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C2QA

Recent Theoretical Developments on Jets

2023 RHIC/AGS ANNUAL USERS' MEETING

CELEBRATING NEW BEGINNINGS AT RHIC and EIC

João Barata, BNL and C2QA

Disclaimer

Brookhaven National Laboratory

sPHENIX I will focus primarily on aspects relevant for jets in HICs RHIC

Limited time: I will omit many interesting new works (check HP23 and QM22 for more complete picture)

A quick overview: jets in and out of matter

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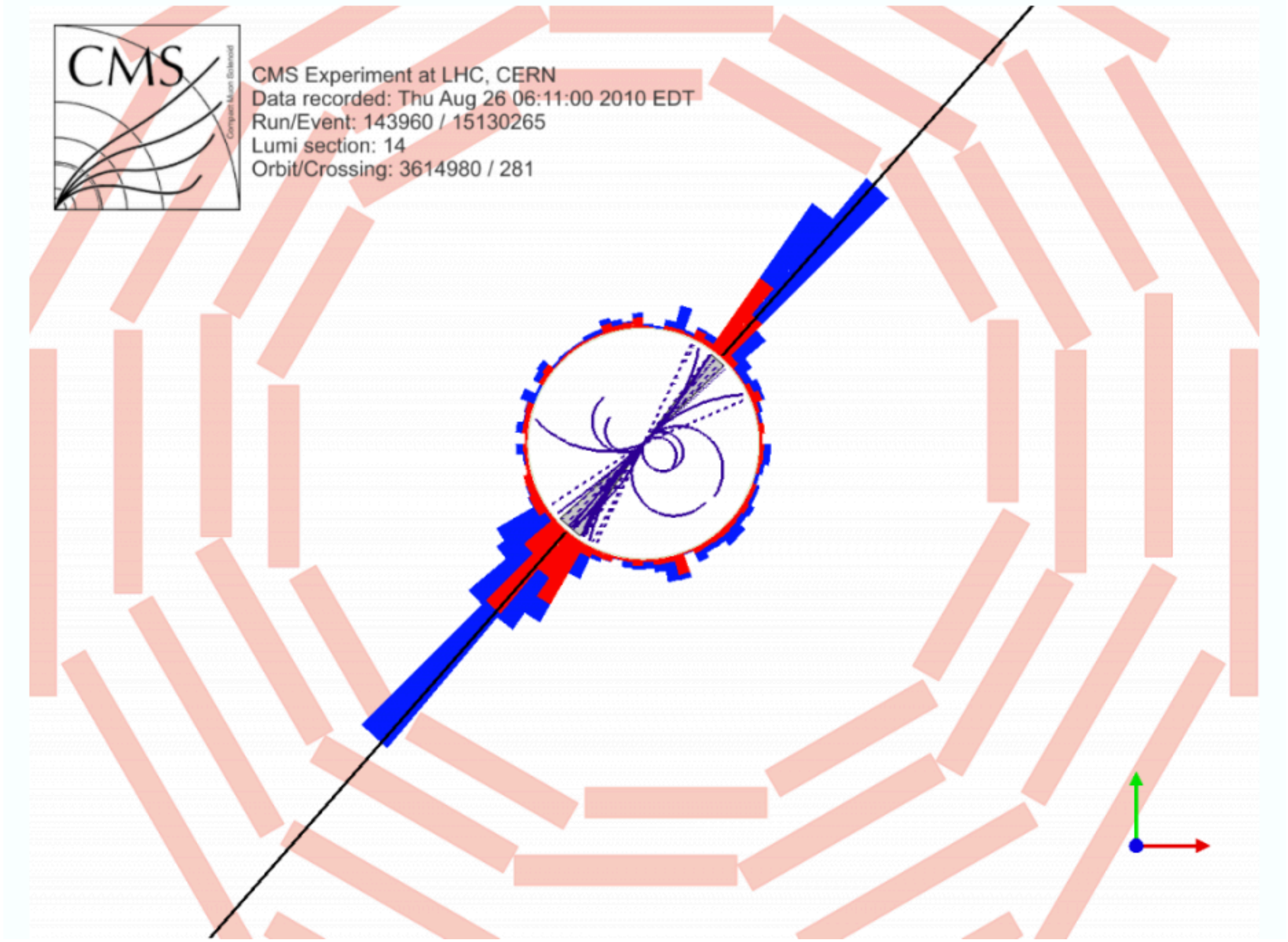
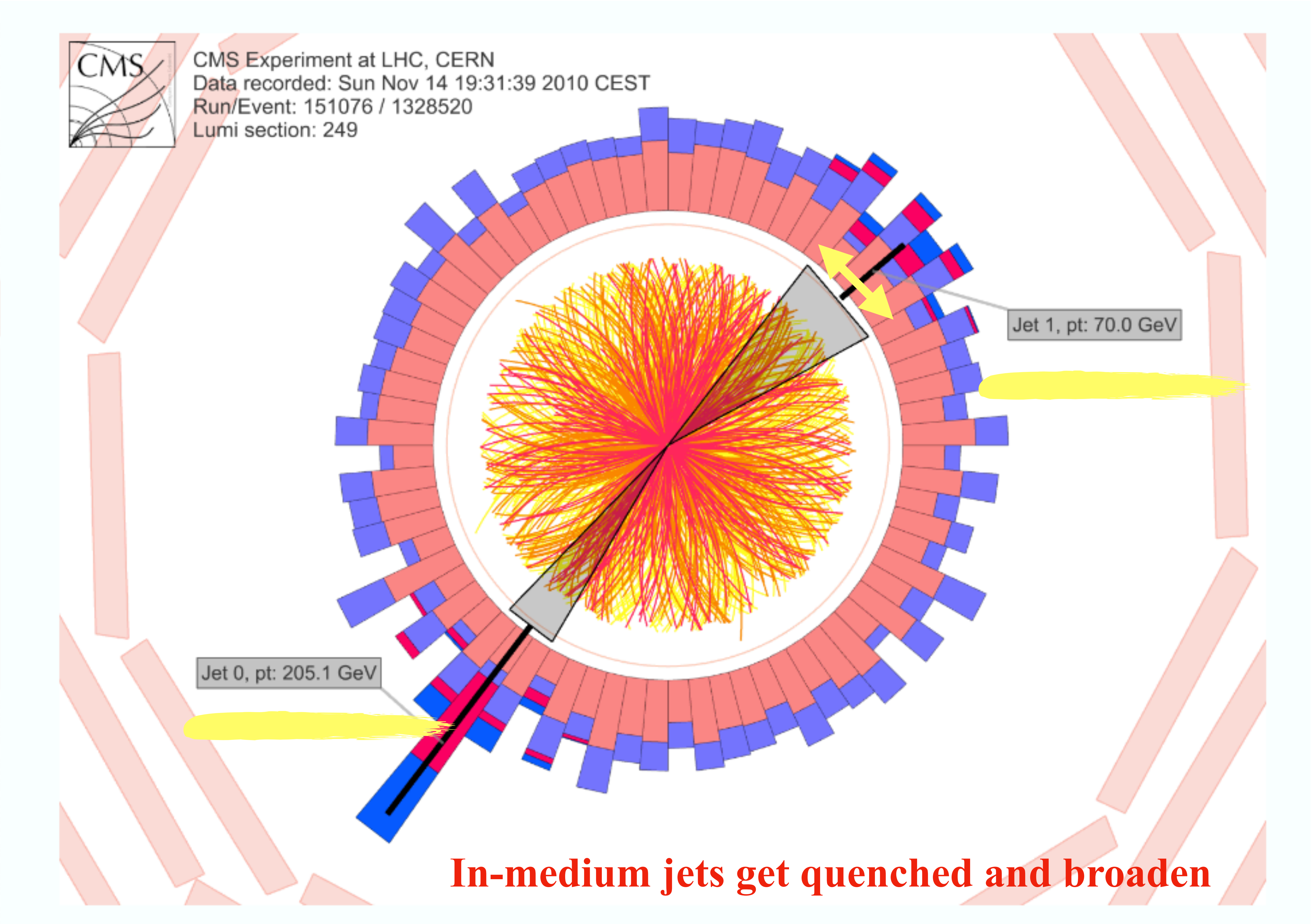
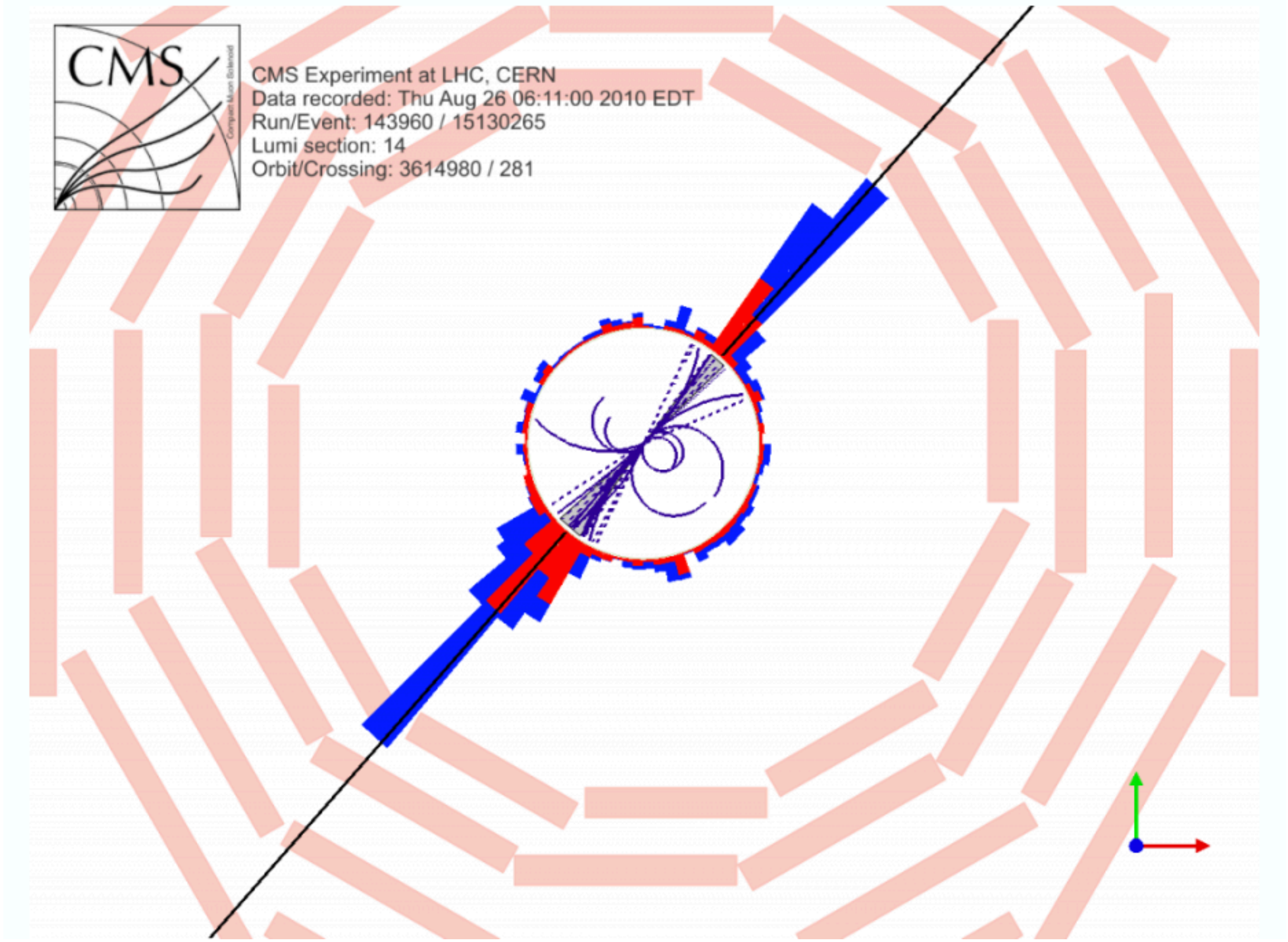


pp dijet event in CMS



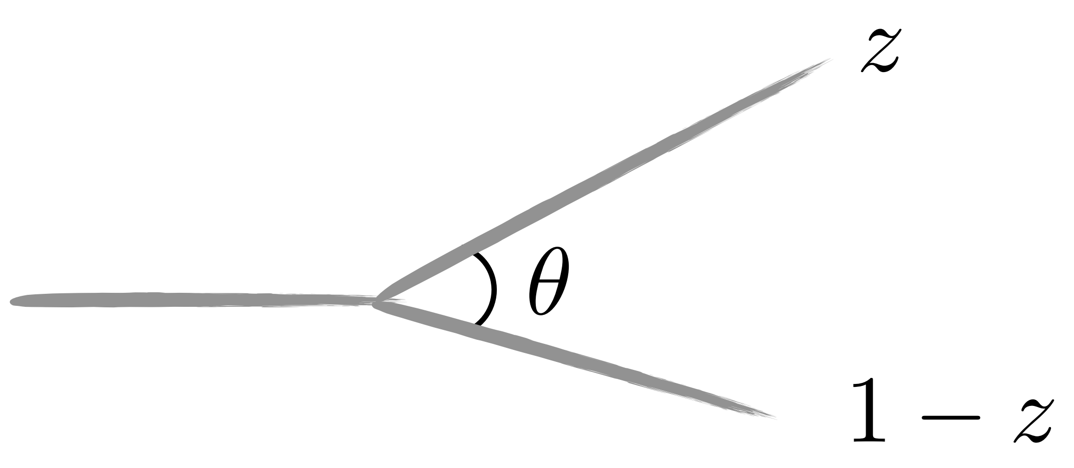
PbPb dijet event in CMS

A quick overview: jets in and out of matter



pp dijet event in CMS

Jet fragmentation in perturbative regime described in collinear limit of the theory



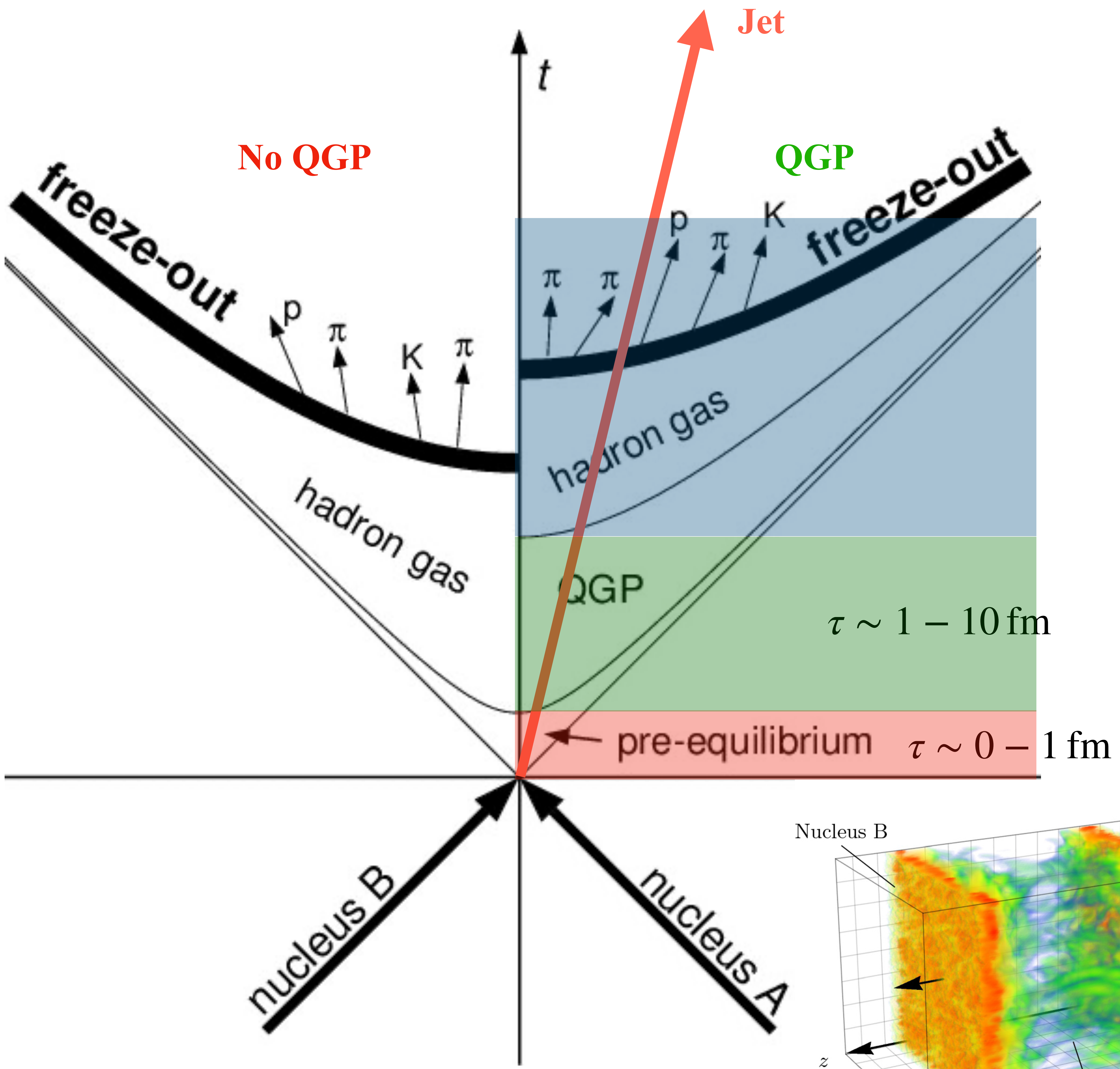
$$\sim \frac{\alpha_s C}{2\pi^2}\frac{d\theta^2}{\theta^2}P(z)dzd\alpha$$

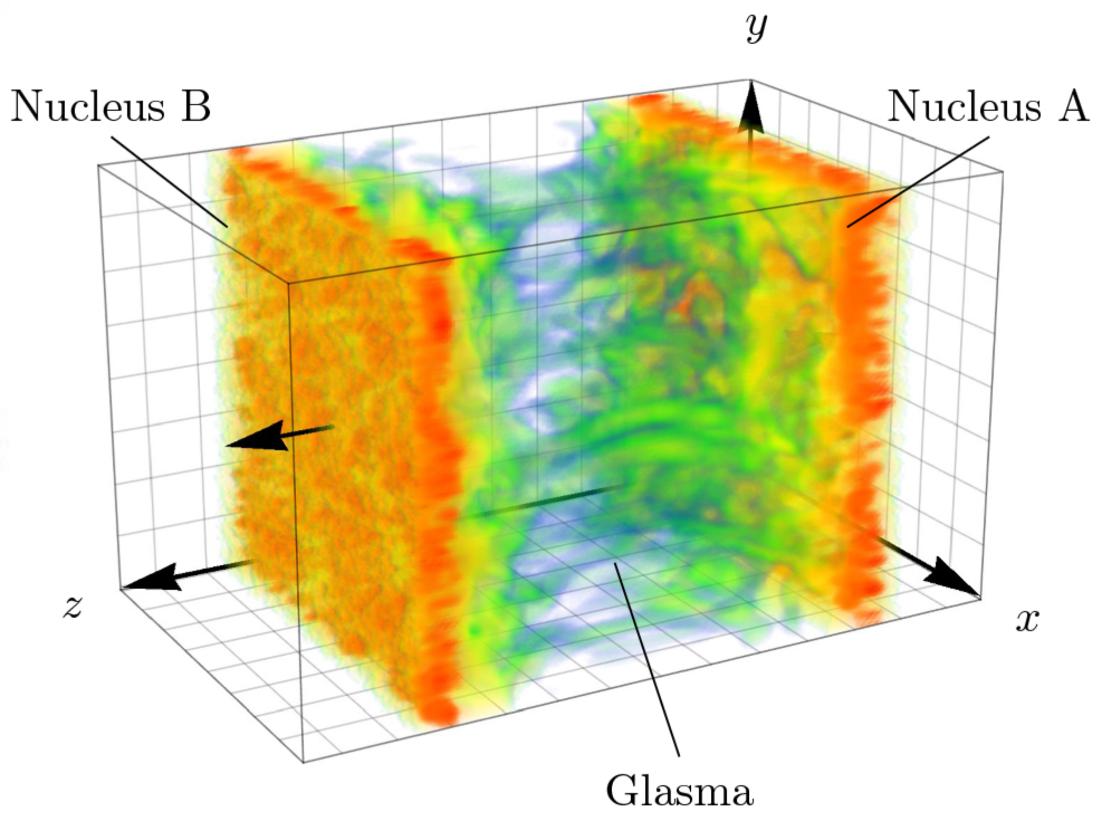
Exhibits singular behavior in soft and collinear limits

→ Observables computed in controlled expansion in the strong coupling constant and large logs

→ In matter: equivalent expansion more complex, no general way to organize it

A quick overview: jets in and out of matter





Jets are produced at the same time as the QGP

They serve as indirect hard probes of the matter

Their evolution happens in parallel to the medium

Early times: Non-equilibrium matter (Glasma)

(too) short times scales ?

Intermediate times : QGP phase

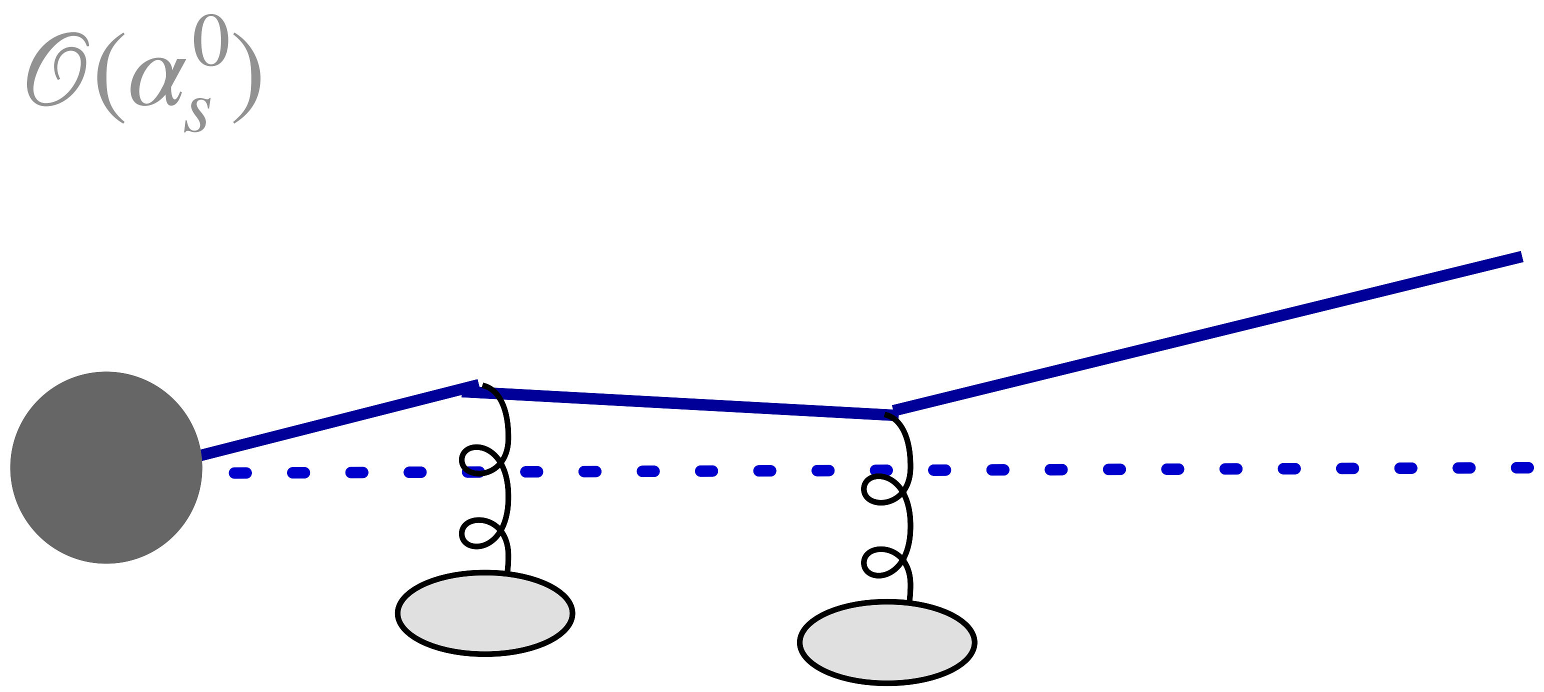
dominant region

Hadronic phase: Long lived

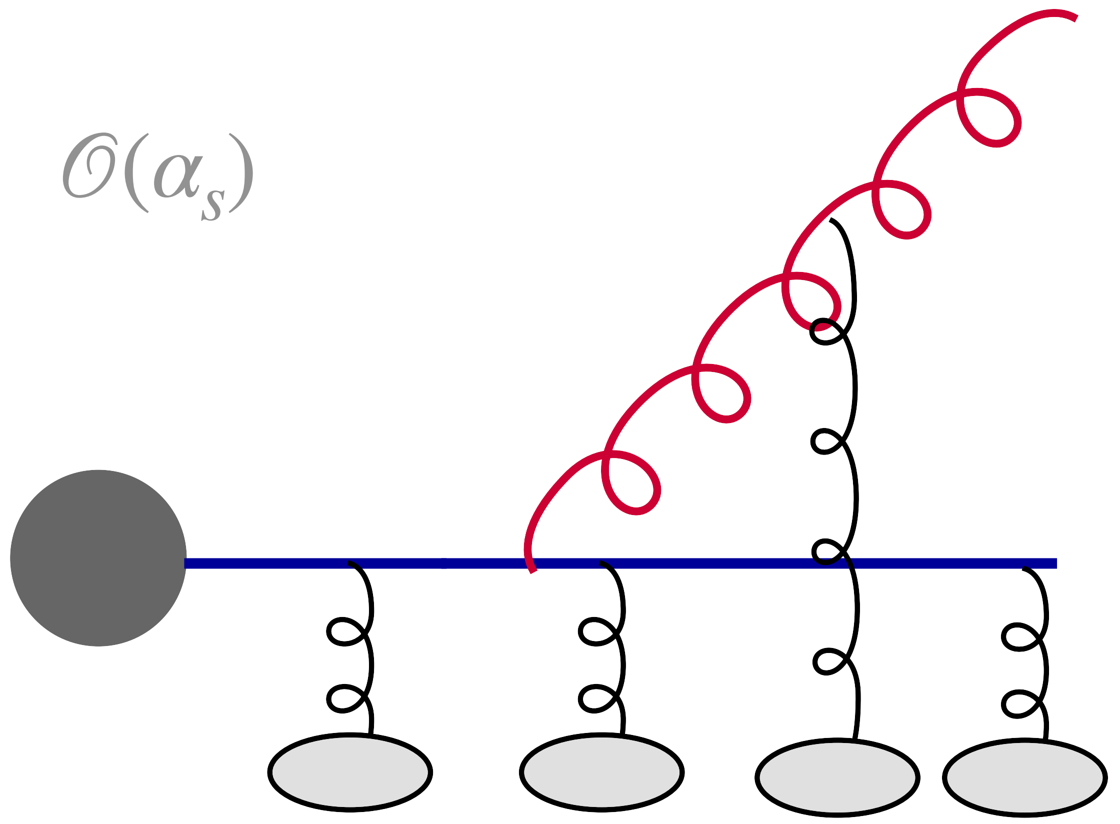
Expected smaller modifications to jets; non- perturbative effects

A quick overview: jets in and out of matter

Studying jets in HICs is a challenging problem! Most work done on lowest order processes



"momentum broadening"

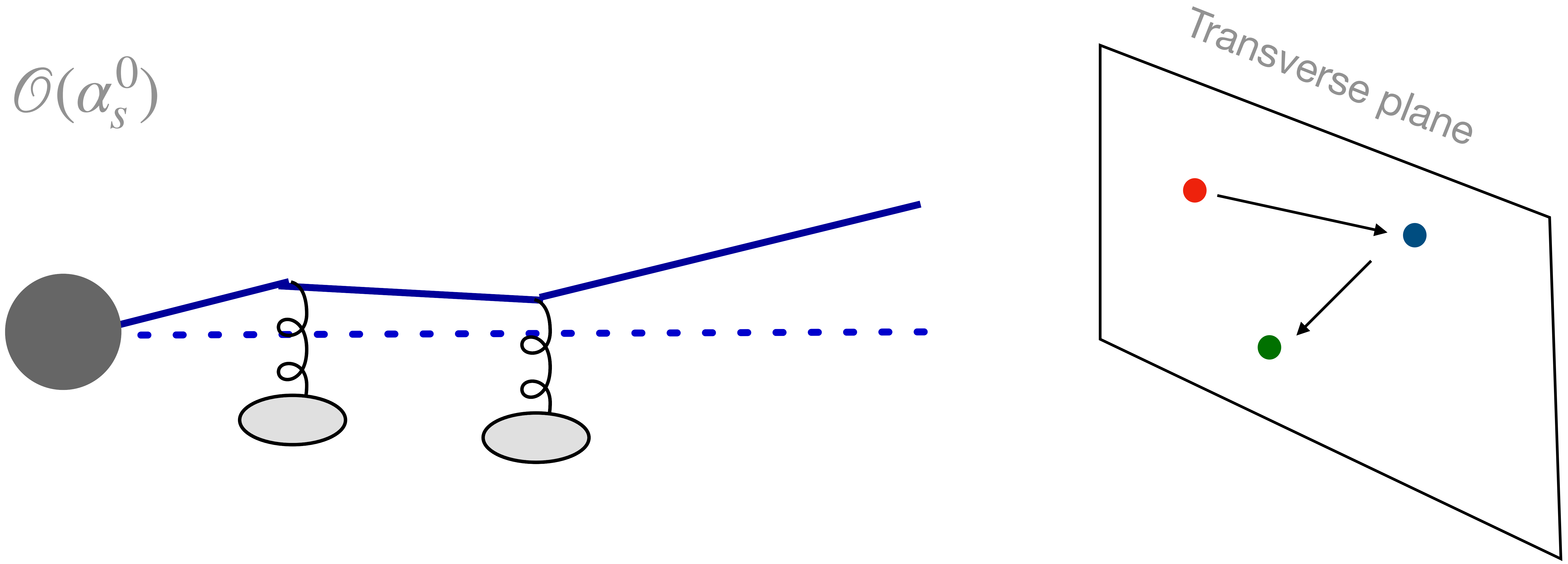


"medium induced gluon emission"

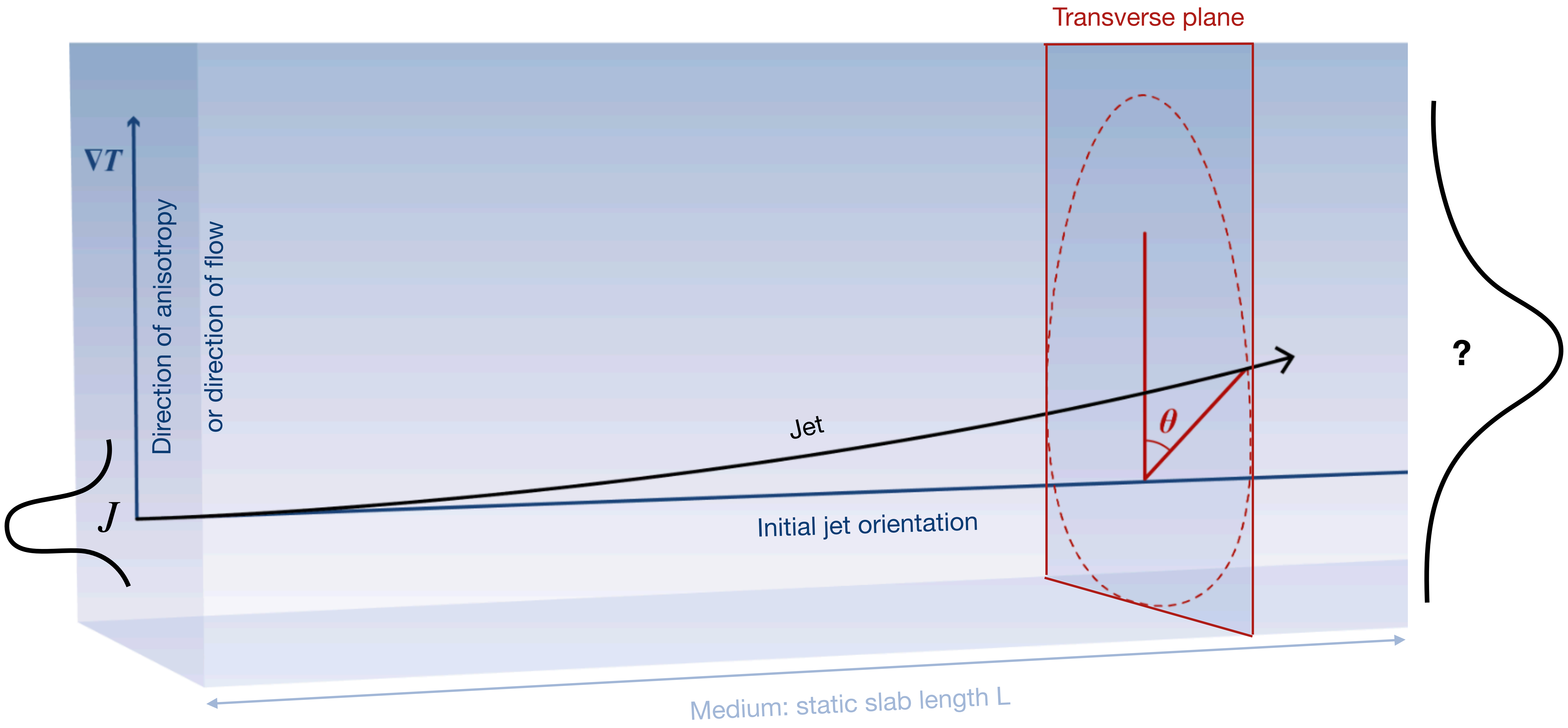
Major approaches to jets in HICs have given us: general picture of the problem, relevant scales and dominant effects

Today: moving towards quantitative/precision description of jets in HICs

Momentum broadening



Momentum broadening in flowing and anisotropic matter



[Sadofyev et al, 2021-2023]

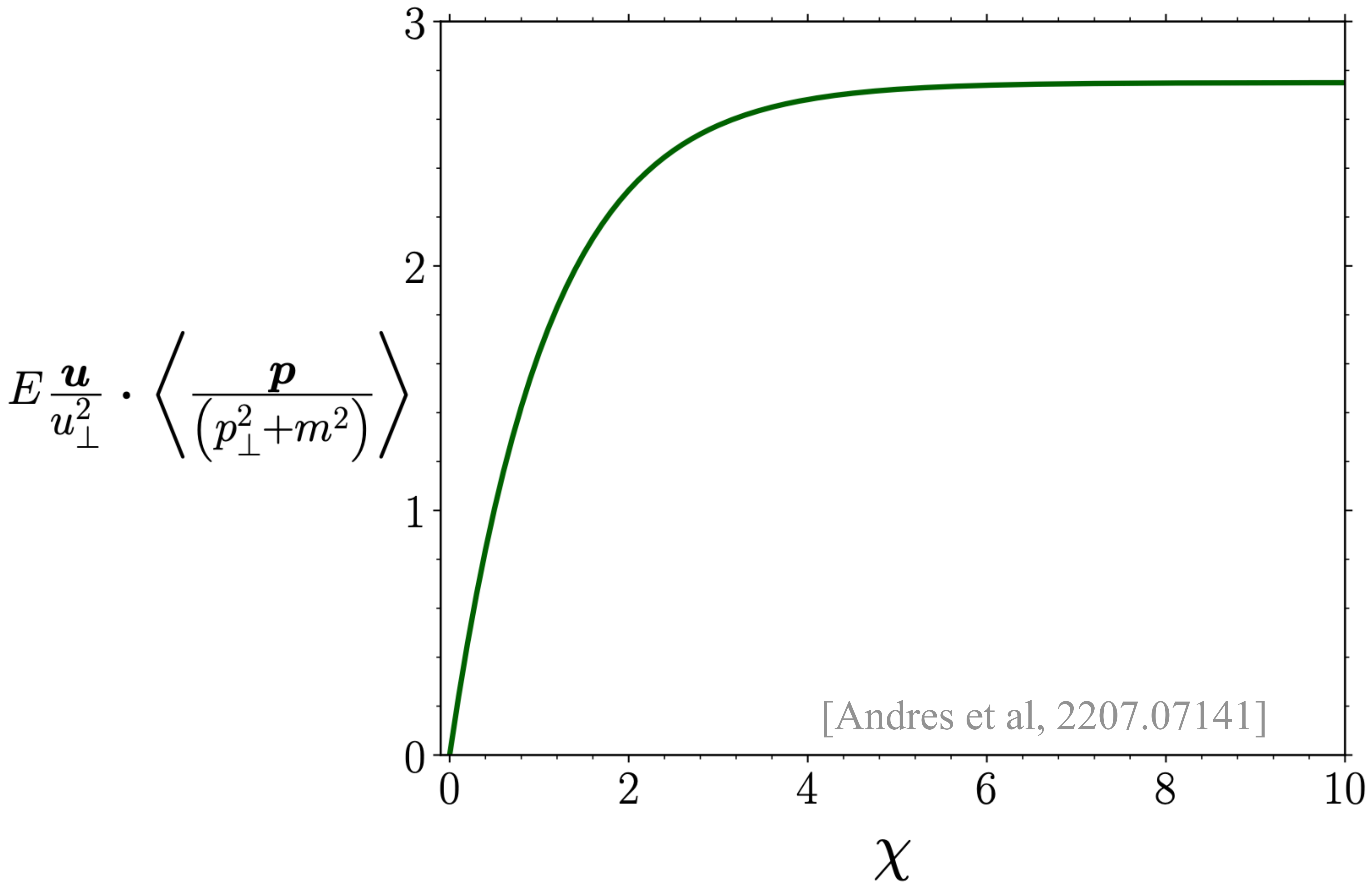
[Fu, Casalderrey-Solana, Wang, 2022]

[Antiporda et al, 2021]

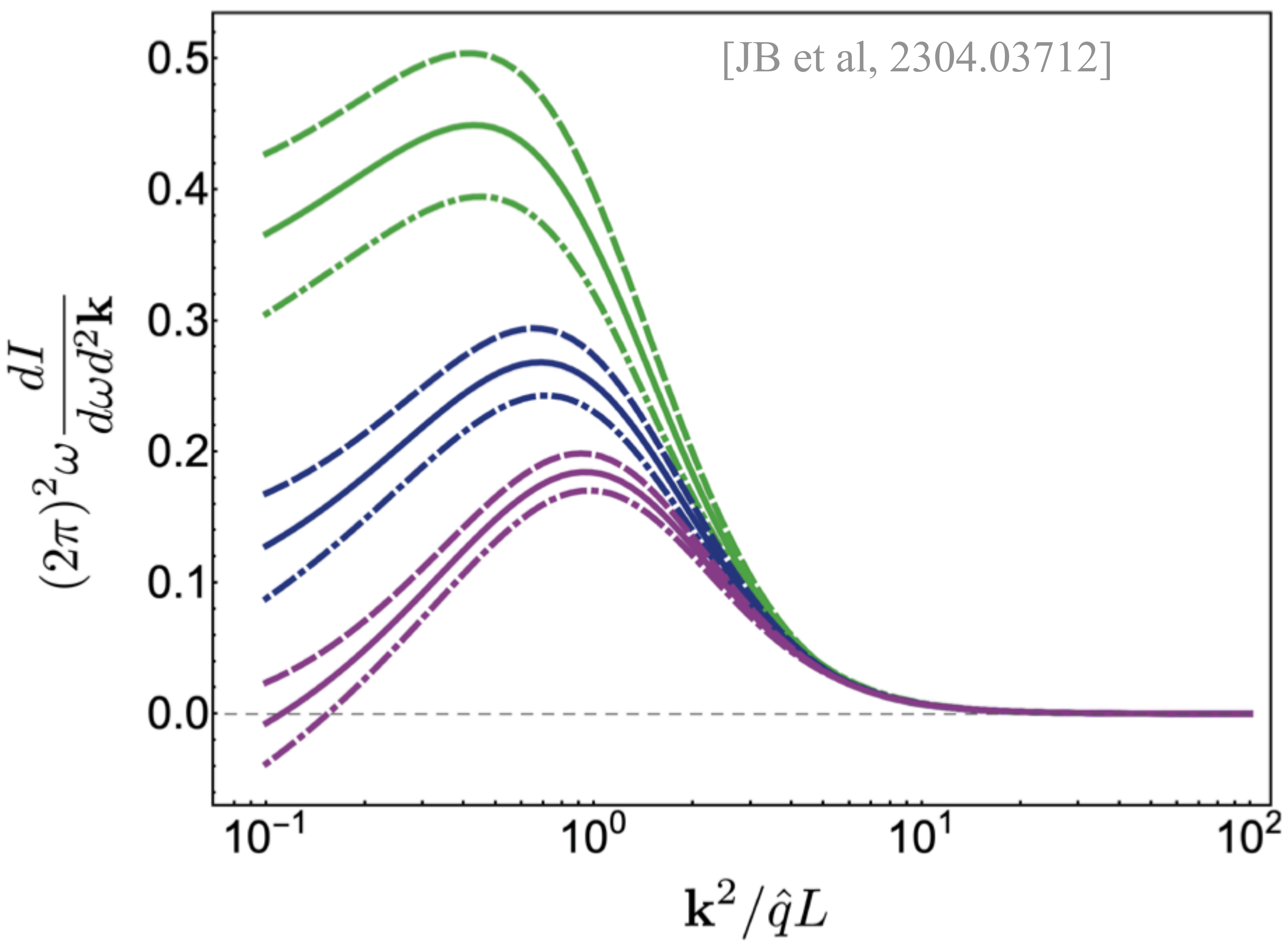
Momentum broadening in flowing and anisotropic matter

QGP is a flowing and structured background: what can jets tell us about these features ?

New: first principle calculations of these effects in jet spectra



Appearance of non-trivial azimuthal structures



New calculations available also for medium induced spectrum

Momentum broadening in flowing and anisotropic matter

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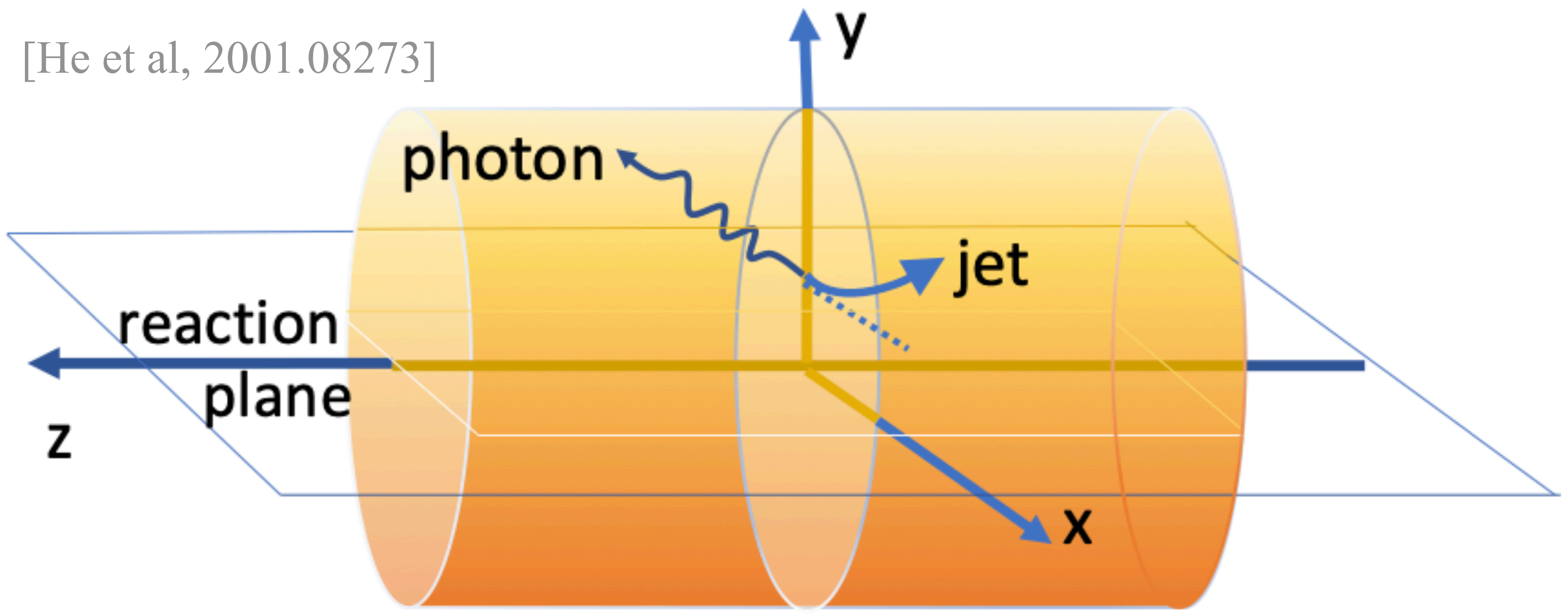
End goal: use jets as tomographic probes of the matter

Open question: which are the ideal observables to be computed?

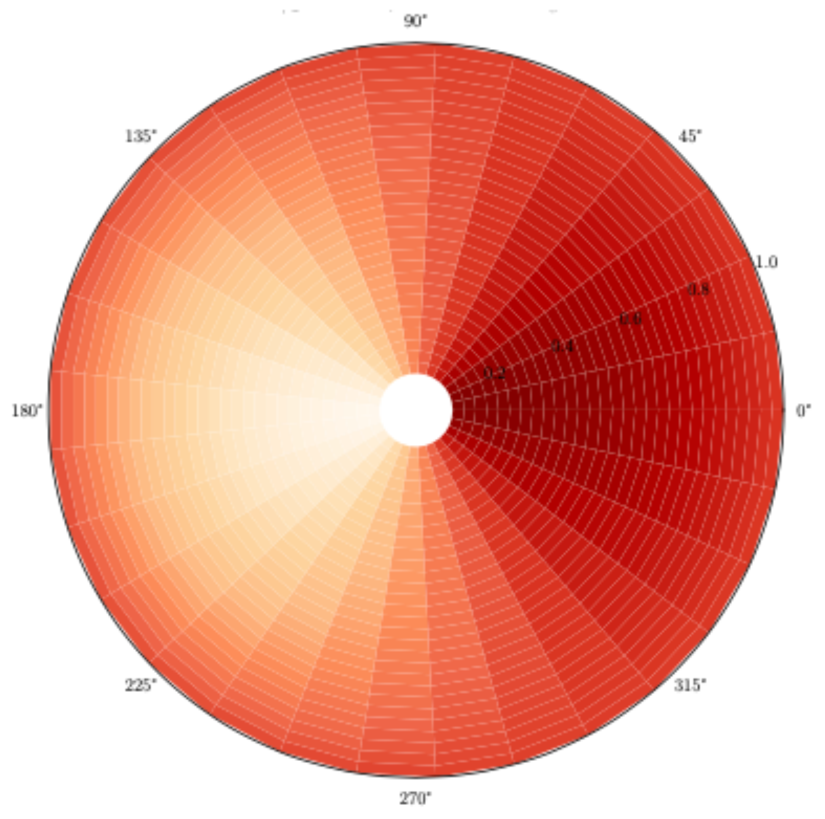
[He et al, 2001.08273]



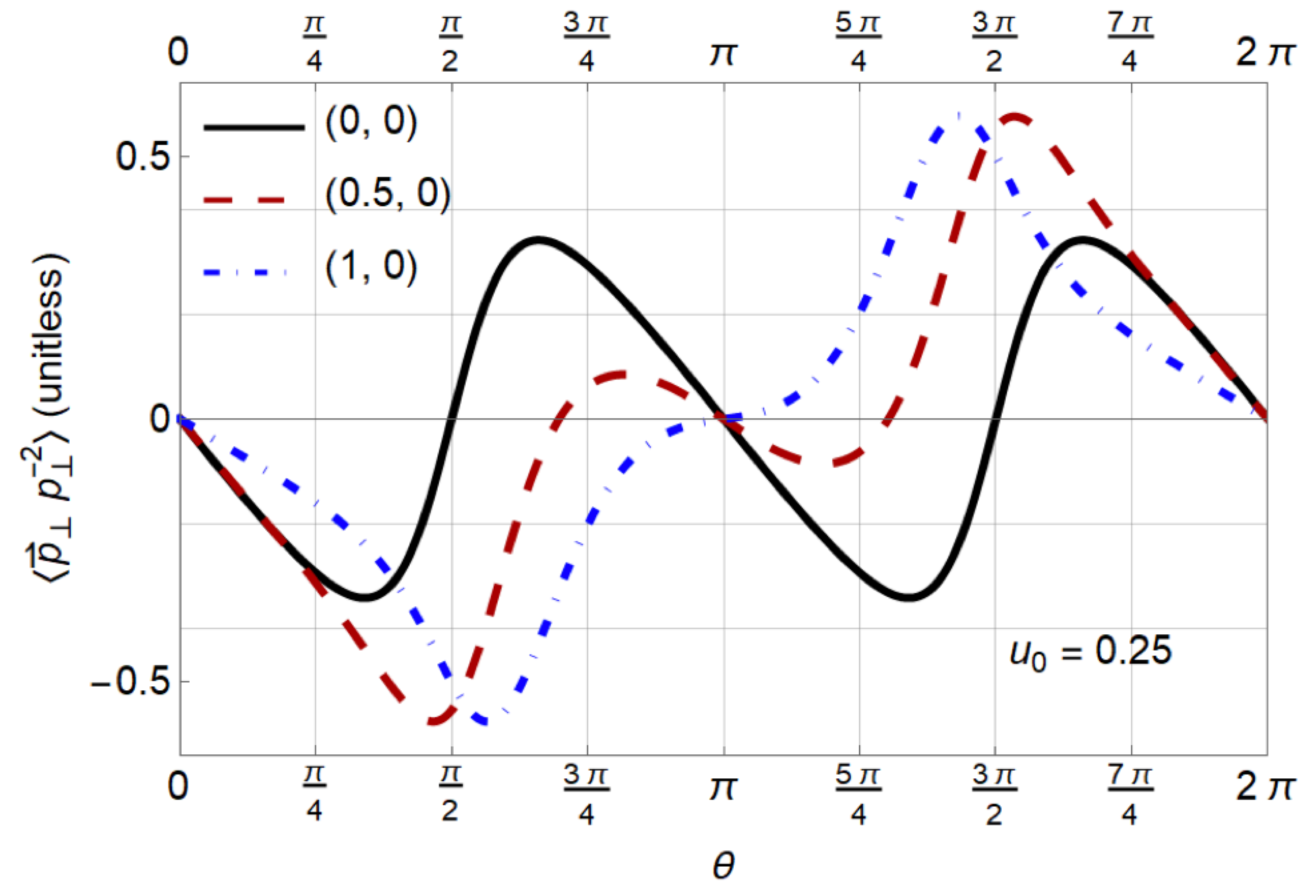
$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k}, \vec{r}) \mathrm{Sign}(\vec{k} \cdot \vec{n})}{\int d^3r d^3k f_a(\vec{k}, \vec{r})}$$

Reconstruct localization of parton using moments of phase space distribution

[JB et al, 2308.xxxxx]

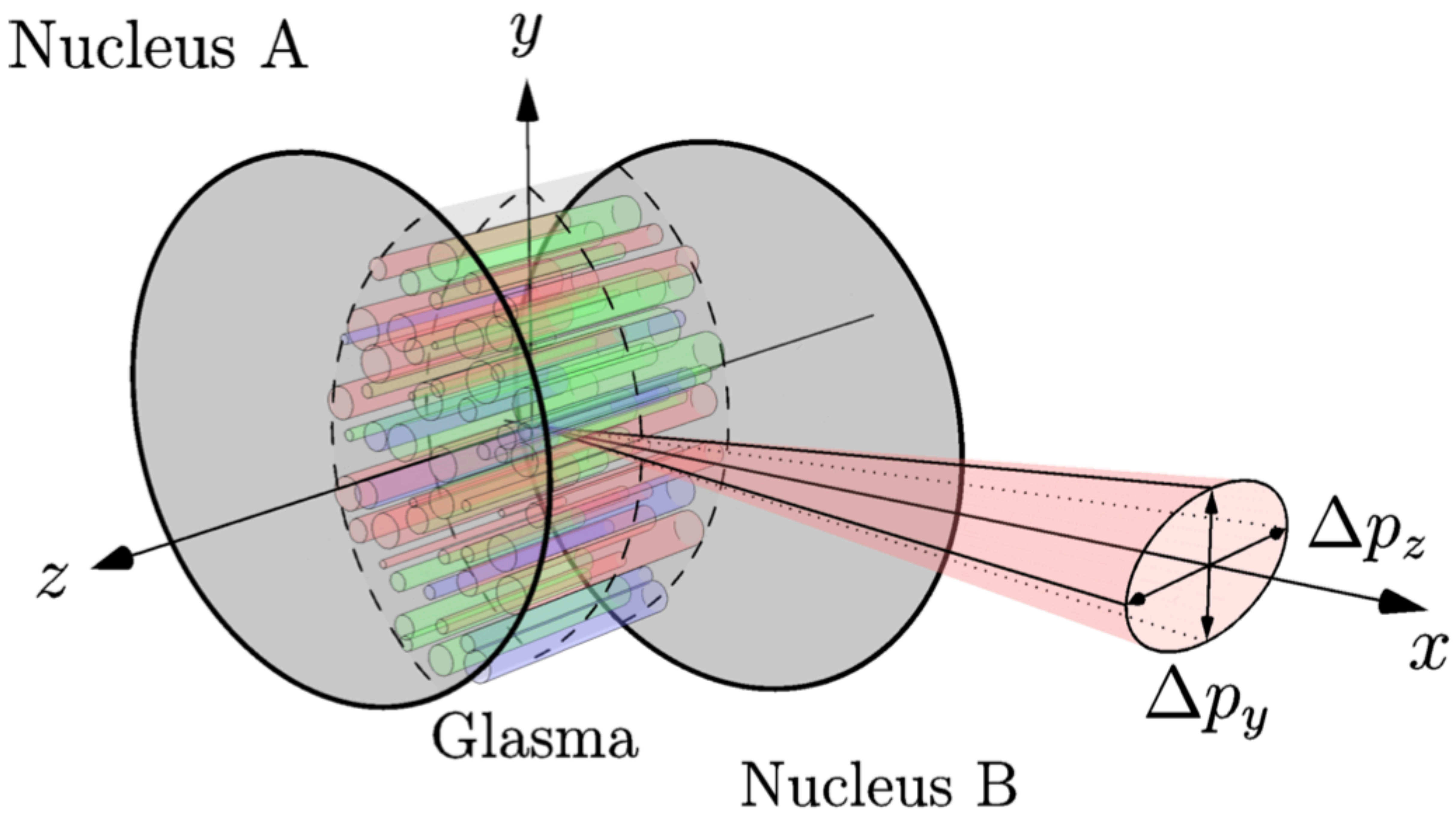


[Antiporda et al, 2110.03590]



Jet observables including these effects are now available

Momentum broadening in glasma phase



[…]
[Ipp et al, 2020]
[Carrington et al, 2021]
[Hauksson, Iancu, 2023]
[Boguslavski, 2023]
[Avramescu, 2023]
[…]

Momentum broadening in glasma phase

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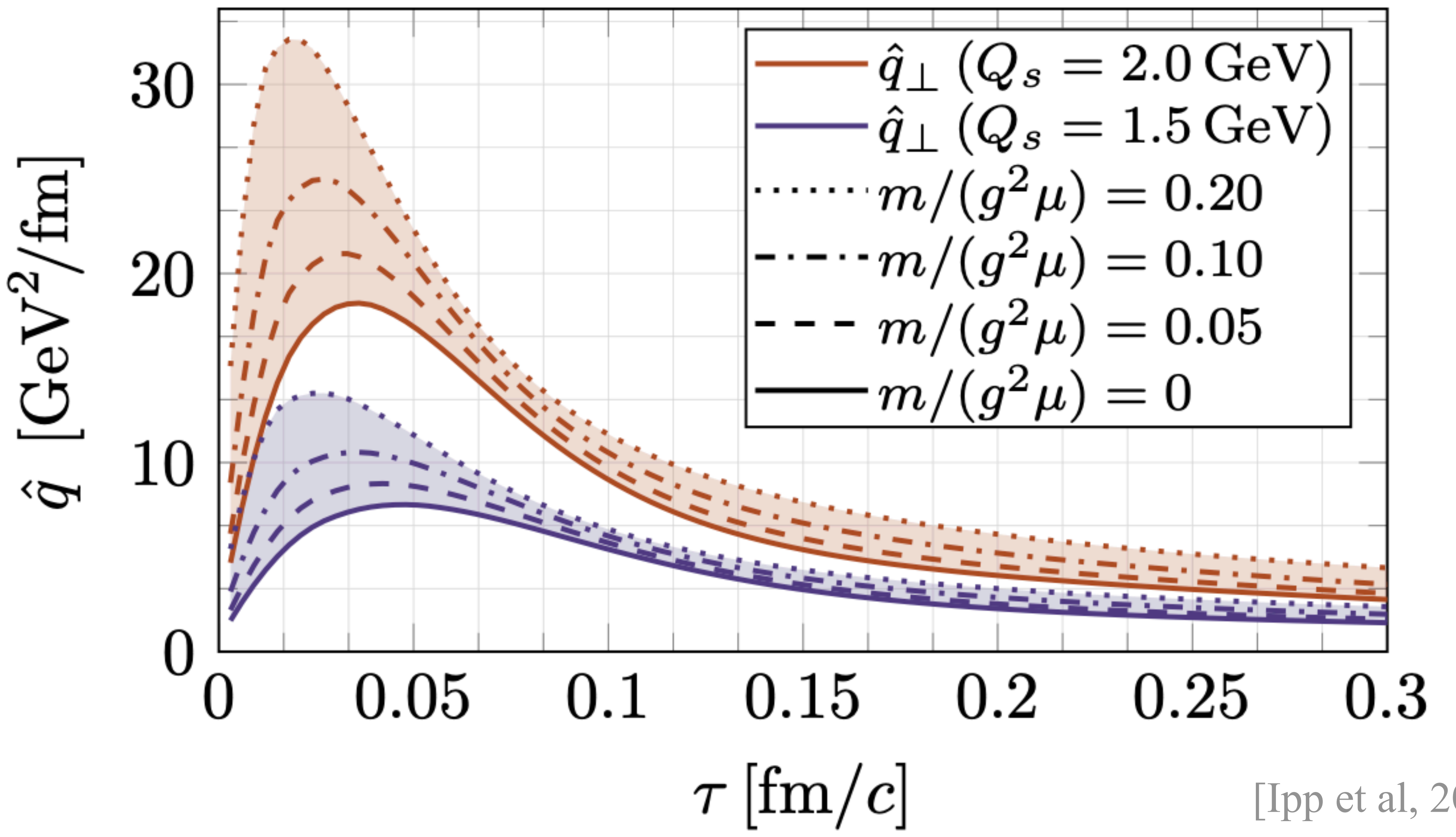
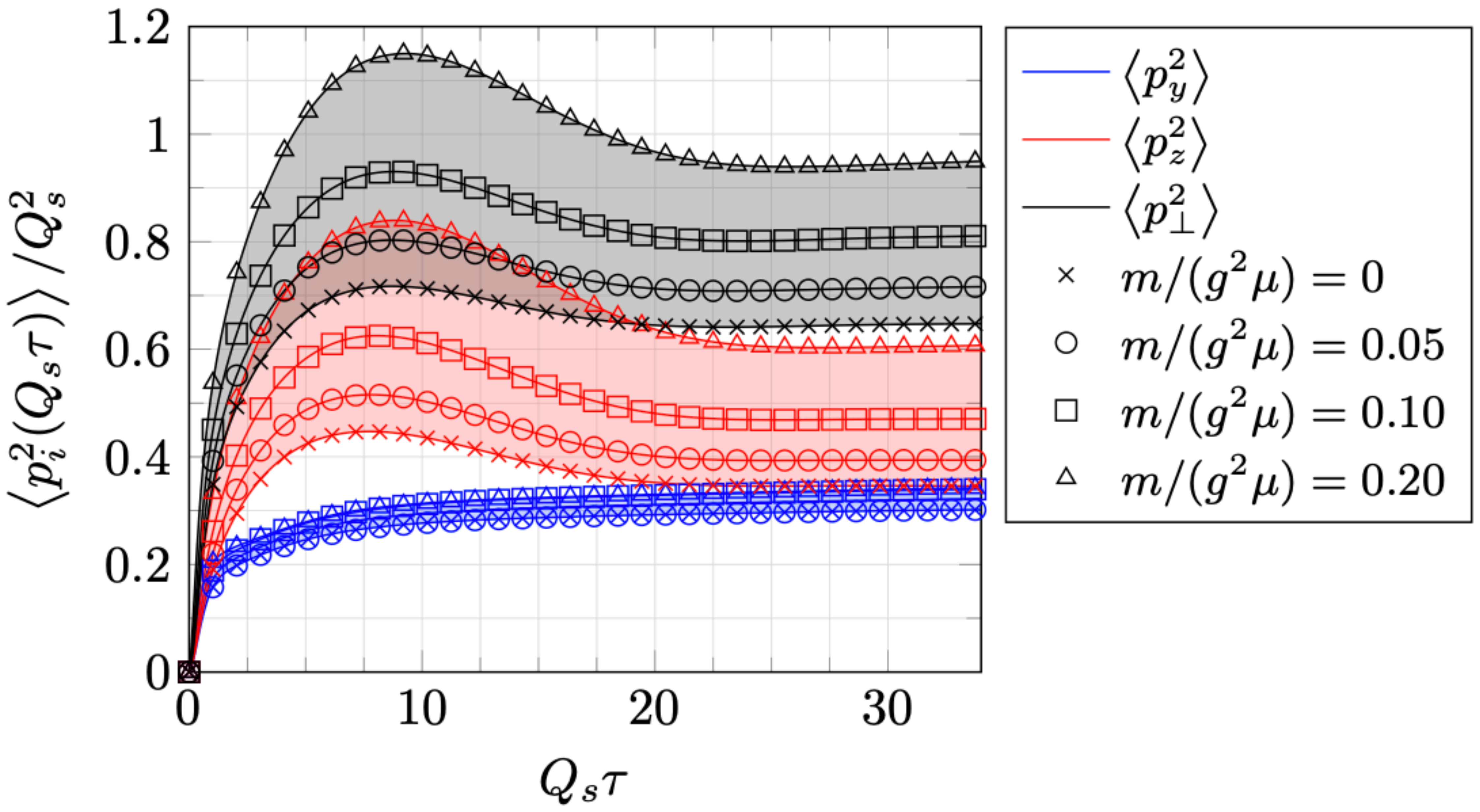
Jets are produced early in the collision and thus can be sensitive to full matter evolution

New: first calculations of jet quenching parameter in Glasma phase

Effect 1: large parameter at early times



Effect 2: anisotropic broadening



[Ipp et al, 2001.10001, 2009.14206]

Momentum broadening in glasma phase

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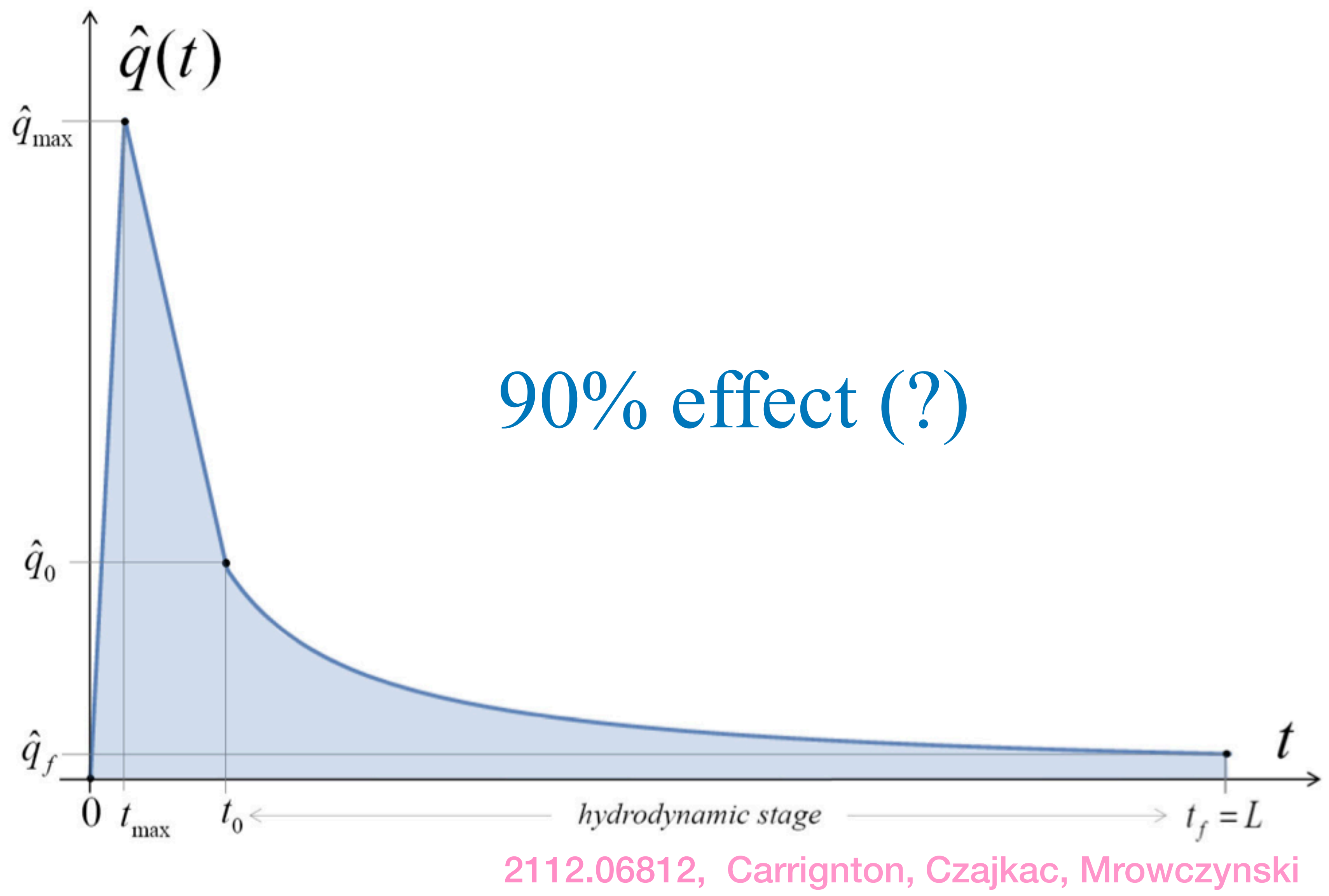
Jets are produced early in the collision and thus can be sensitive to full matter evolution

New: first calculations of jet quenching parameter in Glasma phase

Many open questions: Is the large jet quenching parameter sufficient to compensate short time scales ?

Which types of observables should be sensitive to this stage and not washed out by hydro evolution ?



[Carrington et al, 2112.06812]

Jet polarisation in an anisotropic medium

S. Hauksson and E. Iancu,

of their parents. Based on that, we conclude that a net polarisation for the jet should survive in the final state if and only if the medium anisotropy is sizeable as the jet escapes the medium.

[Hauksson, Iancu, 2303.03914]

Momentum broadening in glasma phase

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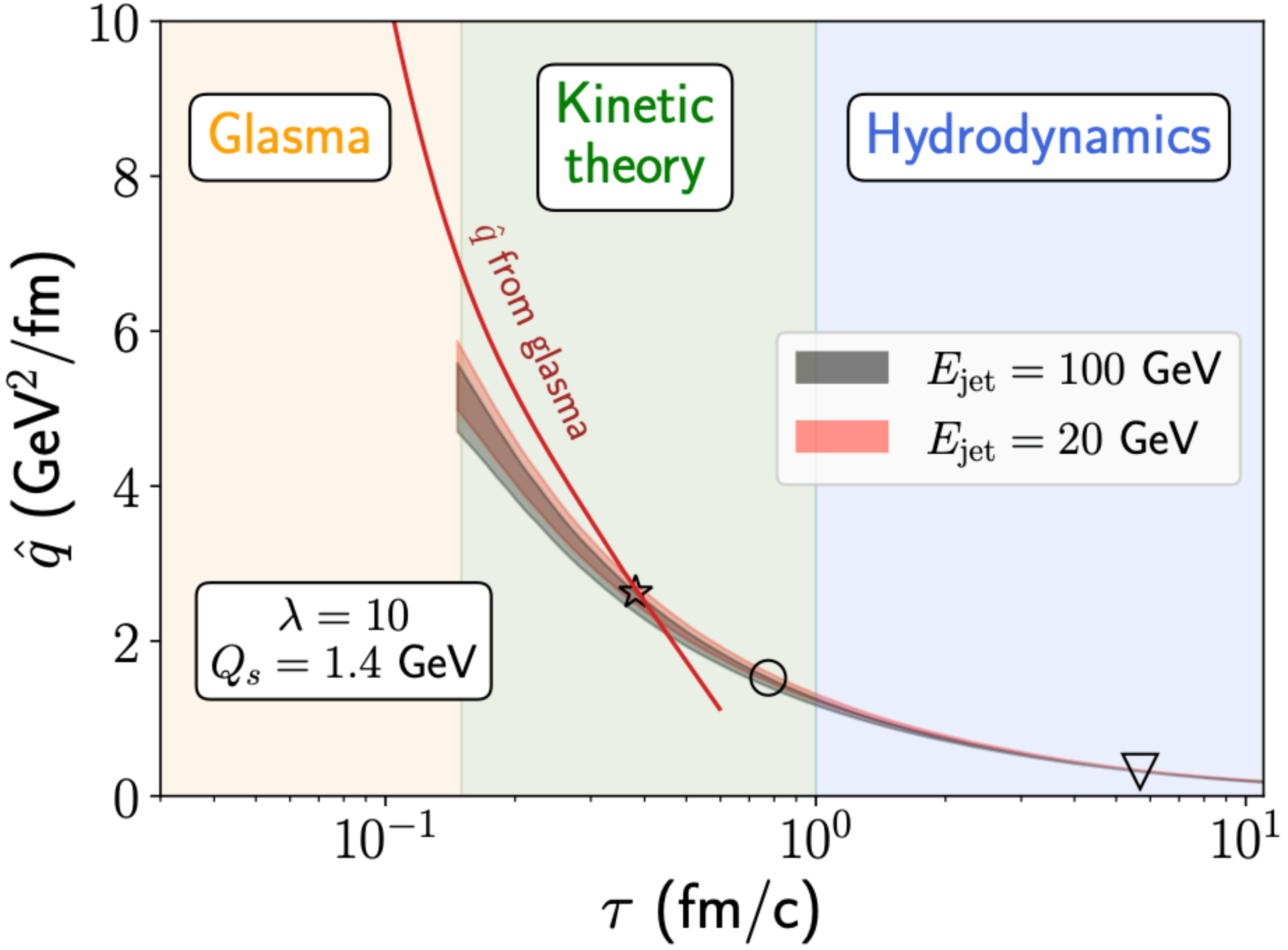
Many open questions: How can we consistently connect all the stages ?

New: EKT approach to connect three stages; similar effects to the glasma phase

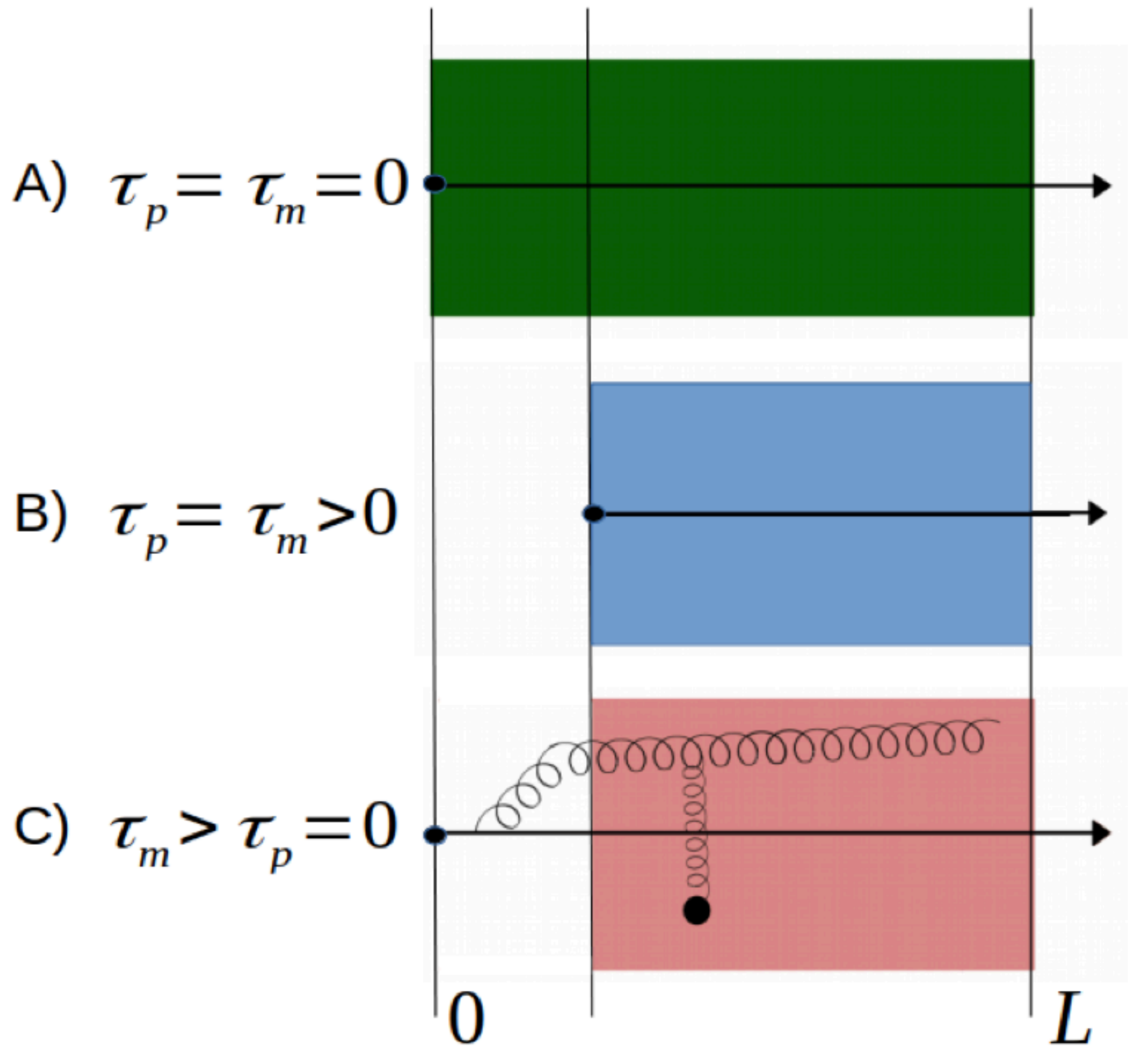


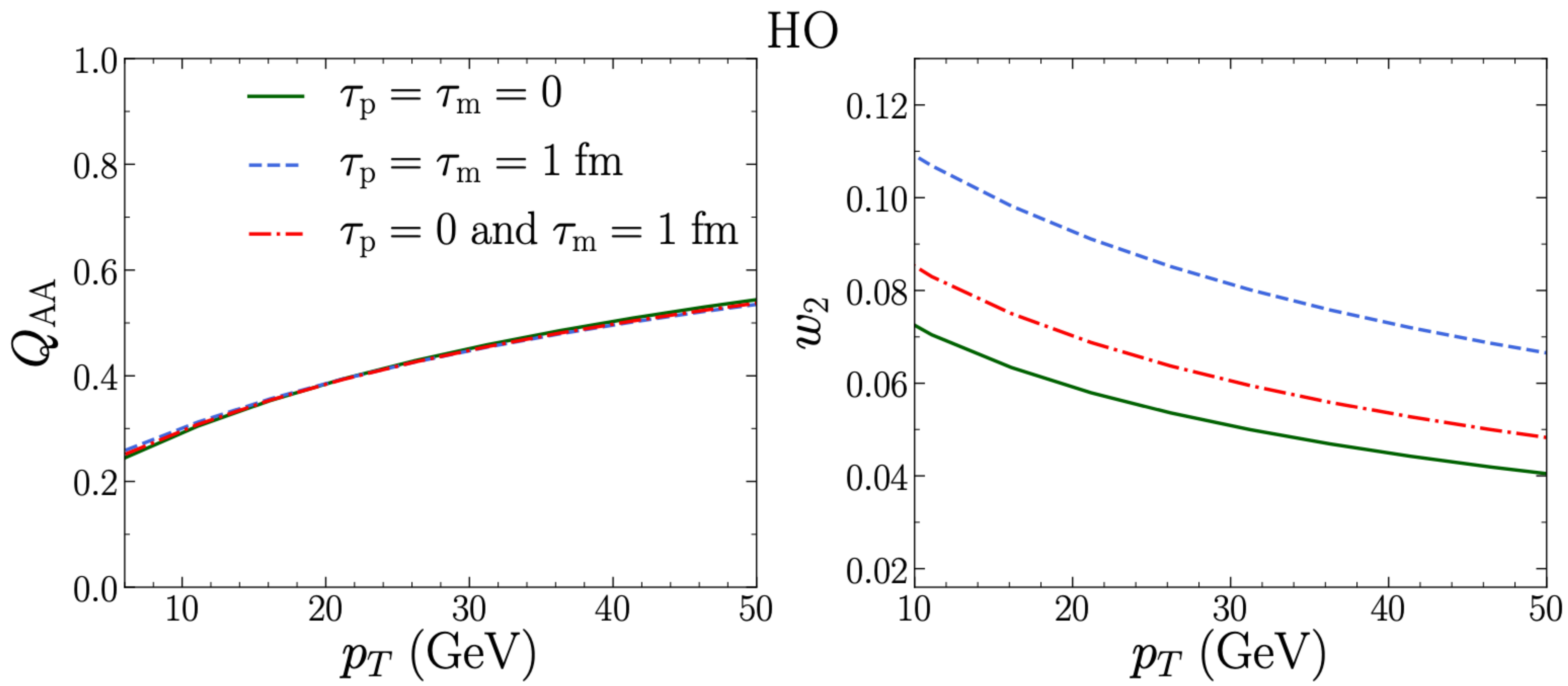
[Boguslavski, 2303.12595]

Momentum broadening in glasma phase

Many open questions: How significant are the early stages for the full evolution of the jet?

Early stages might have important effect in describing harmonics



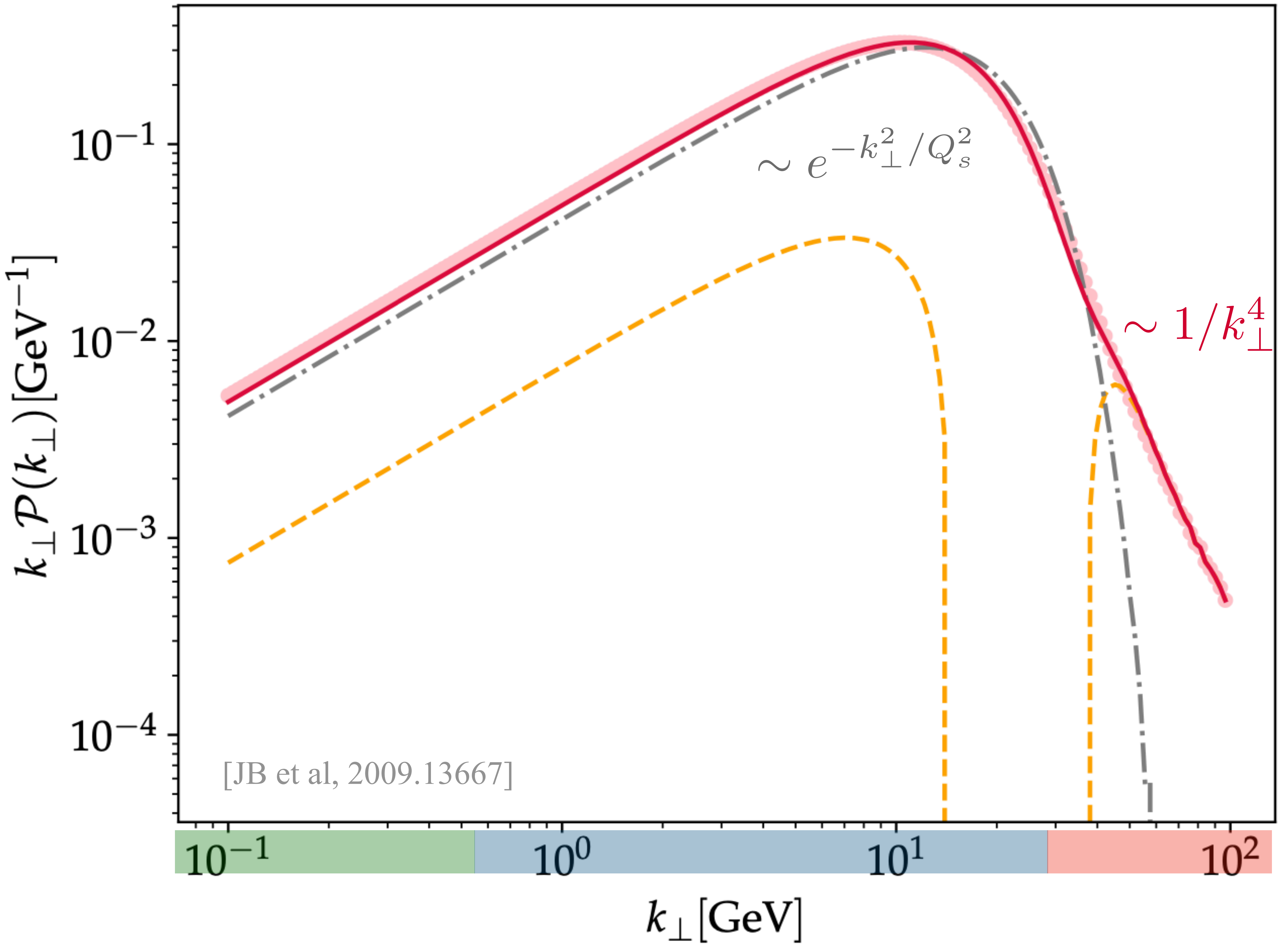


[Andres et al, 2211.10161]

Moliere scattering in the QGP

Jets could be sensitive to the presence of quasi-particles in the QGP

New: Closed description capturing both the soft and hard scattering regimes

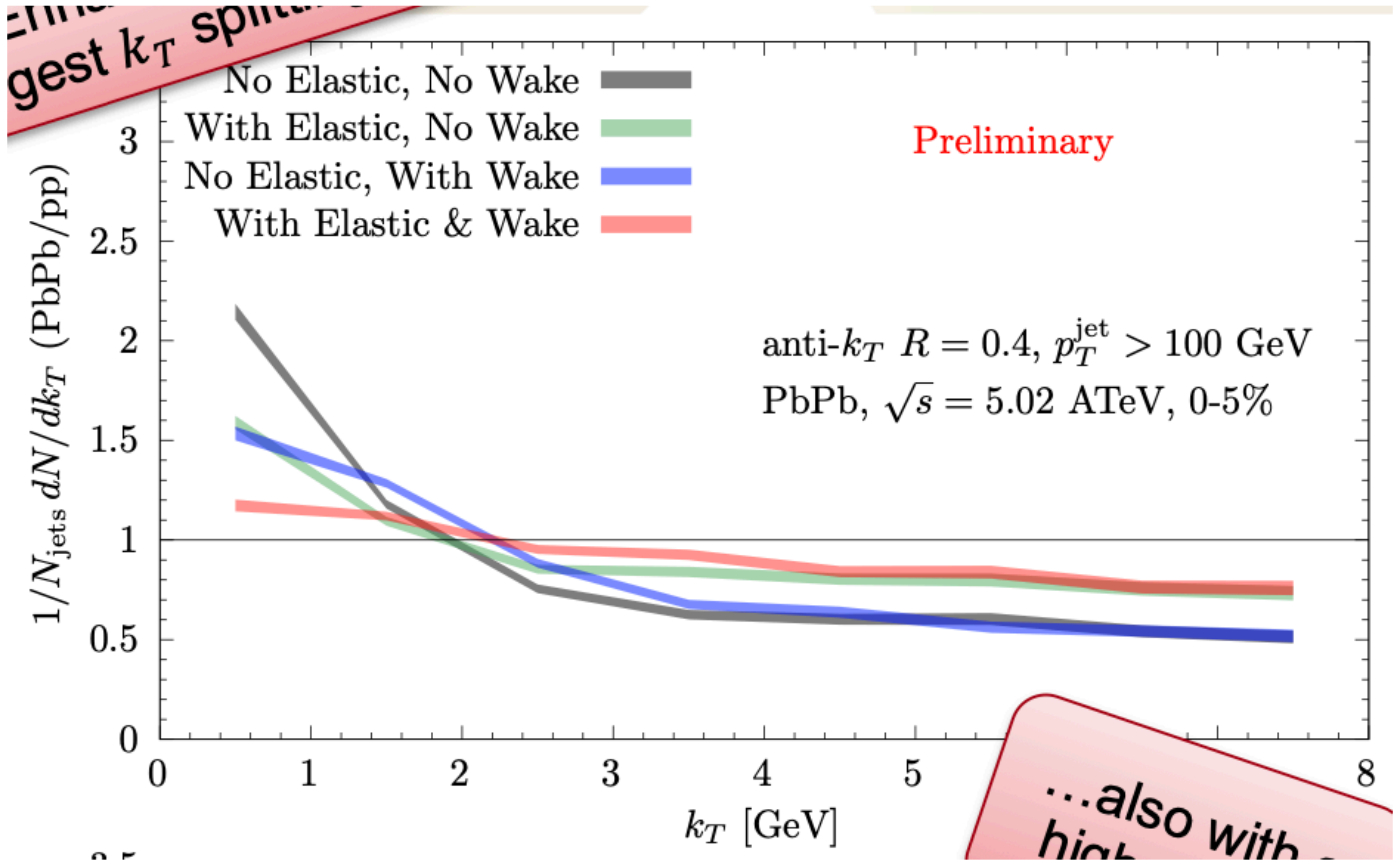


Moliere scattering in the QGP

Useful pheno tool to study observables sensitive to Moliere scattering

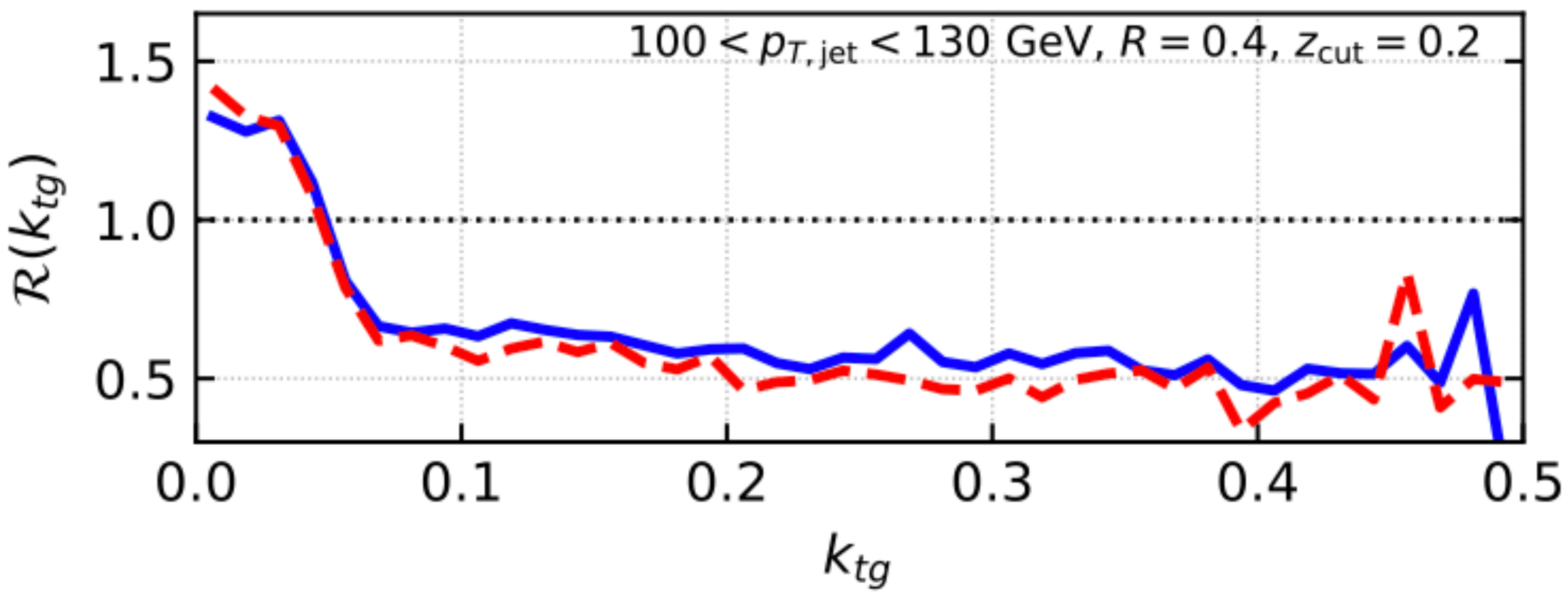
Recent developments in MCs allow further exploration in this direction

[Krishna Rajagopal HP23]



Hybrid model

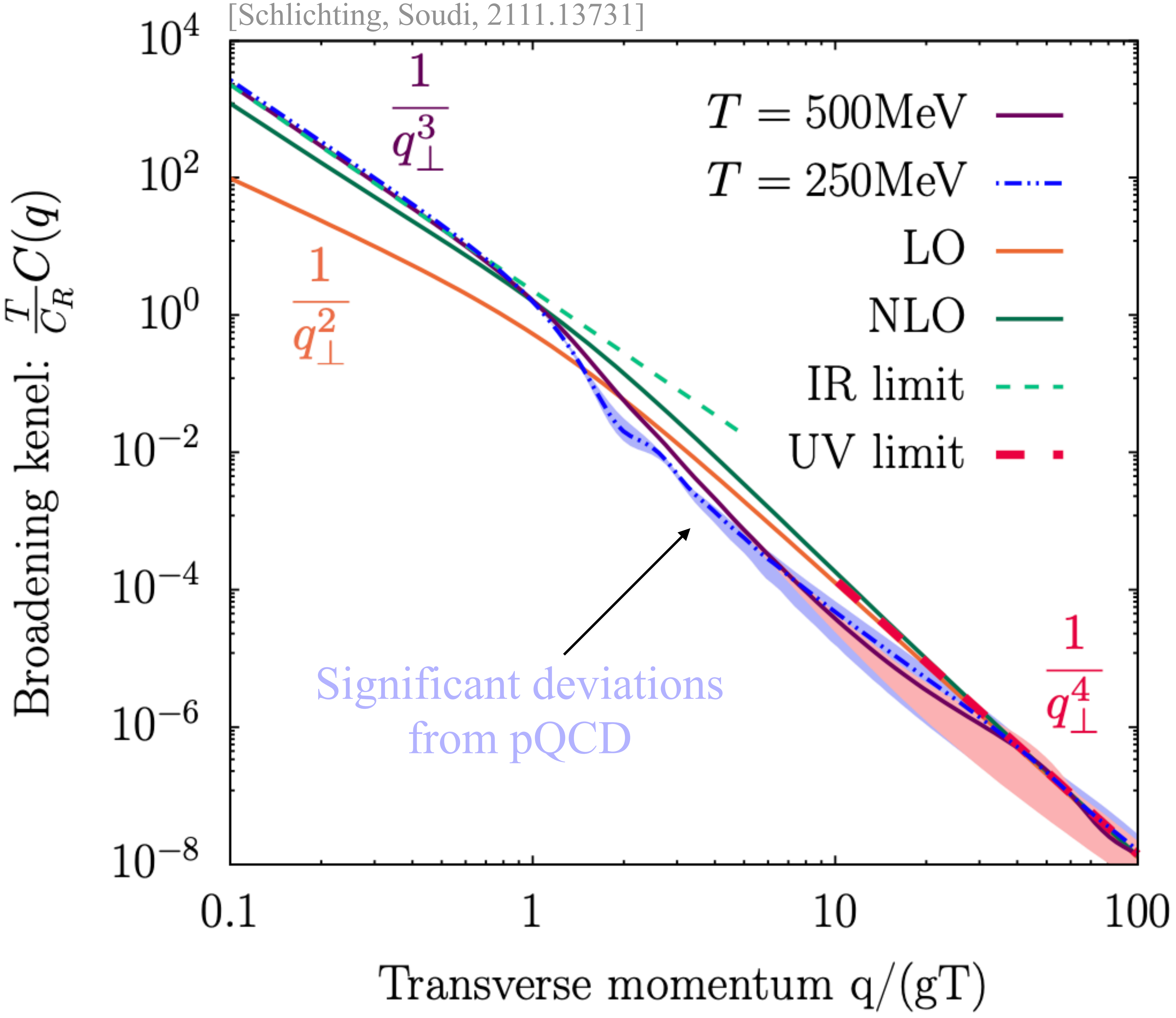
[Edmond Iancu HP23]



JetMed

Open question: are these the correct observables to see large angle kicks?

Corrections to the scattering kernel



New: scattering kernel interpolating between known results in IR and UV

UV: pQCD at NLO

[Arnold, Xiao, 2008]
[Ghiglieri, Kim, 2018]

IR: EQCD

[Aurenche, Gelis, Zaraket, 2002]
[Caron-Huot, 2008]

Behavior in IR modified due to non-perturbative screening

Quantum corrections to scattering rate

LO jet quenching parameter receives radiative corrections

New: DLA resummation of quantum fluctuations in jet quenching parameter

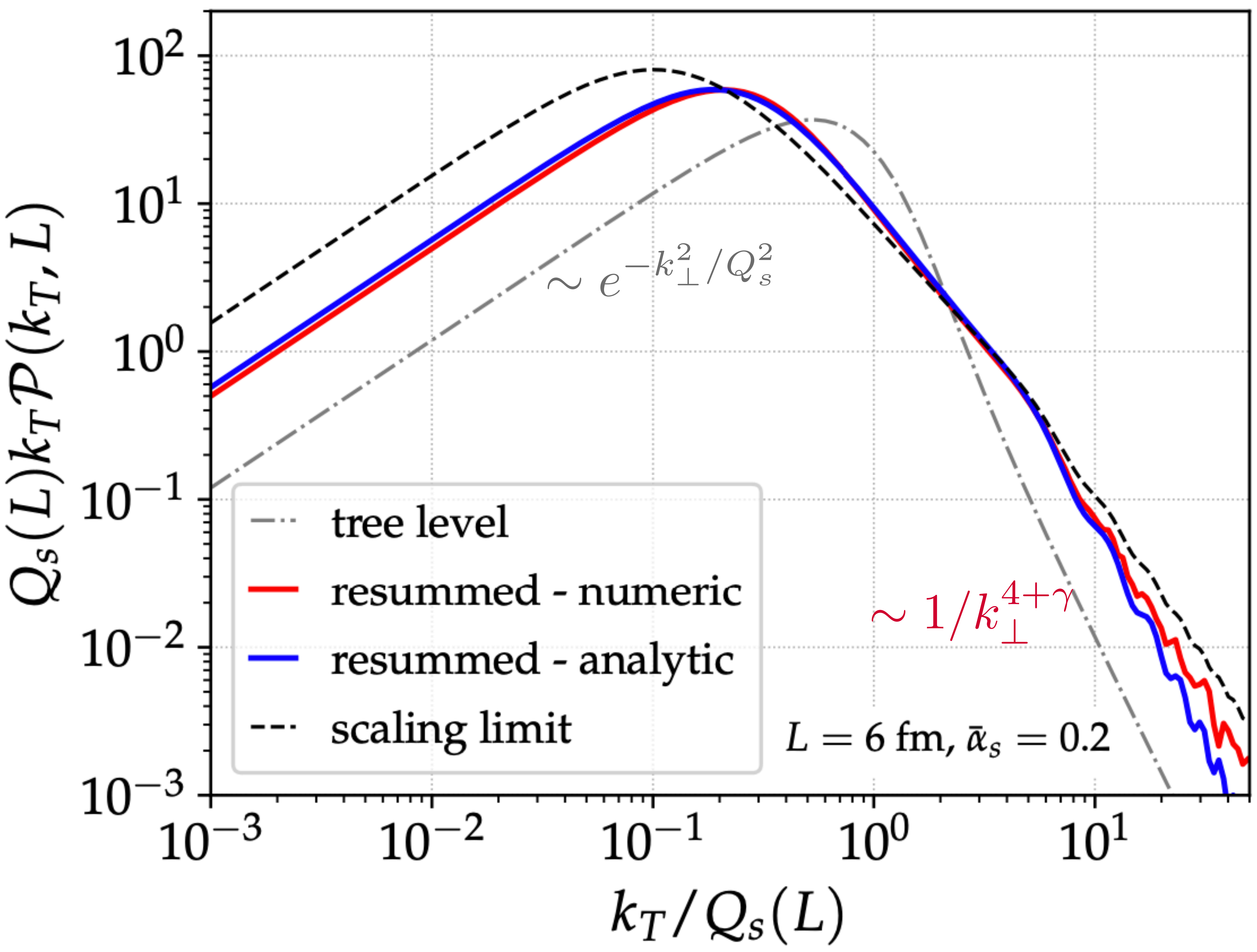
$$\hat{q}(\tau, \boldsymbol{k}_\perp^2) = \hat{q}^{(0)} + \int_{\tau_0}^{\tau} \frac{\mathrm{d}\tau'}{\tau'} \int_{Q_s^2(\tau')}^{\boldsymbol{k}_\perp^2} \frac{\mathrm{d}\boldsymbol{k}_\perp'^2}{\boldsymbol{k}_\perp'^2}\, \bar{\alpha}_s\, \hat{q}(\tau', \boldsymbol{k}_\perp'^2)$$

$$Q_s^2(\tau) = \hat{q}(\tau, Q_s^2(\tau))\tau\,,$$

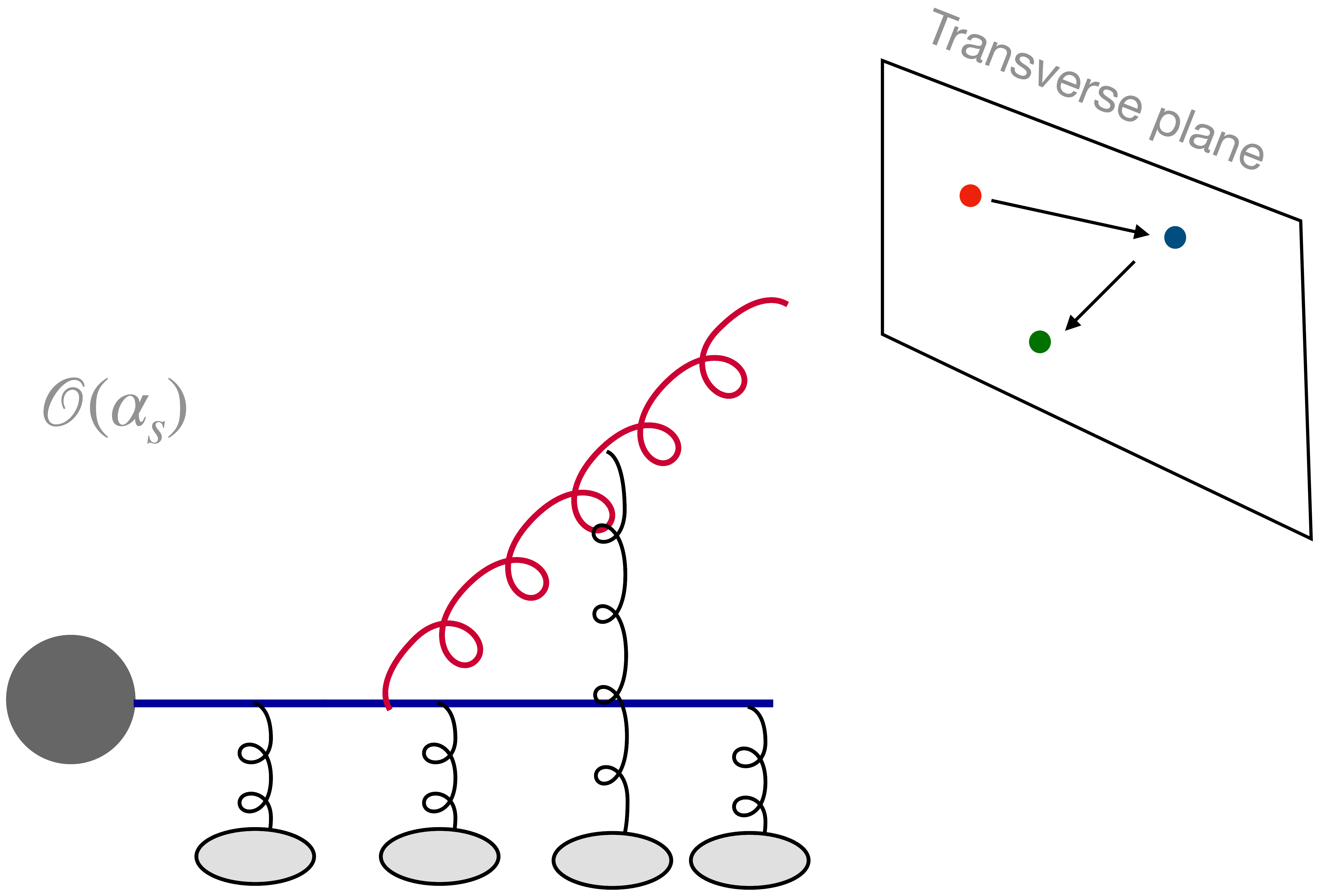
Logs come from gluon receiving a single hard kick from the medium

See also work on including classical corrections: [Ghiglieri, Weitz, 2207.08842]

[Caucal, Mehtar-Tani, 2109.12041]



Medium induced gluon spectrum

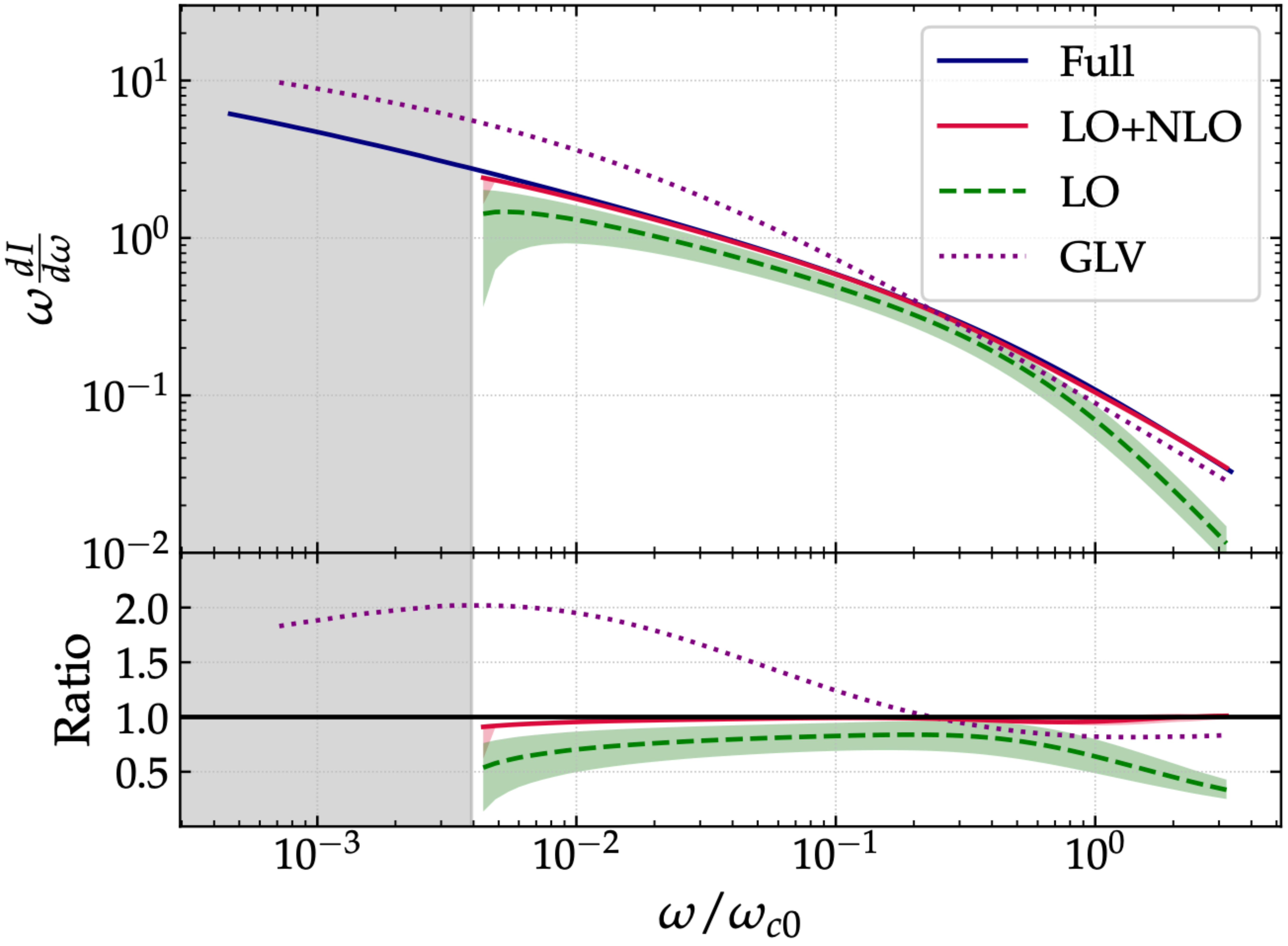


$$+ \quad \frac{dI}{d\omega}$$

In-medium gluon production

Some of the developments for momentum broadening can be extended to radiation

[JB et al, 2106.07402]

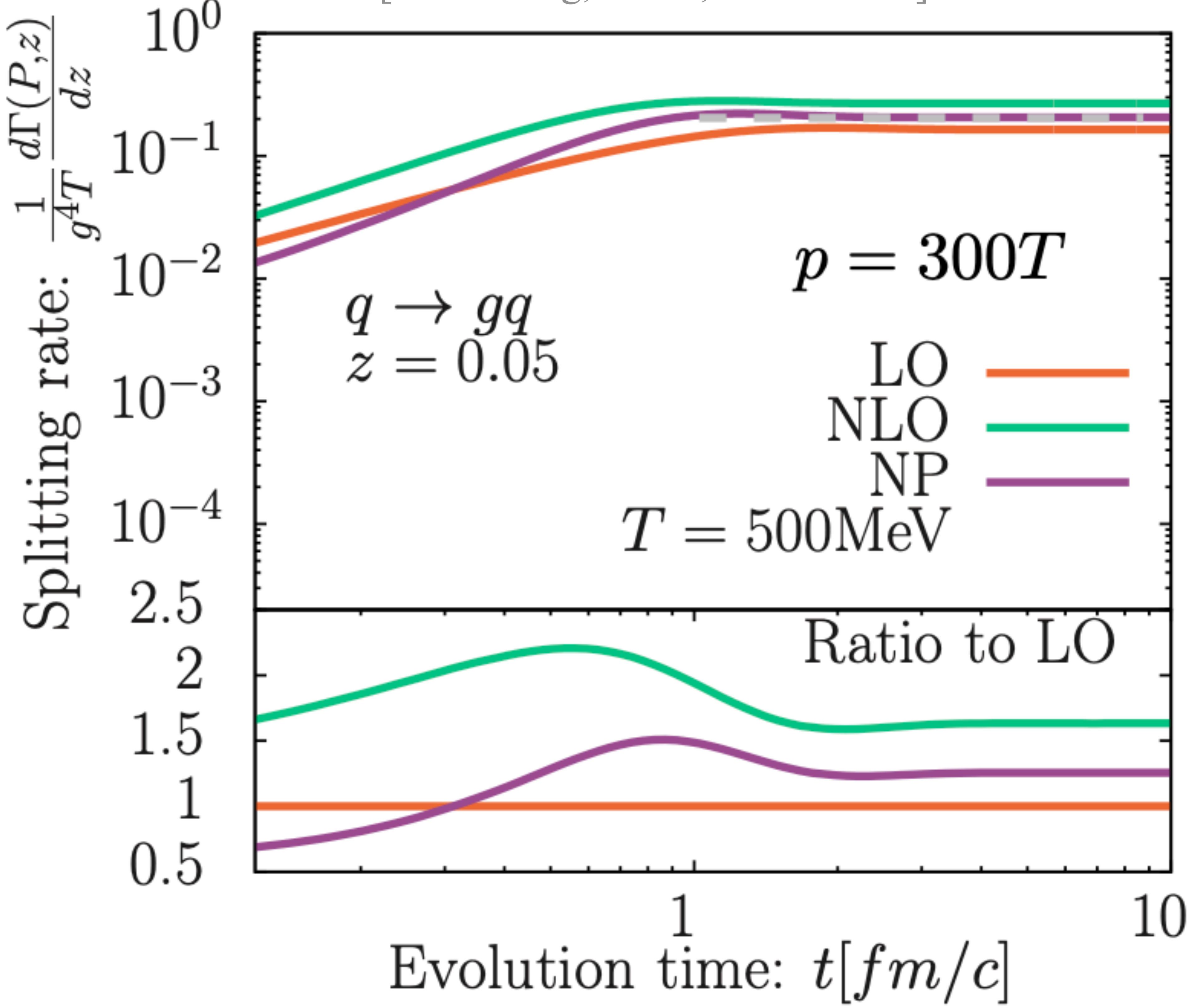


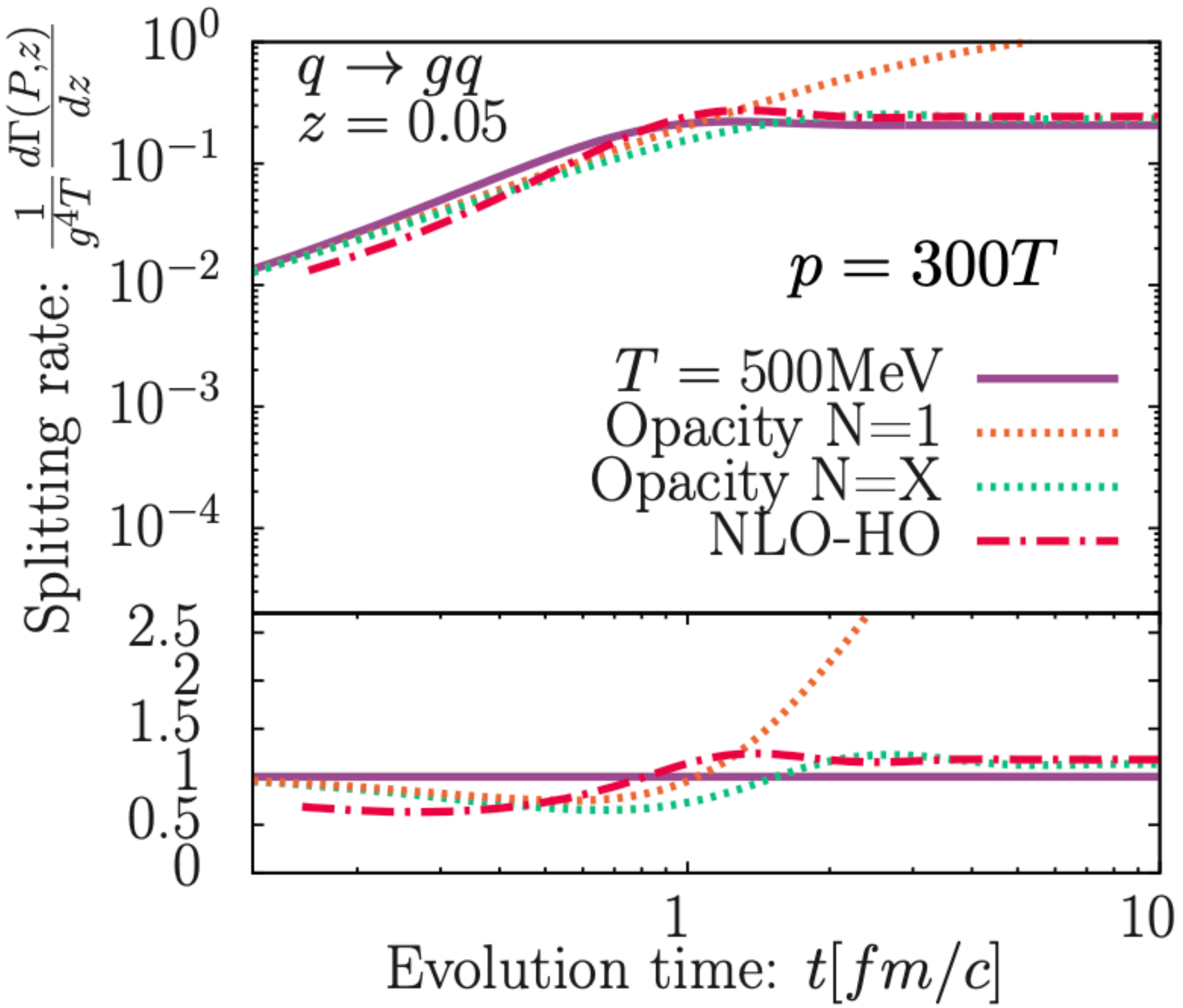
[Feal, 1811.01591]
[Andres, 2002.01517]
[Isaksen, 2206.02811]

In-medium gluon production

Some of the developments for momentum broadening can be extended to radiation

[Schlichting, Soudi, 2111.13731]

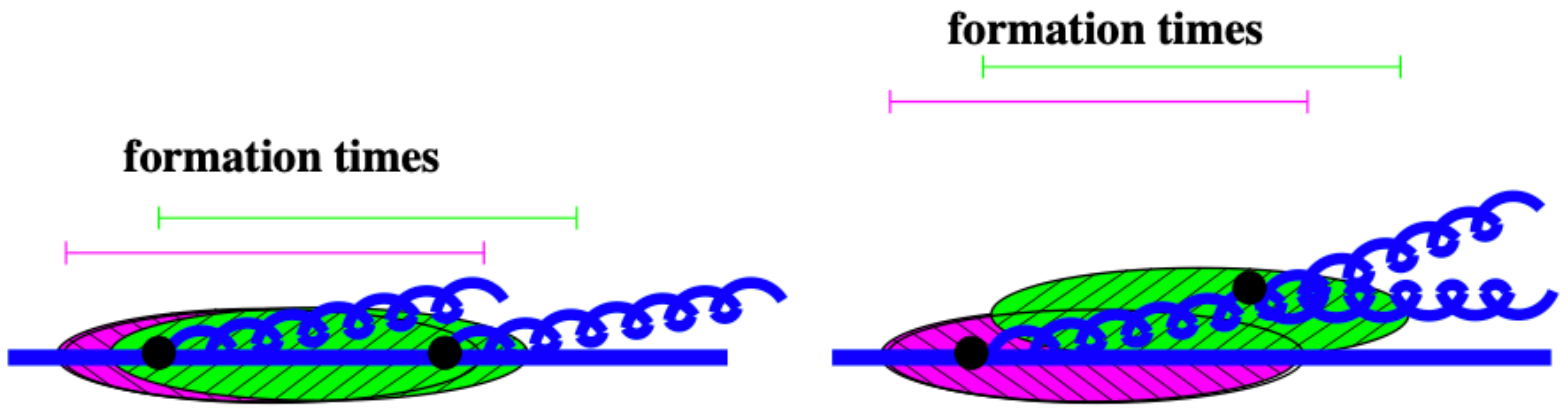




Dominant effect coming from collisional kernel
rather than approximation for the spectrum

Quantum corrections to splitting rate

Impressive multi year calculation to understand structure of double and single logs due to overlapping formation times [Arnold, ~2010-now]



New: corrections to Markovian picture for parton showers in medium are small

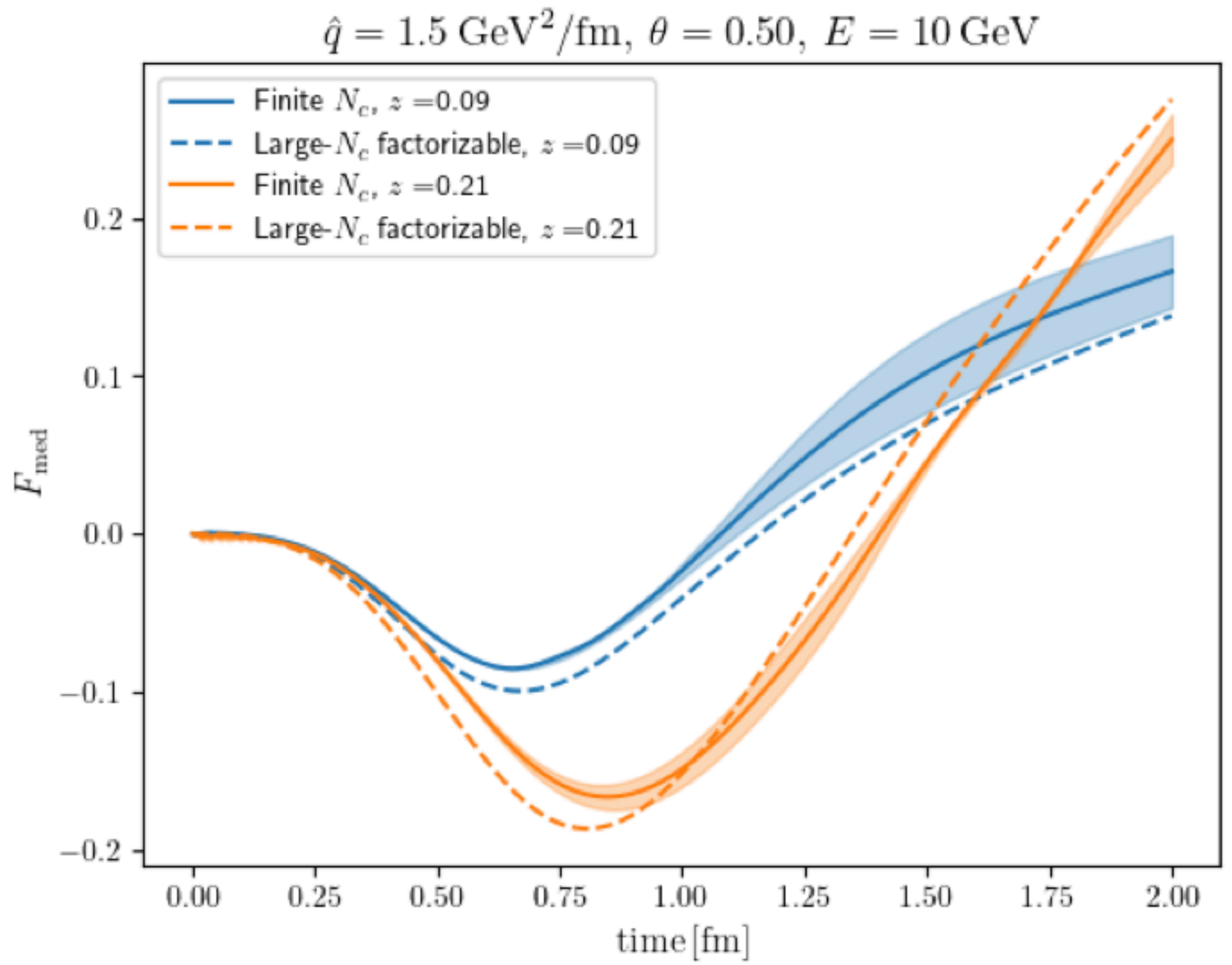
Radiative spectrum with full kinematics

So far, we have only been able to compute the radiative spectrum in the soft gluon limit

New: numerical strategy to compute spectrum at full kinematics

Still, requires solving hard evolution equations

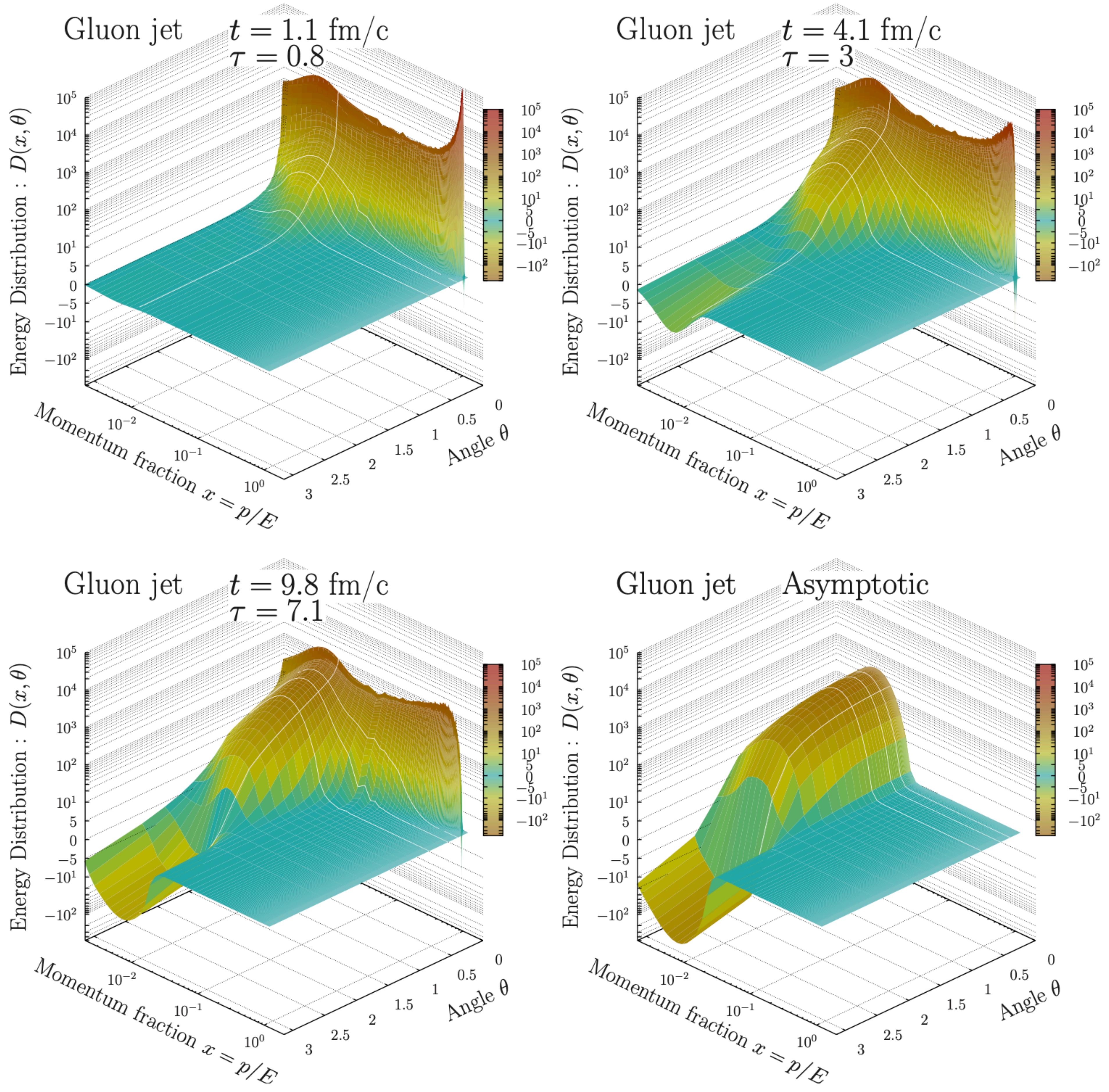
$$\left[i\frac{\partial}{\partial t} + \frac{\partial^2_{\boldsymbol{u}} - \partial^2_{\bar{\boldsymbol{u}}}}{2\omega} - i\mathbb{M}(\boldsymbol{u}, \bar{\boldsymbol{u}})\right] \mathcal{F}(\boldsymbol{u}, \bar{\boldsymbol{u}}|L) = -\frac{\omega}{\pi}\frac{\boldsymbol{u}}{\boldsymbol{u}^2} \cdot \partial_{\bar{\boldsymbol{u}}}\delta^2(\bar{\boldsymbol{u}})\, \mathrm{e}^{i\frac{\omega\Omega}{2}\cot(\Omega L)\boldsymbol{u}^2}$$



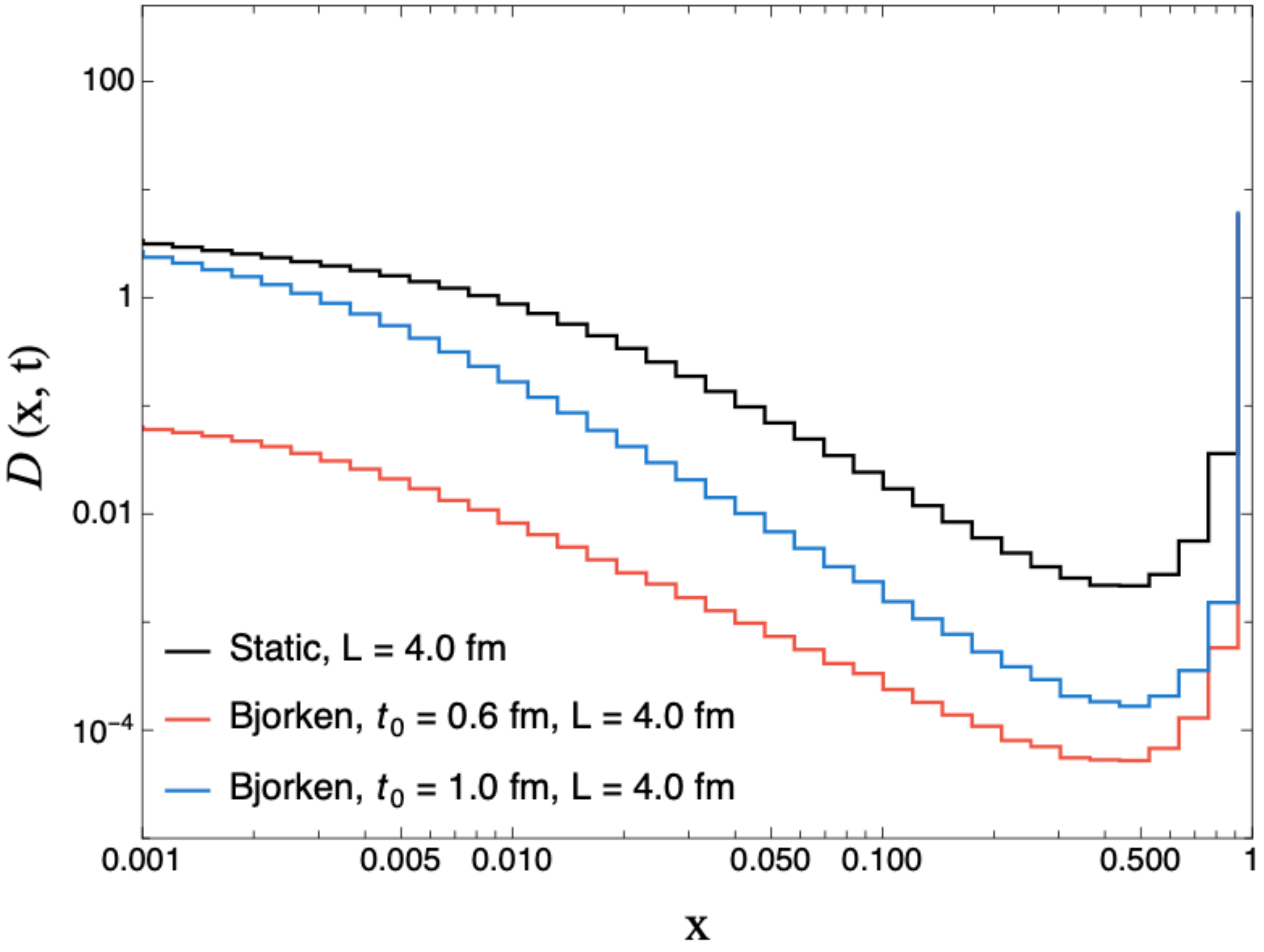
In medium cascade and jet thermalization

New: solutions for EKT describing the jet, including medium response and expansion

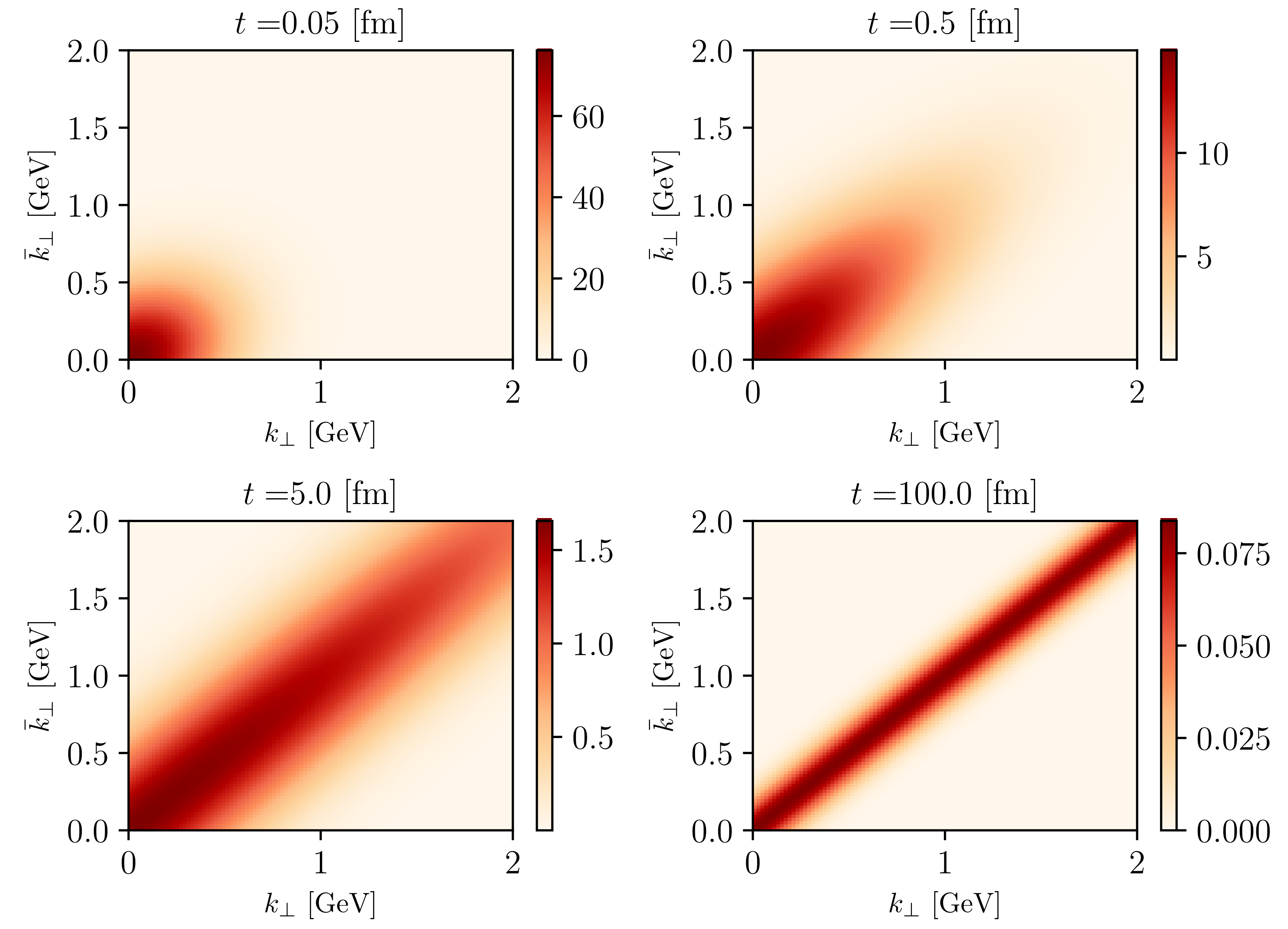
[Mehtar-Tani et al, 2209.10569]



[Adhya et al, 2210.15803]



Some Extra Topics



QIS applications in jet : Quantum simulation

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Parton showers

A quantum algorithm for high energy physics simulations

Benjamin Nachman,* Davide Provasoli,† and Christian W. Bauer‡
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Wibe A. de Jong§

arXiv:1904.03196v2 [hep-ph] 24 Dec 2019

Quantum walk approach to simulating parton showers

Khadeejah Bepari,[a] Sarah Malik,[b] Michael Spannowsky[a] and Simon Williams[c]

arXiv:2109.13975v2 [hep-ph] 5 Sep 2022

Jet clustering optimization

Quantum Algorithms for Jet Clustering

Annie Y. Wei,[1,*] Preksha Naik,[1,†] Aram W. Harrow,[1,‡] and Jesse Thaler[1,2,§]

arXiv:1908.08949v2 [hep-ph] 5 May 2020

Quantum Annealing for Jet Clustering with Thrust*

Andrea Delgado[1,†] and Jesse Thaler[2,‡]

arXiv:2205.02814v1 [quant-ph] 5 May 2022

A Digital Quantum Algorithm for Jet Clustering in High-Energy Physics

Diogo Pires[1,†], Pedrame Bargassa[2,3,††], João Seixas[1,4,‡], and Yasser Omar[1,2,‡‡]

arXiv:2101.05618v1 [physics.data-an] 11 Jan 2021

EFT approaches

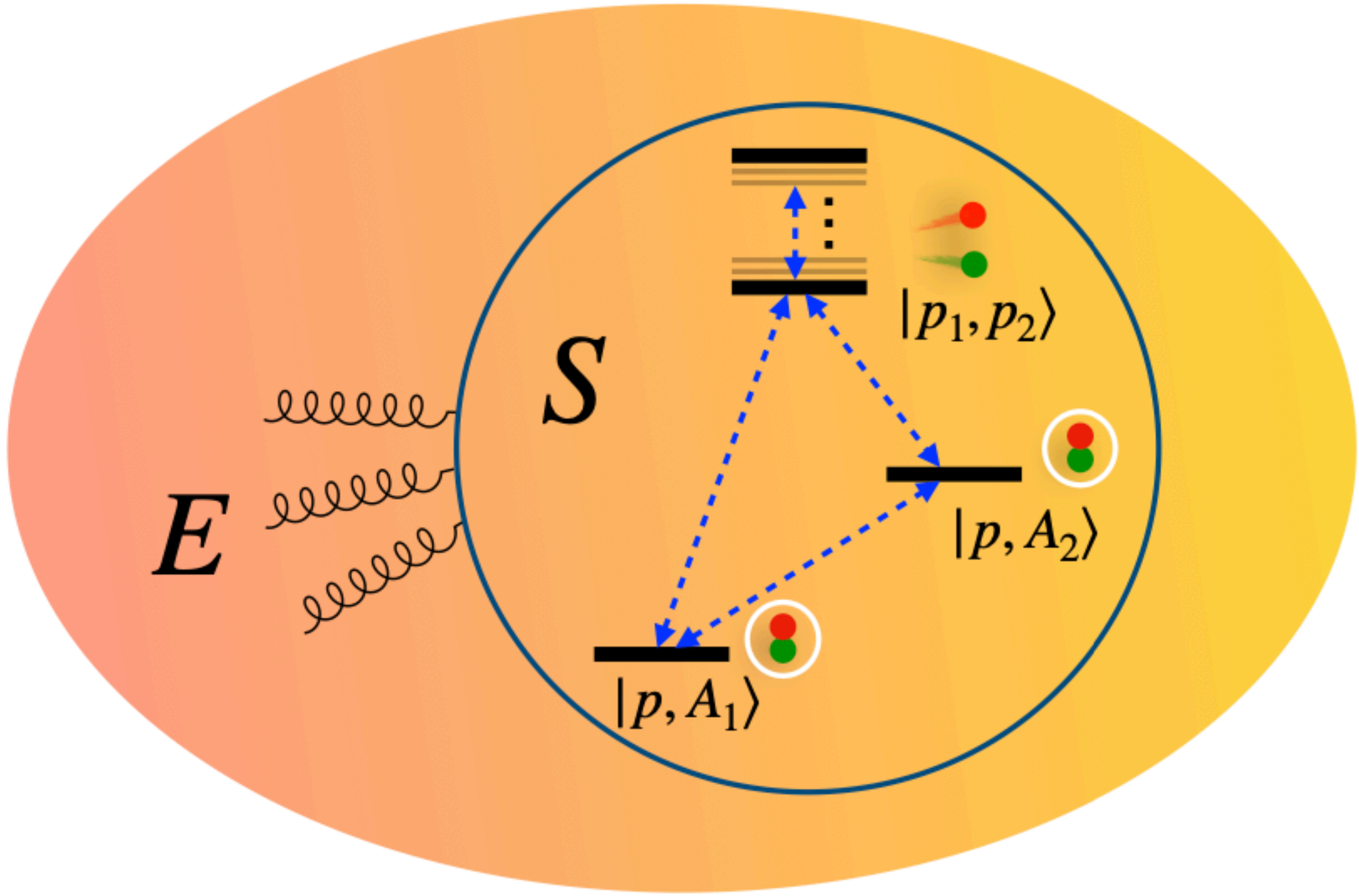
Simulating collider physics on quantum computers using effective field theories

Christian W. Bauer* and Benjamin Nachman† Marat Freytsis‡

arXiv:2102.05044v1 [hep-ph] 9 Feb 2021

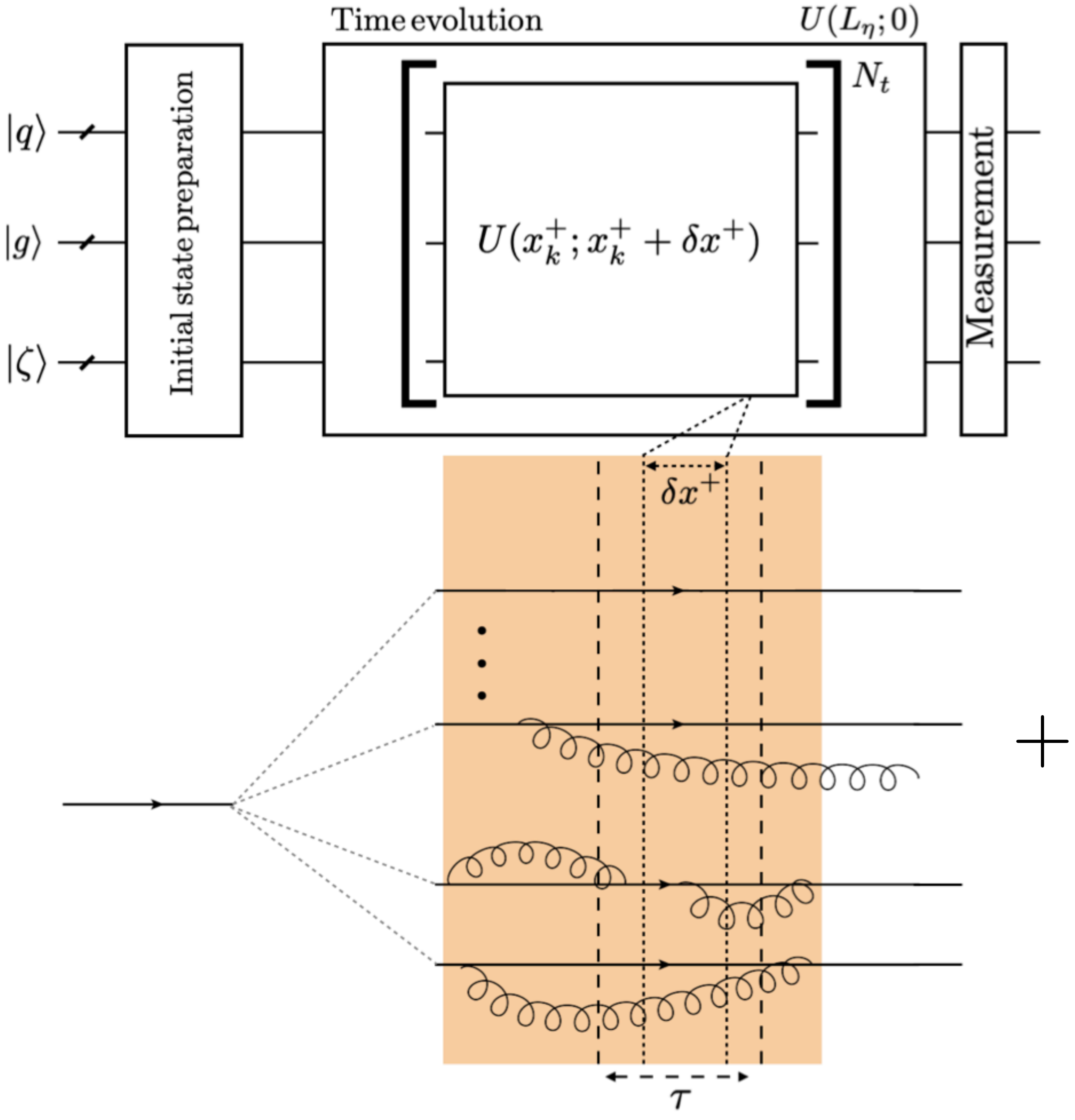
QIS applications in jet : Quantum simulation

[de Jong et al, 2010.0357]



$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_S(t) = -i[H_{S1}(t) + H_L, \rho_S(t)] + \sum_{j=1}^{m}\left(L_j\rho_S(t)L_j^\dagger - \frac{1}{2}\{L_j^\dagger L_j, \rho_S(t)\}\right)$$

[JB et al, 2307.01792]



$+\mathcal{O}(\alpha_s^2)$

QIS applications in jet : Entropy measures

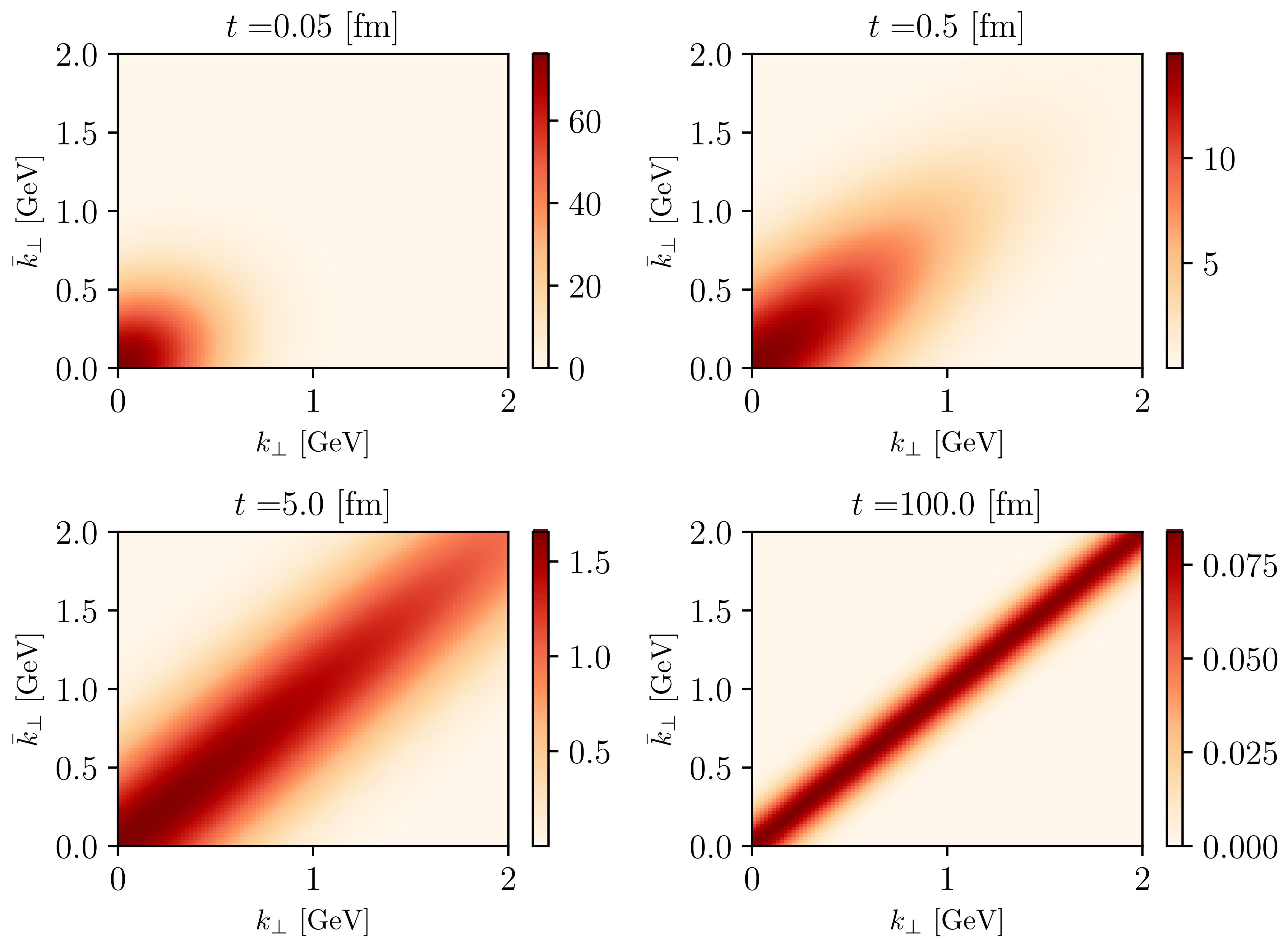
The Entropy of a Jet

Duff Neill[1] and Wouter J. Waalewijn[2, 3]

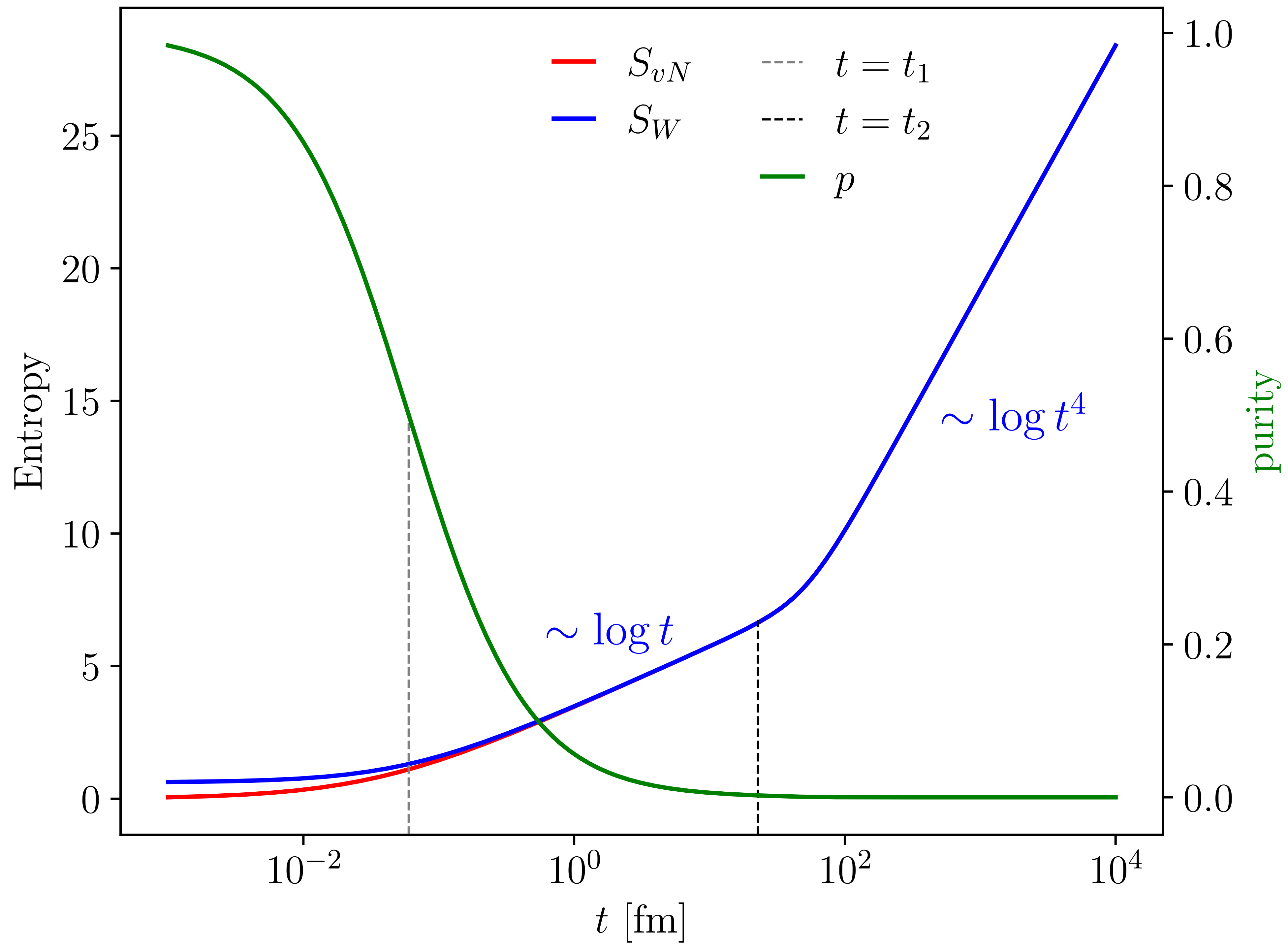
$$\mathcal{S}_i(E,R) = \mathcal{F}_i(E,R) + \int_{z_c}^{1} \frac{\mathrm{d}z}{z} \int_{R_c}^{R} \frac{\mathrm{d}\theta}{\theta} \frac{2\alpha_s(zE\theta)C_i}{\pi} e^{-\Delta_i(R,\theta)} \left[\mathcal{S}_g(zE,\theta) + \mathcal{S}_i(E,\theta)\right],$$

$$\mathcal{F}_i(E,R) = \Delta_i(R,R_c)\, e^{-\Delta_i(R,R_c)} + \int_{z_c}^{1} \frac{\mathrm{d}z}{z} \int_{R_c}^{R} \frac{\mathrm{d}\theta}{\theta} \frac{2\alpha_s(zE\theta)C_i}{\pi} e^{-\Delta_i(R,\theta)} \left[\Delta_i(R,\theta) - \ln\left(\frac{8\pi C_i \alpha_s(zE\theta)\Lambda^2}{z^2\theta^2E^2}\right)\right]$$

New: first steps towards understanding decoherence of jets in the medium



[JB et al, 2305.10476]



Phenomenological developments: ENCs

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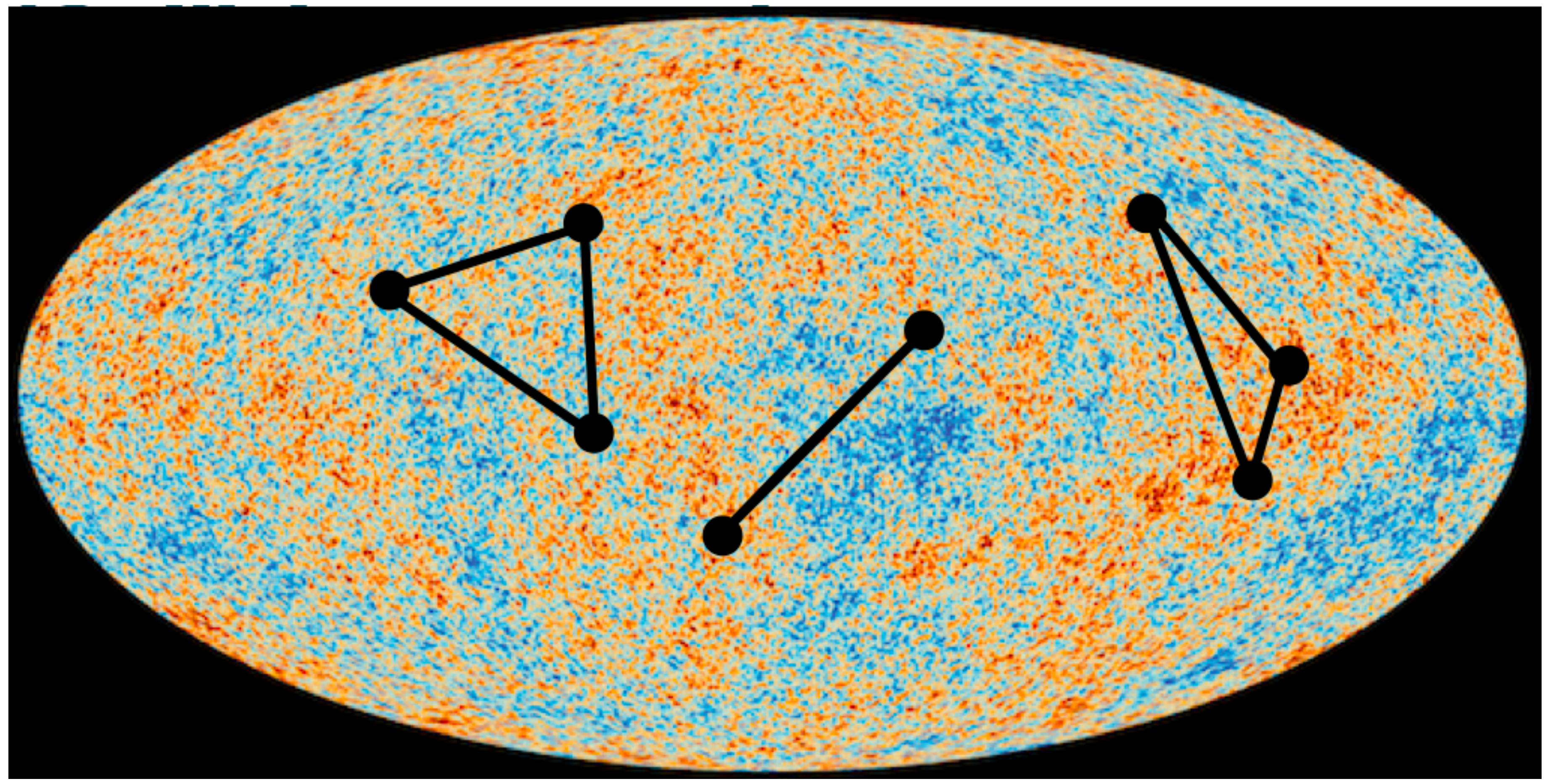
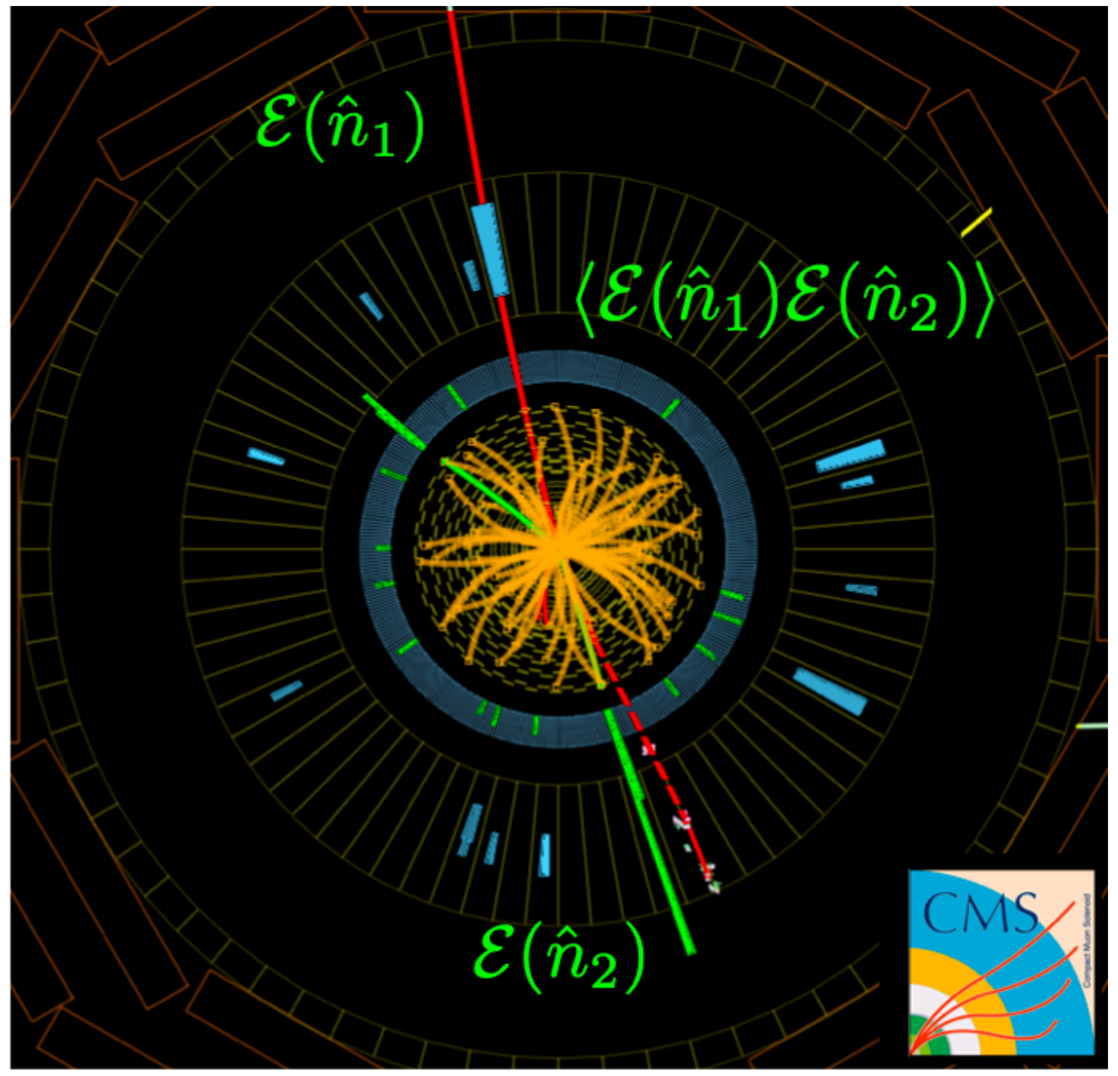
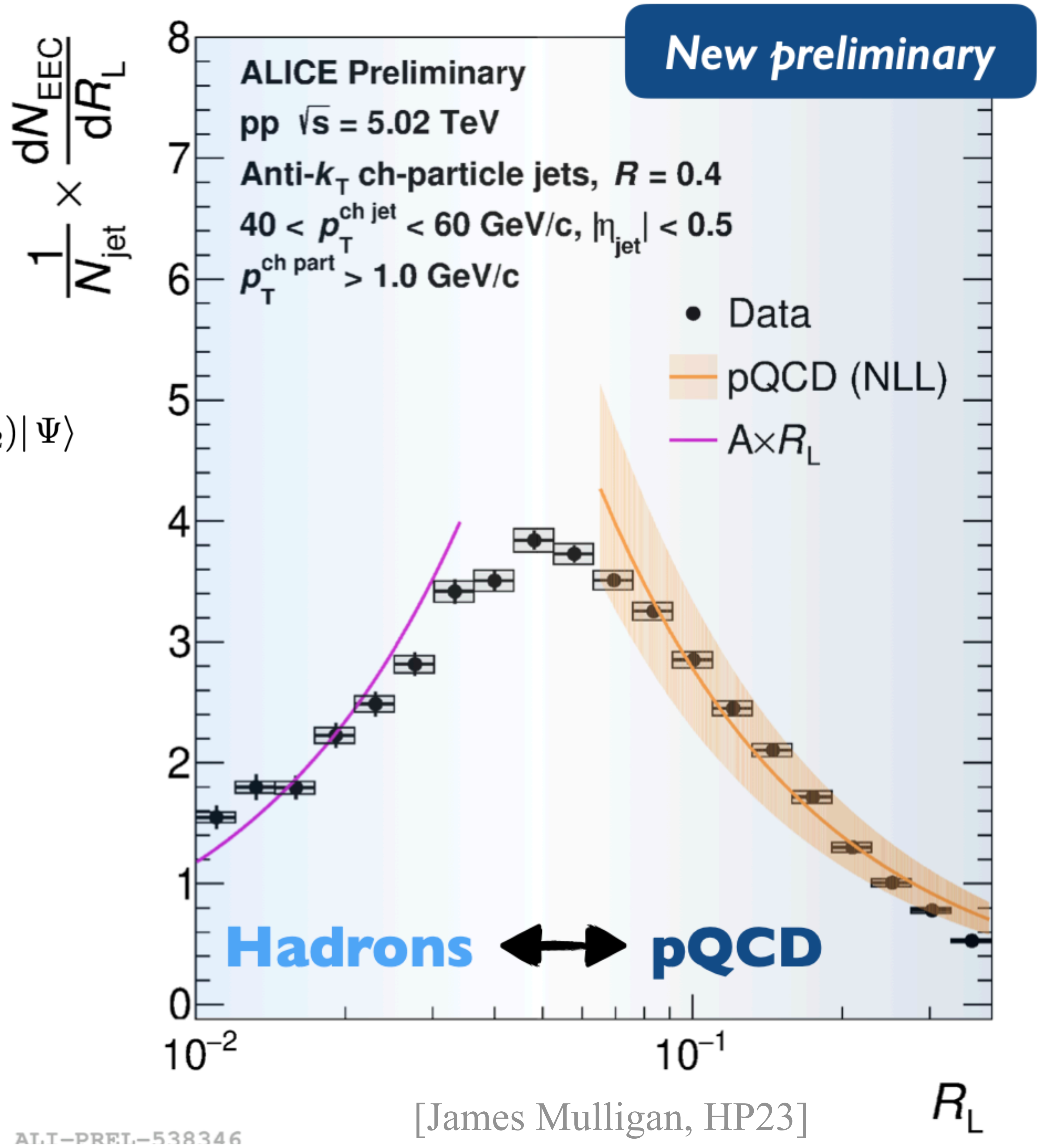


$$\mathcal{E}(\hat{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\hat{n})$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta} = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\theta - \theta_{ij}\right) \sim \langle \Psi | \mathcal{E}(\hat{n}_1) \mathcal{E}(\hat{n}_2) | \Psi \rangle$$



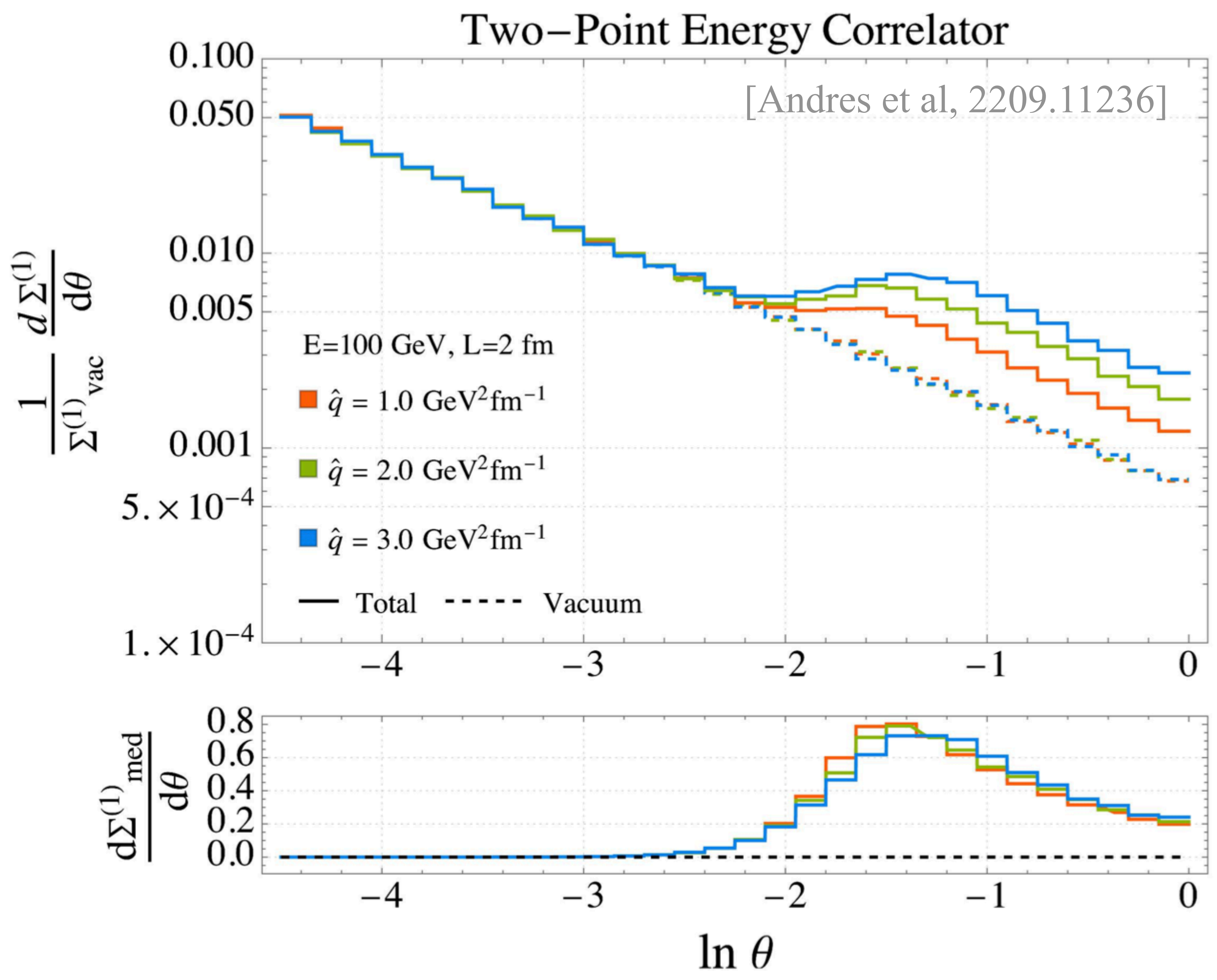
New: Energy correlations within jets provide a new way to study substructure

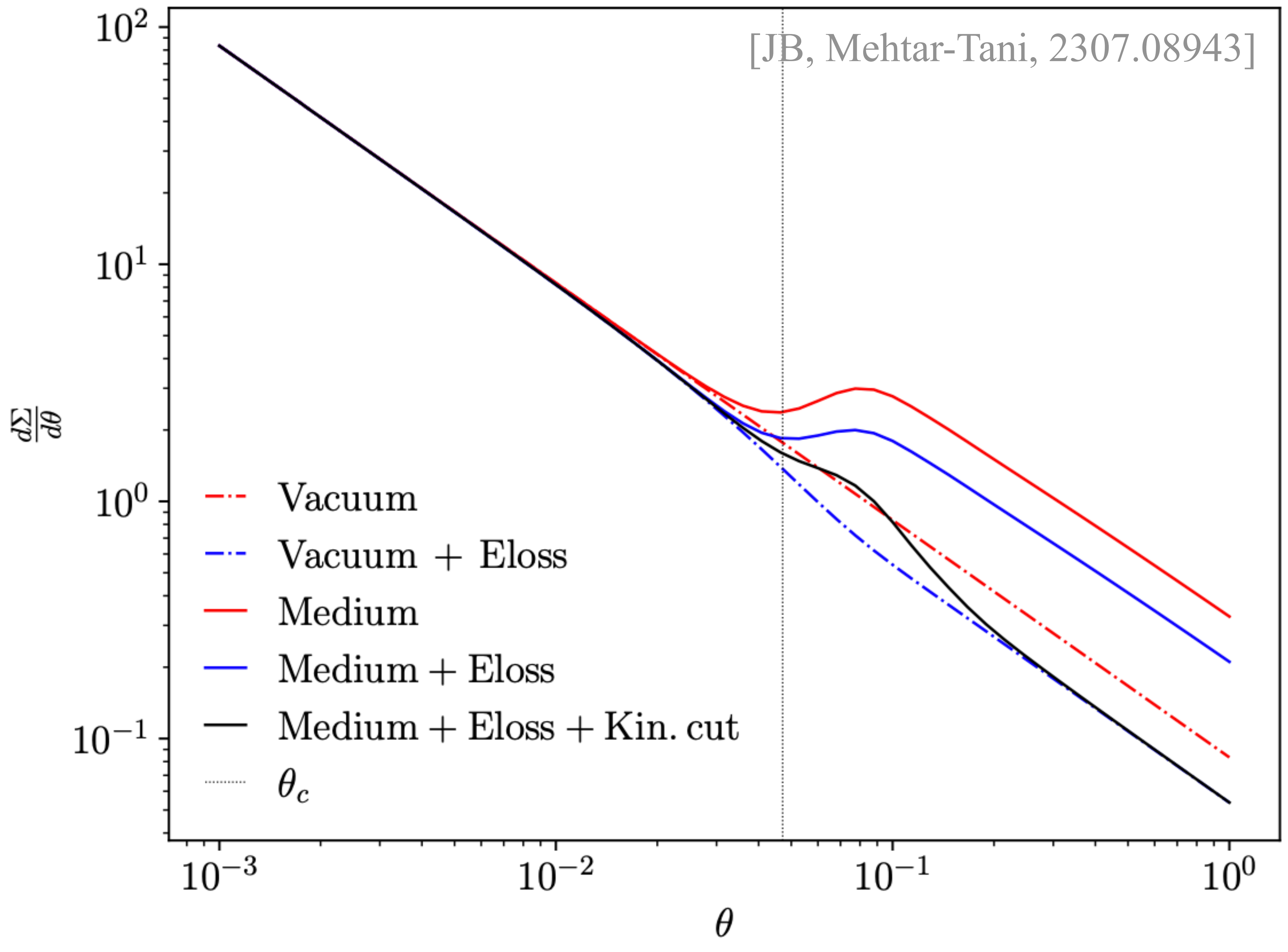


[James Mulligan, HP23]

Phenomenological developments: ENCs

New: EECs can be used to measure critical coherence scale inside the jet





Full picture for this observable in HICs is still not clear, possible competing effects to be studied

Summary

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- I tried to give overall picture of recent developments on jets, in the context of HICs

- Many exciting new developments: Jets in flowing matter

  Jets in matter out of equilibrium

  More complete understanding of the radiative spectrum

  …

- I omitted several new ideas: Medium induced radiation inside the dead cone

  Kinetic theory approach to jet quenching

  MC development and parton showers in matter