Small-x observable in pA collisions: Medium-induced coherent gluon radiation

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arXiv: 1603.01028, with Stéphane Munier and Stéphane Peigné

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Disentangle hot medium from cold nuclear matter effects

Hadron suppression in AA and pA collisions with respect to pp

- ***Hot medium (QGP) effects;***

- ***Cold nuclear matter (CNM) effects:***

Parton shadowing in nuclear PDFs;

J. L. Albacete et al. (2013).
R. Vogt (2015)
E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. Rakotozafindrabe (2013)

Gluon saturation at small x;

H. Fujii and K. Watanabe, (2013).
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Medium-induced coherent radiation in CNM.

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T. Liou and A. H. Mueller, (2014): $(1 \rightarrow 2)$

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This work $(1 \rightarrow 1)$ +

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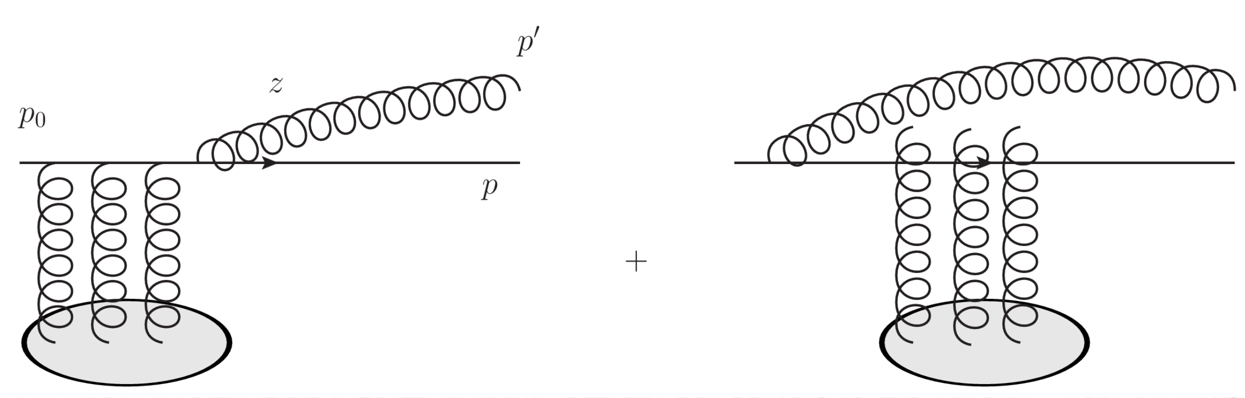
Medium-induced coherent gluon radiation in this work

Associated with q → q and g → g hard forward scattering:

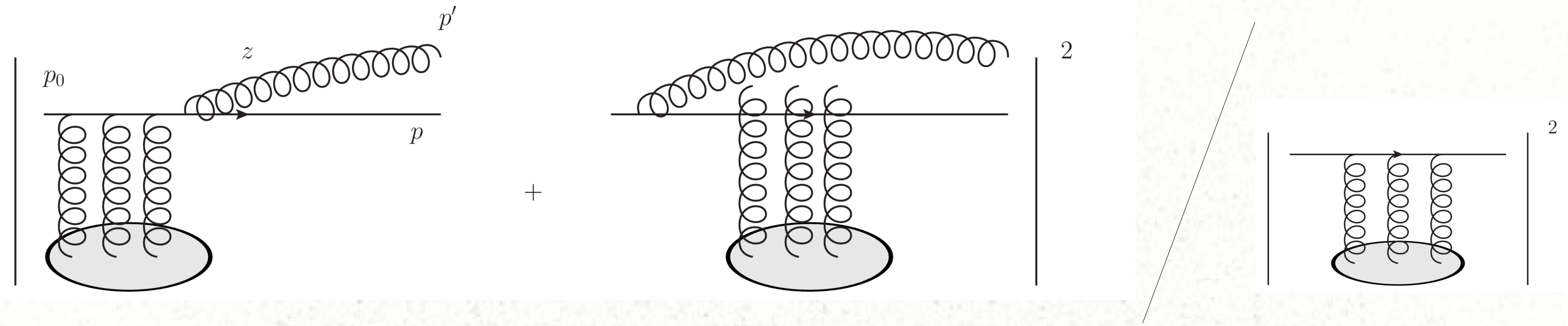
- ***→ in the saturation framework;***
- ***→ MV classical model and Gaussian approximation for the nucleus;***
- ***→ finite Nc;***
- ***→ to leading logs + magnitude of corrections.***



$$a(p_0) + A \to a(p) + g(p') + X$$

- ***→Forward scattering (large*** p^+***);***
- ***→Hard scattering,*** $p_\perp \gg Q_s$;
- ***→Soft gluon radiation,*** $z \equiv p'^+/p_0^+ \ll 1\,.$

Medium-induced spectrum



- proton

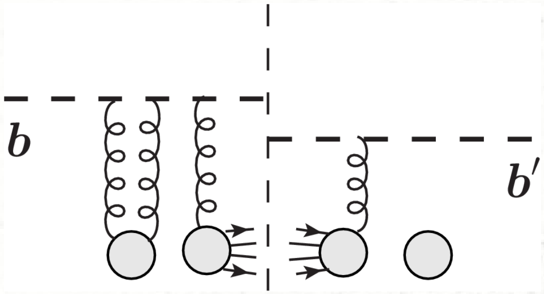
Radiation energy spectrum:

$$z\frac{dI_A}{dz} = p'^{+}\frac{dI_A}{dp'^{+}} = \frac{\dfrac{d\sigma(a+A\to a+g+X)}{dy\,dy'\,d^2p_\perp}}{\dfrac{d\sigma(a+A\to a+X)}{dy\,d^2p_\perp}} = \frac{\dfrac{d\sigma(p+A\to a+g+X)}{dy\,dy'\,d^2p_\perp}}{\dfrac{d\sigma(p+A\to a+X)}{dy\,d^2p_\perp}}$$

Medium induced spectrum, nucleus target – proton target :

$$z\frac{dI}{dz}\bigg|_{ind} \equiv z\frac{dI_A}{dz} - z\frac{dI_p}{dz} \qquad\qquad Q_s^2(x) \sim A^{1/3}\,x^{-0.3}$$

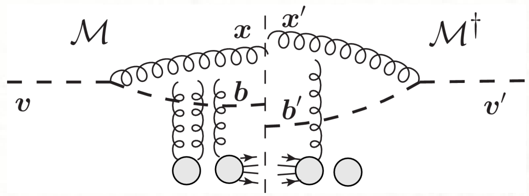
Single parton scattering cross section (denominator)



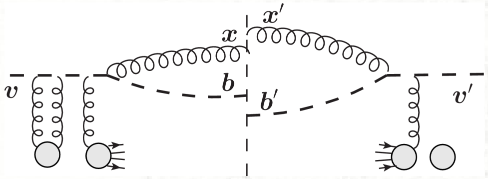
$$S^{(2)} = \frac{1}{d_R} \left\langle \mathrm{tr} \left(U_R(v) U_R{}^{\dagger}(v') \right) \right\rangle$$

$$\frac{d\sigma(\mathrm{pA} \to a + X)}{dy\, d^2p} = \frac{x_p f_{a/p}(x_p, \mu_F^2)}{(2\pi)^2} \int_b \int_{b'} e^{-ip\cdot(b-b')} S_a^{(2)}[b, b']$$

$a \to a + g$ forward production (numerator)



$$S^{(4)} = \frac{1}{d_R C_R} \left\langle \mathrm{tr}\left(T_R^c \, U_R(b) \, U_R{}^\dagger(b') \, T_R^d \right) [V(x) V^\dagger(x')]^{cd} \right\rangle$$



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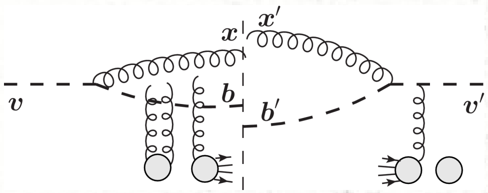
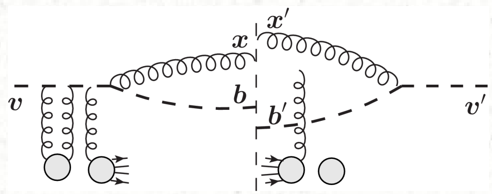




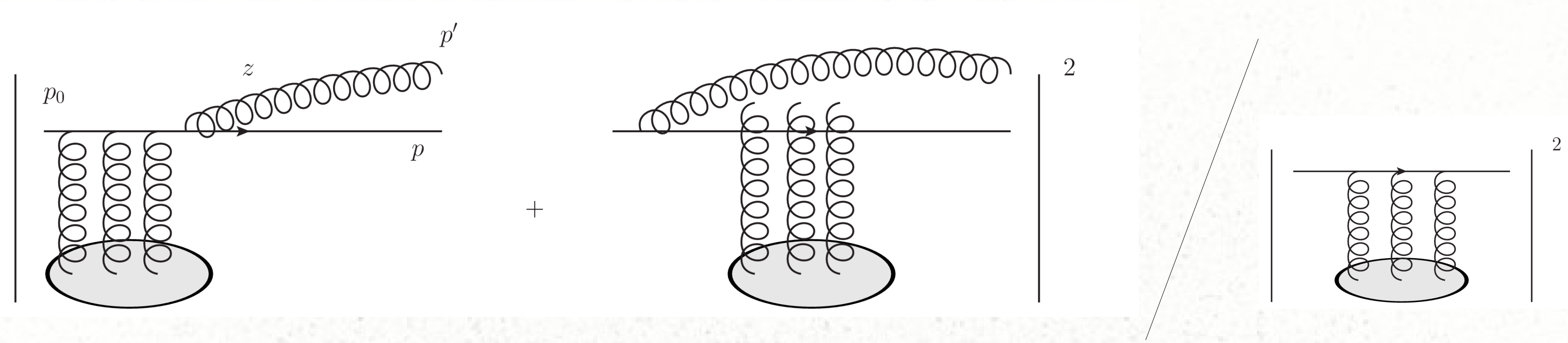
$$S^{(3)} = \frac{1}{d_R C_R} \left\langle \mathrm{tr}\left(T_R^c \, U_R(b) \, T_R^d \, U_R{}^\dagger(v') \right) [V(x)]^{cd} \right\rangle$$

$$\frac{d\sigma(pA \to ag + X)}{dy \, dy' d^2 p} = \frac{\alpha_s}{(2\pi)^4} \, x_\mathrm{p} f_{a/\mathrm{p}}(x_\mathrm{p}, \mu_\mathrm{F}^2) \, z \, (1-z) \, \Phi_a^g(z)$$

$$\times \int_x \int_b \int_{b'} e^{-ip\cdot(b-b')} \, \frac{(x-b)\cdot(x-b')}{(x-b)^2 \, (x-b')^2} \left\{ S_a^{(2)}[b, b'] + S_a^{(2)}[v, v'] - 2 S_a^{(3)}[b, x, v'] \right\}$$

$$x' \to x' + b' \qquad r = b' - b$$

Medium-induced spectrum: General expression in coordinate space



$$z\frac{dI}{dz} = \frac{\frac{d\sigma(p+A\to a+g+X)}{dy\, dy'\, d^2p_\perp}}{\frac{d\sigma(p+A\to a+X)}{dy\, d^2p_\perp}}$$

$$z\frac{dI}{dz} = \frac{2C_R\alpha_s}{\pi^2}\, \frac{\int_r e^{ip\cdot r}\int_x \frac{x\cdot(x+r)}{x^2(x+r)^2}\left\{S_a(r) - S_a^{(3)}[0, x+r, zx+r]\right\}}{\int_r e^{ip\cdot r}\, S_a(r)}\Bigg|_{ind}$$

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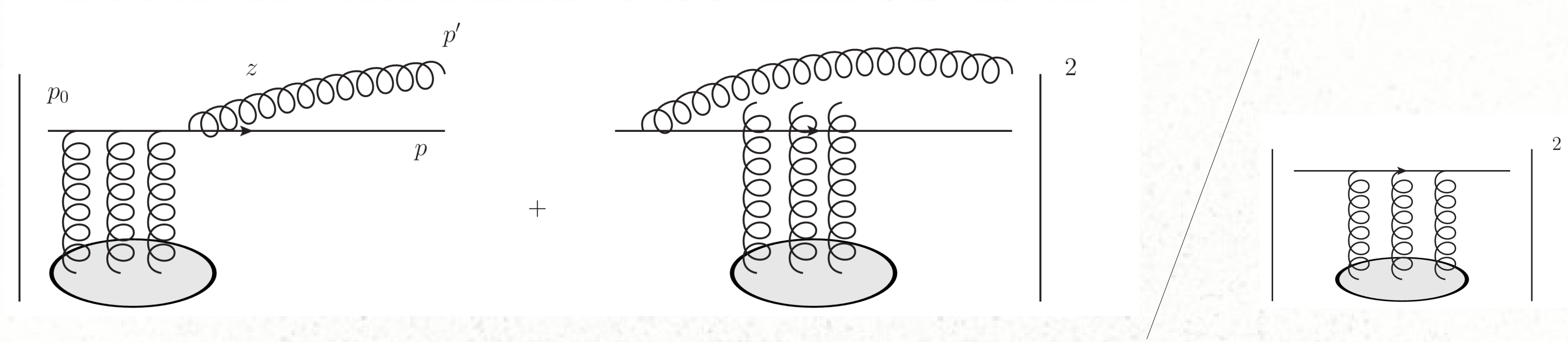

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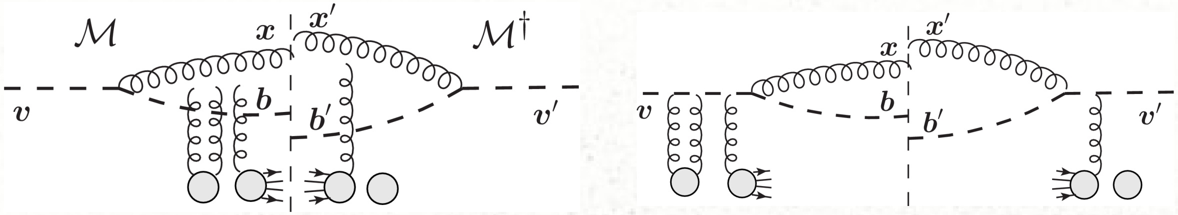
Separation between purely initial/final and interference contribution:

$$z\left.\frac{dI}{dz}\right|_{ind} = z\left.\frac{dI}{dz}\right|_{IS} + z\left.\frac{dI}{dz}\right|_{FS} + z\left.\frac{dI}{dz}\right|_{INT}$$

Medium-induced spectrum: Purely initial/final radiation



$$r = b' - b$$

$$r \sim 1/p \ll 1/Q_s$$

$$z\frac{dI}{dz}\bigg|_{IS} = z\frac{dI}{dz}\bigg|_{FS} = \frac{C_R\alpha_s}{\pi^2}\,\frac{\int_r e^{ip\cdot r}\,[S_a(r)-1]\int_x \frac{x\cdot(x+r)}{x^2(x+r)^2}}{\int_r e^{ip\cdot r}\,S_a(r)}\Bigg|_{ind}$$

→ Gaussian distribution of sources in the nucleus (MV model):

$$S_a(x) \simeq \exp\left[-\frac{Q_a^2}{8}\,x^2\log\left(\frac{1}{x^2\mu^2}\right)\right] \approx 1 - \frac{Q_a^2}{8}\,x^2\log\left(\frac{1}{x^2\mu^2}\right)$$

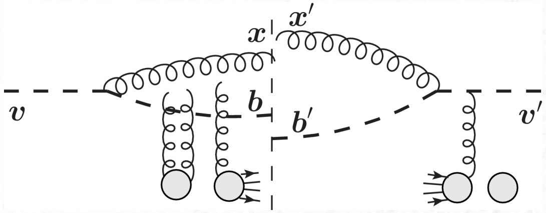
$$\int_r e^{ip\cdot r}\,[S_a(r)-1]\int_x \frac{x\cdot(x+r)}{x^2(x+r)^2} \simeq \frac{2\pi Q_a^2}{|p|^4}\left[\log\left(\frac{p^2}{\mu^2}\right) + \mathcal{O}\left(\frac{Q_a^2}{p^2}\log^2\left(\frac{p^2}{\mu^2}\right)\right)\right]$$

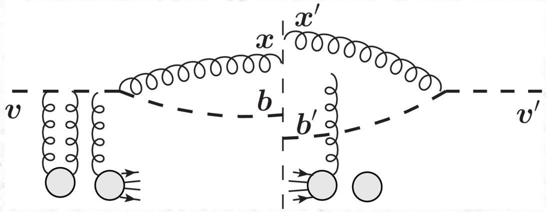
$$\int_r e^{ip\cdot r}\,S_a(r) \simeq \frac{2\pi Q_a^2}{|p|^4}\left[1 + \mathcal{O}\left(\frac{Q_a^2}{p^2}\log\left(\frac{p^2}{\mu^2}\right)\right)\right]$$

$$z\frac{dI}{dz}\bigg|_{IS} = z\frac{dI}{dz}\bigg|_{FS} = 2\frac{\alpha_s C_R}{\pi}\left\{\log\left(\frac{p^2}{\mu^2}\right) + \mathcal{O}\left(\frac{Q_a^2}{p^2}\log^2\left(\frac{p^2}{\mu^2}\right)\right)\right\}\bigg|_{ind}$$

Medium-induced spectrum: Interference

The main contribution comes from the interference terms





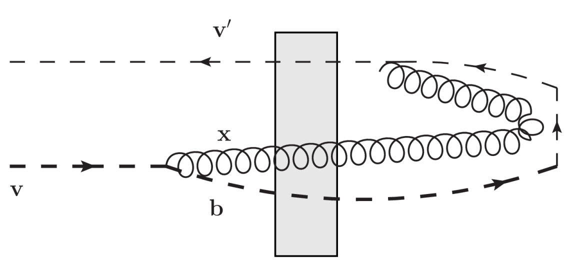
$r \sim 1/p \ll 1/Q_s\,,$

$r \ll x$ **but not** $r \ll zx$

$$z\frac{dI}{dz}\bigg|_{INT} = \frac{2C_R\alpha_s}{\pi^2}\frac{\int_r e^{ip\cdot r}\int_x \frac{x\cdot(x+r)}{x^2(x+r)^2}\left\{1-S_a^{(3)}[0,x+r,zx+r]\right\}}{\int_r e^{ip\cdot r}\,S_a(r)}\Bigg|_{ind}$$

→ ***Gaussian distribution of sources in the nucleus (MV model):***

$$S_a^{(3)}[b,x,v'] = [S_a(b-x)]^{\frac{C_A}{2C_R}}\,[S_a(x-v')]^{\frac{C_A}{2C_R}}\,[S_a(v'-b)]^{\frac{2C_R-C_A}{2C_R}}$$



A. Kovner and U. A. Wiedemann, (2001)
J. P. Blaizot, F. Gelis and R. Venugopalan (2004)
C. Marquet and H. Weigert (2010)

$$z\frac{dI}{dz}\bigg|_{INT} = -(2C_R-C_A)\,\frac{\alpha_s}{\pi^2}\int\frac{d^2x}{x^2}\,e^{-izp\cdot x}\,S_g(x)$$

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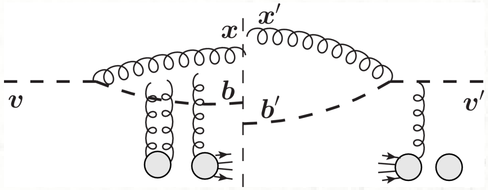

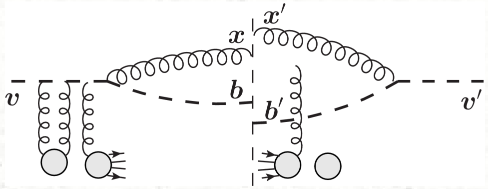

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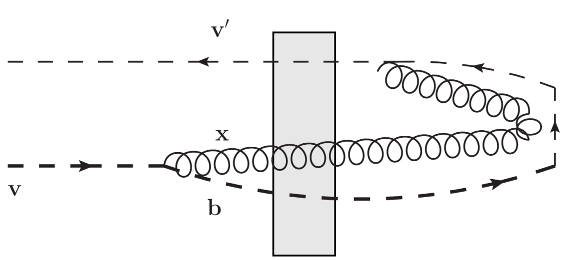

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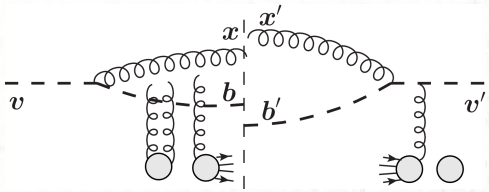

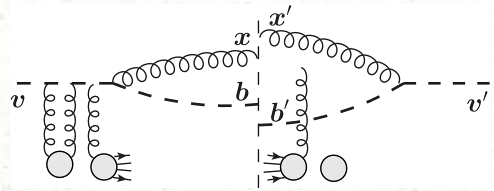

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$g : N_c$ $\qquad$ $q : -\dfrac{1}{N_c}$

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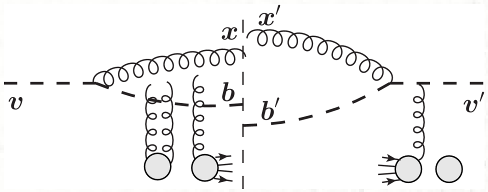

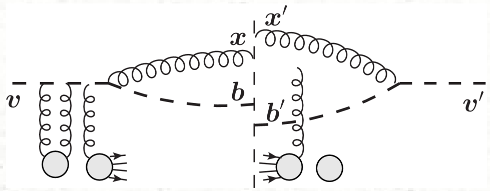

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Opacity expansion:

F. Arleo, R. Kolevatov and S. Peigne, (2016)

N. Armesto, H. Ma, M. Martinez, Y. Mehtar-Tani and C. A. Salgado, (2012, 2013)

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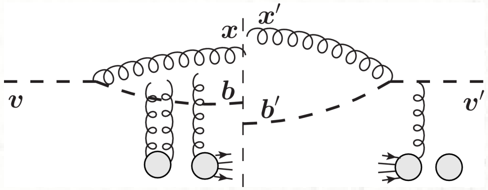

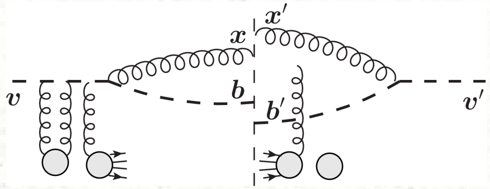

$$r \sim 1/p \ll 1/Q_s \, ,$$

$$r \ll x$$

Parametric limit:

$$z\frac{dI}{dz} \simeq (2C_R - C_A)\,\frac{\alpha_s}{\pi}\log\left(\frac{Q_s^2}{2z^2p^2}\right)$$

Order of corrections:

$$\sim \alpha_s\,\mathcal{O}\left(\frac{Q_a^2}{p^2}\log^2\left(\frac{p^2}{\mu^2}\right)\right)$$

Saturation formalism vs opacity expansion

$$z\frac{dI}{dz}\bigg|_{INT} = \frac{2C_R\alpha_s}{\pi^2}\,\frac{\int_r e^{ip\cdot r}\int_x \frac{x\cdot(x+r)}{x^2(x+r)^2}\left\{1-S_a^{(3)}[0,x+r,zx+r]\right\}}{\int_r e^{ip\cdot r}\,S_a(r)}\Bigg|_{ind}$$

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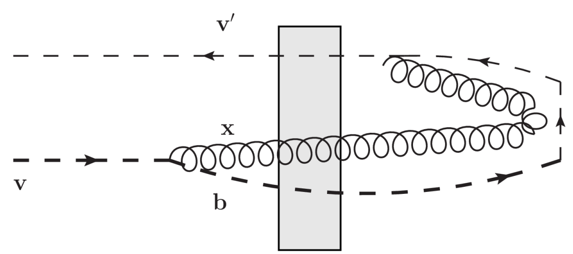
$$S_a(x) = e^{-C_R\hat{\Gamma}(x)}$$

$$z\frac{dI}{dz} = \sum_{m\geq 2}\frac{2\alpha_s}{\pi^2}\,\frac{\int_r e^{ip\cdot r}\int\frac{d^2x}{x^2}\,e^{-izp\cdot x}\,\frac{(-1)^m}{m!}\left\{\frac{2C_R-C_A}{2}\,\hat{\Gamma}(r)+C_A\,\hat{\Gamma}(x)\right\}^m}{\int_r e^{ip\cdot r}\,\hat{\Gamma}(r)}$$



Dominant term: $m\,\hat{\Gamma}(x)^{m-1}\,\hat{\Gamma}(r)$

$$z\frac{dI}{dz} = (2C_R-C_A)\,\frac{\alpha_s}{\pi^2}\int\frac{d^2x}{x^2}\,e^{-izp\cdot x}\sum_{n\geq 1}\frac{(-1)^{n+1}}{n!}\left[C_A\,\hat{\Gamma}(x)\right]^n$$

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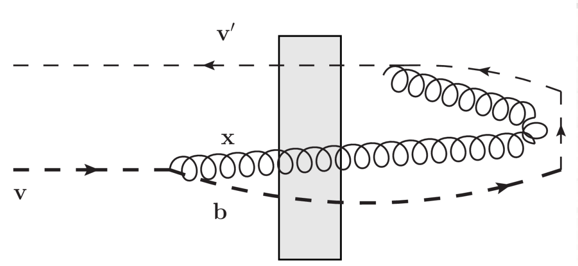


Dominant term: $m\,\hat{\Gamma}(x)^{m-1}\,\hat{\Gamma}(r)$

$\downarrow$

Order m in opacity

(First order in opacity: m=2)

$$z\frac{dI}{dz} = (2C_R - C_A)\,\frac{\alpha_s}{\pi^2}\int \frac{d^2x}{x^2}\, e^{-izp\cdot x}\sum_{n\geq 1}\frac{(-1)^{n+1}}{n!}\left[C_A\,\hat{\Gamma}(x)\right]^n$$

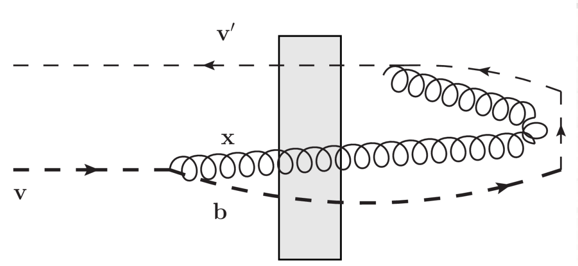
Saturation formalism vs opacity expansion

Saturation formalism:

→ *the calculation is performed in coordinate space;*
→ *the scatterings are resummed (exponentiated) from the start;*

Opacity expansion formalism:

→ *the calculation is performed in momentum space;*
→ *a hard scattering is assumed from the start;*
→ *calculation at first order in opacity, and then generalized to any order n by recurrency relations; the exponentiation appears at a later stage.*



Dominant term: $m\,\hat{\Gamma}(x)^{m-1}\,\hat{\Gamma}(r)$

$$z\frac{dI}{dz} = (2C_R - C_A)\,\frac{\alpha_s}{\pi^2}\int\frac{d^2x}{x^2}\,e^{-izp\cdot x}\sum_{n\geq 1}\frac{(-1)^{n+1}}{n!}\left[C_A\,\hat{\Gamma}(x)\right]^n$$

Conclusions

We derive the induced coherent radiation spectrum for an energetic quark or gluon scattering off a nucleus;

→ ***Saturation framework;***
→ ***Hard, forward scattering;***
→ ***Finite Nc;***
→ ***Gaussian approximation for the field of the nucleus.***

- ***General expression in coordinate space;***
- ***Leading asymptotics from the interference diagrams;***
- ***Order of magnitude of the corrections;***
- ***Explicit connection between the saturation and opacity expansion formalisms.***

Outlook

- ***Implementing small-x evolution in the calculation;***
- ***Phenomenology;***
- ***Energy loss in gluon $\rightarrow$ quark-antiquark scattering in the saturation framework and at finite Nc.***

The main contribution to the induced spectrum comes from the interference term

$$z\frac{dI}{dz} = \frac{\frac{d\sigma(p+A\to a+g+X)}{dy\,dy'\,d^2p_\perp}}{\frac{d\sigma(p+A\to a+X)}{dy\,d^2p_\perp}} = \frac{2C_R\alpha_s}{\pi^2}\,\frac{\int_r e^{ip\cdot r}\int_x \frac{x\cdot(x+r)}{x^2(x+r)^2}\left\{S_a(r)-S_a^{(3)}[0,x+r,zx+r]\right\}}{\int_r e^{ip\cdot r}\,S_a(r)}\Bigg|_{ind}$$

$$\boxed{z\frac{dI}{dz}\bigg|_{INT} = (2C_R-C_A)\,\frac{\alpha_s}{\pi^2}\int\frac{d^2x}{x^2}\,e^{-izp\cdot x}\,\left[S_{gp}(x)-S_g(x)\right]}$$

Parametric limits:

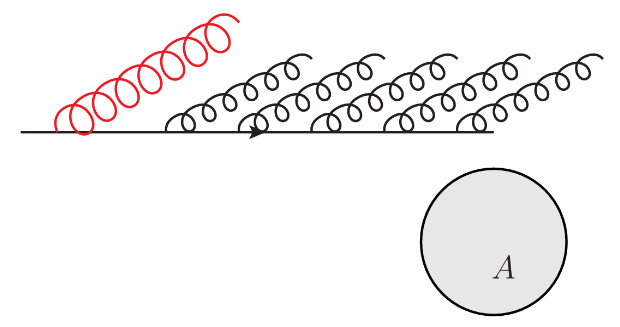
$$z\frac{dI}{dz} \simeq (2C_R-C_A)\,\frac{\alpha_s}{\pi}\times\begin{cases}\log\left(\dfrac{Q_s^2}{2z^2p^2}\right) & \text{if } z\ll\dfrac{Q_s}{p},\\[2ex] \dfrac{Q_s^2}{2z^2p^2} & \text{if } z\gg\dfrac{Q_s}{p},\end{cases}$$

Order of corrections:

$$\boxed{\sim\alpha_s\,\mathcal{O}\left(\frac{Q_a^2}{p^2}\log^2\left(\frac{p^2}{\mu^2}\right)\right)}$$

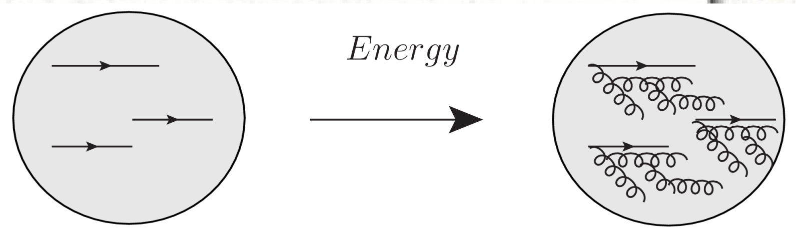
MV model → The saturation scale does not depend on energy.

Small-x evolution



- *In the nucleus rest frame*

Softer gluons factorize in the nuclear parton density.



- *Boosted nucleus*

Non-linear evolution equations for the correlators:

→ *JIMWLK*

→ *Balitsky- Kovchegov (large Nc)*

J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, (1997, 1999)
E. Iancu, A. Leonidov, and L. D. McLerran,(2001)

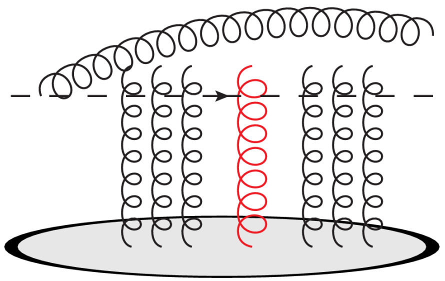
I. Balitsky, (1996)

Y. V. Kovchegov, (1999)

- *MV model + x-dependent saturation scale (finite Nc);*

E. Iancu and D. N. Triantafyllopoulos, (2012)

- *General 1 → 1 hard forward scattering in the opacity expansion formalism.*



S. Peigne, F. Arleo and R. Kolevatov, (2016)

Rule for the color factor:

$$C_R + C_{R'} - C_t$$

- *q → q hard forward scattering in the opacity expansion formalism with a color singlet exchange in the t channel.*

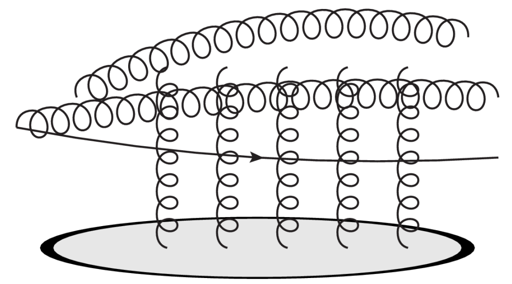
N. Armesto,H. Ma, M. Martinez, Y. Mehtar-Tani and C. A. Salgado, (2012, 2013)

- *q → qg and g → gg in the opacity expansion formalism.*

Rule for the color factor for 1 → n scattering. *S. Peigne and R. Kolevatov, (2015)*

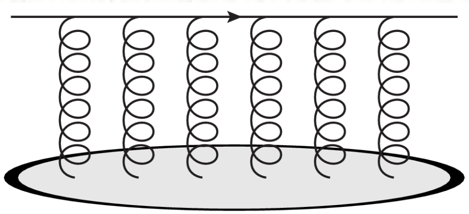
- *q → qg and g → q anti-q in the saturation formalism in the large-Nc limit.*

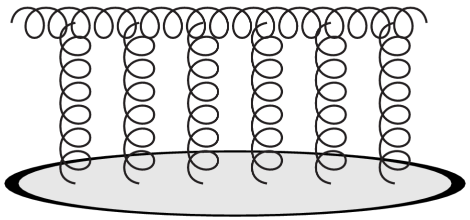
T. Liou and A. H. Mueller, (2014)



Medium-induced coherent gluon radiation in this work

Associated with q → q and g → g hard forward scattering:
- ***→ in the saturation framework;***
- ***→ MV classical model and Gaussian approximation for the nucleus;***
- ***→ finite Nc;***
- ***→ to leading logs + magnitude of corrections.***





$$U_F = \mathcal{P}\exp\left[ig\int dx^+ A_c^-(x^+, x_\perp)\, T_F^c\right] \qquad U_A = \mathcal{P}\exp\left[ig\int dx^+ A_c^-(x^+, x_\perp)\, T_A^c\right]$$

- ***Large ultra-relativistic nucleus; perturbative calculation.***

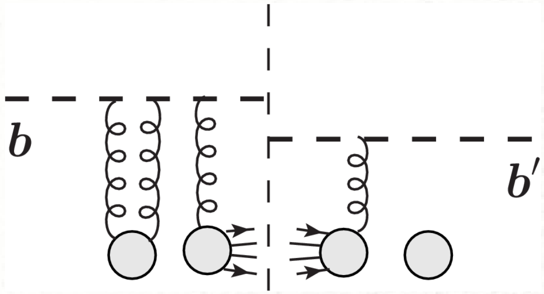
$$Q_s^2(x) \sim A^{1/3}\, x^{-0.3} \gg \Lambda_{QCD}^2 \qquad \alpha_s(Q_s^2) \ll 1$$

- ***High occupation number of gluons; The small-x gluon field is classical.***

McLerran-Venugopalan model

L. D. McLerran and R. Venugopalan, (1994)

Parton elastic scattering cross section (denominator)



$$\frac{d\sigma(\mathrm{pA}\to a+X)}{dy\, d^2p} \sim \int_b \int_{b'} e^{-ip\cdot(b-b')}\, S_a^{(2)}[b,b']$$

Assumptions:

→ ***Infinite transverse nuclear size;***

$$p_\perp \gg Q_s; \quad r_\perp = b'_\perp - b_\perp \sim 1/p \ll 1/Q_s < 1/\Lambda_{QCD};$$

$$S_a^{(2)}[b,b'] \equiv S_a(b'-b)$$

→ ***Gaussian distribution of sources in the nuclear wave function;***

$$S_a(x) \simeq \exp\left[-\frac{Q_a^2}{8}\, x^2 \log\left(\frac{1}{x^2\mu^2}\right)\right]$$

$$S_a^{(3)}[b,x,v'] = [S_a(b-x)]^{\frac{C_A}{2C_R}}\, [S_a(x-v')]^{\frac{C_A}{2C_R}}\, [S_a(v'-b)]^{\frac{2C_R-C_A}{2C_R}}$$