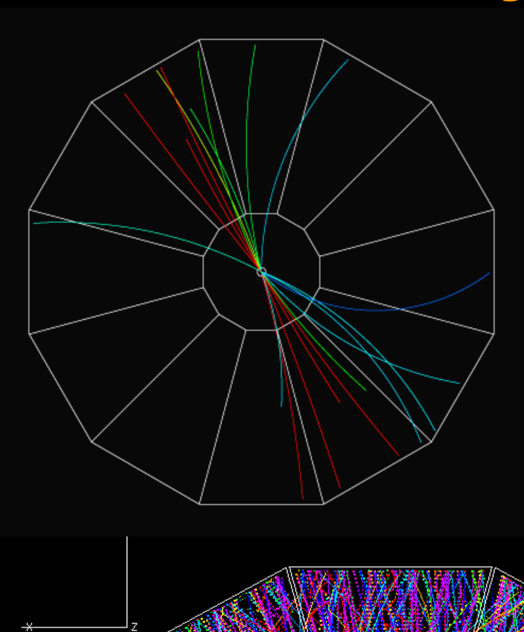
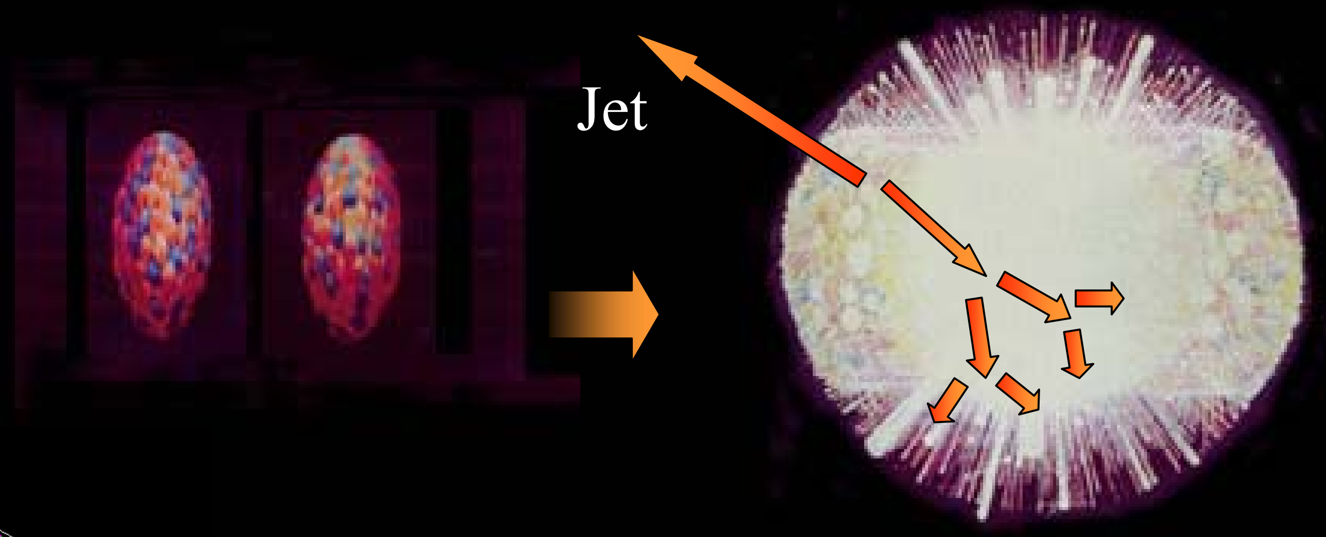
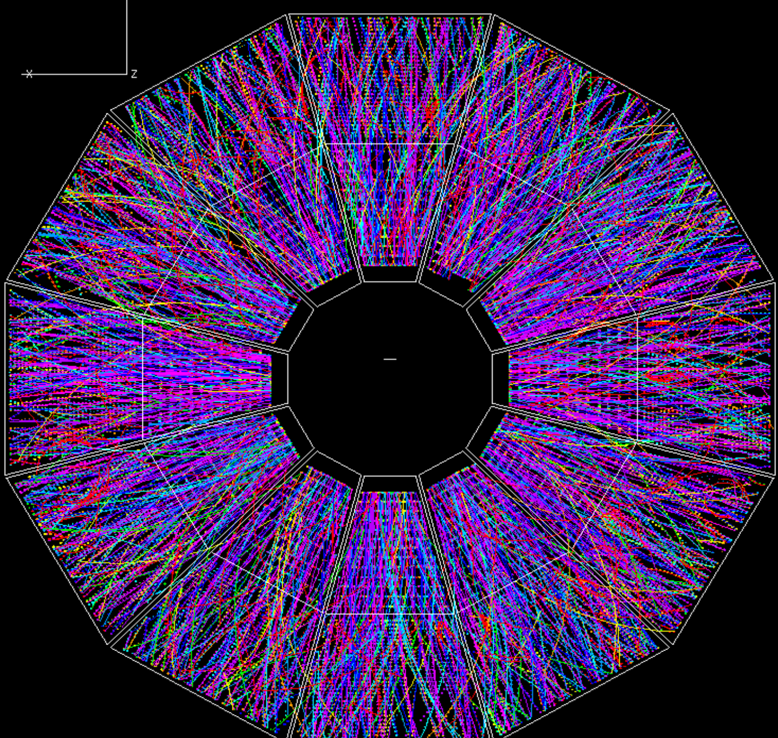
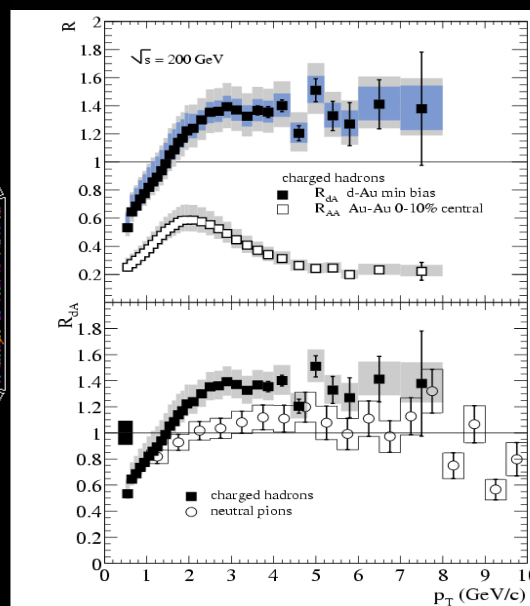
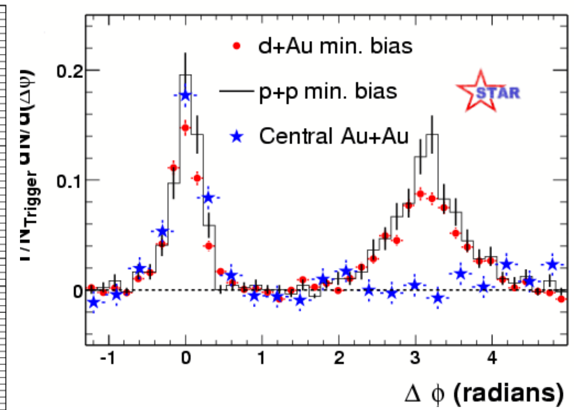
Discovery of Jet Quenching and Beyond











Xin-Nian Wang
LBNL, May 15, 04

Discovery of Jet Quenching and Beyond

RBRC Workshop on: New Discoveries at RHIC

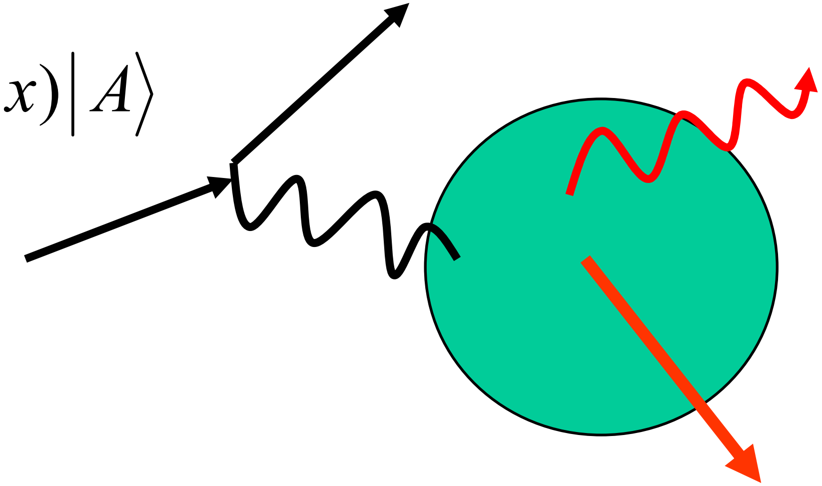
BNL/RIKEN, May 15, 2004

- Introduction: Jet Quenching
- Single hadron: Jet quenching and initial effects
- Dihadron: Modified fragmentation function
- Why the observed energy loss is partonic?
- Beyond the discovery of jet quenching

Xin-Nian Wang (LBNL)

Jet Tomography

$$W_{\mu\nu}(q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x} \langle A | j_\mu^{em}(0) j_\nu^{em}(x) | A \rangle$$



$$W_{DIS}^{\mu\nu} \equiv -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) F_1(x_B) + \frac{1}{p\cdot q}\left(p^\mu - \frac{p\cdot q}{q^2} q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2} q^\nu\right) F_2(x_B)$$

$$x_B = -\frac{q^2}{2p\cdot q}$$

Dynamic System: Photon or dilepton emission

J/Ψ suppression

QCD Response: $j_\mu^{em}(x) \rightarrow j_\mu(x)$ Quark scattering

A Chronicle of Jet Quenching

- 1982, Bjorken (unpublished): elastic dE/dx too small
- 1990,Gyulassy, Pluemer: Evoking inelastic dE/dx
- 1992, Gyulassy, XNW: Suppression of leading hadrons due to jet quenching
- 1994, Gyulassy, XNW: First calculation of radiative parton energy loss with LPM
- 1995, Gyulassy, Pluemer, XNW: Estimate of mono-jet rate in AA at RHIC
- 1996, Huang, Sarcevic, XNW: Medium modified fragmentation function & gamma tagged jet quenching
- 1996, Zakharov: Path integral formulation of dE/dx
- 1997, Baier et al: non-abelian LPM in QCD- interaction with gluonic clouds

A Chronicle- Con' d

- 2000, XNW: First estimate of Cronin at RHIC
- 2000, Gyulassy, Levai, Vitev: Opacity expansion I.
- 2001, Wiedemann: Opacity expansion II
- 2001, Guo, XNW: Higher-Twist expansion and calculation of modified frag. function.
- 2001, XNW, GVW: high p_T v_2 due to jet quenching
- 2002: Suppression of high p_T hadron in Au+Au
- 2003: v_2 at high pt observed
- 2003: Suppression of back-side jet
- 2003, June 18: d+Au results announced
- 2004, azimuthal dependence of away-side jet

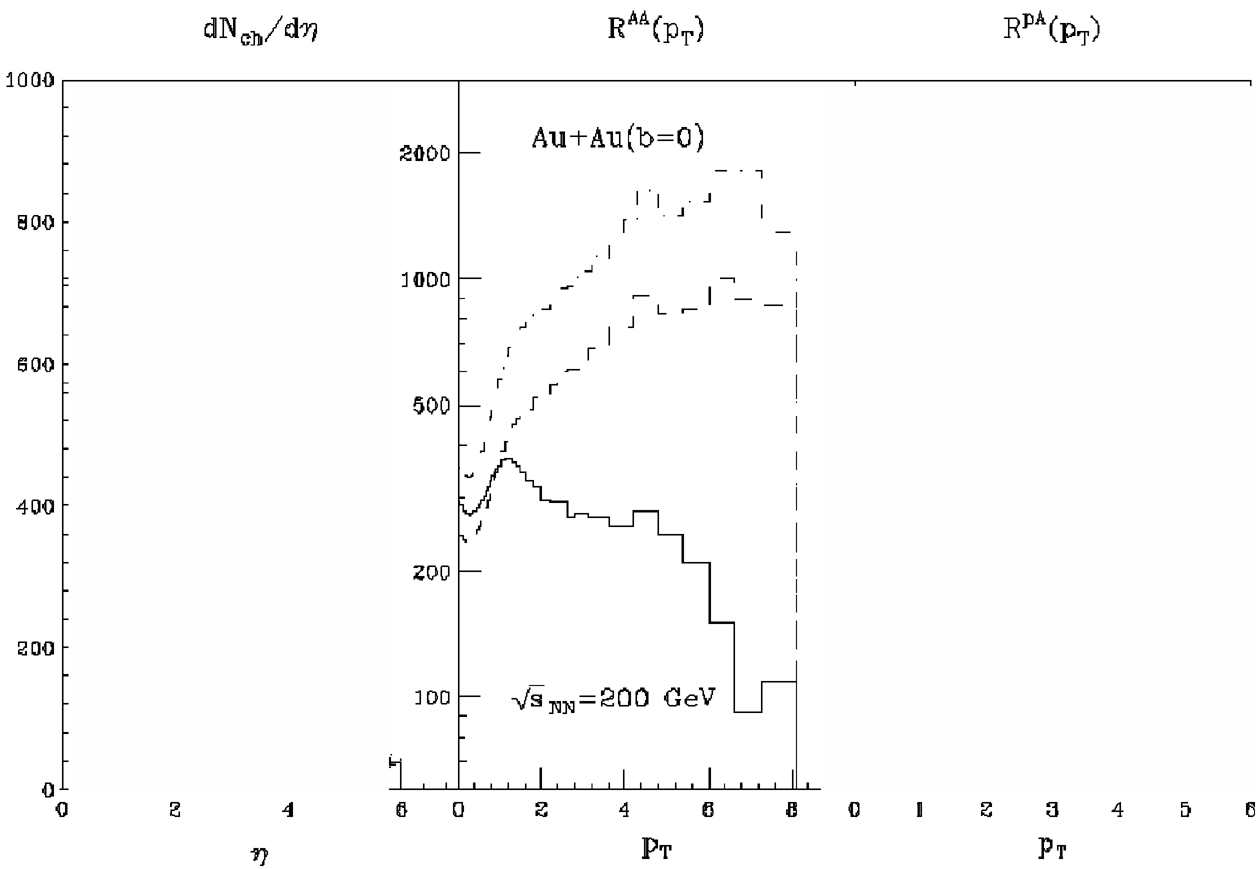
Jet Quenching

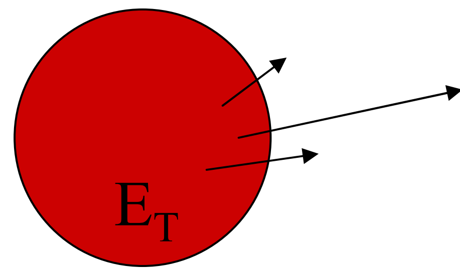
- Jet Quenching – Suppression of high p_T jet in dense medium
- Experimentally:
  - Medium modification of jet fragmentation function (FF)
  - Suppression of the leading hadrons in FF
- Theoretically:
  - Parton energy loss before hadronization
  - Or absorption of leading hadrons from jets

Single Spectra Suppression

Phys. Rev. Lett. **68**, 1480 (1992) **XNW and M. Gyulassy**

Gluon Shadowing and Jet Quenching in A+A Collisions at \sqrt{s}=200 AGeV





Away-side suppression or Mono-jet

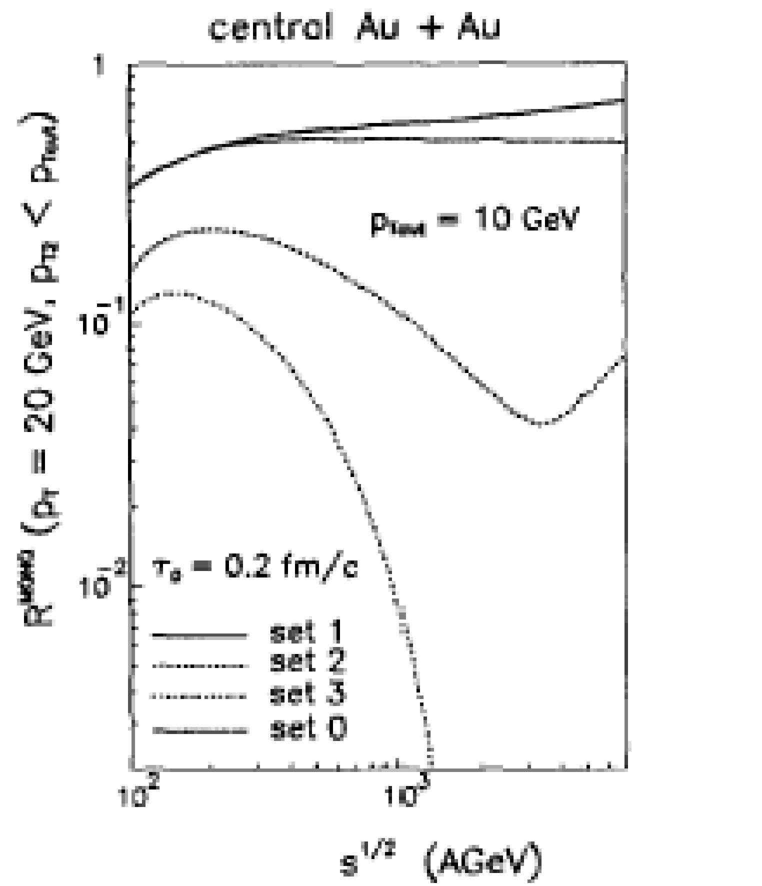
ELSEVIER

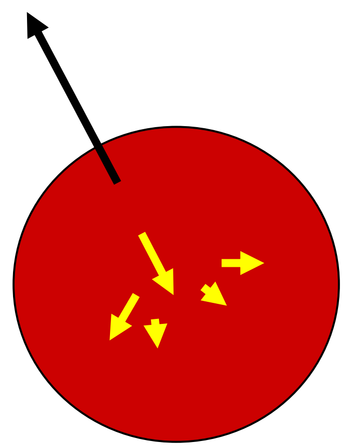
Nuclear Physics A590 (1995) 511c-514c

NUCLEAR PHYSICS A

Jet Quenching and Monojet Rates in Ultrarelativistic Nucleus-Nucleus Collisions*

M. Plümer[a], M. Gyulassy[b] and X.N. Wang[c]

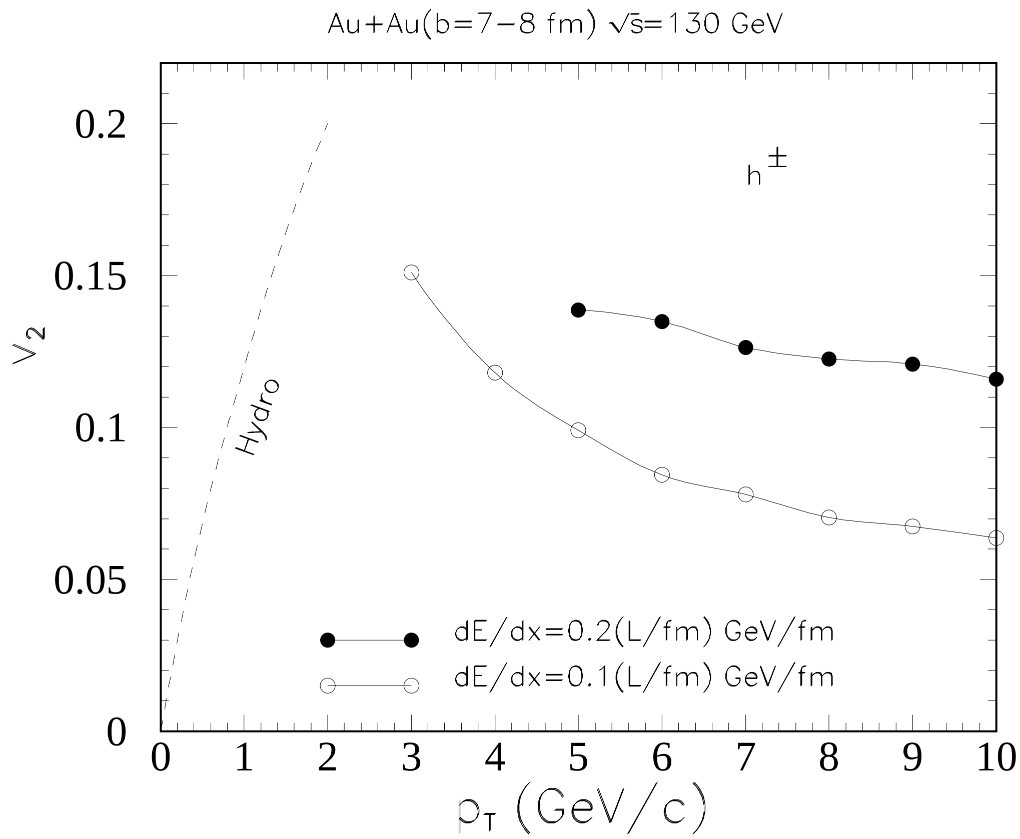


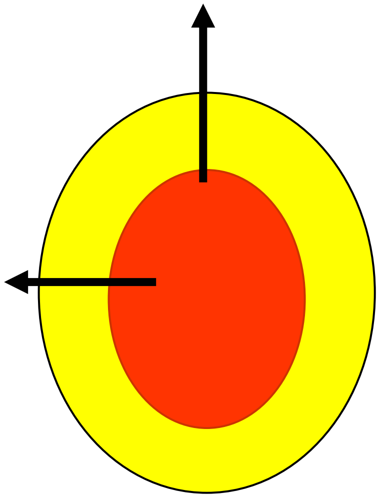


Azimuthal Anisotropy

Phys. Rev. C **63**, 054902 (2001) **XNW**

Jet Quenching and Azimuthal Anisotropy of Large p_T Spectra in Non-central High-energy Heavy-ion Collisions

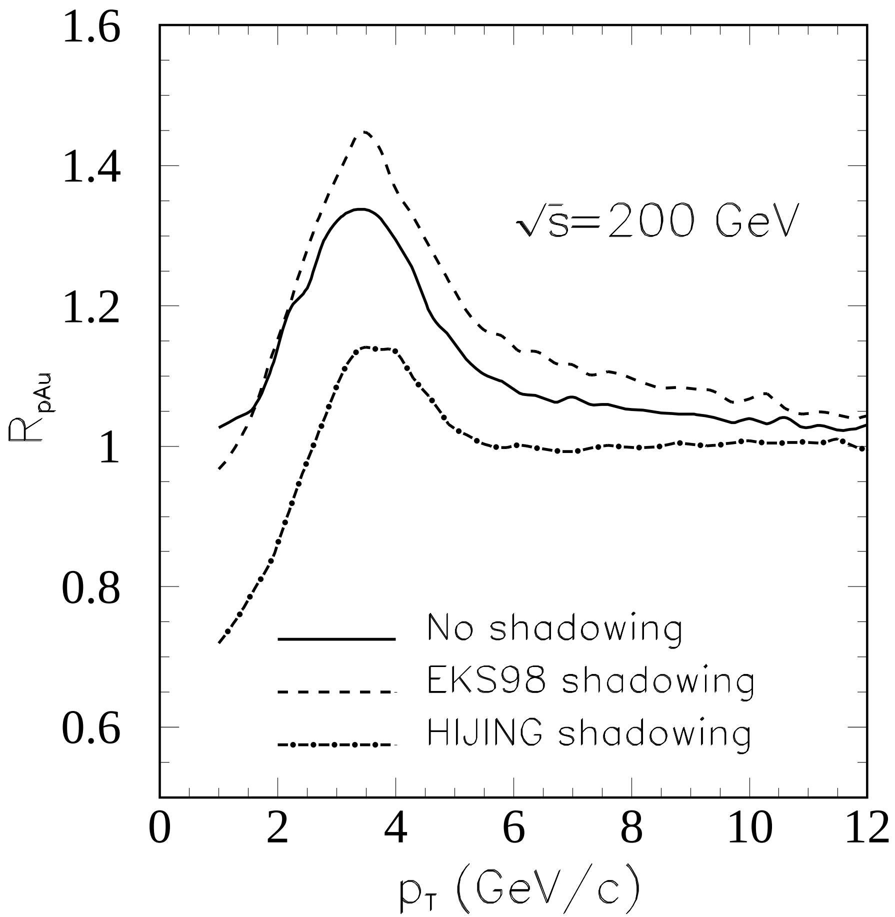


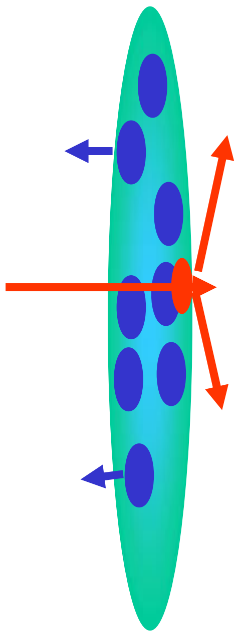


Non-suppression in p+A

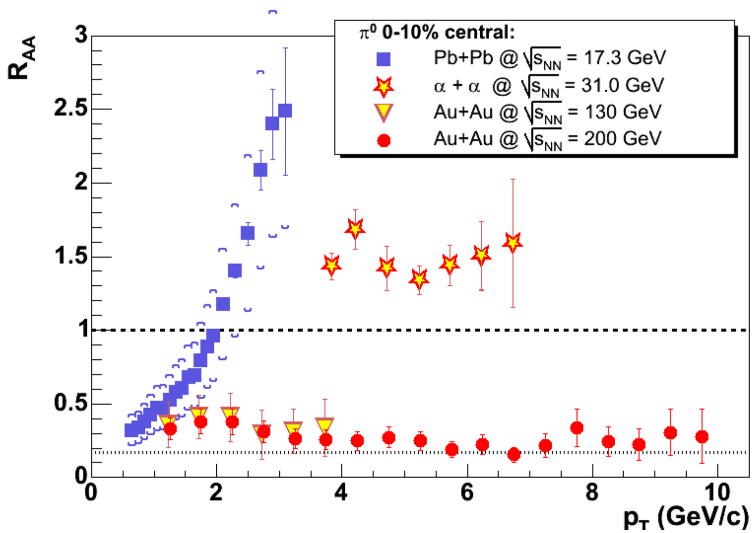
Systematic study of high p(T) hadron spectra in p p, p A and A A collisions from SPS to RHIC energies

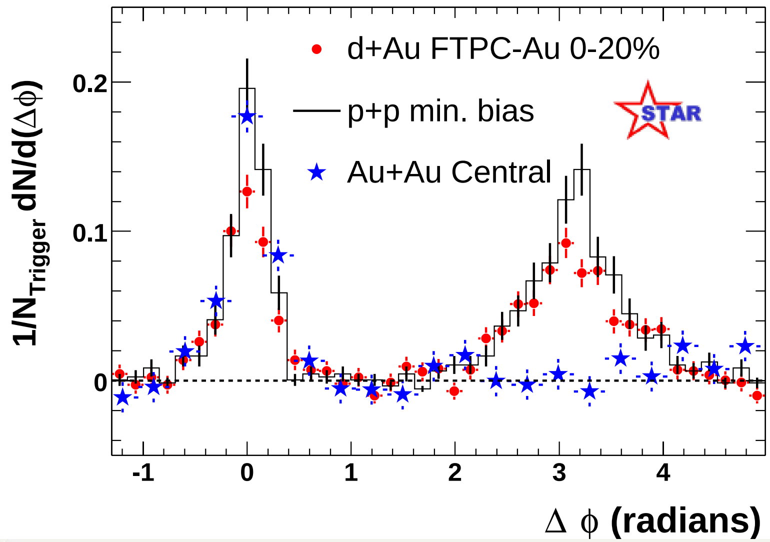
Phys. Rev. C **61**, 064910 (2000) hep-ph/9812021, XNW

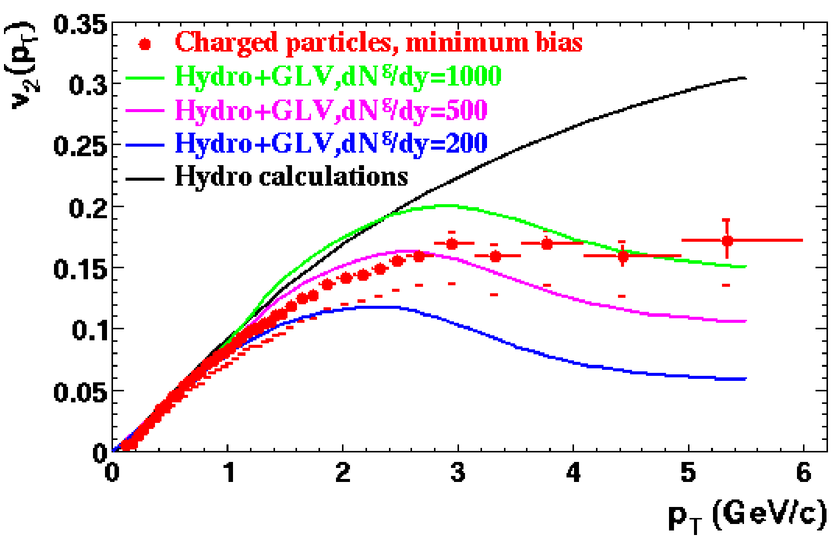


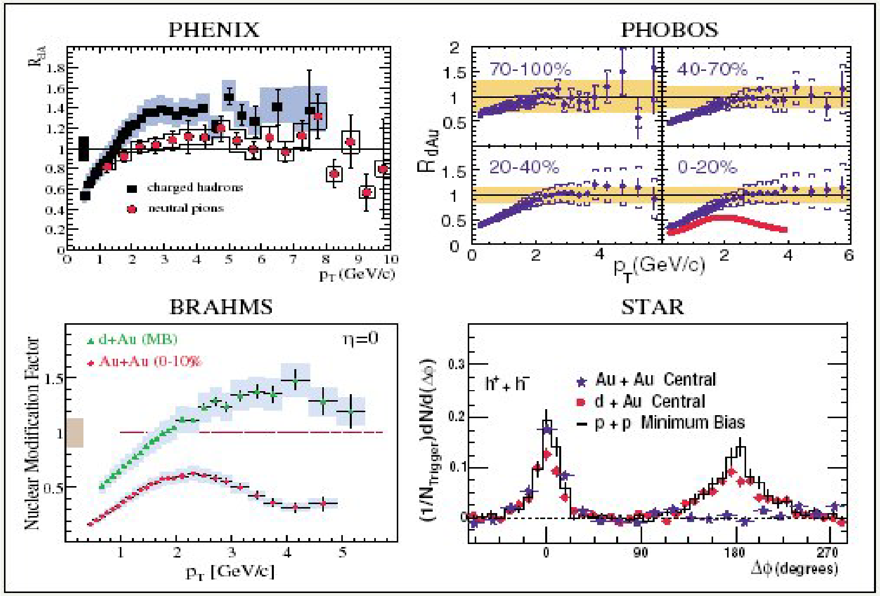


Experimental Evidence

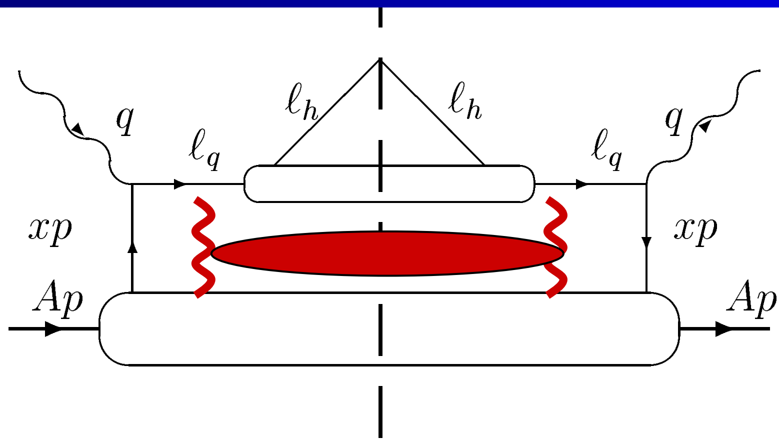




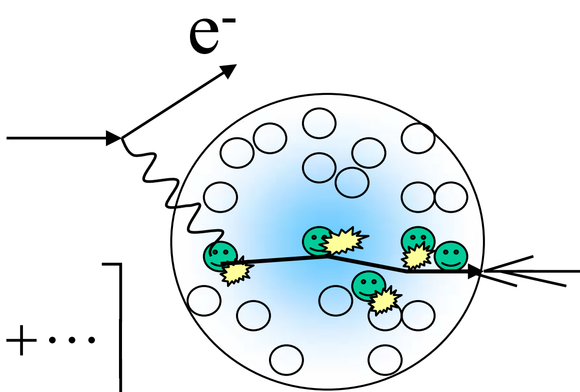




Modified Fragmentation Function



$$\tilde{D}(z_h,Q^2)=D(z_h,Q^2)+\Delta D(z_h,Q^2)$$



$$\Delta D_{q\to h}(z_h,Q^2)=\frac{\alpha_S}{2\pi}\int_0^{Q^2}\frac{d\ell_\perp^2}{\ell_\perp^4}\int_{z_h}^{1}\frac{dz}{z}\left[\Delta\gamma(z,x_L)D_{q\to h}\left(\frac{z_h}{z}\right)+\cdots\right]$$

Modified splitting functions

Guo & XNW'00

$$\Delta\gamma(z,x_L)=\frac{1+z^2}{(1-z)_+}\frac{C_A 2\pi\alpha_S}{N_c}\frac{T_{qg}^A(x,x_L)}{f_q^A(x)}+\cdots(\text{virtual})$$

Quark energy loss = energy carried by radiated gluon

Two-parton correlation:

$$T_{qg}^{A}(x,x_L)=\int\frac{dy^-}{2\pi}dy_1^-dy_2^-e^{-ix_Bp^+y^-}\left\langle A\right|\bar{\psi}(0)\frac{\gamma^+}{2}\psi(y^-)F_\sigma^+(y_1^-)F^{+\sigma}(y_2^-)\left|A\right\rangle\theta(y^--y_1^-)$$

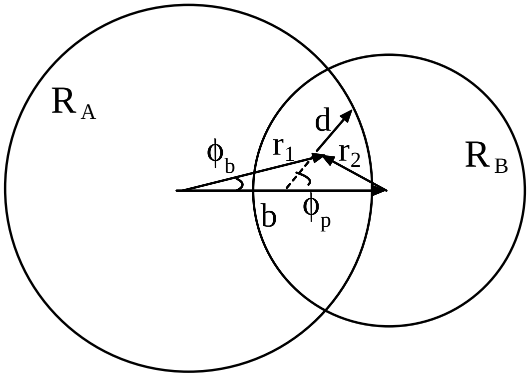
$$\times\left(1-e^{-ix_Lp^+y_2^-}\right)\left(1-e^{ix_Lp^+(y_1^--y^-)}\right)\theta(-y_2^-)$$

$$\frac{T_{qg}^{A}(x,x_L)}{f_q^A(x)}\sim\int dy\mu^2\sigma_g\rho(y)\left[1-\cos\frac{y}{\tau_f}\right]$$

$$\Delta E=\pi C_aC_A\alpha_s^3\int_{\tau_0}^{R}d\tau\rho(\tau)(\tau-\tau_0)\ln\left(\frac{2E}{\tau\mu^2}\right)$$

BDPM
Gyulassy Vitev Levai
Wang & Wang
Wiedemann; Zakharov

Single spectra in A+A collisions



$$\Delta E(b,r,\phi) = \left\langle \frac{dE}{dx} \right\rangle_{1d} \int_{\tau_0}^{\tau_0+\Delta L} d\tau \frac{\tau-\tau_0}{\tau_0\rho_0} \rho(\tau, b, \vec{r}+\vec{n}\tau)$$

$$\rho(\tau,b,r) = \frac{\tau_0\rho_0}{\tau} n_{part}(b,r)$$

Participant Density

Single spectra

$$\frac{d\sigma_{AB}}{dy d^2 p_T} = K \int d^2 b \int d^2 r_1 d^2 r_2 t_A(r_1) t_B(r_2) \sum_{abcd} \int dx_a d^2 k_{\perp a} dx_b d^2 k_{\perp b}$$
$$f_{a/A}(x_a, k_{\perp a}, r_1) f_{b/B}(x_b, k_{\perp b}, r_2) \frac{d\sigma_{ab\to cd}}{dt} \frac{1}{z_c \pi} D_{h/c}(z_c)$$

Dihadron spectra

$$\frac{D_{h/c}(z_c, \Delta E_c)}{z_c^2} \frac{D_{h/d}(z_d, \Delta E_d)}{z_d^2}$$

Nuclear Modification Factor

$$R^{AB} = \frac{\sigma_{AB}}{\langle N_{\text{binary}} \rangle_{AB} \langle \sigma_{NN} \rangle}$$

$$\langle N \rangle_{bin} \equiv \int d^2 b T_{AB}(b)$$

Wang&Wang 2001

Initial state effect: Shadowing & pt broadening: XNW, PRC61(00)064910

Fai, Papp, and Levai (02)

Vitev & Gyulassy (02)

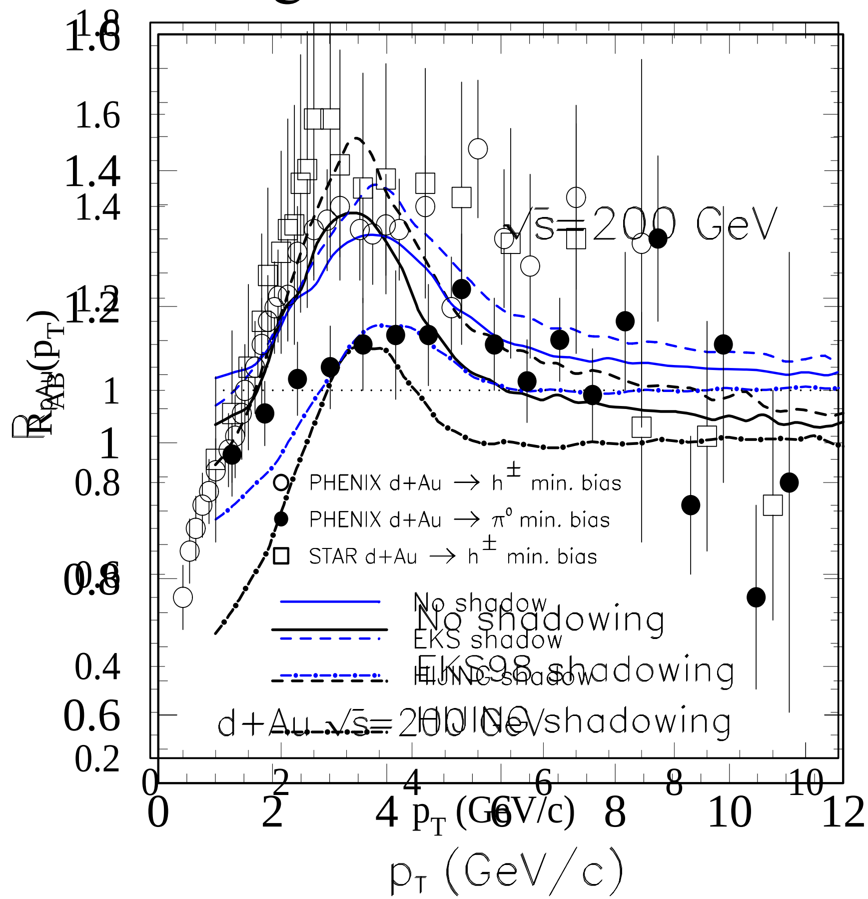
Vitev (03)

LP model

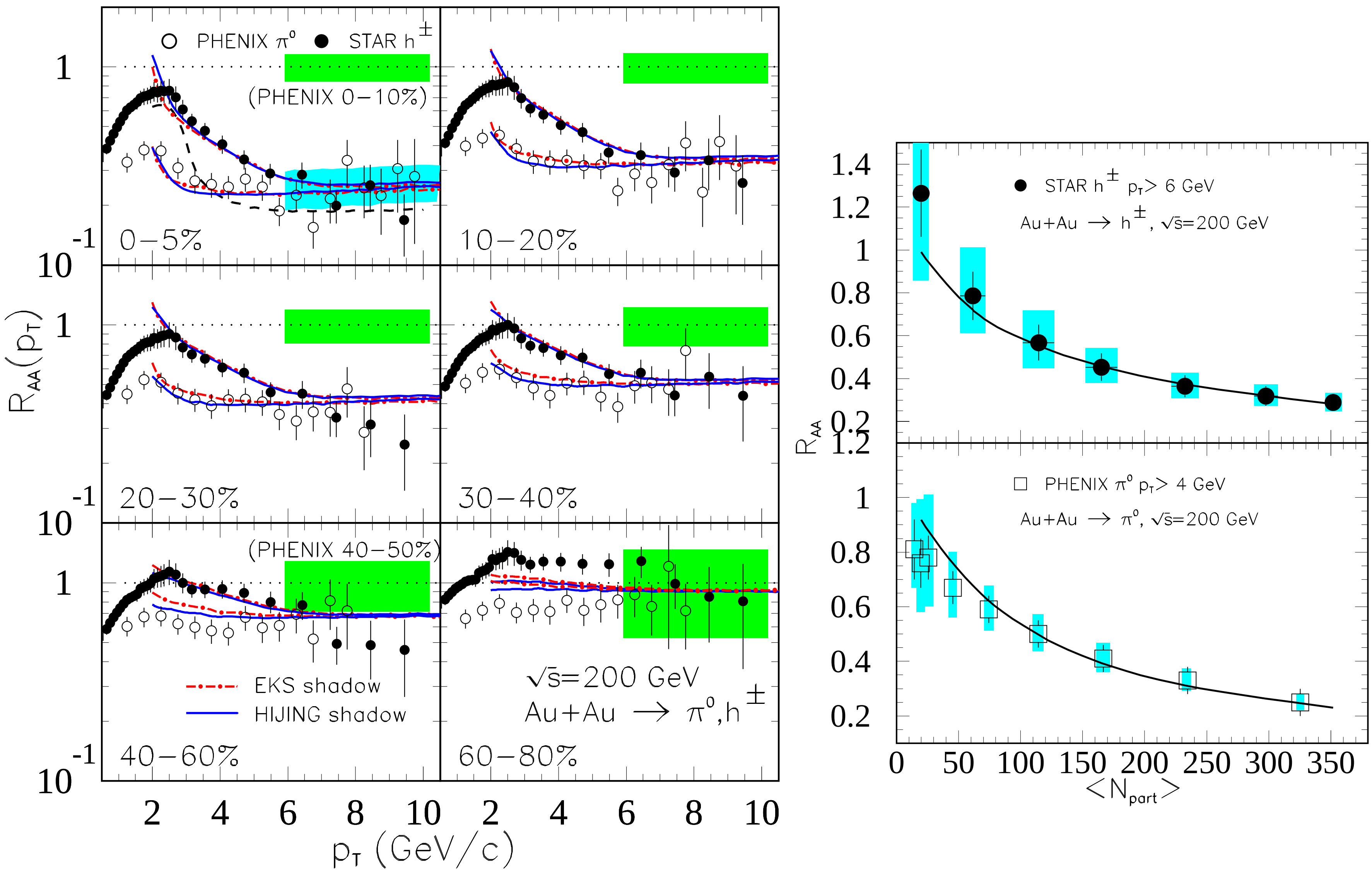
Alberto Accardi (01)

Color dipole model

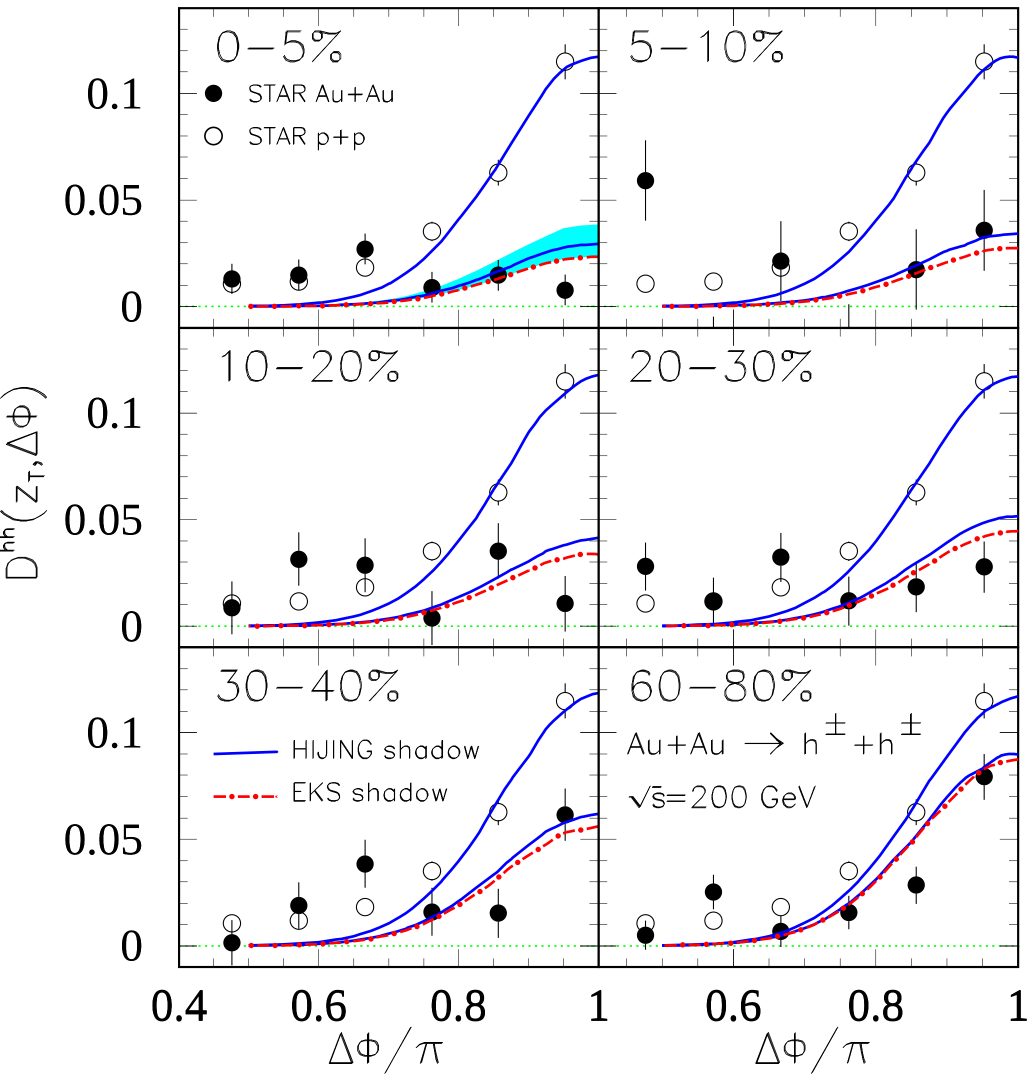
Kopeliovich et al (02)

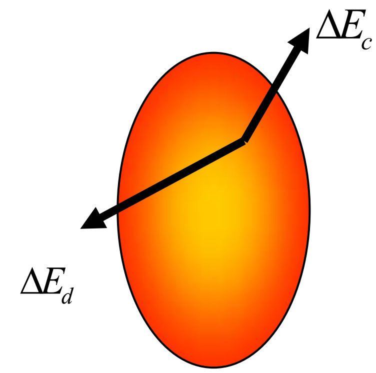


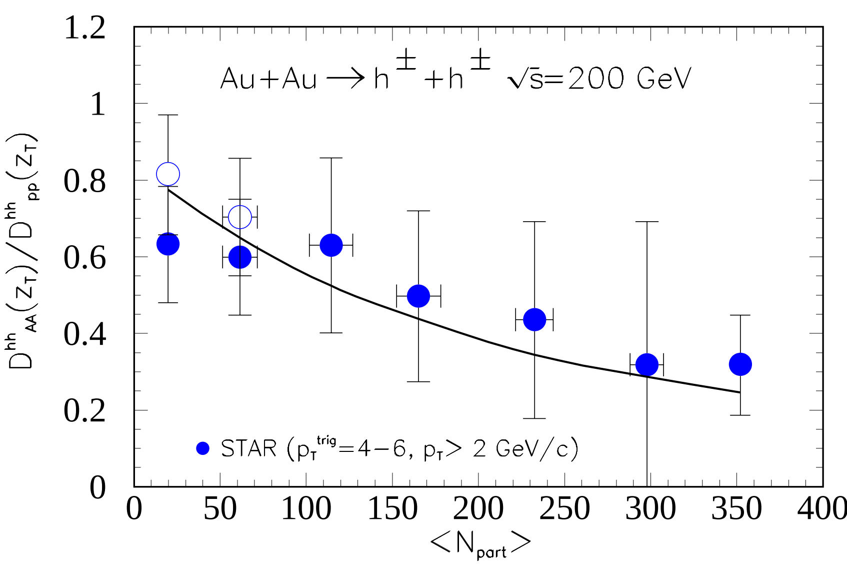
Single hadron suppression



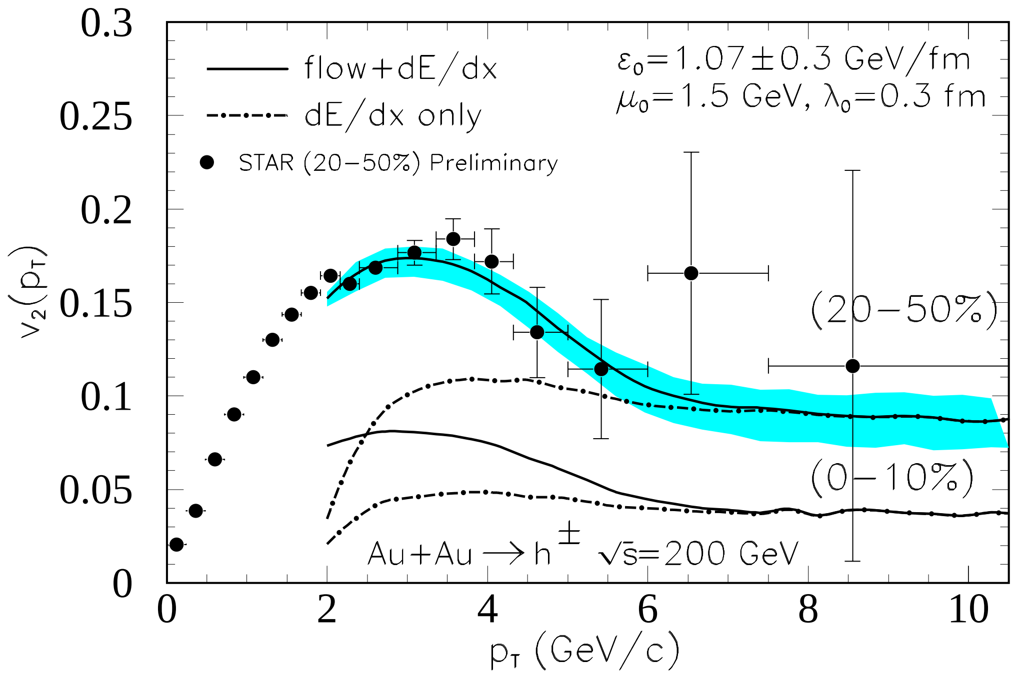
Suppression of away-side jet



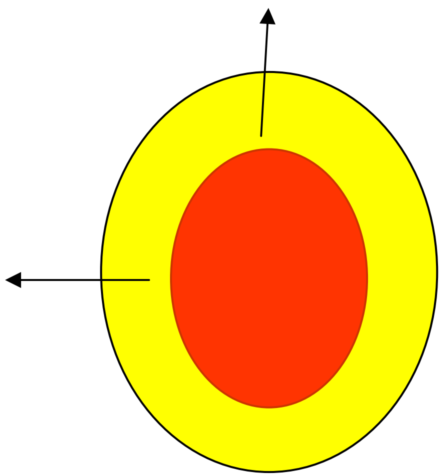




Azimuthal Anisotropy



Single hadron



Intermediate p_T: effects of parton coalescence

Partonic Energy Loss at RHIC

$$\Delta E = \frac{\Delta E_{1d}}{\rho_0 \tau_0 R} \int_{\tau_0}^{R} d\tau \rho(\tau)(\tau - \tau_0)$$

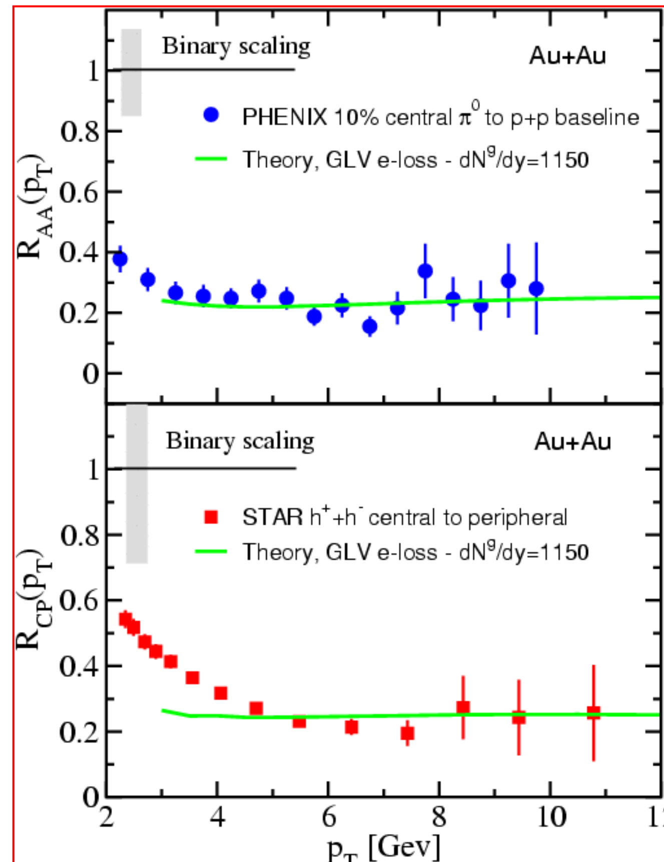
$$\rho(\tau, r) = \rho_0(r) \frac{\tau_0}{\tau} \theta(R - r)$$

E=10 GeV $\quad \tau_0 = 0.2$ fm/c

$$\Delta E = 5.5 \pm 1.6 \quad \text{GeV}$$

$$\left(\frac{dE}{dx}\right)_0 \approx 13.8 \pm 3.9 \text{ GeV/fm}$$

$$\left(\frac{dE}{dx}\right)_{\text{cold matter}} \approx 0.5 \text{ GeV/fm}$$



$$\frac{dN_g}{dy} = 1150$$

$$\rho_0 = 40 \text{ /fm}^3$$

Gyulassy & Vitev;
Barnafoldi et al
Muller
Jeon et al

Quenching is parton energy loss!

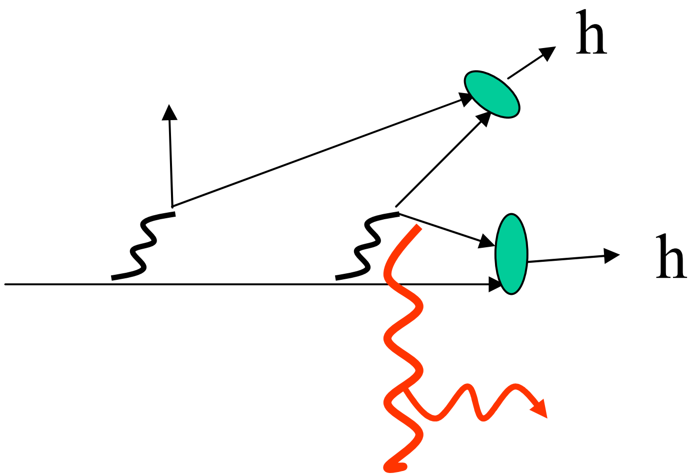
Could it be caused by hadronic absorption or rescattering? **NO!**

Hadron formation time:

$$\tau_f = 70 \text{ fm} \quad \text{for E=10 GeV pion}$$

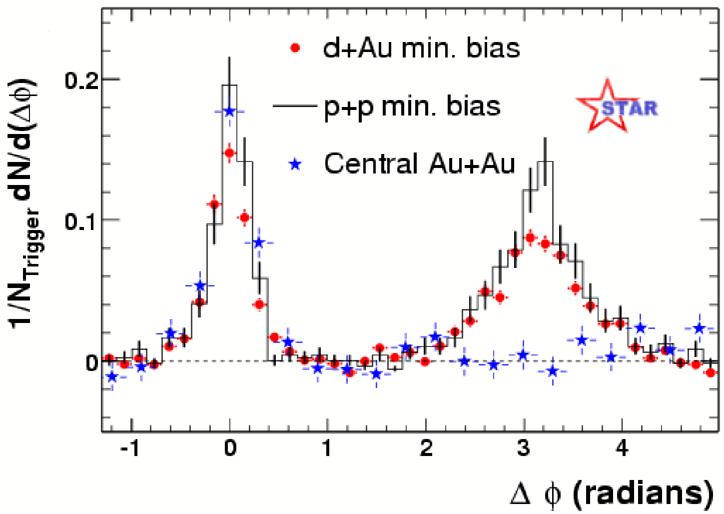
Uncertainty principle:

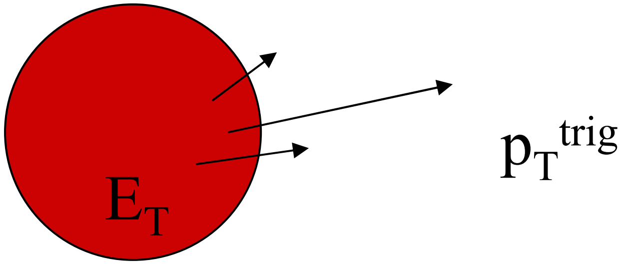
$$\tau_f = r_h \frac{E}{m}$$

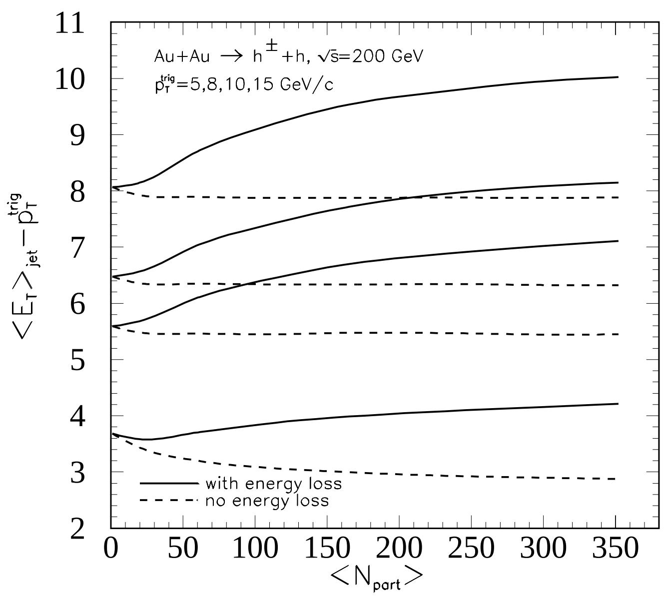


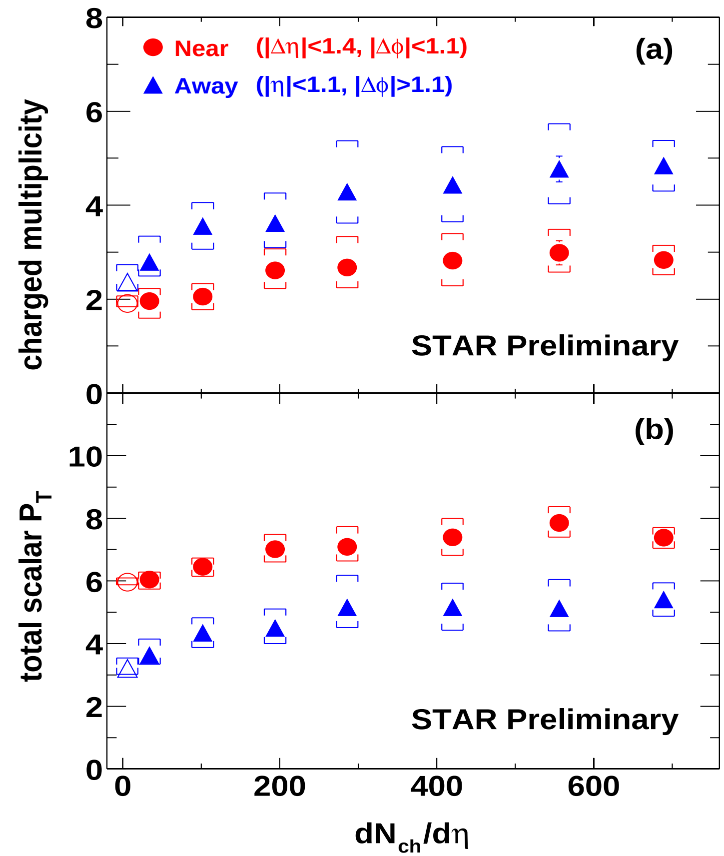
- Energy dependence of jet quenching
- Large v2 →early stage
- Same-side jet profile

Measuring Parton Energy Loss



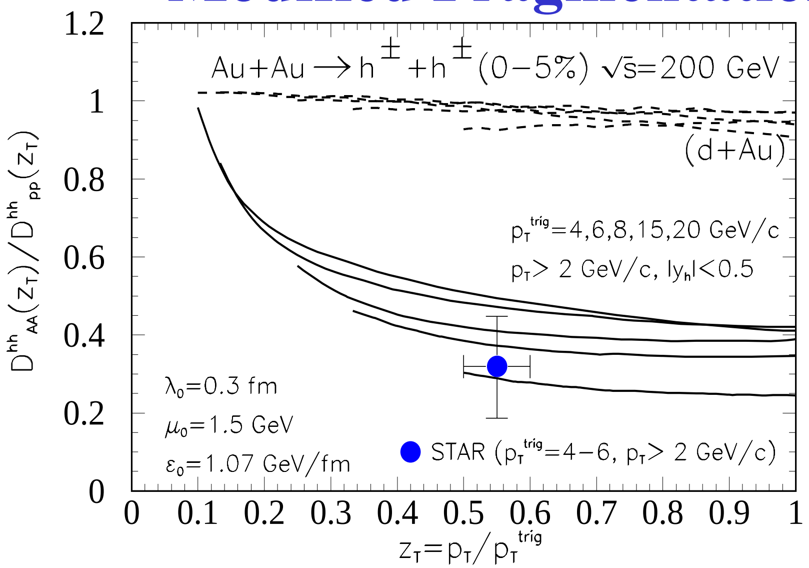


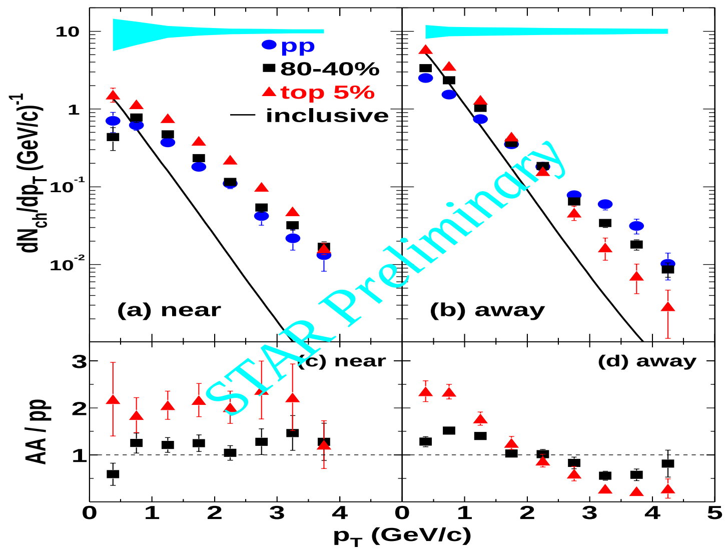


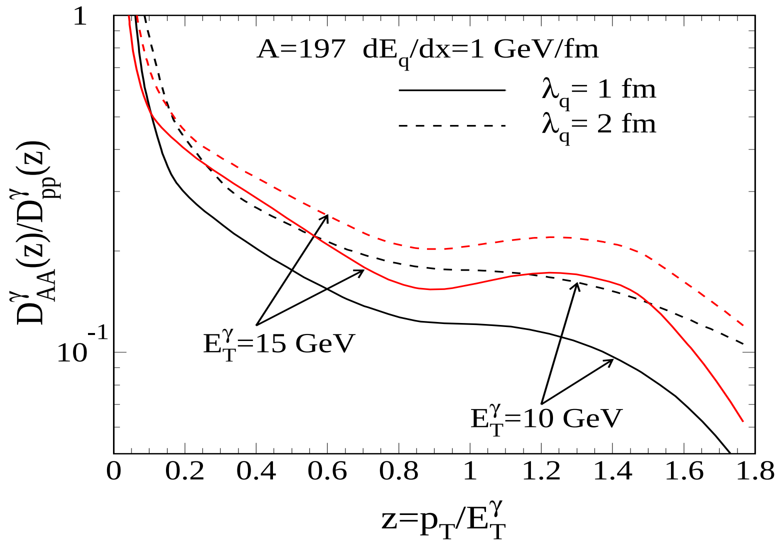


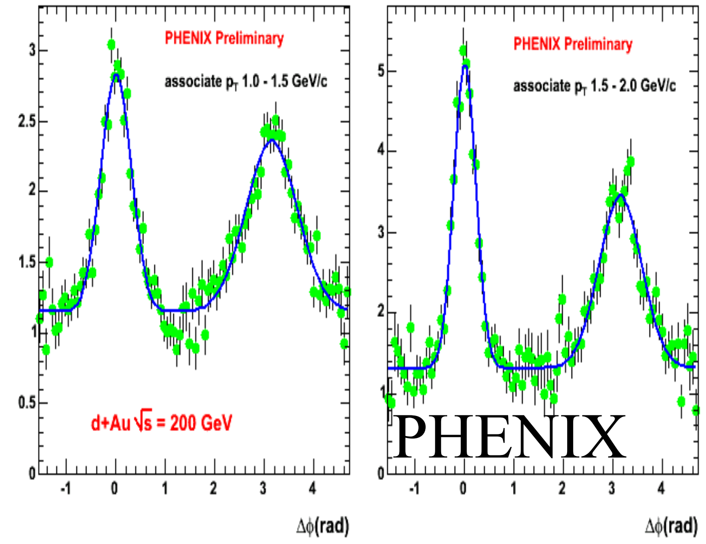
Beyond the discovery I

Modified Fragmentation



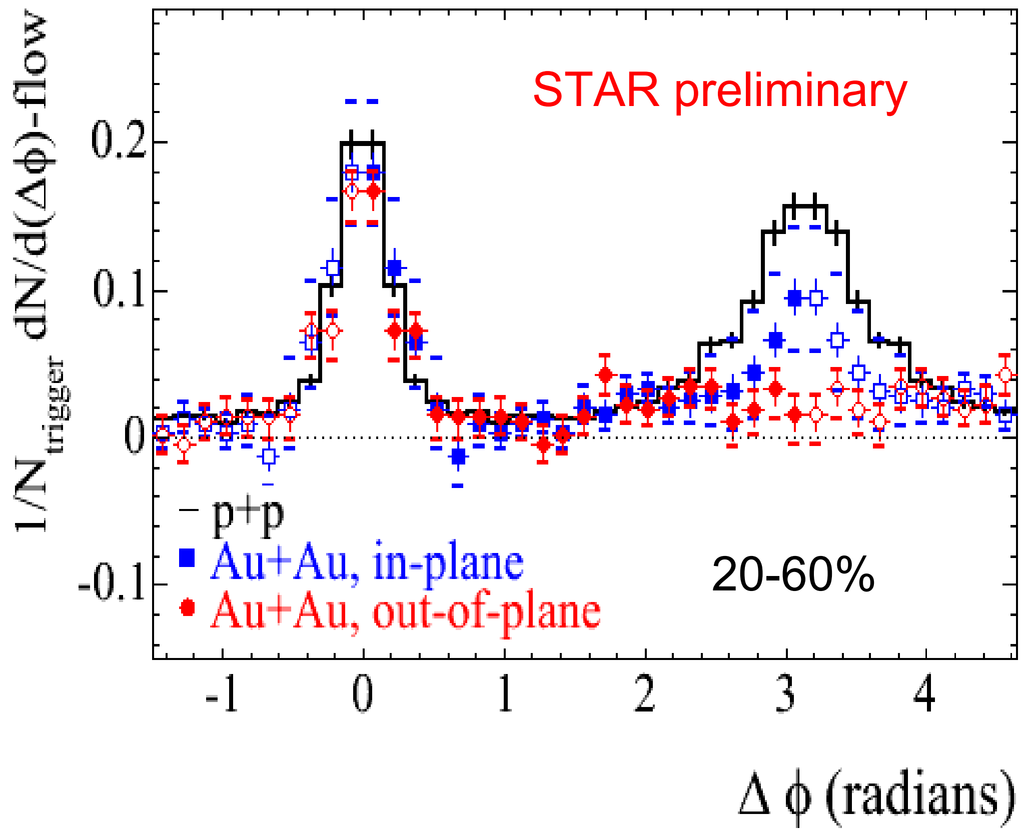




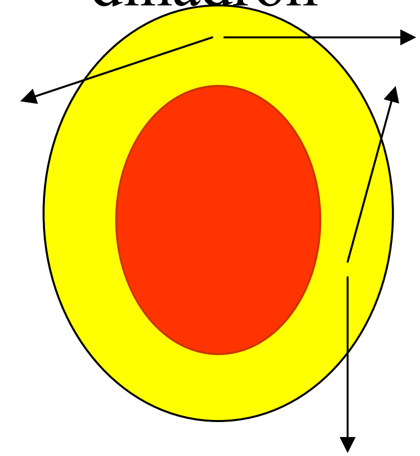


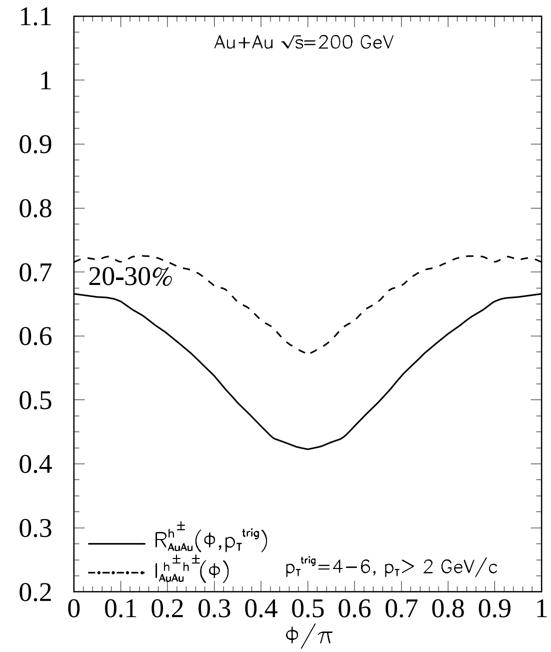
Beyond the Discovery II

Azimuthal Mapping of jet quenching



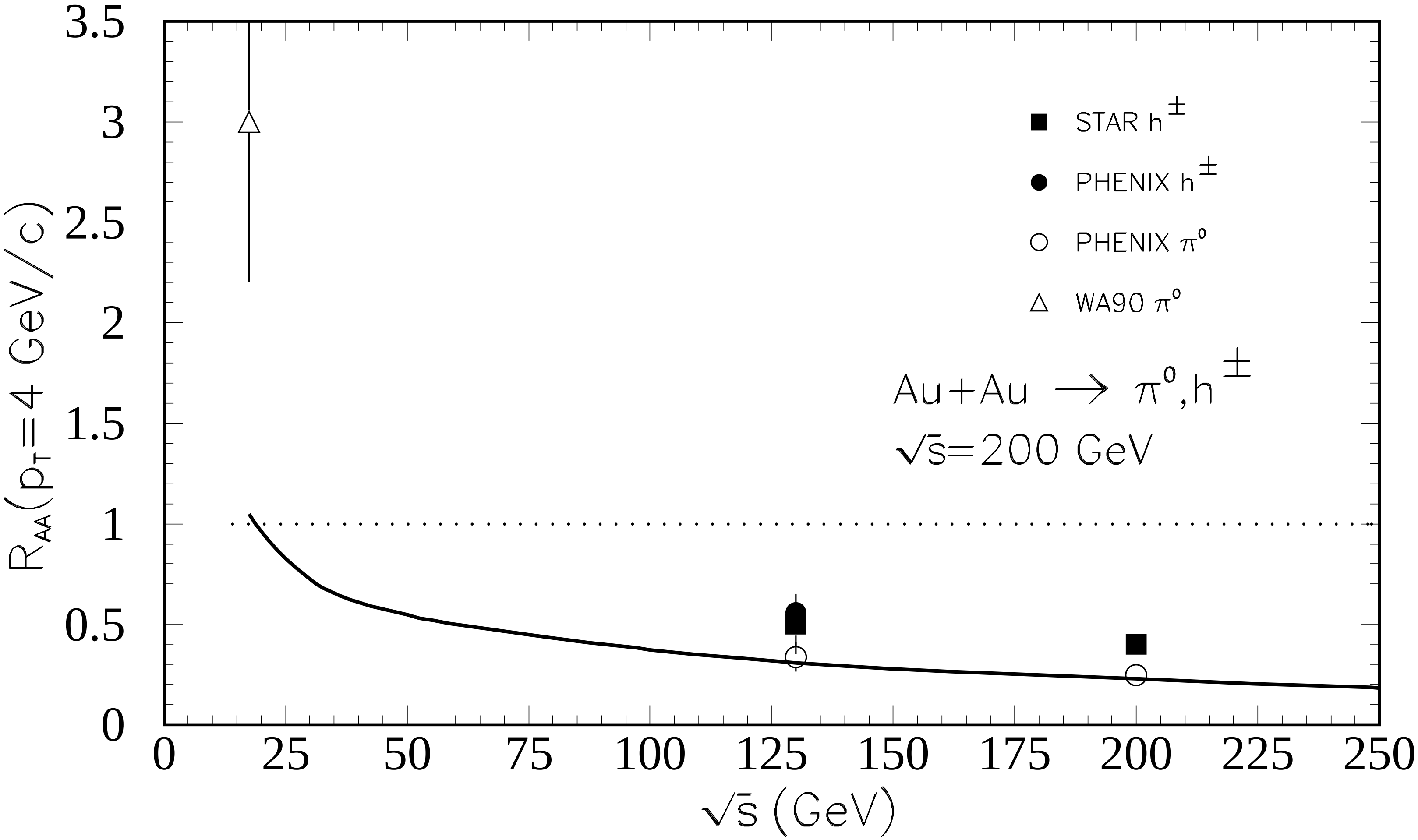
dihadron



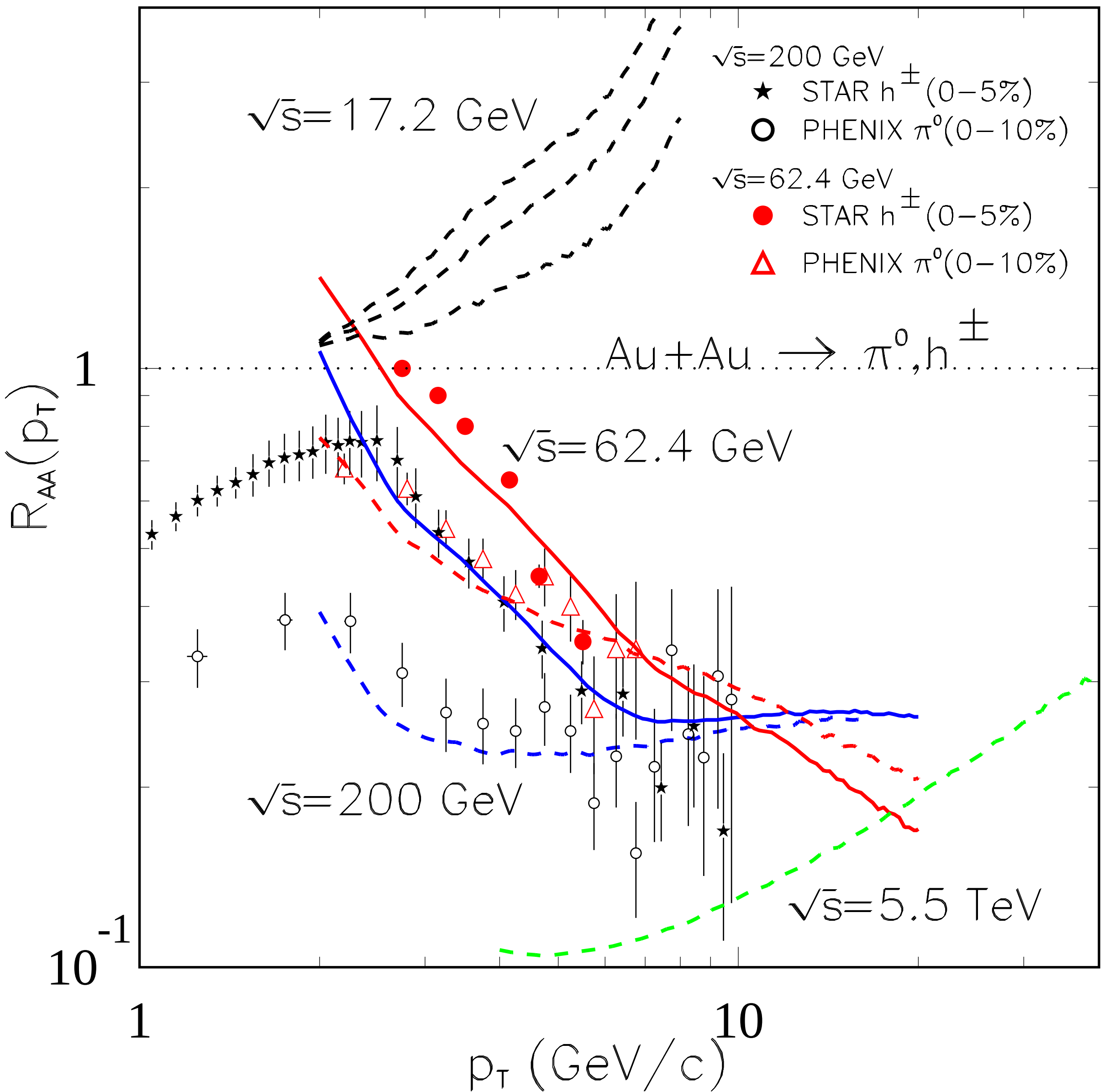


Beyond the discovery III

$$T^{A}_{qg}(x,x_L)=\int\frac{dy^-}{2\pi}dy_1^-dy_2^-e^{-ix_Bp^+y^-}\left\langle A\left|\bar{\psi}(0)\frac{\gamma^+}{2}F_\sigma^+(y_1^-)F^{+\sigma}(y_2^-)\psi(y^-)\right|A\right\rangle$$



Degree of thermalization?



XNW
Adil & Gyulassy
Vitev

Summary

- Discovery of Jet Quenching proves that dense matter is formed
- Jet quenching is caused by partonic energy loss
- Dense matter at RHIC is 30 times higher than cold nuclei
- The matter is strongly interactive
- Jet tomography become useful and power tool for studying properties of dense matter

High Definition Jet Tomography

SPS

RHIC

LHC, RHIC II