System of evolution equations for quark and gluon jet quenching with broadening

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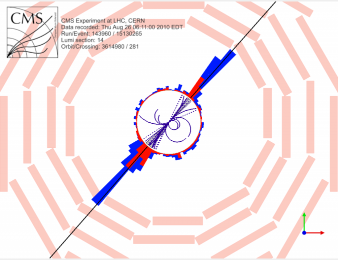
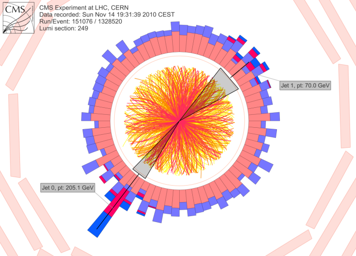
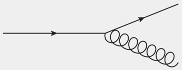
supported by NCN grant No. DEC-2017/27/B/ST2/01985.



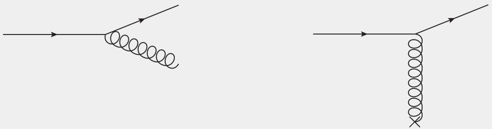


- Jet quenching observed through asymmetrical back to back dijet energy
- Understood as the result of the interaction of the jet with a quark-gluon plasma (QGP)
- Jet as hard probe of QGP



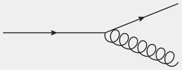
Possible processes

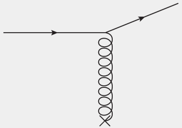
- Bremsstrahlung radiations (as in vacuum)

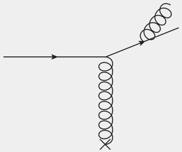


Possible processes

- Bremsstrahlung radiations (as in vacuum)
- Elastic scattering

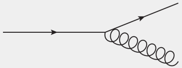


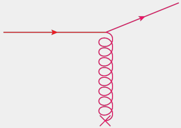


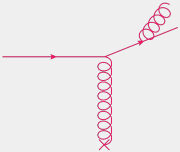


Possible processes

- Bremsstrahlung radiations (as in vacuum)
- Elastic scattering
- Inelastic scattering

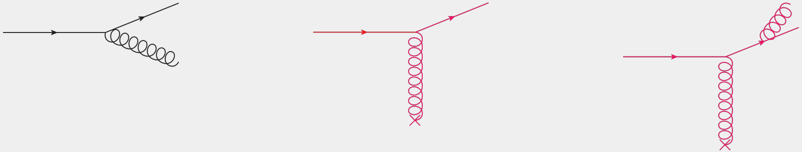






Possible processes

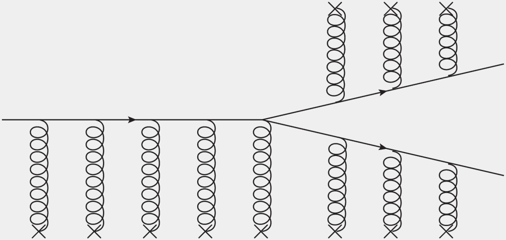
- Bremsstrahlung radiations (as in vacuum)
- Elastic scattering (collisions)
- Inelastic scattering → Medium induced radiations



Possible processes

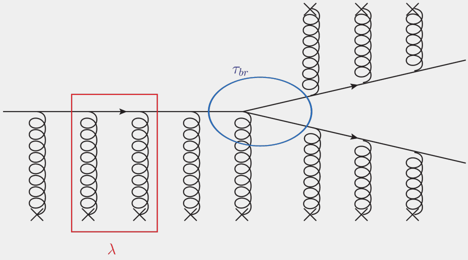
- Bremsstrahlung radiations (as in vacuum)
- Elastic scattering (collisions)
- Inelastic scattering $\rightarrow$ Medium induced radiations

- $P_{ij}(z)$
- $\mathcal{C}(\mathbf{l})$
- $\mathcal{K}_{ij}(z)$



- Static color charges
- Eikonal interaction
- Collinear radiation
- Main parameter : $\hat{q} = \frac{\Delta k_\perp^2}{\Delta l}$

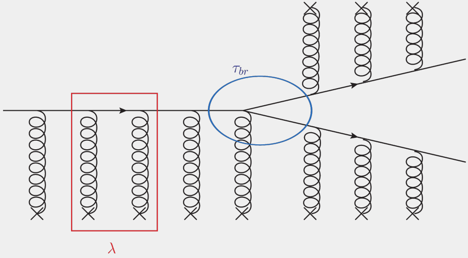
R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff. RADIATIVE ENERGY LOSS OF HIGH-ENERGY QUARKS AND GLUONS IN A FINITE VOLUME QUARK - GLUON PLASMA. ***Nucl. Phys. B*, 483:291–320, 1997**



Time scales

For a radiated parton of energy ω and transverse momentum $k_\perp$

- Formation time : $\tau_f \sim \frac{2\omega}{k_\perp^2}$
- Branching time : $\tau_{br}(\omega) \sim \sqrt{\frac{2\omega}{\hat{q}}}$
- $\tau_{br}(\omega_c) \sim L \rightarrow$ limit on soft emission
- $\tau_{br}(\omega_{BH}) \sim \lambda \rightarrow$ Bethe-Heitler spectrum (incoherent collision)



Limit studied

$$\omega_{BH} \ll \omega \lesssim \omega_c$$

Where medium-induced radiation dominates

Formulation

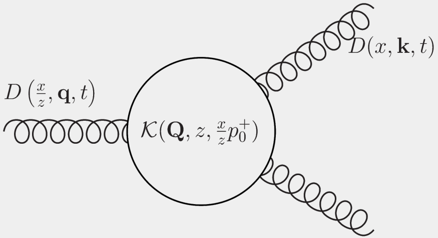
$$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) = \alpha_s \int_0^1 dz \int \frac{d^2 q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+) D\left(\frac{x}{z}, \mathbf{q}, t\right) - \mathcal{K}(\mathbf{q}, z, x p_0^+)\, D(x, \mathbf{k}, t) \right] + \int \frac{d^2 \mathbf{l}}{(2\pi)^2}\, C(\mathbf{l})\, D(x, \mathbf{k} - \mathbf{l}, t)$$

J.-P. Blaizot, F. Dominguez, E. Iancu, and Y. Mehtar-Tani. Probabilistic picture for medium-induced jet evolution. ***JHEP*, 06:075, 2014**

Formulation

$$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) = \alpha_s \int_0^1 dz \int \frac{d^2 q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+) D\left(\frac{x}{z}, \mathbf{q}, t\right) - \mathcal{K}(\mathbf{q}, z, x p_0^+)\, D(x, \mathbf{k}, t) \right] + \int \frac{d^2 \mathbf{l}}{(2\pi)^2}\, C(\mathbf{l})\, D(x, \mathbf{k} - \mathbf{l}, t)$$

$$\boldsymbol{Q} = \boldsymbol{k} - z\boldsymbol{q}$$



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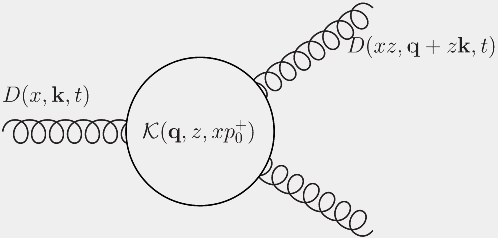

Formulation

$$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) = \alpha_s \int_0^1 dz \int \frac{d^2 q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+) D\left(\frac{x}{z}, \mathbf{q}, t\right) - \mathcal{K}(\mathbf{q}, z, xp_0^+)\, D(x, \mathbf{k}, t) \right] + \int \frac{d^2 \mathbf{l}}{(2\pi)^2} C(\mathbf{l})\, D(x, \mathbf{k} - \mathbf{l}, t)$$

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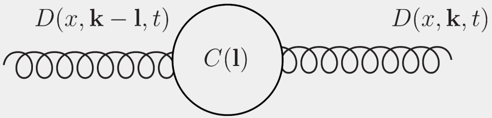
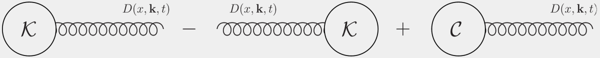


Formulation

$$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) = \alpha_s \int_0^1 dz \int \frac{d^2 q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+) D\left(\frac{x}{z}, \mathbf{q}, t\right) - \mathcal{K}(\mathbf{q}, z, x p_0^+) D(x, \mathbf{k}, t) \right] + \int \frac{d^2 \mathbf{l}}{(2\pi)^2} C(\mathbf{l}) D(x, \mathbf{k}-\mathbf{l}, t)$$

J.-P. Blaizot, F. Dominguez, E. Iancu, and Y. Mehtar-Tani. Probabilistic picture for medium-induced jet evolution. ***JHEP*, 06:075, 2014**

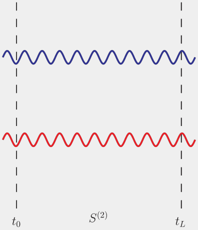
BDIM\ Pure gluon case

$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) =$ 

Formulation

$$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) = \alpha_s \int_0^1 dz \int \frac{d^2 q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+) D\left(\frac{x}{z}, \mathbf{q}, t\right) - \mathcal{K}(\mathbf{q}, z, x p_0^+)\, D(x, \mathbf{k}, t) \right]$$
$$+ \int \frac{d^2 \mathbf{l}}{(2\pi)^2}\, C(\mathbf{l})\, D(x, \mathbf{k} - \mathbf{l}, t)$$

Studied in : E. Blanco, K. Kutak, W. Płaczek, M. Rohrmoser, and R. Straka. Medium induced QCD cascades: broadening and rescattering during branching. ***JHEP*, 04:014, 2021**



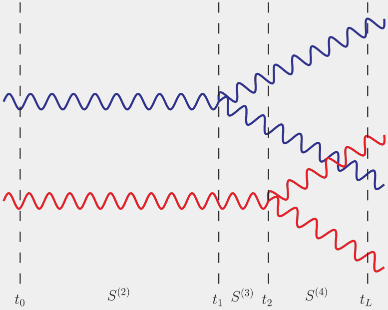
Collision Kernel

$$\mathcal{C}(\boldsymbol{l}) = \left[w(\boldsymbol{l}) - (2\pi)^2\delta^{(2)}(\boldsymbol{l}) \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} w(\boldsymbol{q})\right]$$

For a weakly coupled QGP at high temperature T

$$w(\boldsymbol{l}) = \frac{g^4 n N_c}{\boldsymbol{l}^2(\boldsymbol{l}^2 + m_D^2)}, \quad m_D^2 = (1 + \frac{N_f}{6})g^2T^2, \quad n = m_D^2 \frac{T}{g^2} \propto T^3$$

Miklos G. and X.-N. Wang. Multiple collisions and induced gluon Bremsstrahlung in QCD. ***Nucl. Phys. B*, 420:583–614, 1994**



Splitting Kernel

$$\mathcal{K}(\boldsymbol{Q}, z, p_0^+) = \frac{P_{gg}(z)}{z(1-z)p_0^+} \mathrm{Re} \int_0^\infty \mathrm{d}\Delta t \int \frac{\mathrm{d}^2\boldsymbol{P}}{(2\pi)^2} \frac{\mathrm{d}^2\boldsymbol{l}}{(2\pi)^2} (\boldsymbol{P}\cdot\boldsymbol{Q}) \tilde{S}_{ij}^{(3)}(\boldsymbol{P}, \boldsymbol{Q}, \boldsymbol{l}, z, \Delta t, t)$$

J.-P. Blaizot, F. Dominguez, E.d Iancu, and Y. Mehtar-Tani. Medium-induced gluon branching. ***JHEP*, 01:143, 2013**

Integrated

$$\frac{\partial}{\partial t}D(x,t) = \frac{1}{t^*}\int_0^1 dz\,\mathcal{K}(z)\left[\sqrt{\frac{z}{x}}D\left(\frac{x}{z},t\right)\theta(z-x) - \frac{z}{\sqrt{x}}D(x,t)\right]$$

J.-P. Blaizot, F. Dominguez, E. Iancu, and Y. Mehtar-Tani. Probabilistic picture for medium-induced jet evolution. ***JHEP*, 06:075, 2014**

Integrated

$$\frac{\partial}{\partial t} D(x,t) = \frac{1}{t^*} \int_0^1 dz\, \mathcal{K}(z) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, t\right) \theta(z-x) - \frac{z}{\sqrt{x}} D(x,t) \right]$$

Stopping time : $t^* = \frac{\tau_{br}(\omega)}{\bar{\alpha}} = \frac{1}{\bar{\alpha}} \sqrt{\frac{\omega}{\hat{q}}}, \quad \bar{\alpha} = \frac{\alpha_s N_c}{\pi}$

Integrated

$$\frac{\partial}{\partial t} D(x,t) = \frac{1}{t^*}\int_0^1 dz\, \mathcal{K}(z) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, t\right) \theta(z-x) - \frac{z}{\sqrt{x}} D(x,t)\right]$$

Collinear branching

$$\frac{\partial}{\partial t} D(x, \boldsymbol{k}, t) = \frac{1}{t^*}\int_0^1 dz\, \mathcal{K}(z) \left[\frac{1}{z^2}\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, \frac{\boldsymbol{k}}{z}, t\right) \theta(z-x) - \frac{z}{\sqrt{x}} D(x, \boldsymbol{k}, t)\right] + \int \frac{d^2\boldsymbol{l}}{(2\pi)^2} C(\boldsymbol{l})\, D(x, \boldsymbol{k}-\boldsymbol{l}, t)$$

J.-P. Blaizot, F. Dominguez, E. Iancu, and Y. Mehtar-Tani. PROBABILISTIC PICTURE FOR MEDIUM-INDUCED JET EVOLUTION. ***JHEP*, 06:075, 2014**

Studied in : K. Kutak, W. Płaczek, and R. Straka. SOLUTIONS OF EVOLUTION EQUATIONS FOR MEDIUM-INDUCED QCD CASCADES. ***Eur. Phys. J. C*, 79(4):317, 2019**

System of Equations

$$\frac{\partial}{\partial t}D_g(x,\mathbf{k},t) = \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\mathbf{q}}{(2\pi)^2}\alpha_s\Big\{2\mathcal{K}_{gg}\left(\mathbf{Q},z,\frac{x}{z}p_0^+\right)D_g\left(\frac{x}{z},\mathbf{q},t\right) + \mathcal{K}_{gq}\left(\mathbf{Q},z,\frac{x}{z}p_0^+\right)\sum_i D_{q_i}\left(\frac{x}{z},\mathbf{q},t\right)$$
$$-\left[\mathcal{K}_{gg}(\mathbf{q},z,xp_0^+) + \mathcal{K}_{qg}(\mathbf{q},z,xp_0^+)\right]D_g(x,\mathbf{k},t)\Big\} + \int \frac{\mathrm{d}^2\mathbf{l}}{(2\pi)^2}\,C_g(\mathbf{l})\,D_g(x,\mathbf{k}-\mathbf{l},t)$$

$$\frac{\partial}{\partial t}D_{q_i}(x,\mathbf{k},t) = \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\mathbf{q}}{(2\pi)^2}\alpha_s\Big\{\mathcal{K}_{qq}\left(\mathbf{Q},z,\frac{x}{z}p_0^+\right)D_{q_i}\left(\frac{x}{z},\mathbf{q},t\right) + \frac{1}{N_F}\mathcal{K}_{qg}\left(\mathbf{Q},z,\frac{x}{z}p_0^+\right)D_g\left(\frac{x}{z},\mathbf{q},t\right)$$
$$-\mathcal{K}_{qq}(\mathbf{q},z,xp_0^+)\,D_{q_i}(x,\mathbf{k},t)\Big\} + \int \frac{\mathrm{d}^2\mathbf{l}}{(2\pi)^2}\,C_q(\mathbf{l})\,D_{q_i}(x,\mathbf{k}-\mathbf{l},t)$$

Splitting kernels

$$\mathcal{K}_{ij}(\mathbf{Q}, z, p_0^+) = \frac{2P_{ij}(z)}{z(1-z)p_0^+} \sin\left(\frac{\mathbf{Q}^2}{2k_{\mathrm{br}}^2}\right) \exp\left(-\frac{\mathbf{Q}^2}{2k_{\mathrm{br}}^2}\right)$$

with $k_{\mathrm{br}}^2 = \sqrt{z(1-z)p_0^+ f_{ij}(z)\hat{\bar{q}}}$, $\quad \hat{\bar{q}} = \frac{\hat{q}}{N_c}$ and

$$f_{gg}(z) = (1-z)C_A + z^2 C_A\,, \quad f_{qg}(z) = C_F - z(1-z)C_A\,,$$
$$f_{gq}(z) = (1-z)C_A + z^2 C_F\,, \quad f_{qq}(z) = zC_A + (1-z)^2 C_F$$

Collision kernels

$$w_g(\mathbf{l}) = \frac{N_c\, g^4 n}{\mathbf{l}^2(\mathbf{l}^2 + m_D^2)}, \qquad w_q(\mathbf{l}) = \frac{C_F\, g^4 n}{\mathbf{l}^2(\mathbf{l}^2 + m_D^2)}\,,$$

Method

- Convert the BDIM equation in a Voltera-type equation
- Solve it by iteration
- Calculate the iterative solution through a MCMC algorithm

Programs

BDIM equation solve with 2 MC programs :

- MINCAS$\rightarrow$ solution for D
- TMDICE$\rightarrow$ solution for F

$$F_a(x, \mathbf{k}, t) := \frac{\mathrm{d}^3 N_a}{\mathrm{d}x\, \mathrm{d}^2\mathbf{k}}, \qquad \text{and} \quad D_a(x, \mathbf{k}, t) := xF_a(x, \mathbf{k}, t)$$

M. Rohrmoser. THE TMDICE MONTE CARLO SHOWER PROGRAM AND ALGORITHM FOR JET-FRAGMENTATION VIA COHERENT MEDIUM INDUCED RADIATIONS AND SCATTERING. ***Comput. Phys. Commun.*, 276:108343, 2022**

Other MC programs

- P. Caucal, E. Iancu., A. H. Mueller, and G. Soyez. A NEW PQCD BASED MONTE CARLO EVENT GENERATOR FOR JETS IN THE QUARK-GLUON PLASMA. ***PoS*, HARDPROBES2018:028, 2019**
- JEWEL : K. C. Zapp. JEWEL 2.0.0: DIRECTIONS FOR USE. ***EUR. PHYS. J. C*, 74(2):2762, 2014**

Specificities

With our approach, we aim at :

- non collinear splitting / broadening
- both low and high x region

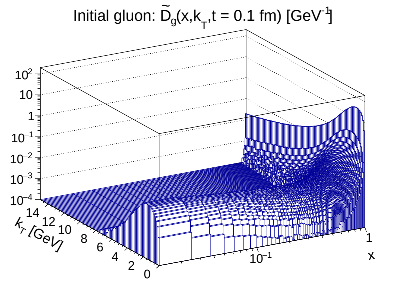
Parameters

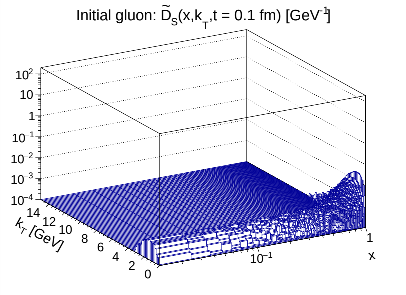
- $x_{\min} = 10^{-4}$
- $\epsilon = 10^{-6}$
- $l_{\min} = 0.1\,\mathrm{GeV}$
- $N_c = 3$
- $N_F = 3$
- $\alpha_s = \pi/10$
- $E = 100\,\mathrm{GeV}$
- $n = 0.243\,\mathrm{GeV}^3$
- $\hat{\bar{q}} = 1\,\mathrm{GeV}^2/\mathrm{fm}$
- $m_D = 0.993\,\mathrm{GeV}$

Singlet distribution

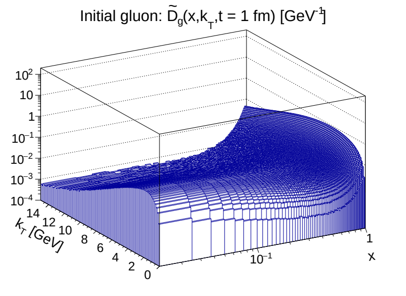
$$D_S(x, \boldsymbol{k}, t) = \sum_{i=1}^{N_f} \left(D_{q_i}(x, \boldsymbol{k}, t) + D_{\bar{q}_i}(x, \boldsymbol{k}, t) \right)$$

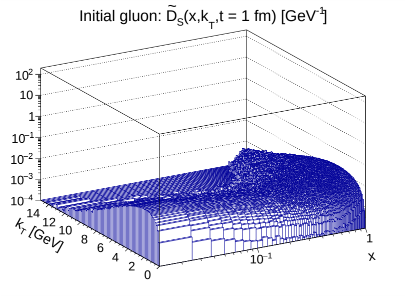
Time : 0.1fm


Initial gluon: $\tilde{D}_g(x,k_T,t = 0.1\ fm)\ [GeV^{-1}]$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

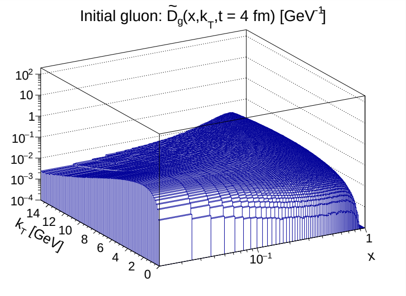

Initial gluon: $\tilde{D}_S(x,k_T,t = 0.1\ fm)\ [GeV^{-1}]$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

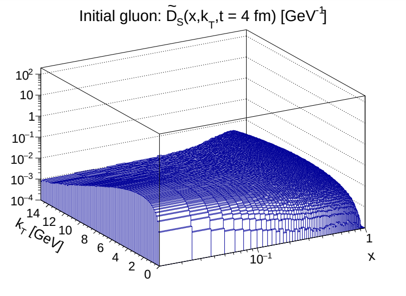
Time : 1fm


Initial gluon: $\tilde{D}_g(x,k_T,t = 1\ fm)$ [GeV^{-1}]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

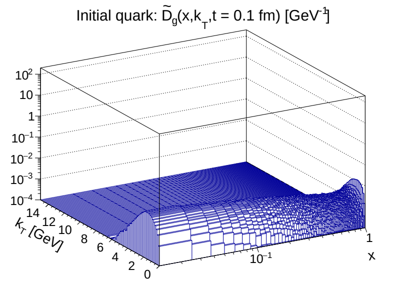

Initial gluon: $\tilde{D}_S(x,k_T,t = 1\ fm)$ [GeV^{-1}]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

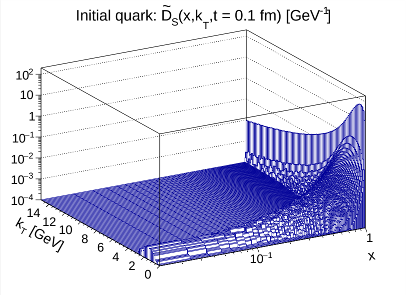
Time : 4fm


Initial gluon: $\tilde{D}_g(x,k_T,t = 4\ \text{fm})$ [GeV^{-1}]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

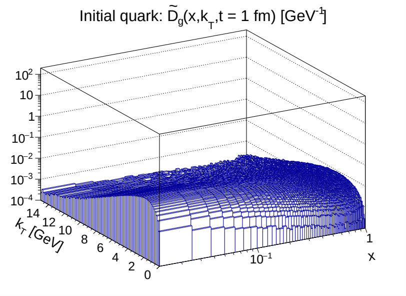

Initial gluon: $\tilde{D}_S(x,k_T,t = 4\ \text{fm})$ [GeV^{-1}]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

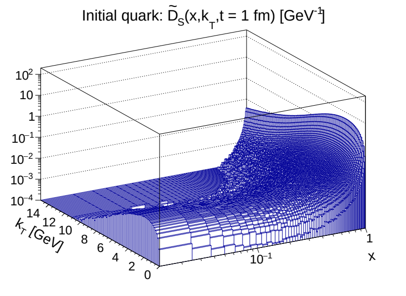
Time : 0.1fm


Initial quark: $\tilde{D}_g(x,k_T,t = 0.1\ \mathrm{fm})\ [\mathrm{GeV}^{-1}]$
k_T [GeV]
x

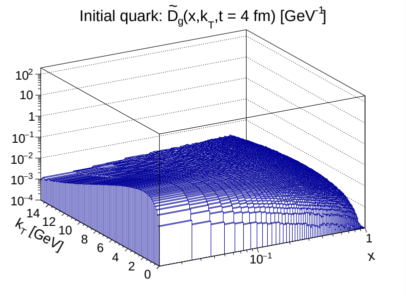

Initial quark: $\tilde{D}_S(x,k_T,t = 0.1\ \mathrm{fm})\ [\mathrm{GeV}^{-1}]$
k_T [GeV]
x

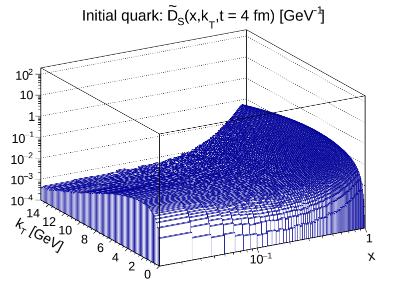
Time : 1fm

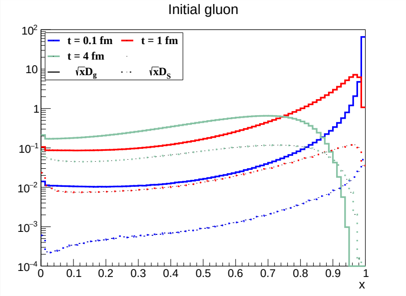

Initial quark: $\widetilde{D}_g(x,k_T,t = 1\ fm)\ [GeV^{-1}]$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

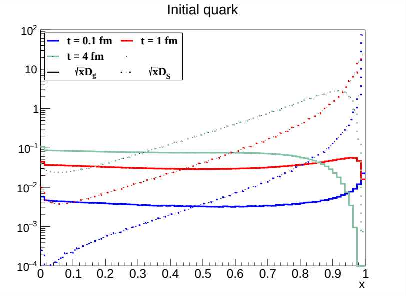

Initial quark: $\widetilde{D}_S(x,k_T,t = 1\ fm)\ [GeV^{-1}]$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x

Time : 4fm

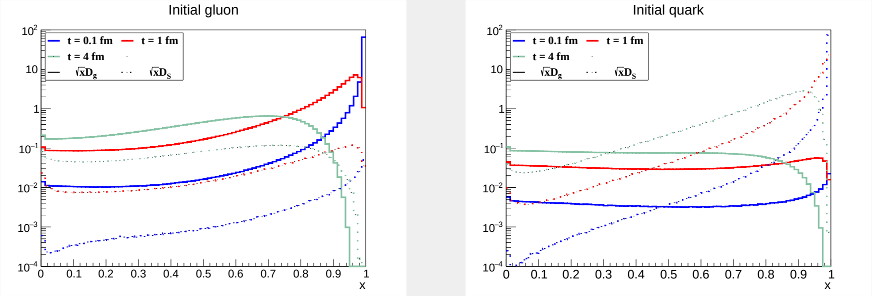

Initial quark: $\tilde{D}_g(x,k_T,t = 4\ fm)\ [GeV^{-1}]$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x


Initial quark: $\tilde{D}_S(x,k_T,t = 4\ fm)\ [GeV^{-1}]$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
k_T [GeV]
14
12
10
8
6
4
2
0
10^{-1}
1
x





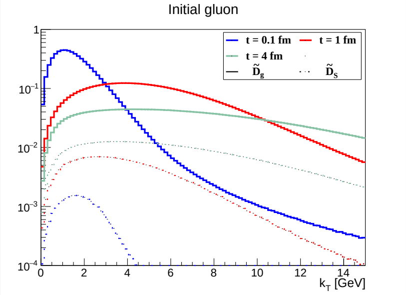
$$D(x,t) = \int \mathrm{d}^2\mathbf{k}\, D_I(x,\mathbf{k},t)$$

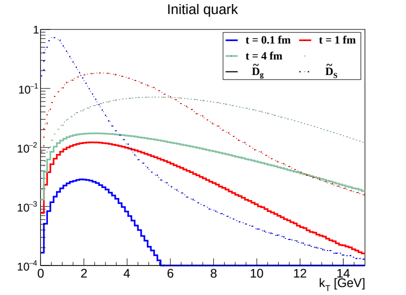


$\frac{1}{\sqrt{x}}$ scaling at low x as shown in :

Y. Mehtar-Tani and S. Schlichting. Universal quark to gluon ratio in medium-induced parton cascade. *JHEP*, 09:144, 2018

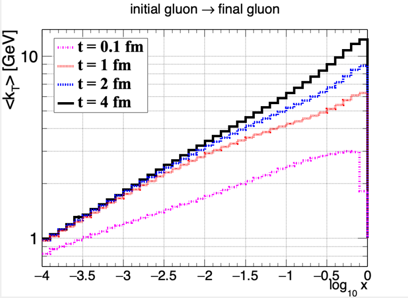
SOLUTIONS\ k_T DISTRIBUTION

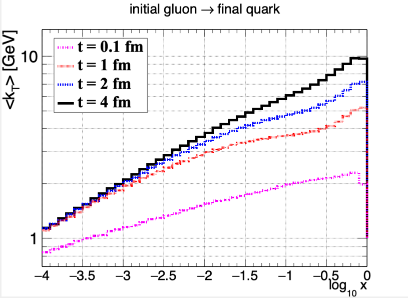




$$\tilde{D}(x, k_T, t) = \int_0^{2\pi} rmd\phi \, k_T \, D_l(x, \mathbf{k}, t)$$

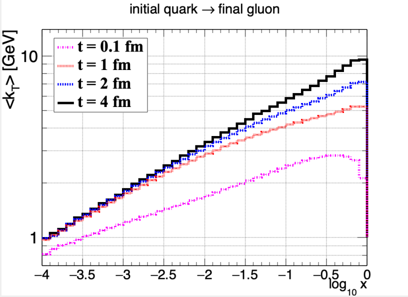
Initial Gluon

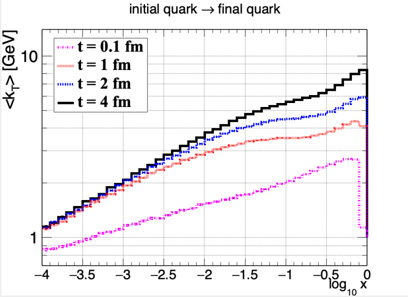




$$\langle k_T \rangle = \frac{\int \mathrm{d}^2\boldsymbol{k}\, |\mathbf{k}| D(x, \mathbf{k}, t)}{\int \mathrm{d}^2\boldsymbol{k}\, D(x, \mathbf{k}, t)} = \frac{\int_0^\infty \mathrm{d}k_T\, k_T^2 D(x, k_T, t)}{\int_0^\infty \mathrm{d}k_T\, k_T D(x, k_T, t)}$$

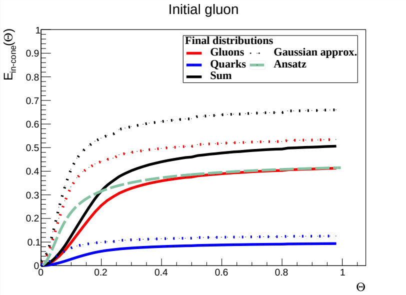
Initial Quark

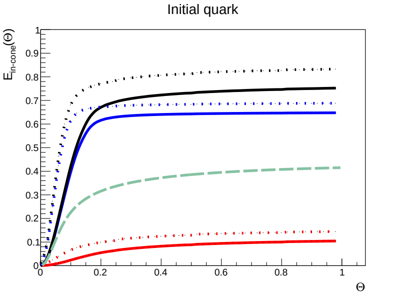




$$\langle k_T \rangle = \frac{\int \mathrm{d}^2\boldsymbol{k}\, |\mathbf{k}| D(x, \mathbf{k}, t)}{\int \mathrm{d}^2\boldsymbol{k}\, D(x, \mathbf{k}, t)} = \frac{\int_0^\infty \mathrm{d}k_T\, k_T^2 D(x, k_T, t)}{\int_0^\infty \mathrm{d}k_T\, k_T D(x, k_T, t)}$$

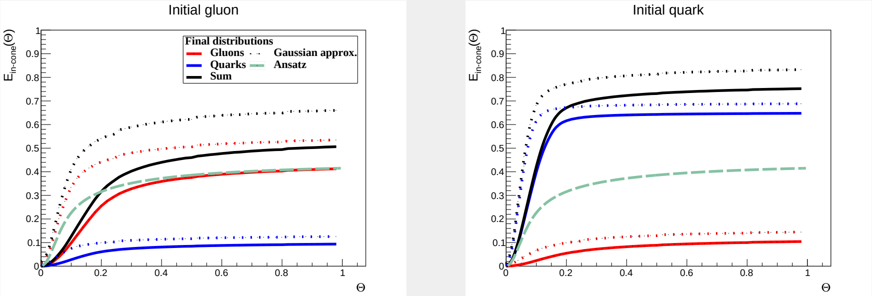
Time : 4fm





$$E_{\text{in-cone}}(\Theta) = \int_0^1 \mathrm{d}x \int_0^{xE\sin\Theta} \mathrm{d}k_T\, \tilde{D}(x, k_T, t)$$

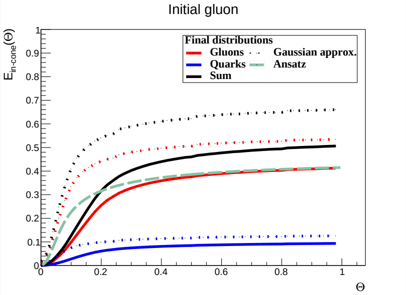
Time : 4fm

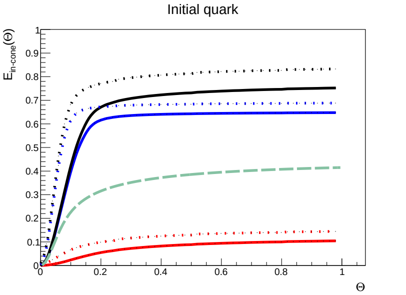


Gaussian approximation

$$D_G(x, \mathbf{k}, t) = D(x, t) \frac{4\pi}{\hat{q}t} \exp\left(-\frac{\mathbf{k}^2}{\hat{q}t}\right)$$

Time : 4fm

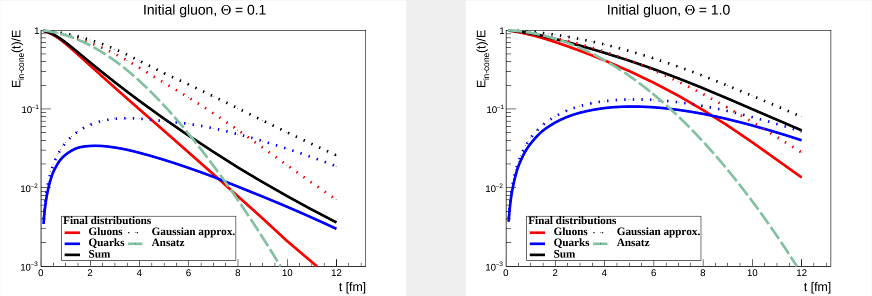




Analytical Ansatz

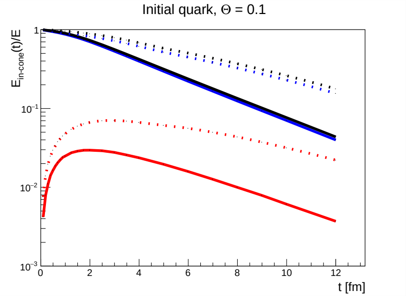
$$D_A(x, \mathbf{k}, t) = \frac{t/t_*}{\sqrt{x(1-x)^3}} \exp\left(-\pi \frac{(t/t_*)^2}{1-x}\right) \frac{4\pi}{\hat{q}t} \exp\left(-\frac{\mathbf{k}^2}{\hat{q}t}\right)$$

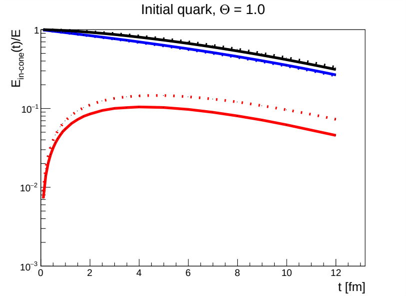
Initial Gluon



$$E_{\text{in-cone}}(\Theta) = \int_0^1 \mathrm{d}x \int_0^{xE\sin\Theta} \mathrm{d}k_T\, \tilde{D}(x, k_T, t)$$

Initial Quark





$$E_{\text{in-cone}}(\Theta) = \int_0^1 \mathrm{d}x \int_0^{xE \sin\Theta} \mathrm{d}k_T \, \tilde{D}(x, k_T, t)$$

Conclusion

- We derived in-medium splitting kernel accounting for broadening for BDIM evolution equation of both quarks and gluons $\rightarrow$ BDMPS-Z beyond eikonal approximation
- We solved this evolution equation through MCMC methods (with MINCASand TMDICE)
- The study of the solutions has shown that :
  - gluons broaden more than gluons in time
  - quarks are more collimated than gluons
  - quarks dominate at late time
  - the $\langle k_T \rangle$ distribution is universal at low-x and late times

Outlook

- Vacuum shower
- Dynamics of the medium (through time or temperature dependence of its parameters)

Thanks for your attention!

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