Energy loss in cold nuclear matter and suppression of forward hadron production.

Rodion Kolevatov[1,3], François Arleo[2], Stephane Peigné[1]

[1]SUBATECH, Nantes

[2]LLR Palaiseau

[3]University of Oslo

ICNFP2015, Kolymbari, Crete

Outline

- Introduction
  - Forward hadron suppression in p A collisions;
  - Interpretation of suppression data.
- Coherent induced radiation
  - Scaling properties of parton energy loss;
  - The coherent induced radiation spectrum.
- Phenomenology
  - Quarkonia;
  - Light hadrons.

References

- F. Arleo, S. Peigné, T. Sami Phys.Rev. D83 (2011) 114036
- F. Arleo, S. Peigné JHEP 1303 (2013) 122 [1212.0434]
- F. Arleo, RK, S. Peigné, M. Rustamova JHEP 1305(2013)155 [1304.0901]
- S. Peigné, F. Arleo, RK arxiv:[1402.1671]
- S. Peigné, RK JHEP 1501 (2015) 141 [1405.4241]

A tool to study hot and dense matter

Nuclear modification factor

- Study of hadron spectra w.r.t. scaled pp and Central/Peripheral ratios

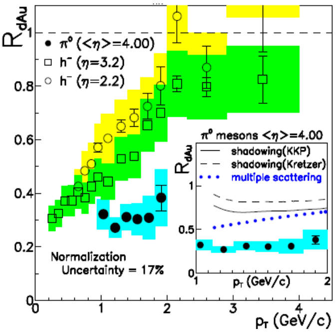
$$R_{AA/pA}(y,p_t) = \frac{\left.\frac{d^2\sigma}{dydp_t}\right|_{AA/pA}}{\langle N_{\rm coll}\rangle \left.\frac{d^2\sigma}{dydp_t}\right|_{pp}}; \quad R_{CP} = \frac{\langle N_{\rm coll}\rangle_P \left.\frac{d^2\sigma}{dydp_t}\right|_{AA/pA,\ C}}{\langle N_{\rm coll}\rangle_C \left.\frac{d\sigma}{dydp_t}\right|_{AA/pA,\ P}}$$

- The importance of proper interpretation of R_{pA}:
  - Baseline for hot matter effect studies
  - Discriminate between possible initial state of fast nucleus and production mechanisms

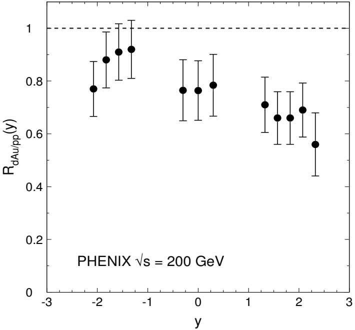
Examples of suppression in RHIC *dAu* data

- Suppression already seen in $p(d)A$ data at forward rapidity
  - Quarkonia production (starting from SPS energies)
  - Forward light hadron production at RHIC
  - Away-side peak in dihadron correlations

Pions at RHIC (BRAHMS&STAR)



J/Ψ at RHIC



Small-x part of parton distribution is probed from the target side

Interpretation of forward hadron suppression

Two different interpretations of forward RHIC data:

- Saturation of gluon densities in nuclear target
  - Smaller target parton densities at low x
    $\Rightarrow$ suppression [Jalilian-Marian'04]
  - Momentum transfer from target partons $k_t \sim Q_s$ ~few GeV
    $\Rightarrow$ dissociation of quarkonia [Fujii Gelis Venugopalan'06]
    $\Rightarrow$ forward dijet decorrelation [T.Lappi, H.Mantysaari'12].
- Parton energy loss interpretation
  - Due to induced gluon radiation, for production in a given 3-momentum bin projectile parton distribution has to be taken at higher x values where it is depleted
  - Only qualitative explanations in some cases.

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This talk: Discuss the mechanism of *coherent* parton energy loss and its application to forward hadron production in pA collisions

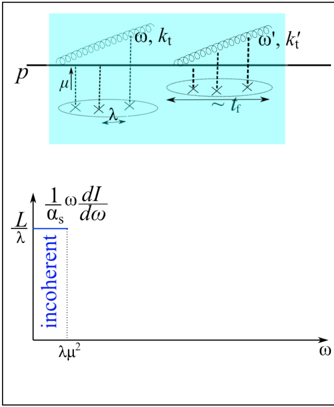
Energy loss regimes

Different e-loss regimes depending on the radiation formation time: $t_f = \omega / k_t^2$

- Bethe–Heitler: $t_f < \lambda,\ \omega < \mu^2 \lambda$

  Each scattering contributes independently

$$\omega \left. \frac{dI}{d\omega} \right|_L = \frac{L}{\lambda} \omega \left. \frac{dI}{d\omega} \right|_{\text{single}} \sim \frac{L}{\lambda} \alpha_s$$



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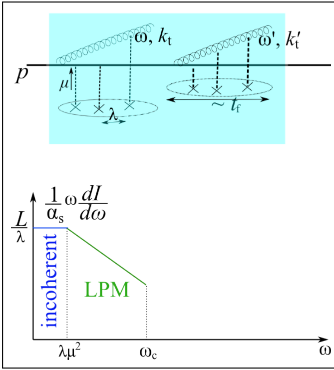
- Landau–Pomeranchuk–Migdal, $\lambda \ll t_f \ll L$

  $$\lambda\mu^2 < \omega < \frac{\mu^2 L^2}{\lambda};\ \left(\omega_c \equiv \hat{q} L \equiv \frac{\mu^2 L^2}{\lambda}\right)$$

  A layer (t_f thick) acts as a single effective scatterer.

$$\omega \frac{dI}{d\omega}\bigg|_L \sim \frac{L}{t_f(\omega, k_t^2 = \frac{\mu^2 L}{\lambda})} \omega \frac{dI}{d\omega}\bigg|_{\text{single}} \sim \sqrt{\frac{\omega_c}{\omega}} \alpha_s$$



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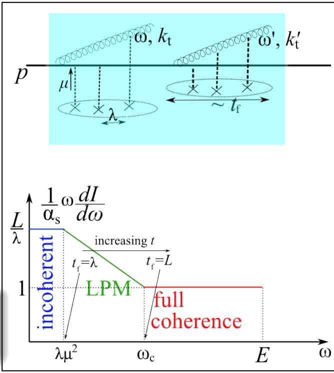
  A layer (t_f thick) acts as a single effective scatterer.
- Fully coherent: $t_f > L$, $\omega_c < \omega < E$
  All scattering centers in the medium act coherently.

Flat $\frac{dI}{d\omega}$ for asymptotic partons traversing the medium.
Large phase space available for radiation.

(A rapid falloff $\frac{dI}{d\omega} \sim \omega_c/\omega$ for partons born in medium)



Two energy loss regimes

LPM energy loss (small formation times ($t_f < L$))

Color charge created/absorbed/suddenly accelerated in the medium;

$\Delta E_{\rm LPM} \propto \alpha_s \hat{q} L^2$, energy independent

- prompt photons, Drell-Yan, weak bosons
- jets and hadrons produced at large angles

Coherent energy loss (large formation times $t_f \gg L$) [Arleo, Peigné, Sami '10]

Small angle scattering of asymptotic color charge

$$\Delta E_{\rm coh} \propto \alpha_s F_c \frac{\sqrt{\hat{q} L}}{M_t} E \quad (\gg \Delta E_{\rm LPM})$$

- Needs color in both initial & final state (otherwise $F_c = 0$);
- forward hadron production in pA collisions.

Theoretical setup

Working in target rest frame

- Compact color object with $M_t^2 \gg \hat{q}L$ in the final state
- Incoming color charge (compact fluctuation) undergoes:
  - a single hard exchange $q_t^2 \gg \hat{q}L$
  - multiple semihard rescatterings $\ell_t^2 \sim \hat{q}L \ll q_t^2$

$\omega \frac{dI}{d\omega}$ derived in the opacity expansion [Gyulassy,Levai,Vitev 2000]

$$dI^{\mathrm{induced}} \equiv dI - dI^{\mathrm{vacuum}} = \sum_{n=1}^{\infty} \frac{d\sigma_{\mathrm{rad}}^{(n)}(p', k)}{d\sigma_{\mathrm{prod}}(p')} \equiv \sum_{n=1}^{\infty} dI^{(n)}$$

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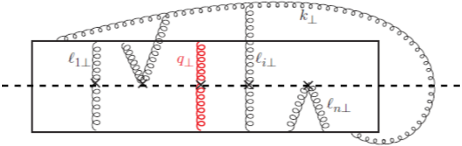
Focus on the dominant contribution to the E-loss with $\Delta E \propto E$

- Implies induced radiation with $t_f \gg L$
- Purely Initial State and Final State radiation are affected by the medium only for $t_f \lesssim L \Rightarrow$ cancel out
- Only interference terms should be accounted for $t_f \gg L$

$dI^{(n)} \propto$ 

Gluon spectrum for $1 \to 1$ hard forward process

Gluon radiation spectrum for $1 \to 1$ hard forward process:

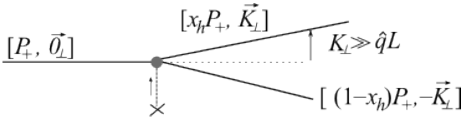
$$\omega \frac{dI}{d\omega} = F_c \frac{\alpha_s}{\pi} \ln\left(1 + \frac{\hat{q} L\, E^2}{M_\perp^2\, \omega^2}\right)$$

- First determined in the simple model, later confirmed rigorously in the GLV opacity expansion
  [Arleo Peigné Sami, 1006.0818, Peigné Arleo RK, 1402.1671]
- Color factor F_c follows from simple color algebra: $F_c = C_R + C_{R'} - C_t$ where $R(R') =$ color rep. of the incoming (outgoing) particle [Peigné Arleo RK, 1402.1671]

$$g \to g\colon\ F_c = N_c + N_c - N_c = N_c$$
$$q \to g\colon\ F_c = C_F + N_c - C_F = N_c$$
$$q \to q\colon\ F_c = C_F + C_F - N_c = -1/N_c \ (< 0!)$$

Gluon spectrum for $1 \to n$ hard forward process

Gluon radiation spectrum for $1 \to 2$ hard forward process (log. accuracy):



- The medium does not resolve the dijet: $\hat{q}L \ll K_\perp^2$
- Possibility for different color charge of the outgoing dijet:
  $q \to qg$, $3 \otimes 8 = 3 \oplus \bar{6} \oplus 15$
  $g \to gg$, $8 \otimes 8 = 1 \oplus 8_a \oplus 8_s \oplus 10 \oplus \overline{10} \oplus 27$
- For a given color of the outgoing dijet the spectrum coincides with $1 \to 1$ case (the soft radiation does not resolve the dijet either):

$$\omega \frac{dI}{d\omega} = F_c \frac{\alpha_s}{\pi} \ln \left(\frac{\hat{q} L\, E^2}{K_\perp^2\, \omega^2} \right)$$

Gluon spectrum for $1 \to n$ hard forward process

Gluon radiation spectrum for $1 \to 2$ hard forward process (log. accuracy):

[Peigné, RK, 1405.4241, Arleo, Peigné, RK (ongoing)]

$$\omega \frac{dI}{d\omega} = \sum_{R'} \mathcal{P}(R'|x_h) F_c \frac{\alpha_s}{\pi} \ln \left(\frac{\hat{q} L \, E^2}{K_\perp^2 \, \omega^2} \right)$$

- $F_c = C_R + C_{R'} - C_t$; where $C_{R'}$ is the Casimir of the compact dijet.
- Color state probabilities $\mathcal{P}(R')$ depend on the dijet kinematics (light-cone momentum sharing btw. dijet components, $[x_h]$:$[1 - x_h]$).
- Provides interpretation of result by Liou and Mueller (4/5 in front of log for $q \to gq$ and $x_h = 1/2$), obtained in *dipole formalism* [Liou, Mueller 2014]
- First determined for $1 \to 2$, conjectured for $1 \to n$.
- "Dynamical color filtering" (similar to Brodsky & Hoyer '89): presumably dijets with least possible color charge (least radiating) survive at large x_F.

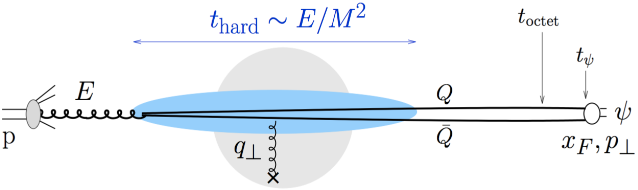
Phenomenology.

Goal

- Explore phenomenological consequences of coherent energy loss
- Approach as simple as possible with the least number of assumptions and minimum parameters
- Observables
  - Quarkonium suppression in pA collisions
  - Light hadron production in pA collisions (preliminary!)

Model for heavy-quarkonium suppression

Physical picture and assumptions



- Originally formulated for Color Octet Model:
  - Color neutralization happens on long time scales: $t_{\text{octet}} \gg t_{\text{hard}}$
  - Hadronization happens outside of the nucleus: $t_\psi \gg L$
  - $Q\bar{Q}$ pair produced by gluon fusion
  - Medium rescattering do not resolve the octet $c\bar{c}$ pair
- Applicable also for CSM assuming that rescatterings and soft radiation do not resolve the compact $[Q\bar{Q}$ + hard $g]$ system.

Model for heavy-quarkonium suppression

Energy shift [Arleo Peigné 1212.0434]

$$\frac{1}{A}\frac{d\sigma^{\psi}_{\rm pA}}{dE}(E,\sqrt{s}) = \int_0^{\varepsilon_{\rm max}} d\varepsilon\,\mathcal{P}(\varepsilon, E|\Delta q_\perp^2)\,\frac{d\sigma^{\psi}_{\rm pp}}{dE}(E+\varepsilon,\sqrt{s})$$

- pp cross section fitted from experimental data

$$E\ d\sigma^{\psi}_{\rm pp}/dE = d\sigma^{\psi}_{pp}/dy \propto (1 - 2M_\perp/\sqrt{s}\cosh y)^{n(\sqrt{s})}$$

- $\mathcal{P}(\epsilon)$: quenching weight, scaling function of $\hat{\omega} = \sqrt{\hat{q}L}/M_\perp \times E$

$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega}\exp\left\{-\int_\epsilon^\infty d\omega \frac{dI}{d\omega}\right\}$$

- Effective length $L_{\rm eff}$ is given by Glauber model, $L_{pp} = 1.5$ fm

$$\hat{q}(L_{eff} - L_{pp}) = \left(\langle N_A^{\rm part}\rangle_\psi - 1\right)\frac{\sigma_{\rm broad}}{\sigma_{\rm inel}}\mu_\perp^2 = \hat{q}\,\frac{\langle N_A^{\rm part}\rangle_\psi - 1}{\sigma_{\rm inel}\rho_0}$$

Procedure

1. Fit $\hat{q}_0$ from J/ψ E866 data on p W vs p Be: $\hat{q}_0 = 0.075\ \mathrm{GeV}^2/\mathrm{fm}$
2. Predict J/ψ and Υ suppression for all nuclei and c.m. energies

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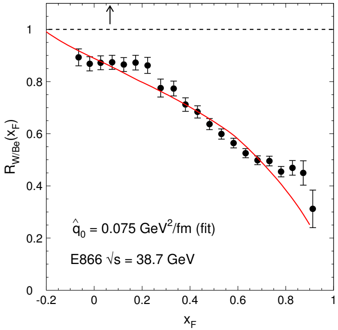
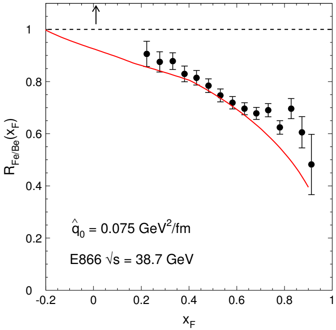
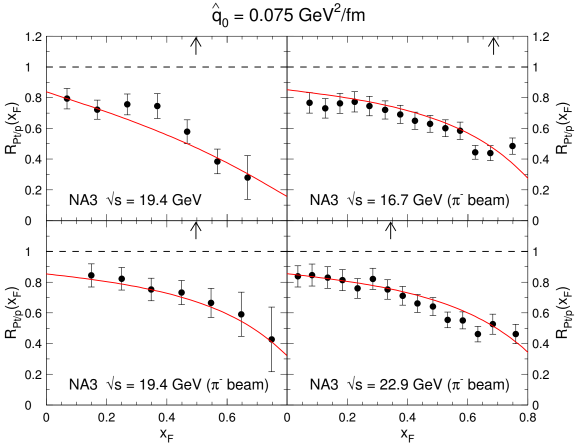




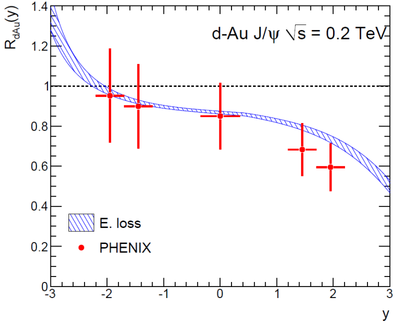
- Fe/Be ratio well described, supporting the L dependence of the model

SPS



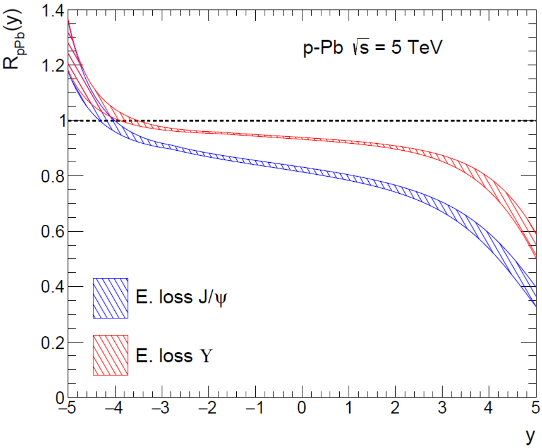
- Agreement when $x_{\mathrm{F}} > x_{\mathrm{F}}^{\mathrm{min}}$ (and even below)
- Natural explanation of the different suppression in p A vs π A from $n_{\pi p} = 1.4$ vs. $n_{\pi p} = 4.3$

RHIC



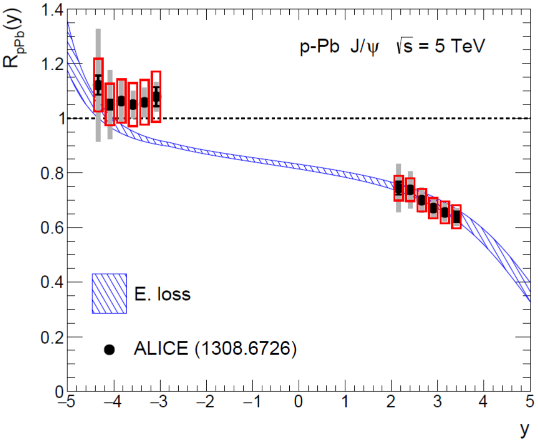
- Good agreement at all rapidity
- Uncertainty in $\hat{q}$ and *pp* cross section parametrization brings comparatively narrow error band.

Comparison with ALICE data



- $R_{pA}(y)$: good agreement despite large uncertainty on normalization
- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$

Comparison with ALICE data



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- Large effects above $y \gtrsim 2 - 3$

Model for light hadron suppression at the LHC

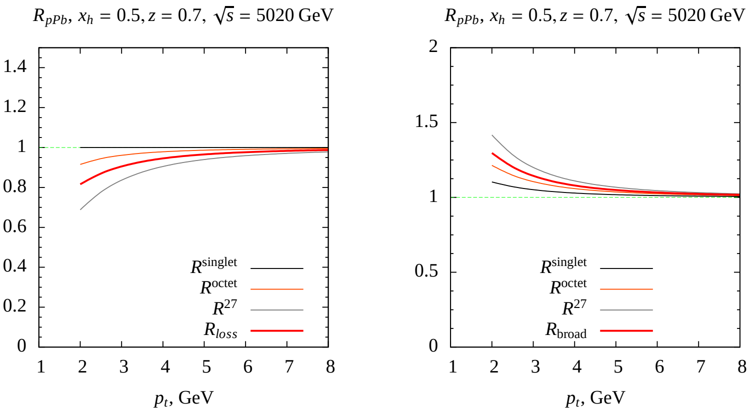
- We assume $g \to gg$ scattering followed by collinear fragmentation
- Broadening ℓ (Cronin effect) deflects the dijet as a whole
  $\Rightarrow$ shifts in transverse momentum $\Delta\vec{p}_t(\ell)$ & rapidity $\delta_{\rm c}(\vec{p}_t, \Delta\vec{p}_t)$
- Due to induced radiation the dijet energy is rescaled ($M_X^2 = \text{const!}$)
  $\Rightarrow$ rapidity shift $\delta_{\rm loss}(\hat{\epsilon})$;
- Average over the color representations of the di-gluon final state:

$$R_{pA}^{R} = \int_{\hat{\epsilon}} \int_{\phi} \mathrm{d}\hat{\epsilon} \hat{\mathcal{P}}_R \left(\hat{\epsilon}, \ell_A(R), P_\perp = \frac{p_\perp}{\langle z \rangle} \right) \frac{d\sigma(y + \delta_{\rm loss}(\hat{\epsilon}) + \delta_c, \vec{p}_t + \Delta\vec{p}_t)}{d\sigma(y, p_t)}$$

$$R_{pA}^{R} = \sum_R R_{pA}^{R} P_R(x_h)$$

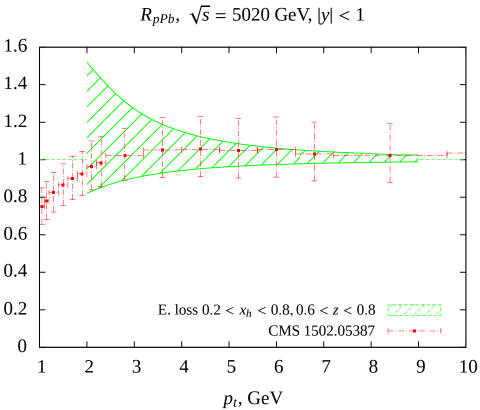
$R = 1, 8, 27$ ($P_{10} = 0$) with Casimirs $C_1 = 0$, $C_8 = N_c$, $C_{27} = 2(N_c + 1)$;
Typical broadening $\langle \ell_A^2(R) \rangle = \hat{q} L (N_c + C_R)/(2N_c)$.

Energy loss vs broadening at the LHC (preliminary)



- Opposite trends between energy loss and broadening effects
- Introducing distribution for the broadening may affect R_{broad}.

Energy loss vs broadening at the LHC (preliminary)

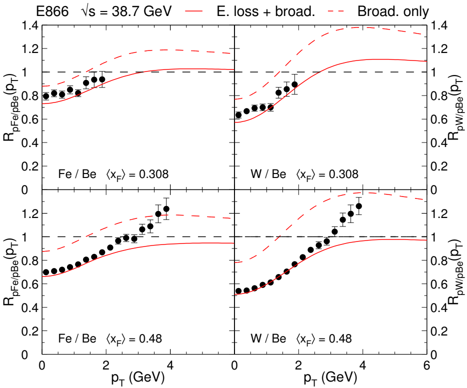


- Calculations consistent with CMS data
- Large uncertainties (mostly from variation of x_h)
- Work in progress!

Summary

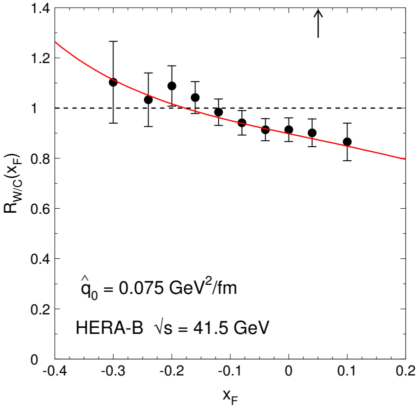
- Energy loss with $\Delta E \propto E$ scaling properties
  - Based on straightforward pQCD calculation of the induced spectrum.
- Quarkonium suppresion in pA collisions
  - Good agreement with all existing data on J/ψ from SPS to LHC
- Light hadrons nuclear modification factor
  - Interplay between energy loss and broadening effects
  - Suppression sensitive to the overall color of the parent dijet
  - Calculations consistent with data (though large errorbands)

E866 p_t dependence



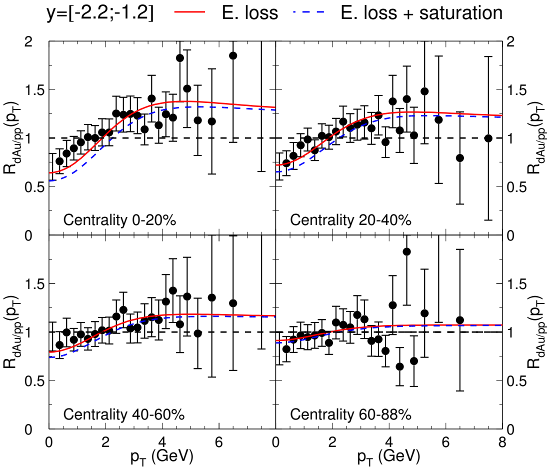
- Good description of $R_{pA/pB}$ for $p_t \lesssim 3$ GeV
- Possible reasons for discrepancy at $p_t > 3$ GeV:
  - Model calculations at fixed x_F rather than averaging
  - p_t dependence from fit to E789 pp data at $x_F = 0$.

Backup - HERA-B



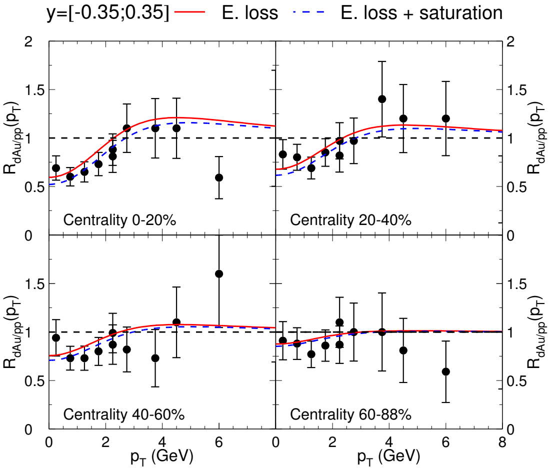
- Also good agreement in the nuclear fragmentation region ($x_F < 0$)
- Enhancement predicted at very negative x_F

RHIC: p_t and centrality dependence



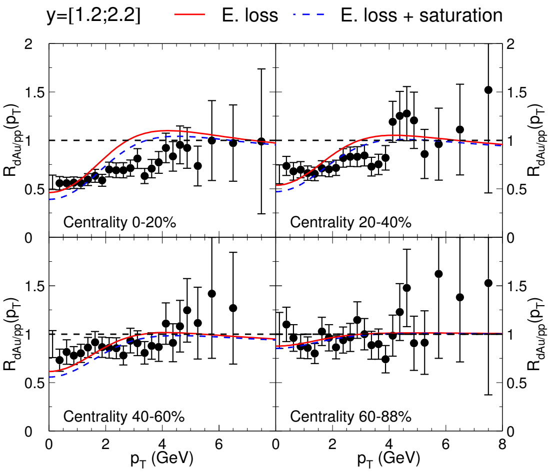
- Good description of $p_\perp$ and centrality dependence at $y = -1.7$

RHIC: p_t and centrality dependence



- Good description of $p_\perp$ and centrality dependence at $y = 0$

RHIC: p_t and centrality dependence



- Good description of $p_\perp$ and centrality dependence at $y = 1.7$

$p_\perp$ dependence

Most general case. The p_t broadening: $|\Delta\vec{p}_\perp| = \hat{q}\,L_{\rm eff}$

$$\frac{1}{A}\frac{d\sigma^{\psi}_{\rm pA}}{dE\ d^2\vec{p}_\perp} = \int_\varepsilon\int_\varphi \mathcal{P}(\varepsilon, E)\,\frac{d\sigma^{\psi}_{\rm pp}}{dE\ d^2\vec{p}_\perp}\,(E+\varepsilon, \vec{p}_\perp - \Delta\vec{p}_\perp)$$

- Parametrization consistent with *pp* experimental data

$$\frac{d\sigma^{\psi}_{\rm pp}}{dy\,d^2\vec{p}_\perp} \propto \left(\frac{p_0^2}{p_0^2+p_\perp^2}\right)^m \times \left(1 - \frac{2M_\perp}{\sqrt{s}}\cosh y\right)^n \equiv \mathcal{N}\times\mu(p_\perp)\times\nu(y, p_\perp)$$

- For $\mathcal{P}(\varepsilon, E)$ peaked at small ε

$$R^{\psi}_{\rm pA}(y, p_\perp) \simeq R^{\rm loss}_{\rm pA}(y, p_\perp)\cdot R^{\rm broad}_{\rm pA}(p_\perp)$$

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$$R^{\psi}_{\rm pA}(y, p_\perp) \simeq R^{\rm loss}_{\rm pA}(y, p_\perp) \cdot R^{\rm broad}_{\rm pA}(y, p_\perp)$$

- Overall depletion due to parton energy loss
- Possible Cronin peak due to momentum broadening

$$R^{\rm broad}_{\rm pA}(y, p_\perp) \equiv \int_\varphi \frac{\mu(|\vec{p}_\perp - \Delta\vec{p}_\perp|)}{\mu(p_\perp)}\,\frac{\nu(E, \vec{p}_\perp - \Delta\vec{p}_\perp)}{\nu(E, p_\perp)};$$

$$R^{\rm loss}_{\rm pA}(y, p_\perp) \equiv \int_\varepsilon \mathcal{P}(\varepsilon, E)\left[\frac{E}{E+\varepsilon}\right]\frac{\nu(E+\varepsilon, p_\perp)}{\nu(E, p_\perp)}$$