Jet quenching in anisotropic media

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CPHT, École polytechnique

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CPHT Centre de Physique Théorique

MARIE CURIE ACTIONS

l'X ÉCOLE POLYTECHNIQUE

How does the non-equilibrium stage affect jet quenching and other hard probes?

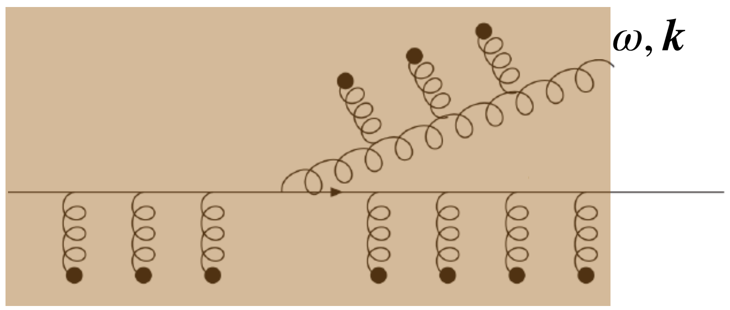
How does the non-equilibrium stage affect jet quenching and other hard probes?

I don’t know!

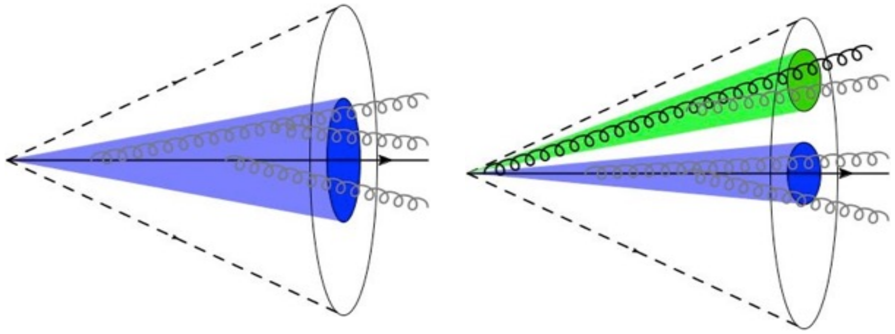
Jet quenching

- Jet quenching: **modifications experienced by jets in HI** with respect to p-p

  - (**Medium-induced)** energy loss
    - Out-of-cone energy loss
    - Jet and hadron suppression



  - **Color coherence** effects
    - Expected to modify the jet inner structure
    - Not yet unequivocally seen in observables



  - **Medium response**
    - Medium recoils become part of the jet
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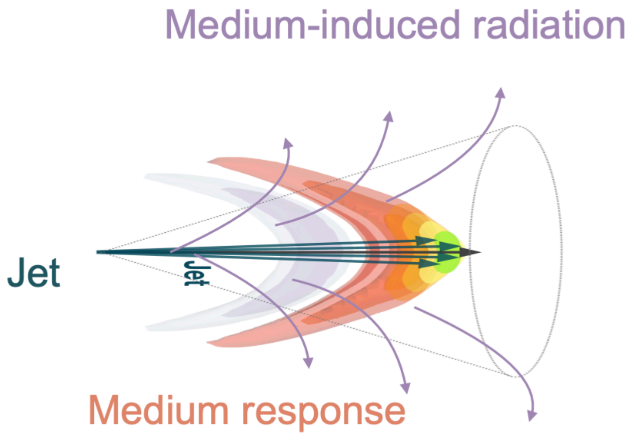

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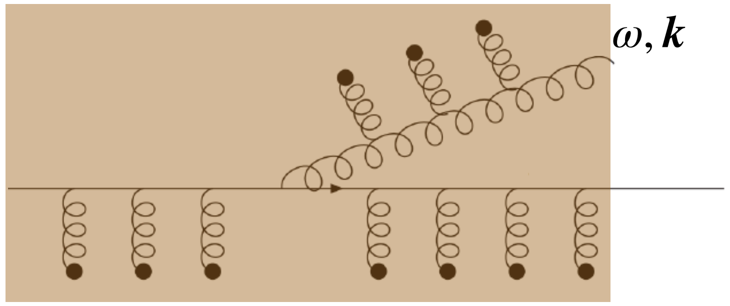

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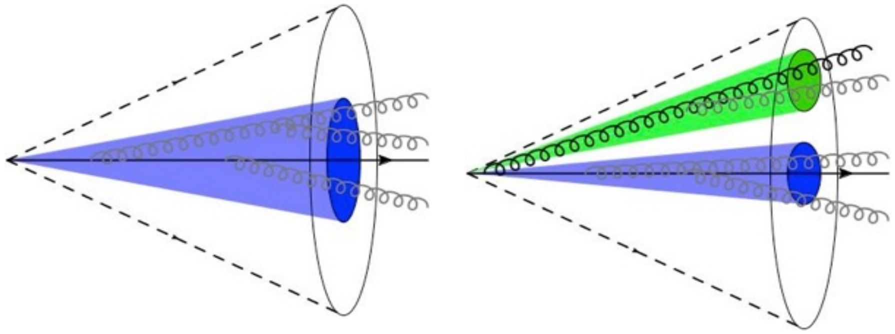

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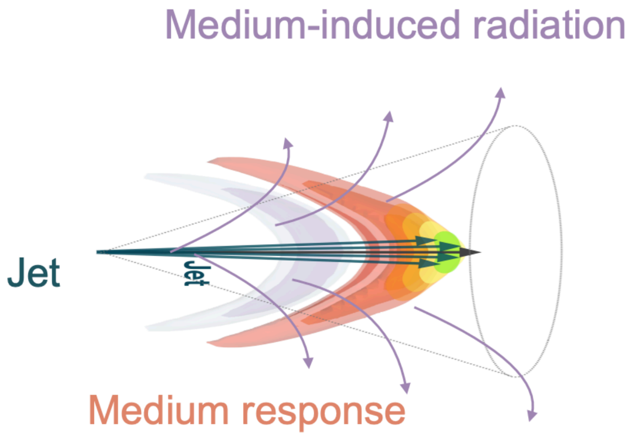


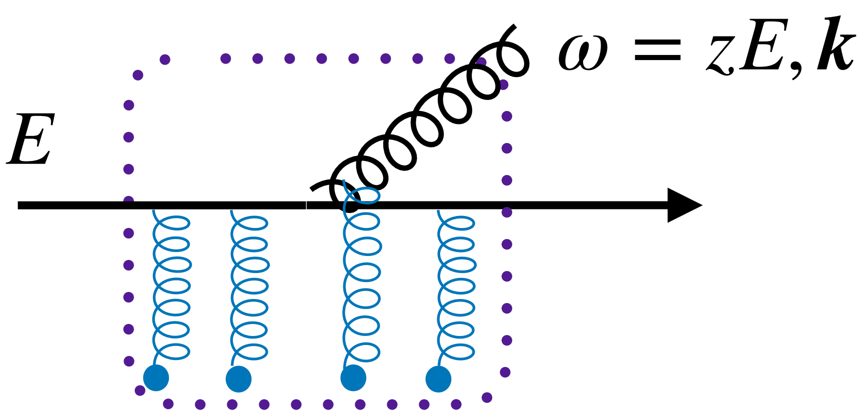
Medium-induced radiation

- The main contribution to energy loss in the QGP is radiative energy loss
  Dominant for light quarks and gluons

High-energy partons experience **multiple scatterings with the medium** which induce **extra gluon radiation** (w.r.t. vacuum)

- During the formation time of the gluon **multiple scatterings** act **coherently**

LPM effect $t_f \sim \frac{\omega}{\boldsymbol{k}^2}$

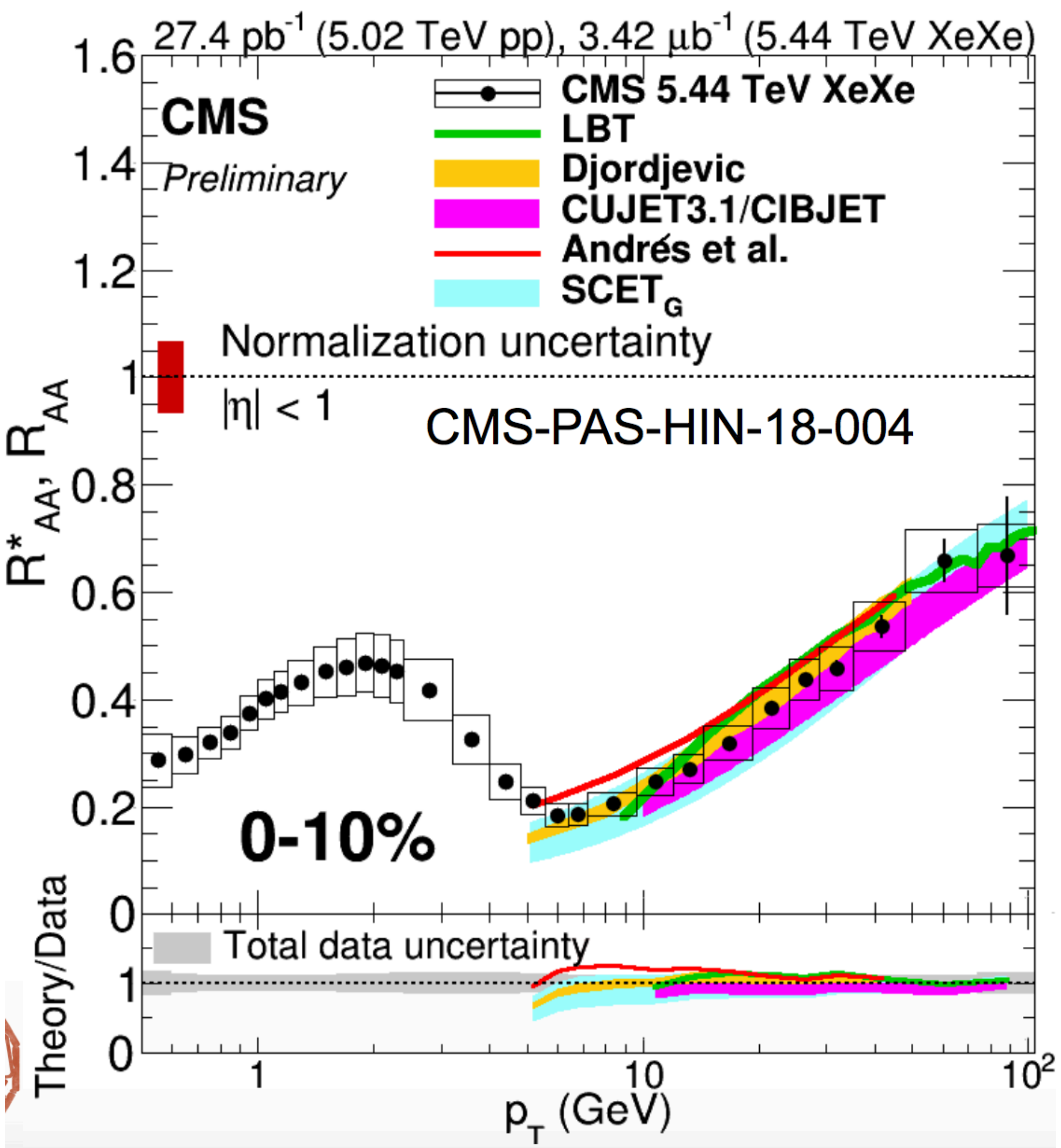


Suppression of the spectrum for **large formation times**

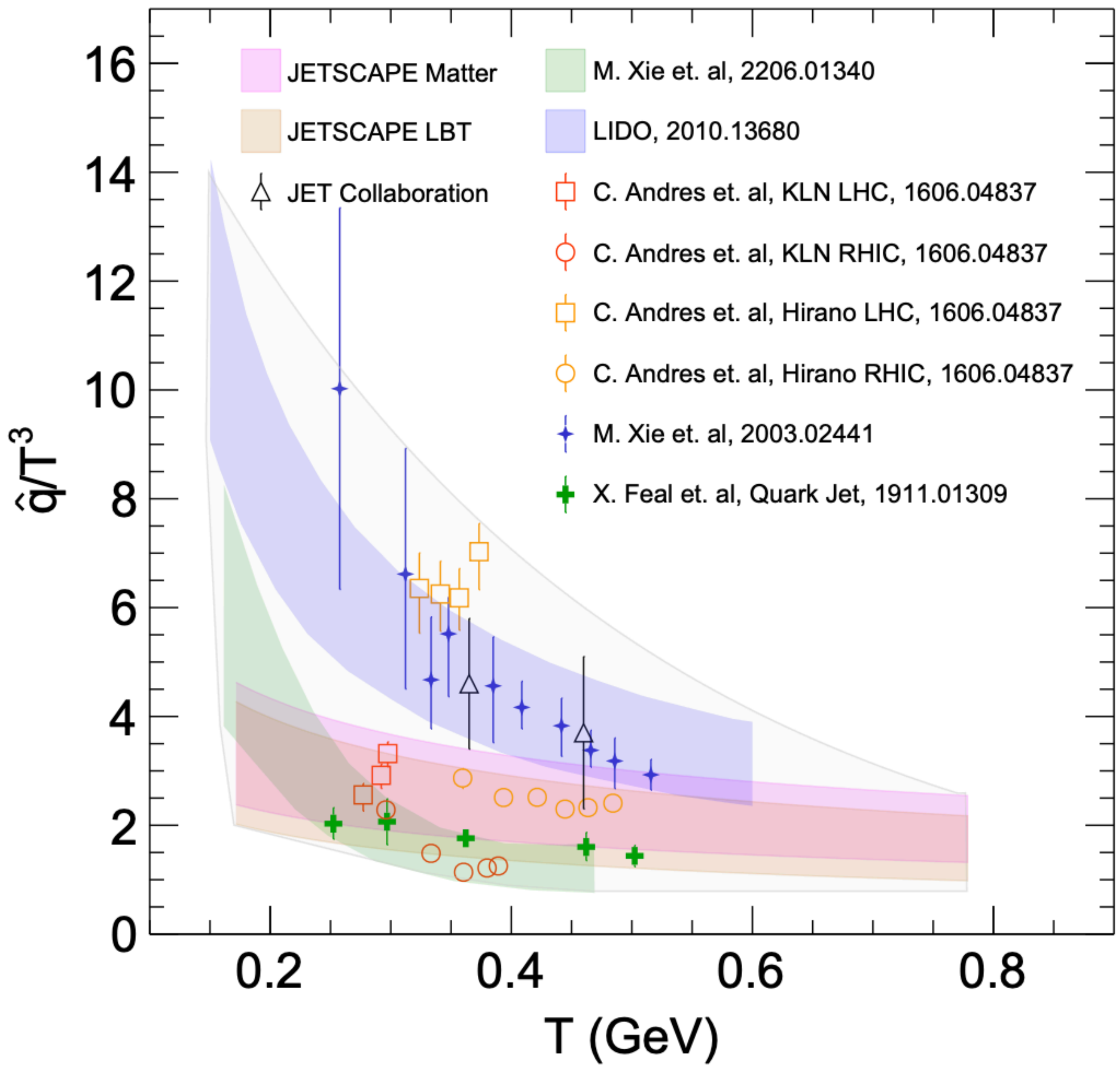
- Resummation of multiple scatterings: **BDMPS-Z formalism**
  Formally in the soft limit : $E \to \infty, z \to 0 \quad (\omega = zE \text{ finite})$

Jet quenching

- Traditionally, jet quenching aims at extracting **properties of the QGP**
- $\hat{q}$: average transverse momentum transfer per unit length



Baty QM2018



Apolinario, Lee, Winn, 2203.16352

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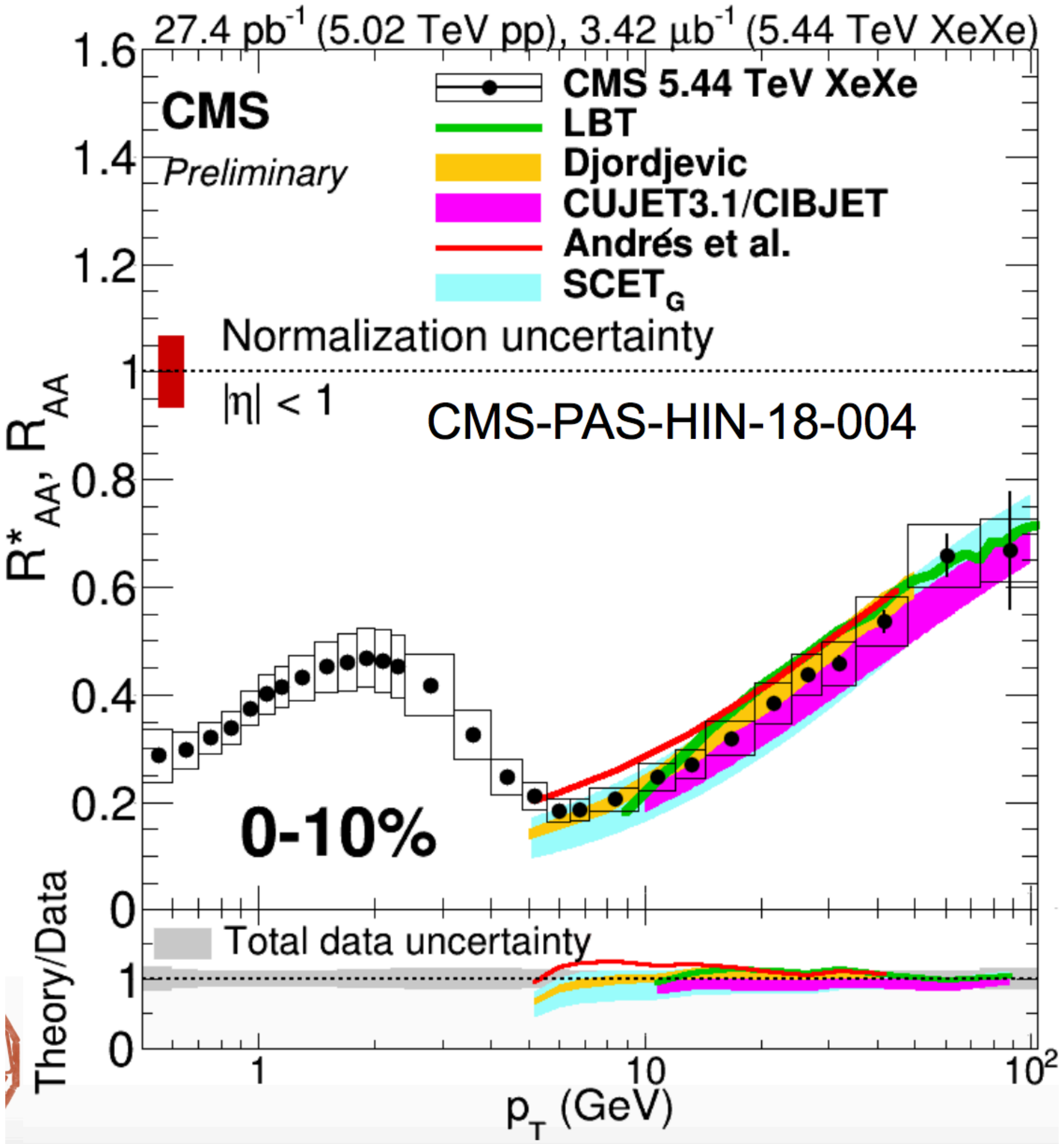

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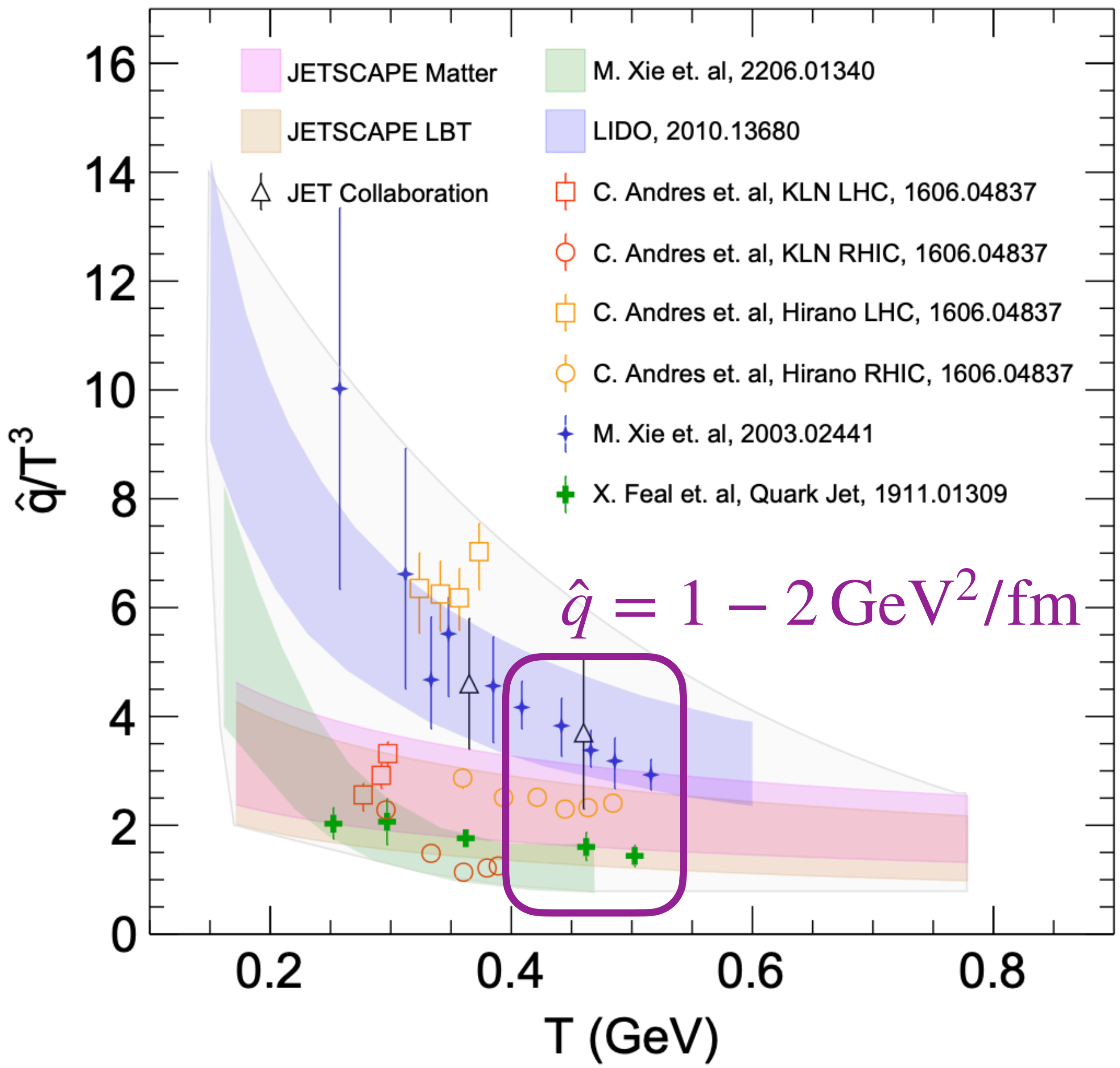


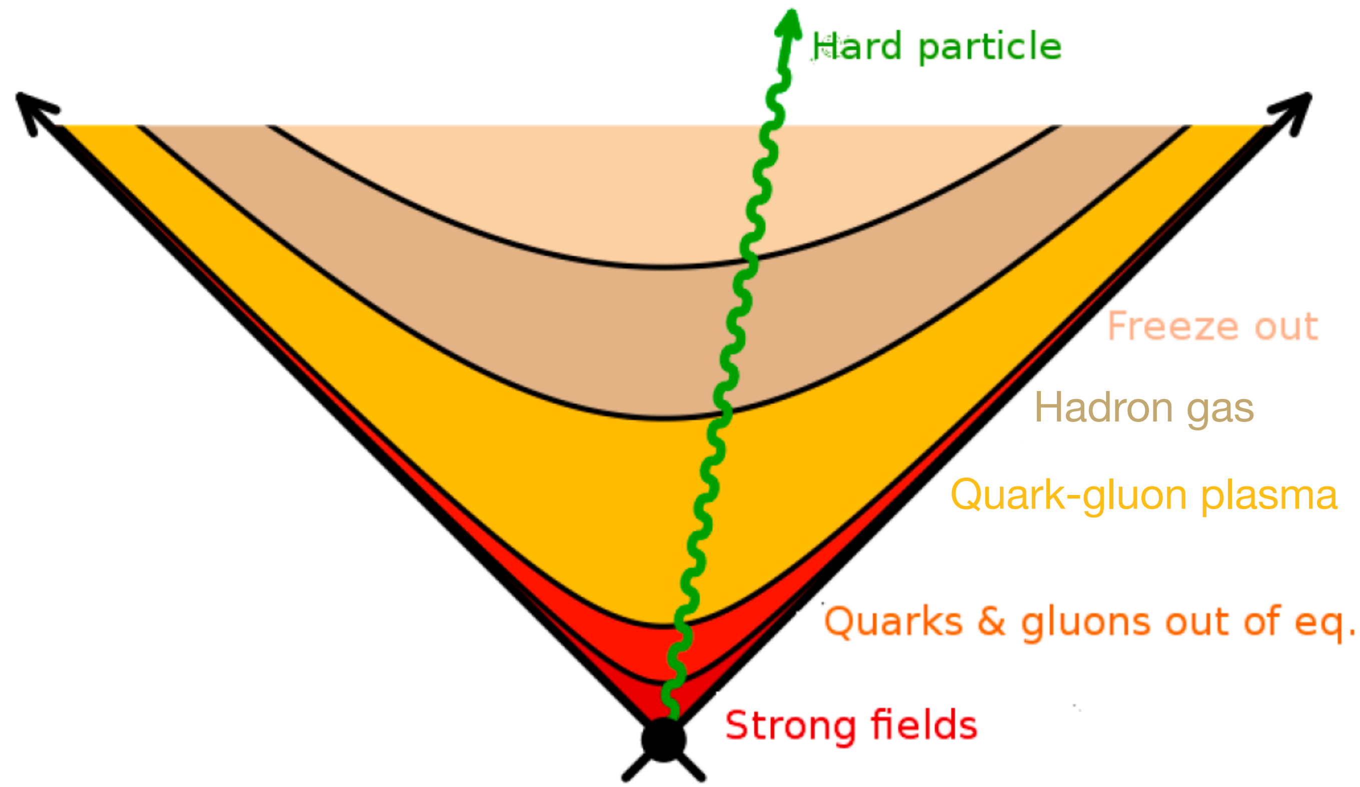
Apolinario, Lee, Winn, 2203.16352

Jets in A-A

- Hard probes/jets ($Q \sim p_\mathrm{T}, M_\mathrm{Q}$) are **produced** in the **initial hard scattering**

$$\tau_\mathrm{p} \sim \frac{1}{Q} \ll \frac{1}{Q_s} \ll \tau_\mathrm{hydro}$$

Jets **witness the space-time system evolution** (including the pre-equilibrium stages)



- Most of jet quenching studies, set the **quenching to start at the initialization time** of the hydro

  No energy loss before hydrodynamization?

- How **sensitive are jet observables to the initial stages**?

  Crucial to understand the apparent lack of energy loss in small systems!

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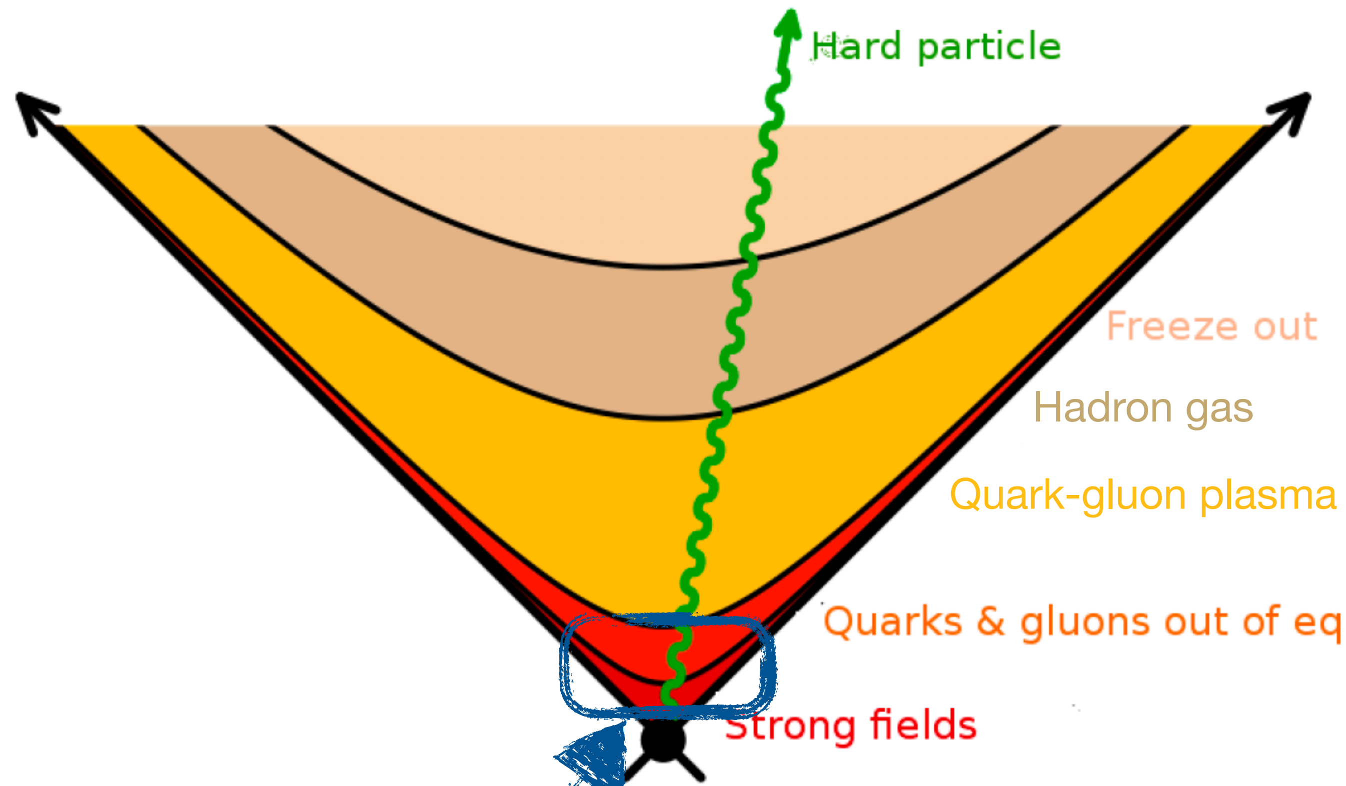

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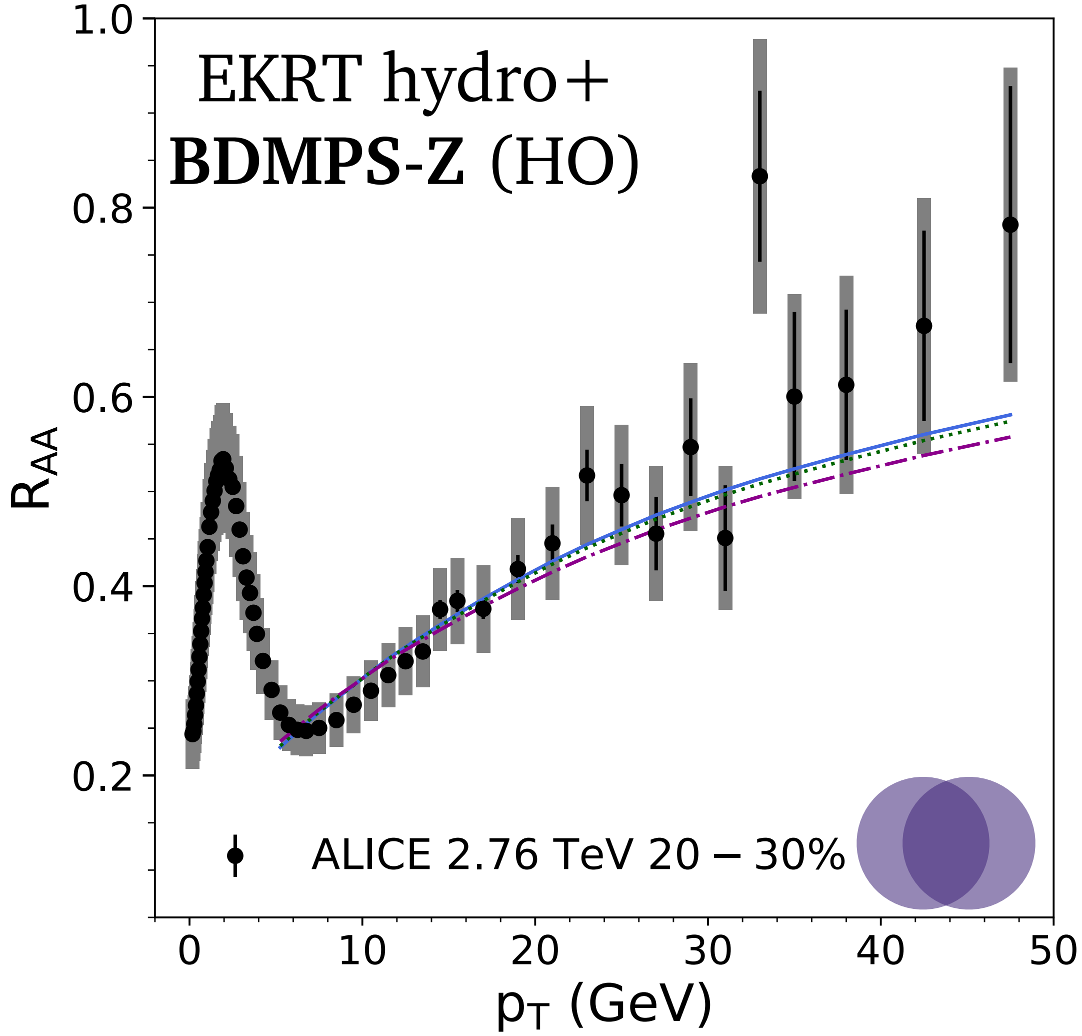
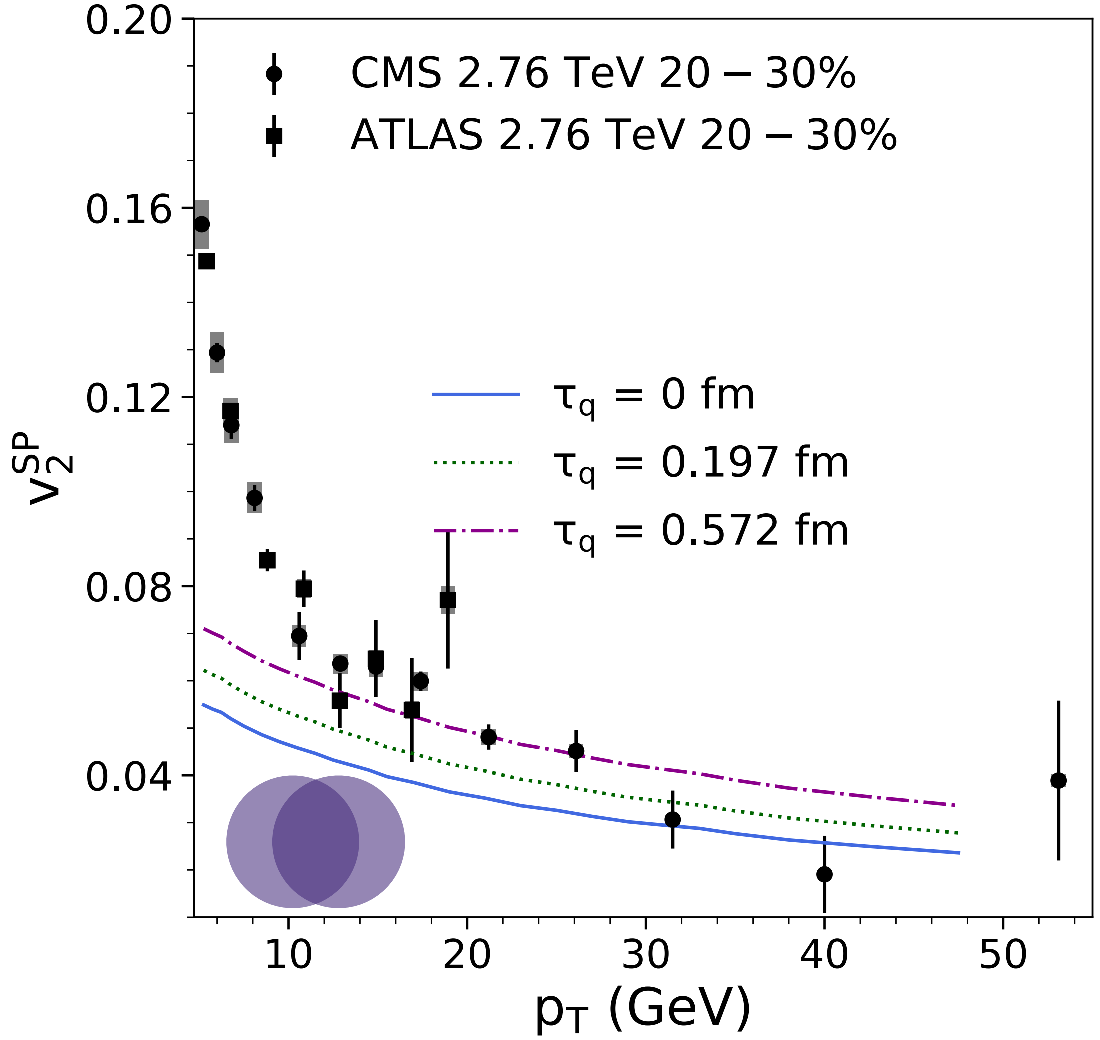
R_{AA} and high-p_T v_2

- Simultaneous description of the **charged hadron** R_{AA} and high-p_T v_2 **sensitive to the quenching in the initial stages**

CA, Armesto, Niemi, Paatelainen, Salgado, 1902.03231





v_2^{SP} definition from: Noronha-Hostler, Betz, Noronha, Gyulassy, 1602.03788

- **Confirmed** also for collisional +**DGLV** energy loss (single scattering)

Zigic, Ilic, Djordjevic, Djordjevic, 1908.11866 ; Stojku, Auvinen, Djordjevic, Huovinen, Djordjevic, 2008.08987

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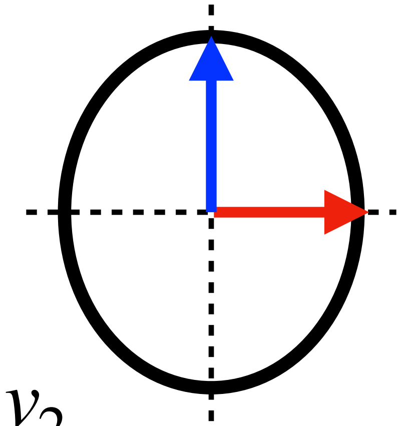

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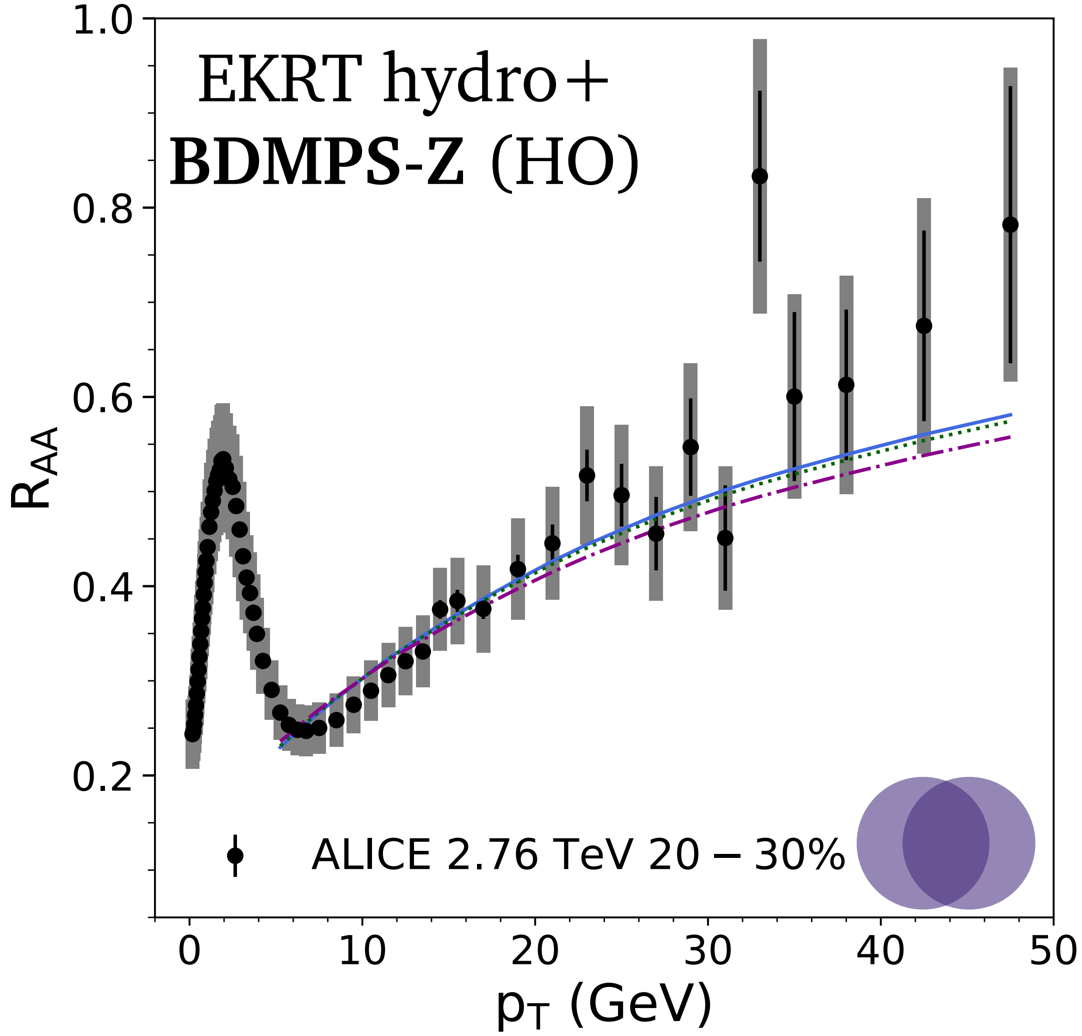

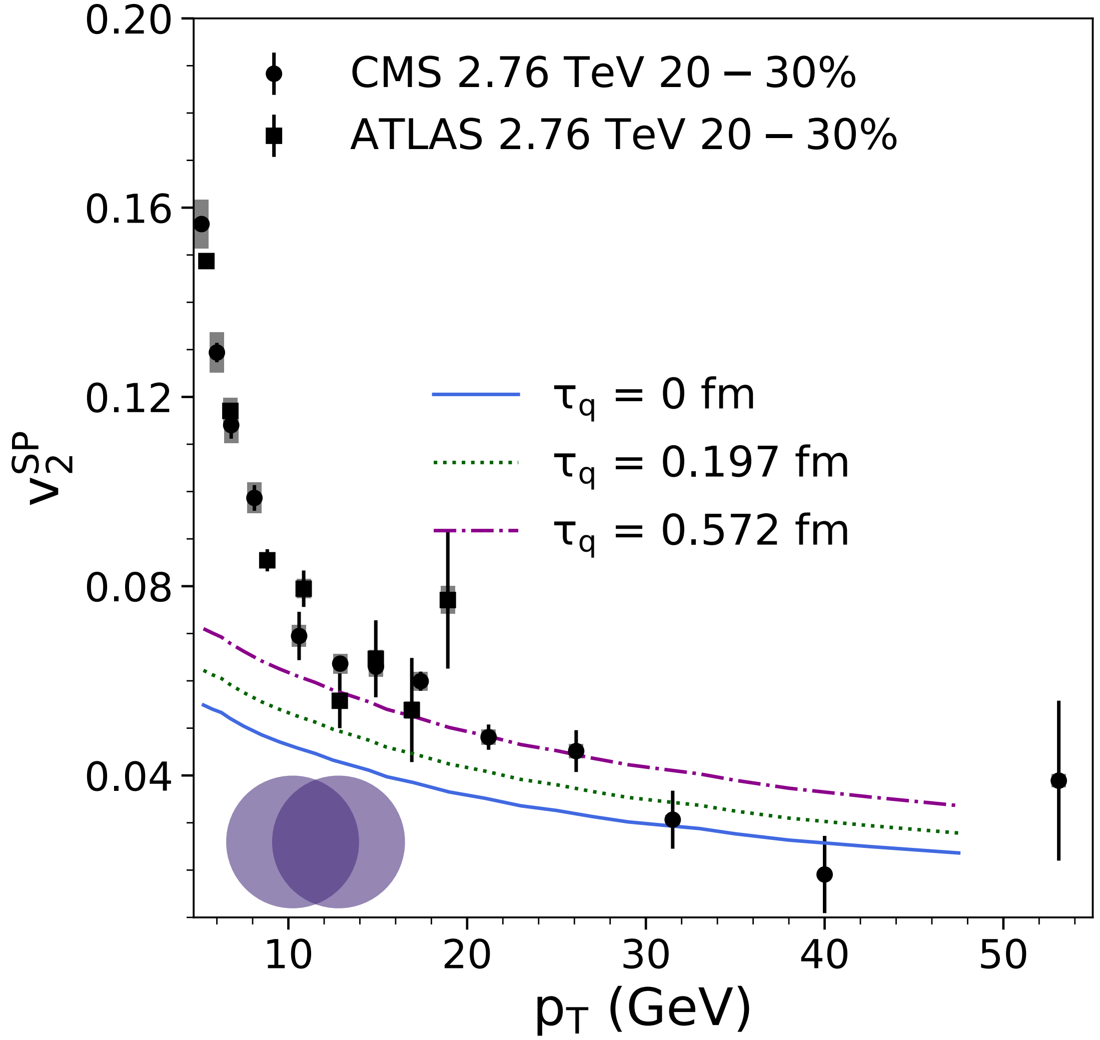

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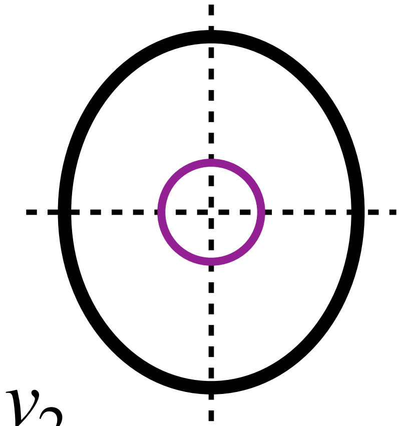

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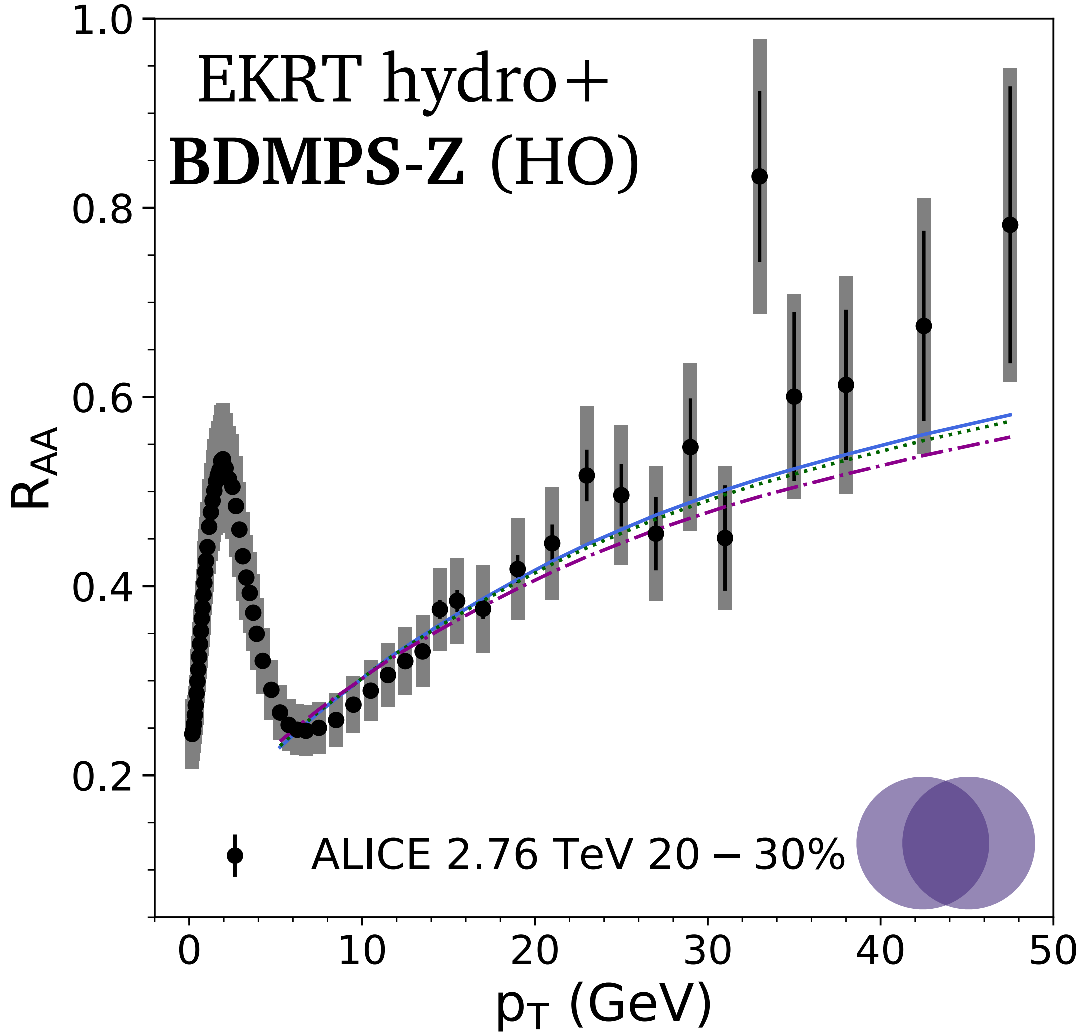

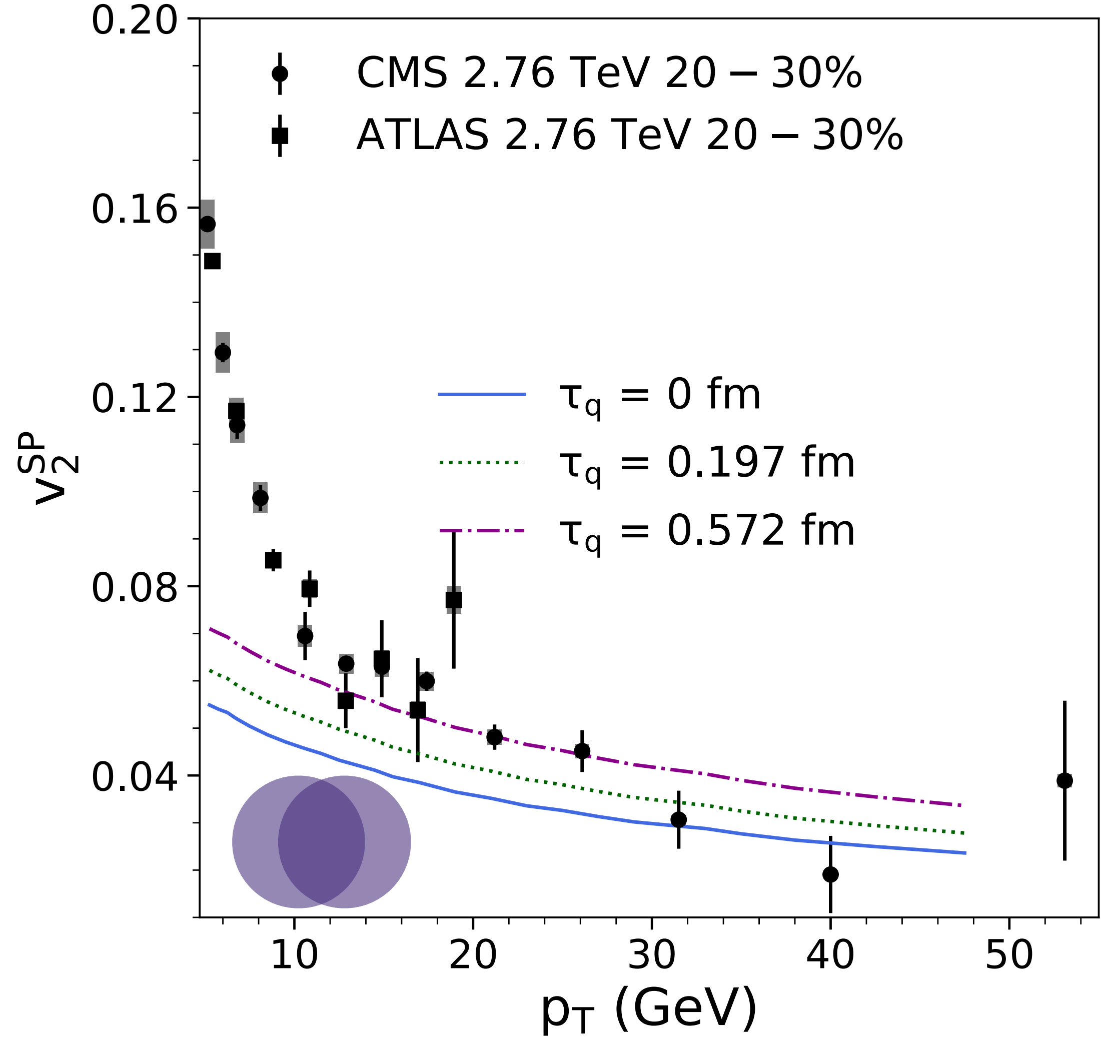

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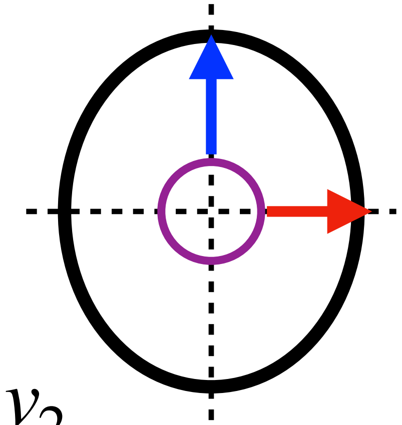

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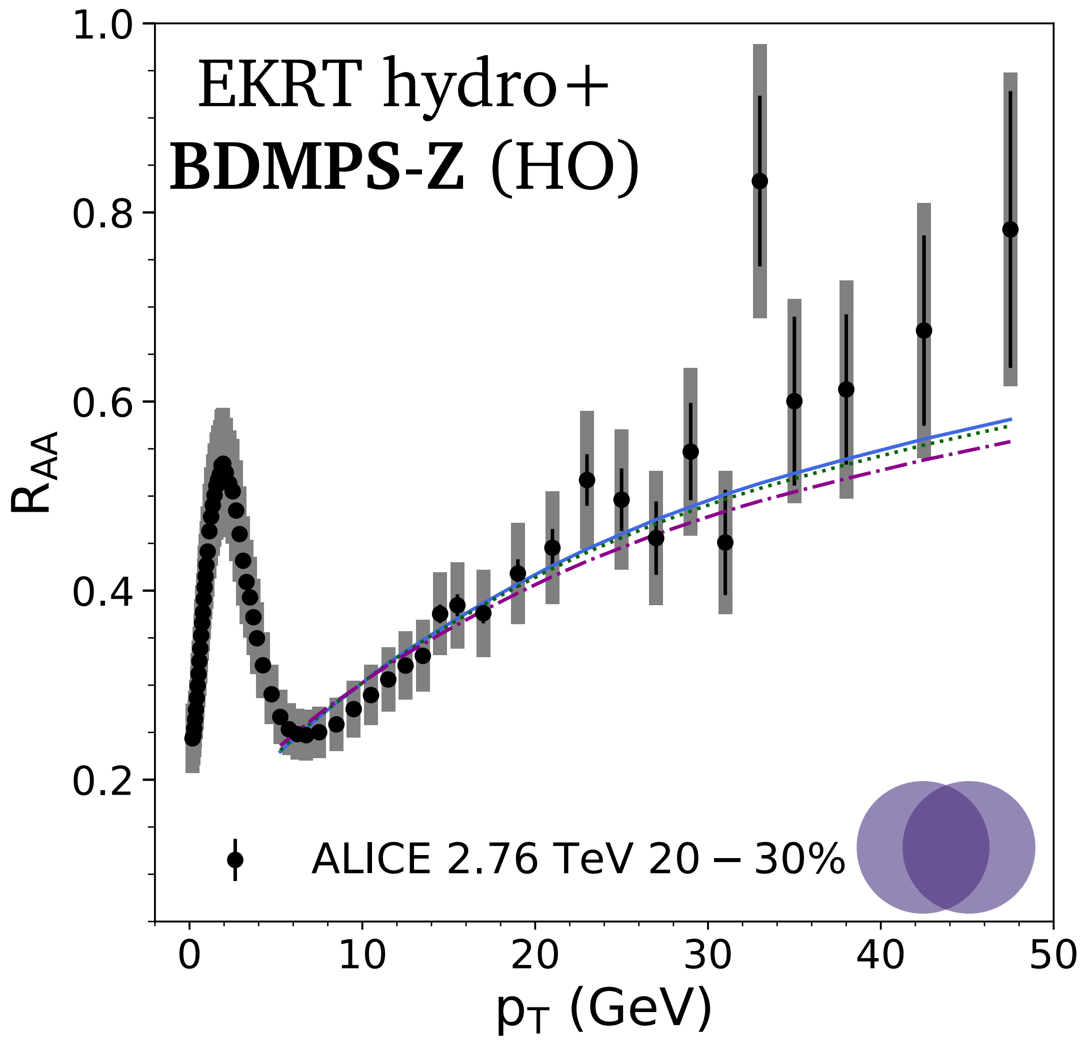

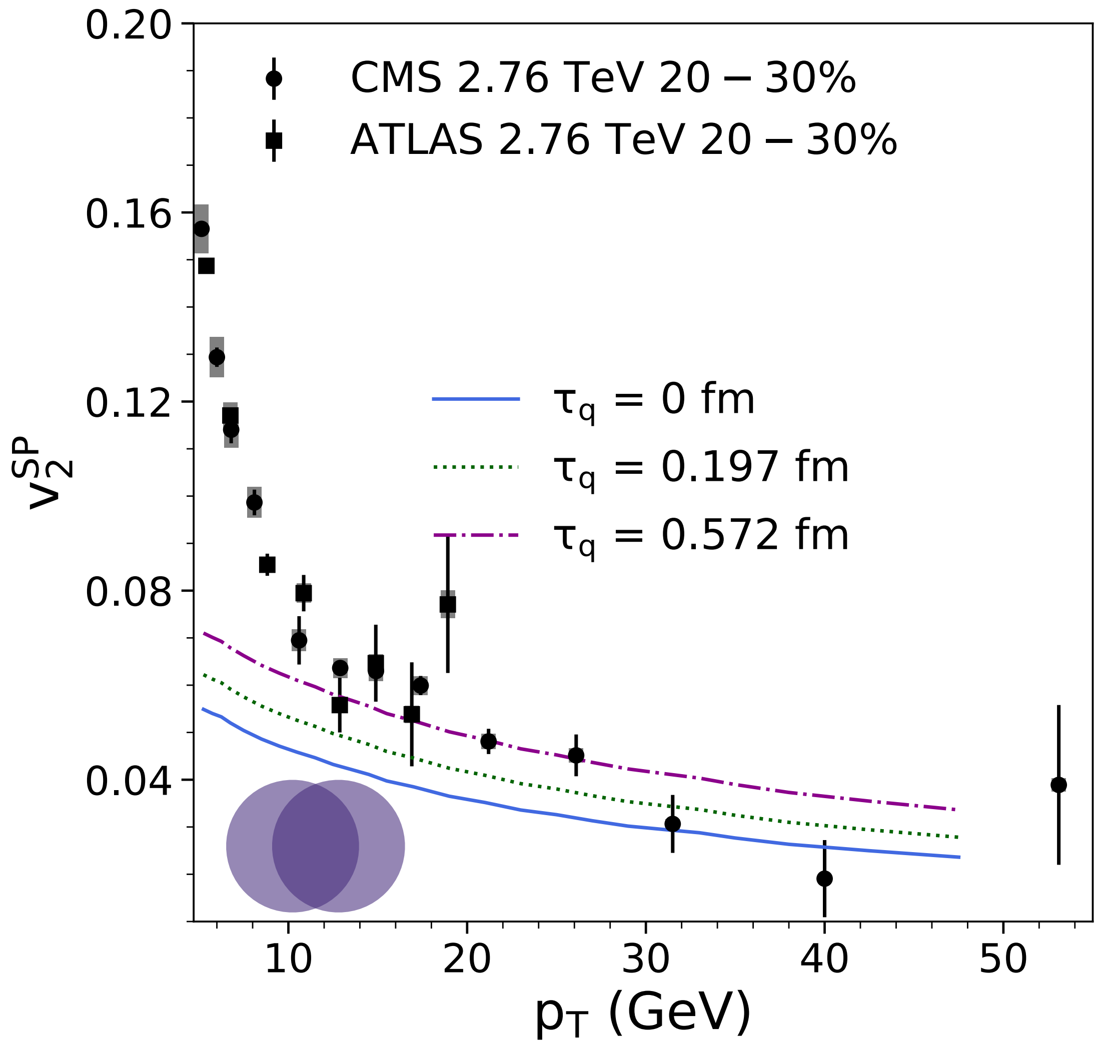

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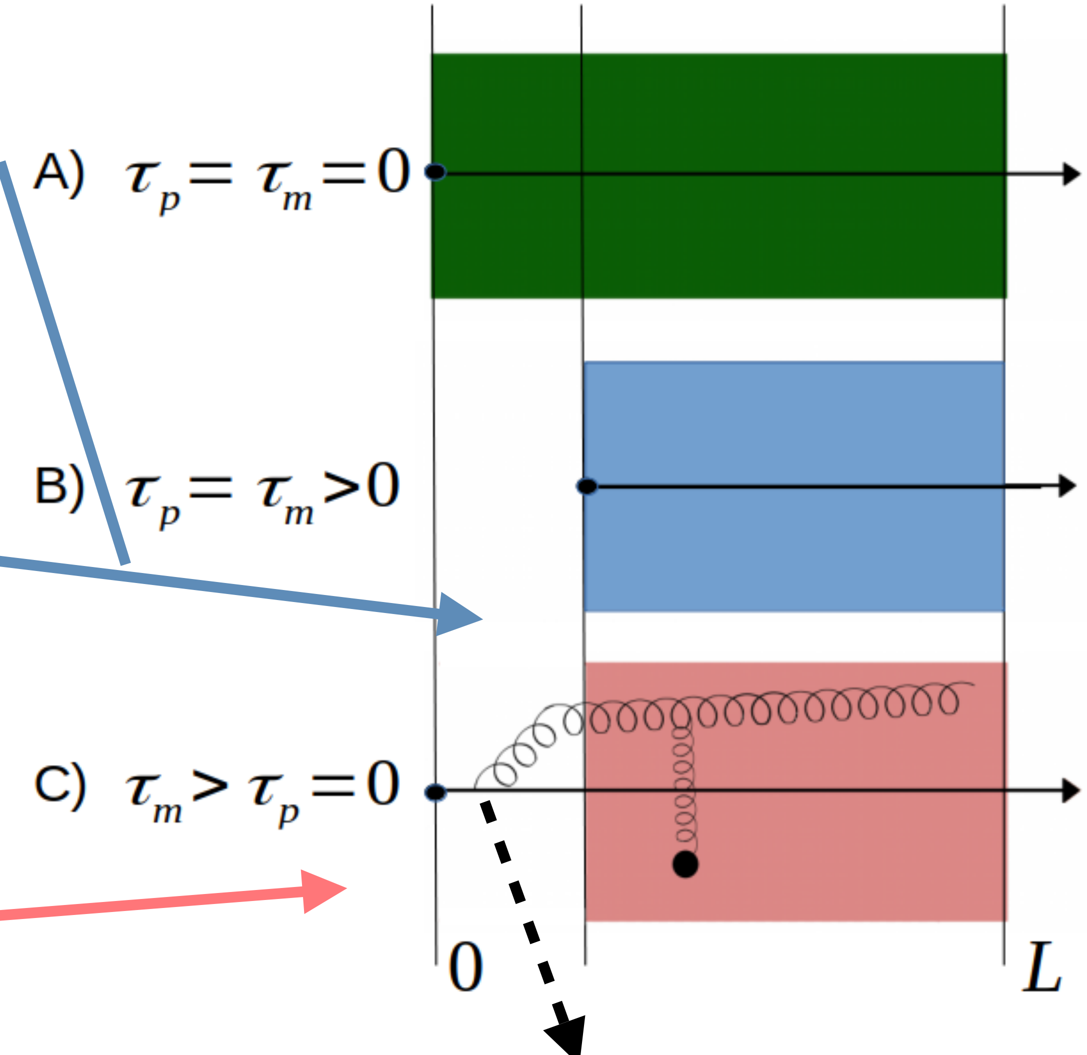
Radiation in the IS

- But… delaying the start of the quenching is not totally correct
- Since we are ignoring (medium-induced) radiation emitted before the formation of the QGP
- To correctly implement no energy loss (vacuum) in the initial stages we need:
  - Emitter produced at $\tau_p \sim 0$
  - Propagates in vacuum from τ_p to $\tau_m = \tau_{\text{hydro}}$
  - In-medium propagation from τ_m to L



Extra medium-induced radiation included

CA, Apolinário, Dominguez, **M. G. Martinez**, Salgado, arXiv: 2112.04593

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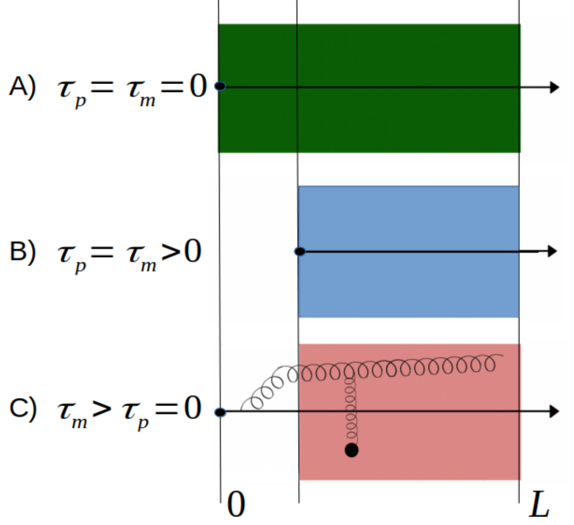
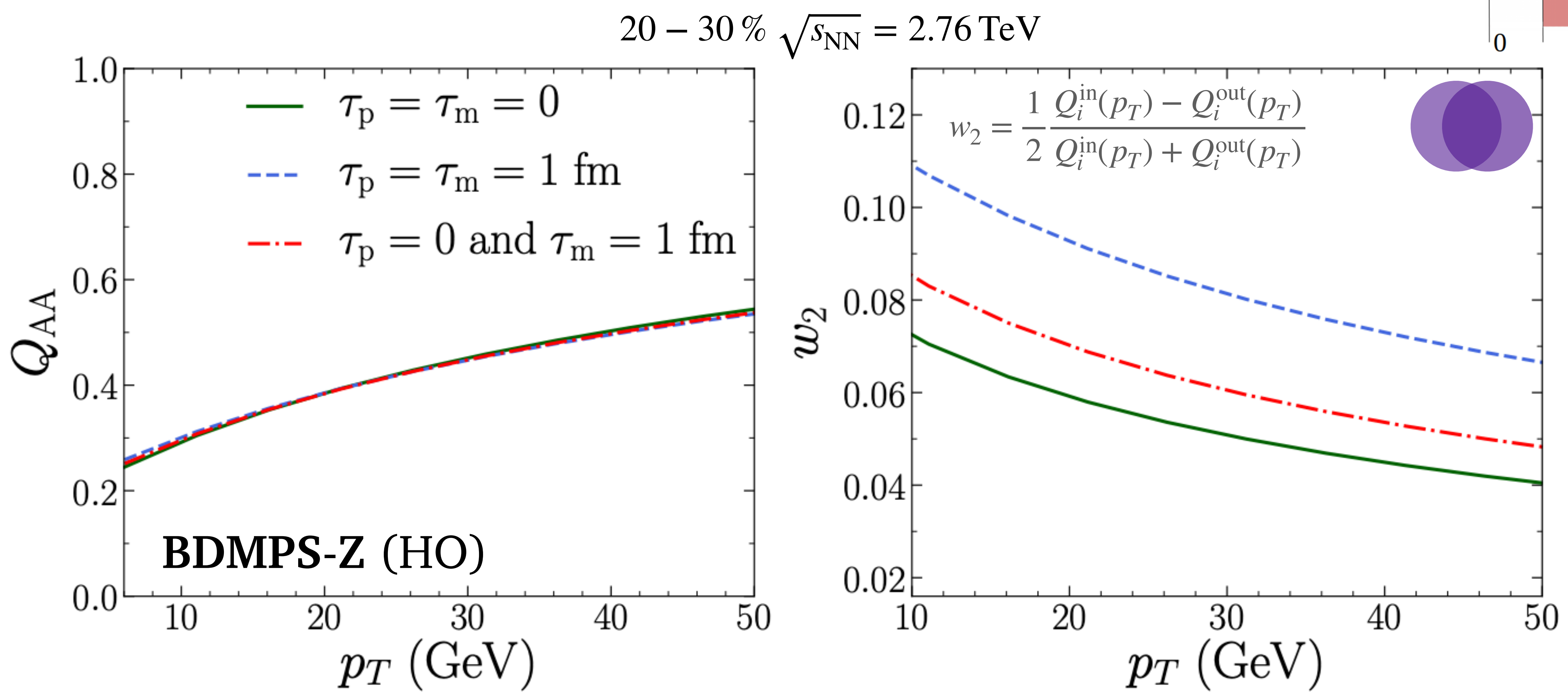




Difference between A) and C) still **sizable**!

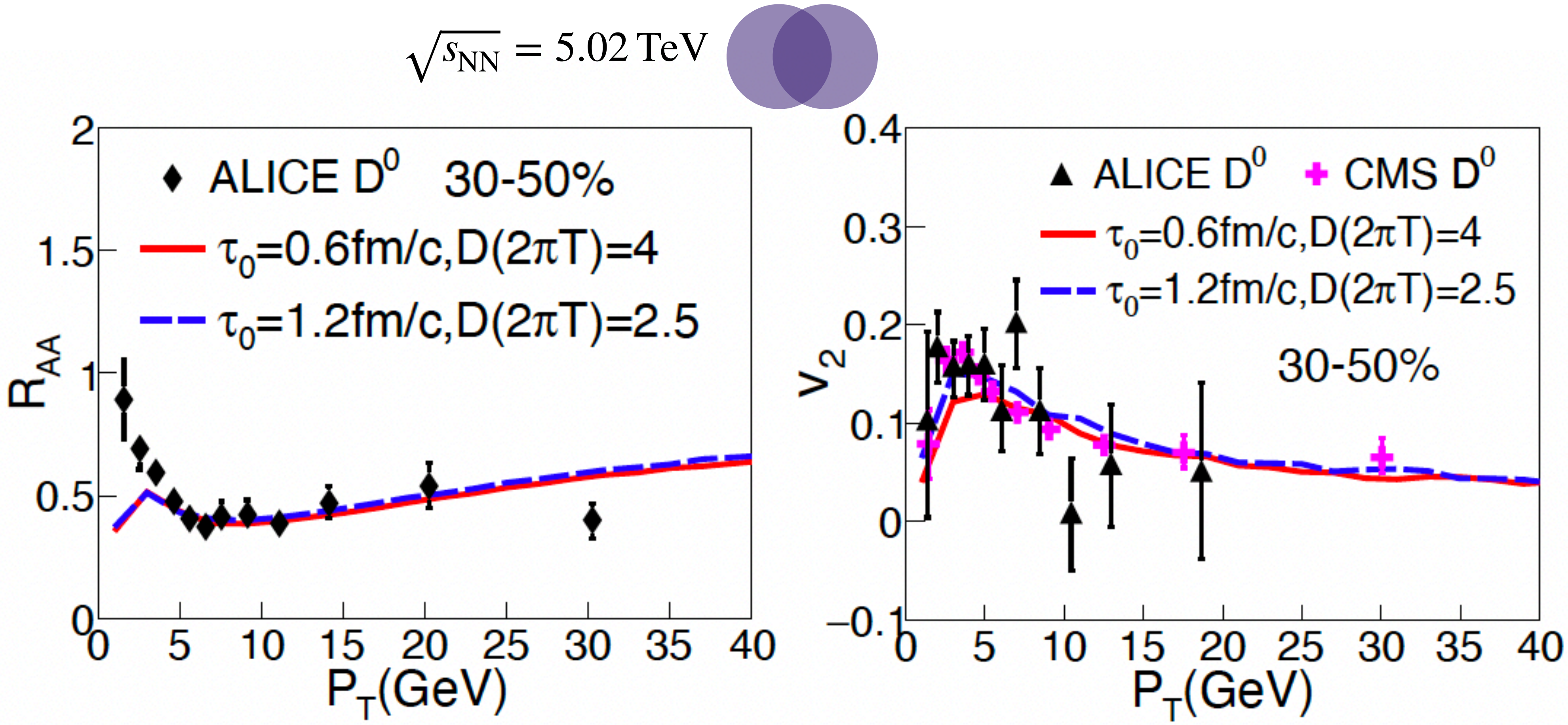
- Also confirmed without using the HO approximation

CA, Apolinário, Dominguez, **M. G. Martinez**, Salgado, 2211.10161

D mesons

- Modified Langevin equation to account for radiative energy loss

Cao, Quin, Bass 1308.0617

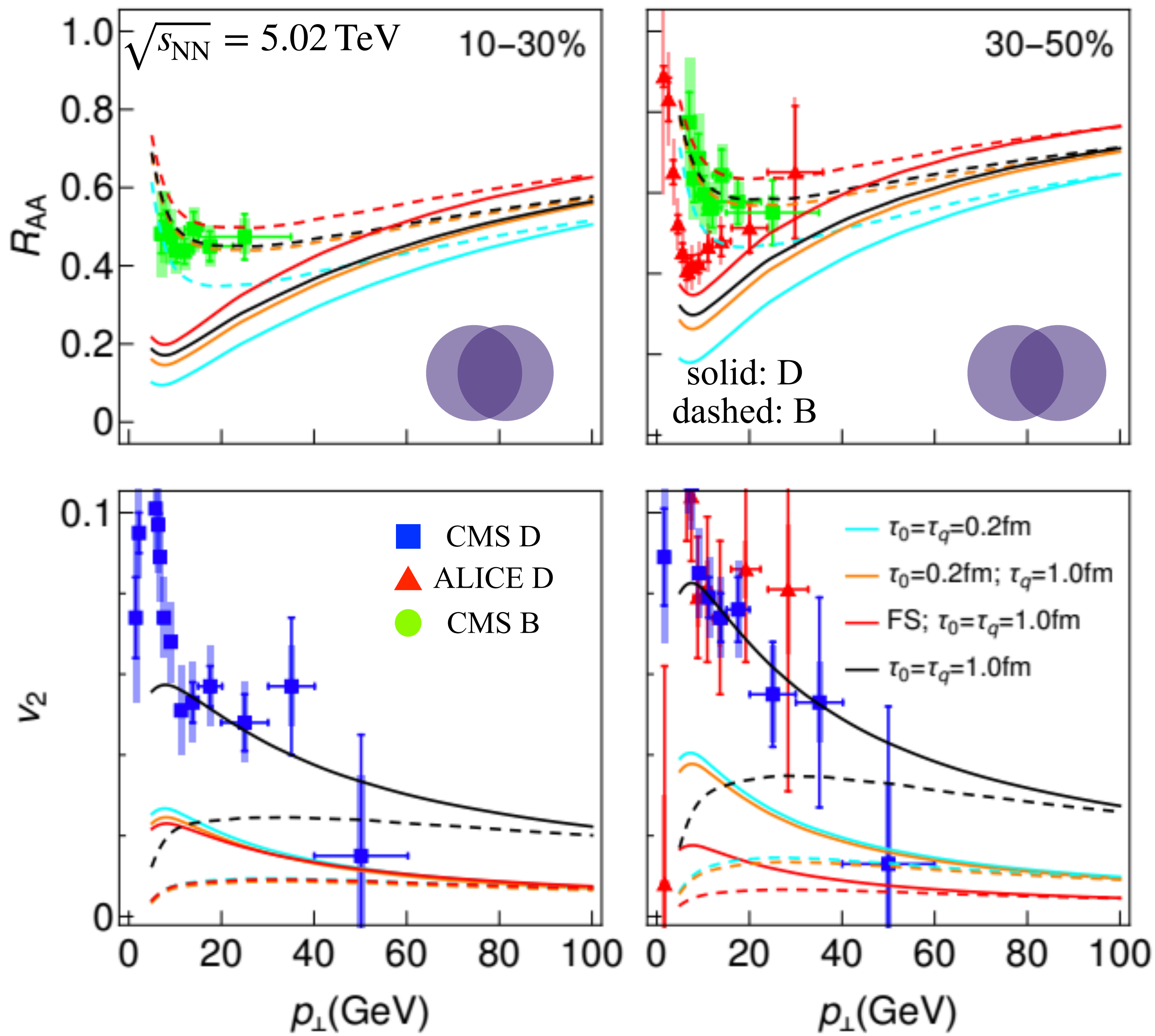


Li, Xing, Liu, Cao, Qin, 2005.03330

- Spatial diffusion coefficient fitted to the $D^0\, R_{AA}$ ALICE data

- **Very little effect** in the hard sector

D mesons

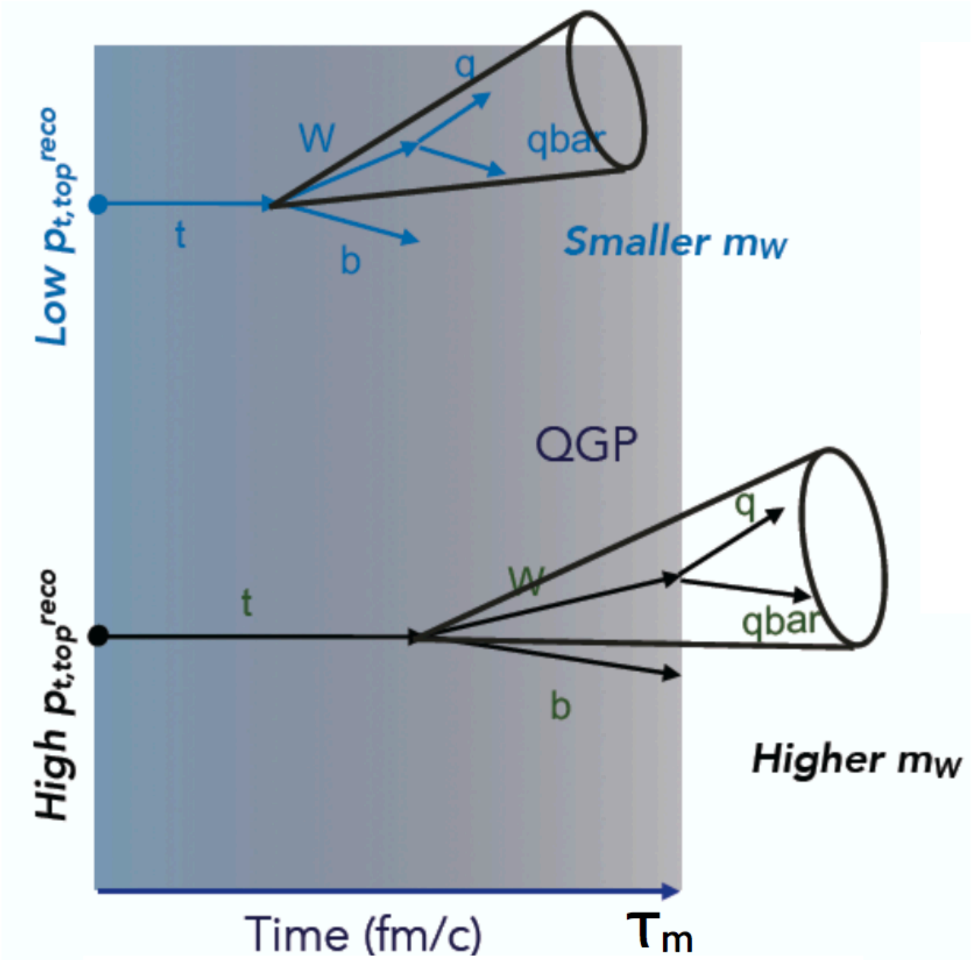


Stojku, Auvinen, Djordjevic, Huovinen, Djordjevic, 2008.08987

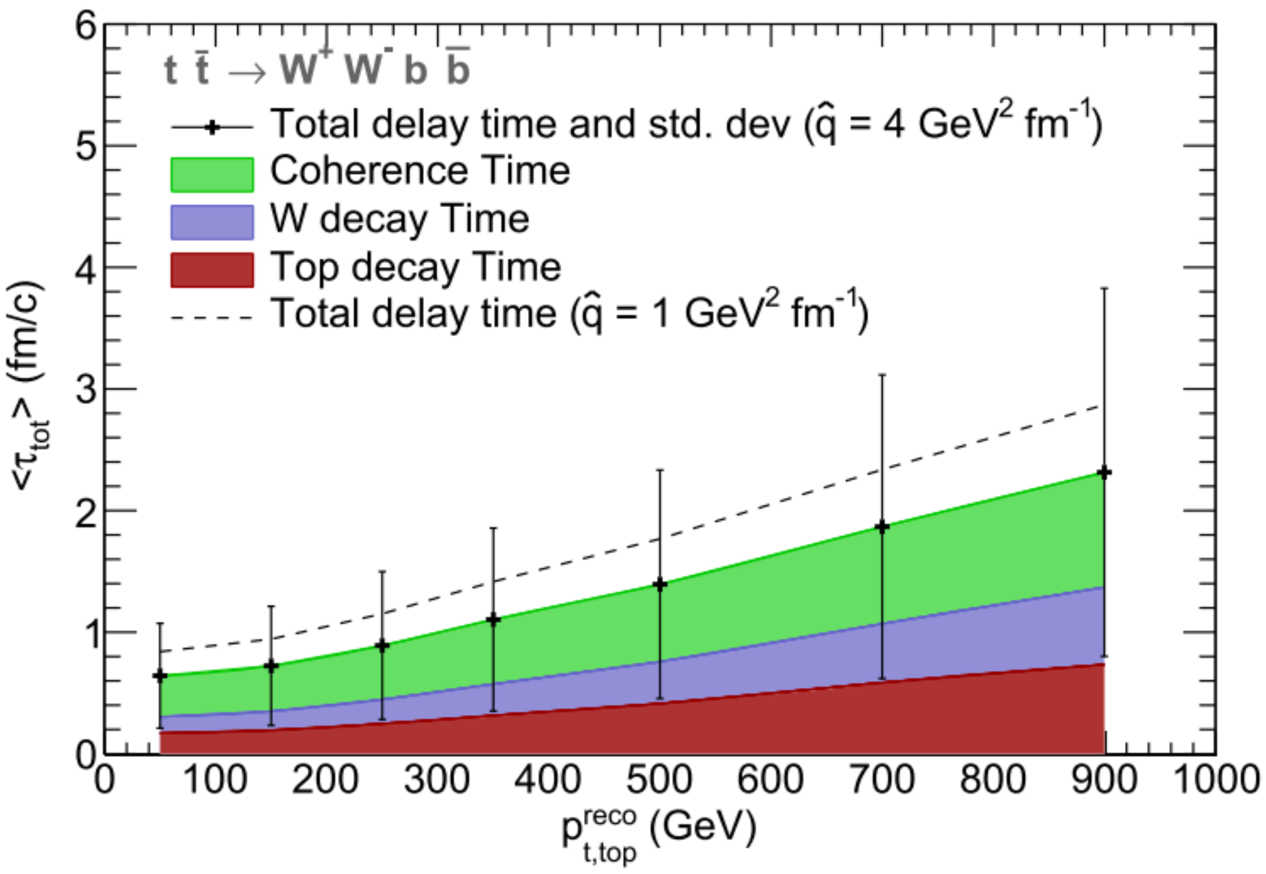
Boosted tops

Apolinário, Milhano, Salam, Salgado
1711.03105

- Jets coming from W decays start interacting *later* with the medium
- **Controlling the boost of the top ⟶ Controlling when jets start to interact** with medium



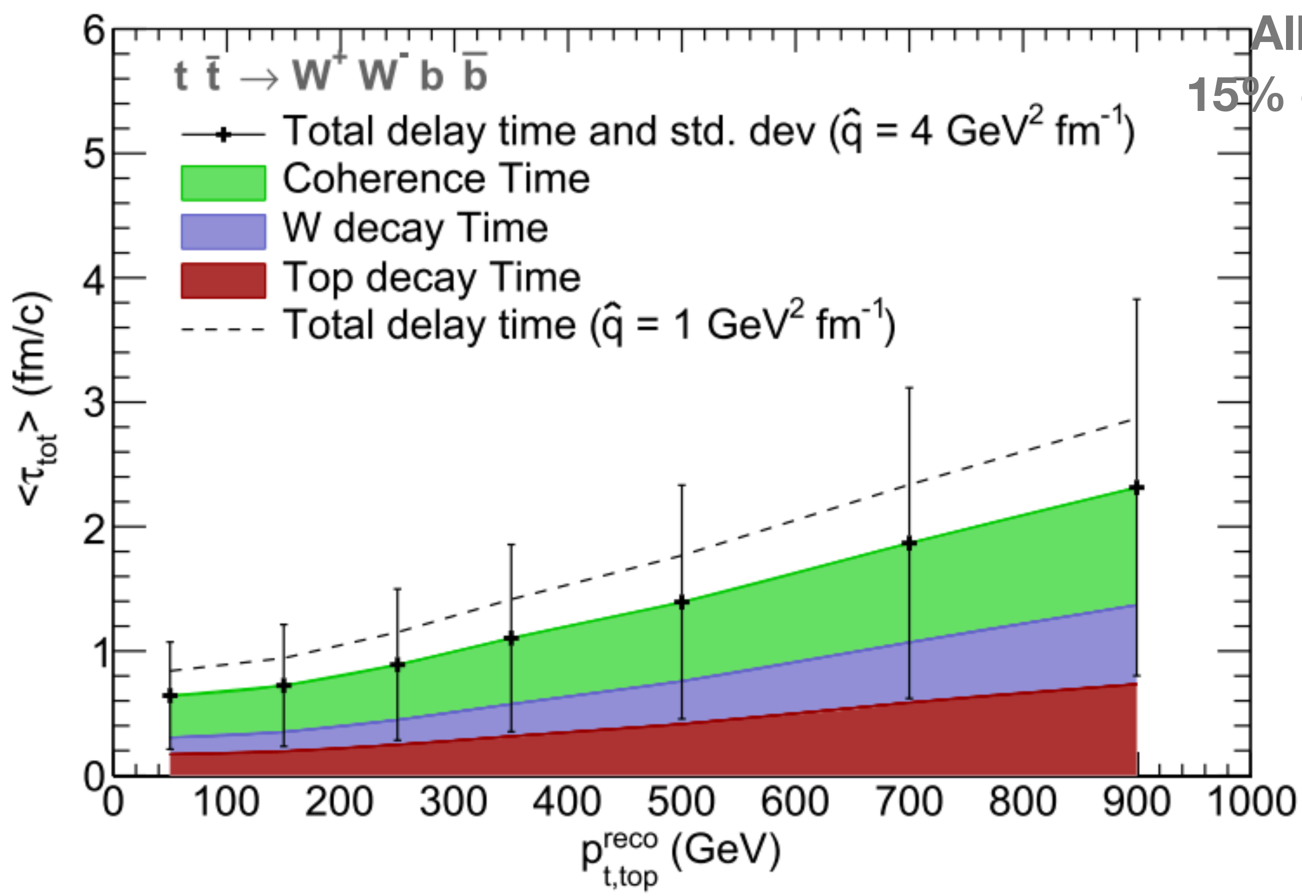
$$\langle\tau_{tot}\rangle = \gamma_{t,top}\tau_{top} + \gamma_{t,W}\tau_W + \tau_d$$

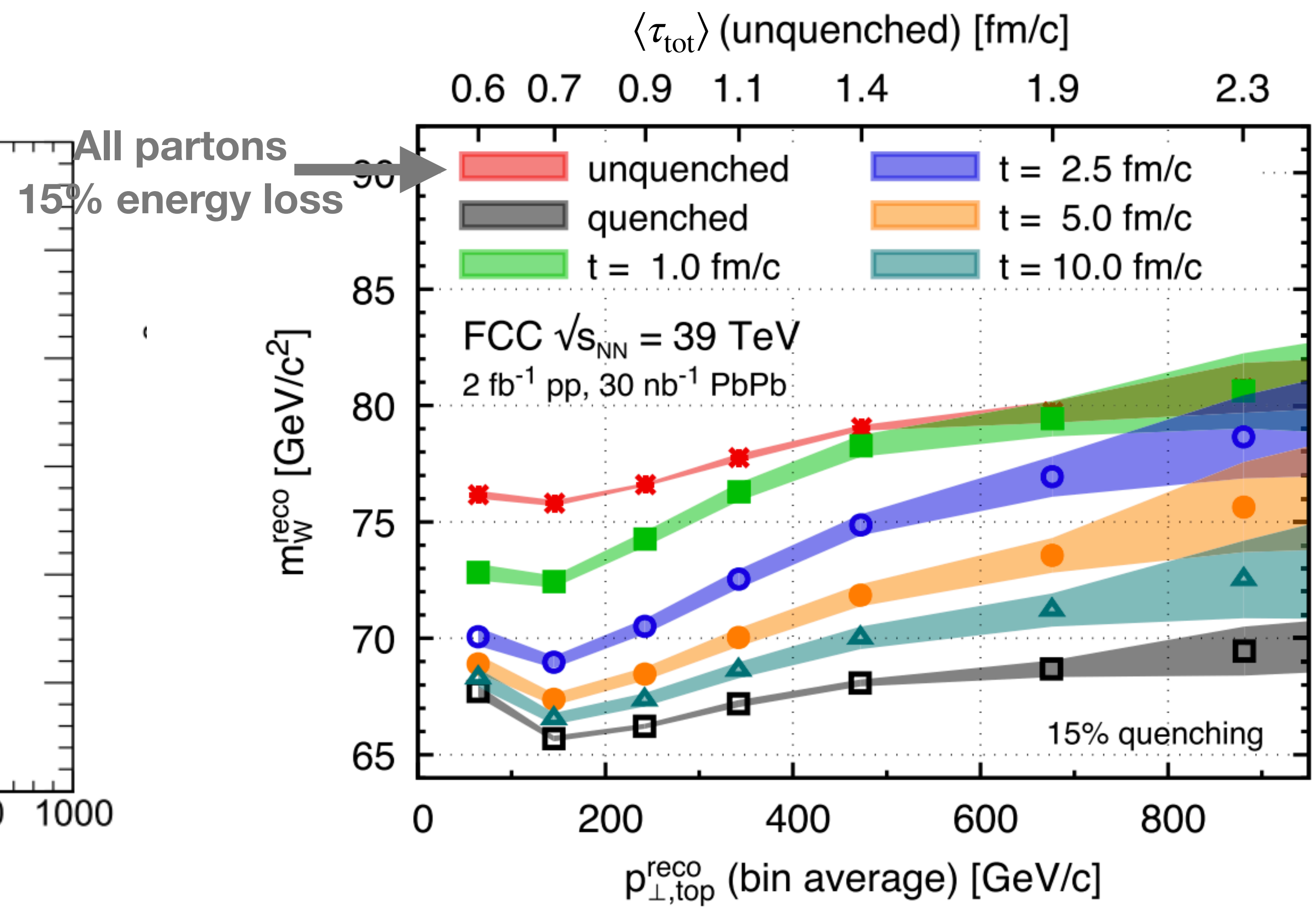


- Energy loss will be reflected in the reconstructed W mass

Boosted tops

- **Reconstructed W mass** as a function of the top p_{T}: **access to the medium time structure**





Apolinário, Milhano, Salam, Salgado, 1711.03105

- What about jets?

The role of time

- **Factorization picture** between vacuum-like and medium induced emissions

  Caucal, Iancu, Mueller, Soyez, 1801.09703

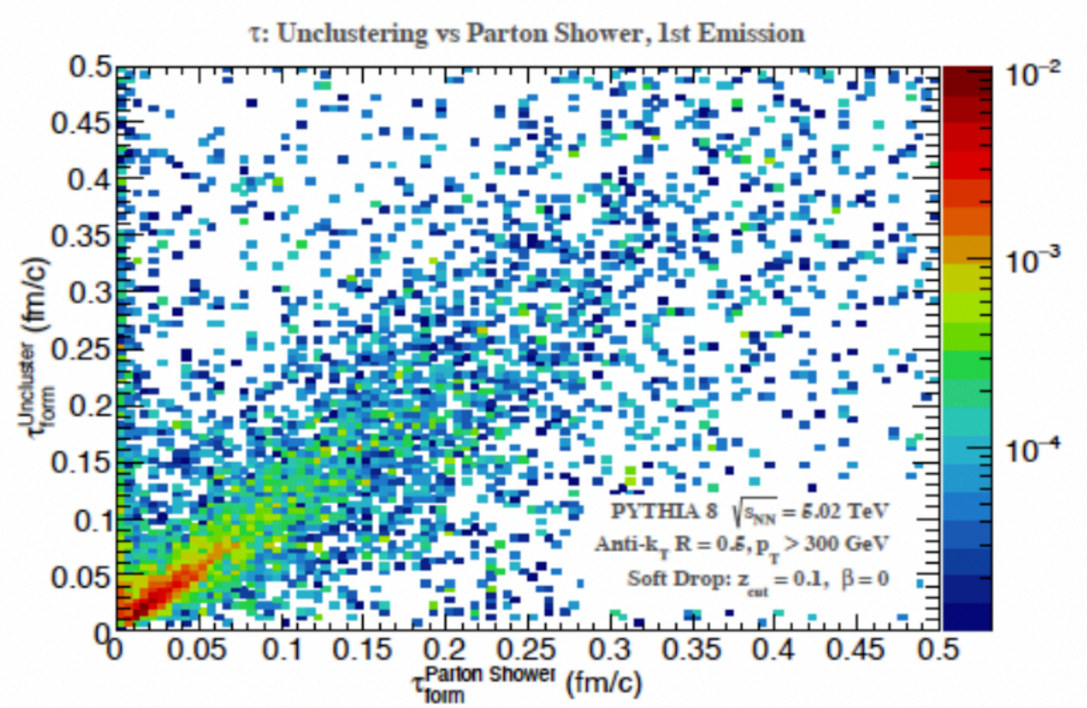
- Studies on impact of the **choice of the evolution variable** in vacuum-like emissions $\longrightarrow$ Different Lund plane trajectories

  See Cordeiro's talk in HP2023

$$\Delta(s_{\rm prev}, s) = \exp\left\{-\frac{\alpha C_R}{\pi}\int_s^{s_{\rm prev}}\frac{{\rm d}\mu}{\mu}\int_{z_{\rm cut}(\mu)}^1\frac{{\rm d}z}{z}\right\}$$

s: virtuality, opening angle, formation time

- To be sensitive to different medium time scales we also need to be able to **reconstruct the shower in formation times**



τ algorithm $(p = 0.5)$

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\frac{\Delta R_{ij}^2}{R^2} \qquad p = 0.5 \to d_{ij} \sim \frac{1}{\tau_f}$$

Apolinário, Cordeiro, Zapp, 2012.02199

Energy correlators in p-p

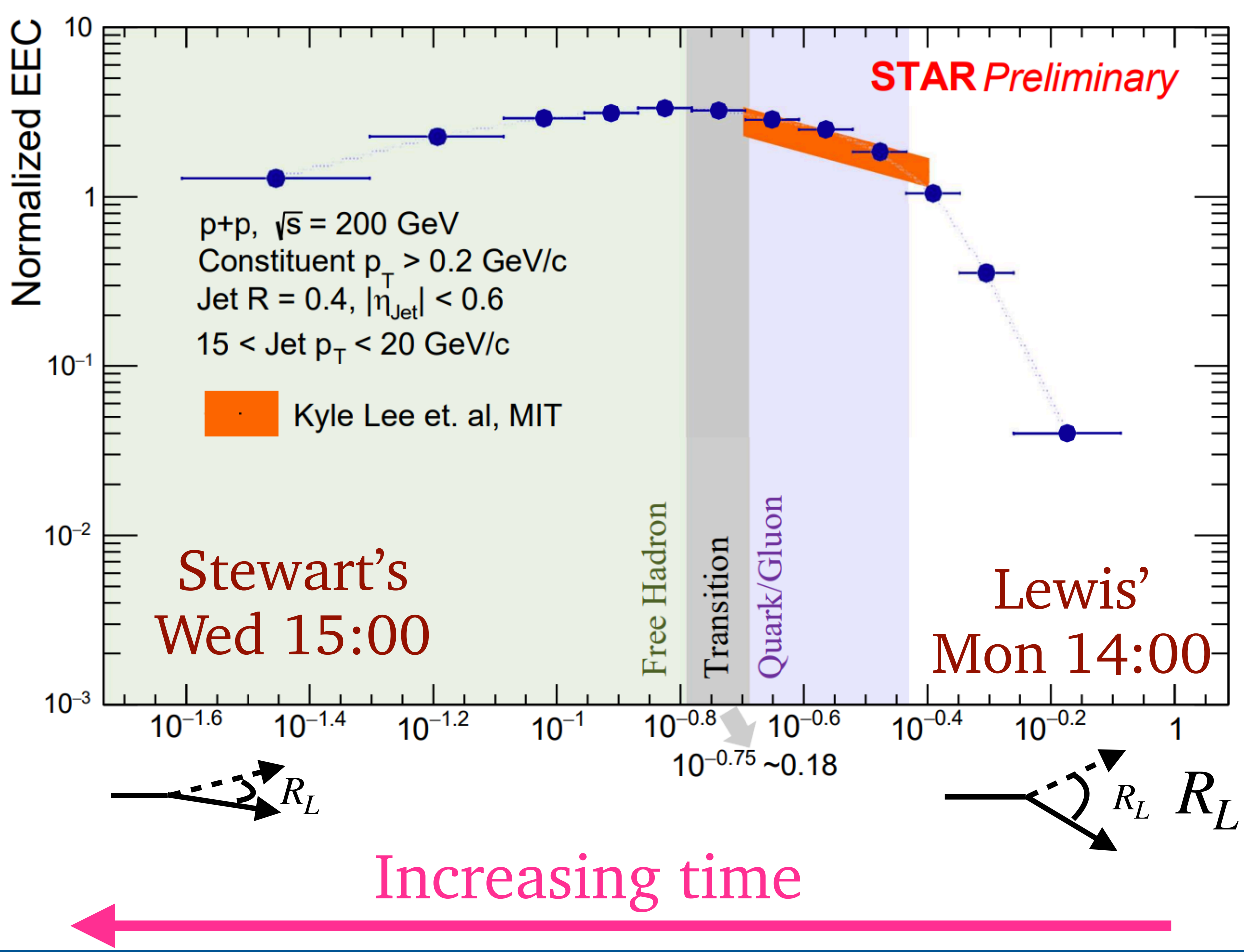
- **2-point energy-energy correlator of a p-p jet** (as a function of the **angle**):

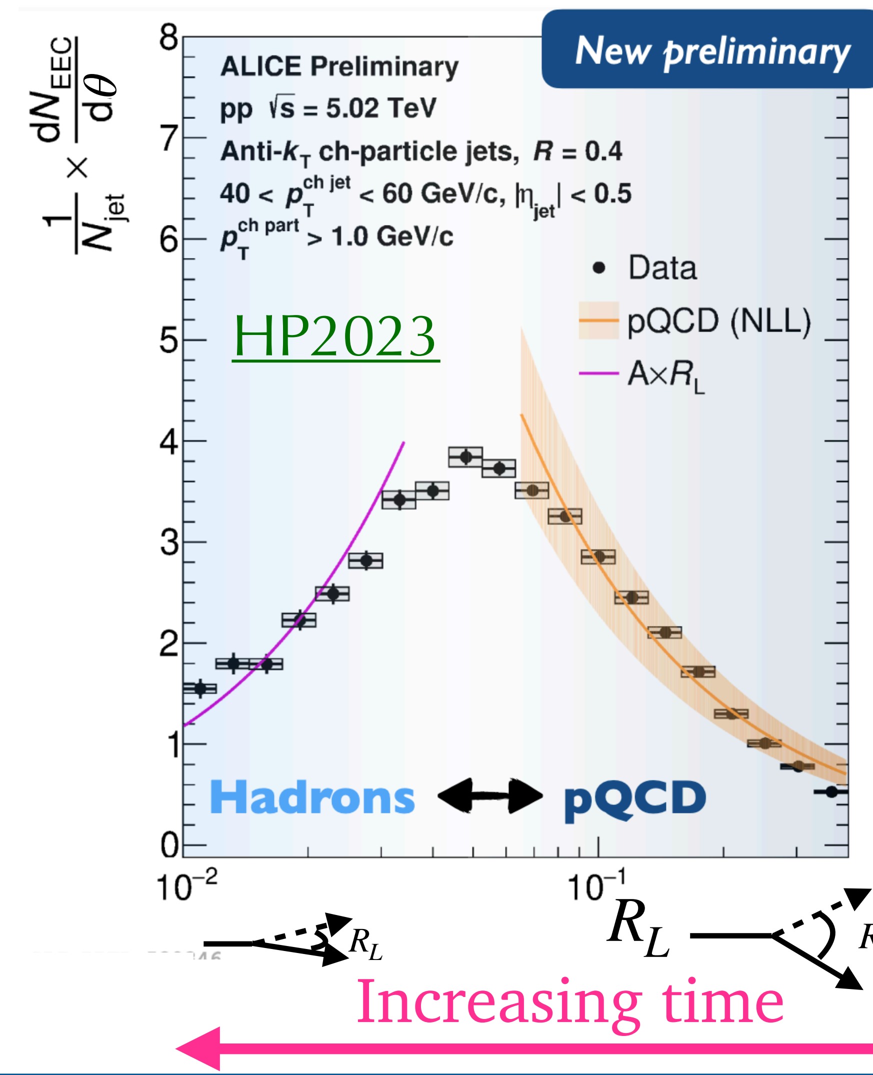
$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma}\sum_{i,j}\int dE_{i,j} \boxed{\frac{d\sigma_{ij}}{dE_i dE_j d\theta}} \frac{E_i^n E_j^n}{\boxed{Q^{2n}}}$$

Hard scale of the process

Inclusive cross section to produce two particles i and j

- **Angular scales** in the 2-point correlator **map into time scales** in the evolution of the jet:





Lee, Meçaj, Moult 2205.03414

Komiske, Moult, Thaler, Zhu 2201.07800

$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

Energy correlators in HI

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vacuum + medium-induced contribuions

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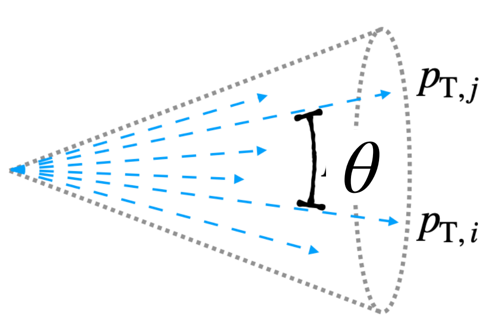

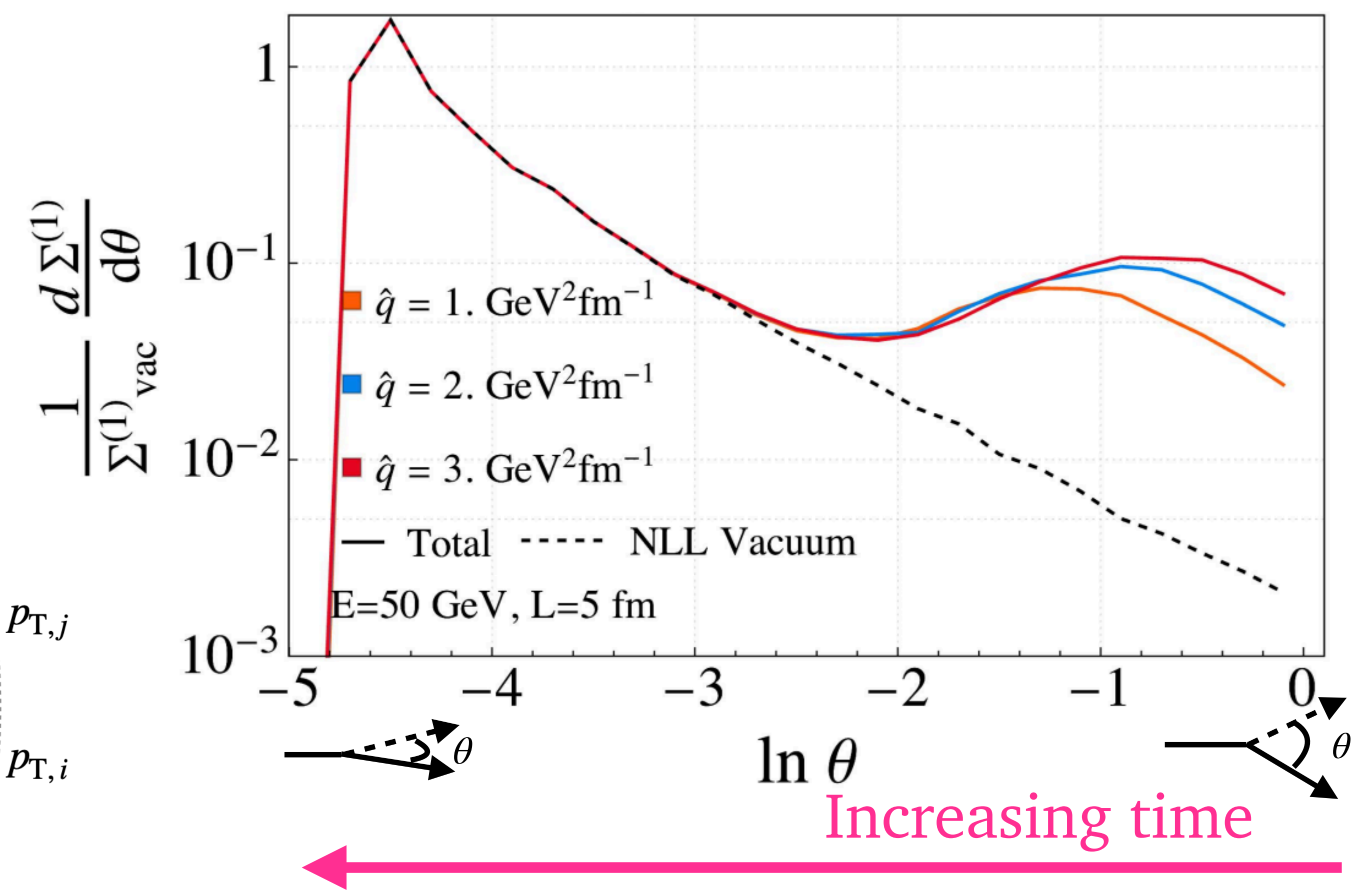

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, 2209.11236

CA, Dominguez, Holguin, Marquet, Moult, 2303.03413

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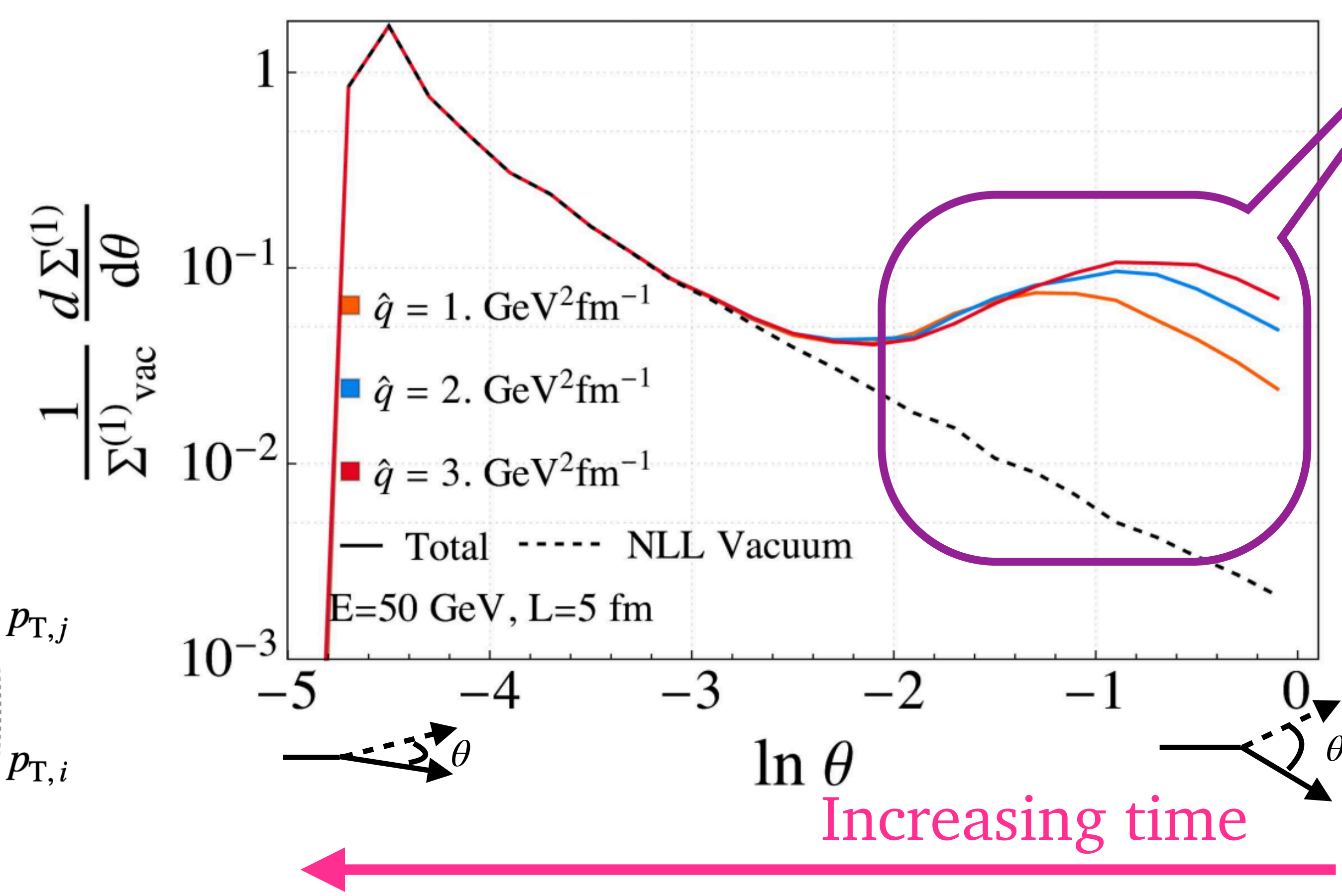
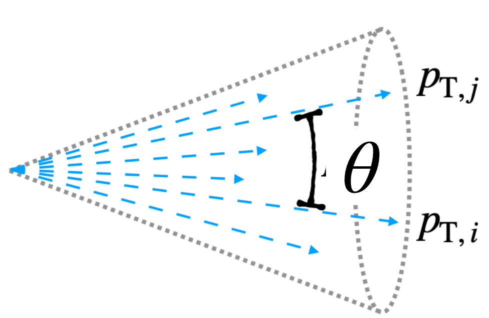
Jet quenching





CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, 2209.11236

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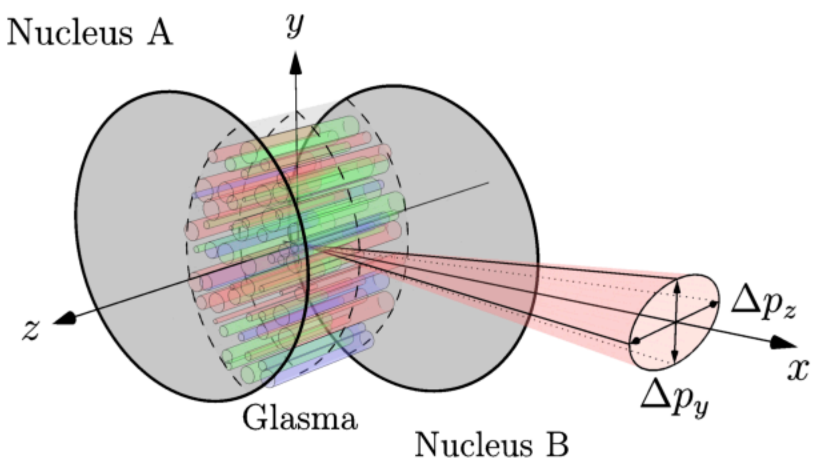
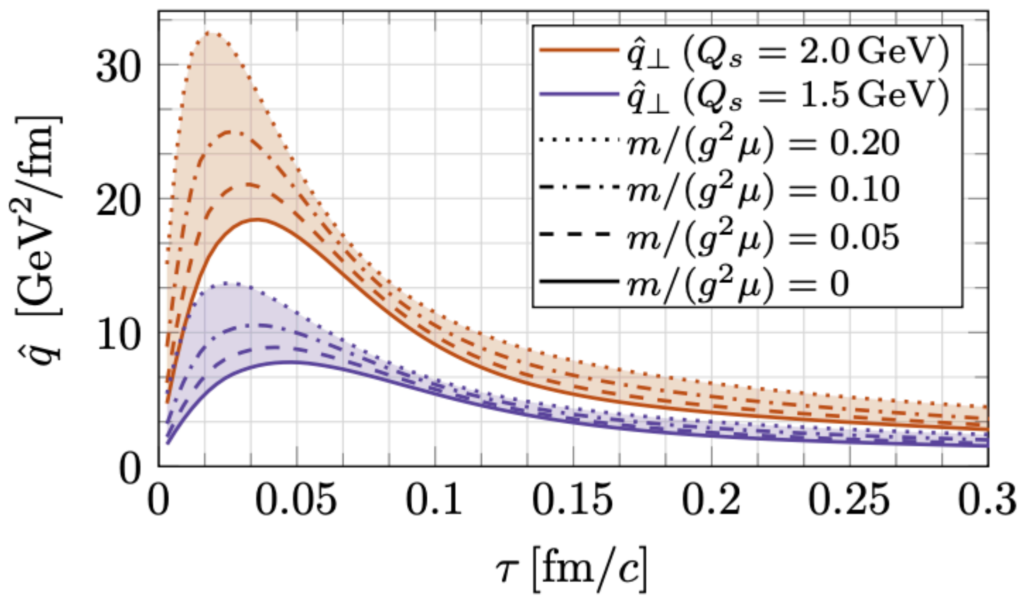
Jet broadening in the Glasma

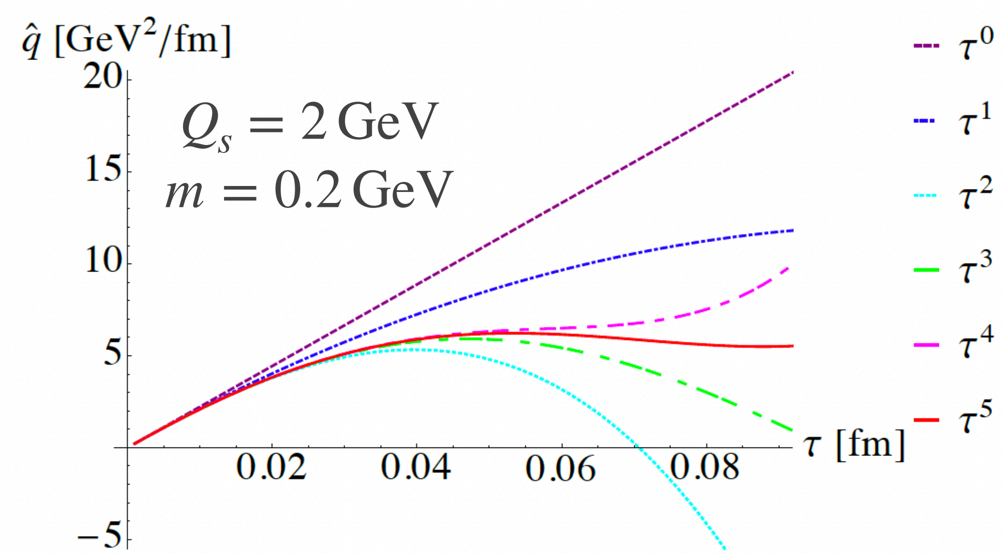
- Hard partons deflected by the chromomagnetic and chromoelectric forces in the Glasma phase



$$\hat{q} = \frac{\mathrm{d}\langle q_\perp^2 \rangle}{\mathrm{d}\tau}$$



Ipp, Müller, Schuh
2001.10001 2009.14206



Carrington, Czajka, Mrówczynski
2112.06812 2202.00357

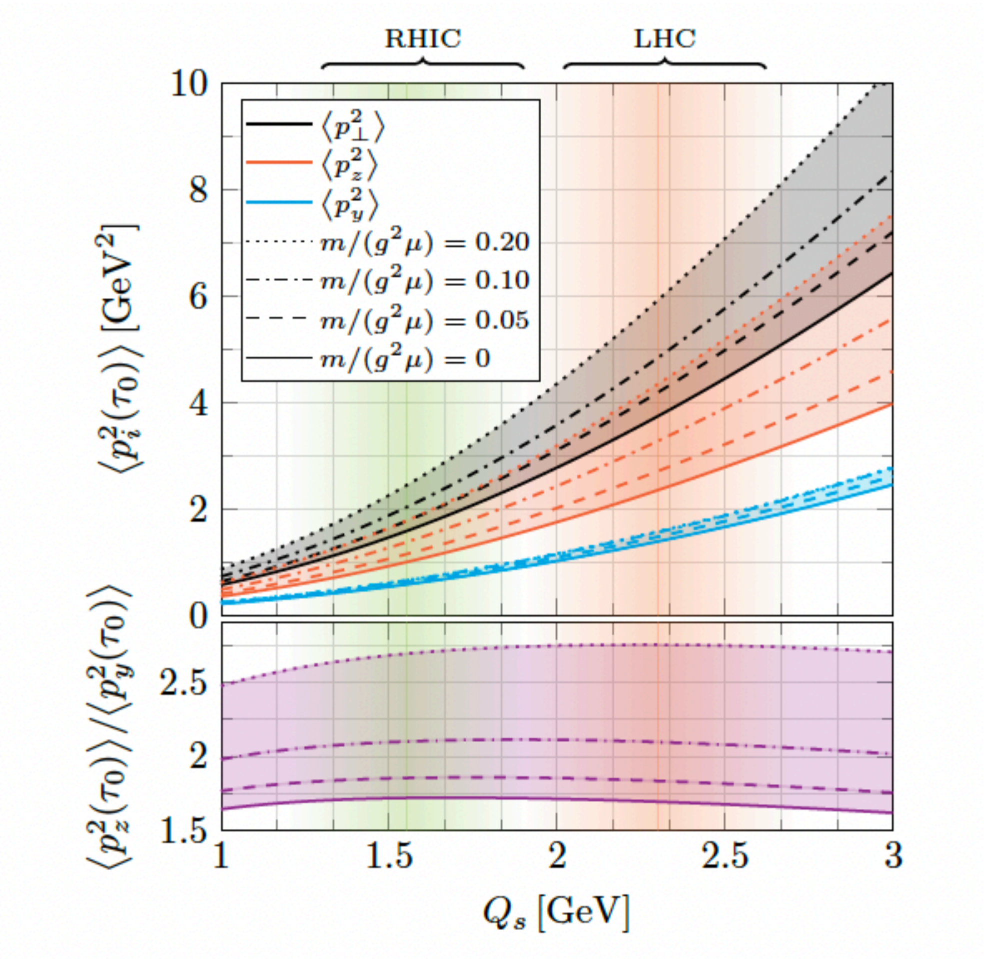
See also: Carrington, Cowie, Friesen, Mrówczynski, Pickering, 2304.03241

$\hat{q}$ relatively large!

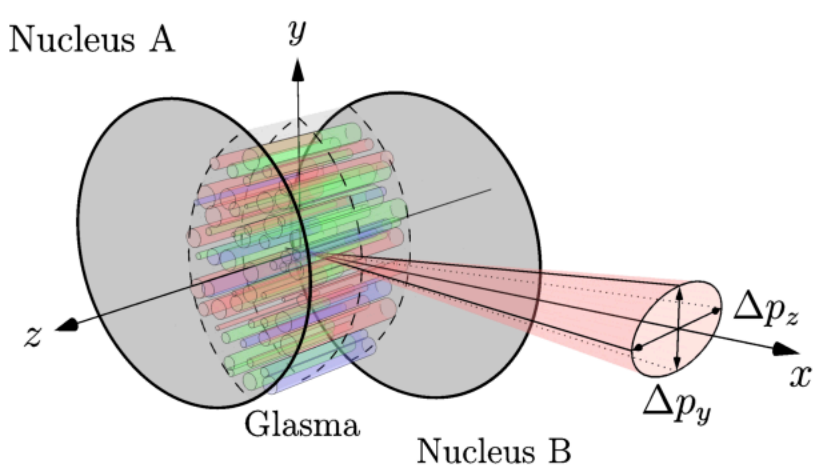
Jet broadening in the Glasma

- **Anisotropic** broadening: **larger along the beam axis** than transverse to it

Accumulated broadening at $\tau_0 = 0.6\,\mathrm{fm}$



Ipp, Müller, Schuh 2009.14206

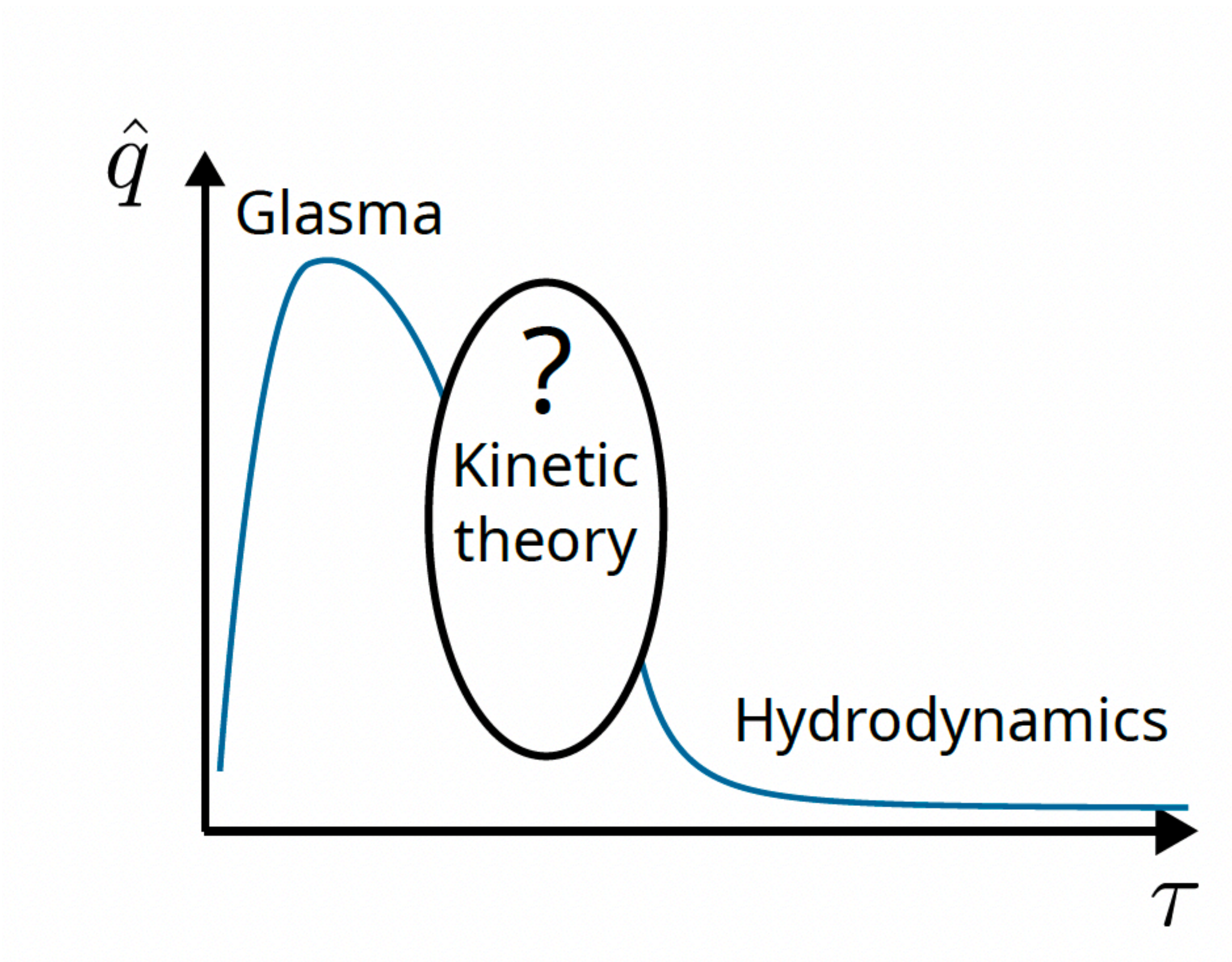


- **Anisotropic** broadening ⟶ polarized emissions

For the QGP phase:
Hauksson, Iancu 2303.03914

Jet broadening in EKT

- Between the Glasma and hydro phases within Effective Kinetic Theory:



$$\hat{q} = \frac{\mathrm{d}\langle q_\perp^2 \rangle}{\mathrm{d}\tau}$$

Lindenbauer's poster

Outcome compatible with the Glasma results

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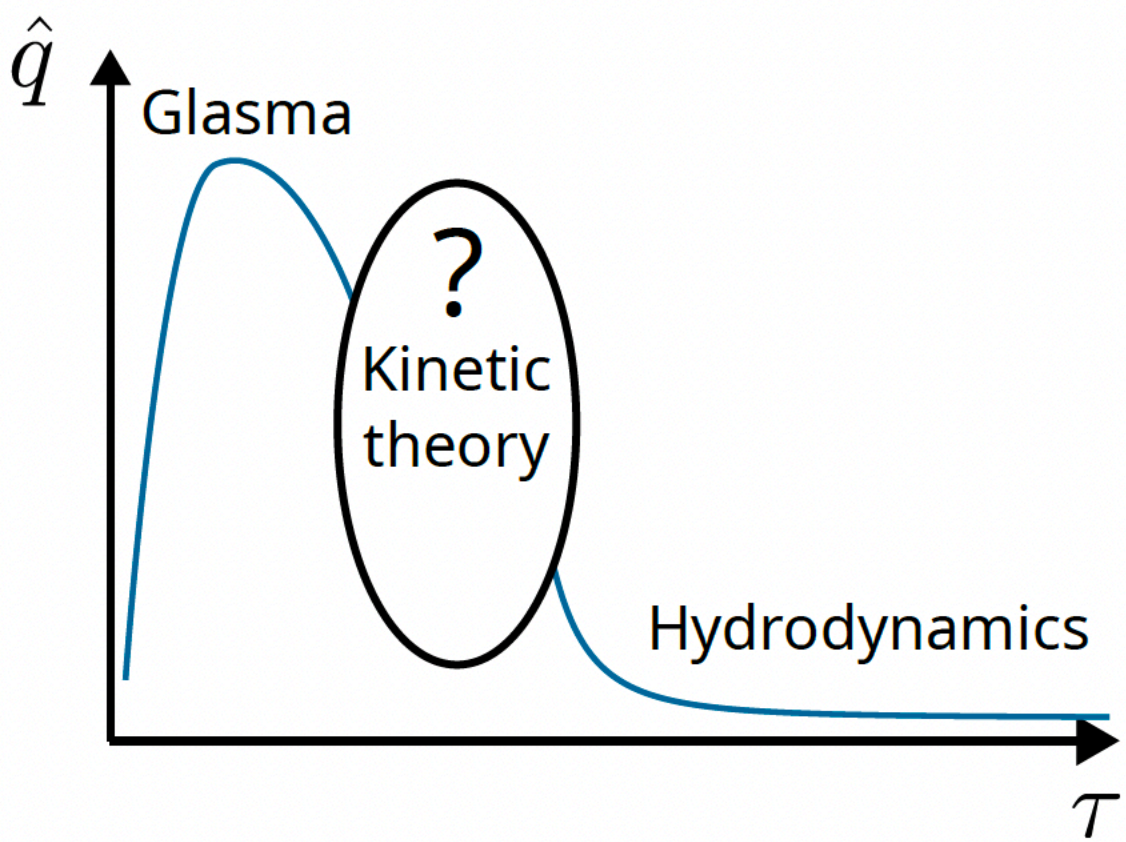
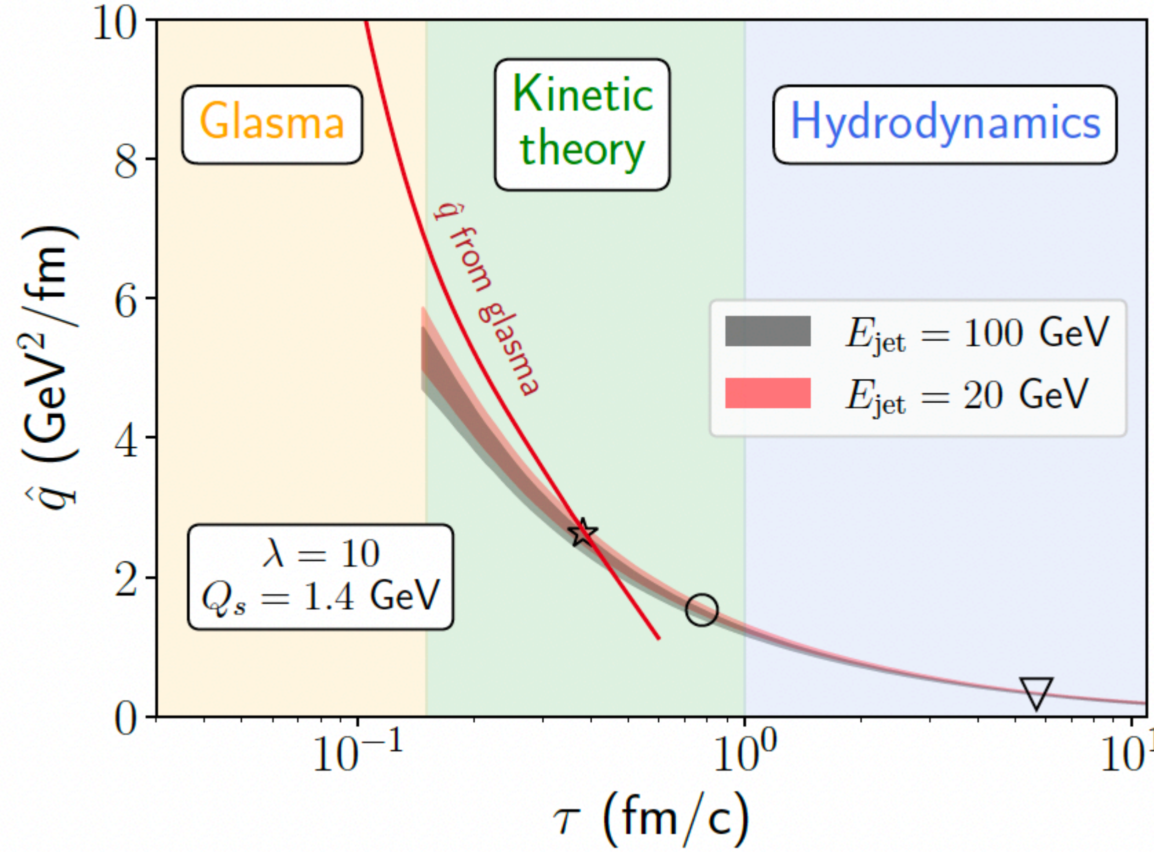


Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12595



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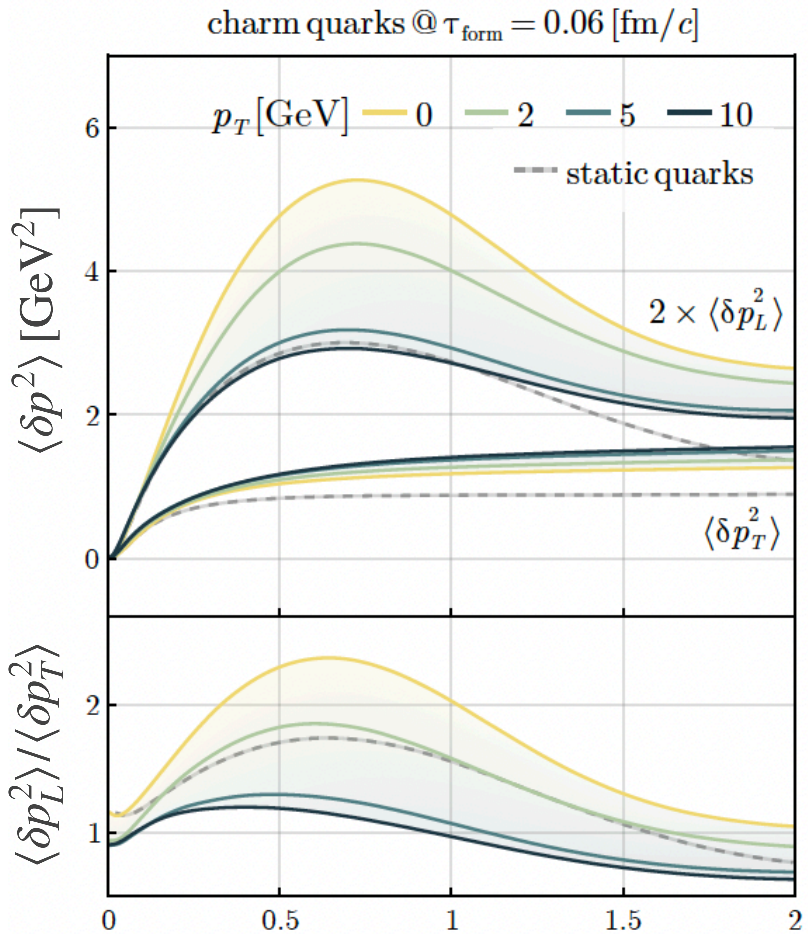
Outcome compatible with the Glasma results

Broadening of heavy quarks

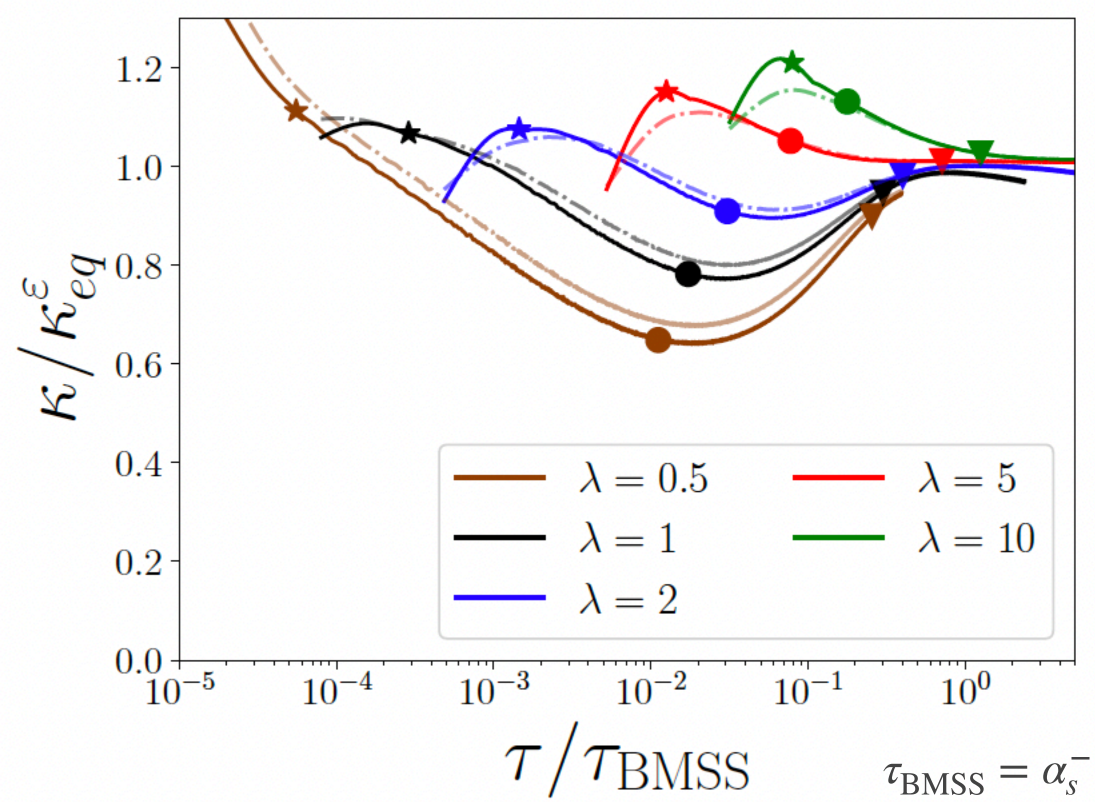
Glasma



Avramescu's poster

Avramescu, Baran, Greco, Ipp, Müller, Ruggieri, 2303.05599

EKT ($m_Q \to \infty$)



$\tau_{\rm BMSS} = \alpha_s^{-13/5} Q_s^{-1}$

Peuron's poster

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12520

Relatively large and anisotropic

See also:

Boguslavski, Kurkela, Lappi, Peuron, 2005.02418
Pooja, Santosh, Das, Oliva, Ruggieri, 2110.14610

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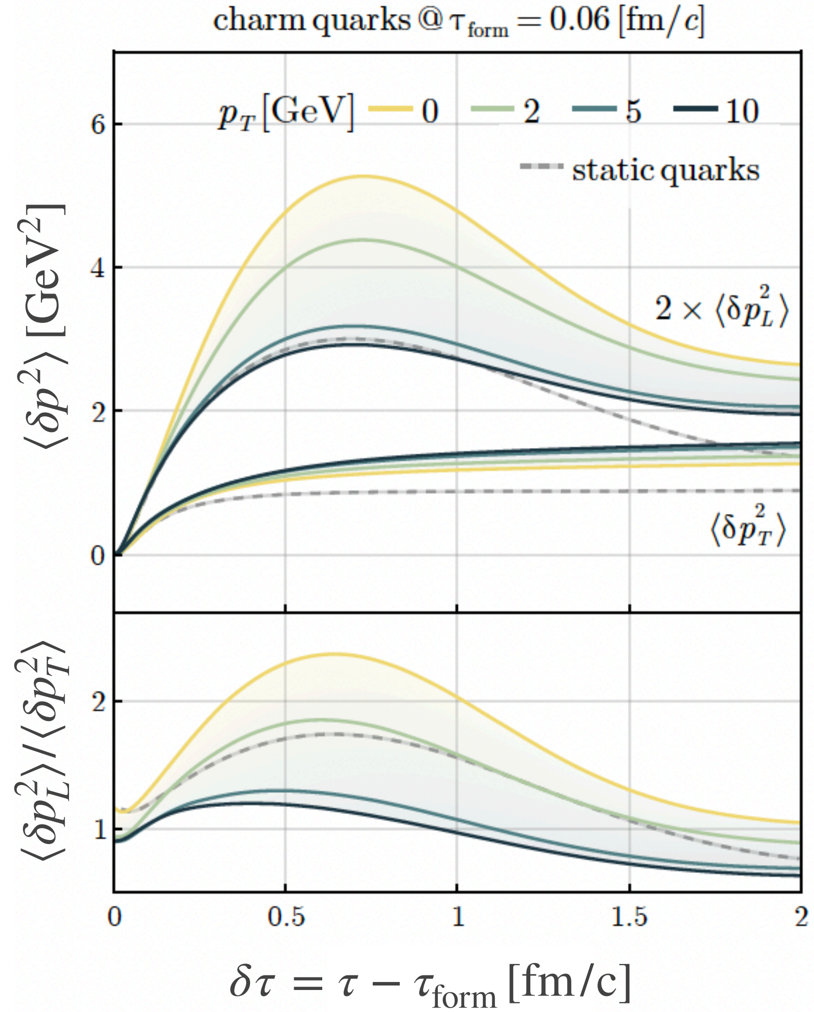

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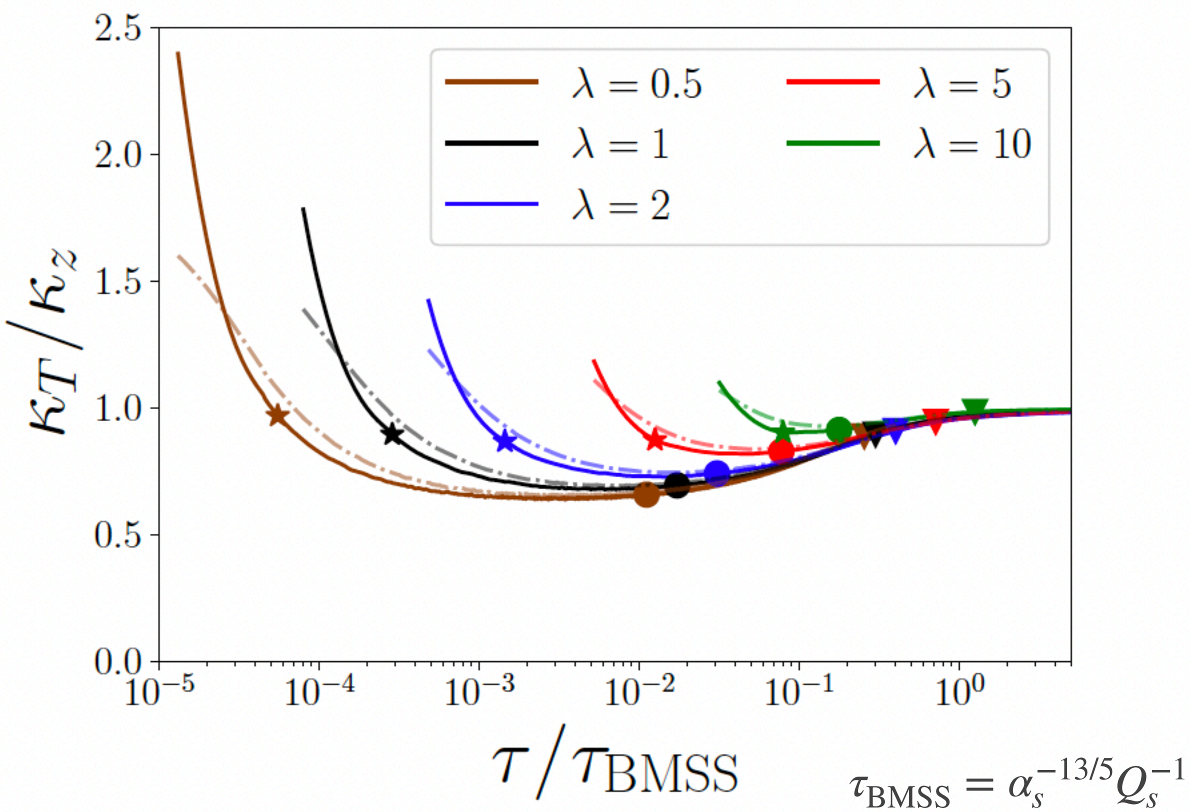

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Conclusions and outlook

- **Jet quenching** analyses **usually neglect** the **initial stages**

- Pre-hydrodynamization stages seem to have an **important impact in some observables**: charged hadron R_{AA} and high-p_T harmonics

  - More observables?

    - Jets are multiscale objects. **Can we use jet substructure**?

- Theory calculations of **broadening in the pre-hydrodynamics phases**

  - **Impact** on jet quenching **phenomenology**?

New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions

February 12-16, 2024, Trento

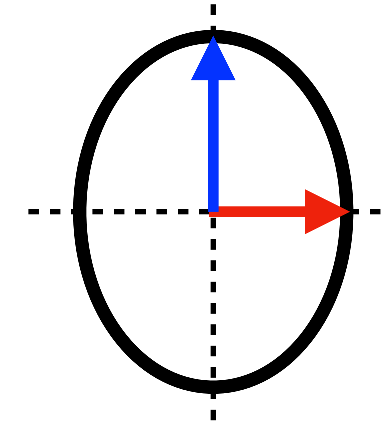
Organizers: CA, João Barata, Andrey Sadofyev, Carlos A. Salgado

FONDAZIONE BRUNO KESSLER

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Thank you!

R_{AA} and high-p_T v_2

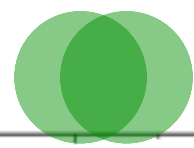


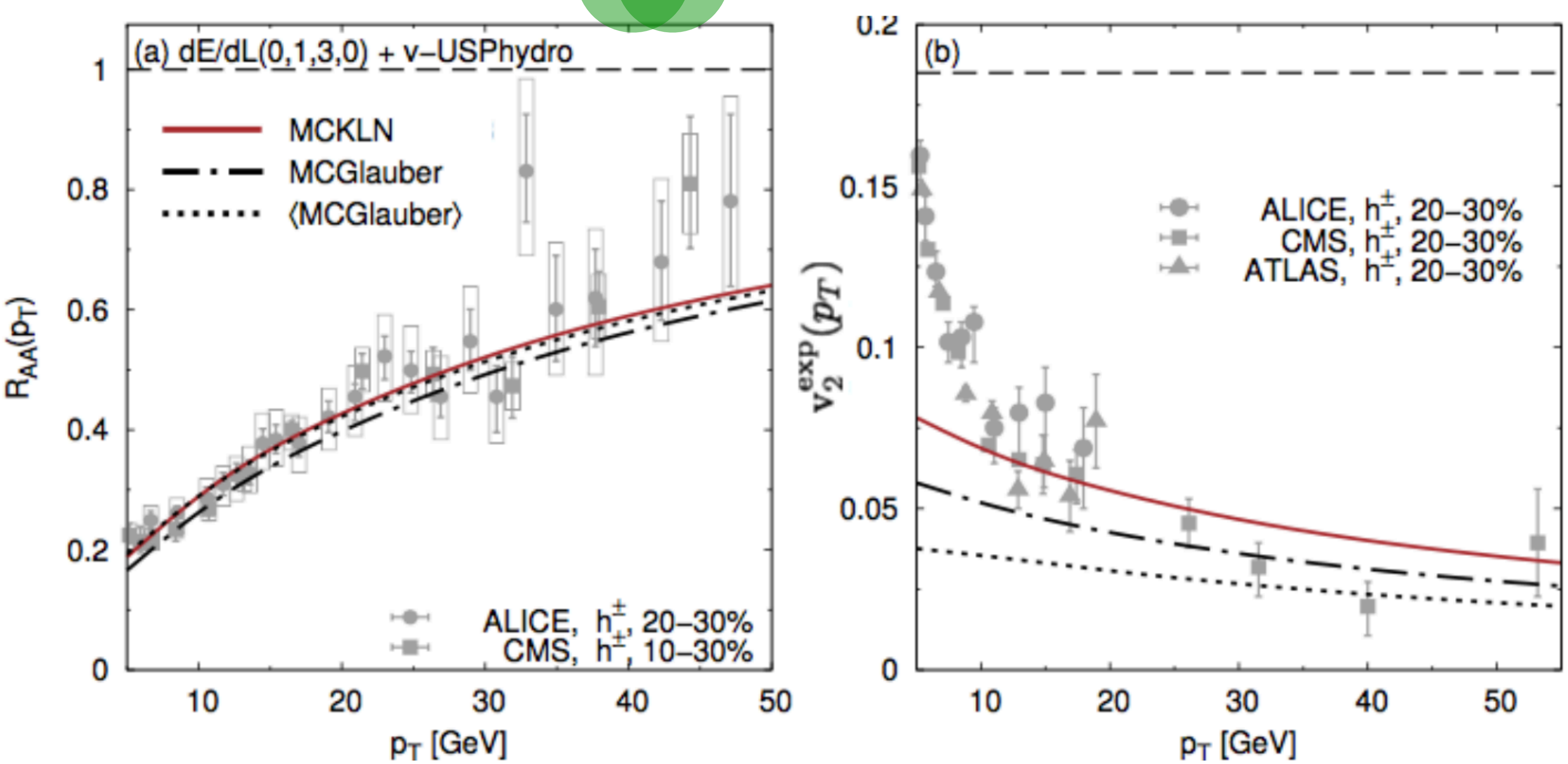
- Inclusive **hadron suppression well reproduced** by energy loss calculations
- Traditionally: **difficulties** to describe also the **high-p_T harmonics**

Renk, Holopainen, Heinz, Shen, 1010.1635 Betz and Gyulassy 1404.6378 Xu, Buzzati, Gyulassy, 1402.2956

- Scalar product (EbyE fluctuations from the low p_T sector):

PbPb 2.76 TeV

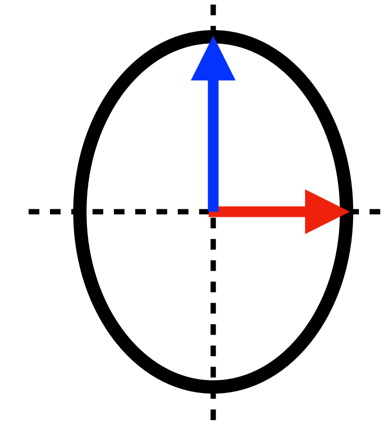




$$\frac{dE}{dL} \sim LT^3$$

Noronha-Hostler, Betz, Noronha, Gyulassy, 1602.03788

R_{AA} and high-p_T v_2



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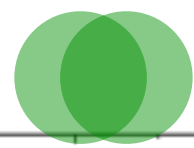
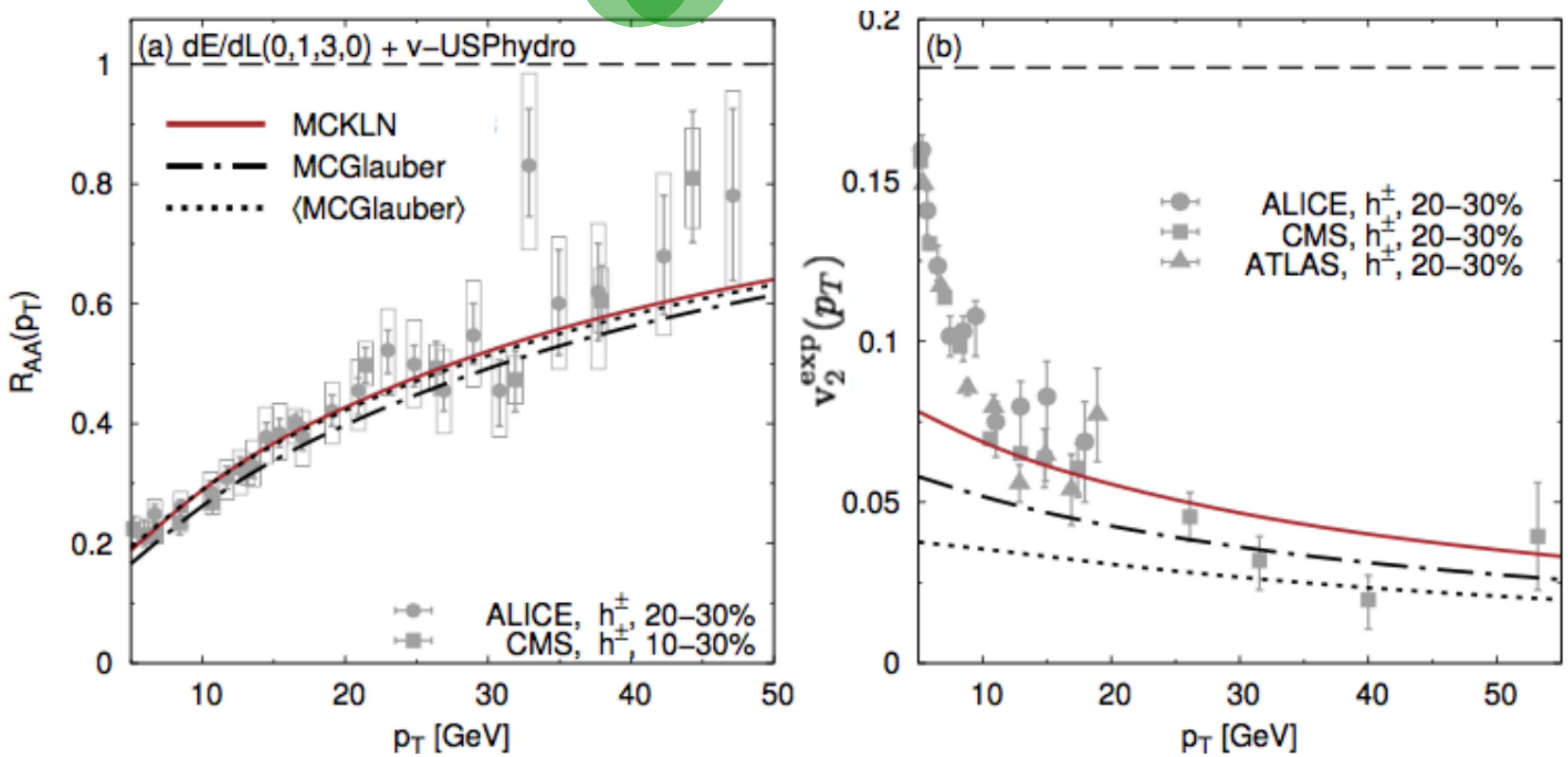




$$\frac{dE}{dL} \sim LT^3$$

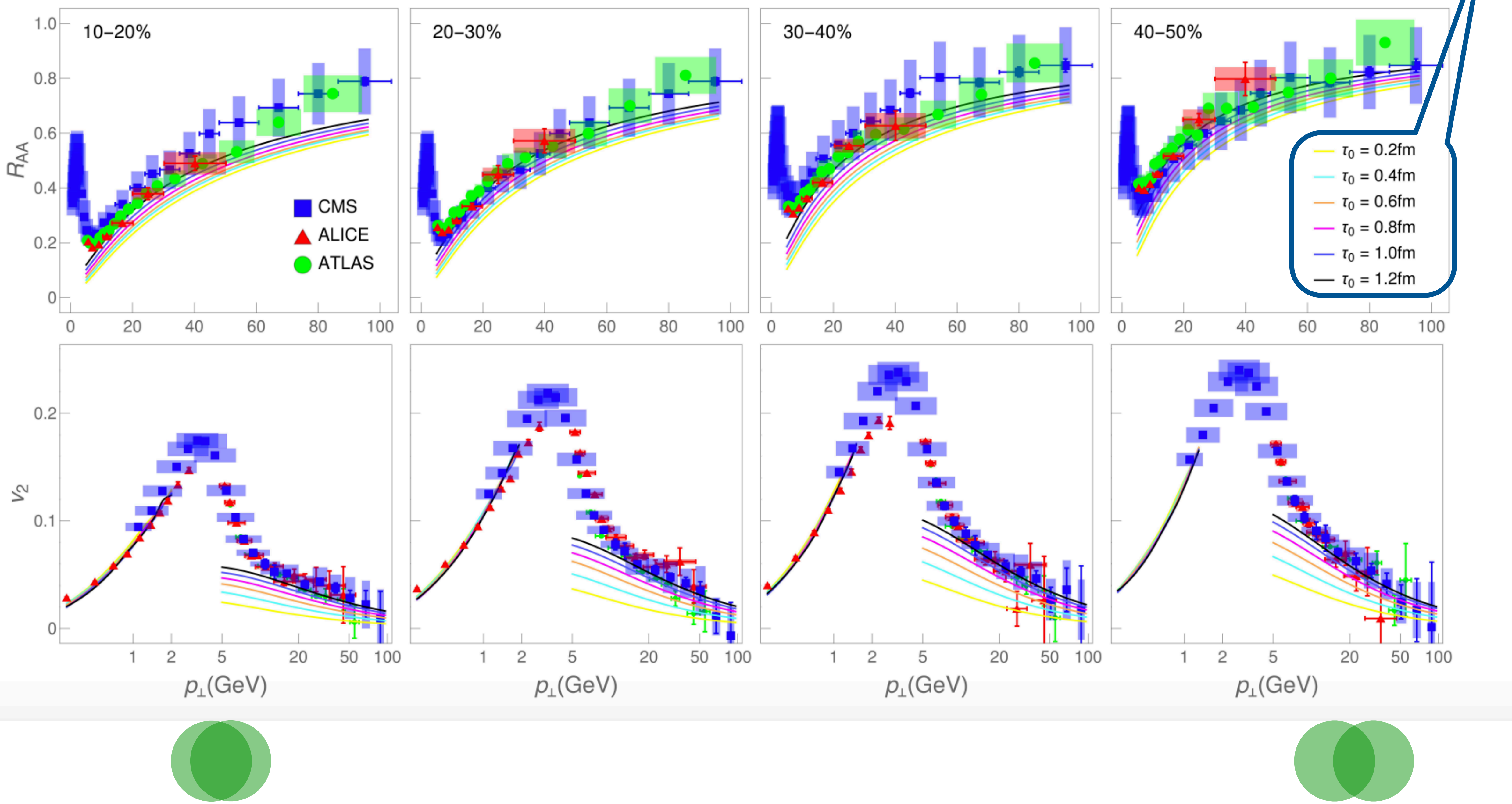
NO energy loss
before $\tau_{\text{hydro}} = 0.6$ fm

Noronha-Hostler, Betz, Noronha, Gyulassy, 1602.03788

R_{AA} and high-p_T v_2

- Also for DGLV (single scattering)!

Initial time of the hydro and of the quenching



Stojku, Auvinen, Djordjevic, Huovinen, Djordjevic arXiv:2008.08987