Jets in strongly interacting matter

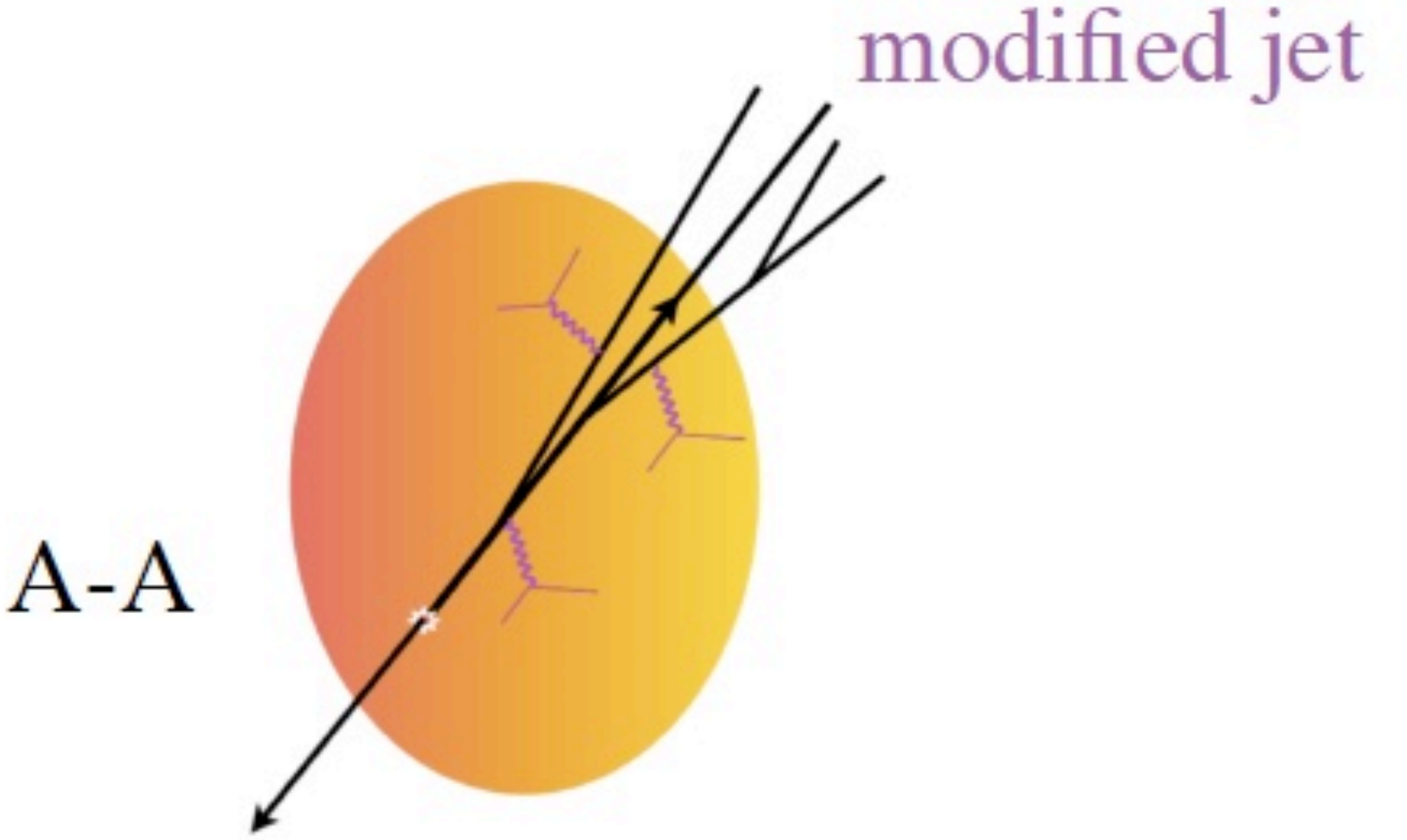
Konrad Tywoniuk (University of Bergen)

2nd Workshop of the Network NA7-HF-QGP of the European program "STRONG-2020" & 'HFHF Theory Retreat 2023'
28 September – 4 October 2023, Giardini Naxos, Italy

Outline

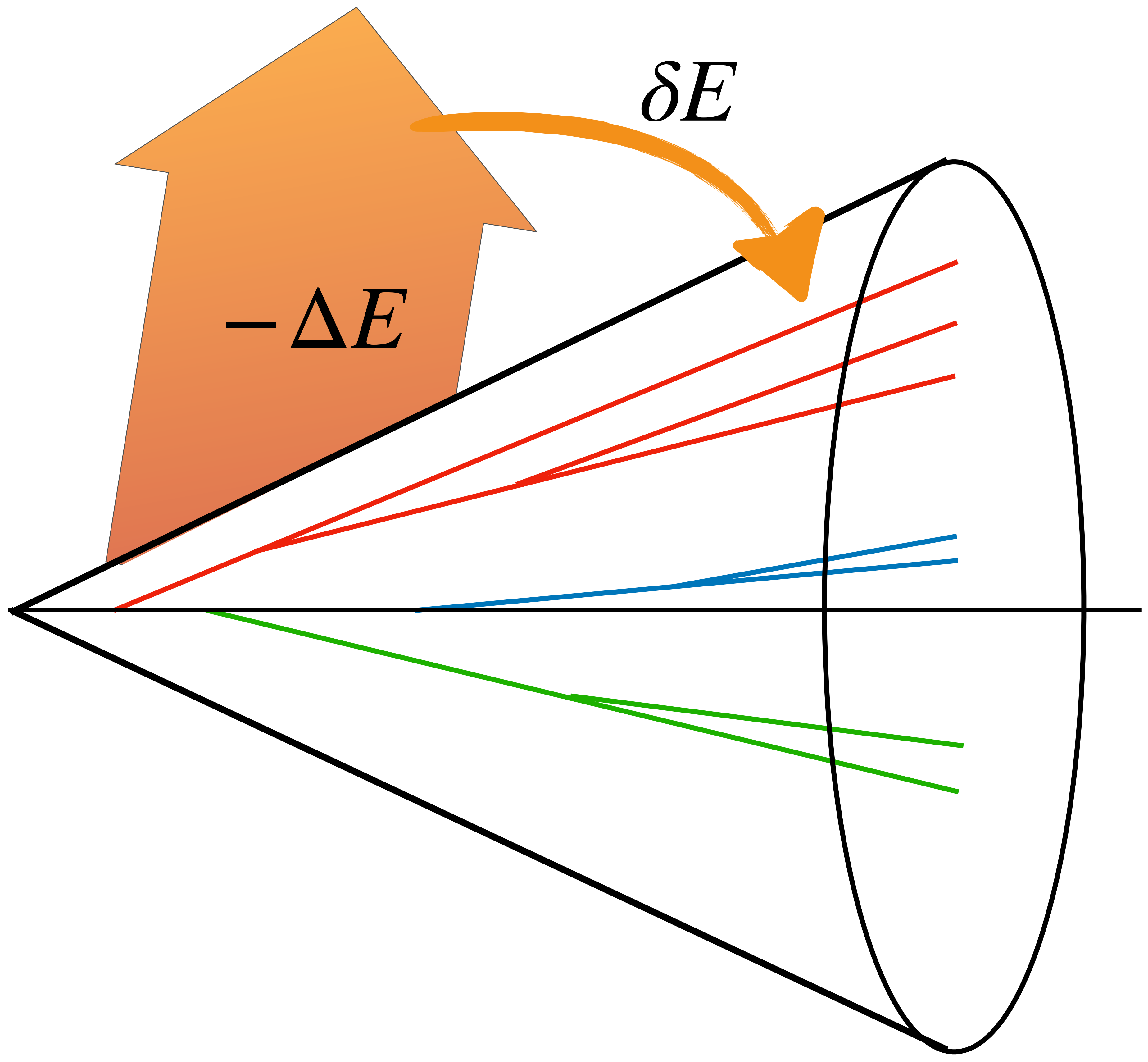
Structure of the lectures

- Lecture 1
  - learning to interpret "jet quenching" in experimental data
  - QCD jets in vacuum
- Lecture 2
  - theory of radiative parton energy loss
- Lecture 3
  - theory of full jet quenching

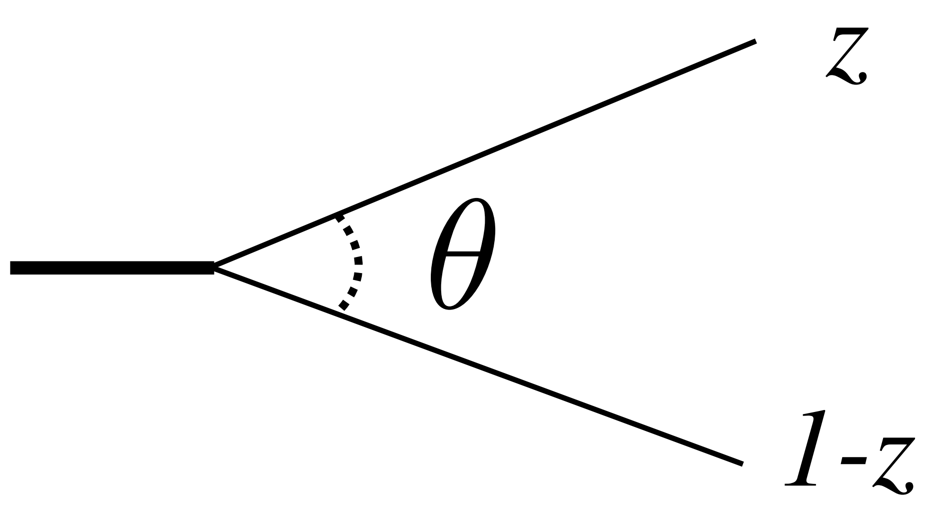


Lecture 3

theory of jet modification in medium



PARTON SPLITTING IN THE VACUUM



Generic 1→2 (on-shell) splitting in QCD:

$$\mathcal{P}_{a\to bc} = \frac{\alpha_s}{\pi}\frac{\mathrm{d}\theta}{\theta}P_{ba}^{(c)}(z)\mathrm{d}z \approx \frac{2\alpha_s C_R}{\pi}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$$

Diverges for soft & collinear radiation!

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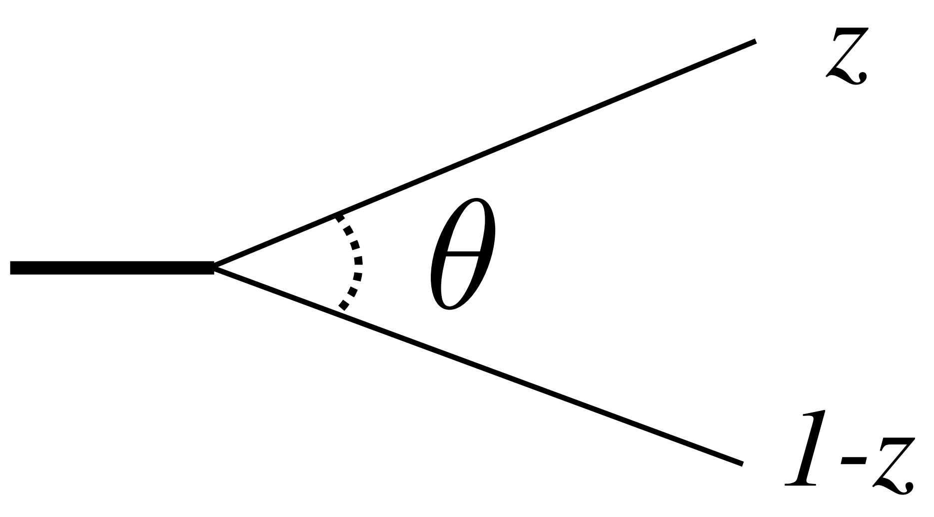

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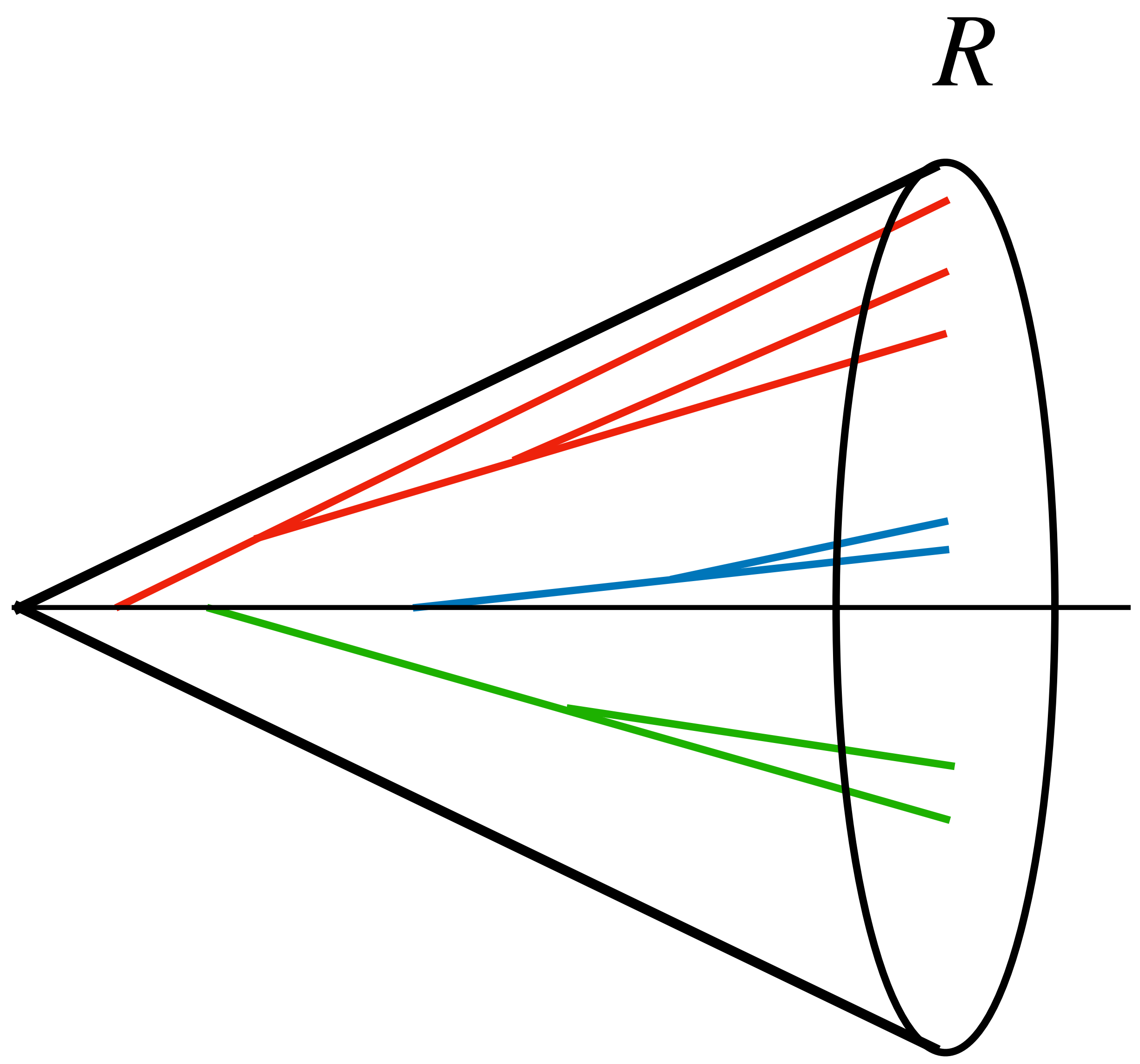

Large phase space for radiation compensates α_s!

$$\mathrm{Prob} = \frac{\alpha_s C_R}{\pi}\log^2\frac{p_T R}{\Lambda_{\mathrm{QCD}}} \gg 1$$

Need for resummation of collinear logarithms for final-state radiation.

$p_T R$ is the jet scale ("virtuality")

SPACE-TIME PICTURE OF QCD JET

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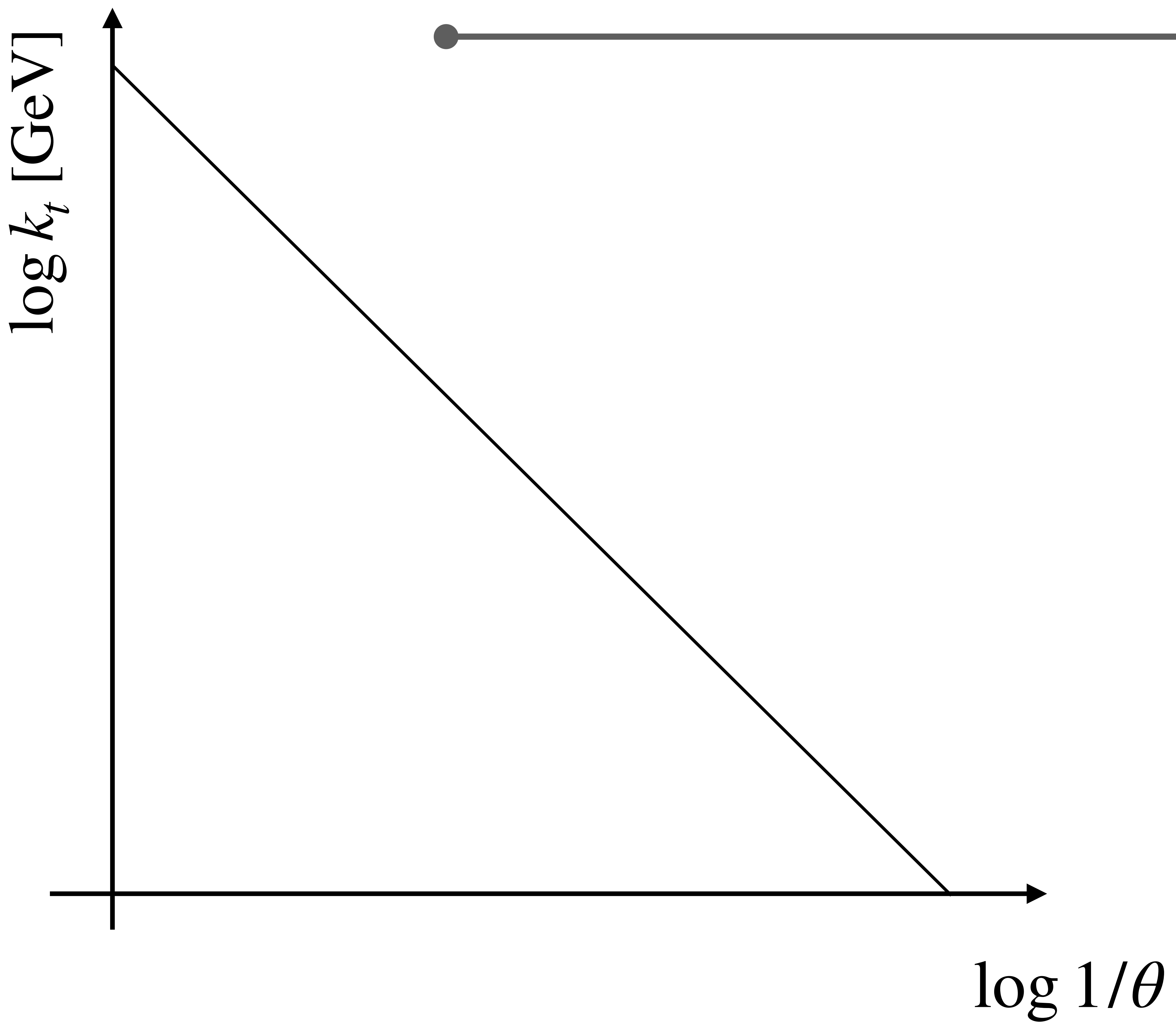
Andersson, Gustafson, Samuelsson NPB (1996)



- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- well-defined objects in experiment & theory.
- multi-scale & long-distance dynamics

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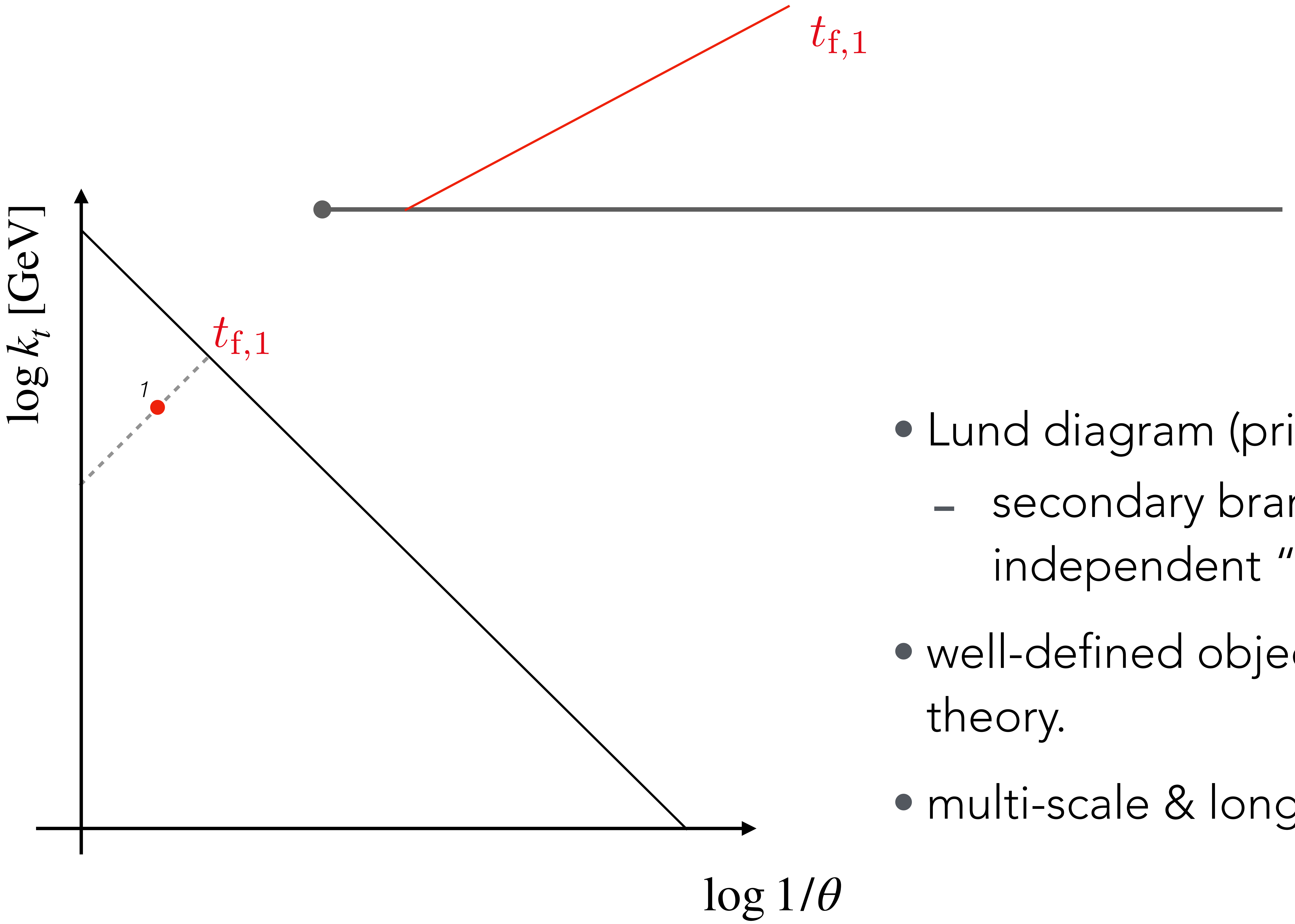

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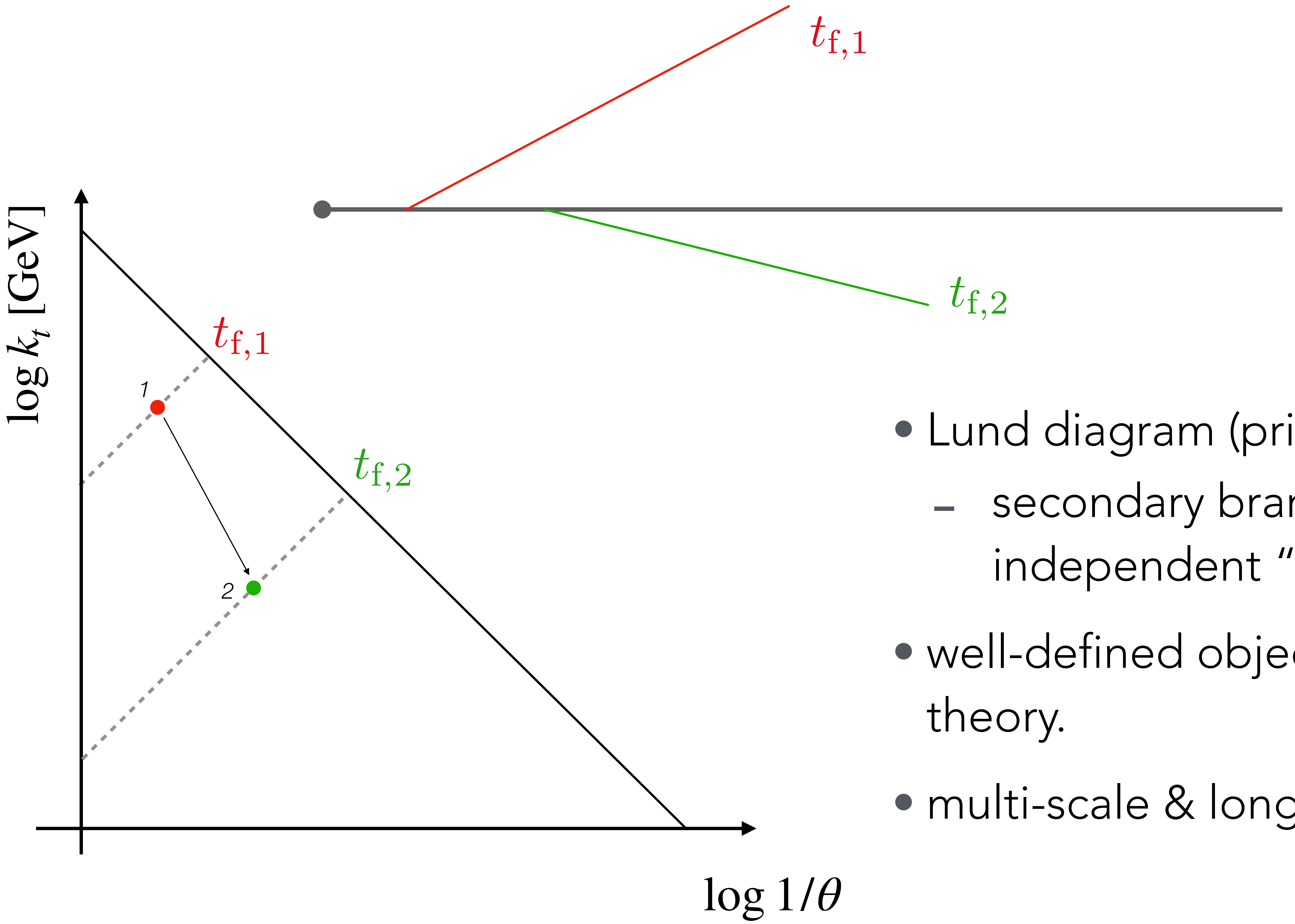

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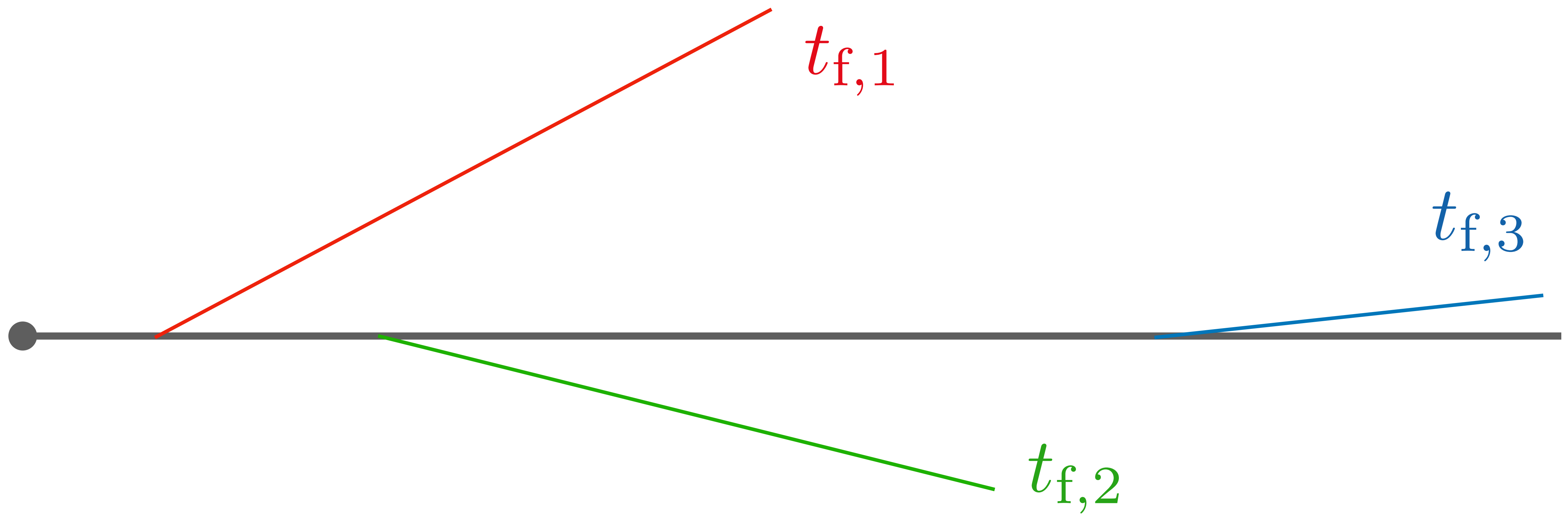

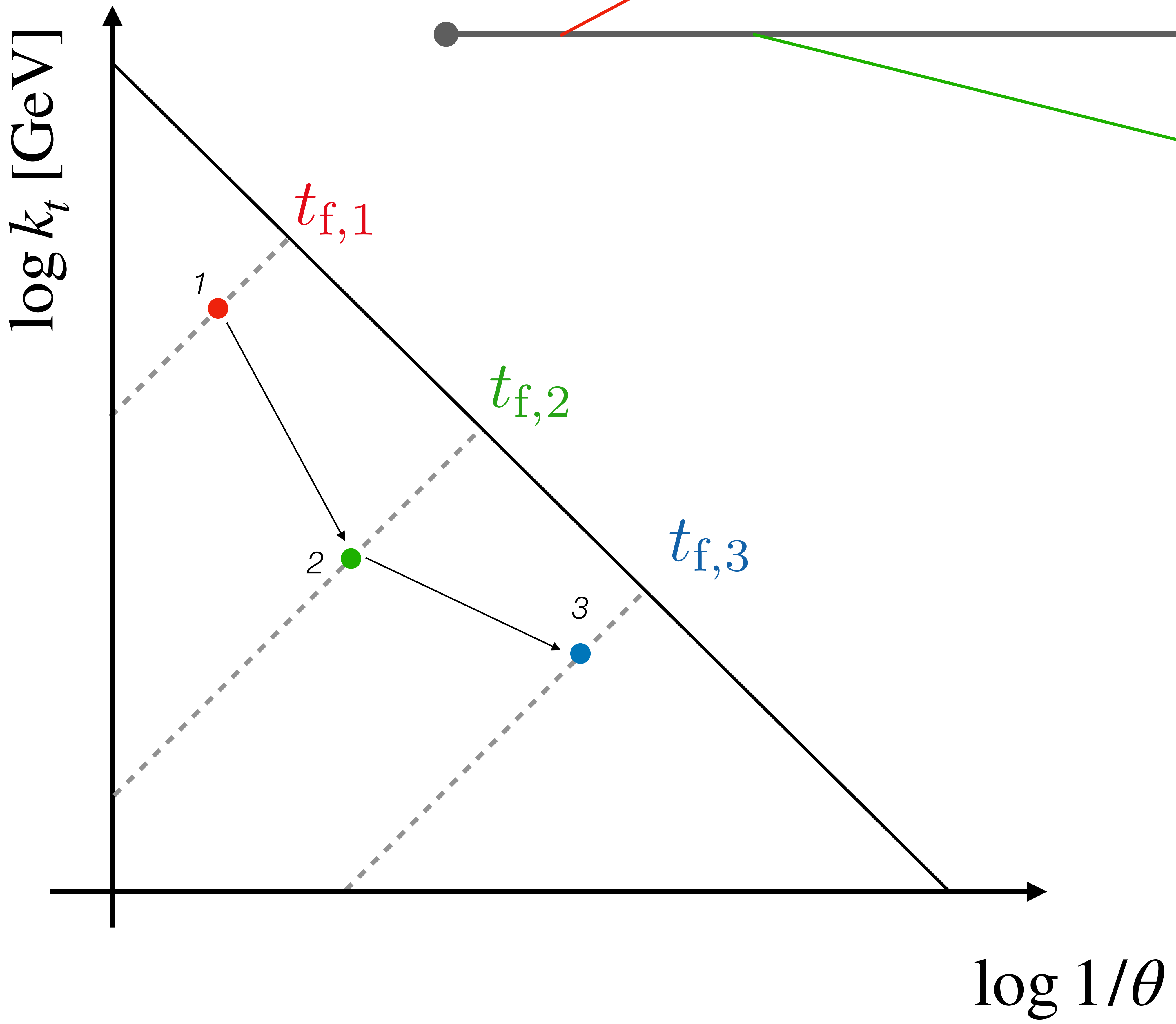

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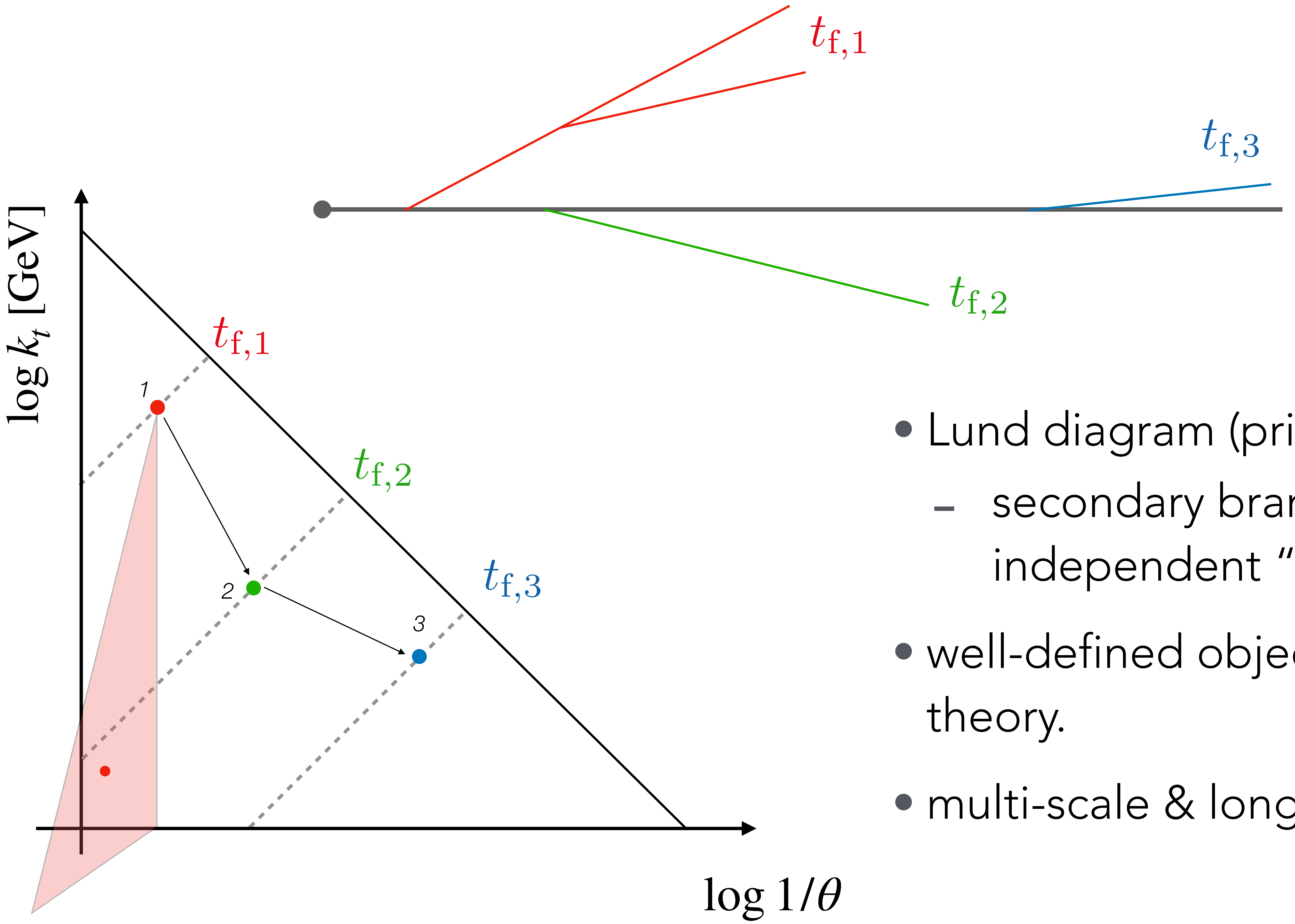

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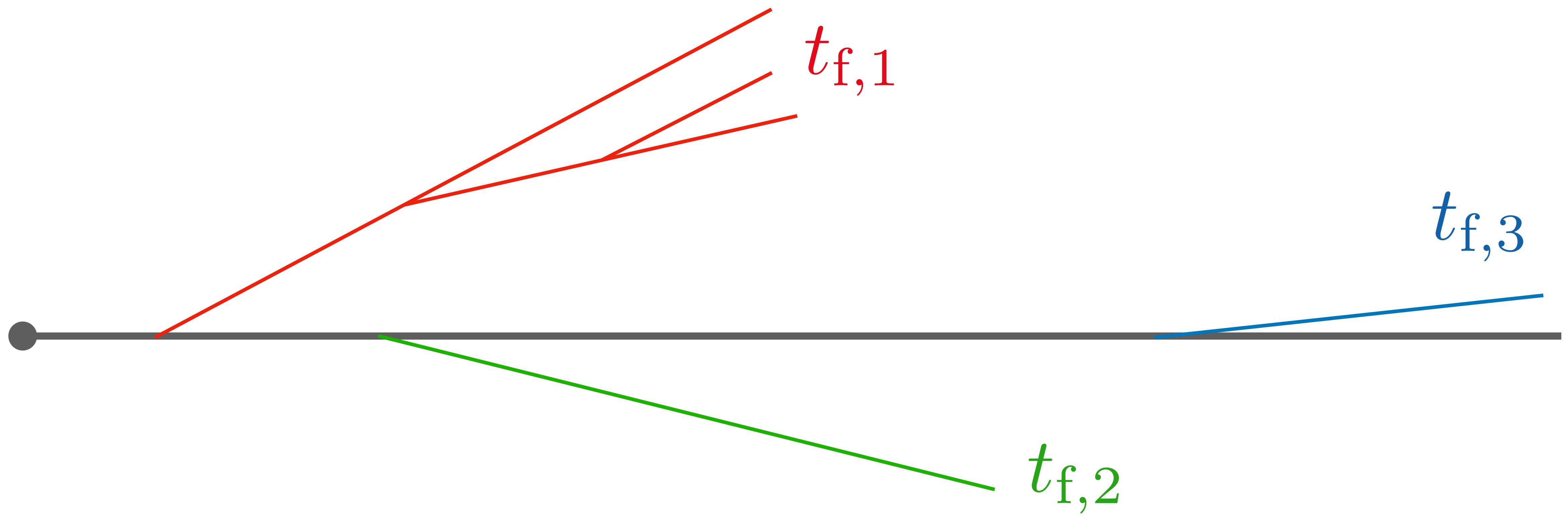

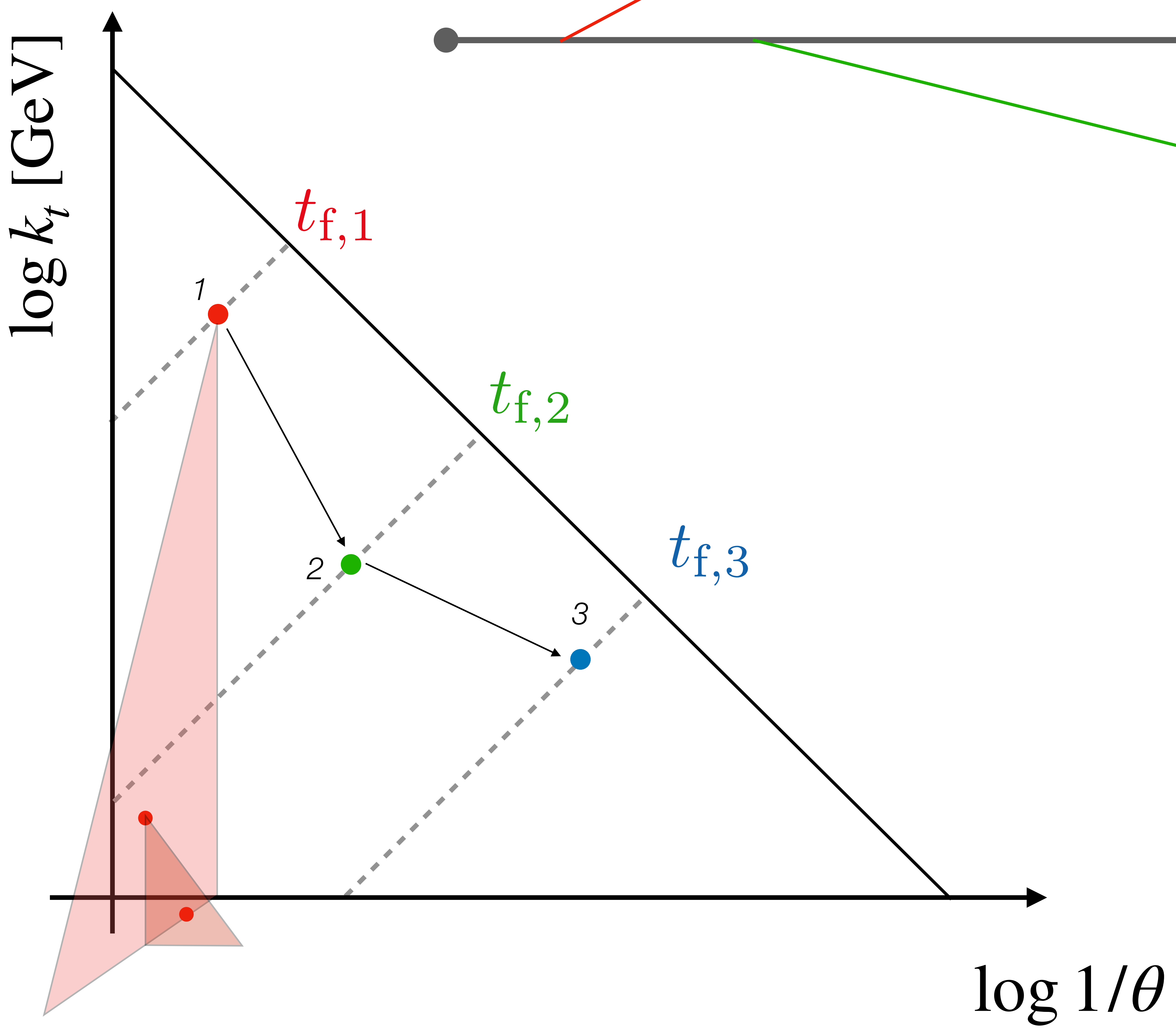

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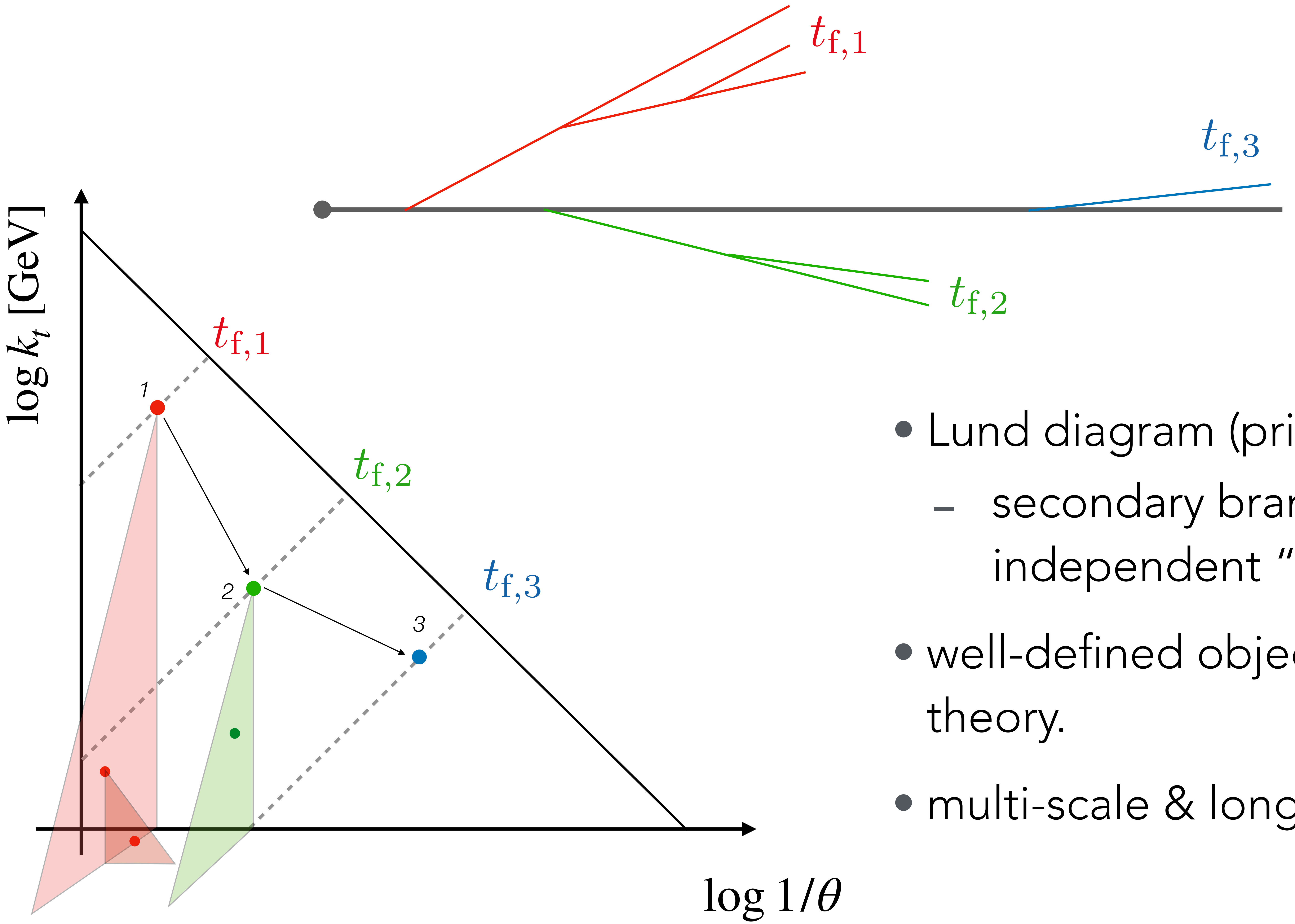

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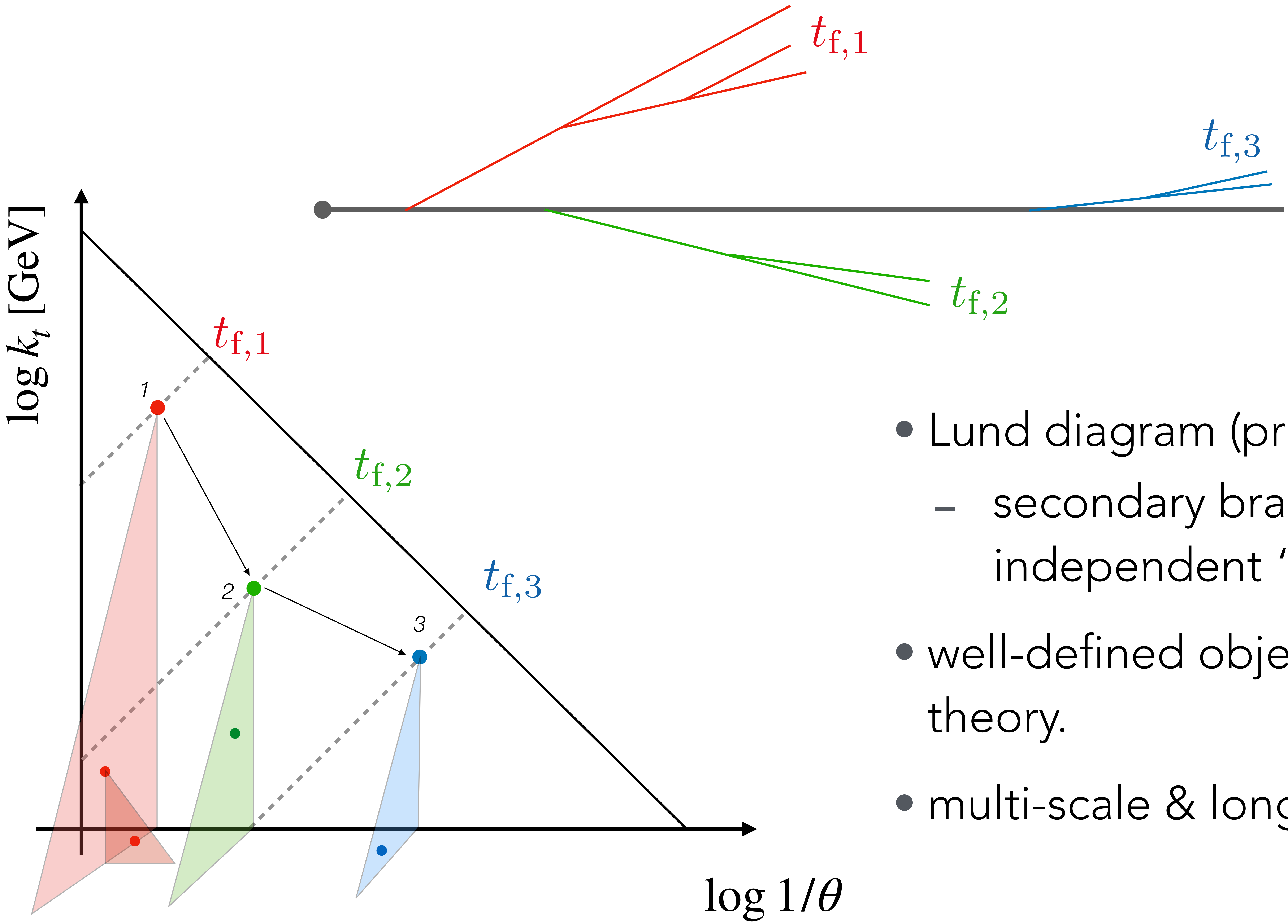

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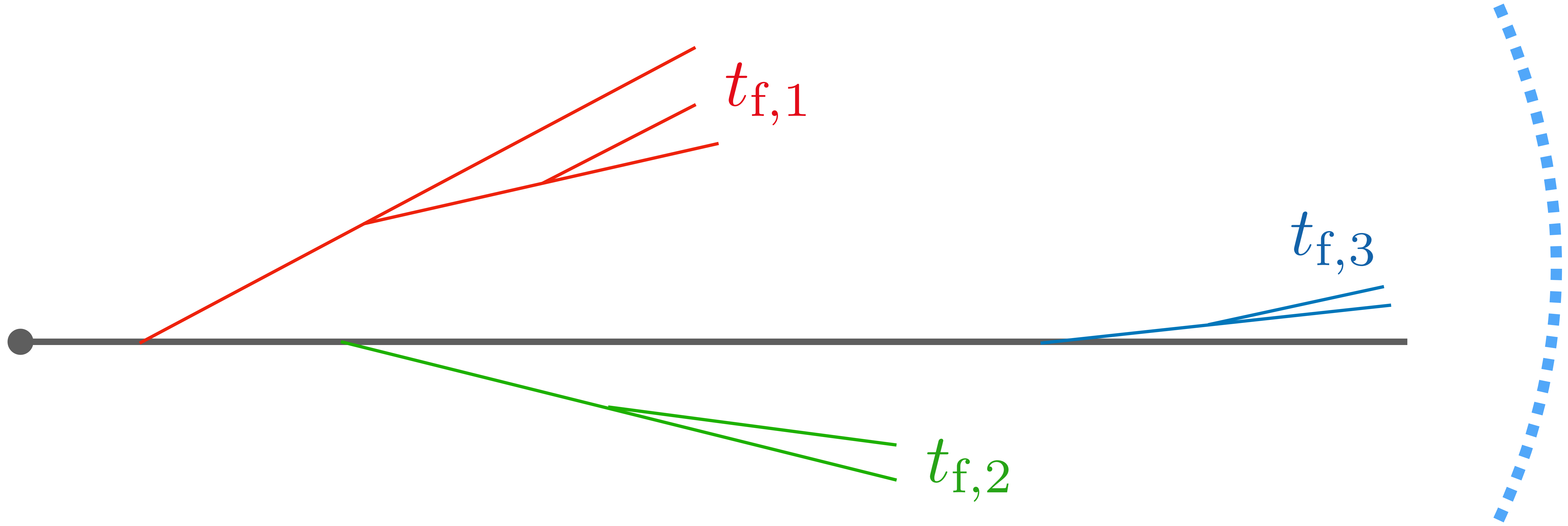
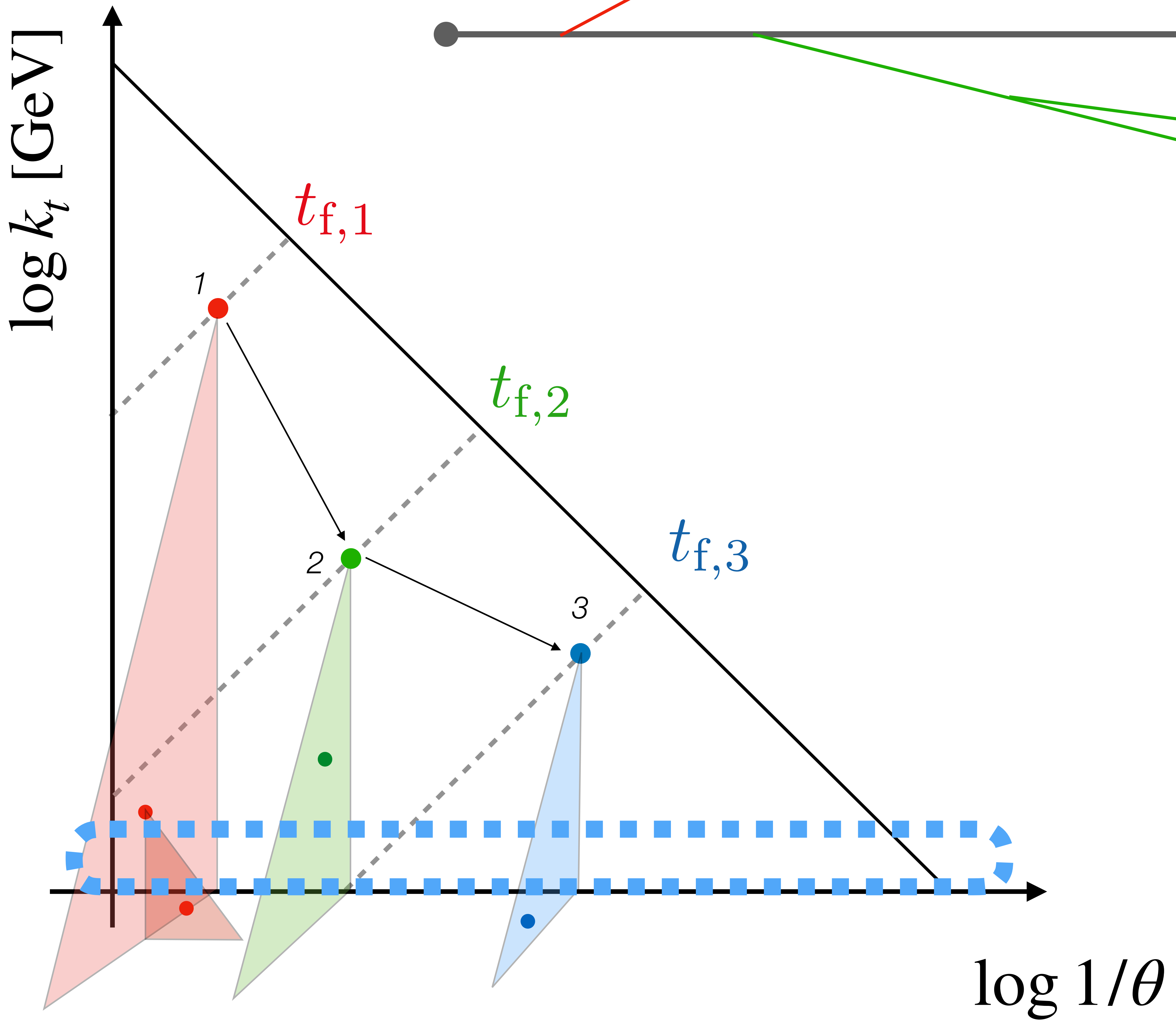


hadronization

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



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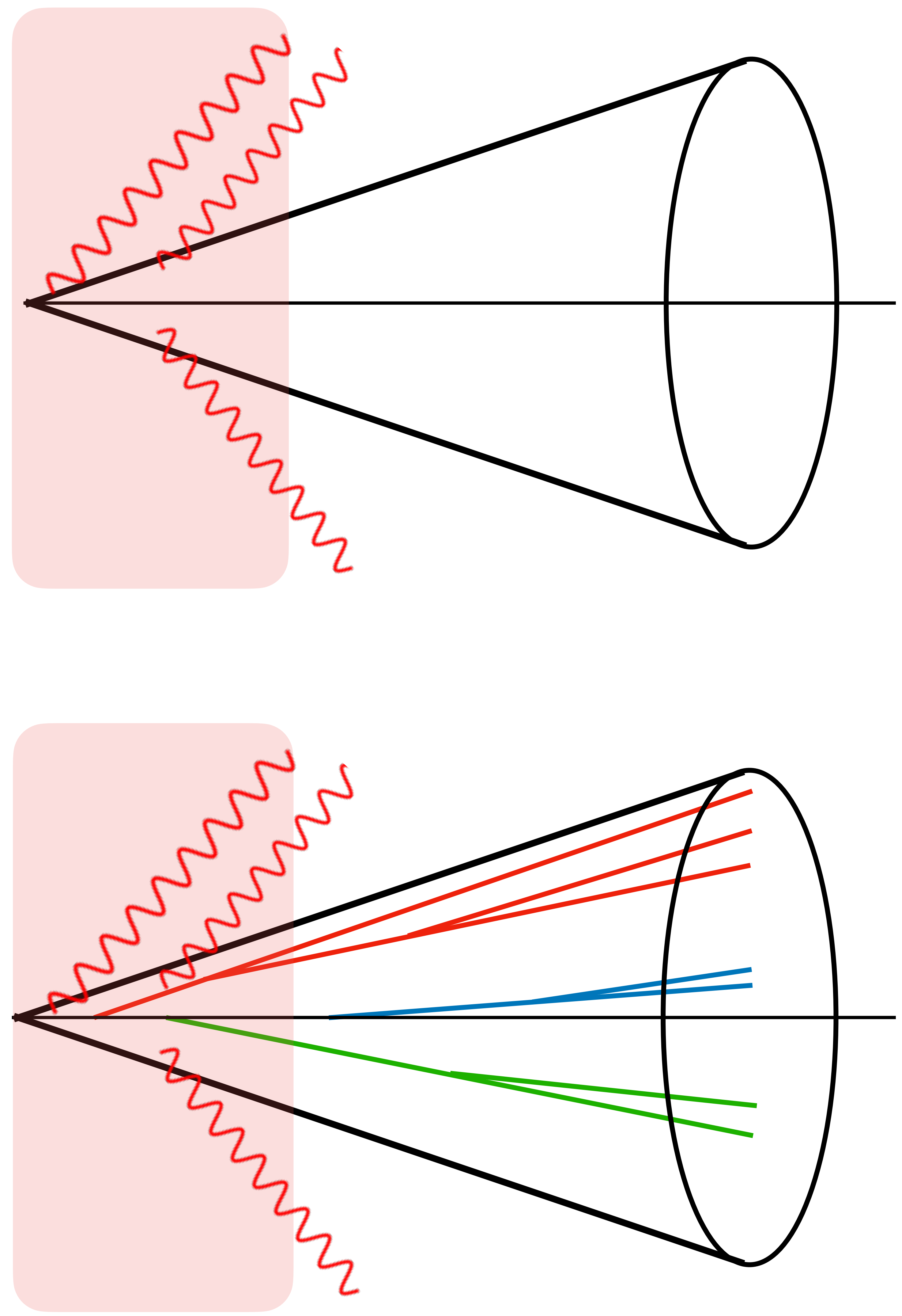
Full jet quenching

Computing energy loss of many color charges



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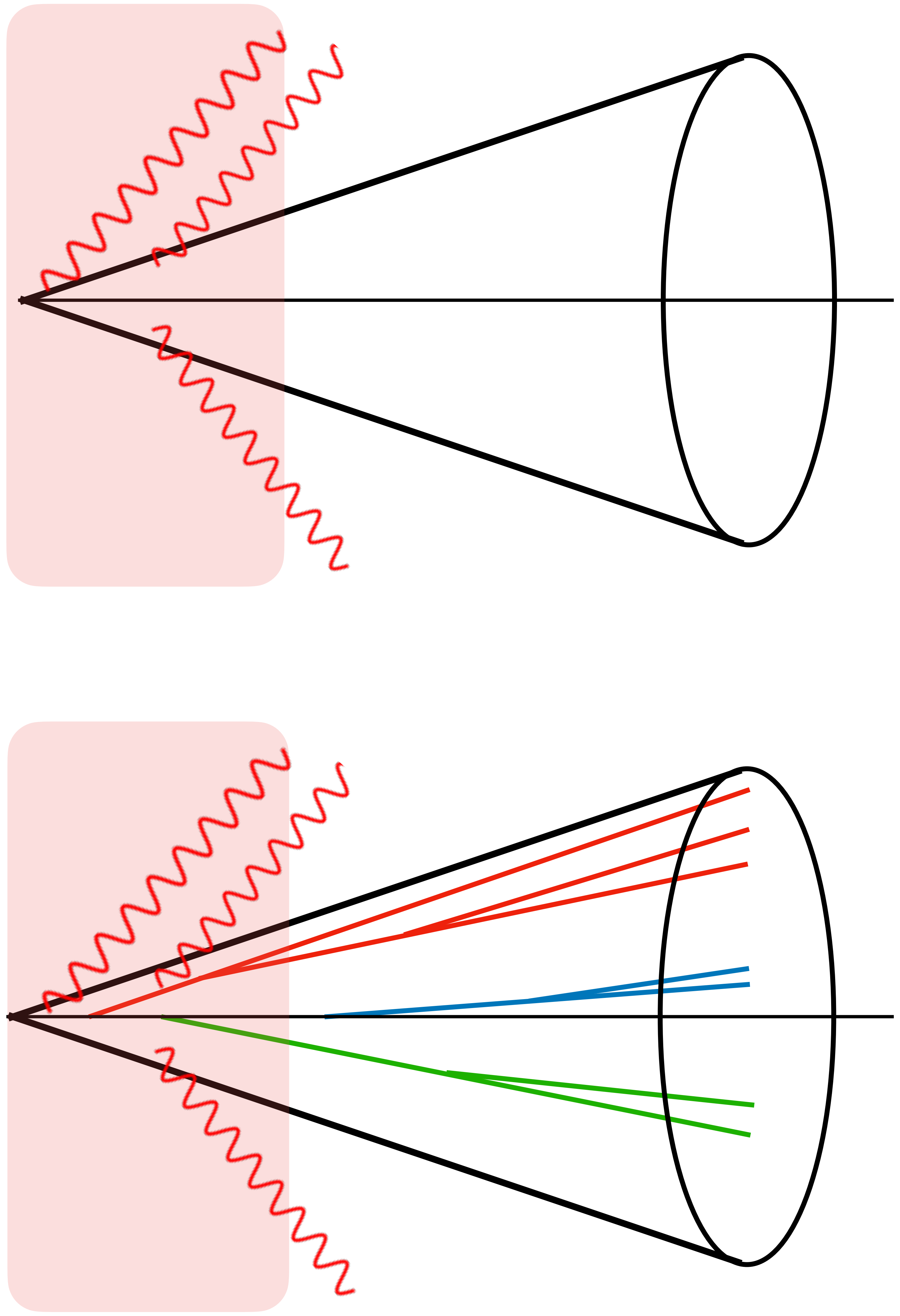
  - assumes that the parton is ~on-shell



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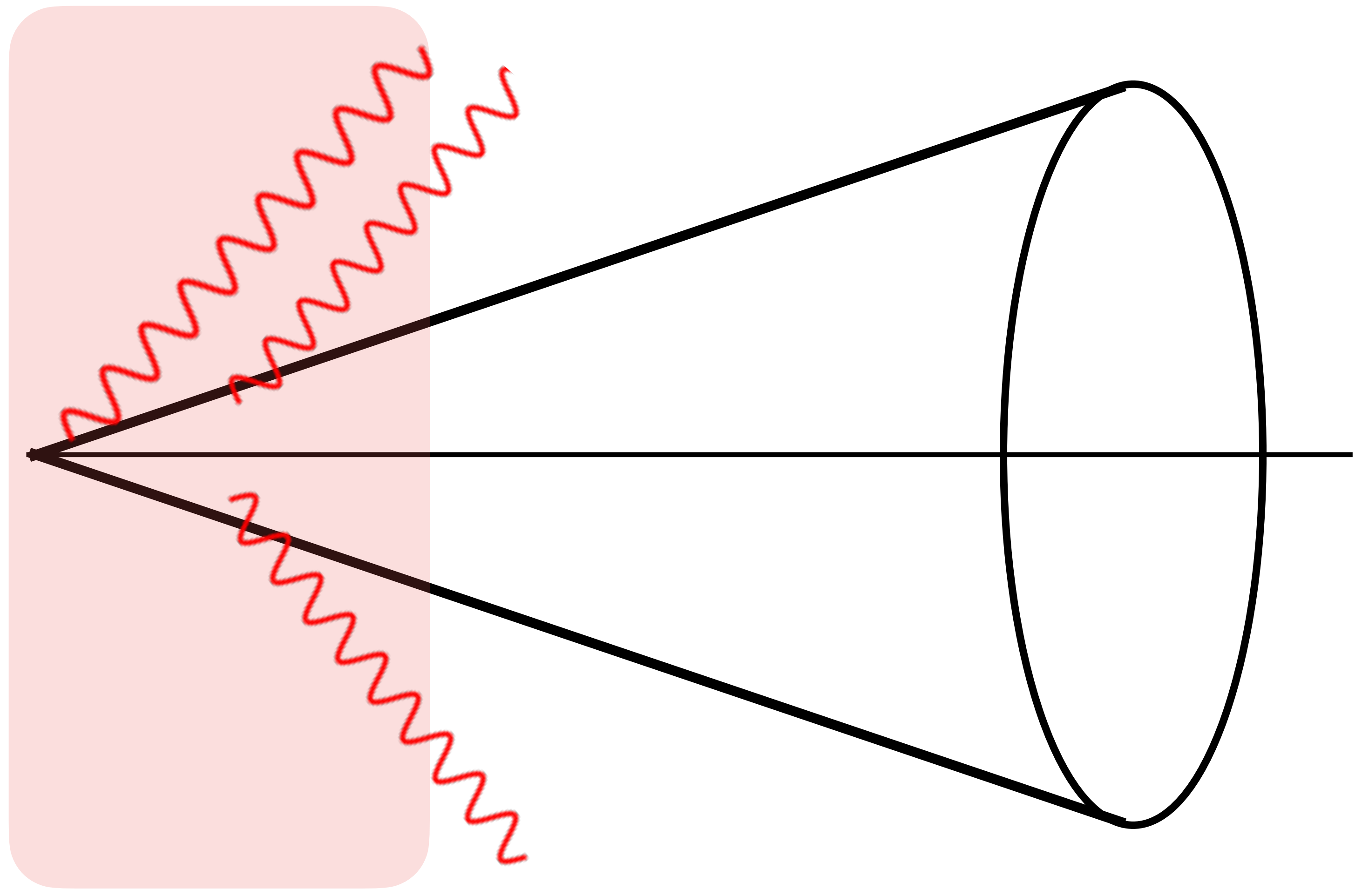

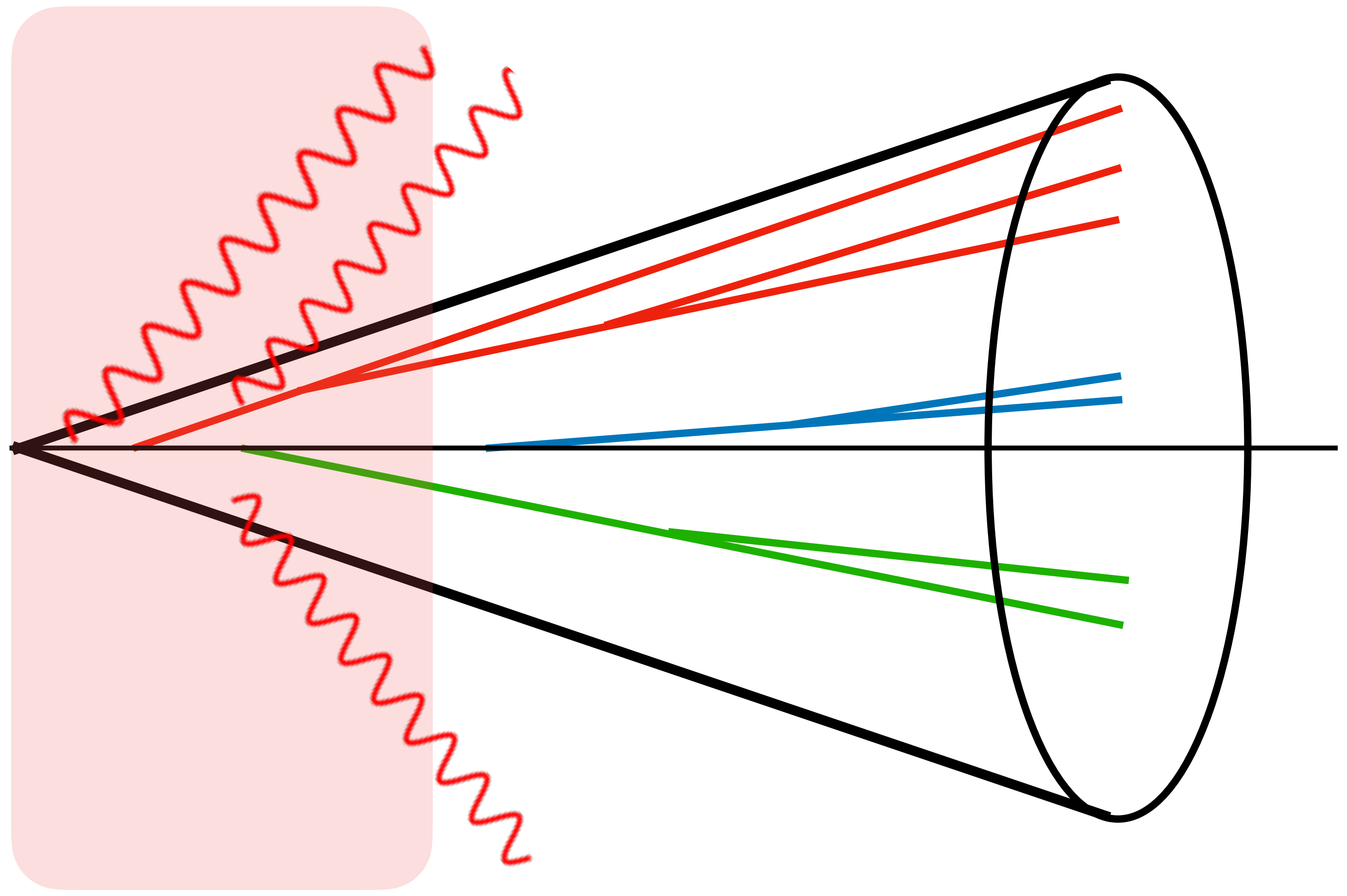

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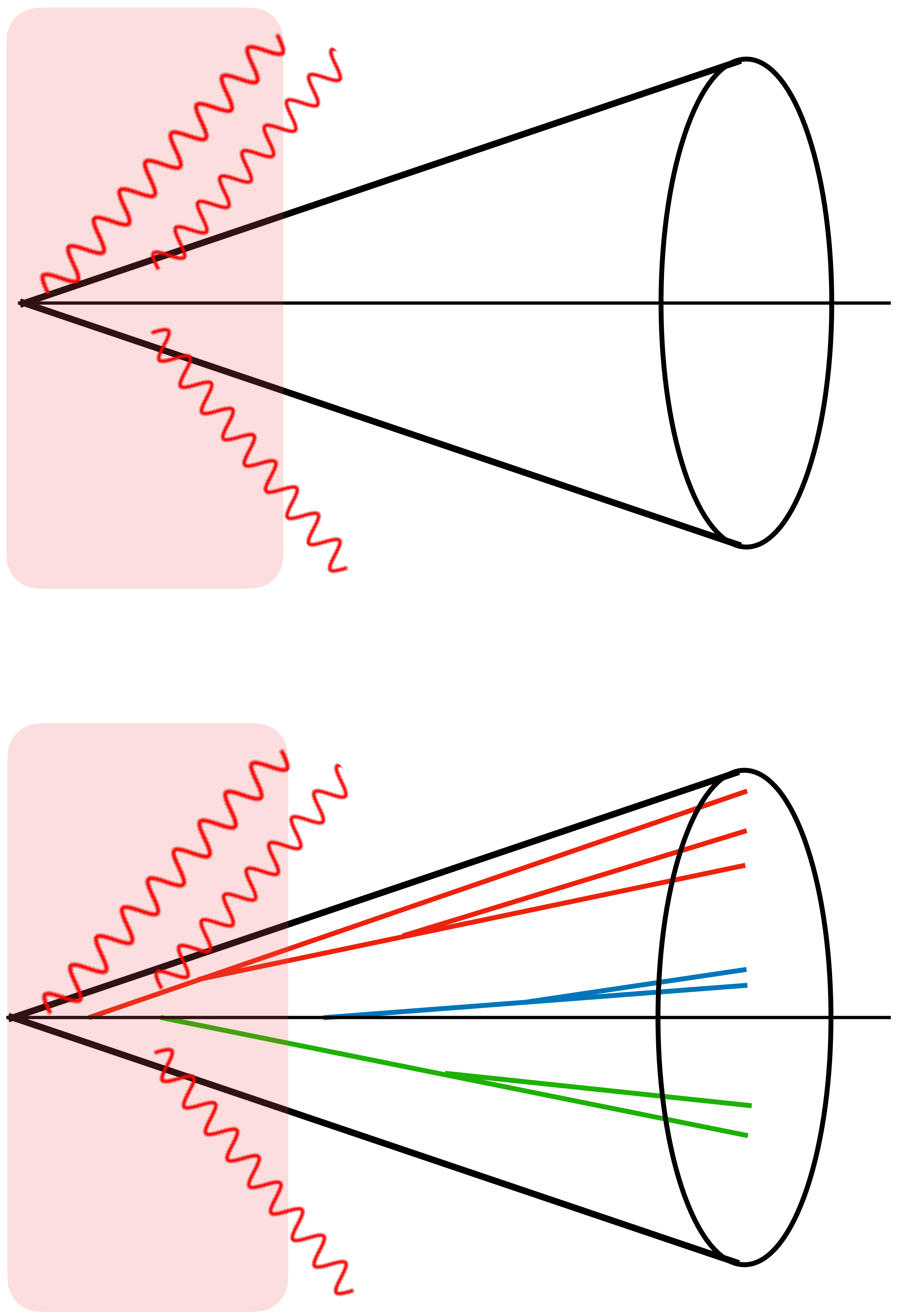

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How do we combine both descriptions?

SURIVAL BIAS IN JET OBSERVABLES

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

quenching weight (prob. distribution)

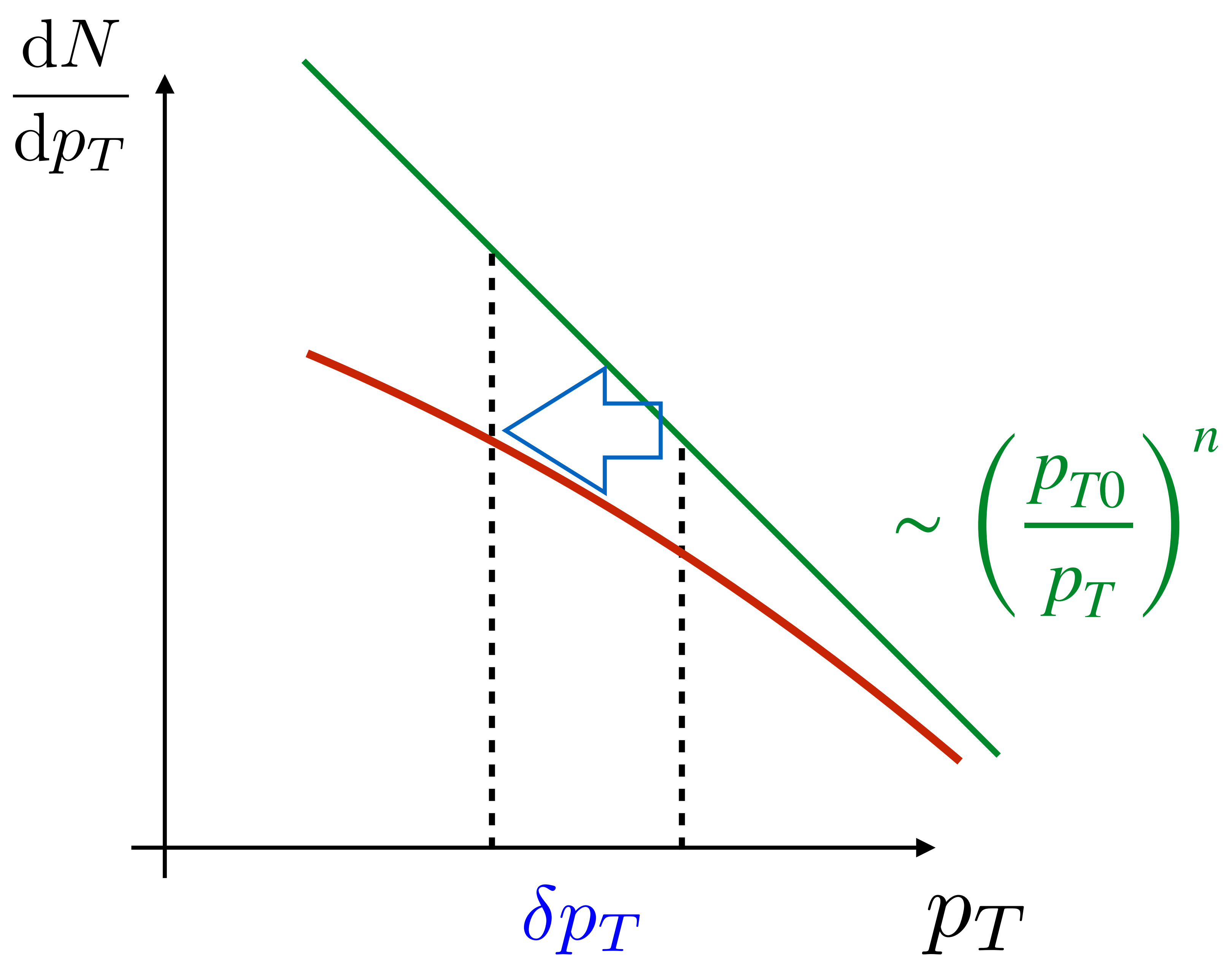
$$\frac{d\sigma_{\rm med}}{dp_T} = \int_0^\infty d\epsilon\, \mathcal{P}(\epsilon)\, \frac{d\sigma_{\rm vac}}{dp'_T}\Big|_{p'_T = p_T + \epsilon}$$

$$\approx \frac{d\sigma_{\rm vac}}{dp_T} \underbrace{\int_0^\infty d\epsilon\, \mathcal{P}(\epsilon) e^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)}$$

$Q(p_T)$ quenching factor

For $\epsilon/p_T \ll 1$ and large n

$$\frac{1}{(p_{\rm T}+\epsilon)^n} \approx \frac{1}{p_{\rm T}^n} e^{-\epsilon n/p_{\rm T}}$$



- steeply falling spectrum induces a strong survival bias → to jets that lost **little** energy
- different quenching weights for hadrons, jets… R dependence!

QUENCHING WEIGHTS

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

Strategy: expand jet in # of emissions/legs and compute energy loss $\mathcal{P}(\epsilon)$!

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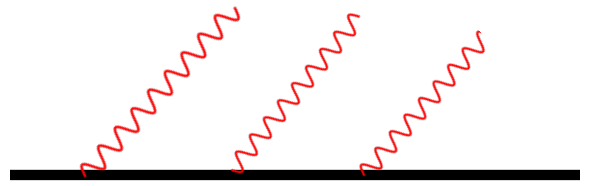
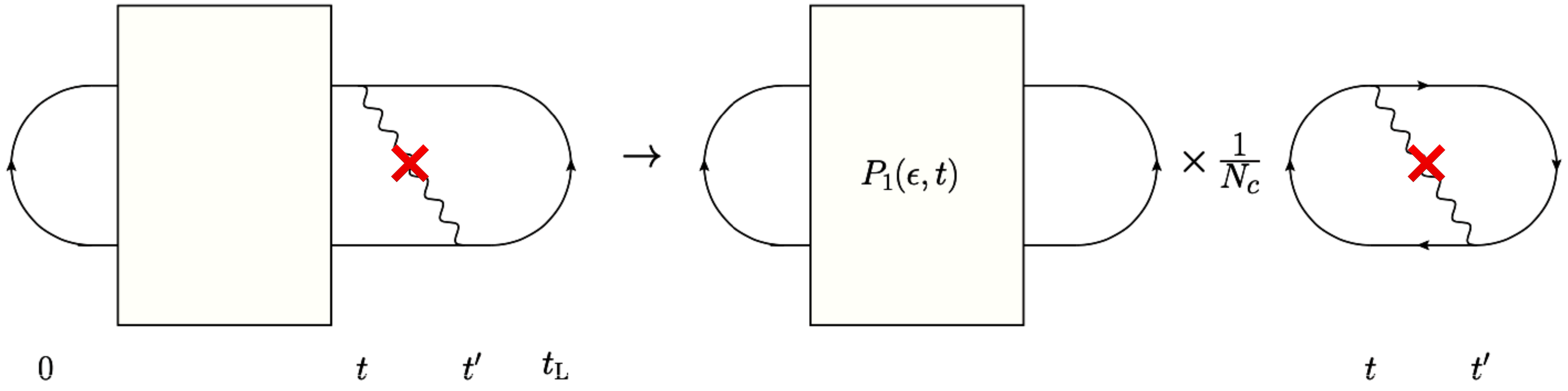
One leg

(amplitude & complex conjugate amplitude)





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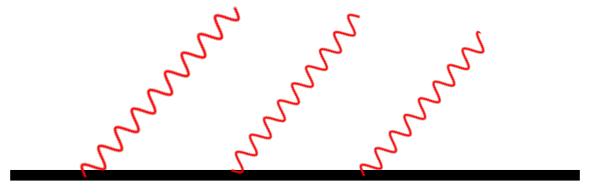
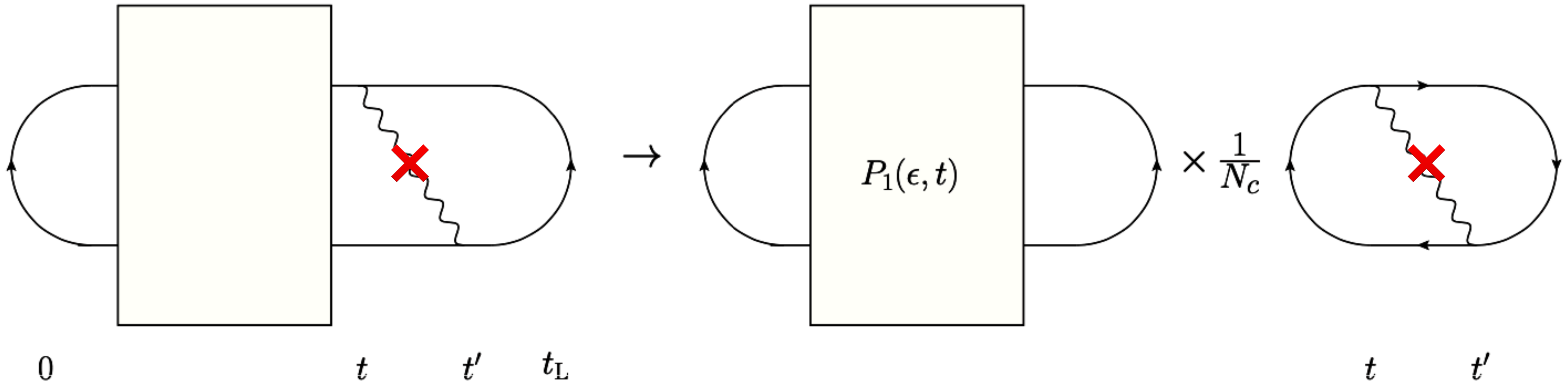
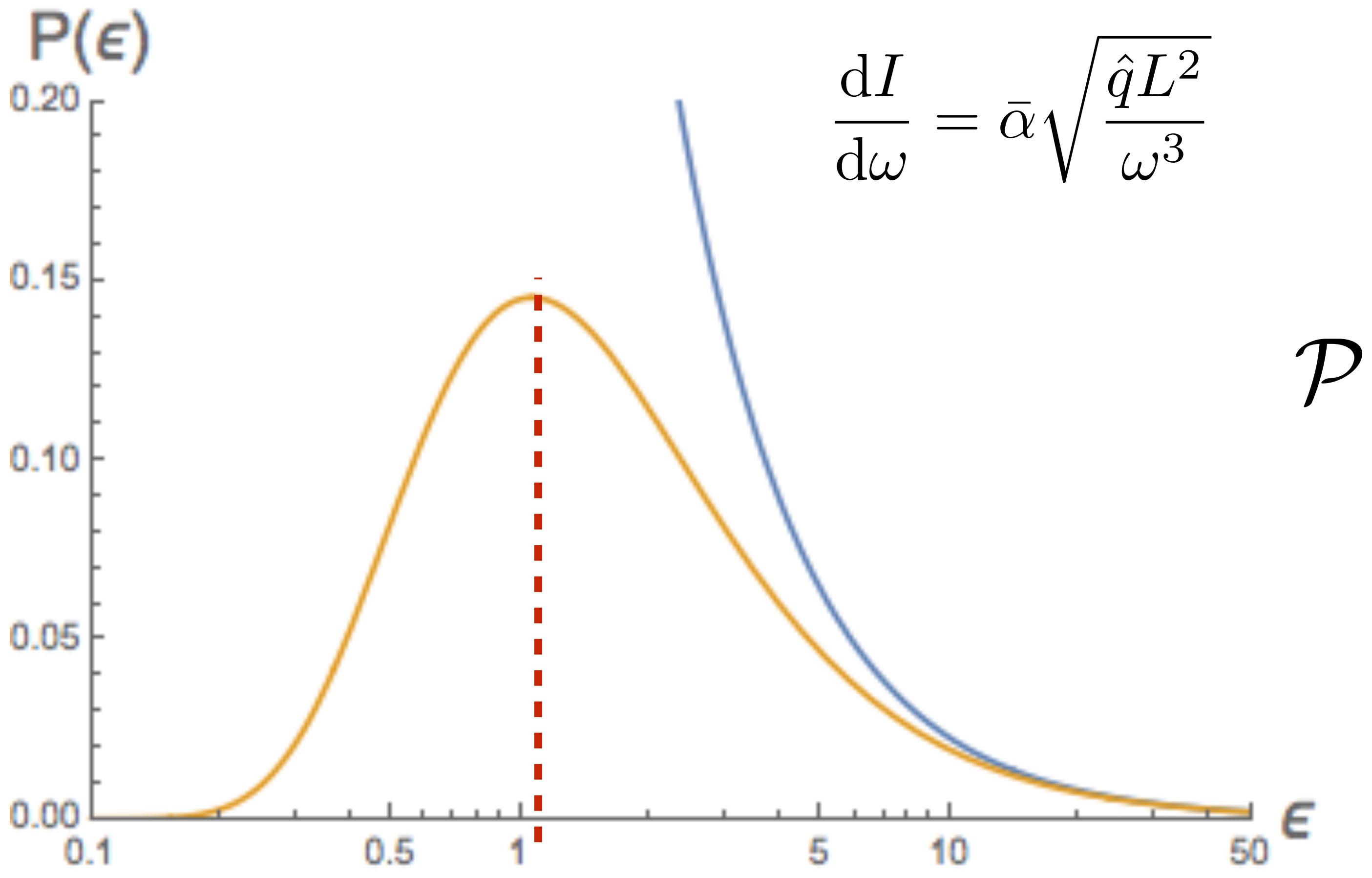




Soft limit: assume emission is quasi-instantaneous

$$\frac{\partial}{\partial t} P_1(\epsilon, t) = \int_0^\infty \mathrm{d}\omega\, \gamma(\omega, t) P_1(\epsilon - \omega, t)$$



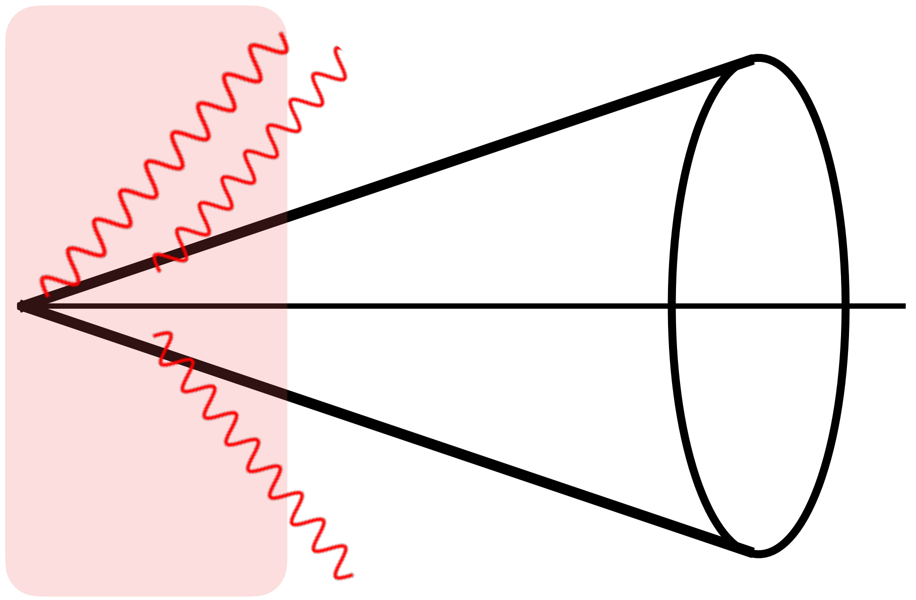
$\omega_s = \bar{\alpha}^2 \hat{q} L^2$

$$\mathcal{P}(\epsilon) = \mathrm{e}^{-\int \mathrm{d}\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}} \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int \mathrm{d}\omega_i \frac{\mathrm{d}I}{\mathrm{d}\omega_i} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

multiple (independent) emissions

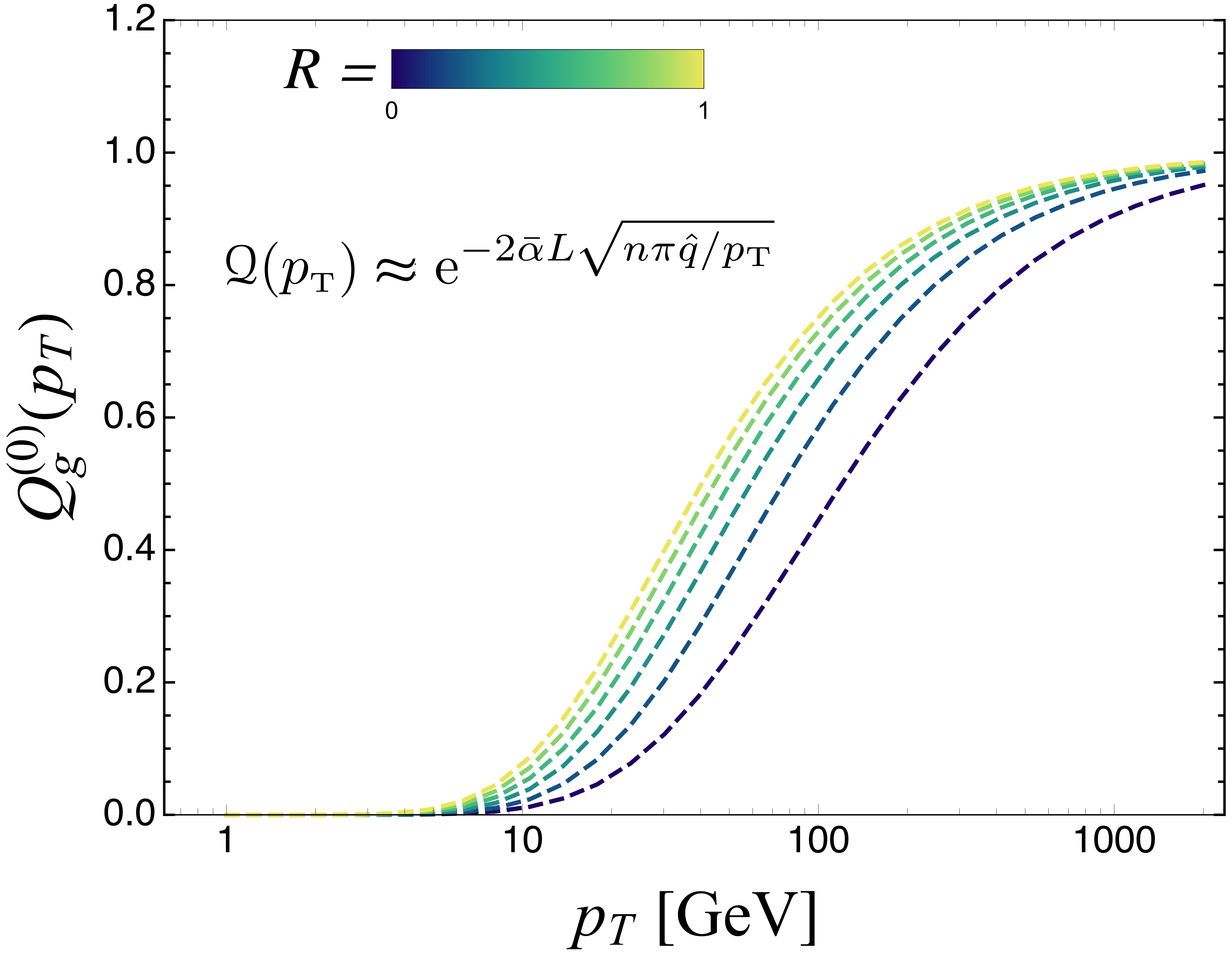
Ubiquitous tool to study jet modifications at RHIC and LHC!

ADDING A CONE AROUND THE JET



$$Q^{(0)}_{>}(p_T, R) = \exp\left[-\int_{T_0}^{\infty} \mathrm{d}\omega \, \frac{\mathrm{d}I_>}{\mathrm{d}\omega}\left(1 - \mathrm{e}^{-\nu\omega(1-\Theta(\omega_s-\omega)R^2/R^2_{\rm rec})}\right)\right]$$

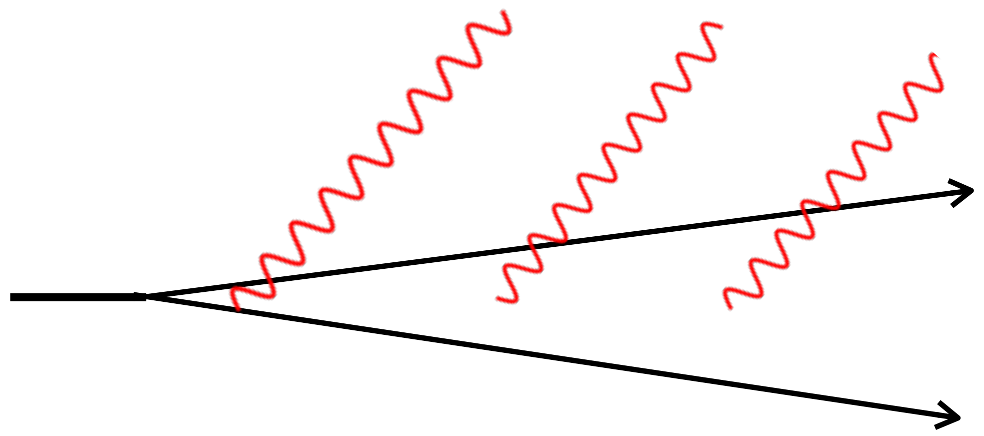
Barata, Mehtar-Tani, Soto-Ontoso, KT 2106.07402



- counting out-of-cone emissions
- dominated by emissions with $\omega_s \sim \alpha_s^2 \hat{q} L^2$.
  - spectrum shifts by $\delta p_T \sim \sqrt{\omega_s p_T}$
- lost energy smeared over the solid angle $R_{\rm rec}$ - free parameter.
- Casimir scaling $Q_g = [Q_q]^{N_c/C_F} \sim Q_q^2$

TWO-BODY ENERGY LOSS

Mehtar-Tani, Salgado, KT PRL (2010), PLB (2012), JHEP (2013); Casalderrey, Iancu JHEP (2011)



Two legs

(related to the 2-jet NLO rate in pQCD)

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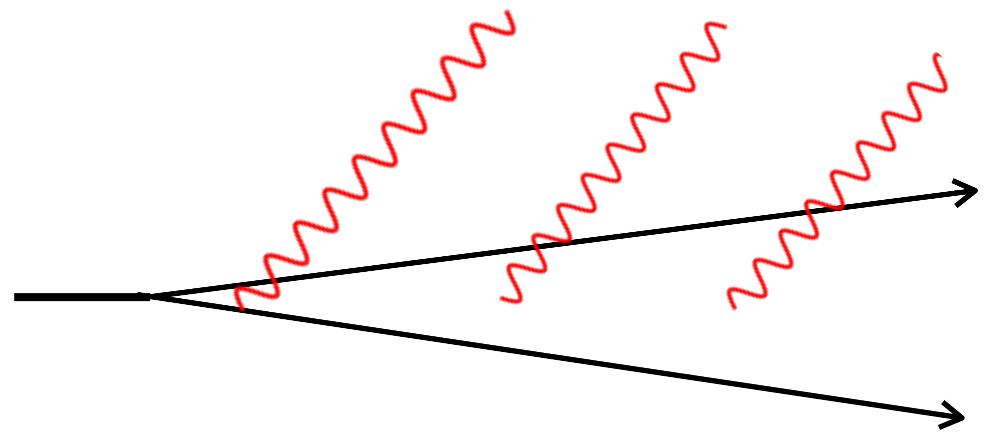
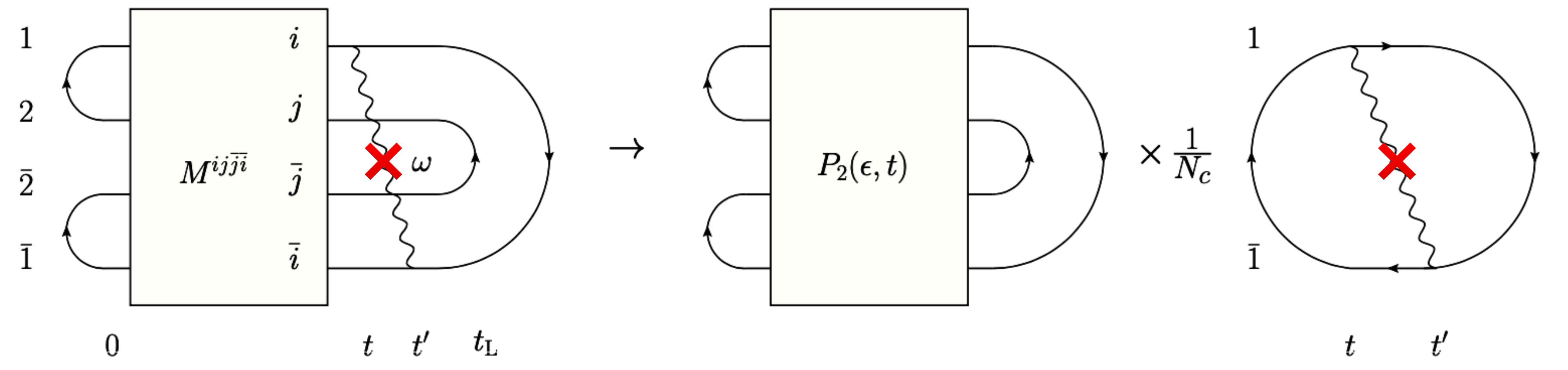
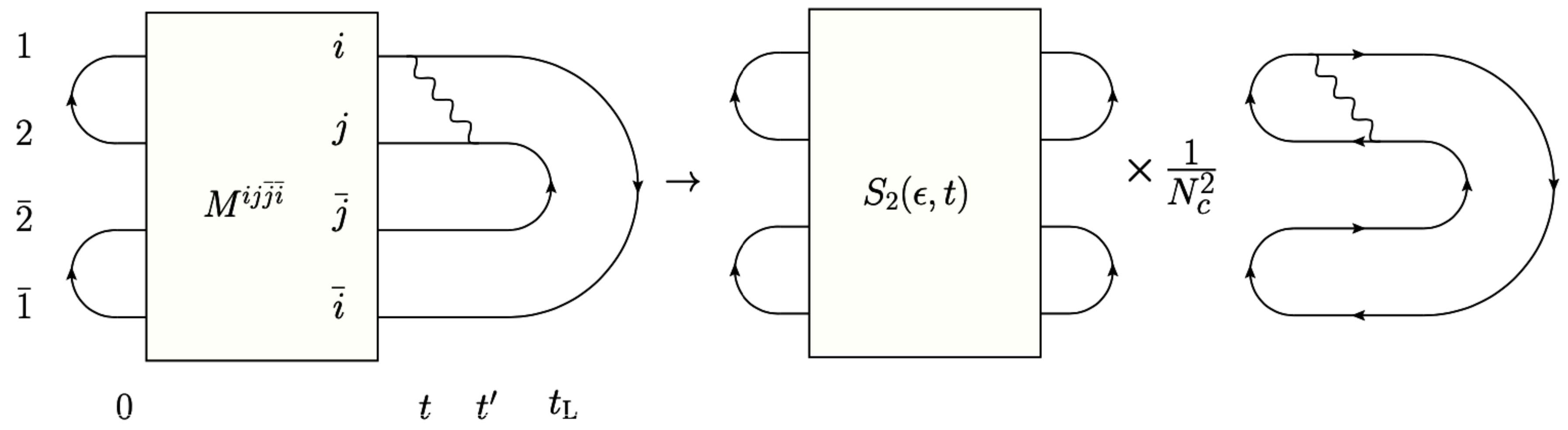


"direct" term $\Gamma_{1\bar{1}}$



interference Γ_{12}



$$\frac{\partial}{\partial t} P_{\rm sing}(\epsilon, t) = \int_0^\infty {\rm d}\omega \sum_i \Gamma_{ii}(\omega, t)\, P_{\rm sing}(\epsilon - \omega, t)$$

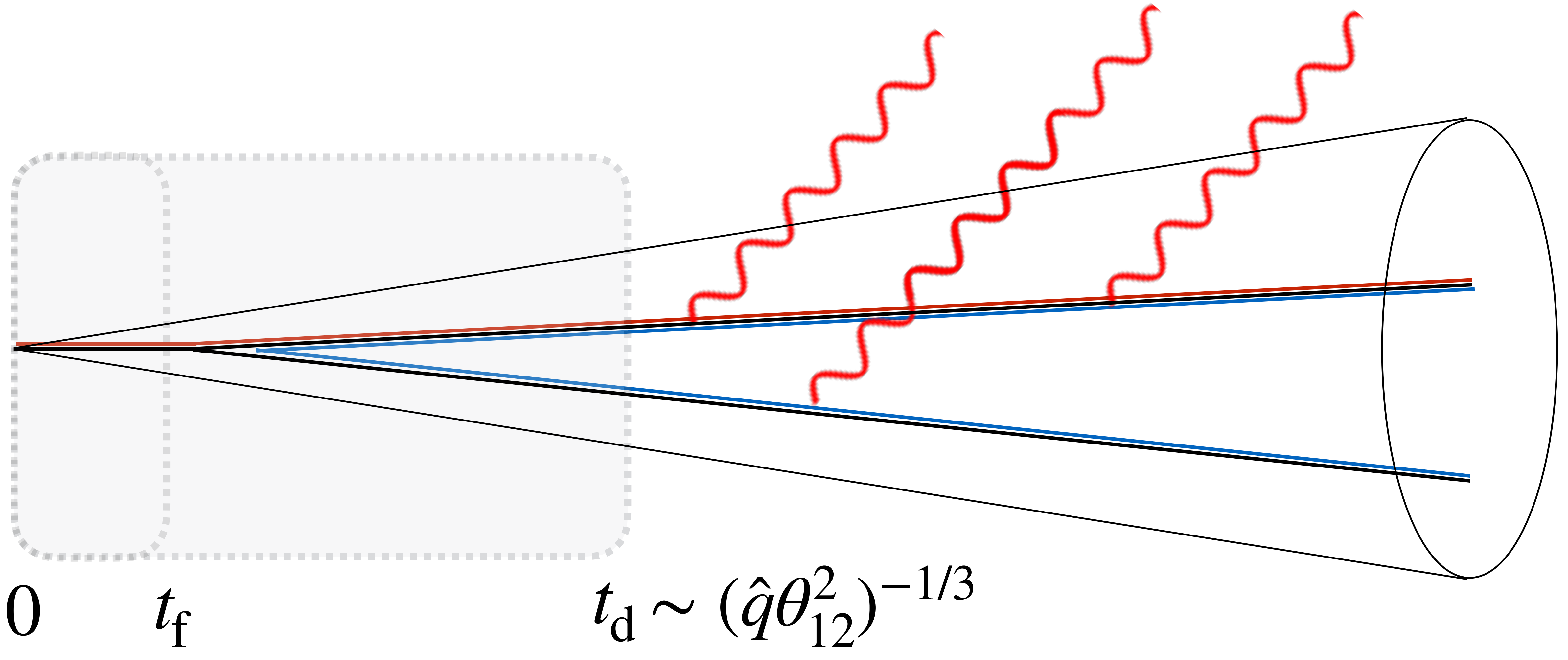
$$+ \int_0^\infty {\rm d}\omega \left[1 - \Delta_{\rm med}(t)\right] \sum_{i \neq j} \Gamma_{ij}(\omega, t) \delta(\epsilon - \omega)$$

coupled set of equations

(truncated in the large-N_c limit)

FROM COHERENCE TO DECOHERENCE

$$r_\perp(t) \sim \theta_{12} t \quad \Leftrightarrow \quad \lambda_{\rm res} \sim (\hat{q} t)^{-1/2}$$



$$t_{\rm d} \sim L$$

$$\Downarrow$$

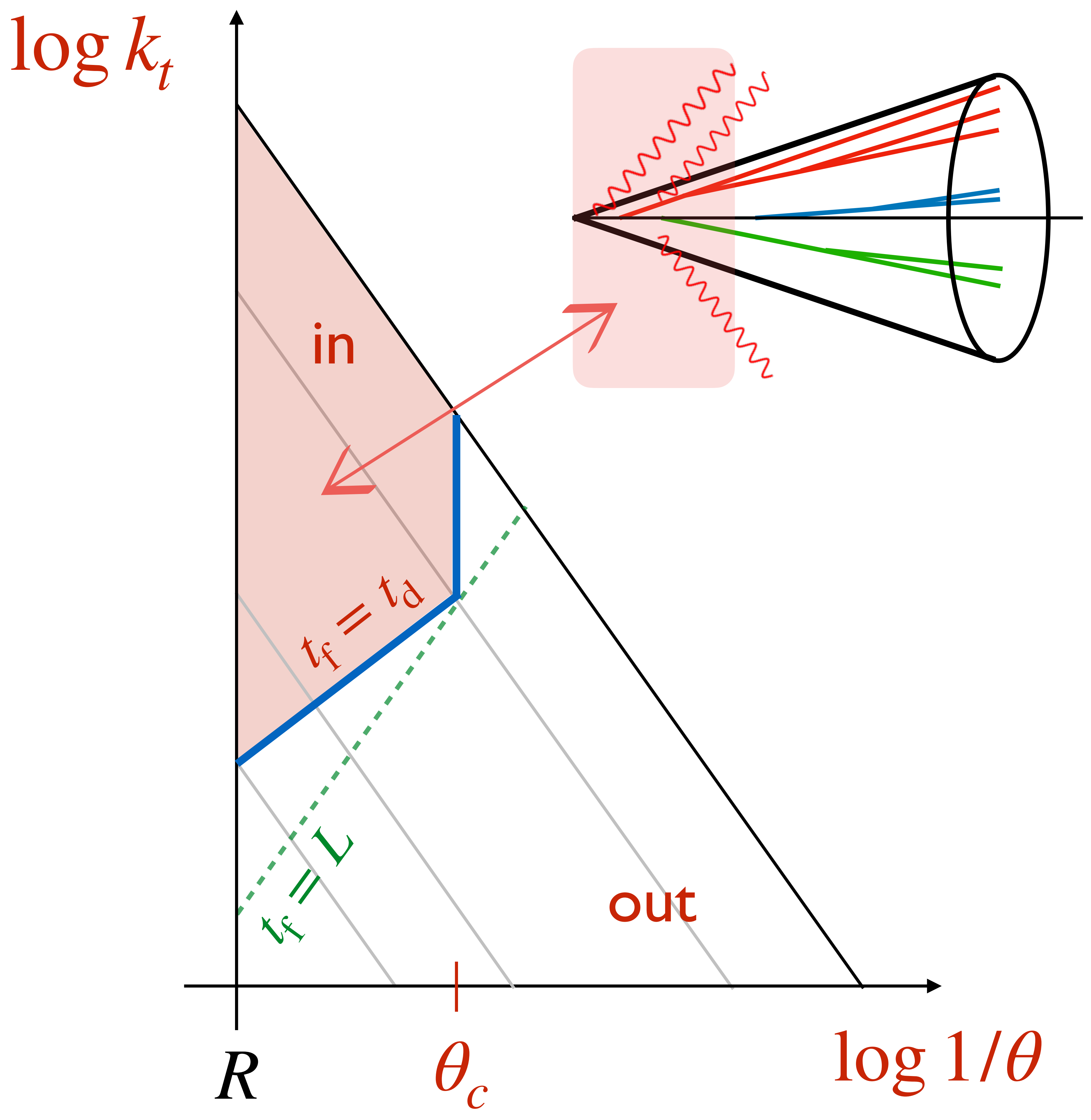
$$\theta_c \sim \sqrt{\frac{1}{\hat{q} L^3}}$$

- at early times coherence: only e-loss of total color charge
- at late times decoherence: e-loss of individual color charges

t_d plays a crucial role → Extend this to multiple emissions!

HOW MANY EMISSIONS IN MEDIUM?

Y. Mehtar-Tani, KT 1706.06047, 1707.07361



Vacuum-like emissions (VLEs) w/ $k_t^2 > \sqrt{\hat{q}\omega}$ and $\theta > \theta_c$ are emitted inside plasma and resolved by the medium.

How many emissions in medium?

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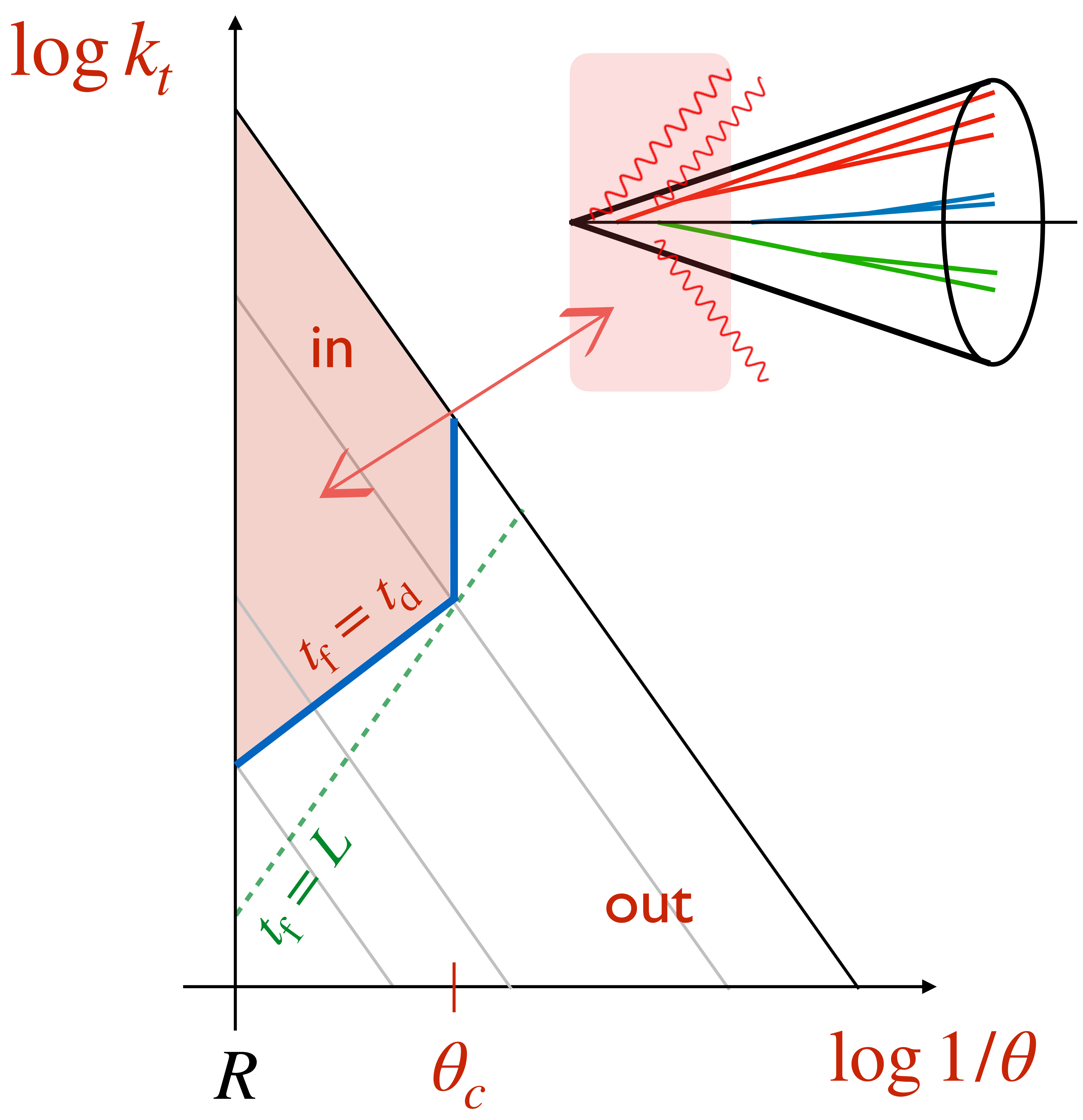


Vacuum-like emissions (VLEs) w/ $k_t^2 > \sqrt{\hat{q}\omega}$ and $\theta > \theta_c$ are emitted inside plasma and resolved by the medium.

# of VLE = area on the Lund plane

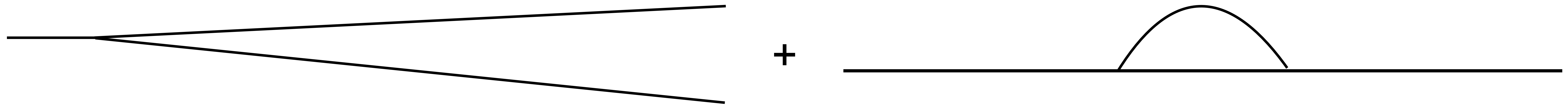
$$(\mathrm{PS})_{\mathrm{in}} \approx 2\frac{\alpha_s C_R}{\pi} \log\frac{R}{\theta_c}\left(\log\frac{p_T}{\omega_c} + \frac{2}{3}\log\frac{R}{\theta_c}\right)$$

Potentially large and needs to be resummed.

Monte Carlo implementations: Caucal, Iancu, Mueller, Soyez 1801.09703
Takacs, Pablos, KT

Higher-order contributions

Y. Mehtar-Tani, KT 1707.07361

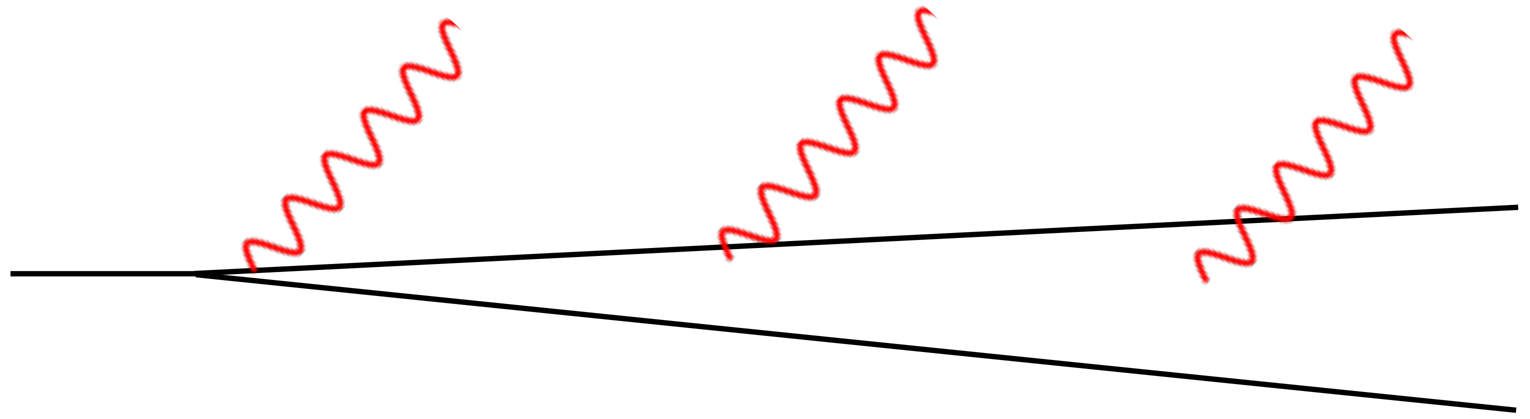


in vacuum:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2} = \frac{\mathrm{d}\sigma_{\mathrm{Born}}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2}\left[1+\alpha_s\left(\int \mathrm{d}\Pi_{\mathrm{real}} - \int \mathrm{d}\Pi_{\mathrm{virt}}\right) + \mathcal{O}(\alpha_s^2)\right]$$

HIGHER-ORDER CONTRIBUTIONS

Y. Mehtar-Tani, KT 1707.07361



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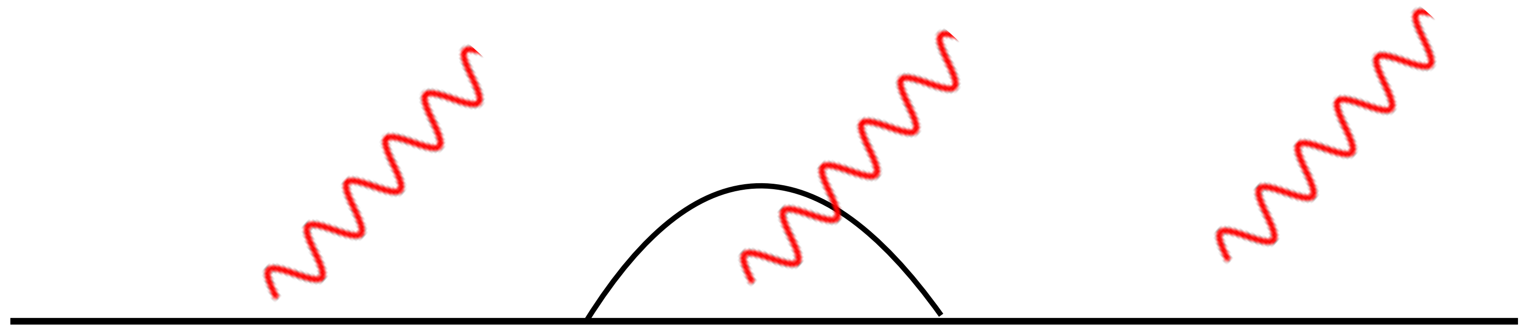


sensitive to quark+gluon quenching

sensitive to quark quenching

in vacuum:
$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2} = \frac{\mathrm{d}\sigma_{\mathrm{Born}}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2}\left[1 + \alpha_s\left(\int \mathrm{d}\Pi_{\mathrm{real}} - \int \mathrm{d}\Pi_{\mathrm{virt}}\right) + \mathcal{O}(\alpha_s^2)\right]$$

expanding the quenching factor

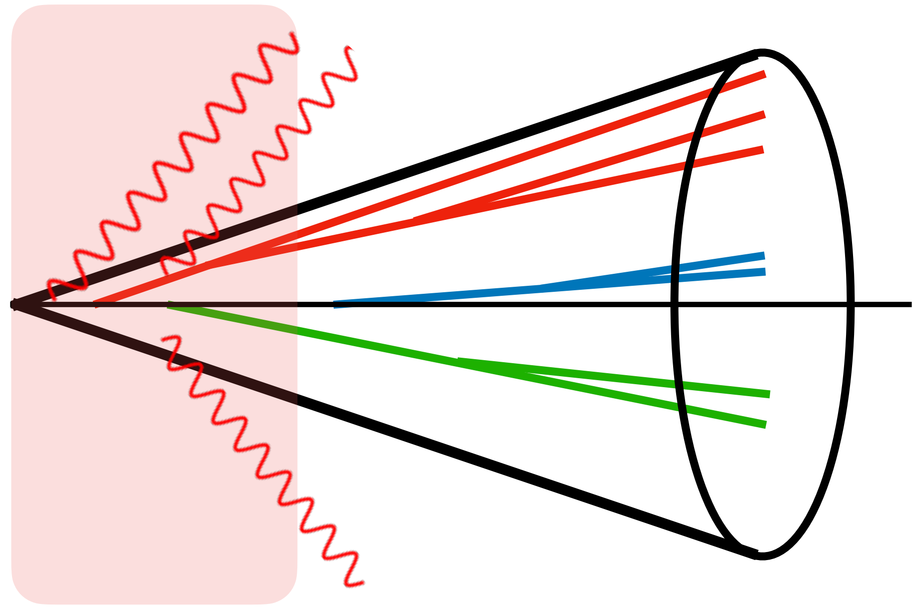
accounts for the quenching of higher-order vacuum emissions

$$R_{\mathrm{jet}} = \mathcal{Q}^{(0)}(p_{\mathrm{T}}) + \mathcal{Q}^{(1)}(p_{\mathrm{T}}) + \mathcal{O}(\alpha_s^2)$$

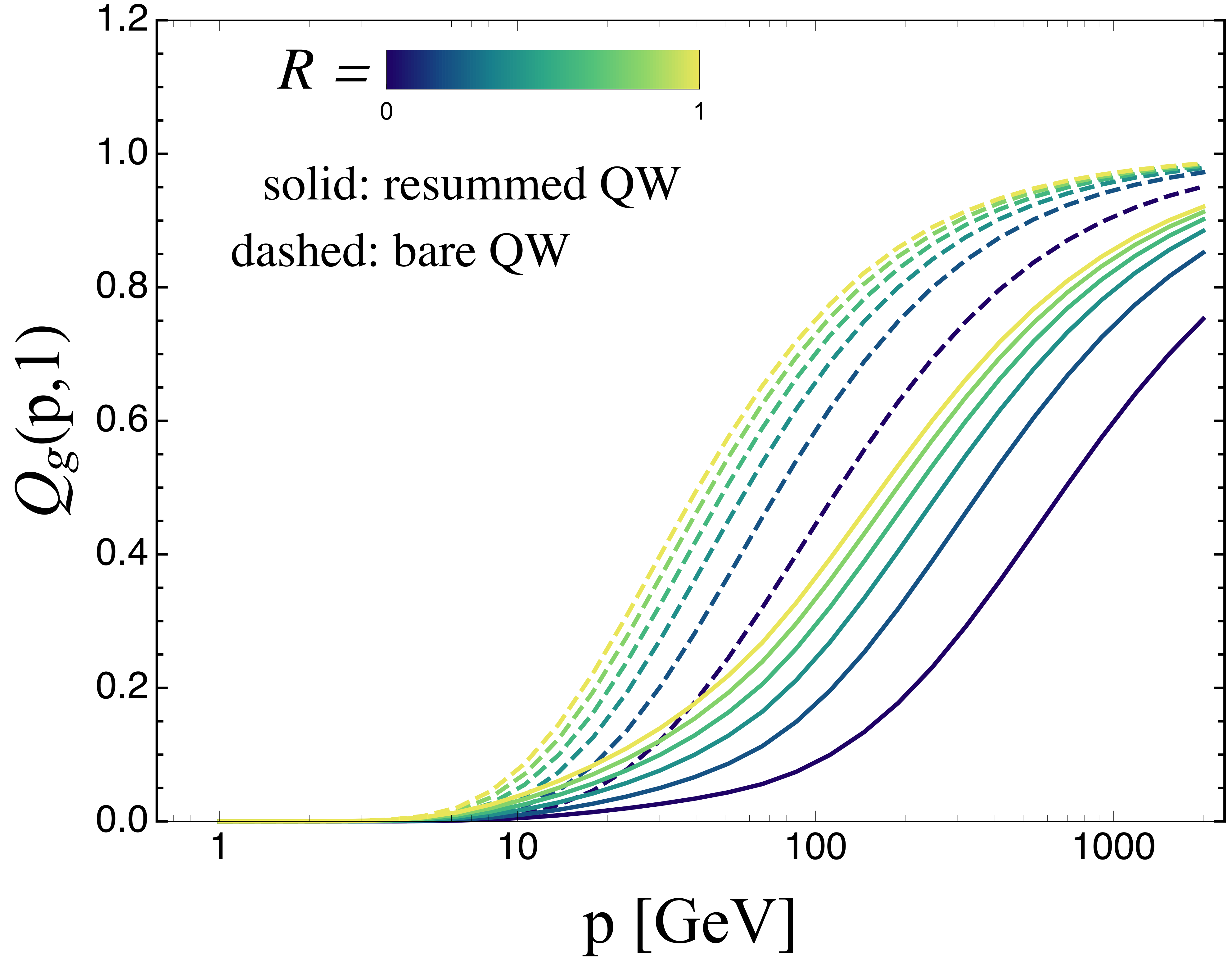
$$\mathcal{Q}^{(1)}(p_{\mathrm{T}}) = \int_0^1 \mathrm{d}z\, P_{gq}(z) \int_0^R \frac{\mathrm{d}\theta}{\theta}\frac{\alpha_s(k_\perp)}{\pi}\left[\mathcal{Q}_{gq}(p_{\mathrm{T}}) - \mathcal{Q}_q(p_{\mathrm{T}})\right] \simeq -\mathcal{Q}_q(p_{\mathrm{T}})N(t_{\mathrm{f}} < L)$$

Non-linear evolution of jet quenching

Mehtar-Tani, KT 1707.07361; Mehtar-Tani, Pablos, KT PRL 127 (2021)



$$\frac{\partial Q_i(p,\theta)}{\partial \log \theta} = \int_0^1 \mathrm{d}z\, \frac{\alpha_s}{2\pi} p_{ij}(z) \Theta_{\rm in} \Big[Q_j(zp,\theta) Q_k((1-z)p,\theta)) - Q_i(p,\theta) \Big]$$



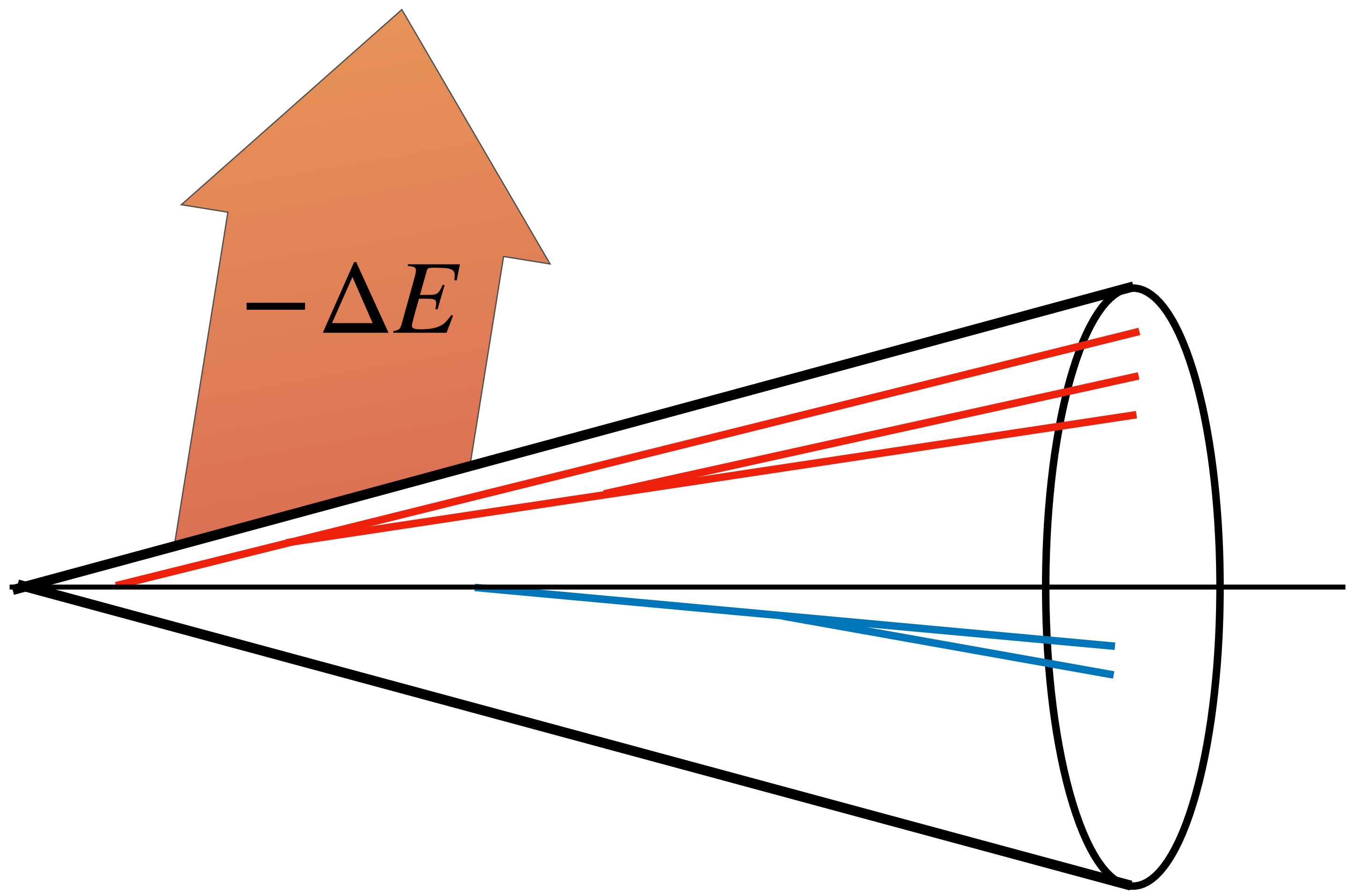
- counts all **in-medium** & **resolved** splittings to compute full jet quenching.
- initial condition
  $Q_i(p,0) = Q^{(0)}_{>,\rm rad}(p_T) \times Q^{(0)}_{\rm el}(p_T) \times \ldots$

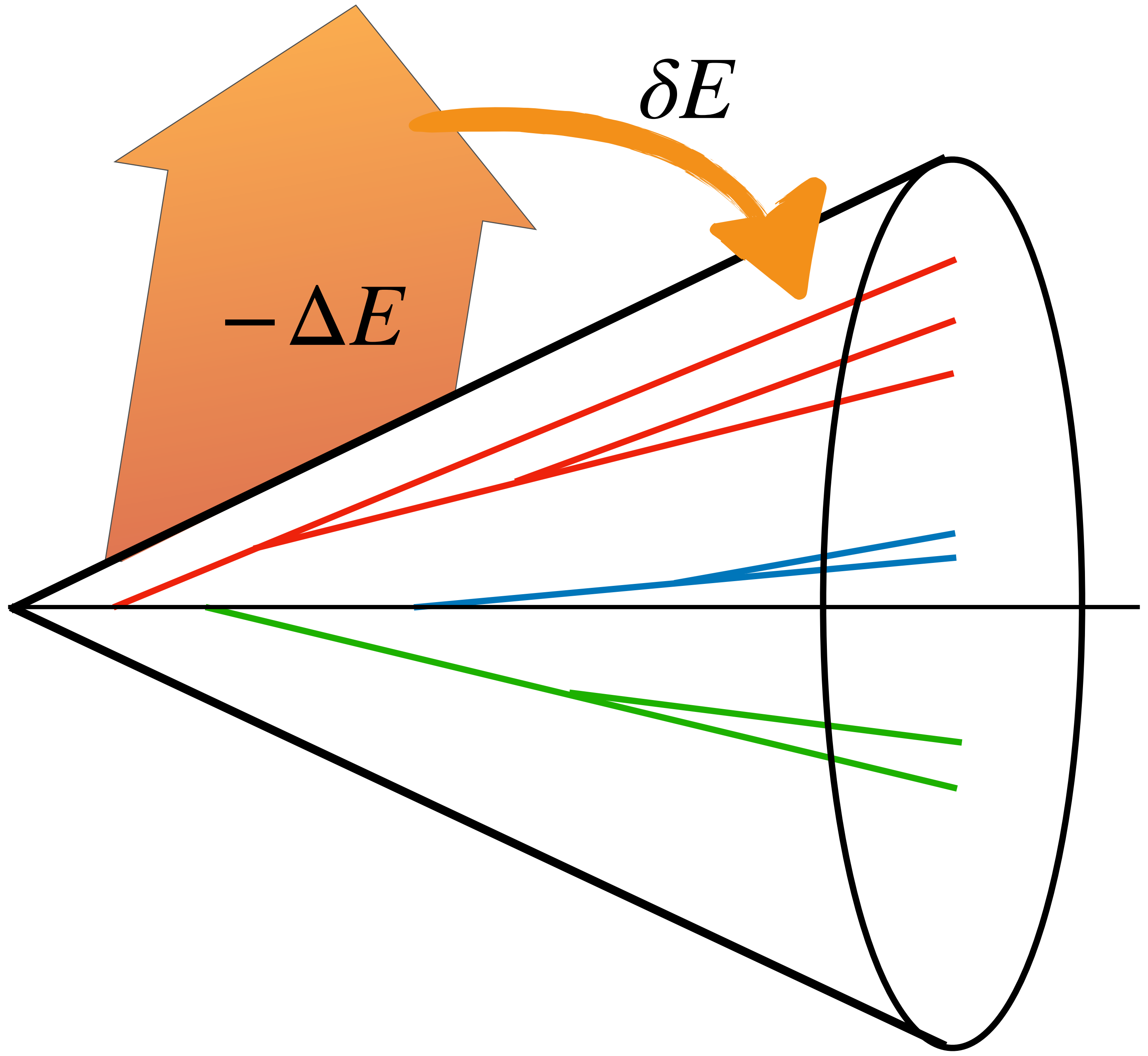
Linearized solution: $Q_i(p_T, R) = Q^{(0)}_{>,i}(p_T, R) \mathrm{e}^{(Q_g^{(0)}-1)\Omega_{\rm in}}$

CONE-SIZE DEPENDENCE

Narrow jets

Wide jets





less energy loss BUT
easier to escape the cone

more energy loss BUT
emitted energy **leaks back** into cone

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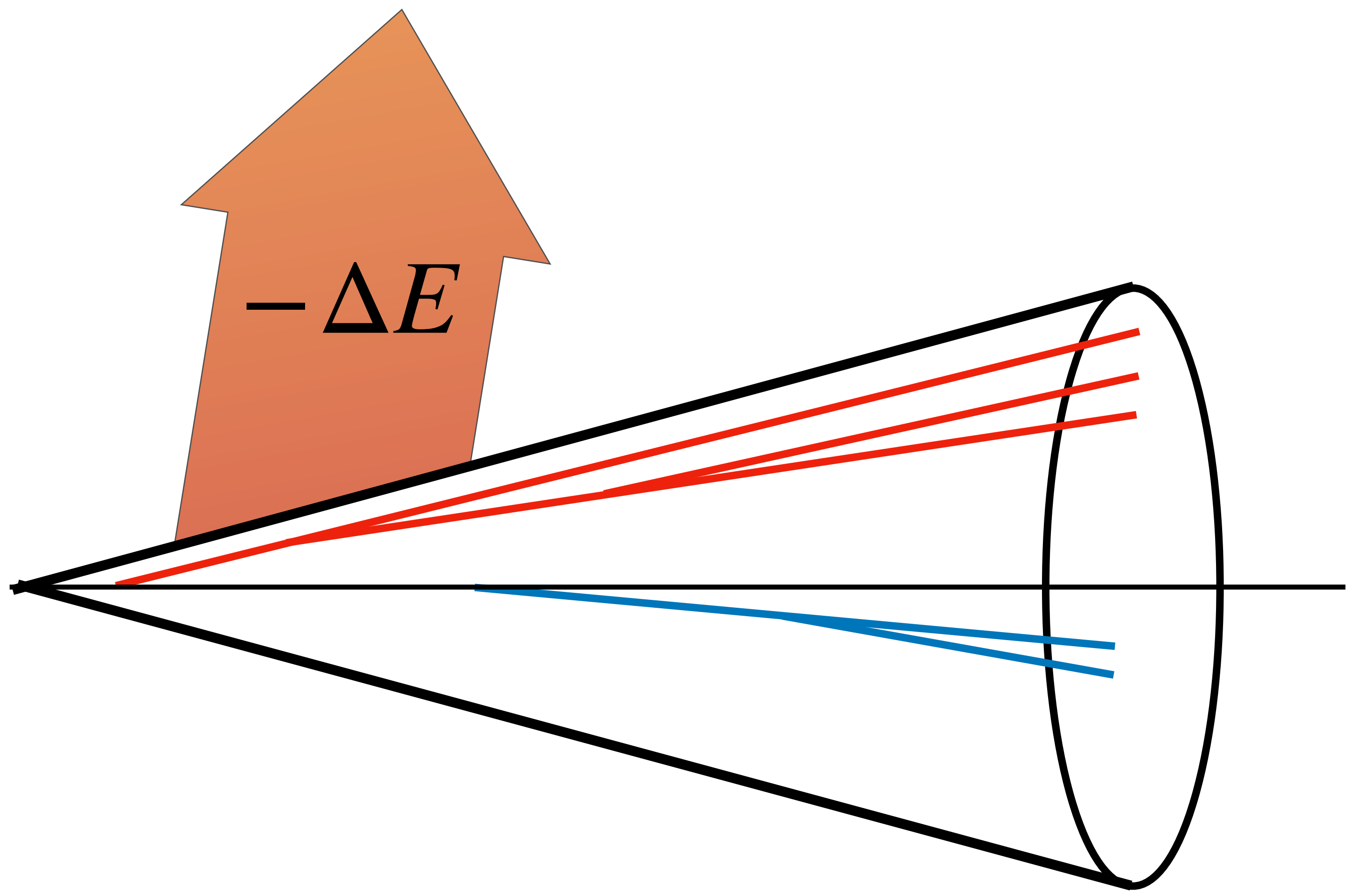

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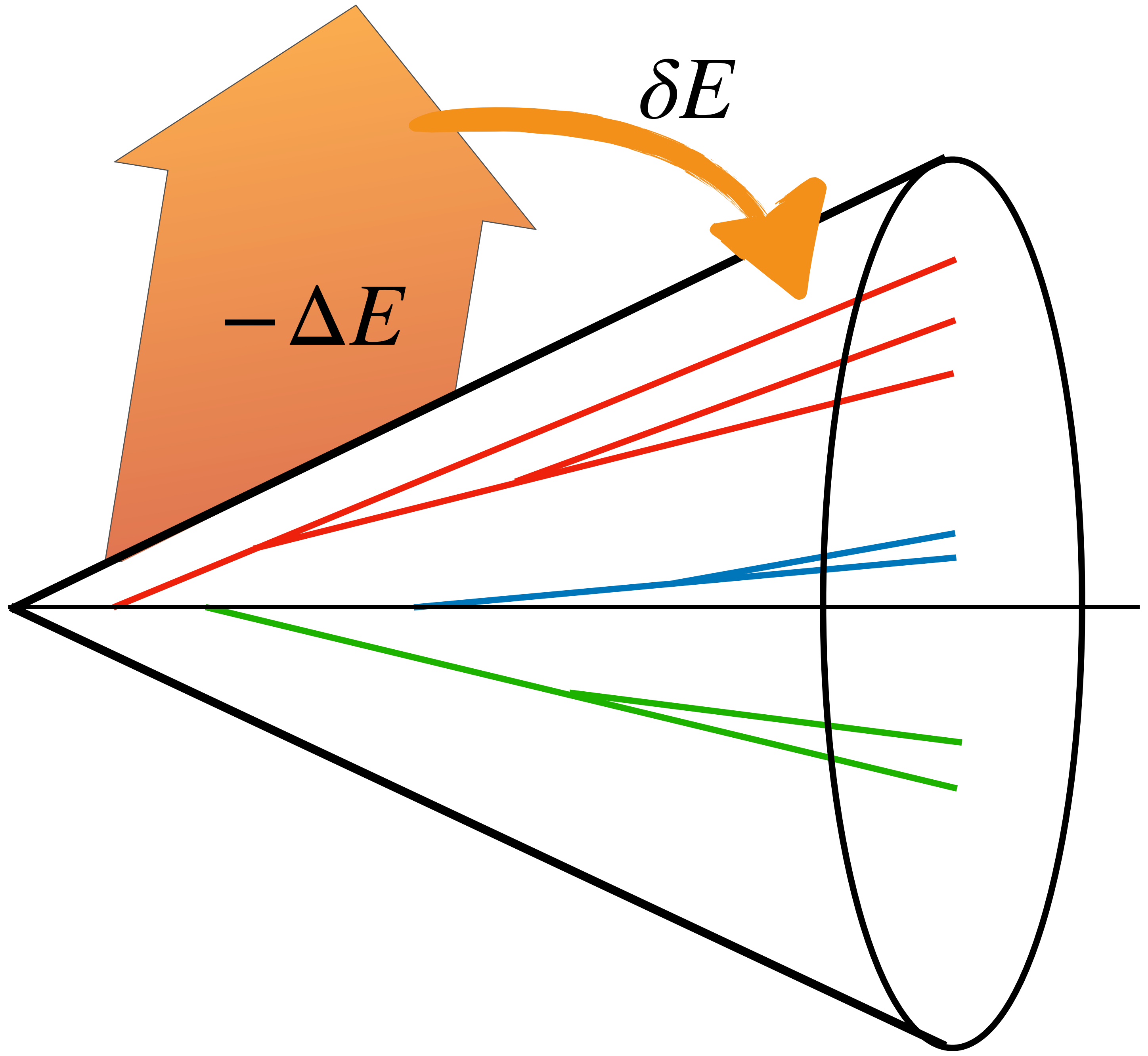
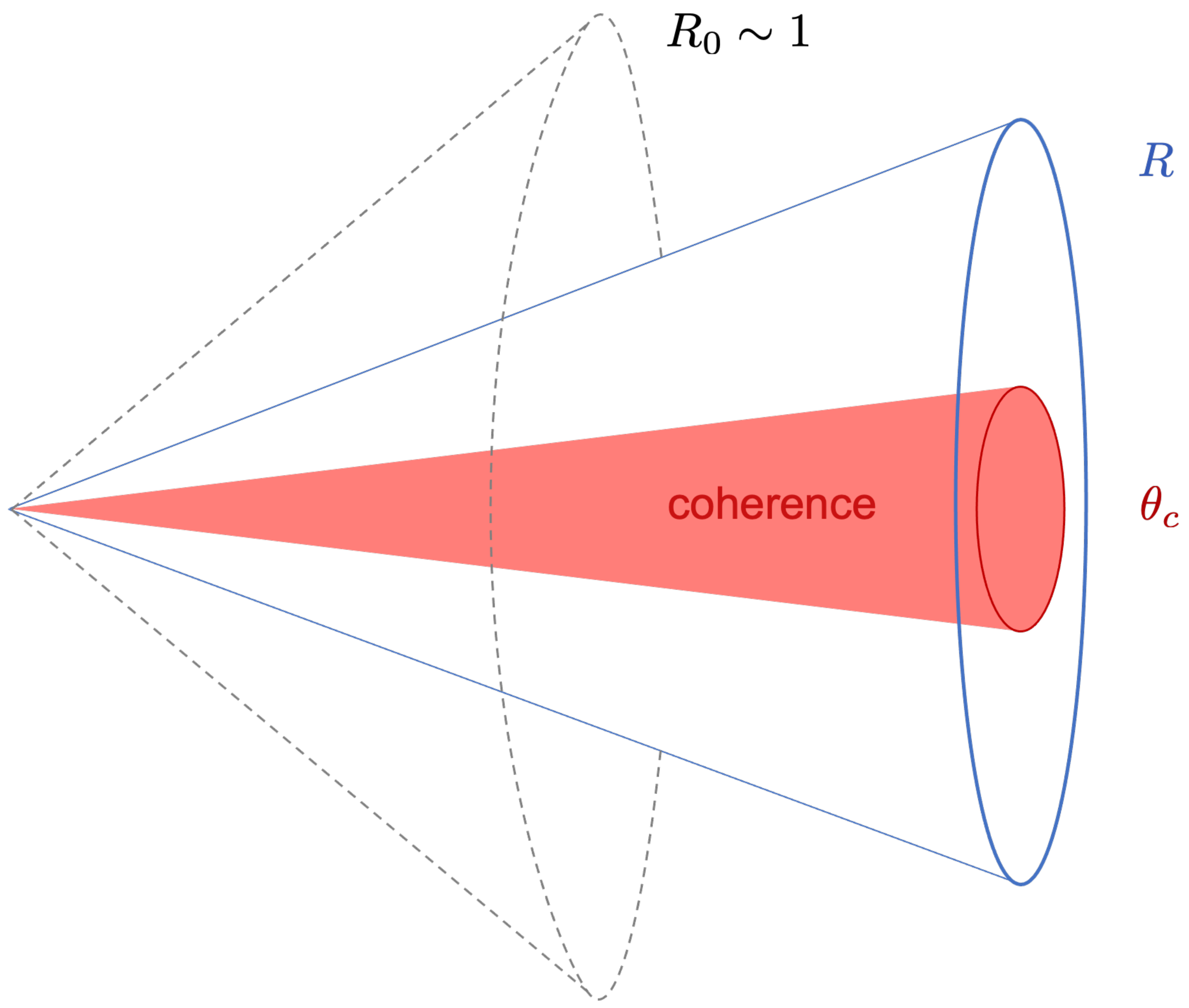


more energy loss BUT
emitted energy **leaks back** into cone

$\Longrightarrow$ new handle on medium effects: $\hat{q}$ affects **resolution** & **energy loss**

JET SUPPRESSION FACTOR

Mehtar-Tani, Pablos, KT Phys. Rev. Lett. 127 (2021); Takacs, KT 2103.14676
Shen, Qiu, Song, Bernhard, Bass, Heinz 1409.8164

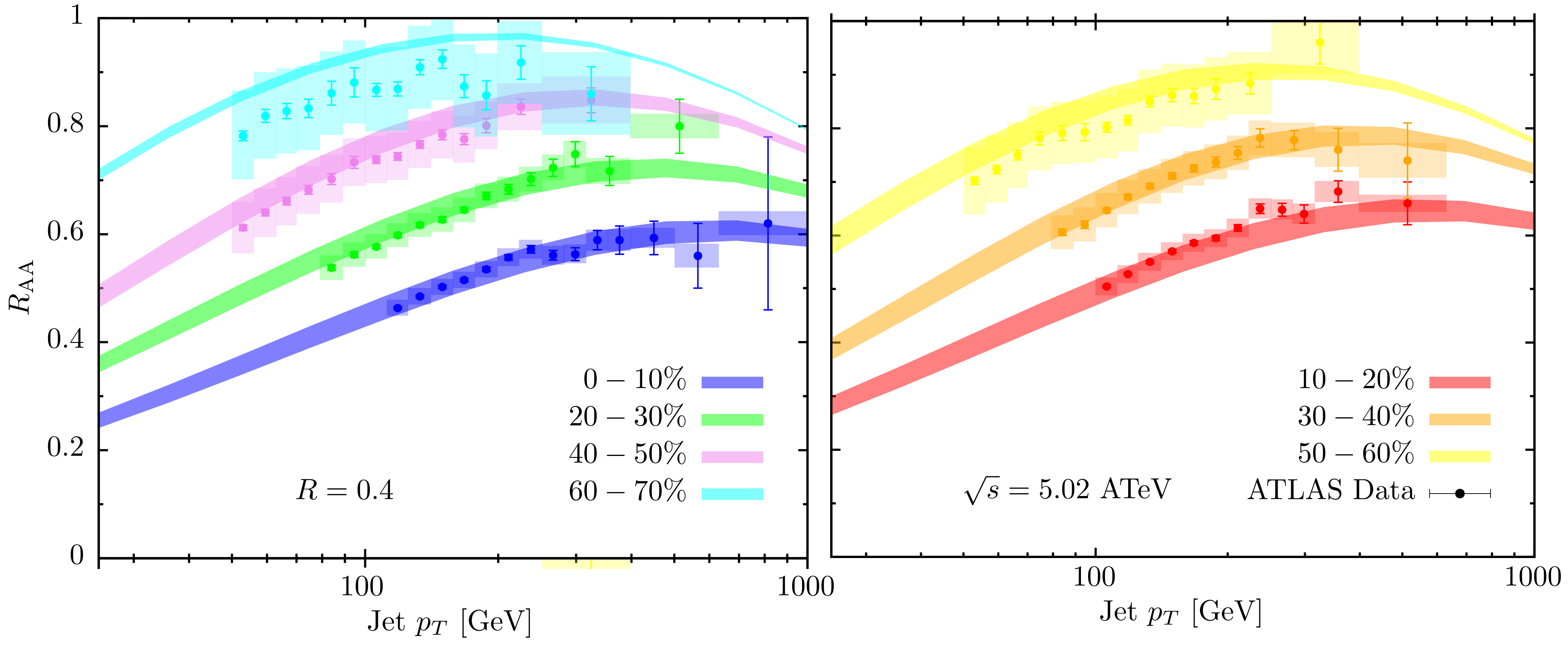


- collinear factorization w/nPDF (EPS09)
- $\log \frac{1}{R}$ resummation (DGLAP)
- full resummation of radiative and elastic processes in the medium
- sampling of geometry and medium evolution (VISHNU)
- only two free parameters: $g_{\rm med}$ and $R_{\rm rec}$

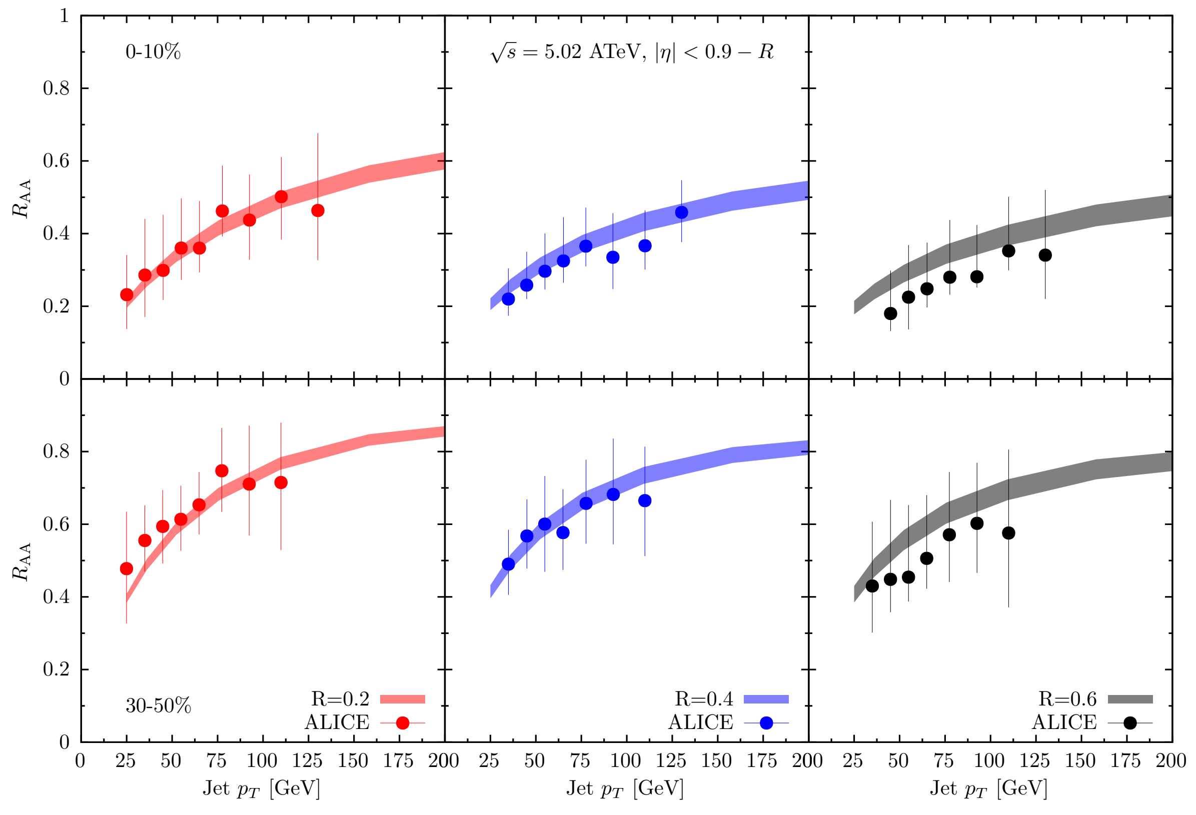
CONE-SIZE DEPENDENCE

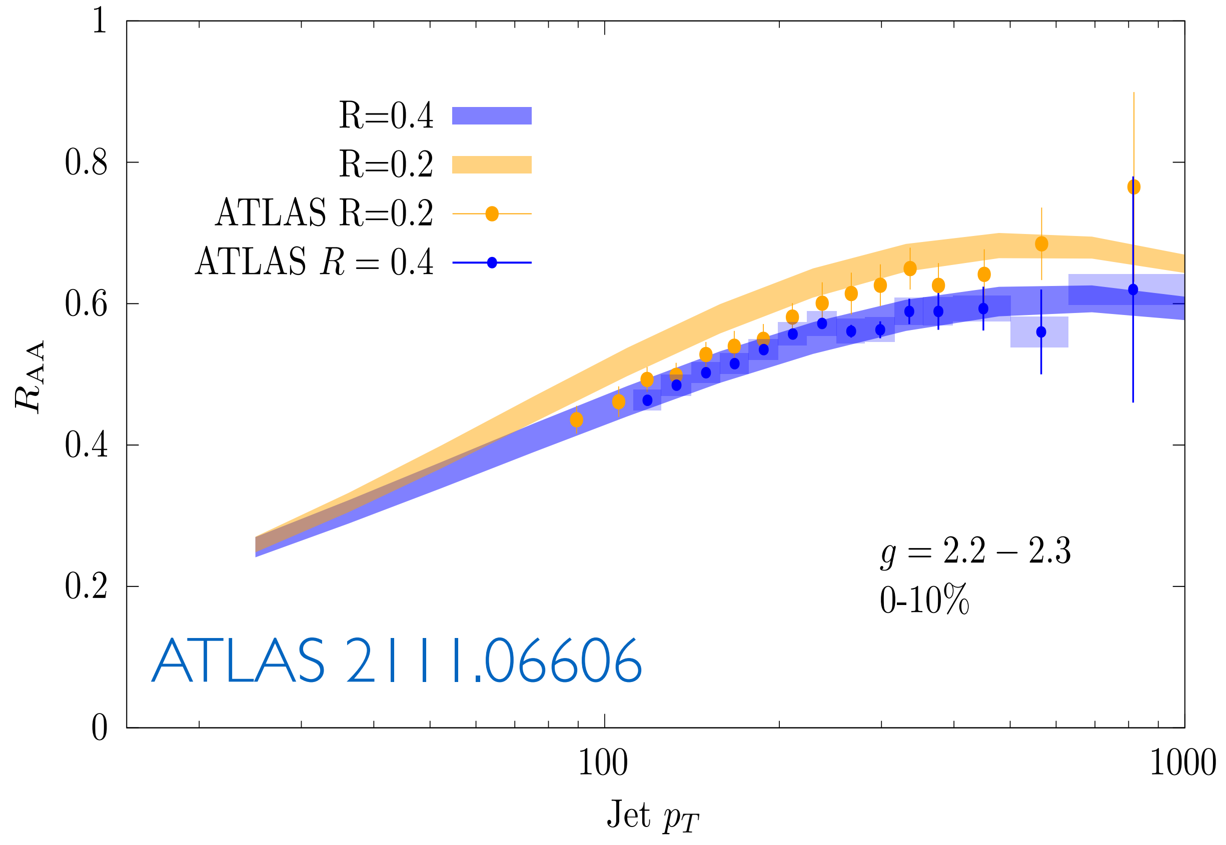
Mehtar-Tani, Pablos, KT PRL 127 (2021)
M. Aaboud et al. (ATLAS) 1805.05635
S. Acharya et al. (ALICE) 1909.09718
CMS-PAS-HIN-18-014

M. Aaboud et al. (ATLAS), 1805.05635



ALICE 2303.00592





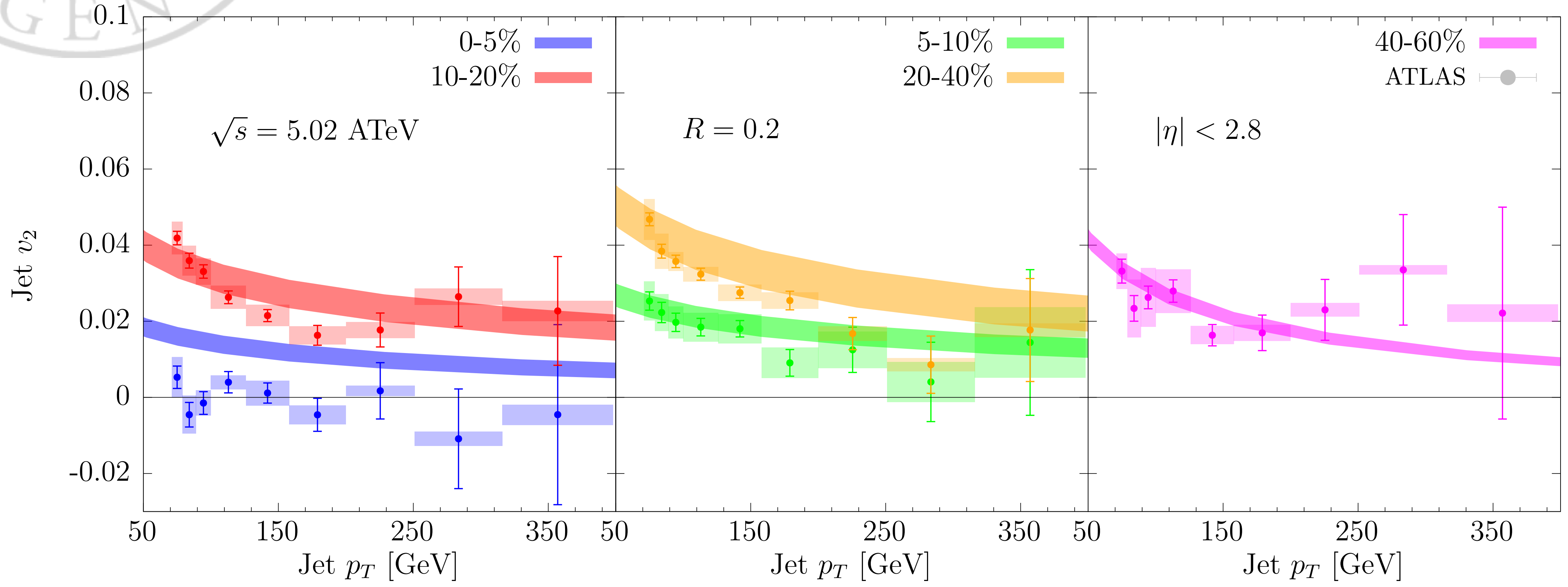
ATLAS 2111.06606

- main uncertainties for $R \leq 0.6$:
  - perturbative sector (vacuum-like emissions + medium-induced $\omega \gtrsim \omega_s$) dominates!
  - details of thermalization/recovery ($R_{\rm rec}$) important at $R \gtrsim 0.6$.

- excellent agreement with existing experimental data!

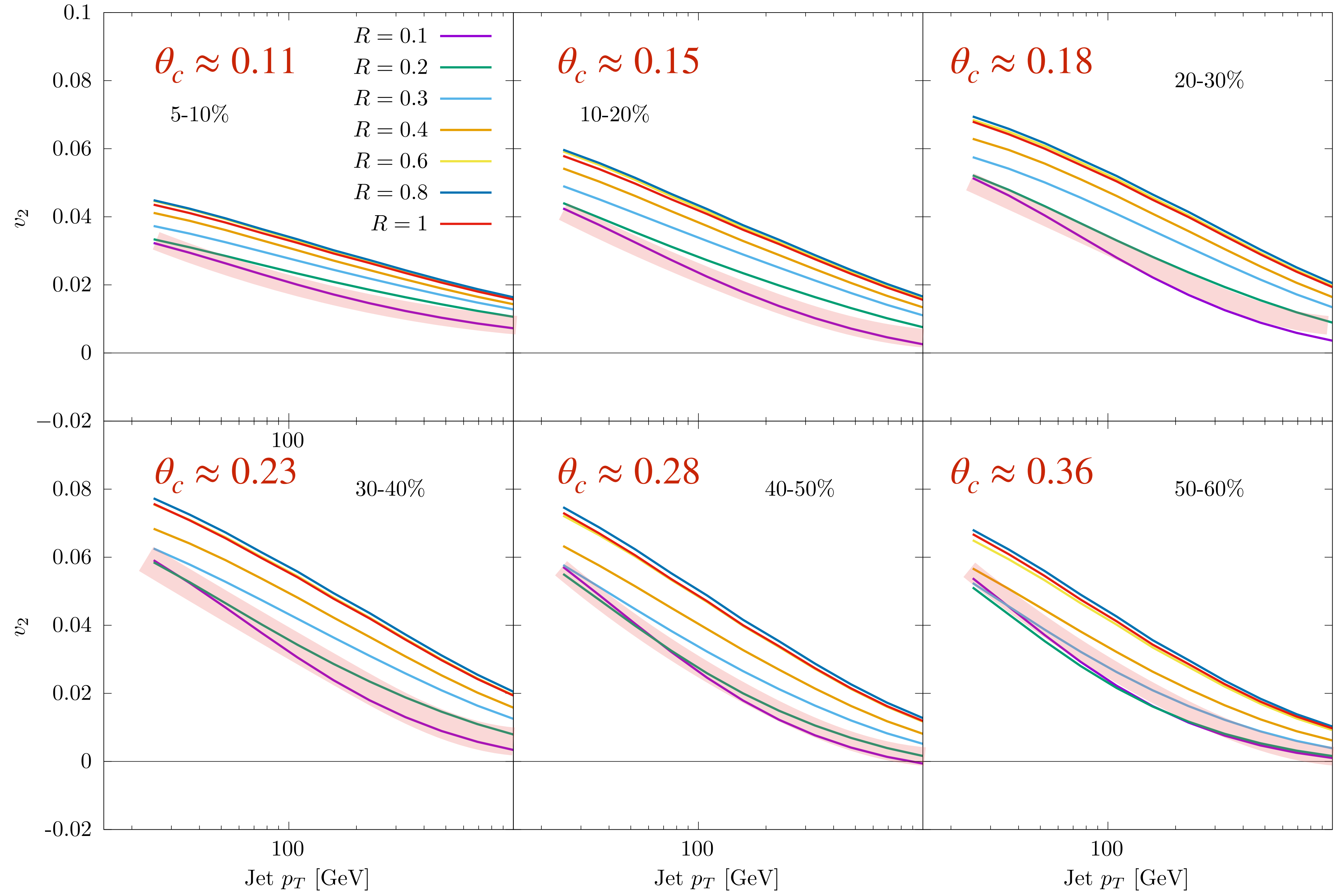
AZIMUTHAL ASYMMETRY

Mehtar-Tani, Pablos, KT (to appear)



$$v_2 \approx \frac{1}{2}\frac{R_{AA}(L) - R_{AA}(L+\Delta L)}{R_{AA}(L) + R_{AA}(L+\Delta L)}$$

$$\frac{v_2^{\text{jet}}}{\text{e}} \approx \begin{cases} \dfrac{v_2^{\text{parton}}}{\text{e}} & \text{for } R < \theta_c \\ \dfrac{v_2^{\text{parton}}}{\text{e}} + \frac{3}{2}\bar{\alpha}\log\frac{p_T}{\omega_c}(1-Q_g) & \text{for } R > \theta_c \end{cases}$$



- jet v_2 receives additional contribution from resolution effects.
- **prediction**: cone-size dependence vs centrality reveal sensitivity to coherence angle (grouping).

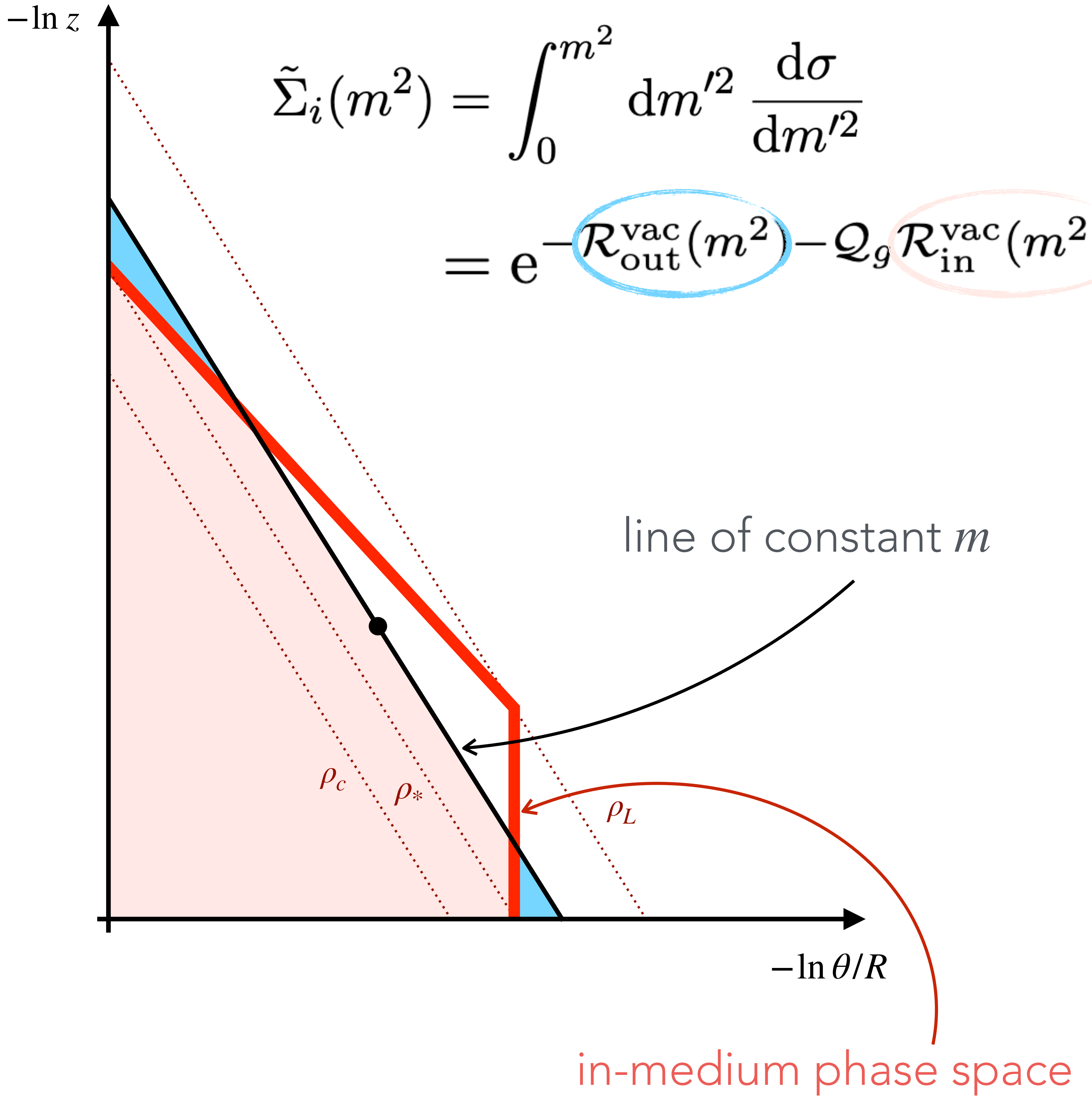
JET SUBSTRUCTURE: MASS

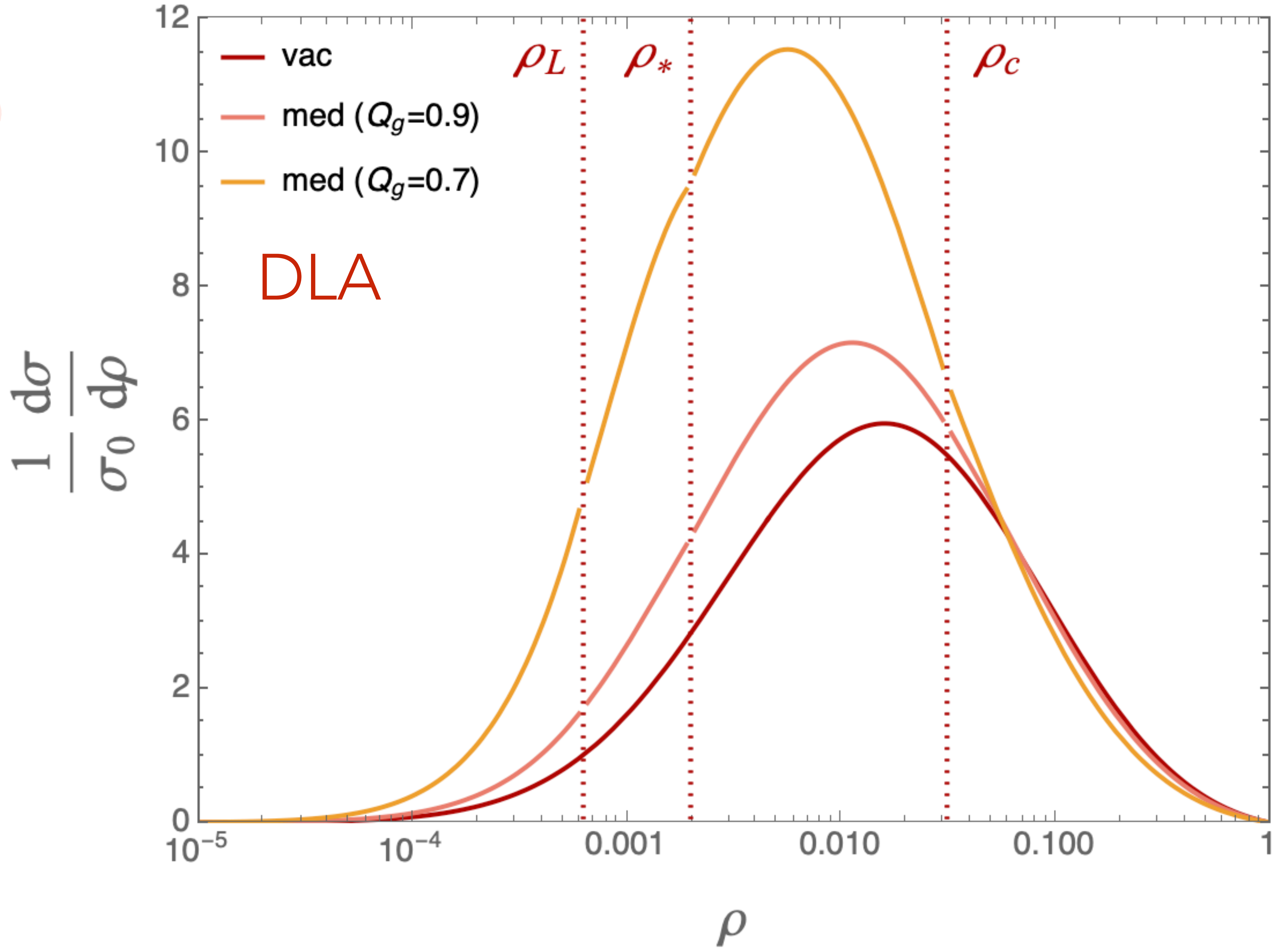
Mehtar-Tani, Takacs, KT (in preparation)
see also Caucal, Soto-Ontoso, Takacs 2111.14768

$$\rho \equiv \frac{m^2}{(p_T R_0)^2} \simeq \sum_{i \in \mathrm{jet}} z_i(1-z_i)\left(\frac{\theta}{R_0}\right)^2$$

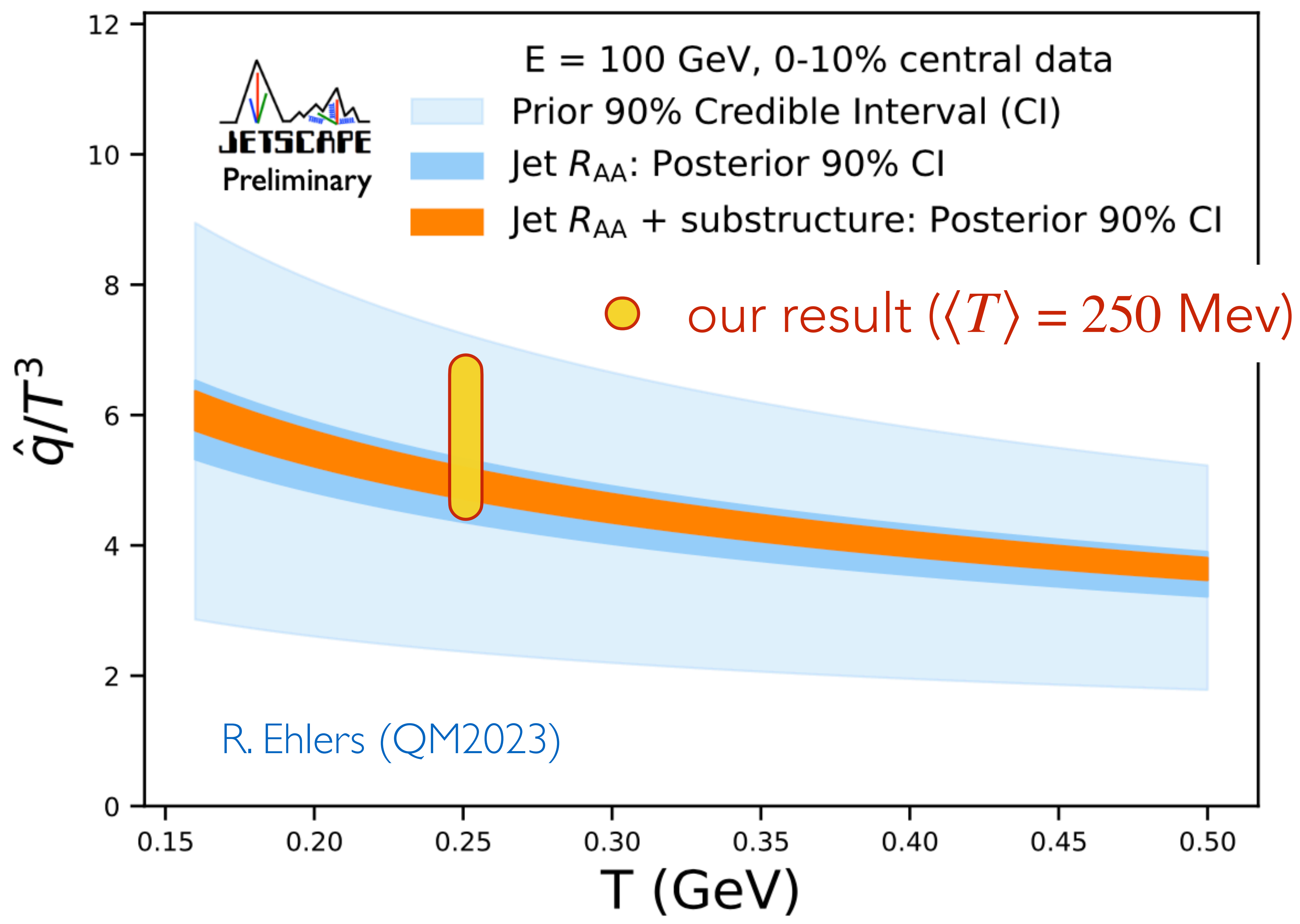
$$\tilde{\Sigma}_i(m^2) = \int_0^{m^2} \mathrm{d}m'^2 \, \frac{\mathrm{d}\sigma}{\mathrm{d}m'^2}$$

$$= \mathrm{e}^{-\mathcal{R}^{\mathrm{vac}}_{\mathrm{out}}(m^2) - \mathcal{Q}_g \mathcal{R}^{\mathrm{vac}}_{\mathrm{in}}(m^2)}$$



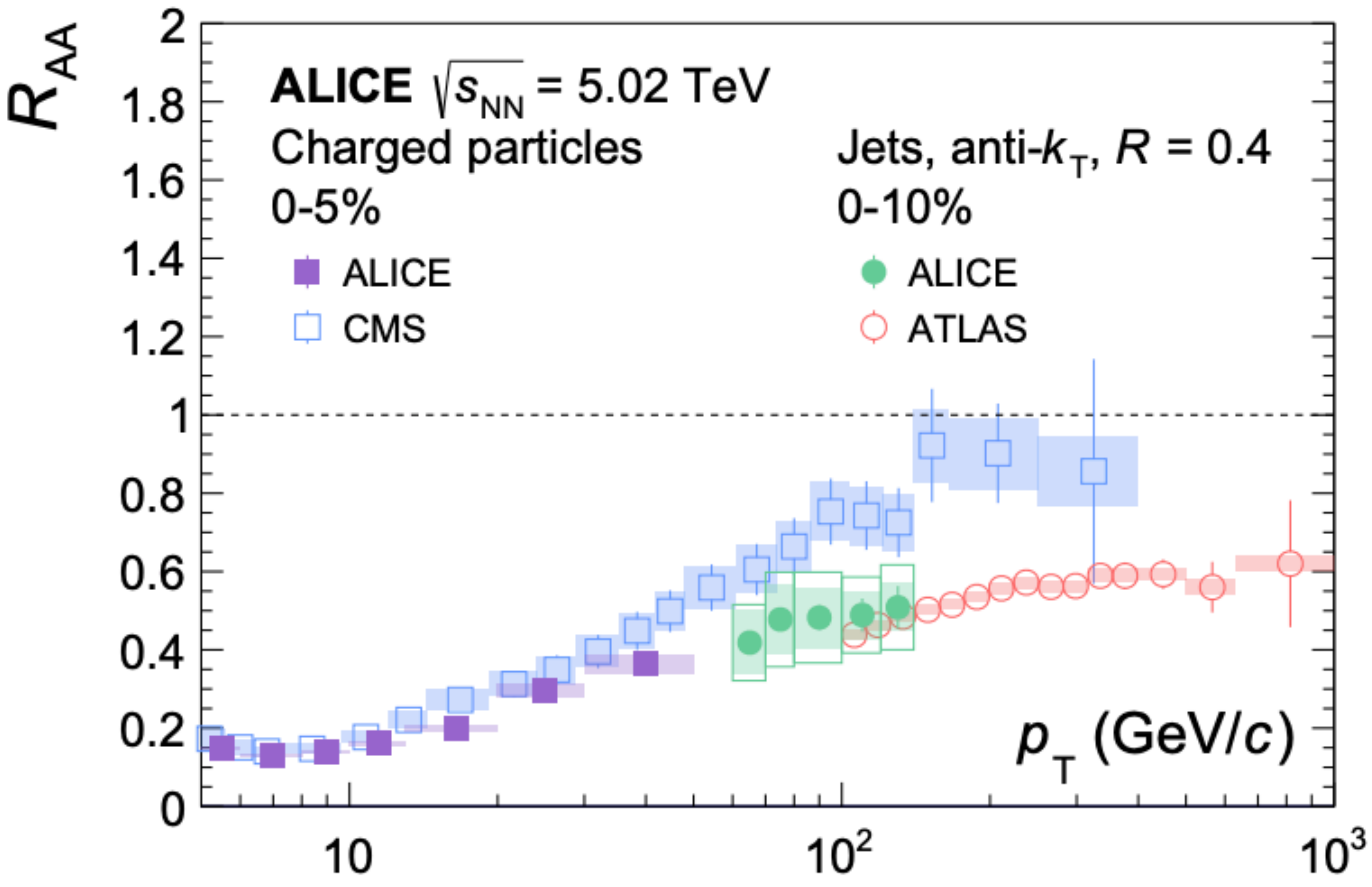


Extraction of medium parameters



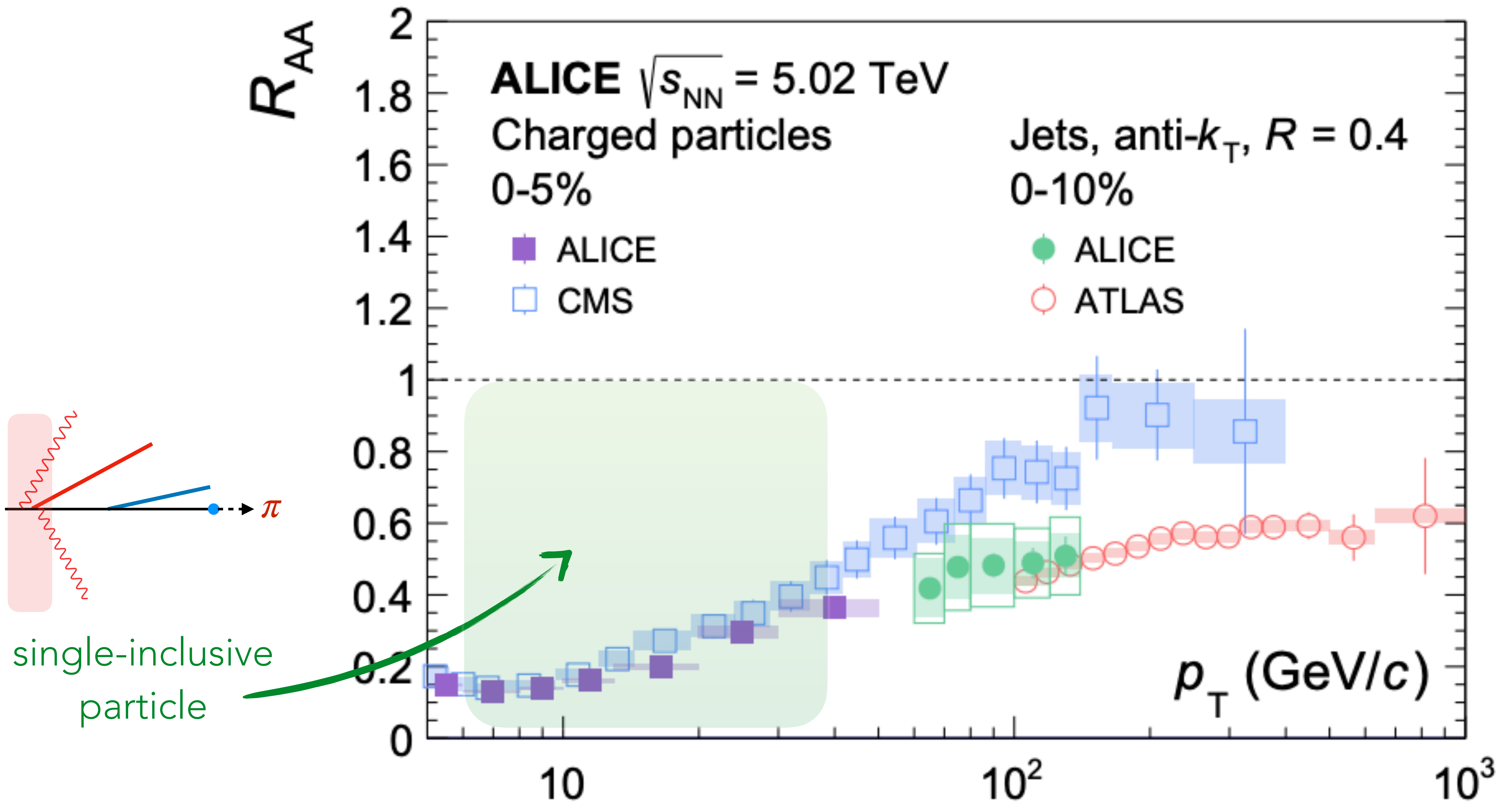
- from extracted parameters ($g_{med} \approx 2.2$) in hydro simulations we compute the effective $\hat{q}/T^3$ ratio
- agrees well with JETSCAPE analysis
- however: different calculations include different set of effects
  - hard to compare "apples to apples"
- other ideas: look for experimental signatures of quasi-particles, …
  - keep in mind bias!

SUMMARY WITH DATA



- kinematic range at LHC allows to probe jet quenching at varying scales.
- interesting set of data connecting **perturbative, length-enhanced and non-perturbative phenomena**

Summary with data



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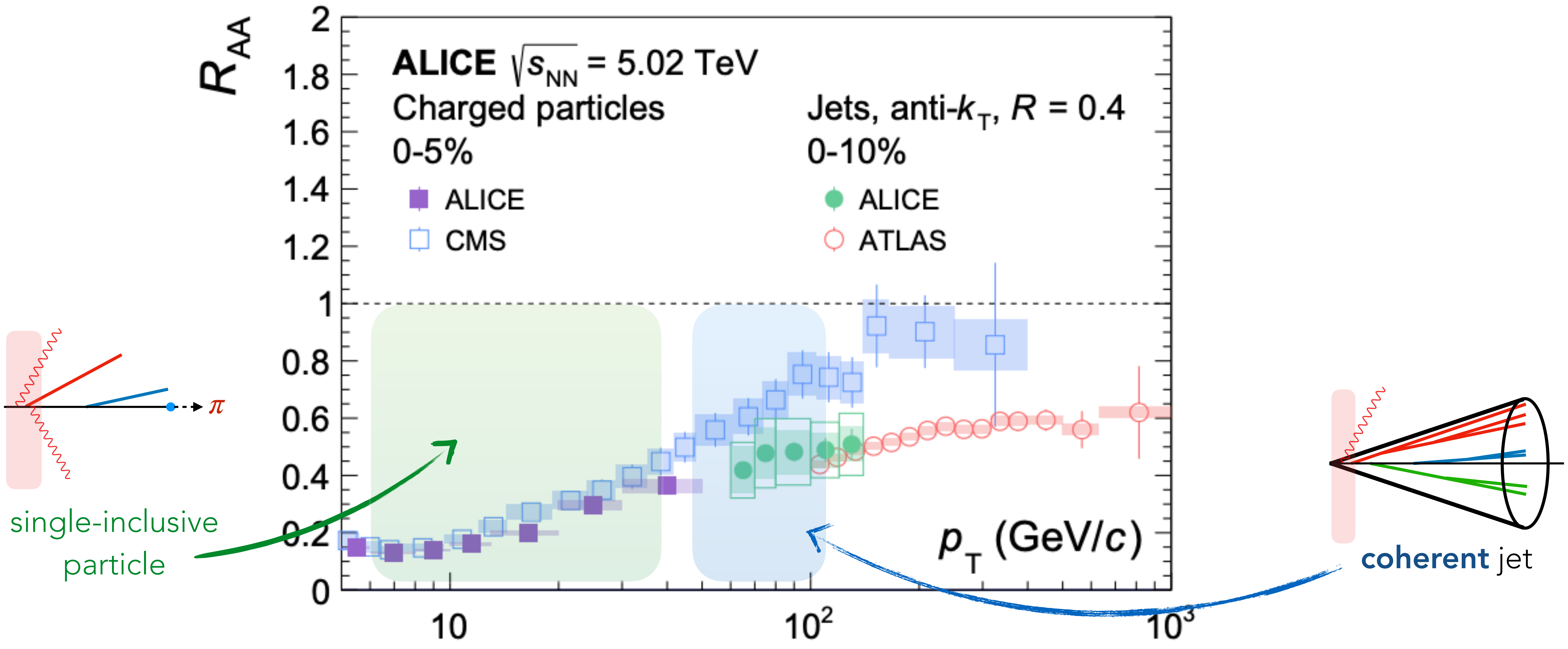

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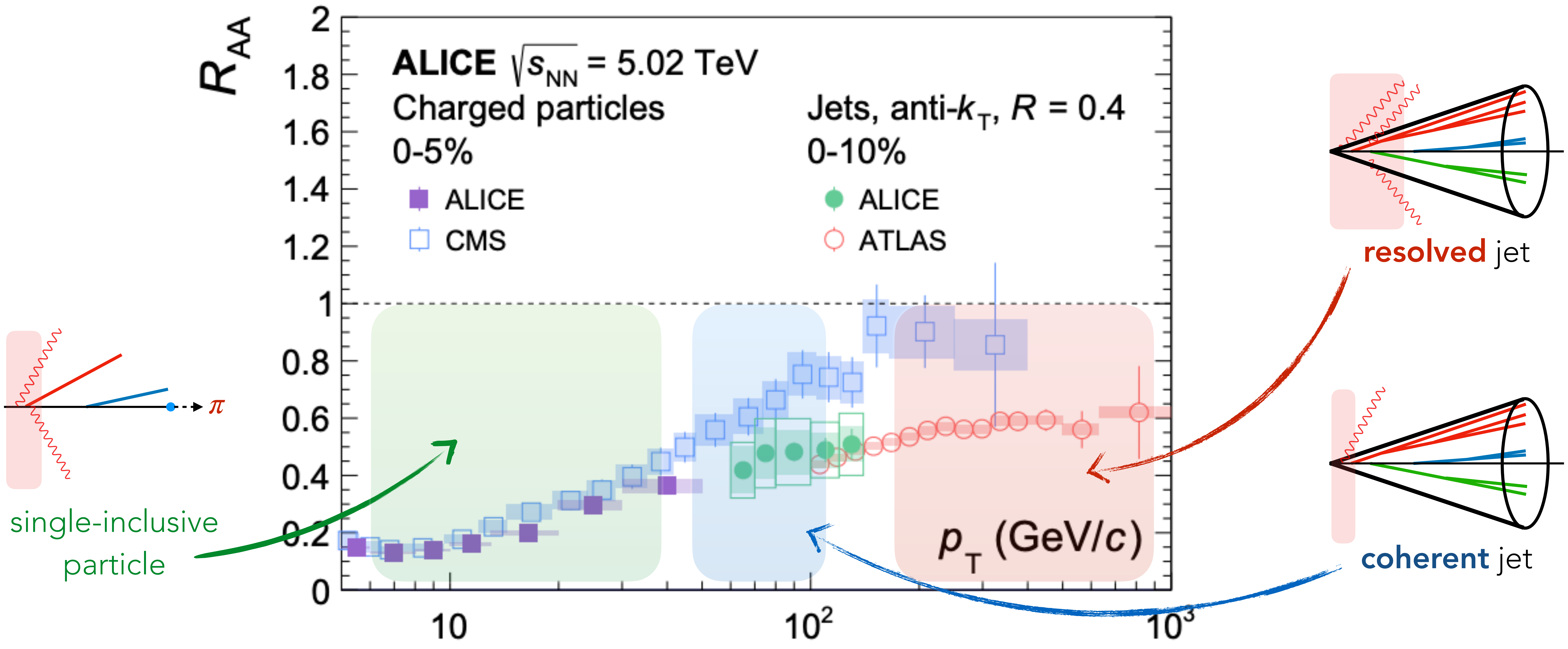

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Thank you!