How to Determine Medium Modifications by Comparing p+p, p+A, and A+A

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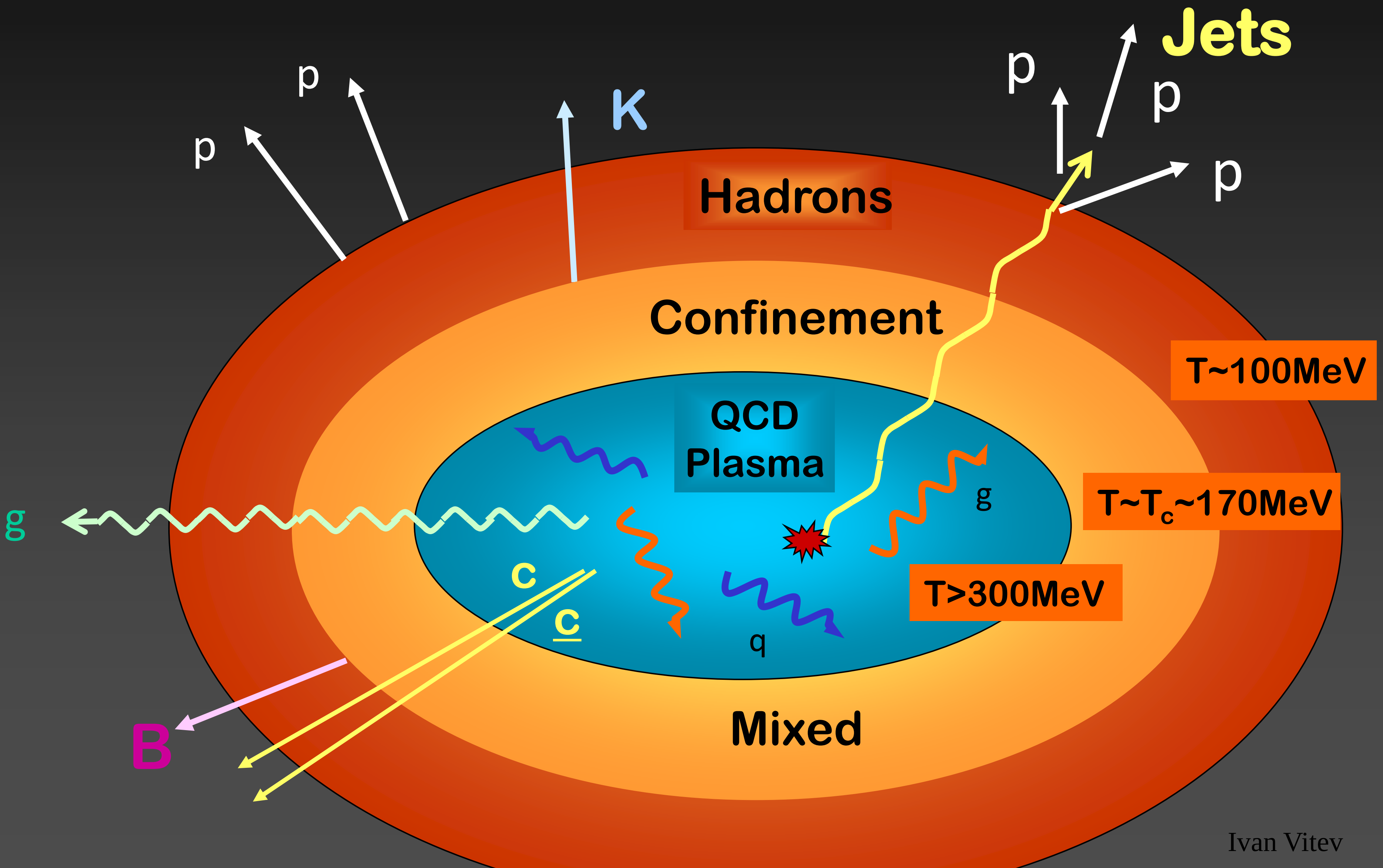
"Hard Probes in Heavy Ion Collisions at the LHC"
CERN, 7-11 October 2002

Outline of the Talk

- Proposed **Medium Induced Modifications** and their **Relation** to **High-p_T Observables**:
  - Nuclear shadowing, Cronin effect, and jet quenching
    - Modification of the fragmentation functions
    - Nuclear modification ratio R_{AA}
  - Broadening of the jet cone
  - Azimuthal correlations and elliptic flow v_2
- A systematic approach to nuclear effects in hadron production:
  - π^0 production in d+Au (Cronin effect and shadowing)
  - π^0 production in Au+Au (same + jet energy loss)
  - Extracting the observable effect of $\Delta E(E_{jet})$

Experimental Probes of Dense Matter in A+A



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A Note on Factorization

1. Hadron-hadron collisions:
   - Leading twist is exact.
   - Twist 4 is broken.

     phenomenological observation:
     formal proof:

At few GeV have few % correction

e.g. Collins, Soper, and Sterman,
Nucl.Phys. B 261, (1985)

Doria, Frankel, and Taylor (1980)
Non-cancellation of IR in Drell-Yan
at $O(*/Q^4)$

e.g. Qiu and Sterman,
Nucl.Phys. B 353, (1991)

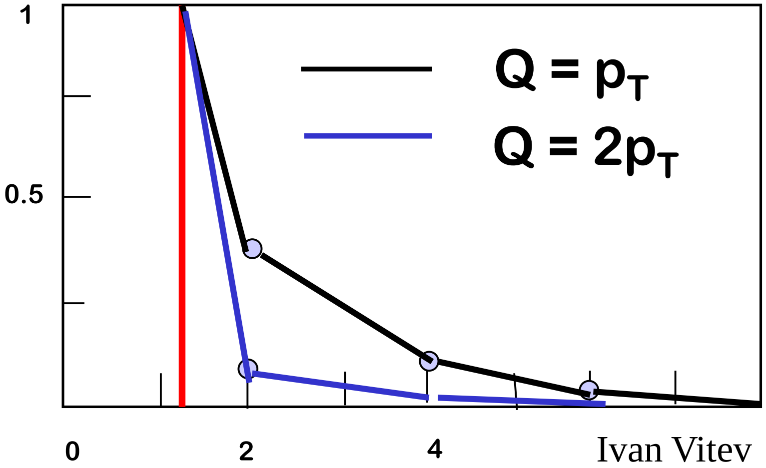
2. Nucleus-nucleus collisions:
   - Nuclear enhanced power corrections

$$*\left(A^{1/3}+B^{1/3}\right)\frac{a_s l^2}{Q^2}C_i p^2 < 1$$

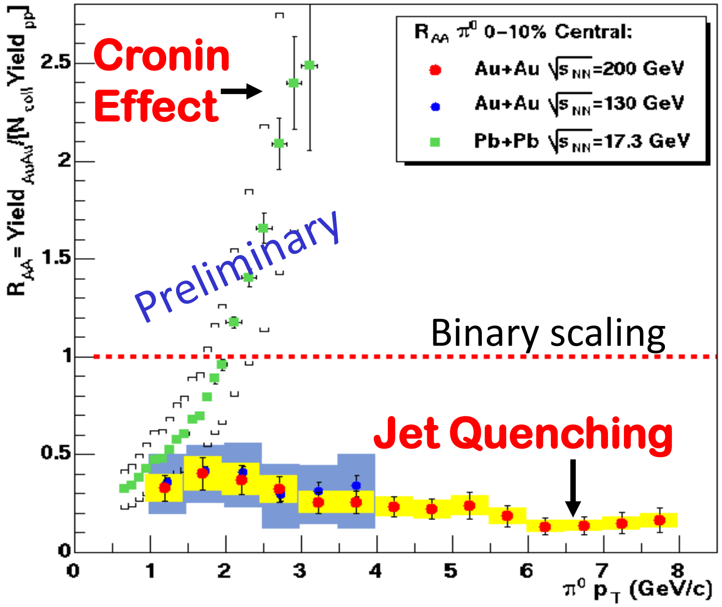
$$*\ ^3\ 1,\ l^2 \ » \ 0.01 GeV^2,\ C_i = (C_A, C_F)$$

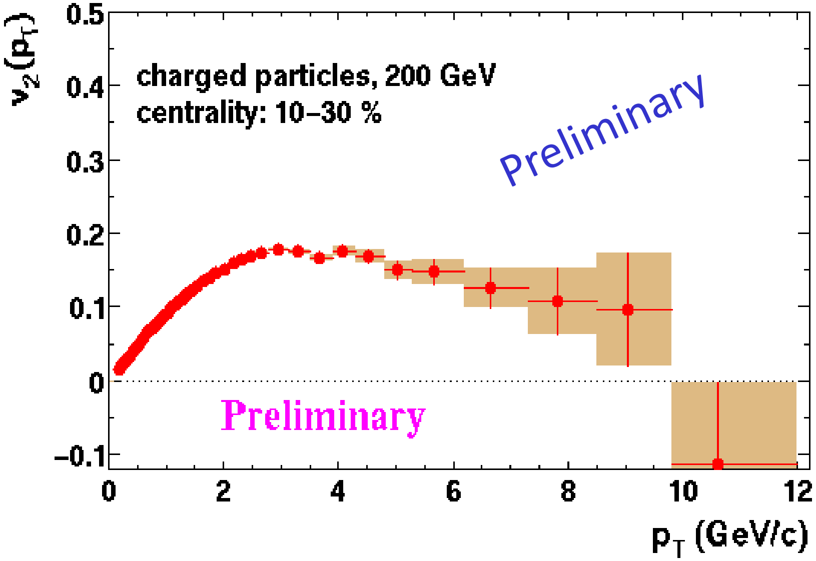
$$Q_{crit}^2 = 1.5 GeV^2$$

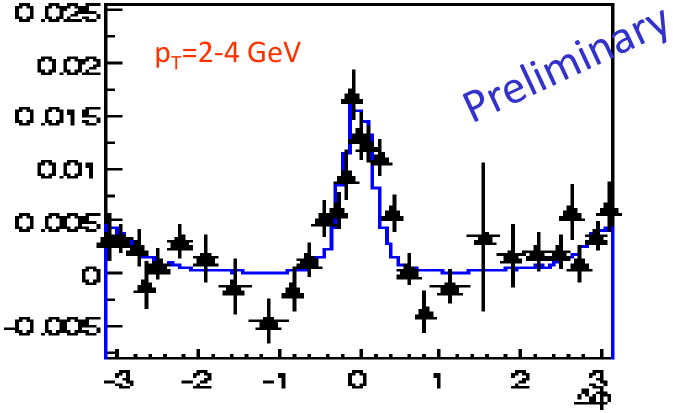
Qiu and Guo,
Phys.Lett. B 532, (2001)



Jets: RHIC Today and LHC in the Near Future are Unique in their Capabilities to Study Hard Processes in A+A



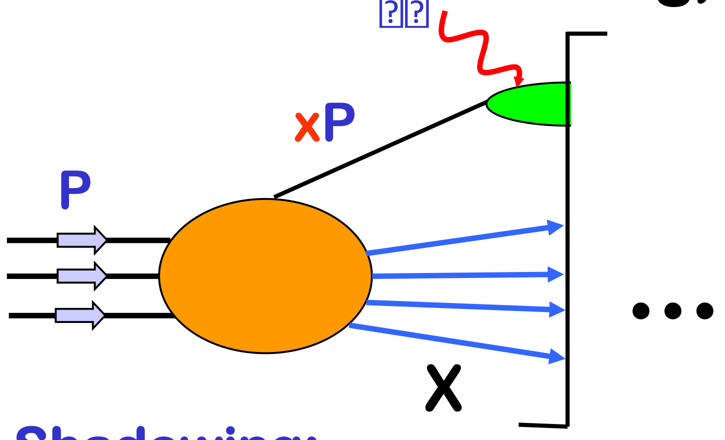


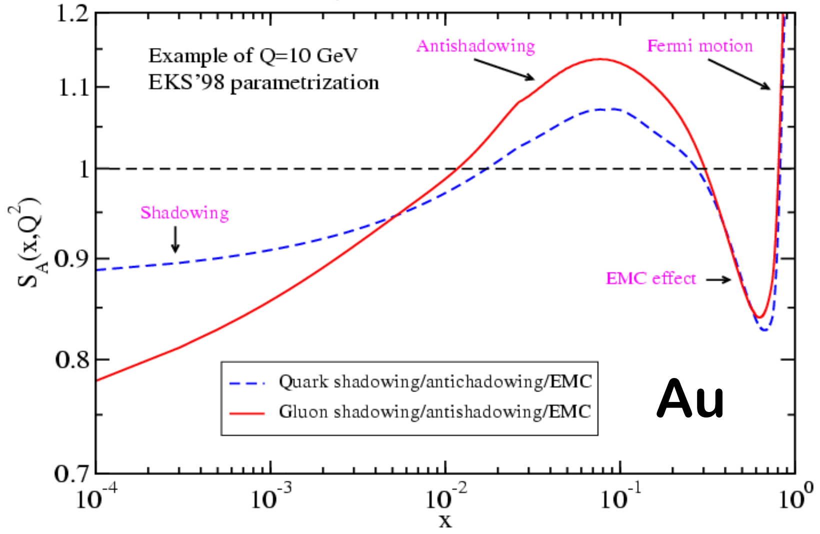


- Huge ~5 suppression of the high-p_T π^0
- Huge azimuthal asymmetry $V_2(p_T)$~15% at high-p_T
- Indications of jet structure?

Nuclear Effects on Hadron Production (From the Point of View of Relativistic Heavy Ions)

Nuclear shadowing, antishadowing, EMC effect





Shadowing:

Partonic model A.Mueller and J.Qiu
Generalized vector dominance model
Eikonal dipole approach: B.Kopeliovich
Leading twist approach: L.Frankfurt, M.Strikman

EMC effect:

Nuclear swelling E.Predazzi
Quark cluster models H.Pirner and J.Vary

Antishadowing:

Constructive interference J.Qiu, S.Brodsky
Partonic model J.Qiu

Fermi motion:

Gain from the motion inside the nucleus

Practical approach: EKS'98 parameterization

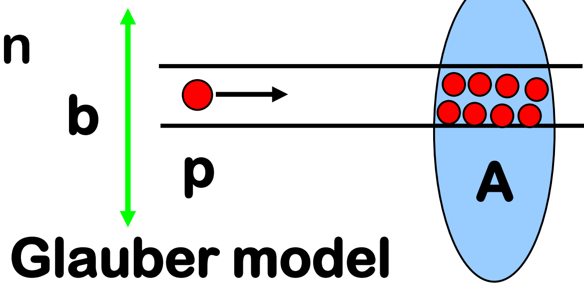
$$f_{a/A}(x,Q^2) = S_{a/A}(x,Q^2)\, f_{a/p}(x,Q^2)$$

K.Eskola,V.Kolhinen,and C.Salgado, Eur.Phys.J. C9 (1999)

The Cronin Effect

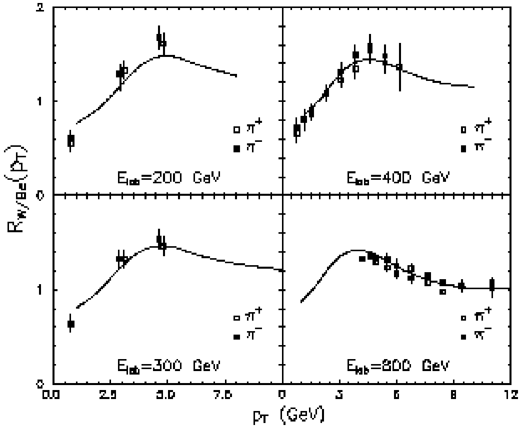
Faster than linear scaling of the p+A cross section with the number of binary collisions

$$d\sigma^{p+A} = d\sigma^{p+p} \left(N_{coll} \right)^{\alpha}, \quad \alpha = \alpha(\mathrm{p_T})$$



Models of the **Cronin effect** are based on multiple **initial state scattering** – helps to **gain p_T** at moderate p_T (and **compensates** at small p_T)

B. Kopeliovich *et al.*,
Phys.Rev.Lett. 88, (2002)



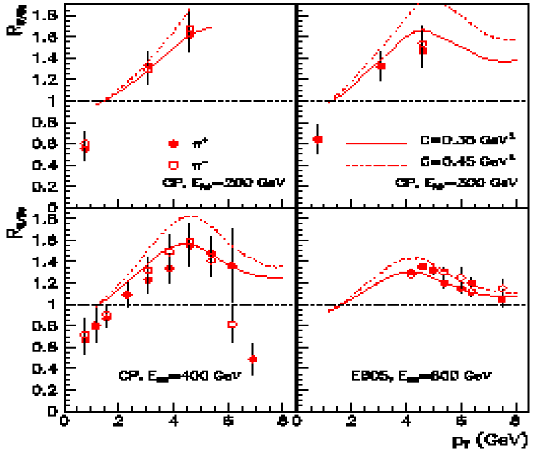
- **Hadronic** scattering
- **Partonic** scattering

- **Gaussian** approximation
- **Deviations** in the case of **few collisions**

1444444444444442 4444444444444443

M.Gyulassy, P.Levai, and I.V.,
Phys.Rev. D66, (2002)

Y. Zhang et al.,
Phys.Rev. C65, (2002)



Compare p+p and p+A. But both ~ $A^{1/3}$

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Gluon Radiation and the Landau-Pomeranchuk-Migdal (LPM) Effect

- **In QED the suppression of the radiative cross section relative to the Bethe-Heitler result.**

(small frequencies)

$$dI/d\omega \propto \sqrt{\omega} \quad \text{vs}$$

$$dI/d\omega \propto const.$$

- **In QCD**

a) Gyulassy-Wang: multiple interactions, arbitrary medium, the transverse gluon dynamics is neglected

M.Gyulassy and X.N.Wang,
Nucl. Phys. B 420 (1994).

$$-\Delta E = \frac{C_R \alpha_s}{p}\langle q^2\rangle \log\frac{C_A E}{C_R \mu^2 \lambda}$$

b) Baier *et al.* (BDMPS): thick medium, large number of scatterings, exclusively the LPM regime

R.Baier,Yu.Dokshitzer,A.Mueller,S.Peigne, and D.Schiff,
Nucl.Phys. B 483, (1997); *ibid* 484 (1997).

$$-\Delta E = \frac{C_R \alpha_s}{4}\frac{\mu^2 L^2}{\lambda}\log\frac{L}{\lambda}$$

c) Zakharov; Wiedemann: thick medium, path integral formalism

B.G.Zhakharov, JETP Lett. 63, (1996);
U.A.Wiedemann, Nucl.Phys. B 588, (2000).

d) Gyulassy *et al.* (GLV): thin media with small to moderate number of scatterings. Low order correlations (few scattering centers) dominate.

M.Gyulassy, P.Levai,and I.V.,
Nucl.Phys. B 583 (2001); Phys.Rev.Lett. 85 (2000).

$$-\Delta E = \frac{C_R \alpha_s}{4}\frac{\mu^2 L^2}{\lambda}\left(\log\frac{2E}{\mu^2 L} + \dots\right)$$

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Modification of the Fragmentation Functions

E.Wang and X.-N.Wang, hep-ph/0202105

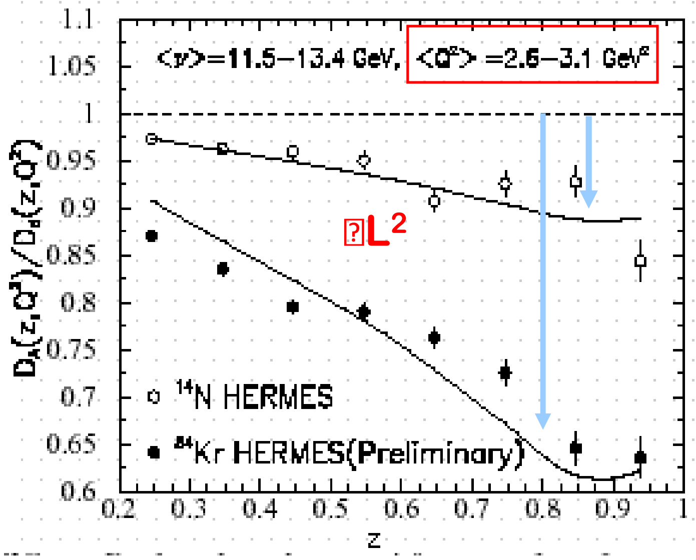
$$\tilde{D}_{a\to b}(z) = \frac{1}{1-\Delta z}\,\tilde{D}_{a\to b}\left(\frac{z}{1-\Delta z}\right)$$

$$\langle \Delta z\rangle_g \approx \tilde{C}\alpha_s^2\,\frac{C_A}{N_c}\,\frac{x_B}{Q^2 x_A^2}\,6\ln\frac{1}{x_B},\quad x_A = \frac{1}{m_N R_A}$$

Find quadratic dependence $\propto L^2$

Hot matter: reduces to GLV

$$\rho(130\,GeV\ \ \mathrm{RHIC}) = (15-20)\,\rho(\mathrm{Cold\ Nuclear})$$



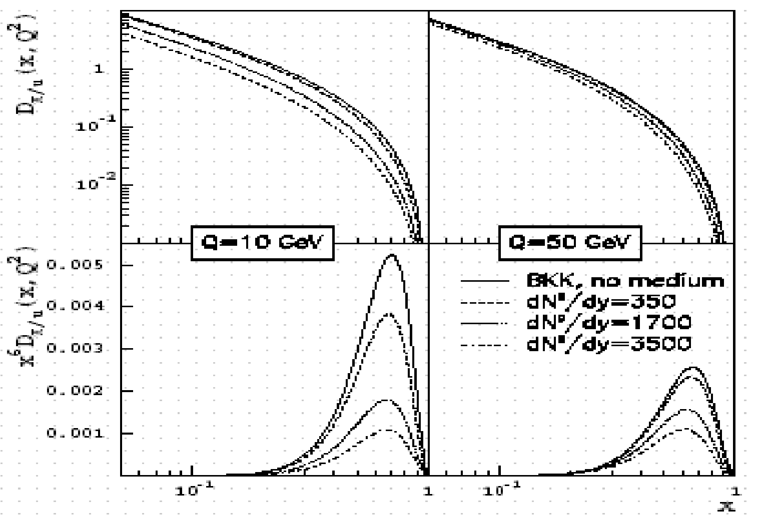
C.Salgado and U.Wiedemann, Phys.Rev.Lett. 89, (2002)

Large # of momentum transfers and

Saddle point approximation to the integrals

$$D_{h/q}(x,Q^2) = \int_0^1 d\epsilon\, P(\epsilon)\,\frac{1}{1-\epsilon}\,D_{h/q}\left(\frac{x}{1-\epsilon},Q^2\right)$$

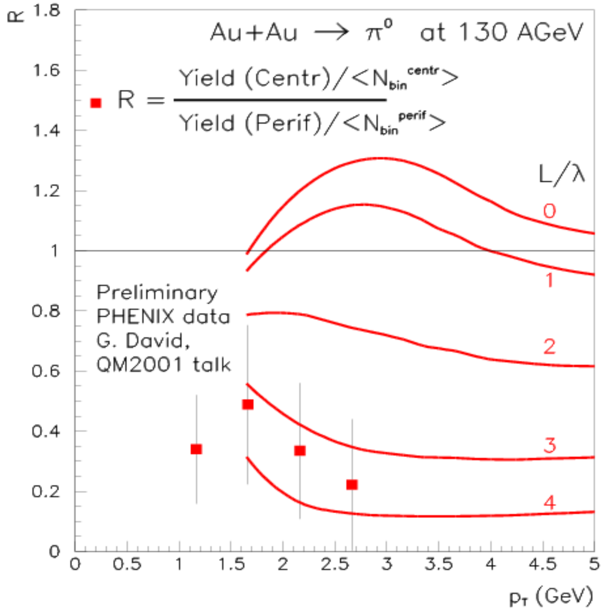
After factoring the leading x⁶ behavior: see the scaling of the modification



Nuclear Modification Factor $R_{AB}(p_T)$

$$E_h \frac{d\sigma}{d^3p} = K_{NLO} \sum_{abcd} \int dx_a dx_b d^2k_a d^2k_b \, g(k_a) g(k_b) \frac{d\sigma^{ab\to cd}}{dt} \times$$

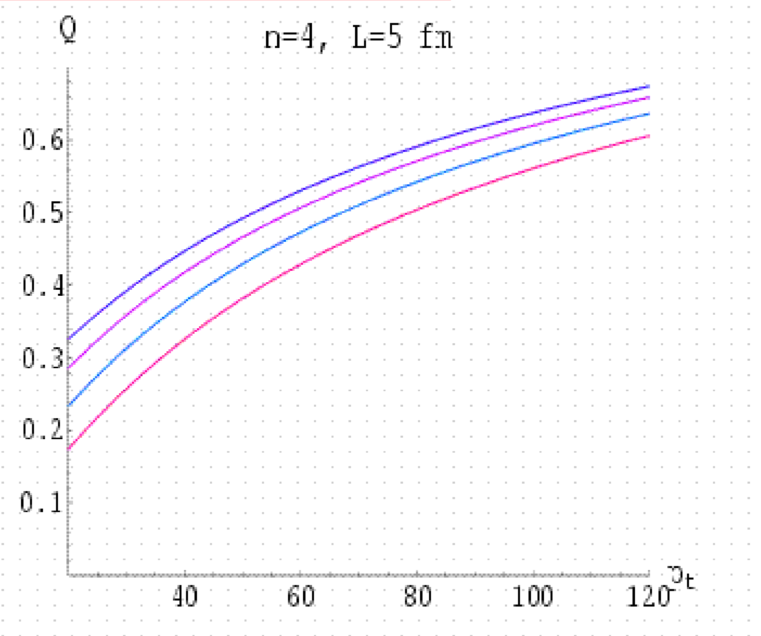
$$\times f_{a/A}(x_1,Q^2) f_{b/A}(x_2,Q^2) \int d\epsilon \, P(\epsilon,p_c) \frac{z_c^*}{z_c} \frac{D_{h/c}(z_c^*,Q^2)}{\pi z_c}$$



P.Levai *et al.*,
Nucl.Phys. A 698, (2002).

R.Baier *et al.*,
JHEP 0109 (2001).

Static plasma limit



$$P(\epsilon) \approx \delta(1 - \langle \epsilon \rangle)$$

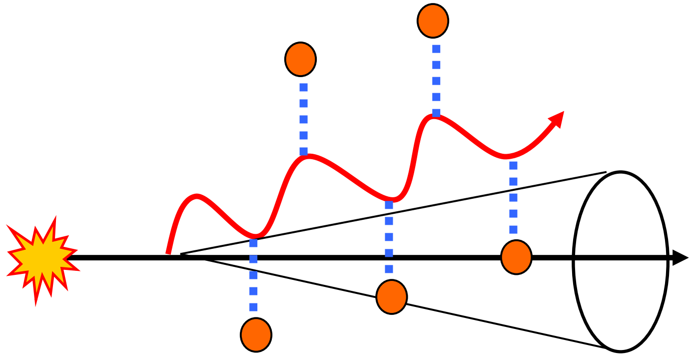
$$\text{Opacity } \chi = \frac{L}{\lambda} \approx 3.5$$

1.Further studies
2.Convert to the same density measure

Fixed power law n=4

Studied the sensitivity to the cut-off rather than $\hat{q}$

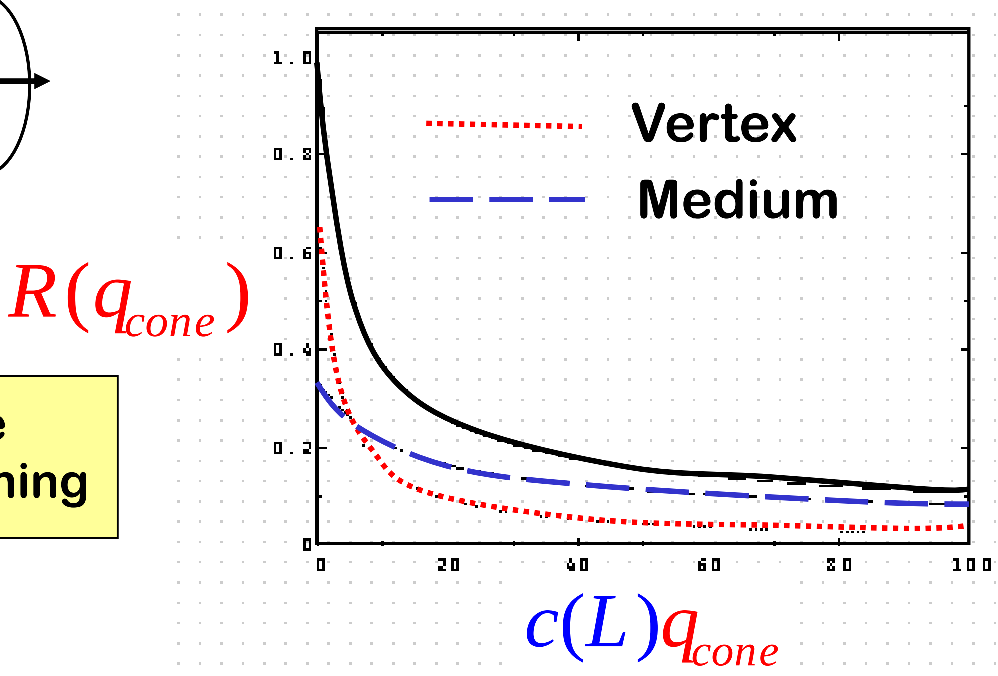
Broadening of the Jet Cone



Physical Picture

All calculations agree on the dominance of gluon broadening

R.Baier *et al.,* Phys.Rev. C60, (2002)



More quantitative estimates are likely needed!

$$R(\theta_{cone}) = \frac{\Delta E(\text{outside } \theta)}{\Delta E(\text{total})} \approx \frac{4\Gamma(1/4)}{5\pi} \frac{1}{(c(L)\theta_{cone})^{1/2}}$$

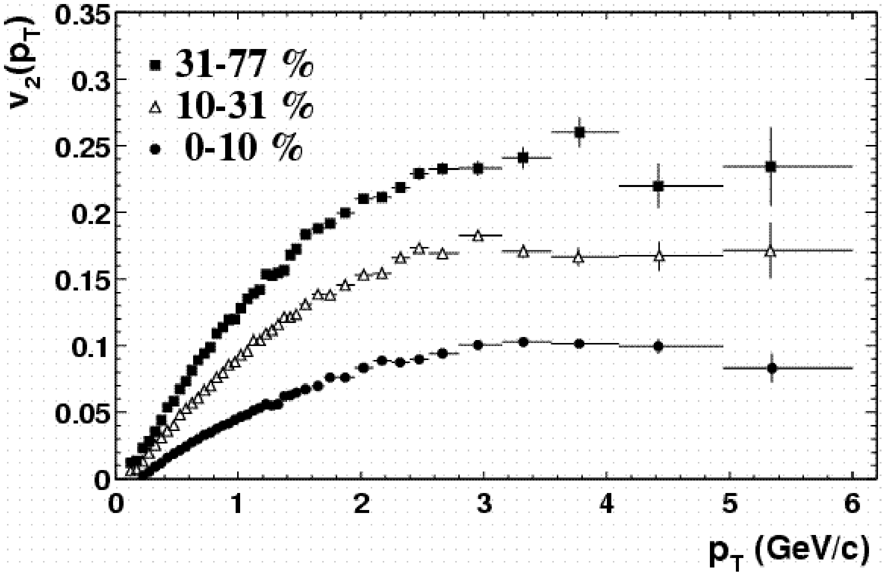
C.Salgado and U.Wiedemann, work in progress (?)

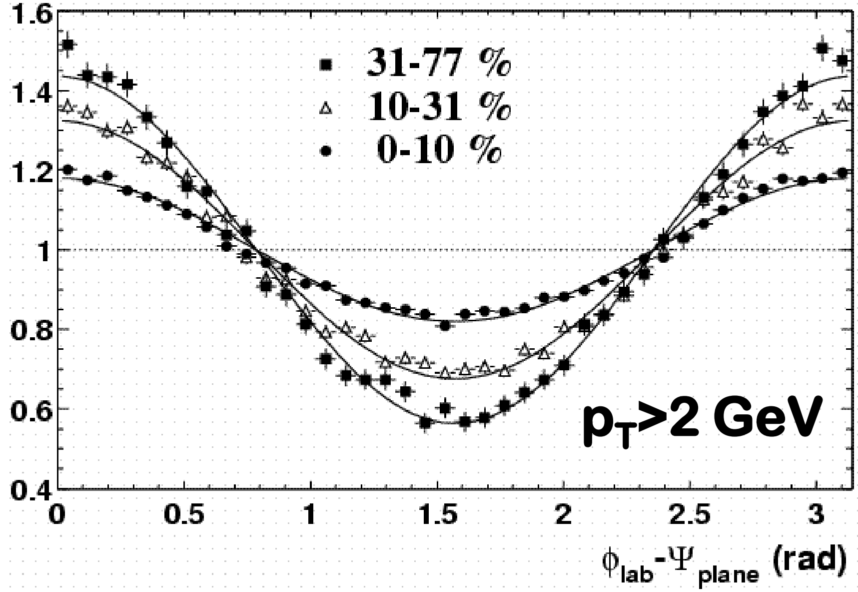
Azimuthal anisotropy and correlations in the hard scattering regime at RHIC

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

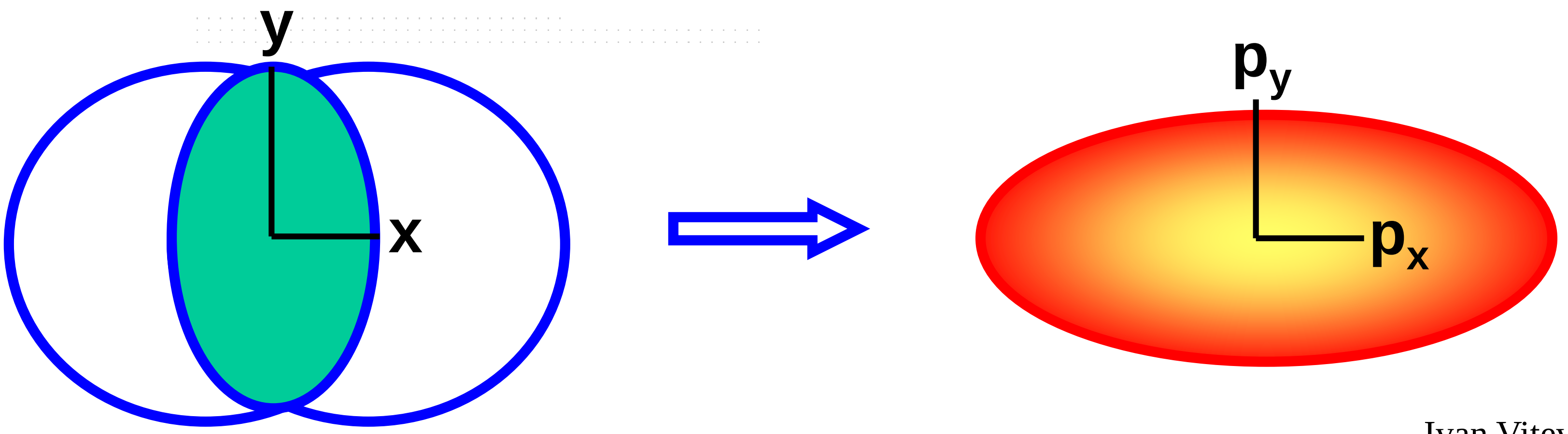
STAR June 2002

$dN_{ch}(p_{\wedge}, f - y_{reac})$





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



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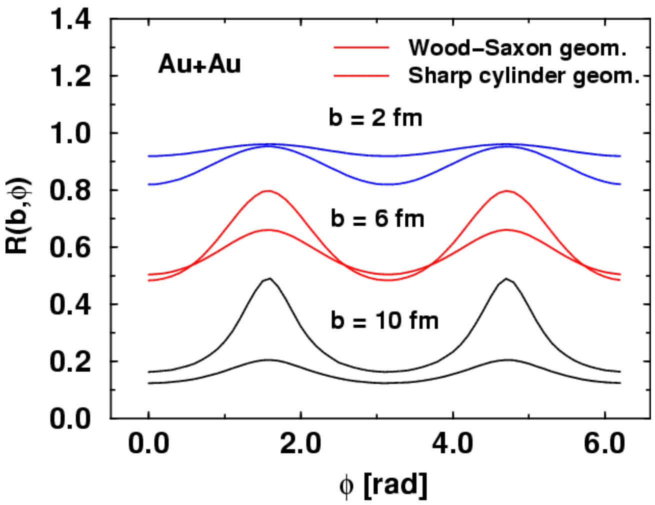
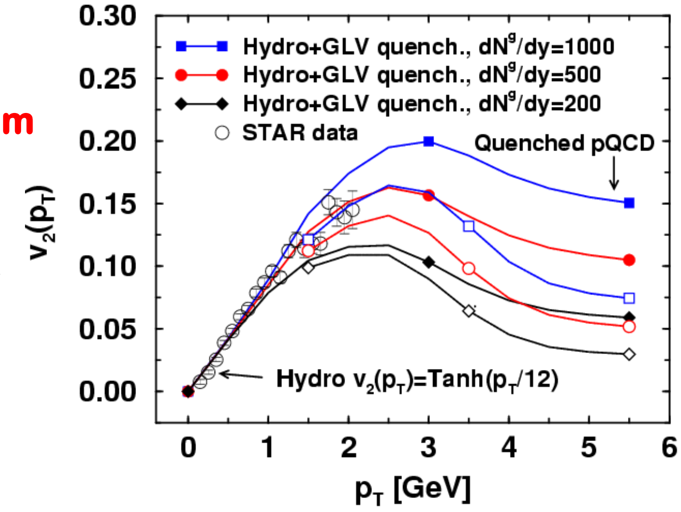
Asymmetric Jet Energy Loss



Spatial anisotropy translates in momentum anisotropy



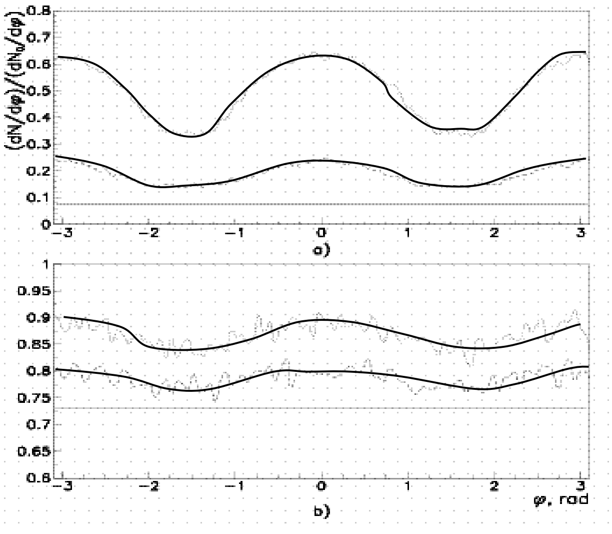
[illegible]

[illegible]

- Typically **off** by a **factor of 2**
- **Decreases** with p_T

Radiative

Collisional



Dedicated simulations at LHC:

I.Lokhtin *et al.*,
Eur.Phys.J. C 16, (2000).

Radiative energy loss dominates

Observable effect at LHC: $E_T > 100 GeV, \ |\eta| \leq 2.5$

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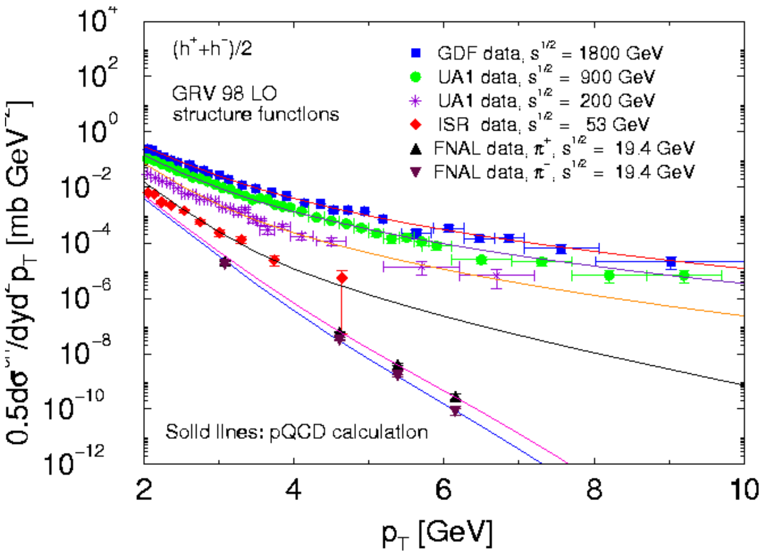
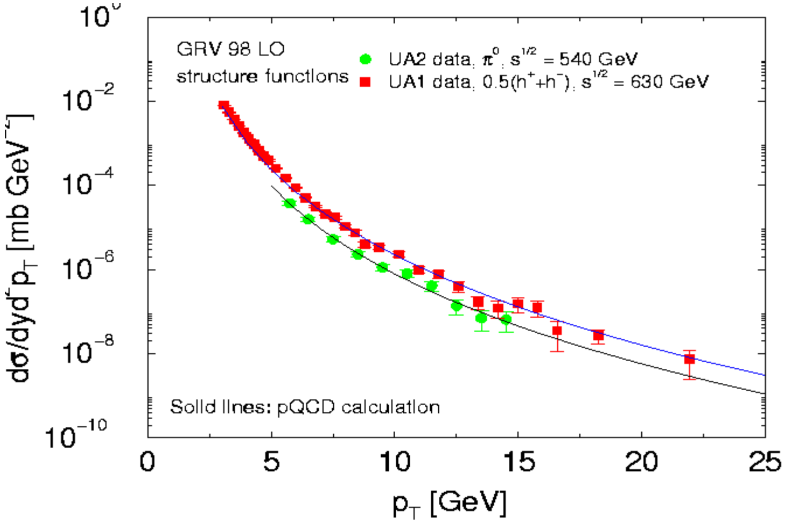
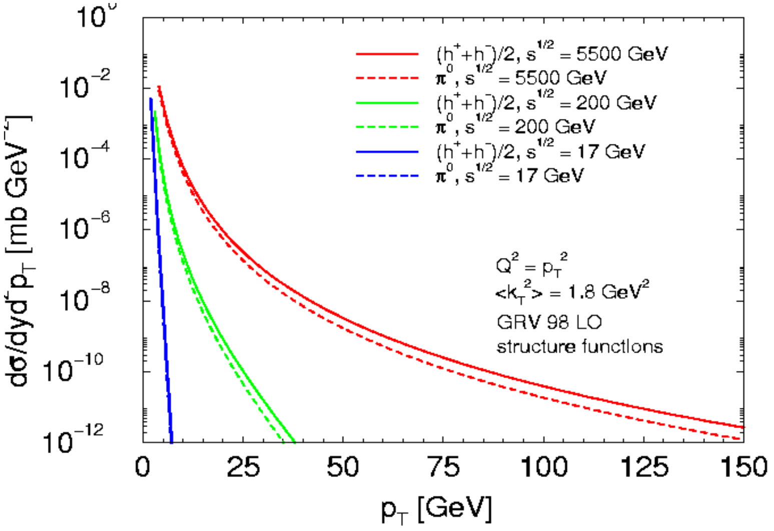
Baseline $p + p$ and $\bar{p} + p$. (Calibrating the Jet Source for Tomography)







Note:

- Significant hardening of hadron spectra with $\sqrt{s}$
- Local dependence of the slope of the distributions on p_T
- Shape is most important for the kinematic effects

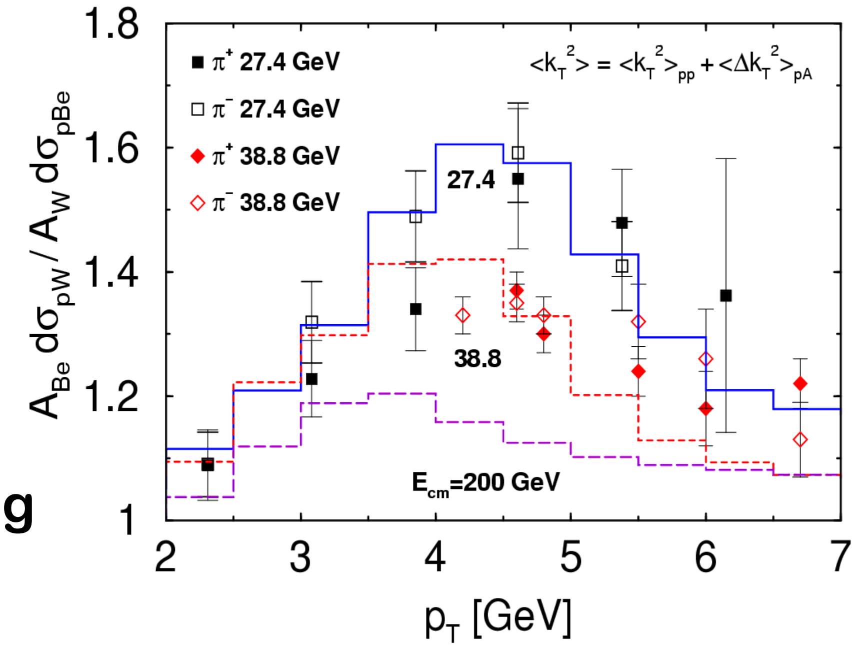
See also: **K.Eskola and H.Honkanen, hep-ph/0205048**

Probing the Transport Coefficient in Cold Nuclear Matter

The interplay of two nuclear effects:

- Shadowing/antishadowing/EMC EKS’98 parameterization
- Multiple initial scattering in thin nuclear medium

In hot nuclear matter (QGP) strong final state energy loss is included



I.V. and M. Gyulassy, hep-ph/0209161

$$E_h \frac{d\sigma}{d^3p} = K_{NLO} \sum_{abcd} \int dx_a dx_b d^2k_a d^2k_b\, g(k_a) g(k_b) \frac{d\sigma^{ab\to cd}}{dt} \times$$

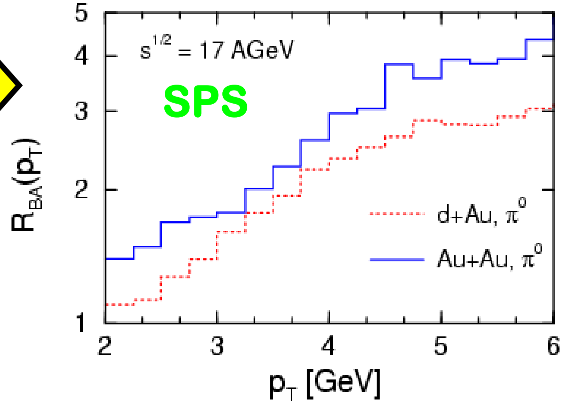
$$\times f_{a/A}(x_1,Q^2) f_{b/A}(x_2,Q^2) \int d\varepsilon\, P(\varepsilon, p_c) \frac{z_c^*}{z_c} \frac{D_{h/c}(z_c^*,Q^2)}{\pi z_c}$$

Find: $\mu^2 / \lambda = 0.05 GeV^2 / fm$

For comparison from Drell-Yan data ~ $0.056 \pm 0.036 GeV^2 / fm$

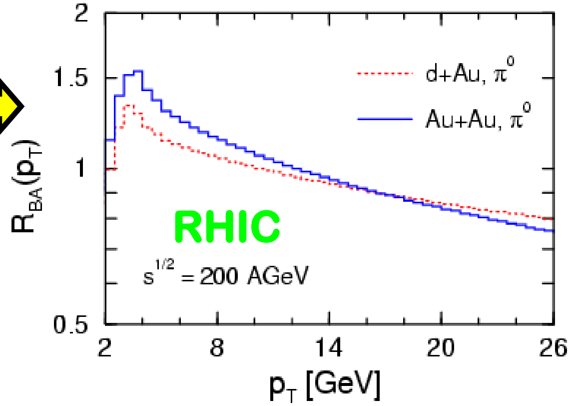
F.Arleo, Phys.Lett. B532, 231 (2002)

Predicted (Y=0) Shadowing+Cronin in d+Au and Au+Au at 17, 200, 5500 AGeV



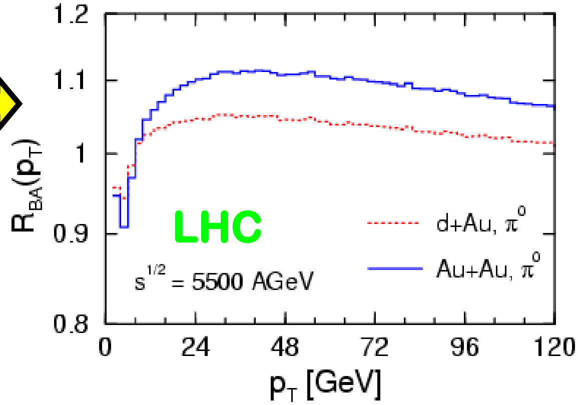
d+Au:
250%

Au+Au:
400%



d+Au:
35%

Au+Au:
65%



d+Au:
4%

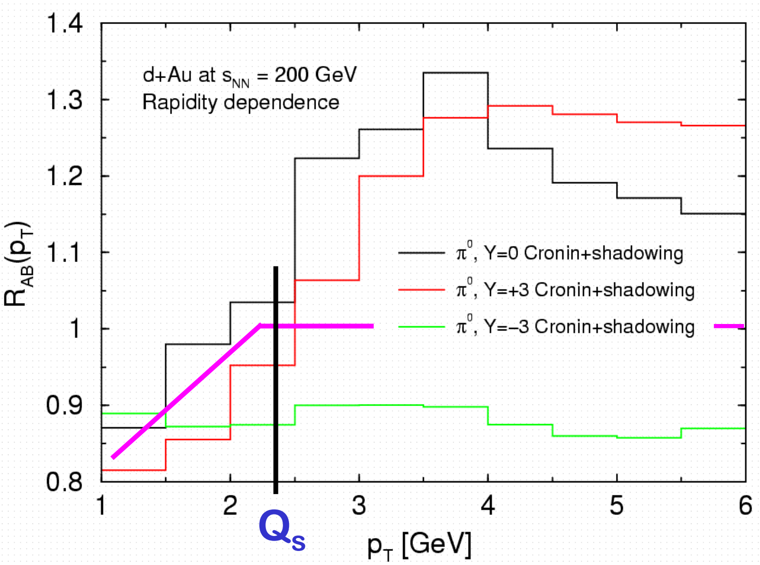
Au+Au:
10%

1. At SPS the Cronin effect is large: does leave room for small suppression due to the non-Abelian energy loss.

2. At RHIC the Cronin effect is comparable (~30% larger) to estimates by X.N.Wang and B.Kopeliovich. In A+A A.Accardi – 1.4 (2.1).

3. At LHC shadowing/antishadowing dominate. Cronin effect is reduced due to the much harder spectra.

Predicted Cronin Effect+Shadowing at Forward and Backward Rapidities



I.V. and M.Gyulassy

The contribution due to shadowing in the backward Y=-3 region is 100%

The contribution due to shadowing in the forward Y=+3 region is 25%

Strong Cronin effect

- **Note the scales**: if **Cronin effect** is detectable **(20%-40%)** at **Y=0** then it should be detectable at **Y=3**
- For p_T<2 GeV: suppression comparable to standard Cronin measurements. For p_T>2 GeV – a much broader enhancement

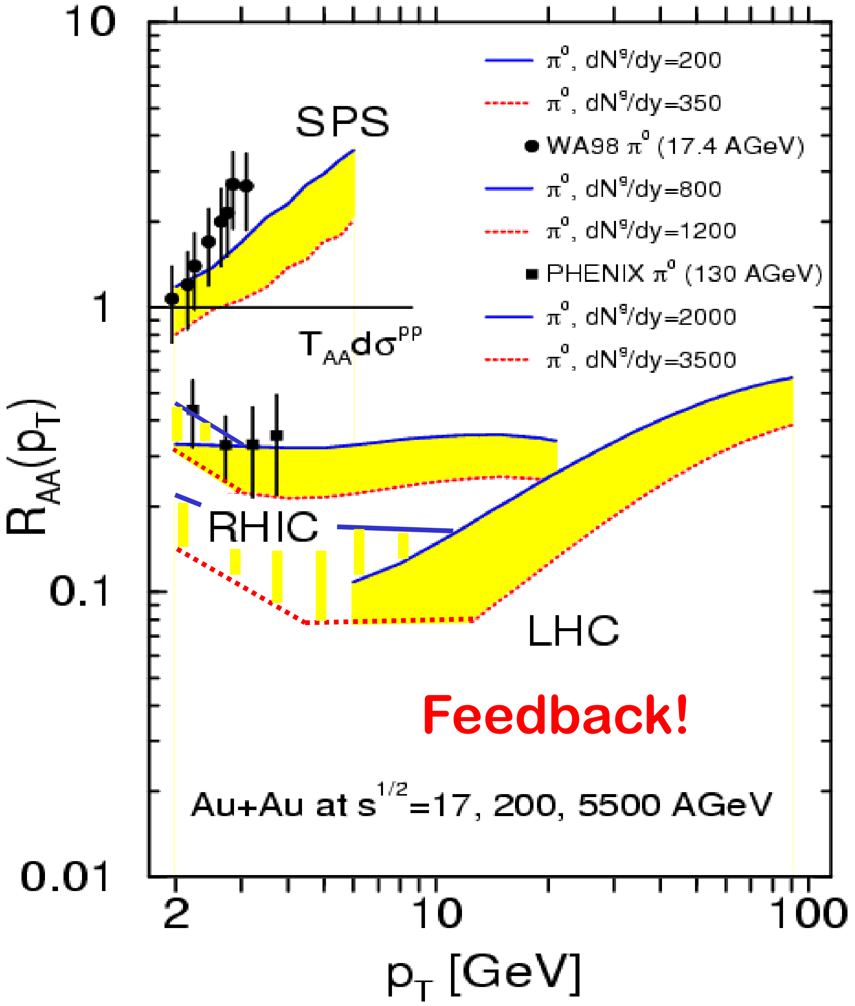
Compared

— with Q_s^2=6.6 GeV^2

A.Dumitru and J.Jalilian-Marian, Phys.Rev.Lett. 89, (2002)

- Strong suppression below Q_s and R_{AB}=1 above

The Center of Mass Energy Systematics of Mono-jet Tomography



I.V. and M.Gyulassy, hep-ph/0209161

1. At **SPS** $\sqrt{s}_{NN} = 17 GeV$ **Cronin effect** dominates. **Even with energy loss** π^0 exhibit noticeable **enhancement**

2. **Cronin effect, shadowing, and jet quenching** conspire to give **flat suppression pattern** out to the highest p_T at **RHIC** $\sqrt{s}_{NN} = 200 GeV$

$$R_{AA}(p_T) = 0.2 - 0.3 \approx N_{part} / N_{bin.}$$

3. At **LHC** $\sqrt{s}_{NN} = 5500 GeV$ the nuclear modification is **completely dominated by energy loss.** Predicts below $N_{part.}$ quenching, strong p_T dependence

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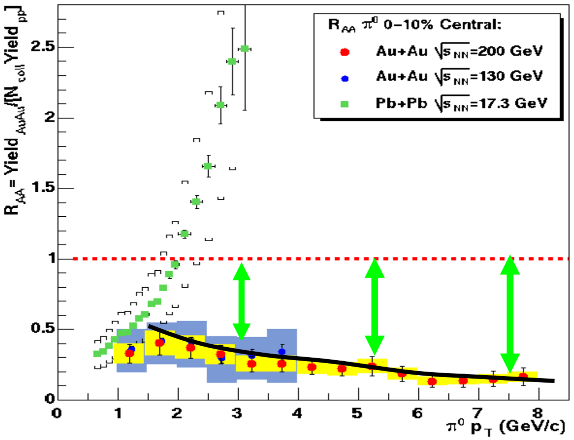
An Approach to Extracting the Effect of Energy Loss

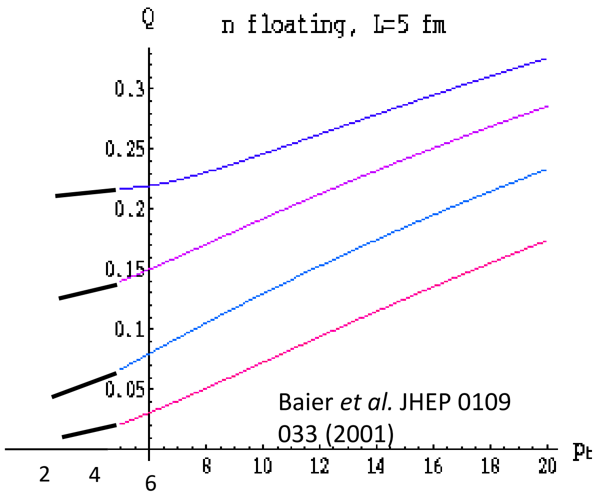


May be $R_{AA} : \Delta E \sim \sqrt{p_T}$

Authors claim:

$$Q(p_T) : Exp\left(-\frac{c}{\sqrt{p_T}}\right)$$

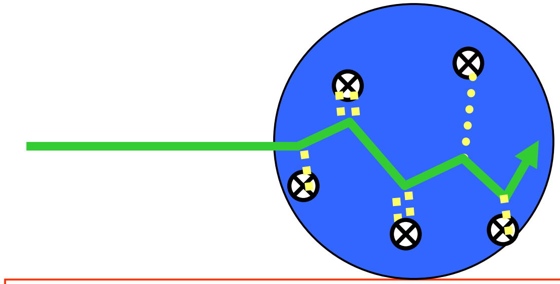
Very different behavior!



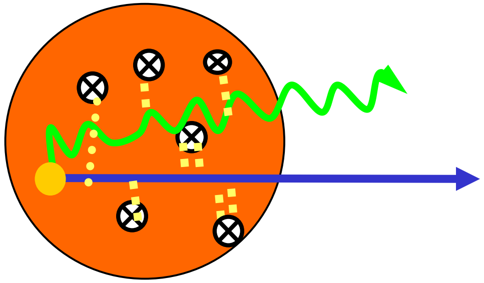
Baier *et al.* JHEP 0109 033 (2001)

Scale extended to small p_T

- **Isolate initial state effects from the measurements of p+p and d+A(p+A): Cronin effect and shadowing/antishadowing/EMC effect**
- **Estimate initial state effects in A+A:**
  1. **Naively:** $S_A(x,Q^2) \to \left(S_A(x,Q^2)\right)^2$, $g(k) \to \left(g(k)\right)^2$ **and** $R_{AA}(p_T)_{initial\ state} \approx \left(R_{dA}\right)^2$
  2. **In fact:** $R_{AA}(p_T)_{initial\ state} \approx 1+\alpha(R_{dA}-1)$, $\alpha \approx 1.8-2-2.5$
- **From d+A and A+A isolate the** ΔE **contribution to** $R_{AA}(p_T)$



Conclusions



❑ A wealth of experimental observables related to medium induced modifications were shown to be experimentally accessible at RHIC and LHC.

❑ Their correlated study is able to give a highly constrained picture of the properties of the quark-gluon plasma (QGP) created in heavy-ion reactions.

❑ The most clear cut separation is between initial and final state interactions.

Tomography results

Cold A	SPS	RHIC	LHC
$\rho_g \leq 1\, fm^{-3}$	$\rho_g \approx 5-10\, fm^{-3}$	$\rho_g \approx 30-55\, fm^{-3}$	$\rho_g \approx 130-275\, fm^{-3}$