Mass effect, broadening and coherence in QCD antenna radiation in medium

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(to appear soon)

Quark Matter
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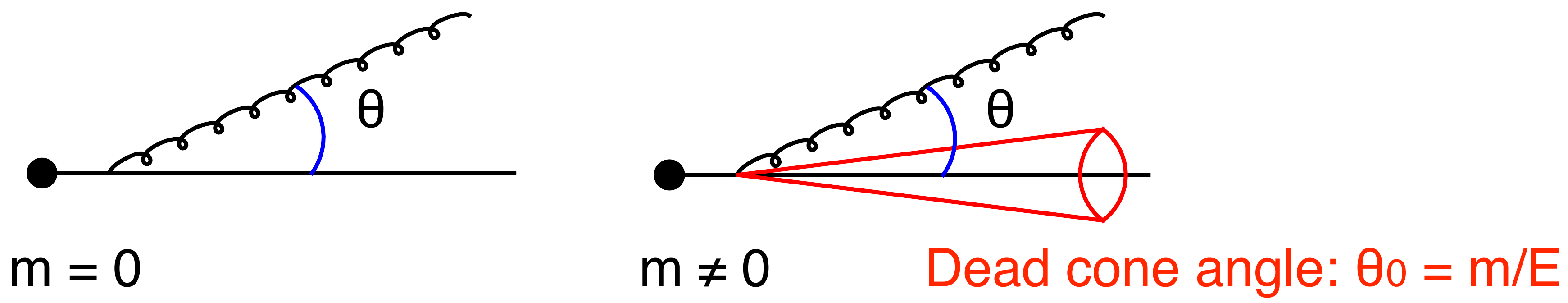
Motivation

- Dead cone effect suppresses radiation in vacuum



⇒ Gluon radiation inside the dead cone is suppressed.

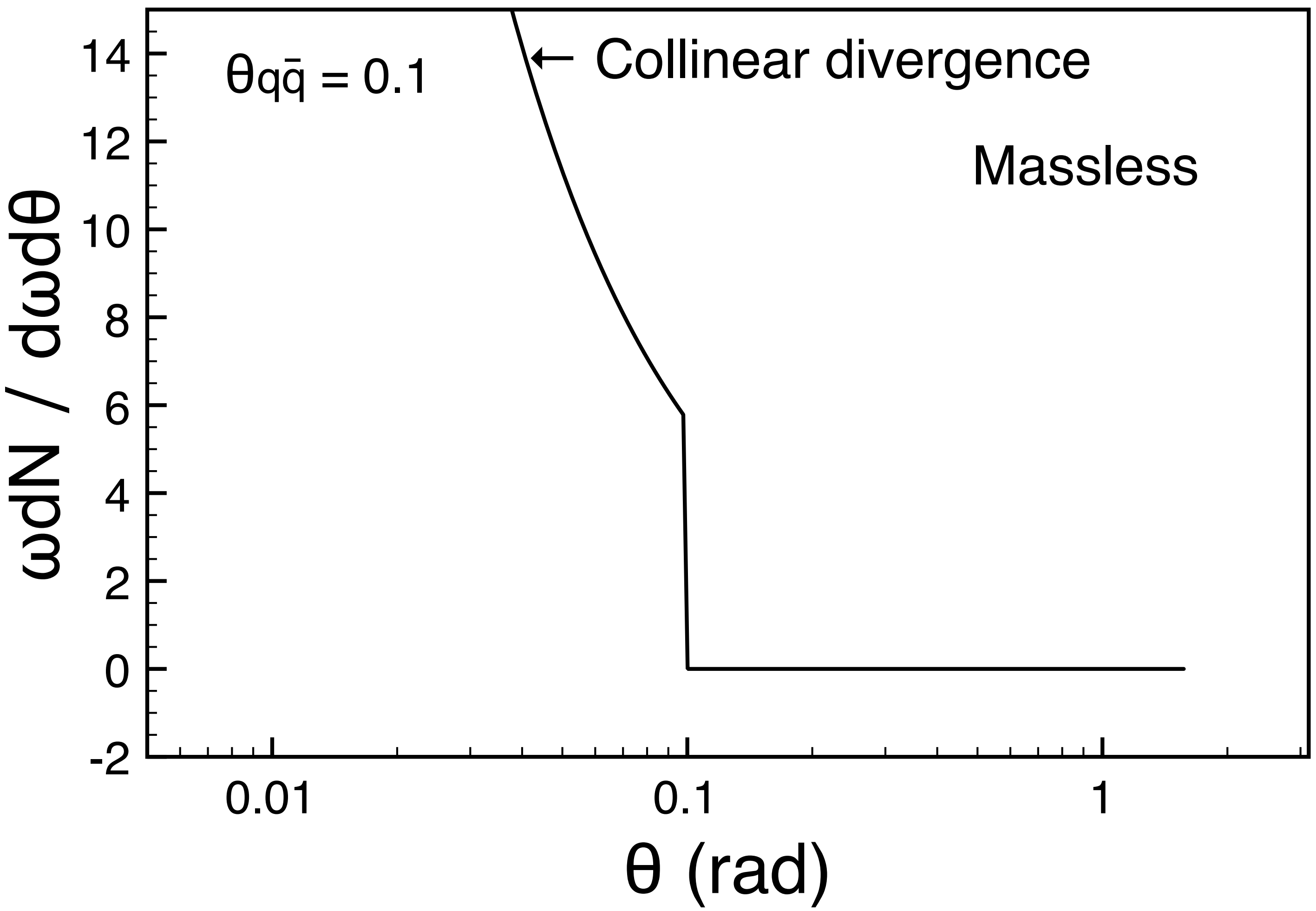
- Mass effects also suppress radiation in medium

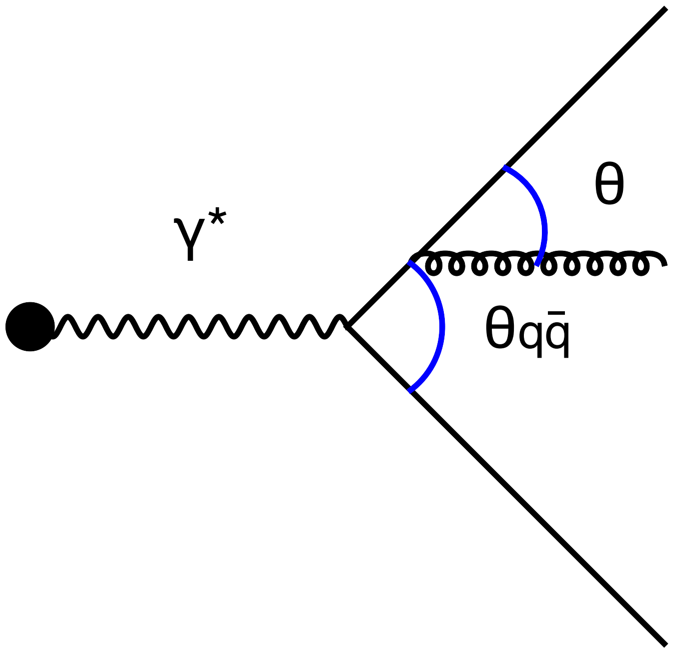
⇒ There are remaining puzzles in RHIC and LHC.

- Study the properties of jets originated by heavy quarks

⇒ LHC will measure the heavy quark jets.

Angular ordering in the soft limit in vacuum

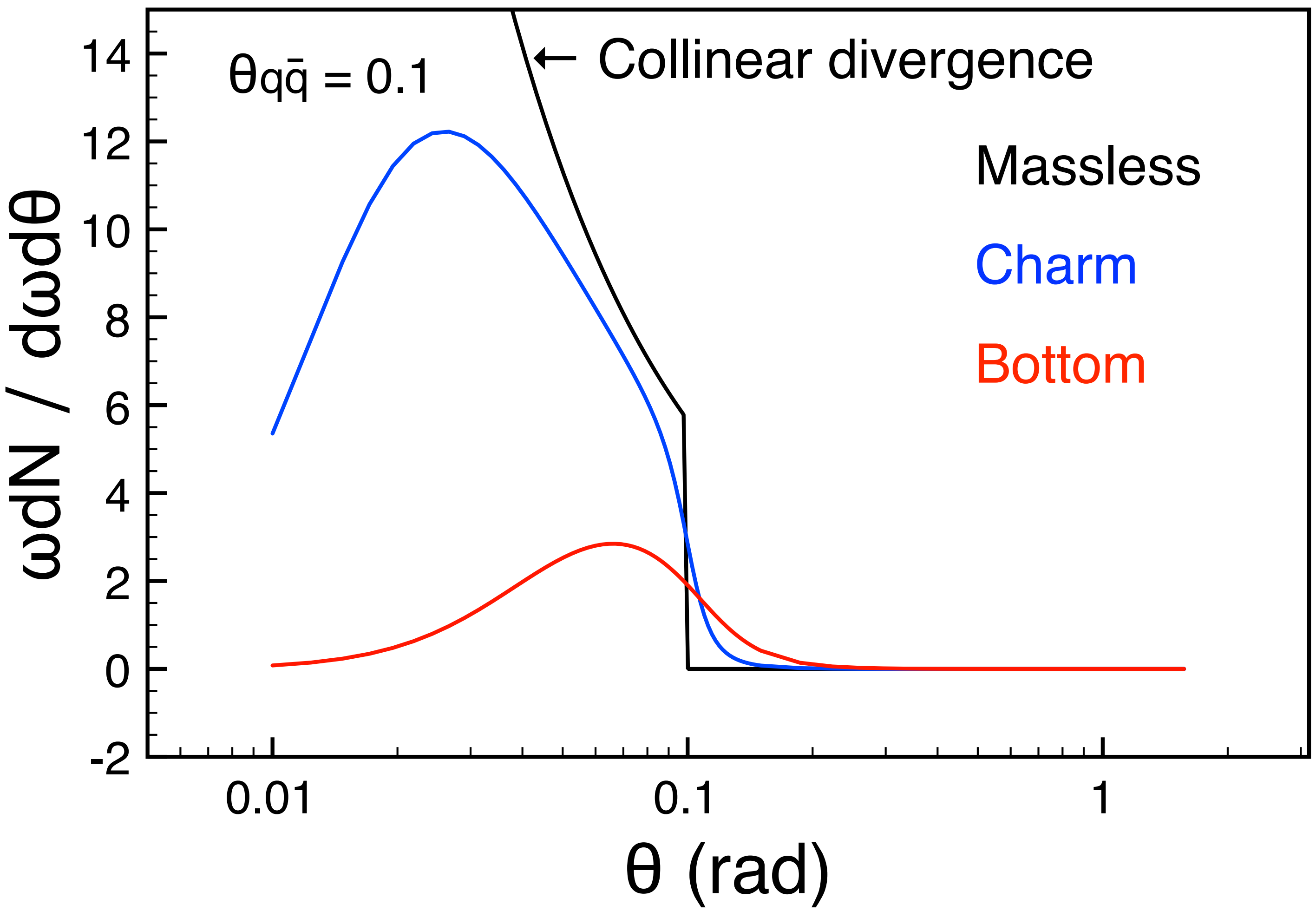


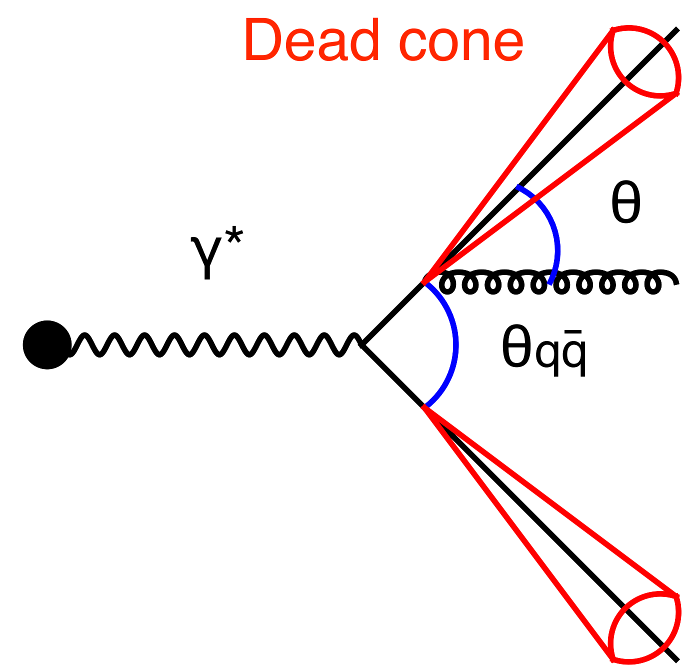


$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{1}{\theta}\,\Theta(\theta_{q\bar{q}} - \theta)$$

Collinear divergence Angular ordering: $\theta_{q\bar{q}} > \theta$

Angular ordering in the soft limit in vacuum





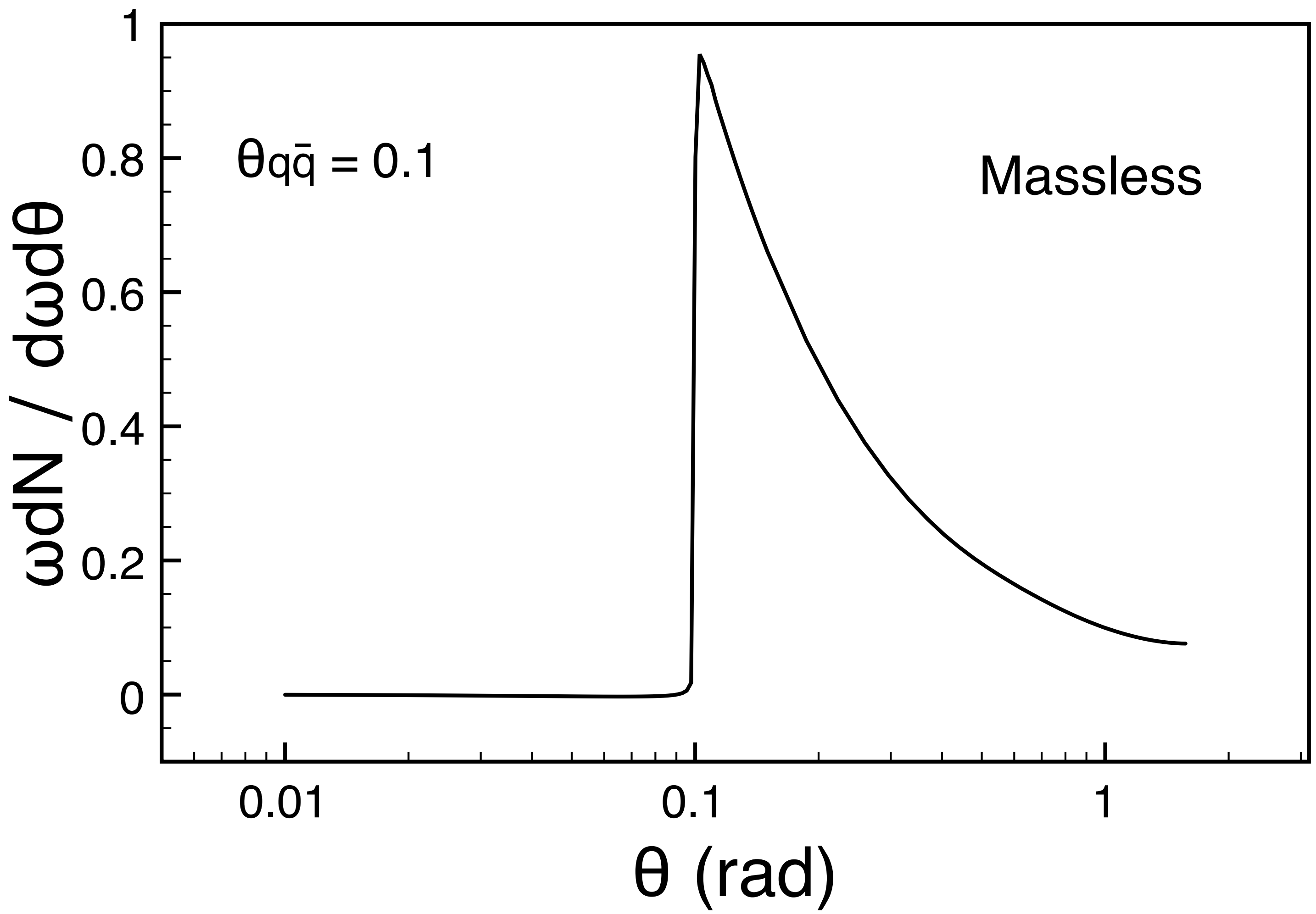
Dead cone angle: $\theta_0 = m/E$

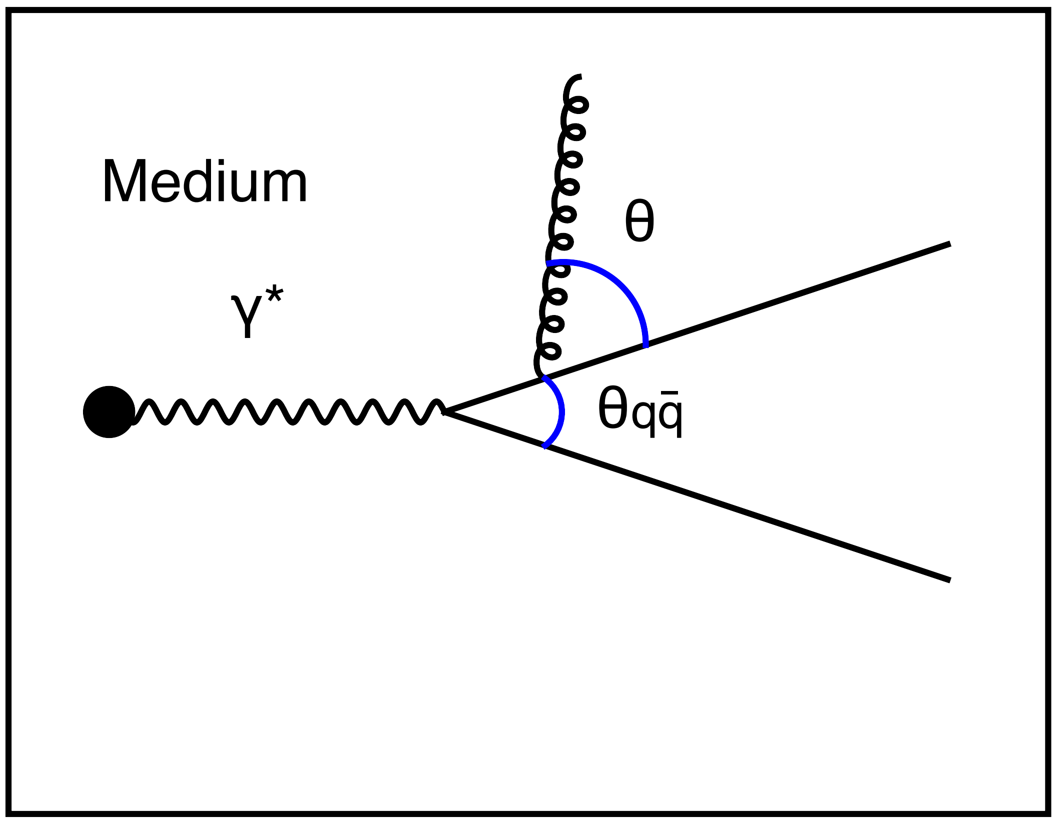
$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}}{\mathrm{d}\omega\, \mathrm{d}\theta} \propto \frac{\theta}{\theta^2 + \theta_0^2} H_{\mathrm{vac}}(\theta_{q\bar{q}}, \theta_0, \theta)$$

⇒ Both collinear divergence and angular ordering are destroyed by the dead cone angle θ_0.

Medium-induced antiangular ordering in the soft limit

First work: Mehtar-Tani, Salgado and Tywoniuk, Phys. Rev. Lett. 106 (2011) 122002





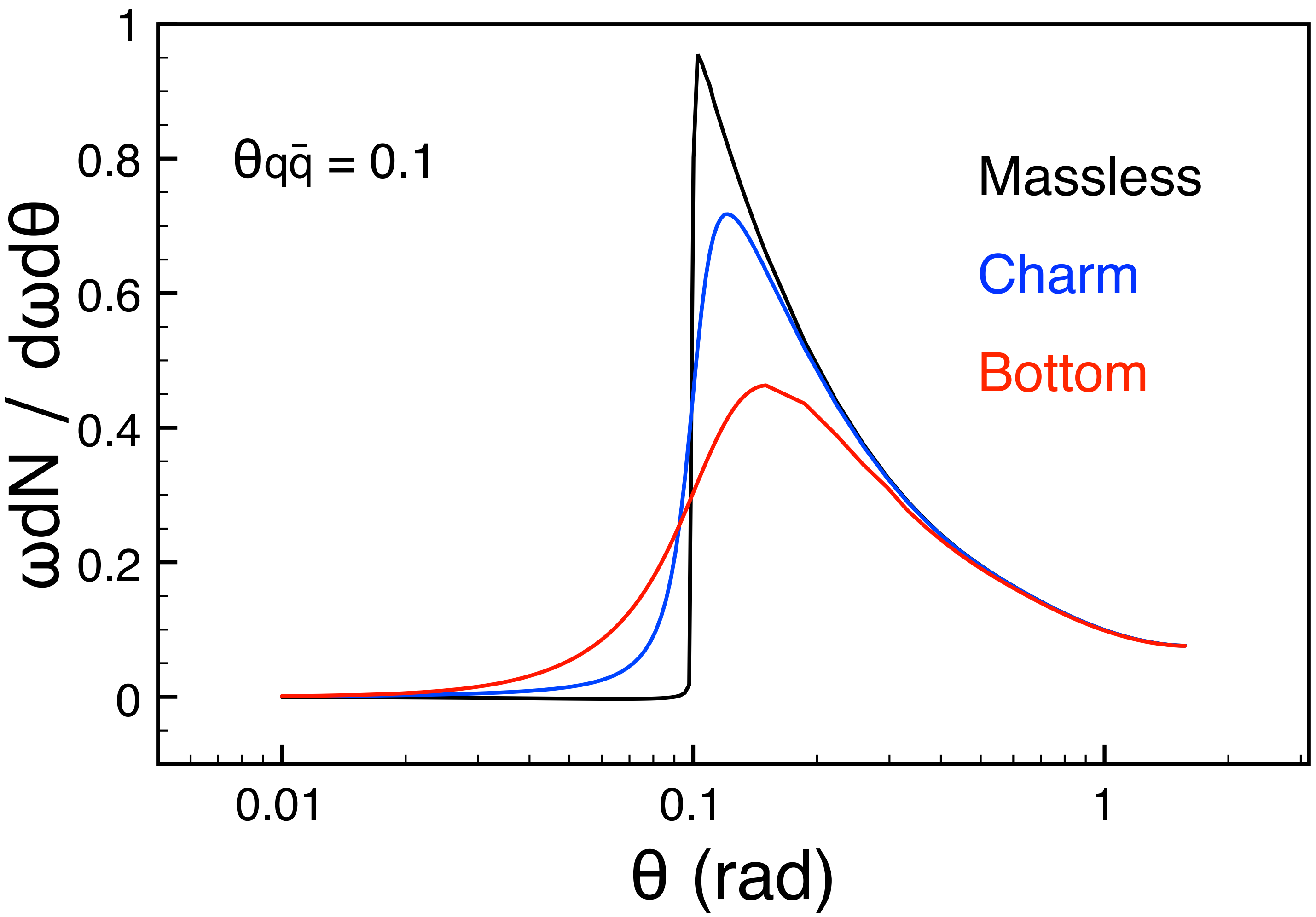
$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{1}{\theta}\,\Theta(\theta-\theta_{q\bar{q}})\,\Delta_{\mathrm{med}}(\theta_{q\bar{q}},L_+)$$

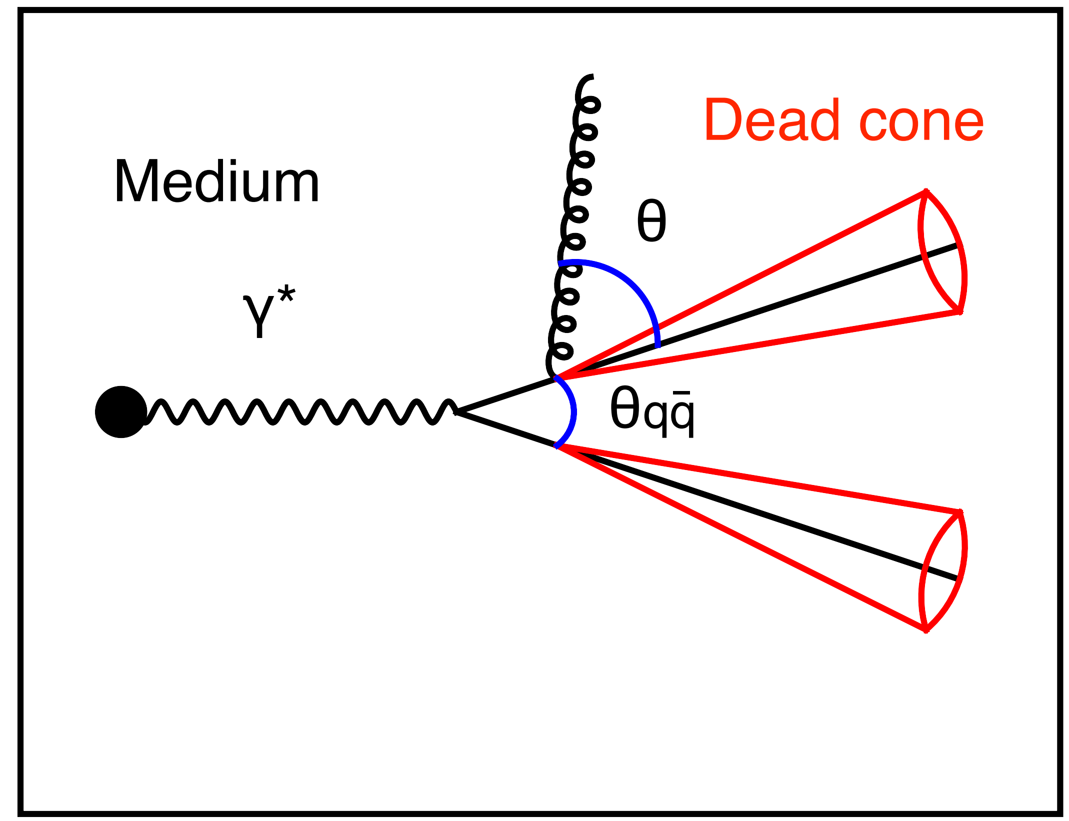
Medium decoherence parameter

$$\Delta_{\mathrm{med}}(\theta_{q\bar{q}},L_+) \propto \hat{q}\,L_+\,|\mathbf{r}_\perp|^2 \sim \hat{q}\,L_+^3\,\theta_{q\bar{q}}^2$$

Collinear convergence $\Leftarrow$ Antiangular ordering: $\theta > \theta_{q\bar{q}}$

Medium-induced antiangular ordering in the soft limit





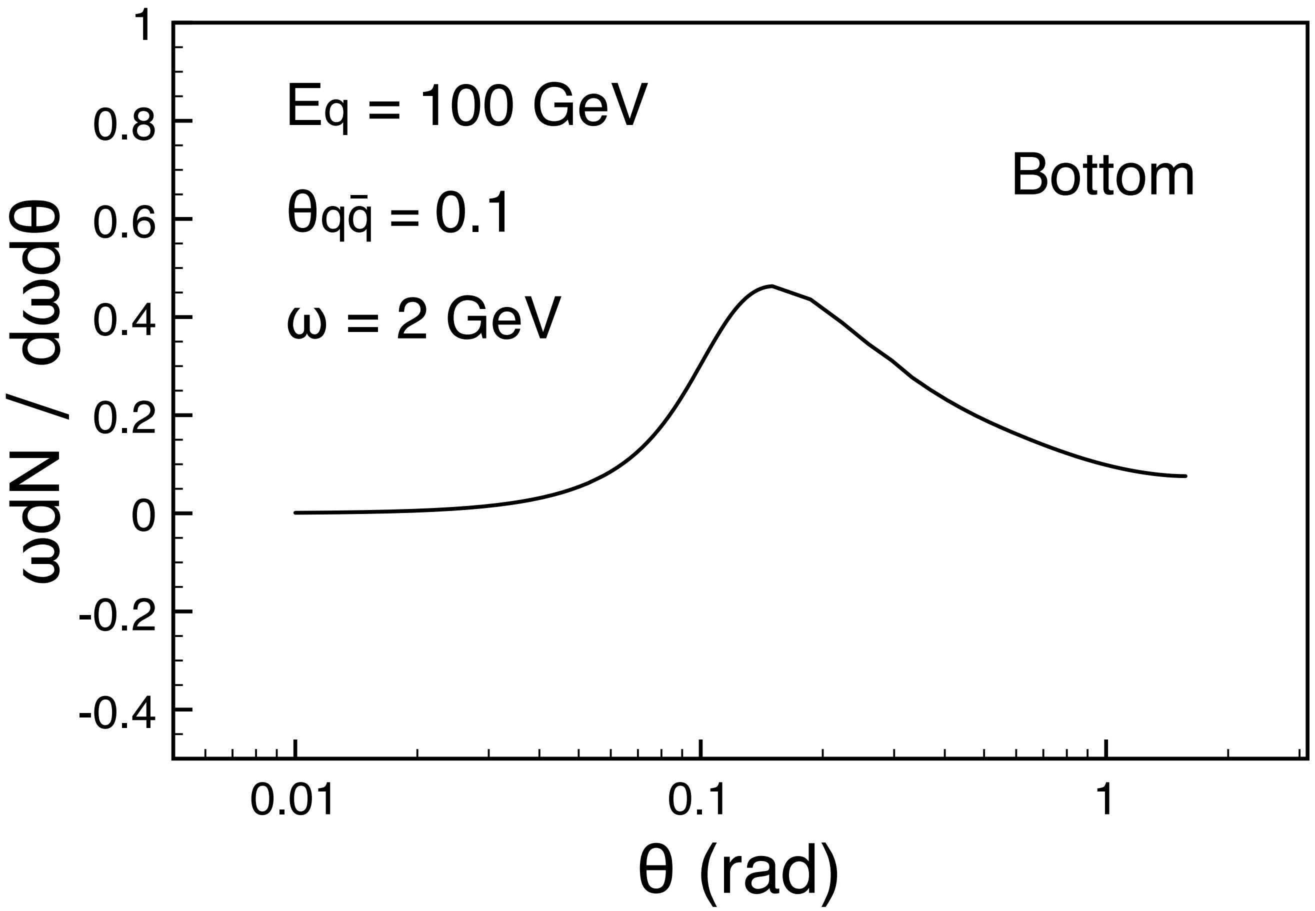
$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{\theta}{\theta^2+\theta_0^2} H(\theta_{q\bar{q}},\theta_0,\theta)\,\Delta_{\mathrm{med}}(\theta_{q\bar{q}},\theta_0,L_+)$$

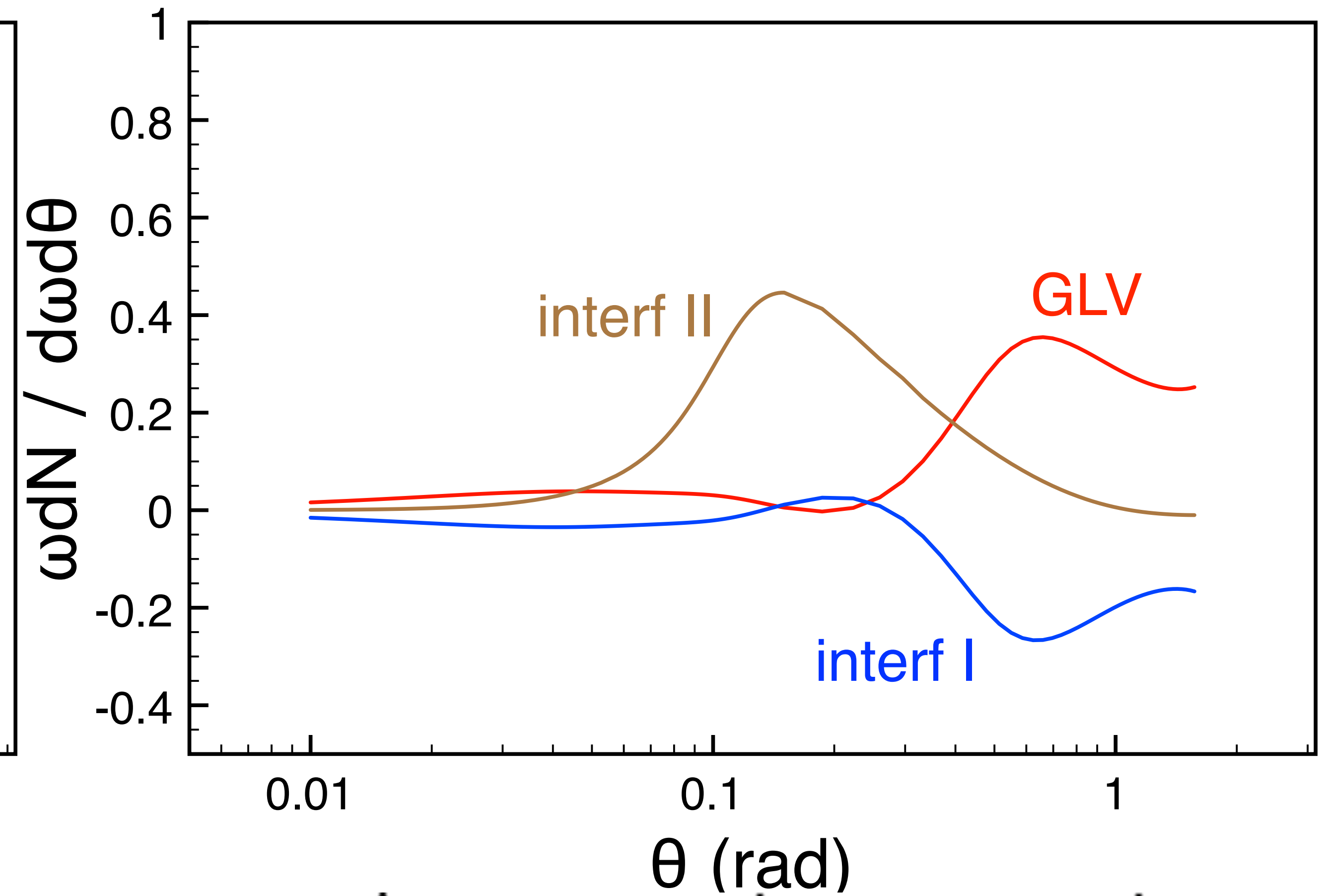
Medium decoherence parameter

⇒ Antiangular ordering is destroyed by the dead cone angle θ_0.

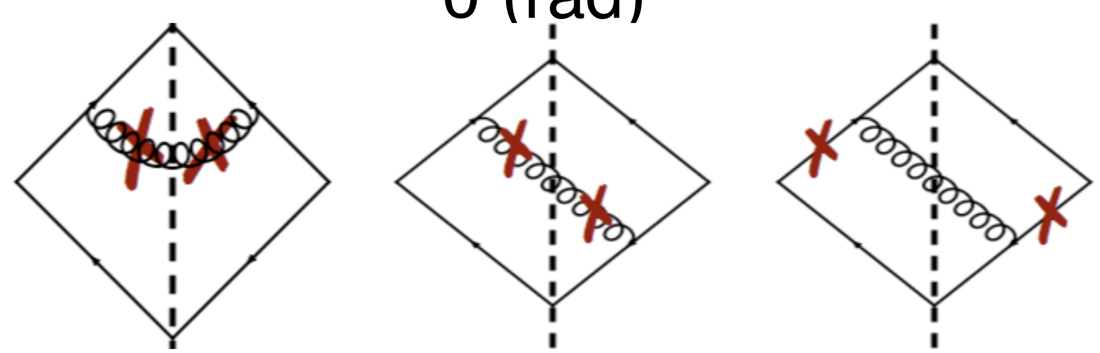
Cancellation in the soft limit extended to the massive case

Massless case: Mehtar-Tani, Salgado and Tywoniuk, Phys. Rev. Lett. 106 (2011) 122002



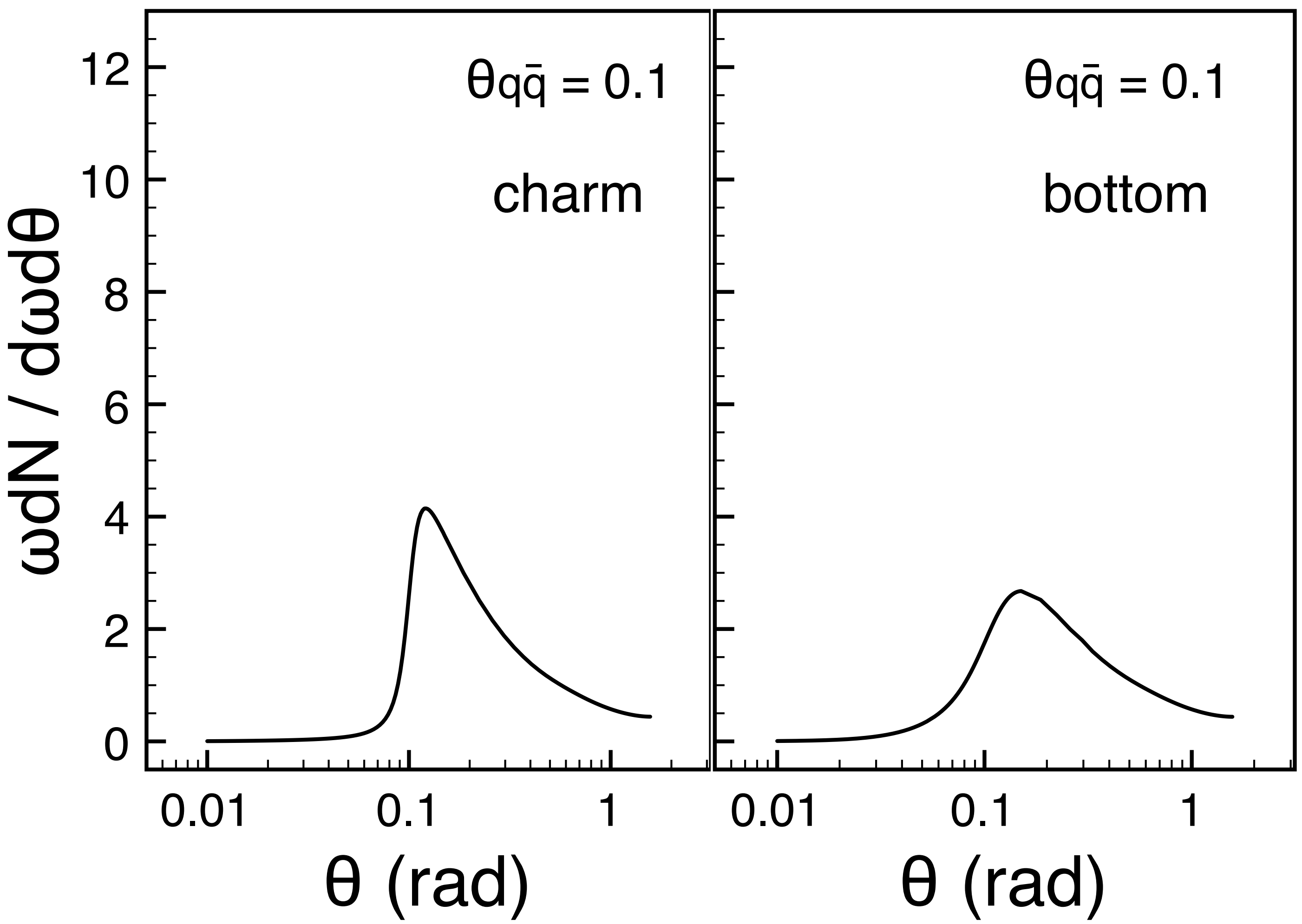


$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta} \sim \mathcal{I}^{\mathrm{GLV}}_{q\bar{q}} + \mathcal{I}^{\mathrm{interf\,I}}_{q\bar{q}} + \mathcal{I}^{\mathrm{interf\,II}}_{q\bar{q}}$$



GLV   interf I   interf II

Decoherence in the soft limit extended to the massive case

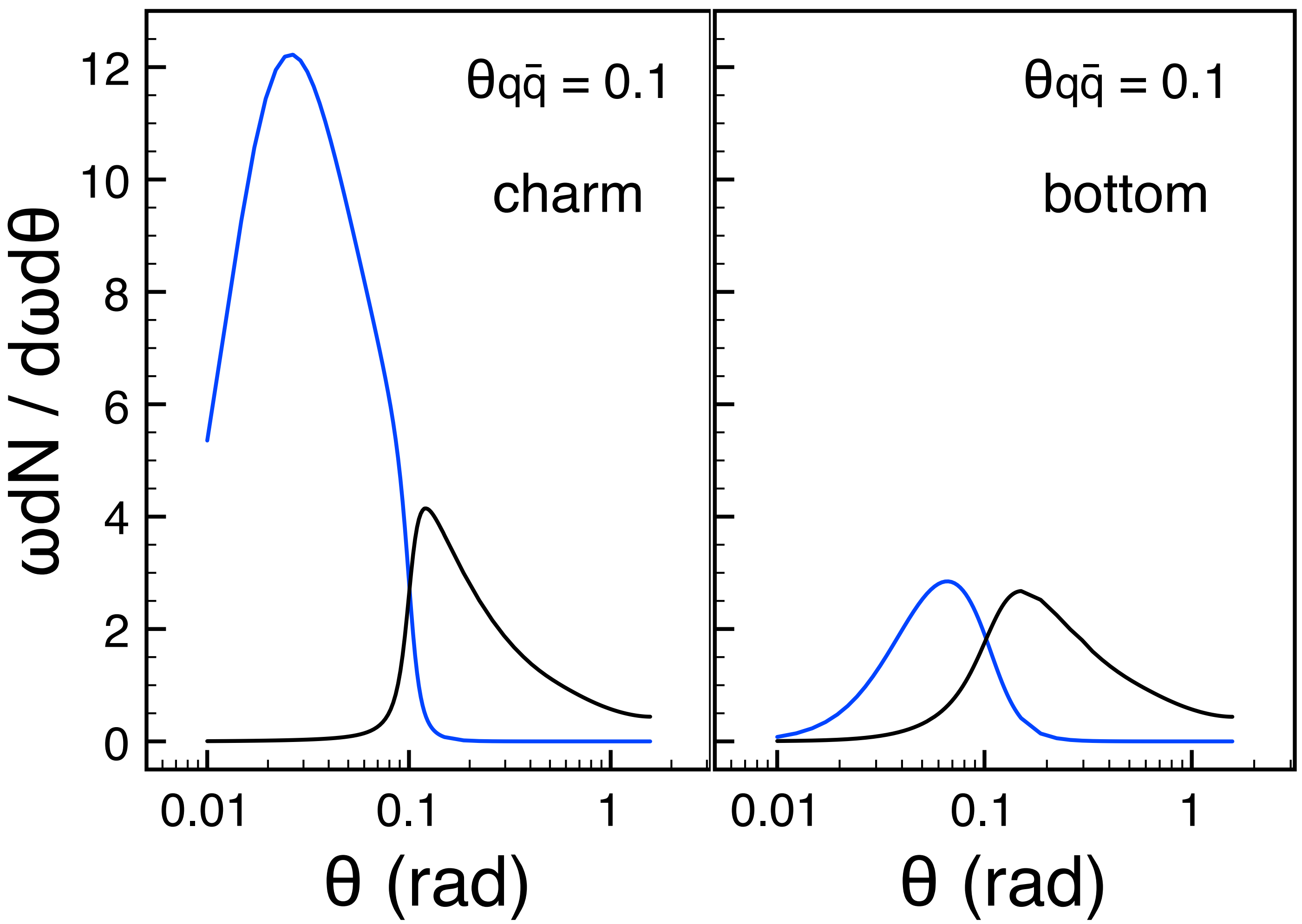


Gluon radiation off a massive antenna in medium rescaled by the reciprocal of the medium decoh. parameter:

$$\Delta_{\rm med}^{-1}\,\omega\,\frac{{\rm d}N}{{\rm d}\omega\,{\rm d}\theta}$$

[Massless ⇒ Anti-angular ord.]

Decoherence in the soft limit extended to the massive case



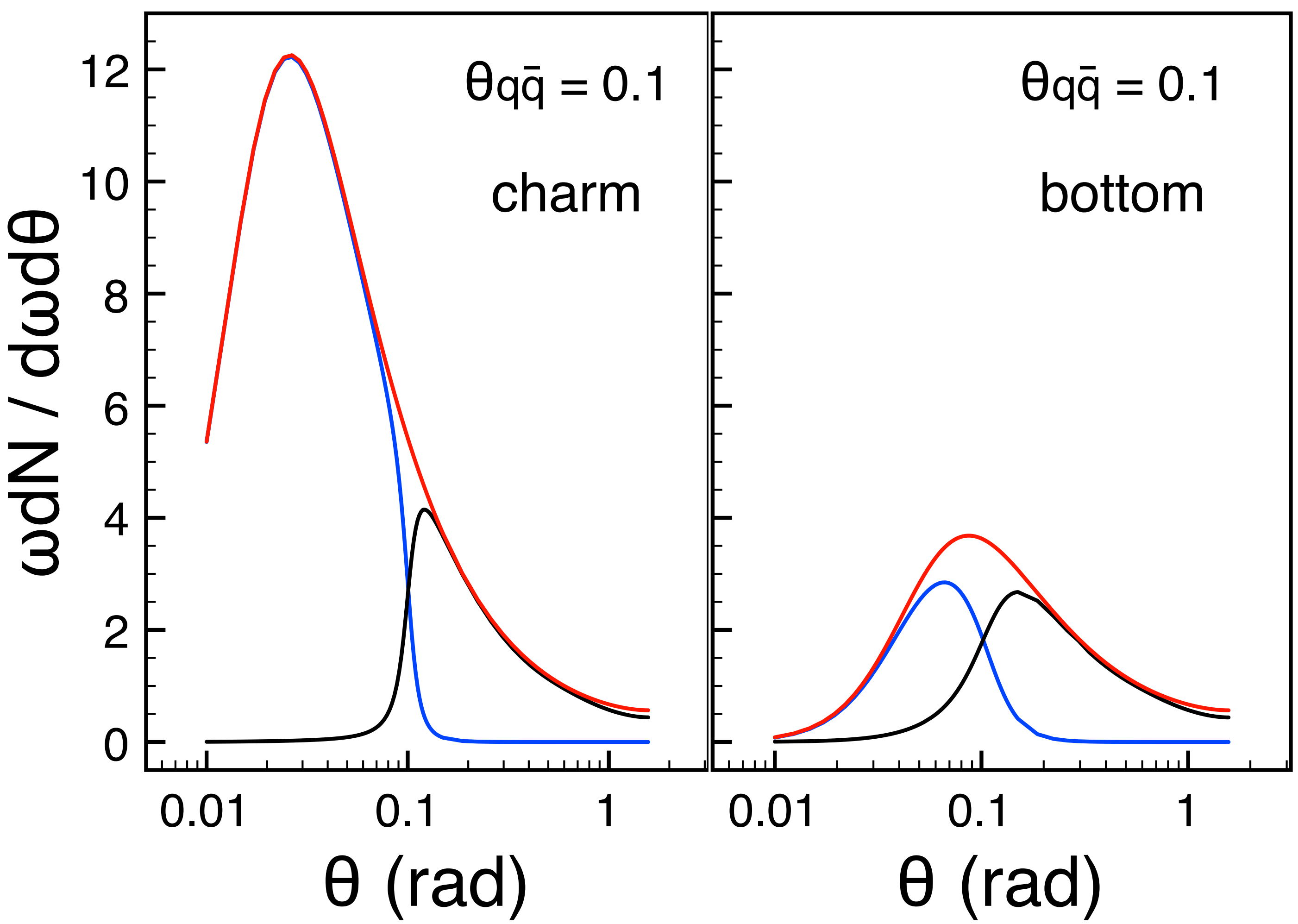
Gluon radiation off a massive antenna in medium rescaled by the reciprocal of the medium decoh. parameter:

$$\Delta_{\rm med}^{-1}\,\omega\,\frac{{\rm d}N}{{\rm d}\omega\,{\rm d}\theta}$$ [Massless ⇒ Anti-angular ord.]

Gluon radiation off a massive antenna in vacuum:

$$\omega\,\frac{{\rm d}N_{\rm vac}}{{\rm d}\omega\,{\rm d}\theta}$$ [Massless ⇒ Angular ord.]

Decoherence in the soft limit extended to the massive case



Massless case: Mehtar-Tani, Salgado and Tywoniuk, arXiv:1102.4317 [hep-ph] and Yacine Mehtar-Tani's talk

$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}^{\mathrm{decoh}}}{\mathrm{d}\omega\,\mathrm{d}\theta} = \omega \frac{\mathrm{d}N_{\mathrm{vac}}}{\mathrm{d}\omega\,\mathrm{d}\theta} + \Delta_{\mathrm{med}}^{-1}\,\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta}$$

Gluon radiation off a massive antenna in medium rescaled by the reciprocal of the medium decoh. parameter:

$$\Delta_{\mathrm{med}}^{-1}\,\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta}$$ [Massless ⇒ Anti-angular ord.]

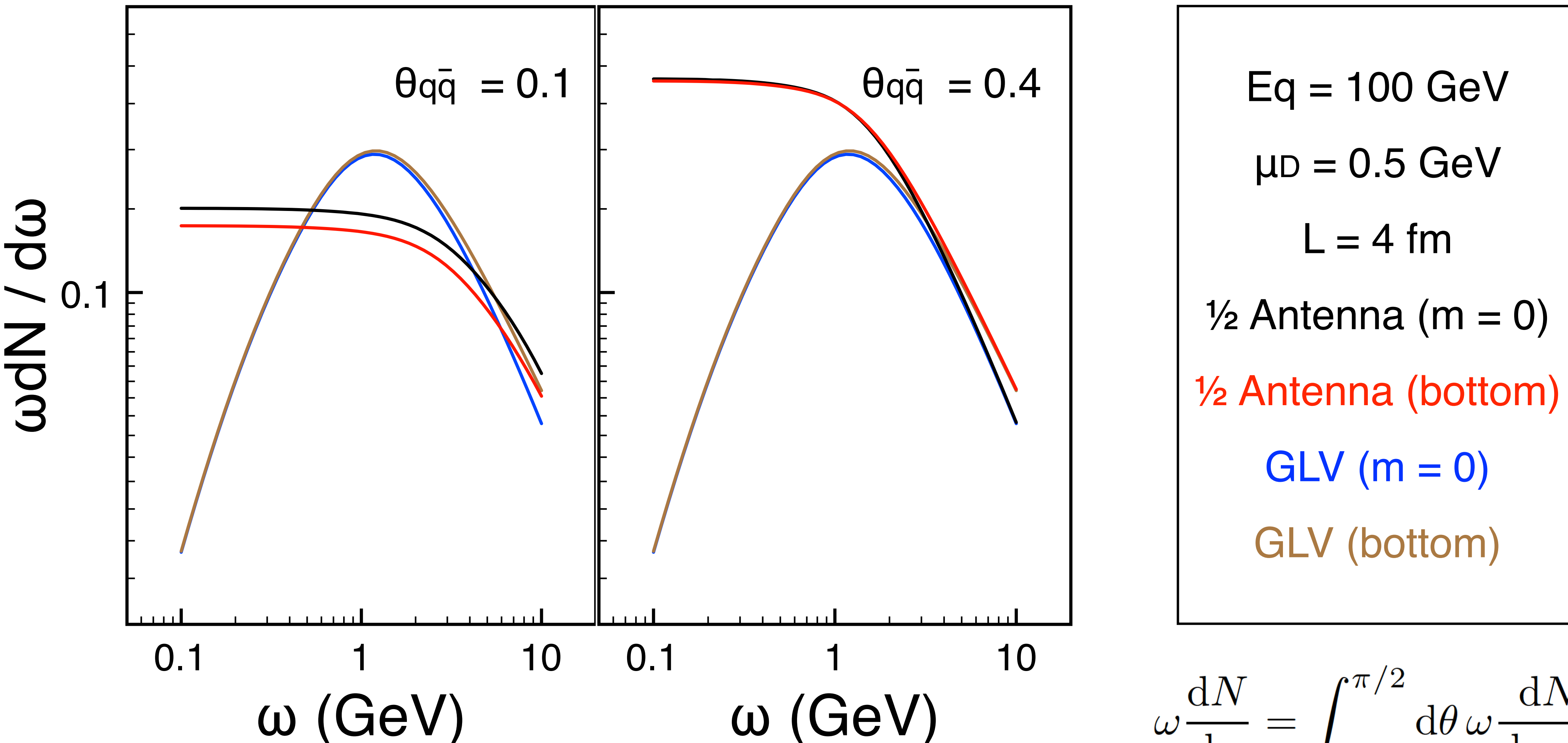
Gluon radiation off a massive antenna in vacuum:

$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}}{\mathrm{d}\omega\,\mathrm{d}\theta}$$ [Massless ⇒ Angular ord.]

Gluon hard vacuum radiation multiplied by 2:

$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}^{\mathrm{decoh}}}{\mathrm{d}\omega\,\mathrm{d}\theta}$$

Medium-induced gluon energy spectrum



$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega} = \int_0^{\pi/2} \mathrm{d}\theta \, \omega \frac{\mathrm{d}N}{\mathrm{d}\omega \, \mathrm{d}\theta}$$

- Antenna opens phase space for soft gluon radiation at relatively large opening angles

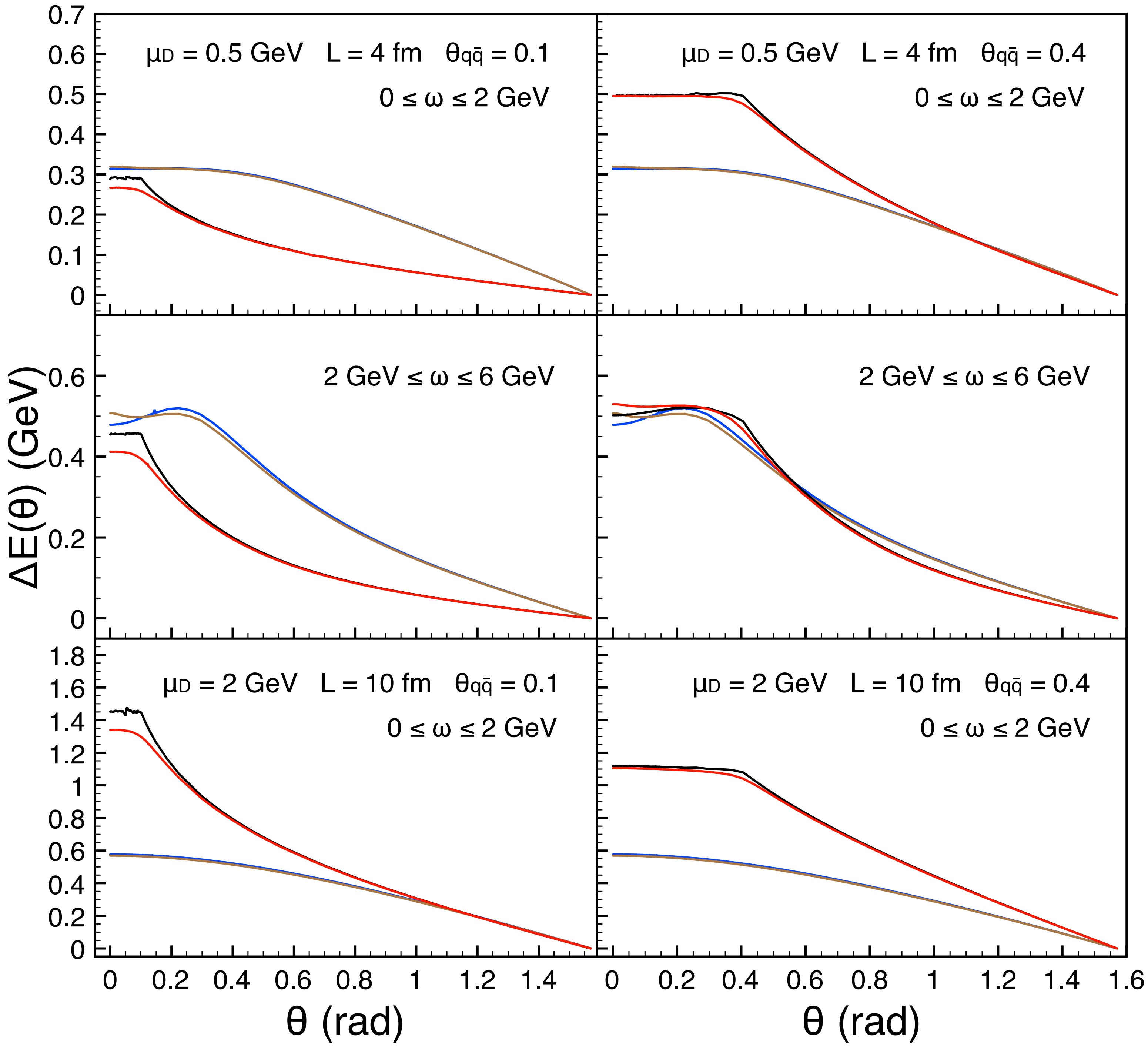
⇒ GLV is suppressed when ω→0.

$$\Rightarrow \Delta_{\rm med}(\theta_{q\bar{q}}, L_+) \propto \hat{q}\, L_+ \, |\mathbf{r}_\perp|^2 \sim \hat{q}\, L_+^3 \, \theta_{q\bar{q}}^2$$

Cut-off scale:

$$\omega_{\rm coh} \sim (\theta_{q\bar{q}}^2 L)^{-1}$$

Angular dependence of gluon energy distribution



Eq = 100 GeV

½ Antenna (m = 0)

½ Antenna (bottom)

GLV (m = 0)

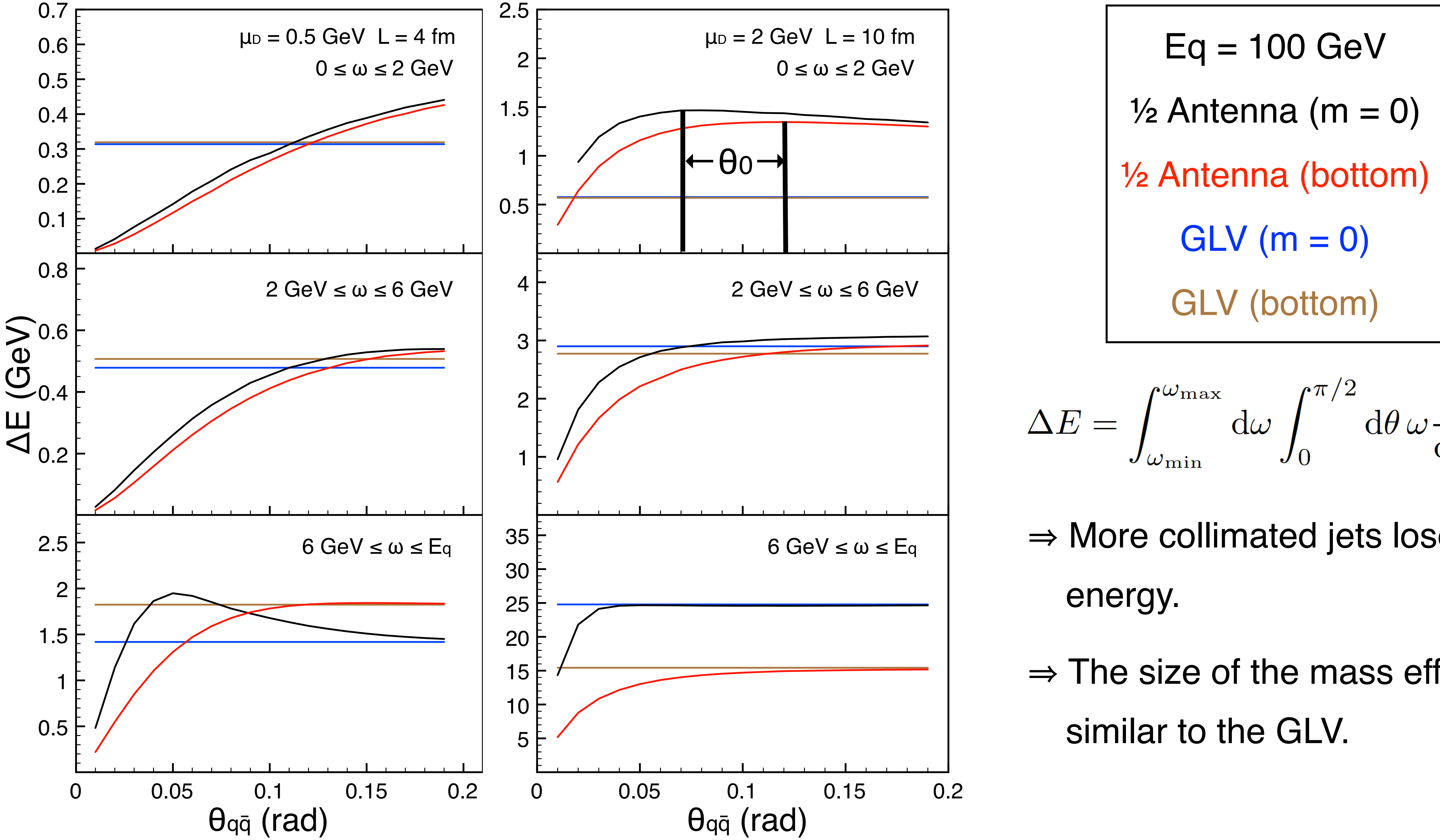
GLV (bottom)

$$\Delta E(\theta) = \int_{\omega_{\min}}^{\omega_{\max}} \mathrm{d}\omega \int_{\theta}^{\pi/2} \mathrm{d}\theta' \, \omega \frac{\mathrm{d}N}{\mathrm{d}\omega \, \mathrm{d}\theta'}$$

⇒ No $\mathbf{k}_\perp$-broadening in Antenna as in GLV for soft sector.

N. Armesto, H. Ma, Y. Mehtar-Tani, C. A. Salgado and K. Tywoniuk, in preparation.

Average energy loss

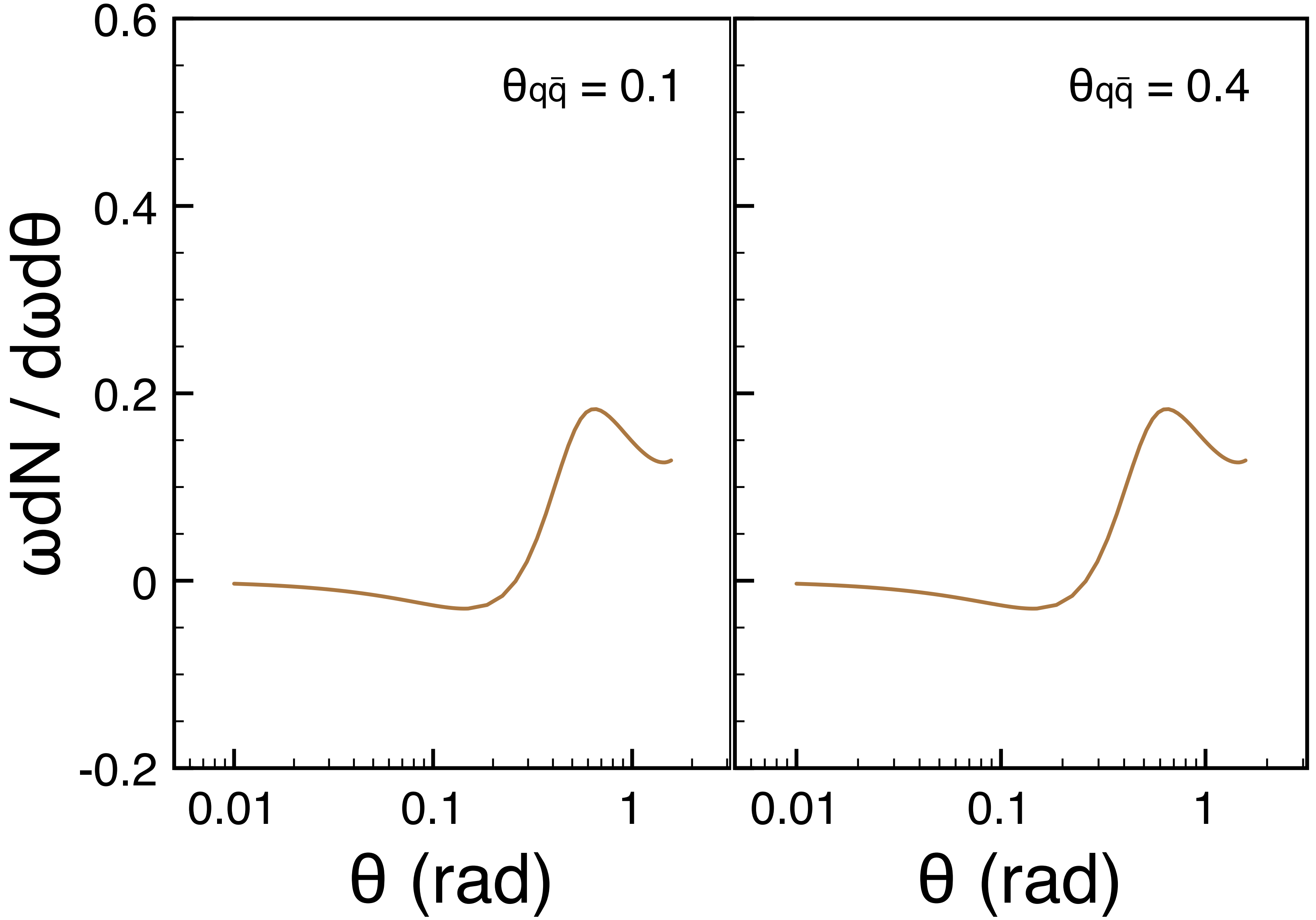


$$\Delta E = \int_{\omega_{\min}}^{\omega_{\max}} \mathrm{d}\omega \int_0^{\pi/2} \mathrm{d}\theta\, \omega \frac{\mathrm{d}N}{\mathrm{d}\omega\, \mathrm{d}\theta}$$

⇒ More collimated jets lose less energy.

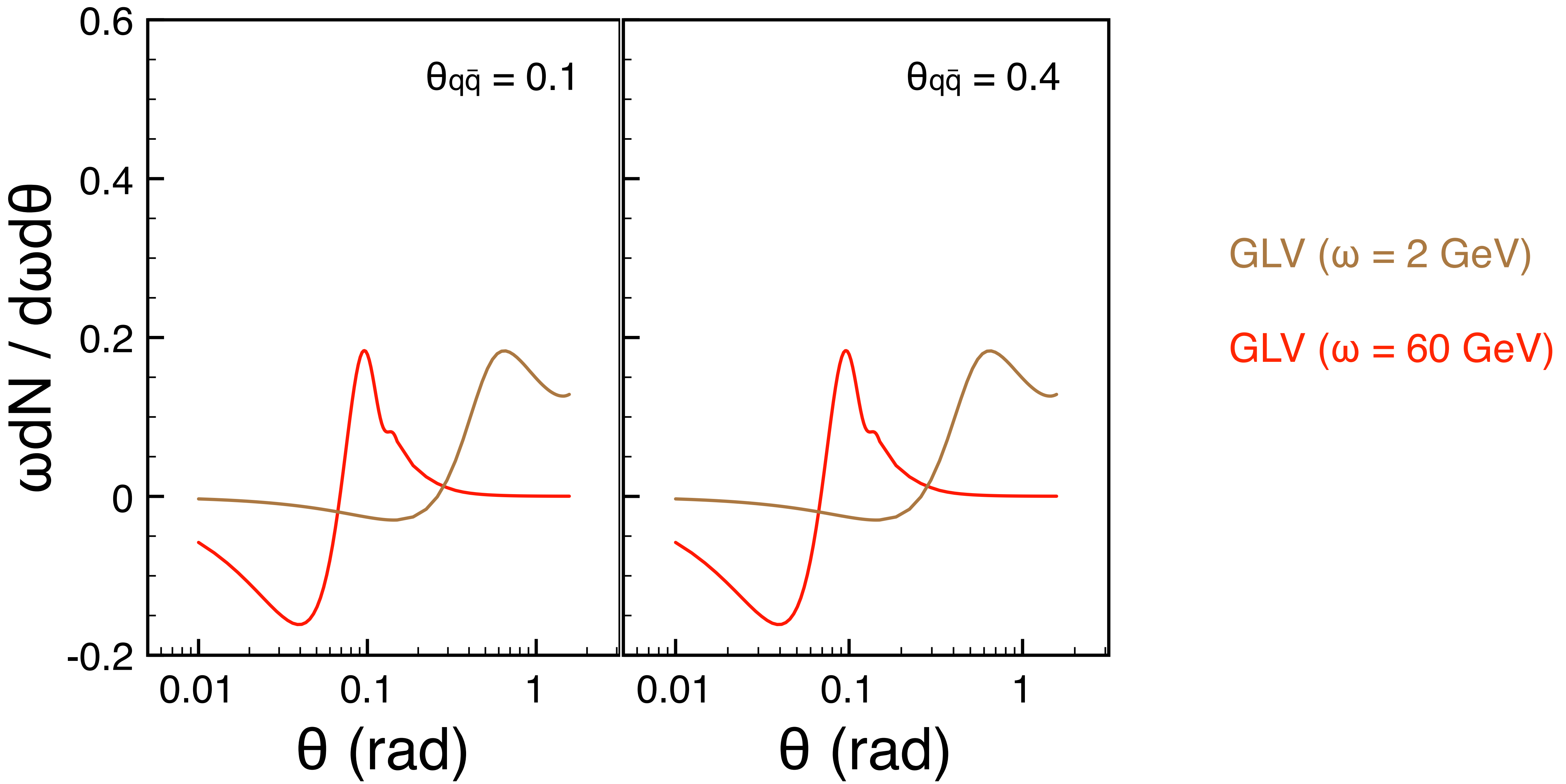
⇒ The size of the mass effect is similar to the GLV.

Transition between the antenna & the GLV

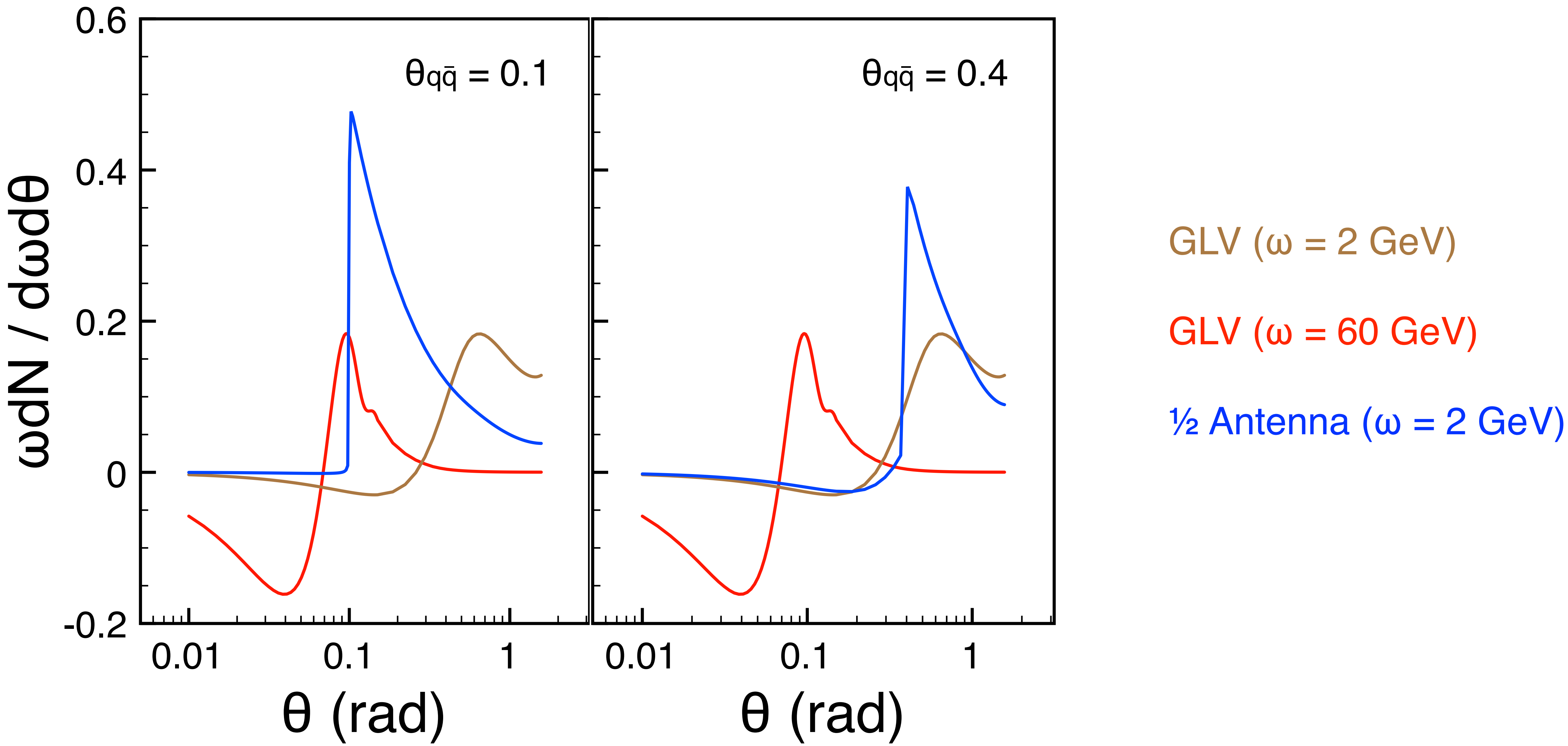


GLV (ω = 2 GeV)

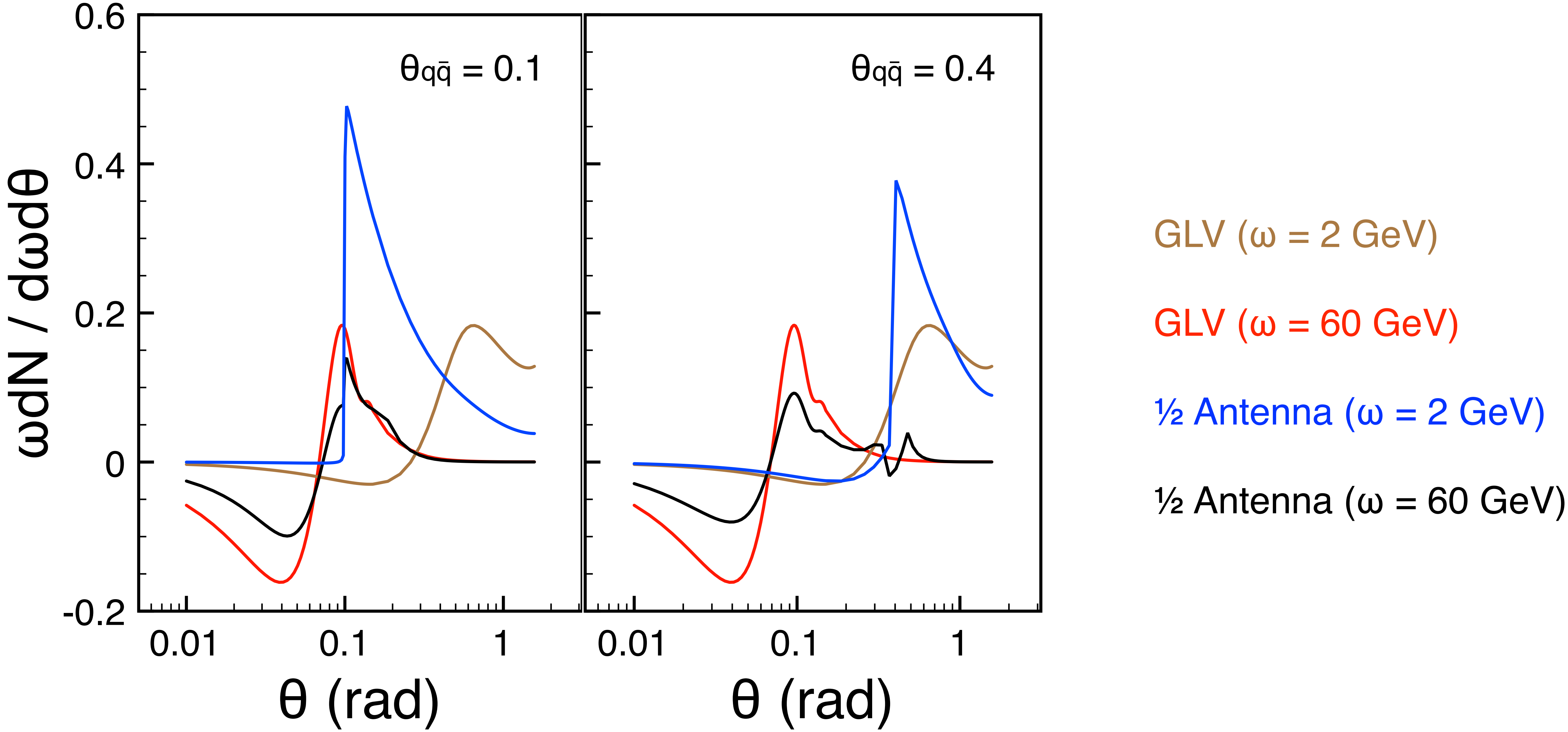
Transition between the antenna & the GLV



Transition between the antenna & the GLV



Transition between the antenna & the GLV



Characteristic energy of the emitted gluon: $\omega_A \sim \frac{\mu_D}{\theta_{q\bar{q}}}$

Conclusion

- Medium-induced antiangular ordering in the soft limit is modified in the massive antenna case because of the dead-cone effect.
- Decoherence in the soft limit is extended to the massive antenna case.
- Antenna opens phase space for soft gluon radiation at relatively large opening angles.
- Both dead-cone effect and non-Abelian LPM effect appear in medium for the massive antenna case.
- More collimated jets lose less energy.
- The size of the mass effect of the antenna is similar to the GLV.

Back-up slides

Back-up

- Massless medium decoh. parameter

$$\Delta_{\rm med}(\theta_{q\bar{q}}, L_+) \approx \frac{1}{6}\,\hat{q}\,L_+\,|\mathbf{r}_\perp|^2 \left(\log\frac{1}{|\mathbf{r}_\perp|\,\mu_D} + \text{const.}\right)$$

- Massless dipole size

$$|\mathbf{r}_\perp| = \frac{\sqrt{2}\sin\theta_{q\bar{q}}\,L_+}{1+\cos\theta_{q\bar{q}}}$$

- Massive medium decoh. parameter

$$\Delta_{\rm med}(\theta_{q\bar{q}}, \theta_0, L_+) \approx \frac{1}{6}\,\hat{q}\,L_+\,|\mathbf{r}_\perp|^2 \left(\log\frac{1}{|\mathbf{r}_\perp|\,\mu_D} + \text{const.}\right)$$

- Massive dipole size

$$|\mathbf{r}_\perp| = \frac{\sqrt{2}\sin\theta_{q\bar{q}}\,L_+}{1+\sqrt{1-\theta_0^2}\cos\theta_{q\bar{q}}}$$

- Gluon formation time

$$t_g^{\rm form} \sim \frac{\omega}{|\mathbf{k}_\perp|^2+\theta_0^2\omega^2}$$

Back-up

- GLV spectrum

$$\mathcal{I}^{\mathrm{GLV}}_{quark} = \int \frac{\mathrm{d}^2\mathbf{q}_\perp}{(2\,\pi)^2} \int_0^{L_+} \mathrm{d}x_+ \, \frac{n_0}{\sqrt{2}} \, \frac{\mu_D^2}{(\mathbf{q}_\perp^2 + \mu_D^2)^2} \, 8\,\alpha_s^2\,(4\,\pi)^2\, C_A\, C_F$$
$$\frac{\mathbf{k}_\perp \cdot \mathbf{q}_\perp}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2\,\mathbf{k}_\perp^2} \left[1 - \cos\left(\frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2}{2\,k_+} x_+ \right) \right]$$

Back-up

- Antenna spectrum

$$\mathcal{I}_{q\bar{q}}^{\text{interf II}} = \int \frac{\mathrm{d}^2\mathbf{q}_\perp}{(2\,\pi)^2} \int_0^{L_+} \mathrm{d}x_+ \, \frac{n_0}{\sqrt{2}} \, \frac{\mu_D^2}{(\mathbf{q}_\perp^2 + \mu_D^2)^2} \, (-2)\, \alpha_s^2 \, (4\,\pi)^2 \, C_A \, C_F$$
$$\frac{\boldsymbol{\kappa}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{p\cdot k \, \bar{p}\cdot k} \left(\cos\left(\frac{p\cdot v}{p_+} x_+ - \frac{\bar{p}\cdot v}{\bar{p}_+} x_+ \right) - \cos\left(\frac{p\cdot k}{p_+} x_+ - \frac{\bar{p}\cdot k}{\bar{p}_+} x_+ \right) \right)$$

$$\Downarrow$$

$$\mathcal{I}_{q\bar{q}}^{\text{interf II}} = \int \frac{\mathrm{d}^2\mathbf{q}_\perp}{(2\,\pi)^2} \int_0^{L_+} \mathrm{d}x_+ \, \frac{n_0}{\sqrt{2}} \, \frac{\mu_D^2}{(\mathbf{q}_\perp^2 + \mu_D^2)^2} \, 2\, \alpha_s^2 \, (4\,\pi)^2 \, C_A \, C_F$$
$$\frac{\frac{\bar{p}_+}{k_+}\, p\cdot k + \frac{p_+}{k_+}\, \bar{p}\cdot k - p\cdot\bar{p}}{p\cdot k\, \bar{p}\cdot k} \cos\left(\Omega_{q\bar{q}}^0 \, x_+\right) \left(1 - \cos(\boldsymbol{\pi}_\perp \cdot \mathbf{q}_\perp \, x_+)\right)$$