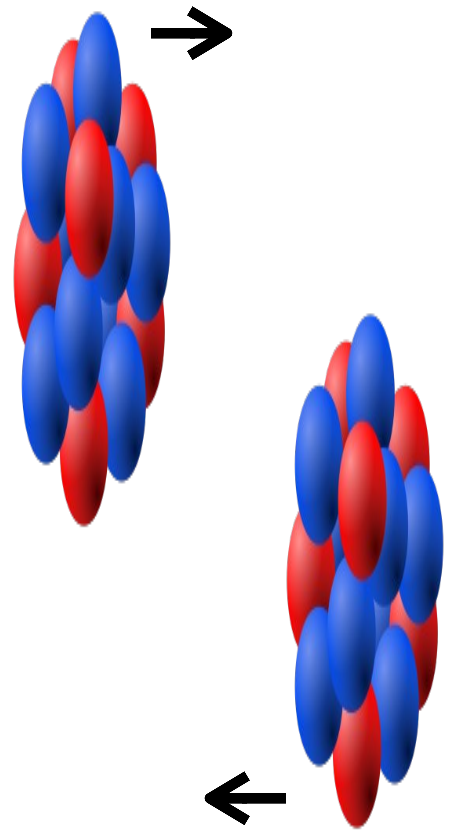
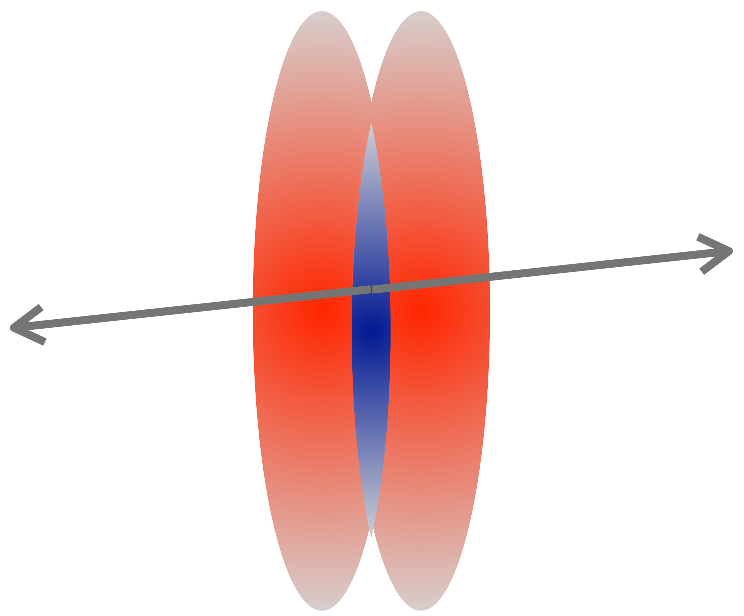
Recap, again



colliding nuclei



collision

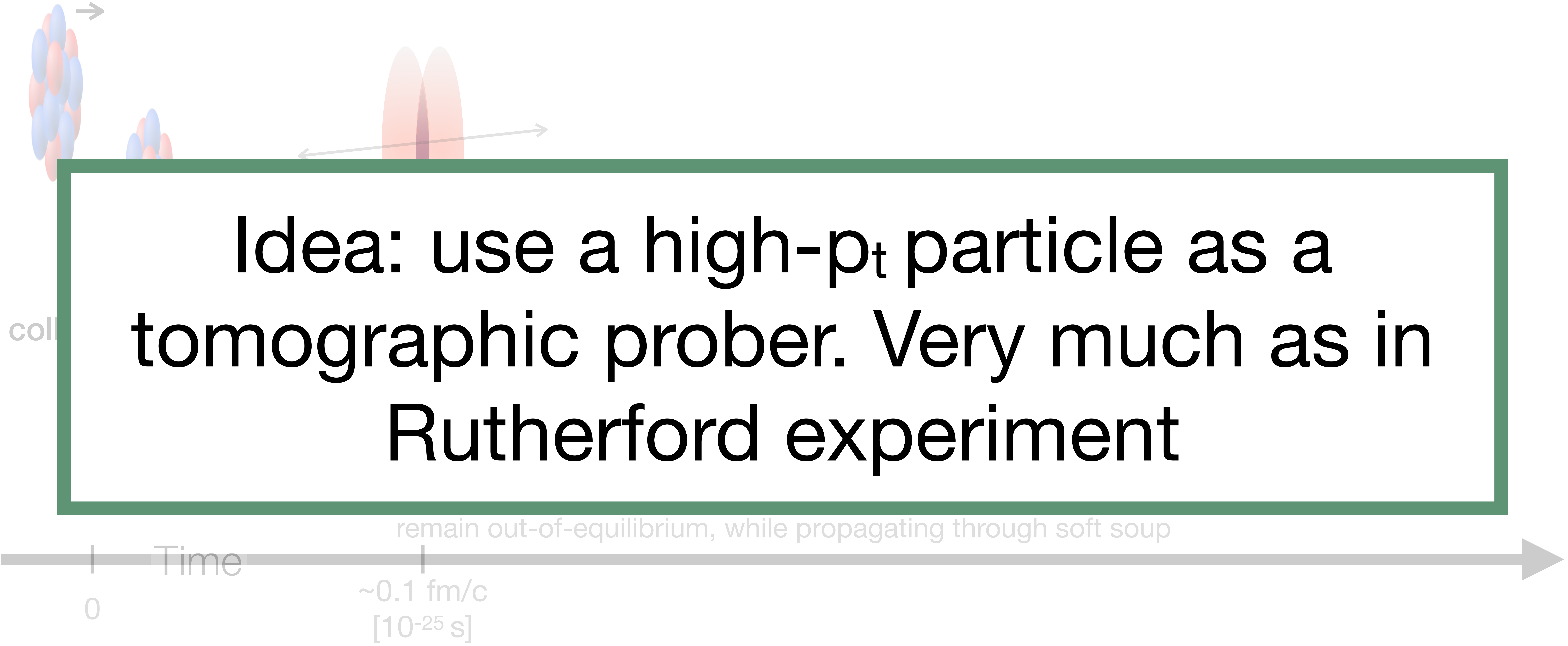
- many soft [small momentum exchange] collisions
  - responsible for bulk low-momentum particle production
  - will quickly hydrodynamize
- very few hard [large momentum exchange] collisions
  - offspring will slowly relax towards hydrodynamization, yet remain out-of-equilibrium, while propagating through soft soup

Time

0

~0.1 fm/c
[10^{-25} s]

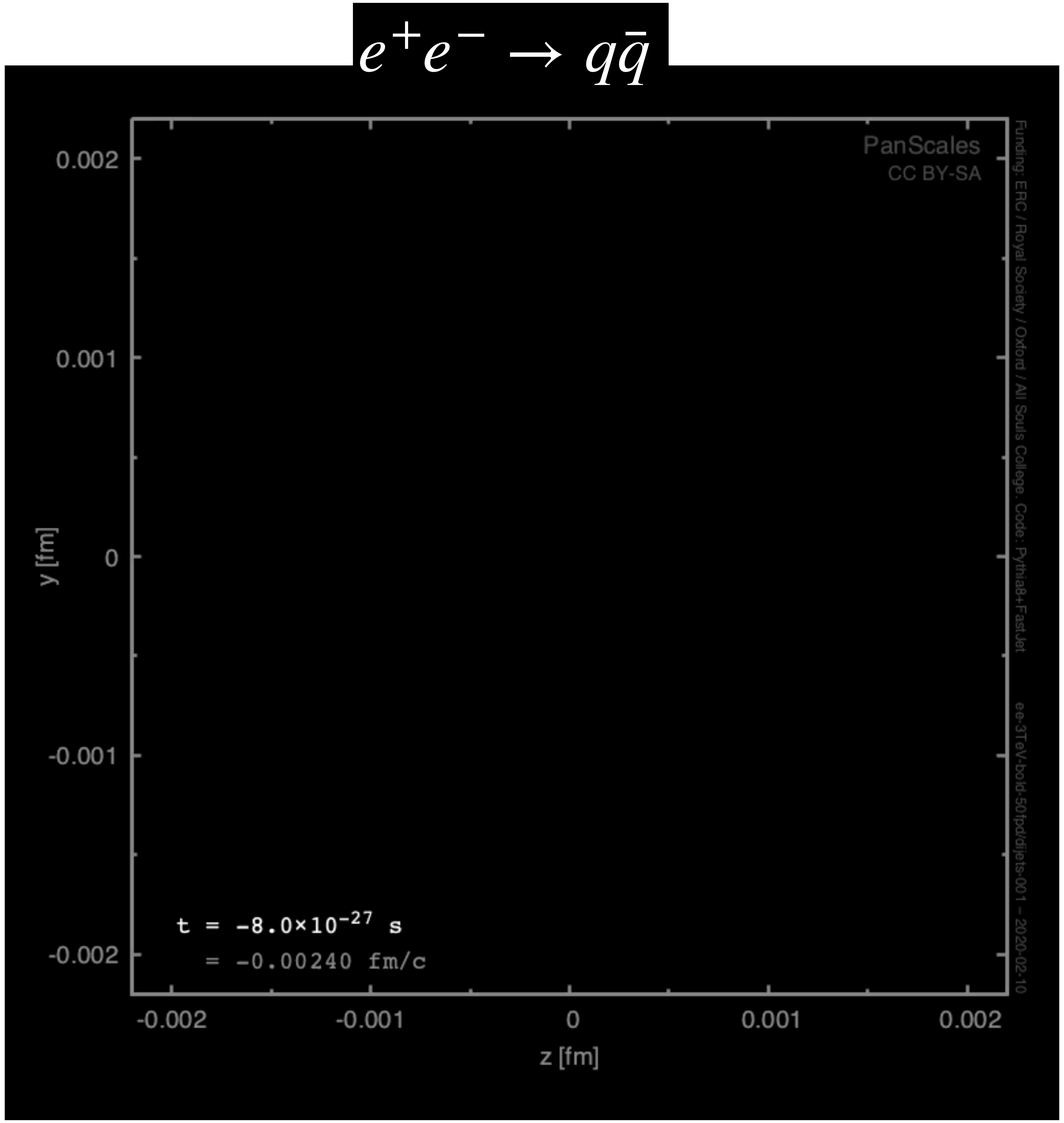
Testing the QGP with hard probes



Idea: use a high-p_t particle as a tomographic prober. Very much as in Rutherford experiment

What happens to high-p_t particles in proton-proton collisions?

[https://gsalam.web.cern.ch/gsalam/panscales/videos.html]



Color coding:

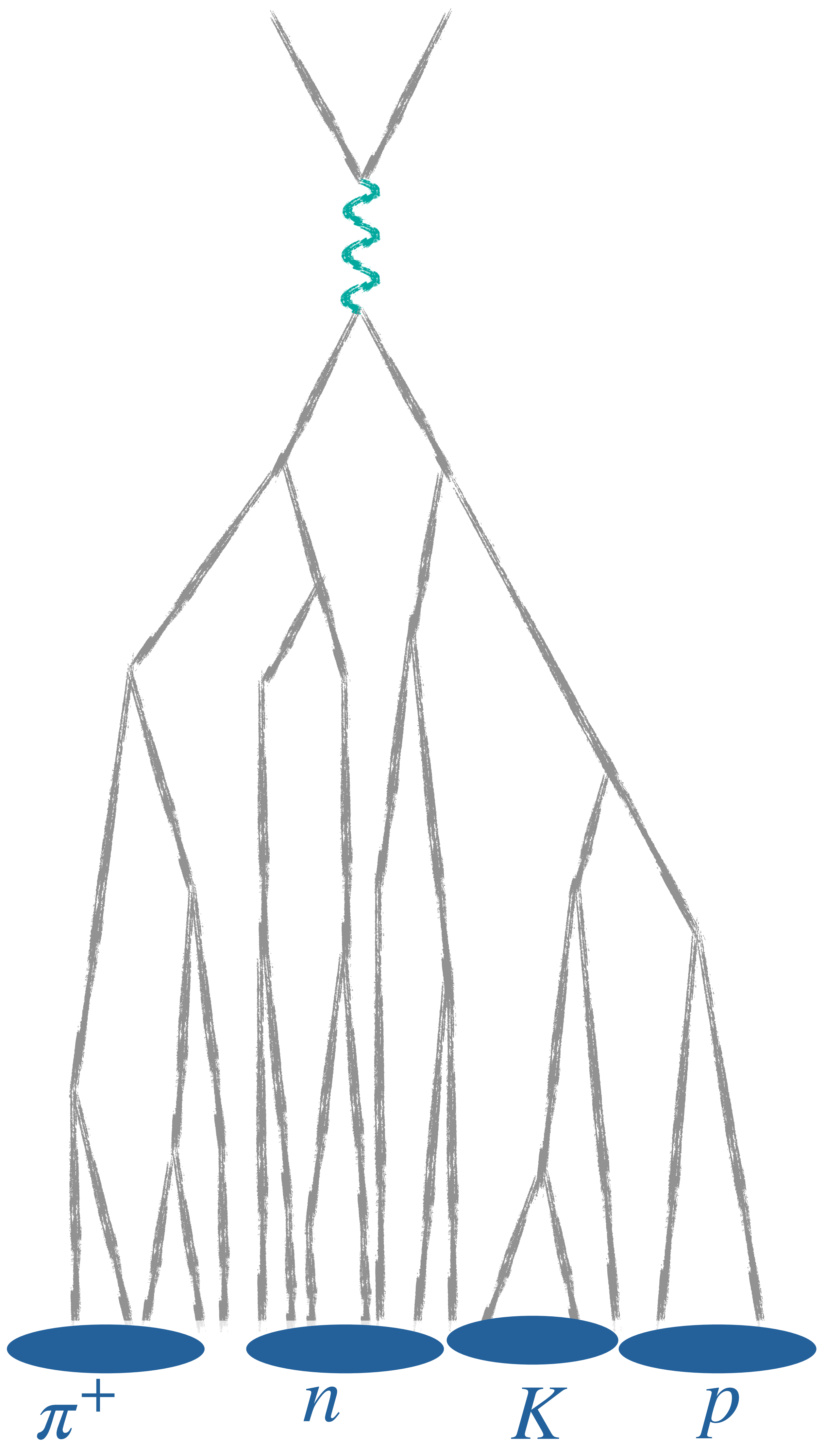
incoming beam particles

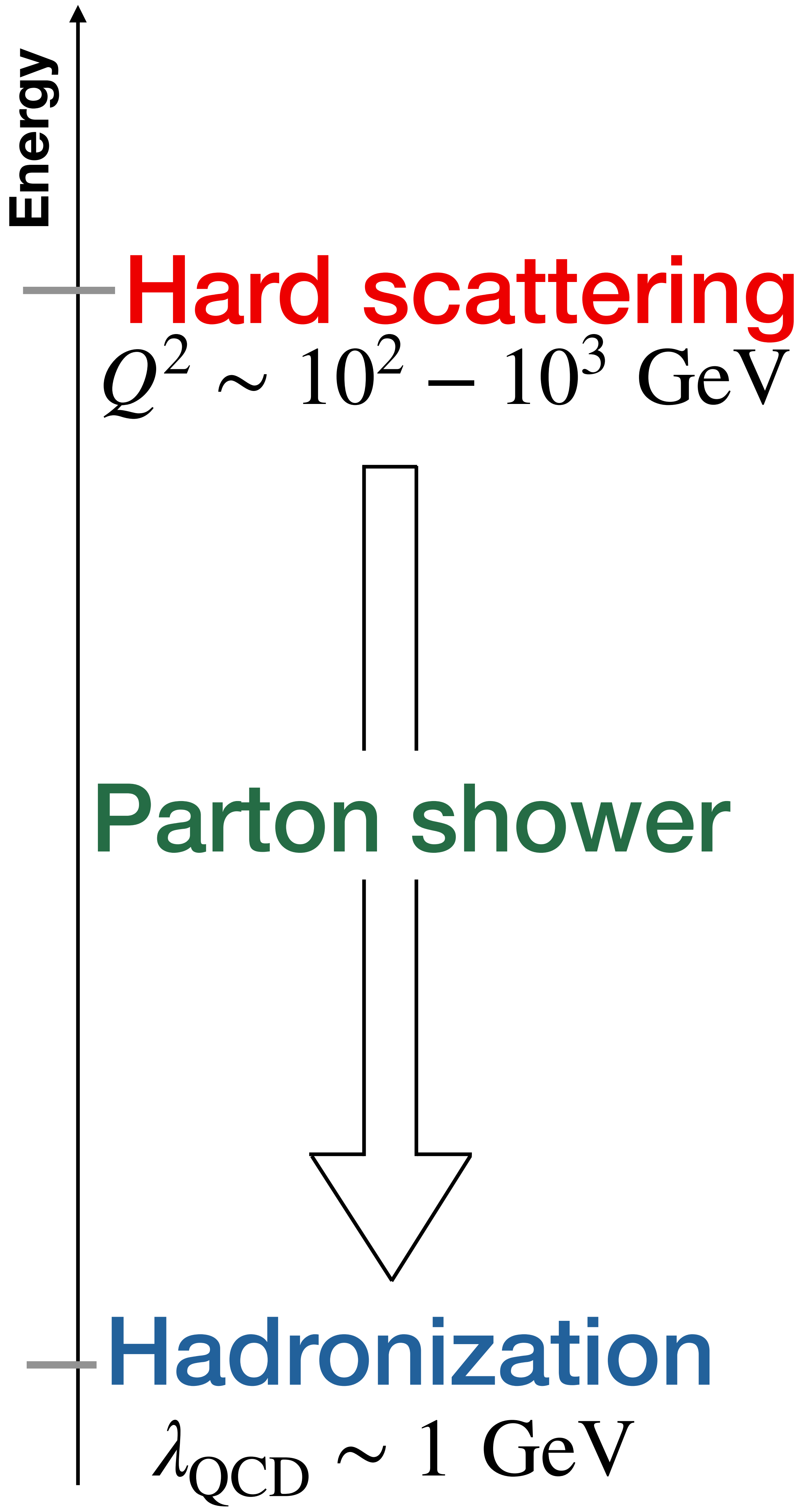
intermediate particles (quarks or gluons)

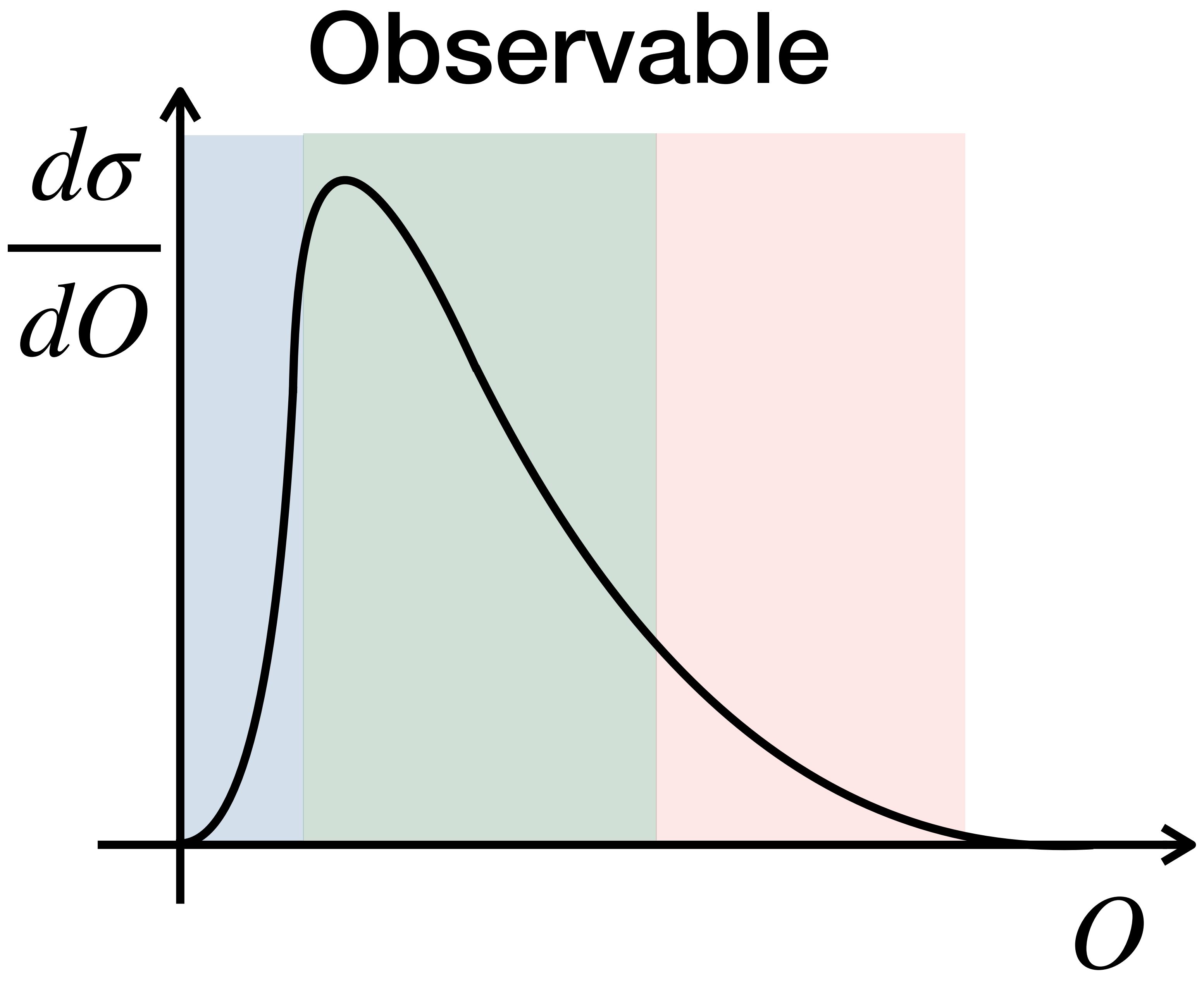
final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time

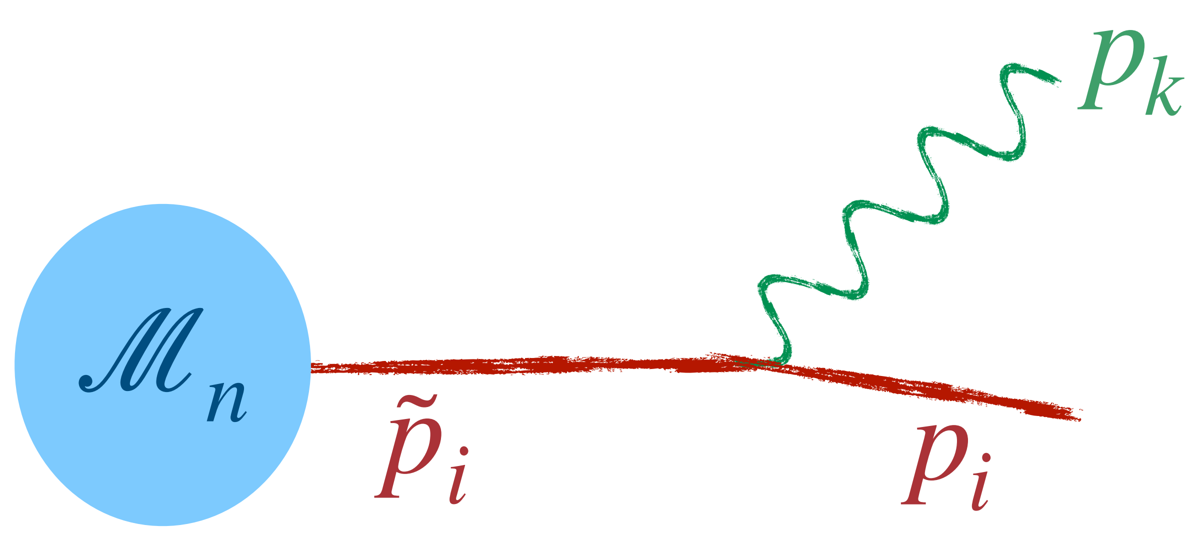
Anatomy of a high-energy process







Factorisation properties of QCD



- Collinear limit: $\tilde{p}_i \cdot p_k \to 0$

$$|\mathcal{M}_{n+1}|^2 \propto \frac{\alpha_s}{(p_i + p_k)^2} P_{\tilde{i}\to ik}(z) \, |\mathcal{M}_n|^2$$

- Soft limit: $p_k \to 0$

$$|\mathcal{M}_{n+1}|^2 \propto \alpha_s \frac{p_i \cdot p_j}{(p_i \cdot p_k)(p_j \cdot p_k)} |\mathcal{M}_n|^2$$

Emission kinematics factorises from matrix element in suitable limits

Single-gluon emission probability at double-logarithmic accuracy

Parton shower basics: example of radioactive decay

[Adapted from Gavin Salam]

Consider decay rate μ per unit time, total time $t_{\max}$. Find distribution of emissions

$$\frac{dP_n}{dt} = -\mu P_n(t) \qquad n \to n+1$$

How to solve this with Monte Carlo methods?

(a) start with $n = 0,\ t_0 = 0$

(b) choose random number $r(0 < r < 1)$ and find t_{n+1} that satisfies

$$r = e^{-\mu(t_{n+1} - t_n)}$$

(c) if $t_{n+1} < t_{\max}$, increment n go to step (b)

Parton shower basics: example of radioactive decay

E.g. for decay rate $\mu = 1$, $t_{\max} = 2$

- start with $n = 0,\ t_0 = 0$
- $r = 0.6 \rightarrow t_1 = t_0 + \ln(1/r) = 0.51$ [emission 1]
- $r = 0.3 \rightarrow t_2 = t_1 + \ln(1/r) = 1.71$ [emission 2]
- $r = 0.4 \rightarrow t_3 = t_2 + \ln(1/r) = 2.63$ [$> t_{\max}$, stop]

How to solve this with Monte Carlo methods?

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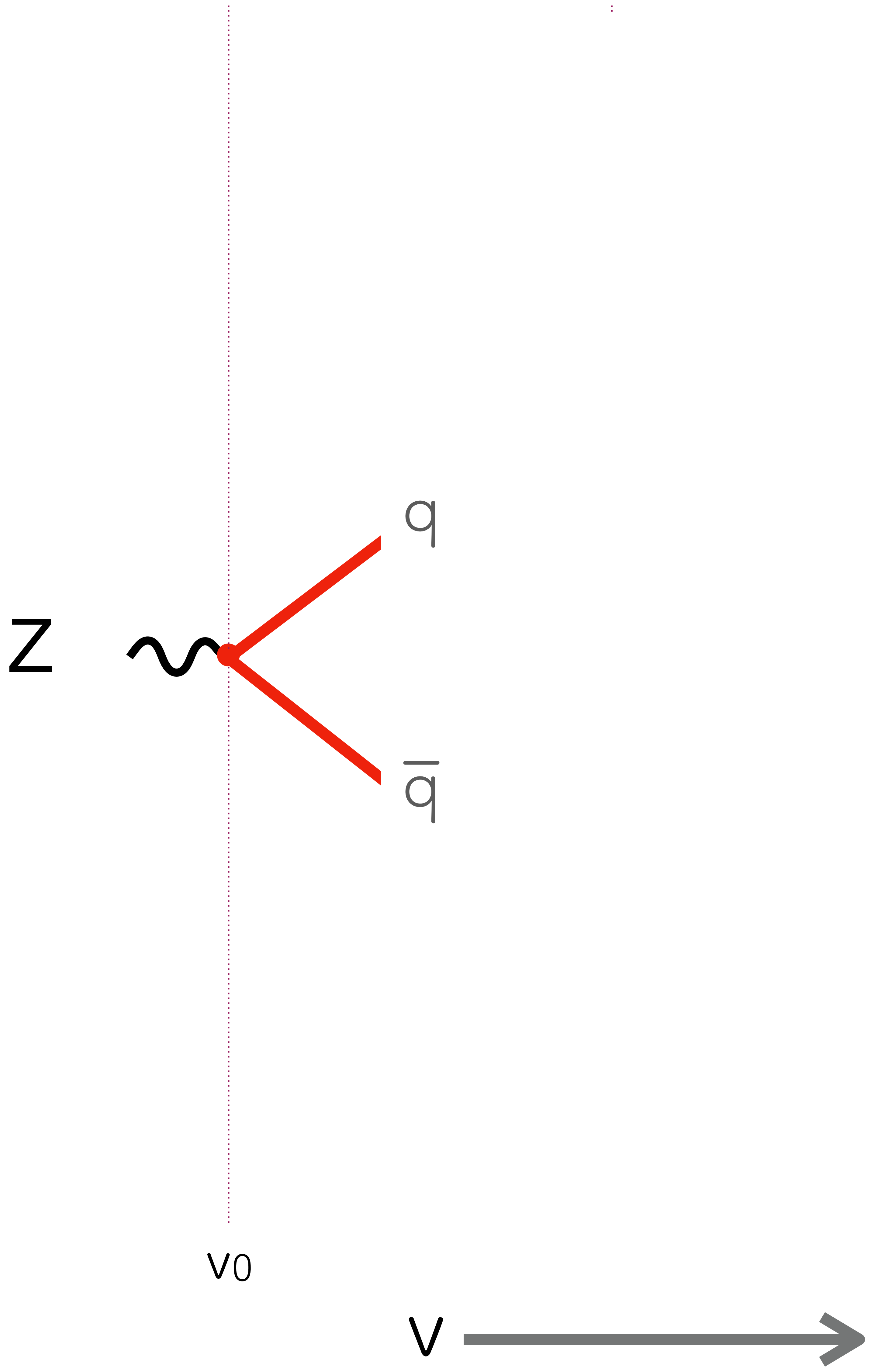
QCD shower: an evolution equation



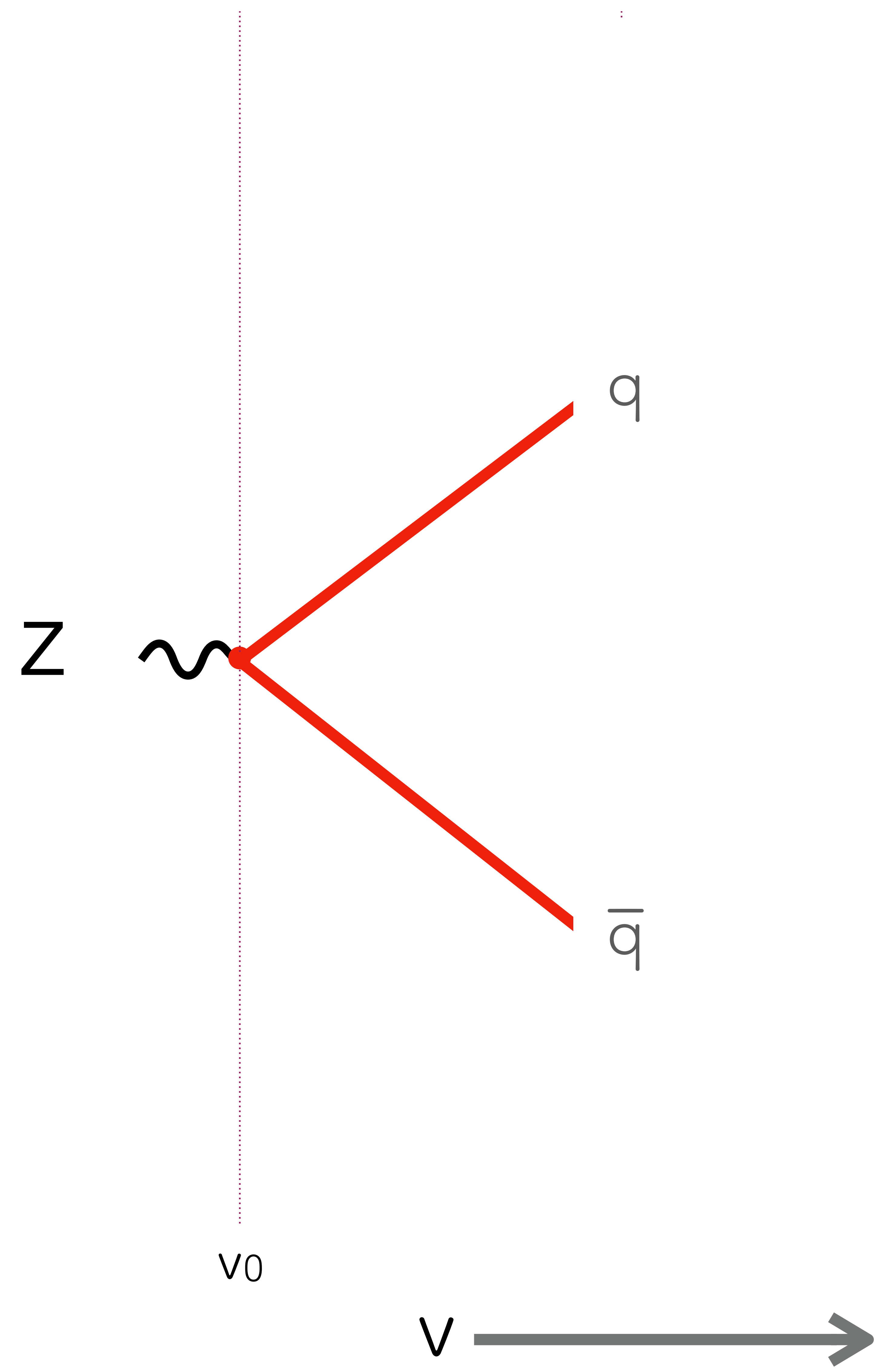
Start with $q\bar{q}$ state.

Throw a random number to determine down to what scale, v, state persists unchanged

$$\frac{\mathrm{d}P_2(v)}{\mathrm{d}v} = -f_{2\to 3}^{q\bar{q}}(v)\,P_2(v)$$

- Evolution variable: $v = k_t, \theta, t_f$

QCD shower: an evolution equation



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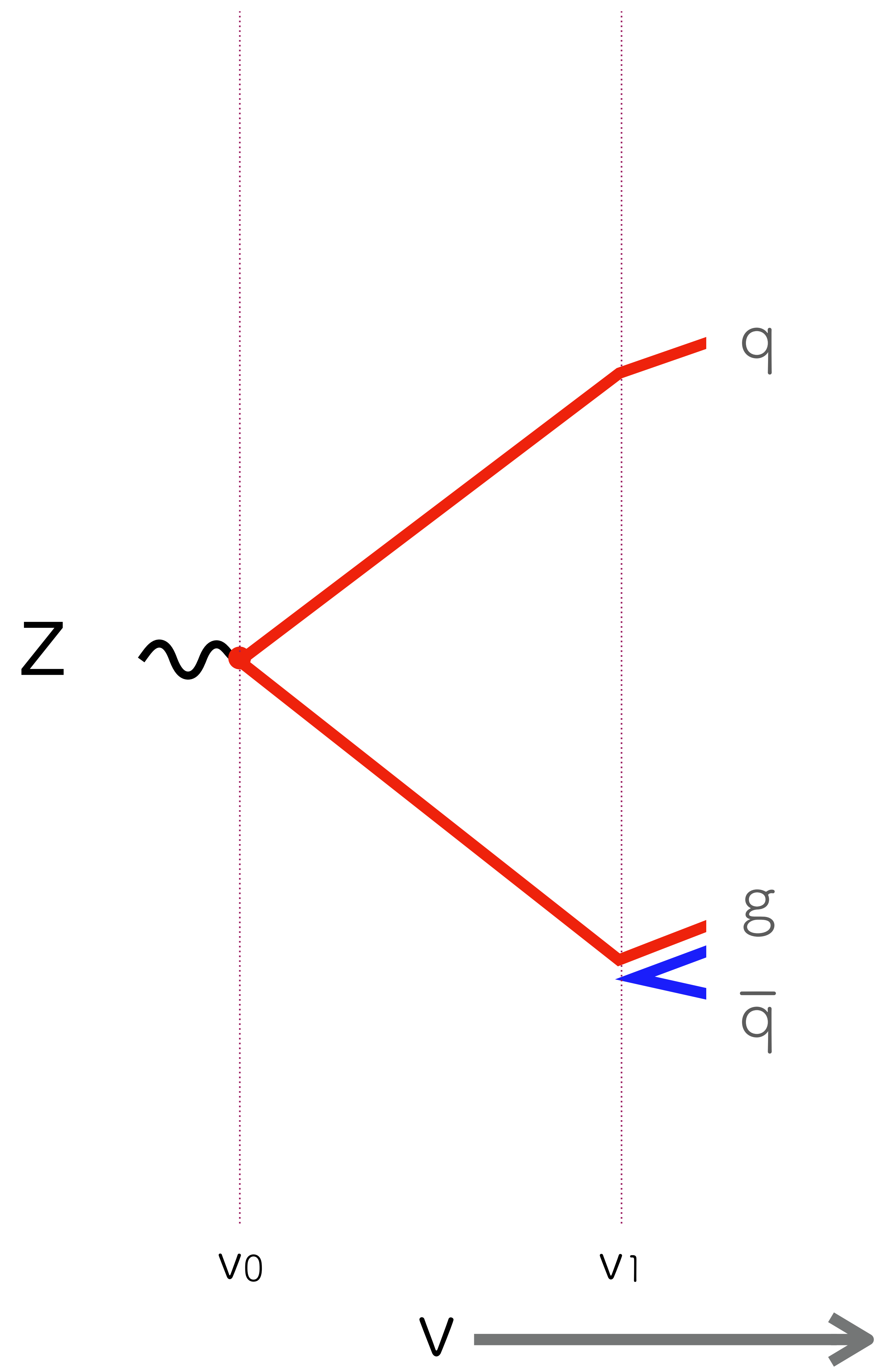
QCD shower: an evolution equation

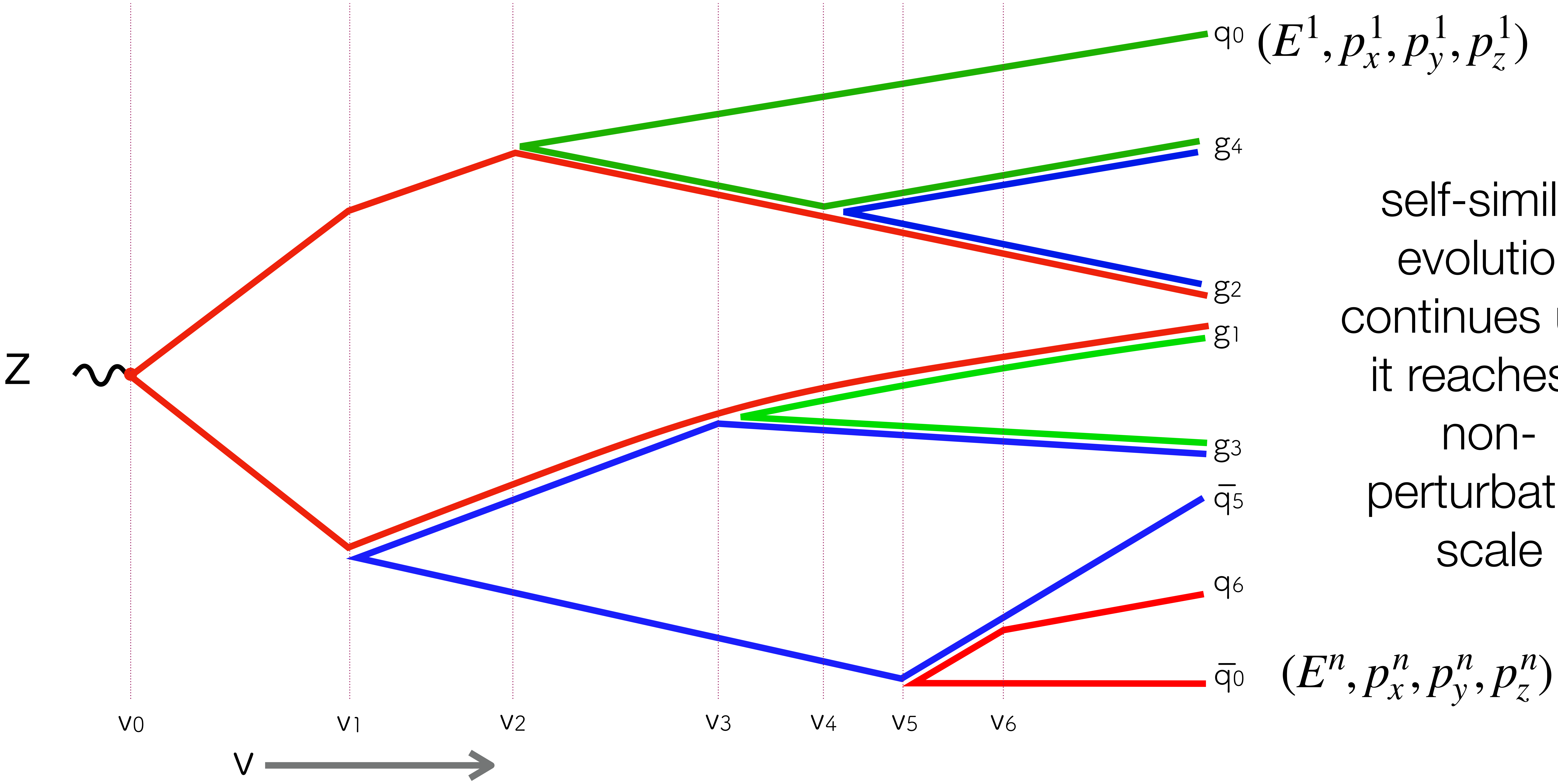


At some point, state splits (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{\mathrm{d}P_3(v)}{\mathrm{d}v} = -\left[f_{2\to3}^{qg}(v) + f_{2\to3}^{g\bar{q}}(v)\right] P_3(v)$$

- Recoil scheme: $\tilde{p}_{q,\bar{q}} \to p_{q,\bar{q},g}$

QCD shower: an evolution equation



self-similar evolution continues until it reaches a non-perturbative scale

Toy parton shower

Probability of emitting a soft and collinear gluon

$$\mathscr{P}_{\mathrm{emit}}(k_T > k_T^{\mathrm{cut}}) = \frac{2\alpha_s C_X}{\pi} \int_{k_T^{\mathrm{cut}}}^{k_T^{\mathrm{max}}} \frac{\mathrm{d}k_T}{k_T} \int_{k_T/k_T^{\mathrm{max}}}^{1} \frac{\mathrm{d}z}{z} = \frac{\alpha_s C_X}{\pi} \ln^2\left(\frac{k_T^{\mathrm{max}}}{k_T^{\mathrm{cut}}}\right)$$

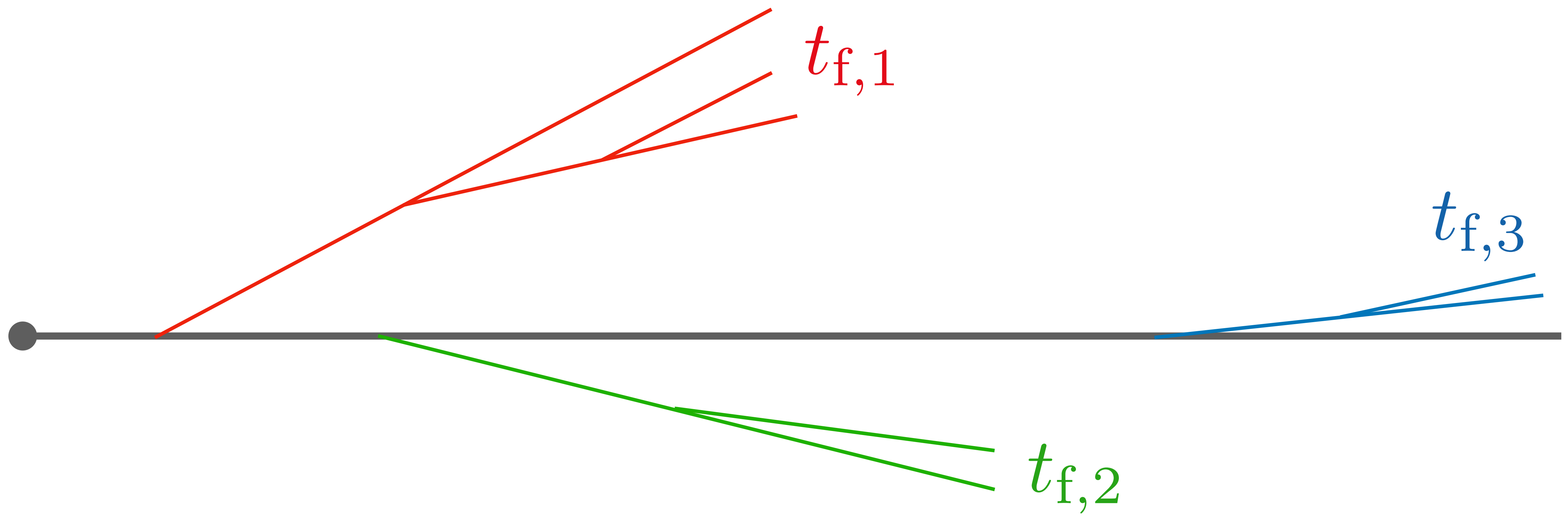
Sudakov form factor: probability of not emitting gluons with momentum $> k_T$

$$\Delta(k_T^{\mathrm{max}}, k_T) = \exp\left\{-\frac{\alpha_s C_X}{2\pi} \ln^2\left(\frac{k_T^{\mathrm{max}}}{k_T}\right)\right\}$$

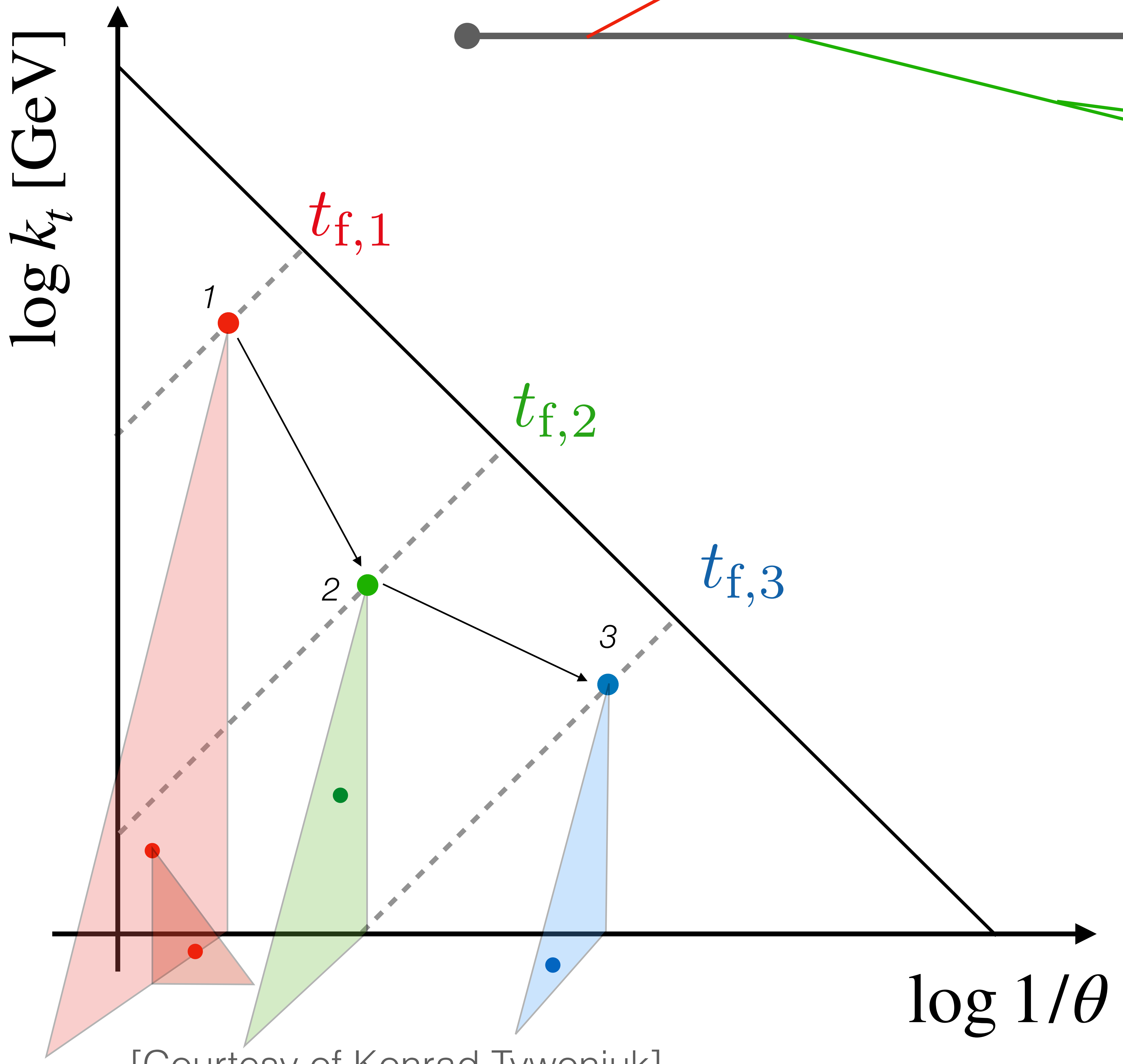
`2024-Granada-heavyion-lectures/toy-shower.ipynb`

Accessing the parton shower: the Lund jet plane

[Andersson et al Z. Phys. C 43, 625 (1989)]
[Dreyer et al. JHEP 12 (2018) 064]



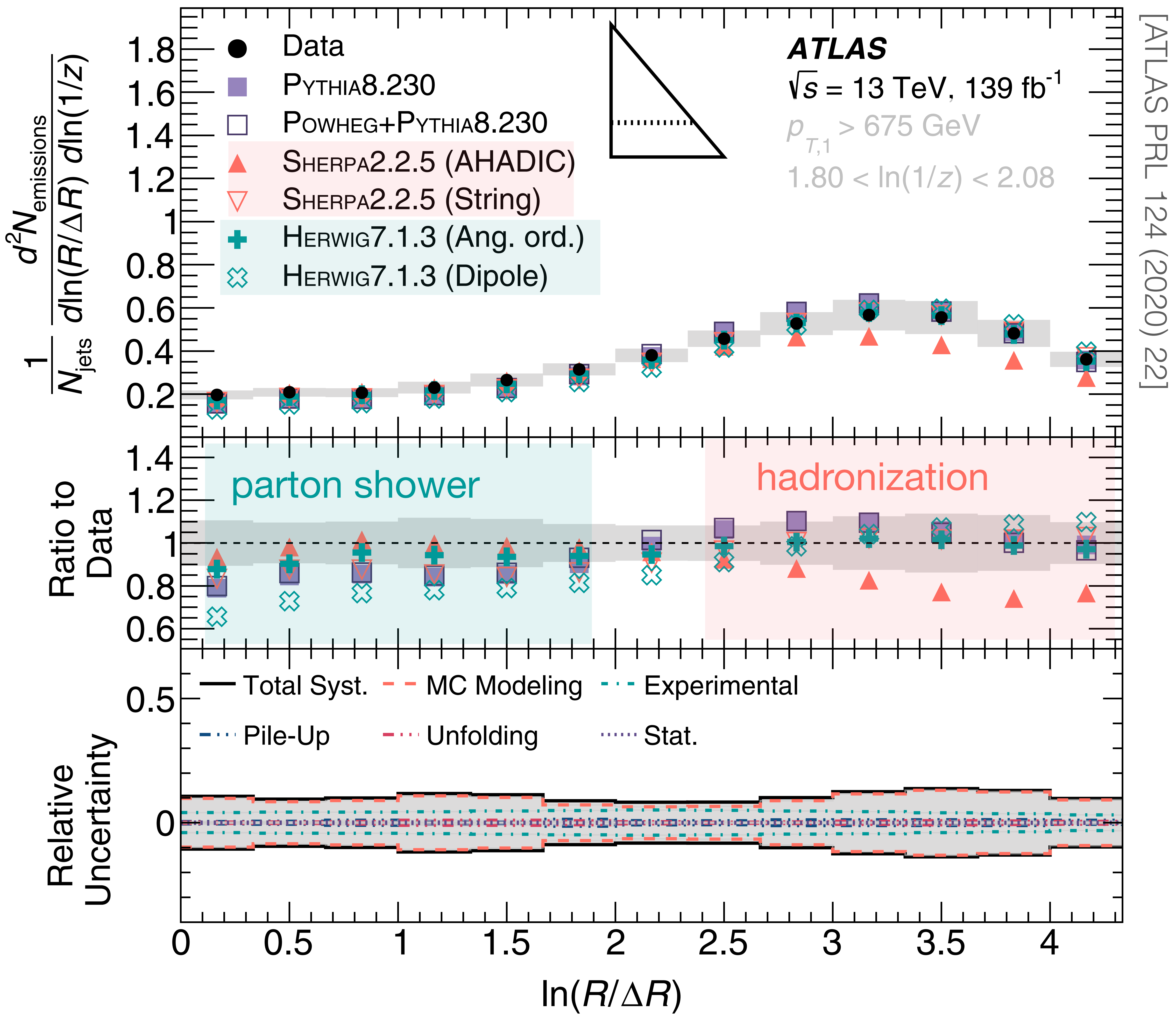
$$t_f = \frac{2z(1-z)p_T}{k_t^2}$$



[Courtesy of Konrad Tywoniuk]

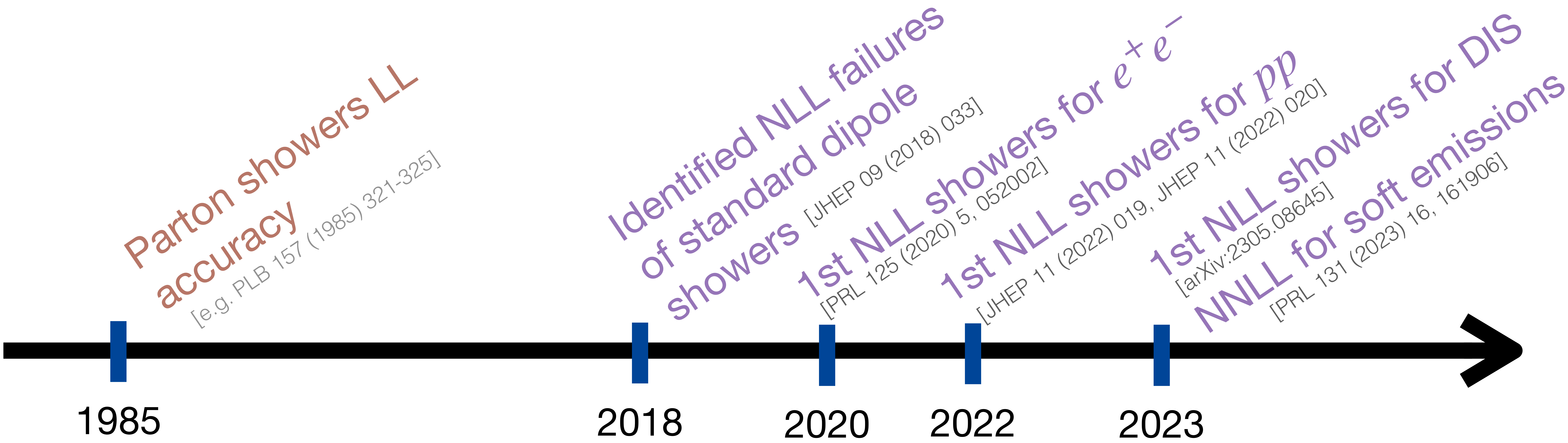
- **Lund diagram** (primary emission plane)
  - secondary branchings located on independent "leaves"
- Accessed in experimental data using jet reconstruction (C/A algorithm)

How well does this actually work?



Current data is able to discriminate between parton showers

Current status of parton shower development



PanScales code

Note work by other groups: JHEP 09 (2020) 014, PRD 104 (2021) 5, 054049, JHEP 10 (2023) 091

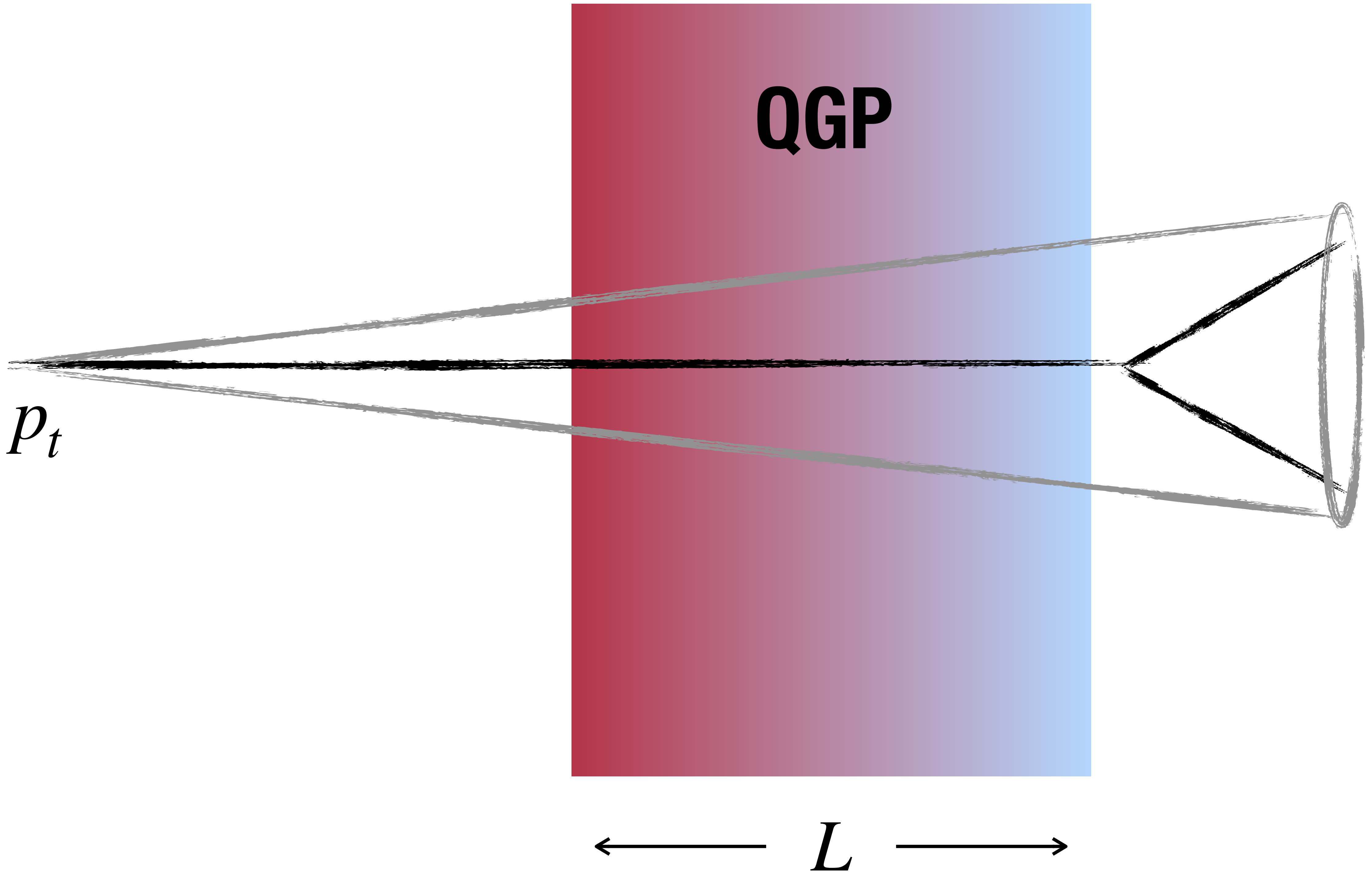
Current status of parton shower development

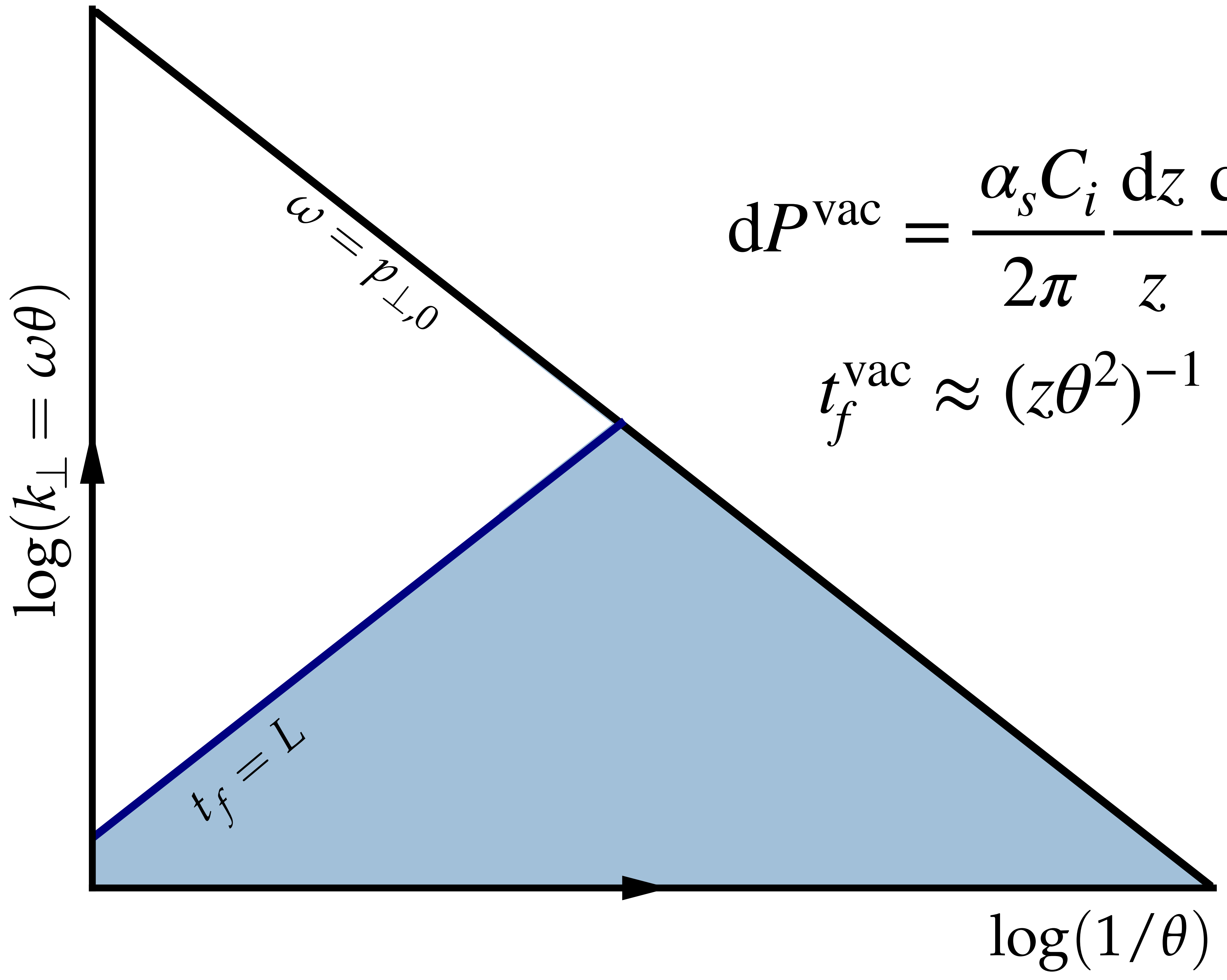
Parton showers in proton-proton collisions are entering the precision era. What about heavy-ions?

Note work by other groups: JHEP 09 (2020) 014, PRD 104 (2021) 5, 054049, JHEP 10 (2023) 091

Jet evolution in a medium: vacuum splittings

— : vacuum splittings (outside the medium)



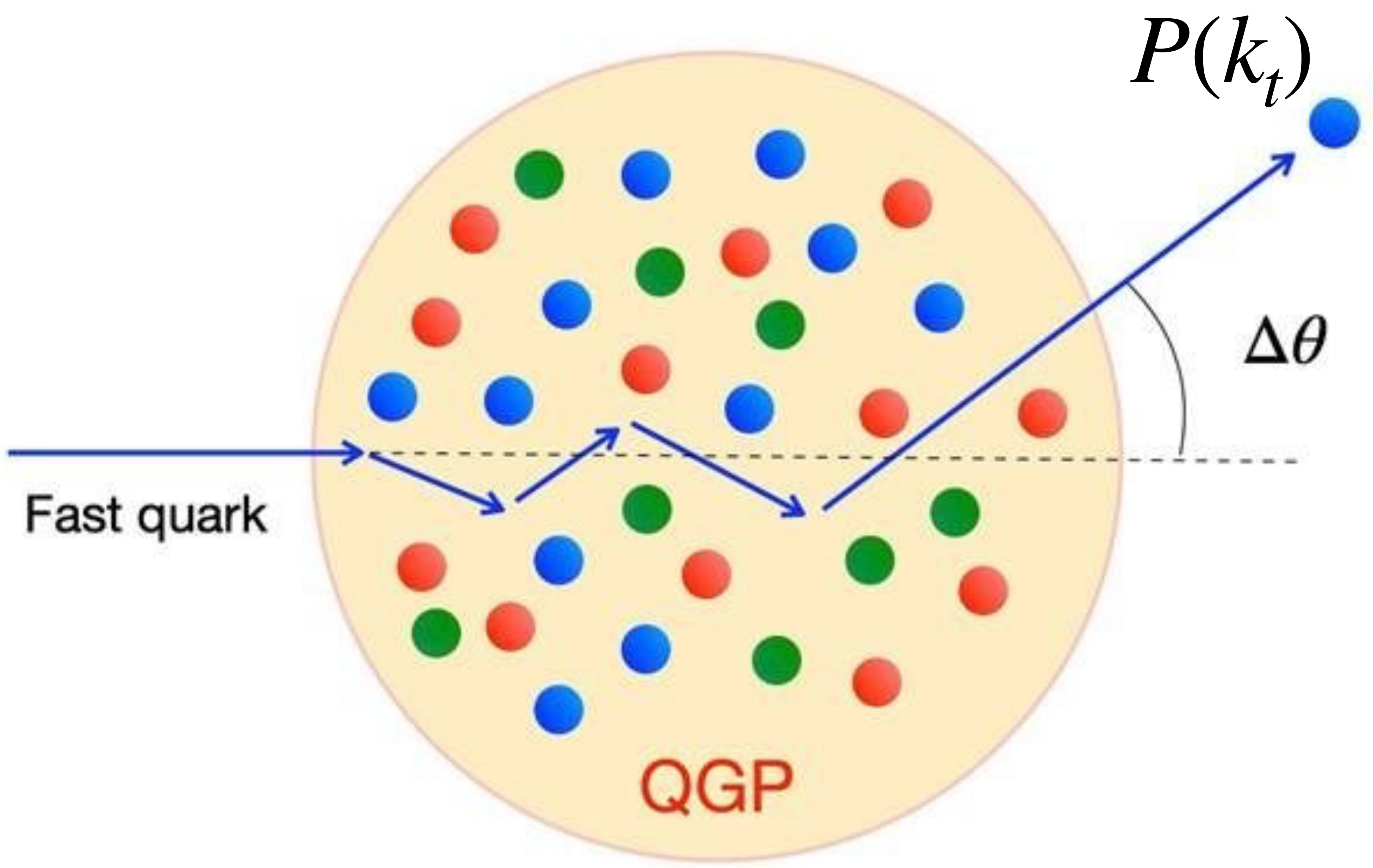


$$\mathrm{d}P^{\mathrm{vac}} = \frac{\alpha_s C_i}{2\pi}\frac{\mathrm{d}z}{z}\frac{\mathrm{d}\theta}{\theta}$$

$$t_f^{\mathrm{vac}} \approx (z\theta^2)^{-1}$$

Jet evolution in a medium: transverse momentum broadening

: no splitting, pure propagation



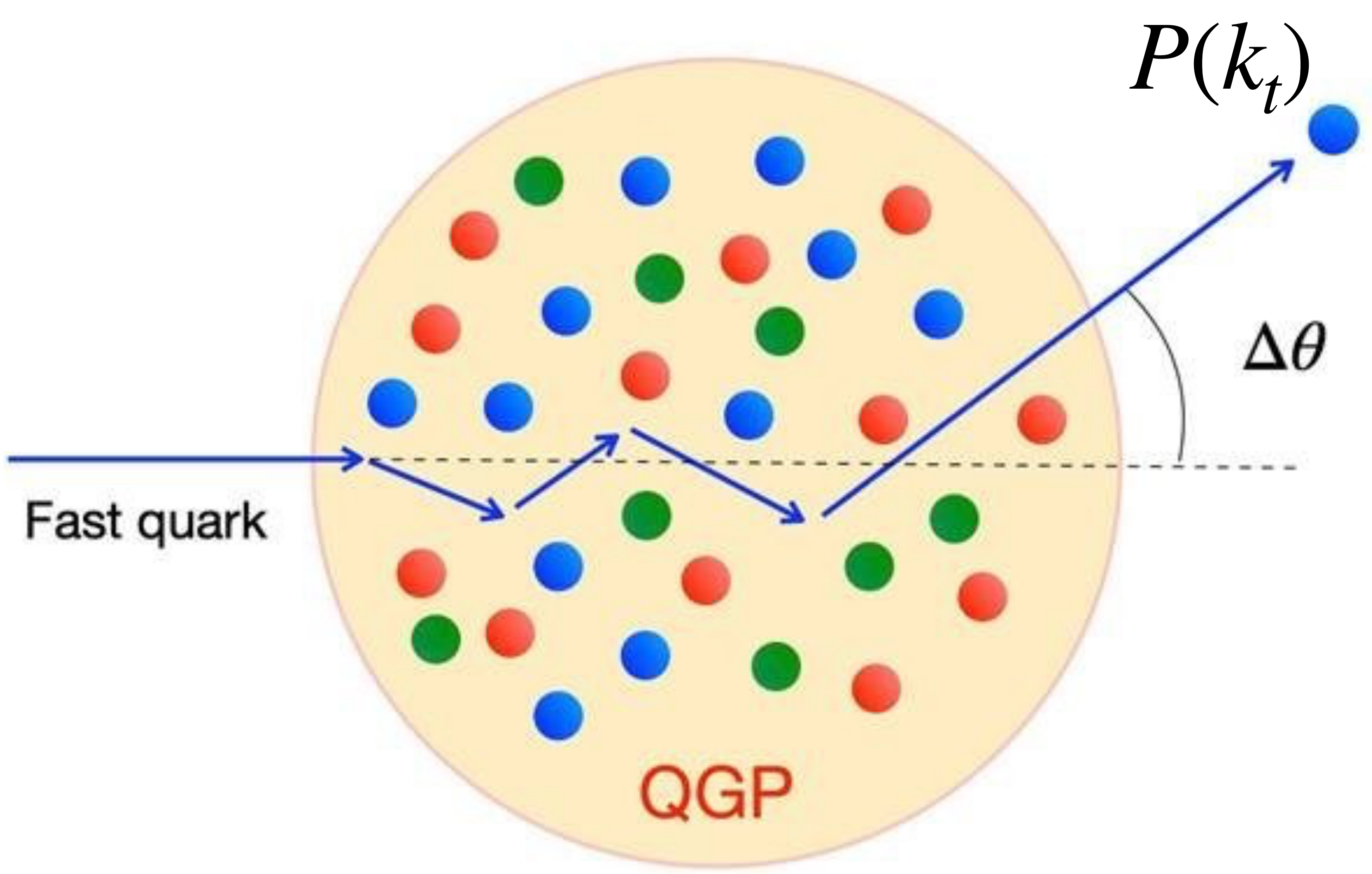
Fokker-Planck equation

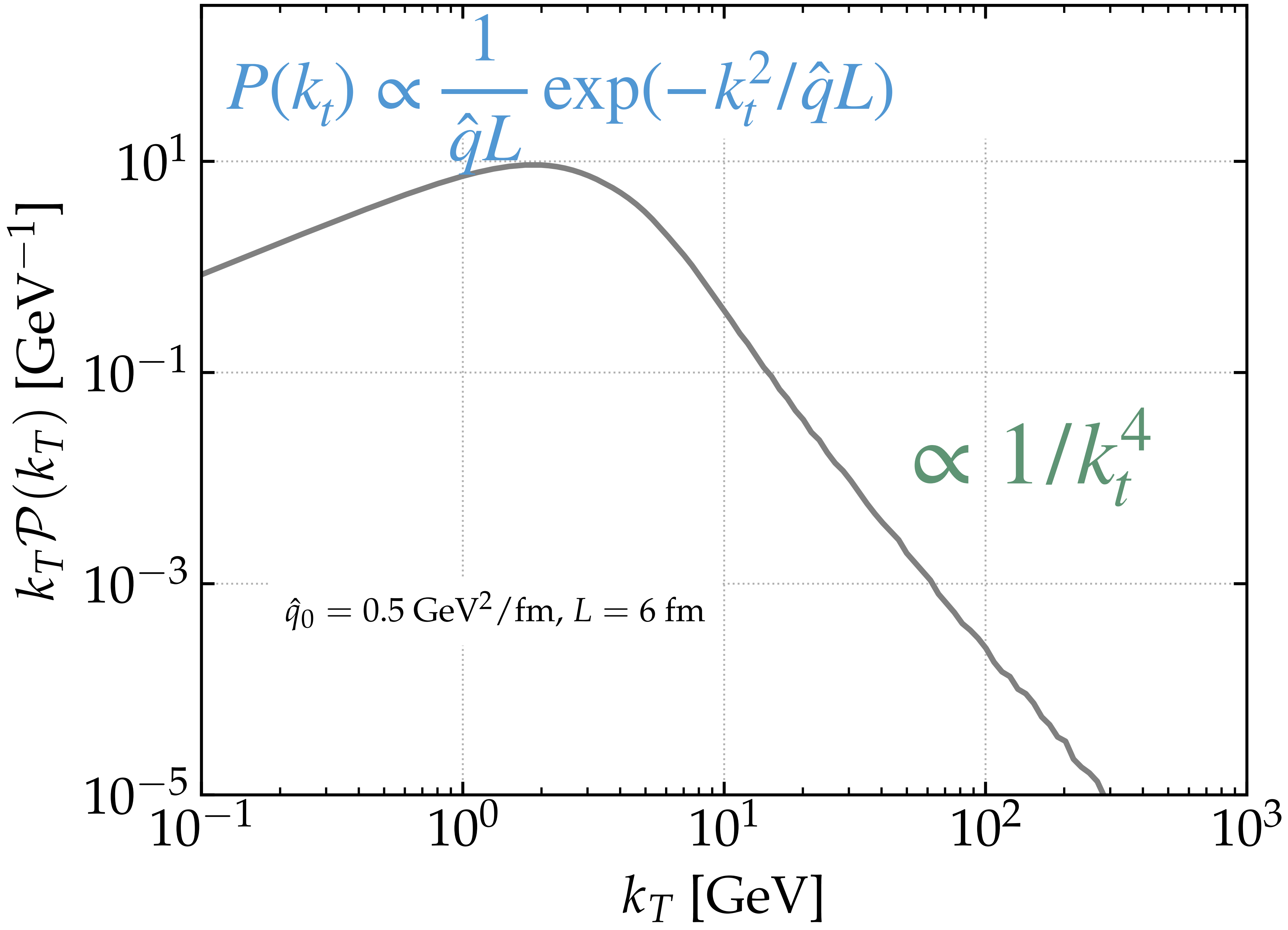
$$\frac{\partial}{\partial t}P(k_t) = \hat{q}\,\nabla_\perp^2 P(k_t)$$

Diffusive process caused by random deflections as the energetic jet interacts with the QGP

Jet evolution in a medium: transverse momentum broadening

: no splitting, pure propagation



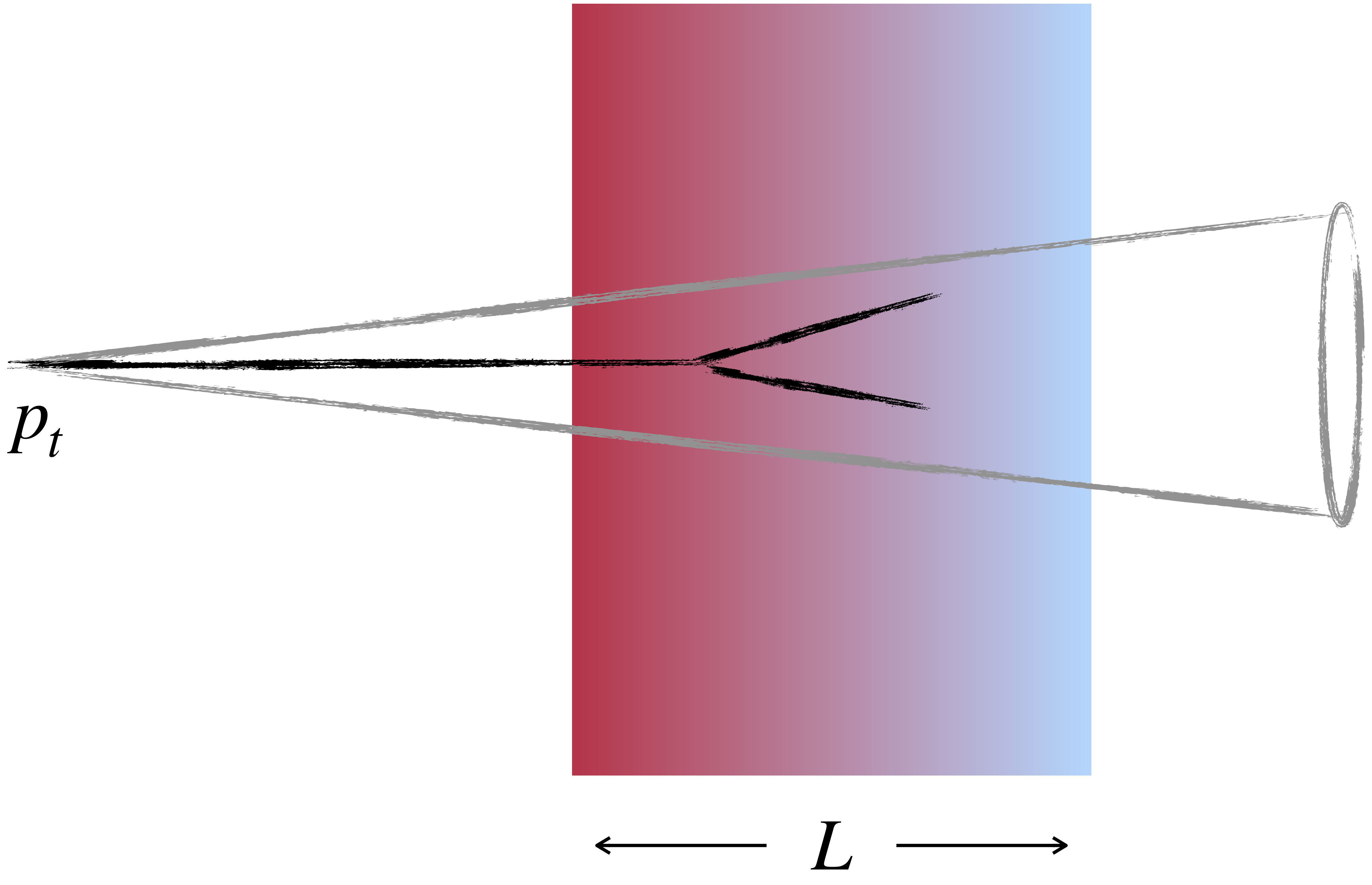


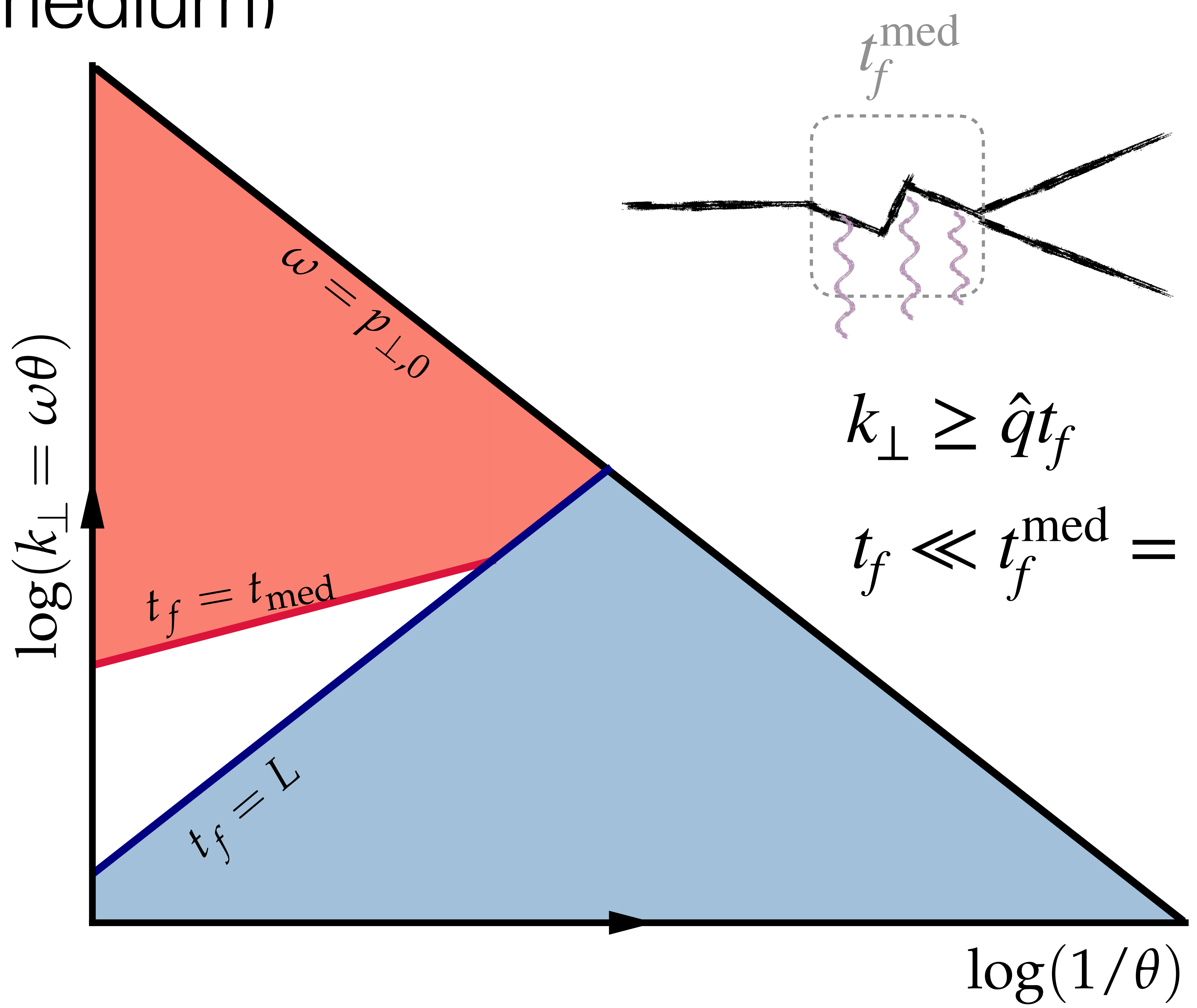
Oversimplified implementation of Gaussian momentum broadening in

`2024-Granada-heavyion-lectures/toy-shower.ipynb`

Jet evolution in a medium: vacuum-like splittings

: vacuum splittings (inside the medium)





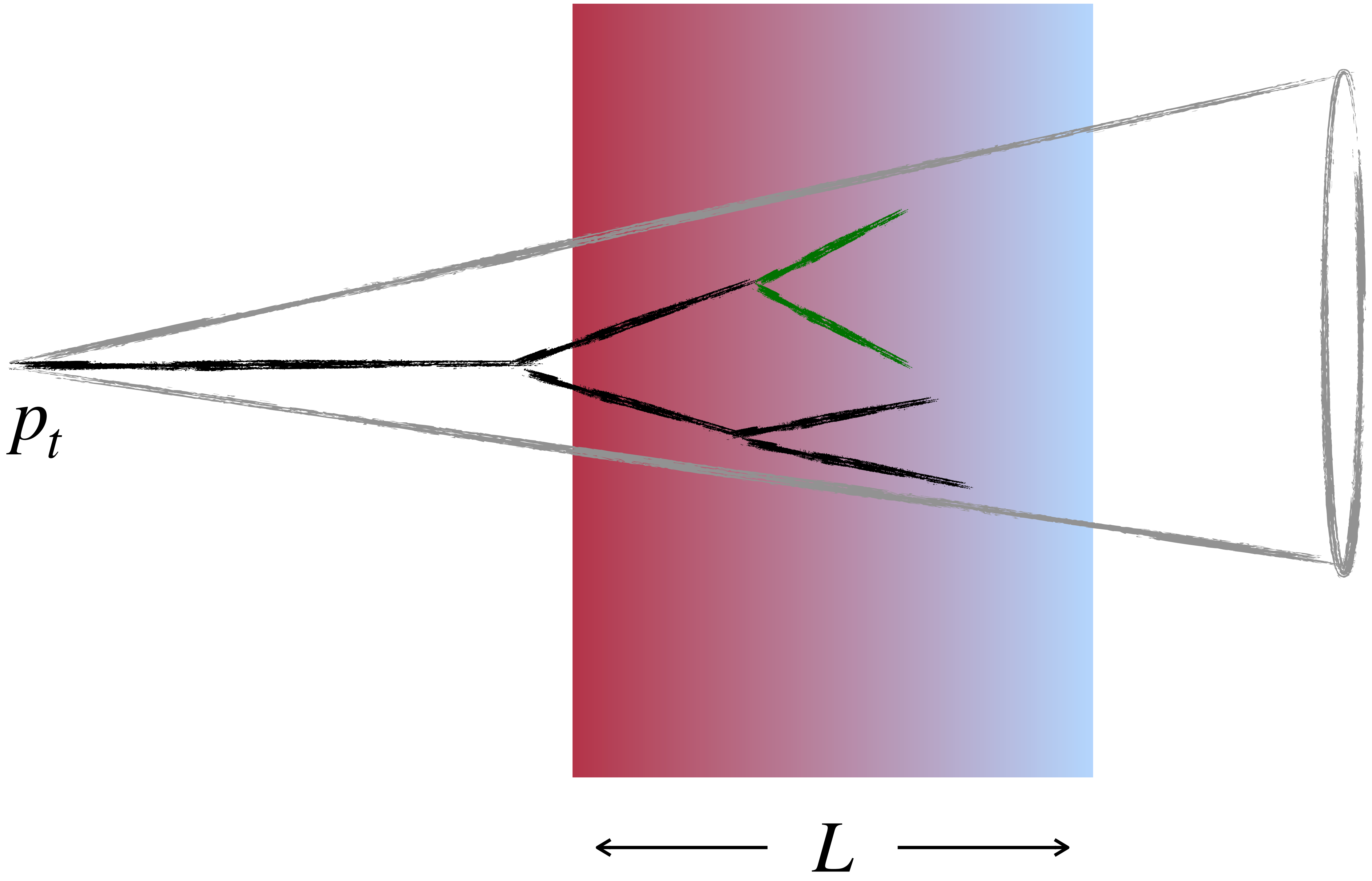
$k_\perp \geq \hat{q} t_f$

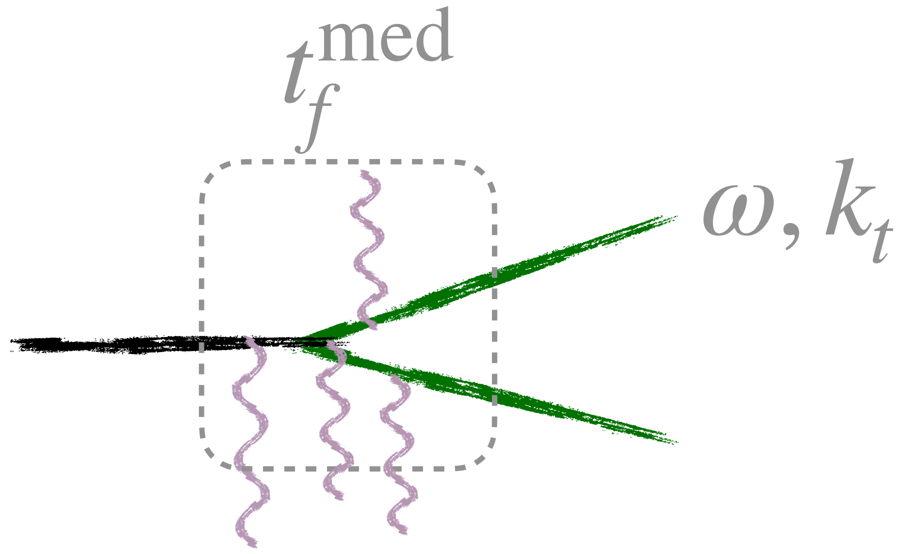
$t_f \ll t_f^{med} = \sqrt{\omega/\hat{q}}$

If the formation time is sufficiently short, emission as in vacuum

Jet evolution in a medium: medium-induced splittings

: vacuum splittings : medium induced splittings

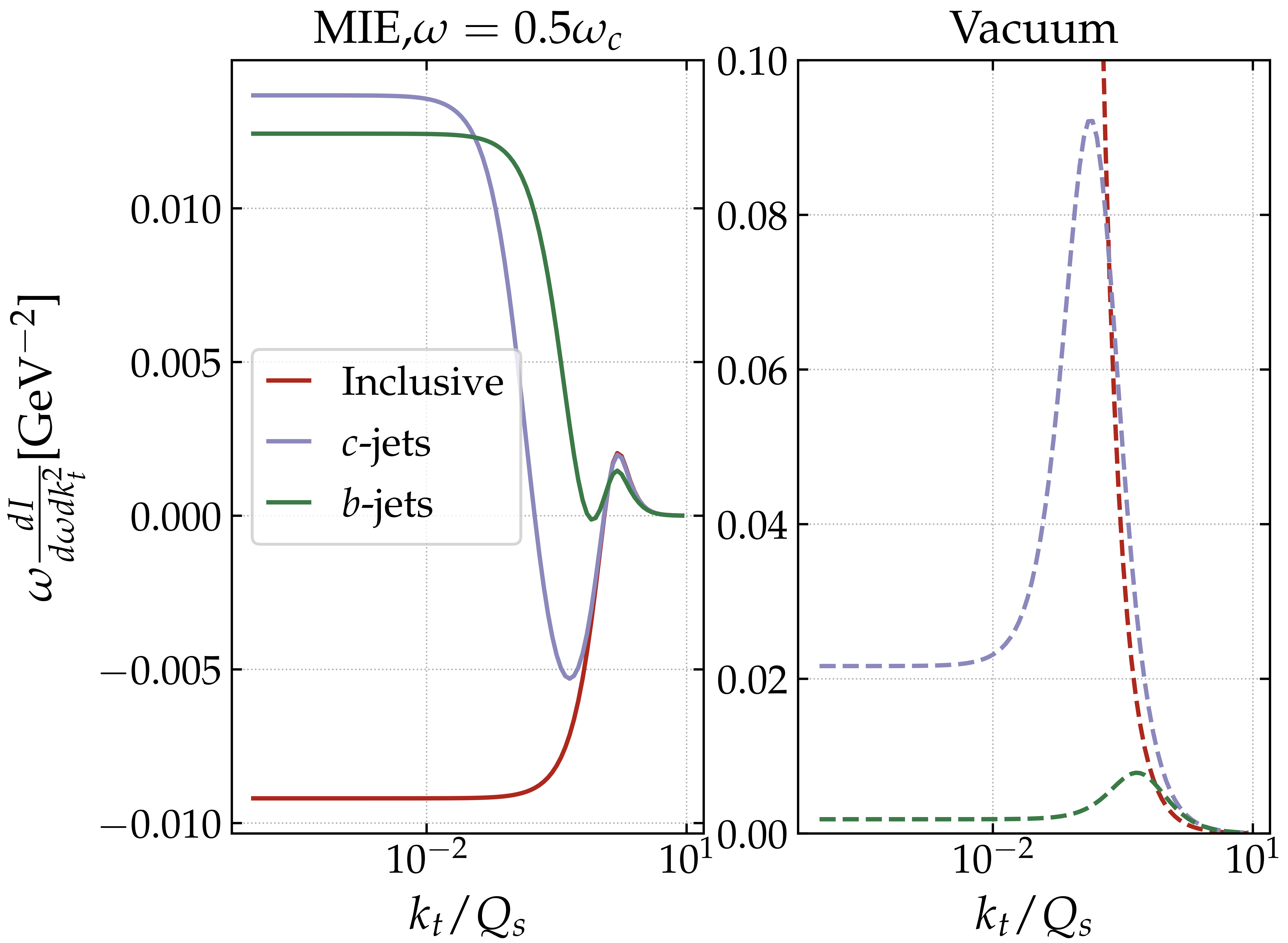




$$\mathrm{d}P^{\mathrm{mie}} = \frac{\alpha_s^{\mathrm{med}} C_i}{2\pi} \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}^2 k_t}$$

Additional emissions triggered by the interactions with the medium

Spectrum of medium induced emissions (multiple soft approx)

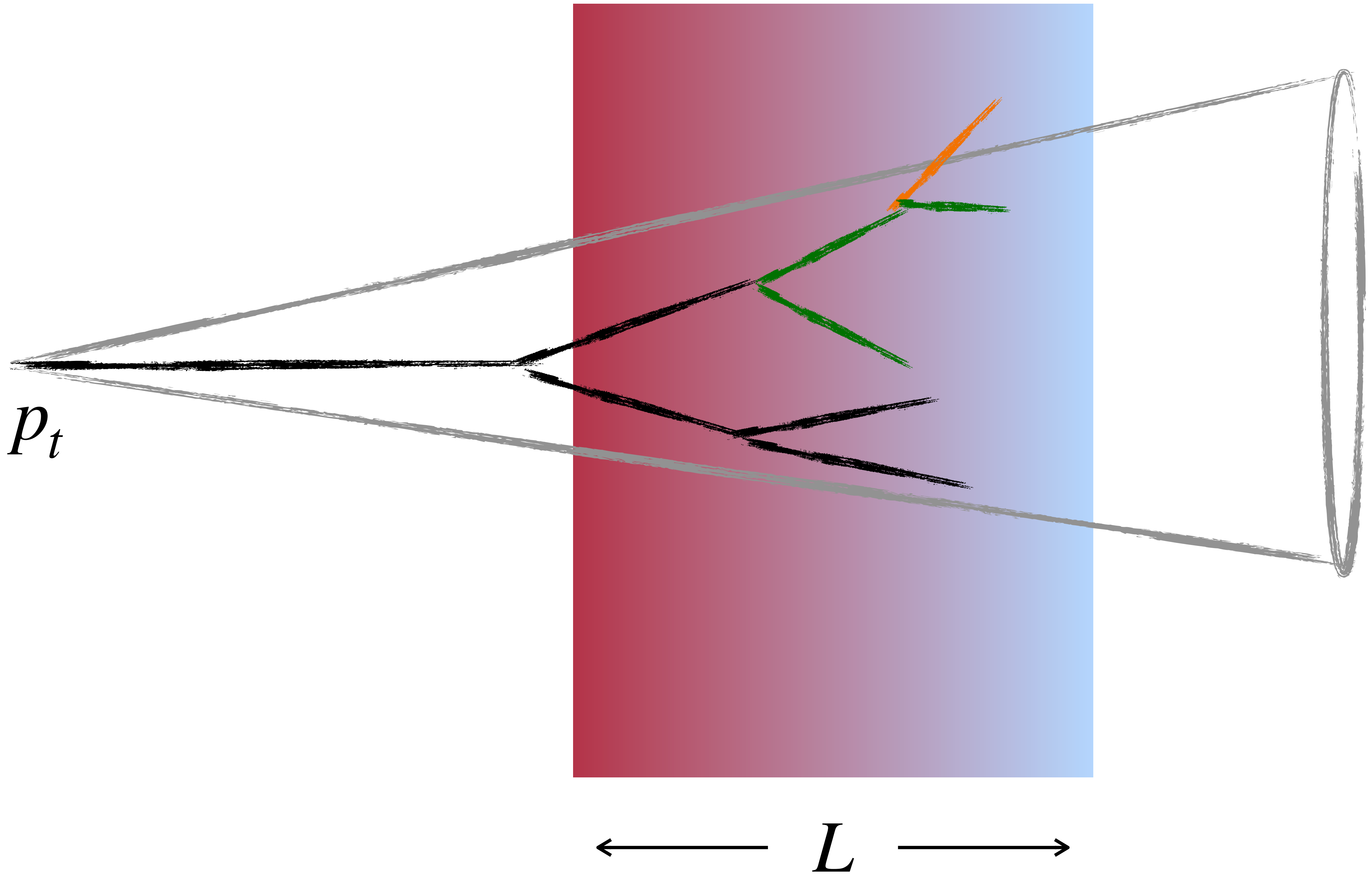


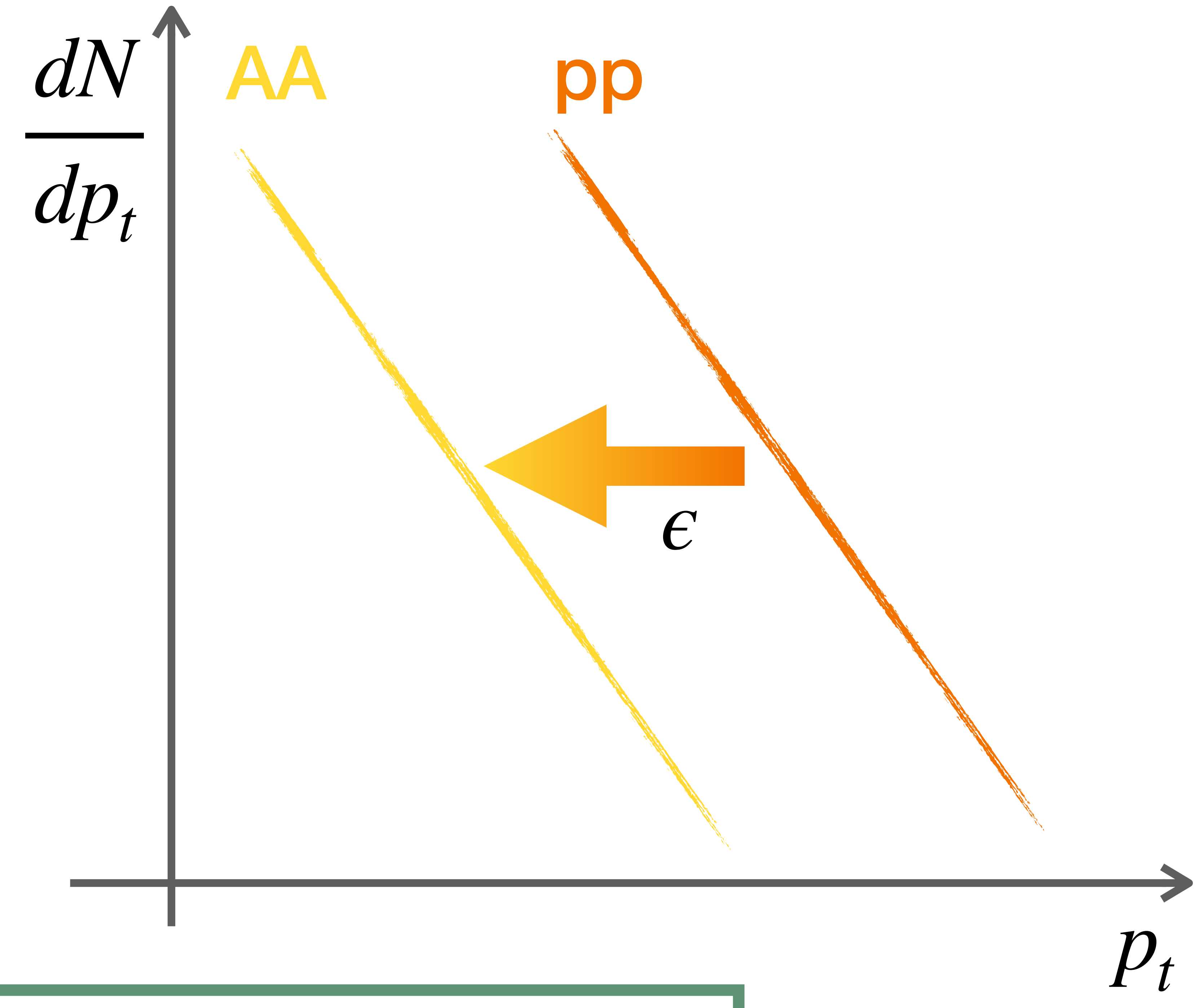
$$\propto \frac{\mathrm{d}z}{z^{3/2}} e^{-\theta^2 p_t^2/Q_s^2} \mathrm{d}\theta$$

Crisp difference wrt vacuum: medium-induced spectrum is collinear finite

Jet evolution in a medium: medium-induced splittings

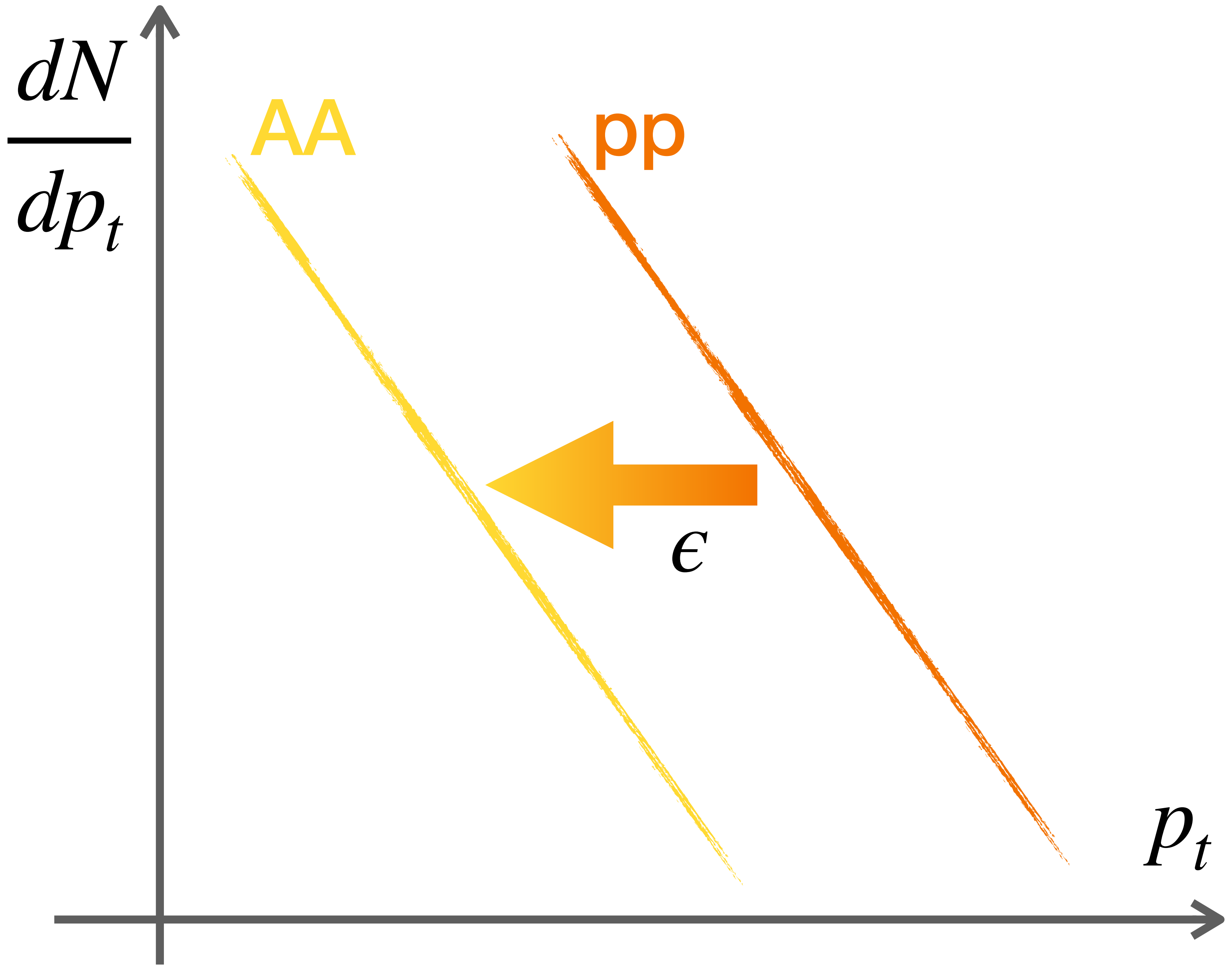
: vacuum splittings : medium induced splittings : energy loss

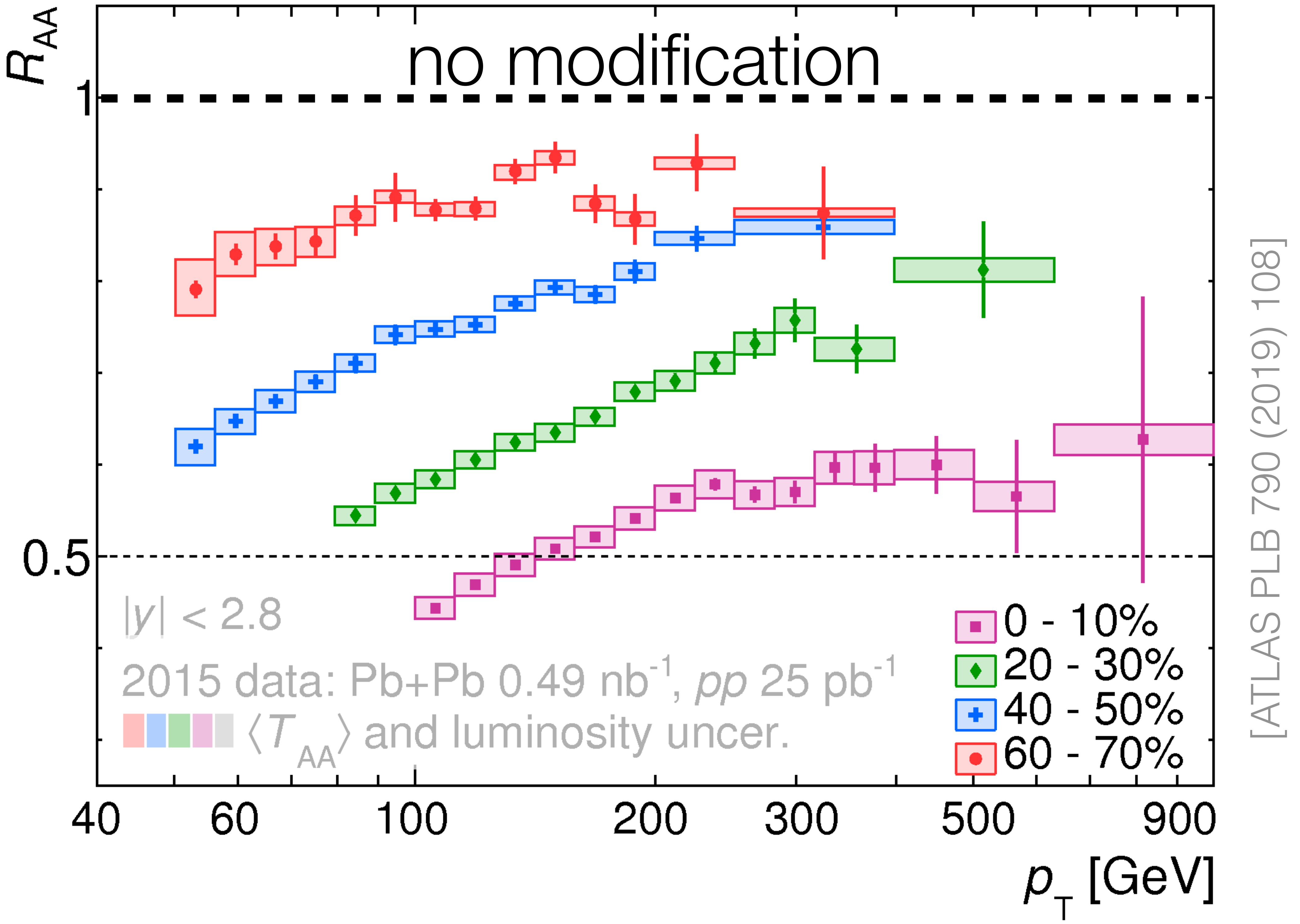


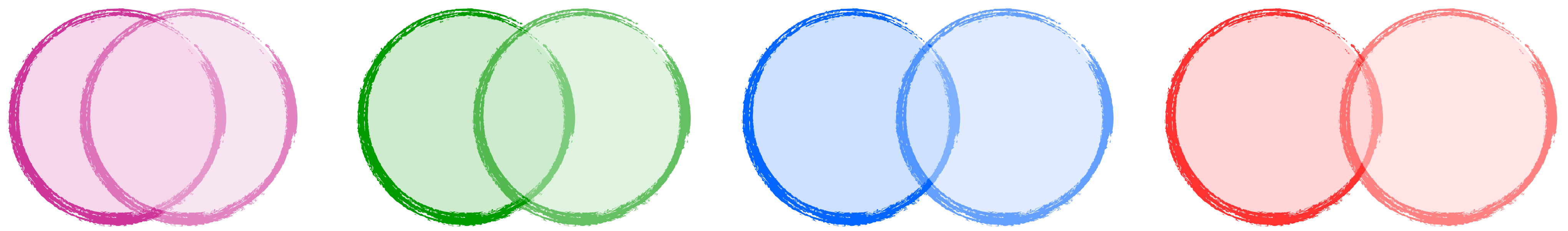


Jet quenching: $\frac{d\sigma_{\text{med}}}{dp_t} = \int_0^\infty P_>(\epsilon) \frac{d\sigma_{\text{vac}}}{d(p_t+\epsilon)} d\epsilon$

Jet quenching: a clean signature of QGP formation



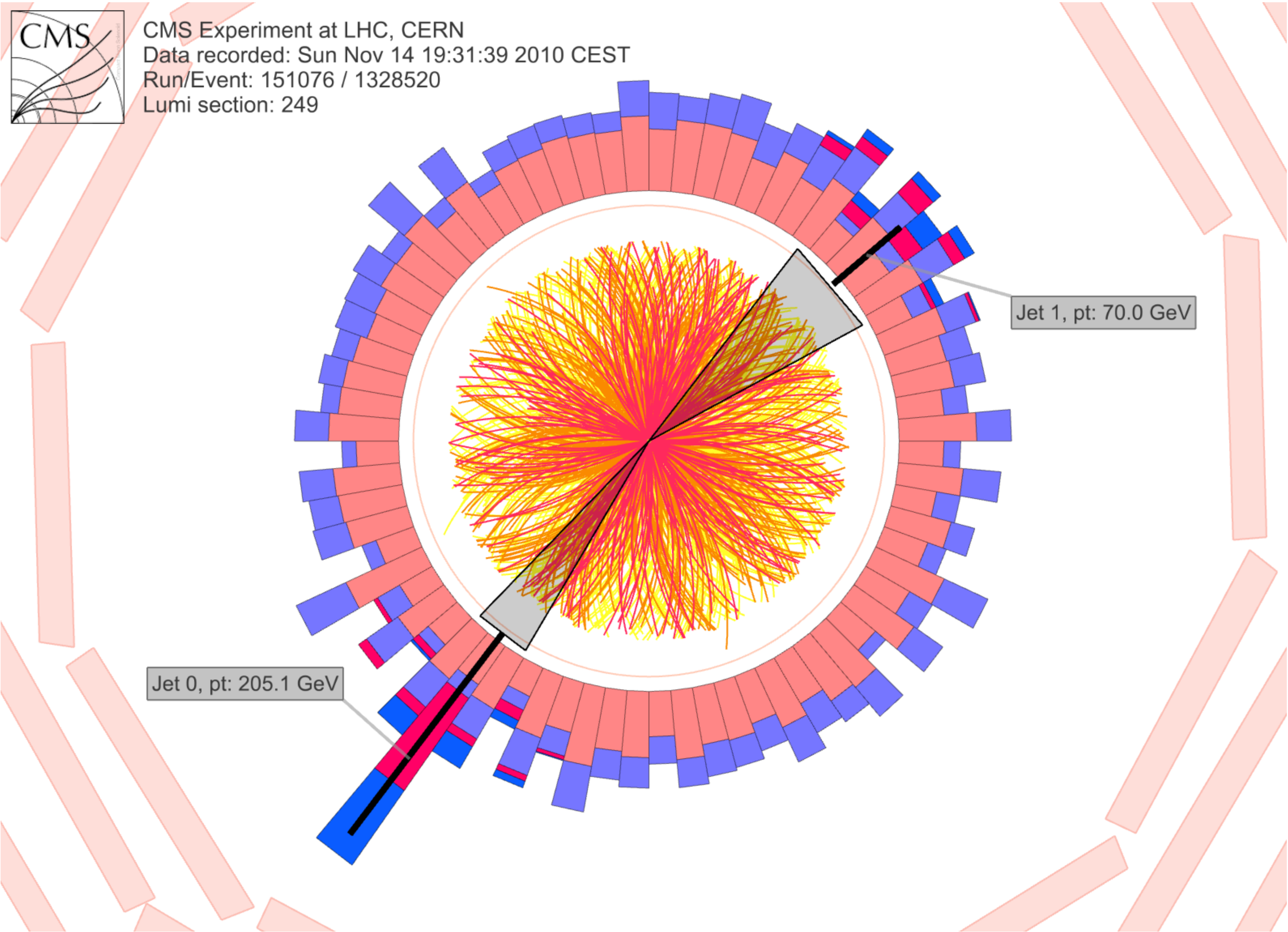




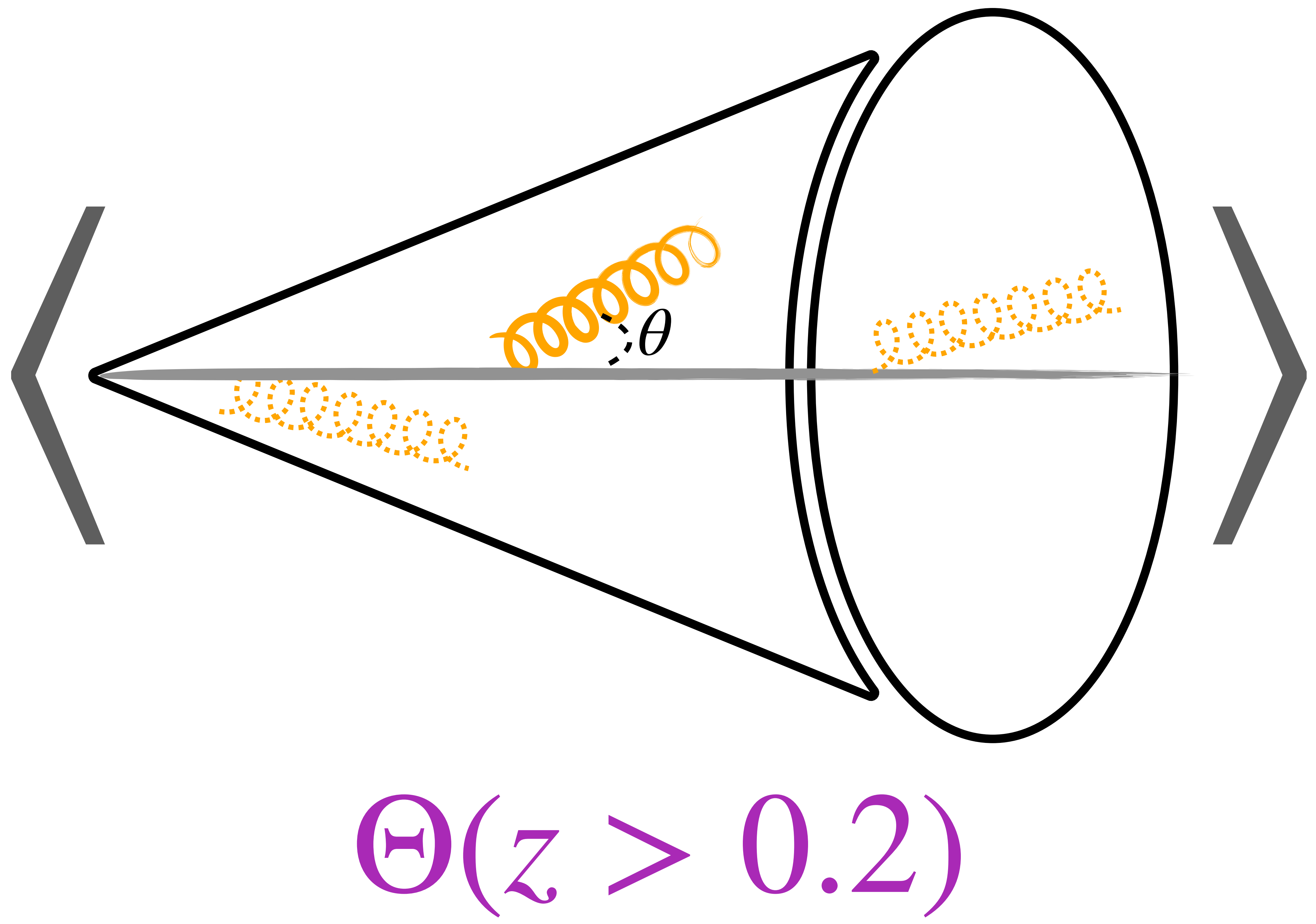
Jets lose energy in the medium

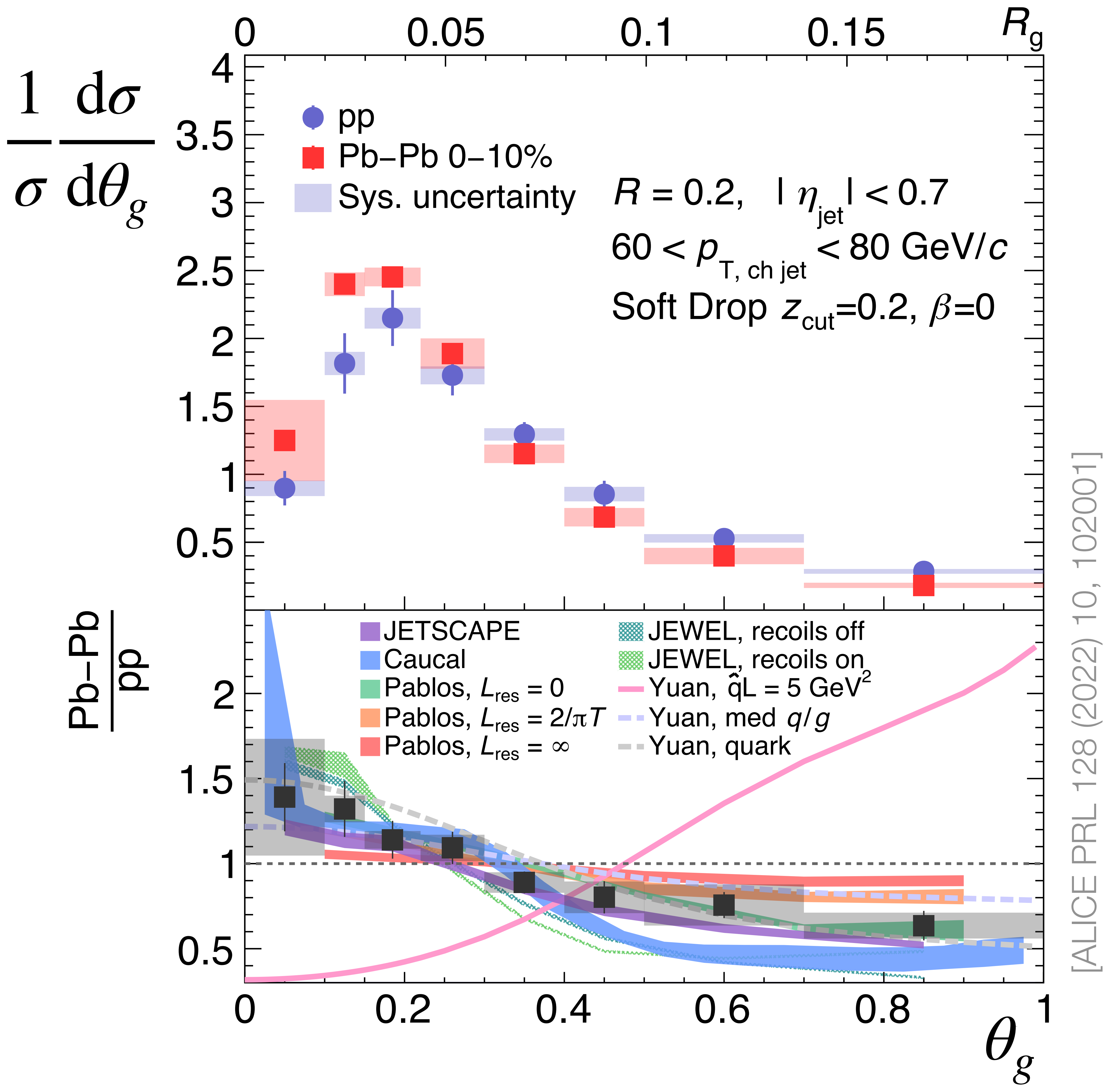
$$R_{AA} \propto \frac{dN/dp_t|_{AA}}{N_{coll} dN/dp_t|_{pp}}$$

Jet quenching: a clean signature of QGP formation (even by eye!)



How well do we simulate jet quenching?

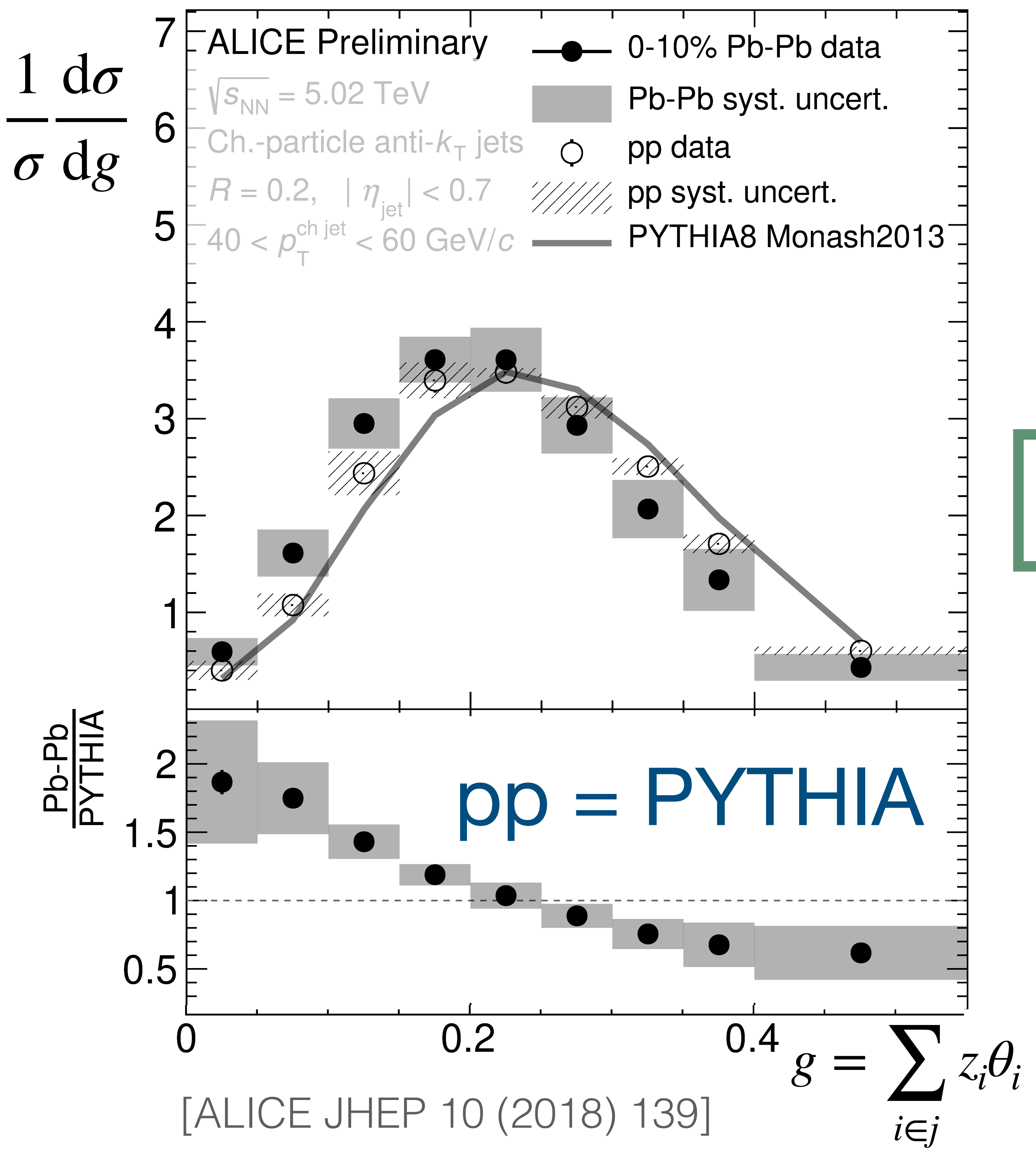




Models with very different physics ingredients seem to agree well with data

How well do we simulate jet quenching?

A precise vacuum benchmark is fundamental for any interpretation of PbPb data

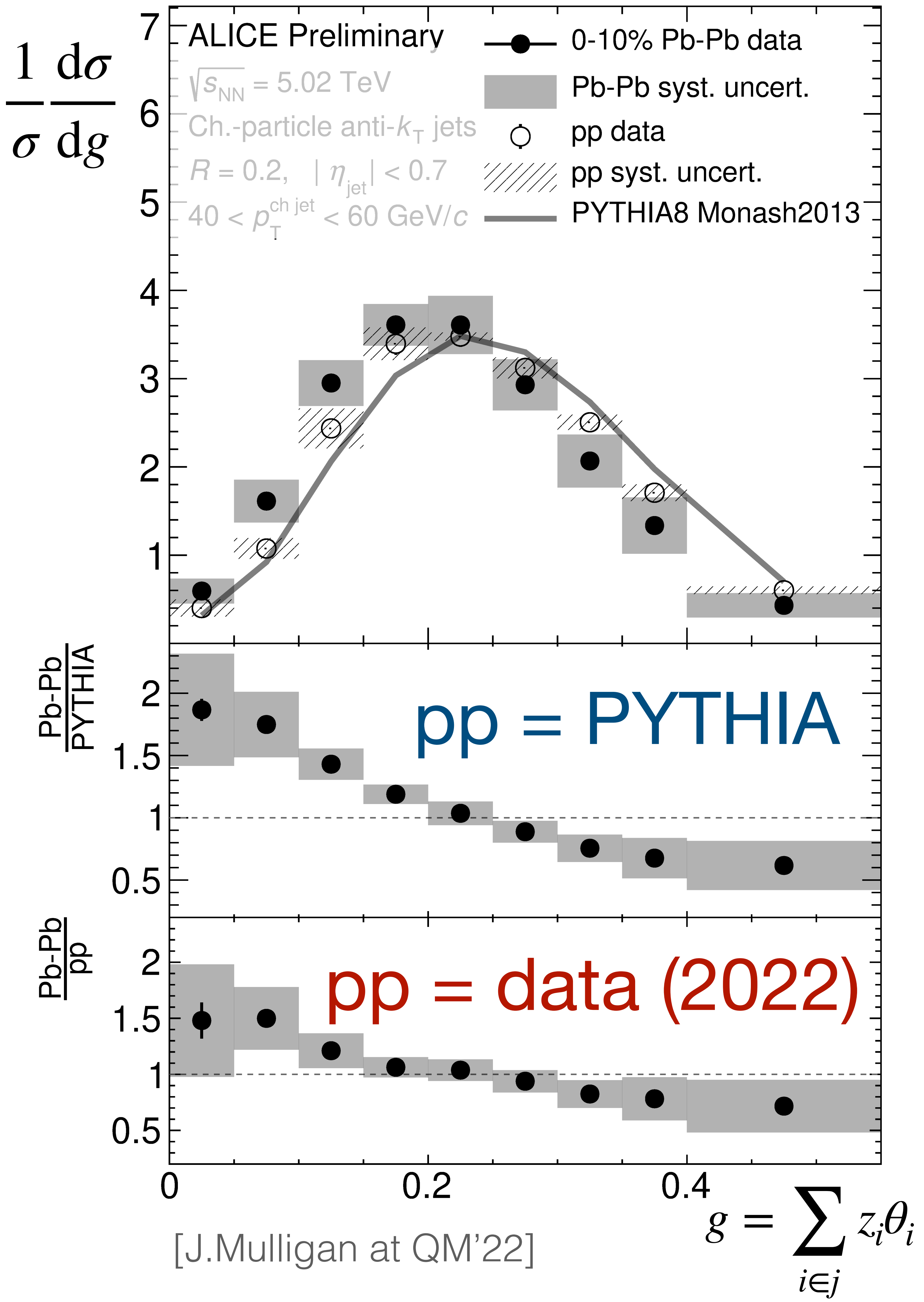


[ALICE JHEP 10 (2018) 139]

Experimental evidence of medium effects?

How well do we simulate jet quenching?

A precise vacuum benchmark is fundamental for any interpretation of PbPb data



[J.Mulligan at QM'22]

Not really…more like a wrong baseline

Some conclusions

- QCD matter exhibits a rich set of emergent phenomena
- Phase-diagram of QCD accesible both in cosmology and colliders
- Heavy-ion physics is a multi-disciplinary field in theory and experiment
- QGP is collective, an almost perfect fluid of standard model particles
- Critical to understand the role of QGP in small collision systems
- Jets can image QGP and help to understand its emergence
- Crucial to incorporate all recent theory developments in parton showers