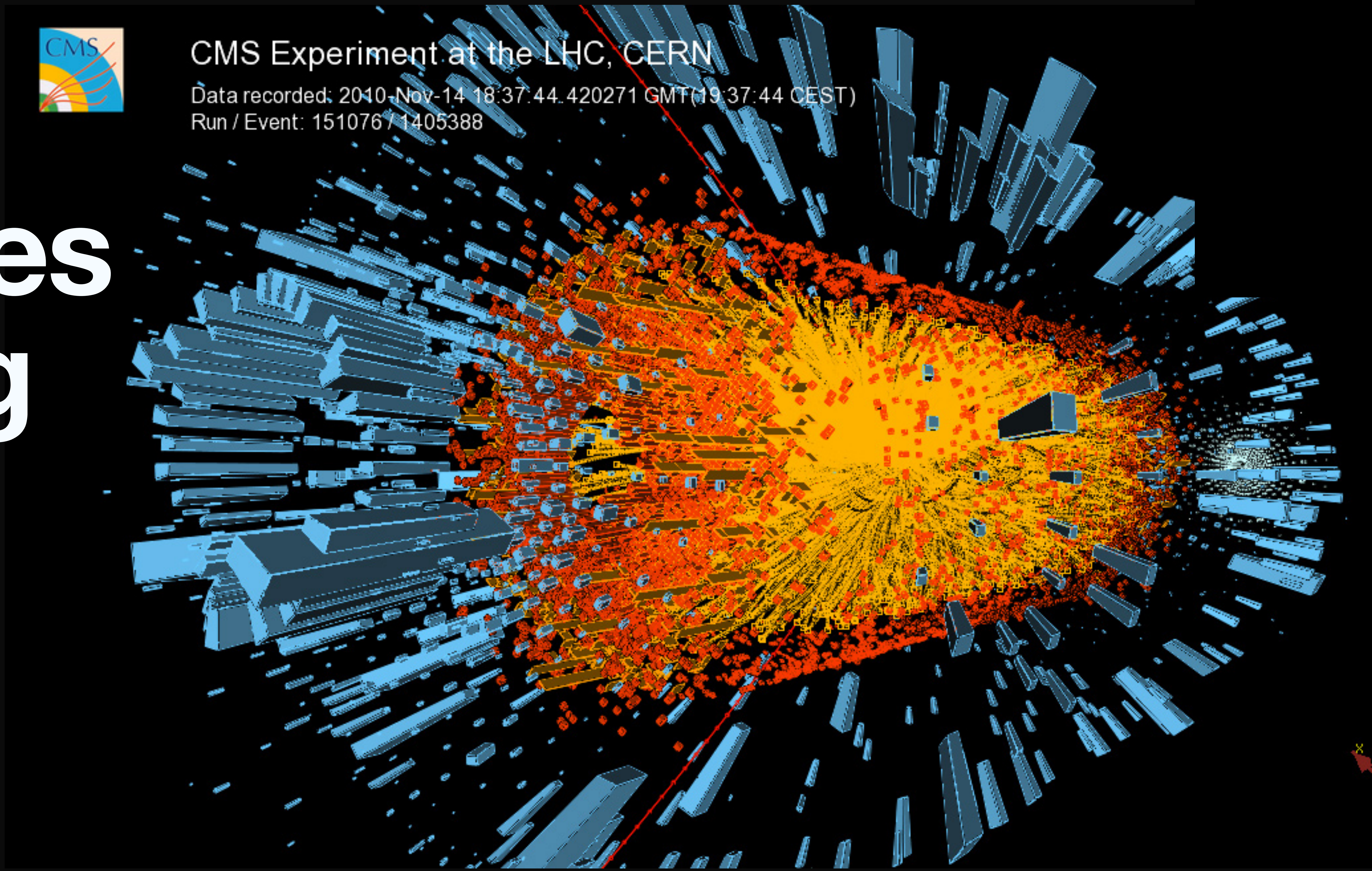
Recent advances in jet quenching theory



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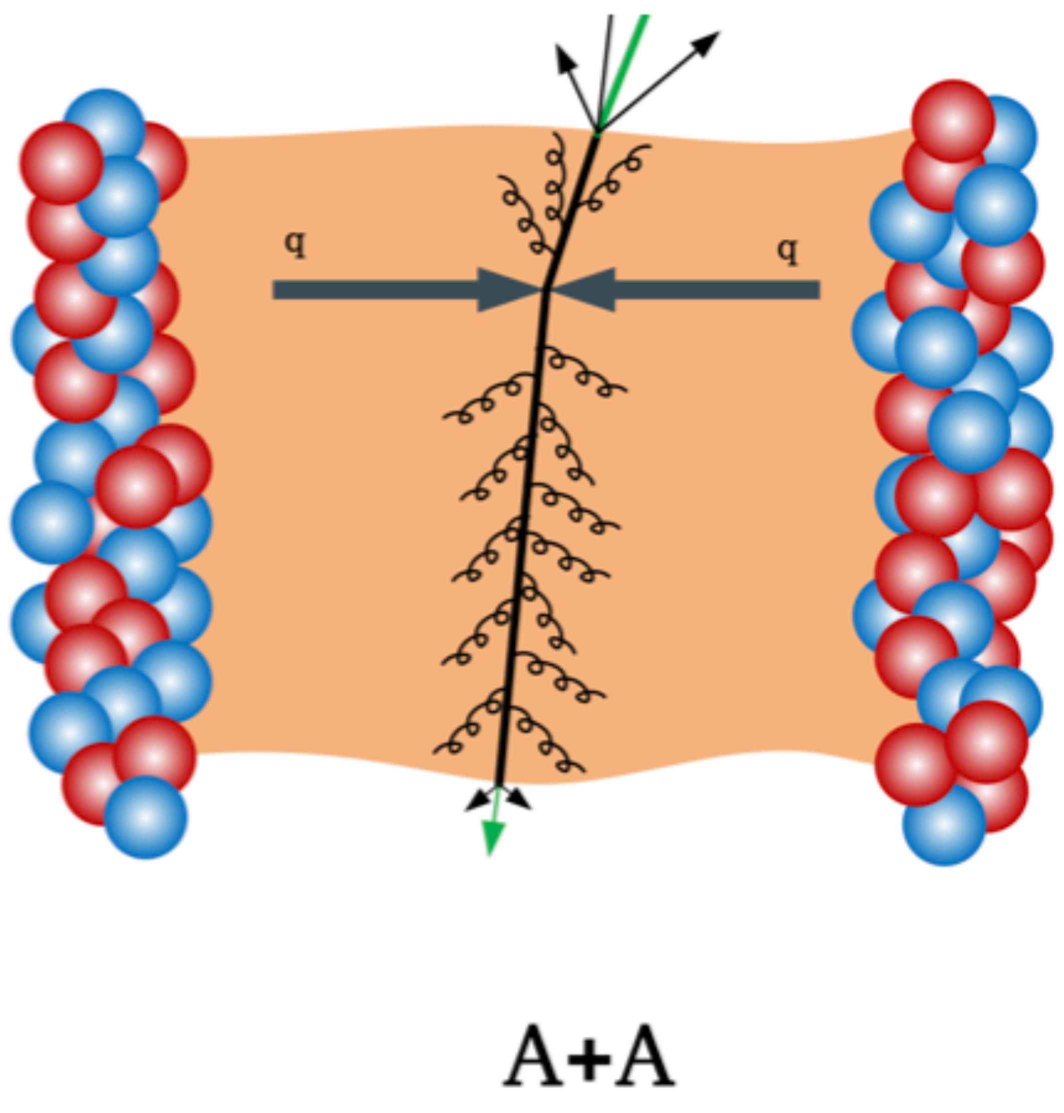
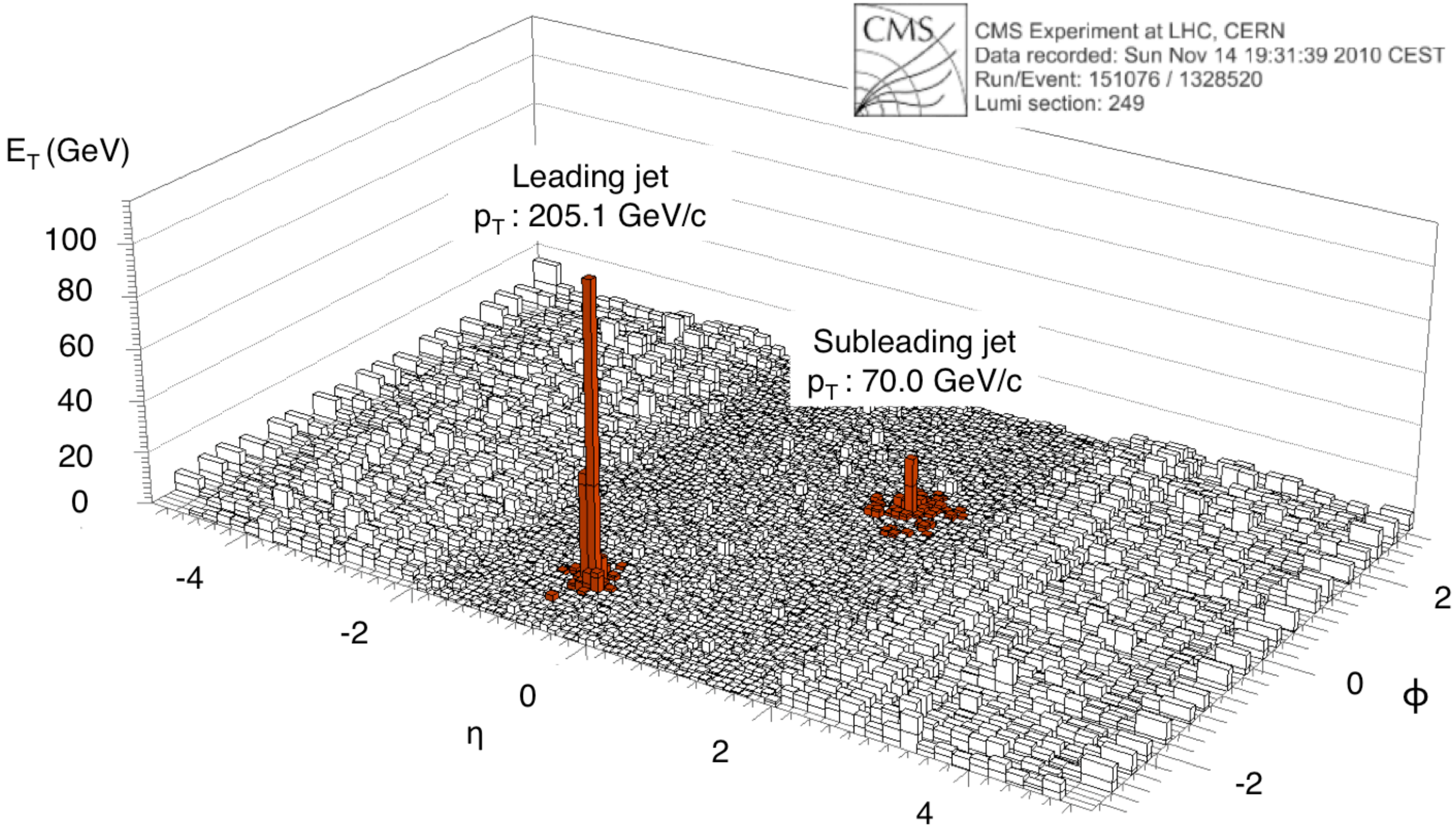
University of South Dakota

based on 2409.05957, 2412.18967
Felix Ringer, Yacine Mehtar-Tani, Balbeer Singh

Jets lose energy and are “Quenched”





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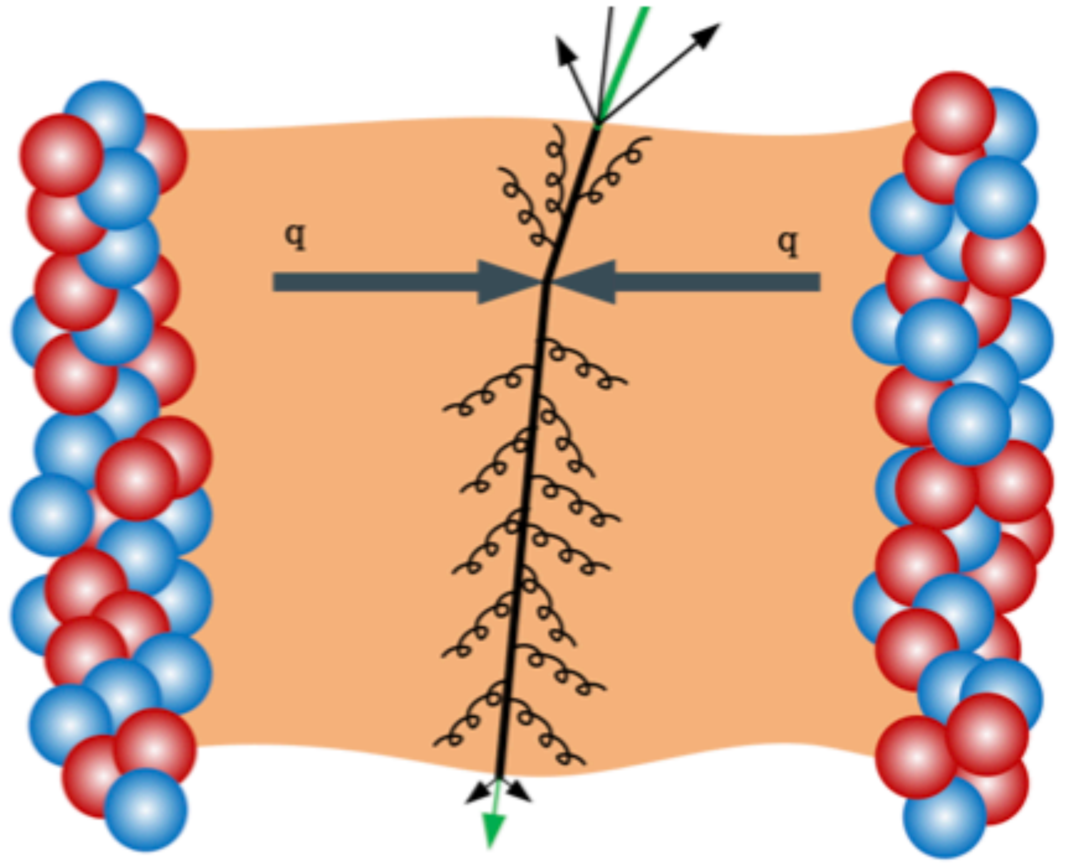

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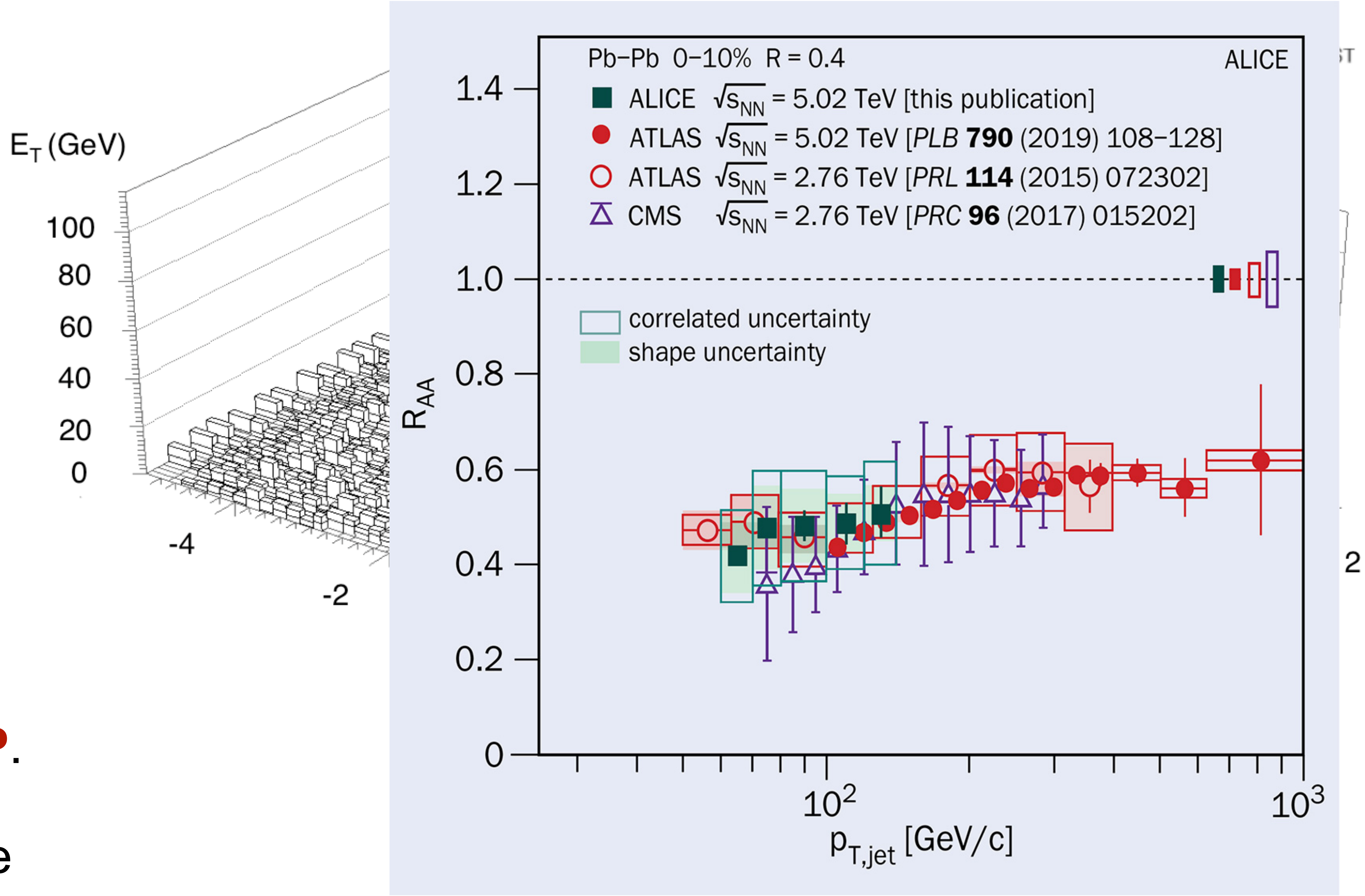
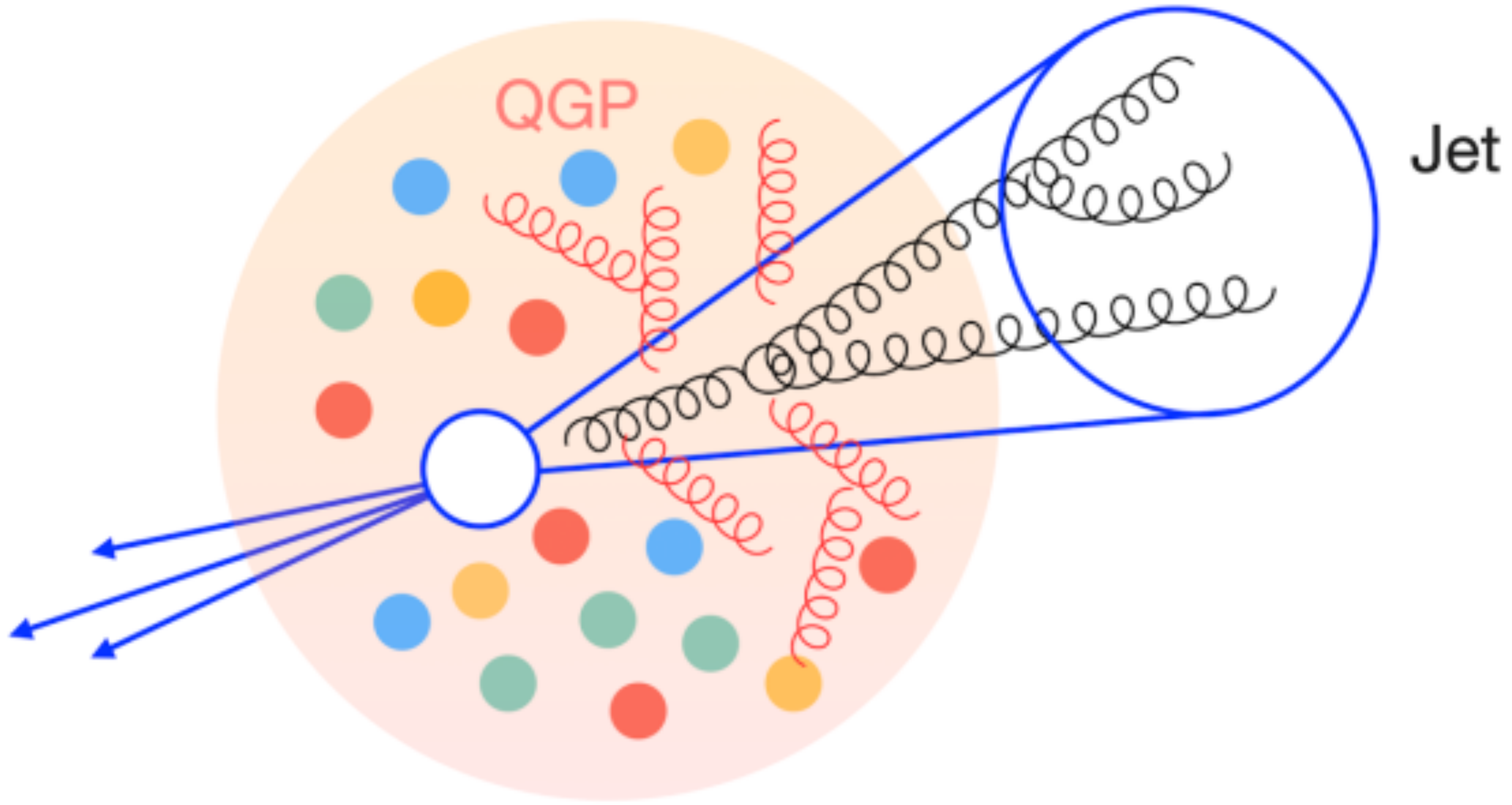


- We can use the jet to access the microscopic structure of the **strongly coupled QGP**.
- How does the jet evolve in the medium?

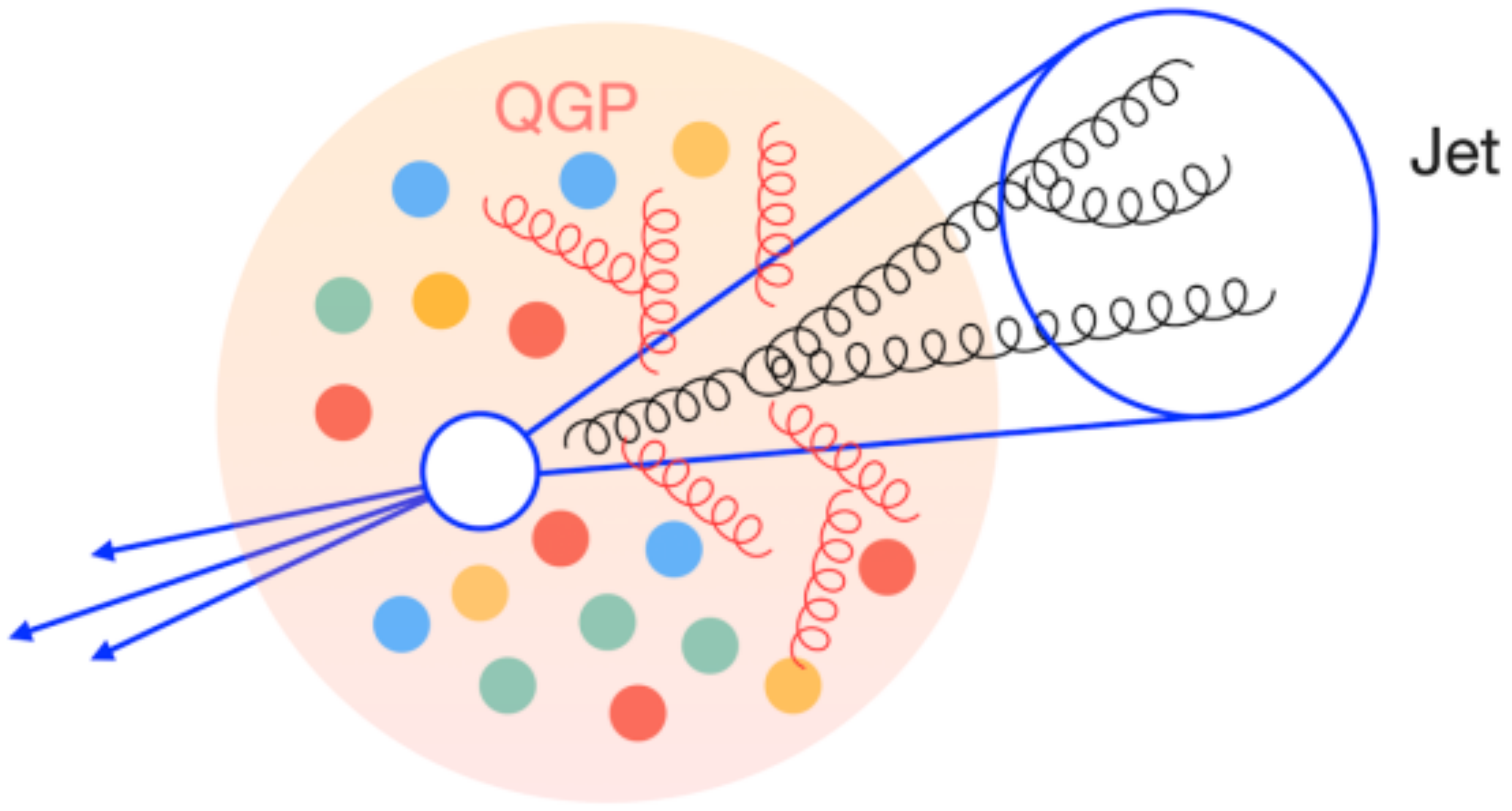
What do we need for quantitative precision?



- Perturbative QCD is insufficient !
- Non-perturbative tools :Holography → qualitative results only.
- Classical Numerical simulations: Too complex and incomplete.

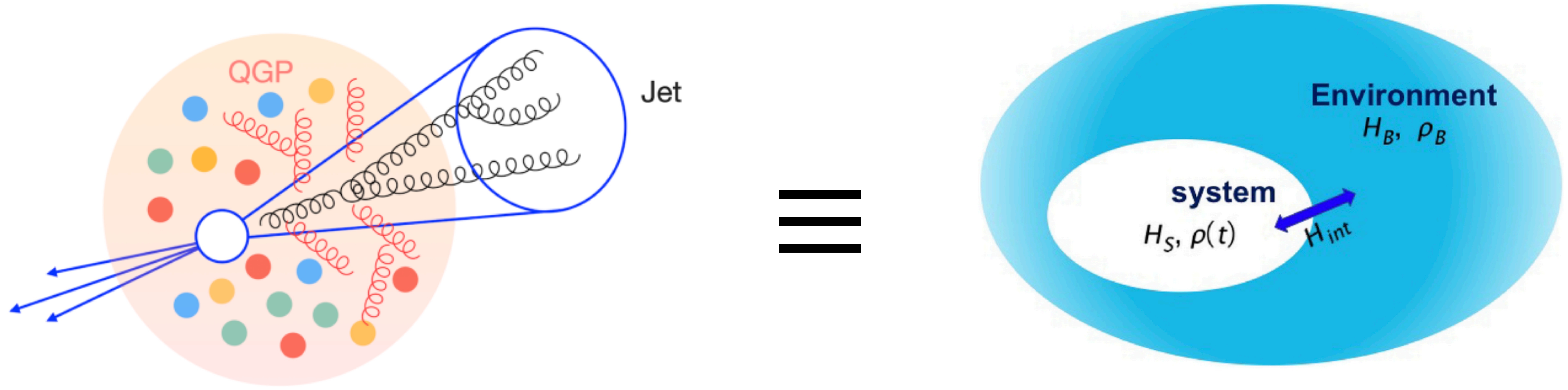
Borrow theoretical techniques from ep , pp where high precision predictions are common

What do we need for quantitative precision?

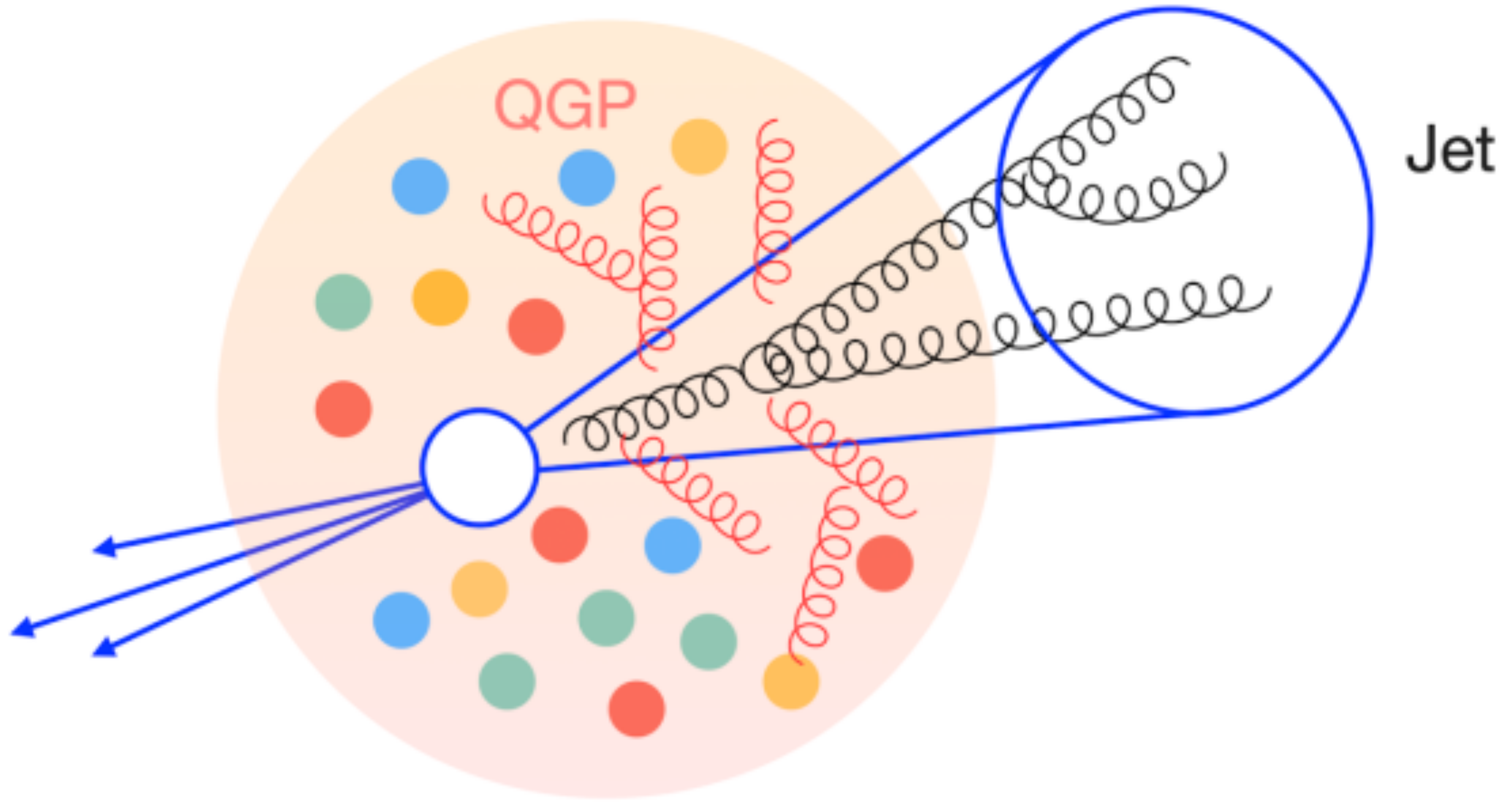


- **Separate** the **perturbative physics** from the non-perturbative by scale → **factorization**
- **Parameterize** the **non-perturbative physics** in terms of Gauge invariant operators → e.g the PDF, TMDPDF in DIS, Drell Yan etc.
- **Prove** (disprove) universality of non-perturbative physics across jet observables → **Universality** gives **predictive power** !

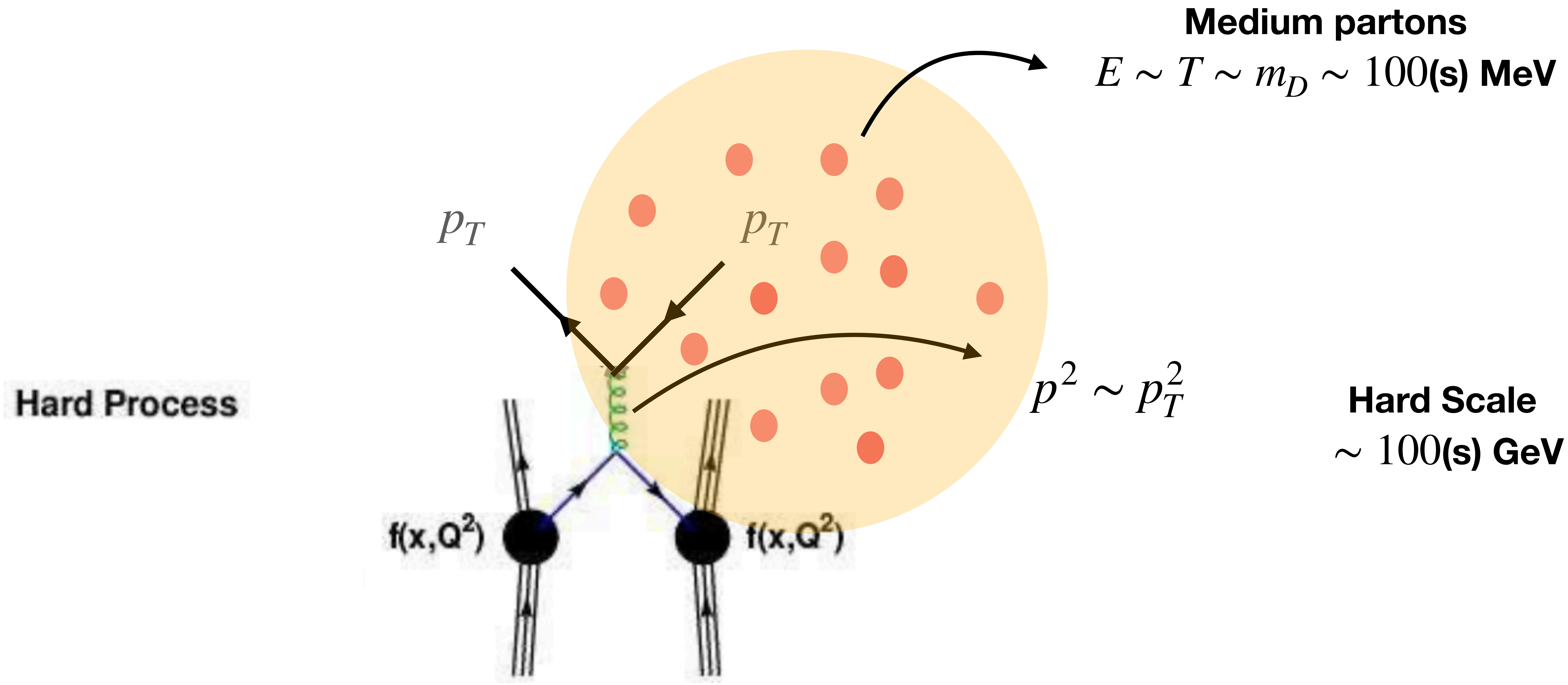
An Open Quantum system EFT



Anatomy of jet evolution



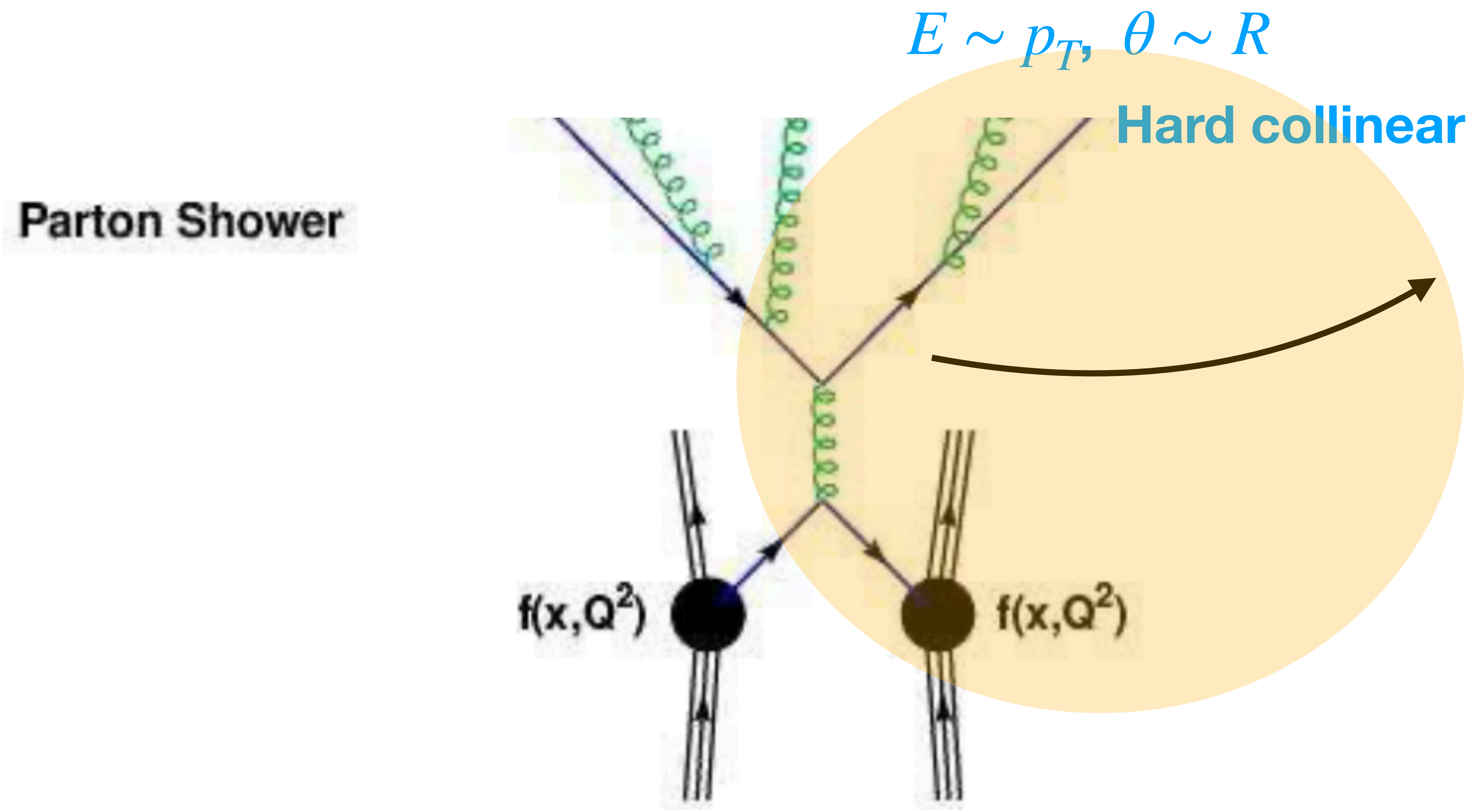
Jet production



Hard Scale
~ 100**(s) GeV**

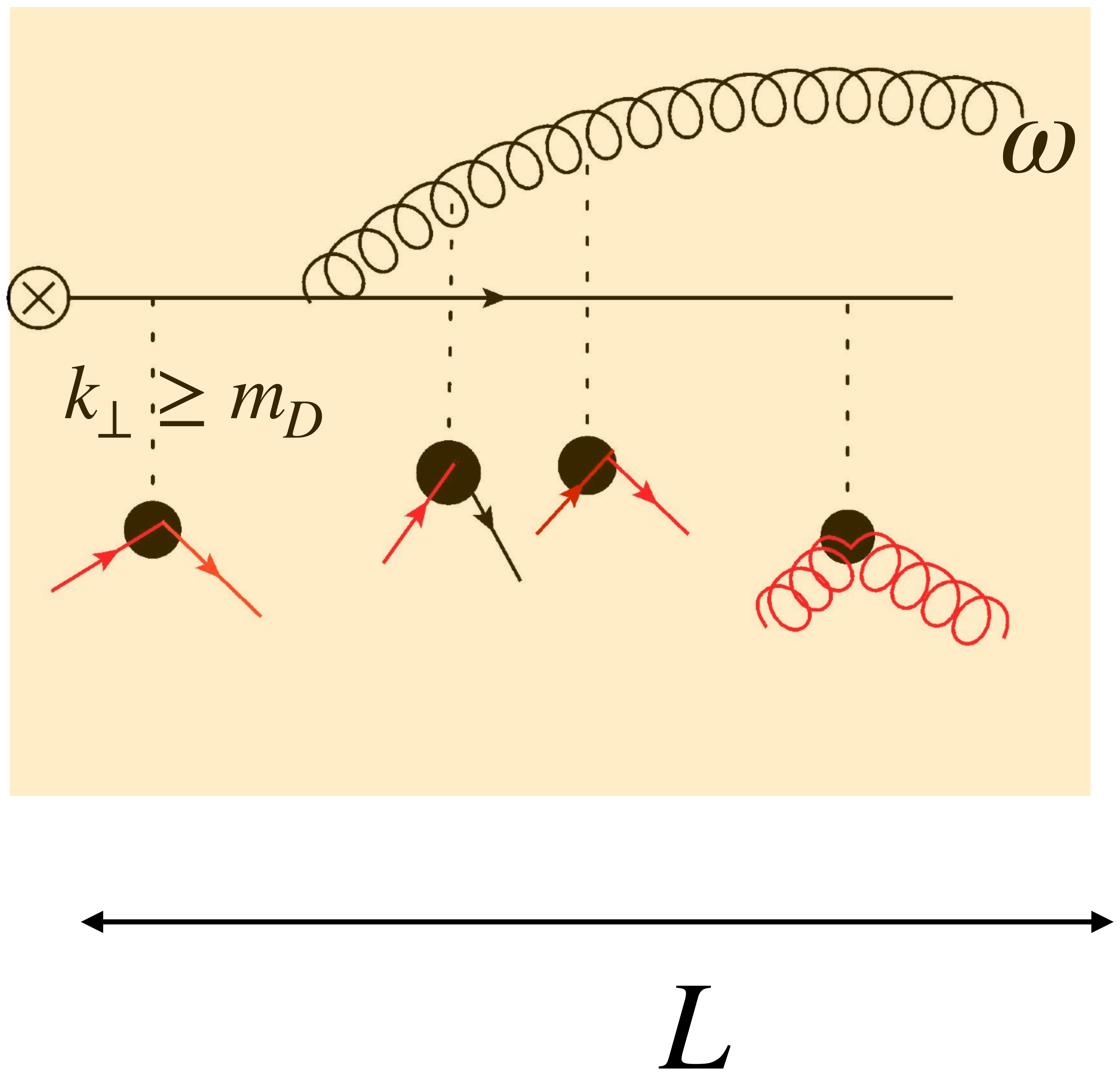
The vacuum parton shower

- Parton splittings preferentially happen at small angles $\rightarrow$" collinear"
- Selecting events with a jet of radius R $\ll 1$ sets the angular scale for collinear splittings.



$p^2 \sim (p_T R)^2$ **Jet Scale 10(s) GeV**

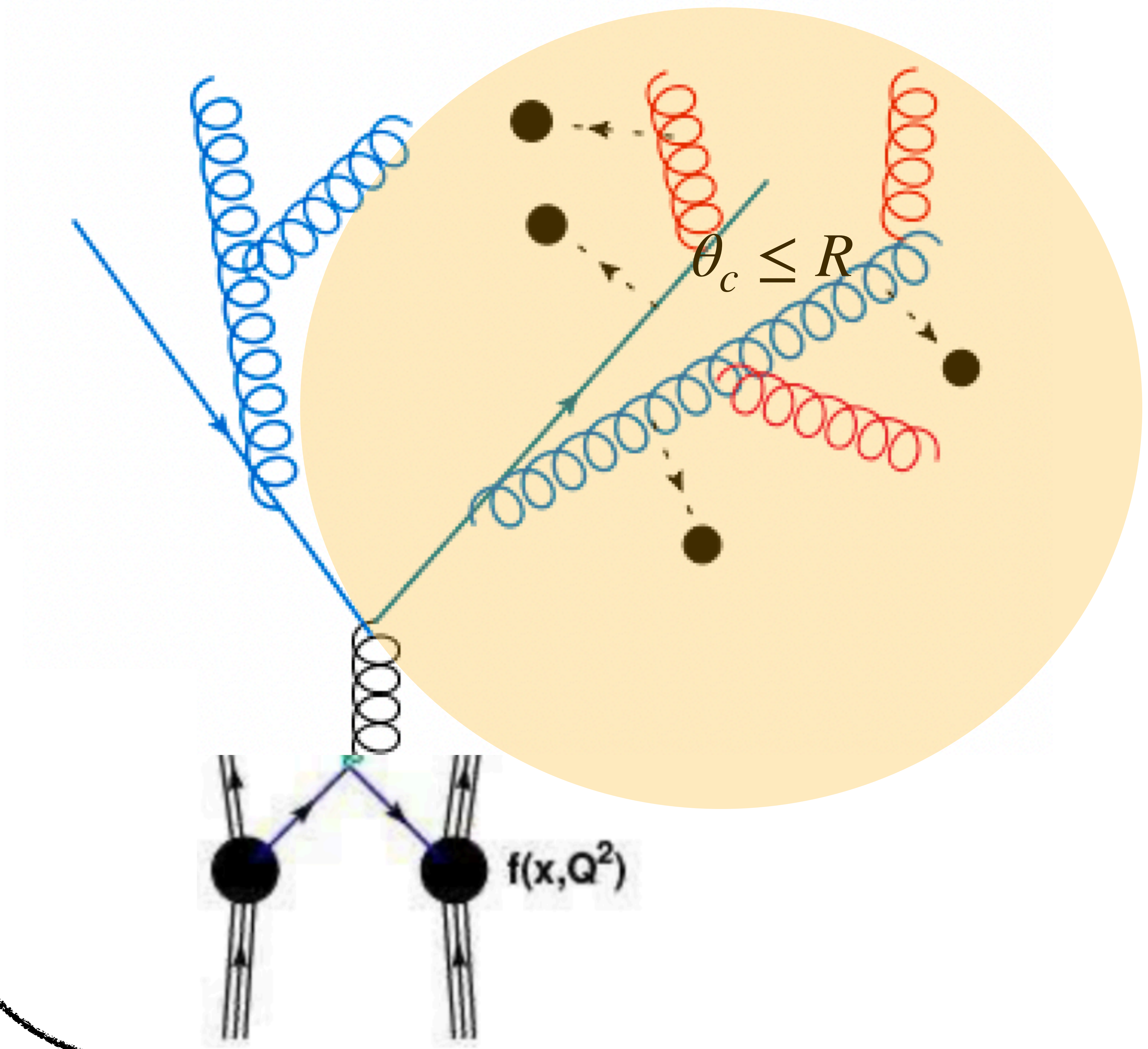
Parton in the medium



- Over multiple interactions radiation acquires a *total* transverse momentum $Q_{\rm med} \gg m_D \sim 1$ (s) GeV → Broadening.
- Medium induced **Collinear soft** radiation $E \sim Q_{\rm med}/R \sim 10$(s) GeV, $\theta \sim R$

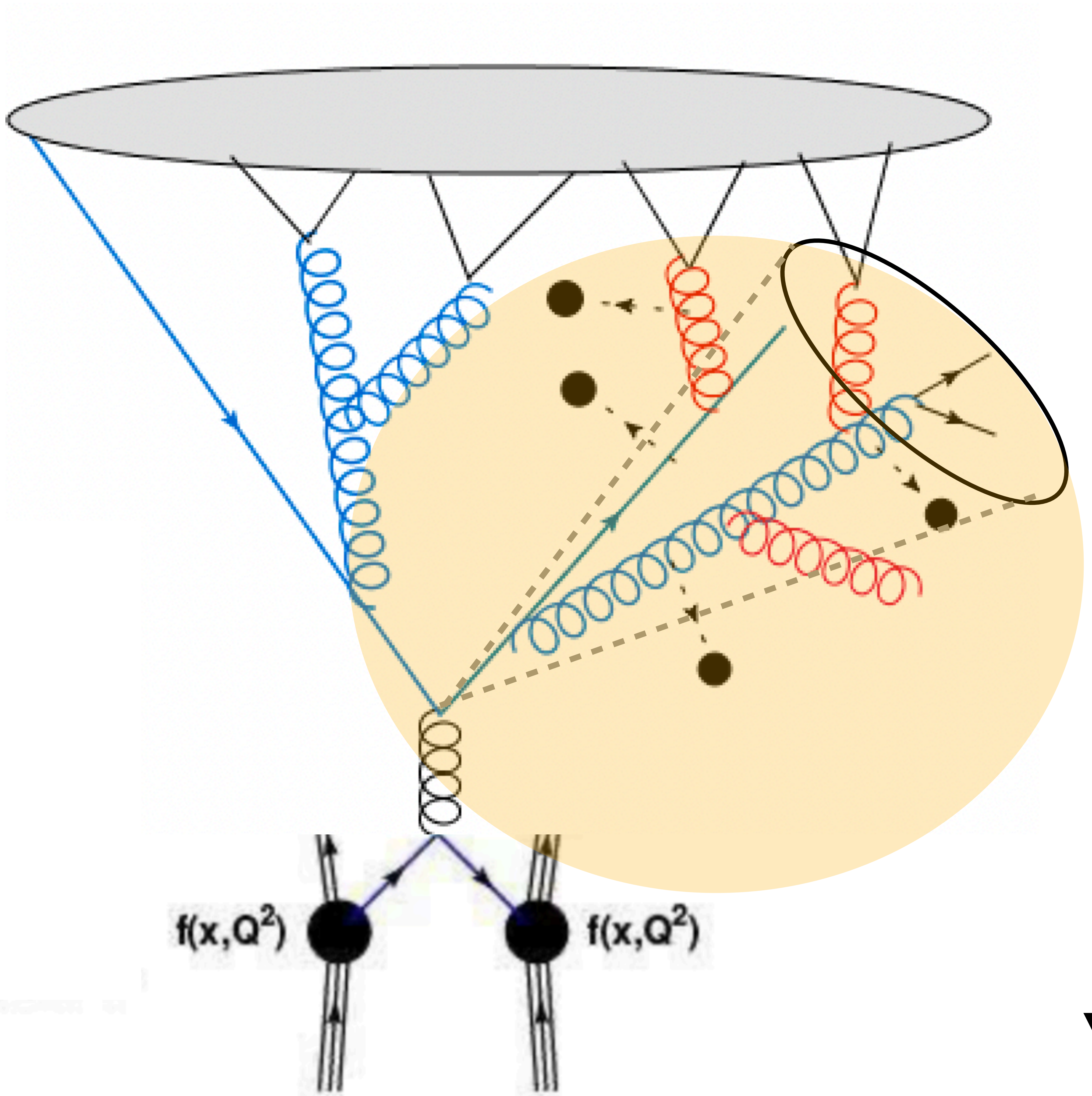
Color Decoherence

collinear soft $\theta \sim R$, $E \sim Q_{\text{med}}/R$ $p^2 \sim Q^2_{\text{med}}$



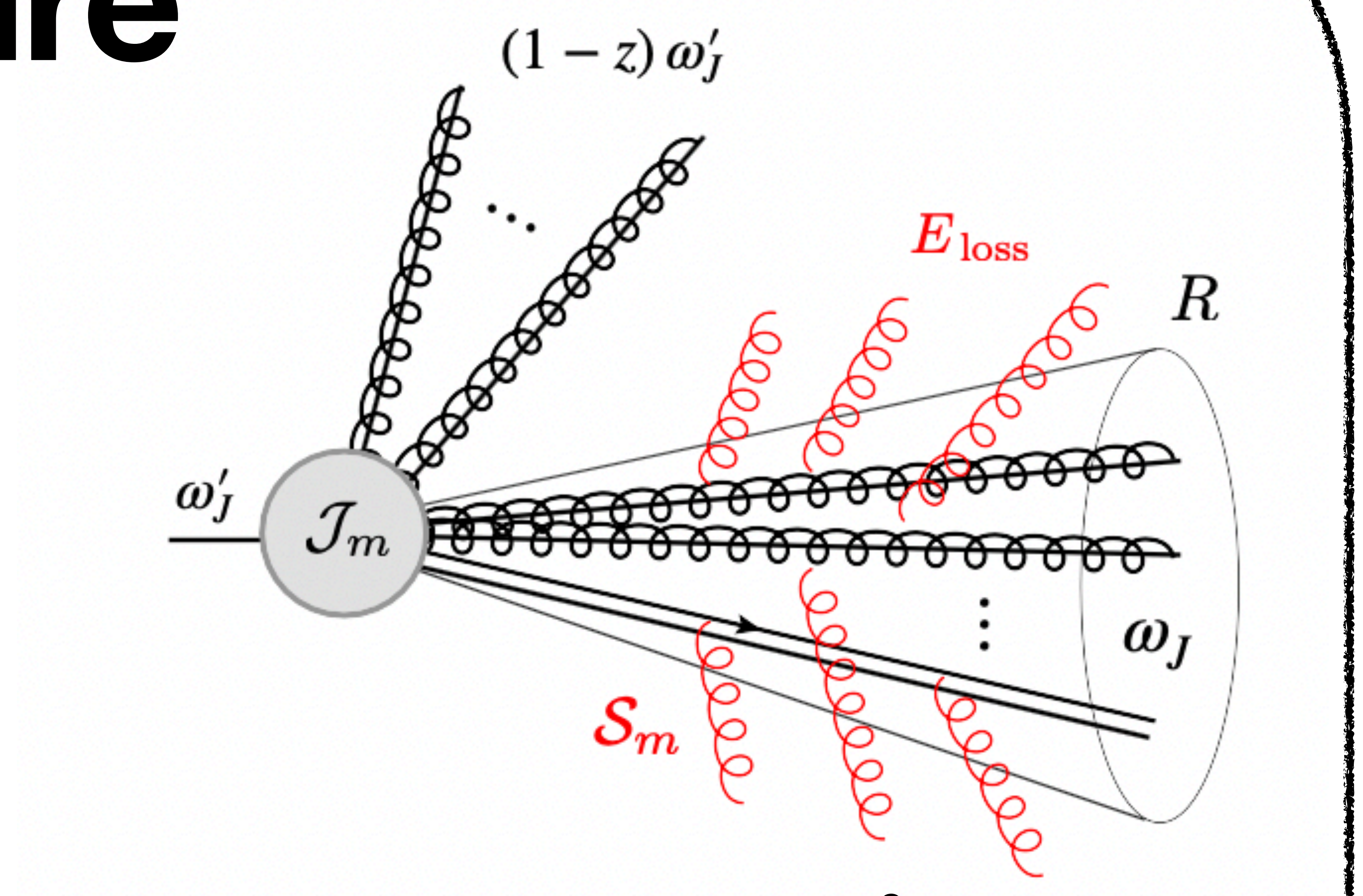
- Each hard collinear parton separated by $\theta_c \sim 1/(Q_{\text{med}}L)$ acts as a source for collinear soft (c-s) radiation.

The hierarchy of scales



$p^2 \sim m_D^2 \sim \Lambda^2_{\text{QCD}}$	100(s) MeV
$p^2 \sim Q^2_{\text{med}}$	1(s) GeV
$p^2 \sim (p_T R)^2 \sim (p_T \theta_c)^2$	10(s) GeV
$p^2 \sim p_T^2$	100(s) GeV

The factorized picture*



$$\frac{d\sigma^{AA\to \text{jet}X}}{dp_T d\eta} = \int \frac{dz}{z} H(z, p_T, \mu)$$

Hard process → Wilson coeff at p_T

$$\times \int_{\omega_J}^{\frac{\omega_J}{z}} d\omega_J' \int d\epsilon\, \delta(\omega_J' - \omega_J - \epsilon) \sum_{m=1}^{\infty} \mathcal{J}_{i\to m}(\omega_J', \mu, \theta_c) \otimes_\theta S_m(\epsilon, \mu) + O(R^2) + O\left(\frac{Q_{\rm med}}{p_T R}\right)^2$$

Create m prongs →
Wilson coeff at $p_T R$

Medium induced
energy loss function
Physics $\leq Q_{\rm med}$

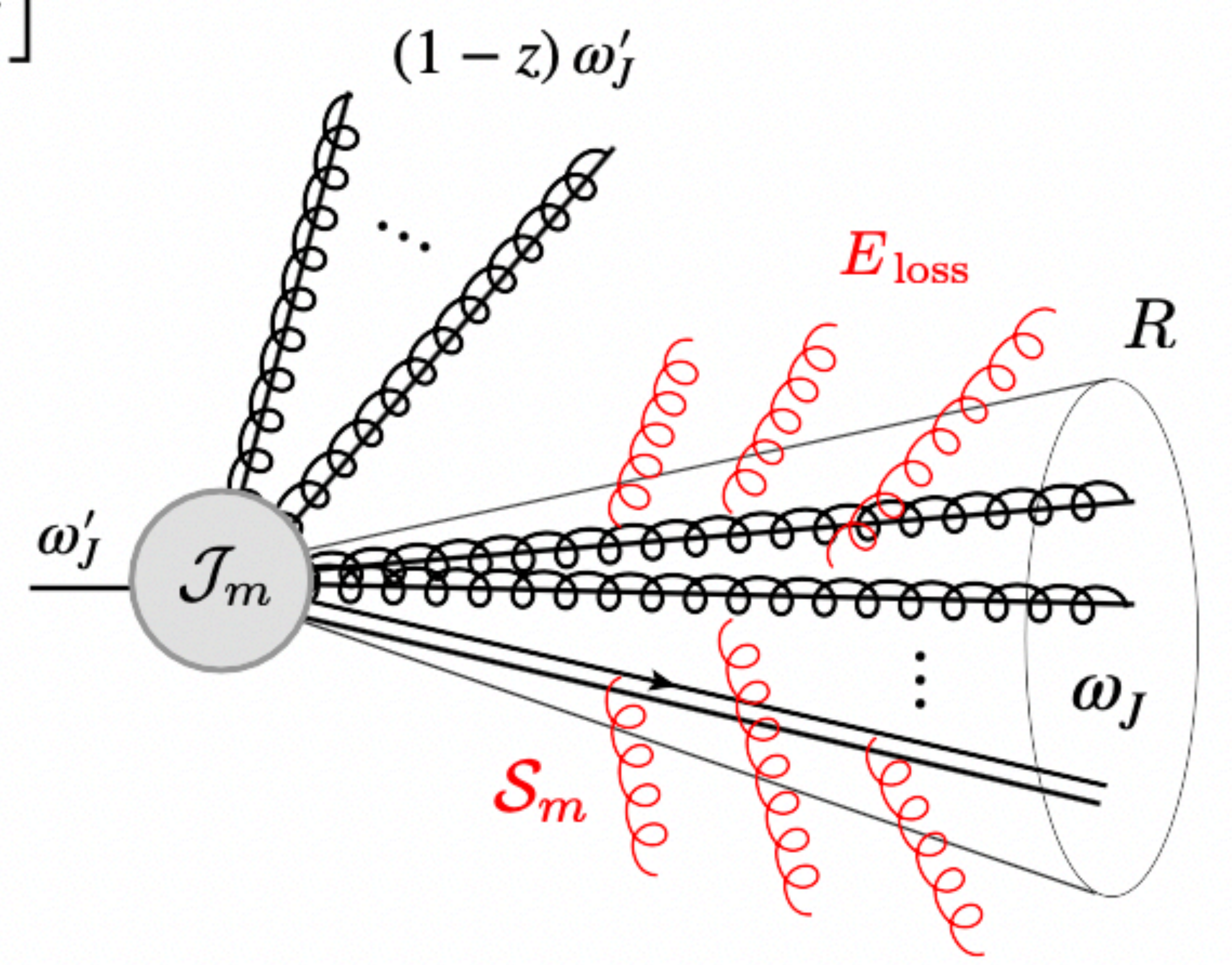
* V. Vaidya et. al. , arXiV: 2409.05957

The medium energy loss function

$$\mathcal{S}_m(\{\underline{n}\},\epsilon) \equiv \mathrm{Tr}\Big[U_m(n_m)...U_1(n_1)U_0(\bar{n})\rho_M U_0^\dagger(\bar{n})U_1^\dagger(n_1)...U_m^\dagger(n_m)\mathcal{M}\Big]$$

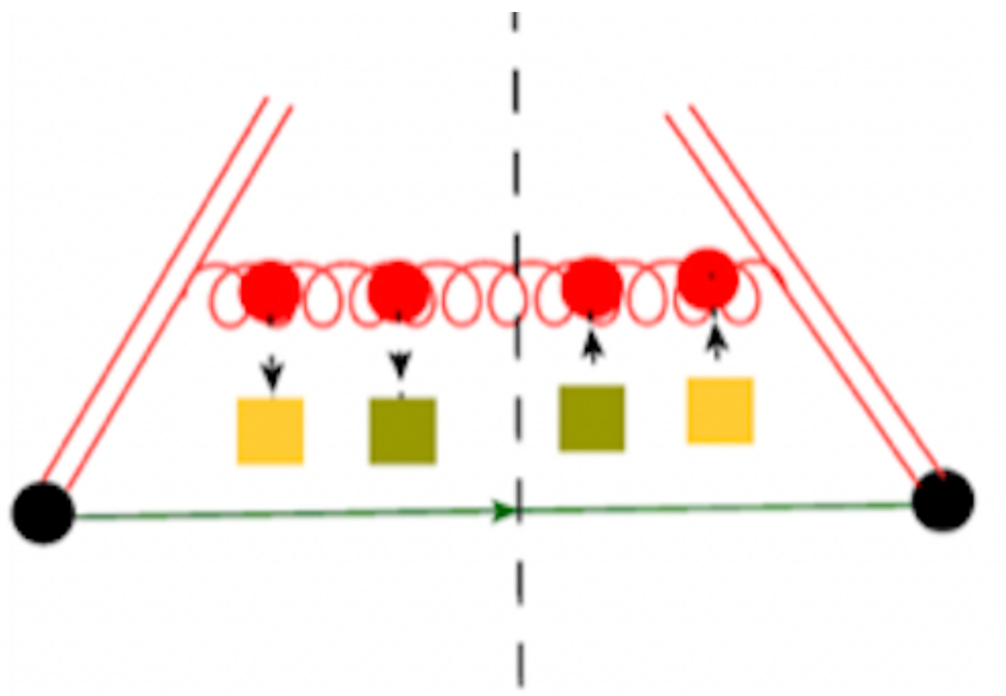
Correlator of m Wilson lines sourced by m subjet prongs.

$$U(n) \equiv \mathcal{P}\exp\left[ig\int_0^{+\infty} \mathrm{d}s\, n\cdot A_{\rm cs}(sn)\right]$$



The medium scale $Q_{\rm med}$ is hidden and can only be seen through an explicit calculation → An emergent scale

A first look* inside the single subjet



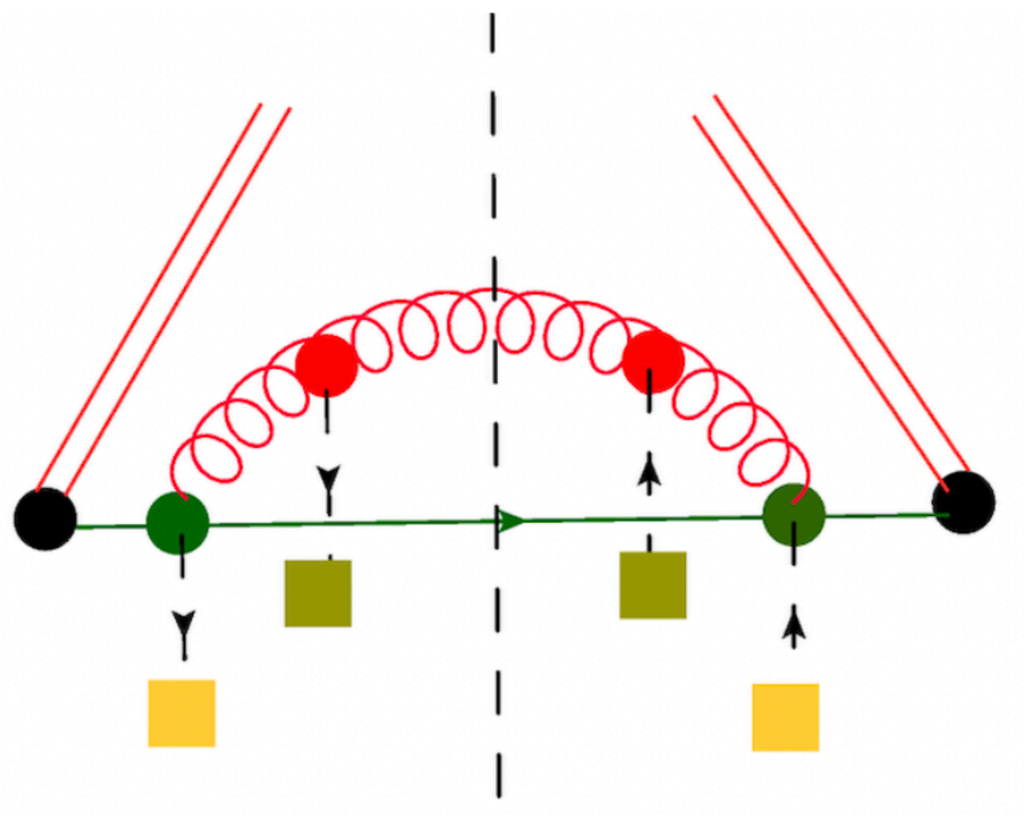
$$\mathcal{S}_1 = \mathrm{Tr}\Big[U(n)U(\bar{n})\mathcal{M}U^\dagger(\bar{n})U^\dagger(n)\Big]$$

Broadening for vacuum induced and medium induced radiation in Markovian approximation

$$\mathcal{S}_1^{(1)} = \int d^2\mathbf{p}F(\mathbf{p},R,m_D)P(\mathbf{p},R,m_D)$$

Probability of gluon production

Probability distribution of broadening



$$\langle|\mathbf{p}|\rangle \sim Q_{\mathrm{med}} \gg m_D$$

An emergent perturbative scale that depends on medium density and interaction strength

A further factorization for complete separation of non-perturbative physics

* V. Vaidya et. al. , arXiV: 2412.18967

A first application*: Going beyond $\hat{q}$

- The current picture of gluon broadening $$P(\mathbf{p}, L) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{-|\mathbf{b}|^2 L\hat{q}}$$

The EFT framework is telling us that this is not the full picture

- **Gluon broadening encoded through two non -perturbative operator matrix elements that depend on the jet radius R**

$$P(\mathbf{p}, L) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{-|\mathbf{b}|^2 L\Phi(\mu, m_D, R)} \times e^{-L\int \frac{d\xi}{\xi} C(\mathbf{b}, R, \xi, \mu) Y(\xi, m_D)} + O\left(\frac{m_D^2}{Q^2_{\text{med}}}\right)$$

Encodes multiple forward (small x) scattering
Obeys BFKL evolution

Encodes multiple hard (large x) scattering
Obeys DGLAP evolution

* V. Vaidya et. al. , arXiV: 2412.18967

Summary and Outlook

- Quantitative precision in a non-perturbative QGP medium requires us to adopt an effective field theory framework.

- A factorization formula for jet quenching that explicitly isolates physics at widely separated scales.

- A new parameterization of gluon broadening in the medium → A significant step beyond $\hat{q}$.

Still to be done …

- Factorization for gluon production mechanism → Will lead to a complete parameterization of non-perturbative physics.

Thank You