Jet energy loss and heavy flavor

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Heavy Flavours from small to large systems
@ Institut Pascal, Paris Saclay U.
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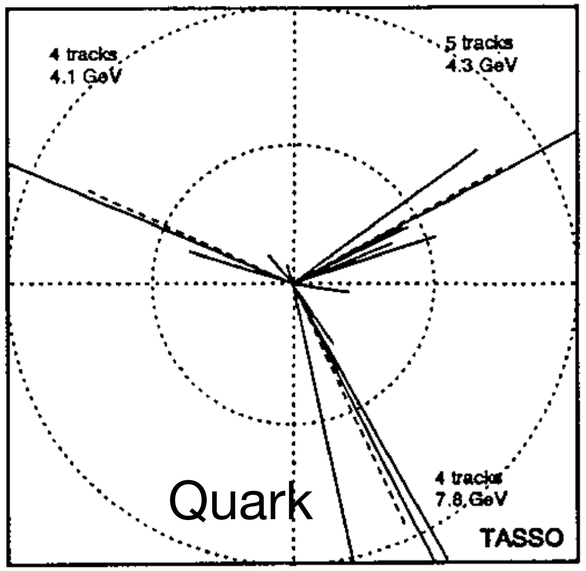
Outline

- QCD jets meet the QGP
- Radiative energy loss and coherence effects in jet quenching
- Nuclear modification factor as substructure observable
- Jet modification with heavy flavor

QCD jets

- Jets are collimated sprays of particles seen high energy collsions
- Jets predicted by QCD: evidence for the gluon from 3 jet events in e^+e^-
- Today: jets provide precision test for QCD and instrumental in the Higgs discovery and BSM searches for which they constitute a large background

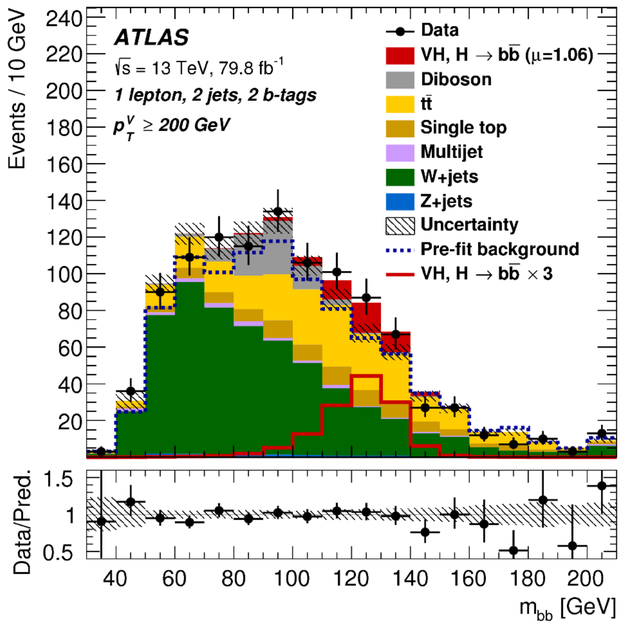
Quark



gluon

Quark

TASSO - PETRA (DESY) (1979)



1808.08238

QCD jets meet the QGP

- 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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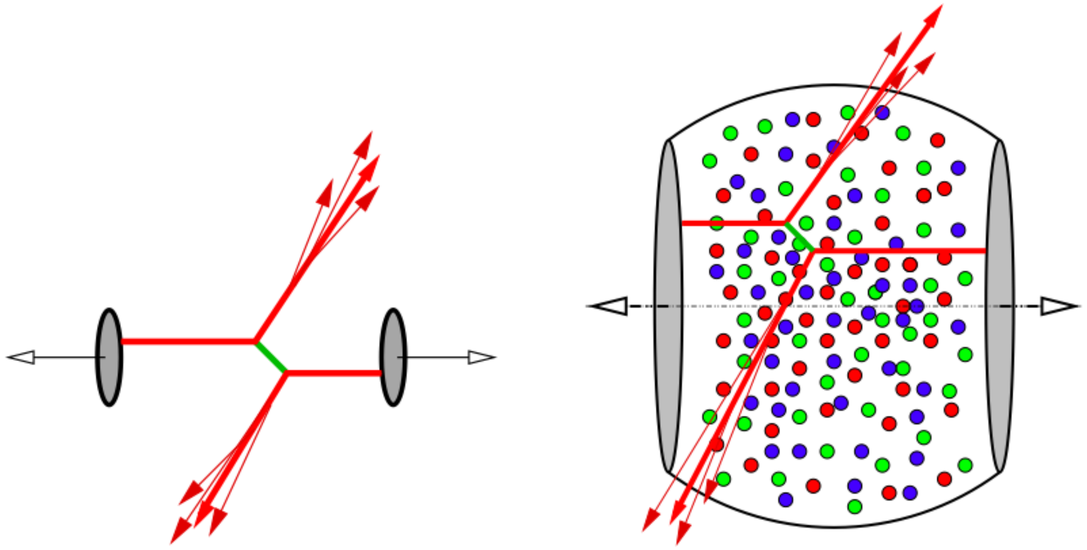
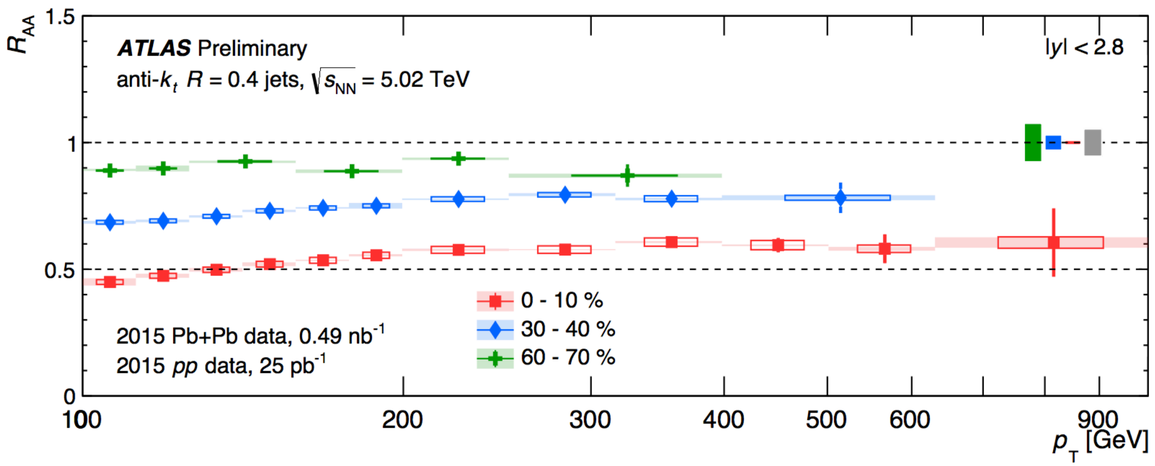
Abstract

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

QCD jets meet the QGP

- Jets in heavy ion collisions: probes of the transport properties of the QGP and out of equilibrium QCD dynamics



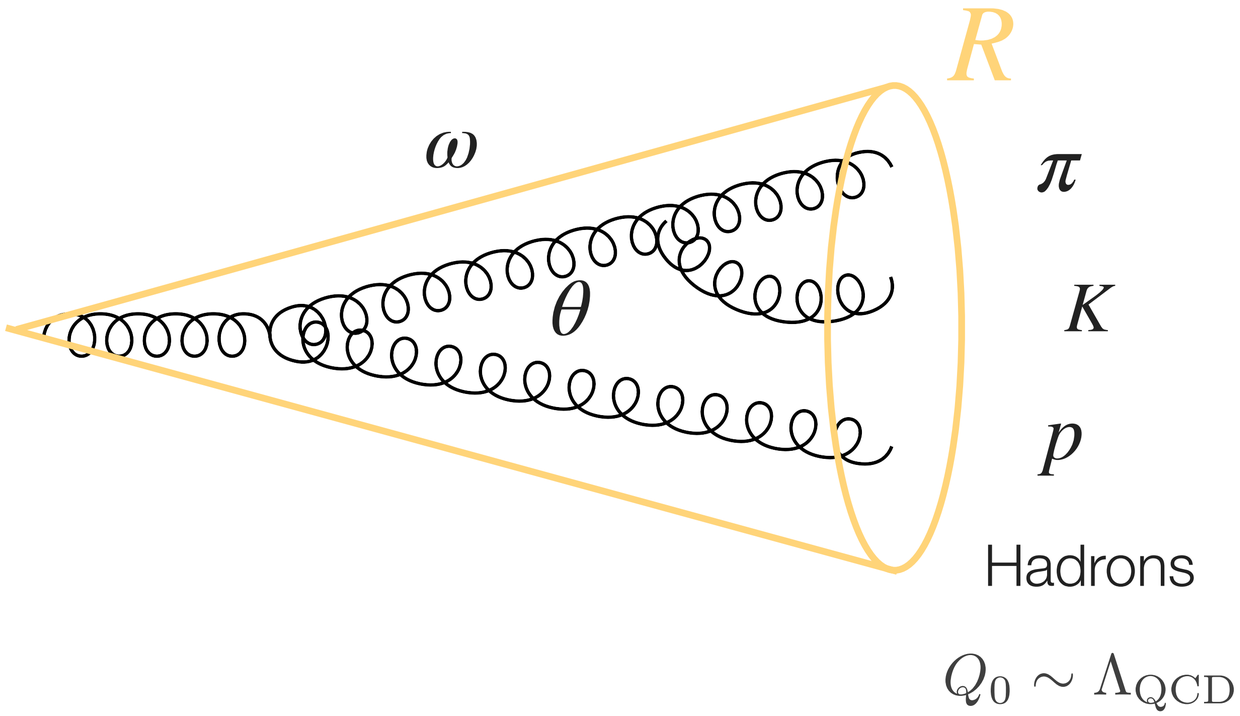


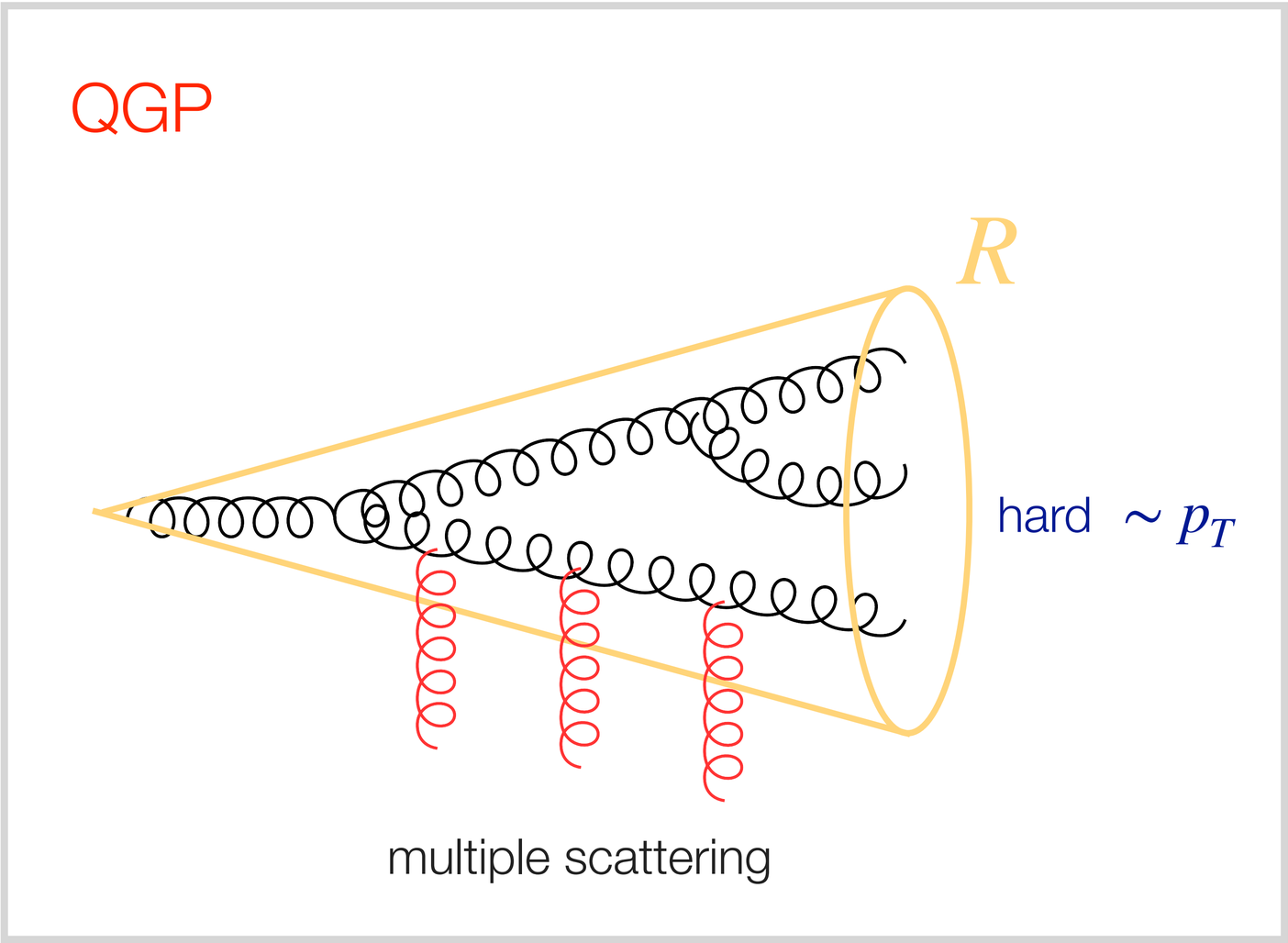
$$R_{AA} \equiv \frac{\text{Yield in AA}}{N_{\text{bin}}\text{Yield in AA}}$$

- Substantial final state interactions: jets lose energy to the QGP
- Strong suppression of hadrons and jets observed at RHIC and LHC

- QCD collinear soft enhancement

$$\mathrm{d}P \equiv \bar{\alpha}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}\omega}{\omega}$$





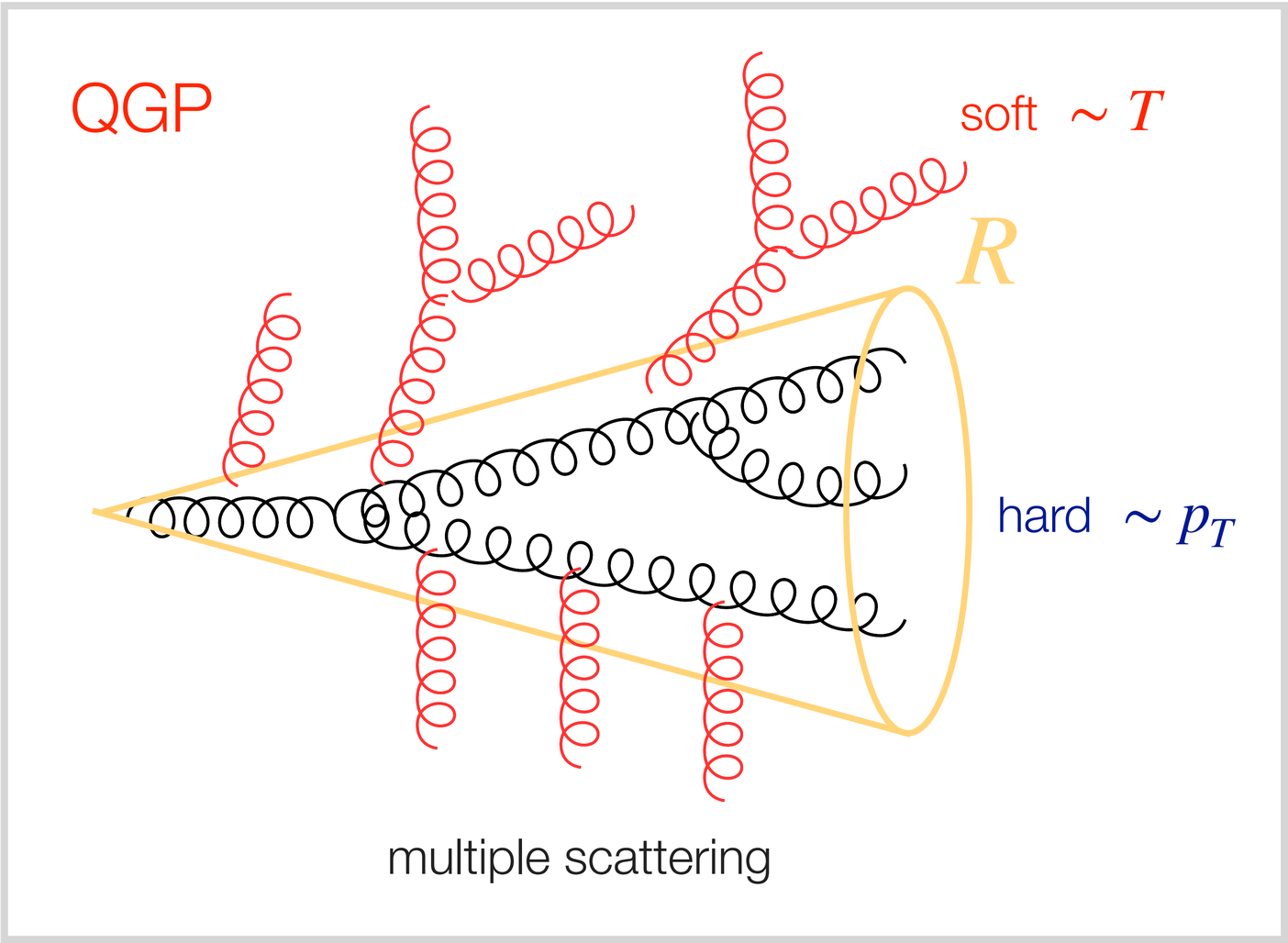
- QCD collinear soft enhancement

$$\mathrm{d}P \equiv \bar{\alpha}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}\omega}{\omega}$$

- Transverse momentum diffusion

$$\frac{\mathrm{d}\langle k_\perp^2\rangle}{\mathrm{d}t} \equiv \hat{q}$$

[Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)
Widemann (2000) Arnold, Moore, Yaffe (2001-2002)]



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$$\mathrm{d}P \equiv \bar{\alpha}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}\omega}{\omega}$$

- Transverse momentum diffusion

$$\frac{\mathrm{d}\langle k_\perp^2\rangle}{\mathrm{d}t} \equiv \hat{q}$$

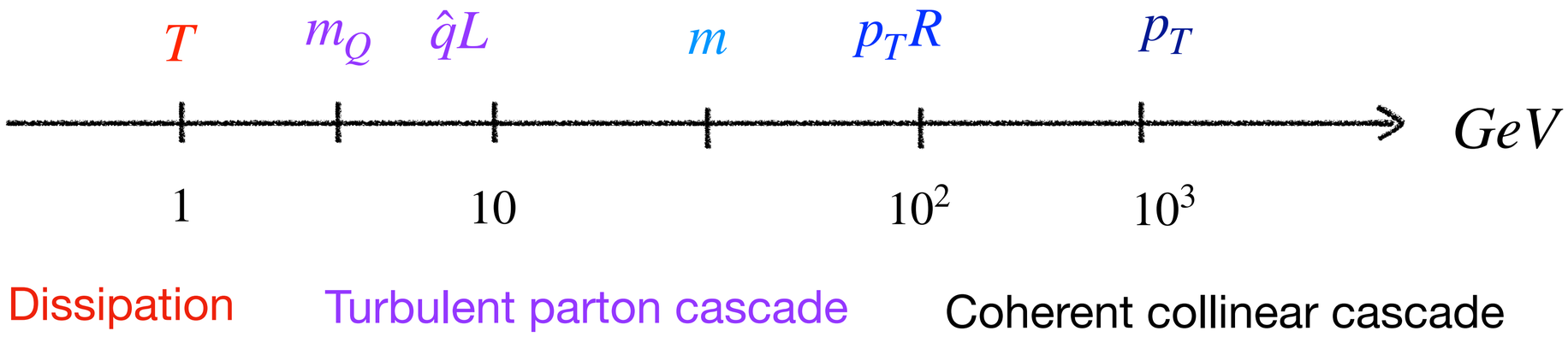
- Medium-induced radiation

$$\omega\frac{\mathrm{d}I}{\mathrm{d}\omega\mathrm{d}t} \equiv \bar{\alpha}\sqrt{\frac{\hat{q}}{\omega}}$$

[Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)
Widemann (2000) Arnold, Moore, Yaffe (2001-2002)]

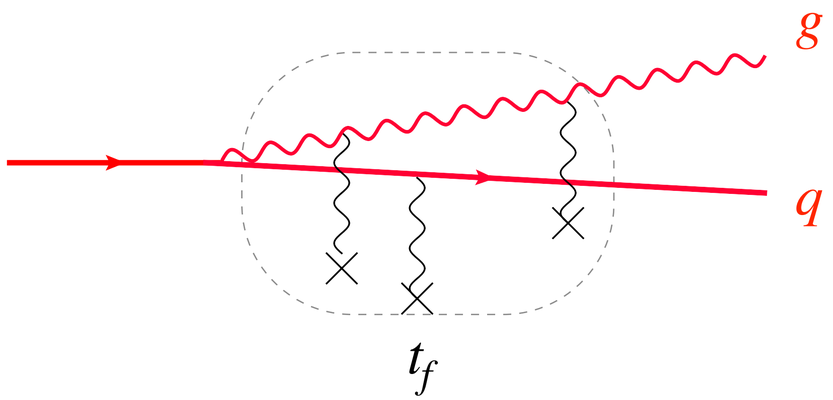
Multi-scale problem:

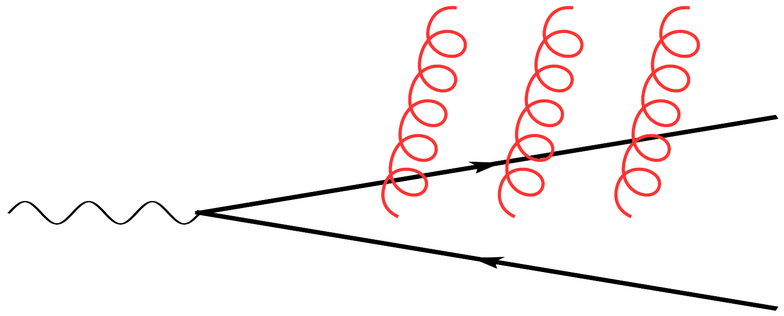
many scales and several processes at play



Coherence effects

- Jets are extended multiple parton system: nonlocal interactions, interferences
  - LPM effect: coherent scattering during gluon radiation time $t_f \sim \sqrt{\omega / \hat{q}}$
  - Color decoherence: coherent energy loss for $\theta < \theta_c$ - if color singlet

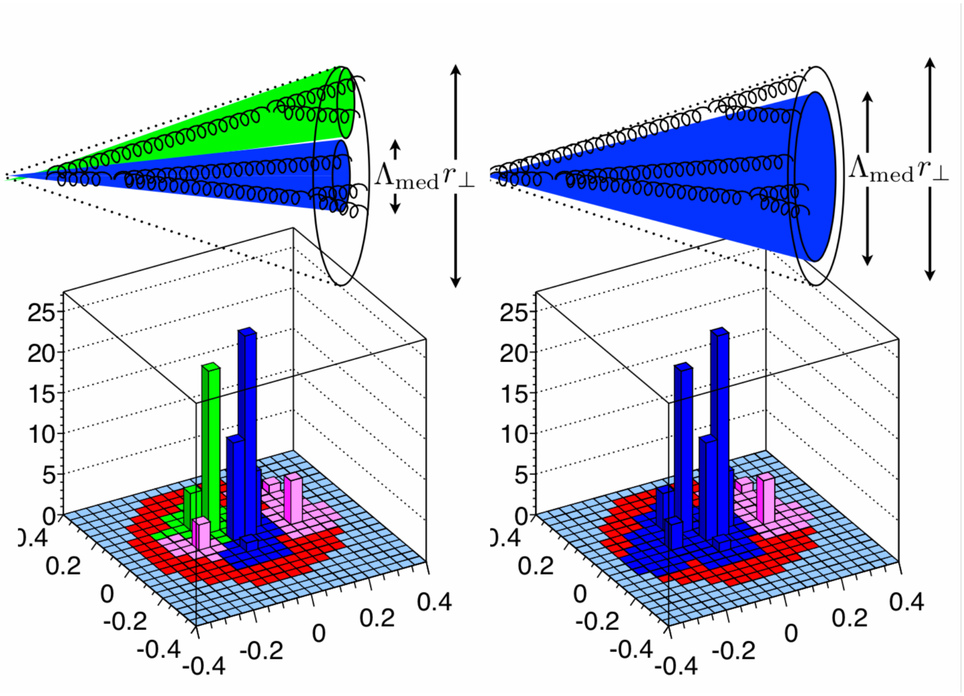




Multi-parton energy loss

- Color coherence: the number of effective color charges that lose energy to the plasma depends on its resolution scale.

- Unresolved (sub)jets lose energy coherently as a single Parton: energy loss is sensitive to jet substructure fluctuations



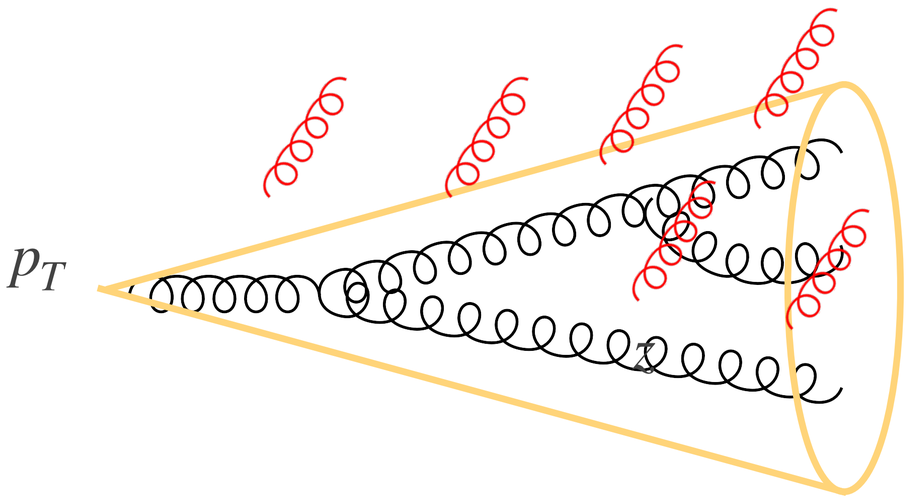
$$\Lambda_{\rm med} \sim k_\perp^{-1} = (\hat{q}L)^{-1/2} \ll r_\perp = RL$$

$$\theta \ll \theta_c \equiv \frac{1}{\sqrt{\hat{q}L^3}} < L$$

MT, Salgado, Tywoniuk (2010-11)
Iancu, Casalderrey-Solana (2011)

Non-linear evolution of quenching weights

- The quenching weights, the suppression of a high pT parton obeys a nonlinear evolution dynamics (at leading log)



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

MT, Tywoniuk (2017)

- N>1 partons lose more energy than a single parton
- Quenching weights:

$$R_{AA} \sim Q < 1$$

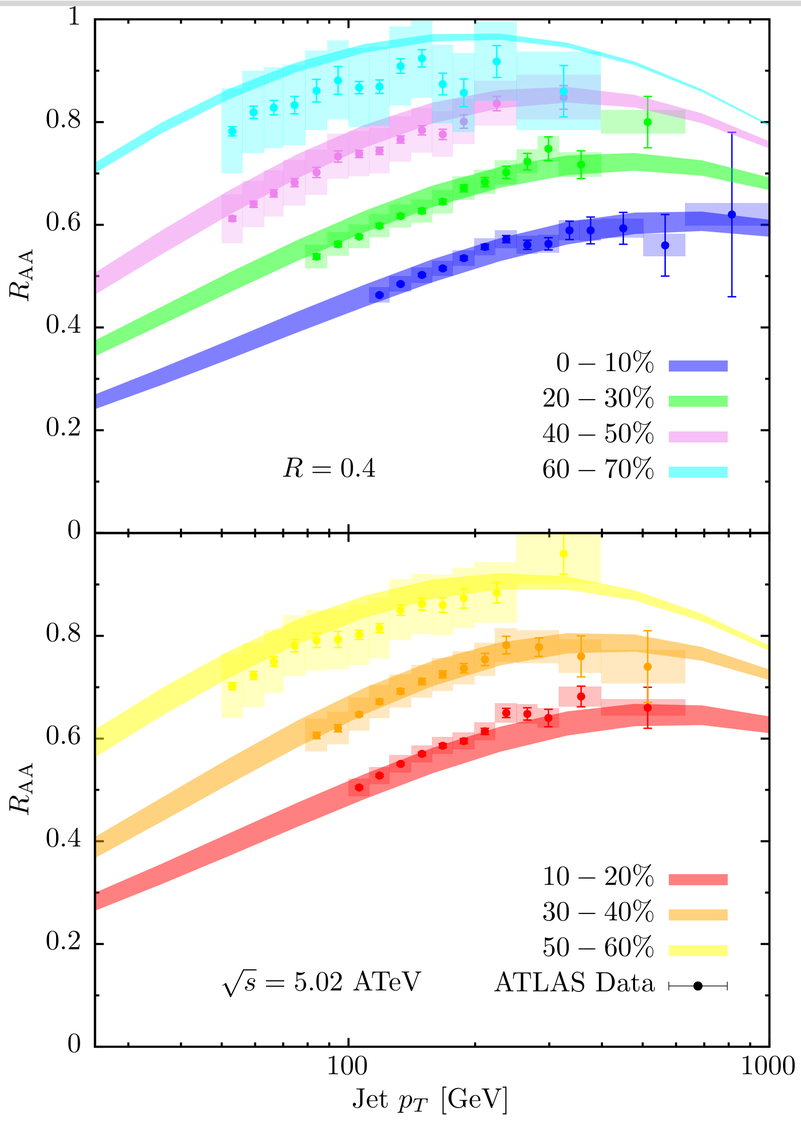
- Phase space for resolved color charges:

$$\theta > \theta_c$$

$$k_\perp > k_{\mathrm{LPM}} \equiv (\hat{q}\omega)^{1/4}$$

Nuclear modification factor: Theory vs. data

- Good description of R_{AA} as function of p_T, R and centrality
- Jet energy loss sensitive to resolution effects via the characteristic angle θ_c
- Small cone size R less sensitive to details of dissipation and medium response < 10%
- Largest uncertainty pertains to the accuracy of the perturbative sector - requires going beyond leading log approximation up to 20 %
- Achieving precision phenomenology: requires control of theoretical uncertainties



YMT, D. Pablos, K. Tywoniuk PRL (2021) 2101.01742 [hep-ph]

Where lost energy goes: jet thermalization

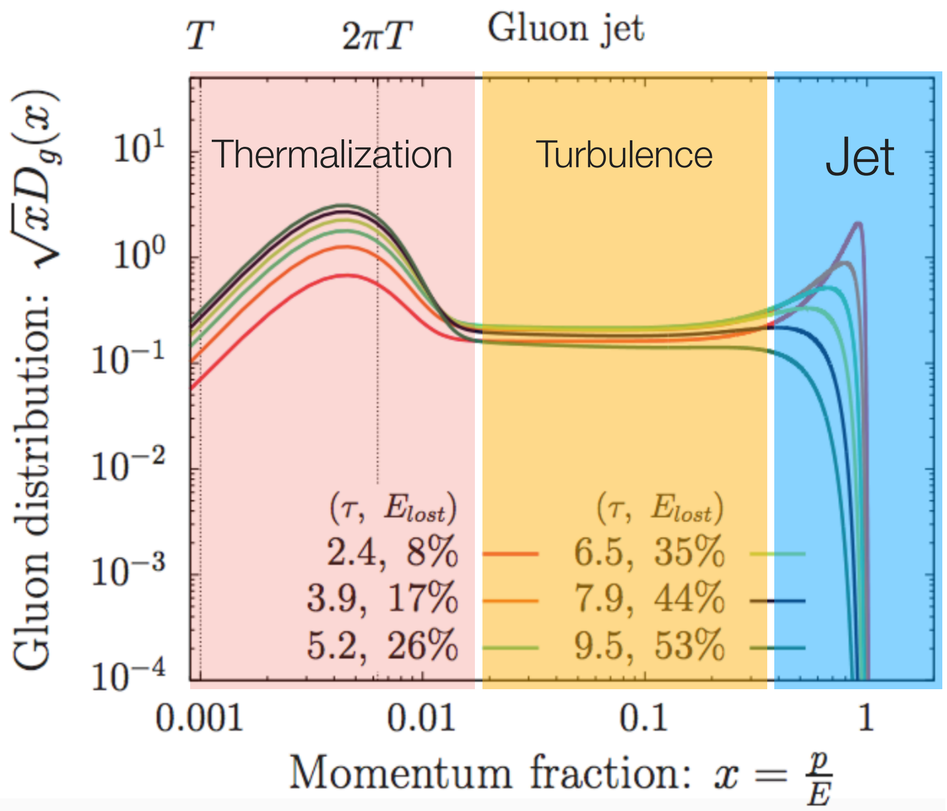
Jet evolution in the QGP is characterized by three regimes:

1. Jet scale: collinear and hard branchings (dominated by vacuum physics)

2. Inertial range: energy transport to large angles via inverse medium-induced turbulent cascade with universal properties (KZ exponent, quark/gluon ratio)

3. Temperature scale: dissipative processes, detailed balance, thermalization

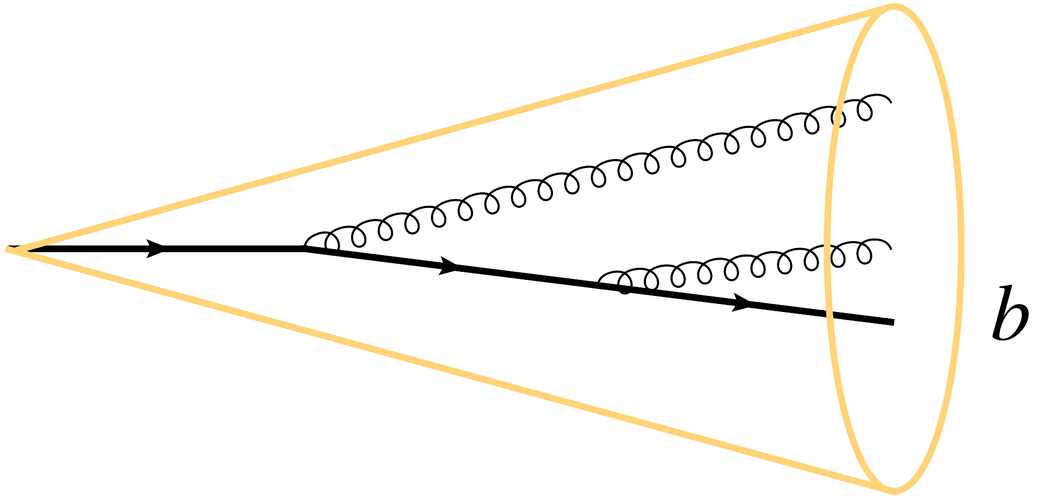
In-medium Fragmentation function



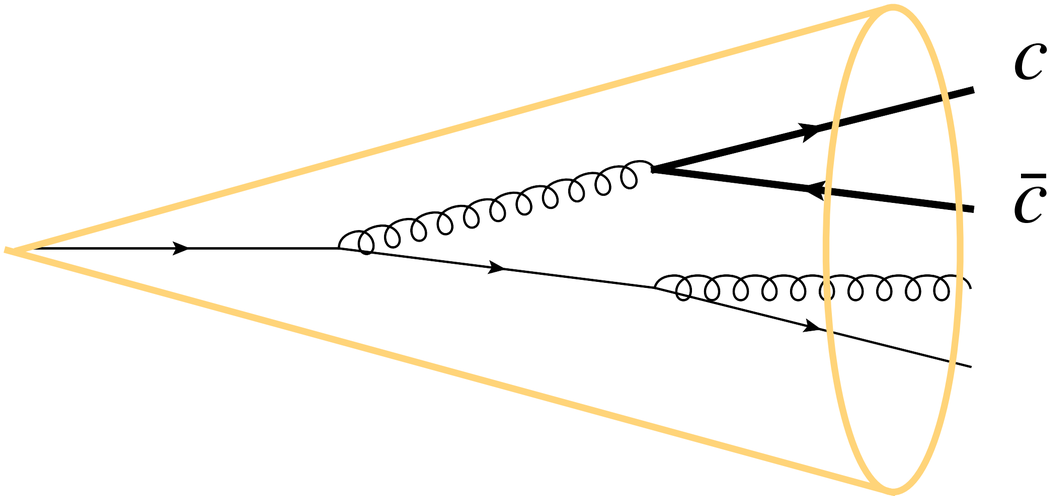
Schlichting, Soudi (2020) MT, Schlichting, Soudi (2022)

Heavy flavor jets: yet another hard probe

- Heavy quark initiated jet: mass dependence of energy loss - p_T spectra - jet mass, etc

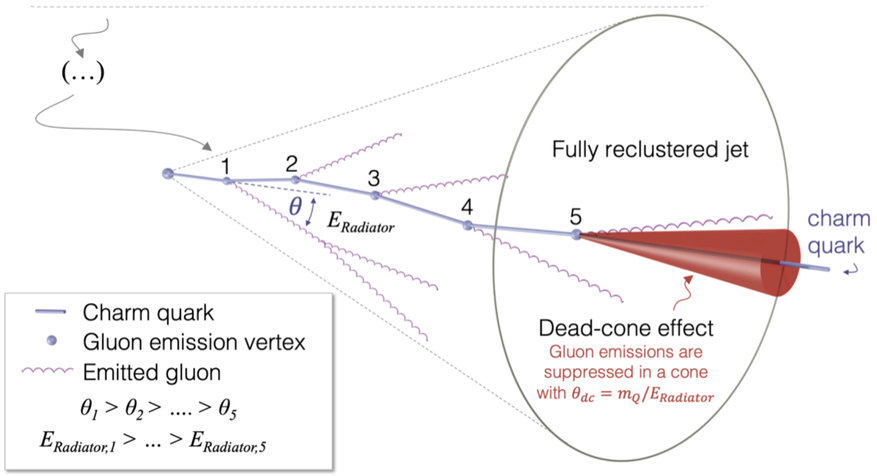


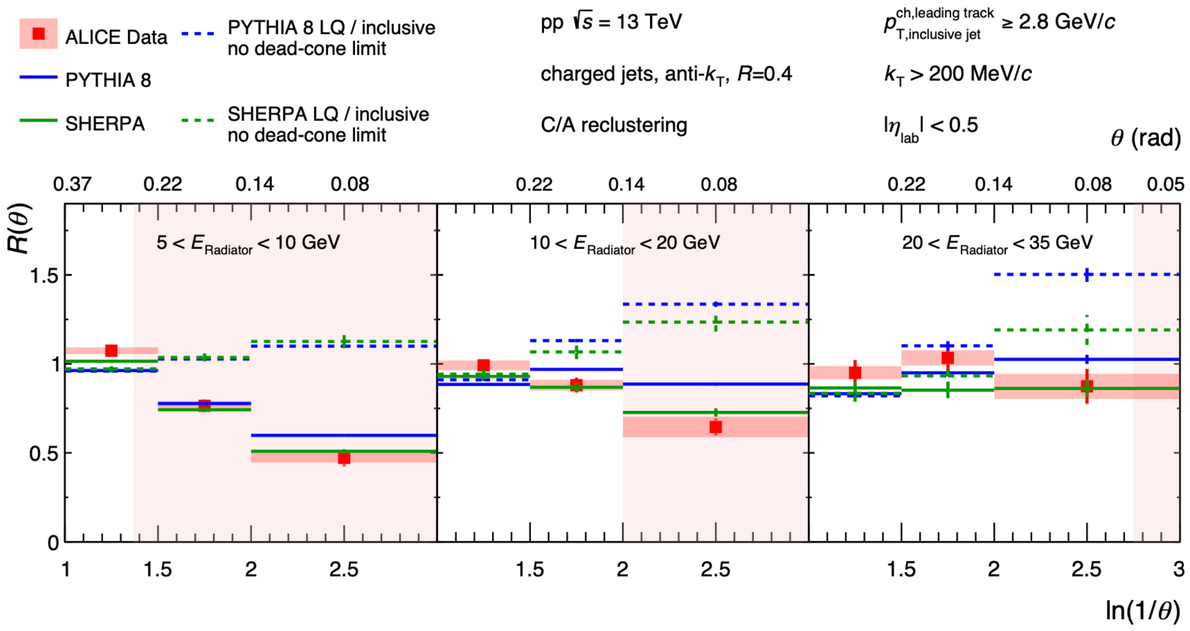
- Jet substructure: medium modification of jet chemistry, parton splitting



Heavy flavor jets: yet another hard probe

- Dead-cone effect in vacuum: heavy flavor initiated jets charactrized by mass dependent depletion of gluon radiation for angles $\theta < M_Q/E$





ALICE Collaboration 2022 Nature **605** 440

Heavy flavor jets: yet another hard probe

- Energy loss mechanisms of heavy flavor hadrons altered by mass effects
- Due to dead-cone effect expect hierarchy of eloss as function of the mass

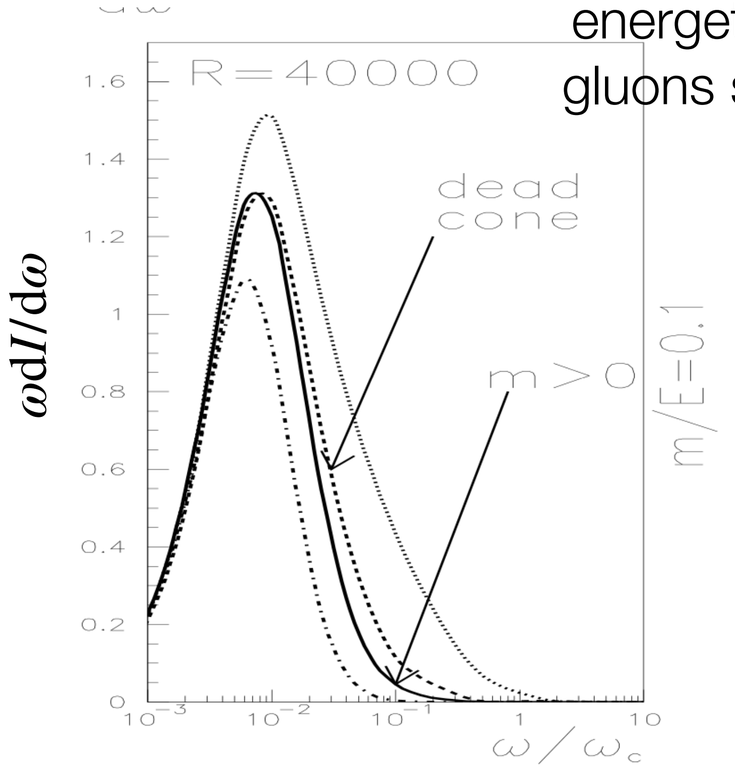
Dokshitzer and Kharzeev (2003)

$$\Delta E_b < \Delta E_c < \Delta E_{\text{light}} < \Delta E_{\text{gluon}}$$

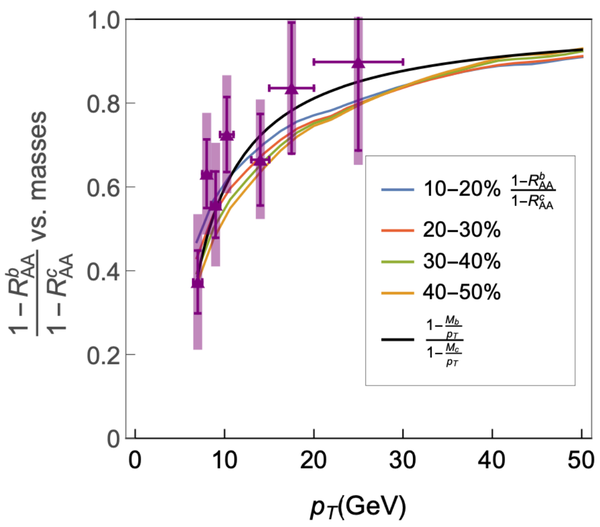
- No experimental evidence of mass ordering between open heavy flavor hadrons - nor HF tagged jets
- Interplay between suppression and fragmentation Dordjevic (2013) and initial spectrum, role of collisional energy loss
- Vanishing difference at high p_T

Medium-induced spectrum

energetic/collinear gluons suppressed

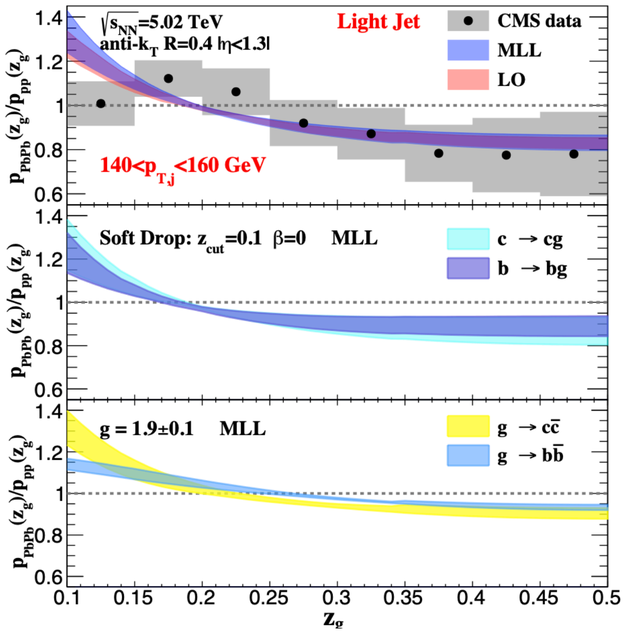


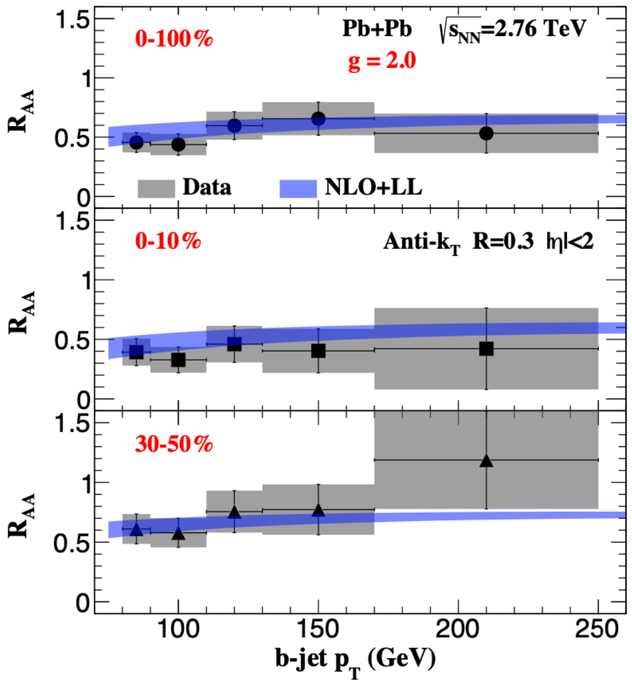
Armesto, Salgado, Wiedemann (2003)

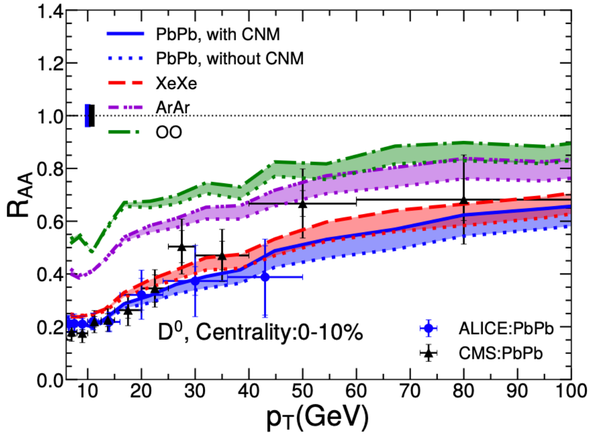


Ilic, Djordjevic (2022)

Li, Vitev (2018-2019)

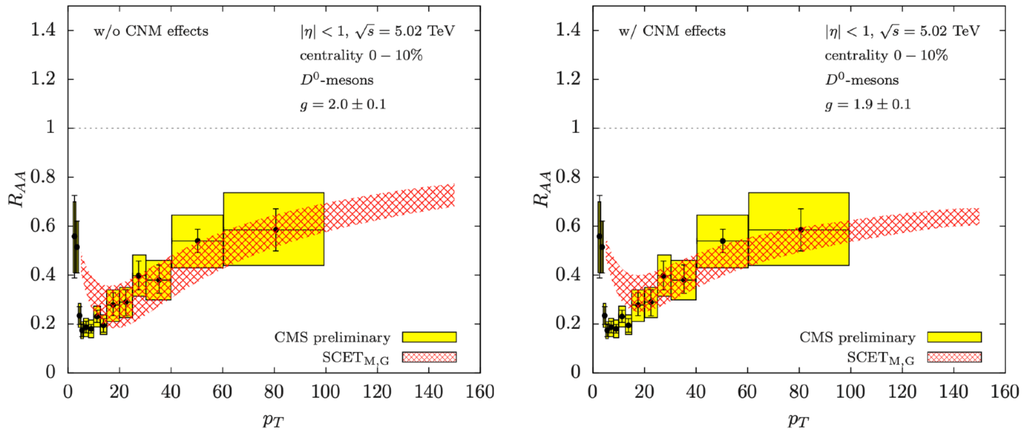






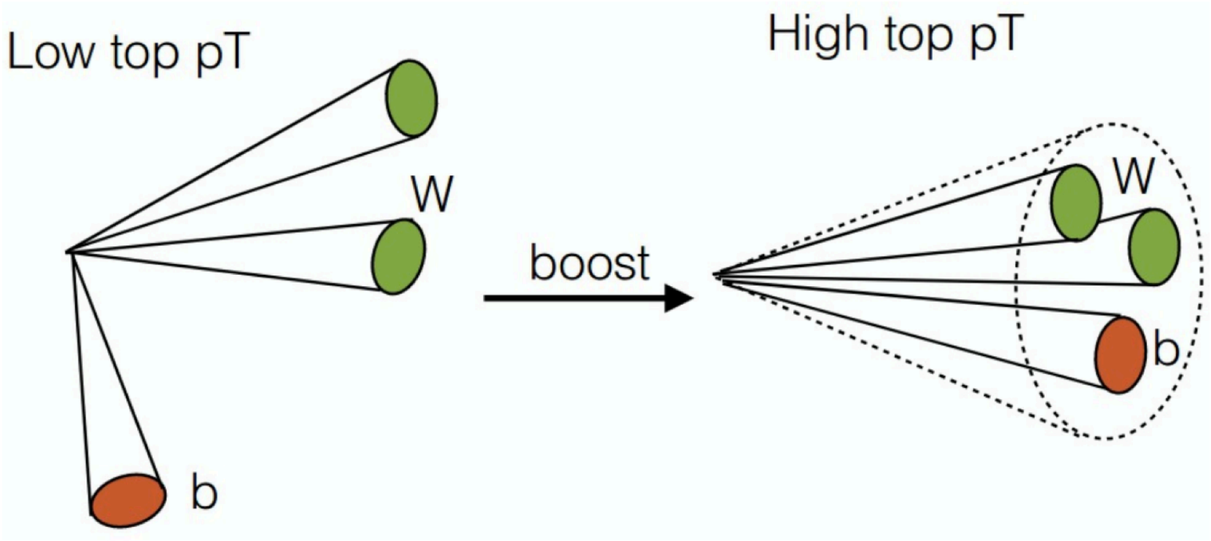
Liu et al (2022)

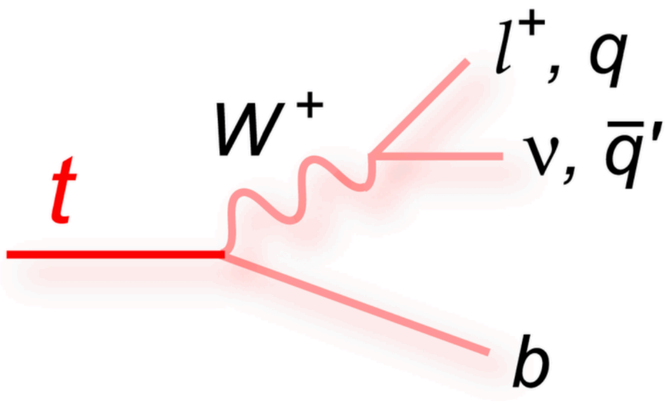
Kang et al (2016)



Boosted tops

- Proposal to use boosted W hadronic decay to probe the space time structure of the QGP: control the time when interaction takes place with the medium?

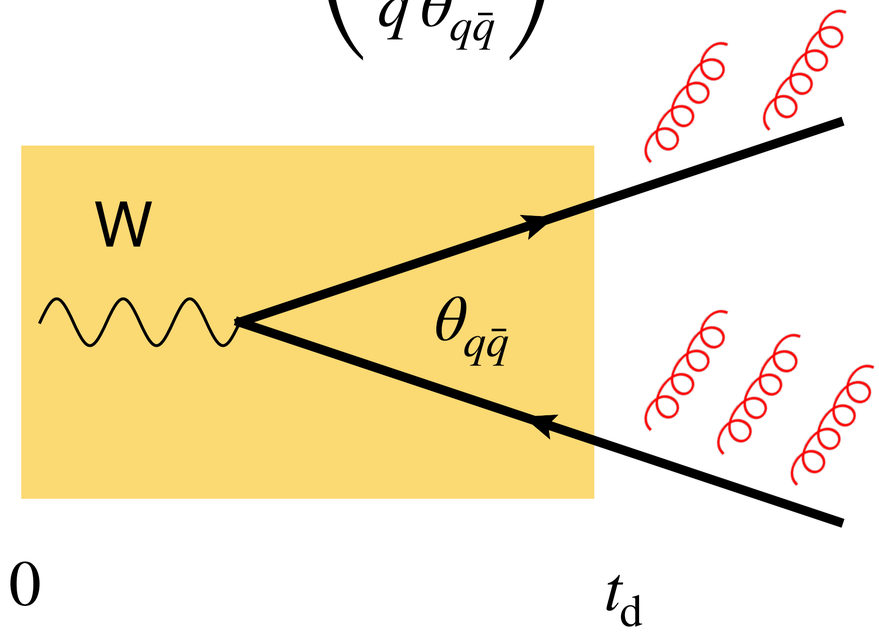




Boosted tops

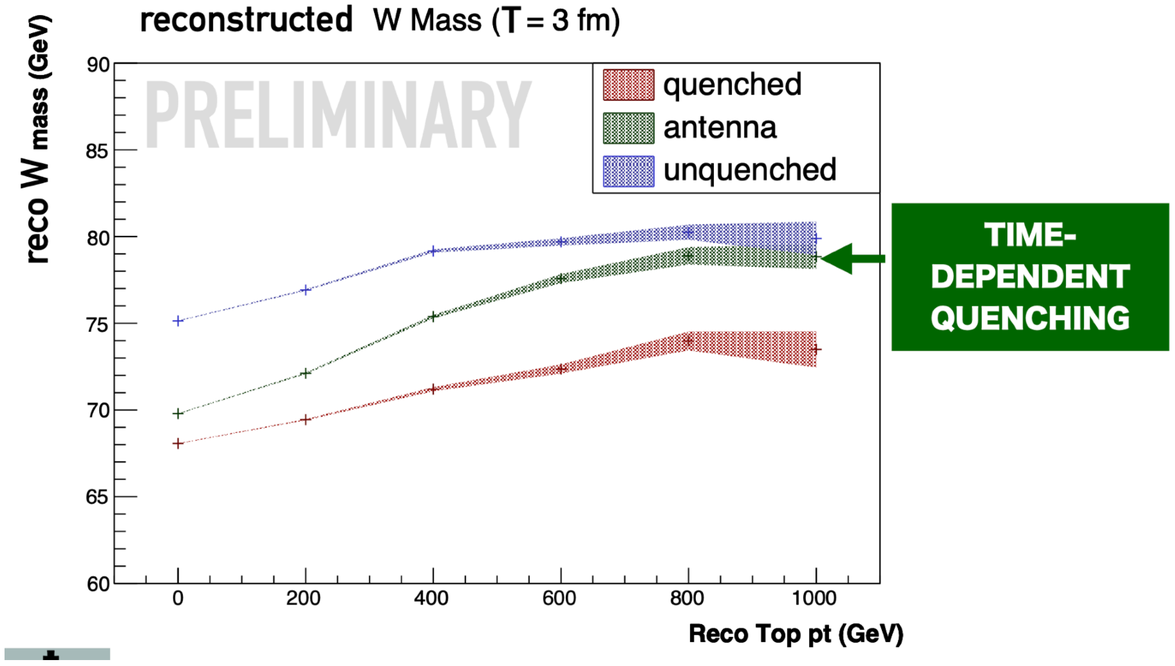
- Color singlet pair does not interact right away with the plasma (color transparency) - it must first decohere

$$t_{\rm d} \equiv \left(\frac{3}{\hat{q}\,\theta_{q\bar{q}}} \right)^{1/3}$$



Armesto, MT, Ma, Salgado, Tywoniuk (2012)

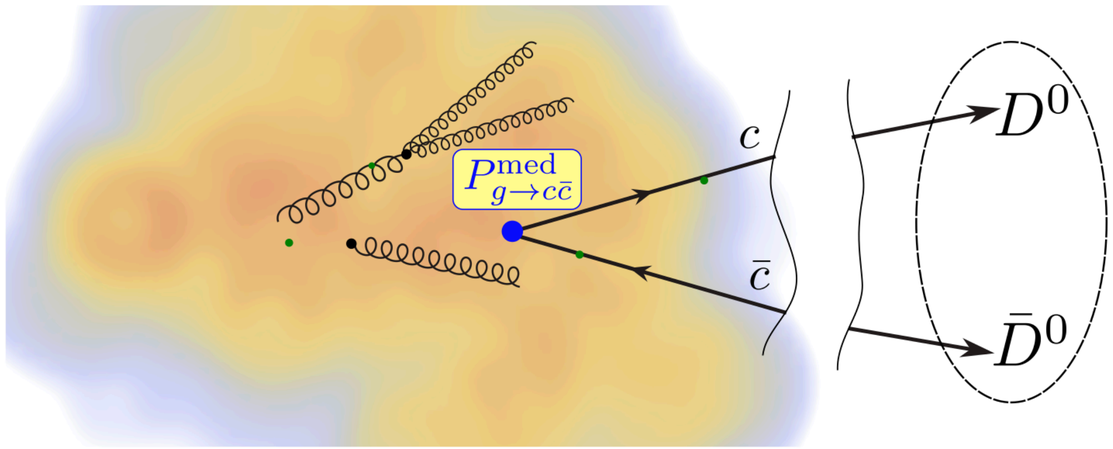
Apolinario, Milhano, Salam, Salgado, PRL (2017)

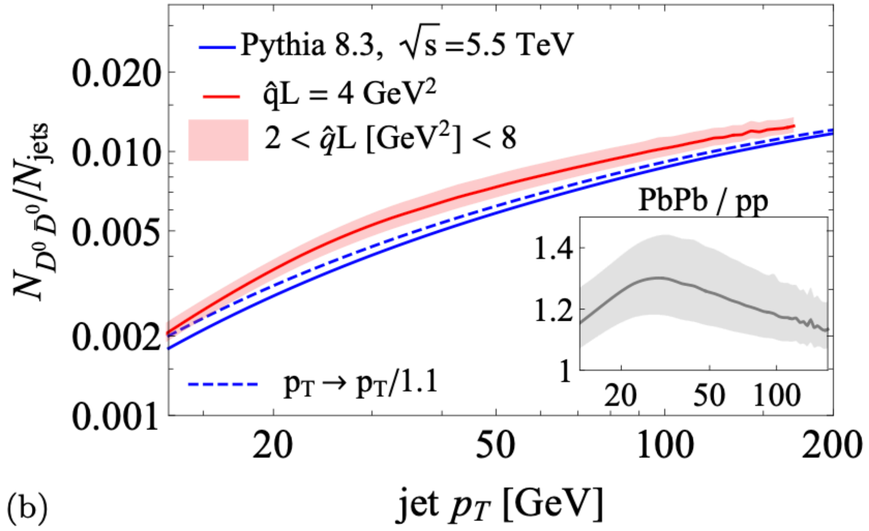


$$t \to b + W \to q\bar{q}$$

Intrajet heavy flavor production

- Medium induced $c\bar{c}$ pair production: possible enhancement in heavy ion collisions
- Testing ground for medium-modified splitting function $P^{\text{med}}_{g\to c\bar{c}}(z)$
- Energy loss (out of con radiation) leads to opposite effect





Attems et al. 2209.13600 [hep-ph]

A lot of progress

- Jet substructure: Caucal, Soto-Ontoso, Takacs 2111.14768 , 2103.06566
- Energy correlators: Andres et al 2209.11236
- EFT applications: Vaidya 2101.02225, 2109.11568
- Splitting functions: Sievert, Vitev, Yoon 1903.06170, 1807.03799, Andres, Apolinario, Dominguez, Gonzalez Martinez 2002.01517 , 2011.06522, Barata, MT, Soto-Ontoso, Tywoniuk 2106.07402, 2009.13667
- Flow and gradient effects: Barata, Sadofyev, Salgado, Andres, Dominguez 2202.08847, 2207.07141, Sievert, Vietev, Sadofyev 2104.09513
- Quantum corrections: MT, Caucal, 2209.08900, 2203.09407, 2109.12041 Ghiglieri, Weitz 2207.08842, Arnold, 2111.05348
- And more

Summary

- Jets as multiple scale systems are unique probe of thee QGP and non-equilibrium QCD dynamics
- Many QCD processes at play that can be tested in heavy collisions: LPM effect, color decoherence, turbulent energy transport, etc
- Control over theory uncertainties in perturbative sector necessary for precision tests
- Heavy flavor provide additional handle to investigate energy loss mechanisms by exploiting chemistry of jet substructure and color singlet boosted topologies