Aspects of parton energy loss in cold nuclear matter

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LAPTH, Annecy

Workshop on high-energy hadron physics with hadron beams

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Outline

- Motivations
  - why energy loss
  - why cold nuclear matter
- Energy loss in various observables
  - Drell-Yan production in p A collisions
  - hadron production in semi-inclusive DIS
- Revisiting energy loss
  - J/ψ production in p A collisions
  - induced gluon radiation associated to a hard process

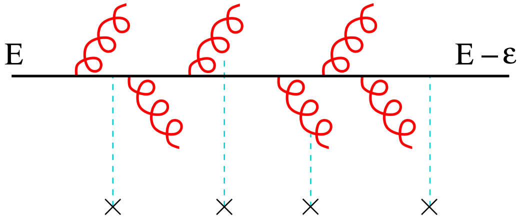
References

- Recent review: A. Accardi, FA, W. Brooks, D. d'Enterria, V. Muccifora, 0907.3534
- FA, S. Peigné, T. Sami, in preparation

Energy loss and gluon radiation

Multiple soft collisions of the hard parton

- Gluon radiation $dI/d\omega$ proportional to the medium density



[Baier, Dokshitzer, Mueller, Peigné, Schiff 1996, 1997]

[Gyulassy, Wang 1994; Gyulassy, Lévai, Vitev 2000]

[Zakharov 1996 1997 1998 ; Wiedemann 2000 2001]

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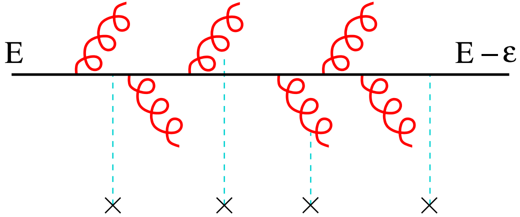

- Energy loss huge in quark-gluon plasma

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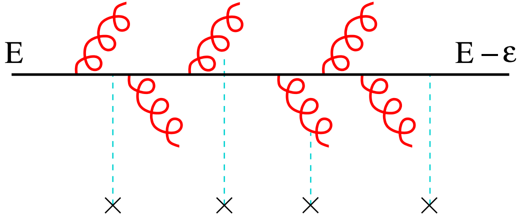

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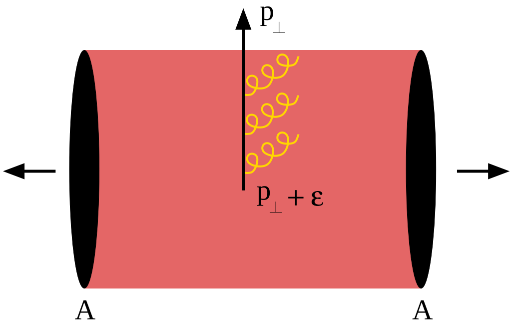
How to probe this mechanism?

Jet quenching

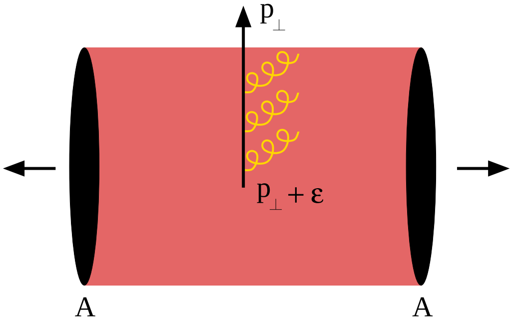


A clear experimental observable

Quenching of jets in heavy ion collisions

[Bjorken 1982; Gyulassy & Wang 1992]

Jet quenching



What about energy loss in cold nuclear matter?

Energy loss in cold vs. hot matter

Transport coefficient

Typical energy loss is proportional to the transport coefficient $\hat{q}$ which characterizes the scattering property of the medium [BDMPS 97]

$$\hat{q} = \frac{\mu^2}{\lambda}$$

- μ : typical momentum transfer in single rescattering (of the order of the Debye mass $m_D \sim gT$)
- λ : radiated gluon mean free path

Energy loss in cold vs. hot matter

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Energy loss in cold nuclear matter (medium length L)

$$-\Delta E = \frac{\alpha_s \; C_R}{4} \; \hat{q} \; L^2$$

Relationship beween energy loss and momentum broadening

$$-\frac{dE}{dz} = \frac{\alpha_s \; N_c}{4} \langle p_\perp^2 \rangle$$

- also correct for hot matter
- independent of the nature of the parton

Perturbative estimates

[BDMPS 97]

Cold matter

$$\hat{q} = \frac{4\,\pi^2\alpha_s\,N_c}{N_c^2-1}\,\rho\;xG(x,Q^2) \simeq 0.02\ \mathrm{GeV}^2/\mathrm{fm}$$

$$-dE/dz \simeq 0.1\ \mathrm{GeV}/\mathrm{fm}\left(\frac{L}{5\ \mathrm{fm}}\right)$$

Hot matter (e.g. $T = 250$ MeV)

$$\mu \sim 500\ \mathrm{MeV},\ \ \lambda \sim 0.5\ \mathrm{fm} \Rightarrow \hat{q} \simeq 0.5\ \mathrm{GeV}^2/\mathrm{fm}$$

Parton energy loss much larger in hot matter than in cold matter

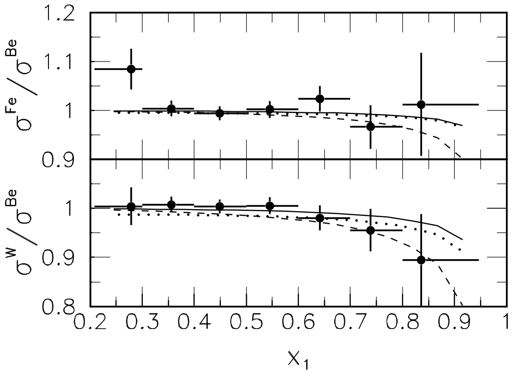
Extracting energy loss from data

Ideal process: Drell-Yan production in p A collisions

$$q^p \ \bar{q}^A \to \gamma^\star \to \ell^+\ell^-$$

- Multiple scattering of the incoming quark in large nuclei
  - allows for checking (in principle) the L dependence of energy loss
- No energy loss in the final state
- Very precise measurements by E866/Nusea
  - wide kinematical range in x_F

Extracting energy loss from data



$$\sigma(pA \to \mu^+\mu^- \mathrm{X}) \propto A^{\alpha}$$

[E866/NuSea Vasiliev et al. 1999]

- $\alpha \lesssim 1$: slight suppression at large x_F

Is the suppression coming from energy loss?

Energy loss and DY data

Longstanding debate on the origin of the nuclear dependence of E866/NuSea p A data

- First attributed as coming from nuclear PDF effects [Vasiliev et al. 1999]
  - shadowing at small x_2 corresponding to large x_F
  - small energy loss: upper limit $-dE/dz < 0.5$ GeV/fm

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Issue

Conclusions were based on the use of EKS98 nPDF set which already included E772 data i.e. same kinematic conditions as E866/NuSea

- Agreement between E866/NuSea and EKS98 somewhat inconclusive
- No room left for energy loss processes

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$$-\frac{dE}{dz} = 2.7 \pm 0.4 \pm 0.5 \ \mathrm{GeV/fm}$$

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  - E722 and E866/NuSea binned in DY mass
  - small shadowing computed within a dipole model

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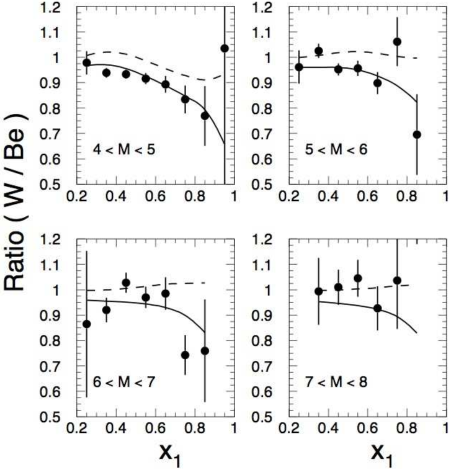
- Later accounted [Johnson et al. 2001]
  - E722 and E8
  - small shadow



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$$-\frac{dE}{dz} = 2.7 \pm 0.4 \pm 0.5 \text{ GeV/fm}$$

- . . . disfavoured by older DY measurements [FA 2002]
  - DY data in π A collisions at SPS

DY data analysis

Ingredients of the model

- Computation of DY production in QCD at leading order
- Shift of the momentum fraction x_1 carried by the quark in the projectile proton to account for energy loss processes
- Nuclear shadowing turned on (using EKS98) or off
- Amount of energy loss fitted to various DY data sets
  - E866/NuSea data at FNAL
  - NA3 data at SPS

DY data analysis

$$\frac{\mathrm{d}\sigma(hA)}{\mathrm{d}x_1} = \frac{8\pi\alpha^2}{9x_1 s}\sum_q e_q^2 \int \frac{\mathrm{d}M}{M}\int \mathrm{d}\epsilon\,\mathcal{P}(\epsilon)$$

$$\Big[Zf_q^h(x_1+\Delta x_1)f_{\bar{q}}^{p/A}(x_2)+(A-Z)f_q^h(x_1+\Delta x_1)f_{\bar{q}}^{n/A}(x_2)$$

$$+Zf_{\bar{q}}^h(x_1+\Delta x_1)f_q^{p/A}(x_2)+(A-Z)f_{\bar{q}}^h(x_1+\Delta x_1)f_q^{n/A}(x_2)\Big]$$

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$$+ Z f_{\bar{q}}^h(x_1 + \Delta x_1) f_q^{p/A}(x_2) + (A-Z) f_{\bar{q}}^h(x_1 + \Delta x_1) f_q^{n/A}(x_2) \Big]$$

$\mathcal{P}(\epsilon)$ probability for a hard parton to lose an energy ϵ

Knowledge of $\mathcal{P}(\epsilon)$ essential for phenomenology

DY data analysis

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$\mathcal{P}(\epsilon)$ probability for a hard parton to lose an energy ϵ

Knowledge of $\mathcal{P}(\epsilon)$ essential for phenomenology

Problem

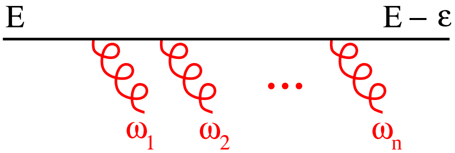
How to relate $\mathcal{P}(\epsilon)$ to the gluon spectrum $dI/d\omega$?

[Baier, Dokshitzer, Mueller, Schiff 2001]

Quenching weight $\mathcal{P}(\epsilon)$

Independent gluon radiation → Poisson approximation

[Baier, Dokshitzer, Mueller, Schiff 2001]



$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \, \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

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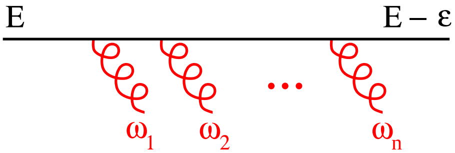

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Unique ingredient

- medium-induced gluon spectrum $dI/d\omega$ computed perturbatively (BDMPS) and characterized by the transport coefficient $\hat{q}$

Numerical calculation

Resumation of the Poisson series [Baier, Dokshitzer, Mueller, Schiff 2001]

$$\mathcal{P}(\epsilon) = \int_C \frac{d\nu}{2\pi i}\, e^{\nu\epsilon} \times \exp\left[-\nu \int_0^\infty d\omega\, e^{-\nu\omega}\, N(\omega)\right]$$

with $N(\omega)$ = gluon multiplicity

$$N(\omega) = \int_\omega^\infty d\omega'\, \frac{dI(\omega')}{d\omega'}$$

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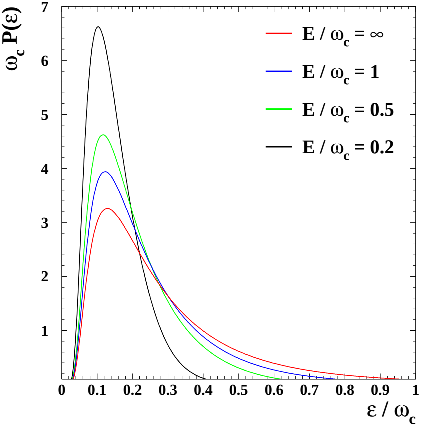


[FA 2002, Salgado, Wiedemann 2002]

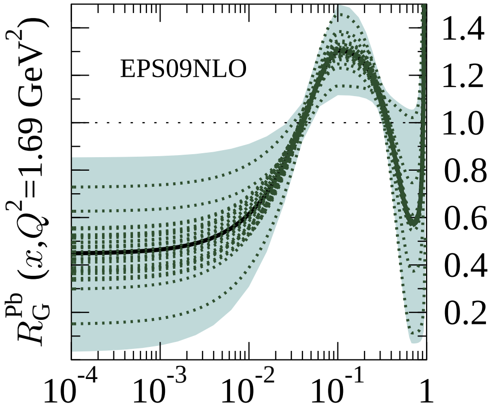
DY data analysis

Main results

DY in p A collisions at FNAL ($\sqrt{s} \simeq 40$ GeV)

- Amount of quark energy loss crucially depends on the poorly known sea-quark shadowing at small x_2
- No reliable extraction of quark energy loss due to nPDF uncertainties

DY data analysis



[from Eskola, Paukkunen, Salgado 2009]

- Many global fit analyses (EKS, EPS, HKM, HKN, nDS) and models
- Huge uncertainties at small x and low scales

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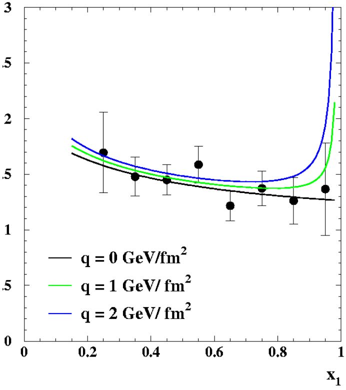
DY in π A collisions at SPS ($\sqrt{s} \simeq 20$ GeV)

- Larger error bars, but. . .
- nPDF effects small and well constrained
  - $x_2 = \mathcal{O}\left(10^{-1}\right)$ between shadowing and EMC region
  - Valence quark (pion beam) constrained in e A DIS

Energy loss and NA3 data



- Large energy loss disfavoured
- Effects stronger at large x_1 due to phase-space restriction for medium-induced gluon radiation

$$\epsilon < (1 - x_1)\ E_{\rm beam}$$

Energy loss and NA3 data

Results

- NA3 fit gives

$$-\frac{dE}{dz} = 0.20 \pm 0.15 \text{ GeV/fm}$$

- Result independent on the assumption regarding nPDF effects (unlike p A collisions at higher energy)

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Remarks

Smaller error bars would help tremendously!

- Exciting data to come at FNAL at lower beam energy (E906)

  [Garvey Peng 02]

- Complementary results at J-PARC
  - P-04: High mass di-muon measurements in p A collisions

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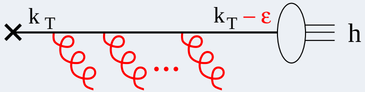
What about energy loss in hadron production?

Energy loss in hadron production

Simplest model for medium-modified "fragmentation functions"

- Fragmentation variable z rescaled to a larger value

[Wang, Huang, Sarcevic 96]



$$z^* = \frac{E_h}{k_\perp - \epsilon} = \frac{z}{1 - \epsilon/k_\perp}$$

- Parton energy shifted from $k_\perp$ to $k_\perp - \epsilon$ with probability $\mathcal{P}(\epsilon, k_\perp)$

[Baier et al. 01]

$$z D_k^{h\,\mathrm{med}}(z, Q^2) = \int_0^{(1-z)k_\perp} d\epsilon \; \mathcal{P}(\epsilon, k_\perp) \; z^* \, D_k^h(z^*, Q^2)$$

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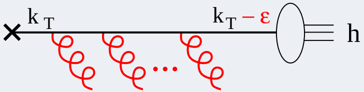

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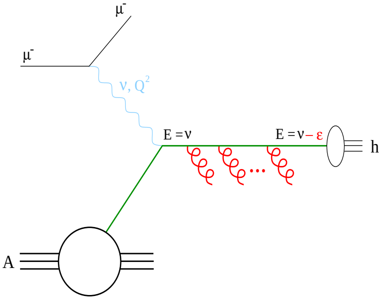
- Hadronization takes places on times scales $\gg$ medium length
- Medium-induced (perturbative) gluons can also fragment into hadrons
- Explicit dependence on the parton energy
- Rescattering and gluon emission does not affect at all the fragmentation dynamics – no Q^2-dependence

Example

Semi-inclusive hadron production in DIS on nuclei: $e\ A \rightarrow h\ \mathrm{X}$

$$R^h_{eA} = \frac{1}{N_{eA}} \frac{dN^h_{eA}(z,\nu)}{d\nu\, dz} \Bigg/ \frac{1}{N_{eD}} \frac{dN^h_{eD}(z,\nu)}{d\nu\, dz}$$



Phenomenological consequences

What trends to be expected from the model?

For simplicity let us assume that $D^h(z) \sim (1-z)^{\eta_i^h}$ at large z

$$R^h_{\rm eA}(z,\nu) \simeq \frac{D_u^{h\,\rm med}(z)}{D_u^h(z)} \simeq 1 + \frac{1}{D_u^h(z)} \frac{\partial D_u^h}{\partial z} \frac{z\,\epsilon}{\nu} \approx 1 - \eta_u^h \times \frac{z\,\epsilon}{\nu(1-z)}$$

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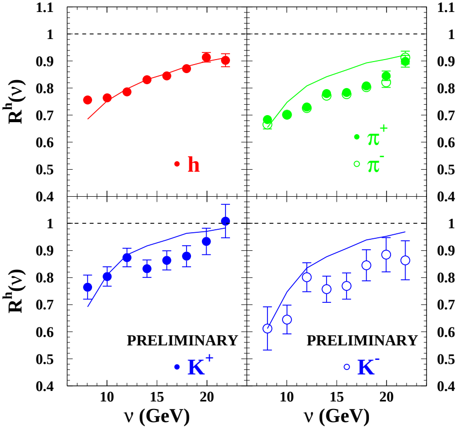
- $R_{\mathrm{eA}} \ll 1$
  - at small parton energy
  - at large z due to phase space shrinkage
- Quenching factor sensitive to the logarithmic slope of fragmentation function η_i^h
  - stronger suppression for gluon induced processes, on top of the C_A/C_F factor in the energy loss
  - stronger suppression for baryons than for mesons (!)

Comparison to HERMES data



[FA 2003, HERMES Airapetian et al. 2003]

- ν and z dependence well reproduced
- $\eta_u^{K^-} > \eta_u^{K^+}$ leads to a stronger K^- suppression as seen in HERMES

Comparison to HERMES data

Caveat: nuclear absorption

Inelastic interaction of the produced hadron might play a role too

[Kopeliovich et al. 1996, Accardi, Muccifora, Pirner 2003, Falter et al. 2004]

- Somewhat depends on hadronization time scales
- (Pre) hadronic cross sections with nuclear matter poorly constrained

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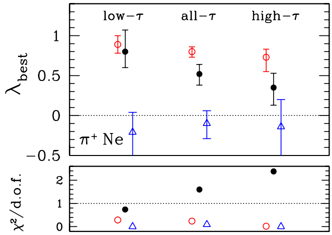
Recent effort to disentangle energy loss and nuclear absorption

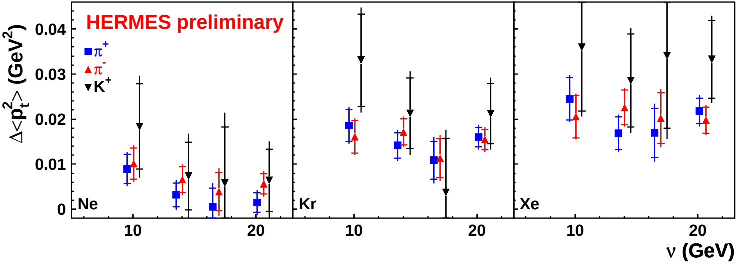
[Accardi 2006-2008]



Transverse momentum broadening

New results

Recent measurements on $\langle k_\perp \rangle$ broadening of produced hadrons in e A semi-inclusive DIS (HERMES, CLAS)



[van Haarlem, Jgoun, Di Nezza 2007]

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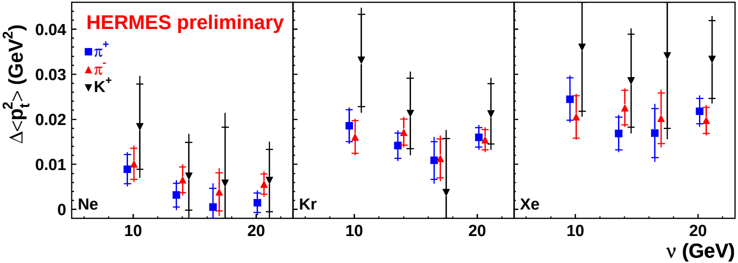


[van Haarlem, Jgoun, Di Nezza 2007]

- Sensitive to details of hadronization dynamics

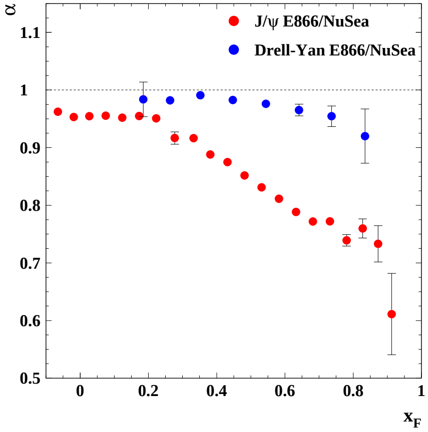
[Accardi 2008, Domdey, Kopeliovich, Pirner 2008]

Nuclear dependence of J/ψ production

J/ψ production in p A collisions

- Very precise measurements
  - E866/NuSea at FNAL ($\sqrt{s} = 40$ GeV)
  - PHENIX at RHIC ($\sqrt{s} = 200$ GeV)

Nuclear dependence of J/ψ production



[E866/NuSea 1999]

- Significant J/ψ suppression
- Much larger than in the DY channel

Nuclear dependence of J/ψ production

Some explanations

- Nuclear absorption
  - could explain mid-rapidity J/ψ and ψ' suppression
  - requires unrealistically large cross sections to explain large x_F data
- Nuclear PDF effects (or saturation)
  - disfavoured by lack of x_2 scaling
- Intrinsic charm [Brodsky Hoyer 1989]
  - J/ψ production from $|uudc\bar{c}\rangle$ soft scattering on nuclei
  - requires high charm content disfavoured by ${F_2}^c$ data
- Parton energy loss [Gavin, Milana 1992]
  - successful explanation assuming $-\Delta E \propto E$
  - violates bound on energy loss in a finite length medium

[Brodsky, Hoyer 1993]

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[Brodsky, Hoyer 1993]

Let us reconsider energy loss processes [FA, S. Peigné, T. Sami]

Induced gluon radiation

2 cases

1. $t_{prod} = 0 \Rightarrow$ accelerated charge radiates : $\Delta E_{\rm vac} \neq 0$

$$\Delta E_{\rm ind} = \Delta E_{\rm med} - \Delta E_{\rm vac}$$

2. $t_{prod} = -\infty \Rightarrow$ on-shell particle doesn't radiate in vacuum : $\Delta E_{\rm vac} = 0$

$$\Delta E_{\rm ind} = \Delta E_{\rm tot}$$

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$$\Delta E_{\rm ind} = \Delta E_{\rm tot}$$

- Case 1 is the usual picture jet quenching picture
- Case 2 is more natural in QED (no confinement)

Induced gluon radiation

$t_{prod} = 0$ case

- In the difference $\Delta E_{\rm med} - \Delta E_{\rm vac}$ only the gluon emissions with small formation time contribute

$$t_f \simeq \frac{\omega}{k_\perp^2} \lesssim L \ \Rightarrow \omega \lesssim \hat{q}\ L^2$$

  leading to ΔE independent of E
- The Brodsky-Hoyer bound applies only in this case!

Induced gluon radiation

"$t_{prod} = -\infty$" case

- Gluon emission is here dominated by large formation times $t_f \gg L$
- Associated radiation arises from interference before and after the hard vertex $\rightarrow$ extra gluon radiation cannot be identified with $\Delta E_{\rm parton}$
- However radiated energy $\Delta E_{\rm ind}$ exhibits the same parametric dependence as $\Delta E_{\rm rad}$ of an asymptotic massive parton

Induced gluon radiation

"$t_{prod} = -\infty$" case

Consequences

- $\Delta E_{\rm ind}$ scales like E (i.e. x_1)
- Should strongly affect processes at forward rapidities for which amplitudes before and after the hard vertex interfere
  - J/ψ, open charm, light hadron (with some $p_\perp$)...
  - and not in Drell-Yan, DIS (large z)

Summary

- Parton energy loss
  - powerful tool to investigate the scattering properties of nuclear matter and QGP
- Energy loss in nuclear matter
  - DY production as a sensitive probe of quark energy loss
  - current situation needs to be clarified with precise data at lower beam energy (e.g. E906 at FNAL and P-04 at J-PARC)
  - wealth of data in SIDIS consistent with DY and small energy loss
- New considerations
  - needs to consider in some cases the associated radiation to a hard process in vacuum/medium instead of "parton energy loss"
  - would qualitatively explain the nuclear dependence of J/ψ (and open charm) production in p A collisions