Mass effect, broadening and coherence in medium-induced QCD radiation off a $q\bar{q}$ antenna

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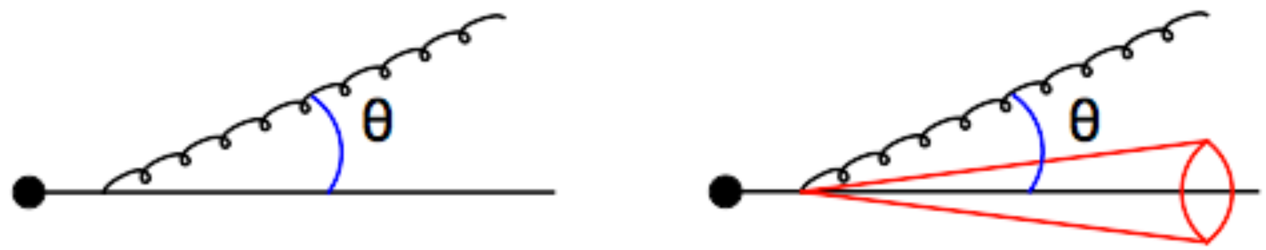
PANIC 11
July 24-29, 2011, MIT

Motivation

- Dead cone effect suppresses radiation in vacuum



m = 0 m ≠ 0 Dead cone angle: $\theta_0 = m/E$

⇒ Gluon radiation inside the dead cone is suppressed.

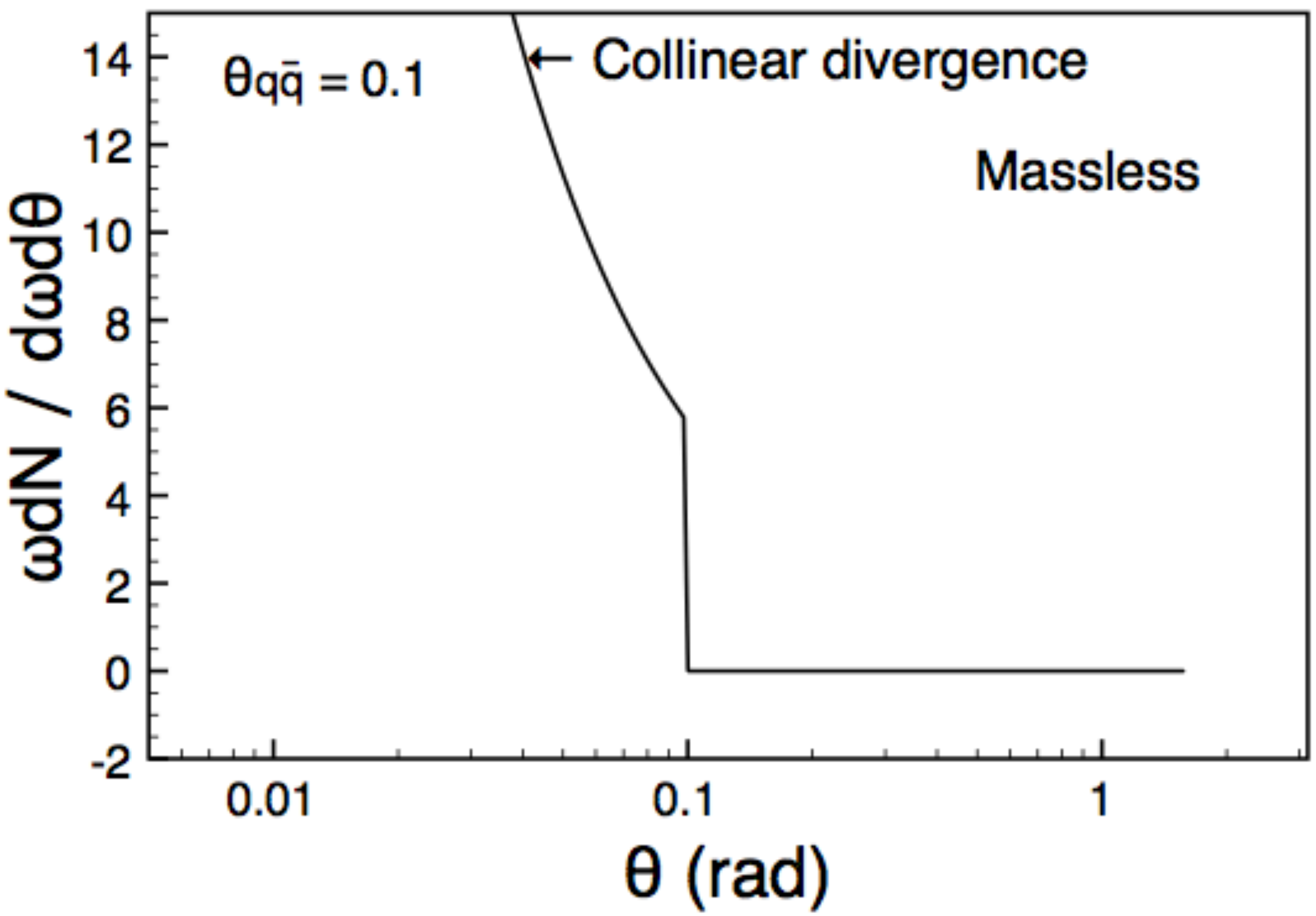
- Mass effects also suppress radiation in medium

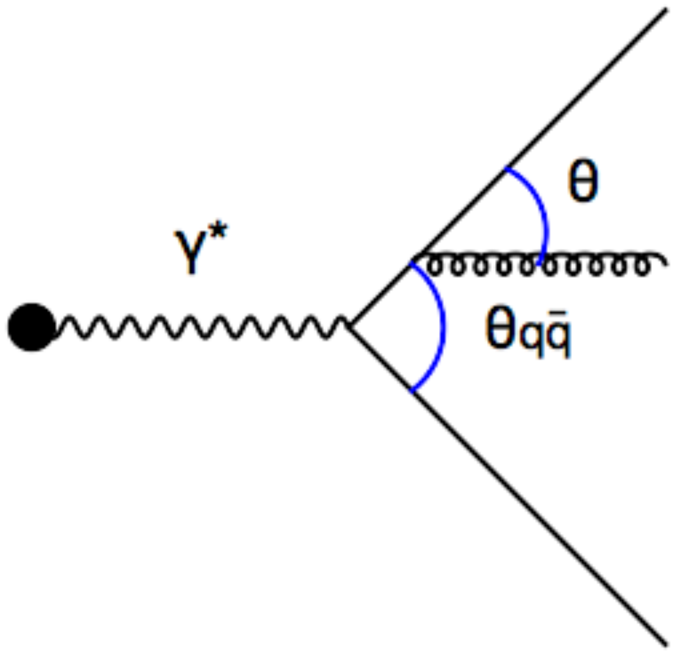
⇒ There are remaining puzzles in RHIC and LHC.

- Study the properties of jets originated by heavy quarks

⇒ LHC measures the heavy quark jets.

Angular ordering in the soft limit in vacuum

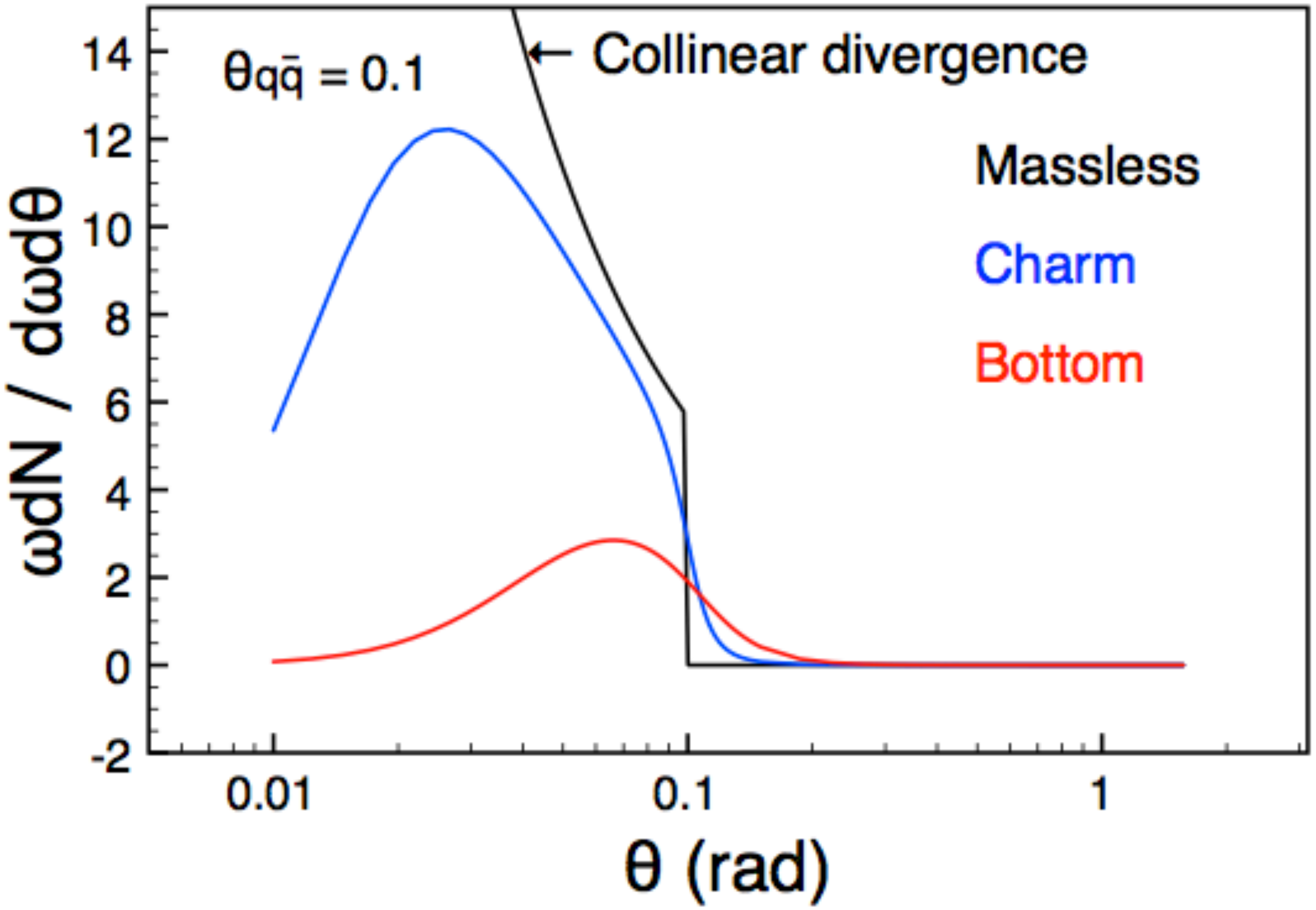


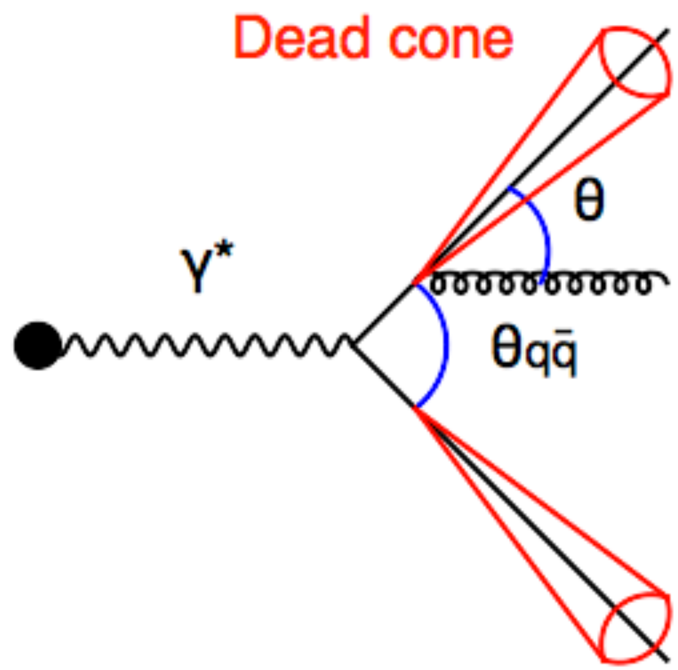


$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{1}{\theta}\,\Theta(\theta_{q\bar{q}} - \theta)$$

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

Angular ordering in the soft limit in vacuum





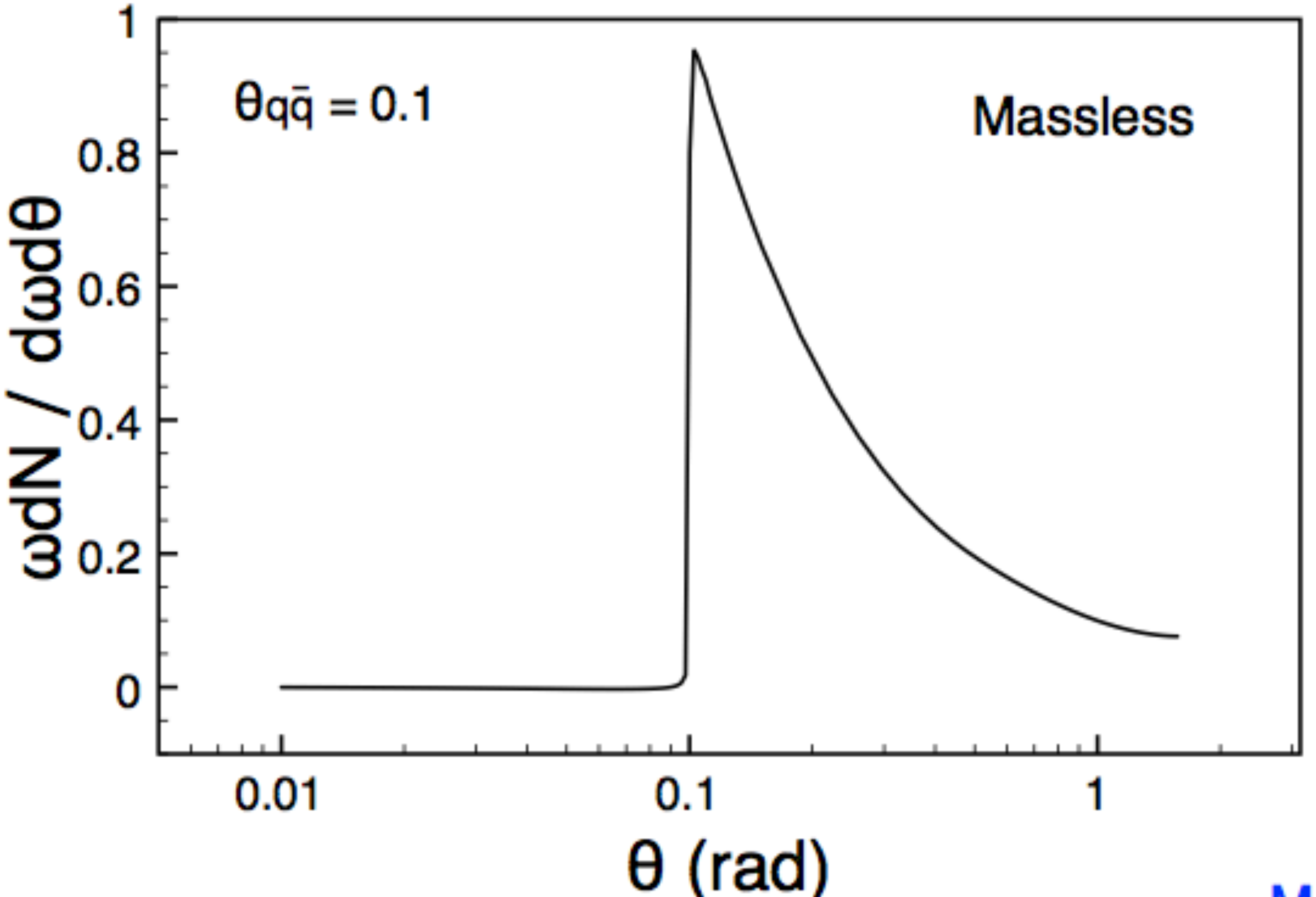
Dead cone angle: $\theta_0 = m/E$

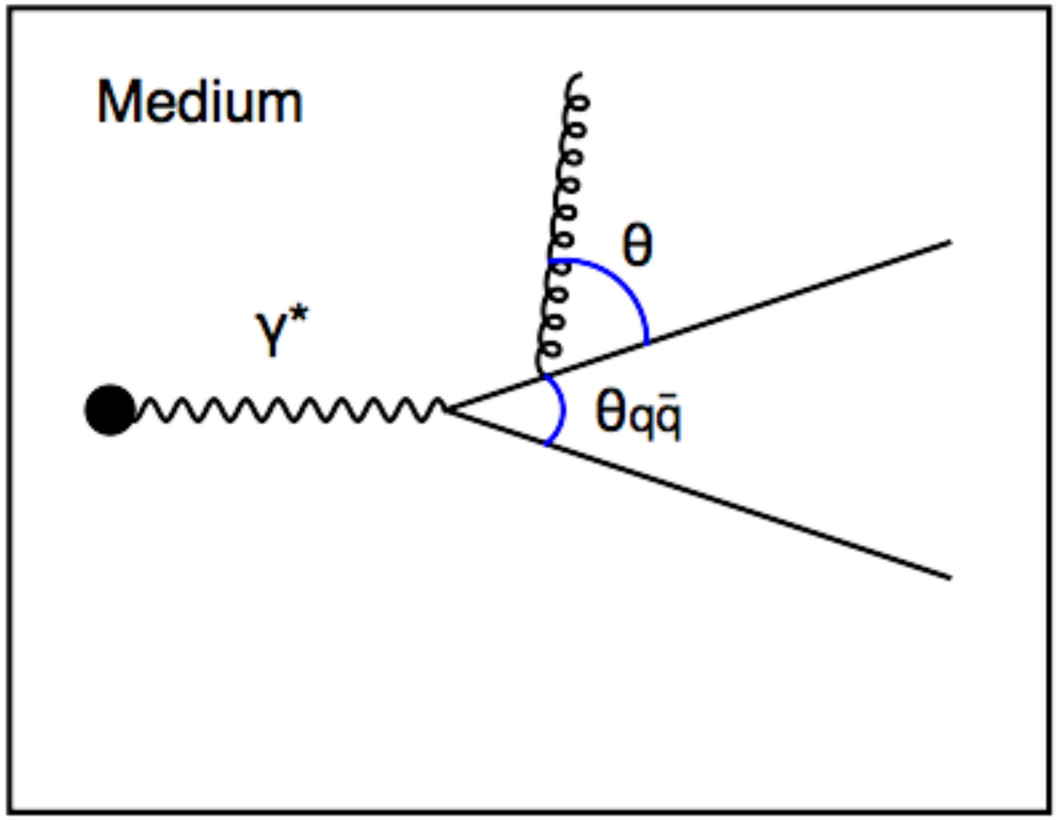
$$\omega \frac{\mathrm{d}N_{\mathrm{vac}}}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{\theta}{\theta^2 + \theta_0^2} H_{\mathrm{vac}}(\theta_{q\bar{q}}, \theta_0, \theta)$$

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

Medium-induced antiangular ordering in the soft limit

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





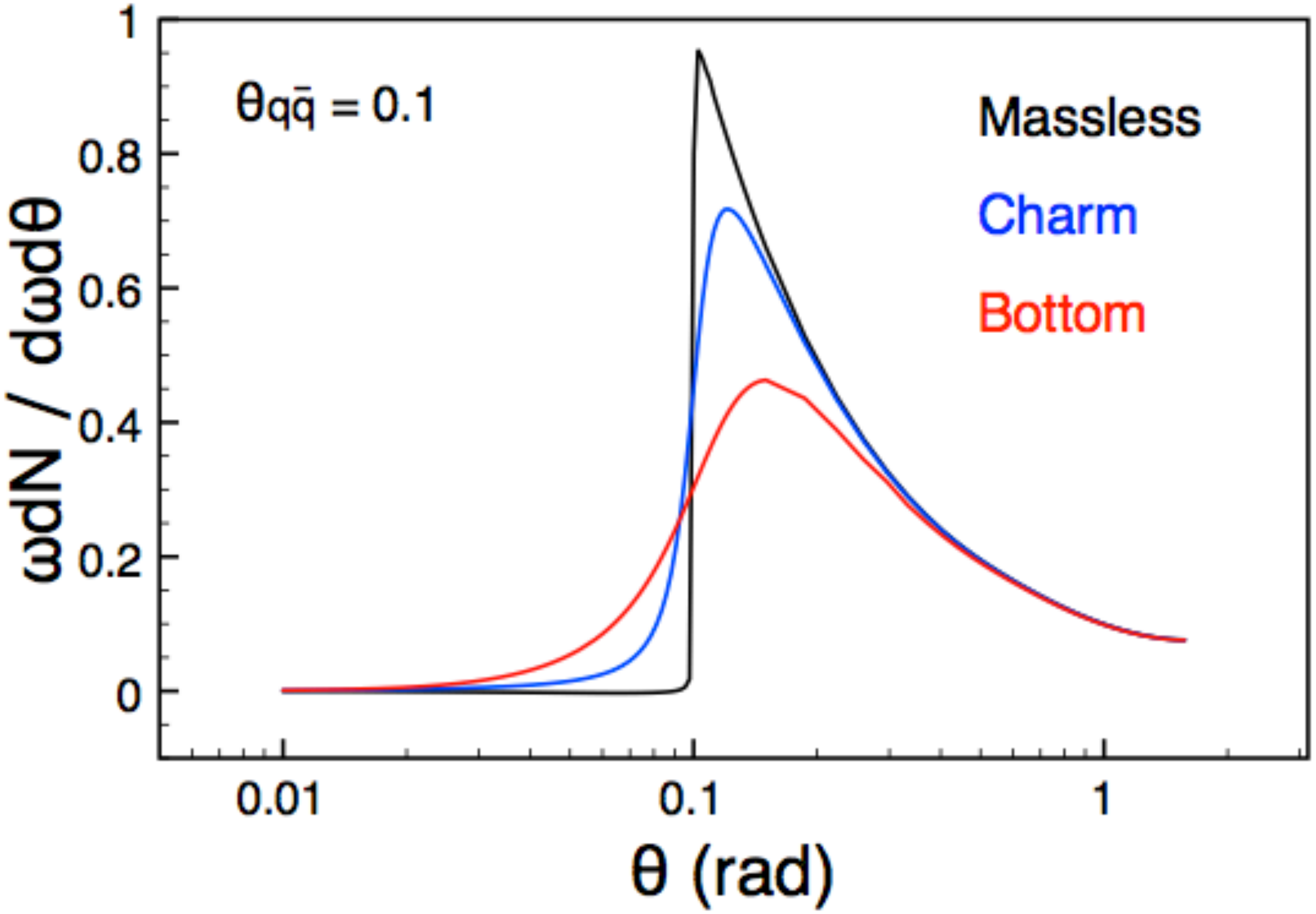
Medium decoherence parameter ($\mu_D\,\theta_{q\bar{q}}\,L_+ \ll 1$):

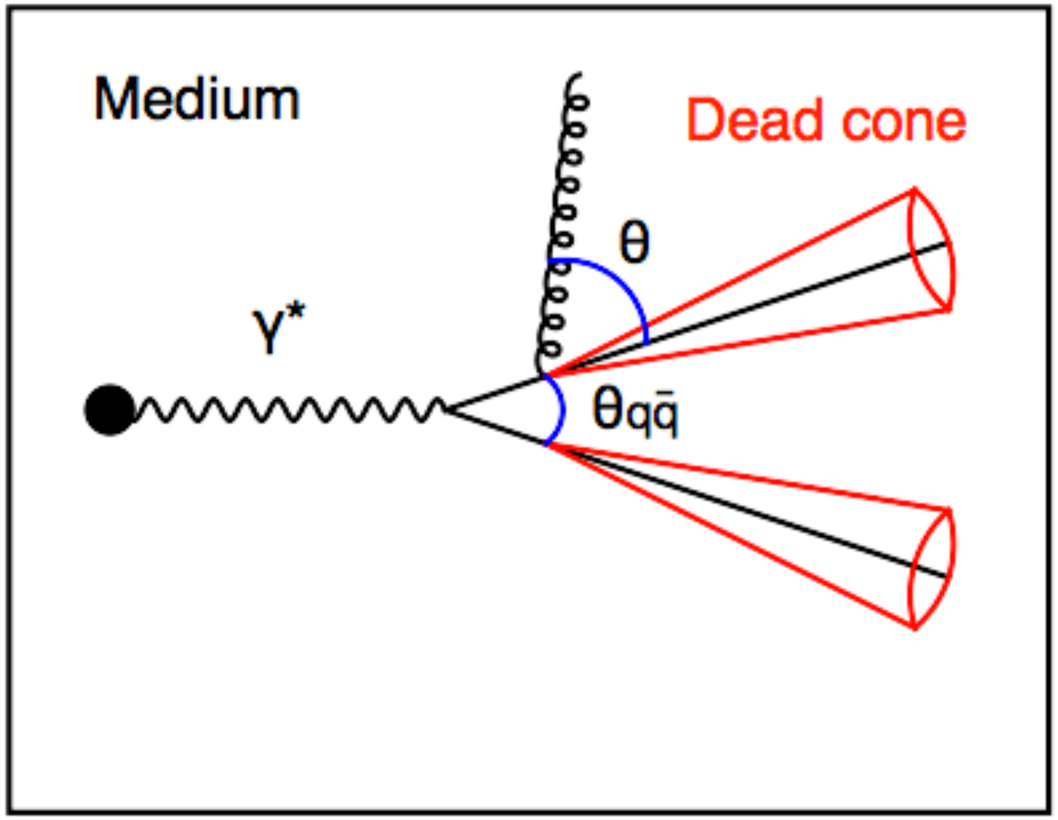
$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{1}{\theta}\,\Theta(\theta - \theta_{q\bar{q}})\,\Delta_{\mathrm{med}}(\theta_{q\bar{q}}, L_+)$$

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

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

Medium-induced antiangular ordering in the soft limit





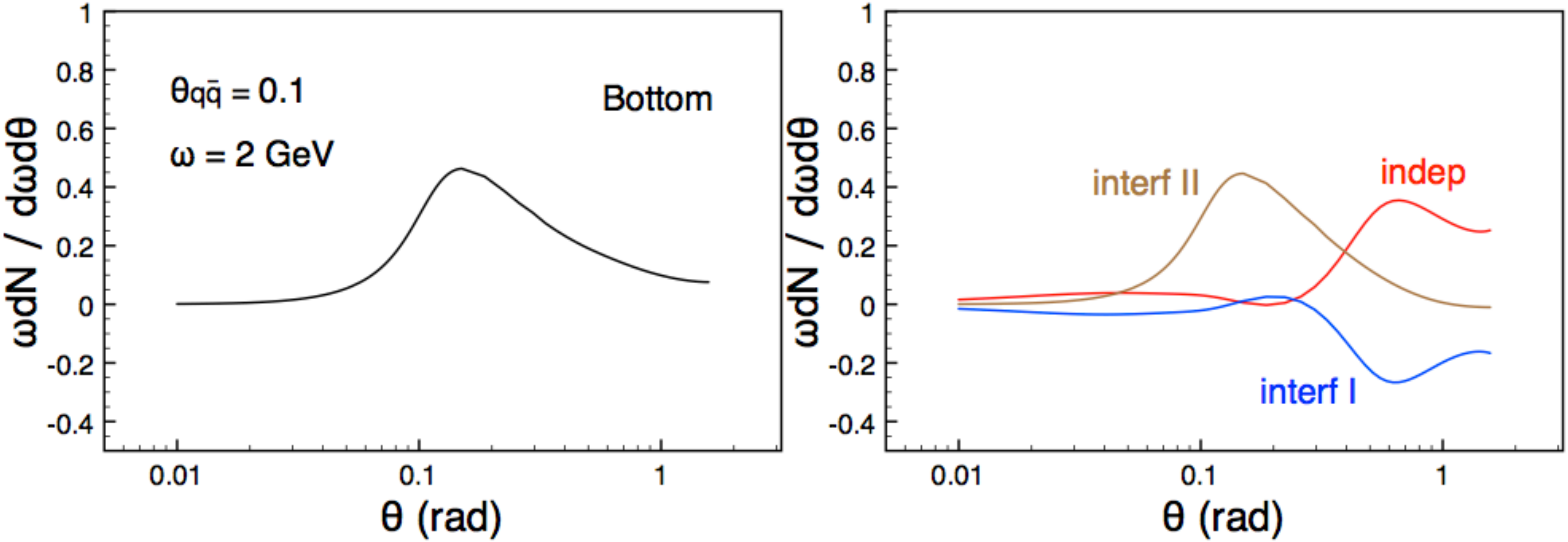
$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta} \propto \frac{\theta}{\theta^2+\theta_0^2} H(\theta_{q\bar{q}}, \theta_0, \theta) \Delta_{\mathrm{med}}(\theta_{q\bar{q}}, \theta_0, L_+)$$

Medium decoherence parameter

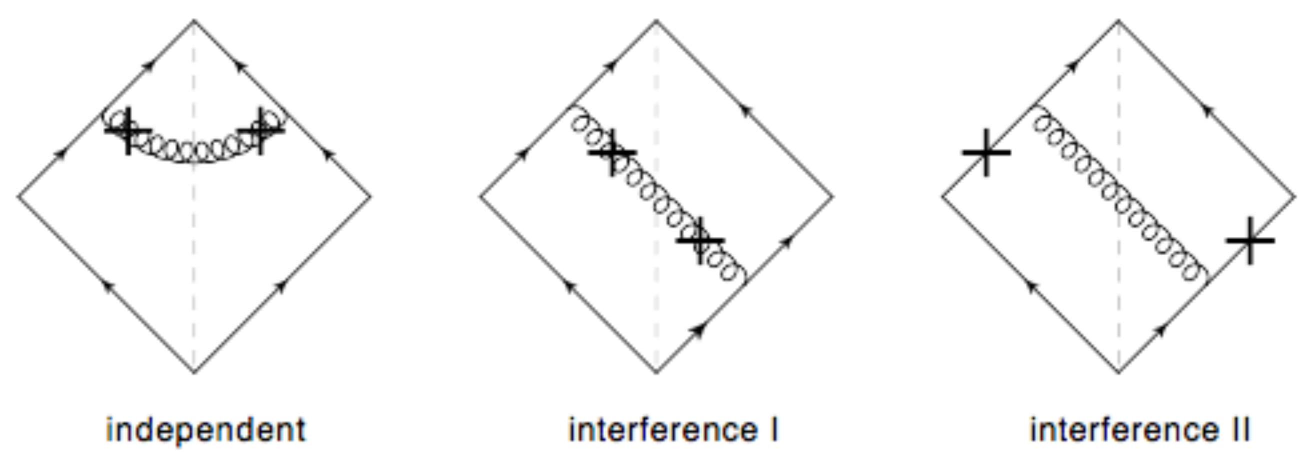
⇒ Antiangular ordering is modified by the dead cone angle θ_0.

Cancellation in the soft limit extended to the massive case

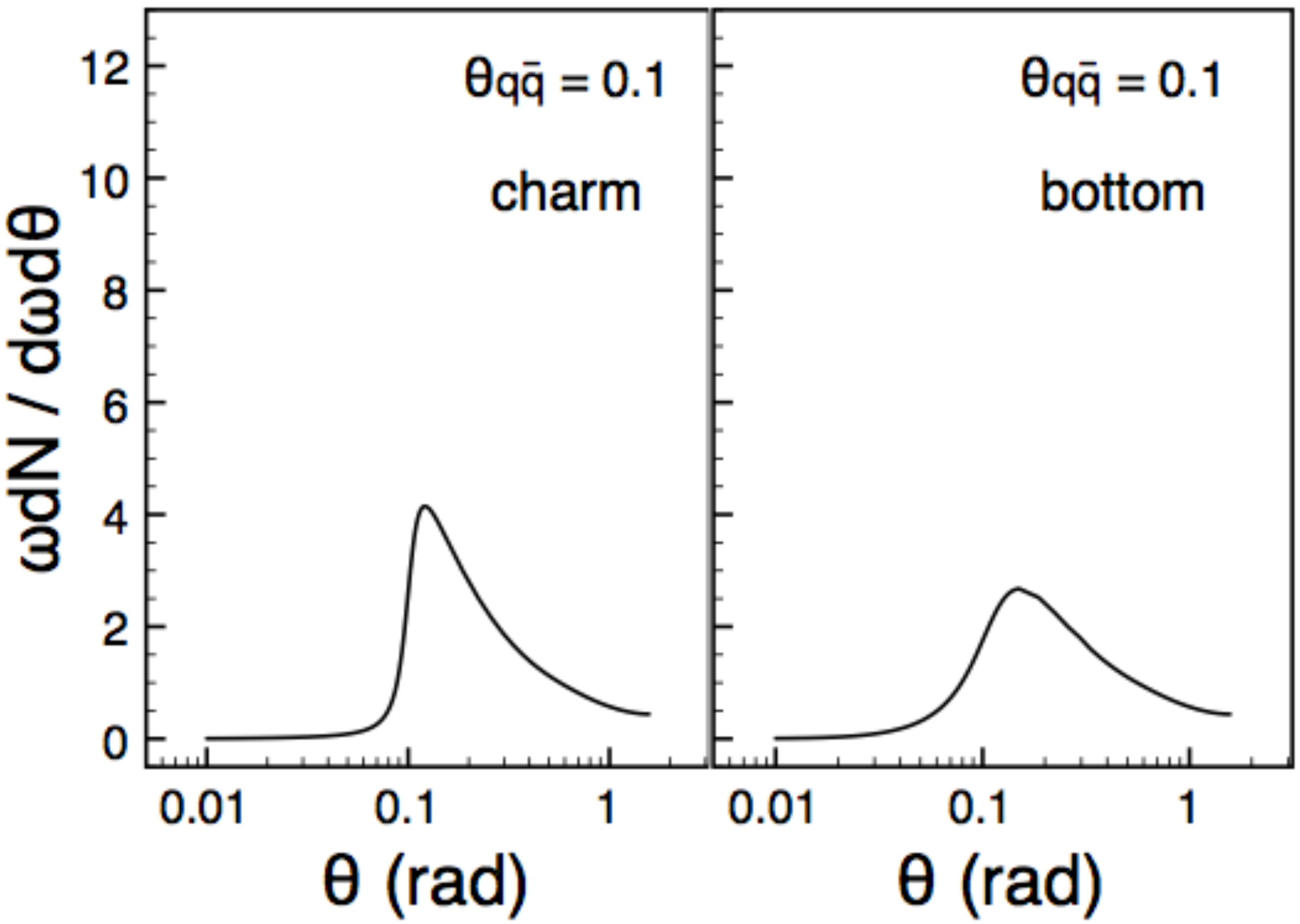
Massless case: Mehtar-Tani, Salgado and Tywoniuk, *Phys. Rev. Lett. 106 (2011) 122002*



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



Decoherence in the soft limit extended to the massive case

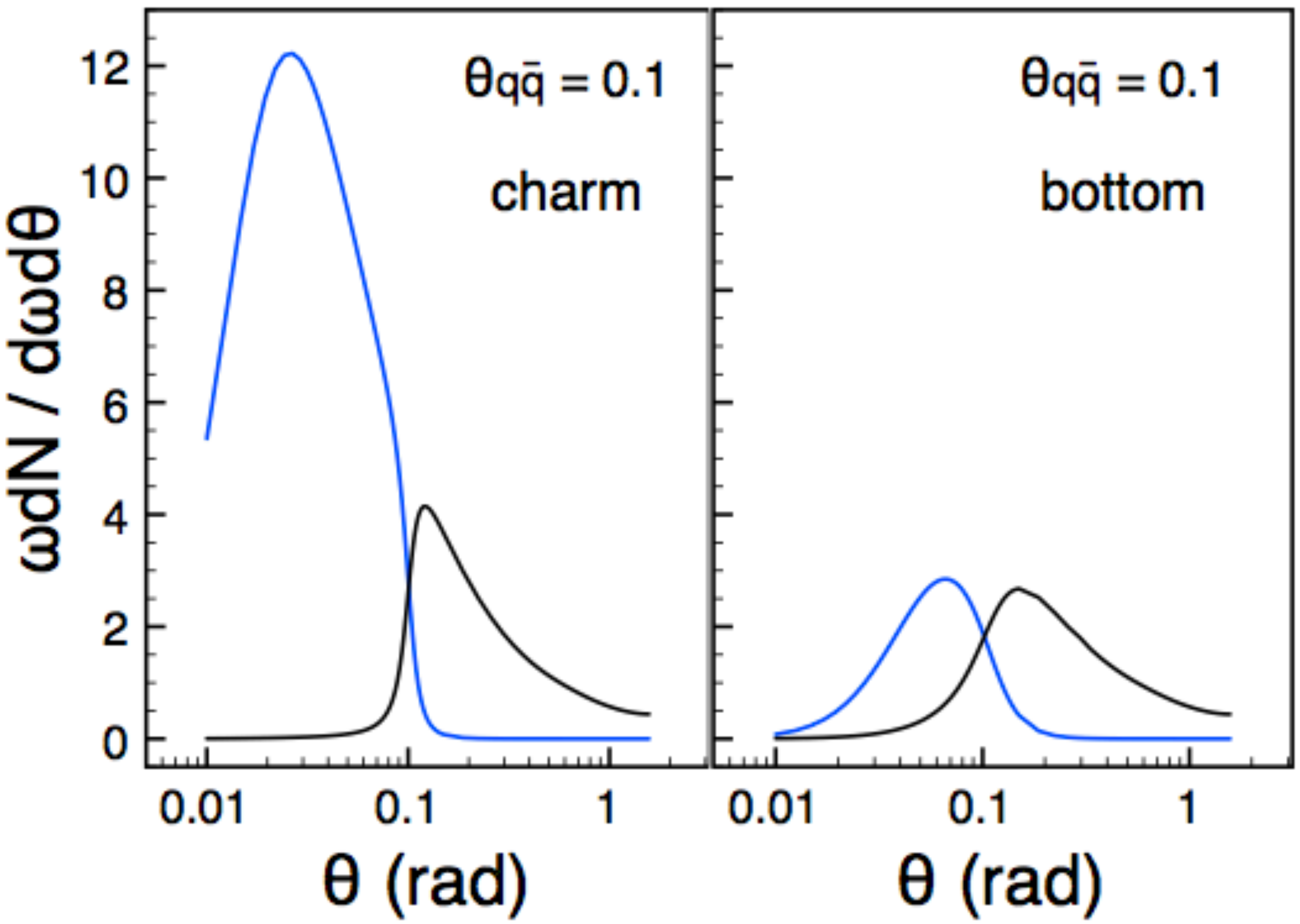


Medium-induced gluon radiation off a massive antenna in the opaque medium limit:

$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta}$$

[Massless ⇒ Antiangular ord.]

Decoherence in the soft limit extended to the massive case



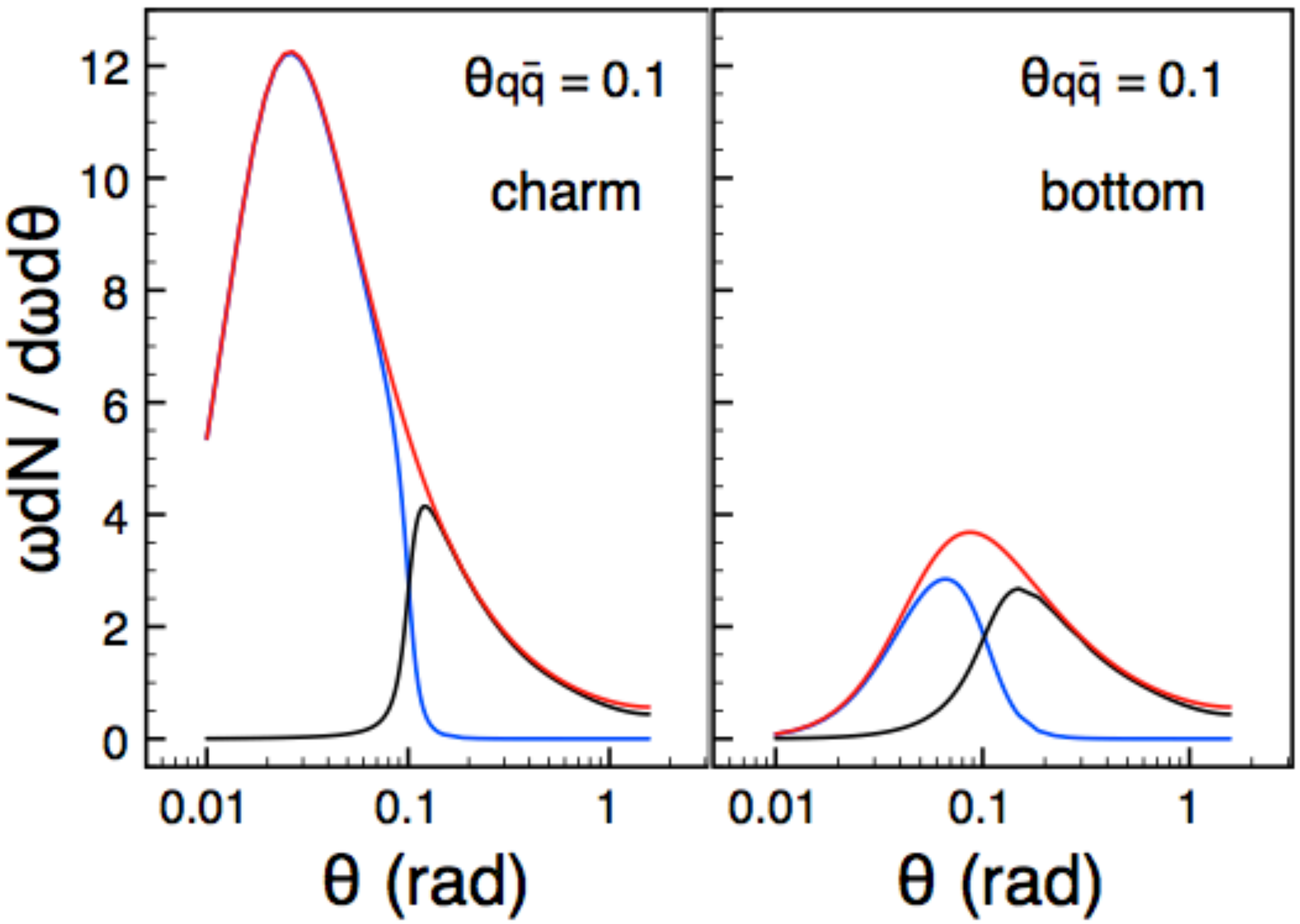
Medium-induced gluon radiation off a massive antenna in the opaque medium limit:

$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta}$$ [Massless ⇒ Antiangular 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.]

Decoherence in the soft limit extended to the massive case



Massless case: Mehtar-Tani, Salgado and Tywoniuk, *arXiv:1102.4317 [hep-ph]*

$$\omega \frac{dN_{\rm vac}^{\rm decoh}}{d\omega\, d\theta} \approx \omega \frac{dN_{\rm vac}}{d\omega\, d\theta} + \omega \frac{dN}{d\omega\, d\theta}$$

Medium-induced gluon radiation off a massive antenna in the opaque medium limit:

$$\omega \frac{dN}{d\omega\, d\theta}$$ [Massless ⇒ Antiangular ord.]

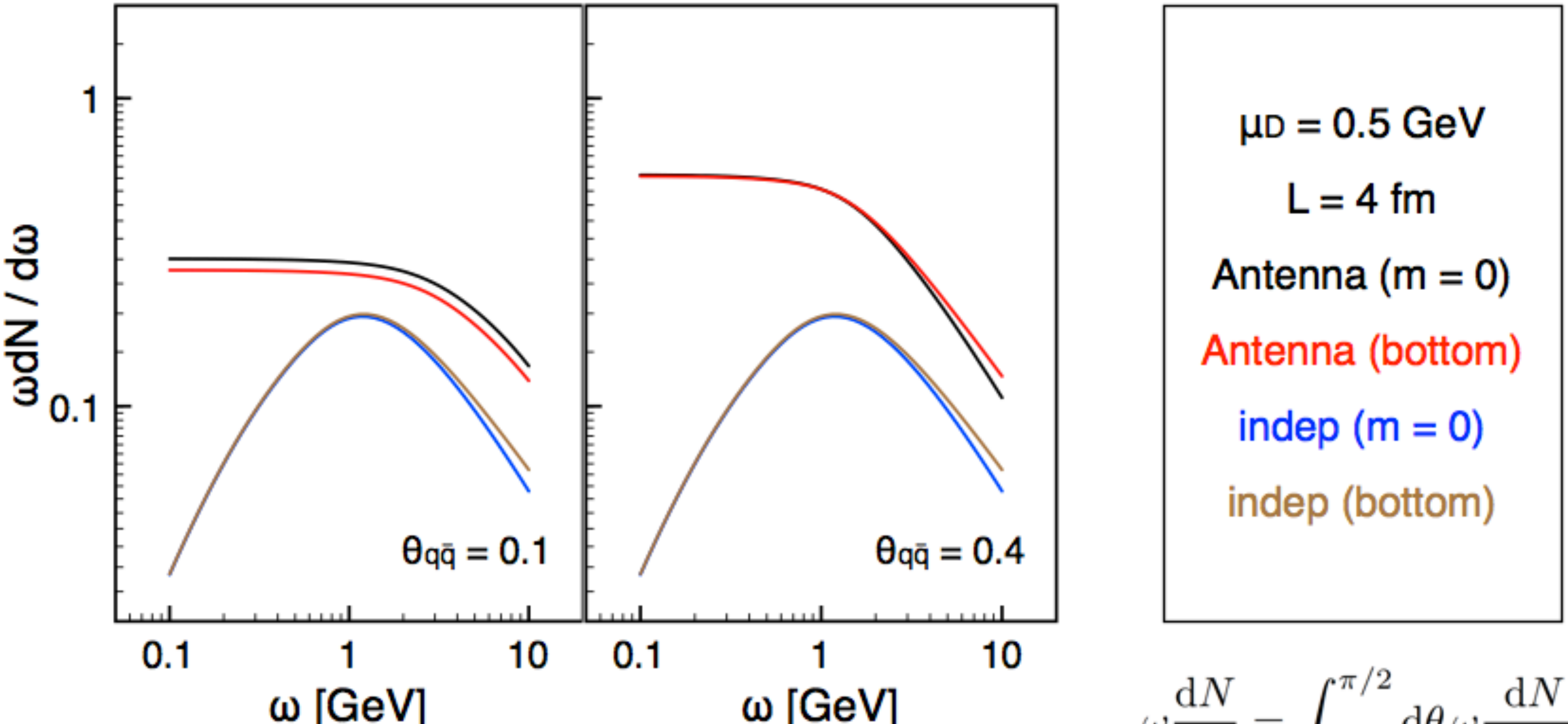
Gluon radiation off a massive antenna in vacuum:

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

Gluon hard vacuum radiation multiplied by 2:

$$\omega \frac{dN_{\rm vac}^{\rm decoh}}{d\omega\, d\theta}$$

Medium-induced gluon energy spectrum

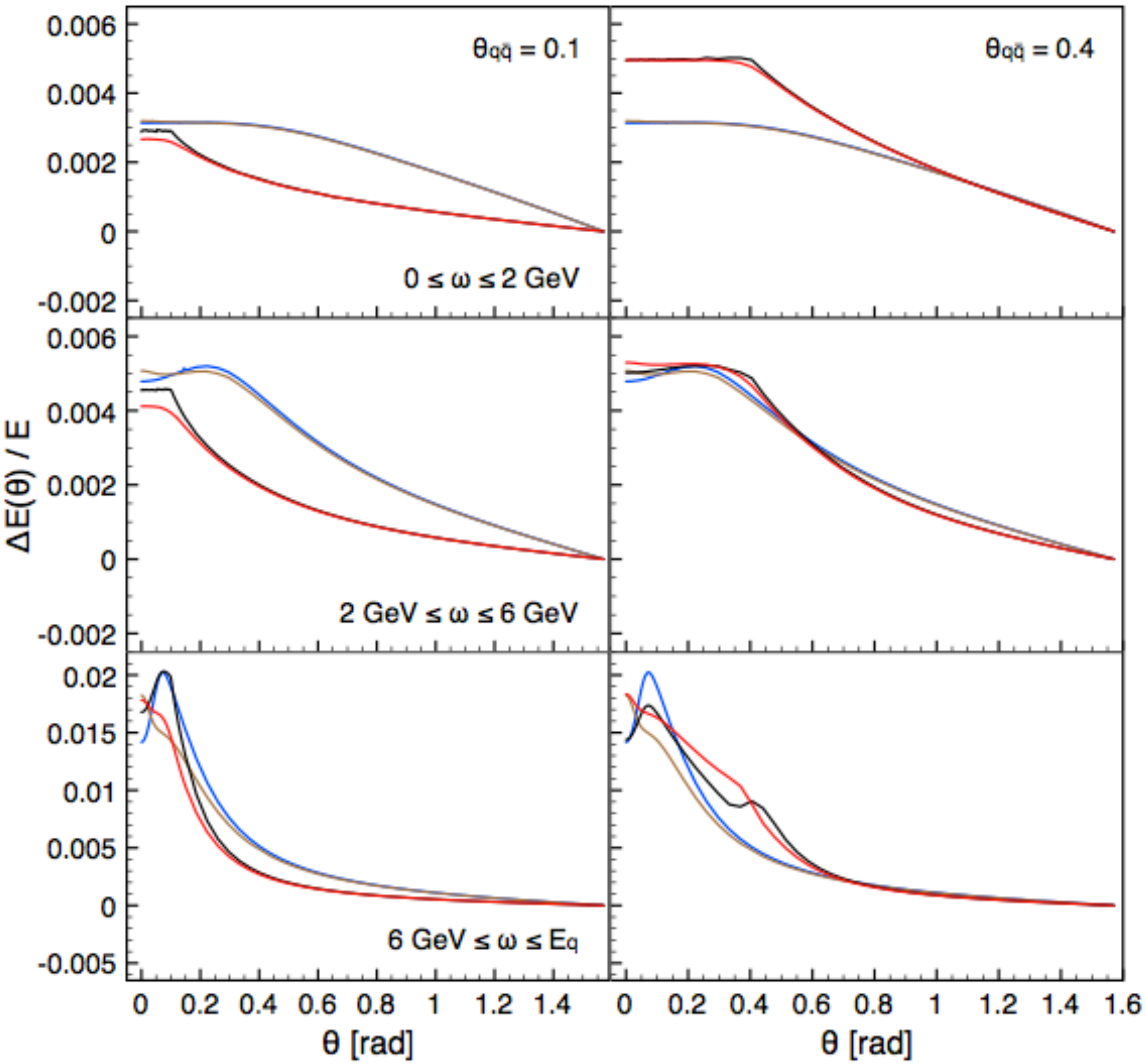


$$\omega\frac{\mathrm{d}N}{\mathrm{d}\omega} = \int_0^{\pi/2} \mathrm{d}\theta\, \omega \frac{\mathrm{d}N}{\mathrm{d}\omega\,\mathrm{d}\theta}$$

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

⇒ indep is suppressed when $\omega \to 0$. Cut-off scale: $\omega_{\rm coh} \sim (\theta_{q\bar{q}}^2 L)^{-1}$

Angular dependence of gluon energy distribution



E = 100 GeV

μ_D = 0.5 GeV

L = 4 fm

½ Antenna (m = 0)

½ Antenna (bottom)

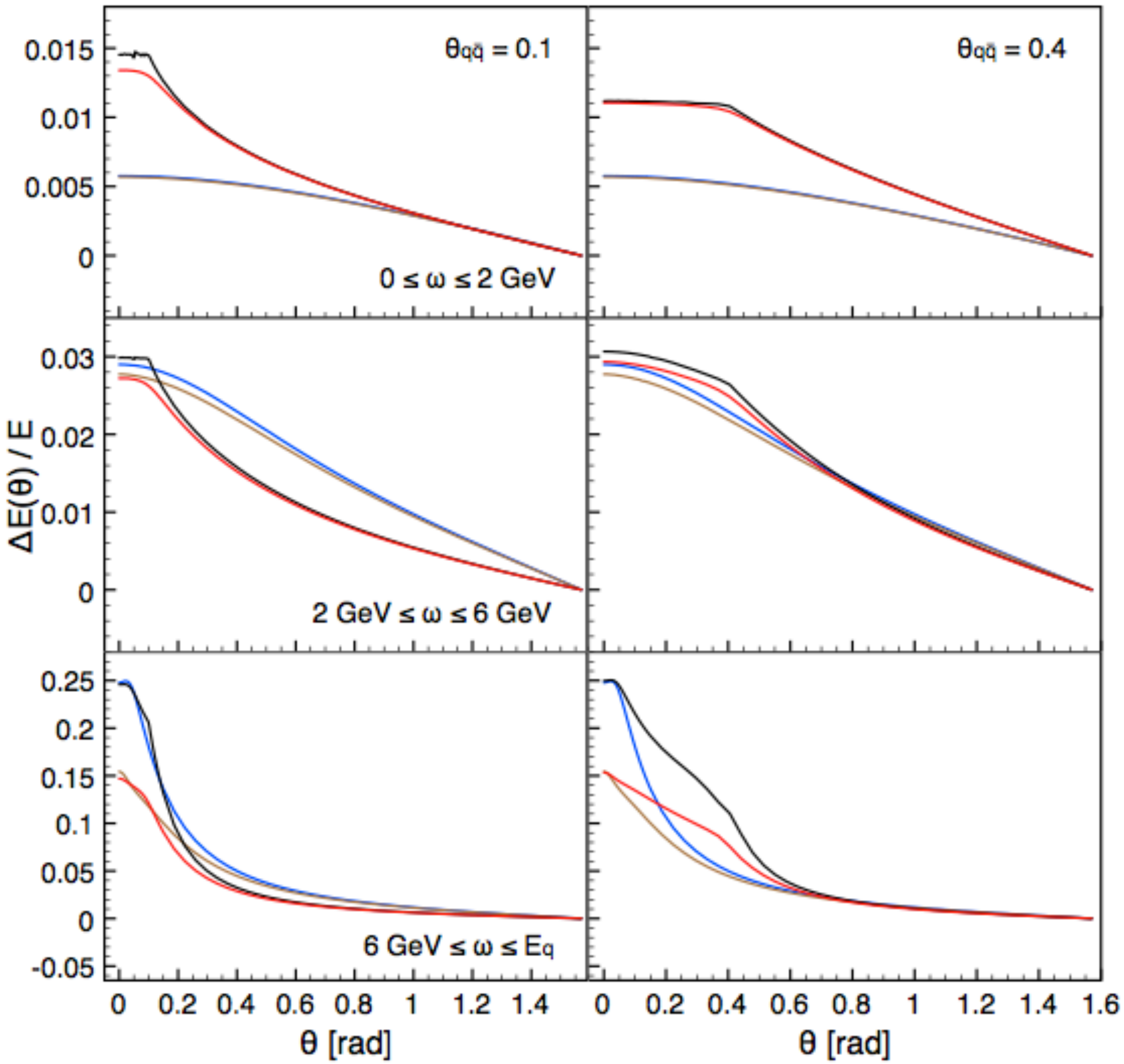
indep (m = 0)

indep (bottom)

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

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

Angular dependence of gluon energy distribution



E = 100 GeV

μD = 2 GeV

L = 10 fm

½ Antenna (m = 0)

½ Antenna (bottom)

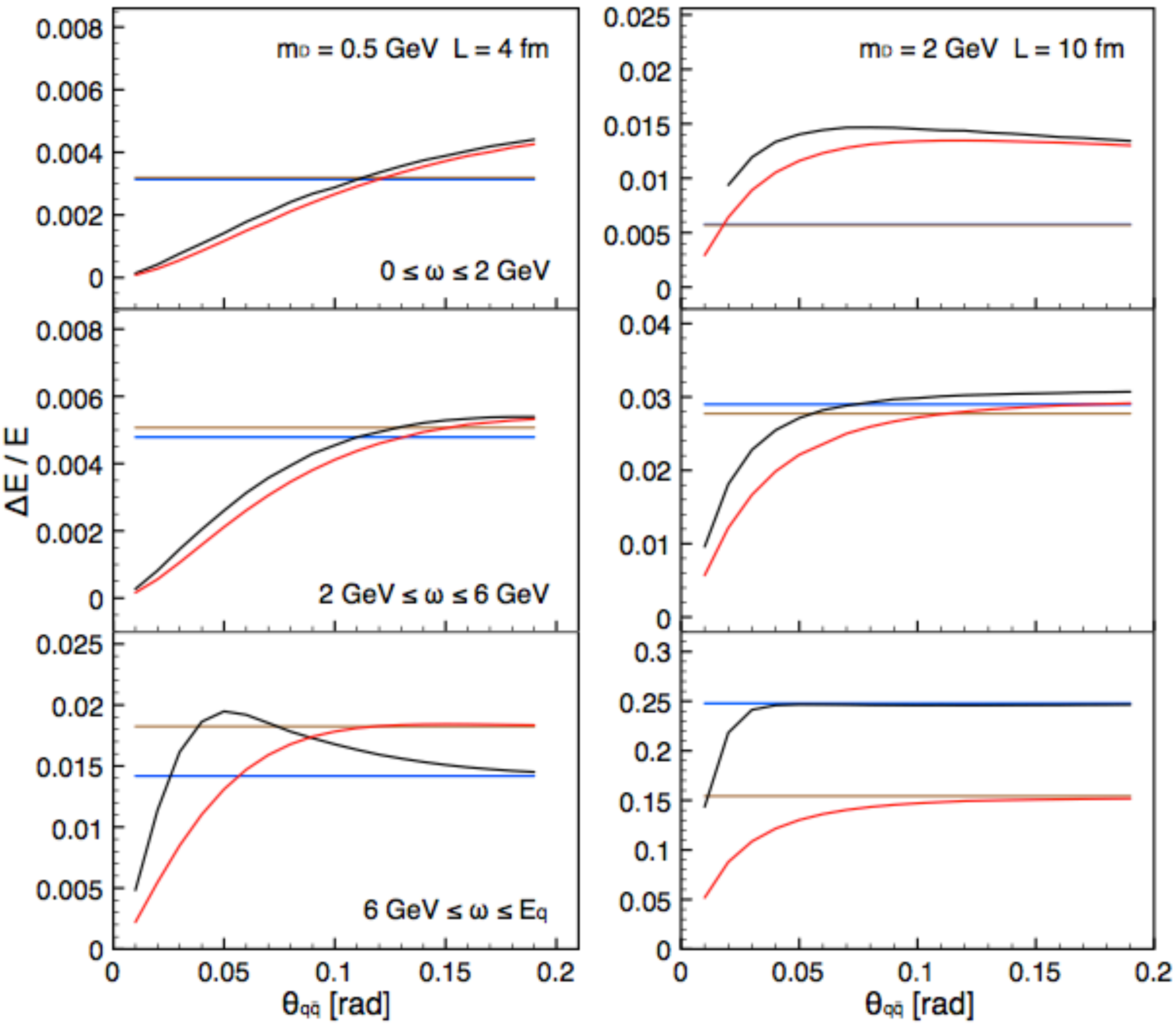
indep (m = 0)

indep (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 indep for the soft sector.

Average energy loss



E = 100 GeV

½ Antenna (m = 0)

½ Antenna (bottom)

indep (m = 0)

indep (bottom)

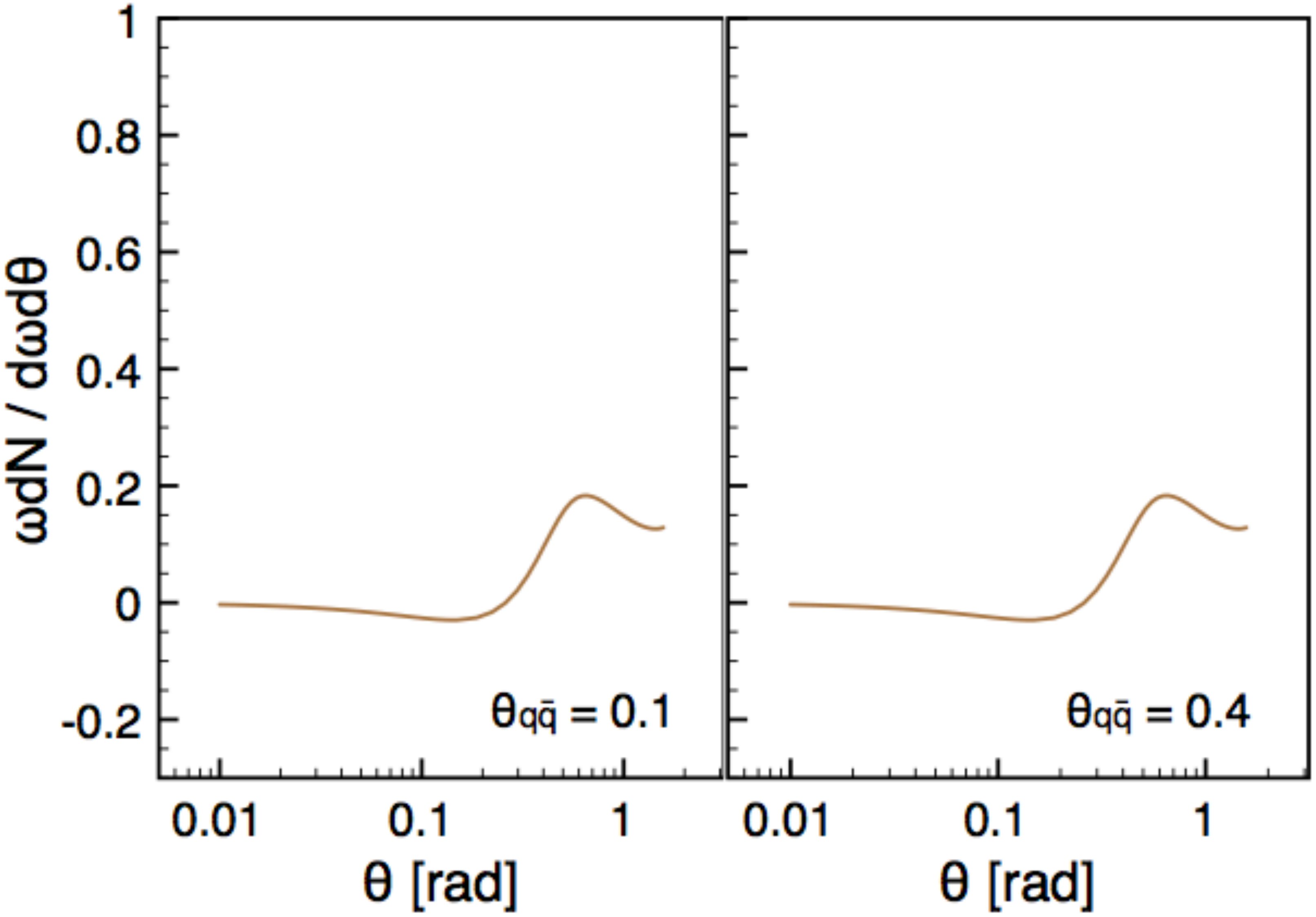
$$\Delta E = \int_{\omega_{\min}}^{\omega_{\max}} d\omega \int_0^{\pi/2} d\theta \, \omega \frac{dN}{d\omega \, d\theta}$$

⇒ More collimated jets lose less energy.

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

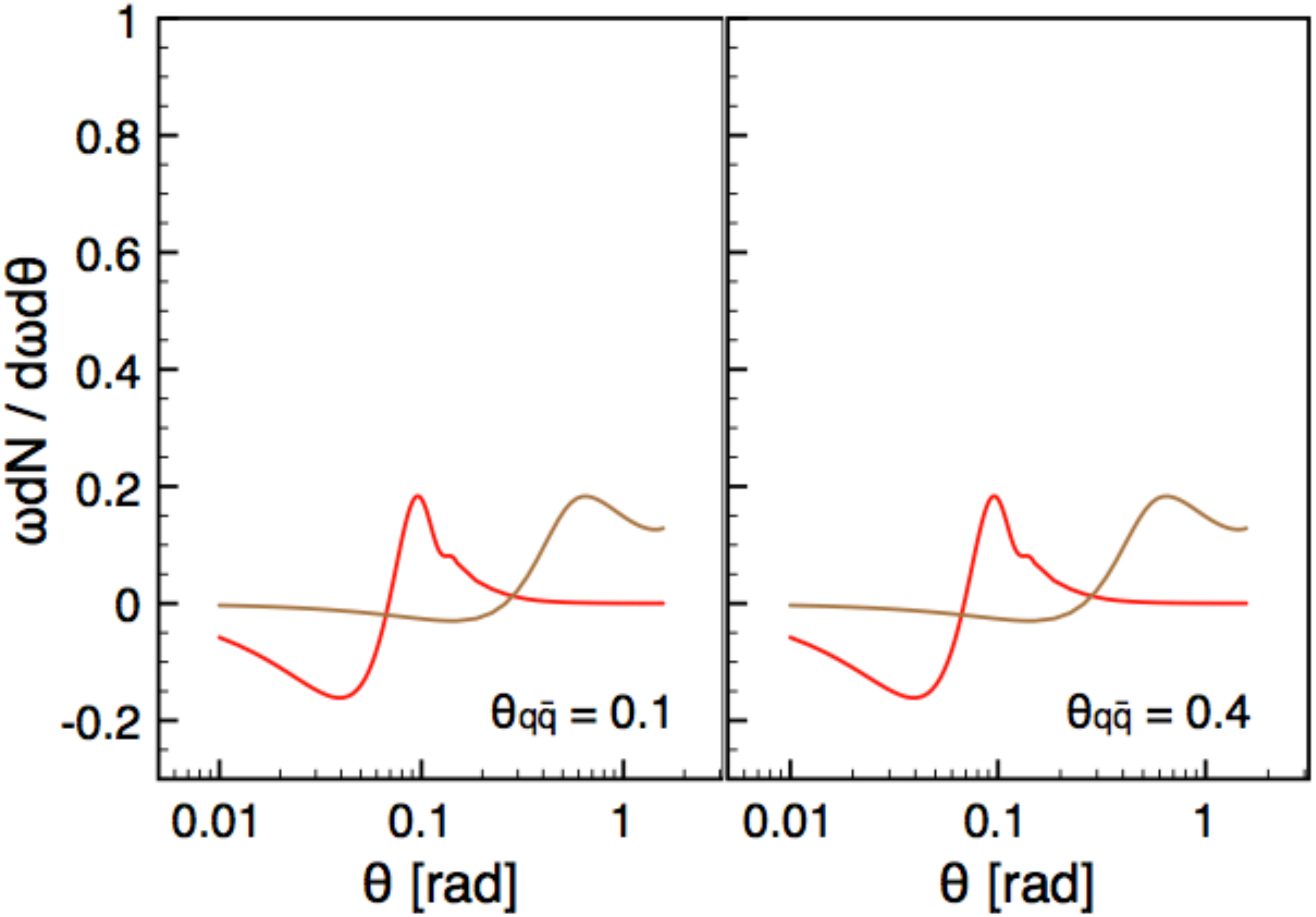
Armesto, Ma, Mehtar-Tani, Salgado and Tywoniuk, *arXiv:1107.0291v1 [hep-ph].*

Transition between the massless antenna & indep



indep (ω = 2 GeV)

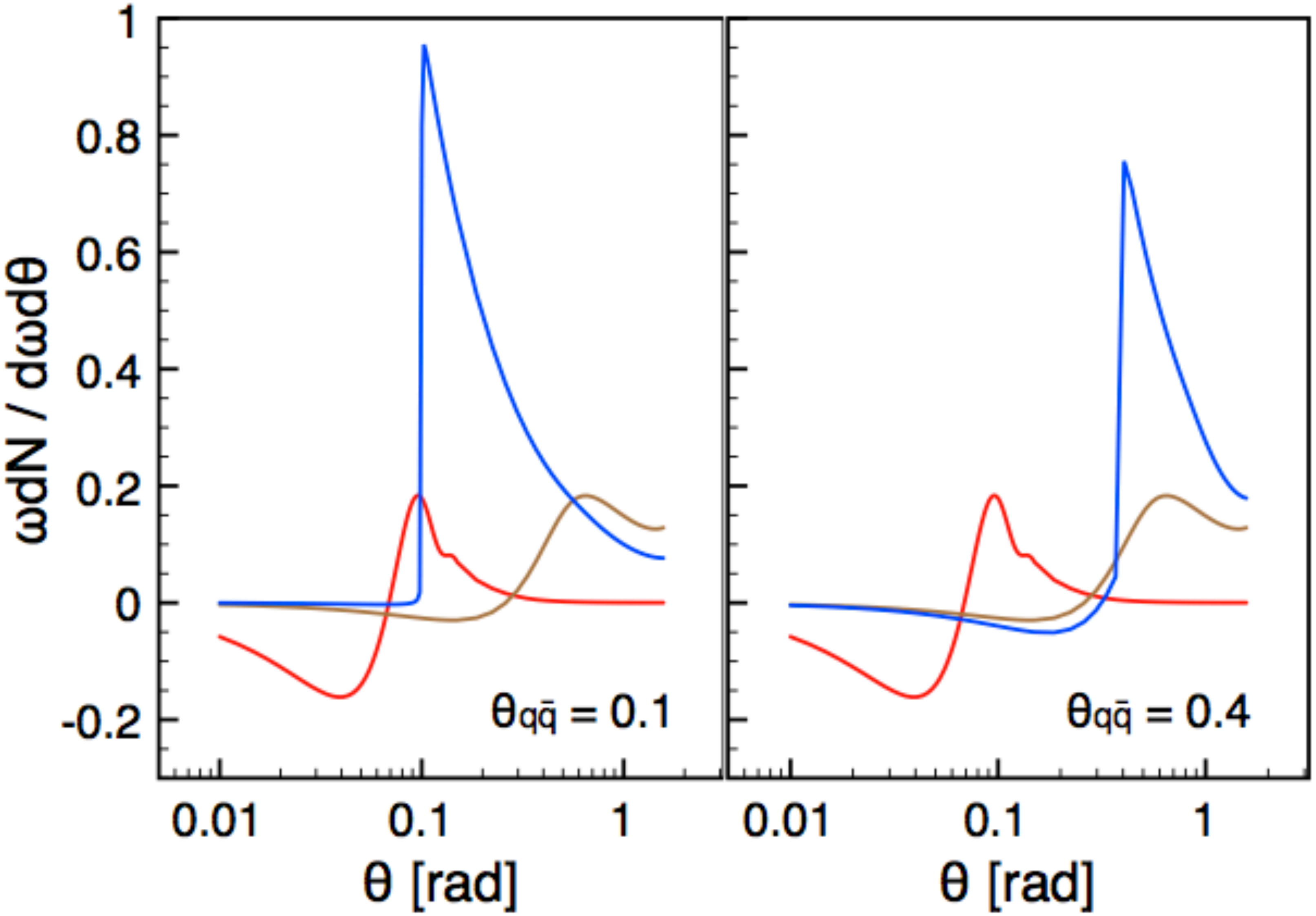
Transition between the massless antenna & indep



indep (ω = 2 GeV)

indep (ω = 60 GeV)

Transition between the massless antenna & indep

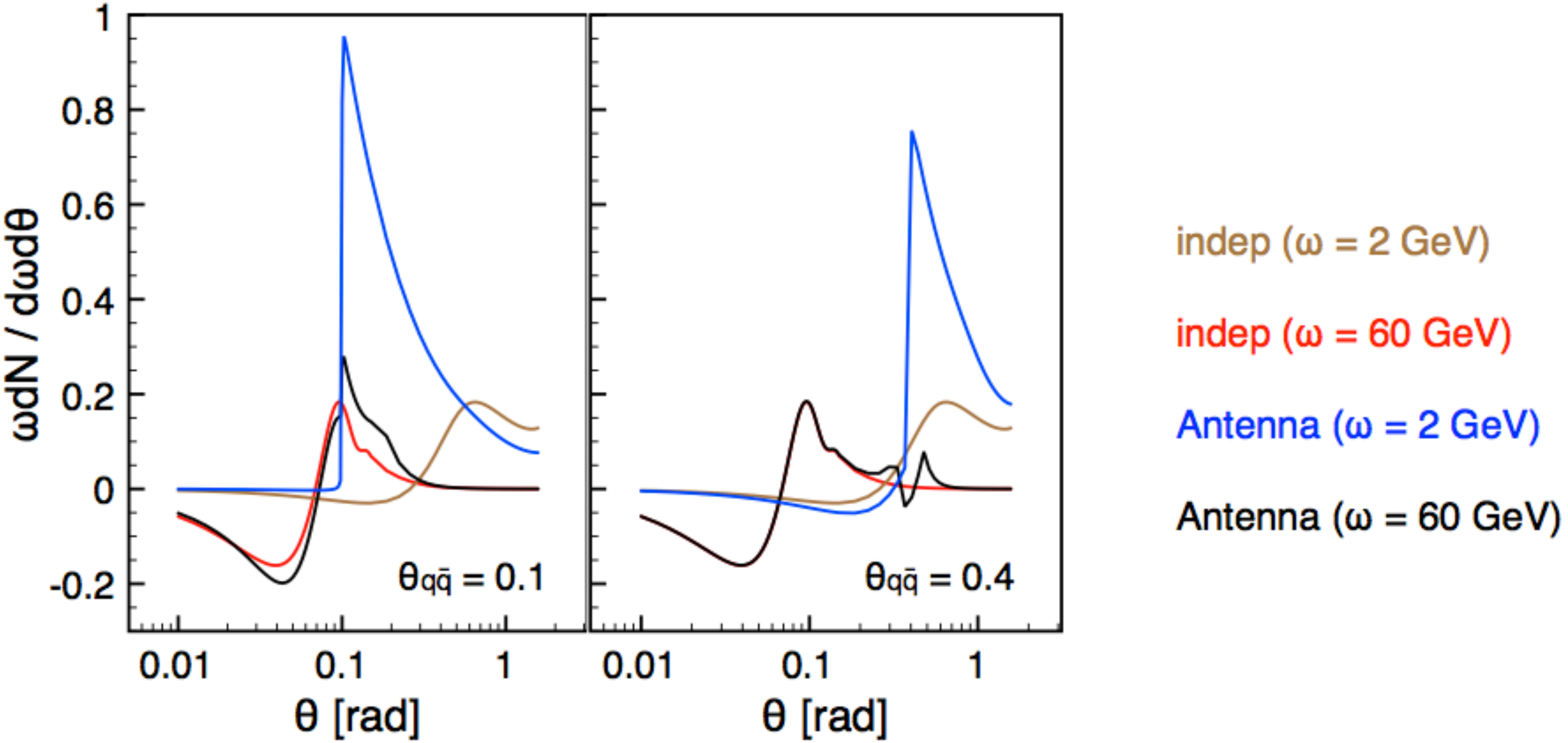


indep (ω = 2 GeV)

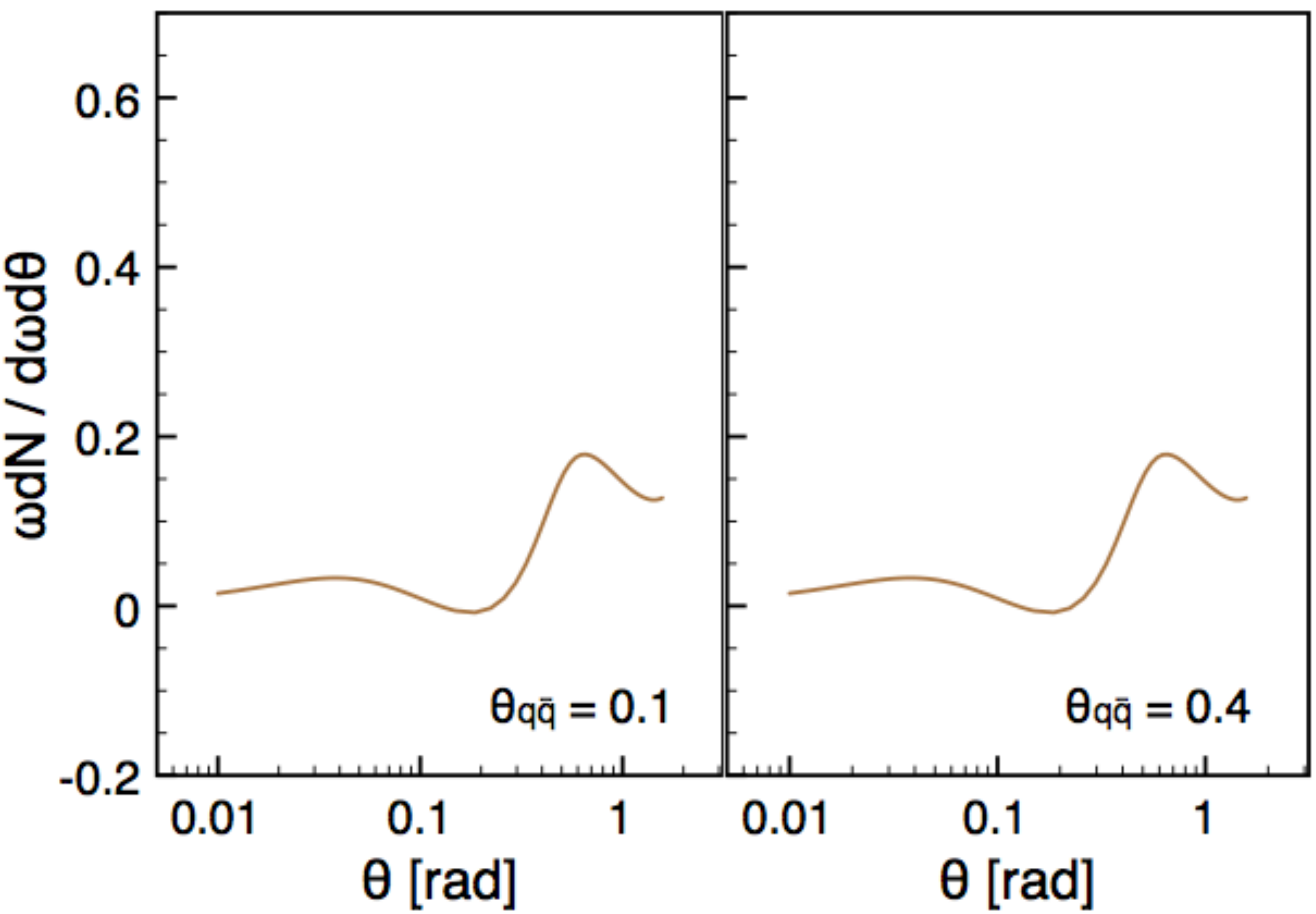
indep (ω = 60 GeV)

Antenna (ω = 2 GeV)

Transition between the massless antenna & indep

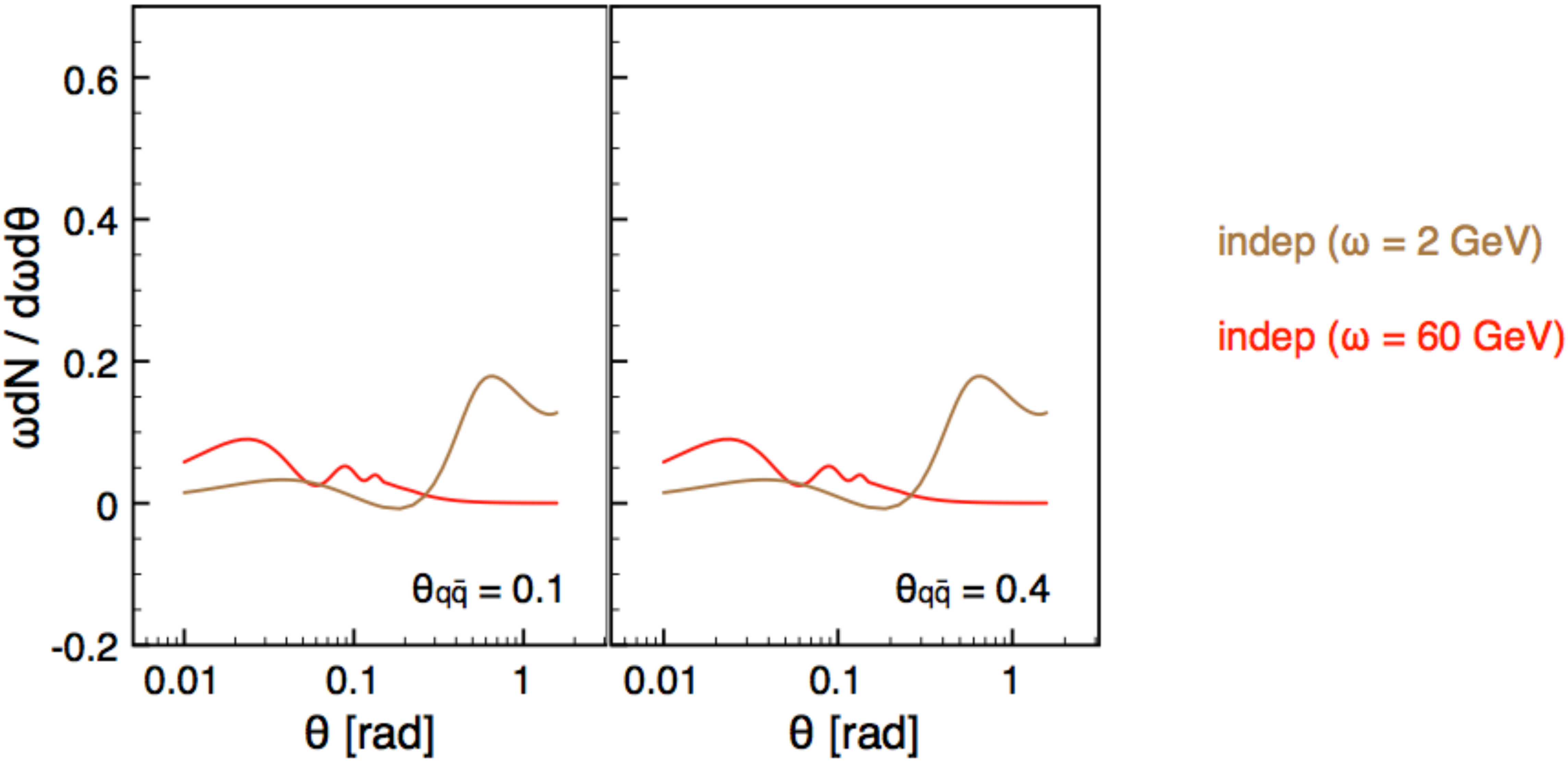


Transition between the bottom antenna & indep

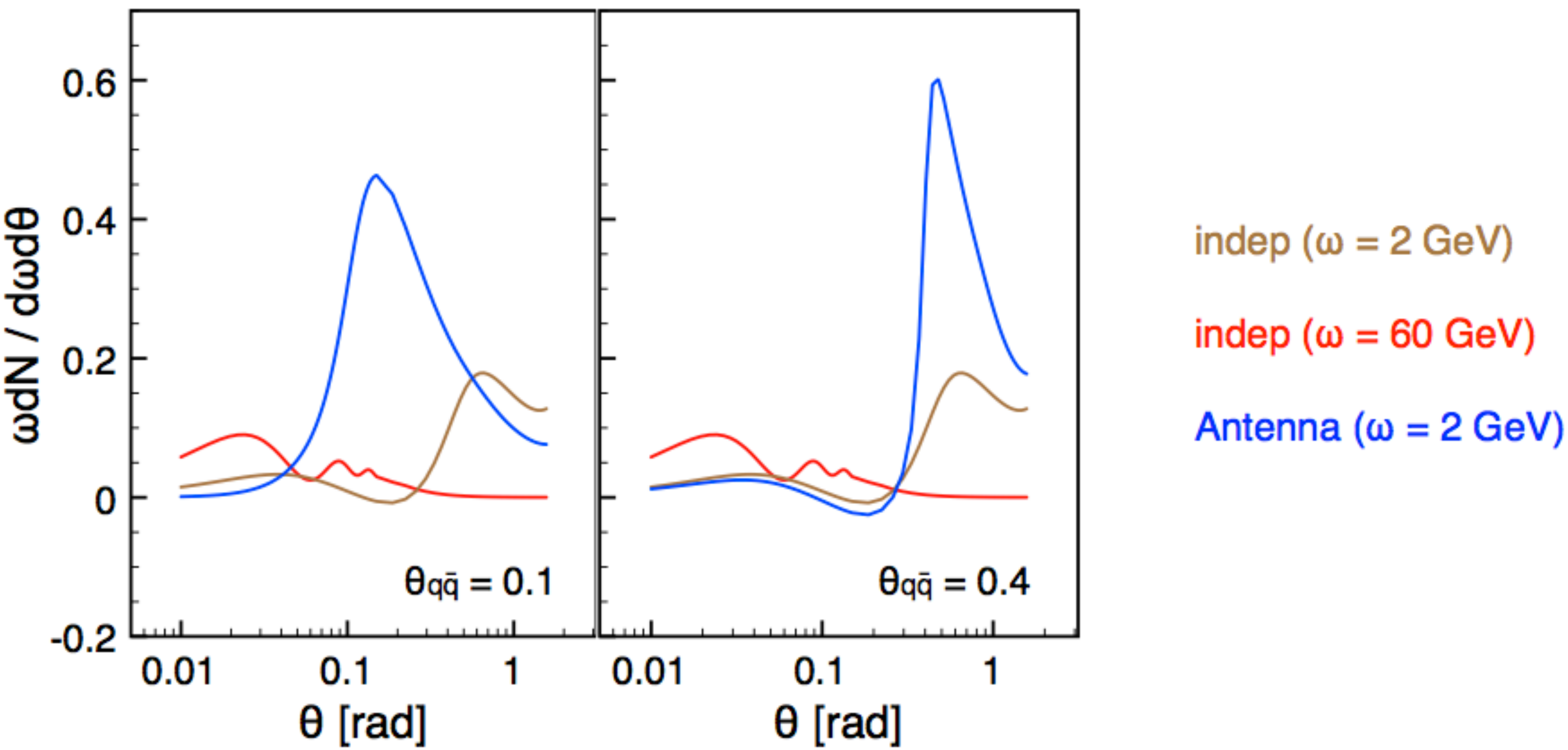


indep (ω = 2 GeV)

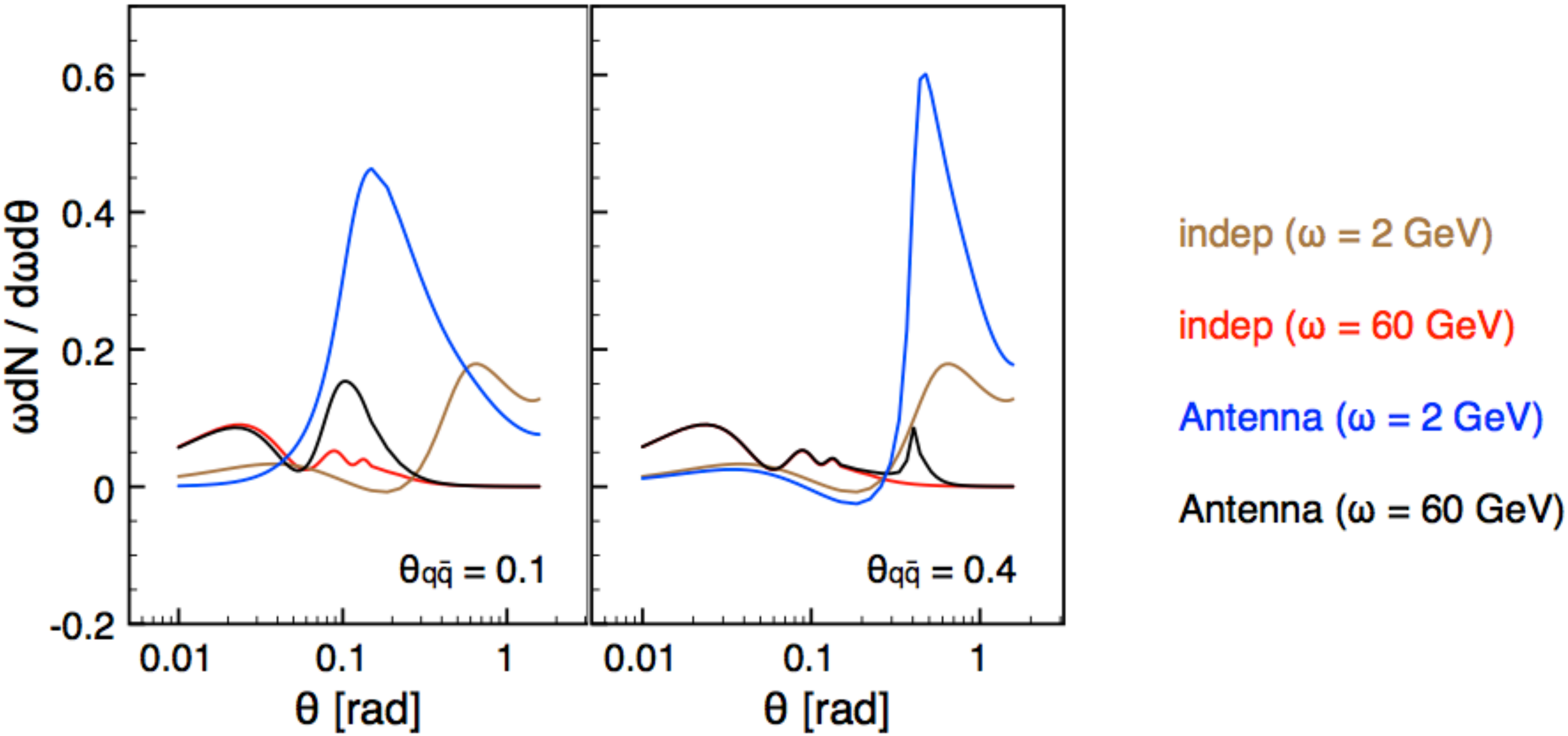
Transition between the bottom antenna & indep



Transition between the bottom antenna & indep



Transition between the bottom antenna & indep



Conclusion

- Medium-induced antiangular ordering in the soft limit is modified in the massive antenna case due to 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 independent emitter.

Back-up slides

Back-up

- Massless medium decoh. parameter

$$\Delta_{\rm med}(\theta_{q\bar{q}}, L_+) = \frac{\hat{q}}{\mu_D^2}\int_0^{L_+} {\rm d}x_+ \left(1 - \frac{|\mathbf{r}_\perp|\,\mu_D\,x_+}{L_+} K_1\left(\frac{|\mathbf{r}_\perp|\,\mu_D\,x_+}{L_+}\right)\right)$$

- 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

$$\Delta_{\rm med}(\theta_{q\bar{q}}, \theta_0, L_+) = \frac{\hat{q}}{\mu_D^2}\int_0^{L_+} {\rm d}x_+ \left(1 - \frac{|\mathbf{r}_\perp|\,\mu_D\,x_+}{L_+} K_1\left(\frac{|\mathbf{r}_\perp|\,\mu_D\,x_+}{L_+}\right)\right)$$

- 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

- independent emitter spectrum

$$\mathcal{I}_{quark}^{\mathrm{indep}} = \int \frac{\mathrm{d}^2\mathbf{q}}{(2\,\pi)^2} \int_0^{L^+} \mathrm{d}x^+\, n_0\, \frac{m_D^2}{(\mathbf{q}^2 + m_D^2)^2}\, 8\,\alpha_s^2\,(4\,\pi)^2\, C_A\, C_F$$
$$\frac{(\mathbf{k}-\mathbf{q})^2\,\mathbf{k}\cdot\mathbf{q} - x^2\, m_q^2\,(\mathbf{k}-\mathbf{q})\cdot\mathbf{q}}{\left[(\mathbf{k}-\mathbf{q})^2 + x^2\, m_q^2\right]^2 (\mathbf{k}^2 + x^2\, m_q^2)} \left[1 - \cos\left(\frac{(\mathbf{k}-\mathbf{q})^2 + x^2\, m_q^2}{2\,k^+}\, x^+\right)\right]$$

Back-up

- Antenna spectrum in the soft limit

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

$$\Downarrow$$

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