



Jet energy loss and its perspective at EIC

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BNL

EIC User Group Meeting 2018
Catholic University of America, Washington DC
July 30 - August 2

Outline

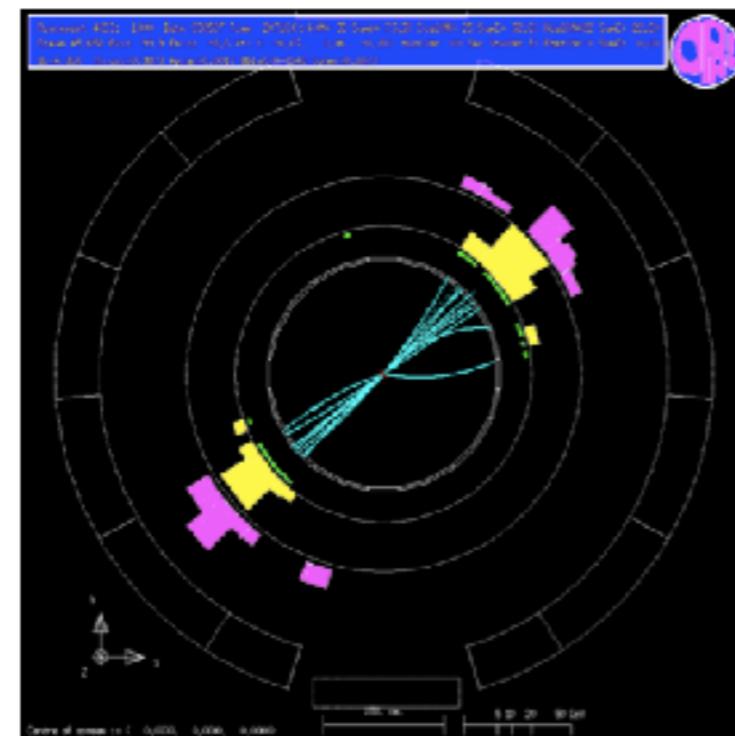
- Elements of jet physics
- In-medium jet energy loss
- Jet in EIC: perspectives

- Jets are collimated sprays of particles produced in high energy collisions

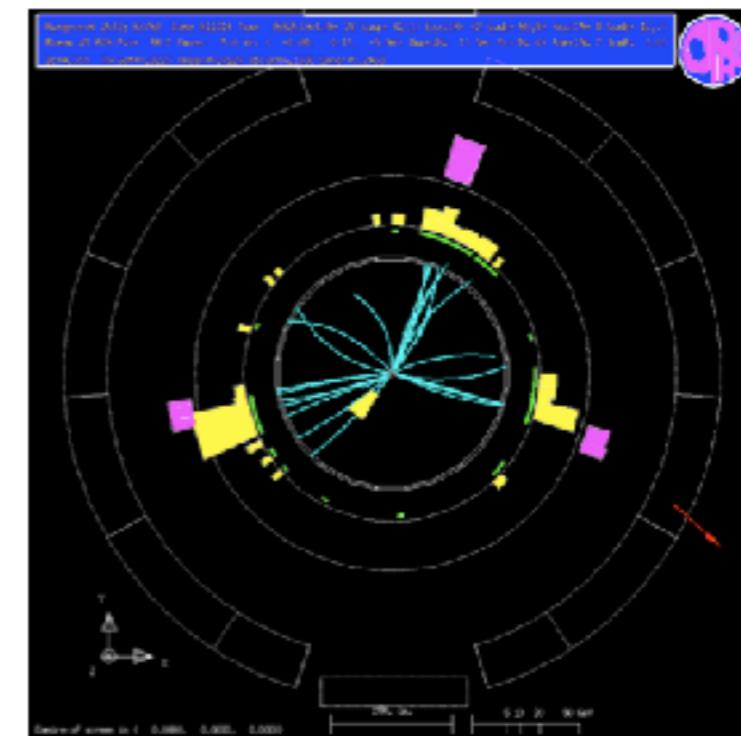
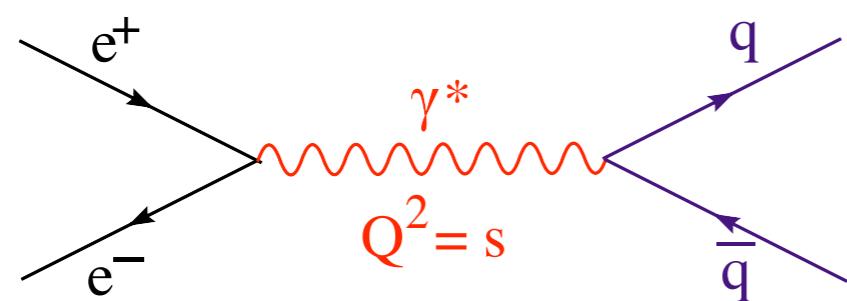
LEP (OPAL)

events

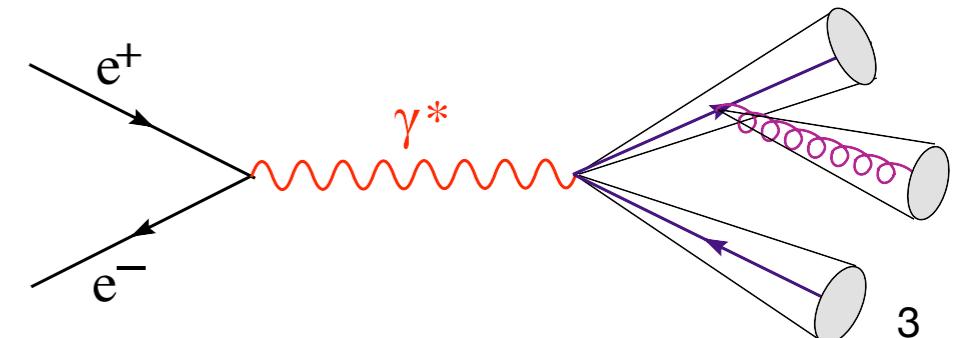
1993



2 jets

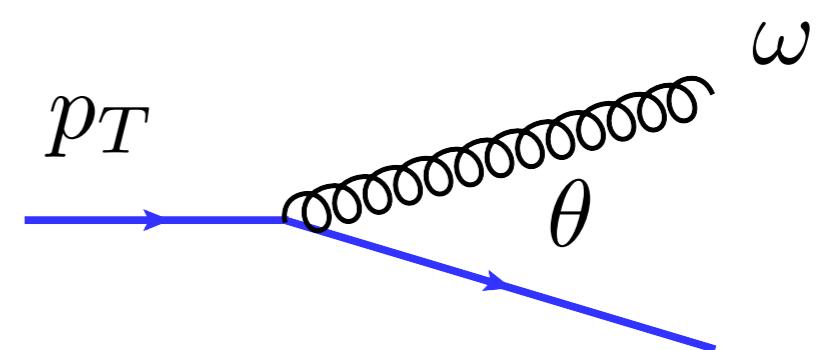


3 jets



- Jet collimation: collinear QCD splittings are enhanced due to mass singularity
- Although the coupling is small the large logarithmic phase-space enhances the probability for multiple splittings

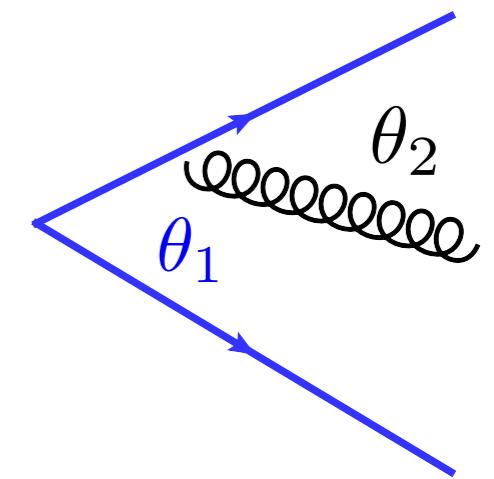
$$dP \sim \alpha_s C_R \frac{d\theta}{\theta} \frac{d\omega}{\omega}$$



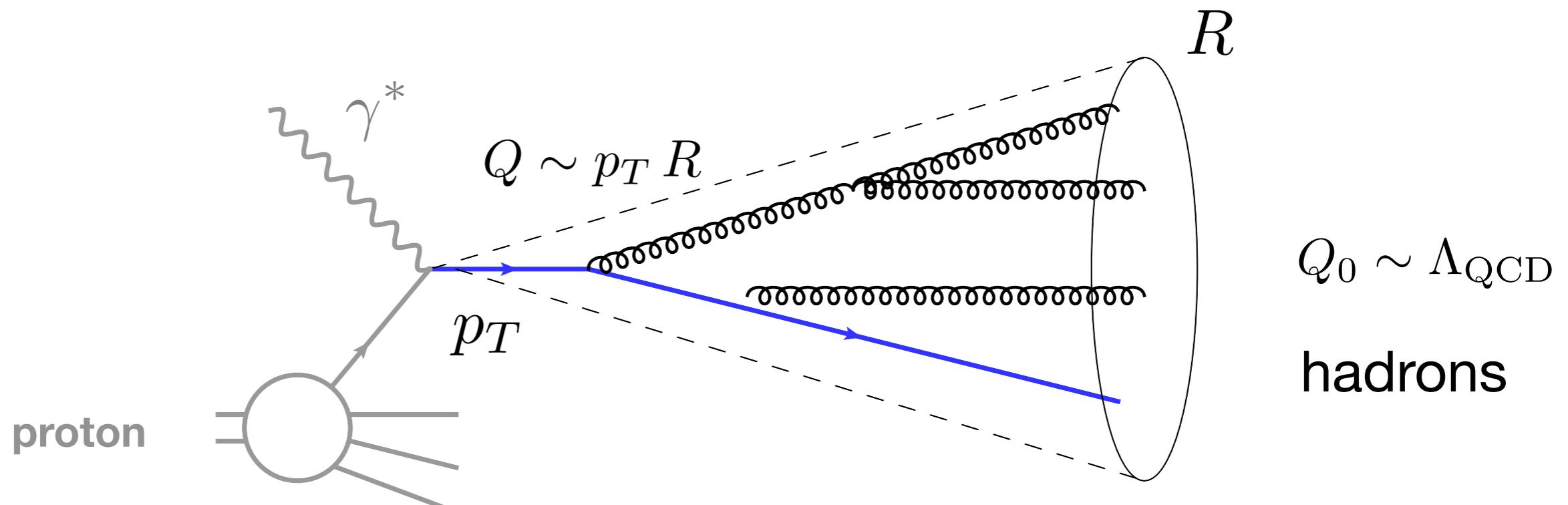
- Collinear factorization: Jet evolution is independent of the process

- Building block for jet evolution: antenna radiation pattern \Rightarrow suppression of large angle soft gluon radiation due to color coherence

$$\theta_1 \gg \theta_2$$



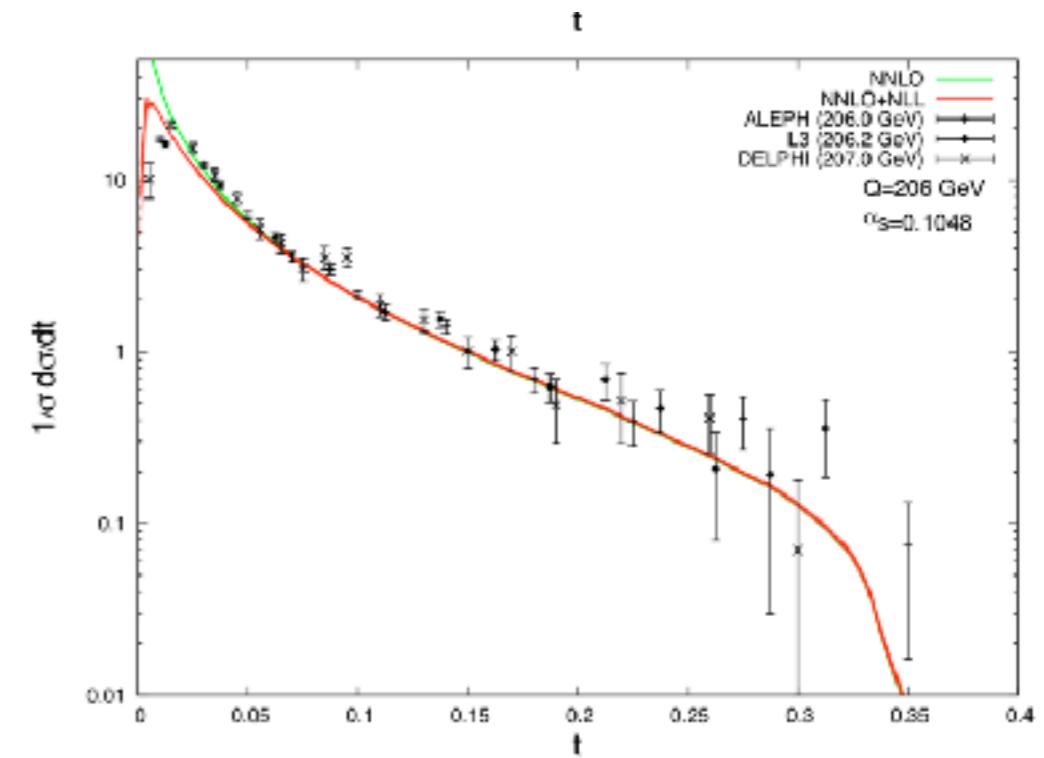
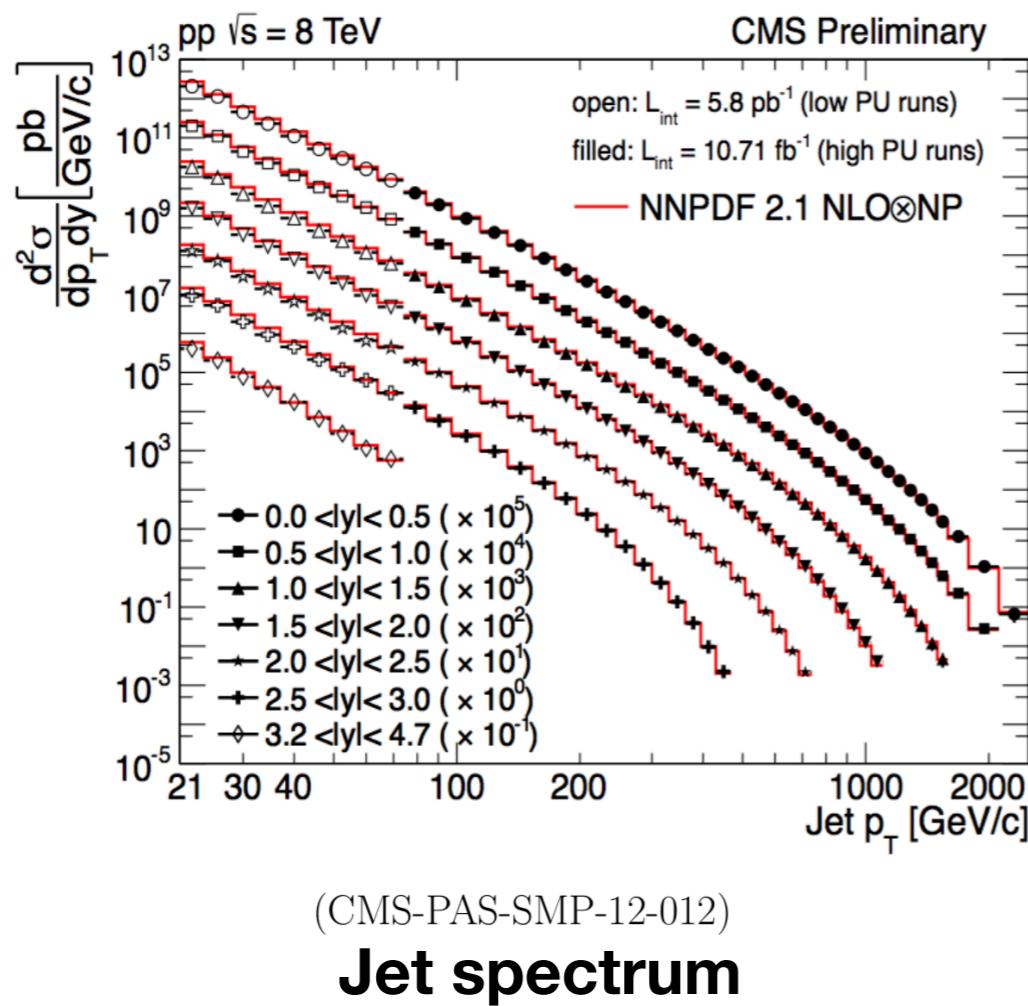
- Coherent branchings: angular ordering of the parton shower



[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Khoze,
Toyan, Collins, Soper, Sterman ... 1980's]

- Two types of observables:

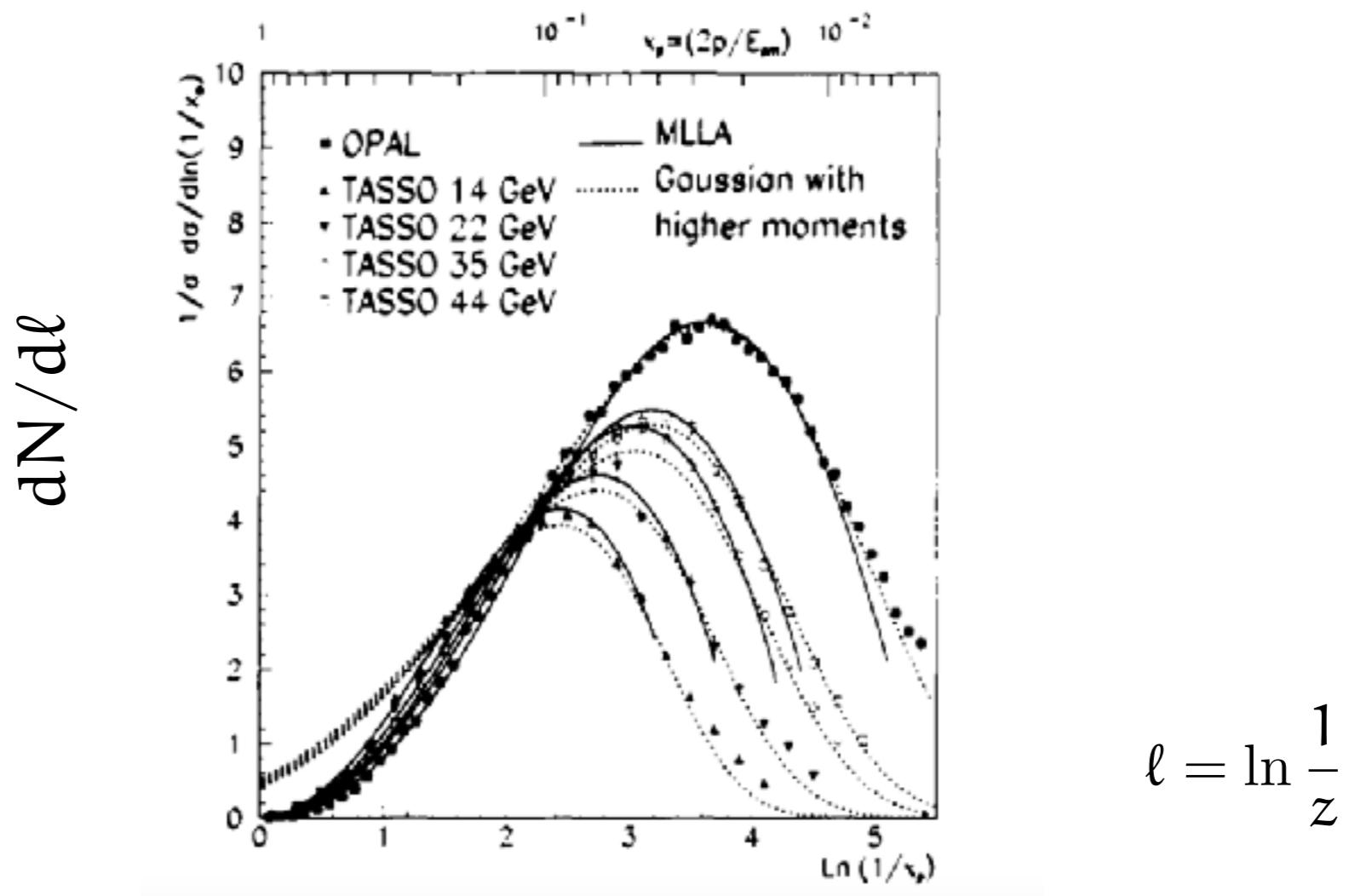
1. Infrared-collinear (IRC) safe (no hadrons in the final-state): Jet spectra, even shape: thrust, jet mass...
May require resummations of large logs and non-perturbative corrections



Thrust $T = \max \frac{\sum_i p_i n}{\sum_i |p_i|}$

- Two types of observables:

2. Infrared sensitive observables: Fragmentation functions, etc. QCD still predictive (factorization, universality, local parton-hadron duality)

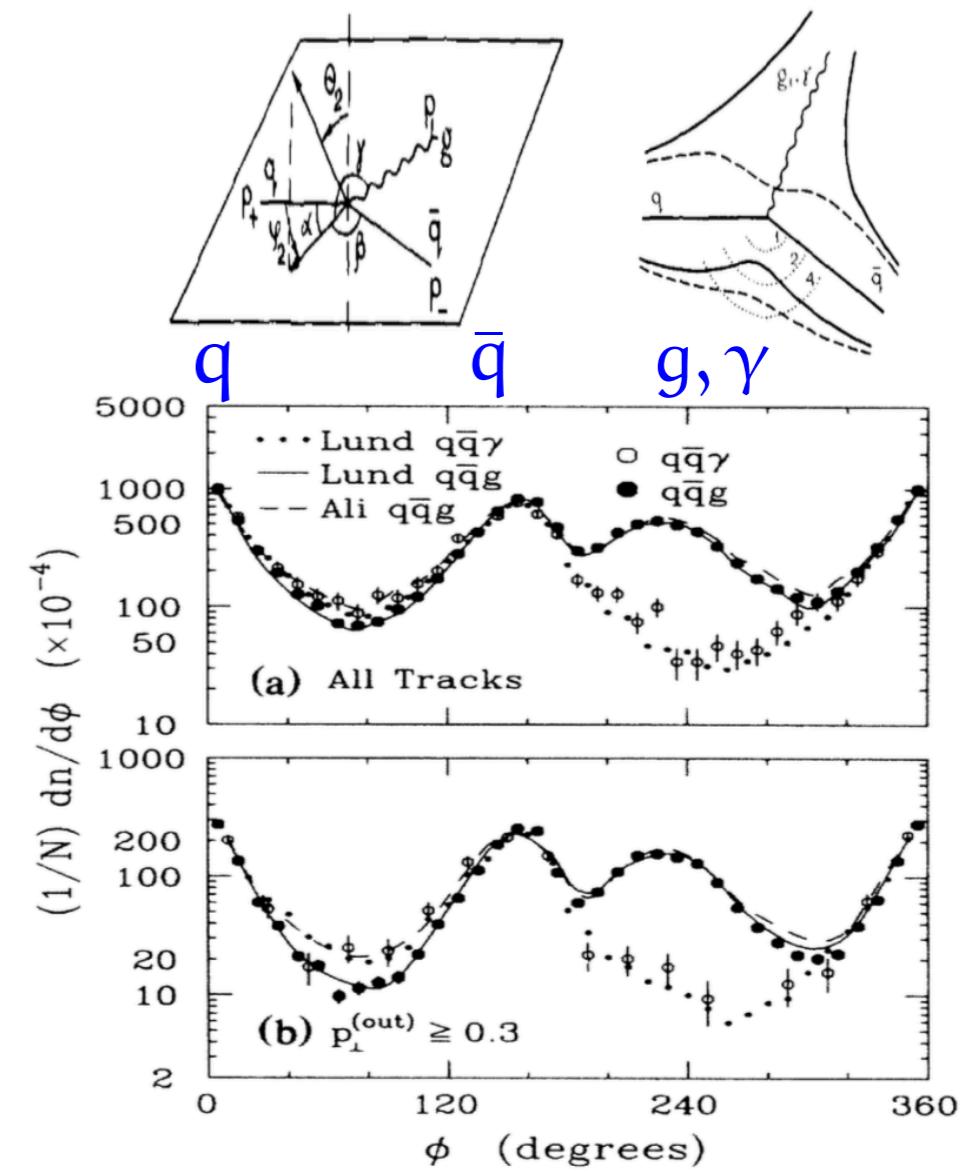
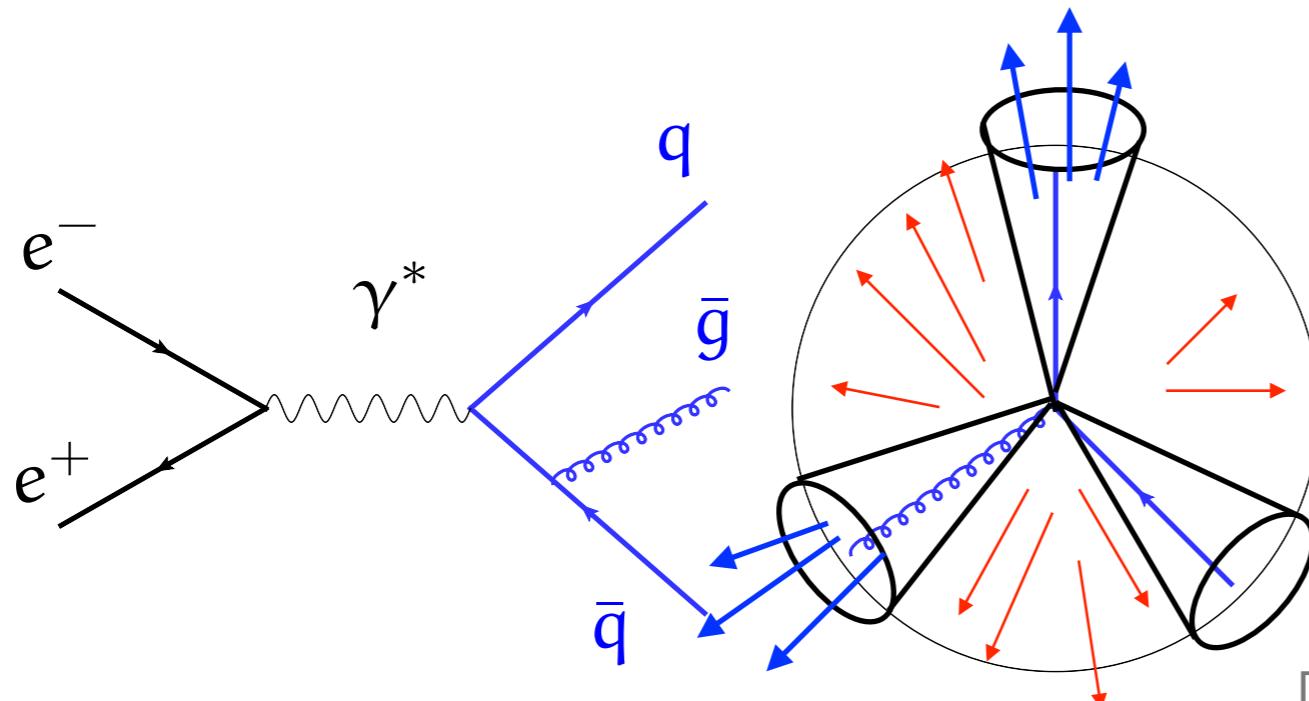


[Azimov, Dokshitzer, Khoze, Troyan (1985)]

- Two types of observables:

2. Infrared sensitive observables: interjet hadronic activity

**“Stringy” fragmentation
from pQCD**



[Azimov, Dokshitzer, Khoze, Troyan (1985)]

- Bjorken (1982) predicted the phenomenon of jet quenching in high energy hadronic collisions as a consequence of elastic energy loss in the quark-gluon plasma

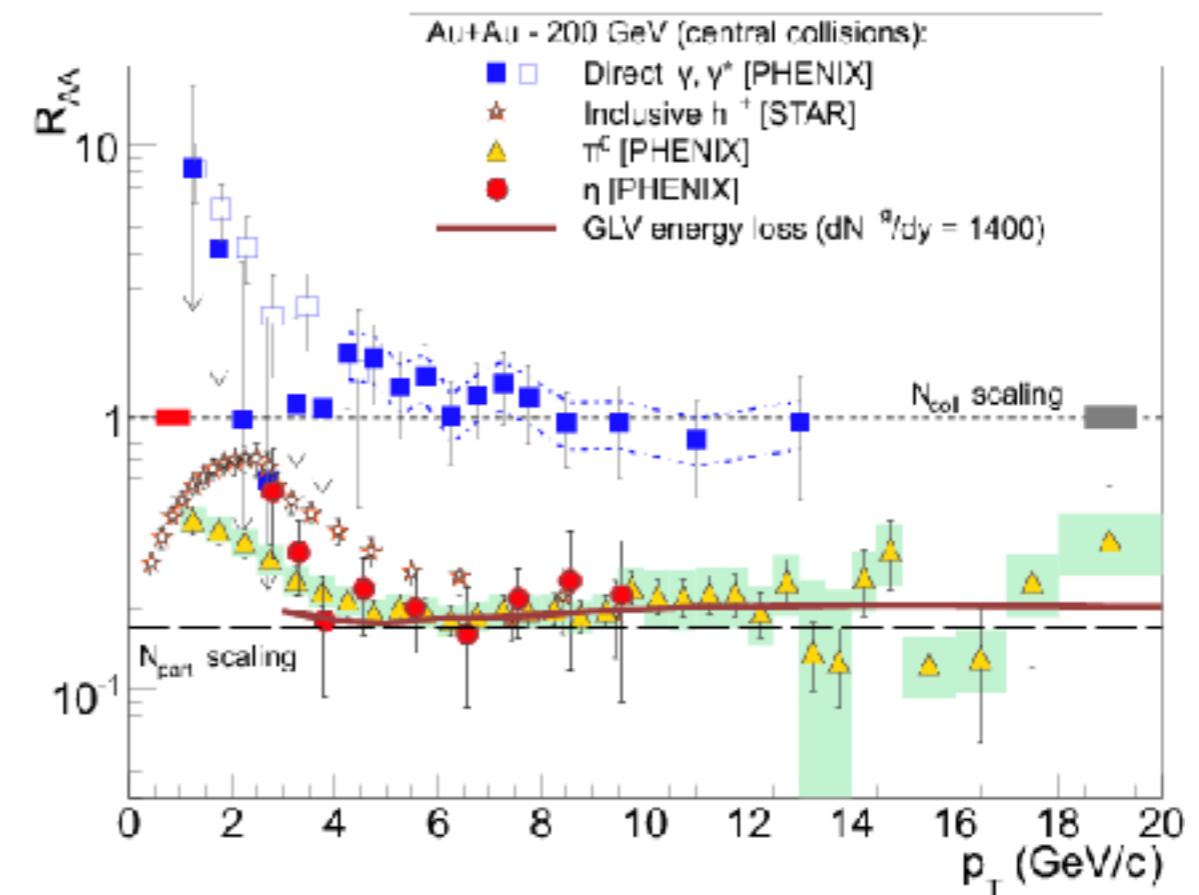
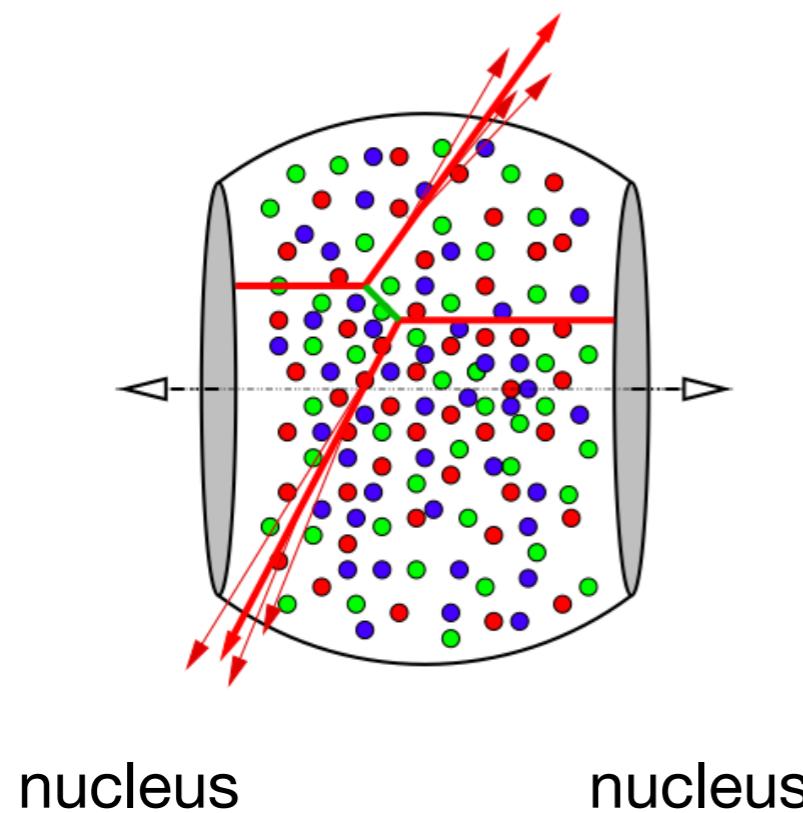
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

- Two decades later this phenomenon was observed at RHIC in the suppression of high-pT hadrons



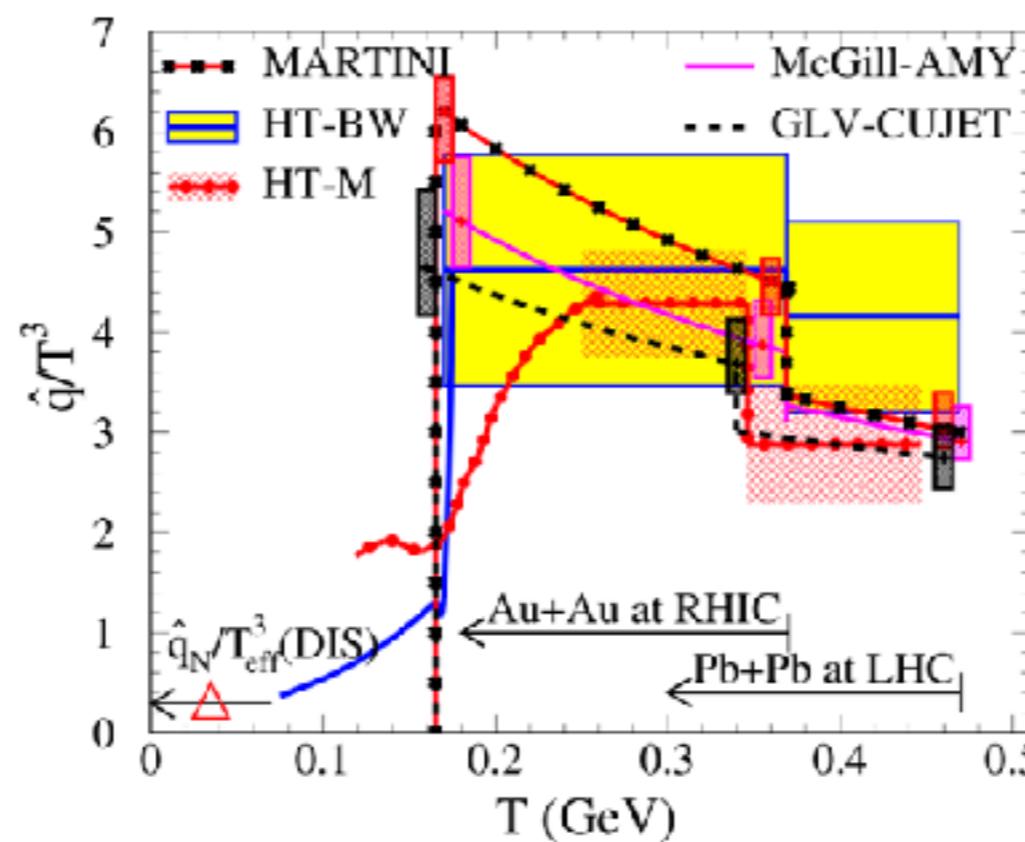
- However, radiative processes dominate over collisional energy loss

$$E_{\text{elastic}} \propto L$$

$$E_{\text{inelastic}} \propto L^2$$

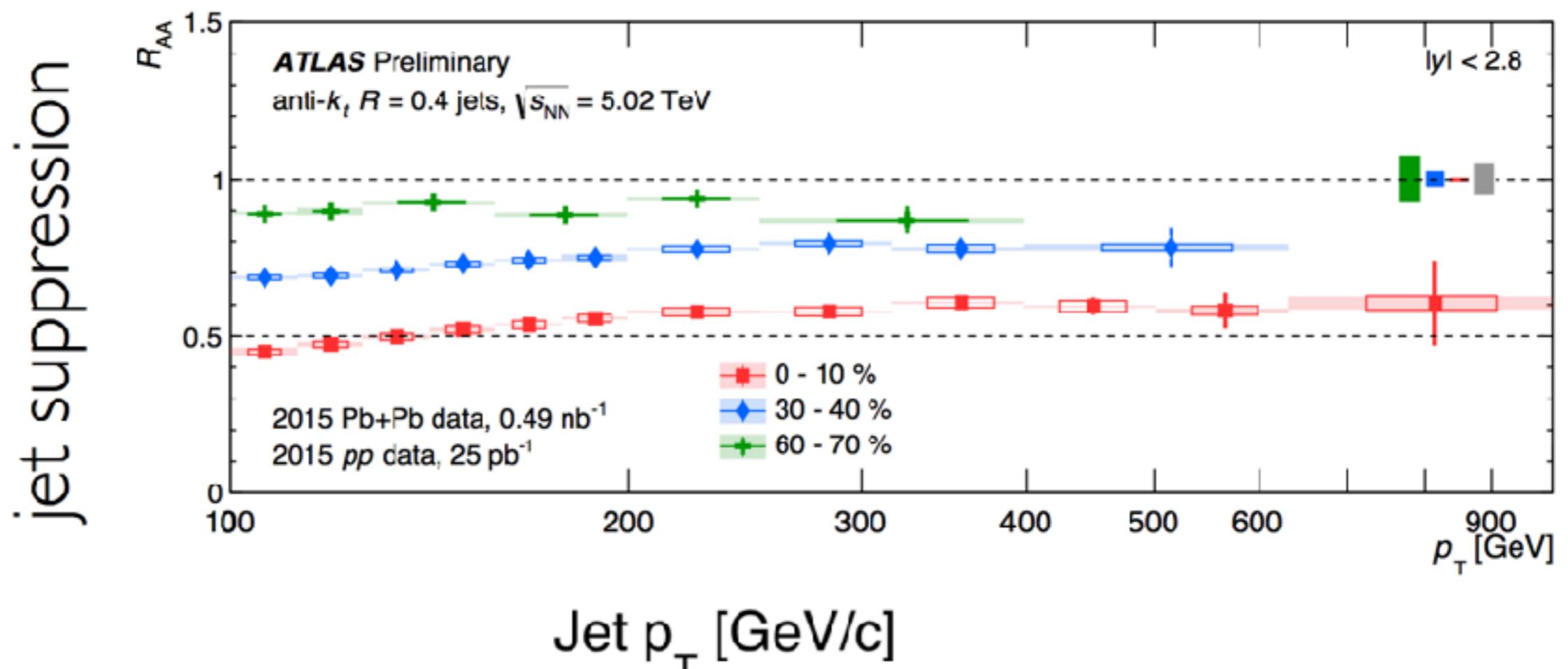
- Successful description of data within different approaches: BDMPS-Z (Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Wiedemann, Salgado), Higher-Twist (Guo, Wang), GLV (Gyulassy, Levai, Vitev), AMY (Arnold, Moore, Yaffe)
- Extraction of the jet quenching parameter (JET Collaboration):

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 & \text{GeV}^2/\text{fm} \text{ at } T=370 \text{ MeV} \\ 1.9 \pm 0.7 & \text{GeV}^2/\text{fm} \text{ at } T=470 \text{ MeV} \end{cases}$$



arXiv:1312.5003

- Currently, fully reconstructed jets are being extensively studied at LHC and RHIC
- Strong jet suppression observed up to ~ 1 TeV



- Power corrections (higher twists) are no longer negligible and therefore, need to be resummed

- What causes such strong suppression?
- How does a jet as a multi-partonic system lose energy to the QGP?

Parton radiative energy loss

- Jets couple to the plasma via (local) transport coefficients

$$\hat{q} \equiv \frac{m_D^2}{\lambda} \sim \frac{(\text{Debye mass})^2}{\text{mean free path}}$$

pt-broadening

$$\langle k_\perp^2 \rangle \sim \hat{q} L$$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000)]

$$\hat{e} \equiv \frac{\hat{q}}{T}$$

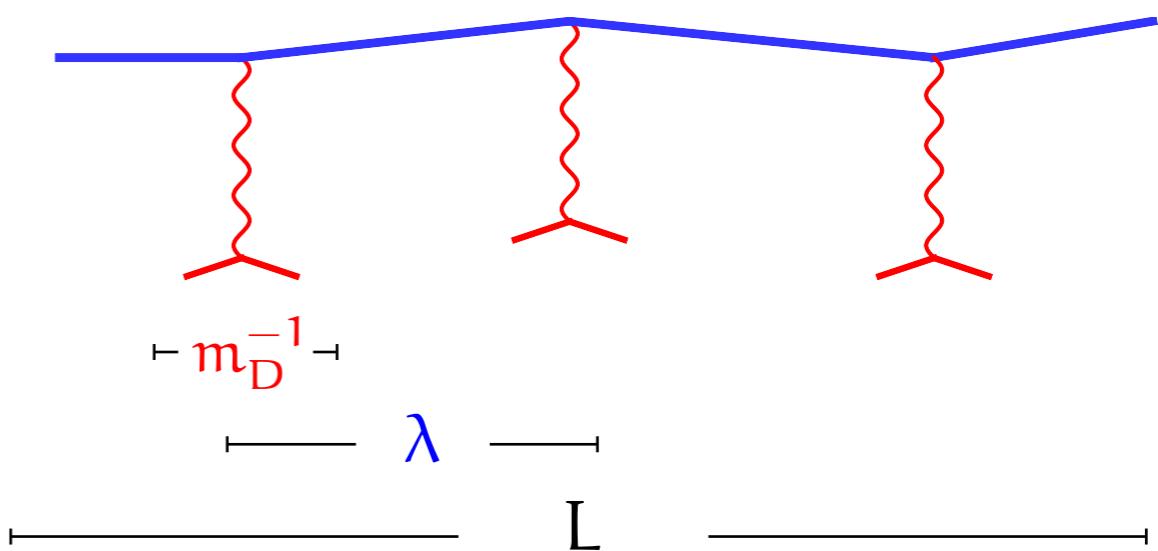
collisional energy loss (drag)

$$\langle \Delta E \rangle_{\text{coll}} \sim \hat{e} L$$

[Majumder (2008)]

correlation length \ll mean-free-path $\ll L$

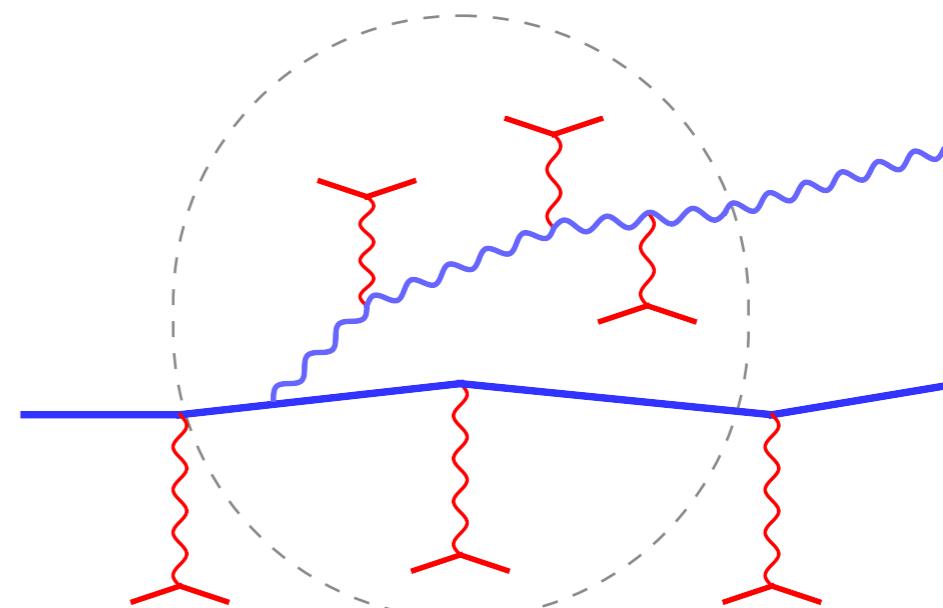
- Weak coupling:
independent multiple scattering approximation



Parton radiative energy loss

- Radiation triggered by coherent multiple scatterings
- Landau-Pomeranchuk-Migdal suppression (coherent radiation)

$$\omega \frac{dN}{d\omega} = \alpha_s \frac{L}{t_f} \equiv \alpha_s N_{\text{eff}}$$



$$t_f = \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \quad \text{formation time}$$

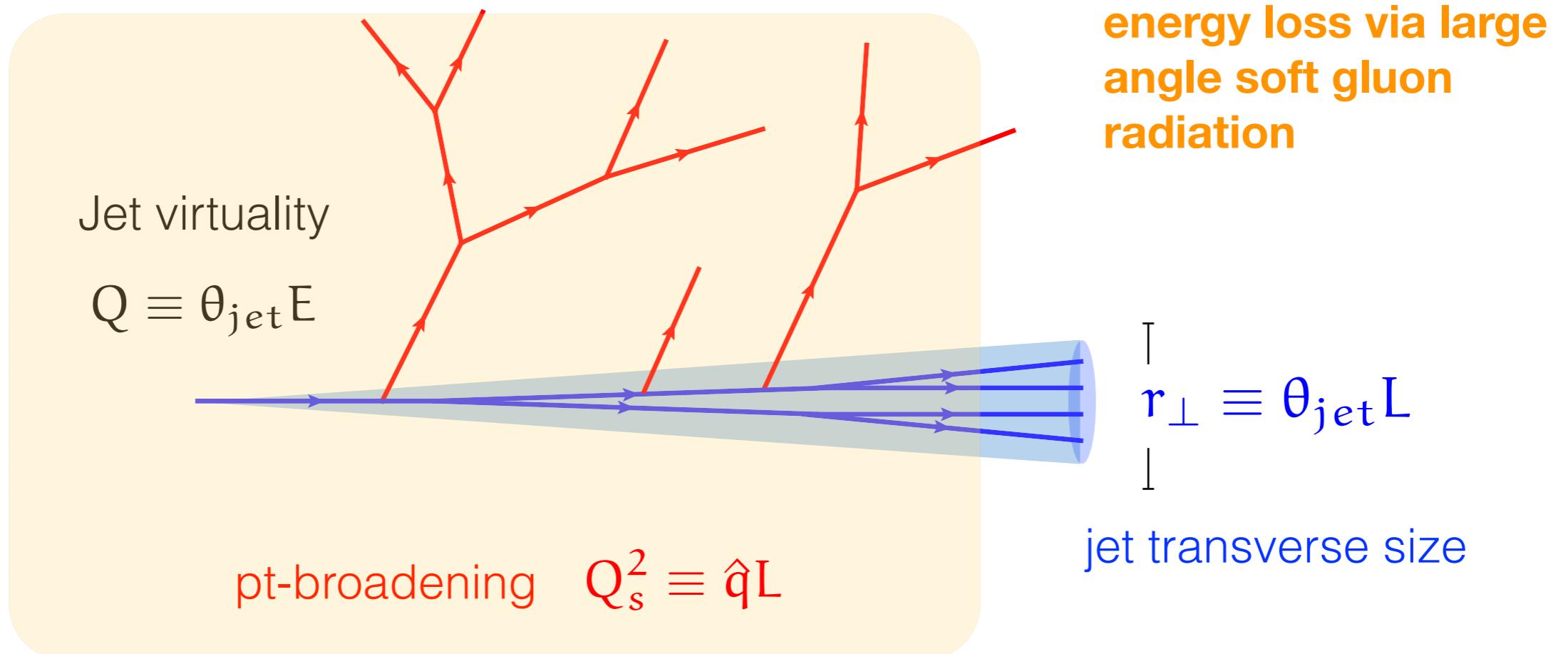
- Maximum suppression when $t_f \gtrsim L \Rightarrow \omega > \omega_c = \hat{q}L^2$
- Minimum radiation angle $\theta > \theta_c \equiv 1/\sqrt{\hat{q}L^3}$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)]

[Wiedemann (2001) Arnold, Moore, Yaffe (2002)]

Jet energy loss (color decoherence)

- When the transverse size r_\perp of the jet is smaller than medium resolution scale Q_s^{-1} **the medium interacts “effectively” with the total charge of the jet** (primary parton)

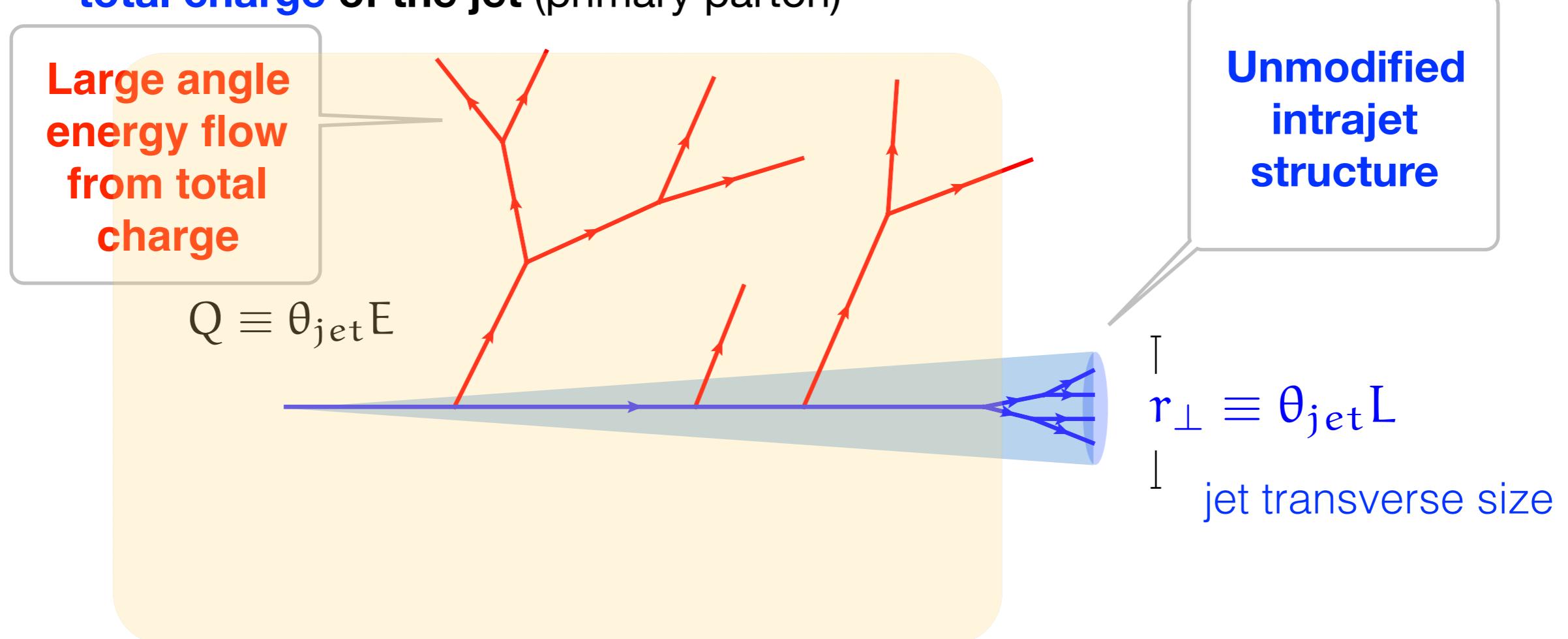


$$r_\perp \ll Q_s^{-1} \implies \theta_{jet} \ll \theta_c \equiv (\hat{q}L^3)^{-1/2}$$

MT, Salgado, Tywoniuk PRL (2011), PLB (2012), JHEP (2011-2012)
Casalderrey-Solana, Iancu JHEP (2012)
Casalderrey-Solana, MT, Salgado, Tywoniuk PLB (2013)

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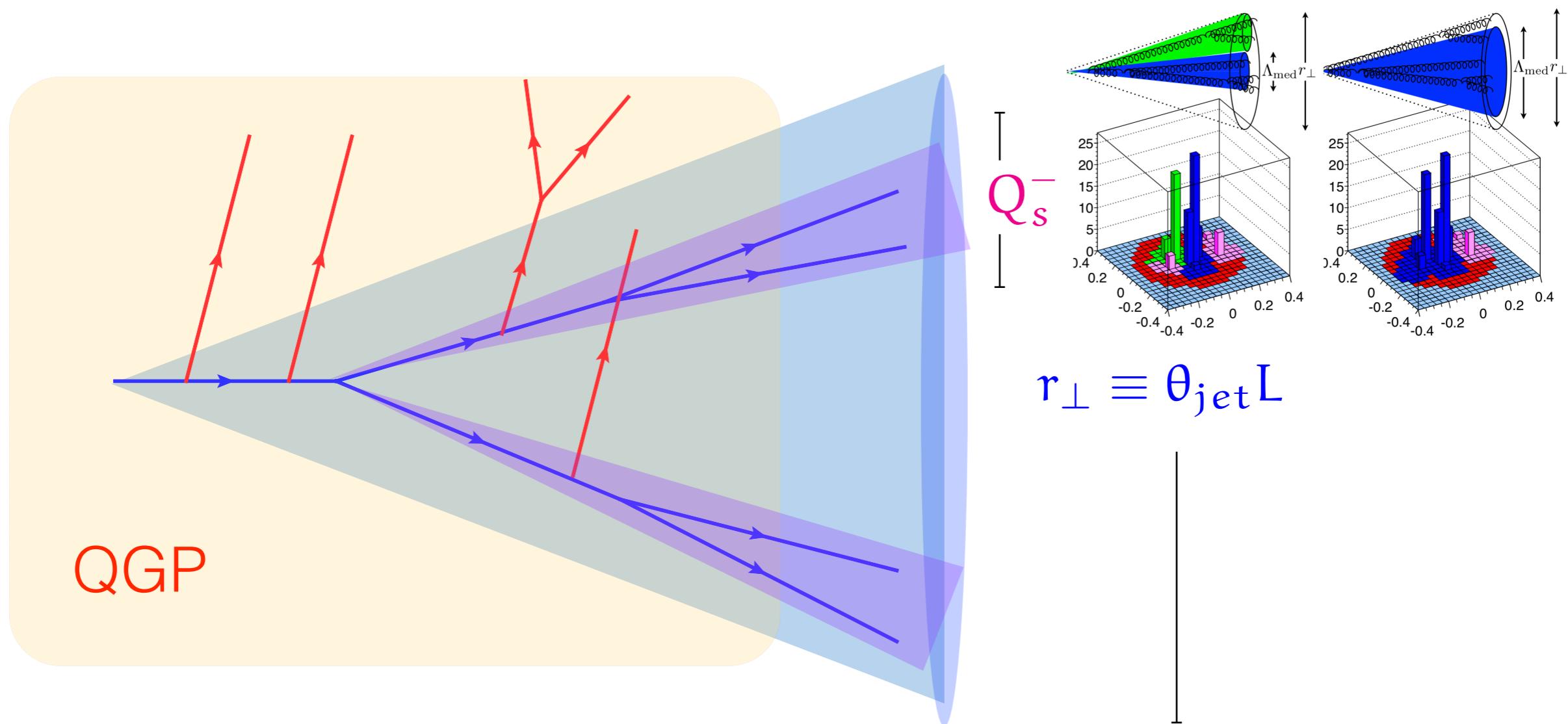


MC prescription (for unresolved jets): medium t -evolution then collinear Q -evolution

[Casalderrey-Solana, MT, Salgado, Tywoniuk (2013)]

Jet energy loss (color decoherence)

- When the transverse size r_{\perp} of the jet is larger than medium resolution scale Q_s^{-1} the medium interacts with **multiple (resolved) color charges** in the jet (in the sketch below, two)



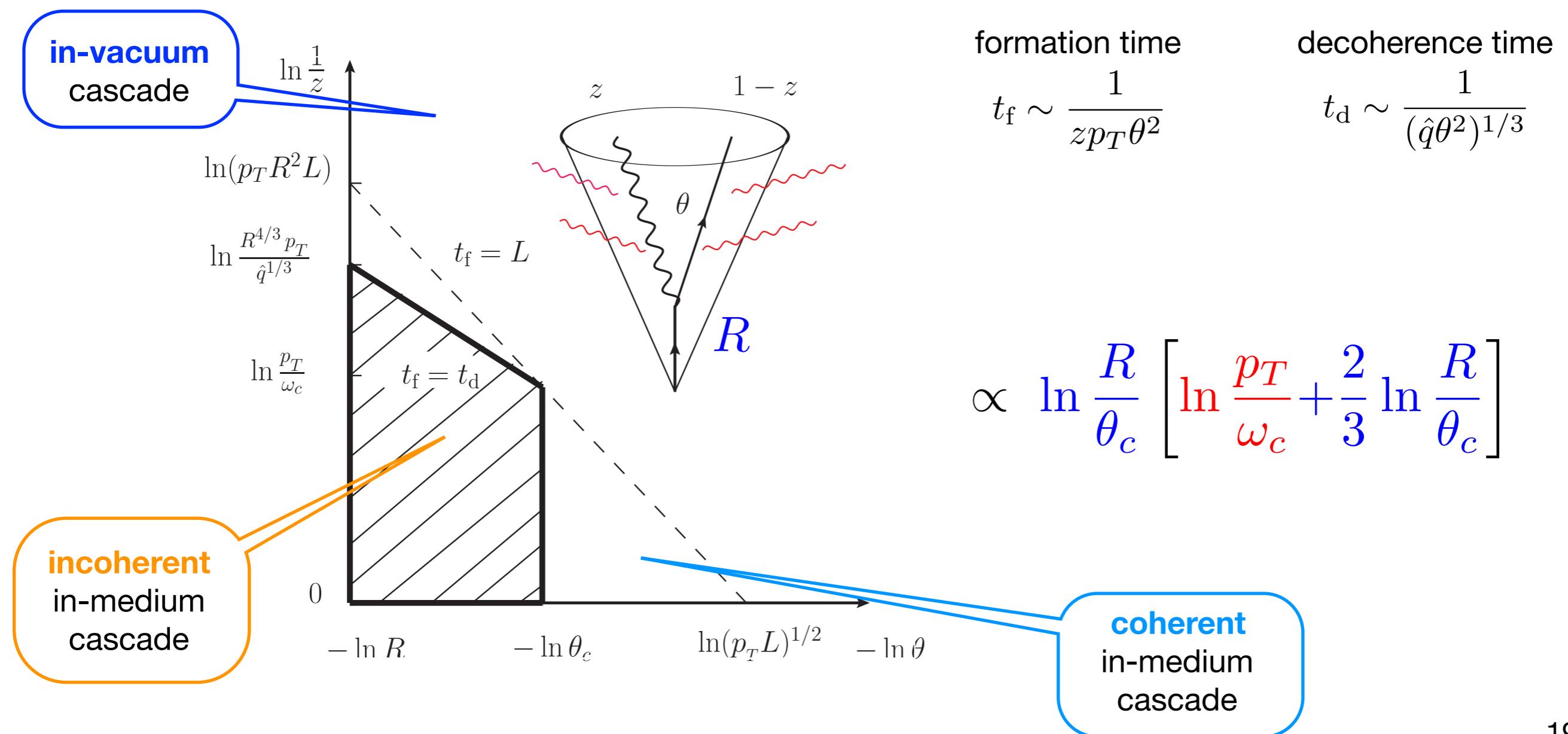
- Energy loss increases with the number of resolved sub-jets

[Casalderrey-Solana, MT, Salgado, Tywoniuk (2013)]

NLO corrections the jet spectrum

K. Tywoniuk, YMT arXiv:1707.07361 [hep-ph]

- To leading logarithmic (LL) accuracy there are exact cancellations between real and virtual corrections as in vacuum except when: $t_f \ll t_d \ll L$



Exponentiation of the Double-Logs

- **Strong quenching limit:** $Q_{\text{tot}}(p_T) \ll 1$ single parton quenching factor

$$Q(p_T) = Q_{\text{tot}}(p_T) \times C(p_T)$$

- The leading logarithms exponentiate into a **Sudakov Form Factor**

$$C(p_T) = \exp \left[-2\bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right) \right]$$

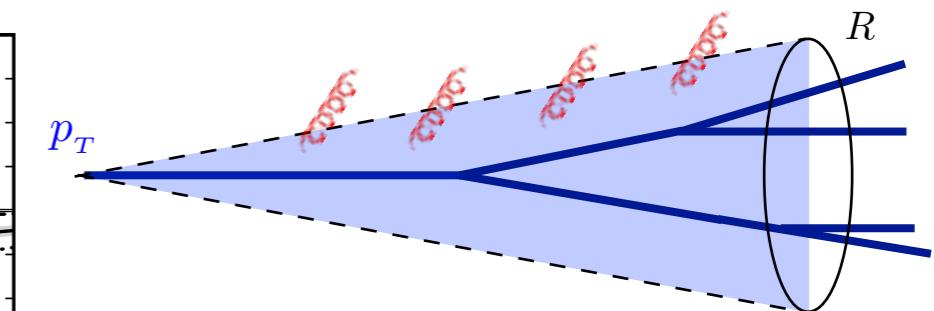
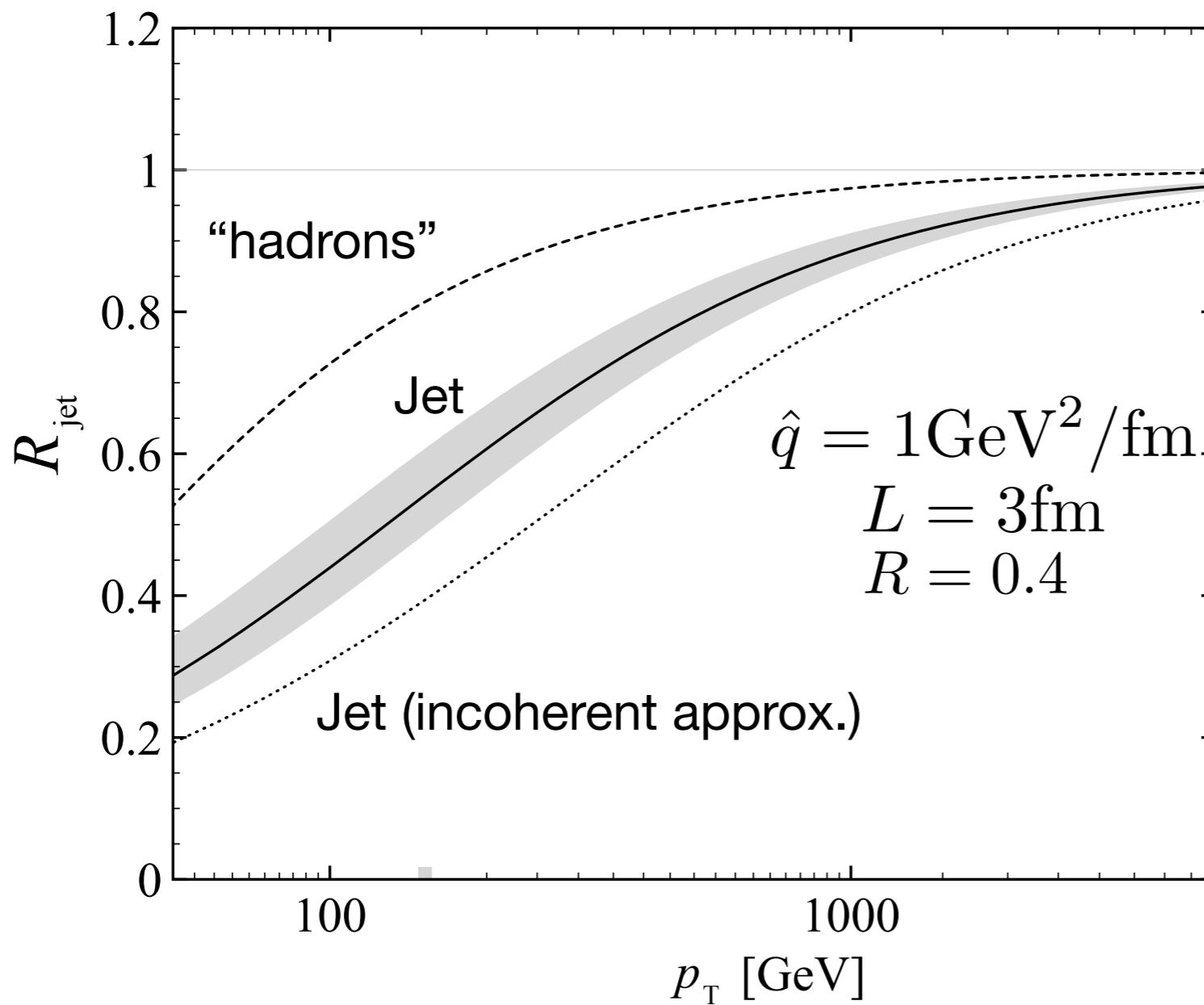
⇒ Fluctuations of the jet substructure yield additional suppression of the jet spectrum

- **Coherent limit:** note that when $R \ll \theta_c$ the medium “sees” only the total charge, in this case
-

$$C(p_T) \rightarrow 1 \quad \text{and} \quad Q(p_T) \rightarrow Q_{\text{tot}}(p_T)$$

Nuclear modification factor

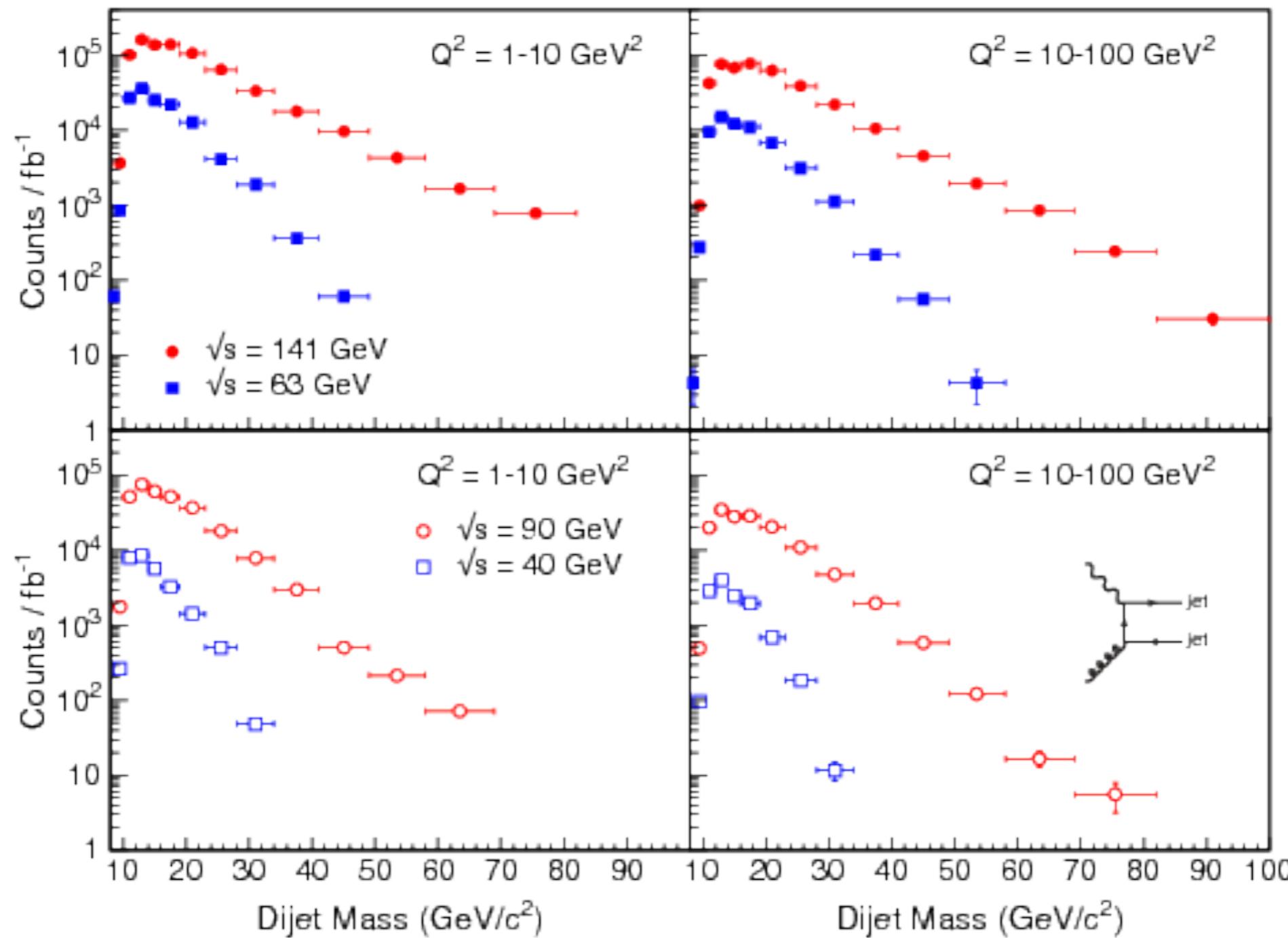
$$R_{\text{jet}} = Q_{\text{tot}}(p_T) \times C(p_T)$$



**Large contribution
from fluctuating jet
substructure**

Qualitatively encoded
in MC event
generators: Hybrid
Model, JEWEL and
MARTINI

Jets at EIC (some thoughts)

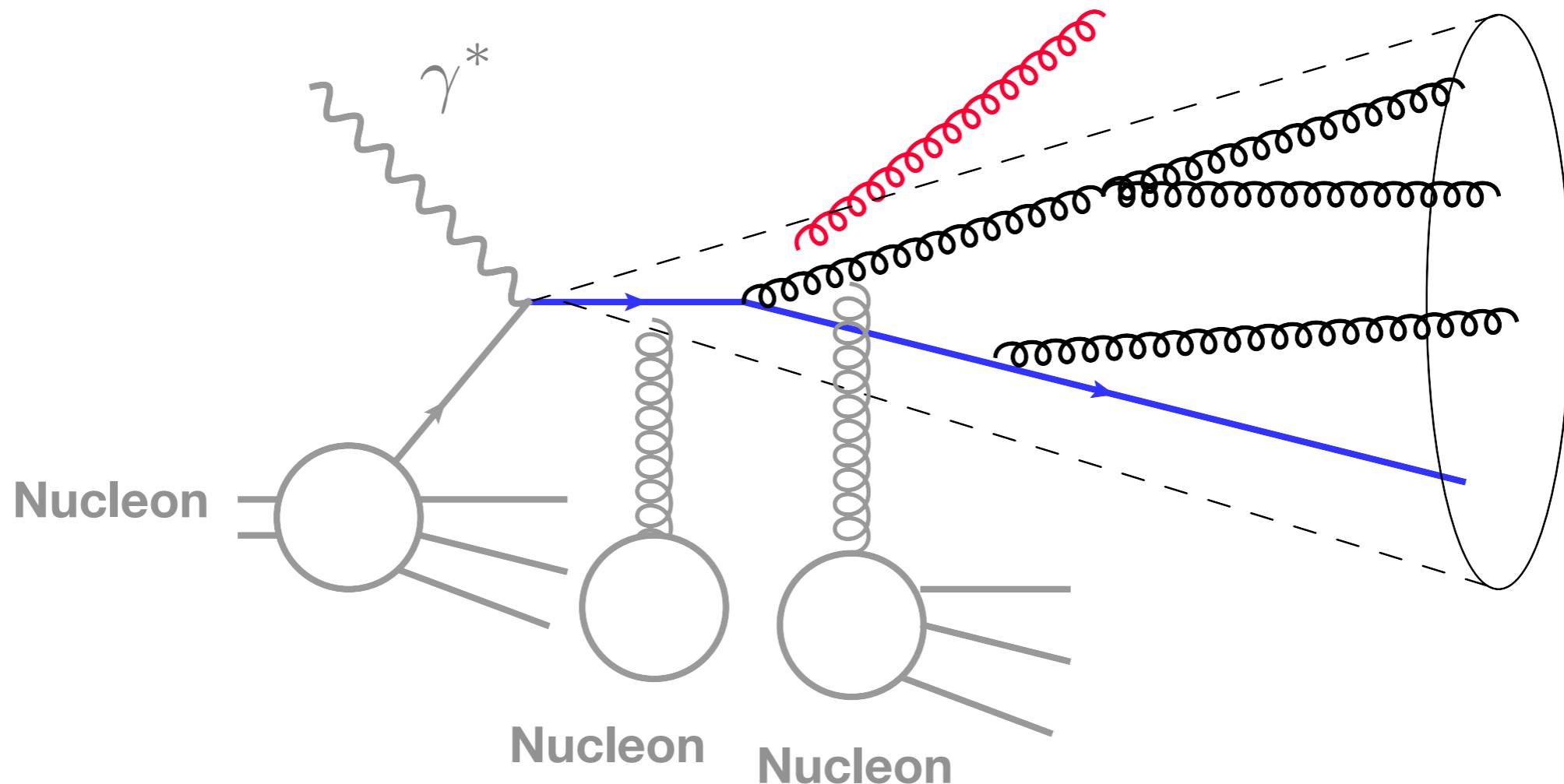


Aschenauer, E.C. et al. arXiv:1708.01527

Jets at EIC (some thoughts)

- Jet quenching heavy ion collisions: intricate interplay between vacuum and medium-induced parton cascades enhanced by large multiplicities at LHC. Not fully understood, large discrepancies between Monte-Carlo Event Generators...
- eA would provide a clean environment (lower multiplicities) with reduced final state interactions: study departures from ep to investigate nuclear matter and its transport properties using jets

Jets at EIC (some thoughts)



- Use jets to study nuclear structure(3D, spin), approach to **color decoherence**, **large angle soft gluon radiation**, **color flow**, hadronization, **power corrections...**
- Investigate jet momentum broadening and energy loss mechanisms (complementary to heavy ion collisions), **correlations**, **interjet radiation...**