Discussion on Hard Scattering at RHIC

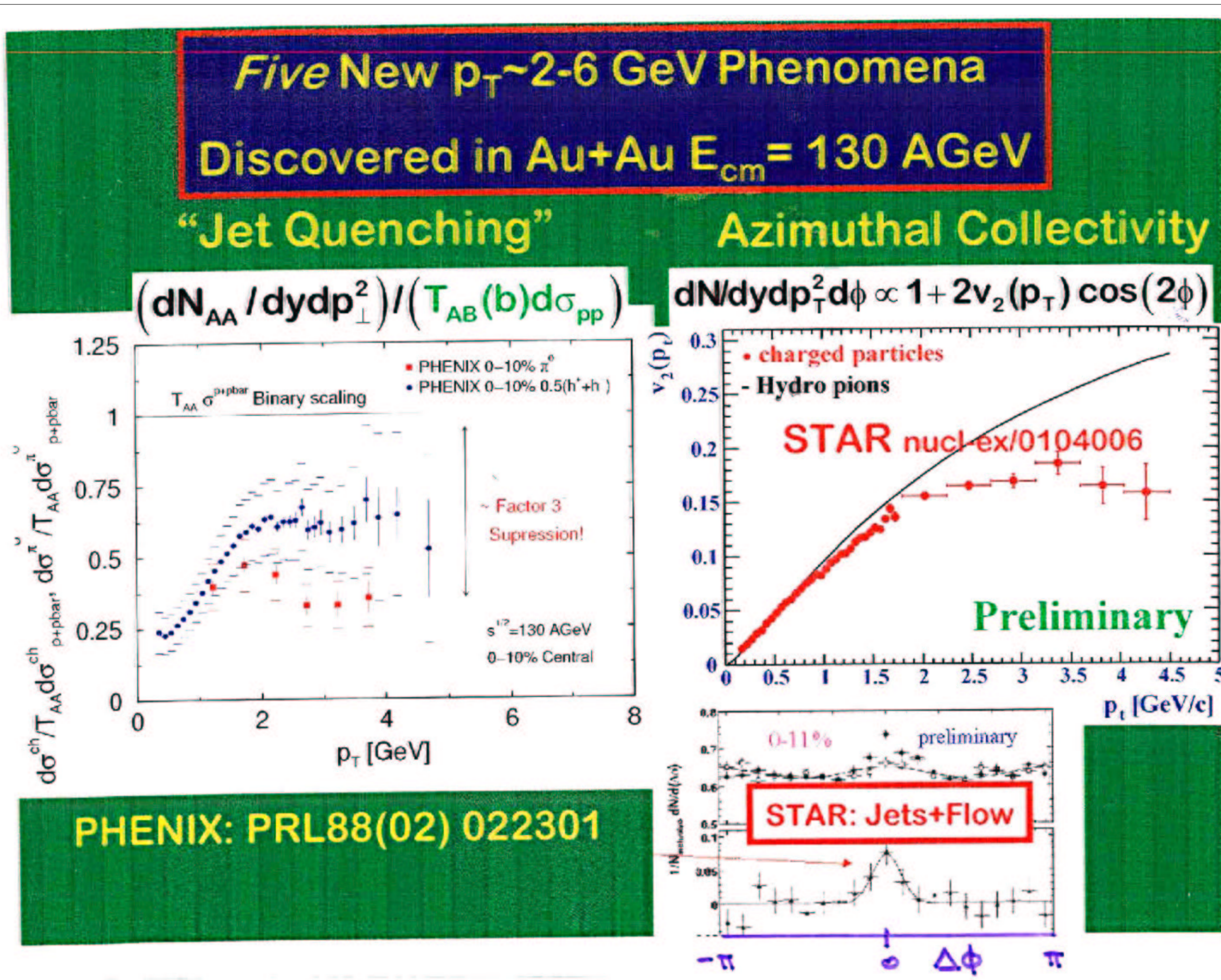
(with John Harris)

May (15, 17) 2002 ITP/UCSB

Miklos Gyulassy

1) Jet Quenching
2) Elliplic Flow at 5 GeV pt

based on work with Ivan Vitev, Peter Levai, Xin-nian Wang



Peter Jacobs ITP Conf 4/02

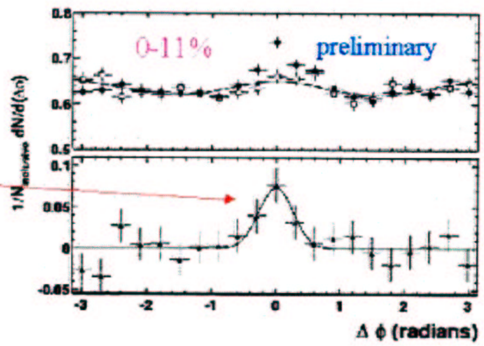
Two Particle Correlations at High p_T

see also J. Harris talk.

- Trigger particle p_T>4 GeV/c, $|\eta|$<0.7
  - azimuthal correlations for p_T>2 GeV/c
  - short range η correlation: jets + elliptic flow
  - long range η correlation: elliptic flow

$\Rightarrow$ subtract correlation at $|\eta_1 - \eta_2|$>0.5
  - NB: also eliminates the away-side jet correlations

- extracted v_2 consistent with reaction-plane method
- what remains has jet-like structure $\Rightarrow$ first indication of jets at RHIC!



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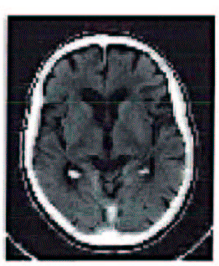
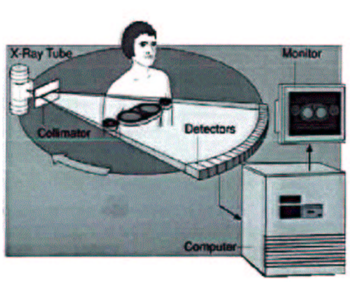
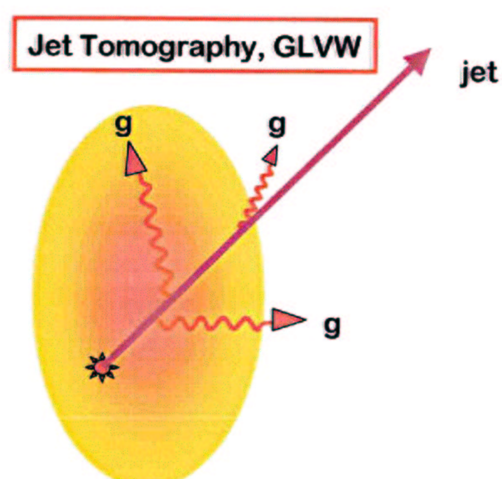
First direct evidence for jettyness at RHIC at Moderate p_t!

A+A Tomography with Jets

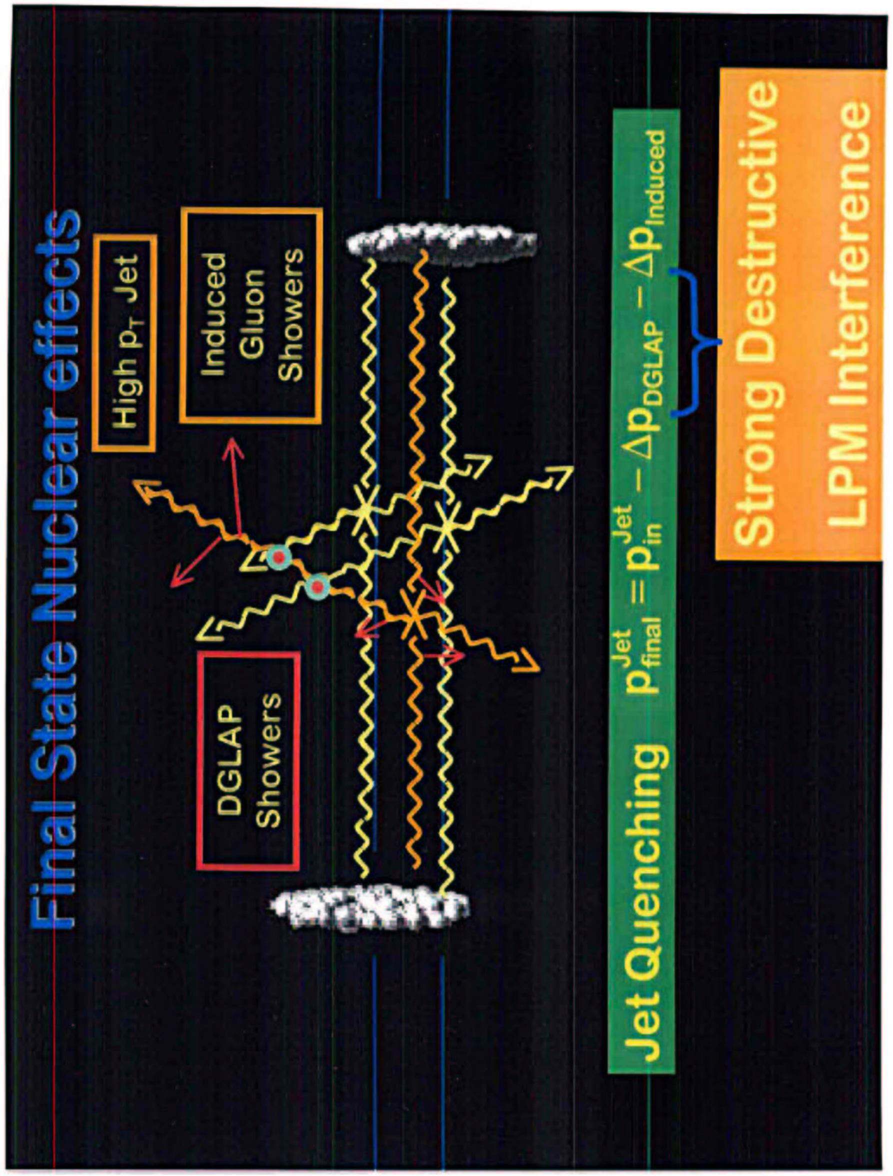
X-ray Tomography

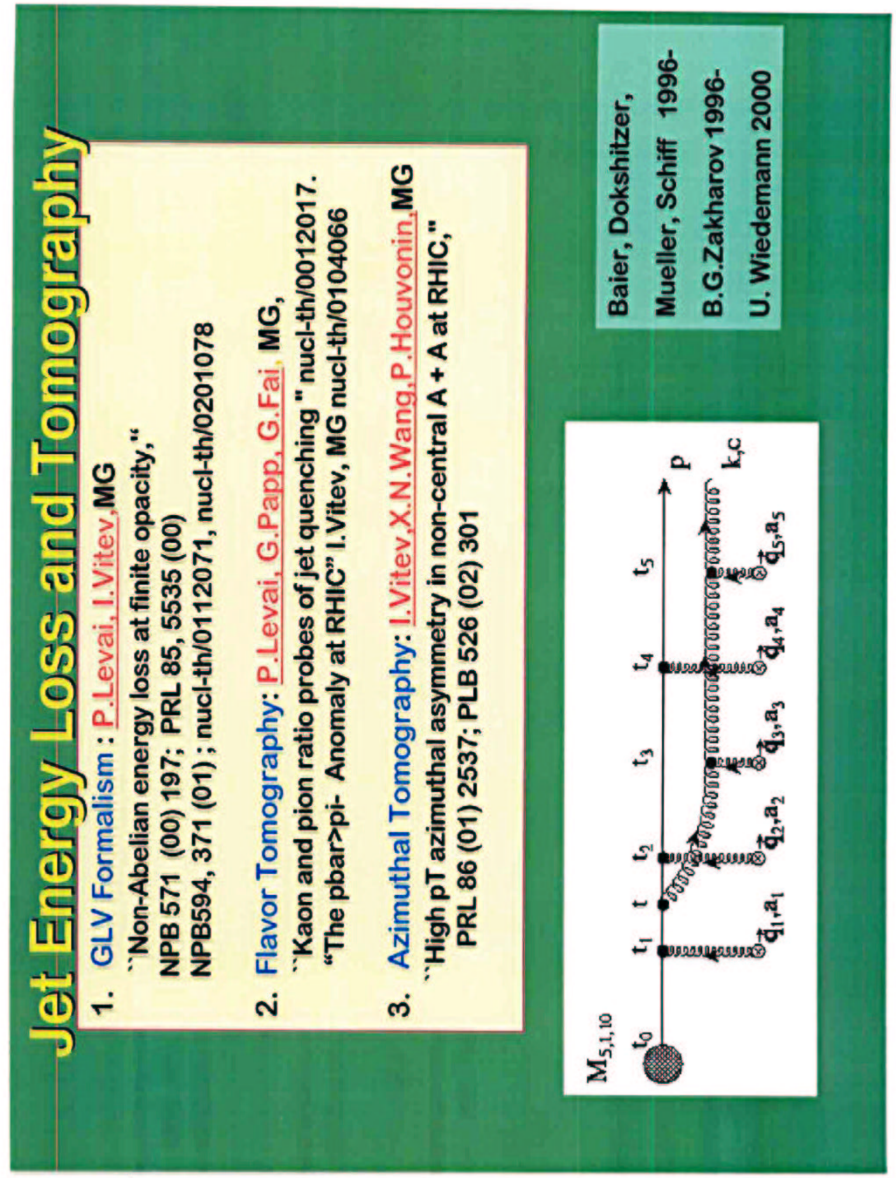






$$\Delta E_{GLV} \sim C_2 \alpha_s^3 E_0^{\delta} \int d\tau \, \tau \rho_{glue}(\tau, r(\tau))$$


Final State Nuclear effects
High p_T Jet
Induced Gluon Showers
DGLAP Showers
Jet Quenching $p^{Jet}_{final} = p^{Jet}_{in} - \Delta p_{DGLAP} - \Delta p_{Induced}$
Strong Destructive LPM Interference


Jet Energy Loss and Tomography
1. GLV Formalism : P.Levai, I.Vitev, MG
"Non-Abelian energy loss at finite opacity,"
NPB 571 (00) 197; PRL 85, 5535 (00)
NPB594, 371 (01) ; nucl-th/0112071, nucl-th/0201078
2. Flavor Tomography: P.Levai, G.Papp, G.Fai, MG,
"Kaon and pion ratio probes of jet quenching " nucl-th/0012017.
"The pbar>pi- Anomaly at RHIC" I.Vitev, MG nucl-th/0104066
3. Azimuthal Tomography: I.Vitev, X.N.Wang, P.Houvonin, MG
"High pT azimuthal asymmetry in non-central A + A at RHIC,"
PRL 86 (01) 2537; PLB 526 (02) 301
Baier, Dokshitzer, Mueller, Schiff 1996-
B.G.Zakharov 1996-
U. Wiedemann 2000
$M_{5,1,10}$
p
k,c

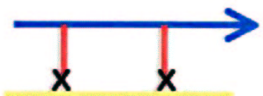
Gluon Double Differential Distributions to All Orders in Opacity

1. Add up all Direct and Virtual FSI at order $\left(\frac{L}{\lambda_g}\right)^n$
2. Use GLV Reaction Operator Formalism to solve recursion relations algebraically

Screened Yukawa

$$x\frac{dN^{(n)}}{dx\,d\mathbf{k}^2} = \frac{C_R\alpha_s}{\pi}\frac{1}{n!}\left(\frac{L}{\lambda_g}\right)^n \prod_{i=1}^{n}\int dq_i \left\{\mu_i^2(\mathbf{q}_i^2+\mu_i^2)^{-2} - \delta^2(\mathbf{q}_i)\right\}$$

$$\left[-2\,\mathbf{C}_{(1,\cdots,n)}\cdot\sum_{j=1}^{n}\mathbf{B}_{(j+1,\cdots,n)(j,\cdots,n)}\left(\cos\left(\sum_{k=2}^{j}\omega_{(k,\cdots,n)}\Delta z_k\right) - \cos\left(\sum_{k=1}^{j}\omega_{(k,\cdots,n)}\Delta z_k\right)\right)\right]$$



$\Delta z_k = z_k - z_{k-1}$

LPM effect →

where

$$\omega_{(j,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q}_j-\cdots-\mathbf{q}_n)^2}{2xE}$$ **Inverse Formation Times**

$$\mathbf{C}_{(j,\cdots,n)} = \frac{\mathbf{k}-\mathbf{q}_j-\cdots-\mathbf{q}_n}{(\mathbf{k}-\mathbf{q}_j-\cdots-\mathbf{q}_n)^2}$$ **Scatt amplitudes**

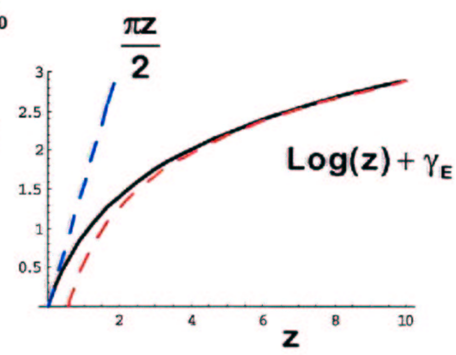
$$\mathbf{B}_{(j+1,\cdots,n)(j,\cdots,n)} = \mathbf{C}_{(j+1,\cdots,n)} - \mathbf{C}_{(j,\cdots,n)}$$

GLV: First Order Radiative Energy Loss

$$\Delta E^{(1)} = \int_0^1 dx\frac{dI^{(1)}}{dx} = E_0\frac{2C_R\alpha_s}{\pi}\int_0^1 dx\int_{z_0}^{\infty} dz\,\sigma(z)\rho(z,z)\,f(Z(x,z))$$

Formation parameter

$$Z(x,z) = \frac{\mu^2(z)}{2xE}(z-z_0) = \frac{\Delta z}{\tau_{form}}$$



Linear Regime: "Thin Plasma"

$$Z(x,z) \ll 1 \;\Rightarrow\; x_c \equiv \frac{\mu^2(z)}{2E}(z-z_0) \ll x \le 1$$

$$\Delta E^{(1)} \approx \frac{2C_R\alpha_s}{\pi}\int_{z_0}^{\infty}\frac{dz}{\lambda_g(z)}\left\{\int_{x_c}^{1}\frac{dx}{x}\frac{\pi}{4}\mu^2(z)(z-z_0) + E\int_0^{x_c}dx\,\log\left[\frac{x_c}{x}\right]\right\}$$

$$\approx \frac{C_R\alpha_s}{2}\int_{z_0}^{\infty}\frac{dz}{\lambda_g(z)}\mu^2(z)(z-z_0)\left\{\mathrm{Log}\frac{2E}{\mu^2(z)(z-z_0)} + \frac{2}{\pi}\right\}$$

Bjorken expansion

$$\rho\tau \approx \frac{dN}{dy}\frac{1}{\pi R^2}$$

Scaling Expansion

$$\frac{d}{d\tau}\rho(\tau)\tau^{\alpha} = 0$$

Transport Property

$\mu^2 / \lambda_g \propto \alpha_s^2 \rho$ **BDMS**

Baier, Dokshitzer,
Mueller, Schiff 1996
B.G.Zakharov 2000
U. Wiedemann 2000

Jet Energy Loss $\propto L^2 \to L^1$.
Expansion Dependent Reduction.

Asymptotic Leading Log Approx

GLV Opacity Expansion in LLA same as BDMS (mod Log $E/\mu^2 L$)

$$\Delta E_{\alpha}(L) = \frac{C_R \alpha_s \mu^2(L) L^{\alpha}}{2\,\lambda(L)} \frac{L^{2-\alpha}}{2-\alpha} \log\frac{2E}{\mu^2 L}$$

For Bjorken 1+1D Expansion

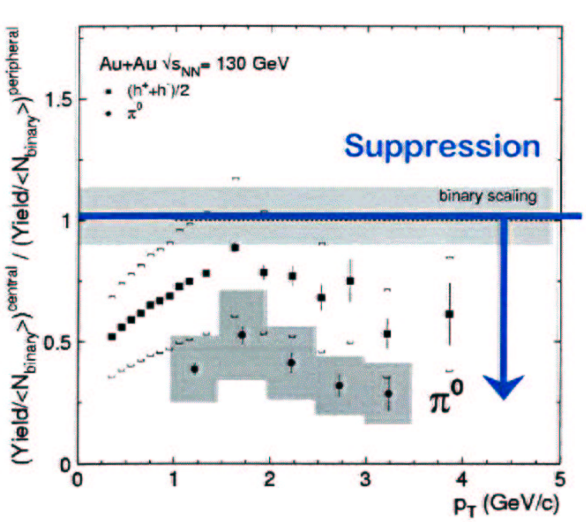
$$\Delta E_{\alpha=1}(L) = \frac{9 C_R \pi \alpha_s^3}{4}\left(\frac{1}{\pi R^2}\frac{dN^g}{dy}\right) L \log\frac{2E}{\mu^2 L}$$

For static medium

$$\Delta E_{\alpha=0}(L) = \frac{9 C_R \pi \alpha_s^3}{8}\left(\frac{1}{z_0 \pi R^2}\frac{dN^g}{dy}\right) L^2 \log\frac{2E}{\mu^2 L}$$

For initial condition driven energy loss there is a factor of $L/2z_0$ reduction for the expanding medium relative to the static one.

PHENIX / RHIC



WA98 / SPS

M.M. Aggarwal et al.: Transverse mass distributions of n

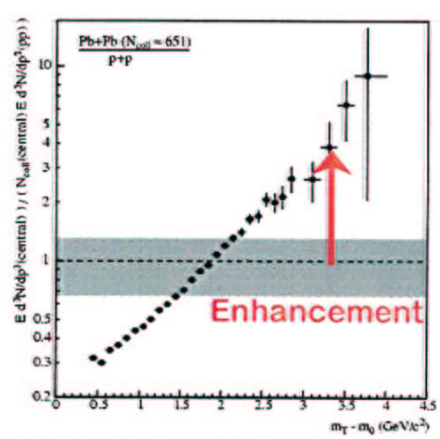


Fig. 12. Ratios of invariant multiplicity distributions of neutral pions for central Pb+Pb reactions to the parameterization of p+p reactions normalized to the number of binary collisions, also called the nuclear modification factor. The grey band shows the estimate of the systematic error due to the calculation of the number of collisions and the absolute cross section normalization relative to p+p.

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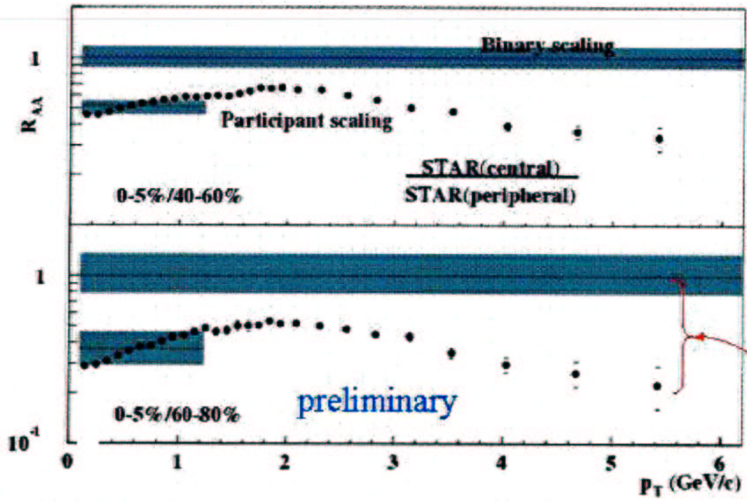
Central/peripheral normalized by <N$_{binary}$>



- Same features but without NN reference uncertainty
- Cent/periph: factor ~4 suppression

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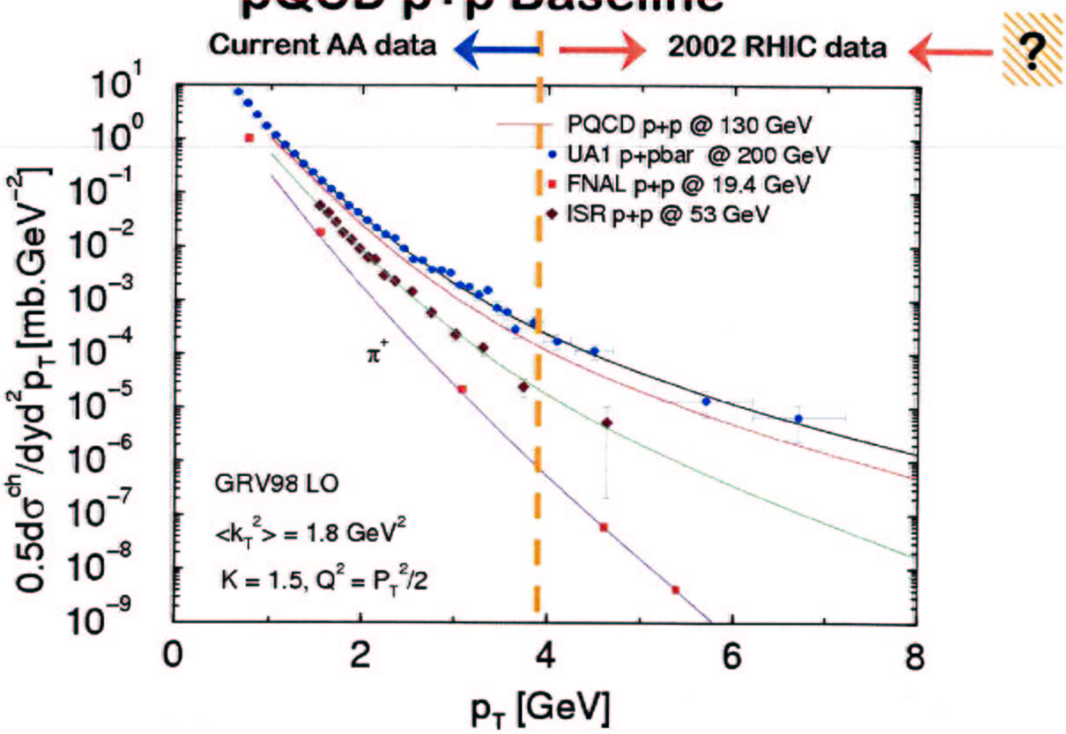
Pion^0 Tomography

$$E_h \frac{d\sigma^{AA}_{\pi^0}}{d^3p} = B^{(0)}_{AA} \sum_{abcd} \int dx_1 dx_2 f_{a/A}(x_1, Q^2) f_{b/A}(x_2, Q^2) \frac{d\sigma}{d\hat{t}} \int d\epsilon P(\epsilon, p_c) \frac{z_c^*}{z_c} \frac{D_{\pi^0/c}(z_c^*, {p_c}^2)}{\pi z_c}$$

Three approximations:

1) $P(\varepsilon,E)$ including Poisson fluctuations
2) $P(\varepsilon,E) \approx \delta(\varepsilon - \Delta E/E)$ Average Energy Loss
3) $P(\varepsilon,E) \approx \delta(\varepsilon - \mathbb{Z}\,\Delta E/E)$ Renormalized ΔE

pQCD p+p Baseline

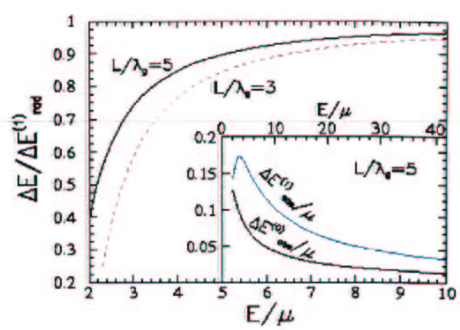


MG, I Vitev, XN Wang, Phys.Rev.Lett.86:2537-2540,2001

Additional Effects that Influence E-Loss

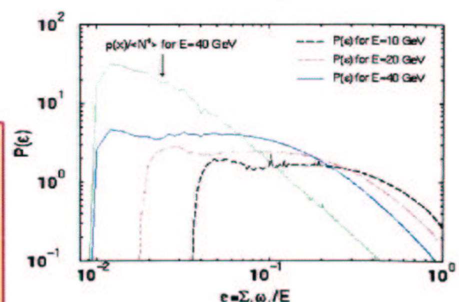
- Absorption effects important for small $E_{jet} < 5\,GeV$

E.Wang, X.N. Wang, PRL 87, 142301 (2001)
(E-loss with detailed balance)



- Multi-gluon fluctuations
  Renormalize ΔE by ~1/2

GLV nucl-th/0112071; BDMS ; Wang[2]



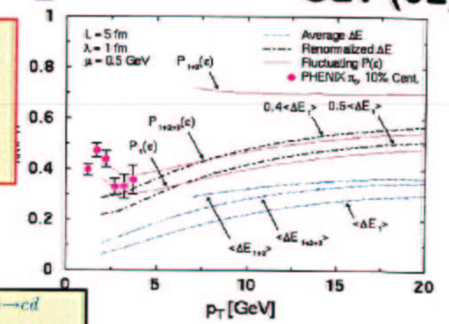
$$P(\varepsilon,E)=\sum_{n=0}^{\infty}P_n(\varepsilon,E) \qquad \frac{\Delta E}{E}=\int_0^{\infty}d\varepsilon\,\varepsilon P(\varepsilon,E)$$

$$P_{n+1}(\varepsilon,E)=\frac{1}{n+1}\int_{x_0}^{1-x_0}dx_n\;\rho(x_n,E)P_n(\varepsilon-x_n,E)$$

$$P_1(\varepsilon,E)=e^{-\langle N_g\rangle}\rho(\varepsilon,E)$$

Effect of Fluctuating En-loss GLV (02)

Similar shape of spectrum renormalization density by factor Z ~ 0.4-0.5 at RHIC



$$E_h \frac{d\sigma}{d^3p} = \sum_{abcd} \int dx_1 dx_2 d^2k_1 d^2k_2 \, g(k_1) g(k_2) \frac{d\sigma^{ab\to cd}}{dt} \times$$

$$\times f_{a/A}(x_1,Q^2) f_{b/A}(x_2,Q^2) \int d\varepsilon \, P(\varepsilon, p_c) \frac{z_c^*}{z_c} \frac{D_{h/c}(z_c^*, Q^2)}{\pi z_c}$$

$$z_c^* = z_c / (1-\varepsilon)$$

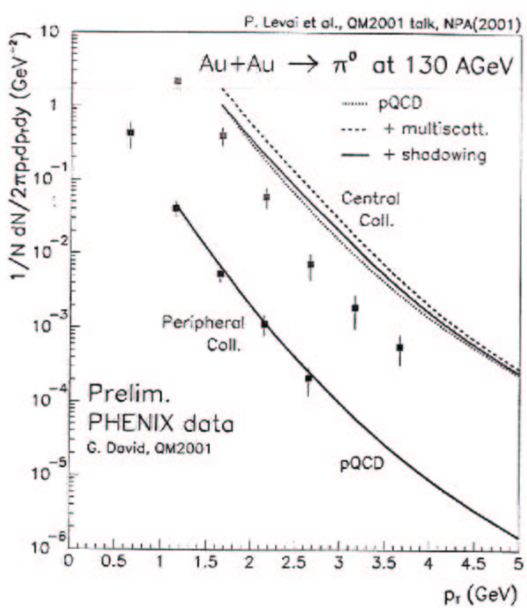
Compare

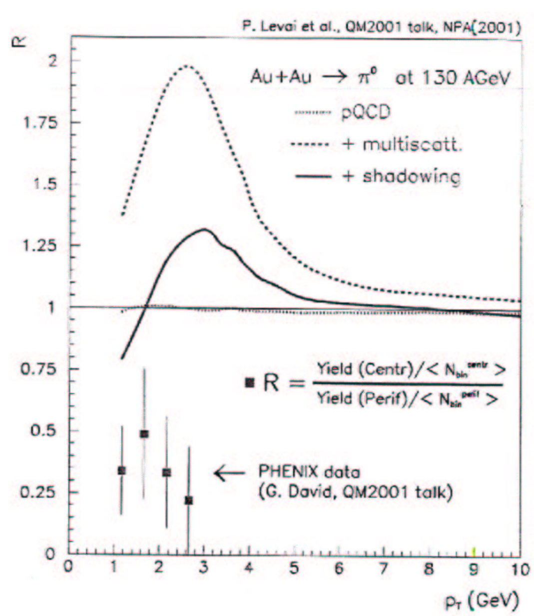
$$P(\varepsilon) = \begin{cases} P(\varepsilon, E) \\ \delta(\varepsilon - Z \otimes \Delta E / E) \end{cases}$$

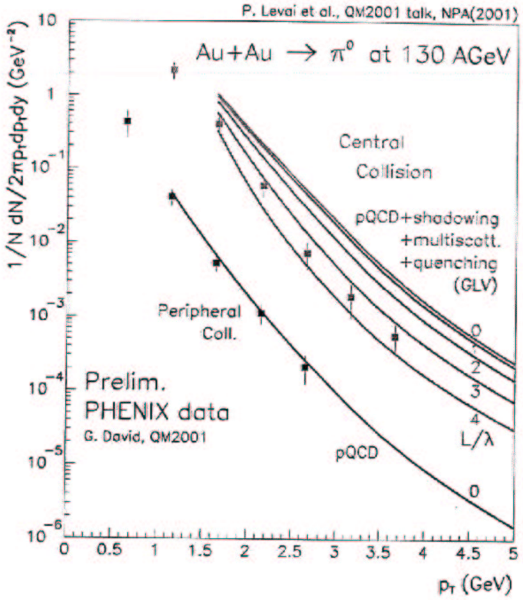
- **Include nuclear shadowing $f_{a/A}(x,Q^2)$. Modification factor taken as in HIJING**
- **Include k_T smearing and Cronin effect via g(k) (assumed to be Gaussian)**

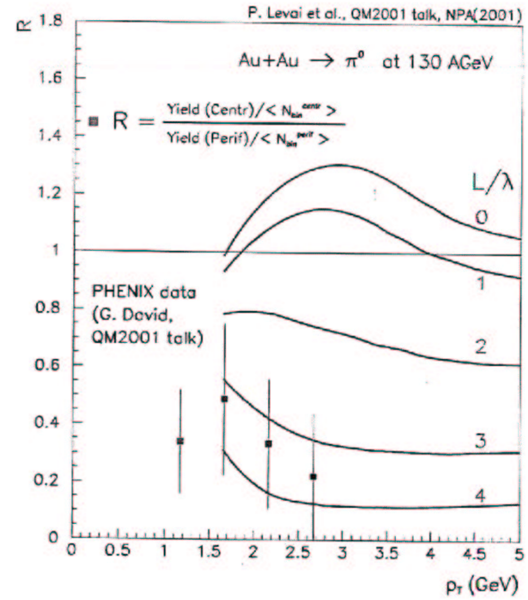
$$\langle k^2 \rangle_{pA} = \langle k^2 \rangle_{pp} + C[\nu(b) - 1]$$

Cronin + Shadow effects

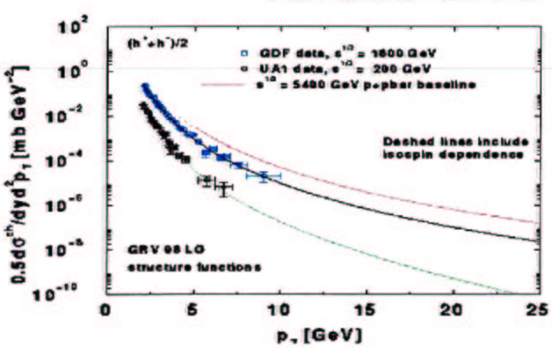


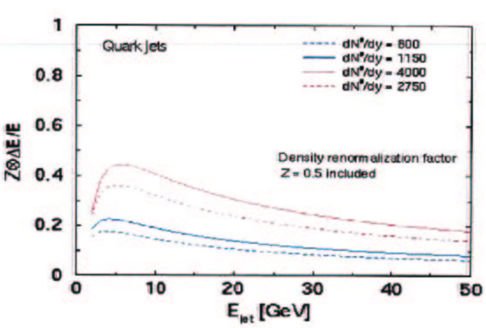


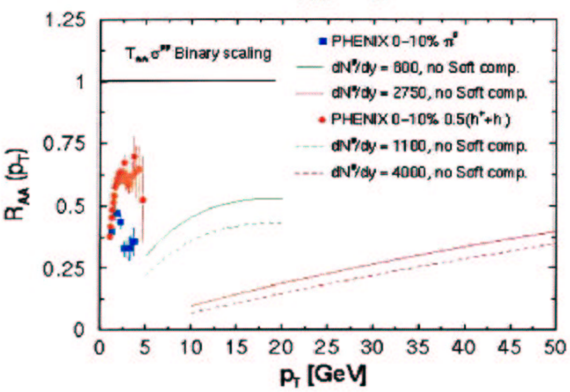




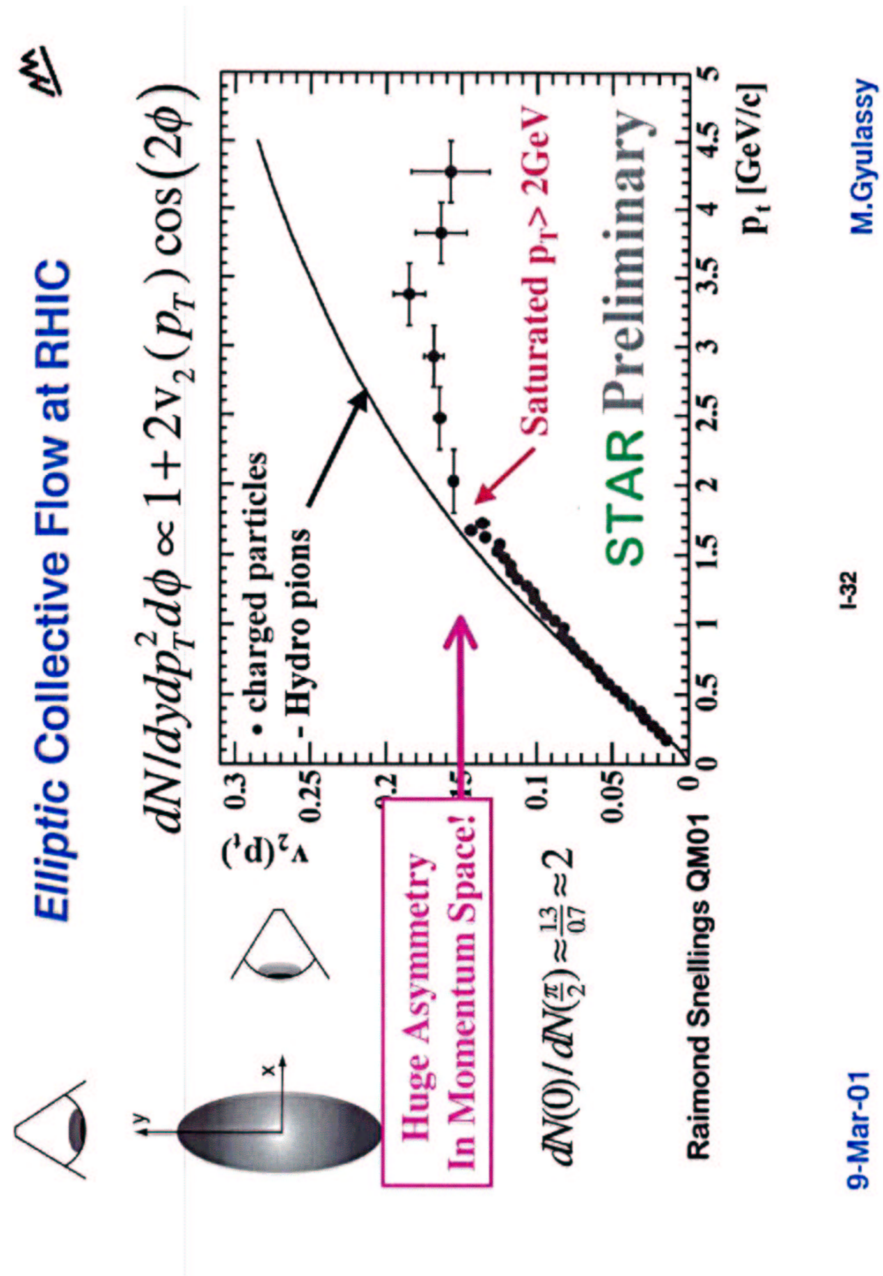
Jet quenching at RHIC (200 AGeV) versus LHC (5400 AGeV)

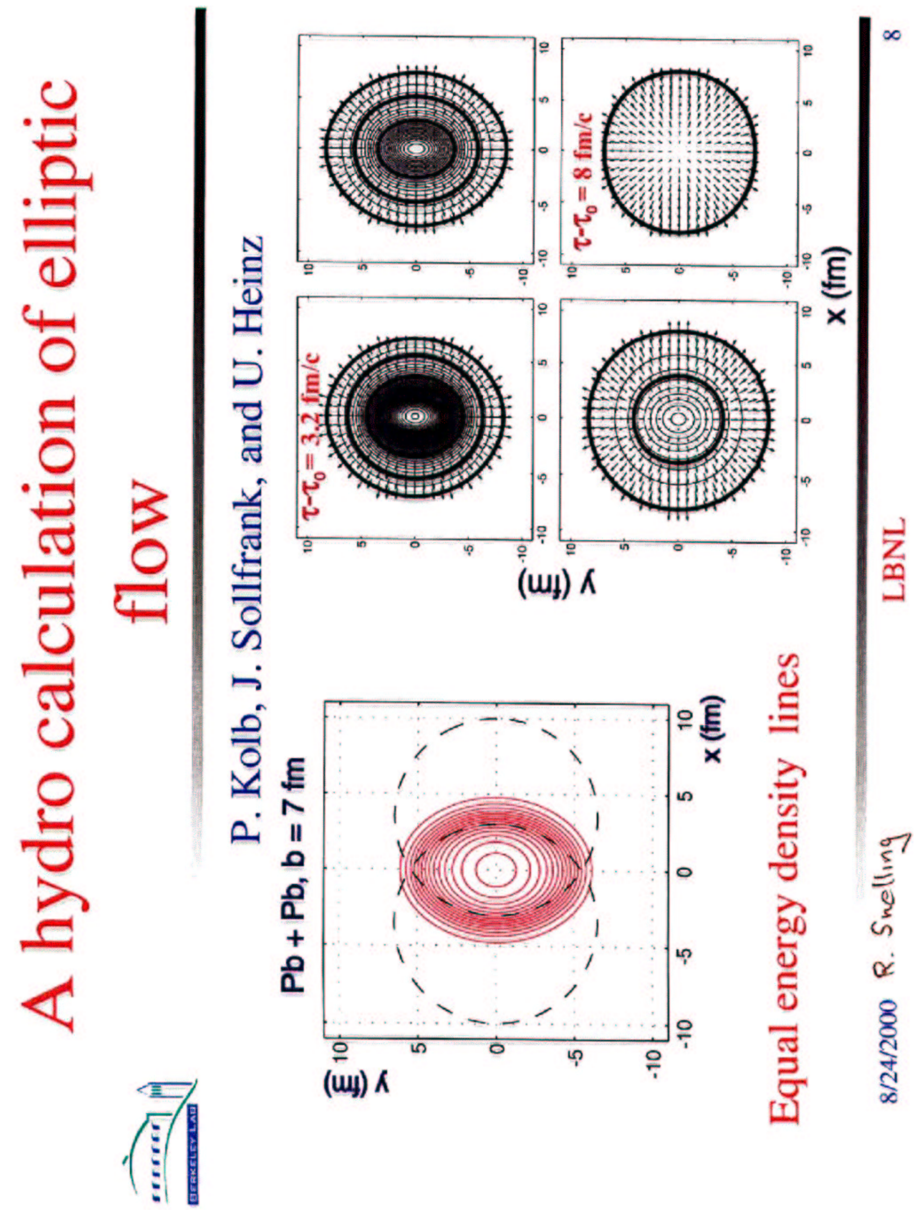






- Increased quenching by a factor of ~3 in the overlapping region (roughly following the density)
- Moderate p_T dependence of the quenching factor


Elliptic Collective Flow at RHIC
$dN/dydp_T^2d\phi \propto 1+2v_2(p_T)\cos(2\phi)$
• charged particles
- Hydro pions
Saturated p_T> 2GeV
STAR Preliminary
$v_2(p_t)$
p_t [GeV/c]
Huge Asymmetry
In Momentum Space!
$dN(0)/dN(\frac{\pi}{2}) \approx \frac{1.3}{0.7} \approx 2$
Raimond Snellings QM01
9-Mar-01
I-32
M.Gyulassy


A hydro calculation of elliptic flow
P. Kolb, J. Sollfrank, and U. Heinz
Pb + Pb, b = 7 fm
y (fm)
x (fm)
$\tau-\tau_0$ = 3.2 fm/c
$\tau-\tau_0$ = 8 fm/c
Equal energy density lines
8/24/2000 R. Snelling
LBNL
8

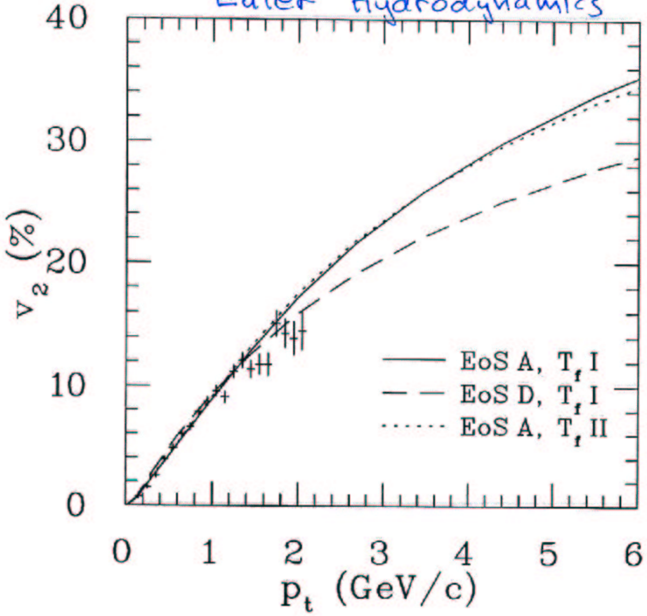
Pasi Huovinen

v_2 @ RHIC
- charged particles
- min. bias

D: $T_c = 200$

- EoS A ⟺ $T_c = 165$ MeV
- T_f I ⟺ $T_f \approx 140$ MeV
- T_f II ⟺ $T_f \approx 125$ MeV

Euler Hydrodynamics



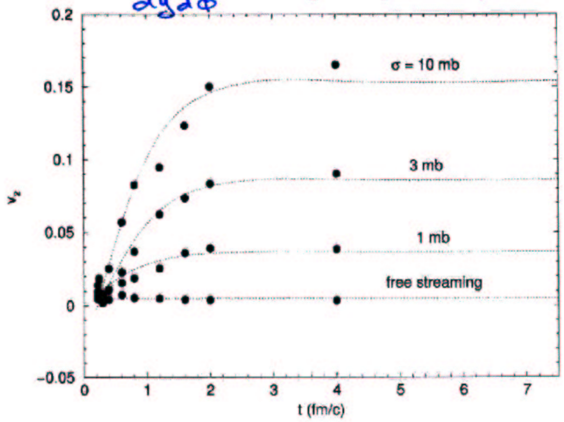
Collective Flow or Final State Interactions ?

Up to how high $p_\perp$ can dissipation λ/R be neglected ?

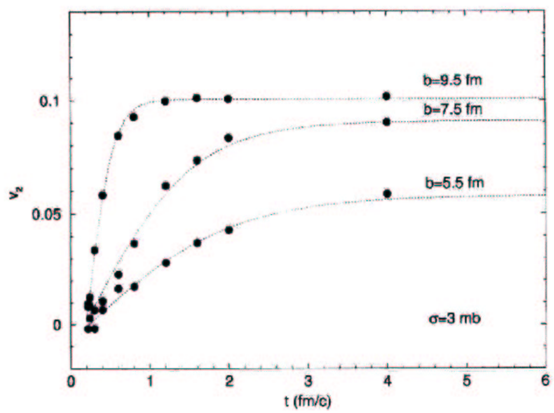
Elliptic Flow from Parton Cascade

Bin Zhang, C.M. Ko, MG
PLB 455 (99) 45

$$\frac{dN_{glue}}{dy\,d\phi} = v_0 + 2v_2\cos 2\phi + \cdots$$

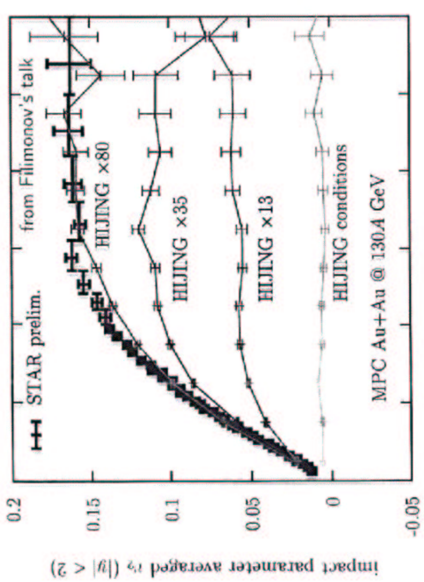


v_2 develops early + sensitive to σ_{gg}

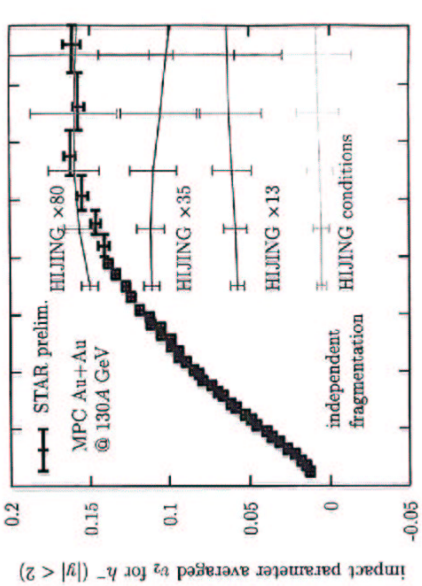


Dénes Molnár, High-p_T Workshop, 11/2/2001

Impact parameter averaged $v_2(p_T)$



a) hadronization via parton-hadron duality



b) independent fragmentation

- 80× more opaque plasma needed than from HIJING to reproduce data
  - → not enough for equilibrium − $\langle N_{coll} \rangle \sim 30$ but rapid expansion
  - → but too opaque for Eikonal dynamics to hold
- little sensitivity to hadronization scheme

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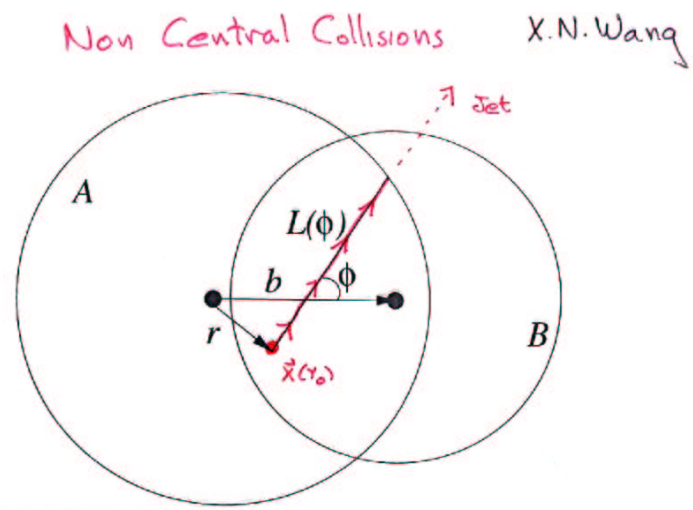

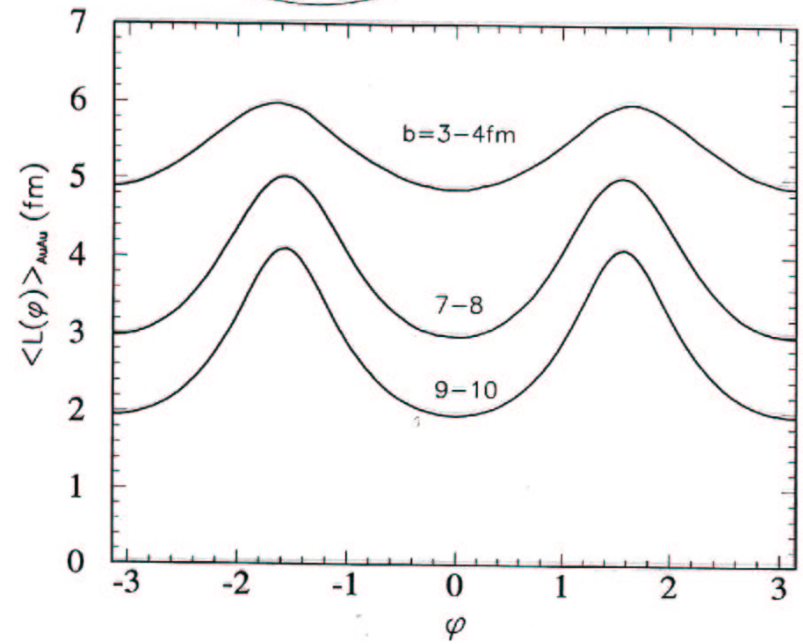

Soft Hydro + GLV Quenched Hard

$$E\frac{dN_{AB}(\mathbf{b})}{d^3p} = N_{part}(\mathbf{b})\frac{dN_s(\mathbf{b})}{dyd^2\mathbf{p}_T} + T_{AB}(\mathbf{b})\frac{d\sigma_h(\mathbf{b})}{dyd^2\mathbf{p}_T}$$

(1) pQCD computable "hard" part:

$$E_h\frac{d\sigma_h}{d^3p} = K\sum_{abcd}\int dx_a dx_b f_{a/p}(x_a,Q_a^2)f_{b/p}(x_b,Q_b^2)$$

$$\frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{D'_{h/c}(z_c,Q_c^2)}{\pi z_c}$$

Medium modified fragmentation

$$z_cD'_{h/c}(z_c,Q_c^2) = z'_cD_{h/c}(z'_c,Q_{c'}^2) + N_g z_g D_{h/g}(z_g,Q_g^2)$$

$$z'_c = \frac{p_h}{p_c - \Delta E_c(p_c,\phi)}\,, \quad z_g = \frac{p_h}{\Delta E_c(p_c,\phi)/N_g}$$

(2) Soft phenom. "hydro" part (P. Huovinen)

$$\frac{dN_s(\mathbf{b})}{dyd^2\mathbf{p}_T} \approx \frac{dn_s}{dy}\frac{e^{-4p_T}}{8\pi}(1+2v_{2s}(p_T)\cos(2\phi))$$

$$v_{2s}(p_T) \approx \tanh(p_T/(10\pm 2\ \mathrm{GeV}))$$