Theory Overview of QGP and Cold Nuclear Matter Effects at RHIC

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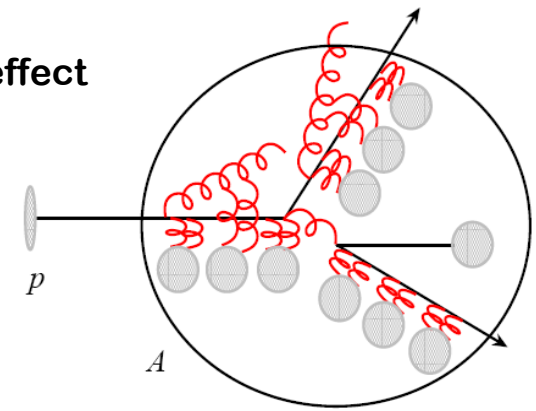
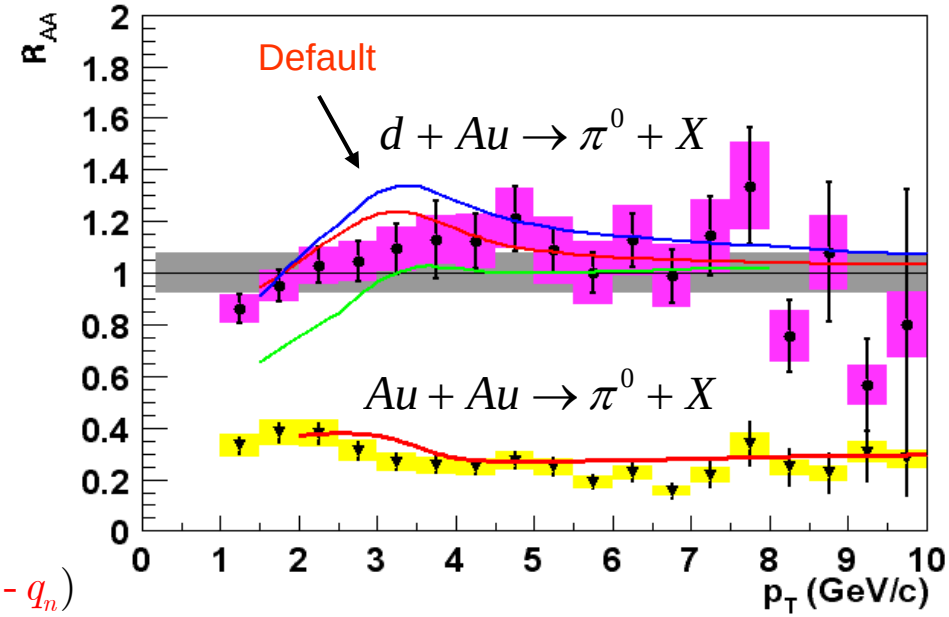
Cronin Effect in p+A Reactions

Scales: $Q \simeq p_T \geq Q_0 \sim 1-2\ GeV \gg \Lambda_{QCD}$

- **Cronin effect**



Good description at mid rapidity



I.V., Phys.Lett.B526 (2003)

$$dN^f(p) = \sum_{n=0}^{\infty} e^{-\chi} \frac{\chi^n}{n!} \int \prod_{i=1}^{n} d^2 q_i \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_i} dN^i(p - q_1 - \ldots - q_n)$$

$$dN^i(k_\perp) = \delta^2(k_\perp) \qquad dN^f(k_\perp) = \frac{1}{2\pi} \frac{e^{-\frac{k_\perp^2}{\chi \mu^2 \xi}}}{\chi \mu^2 \xi}, \qquad \chi = L/\lambda$$

Initial condition **Solution** **Mean number of scatterings**

The approximate solution is that of a 2D diffusion

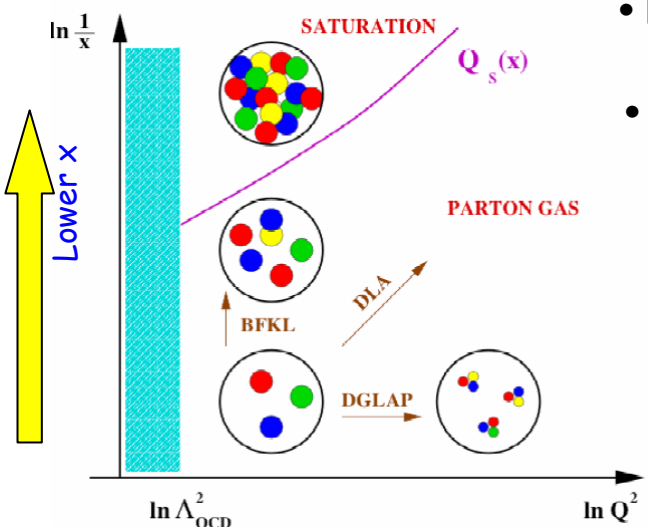
$$\text{For } \langle \Delta k_\perp^2 \rangle_{med} = 2\chi \mu^2 \xi$$

$$\langle \Delta k_\perp^2 \rangle_{tot} = \langle \Delta k_\perp^2 \rangle_{vac} + \langle \Delta k_\perp^2 \rangle_{med}$$

Implemented in the PQCD approach as k_T broadening of the initial state partons

A.Accardi, CERN yellow report, references therein

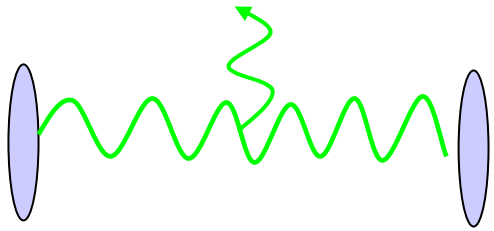
Gluon Saturation Models



- Nonlinear gluon evolution 2 to 1 processes
- Particle production via 2 to 1 processes (monojets)

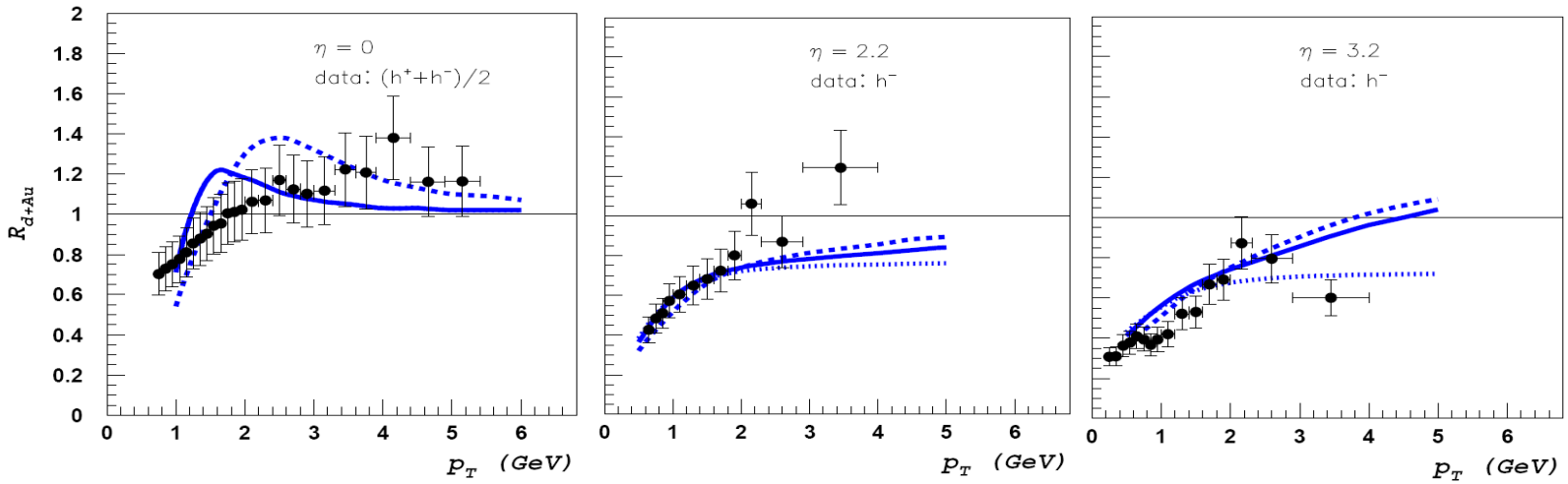
Gribov, Levin, Rishkin, Phys. Rep. (1980)

$$\frac{dN_g}{dy d^2x_T dp_T} \propto \frac{1}{p_T}\int d^2k_T \phi_A(x_1, \frac{\vec{p}_T+\vec{k}_T}{2})\phi_B(x_2, \frac{\vec{p}_T-\vec{k}_T}{2})$$



Brahms hadron forward suppression pattern

Note: are these monojets?



BRAHMS collab., Phys.Rev.Lett. 93 (2004)

Kharzeev, Kovchegov, Tuchin, hep-ph/0405045

Nuclear Shadowing

$$F_T(x,Q^2) = \frac{1}{2}\sum_f Q_f^2 \int d\lambda_0 e^{ix\lambda_0} \left\langle p \left| \bar{\Psi}(0) \frac{\gamma^+}{2p^+} \Psi(\lambda_0) \right| p \right\rangle$$

$$= \frac{1}{2}\sum_f Q_f^2 \, \phi_f(x,Q^2) + \mathcal{O}(\alpha_s) \qquad x_B = \frac{Q^2}{2m_N \nu}$$

- **Simplistic view: modification of the nuclear wave function**

Longitudinal size: $\sim 1/2m_N x$

If $x < 0.1$ **then** $\Delta z > r_0$

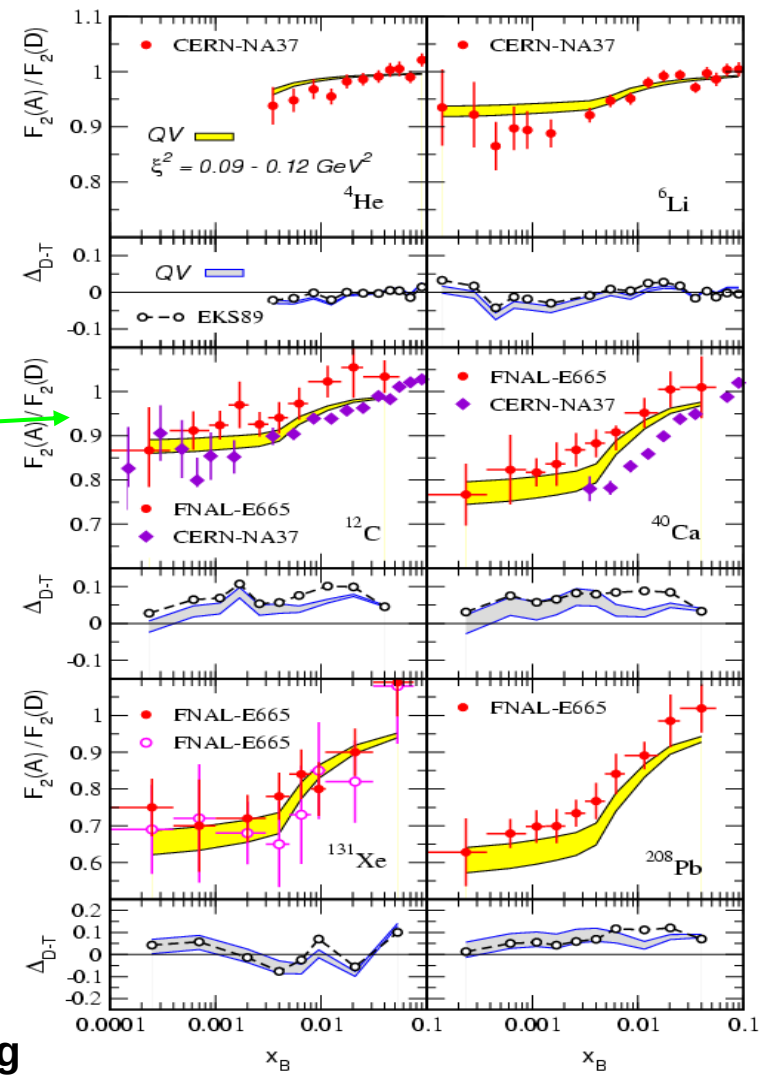
$$F_T^A(x,Q^2) \approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2\right) = A\, F_T^{(LT)}\left(x\left(1+\frac{m_{dyn}^2}{Q^2}\right), Q^2\right)$$

Alternative model: "leading twist" $\sim \ln Q^2$

S.Brodsky et al, Phys.Rev.D65 (2002)

- **Shadowing is dynamically generated in the hadronic collision y coherent final state scattering**

Deviation from A-scaling: $\sigma_A \neq A \times \sigma$

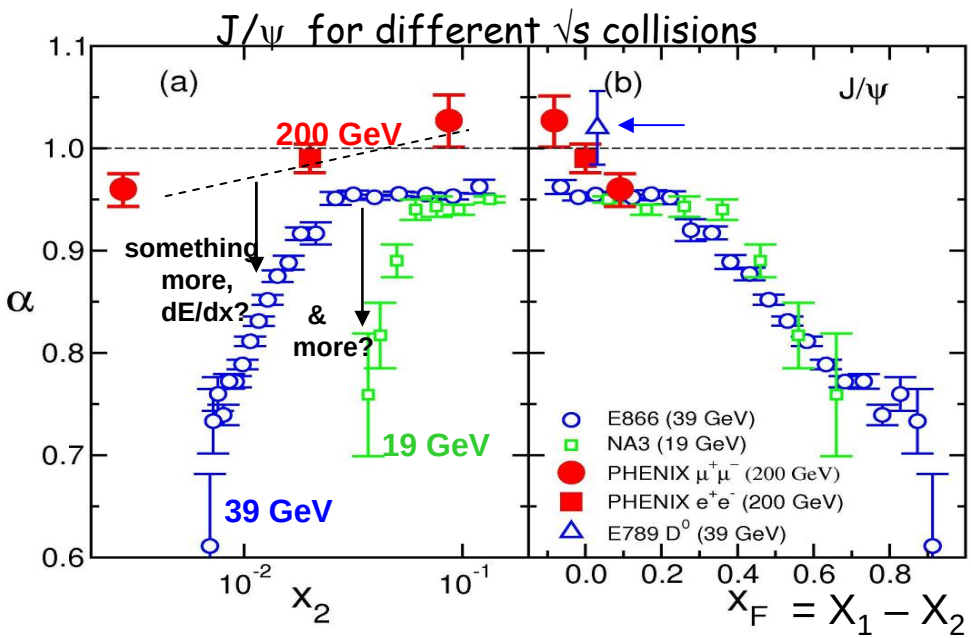


J.W.Qiu, I.V., Phys.Rev.Lett. 93 (2004)

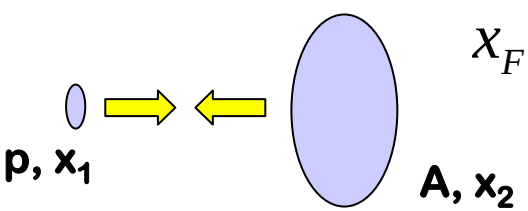
Evidence for Energy Loss

M.Leitch et al. PHENIX,EA866 and NA3 data

Cross section scaling: $\sigma_A = A^{\alpha}\sigma_N$

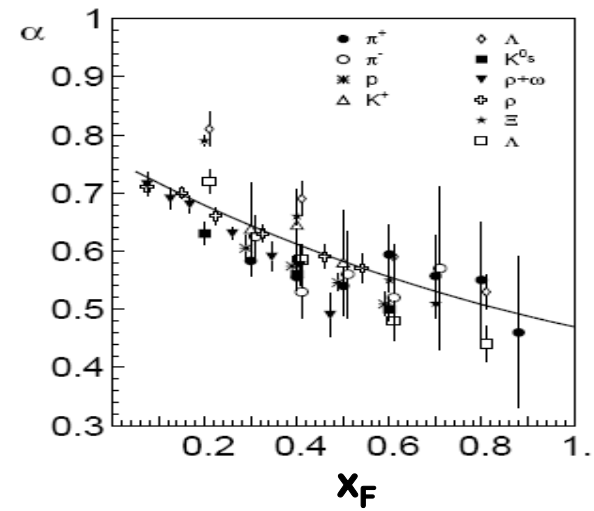


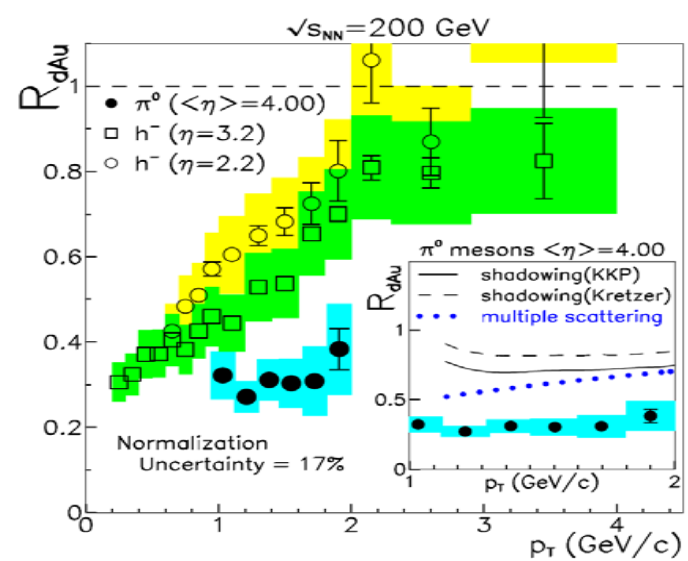
$$x_F \approx x_1, \ if \ x_2 \ll 1$$



- **Energy loss is a dominnant mechanism in the forward rapidity / large x_F suppression**

B.Kopeliovich et al. hep-ph/0501260





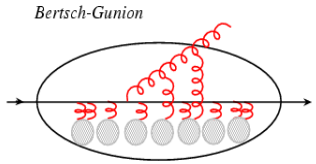
S.S.Adler et al., nucl-ex/0603017

Nuclear Effects at Forward Rapidity

- **Original incoherent result:**

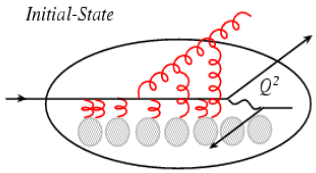
G.Bertsch and F.Gunion, Phys.Rev.D (1982)

$$\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \times const(1) \times \ln \frac{E}{Q_0}$$



- **Original incoherent resu**

$$\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \times const(2) \times \ln \frac{E}{Q_0}$$

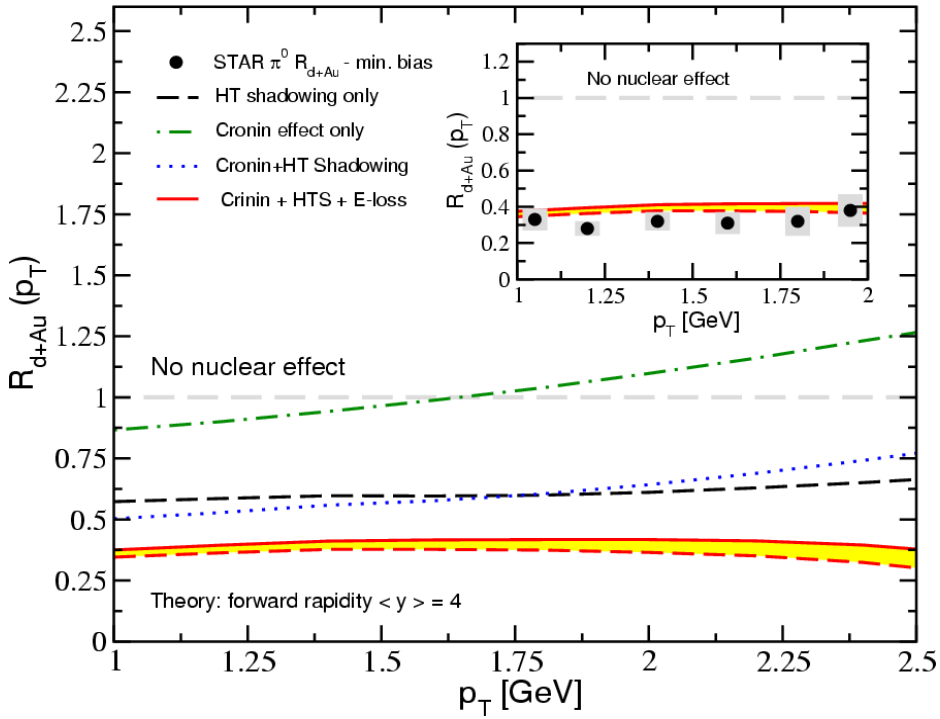


I.V., in preparation (2006)

Six fold cancellation $\frac{const(2)}{const(1)} \approx \frac{1}{6}$

Extreme radiation length $X_0 \approx 100 \ fm$

S.S.Adler et al., nucl-ex/0603017



I.V., T.Goldman, M.B.Johnson, J.W.Qiu, Phys.Rve.D74 (2007)

- **Note the different contributions to an overall suppression effect**
- **The most detailed calculation do far at forward rapidity**

Particle Production Mechanism

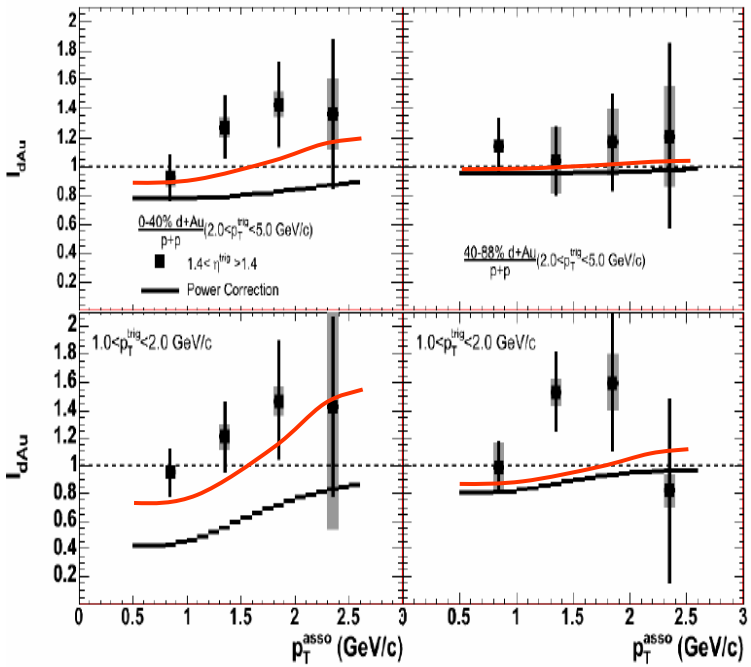
$$I^{c}_{d+Au} = \frac{N^{d+Au}_{asso}/N^{d+Au}_{trig}}{N^{p+p}_{asso}/N^{p+p}_{trig}}$$

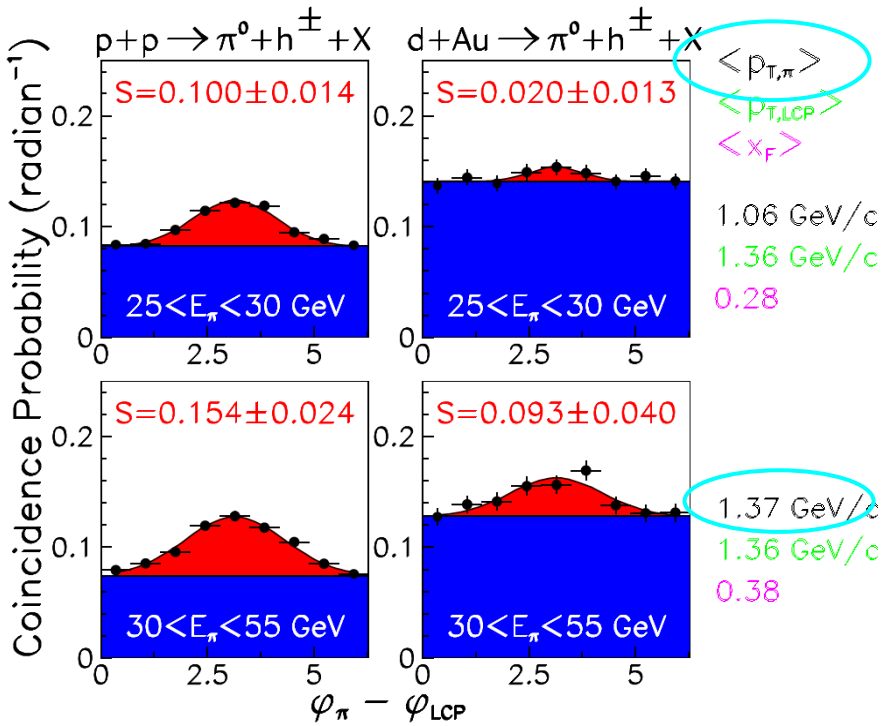
Dijets:

$$\frac{d\sigma^{h_1 h_2}_{NN}}{dy_1 dy_2 d^2 p_{T1} d^2 p_{T2}} = \frac{\delta(\Delta\varphi - \pi)}{p_{T1} p_{T2}} \sum_{abcd} \int_{z_1\,\min}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2) \frac{\phi(\bar{x}_a)\phi(\bar{x}_b)}{\bar{x}_a \bar{x}_b} \frac{\alpha_s^2}{S^2} \left|\bar{M}^{2}_{ab\to cd}\right|$$

Monojets:

$$\frac{dN_g}{dy d^2 x_T dp_T} \propto \frac{1}{p_T} \int d^2 k_T \phi_A(x_1, \frac{\vec{p}_T + \vec{k}_T}{2}) \phi_B(x_2, \frac{\vec{p}_T - \vec{k}_T}{2})$$





- **Excludes:** all the monojet color glass phenomenology, large final state energy loss
- **Compatible with:** Dynamical shadowing, initial state energy loss, leading twist shadowing parameterizations

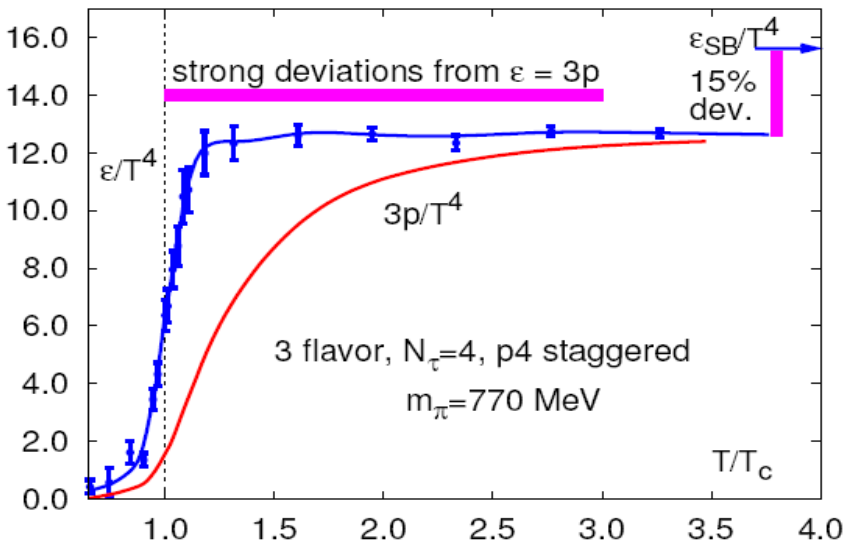
The QCD Phase Transition

Asymptotic freedom:

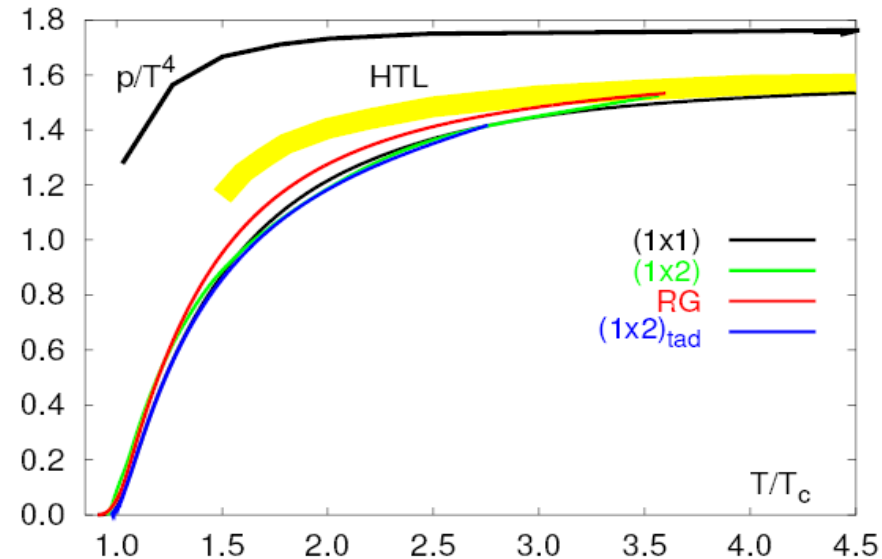
$$\alpha_s^{LO}(Q^2, n_f) = 4\pi / \left(11 - \tfrac{2}{3} n_f\right) \ln \frac{Q^2}{\Lambda_{QCD}^2}$$

$$T \gg gT \gg g^2 T$$

$$\alpha_s(Q^2, n_f) = \alpha_s^{LO}(Q^2, n_f) \left[1 - \frac{1}{4\pi} \frac{102 - \frac{38}{3} n_f}{11 - \frac{2}{3} n_f} \alpha_s^{LO}(Q^2, n_f) \ln \ln \frac{Q^2}{\Lambda_{QCD}^2} \right]$$



F.Karsch,E.Laermann,A.Peikert, Phys.Lett.B487, (2000)



J.P.Blaizot,E.Iancu,A.Rebhan, Phys.Lett.B470, (1999)

- **Deviation from Stefan-Boltzman: the log running of α_s**

Note: recent results T_c~ 190 MeV vs T_c~ 175 MeV

Note on LHC versus RHIC: strongly versus weakly coupled plasmas, beware of logarithmic running

- **Hard thermal loop calculations: improved resummation of the perturbation series**
- **Agreement between HTL and Lattice for $T \geq 3T_c$**

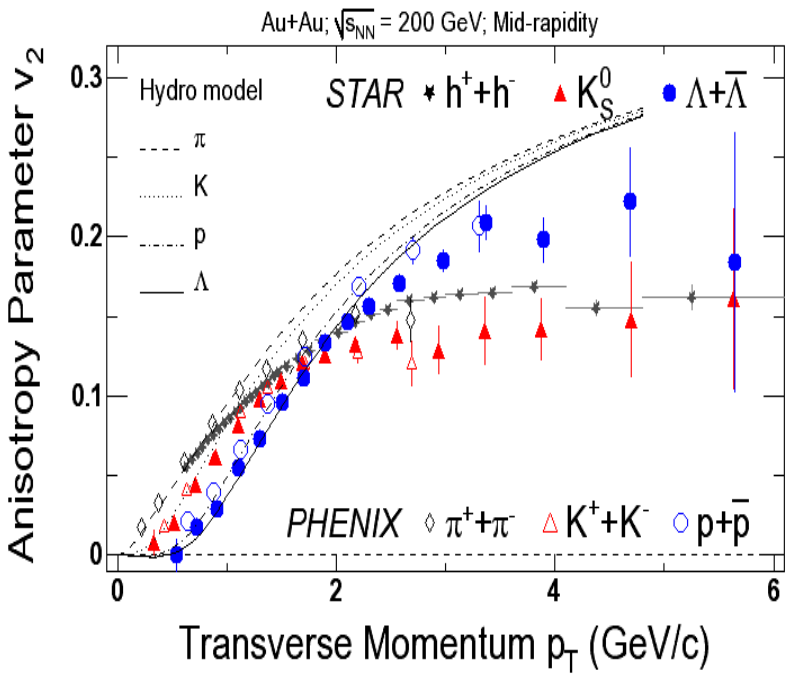
Relativistic Hydrodynamics

$$u^{\mu}(x)$$

$$T^{\mu\nu}(x) = \left(\varepsilon(x) + p(x)\right)u^{\mu}(x)u^{\nu}(x) - p(x)\,g^{\mu\nu}$$

$$j_{\alpha}{}^{\mu}(x) = n_{\alpha}u^{\mu}(x)$$

Ideal hydro, initial conditions

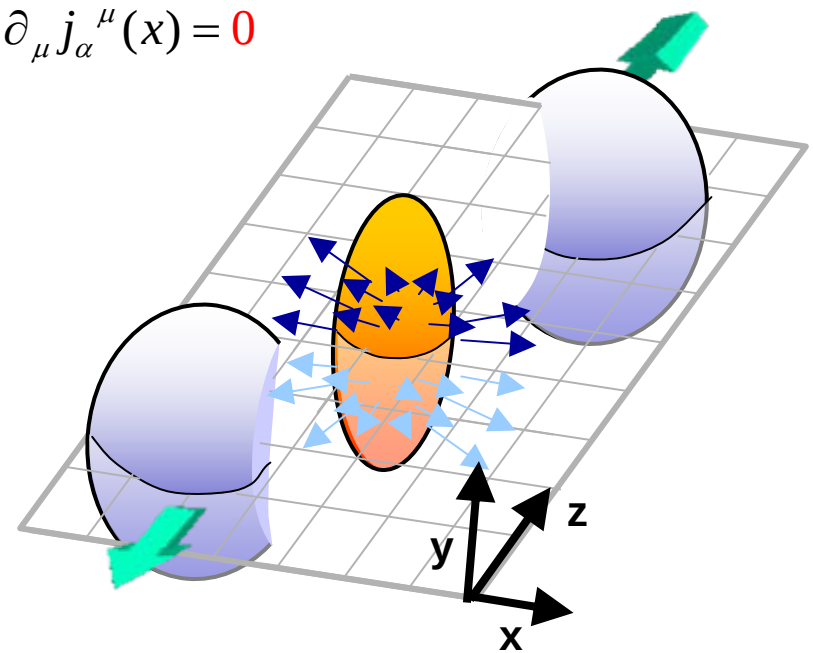


P.Kolb,J.Sollfrank,U.Heinz, Phys.Rev.C62, (2002)

$$\partial_{\mu}T^{\mu\nu}(x) = 0$$

$$\partial_{\mu}j_{\alpha}{}^{\mu}(x) = 0$$

Elliptic flow

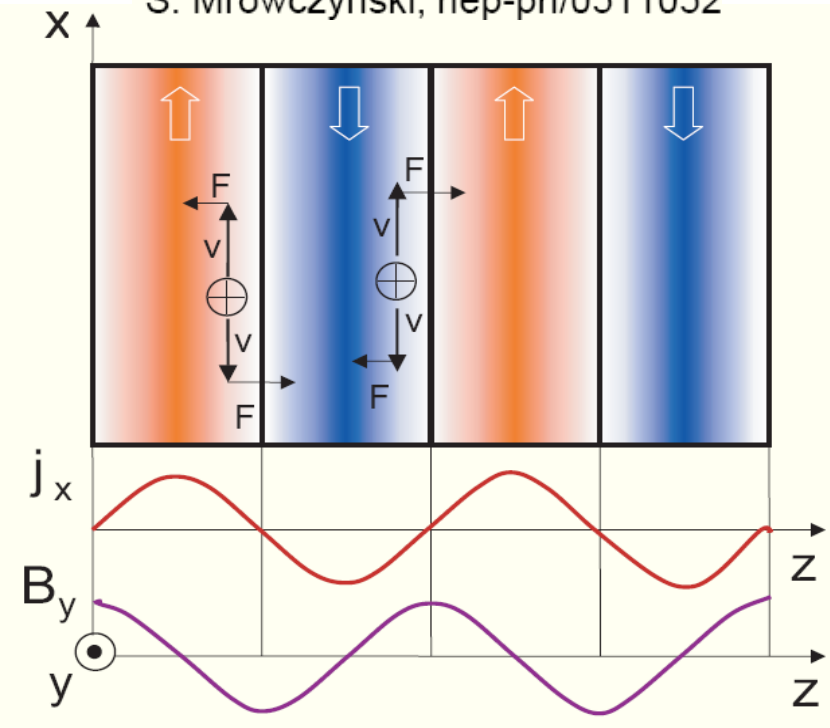


$$\frac{dN^h}{dyd^2p_T d\phi} = \frac{1}{2\pi}\frac{dN^h}{dyd^2p_T}\left(1 + 2v_2(\cos 2\phi) + \ldots\right)$$

- **Favors:** **EoS with QCD phase transition, low viscosity, early thermalization** $\tau_0 < 1\ fm$ **high energy density** $\varepsilon_0 > 15\ GeV/fm^3$

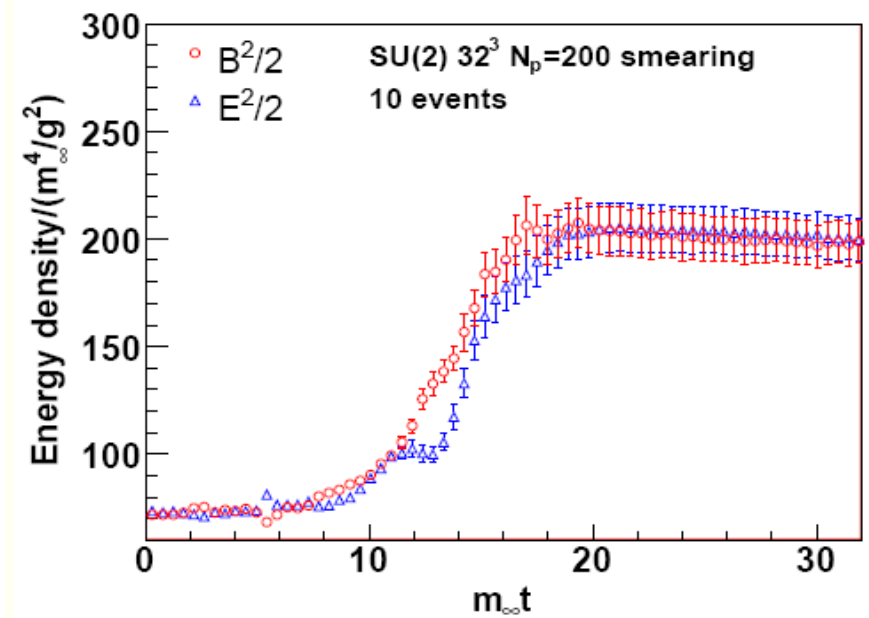
Plasma Instabilities

S. Mrówczyński, hep-ph/0511052



Current filamentation

A. Dumitru, Y. Nara, and M. Strikland , hep-ph/0604149



$L = 5$ fm, $p_{\rm hard} = 16$ GeV,

$g^2\, n_g = 10/\text{fm}^3$, $m_\infty = 0.12$ GeV.

Vlasov equation:

$$p^\mu[\partial_\mu - gq^a F^a_{\mu\nu}\partial^\nu_p - g f_{abc} A^b_\mu q^c \partial_{q^a}] f(x,p,q) = 0$$

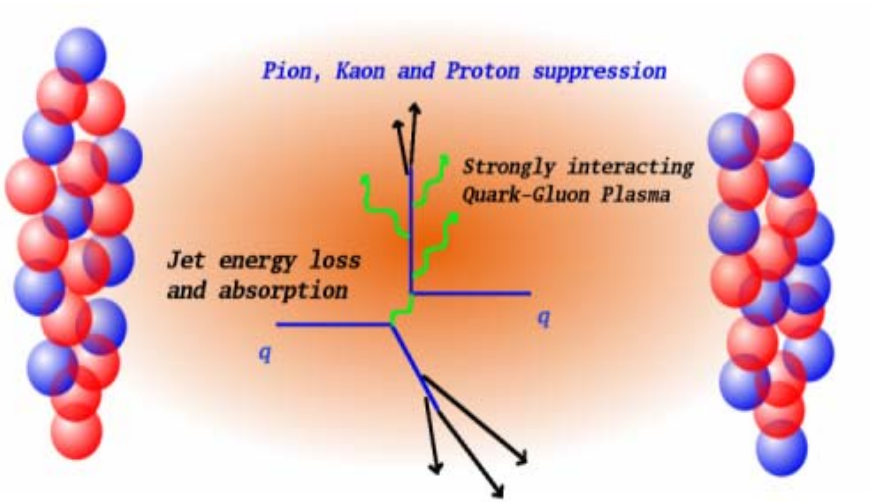
Yang-Mills equation:

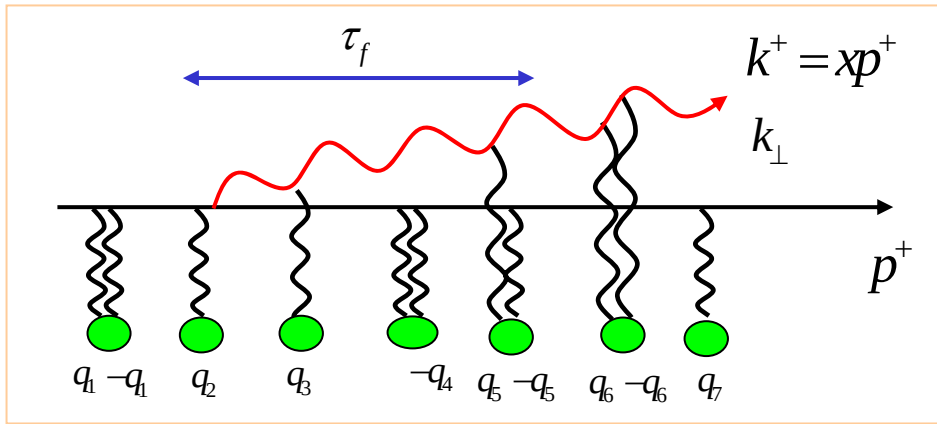
$$D_\mu F^{\mu\nu} = J^\nu = g \int \frac{d^3p}{(2\pi)^3} dq\, q\, v^\nu f(t, \boldsymbol{x}, \boldsymbol{p}, q)$$

Note on time scales: **t = 10 fm, still too large**

Energy Loss in the QGP

- **The most important effect in dense nuclear matter: QGP but also cold nuclei**





LPM = Landau-Pomeranchuk-Migdal

QED: $$\frac{dE^{rad}}{dz} \propto \frac{E}{X_0}$$ ⇒ **QCD:**

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– **Static medium**

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– **1+1D Bjorken**

M.Gyulassy, X.N.Wang, Phys.Rev.Lett.68, (1992)

R.Baier *et al.* Nucl.Phys.B (1997)

M.Gyulassy, P.Levai, I.V., Nucl.Phys.B594, (2001)
Phys.Rev.Lett.85, (2000)

System Size Dependence of Jet Quenching

Identifying nuclear effects:

$$A + A \to \pi^0 + X$$

$$R_{AA}(p_T,\eta) = \frac{1}{< N_{coll} >} \cdot \frac{d^2\sigma^{AA}/d\eta dp_T}{d^2\sigma^{NN}/d\eta dp_T}$$

$$\varepsilon = \frac{\Delta E}{E} = \sum_{i=1}^{\infty} \frac{\omega_i}{E}$$

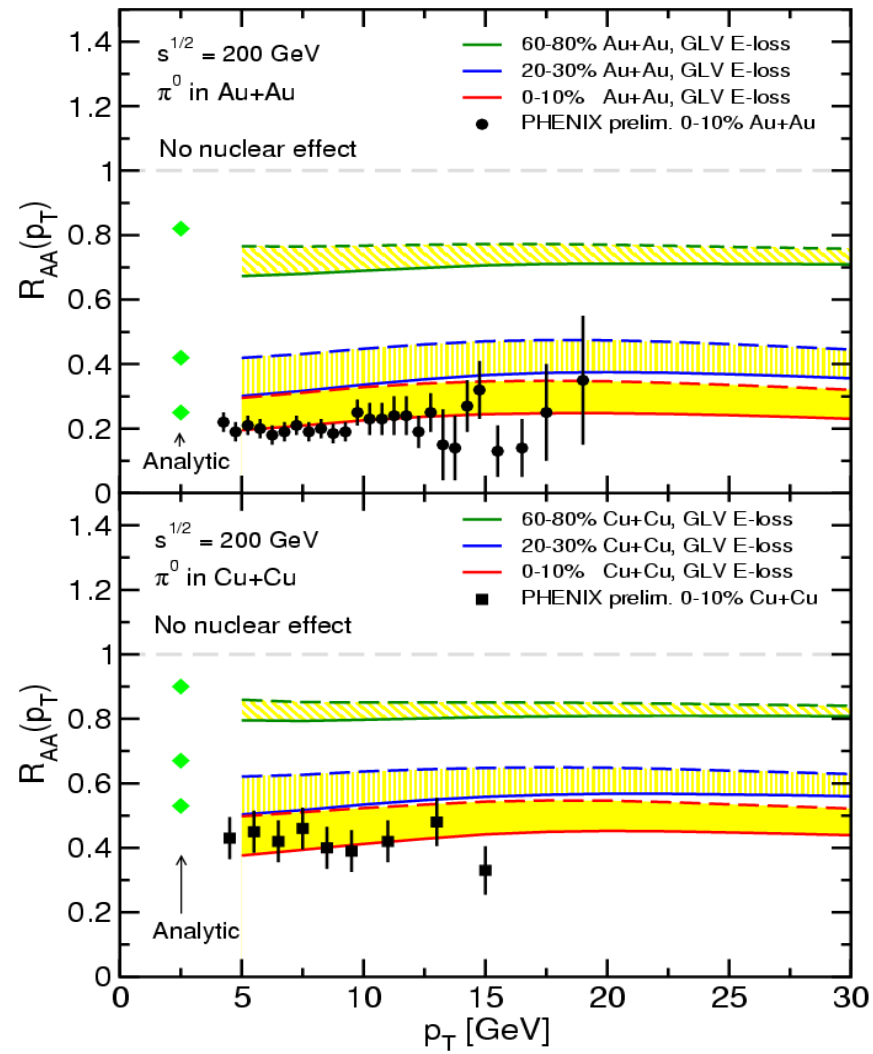
Probability density - $P(\varepsilon)$

$$p_c \to p_c(1-\varepsilon), \quad z_c \to \frac{z_c}{(1-\varepsilon)}$$

$$D'_{h/q}(z,Q^2) = \int_0^1 d\varepsilon\, P(\varepsilon) \frac{1}{1-\varepsilon} D^{vac}_{h/q}\left(\frac{z}{1-\varepsilon}, Q^2\right) + \int_0^1 d\varepsilon \frac{dN^g}{d\varepsilon}(\varepsilon) \frac{1}{\varepsilon} D^{vac}_{h/g}\left(\frac{z}{\varepsilon}, Q^2\right)$$

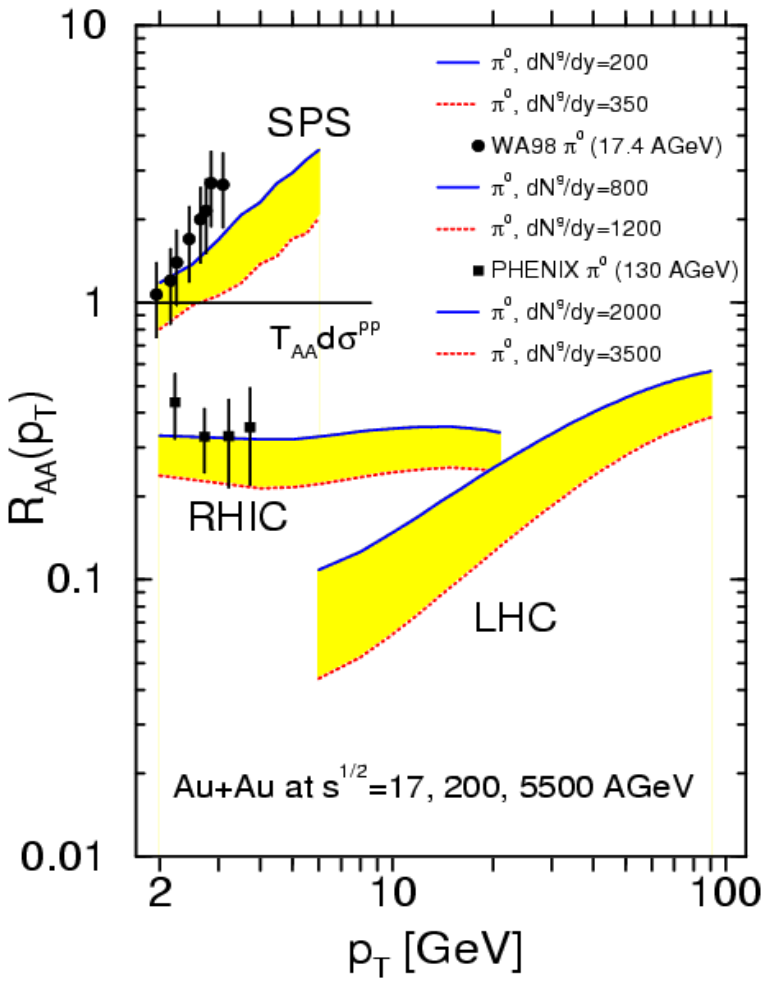
- **In classes with the same N_{part} we find numerically the same suppression R_{AA}**

(For example central Cu+Cu and mid central Au+Au)



I.V., Phys.Lett.B 639 (2006)

Jet Tomography

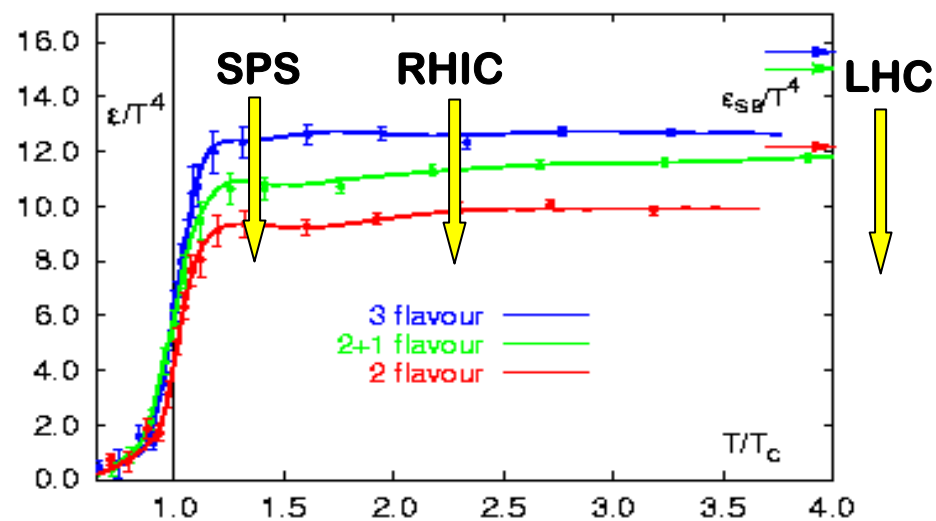


I.V., M.Gyulassy, Phys.Rev.Lett. 89 (2002)

$$I(r) = I_0 e^{-\int_0^r dr' \,/\lambda_{abs}(r')} = I_0 e^{-\int_0^r dr' \,\sigma_{abs}(r')\rho(r')}$$

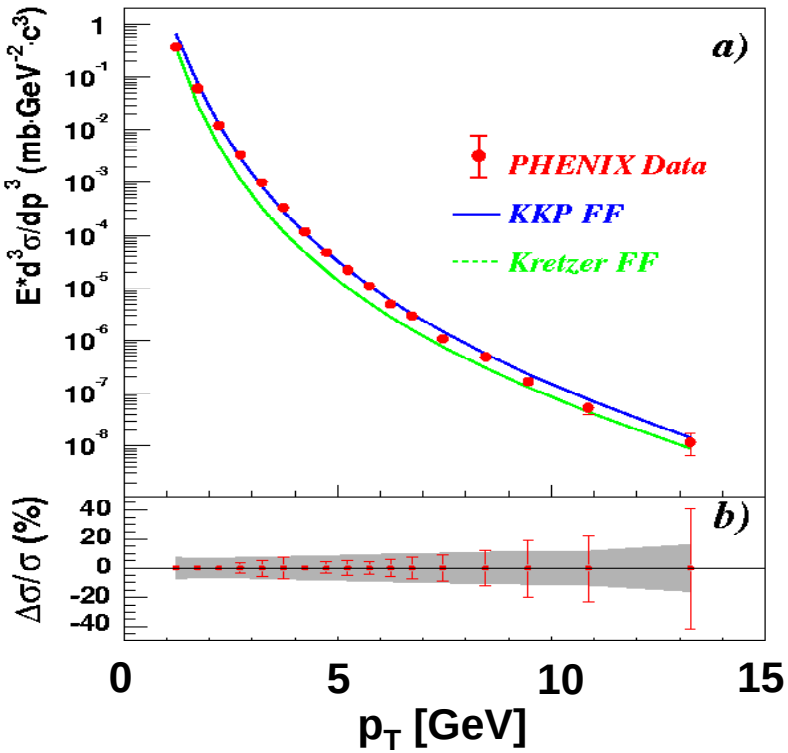
Principles of jet tomography

	τ_0 [fm]	τ_{tot} [fm]	T_0 [MeV]	ϵ_0 $\left[\frac{GeV}{fm^3}\right]$	$\frac{dN^g}{dy}$
SPS	0.8	1.3 – 2.3	205 – 245	1.2 – 2.6	200 – 350
RHIC	0.6	5.5 – 8	360 – 410	12 – 20	800 – 1200
LHC	0.2	13 – 23	710 – 850	170 – 350	2000 – 3500

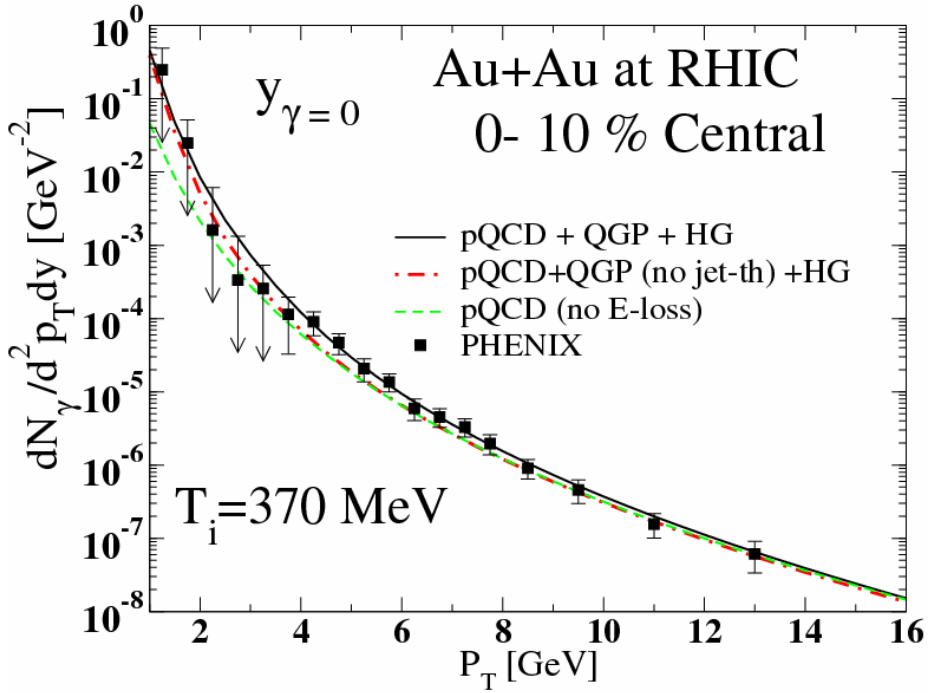


F.Karsch, Nucl.Phys.A698 (2002)

Hard Processes



V.Wogelsang *et al.*, Phys.Rev.D



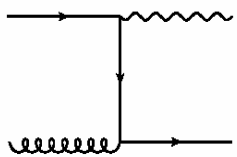
S.Turbide *et al.*, Phys.Rev.C72:014906,2005

$$\frac{d\sigma_{NN}^{h_1}}{dy_1 d^2 p_{T1}} = \sum_{abcd} \int_{x_a\,\min}^{1} dx_a \int_{x_b\,\min}^{1} dx_b\, \phi(x_a)\phi(x_b) \frac{\alpha_s^2}{(x_a x_b S)^2} \left|\bar{M}_{ab\to cd}^{\;2}\right| \frac{D_{h_1/c}(z_1)}{z_1}$$

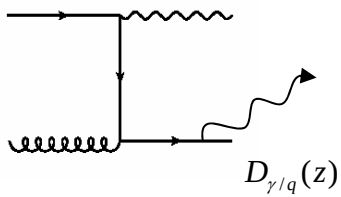
- Particle production: $2 \to 2$ processes
- Direct photons: no final state interactions and no attenuation

Note: prompt versus fragmentation photons

$qg \to q\gamma$

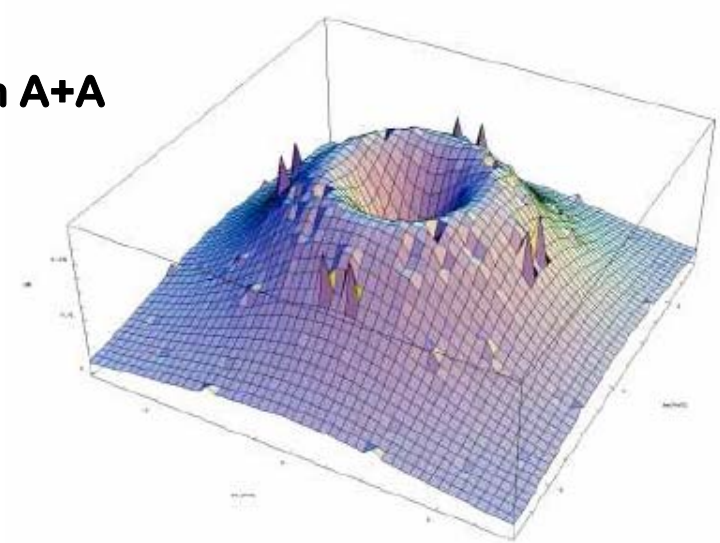


$qg \to qg + \gamma$

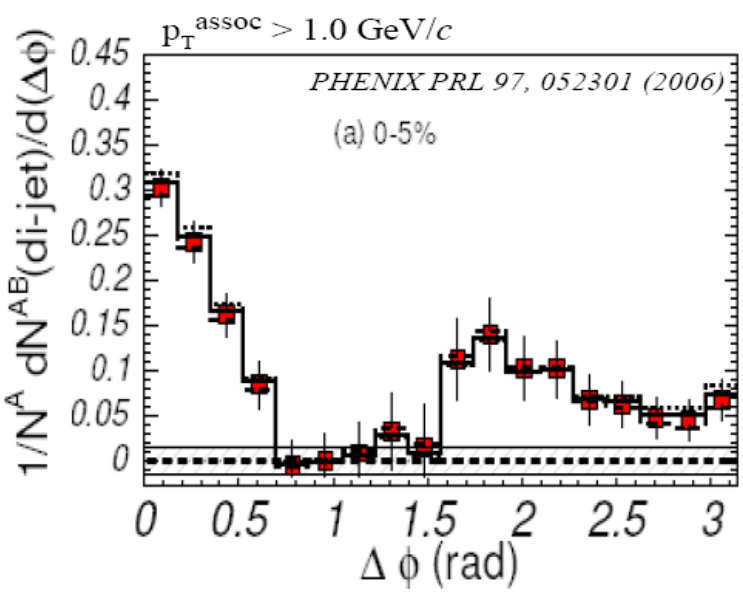


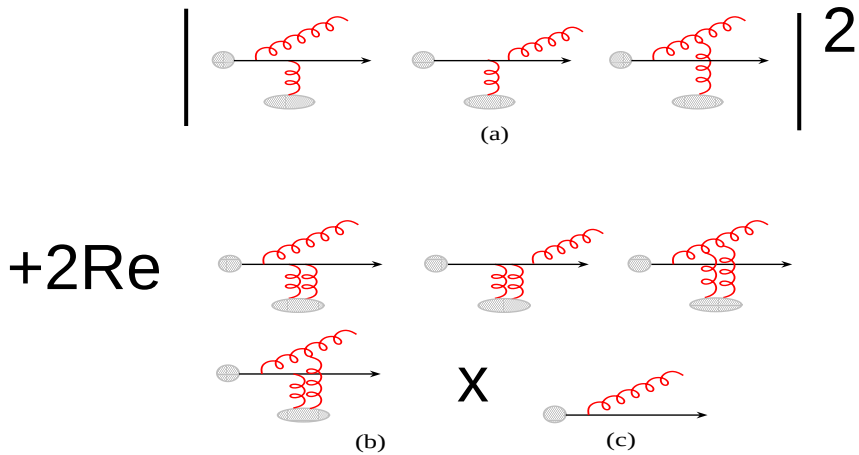
What Happens to Medium-Induced Radiation

In A+A



I.V., Phys.Lett.B630 (2005)





$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^{*} d\delta} \propto \left(\left|M_a\right|^2 + 2\,\mathrm{Re}\,M_b^{*}M_c\right) + \ldots$$

- **Cancellation of collinear radiation**

$$k_\perp \to 0,\ \ k_\perp/\omega \to 0$$

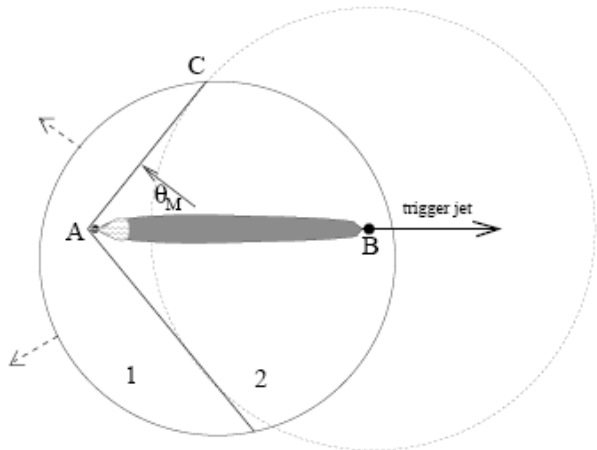
large angle soft gluons and correspondingly more soft hadrons

S.Pal, S.Pratt, Phys.Lett.B574 (2003)

- **It is broad but is it dipped?**

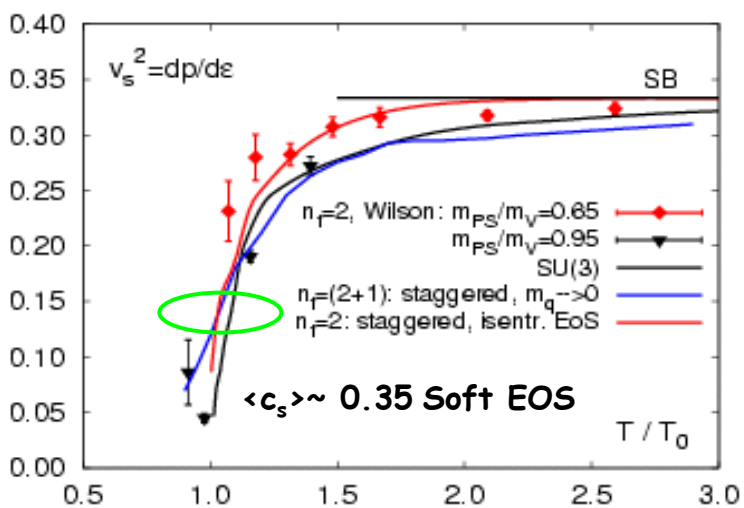
Note: strong theoretical arguments against Strong "dip"

Mach Cones and Sound Velocity

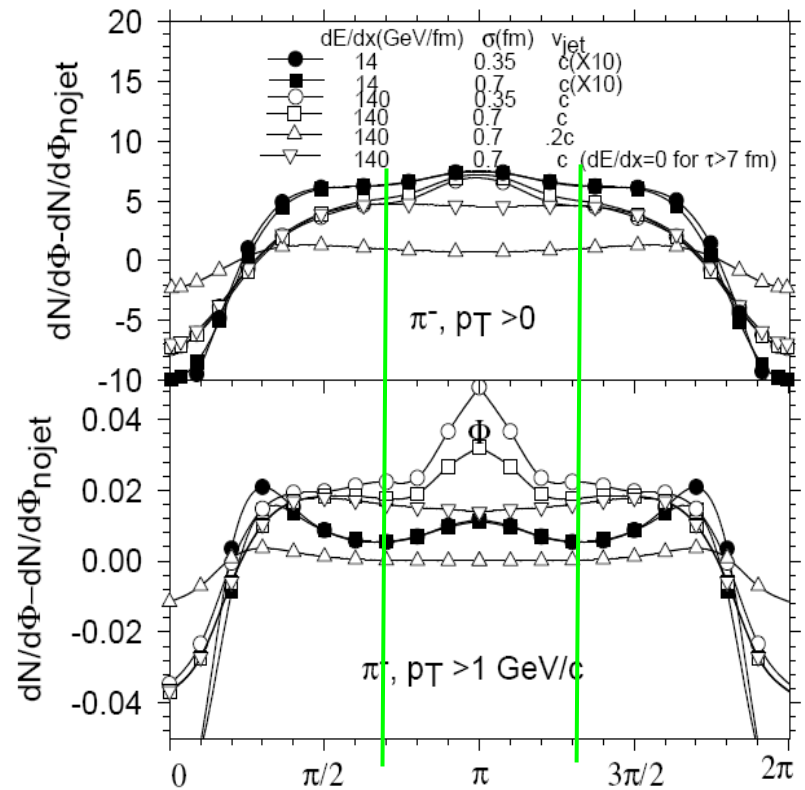


J.Casalderrey-Solana et. al, Nucl. Phys.A774, (2006)

$$\theta_{emission} = \pi \pm arccos(\bar{c}_s/c) \approx 1.9, 4.3$$



F. Karsch, hep-lat/0601013

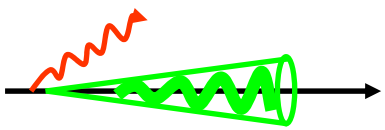


A.Chaudhuri, U.Heinz, Phys.Rev.Lett. 97 (2006)

- Hydro simulations do not confirm such mechanism
- There is no realistic simulation of the di-jet distributions yet!

Heavy Quark Production and Modification

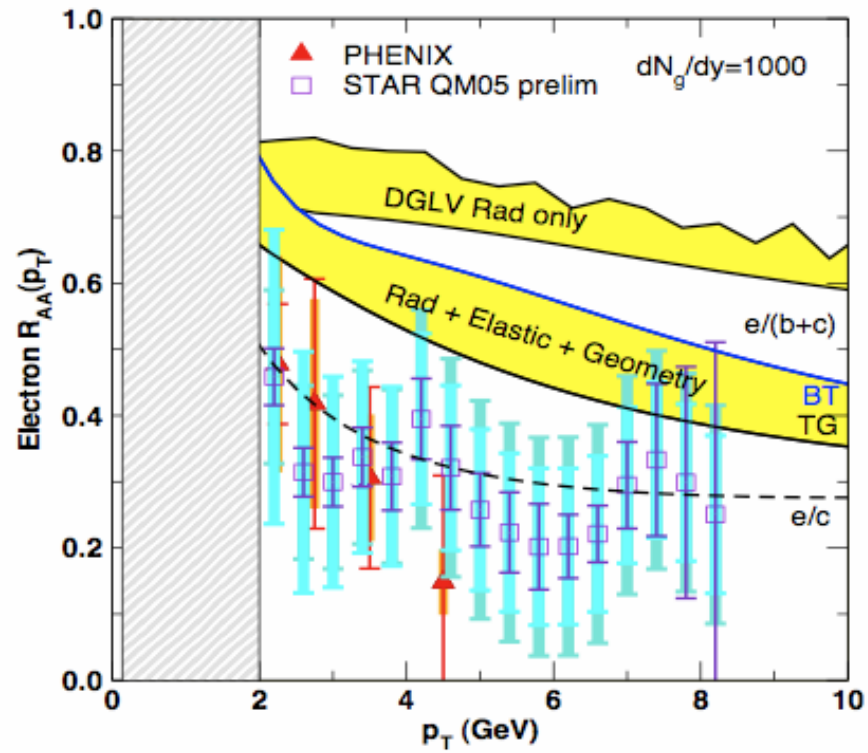
- Single electron measurements (presumably from heavy quarks) may be problematic



$$\left[\omega_{(1\ldots n)}\right]^{-1} \rightarrow \left[\omega_{(1\ldots n)} + \frac{m_g^2 + x^2 M^2}{2xE}\right]^{-1}$$

$$\frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2}} \rightarrow \frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2} + m_g^2 + x^2 M^2}, \quad x = \frac{k^+}{p^+} \approx \frac{\omega}{E}$$

M.Djordgevic, M.Gyulassy, Nucl.Phys.A (2004)



S. Wicks et al., nucl-th/0512076

- Significant interest in collisional energy loss

Note: what is important is consistent evaluation of collisional versus radiative E-loss

- Problem: treated in the same way as light quarks!

$\tau_f(p_T = 10\ GeV)$

π	D	B
10 fm	1.0 fm	0.35 fm

- Interactions beyond the partonic level

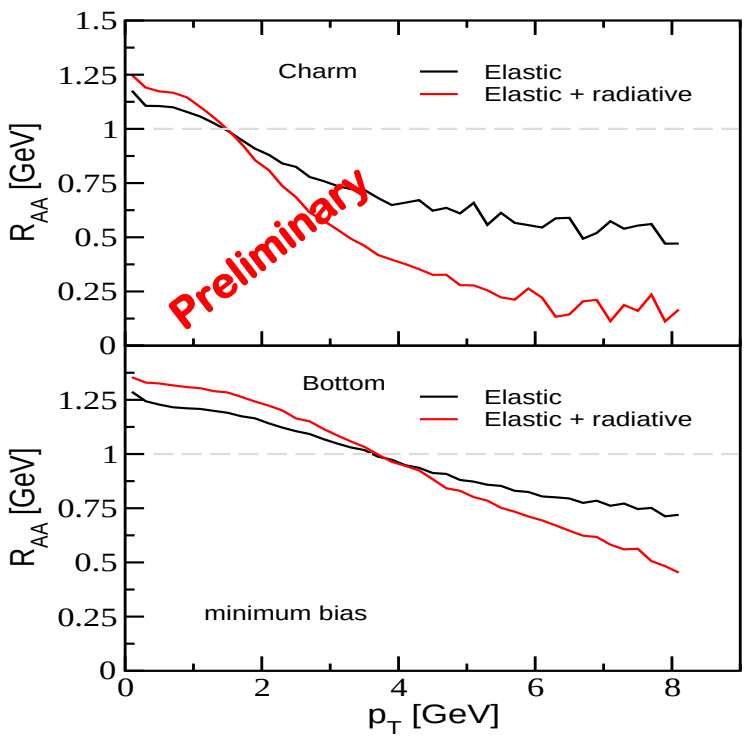
$$\Delta y^+ = \frac{1}{\Delta p^-} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^+}{k_\perp^{\,2} + (1-z)m_h^{\,2} - z(1-z)M_q^{\,2}}$$

Diffusion and Dissociation of Heavy Mesons

H.van Hees, I.V., in preparation

- Langevin simulation of heavy quark diffusion

Drag coefficient: $A_i = \frac{1}{p_i}\frac{\langle \delta p_i \rangle}{\delta t}$

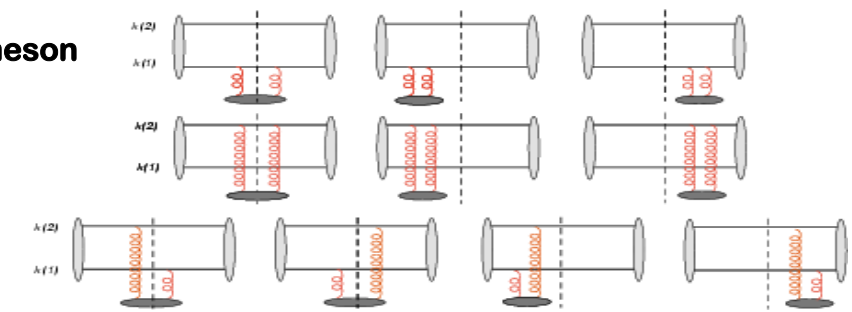


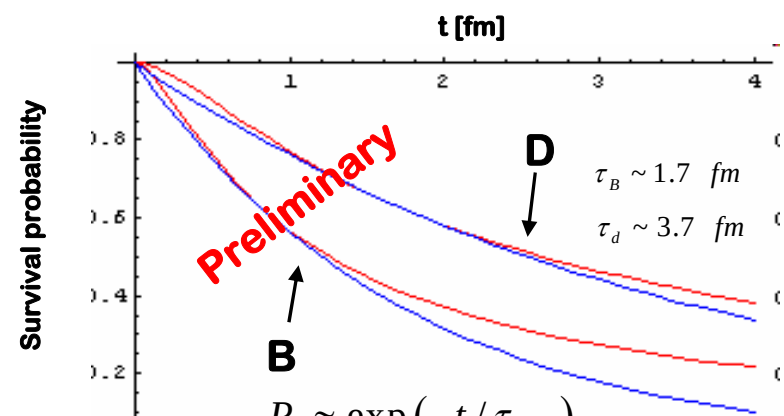
- B is significantly less quenched than D

A.Adil, I.V. in preparation

- Collisional dissociation of heavy mesons

D(B) meson





$$P_s \approx \exp\left(-t/\tau_{diss}\right)$$

$$\left(\Delta E/E\right)_b = 0.2,\ \left(\Delta E/E\right)_c = 0.35$$

- B is comparably quenched to D

Conclusions

▶ Cold nuclear matter effects:

- Particle production consistent with hard parton scattering, no monojets
- Nuclear effects arise dynamically from elastic, inelastic and coherent multiple parton scattering
- "Leading twist" versus "high twist" shadowing theory from final state interactions. Test at EIC. Bring a broader community to EIC
- Theoretical advances in understanding energy loss in cold nuclear matter. It appears to be a dominant effect at forward rapidity p+A reactions
- p+A program at RHIC II, vary C.M. energy. Advance theoretical models

▶ Quark-gluon plasma effects:

- LQCD predicts T_c=175 – 190 MeV, no colored bound states. EoS consistent between LQCD and HTL. Deviations from SB, log running of alpha
- Hydro simulations of v_2 suggest early thermalization, e_0 = 15 GeV/fm^3
- Non-Abelian plasma instabilities: path to isotropisation, time still too long
- Final state non-Abelian energy loss in the QGP is the dominant jet quenching mechanism. Tested against p+A and direct photons
- Jet tomography: e_0 = 15 GeV/fm^3 based on successful PQCD predictions
- Energy redistributed in soft particles. Mach cones? Strong theoretical arguments against. Lack of accurate simulations.
- Heavy flavor still problematic, highlights collisional E-loss. New mechanisms should be explored. Collisional dissociation of mesons, promising.