

# Constraining energy loss with high- $p_T$ azimuthal asymmetries

Carlota Andrés

Jefferson Lab

Hard Probes 2018

Aix-les-Bains, France

October 1-5, 2018

In collaboration with:

N. Armesto, H. Niemi, R. Paatelainen, Carlos Salgado, Pía Zurita

# Constraining energy loss with high- $p_T$ azimuthal asymmetries ?

Carlota Andrés

Jefferson Lab

Hard Probes 2018

Aix-les-Bains, France

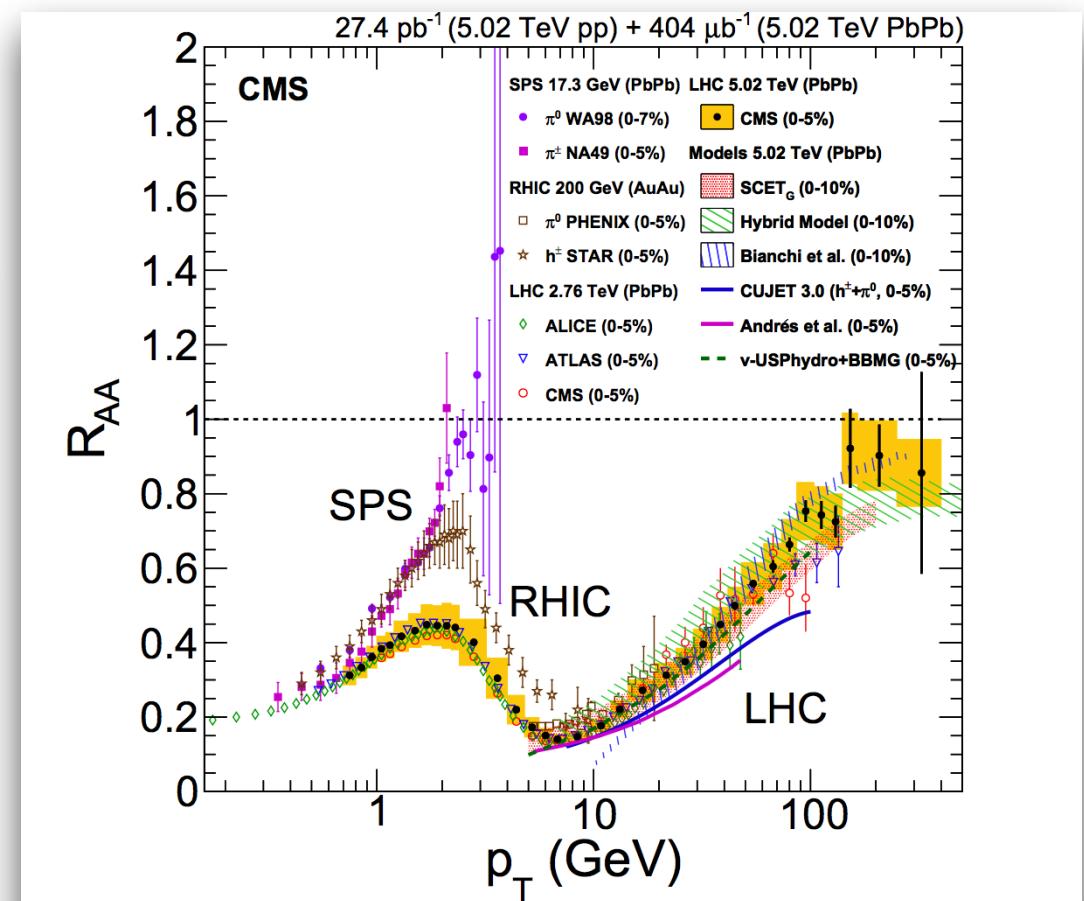
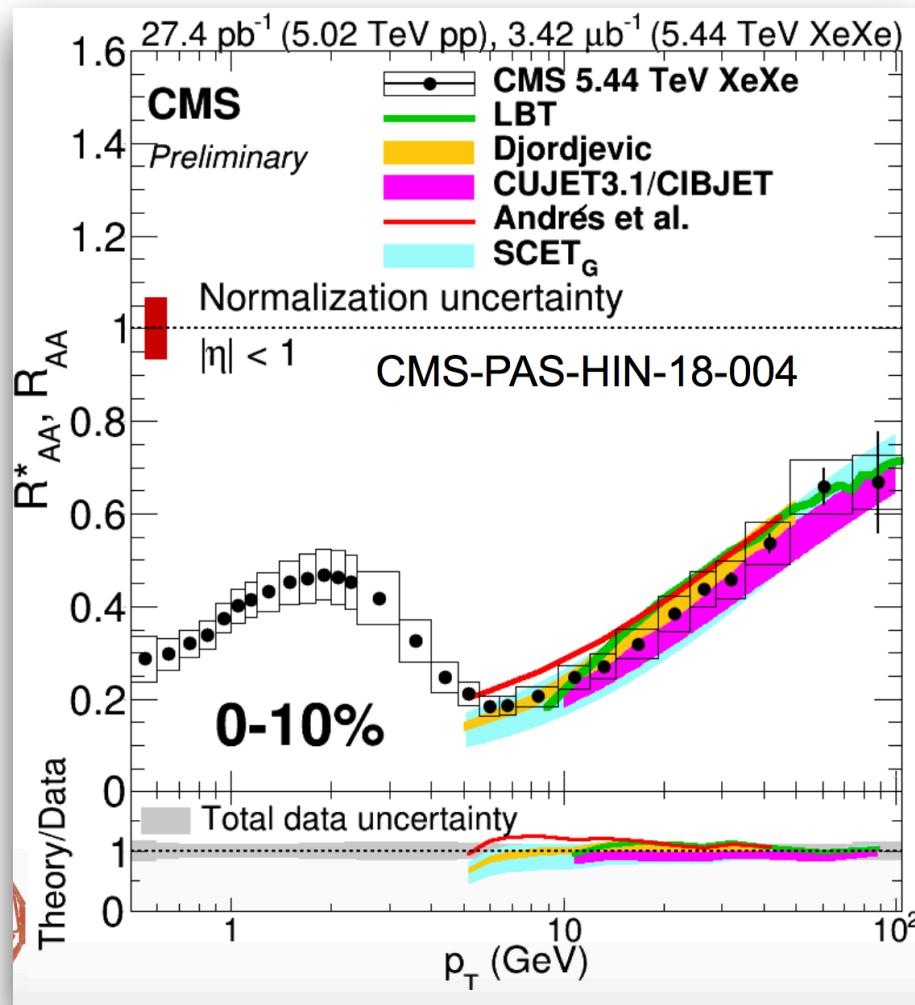
October 1-5, 2018

In collaboration with:

N. Armesto, H. Niemi, R. Paatelainen, Carlos Salgado, Pía Zurita

# Nuclear modification factor

# $R_{AA}$



CMS Collaboration, JHEP 04 039 (2017)

Austin Baty, QM2018

Carlota Andrés

# Formalism

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

- Single-inclusive cross section:

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

CTEQ6.6 + EPS09

- Fragmentation functions:

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

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

- Computed in the Multiple Soft Scattering approximation

$$\sigma(\mathbf{r})n(\xi) \simeq \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2 \quad \text{Perturbative tails neglected}$$

- 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

$$\tau_0 = 0.197 \text{ fm}$$

$$\eta/s = 0.2$$

$$T_{ch} = 175 \text{ MeV}$$

Phys. Rev. C 93, 024907 (2016)

$$T_{dec} = 100 \text{ MeV}$$

- Before thermalization:

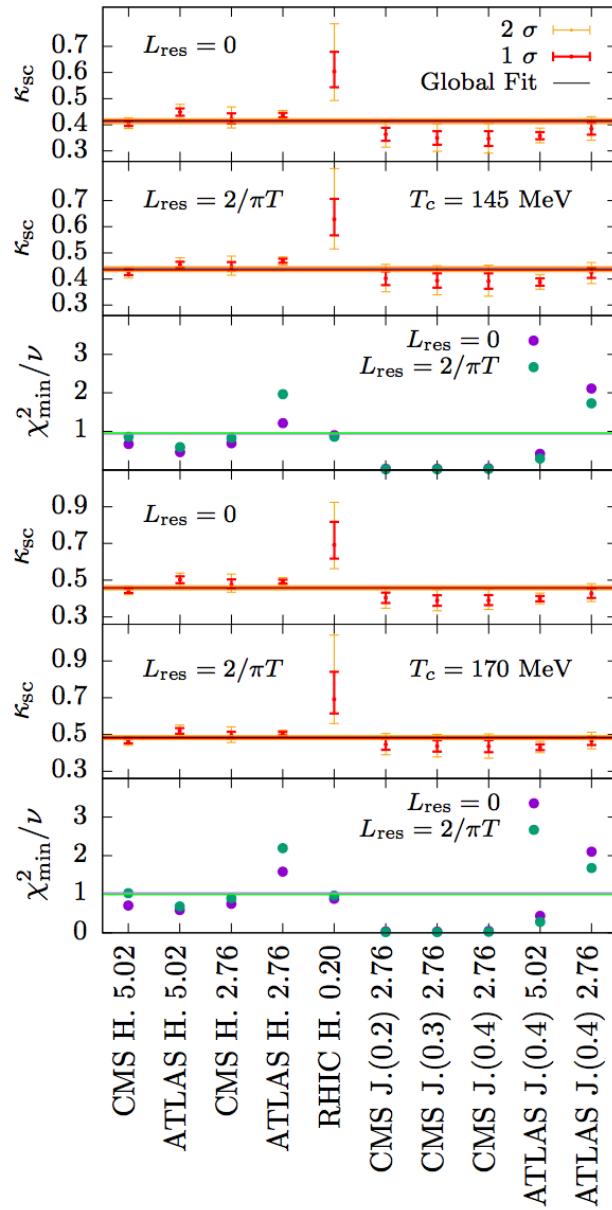
$$\hat{q}(\xi) = \hat{q}(\tau_0) \quad \text{for} \quad \xi < \tau_0$$

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

NO energy loss before thermalization!

# The K-factor puzzle

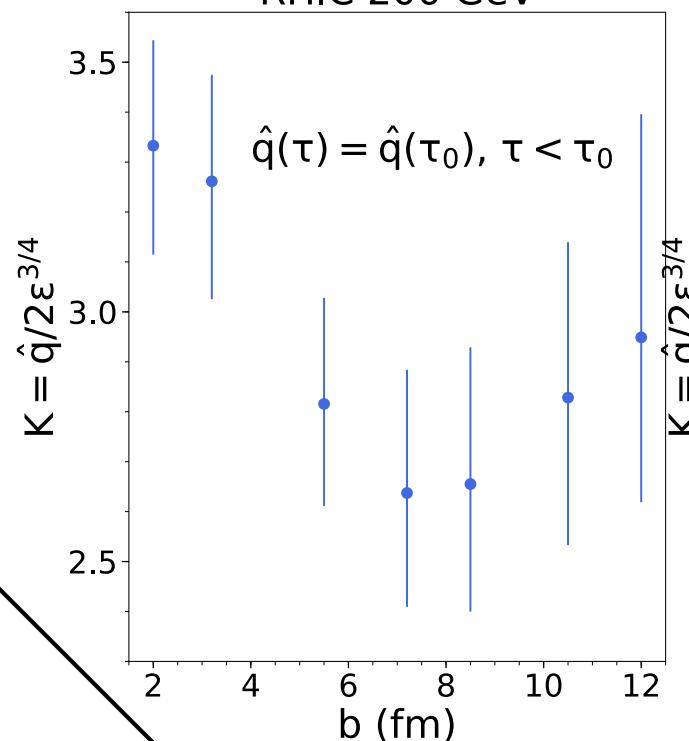
Casalderrey et al. 1808.07386



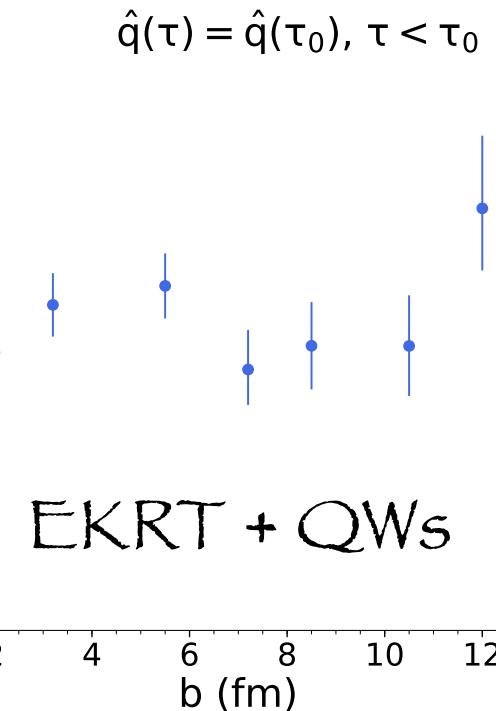
Jet quenching parameter larger at RHIC than at LHC

Eur. Phys. J. C 76, 475 (2016)

RHIC 200 GeV



LHC 2.76 TeV



Hybrid model. Daniel Pablos parallel Thursday

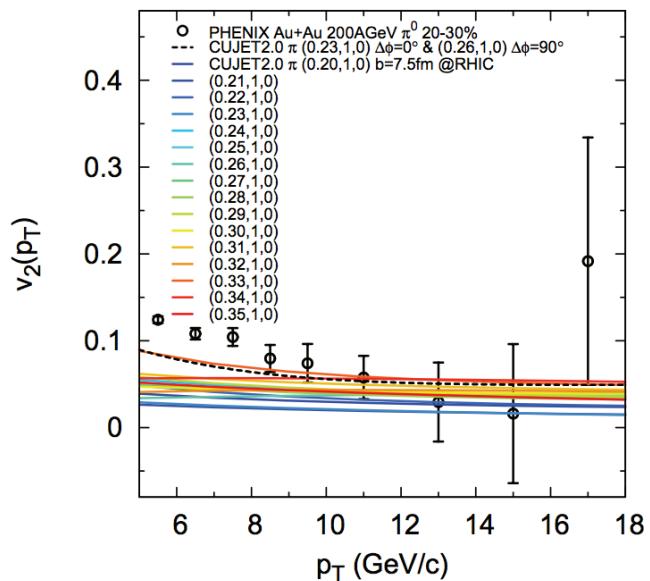
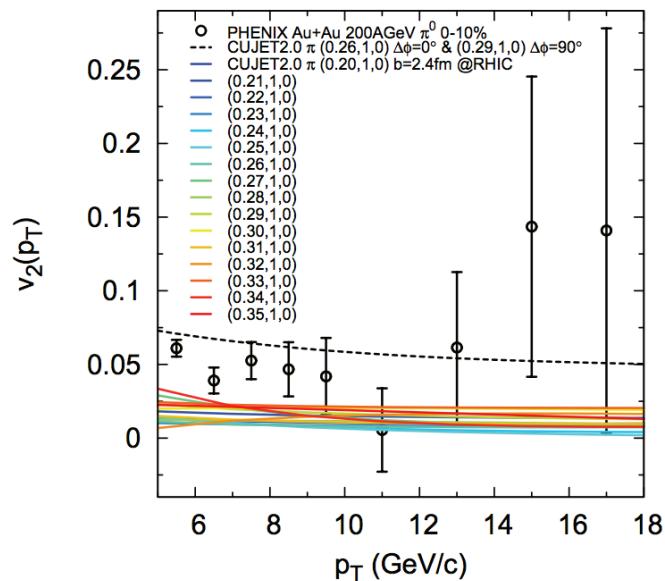
# High- $p_T$ harmonics

# High- $p_T$ $v_2$

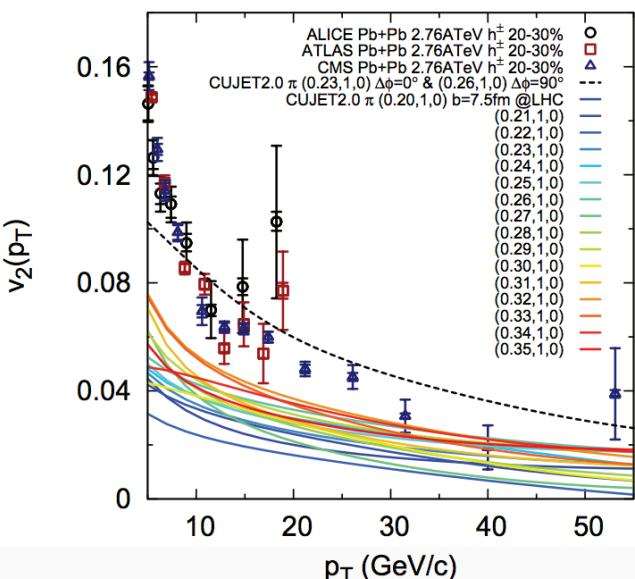
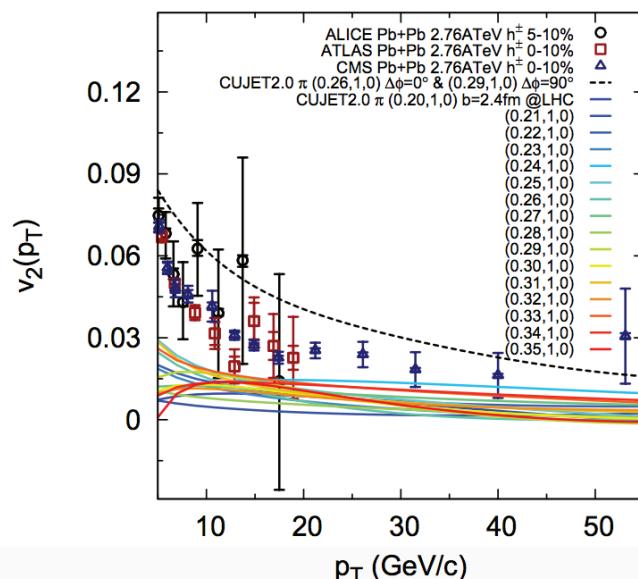
LHC

RHIC

Central



Semiperipheral



J. Xu et al.

JHEP 1408 (2014) 063

# The scalar product

Fourier expansion

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

where:

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

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

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

Scalar product:

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

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- $p_T$ $V_2$

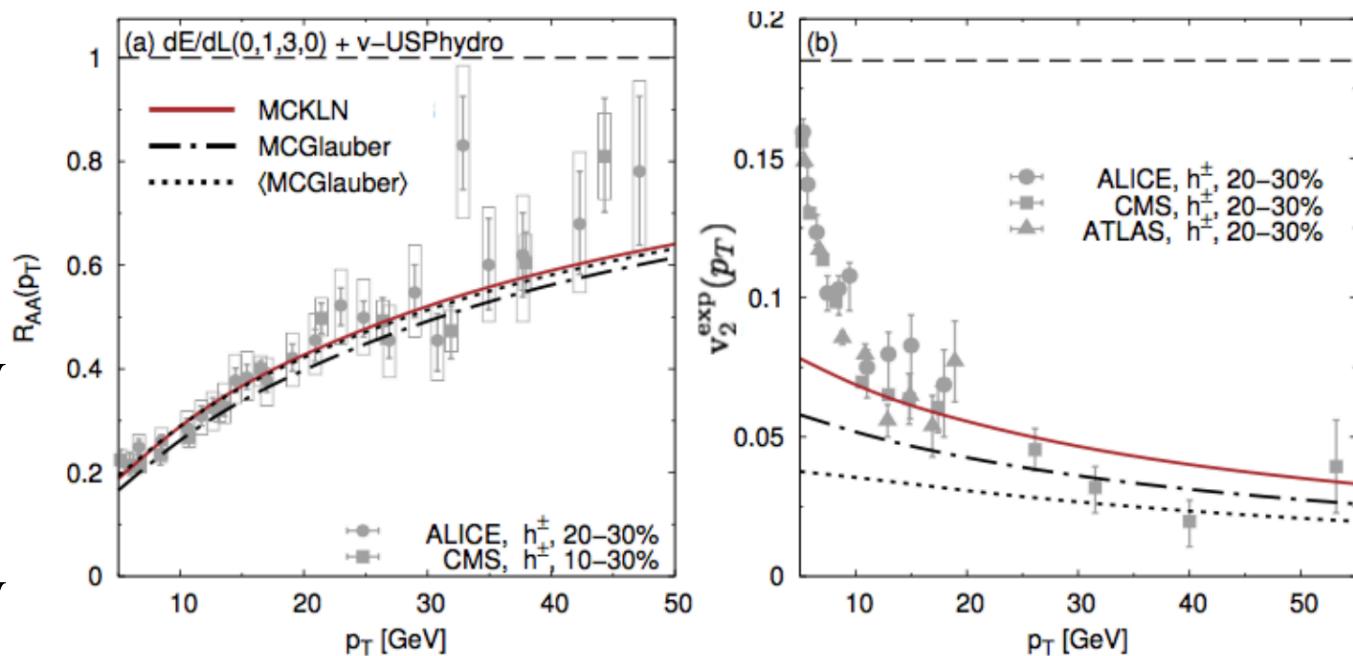
PbPb 2.76 TeV

Hydro: v-USPhydro

$$\tau_0 = 0.6 \text{ fm}$$

McGlauber     $\eta/s = 0.08$   
 $T_F = 130 \text{ MeV}$

MCKLN     $\eta/s = 0.11$   
 $T_F = 120 \text{ MeV}$



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

- $\eta/s$  very different from that of EKRT.  
 Apparently results are quite dependent  
 on the entropy.

See: arXiv: 1609.05171 [nucl-th]

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

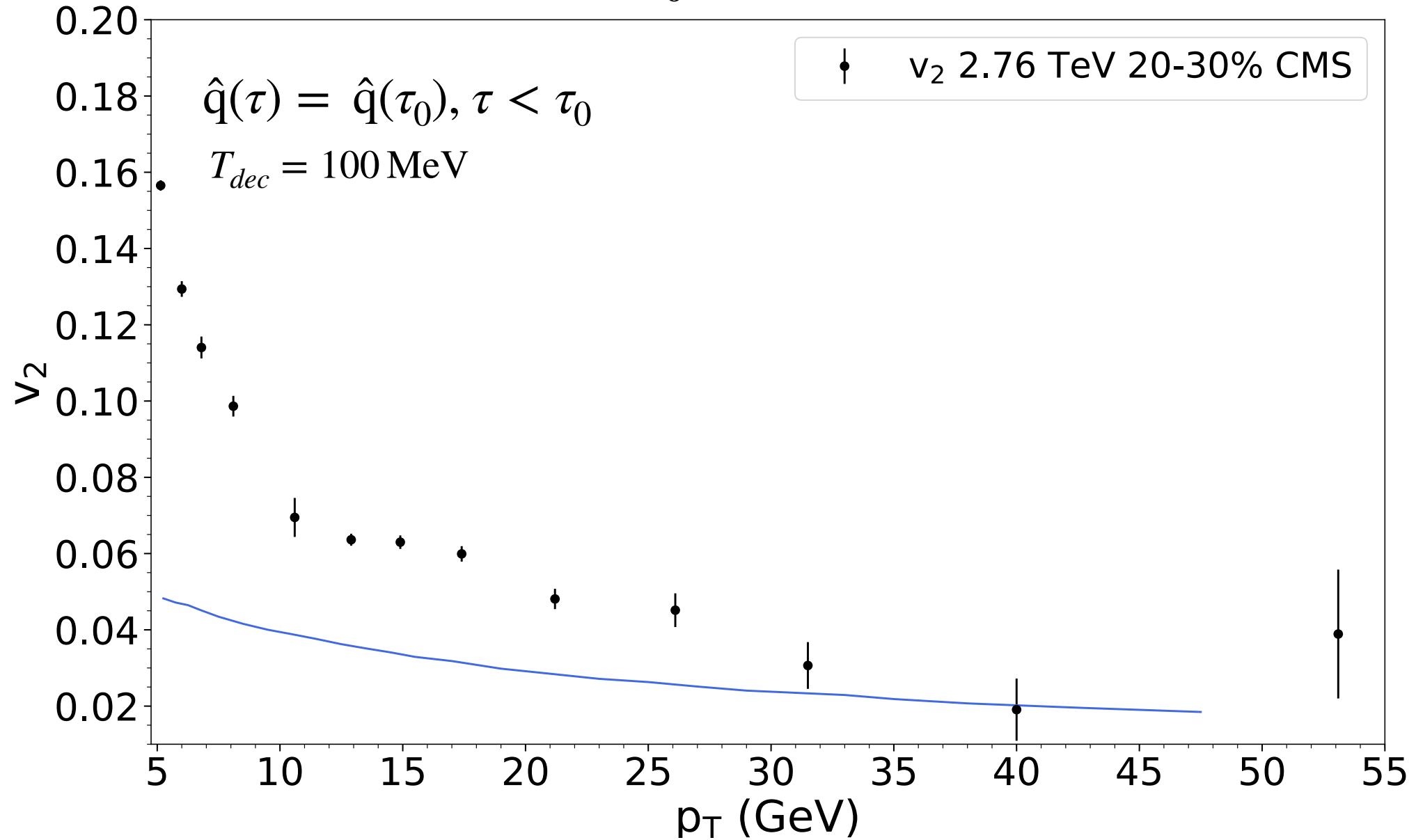
NO energy loss before thermalization

# High- $p_T$ $v_2$

$\eta/s = 0.2$

$\tau_0 = 0.197 \text{ fm}$

EKRT + QWs

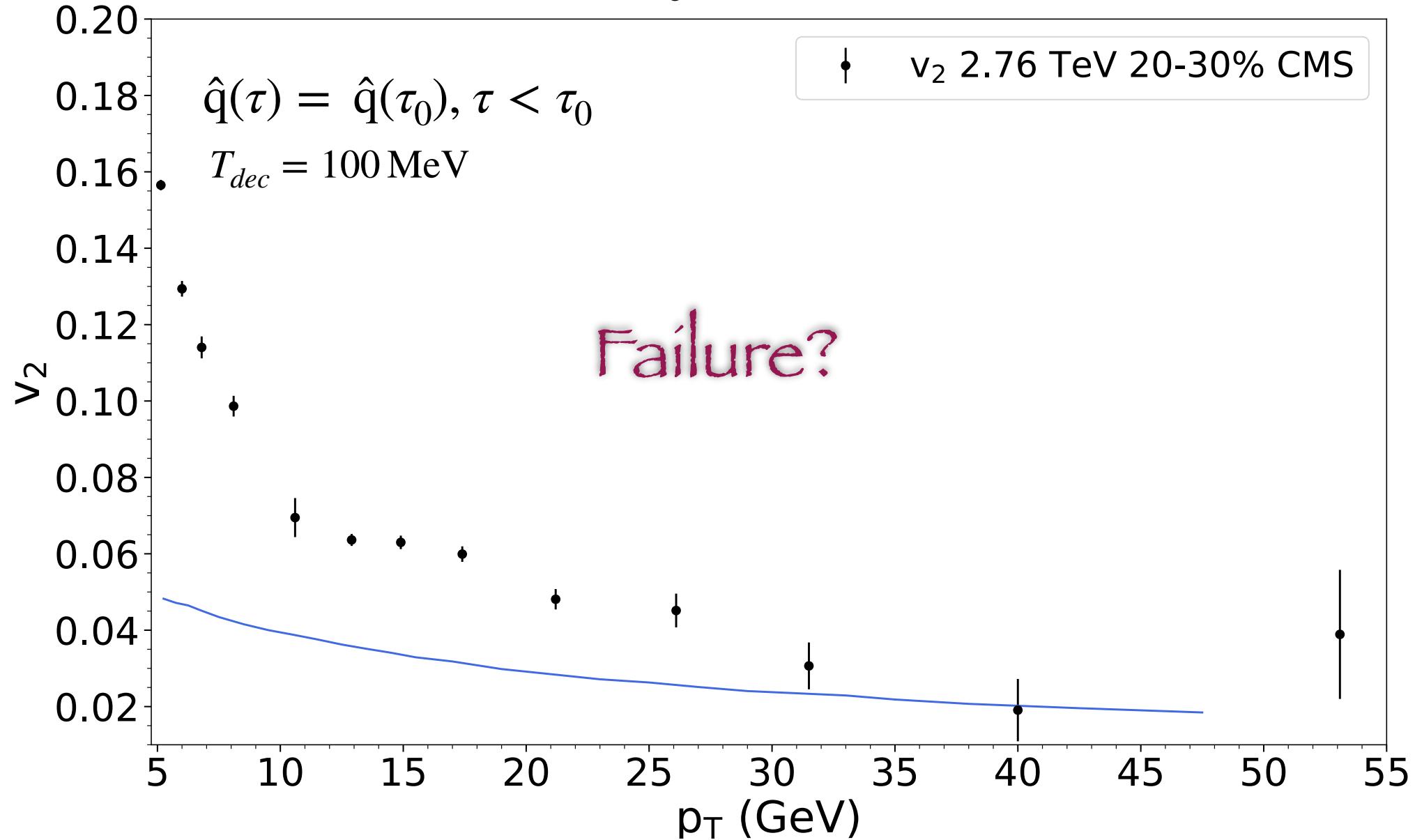


# High- $p_T$ $v_2$

$\eta/s = 0.2$

$\tau_0 = 0.197 \text{ fm}$

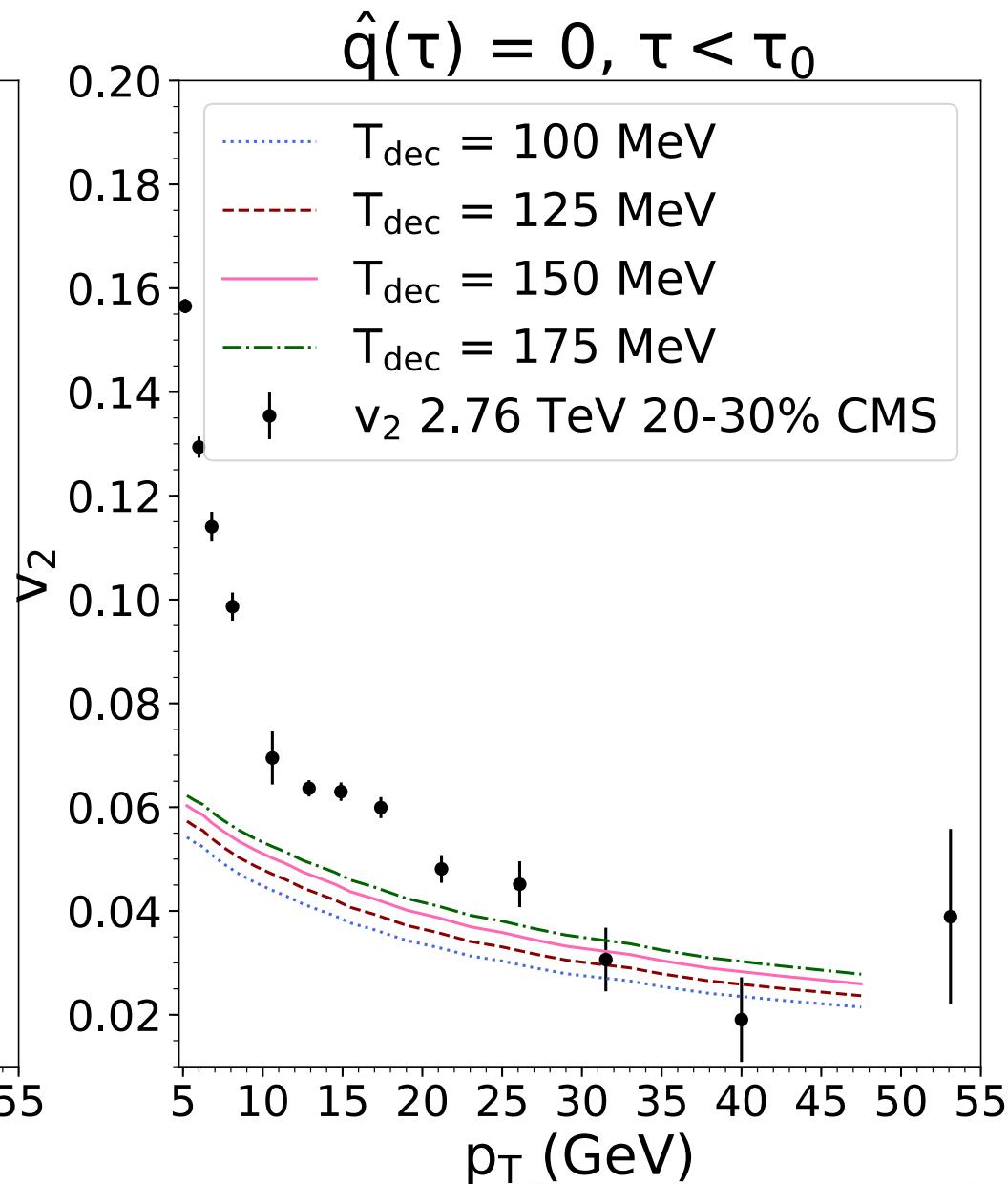
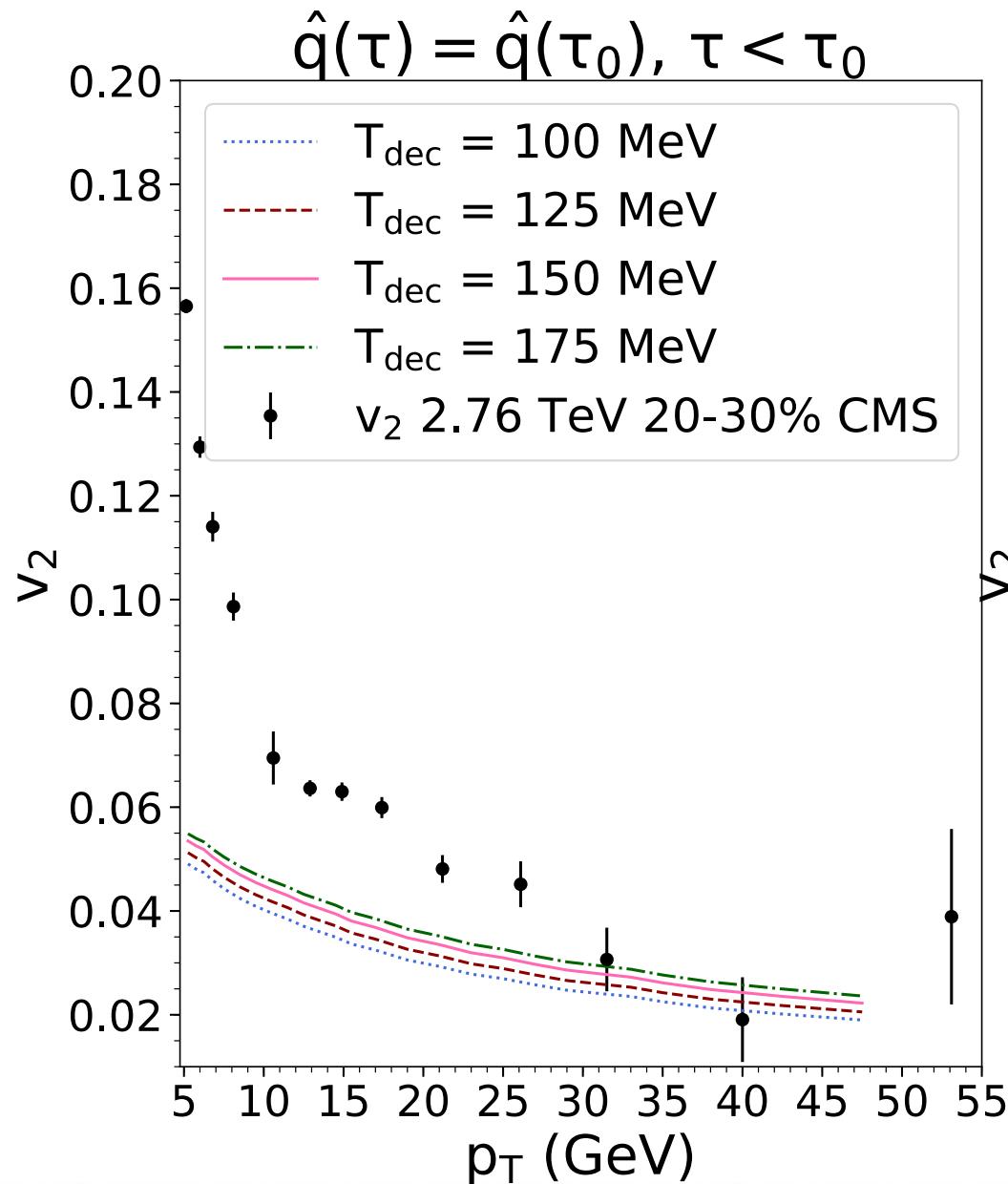
EKRT + QWs



When to stop the energy  
loss?

# High- $p_T$ $v_2$

$\eta/s = 0.2$   
 $\tau_0 = 0.197 \text{ fm}$



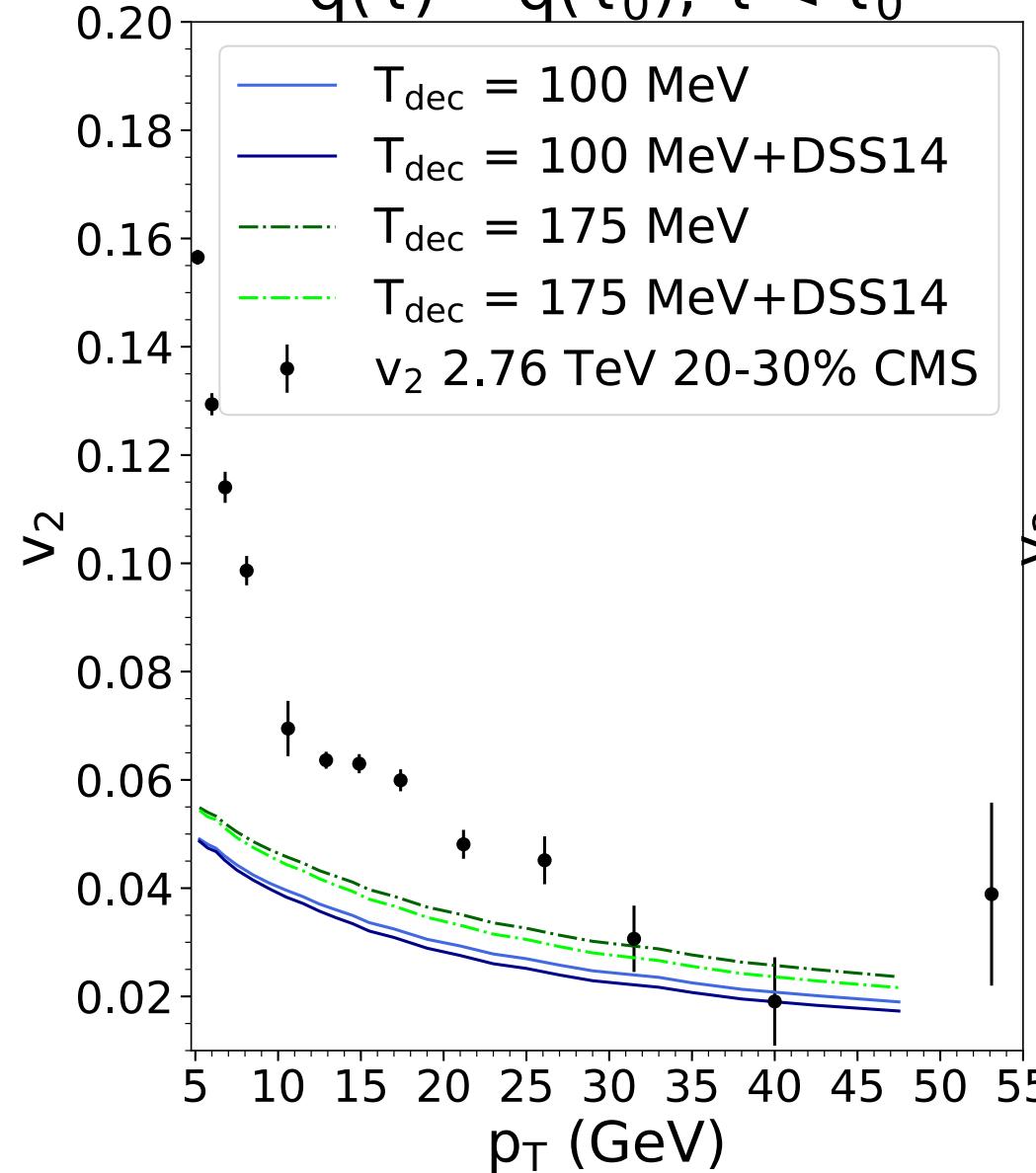
# Dependence on FFs

# High- $p_T$ $V_2$

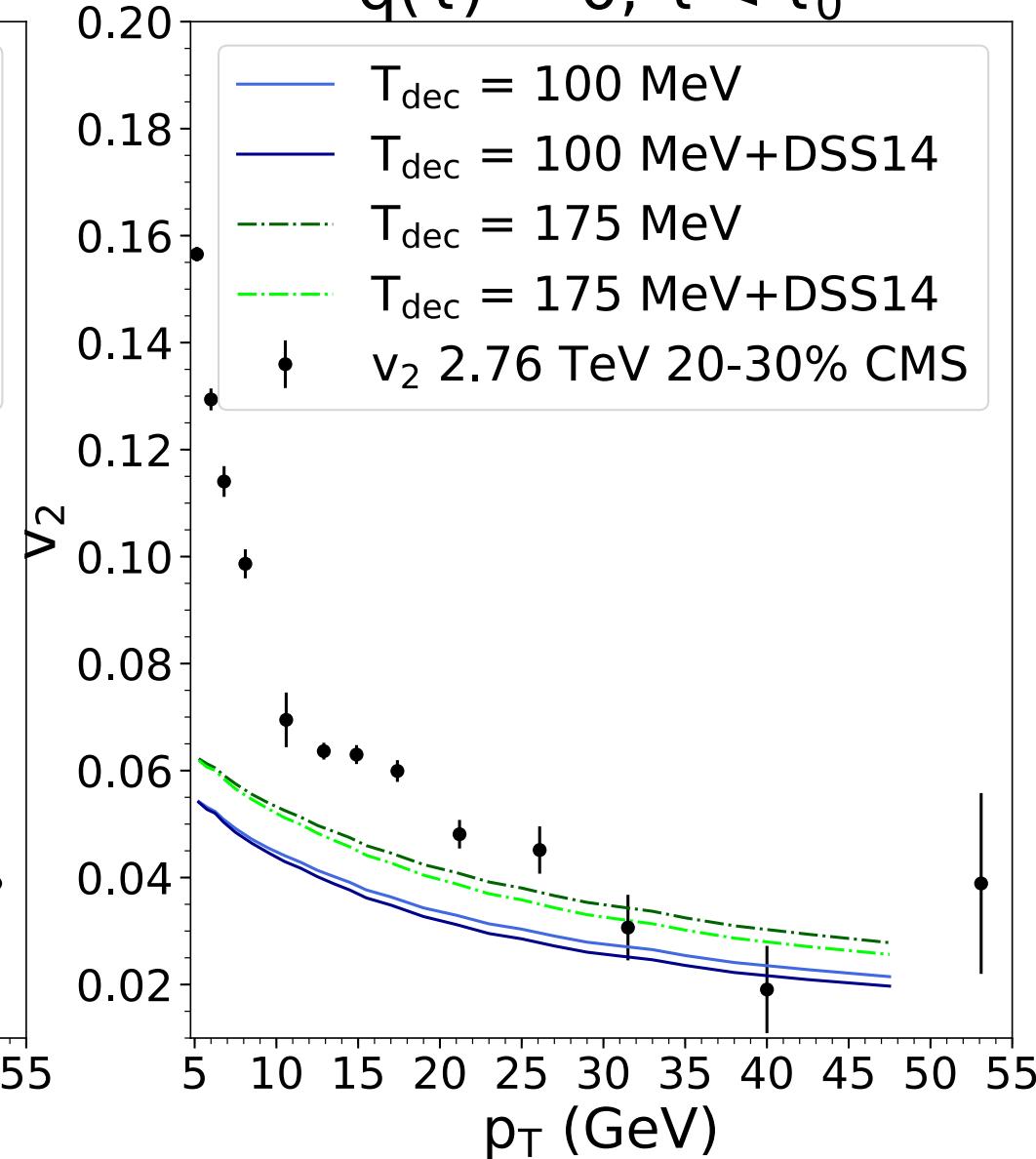
$$\eta/s = 0.2$$

$$\tau_0 = 0.197 \text{ fm}$$

$$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$$



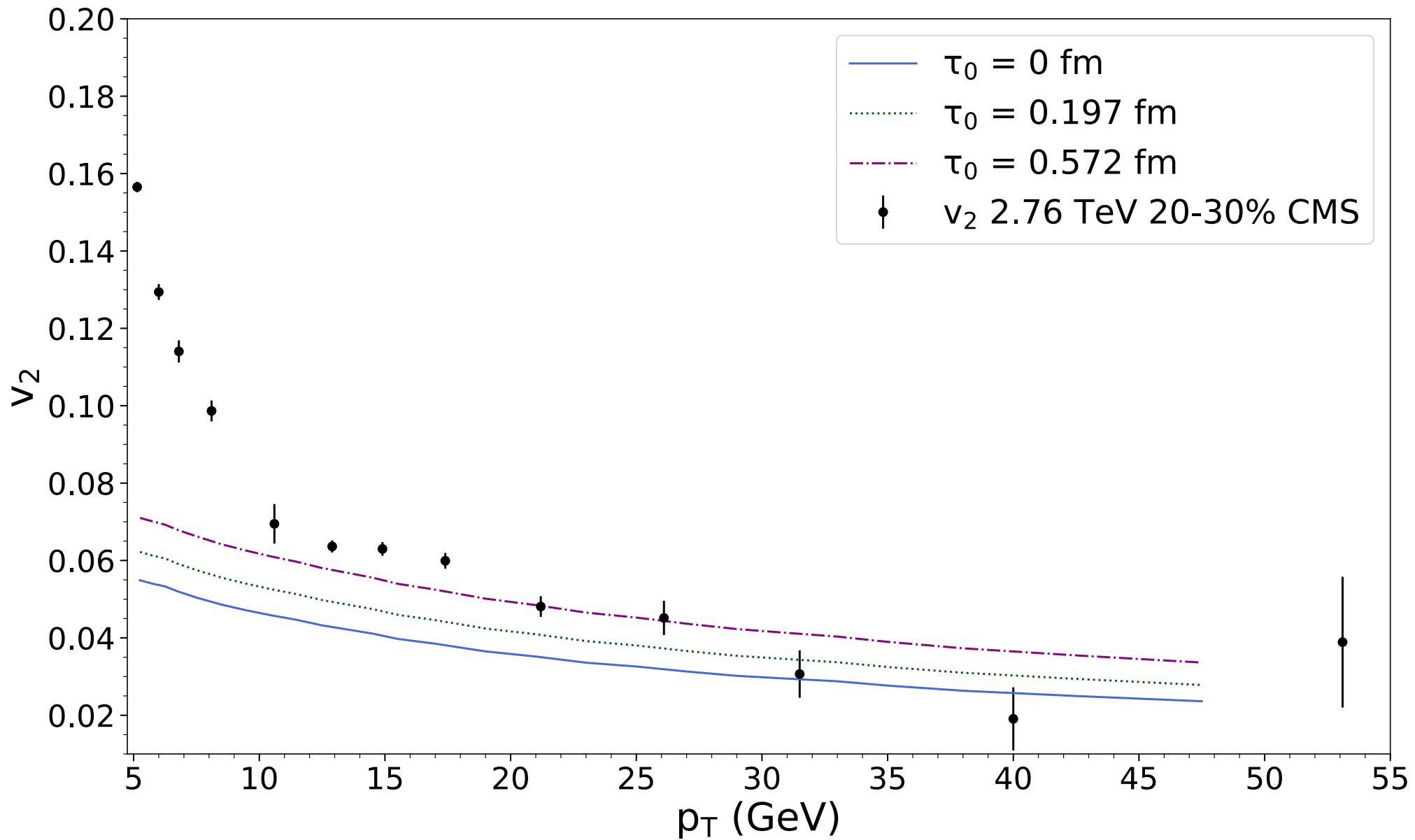
$$\hat{q}(\tau) = 0, \tau < \tau_0$$



# Dependence on $\tau_0$

# High- $p_T$ $v_2$

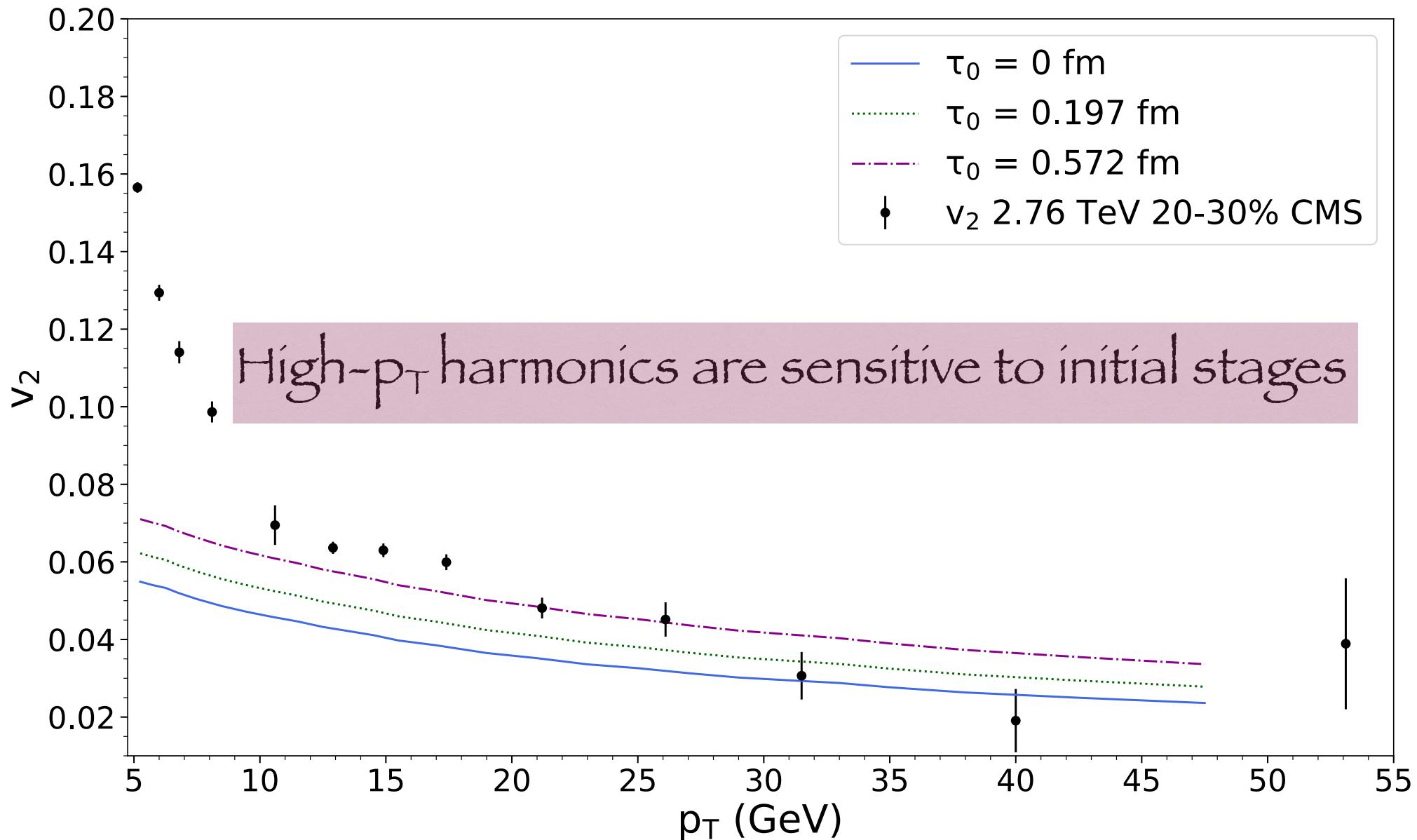
$\eta/s = 0.2$   
 $T_{dec} = 175 \text{ MeV}$



# High- $p_T$ $v_2$

$\eta/s = 0.2$

$T_{dec} = 175 \text{ MeV}$

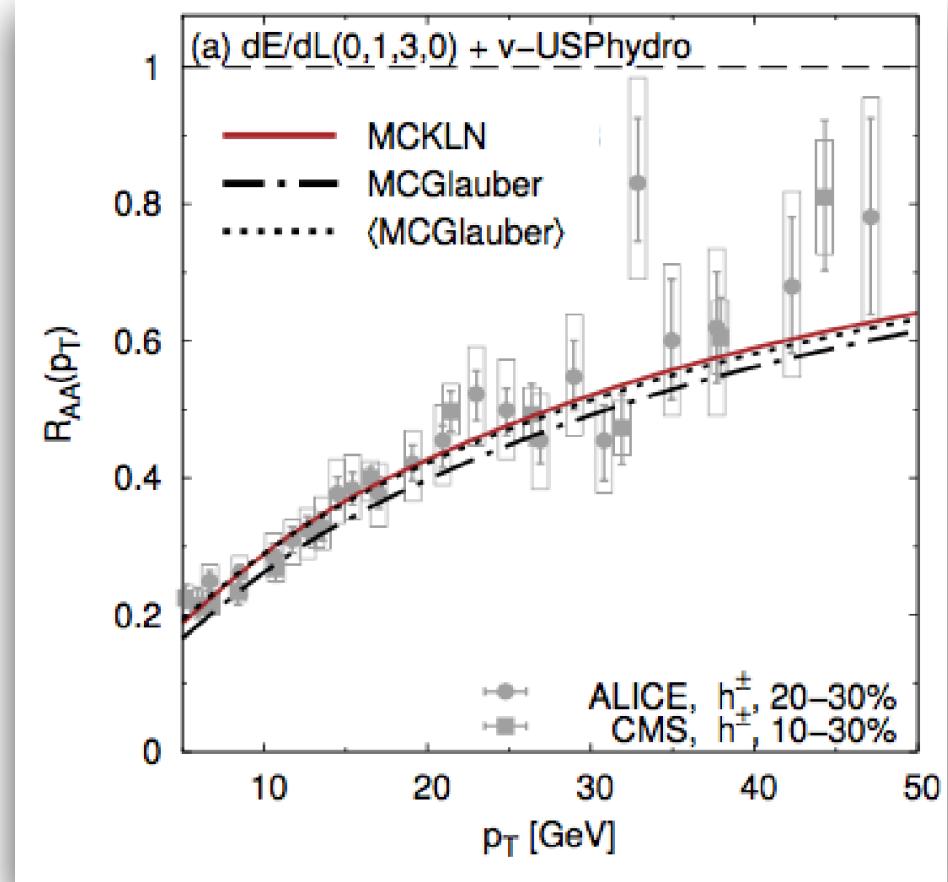
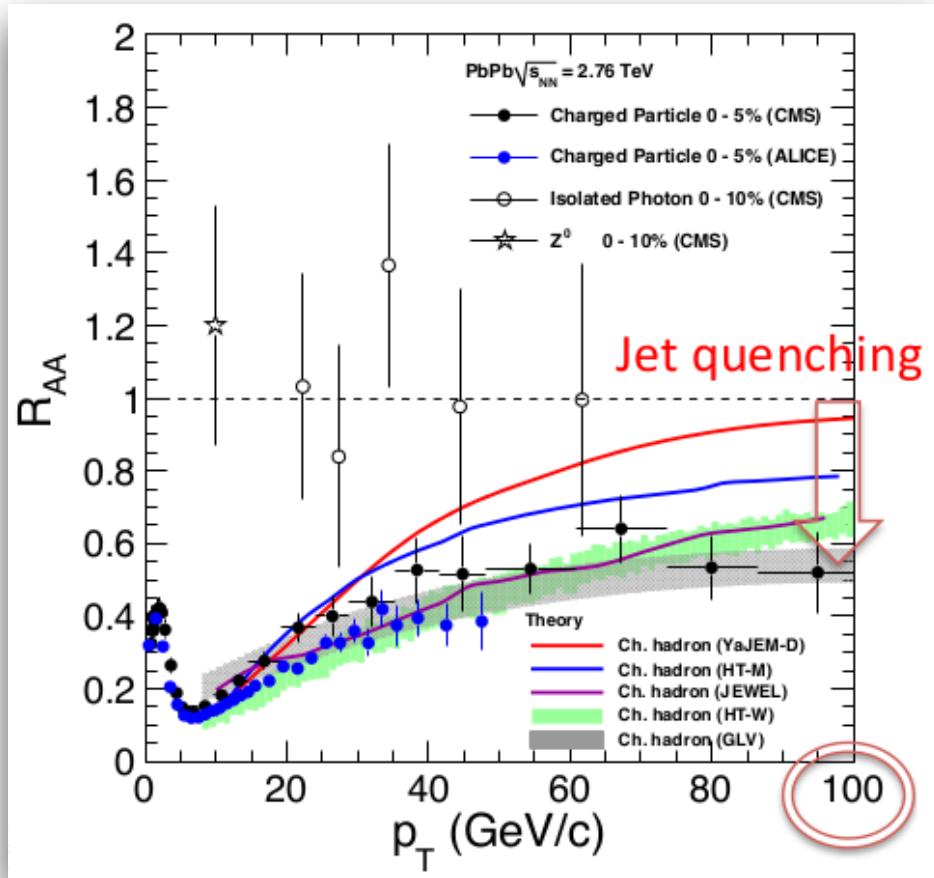


# Conclusions

- The high- $p_T v_2$  puzzle is not as simple as one could think
- The high- $p_T v_2$  shows sensitivity to the FFs employed
- The high- $p_T$  azimuthal asymmetries are very sensitive to the early times
- The high- $p_T v_2$  data show the need of switching off the energy loss for the first  $\sim 0.6$  fm

# Backup slides

# $R_{AA}$



Jacquelyn Noronha-Holster et al.  
Phys. Rev. Lett. 116, 252301 (2016)

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

- Quenching Weights

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

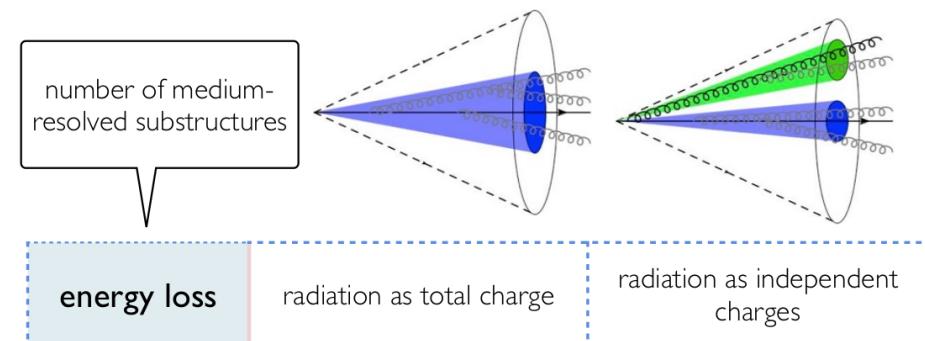
$$\begin{aligned} \omega \frac{dI^{(med)}}{d\omega} &= \frac{\alpha_s C_R}{(2\pi)^2 \omega^2} 2Re \int_{\xi_0}^{\infty} dy_l \int_{y_l}^{\infty} d\bar{y}_l \int d\mathbf{u} \int_0^{\chi\omega} d\mathbf{k}_{\perp} e^{-i\mathbf{k}_{\perp} \cdot \mathbf{u}} e^{-\frac{1}{2} \int_{\bar{y}_l}^{\infty} d\xi n(\xi) \sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \\ &\times \int_{y=0}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r} \exp \left[ i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left( \dot{\mathbf{r}}^2 - \frac{n(\xi) \sigma(\mathbf{r})}{i\omega} \right) \right] \end{aligned}$$

# 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)

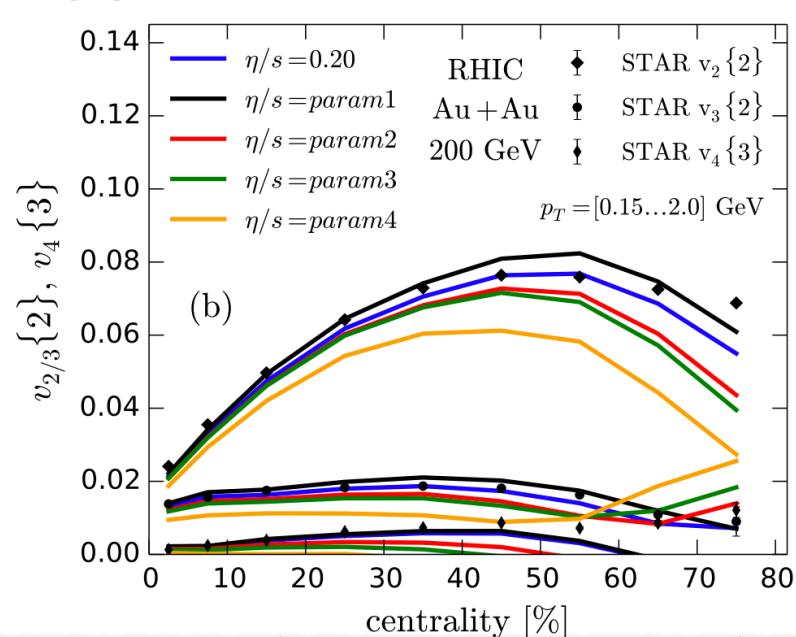
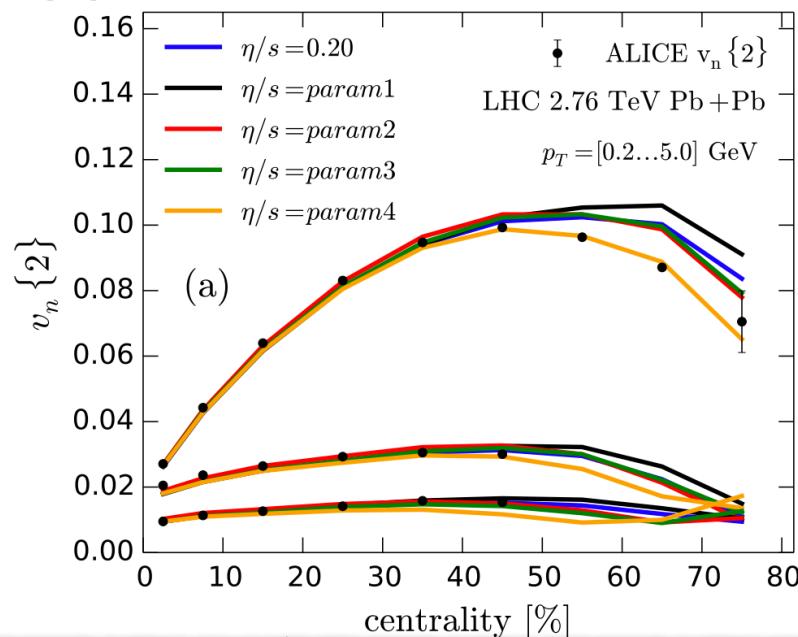
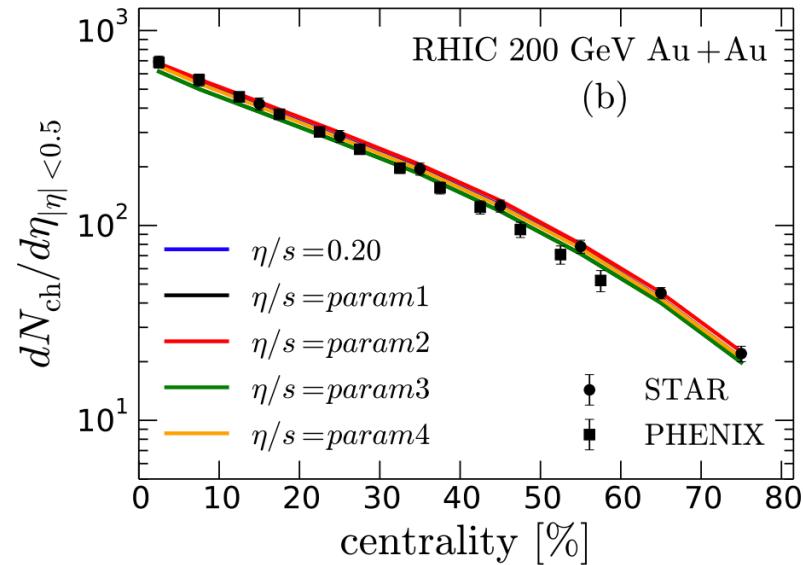
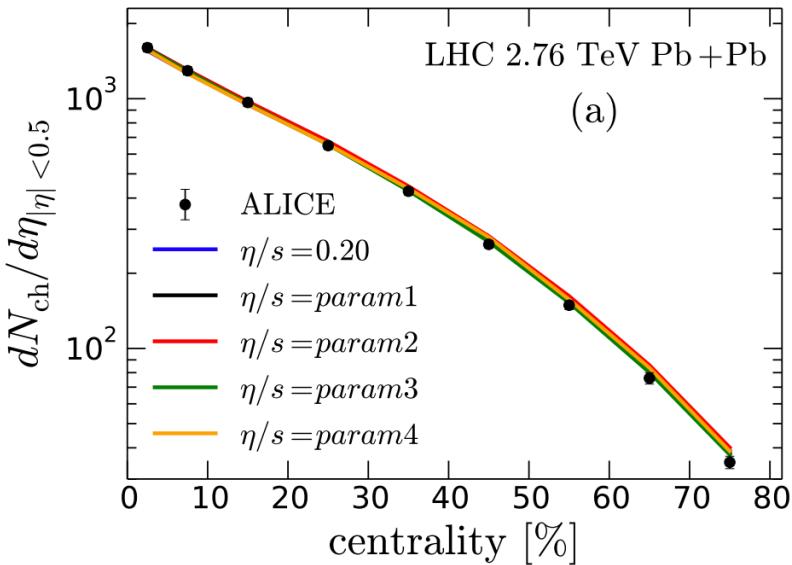
- Gluon emissions are independent

Good approximation for soft radiation

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

# EKRT Hydro

Phys. Rev. C 93, 024907 (2016)



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

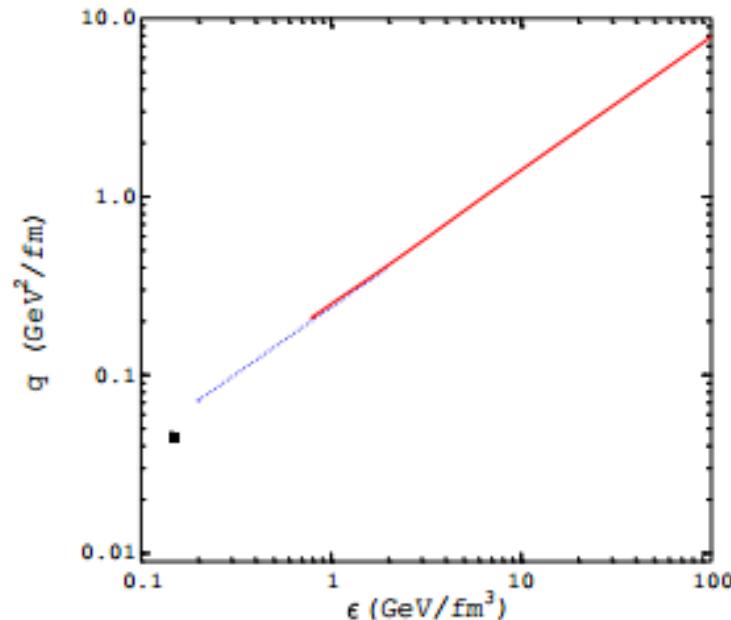


Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)

# K-factor

$\eta/s = 0.2$

20-30%

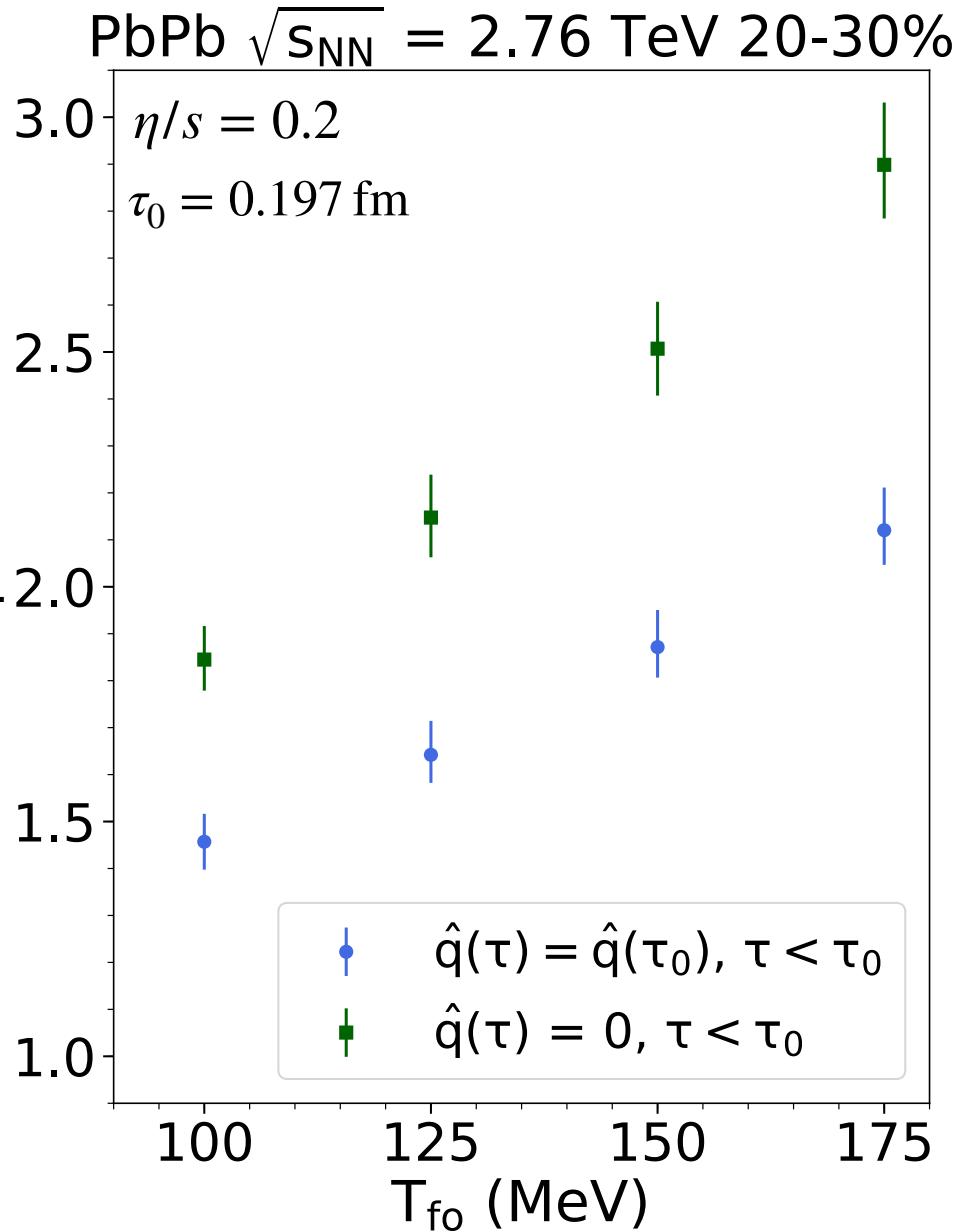
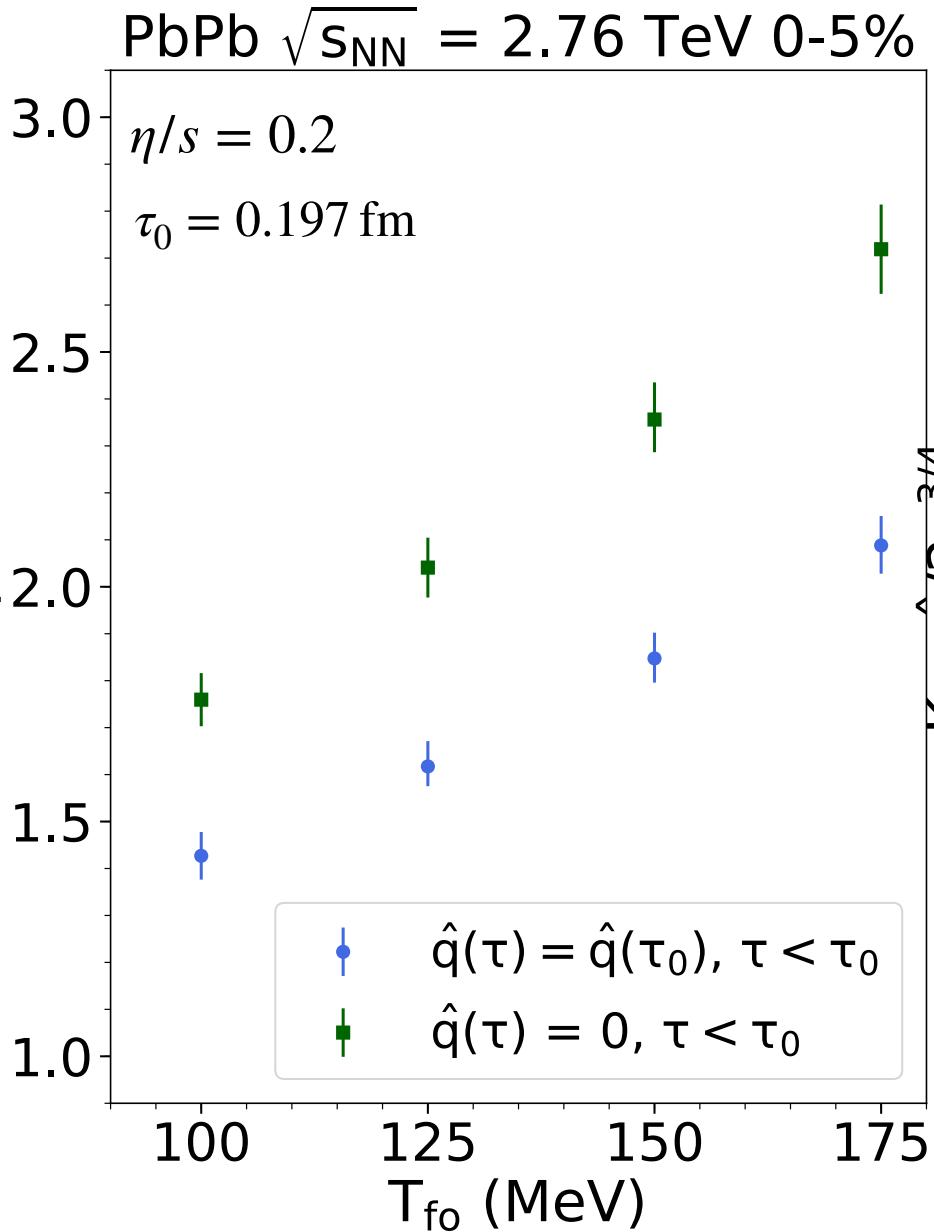
$\tau_0 = 0.197 \text{ fm}$

	$T_{\text{dec}} = 100 \text{ MeV}$	$T_{\text{dec}} = 125 \text{ MeV}$	$T_{\text{dec}} = 150 \text{ MeV}$	$T_{\text{dec}} = 175 \text{ MeV}$
$\hat{q}(\tau) = 0, \tau < \tau_0$	1.84	2.15	2.51	2.90
$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$	1.46	1.64	1.87	2.12

~ what we were doing before (result of page 3)

\*Only central values quoted

# K-factor



# Dependence on FFs

# K-factor: dependence on FFs

$$\hat{q}(\tau) = 0, \tau < \tau_0 \quad \tau_0 = 0.197 \text{ fm}$$

$$K^{\text{DSS14}} > K^{\text{DSS07}}$$

0-5%

$$T_{\text{dec}} \approx 100 \text{ MeV} \quad T_{\text{dec}} \approx 175 \text{ MeV}$$

DSS07

1.76

2.72

DSS14

2.09

3.22

20-30%

$$T_{\text{dec}} \approx 100 \text{ MeV} \quad T_{\text{dec}} \approx 175 \text{ MeV}$$

DSS07

1.84

2.90

DSS14

2.16

3.39

\*Only central values quoted

# K-factor: dependence on FFs

$$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0 \quad \tau_0 = 0.197 \text{ fm}$$

$$K^{\text{DSS14}} > K^{\text{DSS07}}$$

0-5%

$$T_{\text{dec}} \approx 100 \text{ MeV} \quad T_{\text{dec}} \approx 175 \text{ MeV}$$

DSS07

1.43

2.09

DSS14

1.70

2.48

20-30%

$$T_{\text{dec}} \approx 100 \text{ MeV} \quad T_{\text{dec}} \approx 175 \text{ MeV}$$

DSS07

1.46

2.12

DSS14

1.69

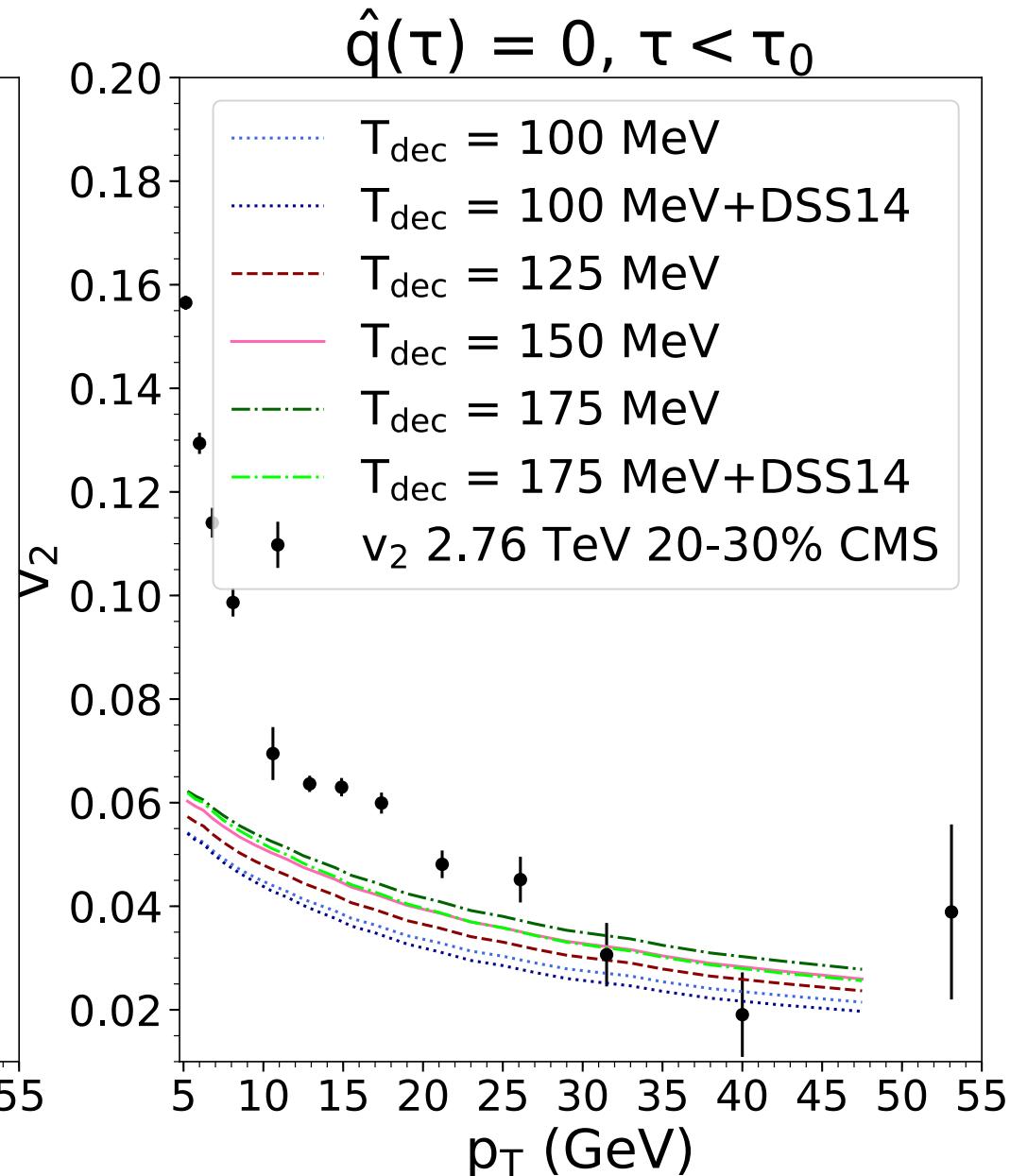
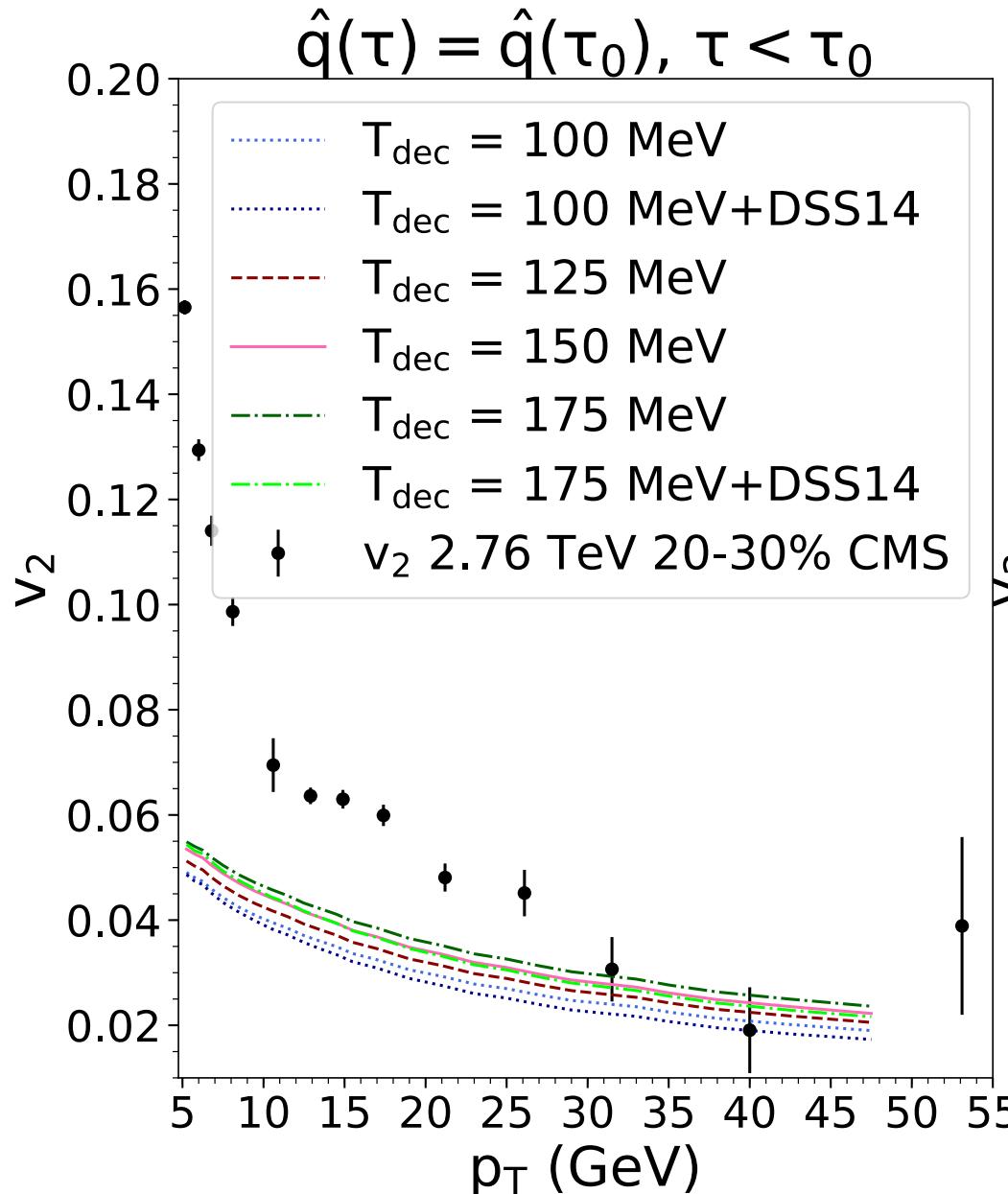
2.47

\*Only central values quoted

# High- $p_T$ $v_2$

$$\eta/s = 0.2$$

$$\tau_0 = 0.197 \text{ fm}$$

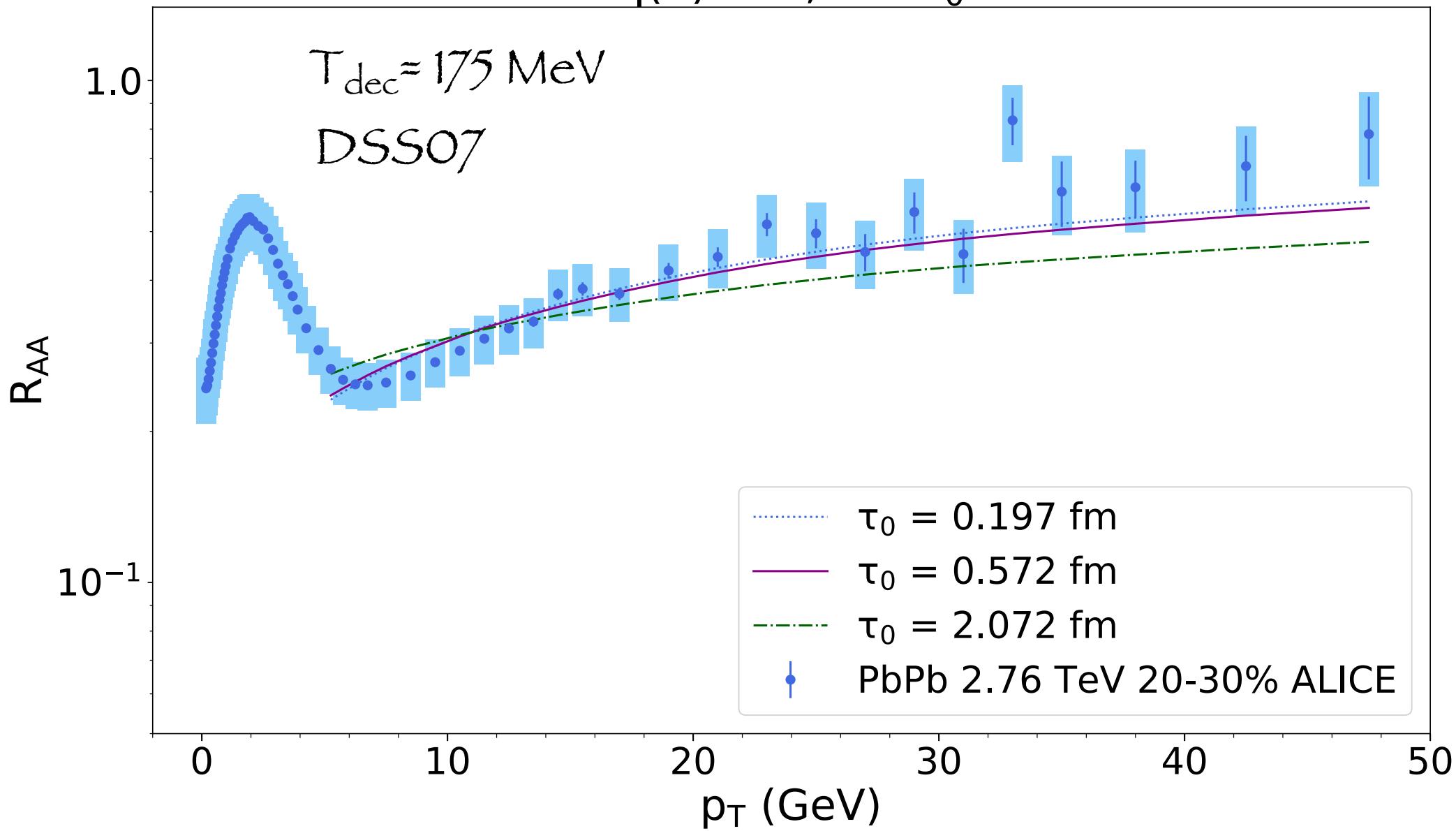


# Dependence on $\tau_0$

# $R_{AA}$

$\eta/s = 0.2$

$$\hat{q}(\tau) = 0, \tau < \tau_0$$

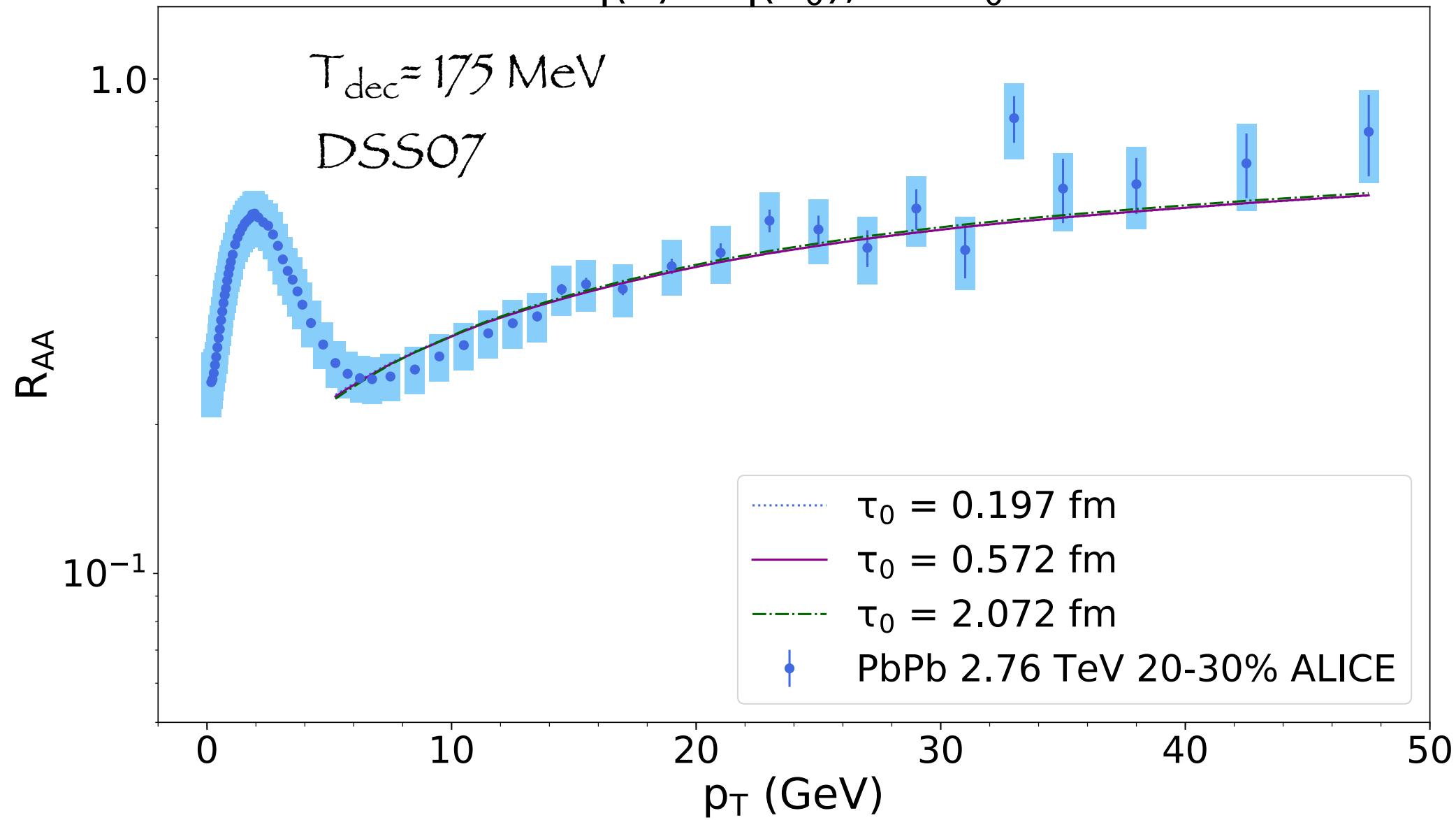


\*Only central values plotted

# $R_{AA}$

$\eta/s = 0.2$

$$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$$



\*Only central values plotted

# K-factor: dependence on $\tau_0$

$\eta/s = 0.2$

FFs: DSS07

20-30%

$T_{dec} \approx 175$  MeV

	$\tau_0 = 0.197$ fm	$\tau_0 = 0.572$ fm	$\tau_0 = 2.072$ fm
$\hat{q}(\tau) = 0, \tau < \tau_0$	2.90	4.56	$36.4 \pm 3.3$
$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$	2.12	2.19	2.64

\*Only central values quoted

# K-factor: dependence on $\tau_0$

$\eta/s = 0.2$

FFs: DSS07

$\tau_0 = 2.072 \text{ fm}$

20-30%

	$T_{\text{dec}} \approx 100 \text{ MeV}$	$T_{\text{dec}} \approx 175 \text{ MeV}$
$\hat{q}(\tau) = 0, \tau < \tau_0$	8.41	$36.4 \pm 3.3$
$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$	1.97**	2.64

\*Only central values quoted

# High- $p_T$ $V_2$

$\eta/s = 0.2$

DSS07

