Jet quenching in pA and AA

Carlota Andrés
Jefferson Lab

Electron Ion Collider User Group Meeting
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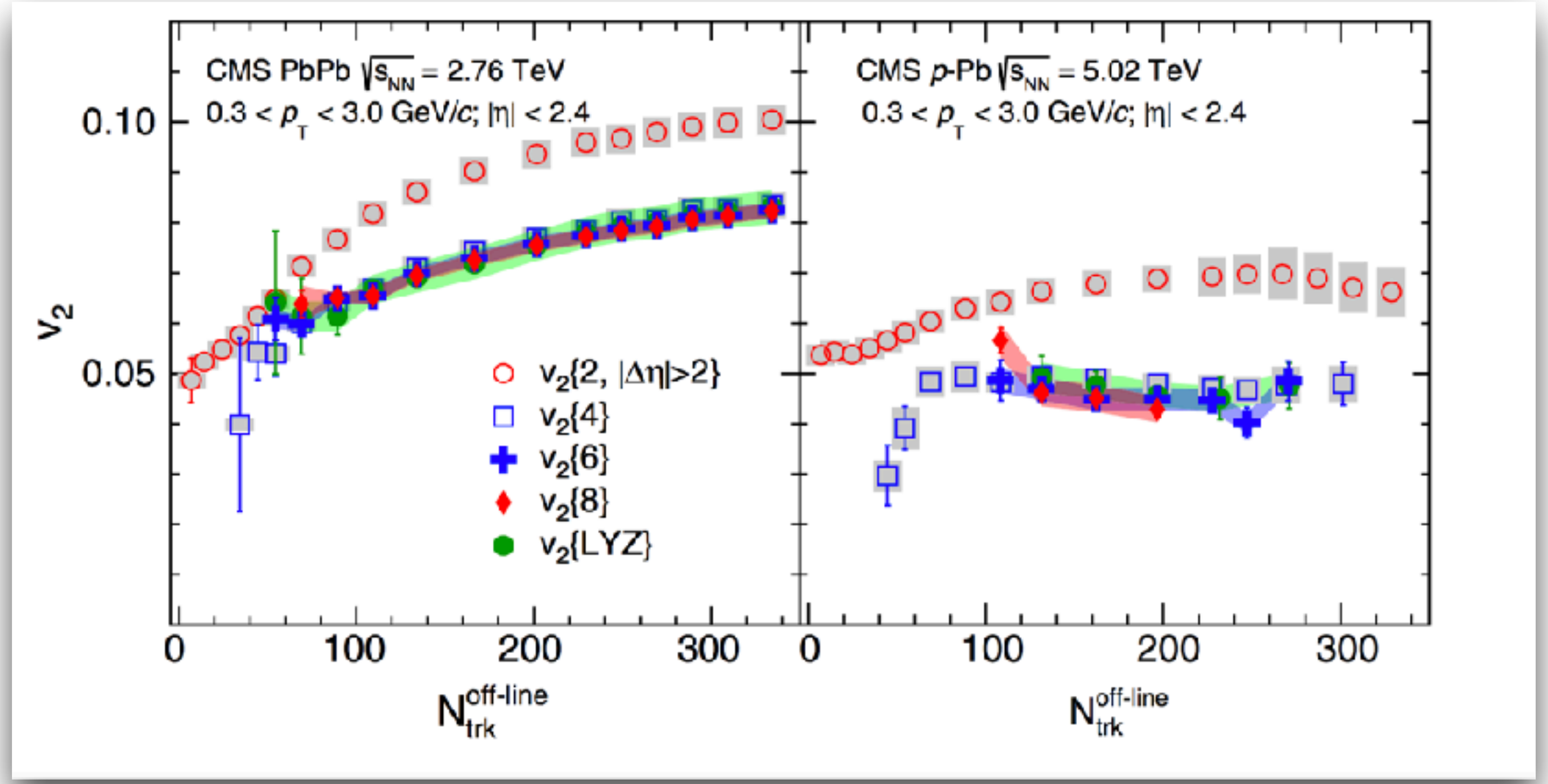
Jefferson Lab
EXPLORING THE NATURE OF MATTER

Collectivity in AA and pA



CMS Collaboration, Phys. Rev. Lett. 115, 012301

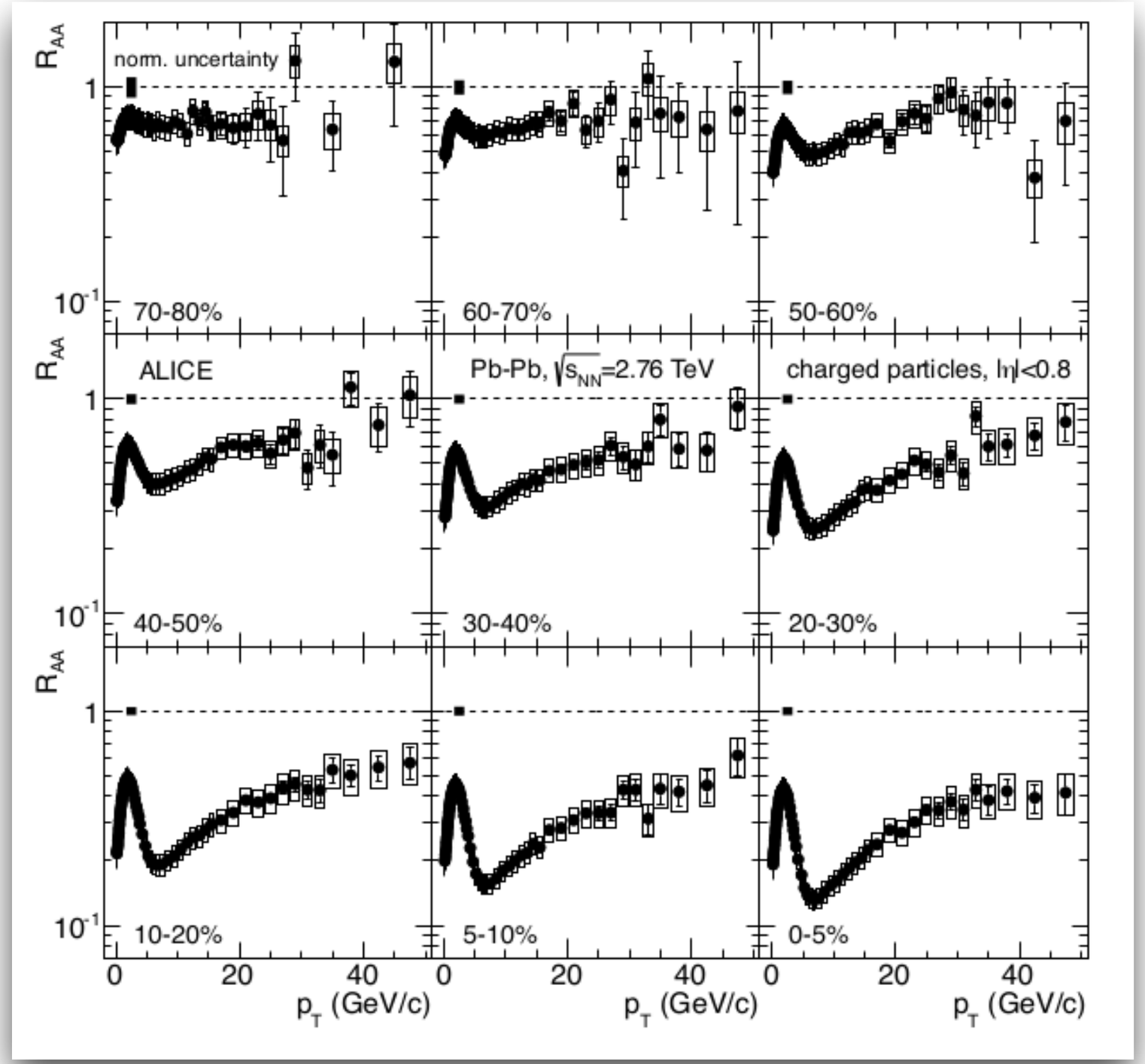
Collective behavior observed in small systems

R_{AA}

$$R_{AA} = \frac{dN_{AA}/d^2p_T dy}{\langle N_{coll}\rangle dN_{pp}/dp_T^2 dy}$$

Suppression of high-pt hadron spectrum AA relative to pp

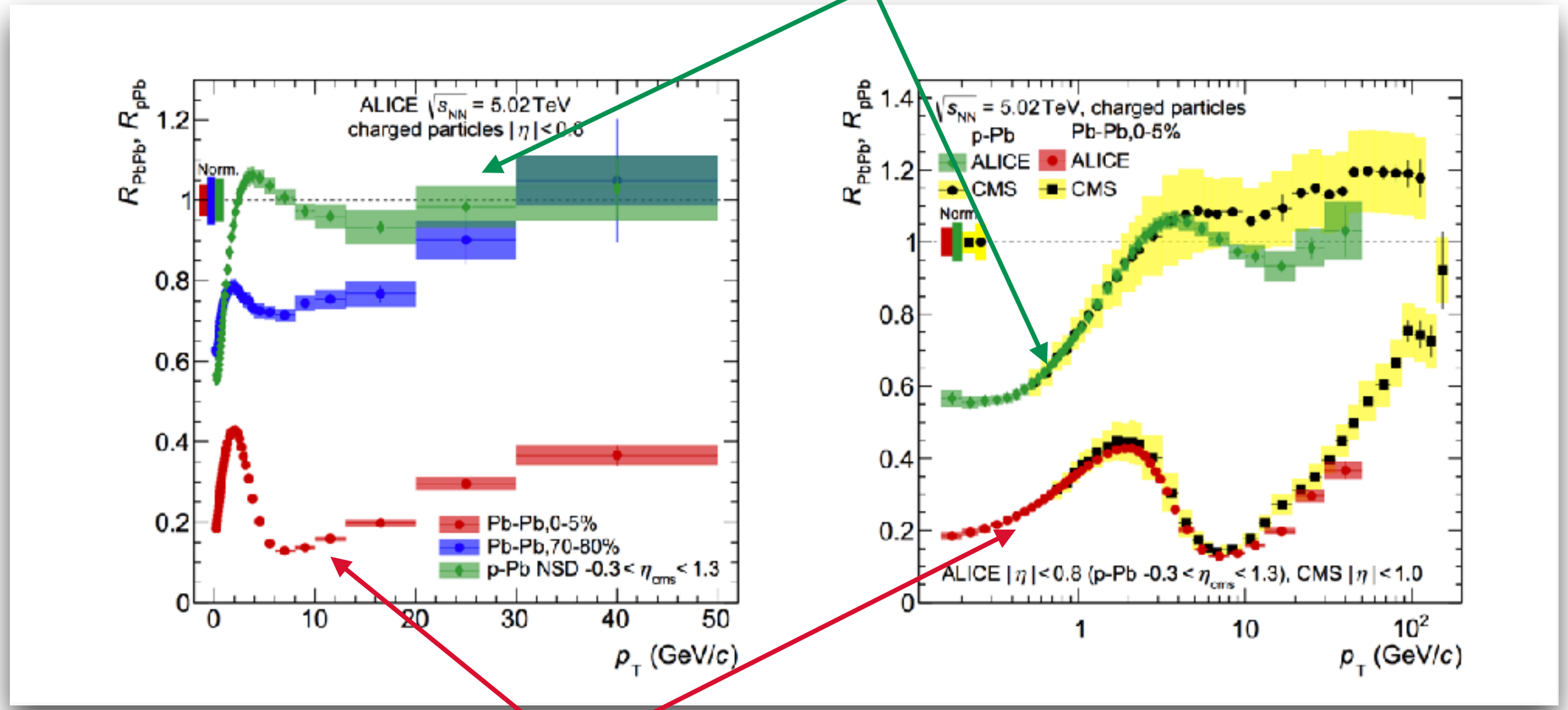
Clear probe of jet quenching



ALICE Collaboration, Phys. Lett. B 720 (2013) 52

R_{pA}

Minimum bias pPb



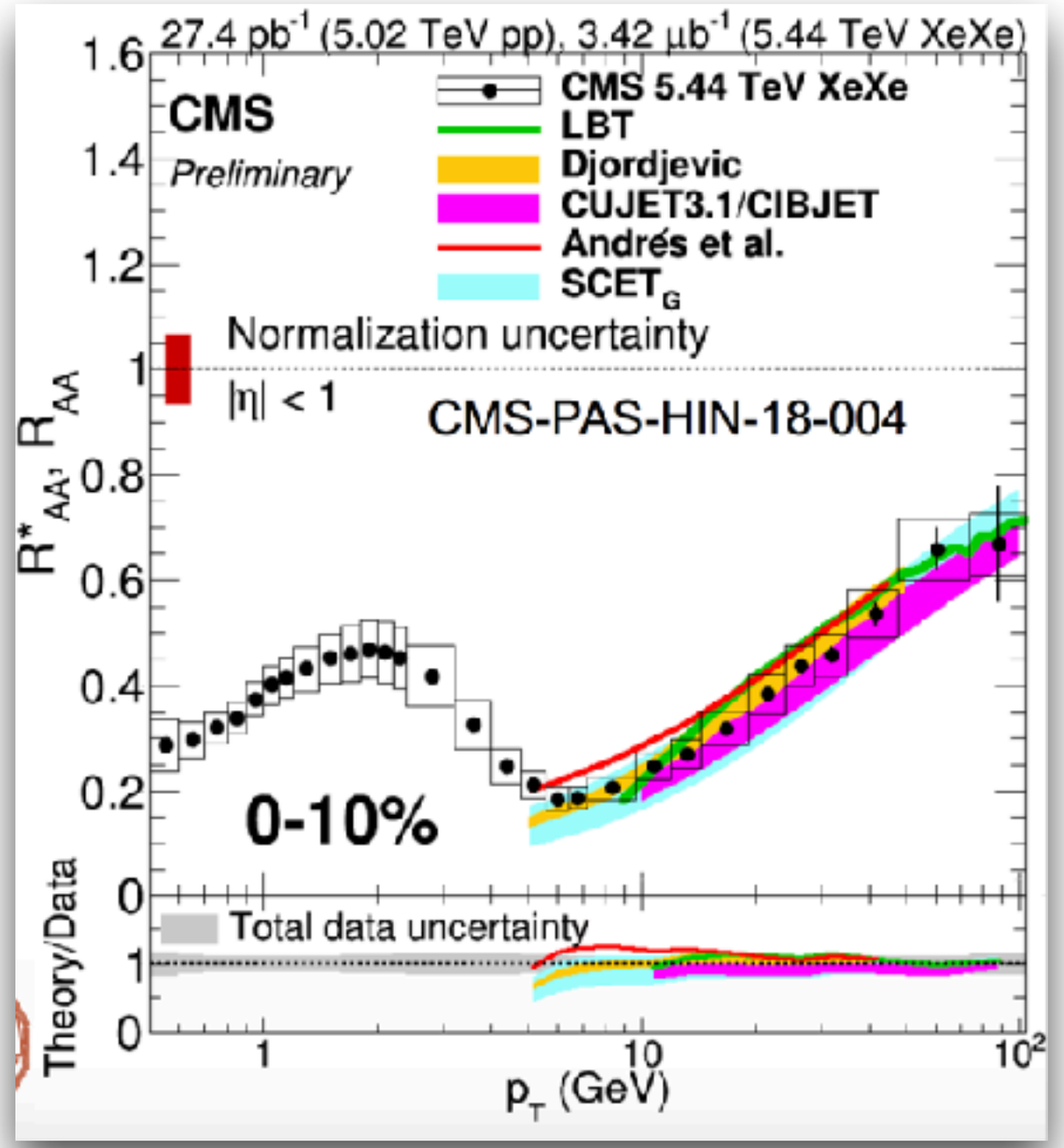
Central PbPb

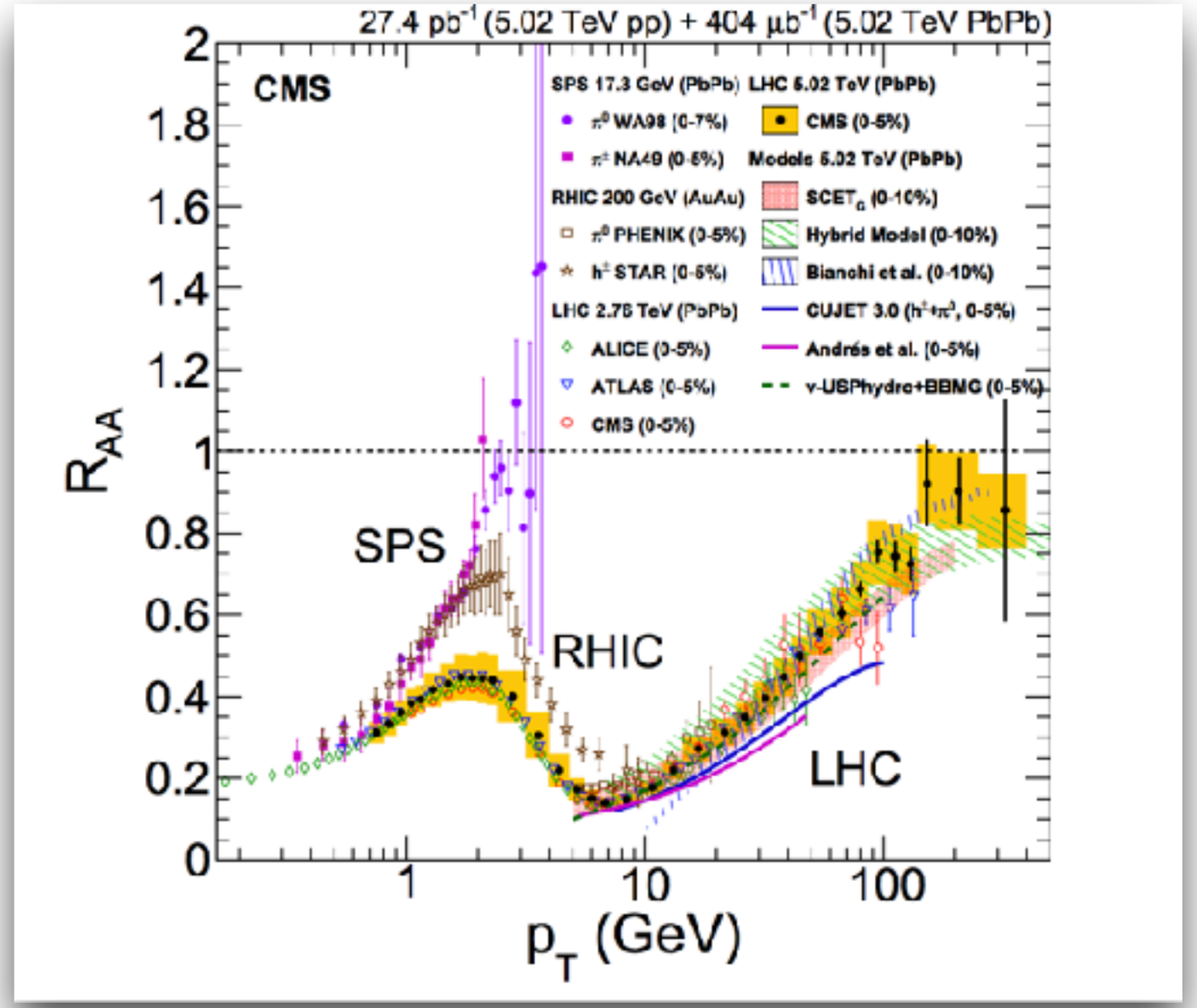
ALICE Collaboration, arXiv:1802.09145

Sign of QGP?

The R_{AA}-high p_T-v_2 puzzle

R_{AA}





CMS Collaboration, JHEP 04 039 (2017)

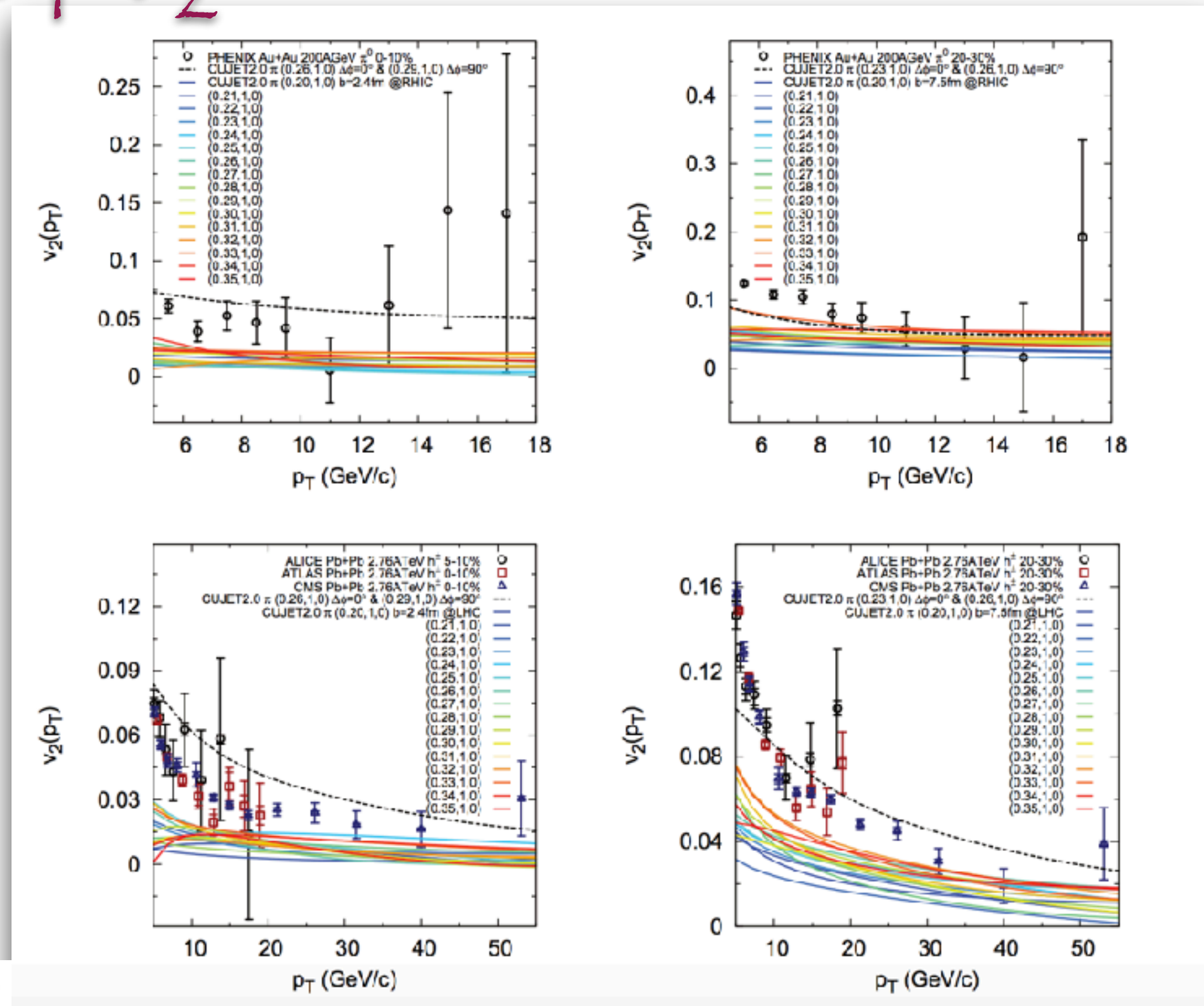
Austin Baty, QM2018

High-p_T V_2

LHC RHIC

Central

Semiperipheral



J. Xu et al.

JHEP 1408 (2014) 063

Formalism

C. Andrés et al.
Eur. Phys. J. C 76, 475 (2016)

- Single-inclusive cross section:

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

CTEQ6.6 + EPS09

- Fragmentation functions:

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

DSS

ENERGY LOSS: ASW Quenching Weights (QWs)

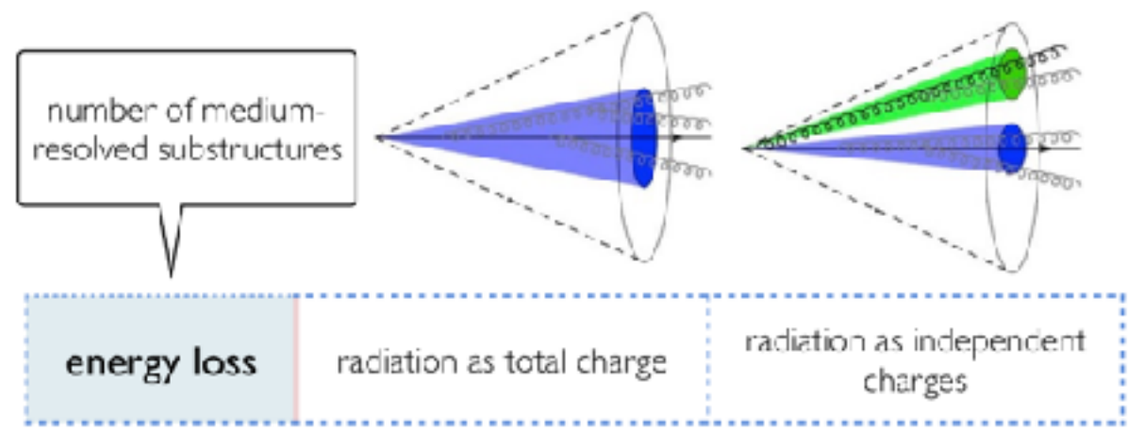
Probability distribution of a fractional energy loss, $\epsilon = \Delta E/E$, of the hard parton in the medium

Quenching Weights

- Based on two assumptions:
  - Fragmentation functions are NOT medium-modified

Total coherence case:

- Jets lose energy as a single parton
- FFs vacuum-like



KT, HP 2016

Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, PLB 725 357 (2013)

- Gluon emissions are independent

Good approximation for soft radiation

J. P. Blaizot, F. Dominguez, E. Iancu and Y. Mehtar-Tani, JHEP 1301 143 (2013)

Quenching Weights II

- Computed in the Multiple Soft Scattering approximation

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

Perturbative tails neglected

- Dynamic medium (Scaling relations):

$$\omega_c^{eff}(x_0, y_0, \tau_{\rm prod}, \phi) \;=\; \int d\xi\, \xi\, \hat{q}(\xi) \qquad R^{eff}(x_0, y_0, \tau_{\rm prod}, \phi) \;=\; \frac{3}{2}\int d\xi\, \xi^2\, \hat{q}(\xi)$$

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

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

Fitting parameter

EKRT hydro

EKRT hydrodynamics

- EKRT event by event hydrodynamics

  Initial conditions: minijets + saturation model

  $\tau_0 = 0.197\,\mathrm{fm}$

  $\eta/s = 0.2$

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

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

  Phys. Rev. C 93, 024907 (2016)

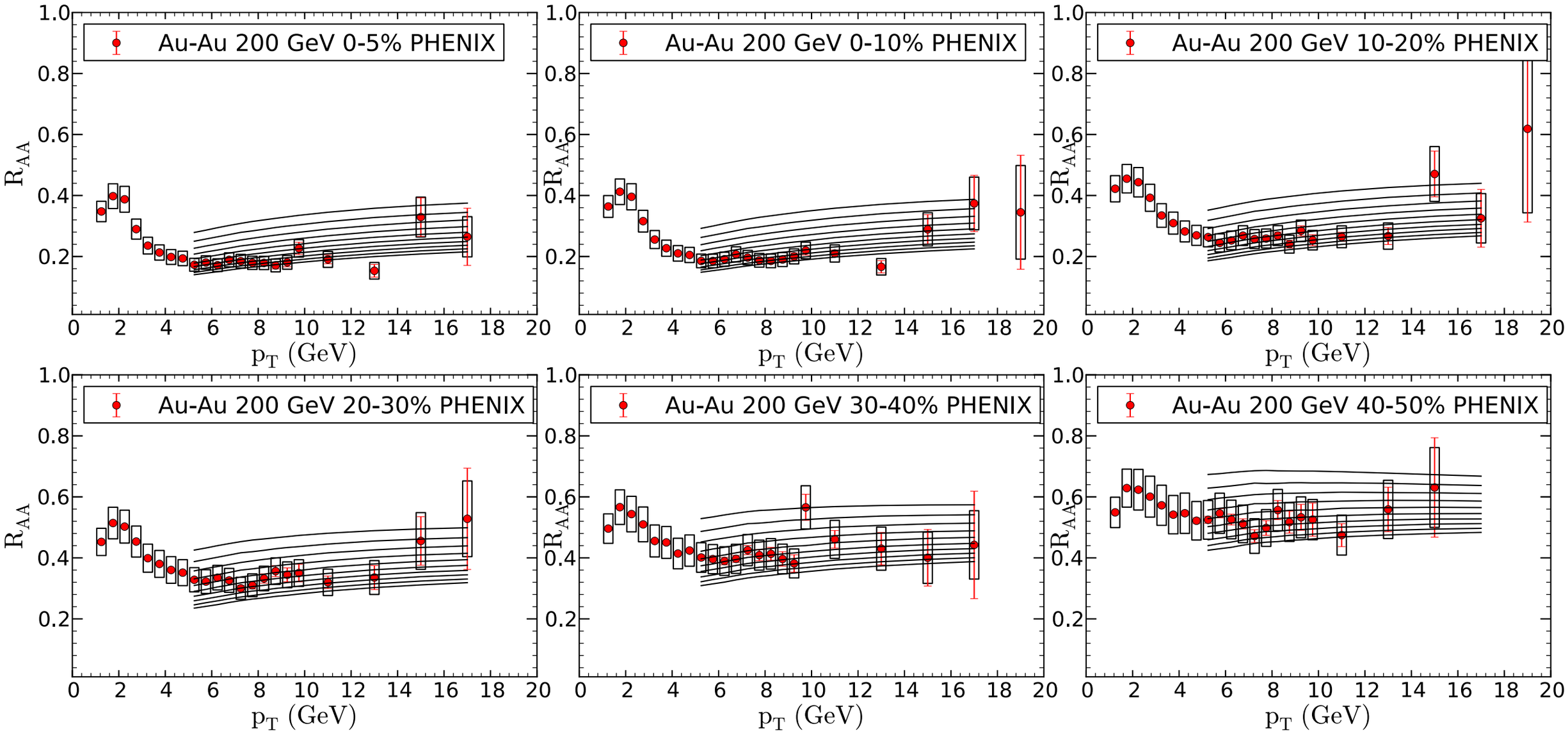
- Before thermalization:

  $\hat{q}(\xi) = \hat{q}(\tau_0) \quad \text{for} \quad \xi < \tau_0$

  $\hat{q}(\xi) = 0 \quad \text{for} \quad \xi < \tau_0$

R_{AA} at 200 GeV

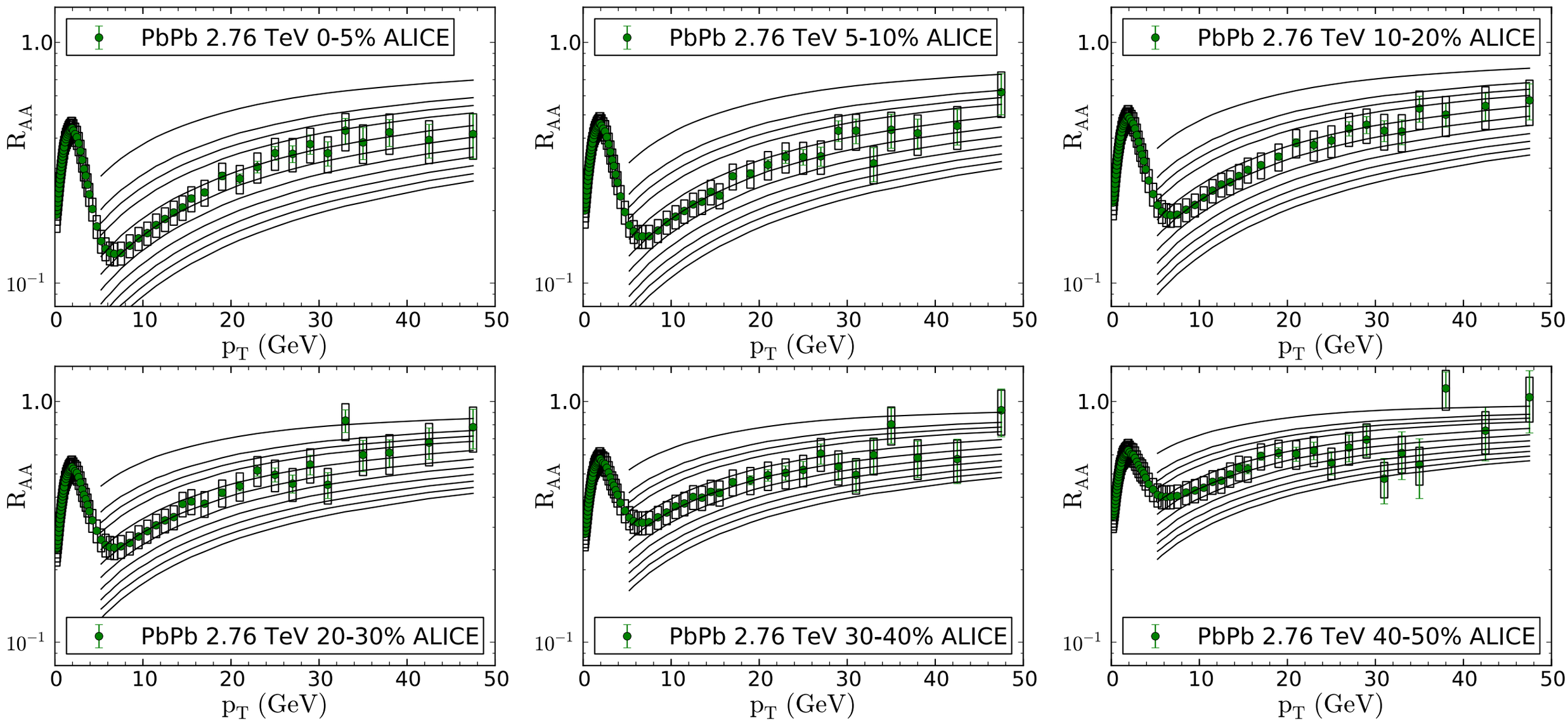
$$\hat{q}(\xi) = \hat{q}(\tau_0) \quad \text{for} \quad \xi < \tau_0$$



χ^2 to obtain the best value of K. $\Delta\chi^2 = 1$.

R_{AA} at 2.76 TeV

$$\hat{q}(\xi) = \hat{q}(\tau_0) \quad \text{for} \quad \xi < \tau_0$$



χ^2 to obtain the best value of K. $\Delta\chi^2 = 1$.

The scalar product

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

where:

$$v_n^{hard}(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\phi \cos\left[n\phi - n\psi_n^{hard}(p_T)\right] R_{AA}(p_T,\phi)}{R_{AA}(p_T)} \qquad \psi_n^{hard} = \frac{1}{n}\arctan\left(\frac{\int_0^{2\pi} d\phi \sin(n\phi)\, R_{AA}(p_T,\phi)}{\int_0^{2\pi} d\phi \cos(n\phi)\, R_{AA}(p_T,\phi)}\right)$$

A description of high-p_T anisotropic flow needs both hard and soft sectors

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

Average over all the events

Matthew Luzum and Jean-Yves Ollitrault, Phys. Rev. C87 (2013) 044907

J. Noronha-Hostler et al., Phys. Rev. Lett. 116, 252301 (2016)

High-p_T V_2

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

PbPb 2.76 TeV

Hydro: v-USPhydro

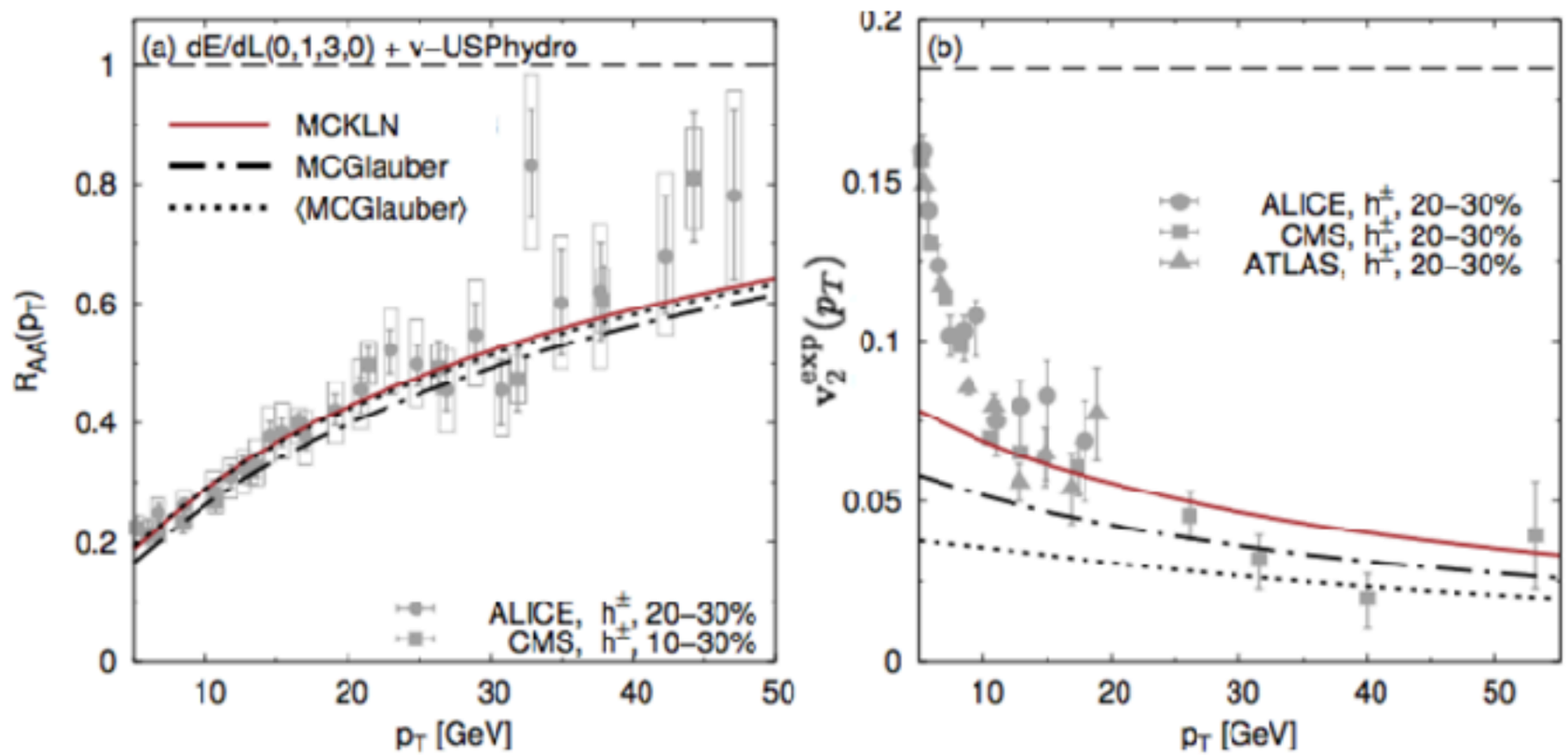
$\tau_0 = 0.6\,\mathrm{fm}$

McGlauber $\eta/s = 0.08$

$T_F = 130\,\mathrm{MeV}$

MCKLN $\eta/s = 0.11$

$T_F = 120\,\mathrm{MeV}$



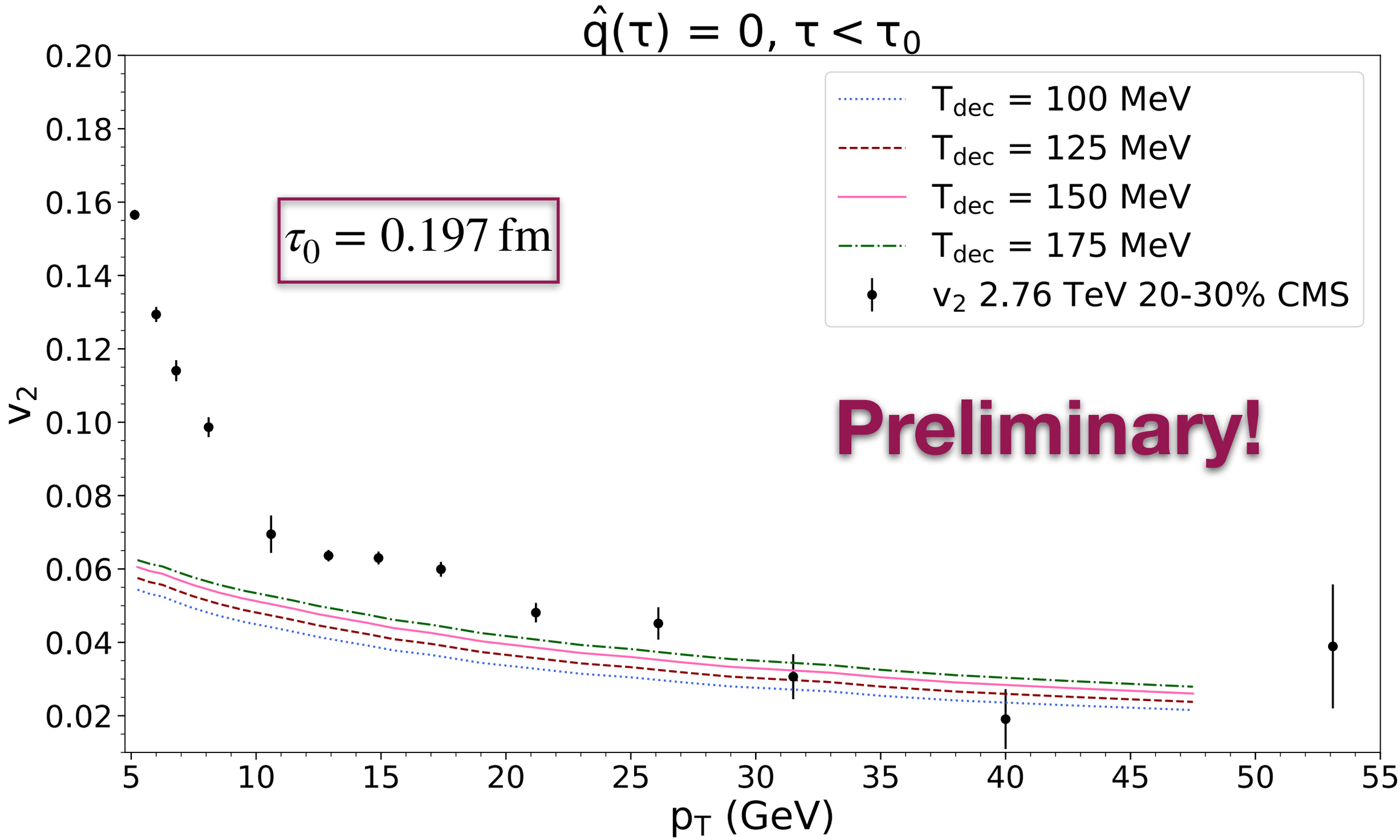
Energy loss $\frac{dE}{dL} \sim L$

J. Noronha-Hostler et al. Phys. Rev. Lett. 116, 252301 (2016)

NO energy loss before thermalization

High-p_T V_2

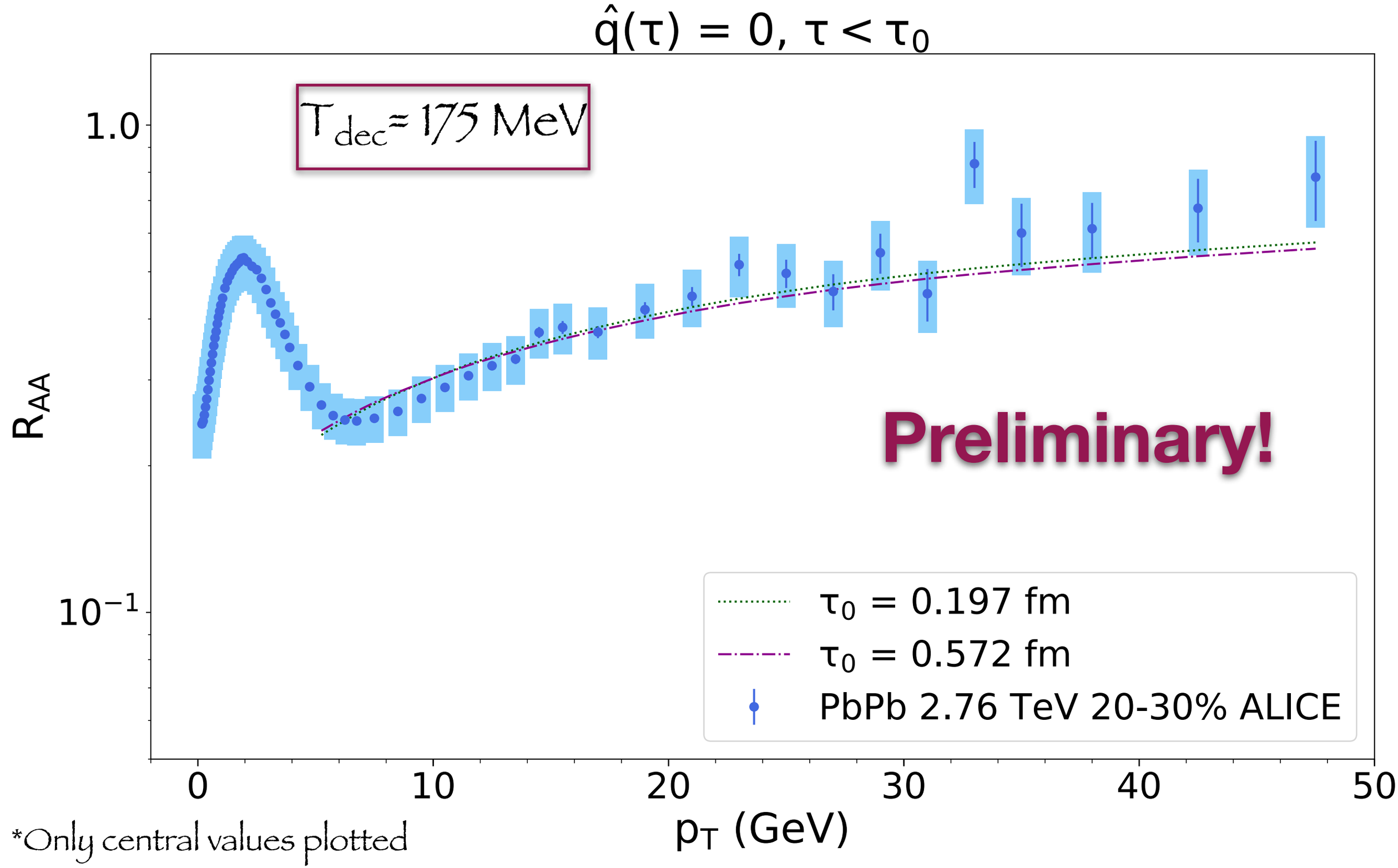
$\eta/s = 0.2$



Dependence on τ_0

R_{AA}

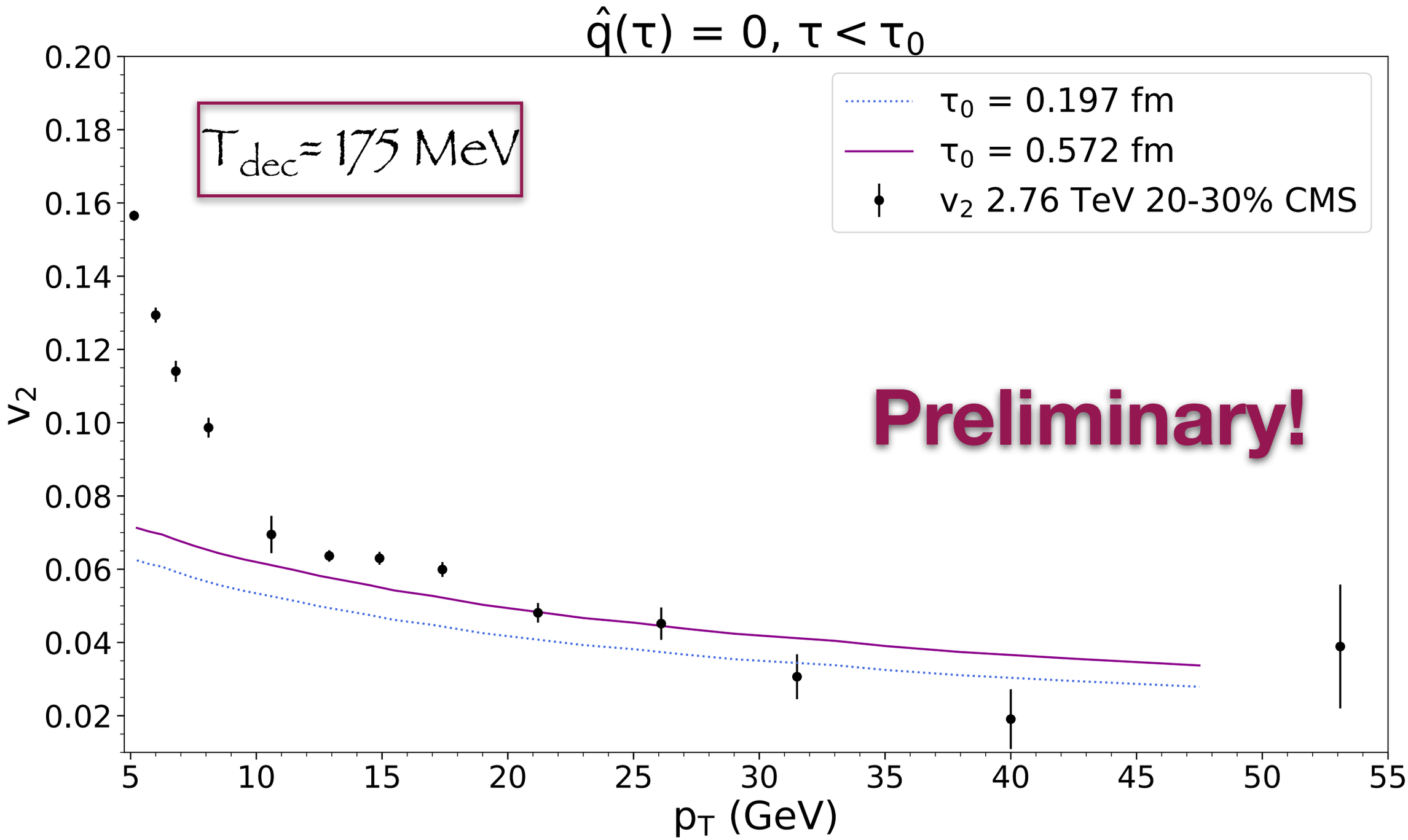
$\eta/s = 0.2$



*Only central values plotted

High-p_T V_2

$\eta/s = 0.2$



Limitations

- Perturbative tails neglected
  Only included in CUJET and AMY

- ASW QWs supported by coherence: if coherence is broken they could fail

- Scaling relations only proven for $\hat{q} \propto 1/\tau^{\alpha}$

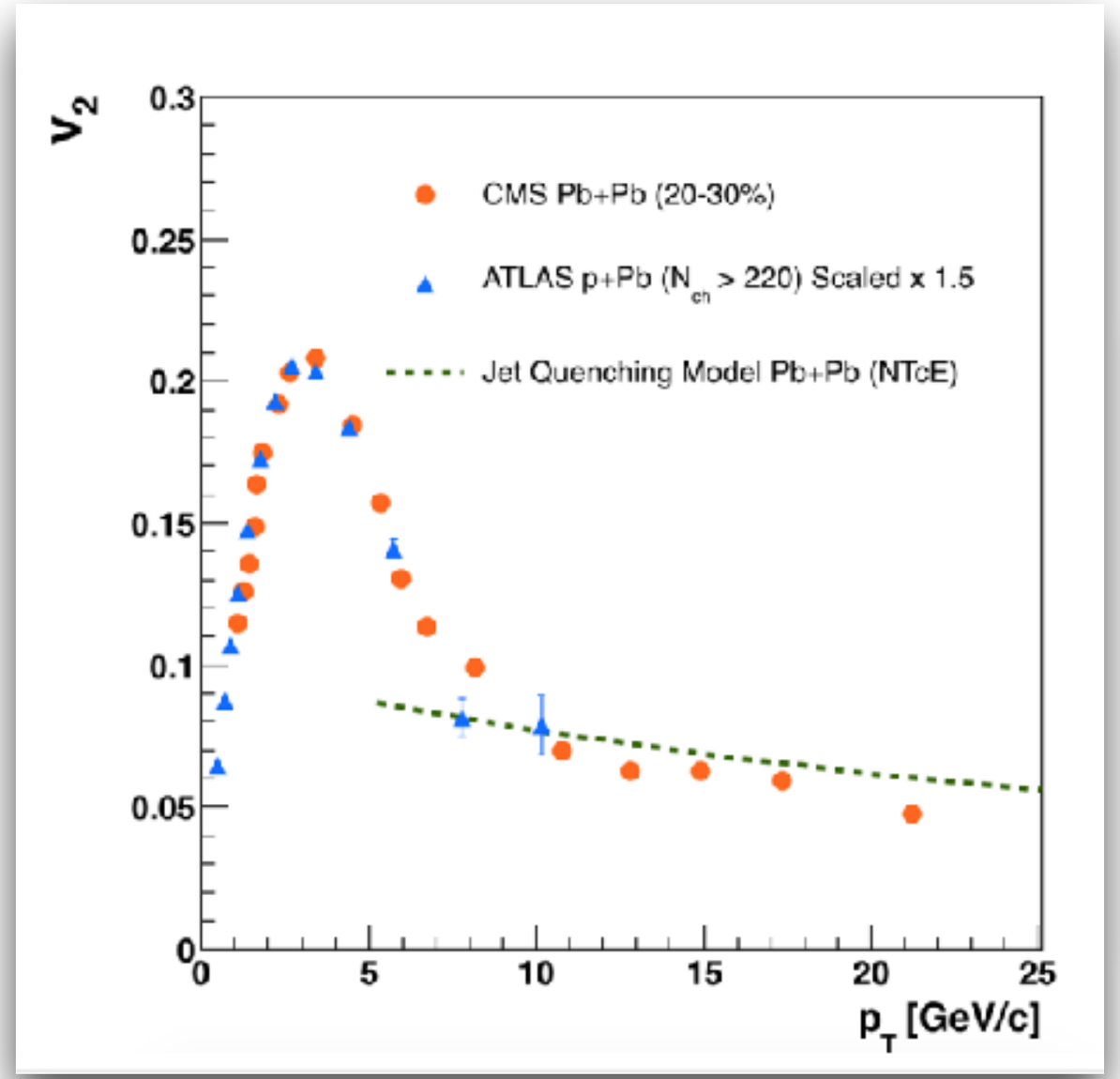
- Collisional energy loss neglected

Open questions

- Is the scalar product the complete solution to the R_{AA}-v_2 puzzle?
- When does the energy loss start? Energy loss before thermalization?
- Do the initial conditions of the hydro play a key role?
- And the freeze-out?
- And the viscosity?
- Could high-p_T harmonics be used to constrain the detailed mechanism of energy loss?

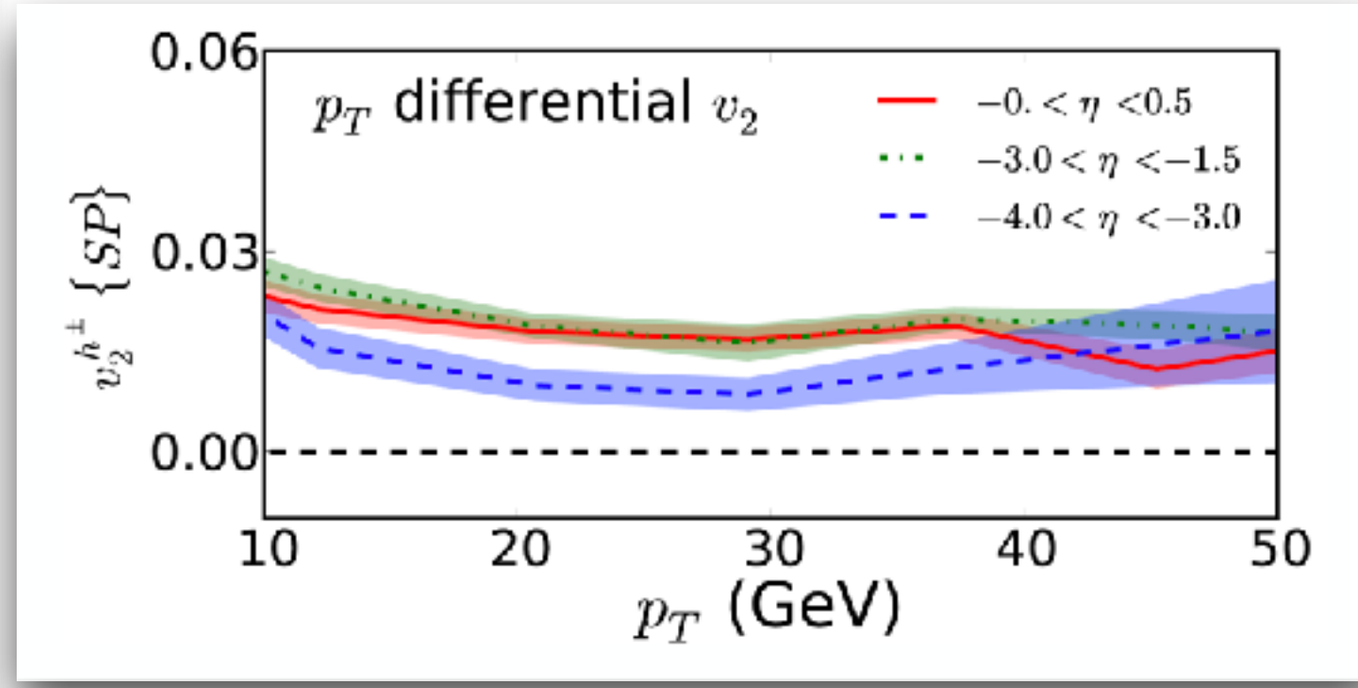
Jet quenching in pA?

High-p_T v_2 in pPb



pPb 5.02 TeV 0-5%

MARTINI + MUSIC



C. Park et al. Nucl. Part. Phys. Proc. 289 (2017)

Backup slides

- Quenching Weights

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

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

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

arXiv:hep-ph/0209038, R. Baier.

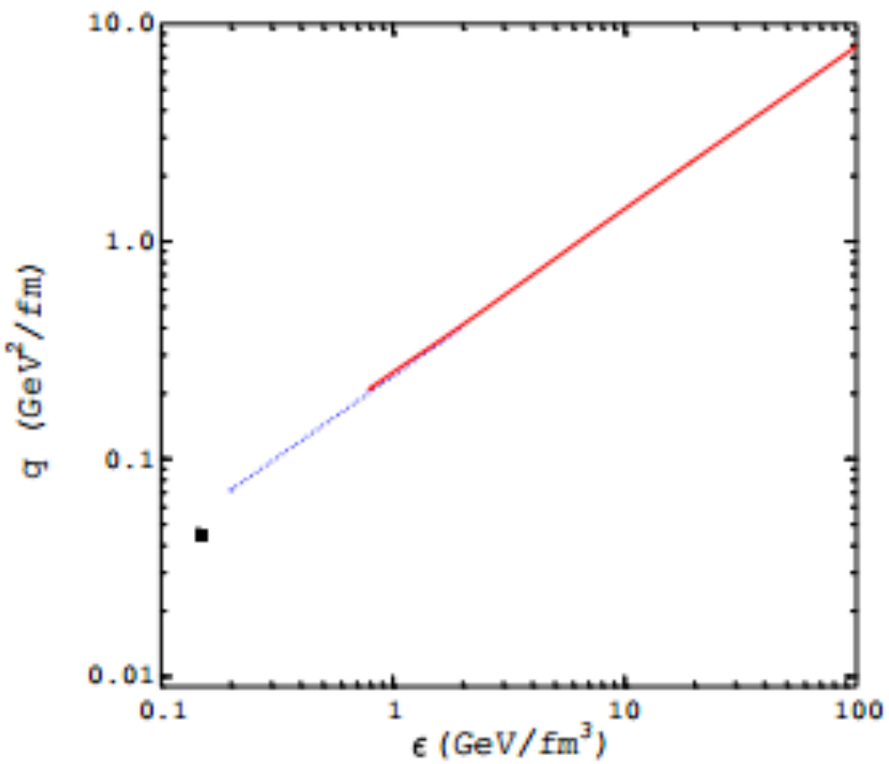
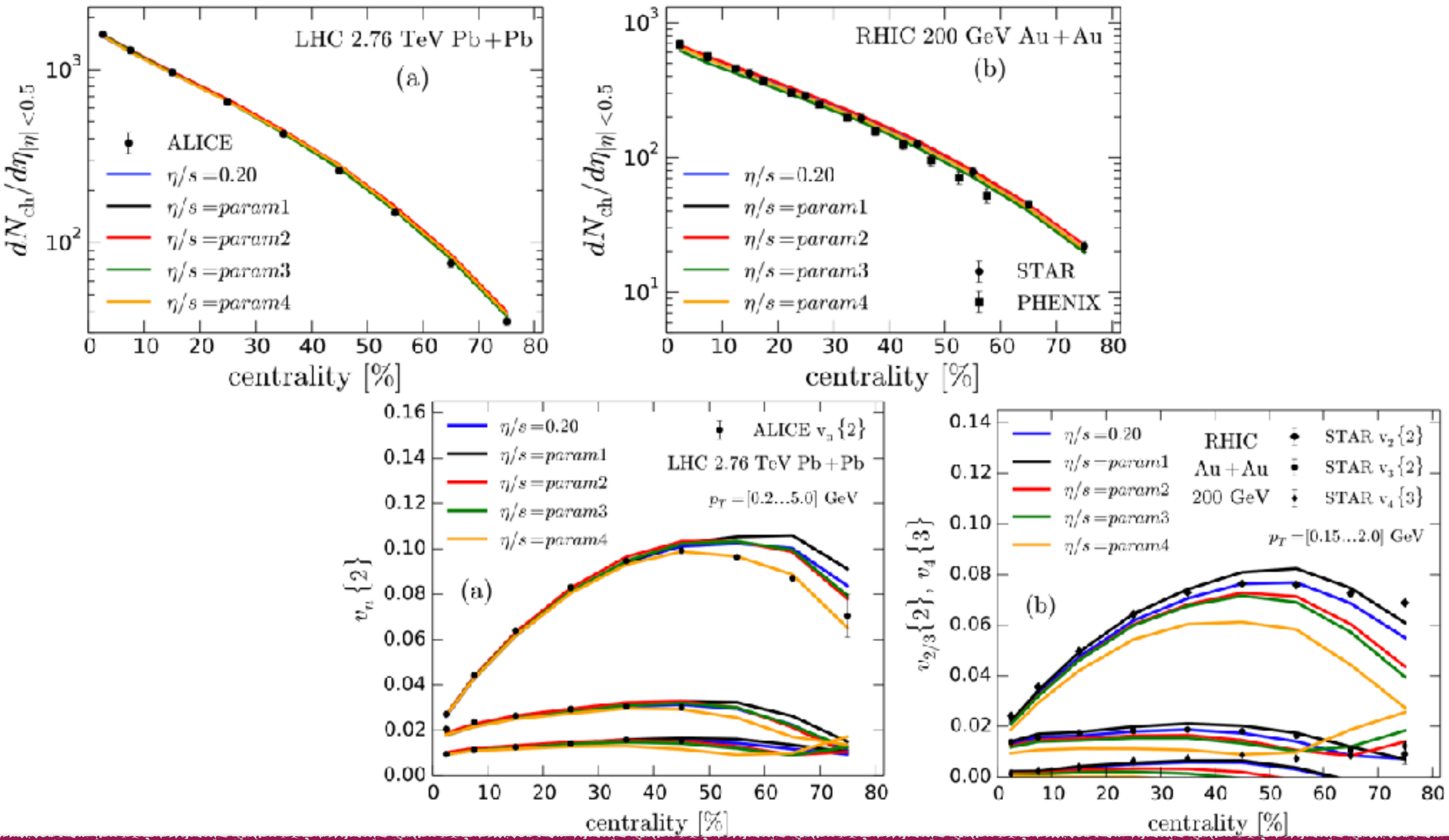


Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)

EKRT Hydro

Phys. Rev. C 93, 024907 (2016)