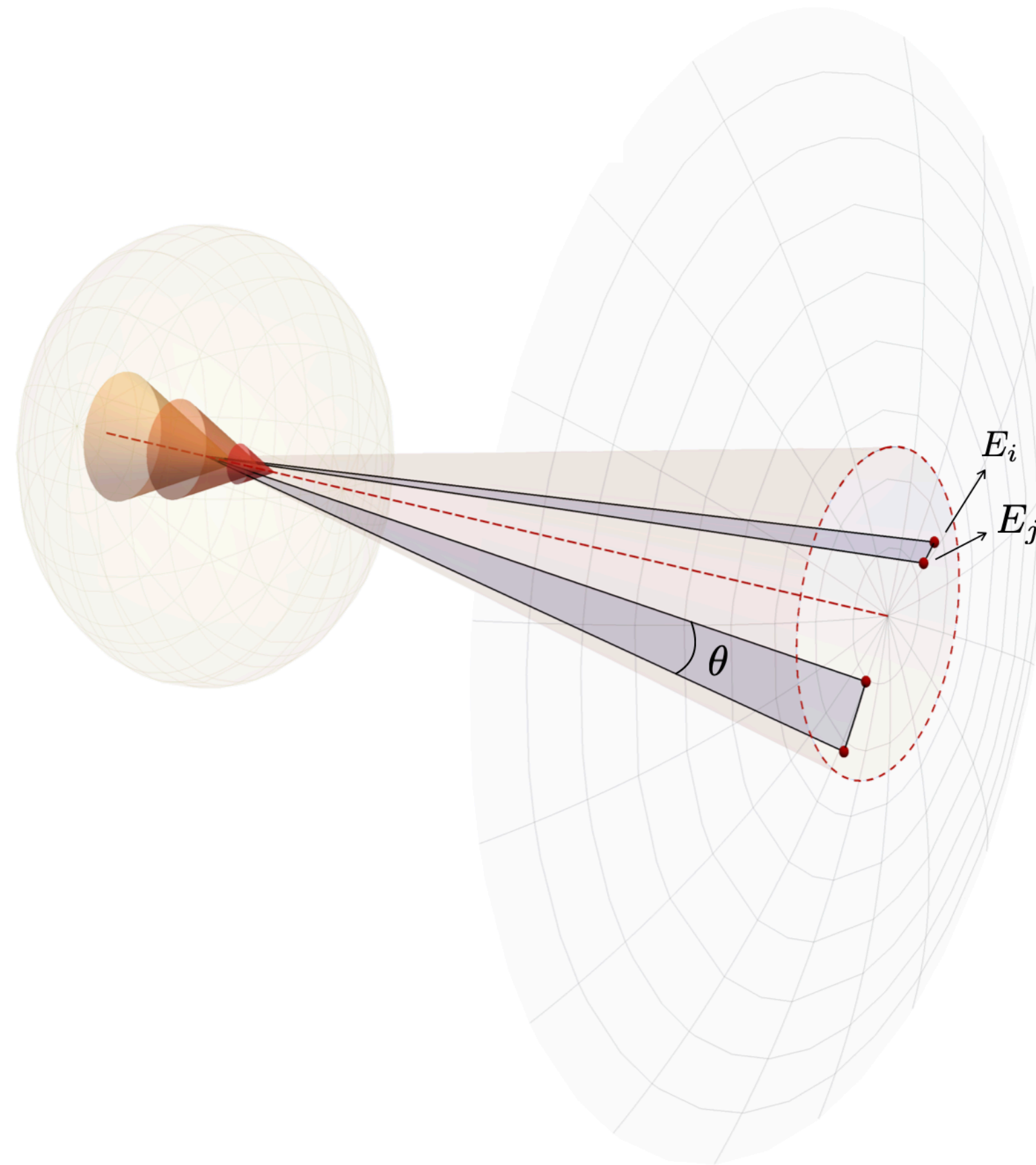


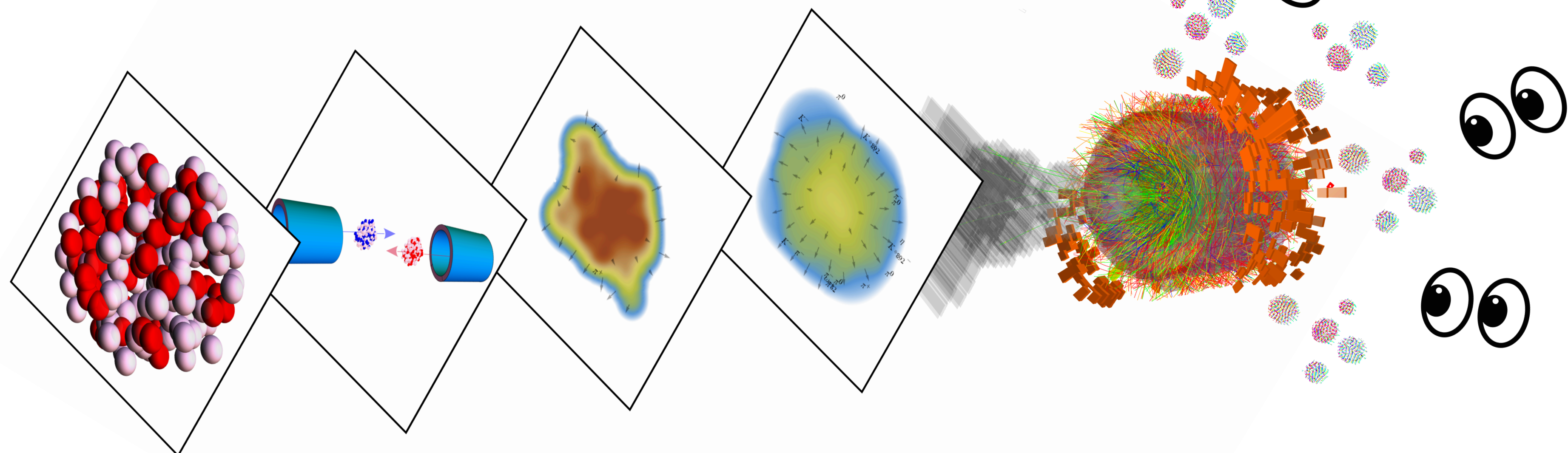
# Jets in Heavy Ion Collisions

*RHIC/AGS User's meeting, 11th May 2026*

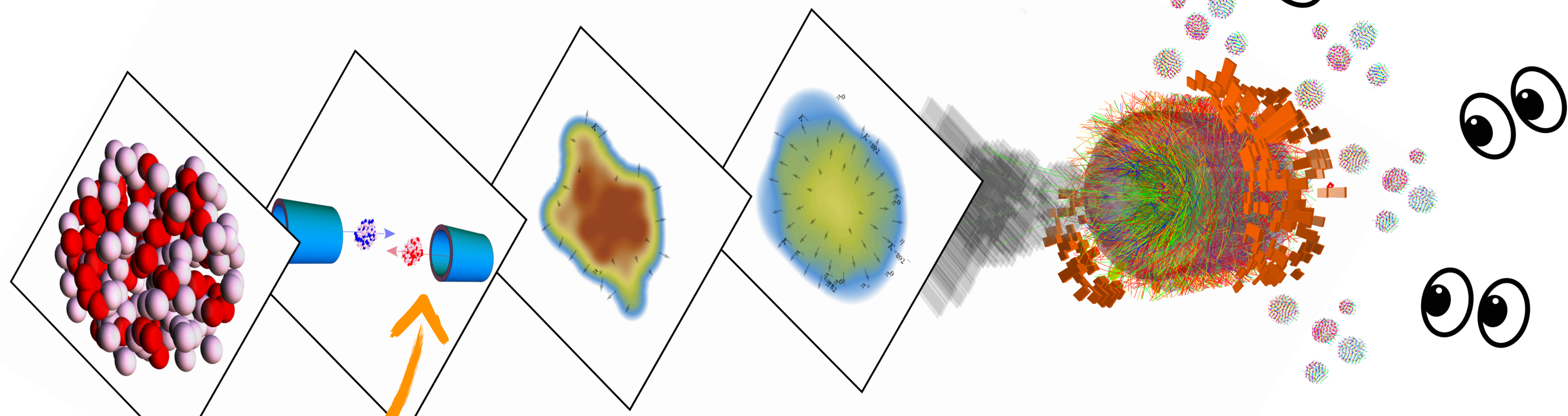


*João Barata, CERN-TH*

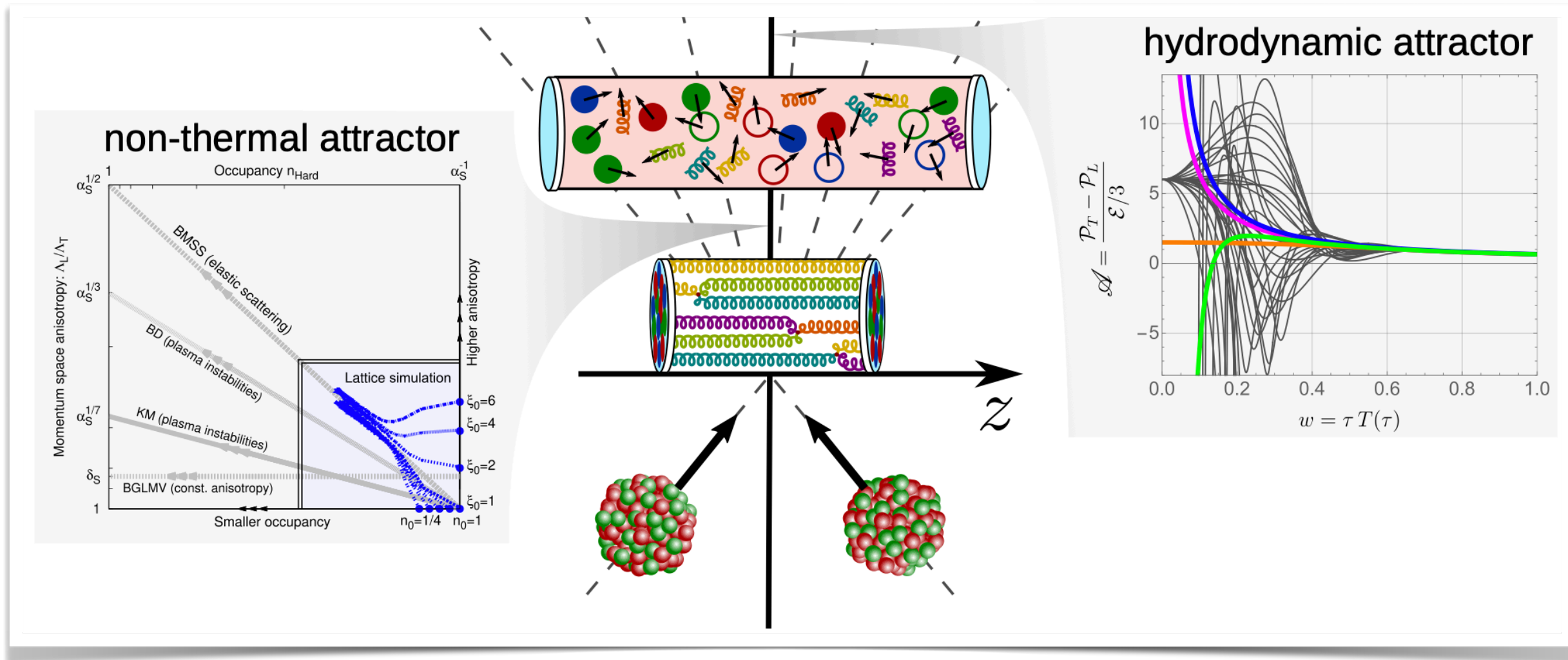
# An overview of heavy ion collisions



# An overview of heavy ion collisions

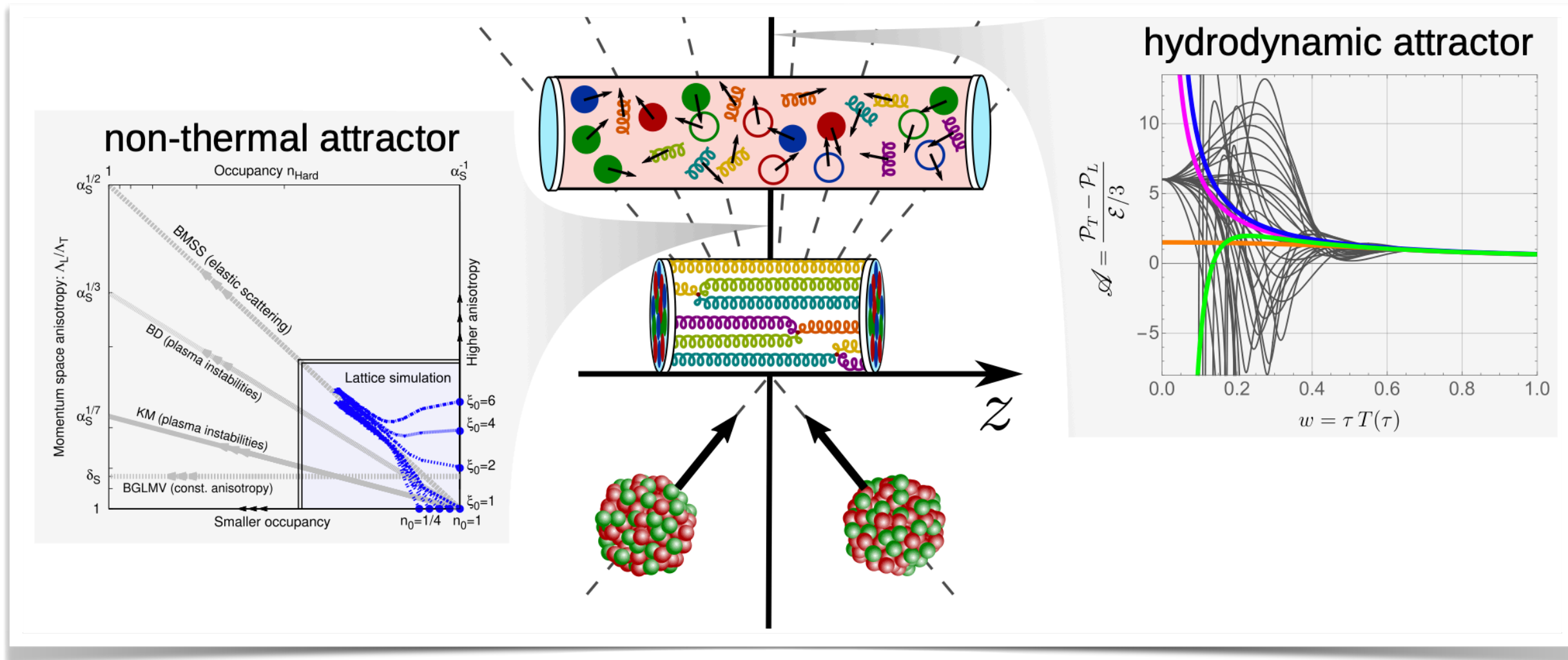
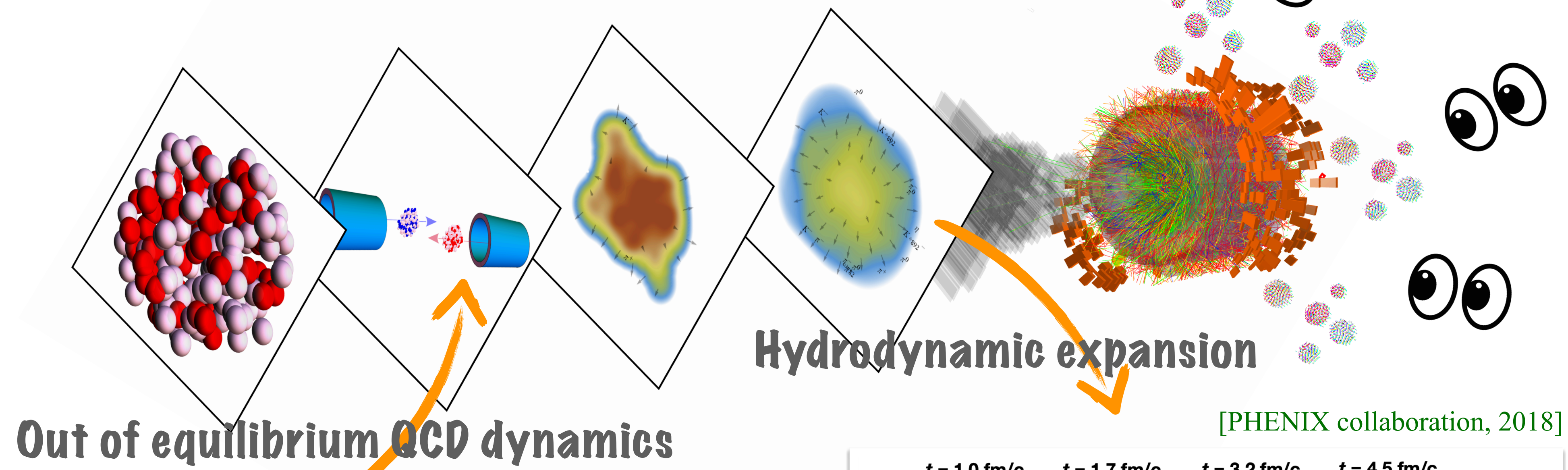


**Out of equilibrium QCD dynamics**

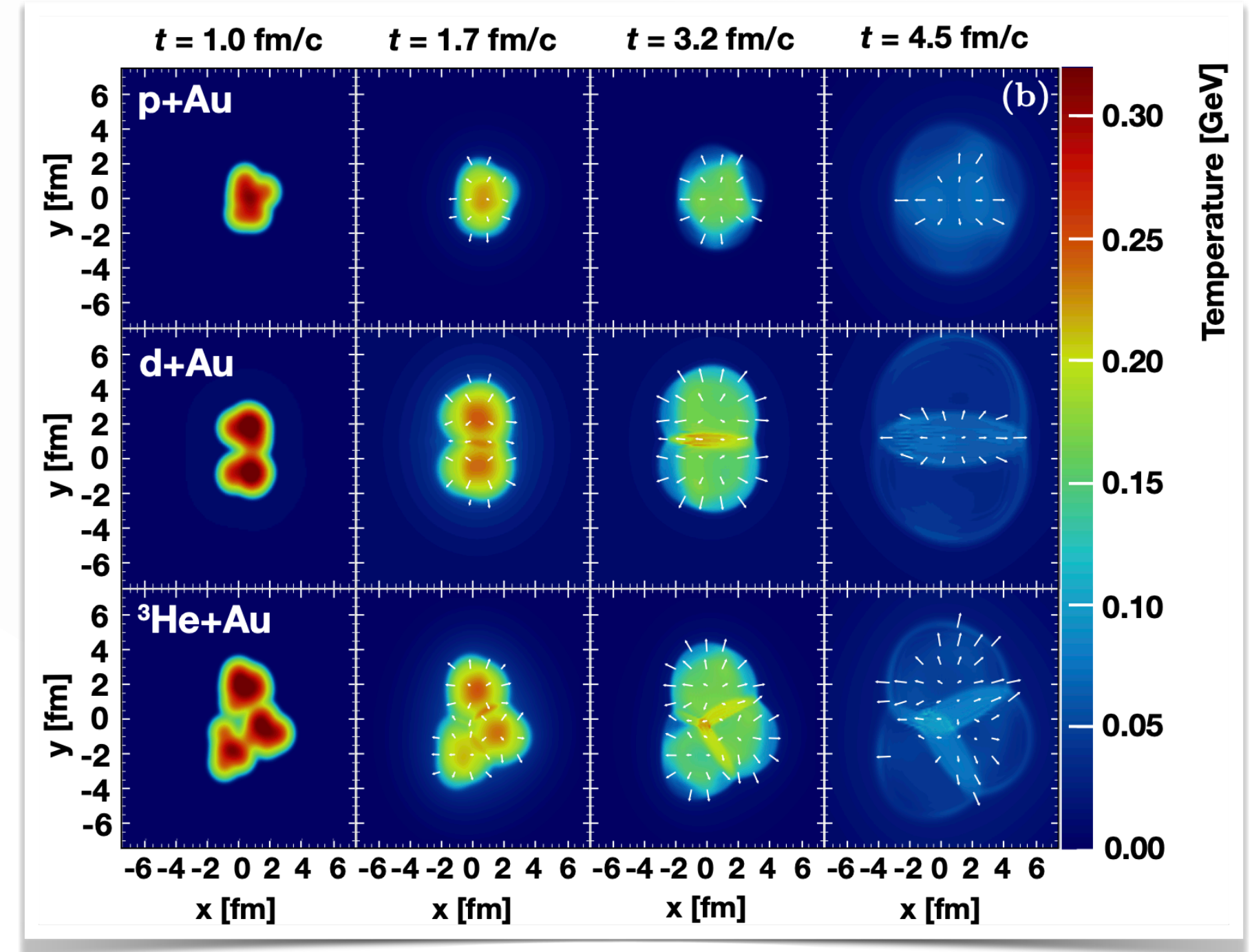


[Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299]

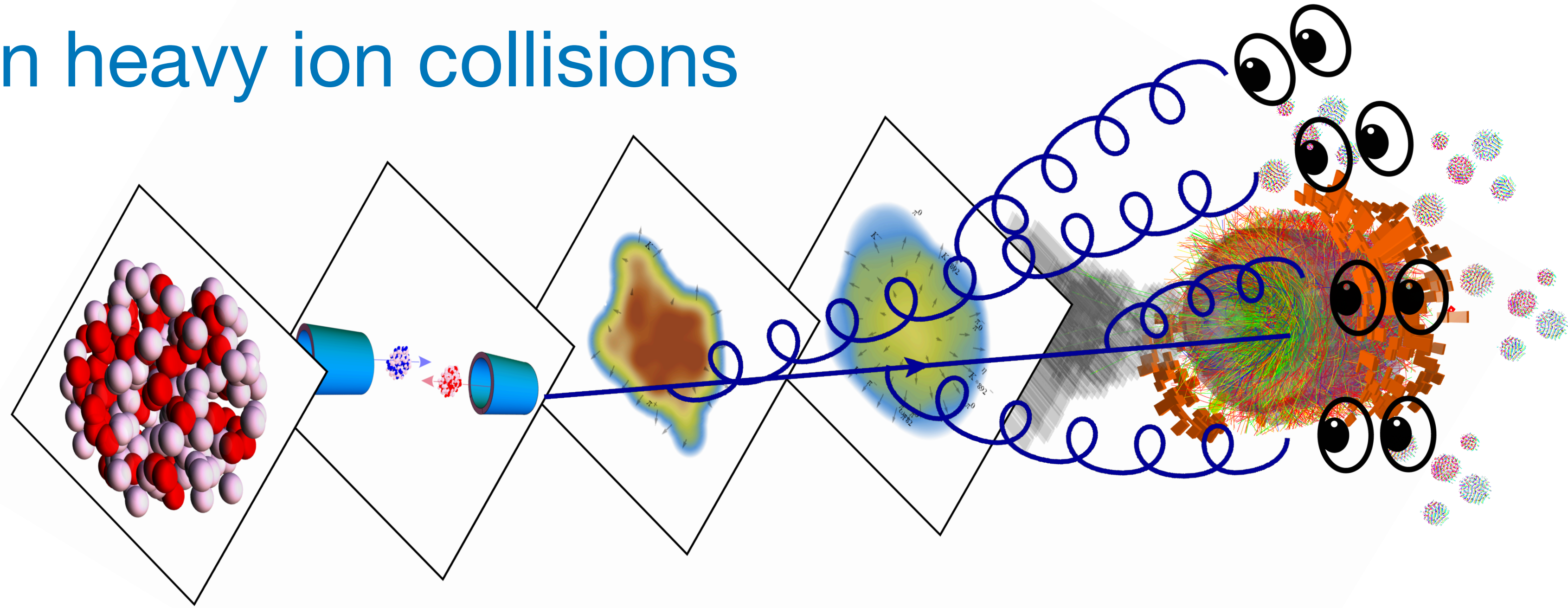
# An overview of heavy ion collisions



[Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299]

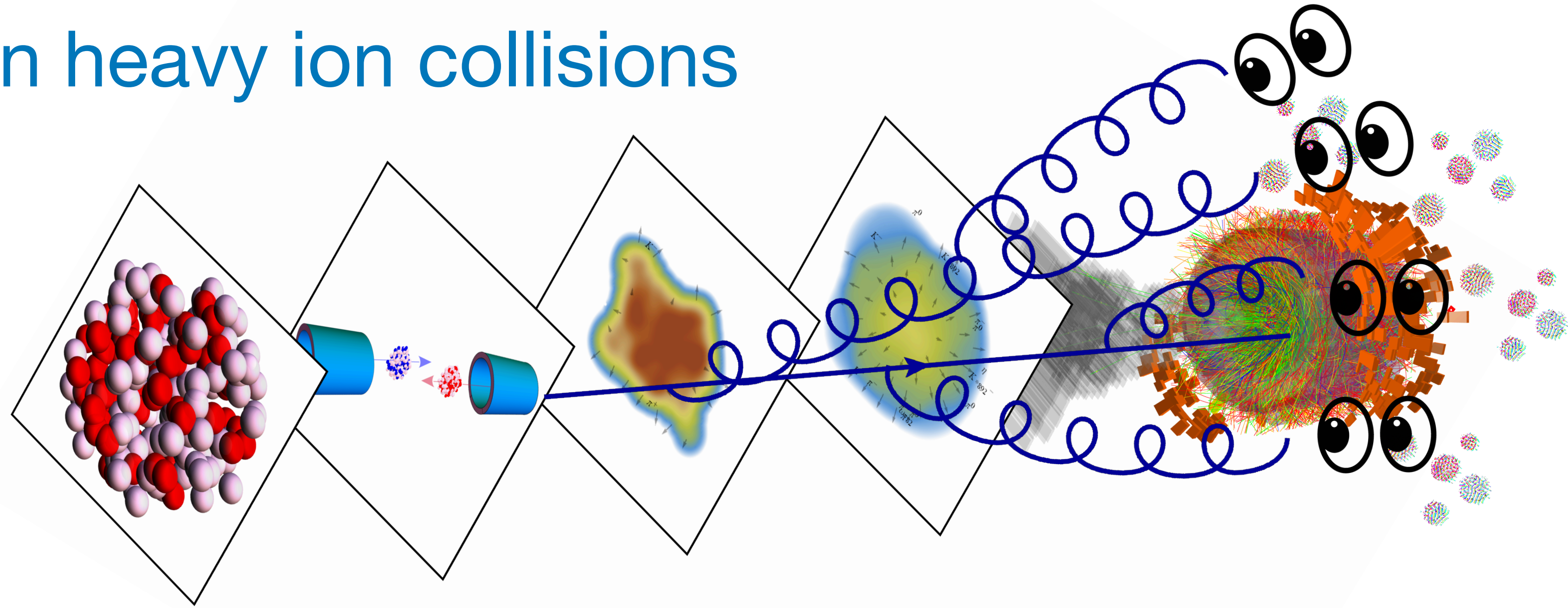


# The birth jets in heavy ion collisions



The measurement of jets offers a complementary (more differential) view of the bulk matter

# The birth jets in heavy ion collisions



The measurement of jets offers a complementary (more differential) view of the bulk matter

FERMILAB-Pub-82/59-THY  
August, 1982

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

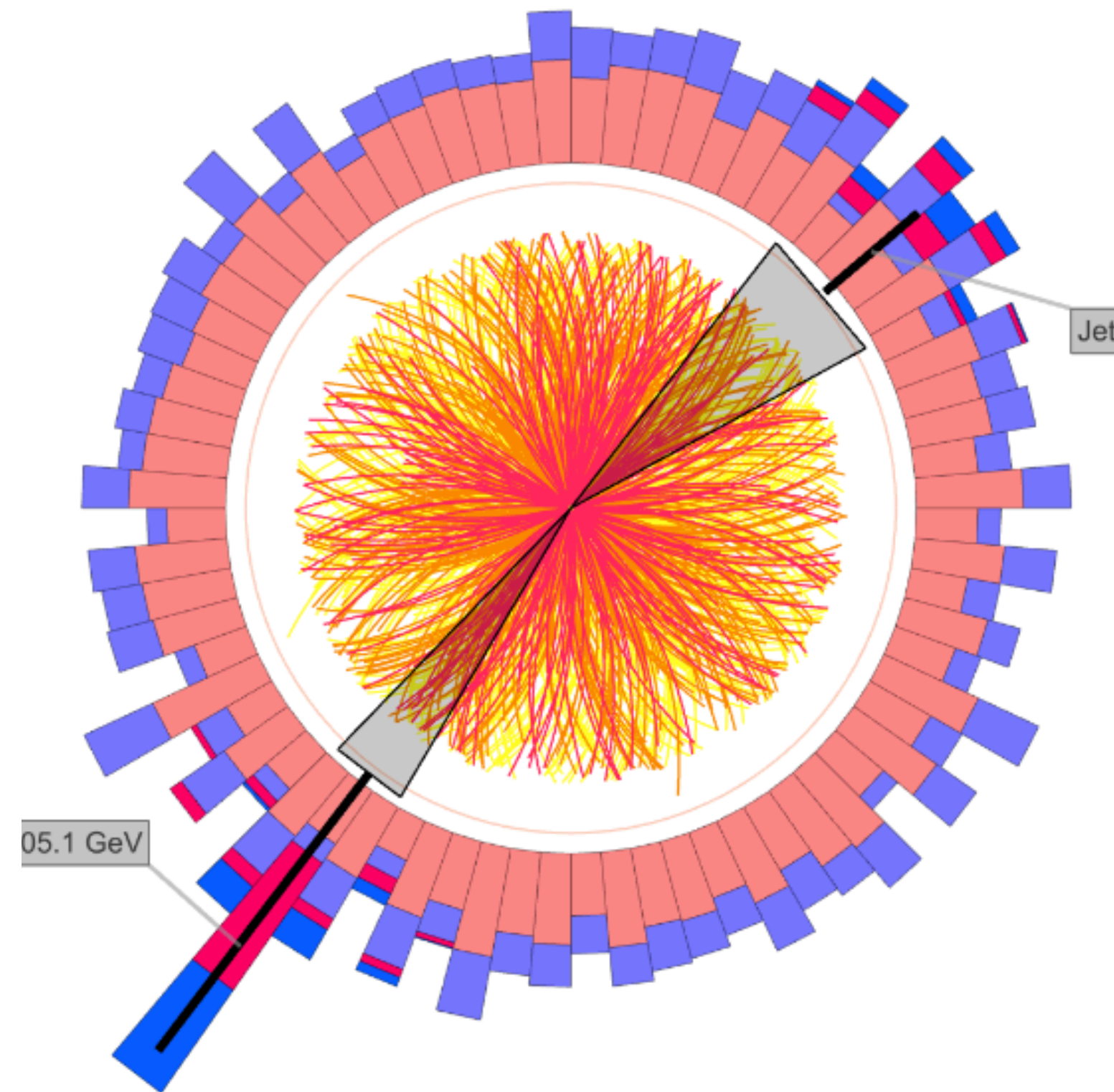
J. D. BJORKEN  
Fermi National Accelerator Laboratory  
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma.

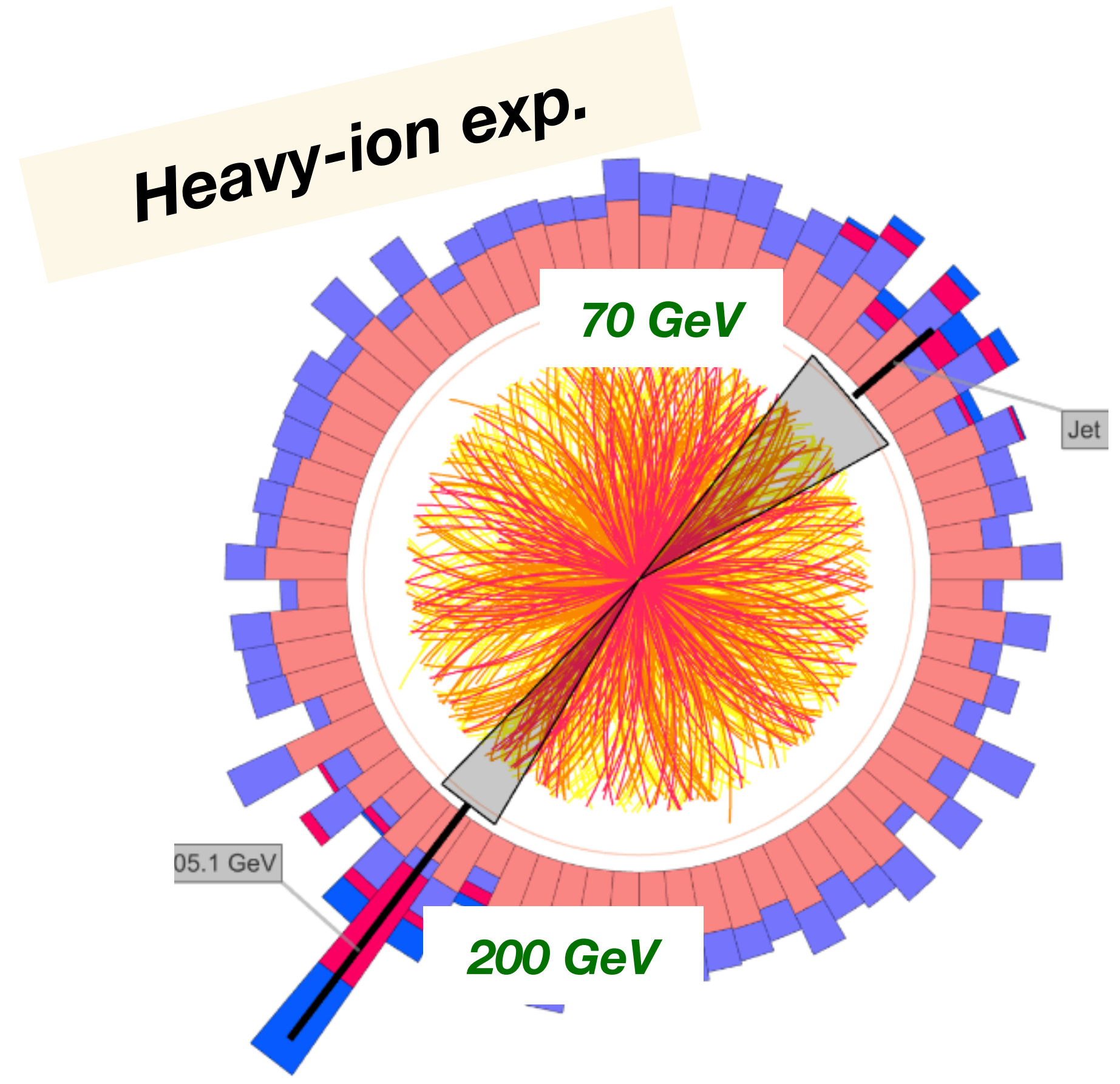
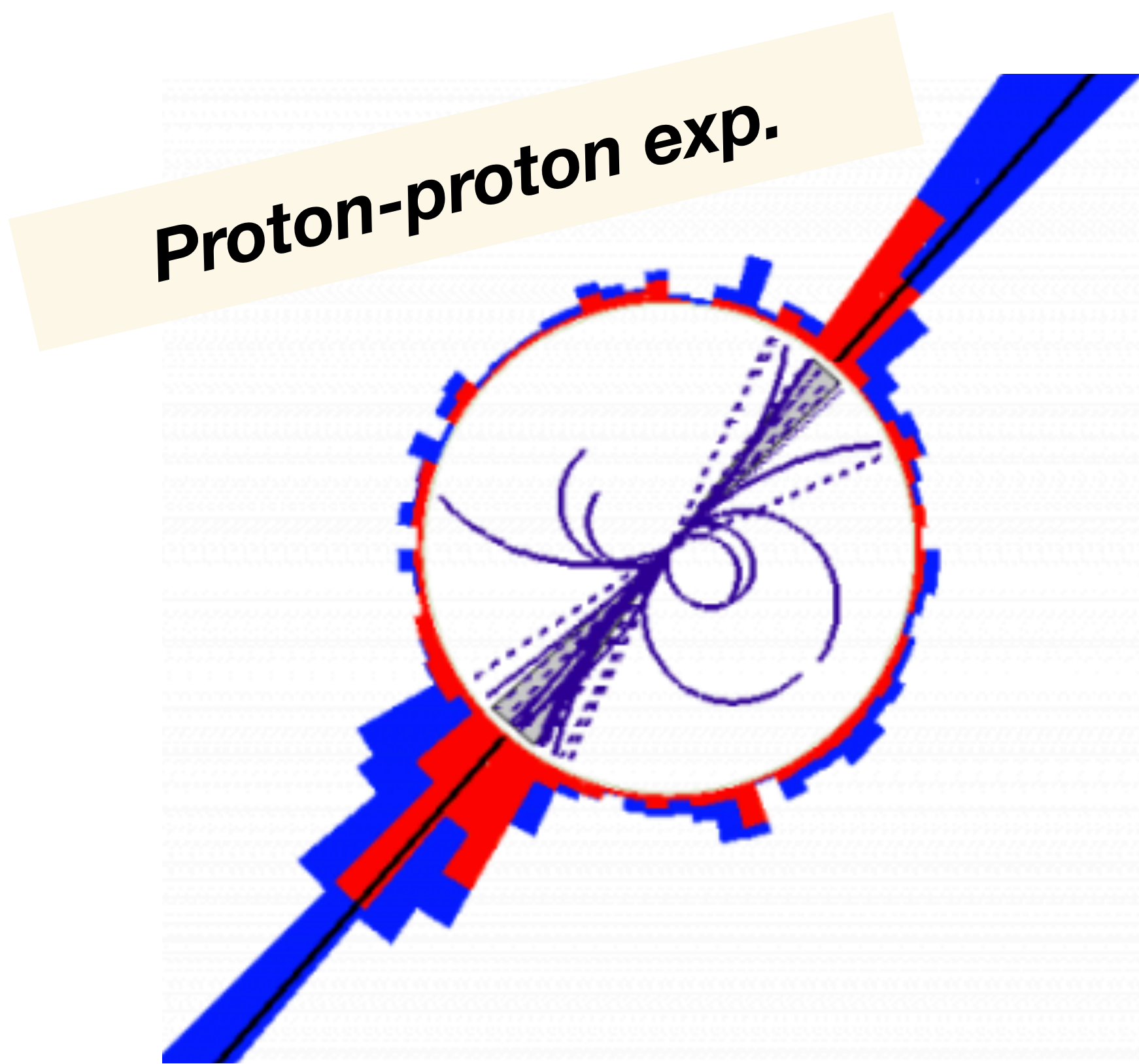
produced secondary high- $p_T$  quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment.

# Global properties of jets in heavy ions



# Medium induced modifications

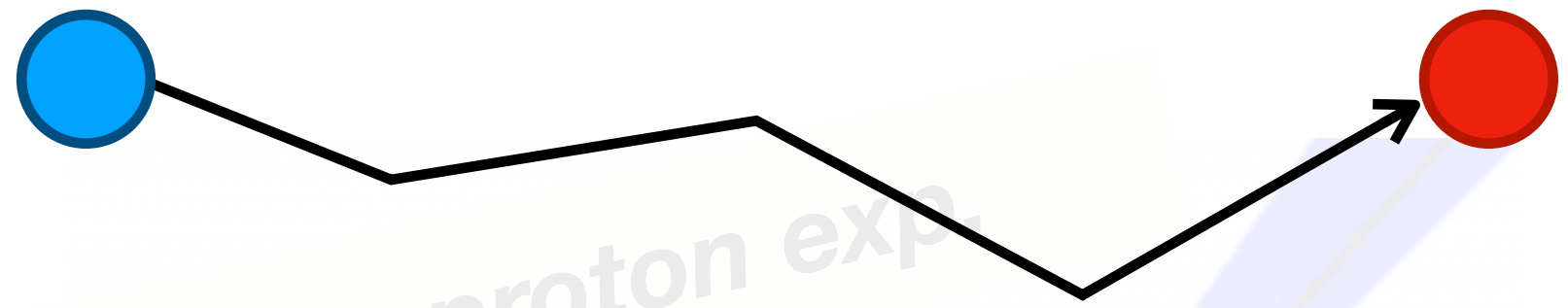
Bjorken's theoretical picture is indeed realized in experiment!



# Medium induced modifications

Initial blue quark

Final red quark



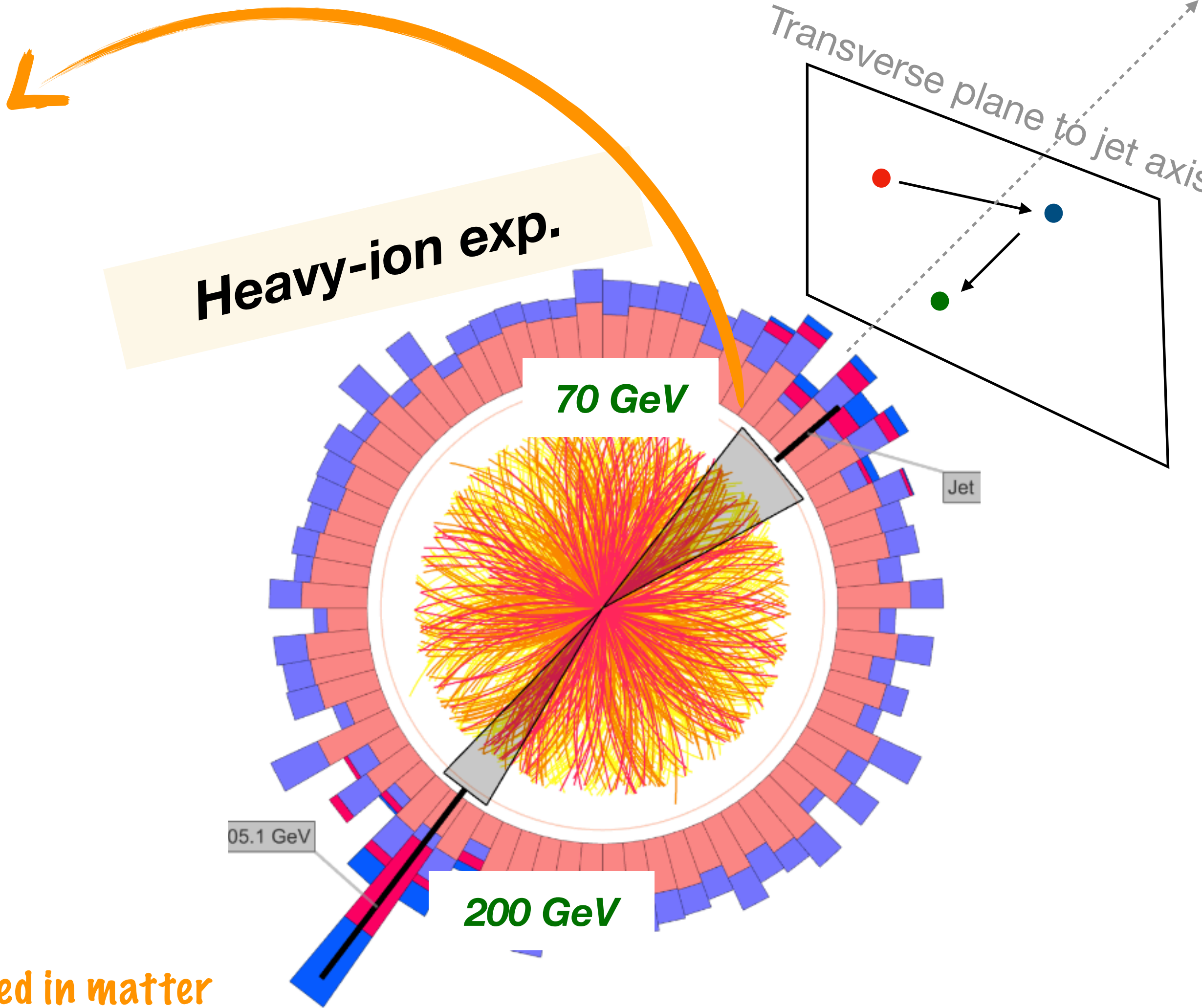
Momentum broadening

$$\langle \mathbf{k} \rangle = 0$$

$$\langle \mathbf{k}^2 \rangle \sim \hat{q}L$$

Jet transport coefficient, diffusion constant

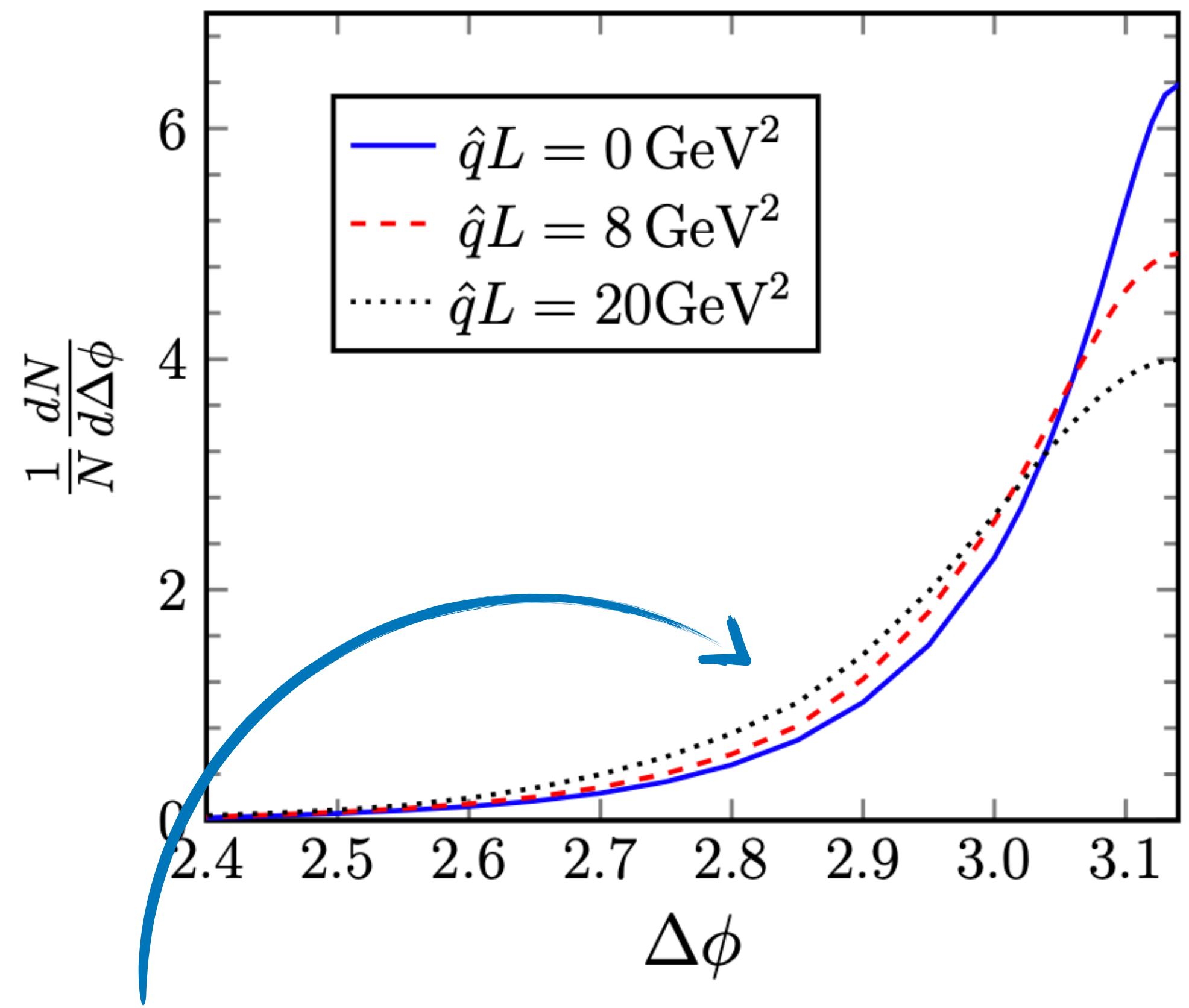
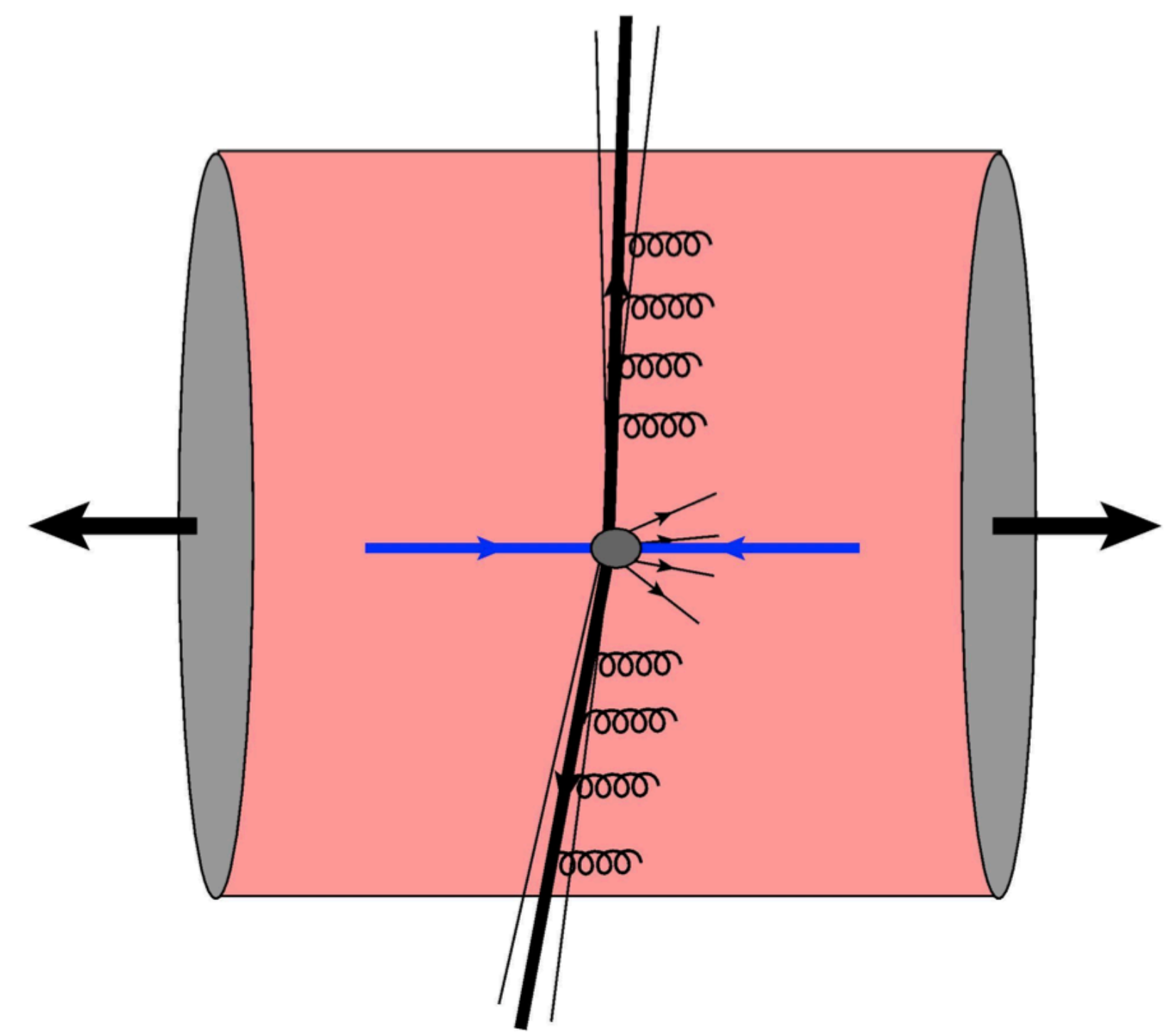
Light-cone time evolved in matter



# Medium induced modifications

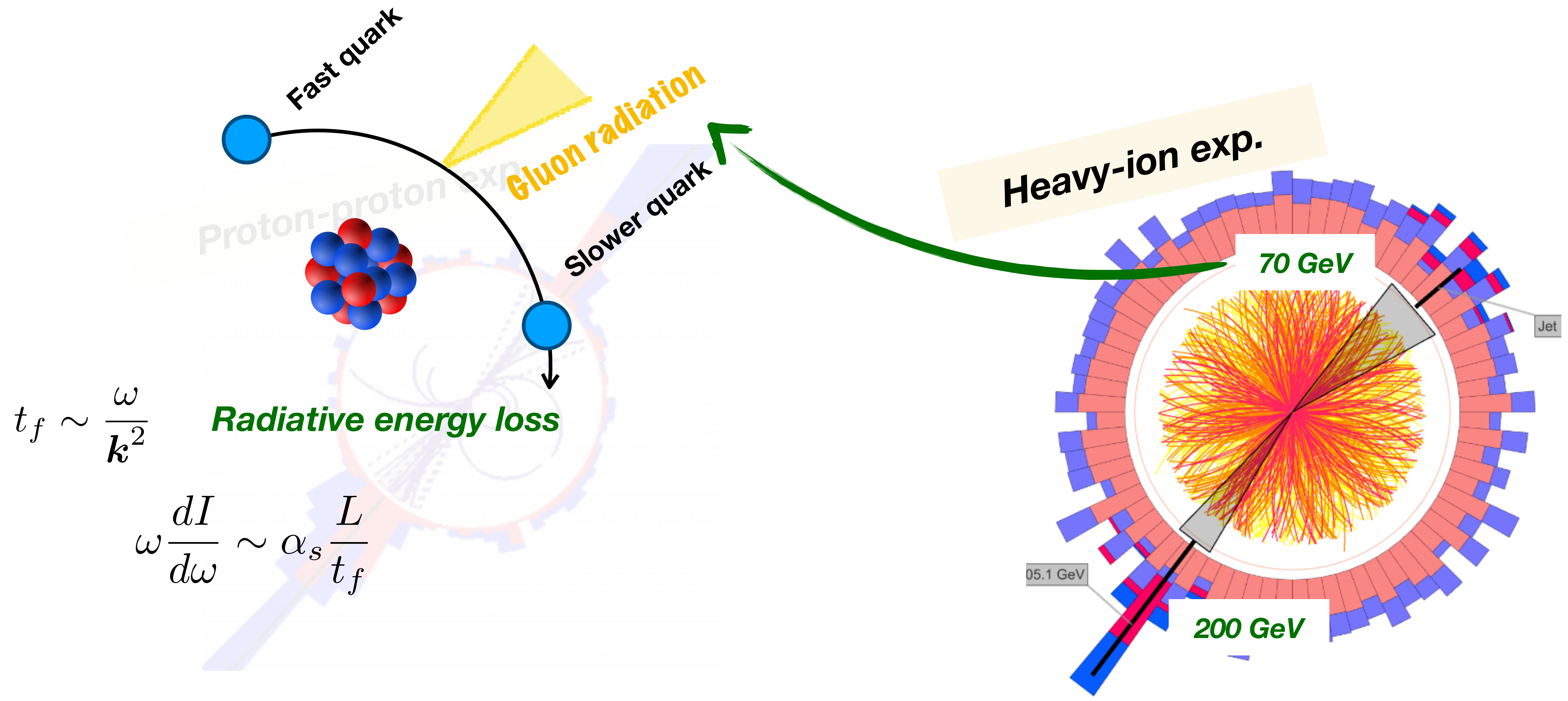
[Mueller, Wu, Xiao, Yuan, 1604.04250]

## Dijet Angular Correlation at RHIC

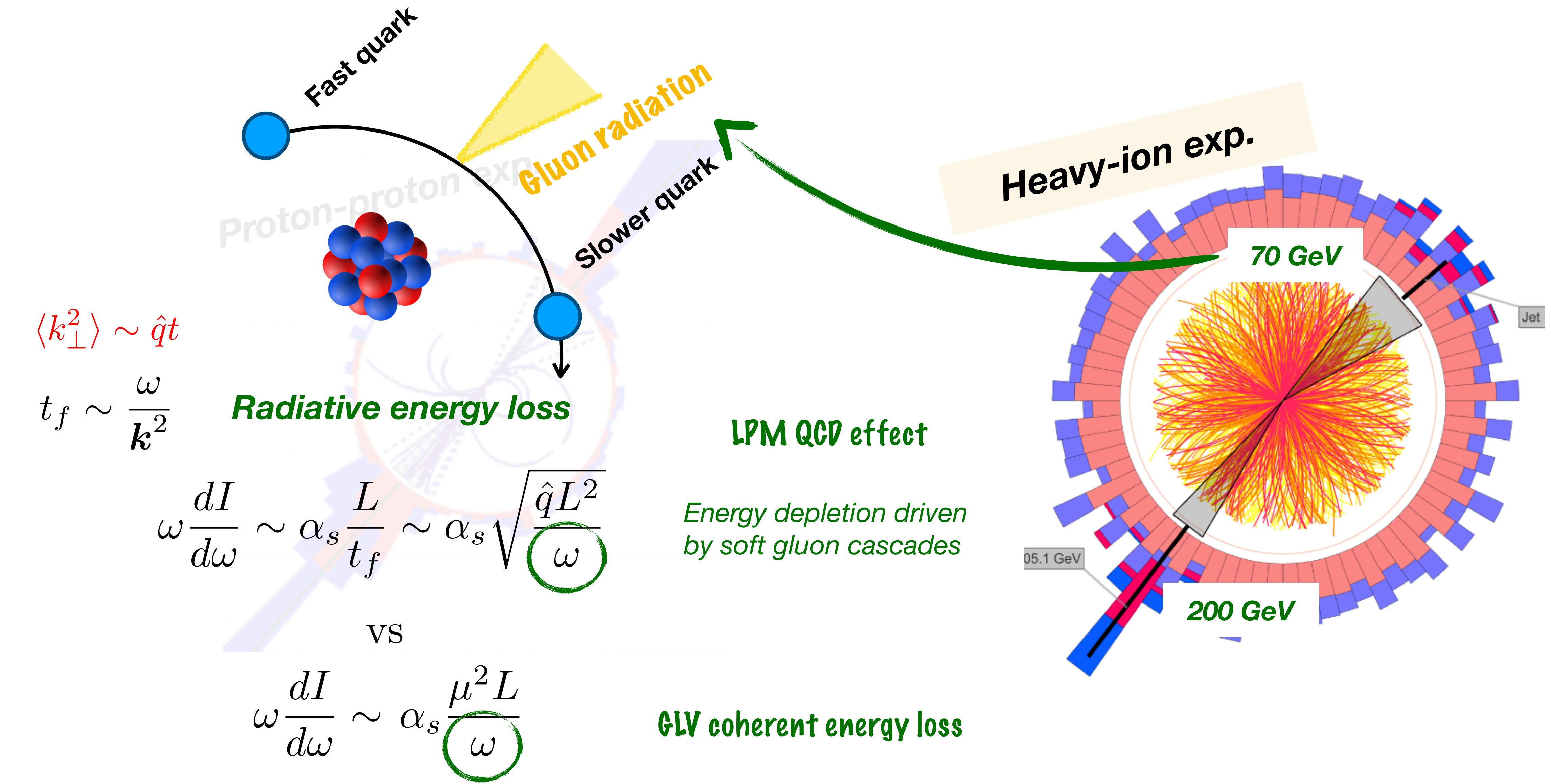


Interactions with the medium decorrelate jet from b2b configuration

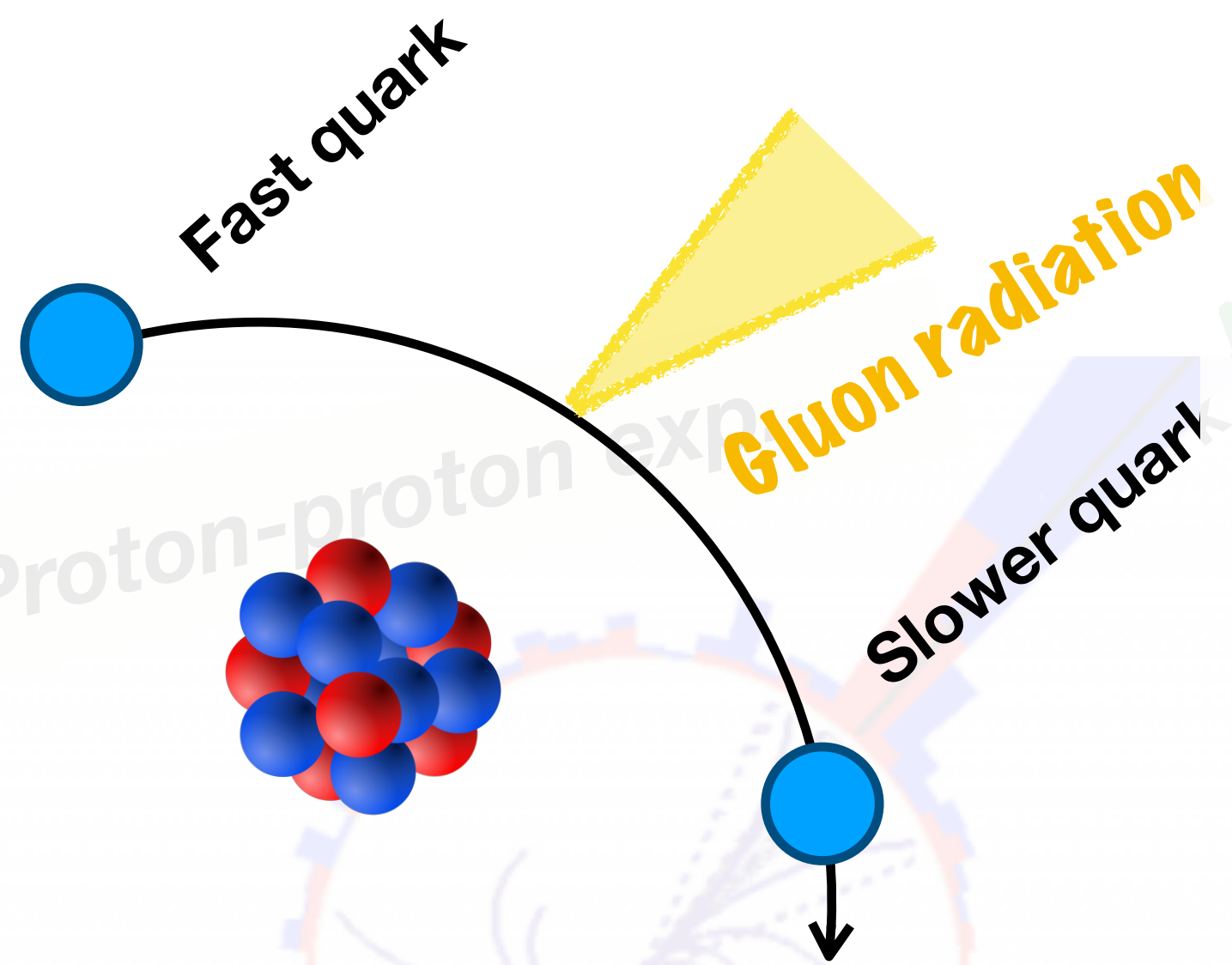
# Medium induced modifications



# Medium induced modifications



# Medium induced modifications



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

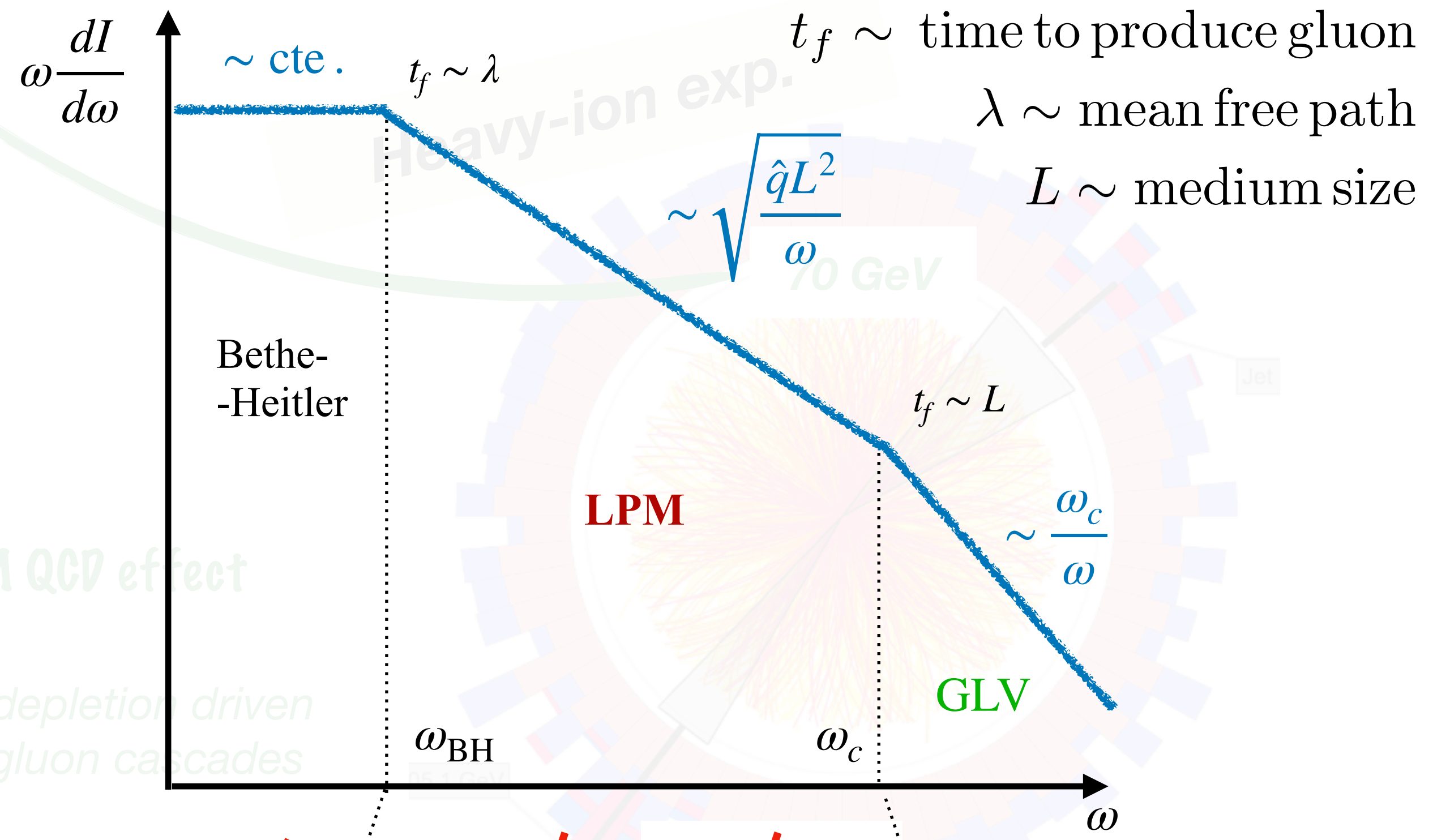
$$t_f \sim \frac{\omega}{k^2}$$

**Radiative energy loss**

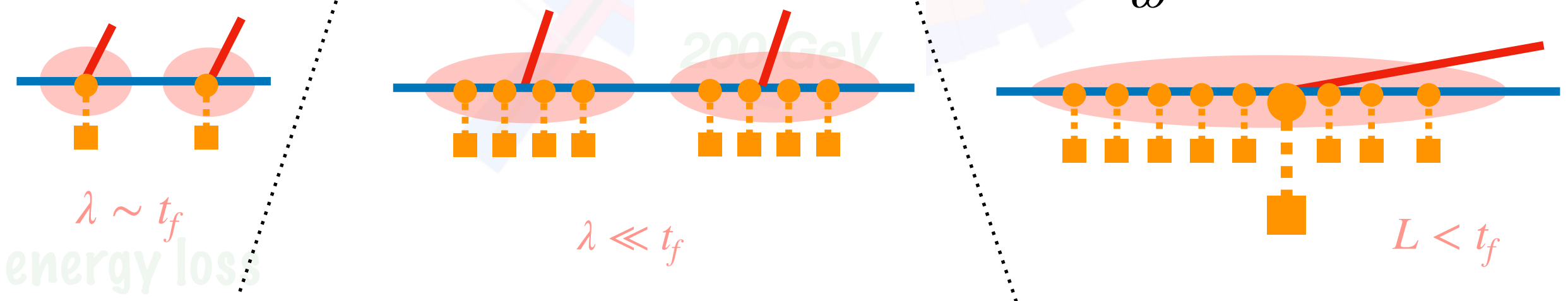
$$\omega \frac{dI}{d\omega} \sim \alpha_s \frac{L}{t_f} \sim \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}}$$

vs

$$\omega \frac{dI}{d\omega} \sim \alpha_s \frac{\mu^2 L}{\omega}$$



Energy depletion driven by soft gluon cascades



# Medium induced modifications

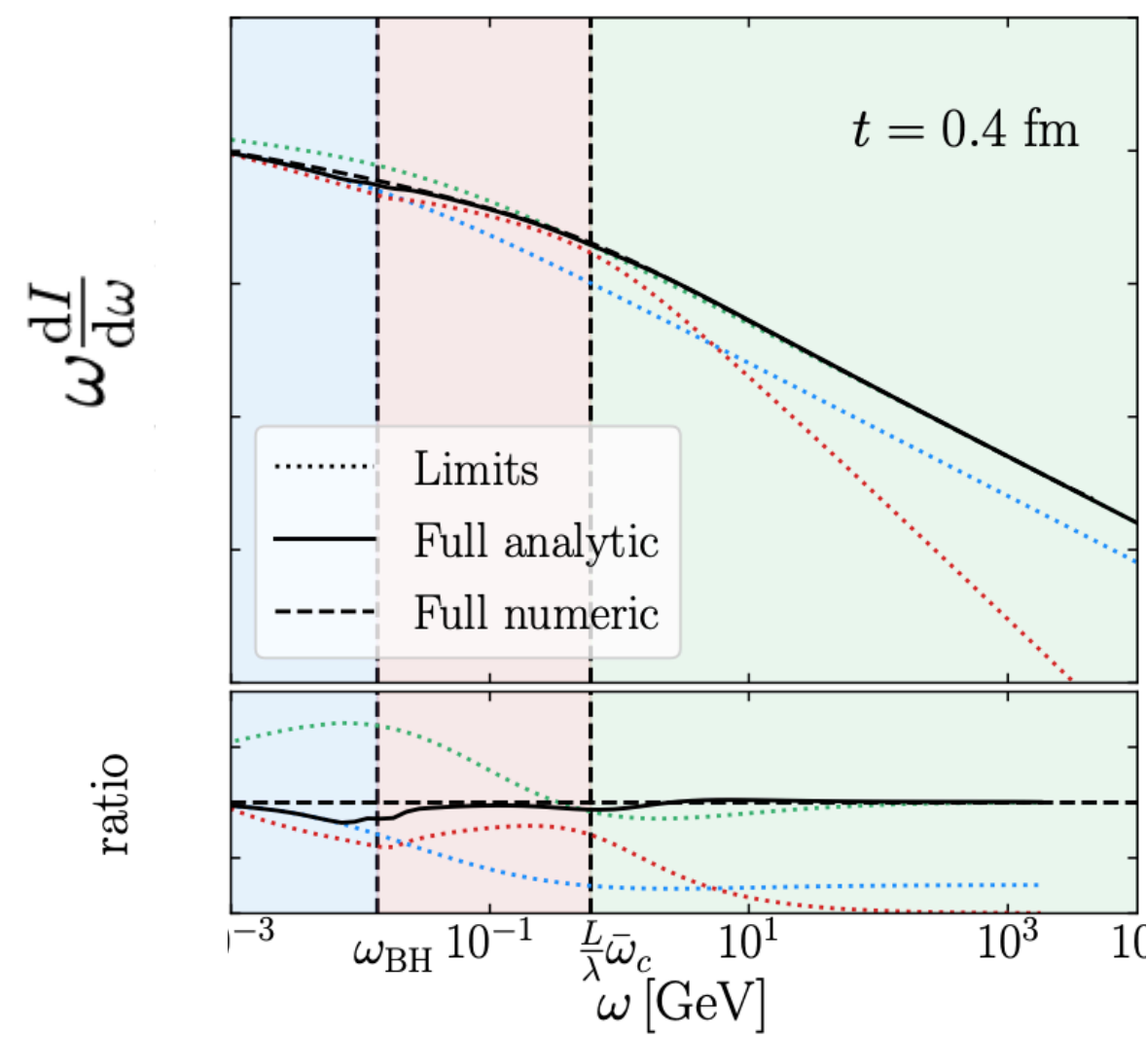
**Several recent contributions towards improving theory description of radiation rate**

# Medium induced modifications

Several recent contributions towards improving theory description of radiation rate



[Isaksen, Takacs, Tywoniuk, 2206.02811]



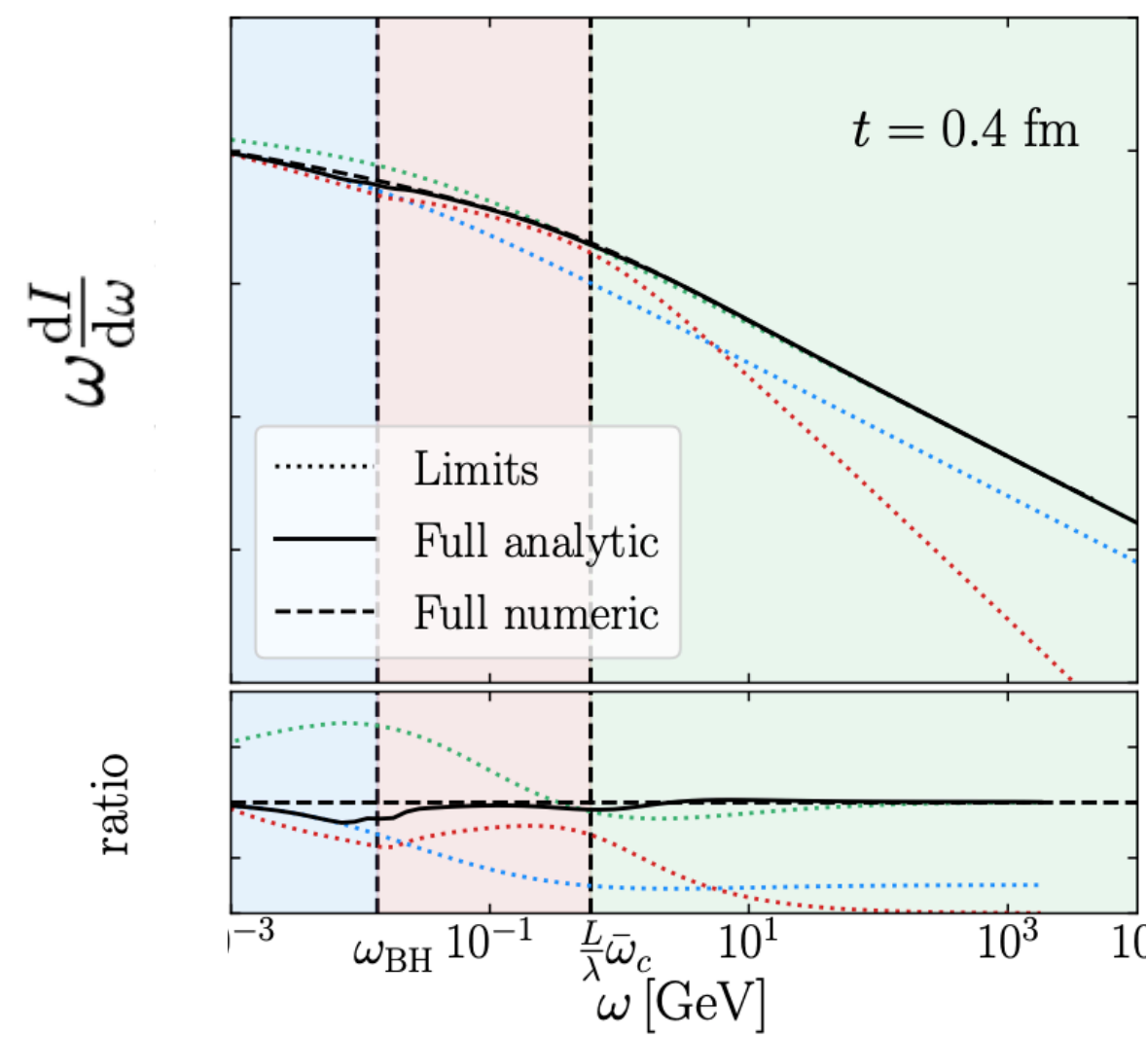
*Compact and practical description of radiation rate*

# Medium induced modifications

Several recent contributions towards improving theory description of radiation rate



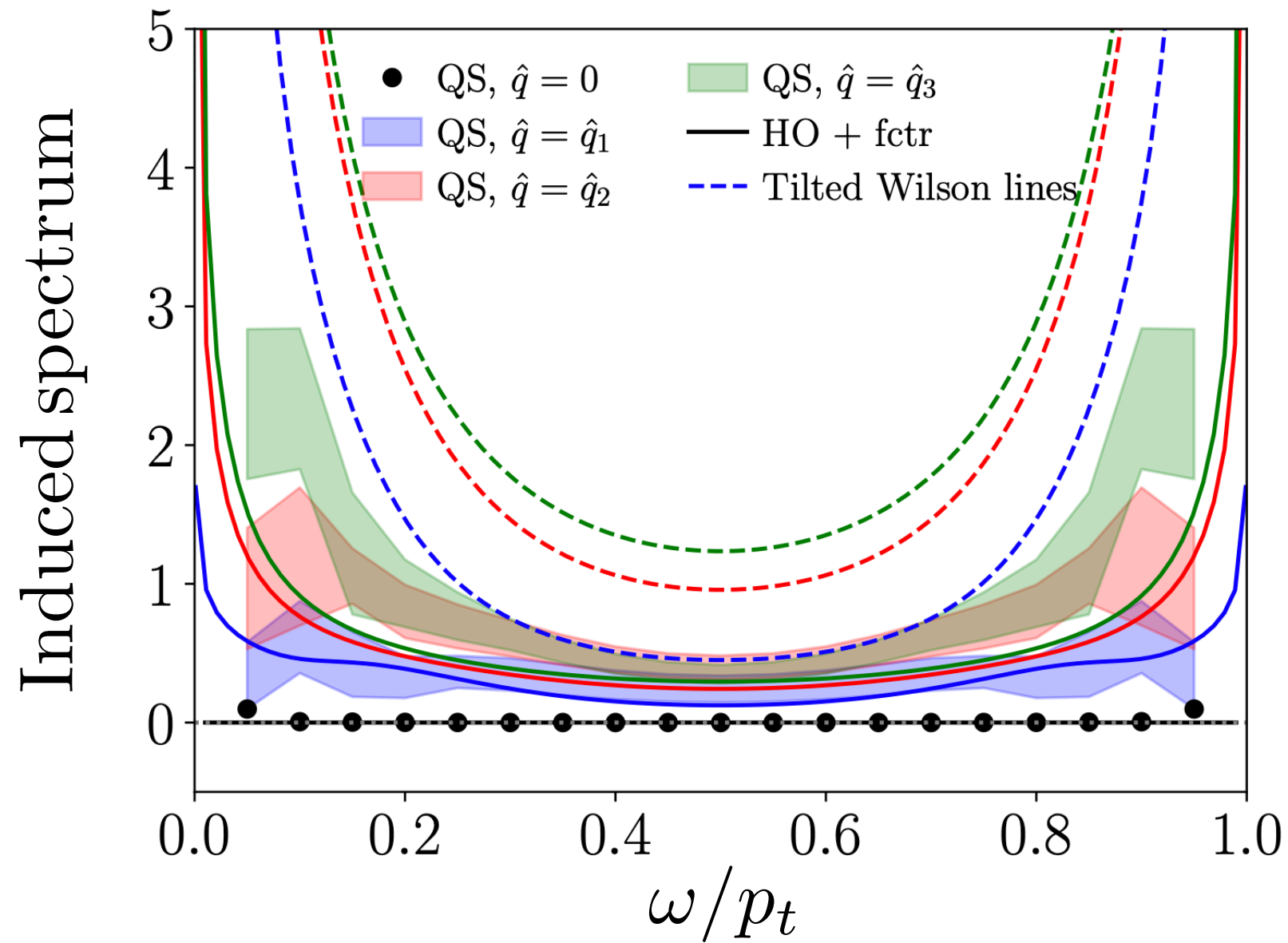
[Isaksen, Takacs, Tywoniuk, 2206.02811]



*Compact and practical description of radiation rate*



[Li, Qian, Silva Salgado, JB , 2604.11616]

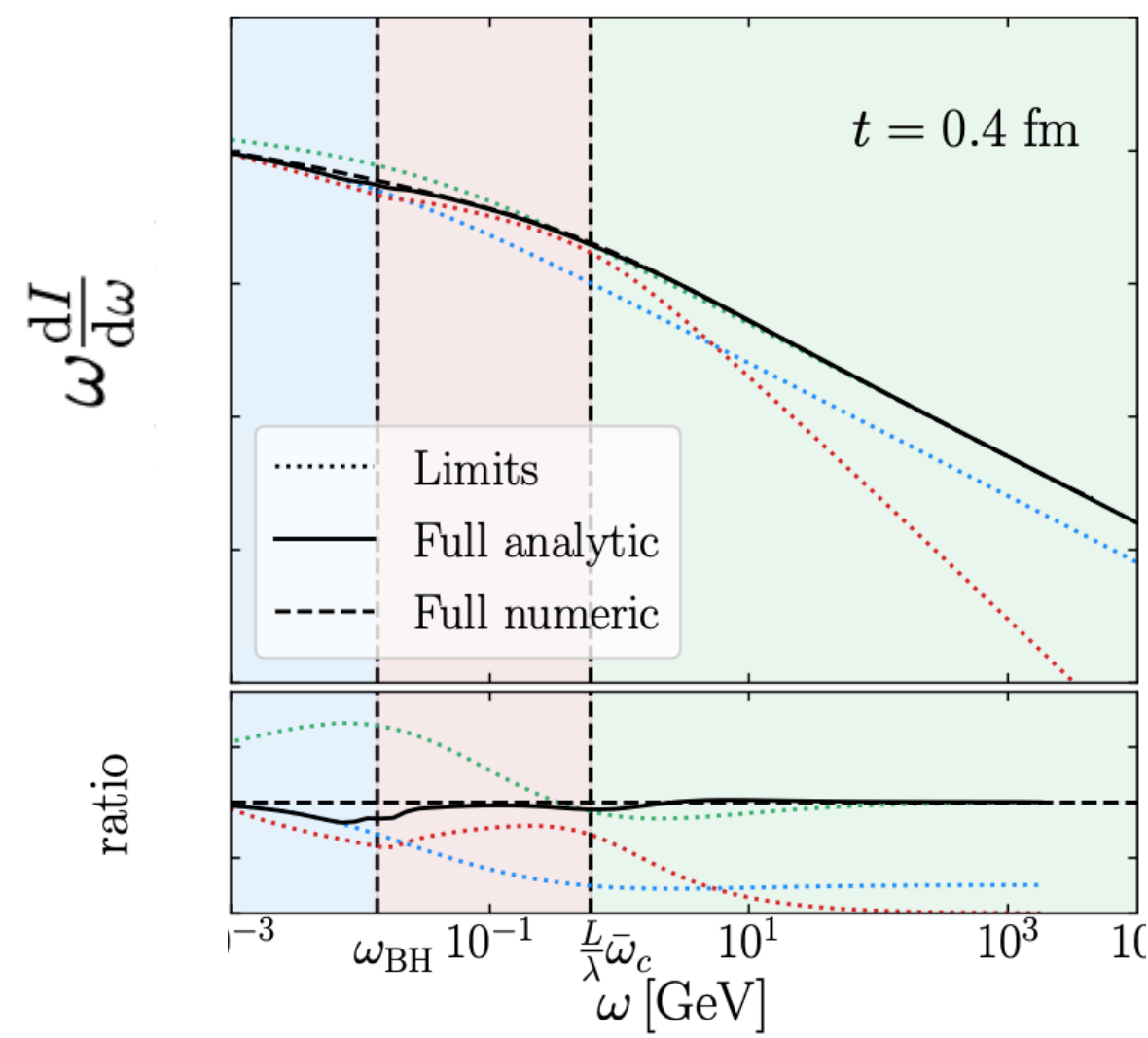


*Full kinematical range*

# Medium induced modifications

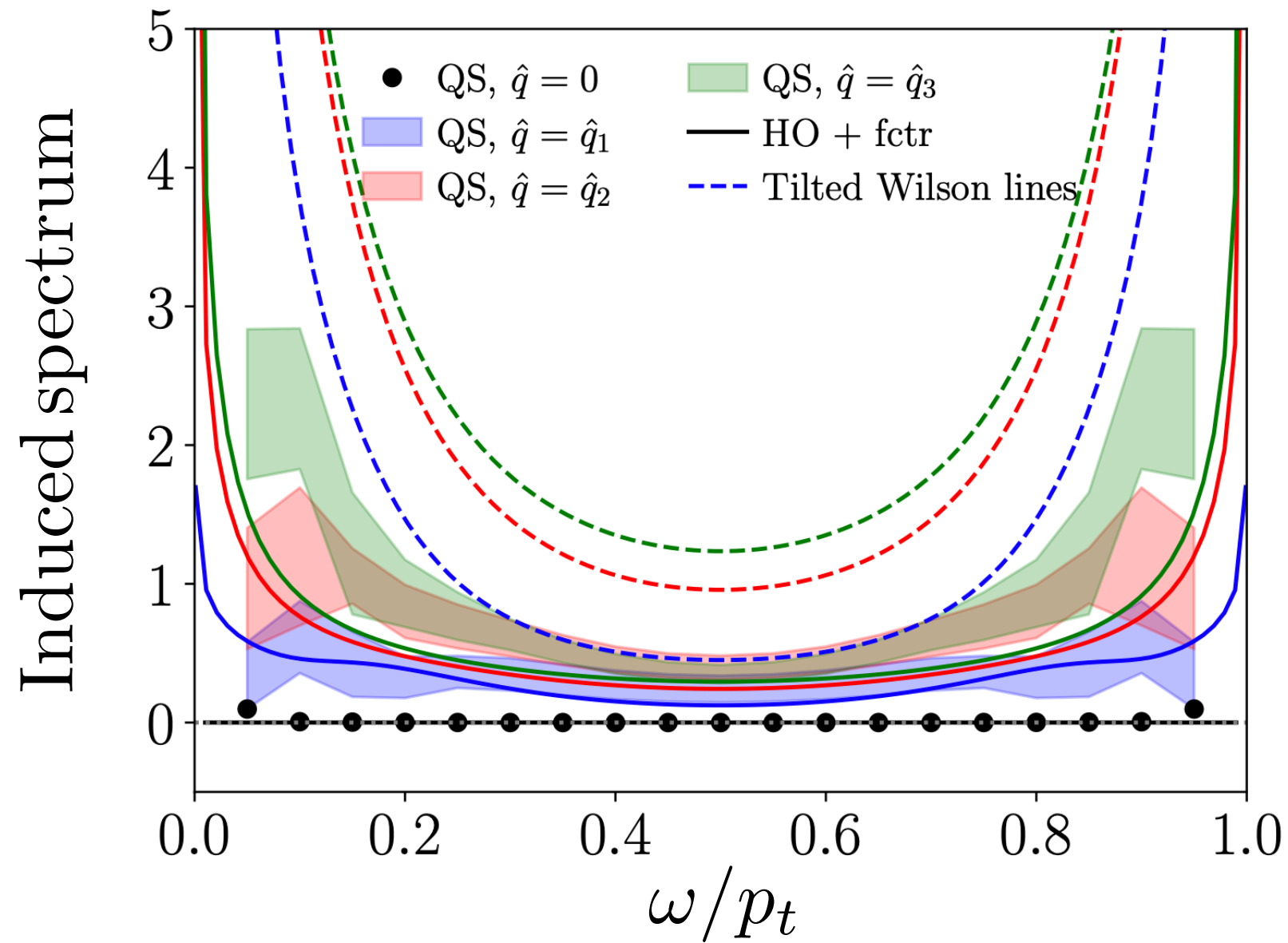
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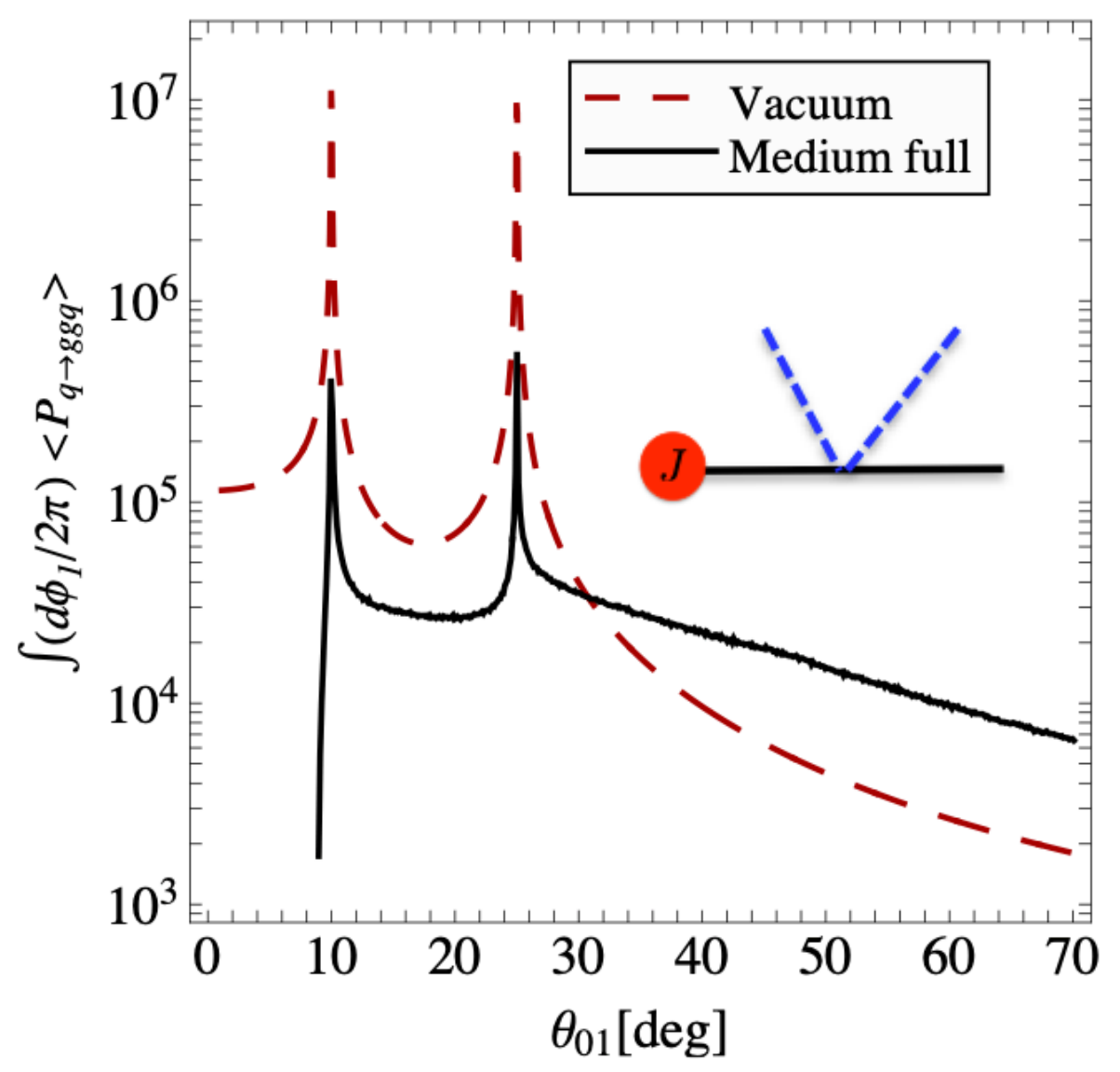
*Compact and practical description of radiation rate*

[Li, Qian, Silva Salgado, JB , 2604.11616]



*Full kinematical range*

[Fickinger, Ovanesyan, Vitev, 1304.3497]

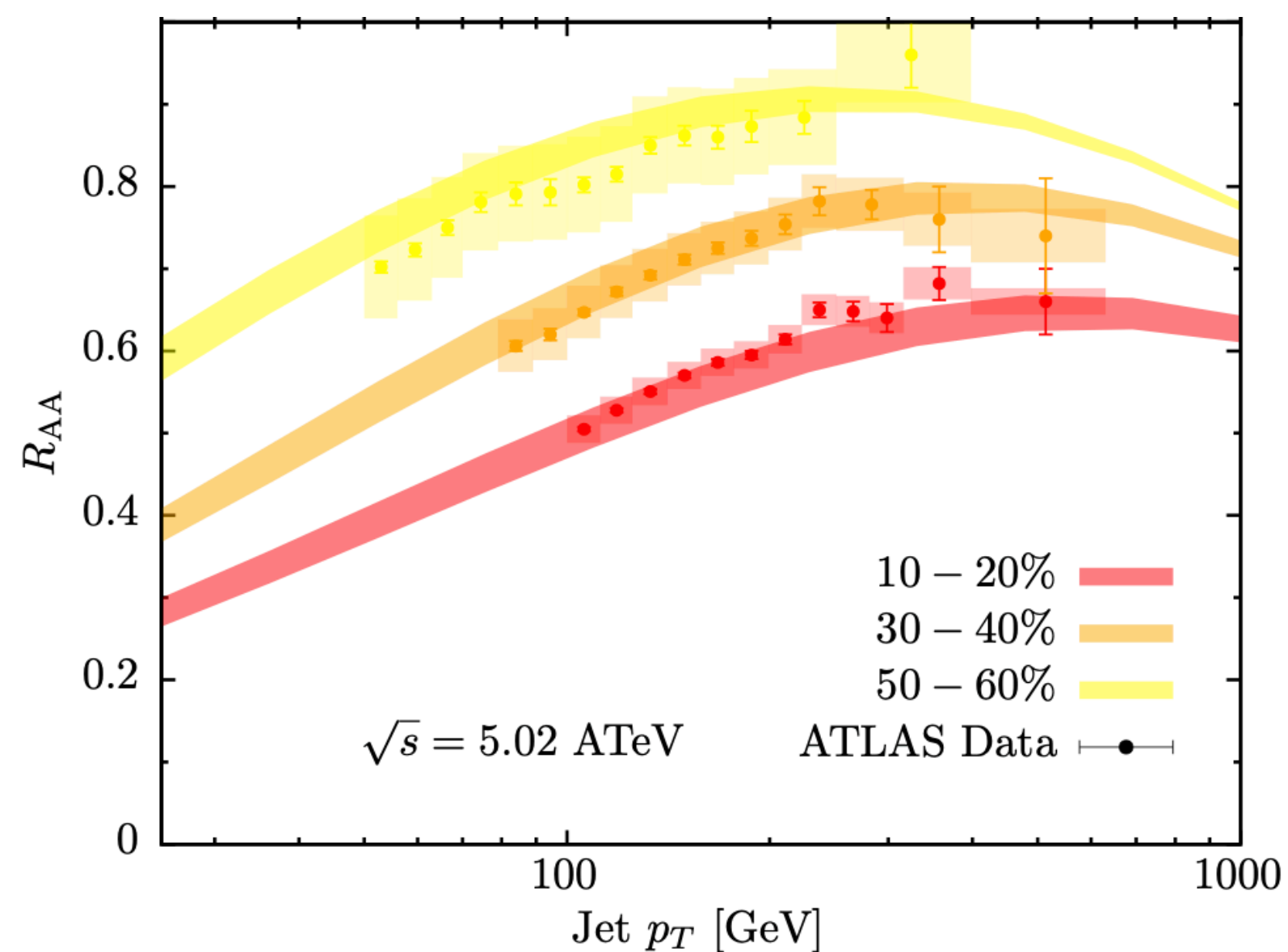


*Higher order pQCD terms*

**A correct description of these elements is critical as they enter any jet observable prediction**

# Medium induced modifications

[Mehtar-Tani, Pablos, Tywoniuk, 2101.01742]



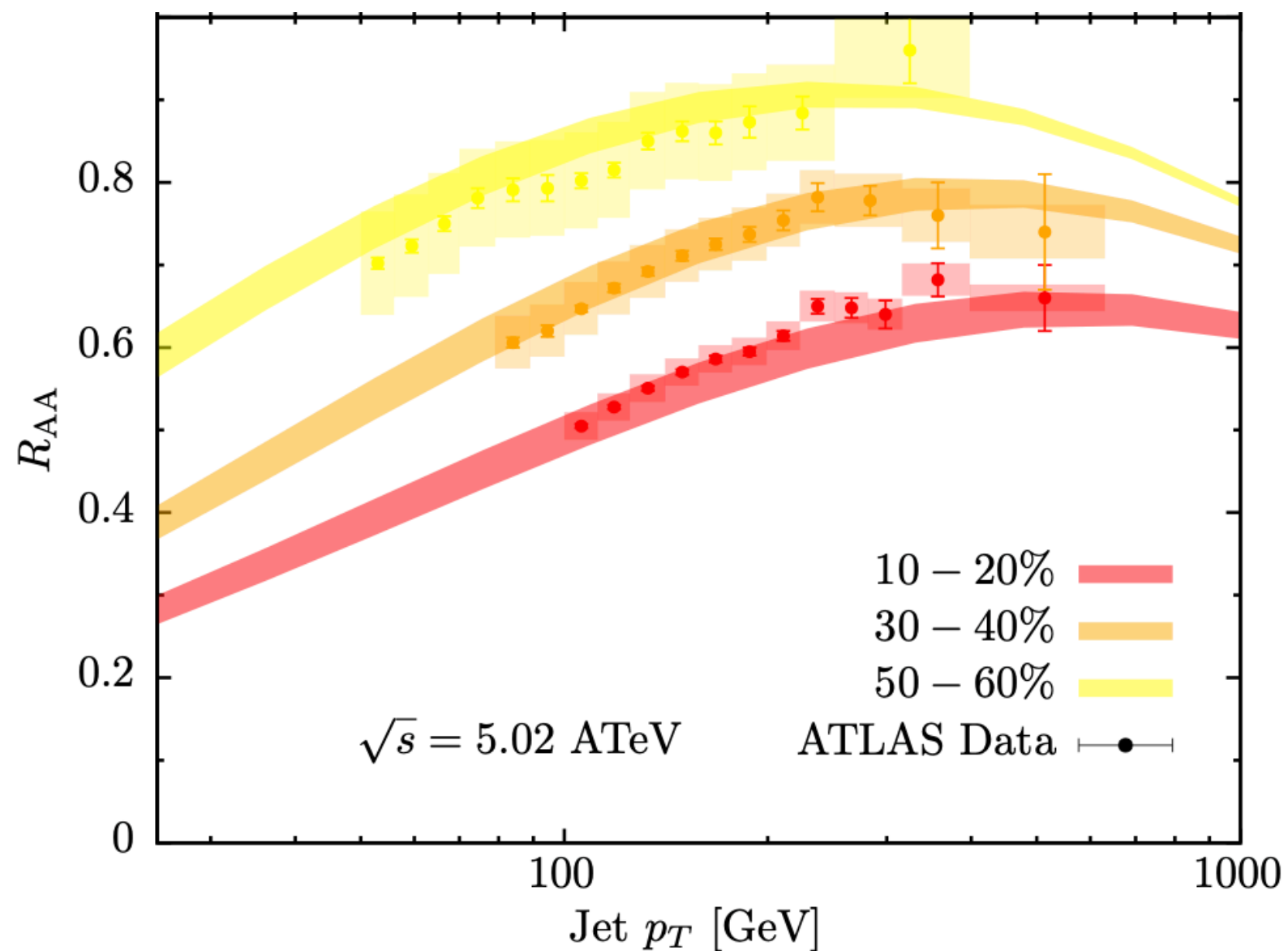
[R. Baier, Y. Dokshitzer, A. H. Mueller, hep-ph/0106347]

$$\frac{d\sigma_q^{\text{med}}}{dp_t d\theta} \approx \frac{d\sigma_q^{\text{vac}}}{dp_t d\theta} \int_0^\infty d\varepsilon D_q(\varepsilon) e^{-\frac{n\varepsilon}{p_t}} \equiv Q_q(p_t) \frac{d\sigma_q^{\text{vac}}}{dp_t d\theta}$$

$$Q_{\text{rad}}^{(0)}(p_T) = \exp \left[ - \int_{\omega_s}^\infty d\omega \frac{dI_{>}}{d\omega} (1 - e^{-\nu\omega}) - \int_T^{\omega_s} d\omega \frac{dI^{(0)}}{d\omega} \left( 1 - e^{-\nu\omega(1 - (\frac{R}{R_{\text{rec}}})^2)} \right) \right]$$

# Medium induced modifications

[Mehtar-Tani, Pablos, Tywoniuk, 2101.01742]

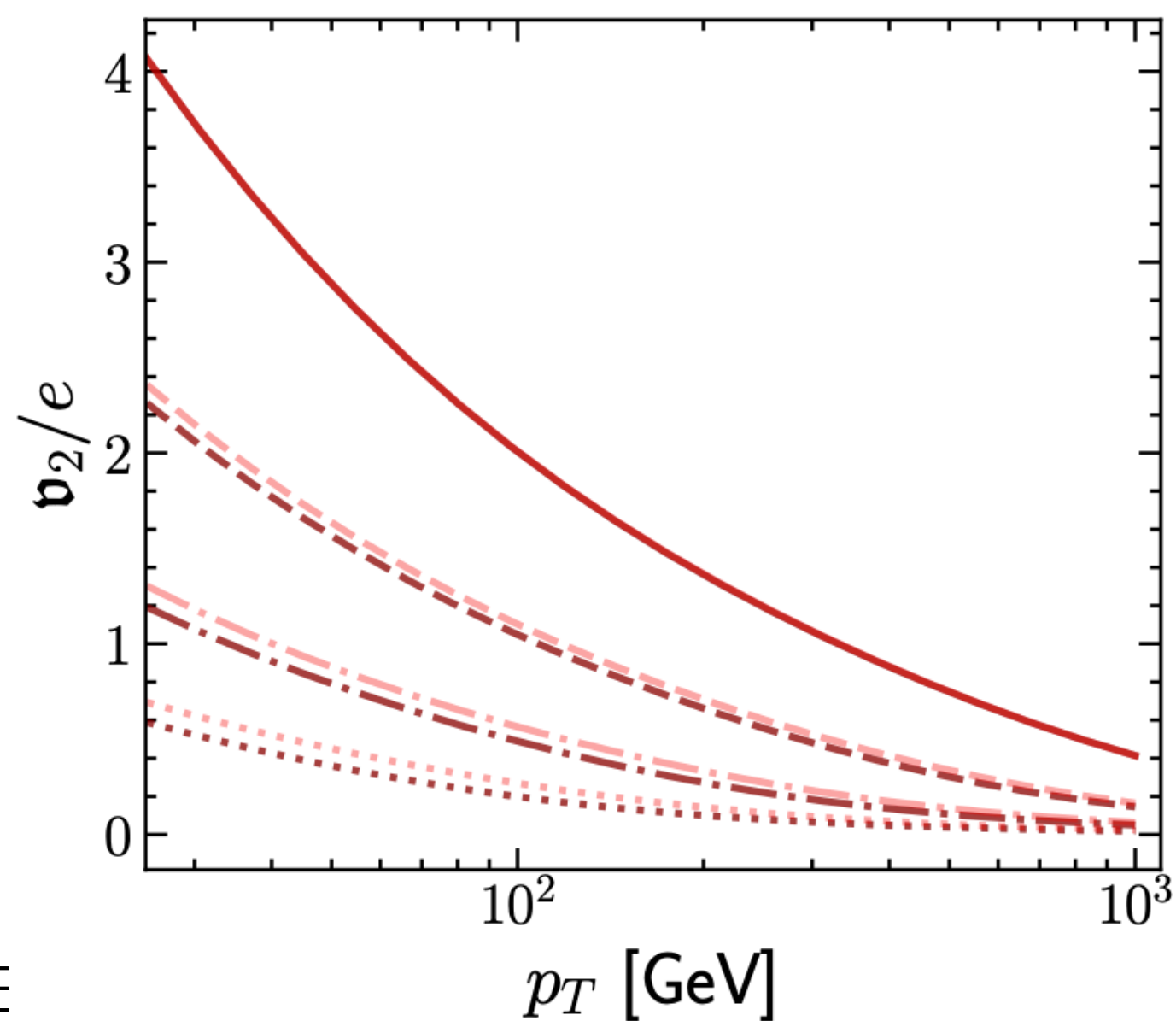


[R. Baier, Y. Dokshitzer, A. H. Mueller, hep-ph/0106347]

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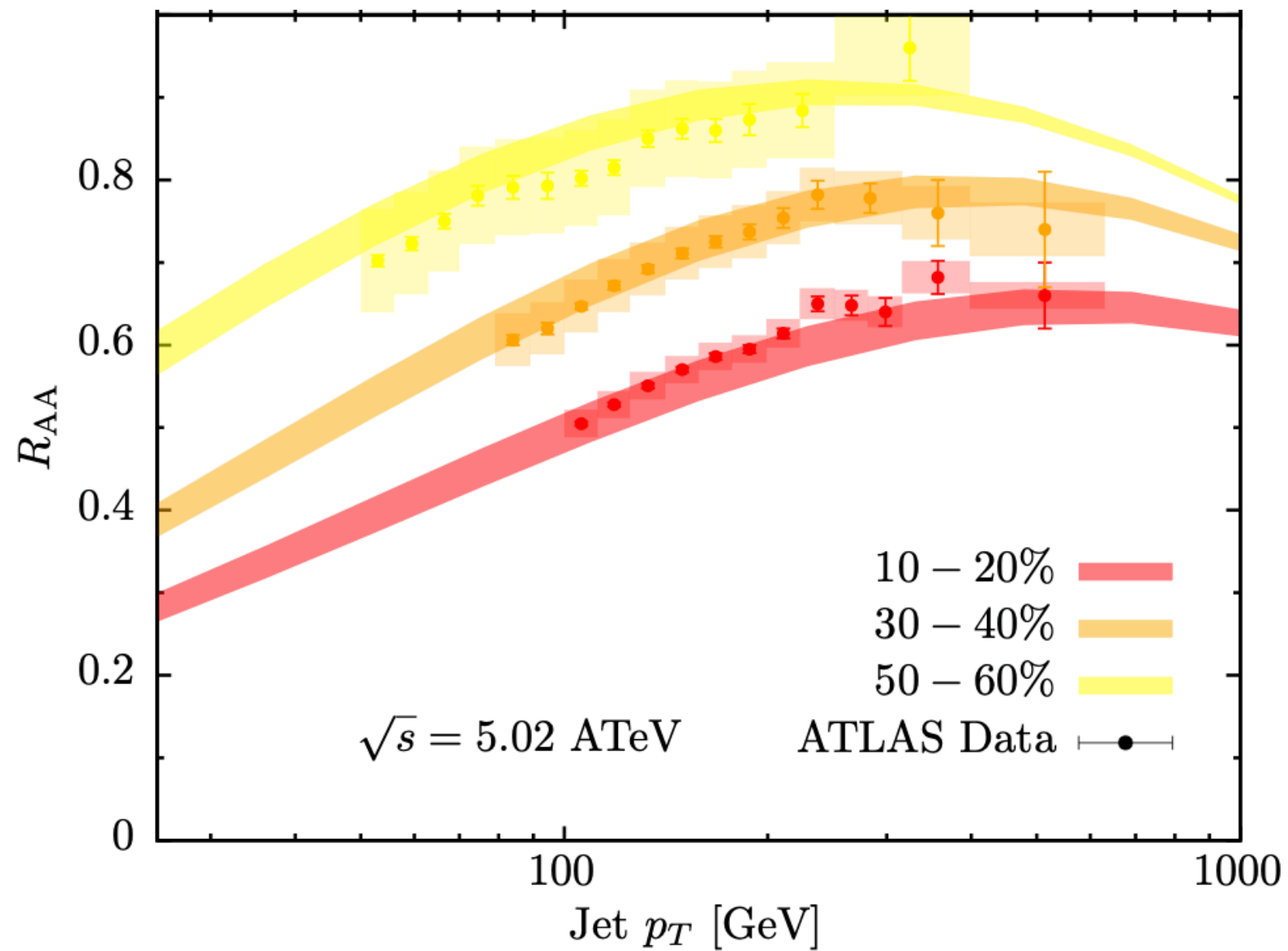
[Adhya, Tywoniuk, 2409.04295]



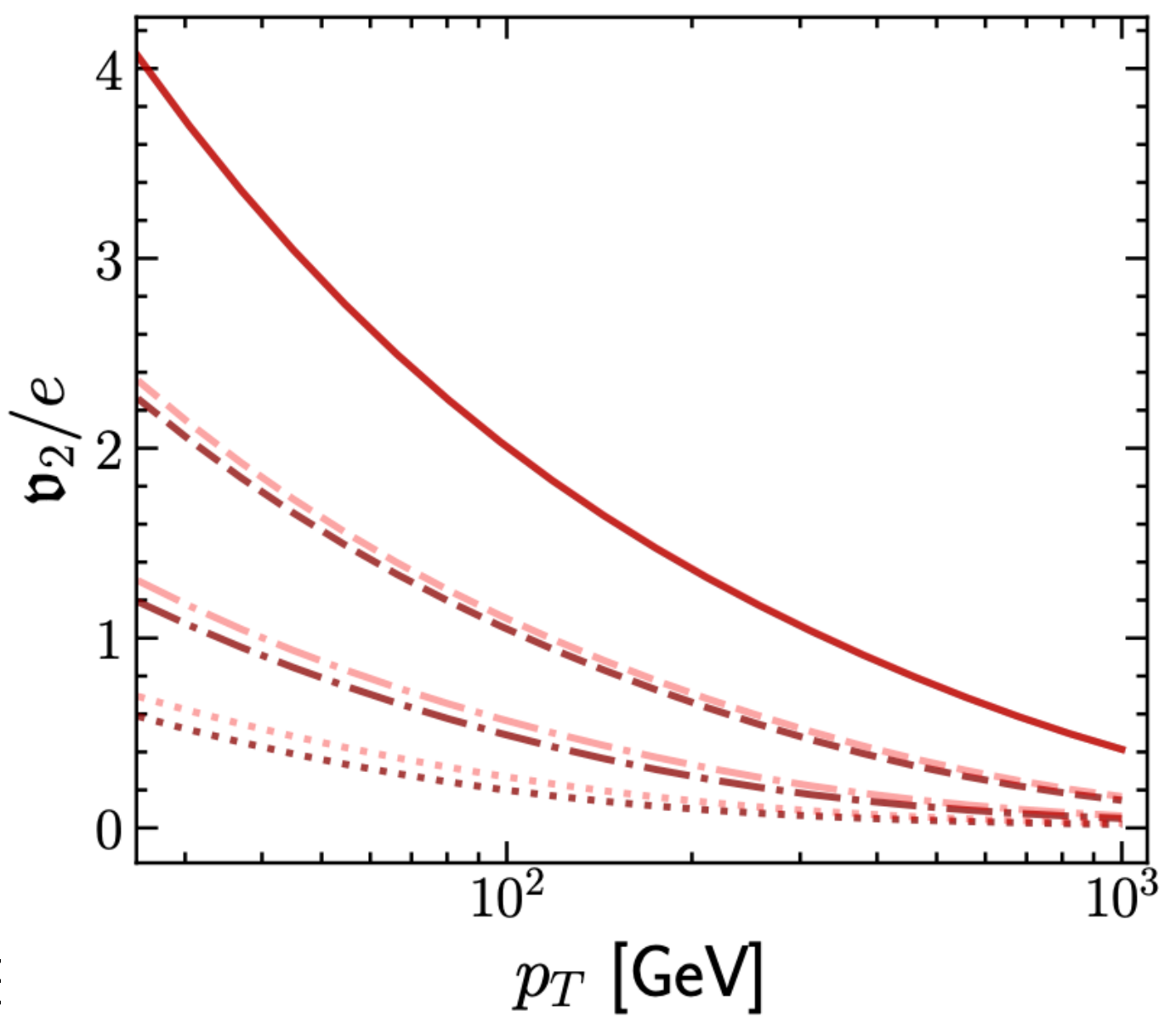
$$v_2(p_T, R) \equiv \frac{\int_{-\pi}^{\pi} d\phi \cos(2\phi) (d\sigma^{\text{AA}}(p_T, R)/d\phi)}{\int_{-\pi}^{\pi} d\phi (d\sigma^{\text{AA}}(p_T, R)/d\phi)}$$

# Medium induced modifications

[Mehtar-Tani, Pablos, Tywoniuk, 2101.01742]



[Adhya, Tywoniuk, 2409.04295]



[R. Baier, Y. Dokshitzer, A. H. Mueller, hep-ph/0106347]

$$\frac{d\sigma_q^{\text{med}}}{dp_t d\theta} \approx \frac{d\sigma_q^{\text{vac}}}{dp_t d\theta} \int_0^\infty d\varepsilon D_q(\varepsilon) e^{-\frac{n\varepsilon}{p_t}} \equiv Q_q(p_t) \frac{d\sigma_q^{\text{vac}}}{dp_t d\theta}$$

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Several open questions when combining both observables:

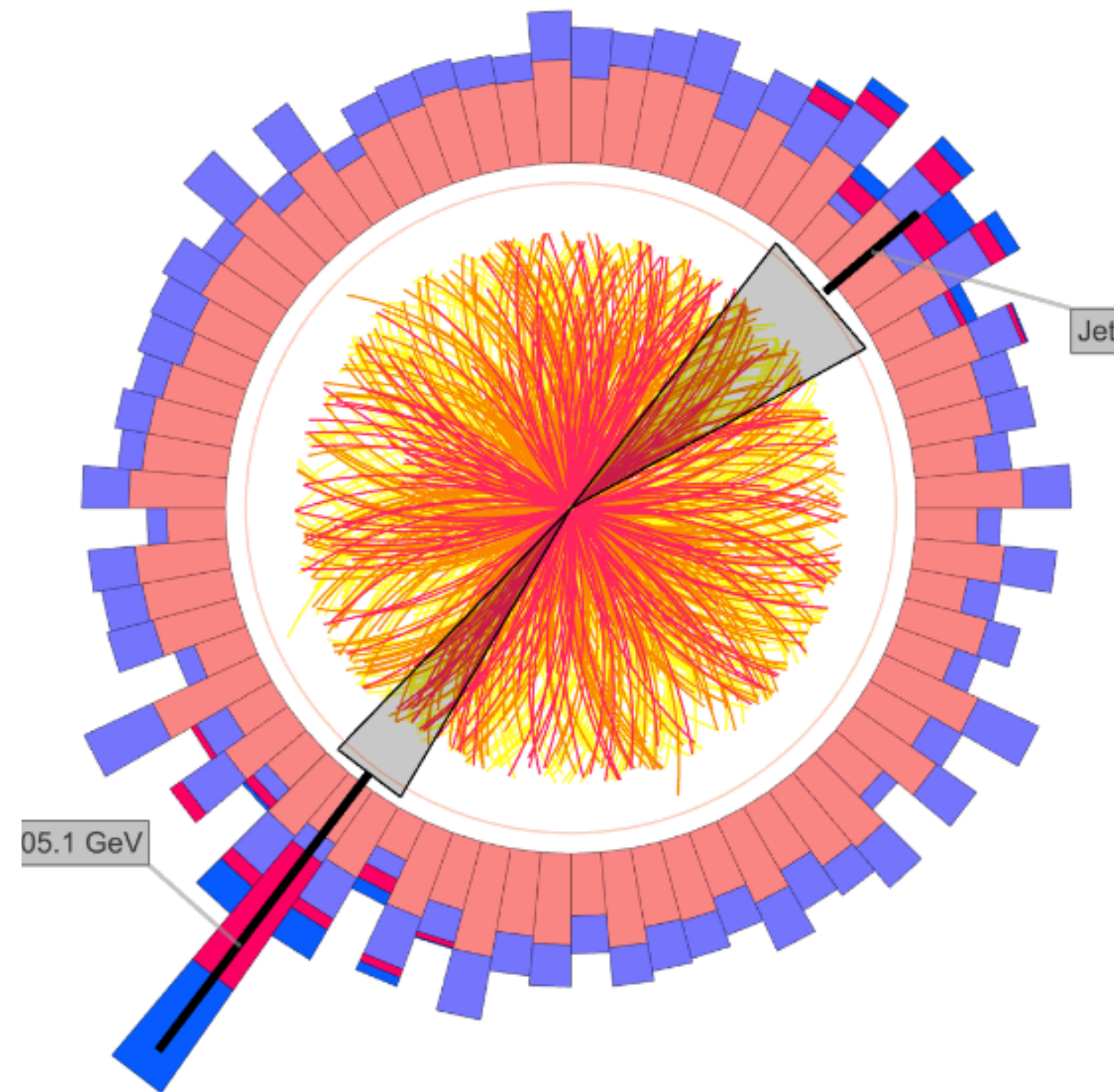
Sensitivity to initial conditions ?

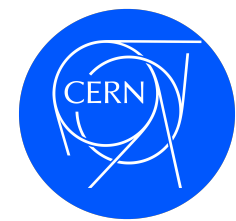
Accurate description of radiation rate ?

Novel physical mechanisms?

Valuable test-bed for basic picture of jets in heavy ions !

# Looking inside jets and their substructure





# Jet substructure in heavy ion collisions

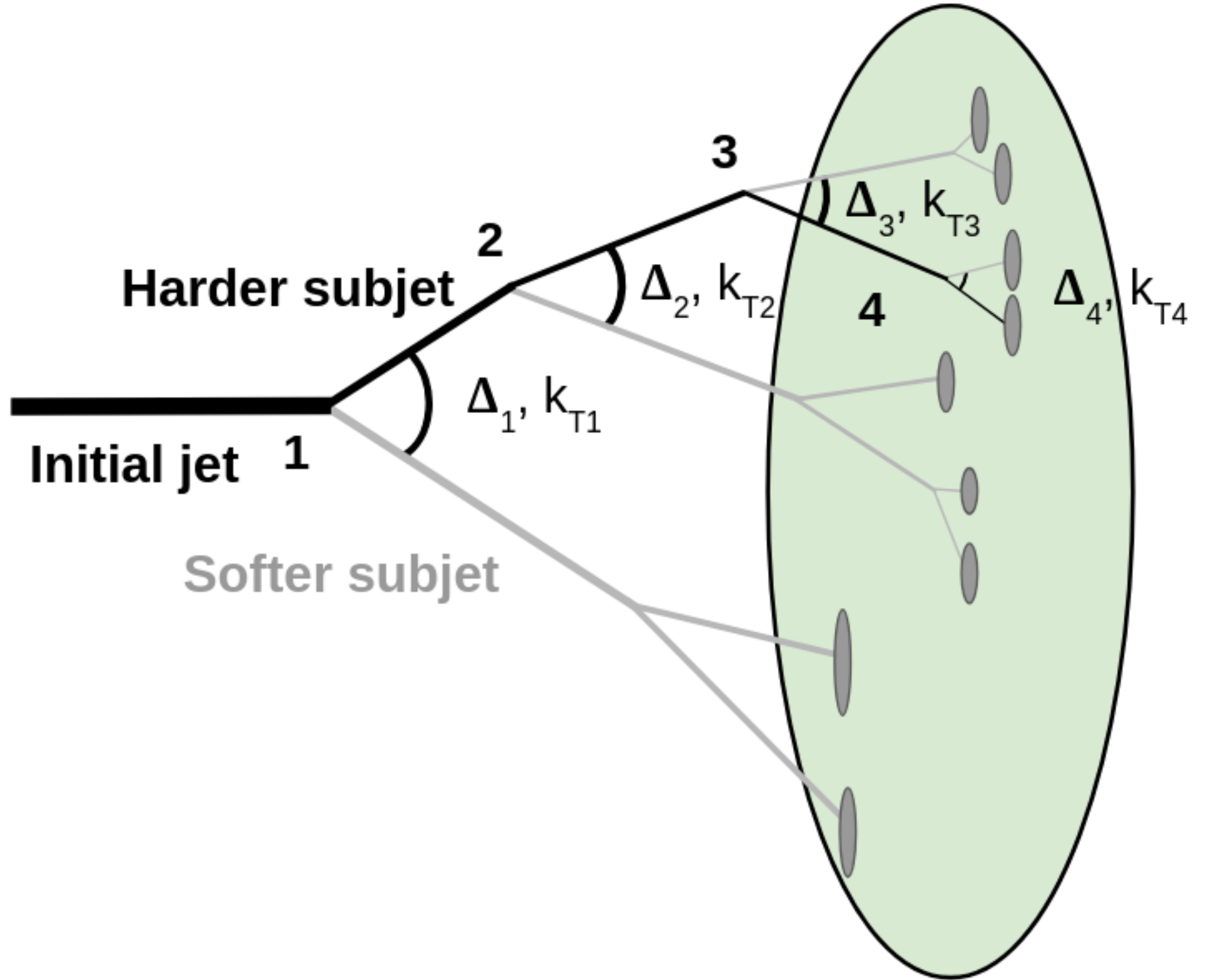
**So far I have focused mainly on global properties of jets, such as their energy and angular opening**

# Jet substructure in heavy ion collisions

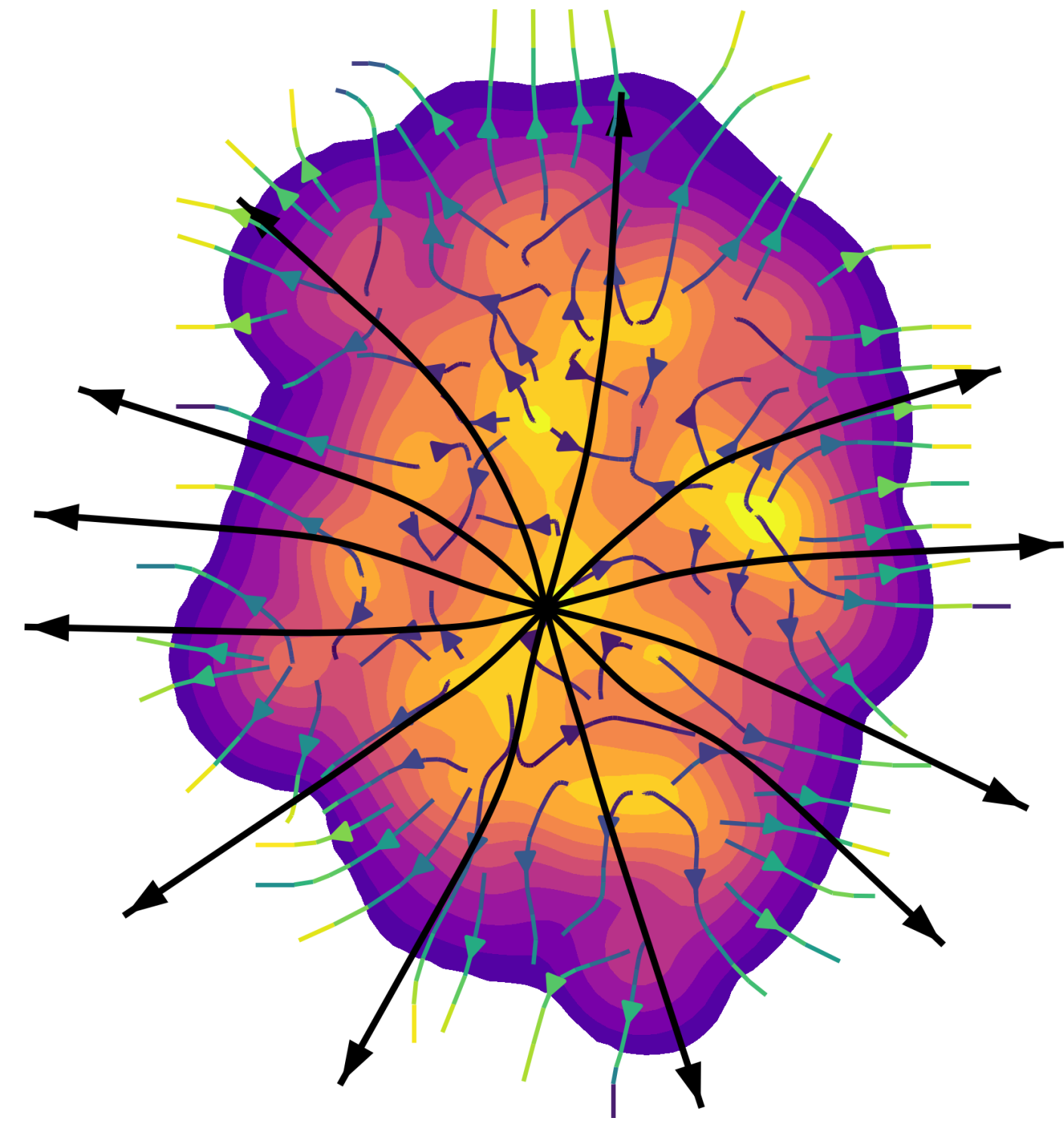
So far I have focused mainly on global properties of jets, such as their energy and angular opening

[for recent reviews: Marzani, Soyez, Thaler , 1901.10342]

[Andrews et al , 1808.03689]



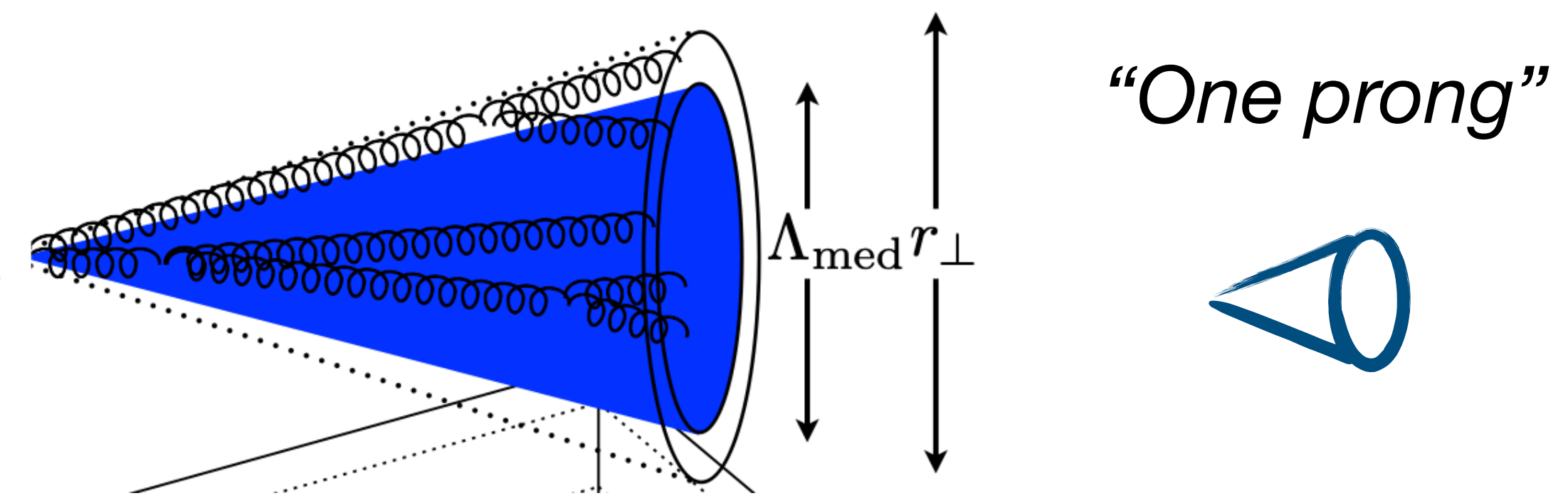
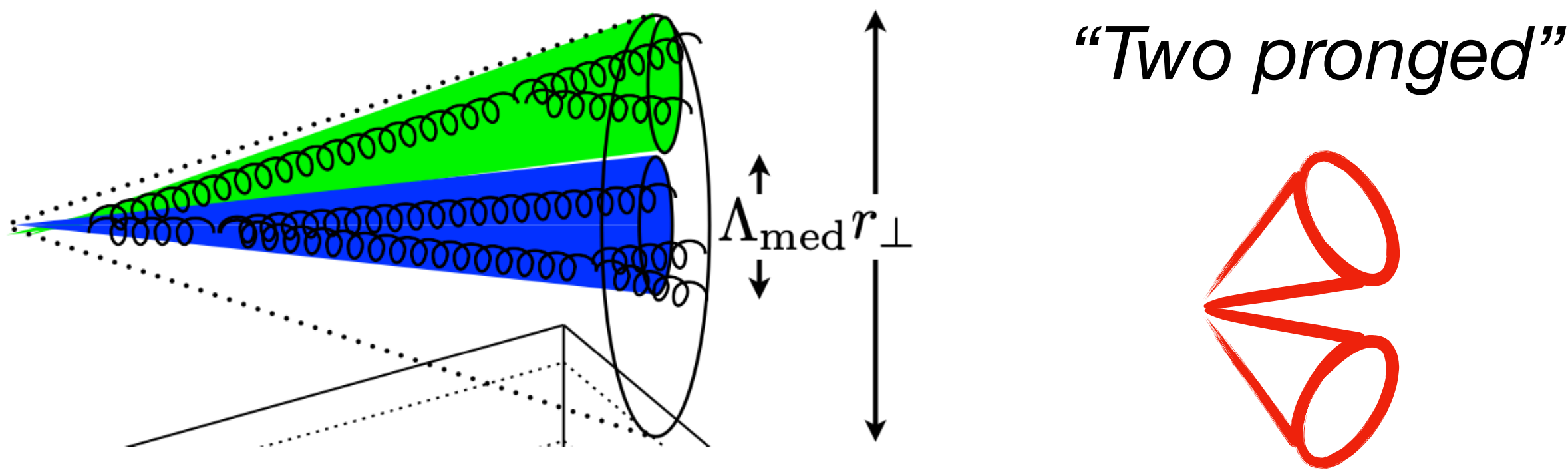
+



But a complete tomographic picture might be possible from learning about the inner structure of jets !

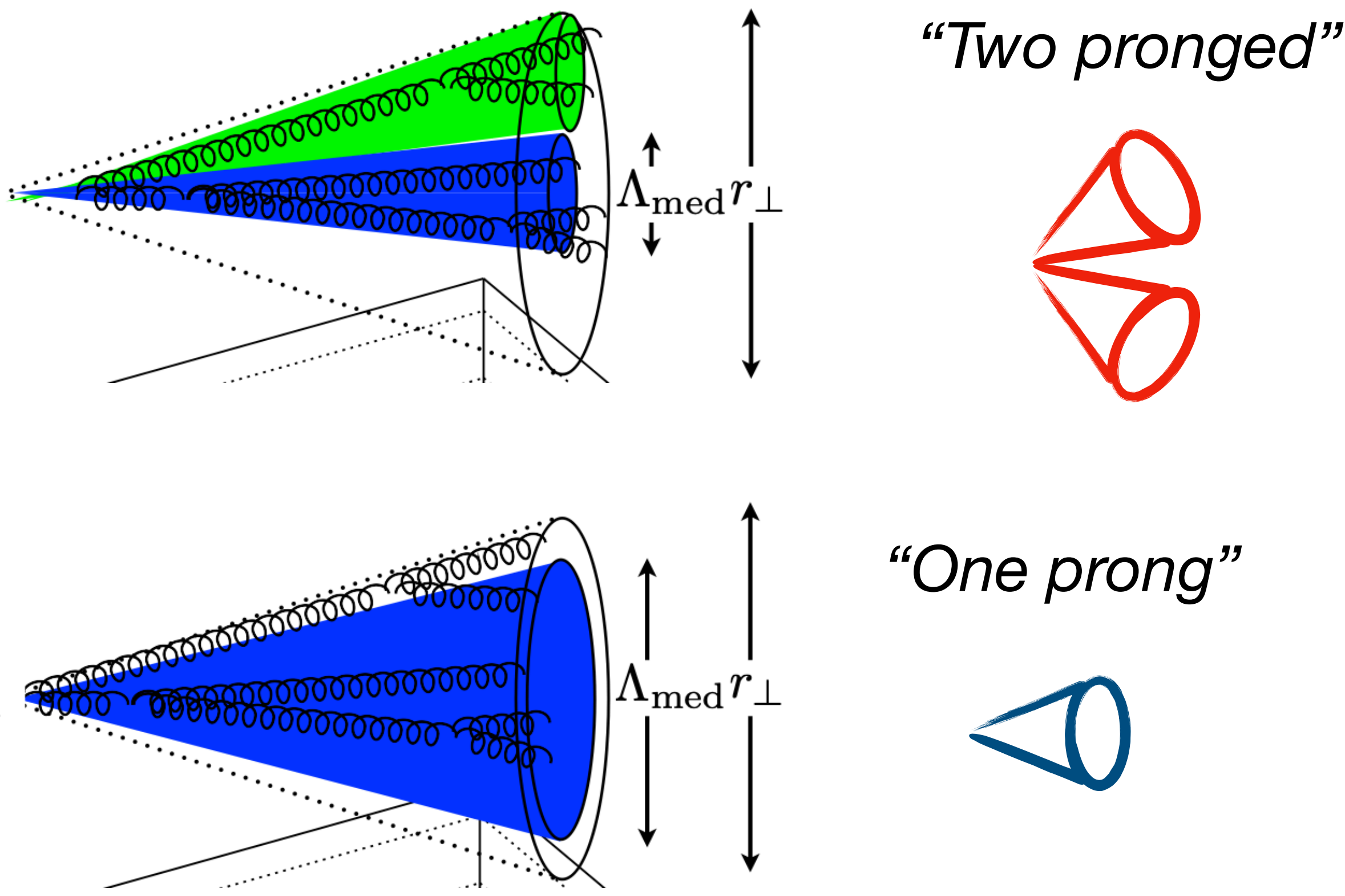
# Jet substructure in heavy ion collisions

[Salgado, Tywoniuk, Mehtar-Tani; Iancu, Casalderrey-Solana, early 2010s]

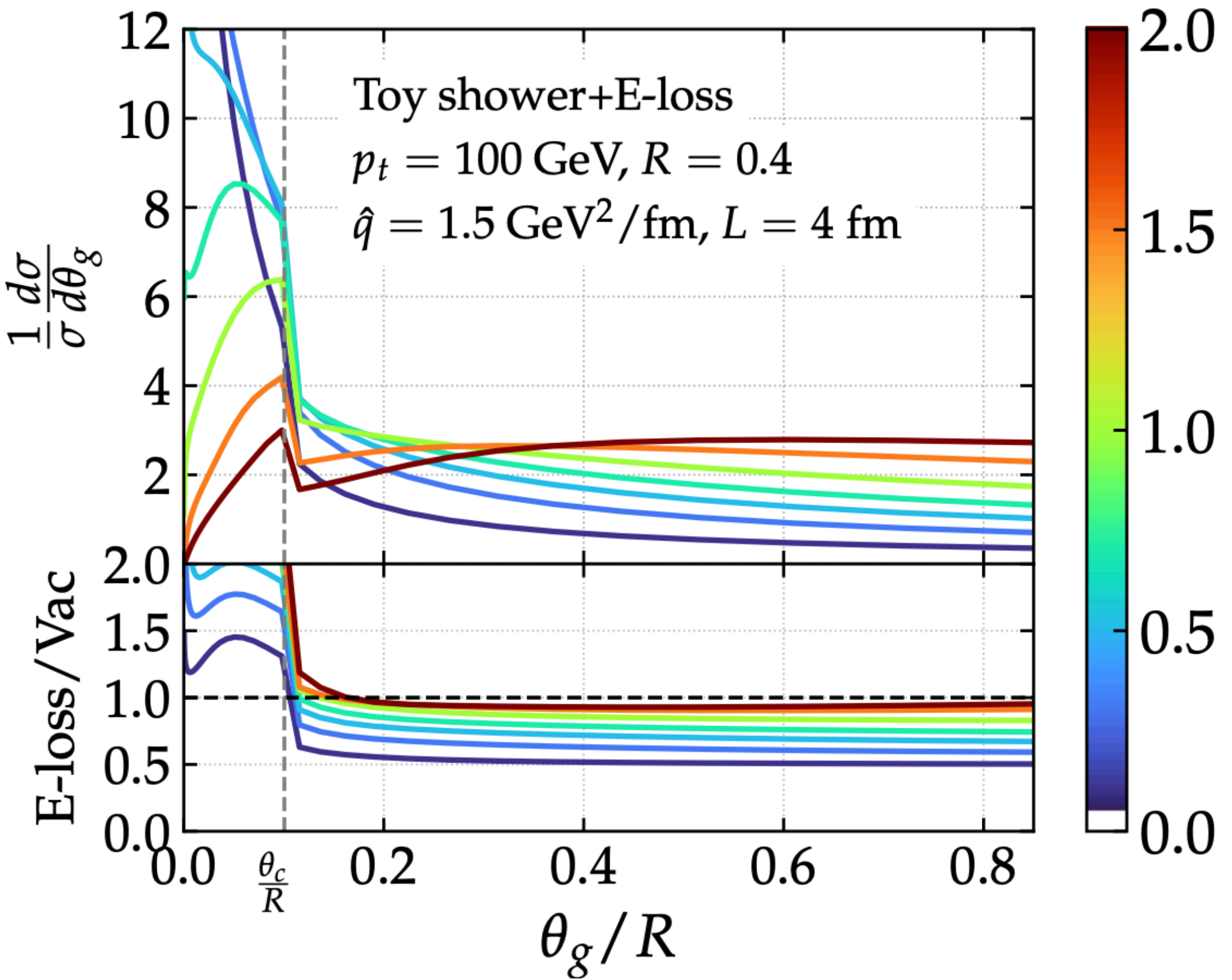


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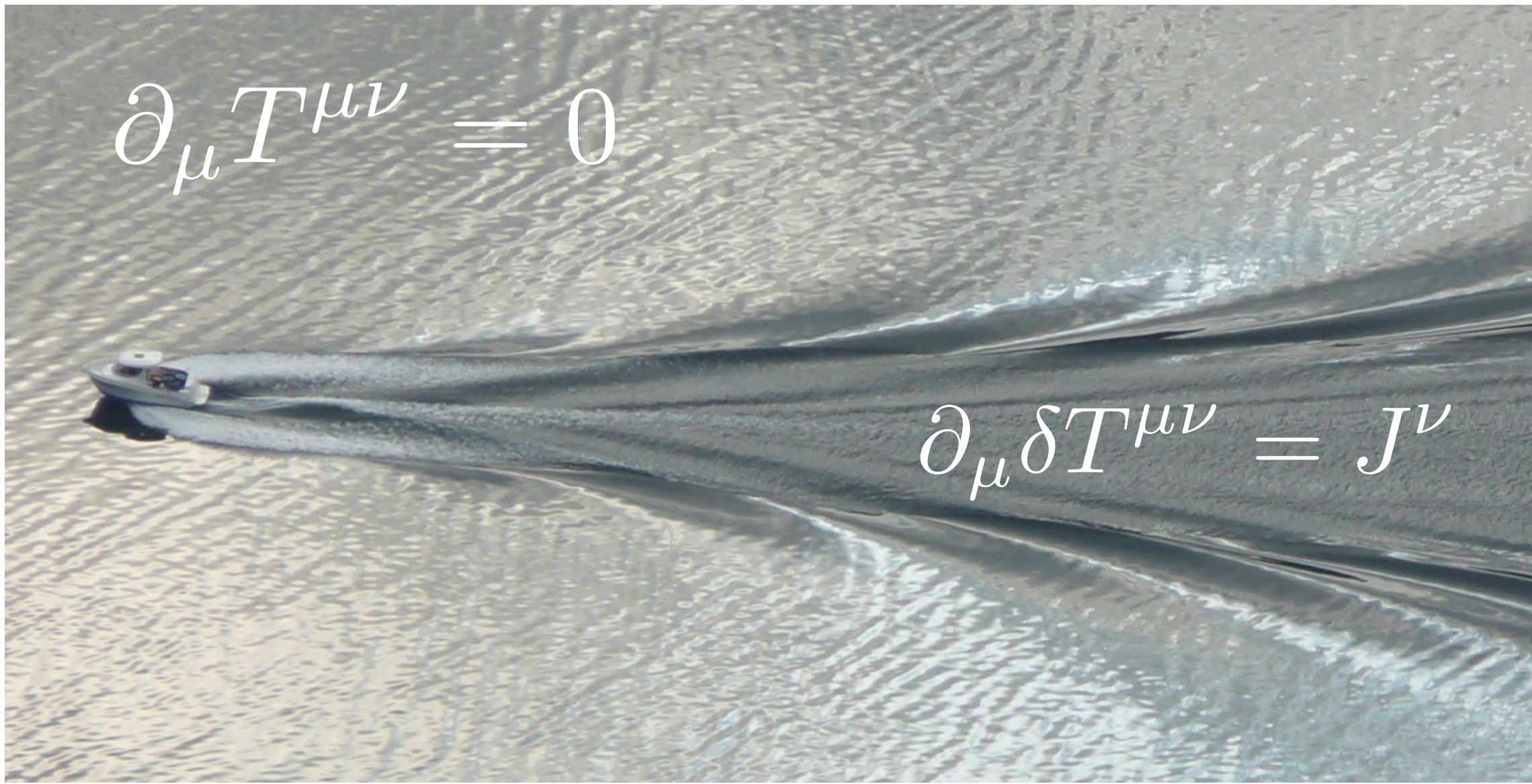


[Caucal, Soto-Ontoso, Takacs, 2111.14768]



# Jet substructure in heavy ion collisions

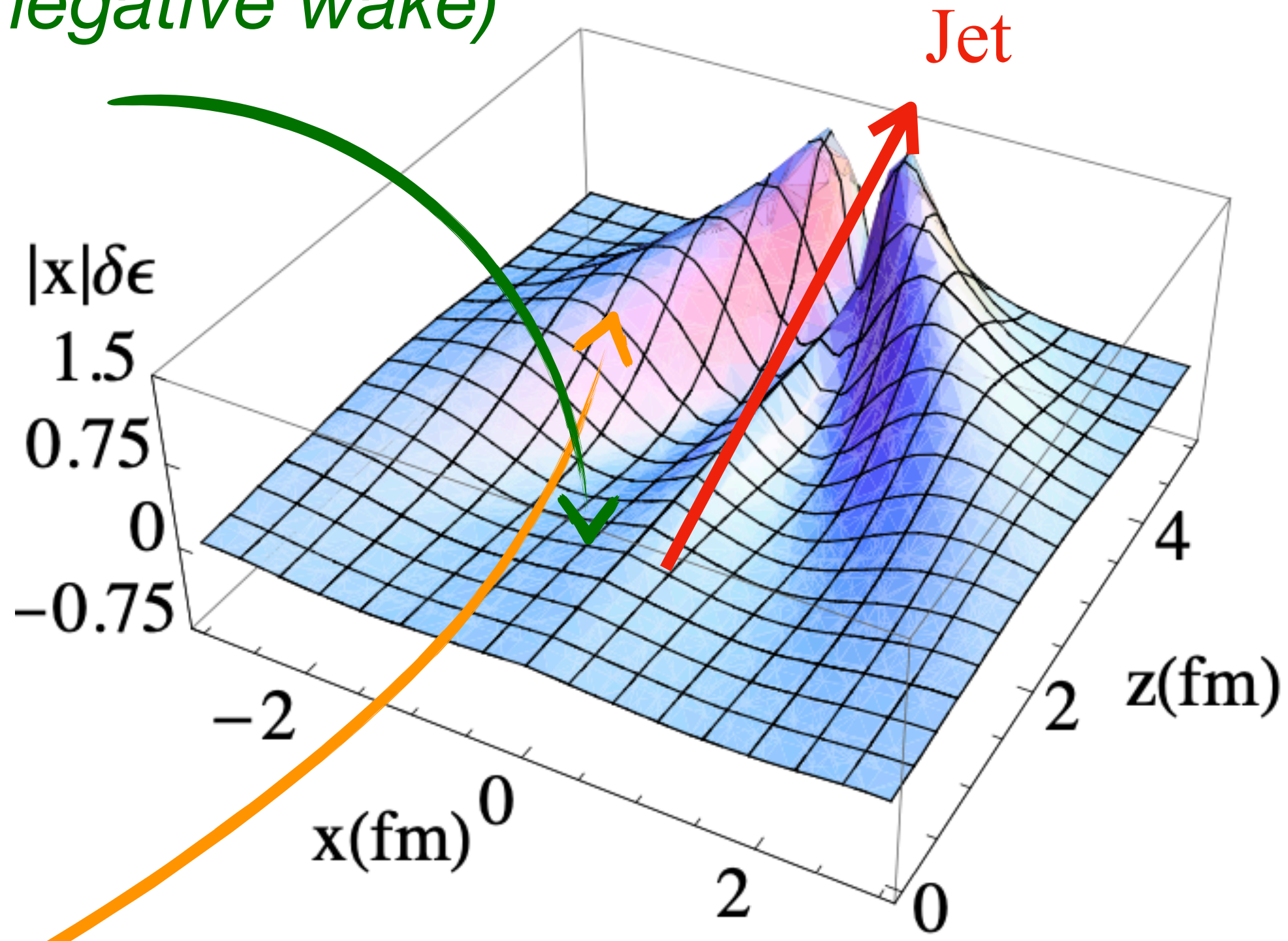
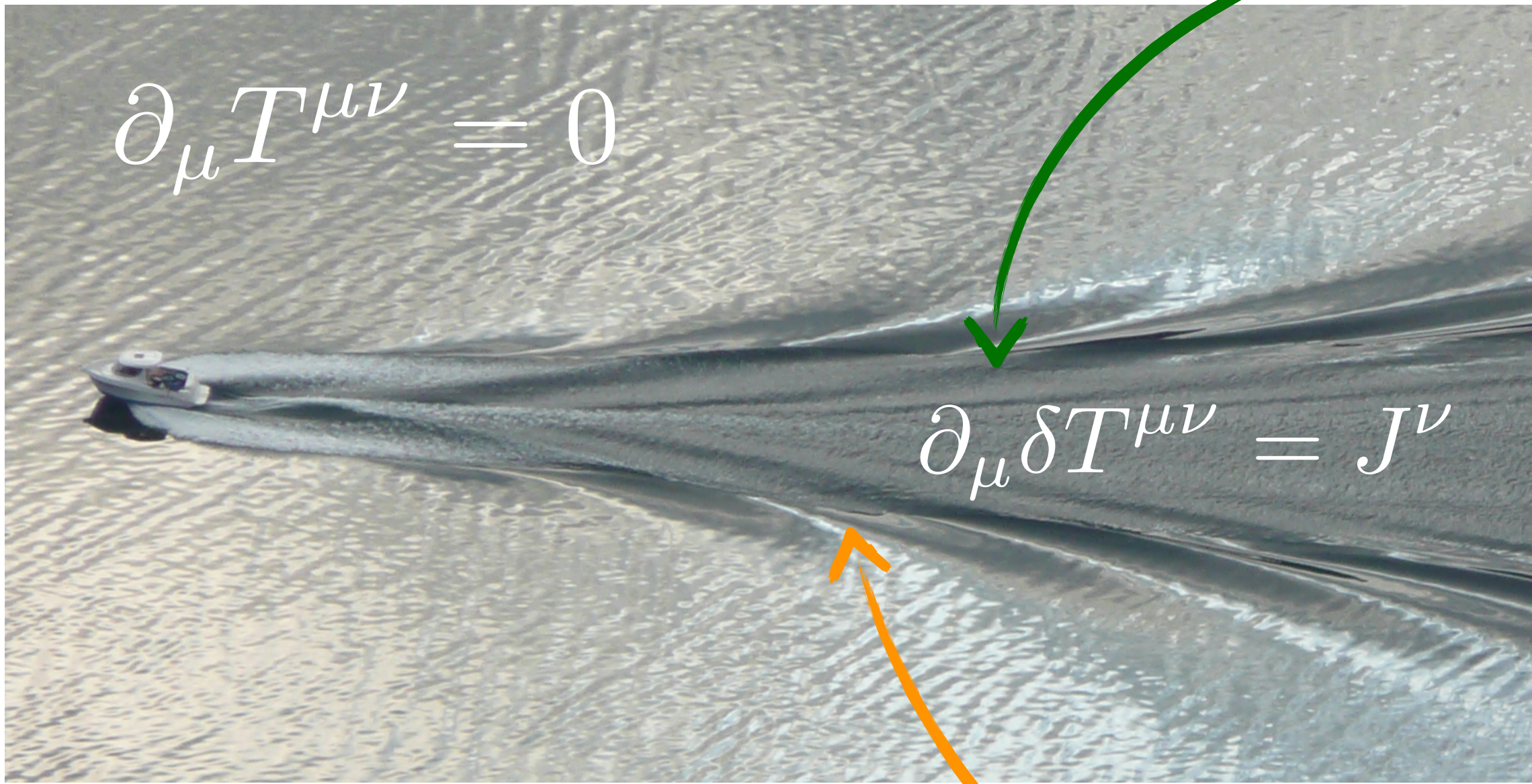
Jets *evolve on top of a bulk* which backreacts; this can inform about *dynamical properties of matter*



# Jet substructure in heavy ion collisions

Jets *evolve on top of a bulk* which backreacts; this can inform about *dynamical properties of matter*

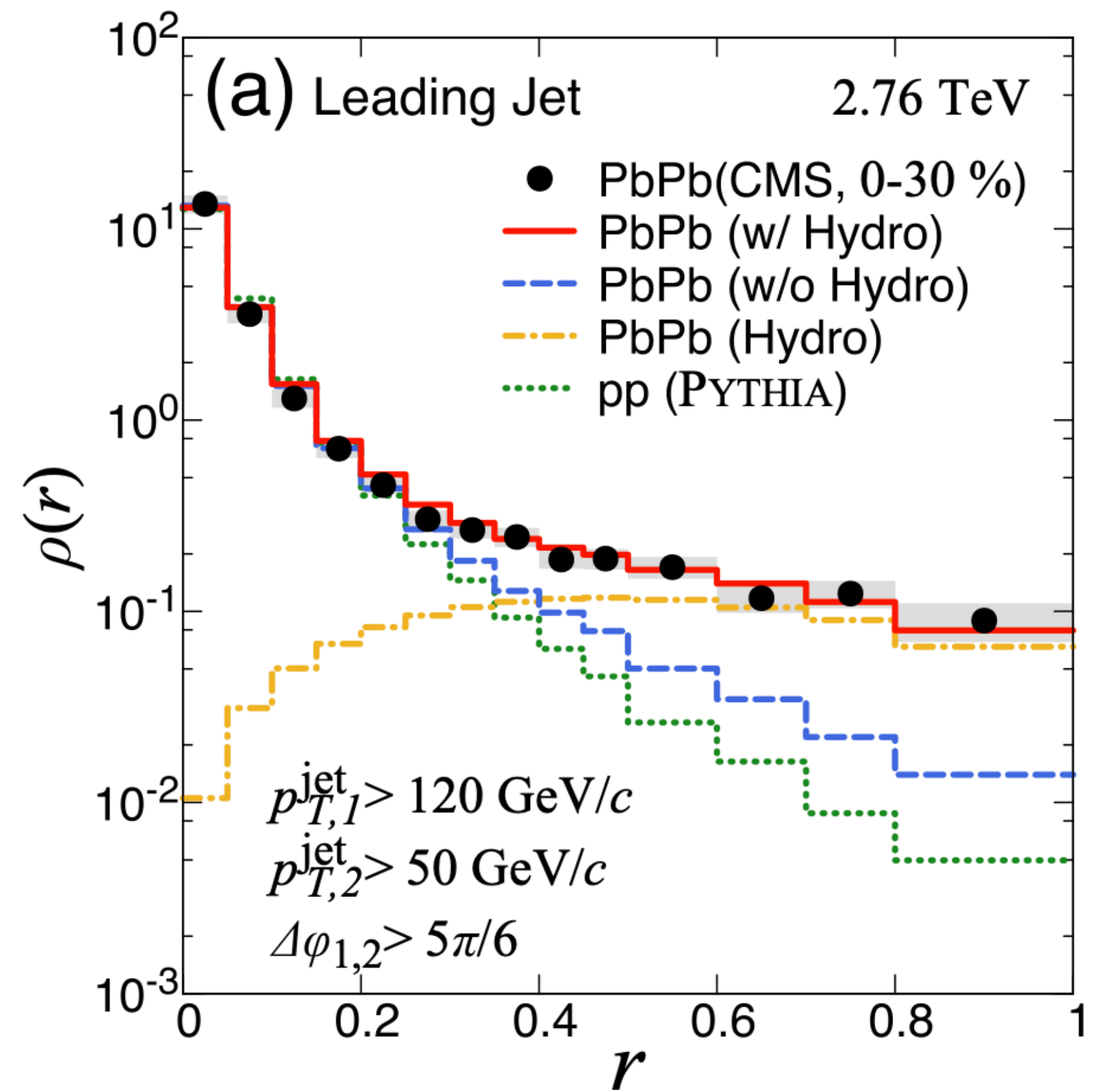
*Depletion of particles (negative wake)*



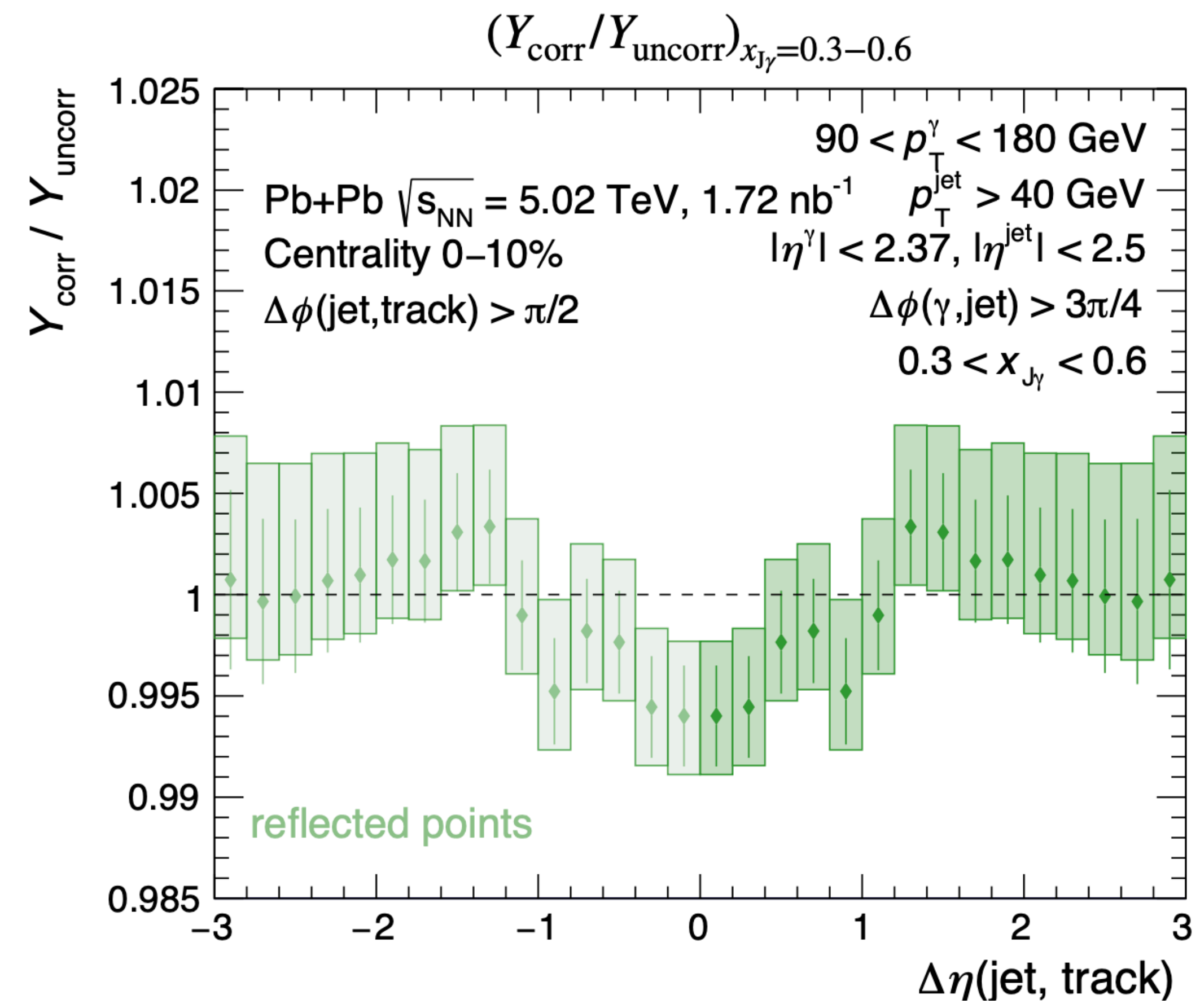
*Mach cone structure* [G.-Y. Qin, A. Majumder, H. Song, U. Heinz, 0903.22255]

# Jet substructure in heavy ion collisions

[Tachibana et al, 1701.07951]



[ATLAS, 2408.08599]

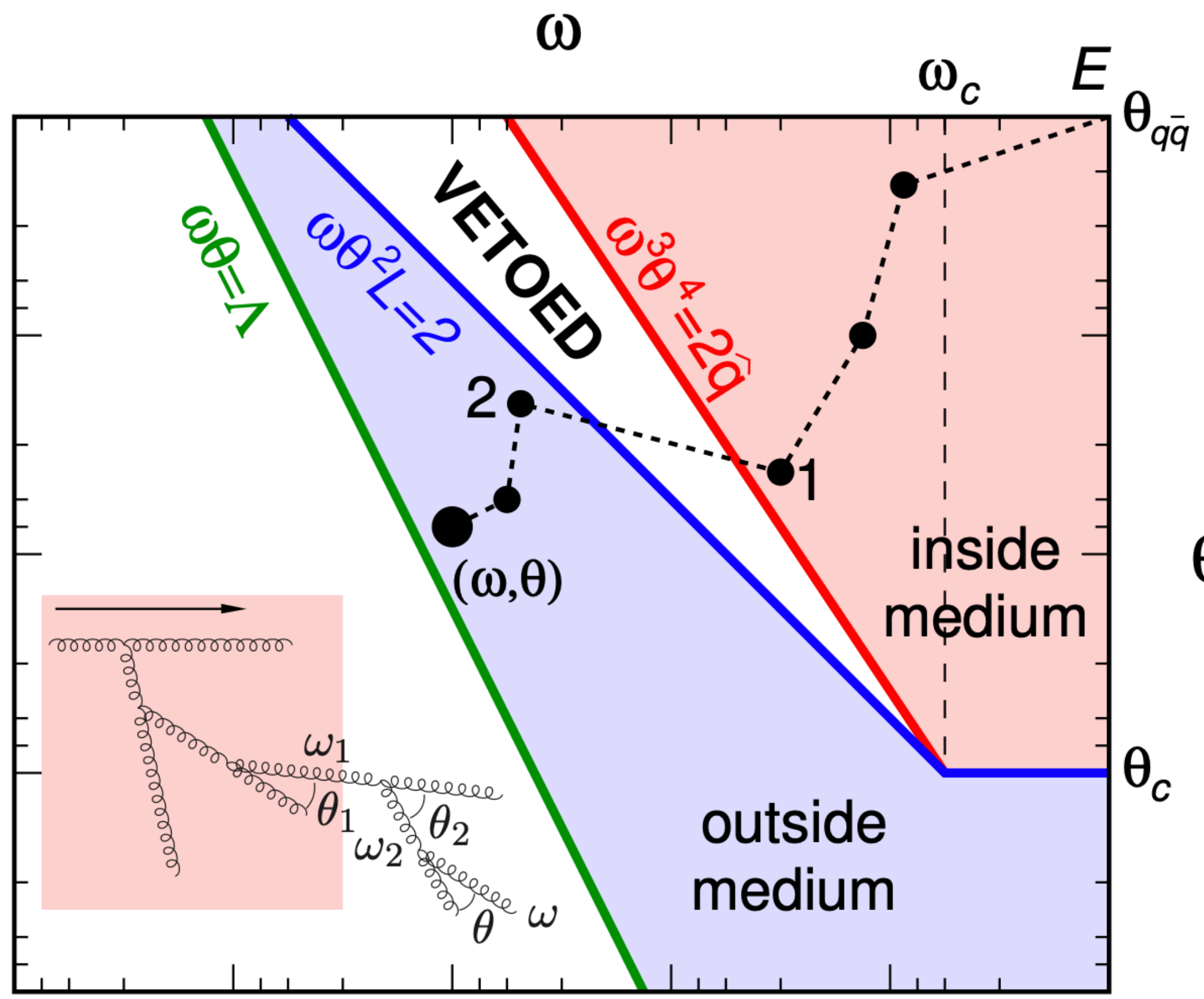


The effects of **hydro response** on jets should be **non-negligible**

Still, **hard to get sharp experimental confirmation** of this effect

# Jet substructure in heavy ion collisions

Medium introduces new scales which can *change virtuality cascade*



Results in reduction of phase space for the virtuality cascade to develop

So far *poor theoretical understanding*; realizations highly model dependent

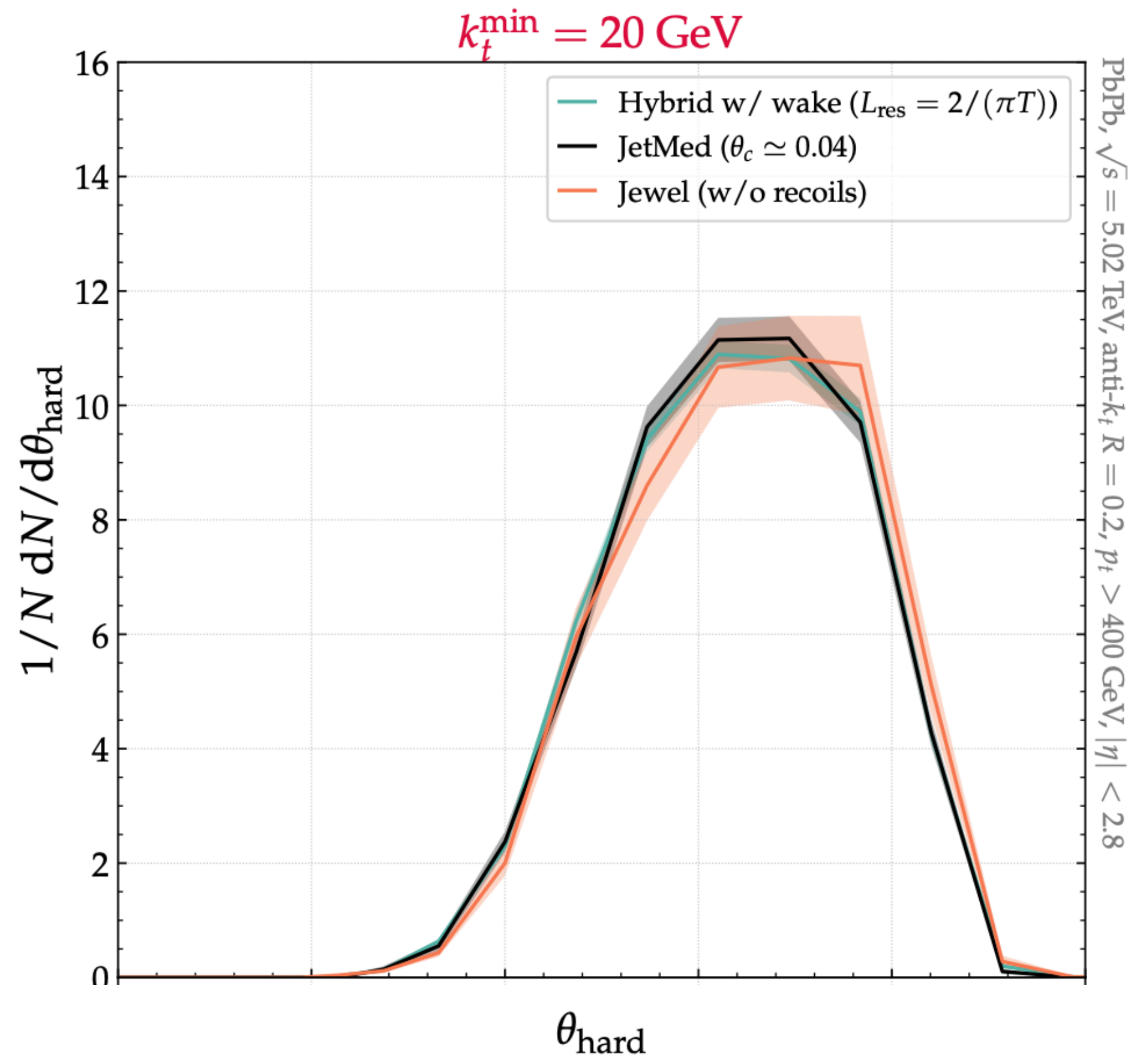
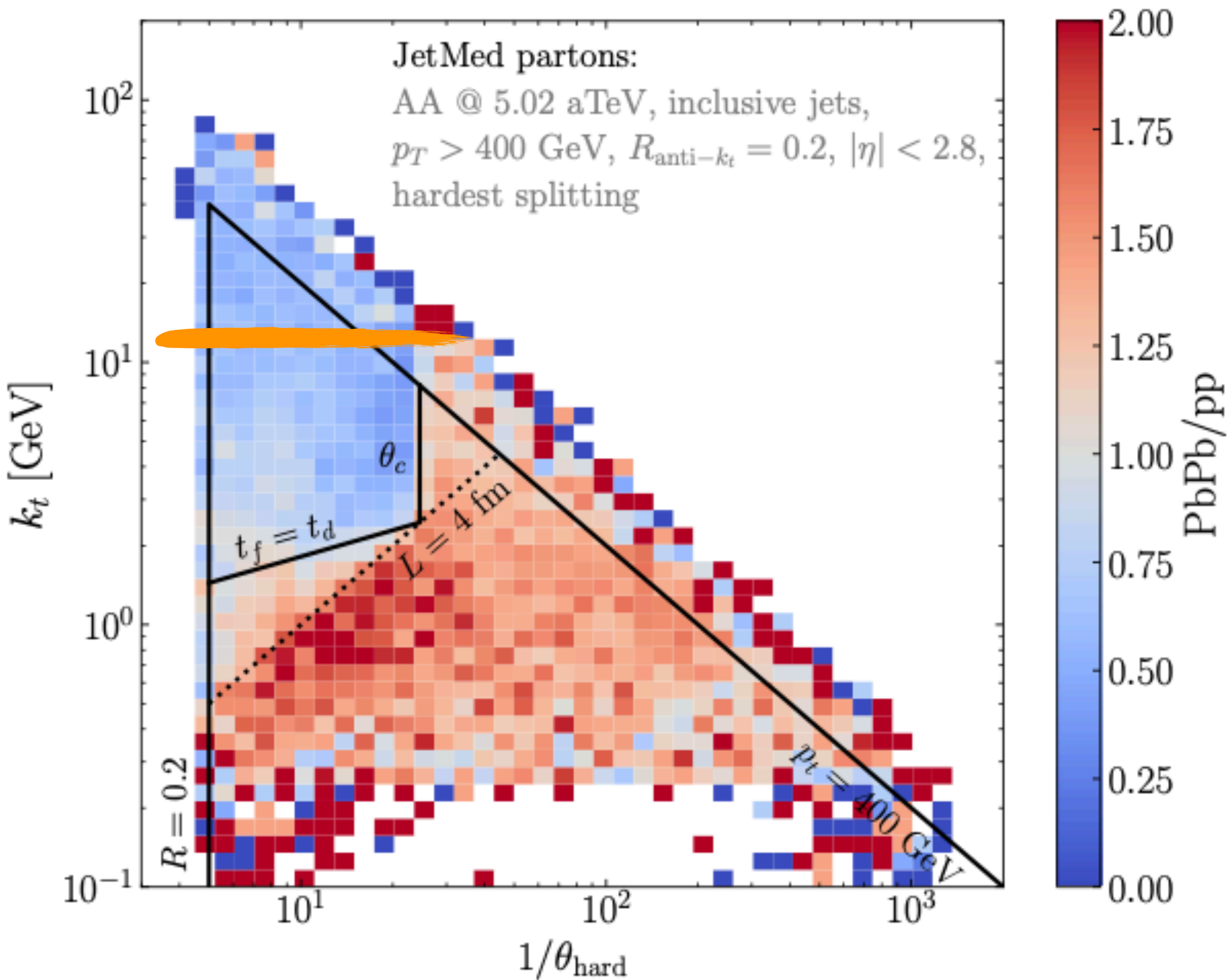
Critical to understand this as a *baseline* for any calculation

[Caucal, Mueller, Iancu, Soyez, 1801.09703]

# Jet substructure in heavy ion collisions

*Several new ideas to explore how the virtuality cascade develops in the medium*

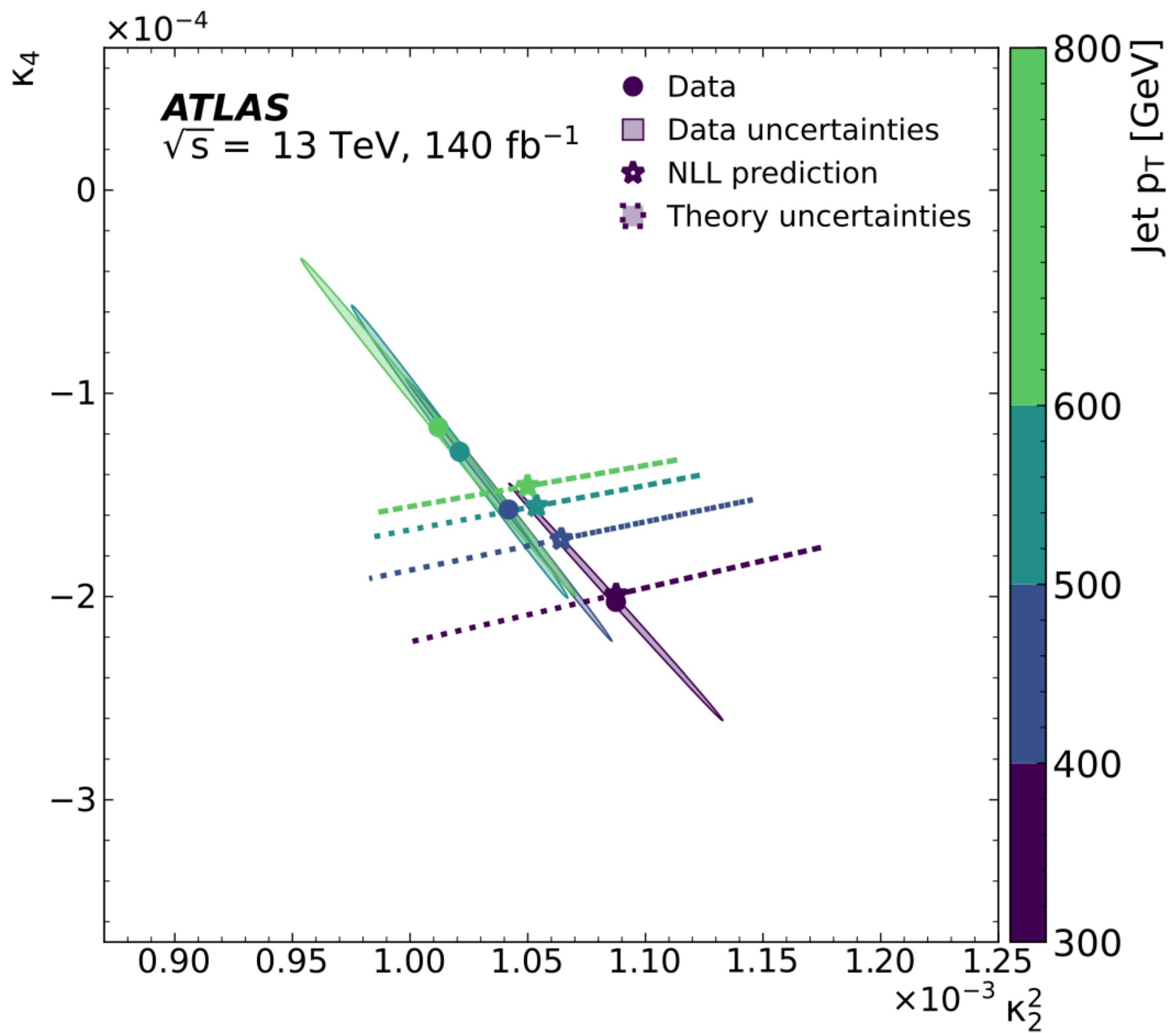
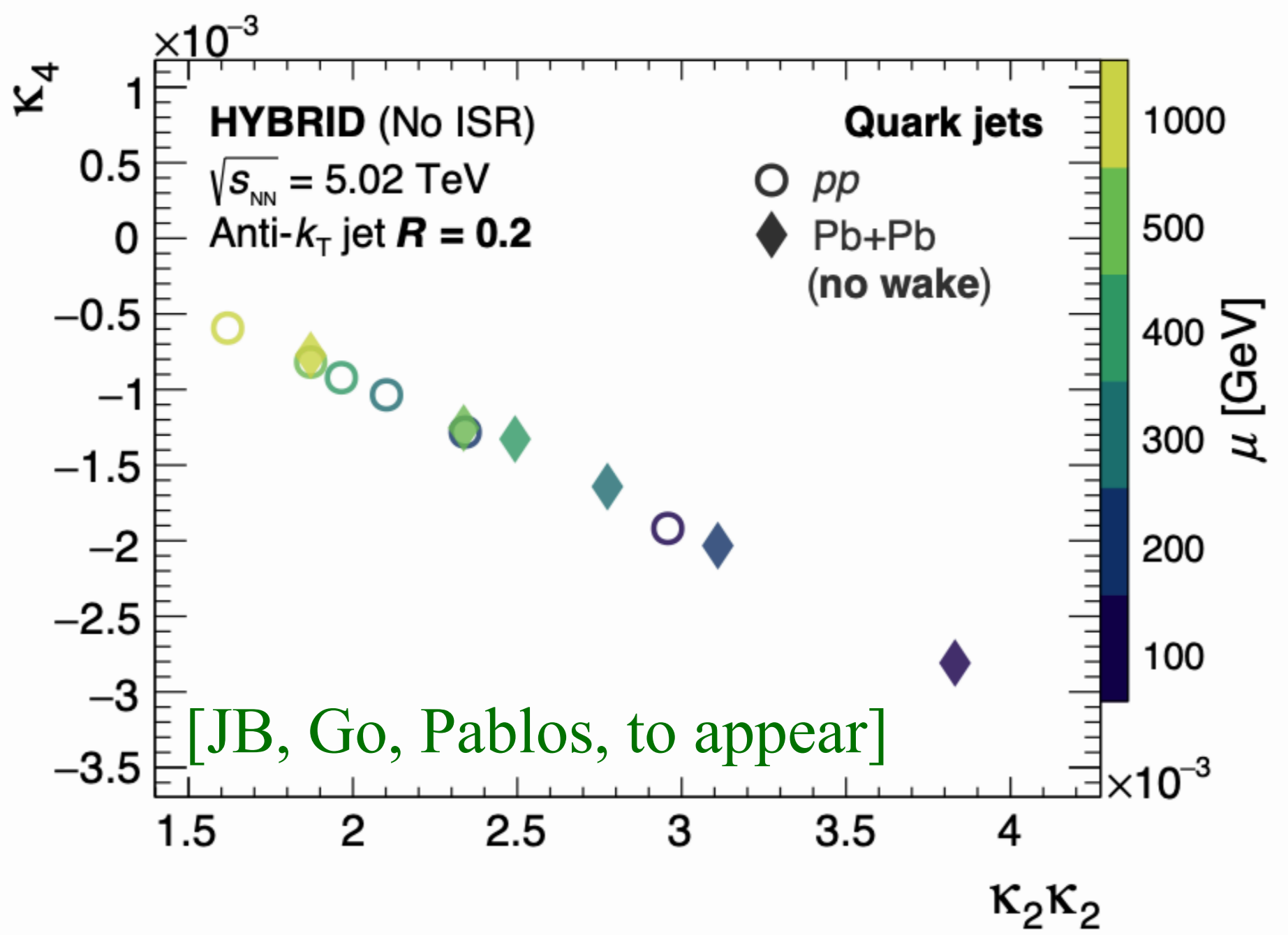
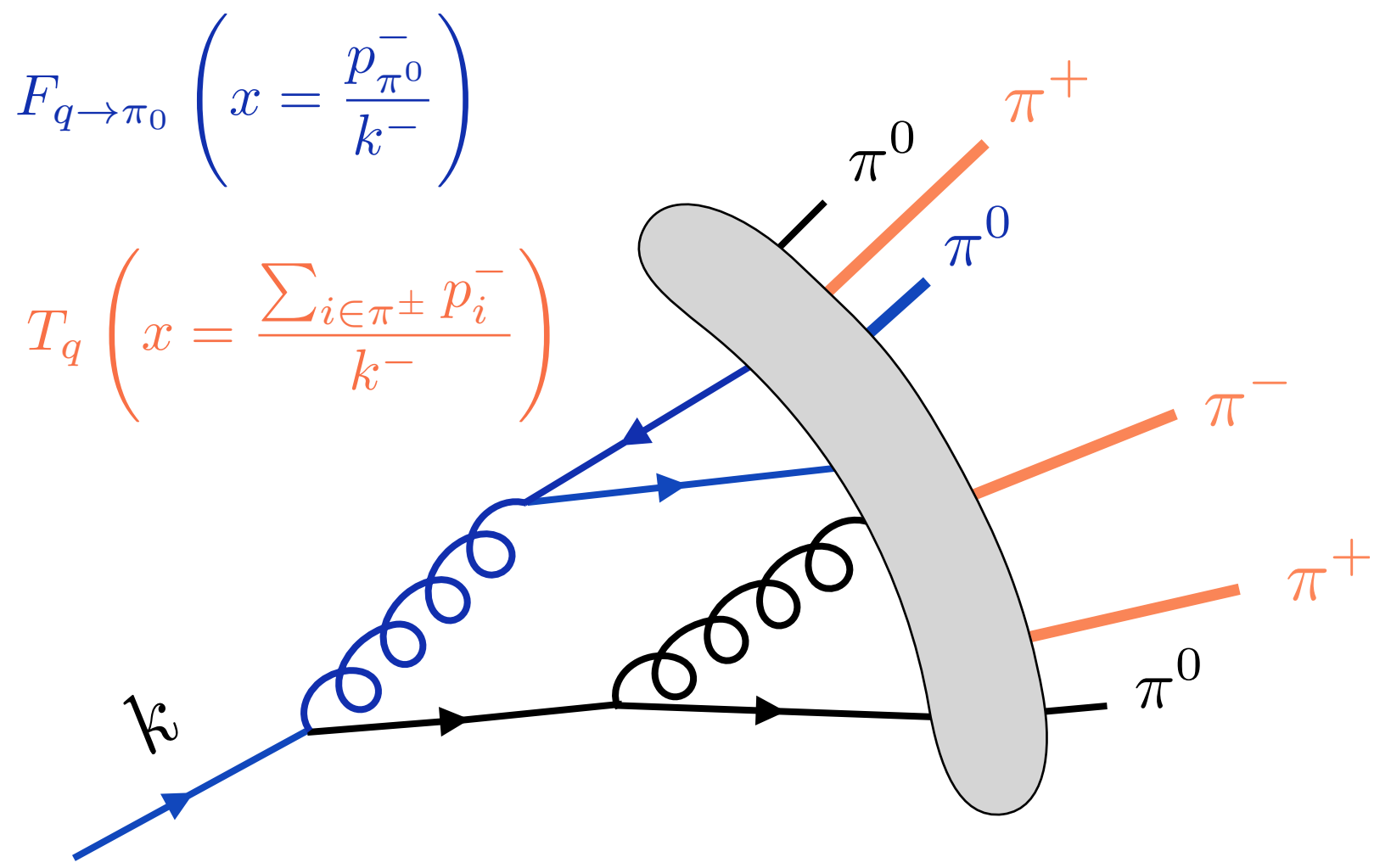
[Cunqueiro, et al, 2311.07643]





# Jet substructure in heavy ion collisions

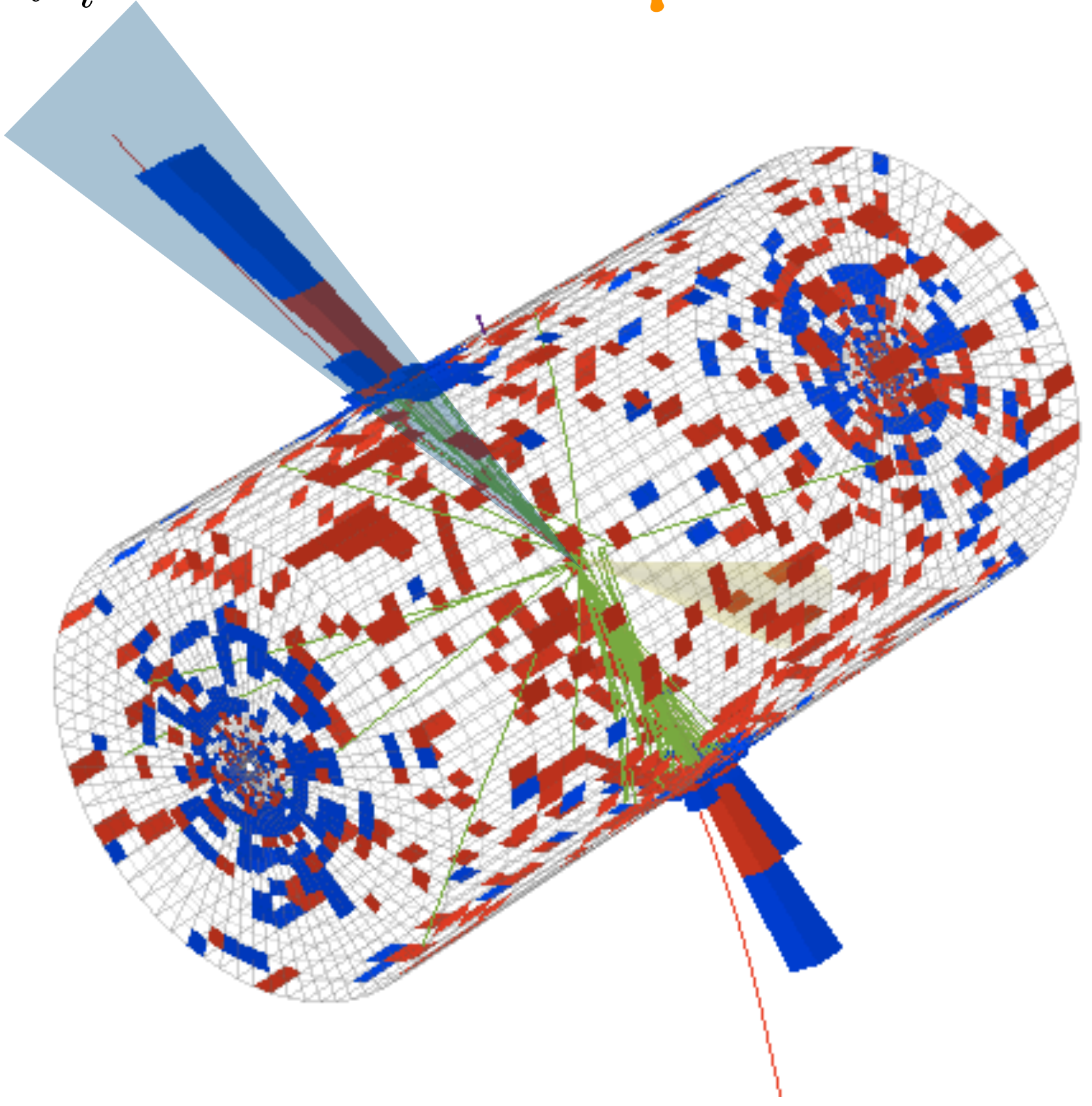
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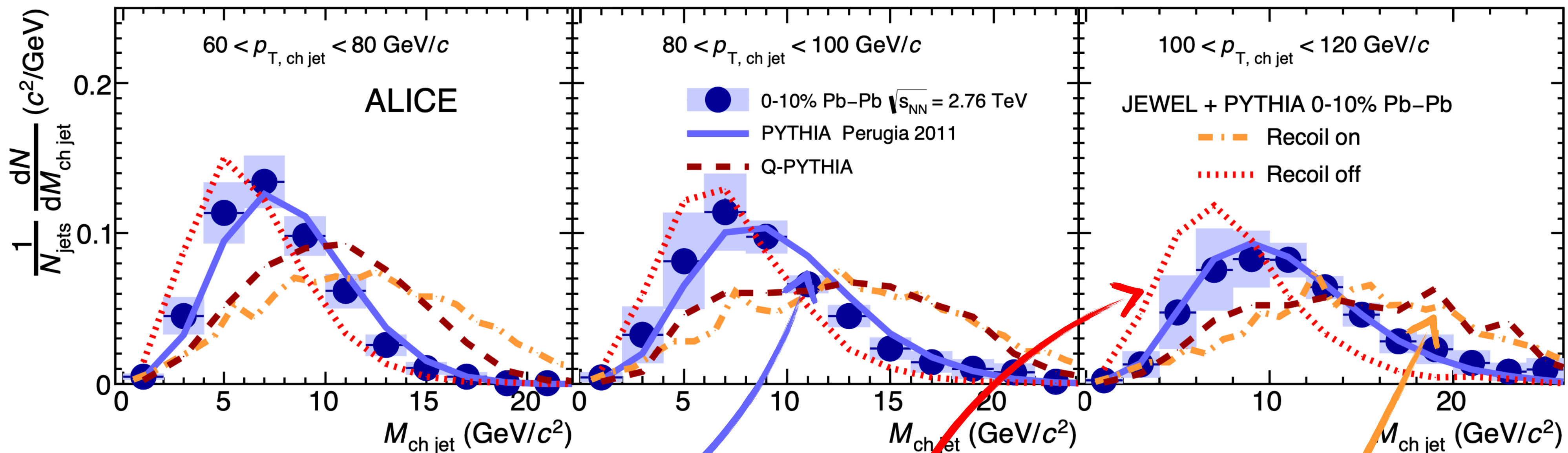
# Jet substructure in heavy ion collisions

$$O_{m^2} = \sum_i z_i \theta_i^2$$

Jet shapes



# Jet substructure in heavy ion collisions

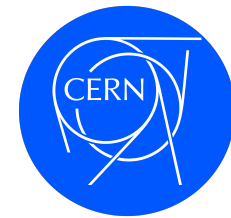


*Perturbative jet cascade (vacuum)*

*Perturbative jet cascade vacuum*

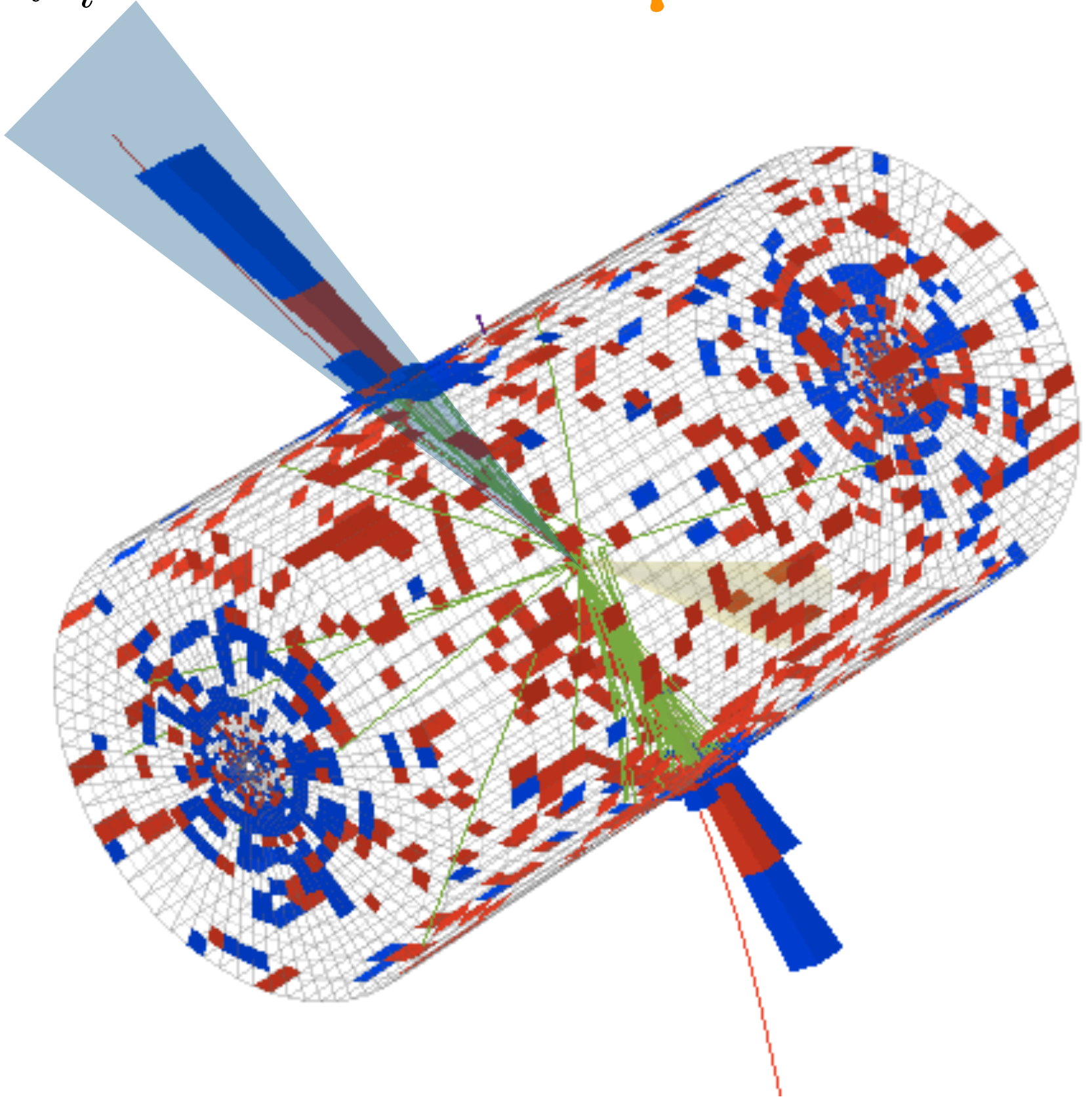
*Including medium response*

***Even for simple shapes, the current description of jet observables is rather poor***

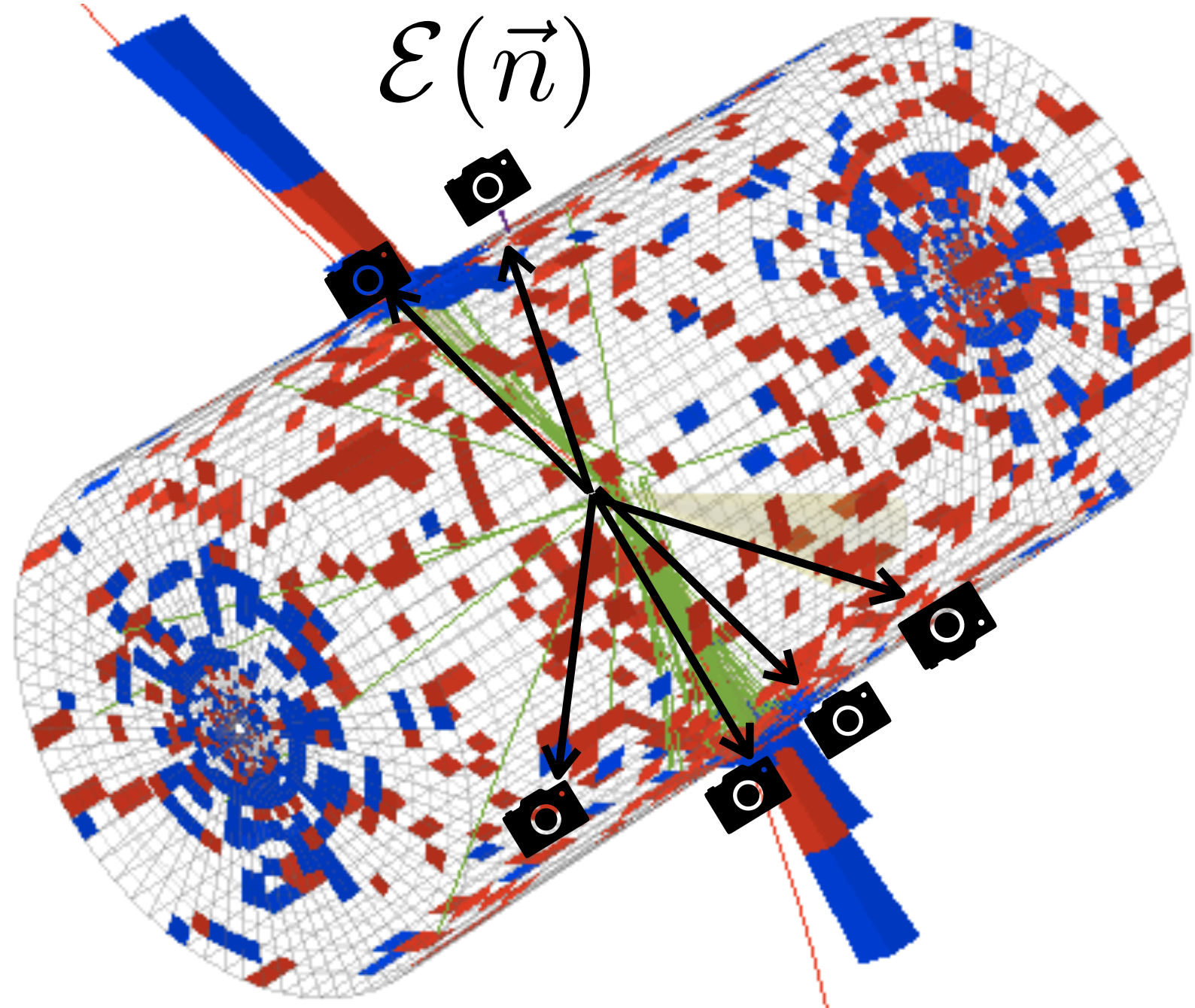


$$O_{m^2} = \sum_i z_i \theta_i^2$$

## Jet shapes

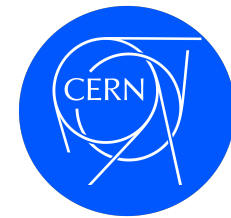


## Energy Flow Correlators

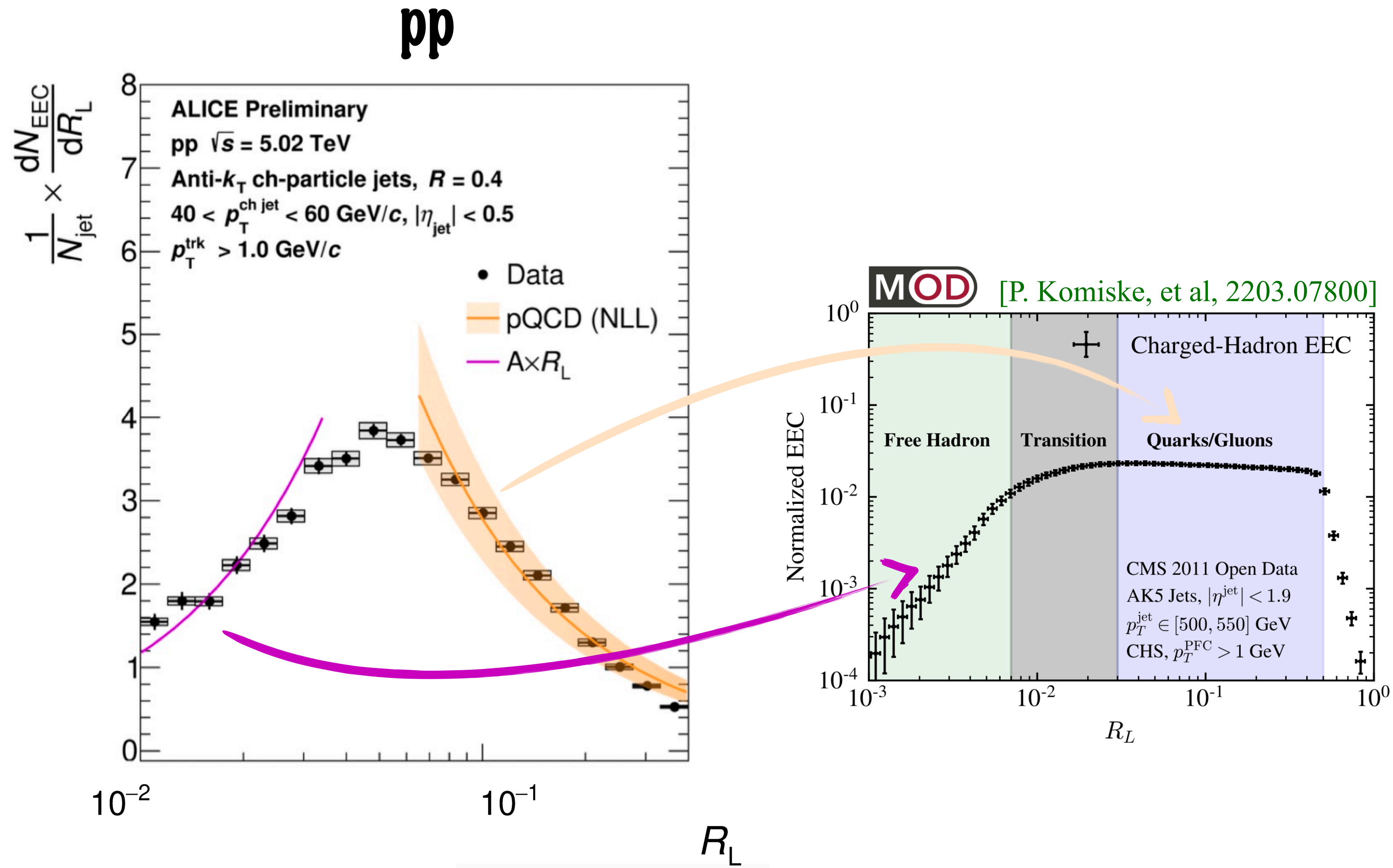


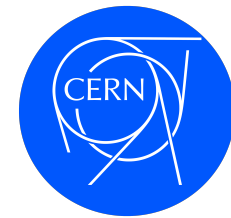
$$\mathcal{E}(\vec{n})|P\rangle = \sum_i E_i \delta(\Omega_{\vec{n}} - \Omega_{\vec{k}_i})|P\rangle$$

*Energy correlators might offer a **clean theoretical and experimental avenue** to dissect medium induced jet modifications*

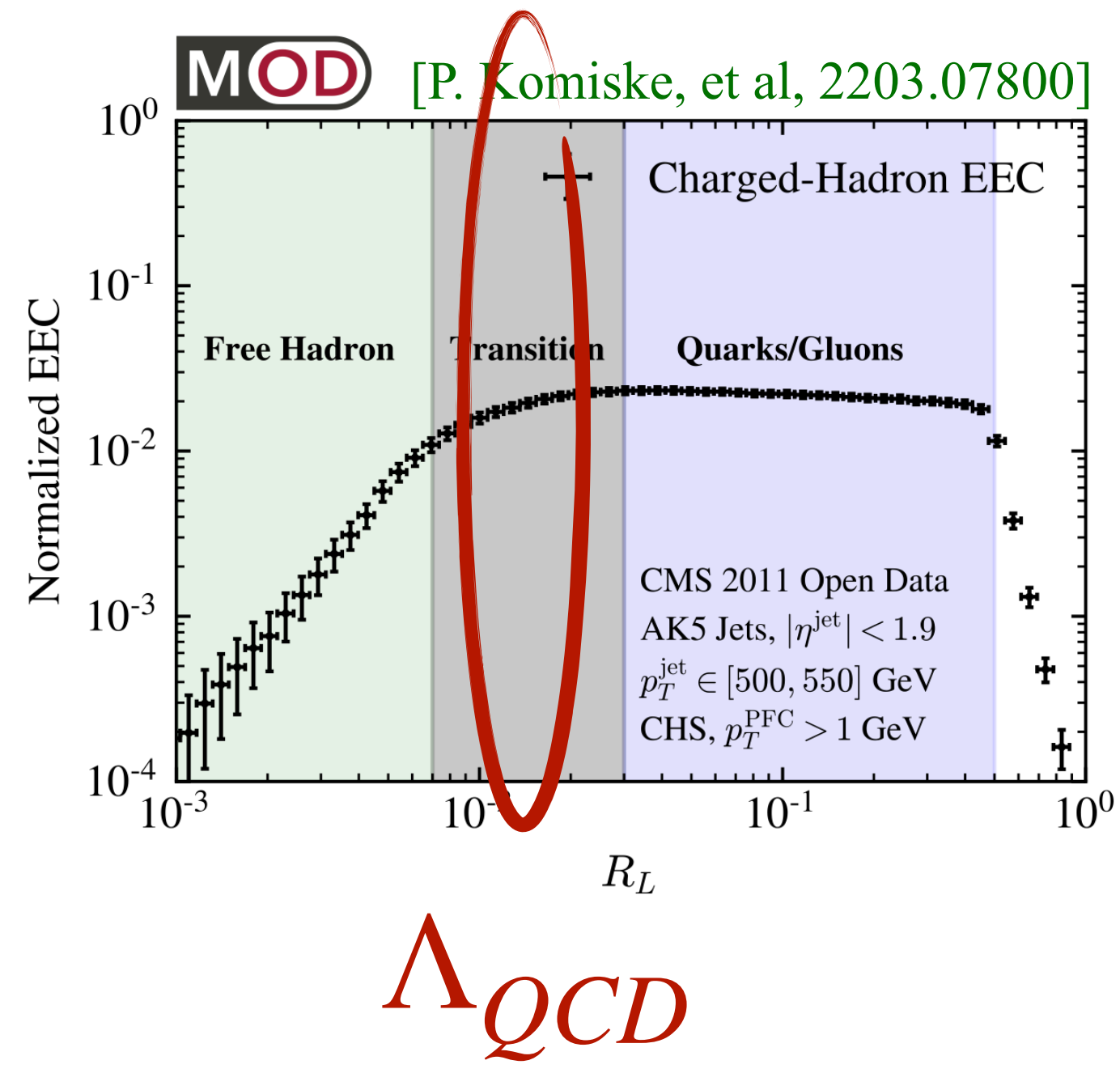
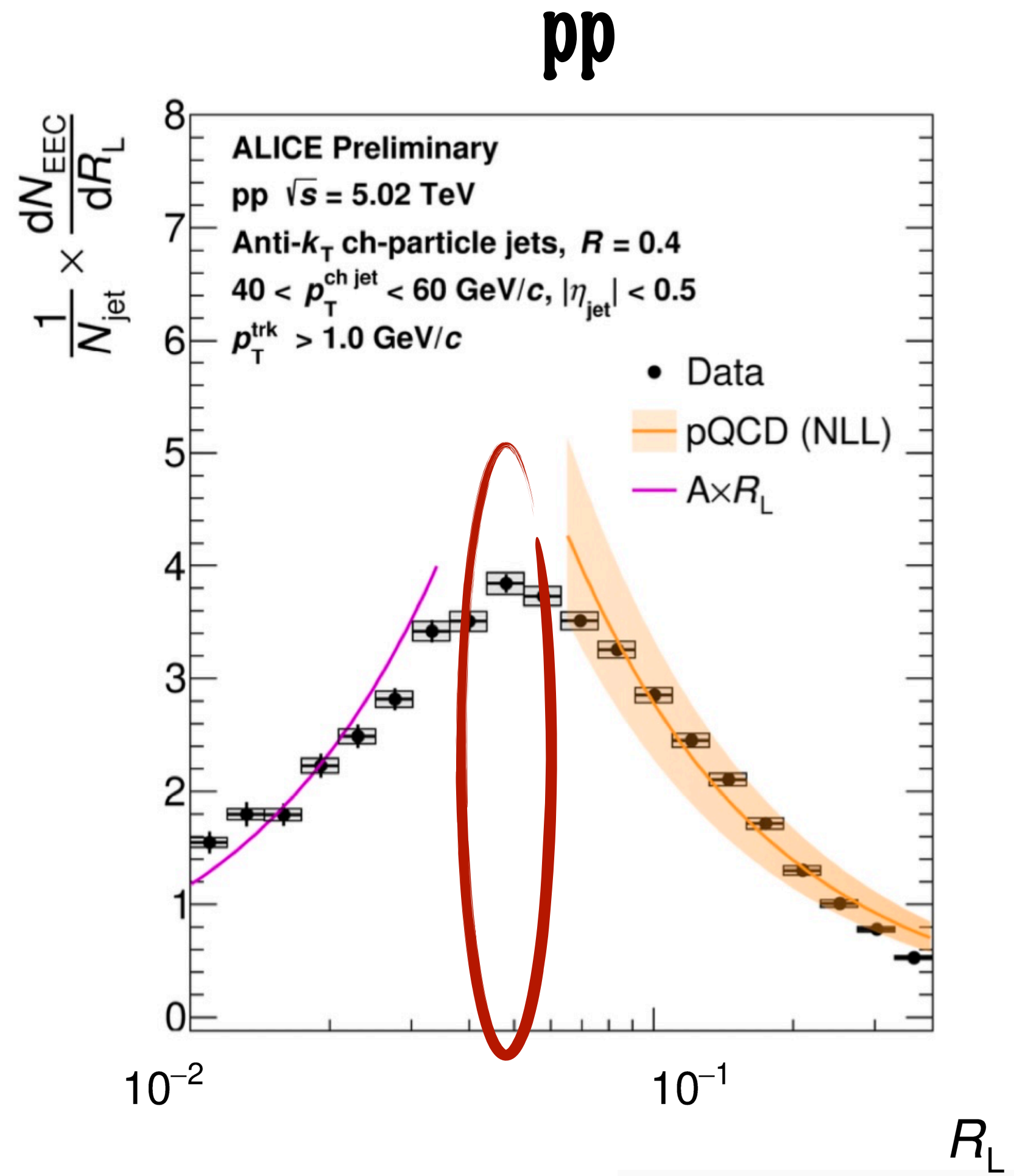


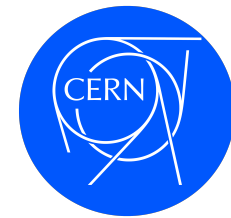
One interesting aspect of energy correlators is their clean resolution of **physical scales**



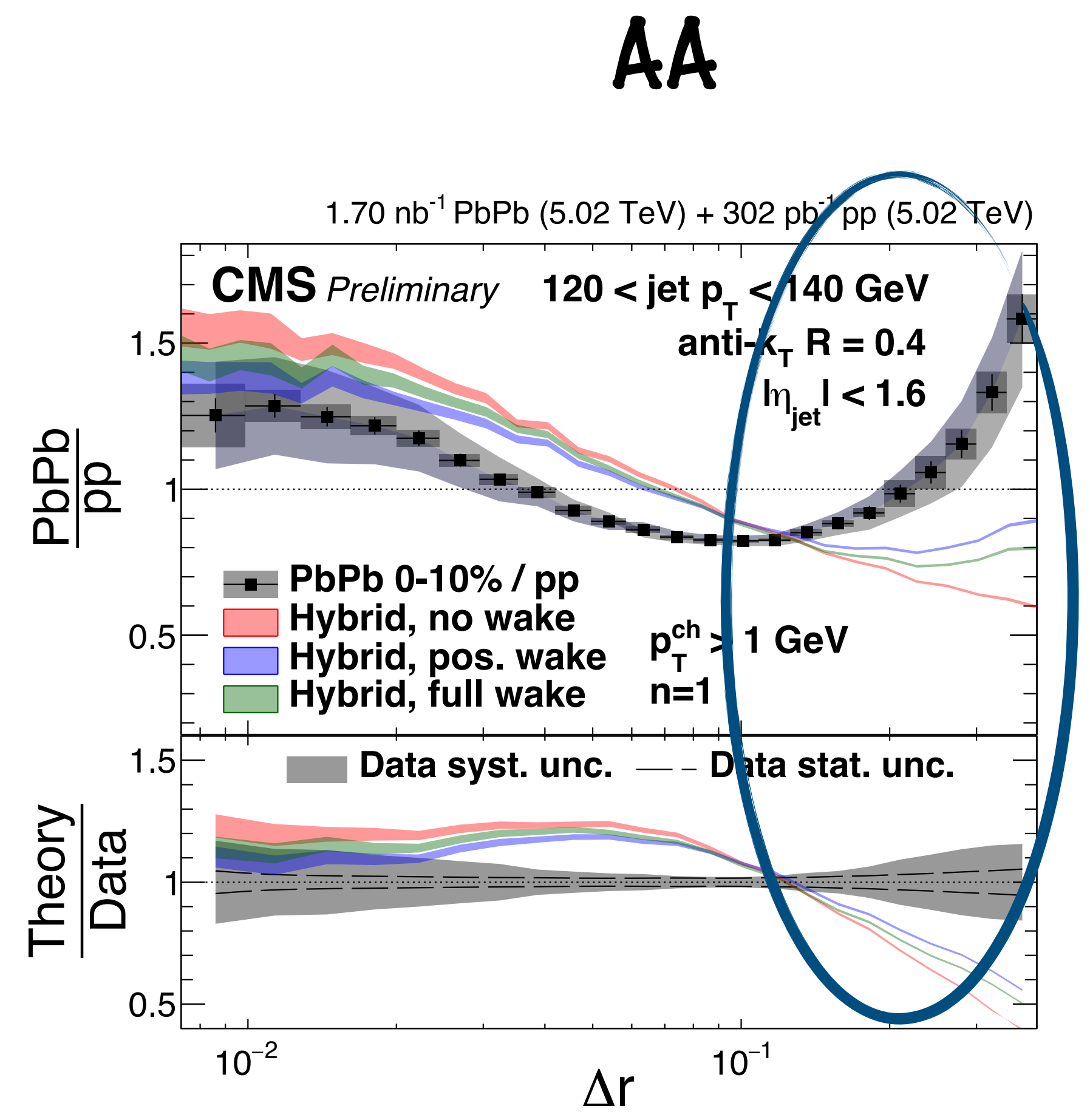
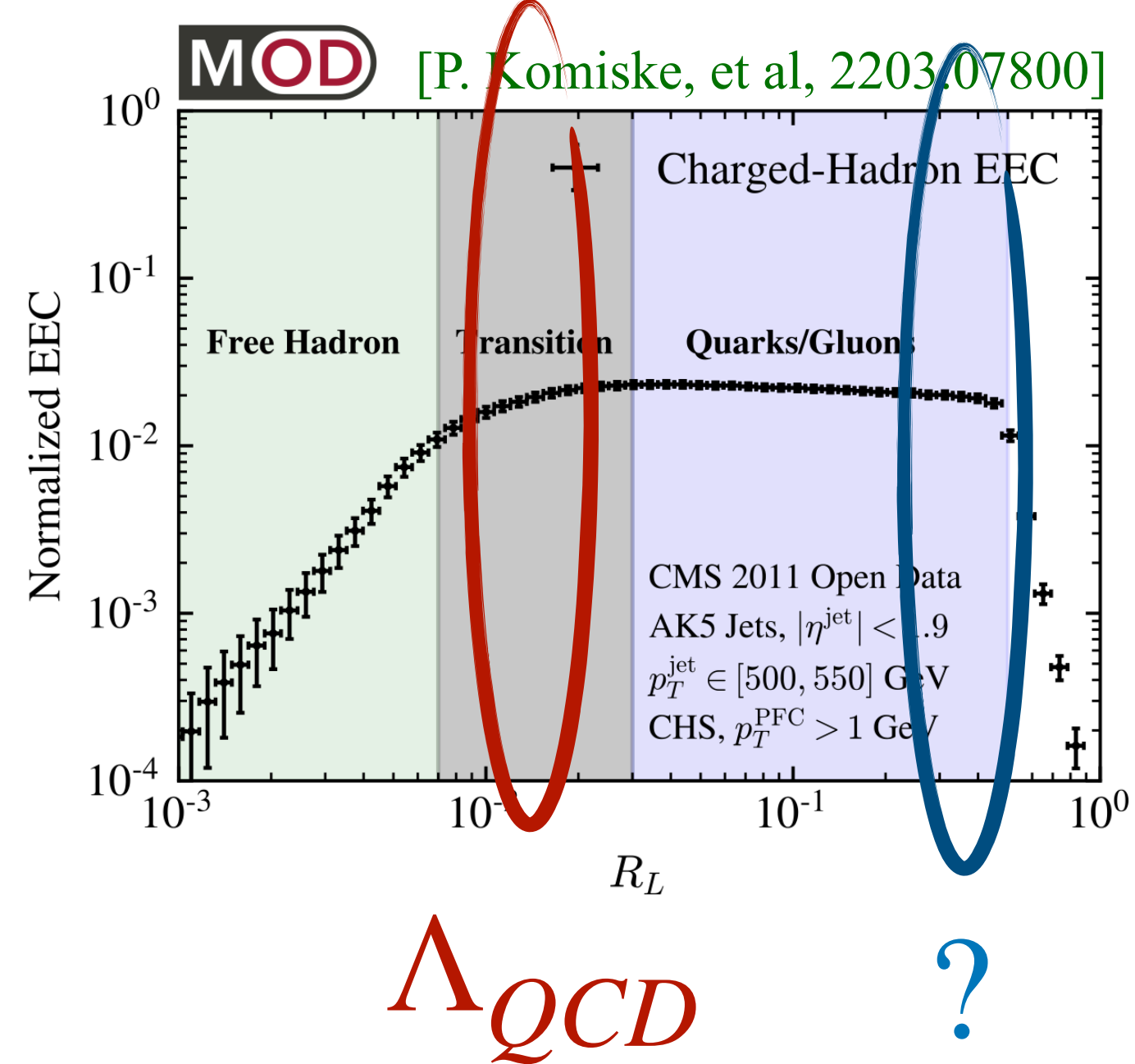
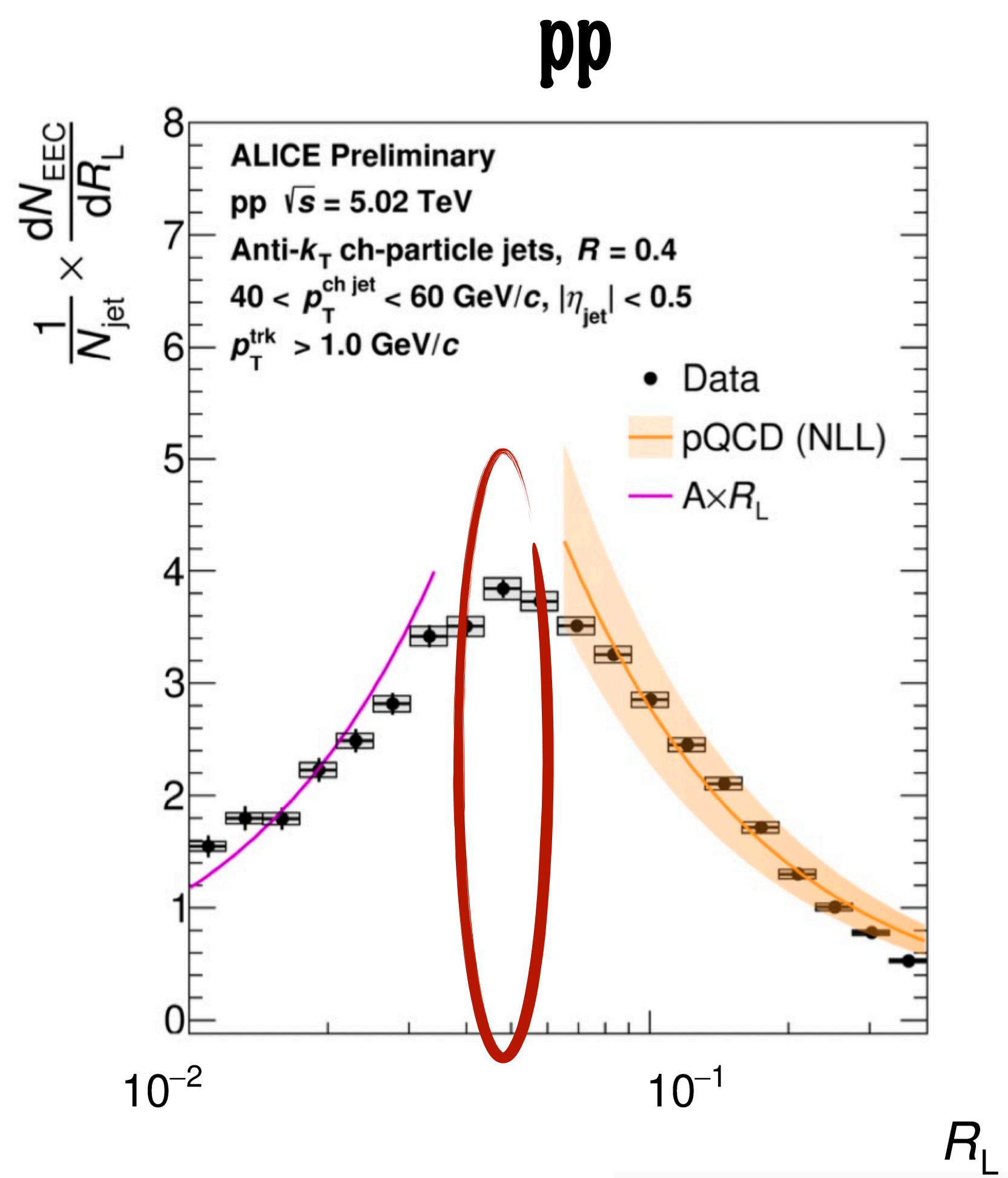


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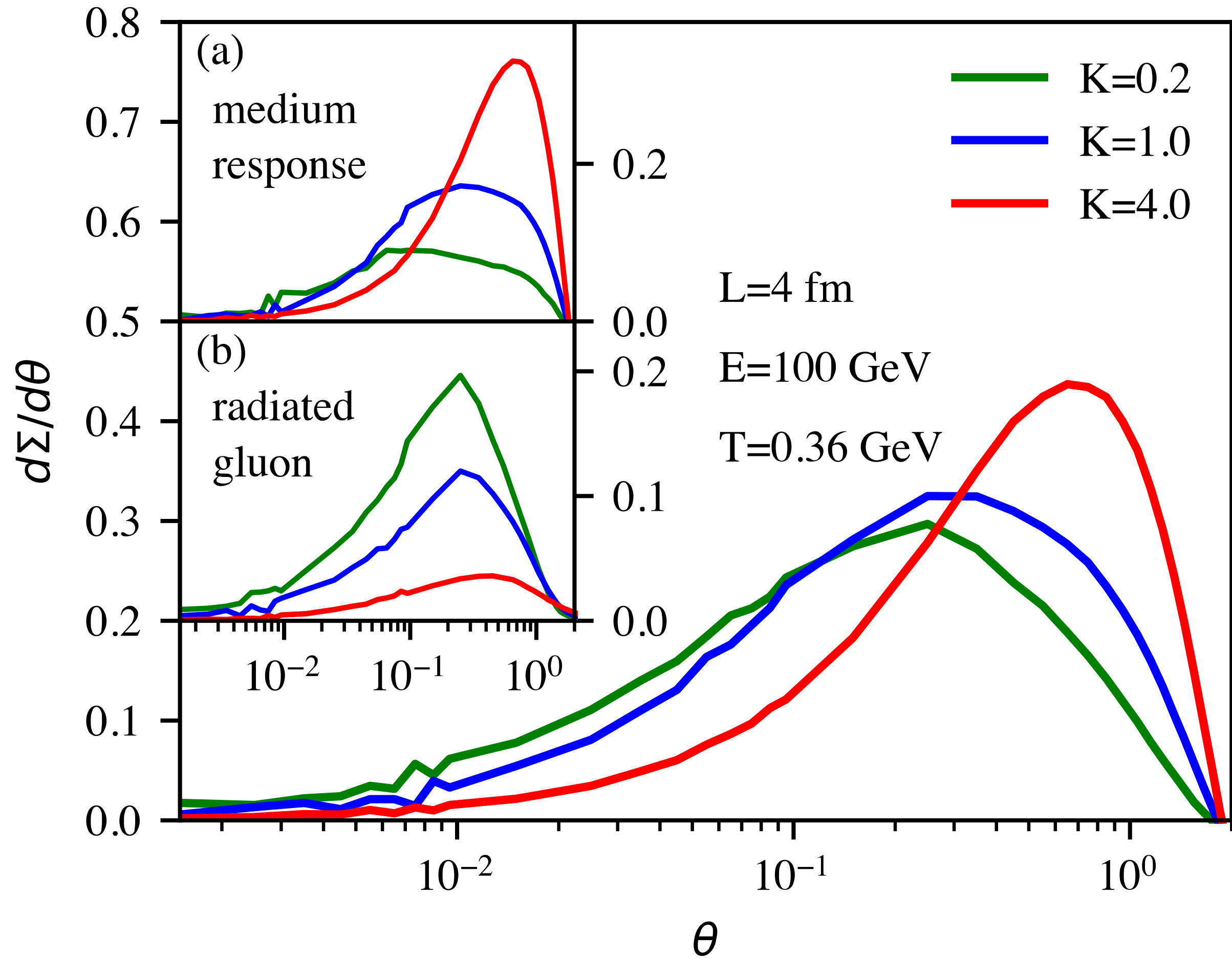


One interesting aspect of energy correlators is their clean resolution of **physical scales**



# Jet substructure in heavy ion collisions

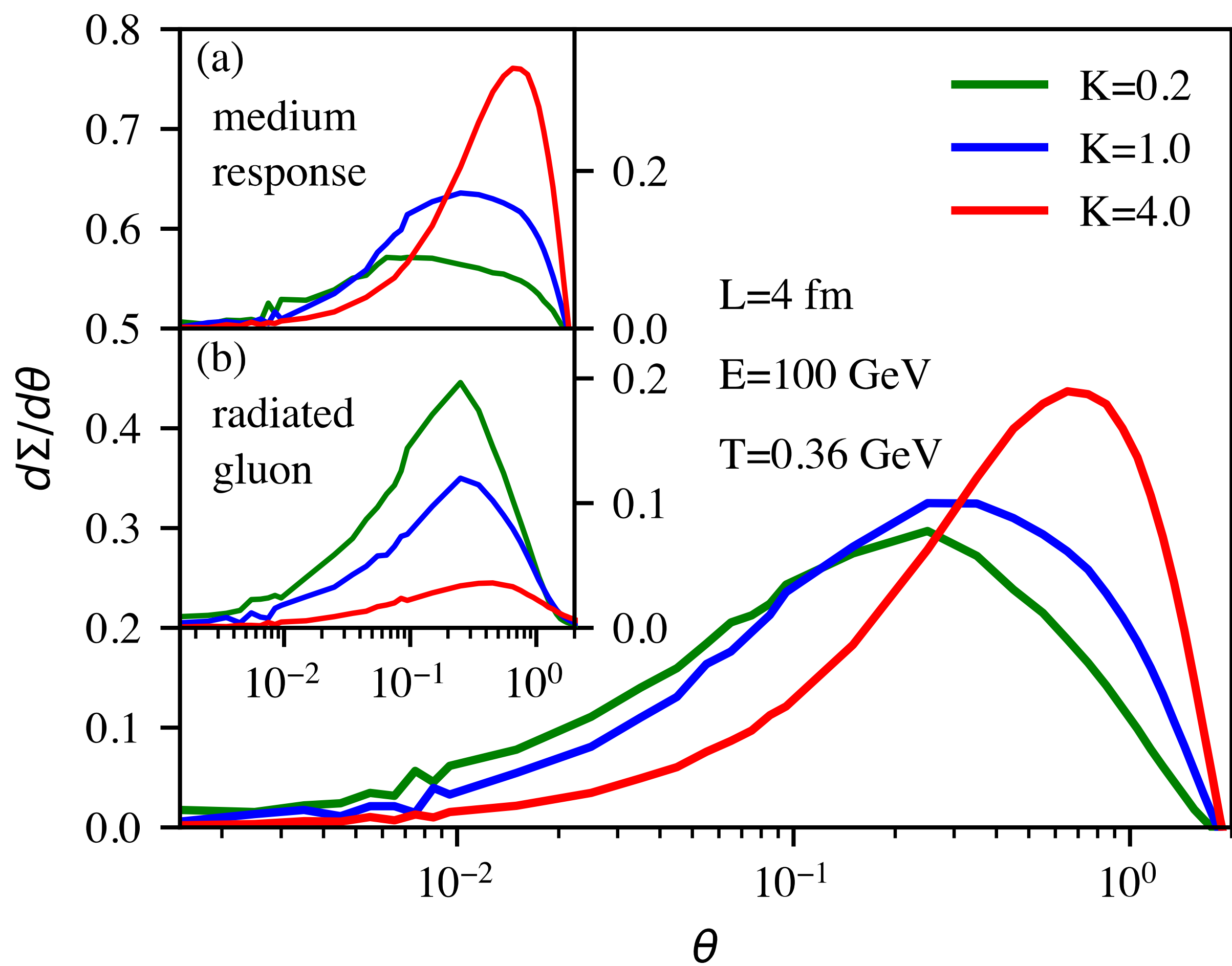
[Z. Yang, et al, 2310.01500]



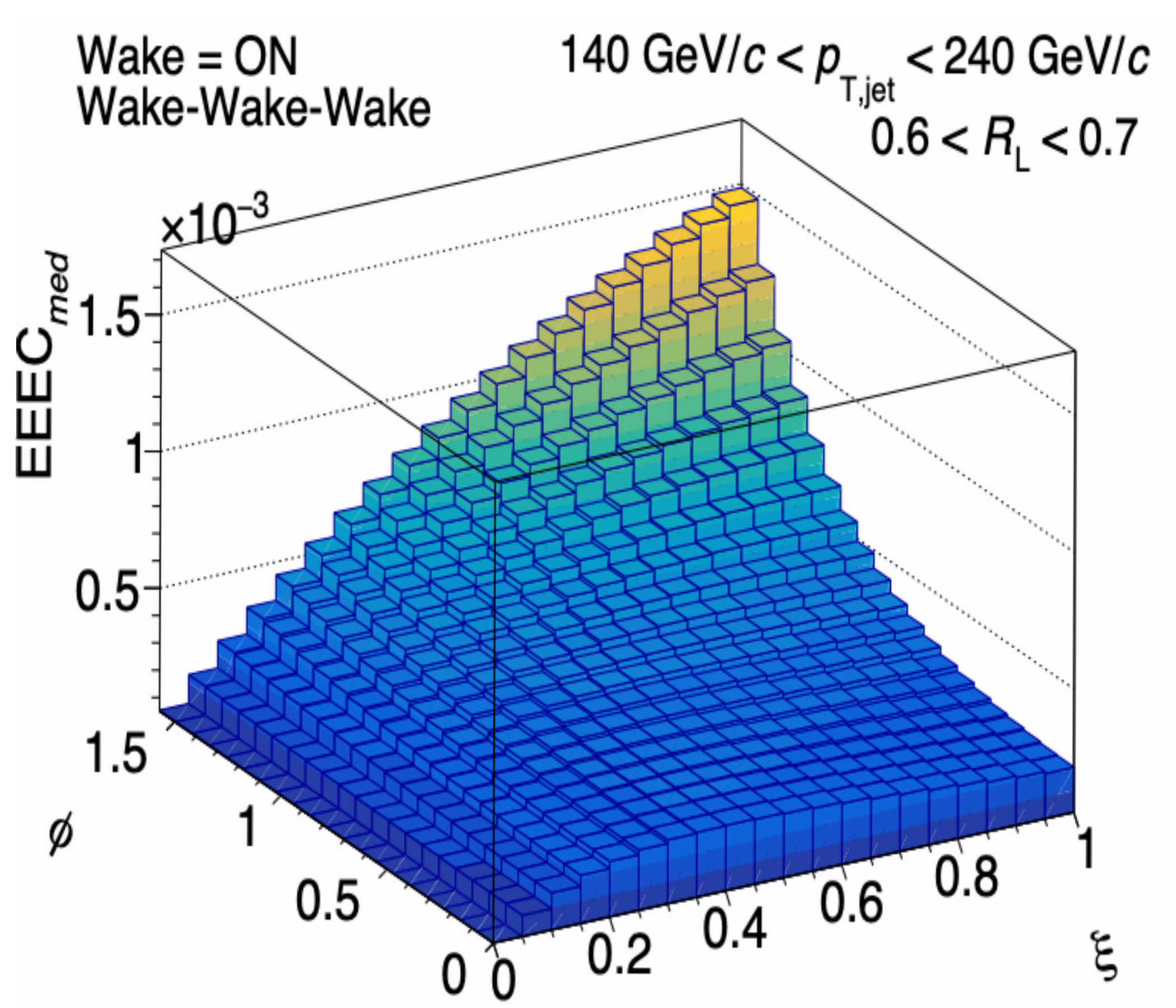
*Scales controlling shape of distributions still poorly understood on theory side*

# Jet substructure in heavy ion collisions

[Z. Yang, et al, 2310.01500]



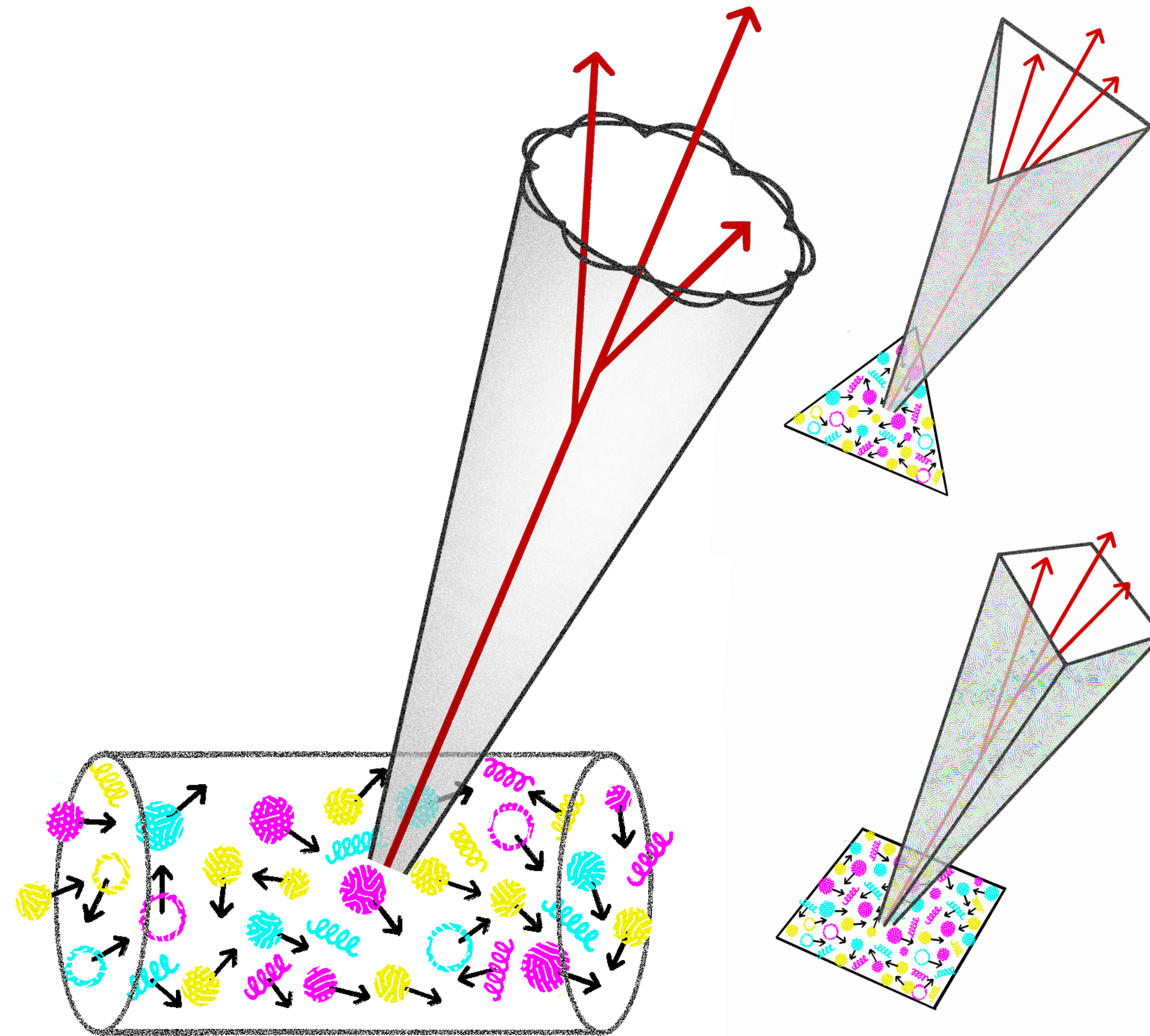
[Bossi et al., JHEP, 2024]



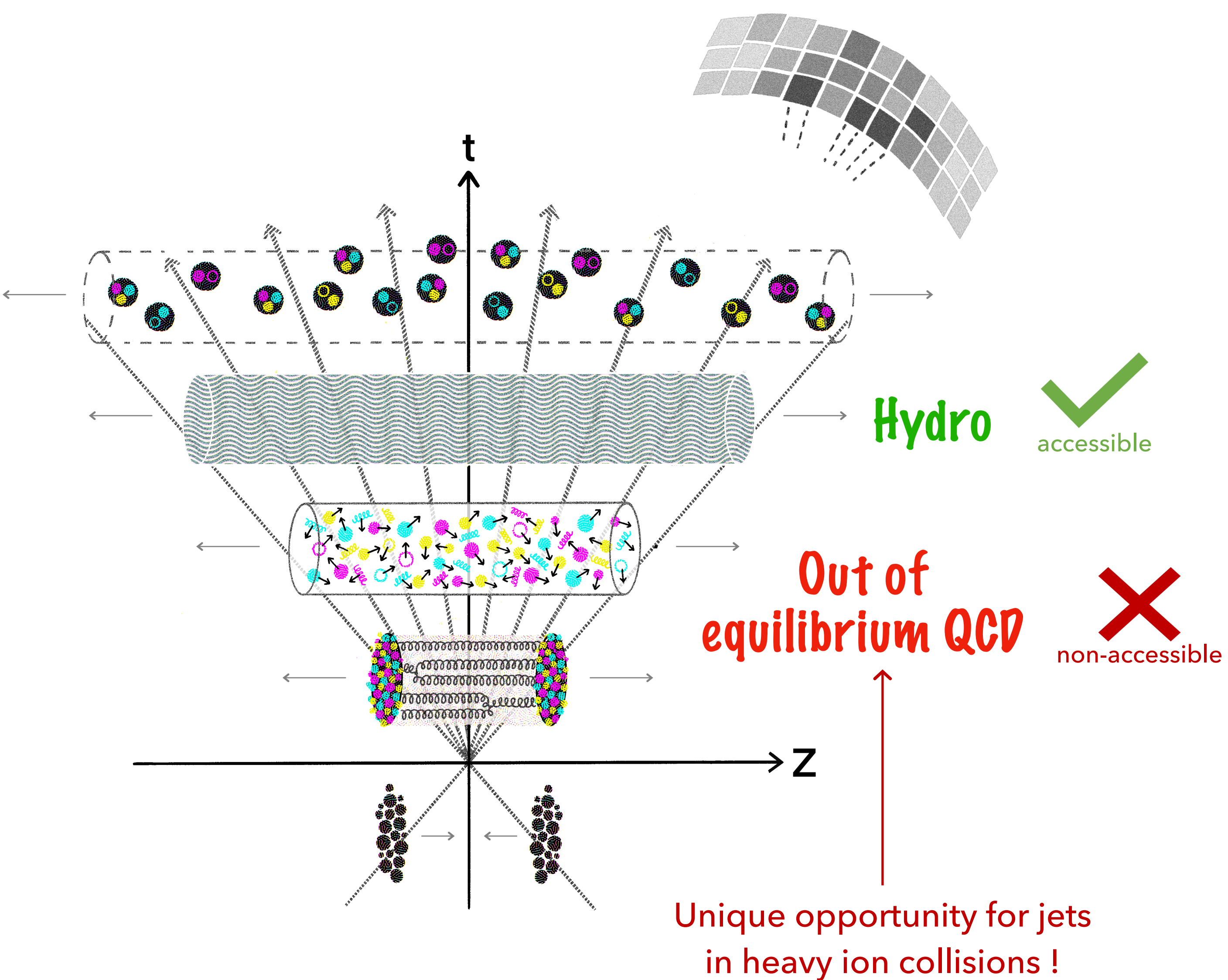
*Scales controlling **shape of distributions** still poorly understood on theory side*

*Exciting opportunity to **realize tomographic jet imaging** with these observables !*

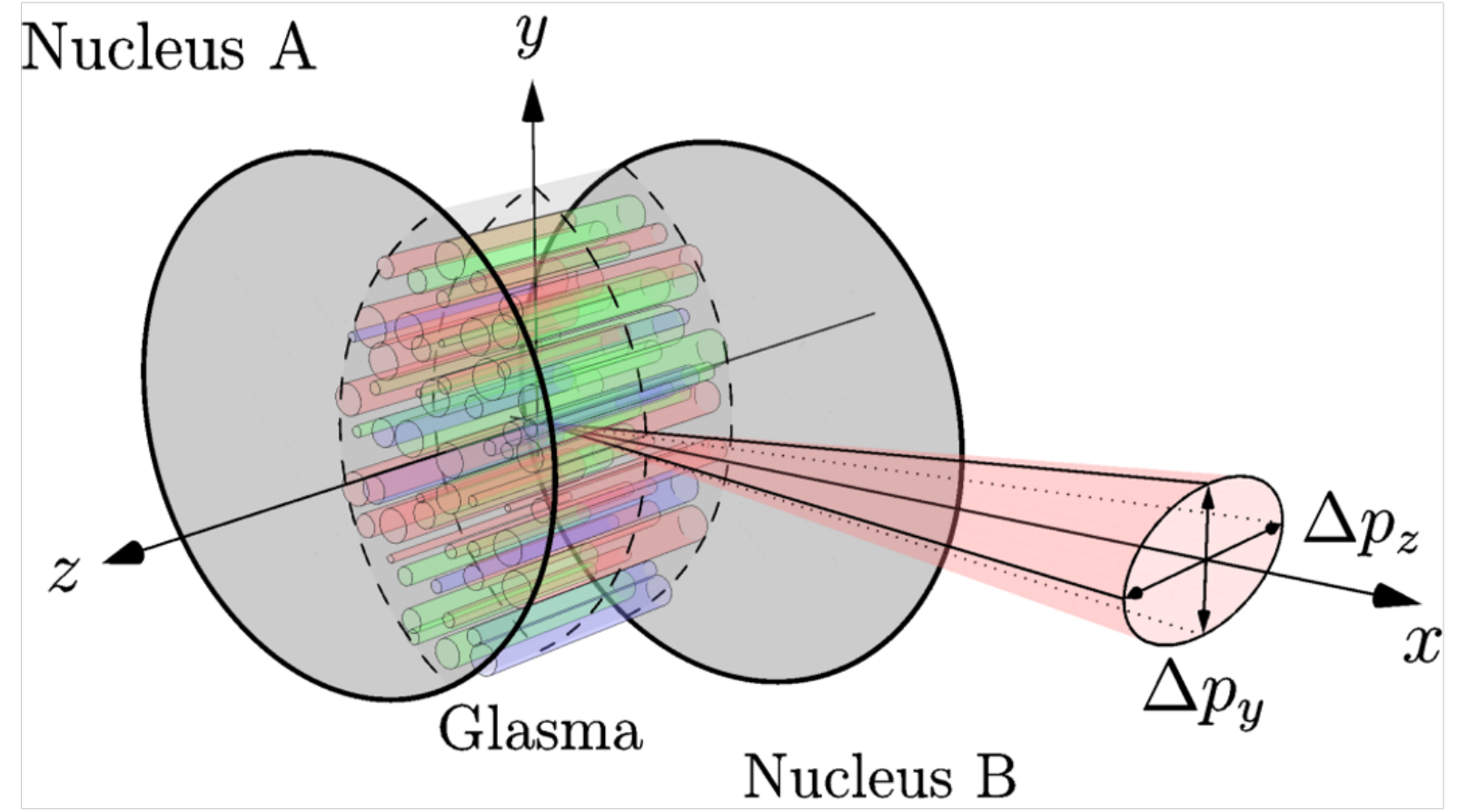
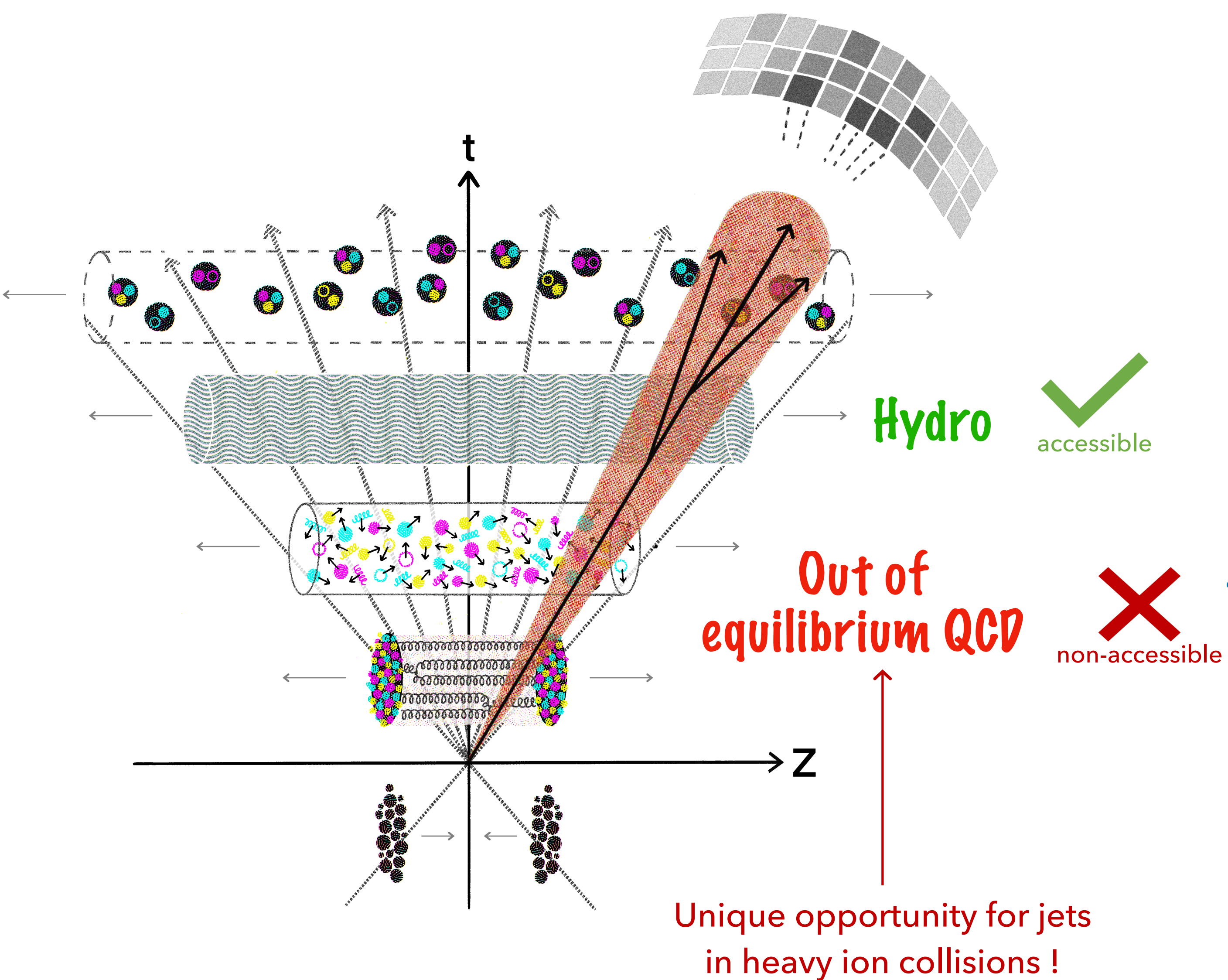
# New opportunities with jets in heavy ions



# The unknown in heavy ion collisions

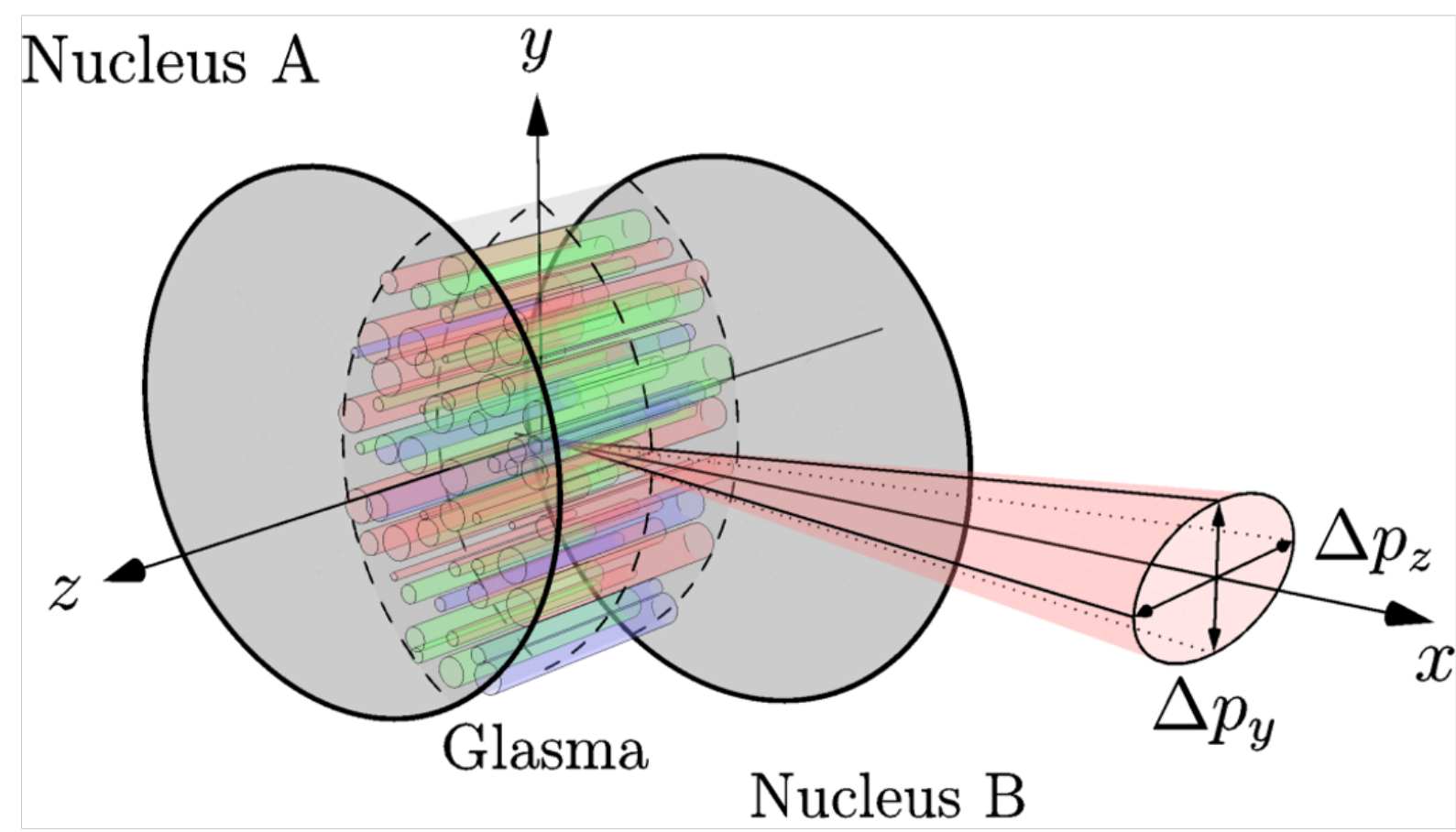
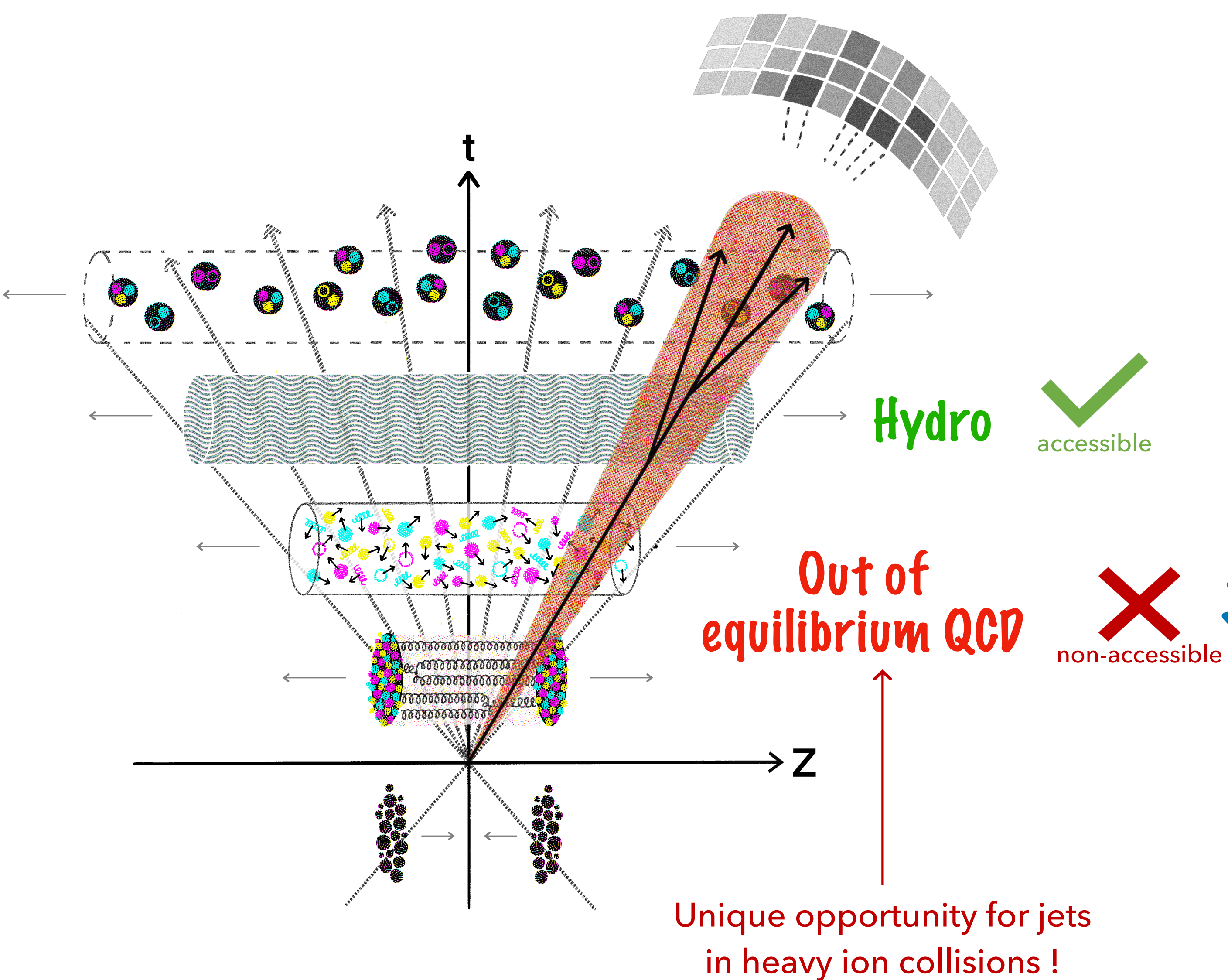


# The unknown in heavy ion collisions

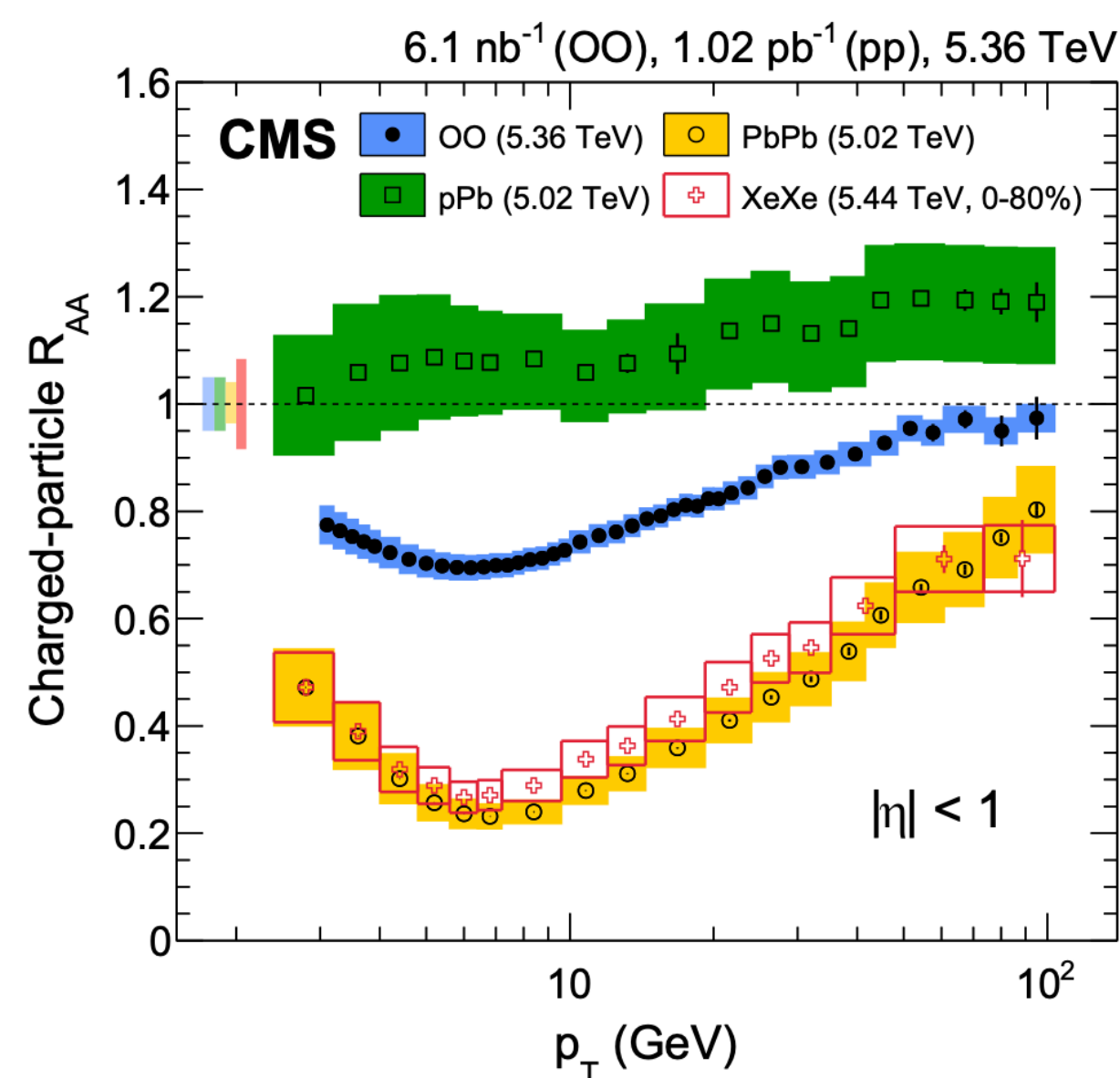


*Jet structure in complex matter*

# The unknown in heavy ion collisions

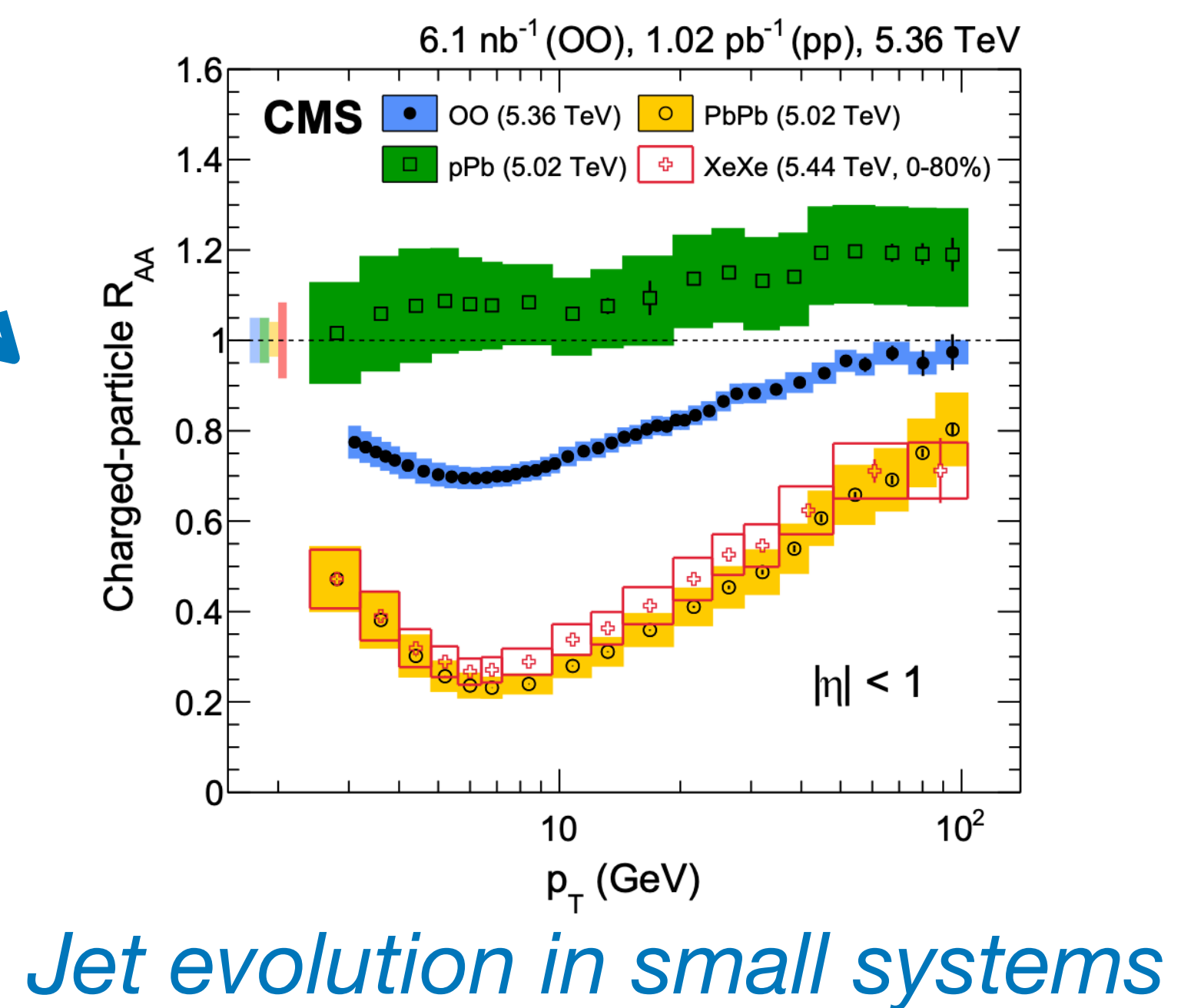
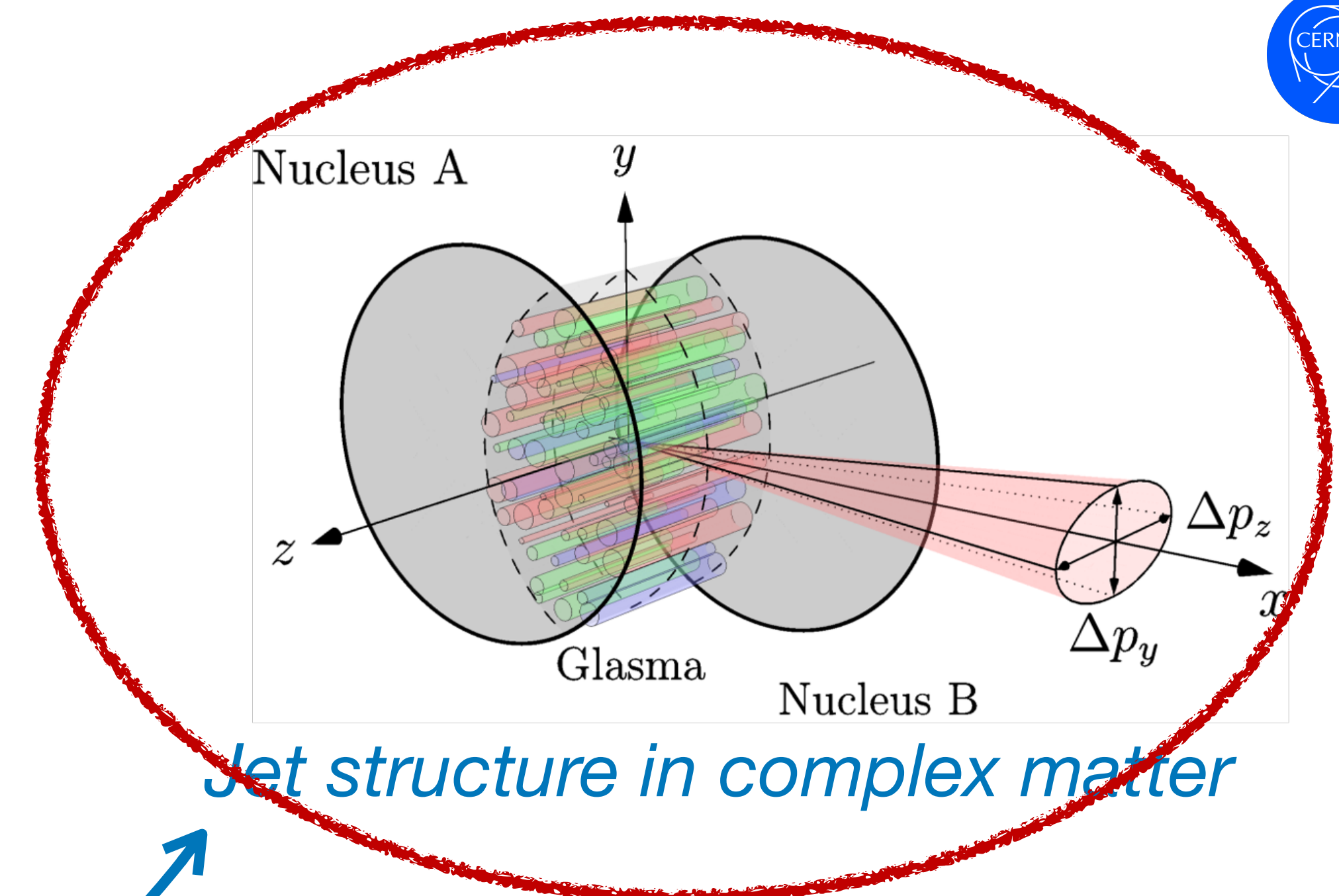
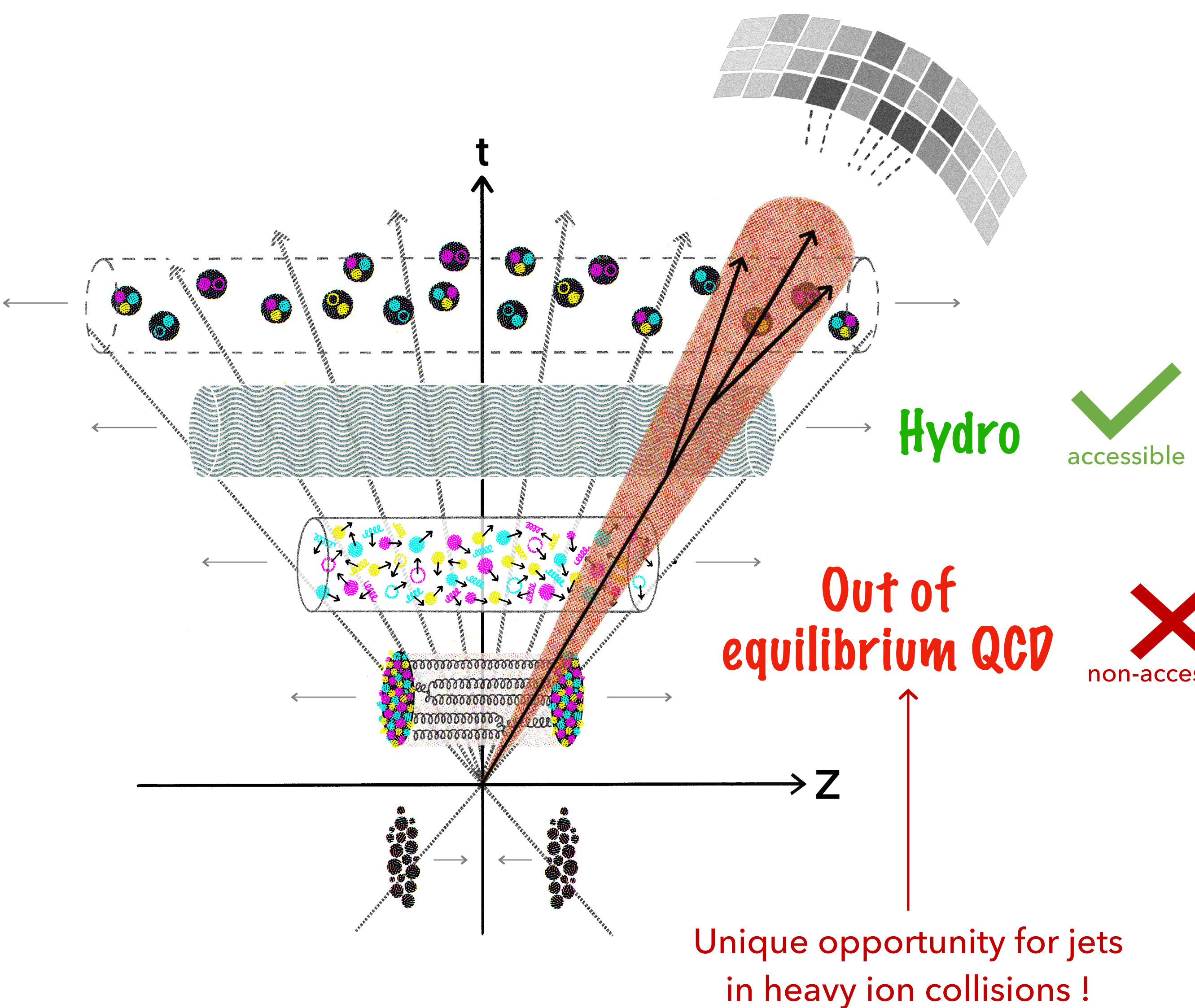


*Jet structure in complex matter*



*Jet evolution in small systems*

# The unknown in heavy ion collisions



# Jet quenching in the early stages

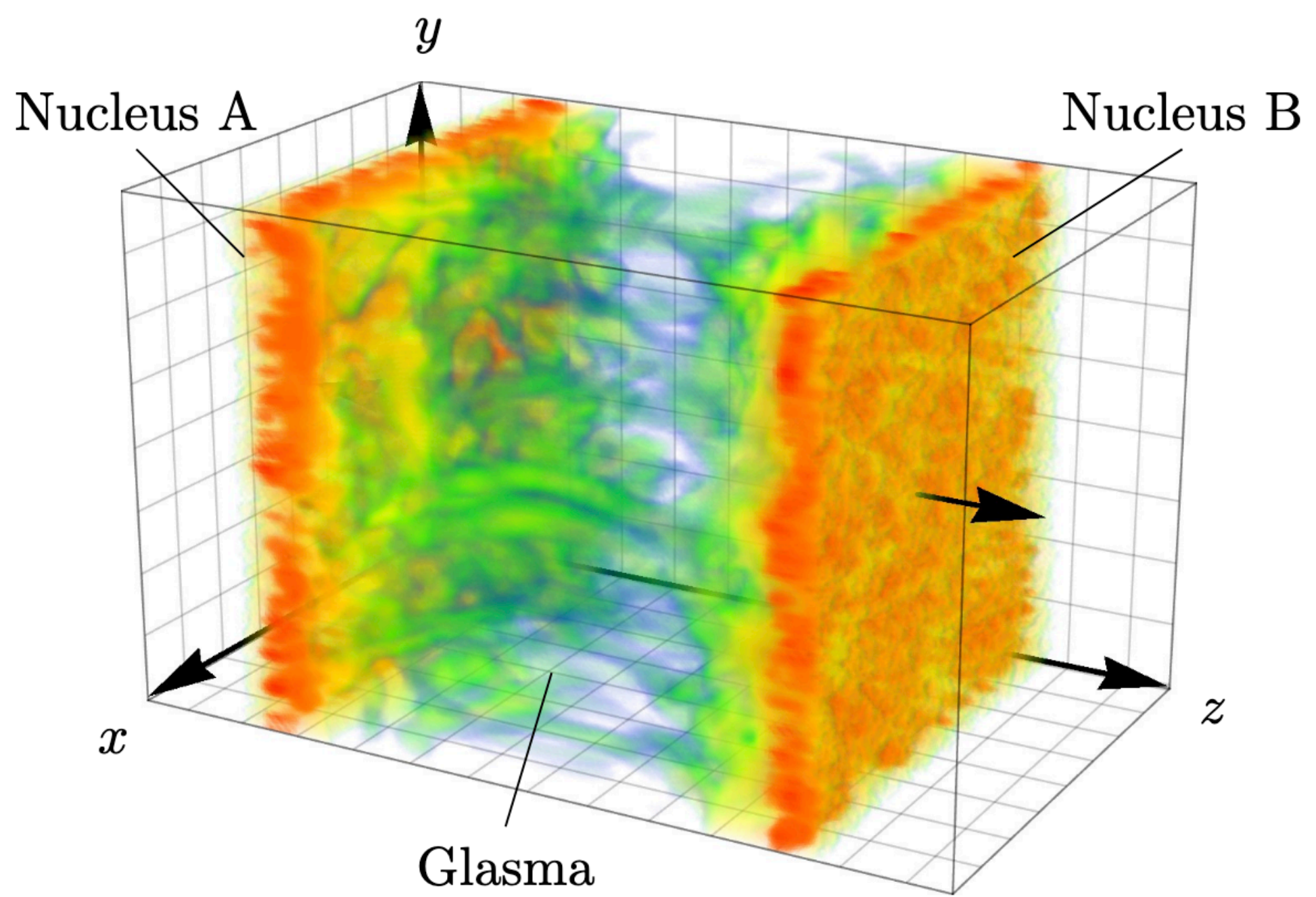
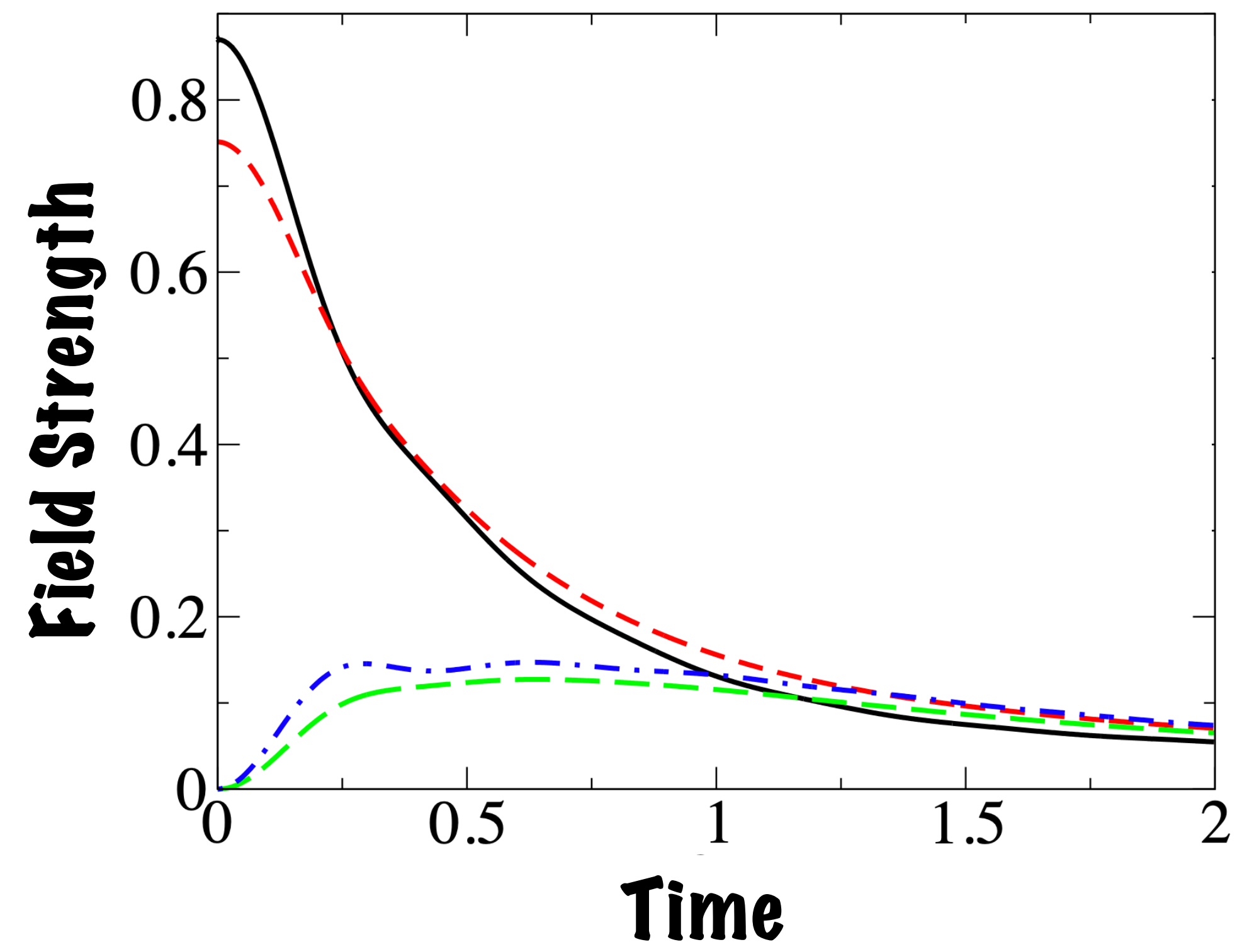


figure from A. Ipp et al.

[Lappi, McLerran, hep-ph/0602189]



*Early time dynamics of heavy ion collisions characterized by highly occupied and anisotropic gluonic state*

# Jet quenching in the early stages

[data from D. Avramescu and F. Lindenbauer]

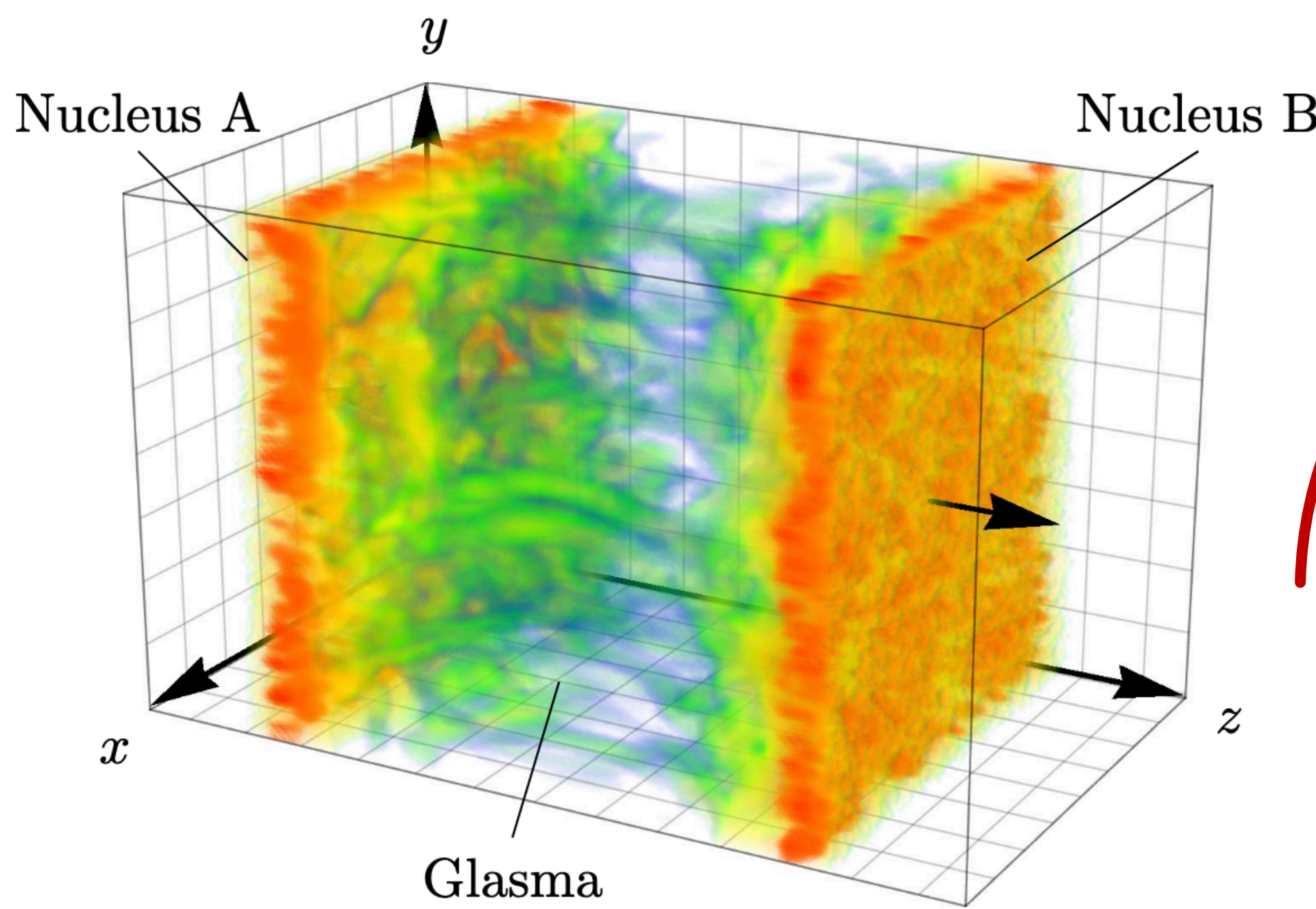
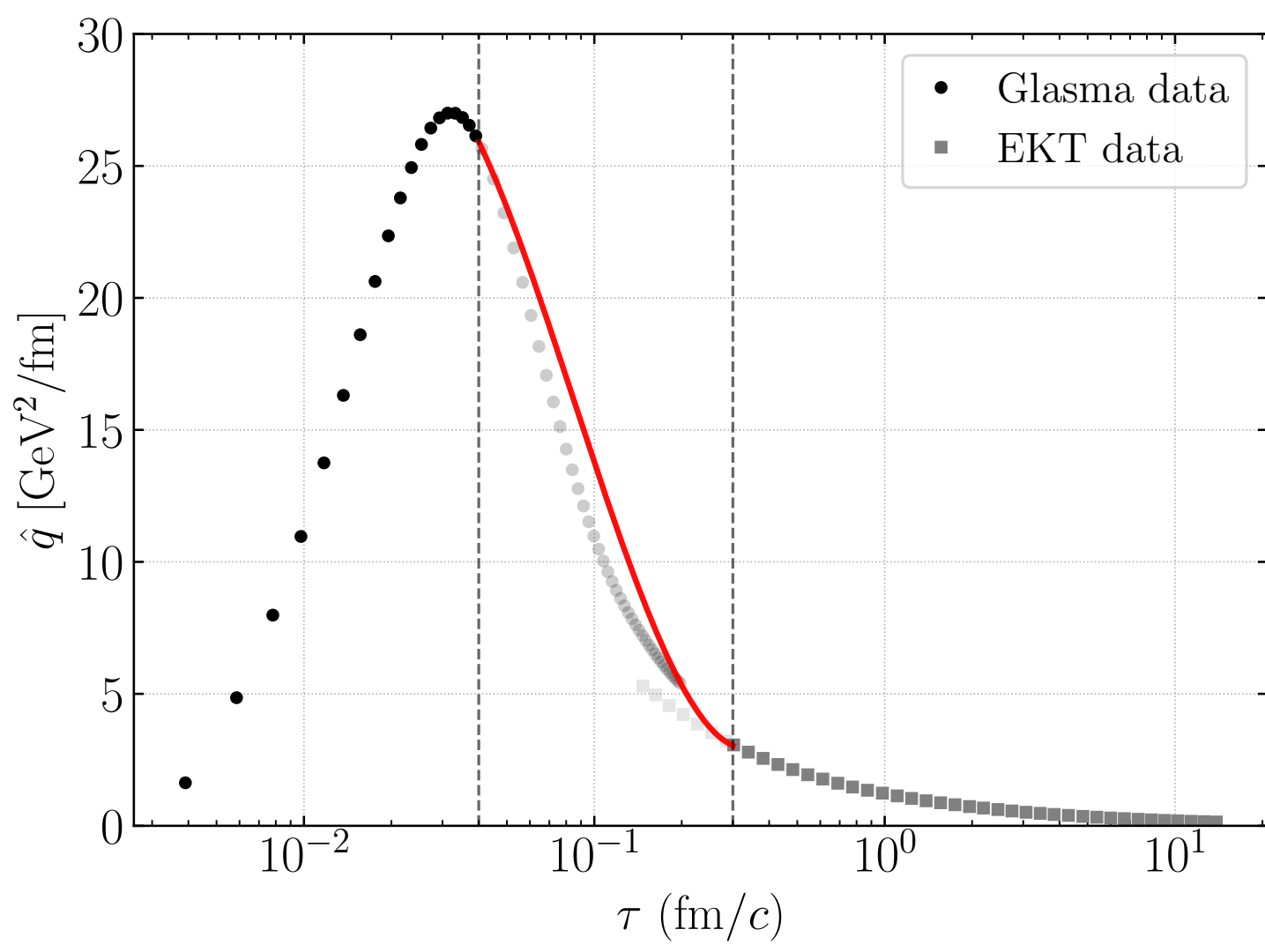


figure from A. Ipp et al.



*Large momentum diffusion at early times*

*Jets can be sensitive to the early stages  
unlike soft bulk hadrons which lost  
memory of this state*

# Jet quenching in the early stages

[data from D. Avramescu and F. Lindenbauer]

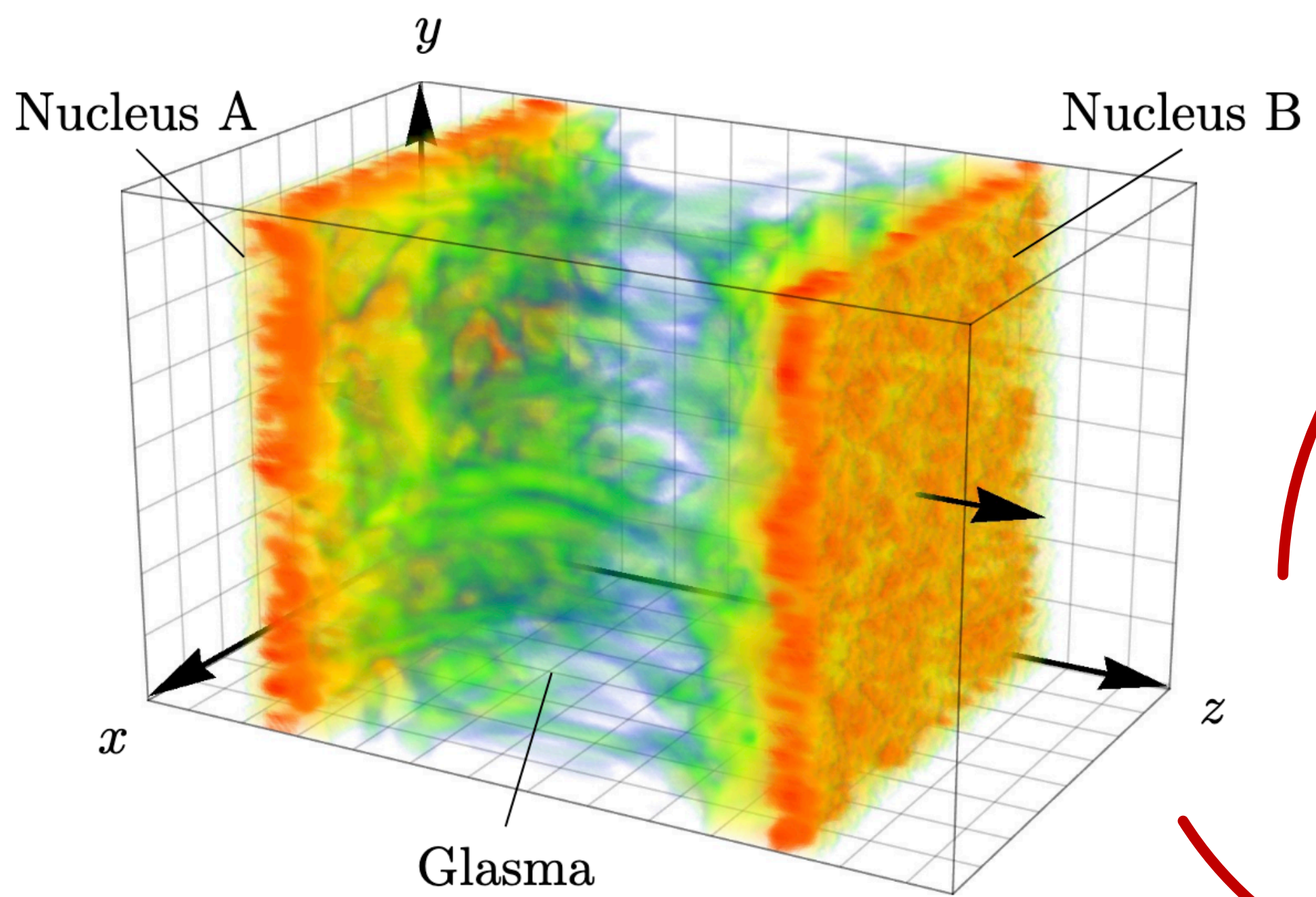
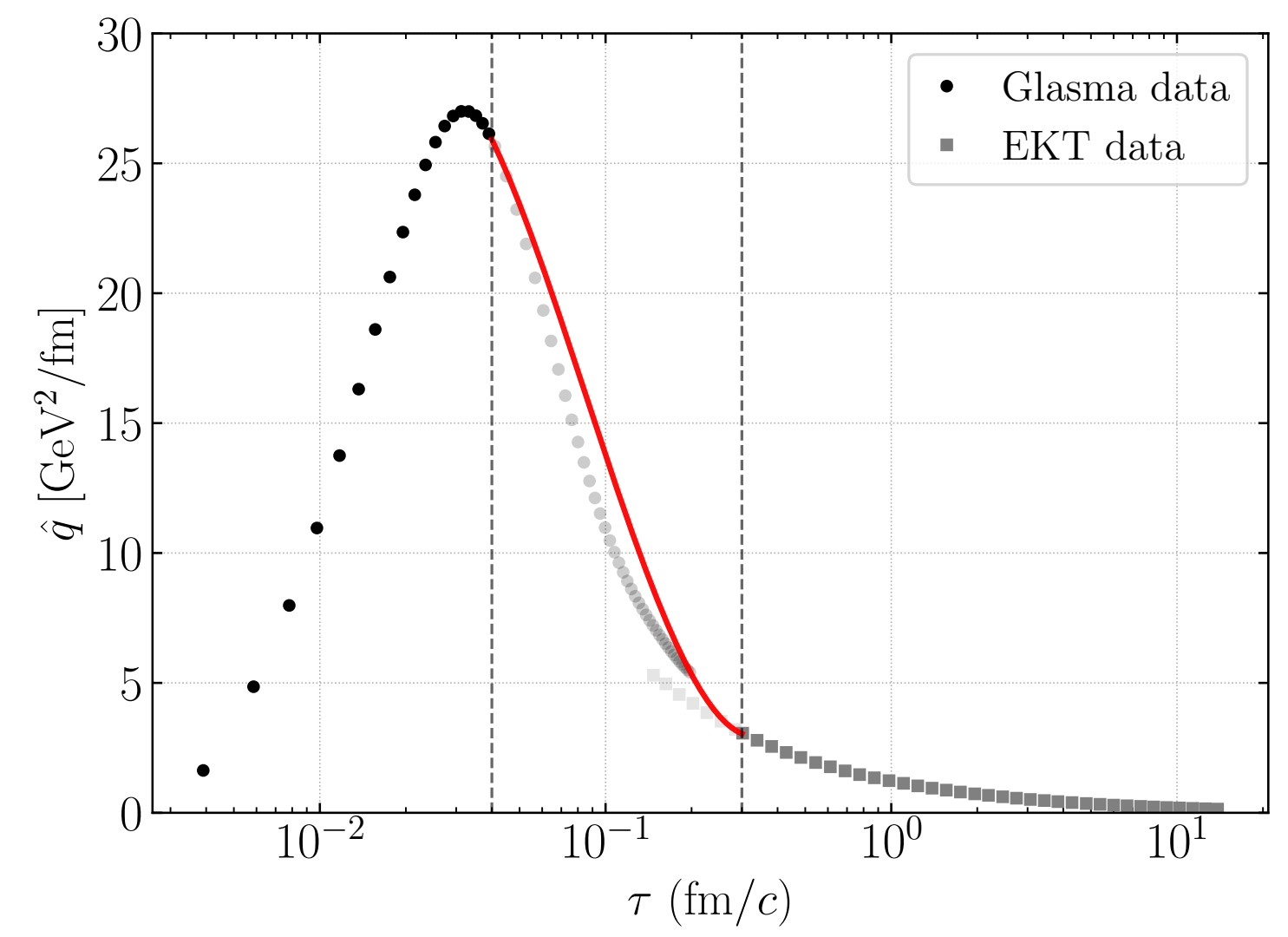
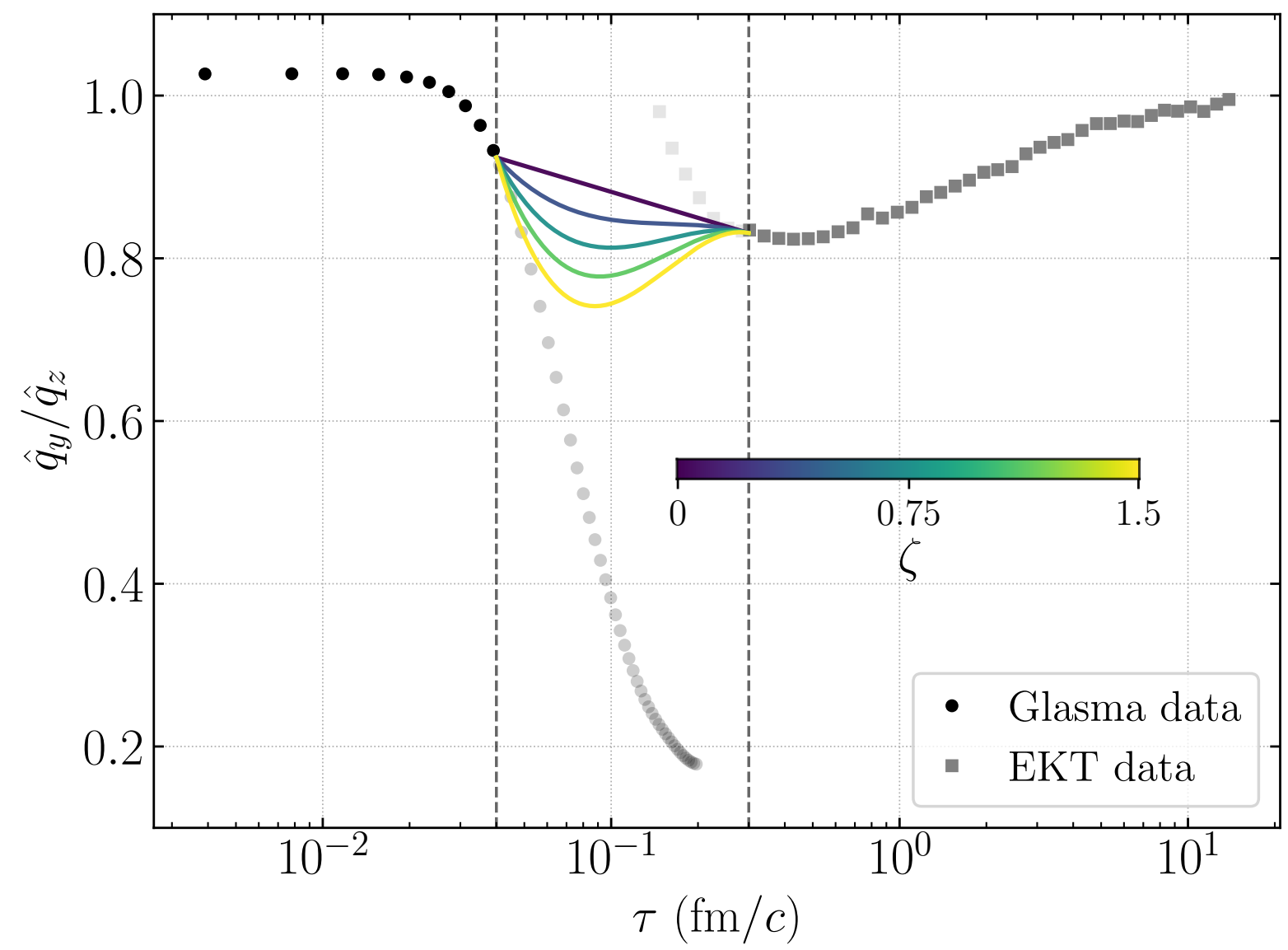


figure from A. Ipp et al.

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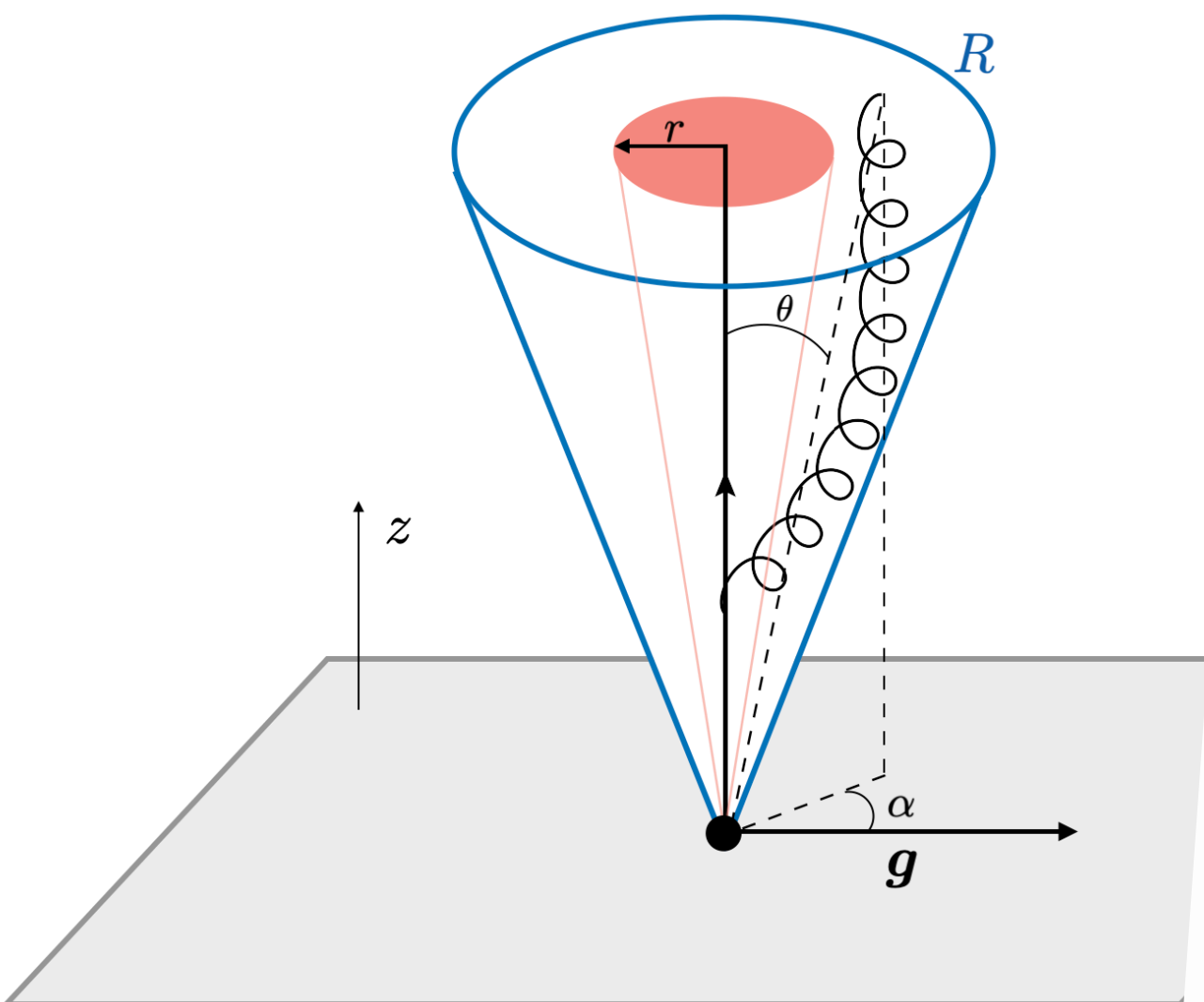


*Large momentum diffusion at early times*

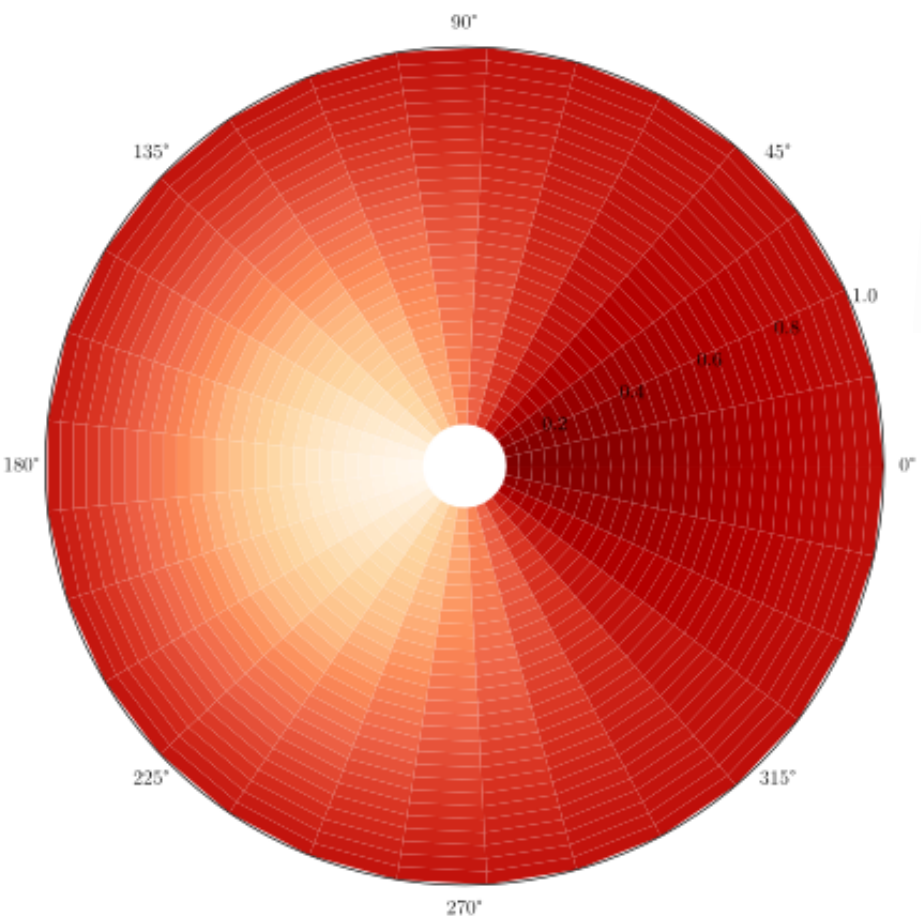
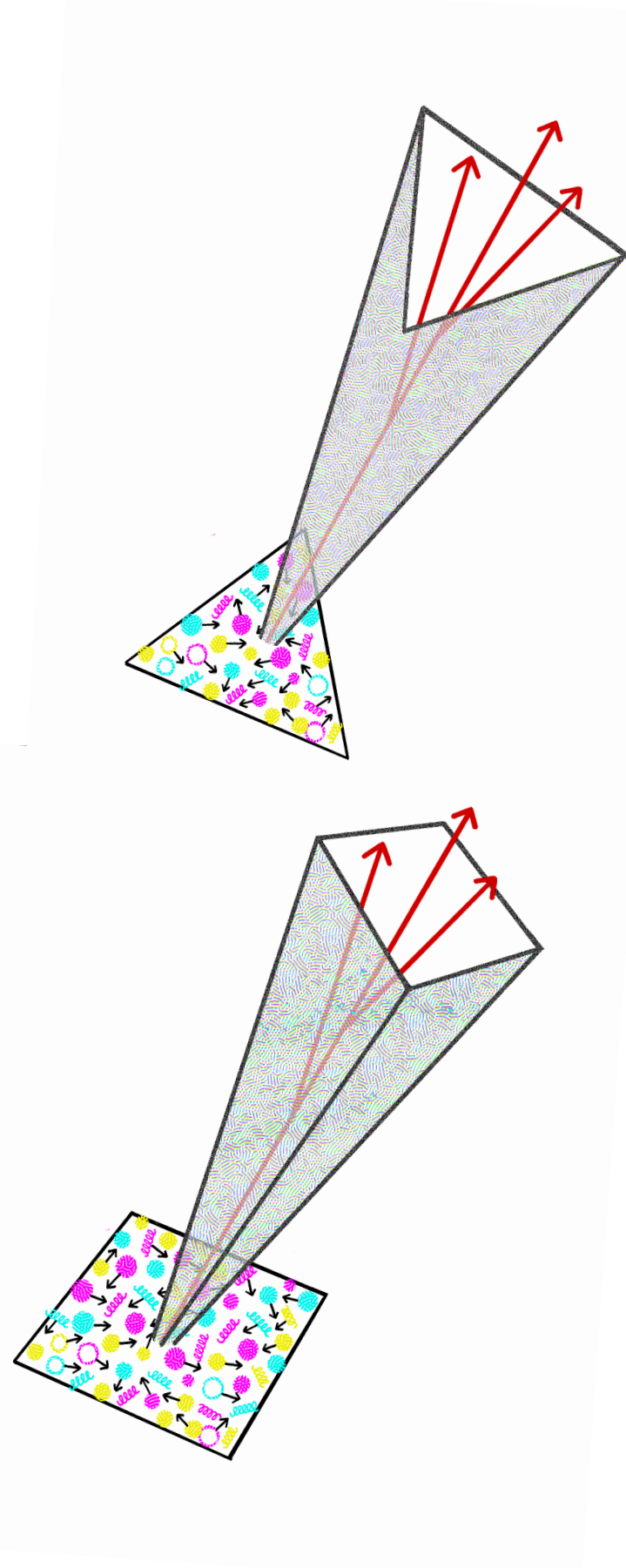


*Anisotropic diffusion at early times*

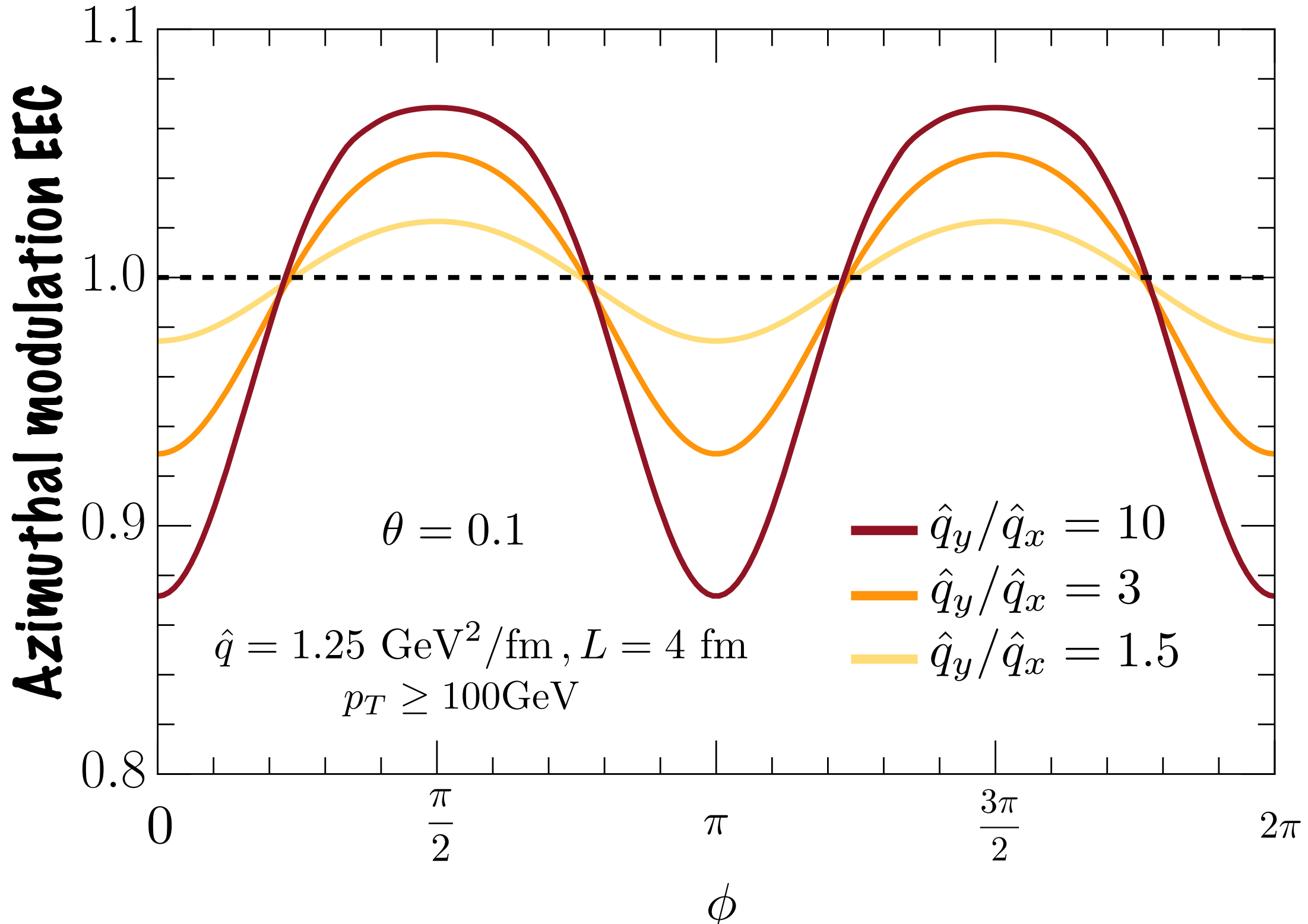
# Jet quenching in the early stages



[JB, Milhano, Sadofyev, 2308.01294]



[JB, Brewer, Lee, Silva, 2508.19404]

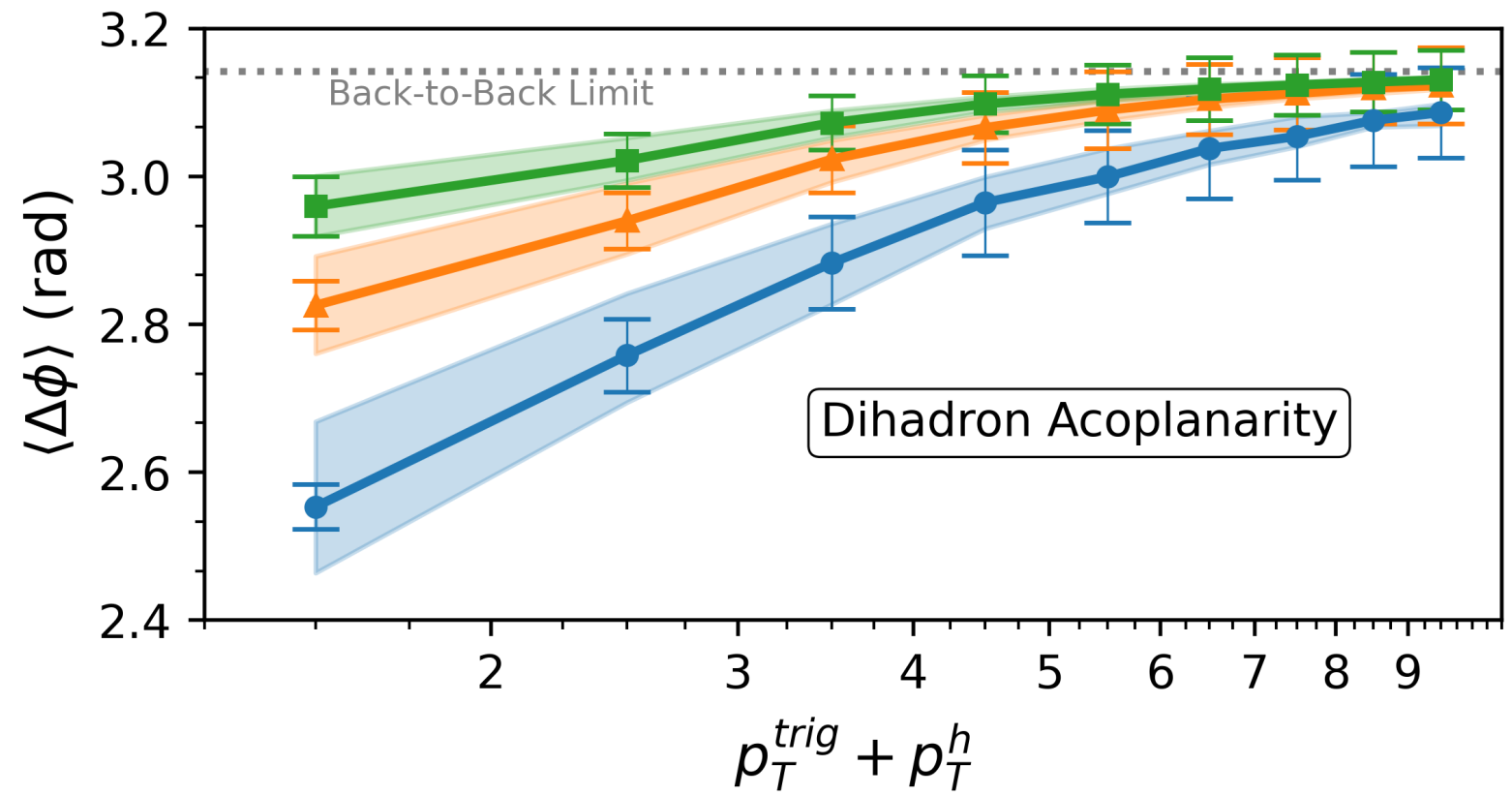
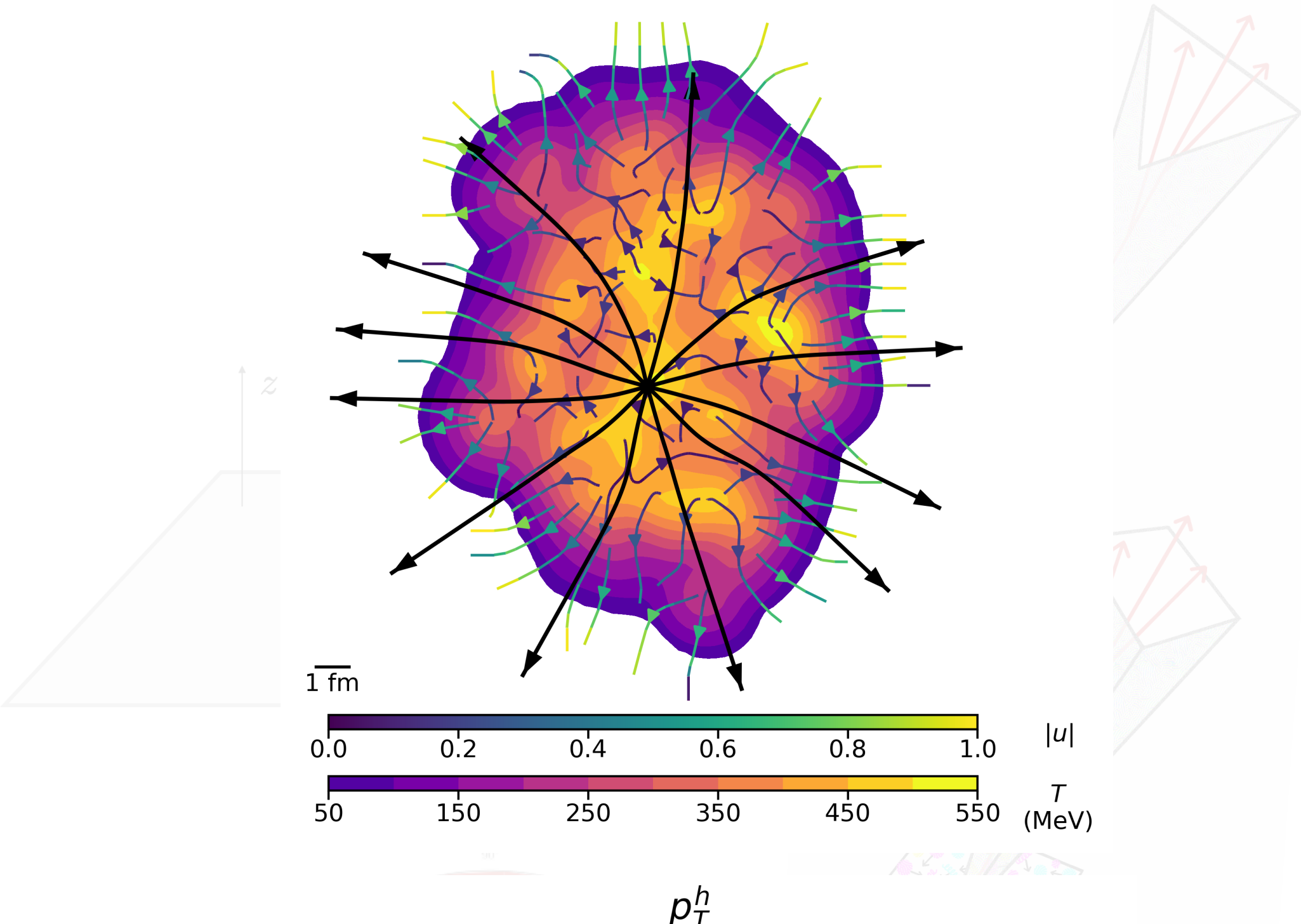


see also [Ke, Terry, Vitev, 2412.12250]

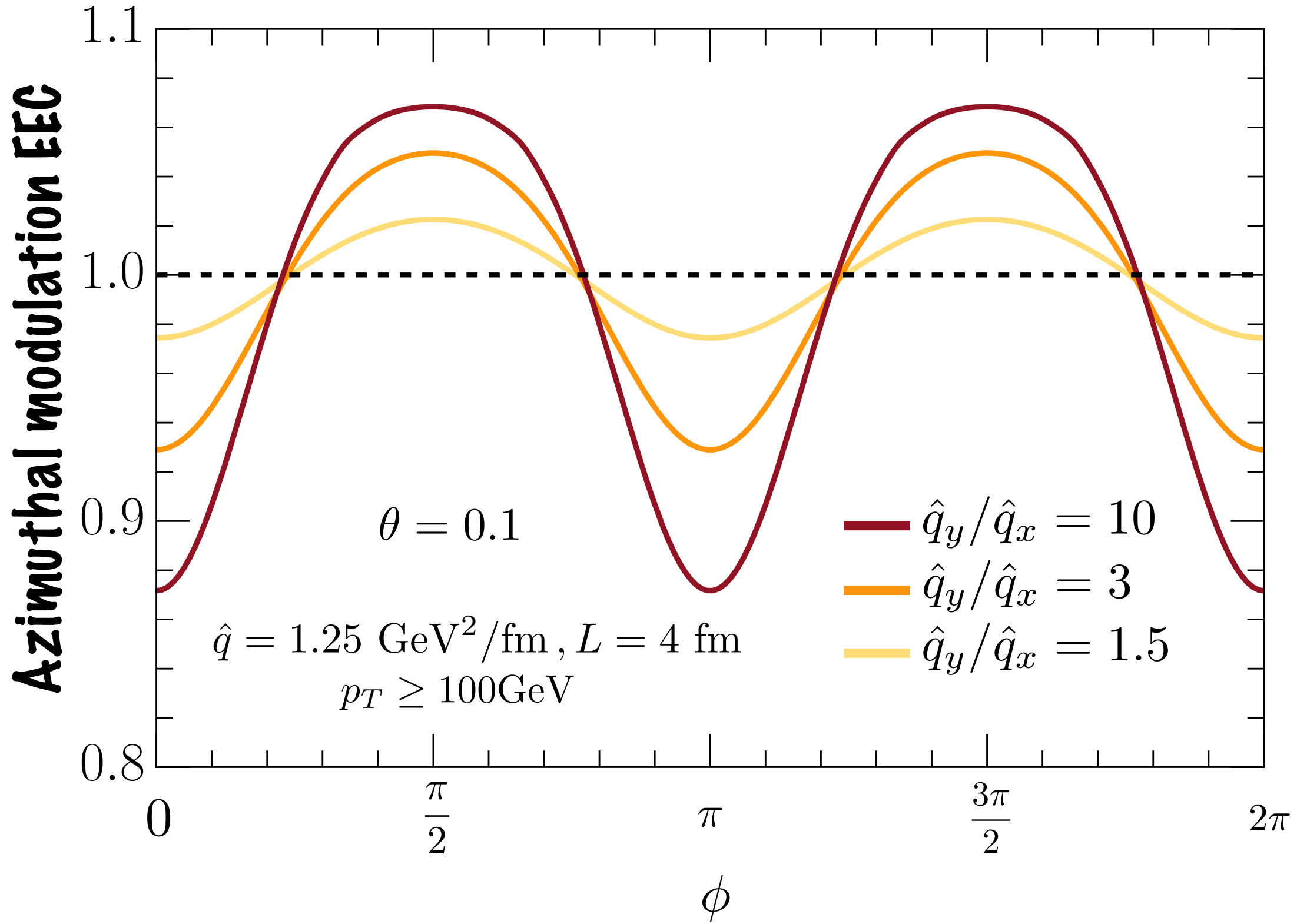
Observing a *vn-like deformation inside jets* would be extremely useful !

# Jet quenching in the early stages

[Bahder, Rahman, Sievert, 2110.03590]



[JB, Brewer, Lee, Silva, 2508.19404]

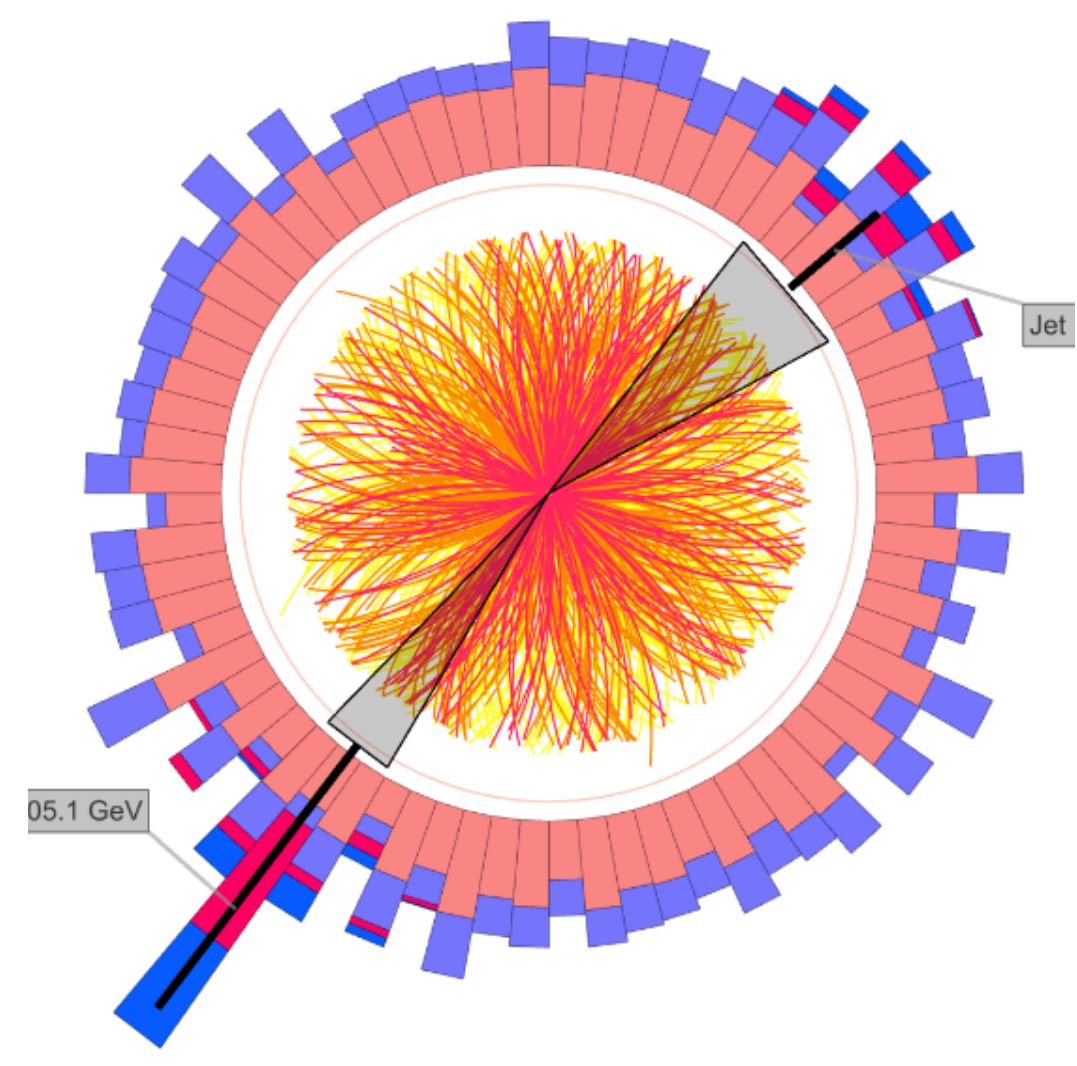
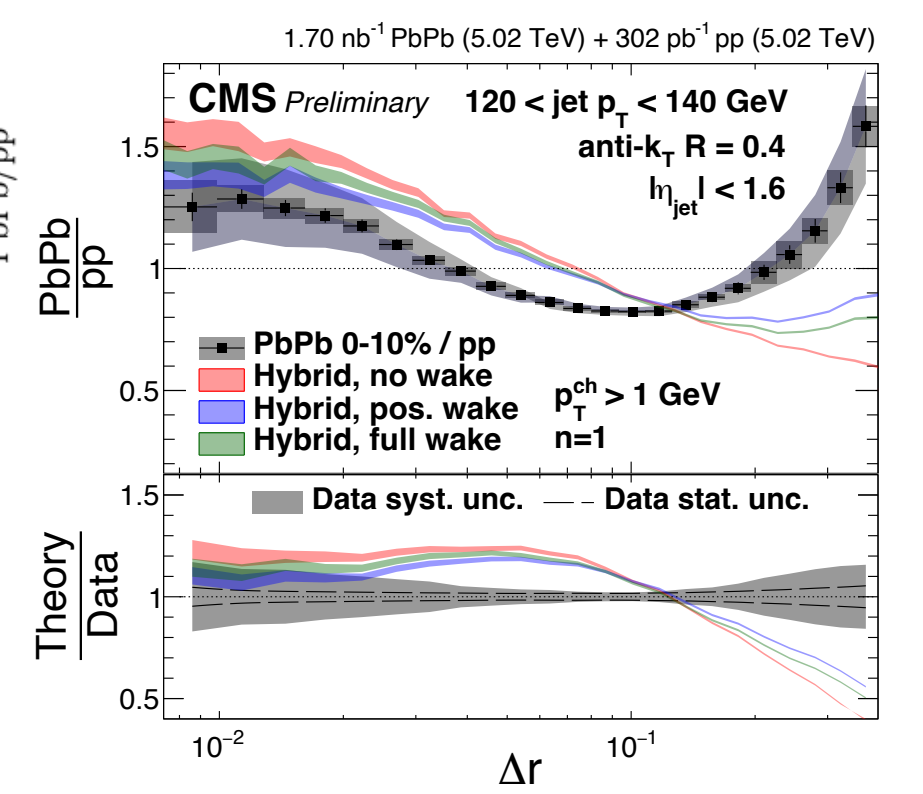
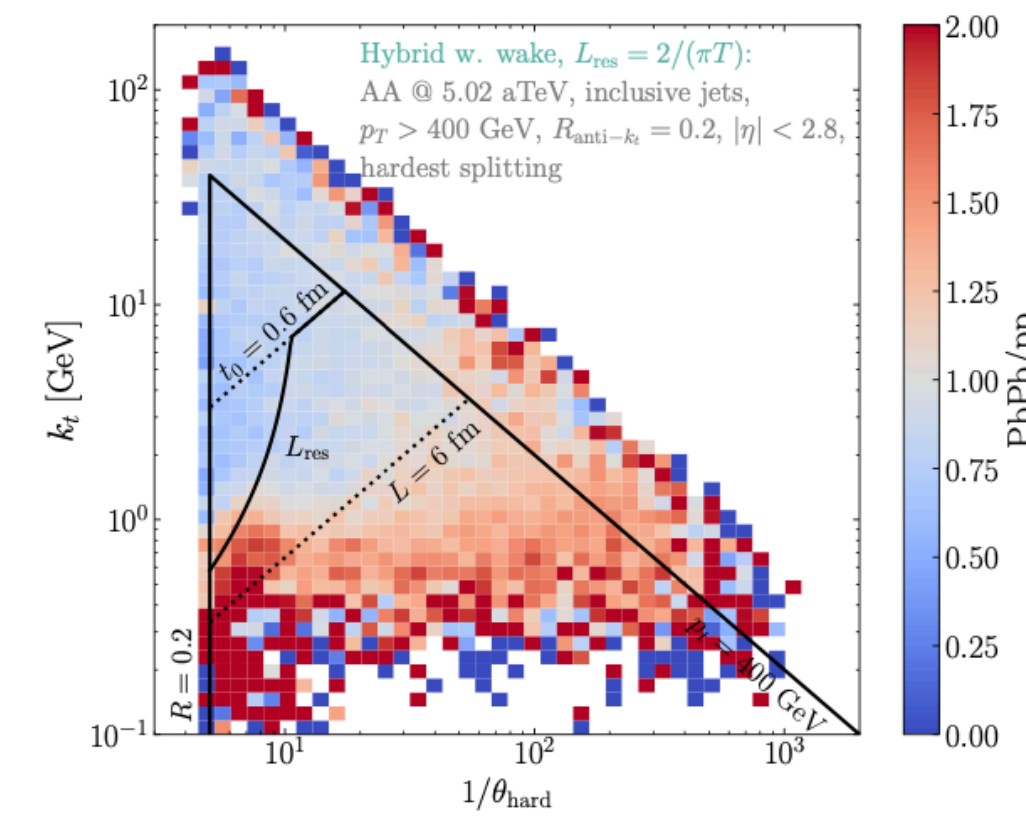
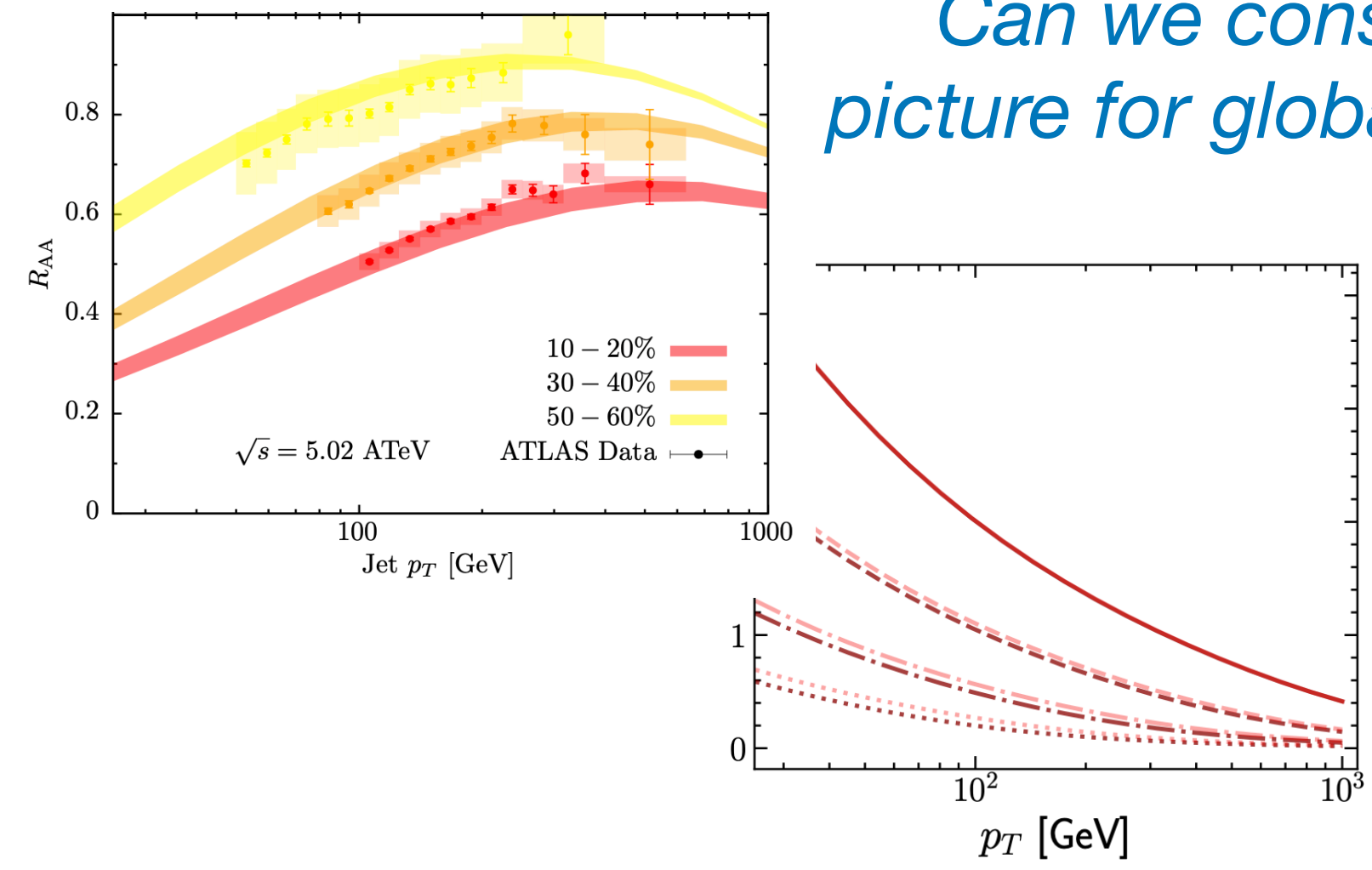


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*Observing a  $vn$ -like deformation inside jets would be extremely useful !*

# Conclusions

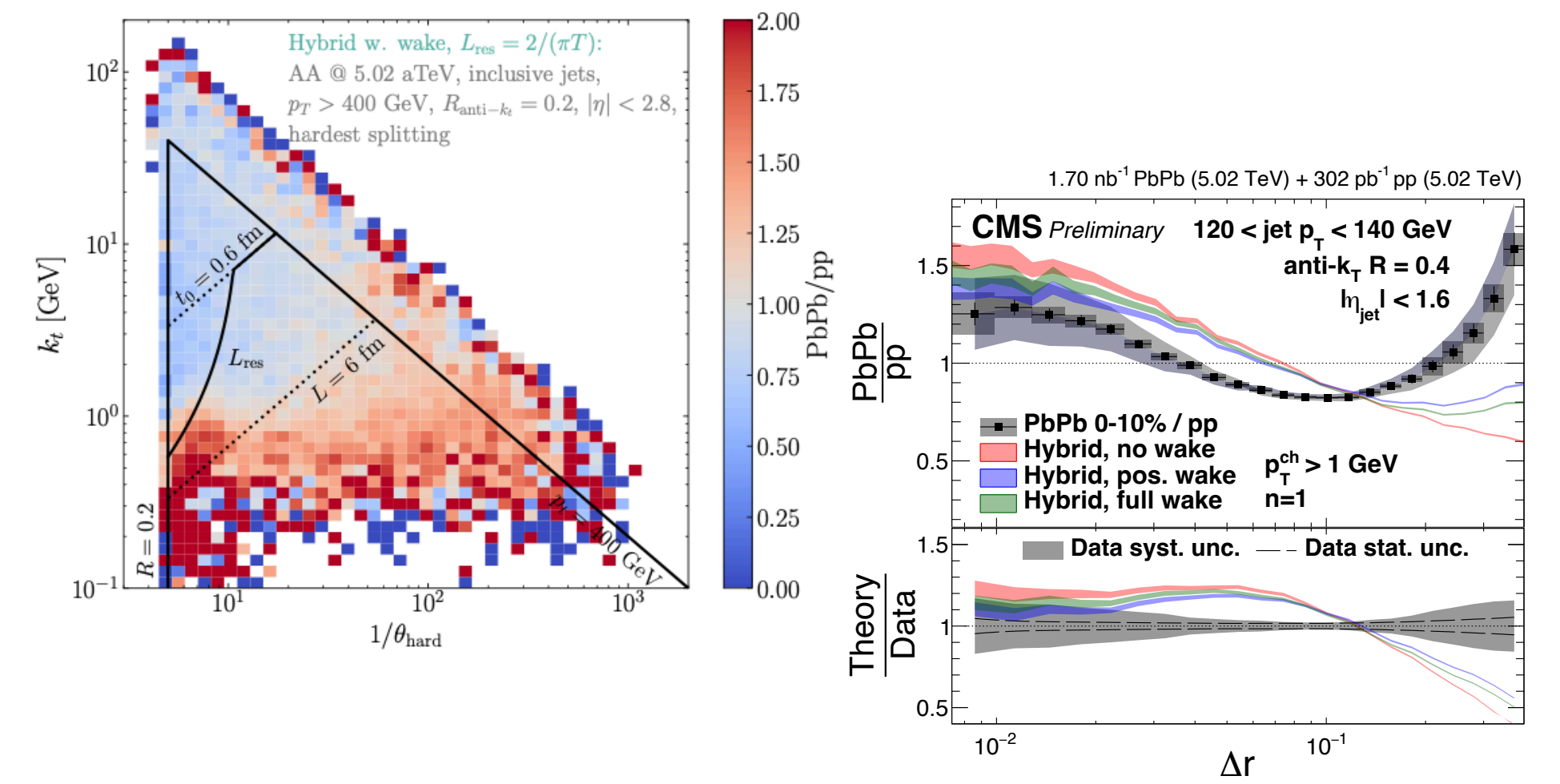
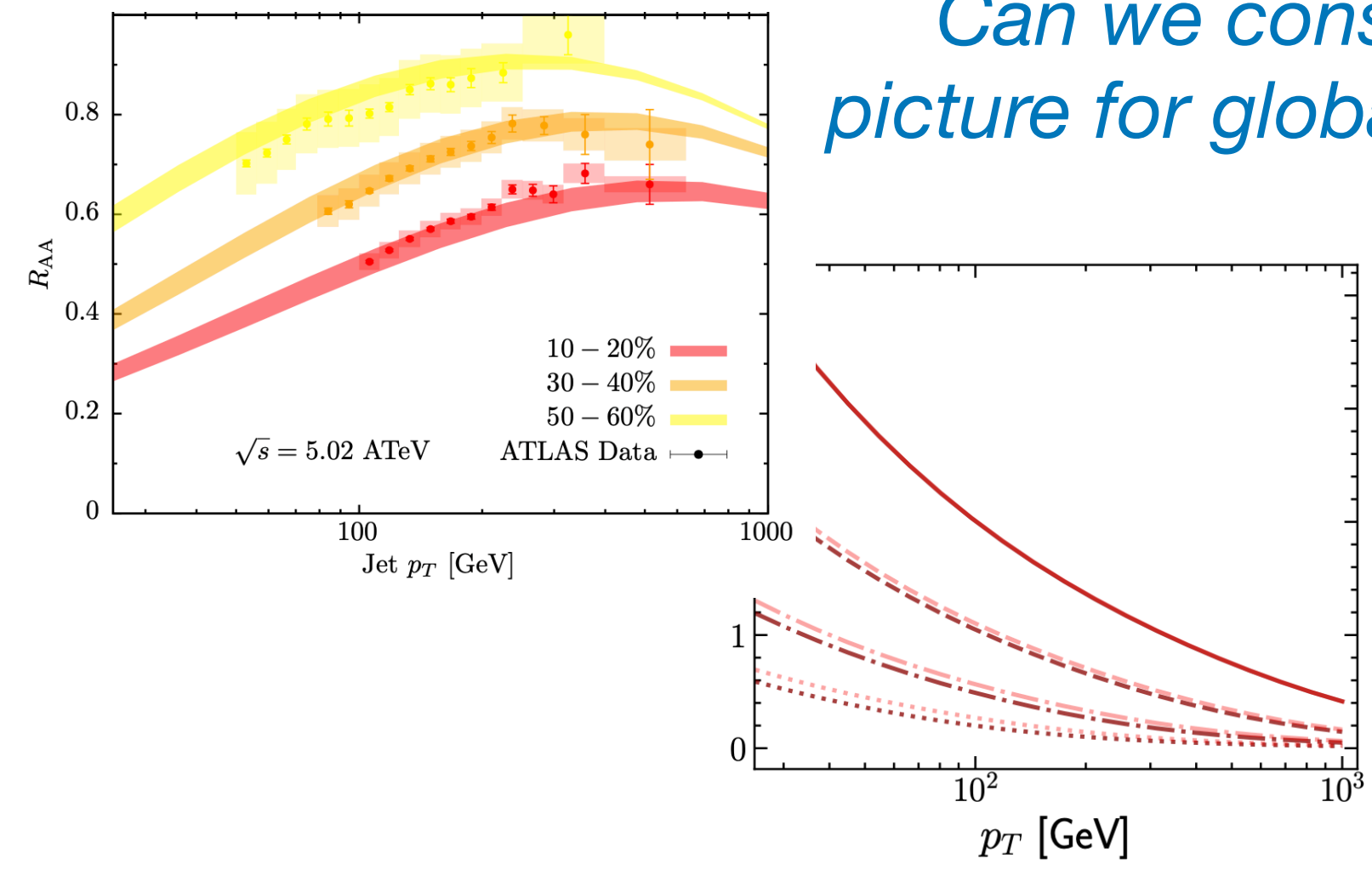
*Can we construct a robust picture for global jet properties ?*



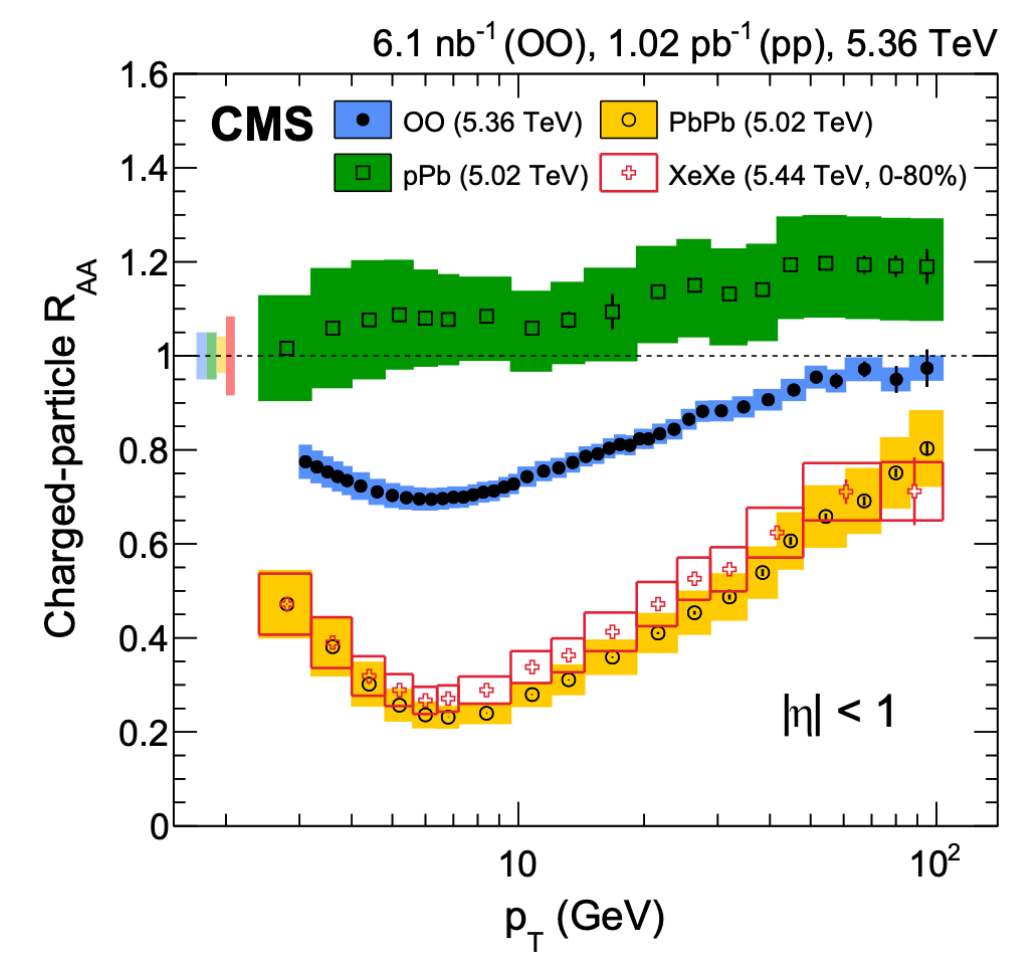
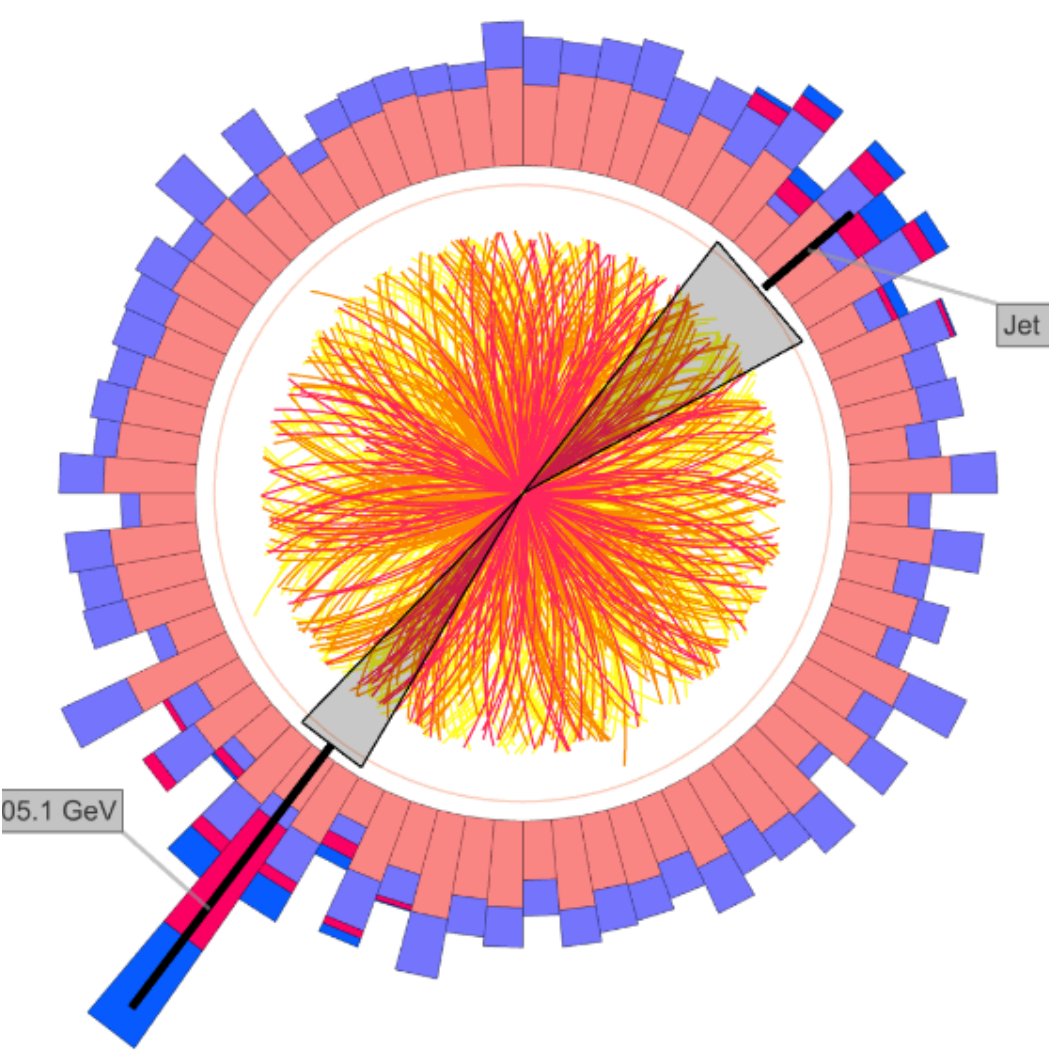
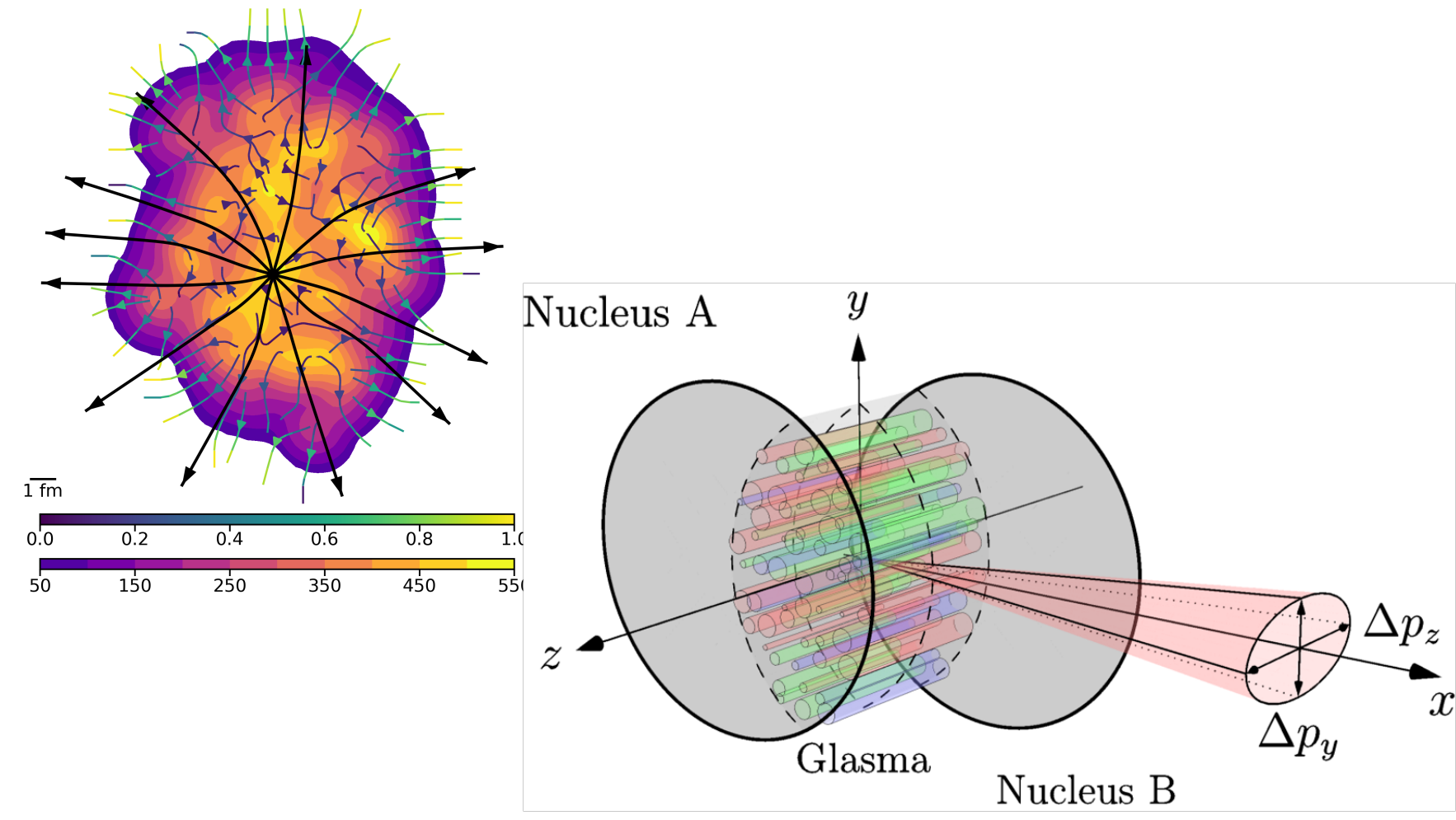
*What can jet substructure tell us about the bulk matter ?*

# Conclusions

*Can we construct a robust picture for global jet properties ?*



*What can jet substructure tell us about the bulk matter ?*



*Can we learn about out of equilibrium QCD properties using jets ?*

*How should the current picture of jets be updated to account for small systems ?*

**Thank you !**

