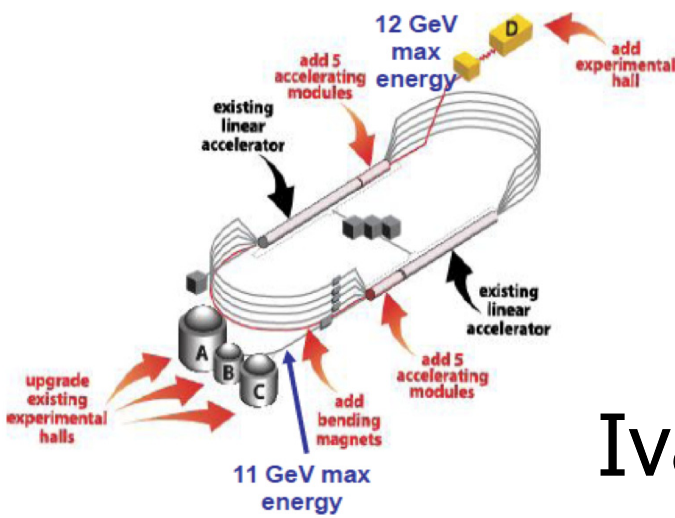
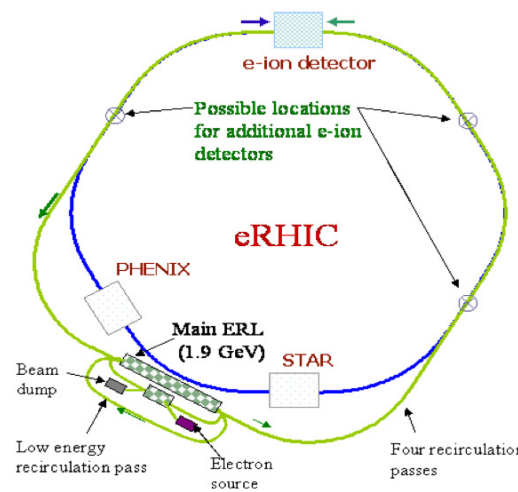
Nuclear Many-Body Physics at High Energies: from Fixed Target Experiments to the EIC



Ivan Vitev



T-2, Los Alamos National Laboratory

Outline of the Talk

Motivation

- Theoretical underpinnings of nuclear effects at high energy
- Importance and experimental opportunities

Initial-state interactions and cold nuclear matter energy loss

- A formalism to address many-body scattering in nuclear matter
- Radiative energy loss in large nuclei: important regimes
- Applications to DY, shortest radiation length in nature

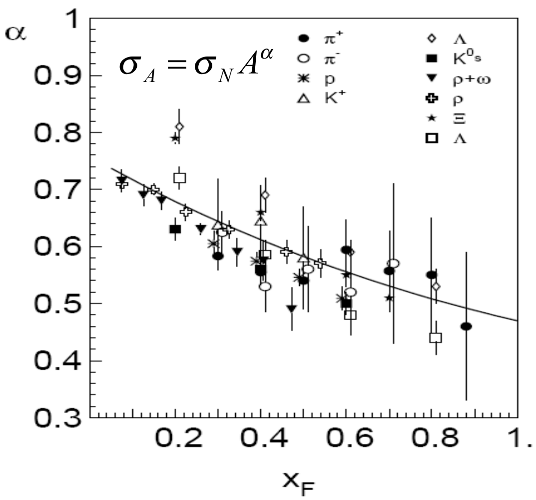
Final-state interactions and medium induced photons

- Induced photons, coherence effects, differences from gluons
- Numerical results, smallness of the gluon bremsstrahlung
- Other final-state effects. Jets in SDIS?

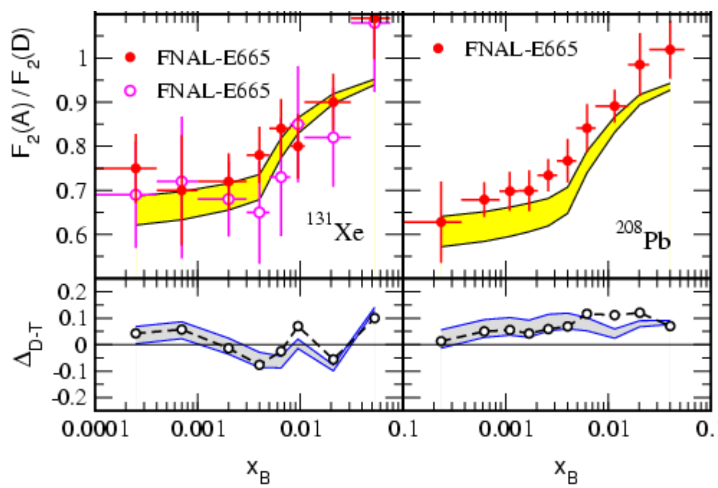
Conclusions

I. The Origin of Nuclear Effects

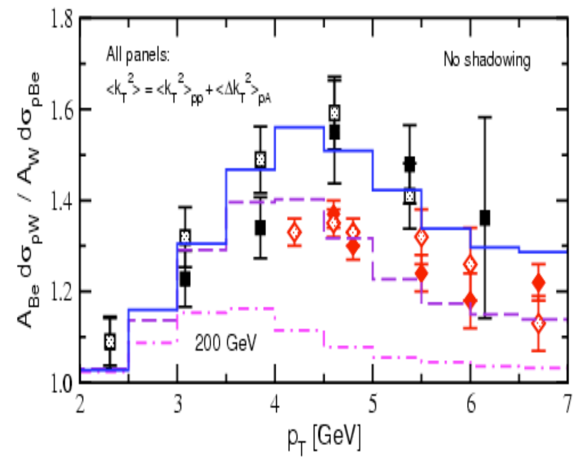
- A number of cold nuclear matter effects observed as modification of the experimentally measured inclusive cross sections



B. Kopeliovich et al, PRC (2005)



J. Qiu, IV, PRL (2004)

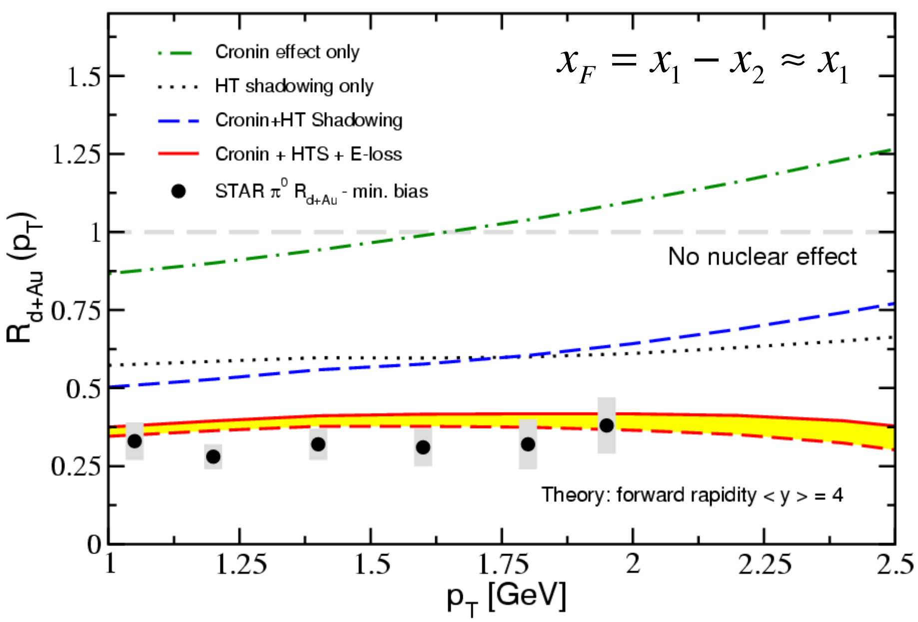


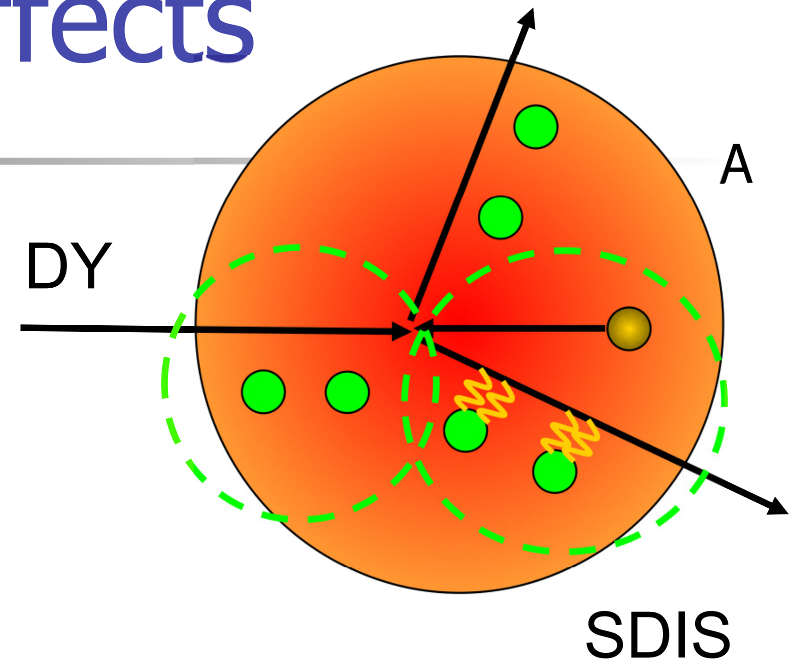
I.V., PLB (2003)

- Two schools of thought: parameterize (universal), compute (process-dependent).

Dynamical Generation of Nuclear Effects

Type	Effect
IS broadening	Cronin
Coherent FS	Shadowing
IS E-loss	Forward x_F suppression
FS E-loss	Quenching of jets, inclusive spectra



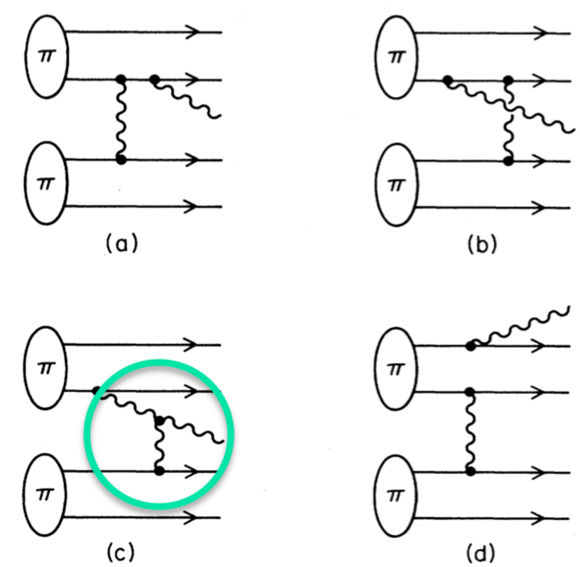


- An example illustrating the importance of these effects is the forward rapidity π^0 suppression at RHIC

II. Parton Energy Loss (Early Work)

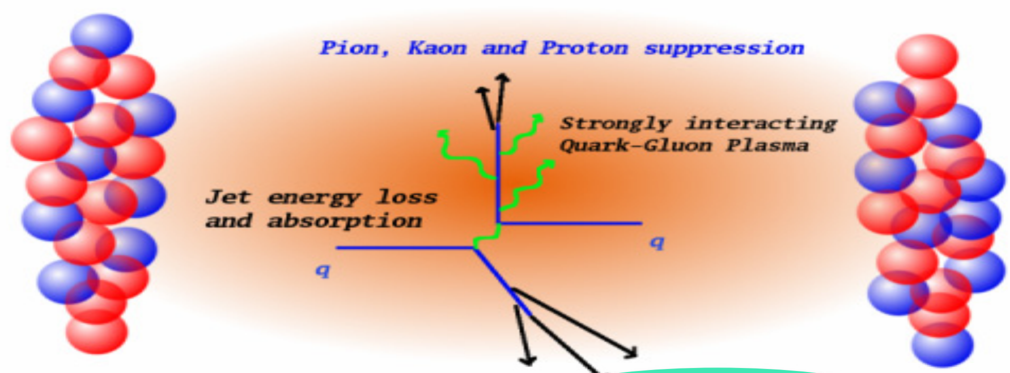
- Focused on soft multiplicities and the incoherent regime $\Delta E^{rad} = c_2 EL$
- Essential physics is the transverse dynamics of the gluon and the color excitation of the quark

G. Bertsch et al, PRD (1982)



$$\frac{\omega dN^g}{d\omega d^2k_\perp} = \left\langle \frac{C_R\alpha_s}{\pi^2} \frac{q_\perp^2}{k_\perp^2(k_\perp - q_\perp)^2} \right\rangle$$

Challenges (2 of them)



$$|M_0 + M_1|^2 = |M_0|^2 + \mathrm{Re}\, M_1^* M_0 + 2|M_1|^2$$

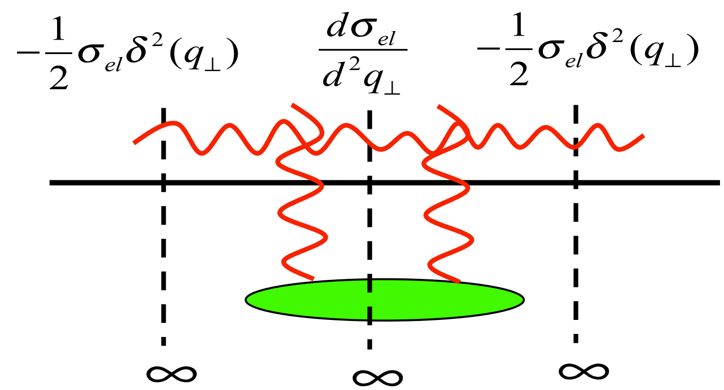
"Medium induced" part

An operator approach to multiple scattering in QCD

- Very general algebraic approach

$$k^+ \frac{dN^n_g}{dk^+ d^2k_\perp} \propto Tr \sum_{i_1 \ldots i_n} \overline{A}^{i_1 \ldots i_n} A_{i_1 \ldots i_n}$$
$$= \overline{A}^{i_1 \ldots i_{n-1}} \left(D^\dagger D + V^\dagger + V \right) A_{i_1 \ldots i_{n-1}}$$
$$= \overline{A}^{i_1 \ldots i_{n-1}} \hat{R} \; A_{i_1 \ldots i_{n-1}}$$

M. Gyulassy et al., NPB (2001)



Number of scatterings **Momentum transfers**

$$k^+ \frac{dN_g}{dk^+ d^2k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN^n{}_g}{dk^+ d^2k_\perp} = \sum_{n=1}^{\infty} \frac{C_R \alpha_s}{\pi^2} \left[\prod_{i=1}^{n} \int_0^{L-\sum_{j=i+1}^{n} \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \int d^2 q_i \left(\frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_i} - \delta^2(q_i) \right) \right]$$
$$\times \left[-2 C_{(1\ldots n)} \cdot \sum_{m=1}^{n} B_{(m+1\ldots n)(m\ldots n)} \left(\cos\left(\sum_{k=2}^{m} \omega_{(k\ldots n)} \Delta z_k \right) - \cos\left(\sum_{k=1}^{m} \omega_{(k\ldots n)} \Delta z_k \right) \right) \right]$$

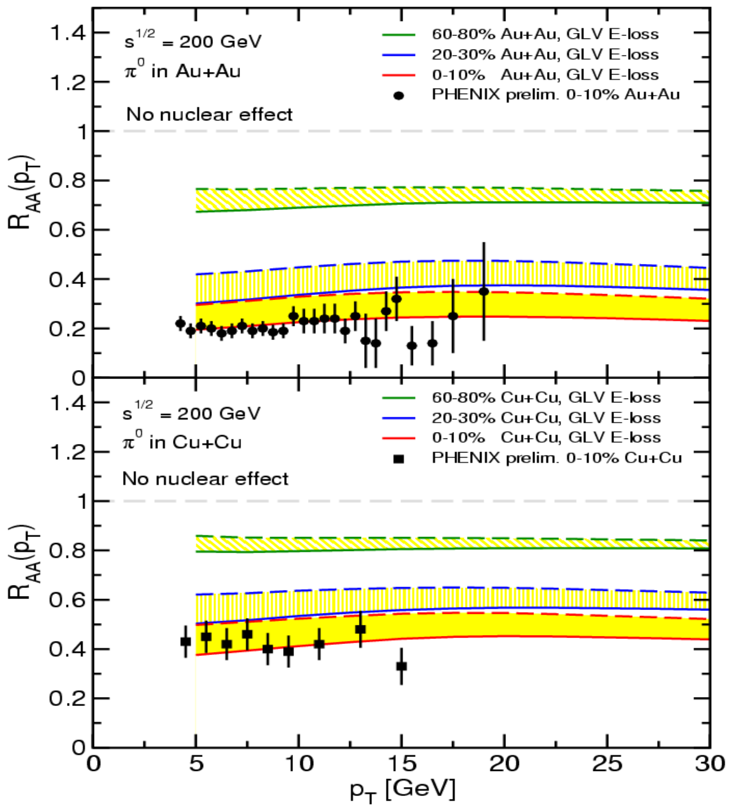
Color current propagators

Coherence phases (LPM effect)

Leading Particle Quenching

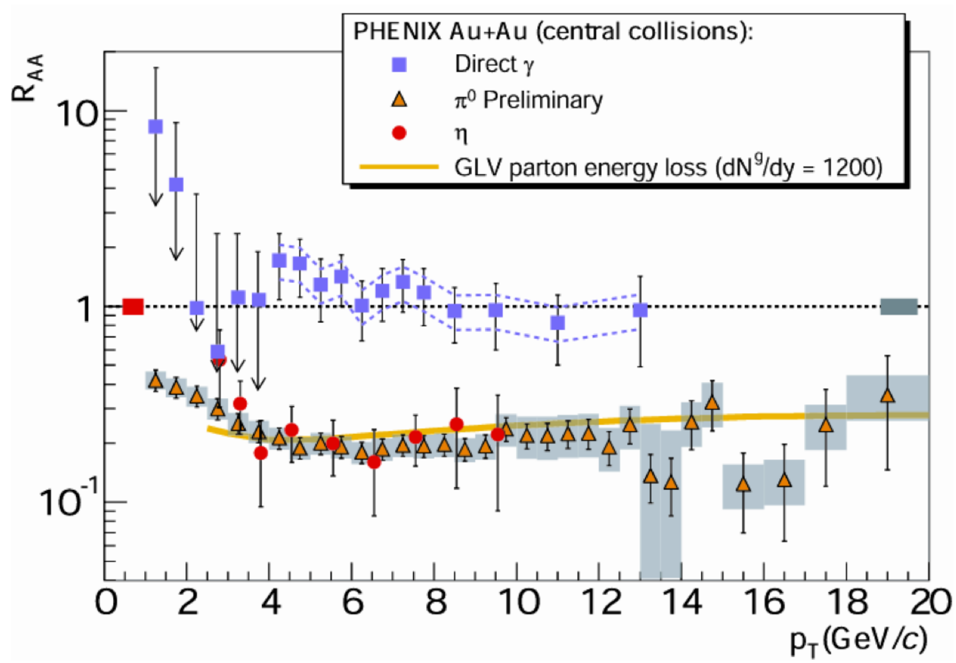
- Nuclear modification factor

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



IV, (2005)

- Predictions of this formalism tested vs particle momentum, C.M. energy, centrality

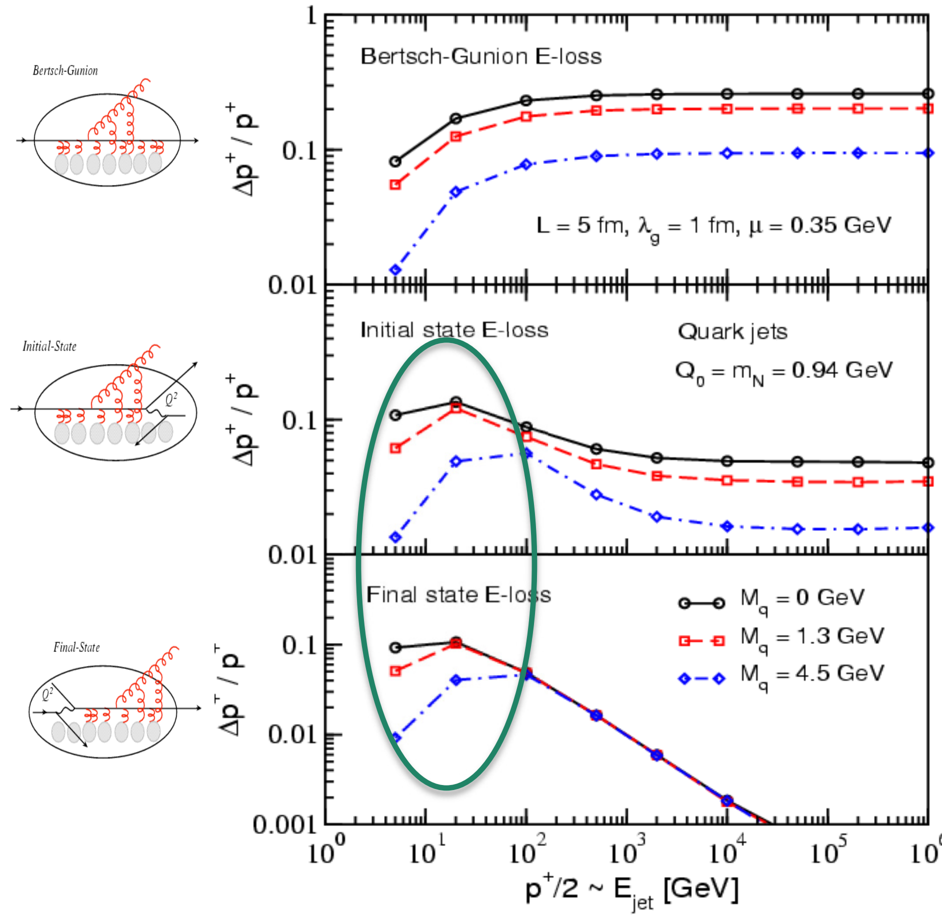


A Note on PQCD Energy Loss Regimes in CNM

$$\frac{\omega dN^{soft}}{d\omega d^2 k_\perp} \sim \frac{q_\perp^2}{k_\perp^2 (k_\perp - q_\perp)^2} \qquad \frac{\omega dN^{hard}}{d\omega d^2 k_\perp} \sim \frac{1}{k_\perp^2}$$

- IS and FS E-losses are different

  - Initial vs Final BC
- CNM energy loss for quarks can be O(5%-10%) in a large (W, Au, Pb…) nucleus
- For E<100 GeV IS and FS E-loss are quite similar. DY and SDIS - complementary

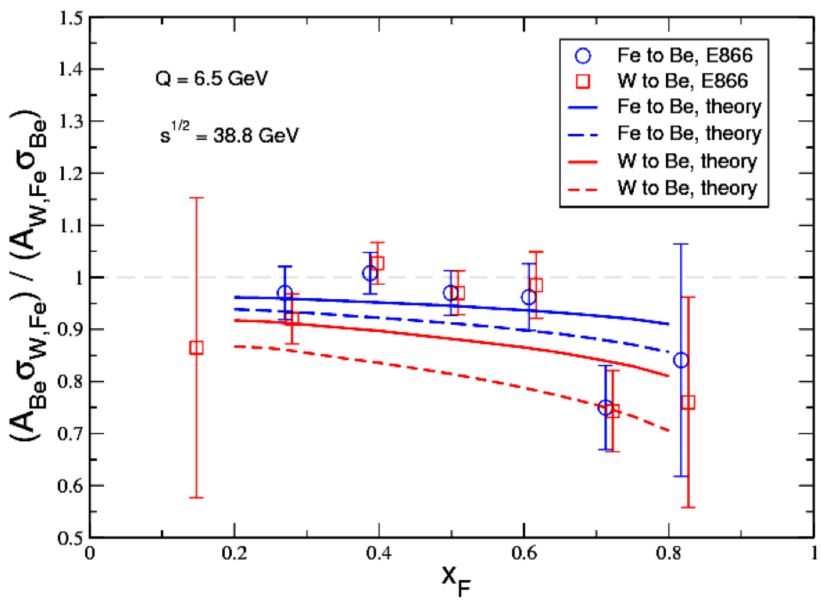


I.V., PRC (2007)

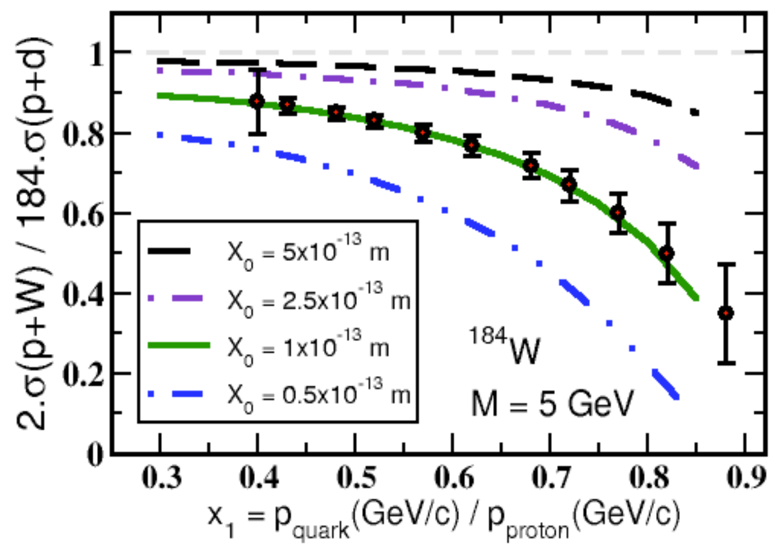
DY and the Determination of the Shortest Radiation Length in Nature

- At tree level for DY shadowing from coherent final-state scattering does not exist. Ideal to determine IS E-loss

$$R_{DY} = \frac{B.\, d\sigma^{pA} \,/\, dQ^2 dx_F}{A.\, d\sigma^{pB} \,/\, dQ^2 dx_F}$$



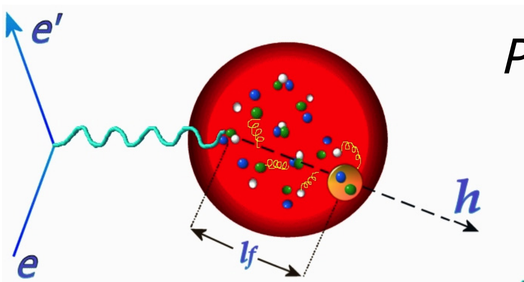
B.W. Zhang, IV, B. Neufeld, in progress



- One expects better accuracy in the large x_F region at Femilab E906

CNM Quenching, Absorption, e.c.t.

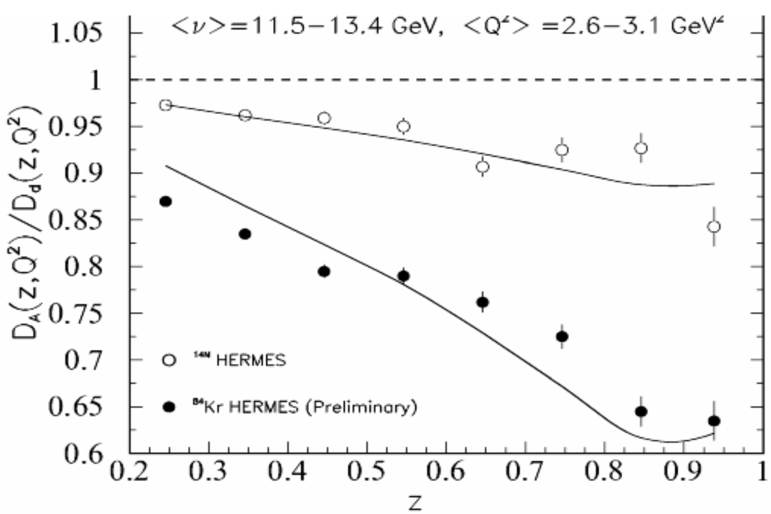
- Design parameters of EIC - center of mass energies: 20 GeV - 100 GeV
- Reasonable reach for jets (high enough E_T)



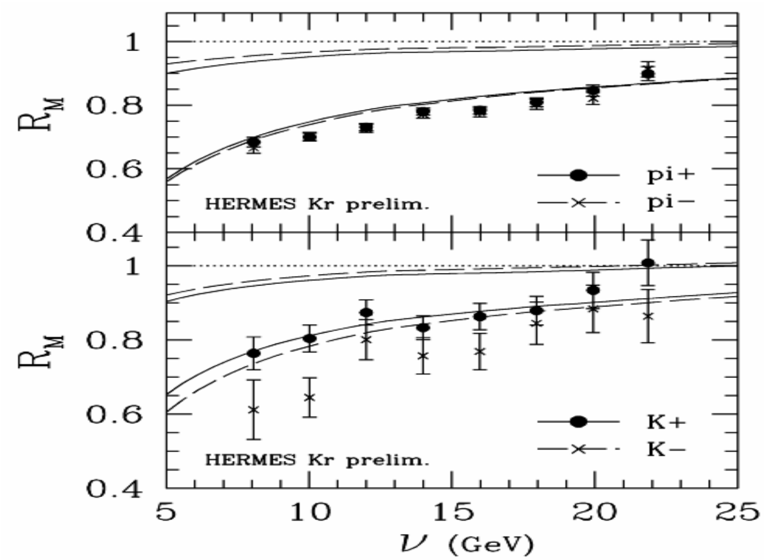
Process - observable

hermes

$$R_M(z,\upsilon) = \frac{\frac{1}{\sigma_{DIS}} \frac{d^2\sigma_h}{dzd\nu}\Big|_A}{\frac{1}{\sigma_{DIS}} \frac{d^2\sigma_h}{dzd\nu}\Big|_D} = \frac{\frac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}\Big|_A}{\frac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}\Big|_D}$$



X.N. Wang et al. PRL (2002)



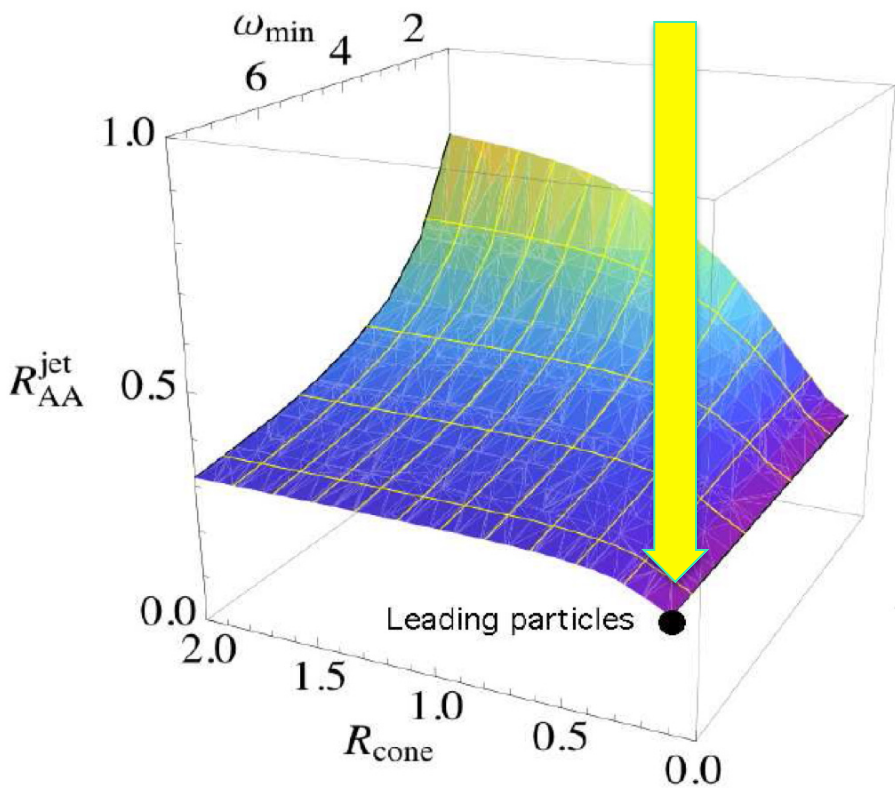
A. Accardi, NPA (2003)

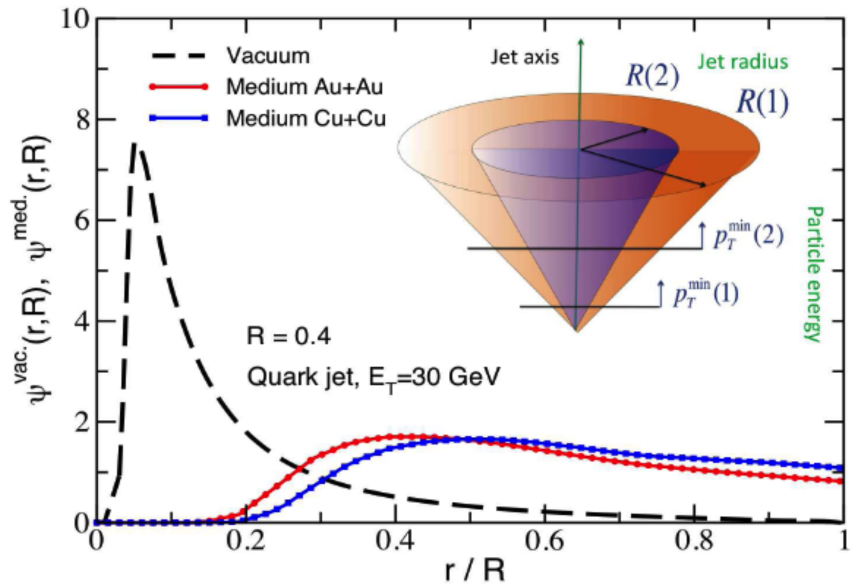
Jet Cross Section and Jet Shapes

Phenomenological approaches focus exclusively on 1 point

IV, S. Wicks, B.-W. Zhang, JHEP (2008)

- Direct access to the characteristics of the in-medium parton interactions





$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\rm jet})_i)} ,$$

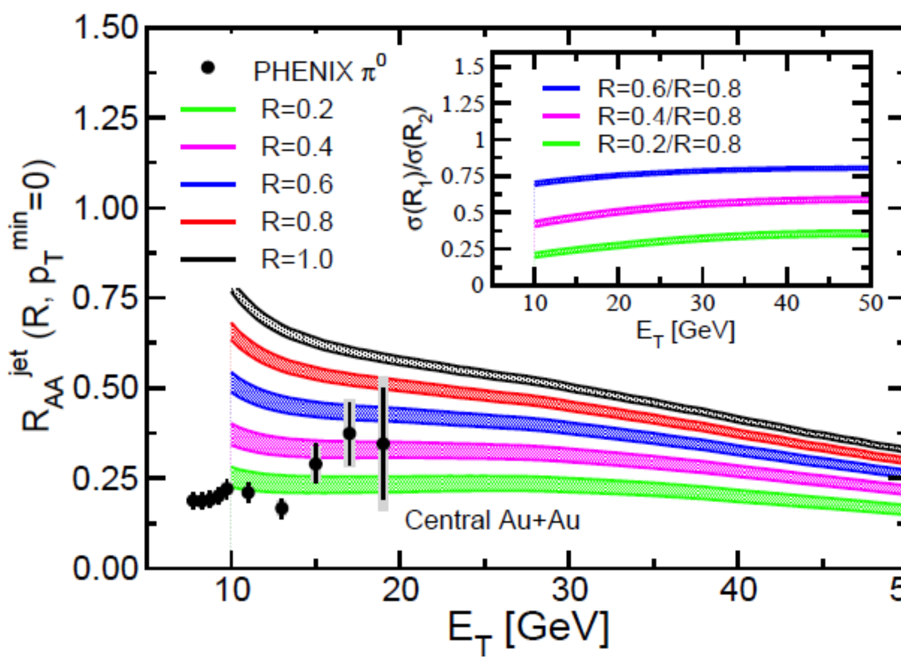
$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr} .$$

Jets in A+A at RHIC

- R_{AA} for jet cross sections with CNM and final-state parton energy loss effect are calculated for different R
- CNM effect contribute ~½ $R_{AA\ jet}$ at the high E_T at RHIC

Definition of the jet modification: includes additional 2D information

$$R^{\rm jet}_{AA}(E_T;R,p_T^{\rm min}) = \frac{\frac{d\sigma^{AA}(E_T;R,p_T^{\rm min})}{dyd^2E_T}}{\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}(E_T;R,p_T^{\rm min})}{dyd^2E_T}}$$



R_{AA} – *CNM effects, QGP quenching and R dependence in p+p*

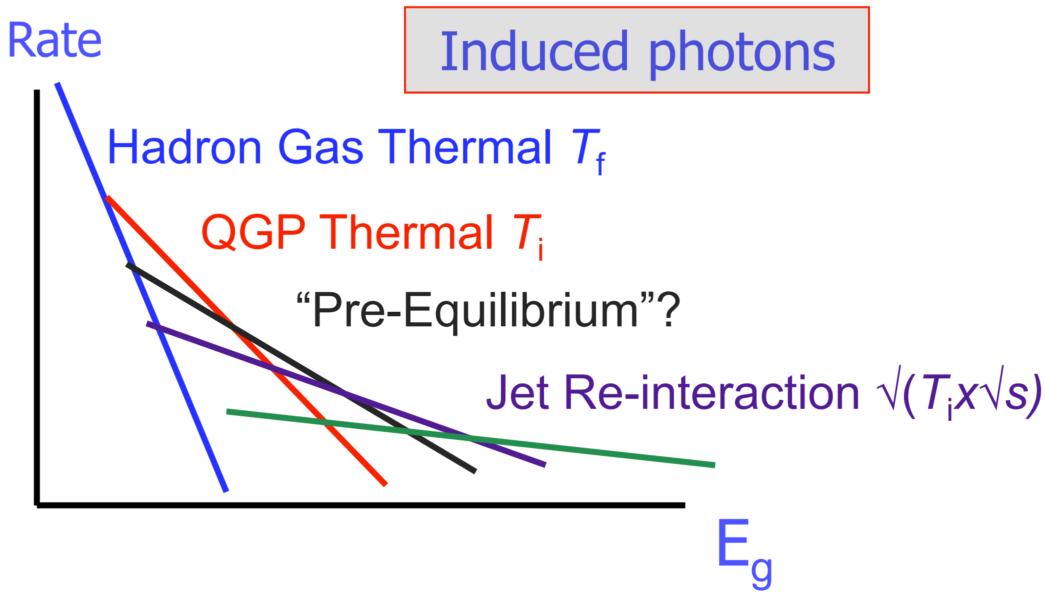
$\sigma(R_1)/\sigma(R_2)$ in A+A – *QGP quenching and R dependence in p+p*

$\sigma(R_1)/\sigma(R_2)$ in p+p – *R dependence in p+p*

IV, B.W. Zhang, PRL (2010)

III. Motivation to Study Photon Emission

- Strong interest, a number of interesting effects predicted: strong enhancement of photon production, negative photon ellipic flow, …



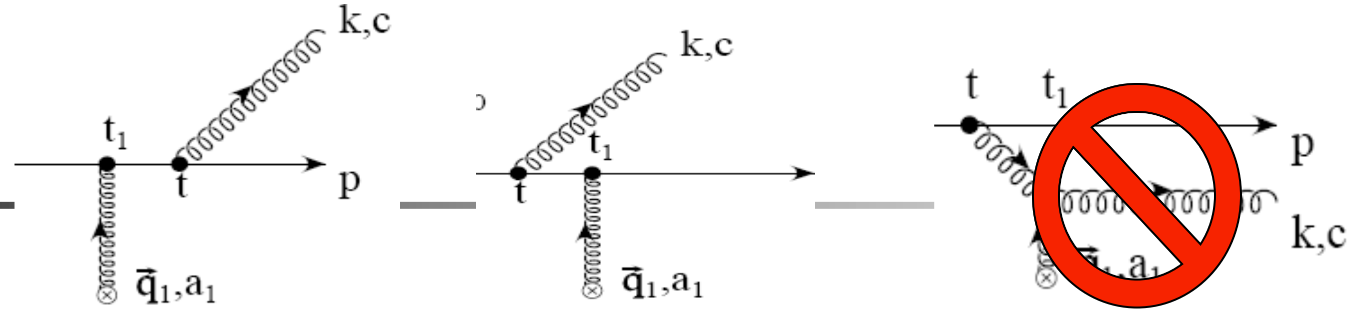
B. Zakharov, JETP Lett. (2004)

R. Fries et al., PRL (2003)

S. Turbide et al., PRC (2005)

- Sadly, most have not been observed

Photon vs Gluon Emission



- Without three-gluon vertex, is photon emission a simple exercise ?
- Gluon radiative amplitude for single scattering of a fast on-shell quark:

$$\mathcal{M}_{rad}(k) \propto 2ig_s\epsilon_\perp \cdot \left(\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} - \frac{(\mathbf{k}-\mathbf{q})_\perp}{(\mathbf{k}-\mathbf{q})_\perp^2} \right) e^{i\frac{\mathbf{k}_\perp^2}{2k^+}z^+}[T^c, T^a]$$

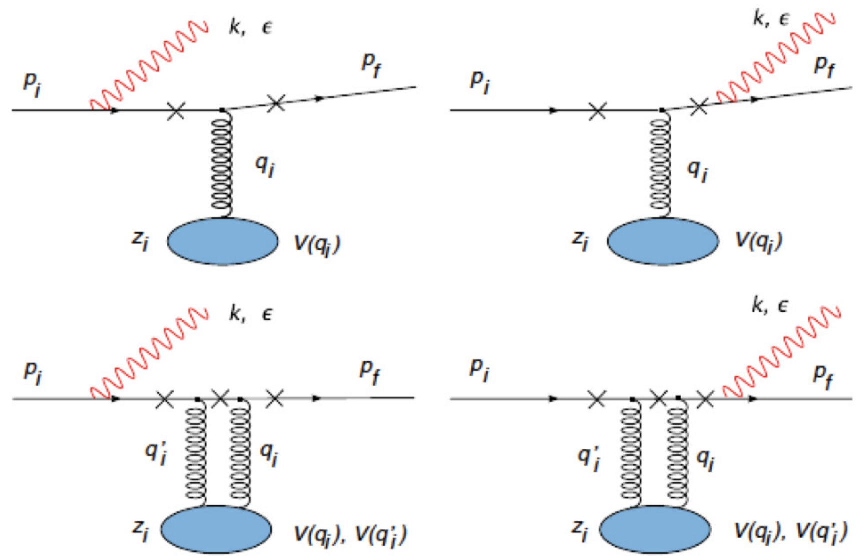
- Theoretical approaches developed to describe gluon emission cannot be directly generalized to photon radiation

Derivation of Photon Emission

- Scattering in the medium: Yukawa

$$V^{\mu,c}(q) = n^\mu \, 2\pi\delta(q^+) \, V^c(q) \, e^{iq\cdot z} \; ,$$

$$g_s V^c(q) \equiv v(q) \, T^c(t), \;\; v(q) \equiv \frac{4\pi\alpha_s}{-q^{\,2} + \mu^2}$$



$$\mathcal{M}_{rad}(k, \{i\}) = e \left(\frac{\epsilon \cdot p_f}{k \cdot p_f} - \frac{\epsilon \cdot p_i}{k \cdot p_i} \right) e^{iz_i^+ k^-} \;\;\Rightarrow\;\; \mathcal{M}^V_{rad}(k) \approx 0$$

Virtual double scattering corrections vanish

Photon Emission: Analytic Results

$$k^+ \frac{dN^\gamma(k)}{dk^+ d^2\mathbf{k}_\perp} = \frac{\alpha_{em}}{\pi^2} \bigg\{ \int \frac{d\Delta z_1}{\lambda_q(z_1)} \int d^2\mathbf{q}_{\perp 1} \frac{1}{\sigma^{\rm el}} \frac{d^2\sigma^{\rm el}}{d^2\mathbf{q}_{\perp 1}}$$
$$\times \left[|\mathcal{M}_{rad}(\{1\})|^2 + 2\mathcal{M}^*_{rad}(\{1\})\mathcal{M}_{rad}(\{0\}) \cos(k^- \Delta z_1^+) \right]$$
$$+ \text{ correction} .$$

$\tau_f^{-1} \approx k^- = \mathbf{k}^2/2k^+$

$k^- \Delta z_i^+ \sim \tau_f^{-1} \lambda$

IV, B.W. Zhang, PLB (2008)

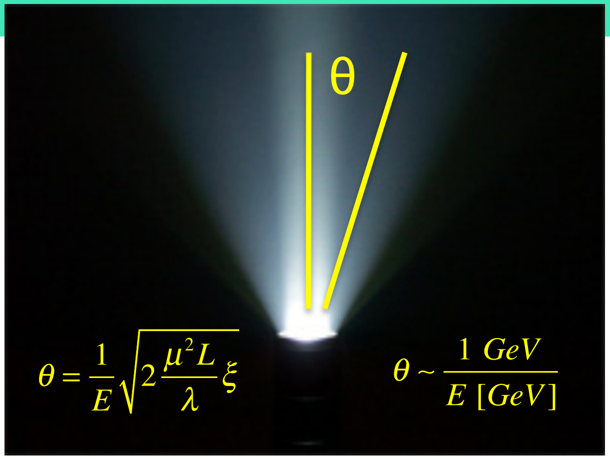
- Two limits; interference is important
- Leading contribution is L-dependence, with non-linear corrections with L
- Number of interactions <n> = $L/\lambda_q \approx 2-3$

Photon Emission: Incoherent Limit

- Recover the known incoherent results
- Very collimated emission in the direction of the incoming and outgoing partons

$$k^+ \frac{dN^\gamma(k;\{i\})}{dk^+ d^2\mathbf{k}_\perp} = \frac{1}{2(2\pi)^3} |\mathcal{M}_{rad}(k,\{i\})|^2$$

$$= \frac{\alpha_{em}}{\pi^2} \frac{\left(\frac{k^+}{E^+}\right)^2 \mathbf{q}^2_{\perp\, i}}{\left(\mathbf{k}_\perp - \frac{k^+}{E^+}\mathbf{Q}_{\perp\, i-1}\right)^2 \left(\mathbf{k}_\perp - \frac{k^+}{E^+}\mathbf{Q}_{\perp\, i}\right)^2}$$



J.Qiu ,IV, PLB (2003)

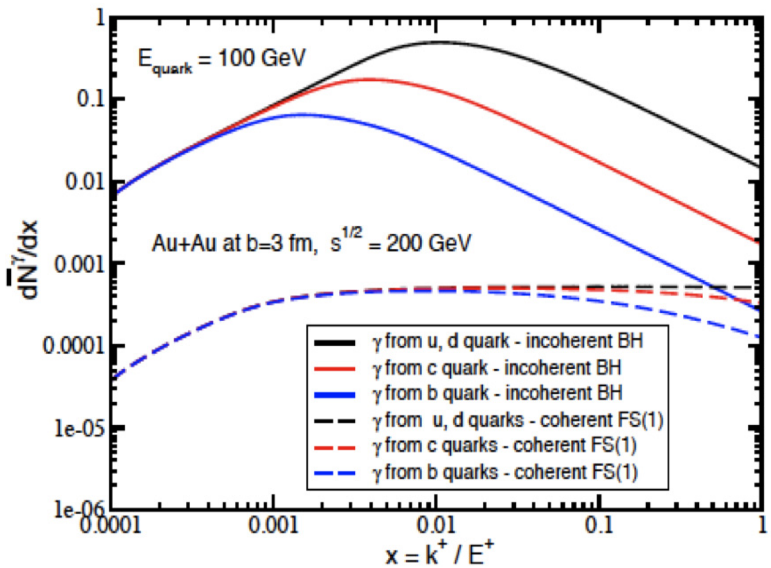
- Known double log result for photon number

$$N^\gamma(\{i\}) \approx 2\frac{\alpha_{em}}{\pi} \ln\frac{k^+_{\max}}{k^+_{\min}} \ln\frac{q^2_{\max}}{m^2}$$

Photon Emission: Numerical Results

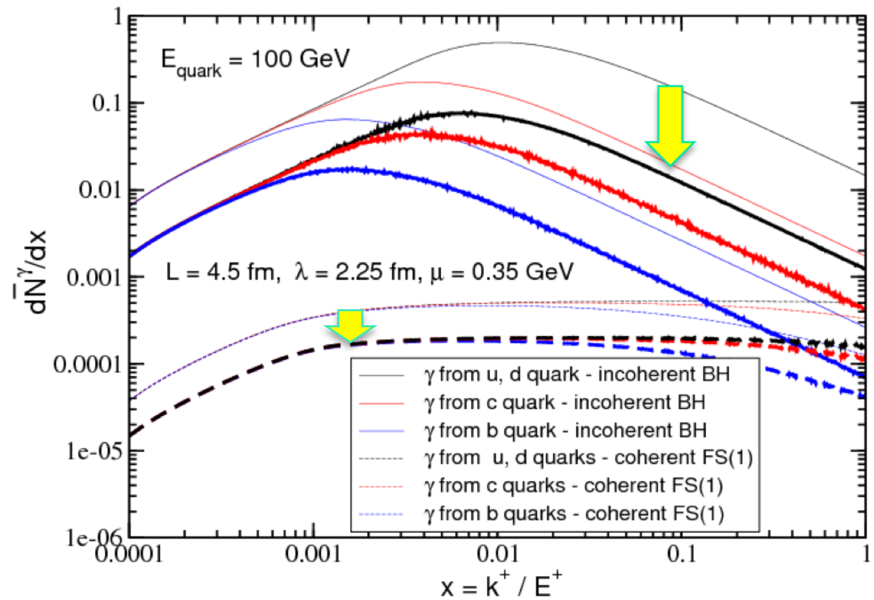
- In the QGP

$$dN^g/dy \simeq 1150, \ \ g_s = 2.5$$

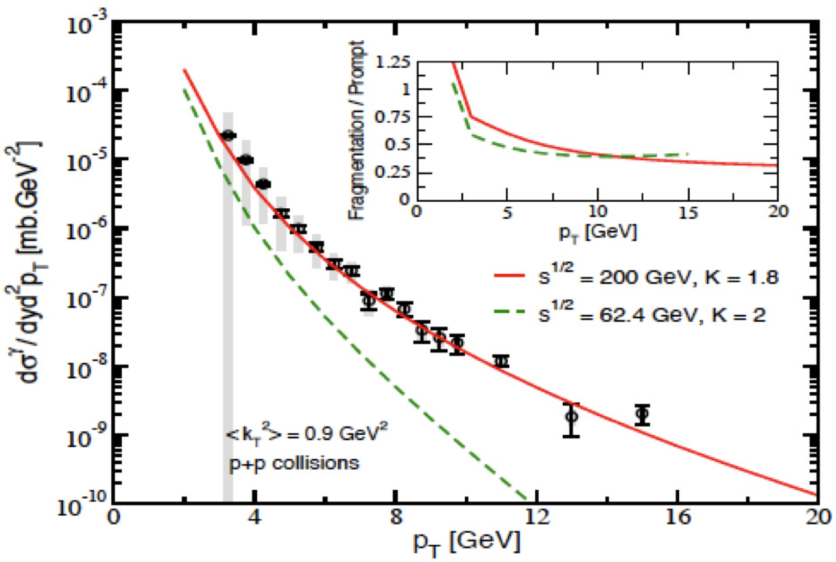


$$d\bar{N}^\gamma/dx = (e/e_q)^2 dN^\gamma/dx$$

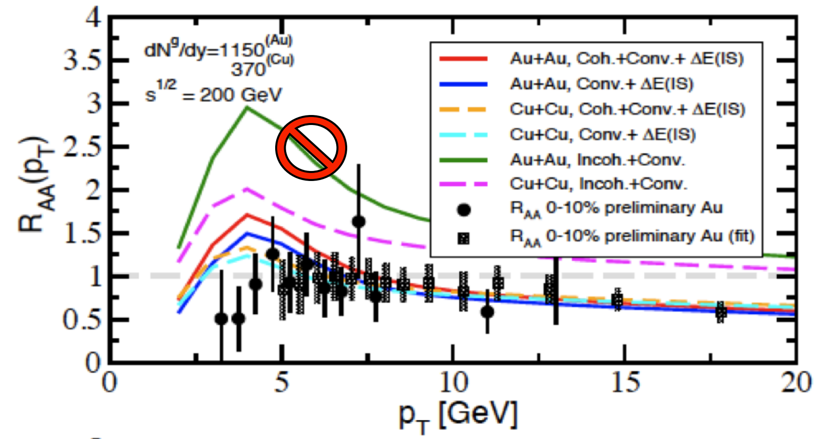
- In a cold nucleus. Parameters constrained by shadowing, Cronin, forward Y (x_F) suppression



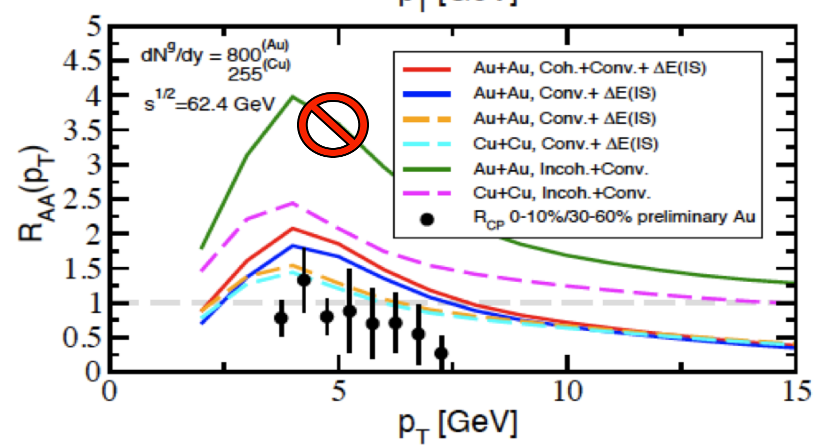
(Im)Probablity for Medium-Induced Photon Observation



$$R_\gamma^{AA} = \frac{.\, d\sigma^{AA} / dp_T dy}{N_{bin} .\, d\sigma^{pp} / d_T dy}$$



- Suppression of photon bremsstrahlung is critical to explain RHIC data



IV, B.W. Zhang, PLB (2008)

Possibly Interesting Features But …

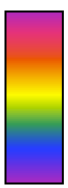
- Suppression of the spectrum implies suppression of the angular distribution

$$\frac{dI^{rad}}{(d\omega)dr}(r) \longrightarrow \frac{dI^{rad}}{d\omega}(\omega) \longrightarrow \Delta E^{rad}$$

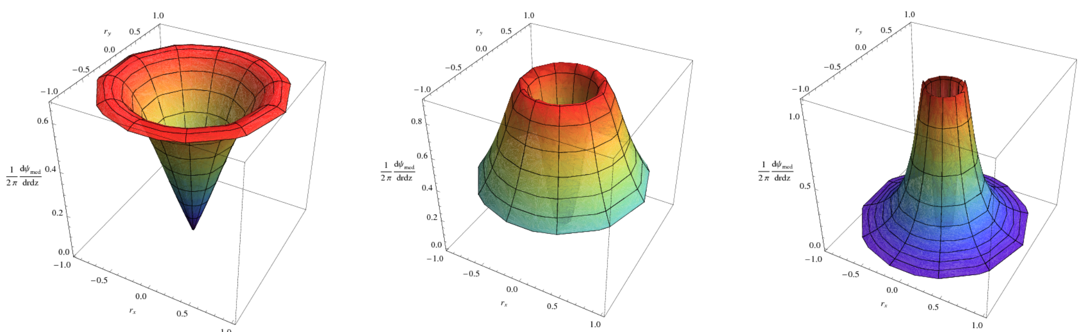
LPM suppressed

IV, PLB (2005)

Intensity scale



$\omega = 1$ GeV $\omega = 3$ GeV $\omega = 10$ GeV



N.B. The calculation is for coherent FS gluon emission. Expect similar pattern for γ

- By the same token it is unlikely that medium-induced photons will be a readily observable in e+A
- Certainly a full calculation is needed to compare to fragmentation photons in SDIS

Summary

- Many-body nuclear effects at high energies can be understood in terms of soft partonic interactions between the projectile and the target: Cronin, shadowing, IS and FS energy loss (forward rapidity, x_F suppression)
- Phenomenologically, these give consistent picture of cold nuclear matter (m.f.p.,momentum transfer)
- Relation between IS and FS energy loss can be explored in DY and SDIS processes. For EIC the physics of jets should become accessible. These provide much more information in comparison to leading particles (already used at RHIC)
- Medium induced photons from FSI derived. BH and LPM regime compared –strong suppression in the production rate, broad conical distribution.
- Unfortunately the induced rate is small (confirmed at RHIC). Studies will be difficult (if at all possible). Quantitative studies needed

From the Dead Sea Scrolls

- "In the abode of light are the origins of truth, and from the source of darkness are the origins of error."

ALL credit for this witty slide goes to my collaborator Ben-Wei Zhang

Thank you!