Understanding jet modifications at LHC

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Work in collaboration with Yacine Mehtar-Tani

HP2013, 4-8 Nov 2013, Stellenbosch, South Africa

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MARIE CURIE ACTIONS

Institut de Ciències del Cosmos

Central question

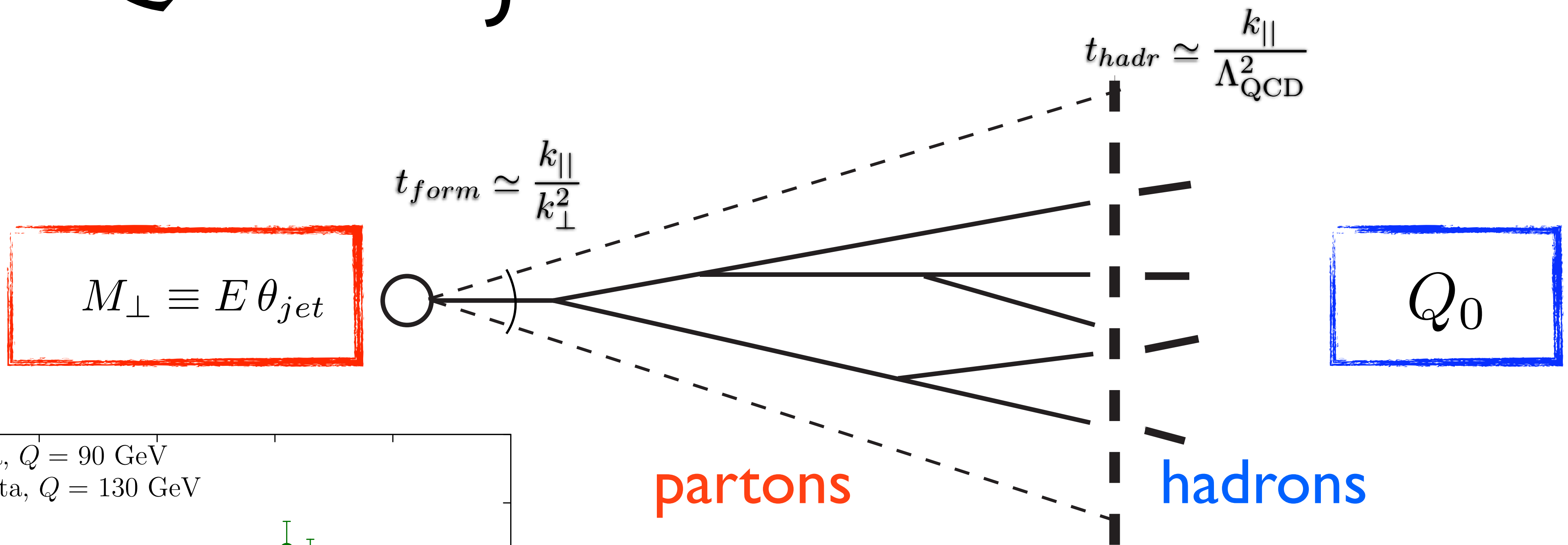
Q: how can one reconcile large and small angle (soft) modifications of jets in HIC?

A: separation of scales: $Q_{jet} \gg Q_{med} \gg Q_0$

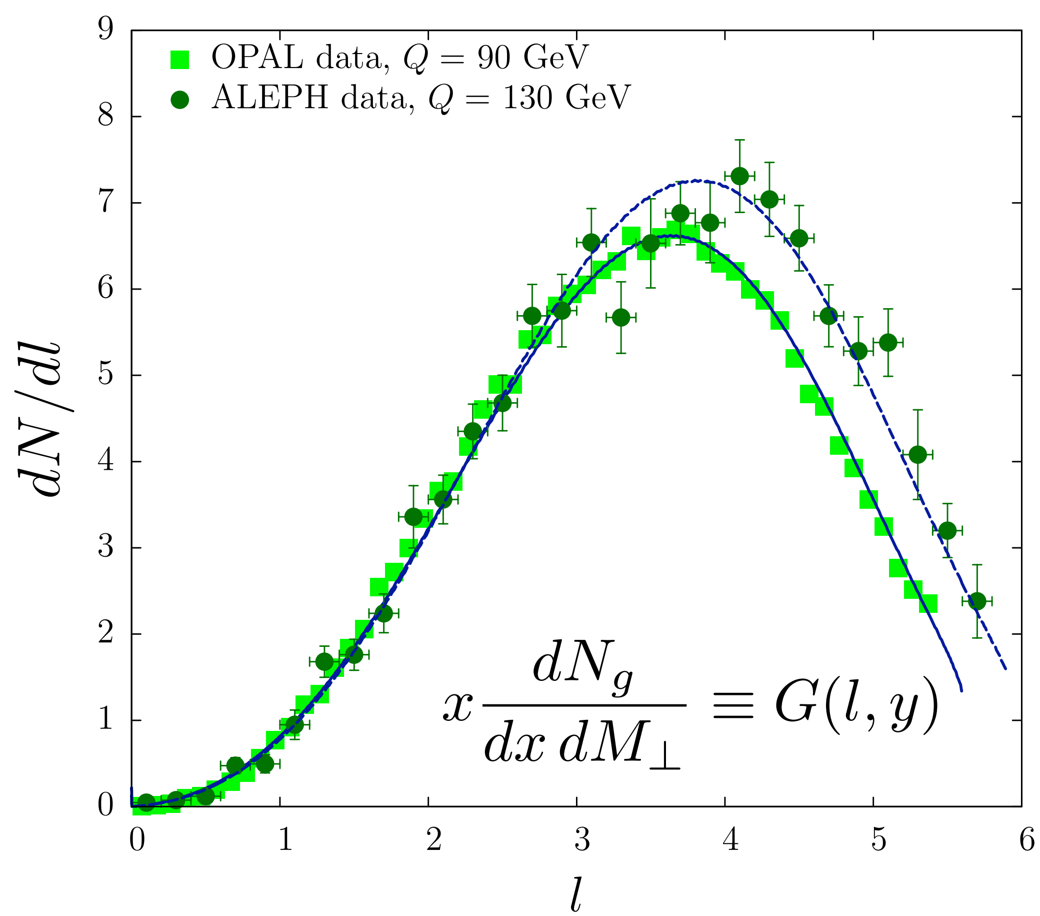
- vacuum: splitting via (quasi-)collinear evolution
- medium: branching & broadening

Simplifications: only glue; studying limiting case, useful for understanding bulk effects; no dynamical medium/geometry

QCD jet in vacuum



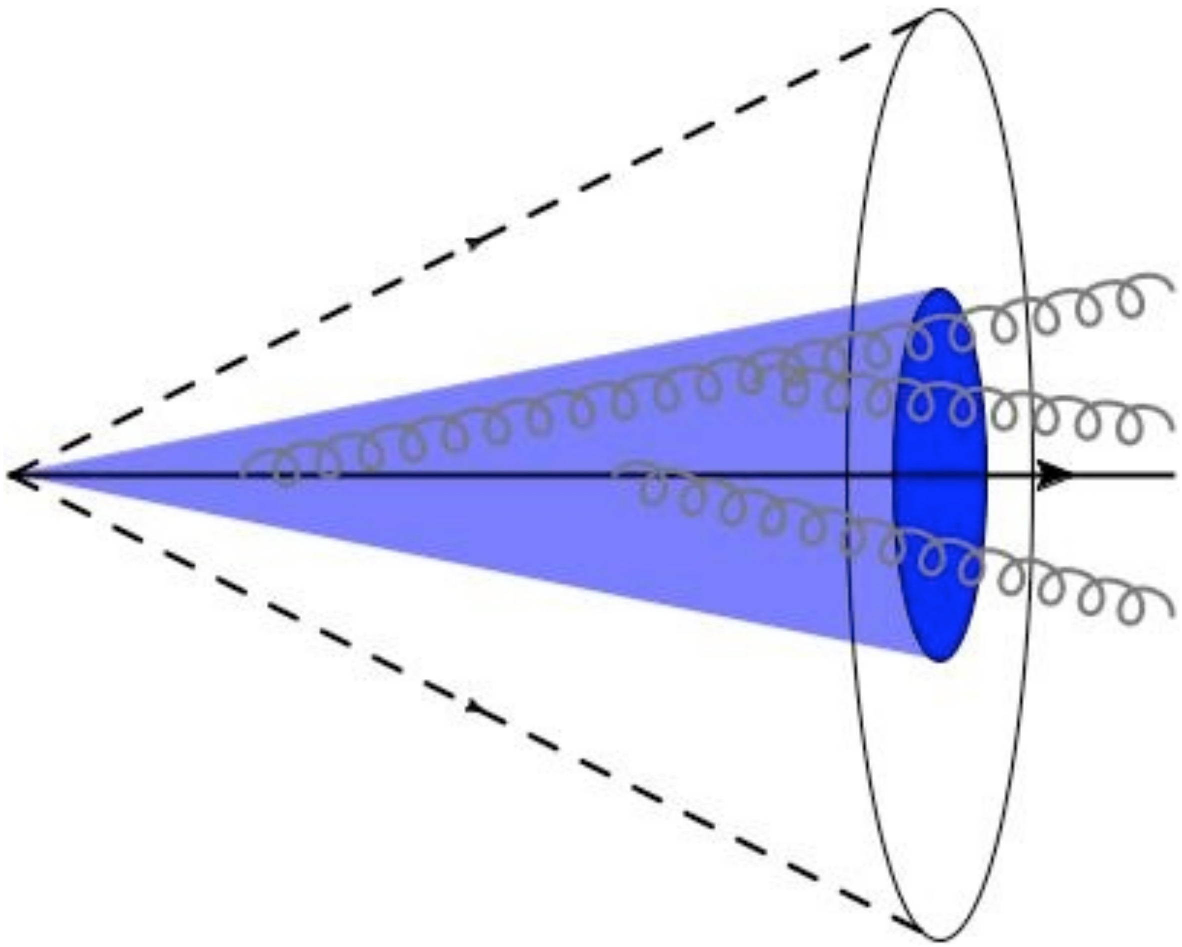
$$l = \ln\left(1/x\right) \qquad y = \ln\left(xM_\perp/Q_0\right) \equiv Y - l$$



- MLLA + LPHD (limiting spectrum $Q_0 = \Lambda_{QCD}$)
- resums double logs and single-log corrections
- perturbative jet scale $M_\perp = Q = E\Theta_{jet}$
- color coherence ⇒ angular ordering (AO)

[Dokshitzer, Khoze, Mueller, Troyan, Kuraev, Fong, Webber...]

General picture



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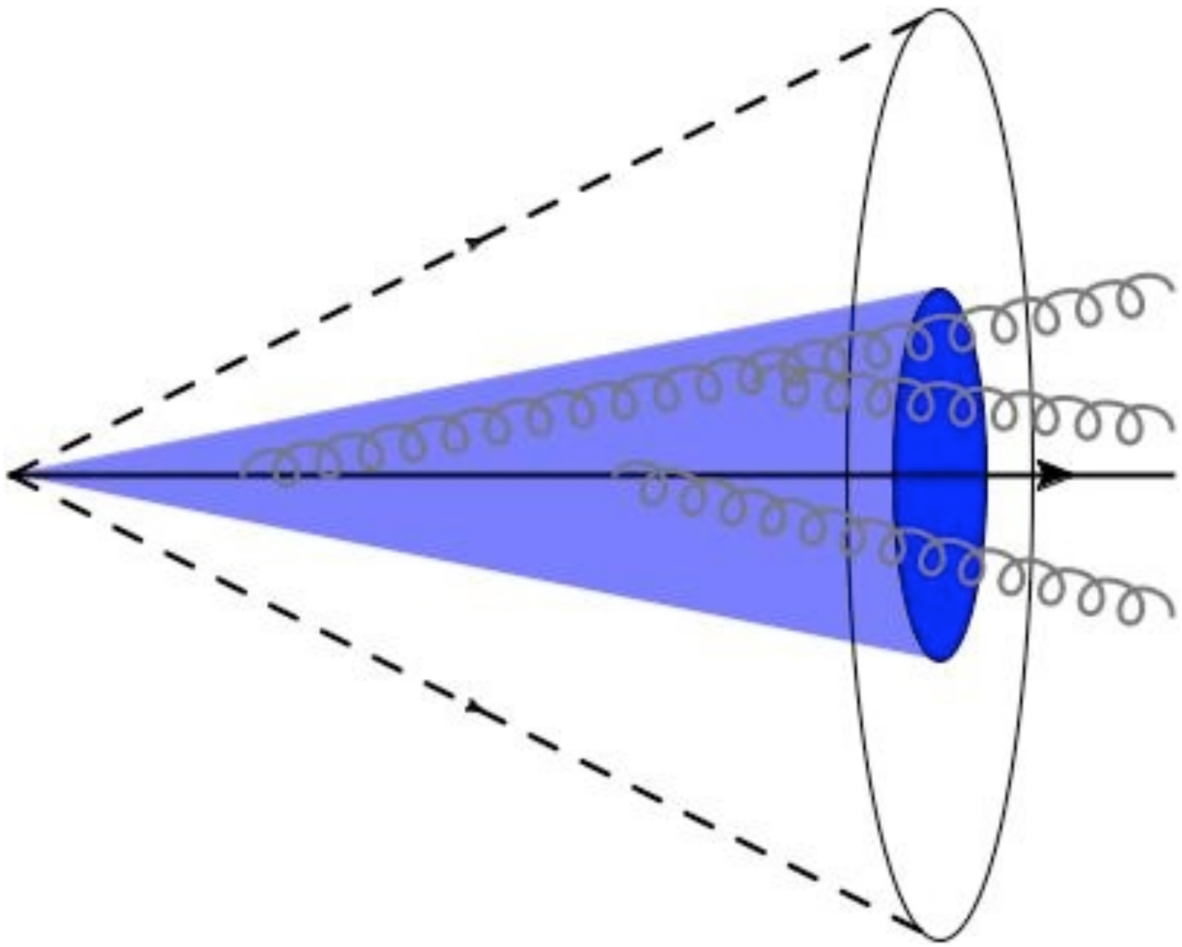

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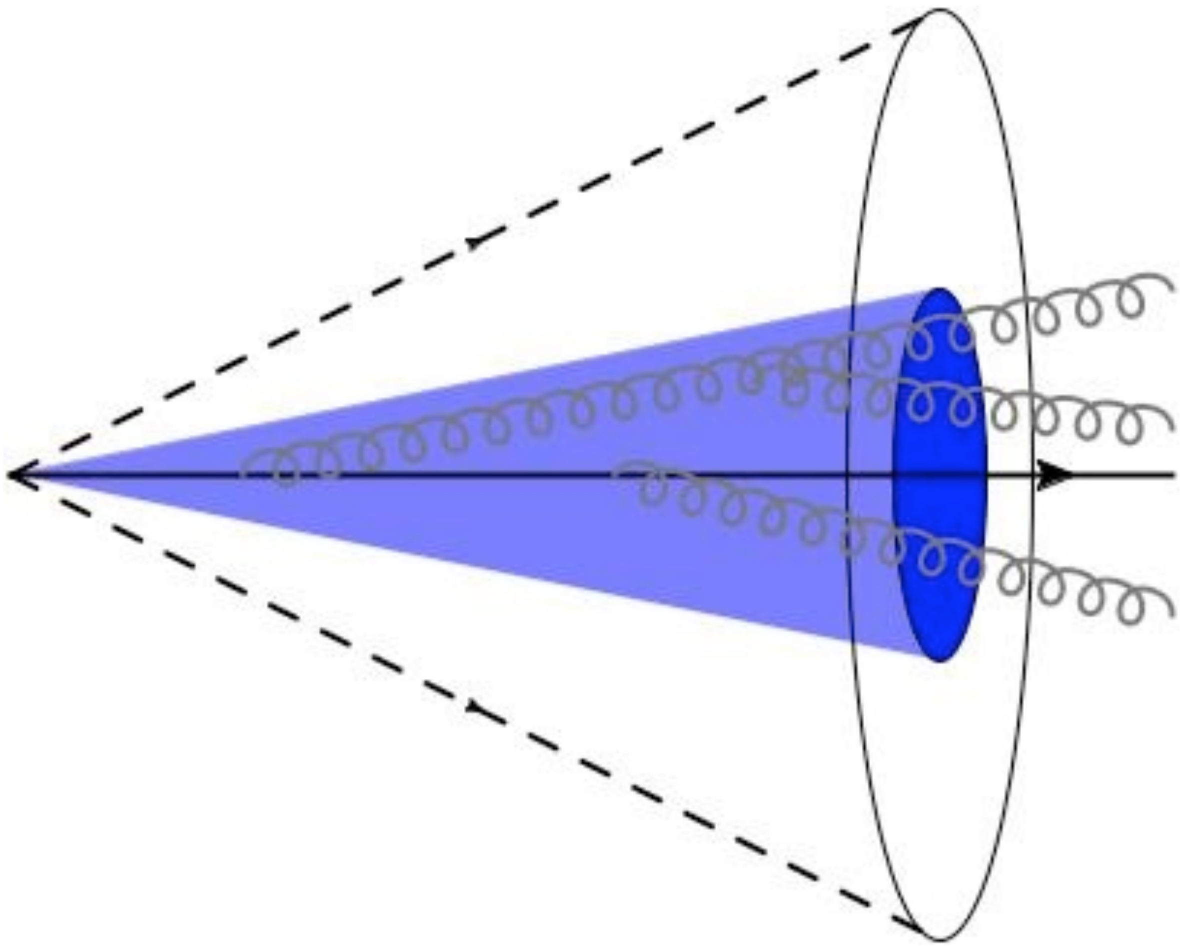

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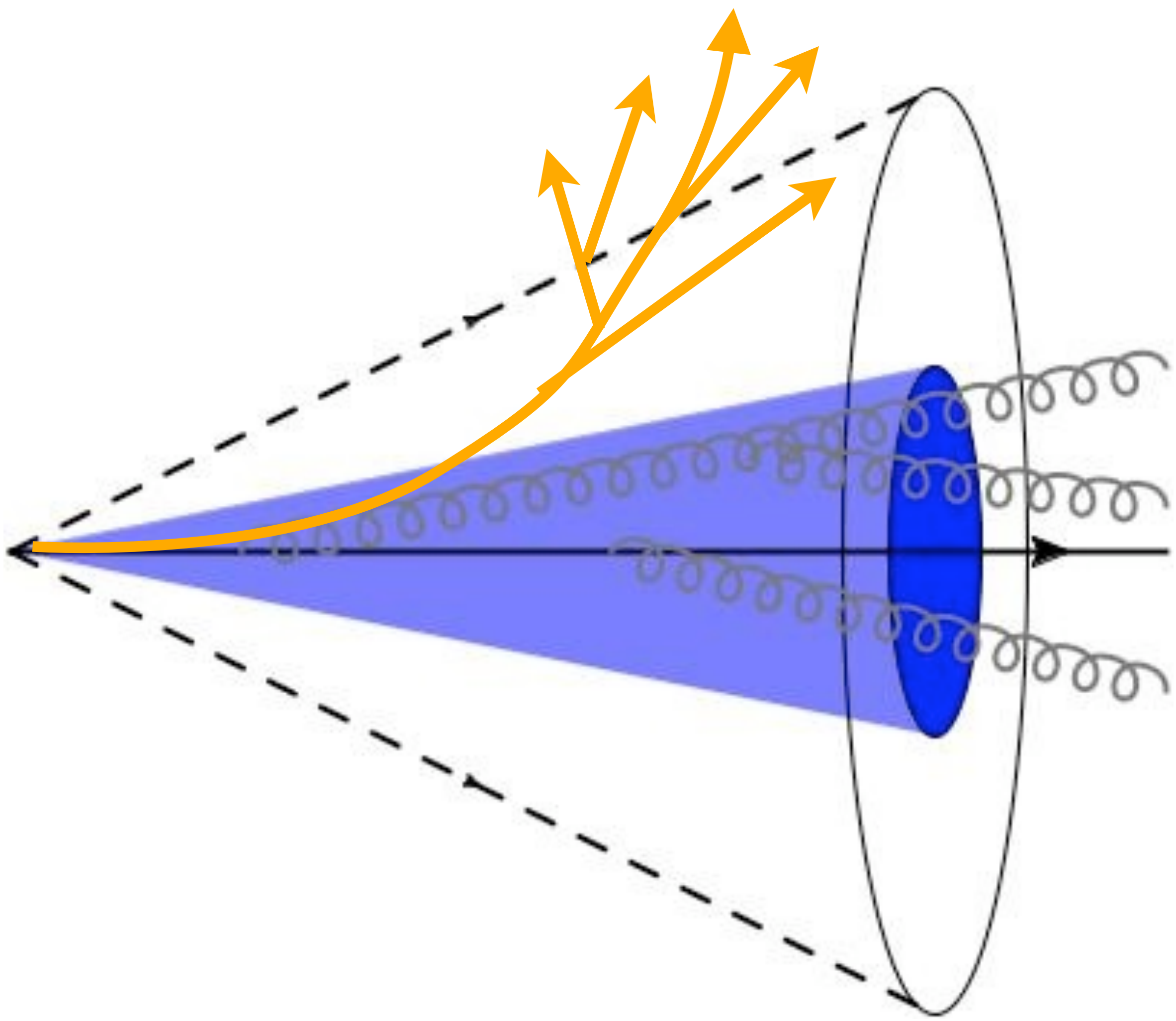

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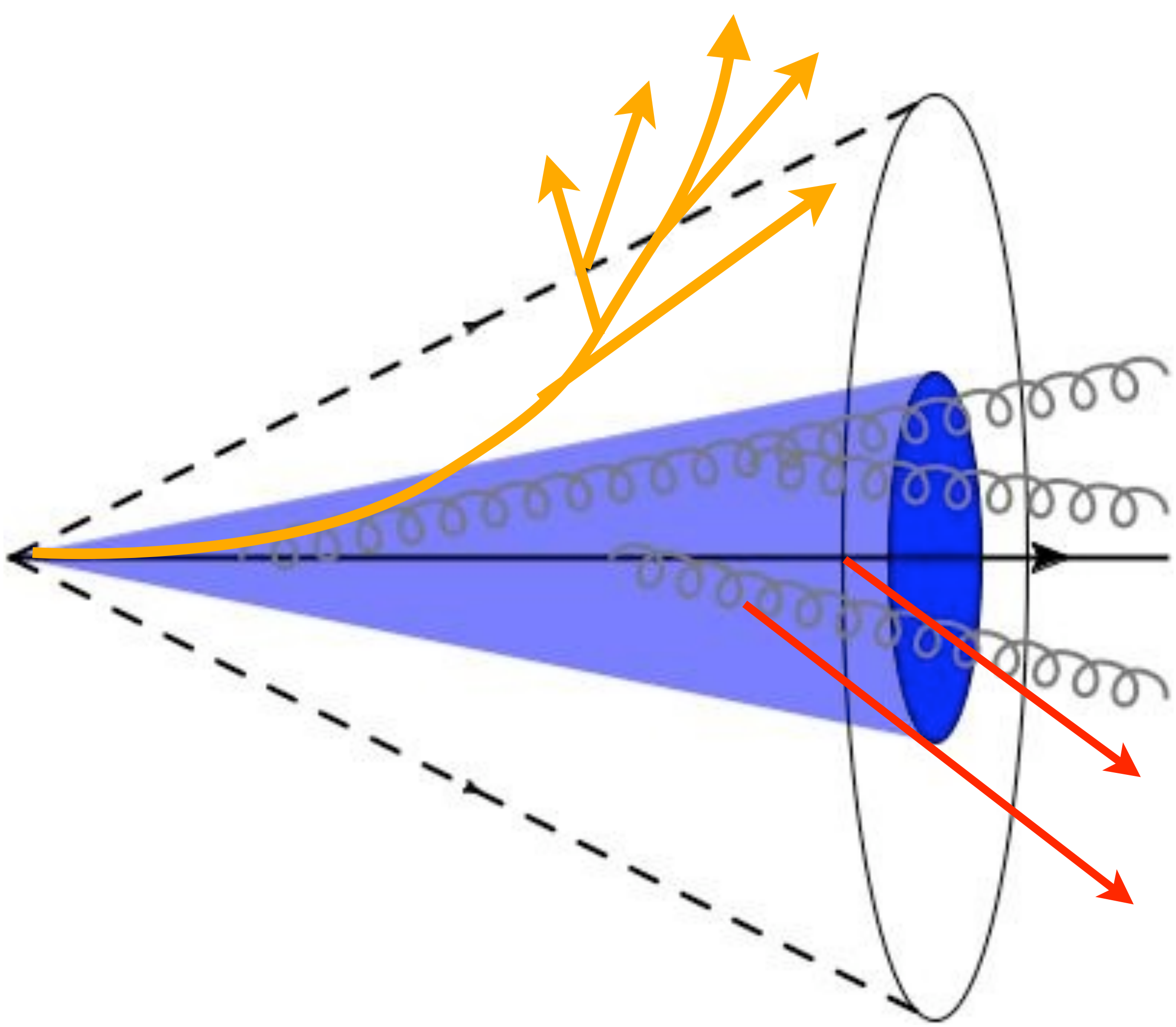

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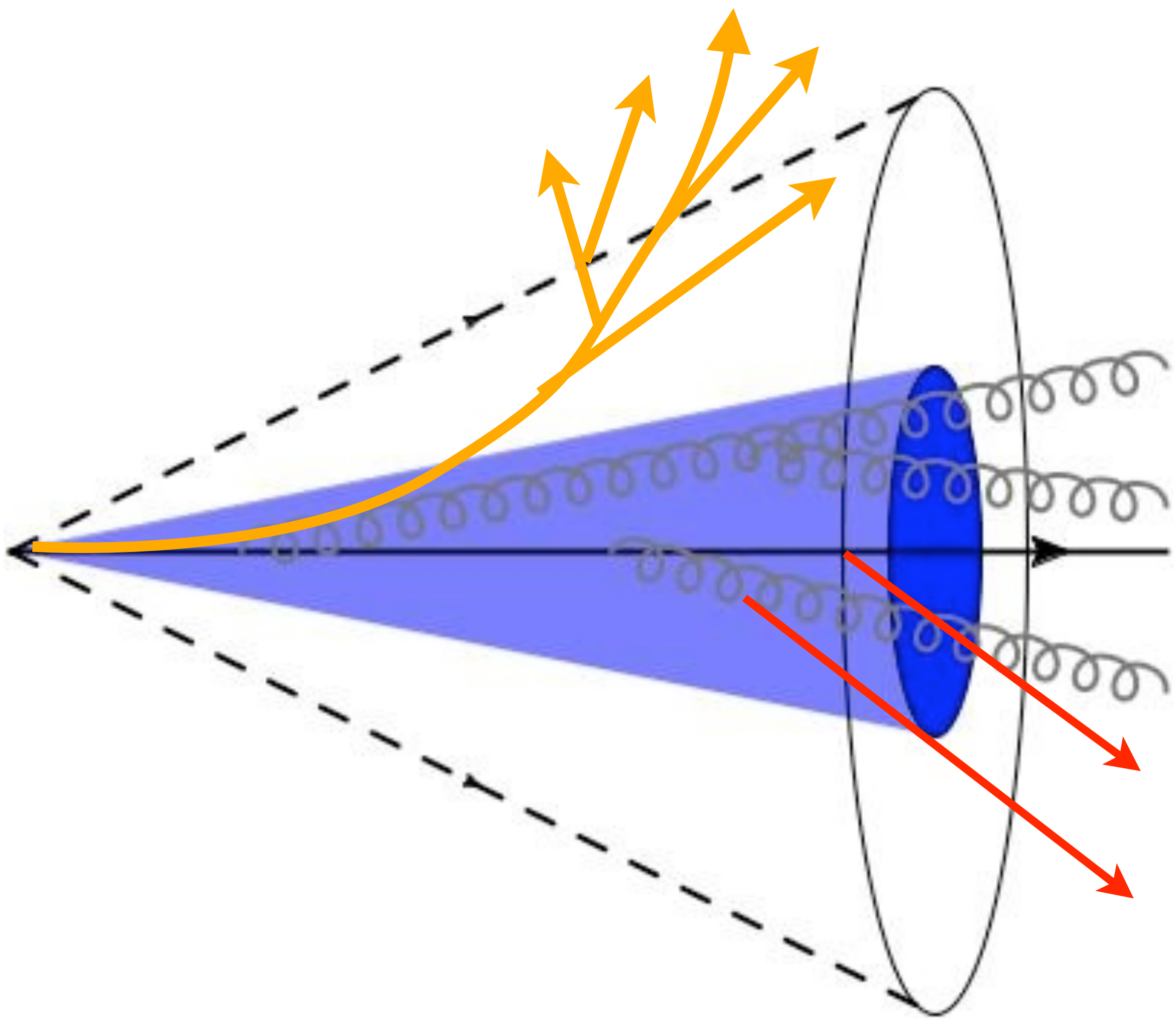

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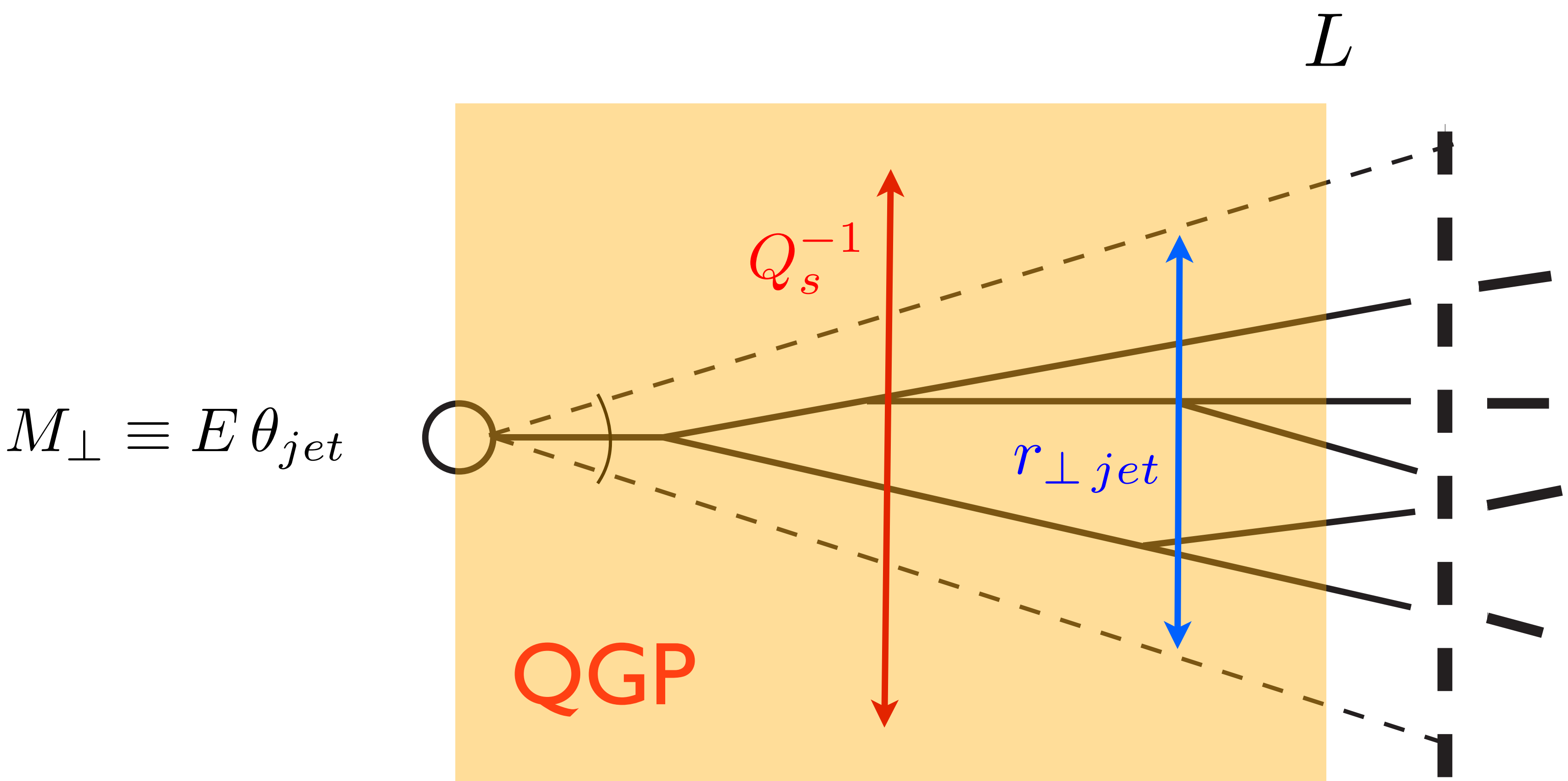
How does this come about?

QCD jet in medium



New scales:

$$M_\perp \equiv E\,\theta_{jet}$$
$$Q_0 \sim \Lambda_{\rm QCD}$$

$+$

$$Q_s \equiv \sqrt{\hat{q}L} \equiv m_D\,\sqrt{N_{\rm scat}}$$
$$r_{\perp\,jet}^{-1} \equiv (\theta_{jet}L)^{-1}$$

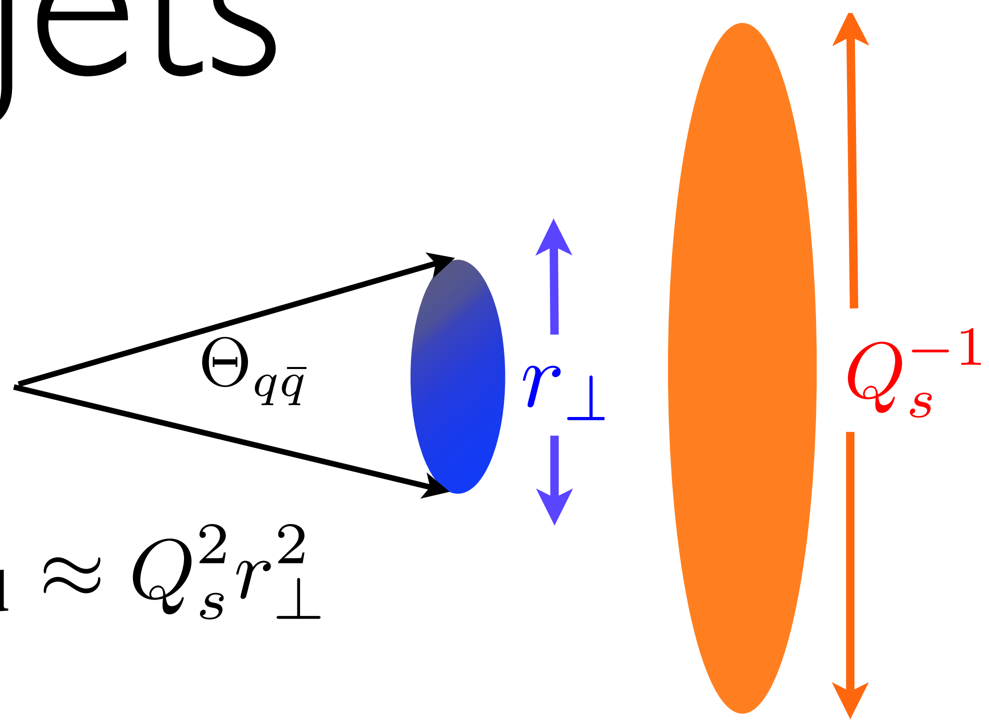
Presently **no available theoretical framework** for describing the in-medium fragmentation :: working models (MC) or **limits!**

Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397
Casalderrrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765; Casalderrrey-Solana, Iancu 1105.1760

Narrow jets

Analyzed in detail in the so-called antenna problem, the "dilute" regime

⇒ color transparency



1-(survival prob. for color coherence) = $\Delta_{\rm med} \approx Q_s^2 r_\perp^2$

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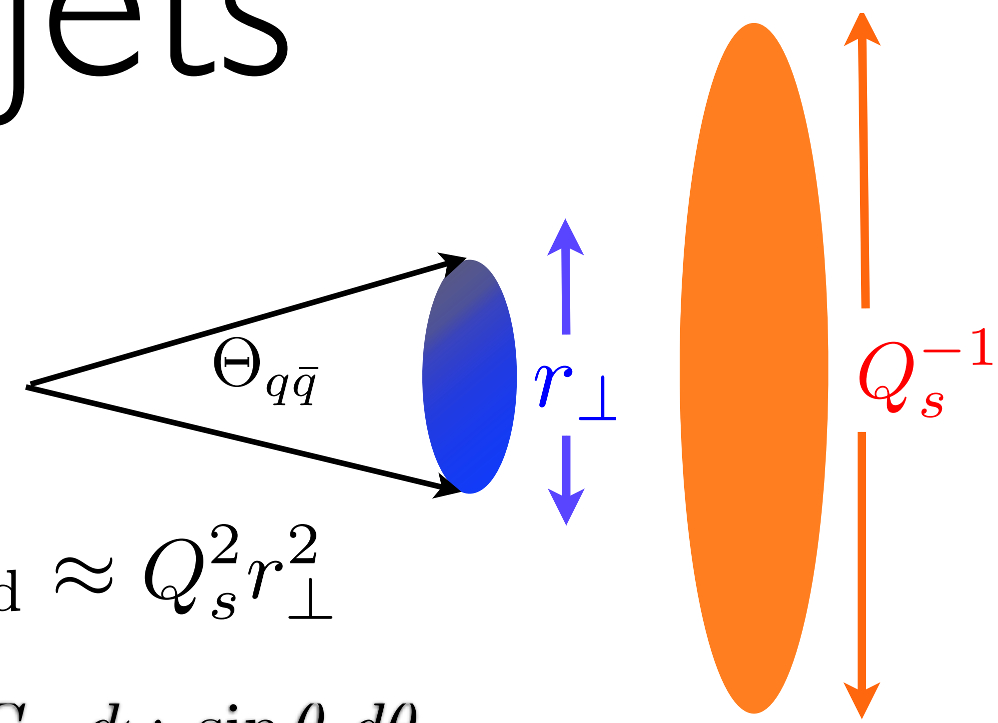

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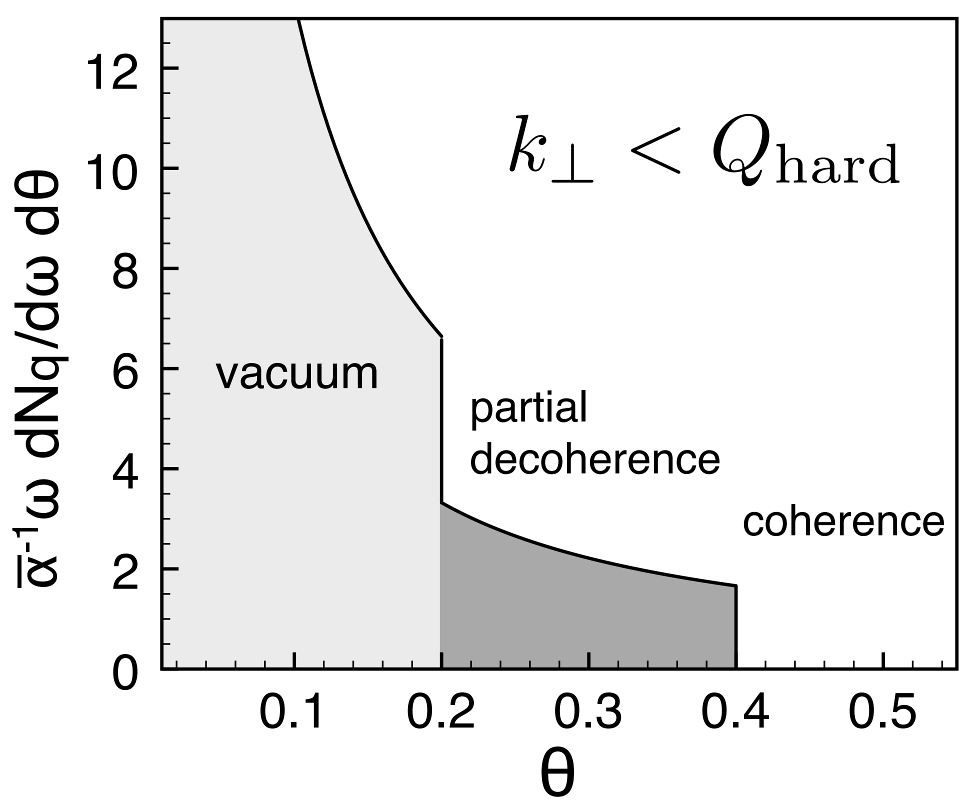

$$dN^{\rm tot}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right]$$

- geometrical separation!
- modifies MLLA @ the second splitting
  - shift of the humpbacked plateau!
- introduces the medium scale $\lambda_2 = \ln Q_s/Q_0$

Mehtar-Tani, Salgado, KT 1009.2965; 1112.5031,
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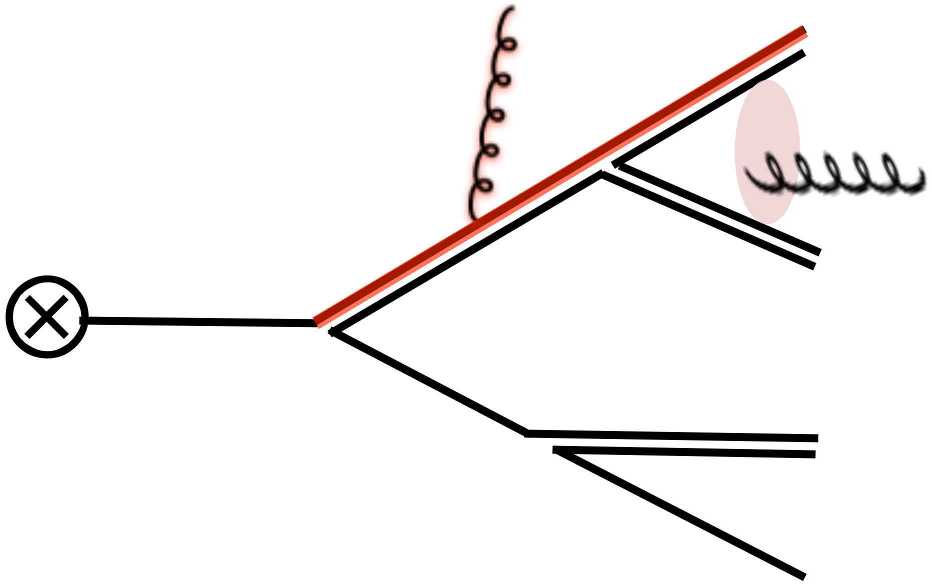
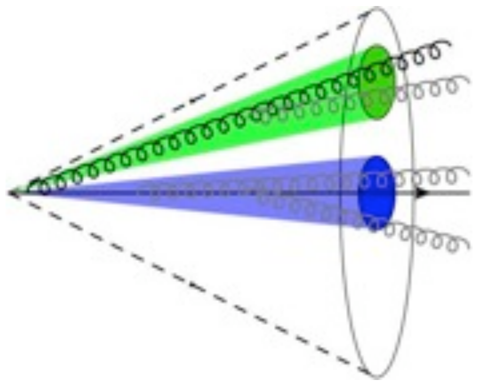
Factorization of energy loss

A "factorization" for leading medium-resolved subjet:



- separation in angles :: only the total charge radiates
- allows to separate the treatment of the two different processes
- interpretation á la AO
- genuine limit of QCD



Fluctuations:

picture improved by including the possibility of resolving several subjets :: solving dynamical problem of decoherence!

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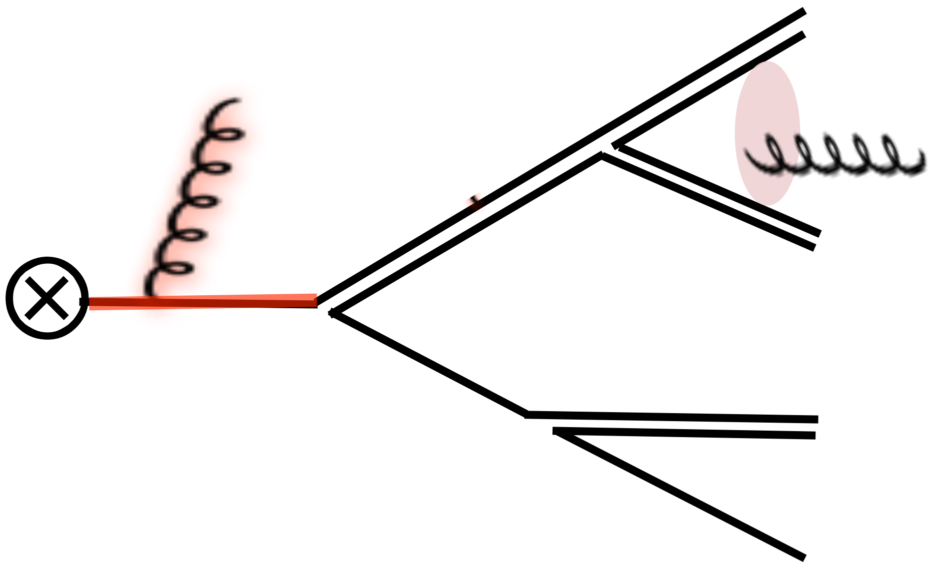

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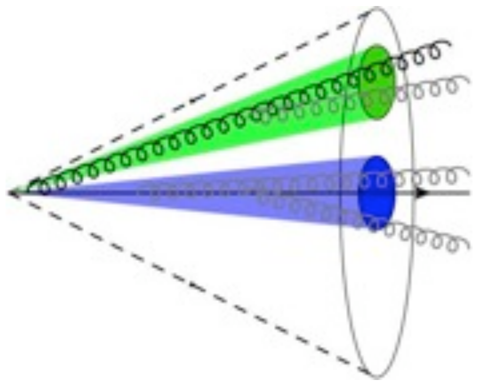

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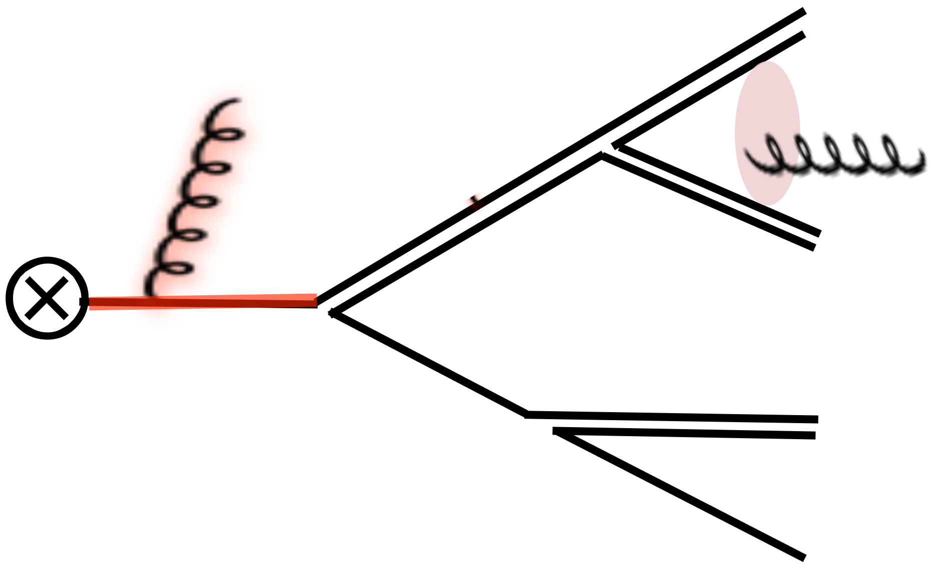

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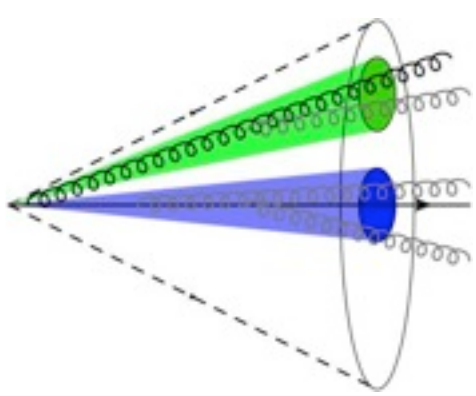
jet produced with given p_T, $D_0(x) = \delta(1-x)$ ⇒ *total charge/ancestor particle lose energy* ⇒ vacuum showering (with reduced energy) starts w/decoherence effects



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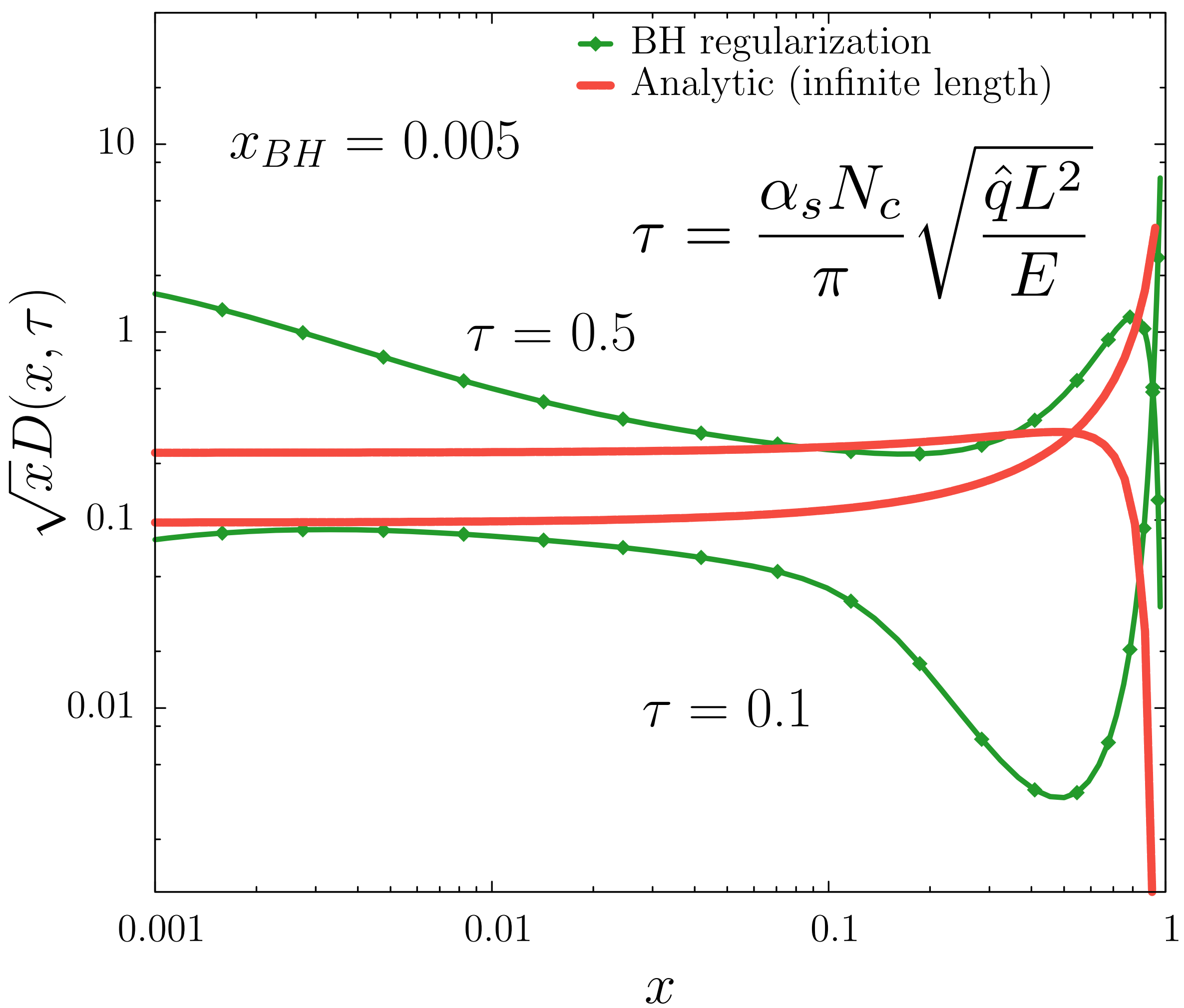
Evolution of med-gluons



- **probabilistic picture:** evolution governed by rate equation
  - hard part :: similar to quenching weights (independent emissions)
  - soft part :: quasi-democratic branching (turbulence)
- **generalizations**
  - high energy jet: E > ω_c
  - infrared regularization (Bethe-Heitler cut-off energy)

Blaizot, Iancu, Mehtar-Tani arXiv:1301.6102
Talks by Y. Mehtar-Tani and E. Iancu

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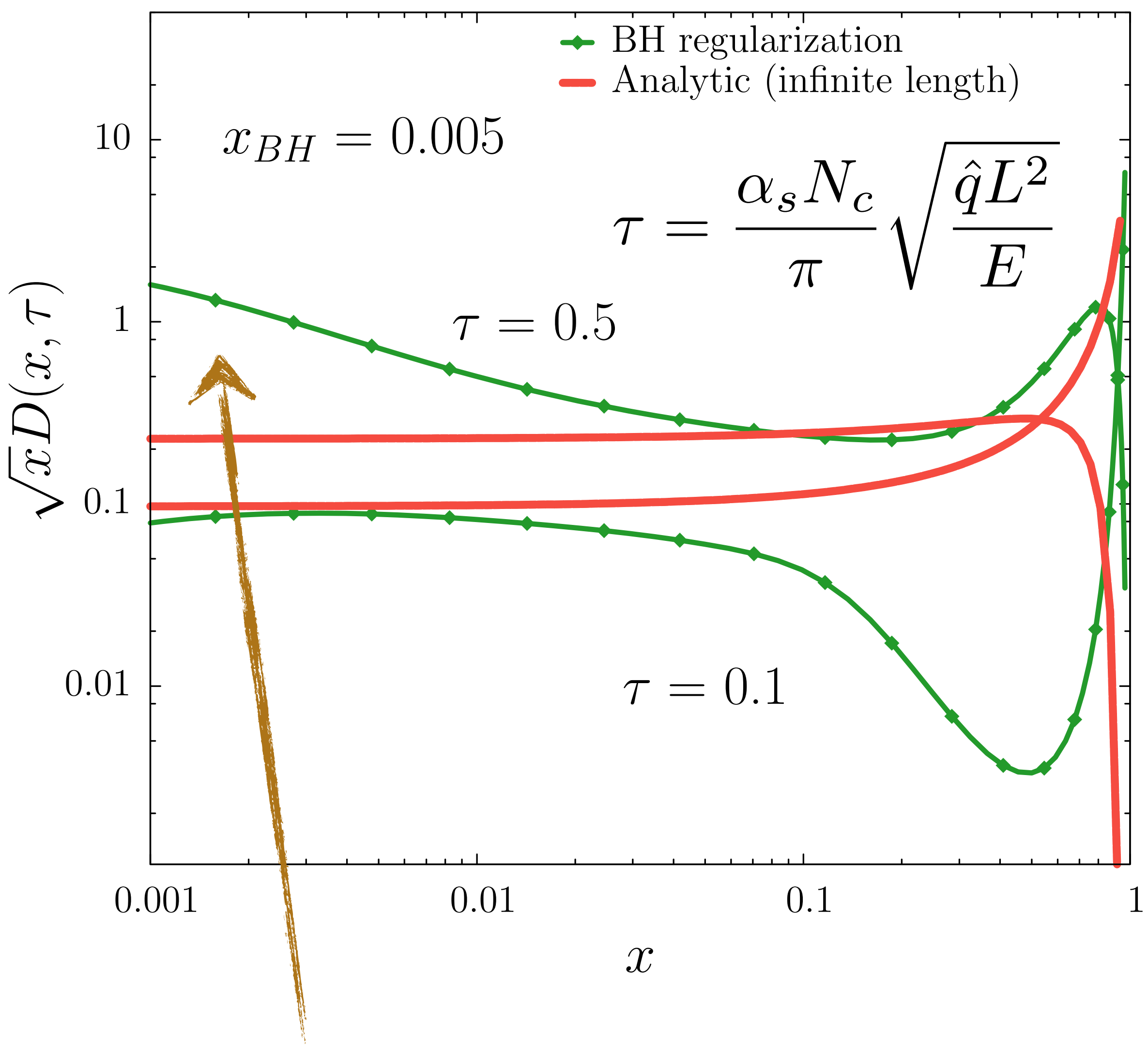

$$x_{\rm BH} = \frac{\omega_{\rm BH}}{E}$$ :: a new scale in the problem! (accumulation of quanta)

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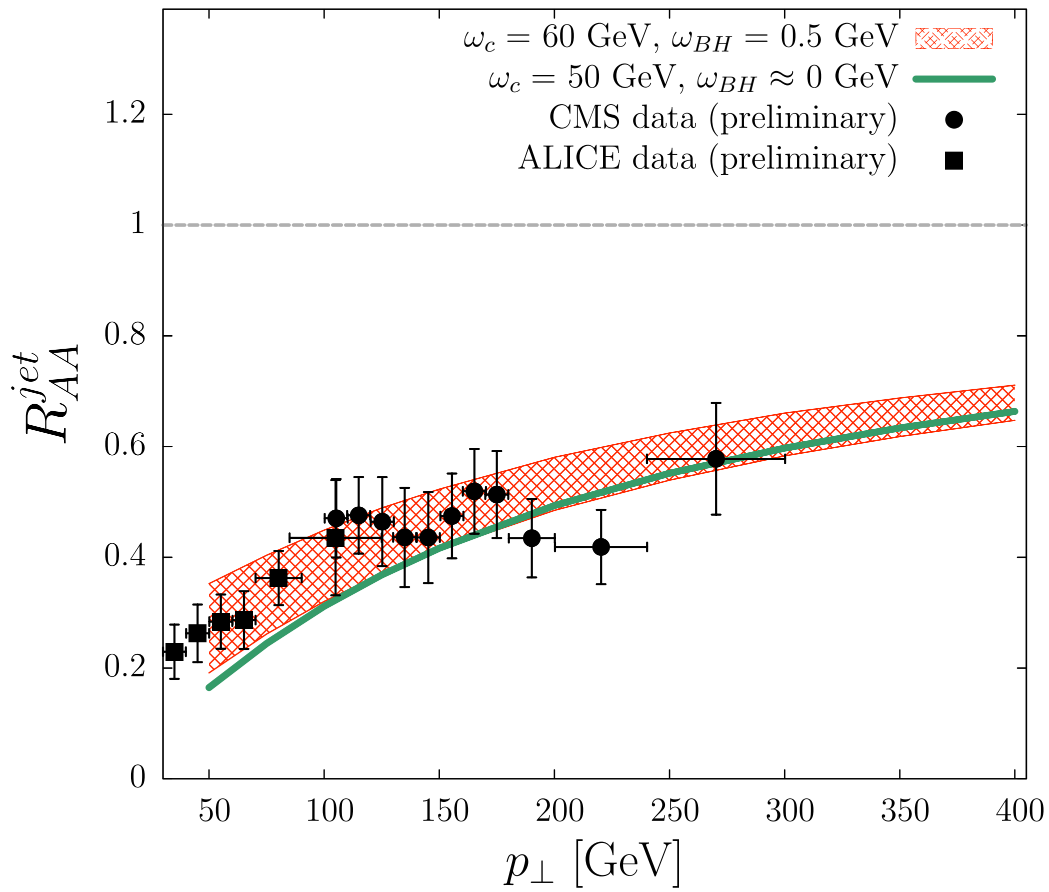
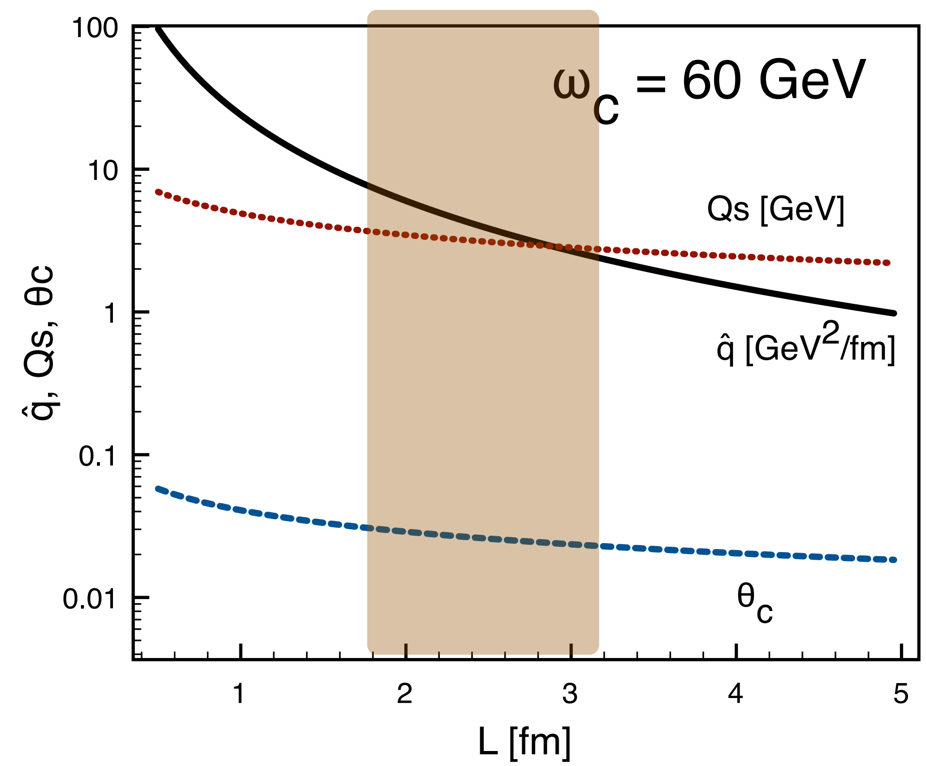
Jet suppression

Calculating quenching factor $Q(p_T)$ for "leading sub-jet"





- follows QW expectation $\delta p_T \sim \sqrt{p_T}$! Low p_T sensitive to sub-leading resolved sujets!
- sensitivity to regularization prescription
- baseline - consistency

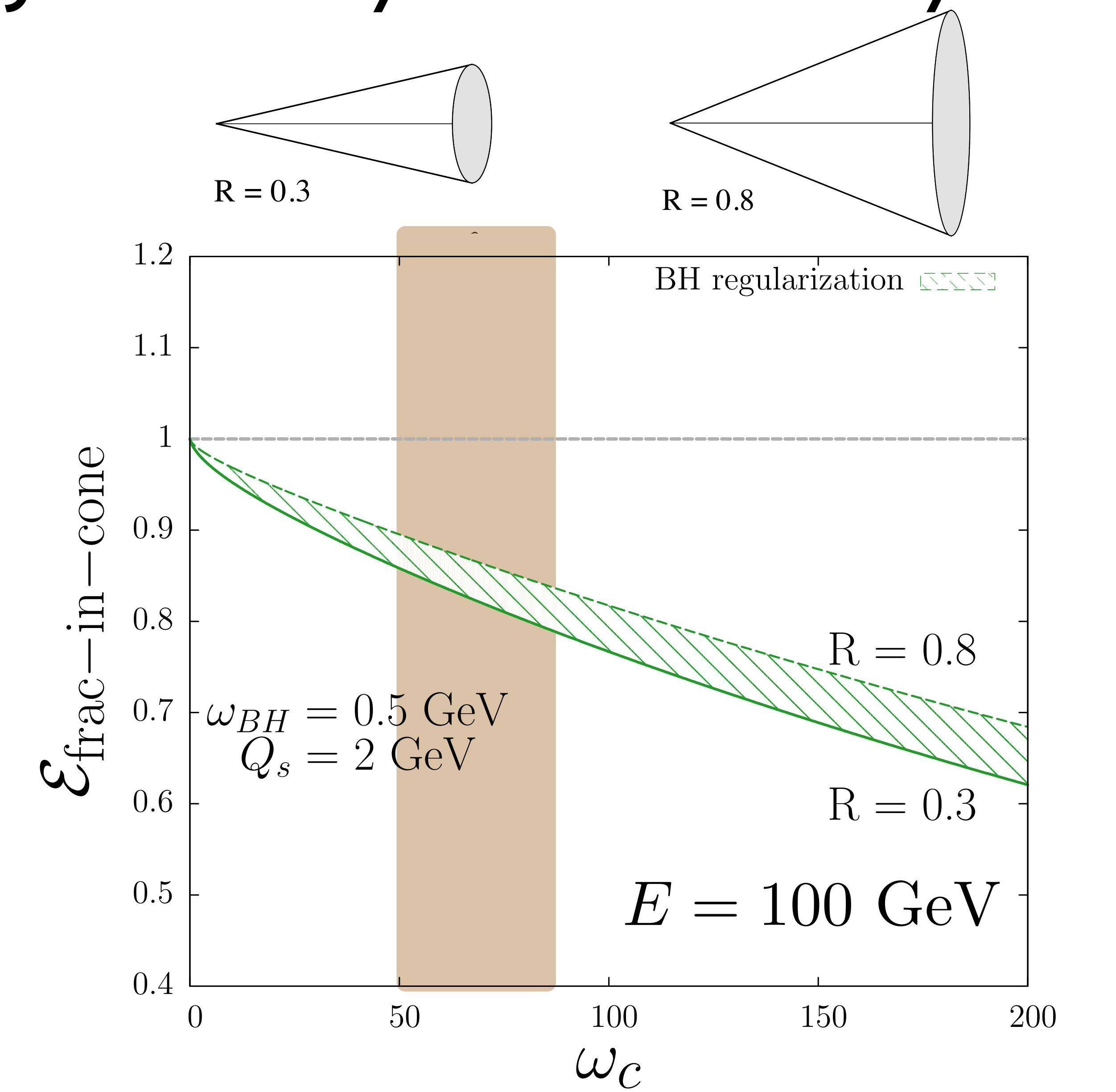
L = 2-3 fm
$\hat{q}$ = 6-2.5 GeV^2/fm

Application to dijet asymmetry

Average broadening (x~1, θ<θ$_c$):

$$D(x,\theta<\Theta_{jet}) = \int^{\Theta_{jet}} \frac{d^2\boldsymbol{k}}{(2\pi)^2}\mathcal{P}(\boldsymbol{k})\,D(x)\,,$$
$$= \left[1-\exp\left(-\frac{x^2M_T^2}{Q_s^2}\right)\right]D(x)$$

- little energy is recovered up to large cone angles, R~0.8
- striking effect due to multiple branching + broadening
- sensitive to regularization prescription (Bethe-Heitler regime)!



Full-fledged evolution for double-differential distribution, see talk by Y. Mehtar-Tani

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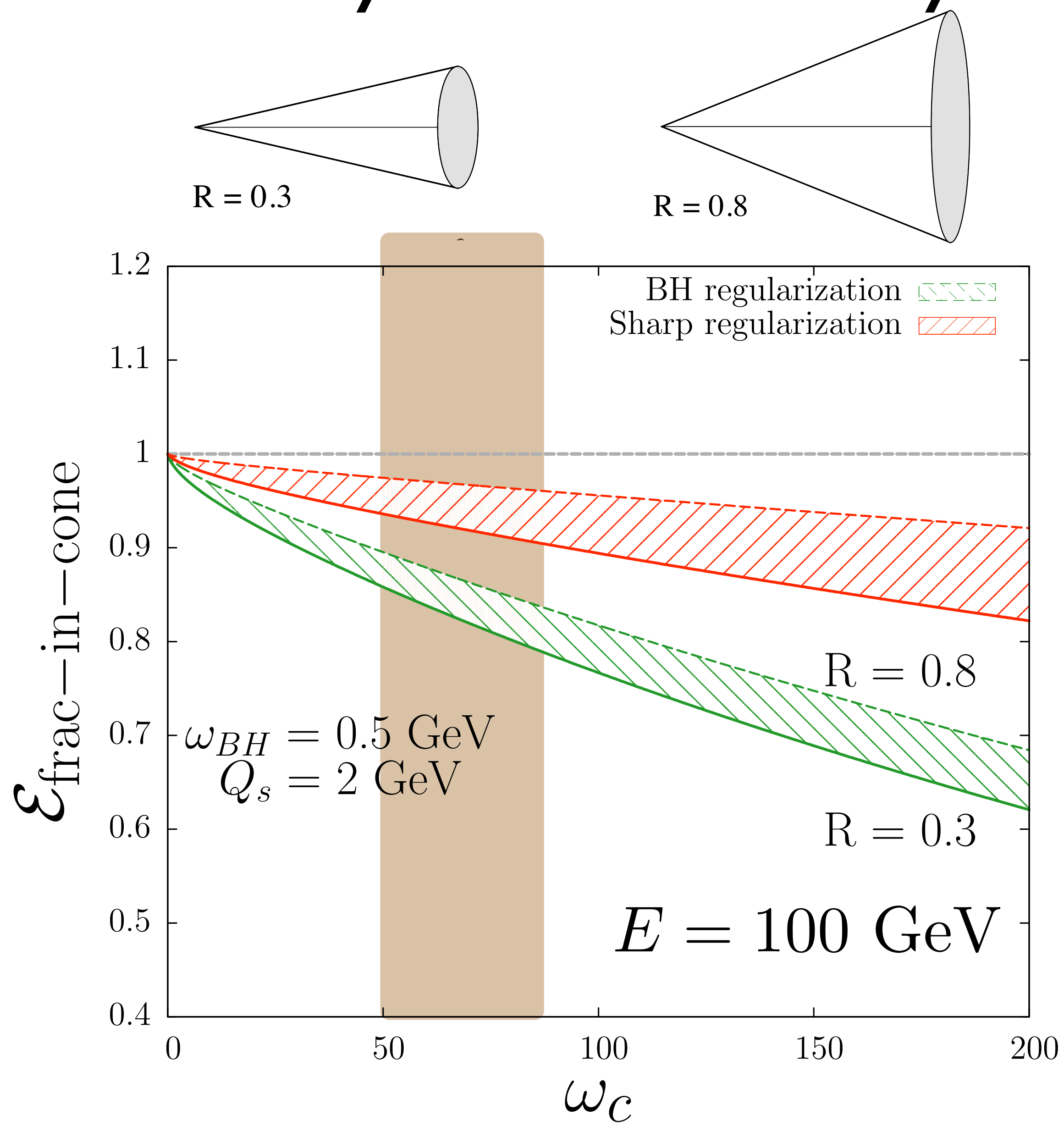

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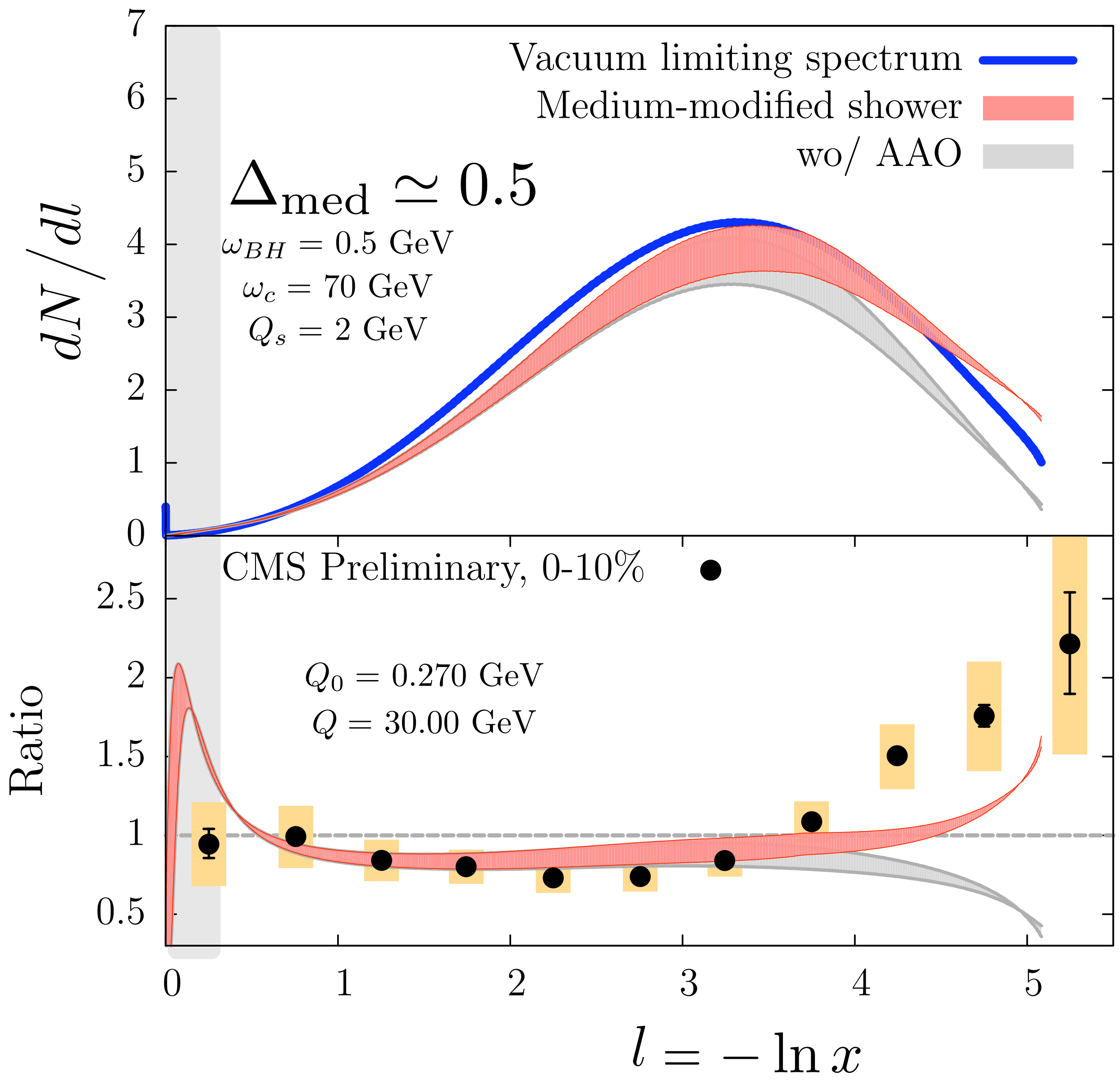
Intra-jet modification

Putting it all together:



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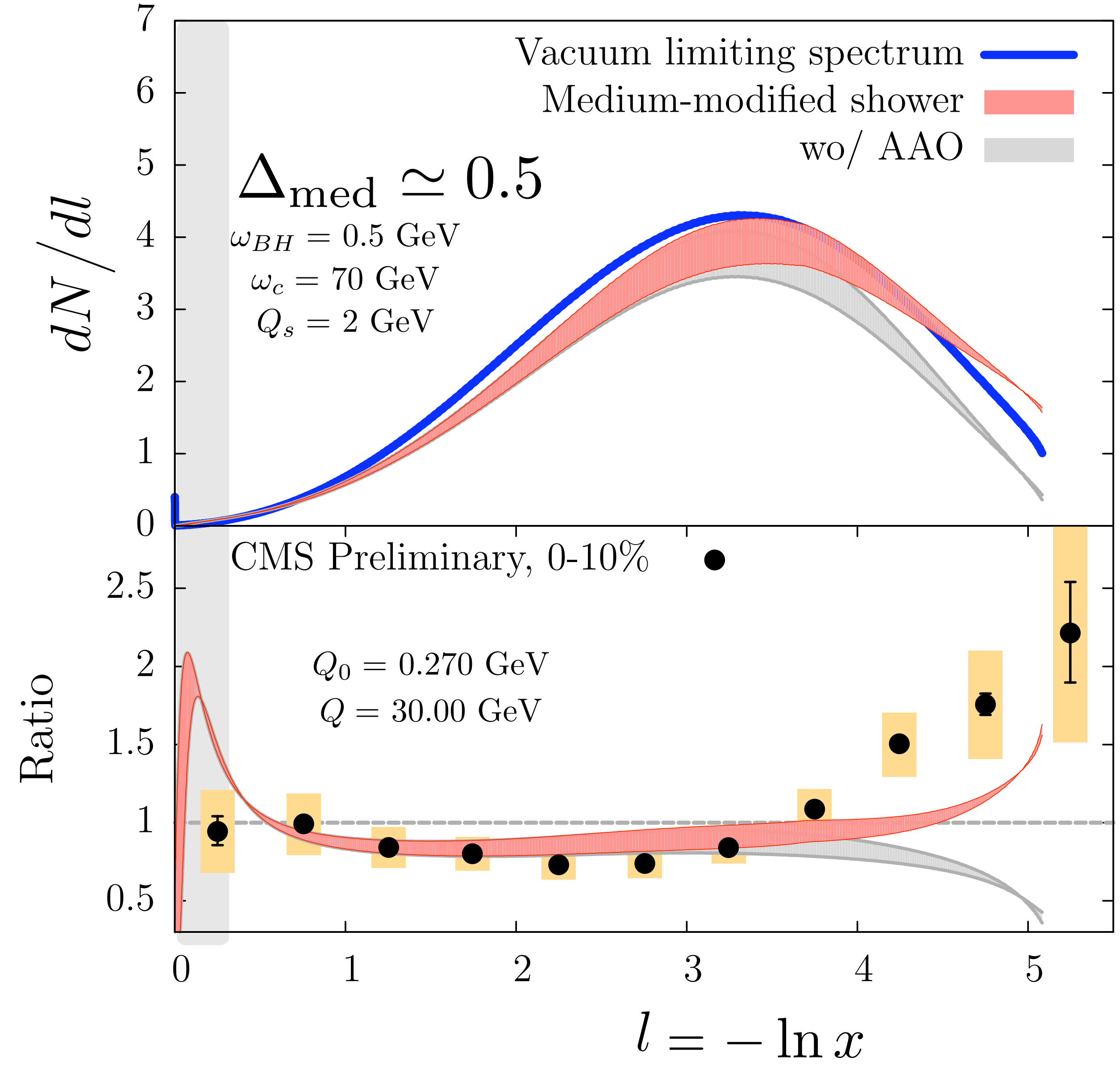
Putting it all together:

- MLLA distribution for pp vacuum



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Intra-jet modification

Putting it all together:

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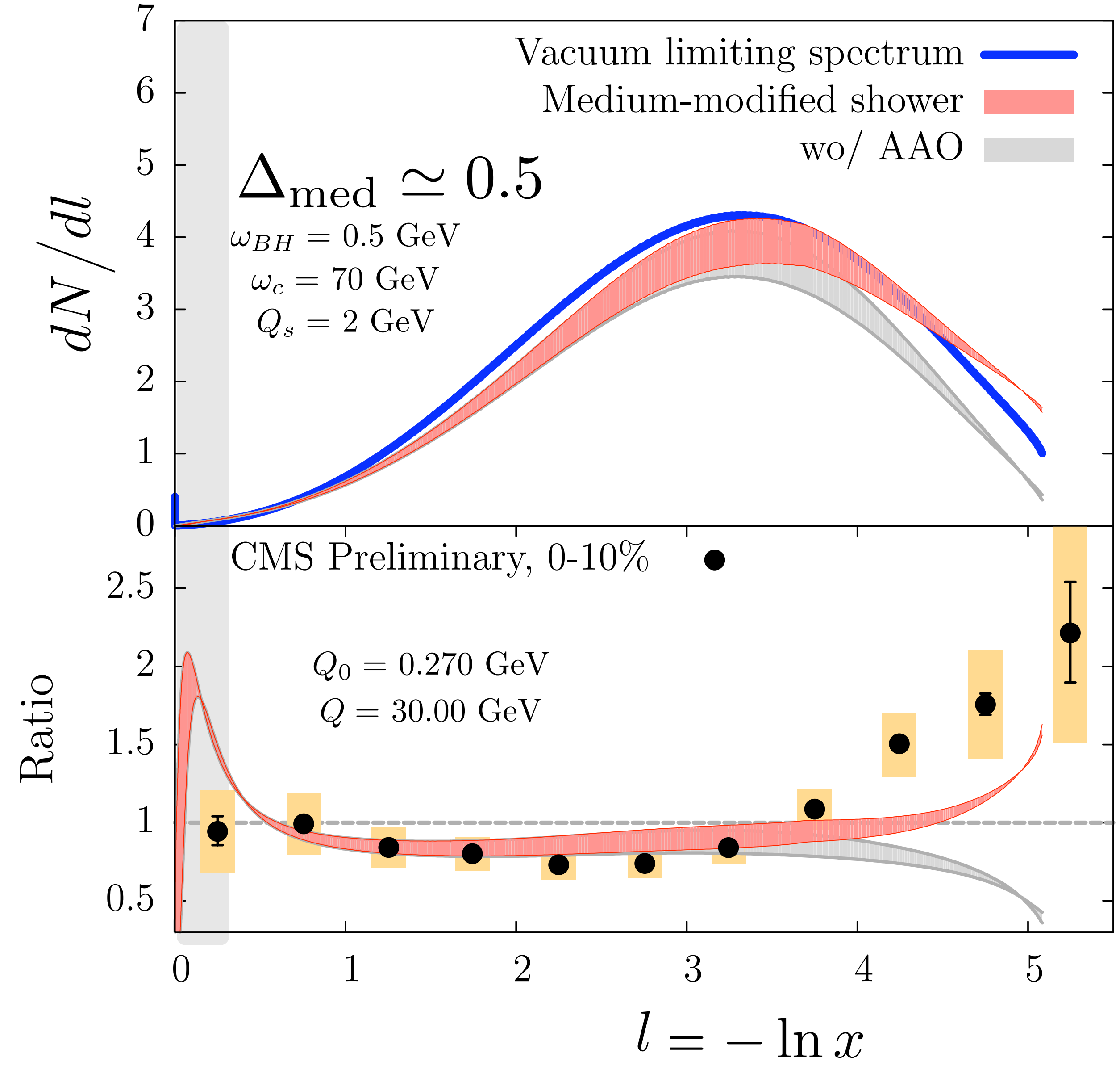

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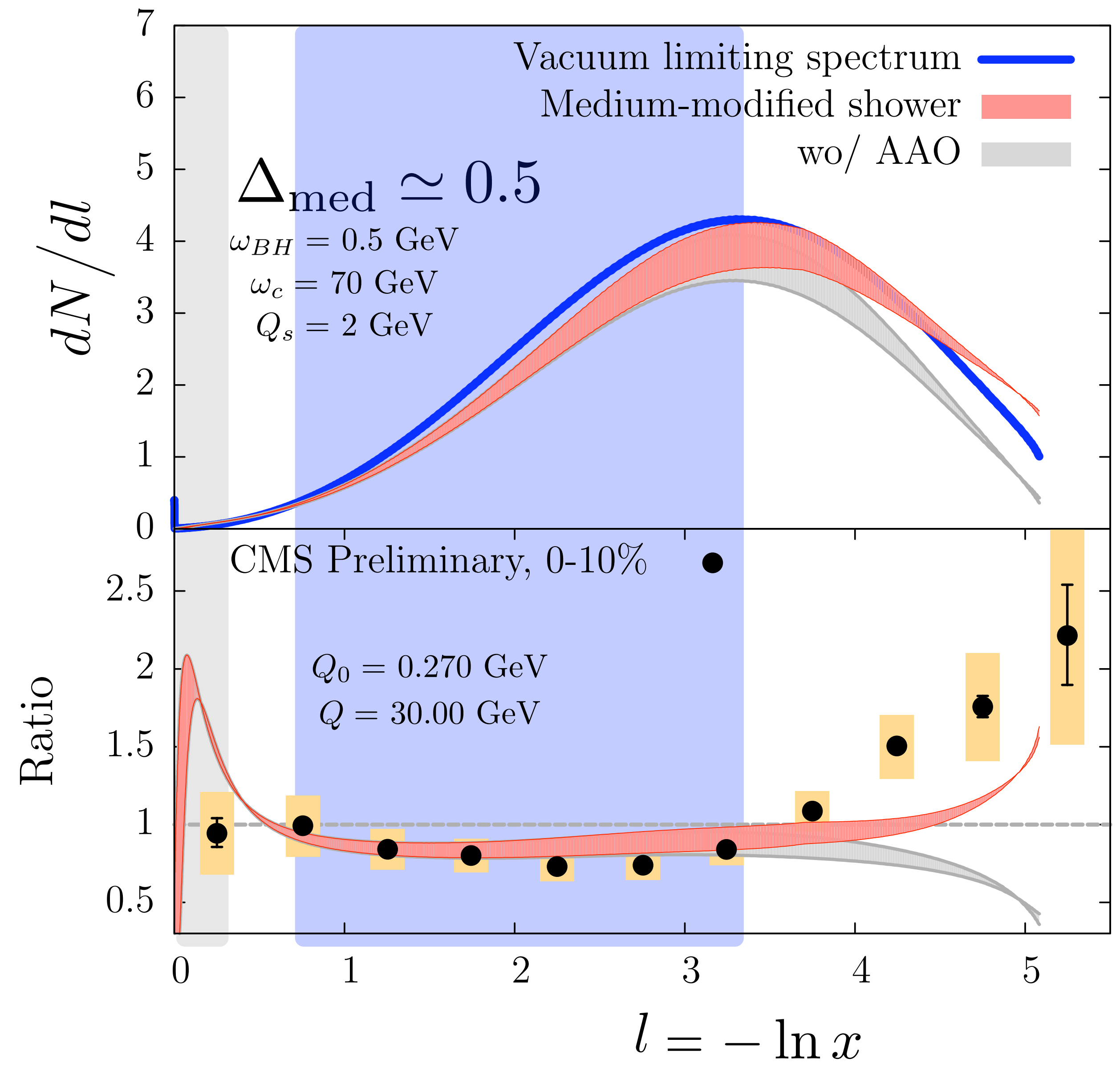

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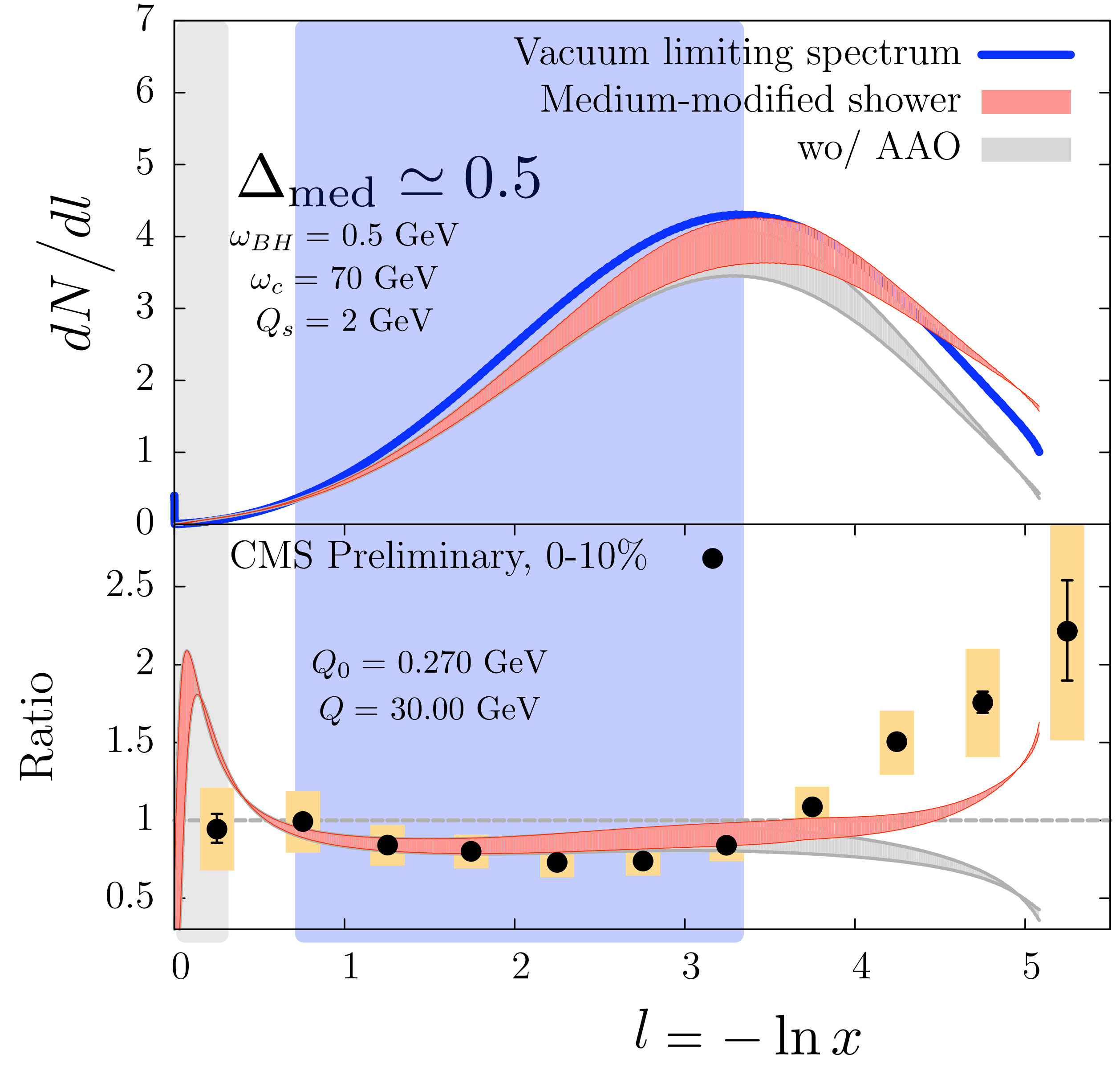

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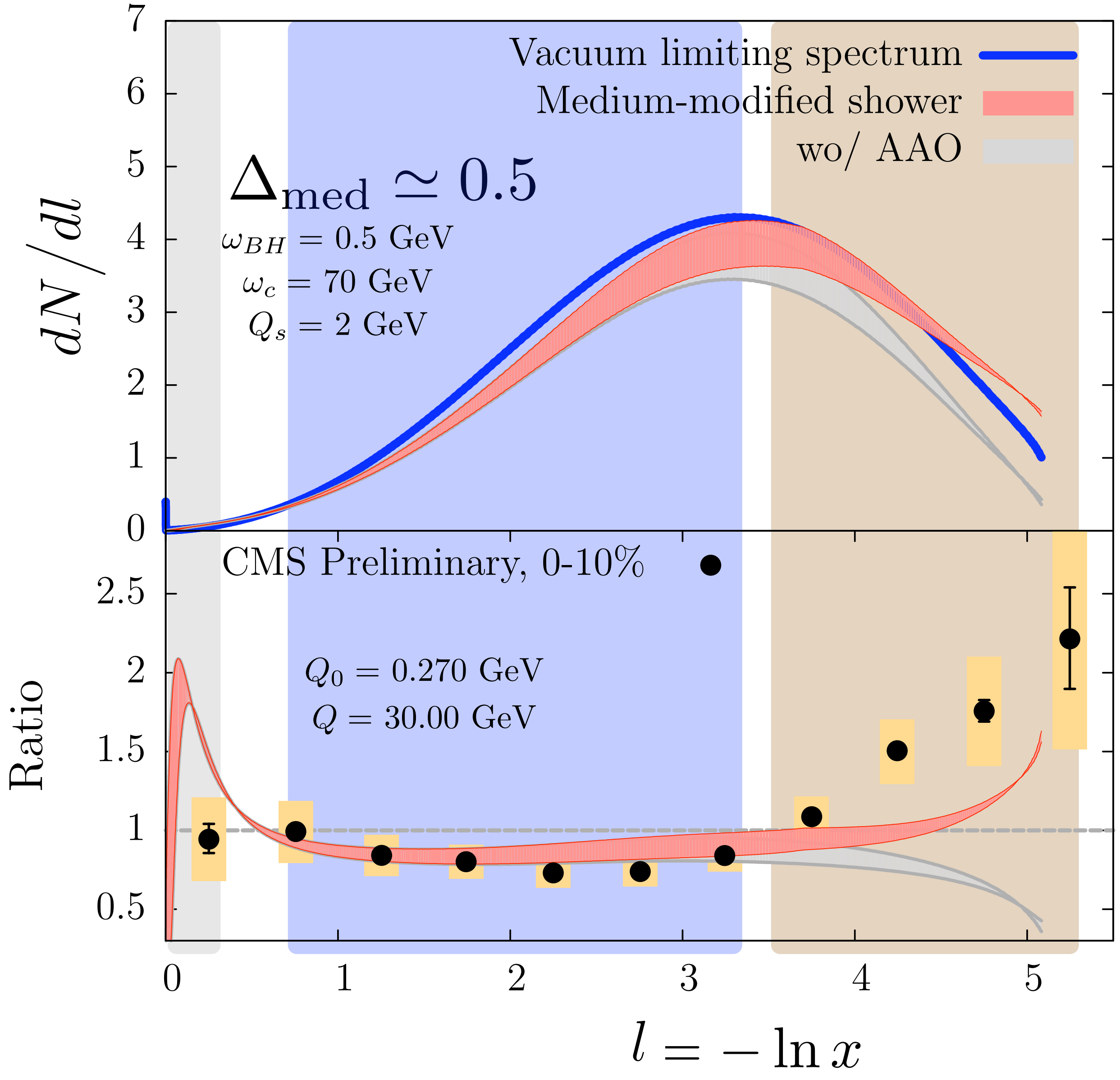
- small angle radiation due to AAO/ decoherence: novel ingredient
  - soft gluons, produced with large formation time :: not affected by broadening
  - responsible for enhancement at low l = shift of humpbacked plateau!



Summary

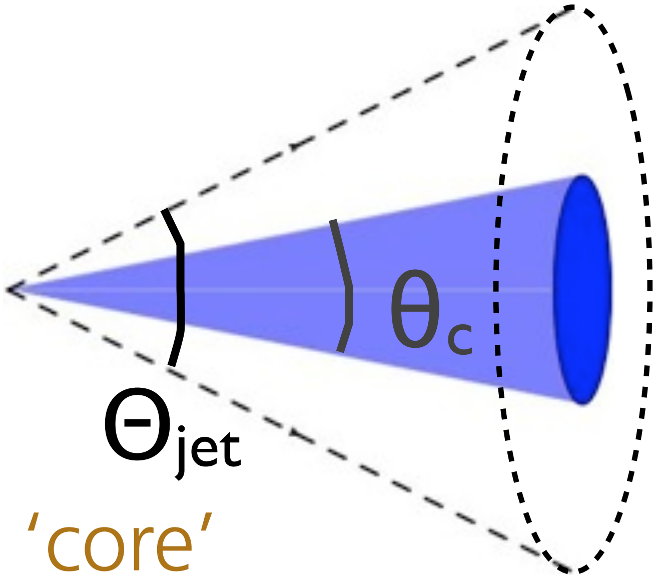
- jet quenching is a powerful tool to access properties of the hot and dense QGP in AA
  - resolved sub-jets are a consequence of color transparency (pQCD)
- gives rise to simple & intuitive picture for jet modifications at high p_T
  - separation of processes: medium cascade (large angles) & partial decoherence (small angles)
- consistent description of three compelling observables
- many improvements in the pipeline: other observables, fluctuations

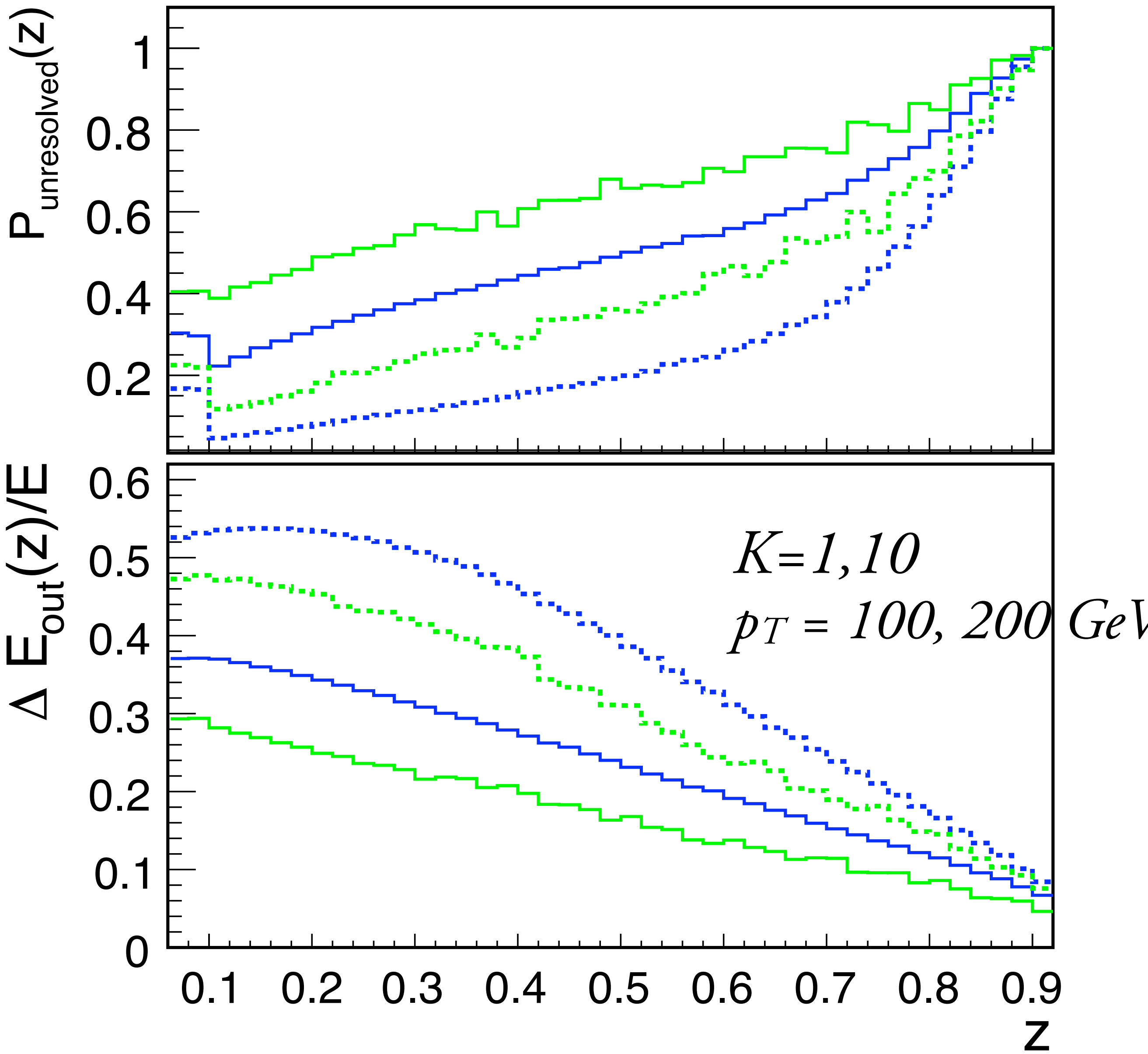
backup

Resolved effective charges

$$\Delta_{\rm med} = 1 - e^{-\Theta_{\rm jet}^2/\theta_c^2}$$

$$\theta_c = 1/\sqrt{\hat{q}L^3}$$





Coherent inner 'core'

- branchings occurring inside the medium with $\theta < \theta_c$
- modes with $\lambda_\perp < Q_s^{-1}$ ($k_\perp > Q_s$)
- $t_f < L \rightarrow Q_s^2 L < \omega < E$
- the core loses energy coherently

Casalderrrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765

:: probability of only finding one leading subjet in the presence of a fragment with mom frac z

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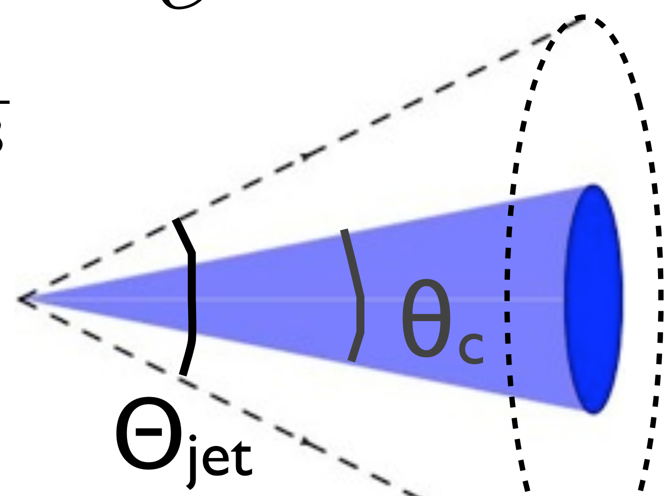

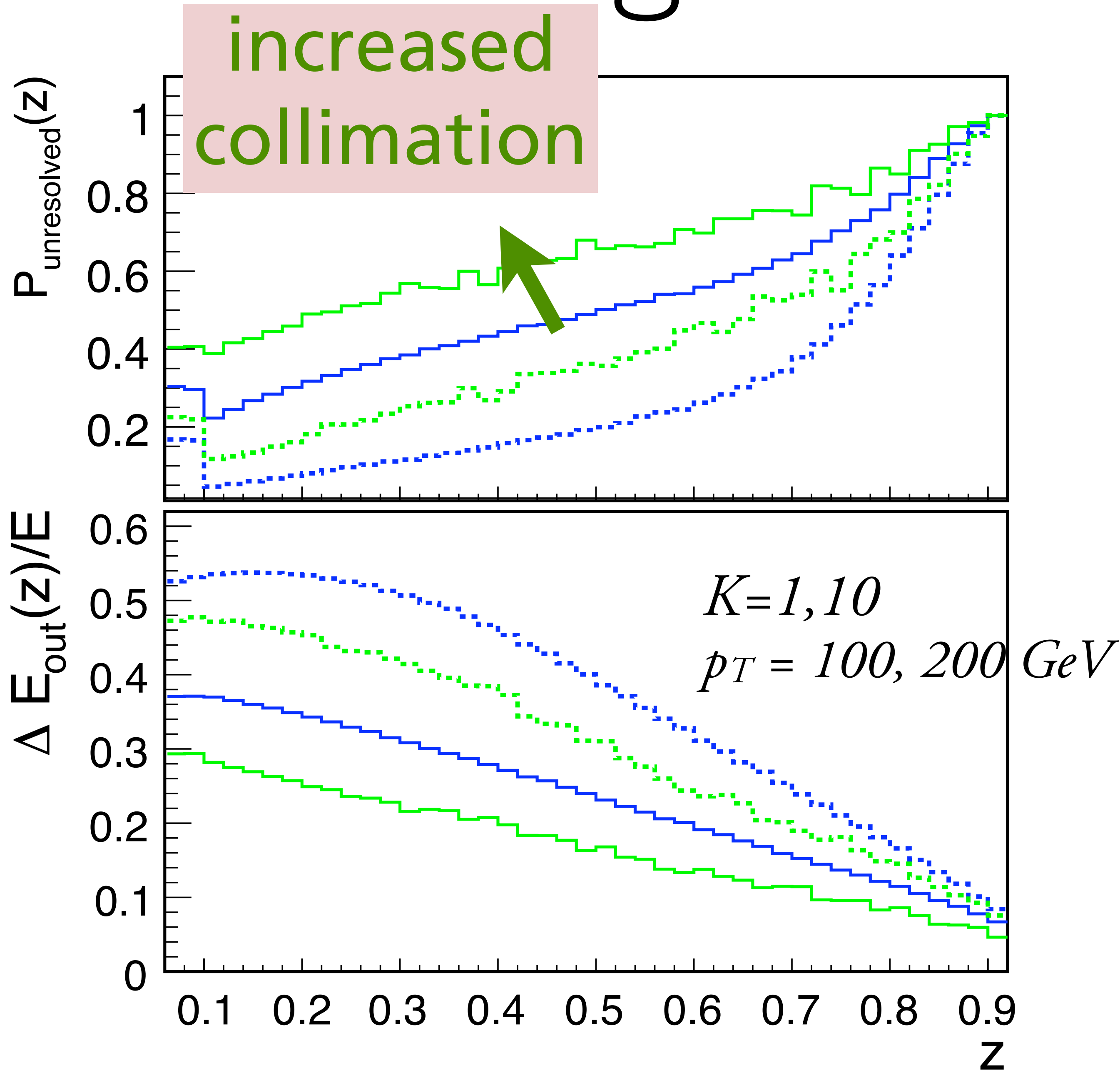

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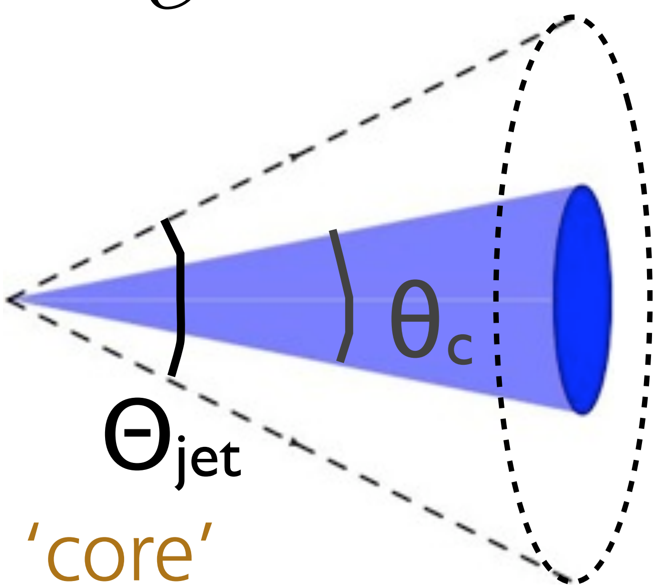

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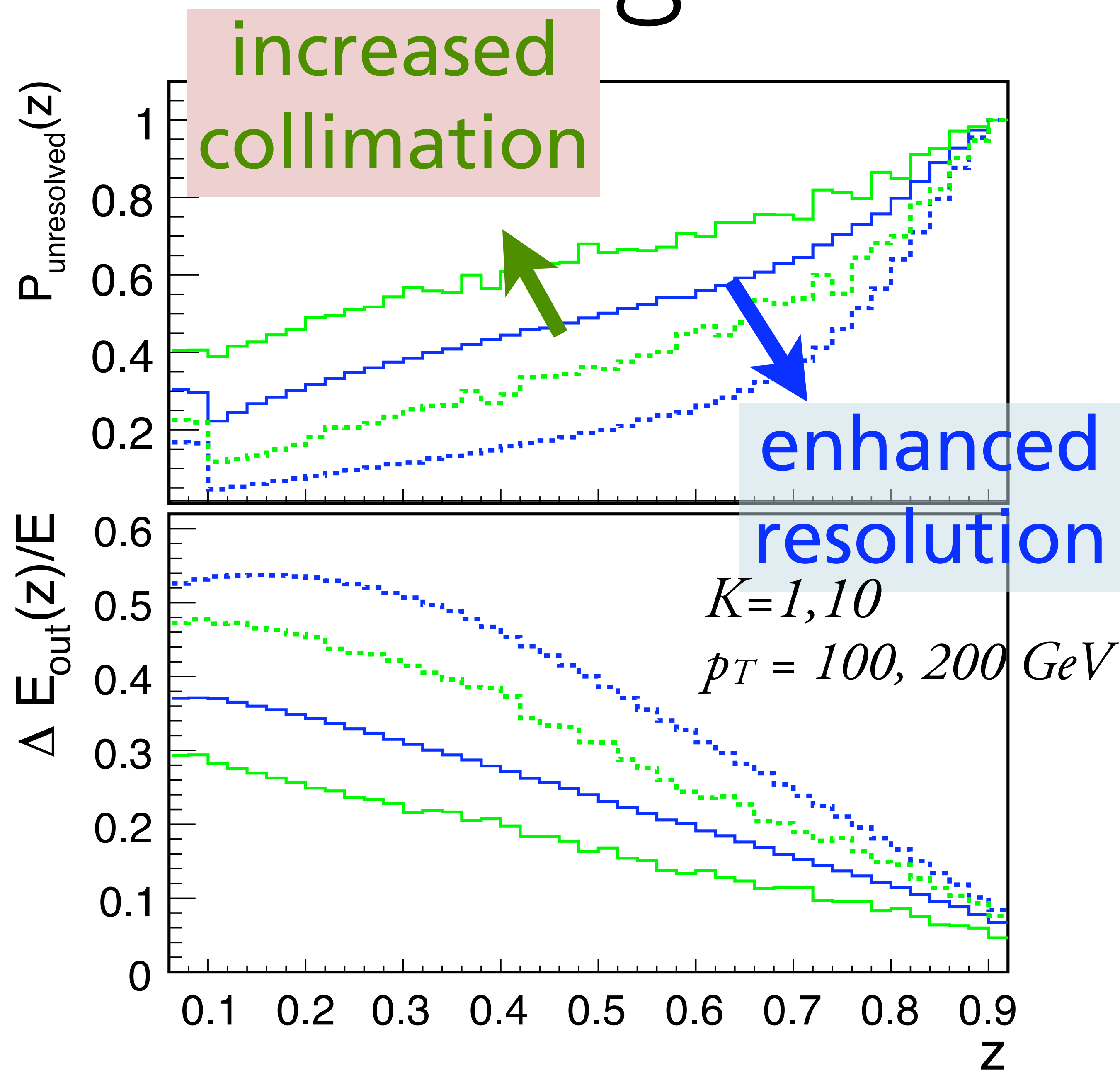

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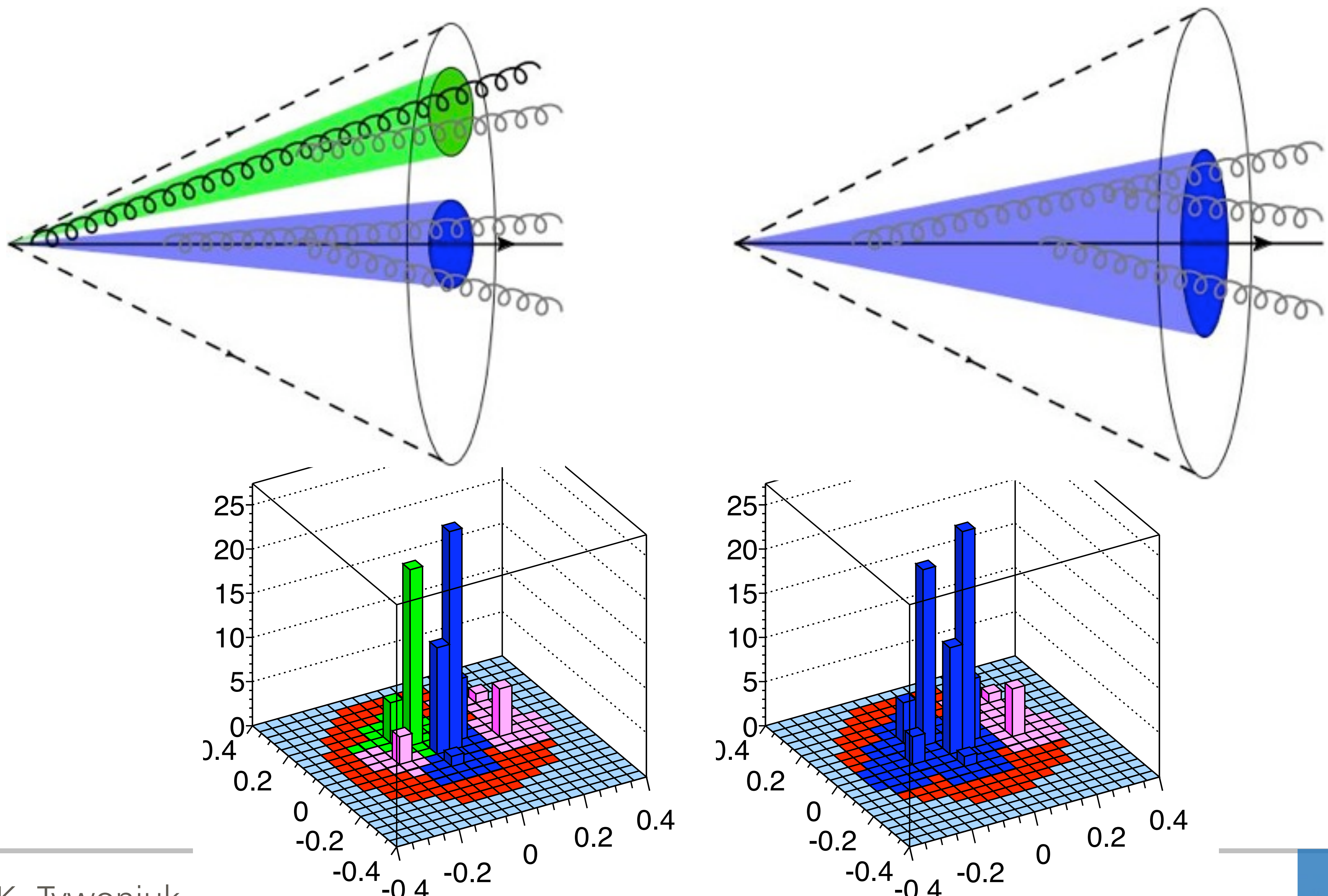
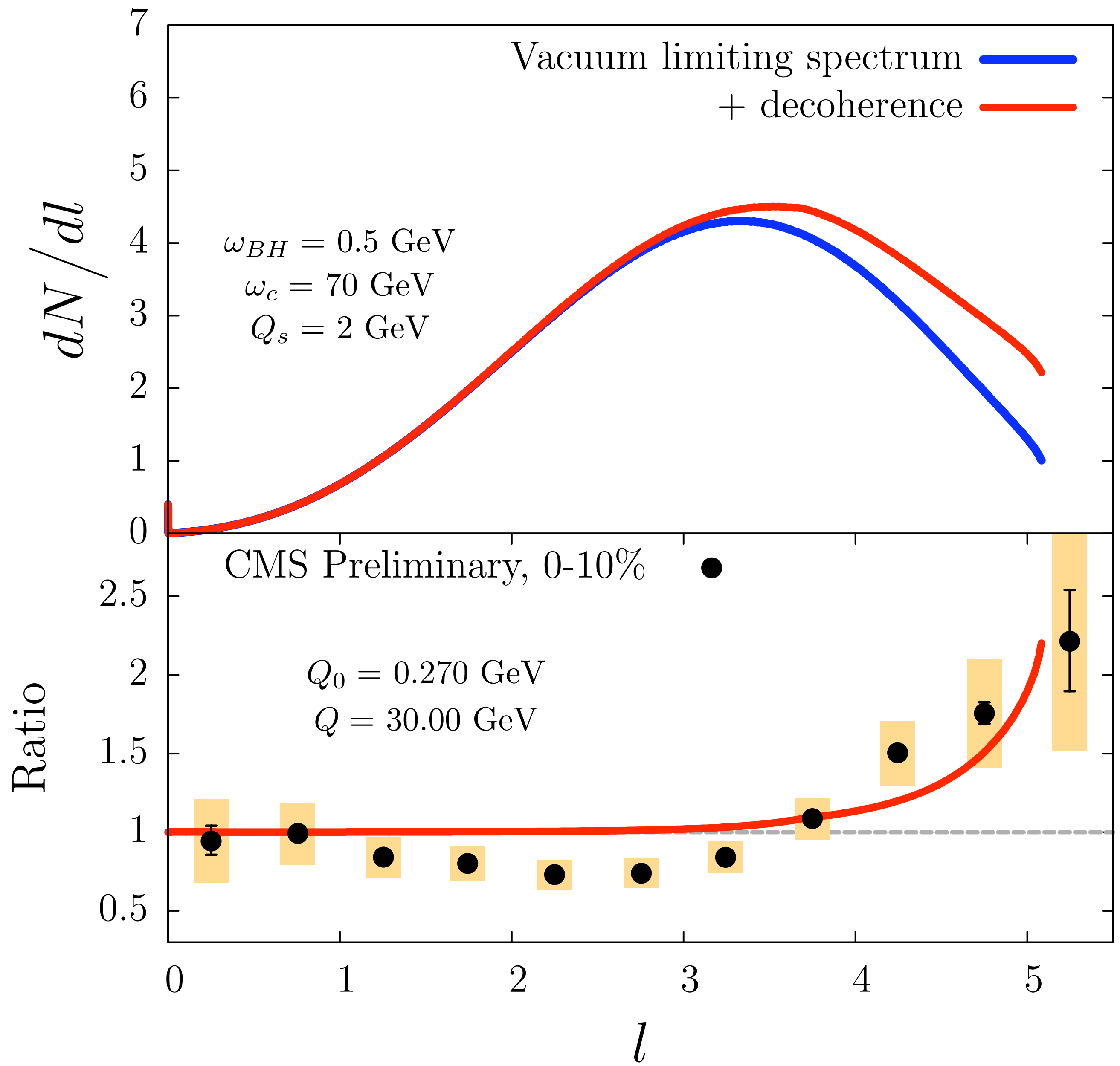


Only decoherence



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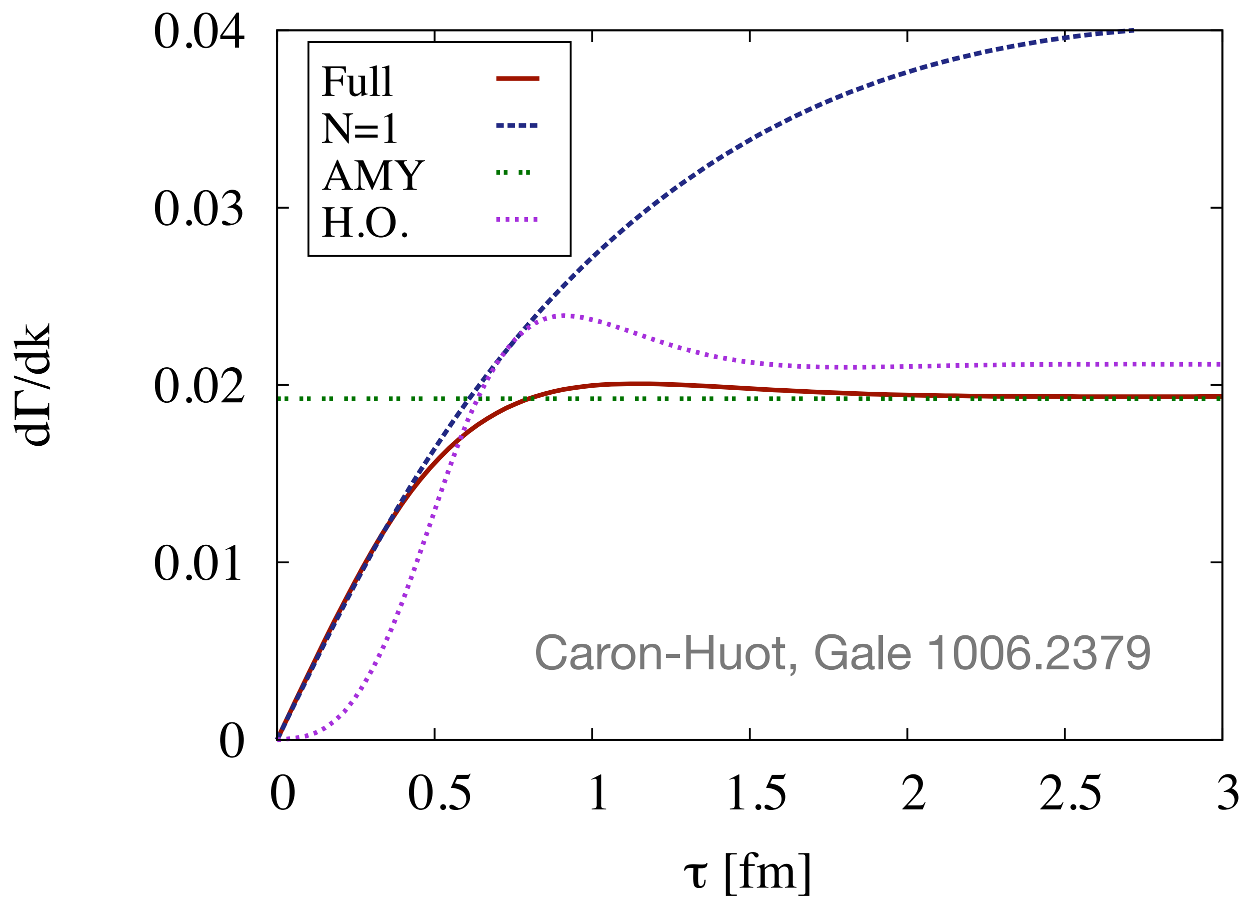
Finite-size effects



- including finite-size effects in the 'harmonic oscillator' approximation
- could be improved by including the full rate or interpolate between N=1 and HO

$$z\frac{dI^{\text{ind}}}{dz} = \frac{\alpha_s}{2\pi} z P_{gg}(z) \ln\left|\cos(1+i)\sqrt{\frac{\hat{q}_{\text{eff}}L^2}{z(1-z)p^+}}\right| \quad \Rightarrow \quad z\frac{dI^{\text{ind}}}{dz\,dL}$$

$$k_{\text{br}}^2 = \sqrt{z(1-z)p_0^+\hat{q}_{\text{eff}}} \qquad \hat{q}_{\text{eff}} = \hat{q}\Big[(1-z)N_c - zC_R\Big]$$

Regularization

$$\frac{d^2\mathcal{P}}{dz d\tau} = \frac{1}{2}\frac{\mathcal{F}(z,x;\tau)}{\sqrt{x}}$$

$$x_c = \omega_c/p_0^+ \qquad \tau \equiv \bar{\alpha}\sqrt{2x_c}$$

$$\mathcal{F}(z,x;\tau) = \tilde{P}_{gg}(z)\mathcal{K}(z)\frac{\sinh\sigma(z,x;\tau) - \sin\sigma(z,x;\tau)}{\cosh\sigma(z,x;\tau) + \cos\sigma(z,x;\tau)}$$

$$\sigma(z,x;\tau) = \frac{\mathcal{K}(z)}{\bar{\alpha}\sqrt{x}}\tau$$

$$\tilde{P}_{gg}(z) = \frac{\big(1 - z(1-z)\big)^2}{[z(1-z)]_{\epsilon_1}}$$

$$\mathcal{K}(z) = \sqrt{\frac{1 - z(1-z)}{[z(1-z)]_{\epsilon_2}}}$$

$$t_{\rm br} \sim \lambda_{\rm mfp} \Rightarrow \omega_{\rm BH} = \lambda_{\rm mfp}^2 \hat{q} \sim m_D^2 \lambda_{\rm mfp}$$

$$k_\perp \sim k_{\rm br} < \omega$$

$$\Downarrow$$

$$\omega < \hat{q}^{1/3}$$

$$\lambda_{\rm mfp} > 1/m_D \Rightarrow \omega_{\rm BH} > \hat{q}^{1/3}$$

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$$\frac{d^2\mathcal{P}}{dz\,d\tau} = \frac{1}{2}\frac{\mathcal{F}(z,x;\tau)}{\sqrt{x}}$$

$x_c = \omega_c/p_0^+ \qquad \tau \equiv \bar{\alpha}\sqrt{2x_c}$

$$\mathcal{F}(z,x;\tau) = \tilde{P}_{gg}(z)\mathcal{K}(z)\frac{\sinh\sigma(z,x;\tau) - \sin\sigma(z,x;\tau)}{\cosh\sigma(z,x;\tau) + \cos\sigma(z,x;\tau)}$$

$$\sigma(z,x;\tau) = \frac{\mathcal{K}(z)}{\bar{\alpha}\sqrt{x}}\tau$$

$$\tilde{P}_{gg}(z) = \frac{\left(1 - z(1-z)\right)^2}{[z(1-z)]_{\epsilon_1}}$$

$$\mathcal{K}(z) = \sqrt{\frac{1 - z(1-z)}{[z(1-z)]_{\epsilon_2}}}$$

$$t_{\rm br} \sim \lambda_{\rm mfp} \Rightarrow \omega_{\rm BH} = \lambda_{\rm mfp}^2\hat{q} \sim m_D^2\lambda_{\rm mfp}$$

$$k_\perp \sim k_{\rm br} < \omega$$

$$\Downarrow$$

$$\omega < \hat{q}^{1/3}$$

$$\lambda_{\rm mfp} > 1/m_D \Rightarrow \omega_{\rm BH} > \hat{q}^{1/3}$$

reg1: $\frac{1}{(1-z)_\epsilon} = \frac{\xi(\xi - x)}{(\xi - x + x_{\rm BH})^2}$ 'strong'

reg2: $\frac{1}{(1-z)_\epsilon} = \frac{\xi}{\xi - x + x_{\rm BH}}$ 'smooth'

$x_{\rm BH} = \omega_{\rm BH}/E$

$\xi = x/z$

→ apply it only to the medium $\mathcal{K}$