

Probing the dynamics of color coherence with energy correlators

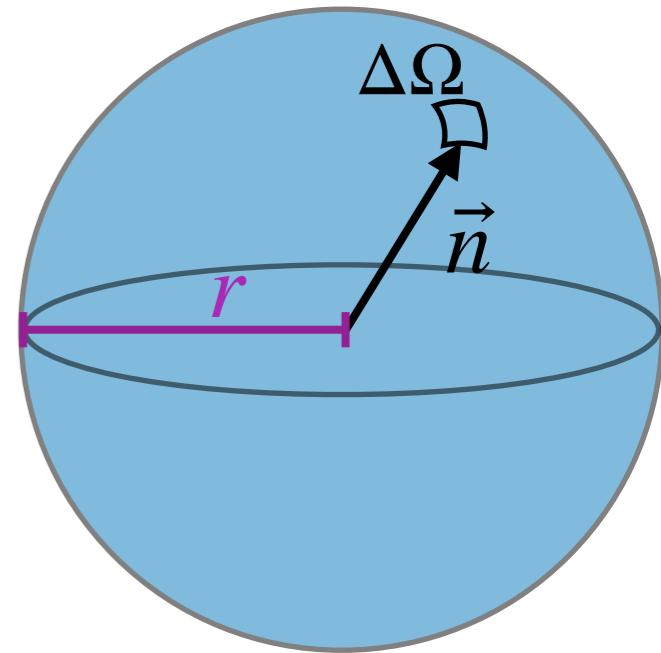
Carlota Andres (she/her)
CPHT, École polytechnique

Quark Matter 2023
Houston, Septemer 3-9 2023

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, arXiv: [2209.11236](https://arxiv.org/abs/2209.11236)
CA, Dominguez, Holguin, Marquet, Moult, arXiv: [2303.03413](https://arxiv.org/abs/2303.03413)



Energy correlators



- Correlators $\langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \cdots \mathcal{E}(\vec{n}_k) \rangle$ of the energy flux:

$$\mathcal{E}(\vec{n}) = \lim_{r \rightarrow \infty} \int dt r^2 n^i T_{0i}(t, r\vec{n})$$

- 1-point correlator: $\langle \mathcal{E}(\vec{n}) \rangle \propto \sum_i E_i$ Total energy flux through an area element
- 2-point correlator:

Inclusive cross section to produce two particles i and j

Energy weights

Hard scale of the process

$$\frac{\langle \mathcal{E}^n(\vec{n}_1) \mathcal{E}^n(\vec{n}_2) \rangle}{Q^{2n}} = \frac{1}{\sigma} \sum_{ij} \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j} \frac{E_i^n E_j^n}{Q^{2n}} \delta^{(2)}(\vec{n}_i - \vec{n}_1) \delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

2-point correlator

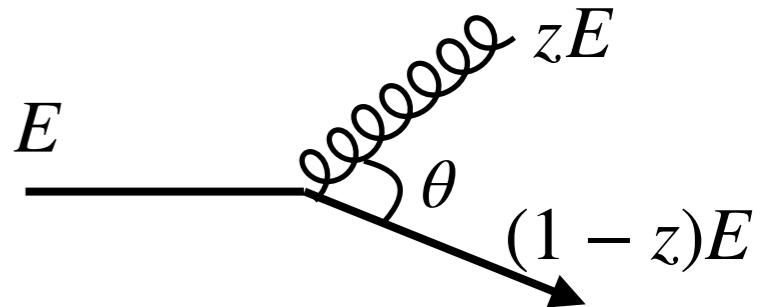
- As function of the relative angle only:

$$\frac{d\Sigma^{(n)}}{d\theta} = \int d\vec{n}_{1,2} \frac{\langle \mathcal{E}^n(\vec{n}_1) \mathcal{E}^n(\vec{n}_2) \rangle}{Q^{2n}} \delta^{(2)}(\vec{n}_1 \cdot \vec{n}_2 - \cos \theta)$$

- Infrared and collinear safe for $n = 1$
- For divergences $1 < n \leq 2$ can be absorbed into track or fragmentation functions
- 2-point correlator (EEC) for a massless quark jet: $Q = E$

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \frac{d\sigma_{qg}}{dz d\theta} z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

Inclusive cross section



μ_s a softer scale over which the cross section is inclusive

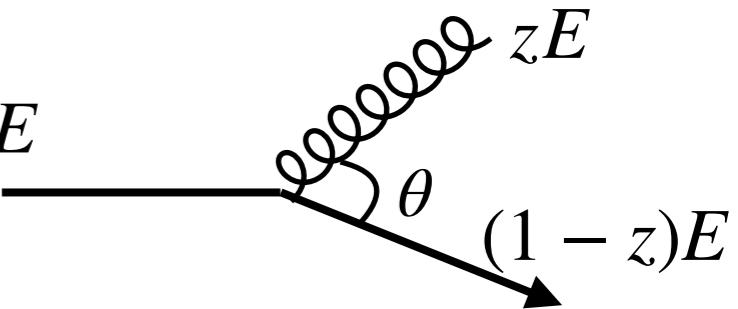
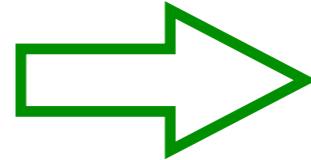
- Reduced sensitivity to soft physics**
- Additional **energy loss** ($E_q + E_g \neq E$) is **subleading**
- qq and gg contributions are higher order

EEC in vacuum

(In the perturbative regime)

- EEC for a **massless** quark jet in **vacuum** at LO:

$$\frac{d\sigma_{qg}^{\text{vac}}}{dz d\theta} = \frac{\alpha_s C_F \sigma}{\pi} \frac{1 + (1 - z)^2}{z \theta} + \mathcal{O}(\alpha_s^2, \theta)$$



$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- EEC for a massless quark jet in **vacuum** at NLO + NLL resummation:

$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

Power-law behavior

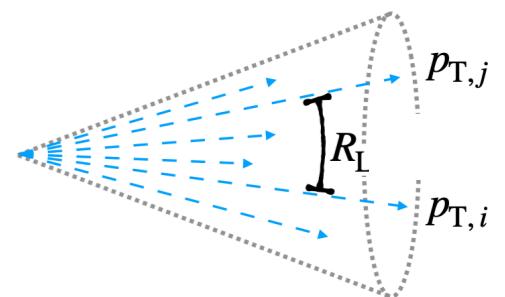
$\gamma(3)$: twist-2 spin-3 QCD anomalous dimension

Hoffman, Maldacena, [0803.1467](#)
Chen, Moult, Sandor, Zhu, [2202.04085](#)

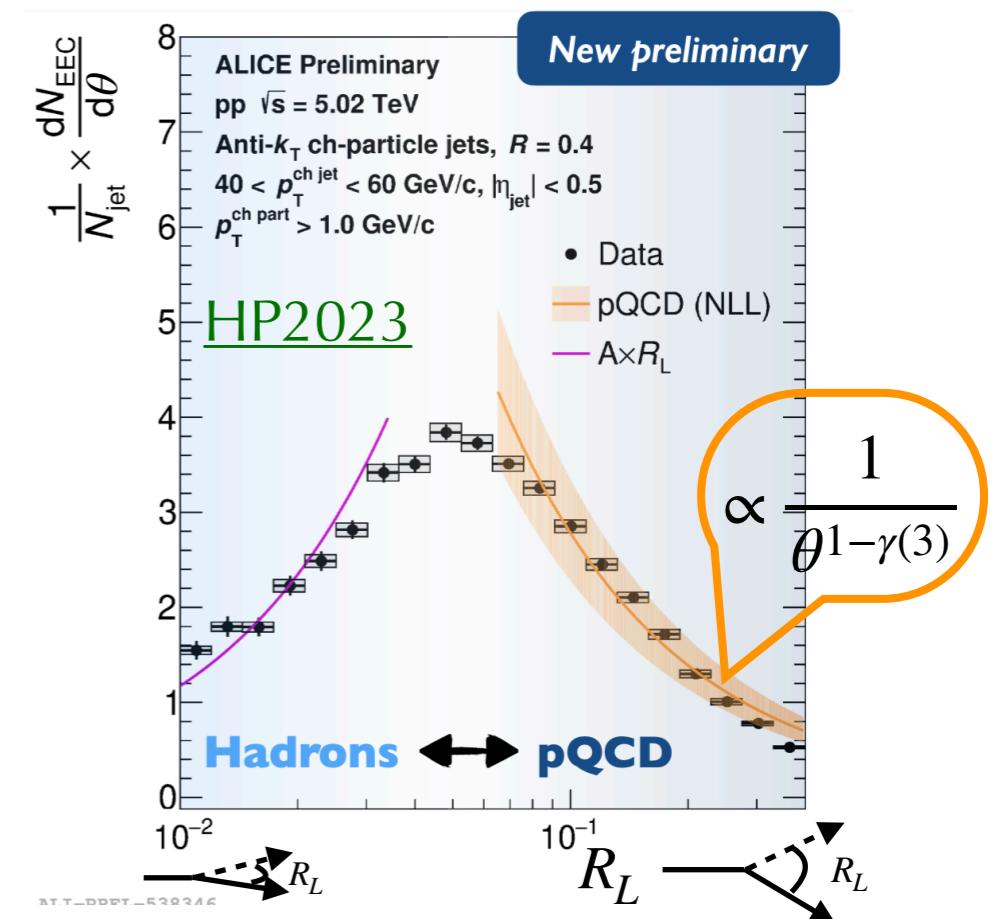
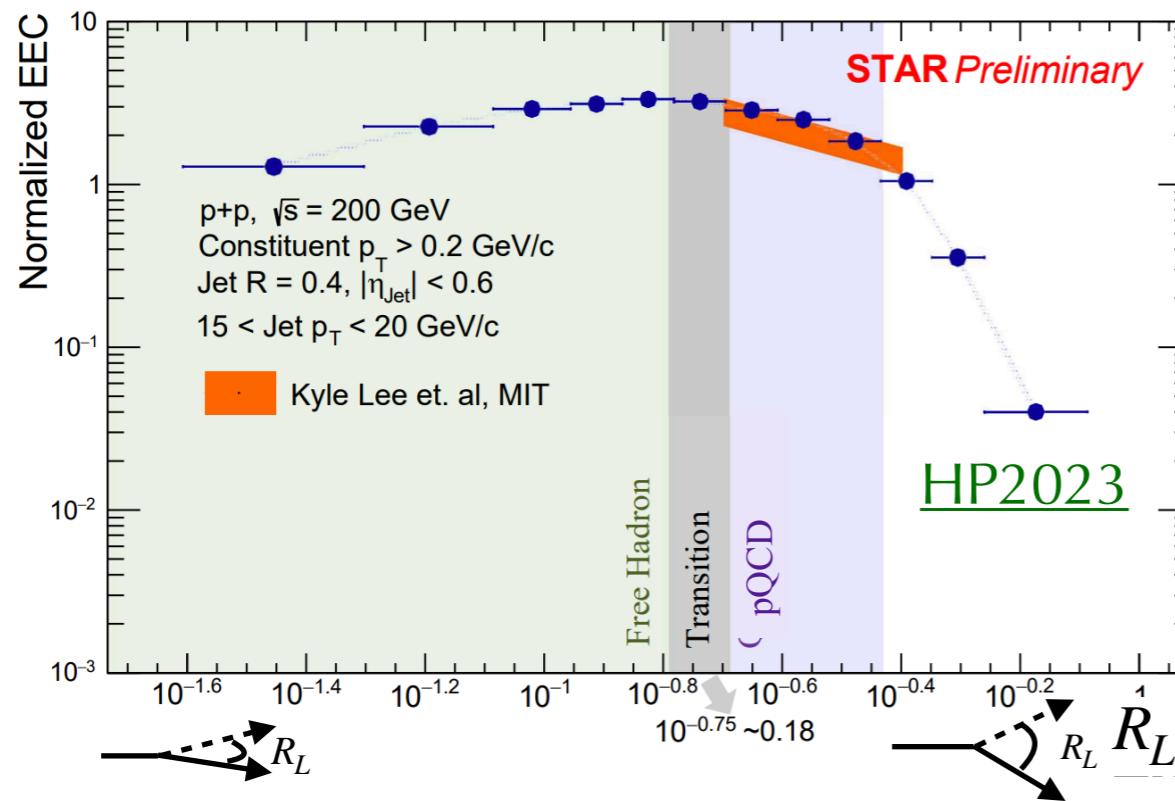
- Higher-orders, uncorrelated soft background, quark/gluon ratios can change the overall normalization but not the power-law behavior

EEC in vacuum

$$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



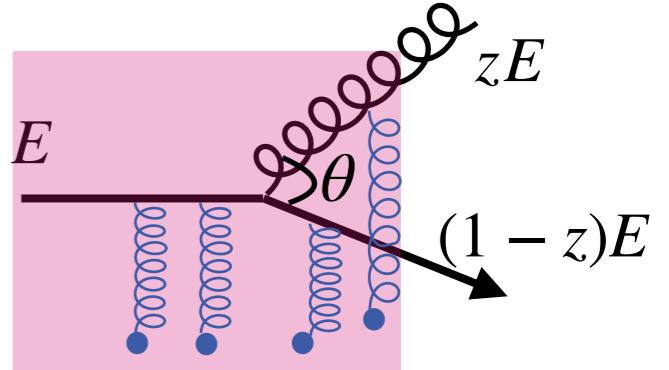
- First measurements of the EEC in p-p collisions announced in HP2023



- Clear separation between perturbative and non-perturbative regimes
- p-p baseline under control (good agreement with pQCD predictions)
- Reduced sensitivity to soft physics

Komiske, Moult, Thaler, Zhu [2201.07800](https://arxiv.org/abs/2201.07800)

EEC in HICs



- EEC for a **heavy-ion** jet initiated by a **massless quark**:

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \frac{d\sigma_{qg}}{dz d\theta} z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

See also:
Barata, Milano, Sadofyev
[2308.01294](#)

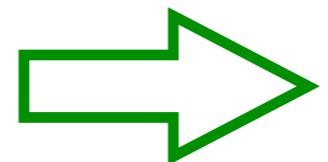
- We can always define F_{med} such as

$$\frac{d\sigma_{qg}}{d\theta dz} = (1 + F_{\text{med}}(z, \theta)) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} \quad F_{\text{med}}(z, \theta) \xrightarrow{\theta < \theta_L} 0$$

- We do not expect medium modification at small angles, thus vacuum collinear resummation should still be valid

$$\frac{d\Sigma^{(n)}}{d\theta} = \left(\frac{1}{\sigma_{qg}} \int dz (g^{(n)}(\theta, \alpha_s) + F_{\text{med}}(z, \theta)) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} z^n (1-z)^n \right) \left(1 + \mathcal{O}\left(\frac{\bar{\mu}_s}{Q}\right) \right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta Q}\right)$$

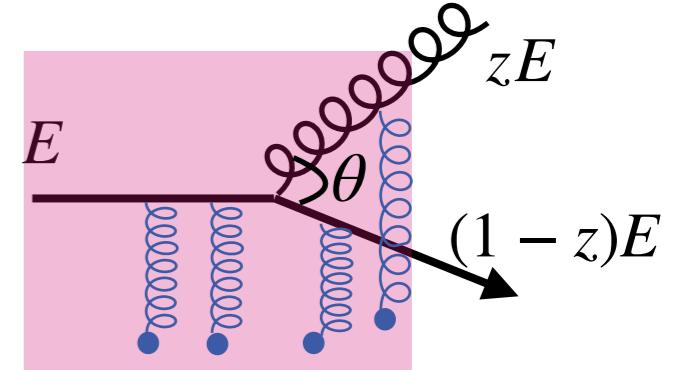
$$g^{(1)}(\theta, \alpha) = \theta^{\gamma(3)} + \mathcal{O}(\theta)$$



$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}^{\text{vac}}$$

For energy loss effects see:
Barata, Mehtar-Tani, [2307.08943](#)

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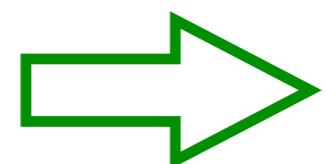
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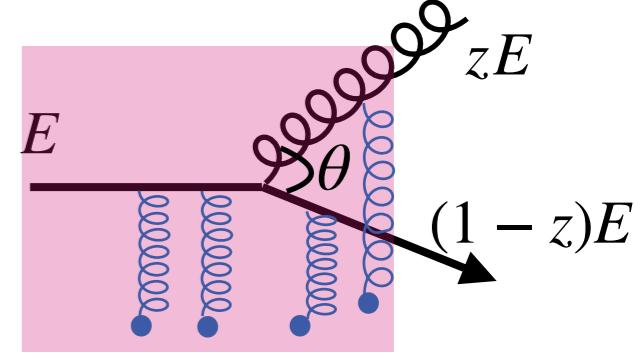
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Our idealized model



- Multiple medium scatterings destroy the color coherence between the daughter partons
- Complete (multiple scatterings) medium-induced emission spectrum **keeping z and θ not yet available**
 - Recent results for the $\gamma \rightarrow q\bar{q}$ case (computationally costly) Isaksen, Tywoniuk, [2303.12119](#)
 - We **use a semi-hard** splittings (z not too small)
 - All partons propagate along straight line trajectories
 - Dominguez, Milhano, Salgado, Tywoniuk, Vila, [1907.03653](#)
 - Isaksen, Tywoniuk [2107.02542](#)
- **Static brick** with length L
- **Harmonic oscillator** (HO) approximation employed $n\sigma(r) \approx \hat{q}r^2/2$
- The strength of the interactions is encoded in the **jet quenching parameter \hat{q}** , which measures the average transverse momentum transferred per unit length

Time and angular scales (HO)

- For a static medium of length L within the HO one can read off the relevant scales directly from the formulas:

2 competing angular scales: θ_L and θ_c

- (Vacuum) formation time:

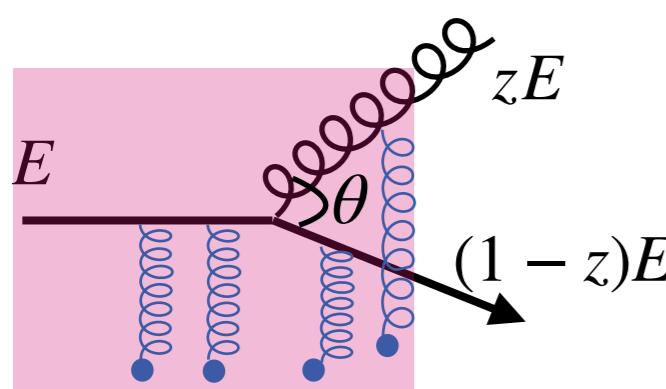
$$t_f = \frac{2}{z(1-z)E\theta^2} \xrightarrow{t_f \leq L} \theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

- Decoherence time:

$$S_{12}(\tau) = e^{-\frac{1}{12}\hat{q}(1+z^2)\theta^2\tau^3} \quad t_d \sim (\hat{q}\theta^2)^{-1/3} \xrightarrow{t_d \leq L} \theta_c \sim (\hat{q}L^3)^{-1/2}$$

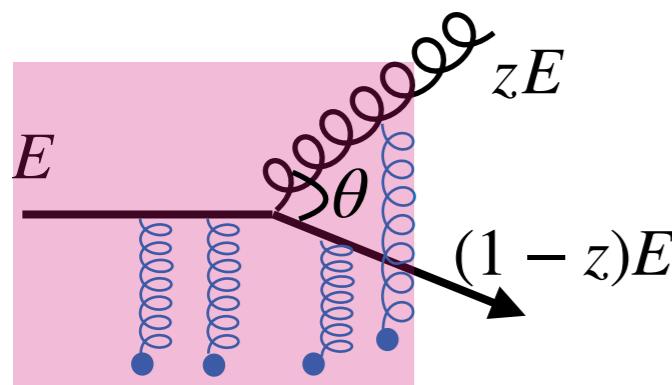
Below θ_c splittings do not color decohere and the medium does not resolve them



If $\theta_L > \theta_c$: θ_c becomes irrelevant

Time and angular scales (HO)

Can be extended to include a more **realistic interactions or expanding media**, but then we would not know the scales directly from the equations

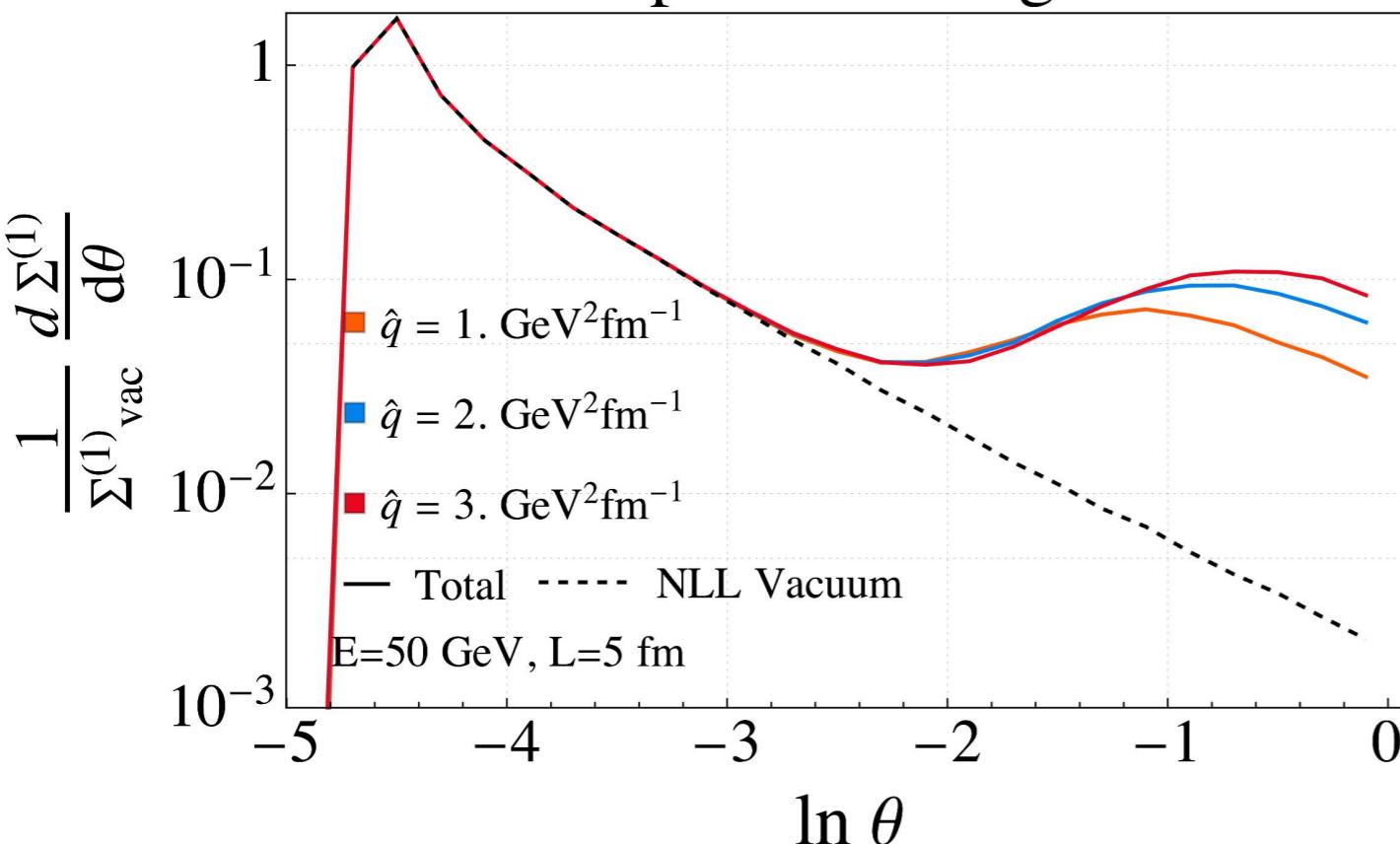


If $\theta_L > \theta_c$: θ_c becomes irrelevant

Results HO

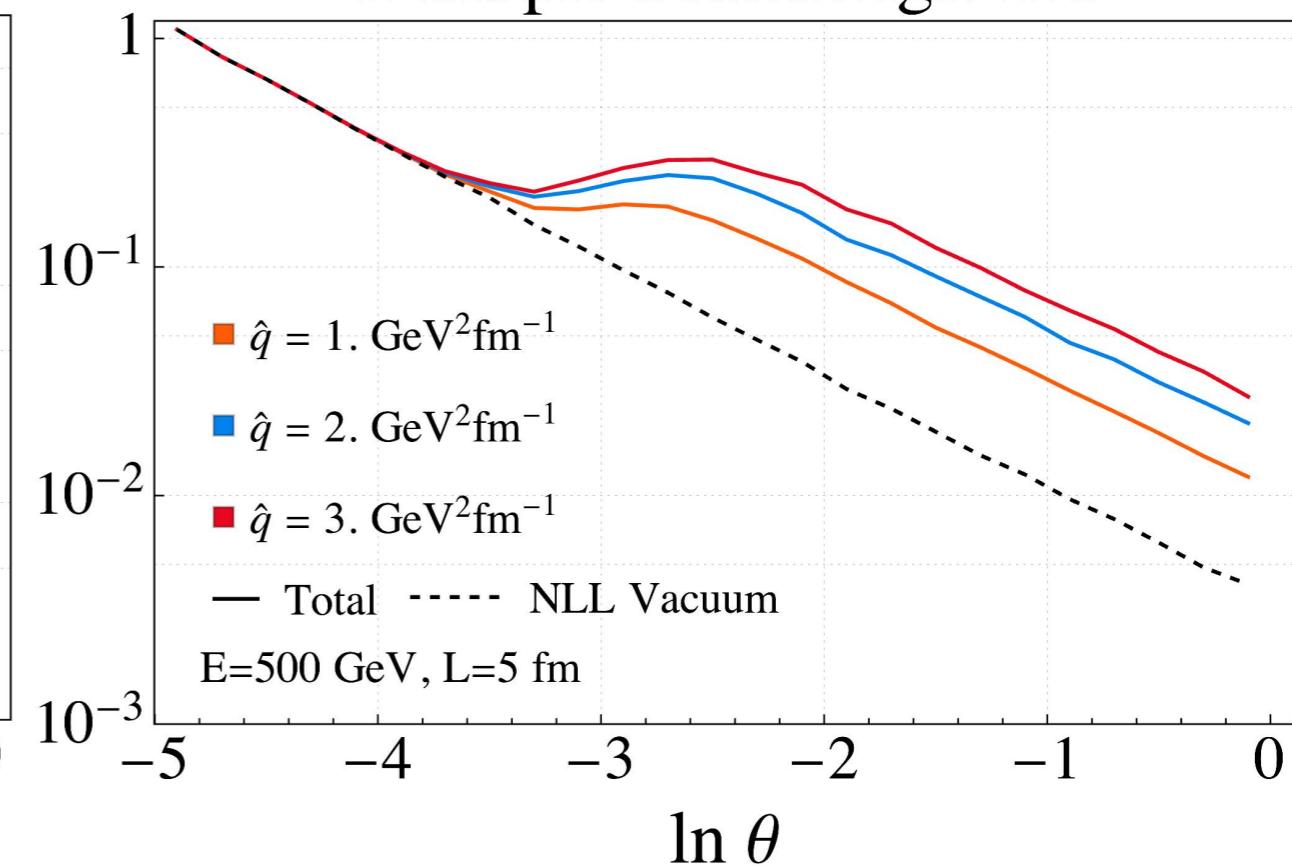
$$\theta_L \gg \theta_c (E \ll \hat{q}L^2)$$

Two–Point Energy Correlator
Multiple Scatterings: HO



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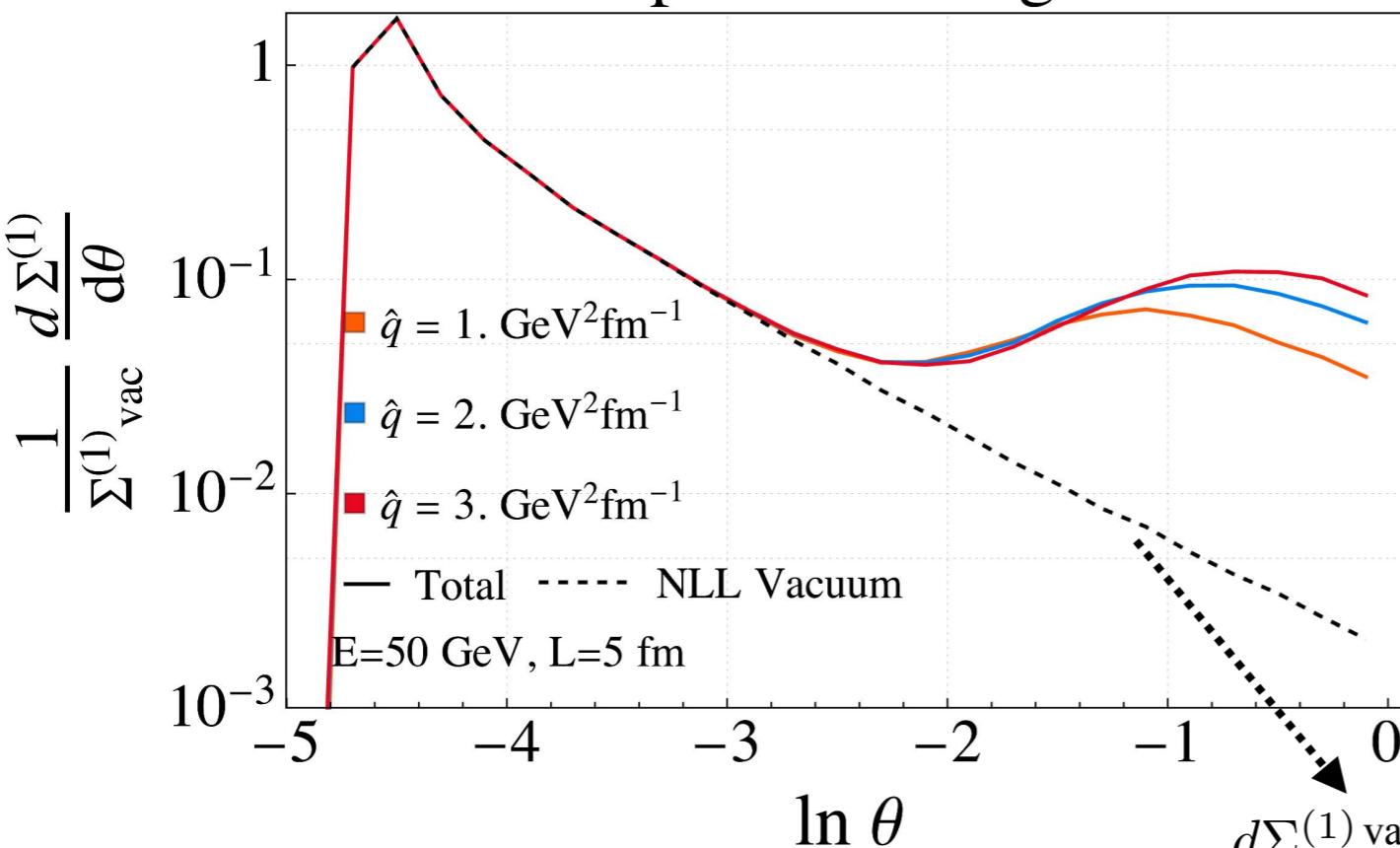
Two–Point Energy Correlator
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Results HO

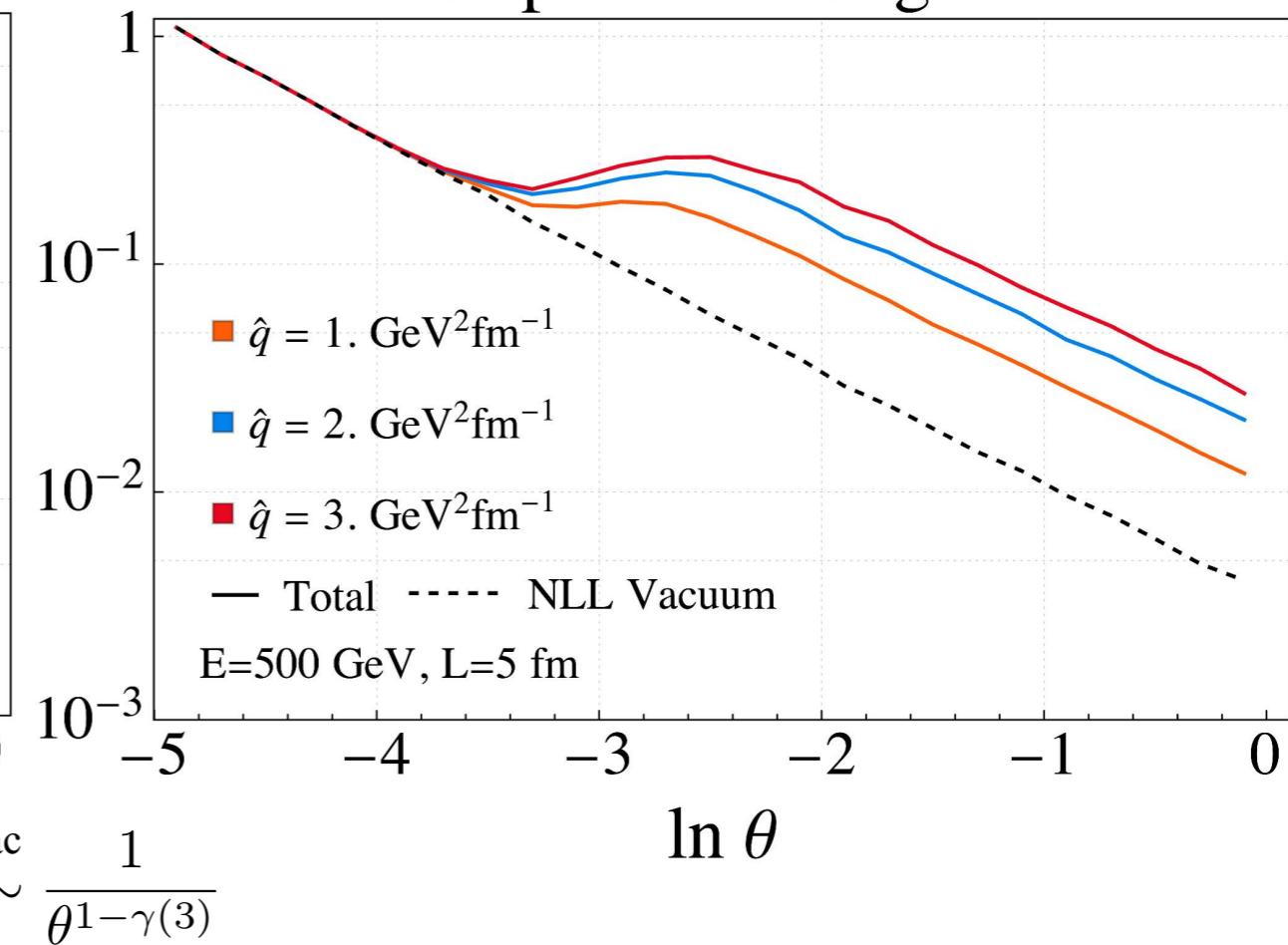
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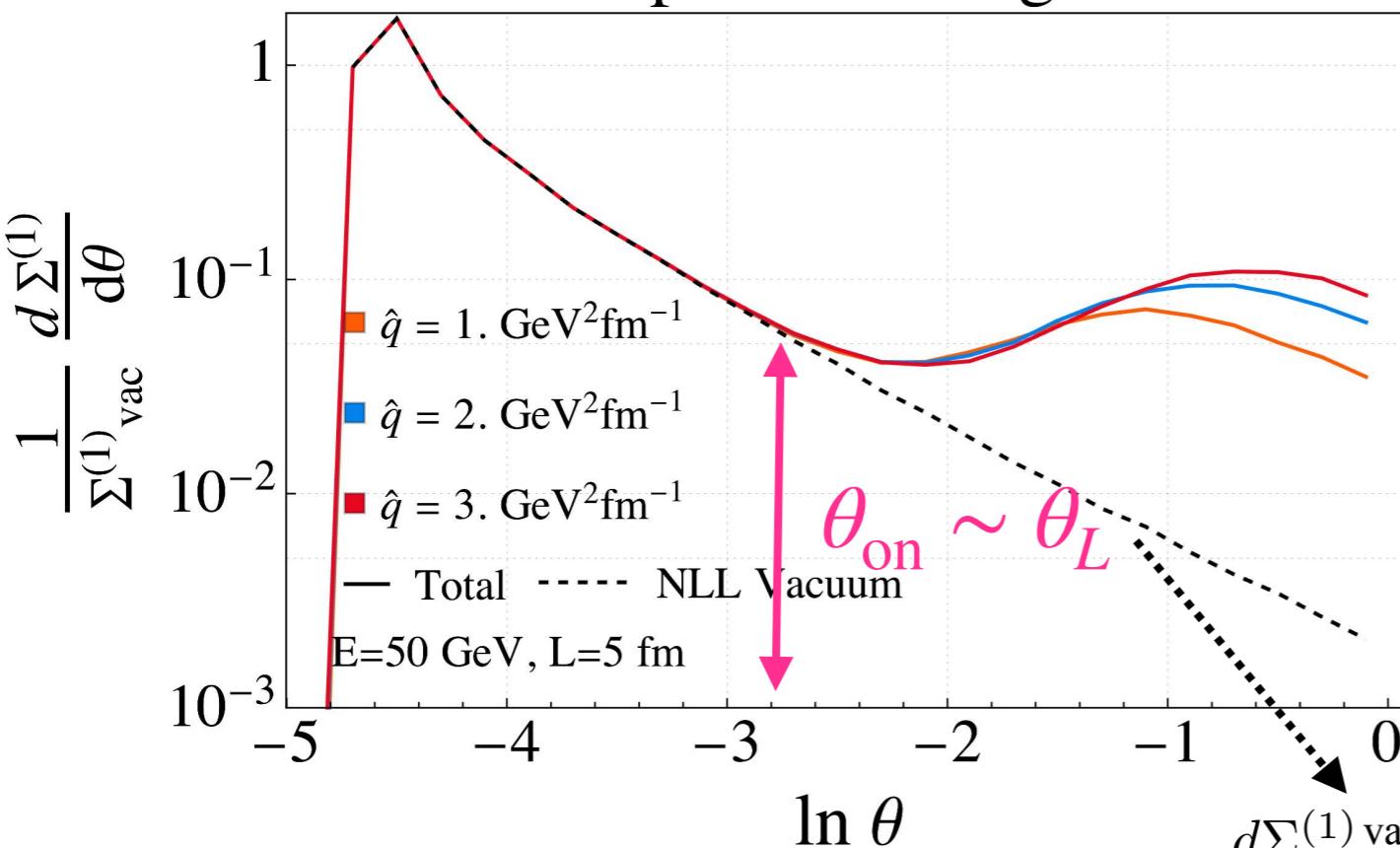
$$\frac{d\Sigma^{(1)}_{\text{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

- No medium-induced enhancement at small angles

Results HO

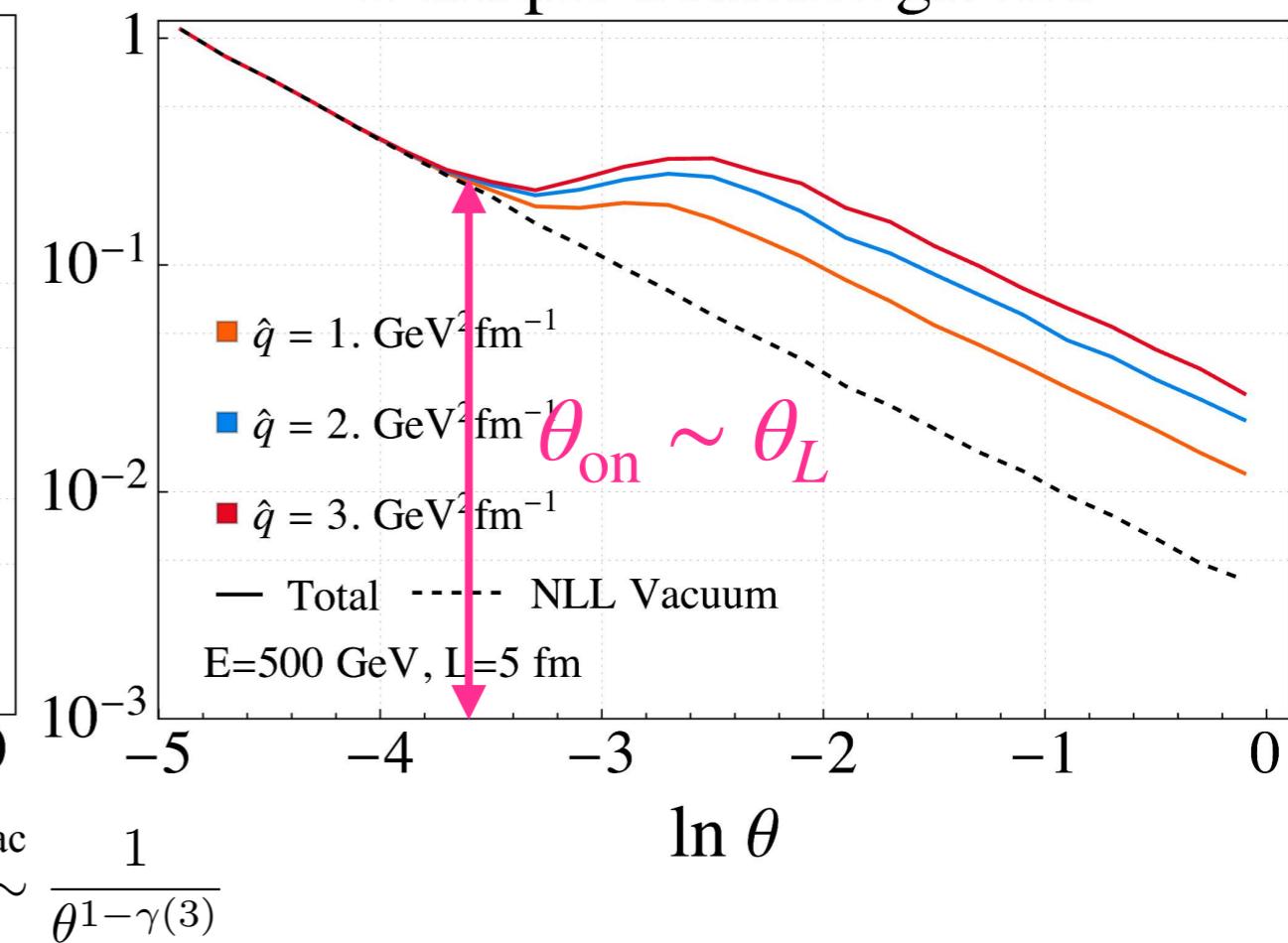
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Two–Point Energy Correlator
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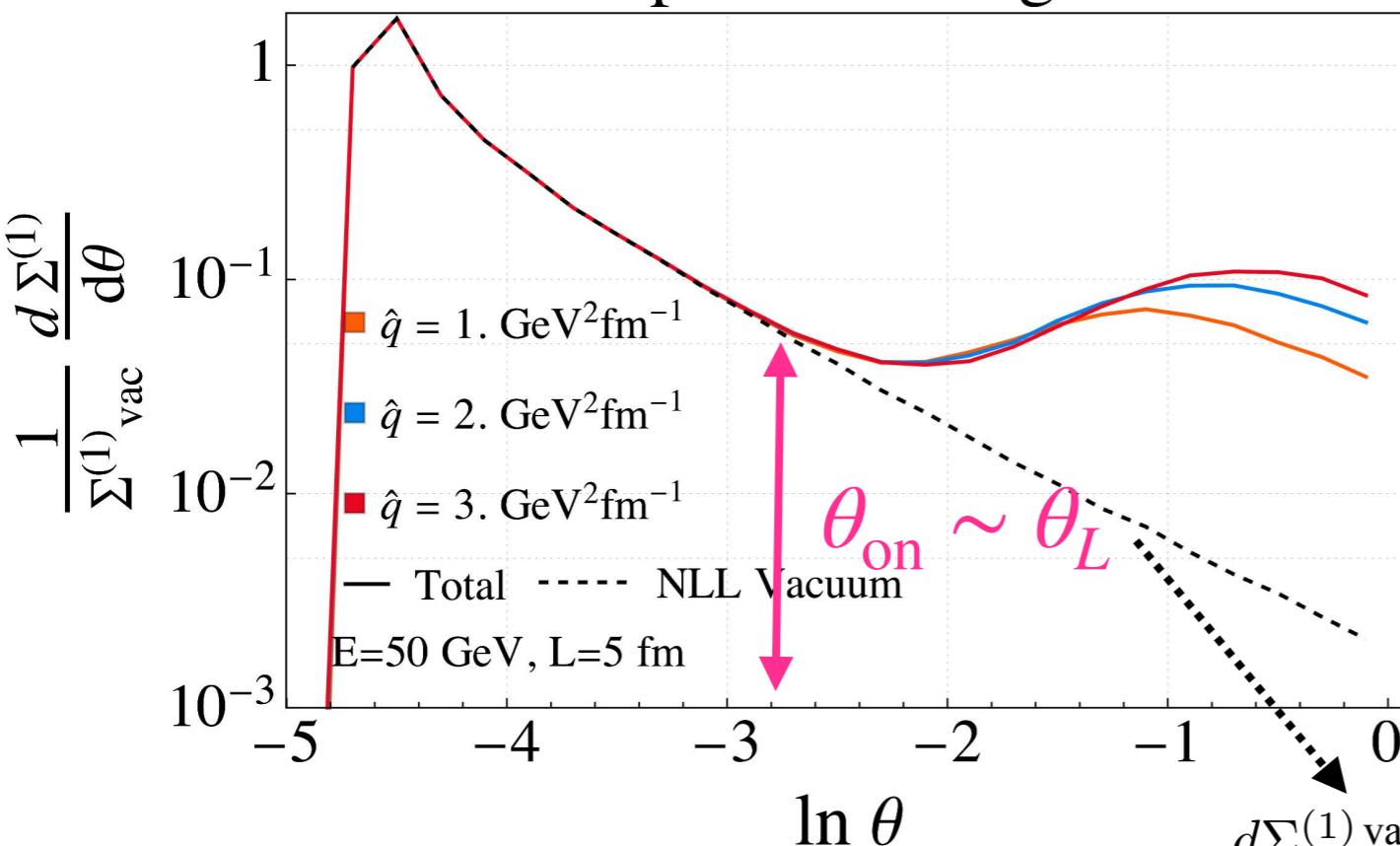
$$\frac{d\Sigma^{(1)}_{\text{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

- No medium-induced enhancement at small angles
- Onset angle seems to be independent of \hat{q}

Results HO

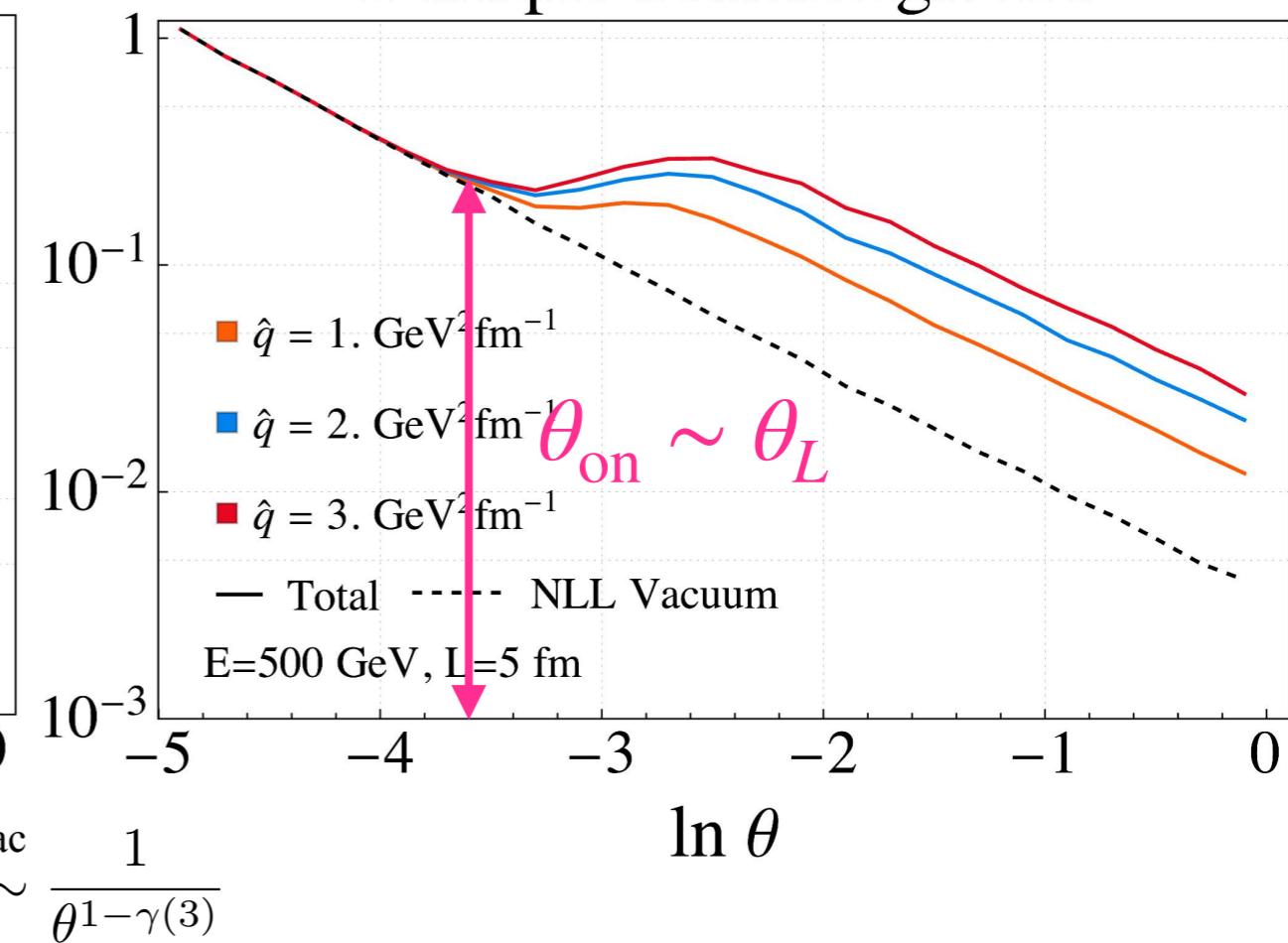
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Two–Point Energy Correlator
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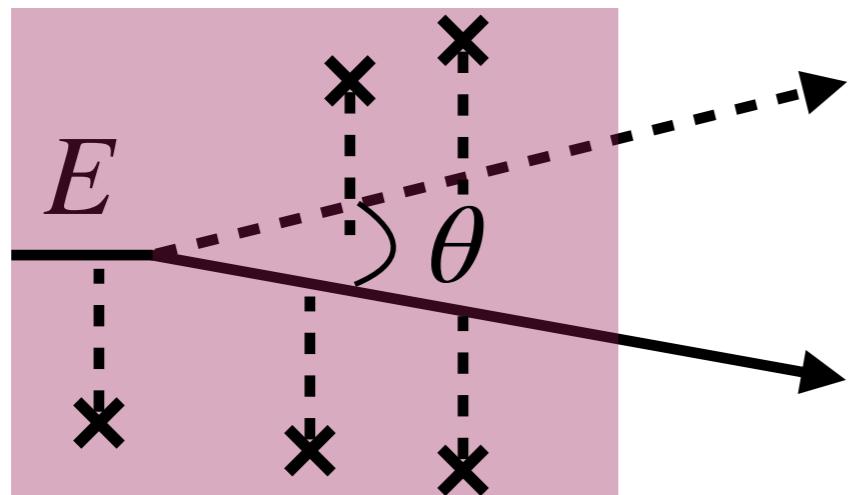
Two–Point Energy Correlator
Multiple Scatterings: HO



- No medium-induced enhancement at small angles
- Onset angle seems to be independent of \hat{q}
- Varying \hat{q} has different effects in the two regimes

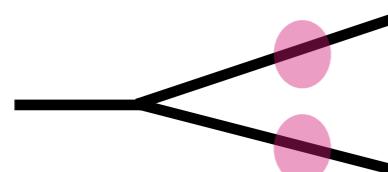
Interpretation

$$\theta_L \gg \theta_c \quad (E \ll \hat{q}L^2)$$

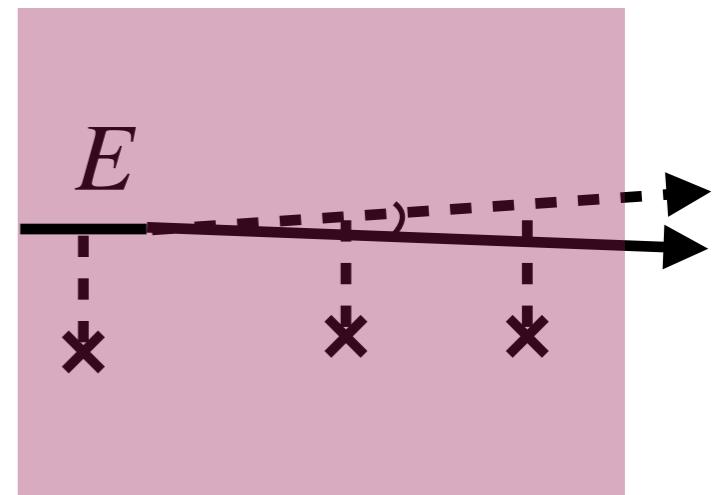


For $\theta \gg \theta_L \Rightarrow \theta \gg \theta_c$

The medium resolves the emission

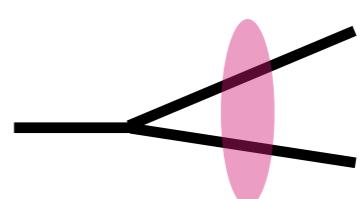


$$\theta_L \ll \theta_c \quad (E \gg \hat{q}L^2)$$

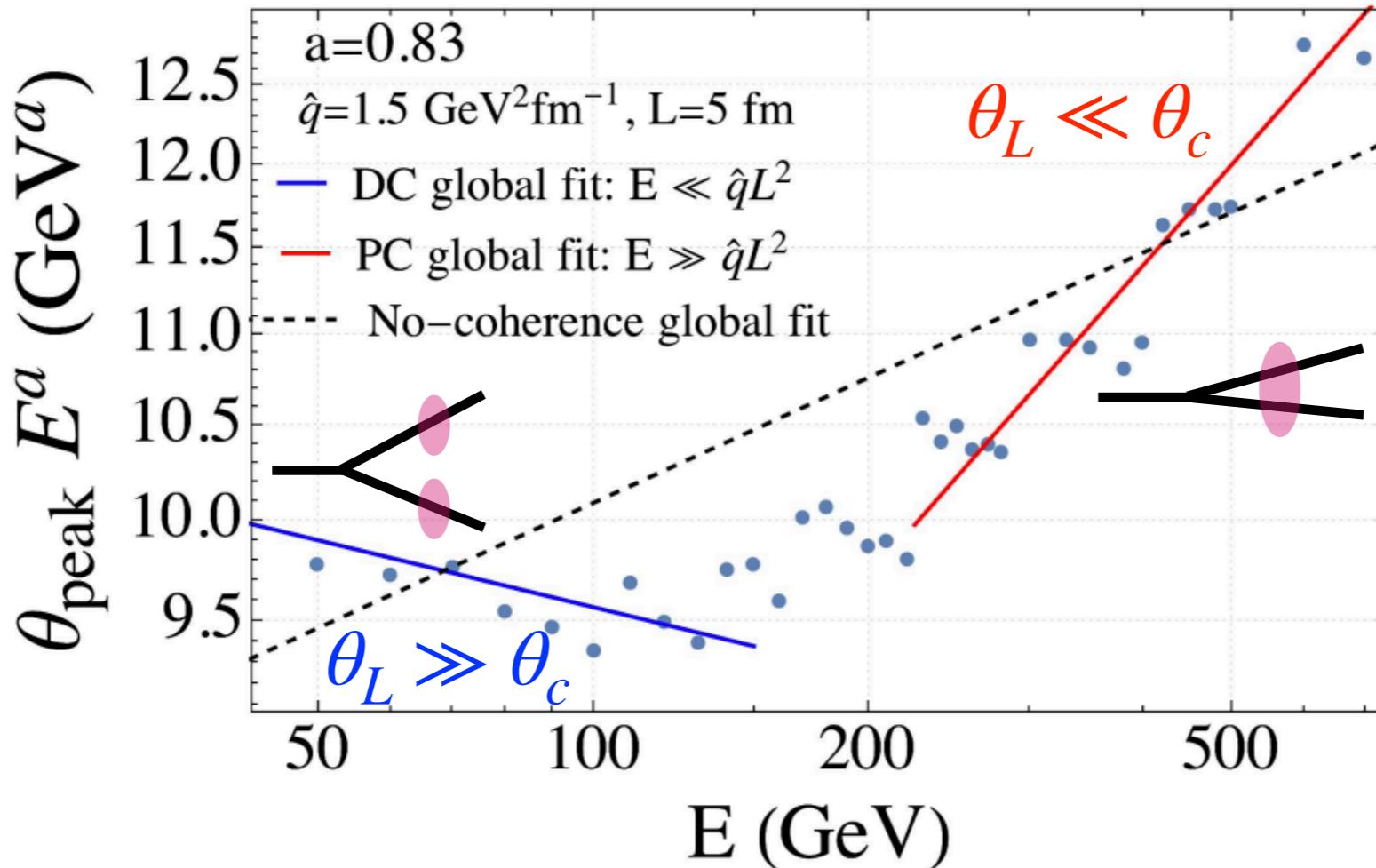


For $\theta_c \gg \theta \gg \theta_L$:

The medium does NOT resolve the emission



Coherence transition

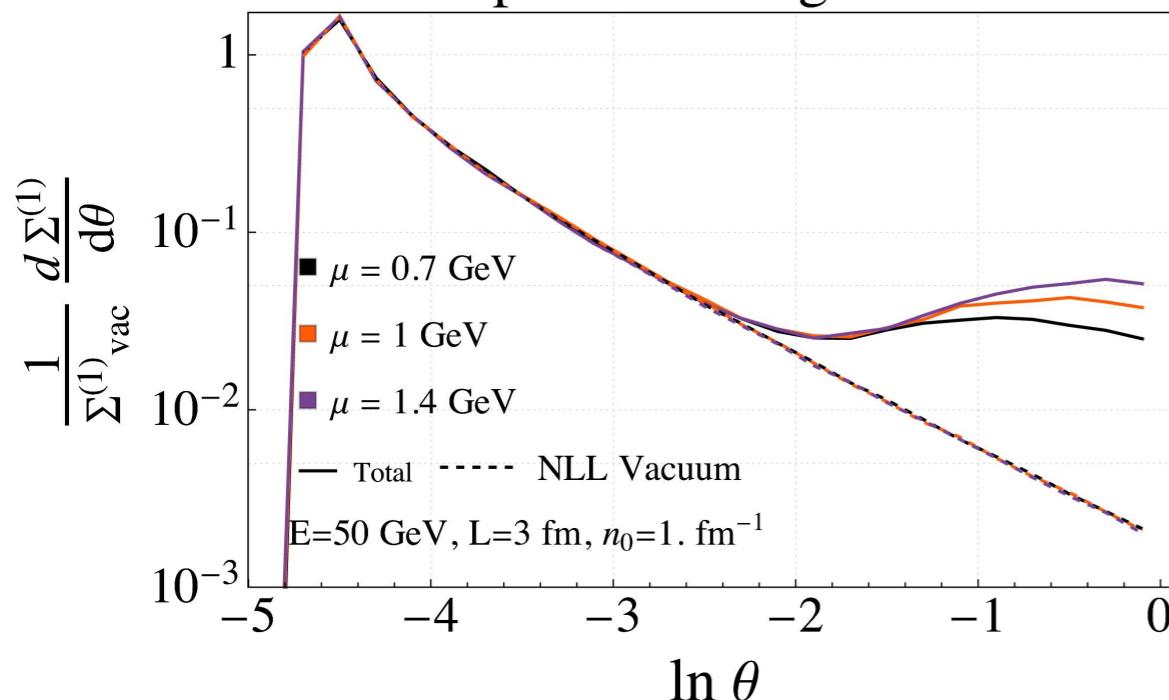


- Extracted the peak angle θ_{peak} for 332 sets of parameters with $E \in [50, 700] \text{ GeV}$, $L \in [0.2, 10] \text{ fm}$, $\hat{q} \in [1, 3] \text{ GeV}^2/\text{fm}$
- Performed **separate fits in the two different regions** for the scaling behavior of the peak angle with respect to the 3 parameters

Results with a Yukawa interaction

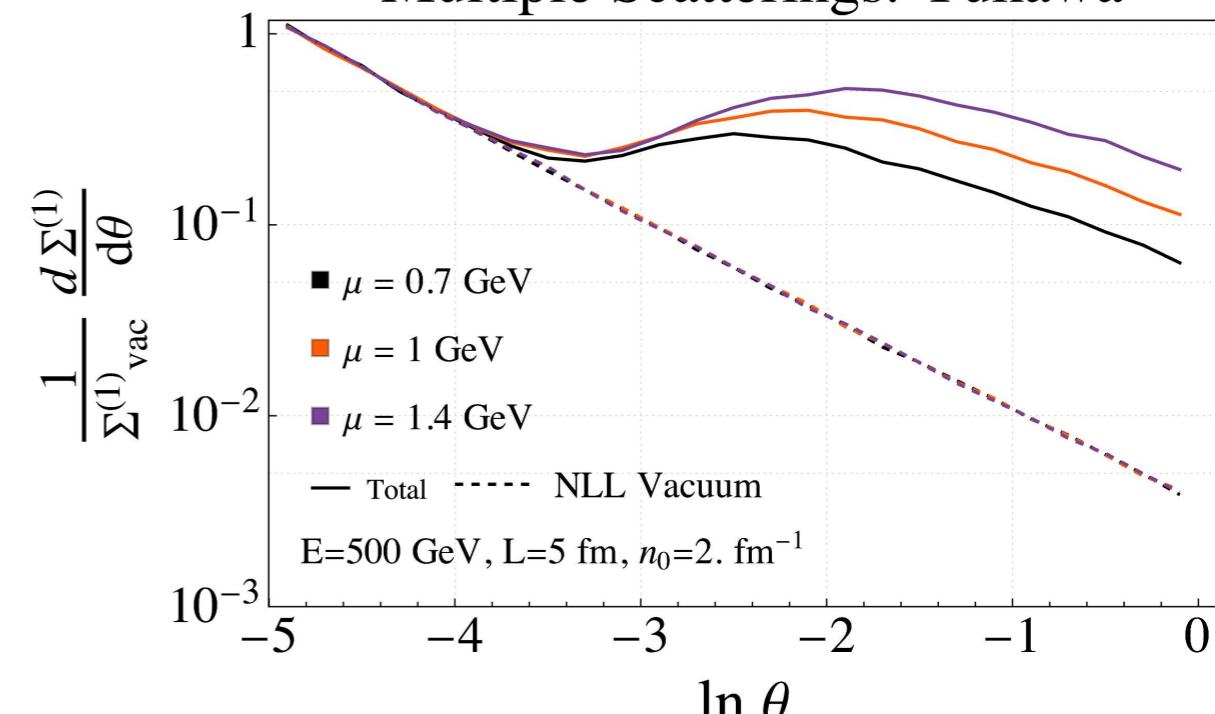
$$\theta_L \gg \theta_c$$

Two–Point Energy Correlator
Multiple Scatterings: Yukawa



$$\theta_L \ll \theta_c$$

Two–Point Energy Correlator
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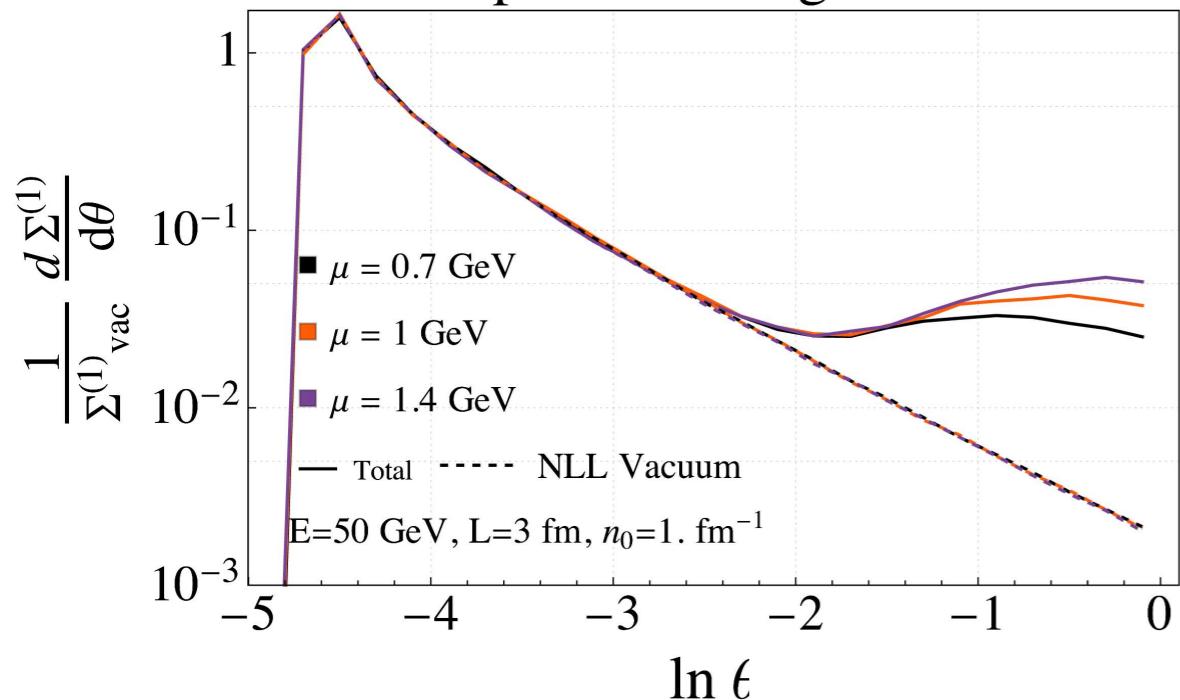
$$V_{\text{yuk}}(\mathbf{q}) = \frac{8\pi\mu^2}{(\mathbf{q}^2 + \mu^2)^2}$$

$$\sigma(\mathbf{q}) \equiv - V(\mathbf{q}) + (2\pi)^2 \delta^2(\mathbf{q}) \int_l V(l)$$

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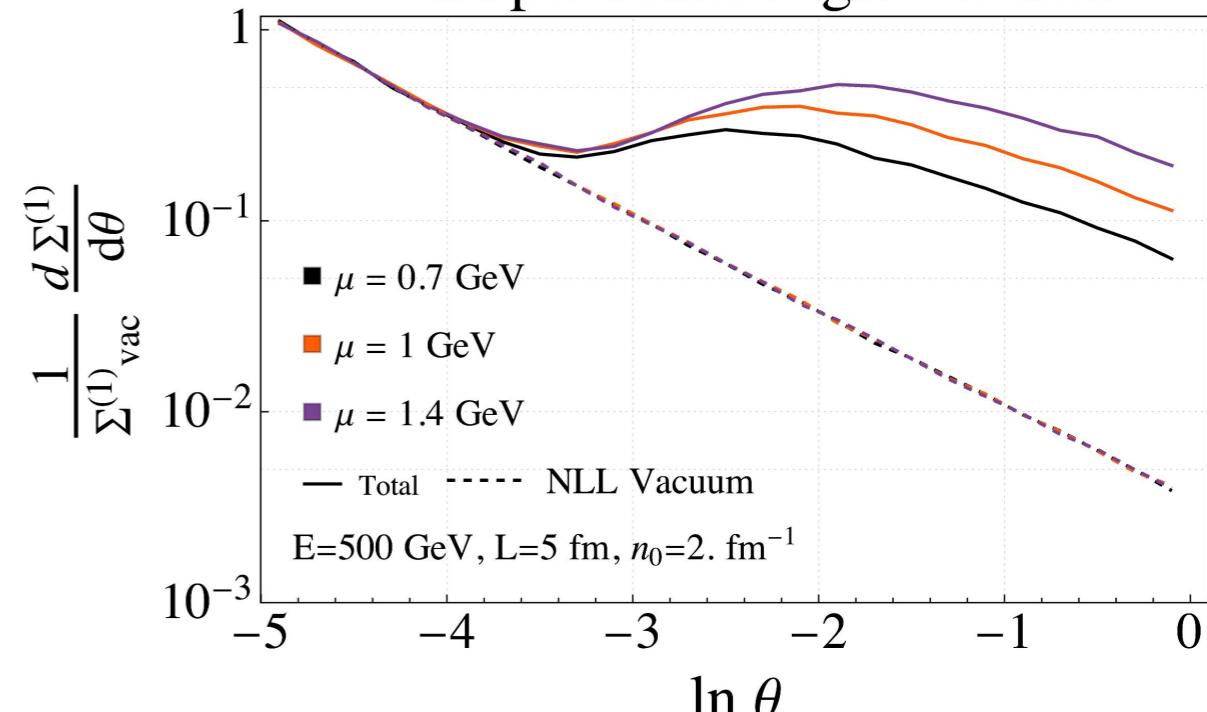
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Two-Point Energy Correlator
Multiple Scatterings: Yukawa



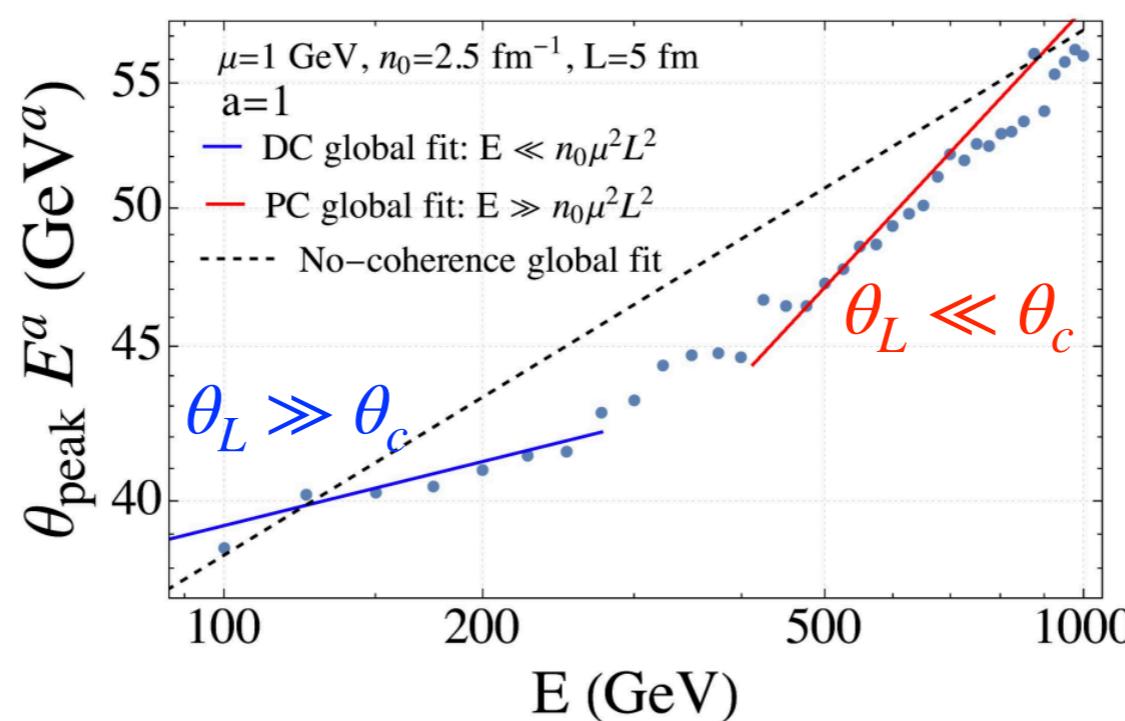
$$\theta_L \ll \theta_c$$

Two-Point Energy Correlator
Multiple Scatterings: Yukawa



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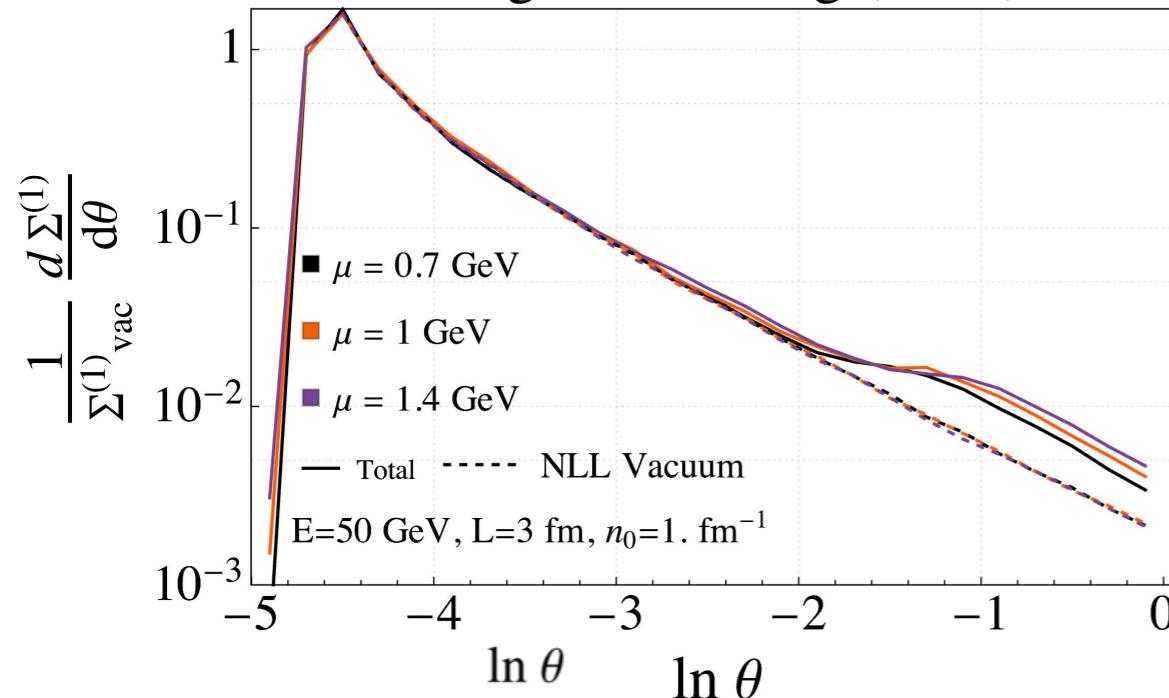


Onset of color
coherence is NOT
a feature of the HO
approximation

Results GLV

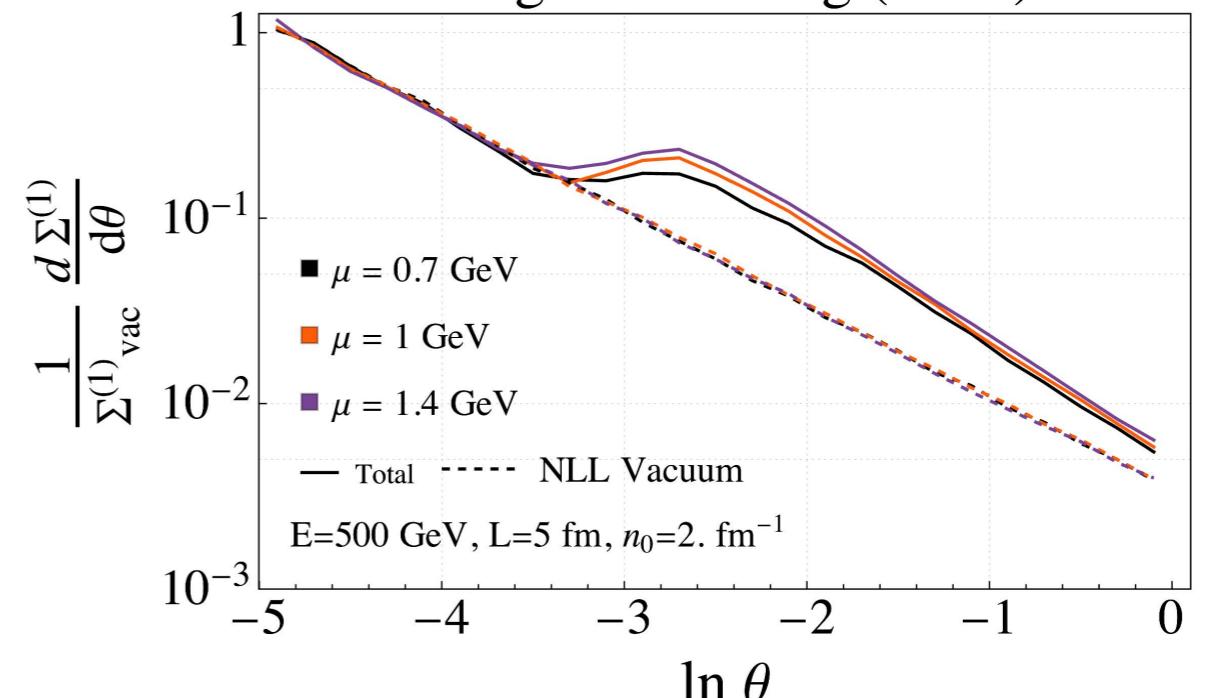
$$\theta_L \gg \theta_c$$

Two–Point Energy Correlator
Single Scattering (GLV)



$$\theta_L \ll \theta_c$$

Two–Point Energy Correlator
Single Scattering (GLV)

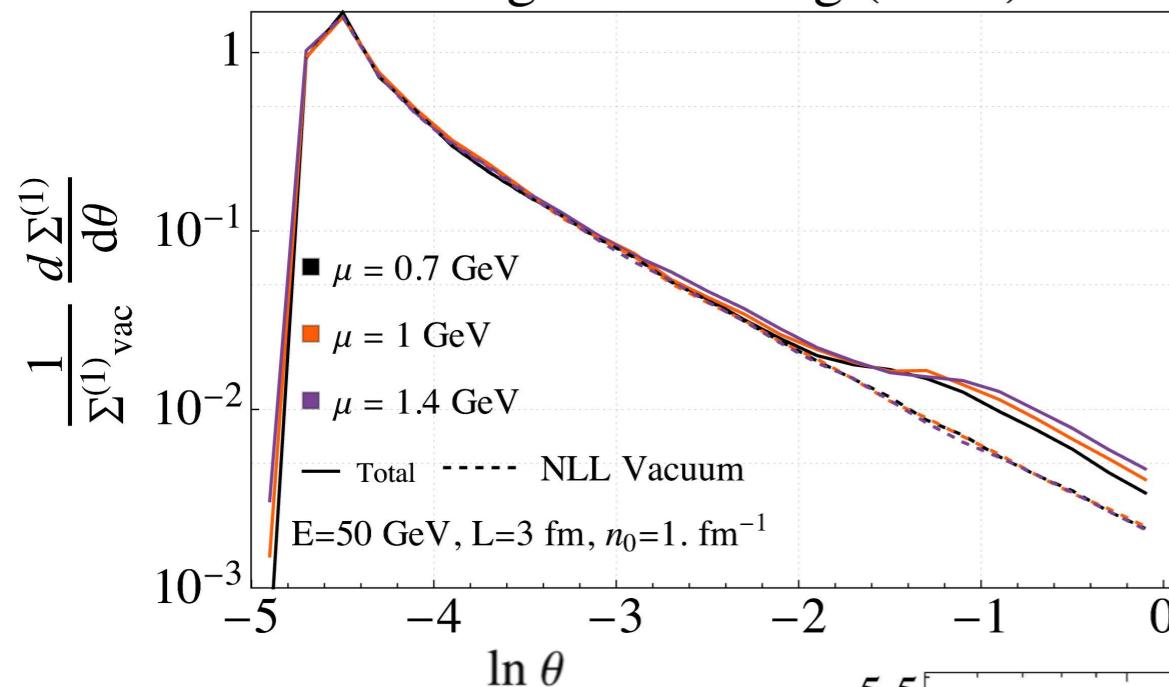


GLV calculation from:
Ovanesyan, Vitev,
[1109.5619](https://arxiv.org/abs/1109.5619)

Results GLV

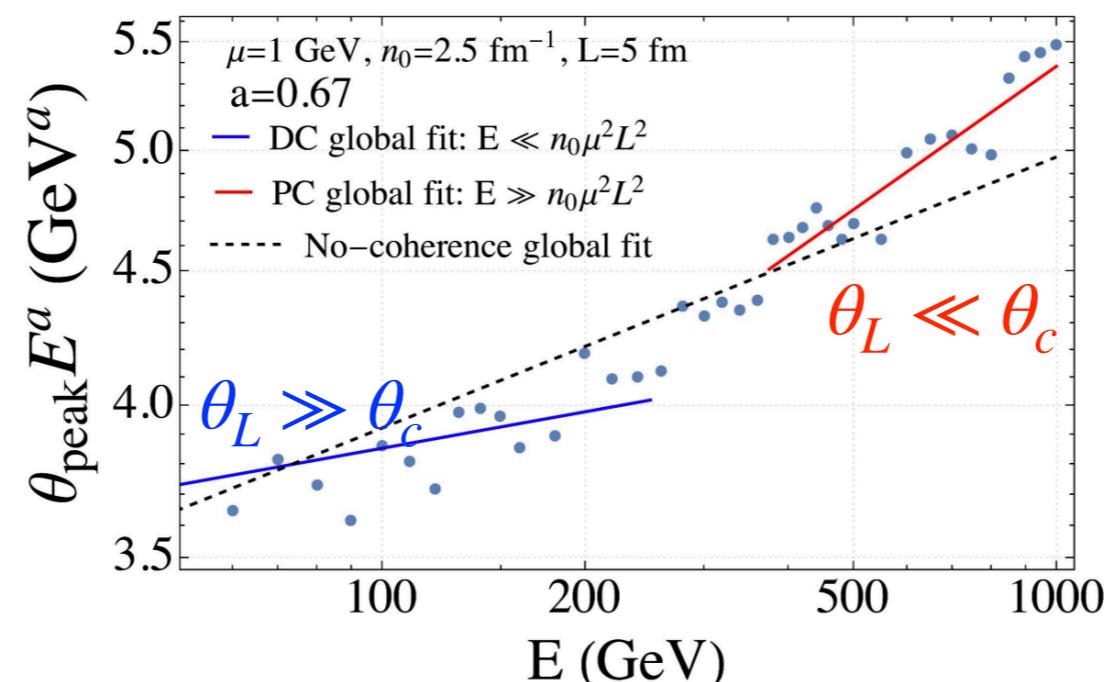
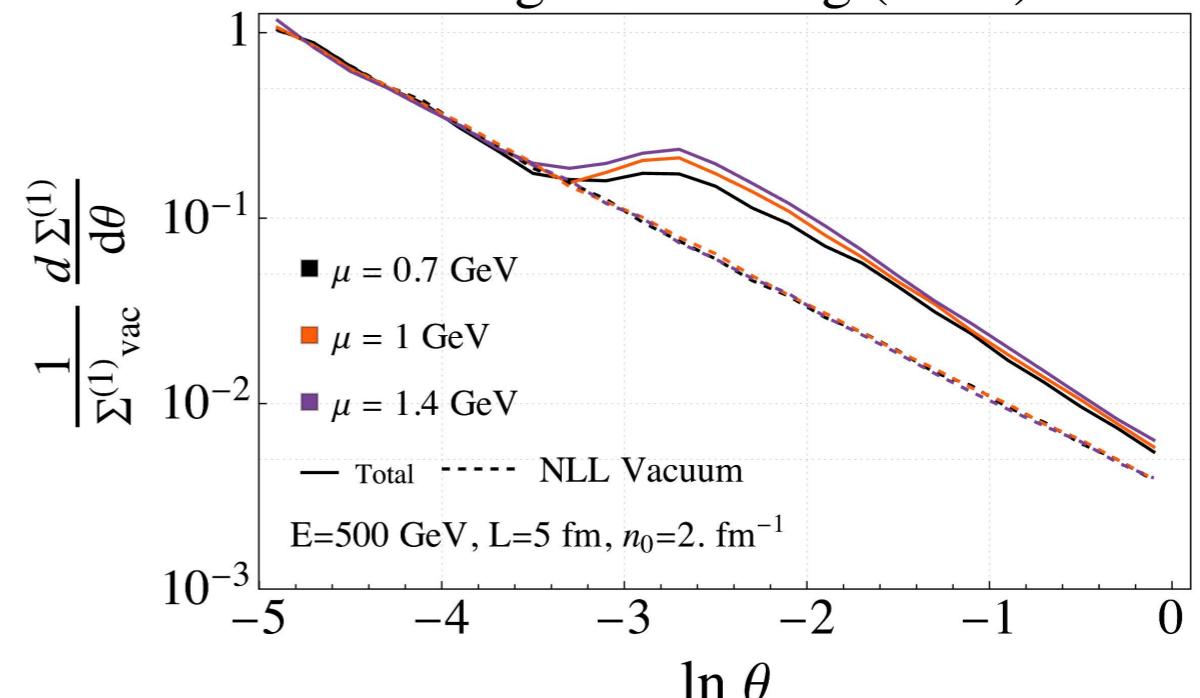
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Two–Point Energy Correlator
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Two–Point Energy Correlator
Single Scattering (GLV)



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Coherence
transition not as
clearly observed
**as in the multiple
scattering case**

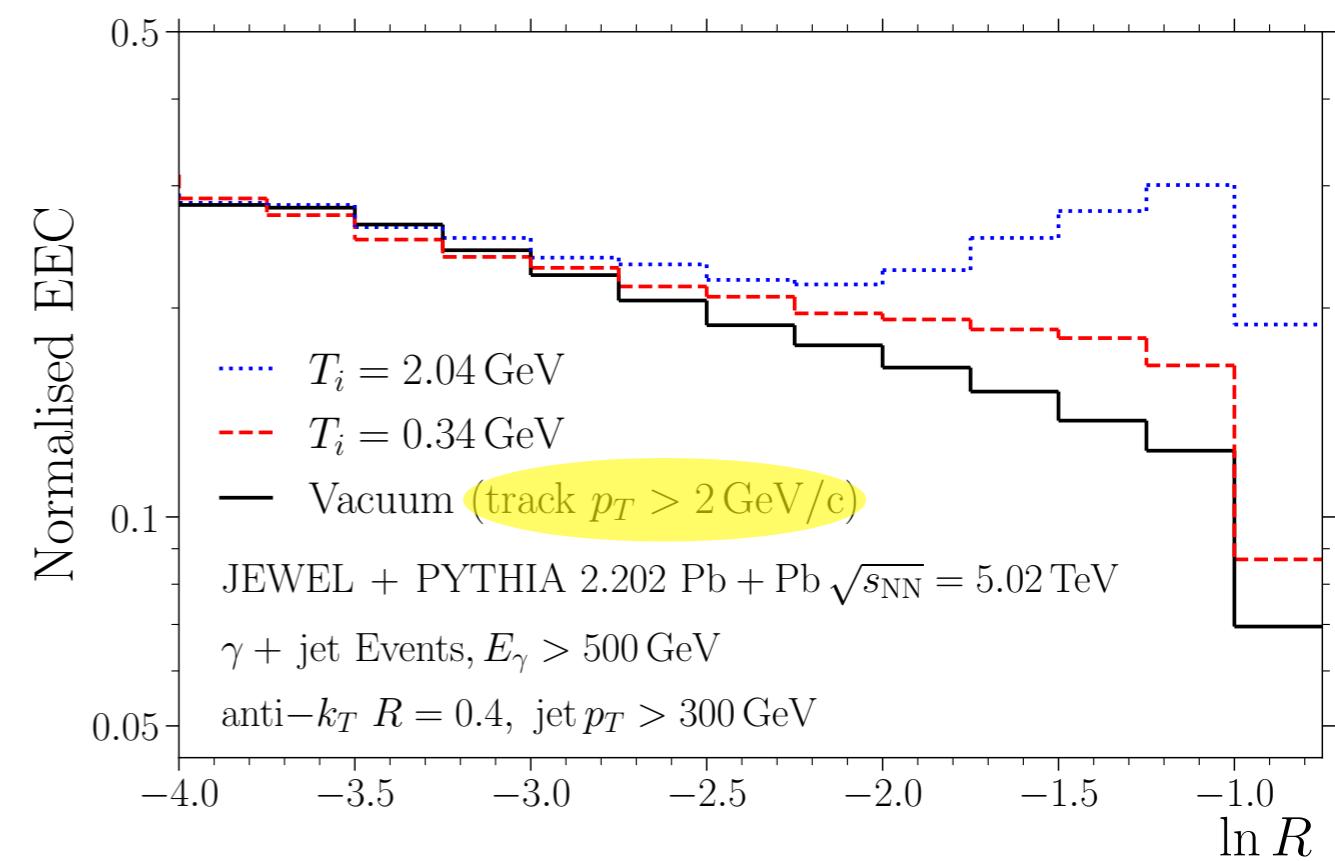
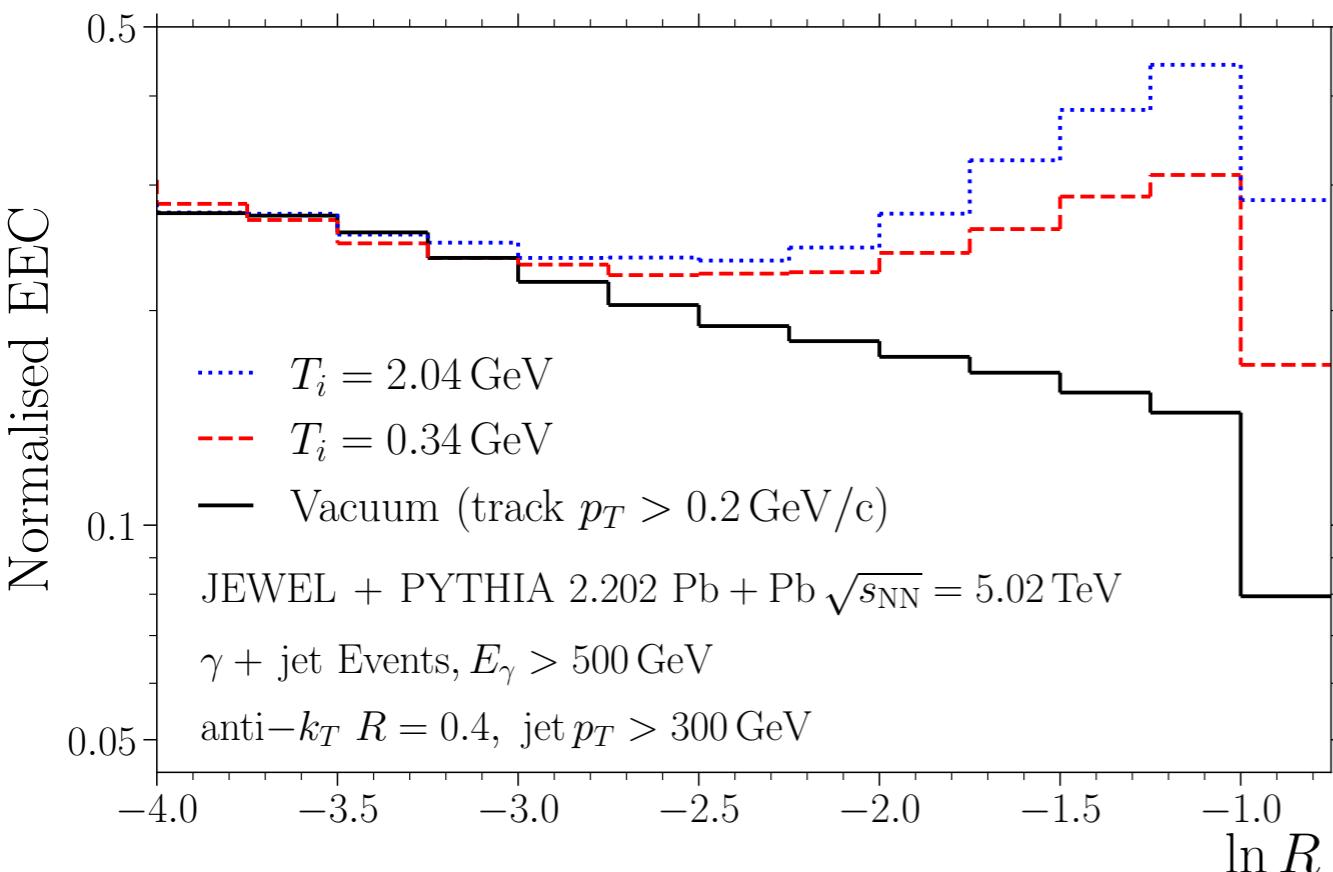
Conclusions

- **Energy Correlators** have **great potential for jet substructure** studies in HICs.
 - Experimentally accessible
 - **No need of de-clustering**
 - Expected to be **less sensitive to soft physics** than traditional jet substructure observables: hadronization, and background are usually subleading
 - In **vacuum**: they can be computed perturbatively at very **high accuracy**
- Characteristic features of the calculation of the in-medium splittings are clearly imprinted in these observables
- 2-point correlator provides an **angular variable** that might be used to probe color coherence

Thank you!

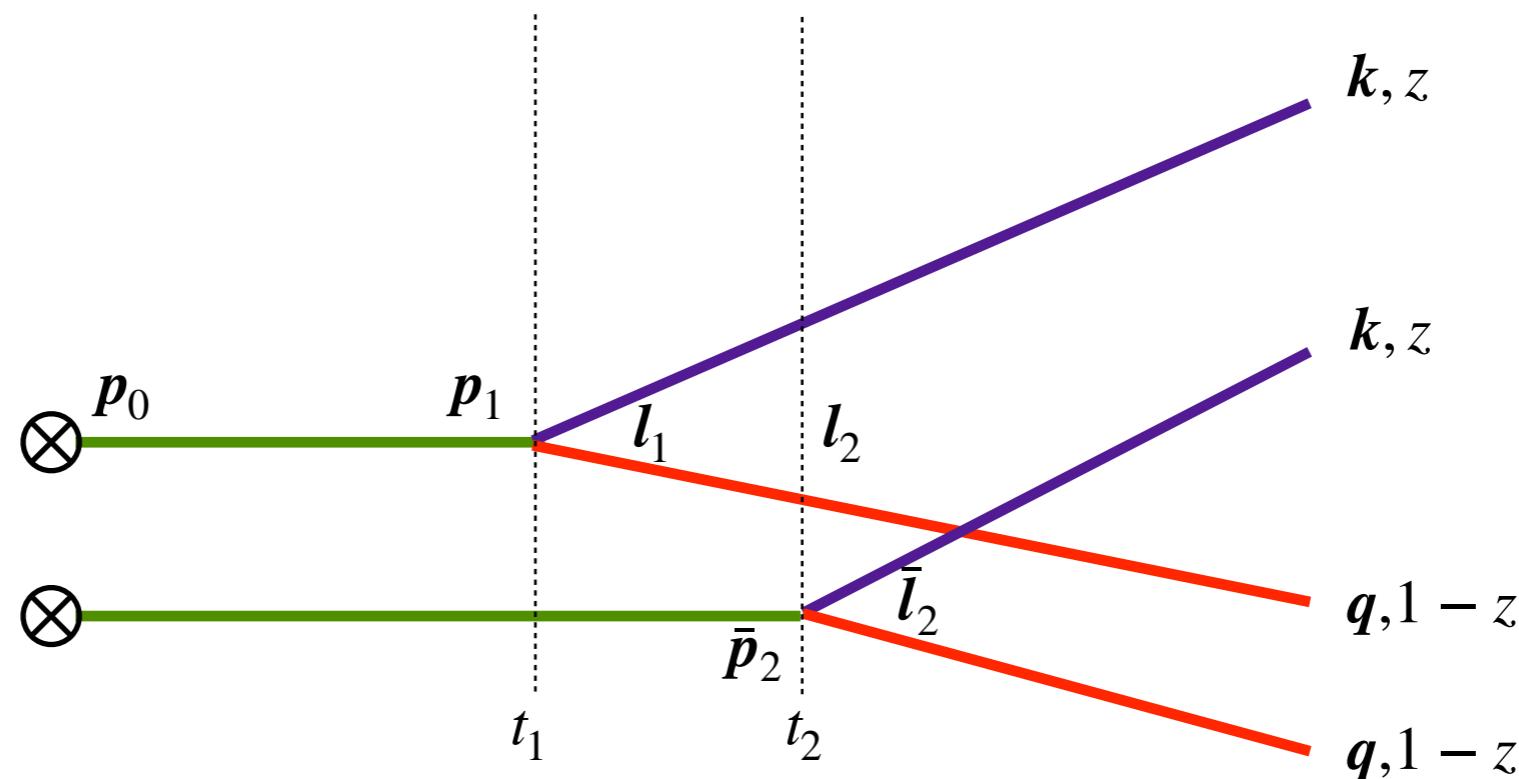
Results from JEWEL

- An analysis on JEWEL is on the way



Features in the curves seem resilient against a hadron cut $p_T \gtrsim 2 \text{ GeV}$

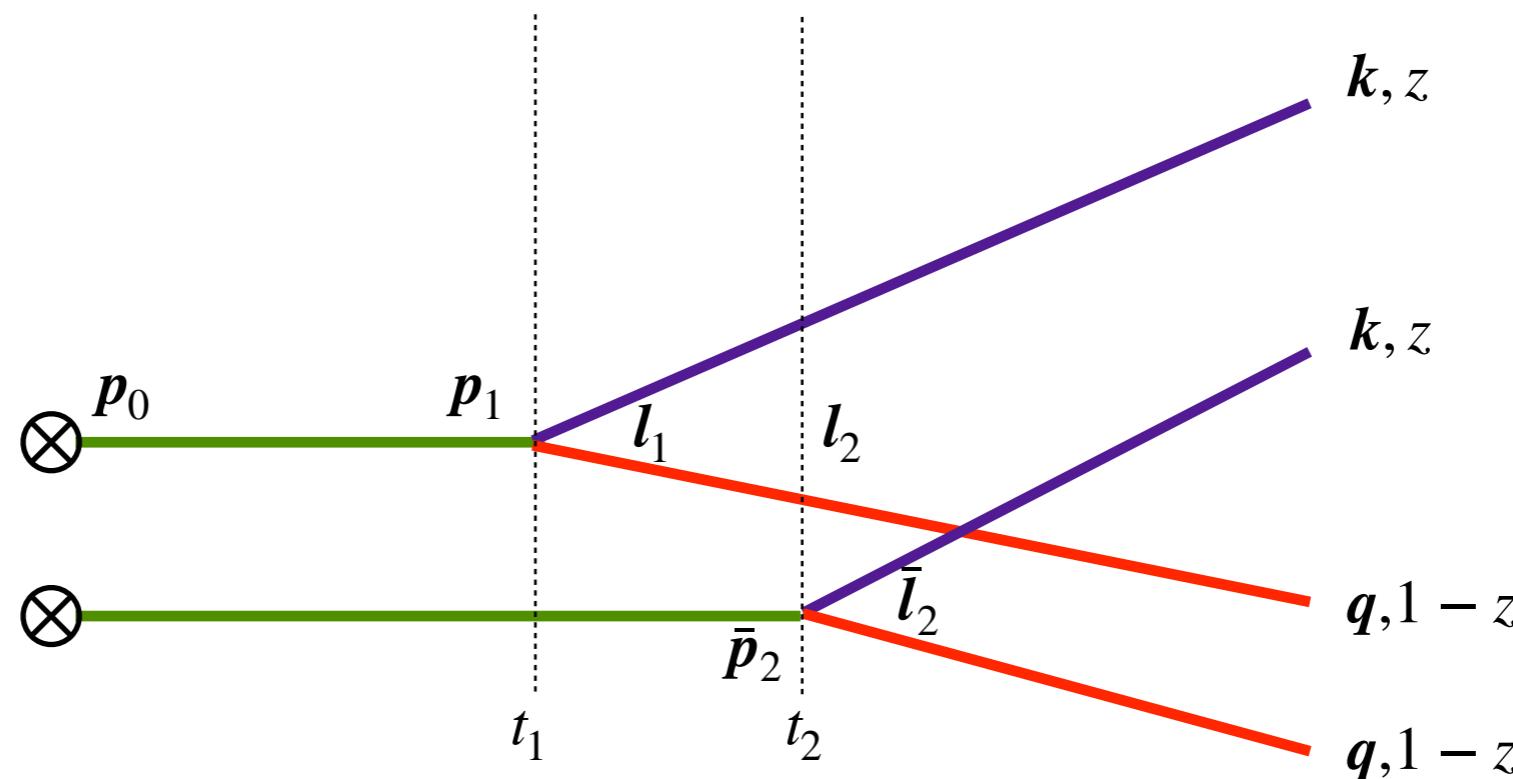
Double differential cross section



$$\begin{aligned}
 \frac{d\sigma}{d\Omega_k d\Omega_q} = & \frac{g^2}{z(1-z)E^2} P_{a \rightarrow bc}(z) 2\text{Re} \int_{\mathbf{p}_0 \mathbf{p}_1 \bar{\mathbf{p}}_2 \mathbf{l}_1 \mathbf{l}_2 \bar{\mathbf{l}}_2} \int_{t_0}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 (\mathbf{l}_1 \cdot \bar{\mathbf{l}}_2) \\
 & \times \mathcal{S}^{(4)}((1-z)\mathbf{k} - z\mathbf{q}, L; \mathbf{l}_2, \bar{\mathbf{l}}_2, t_2; \mathbf{k} + \mathbf{q} - \bar{\mathbf{p}}_2, z) \\
 & \times \mathcal{K}^{(3)}(\mathbf{l}_2, t_2; \mathbf{l}_1, t_1; \bar{\mathbf{p}}_2 - \mathbf{p}_1, z) \mathcal{P}_{R_a}(\mathbf{p}_1 - \mathbf{p}_0; t_1, t_0) \frac{d\sigma_{hard}}{d\Omega_{p_0}}
 \end{aligned}$$

Blaizot, Iancu, FD, Mehtar-Tani [1209.4585](#)
 Apolinario, Armesto, Milhano, Salgado [1407.0599](#)

Double differential cross section



$$\frac{d\sigma}{d\Omega_k d\Omega_q} = \frac{g^2}{z(1-z)E^2} P_{a \rightarrow bc}(z) 2\text{Re} \int_{\mathbf{p}_0 \mathbf{p}_1 \bar{\mathbf{p}}_2 \mathbf{l}_1 \mathbf{l}_2 \bar{\mathbf{l}}_2} \int_{t_0}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 (\mathbf{l}_1 \cdot \bar{\mathbf{l}}_2)$$

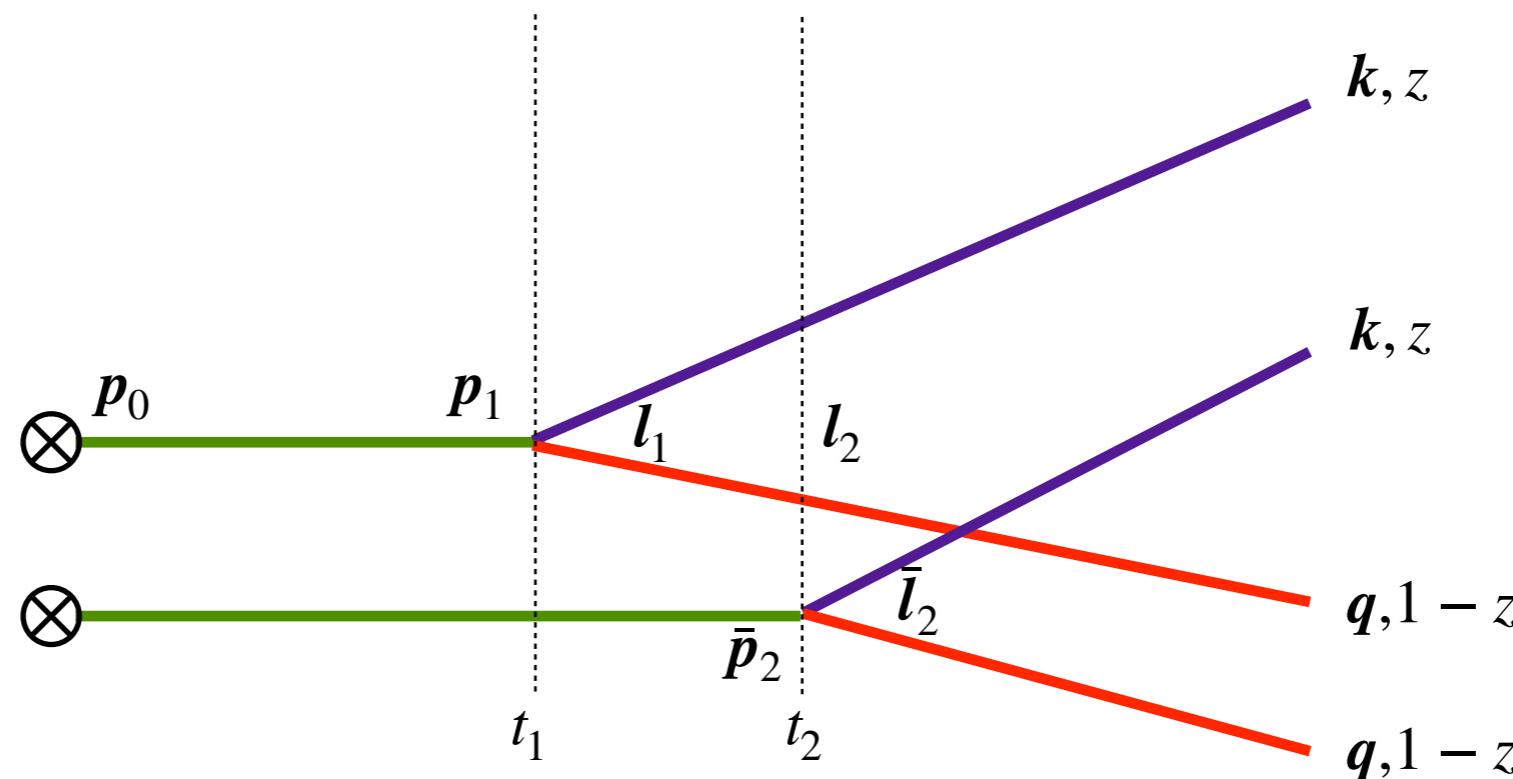
$$\times \mathcal{S}^{(4)}((1-z)\mathbf{k} - z\mathbf{q}, L; \mathbf{l}_2, \bar{\mathbf{l}}_2, t_2; \mathbf{k} + \mathbf{q} - \bar{\mathbf{p}}_2, z)$$

$$\times \mathcal{K}^{(3)}(\mathbf{l}_2, t_2; \mathbf{l}_1, t_1; \bar{\mathbf{p}}_2 - \mathbf{p}_1, z) \mathcal{P}_{R_a}(\mathbf{p}_1 - \mathbf{p}_0; t_1, t_0) \frac{d\sigma_{hard}}{d\Omega_{p_0}}$$

$$\langle \mathcal{G} \mathcal{G}^\dagger \rangle$$

Blaizot, Iancu, FD, Mehtar-Tani [1209.4585](#)
 Apolinario, Armesto, Milhano, Salgado [1407.0599](#)

Double differential cross section

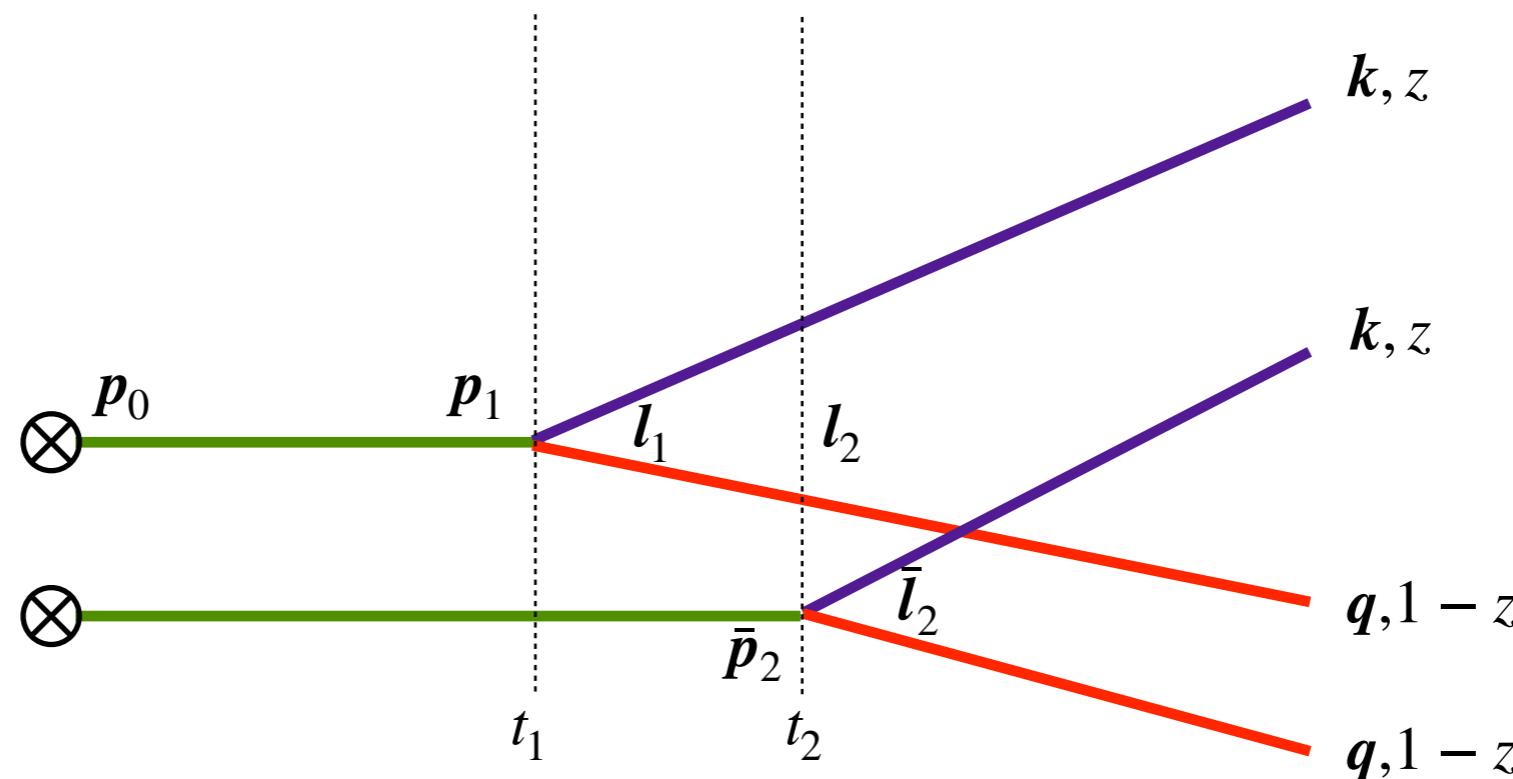


$$\begin{aligned}
 \frac{d\sigma}{d\Omega_k d\Omega_q} = & \frac{g^2}{z(1-z)E^2} P_{a \rightarrow bc}(z) 2\text{Re} \int_{\mathbf{p}_0 \mathbf{p}_1 \bar{\mathbf{p}}_2} \int_{t_0}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 (\mathbf{l}_1 \cdot \bar{\mathbf{l}}_2) \\
 & \times \mathcal{S}^{(4)}((1-z)\mathbf{k} - z\mathbf{q}, L; \mathbf{l}_2, \bar{\mathbf{l}}_2, t_2; \mathbf{k} + \mathbf{q} - \bar{\mathbf{p}}_2, z) \\
 & \times \mathcal{K}^{(3)}(\mathbf{l}_2, t_2; \mathbf{l}_1, t_1; \bar{\mathbf{p}}_2 - \mathbf{p}_1, z) \mathcal{P}_{R_a}(\mathbf{p}_1 - \mathbf{p}_0; t_1, t_0) \frac{d\sigma_{hard}}{d\Omega_{p_0}} \\
 & \times \langle \mathcal{G} \mathcal{G} \mathcal{G}^\dagger \rangle \quad \langle \mathcal{G} \mathcal{G}^\dagger \rangle
 \end{aligned}$$

Blaizot, Iancu, FD, Mehtar-Tani [1209.4585](#)

Apolinario, Armesto, Milhano, Salgado [1407.0599](#)

Double differential cross section



$$\frac{d\sigma}{d\Omega_k d\Omega_q} = \frac{g^2}{z(1-z)E^2} P_{a \rightarrow bc}(z) 2\text{Re} \int_{p_0 p_1 \bar{p}_2 l_1 l_2 \bar{l}_2} \int_{t_0}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 (\mathbf{l}_1 \cdot \bar{\mathbf{l}}_2)$$

$$\times \mathcal{S}^{(4)}((1-z)\mathbf{k} - z\mathbf{q}, L; \mathbf{l}_2, \bar{\mathbf{l}}_2, t_2; \mathbf{k} + \mathbf{q} - \bar{\mathbf{p}}_2, z)$$

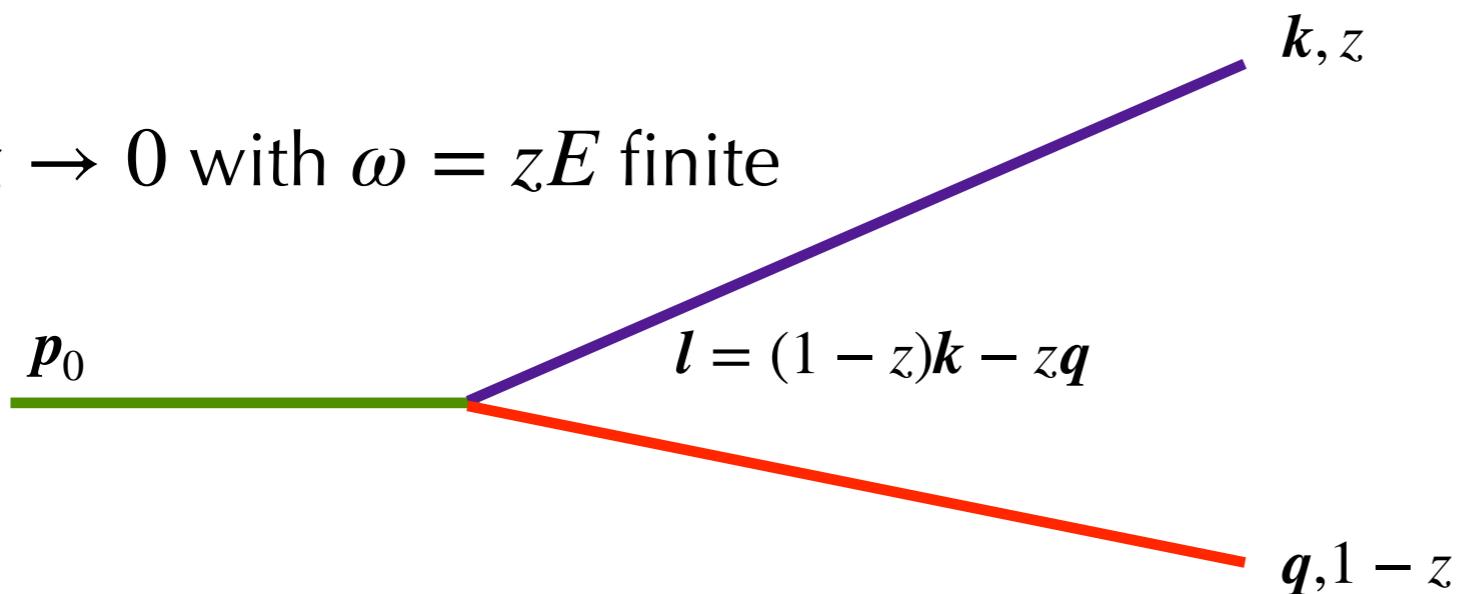
$$\langle g G G^\dagger g^\dagger \rangle \times \mathcal{K}^{(3)}(\mathbf{l}_2, t_2; \mathbf{l}_1, t_1; \bar{\mathbf{p}}_2 - \mathbf{p}_1, z) \mathcal{P}_{R_a}(\mathbf{p}_1 - \mathbf{p}_0; t_1, t_0) \frac{d\sigma_{hard}}{d\Omega_{p_0}}$$

$$\langle g G G^\dagger \rangle \quad \langle G G^\dagger \rangle$$

Blaizot, Iancu, FD, Mehtar-Tani [1209.4585](#)
 Apolinario, Armesto, Milhano, Salgado [1407.0599](#)

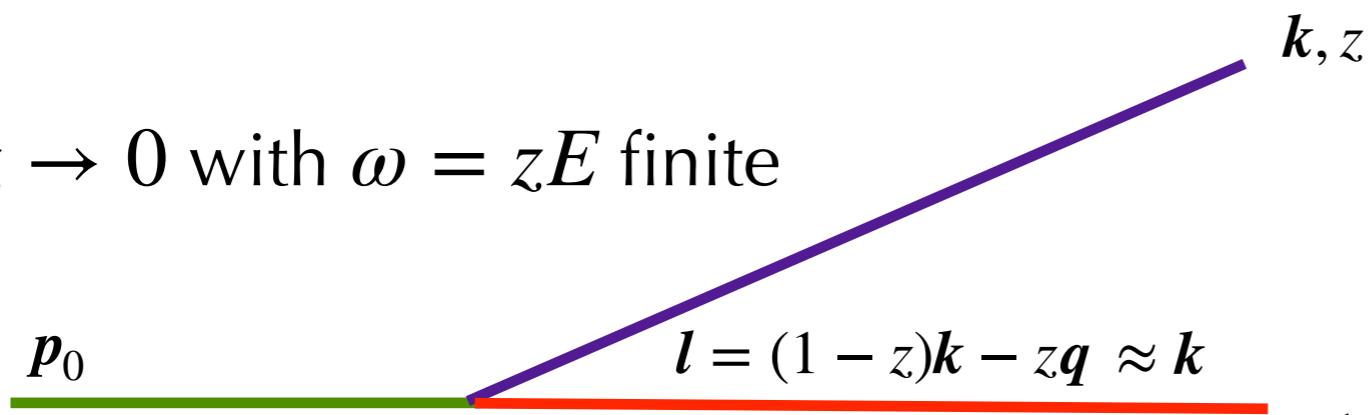
Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite



Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite

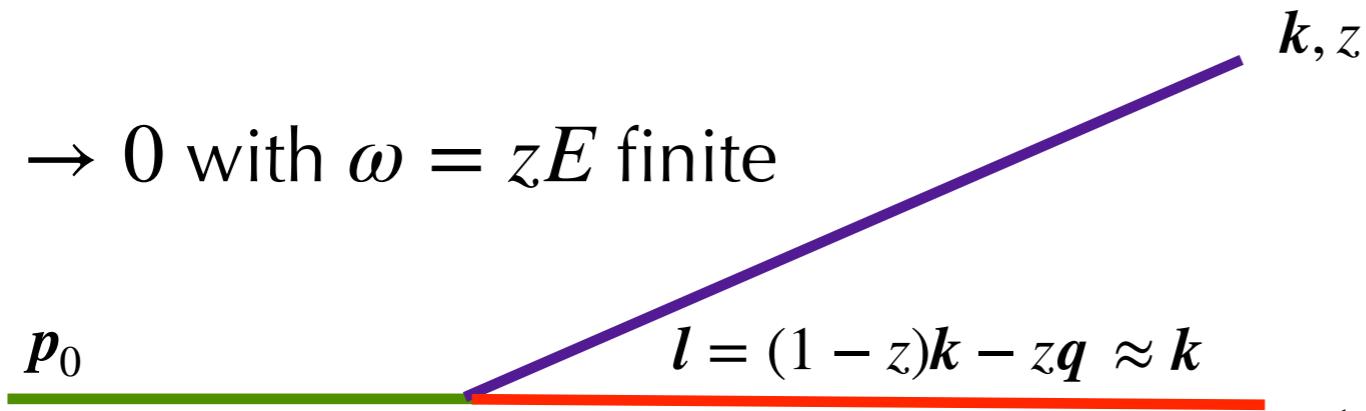


$$l = (1 - z)k - zq \approx k$$

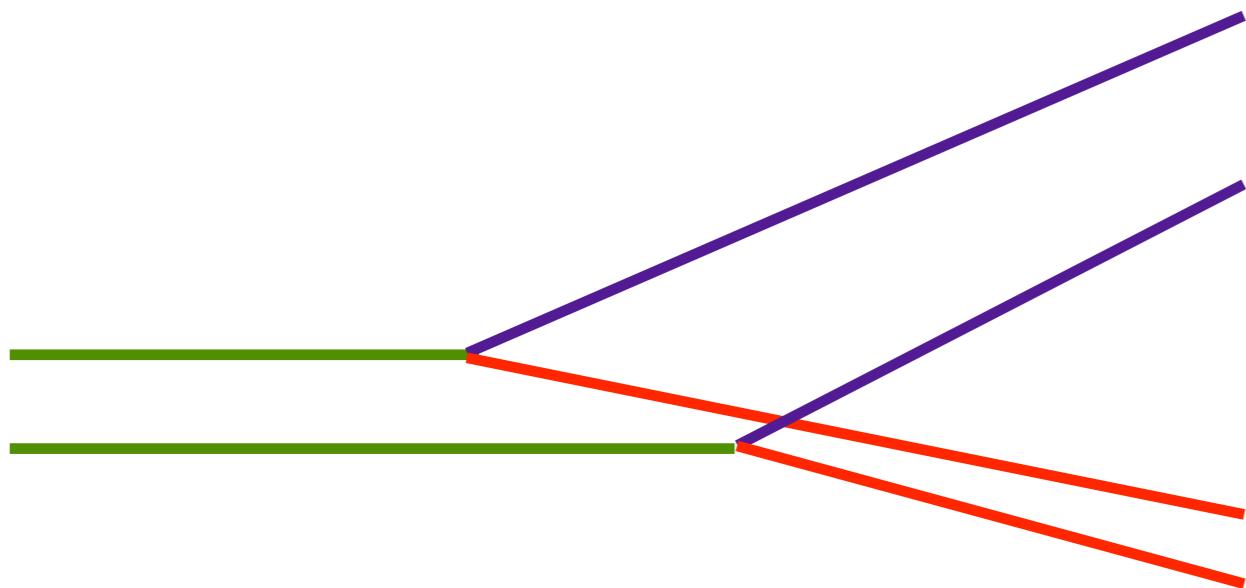
Angle of emission depends
only on transverse momentum
 $q, 1 - z$ of the soft particle

Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite

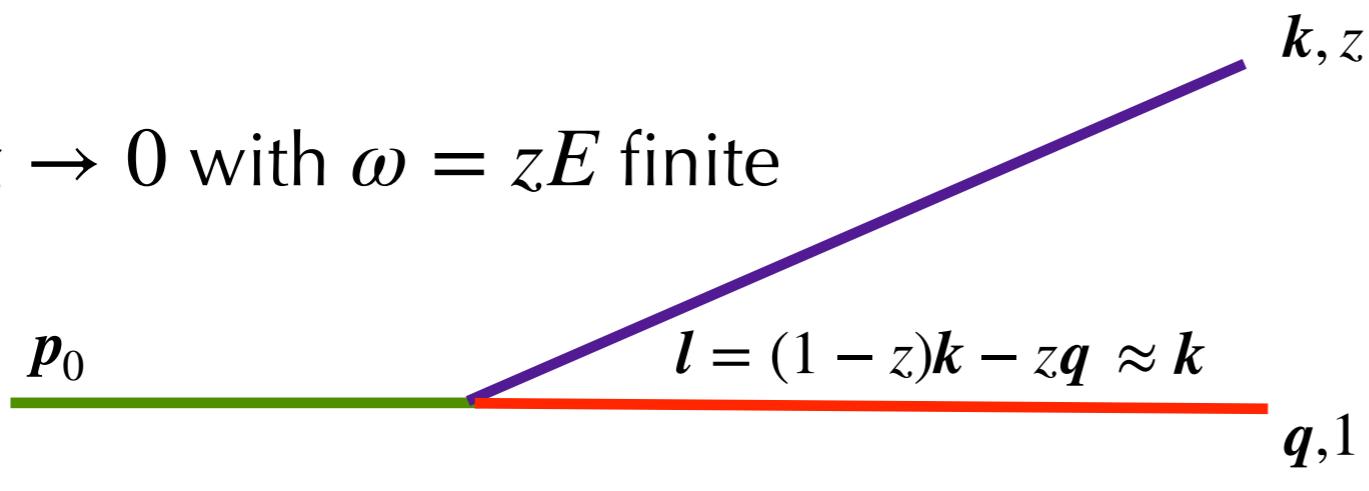


Angle of emission depends
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 $q, 1 - z$ of the soft particle

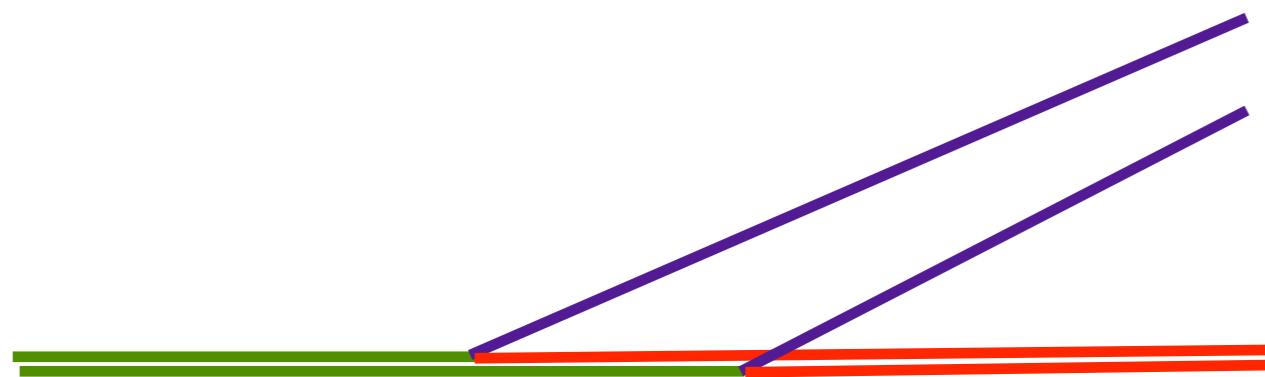


Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite

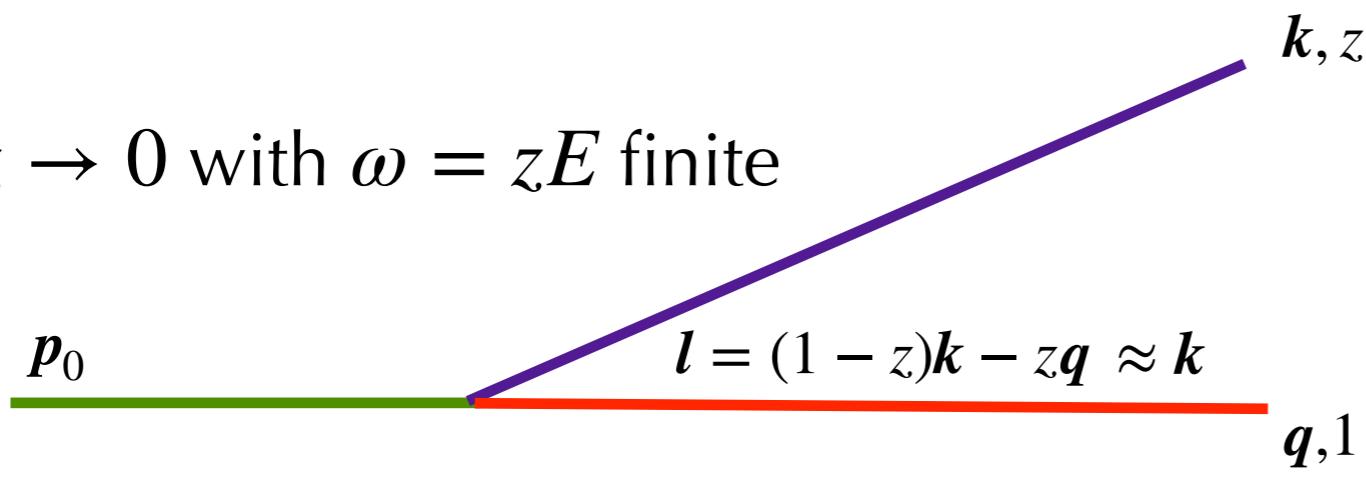


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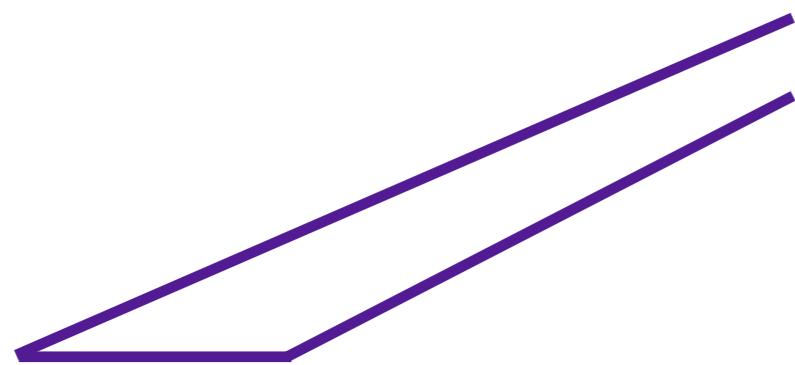


Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite



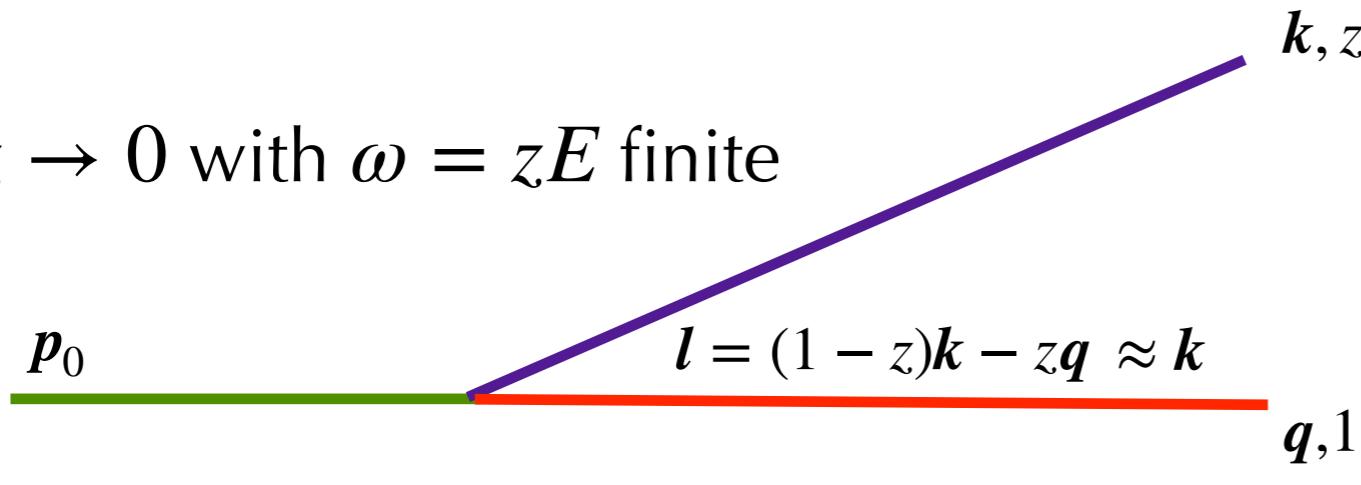
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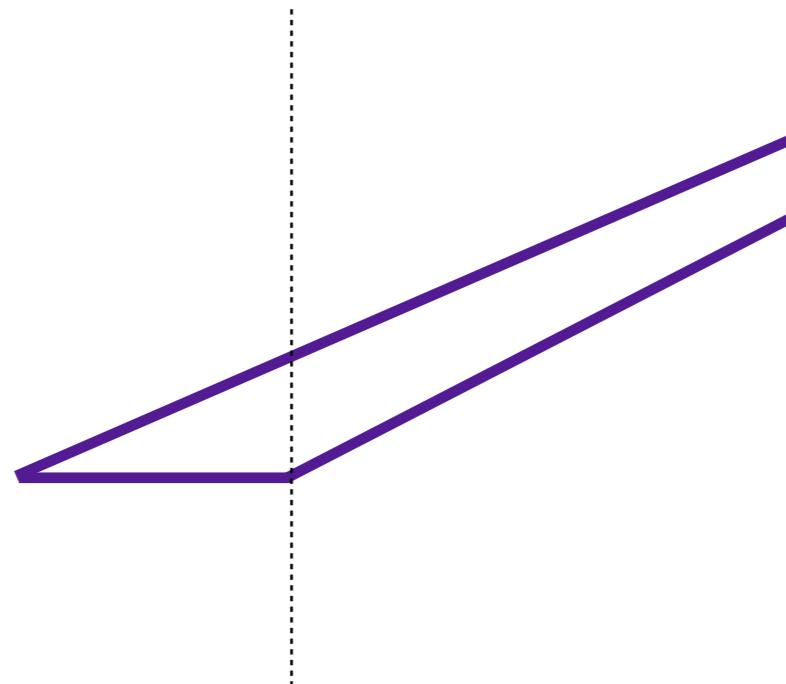
Initial and final broadening of
the hard particle cancels out

Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite



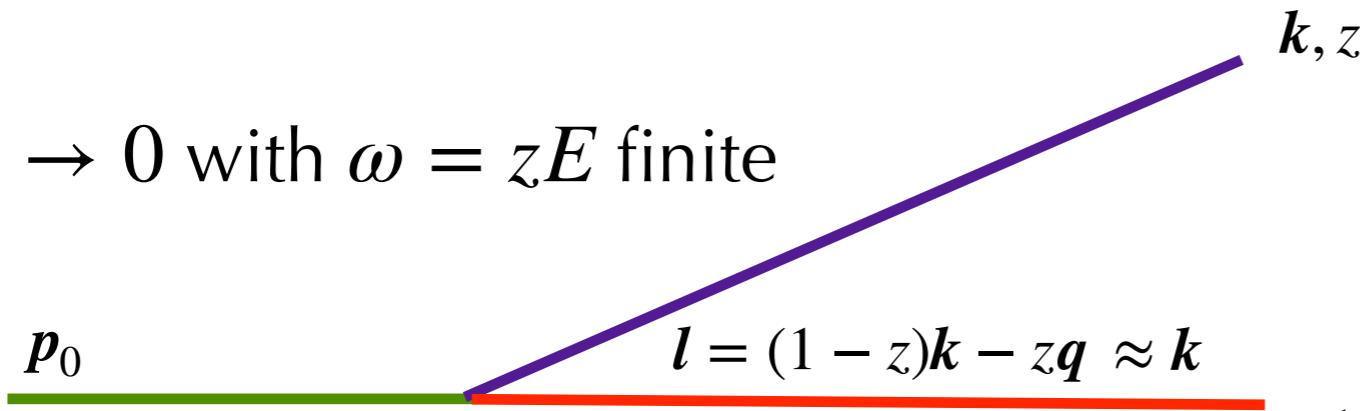
Angle of emission depends
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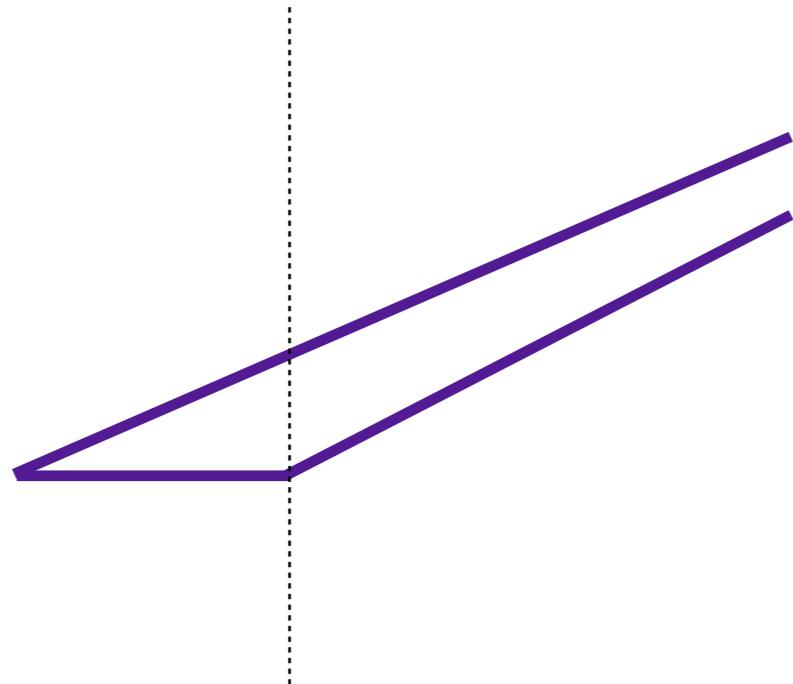
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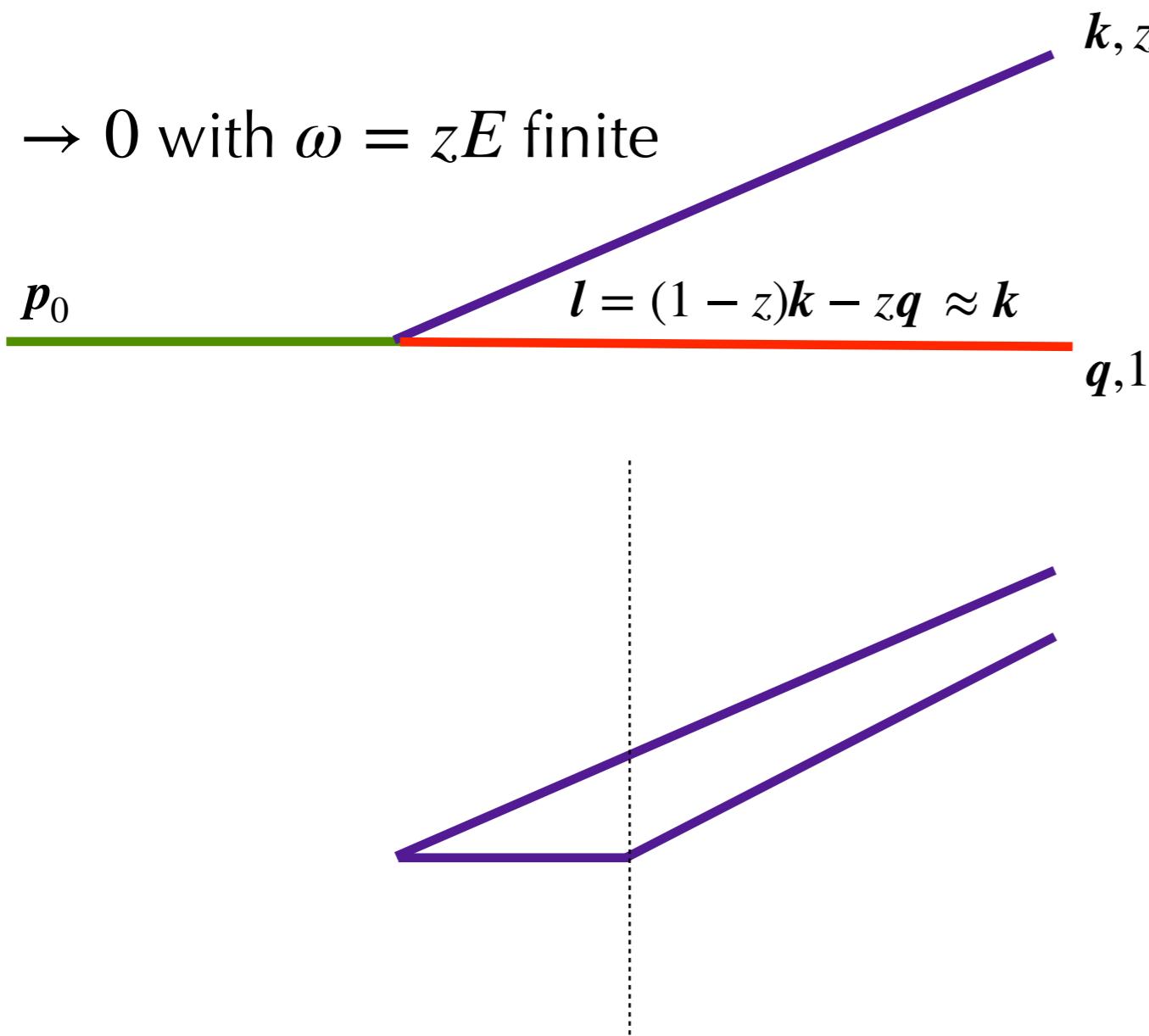


Initial and final broadening of
the hard particle cancels out

$$\omega \frac{dI}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\mathbf{pq}} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) \mathcal{P}(\infty, \mathbf{k}; t', \mathbf{q})$$

Soft limit

$z \rightarrow 0$ with $\omega = zE$ finite



Angle of emission depends
only on transverse momentum
 $\mathbf{q}, 1 - z$ of the soft particle

Initial and final broadening of
the hard particle cancels out

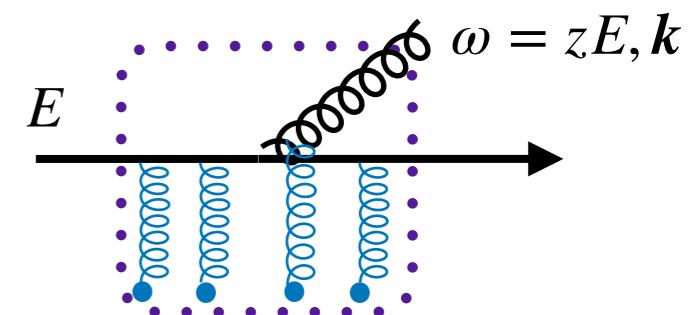
$$\omega \frac{dI}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\mathbf{pq}} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) \mathcal{P}(\infty, \mathbf{k}; t', \mathbf{q})$$

Recently evaluated numerically with multiple
scatterings and realistic interactions

Andres, Apolinario, FD [2002.01517](#)
Andres, FD, Gonzalez Martinez [2011.06522](#)

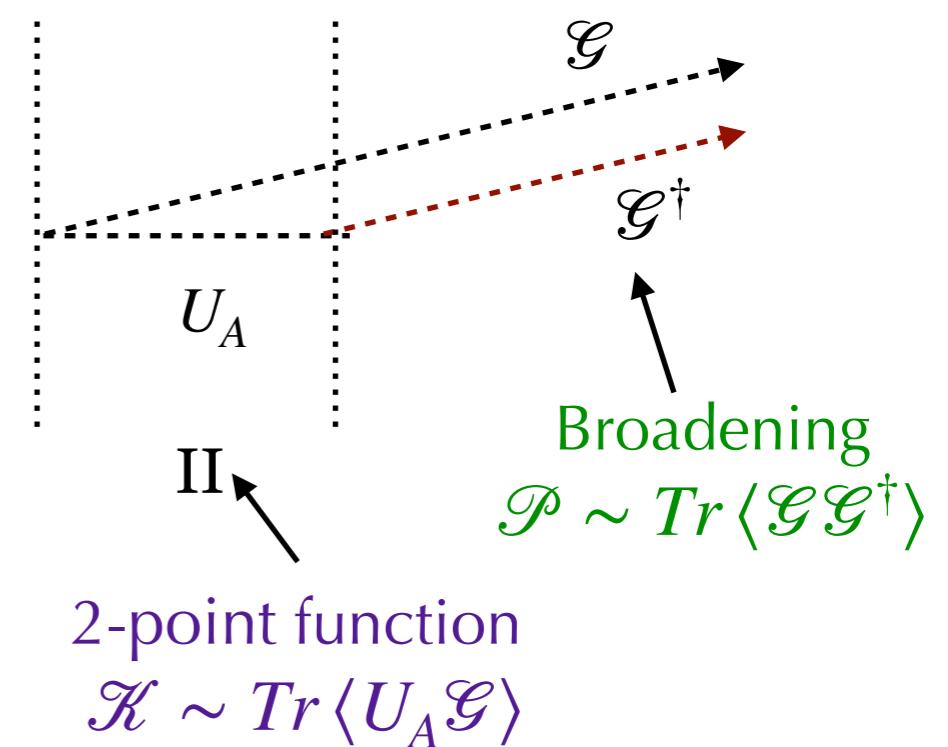
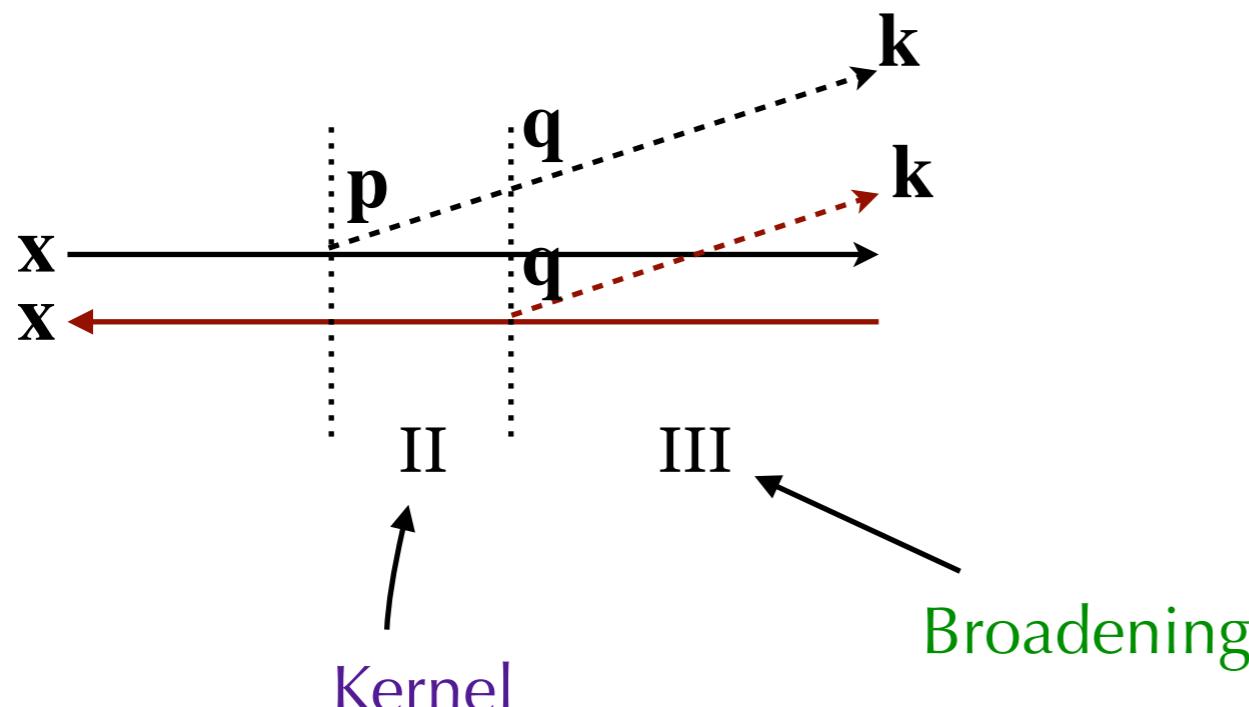
Medium-induced gluon spectrum

- For a soft emitted gluon ($z \ll 1$)



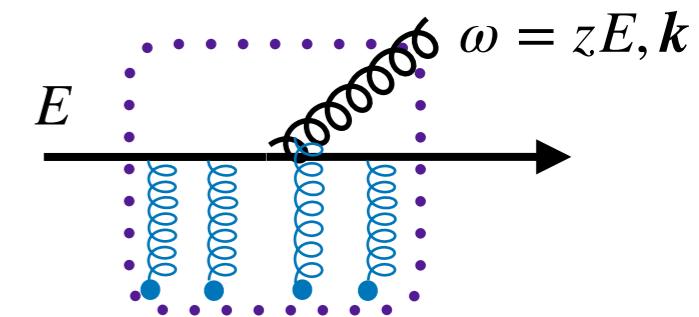
$$\omega \frac{dI}{d\omega d^2k} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \operatorname{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{pq} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) \mathcal{P}(\infty, \mathbf{k}; t', \mathbf{q})$$

BDMPS-Z



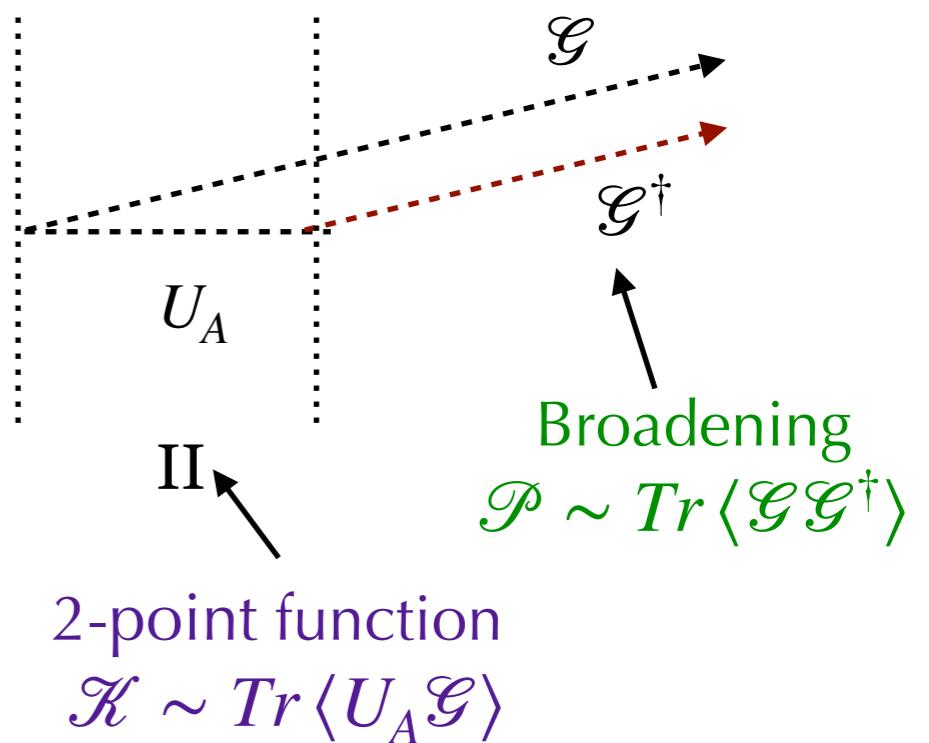
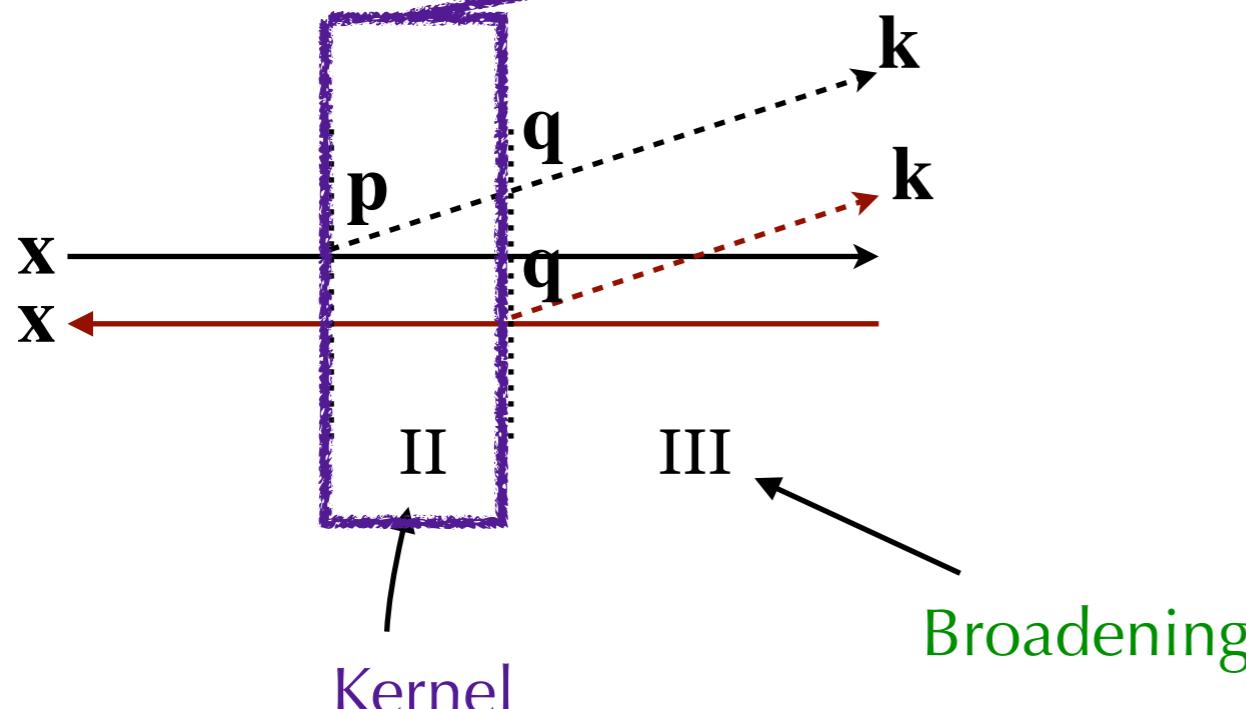
Medium-induced gluon spectrum

- For a soft emitted gluon ($z \ll 1$)



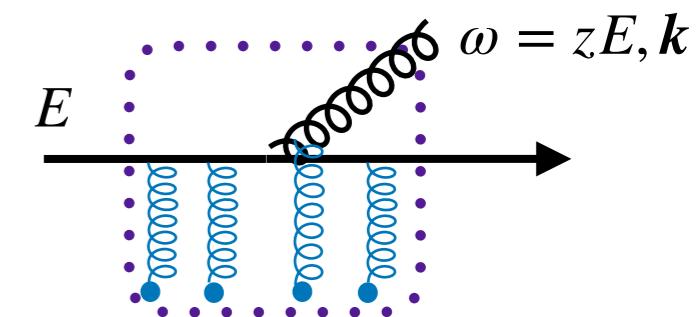
$$\omega \frac{dI}{d\omega d^2k} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{pq} p \cdot q \boxed{\tilde{\mathcal{K}}(t', q; t, p)} \mathcal{P}(\infty, k; t', q)$$

BDMPS-Z



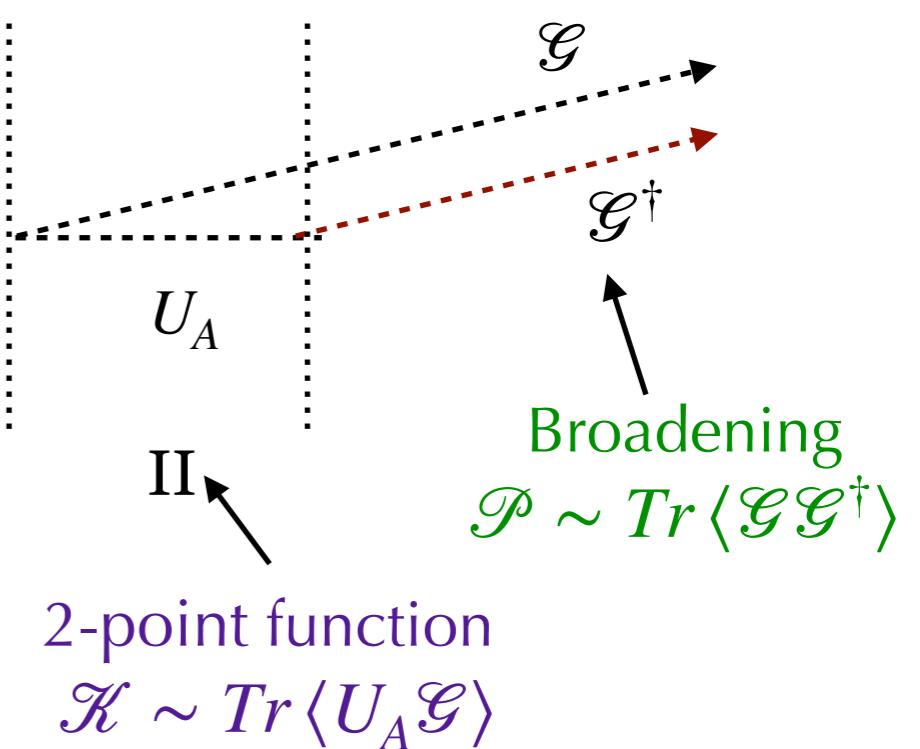
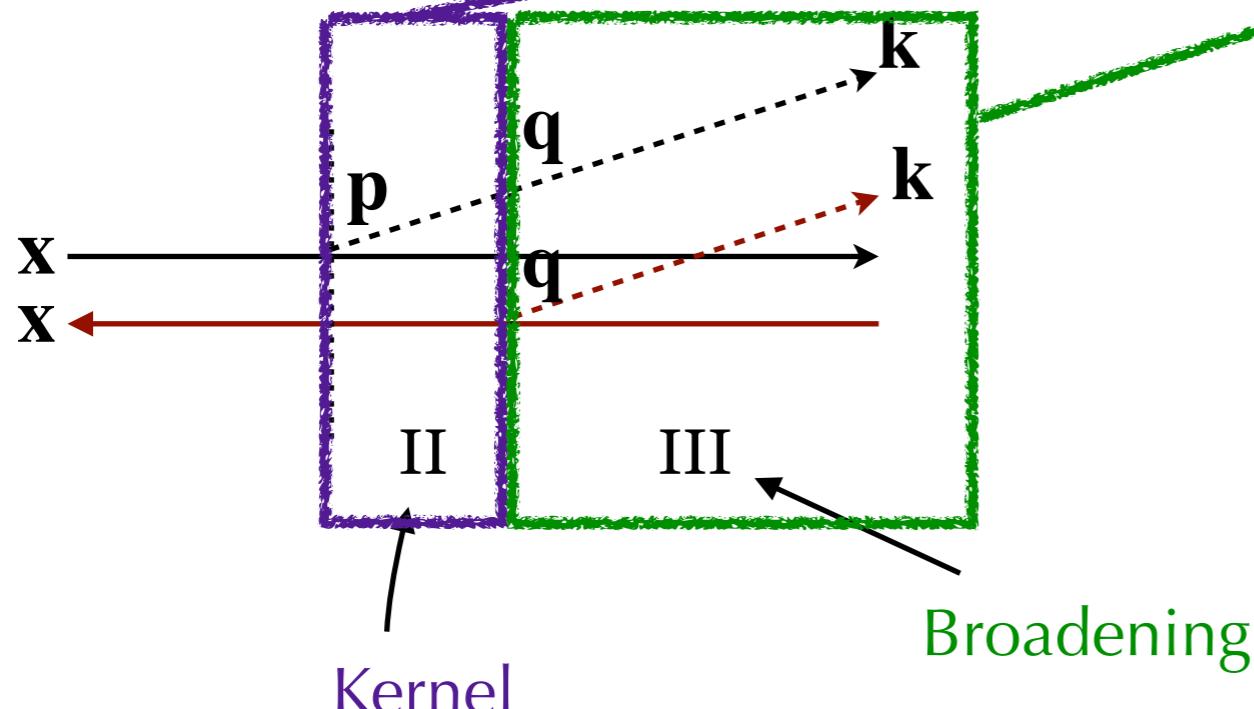
Medium-induced gluon spectrum

- For a soft emitted gluon ($z \ll 1$)



$$\omega \frac{dI}{d\omega d^2k} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{pq} p \cdot q \tilde{\mathcal{K}}(t', q; t, p) \mathcal{P}(\infty, k; t', q)$$

BDMPS-Z



Semi-hard approximation

Dominguez, Milhano, Salgado, Tywoniuk, Vila [1907.03653](#)
Isaksen, Tywoniuk [2107.02542](#)

- Use high-energy limit of propagators: vacuum propagator times a Wilson line in the classical trajectory

$$\mathcal{G}_R(t_2, \mathbf{p}_2; t_1, \mathbf{p}_1; \omega) \rightarrow (2\pi)^2 \delta^{(2)}(\mathbf{p}_2 - \mathbf{p}_1) e^{-i \frac{\mathbf{p}_2^2}{2\omega} (t_2 - t_1)} V_R(t_2, t_1; [\mathbf{n}t])$$

- Calculate averages of Wilson lines in the large- N_c limit (calculations also available for finite N_c). All averages can be expressed in terms of fundamental dipoles and quadrupoles

