



THE LUND PLANE AS A WAY TO CONSTRAIN THE QUARK-GLUON PLASMA

Konrad Tywoniuk



OUTLINE

- I. Lund Plane in heavy-ion collisions
- II. Radiative energy loss in QCD medium
- III. Energy loss of partons and jets: diagrammatic approach & substructure

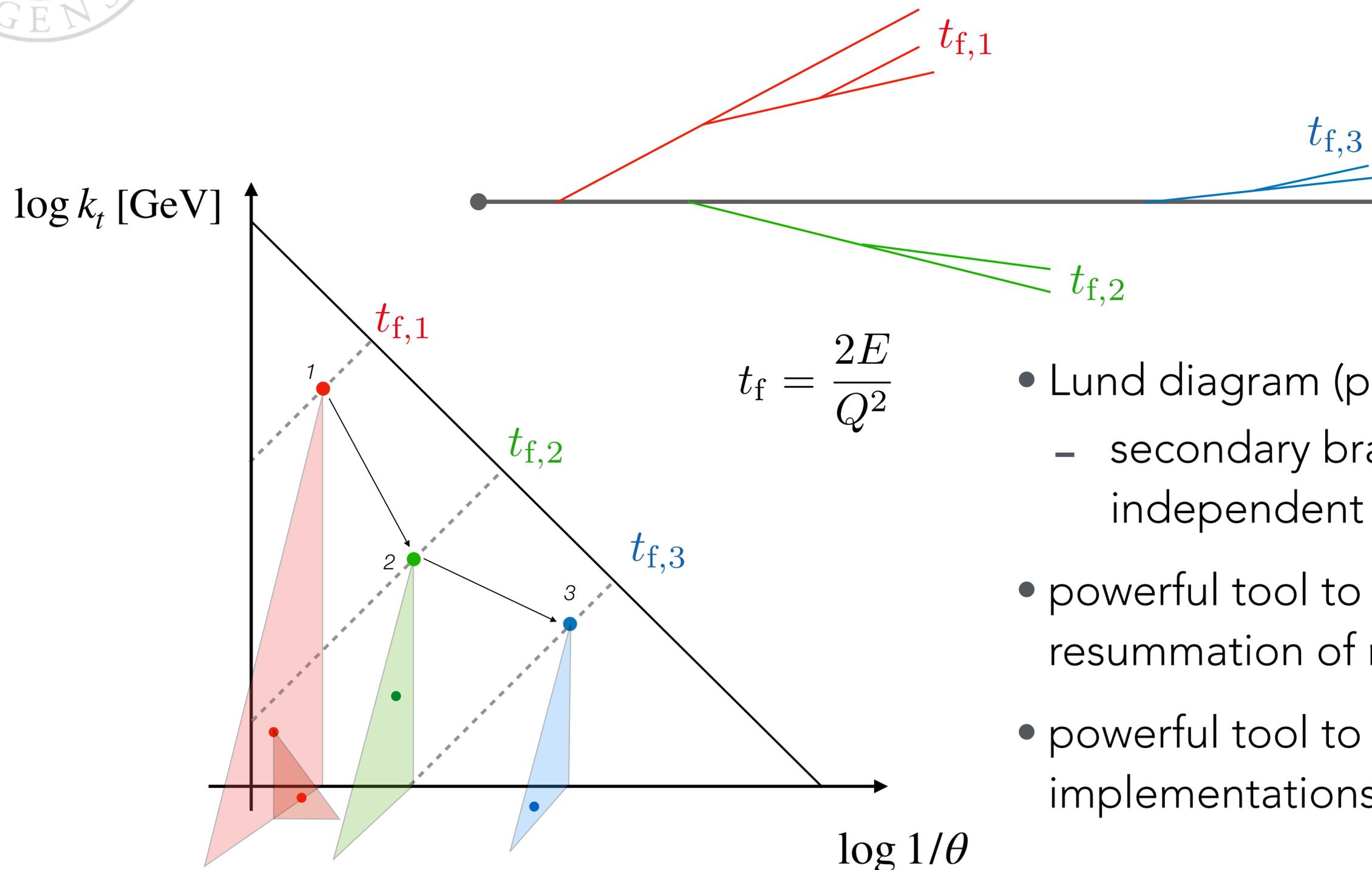
I) LUND PLANE IN HEAVY-ION COLLISIONS





JET BRANCHING HISTORY

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)

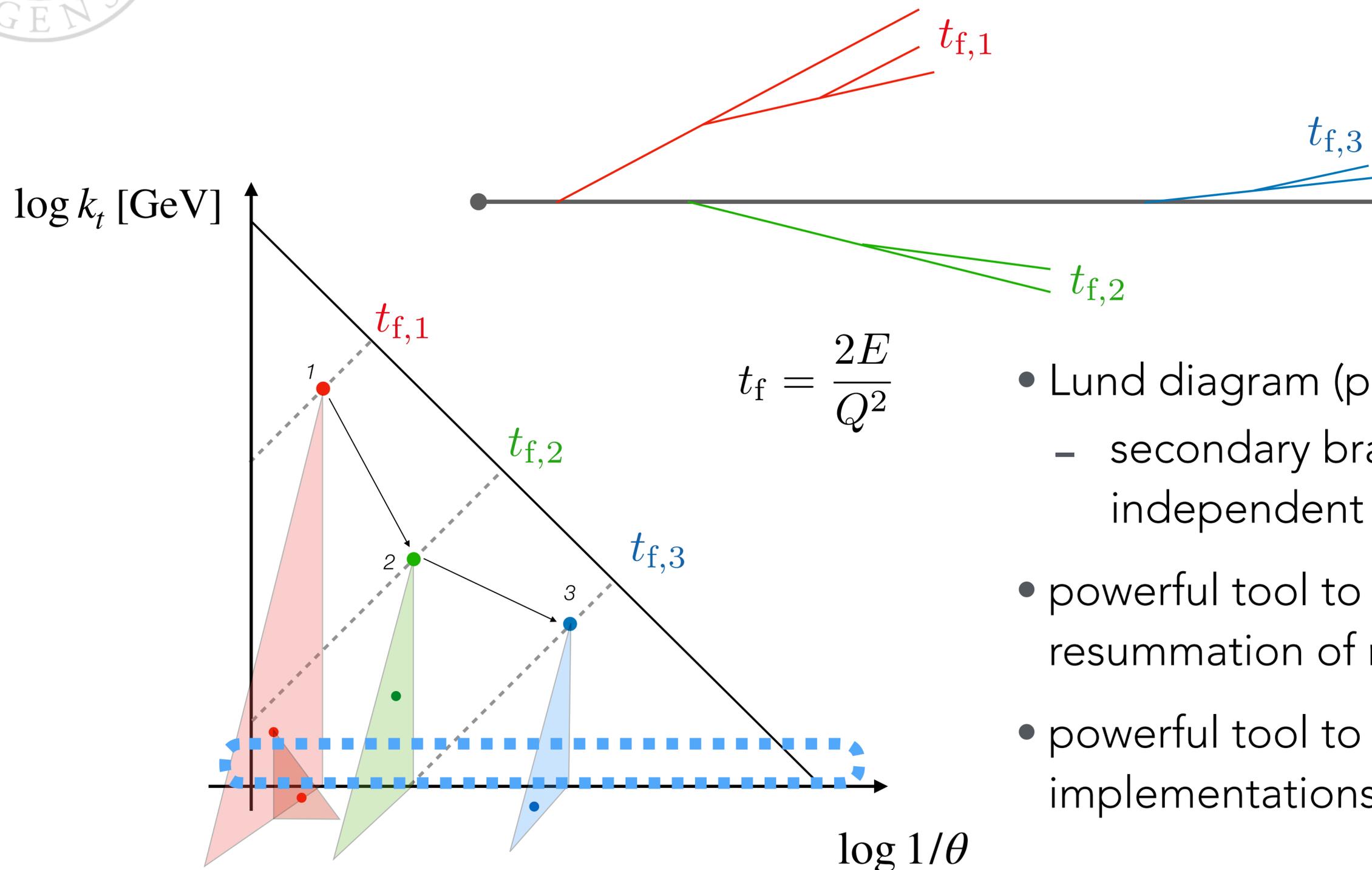


- Lund diagram (primary emission plane)
 - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower



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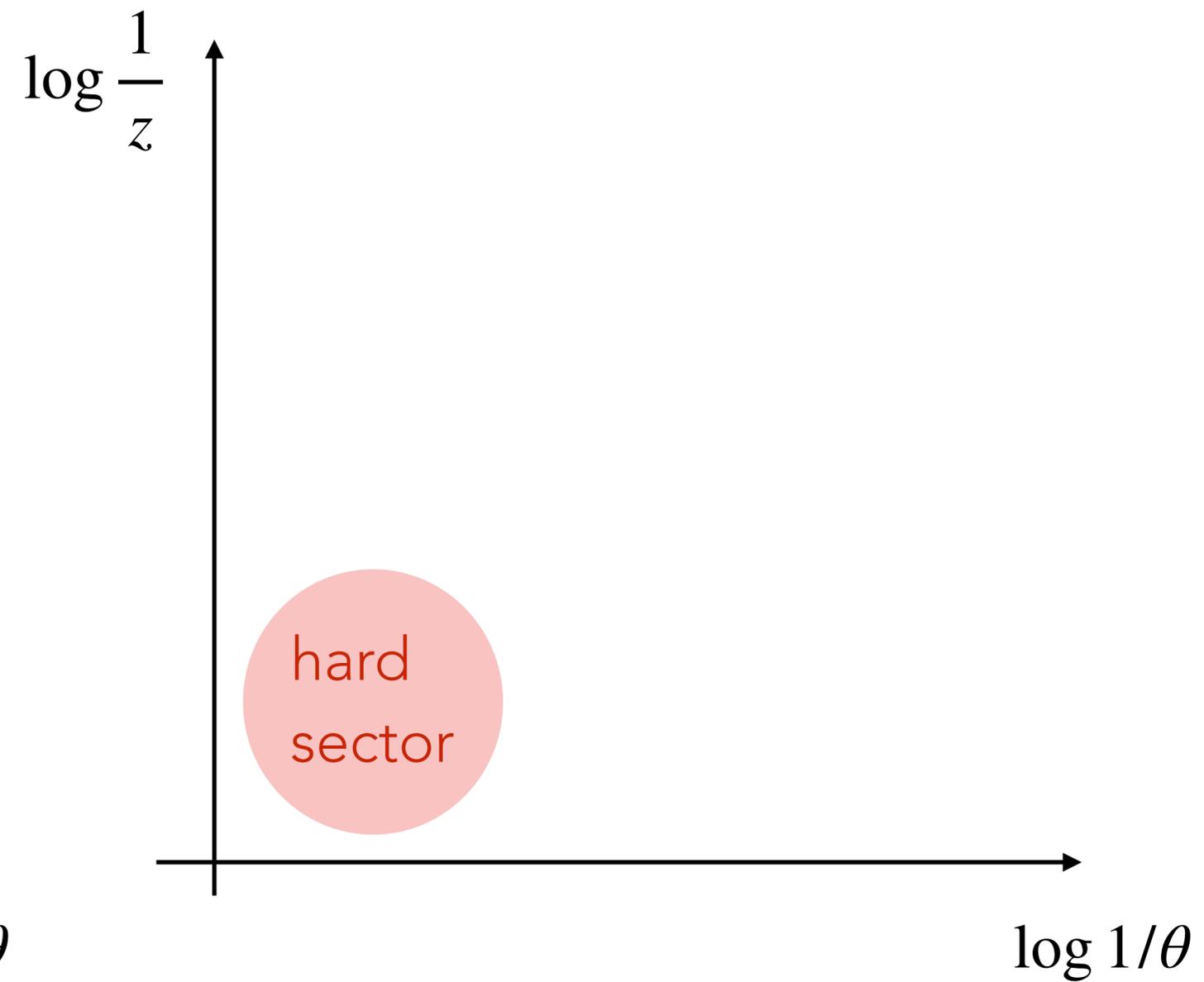
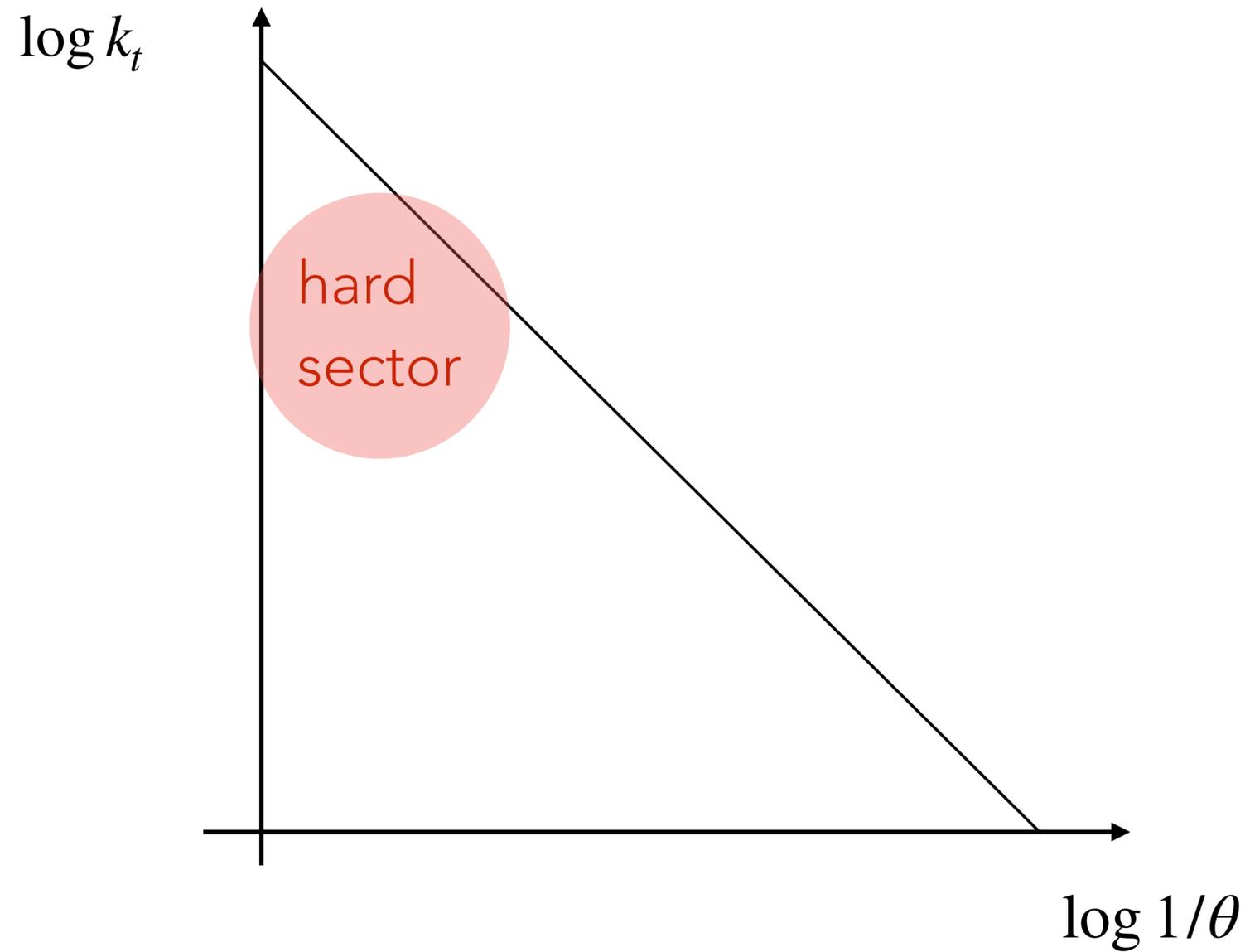
hadronization

from $t_f \sim (Q_0 R)^{-1} \sim 2 \text{ fm}$
 to $t_f \sim E/Q_0^2 \sim 300 \text{ fm}$

- Lund diagram (primary emission plane)
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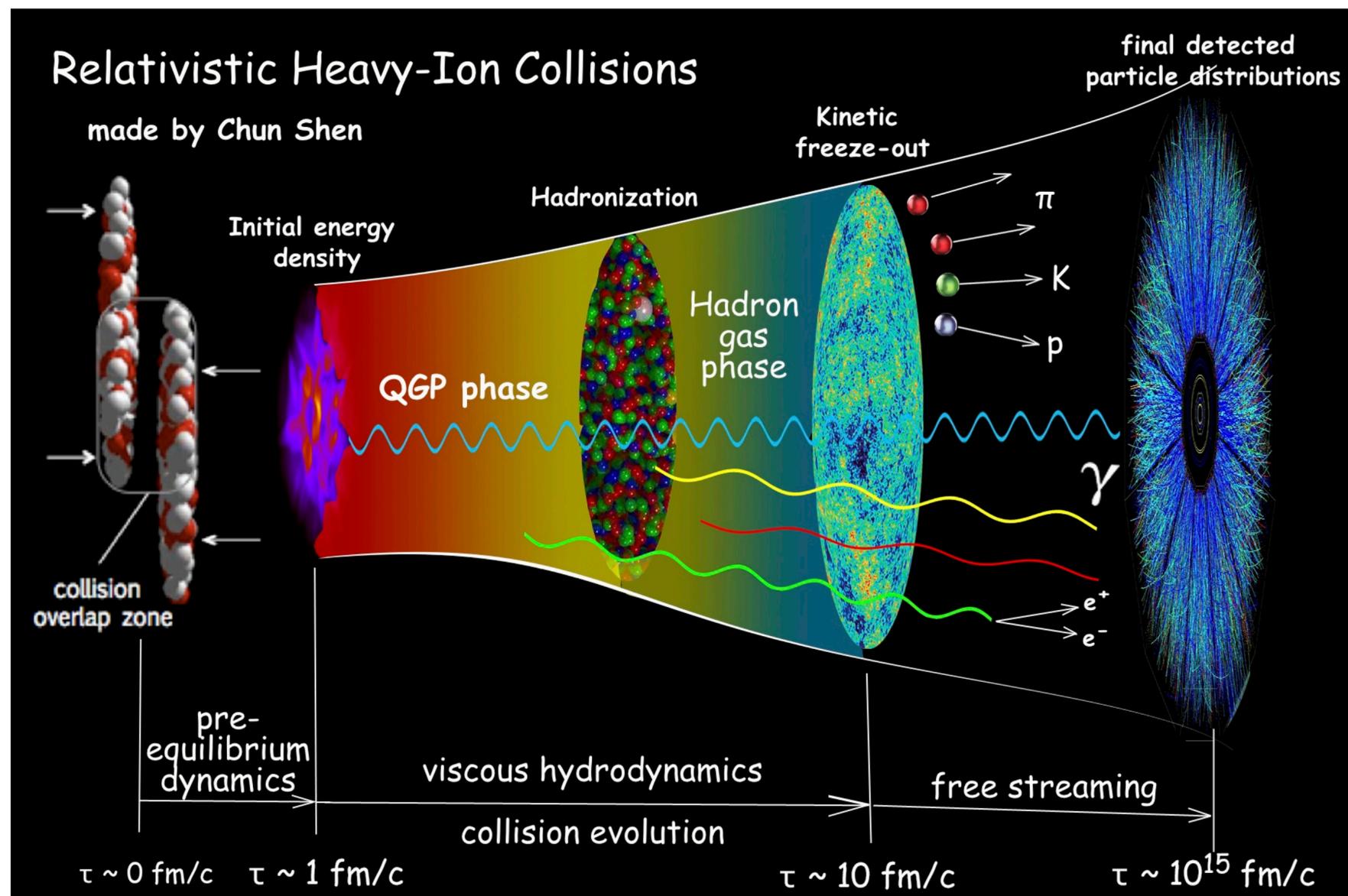


TWO VERSIONS





HEAVY-ION COLLISIONS

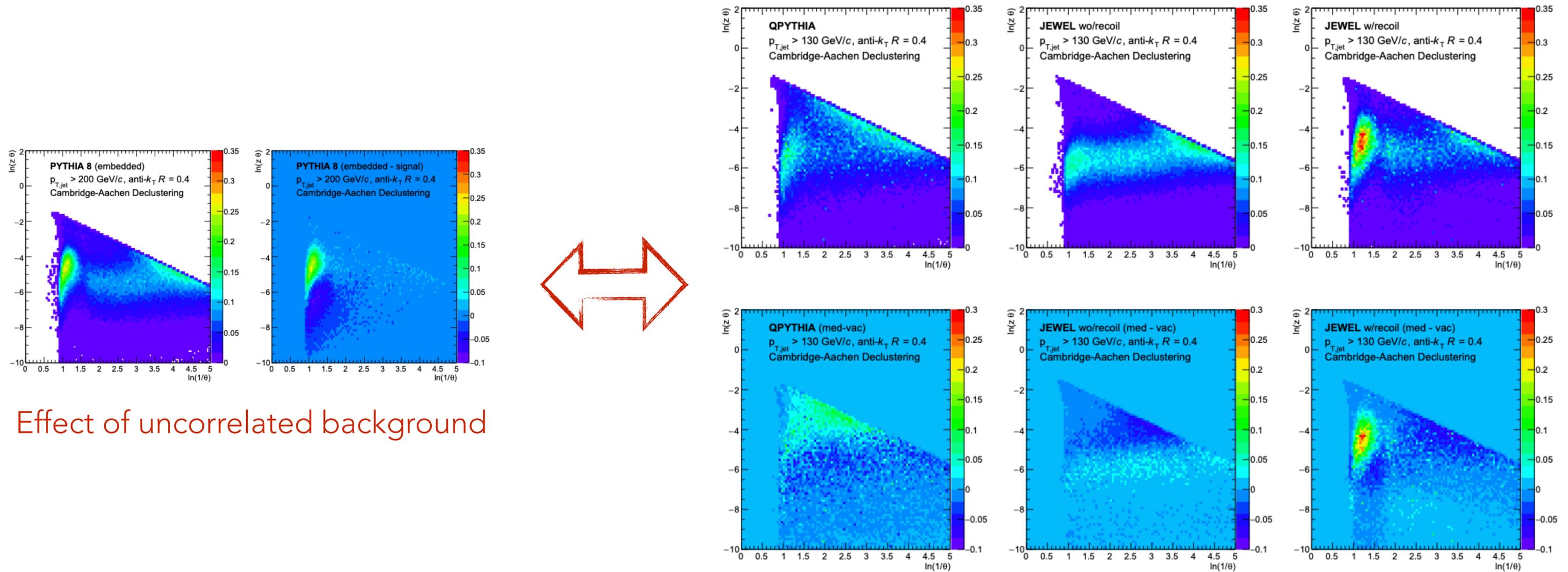


- 10,000 particles created
- jets are created in the early stages $\tau < 0.01$ fm
- substructure continues to evolve during QGP and HG phases



STUDIES OF LUND PLANES IN HEAVY-ION COLLISIONS

CERN TH Institute "Novel tools and observables for jet physics in heavy-ion collisions" (21.08-01.09 2017) [arXiv:1808.03689 [hep-ph]]



Effect of uncorrelated background

Imprints of QGP on jets

II) RADIATIVE PROCESSES IN A QCD MEDIUM

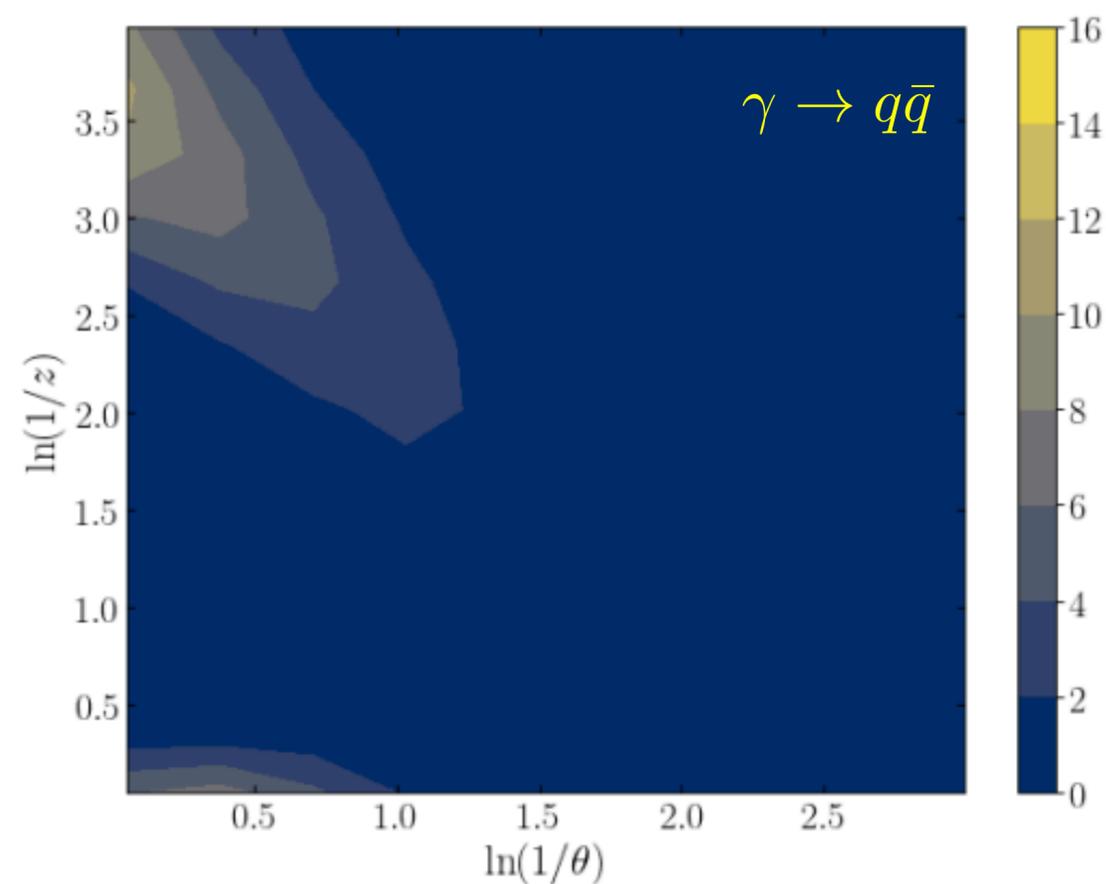




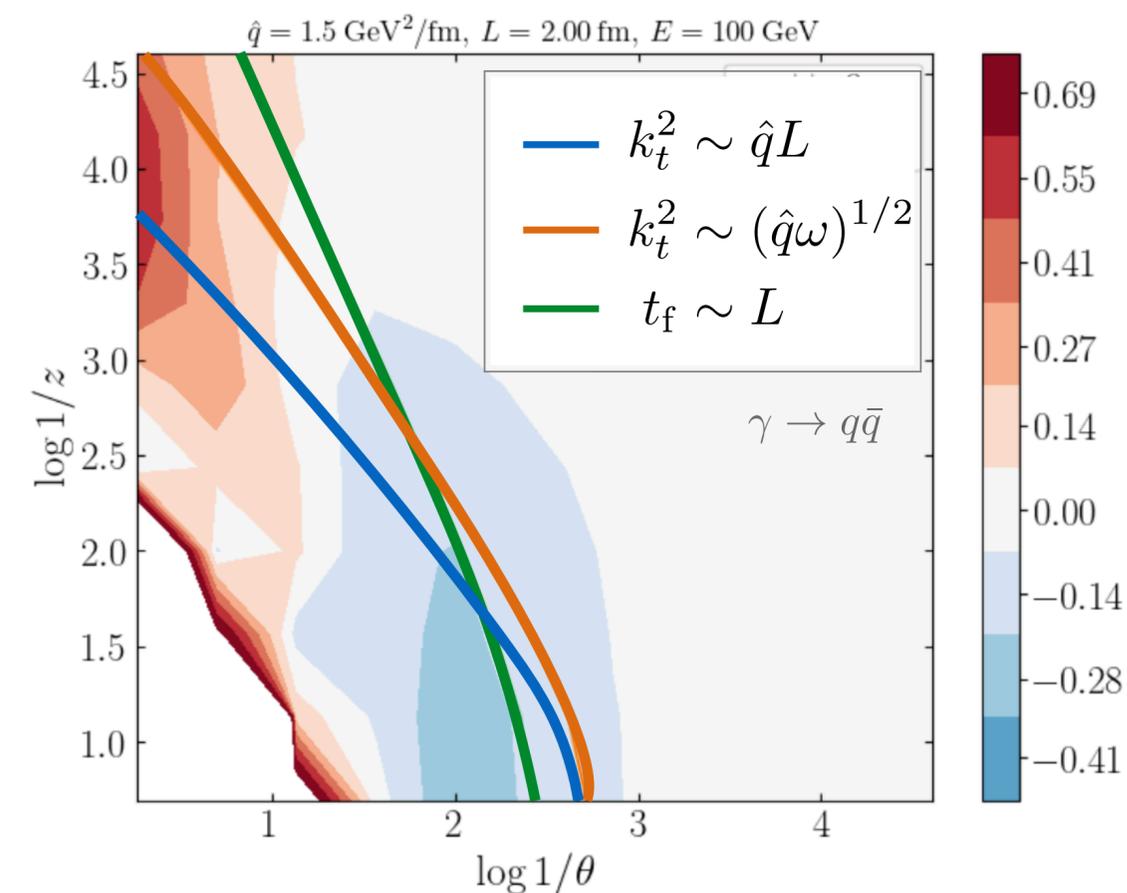
SPLITTING FUNCTION IN MEDIUM

Dominguez, Milhano, Salgado, KT, Vila 1907.03653
Isaksen, KT 2107.02542, 2303.12119

$$\frac{dN^{\text{med}}}{dz d\theta} \bigg/ \frac{dN^{\text{vac}}}{dz d\theta} = 1 + F_{\text{med}}$$



Simplified kinematics & large- N_c



Full kinematics & finite- N_c

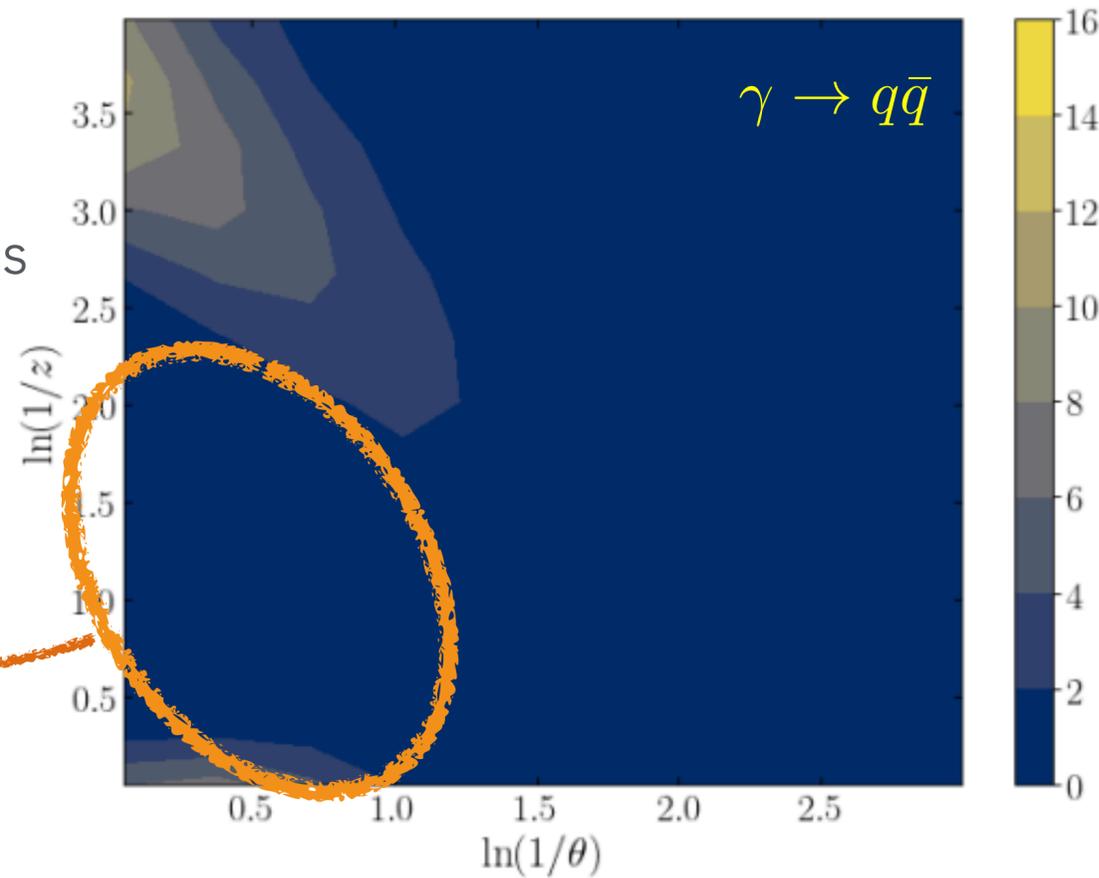
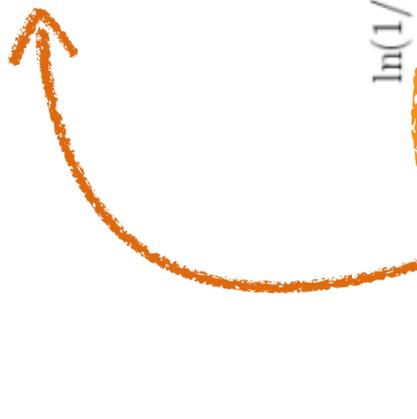


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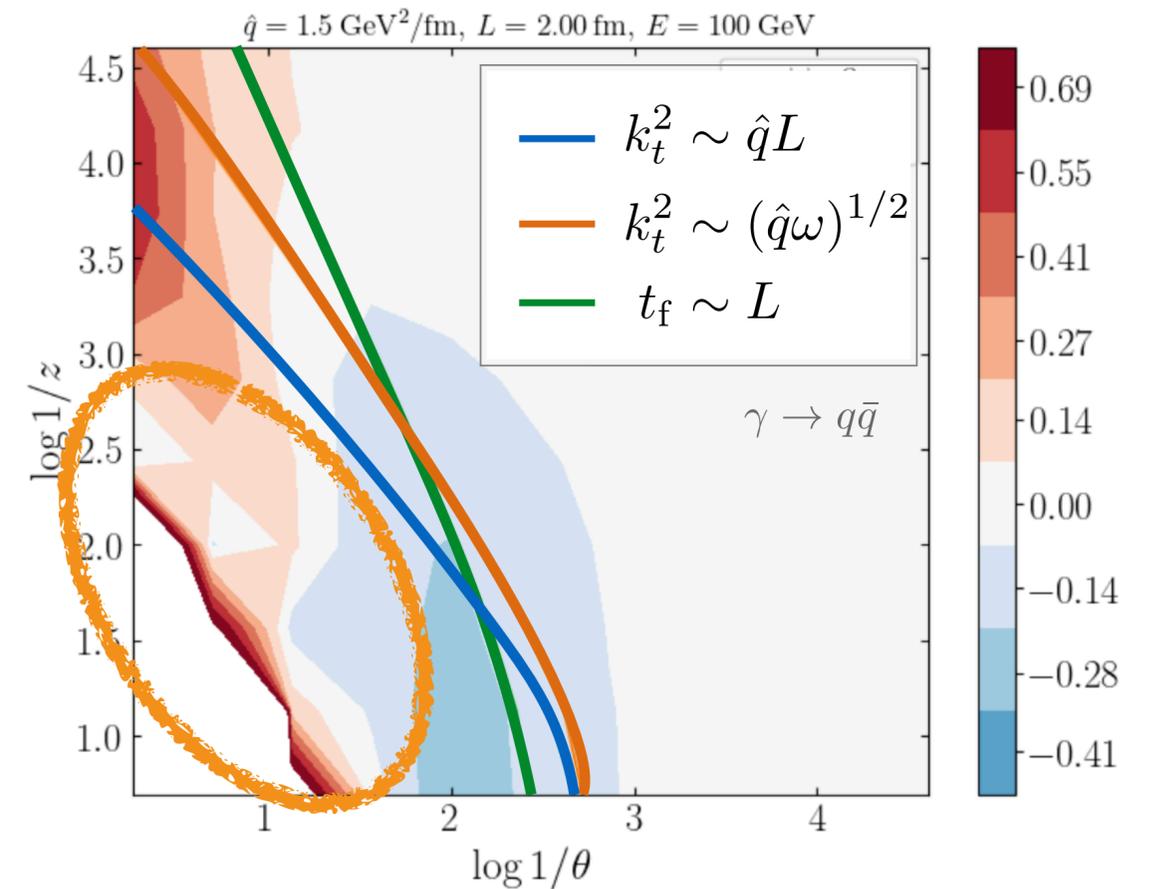
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Hard kinematics:
no medium modifications
(separation of scales)



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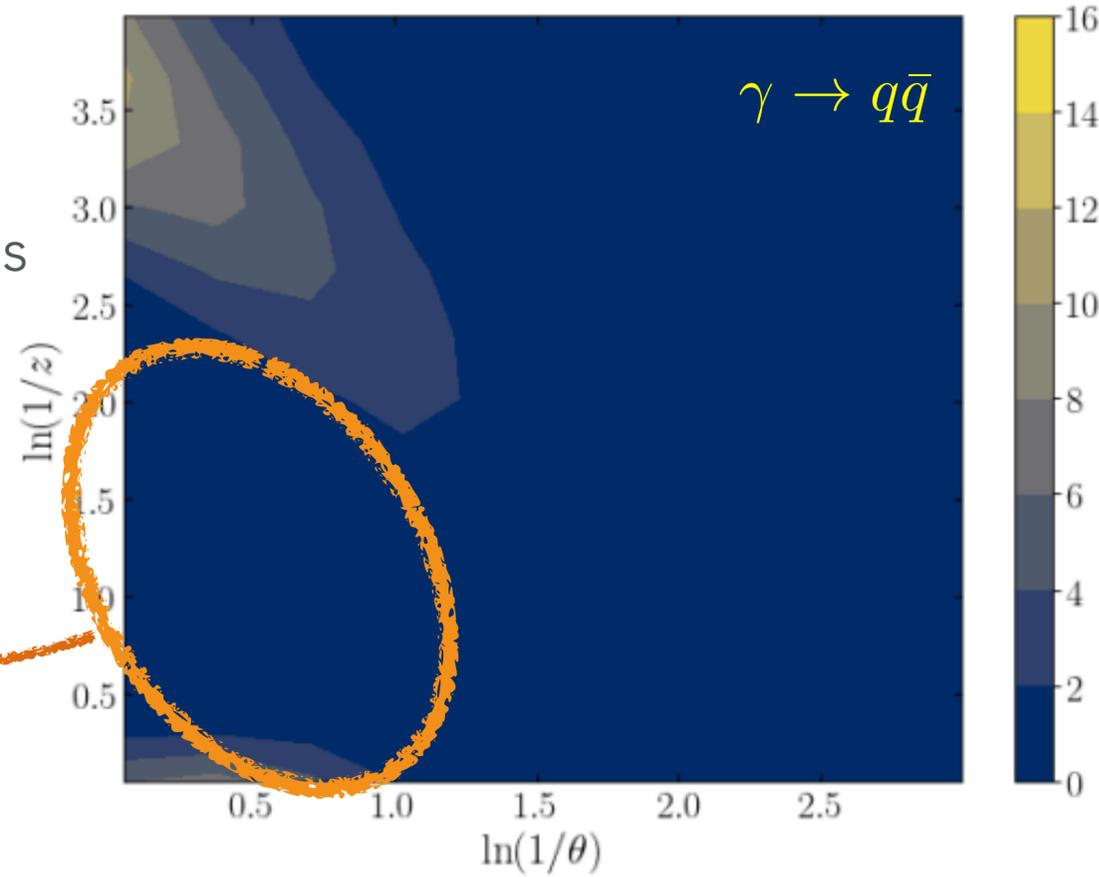
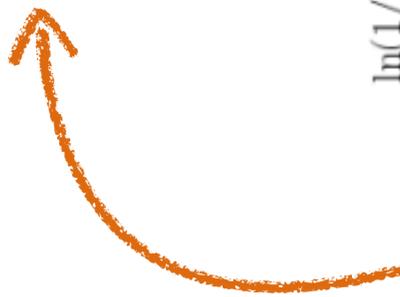


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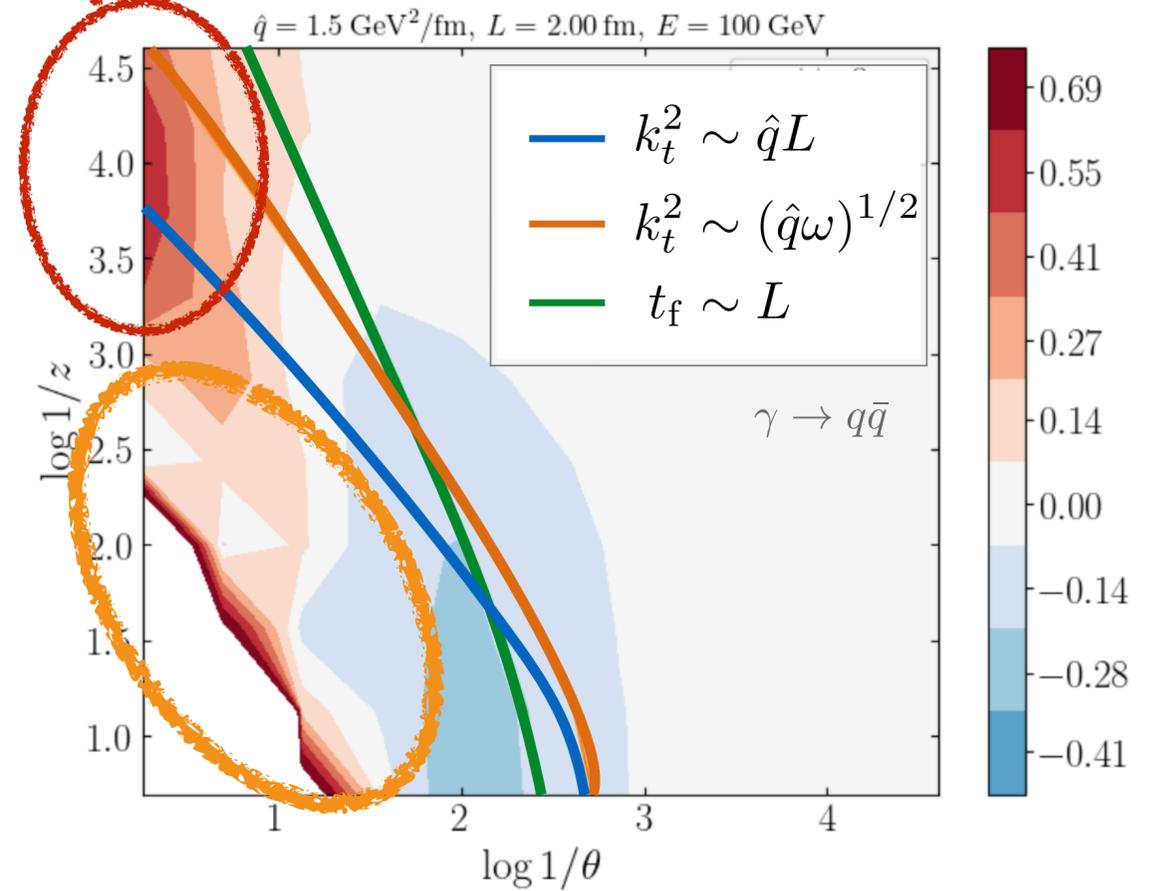
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Simplified kinematics & large- N_c

Medium modifications:
copious production of **large-angle & soft** gluons



Full kinematics & finite- N_c

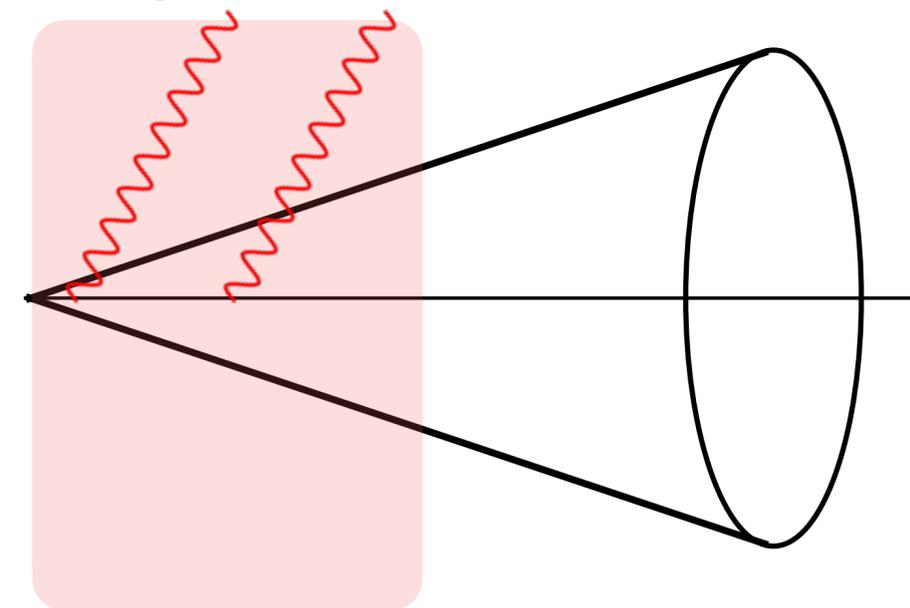


RADIATIVE ENERGY LOSS OF PARTONS

Multiple scattering leads to Gaussian broadening $\langle k^2 \rangle \sim \hat{q}t$

$$t_f \sim \sqrt{\omega l \hat{q}} \Rightarrow k_{\text{br}}^2 \sim \sqrt{\omega \hat{q}} \Rightarrow \theta_{\text{br}} \sim (\hat{q}/\omega^3)^{1/4}$$

Copious large-angle emissions at characteristic $\omega_s \sim \alpha_s^2 \hat{q}L!$



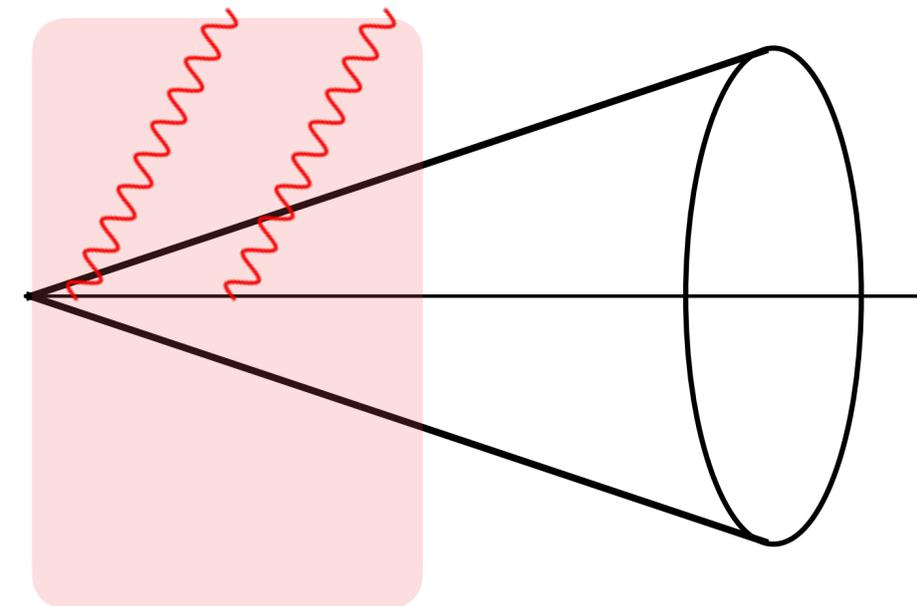


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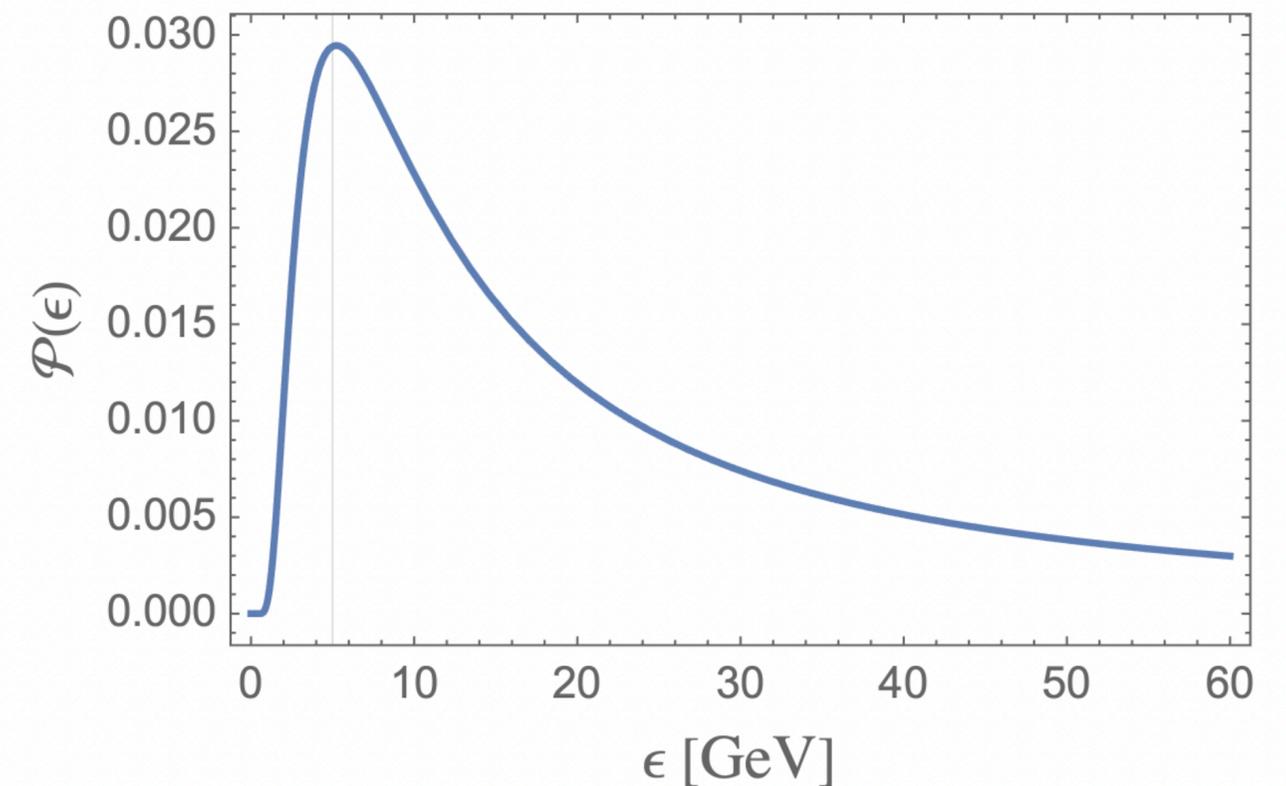
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Effective description:

multiple emissions are resummed into a probability distribution of losing a fixed amount of energy ϵ

$$\mathcal{P}(\epsilon) \simeq \delta(\epsilon) \left[1 - \int_0^\infty d\omega \frac{dI_{>}}{d\omega} \right] + \frac{dI_{>}}{d\epsilon} + \dots$$



III) ENERGY LOSS OF PARTONS AND JETS



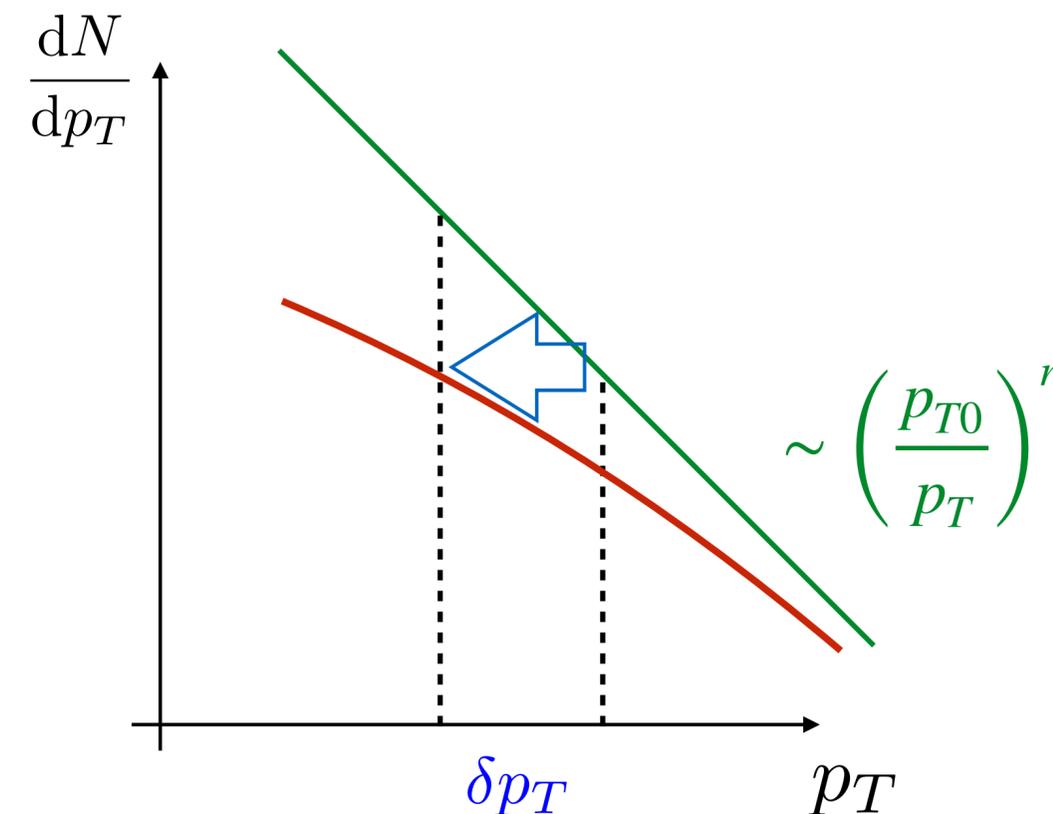


QUENCHING HARD SPECTRUM

Baier, Dokshitzer, Mueller, Schiff (2001)
Salgado, Wiedemann (2003)

quenching weight (prob. distribution)

$$\begin{aligned} \frac{d\sigma_{\text{med}}}{dp_T} &= \int_0^\infty d\epsilon \mathcal{P}(\epsilon) \left. \frac{d\sigma_{\text{vac}}}{dp'_T} \right|_{p'_T=p_T+\epsilon} \\ &\approx \frac{d\sigma_{\text{vac}}}{dp_T} \underbrace{\int_0^\infty d\epsilon \mathcal{P}(\epsilon) e^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)} \end{aligned}$$



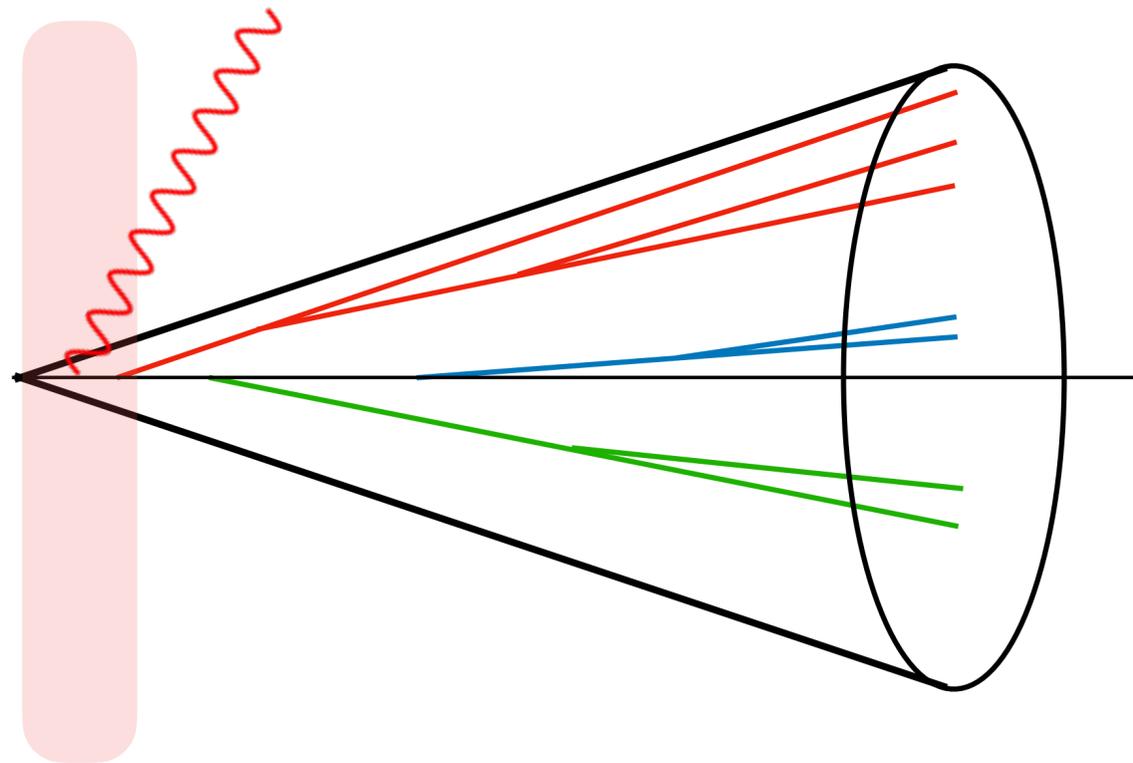
- probability distribution $\mathcal{P}(\epsilon)$ now contains radiative & elastic energy loss
- jet quenching induces an **inherent bias** on all jet observables
- **ignored for now:** medium emissions inside the cone

Good approximation for $\epsilon/p_T \ll 1$ and large n ,

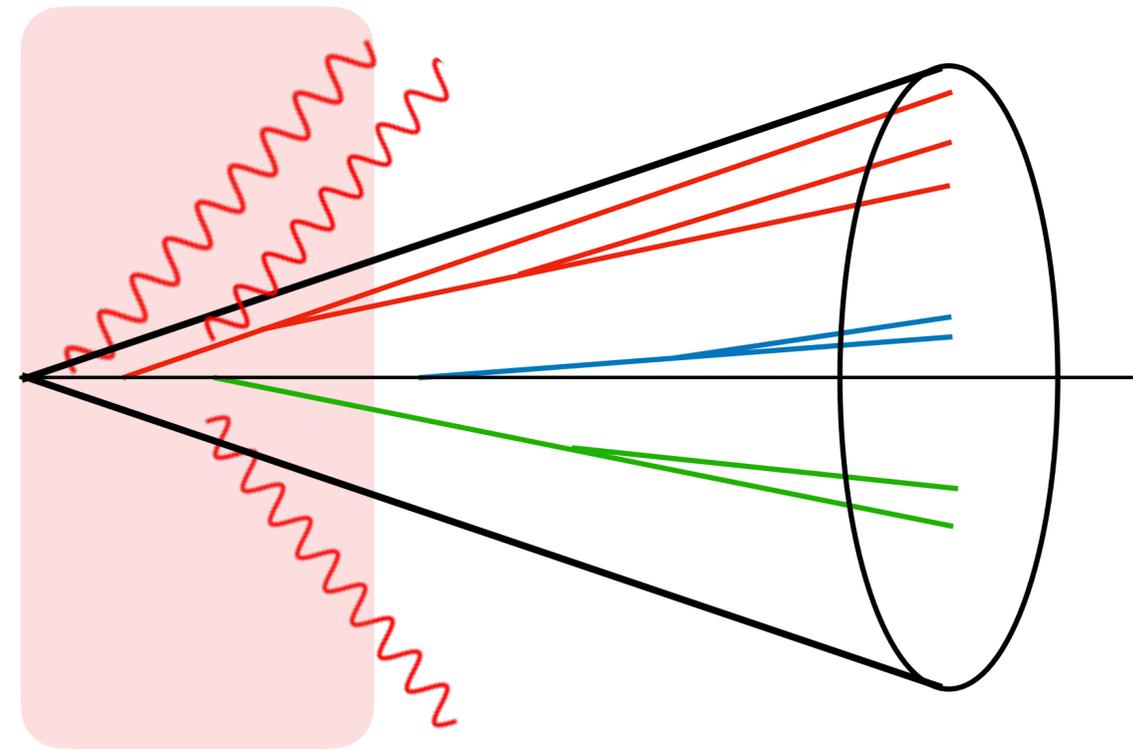
$$\frac{e^{n\epsilon/p_T}}{(1 + \epsilon/p_T)^n} \simeq 1 + \frac{n}{2} \left(\frac{\epsilon}{p_T}\right)^2 + \mathcal{O}\left((\epsilon/p_T)^3\right)$$



QUENCHING OF JETS?



1 emitter (coherence)



n emitters (partial decoherence)



AN ANALOGY

jet quenching \leftrightarrow loss of information

Consider a random variable n generated according to (with $\langle n \rangle = \lambda$): $P(n) = \frac{1}{n!} \lambda^n e^{-\lambda}$



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$P(0)$: analog of
Sudakov supp. factor

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In addition, another random process occurs ("loss" ($Q < 1$)) so that: $\tilde{P}_{\text{final}}(n) = Q^n P(n)$



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Recorded event fraction $C = \sum_{n=0}^{\infty} \tilde{P}_{\text{final}}(n) = e^{(Q-1)\lambda}$

analog of "collimator"
function!



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Final, normalized distribution is simply ($\langle n \rangle = Q\lambda$): $P_{\text{final}}(n) = C^{-1} \tilde{P}_{\text{final}}(n) = \frac{1}{n!} (Q\lambda)^n e^{-Q\lambda}$



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Analog of the quenching factor for n jet prongs is $Q_{\text{tot}} = Q^n e^{(1-Q)\lambda}$



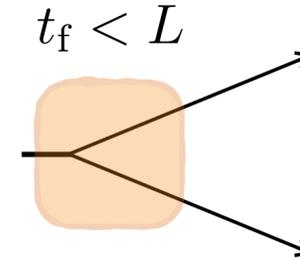
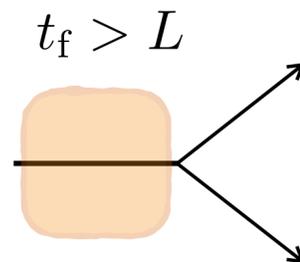
COUNTING SUBJECTS PRODUCED INSIDE THE MEDIUM



Quenching effect very different in the two situations...
(quenching of two vs. quenching of one)

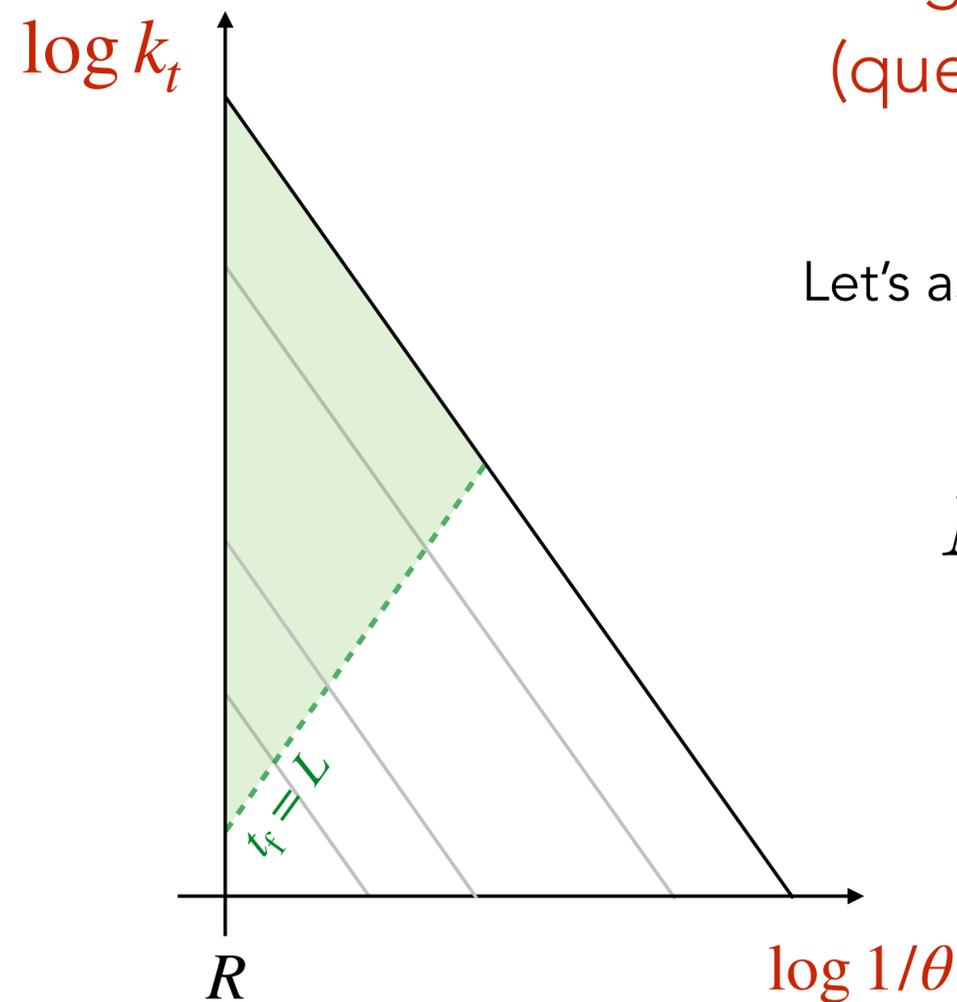


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Let's assume that the medium quenches completely all emissions inside the medium!



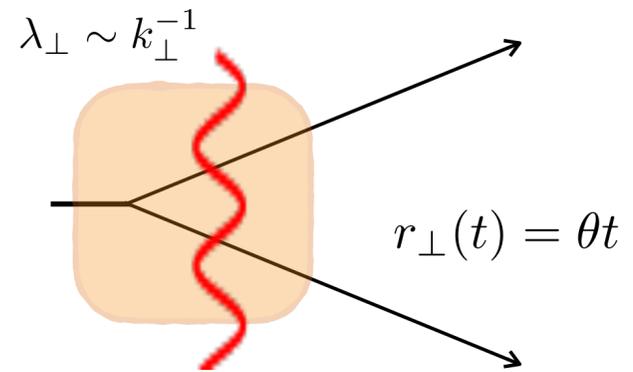
$$N(t_f < L) = \bar{\alpha} \int_{(\omega\theta^2)^{-1} < L} \frac{d\omega}{\omega} \frac{d\theta}{\theta} = \frac{\bar{\alpha}}{4} \log^2 p_T R L$$

👉 could affect many splittings!



PHASE SPACE ANALYSIS

Y. Mehtar-Tani, KT 1706.06047, 1707.07361

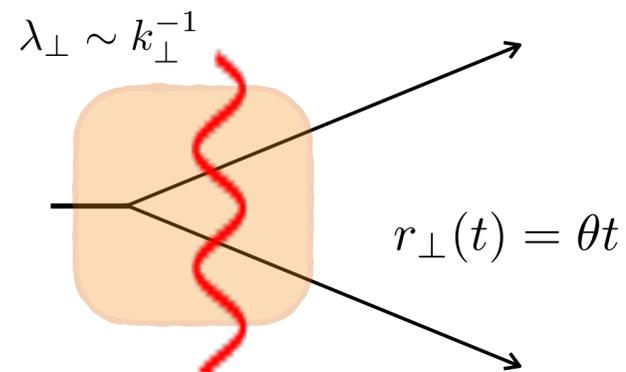


$$r_{\perp}^{-1} = (\theta t)^{-1} \sim (\hat{q}t)^{1/2} \Rightarrow t_d \sim (\hat{q}\theta^2)^{1/3}$$



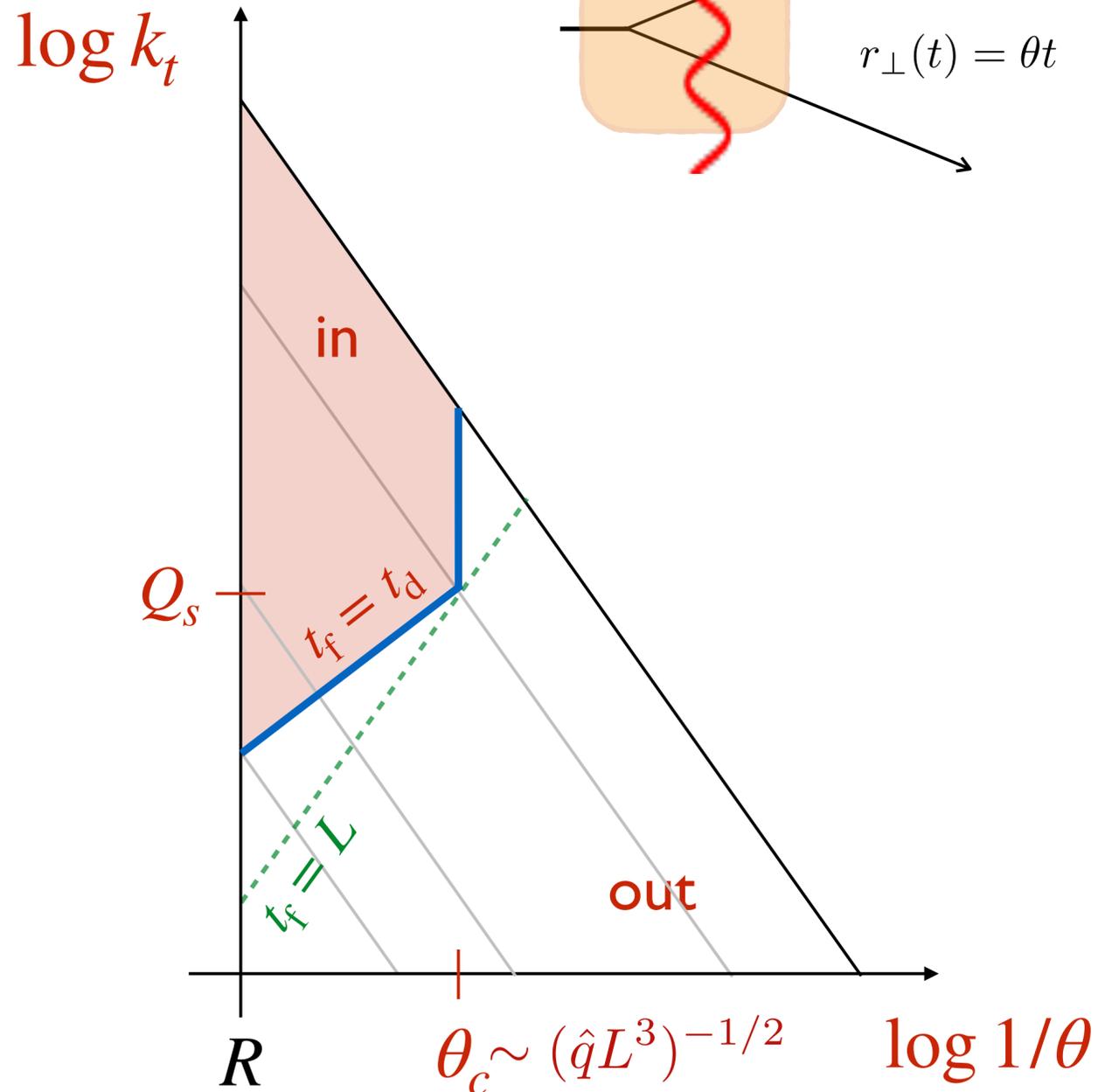
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Accounting for color coherence leads to $t_f < t_d < L$



$$(\text{PS})_{\text{in}} \approx 2 \frac{\alpha_s C_R}{\pi} \log \frac{R}{\theta_c} \left(\log \frac{p_T}{\omega_c} + \frac{2}{3} \log \frac{R}{\theta_c} \right)$$

Interpretation: vacuum-like emissions created on short distances inside the medium act as sources of medium-induced radiation & cascade.

Discussion is **completely generic** & applies any theory or MC implementation!

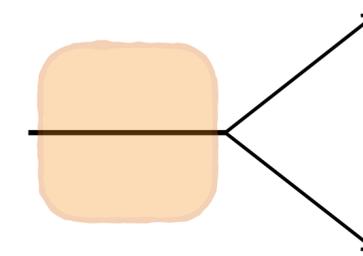
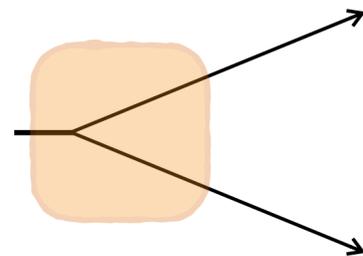


MEDIUM “DECORATED” SPLITTING FUNCTION

Y. Mehtar-Tani, KT 1707.07361

Real emission (“decorated” with energy loss):

$$\frac{d\sigma_i^{\text{med}}}{dz d\theta dp_T} = \Theta_{\text{in}} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 \mathcal{P}_i(\epsilon_1) \mathcal{P}_g(\epsilon_2) P_{gi}(\tilde{z}, \theta) \left. \frac{d\sigma_0}{dp'_T} \right|_{p'_T=p_T+\epsilon_1+\epsilon_2} + (1 - \Theta_{\text{in}}) P_{gi}(z, \theta) \int_0^\infty d\epsilon \mathcal{P}_i(\epsilon) \left. \frac{d\sigma_0}{dp'_T} \right|_{p'_T=p_T+\epsilon}$$



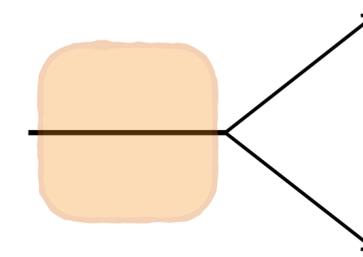
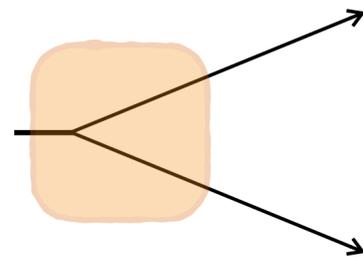


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Leading effect from **energy loss** (neglect modification of momentum sharing fraction):

$$\frac{d\sigma_i^{\text{med}}}{dz d\theta dp_T} = P_{gi}^{\text{vac}}(z, \theta) [\Theta_{\text{in}} \mathcal{Q}_i(p_T) \mathcal{Q}_g(p_T) + (1 - \Theta_{\text{in}}) \mathcal{Q}_i(p_T)] \hat{\sigma}_i(p_T) + \dots$$

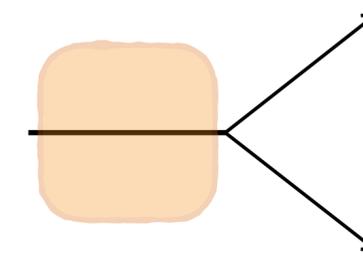
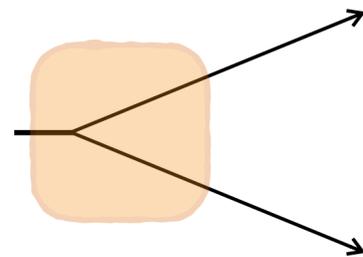


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quenching of total charge

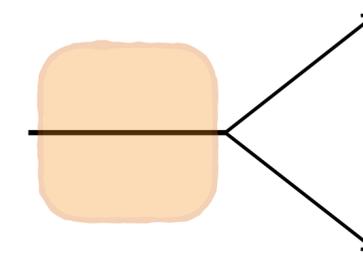
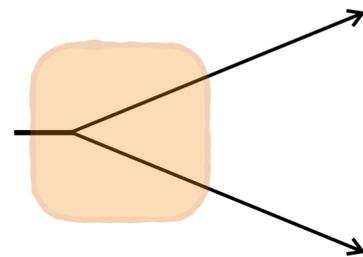


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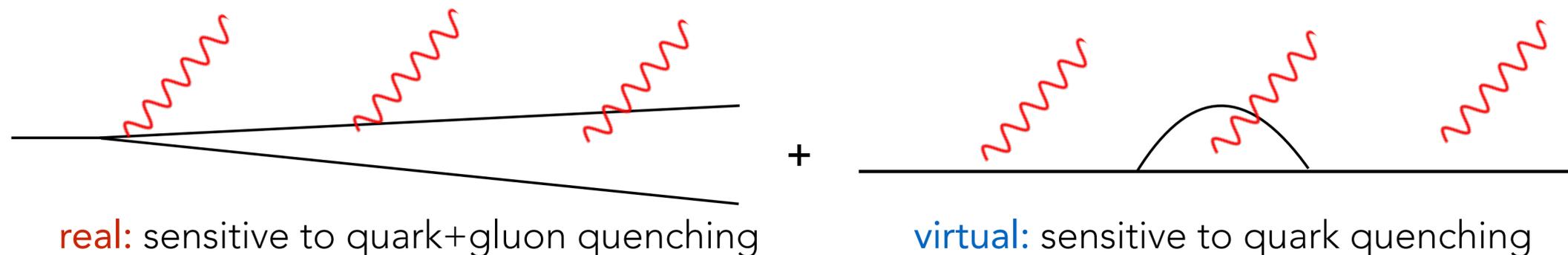
quenching of additional gluon

quenching of total charge



HIGHER-ORDER CORRECTIONS TO ENERGY LOSS

Y. Mehtar-Tani, KT 1707.07361



Perturbative expansion:
~in number of color sources

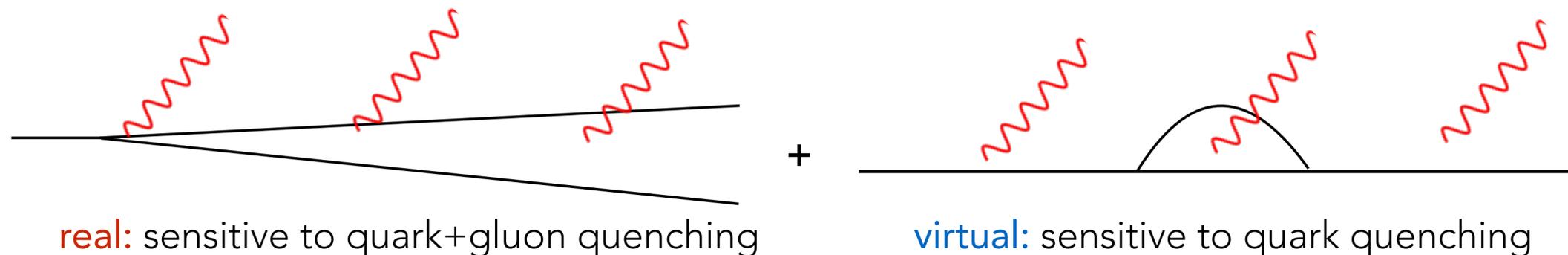
$$\frac{d\sigma_i^{\text{jet}}}{dp_T} = \frac{d\sigma_i^{(0)}}{dp_T} + \alpha_s \frac{d\sigma_i^{(1)}}{dp_T} + \dots$$

$$d\sigma^{(0)}/dp_T = Q_i \hat{\sigma}_i$$



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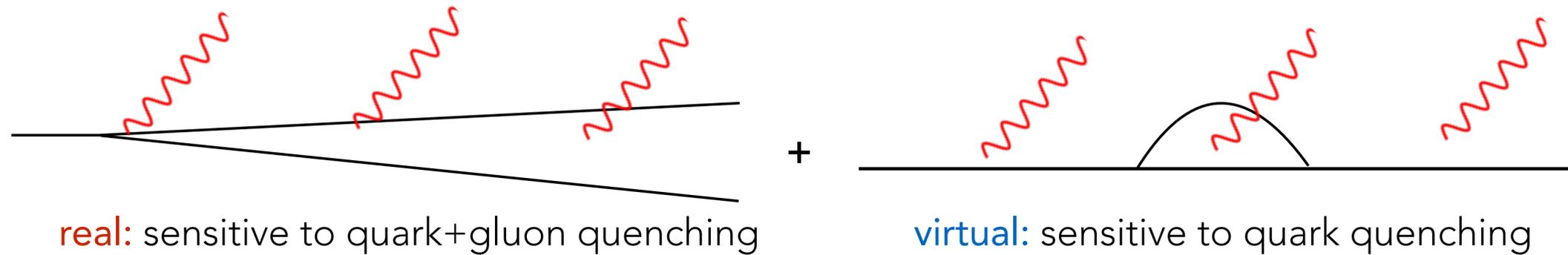
First correction:

$$\alpha_s \frac{d\sigma_i^{(1)}}{dp_T} = \int_0^R d\theta \int_0^1 dz [P_i^{\text{med}}(z, \theta) - Q_i P_i^{\text{vac}}(z, \theta)] \hat{\sigma}_i$$



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~in number of color sources

$$\frac{d\sigma_i^{\text{jet}}}{dp_T} = \frac{d\sigma_i^{(0)}}{dp_T} + \alpha_s \frac{d\sigma_i^{(1)}}{dp_T} + \dots \quad d\sigma^{(0)}/dp_T = Q_i \hat{\sigma}_i$$

First correction:

$$\alpha_s \frac{d\sigma_i^{(1)}}{dp_T} = \int_0^R d\theta \int_0^1 dz [P_i^{\text{med}}(z, \theta) - Q_i P_i^{\text{vac}}(z, \theta)] \hat{\sigma}_i$$

Exponentiation:
"linearized" approximation

$$\begin{aligned} \frac{d\sigma_i^{\text{jet}}}{dp_T} &= Q_i \left[1 + (Q_g - 1) \int d\Pi_i \Theta_{\text{in}} + \dots \right] \hat{\sigma}_i \\ &\simeq Q_i e^{(Q_g - 1) \int d\Pi_i \Theta_{\text{in}}} \hat{\sigma}_i, \end{aligned}$$



RESUMMED QUENCHING FACTOR

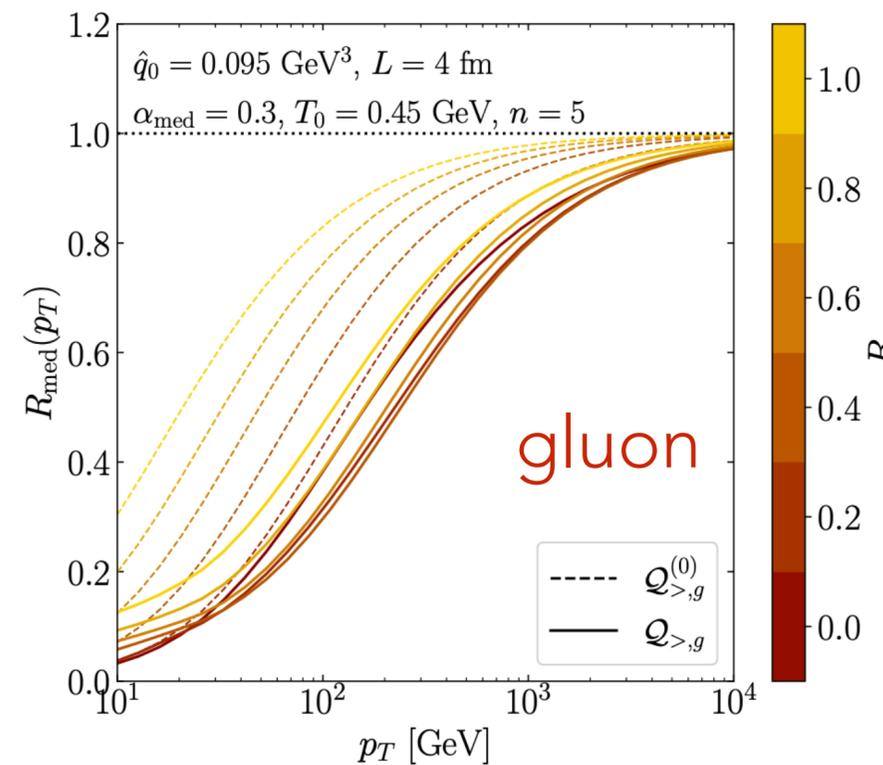
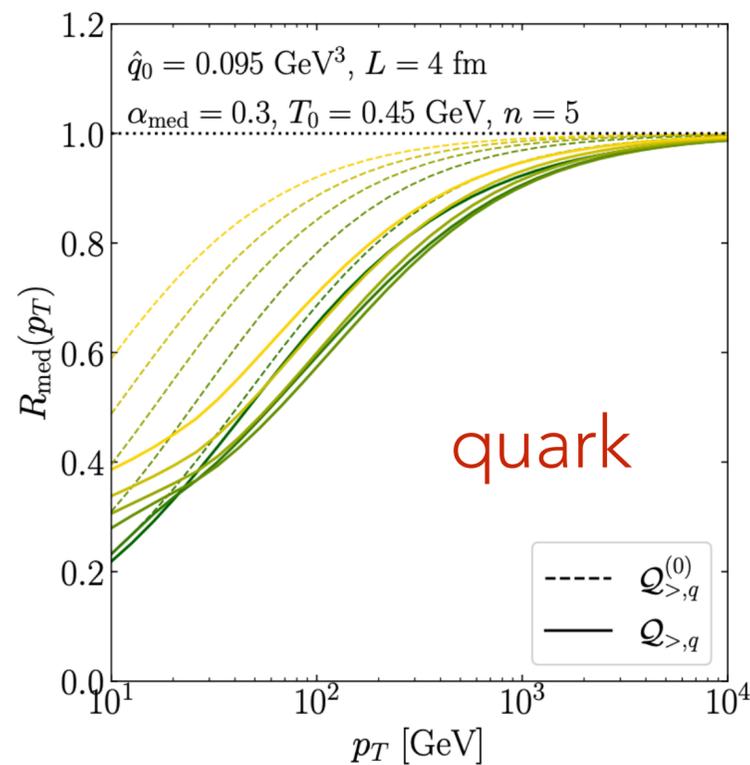
Mehtar-Tani, KT 1707.07361
 Mehtar-Tani, Pablos, KT 2101.01742

Non-linear evolution of jet quenching

Going from parton energy loss $\mathcal{Q}_i(p_T)$ to full jet energy loss.

$$\frac{\partial Q_i(p, \theta)}{\partial \ln \theta} = \int_0^1 dz \frac{\alpha_s(k_\perp)}{2\pi} p_{ji}^{(k)}(z) \Theta_{\text{res}}(z, \theta) [Q_j(zp, \theta) Q_k((1-z)p, \theta) - Q_i(p, \theta)]$$

Takacs, KT 2103.14676



Milder R -dependence than for single-parton quenching!

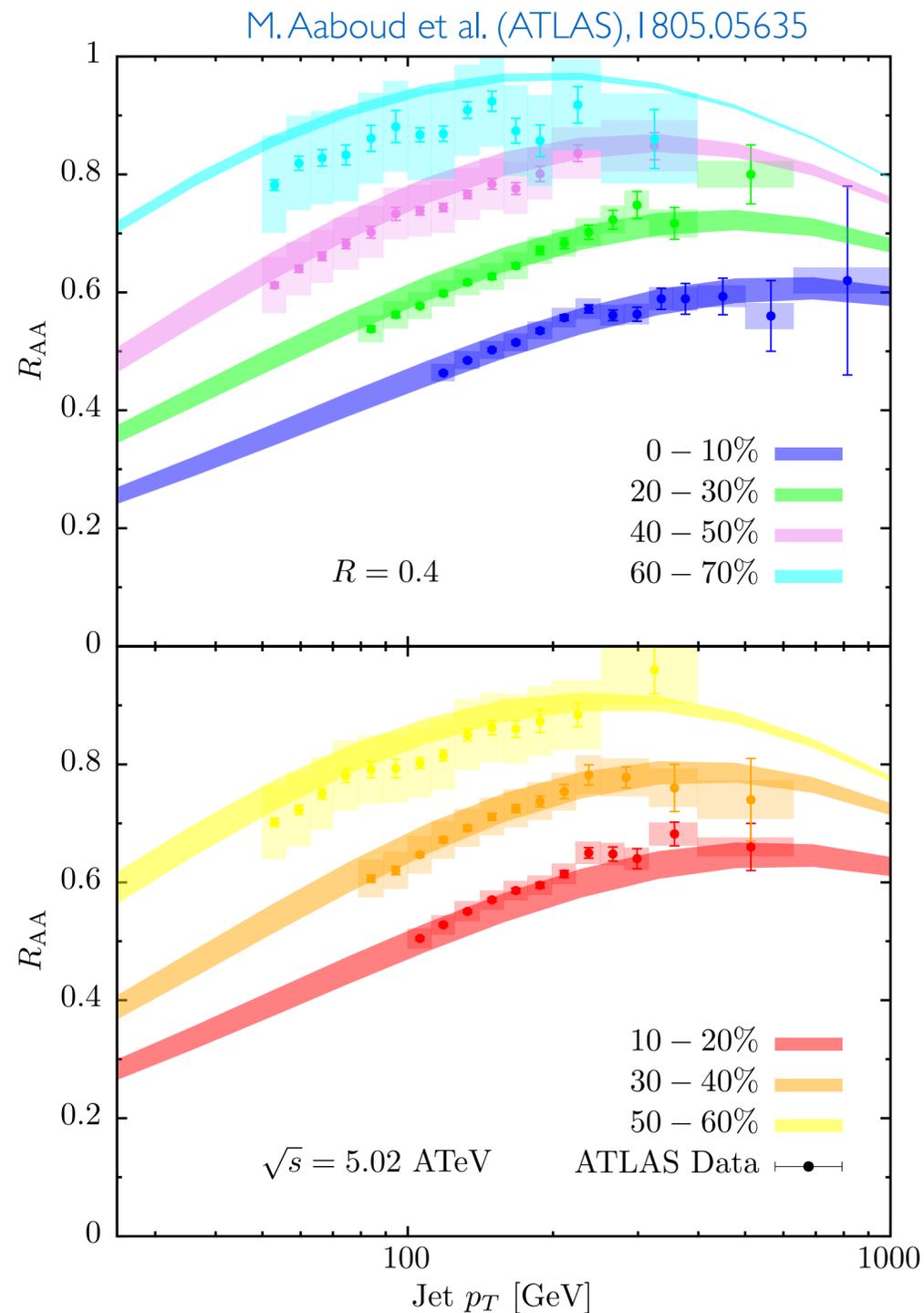
Interplay of two effects:

- recovery of radiated energy at large R
- more color sources from vacuum-like emissions at large R



PHENOMENOLOGICAL STUDIES

Mehtar-Tani, Pablos, KT 2101.01742
Takacs, KT 2103.14676



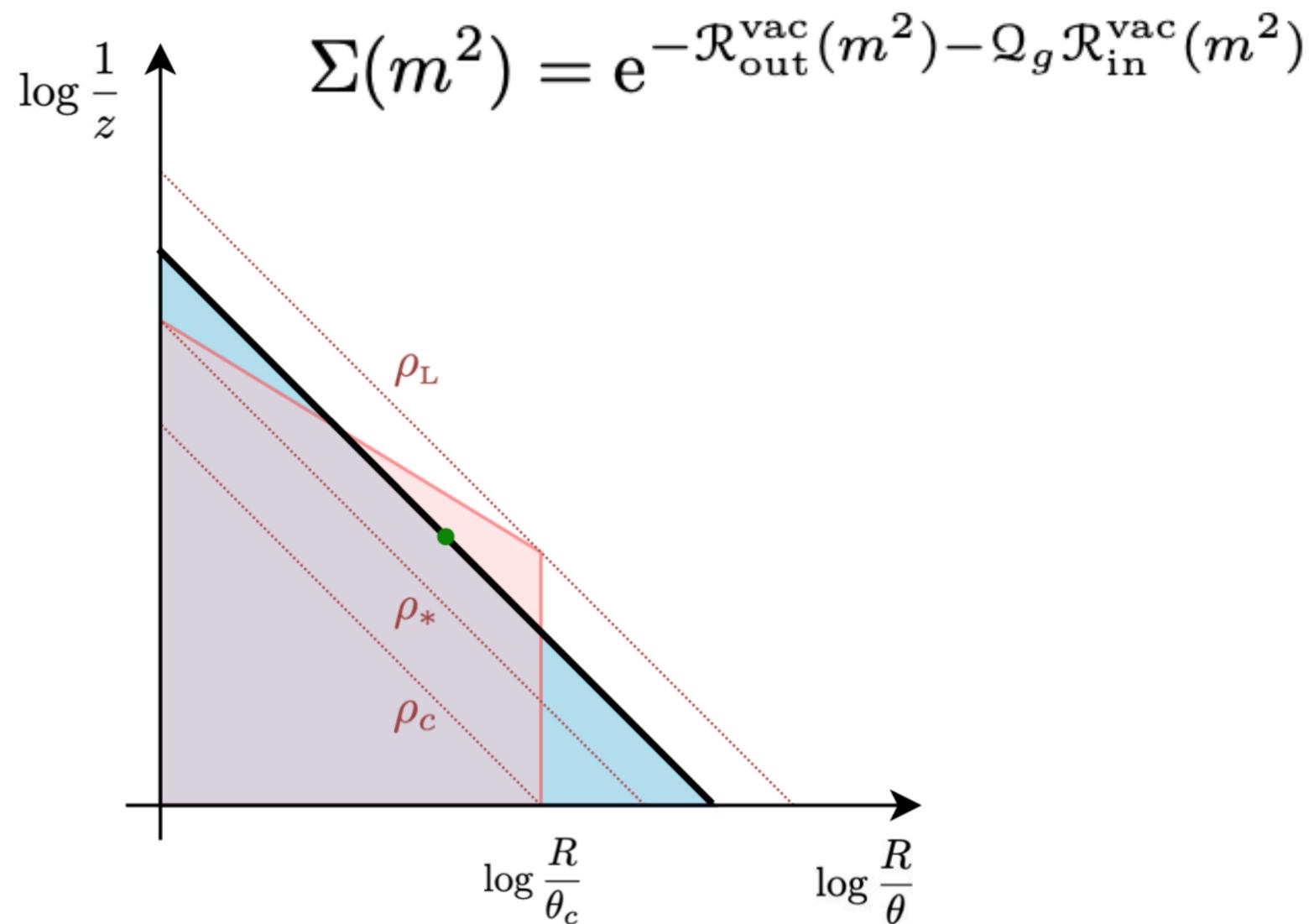
- collinear factorization w/nPDF (EPS09) to obtain quark/gluon jet fractions
- $\log 1/R$ resummation to $R = 0.4$
- full resummation of radiative and elastic processes in the medium
- sampling of geometry and medium evolution (VISHNU) Shen, Qiu, Song, Bernhard, Bass, Heinz | 409.8164
- only two free parameters: g_{med} (medium coupling) and R_{rec} (recovery angle)
- main uncertainty for small- R jets: multiplicity in **in-medium phase space!**



SUBSTRUCTURE OBSERVABLES

Similar expansion carried out for any substructure observable

$$\tilde{\Sigma}_i(m^2) = \int_0^{m^2} dm'^2 \frac{d\sigma}{dm'^2} = \tilde{\Sigma}_i^{(0)}(m^2) + \alpha_s \tilde{\Sigma}_i^{(1)}(m^2) + \mathcal{O}(\alpha_s^2)$$

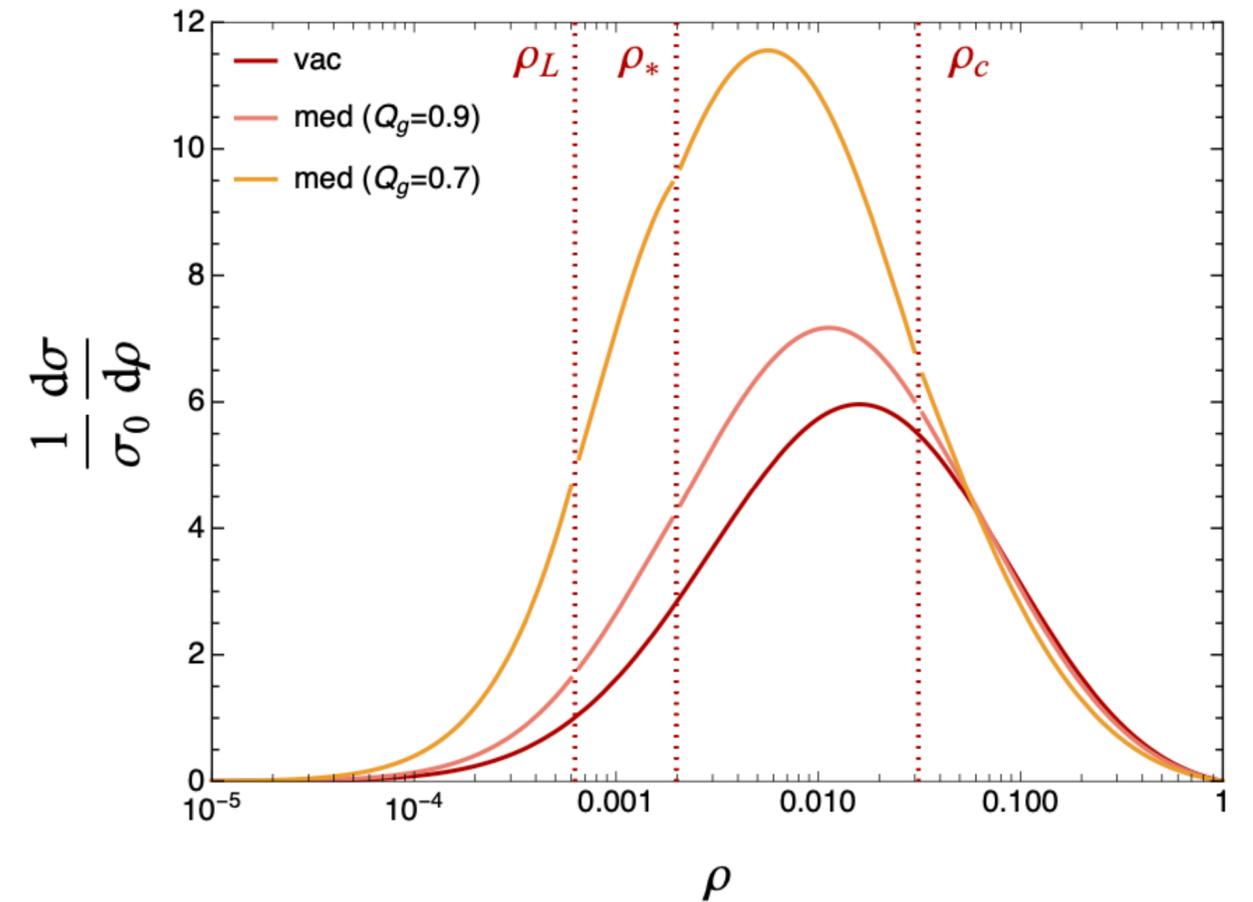
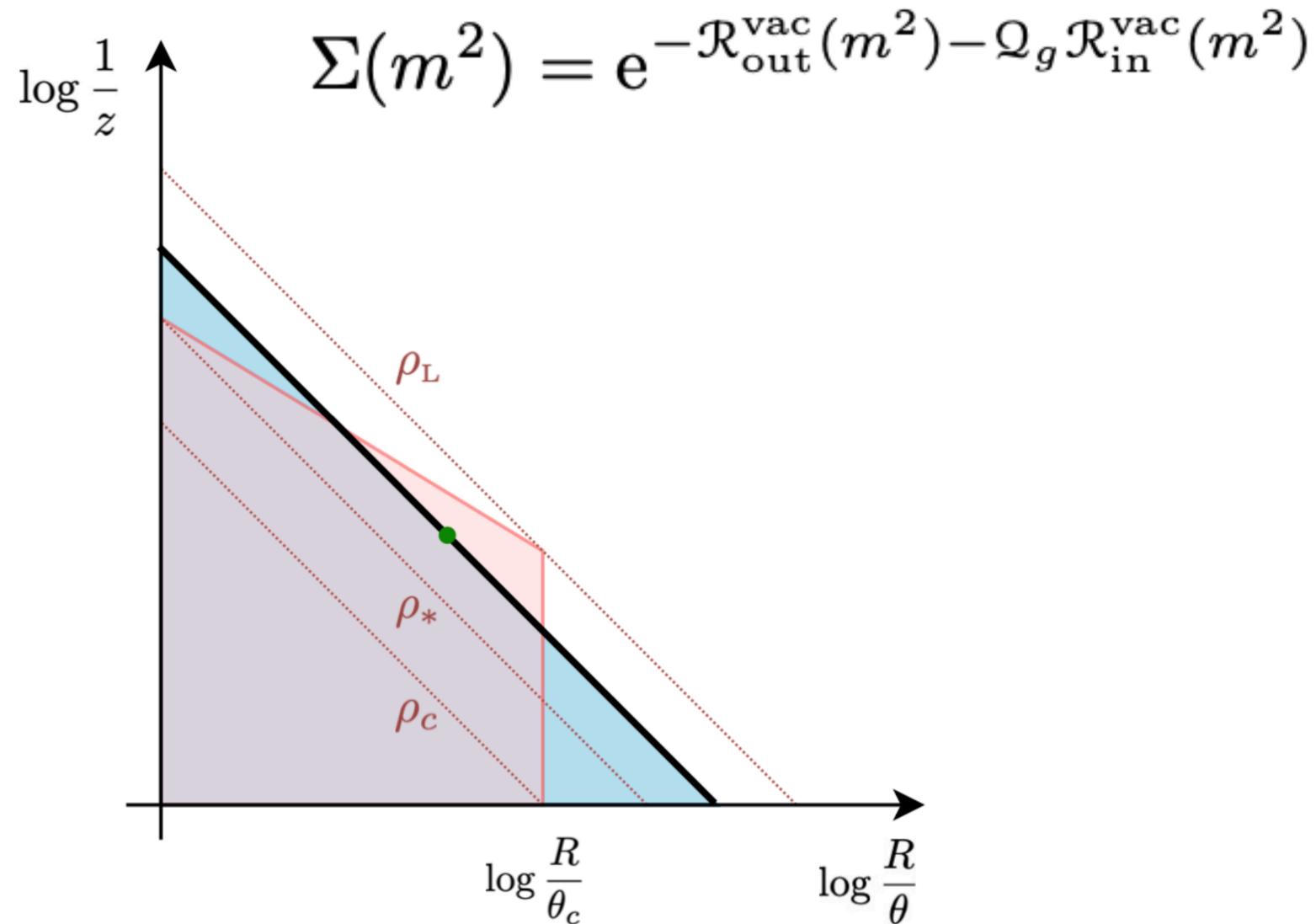




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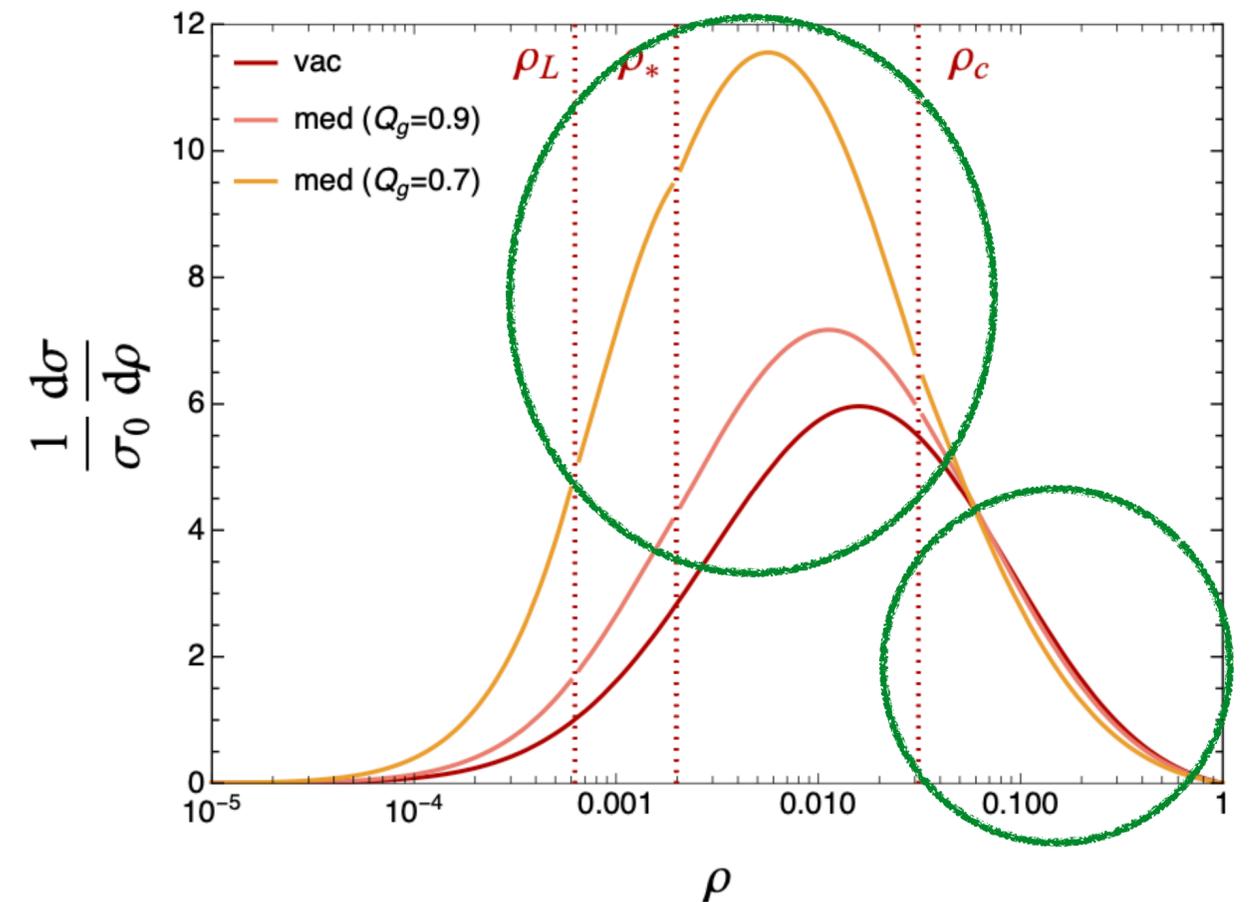
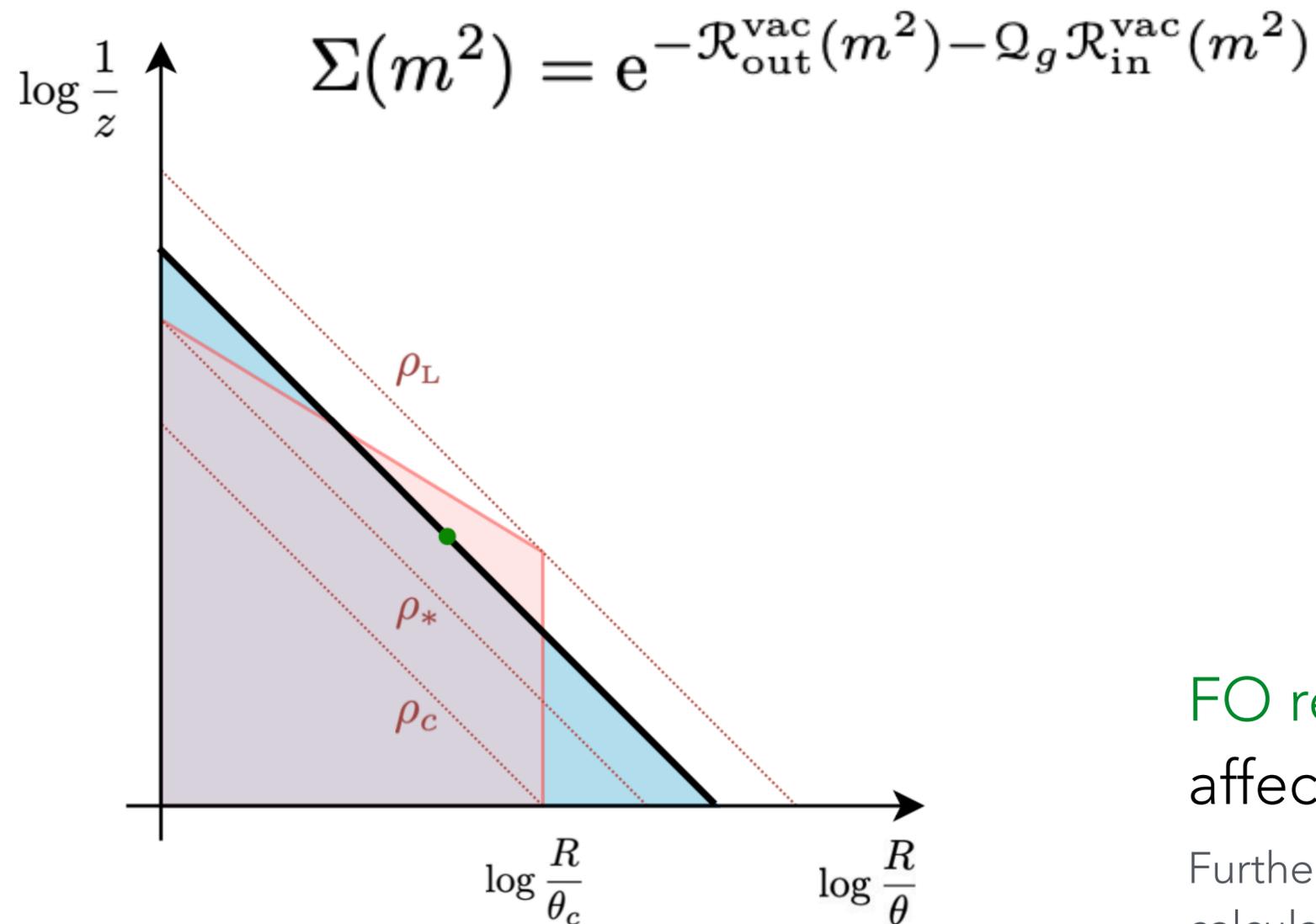




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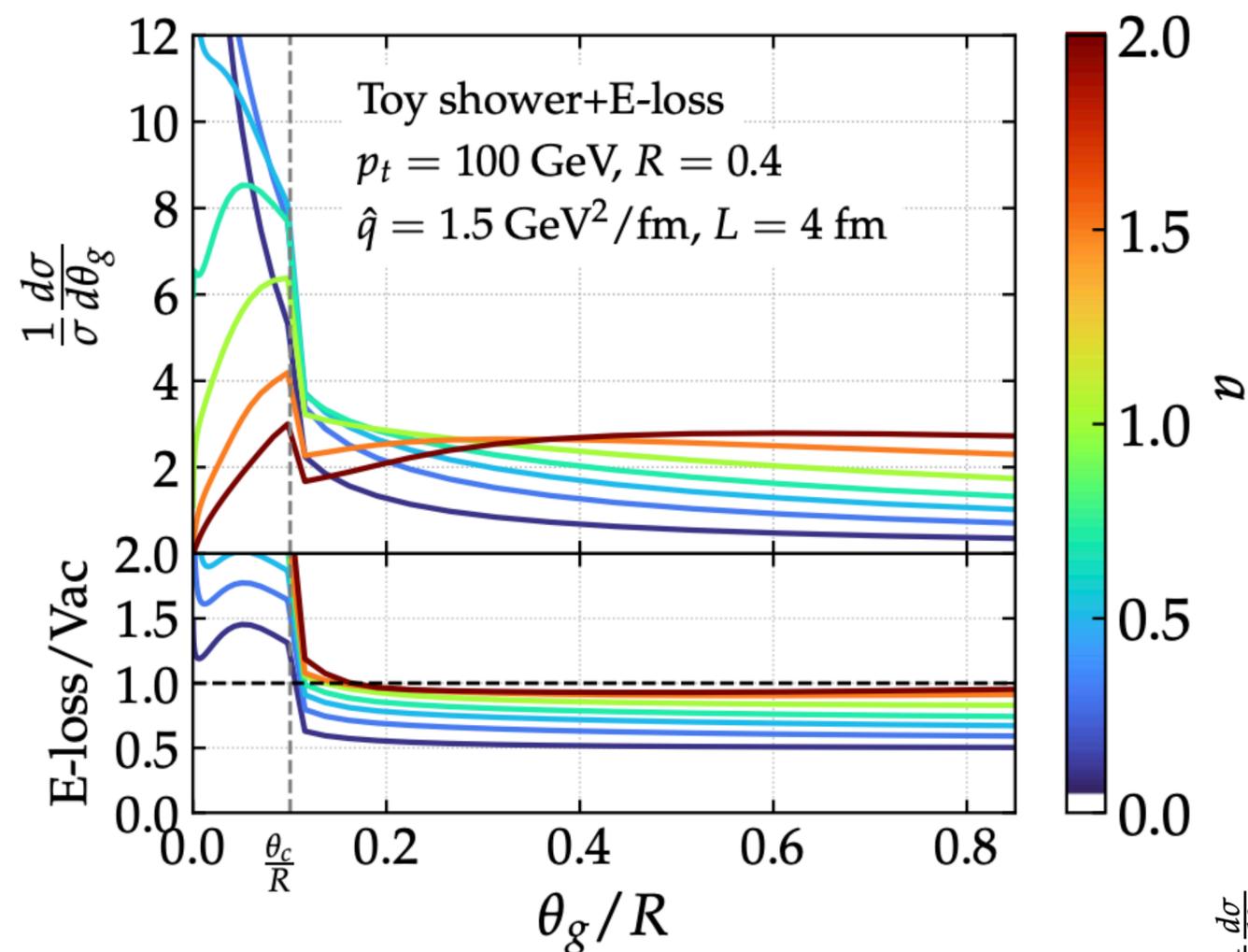
FO regime & resummation of peak strongly affected by quenching & correlated.

Further corrections on FO regime via explicit first-principle calculations is possible!



GROOMED SUBSTRUCTURE

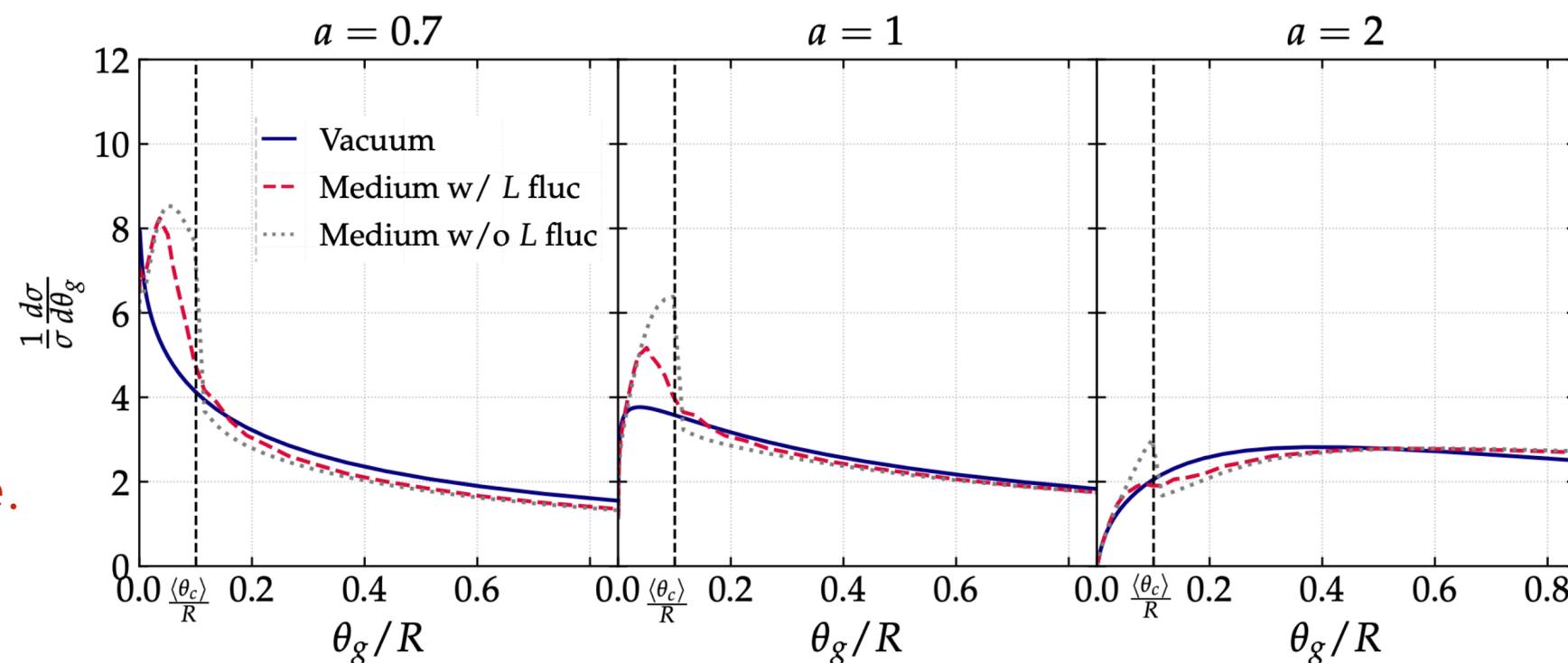
Caucal, Soto-Ontoso, Takacs 2111.14768



Striking sensitivity to θ_c \rightarrow sensitivity to in-medium phase space.

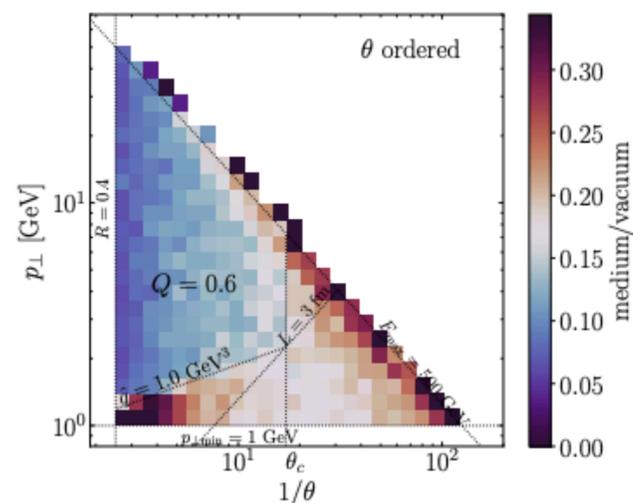
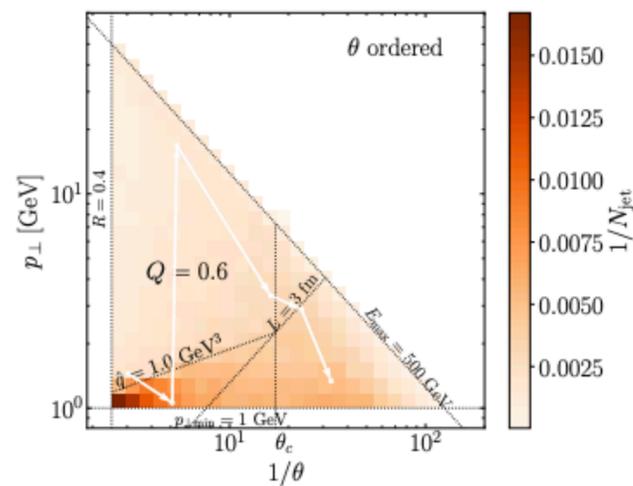
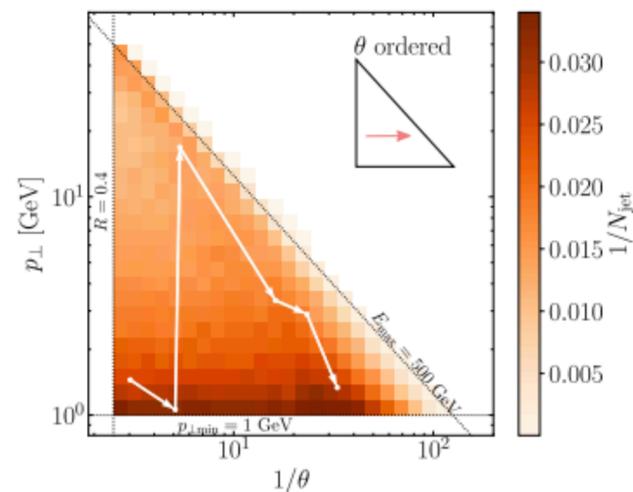
State-of-the-art calculation including energy loss, medium-induced emissions and geometry.

$$\frac{1}{\sigma} \frac{d\sigma}{d\theta_g} \Big|_{p_t} = \mathcal{N}_{\text{med}}^{-1} \sum_{i \in \{q, g\}} \frac{d\sigma_i^h}{dp_t} \int dz_g \mathcal{P}_i^{\text{med}}(z_g, \theta_g) \times [(1 - \Theta_{\text{res}}) \mathcal{Q}_i(p_t, R) + \Theta_{\text{res}} \mathcal{Q}_g(p_t, R) \mathcal{Q}_i(p_t, R)]$$





RE-WEIGHTING ON THE LUND PLANE



- analytical calculations @ DLA support simple procedure
 - any jet re-weighted with quenching of total color charge Q_i
 - n number of hits in Θ_{in} brings another suppression factor Q_g^n
- **caveats:**
 - picture starts breaking down for coincidence measurements in balanced configurations (\sim flat spectrum)...
 - work-around: fixed order calculations



SUMMARY

- jet energy loss in QCD medium induces survival bias on all jet observables in heavy-ion effect
 - strongest effect measured so far: $R_{AA}(p_T)$
- full jet loses energy as a collection of resolved partons emitted deep inside the medium (Lund Plane)
 - resummed quenching factor
- strong constraining power by varying jet scales (p_T, R) and medium scales (mainly L)
- **exciting prospects:** looking for genuine medium-induced splittings/tails directly sensitive to parton-medium interactions

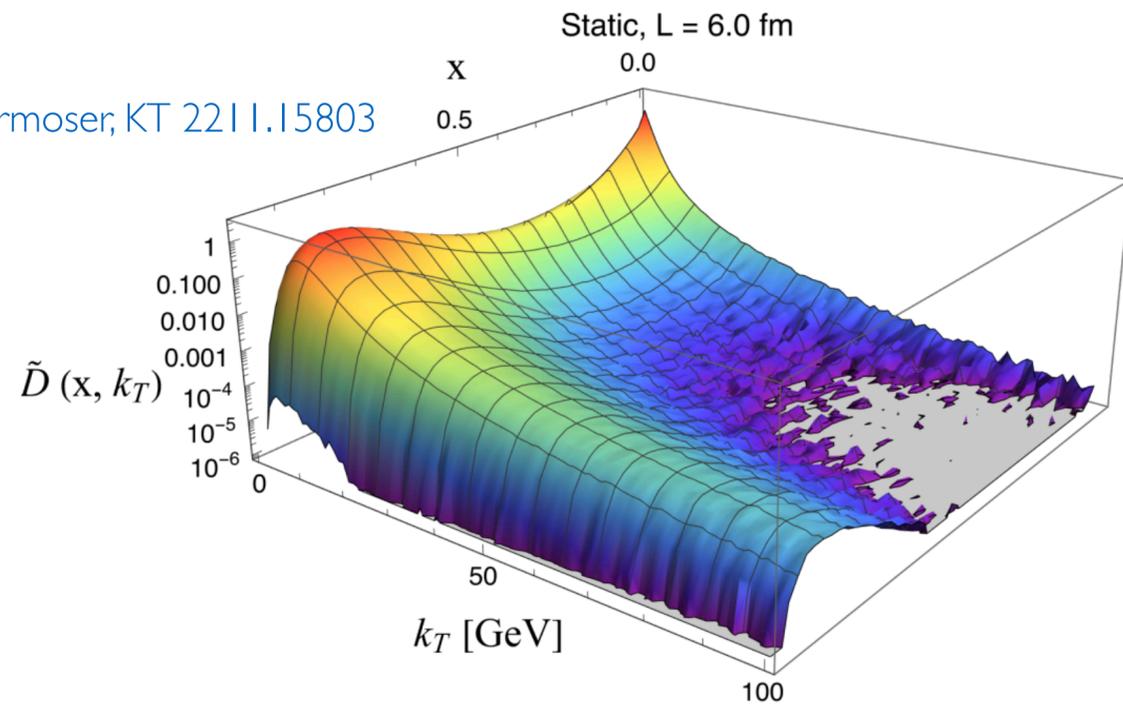
THANK YOU!



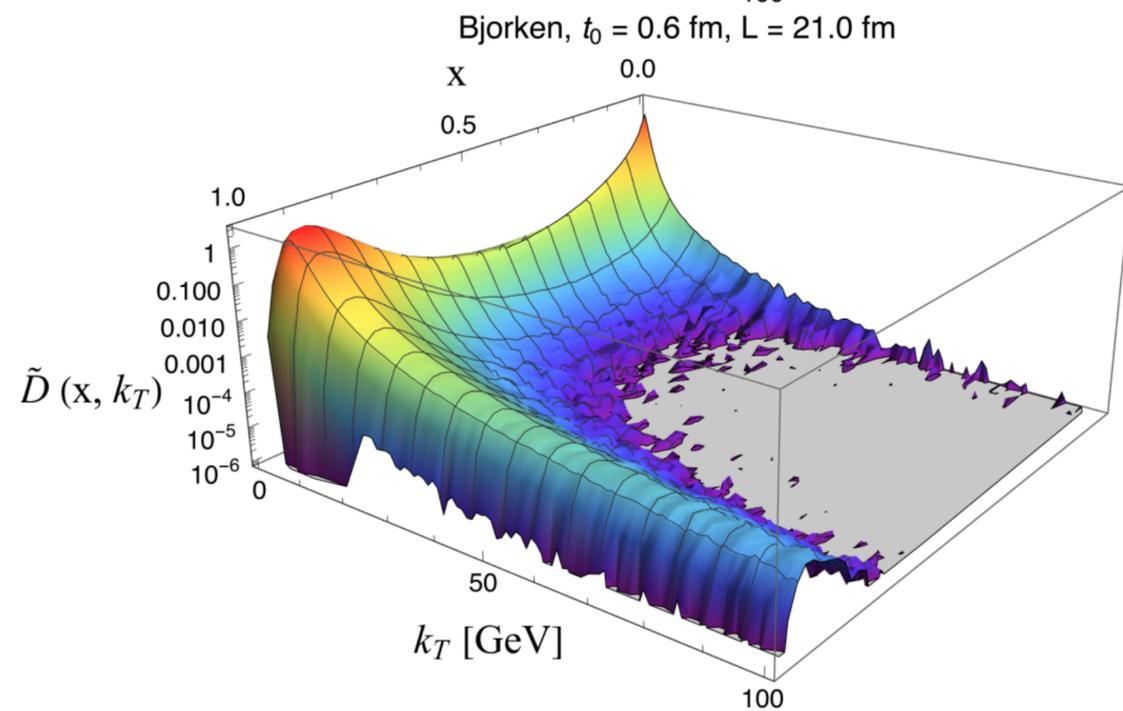


ANGULAR ENERGY PROFILE AFTER MEDIUM

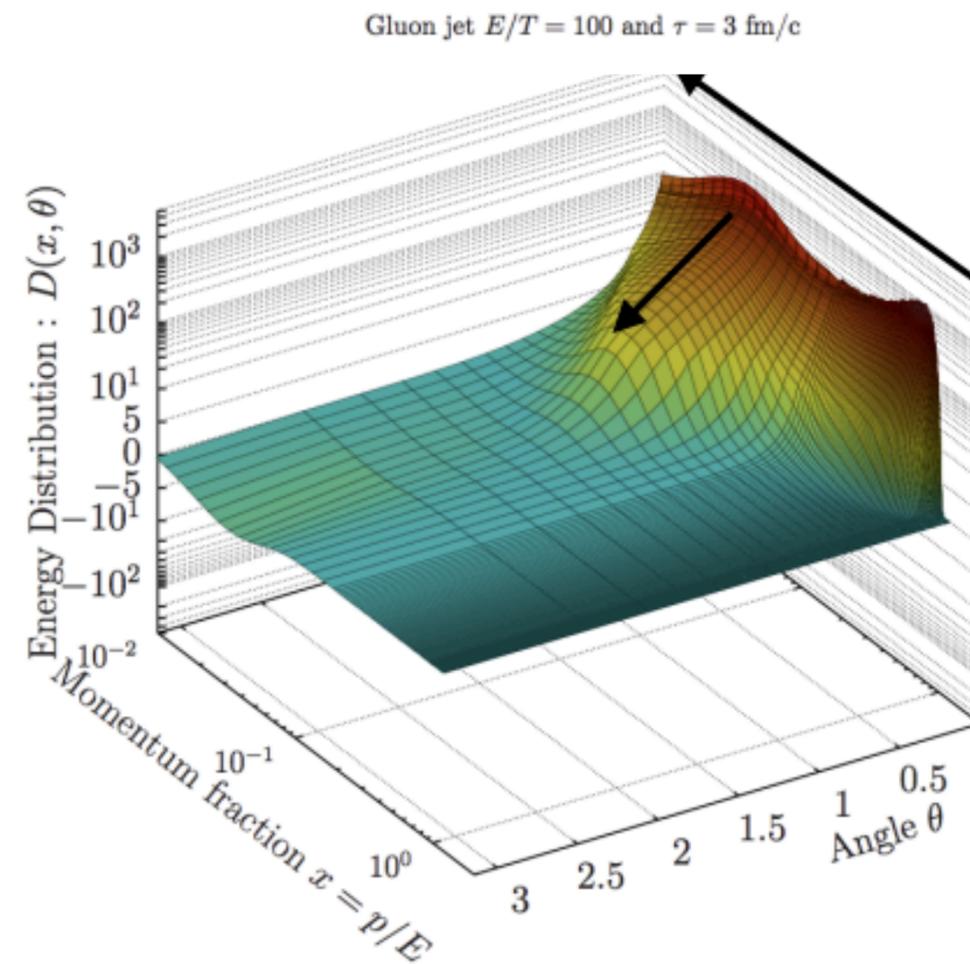
Adhya, Kutak, Płaczek, Rohrmoser; KT 22 | I.15803



expanding
medium



Schlichting, Soudi 2008.04928

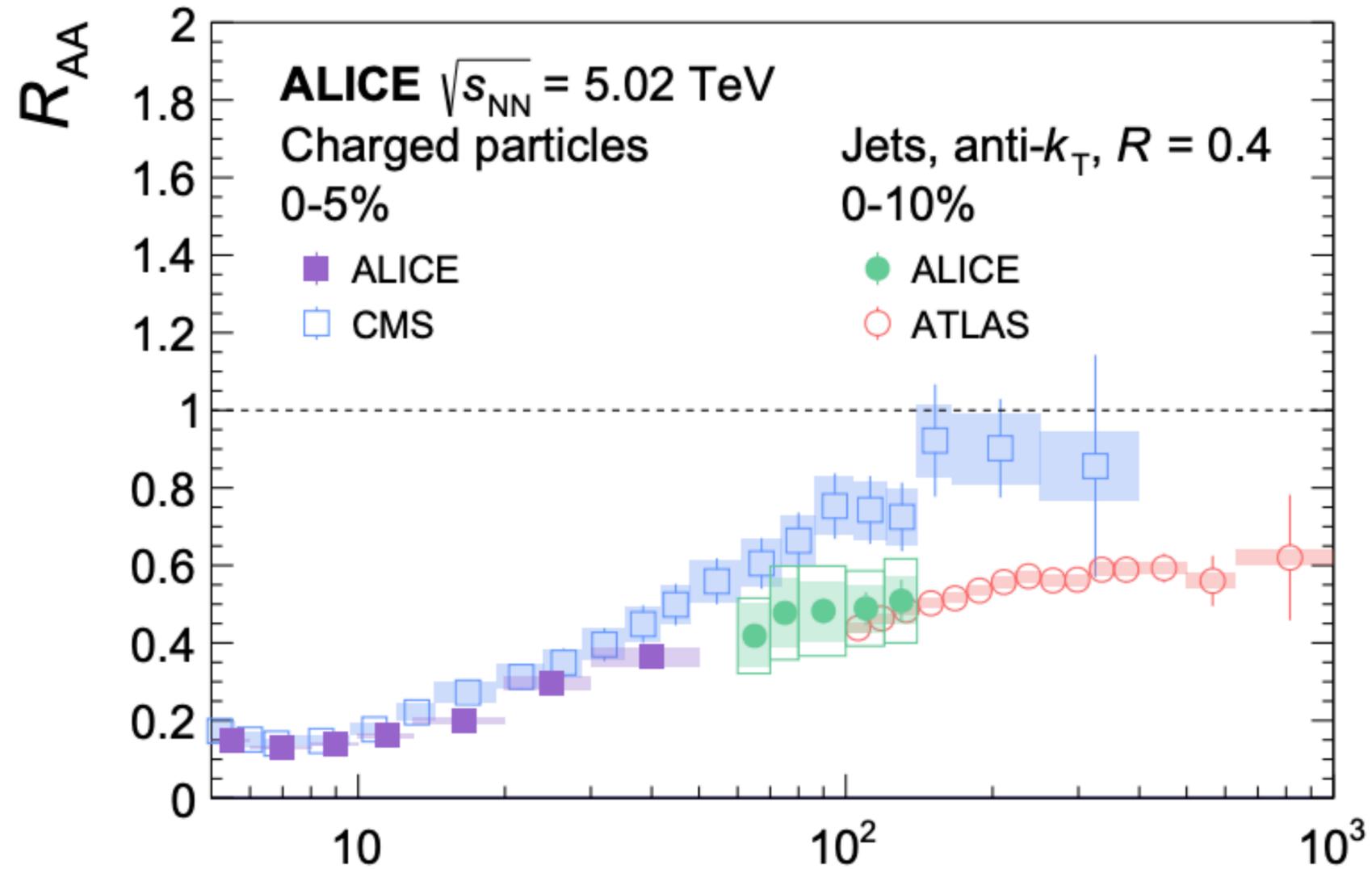


including
recoil



INCLUSIVE JET SUPPRESSION

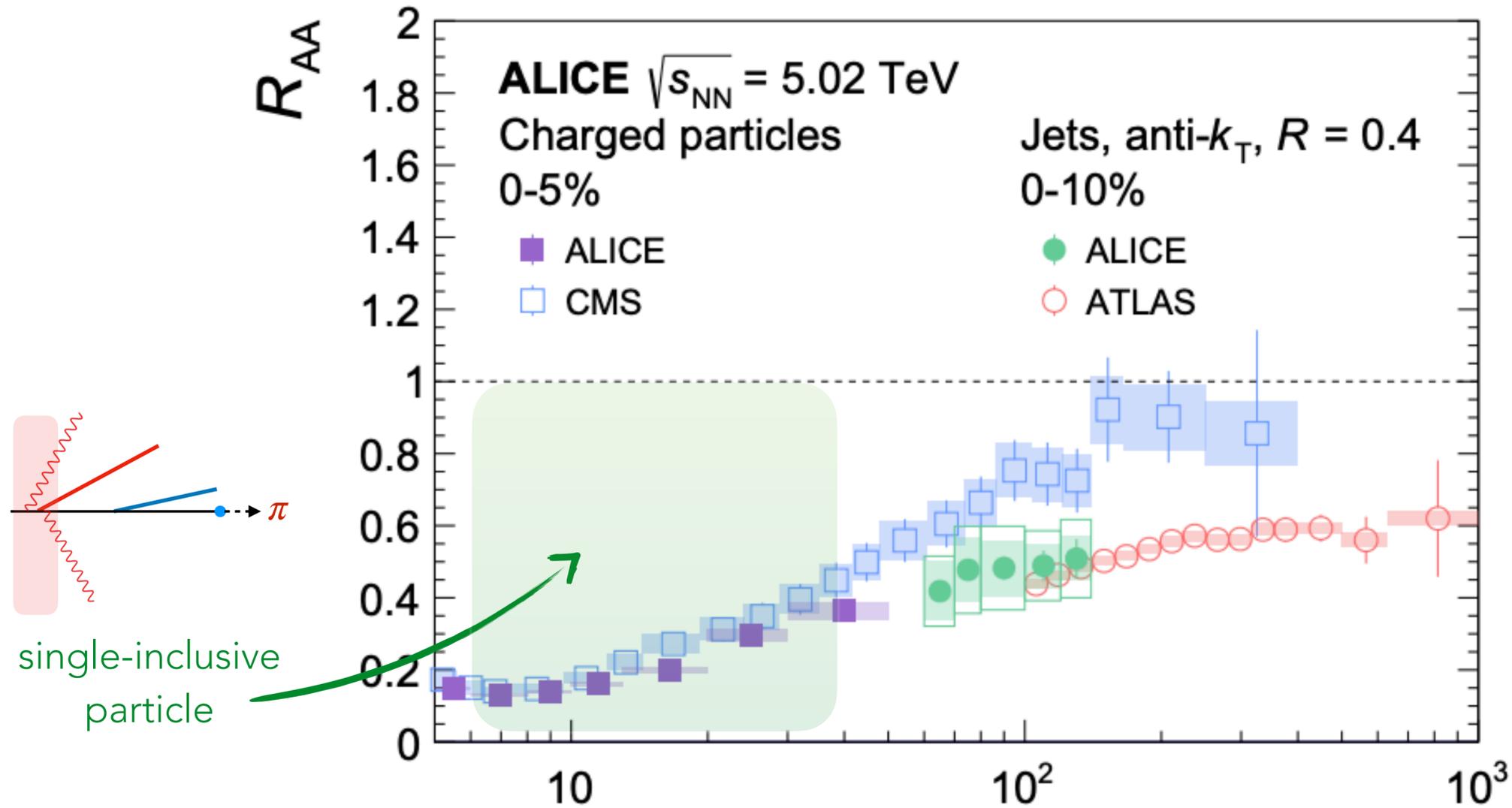
Mehtar-Tani, Pablos, KT PRL2021
Takacs, KT 2103.14676





INCLUSIVE JET SUPPRESSION

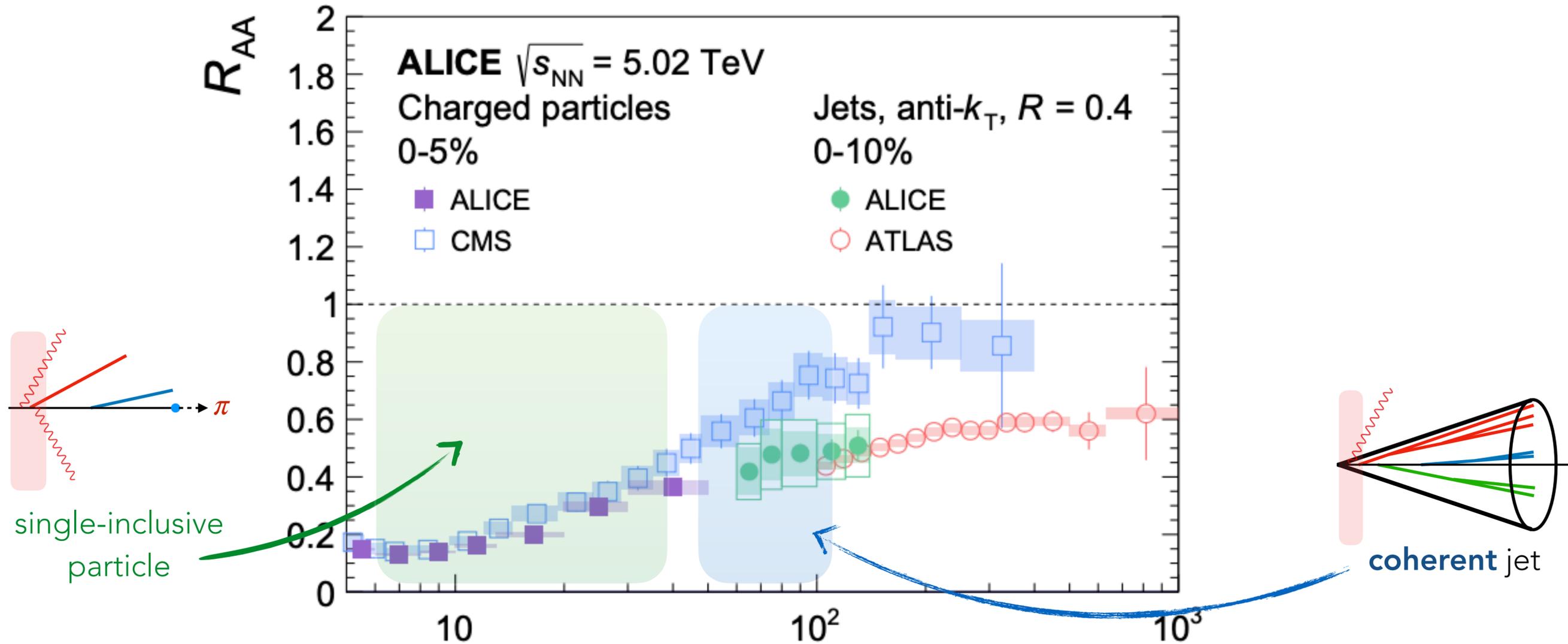
Mehtar-Tani, Pablos, KT PRL2021
Takacs, KT 2103.14676





INCLUSIVE JET SUPPRESSION

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