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VIRTUALITY EVOLUTION OF JETS IN A QCD MEDIUM

Study of heavy-quark pairs within jets using QCD Factorization in heavy-ion collisions

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WORK IN PROGRESS!

CENTROS gus
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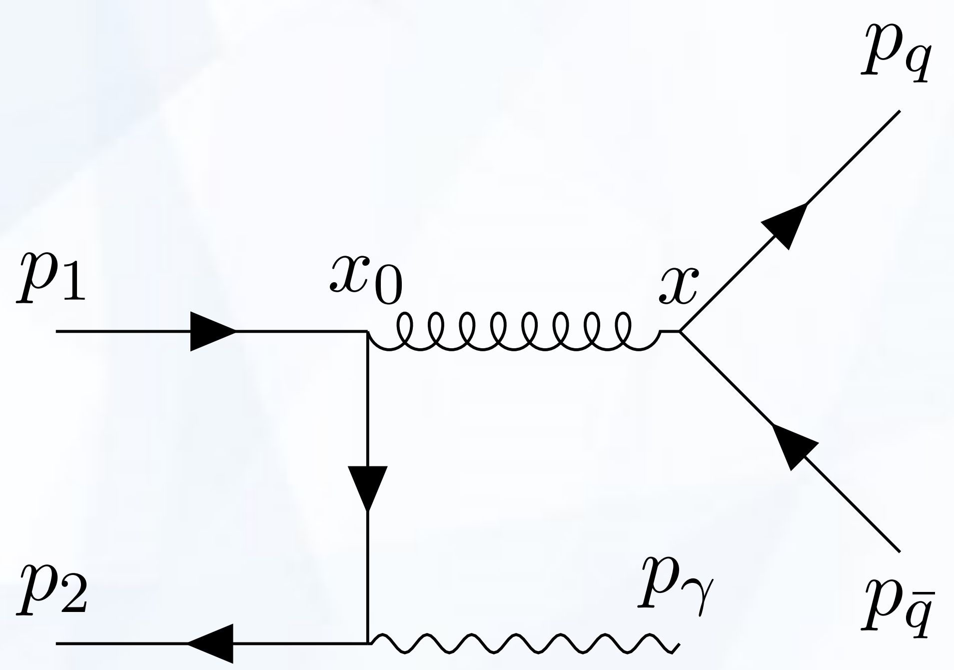
I. FACTORIZATION OF JET CROSS SECTIONS IN HEAVY-ION COLLISIONS

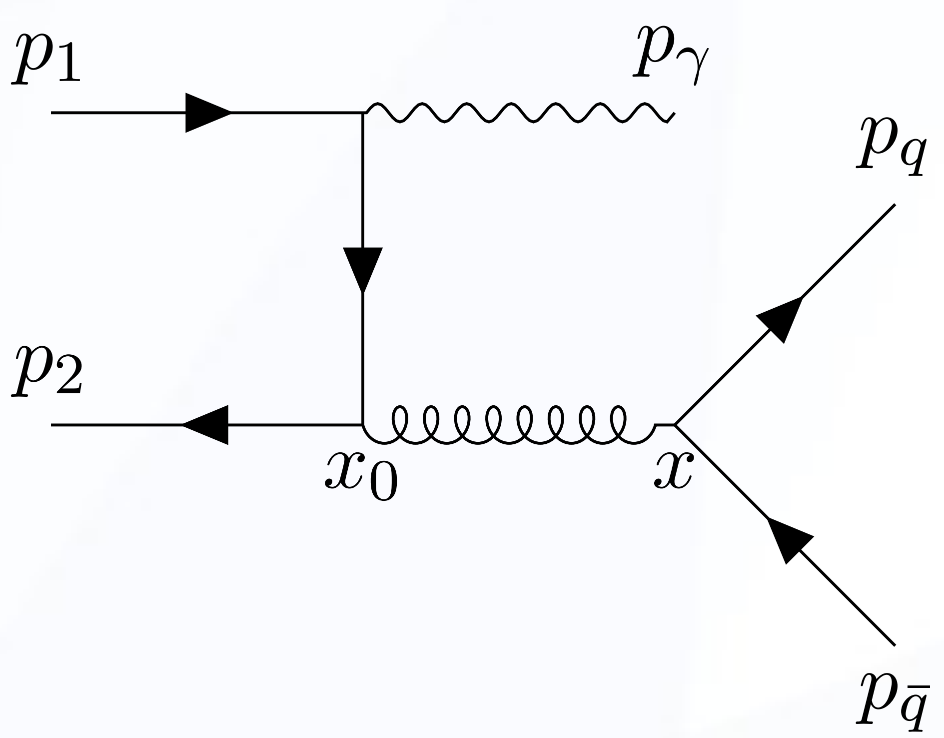
Our HIC model

$$A_1 + A_2 \rightarrow \gamma + \text{Jet} + X$$

- Nucleons inside nuclei are considered to be **uncorrelated**.
- For high momentum scales the hard process is mostly initiated by the collision of **one pair of nucleons**

Parton-level diagrams





Other nucleons **only connect to the jet** in the hard process (see Florian's talk)

The impact parameter dependent cross section

Cross section **divided into jet and hard vertex** sectors

$$\frac{d\sigma}{d^2\mathbf{b}dO} = \int \prod_f \left[d\Gamma_{p_f}\right] \delta(O - O(\{p_f\})) \int d^2\mathbf{X} T_{A_1}(\mathbf{X}) T_{A_2}(\mathbf{X}-\mathbf{b}) \int \frac{d^4x_I d^4p_I}{(2\pi)^4} e^{ip_I\cdot x_I} J_{\mu\nu}(X_T + x_I/2, X_T - x_I/2)$$

$$\times \sum_{X_h} (2\pi)^4 \delta(P_{A_1} + P_{A_2} - p_\gamma - p_I - p_{X_h}) \frac{1}{2s_{NN}} M_h^{*\mu}(P_{A_1}, P_{A_2}; p_\gamma, p_{X_h}) M_h^{\nu}(P_{A_1}, P_{A_2}; p_\gamma, p_{X_h})$$

where $X = (x_0' + x_0)/2$ and $x_I = x_0' - x_0$

We defined the **jet tensor**

$$J^{ab}_{\mu\nu}(x_0', x_0) \equiv \langle\langle\langle 0 | \bar{T}A^a_\mu(x_0') | p_q p_{\bar{q}}\rangle\langle p_q p_{\bar{q}} | TA^b_\nu(x_0) | 0\rangle\rangle\rangle = \frac{\delta^{ab}}{N_c^2 - 1} \langle\langle\langle 0 | \bar{T}A^c_\mu(x_0') | p_q p_{\bar{q}}\rangle\langle p_q p_{\bar{q}} | TA^c_\nu(x_0) | 0\rangle\rangle\rangle$$

Range of validity of factorization

Cross section **still not factorized**

Introduce a light-like vector along p_I direction and define a **new set of LC-coordinates**

$$J_{\mu\nu}(X_T + x_I/2, X_T - x_I/2) \propto g_{\mu\nu} - p_I^+ \frac{p_{I\mu}\bar{n}_\nu + p_{I\nu}\bar{n}_\mu}{(p_I^+)^2 - p_I^2\bar{n}^2} + p_I^2 \frac{\bar{n}_\mu \bar{n}_\nu}{(p_I^+)^2 - p_I^2\bar{n}^2} + \bar{n}^2 \frac{p_{I\mu}p_{I\nu}}{(p_I^+)^2 - p_I^2\bar{n}^2}$$

$$\simeq g_{\perp\mu\nu} + O\left(\frac{m_I^2}{(p_I^+)^2}\right)$$

We must include a **factorization scale**.

Factorized cross section

In the phase space region where collinear factorization works

$$\frac{d\sigma}{d^2\mathbf{b}dod^2\mathbf{p}_\gamma d\eta_\gamma} = \int d^2\mathbf{X} T_{A_1}(\mathbf{X}) T_{A_2}(\mathbf{X}-\mathbf{b}) \int d\Gamma_{p_I} \frac{d}{do} J(\bar{n}\cdot p_I, \vec{n}; \mathbf{X}) \frac{d\sigma_h}{d\Gamma_{p_I} d^2\mathbf{p}_\gamma d\eta_\gamma}(P_{A_1}, P_{A_2}; p_I, p_\gamma)$$

The **hard-cross section** can be computed from the PDFs and tree level amplitude

From now on we will focus on the calculation of the **jet function**

The jet function

$$\frac{d}{do} J(\bar{n}\cdot p_I, \vec{n}; \mu^2, \mathbf{X}) \equiv \int_0^{\mu^2} \frac{dm_I^2}{2\pi} \int d^4x_I \, e^{\frac{i}{2}\bar{n}\cdot p_I n\cdot x_I + \frac{i}{2}\frac{m_I^2}{\bar{n}\cdot p_I}\bar{n}\cdot x_I} \left(\sum_{m=1}^{\infty}\prod_{j=1}^{m}\int d\Gamma_{p_j}\right)\delta(o - o(\{p_j\}))$$

$$\times \frac{-g_\perp^{\mu\nu}}{2(N_c^2-1)} \langle\langle\langle 0 | \bar{T} A_\mu^a(X + x_I/2) | \{p_j\}\rangle\langle\{p_j\} | T A_\nu^a(X - x_I/2) | 0\rangle\rangle\rangle$$

Only valid in **LC-gauge**

For a general gauge we must construct the S-matrix element as **a gauge-invariant object**

II. THE JET FUNCTION FOR $Q\bar{Q}$ PRODUCTION AT LO

The coordinates for the jet function

The hard collision takes place around $X^\mu = (0, \mathbf{X}, 0)$

$t_h \equiv \bar{n} \cdot X$

$x_I^+ \sim 1/p_I^- = 2p_I^+/m_I^2$ needed to account for the **uncertainty of jet production** time around t_h.

$\underline{x_I}$ will account for the **initial position** of the jet

The general formula for $Q\bar{Q}$ spectrum

The **main formula** on our model

$$\frac{dJ}{dzdm_I^2}(p_I^+,\vec{n};m_I^2,X) = \frac{1}{2\pi}\int d^2\underline{x}_I dx_I^+ e^{\frac{i}{2}\frac{m_I^2}{p_I^+}x_I^+}\int \frac{d^2\underline{p}_q}{(2\pi)^2}\frac{d^2\underline{p}_{\bar{q}}}{(2\pi)^2}\frac{1}{8\pi z(1-z)p_I^+}$$
$$\times\frac{-1}{2(N_c^2-1)}\langle\langle\langle 0|\bar{T}A_{a\mu}(X_T+\tilde{x}_I/2)|p_q p_{\bar{q}}\rangle\langle p_q p_{\bar{q}}|TA^{a\mu}(X_T-\tilde{x}_I/2)|0\rangle\rangle\rangle$$

- If we integrate in m_I^2 up to ∞ we go to the **usual limit**

III. SOME PRELIMINAR RESULTS

A. The gluon jet function for $Q\bar{Q}$ in vacuum

B. $g \to g$ due to single scattering

C. $g \to Q\bar{Q}$ due to single scattering

Our model for calculations…

- BDMPS-Z formalism

- Model the effect of other nucleons by **classical fields**

$$\langle A^{a-}(t_1,\underline{x})A^{b-}(t_2,\underline{y})\rangle = \delta(t_1-t_2)\delta^{ab}2n(t)\sigma(\underline{x}-\underline{y})$$

- The gluon jet can extract **as much virtuality from the medium as desired** in a single scattering.

- We will still use it as a **toy model**

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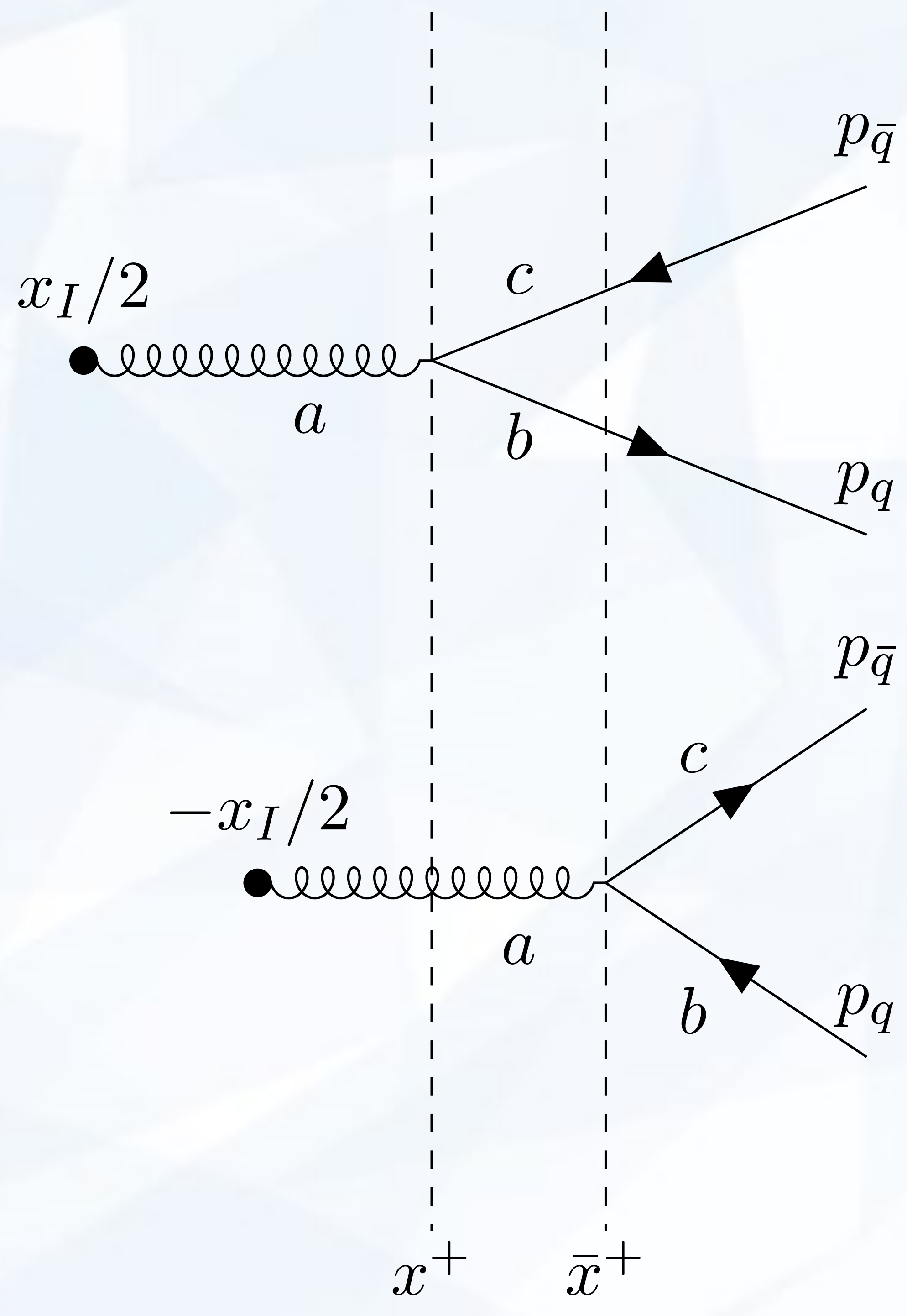
A. The gluon jet function for $Q\bar{Q}$ in vacuum



[Ellis, Stirling, Webber (2011)]

$$\frac{dJ}{dz dm_I^2}(p_I^+, \vec{n}; m_I^2, X) = \frac{\alpha_s}{2\pi}\frac{1}{m_I^2}P_{Q\leftarrow g}(z, m, m_I^2)\theta(z(1-z)m_I^2 - m^2)$$

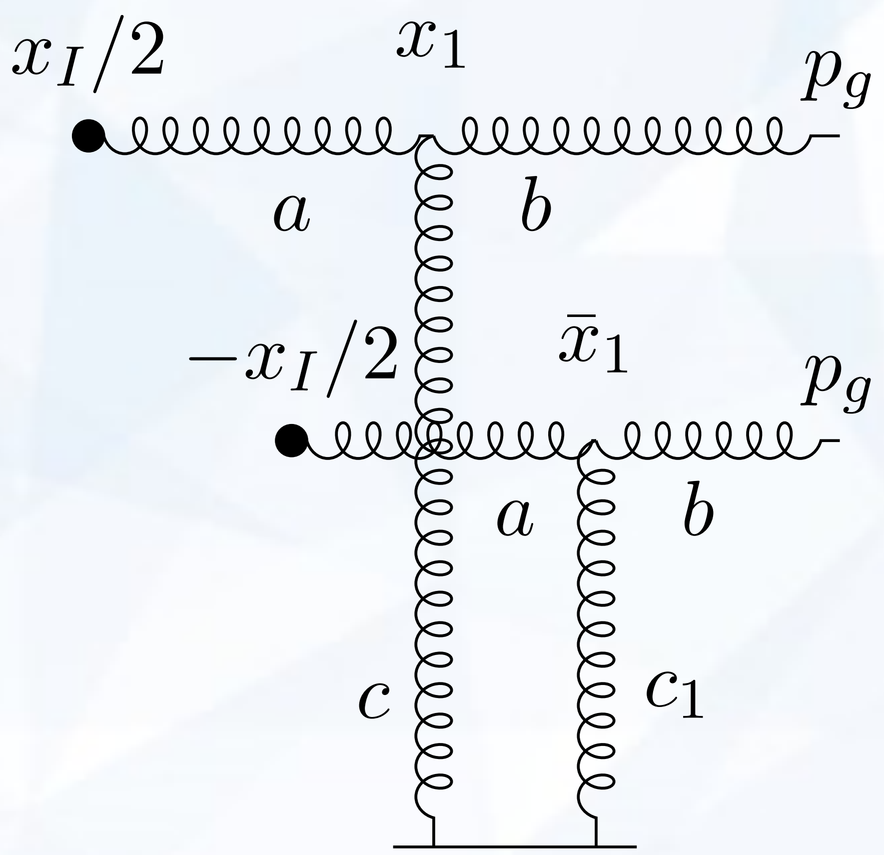
where $P_{Q\leftarrow g}(z, m, m_I^2) \equiv T_F\left[z^2 + (1-z)^2 + \frac{2m^2}{m_I^2}\right]$. Integrating in z and m_I^2

$$J(p_I^+, \vec{n}; \mu^2, X) = \frac{\alpha_s}{6\pi}\left[-\frac{\sqrt{1-\frac{4m^2}{\mu^2}}}{3\mu^2} + 2\log\left(\sqrt{1-\frac{4m^2}{\mu^2}}+1\right) + \log\left(\frac{\mu^2}{4m^2}\right)\right]$$

The factorization scale **regularizes** the UV divergence

B. $g \to g$ due to single scattering

$$\frac{dJ}{dm_I^2}(p_I^+, \vec{n}; m_I^2, X) = \frac{1}{2\pi}\int dx_1^+ \left[g^2 2n(x_1^+)C_A\sigma_T\right]\frac{4p_I^+}{m_I^2}\sin\left(\frac{m_I^2}{p_I^+}x_1^+\right)$$



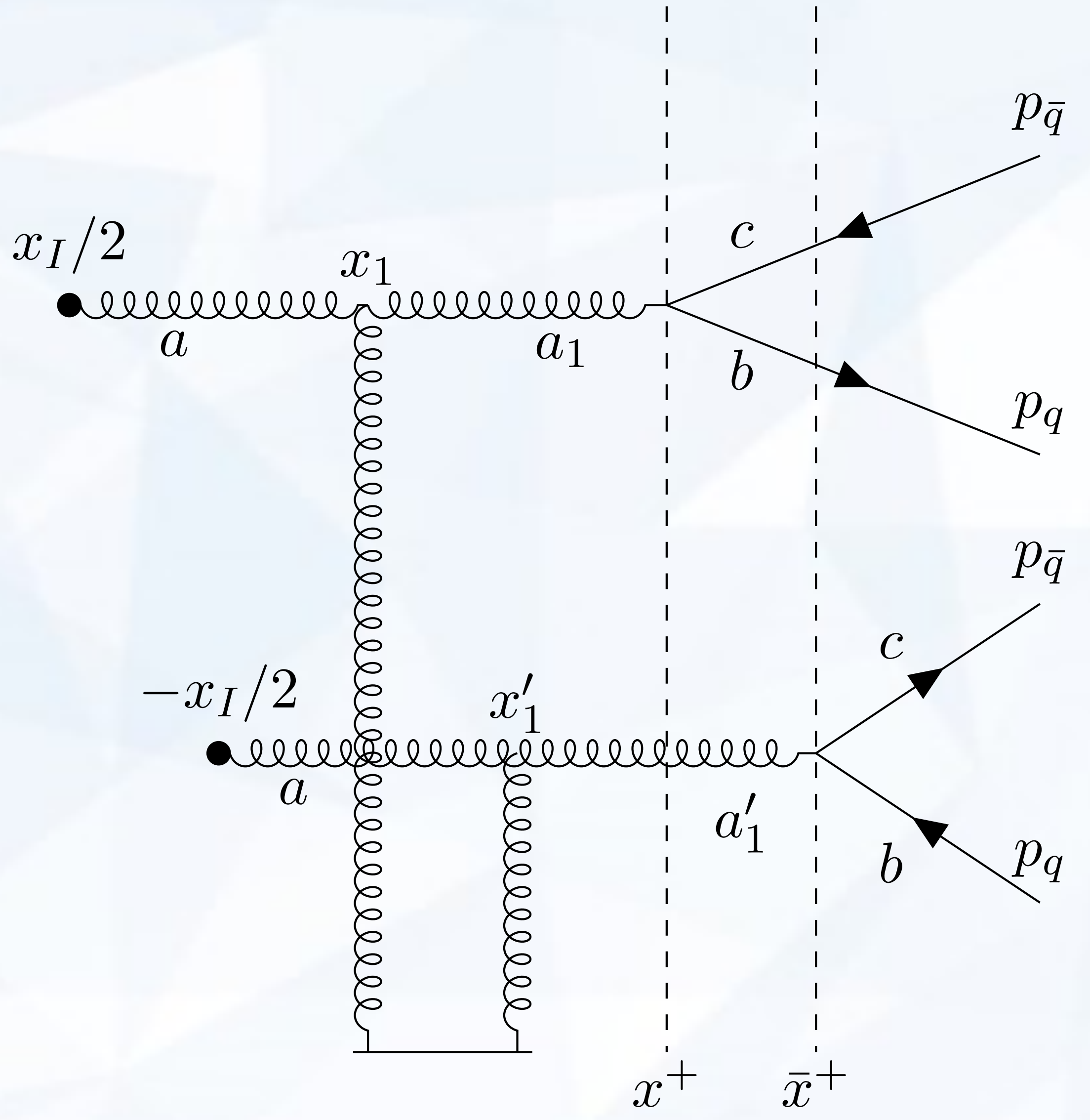
Brick approximation and integration over virtuality

$$J(p_I^+, \vec{n}; \mu^2, X) = \frac{\alpha_s}{2\pi}(2nC_A\sigma_T)4p_I^+\left[\frac{L}{p_I^+}Si\left(\frac{L}{p_I^+}\mu^2\right) + \frac{\cos\left(\frac{L}{p_I^+}\mu^2\right) - 1}{\mu^2}\right]$$

In the $\mu \to \infty$ limit

$$J(p_I^+, \vec{n}; \mu^2 \to \infty, X) = \alpha_S(2nC_A\sigma_T)L = 2C_A\frac{L}{\lambda}$$

C.3. $g \to Q\bar{Q}$ due to single scattering



$$\frac{dJ}{dxdm_I^2}(p_I^+,\vec{n};m_I^2,X) = \alpha_s(\alpha_s 2C_A n\sigma_T)\frac{4p_I^+}{(m_I^2)^2}\left[1-\cos\left(\frac{m_I^2}{p_I^+}L\right)\right]\int\frac{d^2p}{2\pi}\frac{m^2+(z^2+(1-z)^2)p^2}{[p^2+m^2]^2}$$

Virtuality integration

$$\frac{dJ}{dz}(p_I^+,\vec{n};\mu^2,X) = \alpha_s(\alpha_s 2C_A n\sigma_T)4p_I^+\left[\frac{L}{p_I^+}Si\left(\frac{L}{p_I^+}\mu^2\right)+\frac{\cos\left(\frac{L}{p_I^+}\mu^2\right)-1}{\mu^2}\right]\int\frac{d^2p}{2\pi}\frac{m^2+(z^2+(1-z)^2)p^2}{[p^2+m^2]^2}$$

The factorization scale does **no longer regularize** the UV divergence (limitation of our model)

IV. CONCLUSIONS AND OUTLOOK

- We must introduce a **factorization scale** in order to ensure that the jet function can be factorized from the hard process

- Our toy model that allows us to understand some **basic features** of this separation of scales

- Future **improved model** that allows us to keep trace of the virtuality at each step on the process

- Future **resummation** at all orders in opacity