Probing Dense QCD Matter in A+A

Part I

1. Bulk QCD Thermodynamics:

   P(T,m) and collective flow

2. Strong field QCD: saturation

   $a_s(Q_s)\ xG_A(x,Q_s) \sim (Q_sR_A)^2$

Part II

3. pQCD Multiple Scattering:

   Jet quenching and broadening

4. New phenomena:

   Baryon dynamics, CP domains

Bulk QCD Equation of State

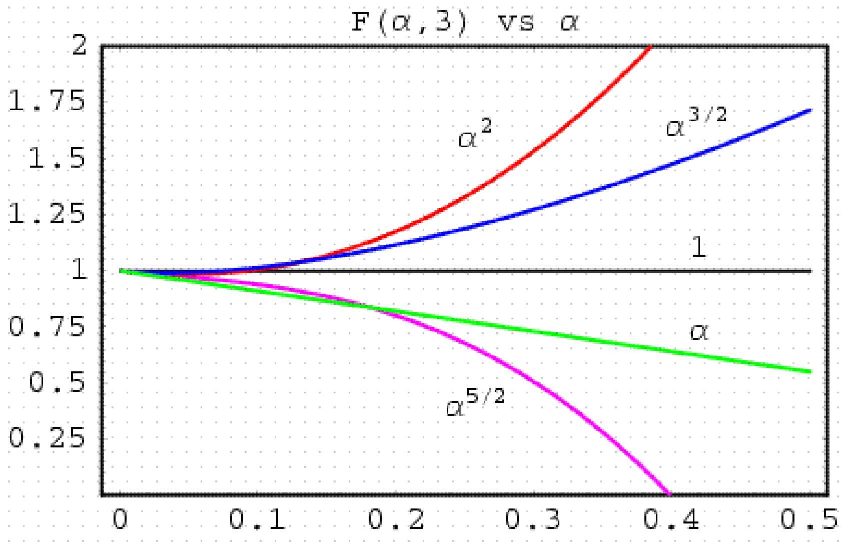
High Temperature QCD Perturbation Theory

(E.Braaten and A. Nieto, PRL 76 (96) 1417)
(C.Zhai and B. Kastening, PRD 52 (95) 7232)

Quark – Gluon Plasma Pressure

$$P = \frac{\pi^2}{90} T^4 \left(2_s 8_c + \frac{7}{8} 2_s 3_c 2 n_f\right) F(\alpha, n_f)$$

$$F(\alpha, 3) = 1 - 0.9\,\alpha + 3.3\,\alpha^{3/2} + (7.1 + 3.5 \log \alpha)\,\alpha^2 - 20.8\,\alpha^{5/2} + (\,?\,)\,\alpha^3 + \ldots$$



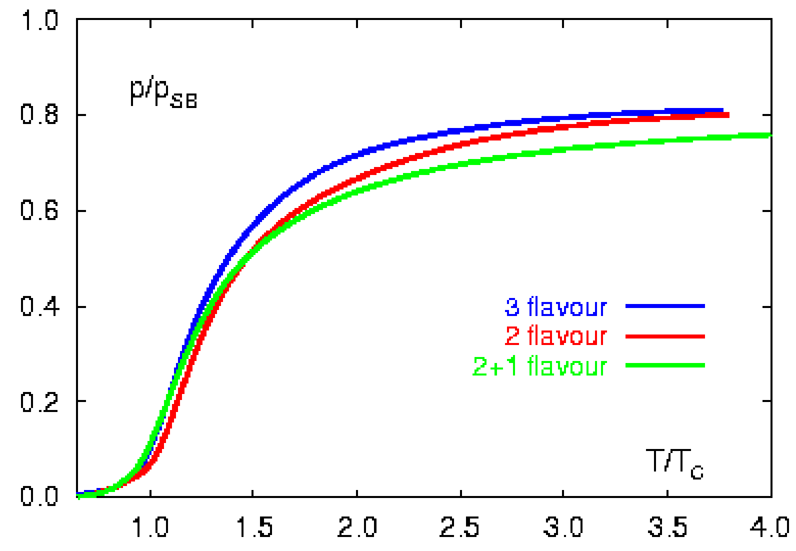
$\alpha(T)$

Lattice QCD

F.Karsch et al, PLB 478 (00) 477

16^3X4 improved gauge and staggered q

$M_{u,d}$~T/4 ,M_s~T



pQCD Jets are Independent

Only in Dilute Limit

$$A_\perp(\text{glue}) = \frac{dN_{\text{glue}}}{dy}\,\frac{c\,\alpha_s(Q)}{Q^2} < \pi R^2$$

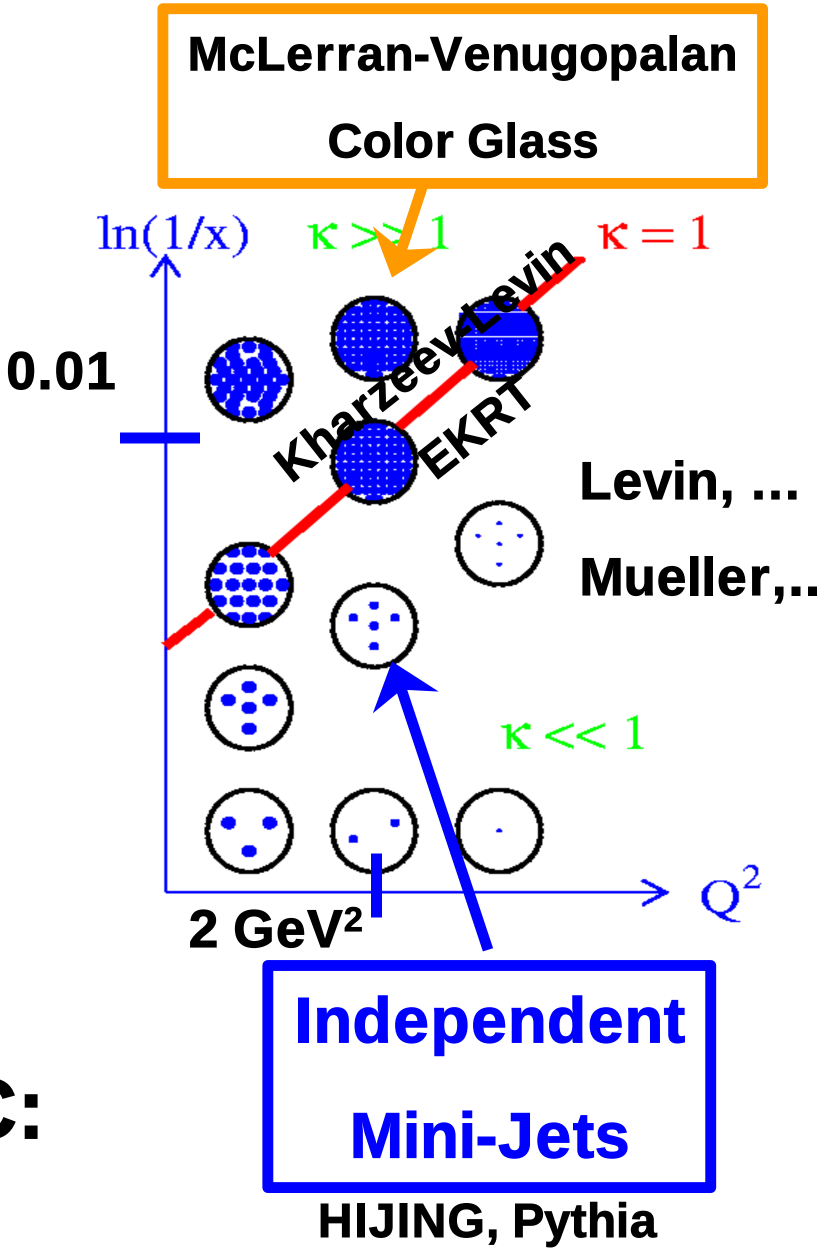
Packing Fraction

$$\kappa = A_\perp(\text{glue})/\pi R^2$$

$$\kappa_{\text{crit}}(x,Q^2) = 1$$

Practical Problem at RHIC:

$$0.01 < x < 0.1 \quad , \quad Q_s^2 \sim 2\,\text{GeV}^2$$



McLerran-Venugopalan

Color Glass

Independent

Mini-Jets

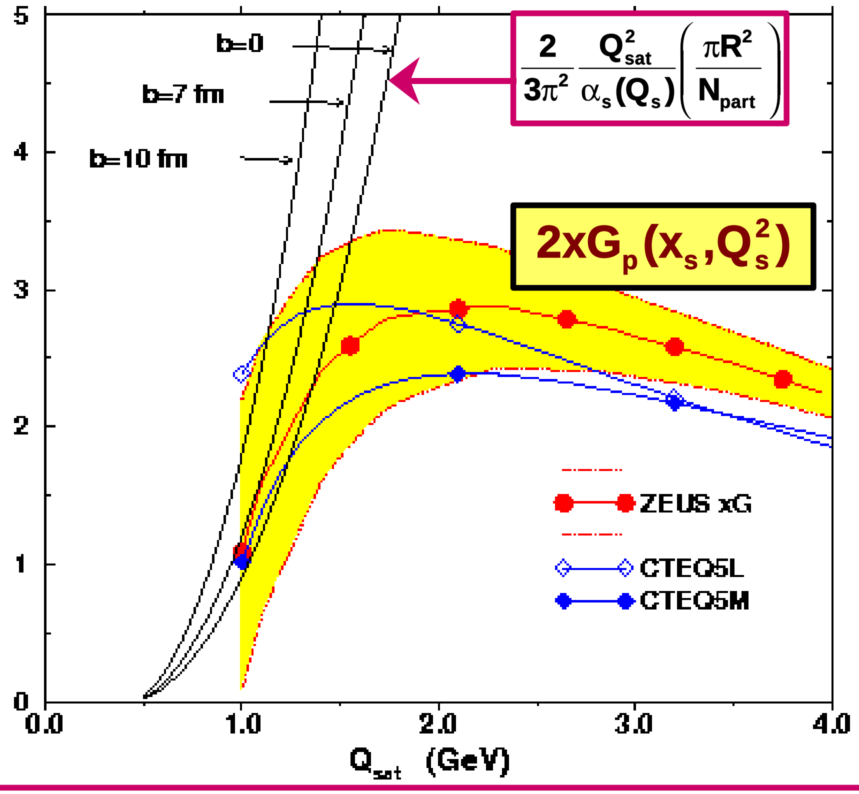
HIJING, Pythia

Initial State Saturation RHIC vs LHC

Kharzeev+Nardi RHIC

Initial State Saturation at E_{cm}=130 AGeV

Au + Au

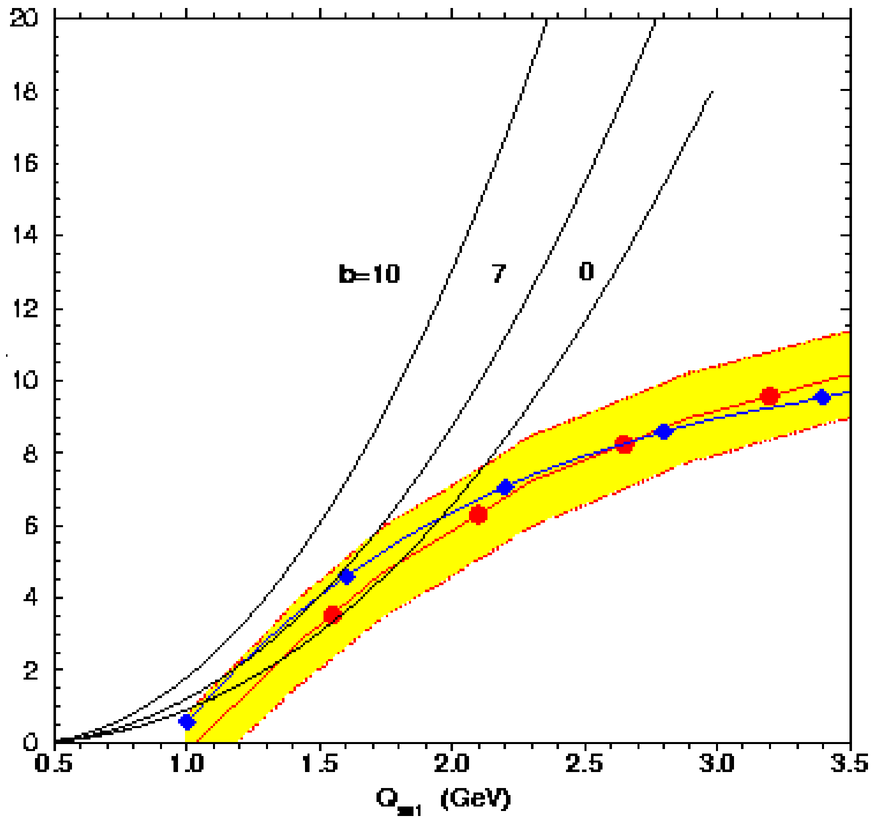


$$\frac{2}{3\pi^2}\frac{Q^2_{sat}}{\alpha_s(Q_s)}\left(\frac{\pi R^2}{N_{part}}\right)$$

$2xG_p(x_s,Q_s^2)$

LHC

Initial State Saturation at E_{cm}= 5400 AGeV



$$2xG_A\left(x=\frac{2Q_{sat}}{\sqrt{s}},Q^2_{sat}\right)=\frac{2c}{3\pi^2}\,\frac{Q^2_{sat}R^2}{\alpha_s(Q_s)}$$

$$2xG_p\left(x=\frac{2Q_{sat}}{\sqrt{s}},Q^2_{sat}\right)=\frac{2c}{3\pi^2}\,\frac{Q^2_{sat}}{\alpha_s(Q_s)}\left(\frac{\pi R^2}{N_{part}}\right)$$

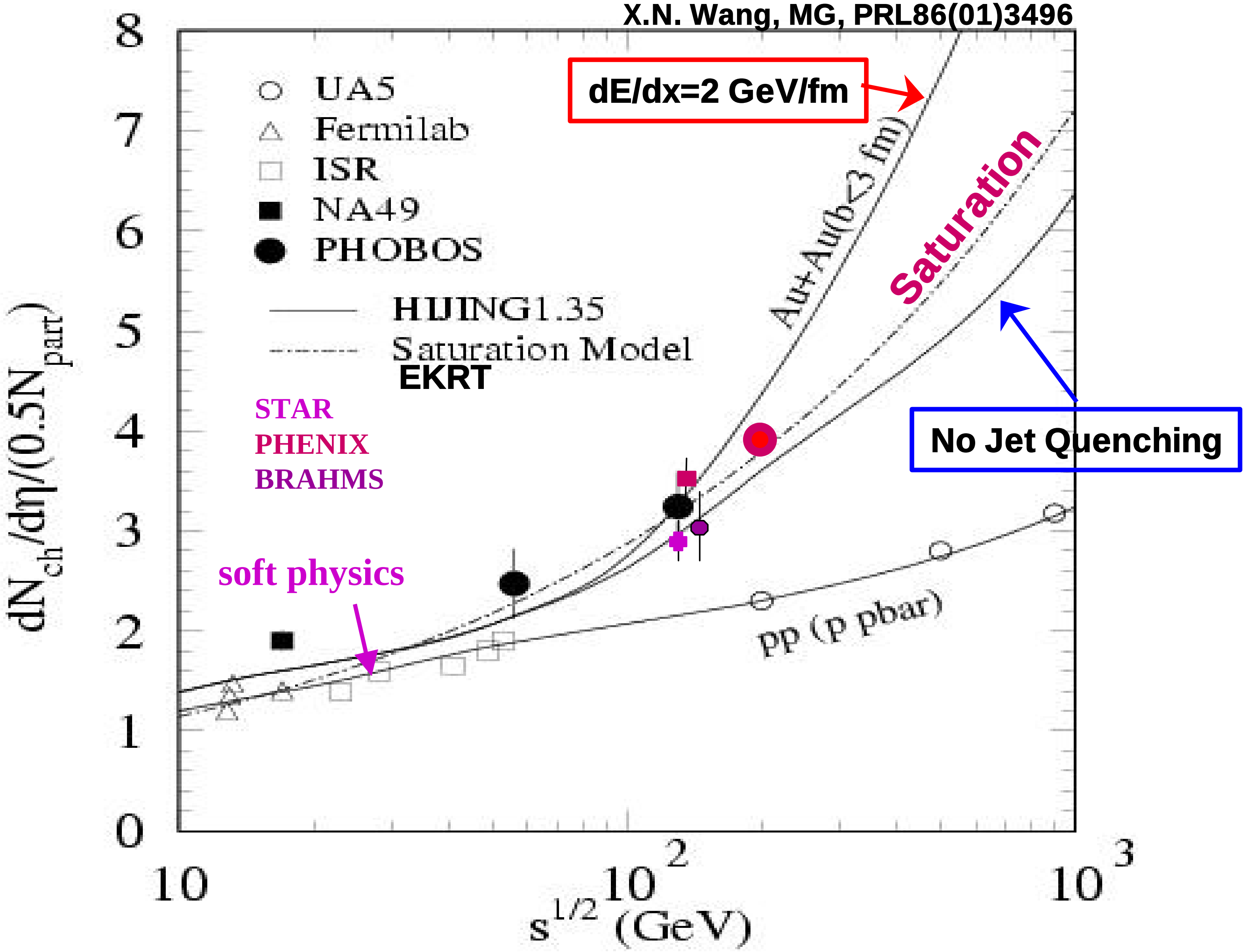
Q_s µ $A^{1/6}s^{l/4}$, l » 0.3

Painfully slow growth!

Mueller, Qiu

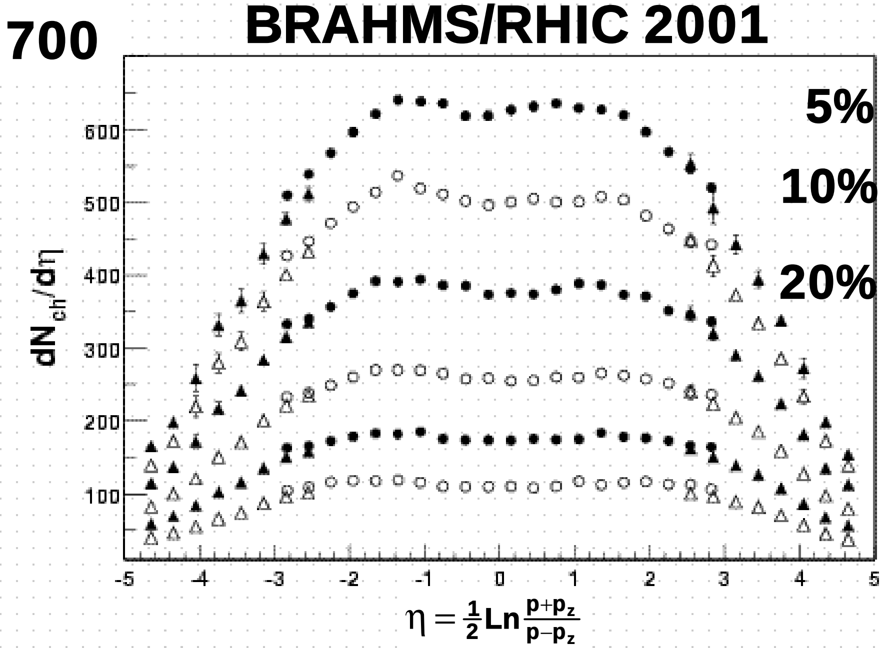
Global Evidence for Minijet Showers at RHIC

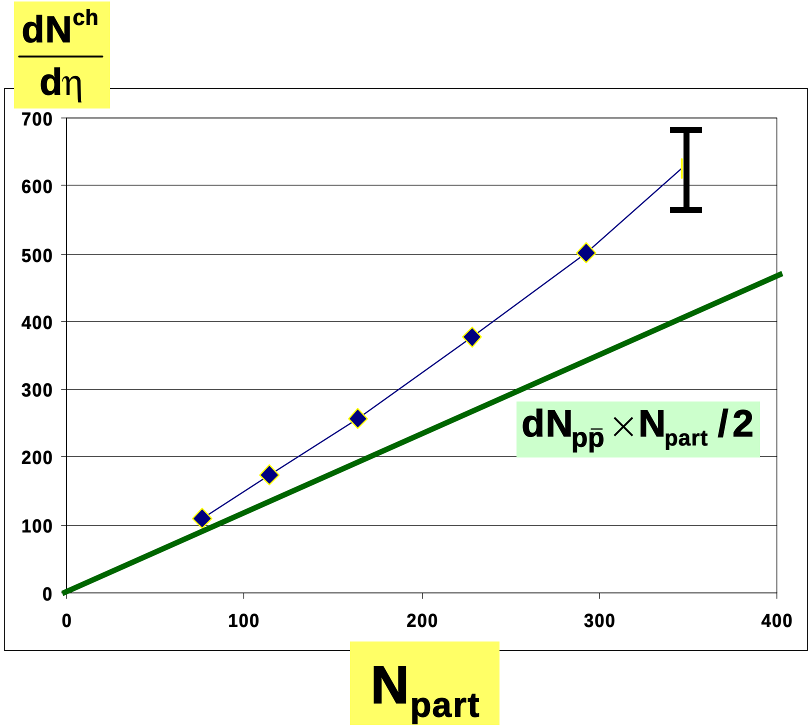
X.N. Wang, MG, PRL86(01)3496



Au^{197}+ Au^{197}--> ~5000 $\pi^{\pm}$ E_{cm}~200 AGeV

dN/dy 1.15 dN/d



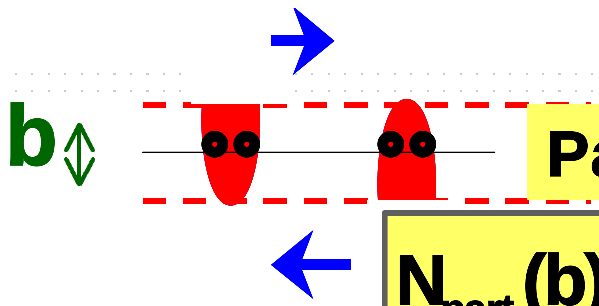


Nuclear Geometry

$$T_A(b)=\int dz\,\rho_A(z,b)\approx 2\rho_0\sqrt{R^2-b^2}$$

$$T_{AB}(b)=\int d^2s\,T_A(b-s)T_B(s)\approx\frac{A^{4/3}}{40\,mb}$$

Binary density

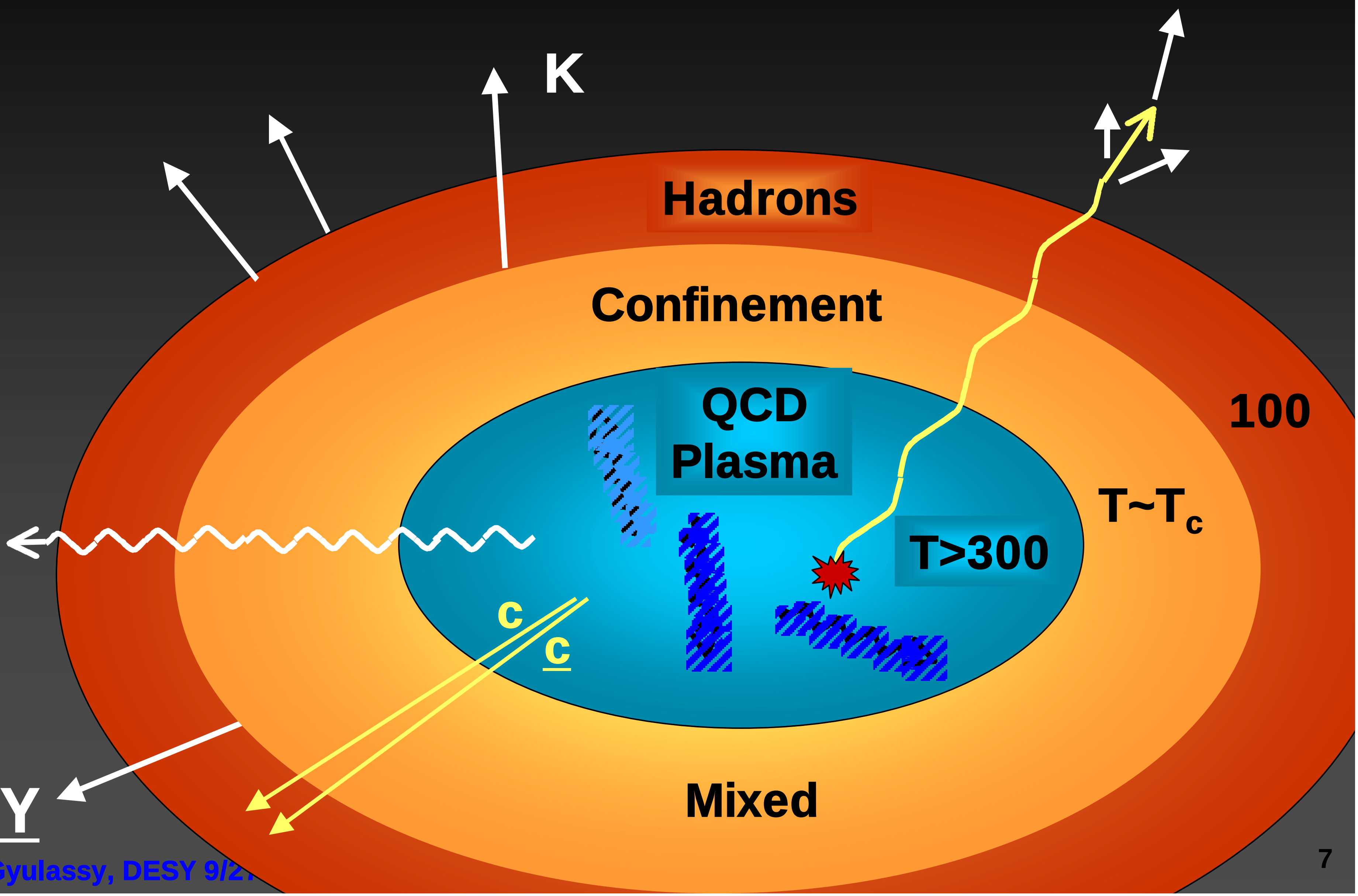


Participating nucleons

$$N_{part}(b)=2\int d^2s\,T_A(s+\tfrac{b}{2})(1-e^{-s\,T_A(s-\frac{b}{2})})$$

M.Gyulassy, DESY 9/27

Experimental Probes of Dense Matter in A+A



Jets

K

Hadrons

Confinement

QCD Plasma

100

$T \sim T_c$

T>300

c

$\underline{c}$

$\underline{Y}$

Mixed

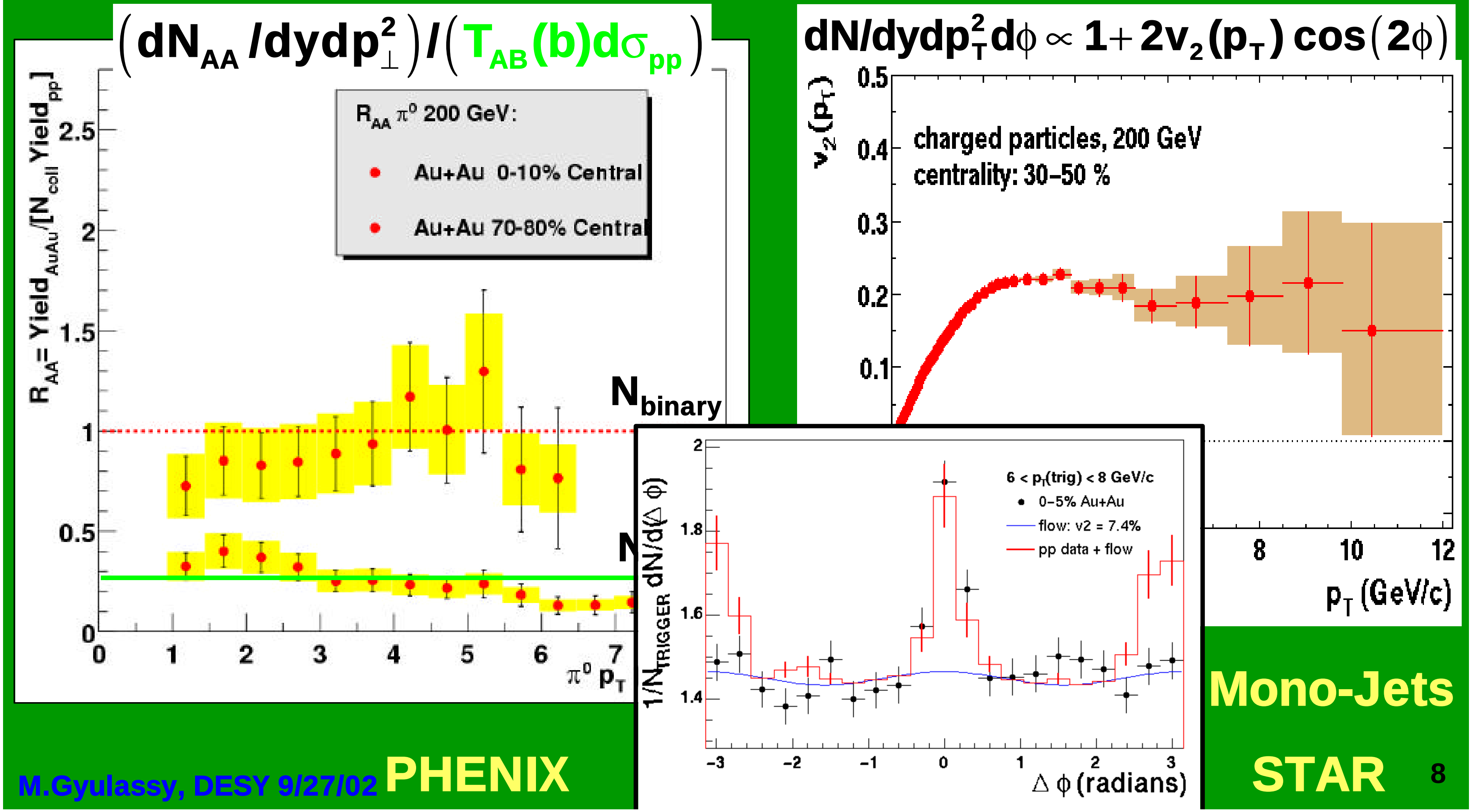
Several New p_T~2-8 GeV Phenomena Observed in Au+Au E_{cm}= 200 AGeV

Jet Quenching

Azimuthal Collectivity

$$\left(dN_{AA}/dydp_{\perp}^{2}\right)/\left(T_{AB}(b)d\sigma_{pp}\right)$$

$$dN/dydp_T^2 d\phi \propto 1+2v_2(p_T)\cos(2\phi)$$



Mono-Jets

PHENIX

STAR

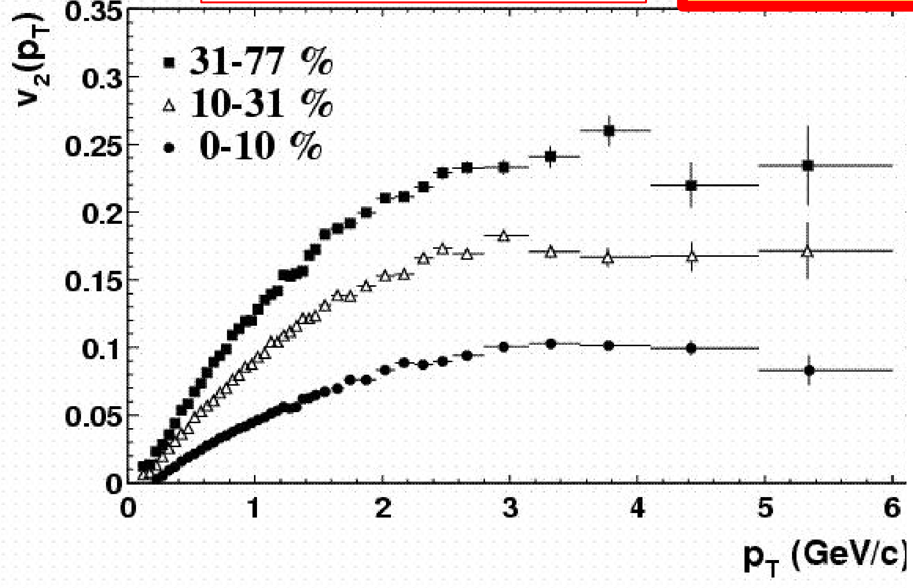
M.Gyulassy, DESY 9/27/02

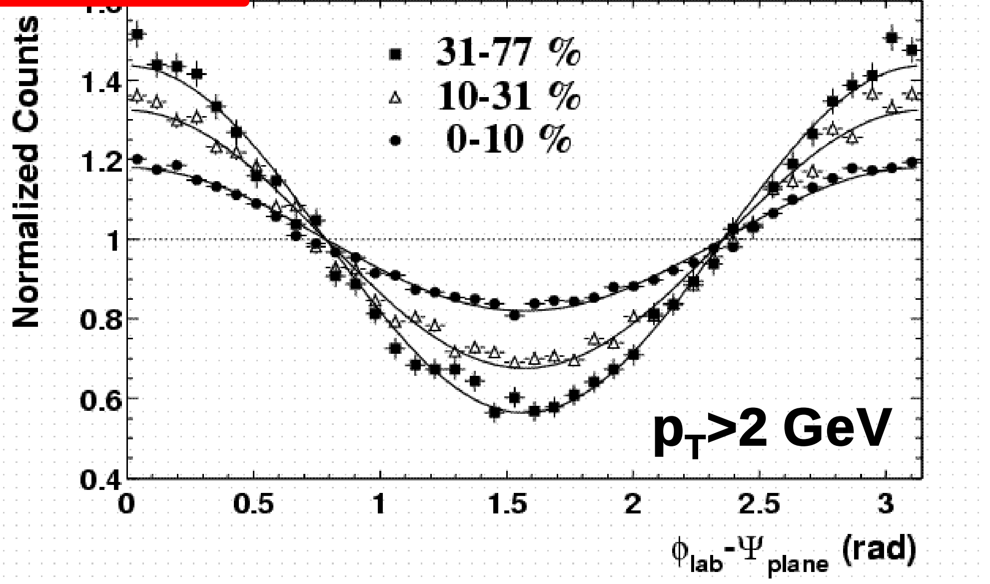
Azimuthal anisotropy and correlations in the hard scattering regime at RHIC

$\langle\cos 2(\phi_{lab} - \Psi_{plane})\rangle$

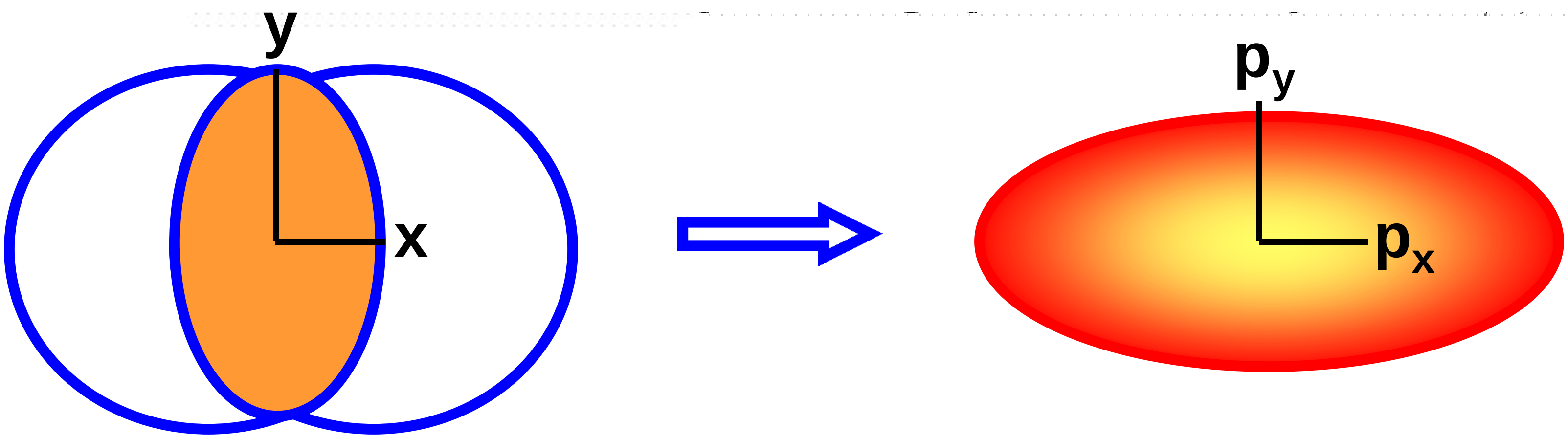
STAR June 2002

$dN_{ch}(p_{\perp}, \phi - \psi_{reac})$





Initial *spatial* anisotropy **Final *momentum* anisotropy**



Ulrich Heinz

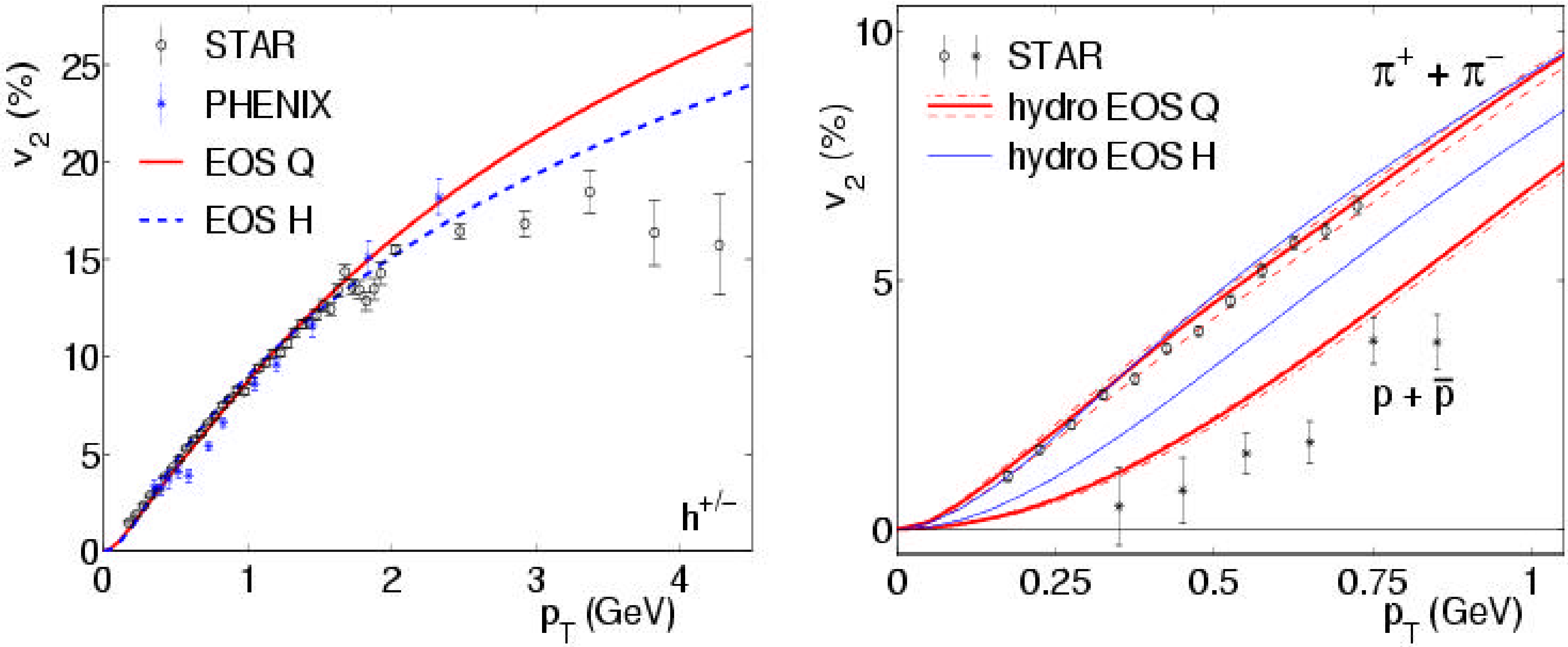
Hydrodynamics: $\partial_\mu \{(e + p)u^\mu u^\nu - g^{\mu\nu}p\} = 0$

P. Huovinen, P Kolb, D. Teany, ...

Elliptic flow at RHIC

Collective longitudinal and transverse velocity field u(x)

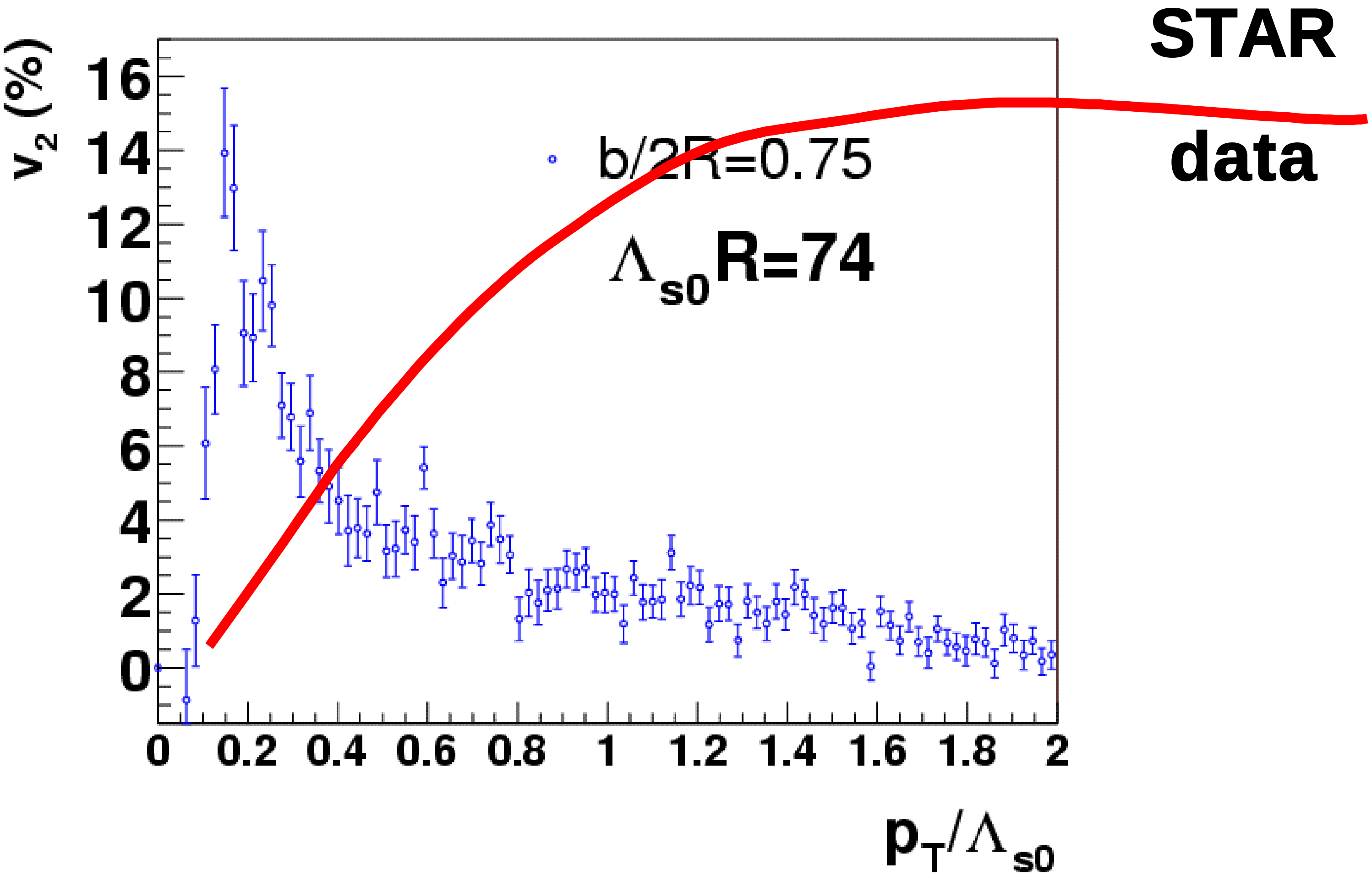
strong elliptic flow v_2, $v_2(p_\perp \leq 2\,\mathrm{GeV})$ exhausts hydrodynamic prediction !



STAR Coll., PRL 86 (2001) 402; 87 (2001) 182301; PHENIX Coll., nucl-ex/020400512 and QM 2001

Elliptic flow of colored glass in high energy heavy ion collisions

Alex Krasnitz,[1] Yasushi Nara,[2] and Raju Venugopalan[3,2]



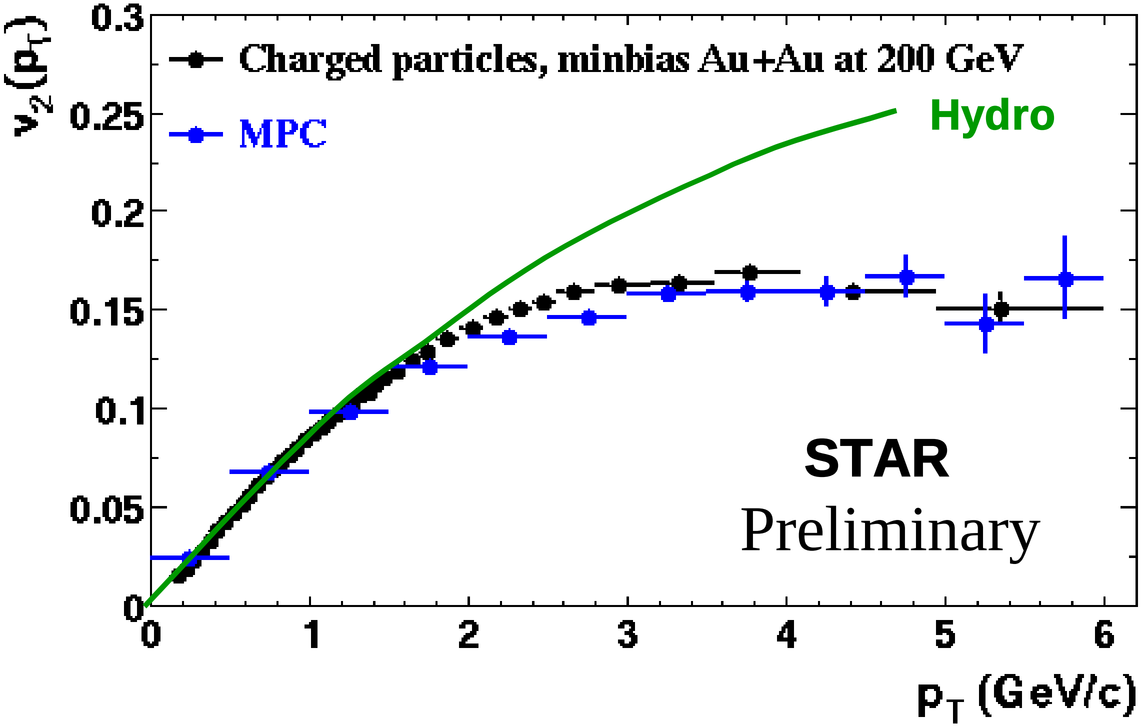
Classical Yang-Mills fails to describe collective elliptic flow

L_{s0}~2 GeV, R~7fm RHIC

Elliptic Flow via parton transport theory: MPC

K.Filiminov QM02

$$p_1 ¶_x f(x,p_1) = \grave{o}\grave{o}\grave{o}_{2\,3\,4}\; ds\, v(f_3 f_4 - f_1 f_2)$$



D. Molnar, MG
NPA 697 (02) 495

dN_g/dy~1000

and

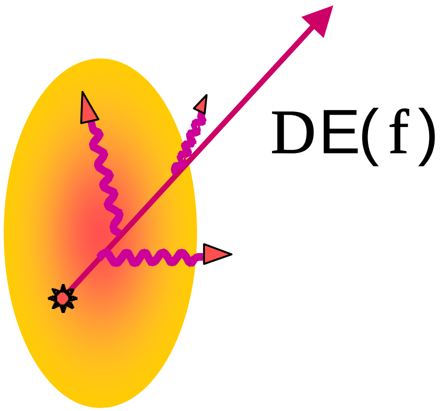
10 x pQCD s(gg→gg) !

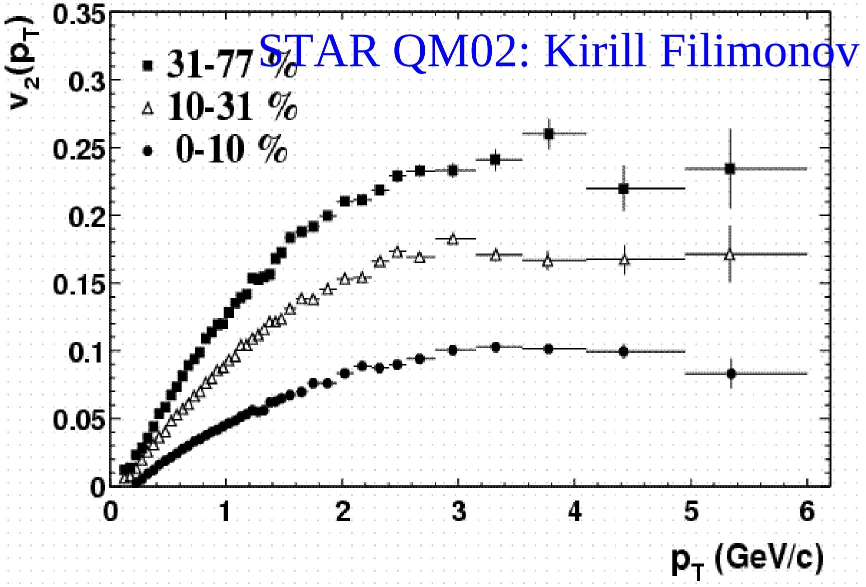
Extremely opaque QCD matter is required to explain saturation and magnitude v2 above 2 GeV

Elliptic Tomography

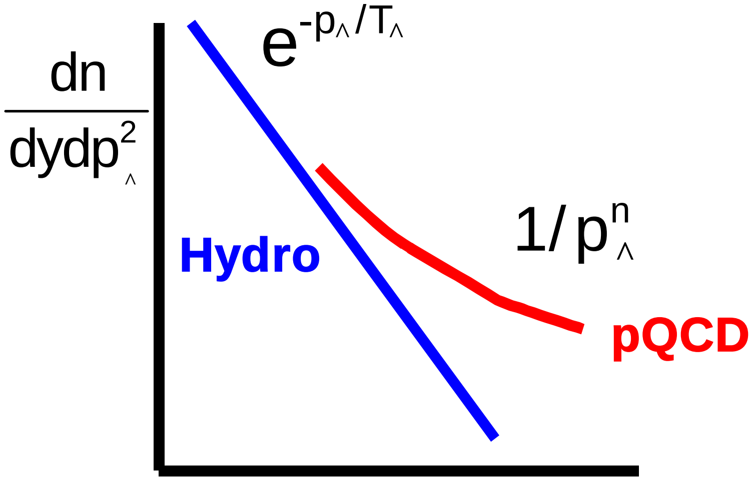
MG, I. Vitev and X.N. Wang, PRL86(01)

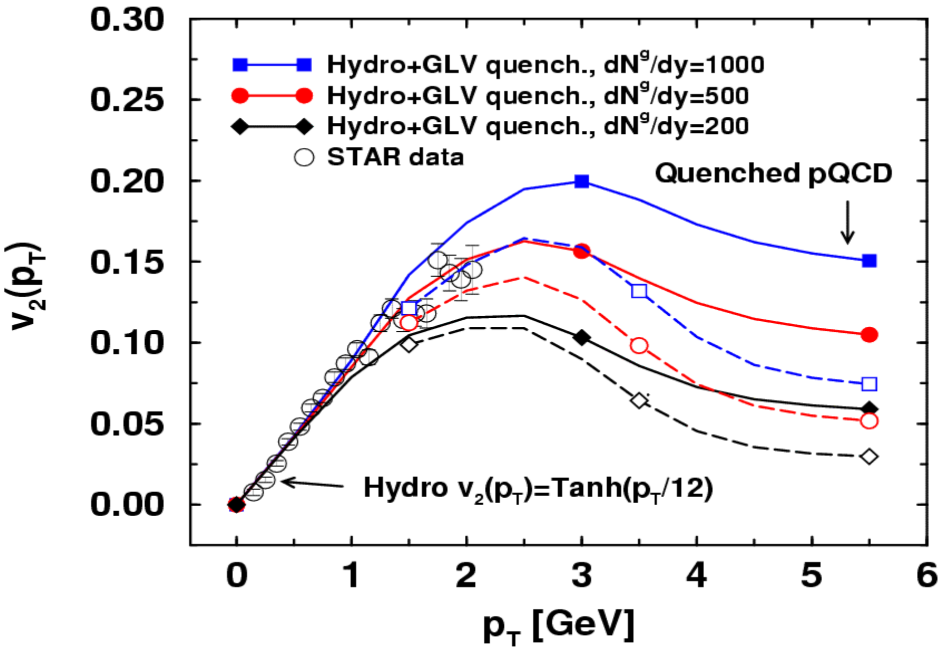
$$\rho_{QGP}(\tau, \mathbf{x}_0 + \hat{\mathbf{n}}\tau)$$





STAR QM02: Kirill Filimonov



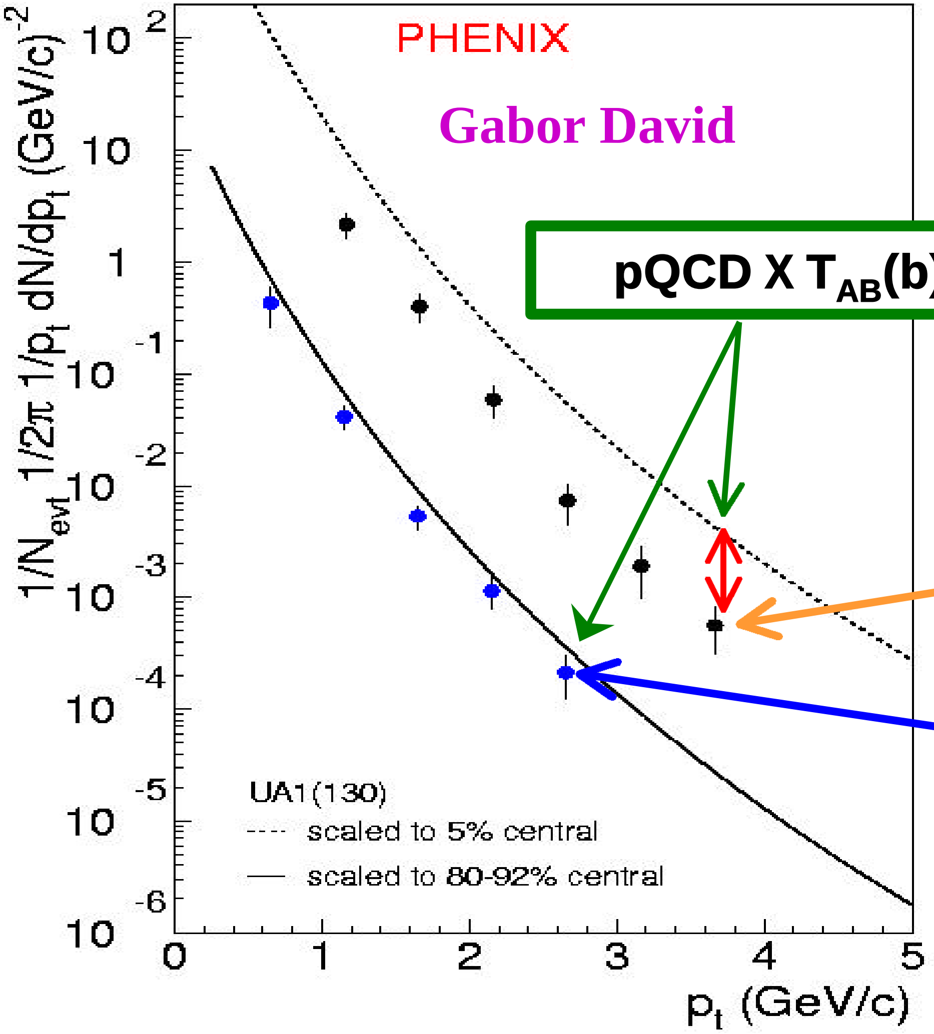


Summary Part 1:

1. **Elliptic collective flow is strongest evidence that**
    - **Local equilibrium may have been achieved**
    - **Hadron flavor dependence favors $P(T,m=0) \sim P_{QCD}$**
2. **Saturation for $p_T>2$ GeV at $v_2 \sim 0.15$ requires**
    - **very short mean free paths MPC**
    - ***or* strong radiative energy loss GLVW**
3. **Unsolved problem: HBT pion interferometry**
    - **decoupling space-time geometry disagrees with predictions of both hydro and transport**

Part II: The Jet Quenching Pattern at RHIC

Au +Au -> ^{0} + X at E_{cm}= 130 AGeV



pQCD X T_{AB}(b)

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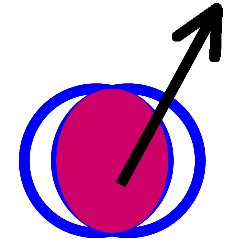
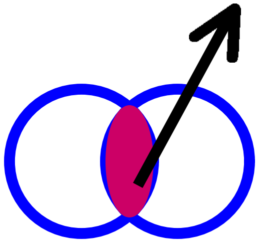
Central 10%



PHENIX

Peripheral 80-95%



Nuclear Modification Factor

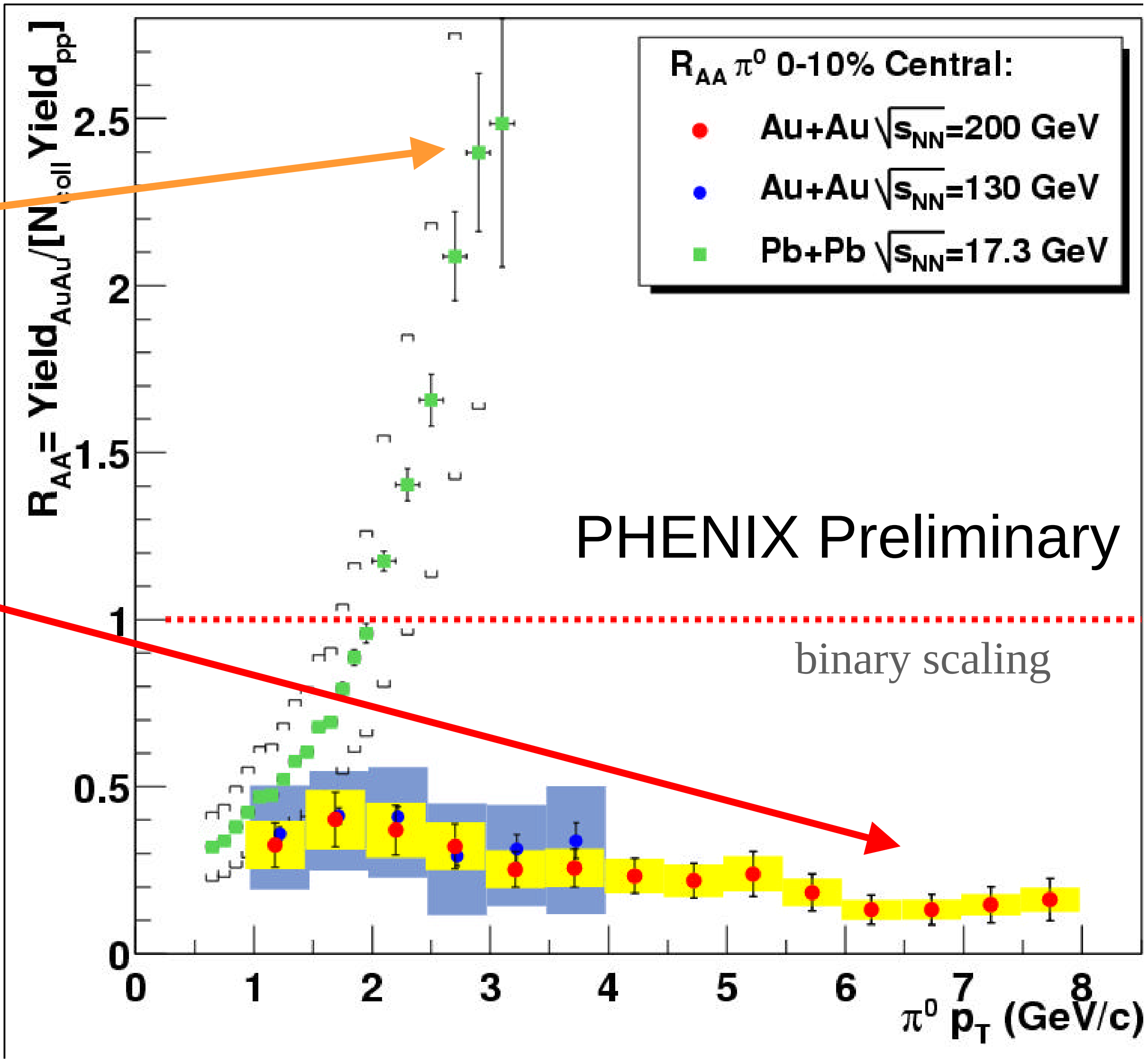
PHENIX

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

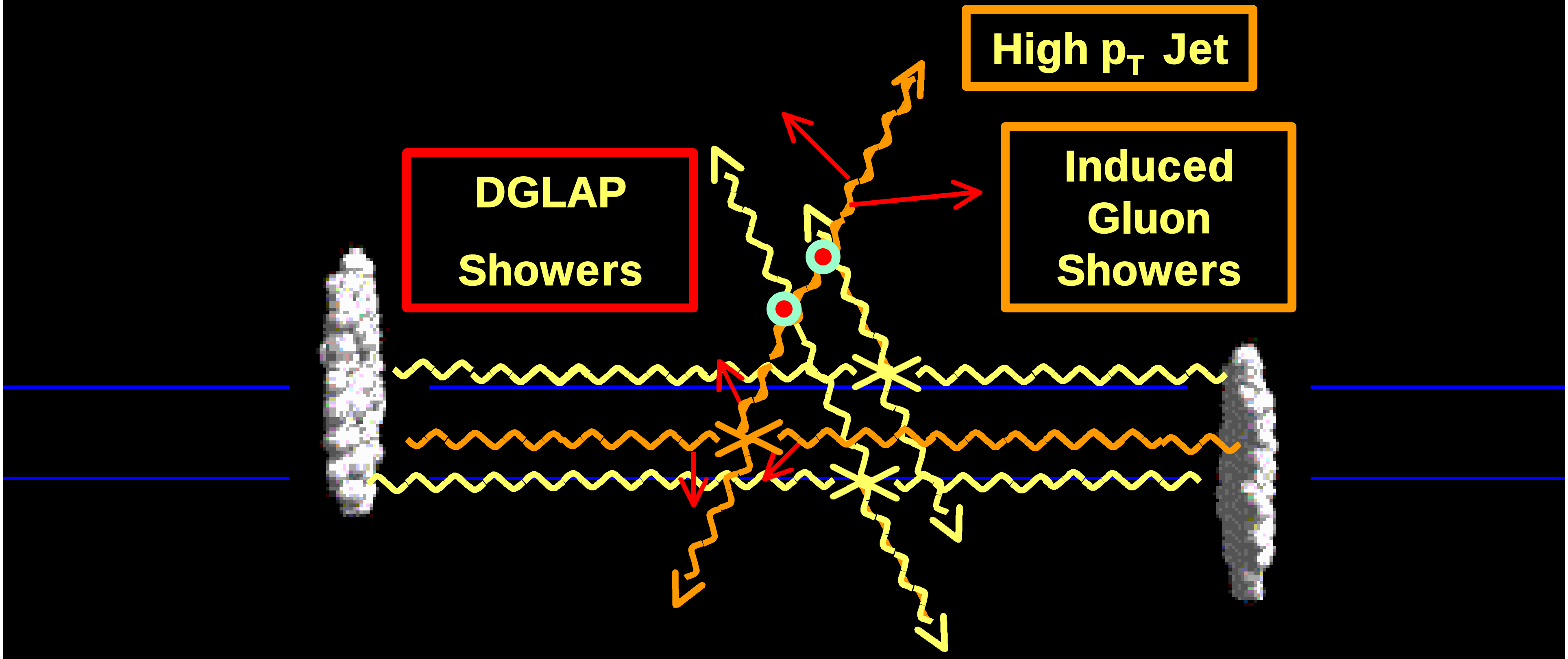
D. d’Enterria QM02

SPS – “Cronin” effect

RHIC – “Jet Quenching”



Final State Nuclear effects



High p_T Jet

DGLAP

Showers

Induced

Gluon

Showers

Jet Quenching $p^{Jet}_{final} = p^{Jet}_{in} - \Delta p_{DGLAP} - \Delta p_{Induced}$

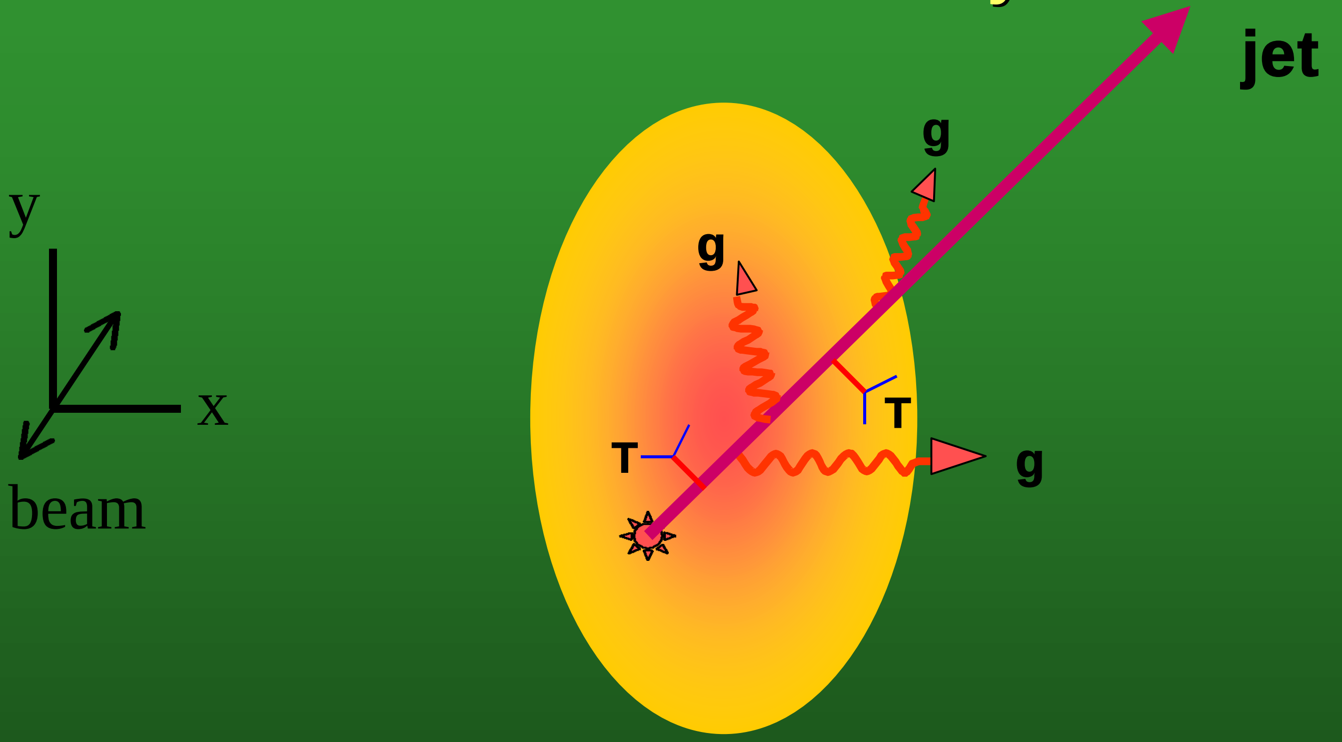
$Dp_{ind} : a_s \left\{ \frac{m^2}{l} \right\} R_A^2$

Strong Destructive

LPM Interference

Jet Tomography:

Using energy loss pattern to map out the matter density



$$\Delta E_{GLV} : C_2 C_A C_T \alpha_s^3 \ \mathrm{Ln}\frac{Q}{\mu^2 L} \int d\tau\, \tau\, \rho\left(\tau, r(\tau)\right)$$

Non-abelian Radiative Energy Loss

QCD Bethe-Heitler

QGP Multiple Collision

- G. Bertsch, F. Gunion, Phys. Rev. **D25** 746 (1982)
- M. Gyulassy, X.-N. Wang, Nucl. Phys. **B420** 583-614 (1994); Phys. Rev. **D51** 3436-3446 (1995)

“Thick” Plasma Limit

$$\Delta E = \alpha\sqrt{\omega_c E} \; : \; 10\,\mathrm{GeV}\left(\frac{L}{5\,\mathrm{fm}}\right)$$

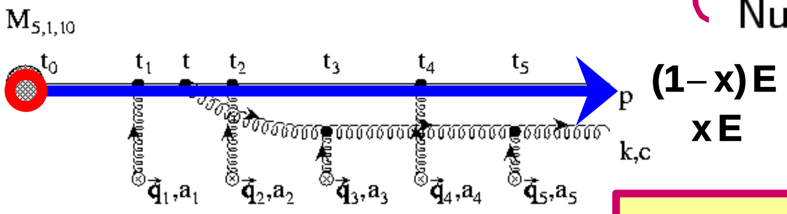
$$E < \omega_c = \left\langle \frac{q^2}{\lambda} \right\rangle \frac{L^2}{2} \approx 60\ \mathrm{GeV}$$

- R. Baier, Yu. Dokshitzer, A. Mueller, S. Peigne, D. Schiff, Nucl. Phys. **B483** 291-320 (1997); Phys. Rev. **C58** 1706-1713 (1998)
- B. Zakharov, JETP Lett. **65** 615-620 1997, JETP Lett. **73** 49-52 (2001)

“Thin” Plasma Limit

L/λ_g Opacity Expansion

- M. Gyulassy, P. Levai, **Ivan Vitev NPB 595** 371-419 (2001); Phys. Rev. Lett. **85** 5535-5538 (2000)
- U. Wiedemann, Nucl. Phys. **B588** 303-344 (2000), Nucl. Phys. **B582** 409-450 (2000)



1+1D expansion

$$\Delta E^{(1)} \; : \; C_2\alpha_s^3\,\frac{9\pi}{4}\left(\frac{1}{\pi R^2}\,\frac{dN_g}{dy}\right)\left\{\mathrm{Log}\,\frac{p_T}{\mu^2 R}\right\} R(\phi)$$

M.Gyulassy, DESY 9/27/02

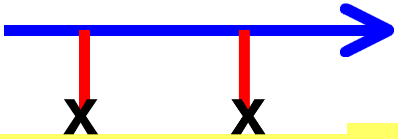
Gluon Double Differential Distributions to All Orders in Opacity

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 $m_i = gT_i$

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

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



$$\Delta z_k = z_k - z_{k-1} \sim \frac{L}{n+1}$$

LPM effect →

where

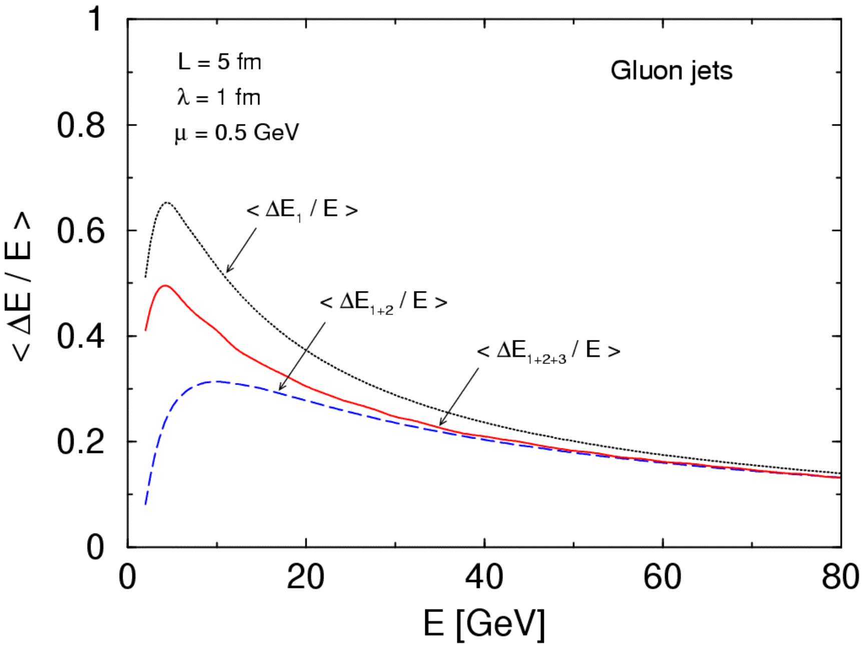
$$\omega_{(j,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q}_j-\cdots-\mathbf{q}_n)^2}{2xE}$$

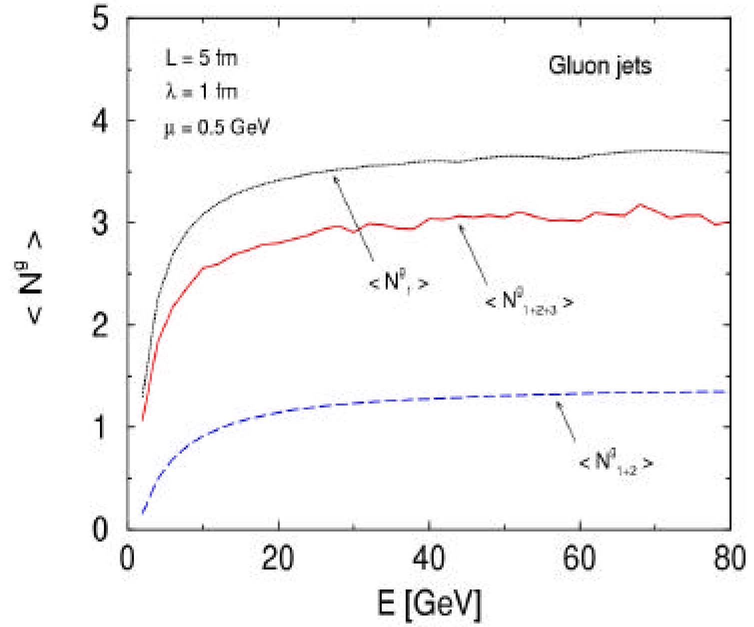
Inverse Formation Times

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

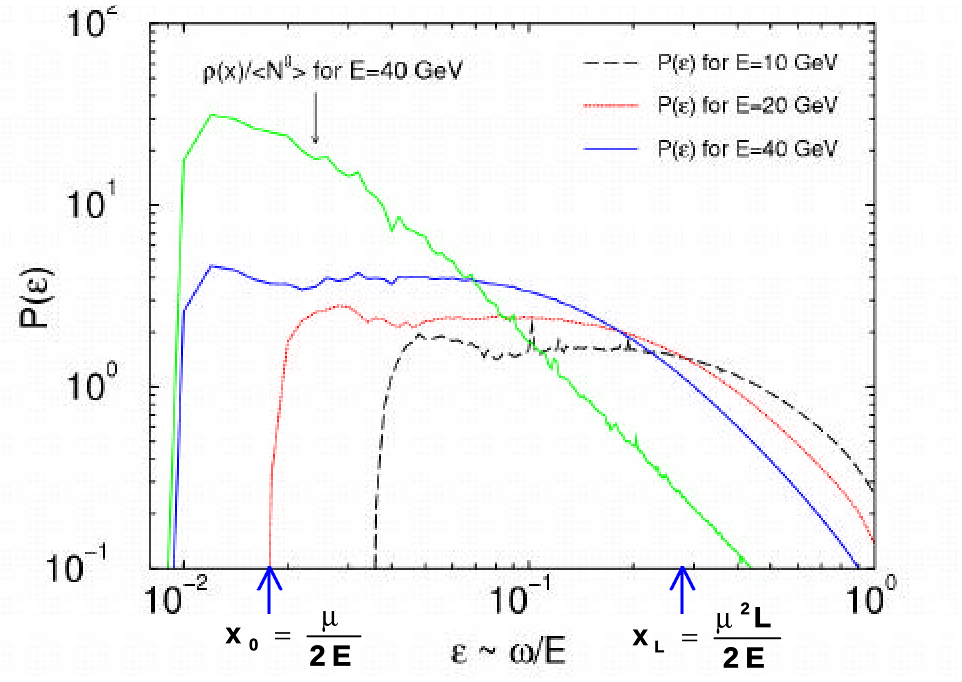
Scatt amplitudes

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





Rapid Convergence of Alternating Opacity Series



GLV:

M.Gyulassy, DESY 9/27/02

Quenched Single Hadron Spectrum

$$\frac{1}{G}\left\{\begin{array}{c}\dfrac{d\sigma^{dA}}{dyd^2\mathbf{p}_T}\\ \dfrac{dN^{AA}(b)}{dyd^2\mathbf{p}_T}\end{array}\right\} = K\sum_{abcd}\int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b \, g(\mathbf{k}_a)g(\mathbf{k}_b)$$
$$\times \, S_A(x_a,Q_a^2)S_B(x_b,Q_b^2)$$
$$\times \, f_{a/A}(x_a,Q_a^2)f_{b/B}(x_b,Q_b^2)\,\frac{d\sigma^{ab\to cd}}{d\hat{t}}$$
$$\times \int_0^1 d\epsilon \, P(\epsilon)\frac{z_c^*}{z_c}\frac{D_{h/c}(z_c^*,Q_c^2)}{\pi z_c} \, . \qquad (2)$$

In Eq.(2) x_a, x_b are the initial momentum fractions carried by the hard-scattered partons with probabilities sampled from the parton distribution functions (PDFs) $f_{\alpha/A}(x_\alpha,Q_\alpha^2)$. The momentum fraction carried away by the leading hadron $z_c = p_h/p_c$ is sampled from the fragmentation functions (FFs) $D_{h/c}(z_c,Q_c^2)$. We use

$$\boxed{z = p_h/p_c \to z^* = z/(1-\epsilon).}$$

to include medium induced energy loss

geometry $G = \begin{cases} 2A & \text{for } d\sigma^h \text{ in } d+A \\ T_{AA}(b) & \text{for } dN^h \text{ in } A+A \end{cases}$

Intrinsic kT + Nuclear Cronin

$$\boxed{\left\langle k_\wedge^2 \right\rangle_{pA} = \left\langle k_\wedge^2 \right\rangle_{pp} + L\,\frac{m^2}{l}\log(1+\frac{p_\wedge^2}{5})}$$

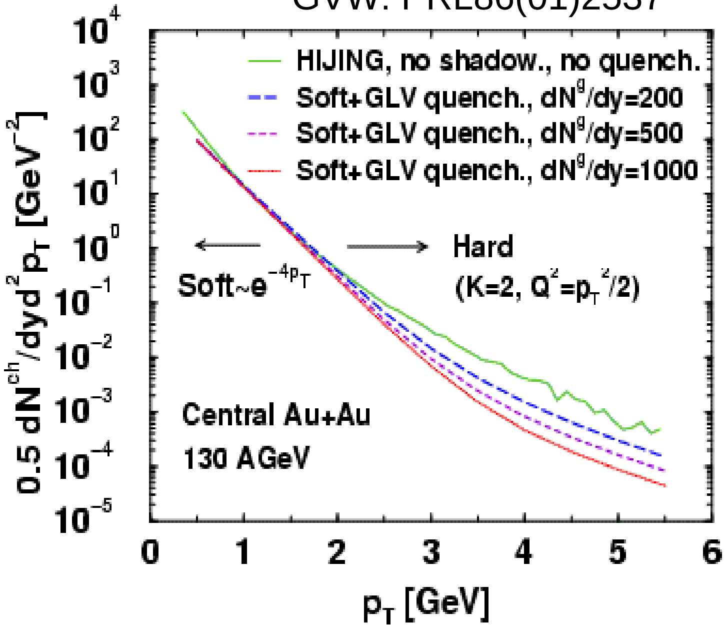
EKS98 shadow/EMC S_A

GRV98 pdf

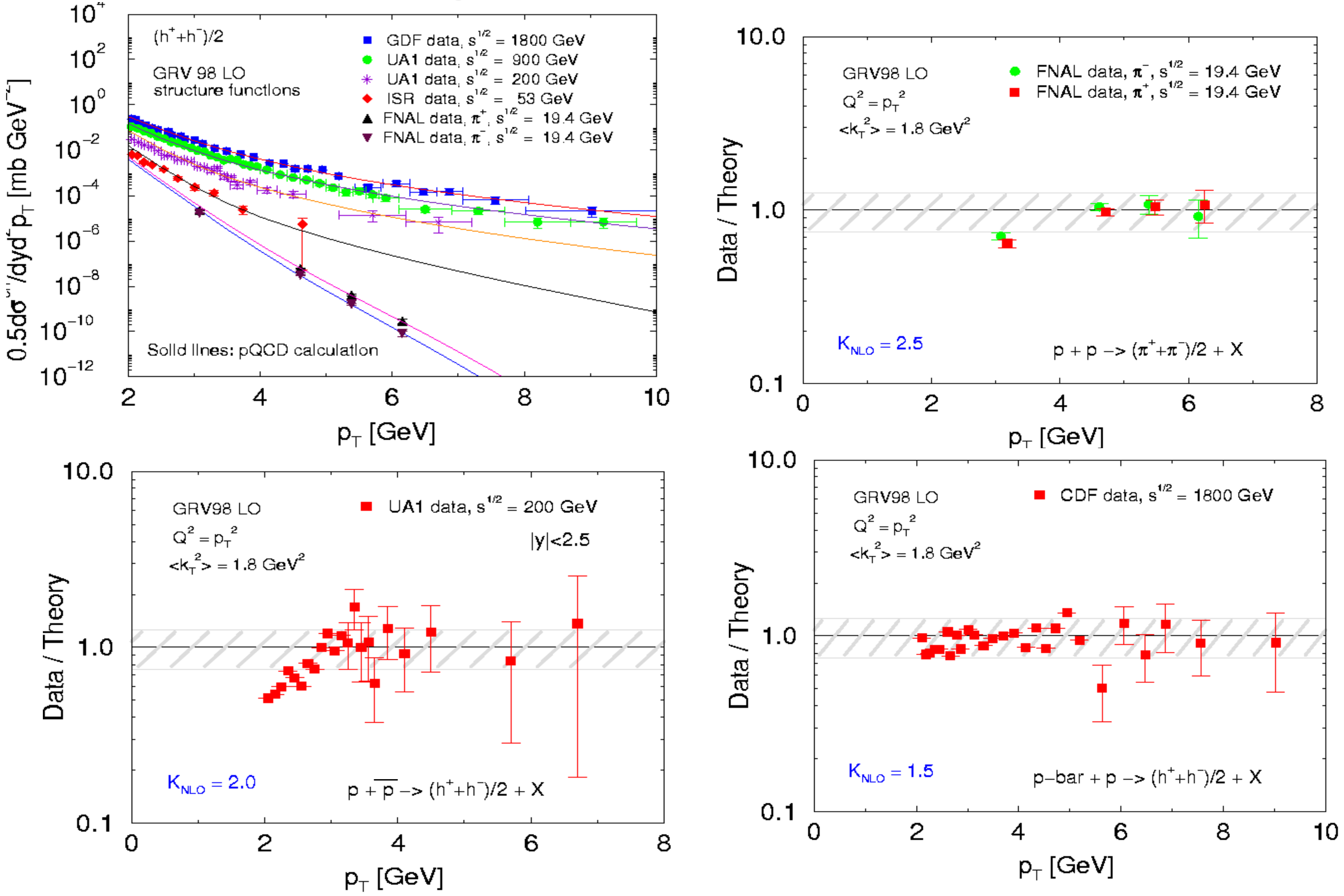
BKK ff

P(e) from GLV

GVW: PRL86(01)2537



Tuning K to Nucleon-Nucleon



Error bands: ± 25%

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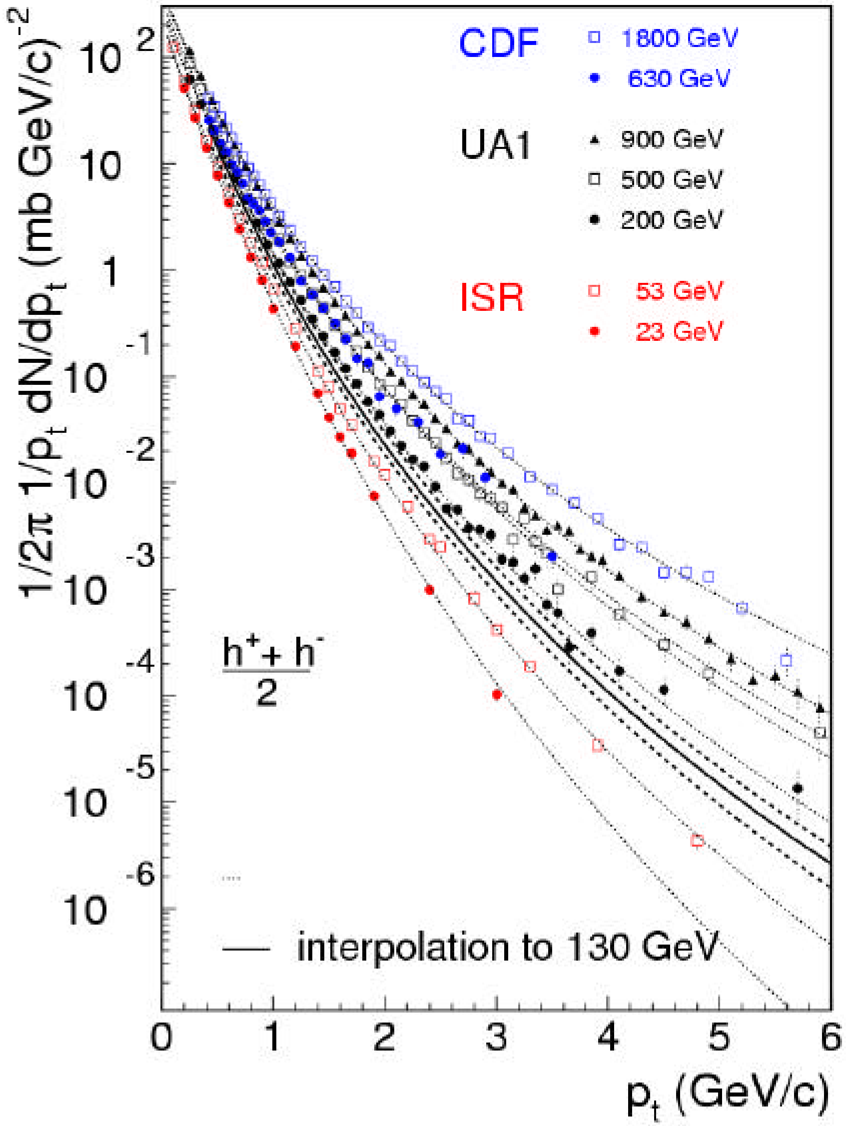
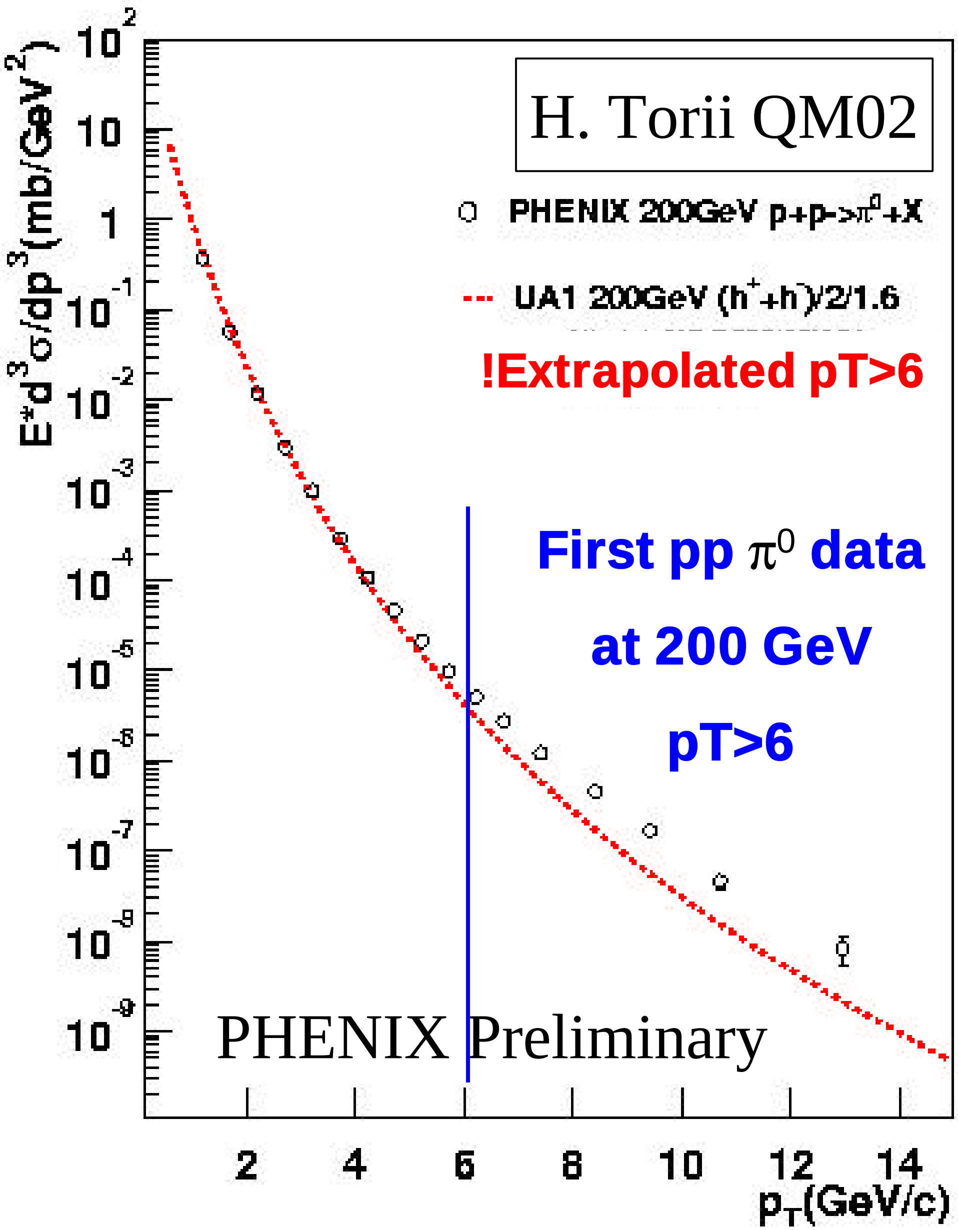
p+p ->h^{ch}

Baseline

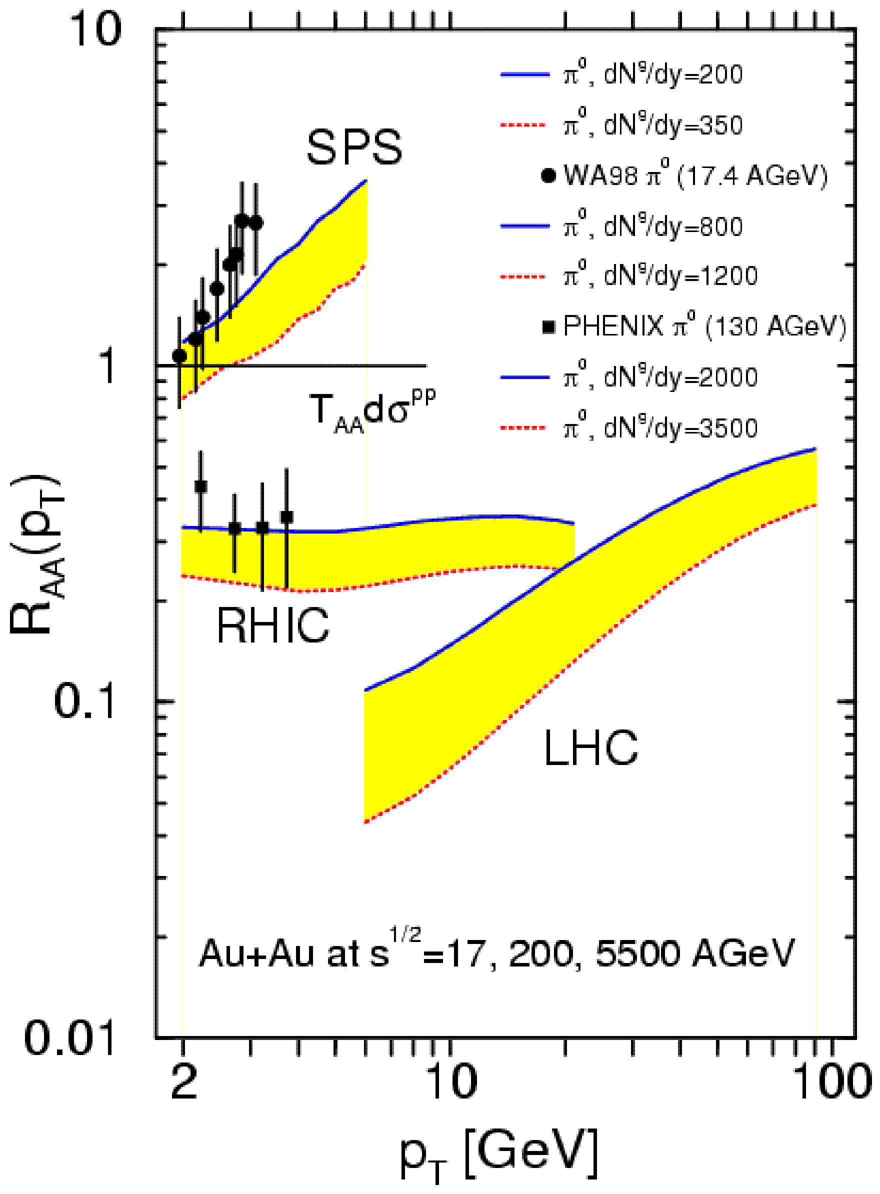


pp->π^0 data



Single Hadron Tomography from SPS, RHIC, LHC

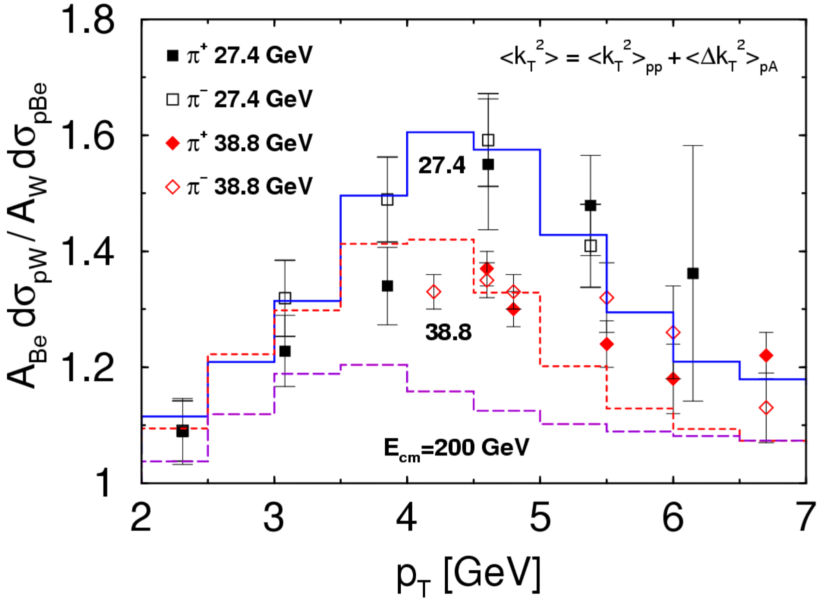
I. Vitev, MG, hep-ph/0209161

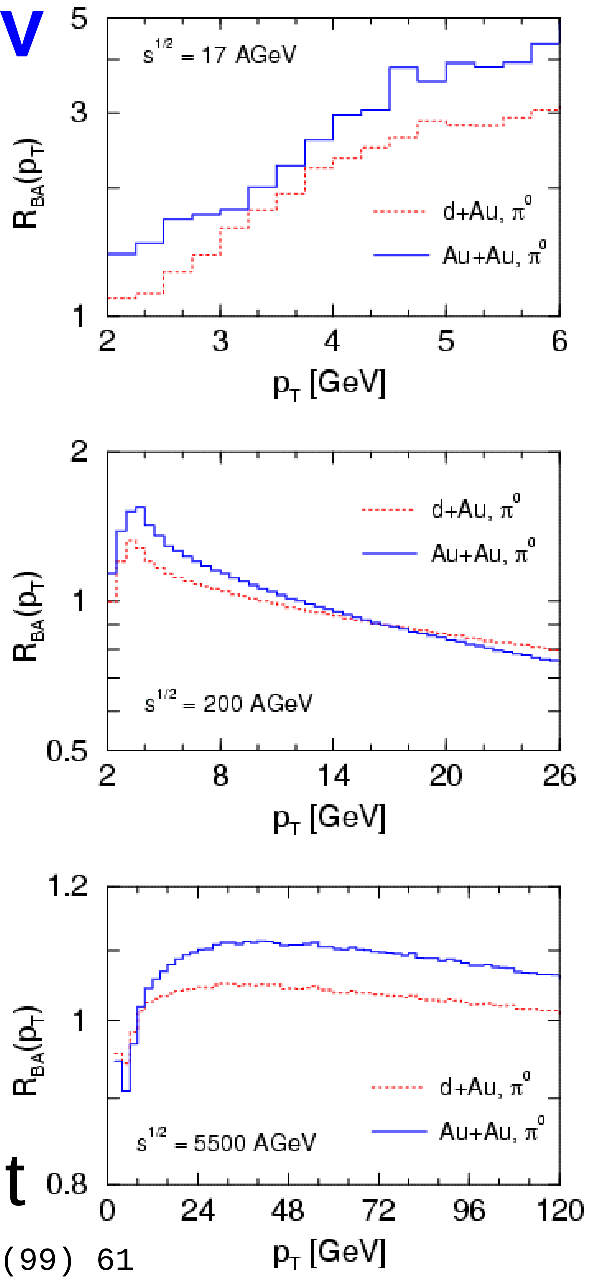


1. **Dominance of Cronin at 20 AGeV**
2. **Cronin+Quench+Shadow conspire to give flat suppression out to highest pT at RHIC with $R \sim N_{part}/N_{bin}$**
3. **Predicts below N_{part} quench, positive pT slope of R at LHC and $R_{LHC}(40) \sim R_{RHIC}(40)$**

Test of Cronin vs Shadow/Anti-Shad/EMC in p,d+Au 20,200, 5500 AGeV

I. Vitev, MG, hep-ph/0209161





Tests two key assumptions:

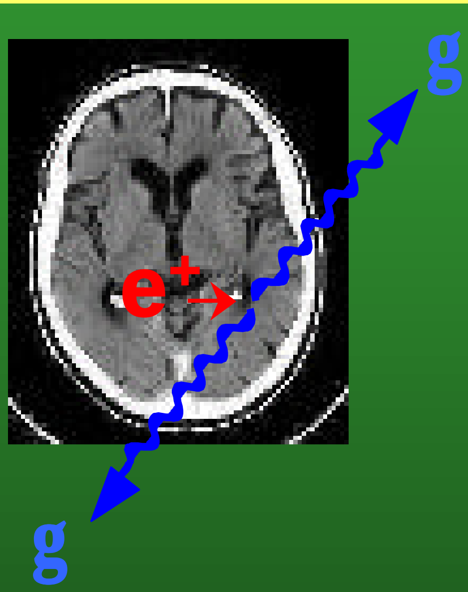
1. $\left(\frac{\mu^2}{\lambda} \right)_{\text{cold A}} \approx 0.05 \frac{\text{GeV}^2}{\text{fm}}$

2. EKS98 glue shadow/EMC fit

K.J.Eskola,V.J. Kolhinen,C.A. Salgado, Eur. PJC 1 (99) 61

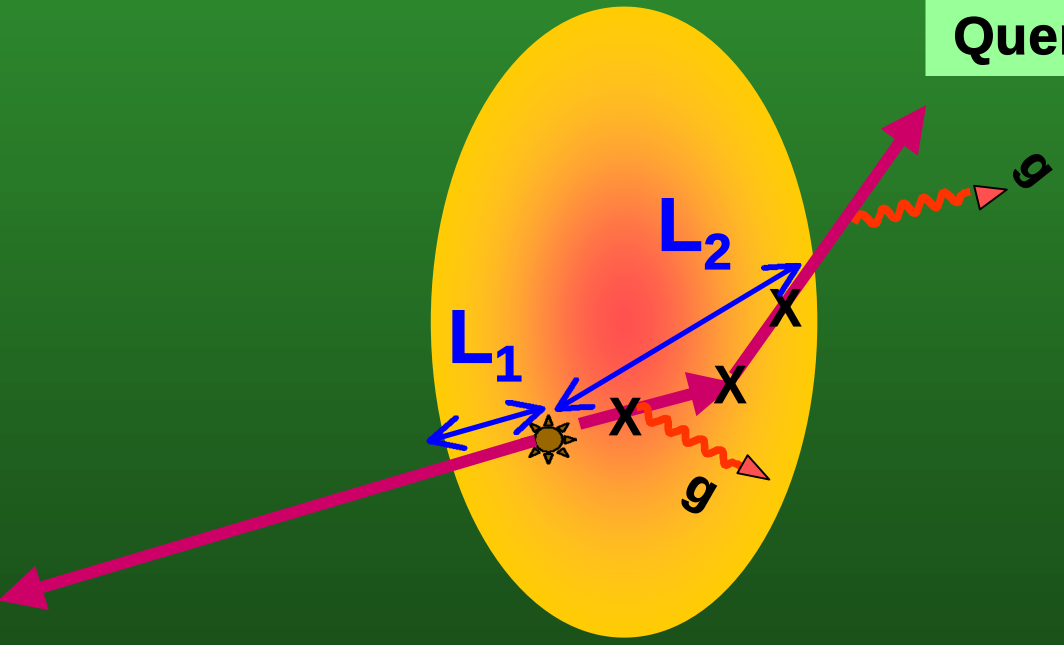
Correlated Two particle or Di-Jet Tomography

e^+e^- ->gg Tomography



Di-Jet Tomography

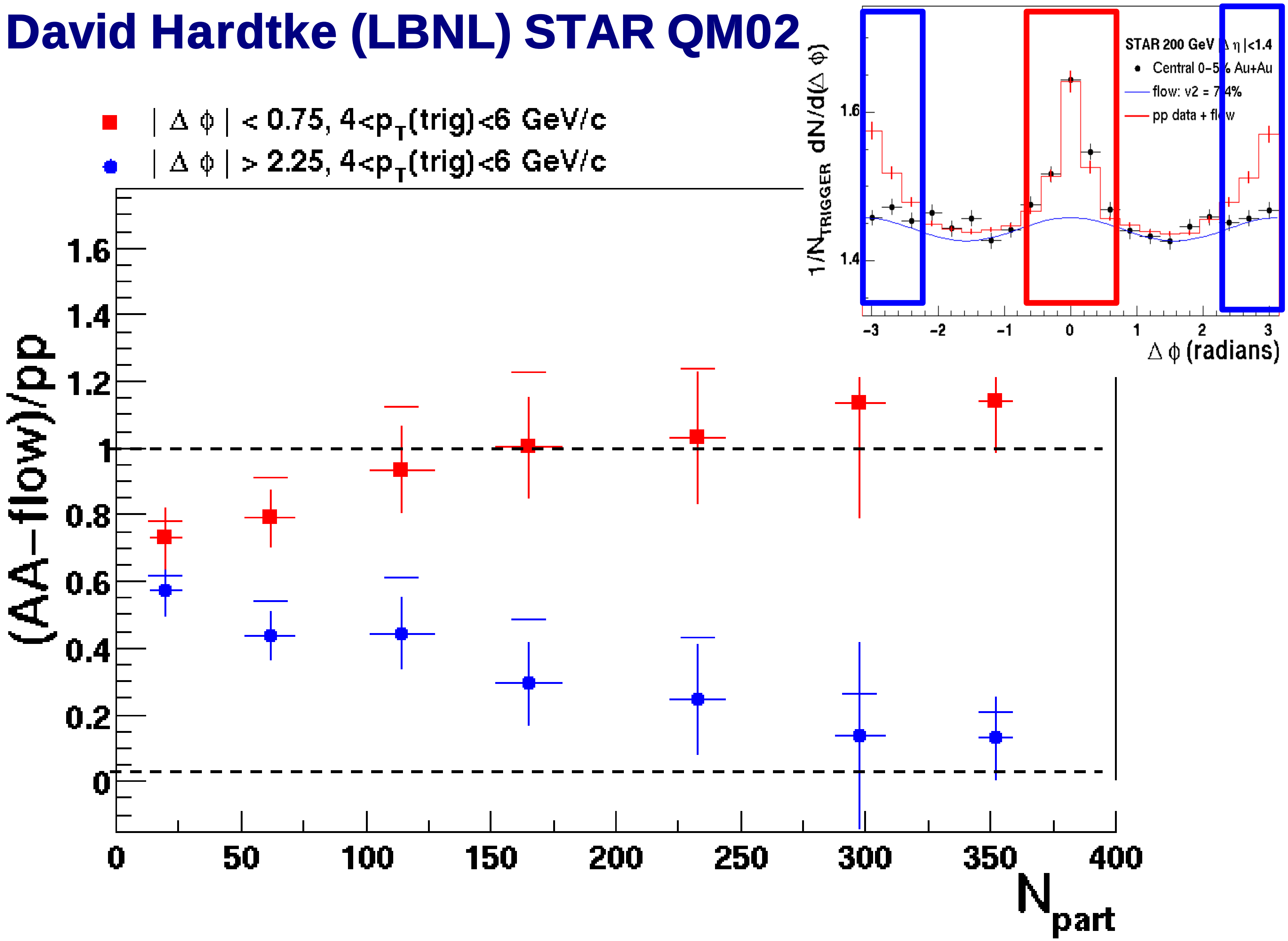
Acoplaner Quenched jet



High p_T "Mono"- jet

$$\Delta E : \alpha_s \frac{\mu^2}{\lambda_g} L_i^2 \quad , \quad \langle \Delta p_\perp^2 \rangle \sim \frac{\mu^2}{\lambda_g} L_i \quad , \quad i = 1,2$$

David Hardtke (LBNL) STAR QM02



Summary

1. **Global dN/dy(s,N_{part}) consistent with gluon showers 200<dN_g/dy<1000 at RHIC**

2. **Strong *Final State* Collectivity $v_2(p_T)$ Observed**

   is strongest constraint yet on QCD equation of state

1. **Factor ~3 Suppression of p_T>2GeV pions**

   Tomography via Jet Quench --> dN_g/dy~500-1000)

1. **First RHIC dijet systematics reported at QM02**
   will provide a new 10 dim probe of AA dynamics soon

Puzzles

1. **Gluon shadowing? Cronin? (need d+A 2003)**

2. **Is there Q_{sat}~1 GeV gluon saturation at RHIC?**

3. **Pion Interferometry puzzling R_{out}<R_{side} ?**