Impact of pre-equilibrium physics on jet quenching

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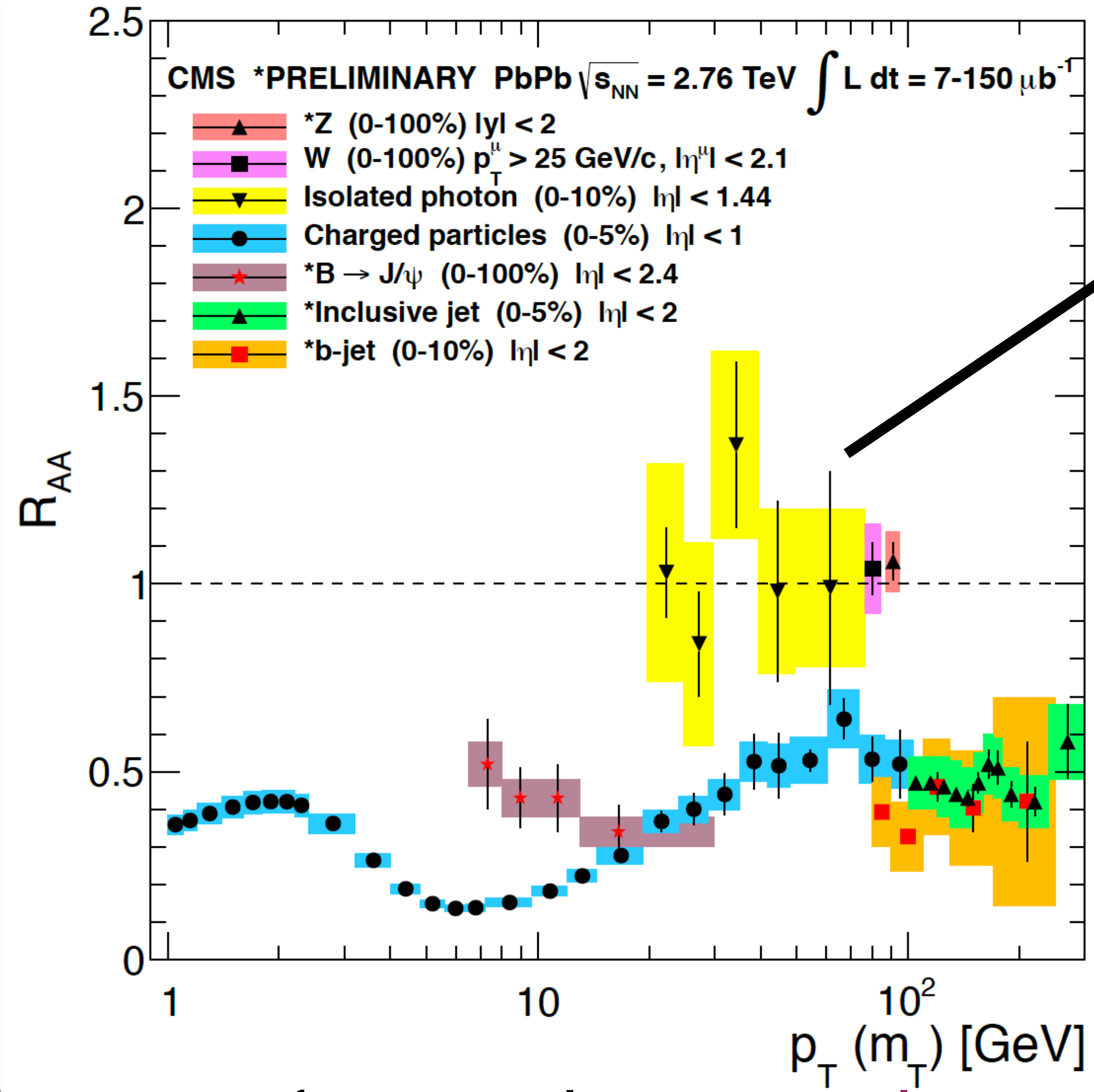
From initial gluons to hydrodynamics

Jet quenching

- Jet quenching: high-energy partons interact with the QGP losing energy

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}^2p_T\,\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle\,\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}^2p_T\,dy}$$

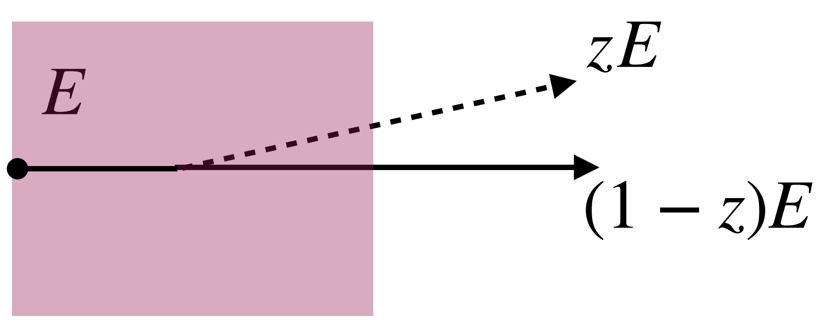


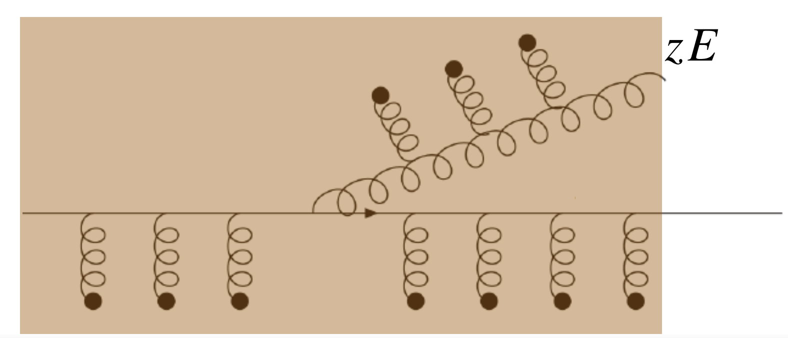
[A. Florent - Hard Probes 2013]

Colorless probes: no suppression

Jet quenching

- The principal mechanism of energy loss is medium-induced radiation



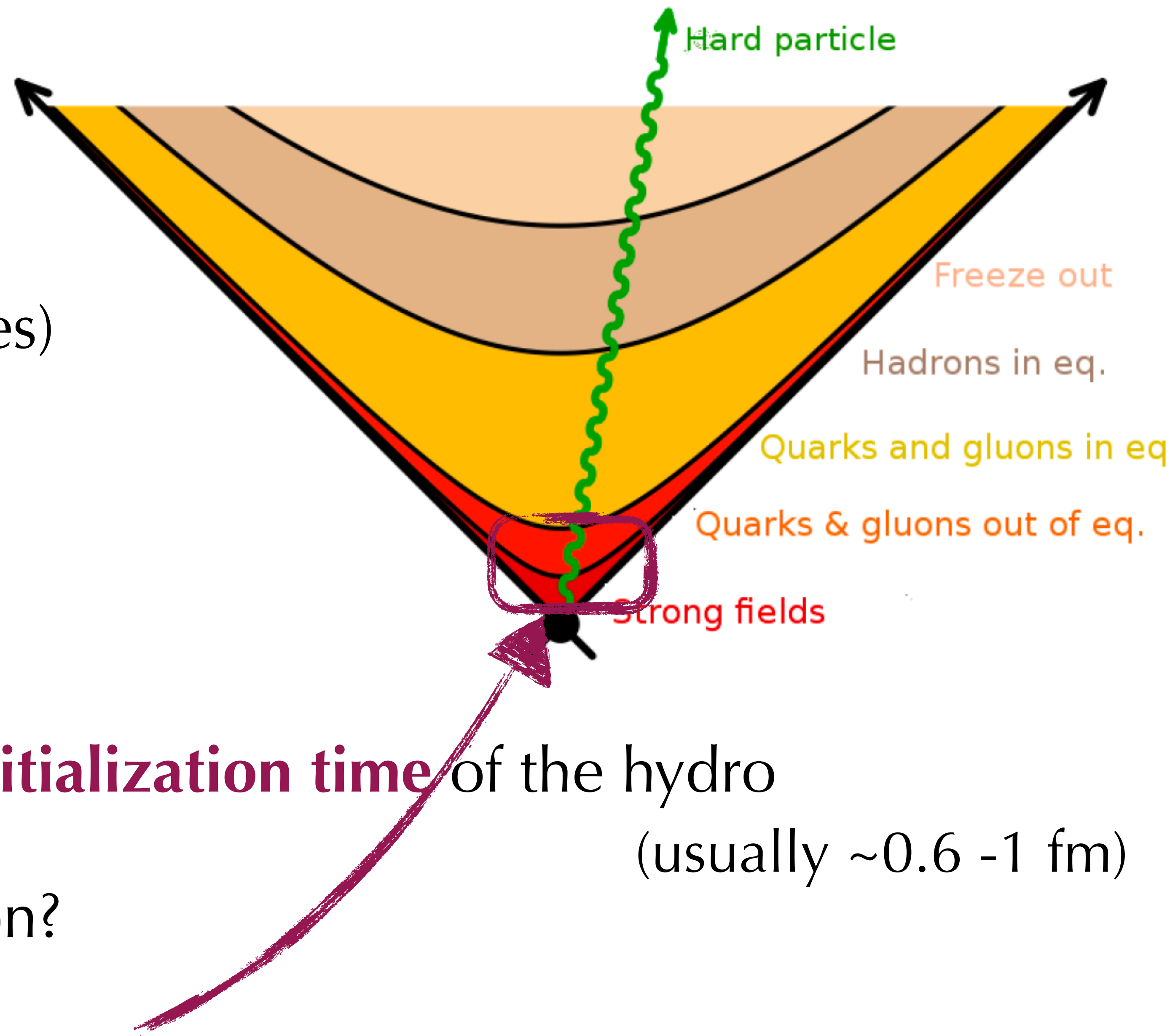


Jets in A-A

- Hard probes/jets are produced in the initial hard scattering

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

- Mainly used to study **jet quenching**



- The **quenching set to start at the initialization time** of the hydro (usually ~0.6 -1 fm)

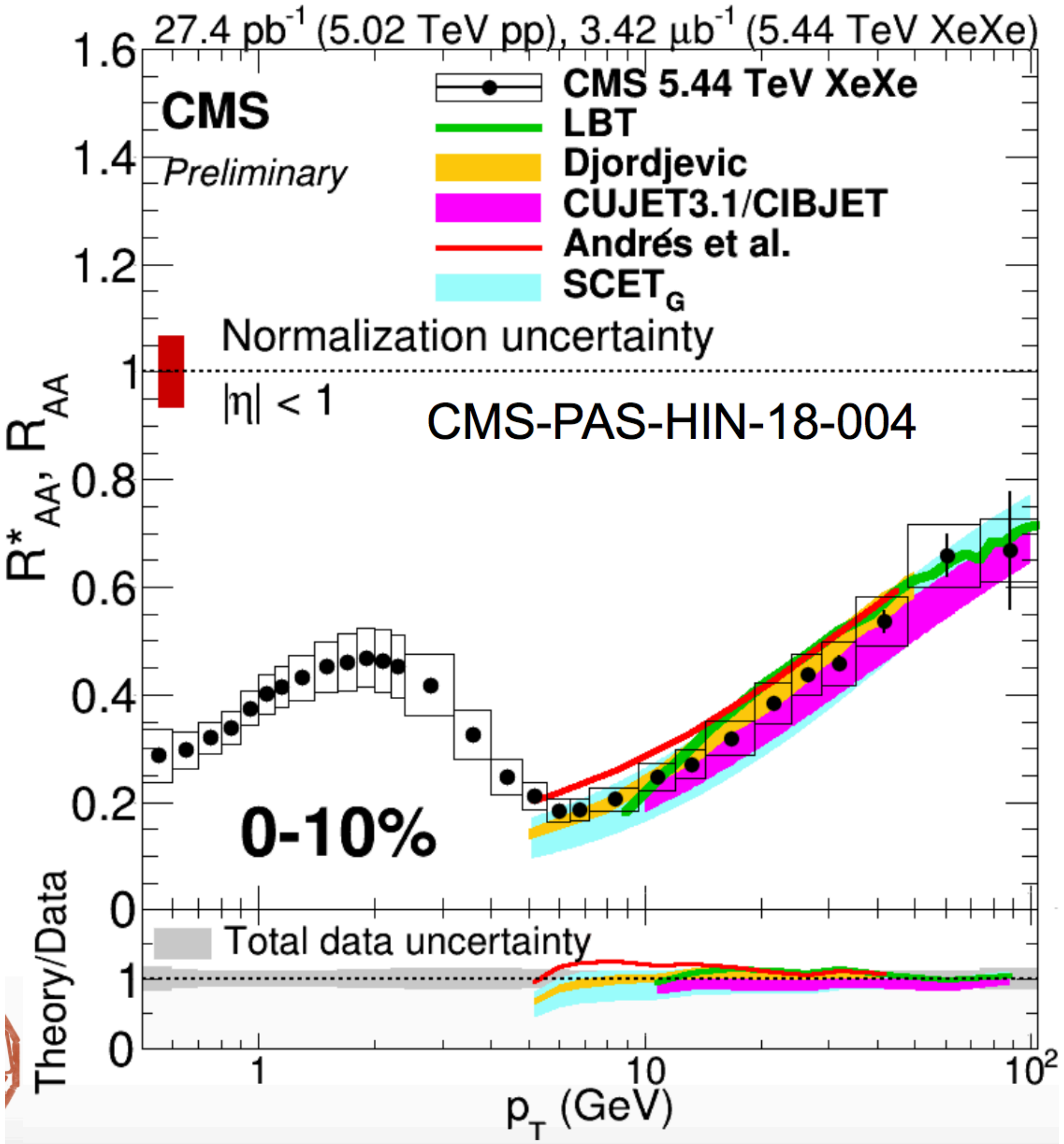
  No energy loss before thermalization?

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

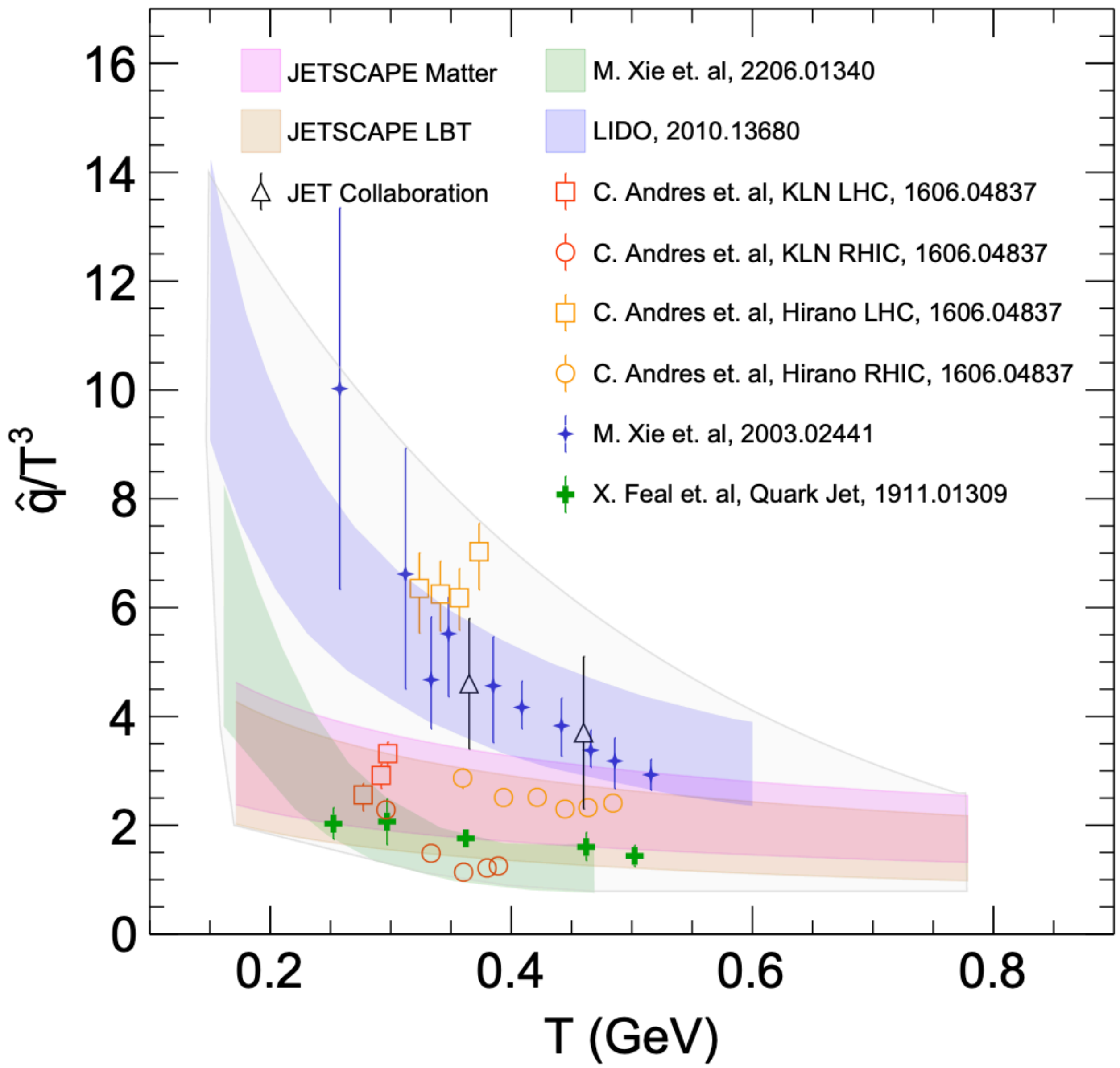
  Crucial to understand the apparent lack of energy loss in small systems

Jet quenching parameter

- Jet quenching: extract properties of the QGP
- $\hat{q}$: average transverse momentum transfer per unit length

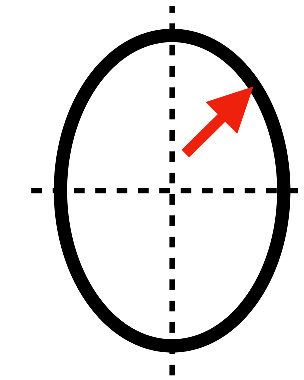


Austin Baty, QM2018



Apolinario, Lee, Winn, arXiv: 2203.16352

Formalism



- Single-inclusive cross section:

$$\frac{d\sigma^{AA\to h+X}}{dp_T dy} = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{dz}{z}\sum_{i,j,k} x_1 f_{i/A}(x_1,Q^2)\, x_2 f_{j/A}(x_2,Q^2)\frac{d\hat{\sigma}^{ij\to k}}{d\hat{t}} D^{(med)}_{k\to h}(z,\mu_F^2)$$

nPDFs

- Fragmentation functions:

$$D^{(med)}_{k\to h}(z,\mu_F^2) = \int_0^1 d\epsilon P_E(\epsilon)\frac{1}{1-\epsilon}D^{(vac)}_{k\to h}\left(\frac{z}{1-\epsilon},\mu_F^2\right)$$

FFs

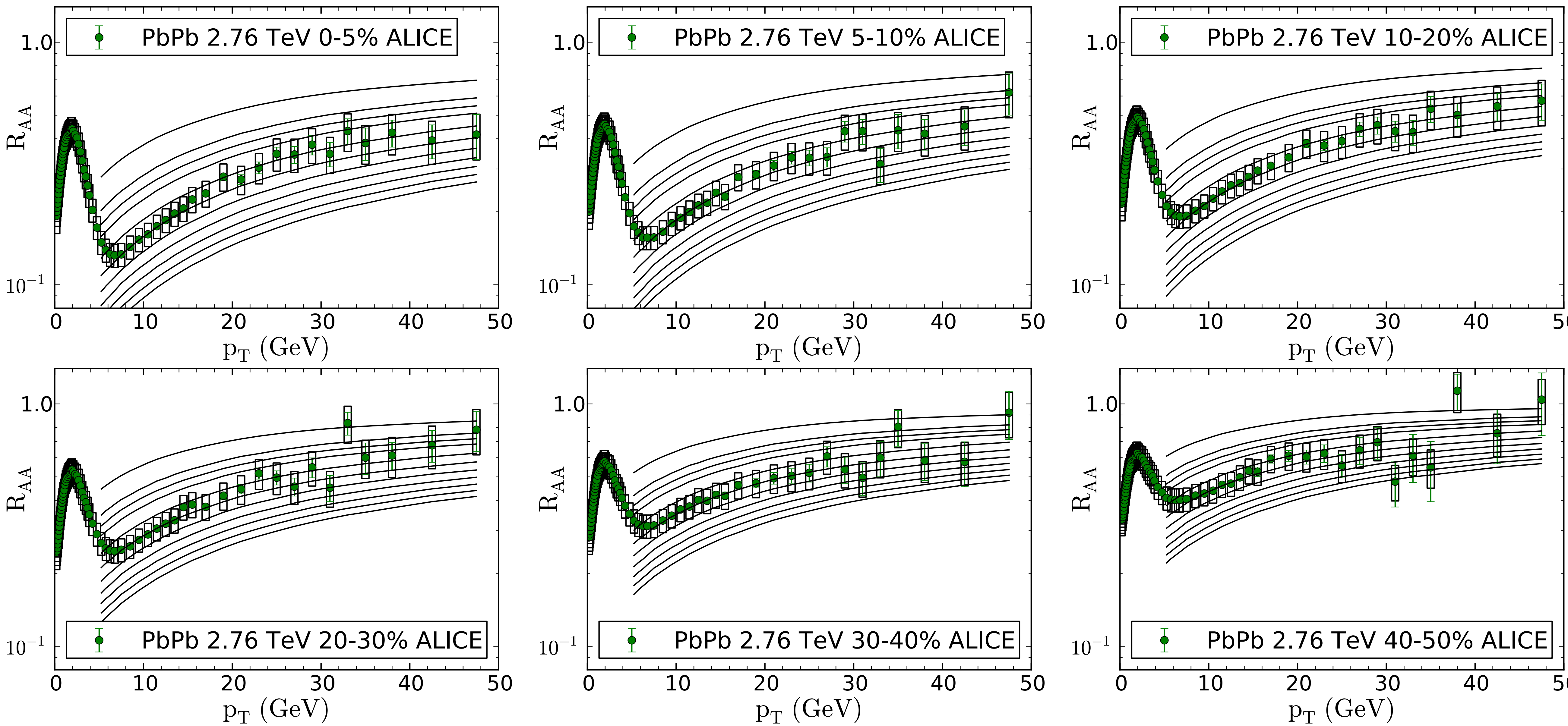
Local medium energy density

ENERGY LOSS: Quenching Weights (QWs)

$$\hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi)$$

Probability distribution of a fractional energy loss $\epsilon = \Delta E/E$ of the hard parton in the medium

R_{AA} at 2.76 TeV



Formalism

- Energy density taken from the hydro

  Viscous 2+1 hydrodynamics

  $\eta/s = 0.16$

  $\tau_{\text{hydro}} = 1$ fm

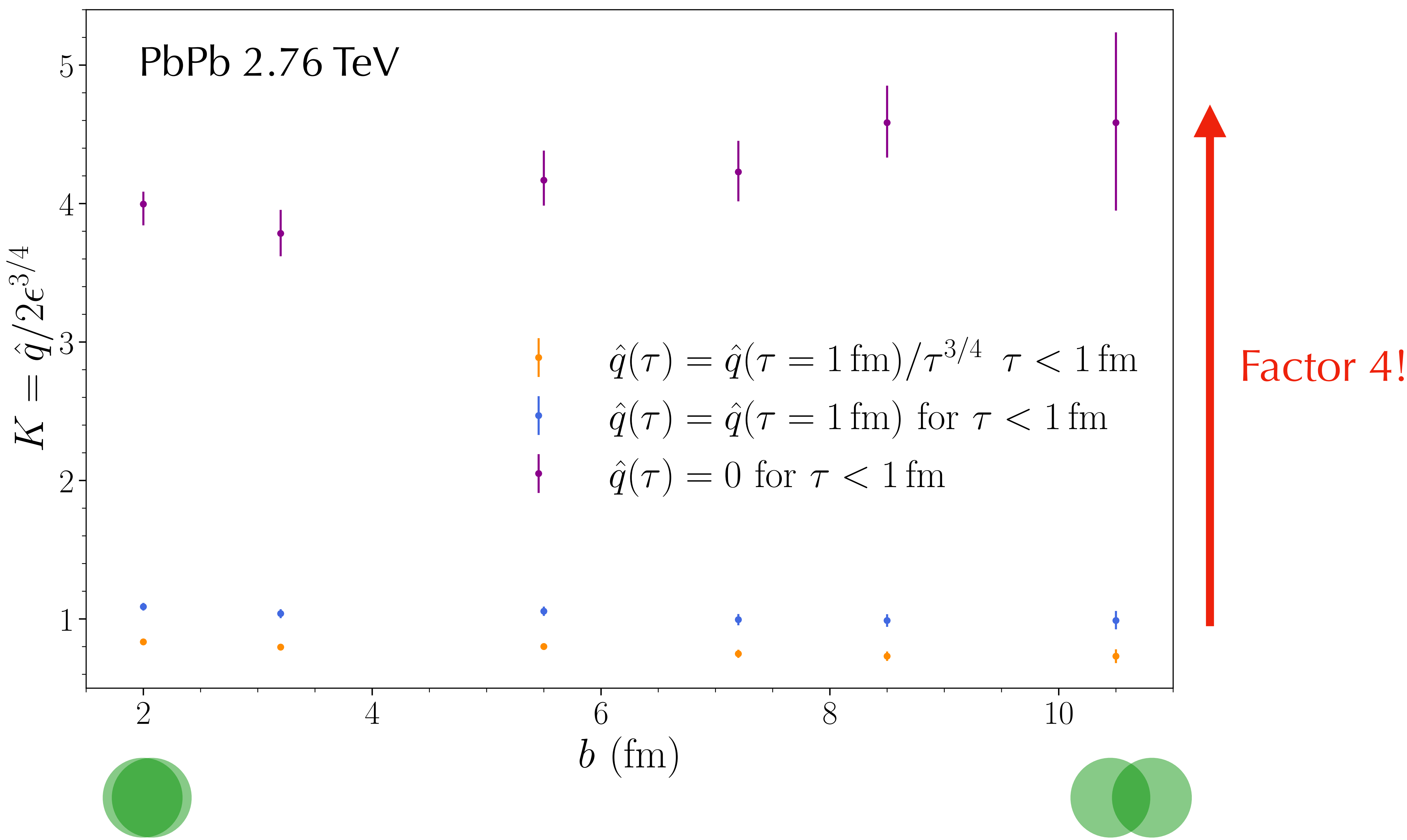
  Luzum and Romatsche arXiv:0804.4015 arXiv:0901.4588

  fKLN model for the initial condition

- Before τ_{hydro} ?

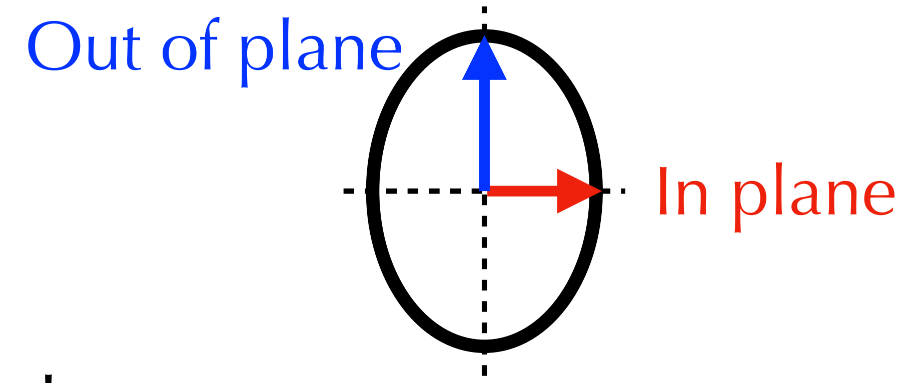
  - $\hat{q}(\tau) = \hat{q}(\tau_{\text{hydro}})/\tau^{3/4}$ for $\tau < \tau_{\text{hydro}}$
  - $\hat{q}(\tau) = \hat{q}(\tau_{\text{hydro}})$ for $\tau < \tau_{\text{hydro}}$
  - $\hat{q}(\tau) = 0$ for $\tau < \tau_{\text{hydro}}$ → Energy loss delayed 1 fm

Jet quenching parameter



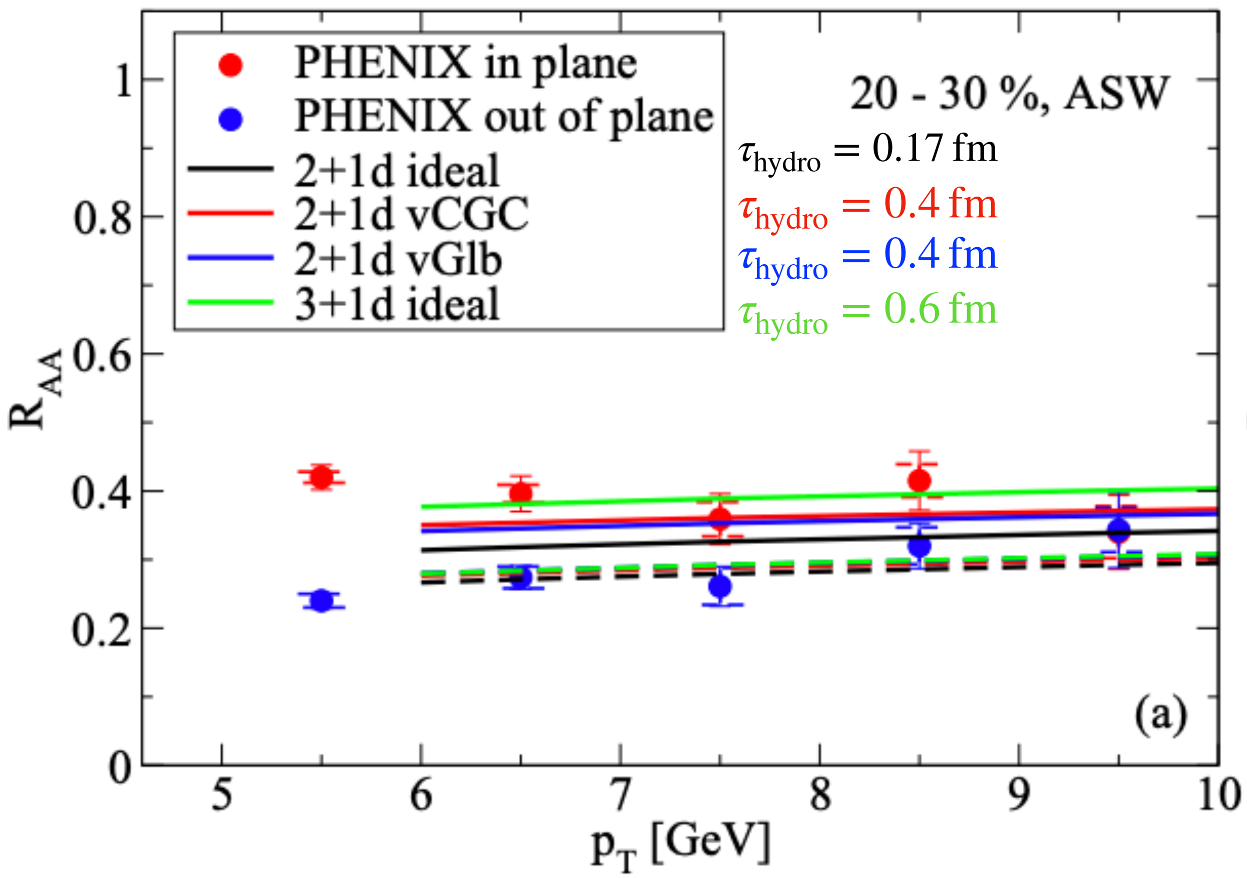
R_{AA} and high-p_T v_2

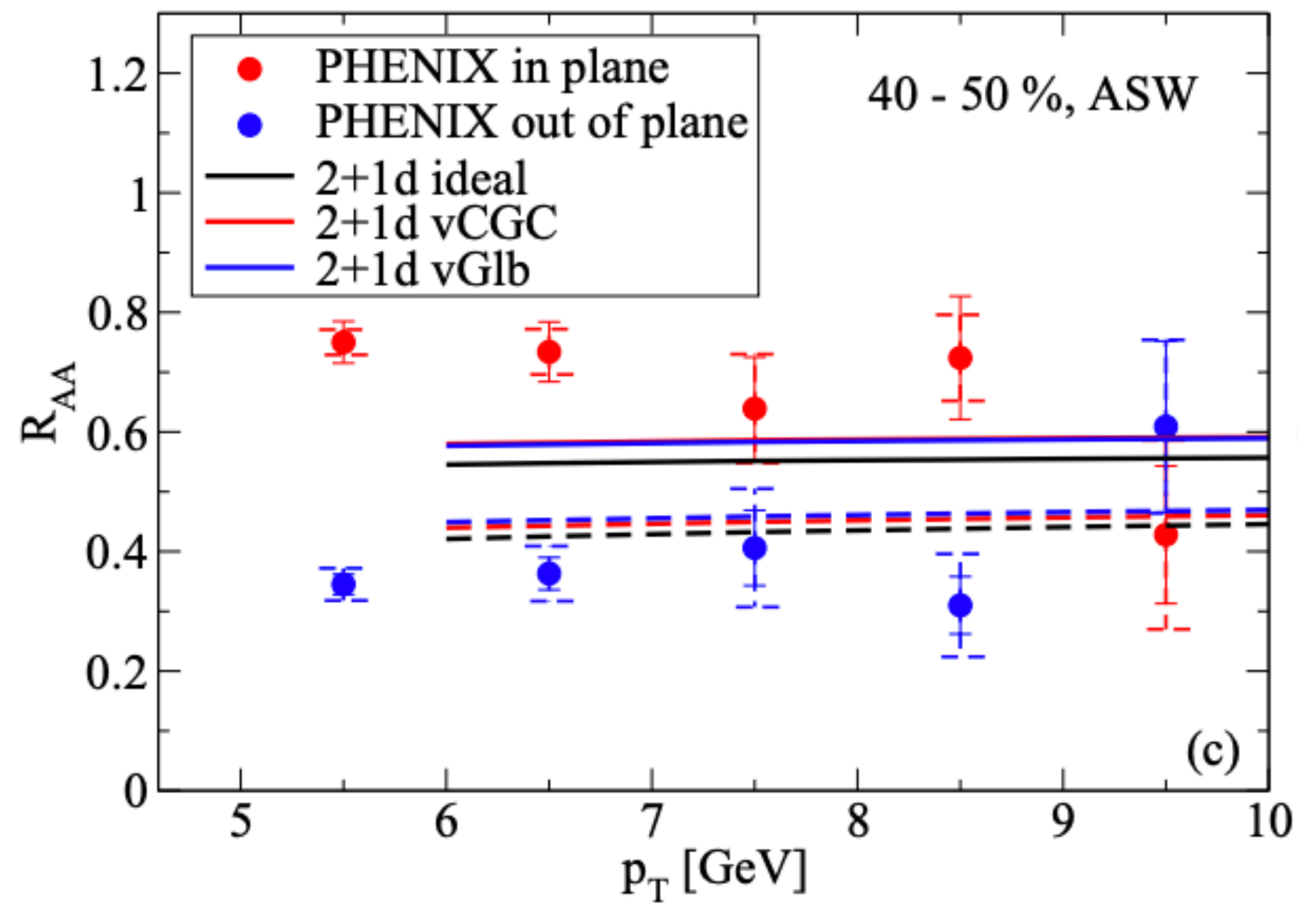
High-p_T v_2

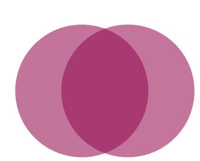


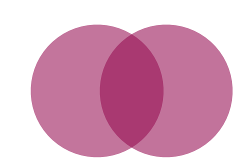
QWs + smooth averaged hydros

AuAu 200 GeV









NO energy loss before τ_{hydro}

T. Renk et al. arXiv:1010.1635

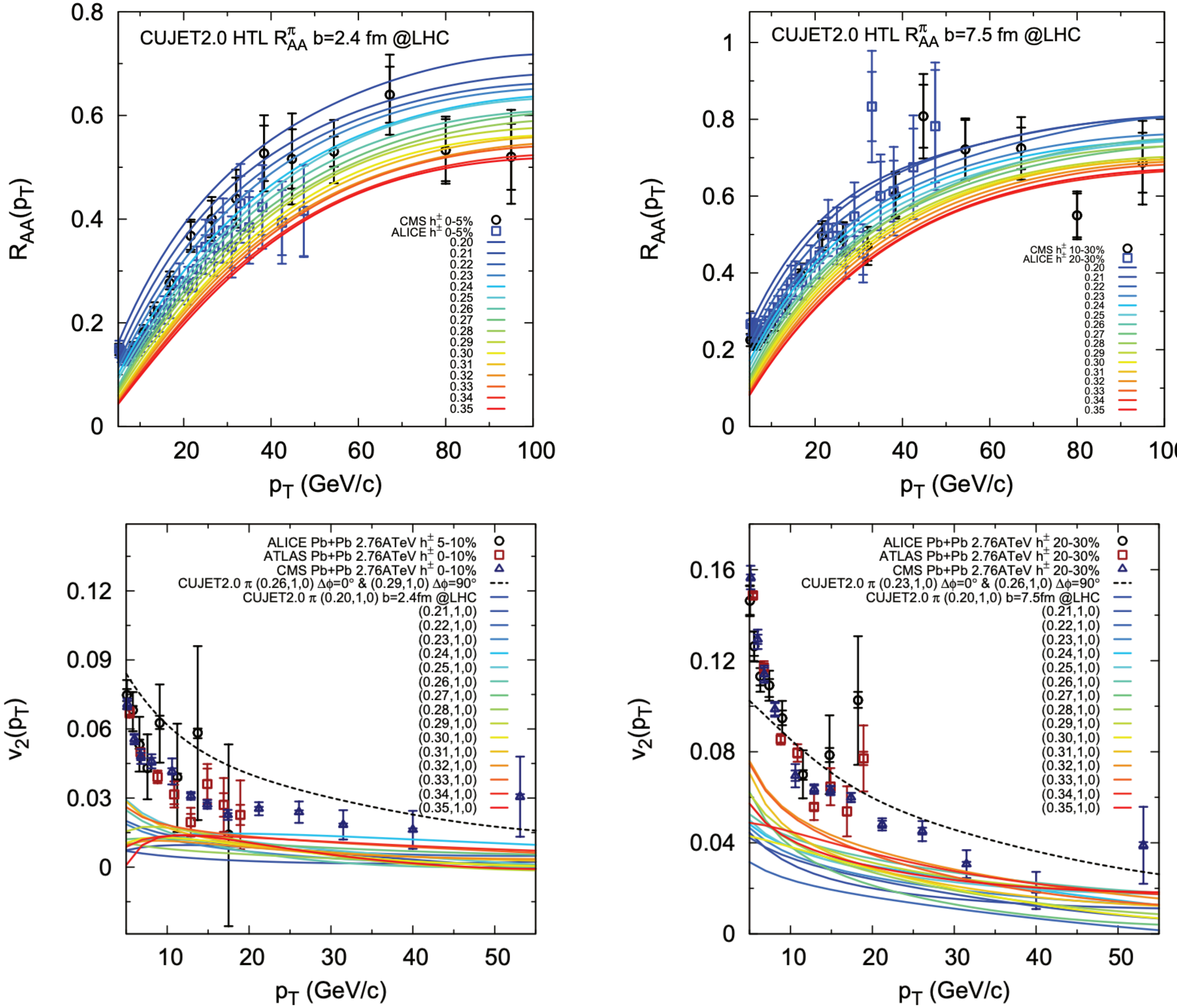
R_{AA} and high-p_T v_2

PbPb 2.76 TeV

DGLV + running coupling
+ viscous hydro $\tau_{hydro} = 0.6$ fm

NO energy loss before τ_{hydro}

Imposible to describe simultaneously R_{AA} and high-p_T v_2



Xu, Buzzati, Gyulassy
arXiv:1402.2956

The scalar product

$$\frac{R_{AA}(p_T,\phi)}{R_{AA}(p_T)} = 1 + 2\sum_{n=1}^{\infty} v_n^{hard}(p_T)\cos\left[n\phi - n\psi_n^{hard}(p_T)\right]$$

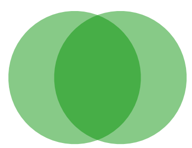
Average over all the events

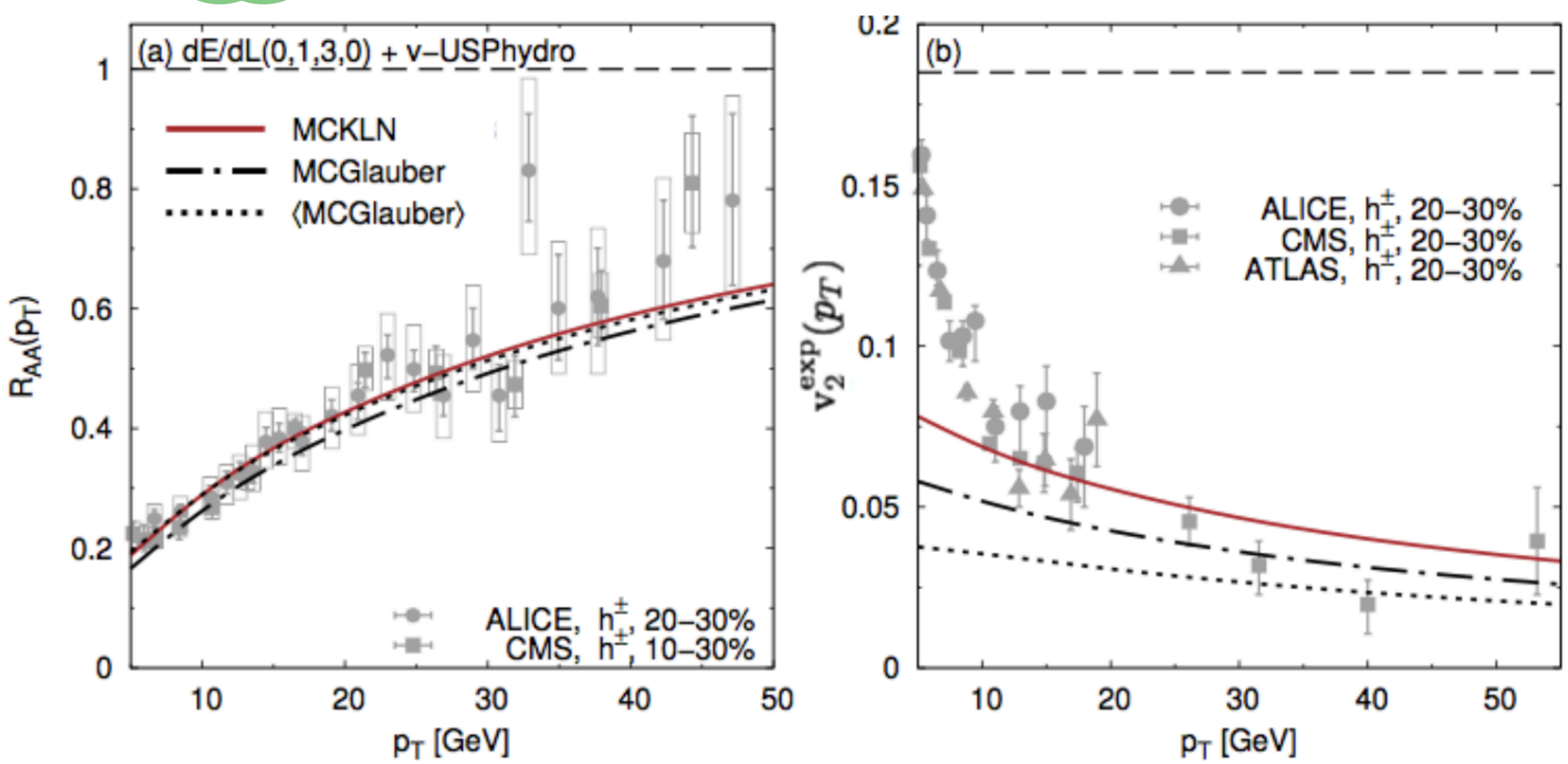
$$v_n^{exp}(p_T) = \frac{\left\langle v_n^{soft}\, v_n^{hard}(p_T)\cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right)\right]\right\rangle}{\sqrt{\left\langle\left(v_n^{soft}\right)^2\right\rangle}}$$

Matthew Luzum and Jean-Yves Ollitrault, arXiv:1209.2323

Noronha-Hostler et al., arXiv: 1602.03788

PbPb 2.76 TeV





Hydro: v-USPhydro

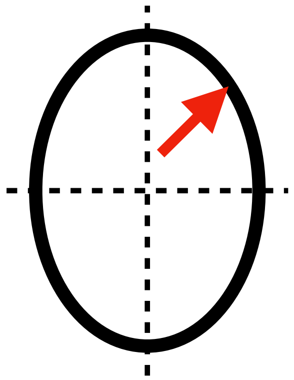
$\tau_{\rm hydro} = 0.6\,{\rm fm}$

Energy loss

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

NO energy loss before $\tau_{\rm hydro}$

Proof of concept



CA, Armesto, Niemi, Paatelainen, Salgado
arXiv: 1902.03231

- Take an EbyE hydro
  - EKRT EbyE hydrodynamics

    Initial conditions: minijets + saturation model

    $\tau_f = 0.197\,\mathrm{fm}$ (**smaller** than usual)

    $T_{ch} = 175\,\mathrm{MeV}$

    $T_{dec} = 100\,\mathrm{MeV}$

Niemi, Eskola, Paatelainen
arXiv:1505.02677

- Take an energy loss model (same as before)
  - Quenching Weights (QWs) in the HO approximation

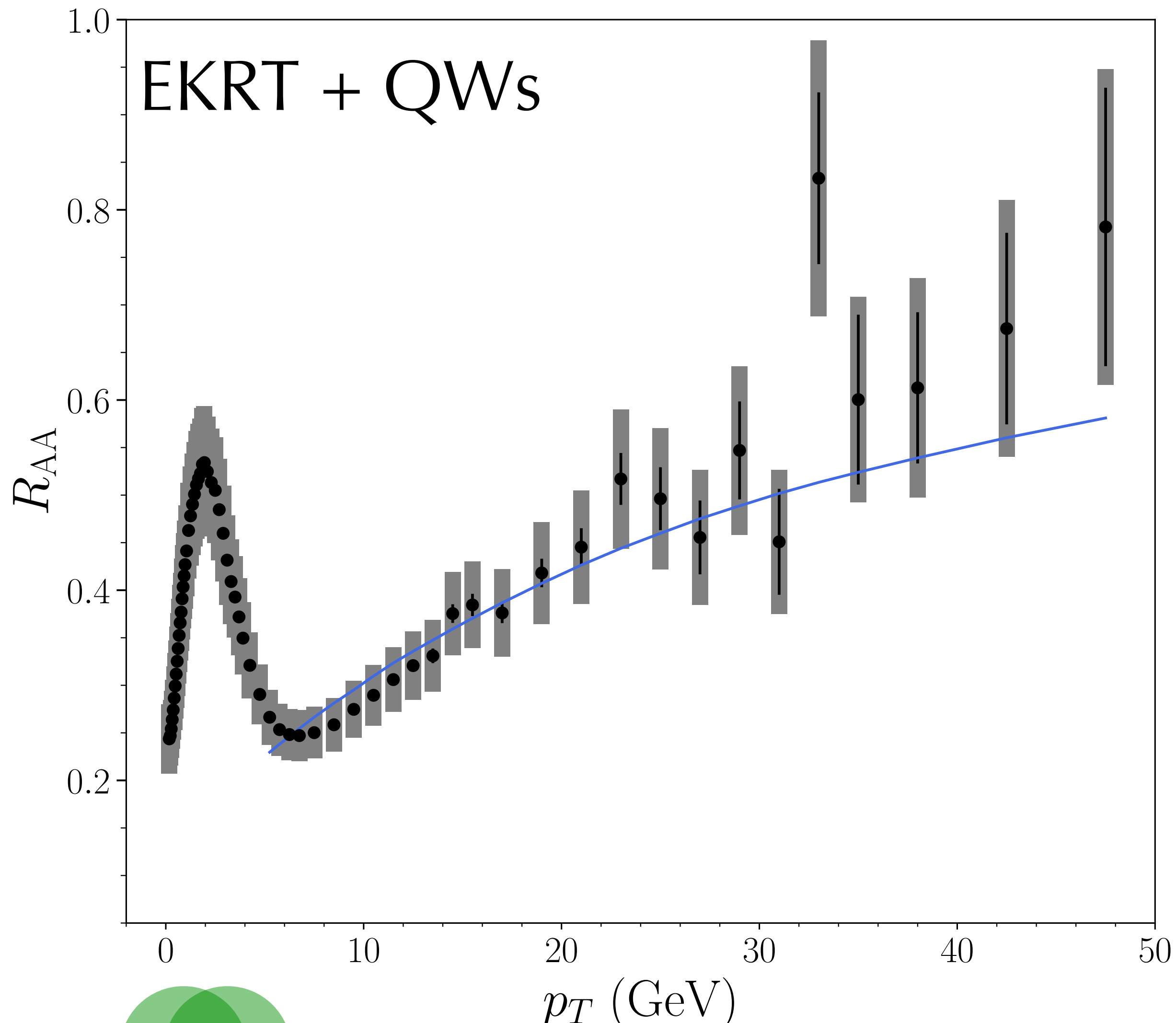
Salgado and Wiedemann
arXiv:hep-ph/0302184

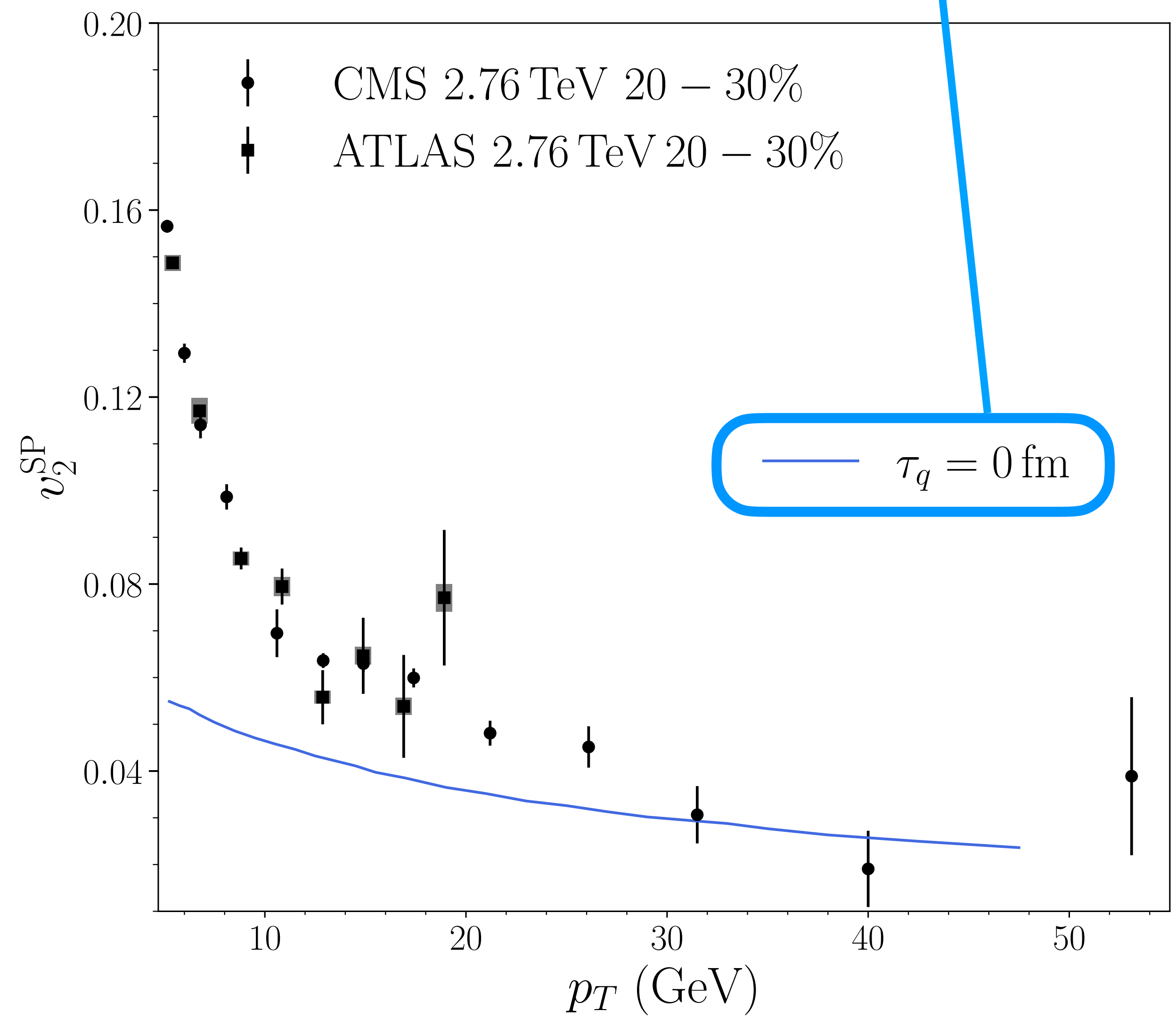
$$\hat{q}(\xi) \;=\; K \cdot 2\epsilon^{3/4}(\xi)$$

- Fit K to the R_{AA} data
- Compute v_2 in the hard sector (using the scalar product)

R_{AA} and high-p_T v_2

$\hat{q}(\tau) = \hat{q}(\tau = 0.197\ \mathrm{fm})$ for $\tau < 0.197$ fm

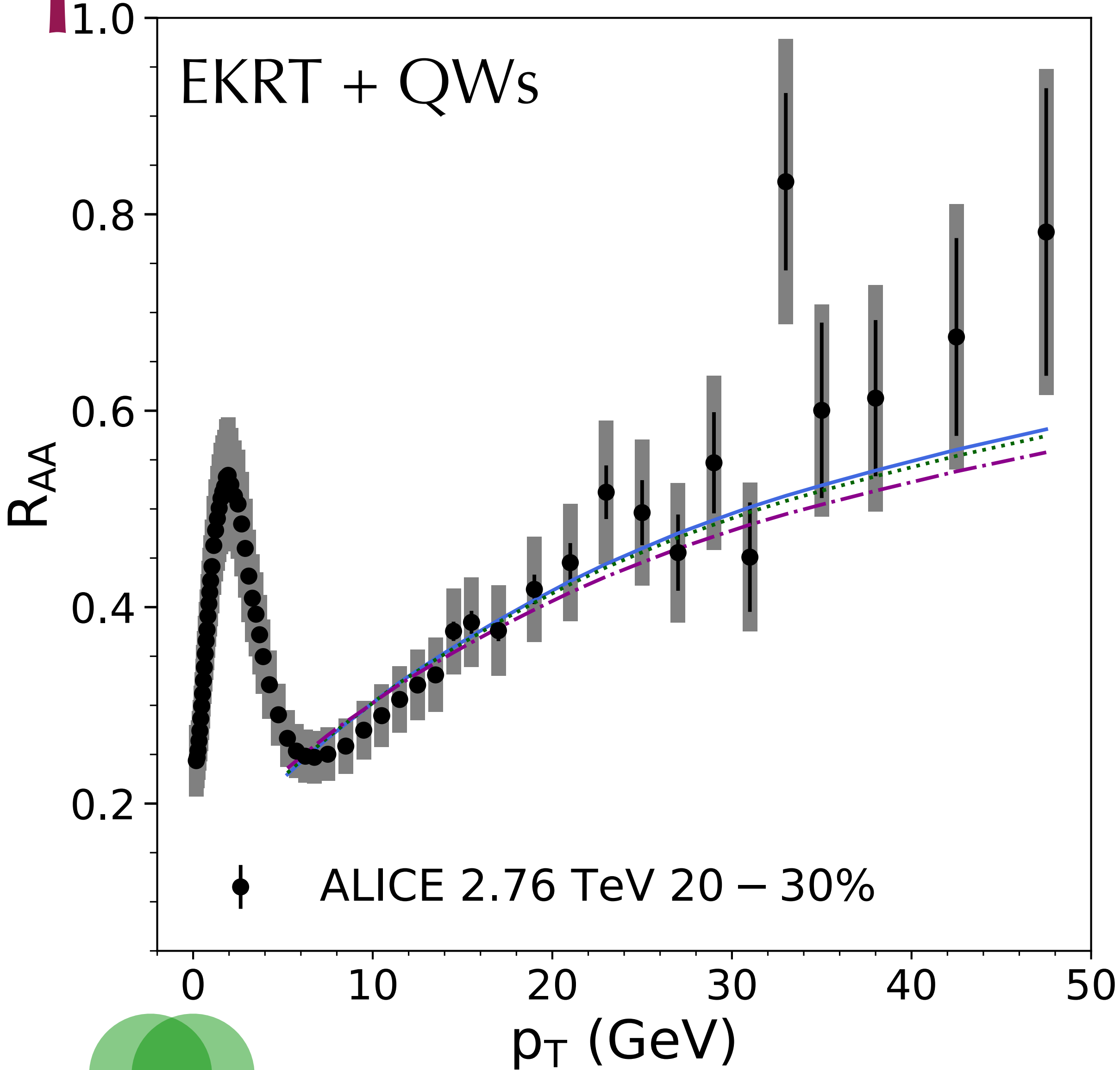


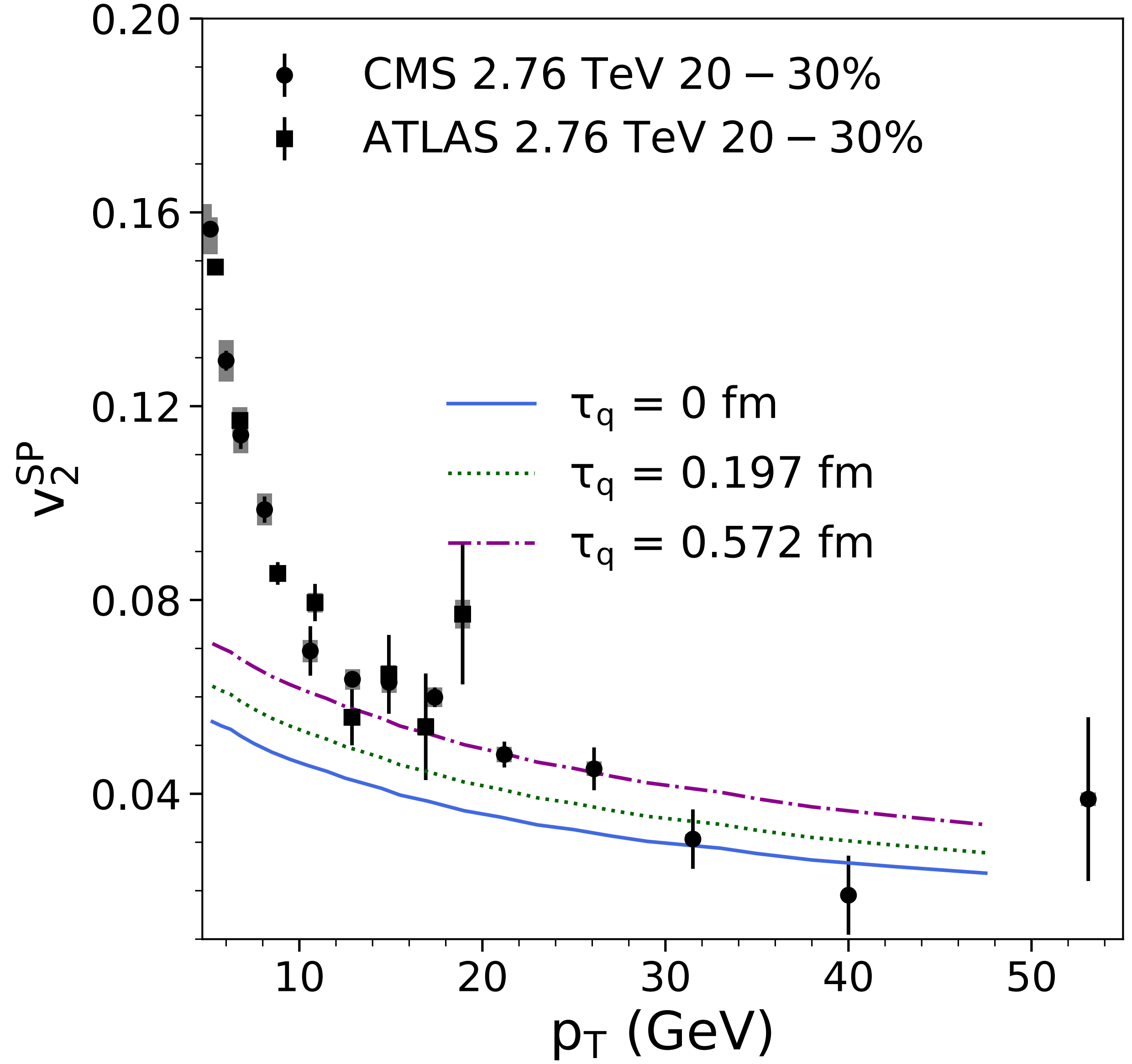


CA, Armesto, Niemi, Paatelainen, Salgado
arXiv:1902.03231

Failure ??

R_{AA} and high-p_T v_2 as a probe of IS



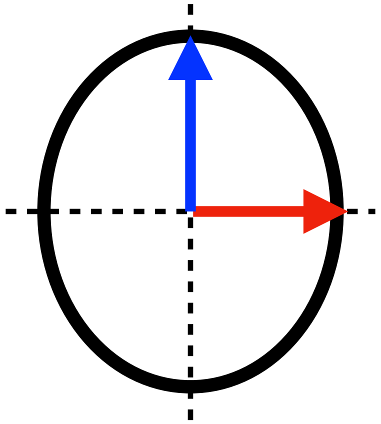


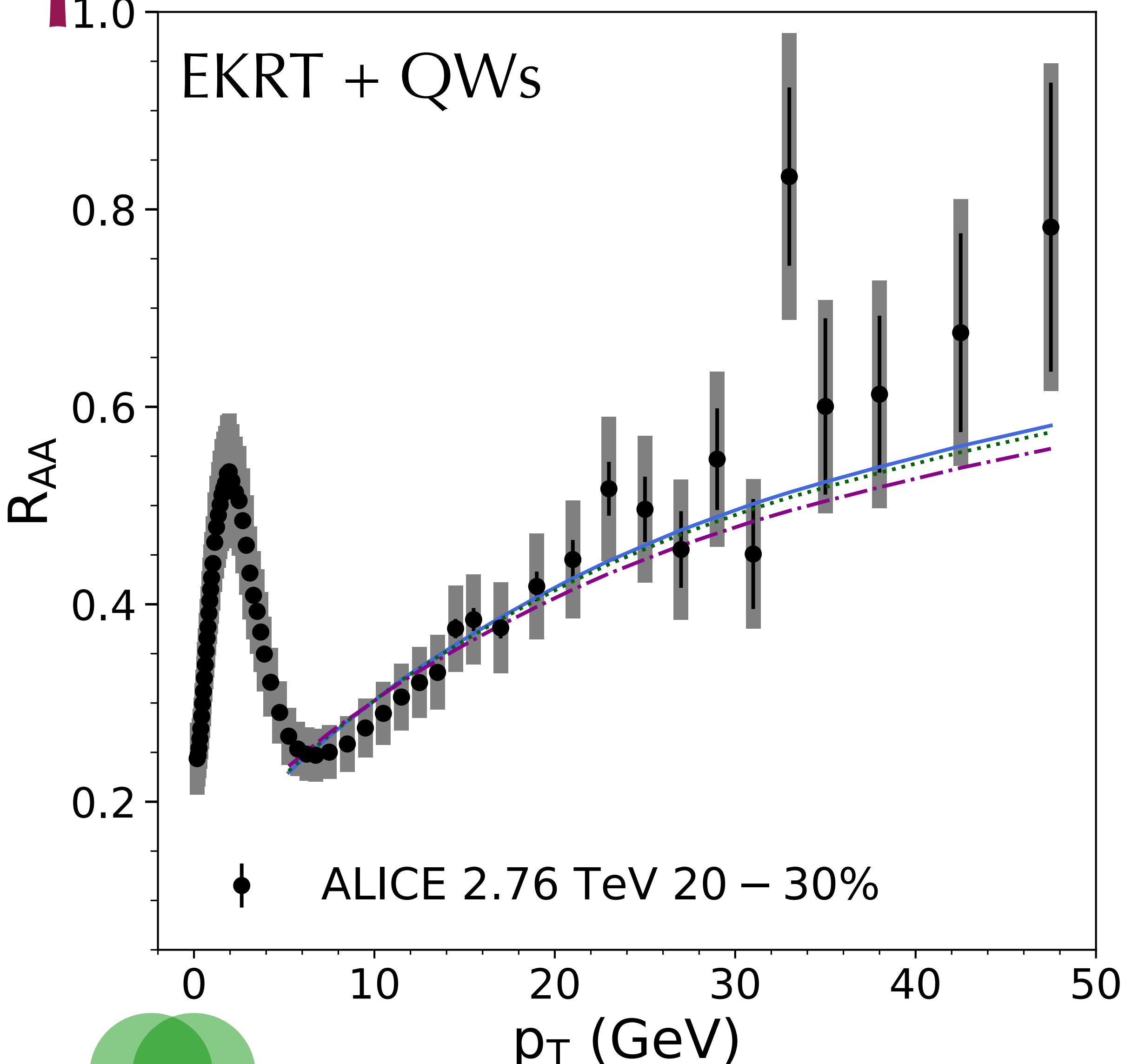
CA, Armesto, Niemi, Paatelainen, Salgado
arXiv:1902.03231

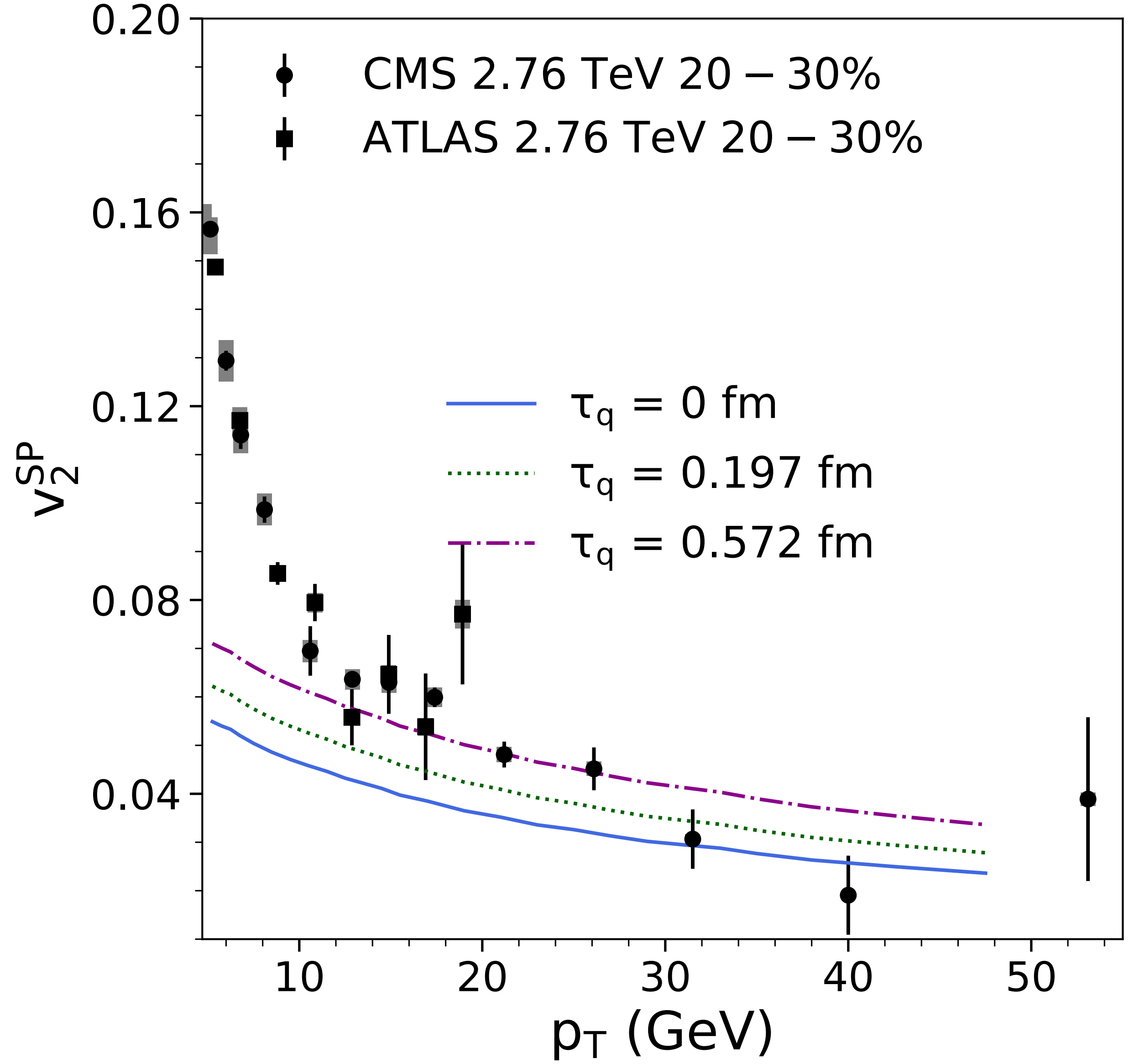
Very sensitive to the initial stages!

Confirmed later by: Stojku et al. arXiv:2008.08987

R_{AA} and high-p_T v_2 as a probe of IS







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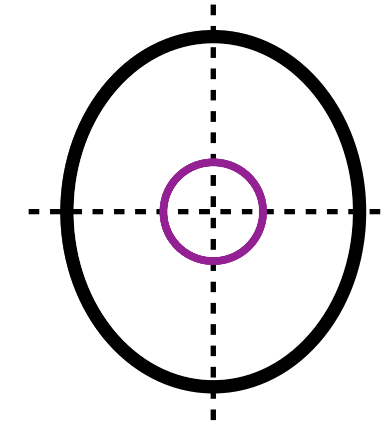

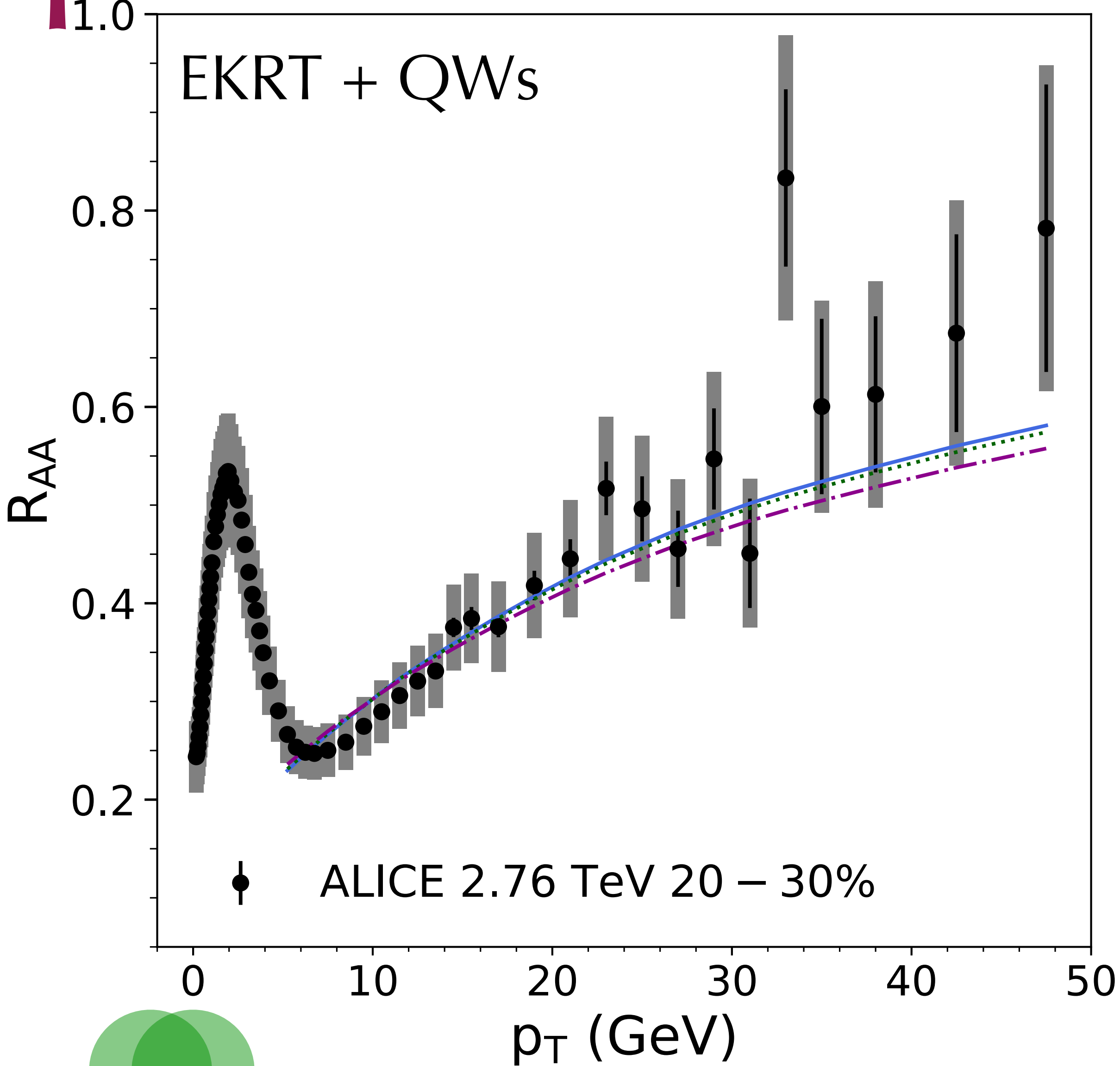

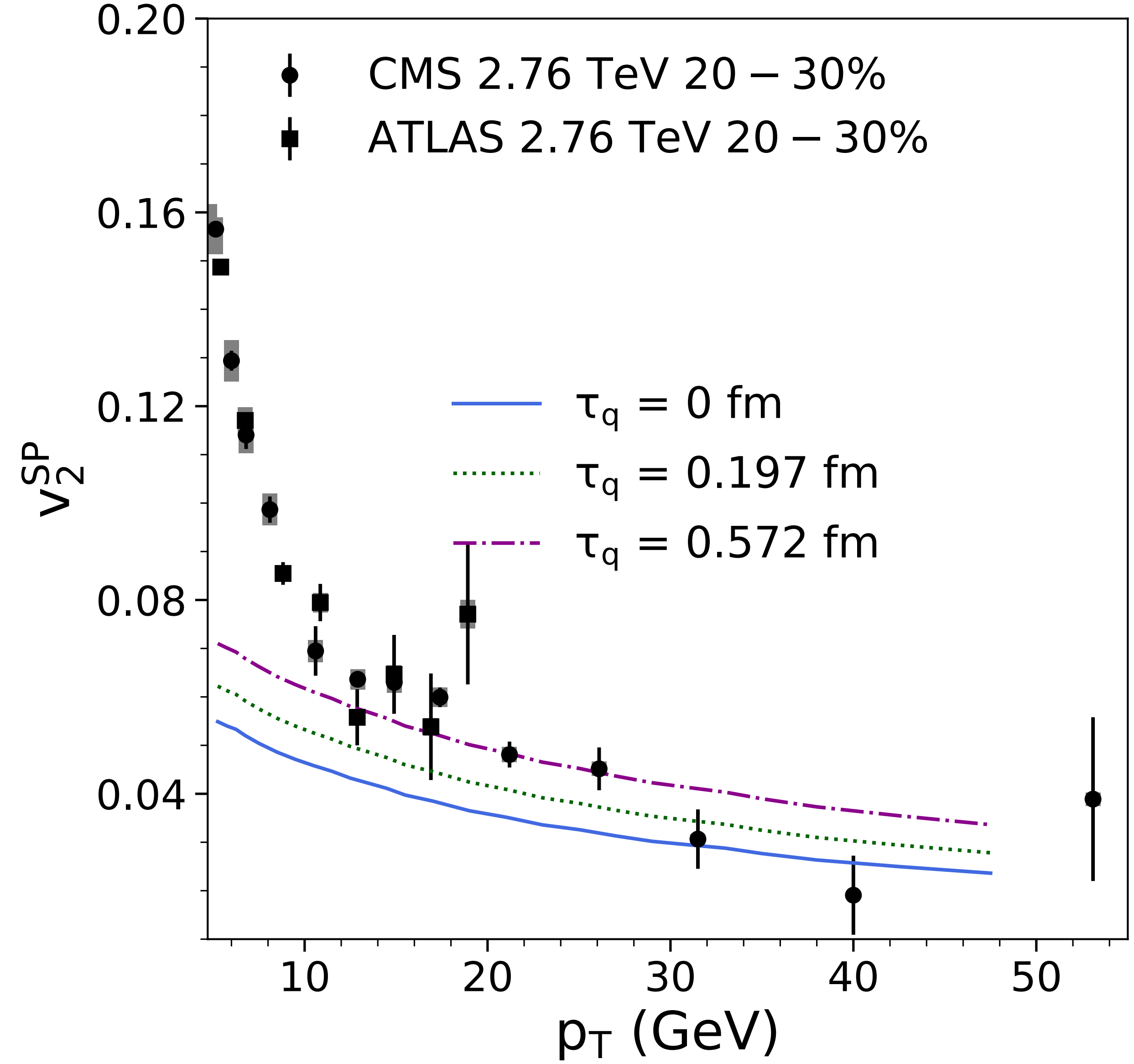

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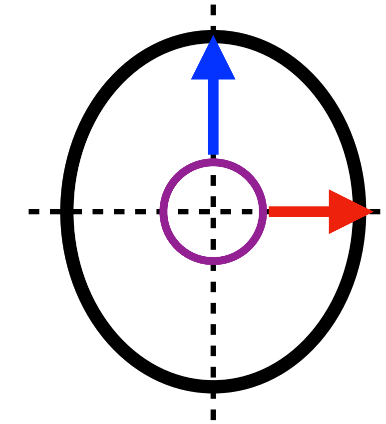

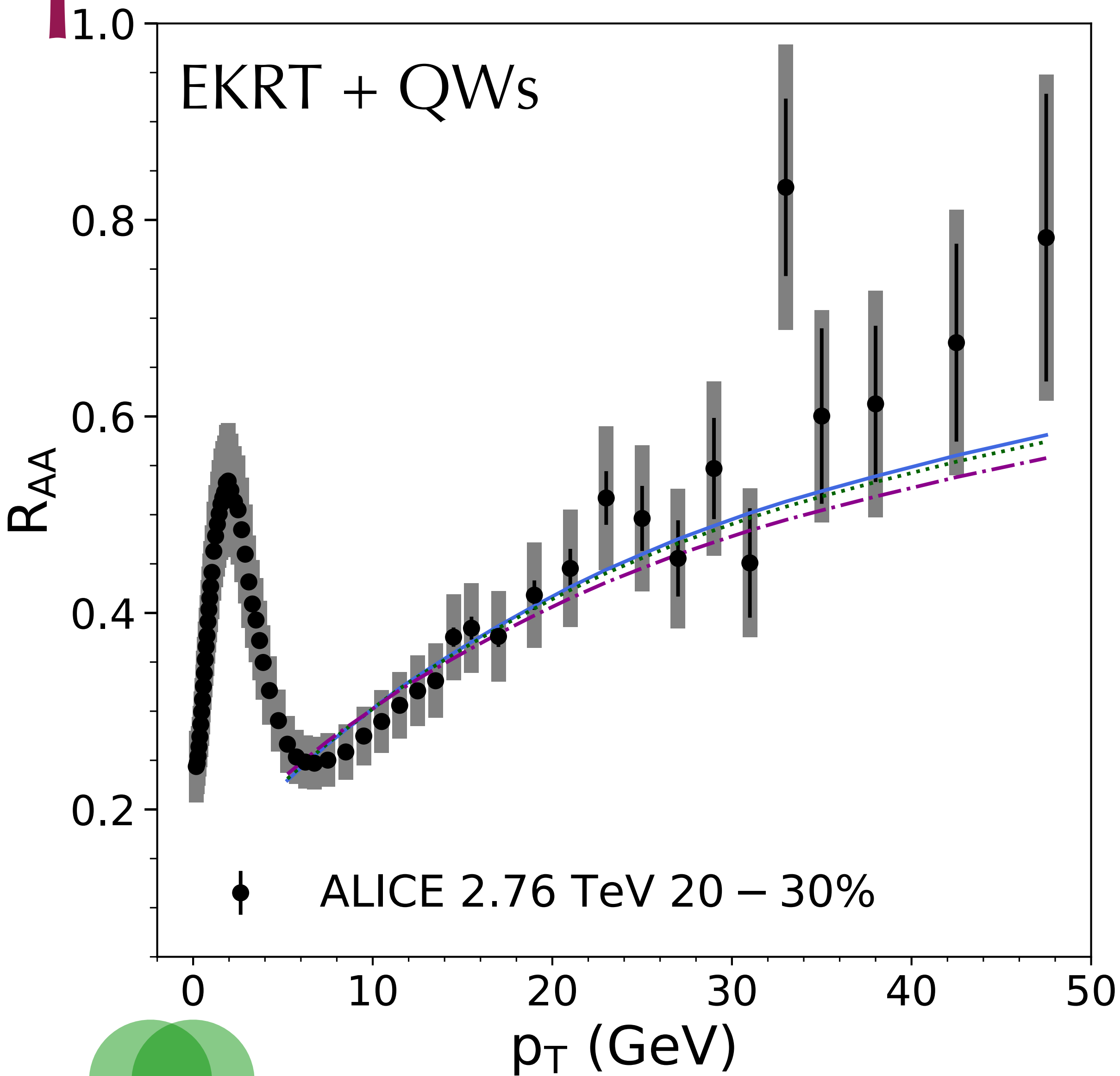

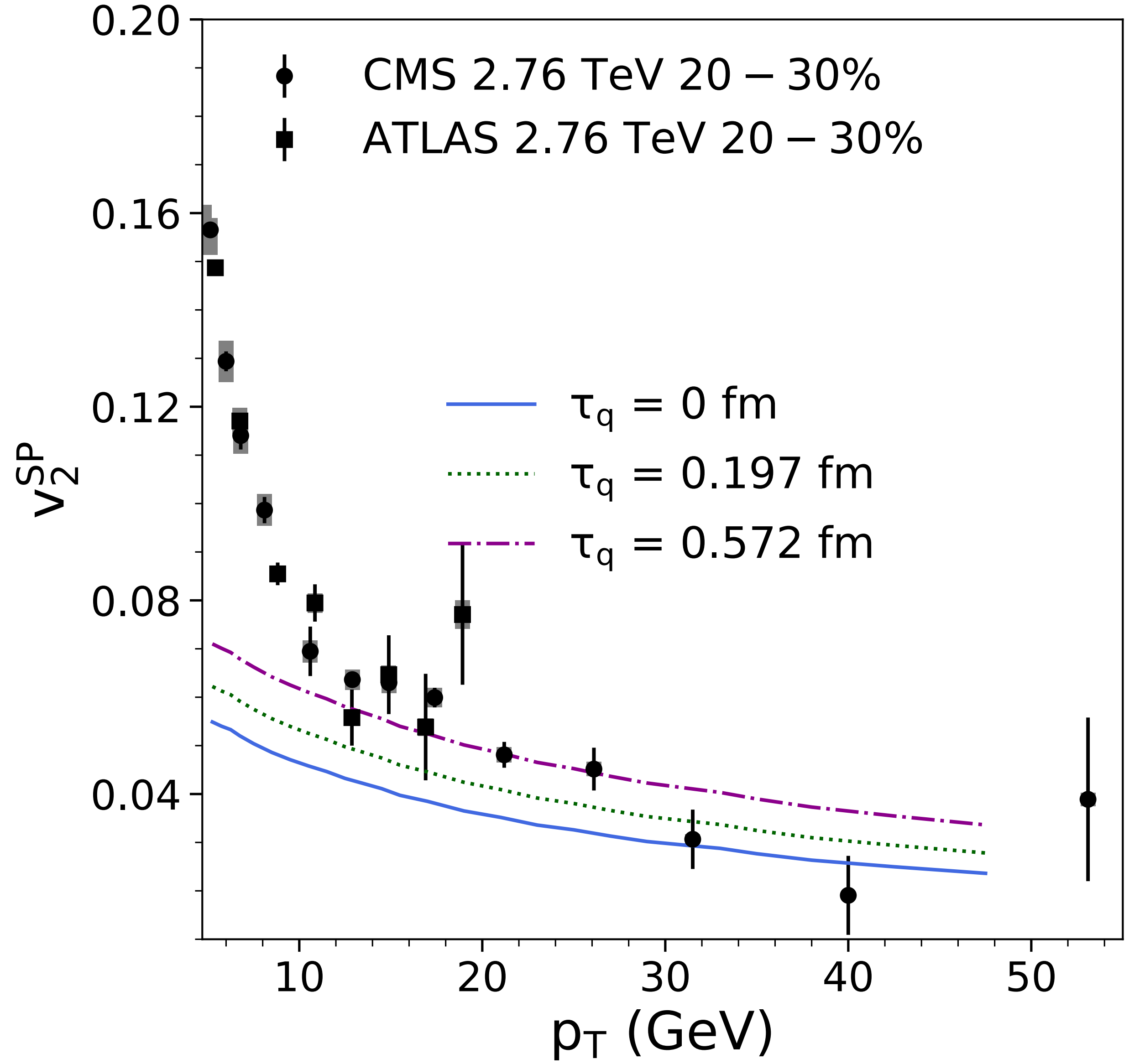

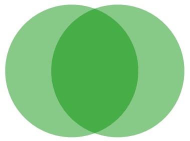

CA, Armesto, Niemi, Paatelainen, Salgado arXiv:1902.03231

Very sensitive to the initial stages!

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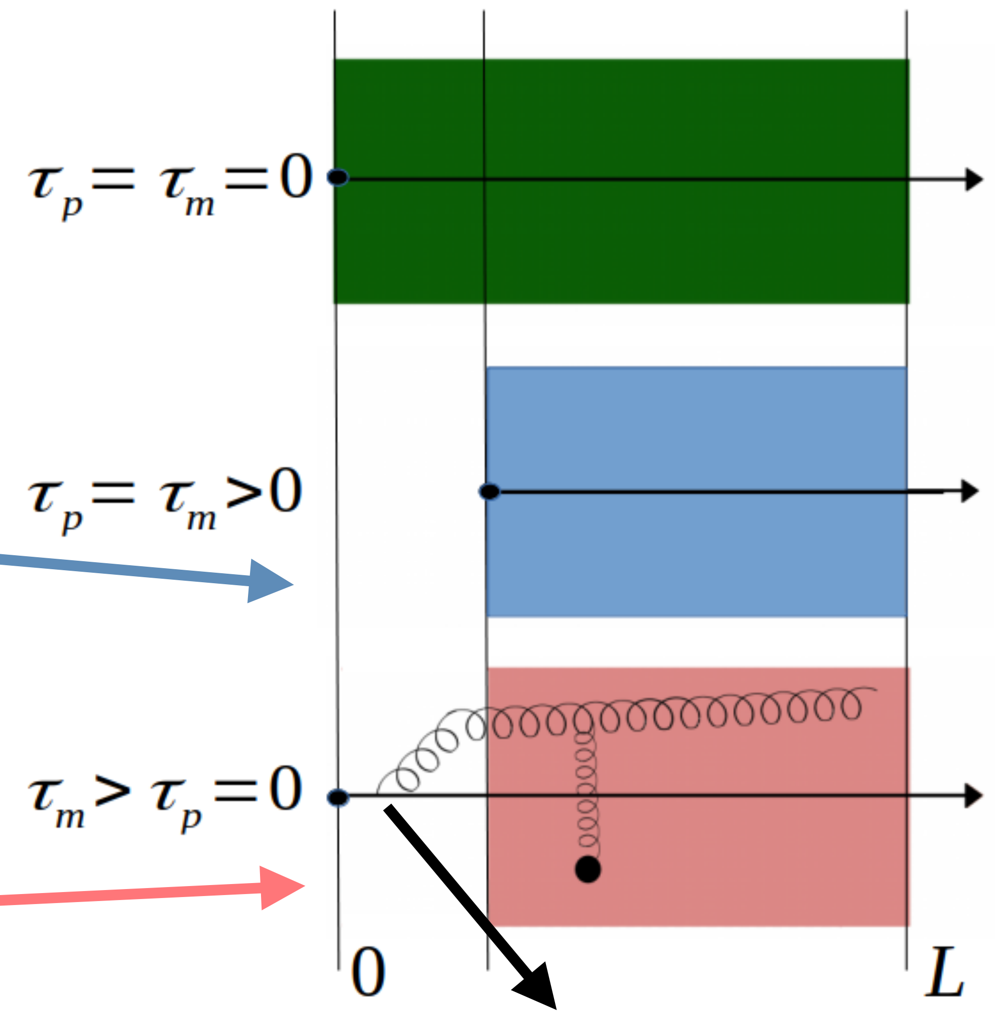
Radiation in the IS

- Up to here: parton set to be produced <u>*inside*</u> the QGP
- We were ignoring (medium-induced) radiation emitted before the formation of the QGP
- How to isolate the effects due to this initial radiation?
  - Emitter produced at $\tau_p \sim 0$
  - Propagates in vacuum from τ_p to $\tau_m = \tau_{\rm hydro}$
  - In-medium propagation from τ_m to L



Extra medium-induced radiation

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

Radiation in the IS

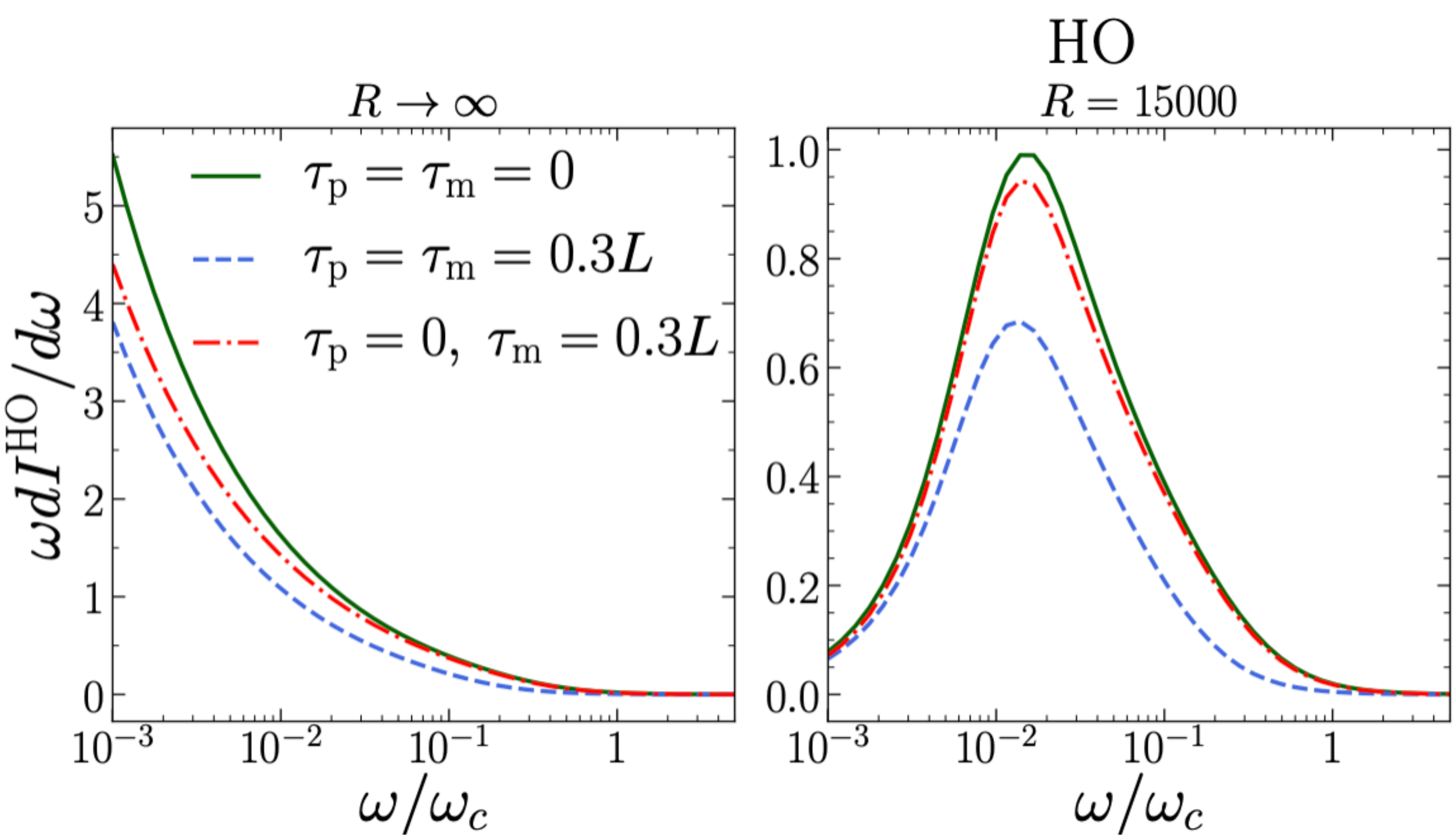
- HO spectrum

$$\omega \frac{dI^{\rm HO}}{d\omega} = \frac{2\alpha_s C_R}{\pi} \ln \left| \cos\left[\Omega L\left(1-\frac{\tau_{\rm m}}{L}\right)\right] - \Omega L \frac{\tau_{\rm m}-\tau_{\rm p}}{L} \sin\left[\Omega L\left(1-\frac{\tau_{\rm m}}{L}\right)\right] \right|$$

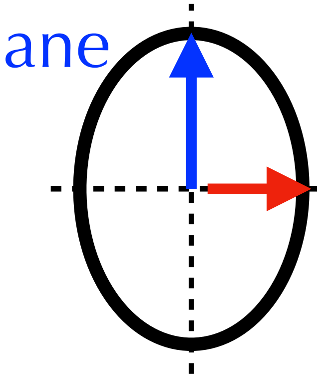
$$\Omega L \equiv (1-i)\sqrt{\frac{\omega_c}{2\omega}}$$

$$\omega_c \equiv \frac{1}{2}\hat{q}L^2$$

Extra medium-induced radiation



R_{AA} and high-p_T v_2



- Compute the HO spectrum for a power-law expanding medium

$$\hat{q}(\tau) = K_1 T^3(\tau) \qquad T(\tau) = T_0 \left(\frac{\tau_0}{\tau + \tau_0} \right)^c$$

Parameters fixed to Luzum and Romatsche's hydro

- Compute the QWs (using the spectrum)

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI^{(med)}(\omega_i)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int_0^{\infty} d\omega \frac{dI^{(med)}}{d\omega} \right]$$

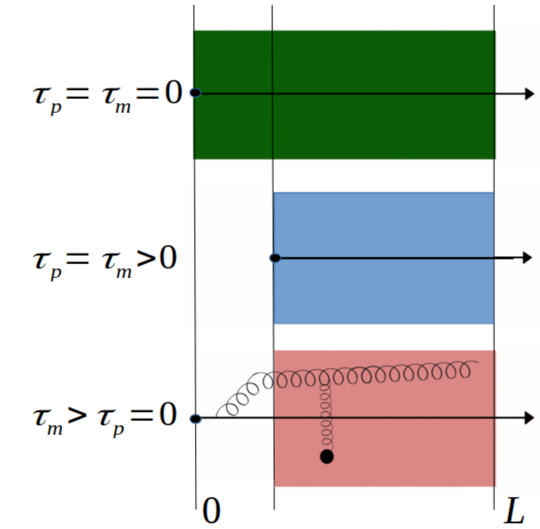
- Compute the hadron suppression factor

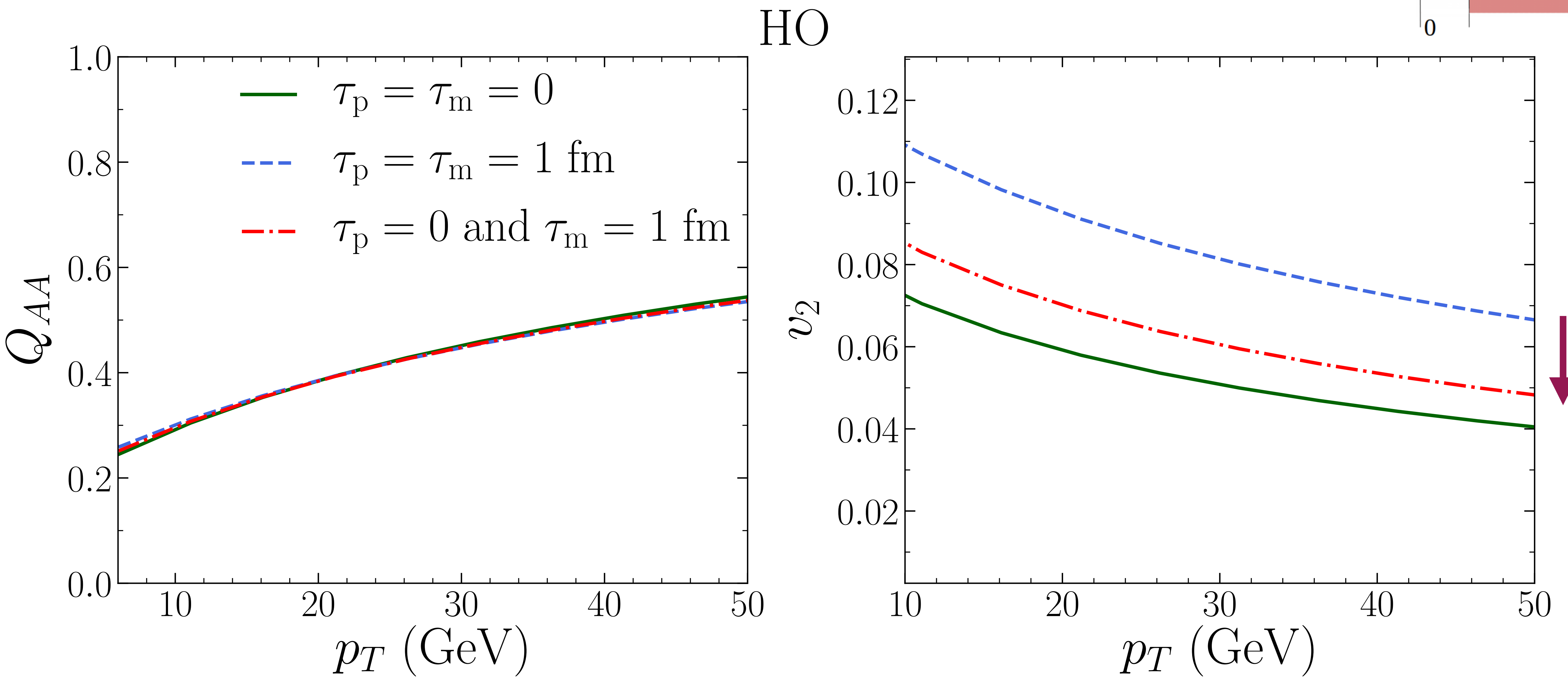
$$Q_f(p_T) = \frac{d\sigma^{med}(p_T)/dp_T}{d\sigma^{vac}(p_T)/dp_T} \sim \int d\Delta E \, P(\Delta E) \left(\frac{p_t}{p_T + \Delta E} \right)^n$$

- Compute the high-p_T v_2

$$v_2 = \frac{1}{2} \frac{Q_i^{\text{in}}(p_T) - Q_i^{\text{out}}(p_T)}{Q_i^{\text{in}}(p_T) + Q_i^{\text{out}}(p_T)}$$

R_{AA} and high-p_T v_2





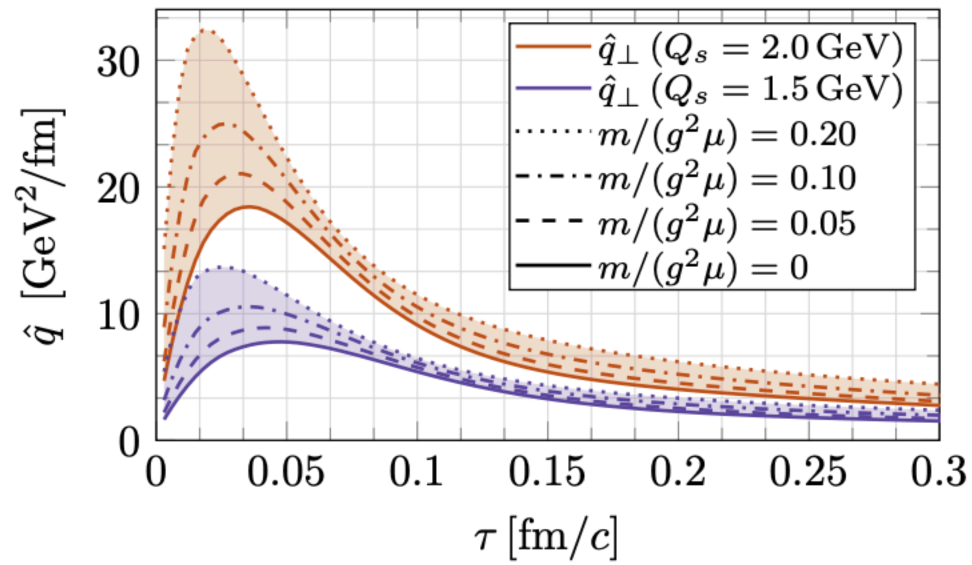
Including the initial radiation makes the high-p_T v_2 decrease

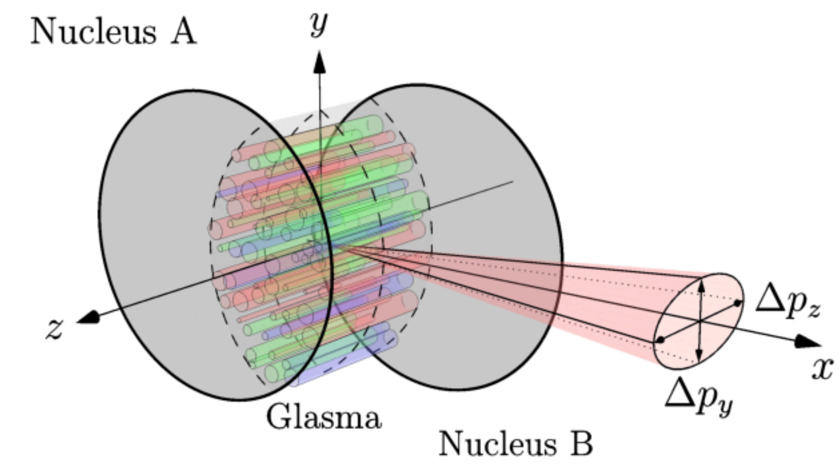
CA, Apolinário, Domingue
M. G. Martinez, Salgado
in preparation

Jet broadening in the glasma

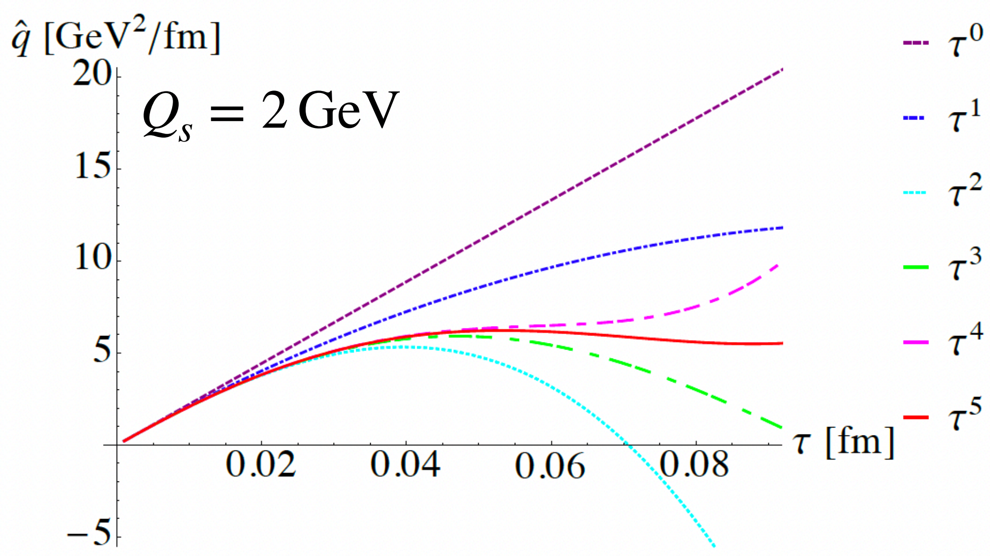
- Hard partons deflected by the chromomagnetic and chromoelectric forces in the Glasma phase

Ipp, Müller, Schuh
arXiv:2001.10001
arXiv:2009.14206





Carrington, Czajka, Mrówczynski
arXiv:2112.06812
arXiv:2202.00357



$\hat{q}$ relatively large!

Conclusions

- Jets in heavy-ion collisions witness the full system's evolution
- Jet quenching studies usually neglect energy loss in the initial stages
- Extracting properties of the QGP as $\hat{q}$ requires understanding of the IS
- Simultaneous description of R_{AA} and high-p_T v_2 very sensitive to IS

  Jet quenching for IS?

Understanding jet quenching in the initial stages is crucial to understand the apparent lack of energy loss in small systems

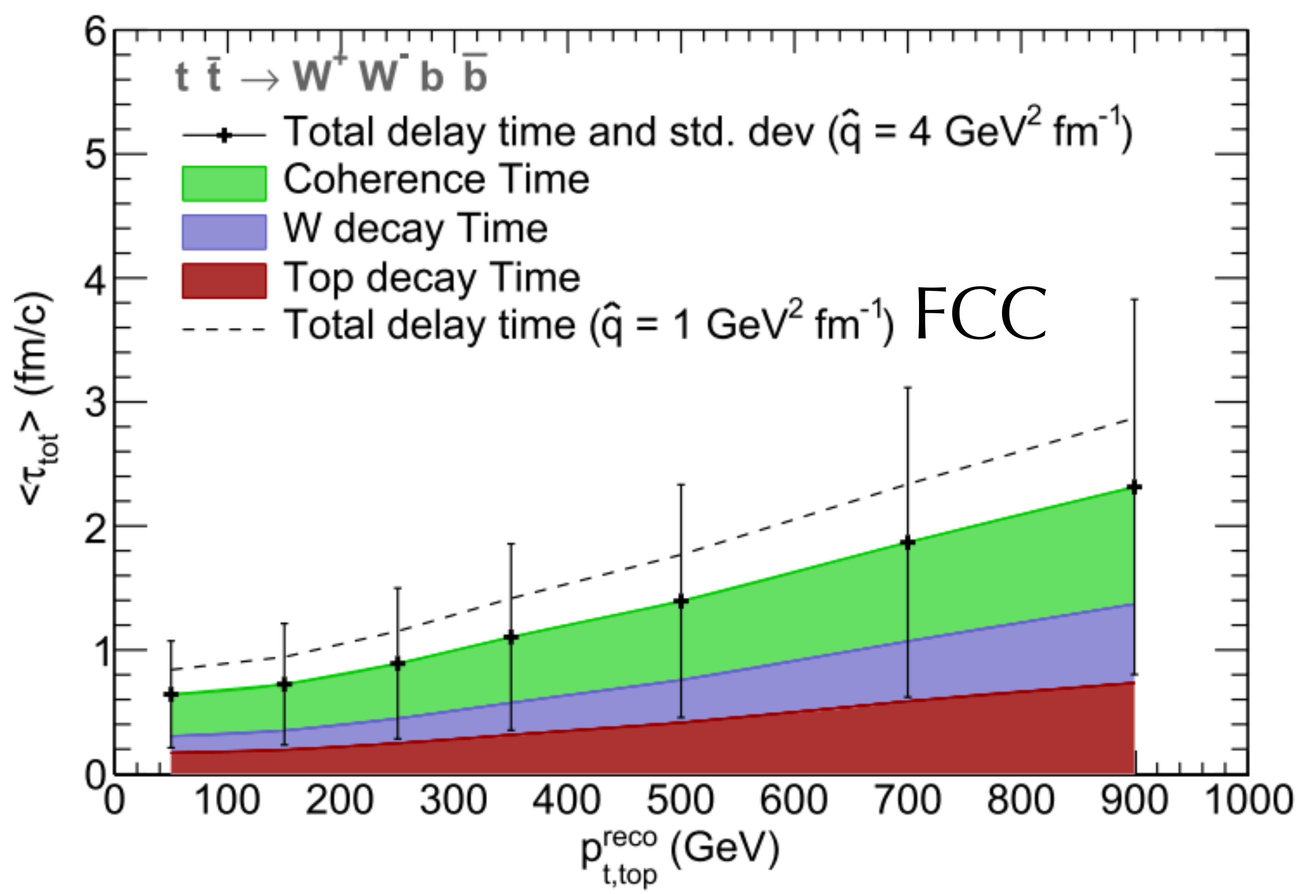
Thanks!

Boosted tops

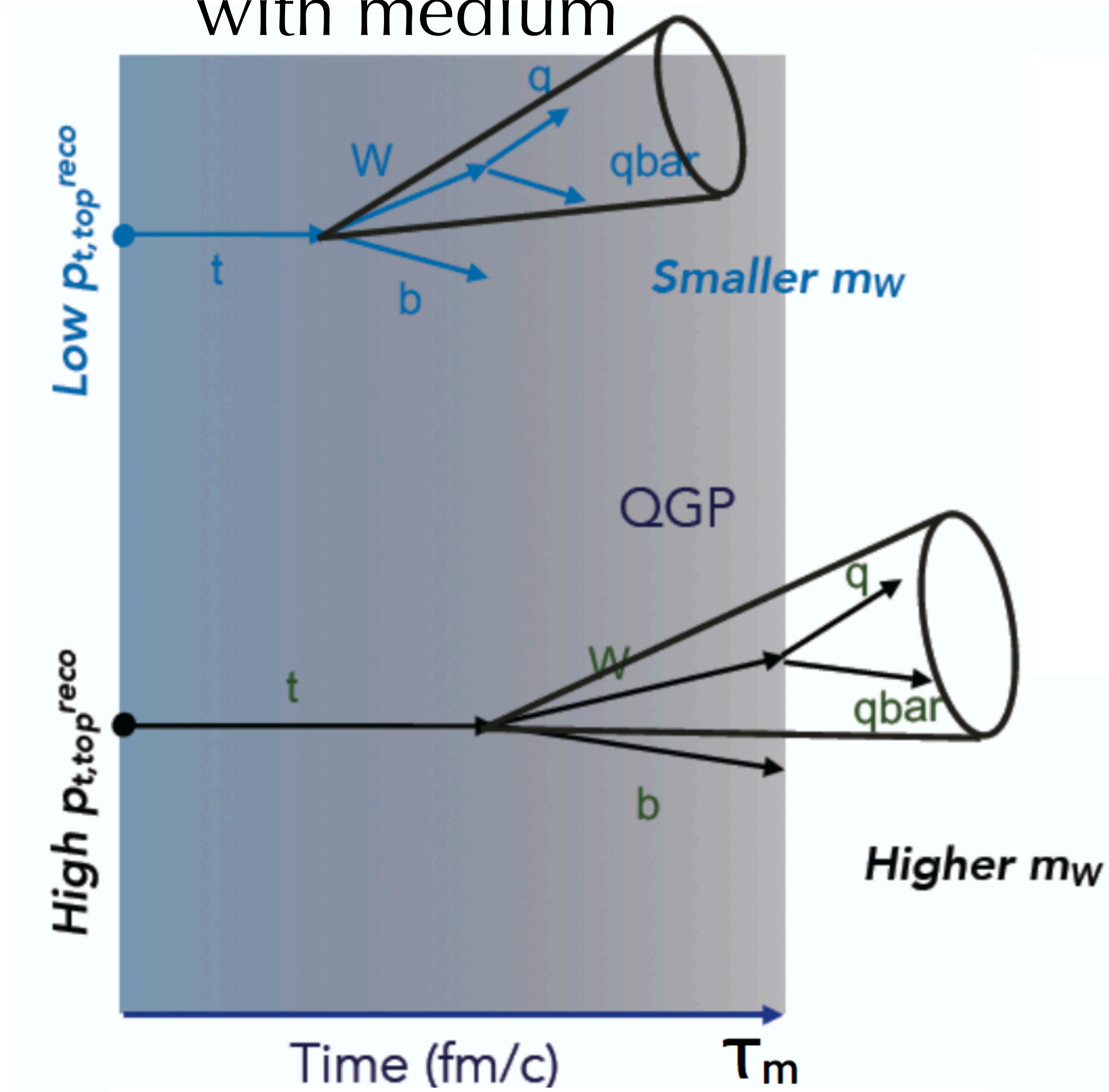
Apolinário, Milhano, Salam, Salgado
PRL 120, 232301 (2018)

- Large energies (FCC) make boosted tops available

- Controlling the boost of the top ⟶ **Controlling when jets start to interact** with medium



$0.5 < t < 3$ fm

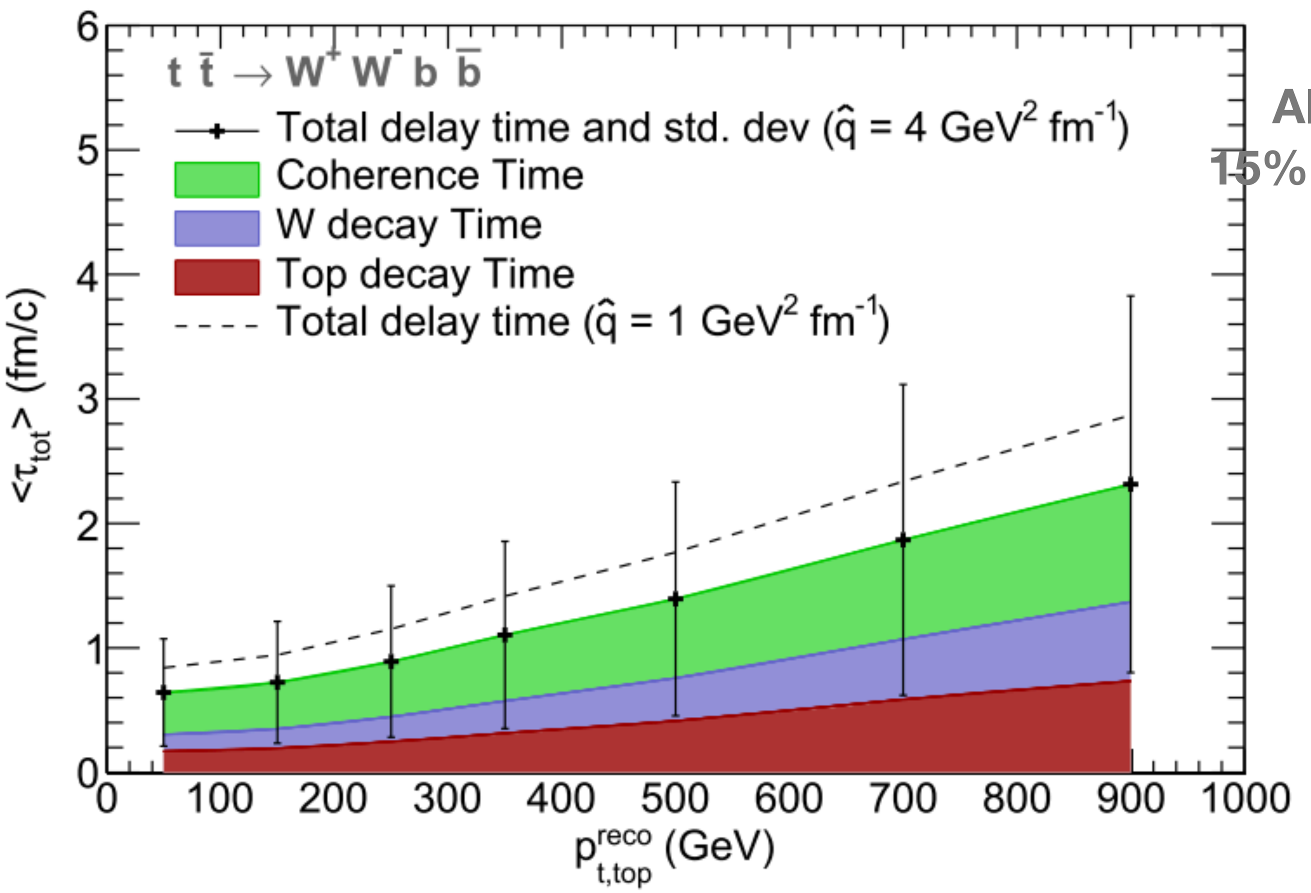


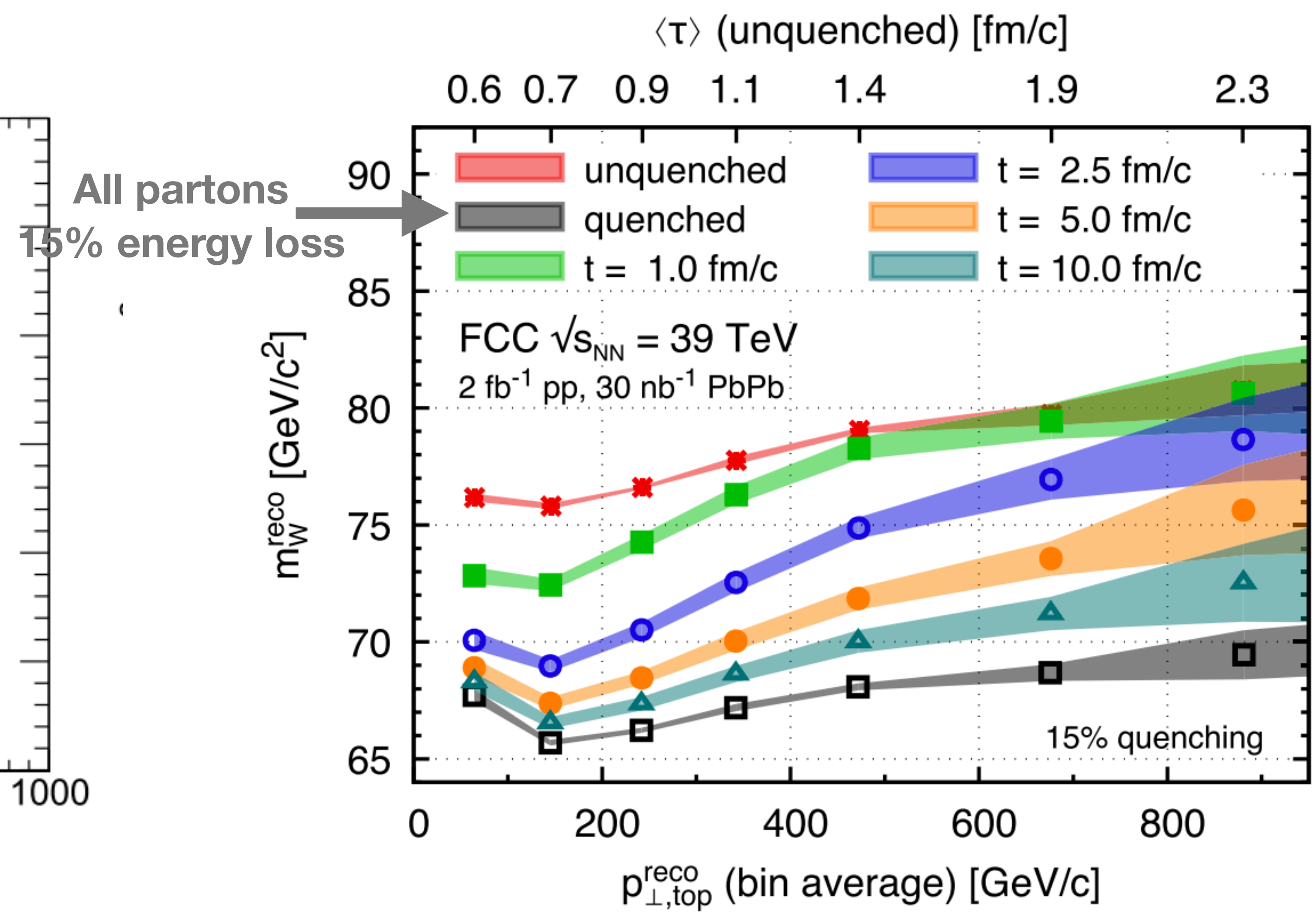
$$\langle \tau_{\rm tot} \rangle = \gamma_{t,{\rm top}} \tau_{\rm top} + \gamma_{t,W} \tau_W + \tau_d$$

Boosted tops

Apolinário, Milhano, Salam, Salgado
PRL 120, 232301 (2018)

- **Reconstructed W mass** as a function of the top p_T: useful to probe **QGP evolution**





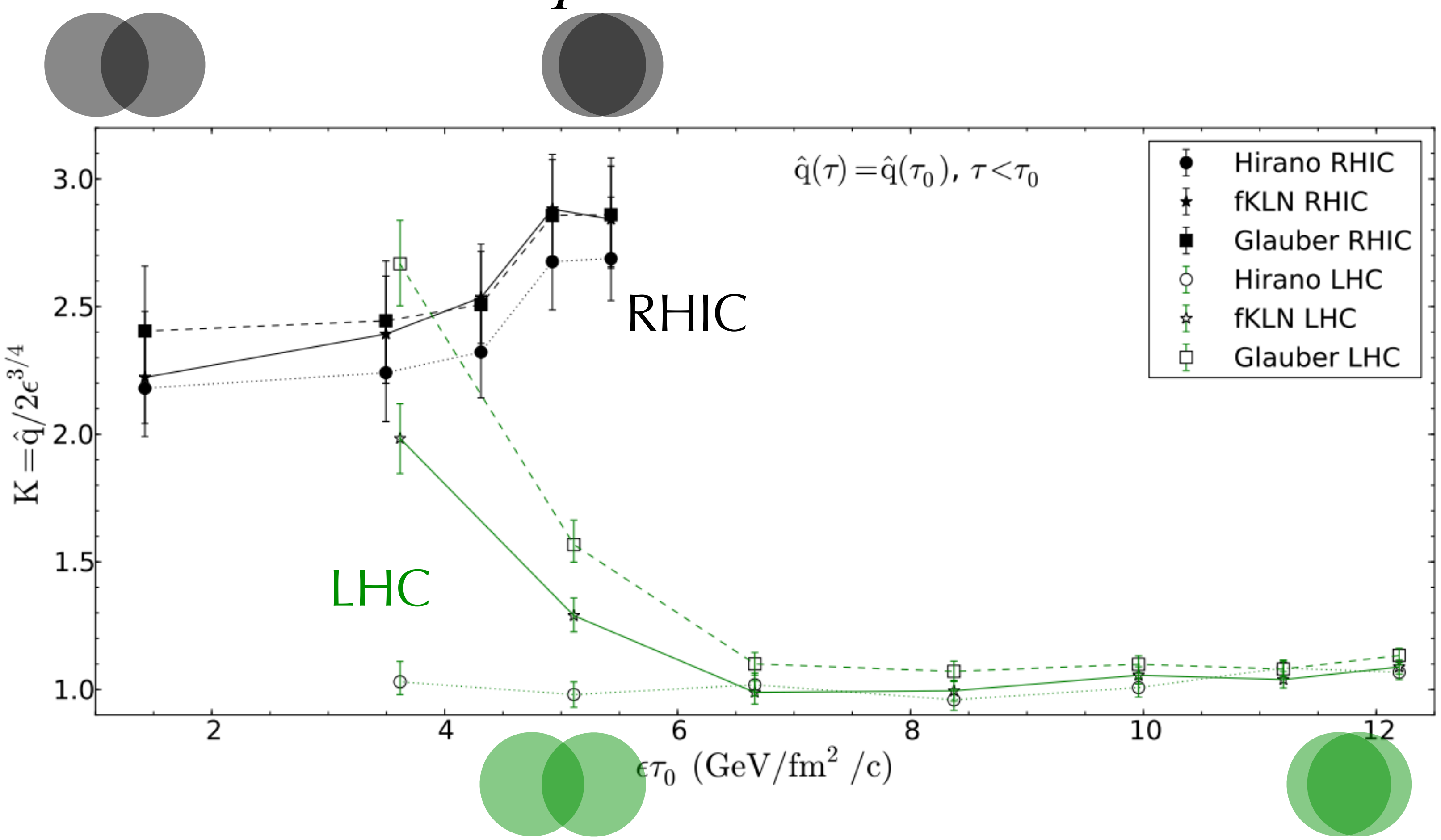
- **Access** to both **small and large times** of the medium evolution with jet quenching

Jet quenching as a chronometer of the yoctosecond structure of the evolution process

The jet quenching parameter

- The jet quenching parameter $\hat{q}$ has been subject of numerous studies

- First extraction of $\hat{q}$ across centralities at RHIC and at the LHC



CA, Armesto, Luzum, Salgado, Zurita, Eur. Phys. J.C 76 (2016) 9, 475

Jet quenching parameter at RHIC larger than at the LHC?

A new puzzle?

- Need to improve the energy loss calculations/implementations???

- $\hat{q}$ extraction still under debate

The jet quenching parameter

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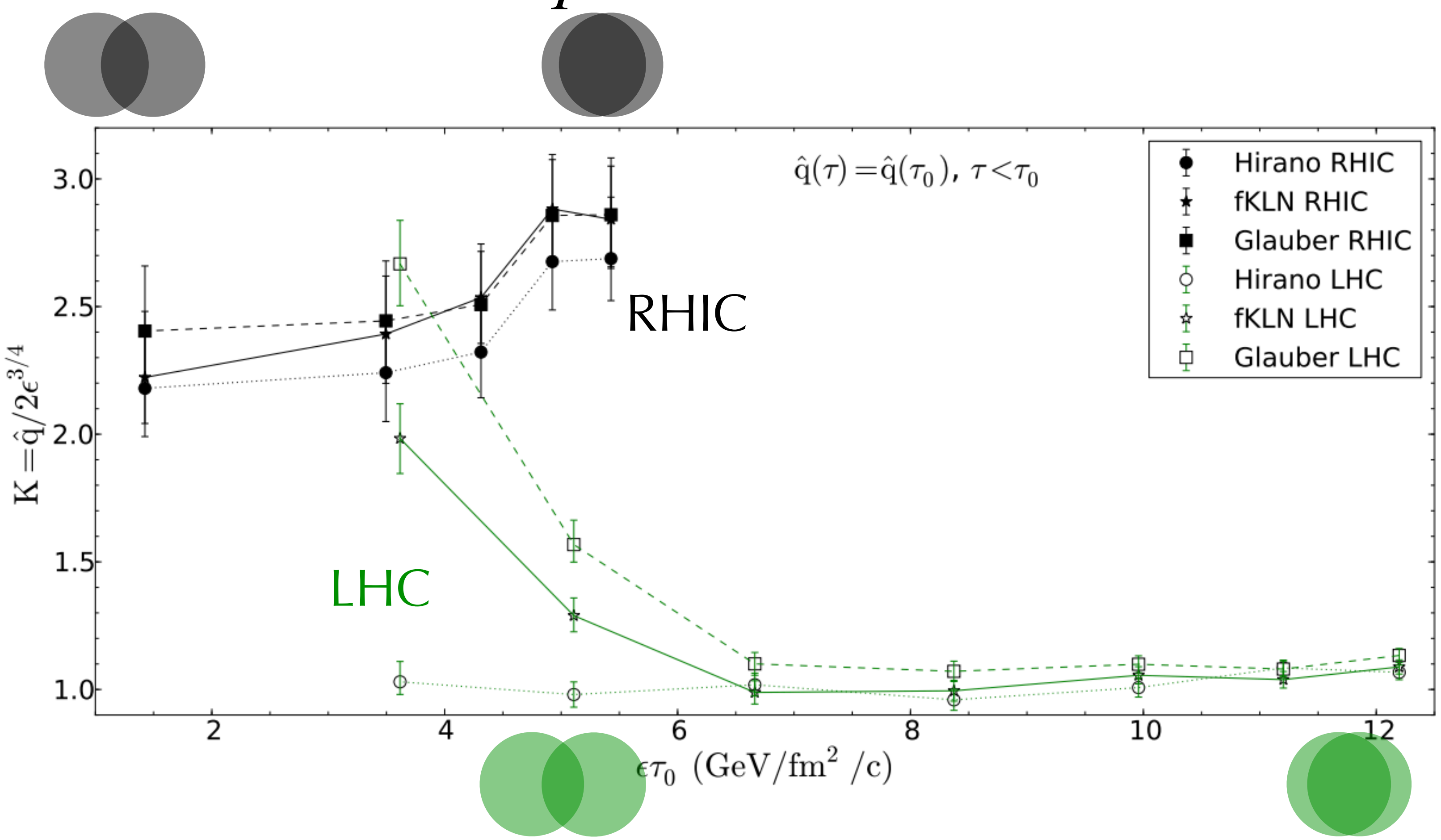
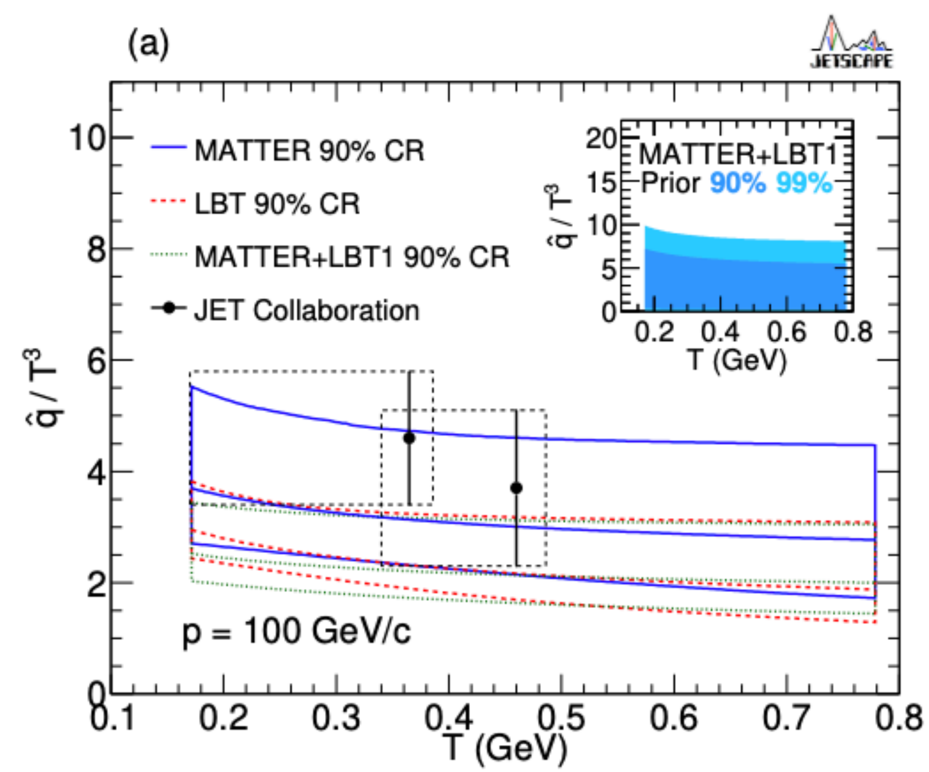
- First extraction of $\hat{q}$ across centralities at RHIC and at the LHC

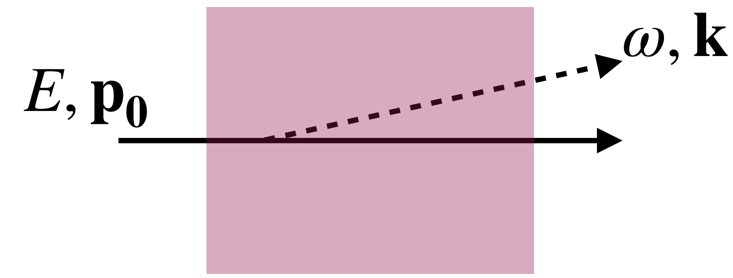




JETSCAPE arXiv: 2102.11337

- Need to improve the energy loss calculations/implementations???

- $\hat{q}$ extraction still under debate



- Quenching Weights

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI^{(med)}(\omega_i)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int_0^{\infty} d\omega \frac{dI^{(med)}}{d\omega} \right]$$

- BDMPS-Z

$$\omega \frac{dI^{(med)}}{d\omega} = \frac{\alpha_s C_R}{(2\pi)^2 \omega^2} 2Re \int_{\xi_0}^{\infty} dy_l \int_{y_l}^{\infty} d\bar{y}_l \int d\mathbf{u} \int_0^{\chi\omega} d\mathbf{k}_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{u}} e^{-\frac{1}{2}\int_{\bar{y}_l}^{\infty} d\xi n(\xi)\sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}}$$

$$\times \int_{y=0}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r} \exp\left[i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\sigma(\mathbf{r})}{i\omega} \right) \right]$$

Quenching Weights

- Computed in the Multiple Soft Scattering (HO) approximation

$$\sigma(\mathbf{r})n(\xi) \simeq \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2$$

Perturbative tails neglected

- Relation between $\hat{q}$ and the hydrodynamic properties of the medium

$$\hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi)$$

K → Fitting parameter

$\epsilon^{3/4}(\xi)$ → hydro

Baier arXiv:hep-ph/0209038

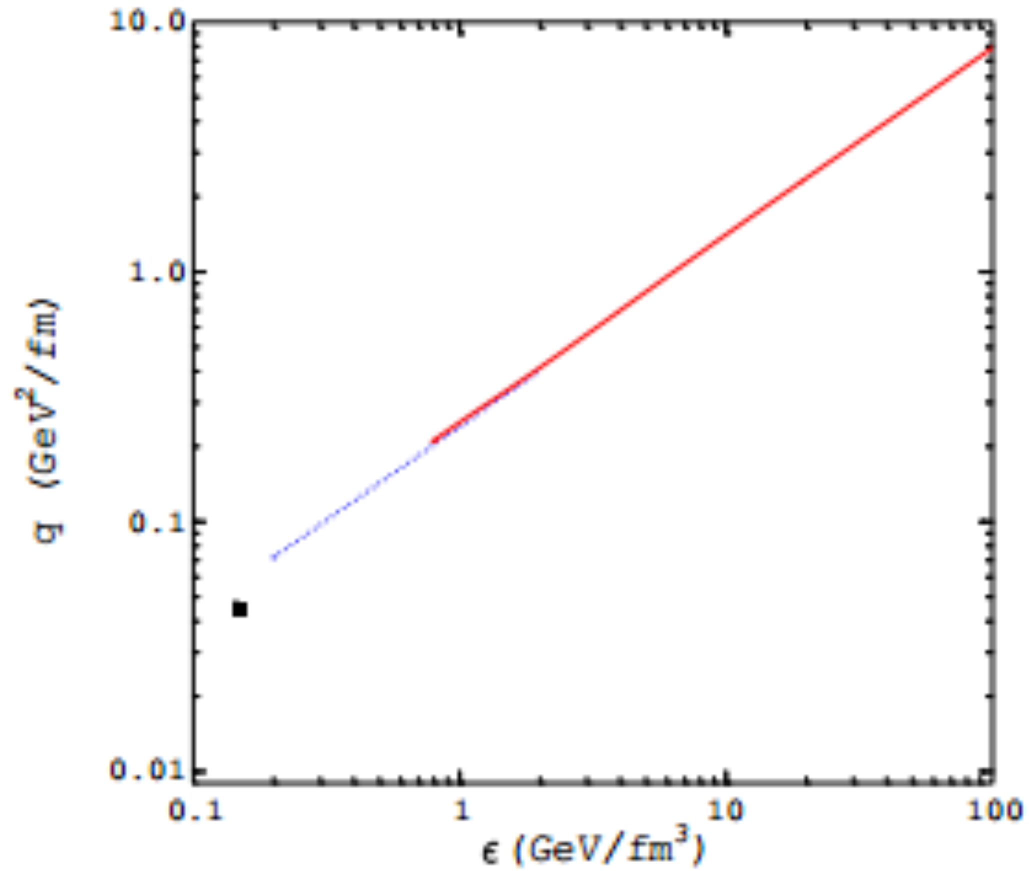


Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)

EKRT hydrodynamics

- EKRT event by event hydrodynamics

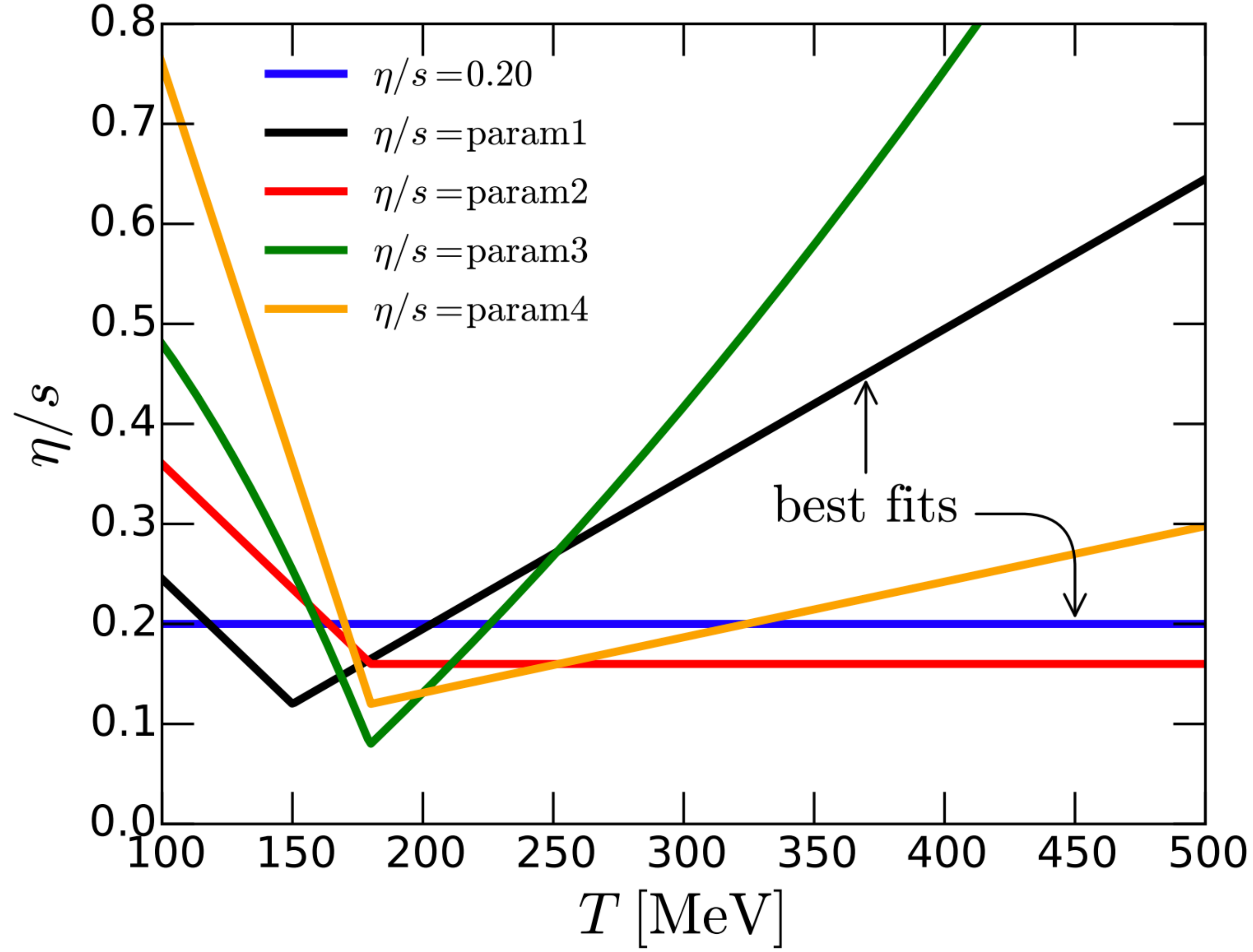
Initial conditions: minijets + saturation model

$\tau_f = 0.197$ fm

$\eta/s = param1$

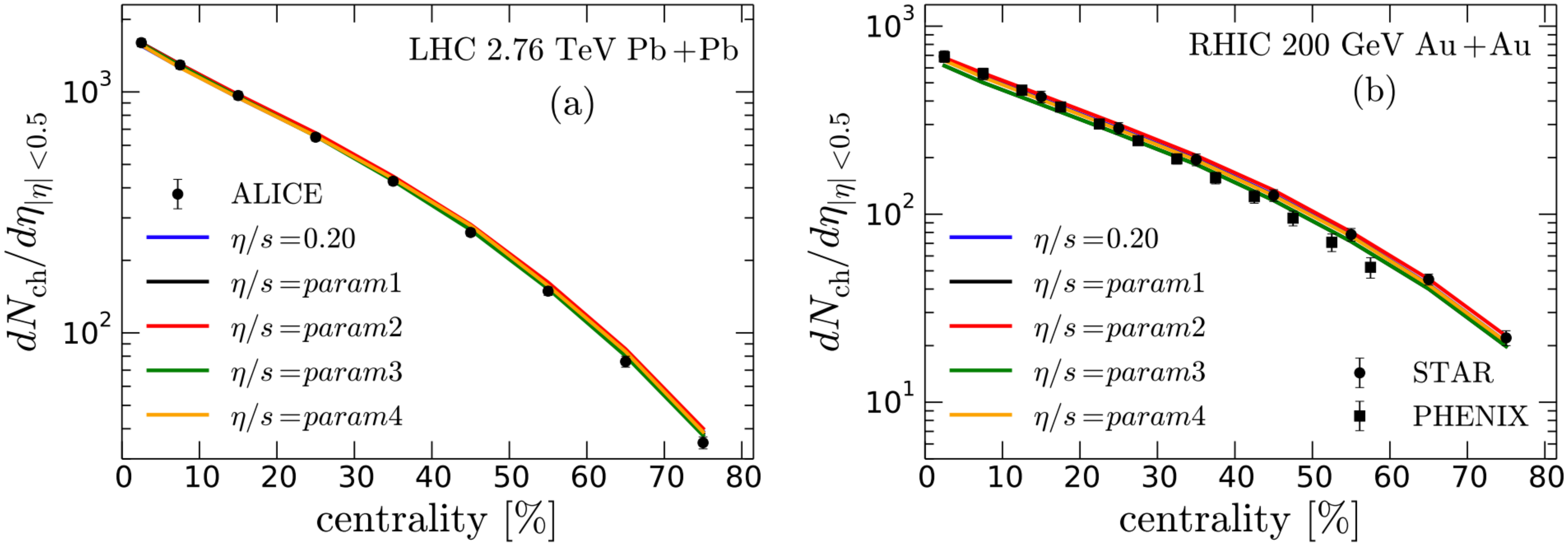
$T_{ch} = 175$ MeV

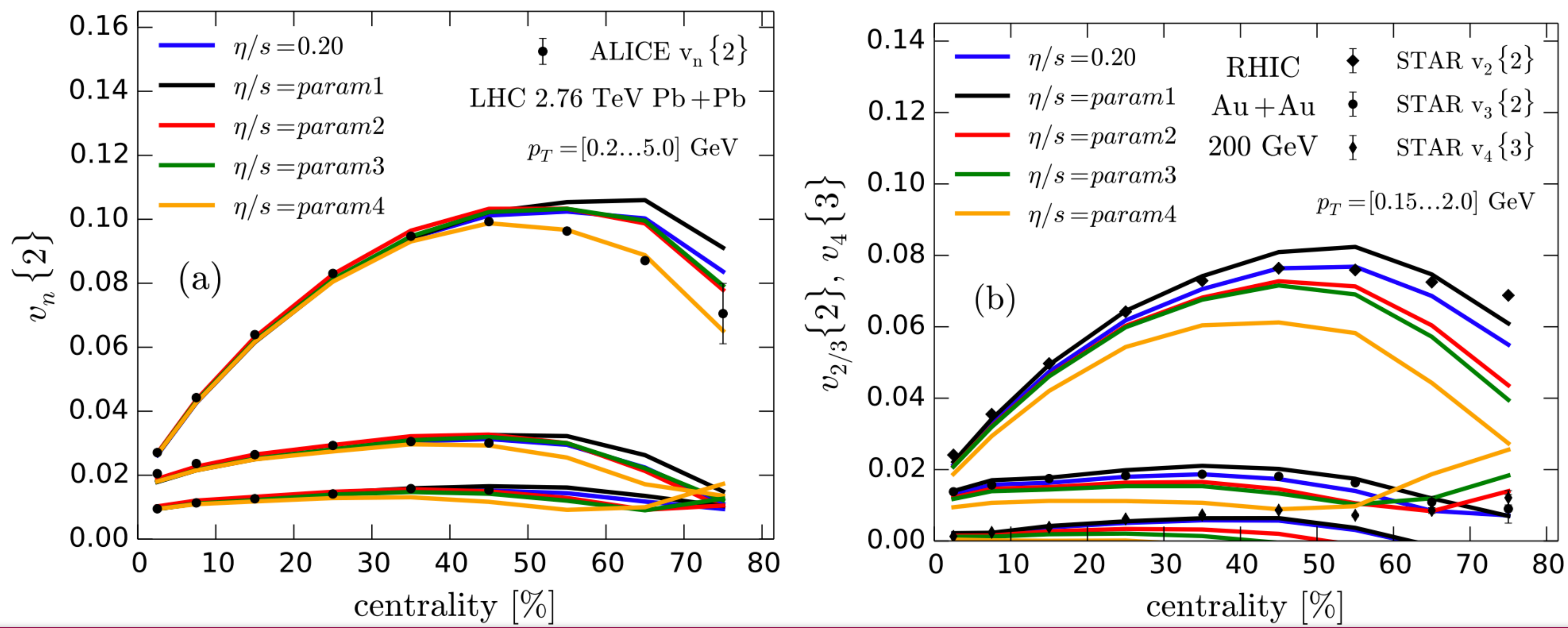
$T_{dec} = 100$ MeV



arXiv:1505.02677

EKRT hydro





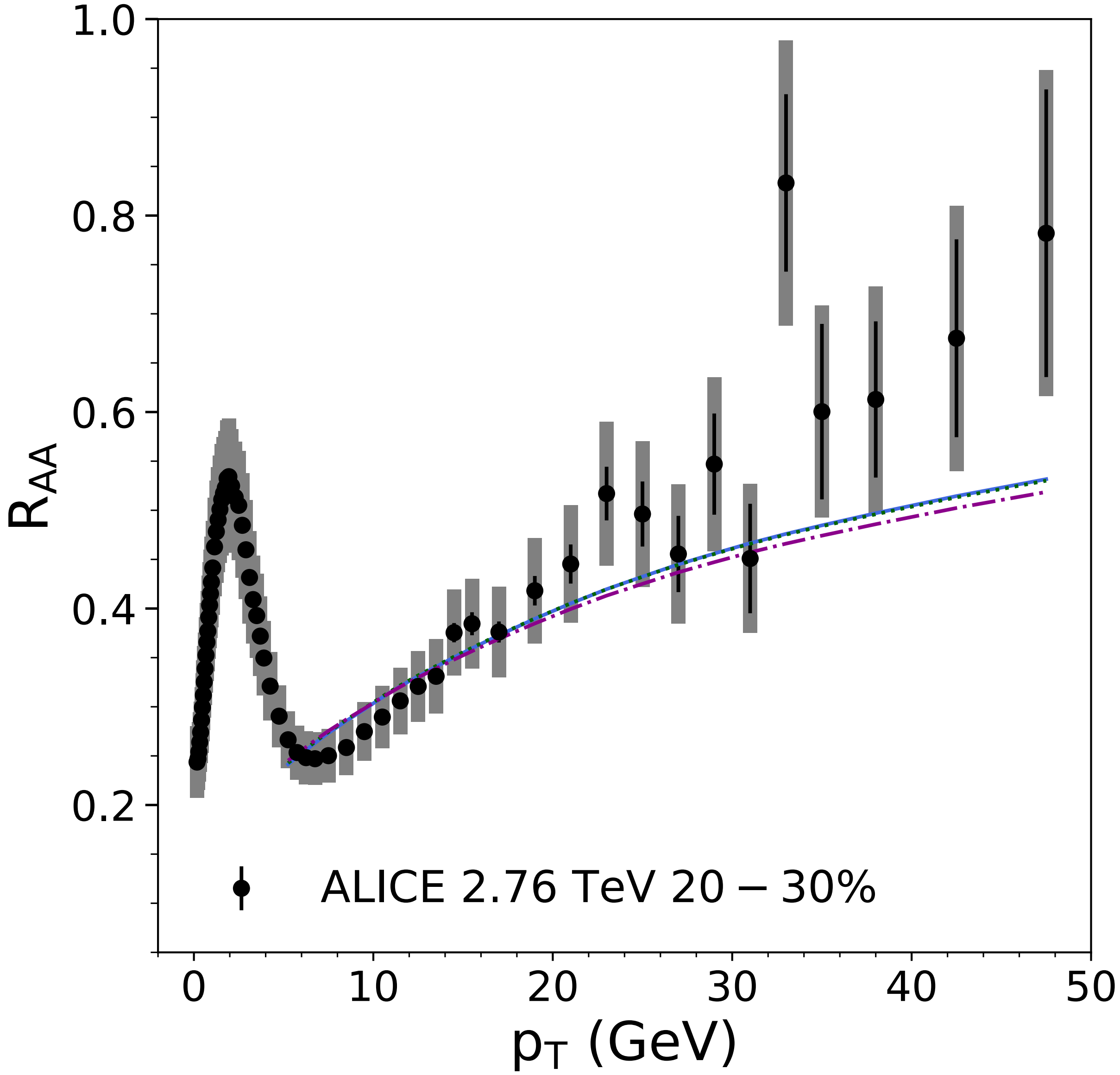
arXiv:1505.02677

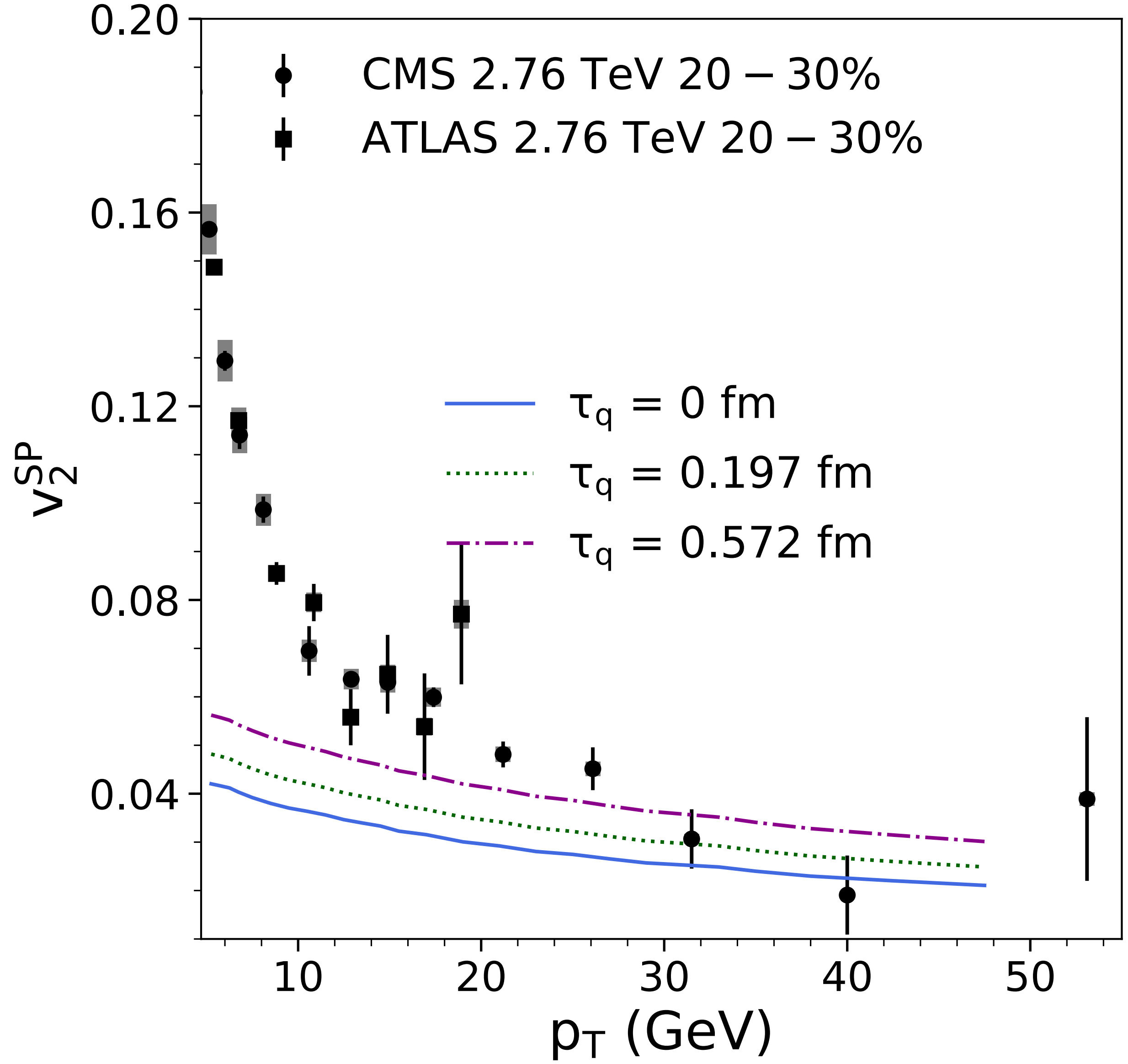
N=1 opacity

DSS07

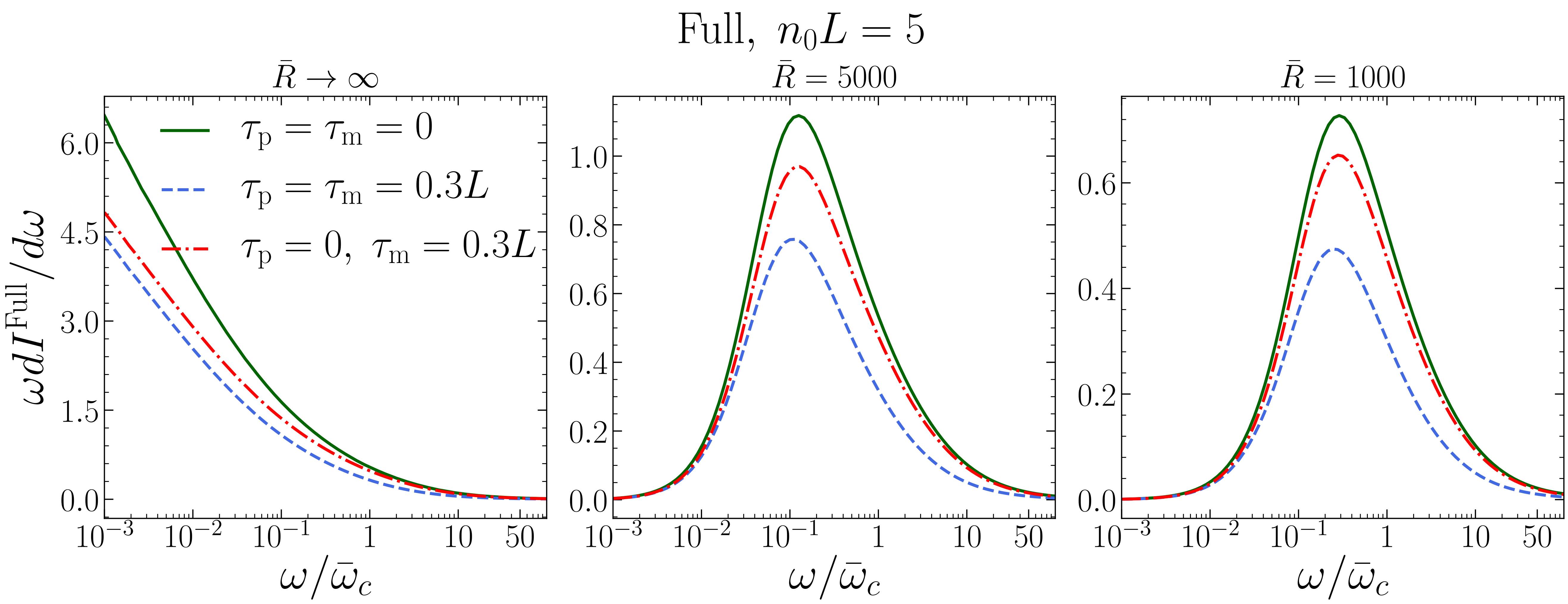
T_{dec}= 175 MeV

$\eta/s = param1$





Spectrum


Full, $n_0L = 5$
$\bar{R} \to \infty$
$\bar{R} = 5000$
$\bar{R} = 1000$
$\tau_p = \tau_m = 0$
$\tau_p = \tau_m = 0.3L$
$\tau_p = 0, \ \tau_m = 0.3L$
$\omega dI^{\mathrm{Full}}/d\omega$
$\omega/\bar{\omega}_c$
0.0
1.5
3.0
4.5
6.0
0.2
0.4
0.6
0.8
1.0
10^{-3}
10^{-2}
10^{-1}
1
10
50

R_{AA} and high-p_T v_2