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Coherence effects between initial and final state radiation in a dense QCD medium

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with H. Ma, M. Martínez, Y. Mehtar-Tani and C.A. Salgado,
arXiv:1308.2186;
with T. Altinoluk, G. Beuf, M. Martínez and C.A. Salgado,
work in progress

Contents:

1. Introduction.

2. Coherence effects between initial and final state radiation:
   - Setup and semiclassical method.
   - Results.

(with H. Ma, M. Martínez, Y. Mehtar-Tani and C. A. Salgado, arXiv:1308.2186)

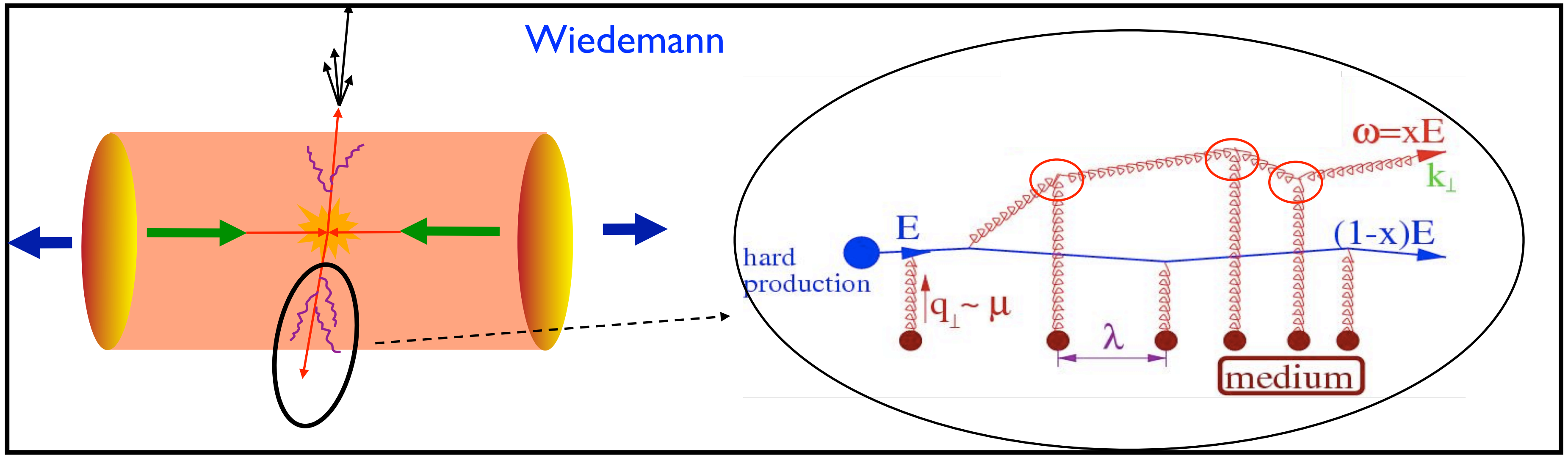
3. Particle production in pA and k_T factorisation:
   - Totally coherent case.
   - Non-eikonal corrections.

(with T. Altinoluk, G. Beuf, M. Martínez and C. A. Salgado, work in progress)

4. Summary.

Radiative eloss:

- 'Classical' radiative eloss models (BDMPS-Z (ASW), GLV, AMY, HT) based on this picture:



Limitations:

- Extracted qhat depends on medium model ⇒ interface with realistic medium.
- High-energy approximation: only soft emissions, energy-momentum conservation imposed a posteriori (only softest particle undergoes Brownian motion, no recoil of scattering centers).
- Multiple gluon emission: Quenching Weights, independent (Poissonian) gluon emissions assumed.
- No role of virtuality in medium emissions; medium and vacuum treated differently (ordering variables for the shower?).

Recent theory developments:

- Relaxing the high-energy approximation by allowing Brownian motion of all partons and some recoil: in the BDMPS-Z approach (Apolinario, NA, Salgado '12; Blaizot, Dominguez, Iancu, Mehtar-Tani '12), in SCET (Ovanesyan, Vitev '11; D'Eramo, Lekaveckas, Liu, Rajagopal, '10-).

- Monte Carlo models: PYQUEN, Q-PYTHIA, BAMPS, YaJem(s), JEWEL(s), CUJET,...

- Coherence between emitters: in the BDMPS-Z approach (Mehtar-Tani, Salgado, Tywoniuk, '10-; Casalderrey, Iancu '12).

- Multiple emissions in a medium: in the BDMPS-Z approach (Blaizot, Dominguez, Iancu, Mehtar-Tani '12), in SCET (Fickinger, Ovanesyan, Vitev '13).

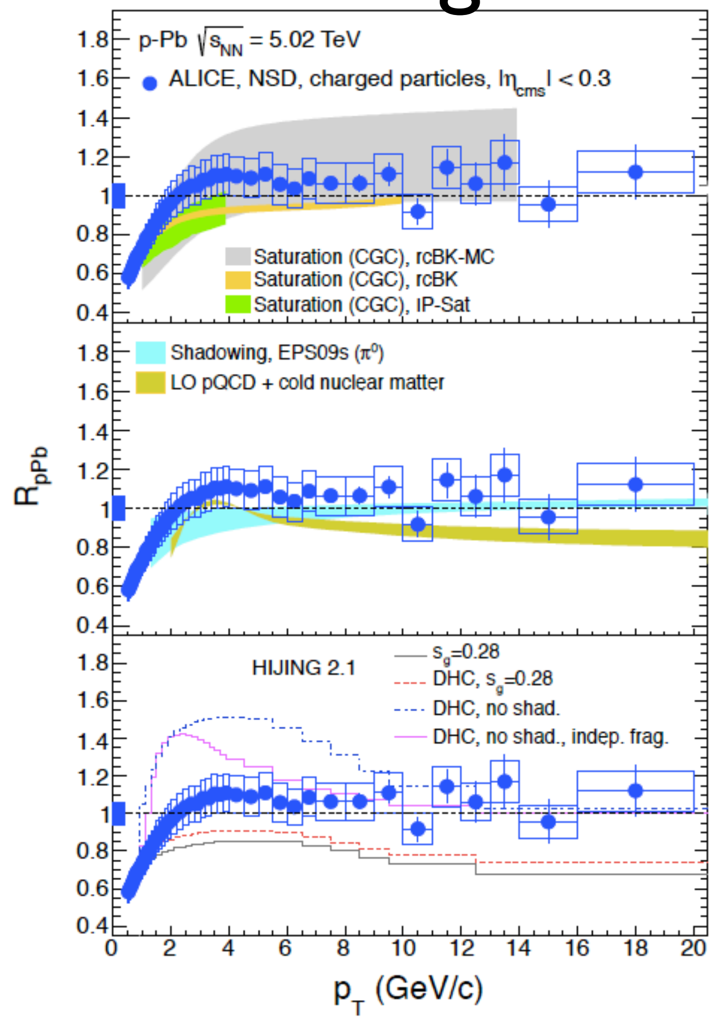
- qhat: lattice (Majumder '12, Panero et al '13), EFT (Benzke et al '13).

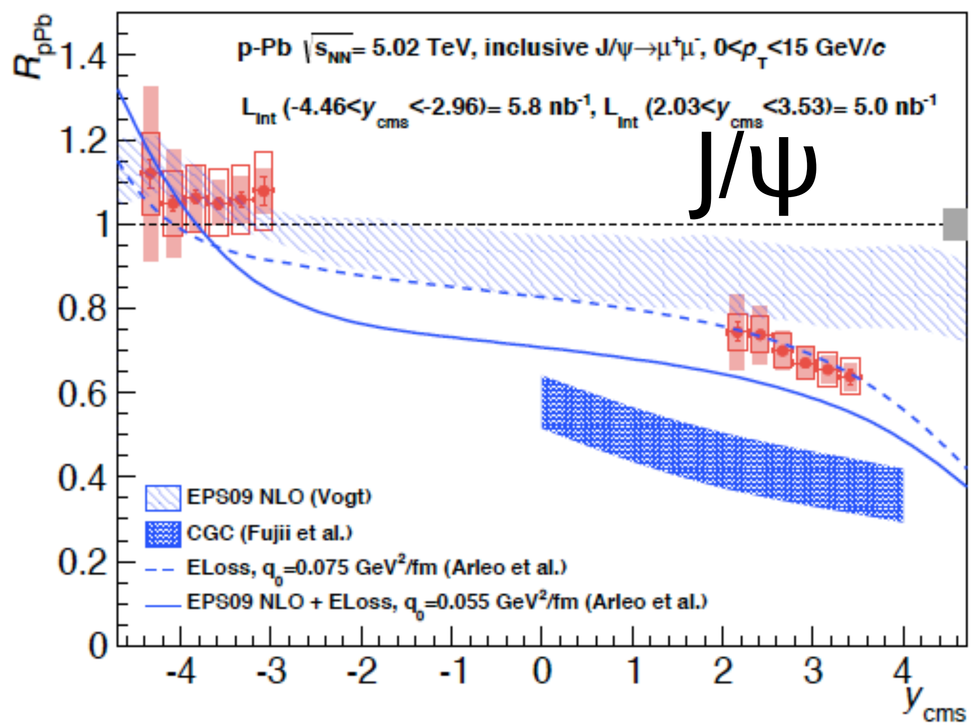
- Strong coupling (AdS/CFT): in the BDMPS-Z approach (Kharzeev, '08-; Chesler, Ho, Rajagopal '12;...).

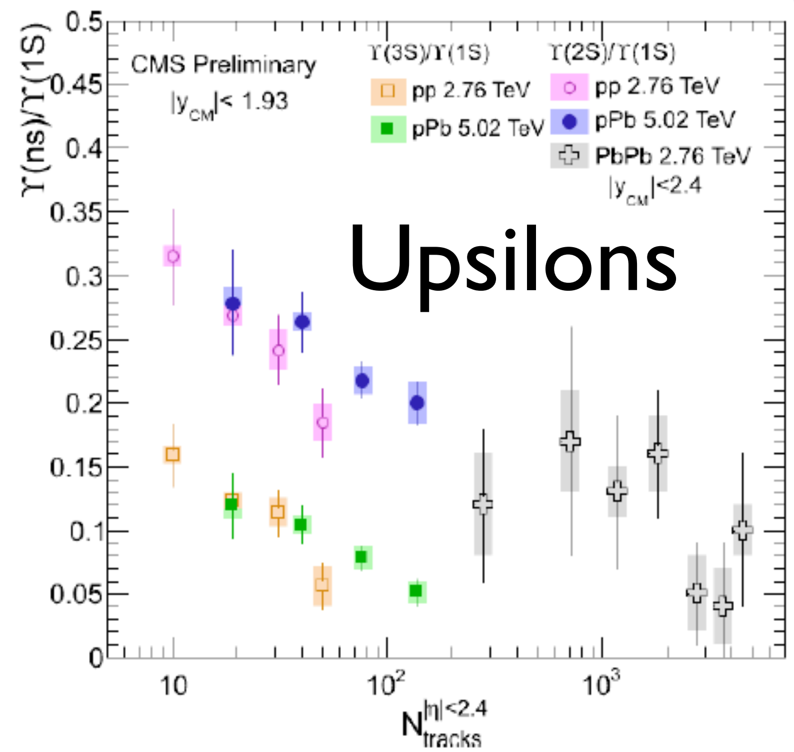
pPb at the LHC:

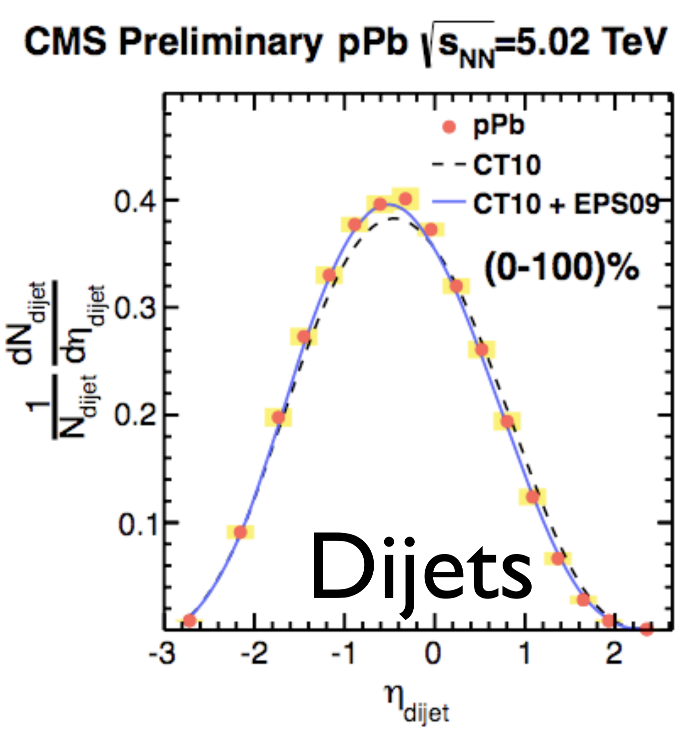
- pPb data the LHC show striking features: formation of a collective medium?

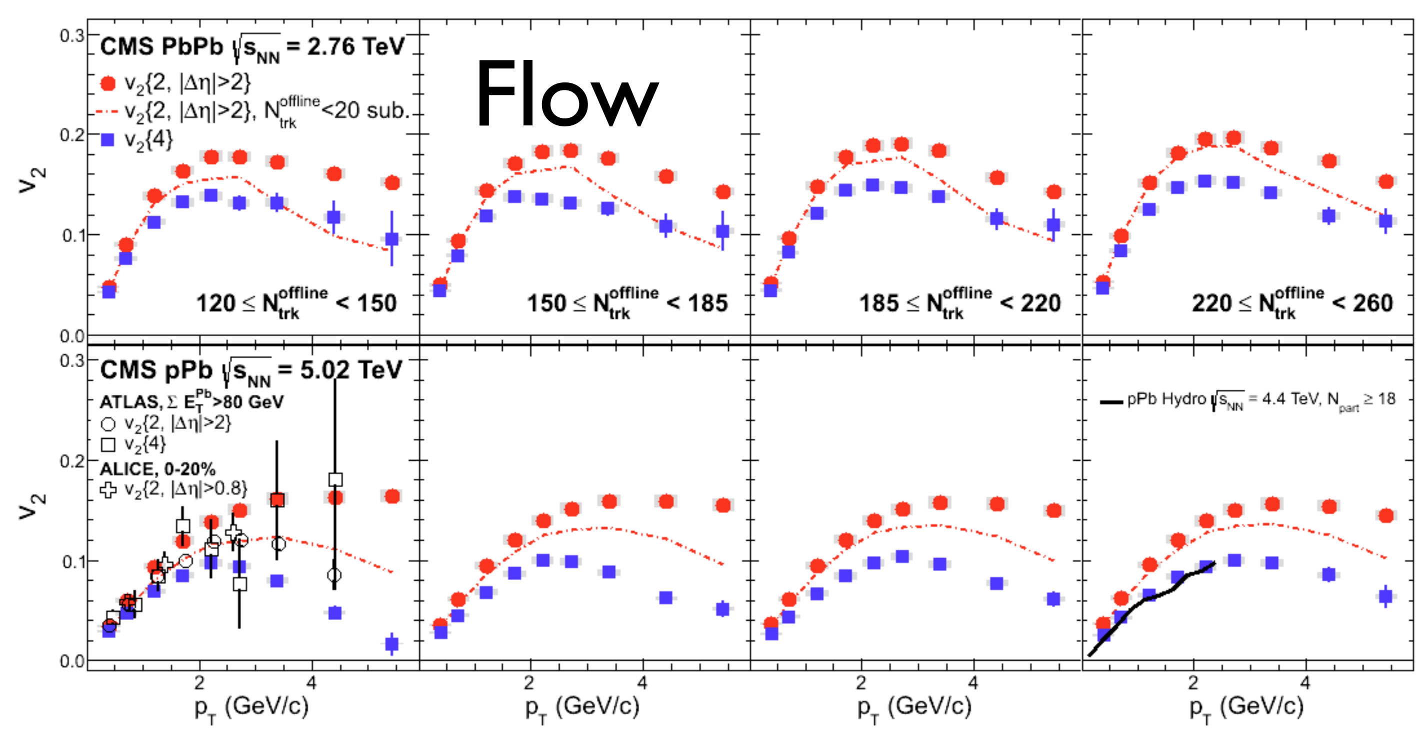
Charged











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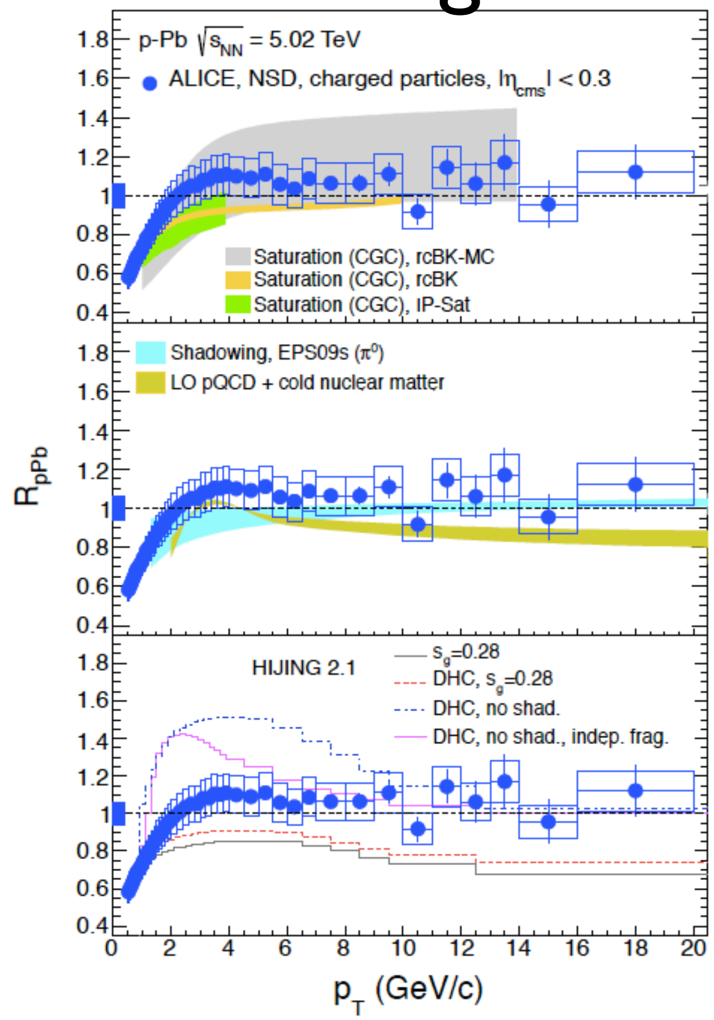
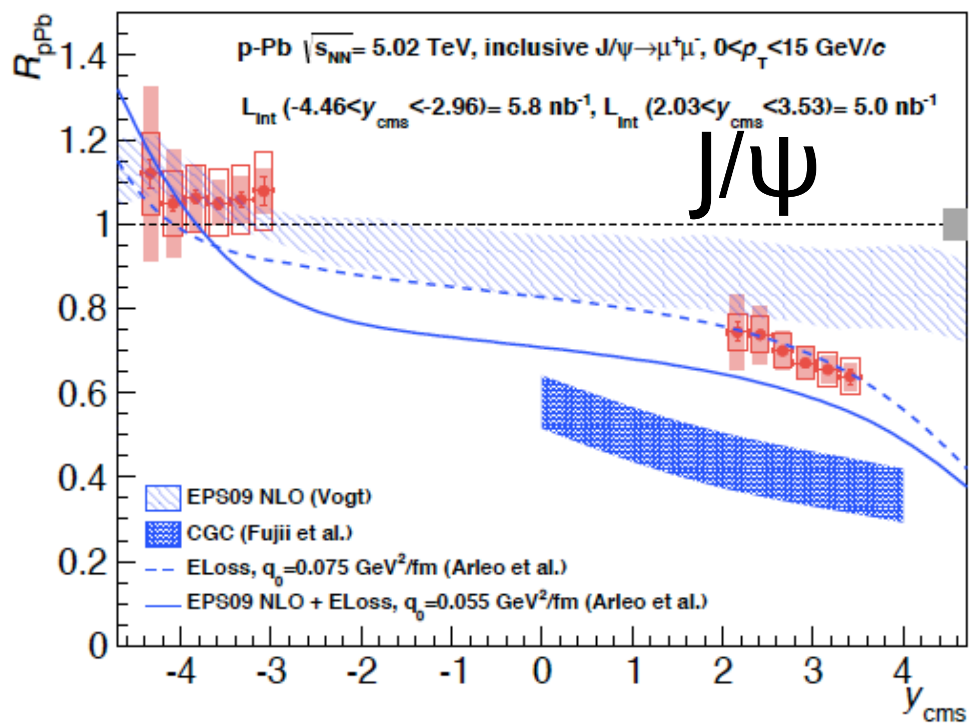
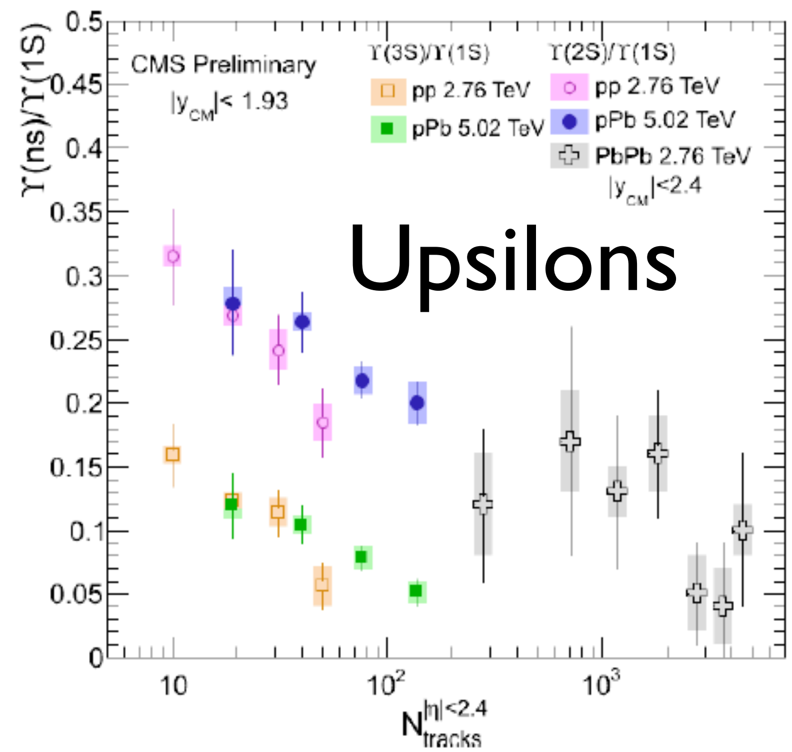
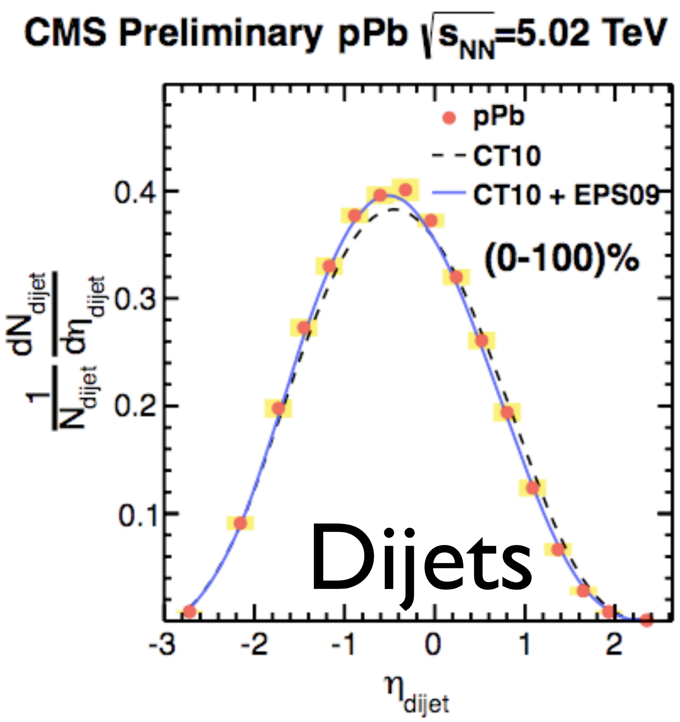
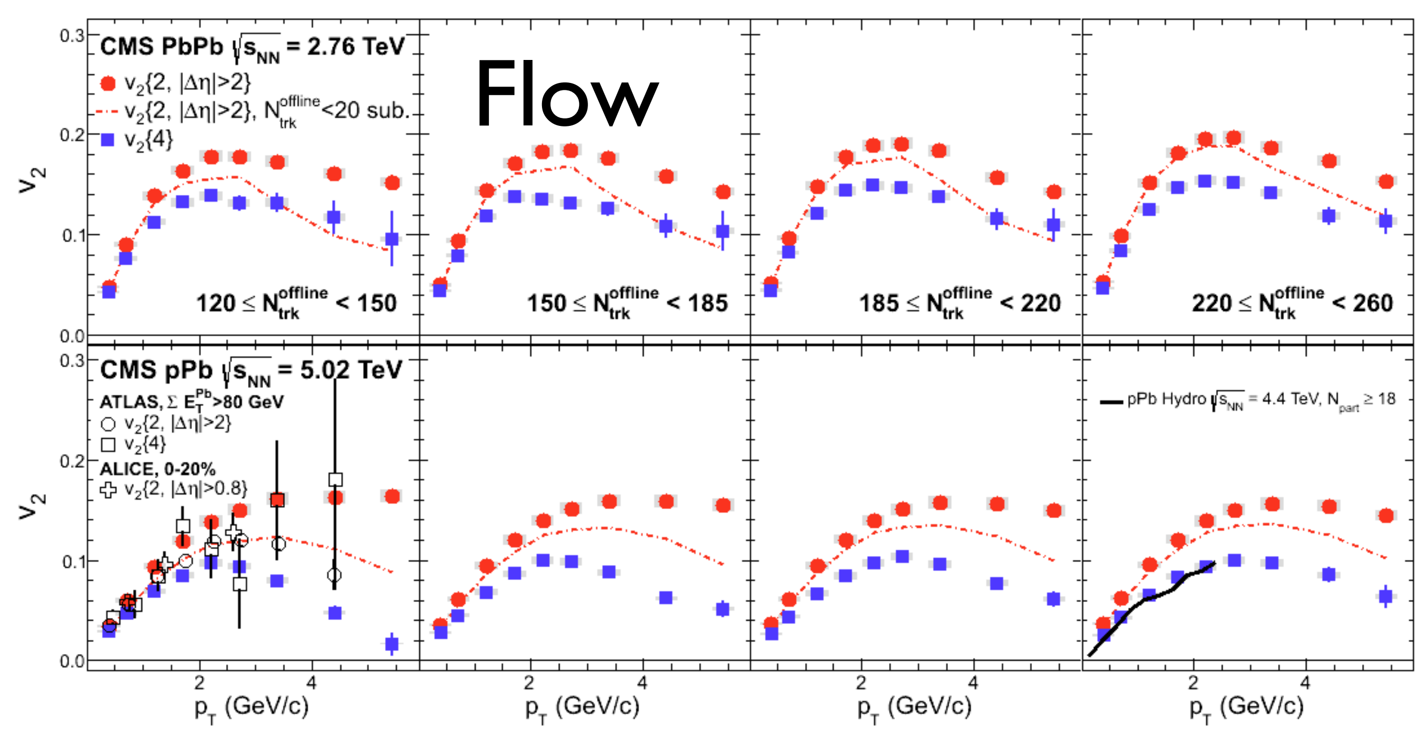








- How can we reconcile this with our ideas of flow and eloss?



Our motivation:

Finite size medium
Collinear factorisation

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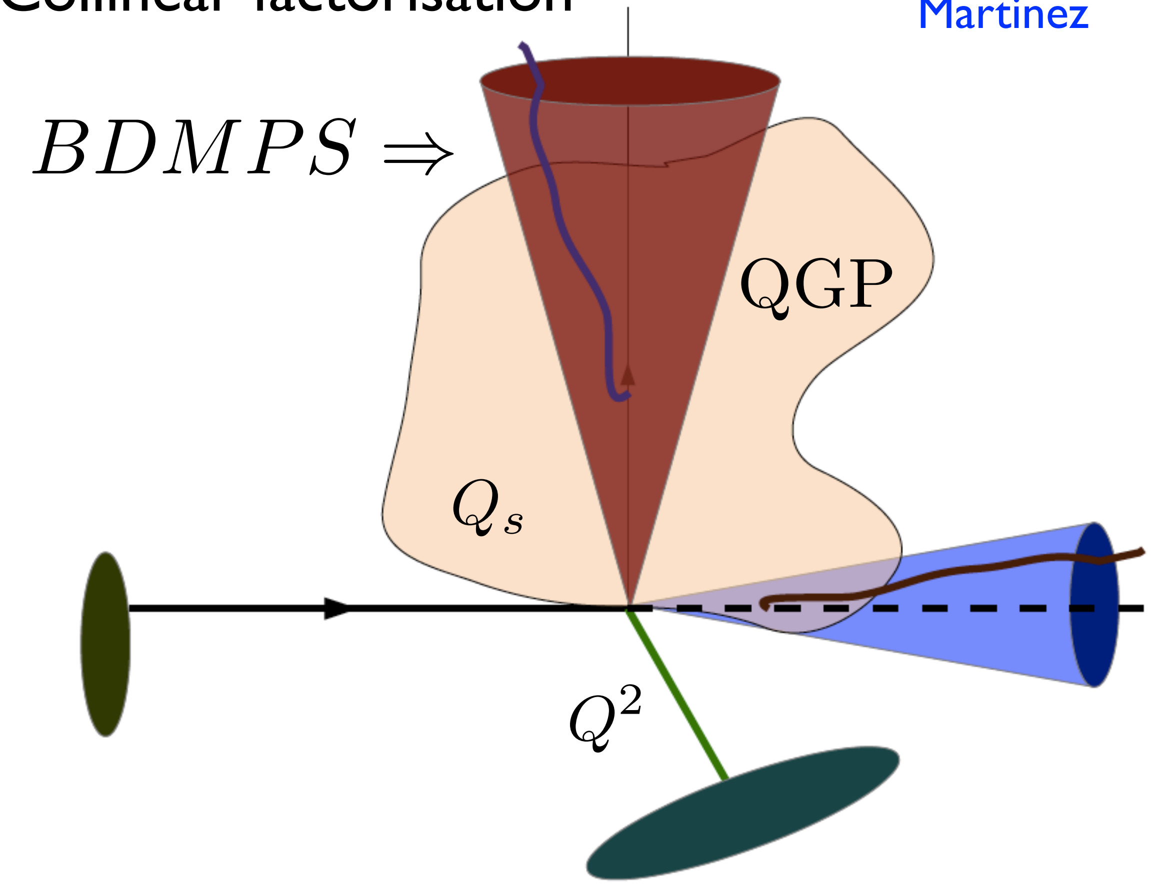

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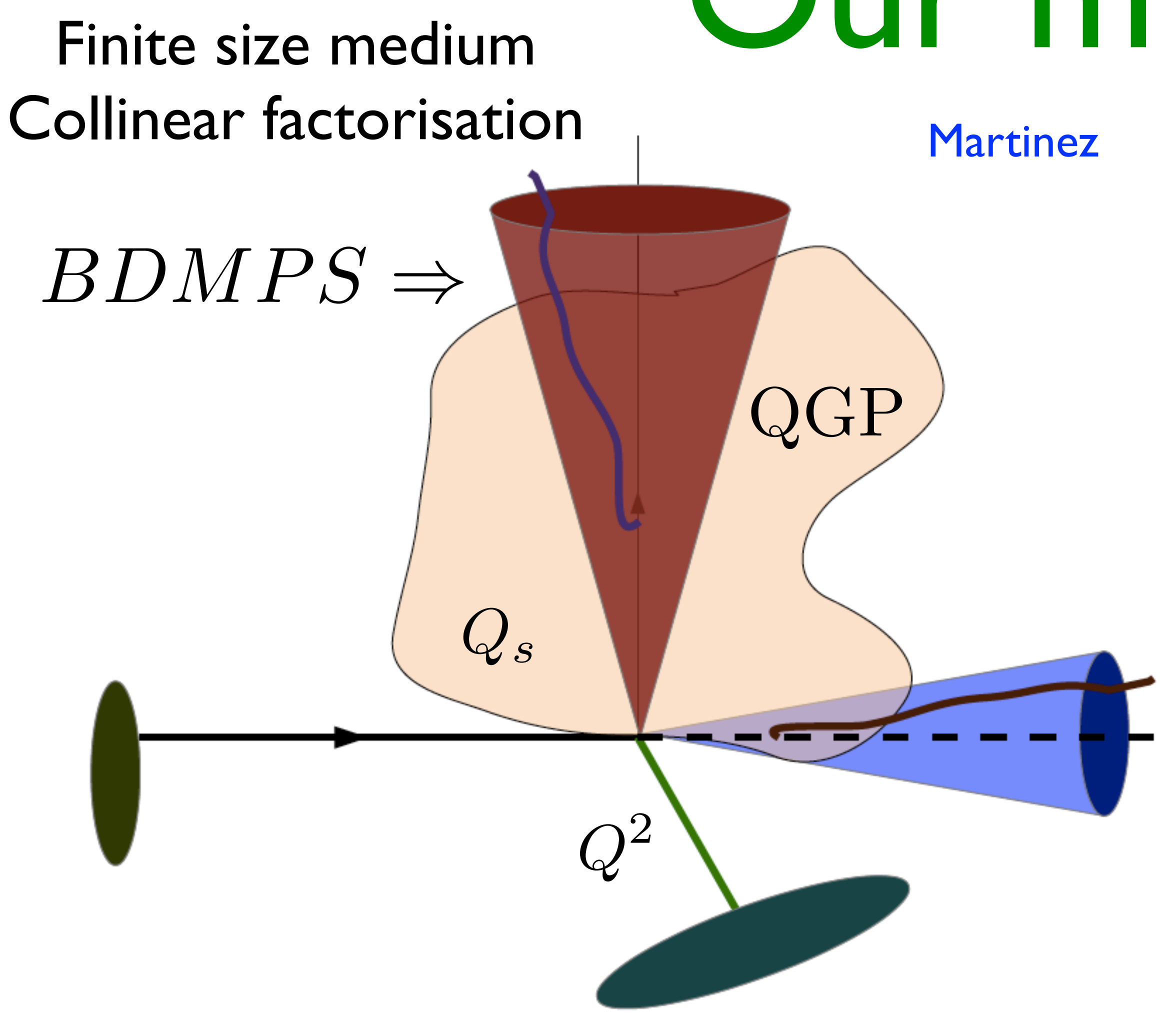

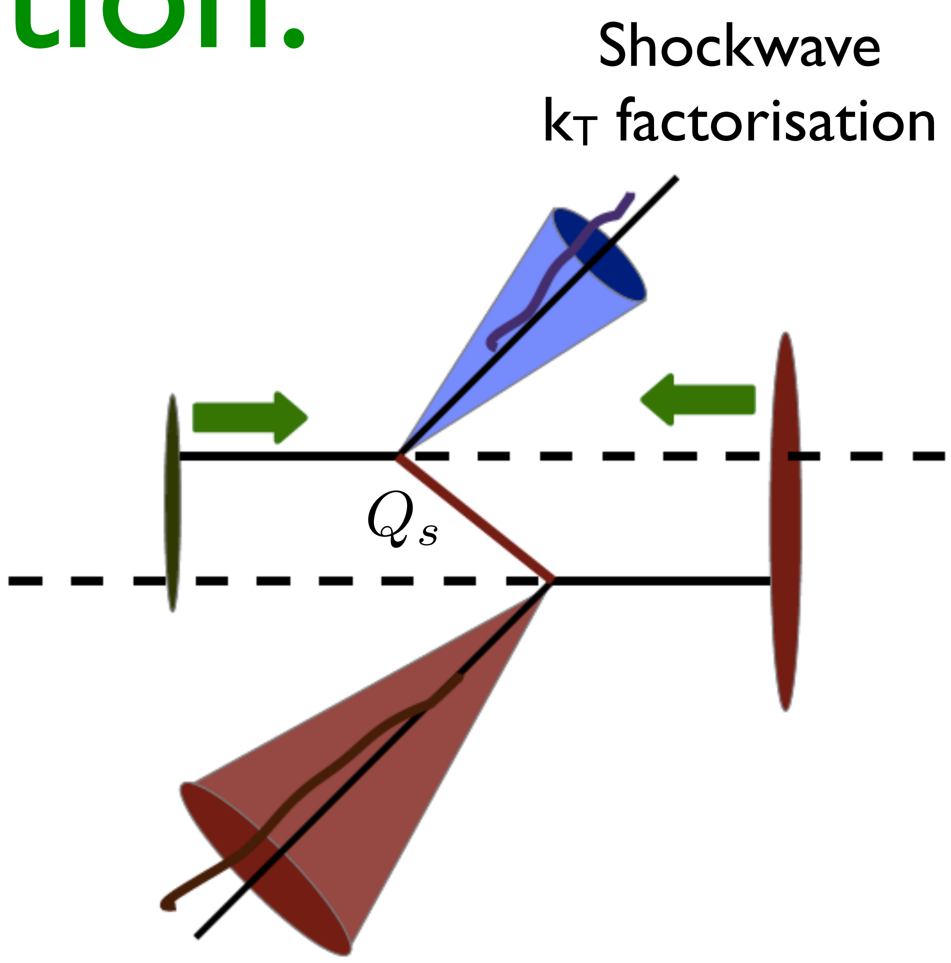

Our motivation:

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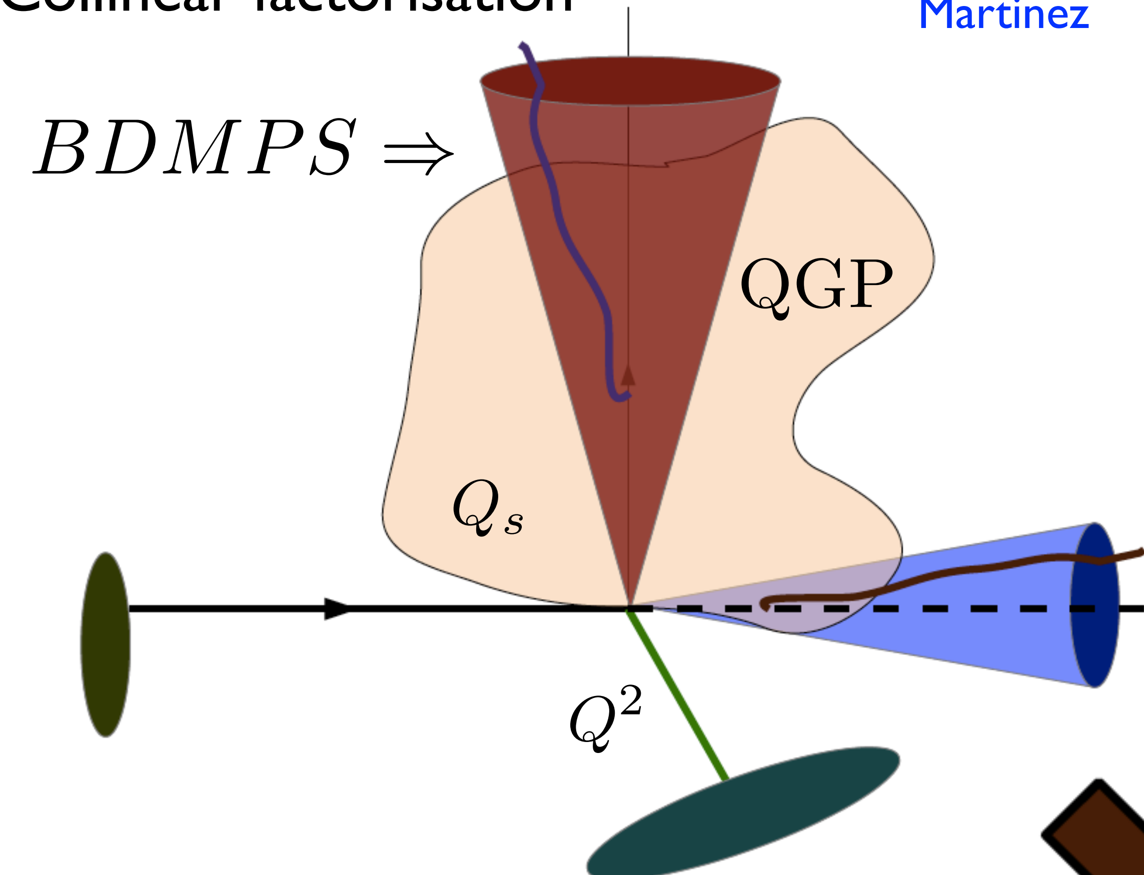
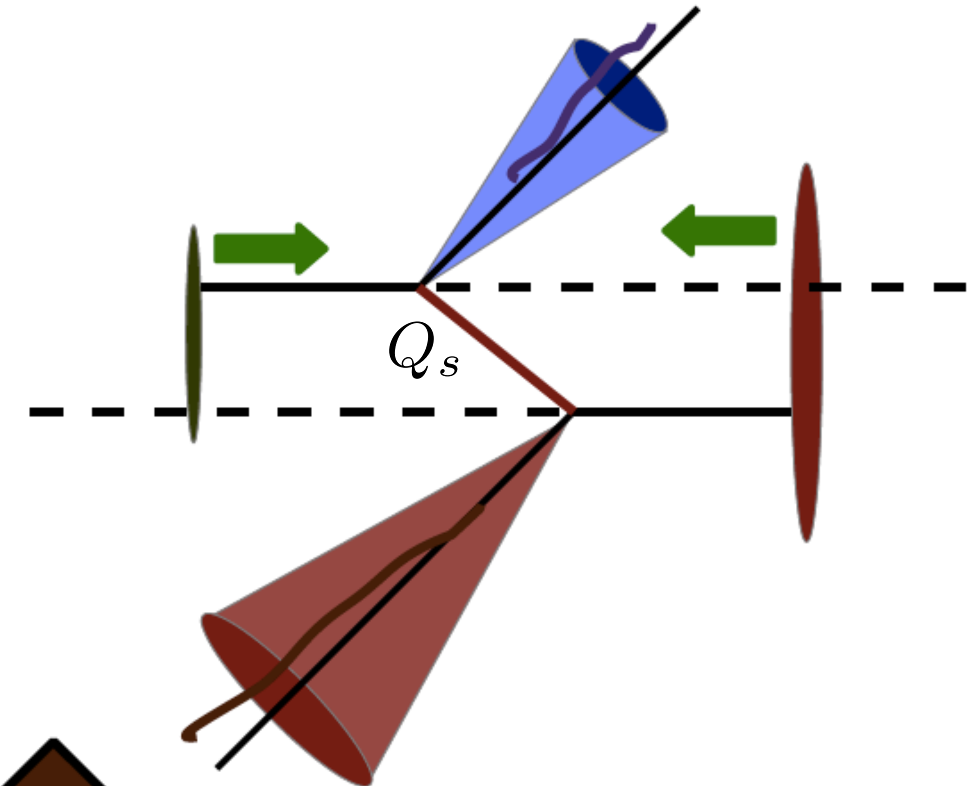
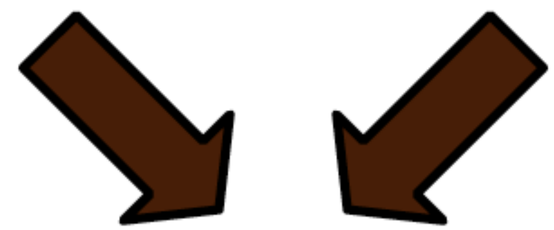
Shockwave
k_T factorisation





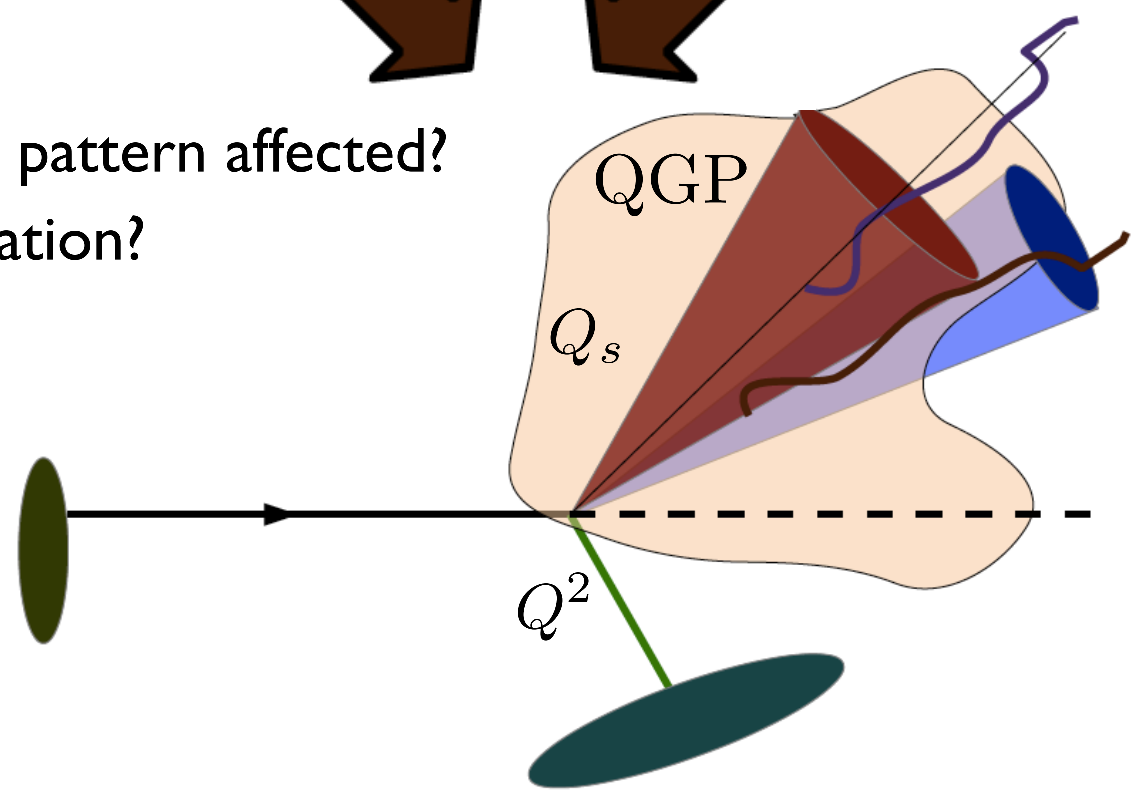


How is the vacuum coherence pattern affected?

Do we have: Collinear factorization?

k_T Factorization?

Something else?



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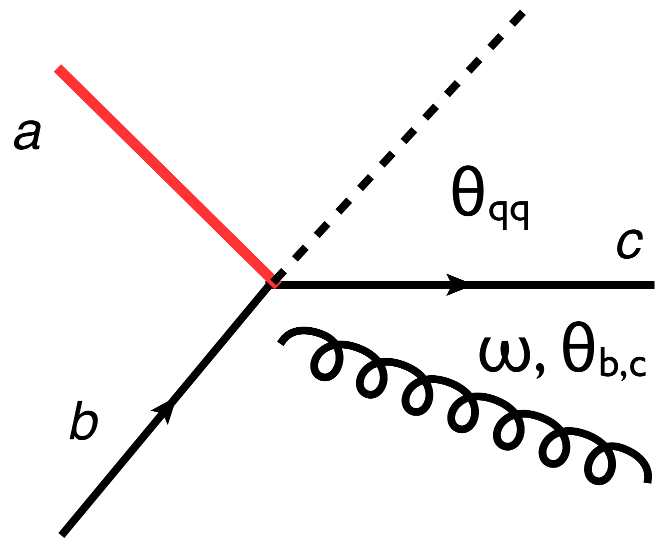
Colour coherence in the soft limit:



ω→0

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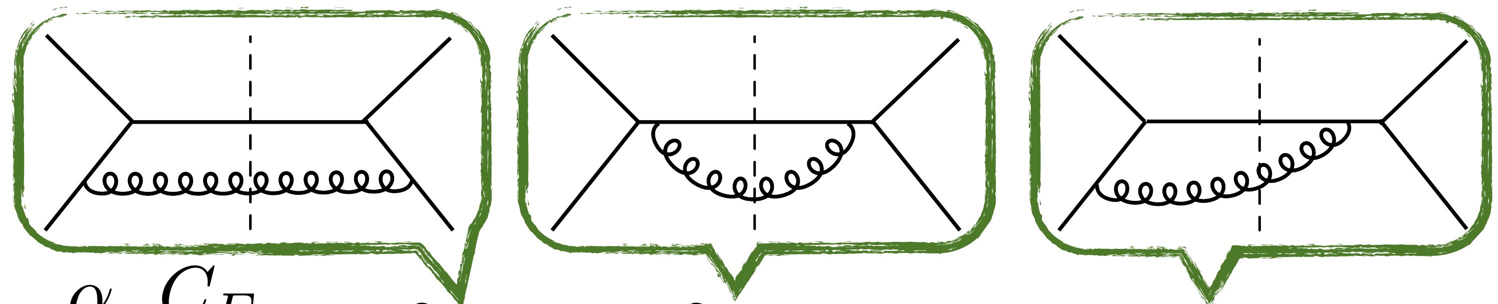


$$\omega \frac{dN}{d^3\vec{k}} = \frac{\alpha_s\, C_F}{(2\pi)^2\,\omega^2}\left[Q_b^2 \mathcal{R}_b + Q_c^2 \mathcal{R}_c + 2\, Q_b \cdot Q_c \mathcal{J}\right]$$

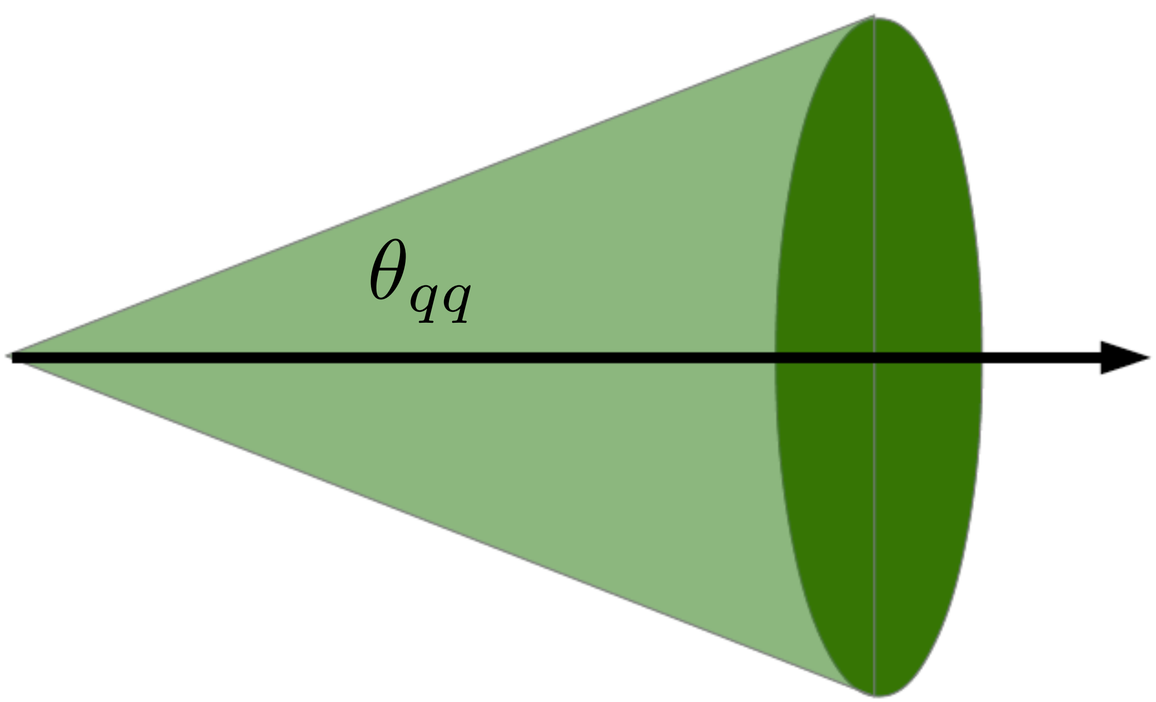
$$= \frac{\alpha_s\, C_F}{(2\pi)^2\,\omega^2}\left[Q_b^2 (\mathcal{R}_b - \mathcal{J}) + Q_c^2 (\mathcal{R}_c - \mathcal{J}) + Q_a^2 \mathcal{J}\right]$$

Coherent radiation

Total charge

$$Q_a = 0 \Rightarrow Singlet$$

$$Q_a \neq 0 \Rightarrow Octet$$

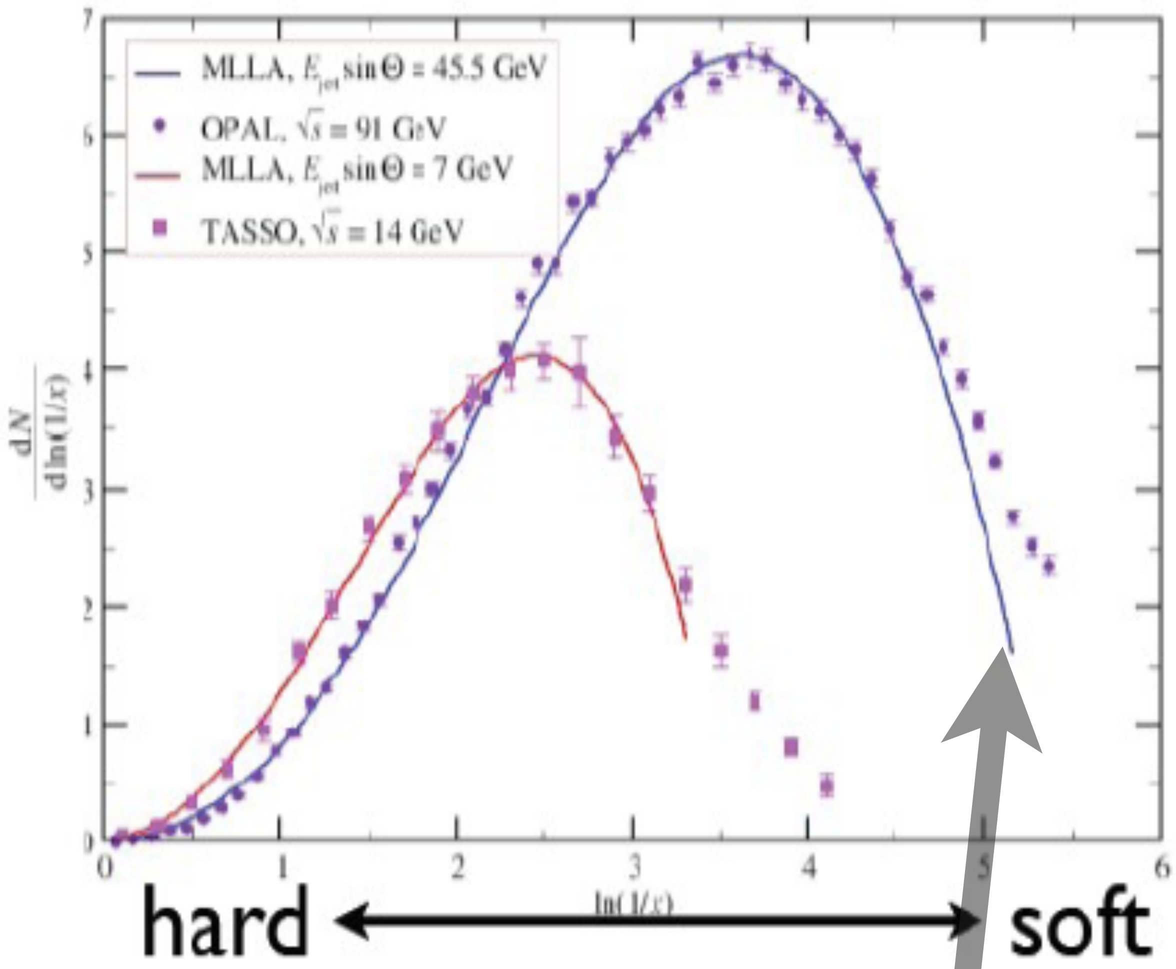


Coherent spectrum

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

Collinear and soft divergence

Colour coherence in the soft limit:



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

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

Suppression of soft gluons

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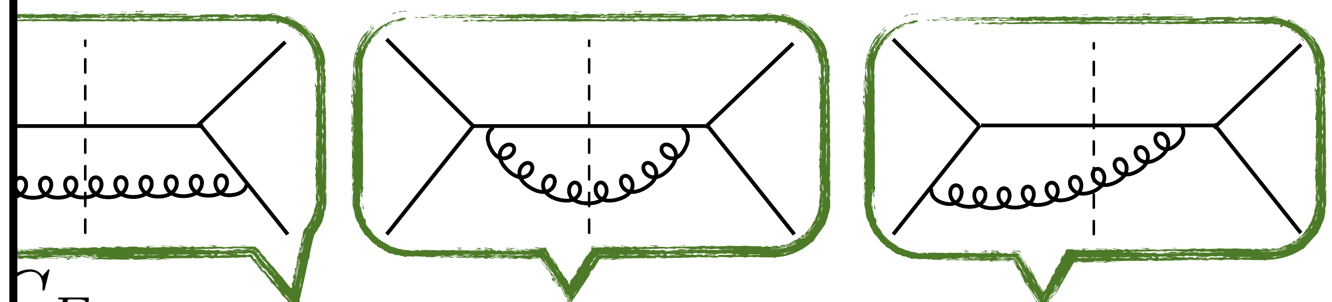

$$\frac{C_F}{\omega^2}\left[Q_b^2\mathcal{R}_b + Q_c^2\mathcal{R}_c + 2\,Q_b\cdot Q_c\mathcal{J}\right]$$

$$\frac{C_F}{\omega^2}\left[\underbrace{Q_b^2(\mathcal{R}_b - \mathcal{J}) + Q_c^2(\mathcal{R}_c - \mathcal{J})}_{\text{Coherent radiation}} + \underbrace{Q_a^2\mathcal{J}}_{\text{Total charge}}\right]$$

Coherent spectrum

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

ollinear and soft divergence

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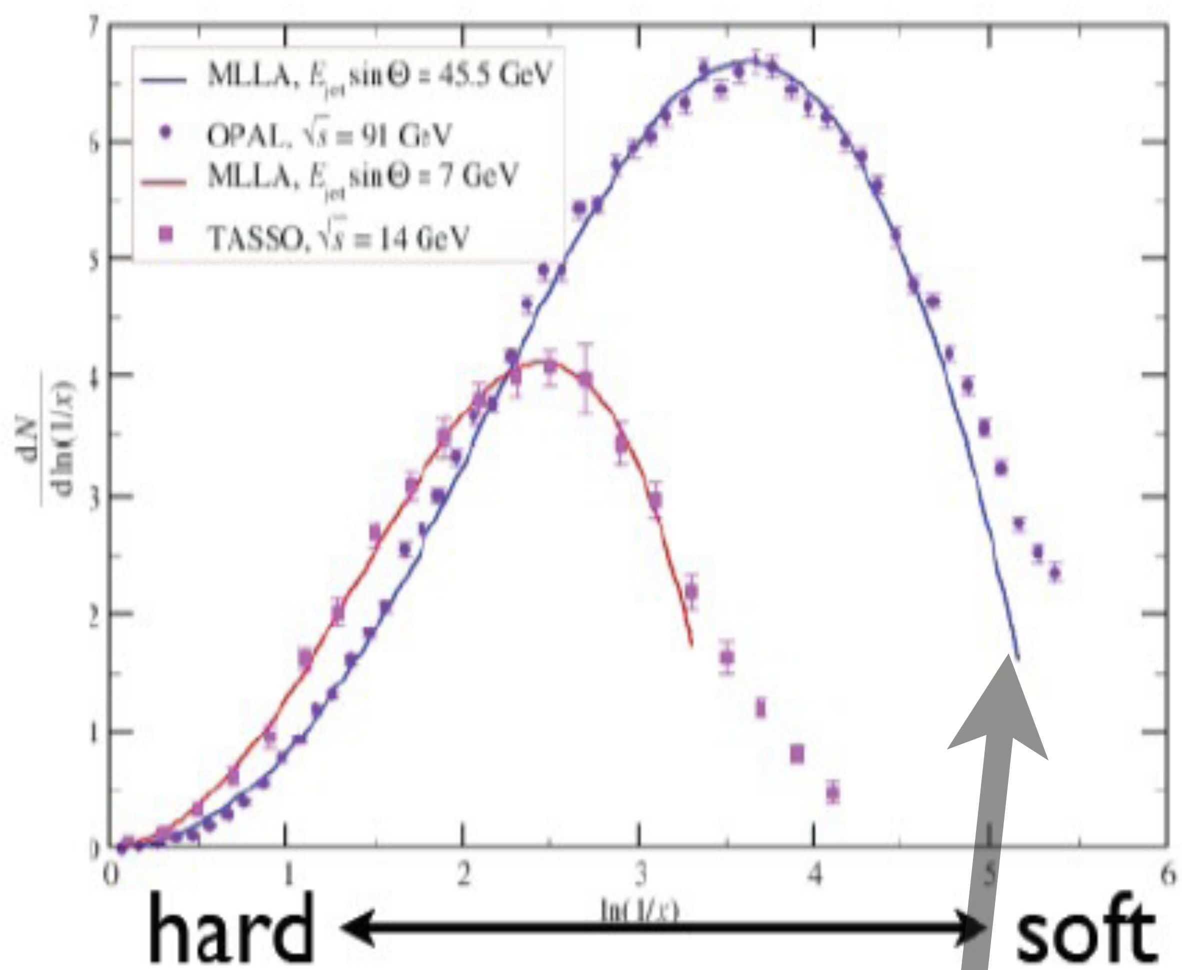

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Suppression of soft gluons

What happens in a QCD medium?

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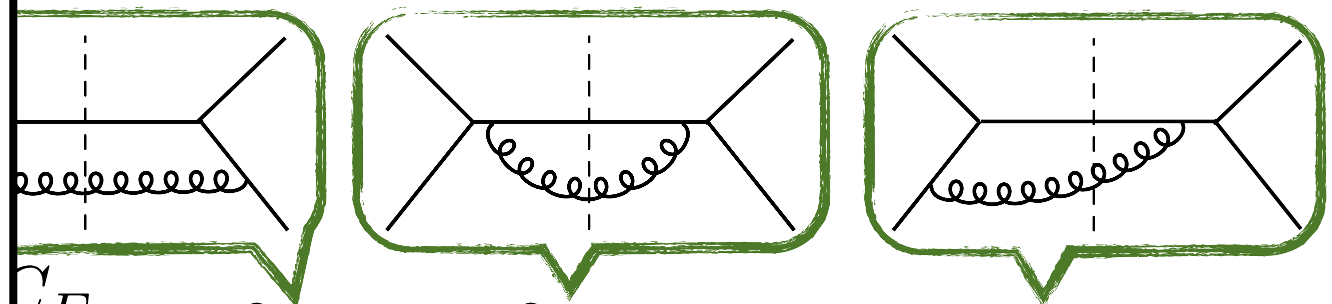

$$\frac{C_F}{\omega^2}\left[Q_b^2\mathcal{R}_b + Q_c^2\mathcal{R}_c + 2\,Q_b\cdot Q_c\mathcal{J}\right]$$

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

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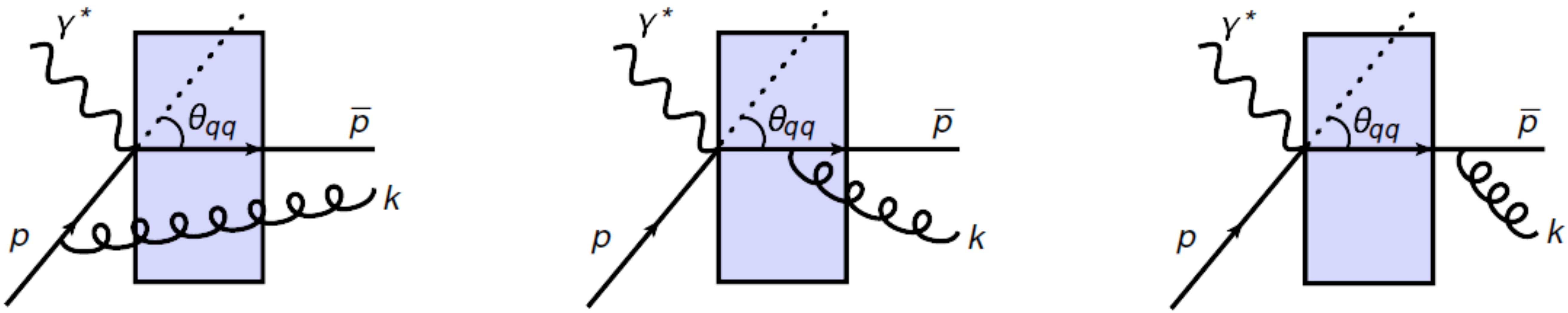
The setup:



- Setup to study IS/FS interferences (similar one in Vitev '07).

- It maybe relevant for forward particle production in heavy-ion collisions: hard exchange, with a medium produced simultaneously.

- Valid for any colour exchange in the soft limit.

- We use the semiclassical method (CGC): equivalent to the diagrammatic method (path integral approach, opacity expansion) (Mehtar-Tani '06) but more economical (e.g. 39 diagrams at N=1).

Semiclassical method (I):

- Equations: CYM + colour conservation.

$$\left[D_\mu, F^{\mu\nu}\right] = \mathcal{J}^\nu$$
$$\left[D_\mu, \mathcal{J}^\mu\right] = 0$$

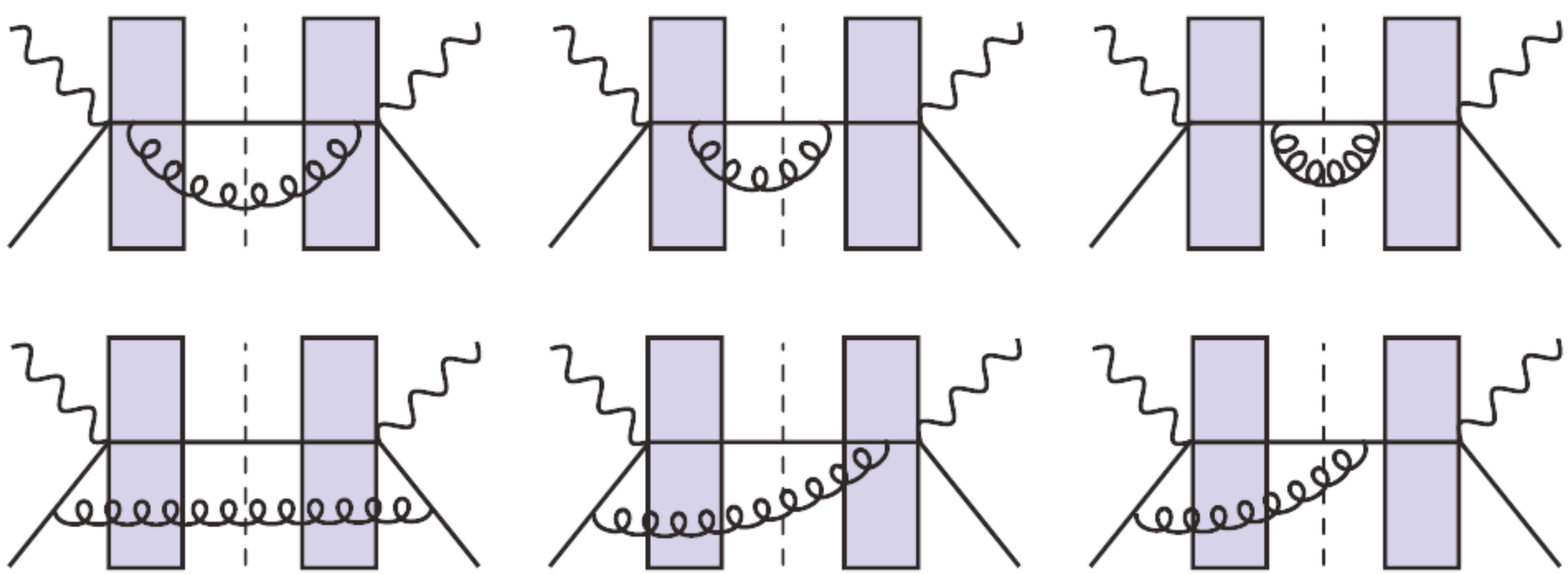
- Linearization around a background field (LC gauge with b.c.).

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

- Use of reduction formula.

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

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

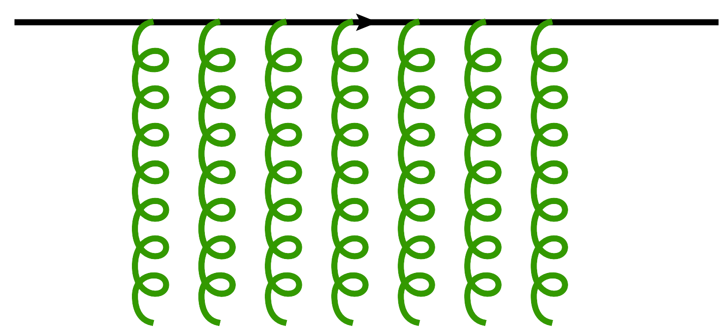


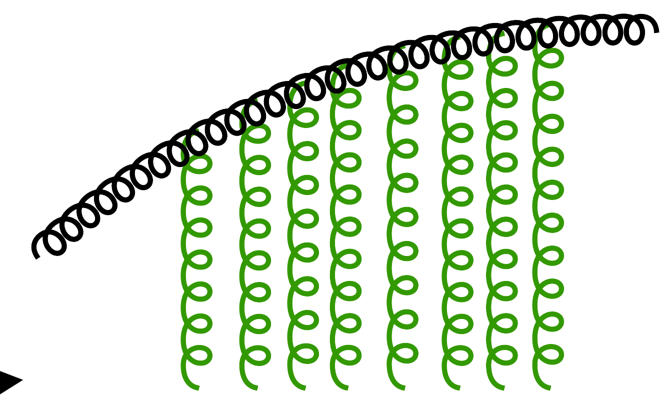
Semiclassical method (II):

• Hard partons: eikonal trajectory 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 partons: colour rotation plus Brownian motion.

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

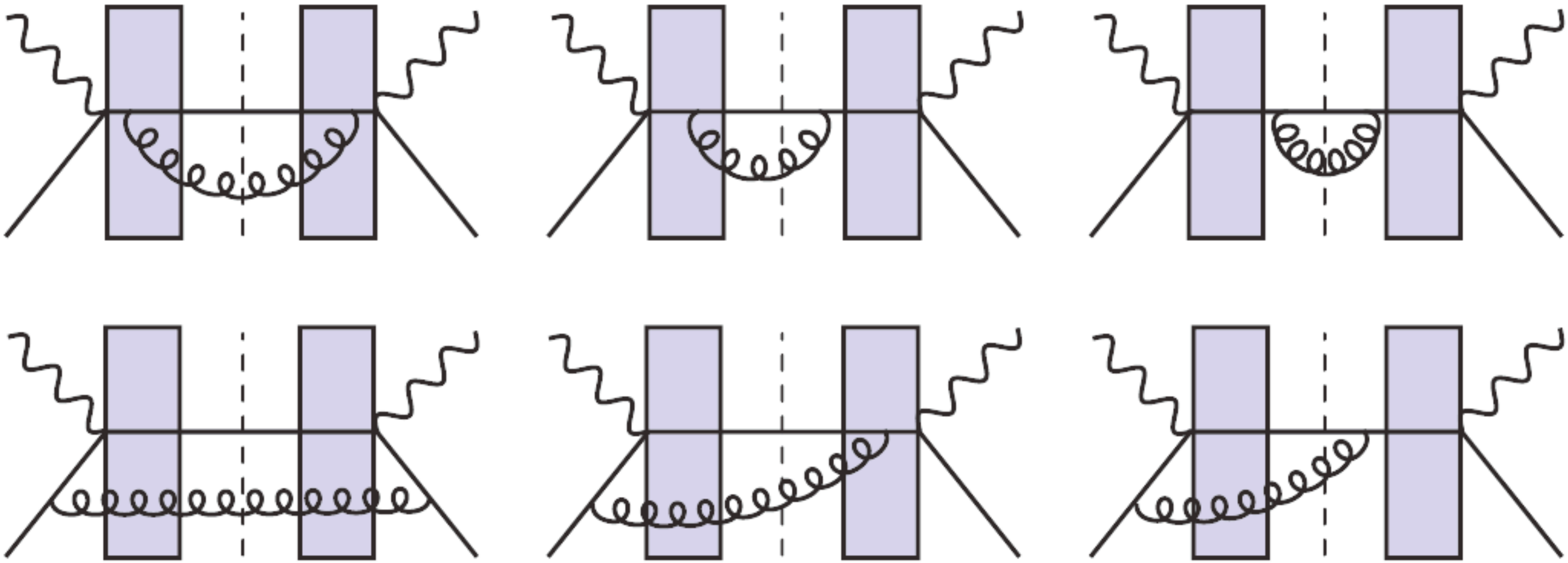
• Medium: background field, Gaussian noise (MV model).

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

$$\lambda_{mfp} \gg m_D^{-1} \qquad \mathcal{V}^2(\mathbf{q}) = \frac{m_D^2}{(2\pi)^2(\mathbf{q}^2+m_D^2)^2}$$

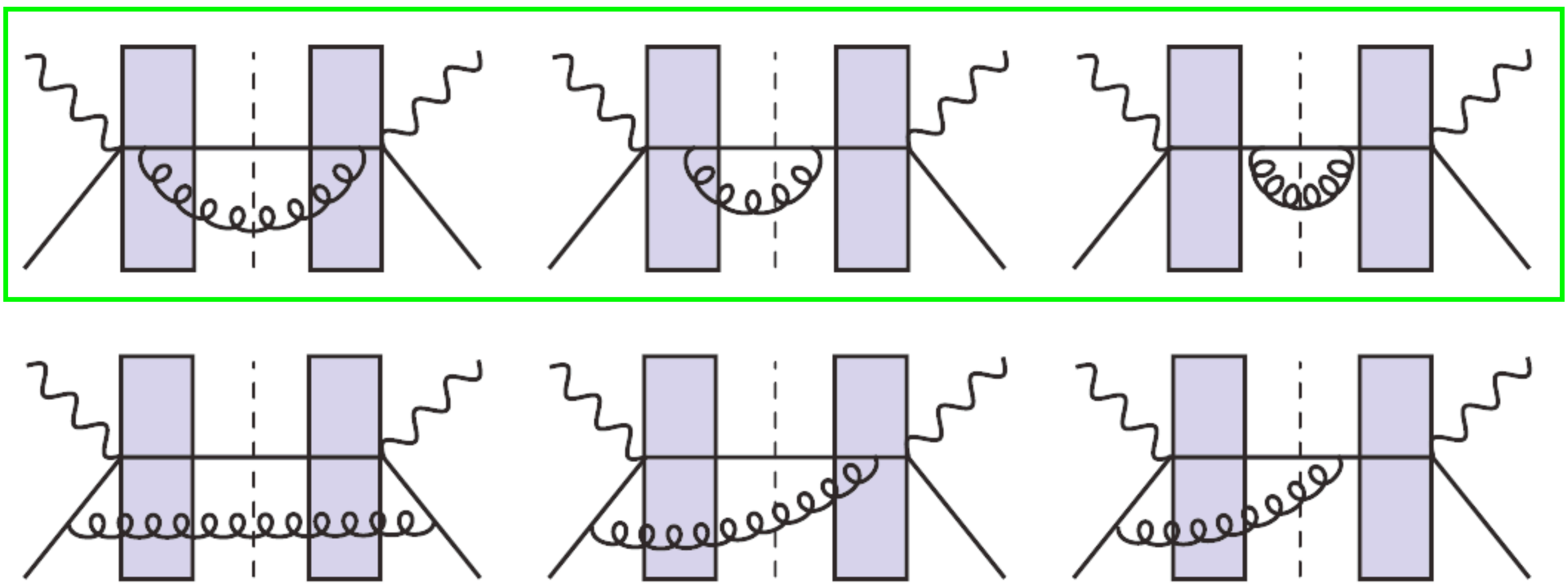
Usual choice: GW model

Gluon spectrum:



Gluon spectrum:

BDMPS-Z + vacuum



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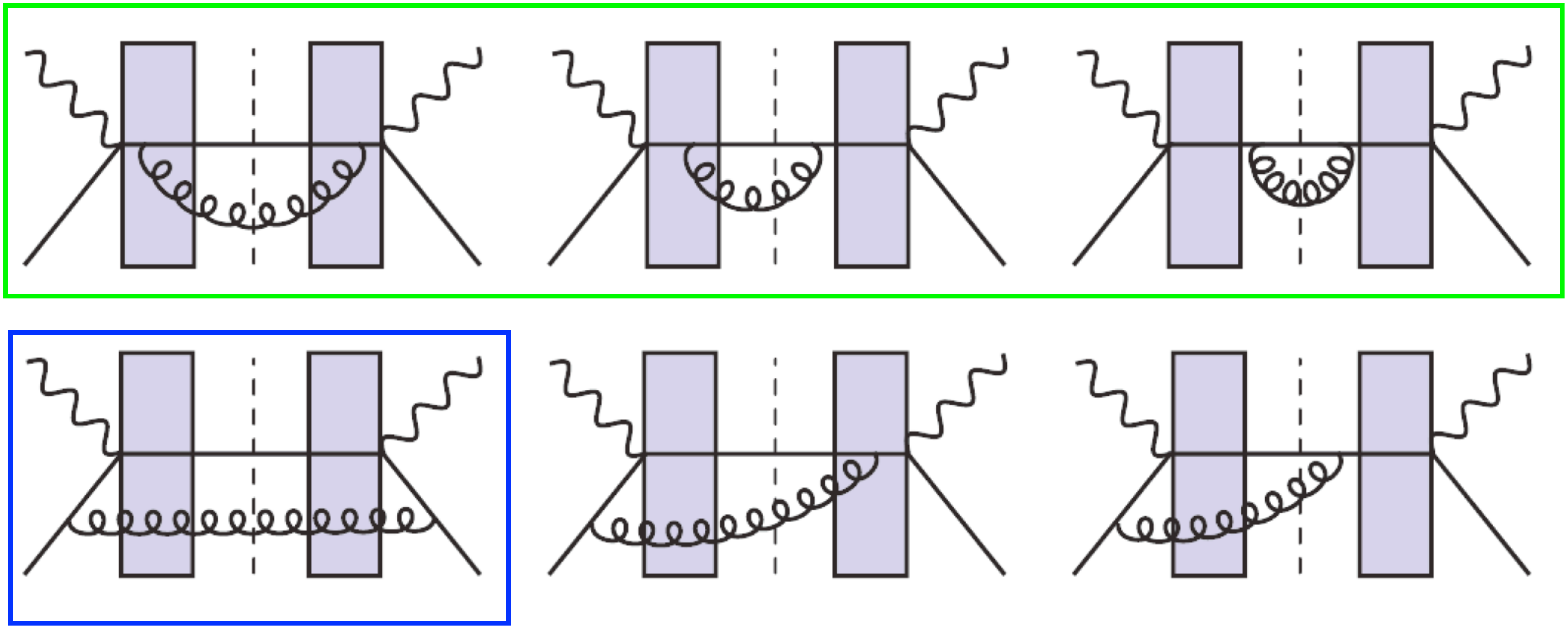

p_T broadening of IRS

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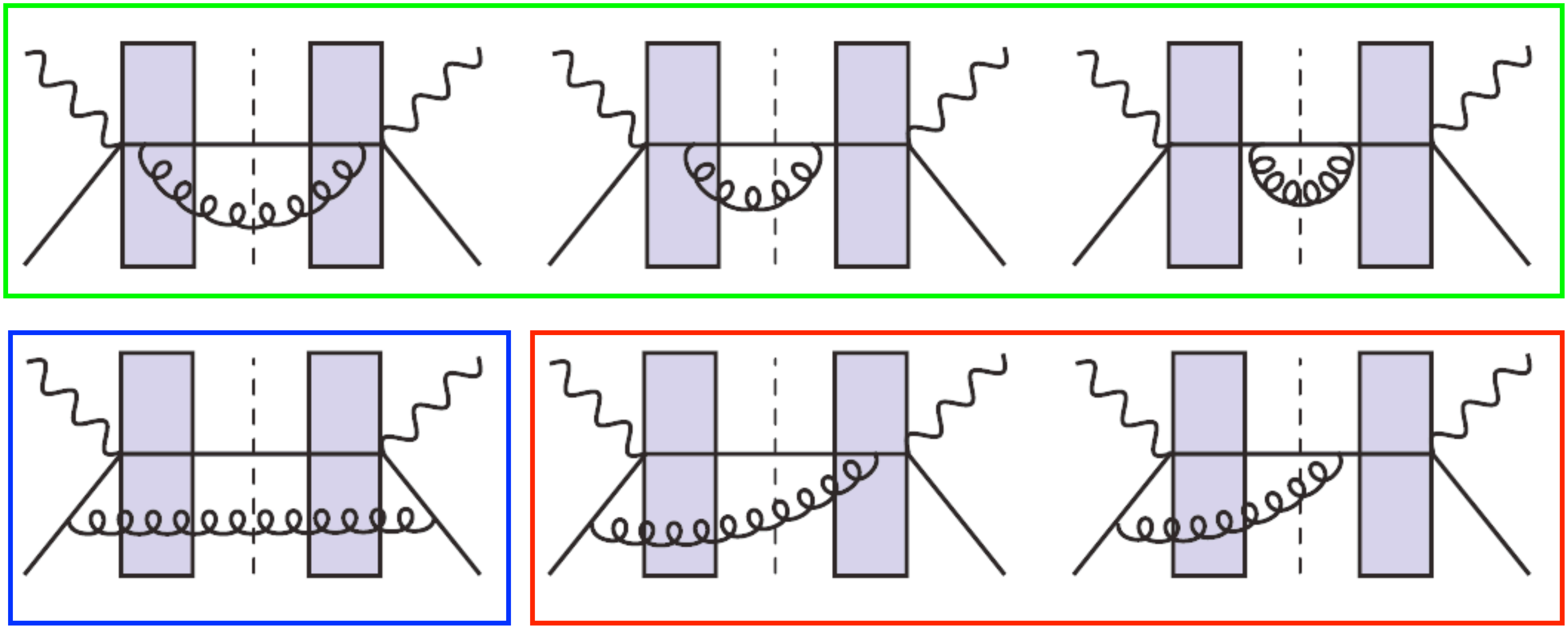
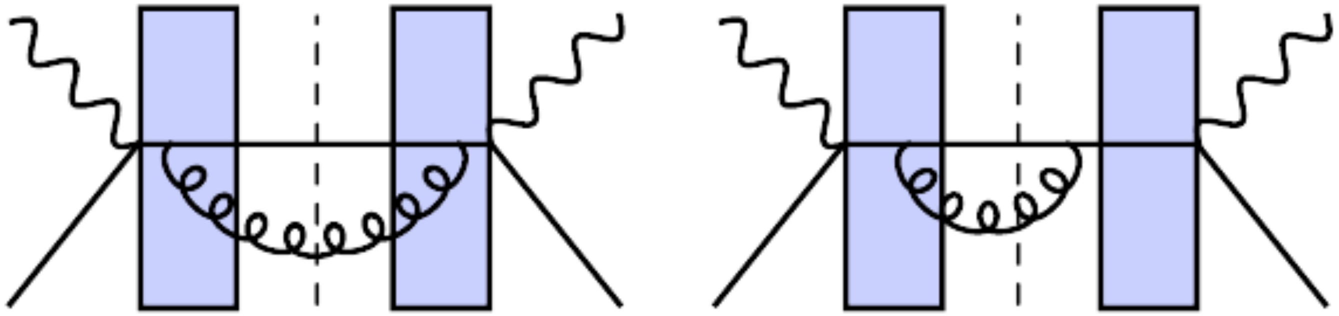
BDMPS-Z + vacuum



p_T broadening of IRS

In-medium interferences: new!

Results (I):



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

- BDMPS-Z can be approximated by: quantum emission plus classical p_T broadening.

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

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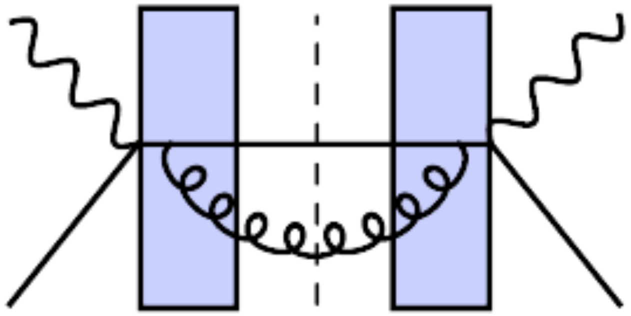

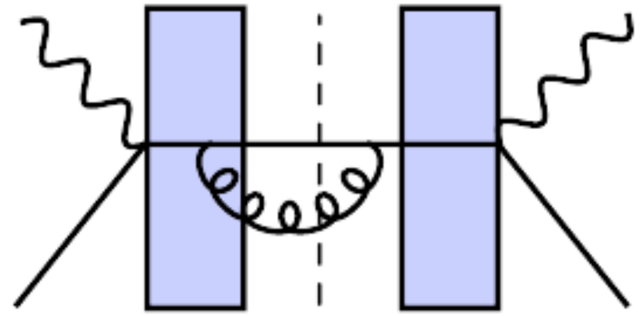

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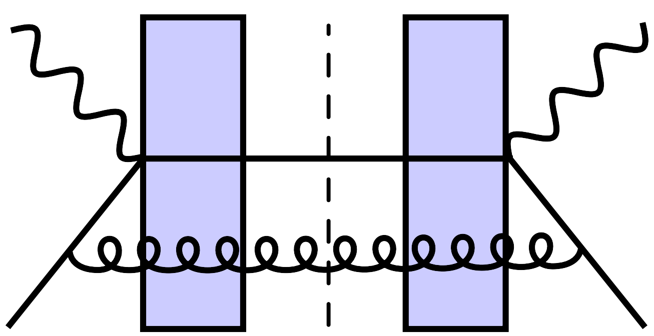


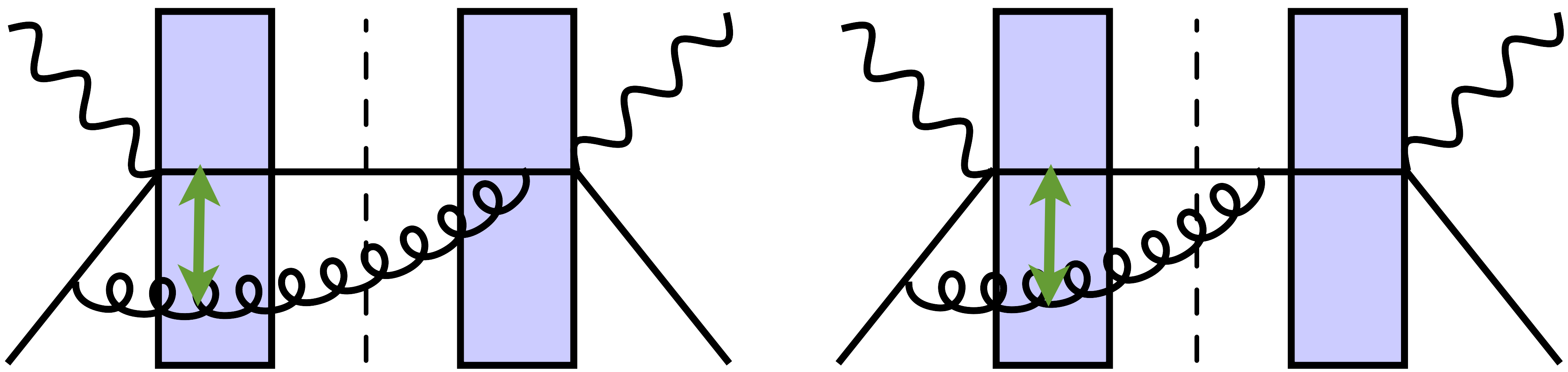
- p_T broadening of ISR contains classical p_T broadening plus collinear divergence.

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

$$\langle k_T \rangle \sim Q_s = \sqrt{\hat{q}L^+}$$

$$\bar{\kappa} \sim \mathbf{k}$$

Results (II):



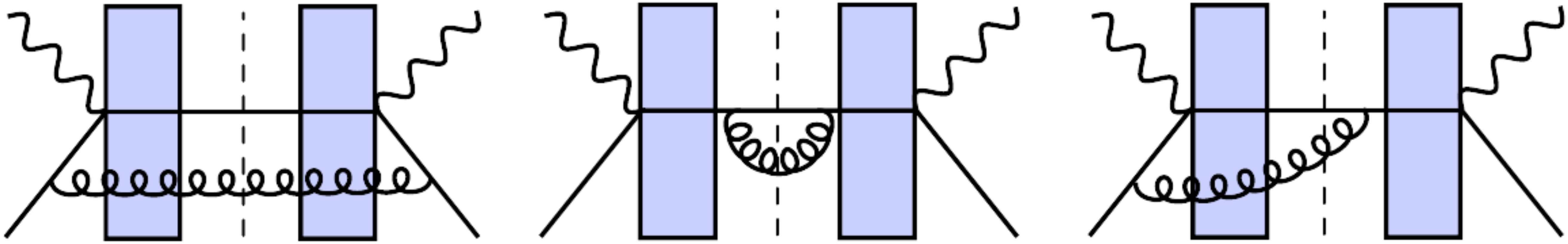
- Interferences controlled by the size of the qg system:
  - → If the hard scattering is the largest scale, coherent qg propagation.
  - → If the medium-induced momentum is the largest, qg decoherence.

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

$n\sigma(\mathbf{r}) \approx \hat{q}\mathbf{r}^2$: harmonic oscillator approximation

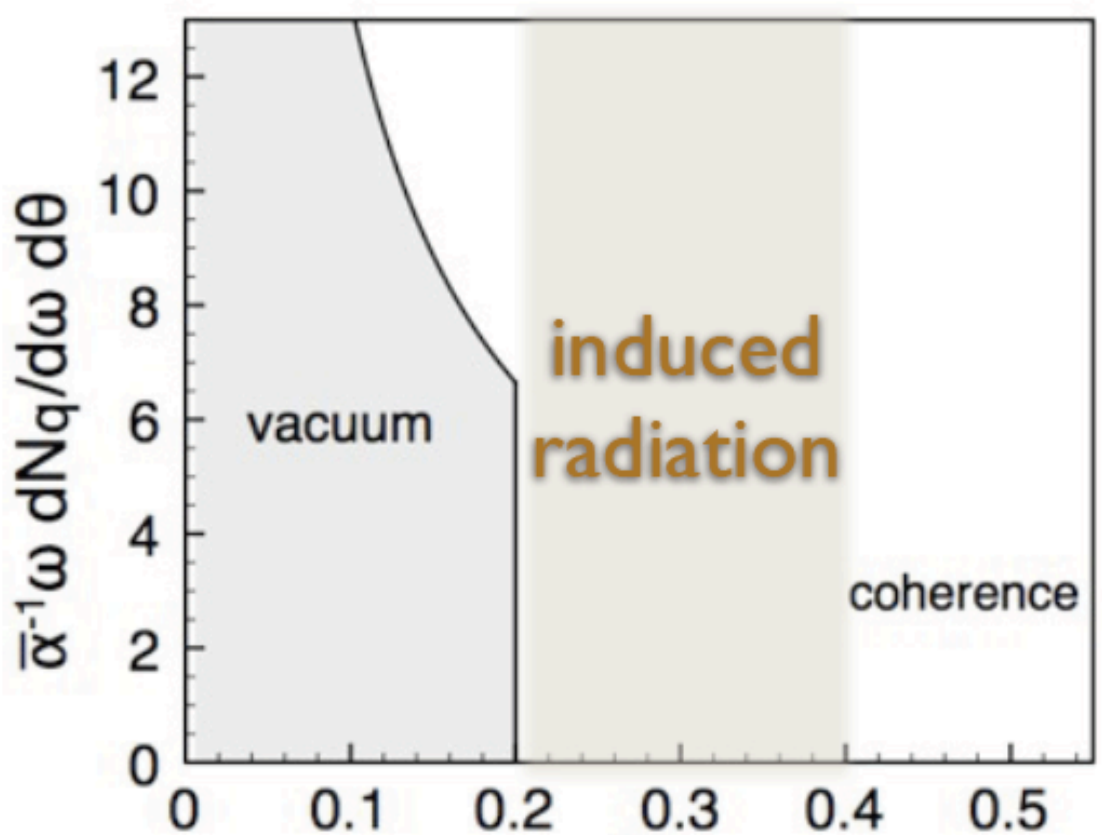
- Two opposite regimes:
  - → Coherent (high energies), $\tau_f \sim \sqrt{\omega/\hat{q}} \gg L^+$
  - → Incoherent (low energies or large medium), $\tau_f \sim \sqrt{\omega/\hat{q}} \ll L^+$

Coherent regime:

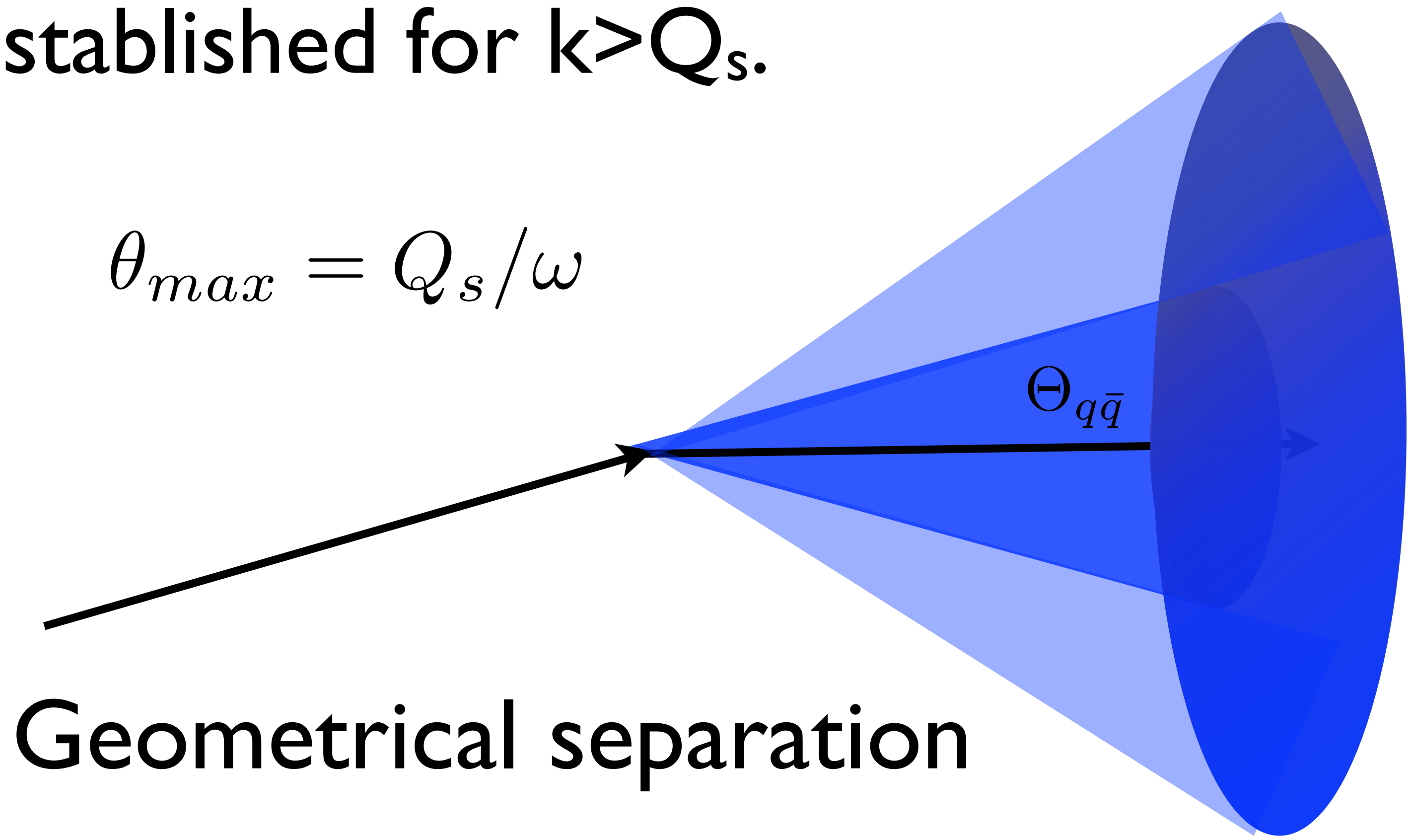


- Medium as a single scattering center.
- Interferences suppressed for $k<Q_s$.
- Vacuum coherent pattern reestablished for $k>Q_s$.

$\omega \rightarrow 0$

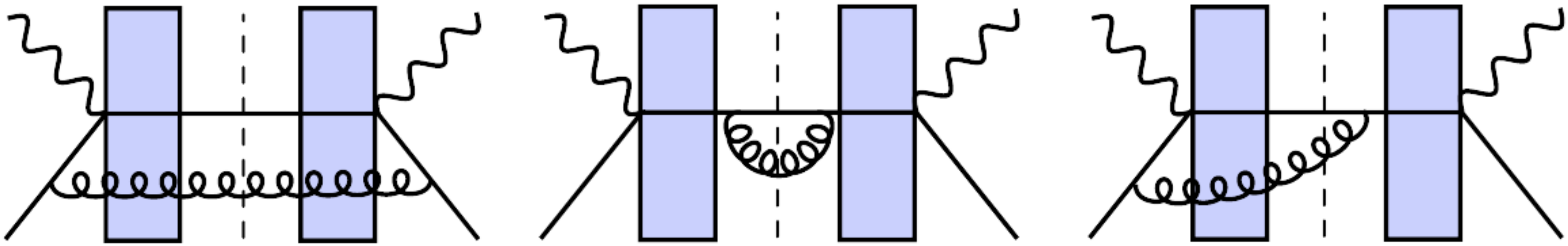


$\theta_{max} = Q_s/\omega$



Geometrical separation

Coherent regime:



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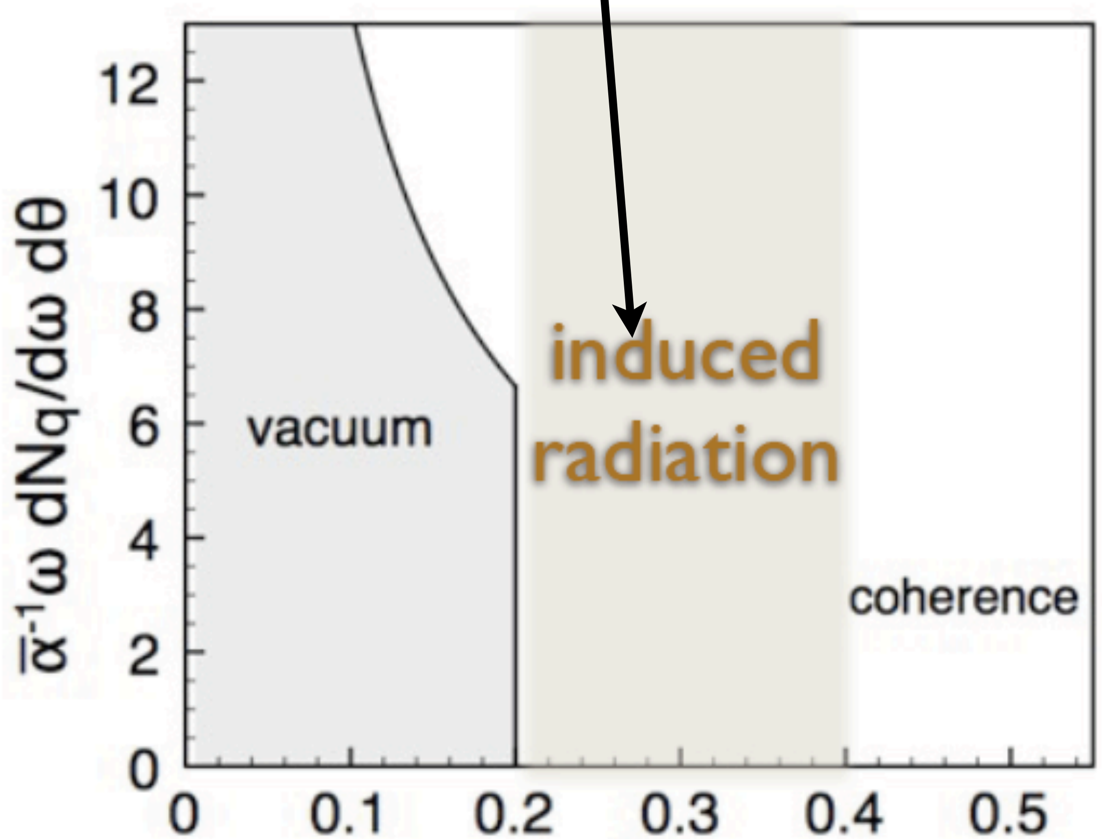
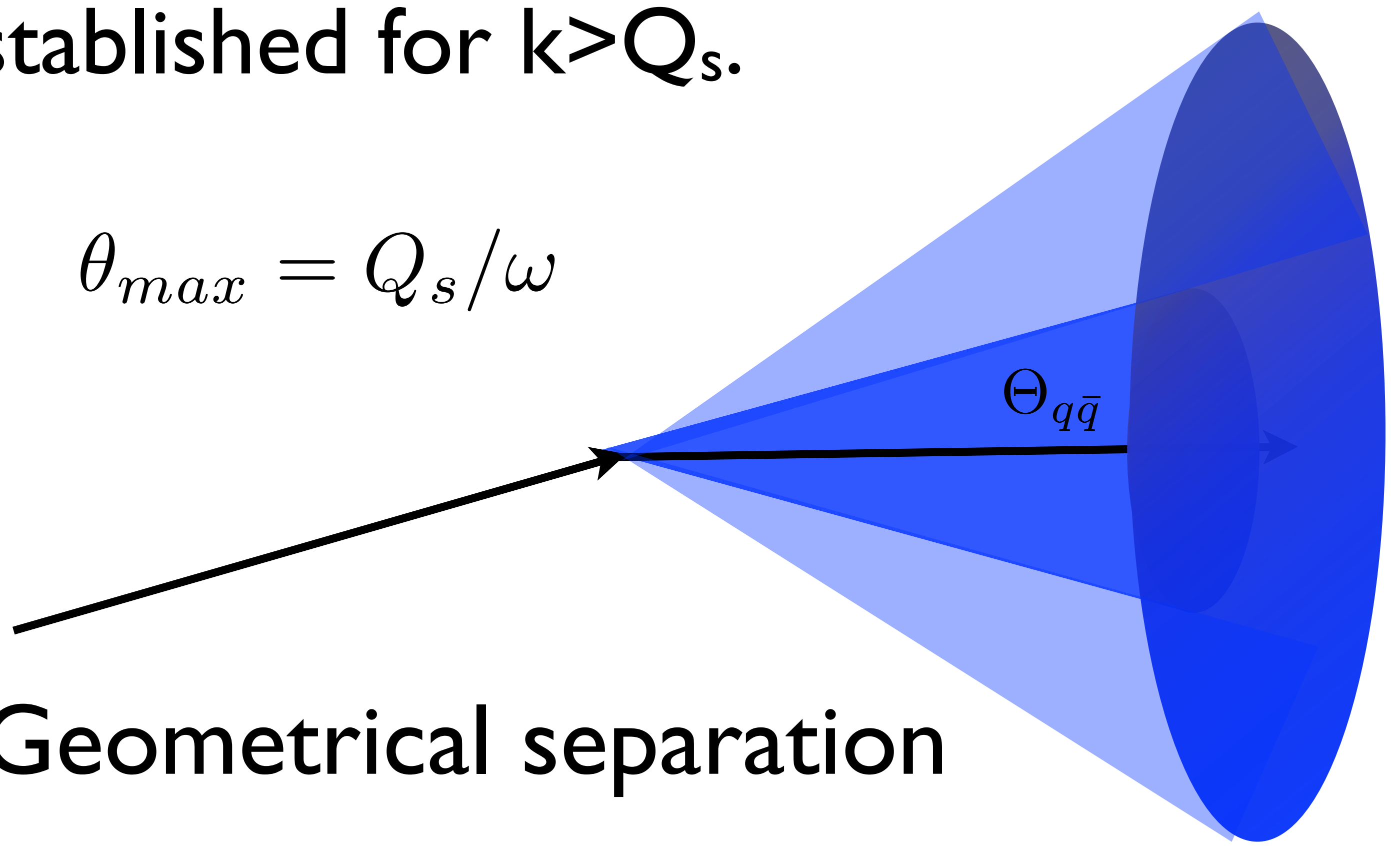
- Vacuum coherent pattern reestablished for $k>Q_s$.

$\omega \to 0$

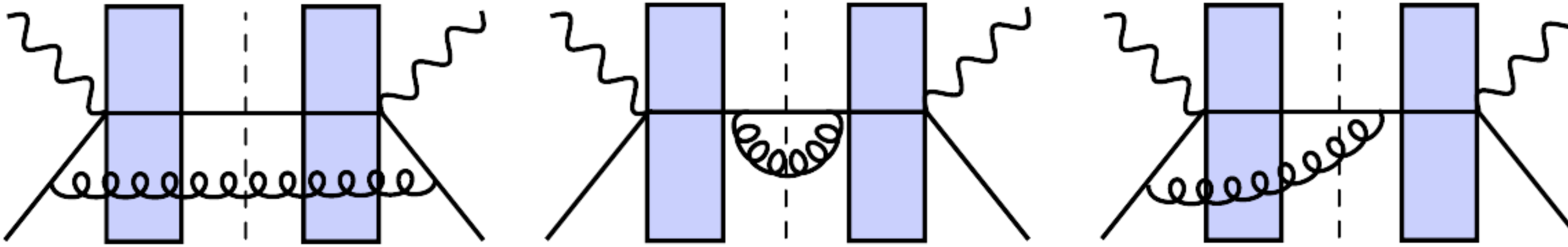


$$\theta_{max} = Q_s/\omega$$

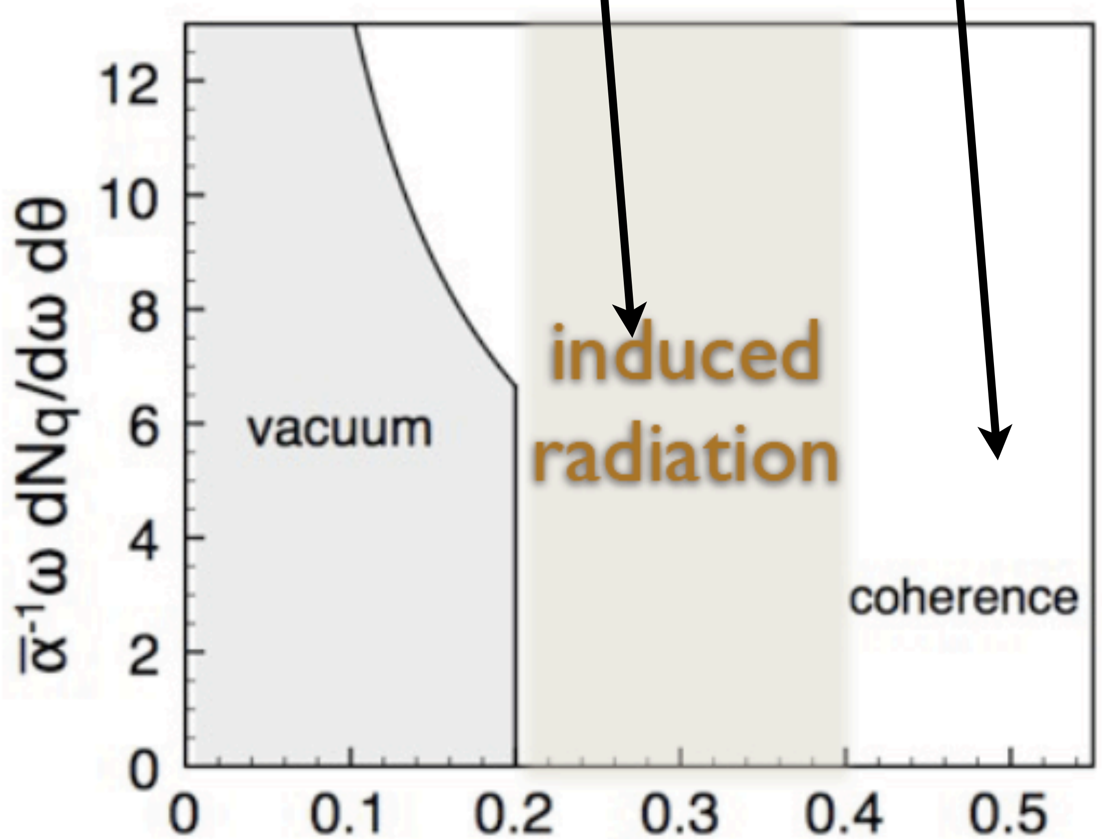


Geometrical separation

Coherent regime:



- Medium as a single scattering center.
- Interferences suppressed for $k<Q_s$.
- Vacuum coherent pattern reestablished for $k>Q_s$.



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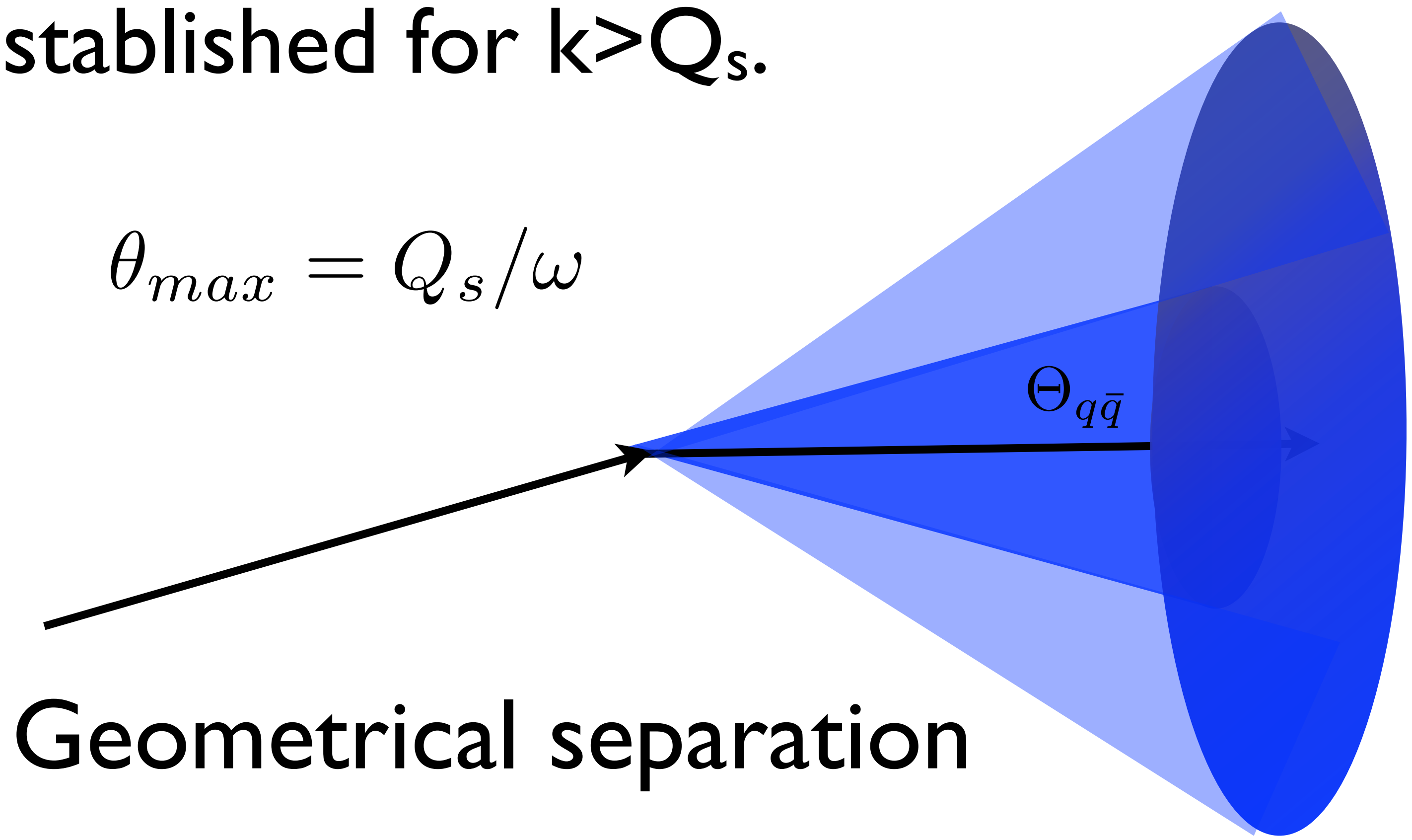

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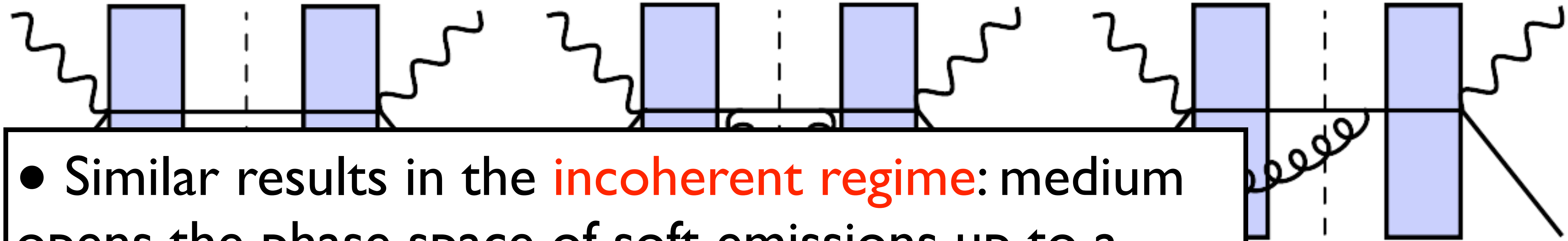
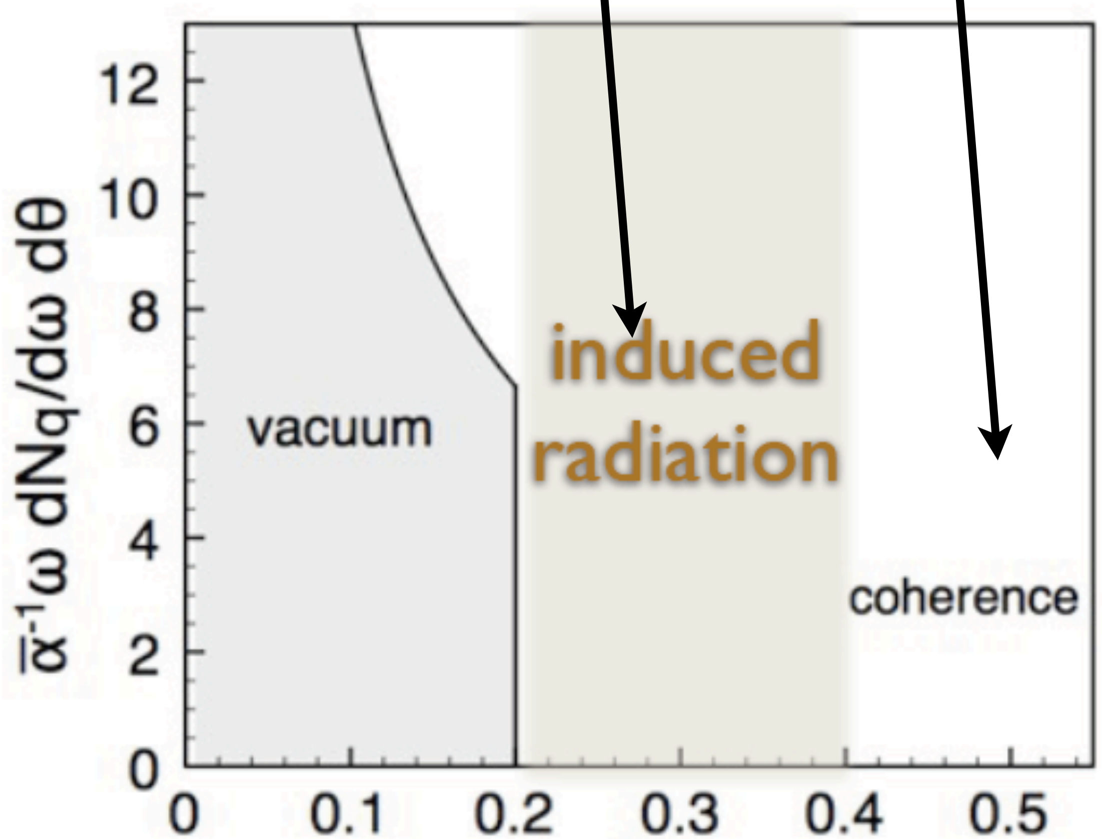


- Similar results in the incoherent regime: medium opens the phase space of soft emissions up to a maximum angle.

- Interferences suppressed for $k<Q_s$.
- Vacuum coherent pattern reestablished for $k>Q_s$.

$\omega \to 0$



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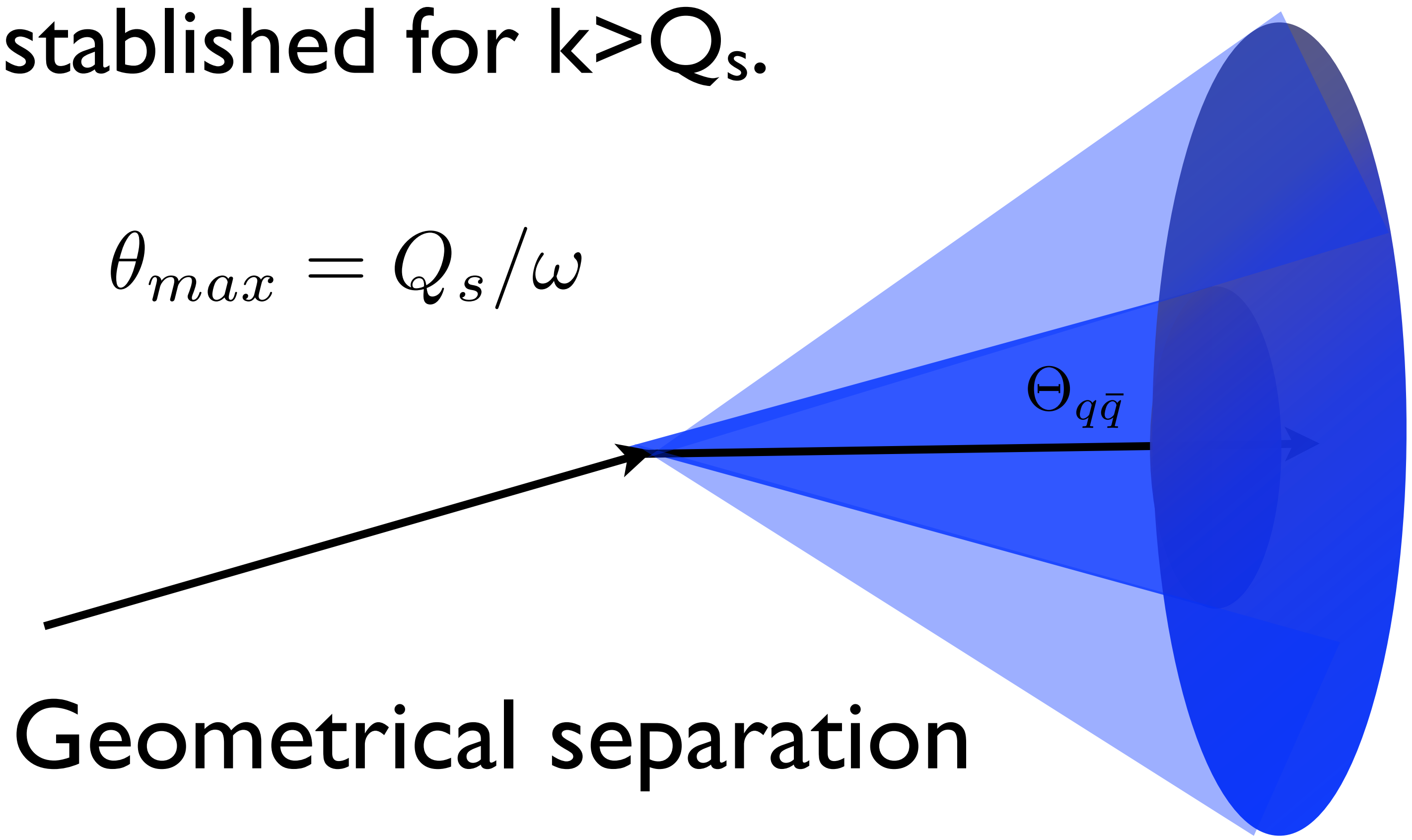


Geometrical separation

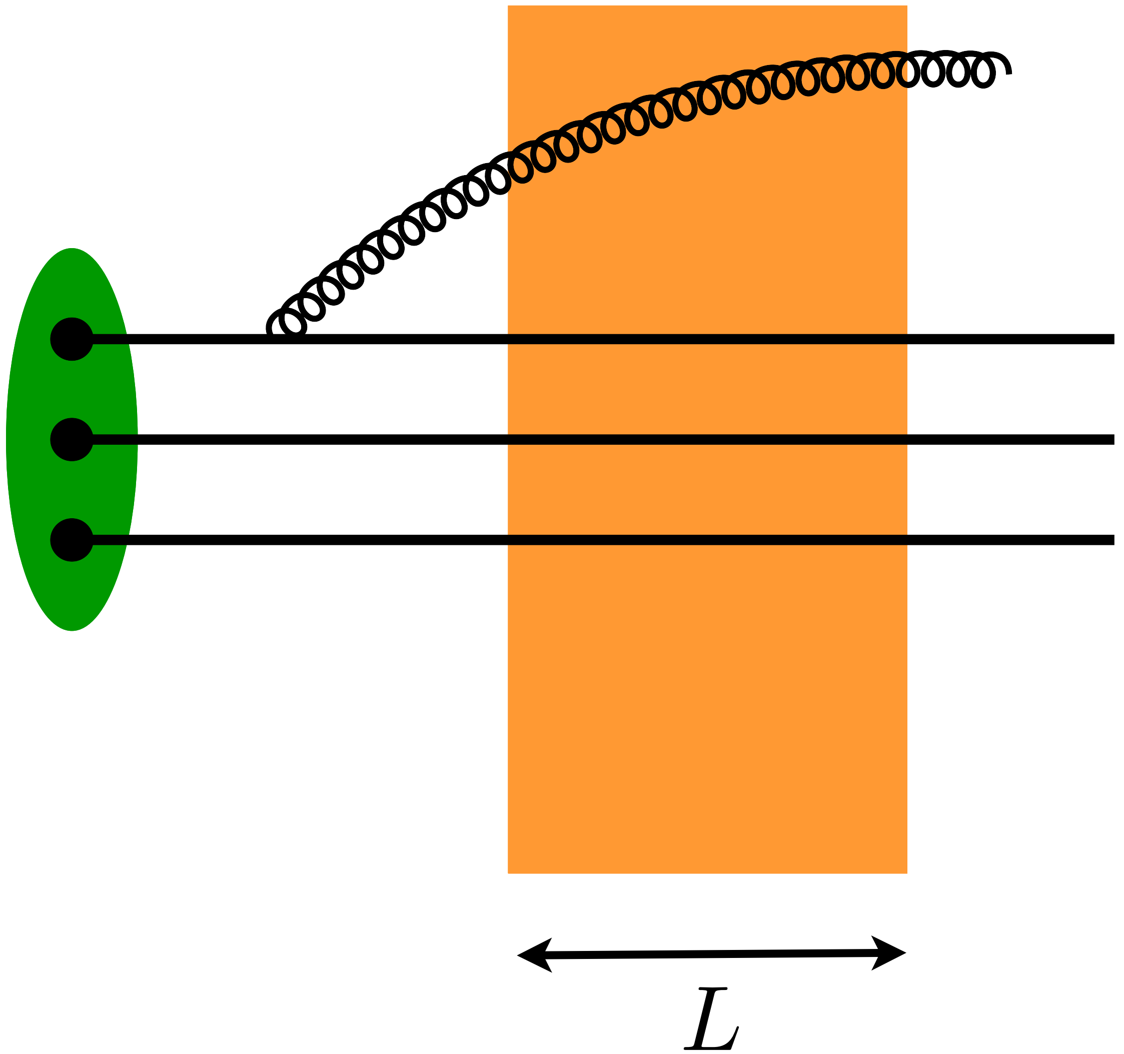
Contents:

Aim:

- Apply the same techniques for forward particle production in pA: incoming complex object.

- Compare with CGC results: k_T factorisation (Kovchegov et al '98, '01; NLO calculations in Chirilli et al '11), hydrid formalism (Dumitru et al '05; Altinoluk et al '11).

- Consider deviations from the totally coherent limit: finite length or energy corrections.



Related works of Kopeliovich et al, Strikman et al, Kaidalov et al.

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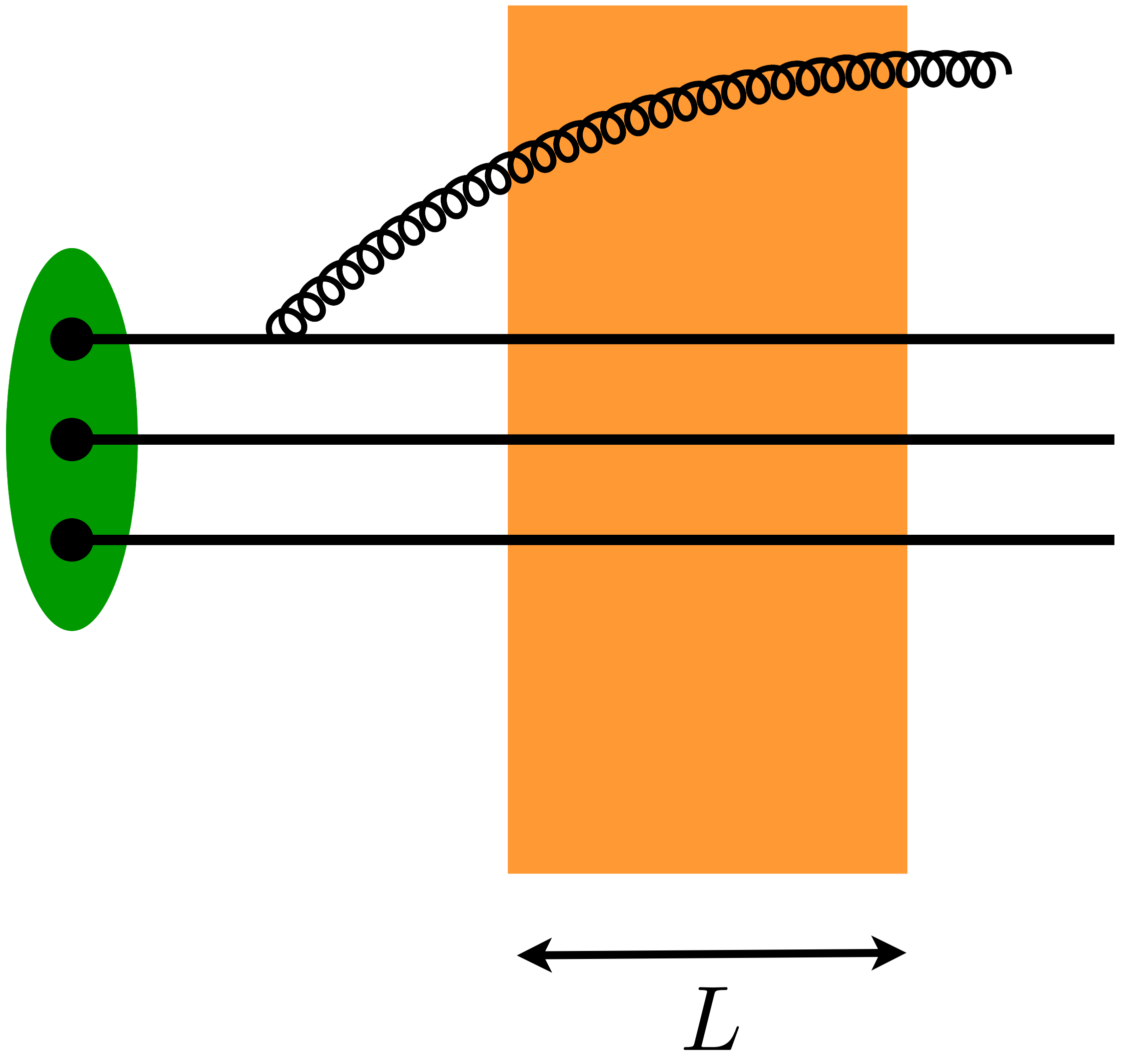

• Projectile described in the parton model (dilute).

• Target as a Gaussian ensemble of colour configurations (dense).

• Gluon follows a non-eikonal trajectory.

Coherent limit (high energy):

Probability for soft gluon emission

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

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

Gluon scattering with colour configuration of the target

Projectile distribution

- Consistency check: we recover the k_T factorised formula.

- Obtainable from the previous results by setting $\theta_{qq}=0$.

- From this, we can get the so-called elastic and inelastic pieces in the hybrid formalism.

Generalisation to finite energy:

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

Probability to emit a soft gluon

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

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

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

Scattering probability of the partonic system

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

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

- This equation contains, in a factorised form, both finite length (energy) corrections and colour correlation effects.
- To be further elaborated...

Generalisation to finite energy:

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

Probability to emit a soft gluon

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

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

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

Projectile distribution

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Summary:

- We have studied the medium effects on the interference pattern between initial and final state radiation.

- Colour decoherence opens the phase space for large angle soft emissions, forbidden in the vacuum: change of multiplicities.

- We are currently studying, within the same formalism, particle production in pA, recovering k_T factorisation in the high-energy limit and the corrections due to finite energies.

- **Outlook**:

  → Phenomenological consequences on jet production in the forward region in pA and AA.

  → Hybrid formalism beyond the high-energy limit.

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Thank you very much for your attention!!!

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