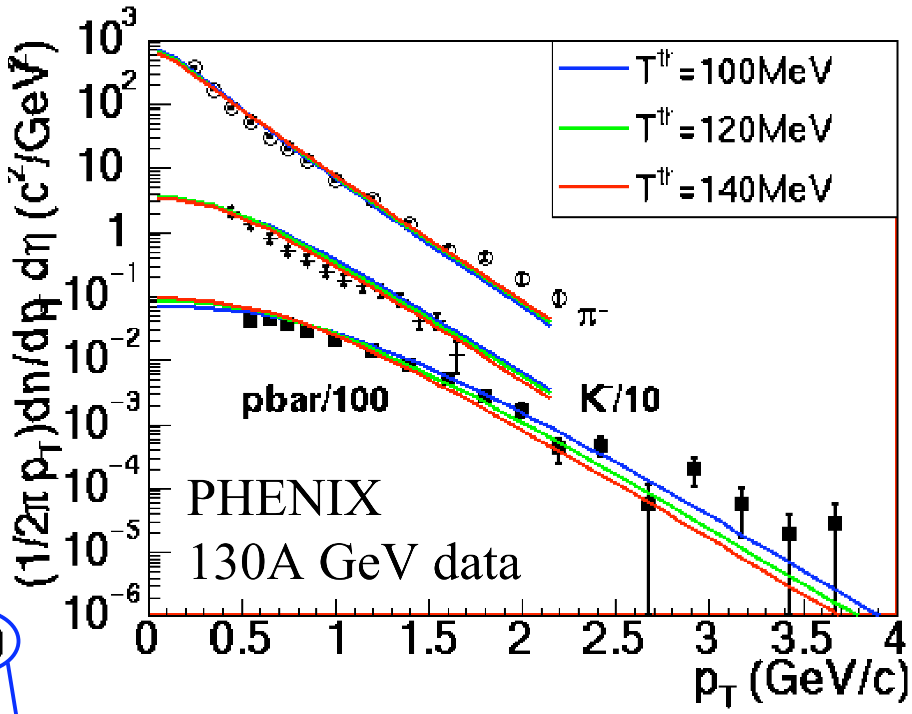
- $T^{ch} \neq T^{th}$!

➢Suppression of radial, elliptic flow and HBT radii in comparison with the conventional hydro results.

T.Hirano and K.Tsuda, nucl-th/0205043 (Phys.Rev.C, in press).

Brief Summary of Our Hydro Results (contd.)

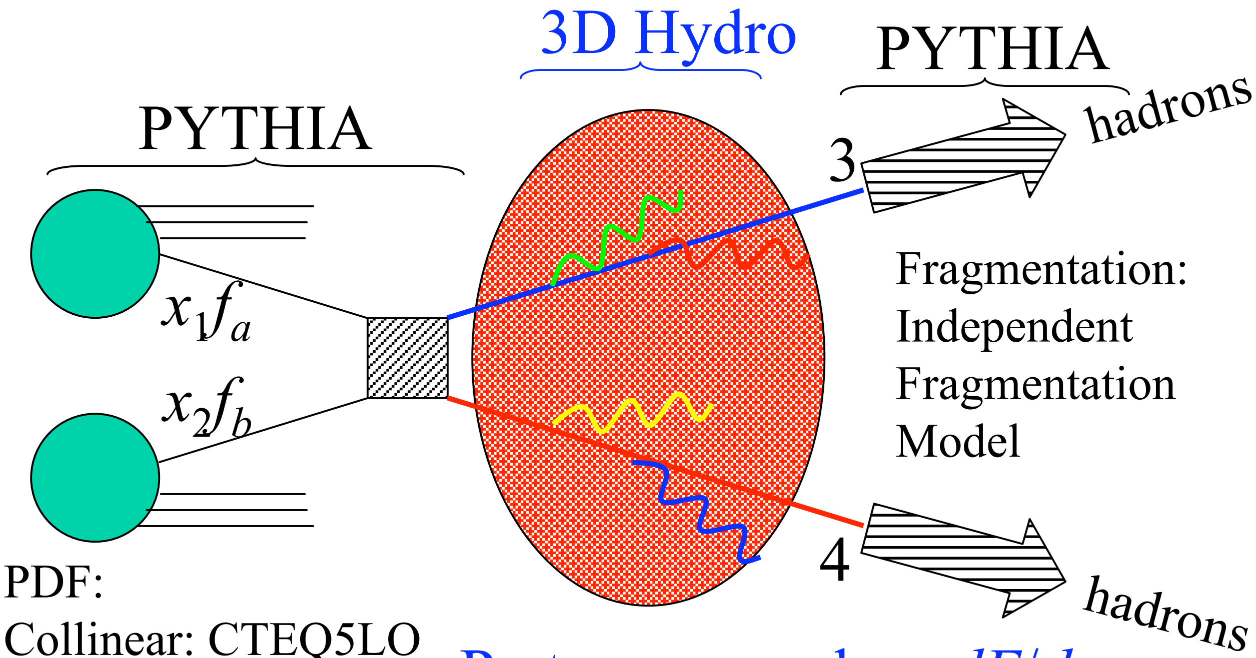




- Suppression of radial flow as a result of chemical non-equilibrium properties

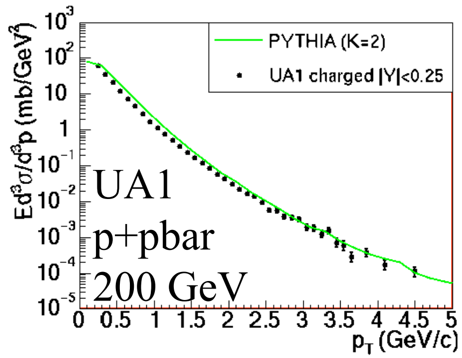
- p_T slopes become insensitive to T^{th}.
→Need hard components

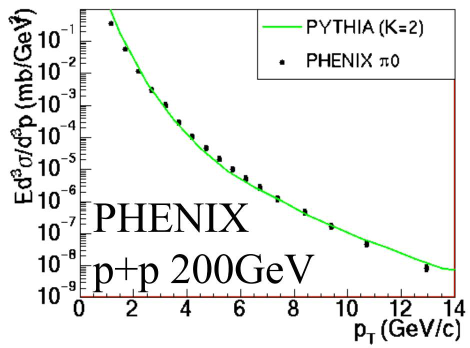
The Hydro+Jet Model



PDF:
Collinear: CTEQ5LO
k_T: Gaussian
$\langle k_T^2 \rangle = 1\,\mathrm{GeV}^2/c^2$

Parton energy loss: dE/dx
(I will discuss later…)





$$E\frac{d\sigma^{pp}_{\mathrm{jet}}}{d^3p} = K\sum_{ab}\int g(k_{\mathrm{T},a})k_{\mathrm{T},a}dk_{\mathrm{T},a}\,g(k_{\mathrm{T},b})k_{\mathrm{T},b}dk_{\mathrm{T},b}$$

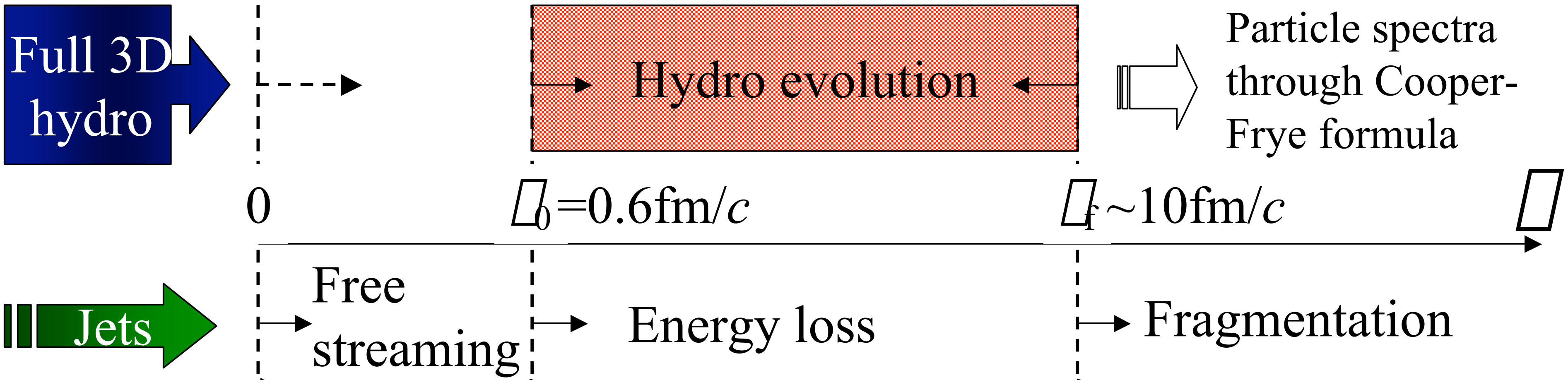
$$\times\int f_a(x_1,Q^2)dx_1 f_b(x_2,Q^2)dx_2\, E\frac{d\sigma^{ab\to cd}}{d^3p}$$

pQCD LO:

$$q+q' \to q+q',\quad q+\bar{q} \to q'+\bar{q}'$$
$$q+\bar{q} \to g+g,\quad q+g \to q+g$$
$$g+g \to q+\bar{q},\quad g+g \to g+g$$

*Initial and final state radiation are included.

Time Evolution in the Hydro+Jet Model



- Formation time~0 fm
For jets with p_T>2GeV/c, $1/p_T$<0.1fm/c<<1fm/c

- Momentum dist. from PYTHIA ver. 6.2

- Thermalization time
= Initial time of fluids

- Initial parameters in hydro have been already tuned.

- After hydro simulation, all survival jets fragment into hadrons.

- We neglect interaction of fragmented hadrons.

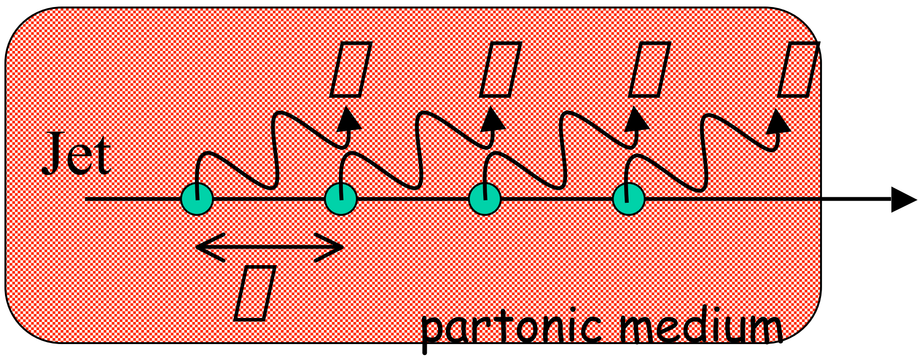
Phenomenological Parton Energy Loss

- **Incoherent Model:**

$$\frac{dE}{dx} = \frac{\varepsilon}{\lambda} = \varepsilon\sigma\rho\left(\tau, x(\tau)\right)$$

From hydro simulation

ε: energy deposit per scattering
λ: mean free path
σ: parton-parton cross section
ρ: thermalized parton density

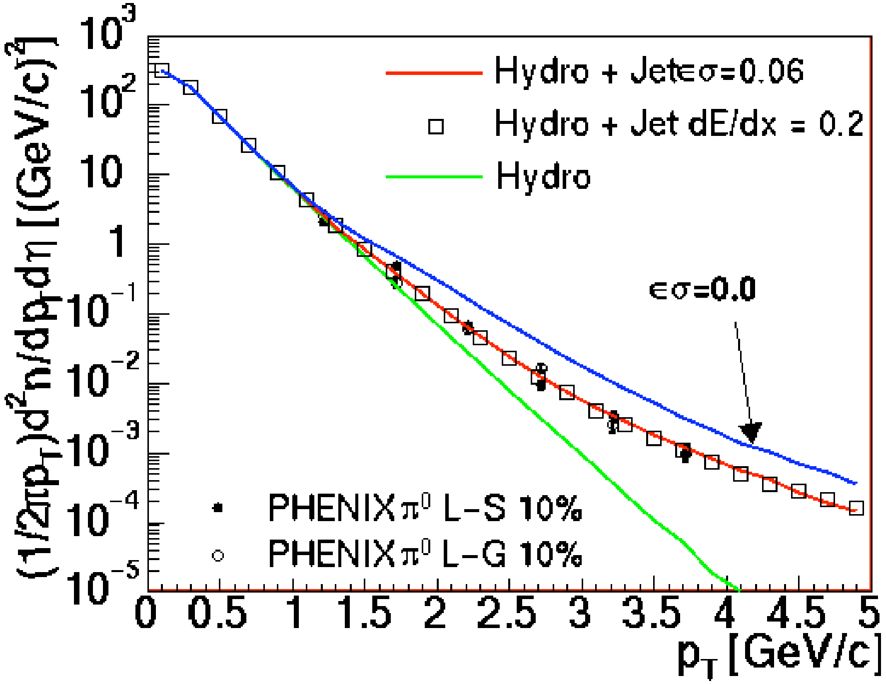


*Neglecting energy loss in the hadron phase.

$$\rho_{\mathrm{mixed}} = f_{\mathrm{QGP}}(\tau, \boldsymbol{r})\rho(T_{\mathrm{C}})$$

$$f_{\mathrm{QGP}} = \frac{E(\tau, \boldsymbol{r}) - E_{\mathrm{had}}}{E_{\mathrm{QGP}} - E_{\mathrm{had}}}$$

π^0 Spectra in $s_{NN}^{1/2}$=130 GeV Central Collisions



- <dE/dx>~0.85 GeV/fm @τ_0=0.6 fm/c
- Onset of hard component p_T~1.5 GeV/c

$$\frac{dE}{dx} = \underline{0.06}\,\rho(\tau, r)\ (\mathrm{GeV/fm}) \approx 0.2\ (\mathrm{GeV/fm})$$

the best fit value

HIJING:
$dE/dx = 0.25$ (GeV/fm)

X.-N. Wang, NPA698(2002)296c

Models for Parton Energy Loss

- **Incoherent model**

$$\frac{dE}{dx} = 0.06\,\square\left(\square, \boldsymbol{x}\left(\square\right)\right)$$

- **Coherent (LPM) model**

A model motivated by

a) GLV 1st order, or b) BDMPS for $E > E_{\mathrm{cr}}$

$$\square E = a\hat{q}L_{\mathrm{eff}}^{2}\,,$$ *a*: free (adjustable) parameter

"Transport" coefficient *q*

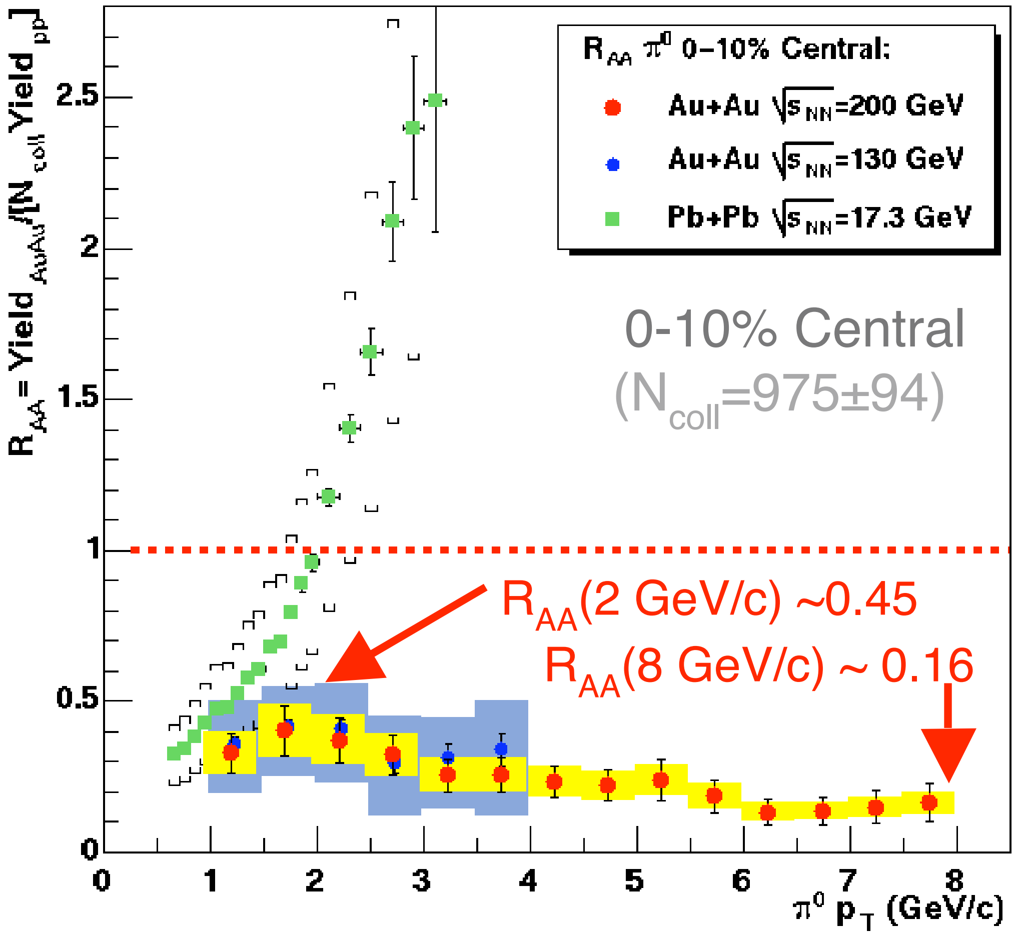
$$\hat{q}L_{\mathrm{eff}}^{2} = \int_{\square_0}^{\square_f} d\square\,\square\,\square\left(\square, \boldsymbol{x}\left(\square\right)\right)\left(\square\,\square\,\square_0\right)\log\square 1 + \frac{2E}{L\square^{2}}\square$$

$L \sim R_{\mathrm{Au}}$

$\square$=0.5 GeV/c

M.Gyulassy *et al*., Nucl.Phys.**B571**(2000)197; R.Baier *et al*., Nucl.Phys.**B483**(1997)291.

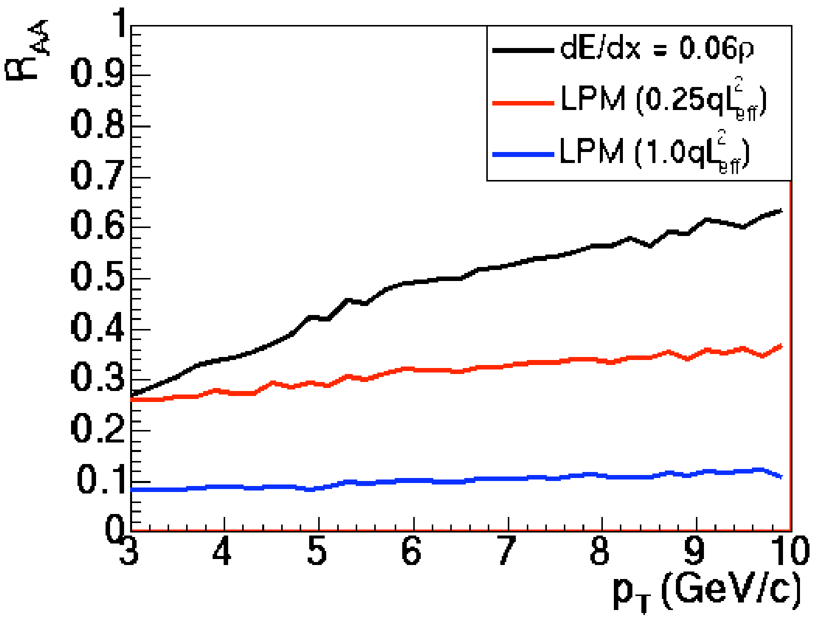
Suppression Factor (PHENIX)



$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{d^2N^{\mathrm{A+A}}/dp_{\mathrm{T}}d\square}{\langle N_{\mathrm{binary}}\rangle d^2N^{\mathrm{N+N}}/dp_{\mathrm{T}}d\square}$$

From D. d'Enterria, talk at QM2002.

Suppression Factor in $s_{NN}^{1/2}$=200 GeV Central Collisions



•Suppression factor R_{AA}

Incoherent model: increase

Coherent model: almost flat

•Experimental data (PHENIX):

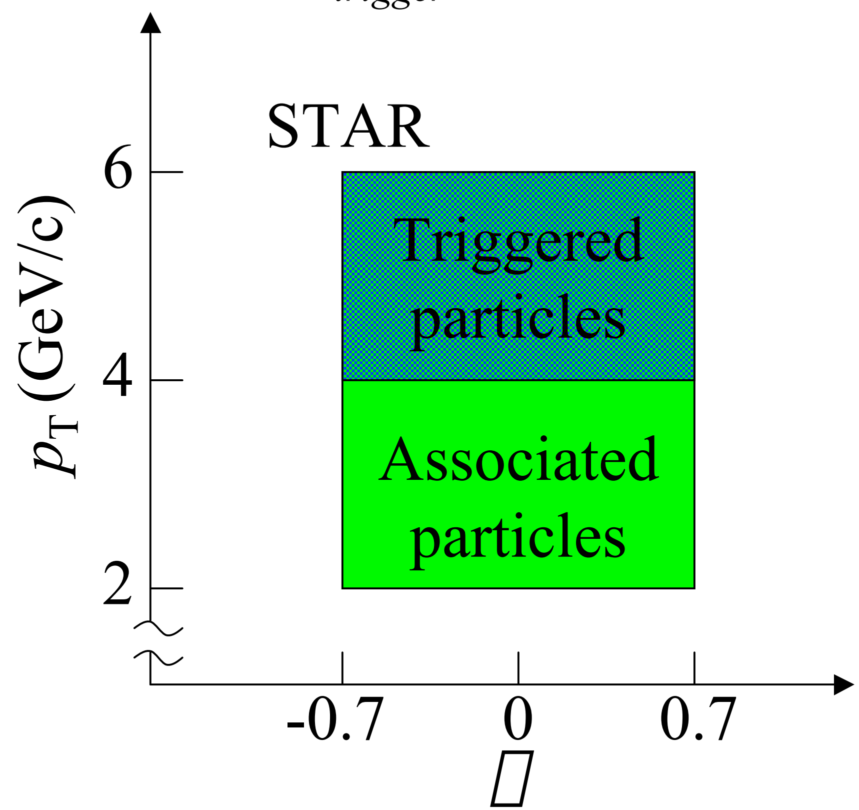
→ gradually decrease

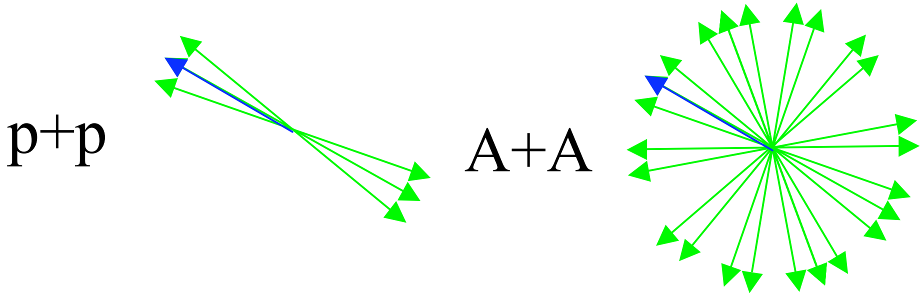
$$R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_T d\eta}{\langle N_{binary} \rangle d^2N^{N+N}/dp_T d\eta}$$

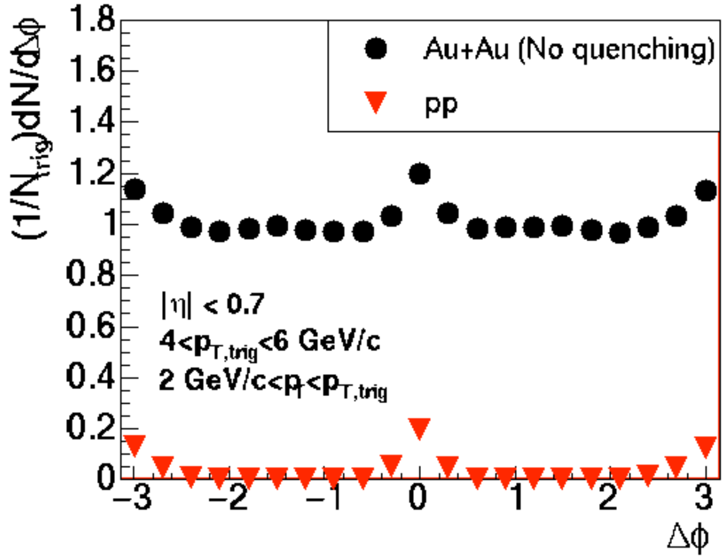
$R_{AA}(p_T)$ depends on the models of parton energy loss.

Back-to-Back Correlations of High p_T Hadrons

$$C_2(\Delta\phi) = \frac{1}{N_{trigger}} \int d\Delta\eta \frac{dN}{d\Delta\phi\, d\Delta\eta}$$

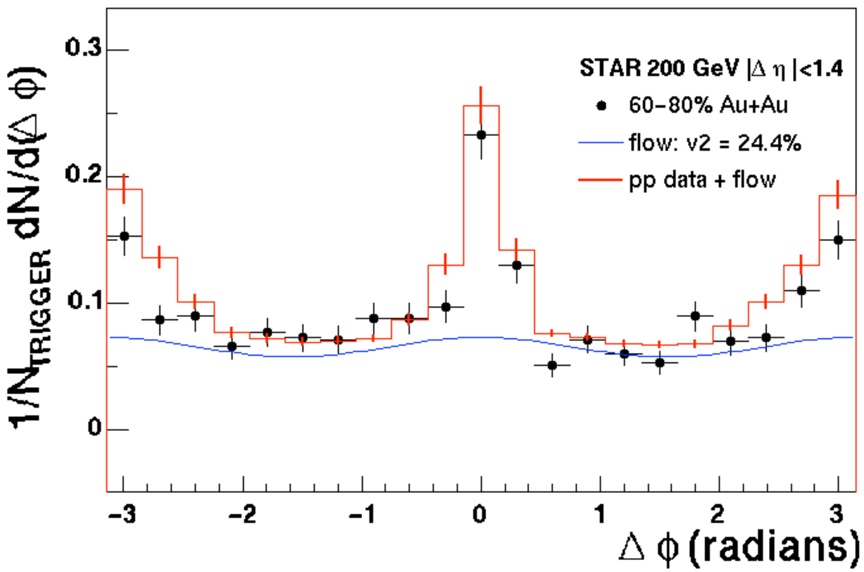




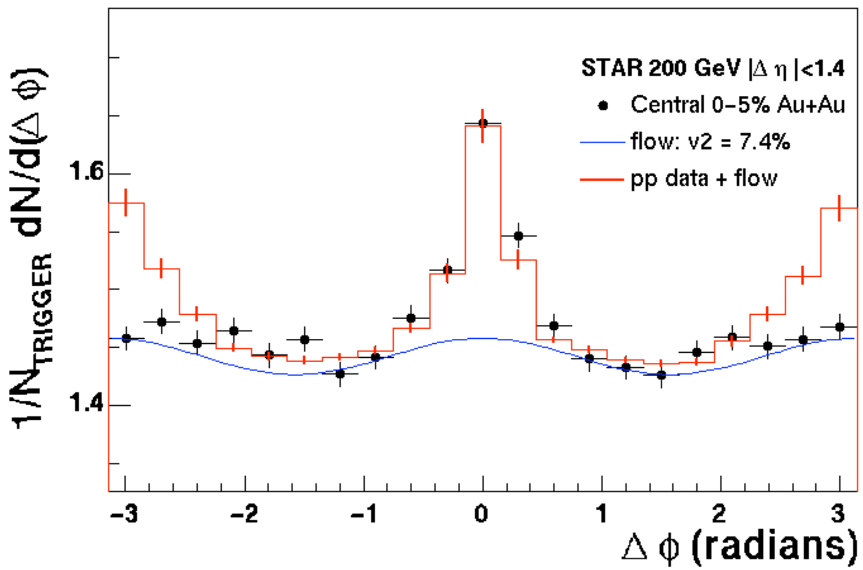


Back-to-Back Correlation (STAR)

4<pt(trig)<6 GeV/c data



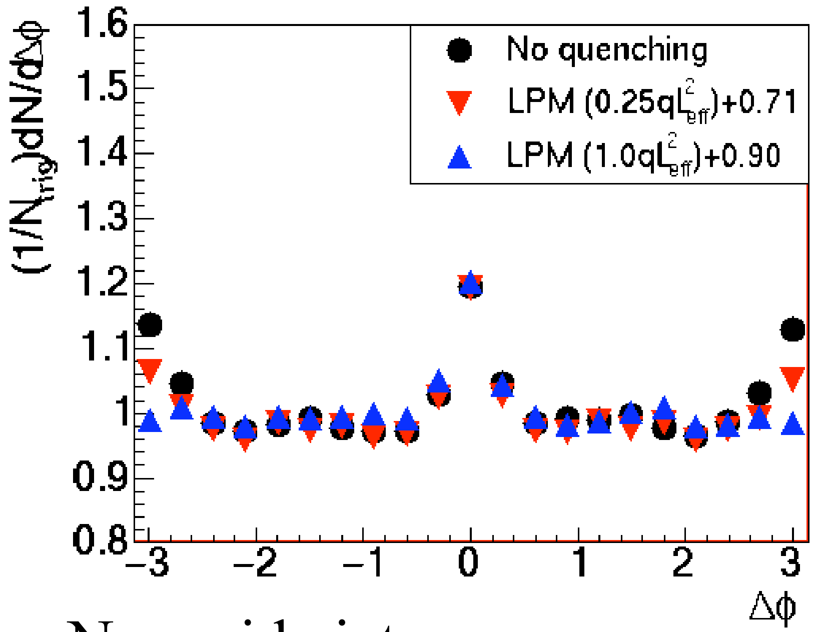
Peripheral 60-80%

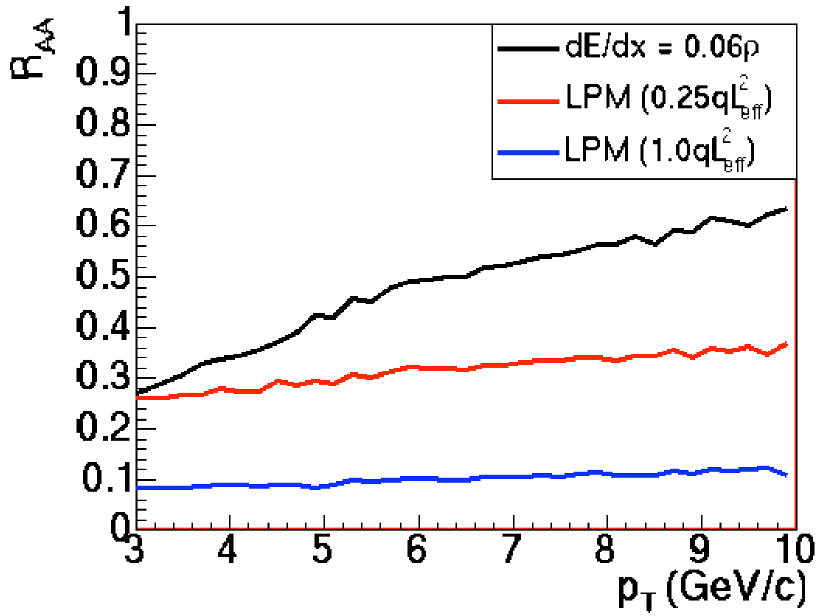


Central 0-5%

From D.Hardtke, talk at QM2002.

R_{AA} and C_2 in $s_{NN}^{1/2}$=200 GeV Central Collisions





- Near-side jets:

  Almost independent

- Away-side jets:

  Depend on magnitude of energy loss

We fail simultaneous reproduction of R_{AA} and C_2.
→Need another mechanism

今後の課題

- 3K：高統計、高精度、高運動量
- 粒子の種類
  - パートンの種類：クォークの質量の違い
    - 電磁シャワーでは、電子とミューオンの質量の違いにより大きな差。QCD gluon bremstrahlung でも同様か？
    - パイオンとK中間子（？）
  - パートンの種類：グルーオンとクォークの違い
    - Stopping power が違うか？
    - 粒子・反粒子の運動量分布の N_{coll} 依存性