COHERENCE EFFECTS BETWEEN INITIAL AND FINAL STATE RADIATION IN A DENSE QCD MEDIUM

Mauricio Martínez

UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

N. Armesto, H. Ma, Y. Mehtar-Tani and C. Salgado

arXiv:1308.2186

Motivation

A hot and dense deconfined coloured medium (QGP) is produced in Ultrarelativistic Heavy Ion Collisions

$\Rightarrow$ Nuclear modifications to the fragmentation functions and PDFs

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A hot and dense deconfined coloured medium (QGP) is produced in Ultrarelativistic Heavy Ion Collisions

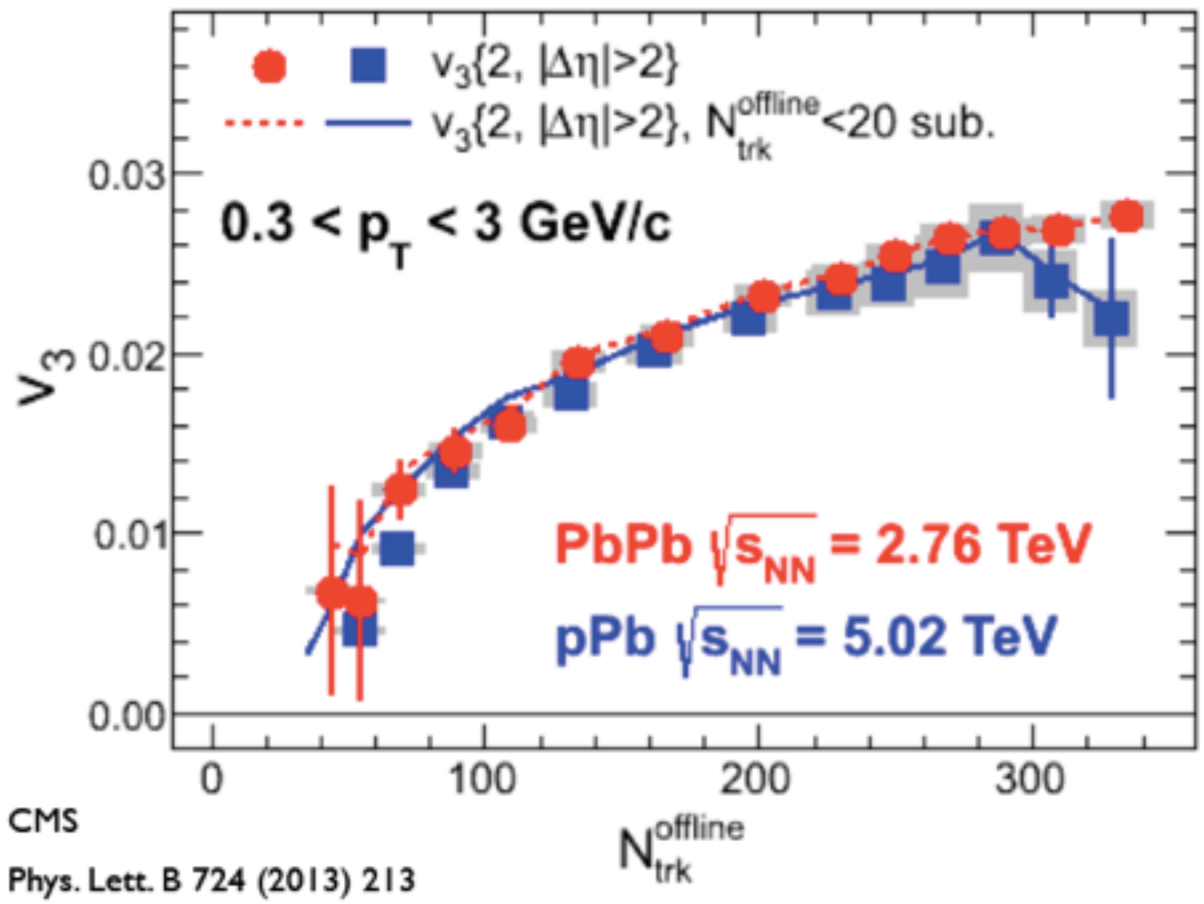
⇒ Nuclear modifications to the fragmentation functions and PDFs

Observables in HI Collisions are related to the properties of the QGP

⇒ Using pA to constrain nuclear PDFs

⇒ Assume no final state interactions. But....

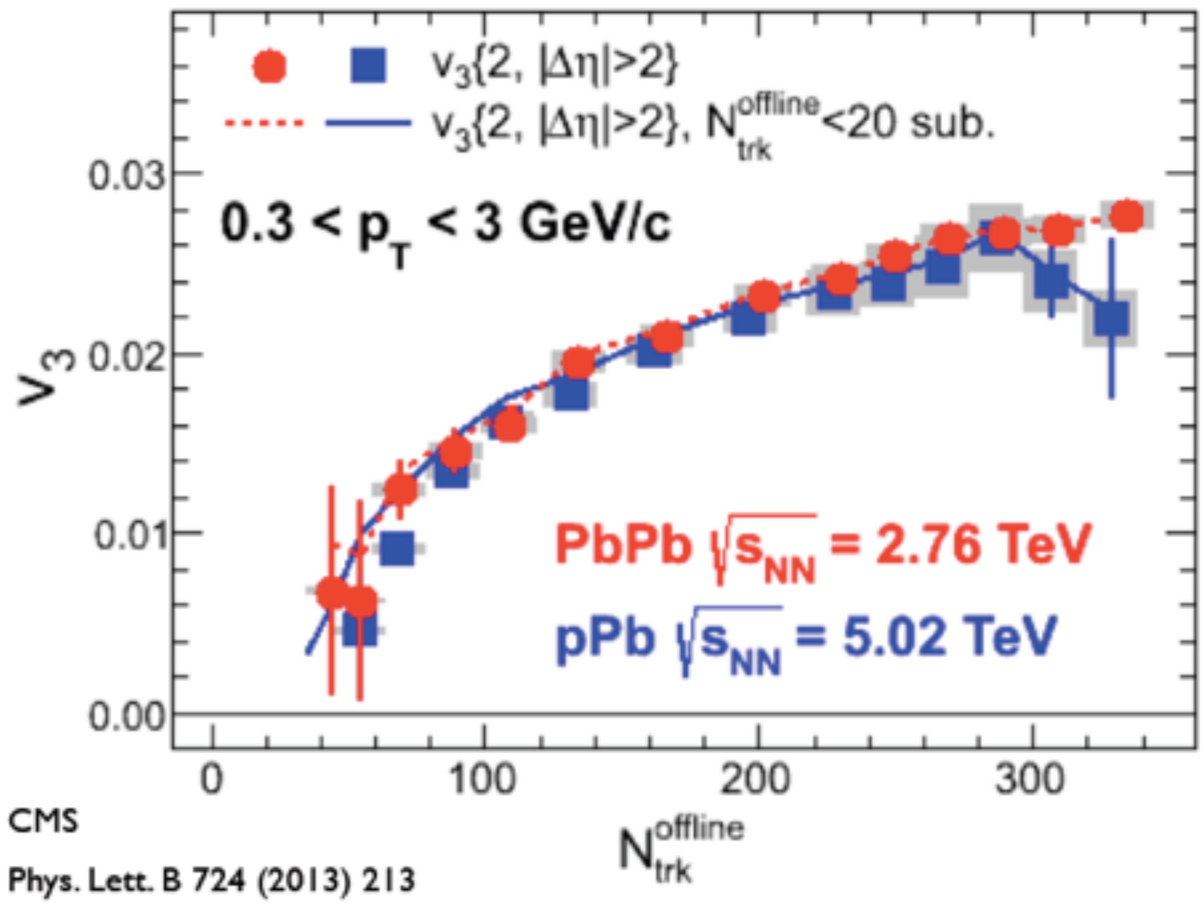
Motivation



Possible evidence of final state interactions in pA

⇒ Flow harmonics comparable to AA

Motivation



Possible evidence of final state interactions in pA

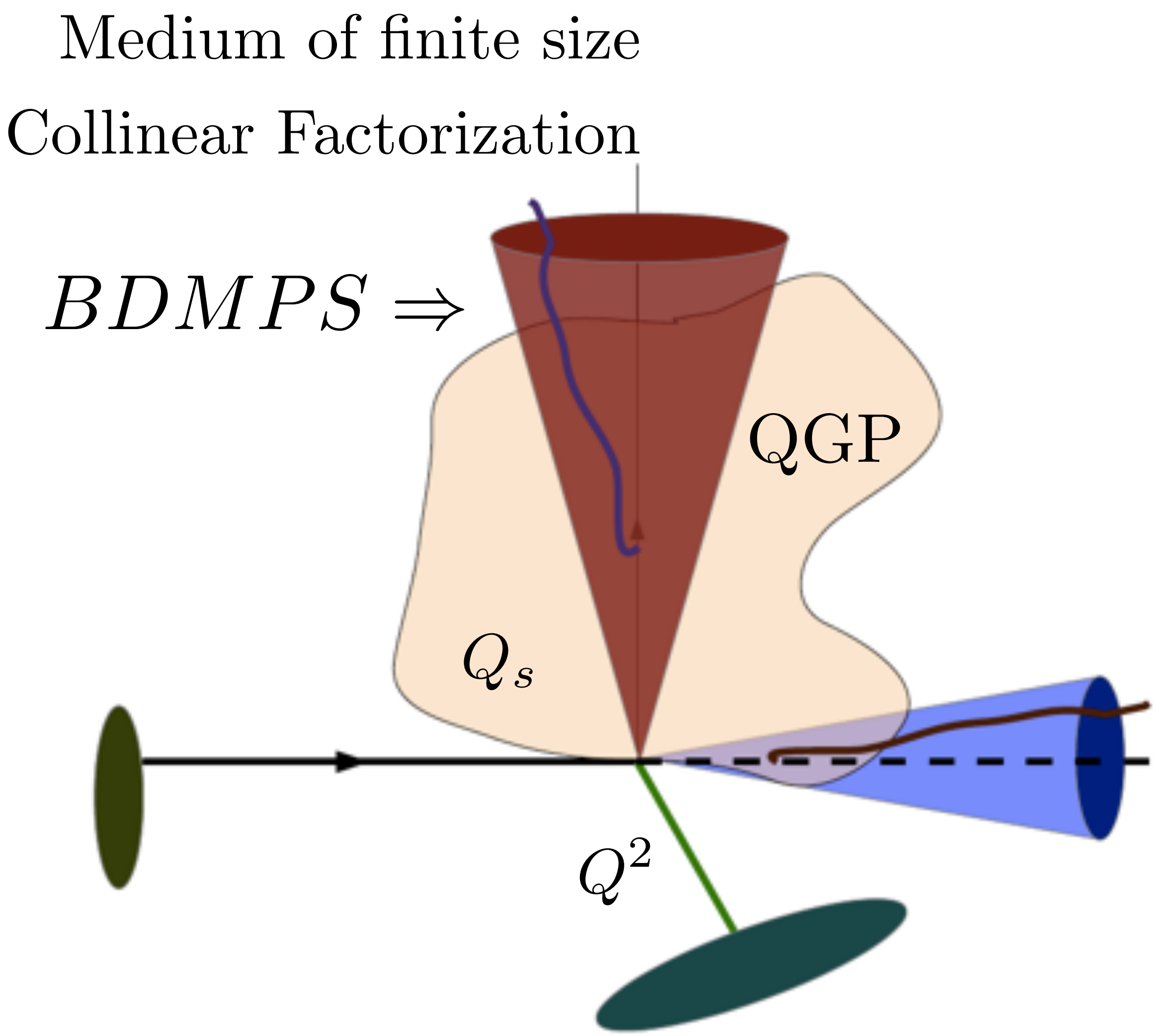
⇒ Flow harmonics comparable to AA

QCD medium of finite size leads to color decoherence effects

⇒ Modifications to the hadronic outcome subsist for large pT

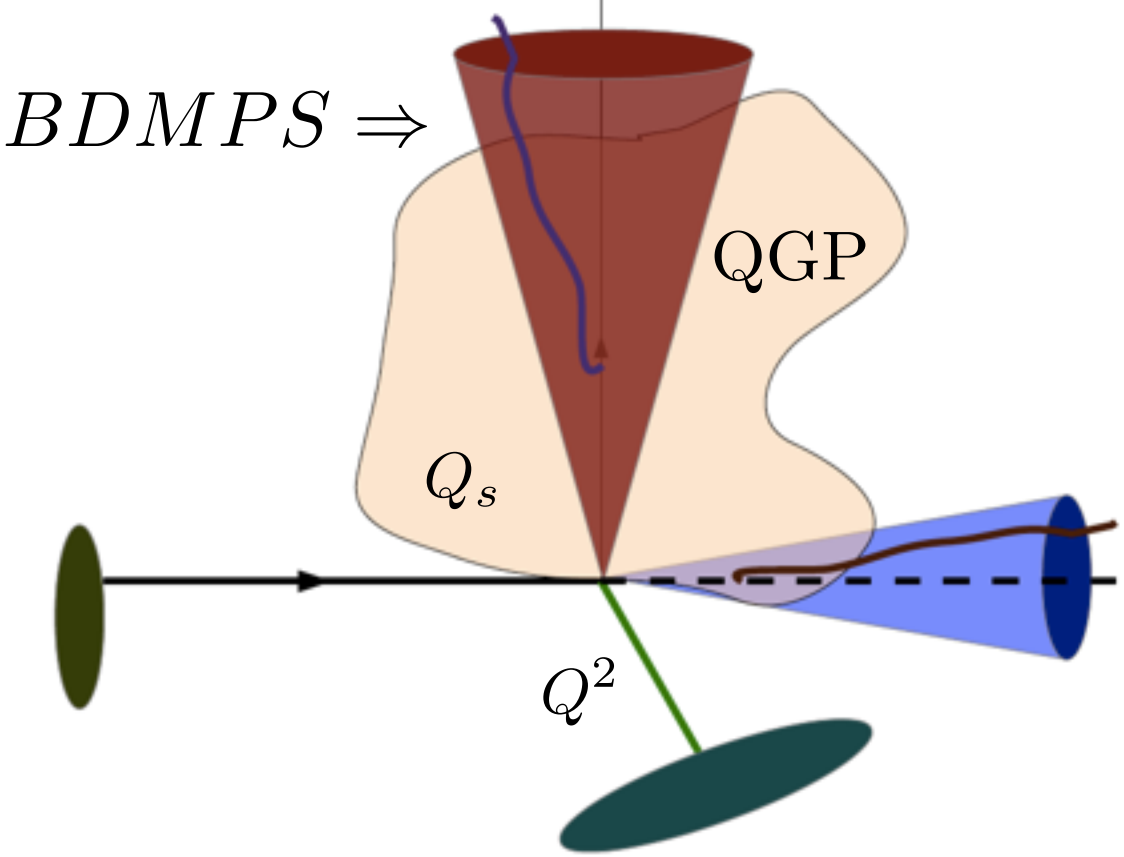
⇒ Jet quenching effects might be seen in pA

See K. Tywoniuk's talk


Medium of finite size
Collinear Factorization
$BDMPS \Rightarrow$
QGP
Q_s
Q^2

Medium of finite size

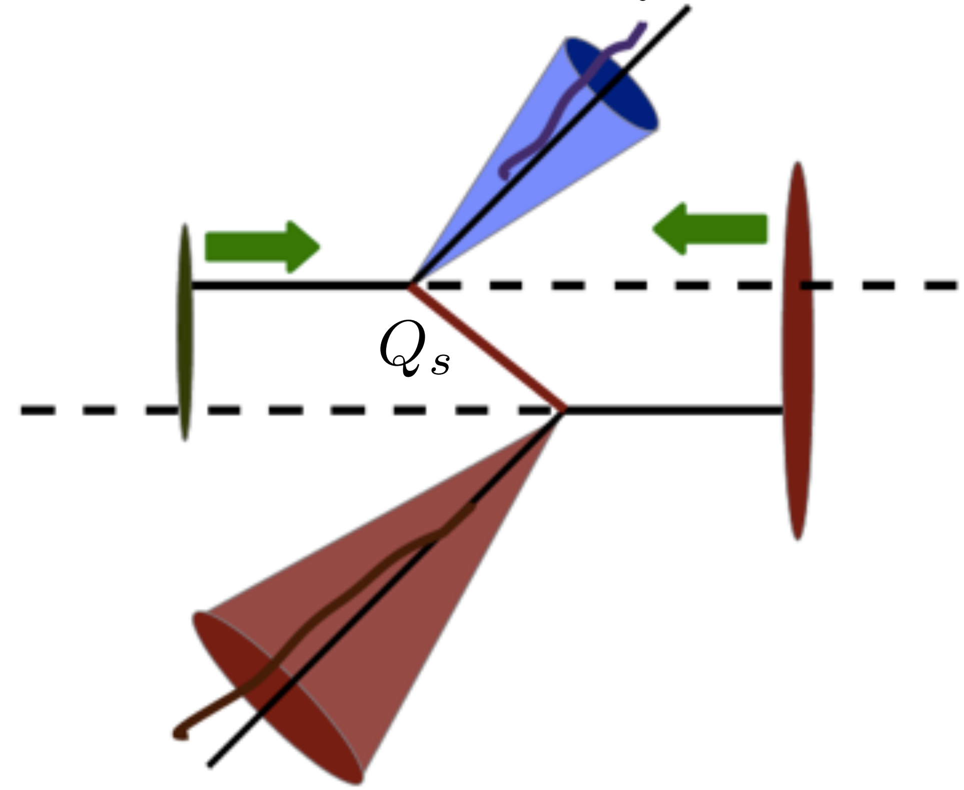
Collinear Factorization



Shockwave

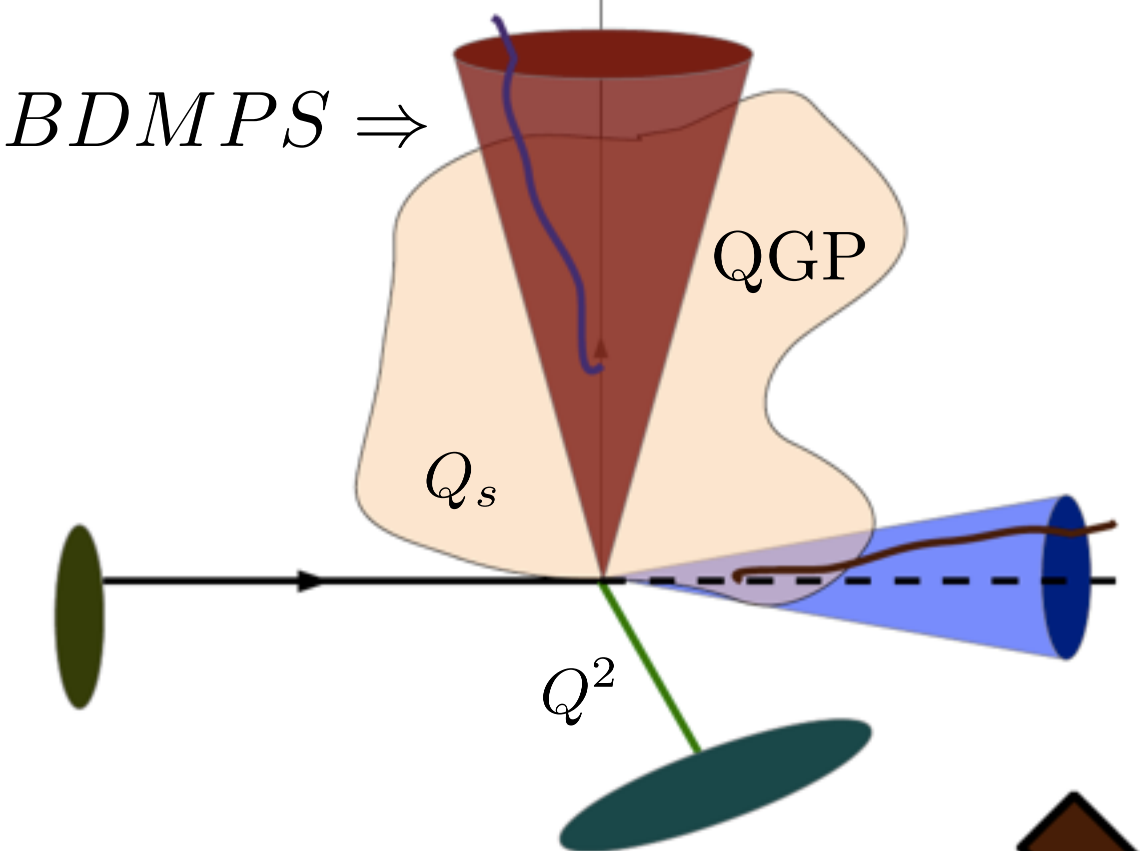
k_T factorization

Hybrid formalism



Medium of finite size

Collinear Factorization



Shockwave

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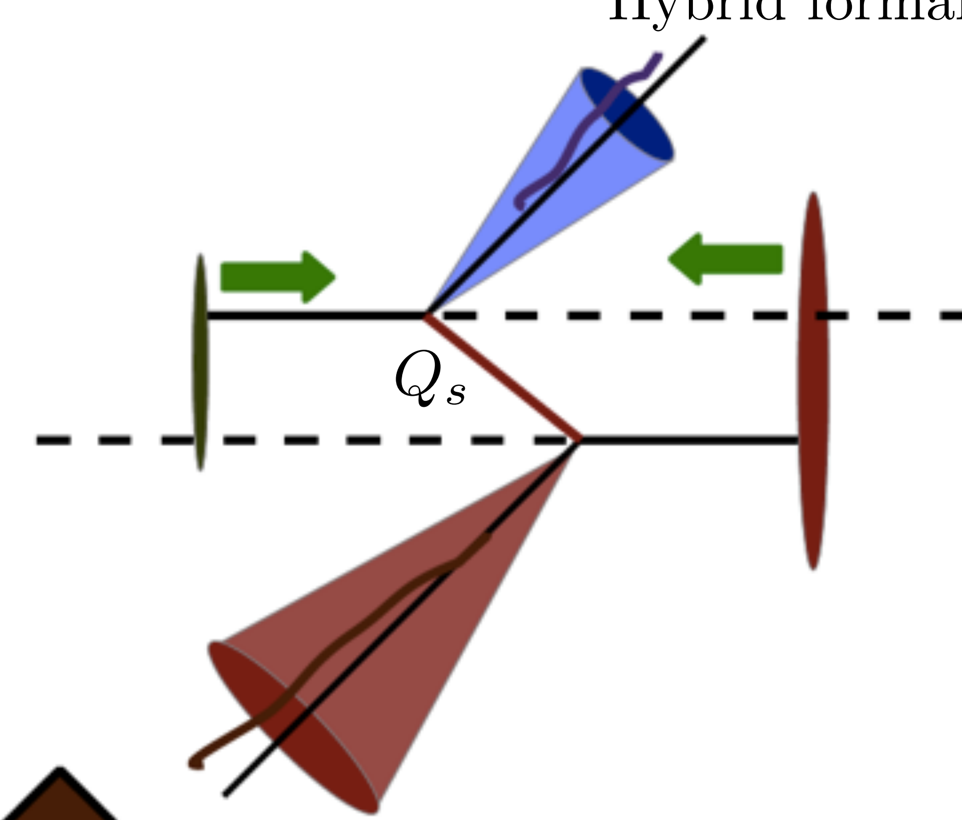
Hybrid formalism

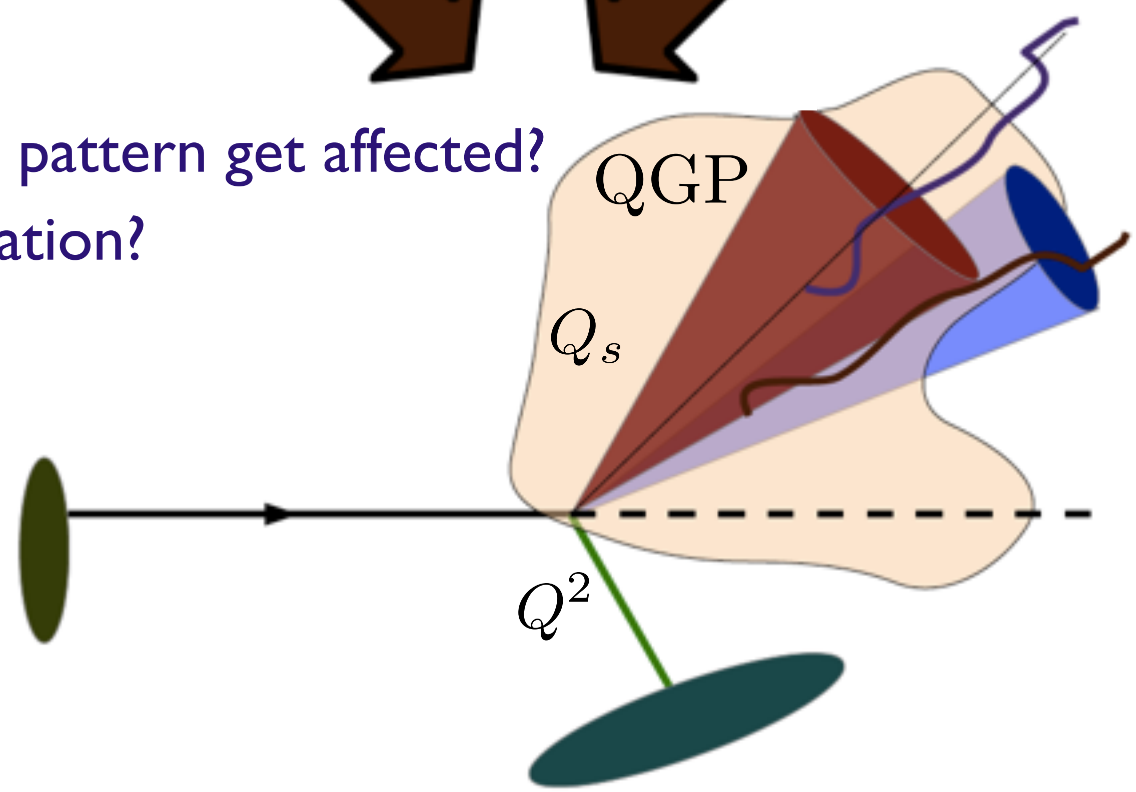


How is the vacuum coherence pattern get affected?

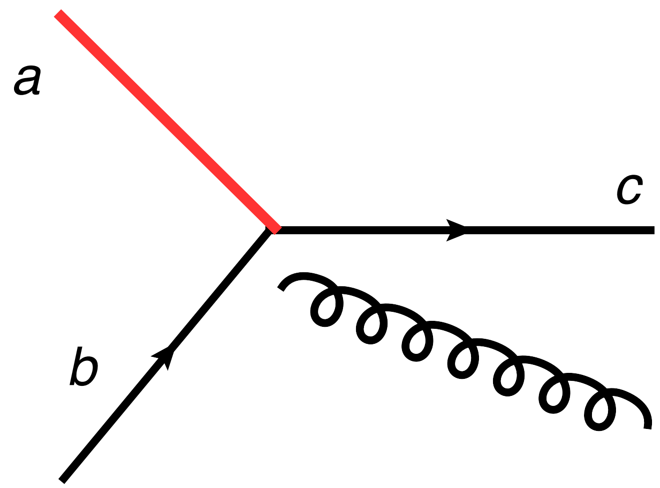
Do we have: Collinear factorization?

k_T Factorization?

Something else?

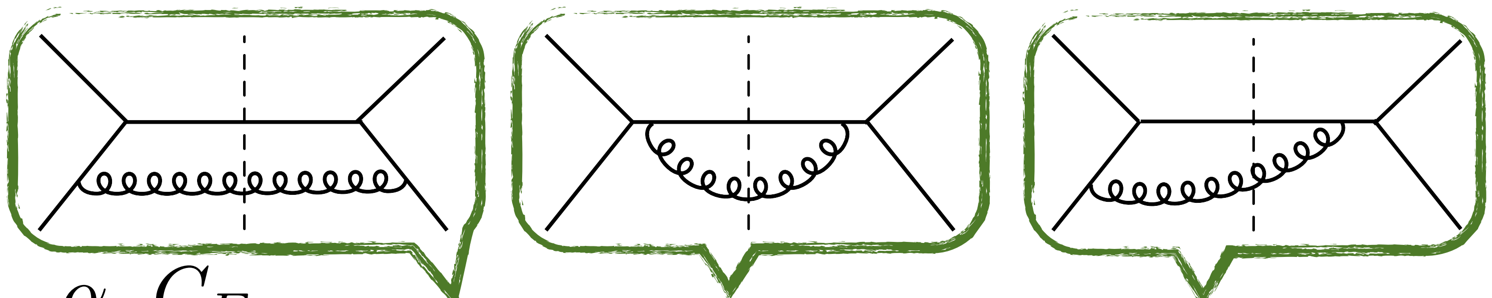


Color coherence in a DIS-like process



$Q_a = 0 \Rightarrow Singlet$

$Q_a \neq 0 \Rightarrow Octet$

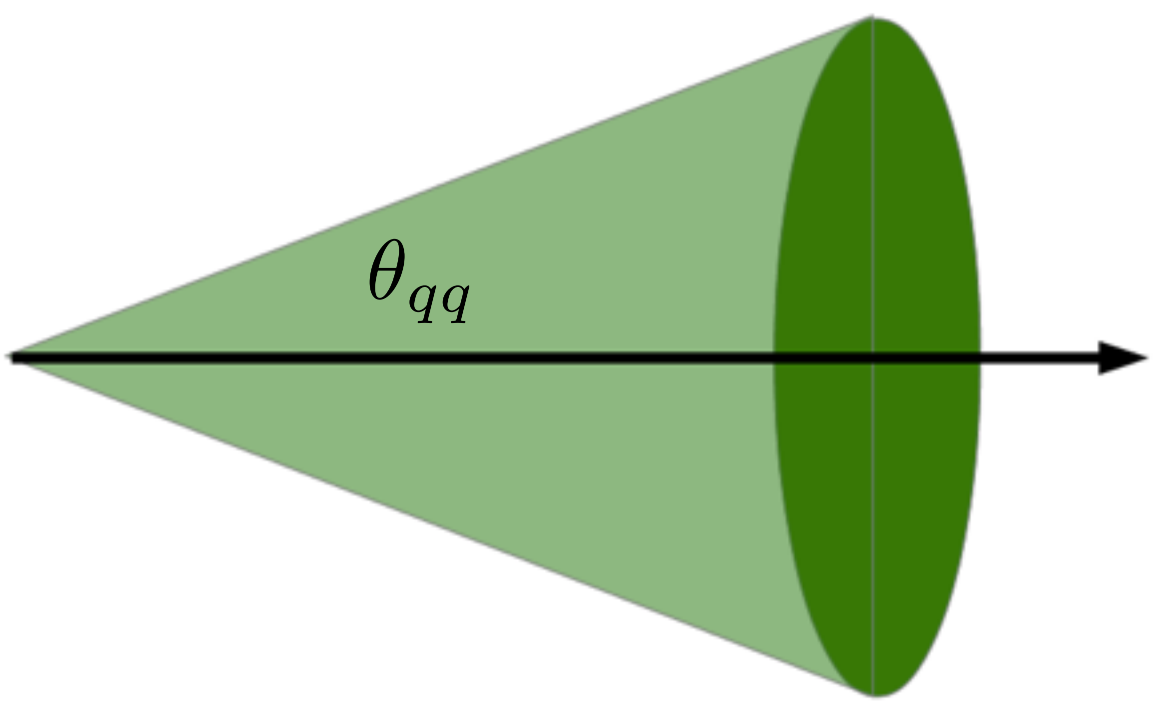


$$\omega \frac{dN}{d^3\vec{k}} = \frac{\alpha_s C_F}{(2\pi)^2\,\omega^2}\left[Q_b^2 \mathcal{R}_b + Q_c^2 \mathcal{R}_c + 2\,Q_b \cdot Q_c \mathcal{J}\right]$$

$$= \frac{\alpha_s C_F}{(2\pi)^2\,\omega^2}\left[Q_b^2(\mathcal{R}_b - \mathcal{J}) + Q_c^2(\mathcal{R}_c - \mathcal{J}) + Q_a^2 \mathcal{J}\right]$$

Coherent radiation

Total charge

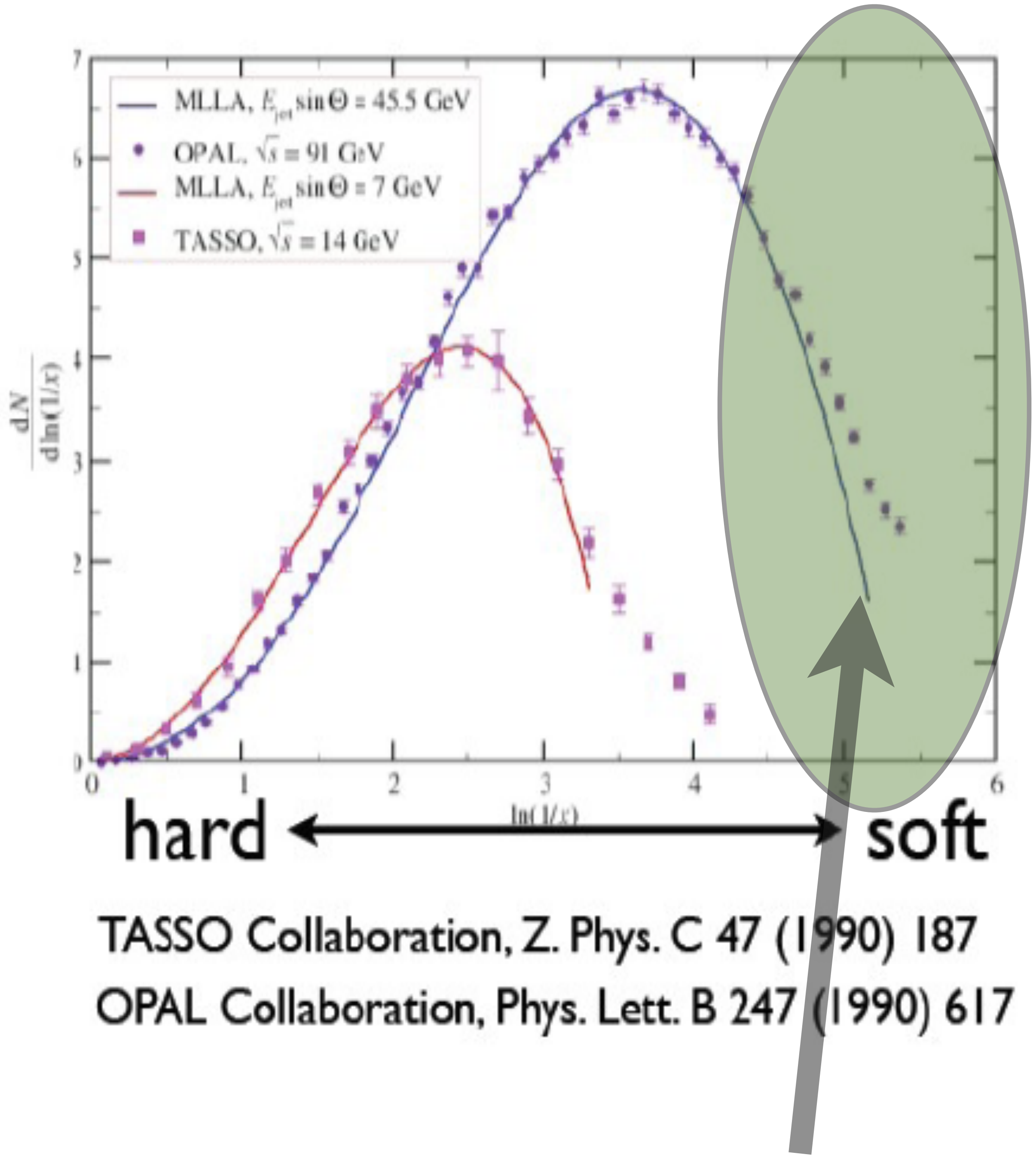


Coherent spectrum

$$\langle dN_i \rangle_\phi = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta_i}{\theta_i} \Theta\left(\theta_{qq} - \theta_i\right)$$

Collinear and soft divergence

Color coherence: MC implementation and experimental evidence

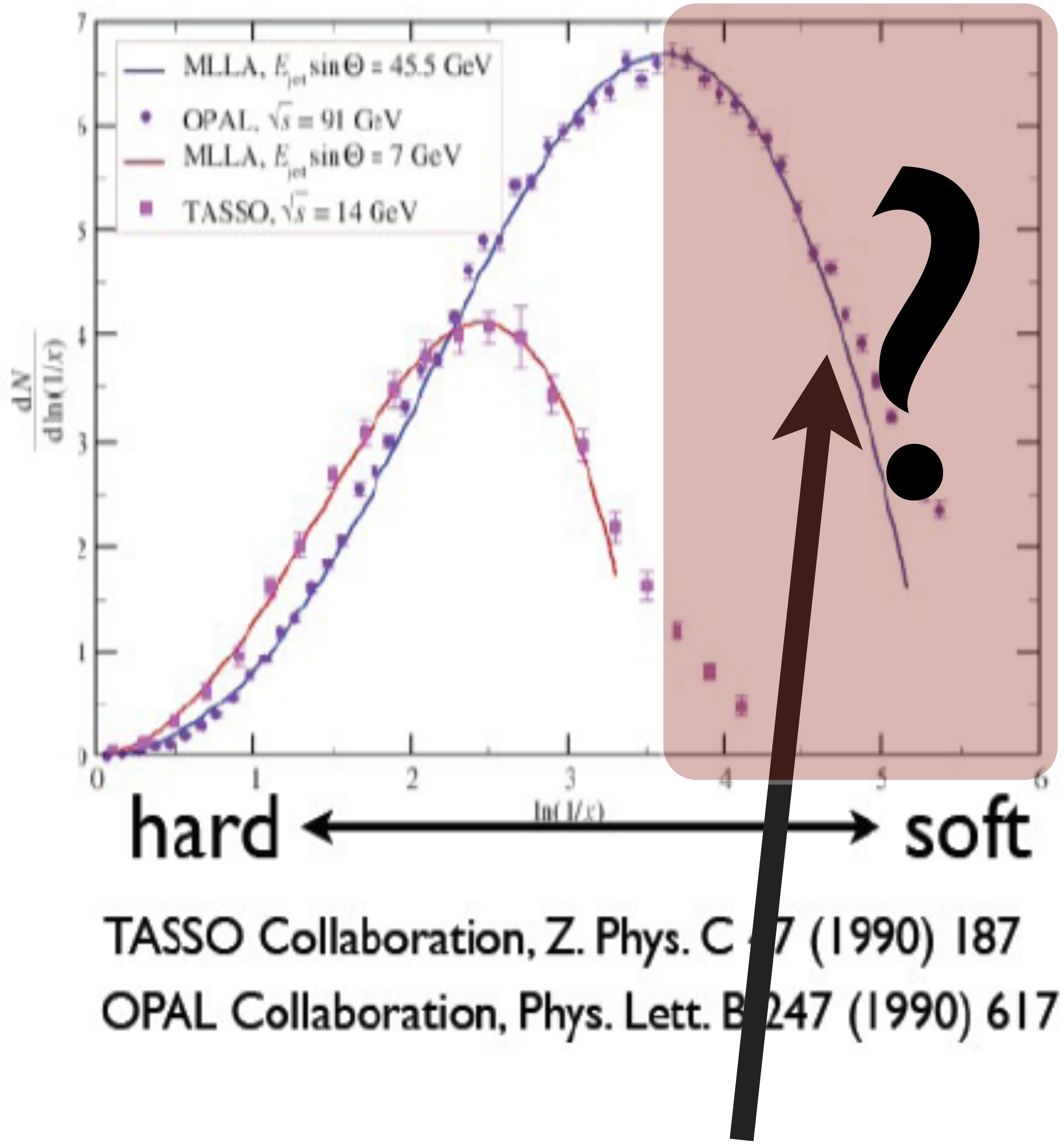


TASSO Collaboration, Z. Phys. C 47 (1990) 187

OPAL Collaboration, Phys. Lett. B 247 (1990) 617

Suppression of soft gluons

A natural question



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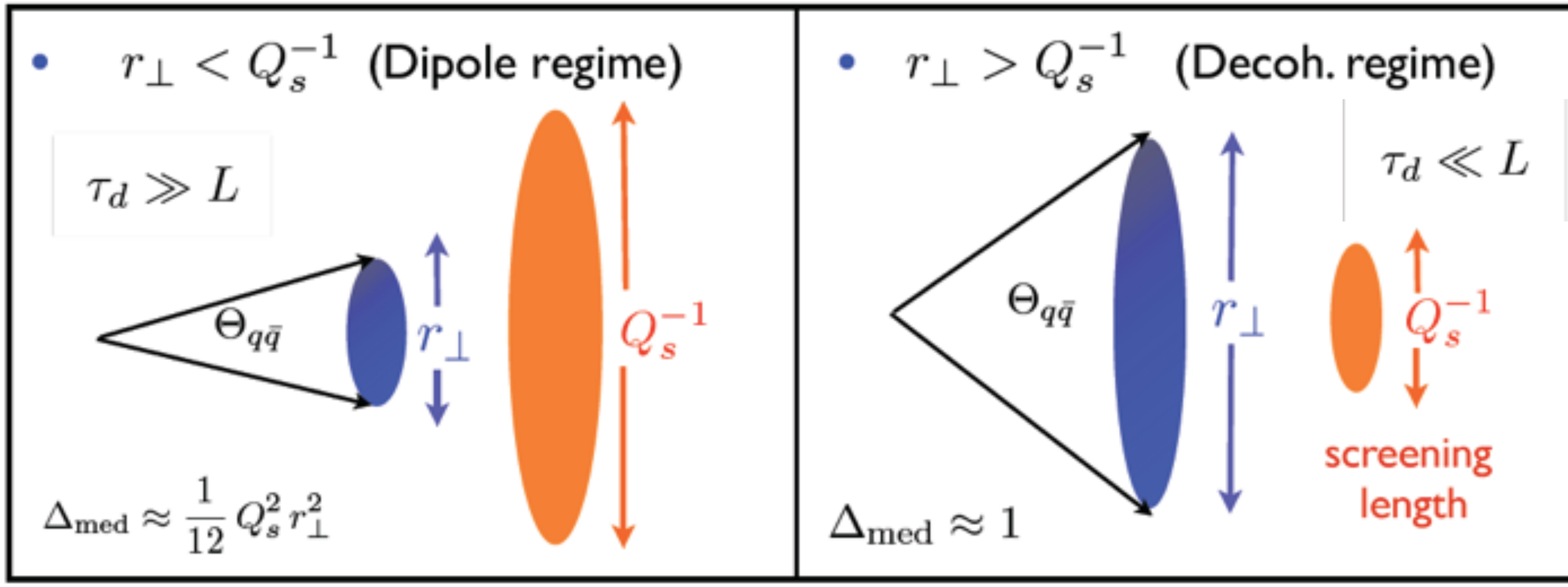
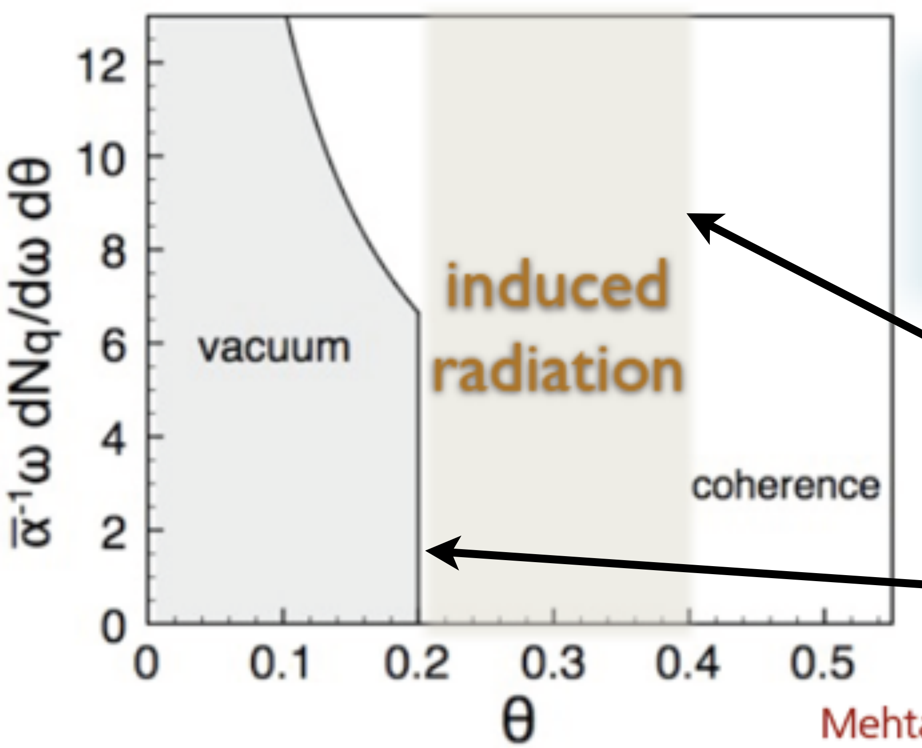
OPAL Collaboration, Phys. Lett. B 247 (1990) 617

What happens in a QCD medium?

First steps: antenna inside a QCD medium





$$1 - \Delta_{\text{med}}(t, 0) \simeq \exp\left[-\frac{1}{12}\hat{q}\theta_{q\bar{q}}^2 t^3\right] \Rightarrow \tau_d = \left(\hat{q}\theta_{q\bar{q}}^2\right)^{-1/3}$$

decoherence parameter

characteristic decoherence time

Q_{hard}/ω

$\theta_{q\bar{q}}$

$$Q_{hard} = \max(r_\perp^{-1}, Q_s)$$

$$Q_s^2 = \hat{q}L, \qquad r_\perp = \theta_{q\bar{q}} L$$

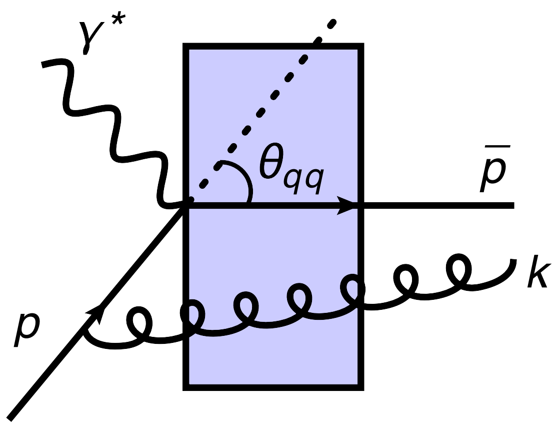
Armesto, Mehtar-Tani, Salgado, Tywoniuk, Iancu, Casalderrey-Solana

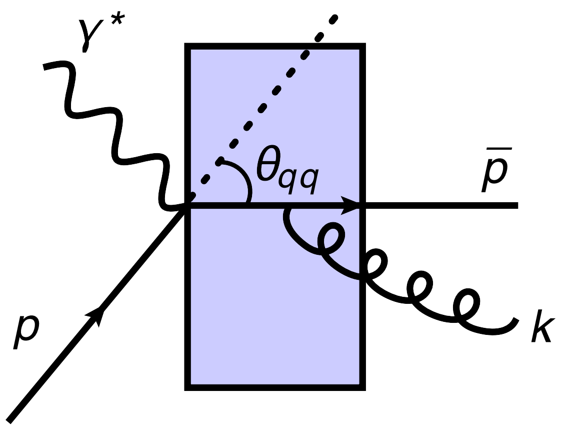
Medium modifications to the initial and final state interference pattern

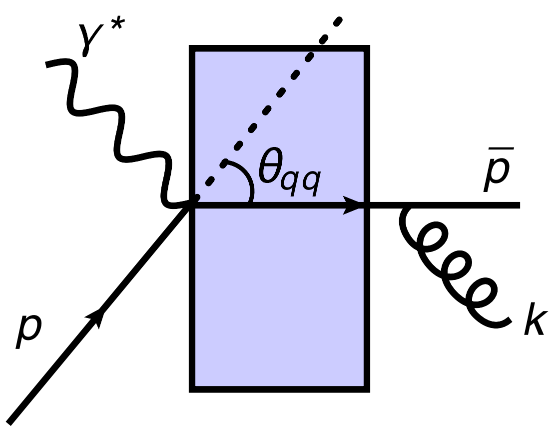
N. Armesto, Hao Ma, M. Martinez, Yacine Mehtar-Tani, C. Salgado

Dilute regime: PLB 717 (2012) 280-286

Dense regime: 1308.2186⇒ *In this talk!!!*







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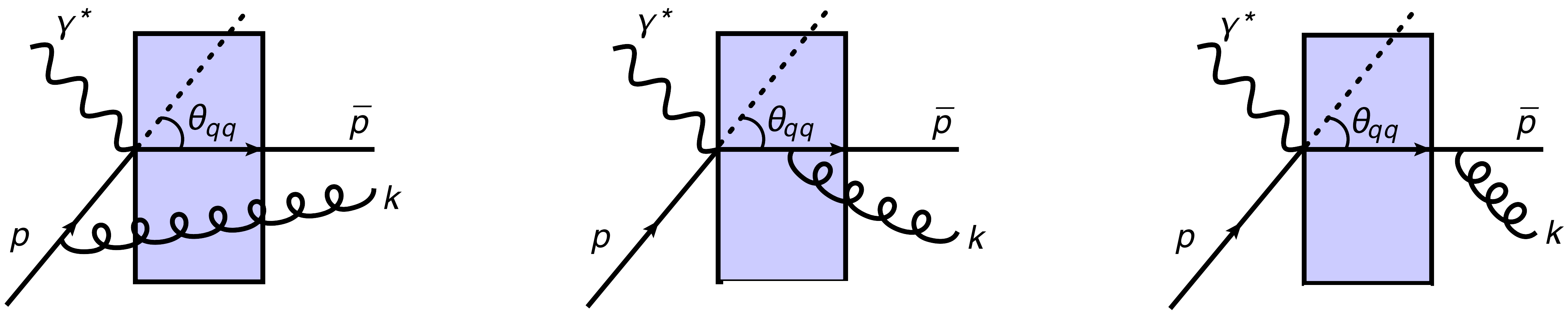

GOALS

✯ Study another configuration relevant to HI collisions

✯ Playground to investigate medium modifications to the Initial State Radiation

Classical Yang-Mills Eqs. I

Evolution of the gauge field: $\left[D_\mu, F^{\mu\nu}\right] = \mathcal{J}^\nu$

Color charge conservation: $\left[D_\mu, \mathcal{J}^\mu\right] = 0$

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Linearizing around a background field: $\mathcal{A}^\mu = A^\mu_{med} + a^\mu$

$$\Box_x a^i - 2ig\left[\mathcal{A}^-_{med}, \partial_- a^i\right] = \mathcal{J}^i - \partial^i \left(\frac{\mathcal{J}^+}{\partial_-}\right)$$

LC gauge

Classical Yang-Mills Eqs. I

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Reduction formula: $\mathcal{M}^a_\lambda = \lim_{k^2\to 0}\int d^4x e^{ik\cdot x}\Box_x \mathcal{A}^a_\mu(x)\epsilon^\mu_\lambda(\vec{k})$

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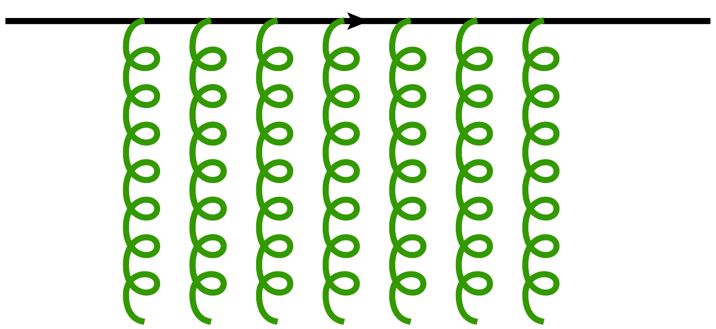
Gluon spectrum:

$$(2\pi)^3 2k^+\frac{dN}{d^3k} = \sum_{\lambda=1,2}|\mathcal{M}^a_\lambda(\vec{k})|^2$$

Classical Yang-Mills Eqs. II

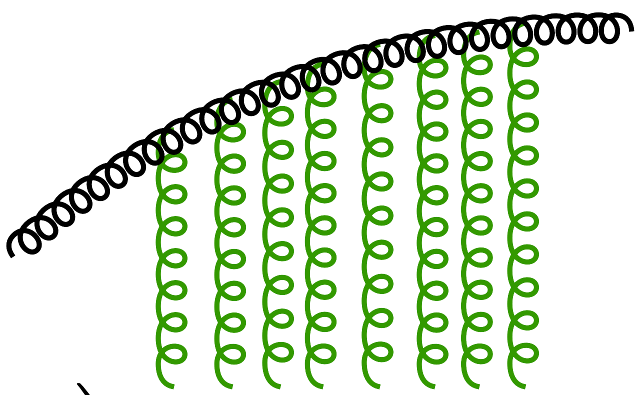
Eikonal parton in a background field:



$$\mathcal{J}^{\mu}(x)_a = g\, v^{\mu}\, \mathcal{U}^{ab}(x^+, 0)\, \delta^3(\vec{x} - \vec{v}t)\, \theta(t)\, Q_b$$

$$\mathcal{U}^{ab}(x^+, y^+) = \mathcal{P} \exp\left[ig \int_{y^+}^{x^+} dz^+\, \mathcal{A}^-_{med}\left(z^+, \boldsymbol{r}(z^+)\right)\right]^{ab}$$

Soft gluon follows a non-eikonal trajectory



$$\mathcal{G}_{ab}(x^+, \mathbf{x}; y^+, \mathbf{y}|k^+) = \int_{\mathbf{r}(y^+)=\mathbf{y}}^{\mathbf{r}(x^+)=\mathbf{x}} \mathcal{D}\mathbf{r} \exp\left(i\frac{k^+}{2} \int_{y^+}^{x^+} dz\, \dot{\mathbf{r}}^2(z) \right) \mathcal{U}_{ab}(x^+, y^+)$$

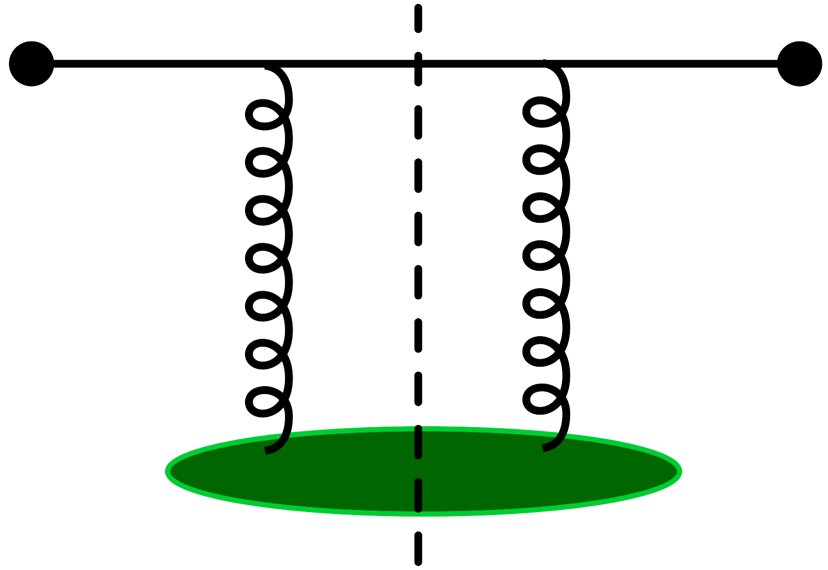
Modeling the medium

Medium is described as a classical background field:

$$-\partial_{\mathbf{x}}^2 \mathcal{A}^-_{med}(x^+, \mathbf{x}) = \rho(x^+, \mathbf{x})$$

The distribution of color charges is considered to be a Gaussian noise:

$$\langle \mathcal{A}^{a,-}_{med}(x^+, \boldsymbol{q}) \mathcal{A}^{*b,-}_{med}(x'^+, \boldsymbol{q}')\rangle = \delta^{ab} n(x^+)\delta(x^+ - x'^+)\delta^{(2)}(\boldsymbol{q} - \boldsymbol{q}')\mathcal{V}^2(\boldsymbol{q})$$

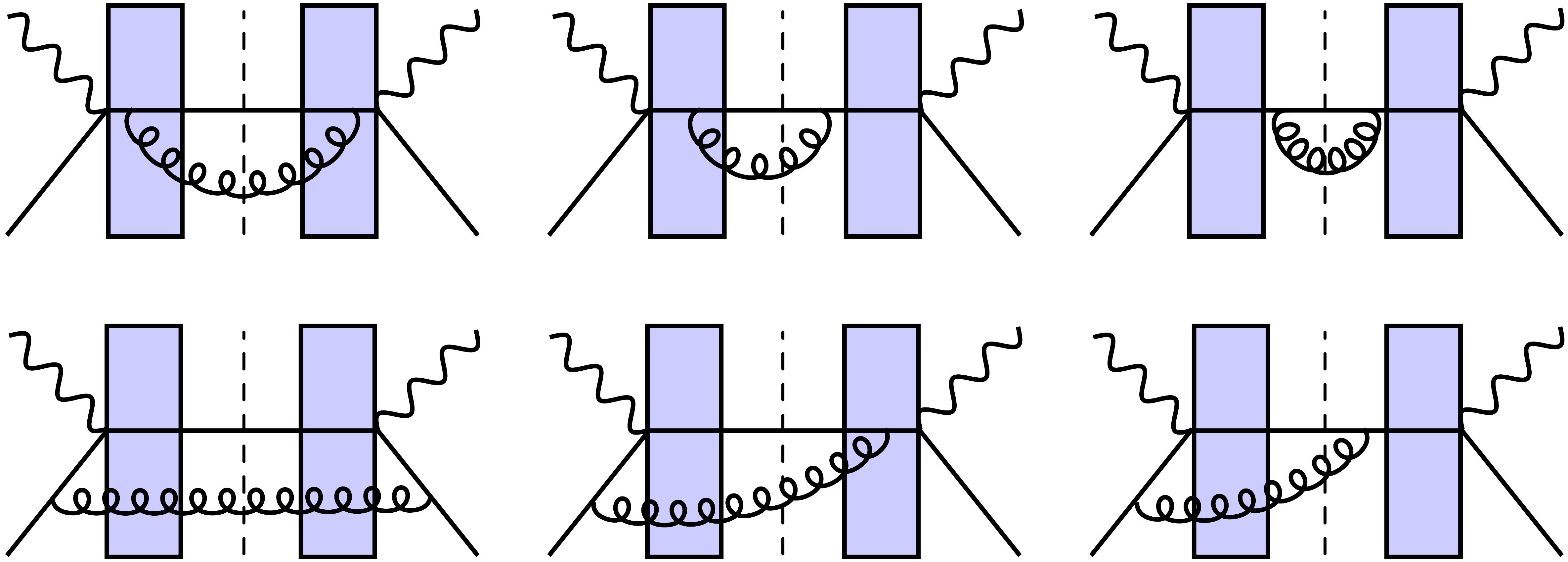


$$\lambda_{mfp} \gg m_D^{-1}$$

$$\mathcal{V}^2(\mathbf{q}) = \frac{m_D^2}{(2\pi)^2(\mathbf{q}^2 + m_D^2)^2}$$

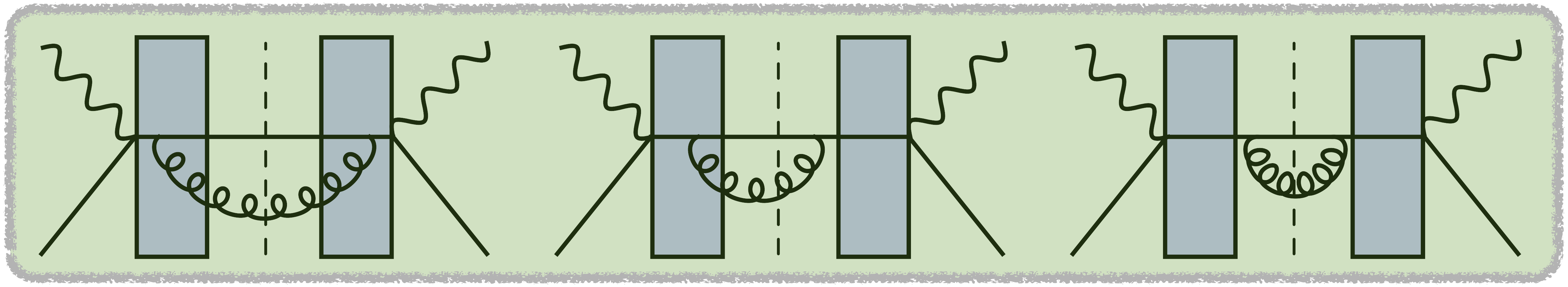
Gyulassy-Wang model: Nucl. Phys. B 420, (1994) 583

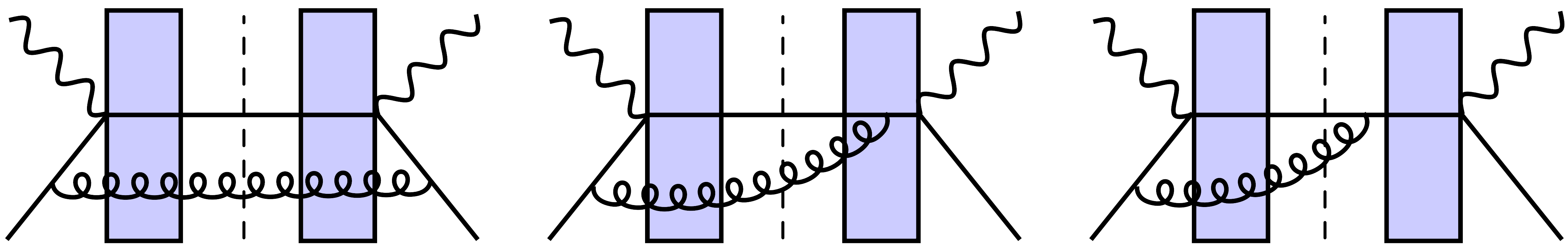
Gluon spectrum



Gluon spectrum

BDMPS-Z + vacuum





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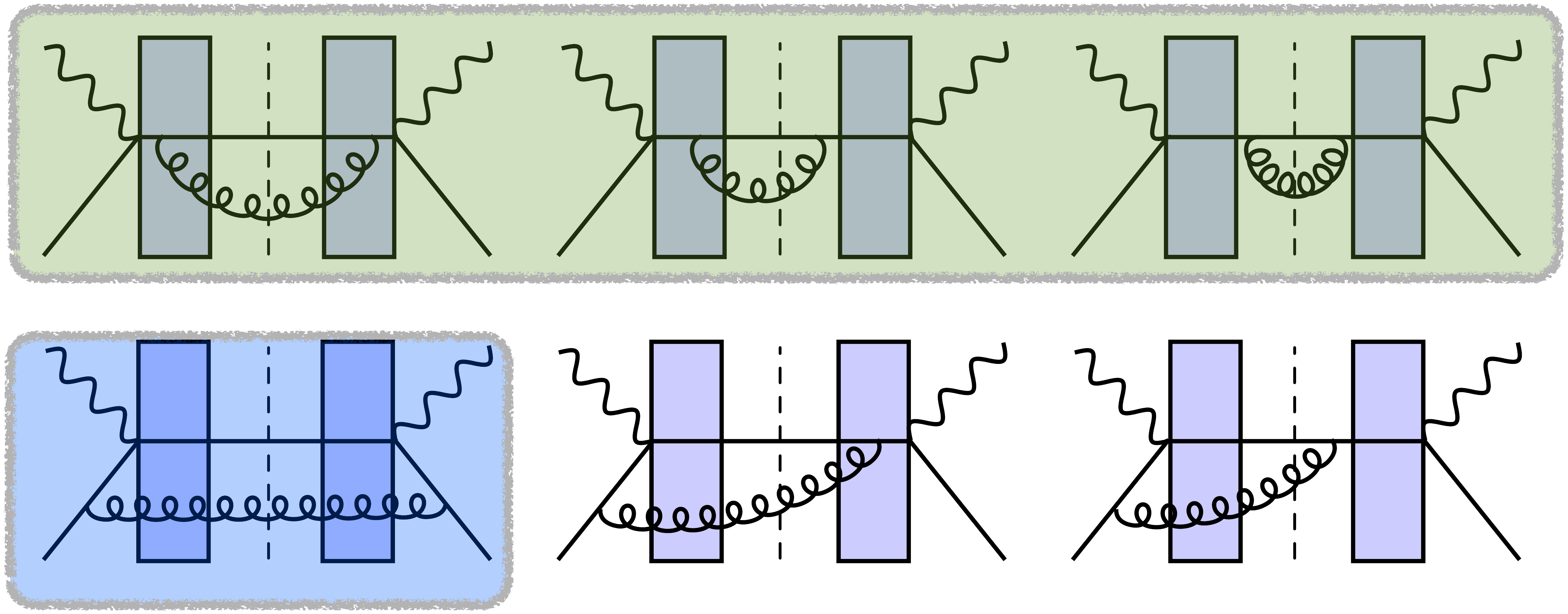
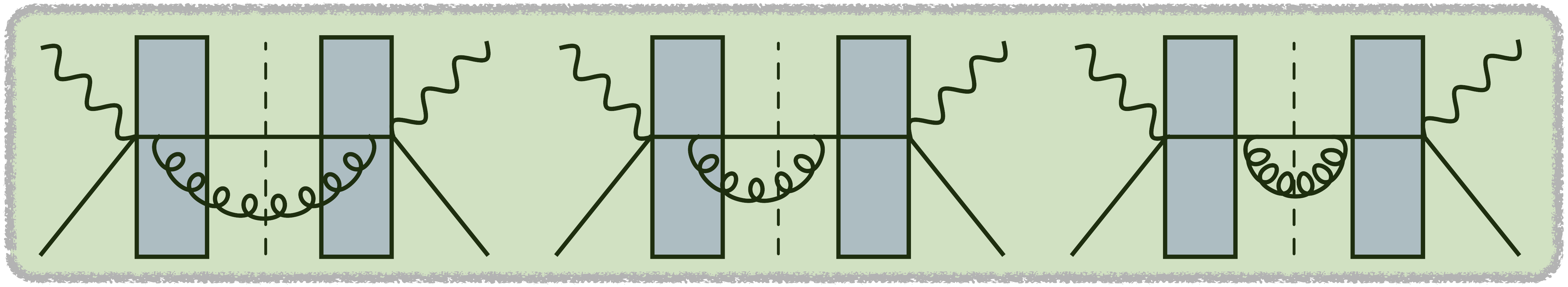
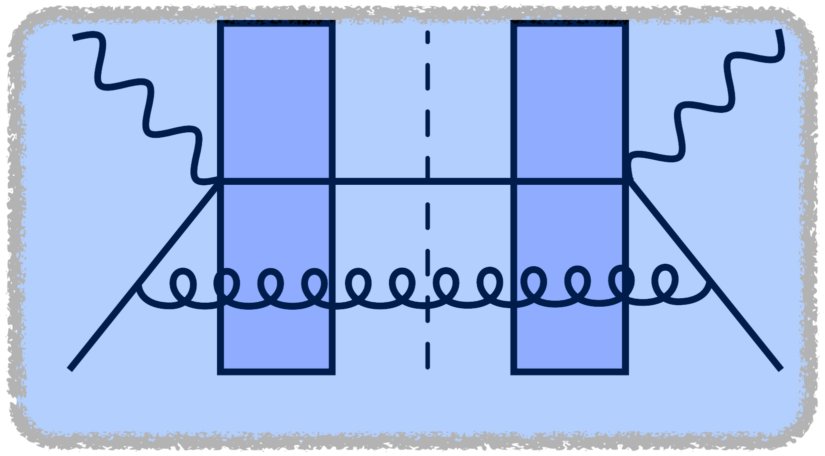


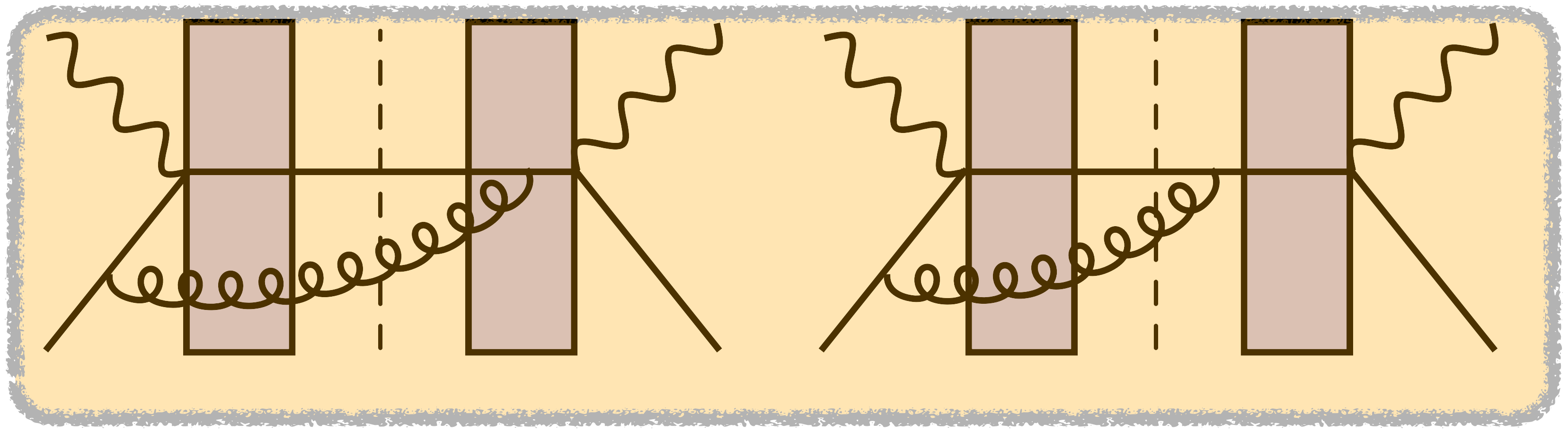
PT broadening of ISR

Gluon spectrum

BDMPS-Z + vacuum



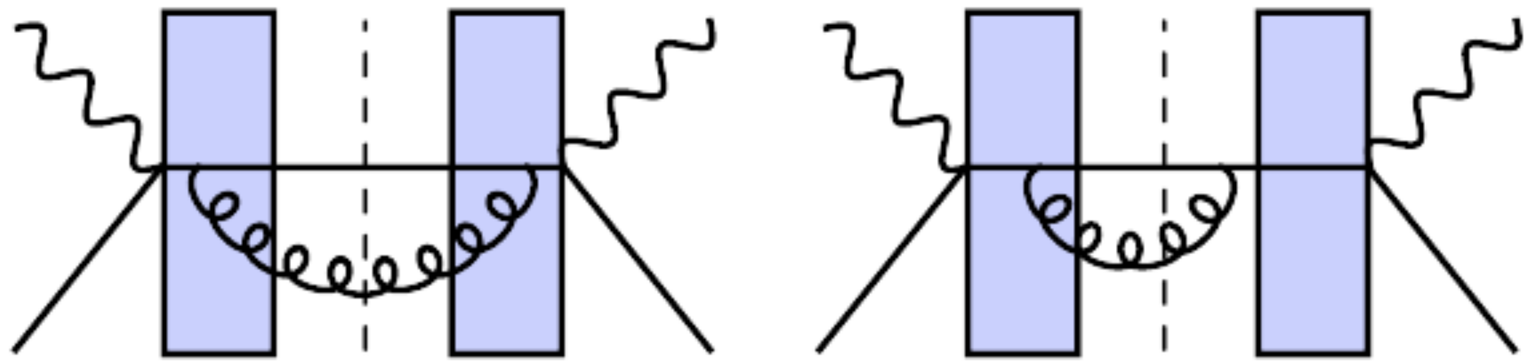




P_T broadening of ISR

Interferences in the medium: *New!!*

BDMPS-Z



$$k_f = \sqrt{\omega \hat{q}}$$

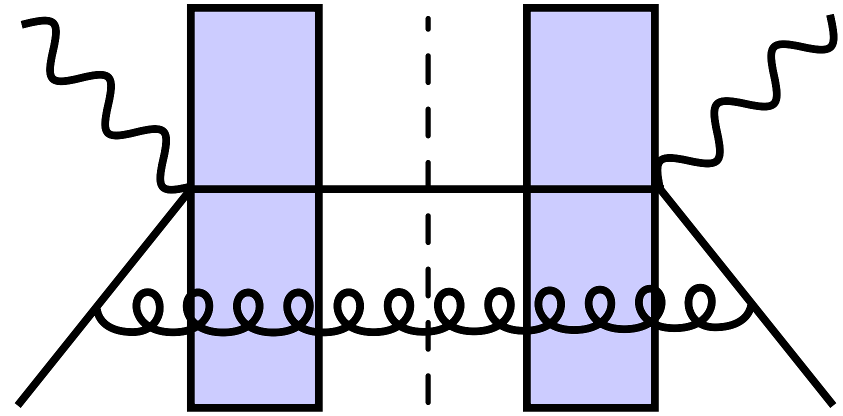
$$\sim \int_0^L dt' \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k}-\boldsymbol{k}', L-t') \sin\left(\frac{\boldsymbol{k}'^2}{2k_\mathrm{f}^2}\right) e^{-\frac{\boldsymbol{k}'^2}{2k_\mathrm{f}^2}}$$

$$\mathcal{P}(k,\xi) = \frac{4\pi}{\hat{q}\xi} e^{-\frac{k^2}{\hat{q}\xi}}$$

Medium induced radiation is a two step process

- Quantum emission + classical broadening
- Scales with the length of the medium

P_t broadening of ISR



$$\mathcal{P}(k,\xi) = \frac{4\pi}{\hat{q}\xi} e^{-\frac{k^2}{\hat{q}\xi}}$$

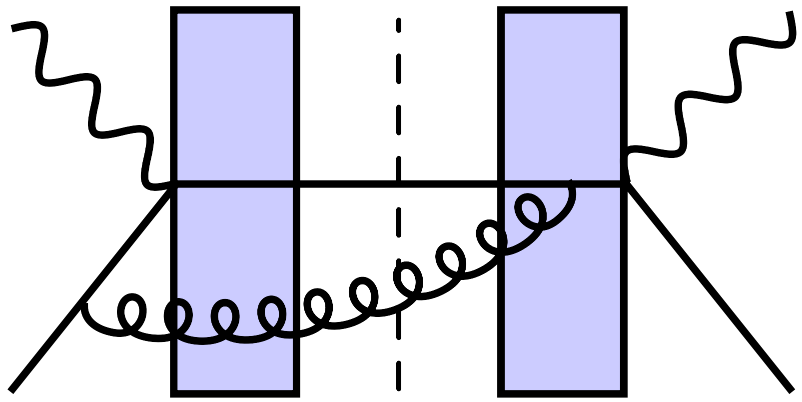
$$\sim \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \frac{\mathcal{P}(\boldsymbol{k}' - \bar{\boldsymbol{\kappa}}, L^+)}{\boldsymbol{k}'^2}$$

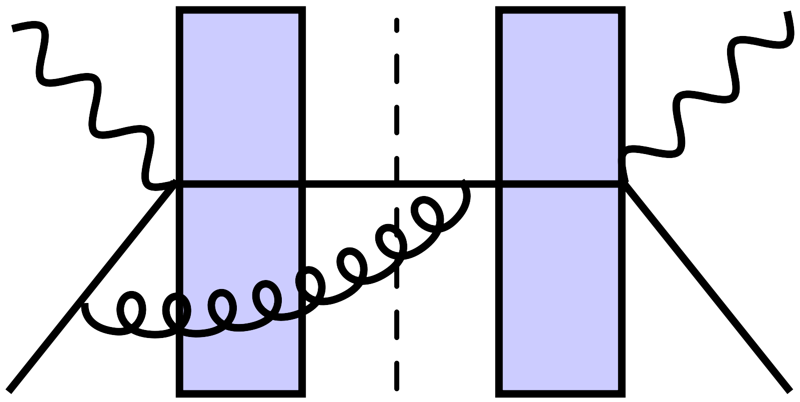
P_T broadening of ISR is a two step process:

- Collinear Emission + classical broadening
- Reshuffling of the momentum of the gluon emissions

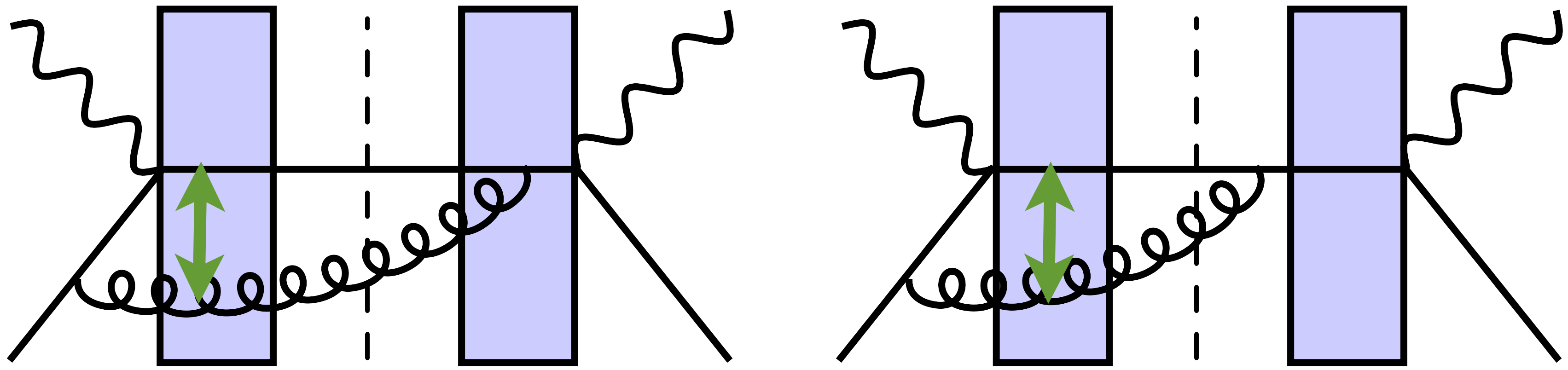
⇒ Typical value of the gluon momenta ~$Q_s = \hat{q}L$

Interferences





Interferences



Transverse size of the Quark-gluon system

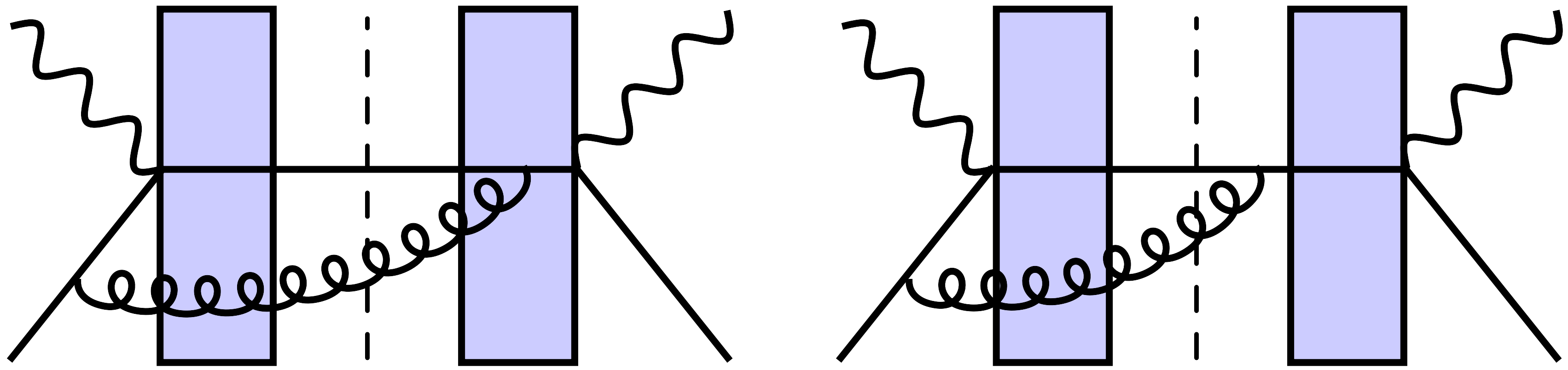
- If hard scattering is the largest scale:

⇒ Insensitive to the medium

- If typical medium induced momentum is the largest scale

⇒ Medium is able to resolve the qg system

Interferences



The Color correlation of the Quark-gluon system is measured by

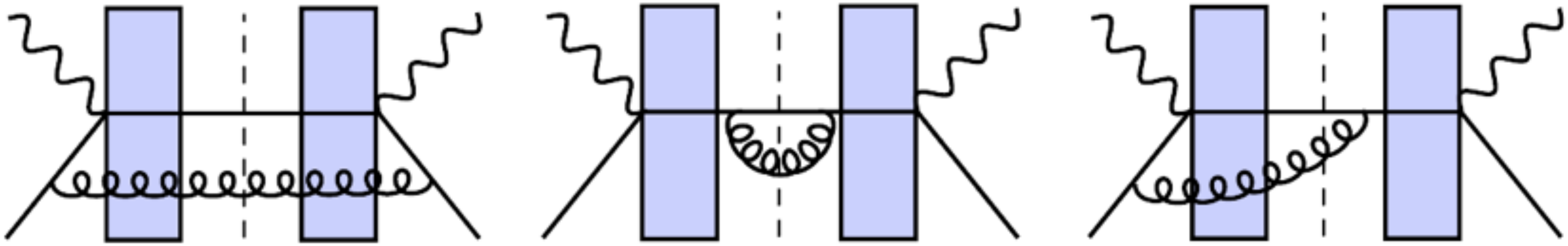
$$\mathcal{K}(x^+, \boldsymbol{x}; y^+, \boldsymbol{y}|k^+) = \int_{\boldsymbol{r}(y^+)=\boldsymbol{y}}^{\boldsymbol{r}(x^+)=\boldsymbol{x}} \mathcal{D}\boldsymbol{r}\, \exp\left[\int_{y^+}^{x^+} d\xi \left(i\frac{k^+}{2}\dot{\boldsymbol{r}}^2(\xi) - \frac{1}{2}n(\xi)\sigma\left(\boldsymbol{r}(\xi)\right)\right)\right]$$

- Describes the Brownian motion of the gluon
- Harmonic oscillator approximation: $n\sigma(\mathbf{r}) \approx \hat{q}\mathbf{r}^2$
- Two extreme limits

⇒ High Energy Limit (Shockwave) $\tau_f \gg L$

⇒"Infinite" medium length $\tau_f \ll L$

Gluon spectrum: High Energy limit



- Medium acts as a unique scattering center
- Interferences are suppressed if $\mathbf{k} < Q_s$
- Vacuum color coherence is reestablished for $\mathbf{k} > Q_s$

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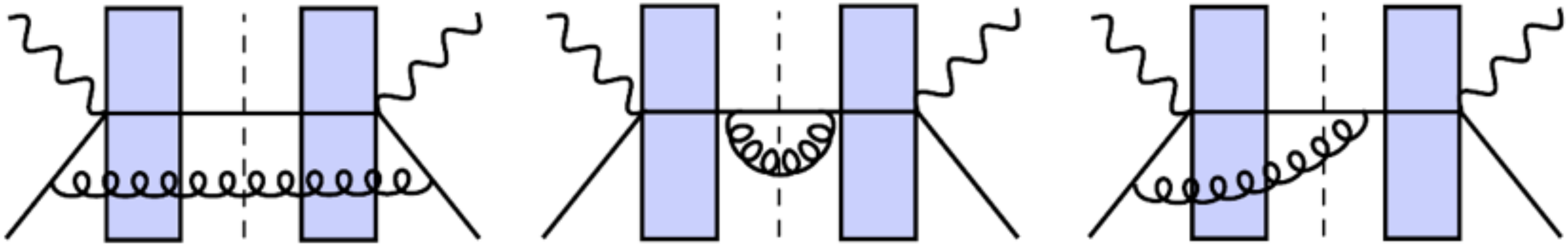
Gluon spectrum: High Energy limit



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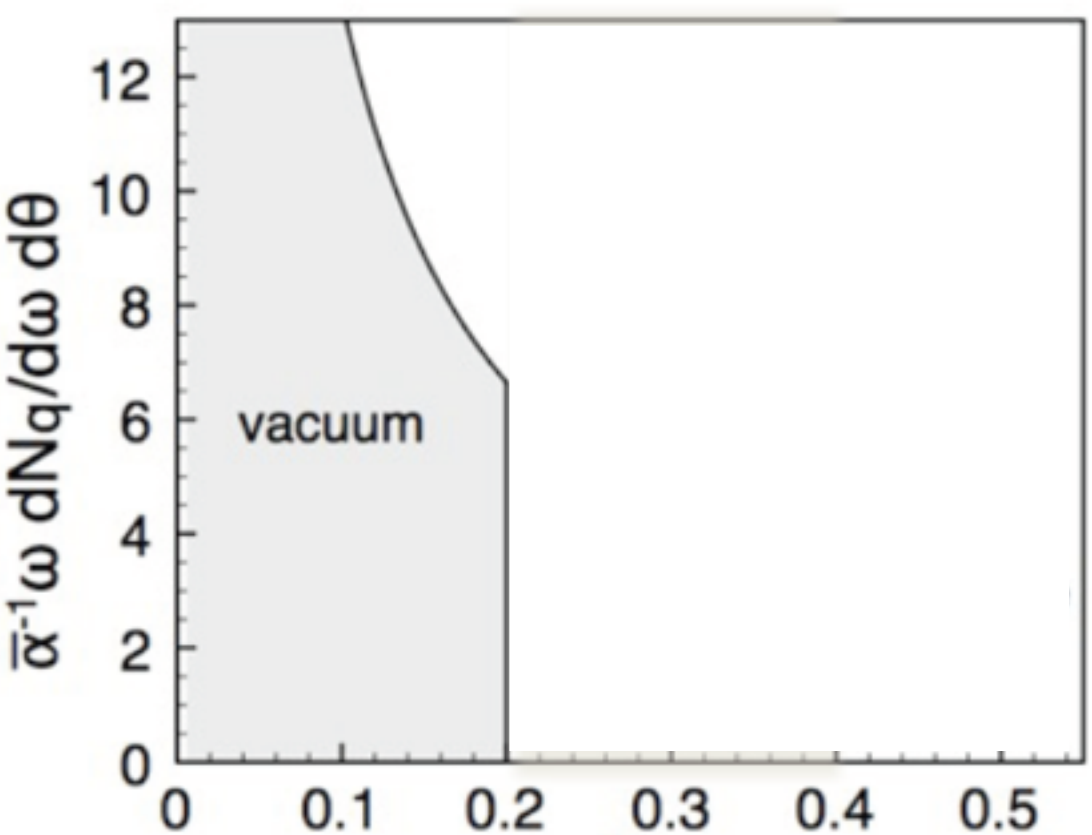

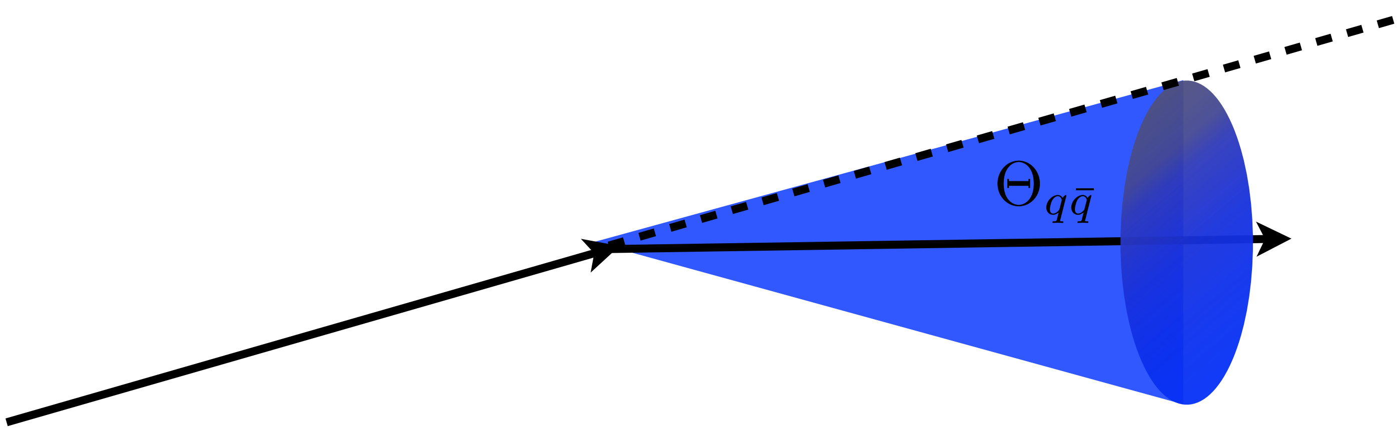

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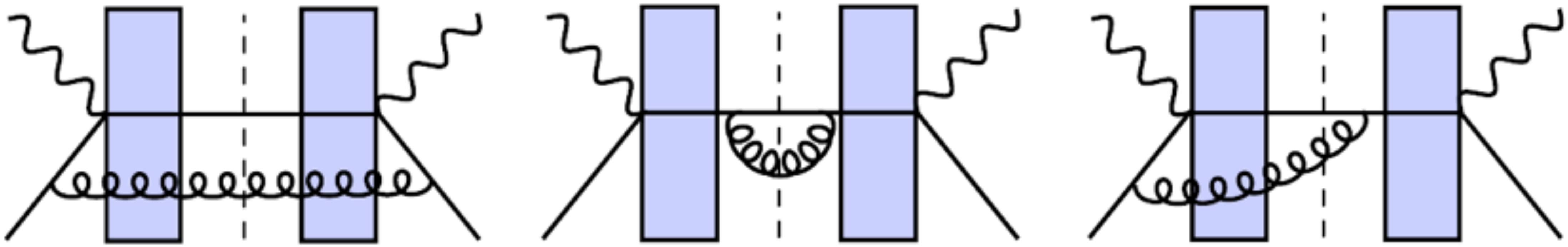

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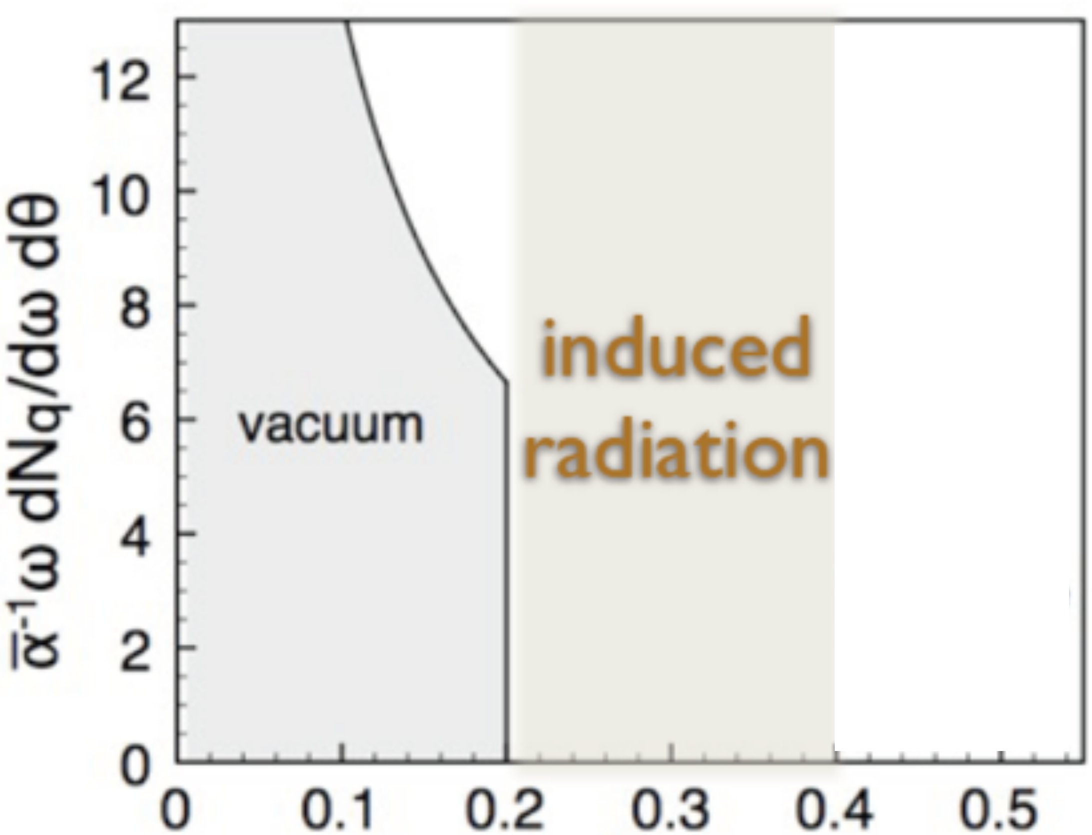

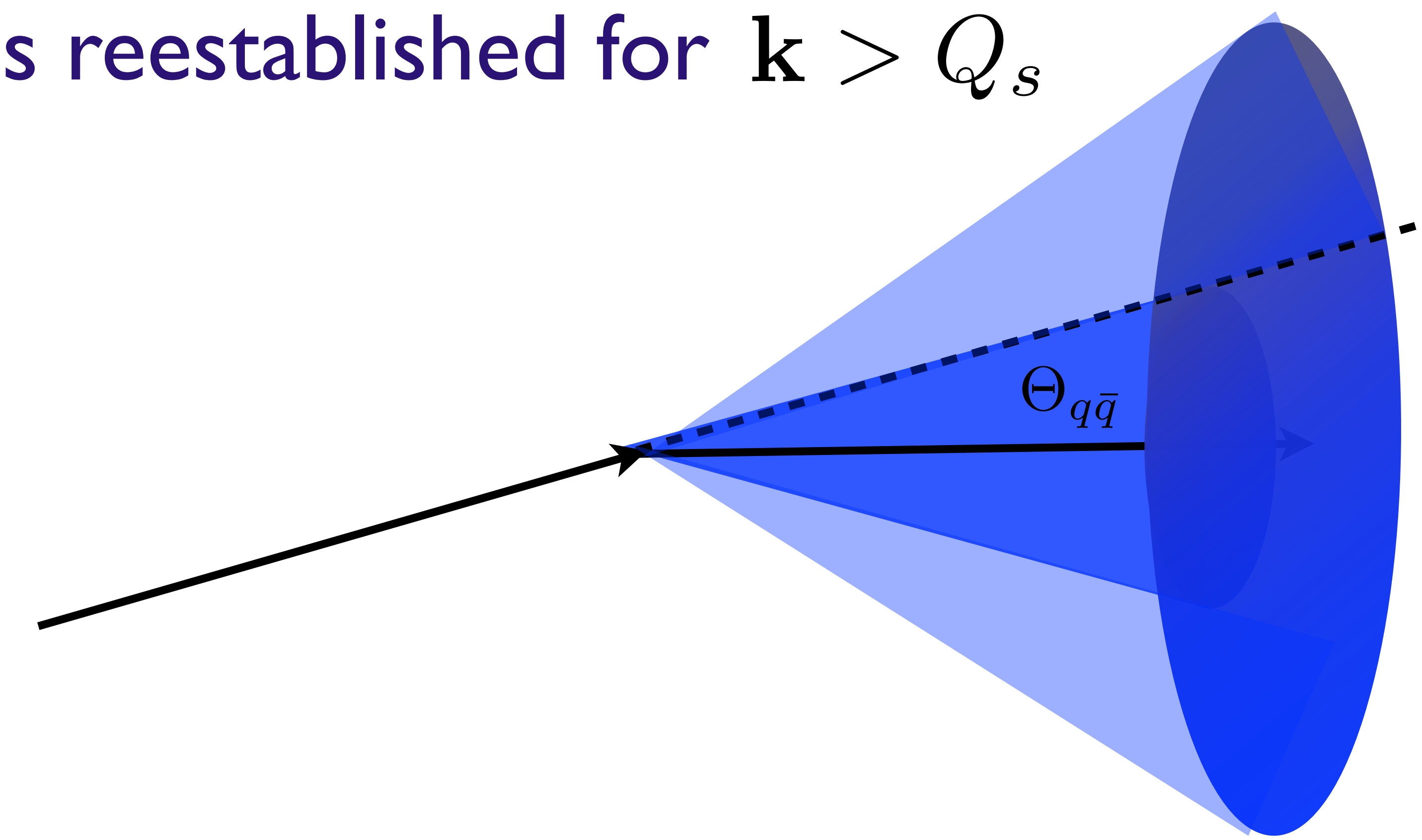

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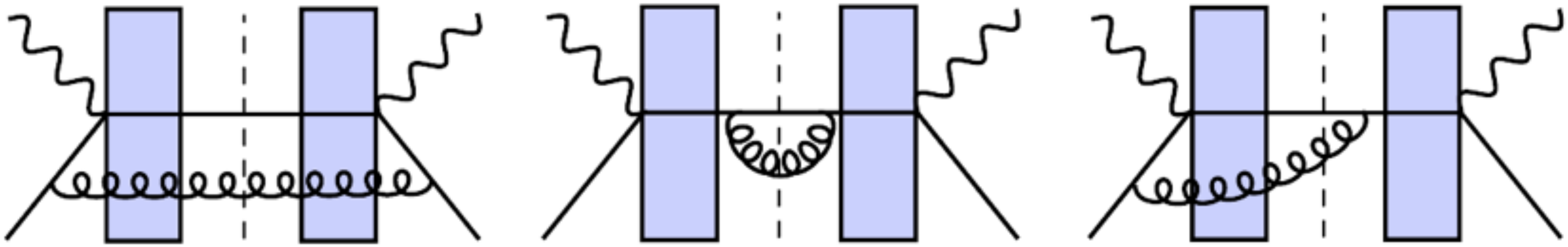

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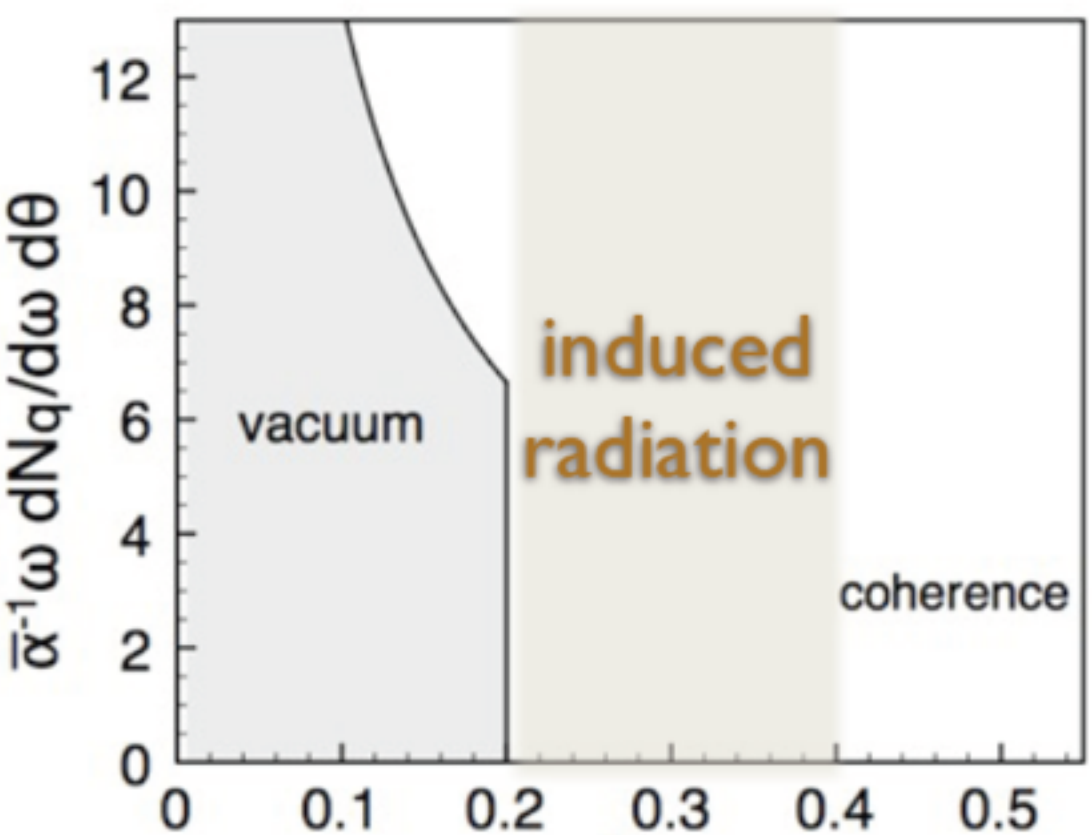
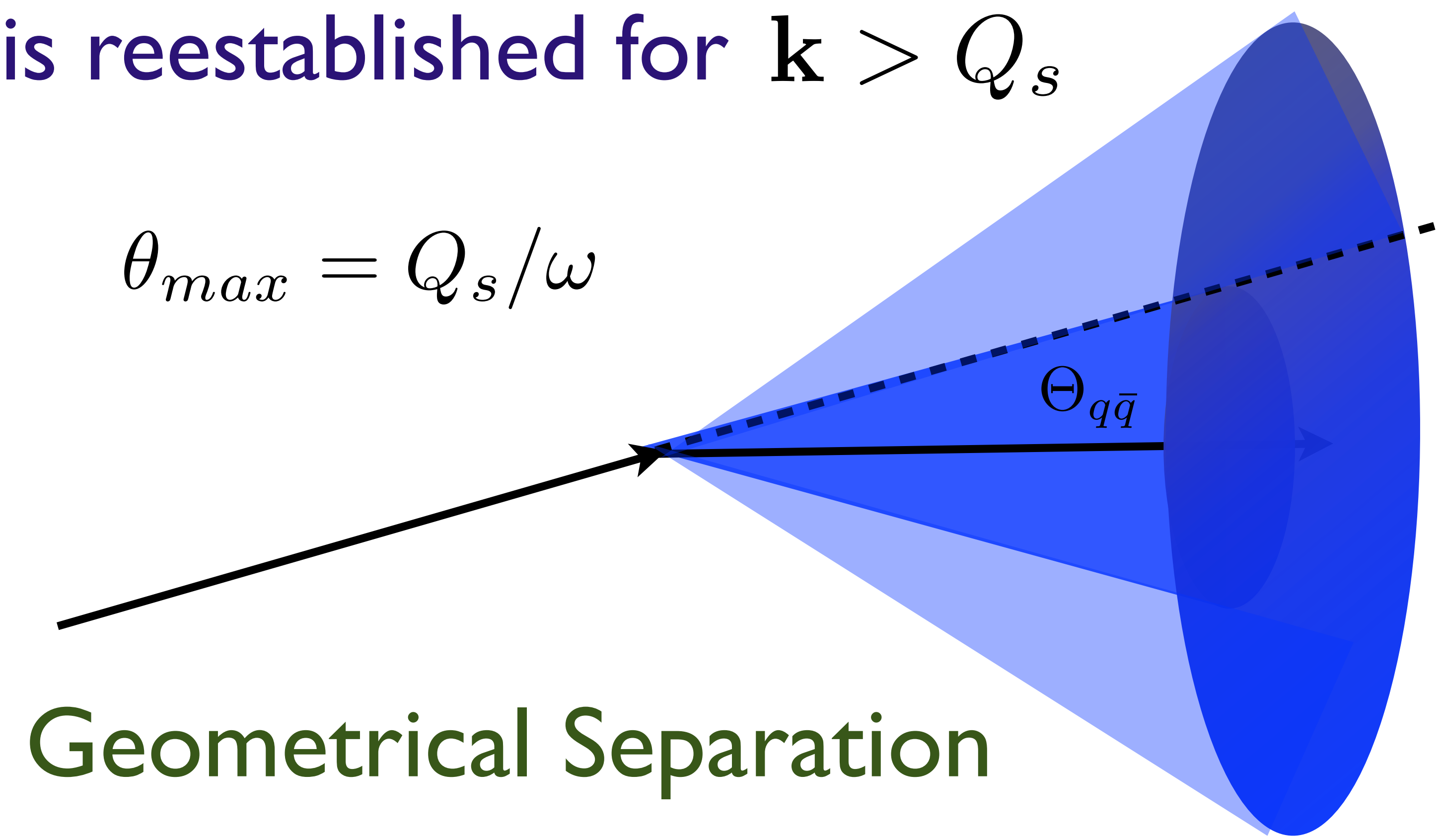
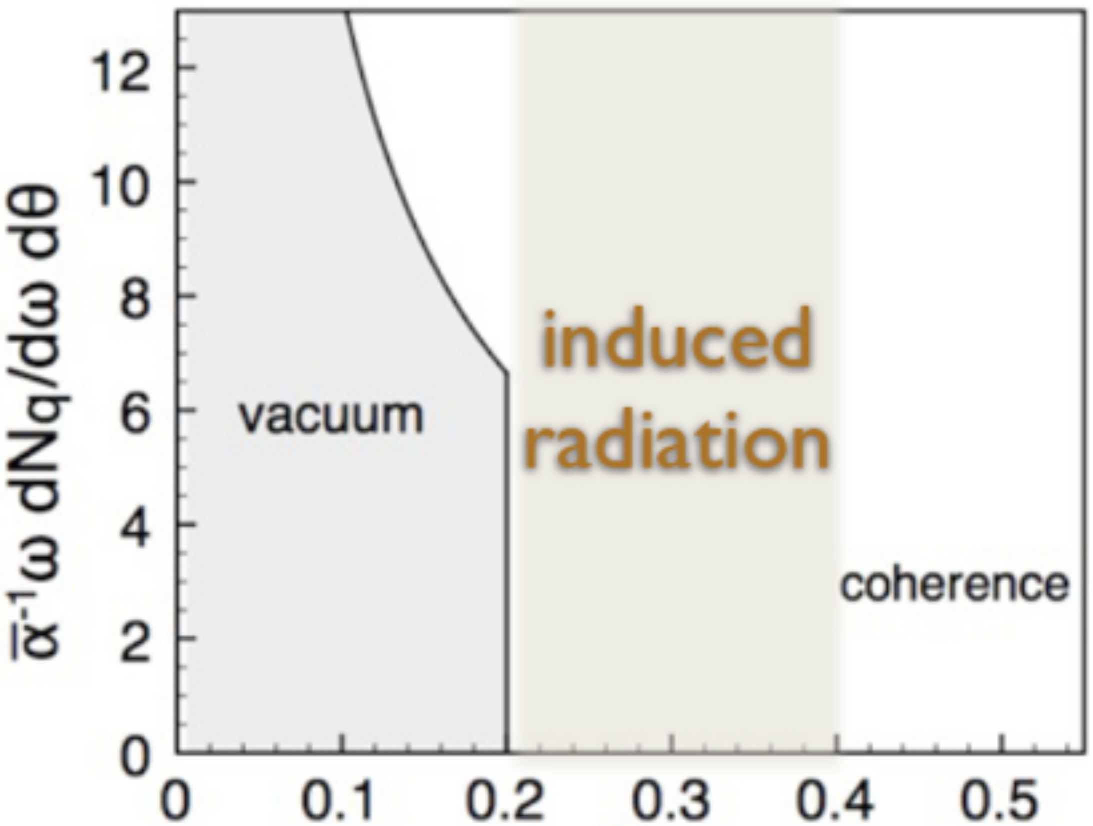
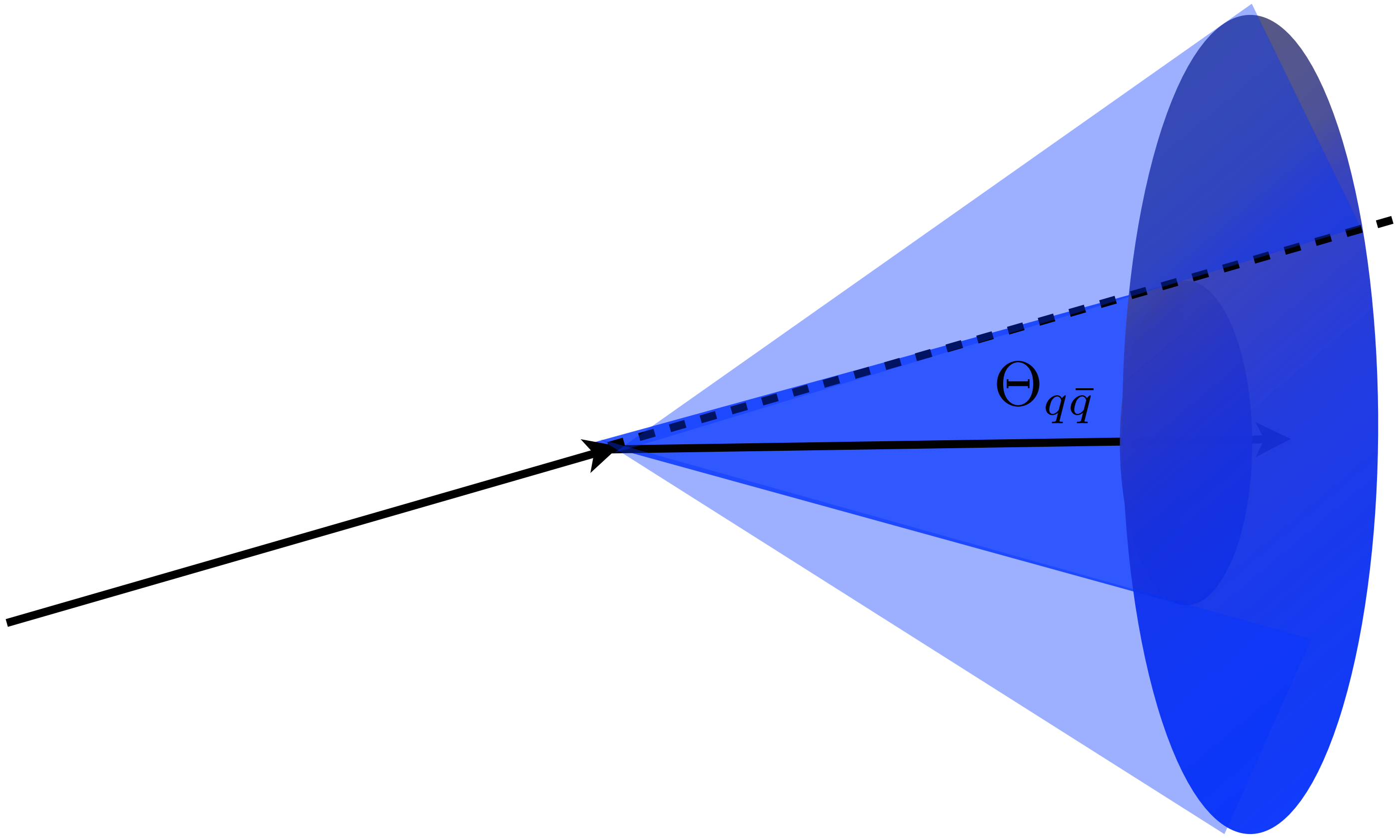




Gluon spectrum: "Infinite" medium limit





- Interferences play a role at early-times
- Gluon loses vacuum coherence

  ⇒ Open phase space at large angle emissions up to $\theta_{max} = Q_s/\omega$

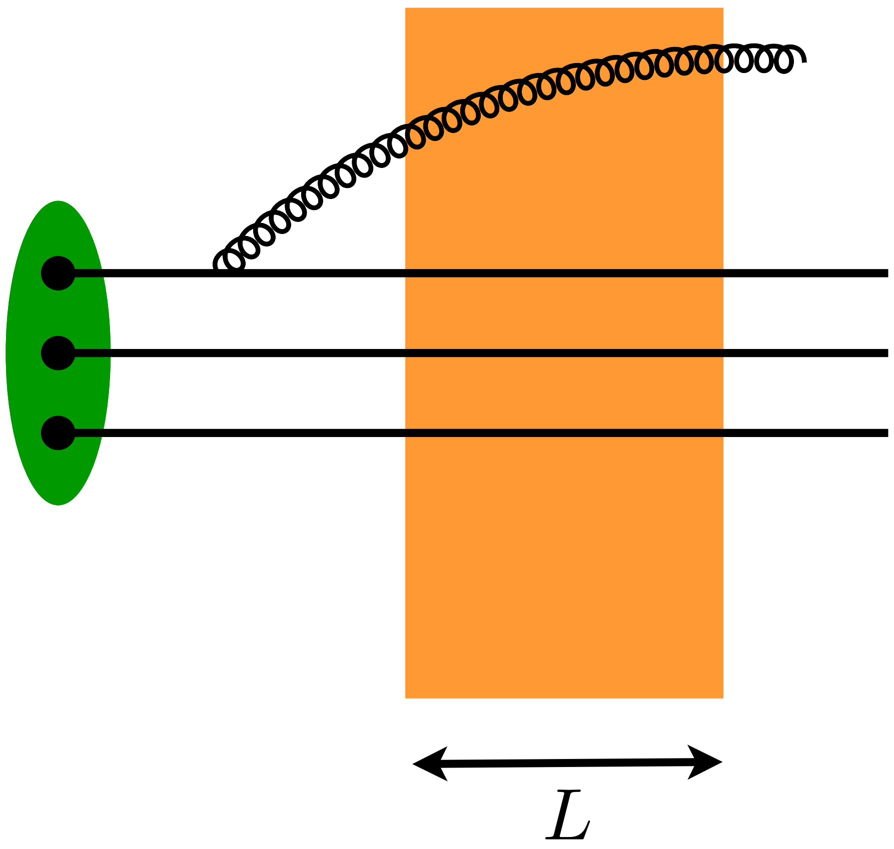
- Typical ``medium induced'' gluon momentum ~ $Q_s = \hat{q}L$

pA case

We want:

⇒ Include finite target size effects !!!!

⇒ Study color decoherence in pA !!!!



Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

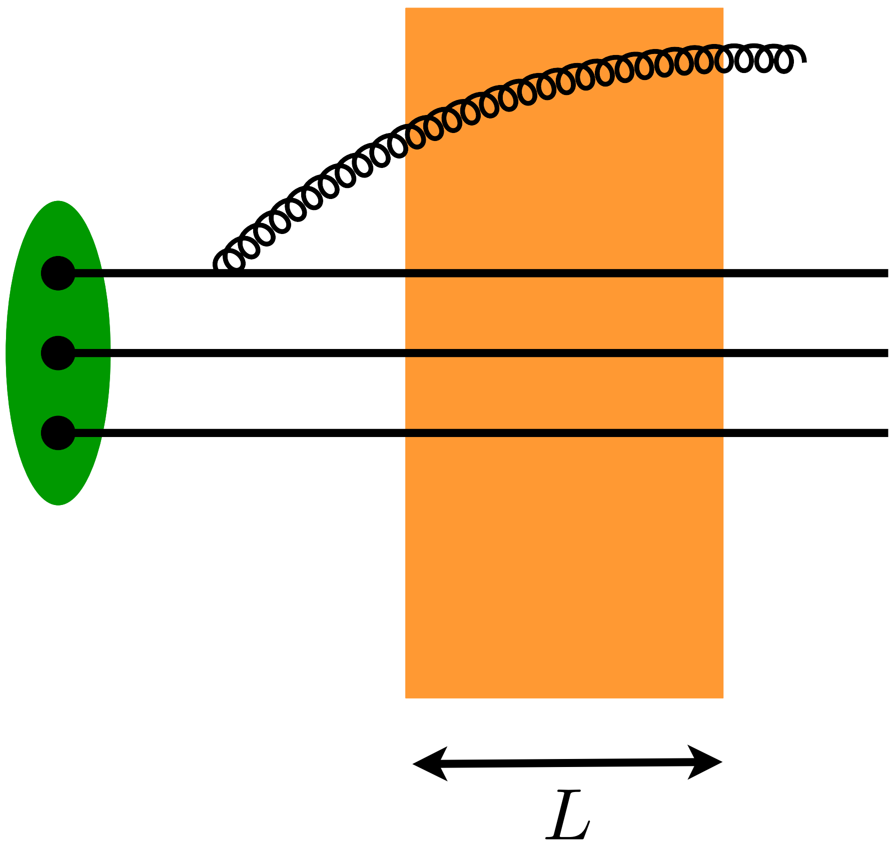
pA case

We want:

⇒ Include finite target size effects !!!!

⇒ Study color decoherence in pA !!!!

- Projectile described by QCD parton model



Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

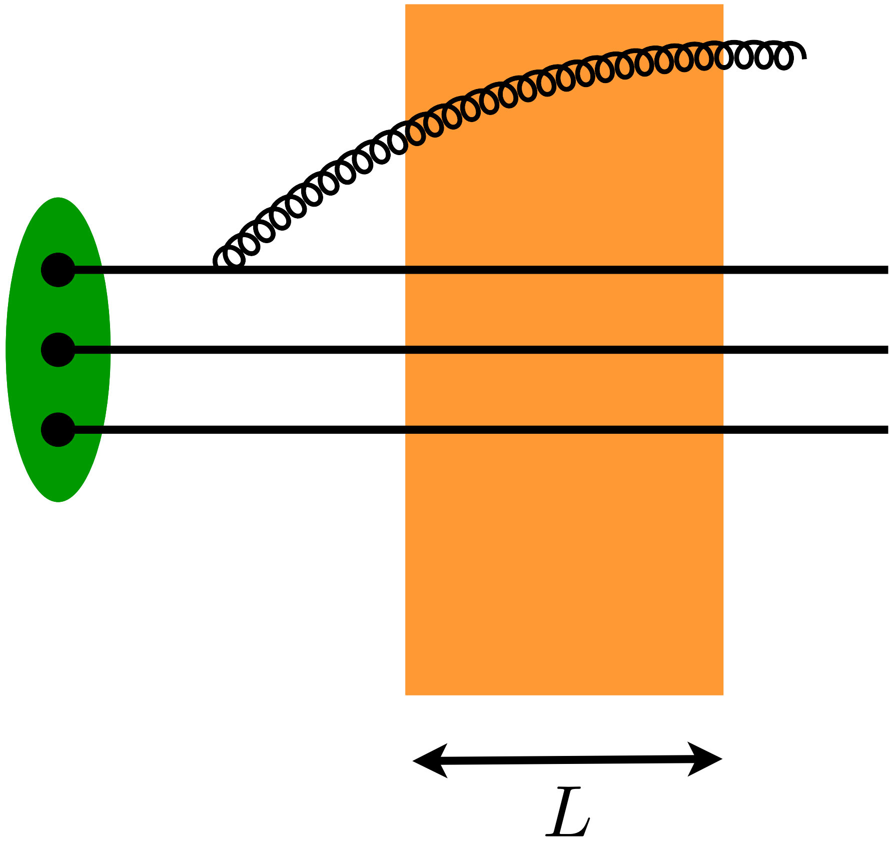
pA case

We want:

⇒ Include finite target size effects !!!!

⇒ Study color decoherence in pA !!!!

- Projectile described by QCD parton model
- Target described by a gaussian distr. of color charges.



Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

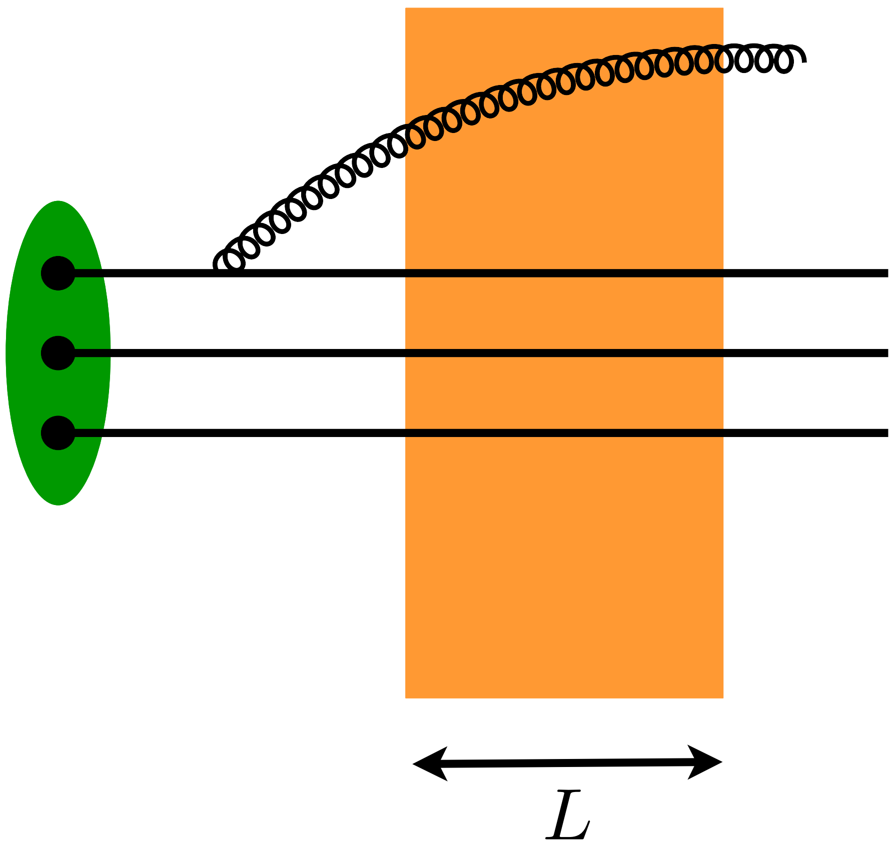
pA case

We want:

⇒ Include finite target size effects !!!!

⇒ Study color decoherence in pA !!!!

- Projectile described by QCD parton model
- Target described by a gaussian distr. of color charges.
- Emitted gluon follows a non-eikonal trajectory.



Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

pA case

Factorized formula:

Finite medium size corrections + Color decoherence effects

$$\omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{\boldsymbol{y},\boldsymbol{z},\bar{\boldsymbol{y}},\bar{\boldsymbol{z}},y^+,\bar{y}^+} e^{-i\boldsymbol{k}\cdot(\boldsymbol{z}-\bar{\boldsymbol{z}})} \frac{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})\cdot(\boldsymbol{z}-\boldsymbol{y})}{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

Probability to emit a soft gluon

$$\Big\{ \bar{\delta}_0 \int_{\bar{\boldsymbol{z}}'} e^{-i\boldsymbol{k}\cdot(\bar{\boldsymbol{z}}-\bar{\boldsymbol{z}}')} \mathcal{G}^\dagger(L^+,\bar{\boldsymbol{z}}';\bar{y}^+,\bar{\boldsymbol{z}})$$

$$-\mathcal{U}^\dagger(\bar{y}^+,0,\bar{\boldsymbol{y}}) \Big[\bar{\delta}_{L^+} - \frac{1}{ik^+} \int_{\bar{\boldsymbol{z}}'} e^{-i\boldsymbol{k}\cdot(\bar{\boldsymbol{z}}-\bar{\boldsymbol{z}}')} \tilde{\partial}^{\bar{z}} \mathcal{G}^\dagger(L^+,\bar{\boldsymbol{z}}';\bar{y}^+,\bar{\boldsymbol{z}}) \Big] \Big\}^{bd}$$

$$\Big\{ \delta_0 \int_{\boldsymbol{z}'} e^{i\boldsymbol{k}\cdot(\boldsymbol{z}-\boldsymbol{z}')} \mathcal{G}(L^+,\boldsymbol{z}';y^+,\boldsymbol{z})$$

Scattering probability of the partonic system

$$-\Big[\delta_{L^+} + \frac{1}{ik^+} \int_{\boldsymbol{z}'} e^{i\boldsymbol{k}\cdot(\boldsymbol{z}-\boldsymbol{z}')} \tilde{\partial}^{z} \mathcal{G}(L^+,\boldsymbol{z}';y^+,\boldsymbol{z}) \Big] \mathcal{U}(y^+,0,\boldsymbol{y}) \Big\}^{dc}$$

$$\langle \rho^b(\bar{\boldsymbol{y}})\rho^c(\boldsymbol{y}) \rangle$$

Projectile distribution

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

pA case

Factorized formula:

Finite medium size corrections + Color decoherence effects

$$\omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{\boldsymbol{y},\boldsymbol{z},\bar{\boldsymbol{y}},\bar{\boldsymbol{z}},y^+,\bar{y}^+} e^{-i\boldsymbol{k}\cdot(\boldsymbol{z}-\bar{\boldsymbol{z}})} \frac{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})\cdot(\boldsymbol{z}-\boldsymbol{y})}{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

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Non-eikonal corrections!!!

Scattering probability of the partonic system

$$\langle \rho^b(\bar{\boldsymbol{y}})\rho^c(\boldsymbol{y})\rangle$$

Projectile distribution

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

pA case

Factorized formula:

Finite medium size corrections + Color decoherence effects

$$\omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{\boldsymbol{y},\boldsymbol{z},\bar{\boldsymbol{y}},\bar{\boldsymbol{z}},y^+,\bar{y}^+} e^{-i\boldsymbol{k}\cdot(\boldsymbol{z}-\bar{\boldsymbol{z}})} \frac{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})\cdot(\boldsymbol{z}-\boldsymbol{y})}{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

Probability to emit a soft gluon

$$\Big\{ \bar{\delta}_0 \int_{\bar{\boldsymbol{z}}'} e^{-i\boldsymbol{k}\cdot(\bar{\boldsymbol{z}}-\bar{\boldsymbol{z}}')} \mathcal{G}^\dagger(L^+,\bar{\boldsymbol{z}}';\bar{y}^+,\bar{\boldsymbol{z}})$$
$$-\mathcal{U}^\dagger(\bar{y}^+,0,\bar{\boldsymbol{y}}) \Big[\bar{\delta}_{L^+} - \frac{1}{ik^+} \int_{\bar{\boldsymbol{z}}'} e^{-i\boldsymbol{k}\cdot(\bar{\boldsymbol{z}}-\bar{\boldsymbol{z}}')} \tilde{\partial}^{\bar{z}} \mathcal{G}^\dagger(L^+,\bar{\boldsymbol{z}}';\bar{y}^+,\bar{\boldsymbol{z}}) \Big] \Big\}^{bd}$$
$$\Big\{ \delta_0 \int_{\boldsymbol{z}'} e^{i\boldsymbol{k}\cdot(\boldsymbol{z}-\boldsymbol{z}')} \mathcal{G}(L^+,\boldsymbol{z}';y^+,\boldsymbol{z})$$
$$-\Big[\delta_{L^+} + \frac{1}{ik^+} \int_{\boldsymbol{z}'} e^{i\boldsymbol{k}\cdot(\boldsymbol{z}-\boldsymbol{z}')} \tilde{\partial}^{z} \mathcal{G}(L^+,\boldsymbol{z}';y^+,\boldsymbol{z}) \Big] \mathcal{U}(y^+,0,\boldsymbol{y}) \Big\}^{dc}$$

$$\langle \rho^b(\bar{\boldsymbol{y}}) \rho^c(\boldsymbol{y}) \rangle$$

Non-eikonal corrections!!!

Scattering probability of the partonic system

Finite length Corrections!!

Projectile distribution

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

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pA case

High Energy limit ⇒ k_T factorized formula

$$\omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{\boldsymbol{y},\boldsymbol{z},\bar{\boldsymbol{y}},\bar{\boldsymbol{z}}} e^{i\boldsymbol{k}\cdot(\bar{\boldsymbol{z}}-\boldsymbol{z})} \frac{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})\cdot(\boldsymbol{z}-\boldsymbol{y})}{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

$$\mathrm{Tr.}\left[\mathcal{U}^\dagger_{\bar{\boldsymbol{z}}}\mathcal{U}_{\boldsymbol{z}} + \mathcal{U}^\dagger_{\bar{\boldsymbol{y}}}\mathcal{U}_{\boldsymbol{y}} - \mathcal{U}^\dagger_{\bar{\boldsymbol{z}}}\mathcal{U}_{\boldsymbol{y}} - \mathcal{U}^\dagger_{\bar{\boldsymbol{y}}}\mathcal{U}_{\boldsymbol{z}}\right] \langle \rho^a(\bar{\boldsymbol{y}})\rho^a(\boldsymbol{y})\rangle$$

This equation leads to the Hybrid Formalism

See T. Altinoluk and A. Kovner; PRD83 (2011)105004

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

pA case

High Energy limit ⇒ k_T factorized formula

$$\omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{\boldsymbol{y},\boldsymbol{z},\bar{\boldsymbol{y}},\bar{\boldsymbol{z}}} e^{i\boldsymbol{k}\cdot(\bar{\boldsymbol{z}}-\boldsymbol{z})} \frac{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})\cdot(\boldsymbol{z}-\boldsymbol{y})}{(\bar{\boldsymbol{z}}-\bar{\boldsymbol{y}})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

$$\mathrm{Tr.}\left[\mathcal{U}^\dagger_{\bar{\boldsymbol{z}}}\mathcal{U}_{\boldsymbol{z}} + \mathcal{U}^\dagger_{\bar{\boldsymbol{y}}}\mathcal{U}_{\boldsymbol{y}} - \mathcal{U}^\dagger_{\bar{\boldsymbol{z}}}\mathcal{U}_{\boldsymbol{y}} - \mathcal{U}^\dagger_{\bar{\boldsymbol{y}}}\mathcal{U}_{\boldsymbol{z}}\right] \langle \rho^a(\bar{\boldsymbol{y}})\rho^a(\boldsymbol{y})\rangle$$

This equation leads to the Hybrid Formalism

See T. Altinoluk and A. Kovner; PRD83 (2011)105004

To do list (Keep tuned !!!!)

- Determine the dominant logarithmic behavior:
  ⇒ Identify the "medium" induced elastic and inelastic terms.
- Make contact and generalize hybrid formalism.

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)

Conclusions

- Interference pattern between the initial and final SR is indeed affected in the presence of a QCD medium.
- We observe a partial color decoherence between both emitters
  ⇒ Opening of phase space for large angle emissions
- We can generalize this setup for pA (work in progress)
  ⇒ phenomenological consequences at LHC (keep tuned!!!)

BACKUP SLIDES

Correlators

Quark-gluon dipole

$$\frac{1}{N_c^2-1}\langle \mathcal{G}(x^+,\mathbf{x};y^+,\mathbf{y})\mathcal{U}^\dagger(x^+,y^+)\rangle = \mathcal{K}(x^+,\mathbf{x};y^+,\mathbf{y}|k^+)$$

$$\mathcal{K}(x^+,\boldsymbol{x};y^+,\boldsymbol{y}|k^+) = \int_{\boldsymbol{r}(y^+)=\boldsymbol{y}}^{\boldsymbol{r}(x^+)=\boldsymbol{x}} \mathcal{D}\boldsymbol{r}\,\exp\left[\int_{y^+}^{x^+} d\xi \left(i\frac{k^+}{2}\dot{\boldsymbol{r}}^2(\xi) - \frac{1}{2}n(\xi)\sigma\left(\boldsymbol{r}(\xi)\right)\right)\right]$$

Gluon dipole

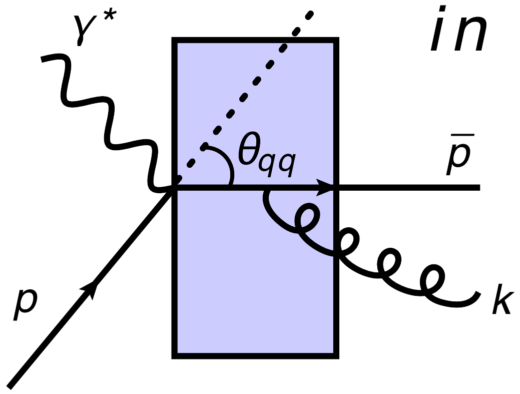
$$\int d\mathbf{x}\,d\mathbf{x}' e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}\frac{1}{N_c^2-1}\langle \mathcal{G}(x^+,\mathbf{x};y^+,\mathbf{y})\mathcal{G}^\dagger(x^+,y^+)\rangle = \mathcal{S}(x^+,y^+,\mathbf{x}-\mathbf{y})$$

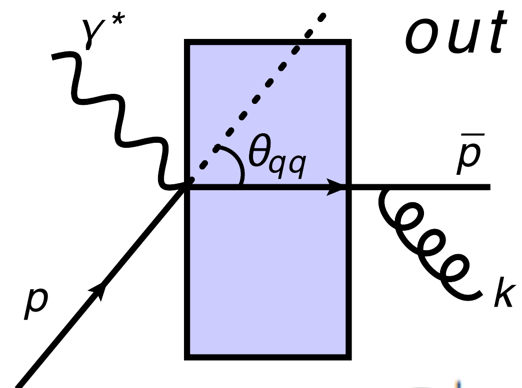
$$\mathcal{S}(x^+,y^+;\boldsymbol{x}-\boldsymbol{y}) = \exp\left[-\frac{1}{2}\int_{y^+}^{x^+} d\xi\, n(\xi)\,\sigma(\boldsymbol{x}-\boldsymbol{y})\right]$$

Dipole cross section

$$\sigma(\boldsymbol{r}) = \int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\mathcal{V}(\boldsymbol{q})\left[1-\cos(\boldsymbol{r}\cdot\boldsymbol{q})\right]$$

Scattering amplitude from CYM Eqs.





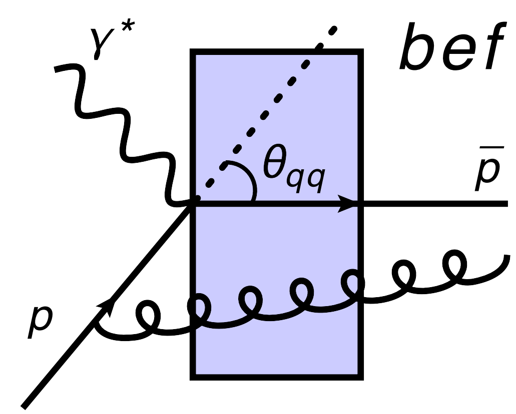
Outcoming parton

$$\mathcal{M}^a_{\lambda,in}(\vec{k}) = \frac{g}{k^+}\int d^2\boldsymbol{x} e^{i(k^- L^+ - \boldsymbol{k}\cdot\boldsymbol{x})}\int_0^{L^+} dy^+ e^{ik^+\bar{u}^- y^+}$$
$$\times\ \boldsymbol{\epsilon}_\lambda\cdot(i\boldsymbol{\partial}_y + k^+\bar{\boldsymbol{u}})\mathcal{G}_{ab}(L^+,\boldsymbol{x},y^+,\boldsymbol{y}=\bar{\boldsymbol{u}}y^+|k^+)\,\mathcal{U}_{bc}(y^+,0)Q^{out}_c$$

$$\mathcal{M}^a_{\lambda,out}(\vec{k}) = -2i\frac{\boldsymbol{\epsilon}_\lambda\cdot\bar{\boldsymbol{\kappa}}}{\bar{\boldsymbol{\kappa}}^2}\, e^{i(k\cdot\bar{u})L^+}\,\mathcal{U}_{ab}(L^+,0)Q^{out}_b\ ,$$

Incoming parton

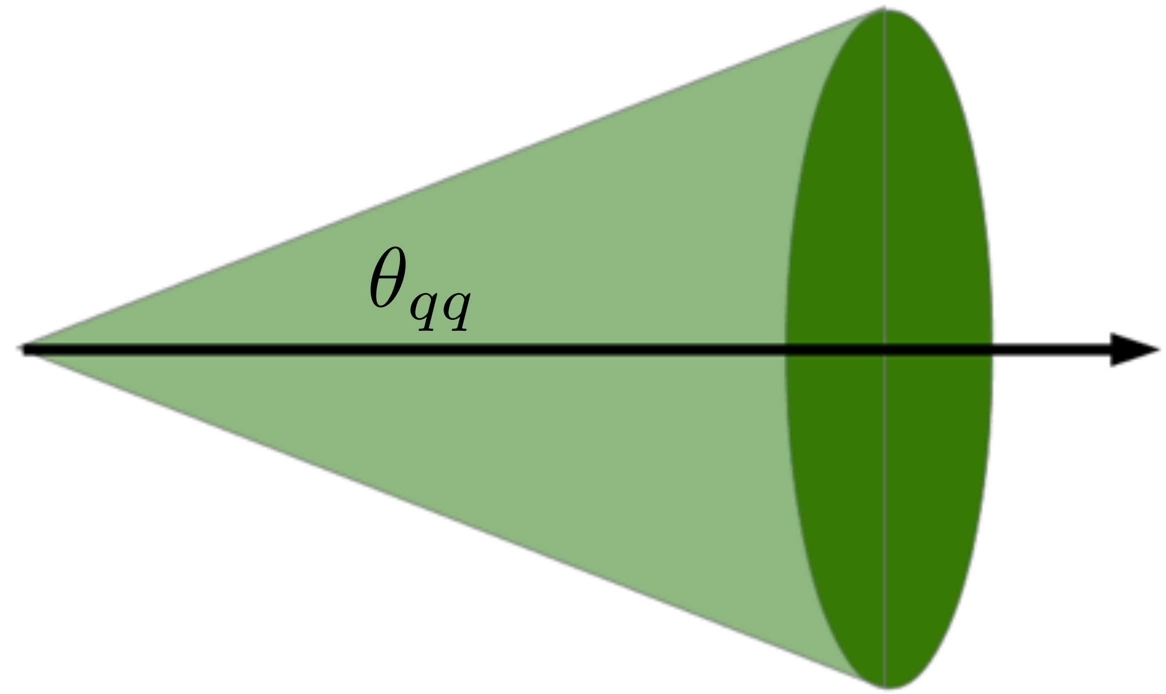
$$\mathcal{M}^a_{\lambda,bef}(\vec{k}) = \frac{g}{k^+}\int_{x^+=\infty} d^2\boldsymbol{x}\, e^{i(k^- x^+ - \boldsymbol{k}\cdot\boldsymbol{x})}\int_{-\infty}^{0} dy^+ e^{ik^+ u^- y^+}$$
$$\times\ \boldsymbol{\epsilon}_\lambda\cdot(i\boldsymbol{\partial}_y + k^+\boldsymbol{u})\mathcal{G}_{ab}(x^+,\boldsymbol{x},y^+,\boldsymbol{y}=\boldsymbol{u}y^+|k^+)\, Q^{in}_b$$



Leading logs and AO

$$\kappa^{\mathbf{2}} < \delta\mathbf{k}^{\mathbf{2}} \qquad \delta\mathbf{k}^{\mathbf{2}} \equiv \mathbf{Q}^{\mathbf{2}}$$

$$\omega \frac{dN}{d\omega d\kappa^2} = \frac{1}{\kappa^{\mathbf{2}}} \qquad \text{(DGLAP)}$$

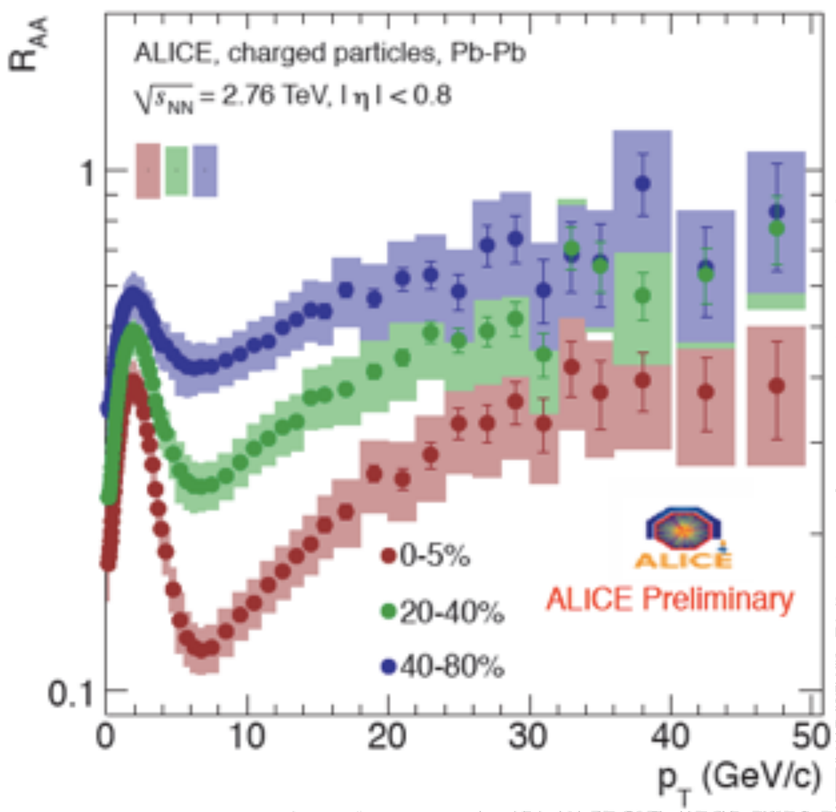


$$\omega \frac{dN}{d\omega} = \int_{Q_0^2}^{\delta\mathbf{k}^{\mathbf{2}}} \frac{d\kappa^{\mathbf{2}}}{\kappa^{\mathbf{2}}} = \log\left(\frac{\delta\mathbf{k}^{\mathbf{2}}}{Q_0^2}\right) \sim \log\left(\frac{Q^2}{Q_0^2}\right) \qquad \text{L. L.}$$

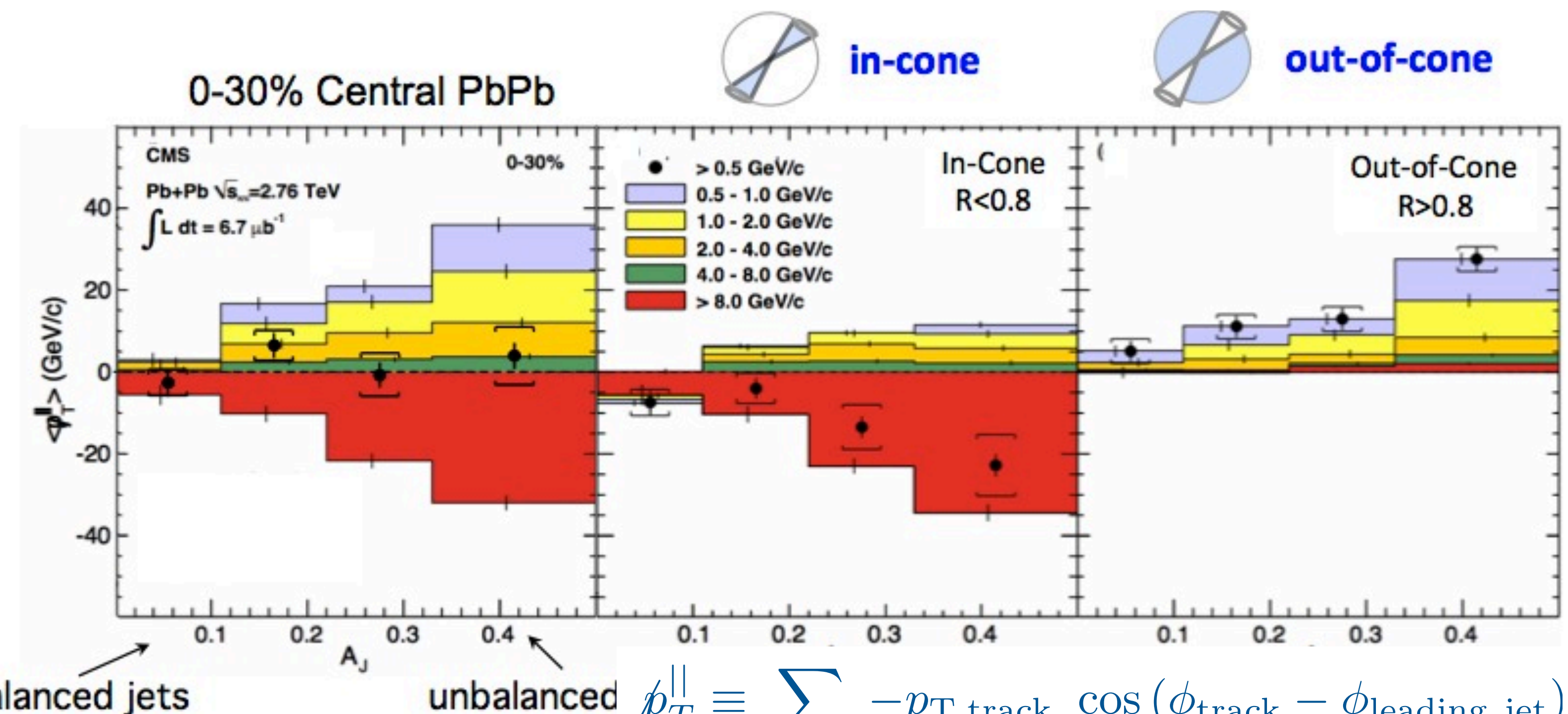
$$N \propto \int_{Q_0^2}^{Q^2} \omega \frac{dN}{d\omega} = \frac{1}{2}\left[\log\left(\frac{Q^2}{Q_0^2}\right)\right]^2 \qquad \text{D. L. L.}$$

Jets in HIC @ LHC

(i) Suppression of high-p_T hadrons



(ii) Soft large angle emissions



$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

$$\Delta\phi > \pi/2$$

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

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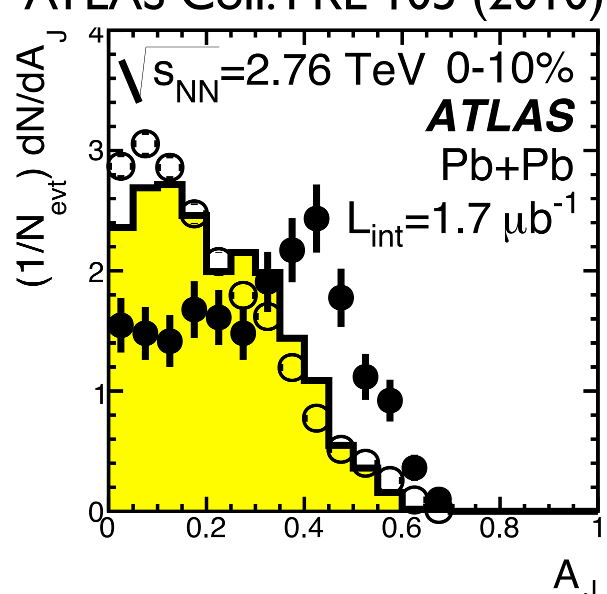
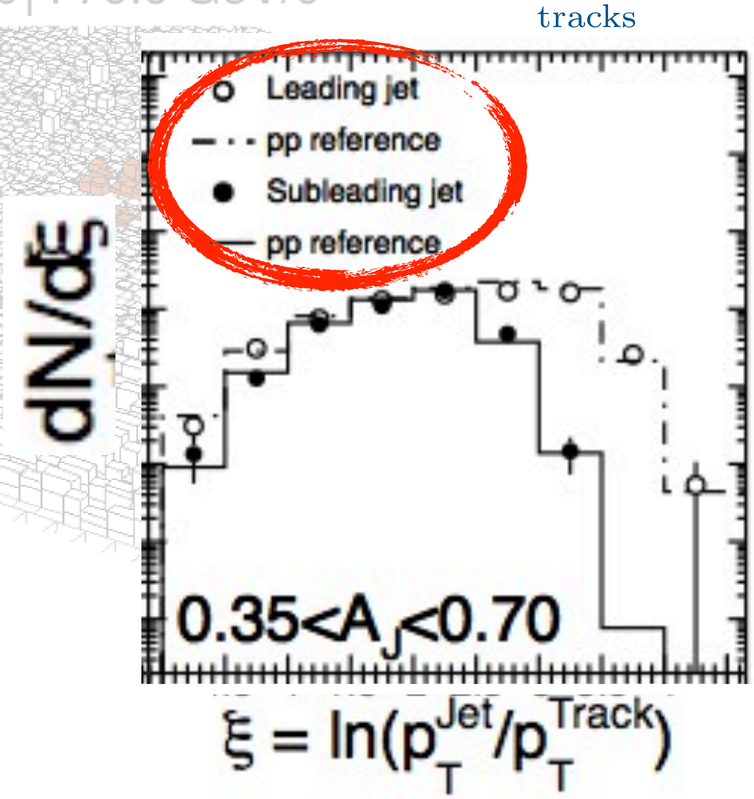


(iii) Significant dijet asymmetry



(iv) Vacuum-like fragmentation function