LUNDS UNIVERSITET

Advancing QCD-based calculations of energy loss

Konrad Tywoniuk

Hard Probes 2012

5th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear collisions

27 May - 1 June 2012, Cagliari (Sardinia, Italy)

Thanks to: Y. Mehtar-Tani, C. A. Salgado, N. Armesto, G. Milhano

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  - improved calculus: going beyond approximations

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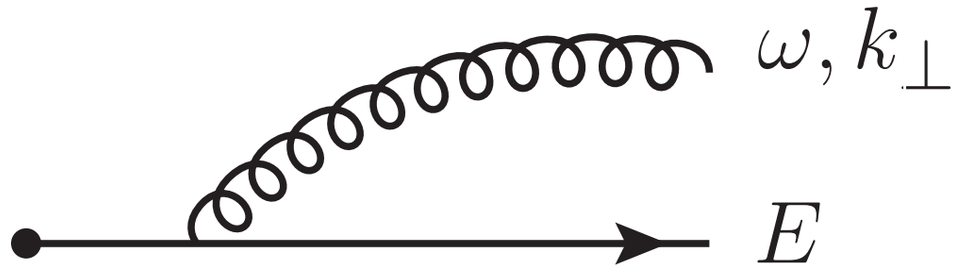
Disclaimer: discuss concepts rather than formulas or data comparisons

Radiation: two kinds

High-energy (eikonal) approximation: $E \gg \omega \gg k_\perp, q_\perp$

- in vacuum (off-shell):
  - bremsstrahlung off an accelerated charge
    - driven by the virtuality



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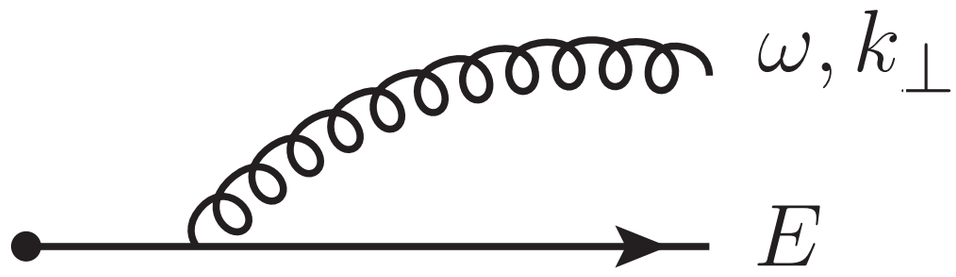

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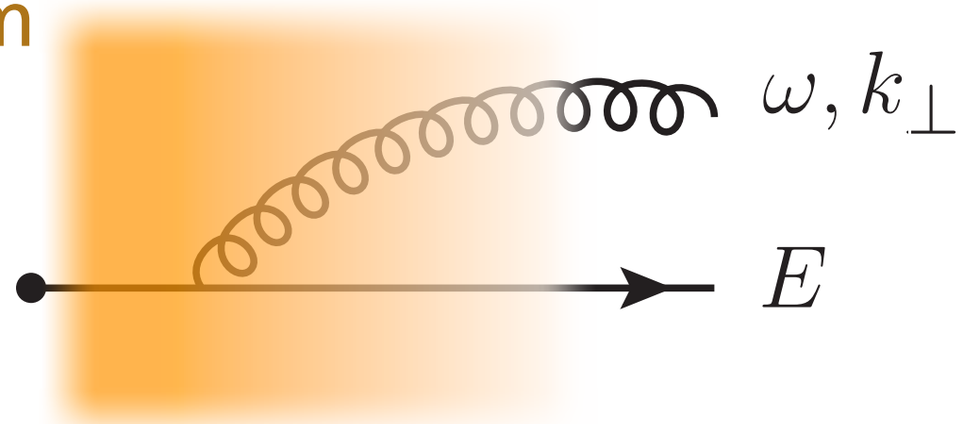
- in the presence of a medium (off-shell + on-shell):
  - bremsstrahlung
  - medium-induced
    - driven by medium characteristics



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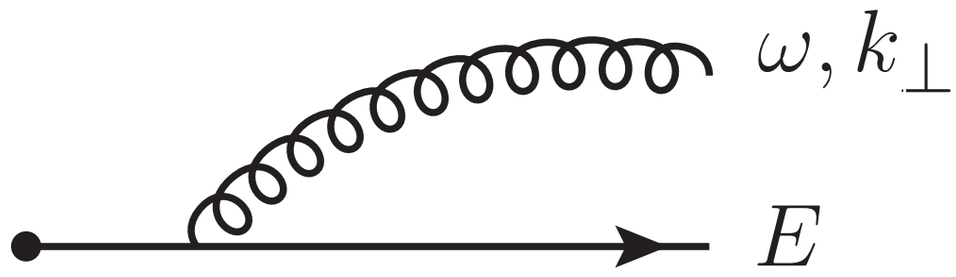

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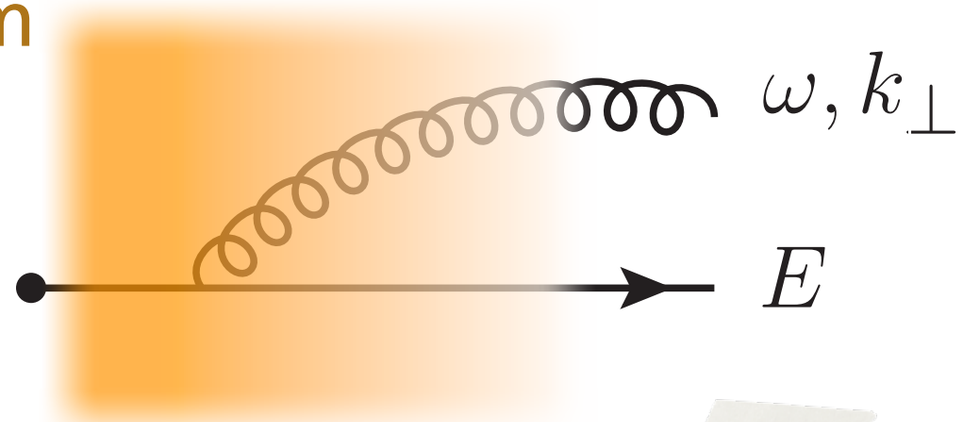


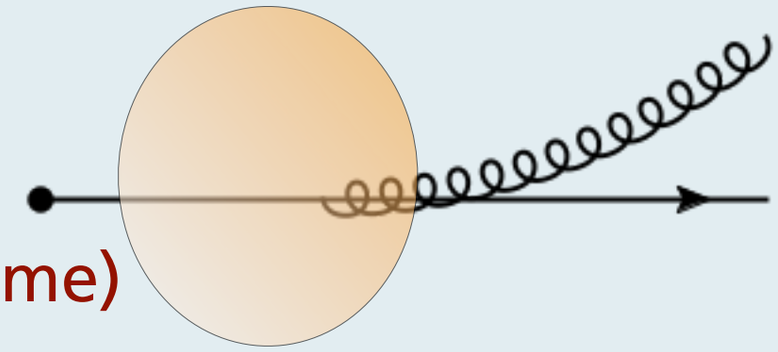
Local transport parameter(s): $\hat{q}(t) = \frac{d\langle p_\perp^2 \rangle}{dt}$

M. Benzke, Mon 14:20
A. Majumder, Tue 15:15
M. Bluhm, Mon 15:00

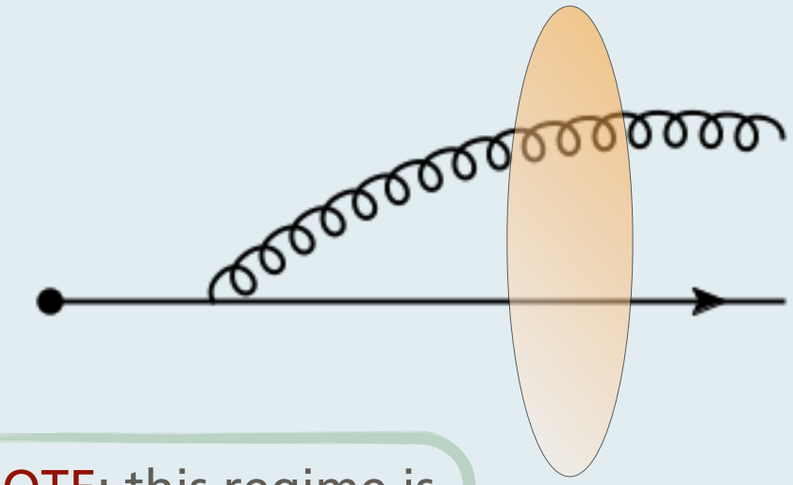
The vacuum component

Usually neglected/subtracted from medium-induced spectrum.

- bremsstrahlung off accelerated charge
  - after the medium
    - does not resolve the medium
    - soft radiation (long formation time)



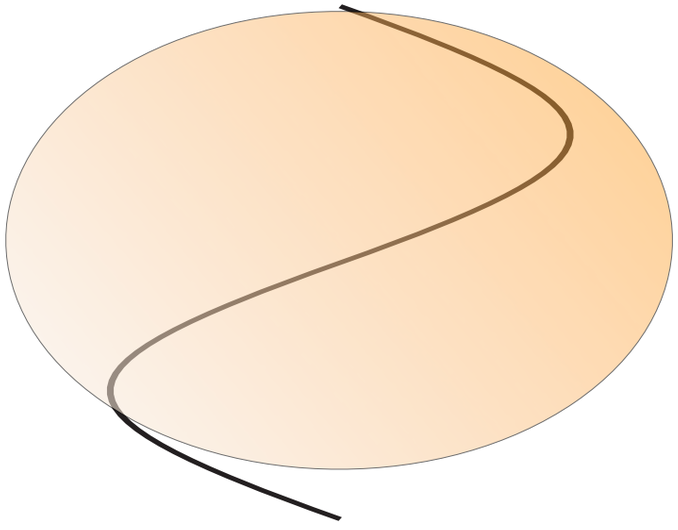
  - early in the medium
    - medium does not resolve it (very short formation times)
    - can feel broadening



NOTE: this regime is governed by hard medium interactions

Mehtar-Tani, Salgado, KT arXiv:1205:5739

Decoherence of radiation



How is the medium resolved?

- medium fluctuates with typical transverse wave length $\mathbf{Q_s^{-1}}$
  - zero color on average
  - resolved by $\mathbf{r_\perp < Q_s^{-1}}$

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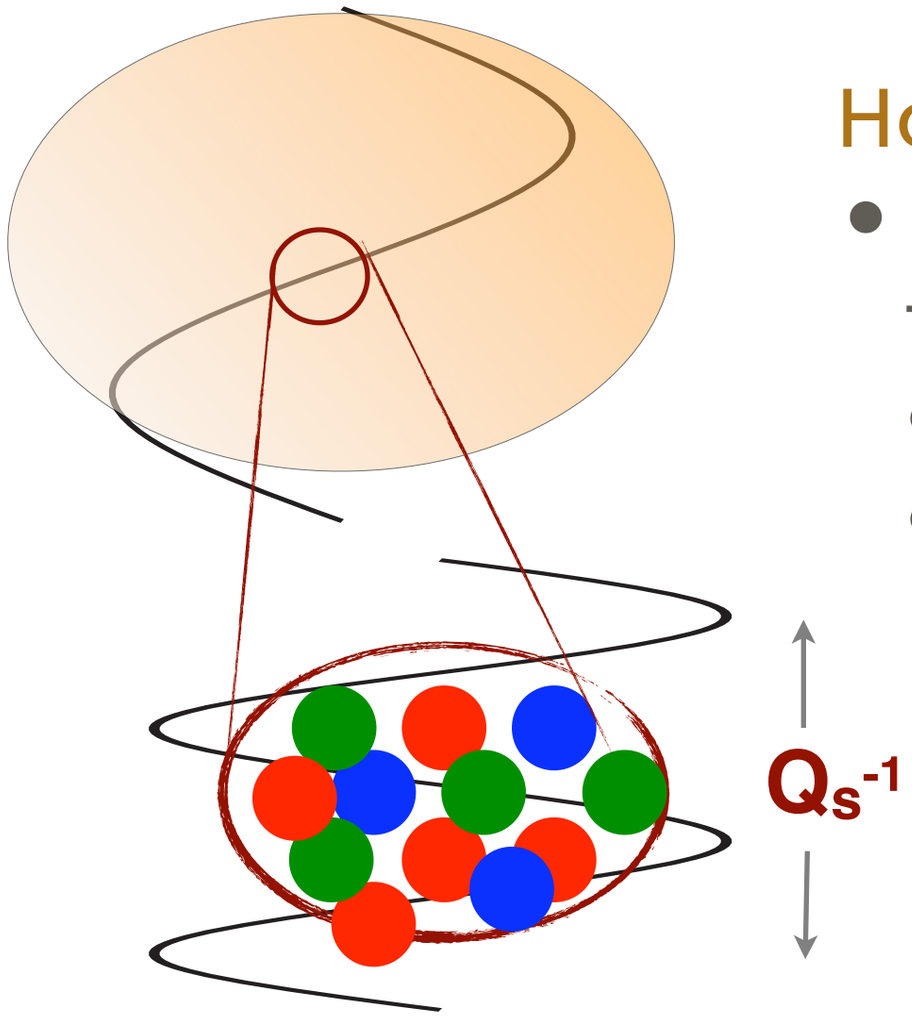

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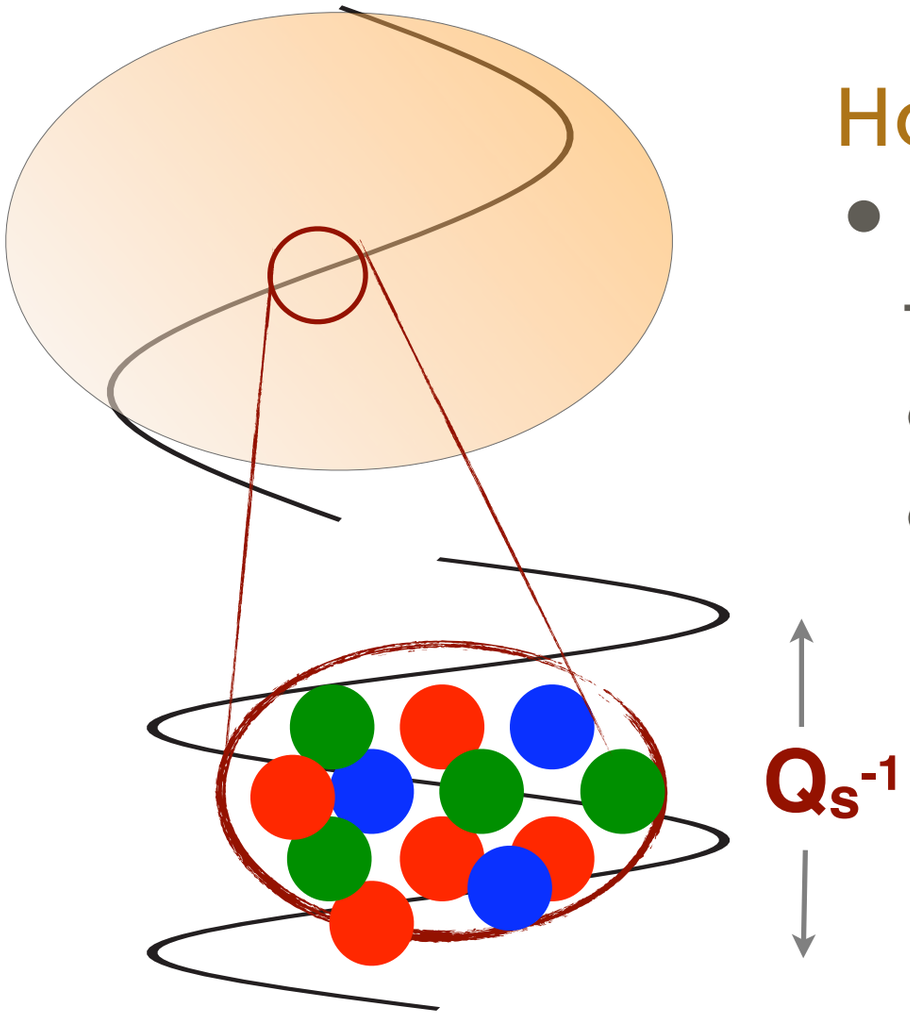

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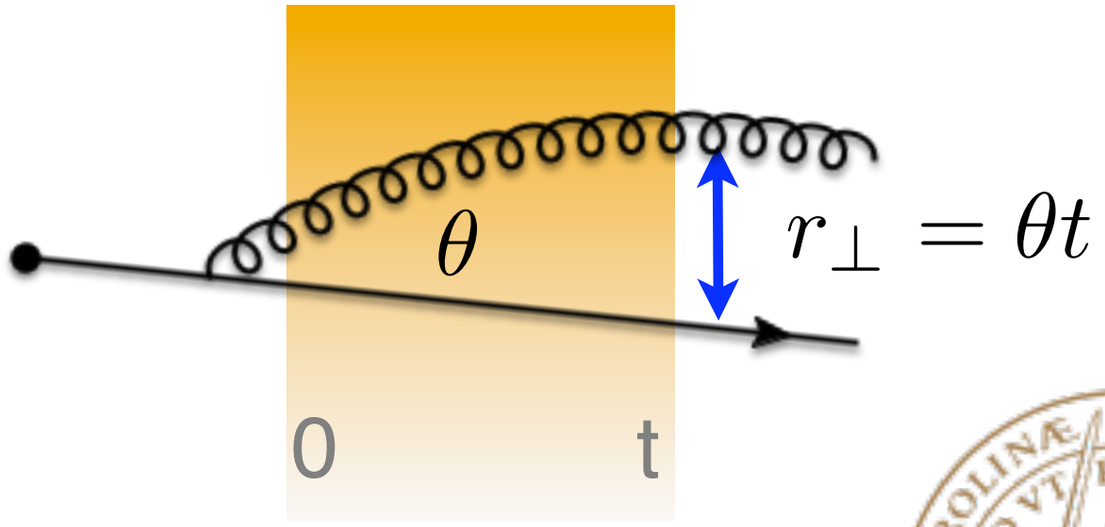

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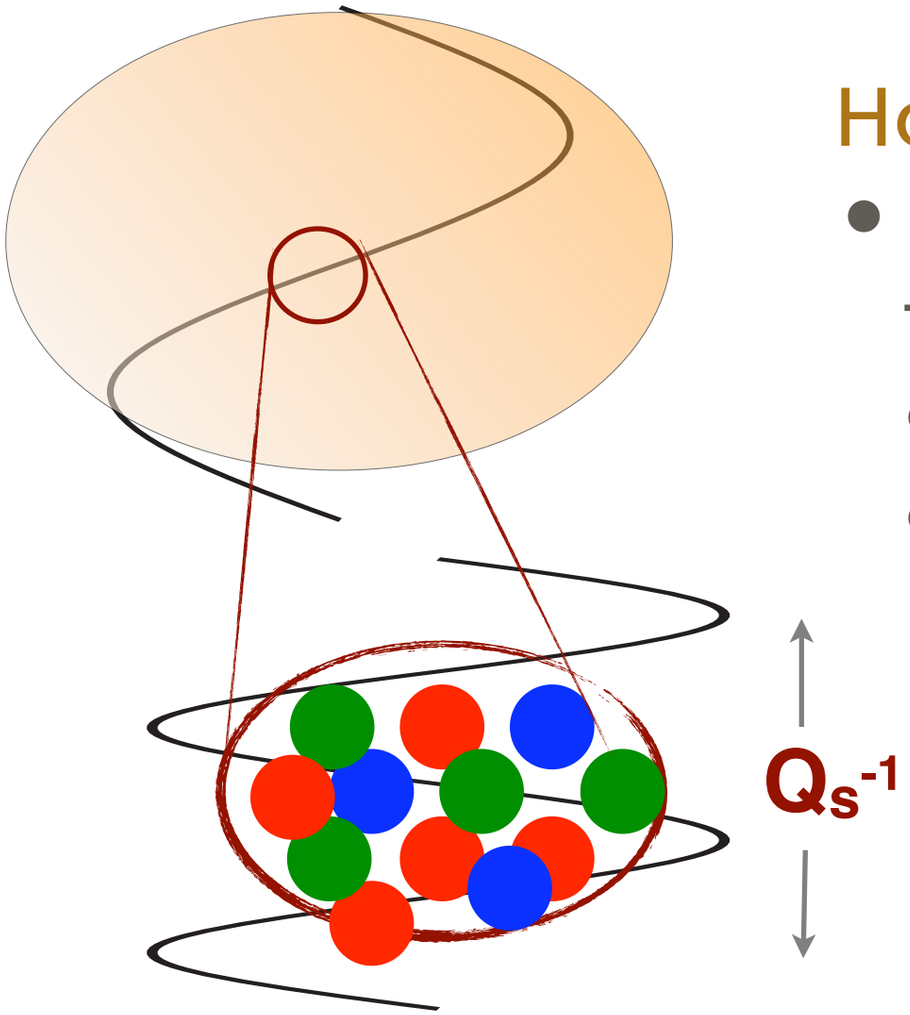

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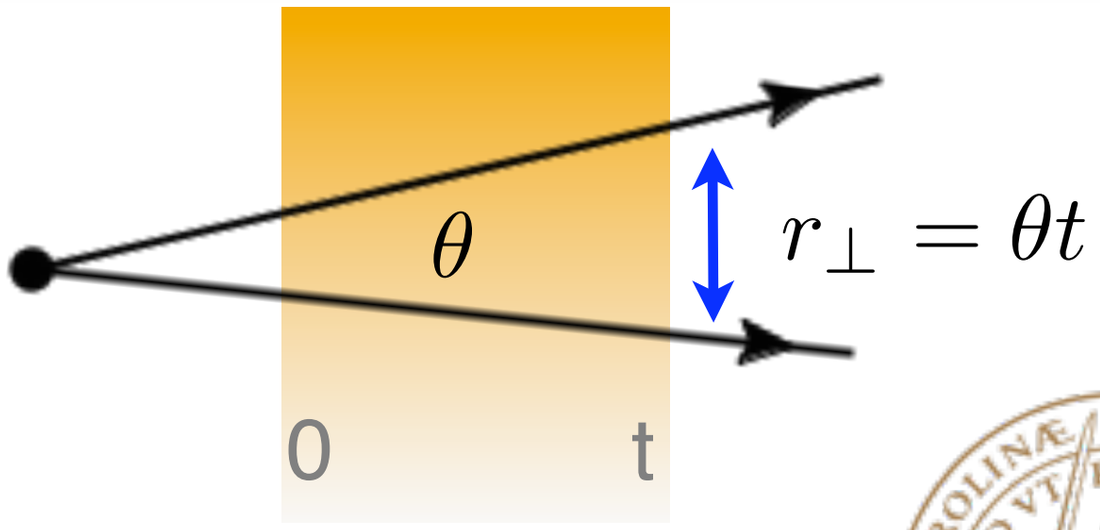

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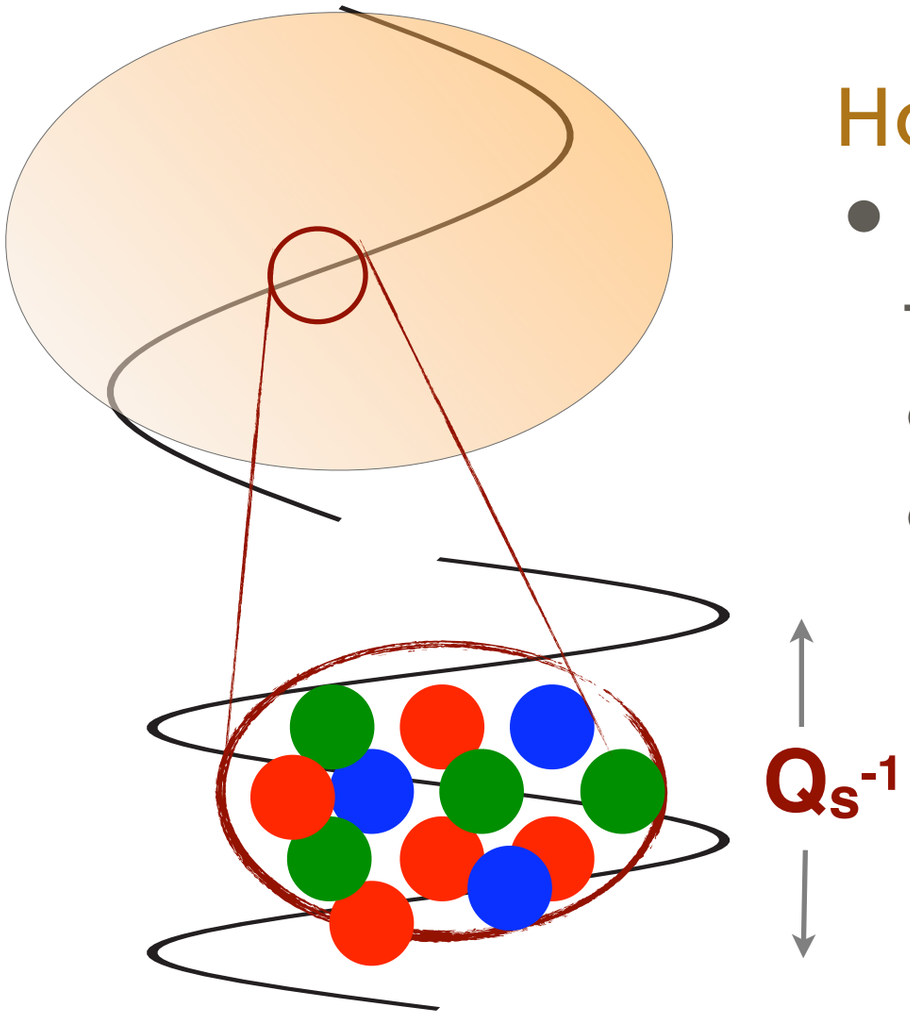

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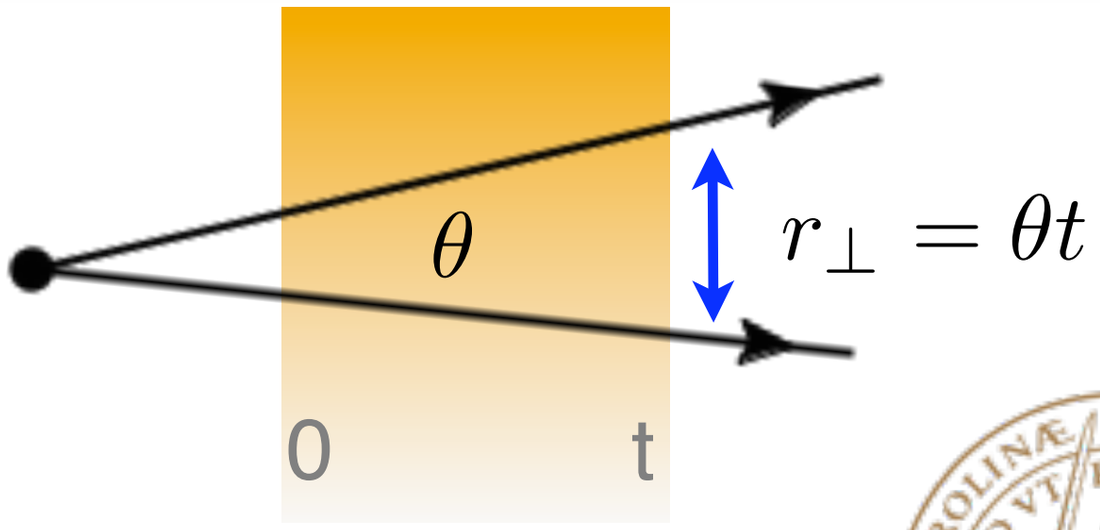
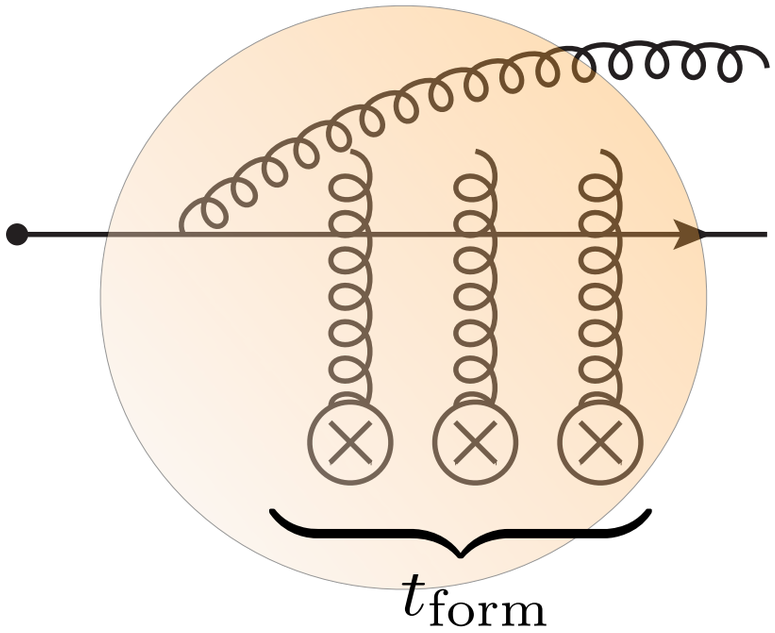


What are the typical dipole transverse sizes?

Medium-induced radiation



Longitudinal coherence

- induces a characteristic formation time larger than mean free path

$$t_{\mathrm{form}} = \lambda_{\mathrm{mfp}} N_{\mathrm{coh}}$$

$$k_{\mathrm{ind}}^2 = \mu^2 N_{\mathrm{coh}}$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

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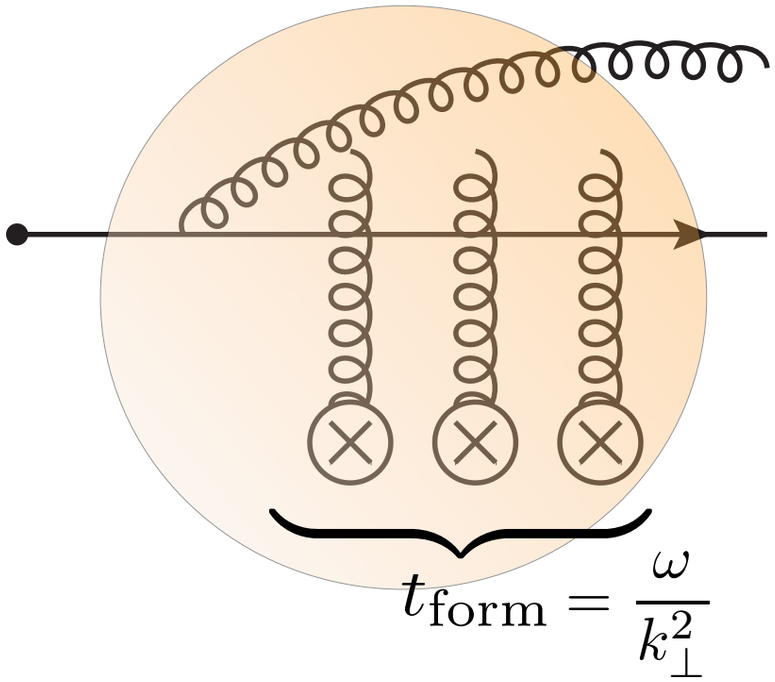

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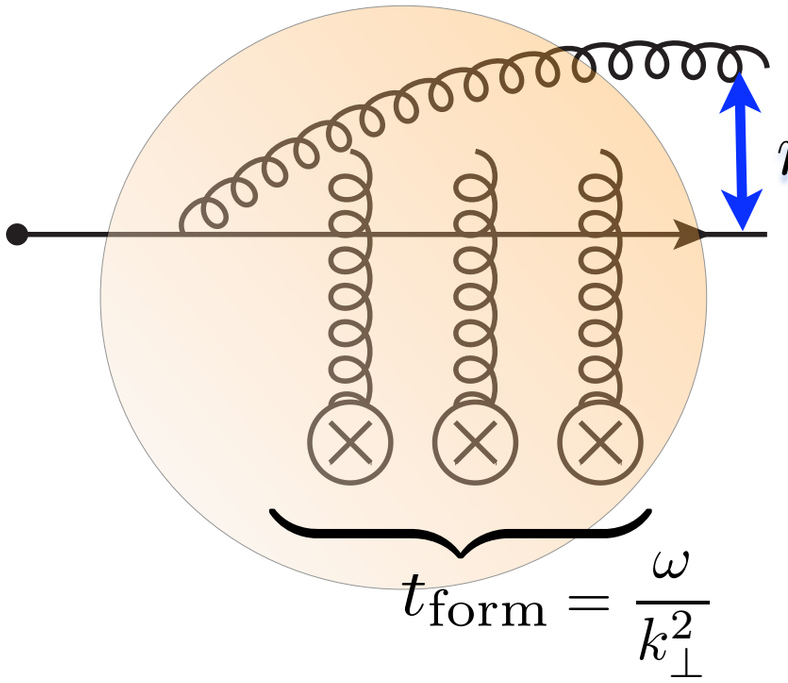

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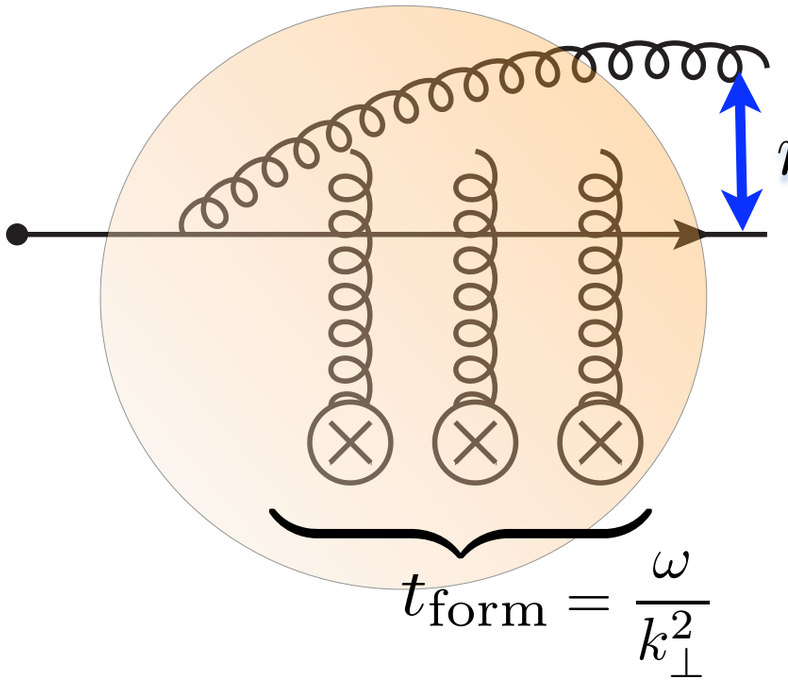

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Coherent spectrum

$$\omega \frac{dN}{d\omega} \propto \alpha_s \frac{L}{t_{\rm form}} = \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}}$$

- short formation times!

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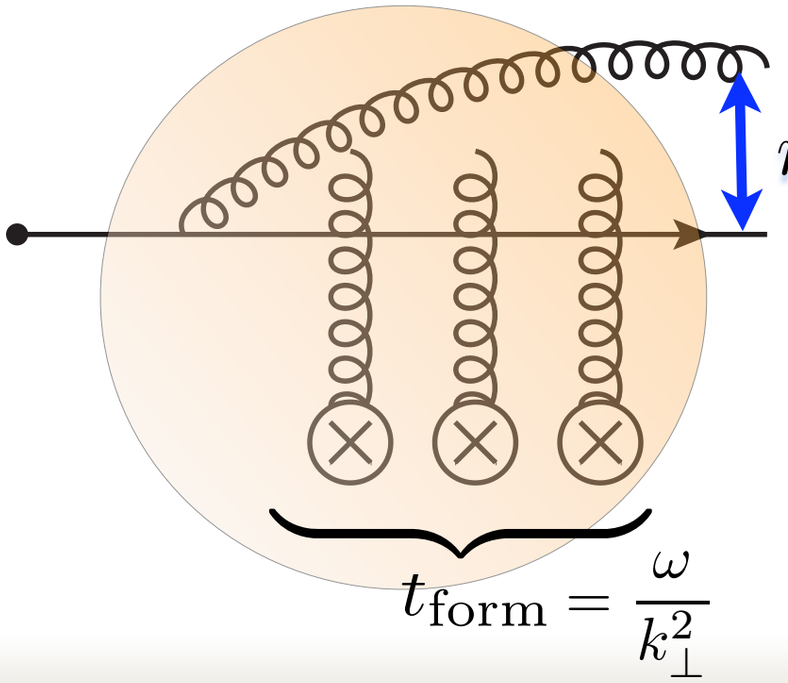

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$$t_{\rm form} = L \quad \Rightarrow \quad k_{\rm ind}^2 = \hat{q}L \equiv \mathbf{Q_s}$$

Medium acts as one scat. center

- spectrum suppressed $t_{form} \gg L$

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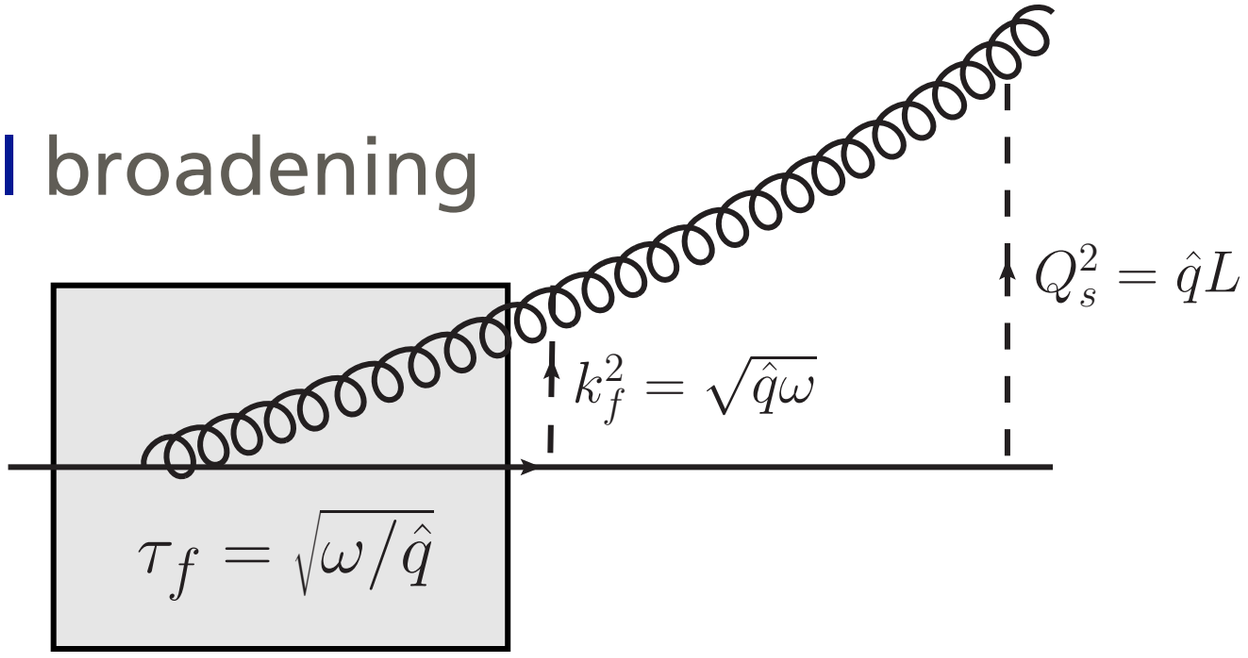
Induced gluon spectrum

$$\mathcal{R}_q \simeq 4\omega \int_0^L dt \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k}-\boldsymbol{k}', L-t) \sin\left(\frac{\boldsymbol{k}'^2}{2\sqrt{\hat{q}\omega}}\right) \exp\left(-\frac{\boldsymbol{k}'^2}{2\sqrt{\hat{q}\omega}}\right)$$

Two step process

- quantum emission + classical broadening
  - can transport gluons up to very large angles!
- emission all along L
- soft & collinear safe!



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quantum emission of gluon with mom. **k′**

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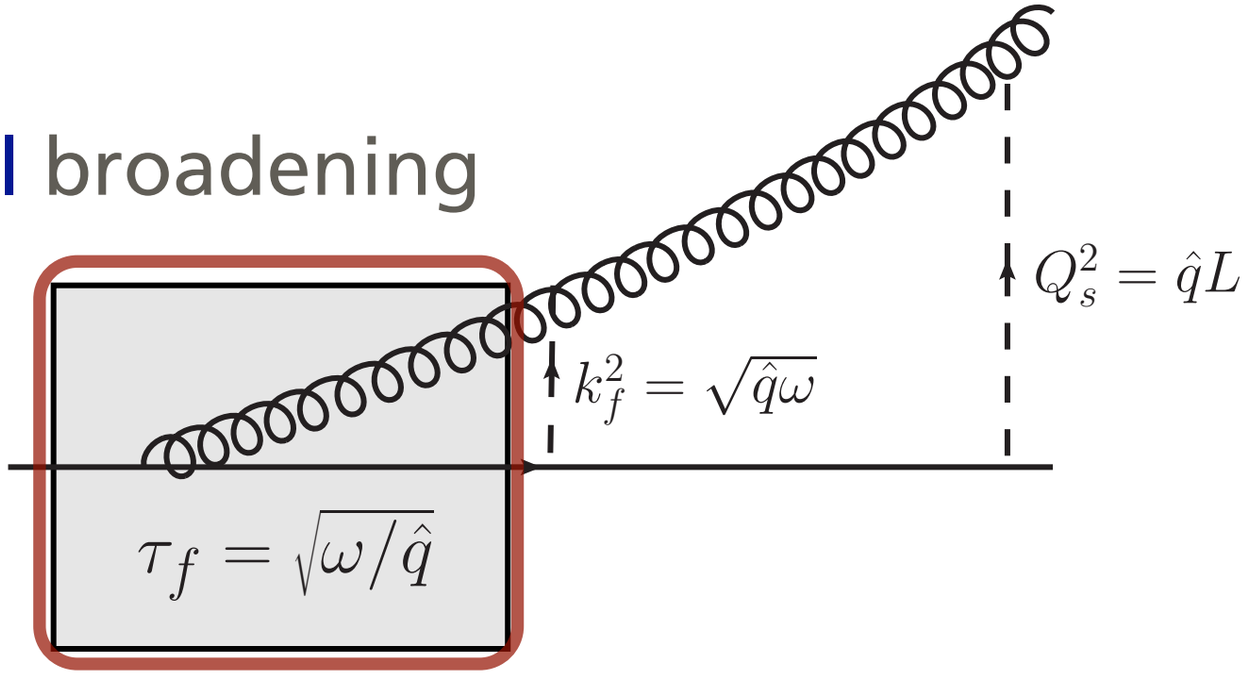

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prob. of acquiring mom. **k-k′** after L-t

quantum emission of gluon with mom. **k′**

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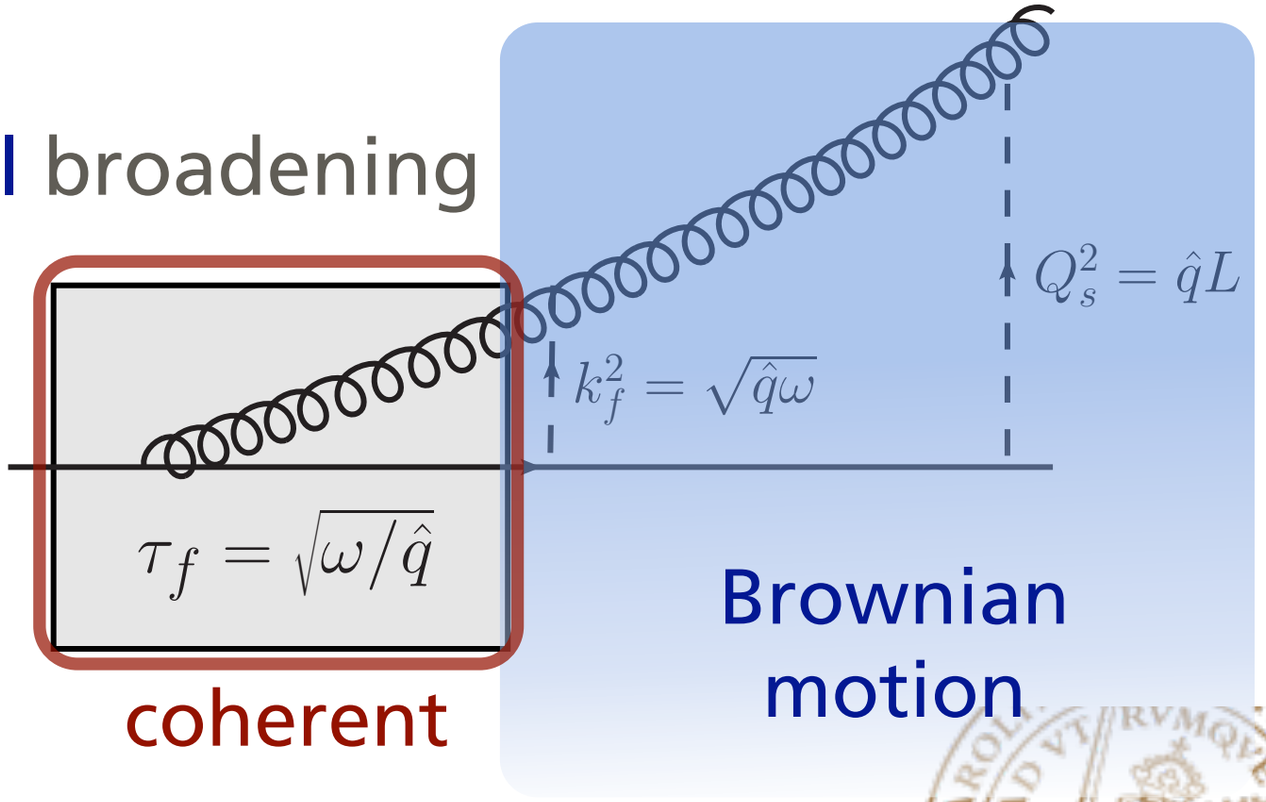

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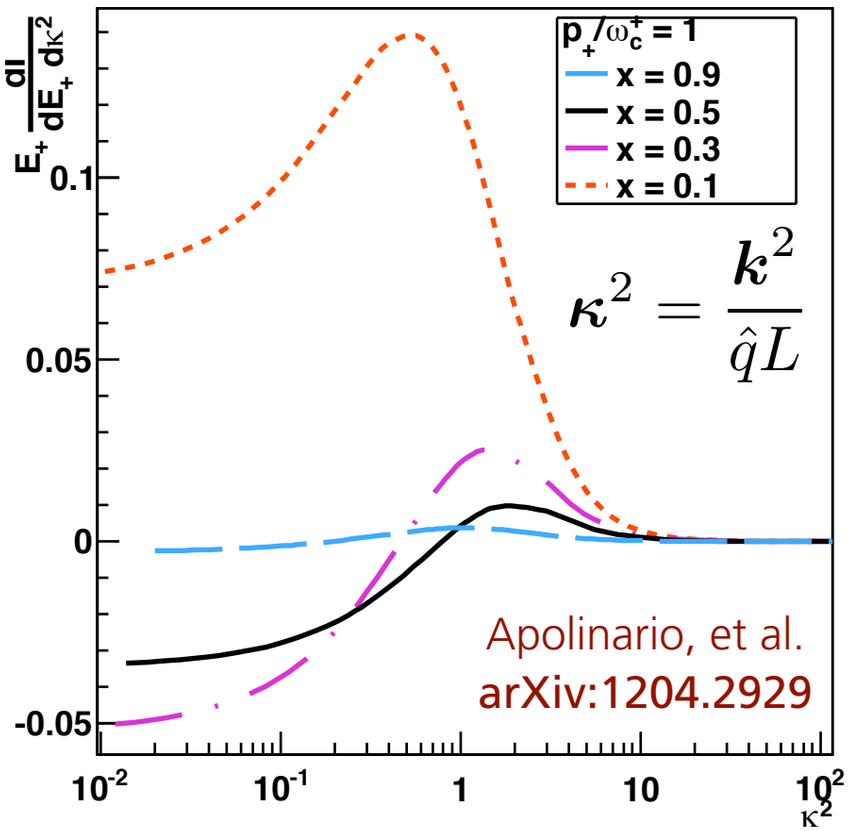

- input: collision geometry + $\hat{q}(t)$
- basis for HIC phenomenology
- sensitive to large angle radiation
- large uncertainties associated

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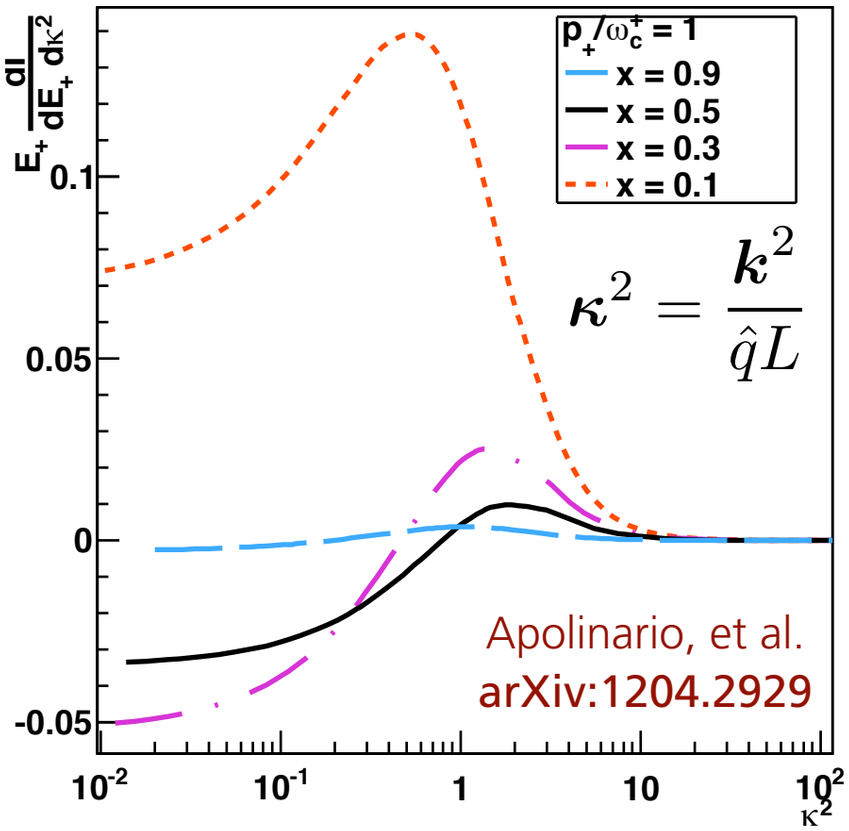

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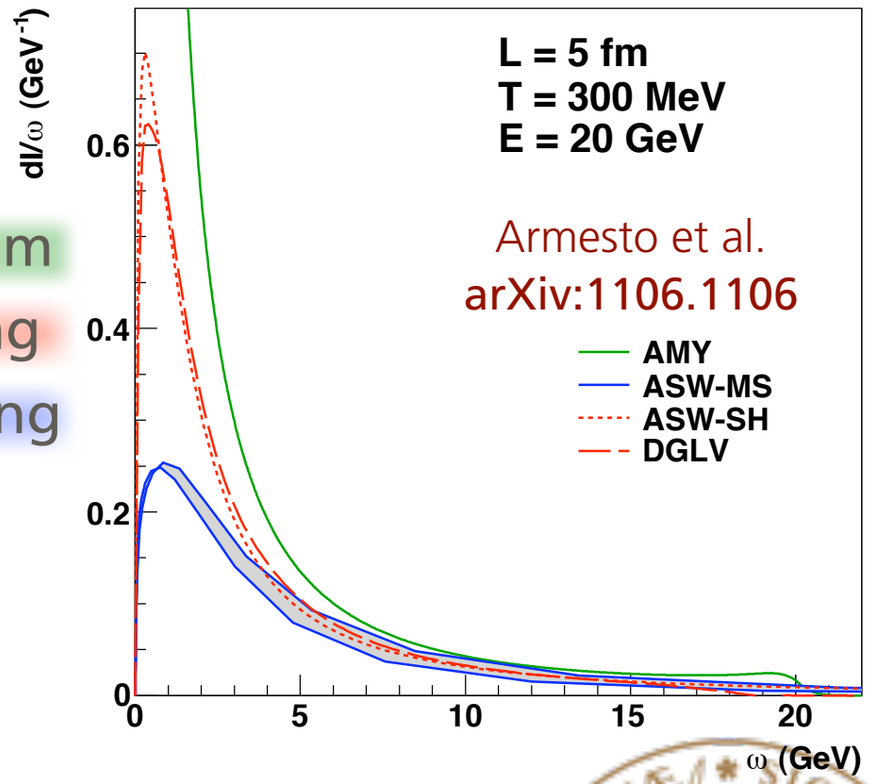
thermal medium

one (hard) scattering

multiple soft scattering



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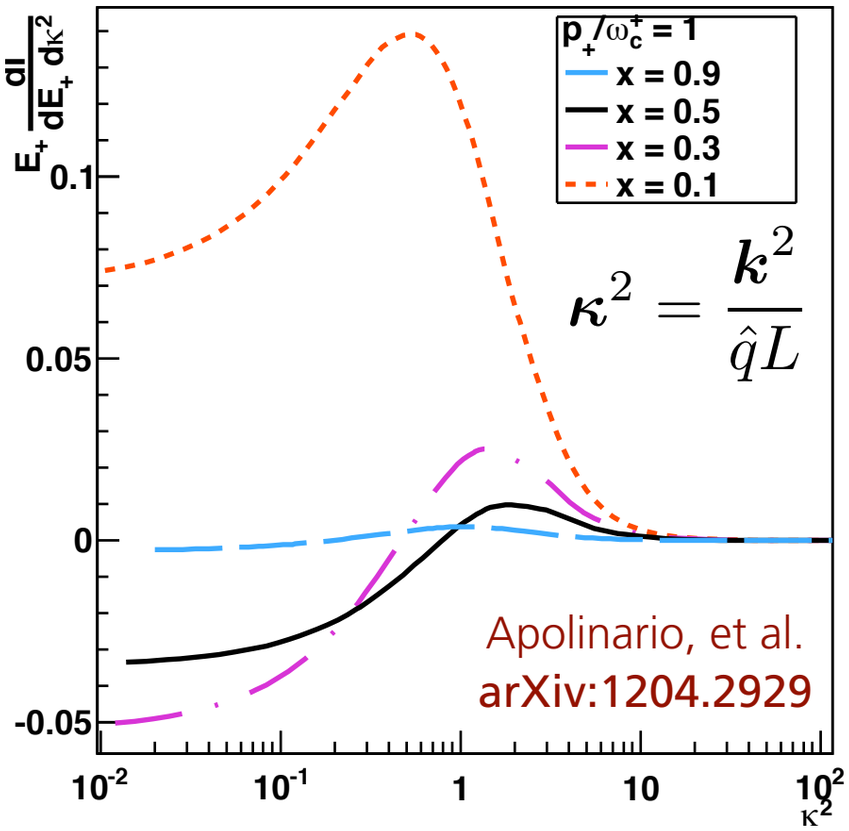
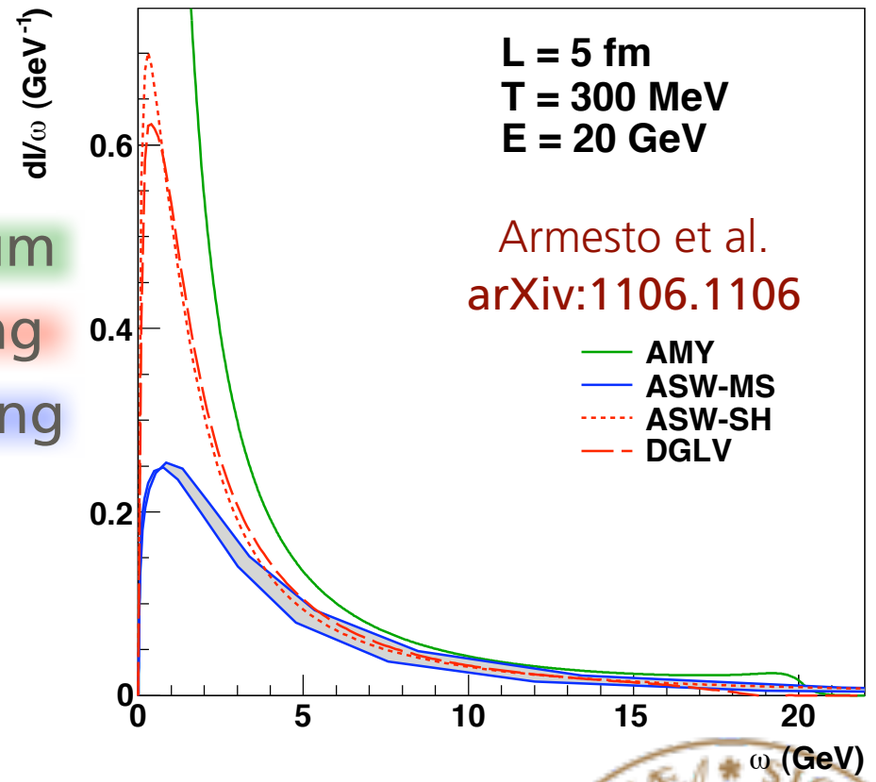


- input: collision geometry + $\hat{q}(t)$
- basis for HIC phenomenology
- sensitive to large angle radiation
- large uncertainties associated

thermal medium

one (hard) scattering

multiple soft scattering



Further improvements:

- full solution for medium potential
- implementations with thermal effects
- kinematics of splitting

Caron-Huot, Gale **PRC 82 (2010) 064902**

Ovanesyan, Vitev **JHEP 1106, 080; PLB 706 (2012) 371**

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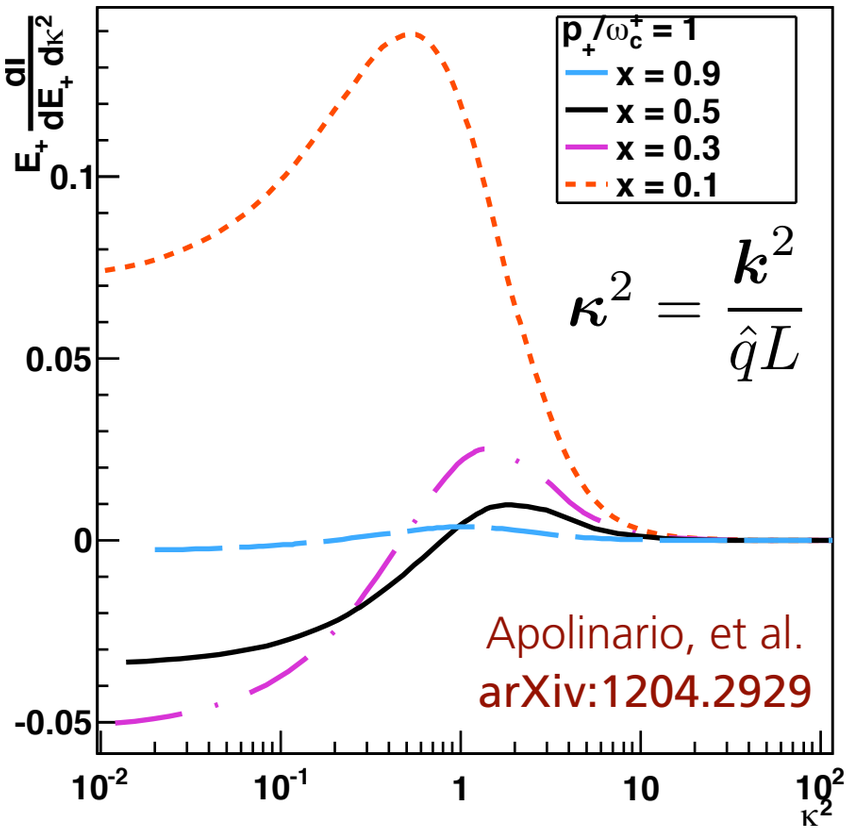

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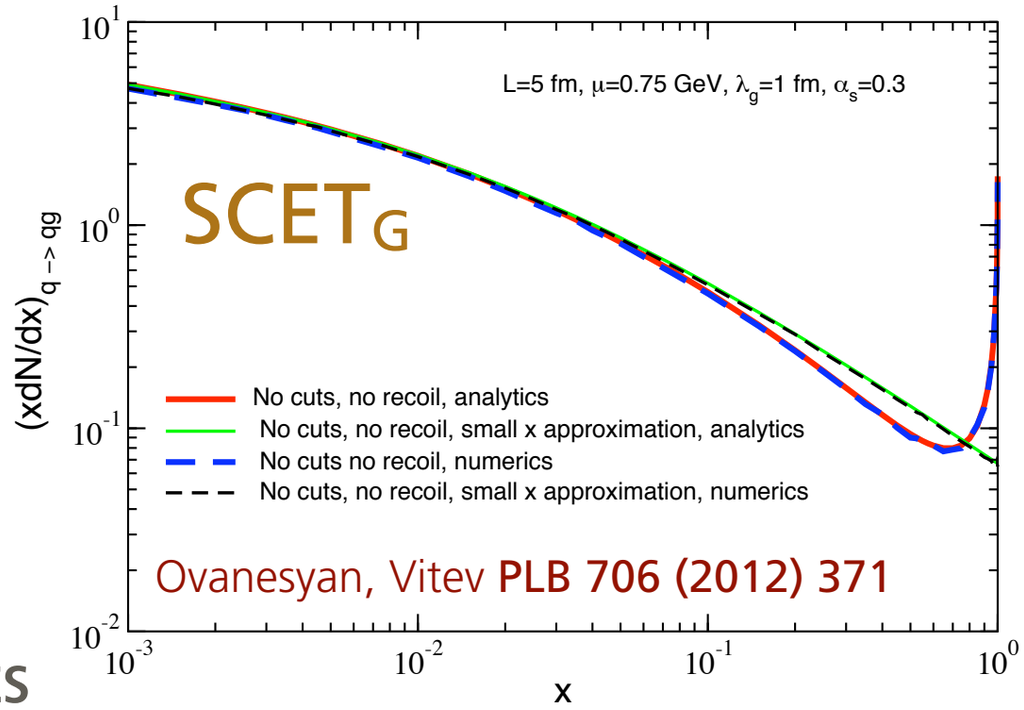

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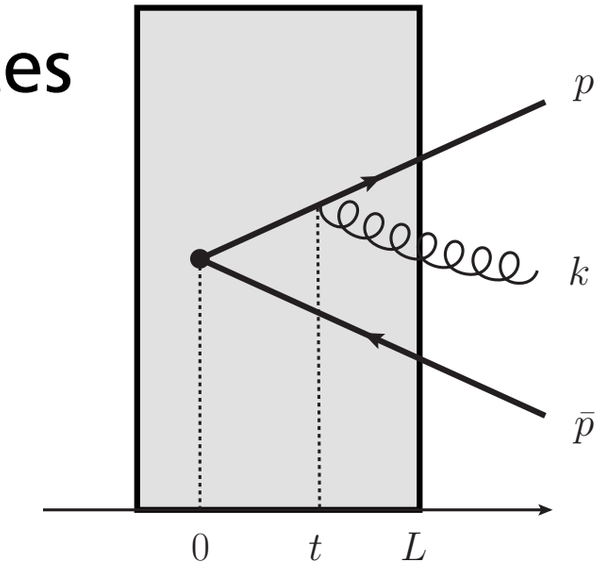

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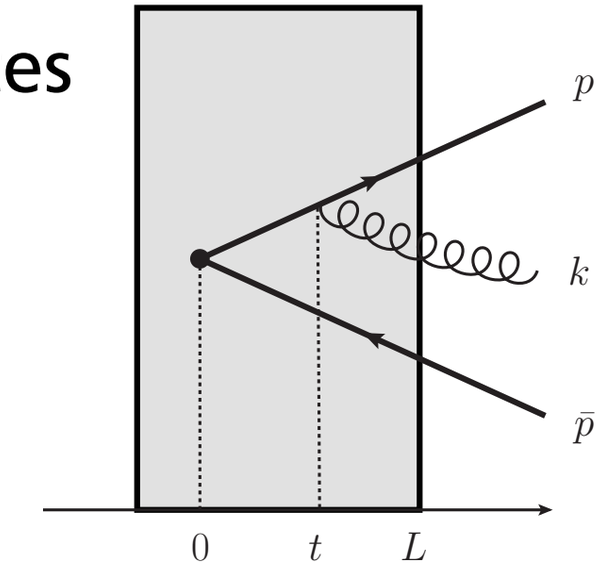

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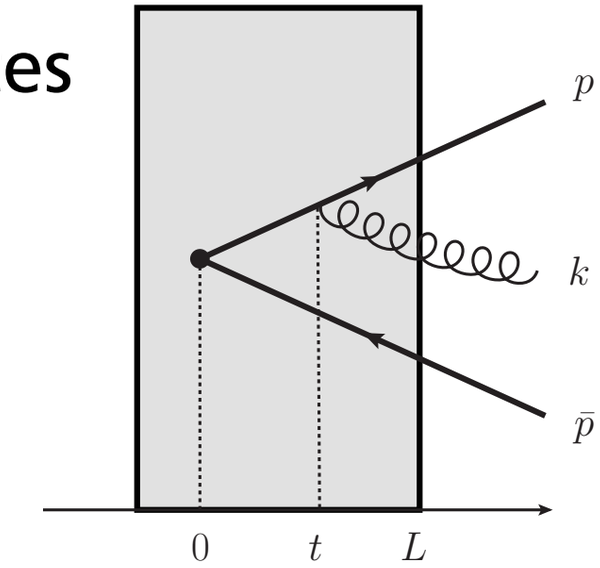

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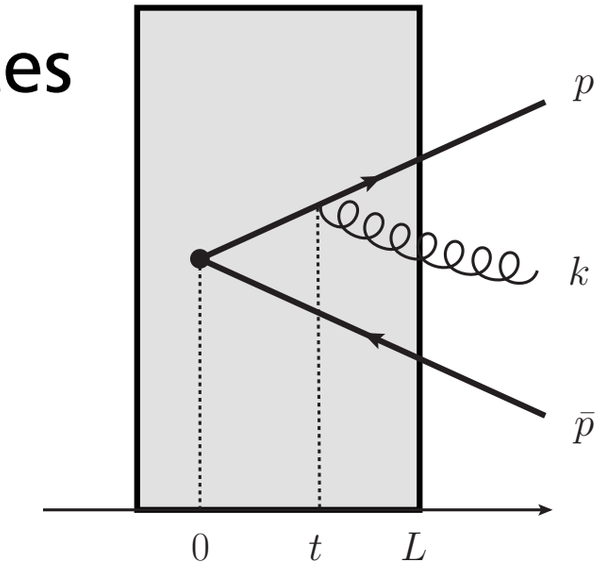

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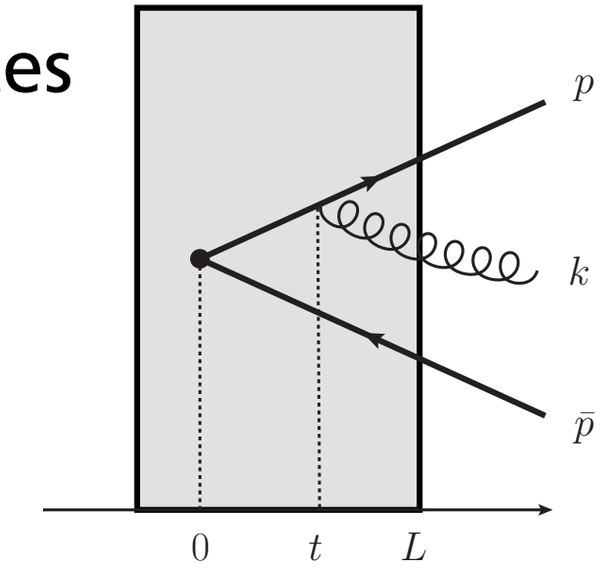

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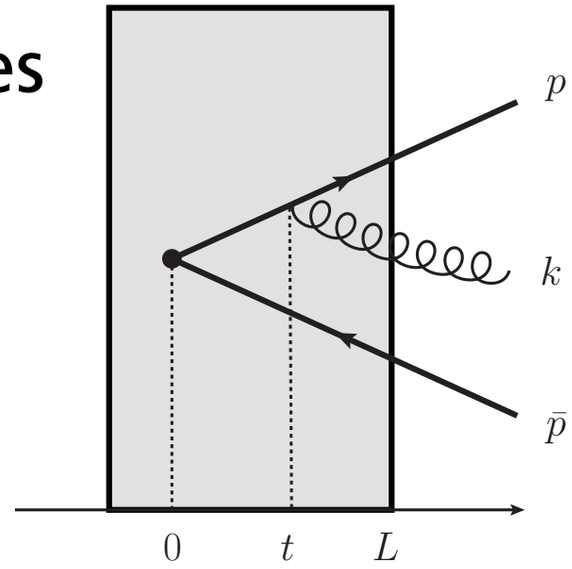

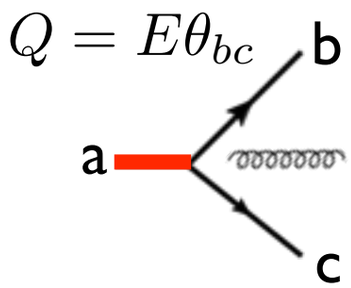

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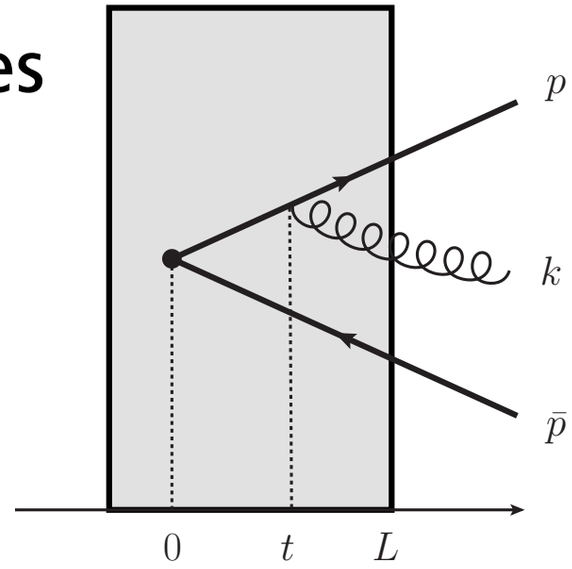

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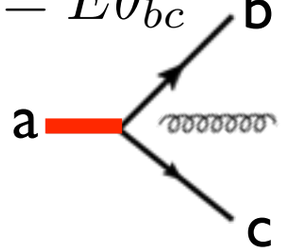

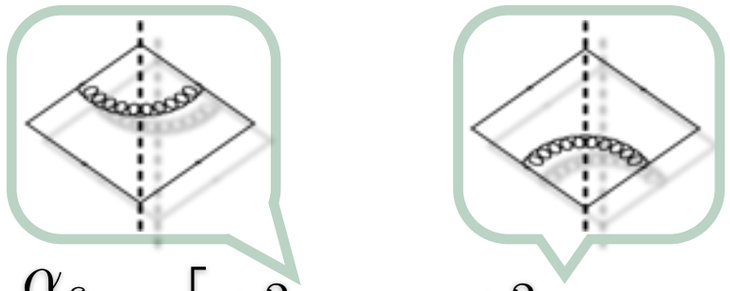

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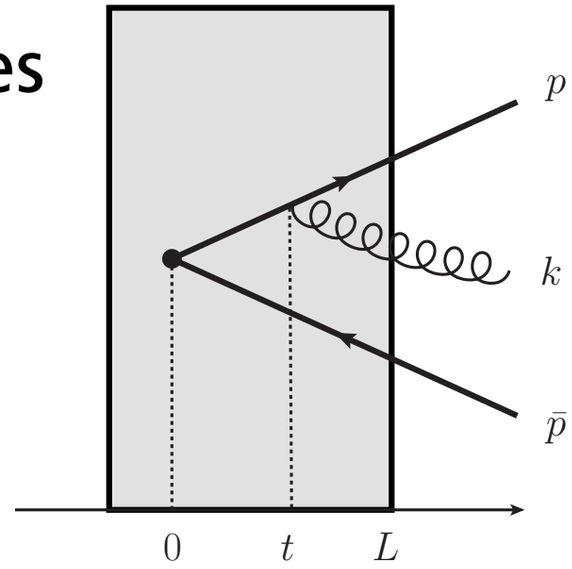

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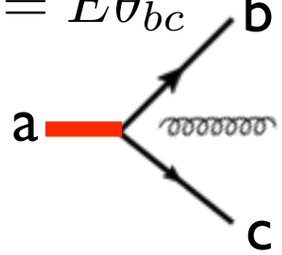

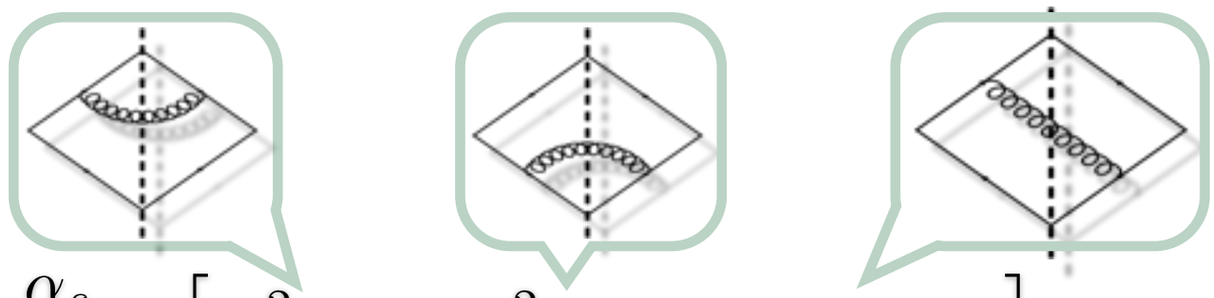

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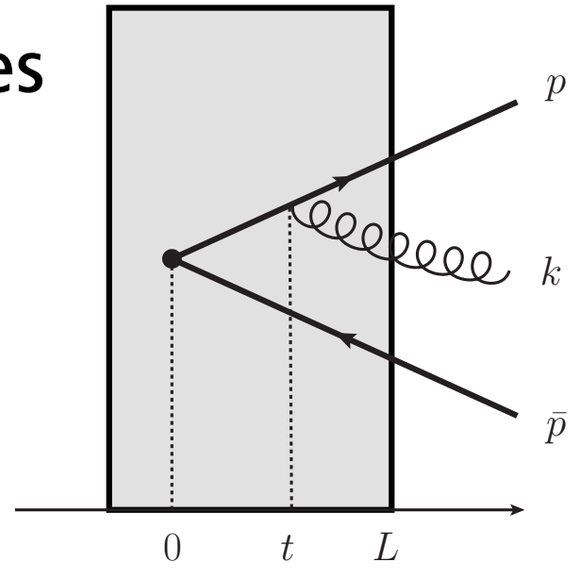

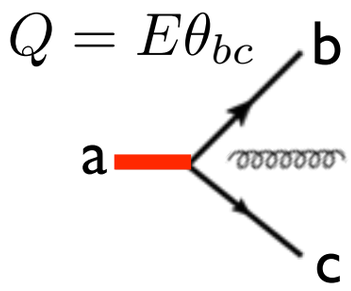

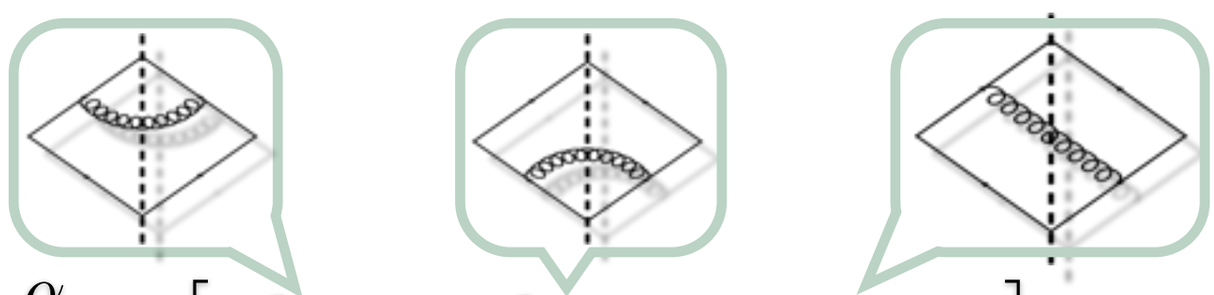

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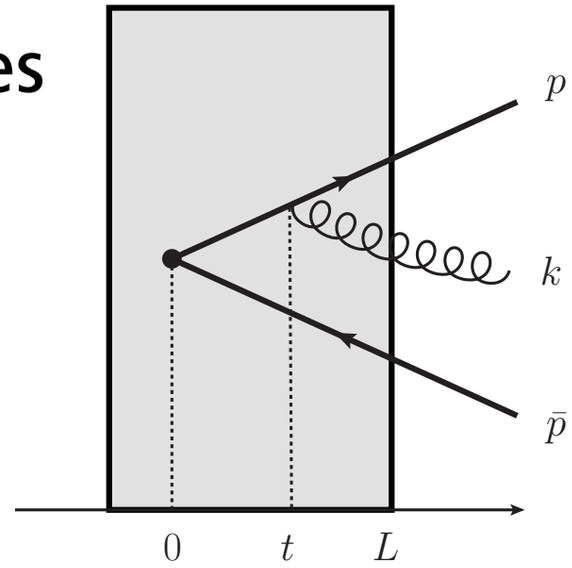

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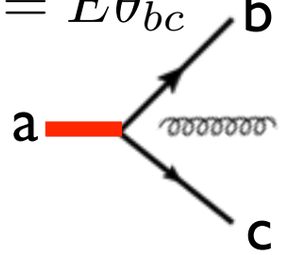

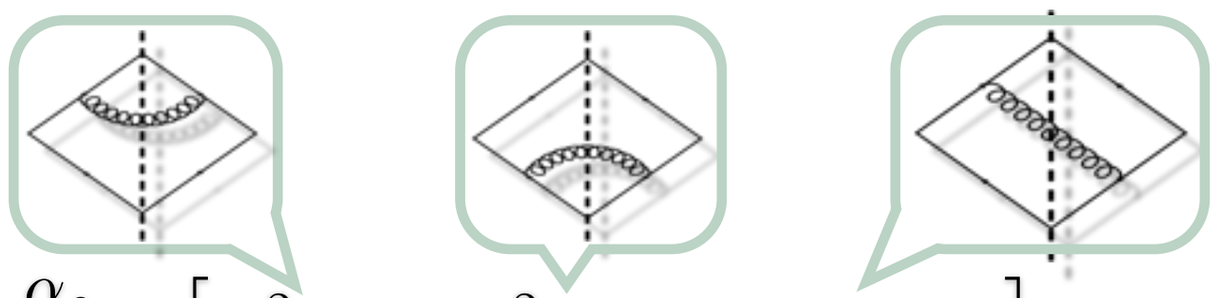

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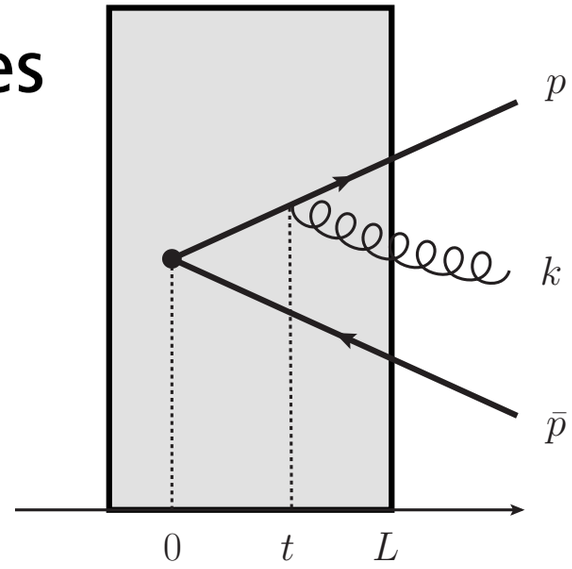

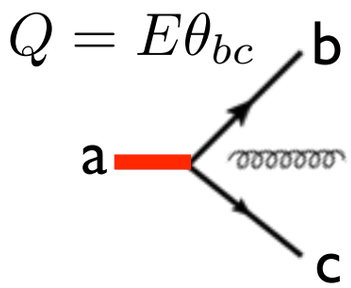

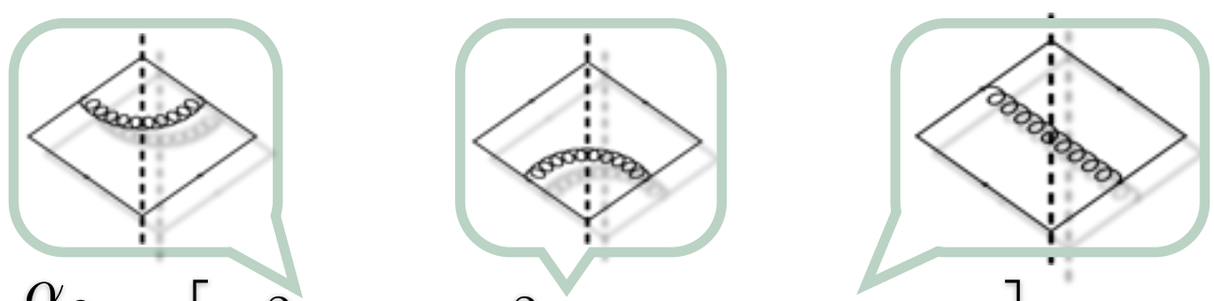

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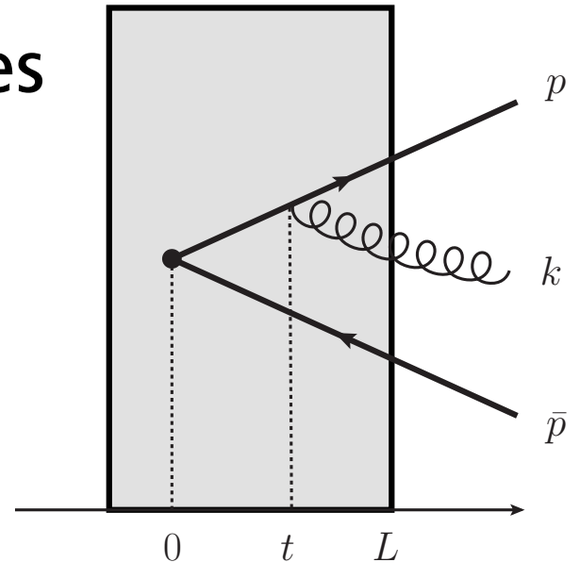

M. Martinez, Tue 14:35

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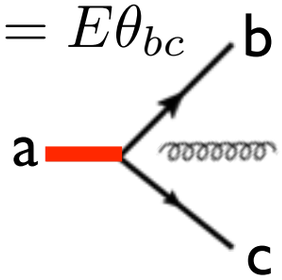

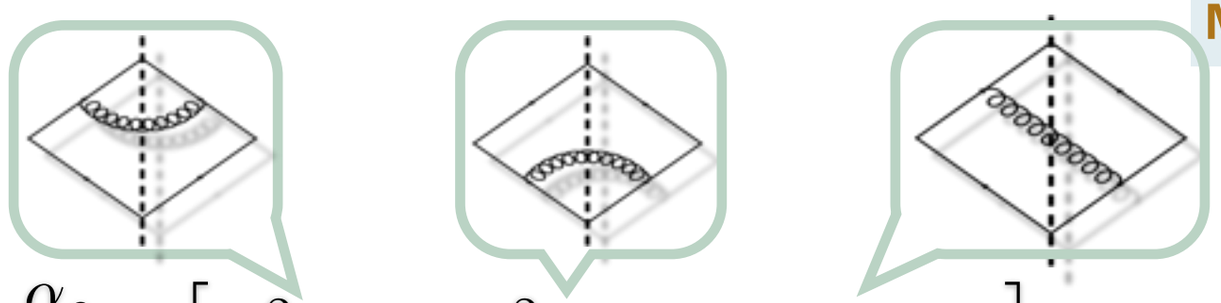

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Importance of interferences:

- condition: color correlation between emitters
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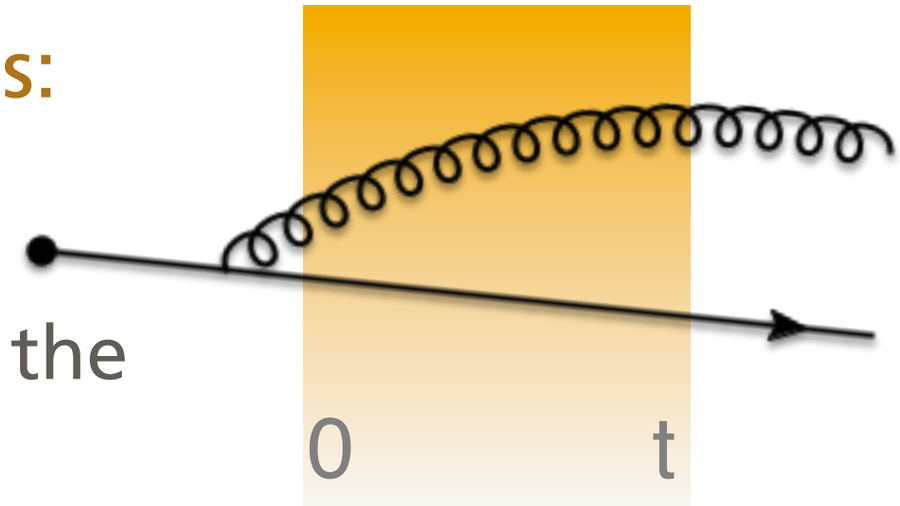

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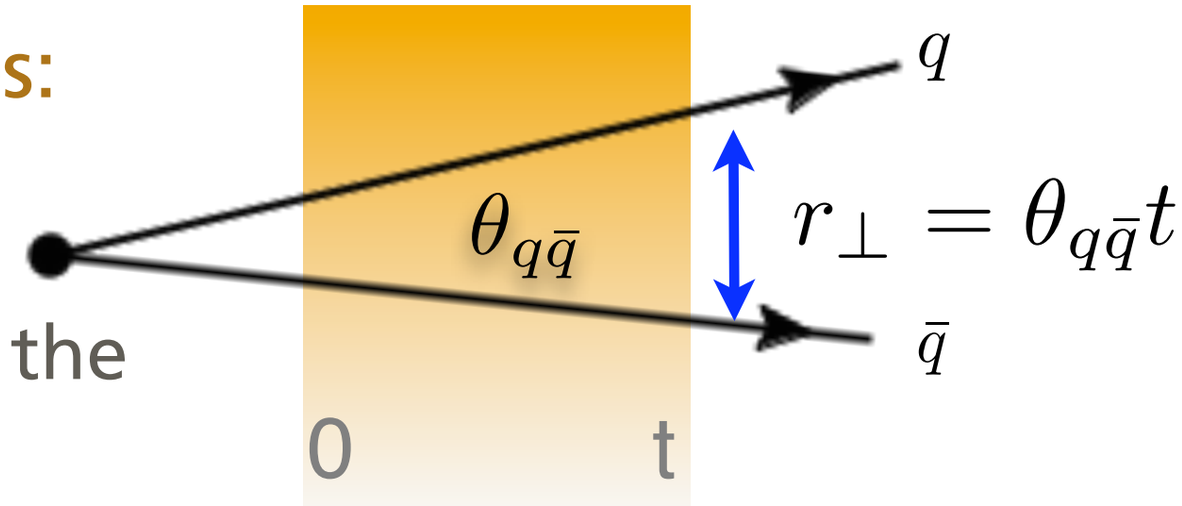

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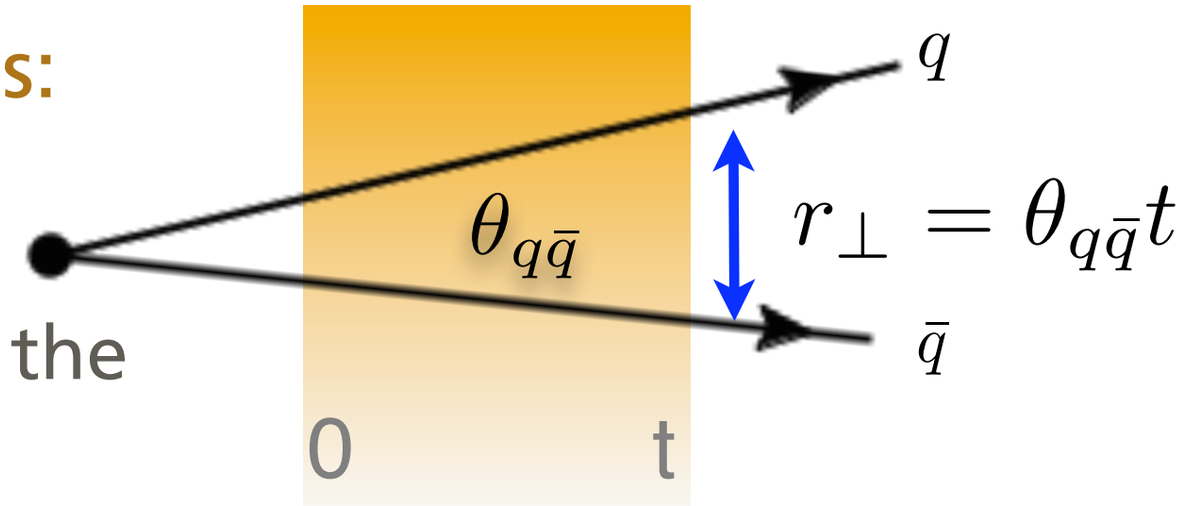

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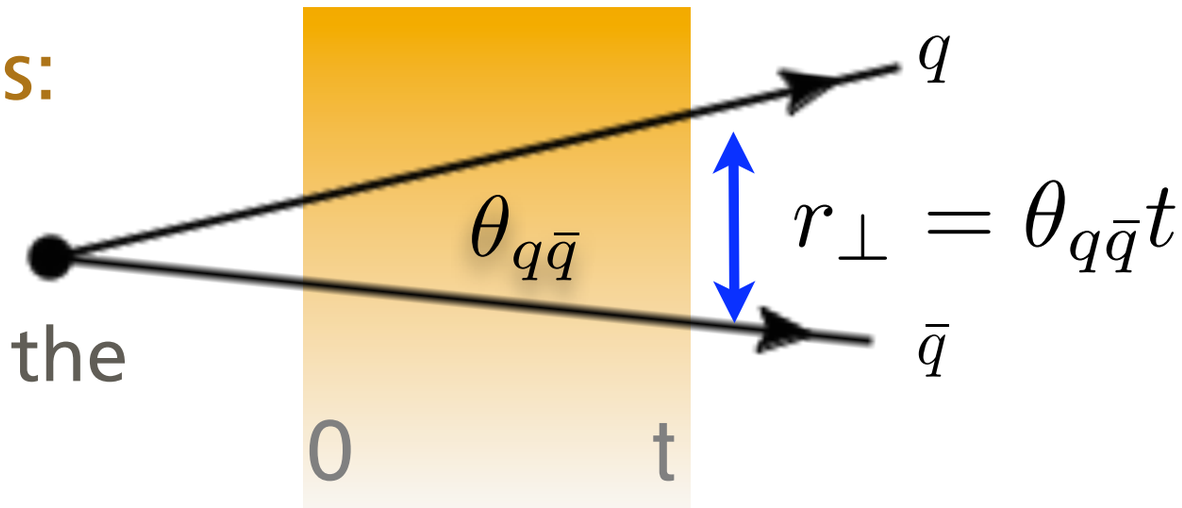

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decoherence parameter

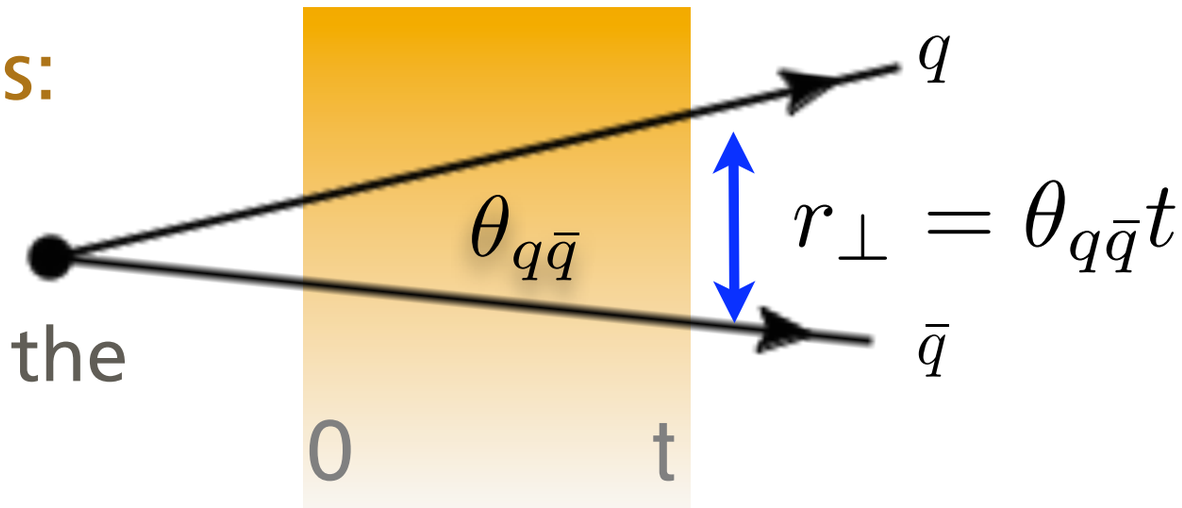
characteristic decoherence time

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; arXiv:1205.5739**
Casalderrey-Solana, Iancu **JHEP 1108 (2011) 015**

Interferences: analysis

Importance of interferences:

- condition: color correlation between emitters
- what is the probability that the pair remains correlated?



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

decoherence parameter

characteristic decoherence time

- processes at $t > \tau_d$: independent radiation
- processes at short timescales sensitive to interferences

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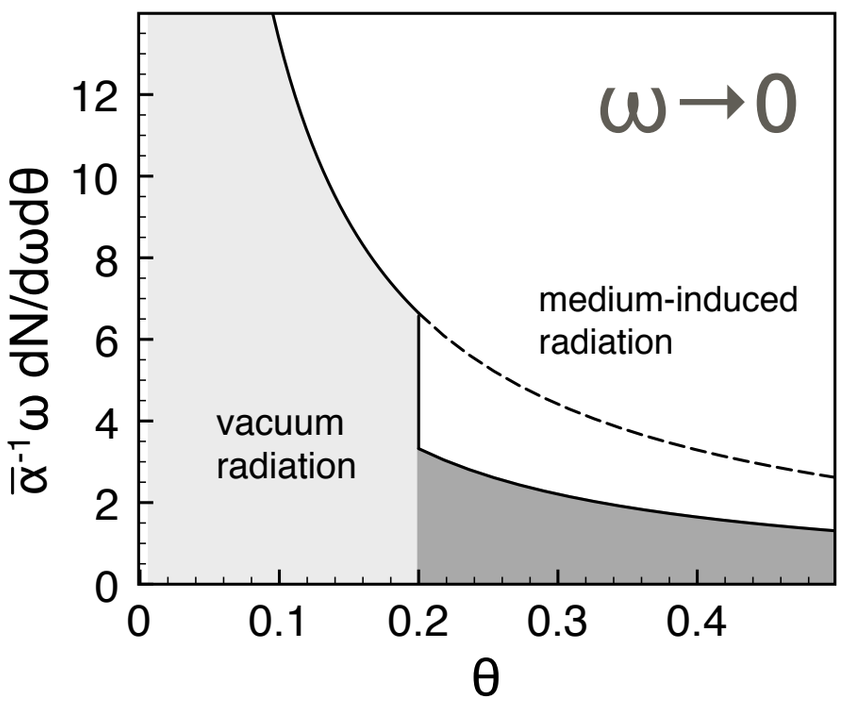
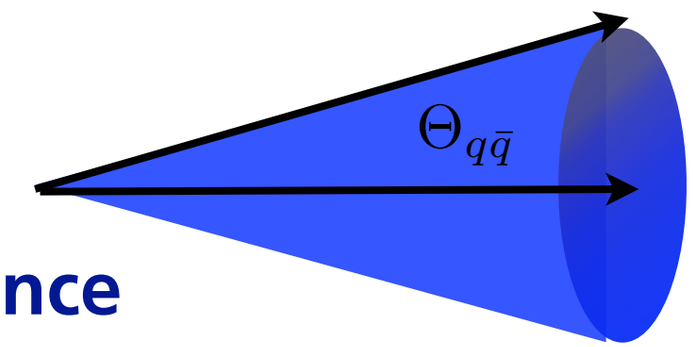
Onset of decoherence

- in the soft sector



$\Delta_{\rm med} \to 0$ **Coherence**



Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002; PLB 707 (2011) 156**

Onset of decoherence

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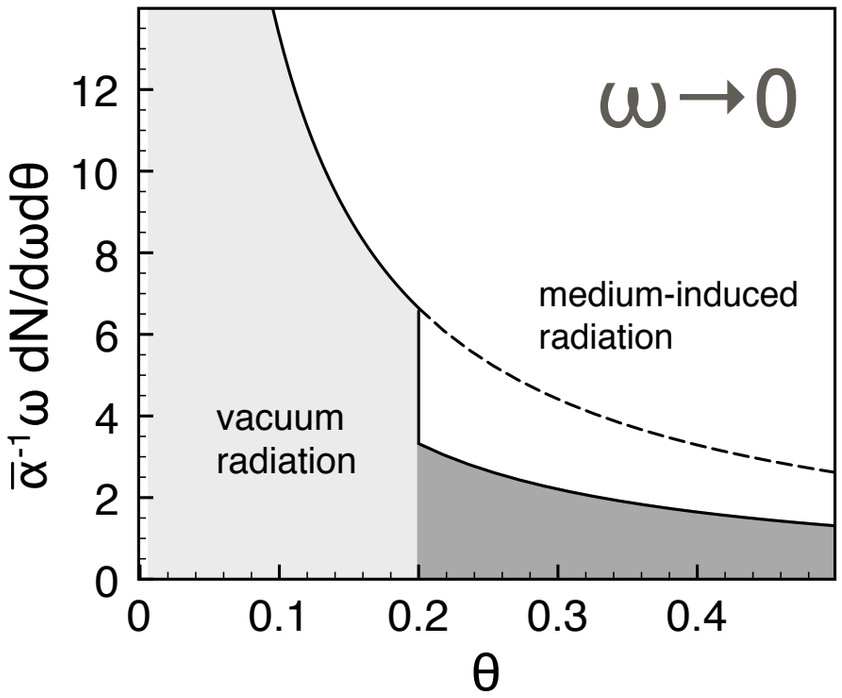
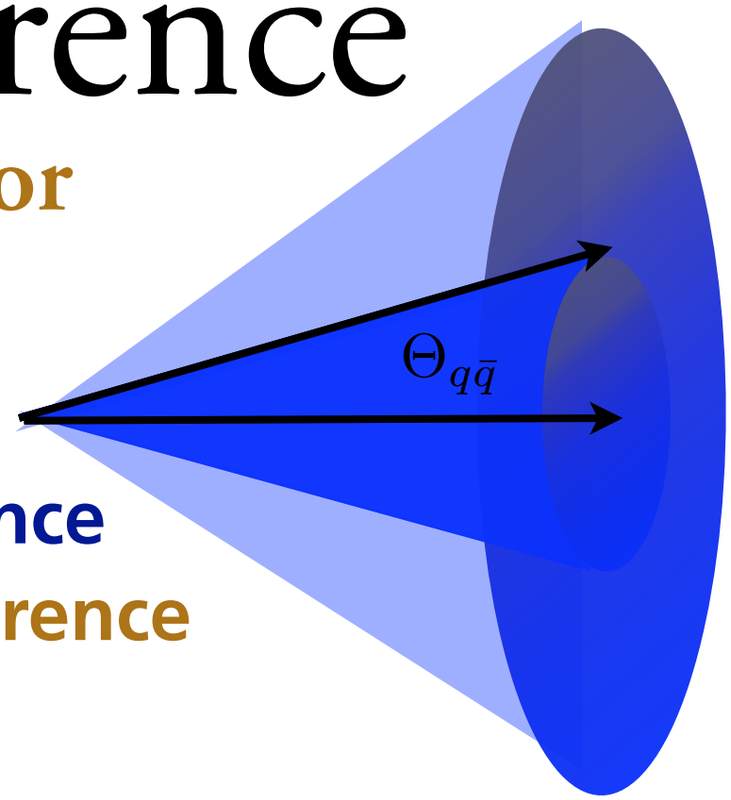


$\Delta_{\rm med} \to 0$ **Coherence**

$\Delta_{\rm med} \to 1$ **Decoherence**



Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002; PLB 707 (2011) 156**

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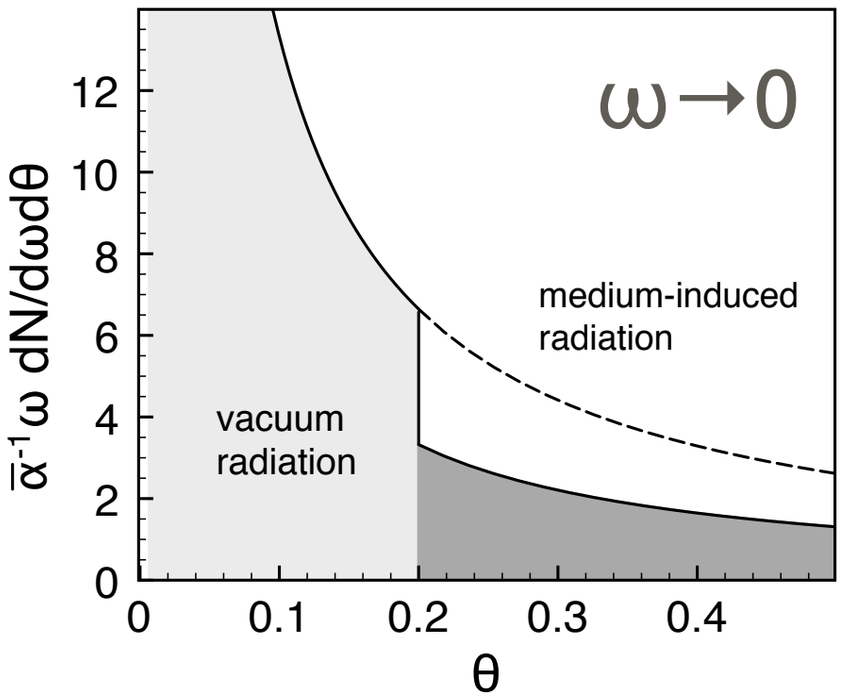

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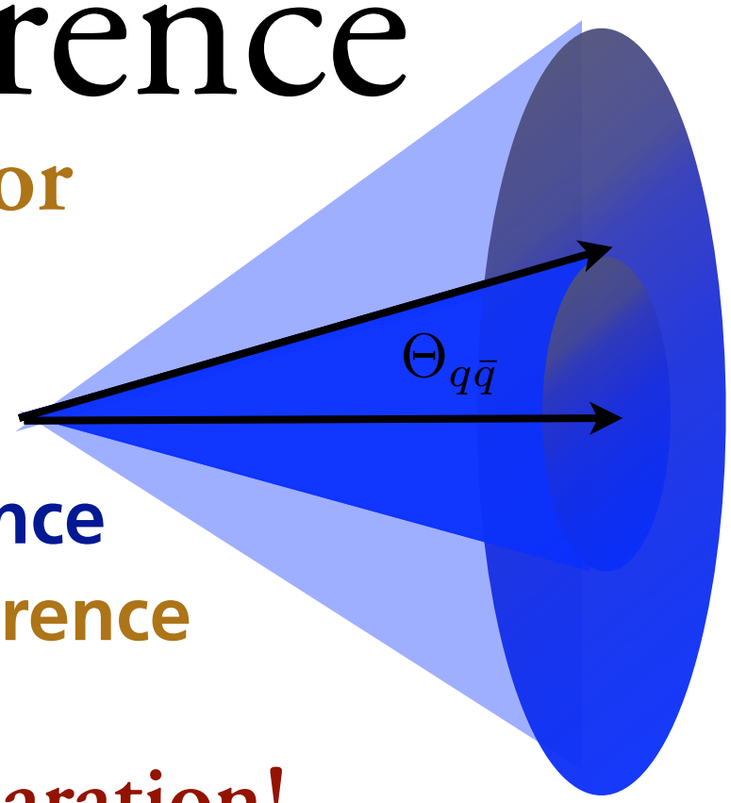

Geometrical separation!

Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002; PLB 707 (2011) 156**

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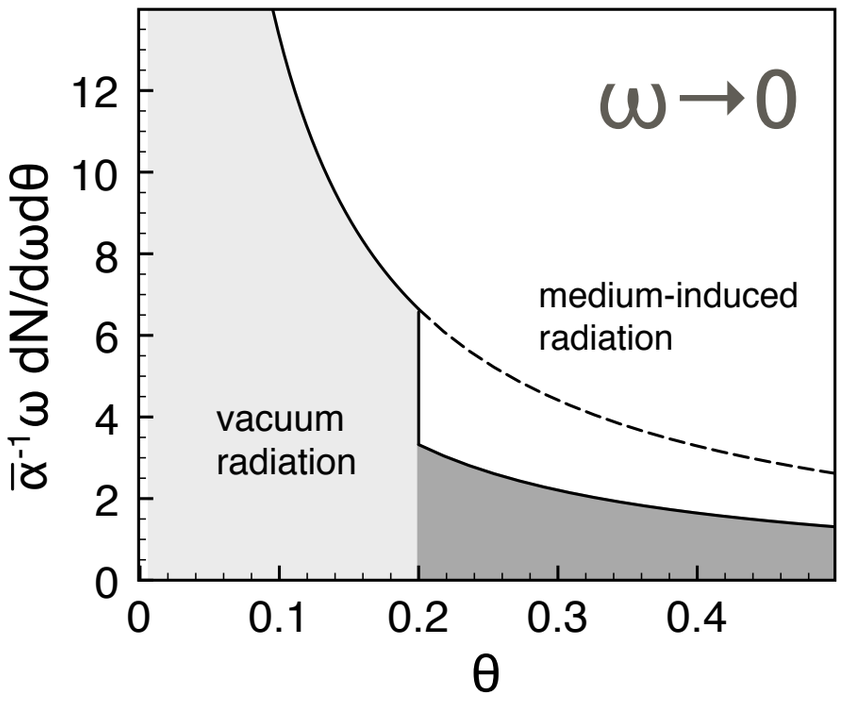
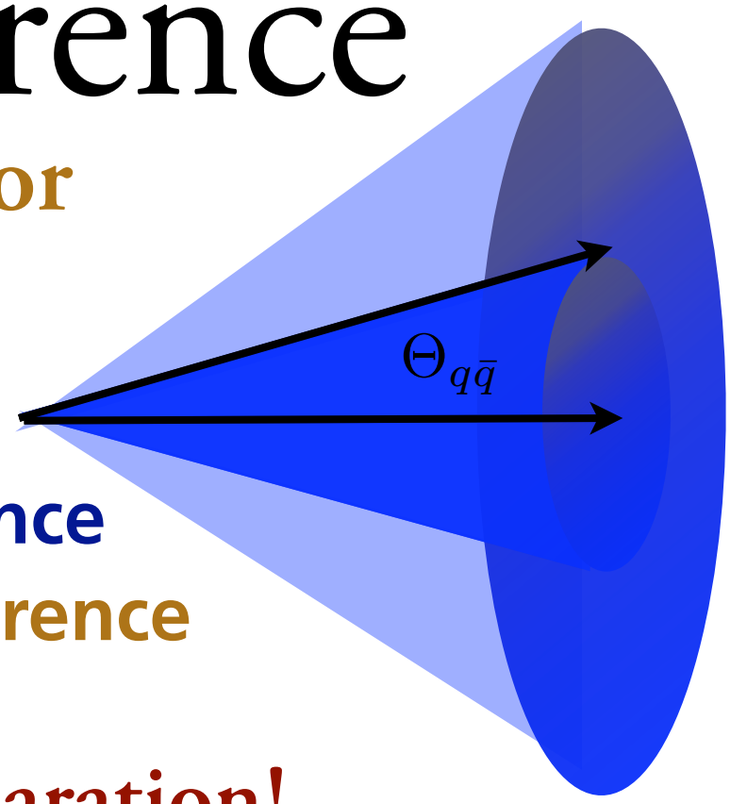




$\Delta_{\rm med} \to 0$ **Coherence**

$\Delta_{\rm med} \to 1$ **Decoherence**

Geometrical separation!

$$dN^{\rm tot}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta}\left[\Theta(\cos\theta-\cos\theta_{q\bar{q}})+\Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}}-\cos\theta)\right]\ .$$

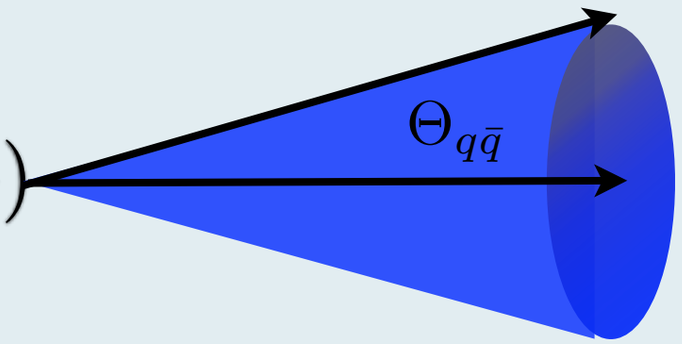
Soft gluons with long formation times

- particles radiate independently
- "memory loss": no color correlation to parent

Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002; PLB 707 (2011) 156**

Vacuum: a reminder

$$\langle dN_q \rangle_\varphi = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta} \Theta(\cos\theta - \cos\theta_{q\bar{q}})$$



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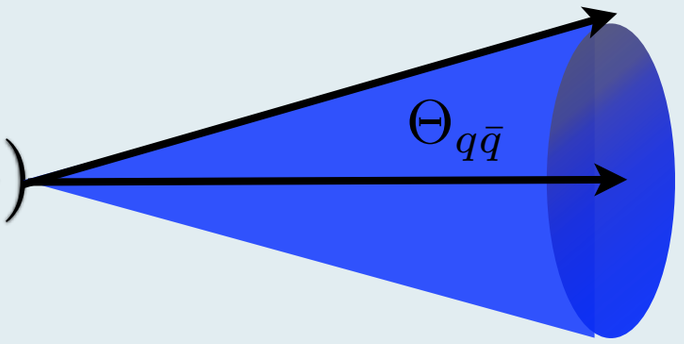
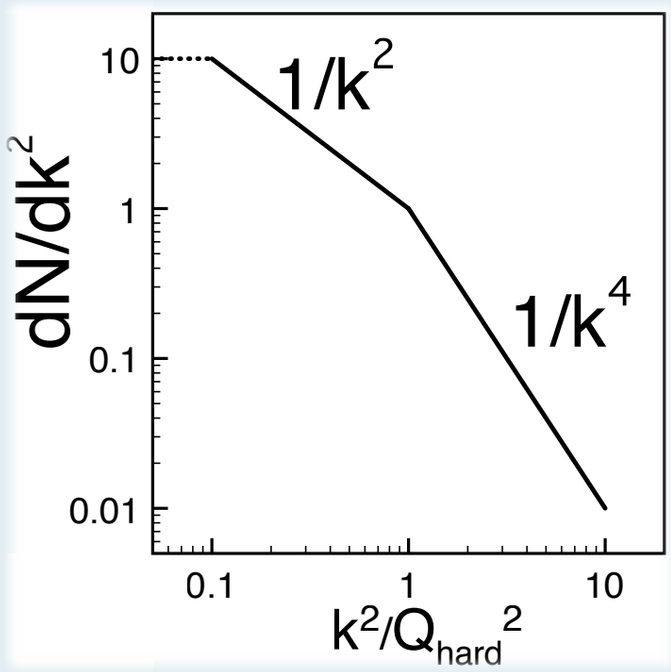


$$\omega \frac{dN_{\gamma^*}}{d^3k} = \frac{\alpha_s C_F}{\pi} \begin{cases} \frac{1}{\boldsymbol{k}^2} & \boldsymbol{k} \ll \delta\boldsymbol{k}, \text{ or } \theta \ll \theta_{q\bar{q}} \\ \frac{\delta\boldsymbol{k}^2}{\boldsymbol{k}^4} & \boldsymbol{k} \gg \delta\boldsymbol{k}, \text{ or } \theta \gg \theta_{q\bar{q}} \end{cases}$$



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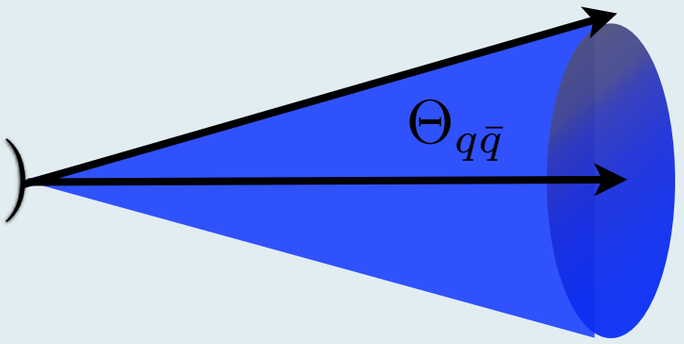

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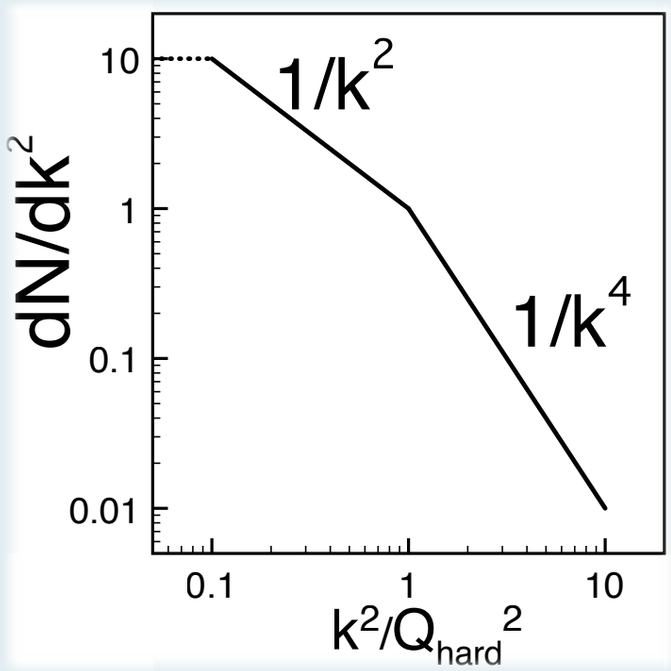

Hard scale of the problem: $|\delta\boldsymbol{k}| \simeq \omega\theta_{q\bar{q}}$

- determines the **maximal transverse momentum** of gluons

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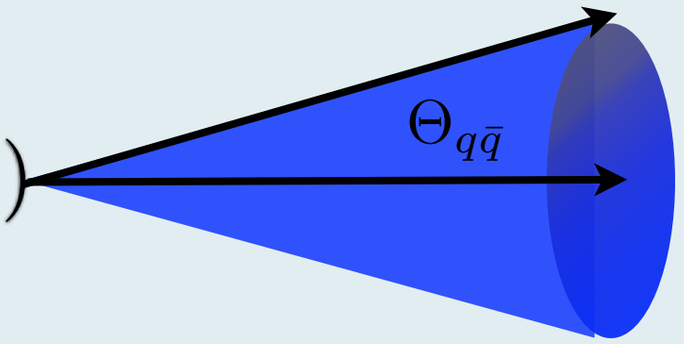

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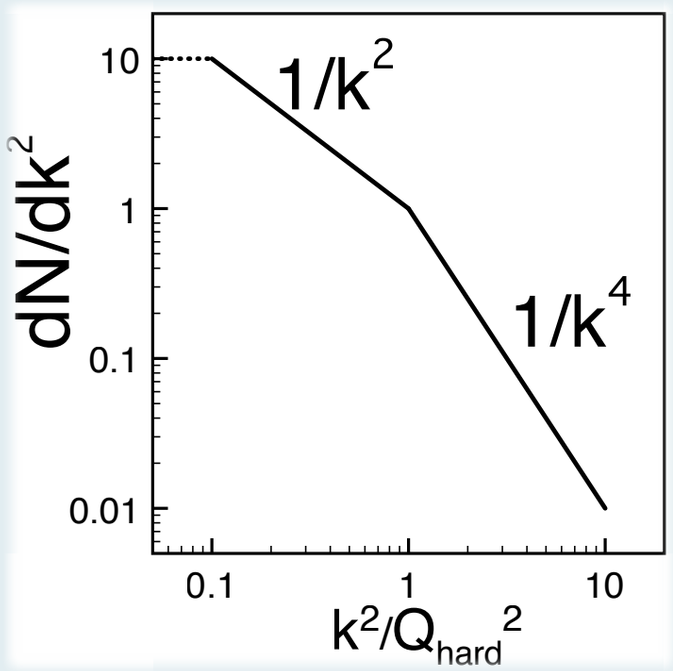

Hard scale of the problem: $|\delta\boldsymbol{k}| \simeq \omega\theta_{q\bar{q}}$

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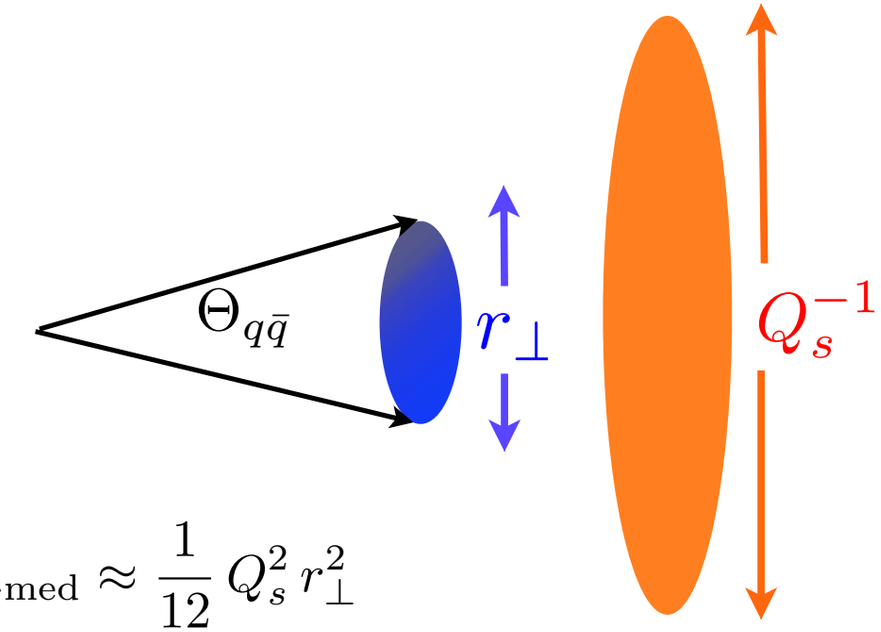
What are the relevant hard scales in the medium?

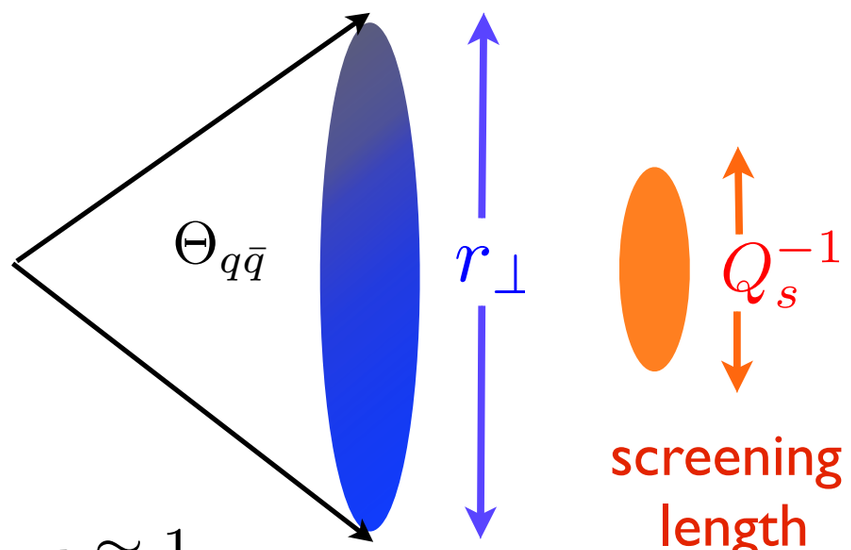
Hard scale analysis

- $r_\perp < Q_s^{-1}$ (Dipole regime)



$$\Delta_{\text{med}} \approx \frac{1}{12} Q_s^2 \, r_\perp^2$$

- $r_\perp > Q_s^{-1}$ (Decoh. regime)



$$\Delta_{\text{med}} \approx 1$$

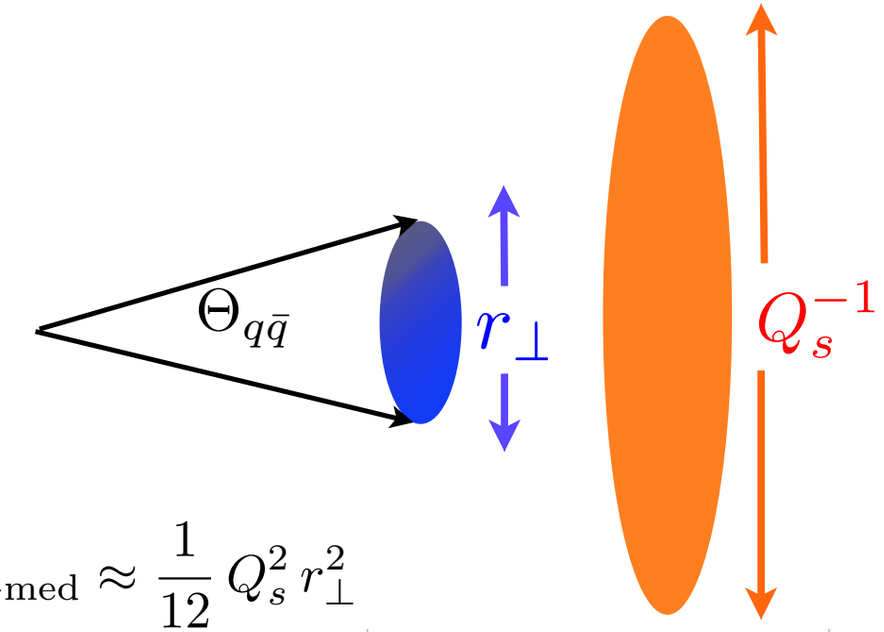
$$\Delta_{\text{med}} \approx 1 - \exp[-\frac{1}{12} Q_s^2 \, r_\perp^2]$$

$r_\perp = \theta_{q\bar{q}} L$

Q_s: characteristic momentum scale of the medium

Hard scale analysis

- $r_\perp < Q_s^{-1}$ (Dipole regime)



$\Delta_{\rm med} \approx \frac{1}{12} Q_s^2 r_\perp^2$

$\tau_d \gg L$

$\Delta_{\rm med} \approx 1 - \exp[-\frac{1}{12} Q_s^2 r_\perp^2]$

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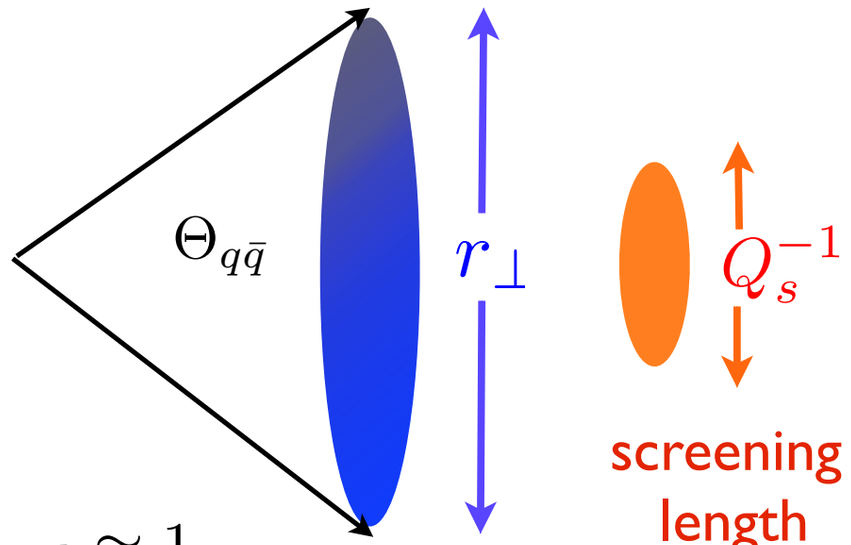

$\Delta_{\rm med} \approx 1$

$\tau_d \ll L$

$r_\perp =$

Q_s: characteristic momentum scale of the medium

Finite energies

Hard scale of the problem: $Q_{\mathrm{hard}} = \max\left(r_{\perp}^{-1}, Q_s, \delta\boldsymbol{k}\right)$

$k_\perp > Q_{\mathrm{hard}}$: coherence!

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; arXiv:1205.5739**

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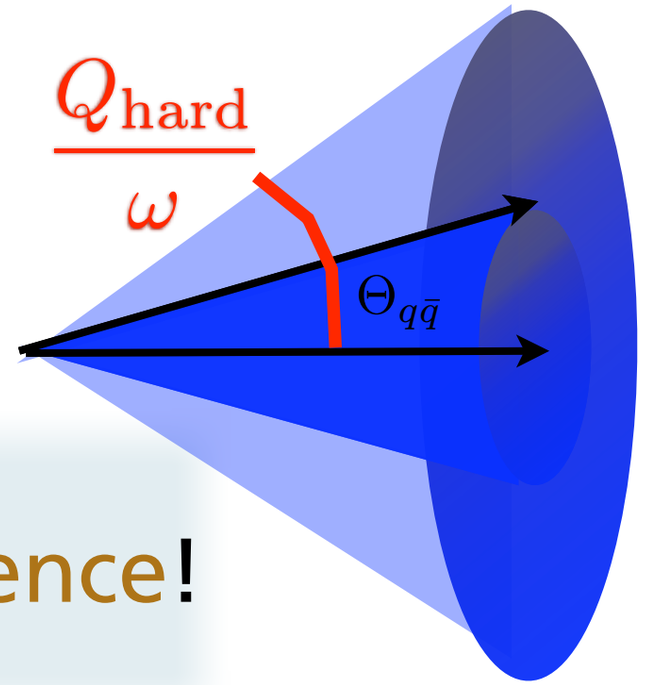
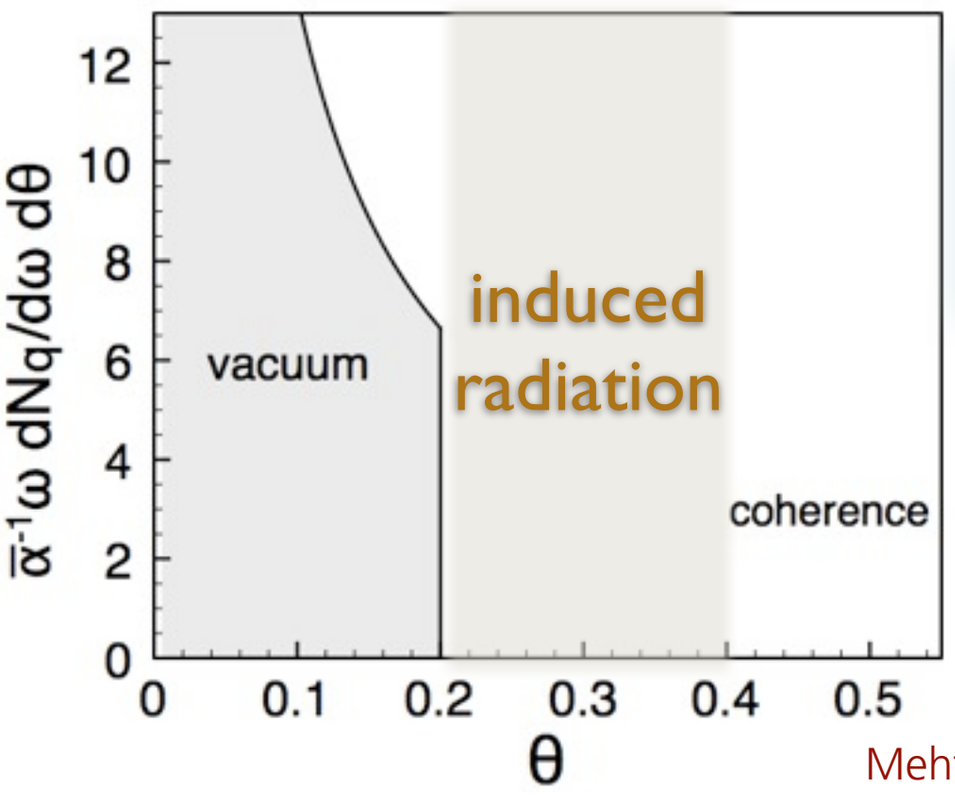


$\theta > Q_{\mathrm{hard}}/\omega$: coherence!



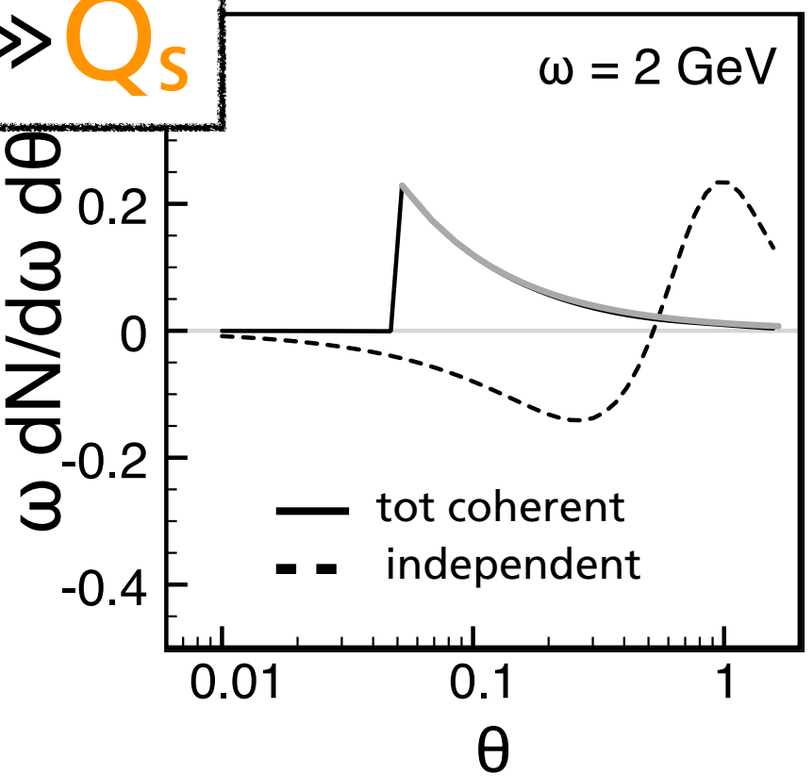
Medium scales open phase space!

- hard bremsstrahlung necessary to restore coherence at large angles

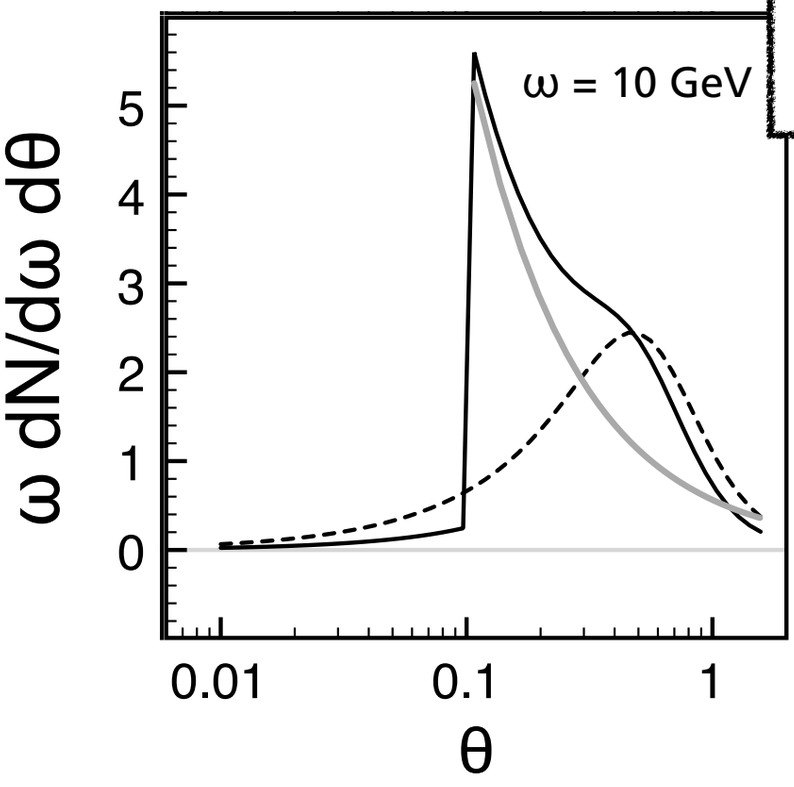
Mehtar-Tani, Salgado, KT JHEP 1204, 064; arXiv:1205.5739

Angular spectrum

$r_\perp^{-1} \gg Q_s$



$r_\perp^{-1} \ll Q_s$



$\hat{q}$ = 10 GeV²/fm
L = 5 fm

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; arXiv:1205.5739**

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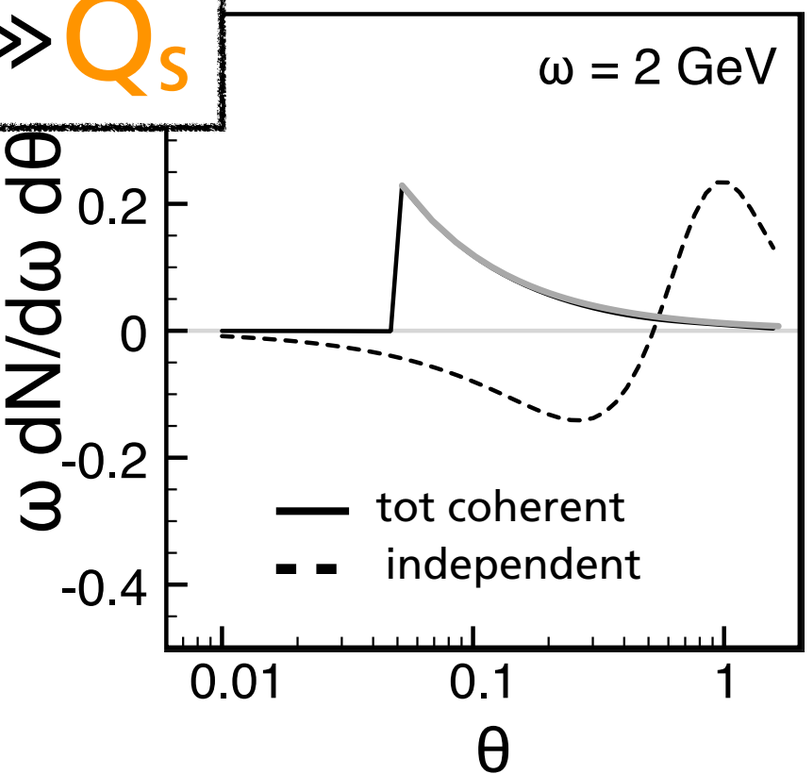

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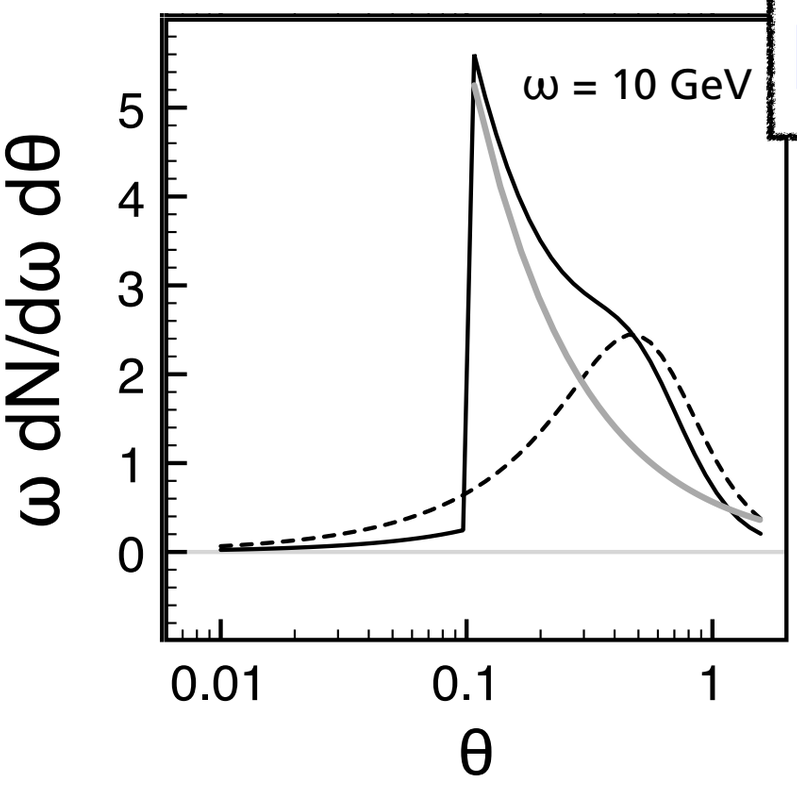

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"Dipole" regime

- antiangular spectrum
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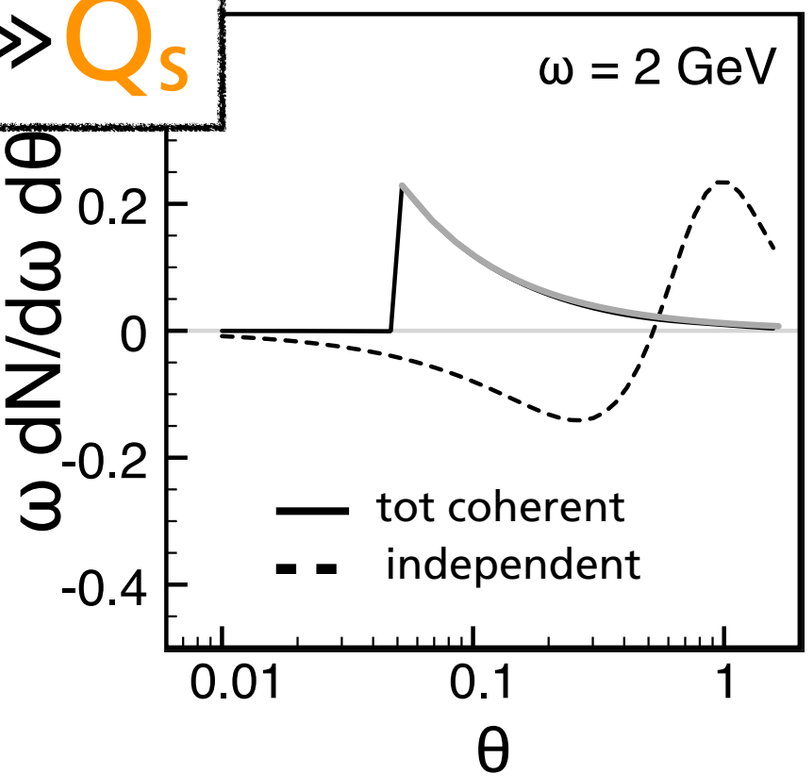

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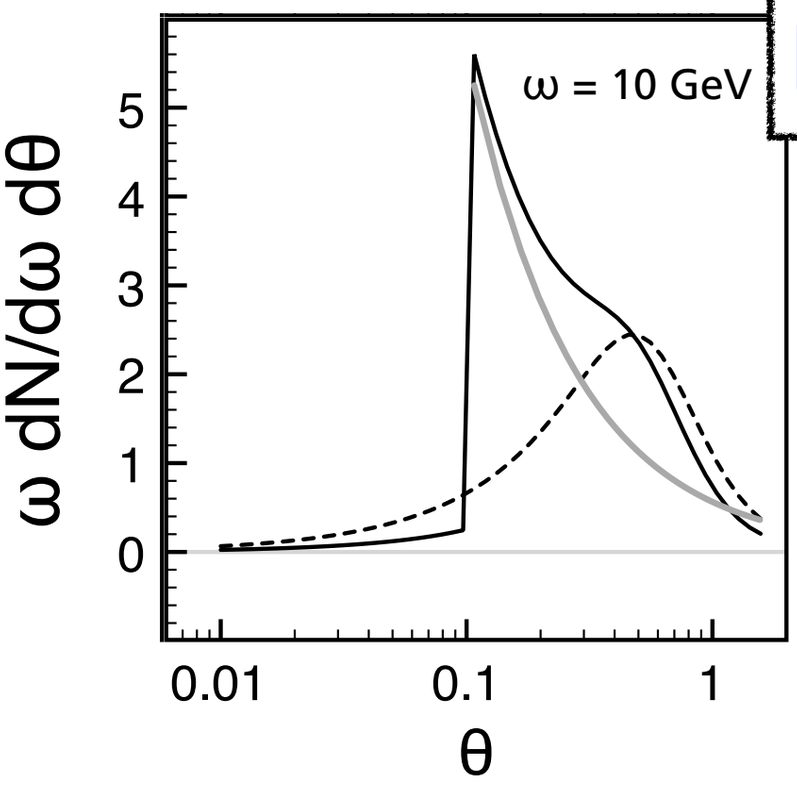

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"Dipole" regime

- antiangular spectrum
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"Decoherence" regime

- medium-induced rad. + antiangular spectrum
- soft sector universal

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; arXiv:1205.5739**

Multi-gluon emissions

- Poisson distribution

  Baier, Dokshitzer, Mueller, Schiff JHEP 0109 (2001) 033
  Salgado, Wiedemann PRD 68 (2003) 014008

  - kinematics ok for small-x
  - uncorrelated gluon emissions
- modification of DGLAP equations
  - imposes $k_\perp$-ordering

  Wang, Guo PRL 85 (2000) 3591, NPA 696 (2001) 787
  Majumder PRD 85 (2012) 014023
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  Arnold, Moore, Yaffe JHEP 12 (2001) 009, JHEP 11 (2001) 057, JHEP 06 (2002) 030
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  Caron-Huot, Gale PRC 82 (2010) 064902

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Improved theoretical control needed!
Make use of the physics of decoherence?

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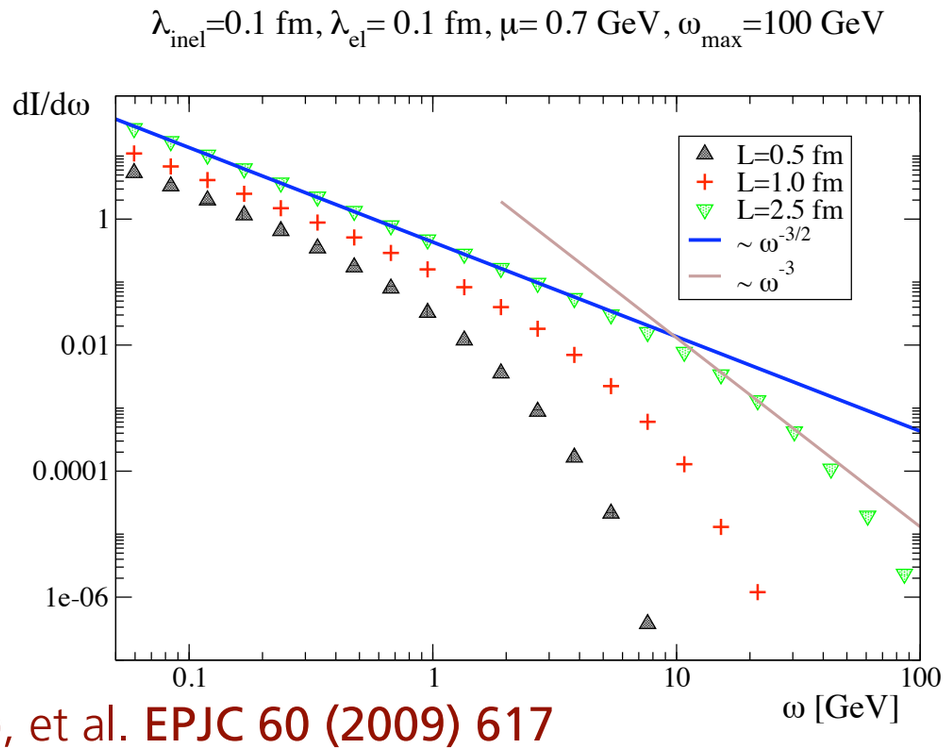
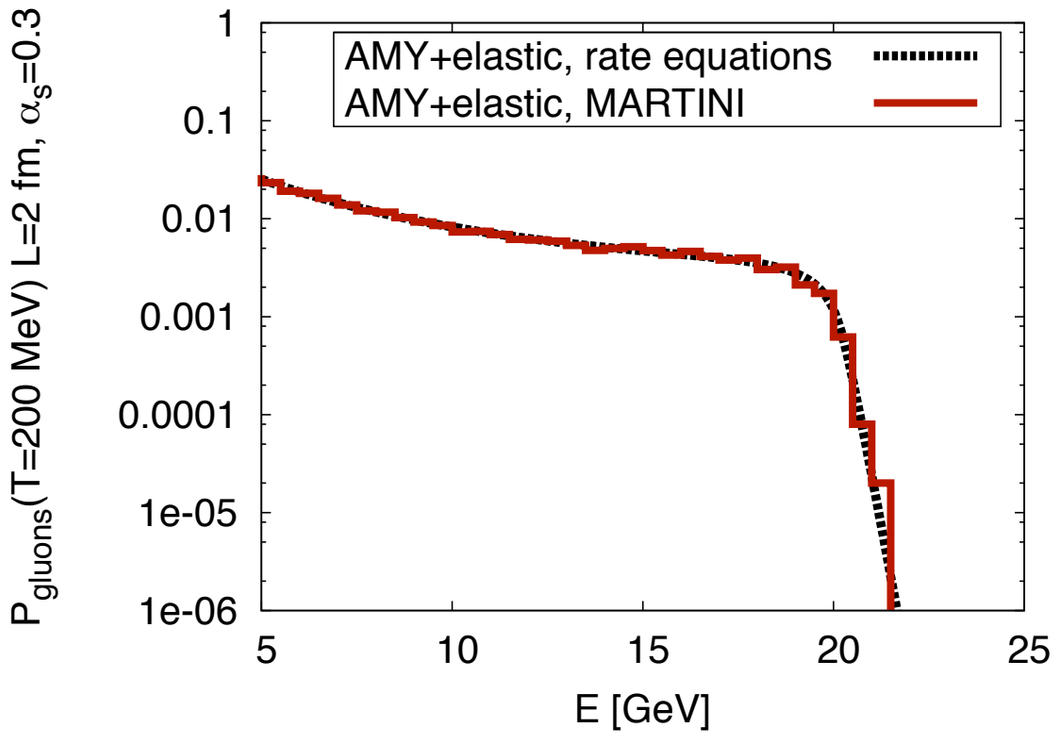
Y. Mehtar-Tani, Mon 17:50

Monte-Carlo approaches



Zapp, et al. **EPJC 60 (2009) 617**
Stachel, Wiedemann, Zapp **PRL 103 (2009) 152302**
Stachel, Wiedemann, Zapp **JHEP 1107 (2011) 118**



Gale, Jeon, Schenke **PRC 80 (2009) 054913**

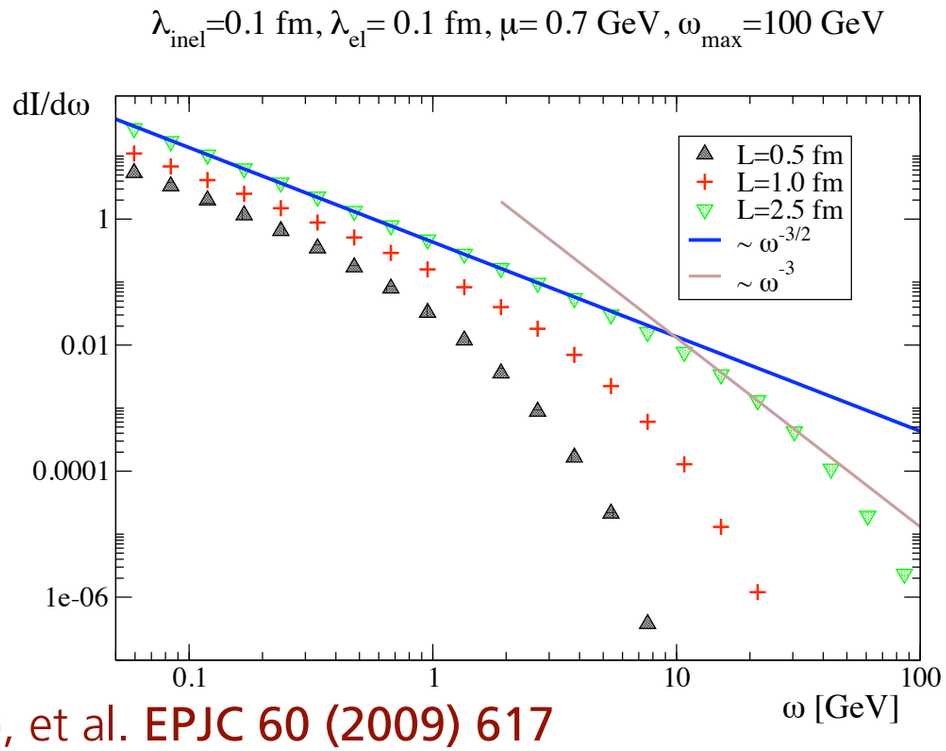
JEWEL: probabilistic cascade

- defines λ_{el} and λ_{inel}
- MC realization of the LPM suppression

MARTINI: rate equations

- PYTHIA initial condition
- includes thermal effects

Monte-Carlo approaches



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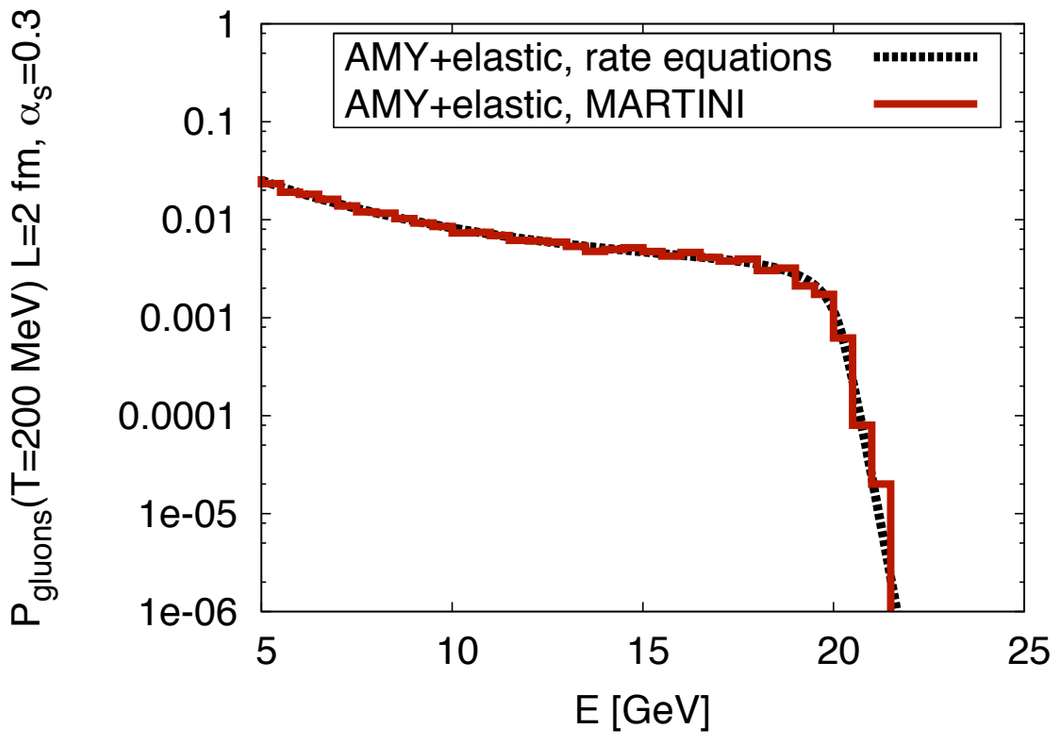

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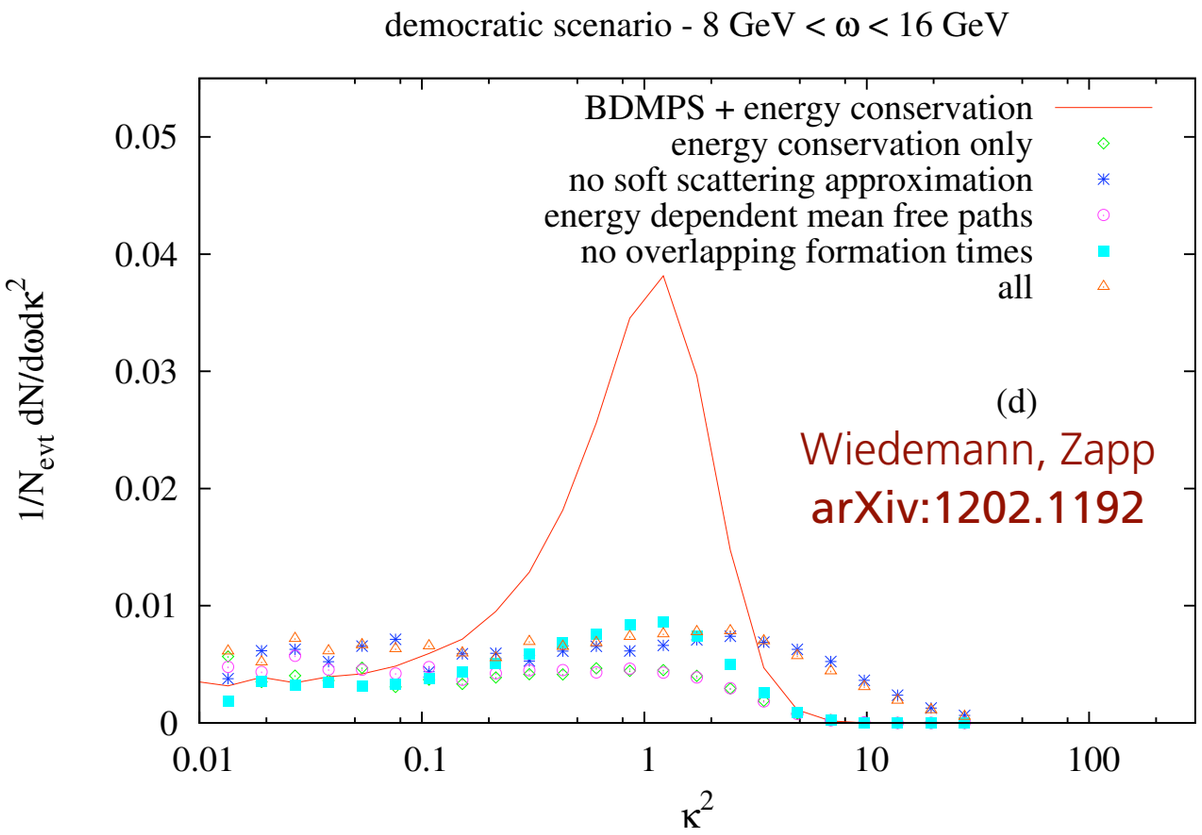
Other models: HIJING, HYDJET, Q-PYTHIA, Q-HERWIG, YaJEM…

T. Renk, Tue 09:00

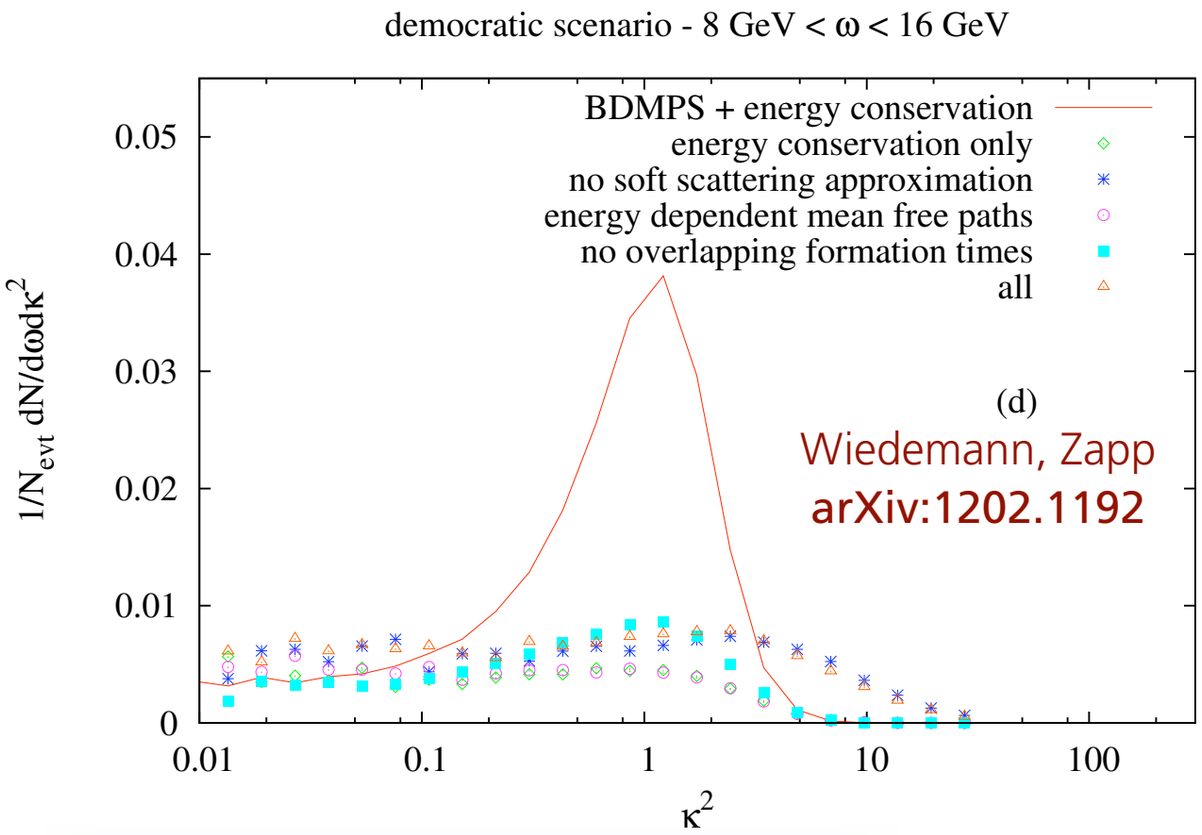
Monte-Carlo: going beyond



A flexible framework

- test against theory in a well-controlled limit
- allows for improvements going beyond
- implement physics of (de)coherence

Monte-Carlo: going beyond

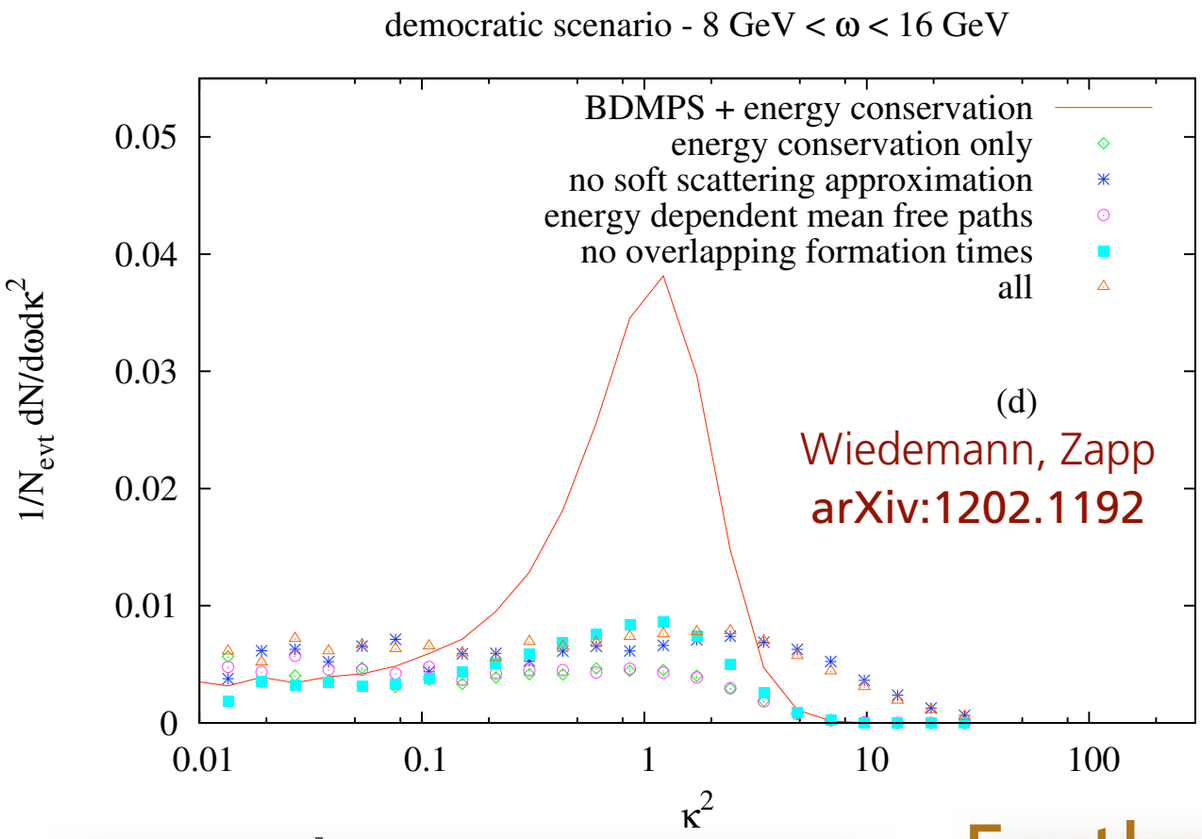


- nuclear geometry
- medium evolution
- medium recoil
- hadronization
- non-pert. effects

A flexible framework

- test against theory in a well-controlled limit
- allows for improvements going beyond
- implement physics of (de)coherence

Monte-Carlo: going beyond



A flexible framework

- test against theory in a well-controlled limit
- allows for improvements going beyond
- implement physics of (de)coherence

- nuclear geometry
- medium evolution
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- non-pert. effects

Further guidance

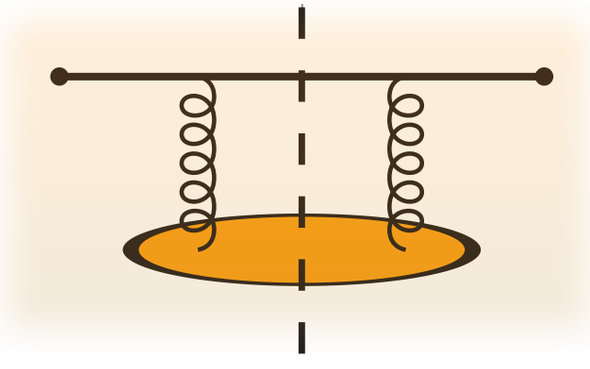
- need a handle on each of these components
- what are the uncertainties?
- relevant observables?

Outlook

- role of color coherence in medium
  - essential for medium-induced rad. & in vacuum
  - taking it further: the role of the hard scale
- single-gluon inclusive spectrum
  - energy loss calculations
  - many subtle issues - room for improvement!
- multi-gluon emissions
  - essential for jet substructure
  - the role of interferences?
  - space-time evolution: challenge from QGP physics

Backup

Modeling the medium



$$V^2(\boldsymbol{q}) = \frac{m_D^2}{(2\pi)^2\left(\boldsymbol{q}^2 + m_D^2\right)^2}$$

static scattering centers

M. Gyulassy, X. Wang
NPB 420 (1994) 583

$$\lambda_{\mathrm{mfp}} \gg 1/m_D$$

$$\langle A^a_{\mathrm{med}}(t,\boldsymbol{q}) A^{*\,b}_{\mathrm{med}}(t',\boldsymbol{q}')\rangle = \delta^{ab}\delta(t-t')\delta(\boldsymbol{q}-\boldsymbol{q}')V^2(\boldsymbol{q})$$

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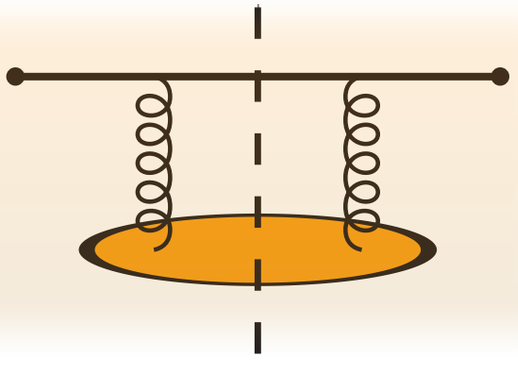

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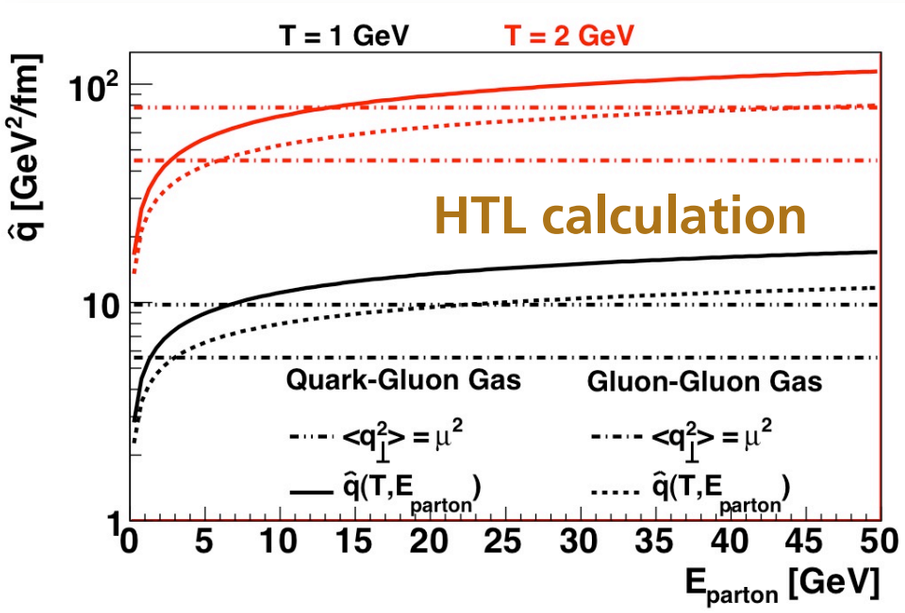


Armesto, Cole et al. arXiv:1106.1106

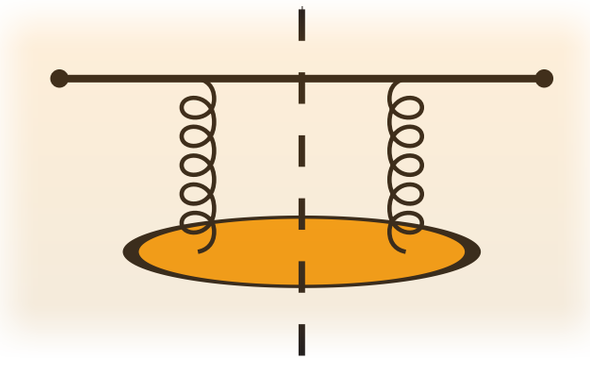
Transport parameter in the medium:

$$\hat{q} = n(x^+)\int^{q_{\max}} d^2\boldsymbol{q}\,\frac{d\Gamma_{\mathrm{el}}}{d^2\boldsymbol{q}}\boldsymbol{q}^2$$

$$q_{\max} \sim \sqrt{m_D E}$$

M. Benzke, Mon 14:20
A. Majumder, Tue 15:15

Modeling the medium



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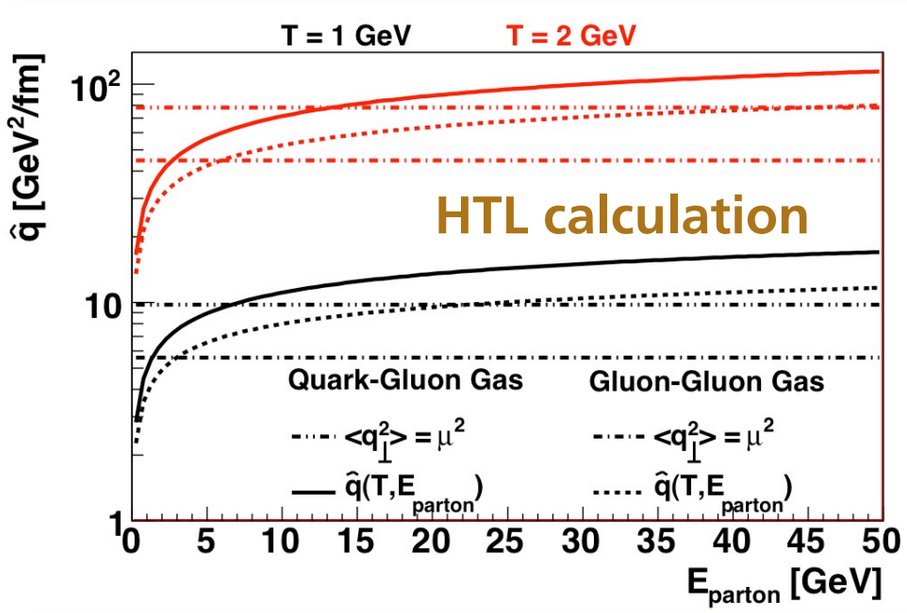

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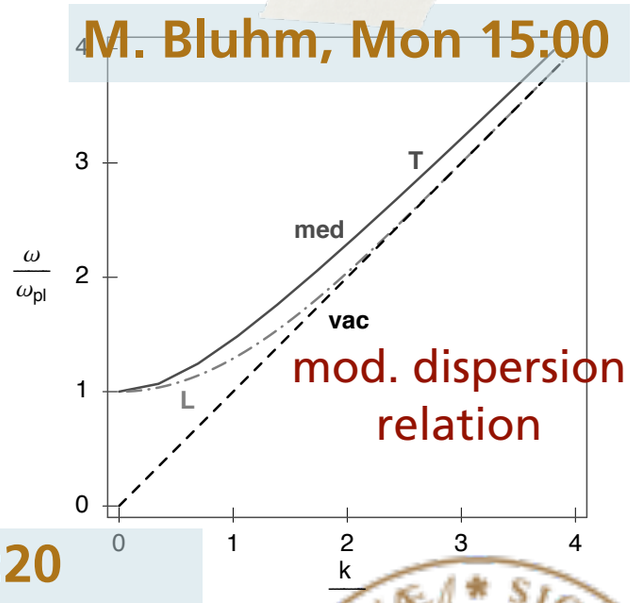
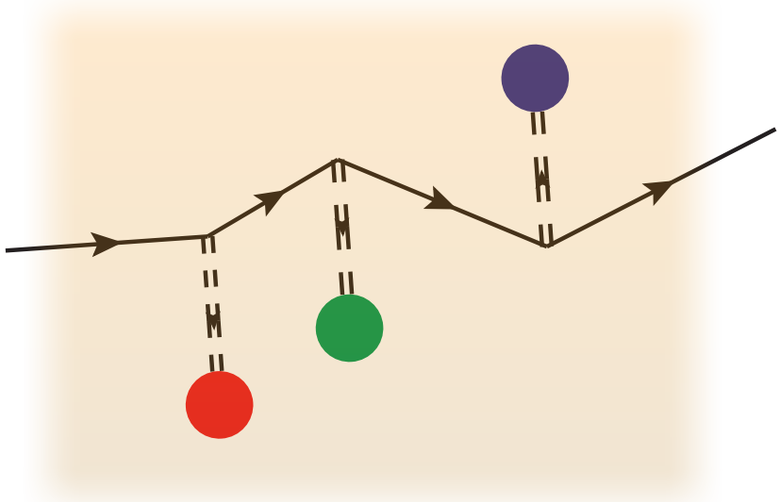
Djordjevic JPG 39 (2012) 045007; Arnold, Moore, Yaffe JHEP 12, 009; JHEP 11, 057; JHEP 06, 030

M. Bluhm, Mon 15:00



In-medium propagation



Multiple scattering in the medium:

- conservation of energy
- no spin-flip
- transverse momentum broadening
- color precession

$$\left(i\partial^- + \frac{\boldsymbol{\partial}^2}{2k^+} + g\,T\cdot A^-_{\rm med}\right)\,\mathcal{G}(x^+,\boldsymbol{x}\,;\,y^+,\boldsymbol{y}|k^+) = i\delta(x^+-y^+)\delta(\boldsymbol{x}-\boldsymbol{y})$$

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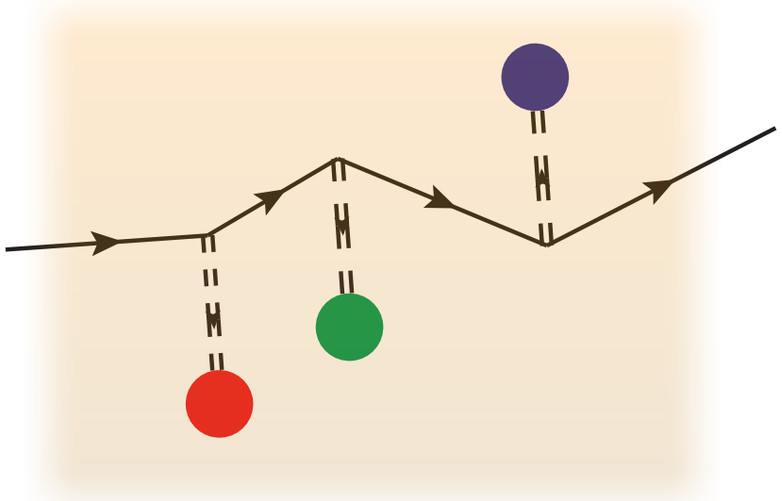

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Solution: $$\mathcal{G}\left(x^+,\boldsymbol{x};y^+,\boldsymbol{y}|k^+\right) = \int\mathcal{D}[\boldsymbol{r}]\,\exp\left[i\frac{k^+}{2}\int_{y^+}^{x^+}d\xi\,\dot{\boldsymbol{r}}^2(\xi)\right]U(x^+,y^+;[\boldsymbol{r}])$$

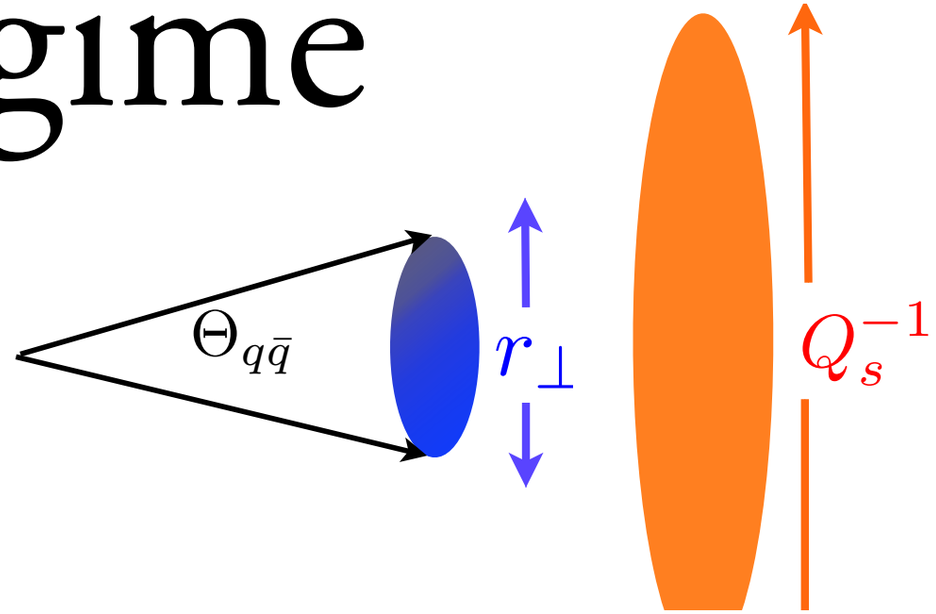
Wilson line: $$U(x^+,0;[\boldsymbol{r}]) \equiv \mathcal{P}_\xi\exp\left[ig\int_0^{x^+}d\xi\,T\cdot A^-_{\rm med}\left(\xi,\boldsymbol{r}(\xi)\right)\right]$$

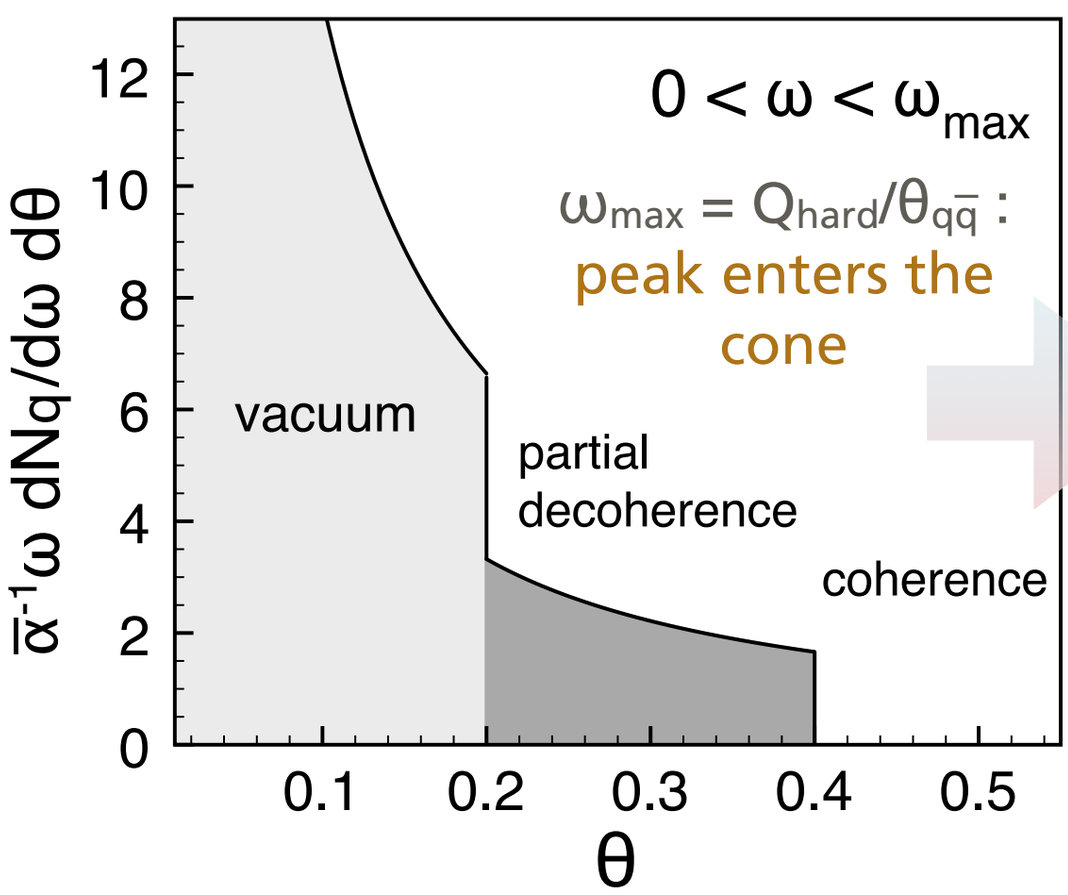
many authors: e.g. Zakharov, Wiedemann, Kovner...

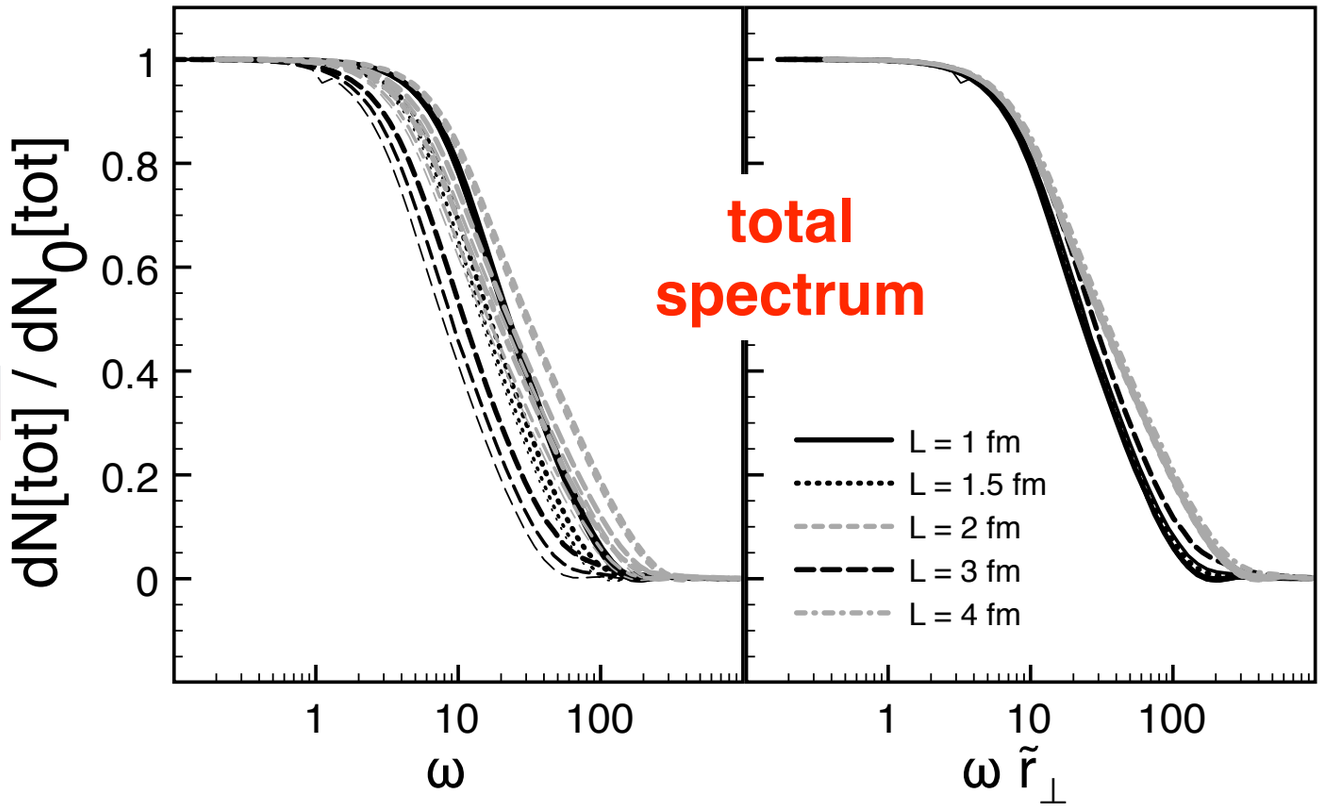
“Dipole” regime

Color transparency

- pair remains color correlated
- radiates coherently: antiangular
- no medium-induced component!





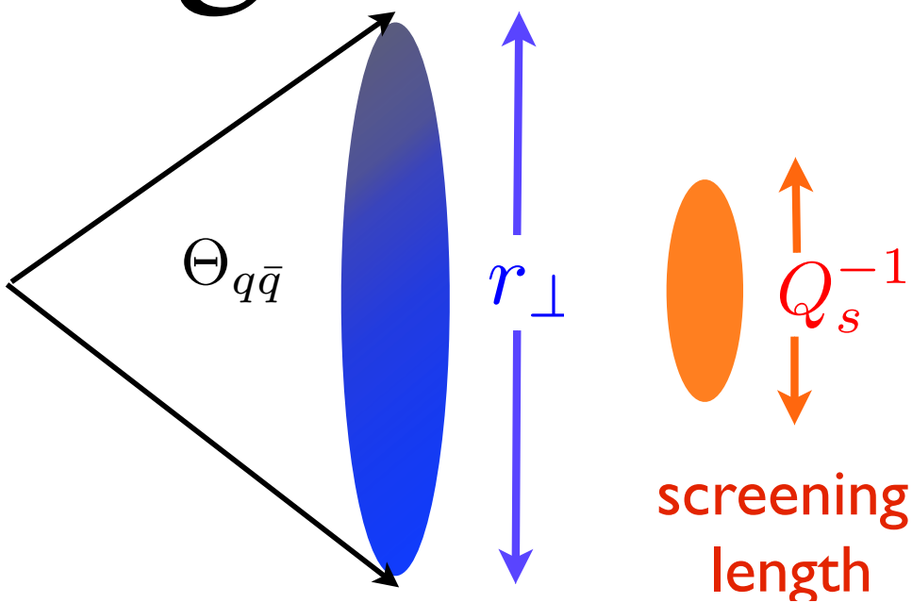


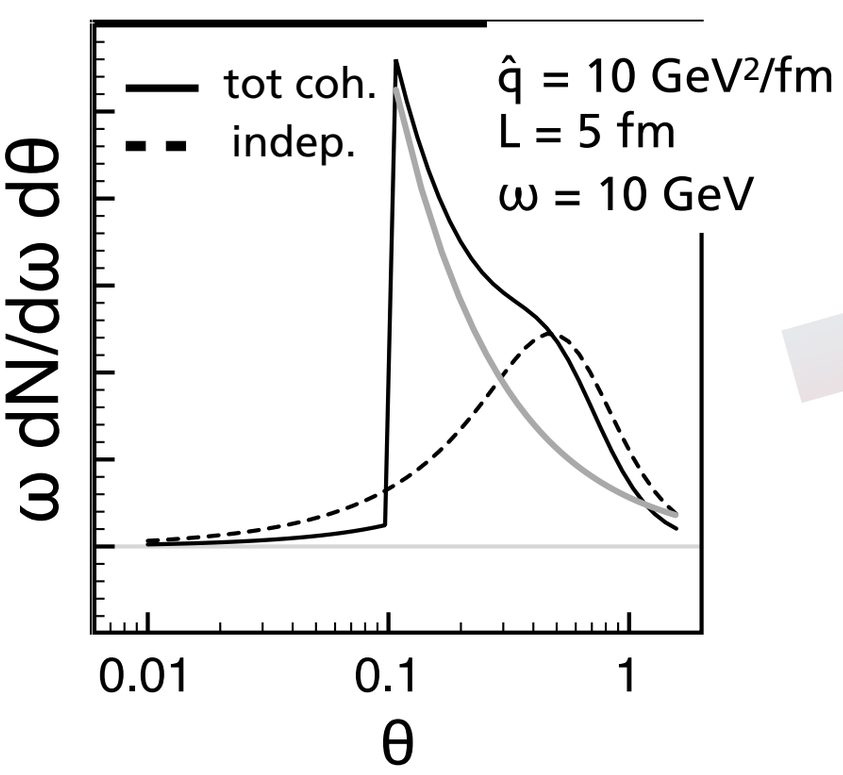
o, KT PRL106 (2011) 122002, JHEP 1204 (2012) 064

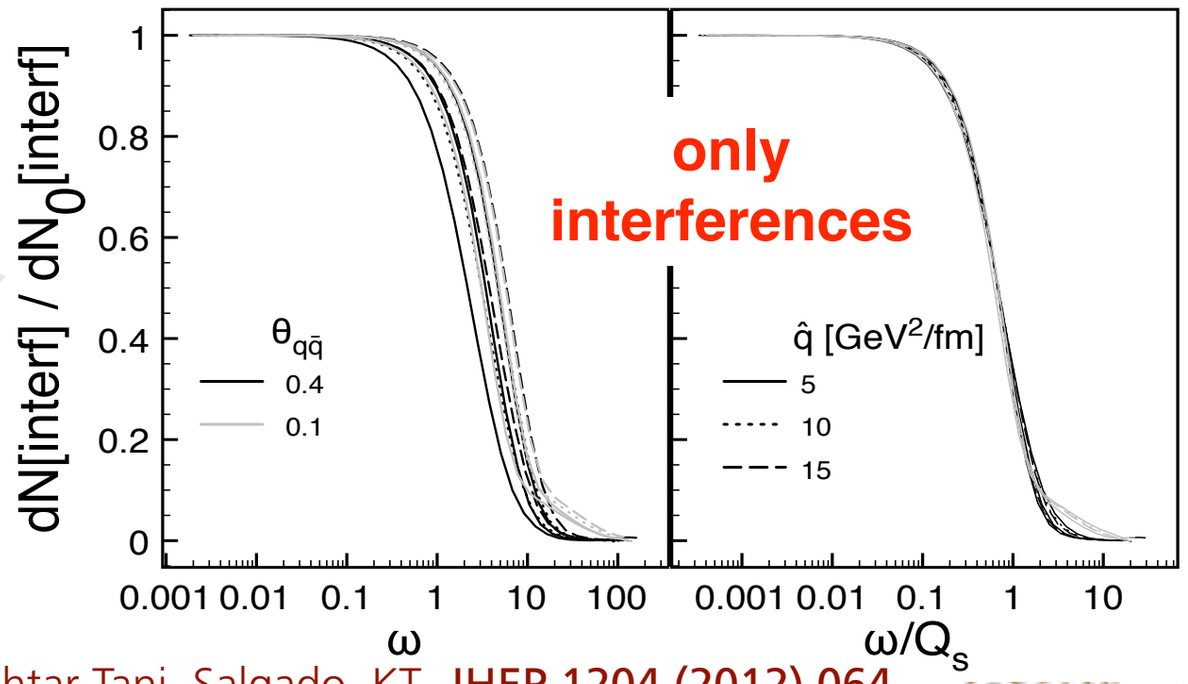
“Decoherence” regime

Two-component spectrum

- pair decorrelates rapidly
- medium induces radiation off each of the legs independently
  - interferences scale like τ_d
- vacuum-radiation up to Q_s!







Mehtar-Tani, Salgado, KT **JHEP 1204 (2012) 064**

J. Casalderrey-Solana, E. Iancu **JHEP 1108 (2011) 015**