Energy loss and (de)coherence effects beyond the eikonal approximation

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Introduction

- Main Goal of Hard Probes: probe the hot and dense medium formed in heavy-ion collisions (QGP)
  - How? Indirect measurement through the modifications observed on jets (Jet Quenching)

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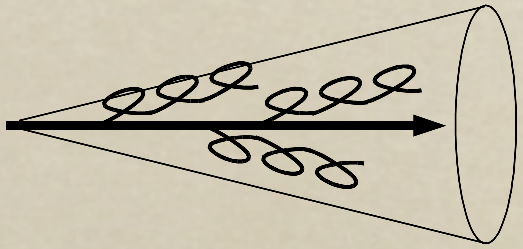

Parton branching described by pQCD:

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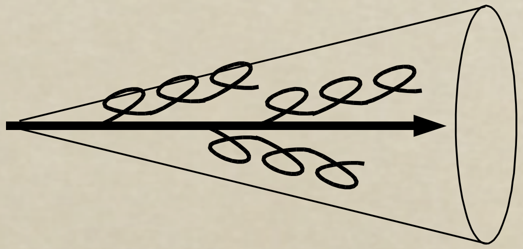

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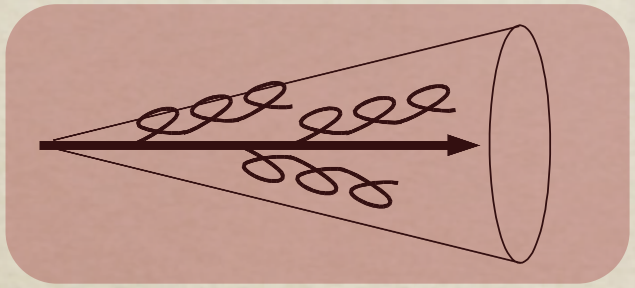

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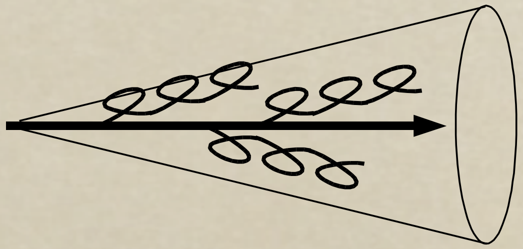

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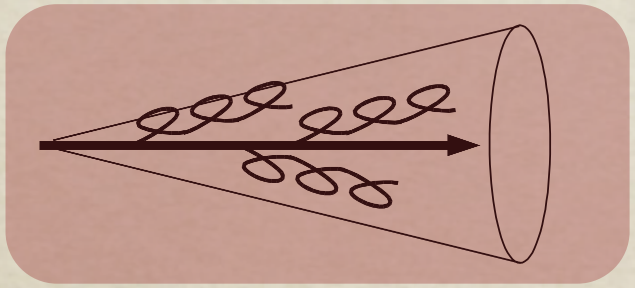

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In this talk!

Jet Quenching

[Ovanesyan et al 11, D'Eramo et al 11, LA et al 12]

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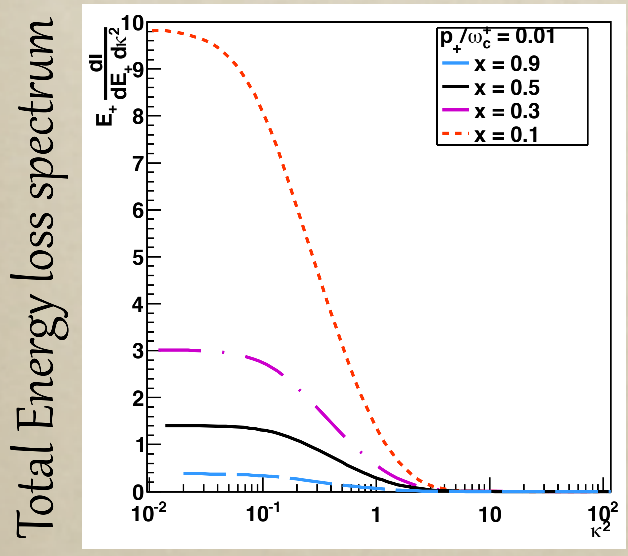

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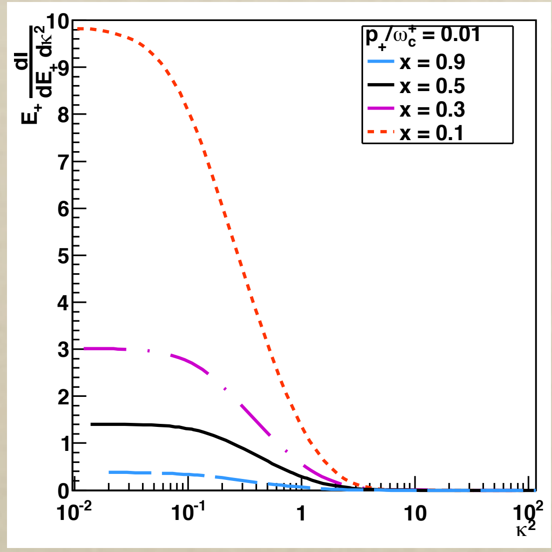

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Broadening calculations:

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  - Only softest particle able to acquire transverse momentum
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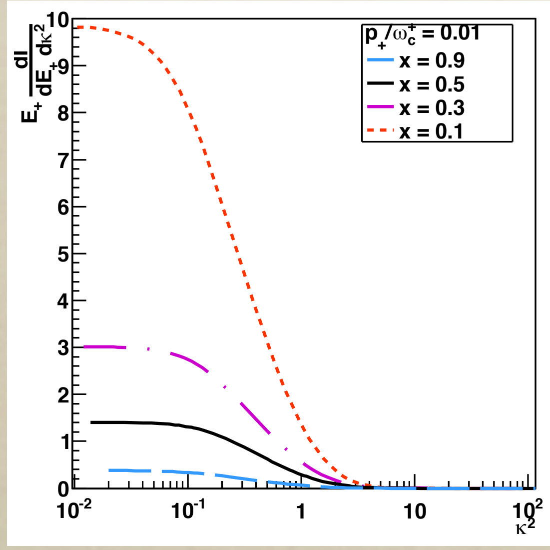

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Factorization of parton branching — Blaizot, Dominguez, Iancu and Mehtar-Tani [1311.5823]

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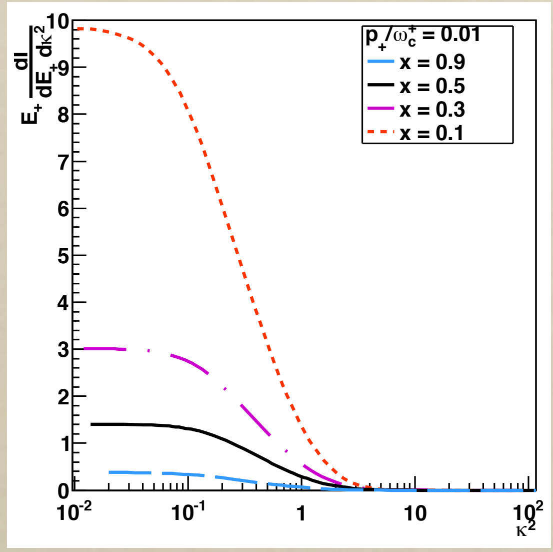

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Factorization of parton branching

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(Anti)angular ordering:

- Coherent regime:
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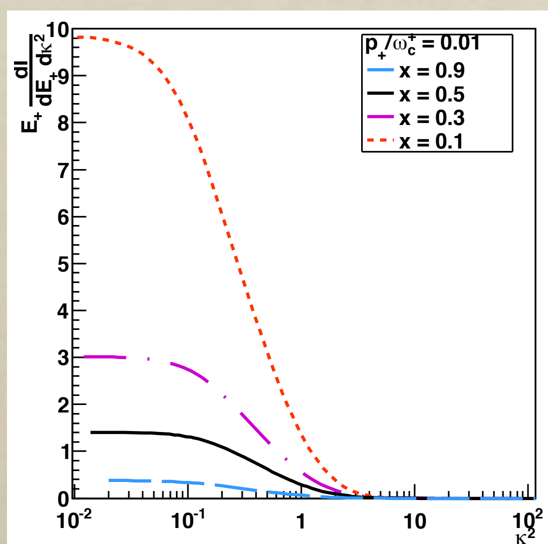

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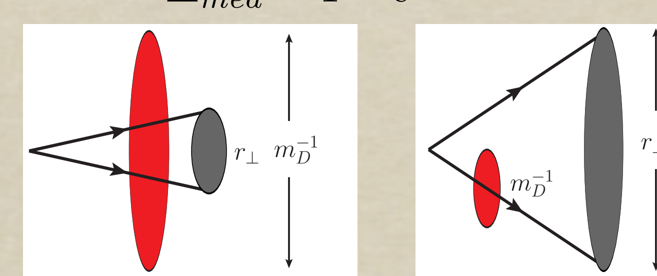
Two different scales

$$\Delta_{med} \approx 1 - \mathrm{e}^{-\frac{1}{12}\hat{q}\,\theta_{q\bar{q}}^2 L^3}$$



Mehtar-Tani, Salgado and Tywoniuk [1112.5031]

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Kinematical Setup

- Extend previous works to account for:
  - Finite energy corrections to the energy loss;
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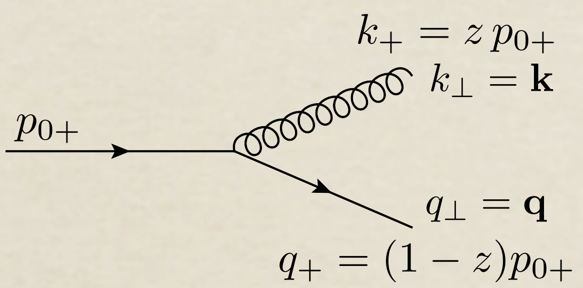

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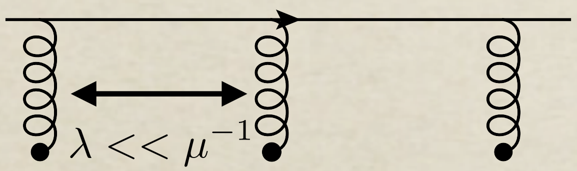

Independent medium scatterings
Static scattering centers

  - High-energy limit: $p_{0+} >> |\mathbf{k}|, |\mathbf{q}|$

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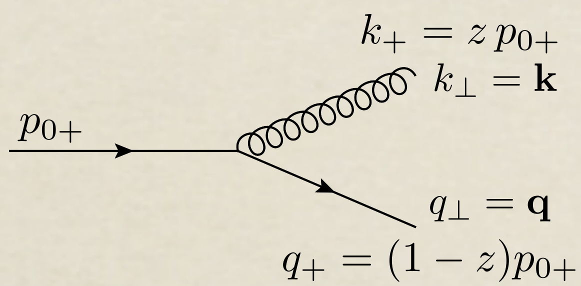

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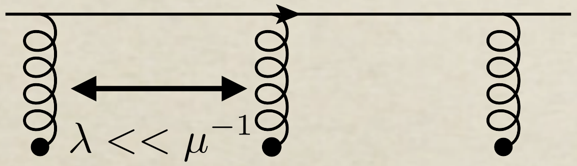

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$$G(x_{0+}, \mathbf{x}_0; L_+, \mathbf{x}|p_+) = \int_{\mathbf{r}(x_{0+})=\mathbf{x}_0}^{\mathbf{r}(L_+)=\mathbf{x}} \mathcal{D}\mathbf{r}(\xi) \exp\left\{ \frac{ip_+}{2} \int_{x_{0+}}^{L_+} d\xi \left(\frac{d\mathbf{r}}{d\xi}\right)^2 \right\} W(x_{0+}, L_+; \mathbf{r}(\xi))$$

where: $W(x_{0+}, L_+; \mathbf{x}) = \mathcal{P} \exp\left\{ ig \int_{x_{0+}}^{L_+} dx_+ A_-(x_+, \mathbf{x}) \right\}$

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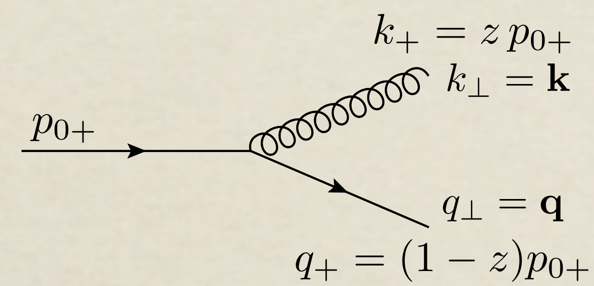

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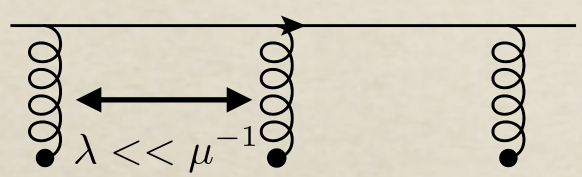

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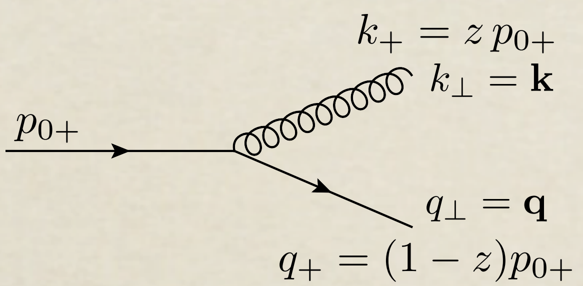

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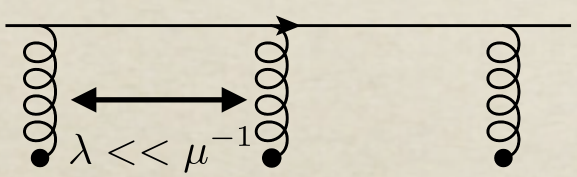

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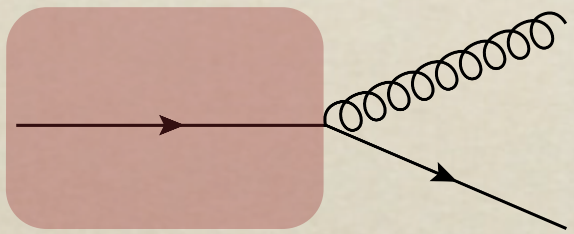
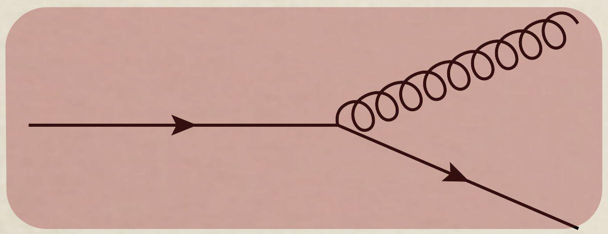
Amplitudes and X-Section

- Contributions for a finite medium:





$$S_{out} = -2\pi\delta(k_+ + q_+ - p_{0+})\frac{g}{4(k\cdot q)}T^a_{BA}\int_{\mathbf{x_0},\mathbf{x_1}} \mathrm{e}^{i\mathbf{x_0}\cdot\mathbf{p_0}-i\mathbf{x_1}\cdot(\mathbf{k}+\mathbf{q})}$$
$$\times G_{AA_1}(x_{0+},\mathbf{x_0};L_+,\mathbf{x_1}|p_{0+})\bar{u}(q)\not\epsilon^*_k(\not k+\not q)\gamma_+\gamma_- M_h(p_0)$$

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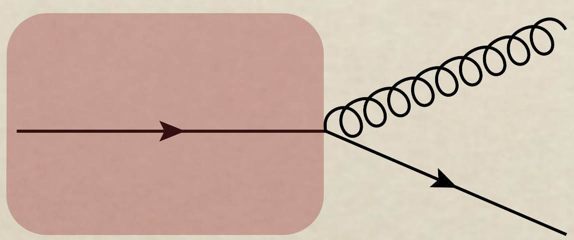

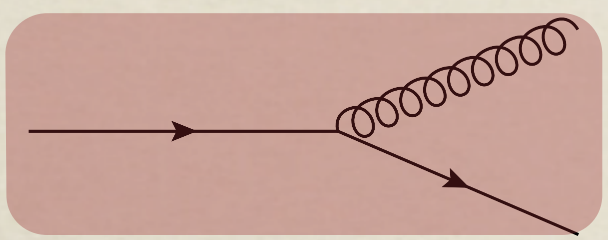

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- Differential cross-section:

$$\frac{d^2I^{tot}}{d\Omega_q d\Omega_k} = \frac{1}{\sigma_{el}}|S_{tot}|^2 = \frac{1}{\sigma_{el}}\left(|S_{out}|^2 + |S_{in}|^2 + 2\,\mathrm{Re}\,|S_{in}S^\dagger_{out}|\right)$$

with:
$$d\Omega_p = \frac{dp_+ d\mathbf{p}}{2p_+(2\pi)^3}$$
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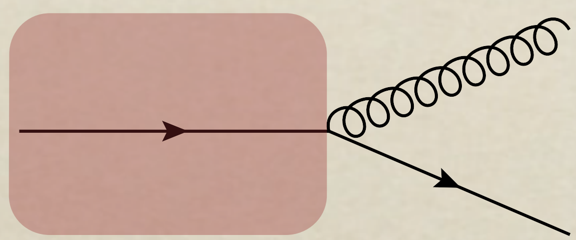

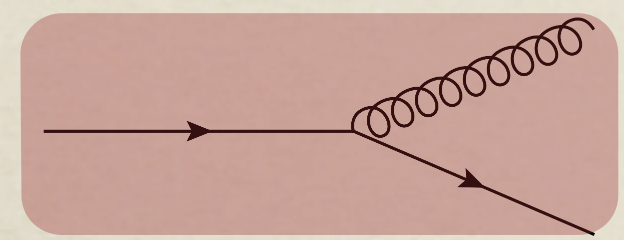

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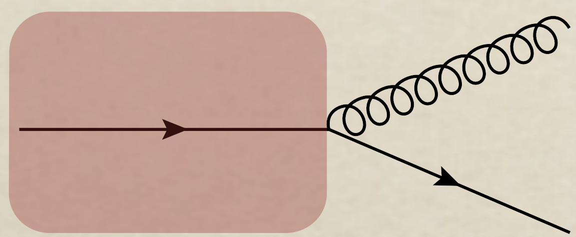
when $\hat{q}_F L_+ \to \infty$ vacuum spectrum is recovered

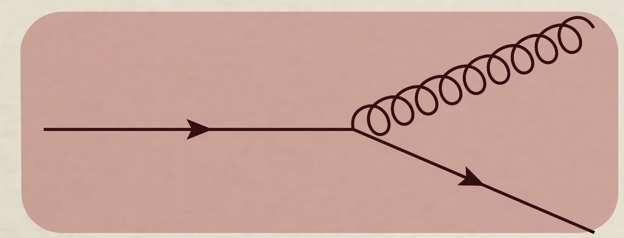
Medium Component

| ... |² = average over spins, colour and medium profile

Amplitudes and X-Section

- Contributions for a finite medium:





$$S_{out} = -2\pi\delta(k_+ + q_+ - p_{0+})\frac{g}{4(k\cdot q)}T^a_{BA}\int_{\mathbf{x_0},\mathbf{x_1}} \mathrm{e}^{i\mathbf{x_0}\cdot\mathbf{p_0} - i\mathbf{x_1}\cdot(\mathbf{k}+\mathbf{q})}$$
$$\times G_{AA_1}(x_{0+},\mathbf{x_0}; L_+, \mathbf{x_1}|p_{0+})\bar{u}(q)\not\epsilon^*_k(\not k + \not q)\gamma_+\gamma_- M_h(p_0)$$

$$S_{in} = 2\pi\delta(k_+ + q_+ - p_{0+})\frac{ig}{2}\int_{\mathbf{x_0},\mathbf{x_1},\mathbf{y},\mathbf{z}}^{x_{0+},x_{1+},y_+} \mathrm{e}^{i\mathbf{x_0}\cdot\mathbf{p_0} - i\mathbf{y}\cdot\mathbf{q} - i\mathbf{z}\cdot\mathbf{k}}$$
$$\times G_{BB_1}(x_{1+},\mathbf{x_1}; L_+, \mathbf{y}|q_+)T^{a_1}_{B_1A}G_{AA_1}(x_{0+},\mathbf{x_0}; x_{1+}, \mathbf{y}|p_{0+})$$
$$\times G_{aa_1}(x_{1+},\mathbf{x_1}; L_+, \mathbf{z}|k_+)\bar{u}(q)\not\epsilon^*_k\gamma_- M_h(p_0)$$

- Differential cross-section:

$$\frac{d^2 I^{tot}}{d\Omega_q d\Omega_k} = \frac{1}{\sigma_{el}}|S_{tot}|^2 = \frac{1}{\sigma_{el}}\left(|S_{out}|^2 + |S_{in}|^2 + 2\,\mathrm{Re}\,|S_{in}S^\dagger_{out}|\right)$$

with: $d\Omega_p = \frac{dp_+ d\mathbf{p}}{2p_+(2\pi)^3}$

$\sigma_{el} = \sqrt{2}\,(2\pi)^3|M_h(p_{0+})|^2$

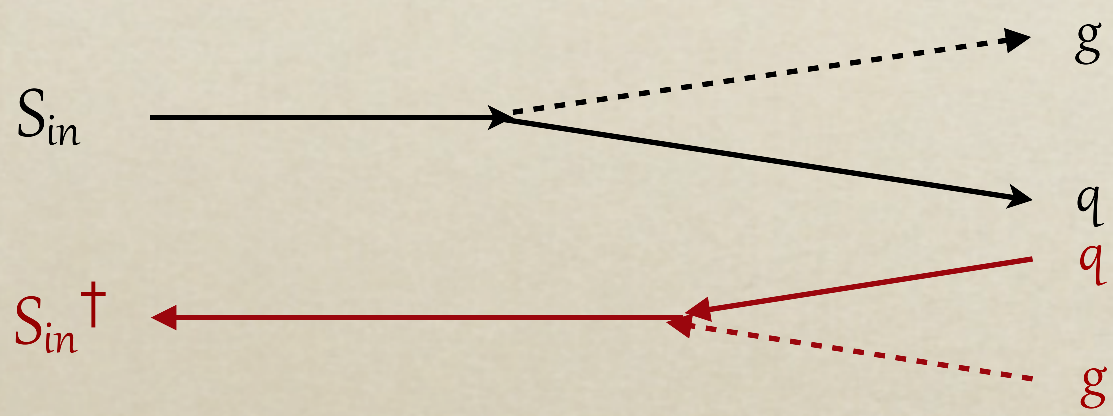
when $\hat{q}_F L_+ \to \infty$ vacuum spectrum is recovered

Medium Component

| ... |² = average over spins, colour and medium profile

Medium averages

- Schematic representation of the in-in term of the spectrum ($|S_{in}|^2$):



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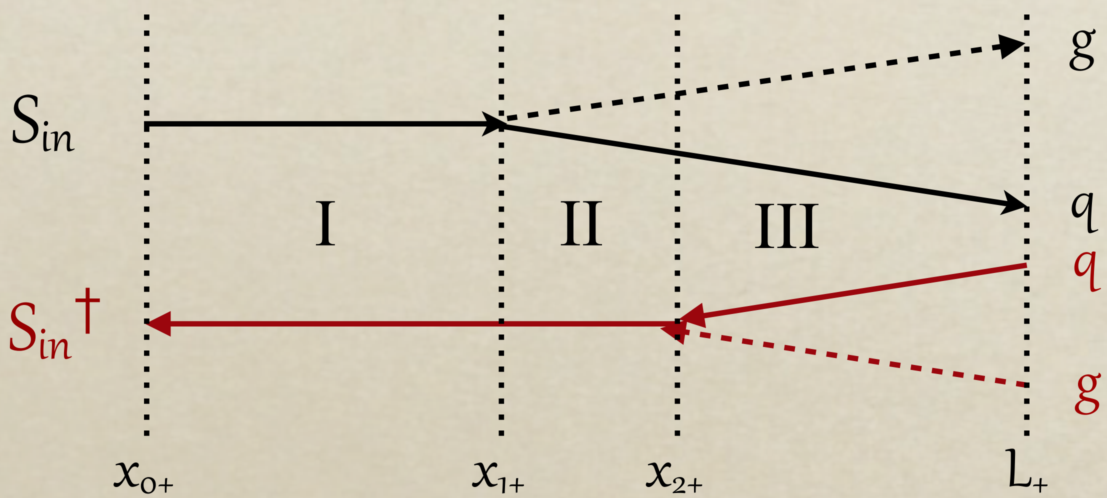

High energy approximation:

⇒ Decomposition with a fixed number of propagators:

⇒ 3 different regions

$t_{form} = x_{2+} - x_{1+}$

Medium averages

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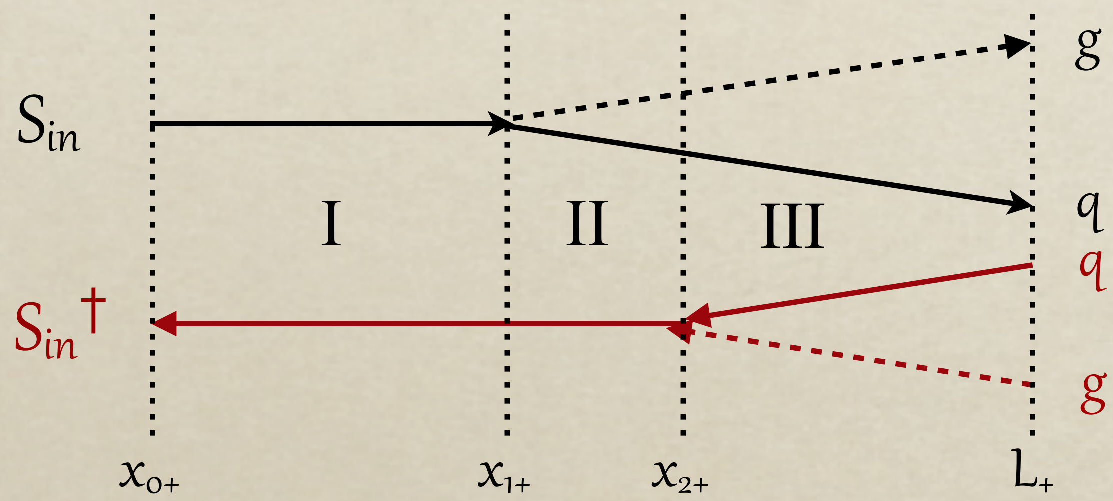


High energy approximation:

$\Rightarrow$ Decomposition with a fixed number of propagators:

$\Rightarrow$ 3 different regions

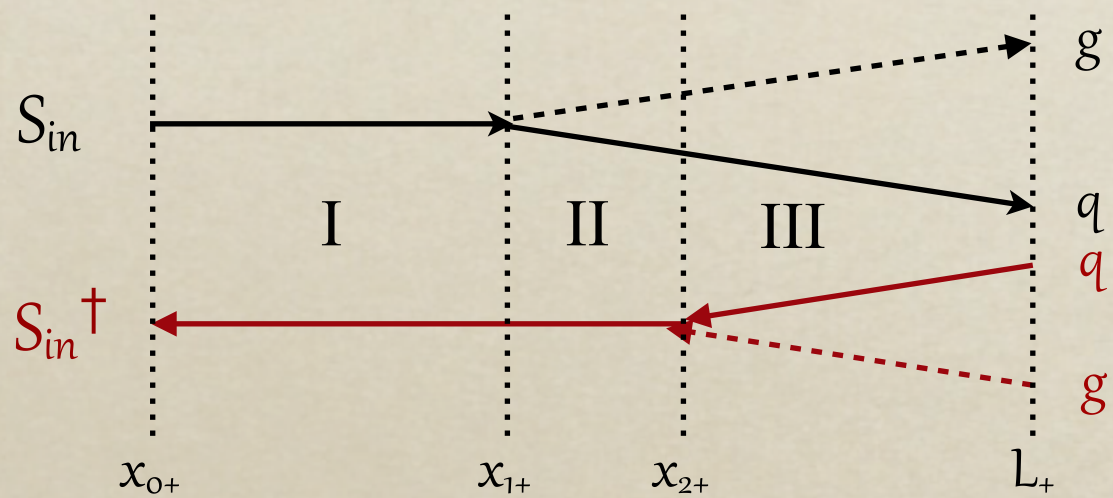
$t_{form} = x_{2+} - x_{1+}$

Factorisation of the colour structure and transverse momentum dynamics:

$$G_{AB}(x_+, \mathbf{x}; y_+, \mathbf{y}) = \underbrace{\int_{\mathbf{r}(x_+)=\mathbf{x}}^{\mathbf{r}(y_+)=\mathbf{y}} \mathcal{D}\mathbf{r}(\xi) \exp\left\{\frac{ip_+}{2}\int_{x_+}^{y_+} d\xi \left(\frac{d\mathbf{r}}{d\xi}\right)^2\right\}}_{\text{Kinetic part (Broadening)}} \underbrace{W_{AB}(x_+, y_+; \mathbf{r}(\xi))}_{\text{Colour part}}$$

Medium averages

- Schematic representation of the in-in term of the spectrum ($|S_{in}|^2$):



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Kinetic part (Broadening)

⇓

Implies path integrals evaluation

Colour part

⇓

Implies computation of n-field correlators

Medium averages

- Path integral resolution:
  - Dipole approximation: $C_F n(\xi)\sigma(\mathbf{r}) \simeq \frac{1}{2}\hat{q}_F \mathbf{r}^2 + \mathcal{O}(\mathbf{r}^2 \ln \mathbf{r}^2)$
  - Semi-classical method:

$$G_0(x_+,\mathbf{x};y_+,\mathbf{y}) = \int_{\mathbf{r}(x_+)=\mathbf{x}}^{\mathbf{r}(y_+)=\mathbf{y}} \mathcal{D}\mathbf{r}(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_+}^{y_+} d\xi \left(\frac{d\mathbf{r}}{d\xi}\right)^2\right\}$$

$$= \frac{1}{(2\pi i)^{D/2}}\left|\det\left(-\frac{\partial^2 R_{cl}}{\partial \mathbf{y}_i \partial \mathbf{x}_i}\right)\right|^{1/2} e^{iR_{cl}(x_+,\mathbf{x};y_+,\mathbf{y})}$$

D = nº of dimensions

Classical action: $R_{cl} = \int d\xi \mathcal{L}(\xi)$

EOM: $\frac{d}{d\xi}\frac{\partial \mathcal{L}}{\partial \dot{\mathbf{r}}} - \frac{\partial \mathcal{L}}{\partial \mathbf{r}} = 0 \Rightarrow \mathbf{r} = \mathbf{r}_{cl}(\xi)$

Dominant contribution for the average trajectory given by the classical path

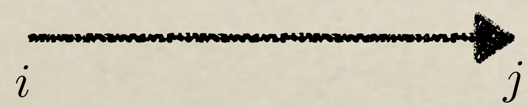
+ Fluctuations of the classical action

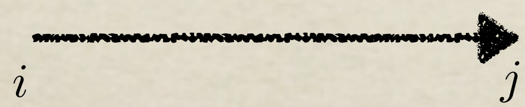
Medium averages

- Calculation of n-field correlators (at large N_c):

Infinitesimal expansion of the Wilson line:

$$W_{ij}(x_{0+}, L_+; \mathbf{x}) = \left[\delta_{i\alpha}\left(1 - \frac{C_F}{2} B(\xi, L_+; \mathbf{0})\right) + ig \int_{x_{0+}}^{\xi} dx_+ A_-(x_+, \mathbf{x}) T^a_{i\alpha}\right] V_{\alpha j}(\xi, L_+; \mathbf{x})$$





where: $\delta^{ab} B(x_{i+}, x_{f+}; \mathbf{x} - \mathbf{y}) = g^2 \int_{x_{i+}}^{x_{f+}} dx_+ dy_+ \left\langle A^a_-(x_+, \mathbf{x}) A^b_-(y_+, \mathbf{y}) \right\rangle$

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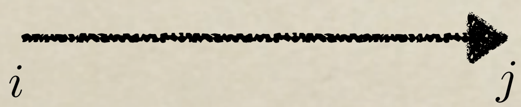

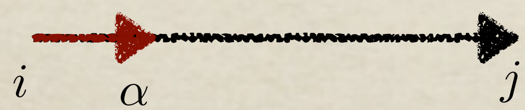

where: $\delta^{ab}B(x_{i+}, x_{f+}; \mathbf{x}-\mathbf{y}) = g^2\int_{x_{i+}}^{x_{f+}} dx_+ dy_+ \left\langle A^a_-(x_+, \mathbf{x})A^b_-(y_+, \mathbf{y})\right\rangle$

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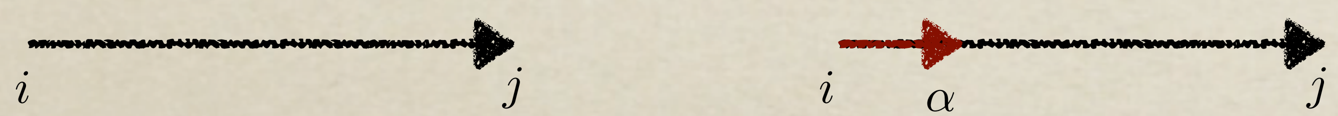

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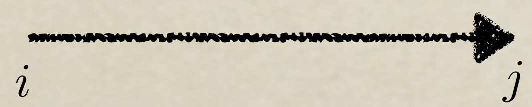

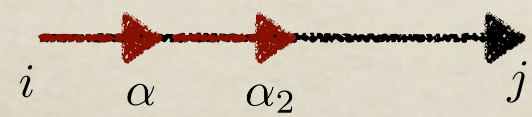

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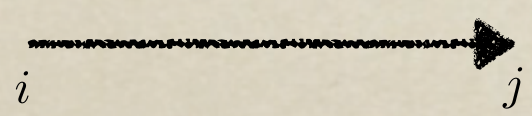

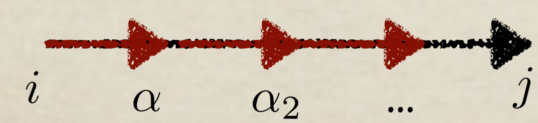

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- Calculation of n-field correlators (at large N$_c$):

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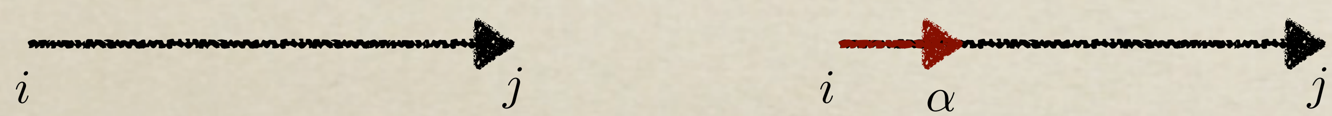


where: $\delta^{ab}B(x_{i+}, x_{f+}; \mathbf{x}-\mathbf{y}) = g^2\int_{x_{i+}}^{x_{f+}} dx_+ dy_+ \left\langle A^a_-(x_+, \mathbf{x}) A^b_-(y_+, \mathbf{y})\right\rangle$

Applying to a 2-field correlator: $\frac{1}{N}\mathrm{Tr}\left\langle W(\mathbf{x})W^\dagger(\mathbf{y})\right\rangle = \mathrm{e}^{-C_F v(\mathbf{x}-\mathbf{y})}$

where: $v(\mathbf{x}-\mathbf{y}) = B(\mathbf{0}) - B(\mathbf{x}-\mathbf{y}) = \frac{1}{2}\int dx_+ \sigma(\mathbf{x}-\mathbf{y}) n(x_+)$

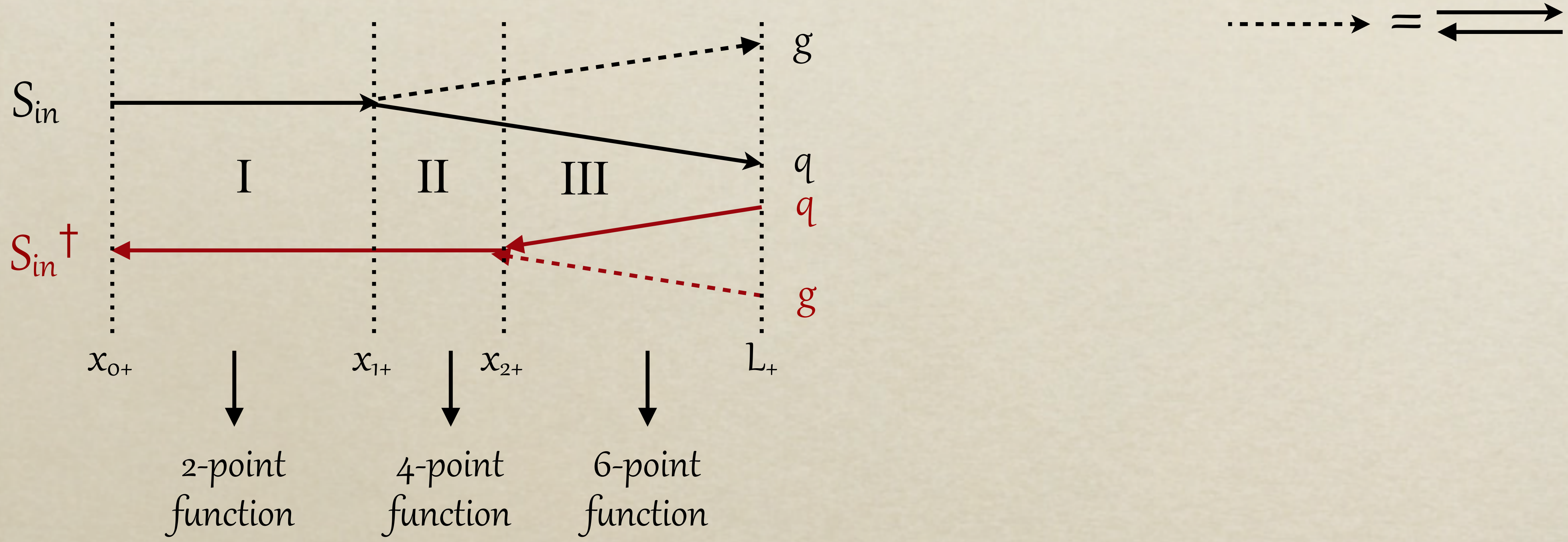
Dipole cross-section:

Medium density

$$\sigma(\mathbf{x}-\mathbf{y}) = 2g^2\int \frac{d\mathbf{q}}{(2\pi)^2}|a(\mathbf{q})|^2\left(1 - \mathrm{e}^{-i\mathbf{q}\cdot(\mathbf{x}-\mathbf{y})}\right)$$

Medium averages

- Schematic representation of the in-in term of the spectrum ($|Sin|^2$) at large N_c:



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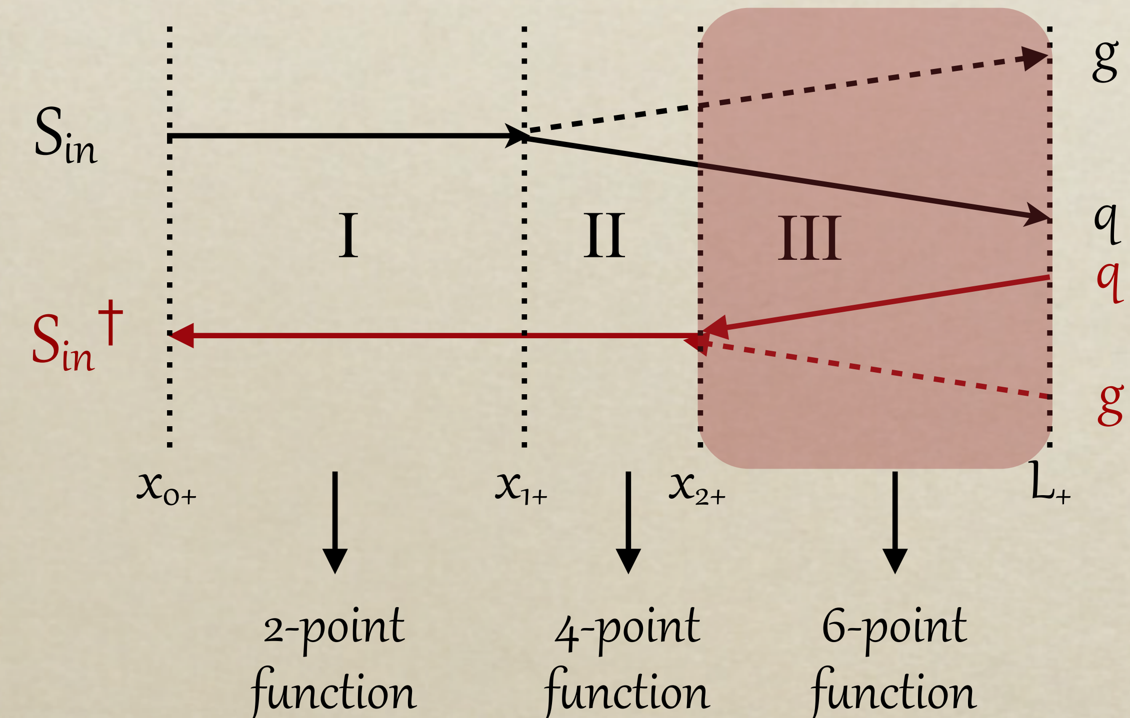

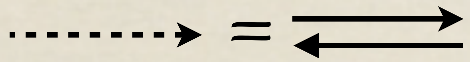

$$\langle \mathrm{Tr}\left[W(\mathbf{x}_g)W^\dagger(\mathbf{x}_{\bar{g}})\right] \mathrm{Tr}\left[W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar{g}})W^\dagger(\mathbf{x}_{\bar{q}})W(\mathbf{x}_q)\right]\rangle =$$
$$= \mathrm{Tr}\,\langle W(\mathbf{x}_g)W^\dagger(\mathbf{x}_{\bar{g}})\rangle\, \mathrm{Tr}\,\langle W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar{g}})W^\dagger(\mathbf{x}_{\bar{q}})W(\mathbf{x}_q)\rangle$$

At large N_c: factorization into a dipole x quadrupole

Medium averages

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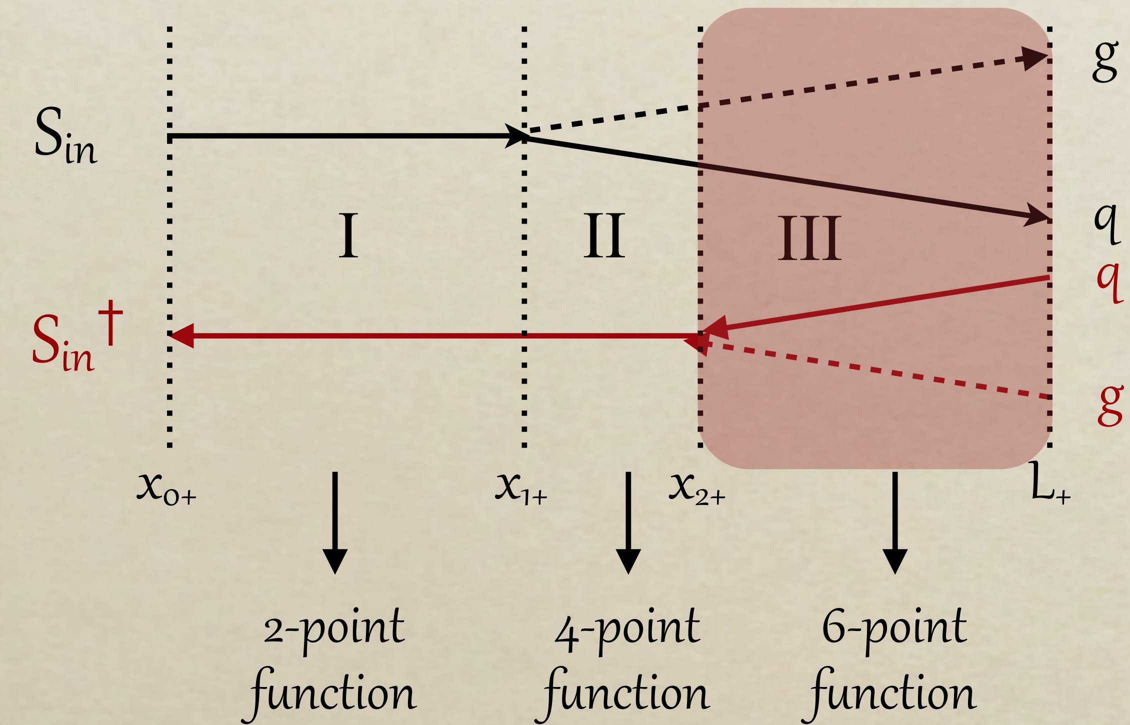

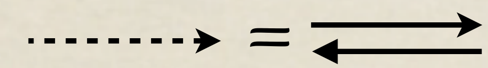

$$\langle \mathrm{Tr}\left[W(\mathbf{x}_g)W^\dagger(\mathbf{x}_{\bar g})\right] \mathrm{Tr}\left[W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar g})W^\dagger(\mathbf{x}_{\bar q})W(\mathbf{x}_q)\right]\rangle =$$
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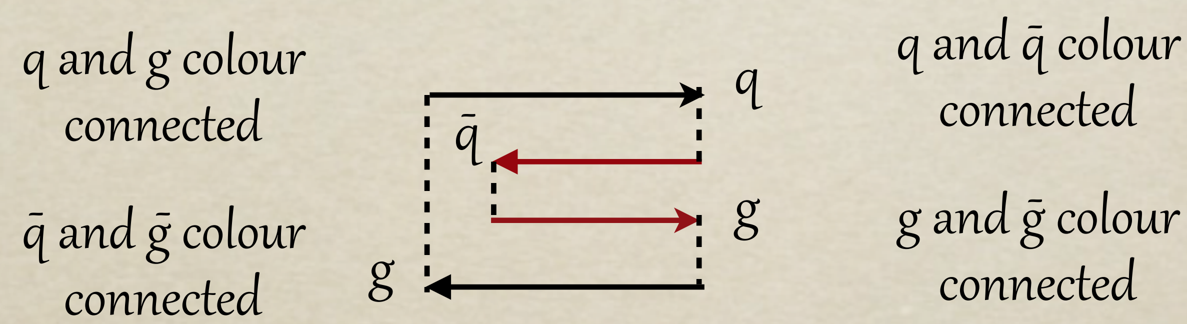
At large N_c: factorization into a dipole x quadrupole



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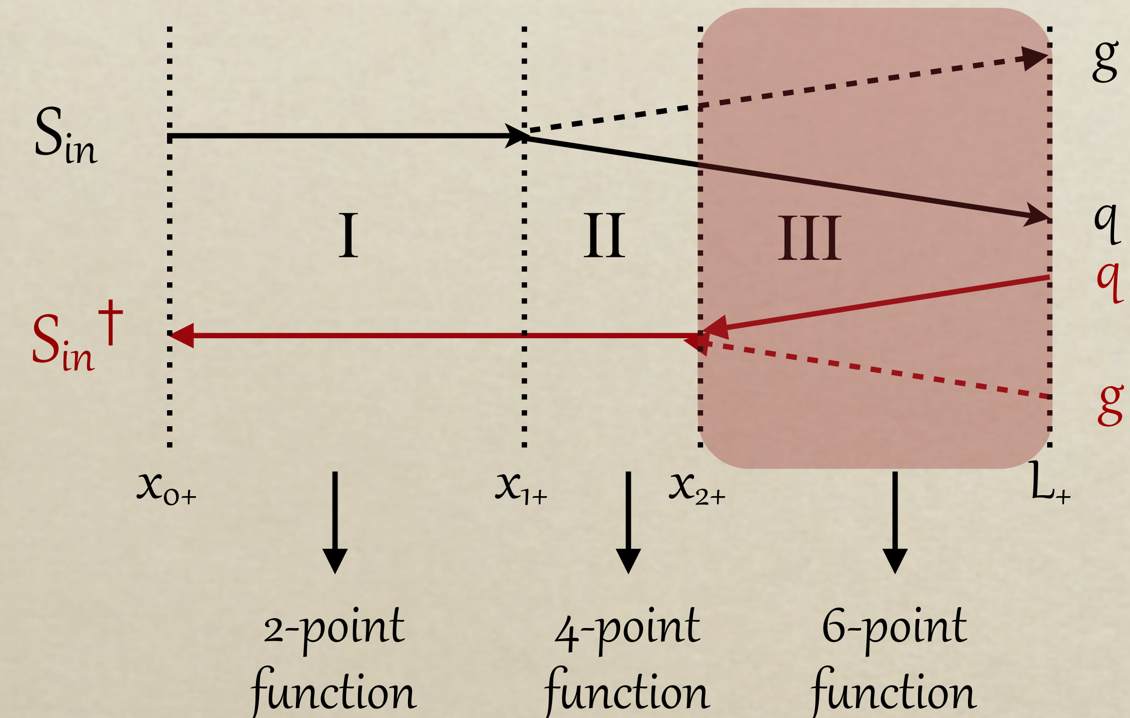

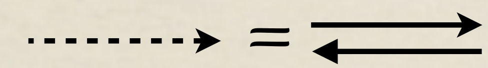

$$\left\langle \mathrm{Tr}\left[W(\mathbf{x}_g)W^\dagger(\mathbf{x}_{\bar g})\right]\,\mathrm{Tr}\left[W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar g})W^\dagger(\mathbf{x}_{\bar q})W(\mathbf{x}_q)\right]\right\rangle = $$
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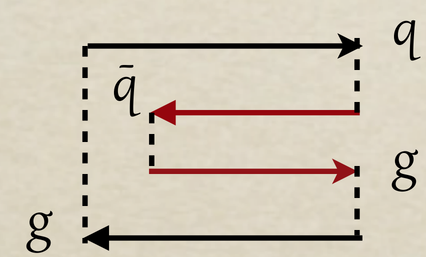
At large N_c: factorization into a dipole x quadrupole

q and g colour connected

$\bar q$ and $\bar g$ colour connected



q and $\bar q$ colour connected

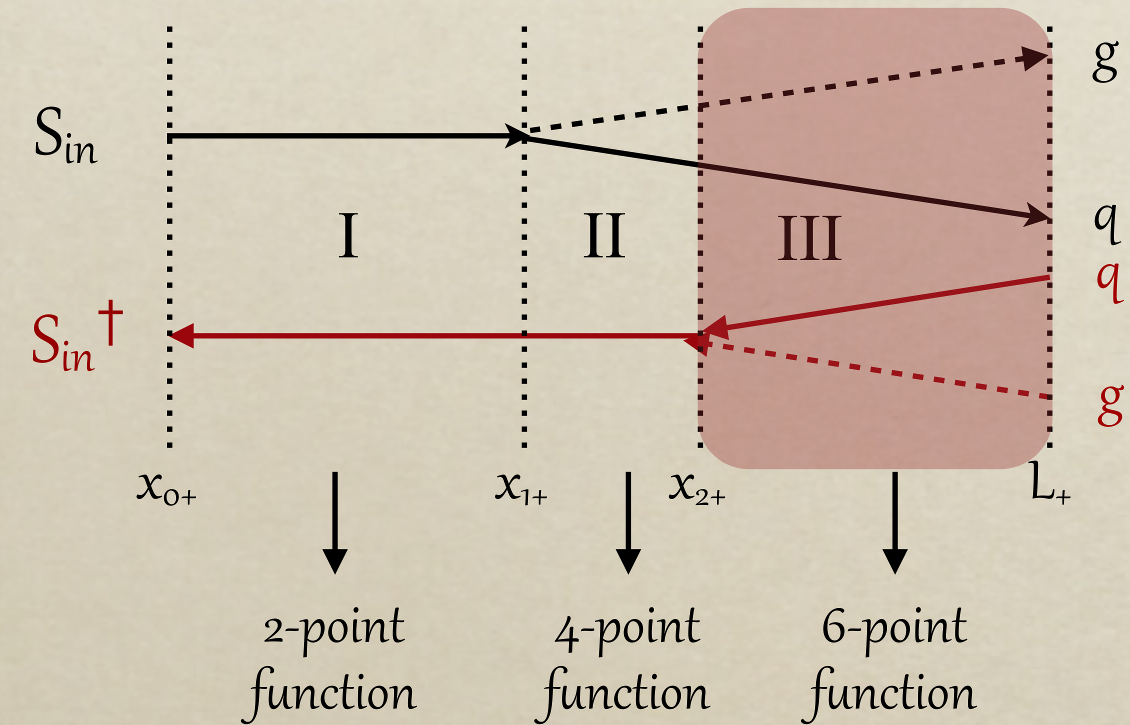
g and $\bar g$ colour connected

Coherent state

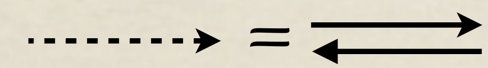
Decoherent state

Medium averages

- Schematic representation of the in-in term of the spectrum ($|S_{in}|^2$) at large N_c:



(larger number of swaps suppressed by $O(N^{-2})$)



$$\langle \mathrm{Tr}\left[W(\mathbf{x}_g)W^\dagger(\mathbf{x}_{\bar g})\right] \mathrm{Tr}\left[W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar g})W^\dagger(\mathbf{x}_{\bar q})W(\mathbf{x}_q)\right]\rangle =$$
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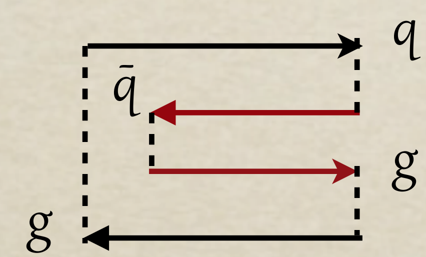
At large N_c: factorization into a dipole x quadrupole

q and g colour connected

$\bar{q}$ and $\bar{g}$ colour connected



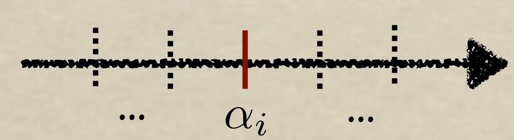
q and $\bar{q}$ colour connected

g and $\bar{g}$ colour connected

Coherent state

somewhere, in between, there should be a swap between the colour configurations

Decoherent state



Medium averages

- Result of the quadrupole:

$$\mathrm{Tr}\left\langle W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar g})W^\dagger(\mathbf{x}_{\bar q})W(\mathbf{x}_q)\right\rangle_{(x_{2+},L_+)} = \mathrm{e}^{Nm_{22}} + \int_{x_{2+}}^{L_+} d\tau\, \mathrm{e}^{Nm_{11}(x_{2+},\tau)}\, m_{12}(\tau)\, \mathrm{e}^{Nm_{22}(\tau,L_+)}$$

where: $m_{11} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar g}-\mathbf{x}_{\bar q}) + v(\mathbf{x}_q-\mathbf{x}_g)\right]$ (coherent prop.):

$m_{22} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar g}-\mathbf{x}_g) + v(\mathbf{x}_q-\mathbf{x}_{\bar q})\right]$ (independent prop.):

$m_{12} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar g}-\mathbf{x}_{\bar q}) - v(\mathbf{x}_q-\mathbf{x}_g) - v(\mathbf{x}_{\bar g}-\mathbf{x}_q) - v(\mathbf{x}_{\bar q}-\mathbf{x}_g)\right]$

Medium averages

- Result of the quadrupole:

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complete
independent piece

where:

$$m_{11} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar{g}}-\mathbf{x}_{\bar{q}}) + v(\mathbf{x}_q-\mathbf{x}_g)\right] \quad \text{(coherent prop.):}$$

$$m_{22} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar{g}}-\mathbf{x}_g) + v(\mathbf{x}_q-\mathbf{x}_{\bar{q}})\right] \quad \text{(independent prop.):}$$

$$m_{12} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar{g}}-\mathbf{x}_{\bar{q}}) - v(\mathbf{x}_q-\mathbf{x}_g) - v(\mathbf{x}_{\bar{g}}-\mathbf{x}_q) - v(\mathbf{x}_{\bar{q}}-\mathbf{x}_g)\right]$$

Medium averages

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complete independent piece — coherent propagation up to $\boldsymbol{\tau}$

where:

$$m_{11} = -\frac{1}{2}\left[v(\mathbf{x}_{\bar{g}} - \mathbf{x}_{\bar{q}}) + v(\mathbf{x}_q - \mathbf{x}_g)\right] \quad \text{(coherent prop.):}$$

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Medium averages

- Result of the quadrupole:

$$\mathrm{Tr}\left\langle W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar g})W^\dagger(\mathbf{x}_{\bar q})W(\mathbf{x}_q)\right\rangle_{(x_{2+},L_+)} = \mathrm{e}^{Nm_{22}} + \int_{x_{2+}}^{L_+} d\tau\, \mathrm{e}^{Nm_{11}(x_{2+},\tau)}\, m_{12}(\tau)\, \mathrm{e}^{Nm_{22}(\tau,L_+)}$$

complete independent piece | coherent propagation up to **τ** | Local swap at **τ**

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Δ_{med} by definition

Generalized Δ_{med}

- Generalized Δ_{med} accounts for the broadening of the particles:

$$\Delta_{med} = 1 + \int_{x_{2+}}^{L_+} d\tau \, \mathrm{e}^{N(m_{11}-m_{22})(x_{0+},\tau)} N m_{12}(\tau)$$

$$= 1 + \int_{x_{2+}}^{L_+} d\tau \, \hat{q}_F \, (\mathbf{x}_q - \mathbf{x}_{\bar{q}}) \cdot (\mathbf{x}_g - \mathbf{x}_{\bar{g}})|_\tau \, \mathrm{e}^{-\hat{q}_F \int_{x_{2+}}^{\tau} d\xi (\mathbf{x}_q - \mathbf{x}_{\bar{g}}) \cdot (\mathbf{x}_{\bar{q}} - \mathbf{x}_g)}$$, in the dipole approximation

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    - Infinite medium (small t_{form}):

$$\exp\left\{-\hat{q}_F \int_{x_{2+}}^{\tau} d\xi\, (\mathbf{x}_q - \mathbf{x}_{\bar{g}}) \cdot (\mathbf{x}_{\bar{g}} - \mathbf{x}_g)\right\} \leq \exp\left\{-\hat{q}_F\, (\mathbf{x}_q - \mathbf{x}_{\bar{g}}) \cdot (\mathbf{x}_{\bar{q}} - \mathbf{x}_g)|_{x_{2+}} (\tau - x_{2+})\right\}$$

$$\Delta r \sim \frac{1}{\Delta p} \sim \frac{1}{\sqrt{\hat{q}_F L_+}} \Rightarrow \Delta_{med} \approx 1 + \int_{x_{2+}}^{L_+} d\tau \frac{1}{L} \exp\left\{-\frac{\tau - x_{2+}}{x_{2+}}\right\}$$

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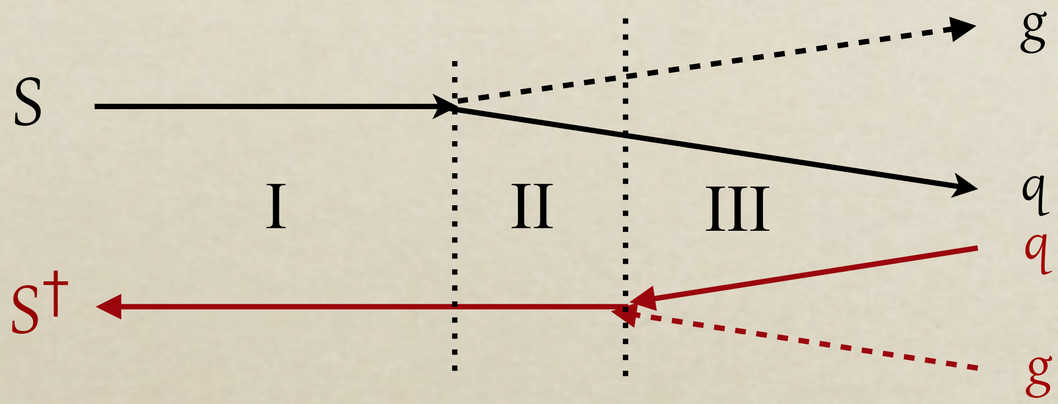
Suppressed by L_+

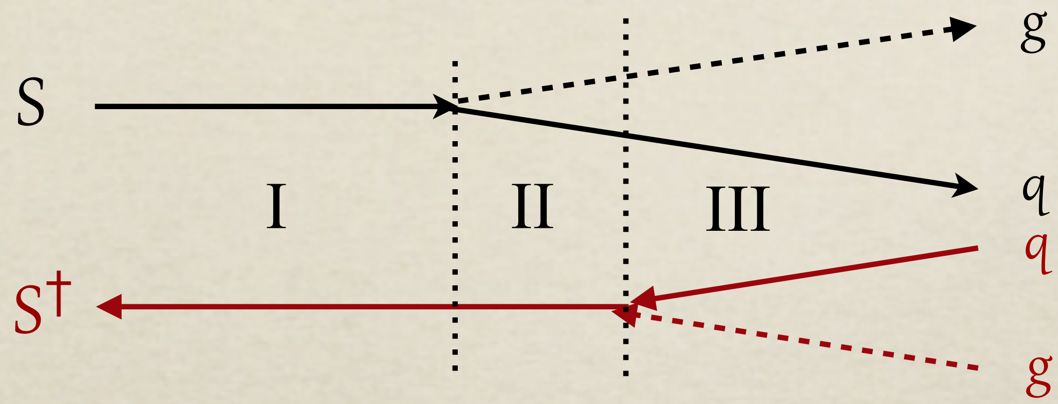
When $L_+ \rightarrow \infty \Rightarrow \Delta_{med}=1$ OK!

Blaizot, Dominguez, Iancu and Mehtar-Tani [1311.5823]

Resulting picture

- Two different regimes:





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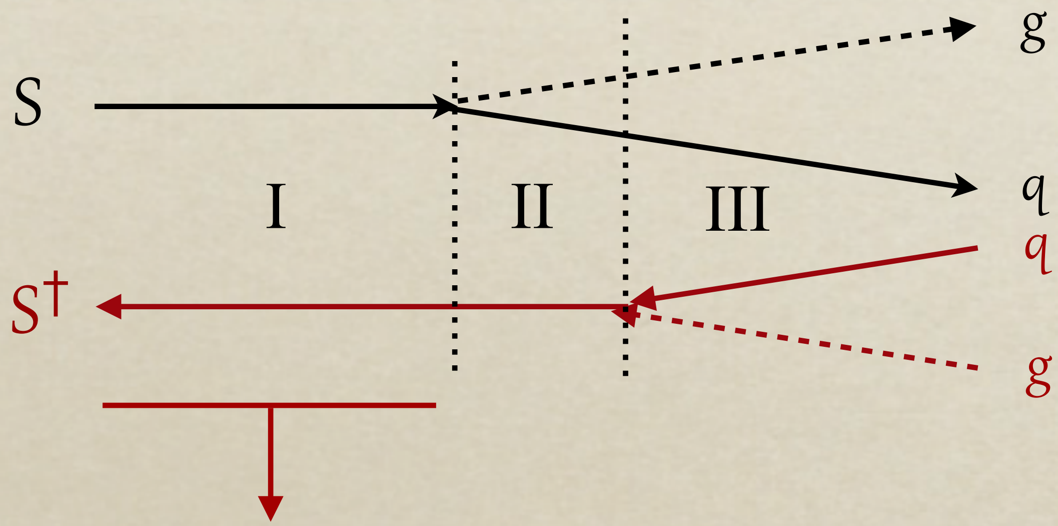

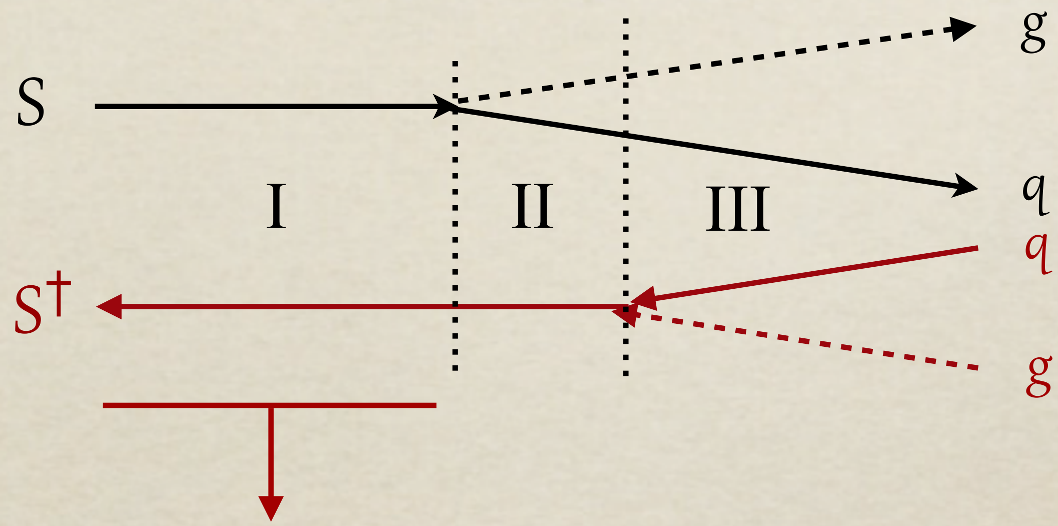

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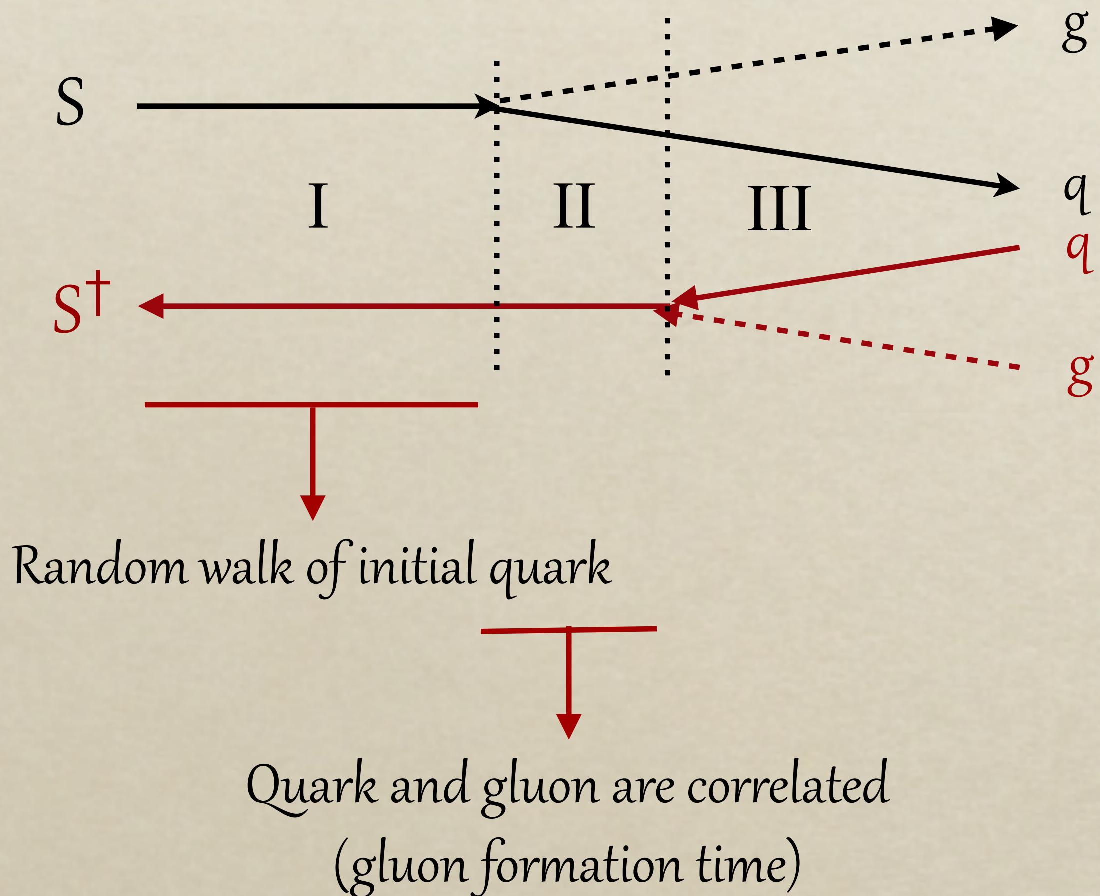

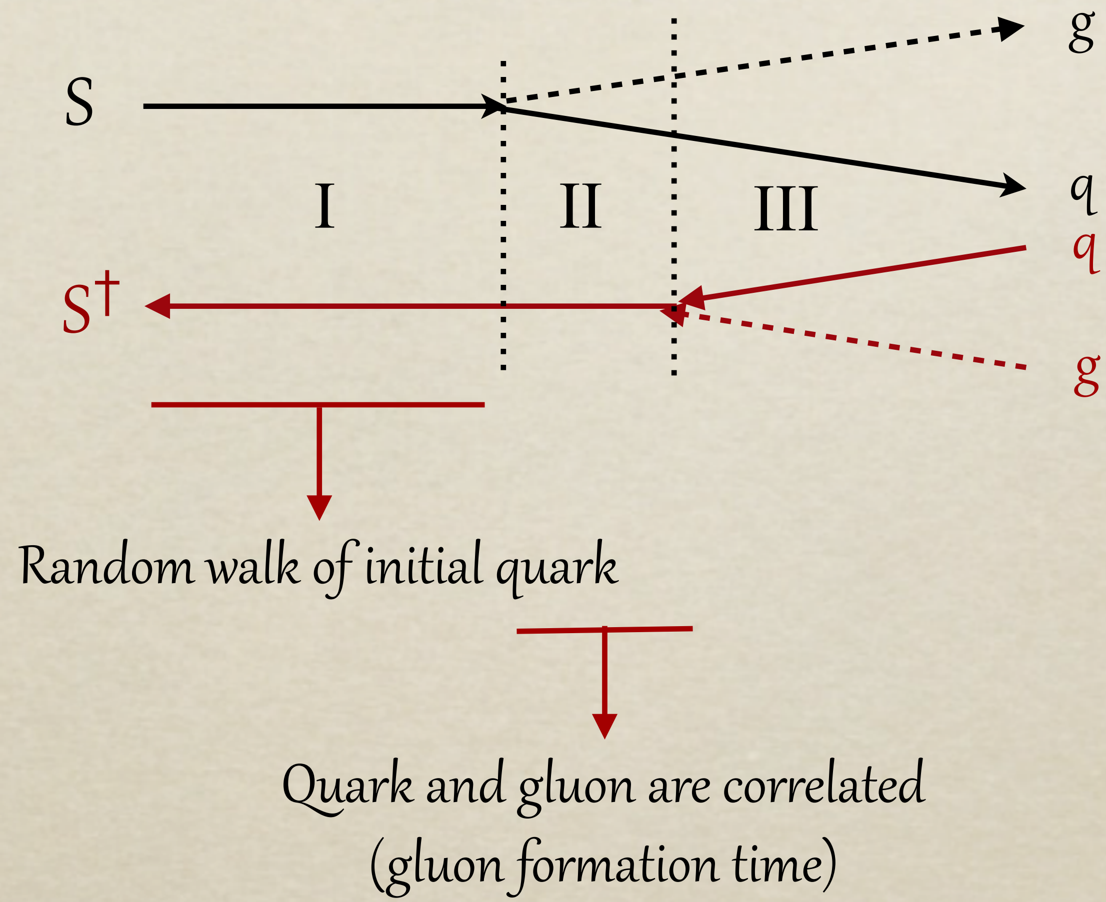

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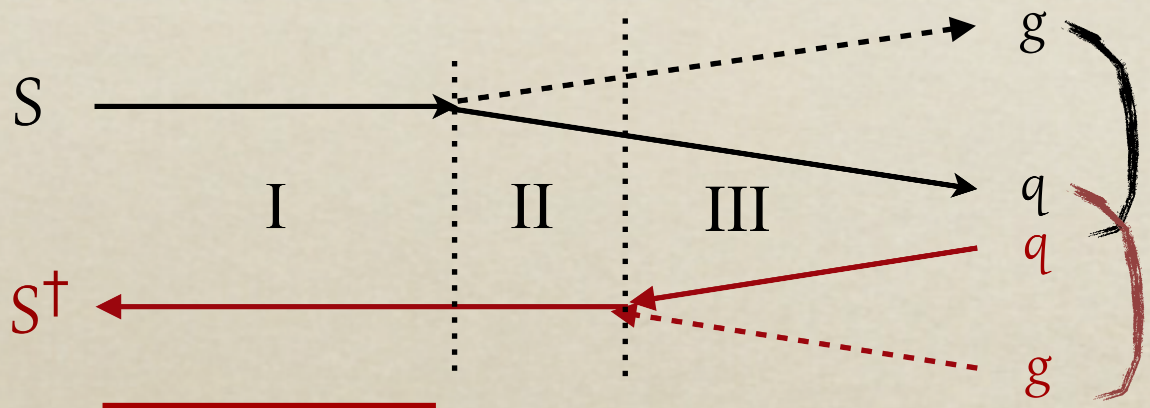

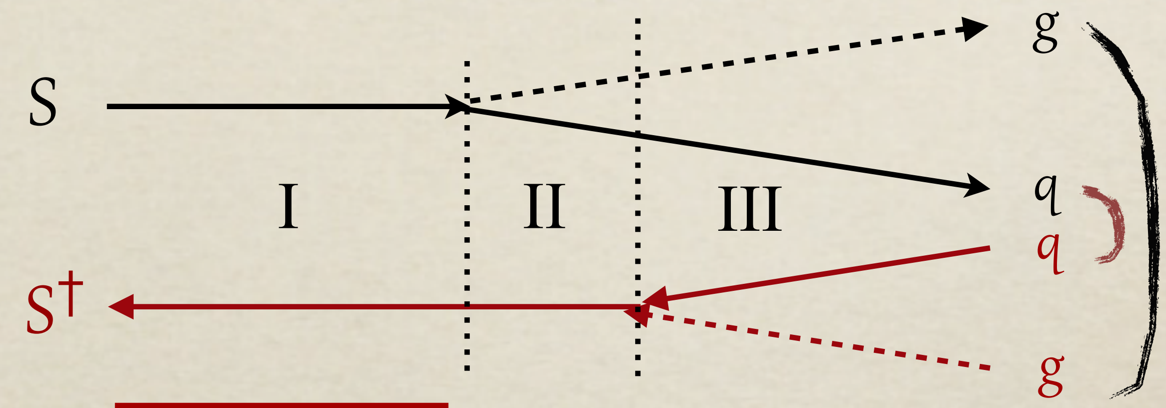

Random walk of initial quark	Random walk of initial quark
Quark and gluon are correlated (gluon formation time)	Quark and gluon are correlated (gluon formation time)
Quark and gluon act coherently (coherent propagation controlled by dipole distance)	Independent broadening of final partons

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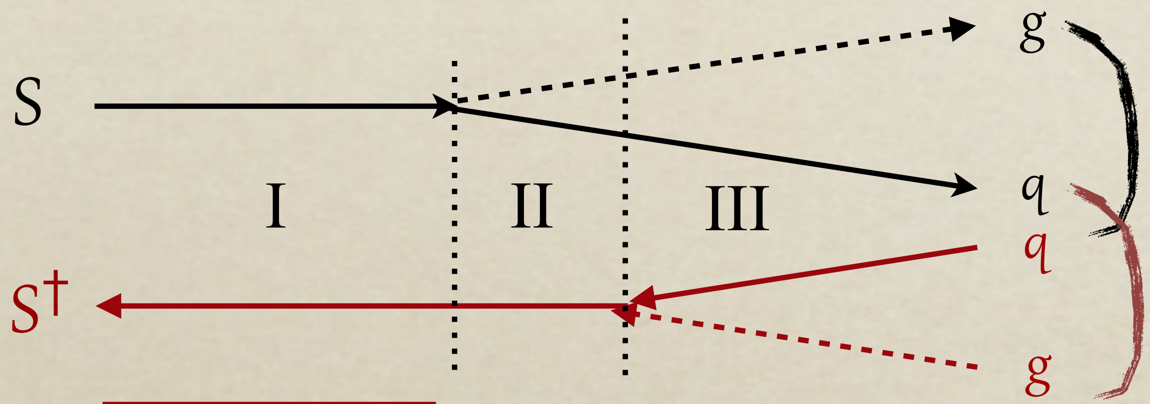

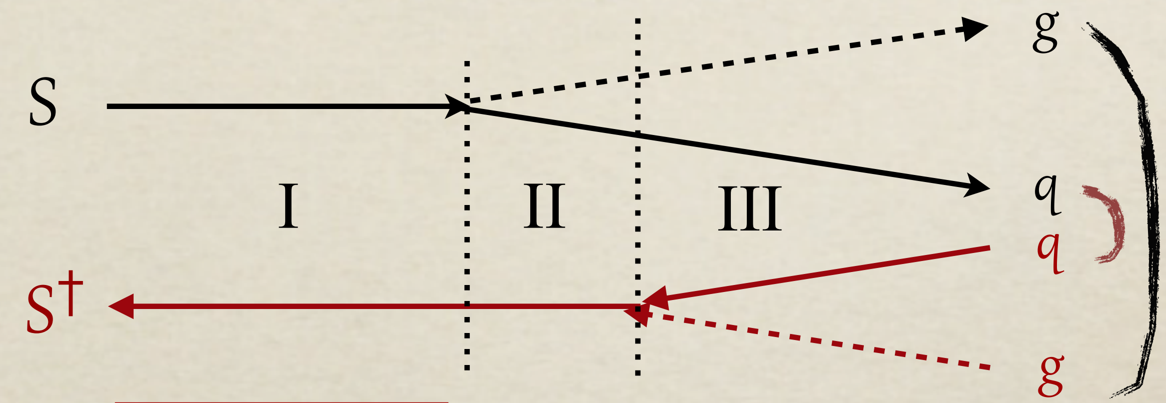

Random walk of initial quark

Quark and gluon are correlated
(gluon formation time)

Quark and gluon act coherently
(coherent propagation controlled by dipole distance)

Medium-induced gluon radiation is suppressed

Random walk of initial quark

Quark and gluon are correlated
(gluon formation time)

Independent broadening of final partons

Loss of energy is more efficient

Conclusions

- Able to unify in a single expression:

Broadening:

- Eikonal approximation:
- Beyond eikonal approximation:

Energy loss:

- Soft gluon radiation limit;
- Extensions to account for hard limit;

$$\int \mathcal{D}\mathbf{x}_q(\xi)\,\mathcal{D}\mathbf{x}_{\bar{q}}(\xi)\,\mathcal{D}\mathbf{x}_g(\xi)\,\mathcal{D}\mathbf{x}_{\bar{g}}(\xi)\exp\left\{\frac{ip_{0+}}{2}\int_{x_{2+}}^{L_+} d\xi\,\left[(1-z)\left(\dot{\mathbf{x}}_q^2-\dot{\mathbf{x}}_{\bar{q}}^2\right)+z\left(\dot{\mathbf{x}}_g^2-\dot{\mathbf{x}}_{\bar{g}}^2\right)\right]\right\}$$
$$\times \mathrm{e}^{-\frac{N}{2}v(\mathbf{x}_g-\mathbf{x}_{\bar{g}})}\left\{\mathrm{e}^{Nm_{22}}+\int_{x_{2+}}^{L_+} d\tau\,\mathrm{e}^{Nm_{11}(x_{0+},\tau)}\,Nm_{12}\,\mathrm{e}^{Nm_{22}(\tau,L_+)}\right\}$$

(Anti)angular ordering:

- Coherent regime:
- Decoherent regime: