Energy Loss and Nuclear Final State Effects

Rainer J. Fries

University of Minnesota

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Hard Processes in a Nuclear Environment

- Hard processes involving large nuclei:
  Importance of initial and final state interactions increases with size.

- Partons have to travel through nuclear matter:
  - energy loss
  - momentum broadening
  - modification of PDFs/fragmentation functions

- Theory of multiple scattering:
  - higher twist contributions in pQCD
  - phenomenological descriptions

- A+A: huge final state effects, jet quenching at RHIC.

- e+A collisions: final state effects in cold nuclear matter

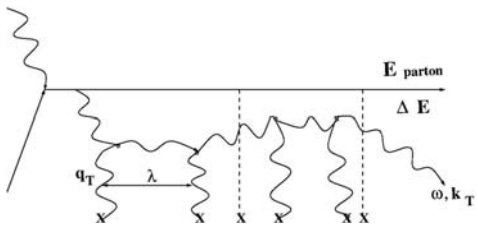
Overview

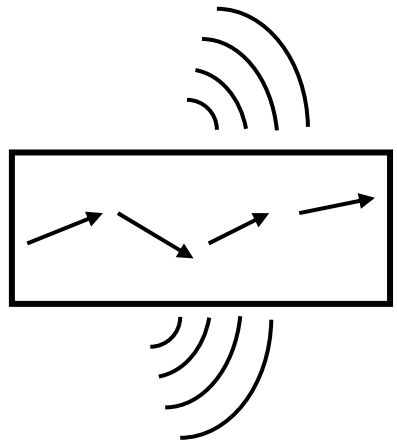
- Motivation
- LPM effect, BDMPS approach
- LQS theory, higher twist
- Medium-modified fragmentation functions
- Other developments
- Connection with RHIC
- Comparison of models
- Outlook

Coherent and incoherent scattering

Two length scales given by the medium:

- mean free path $\lambda = 1/\rho\sigma$
- length of the medium L





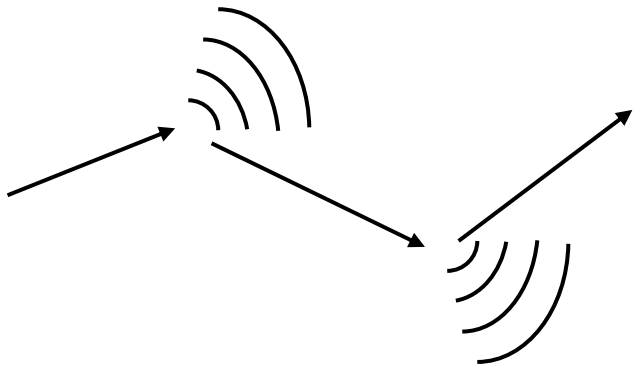
Formation time for radiation $t_{form} = \omega/k_T^2$

Coherence length $$l_{\rm coh} = \frac{\omega}{\langle k_T^2 \rangle_{coh}}$$

Coherent scattering $t_{form} >> \lambda$

Transverse momentum accumulated through random walk:

$$\langle k_T^2 \rangle_{\rm coh} \sim N_{\rm coh}\mu^2 = \frac{l_{\rm coh}}{\lambda}\mu^2$$



$$\Rightarrow \quad l_{\rm coh} = \sqrt{\frac{\lambda}{\mu^2}\omega} \qquad N_{\rm coh} = \sqrt{\frac{\omega}{E_{\rm LPM}}}$$

$$E_{\rm LPM} = \lambda\mu^2$$

Incoherent scattering $t_{form} << \lambda$

LPM Effect

- $\omega < E_{\mathrm{LPM}}$, $l_{\mathrm{coh}} < \lambda$: Incoherent regime

$$\omega \frac{dI}{d\omega dz} \sim I_0 \frac{1}{\lambda}$$

- $E_{\mathrm{LPM}} < \omega < \omega_L$, $\lambda < l_{\mathrm{coh}} < L$: LPM regime

$$\omega \frac{dI}{d\omega dz} \sim I_0 \frac{1}{l_{\mathrm{coh}}} = I_0 \sqrt{\frac{\mu^2}{\lambda\omega}}$$

$$\omega_L = \frac{\mu^2}{\lambda} L^2 = E_{\mathrm{LPM}} \frac{L^2}{\lambda^2} \qquad I_0 = \frac{\alpha_s}{\pi} N_c$$

$\Rightarrow$ LPM suppression factor $\sqrt{E_{\mathrm{LPM}}/\omega}$

- $\omega_L < \omega < E$, $l_{\mathrm{coh}} > L$: Coherent regime

$$\omega \frac{dI}{d\omega dz} = I_0 \frac{1}{L}$$

LPM energy loss:

$$\frac{dE}{dz} \sim -I_0 \sqrt{\frac{\mu^2}{\lambda}\omega_L} = -I_0 \frac{\mu^2}{\lambda} L$$

For $E < \omega_L$:

$$\frac{dE}{dz} \sim -I_0 \frac{1}{\lambda} \sqrt{E_{\mathrm{LPM}} E}$$

Jet Broadening

Transport coefficient: $\hat{q} \sim \frac{\mu^2}{\lambda} \sim \rho \int d^2 q_T \, q_T^2 \frac{d\sigma}{d^2 q_T}$

Total momentum broadening: $\langle k_T^2 \rangle \sim \hat{q} L \sim -\frac{dE}{dz}$

Relation between momentum broadening and energy loss independent of the medium.
$\Rightarrow$ Test our understanding

In cold nuclear matter: use 1-gluon exchange approximation to connect to the gluon distribution:

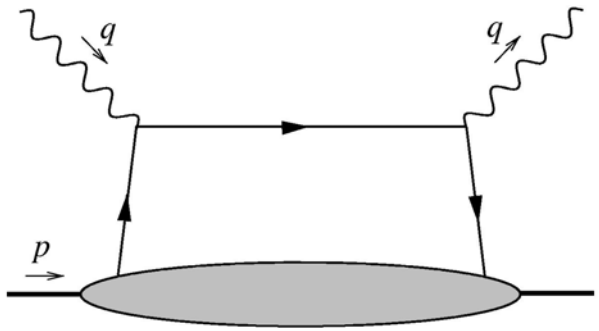
$$\boxed{\hat{q} = \frac{4\pi^2 \alpha_s}{2N_c} \rho x G(x, \mu_s)} \quad \Rightarrow \quad \hat{q} \approx 0.045 \, \mathrm{GeV}^2 / \mathrm{fm}$$

Baier, Dokshitzer, Muller, Peigne, Schiff
Zakharov
Salgado, Wiedemann
Gyulassy, Vitev

Leading Twist Factorization

- pQCD factorization separates hard and soft physics
- E.g. deep inelastic scattering:

$$\sigma_{\gamma+p} = f_{a/A} \otimes H_{\gamma+a}$$



- Production of hadrons:

$$\sigma_{\gamma+p} = f_{a/A} \otimes H_{\gamma+a} \otimes D_a^H$$

Factorization theorems:

- f non-perturbative but universal, observable
- H perturbatively calculable
- Leading twist approximation: holds up to corrections of order λ^2/Q^2

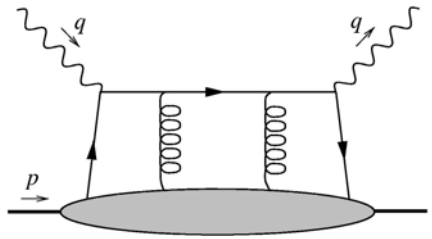
Collins, Soper, Sterman; Qiu, Sterman; ...

Corrections to Leading Twist

- Leading twist: one single hard scattering, parton entering the hard part of the cross section described by a parton distribution.

$$f_{q/P}(x) = \int \frac{dy^-}{2\pi} \mathrm{e}^{ixP^+y^-} \frac{1}{2} \left\langle P \middle| \bar{q}(0)\gamma^+ q(y^-) \middle| P \right\rangle$$

- Double scattering: need more parton operators $\Rightarrow$ twist-4
- Two different contributions for large nuclei:



Luo, Qiu and Sterman, PLB 279, 377 (1992); PRD 49, 4493 (1994)

$$T_{qg}^{\mathrm{DH}}(x_a, x_b) = \frac{1}{x_b} \int dz_4^- \frac{dz_3^-}{2\pi} \frac{dz_1^-}{2\pi} \Theta(z_1^- - z_3^-)\Theta(-z_4^-) \mathrm{e}^{ix_a P^+ z_1^-} \mathrm{e}^{ix_b P^+ (z_3^- - z_4^-)} \frac{1}{2} \left\langle P \middle| F^{\omega+}(z_4^-) \bar{q}(0)\gamma^+ q(z_1^-) F_\omega^+(z_3^-) \middle| P \right\rangle$$

$$T_{qg}^{\mathrm{SH}}(x) = \int dz_4^- \frac{dz_3^-}{2\pi} \frac{dz_1^-}{2\pi} \Theta(z_1^- - z_3^-)\Theta(-z_4^-) \mathrm{e}^{ixP^+ z_1^-} \frac{1}{2} \left\langle P \middle| F^{\omega+}(z_4^-) \bar{q}(0)\gamma^+ q(z_1^-) F_\omega^+(z_3^-) \middle| P \right\rangle$$

Nuclear Enhancement

- Nuclear PDF scale with A modulo shadowing corrections.
- DH and SH matrix elements have one unbound integration on the light cone $\Rightarrow$ additional factor $A^{1/3}$

$$\langle \bar{q}q \rangle \xleftrightarrow{R_A} \langle FF \rangle$$

Nuclear Enhancement

- Effective twist expansion in powers of $A^{1/3}\,\Lambda^2/Q^2$
- New matrix elements have to be measured by experiment.
- Cheapest model: factorize $\langle O_1 O_2 \rangle \approx \langle O_1 \rangle \langle O_2 \rangle$

$$T_{qg}^{\mathrm{DH}}(x_a, x_b) = C A^{4/3} f_q(x_a) f_g(x_b)$$

$$T_{qg}^{\mathrm{SH}}(x) = \lambda^2 A^{4/3} f_q(x)$$

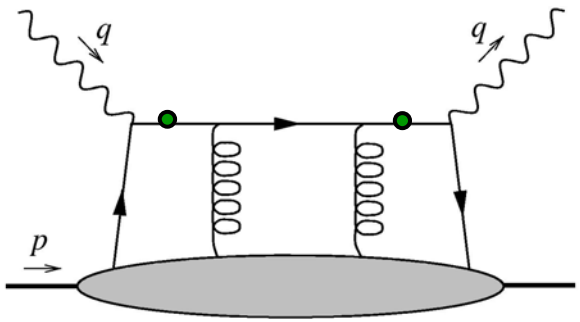
C, λ^2 normalization constants

$\lambda^2 = 0.01\ \mathrm{GeV}^2$ (DY q_T broadening)

$C = 0.005\ \mathrm{GeV}^2$

LQS formalism

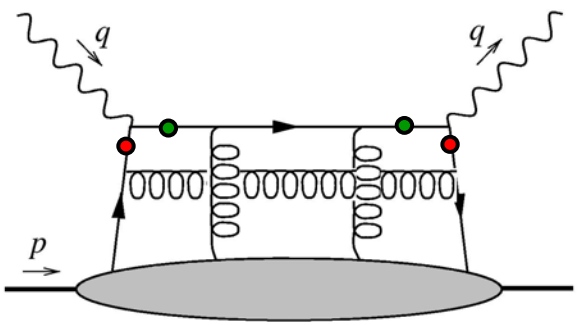
- Guo: Transverse momentum broadening of jets.



- Soft pole

$$\Delta\left\langle l_T^2\right\rangle = \frac{4\pi^2\alpha_s}{N_c}\frac{\sum_q e_q^2 T_{qg}^{\mathrm{SH}}(x)}{\sum_q e_q^2 f_q(x)} \approx \frac{4\pi^2\alpha_s}{N_c}\lambda^2 A^{1/3}$$

- Luo, Qiu, Sterman: FS interactions of jets in DIS and photoproduction



- Soft pole
- Hard pole

$$x_{\mathrm{soft}} << x_{\mathrm{hard}}$$

Soft Hard & Double Hard

By integrating the propagators:

$$M \sim \int dx \frac{1}{x - x_{\text{soft}} + i\varepsilon} \frac{1}{x - x_{\text{hard}} + i\varepsilon} F(x) = \frac{F(x_{\text{soft}})}{x_{\text{soft}} - x_{\text{hard}}} - \frac{F(x_{\text{hard}})}{x_{\text{soft}} - x_{\text{hard}}} = M_{sh} - M_{dh}$$

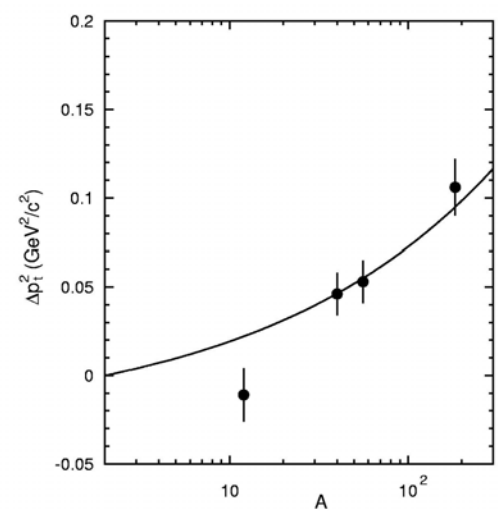
Neglect SH - DH interference (no nuclear enhancement!)

$$|M|^2 \sim |M_{sh}|^2 + |M_{dh}|^2$$

Luo, Qiu, Sterman: momentum imbalance
FNAL E638 $\lambda^2 \approx 0.05 \ldots 0.1\,\text{GeV}^2$

Guo: DY broadening $\lambda^2 \approx 0.01\,\text{GeV}^2$
FNAL E772

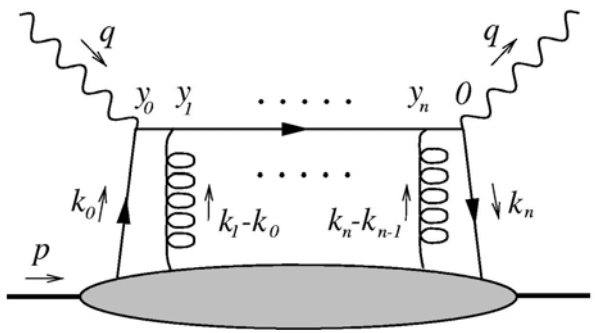
Inconsistency??



E772

n-scattering

So far: double scattering = twist-4



Beyond double scattering:
triple, ... n-scattering

Resummation of higher twist.

☞ feasible for certain class of contributions

RJF, PRD 68, 074013, 2003: momentum broadening

$$\sim \frac{d^n}{dq_T^{2n}} \delta(q_T^2)$$

Qiu and Vitev, hep-ph/0309094: shadowing

$$\sim \frac{d^n}{dx^n} f(x)$$

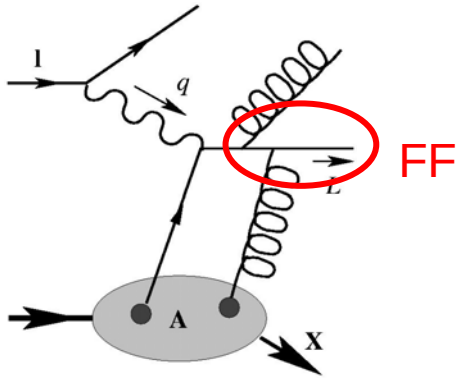
Exponentiation $\Rightarrow$ shift operators

Medium-modified fragmentation functions

X.F. Guo & X.N. Wang, E. Wang & X.N. Wang:

DGLAP evolution (splitting) + medium induced radiation,

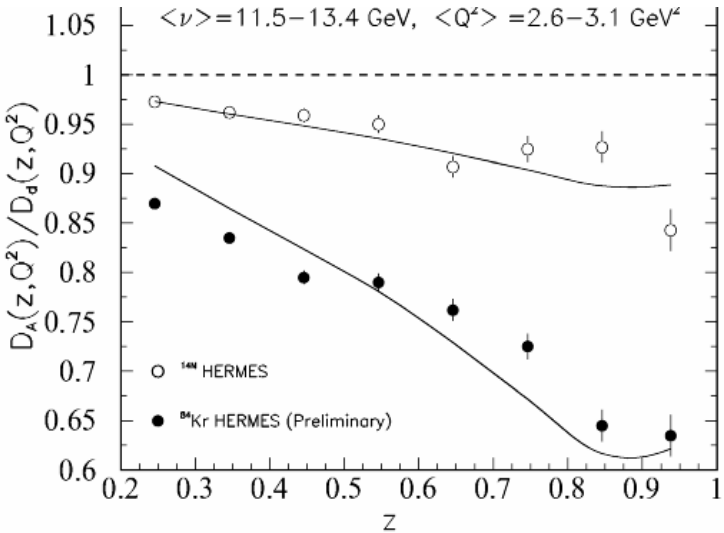
using LQS formalism, soft-hard interference ~ LPM effect



E. Wang & X.N. Wang: model for medium-modified fragmentation functions

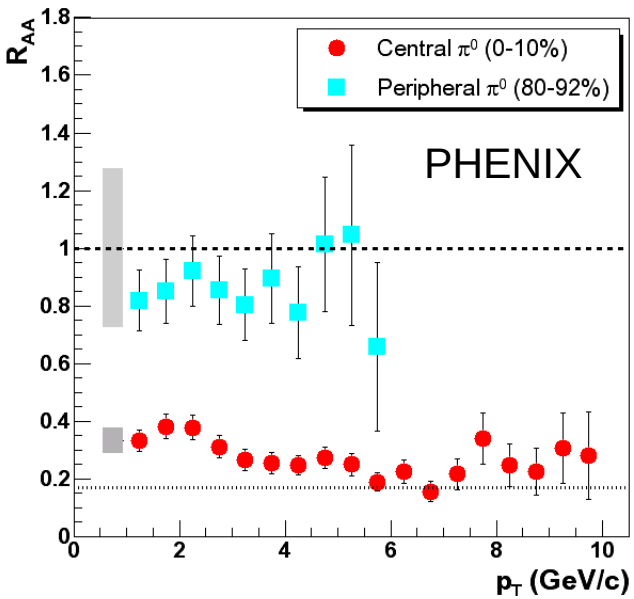
$$\hat{D}_a^H(z) = \int_0^{1-z} \frac{d\varepsilon}{1-\varepsilon} P(\varepsilon) D_a^H\left(\frac{z}{1-\varepsilon}\right)$$

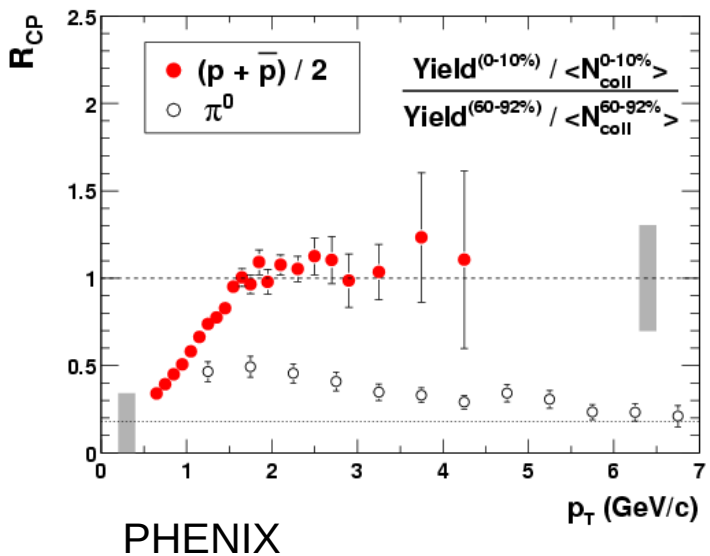
ε = energy loss



Jet Quenching at RHIC

Very strong jet quenching (~ 0.2) seen in central Au+Au collisions at RHIC





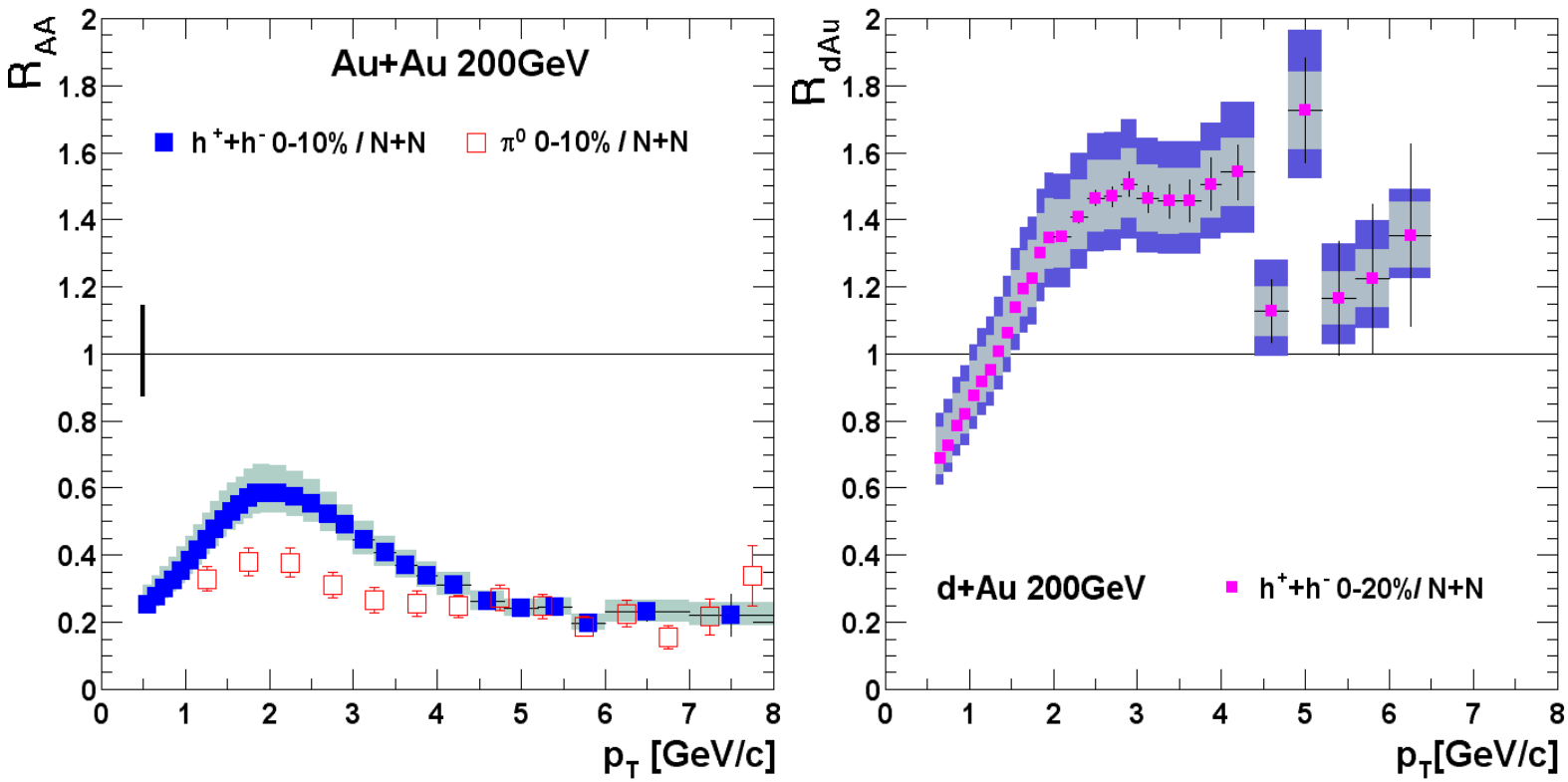
Careful: Baryon enhancement at intermediate P_T: soft physics

$\Rightarrow$ above 5 GeV/c: parton energy loss

dAu control experiment: this is no saturation effect.

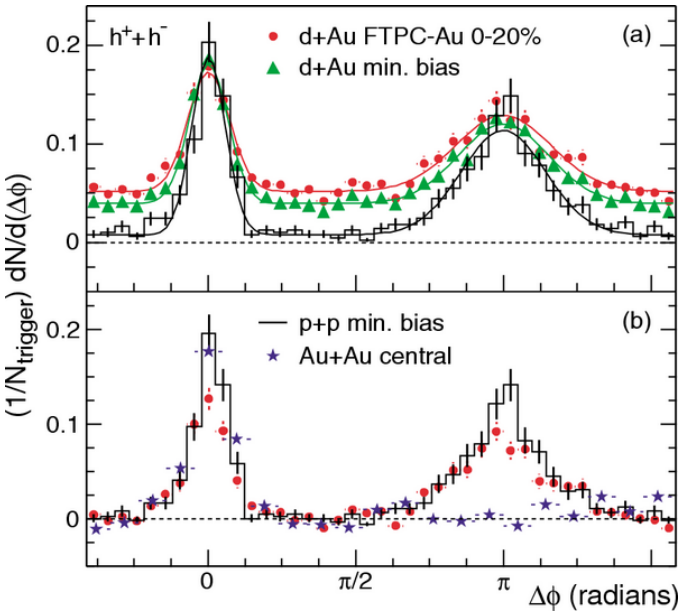
d+Au at RHIC

- Large Cronin enhancement for P_T > 1 GeV/c
- Cronin >> shadowing + energy loss in cold nuclear matter!
- B. Müller: picture of energy loss not conclusive yet.



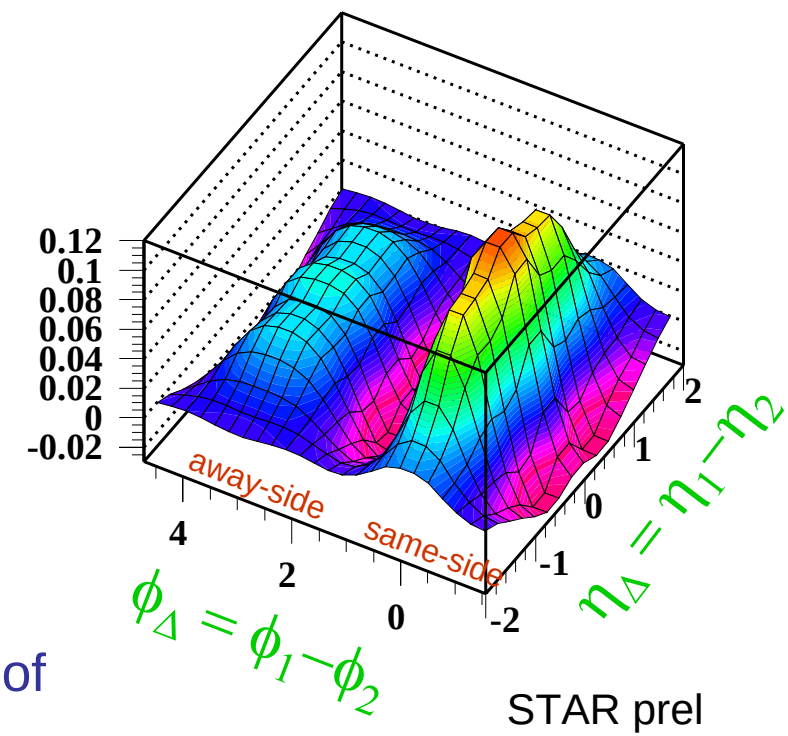
PHENIX

Jet Correlations



STAR

RHIC: 2-particle correlations to study jets



STAR prel

p+p → d+Au

What happens to height and width of away-side peak?

⇒ Tool to measure energy loss and momentum broadening?

Comparison of different approaches

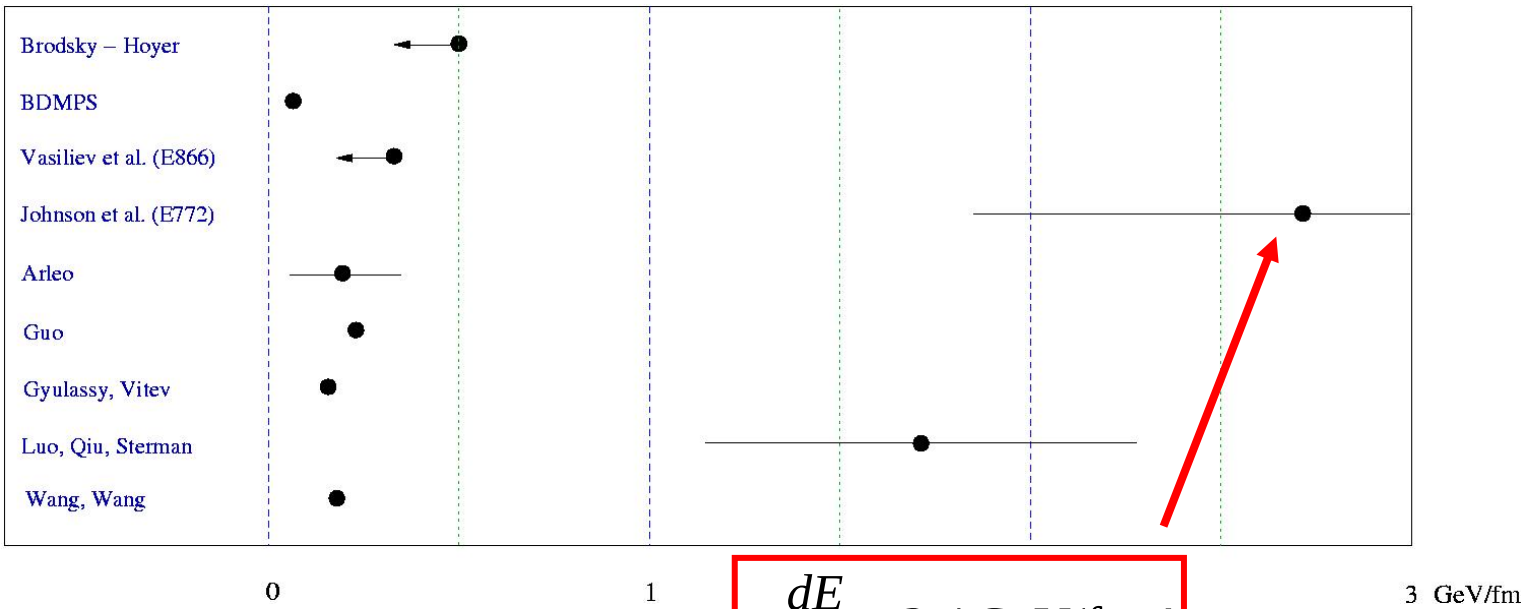
From equating momentum broadening in LQS and BDMPS approach:

$$\hat{q} = C_A \pi^2 \alpha_s \frac{A^{1/3}}{L} \lambda^2$$

BDMPS $\hat{q} = 0.045\,\mathrm{GeV}^2/\mathrm{fm}$ $\lambda^2 = 0.0029\,\mathrm{GeV}^2$

LQS $\hat{q} = 0.16\,\mathrm{GeV}^2/\mathrm{fm}$ $\lambda^2 = 0.01\,\mathrm{GeV}^2$

Average energy loss dE/dz per unit length for a quark (L = 5 fm) [F. Arleo]



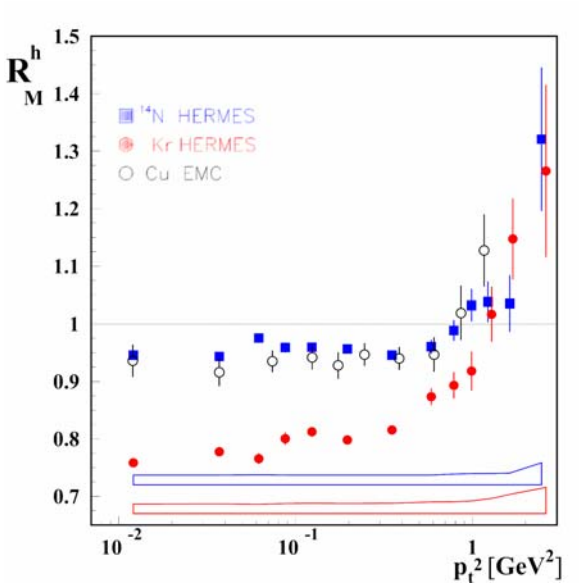
Kopeliovich, Johnson et al.: $-\frac{dE}{dz} = 2.4\,\mathrm{GeV/fm}$!

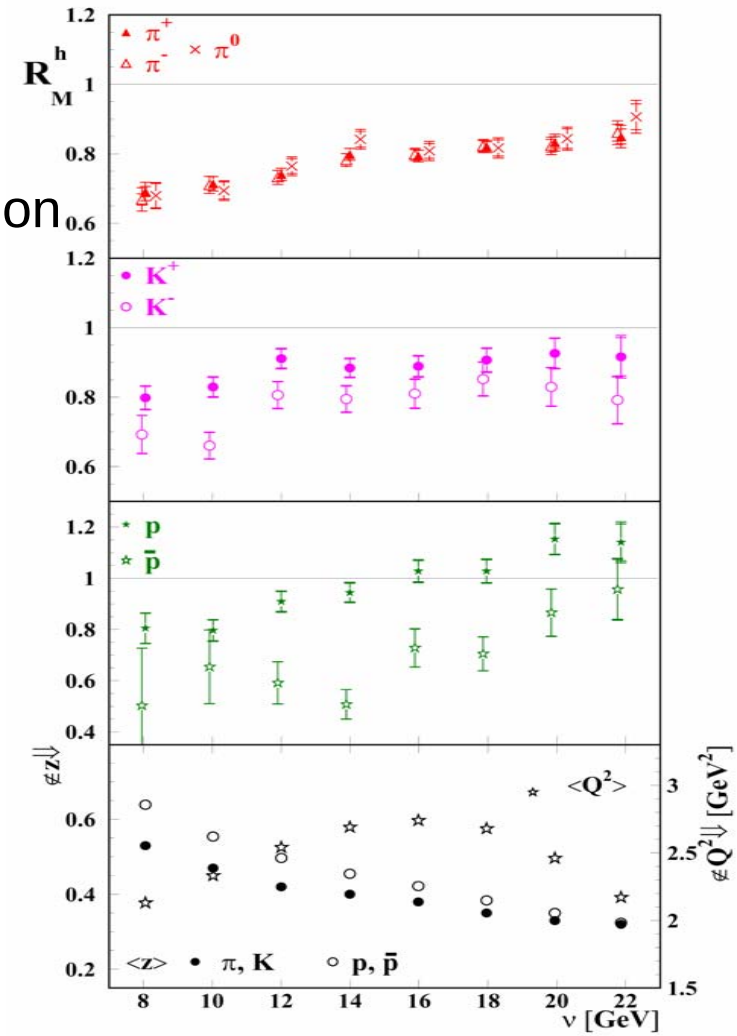
from Drell Yan in FNAL E772; claim: shadowing not very important

New HERMES data

New precise HERMES data:

z, ν, p_T dependence of nuclear modification for identified hadrons



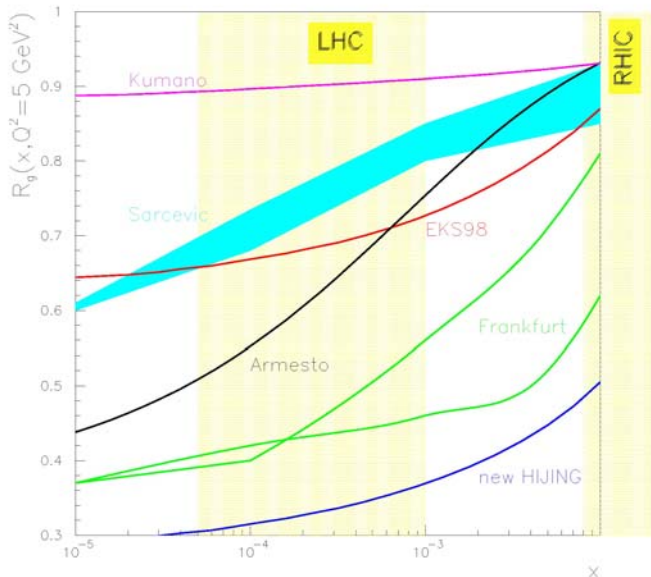


Outlook

- It's time to test our theoretical understanding of energy loss!
- RHIC & HERMES data
- EIC: more data in a clean environment
- Disentangle different effects: shadowing, IS scattering, FS interaction
- Dependence on particle species important.
- -dE/dz ~ 0.2 GeV/fm ??

Backup

Gluon Ratios for Pb at $Q^2 = 5$ GeV^2

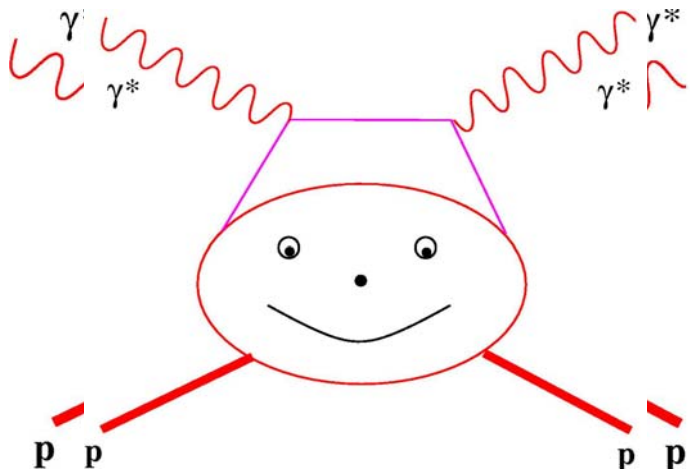


Kumano: M. Hirai *et al.* Phys Rev **D64** 034003.
EKS98: K.J. Eskola *et al* Nucl. Phys **B535** 351; Eur. Phys. J. **C9**, 61.
Sarcevic: Z. Huang *et al.* Nucl. Phys. A **637**, 79.
Frankfurt *et al* JHEP **0202**, 027.
Armesto *et al* Eur. Phys. J. C **22** 351.
new HIJING: S. y. Li and X. N. Wang, Phys. Lett. B **527** 85.

Leading Twist Factorization

- pQCD factorization separates hard and soft physics
- E.g. deep inelastic scattering:

$$\sigma_{\gamma+p} = f_{a/A} \otimes H_{\gamma+a}$$



- Drell Yan:

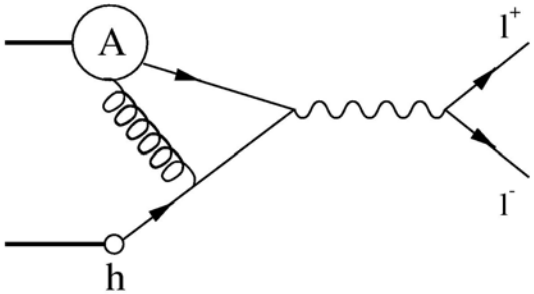
$$\sigma_{A+B\to\gamma^*} = f_{a/A} \otimes H_{a+b\to\gamma^*} \otimes f_{b/B}$$

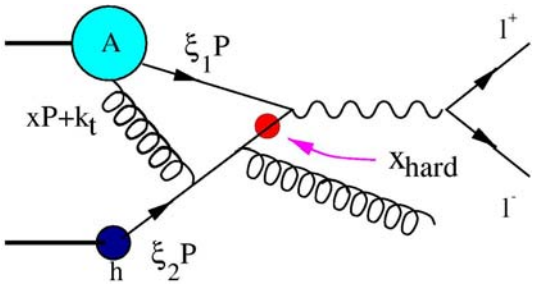
Factorization theorems:

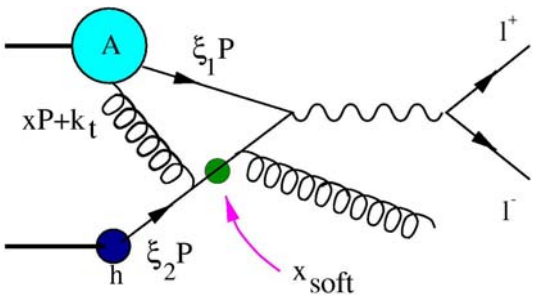
- f non-perturbative but universal, observable
- H perturbatively calculable
- Leading twist approximation: holds up to corrections of order λ^2/Q^2

Collins, Soper, Sterman; Qiu, Sterman; ...

Soft-hard and double-hard scattering







- Leading order double scattering: one pole from the propagator makes gluon soft $\Rightarrow$ T^{SH}

- Next order in α_S: two poles Gluon can be hard or soft.

$$x_{\text{soft}} = \frac{k_T^2}{\xi_2 S} << x_{\text{hard}}$$

- As soon as $q_T << Q$, the hierarchy breaks down.

$$x_{\text{soft}} \sim x_{\text{hard}}$$