

SENSITIVITY OF D MESON AZIMUTHAL ANISOTROPIES TO SYSTEM SIZE AND NUCLEAR STRUCTURE UCLA 2019

Jacquelyn Noronha-Hostler

Collaborators: **Roland Katz**, **Caio A.G. Prado**, **Alexandre A.P. Suaide**, **Marcelo G. Munhoz** [arXiv:1812.08009](https://arxiv.org/abs/1812.08009) & to appear shortly



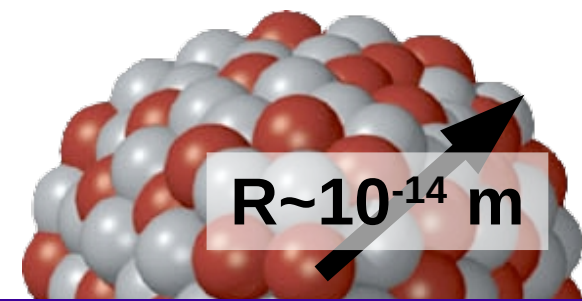
RUTGERS
UNIVERSITY



The Quark
Gluon
Plasma is
the ...



Smallest



nature
physics

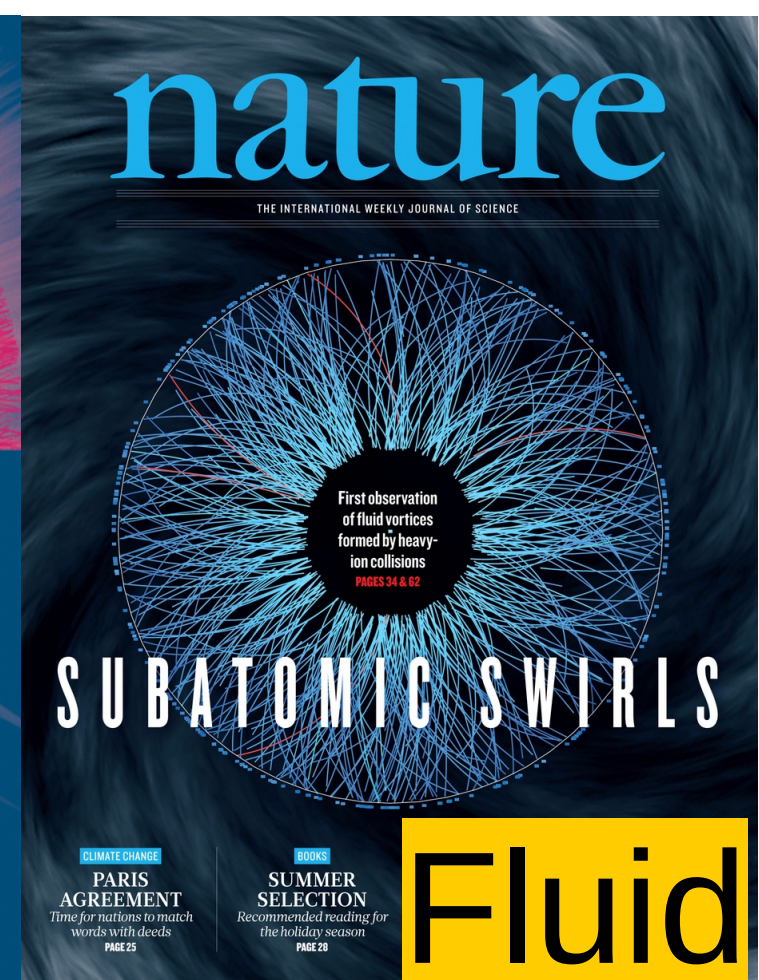
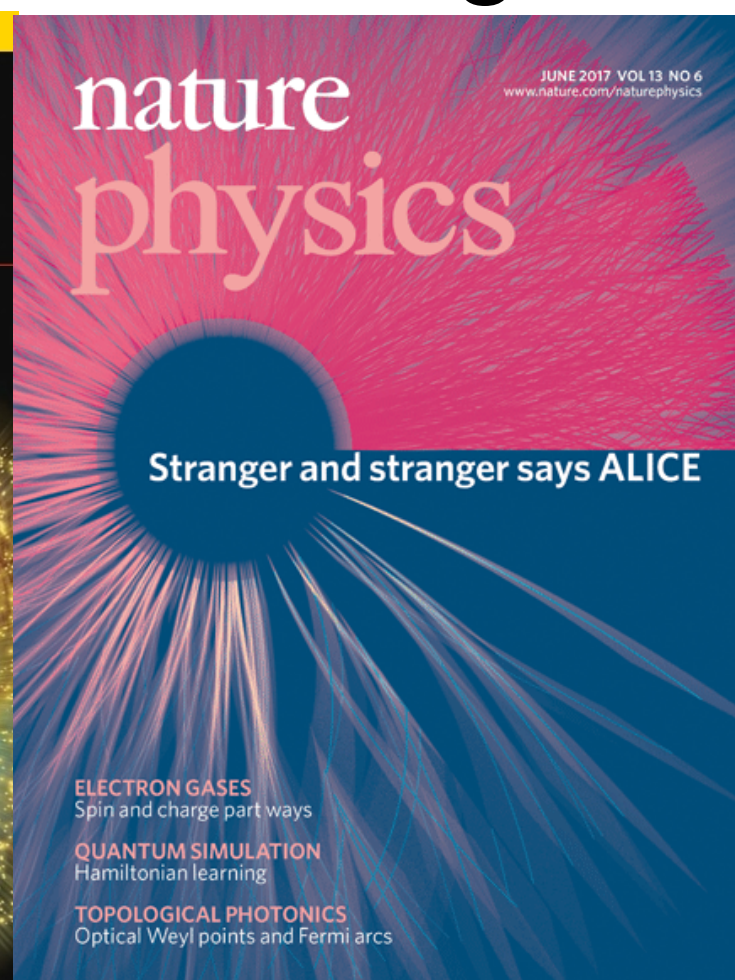
Letter | Published: 10 December 2018

Creation of quark-gluon plasma droplets
with three distinct geometries

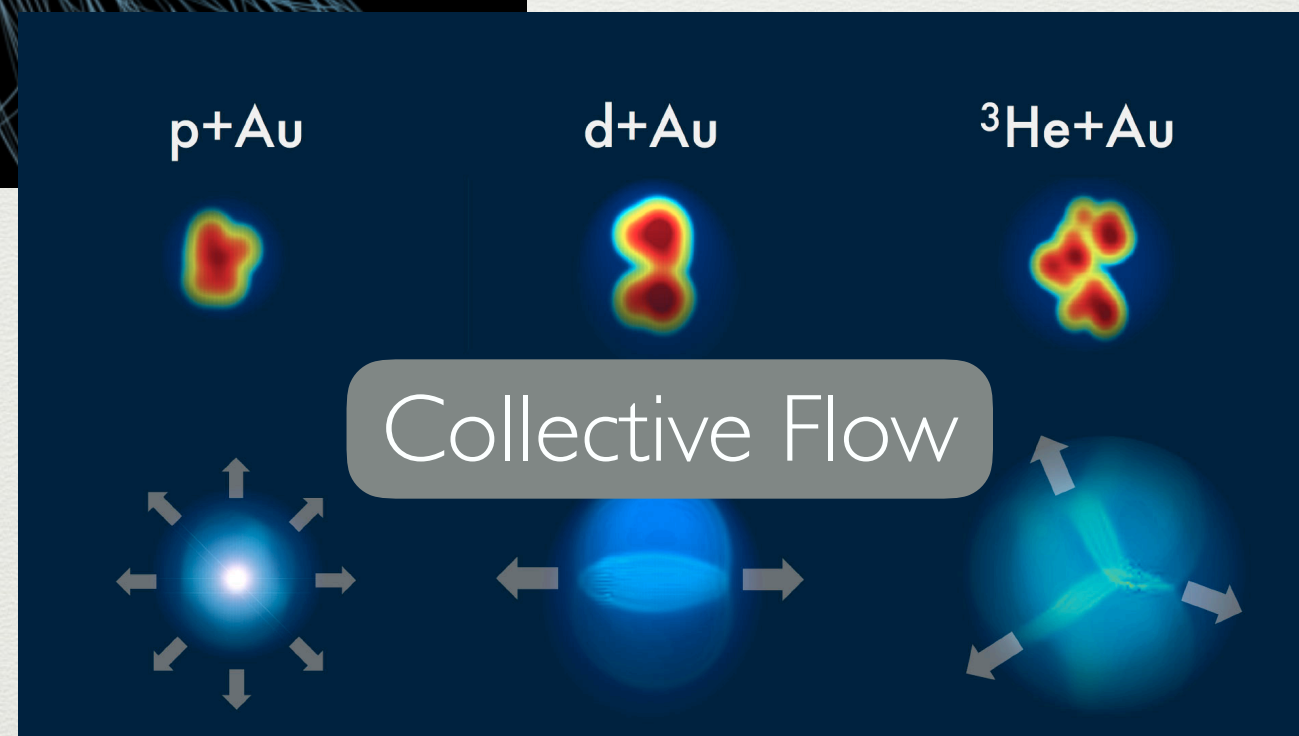
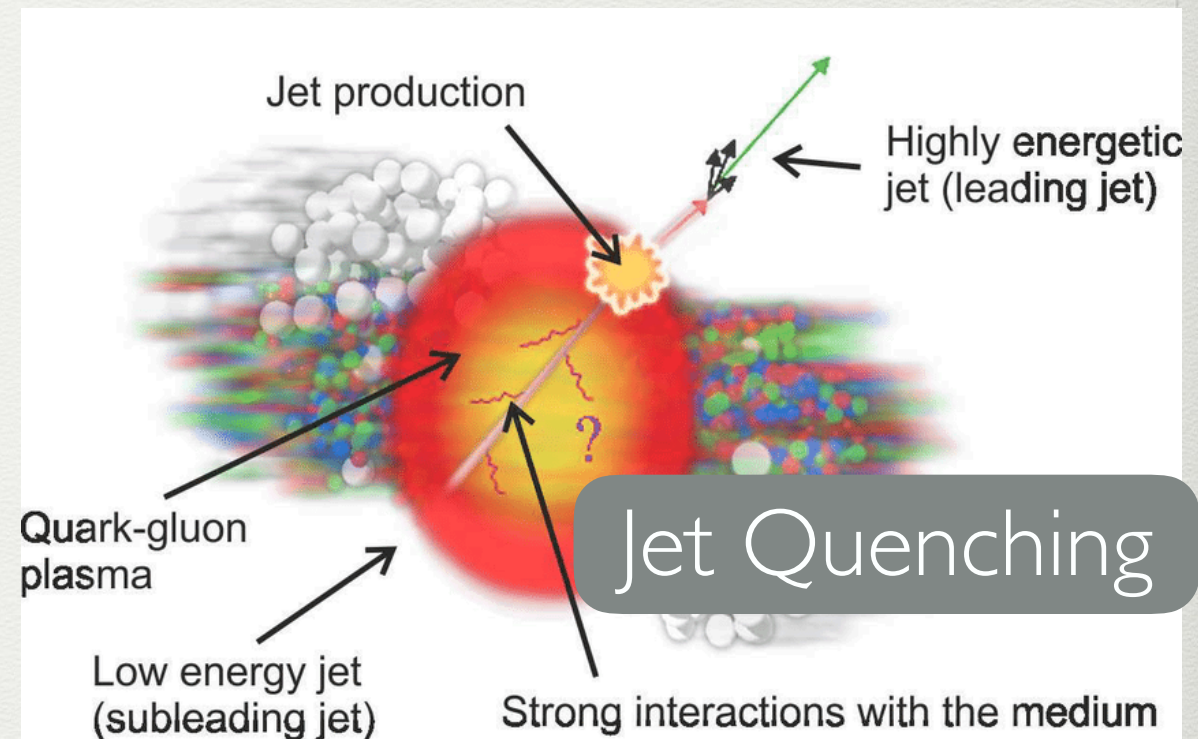
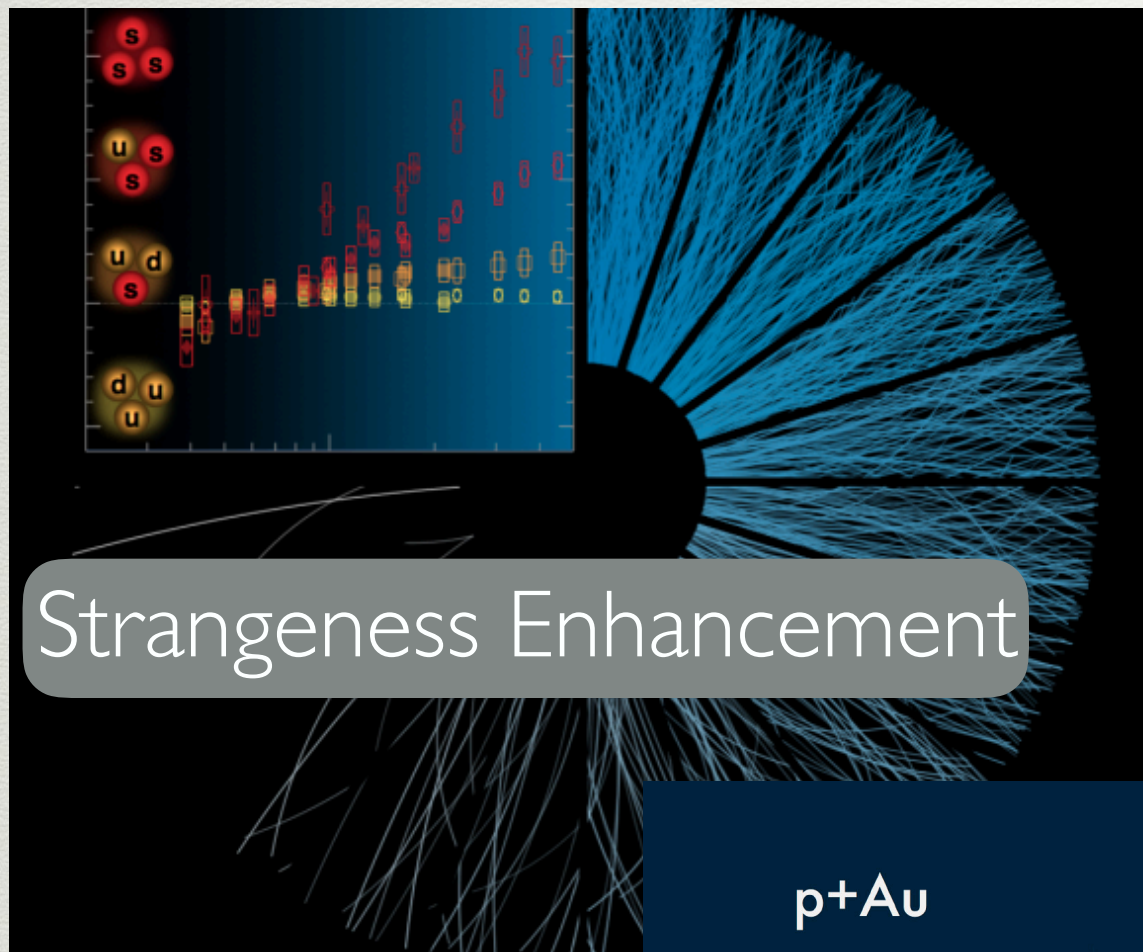
Most Perfect

Strange

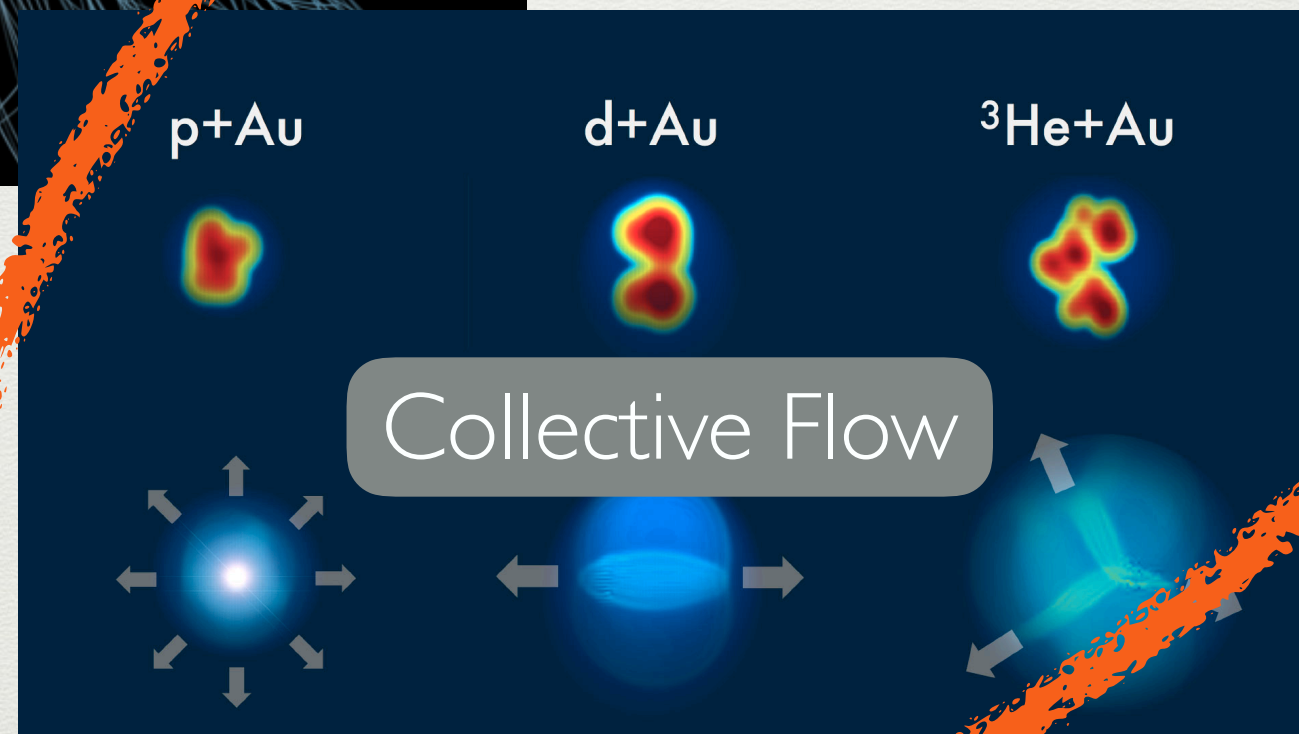
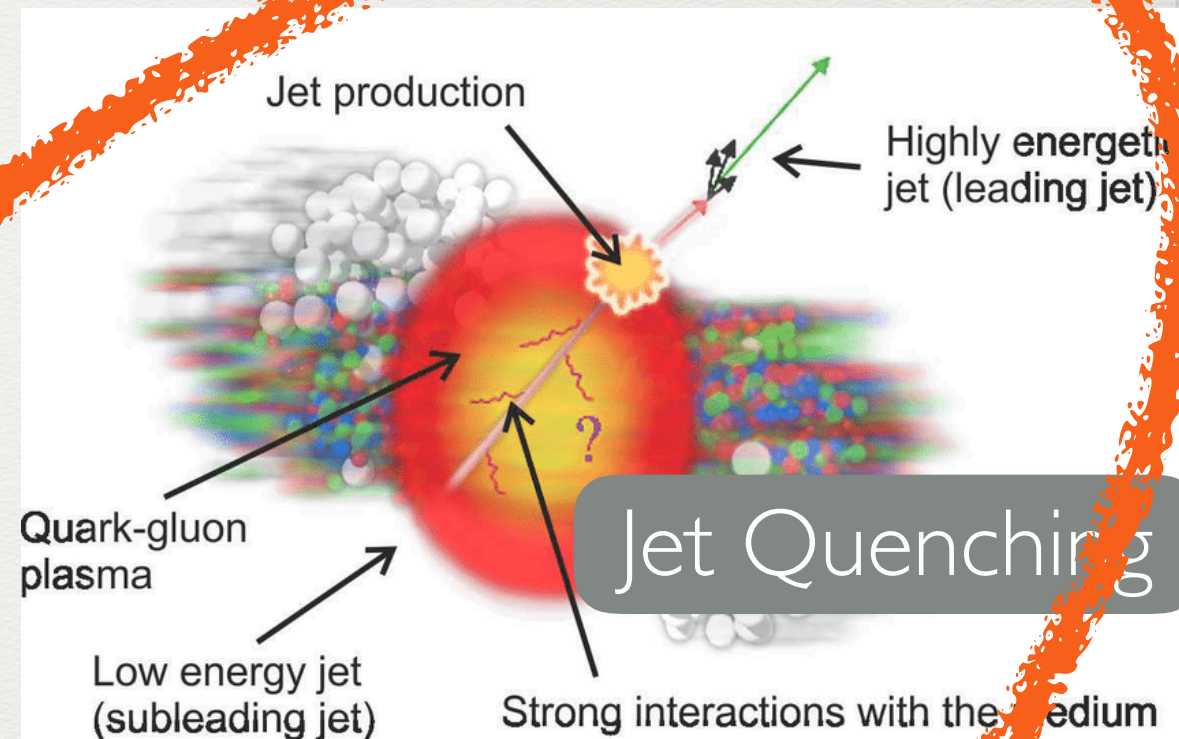
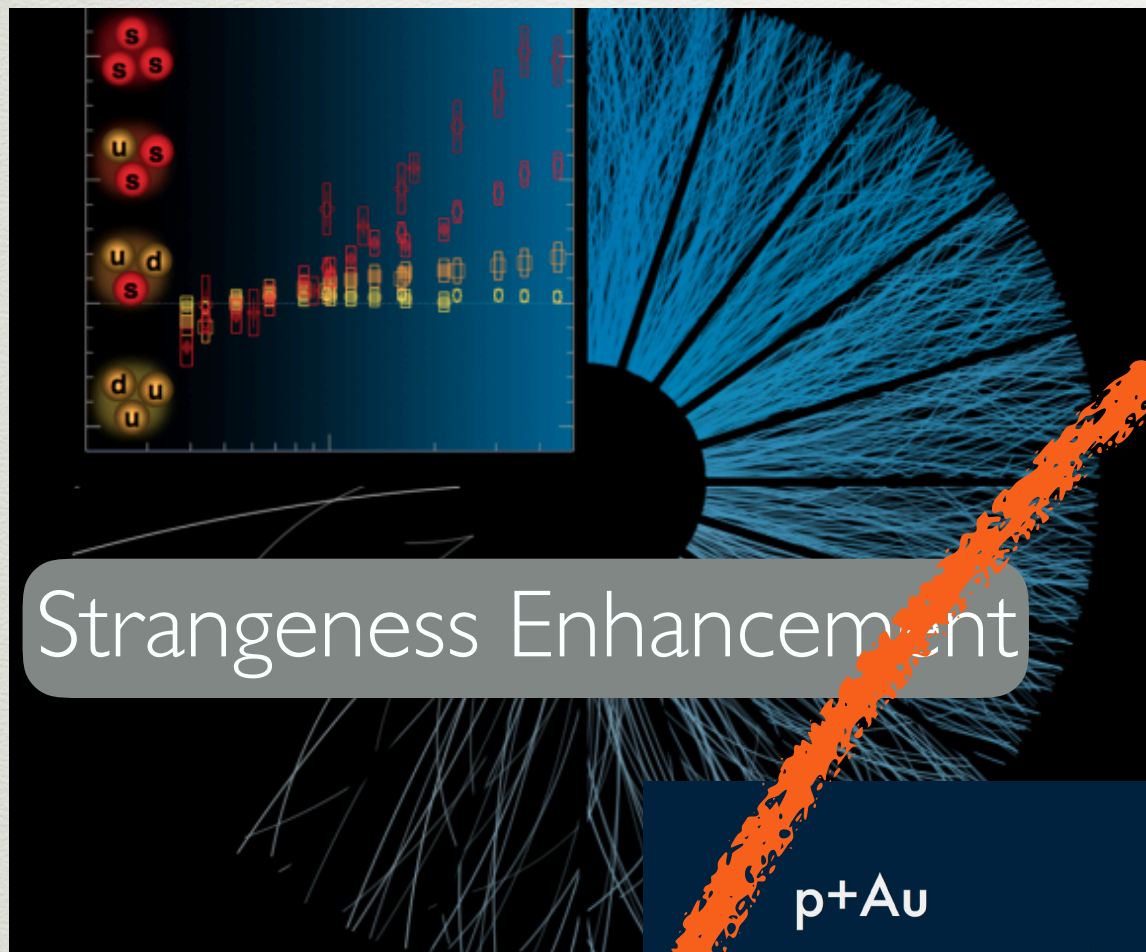
Most Vortical



SIGNALS OF THE QGP



SIGNALS OF THE QGP

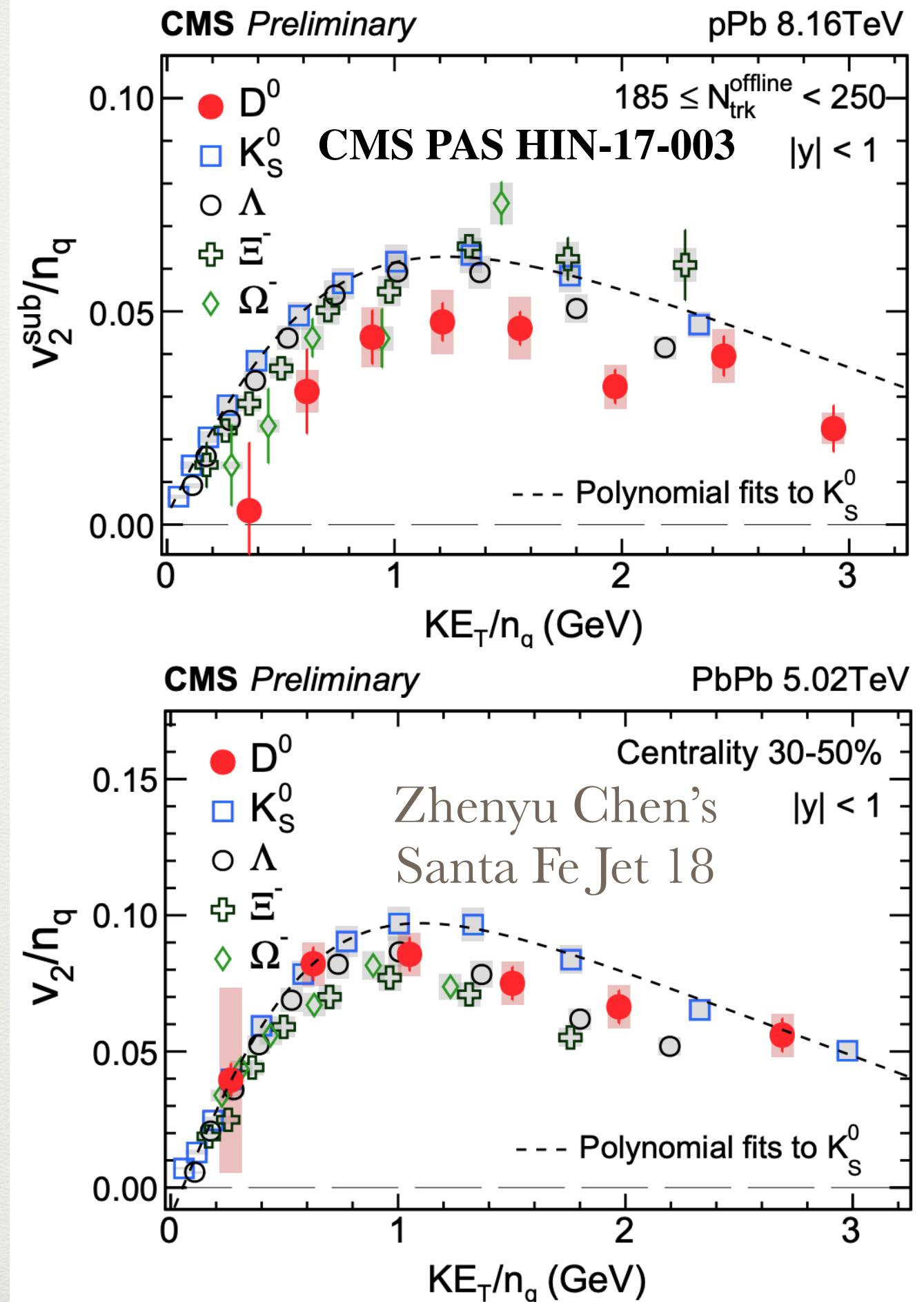


Motivation 1: D meson scaling with system size

Can we understand system
size dependence of energy
loss?

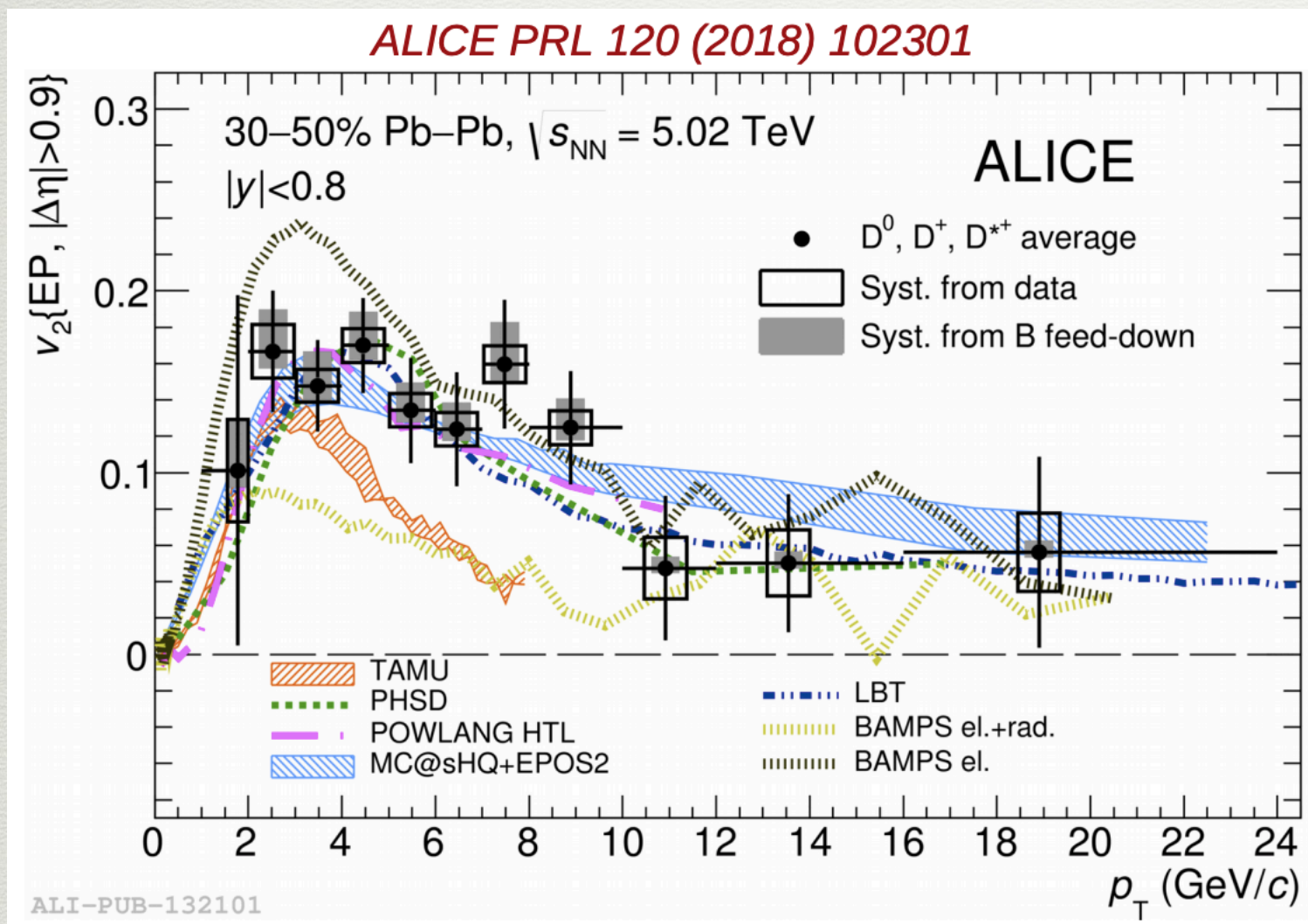
Comparisons between soft
and hard sector?

See also I. C. Arsene's
talk Monday



Motivation 2:

What makes theory match data?



As Anne Sickles said on Monday, we have all this theory and data, but what is it actually telling us?

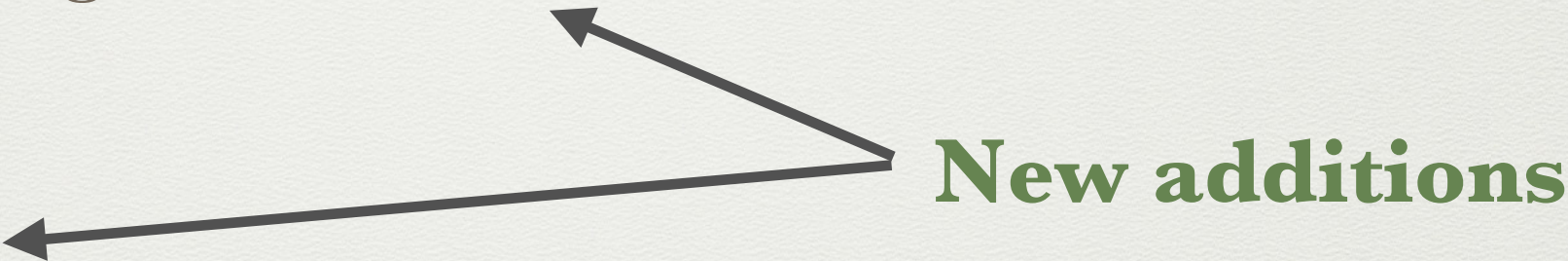
See also I. C. Arsene's talk Monday

(Bayesian) Yingru Xe et al,
Phys.Rev. C97 (2018) no.1,
014907

MODEL

DAB-MOD

C. Prado, JNH, R. Katz et al, Phys. Rev. C96, 064903 (2017)

- Heavy flavor (D and B mesons) package that allows for a variety of parameterized energy loss models or *relativistic Langevin models*.
 - *Coalescence*
 - Event-by-event relativistic viscous hydrodynamics
v-USPhydro JNH et al, PRC88(2013)no.4,044916; PRC90(2014)no.3,034907
 - pQCD FONLL calculations for initial quark distributions
- 
- The text "New additions" is written in green. Two black arrows originate from it: one points to the word "Coalescence" in the second bullet point, and the other points to the phrase "relativistic Langevin models" in the first bullet point.

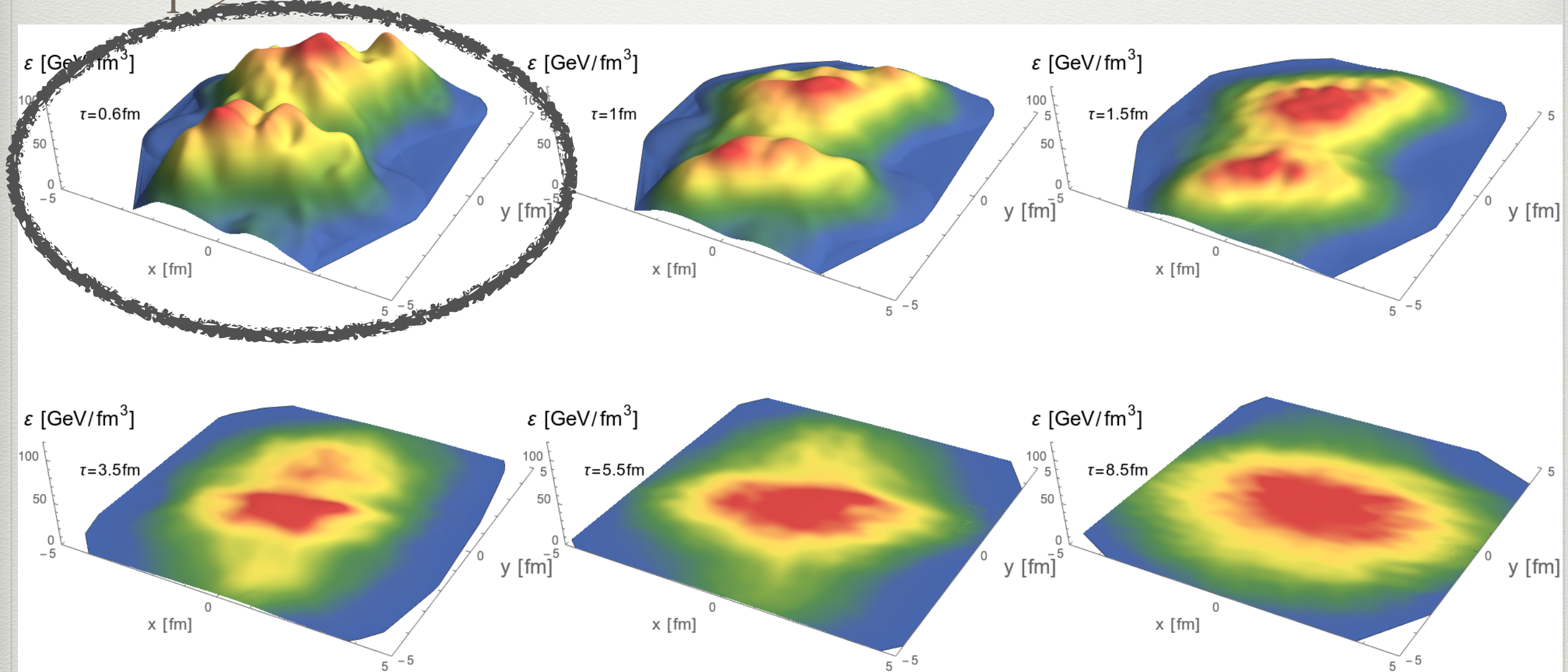
Initial conditions:

Trento/mckln

Heavy Quark Sampling:

pQCD FONLL

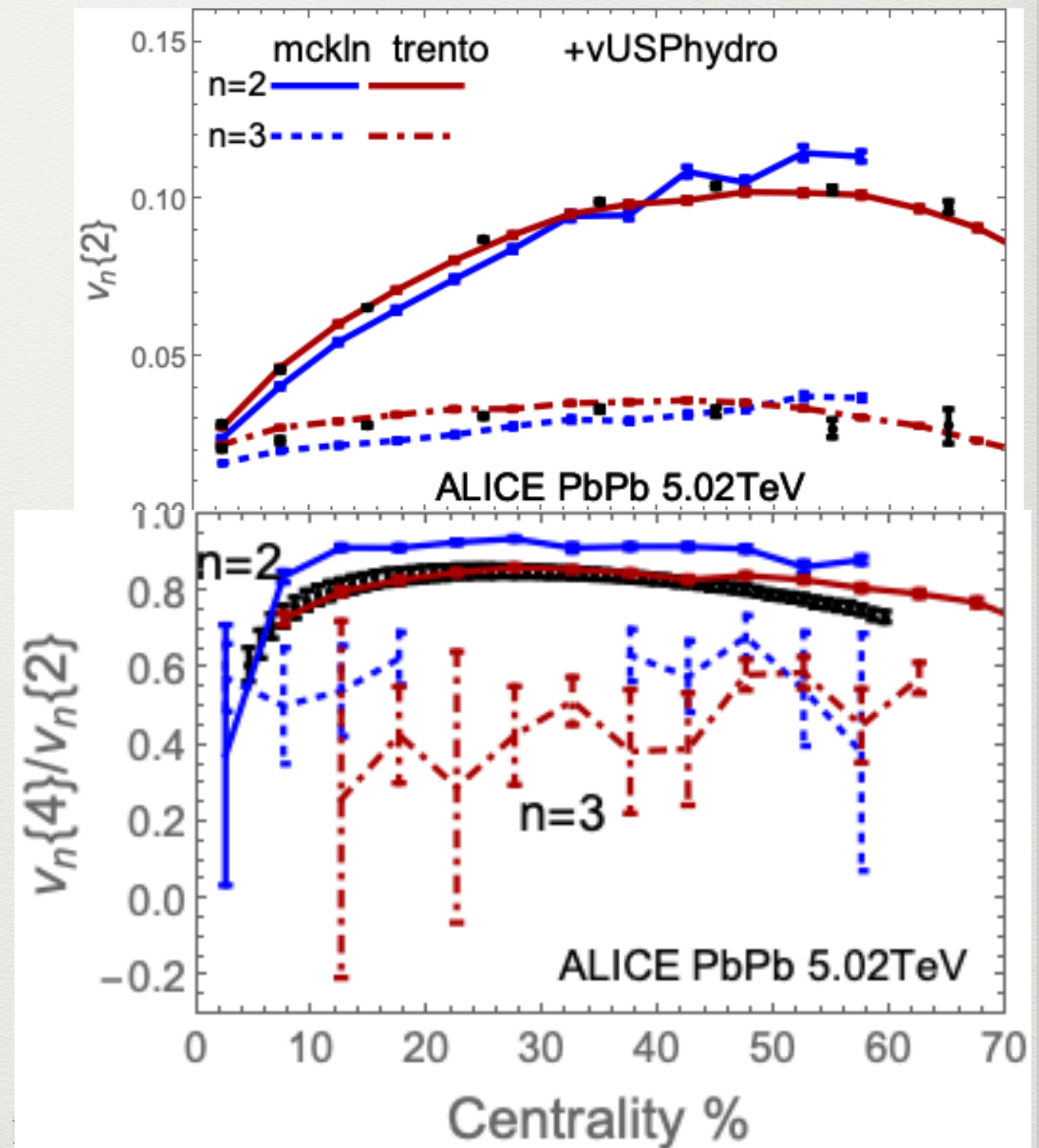
Oversampling of heavy quarks
No cold nuclear matter effects or
shadowing



Minimum 1000 initial conditions/centrality

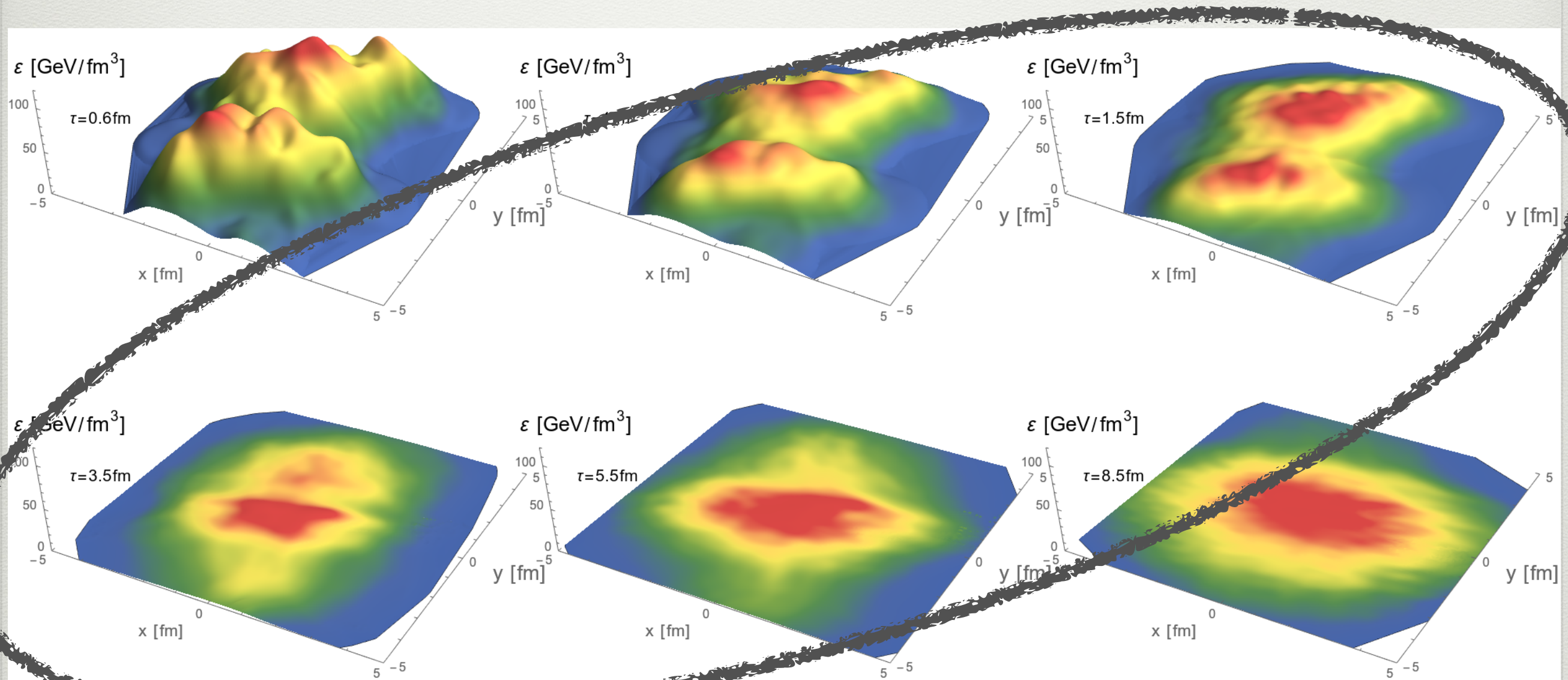
Initial conditions: Trento vs. mckln

- Trento like IP-Glasma
Moreland, Bernhard, Bass Phys.Rev. C92 (2015) no.1, 011901
Hydro: Alba et al, Phys.Rev. D96 (2017) no.3, 034517
- mckln
Drescher et al, Phys. Rev. C74, 044905 (2006); Phys. Rev. C76, 041903 (2007); Phys. Rev. C75, 034905 (2007)
Hydro: JNH et al, Phys.Rev. C95 (2017) no.4, 044901
- At LHC run 2, Trento generally works best.



Hydro evolution: v-USPhydro

Heavy quark evolution: Either parameterized energy loss or relativistic Langevin model



Hydrodynamic parameters tuned to reproduce soft observables

Updates to hydro background

Beware
different hydro
parameters

mckln

JNH et al, Phys.Rev. C95 (2017) no.4, 044901

- Equation of State: S95n-v1 (from 2009)
- Viscosity $\eta/s = 0.05$
- Freeze-out $T_{FO} = 120 \text{ MeV}$
- PDG05

mckln lower T_0 , shorter $\Delta\tau$.

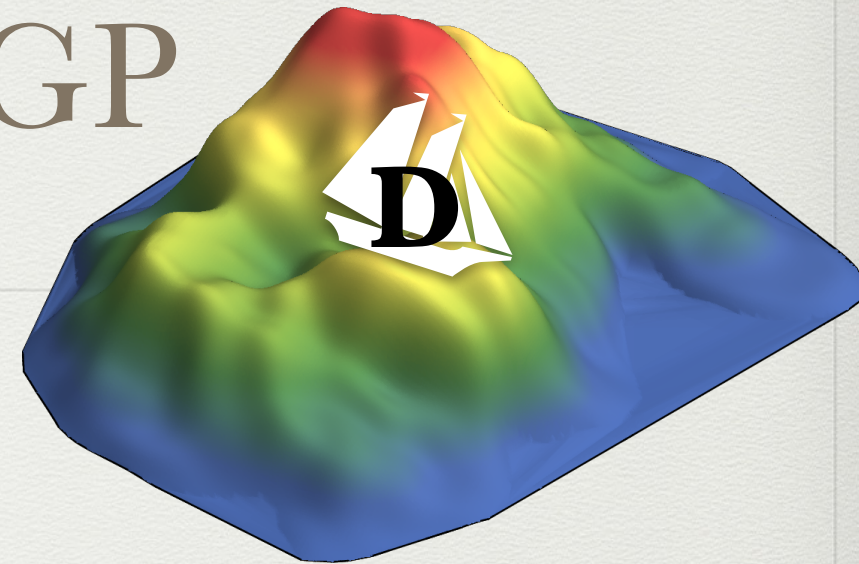
Trento

Alba et al, Phys.Rev. D96 (2017) no.3, 034517

- Equation of State: EOS2+1 from Lattice QCD
- Viscosity $\eta/s = 0.047$
- Freeze-out $T_{FO} = 150 \text{ MeV}$
- PDG16+ [WB] Phys.Rev. D96 (2017) no.3, 034517

Trento higher T_0 , longer $\Delta\tau$.

Heavy Quarks in a hot QGP



- Parameterized **Energy loss** model

$$\frac{dE}{dL} = -f(T, p, L)\zeta\Gamma_{flow}$$

- Parameterized Energy loss fluctuations ζ

Betz&Gyulassy JHEP 1408 (2014) 090

- Medium contribution

$$\Gamma_{flow} = \gamma \left[1 - v_{flow} \cos(\phi_q - \phi_{flow}) \right]$$

- **Langevin Model**
(QCD+HTL)

$$dp_i = -\Gamma(\vec{p})p_i dt + \sqrt{dt}\sqrt{\kappa}\rho_i$$

$$\kappa = 2T^2/D$$

Diffusion coefficients from:

- M&T $D \propto 1/(2\pi T)$

Moore & Teaney Phys. Rev. C71, 064904 (2005)

- G&A running coupling

Gossiaux & Aichelin, Phys. Rev. C 78, 014904 (2008)

Energy loss fluctuations

Gaussian

$$f(\zeta) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-(\zeta - 1)^2 / 2\sigma^2 \right]$$

Uniform

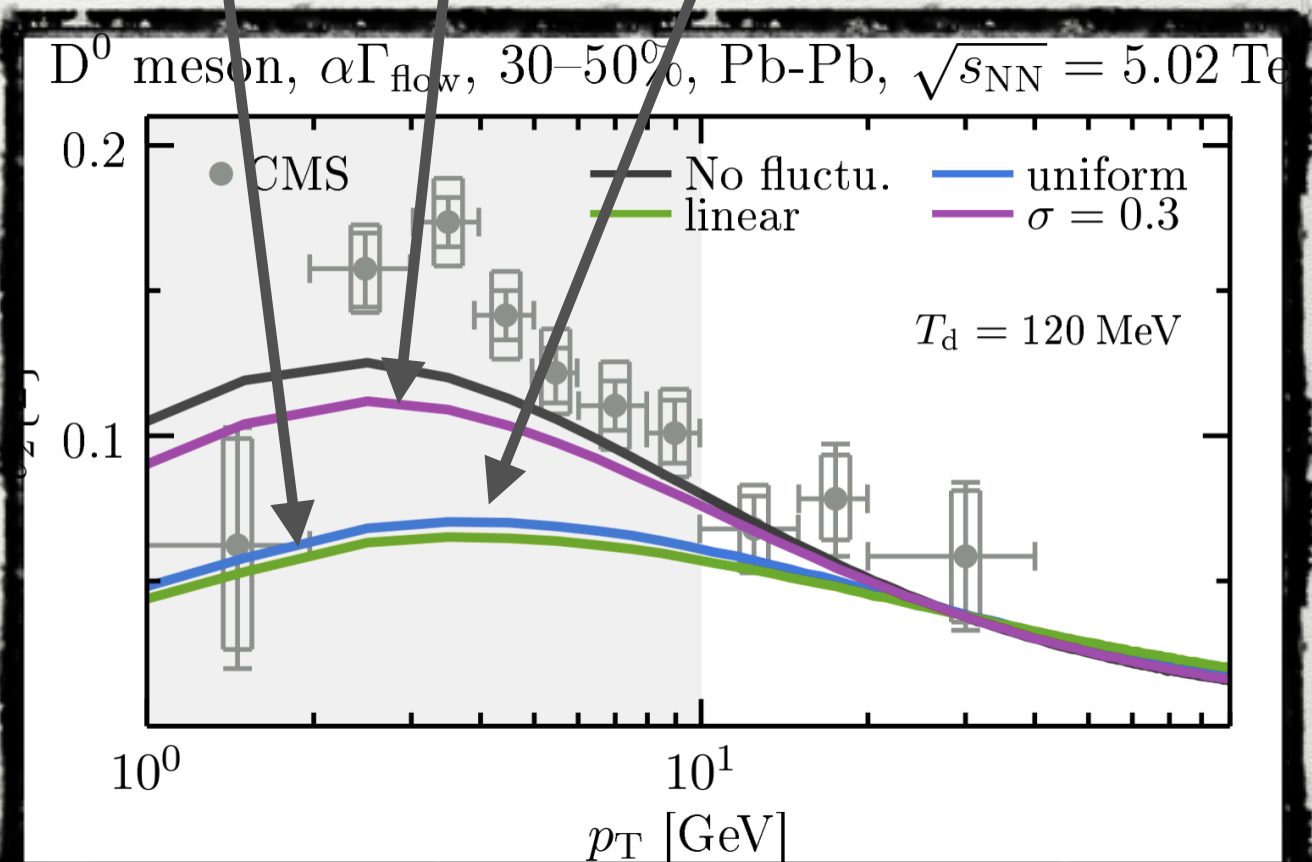
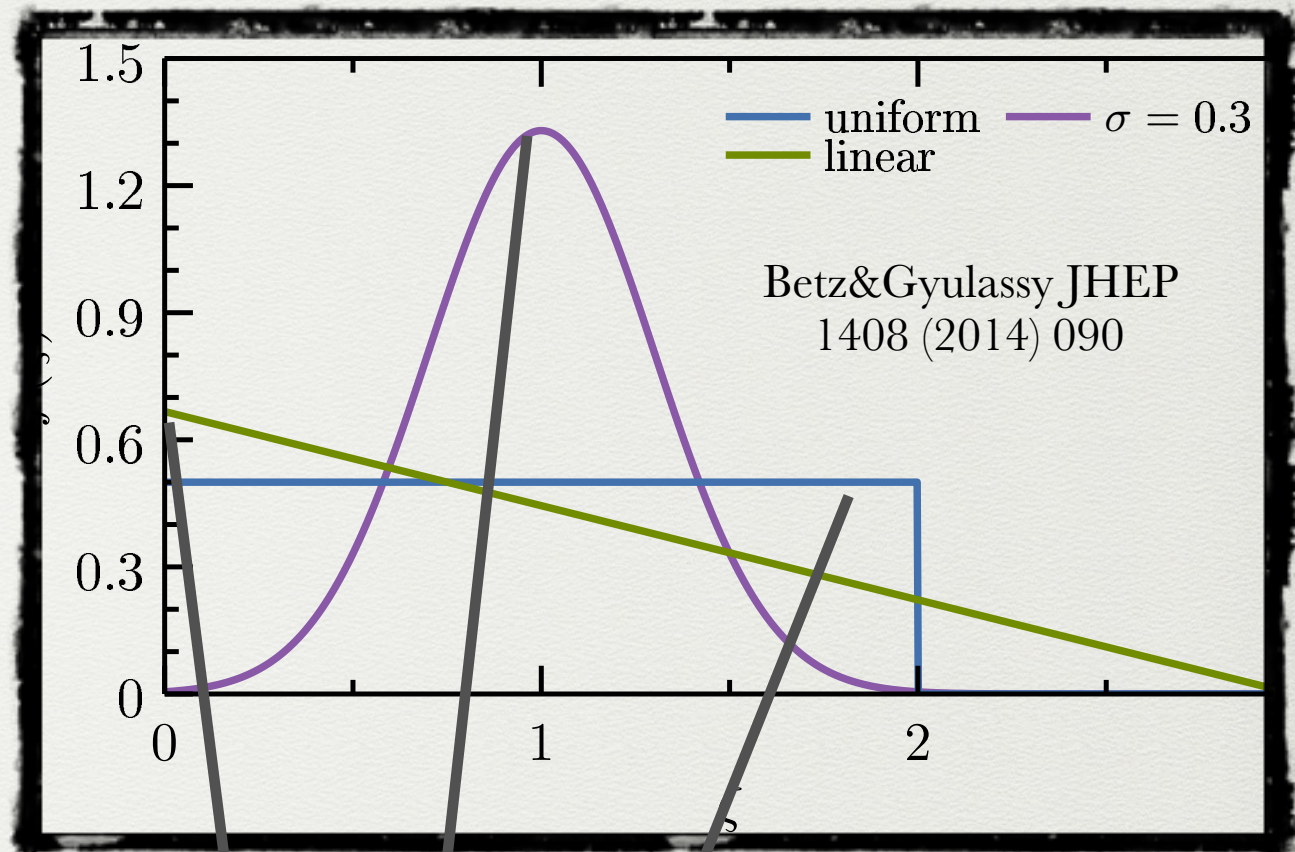
$$f(\zeta) = 0.5 \quad \text{For} \quad 0 \leq \zeta \leq 2$$

Linear

$$f(\zeta) = 2/3 - (2/9)\zeta$$

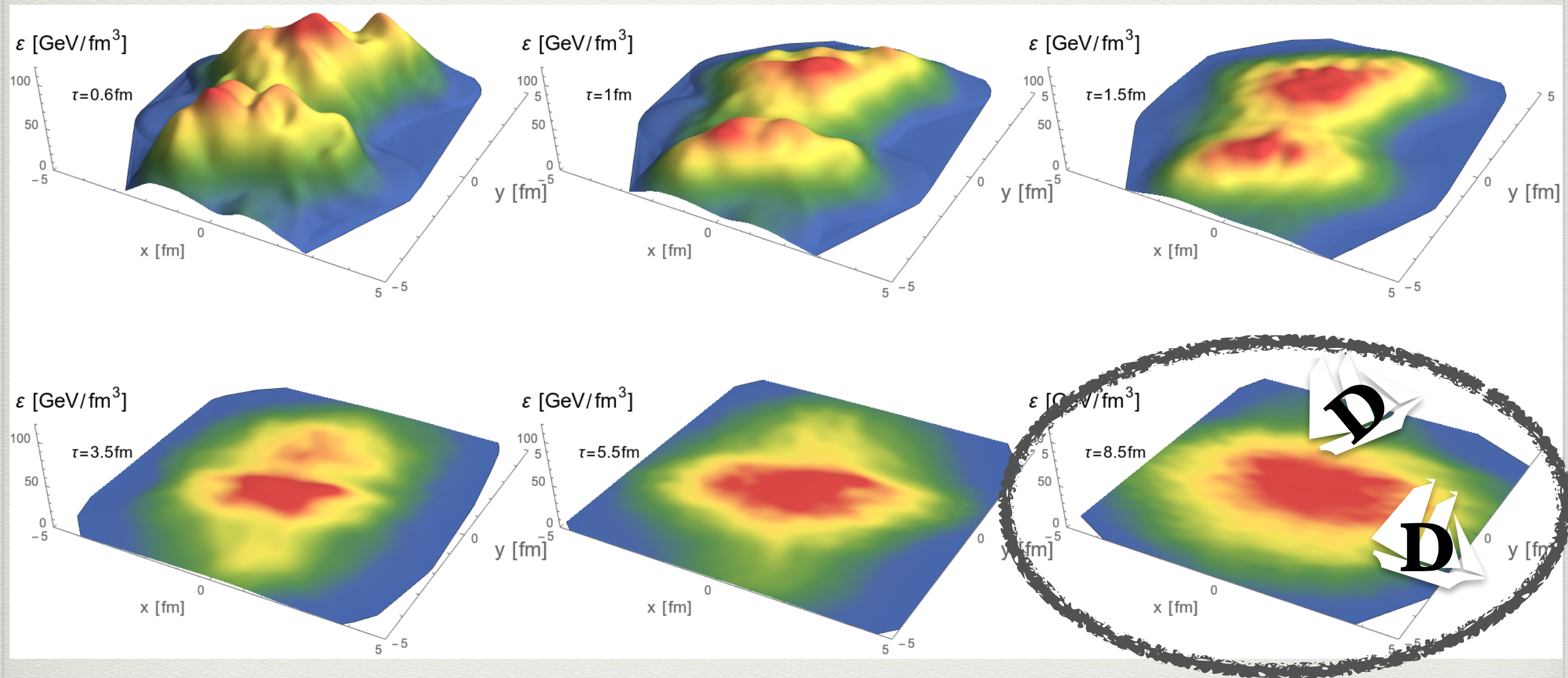
for

$$0 \leq \zeta \leq 3$$



Hydro particlization: Cooper-Frye+decays

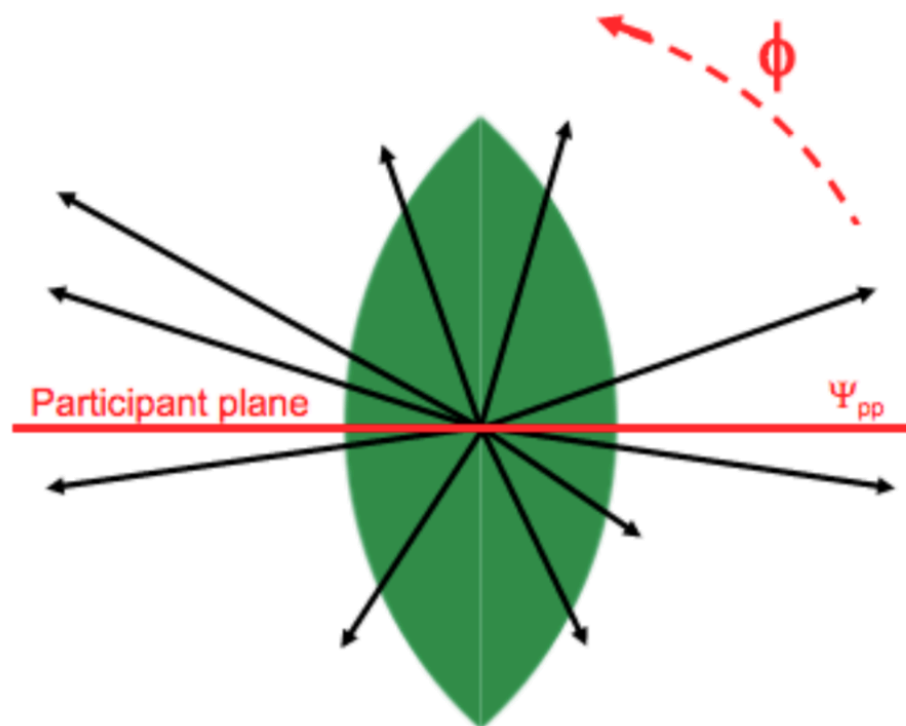
Heavy quark fragmentation: Petersen fragmentation function+light/heavy quark coalescence



Semi-leptonic decays done in Pythia8

Path length dependence

Correlate 1 high p_T particle with 1(+) soft particles



- More high p_T particles are emitted aligned with the event plane
- High p_T particles sensitive to the path length (initial state)

First suggested in early 2000's

Xin-Nian Wang Phys.Rev. C63 (2001) 054902 ; Gyulassy, Vitev, Wang Phys.Rev.Lett. 86 (2001) 2537-2540

Azimuthal anisotropies (hard/heavy)

Scalar Product [1]- 1 soft+1 hard particle correlation

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

Rapidity gap to suppress non-flow

Averaging over events [2] ($\sim 5\%$ effect theoretically [3])

- Calculated in 0.5% centrality bins
- $\langle \dots \rangle \rightarrow$ multiplicity weighing
- 0.5% rebinned into 5% or 10%

[1] Luzum and Ollitrault PRC87 (2013) no.4, 044907; JNH, Betz, Noronha, Gyulassy Phys.Rev.Lett. 116 (2016) no.25, 252301

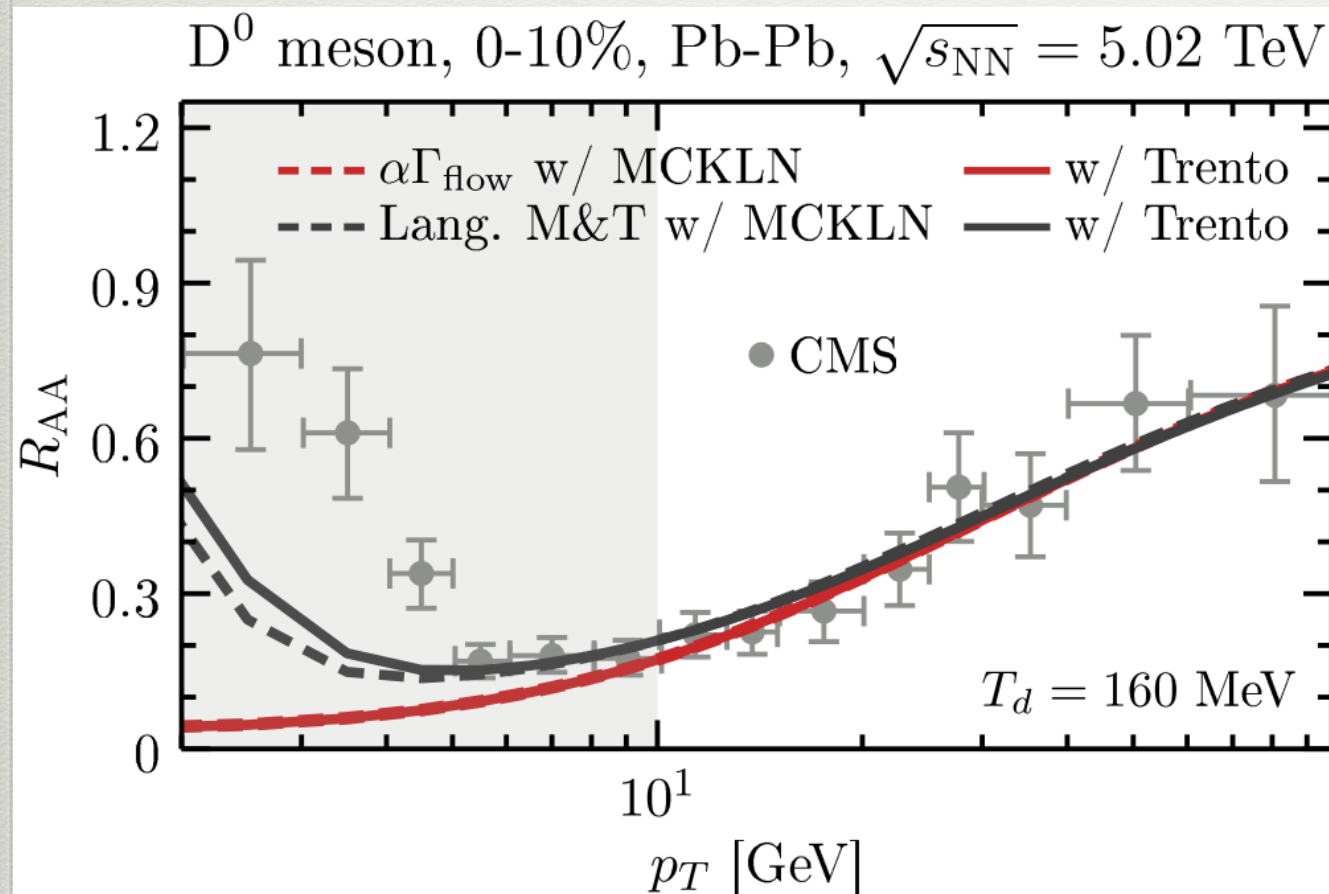
[2] Bilandzic et al, PRC83(2011)044913; PRC89(2014)no.6,064904

[3] Gardim, Grassi, Luzum, Noronha-Hostler, Phys. Rev. C 95, 034901 (2017); JNH, Betz, Gyulassy, Luzum, Noronha, Portillo, Ratti Phys. Rev. C 95, 044901 (2017)

PbPb results

Can D mesons “see” the difference between
initial conditions?

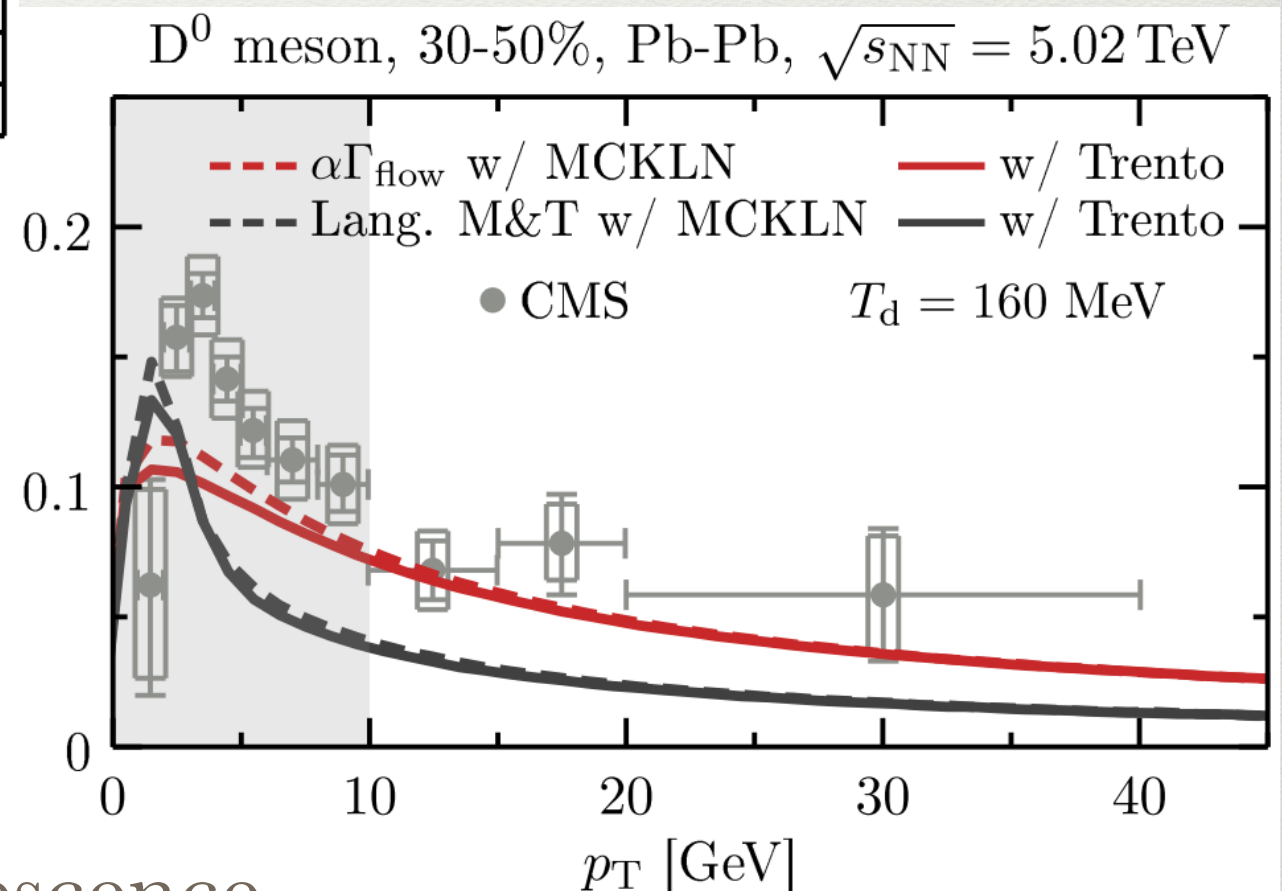
D MESONS*: MCKLN VS TRENTO



$v_2\{2\}$

Elliptical flow sensitive to initial conditions below

$p_T < 10$ GeV



R_{AA}

Nuclear modification factor
robust regardless of initial
conditions

* no coalescence

v_2 fluctuations of D mesons

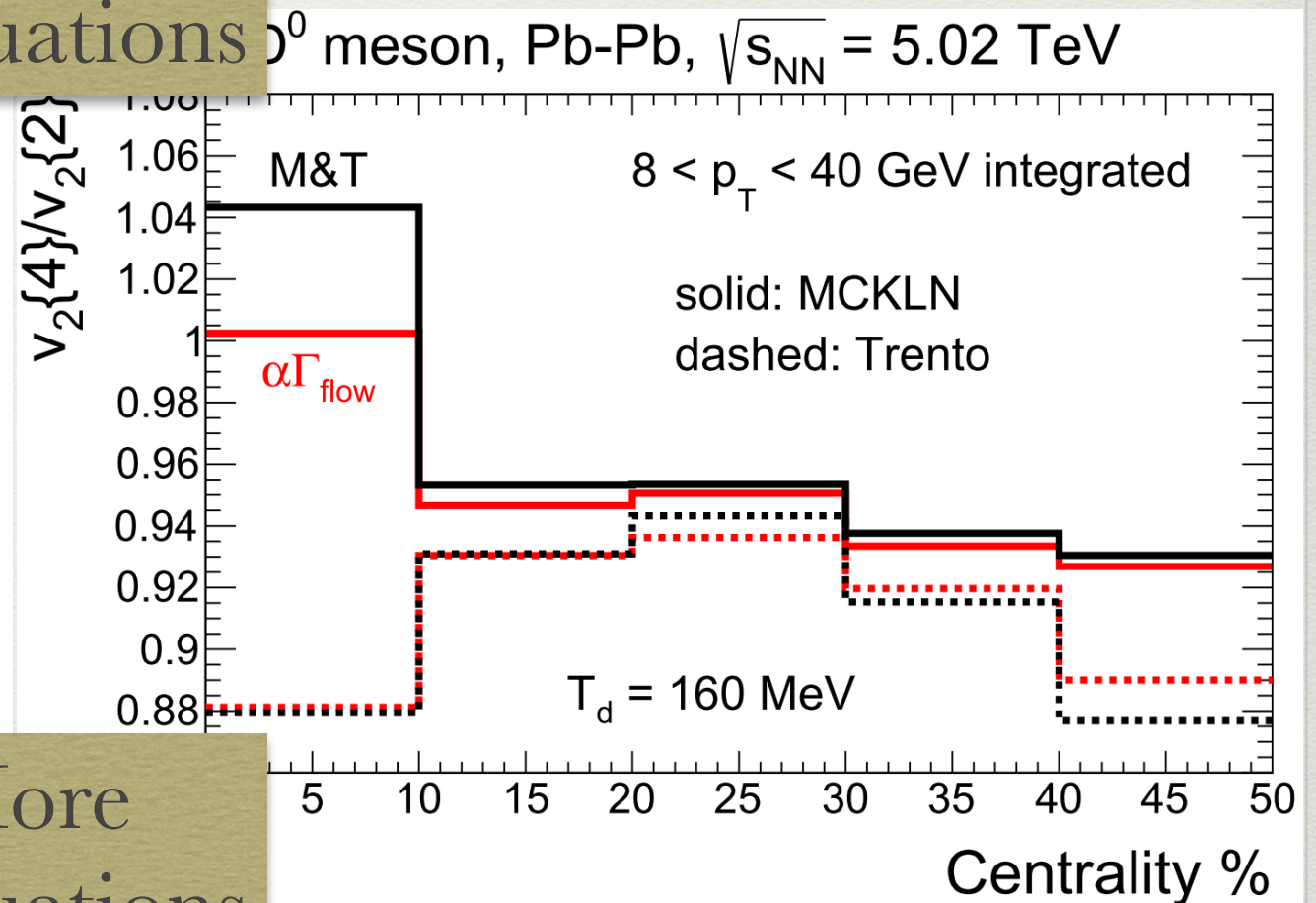
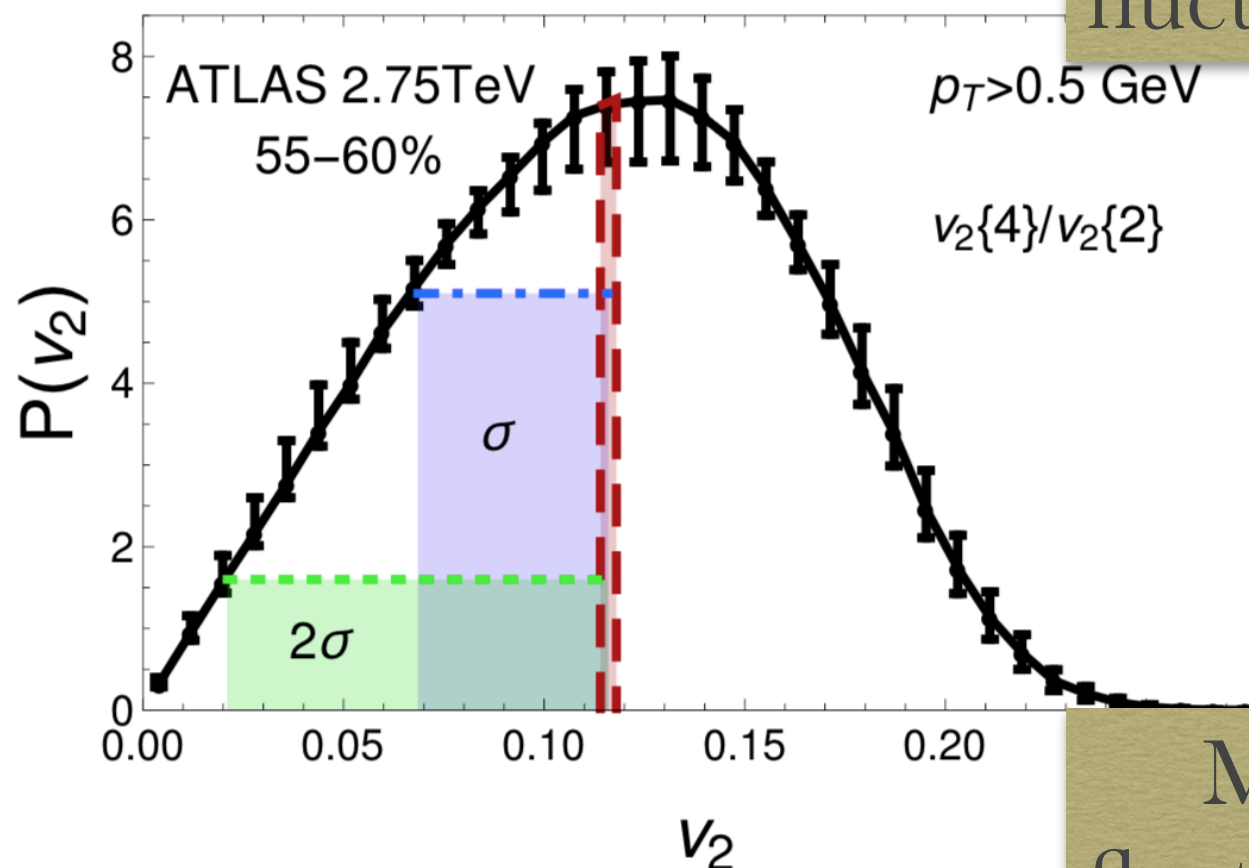
Soft sector: fluctuations in elliptical flow primarily driven by initial conditions

Heavy sector: still driven by initial conditions

Very different behavior predicted for central collisions

$v_2\{4\}/v_2\{2\}$ = fluctuation

Less fluctuations



More fluctuations

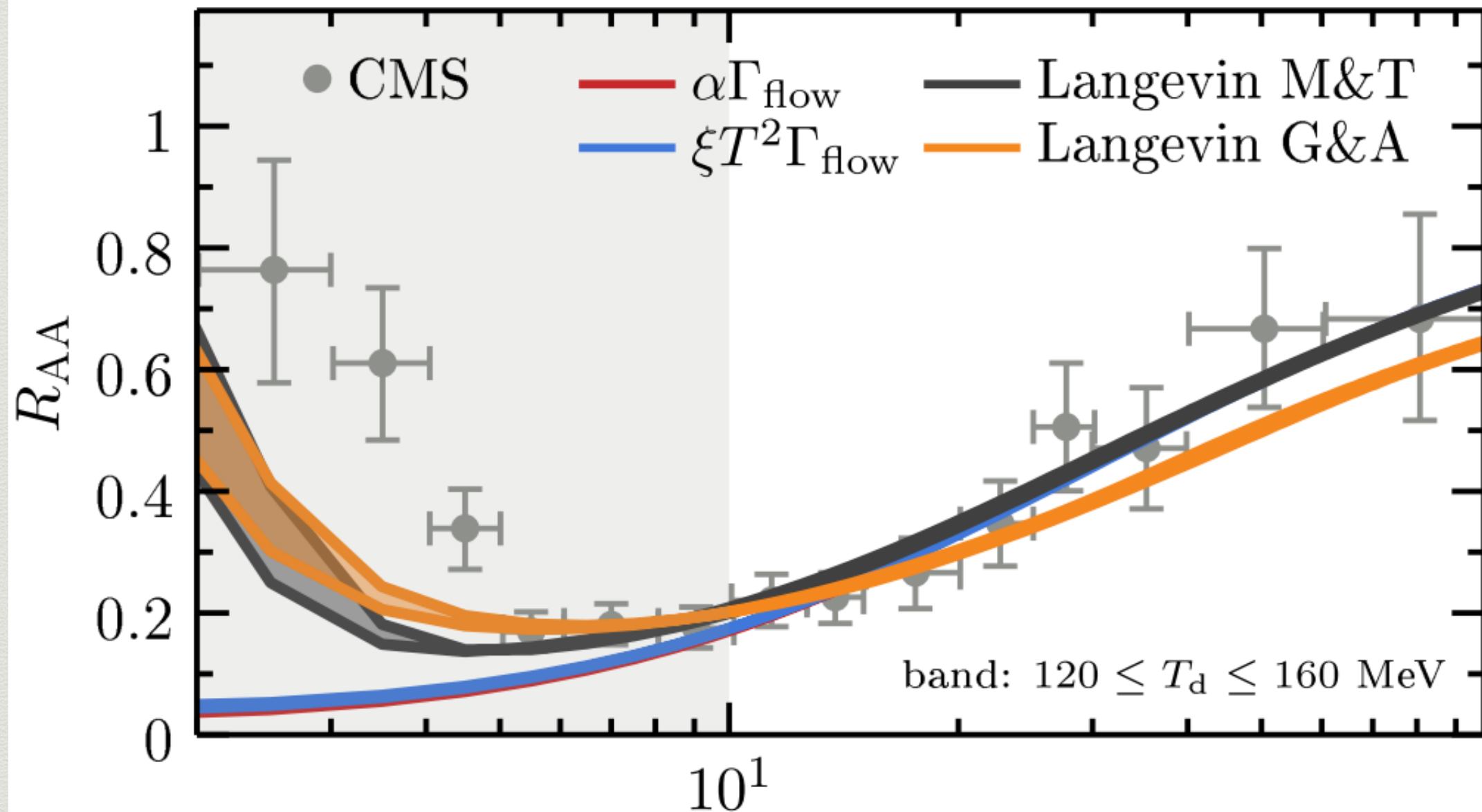
Can D mesons “see” the difference between initial conditions?

Yes, but not much in R_{AA} and $v_n \{2\}$ calculations, much more in $v_2 \{4\}/v_2 \{2\}$

How do energy loss models compare to
Langevin?

Energy loss vs. Langevin

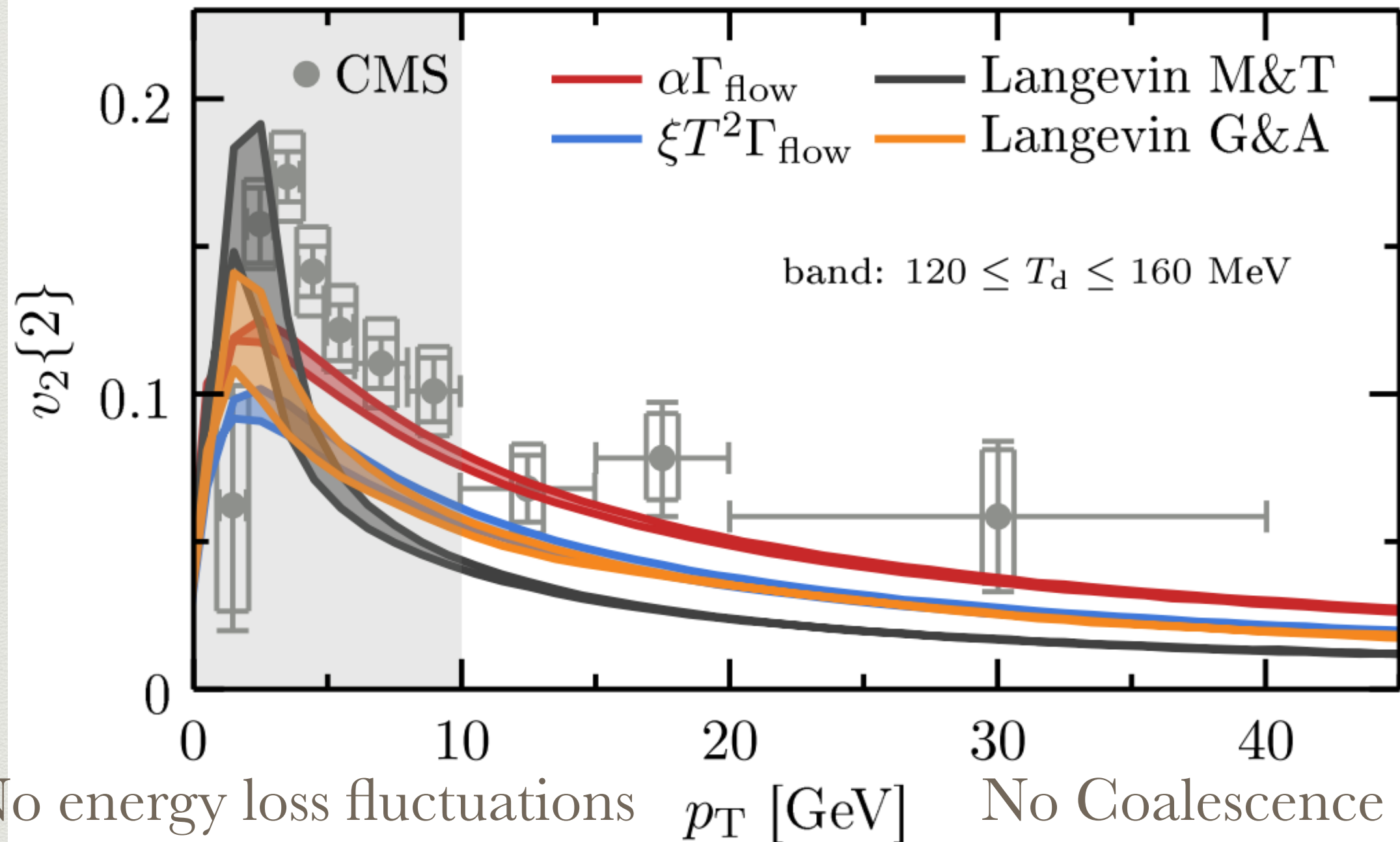
D^0 meson, 0-10%, MCKLN, Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV



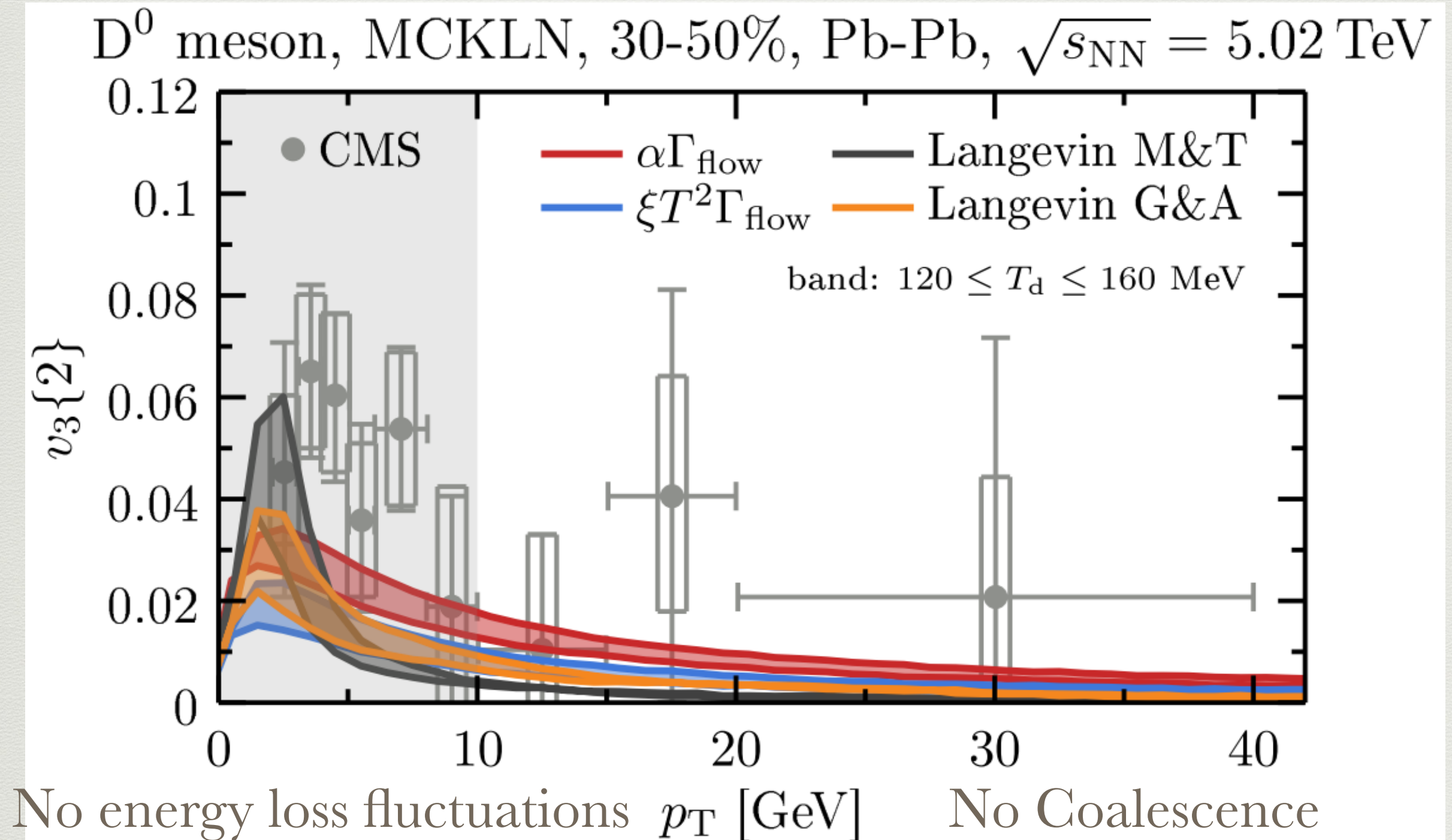
No energy loss fluctuations p_T [GeV] No Coalescence

Energy loss vs. Langevin

D^0 meson, 30-50%, MCKLN, Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV



Energy loss vs. Langevin



How do energy loss models compare to Langevin?

Different pictures emerge at different pT scales.

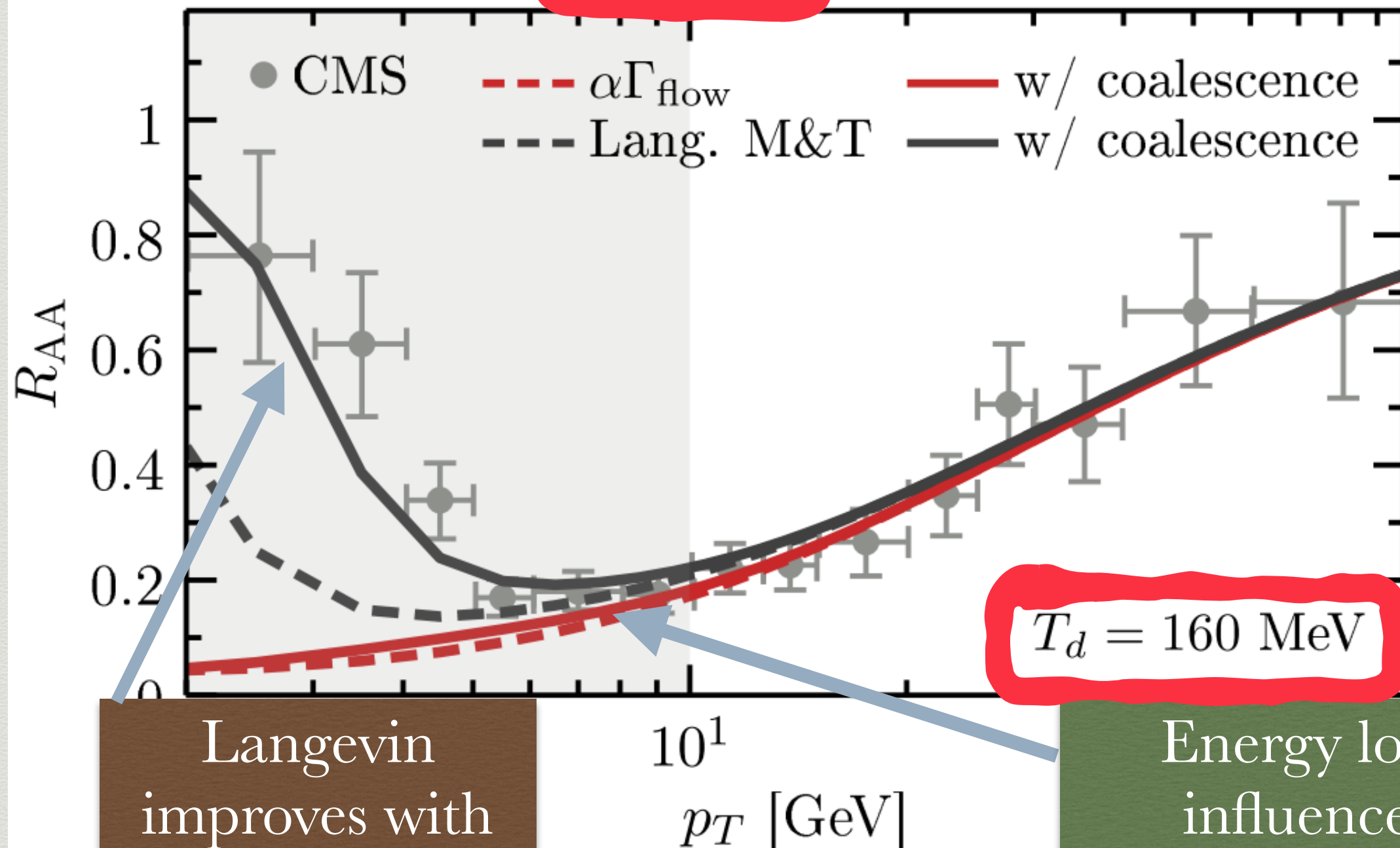
At low pT, Langevin generally produces a larger R_{AA} and $v_n \{2\}$, closer to experimental data.

At high pT, a constant energy loss model produces nearly the same R_{AA} as Langevin, but produces a larger $v_n \{2\}$, more closely matching experimental data.

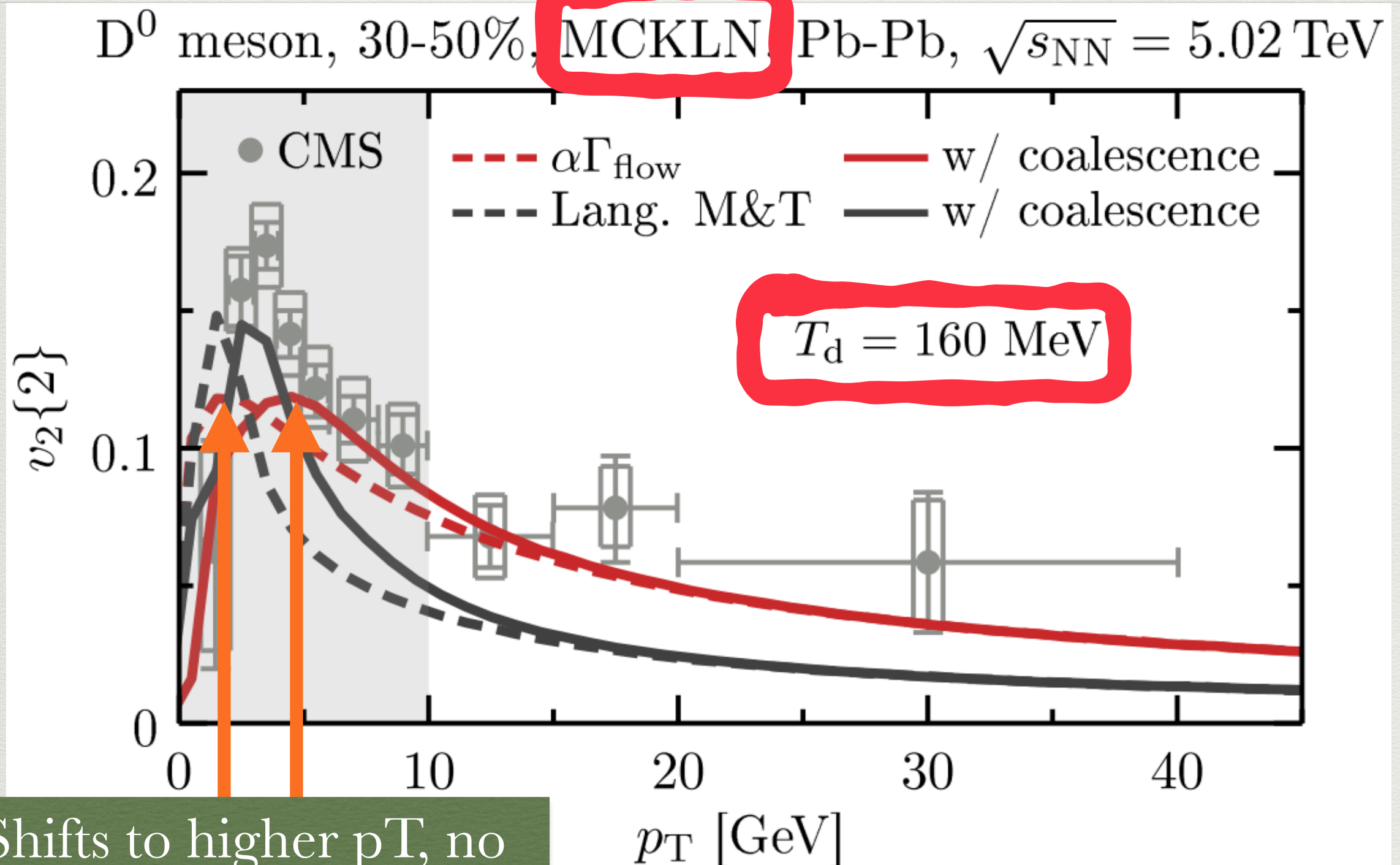
What roles does coalescence play?

Influence of coalescence on R_{AA}

D⁰ meson, 0-10%, MCKLN Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

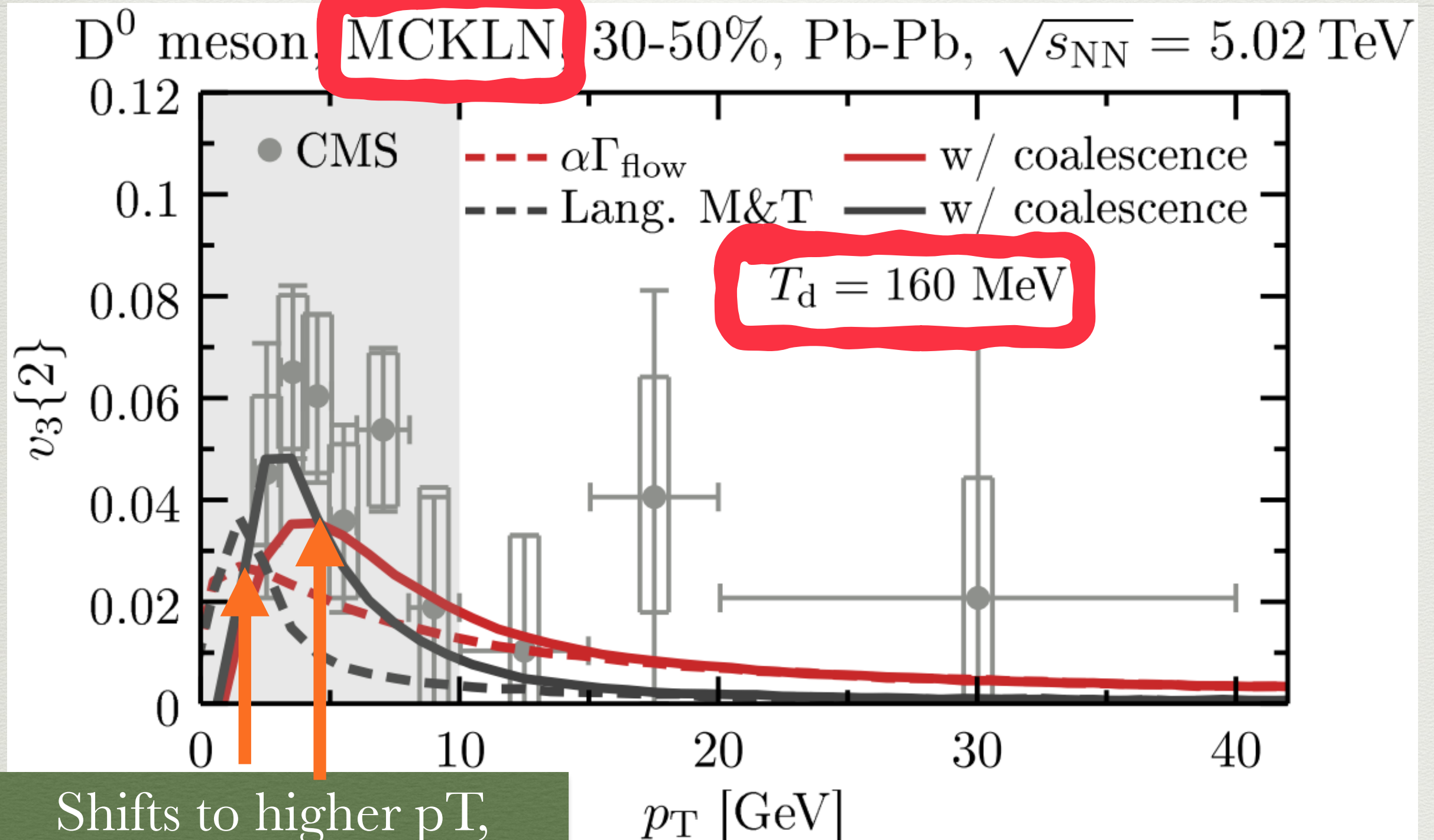


Azimuthal anisotropies and coalescence



Shifts to higher p_T , no change in magnitude

Azimuthal anisotropies and coalescence



Shifts to higher p_T ,
increases magnitude

What roles does coalescence play?

- R_{AA} Increases Langevin, not relevant for energy loss
- $v_2 \{2\}$ Shifts peak to higher pT
- $v_3 \{2\}$ Shifts peak to higher pT and increases magnitude

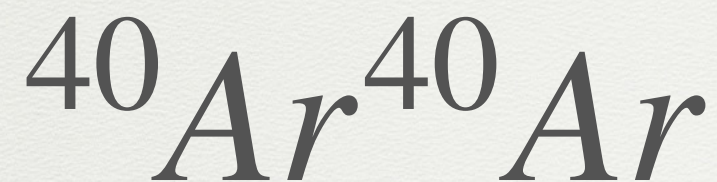
See also Nahrgang et al Phys.Rev. C91 (2015) no.1, 014904

Best fit

- **$p_T < 5 \text{ GeV}$** : Langevin (Moore & Teaney)
+coalescence
- **$p_T > 5 \text{ GeV}$** : Constant Energy loss+Gaussian
Energy Loss fluctuations+coalescence

SYSTEM SIZE

PROPOSAL FOR COLLISIONS



[arXiv:1812.06772](https://arxiv.org/abs/1812.06772)

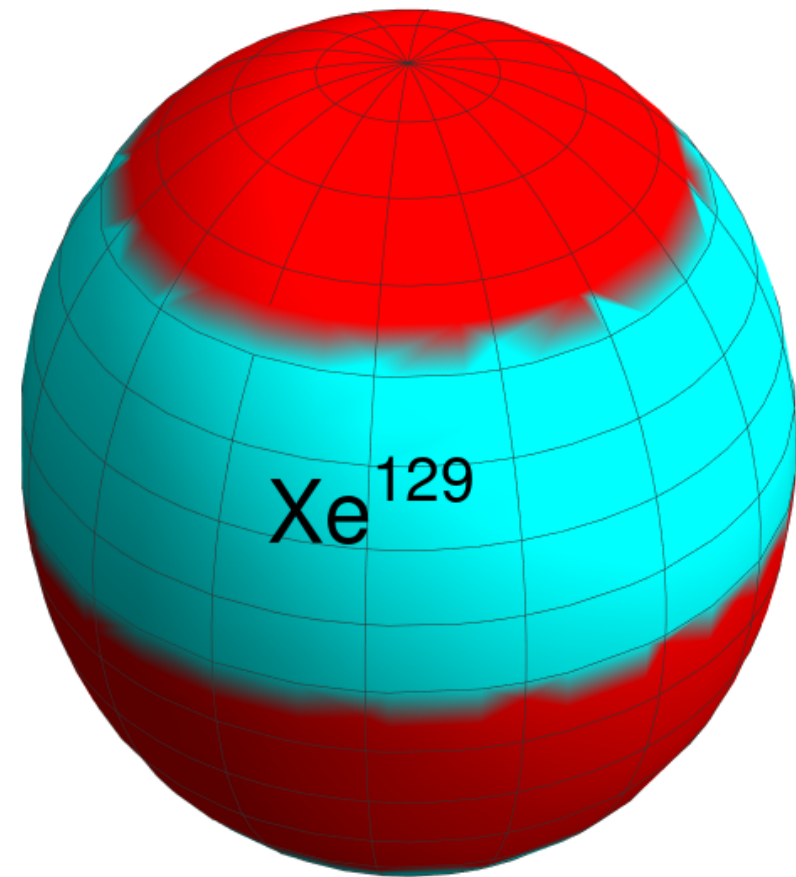
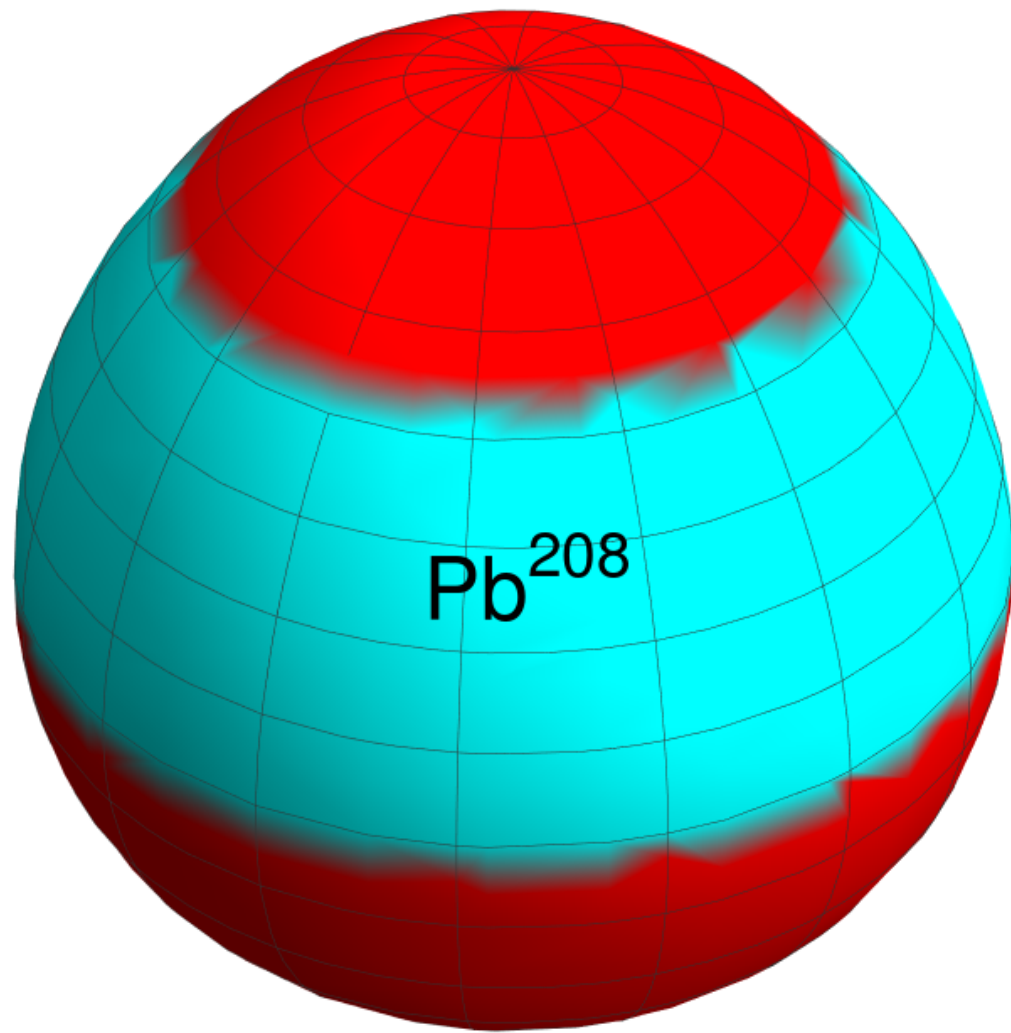
CERN-LPCC-2018-07
December 18, 2018

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

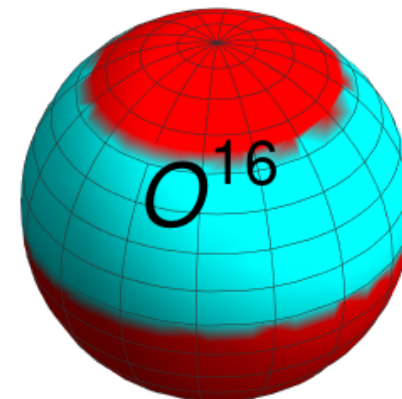
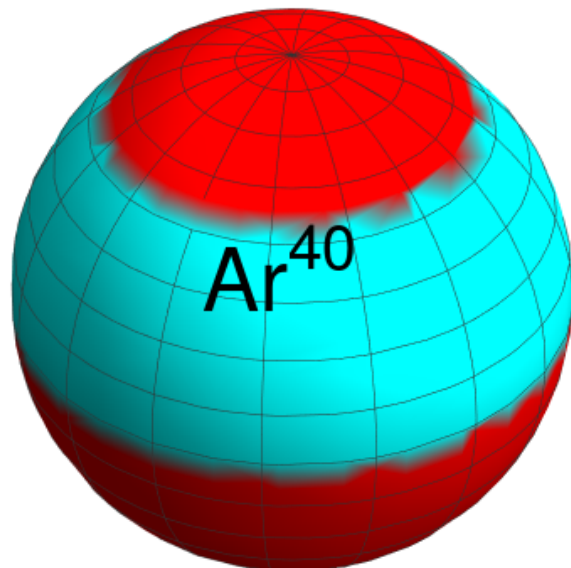
Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

Hydro already worked well with XeXe collisions

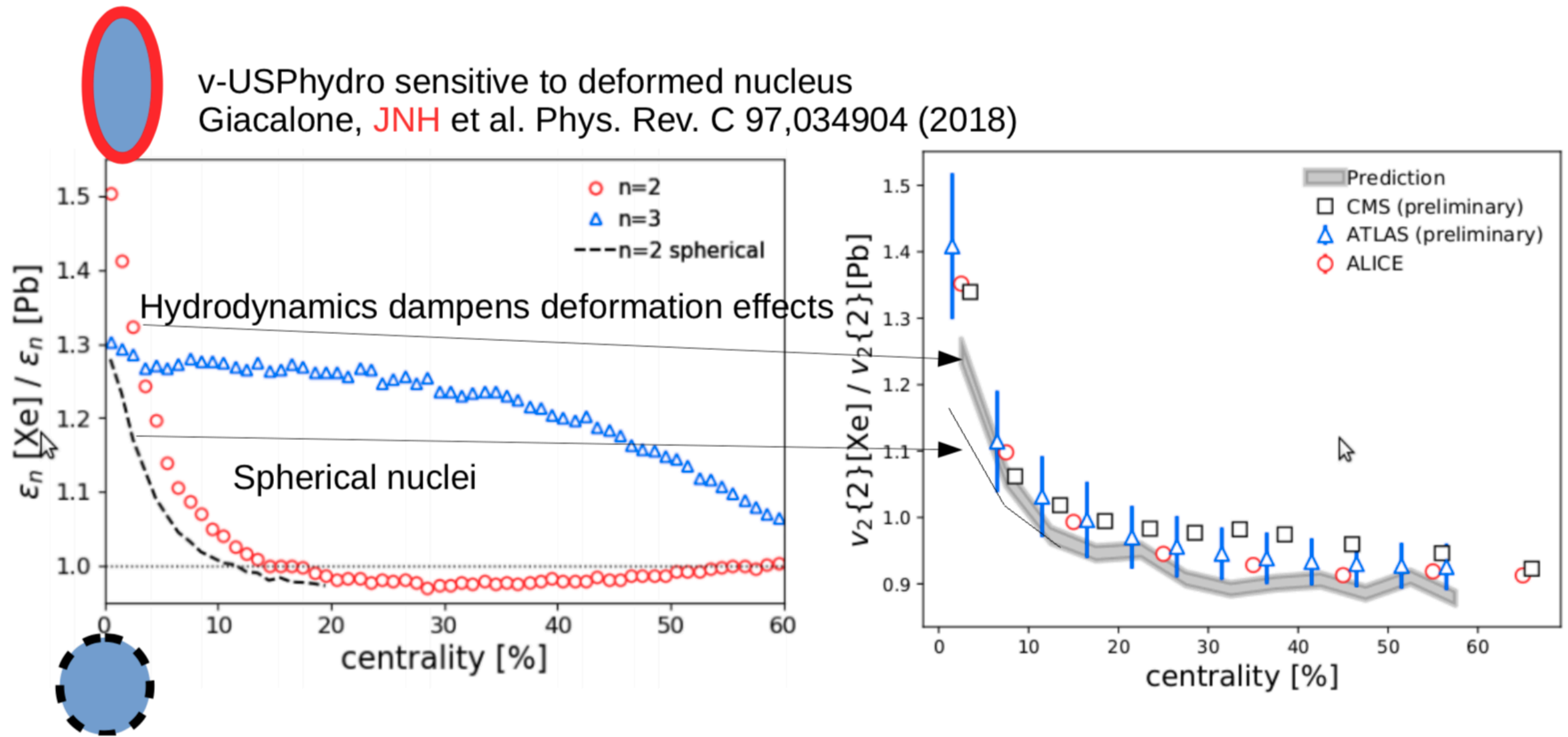
Giacalone, JNH, Phys.Rev. C97 (2018) no.3, 034
35



LHC system size scan



XE DEFORMATION MEASURED

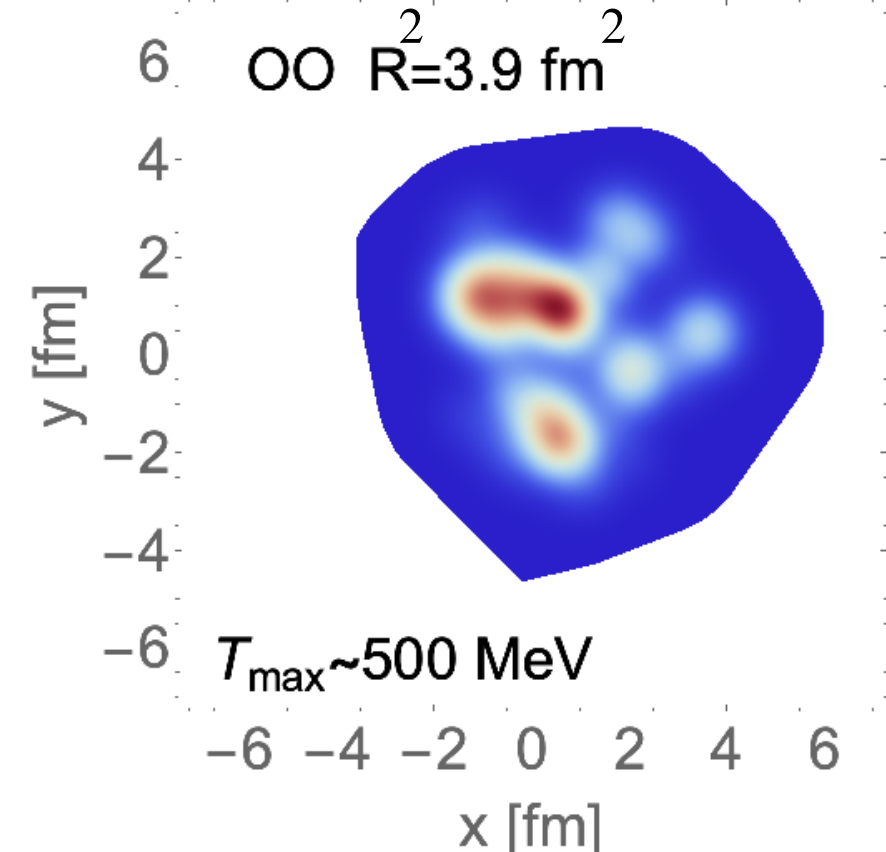
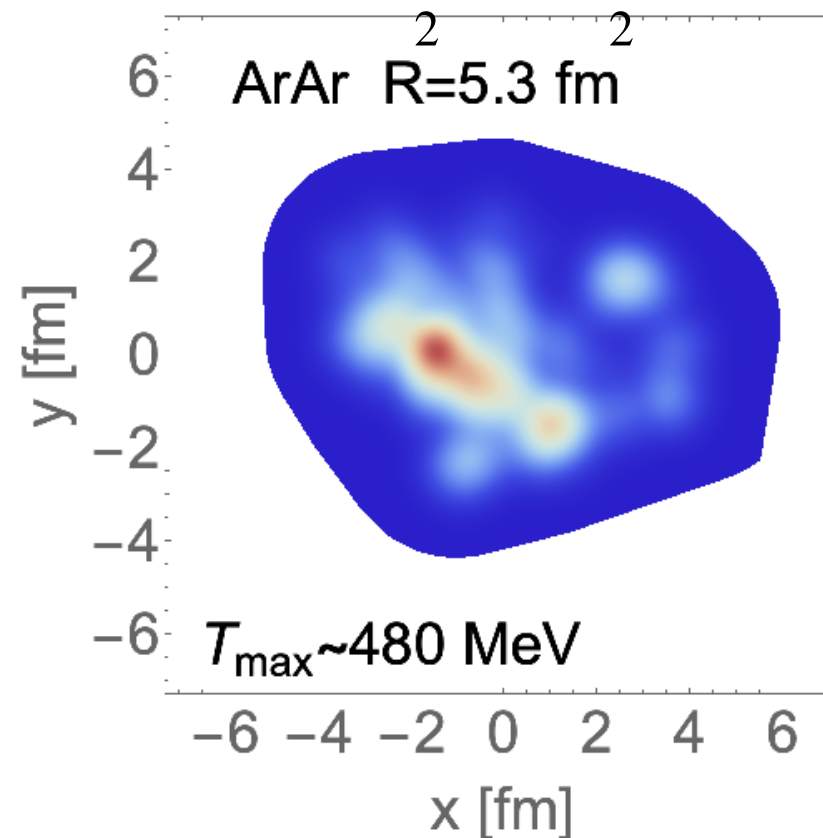
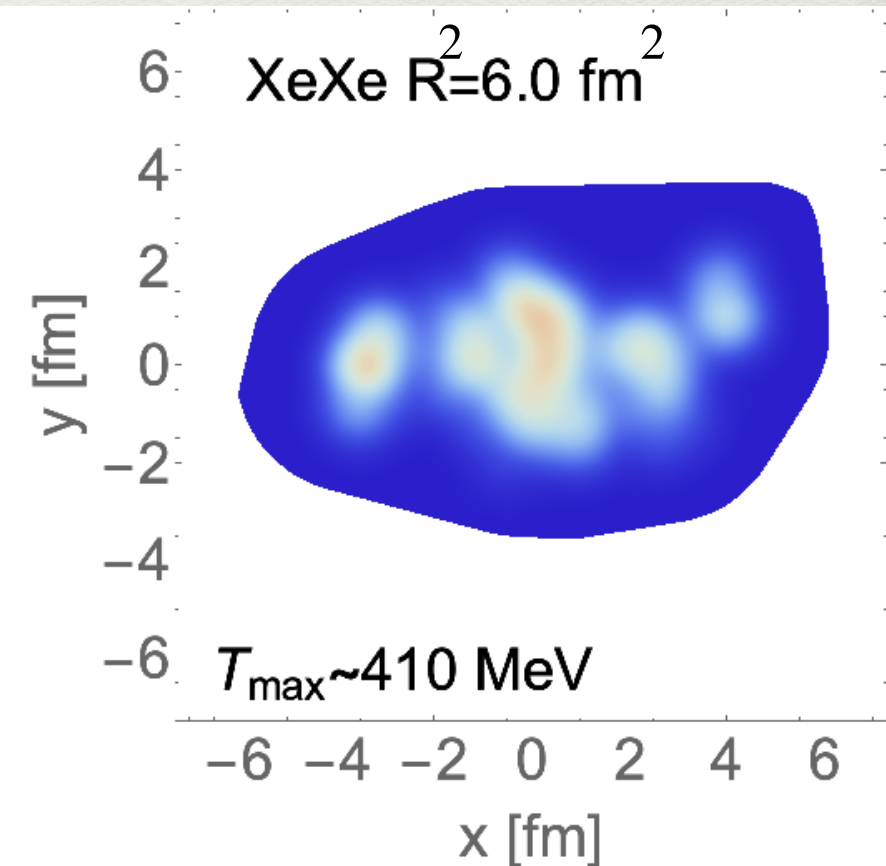
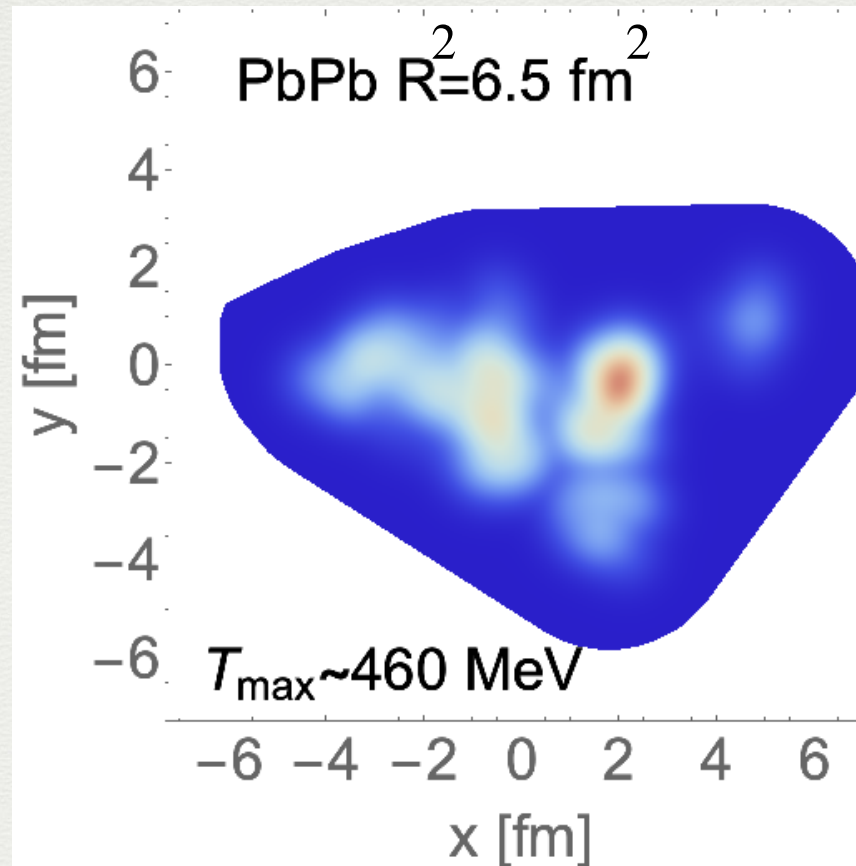


TYPICAL EVENTS

PbPb and XeXe
events larger, more
elliptical.

ArAr and OO
smaller and rounder.

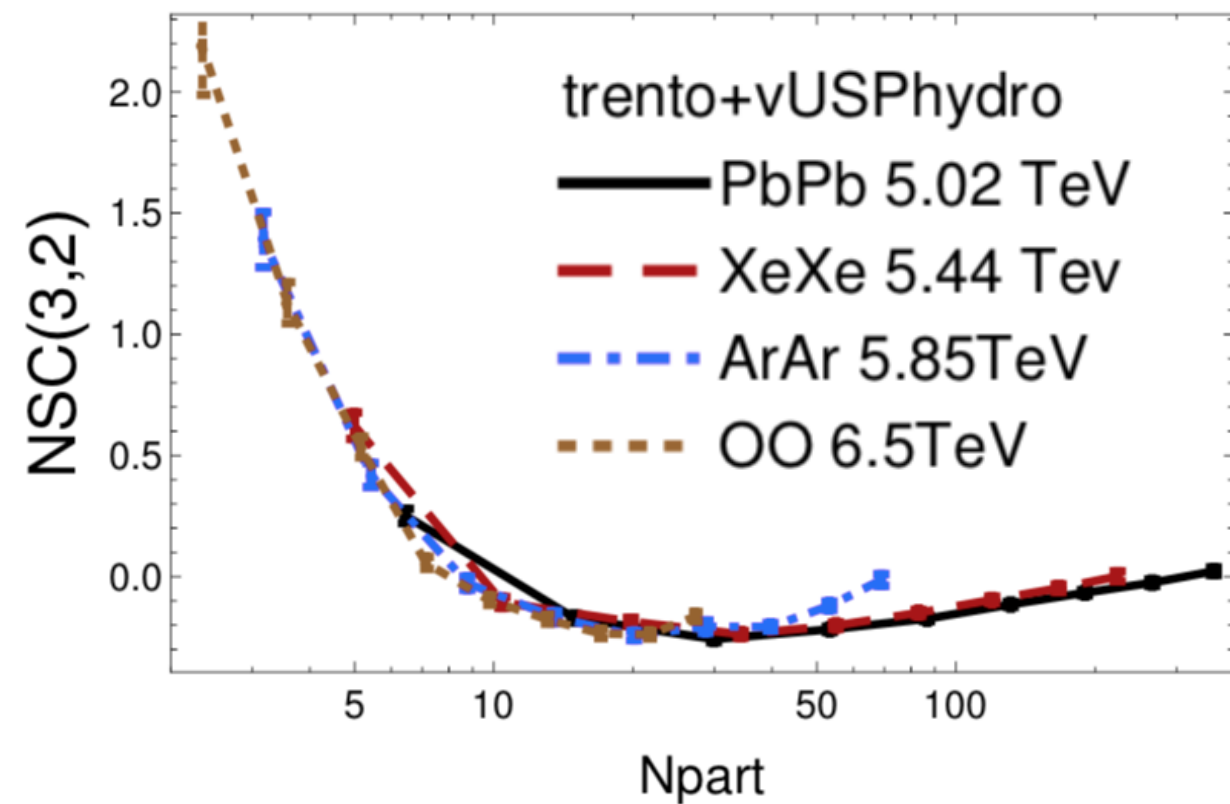
Small systems
are hotter



SOFT SECTOR: UNIVERSAL SCALING VS. HIERARCHY

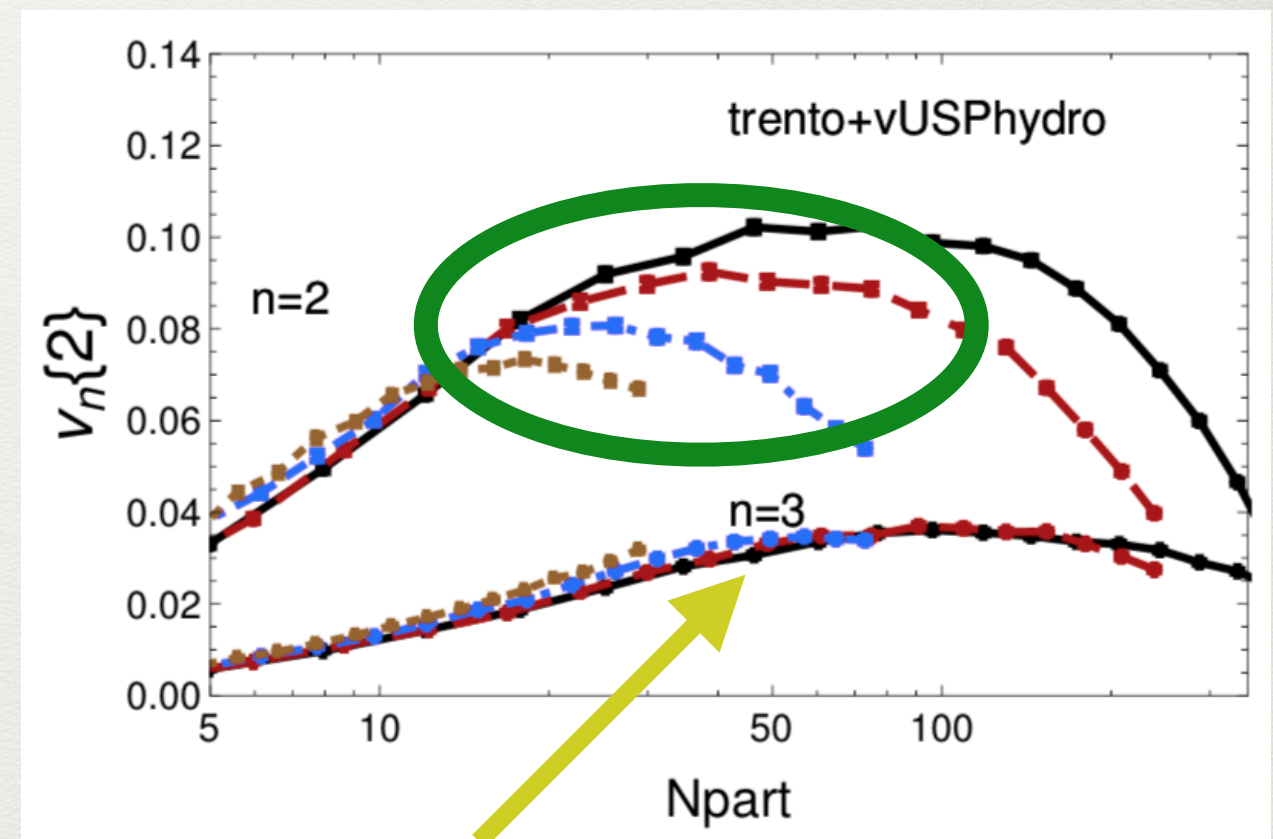
Sievert, JNH, [arXiv:1901.01319](https://arxiv.org/abs/1901.01319)

Universal Scaling



$$NSC(m, n) = \frac{v_3\{4\}}{v_3\{2\}}$$

Size Hierarchy



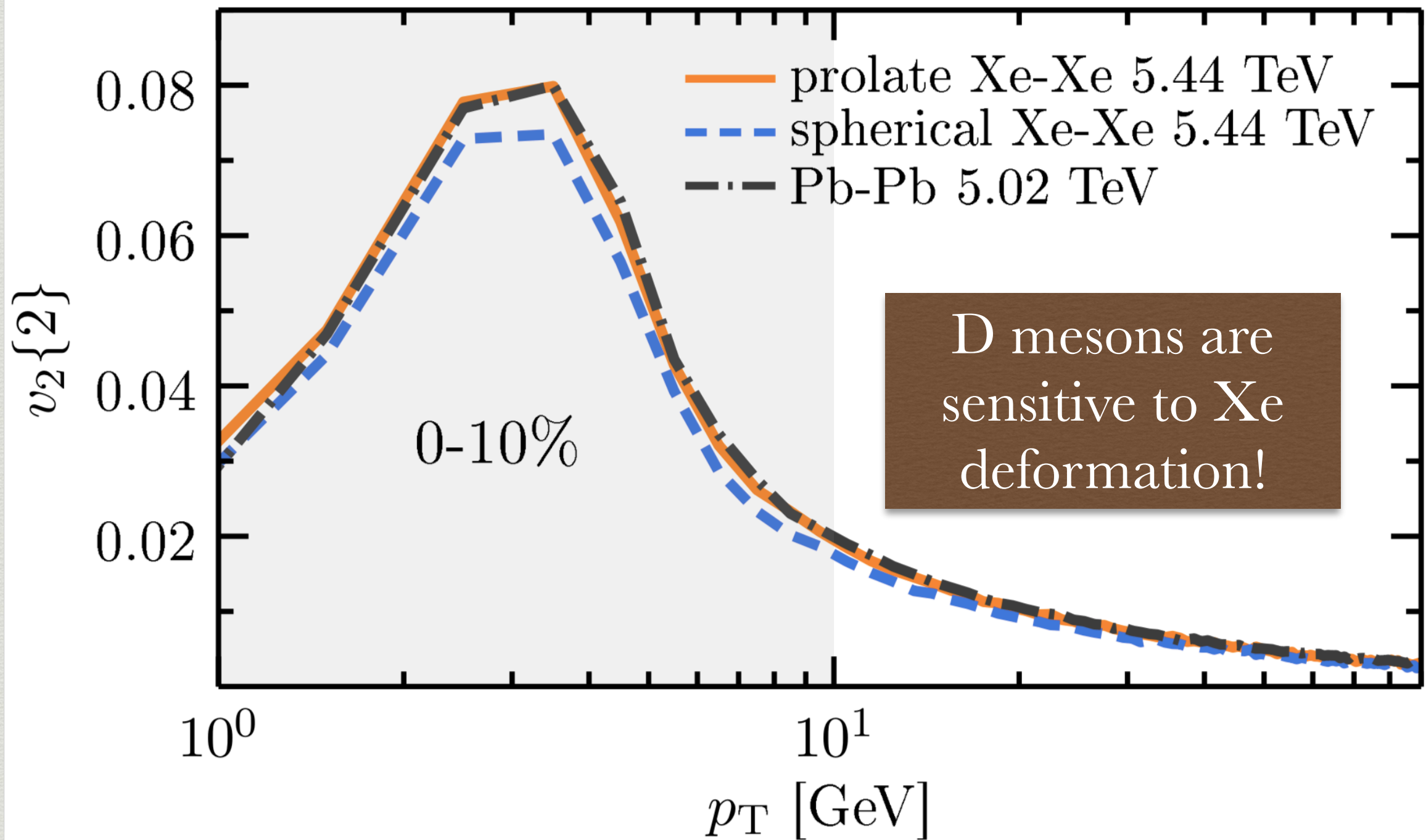
$$\langle p_T \rangle \quad v_2\{2\} \quad \frac{v_2\{4\}}{v_2\{2\}}$$

Event plane correlations

Comparing are best fit PbPb to XeXe collisions

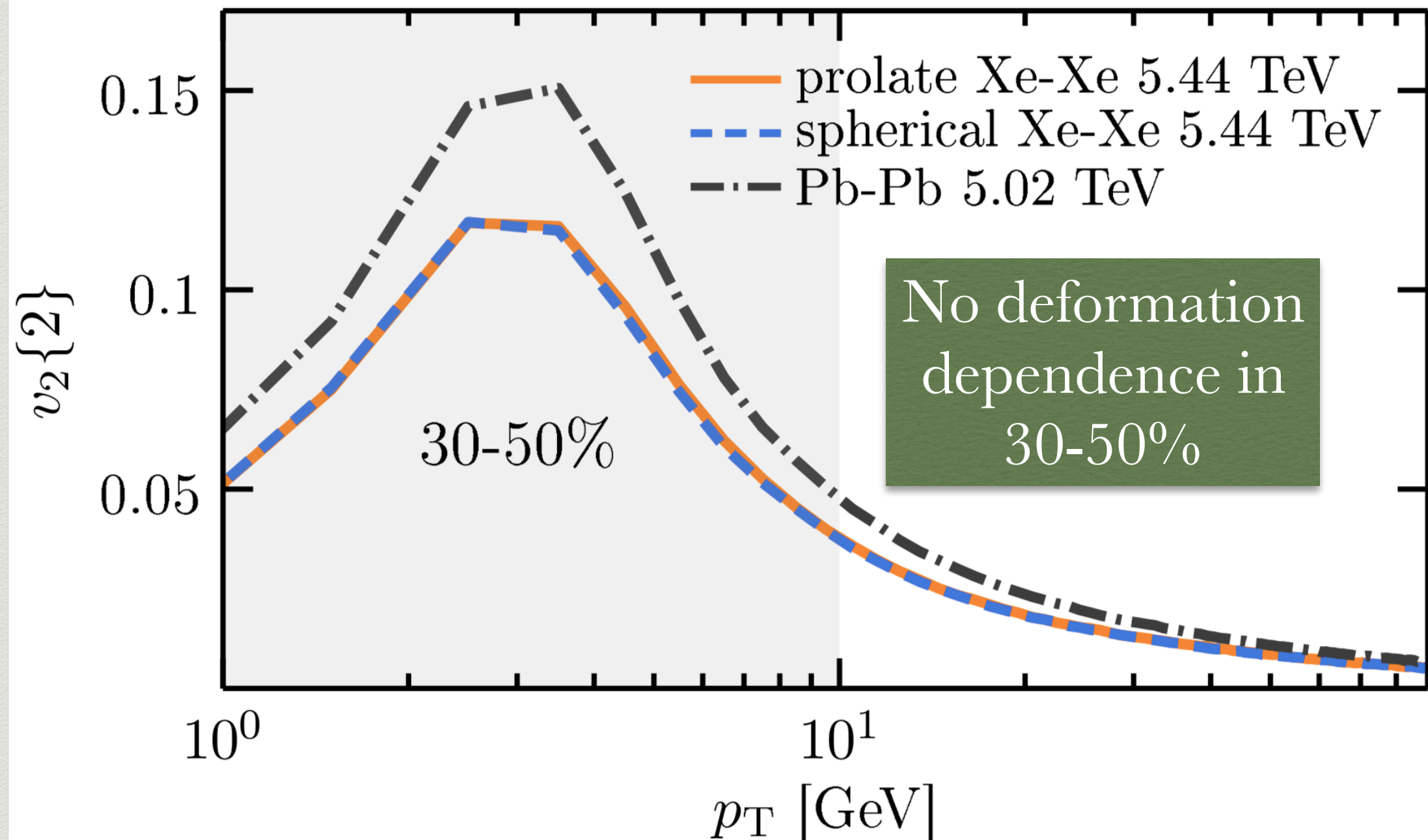
D mesons in XeXe collisions

D^0 meson, Trento, Langevin, frag. & coal., $T_d = 160$ MeV



D meson v_2 suppressed in “small” system

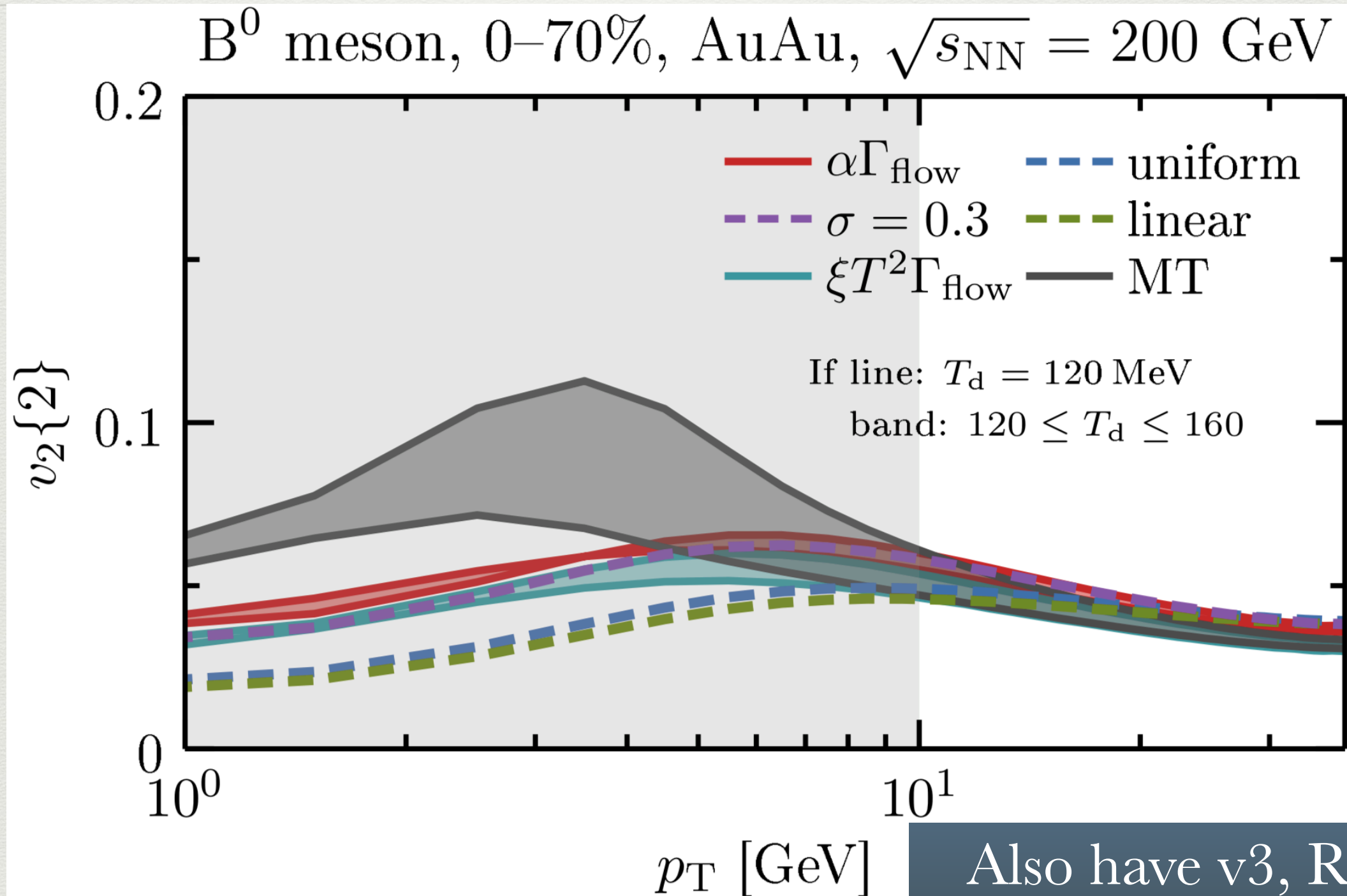
D^0 meson, Trento, Langevin, frag. & coal., $T_d = 160$ MeV



RHIC

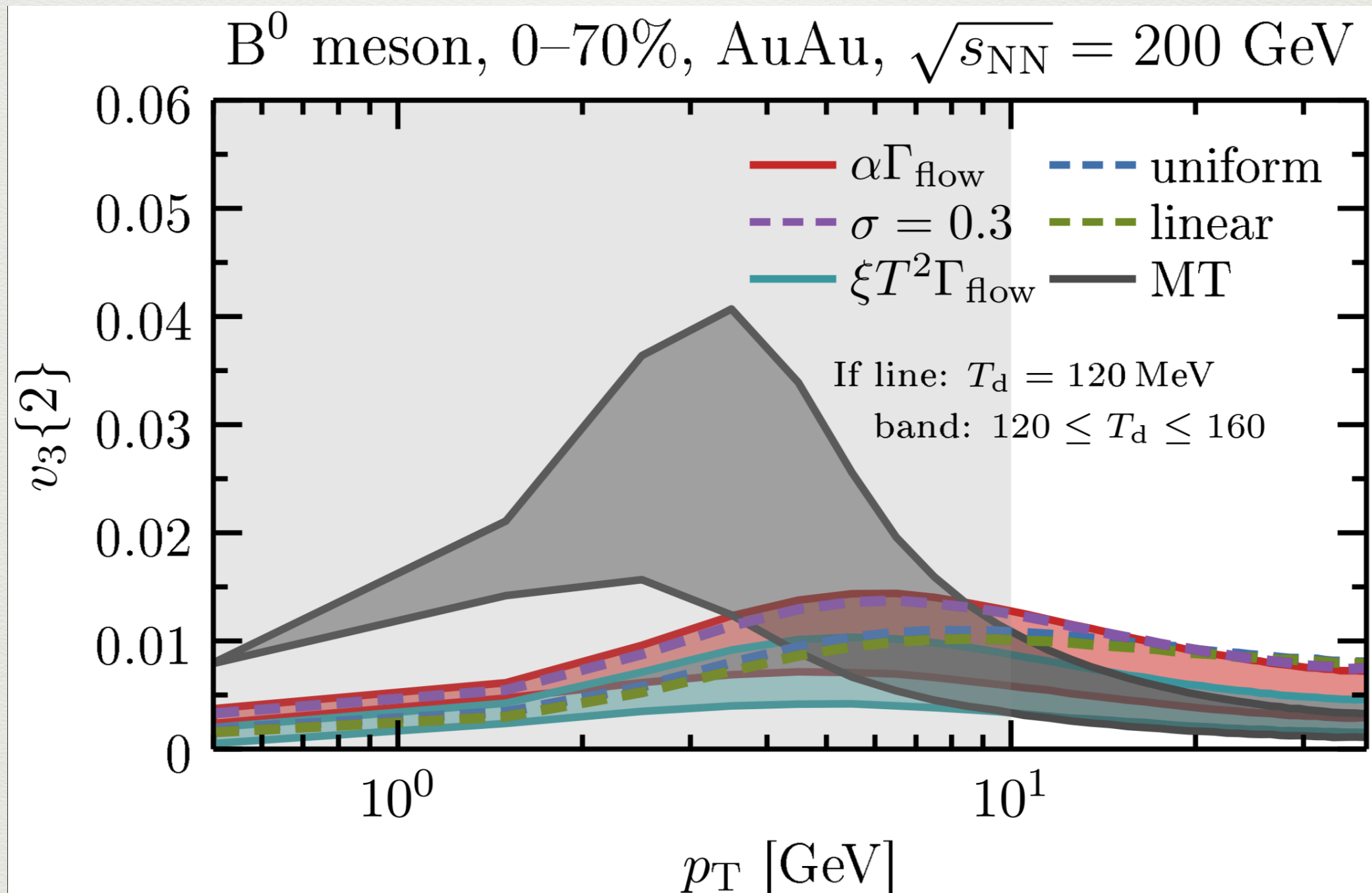
See Xin Dong (STAR/sPHENIX) and Kazuya Nagashima's
(PHENIX) talks on Monday

sPHENIX predictions ($v_2\{2\}$)



Also have v_3 , RAA,
muons, and electrons

sPHENIX predictions ($v_3\{2\}$)



CONCLUSIONS

Conclusions and Outlook

- DAB-MOD is a modular heavy flavor code that can compare energy loss vs. Langevin directly with the same hydrodynamic backgrounds
 - Langevin works best at low p_T and Energy loss at high p_T
- Comparing PbPb to XeXe collisions:
 - D mesons sensitive to deformed nucleus
 - v_2 of D mesons suppressed in smaller system
- Explore hard probes in a system size scan of PbPb, XeXe, ArAr, and OO collisions. More RHIC/sPHENIX results to come.

BACKUP

Fragmentation & Coalescence

- Create D mesons at decoupling temperature $T_d \geq T_{FO}$
- Fraction of heavy quarks z from Peterson frag. function
$$f(z) \propto \left[z \left(1 - 1/z - \epsilon_Q/(1 - z) \right) \right]$$
-

Multi particle cumulants

Correlate 1 high p_T particles with $n-1$ soft particles.

$$\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} = \frac{v_n\{4\}}{v_n\{2\}} \left[1 + \left(\frac{v_n\{2\}}{v_n\{4\}} \right)^4 \underbrace{\left(\frac{\langle v_n^4 \rangle}{\langle v_n^2 \rangle^2} - \frac{\langle v_n^2 V_n V_n^*(p_T) \rangle}{\langle v_n^2 \rangle \langle V_n V_n^*(p_T) \rangle} \right)}_{\text{soft-hard fluctuations}} \right] \quad (1)$$

If there's no hard physics,

$$\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} = \frac{v_n\{4\}}{v_n\{2\}}$$

Multiparticle cumulants

Reconstructing the v_n distribution with cumulants

$$v_n\{2\}^2 = \langle v_n^2 \rangle,$$

$$v_n\{4\}^4 = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle,$$

$$v_n\{6\}^6 = \frac{1}{4} \left[\langle v_n^6 \rangle - 9\langle v_n^2 \rangle \langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3 \right],$$

$$v_n\{8\}^8 = \frac{1}{33} \left[144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2 \langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2 \right. \\ \left. + 16\langle v_n^2 \rangle \langle v_n^6 \rangle - \langle v_n^8 \rangle \right],$$

where collectivity $\rightarrow v_n\{2\} > v_n\{4\} \sim v_n\{6\} \sim v_n\{8\}$ but there are differences between higher order cumulants!

Soft-hard multi particle cumulants

Scalar product, $v_2\{2\}(p_T) \equiv v_2\{SP\}$

Avoids well-known problems with the event-plane method
comparing between theory and experiments.

See Luzum and Ollitrault PRC87 (2013) no.4, 044907

$v_n\{2\}(p_T)$ Two particle correlation (one soft, one hard)

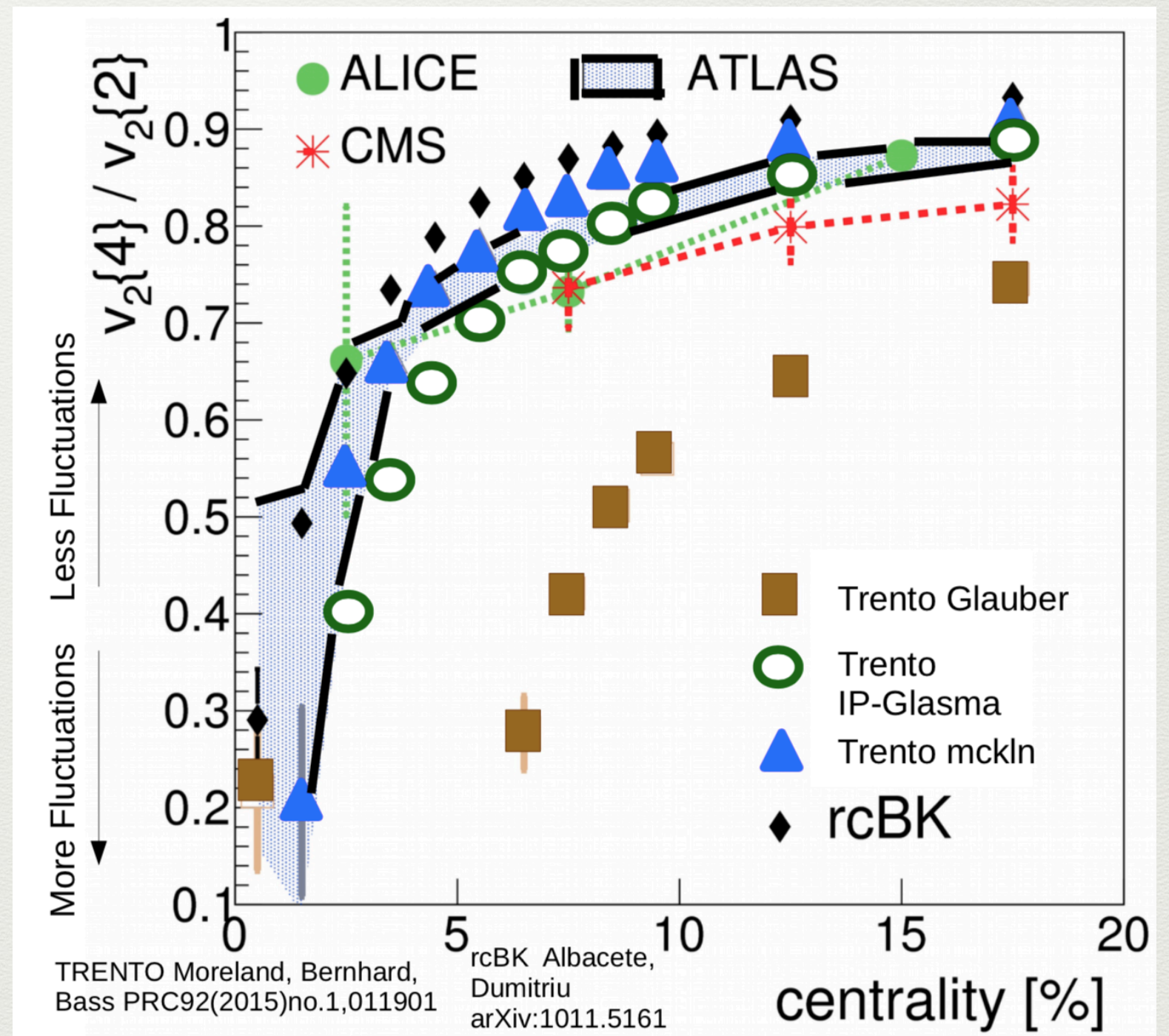
$$\frac{\langle v_n^{soft} v_n^{hard}(p_T) \cos \left(n \left[\psi_n^{soft} - \psi_n^{hard}(p_T) \right] \right) \rangle}{\sqrt{\langle (v_n^{soft})^2 \rangle}}$$

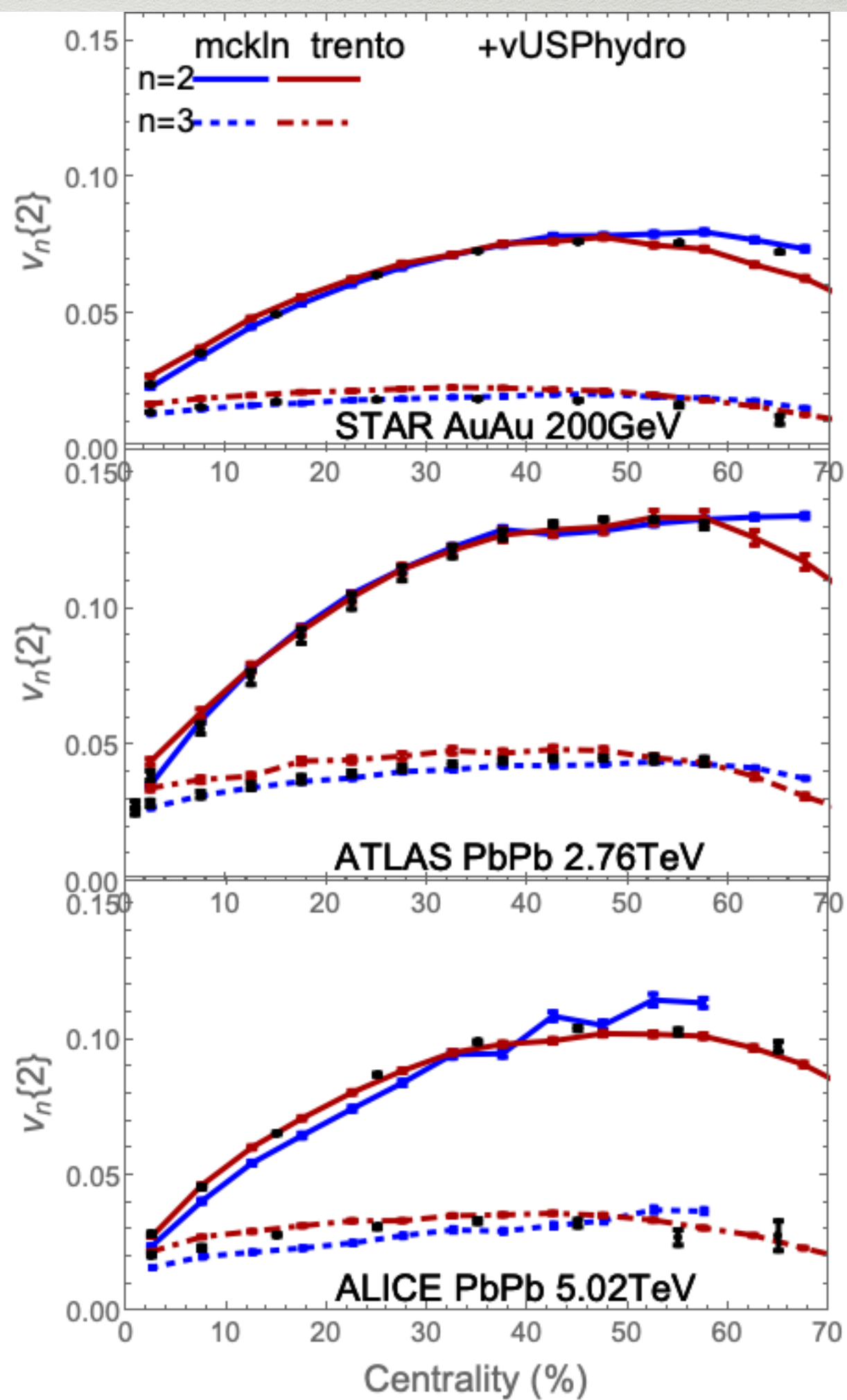
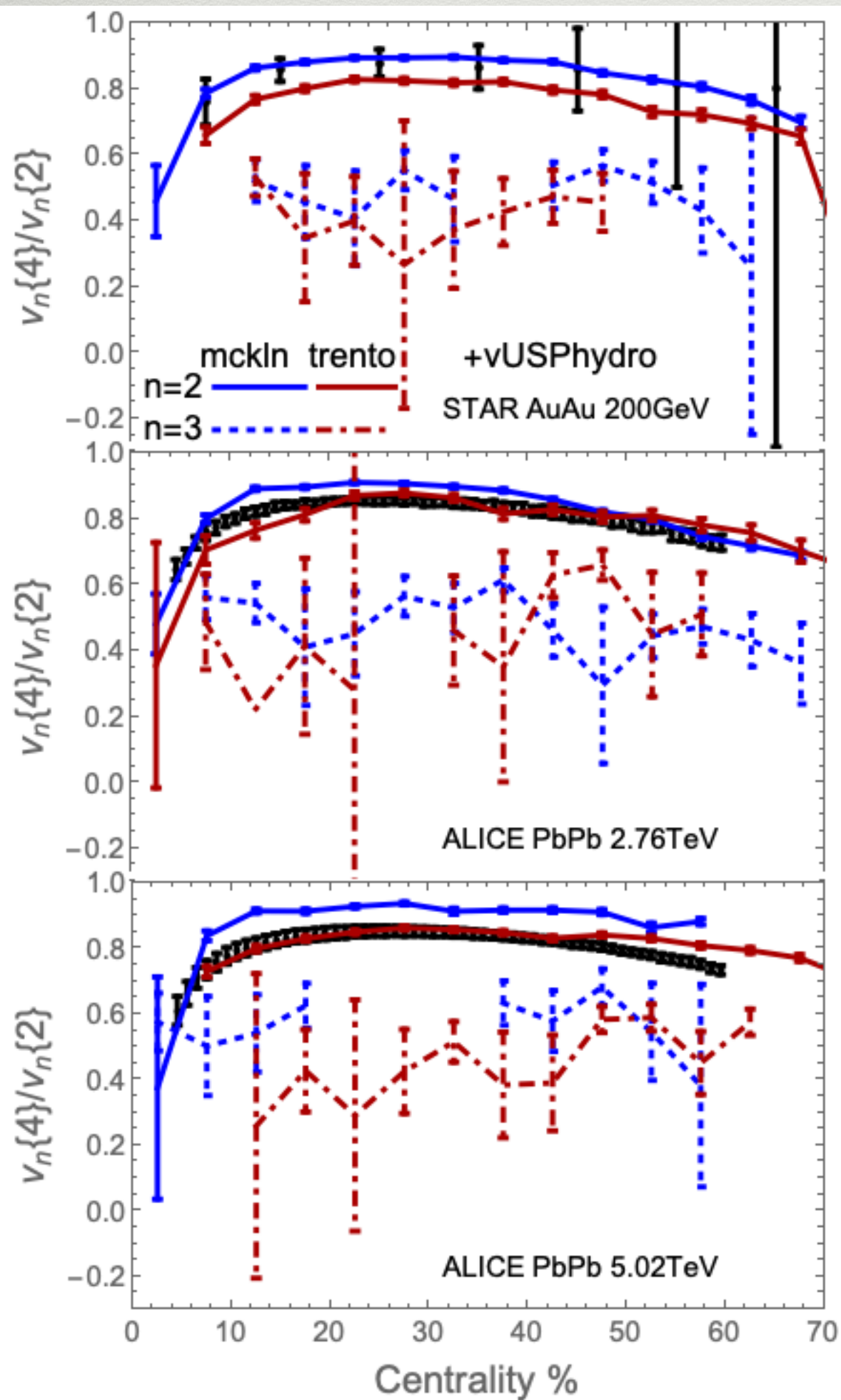
$v_2\{4\}(p_T)$ Four particle correlation (three soft, one hard)

$$\frac{2\langle |v_n^{soft}|^2 \rangle \langle v_n^{soft} v_n^{hard}(p_T) \cos \left[n \left(\psi_n^{soft} - \psi_n^{hard}(p_T) \right) \right] \rangle - \langle (v_n^{soft})^3 v_n^{hard}(p_T) \cos \left[n \left(\psi_n^{soft} - \psi_n^{hard}(p_T) \right) \right] \rangle}{(v_n^{soft}\{4\})^{3/4}}$$

Constraints on initial conditions

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Ollitrault Phys.Rev.
C95 (2017) no.5,
054910





Transport Coefficients

