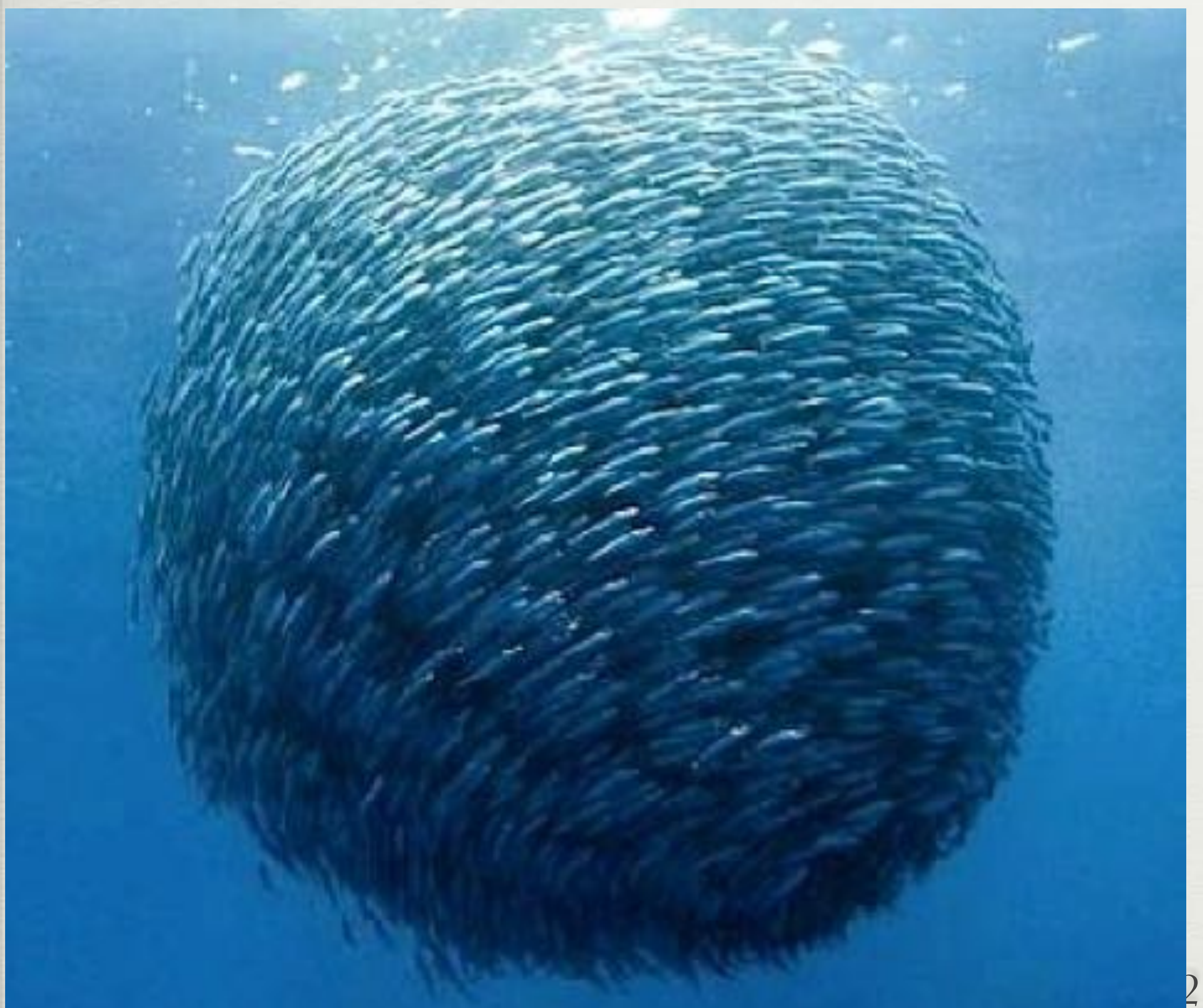
System size scan of D meson R_{AA} and v_n using PbPb, XeXe, ArAr, and OO collisions at LHC

Jacquelyn Noronha-Hostler
Collaborators: **Roland Katz, Caio A.G. Prado**, Alexandre A.P. Suaide arXiv:1906.10768 & arXiv:1907.03308

When is fluid dynamics still applicable?

When do you have too few particles to use hydrodynamics?

$$Kn \sim \frac{\text{Small scale}}{\text{Large scale}} \sim 1$$



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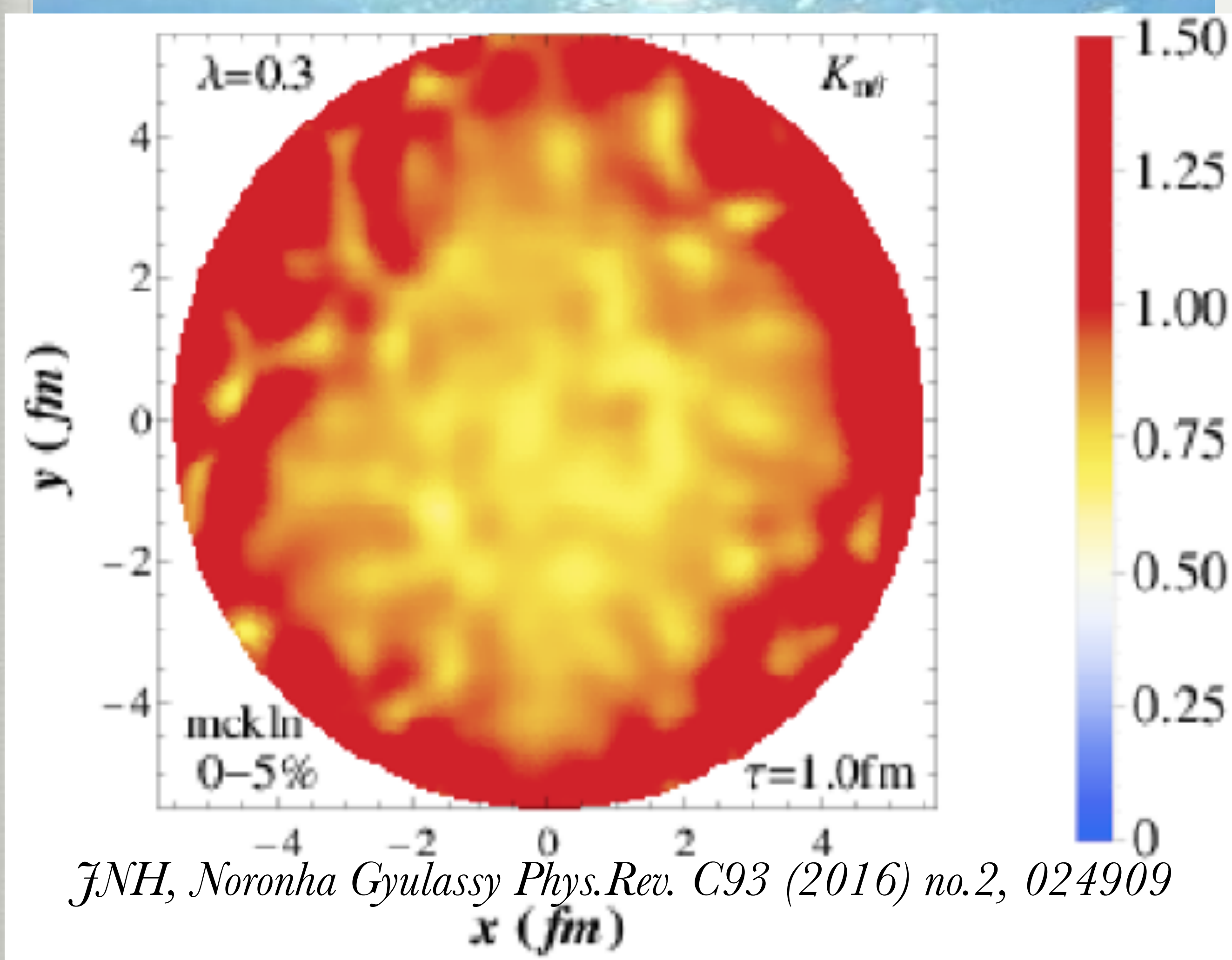
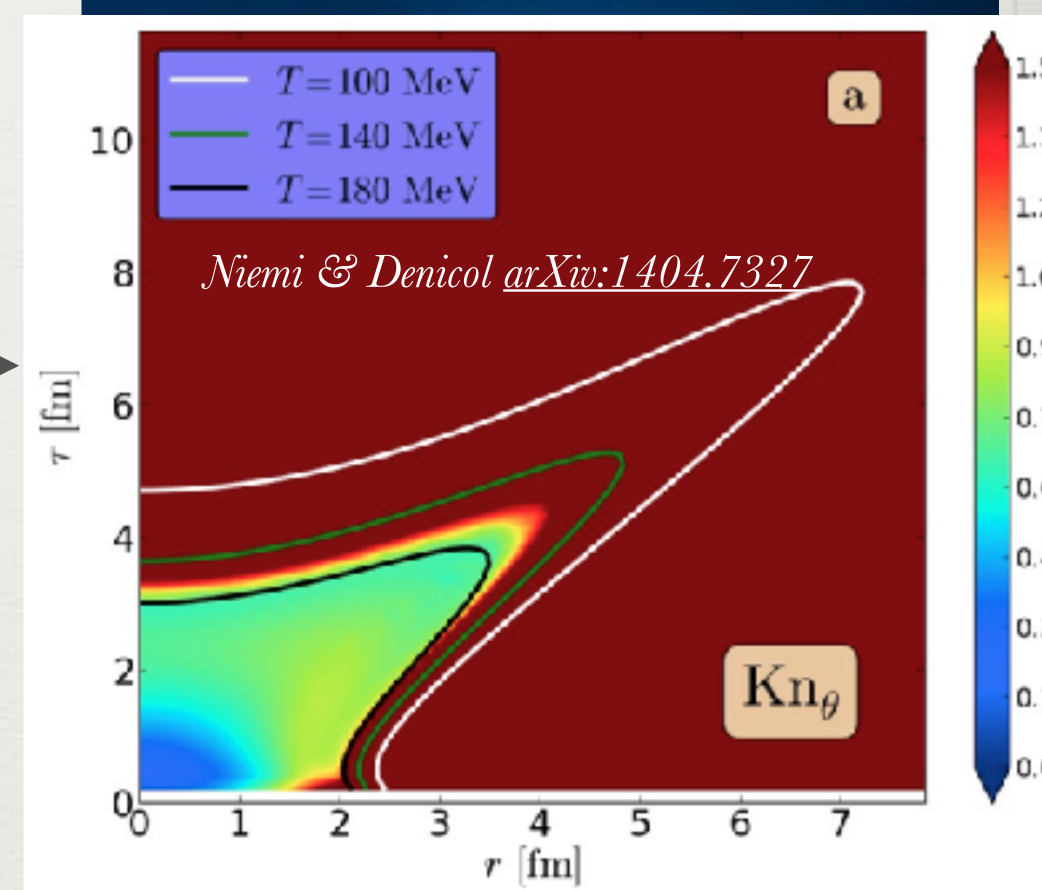
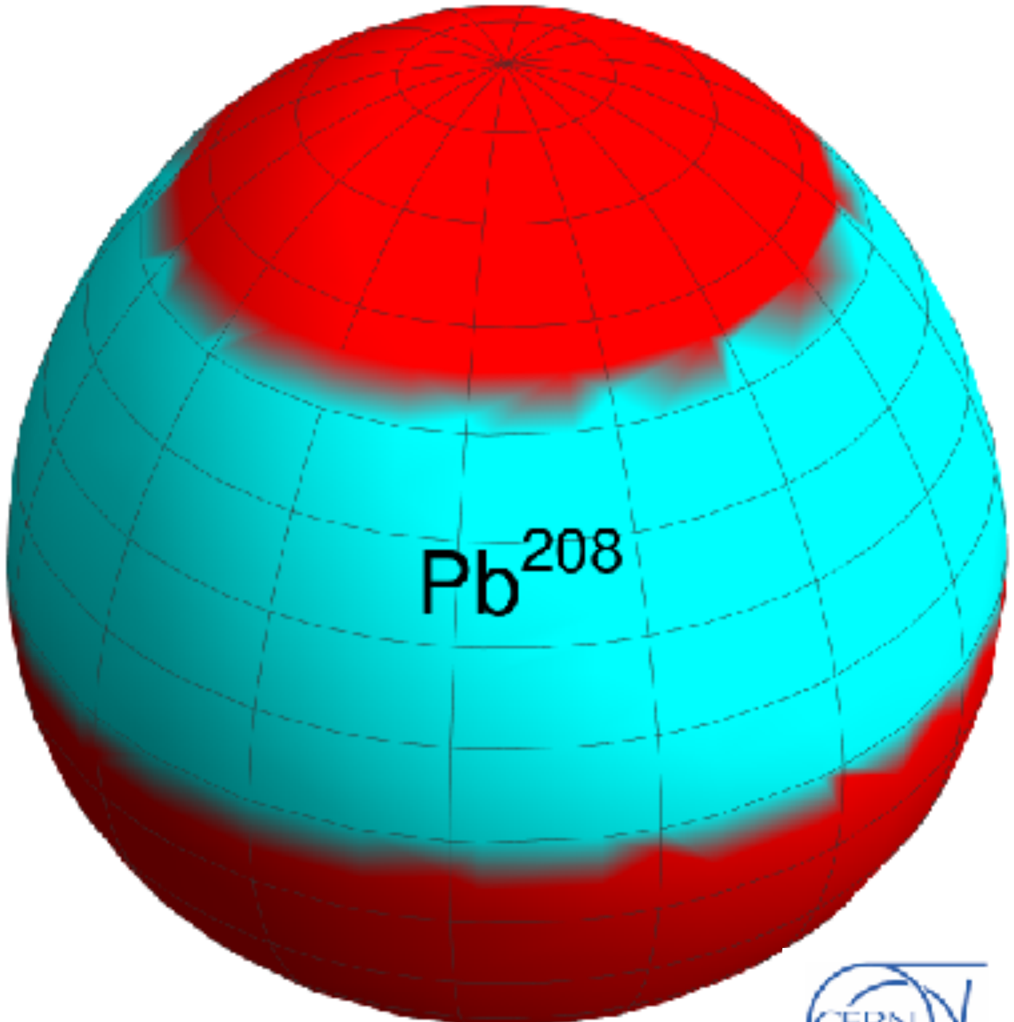
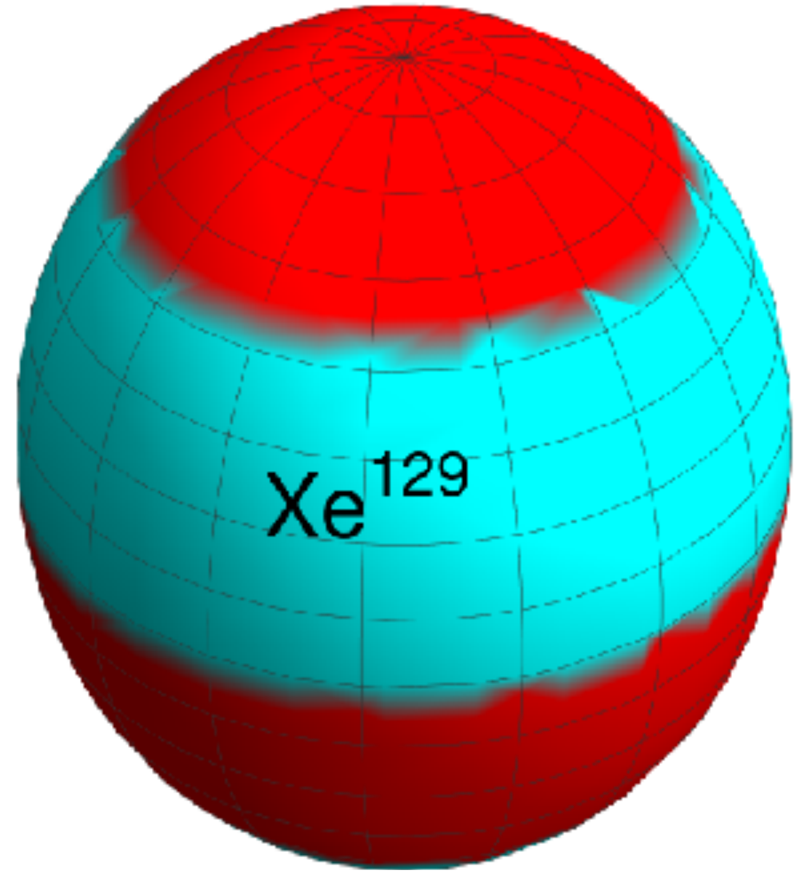


JNH, Noronha Gyulassy Phys.Rev. C93 (2016) no.2, 024909



Niemi & Denicol arXiv:1404.7327



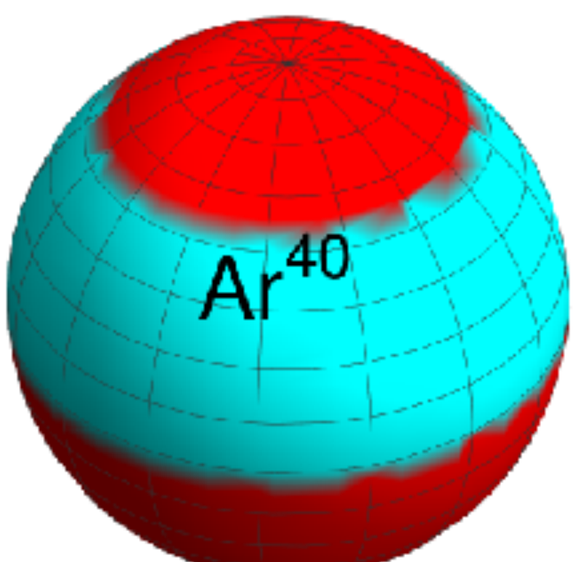


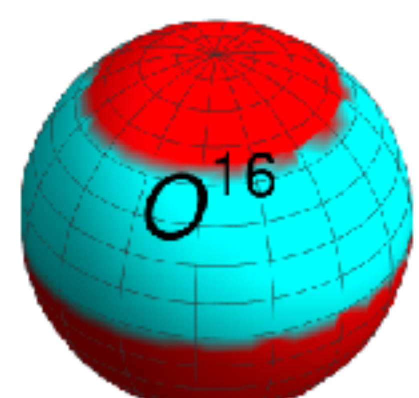
arXiv:1812.06772

CERN-LPCC-2018-07
December 18, 2018

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

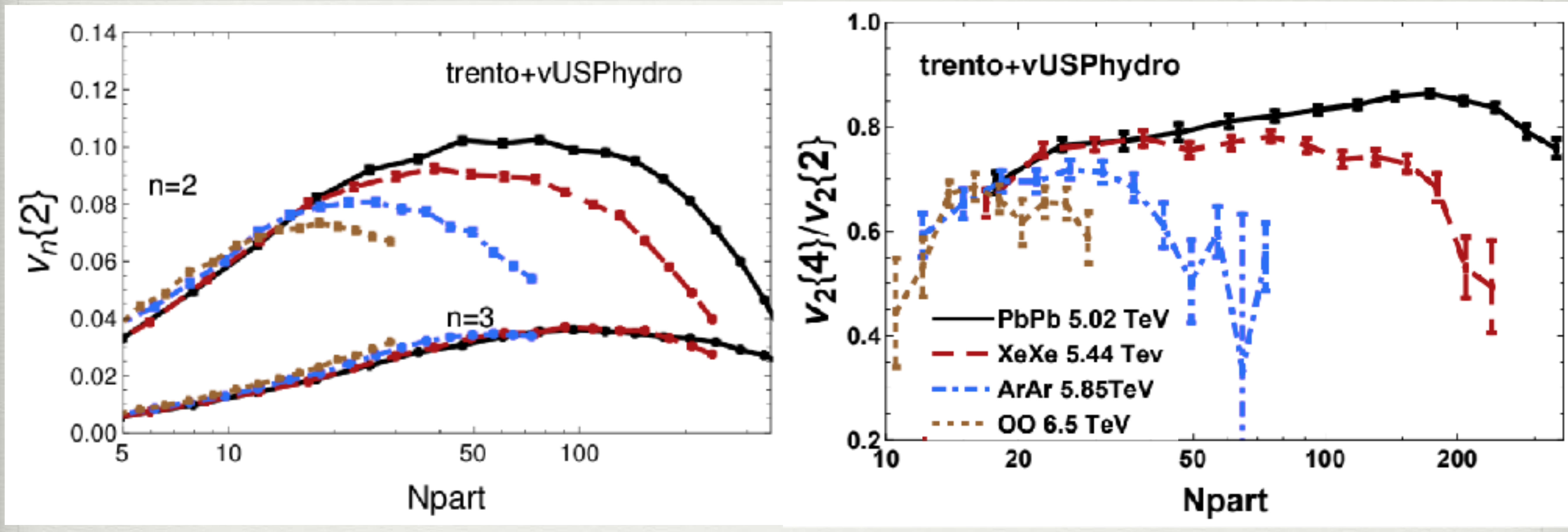
Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC





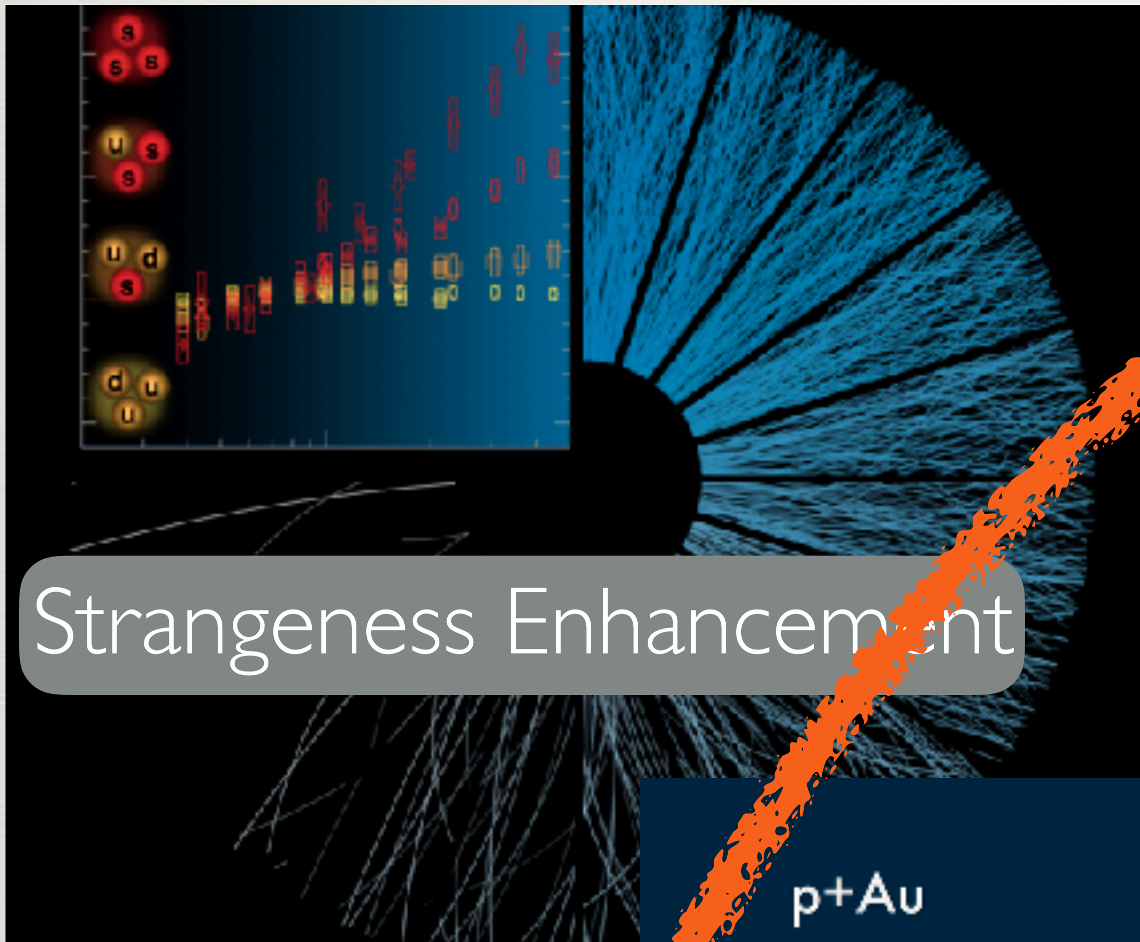
Collective flow effects (WWND19)

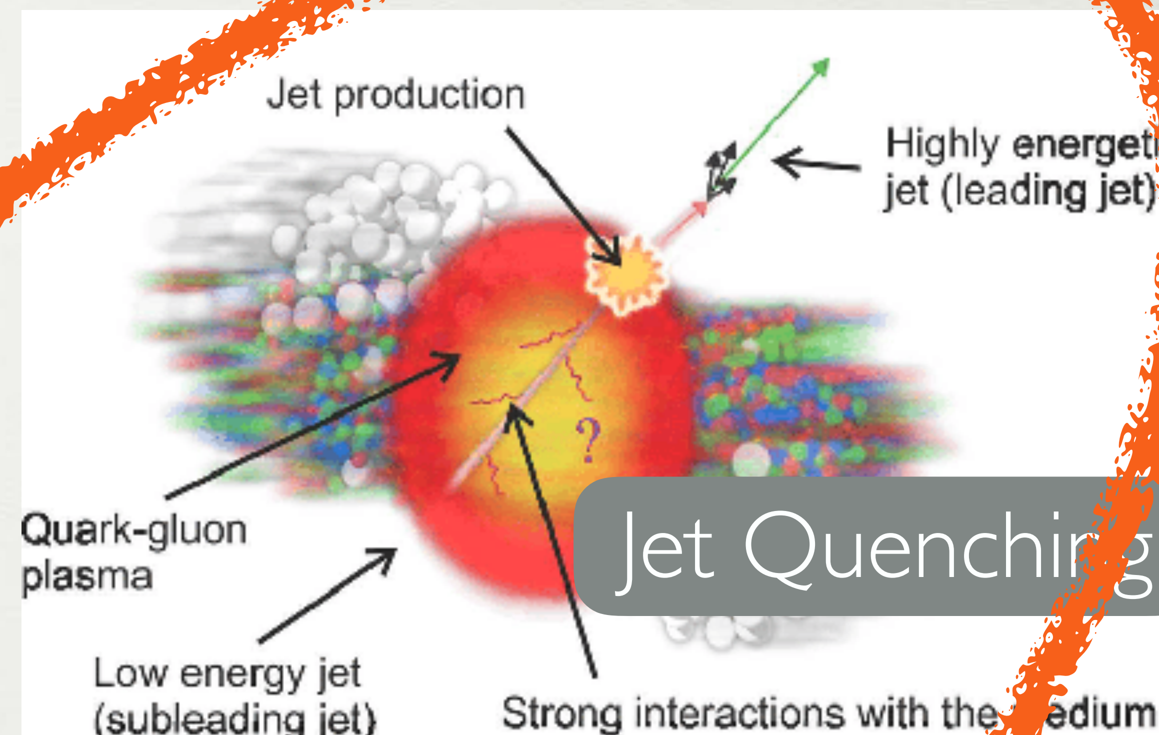
Sievert, JNH Phys.Rev. C100 (2019) no.2, 024904

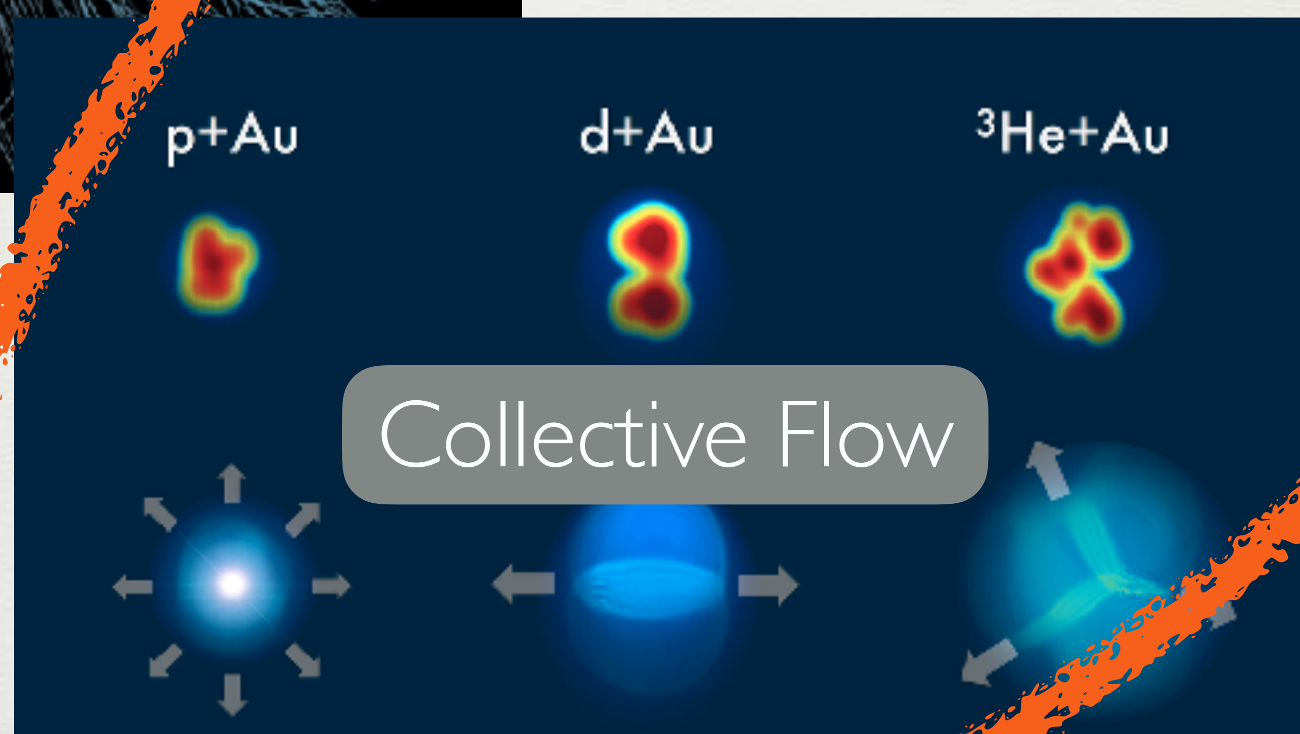


- Hierarchy: Expect universal scaling only at low Npart (dN/dy) e.g. v_2, $v_2\{4\}/v_2\{2\}$
- Certain quantities (e.g. v_3 and $SC(m,n)$) universal across system size

SIGNALS OF THE QGP





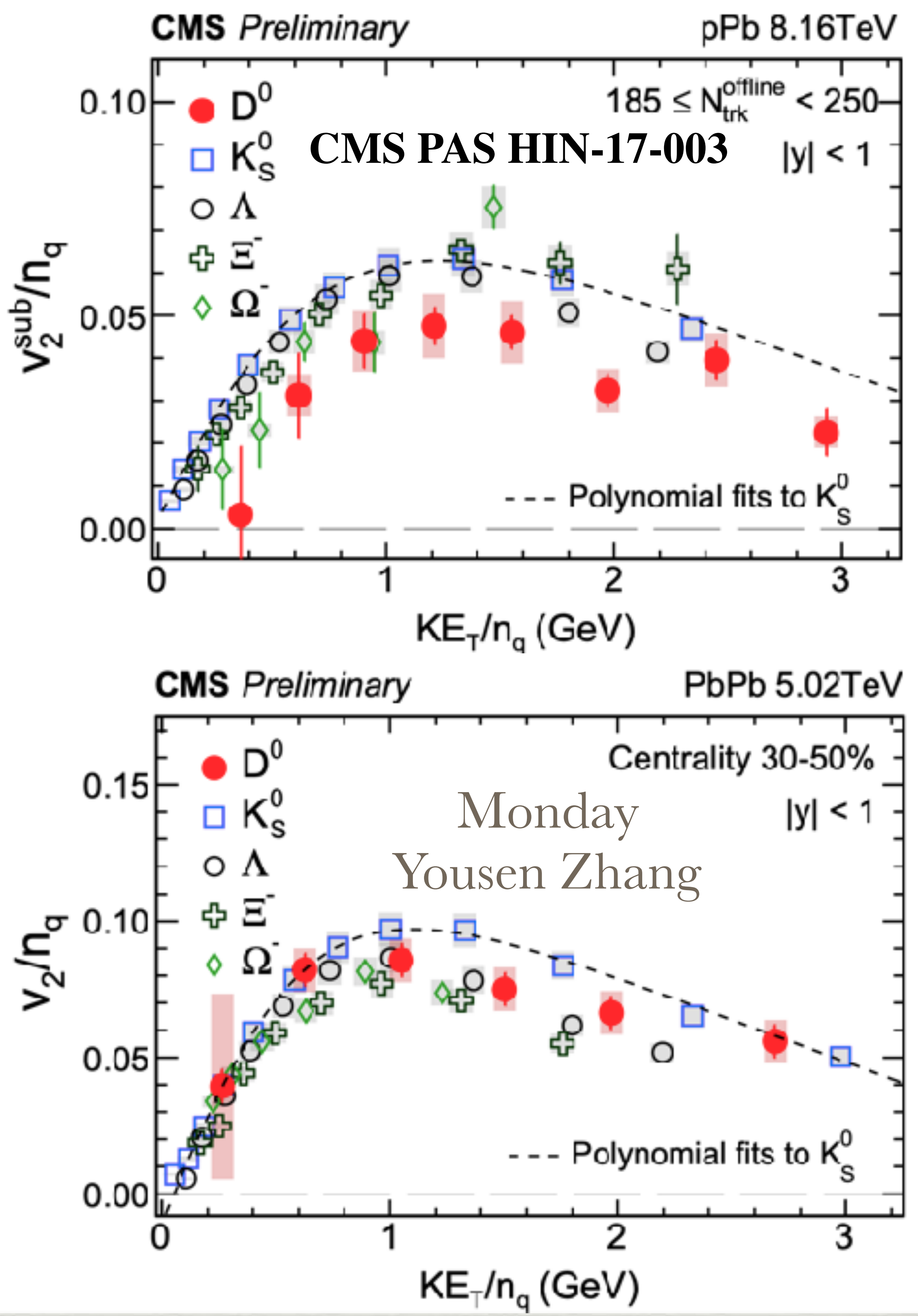


Motivation 1:

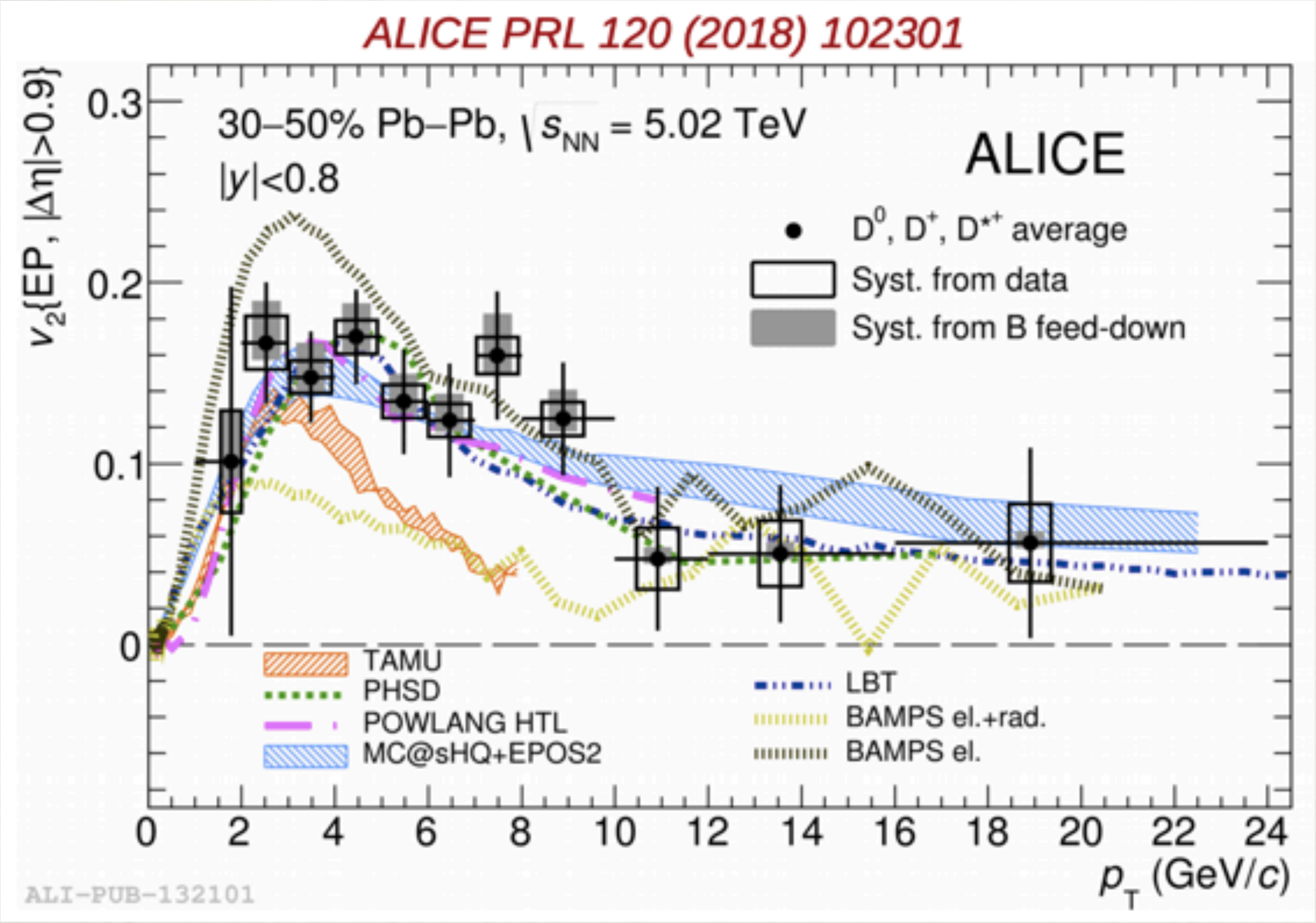
D meson scaling with system size

Can we understand system size dependence of energy loss?

Comparisons between soft and hard sector?



Motivation 2:
What makes theory match data?



What is the data actually telling us?

(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)

Roland Katz, Caio A.G. Prado, *Alexandre A.P. Suaide arXiv:1906.10768 & arXiv:1907.03308*

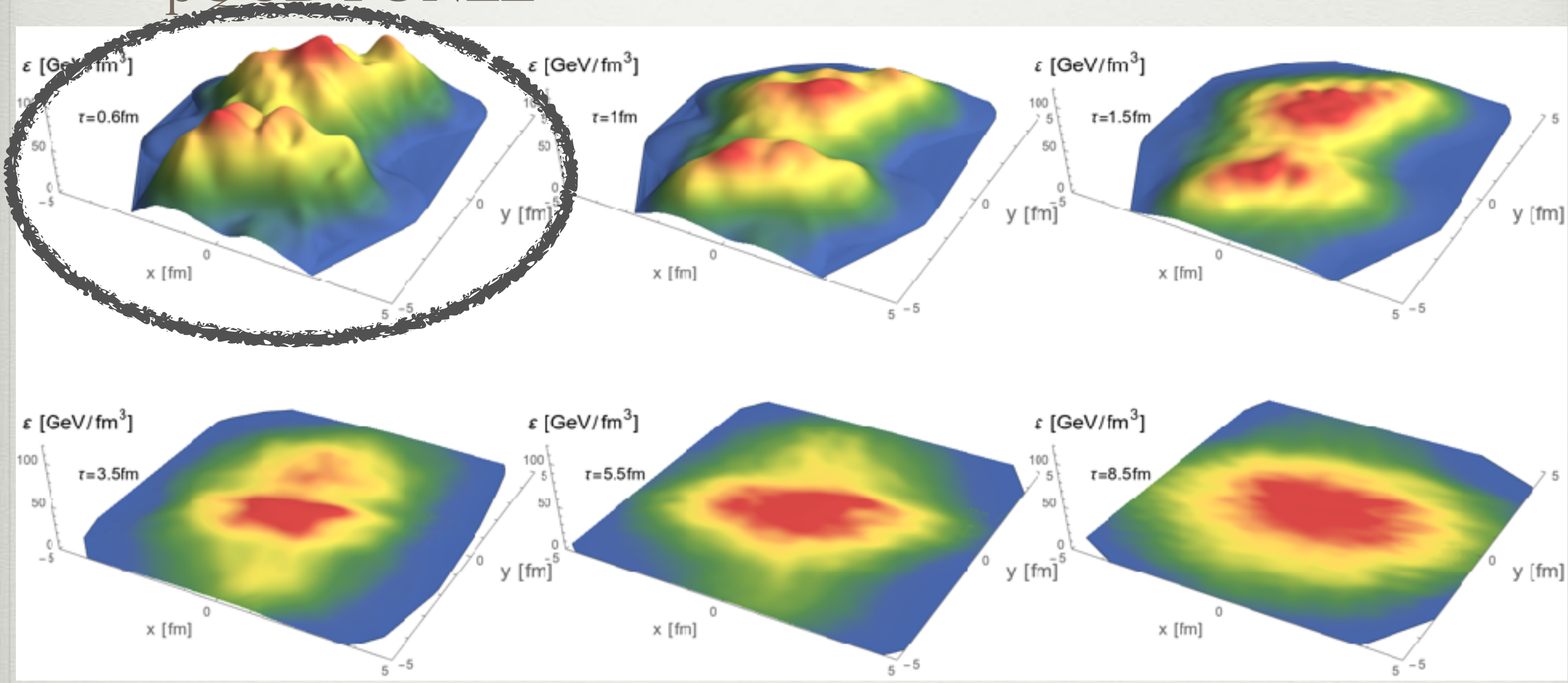
- Heavy flavor (D and B mesons) package that allows for a variety of parameterized energy loss models or *relativistic Langevin models*.
- *Coalescence*

New additions

- 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

Initial conditions:
Trento/mckln
Heavy Quark Sampling:
pQCD FONLL

Oversampling of heavy quarks
No cold nuclear matter effects or shadowing



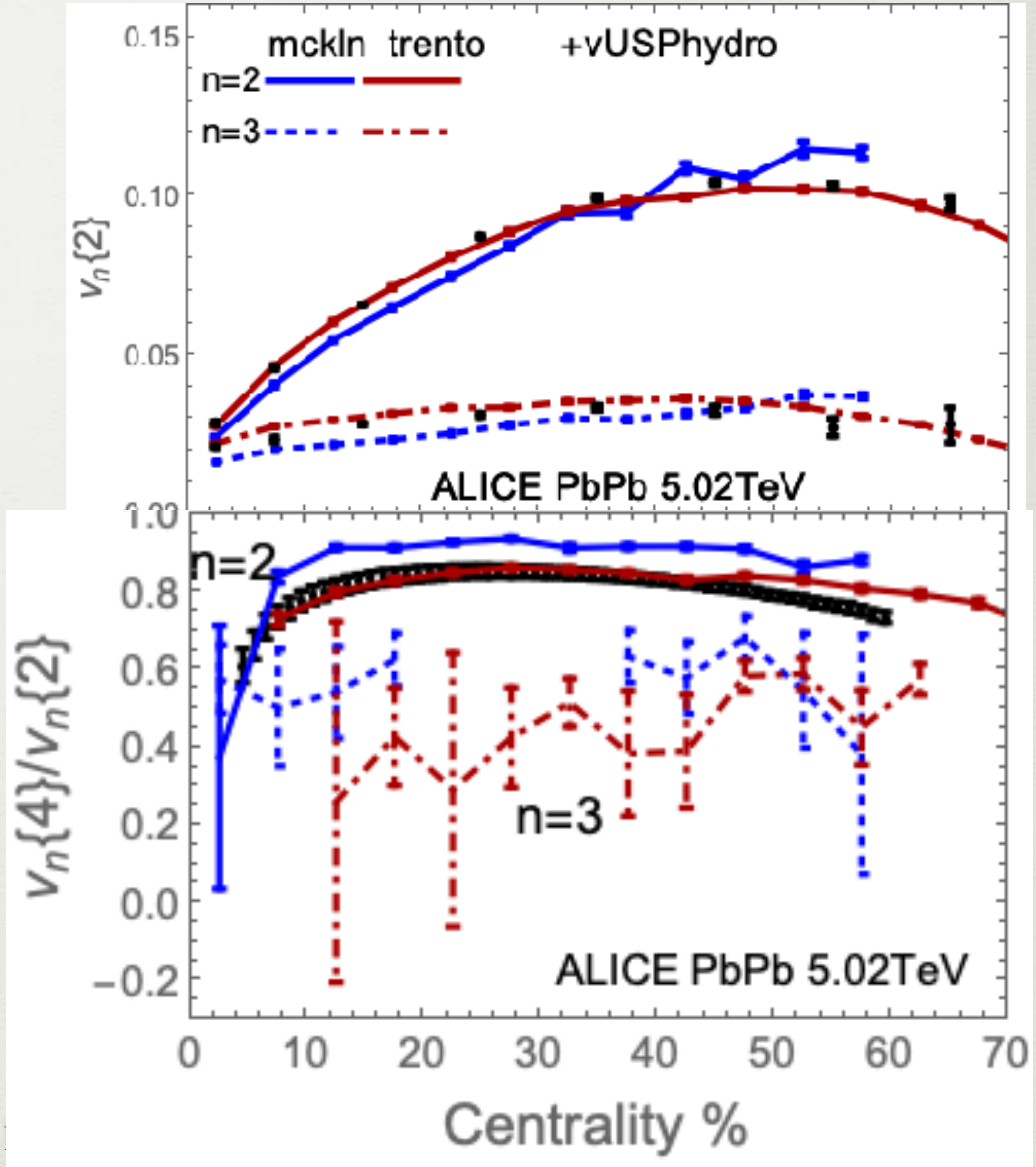
Minimum 1000 initial conditions/centrality

Initial conditions: Trento vs. mckln

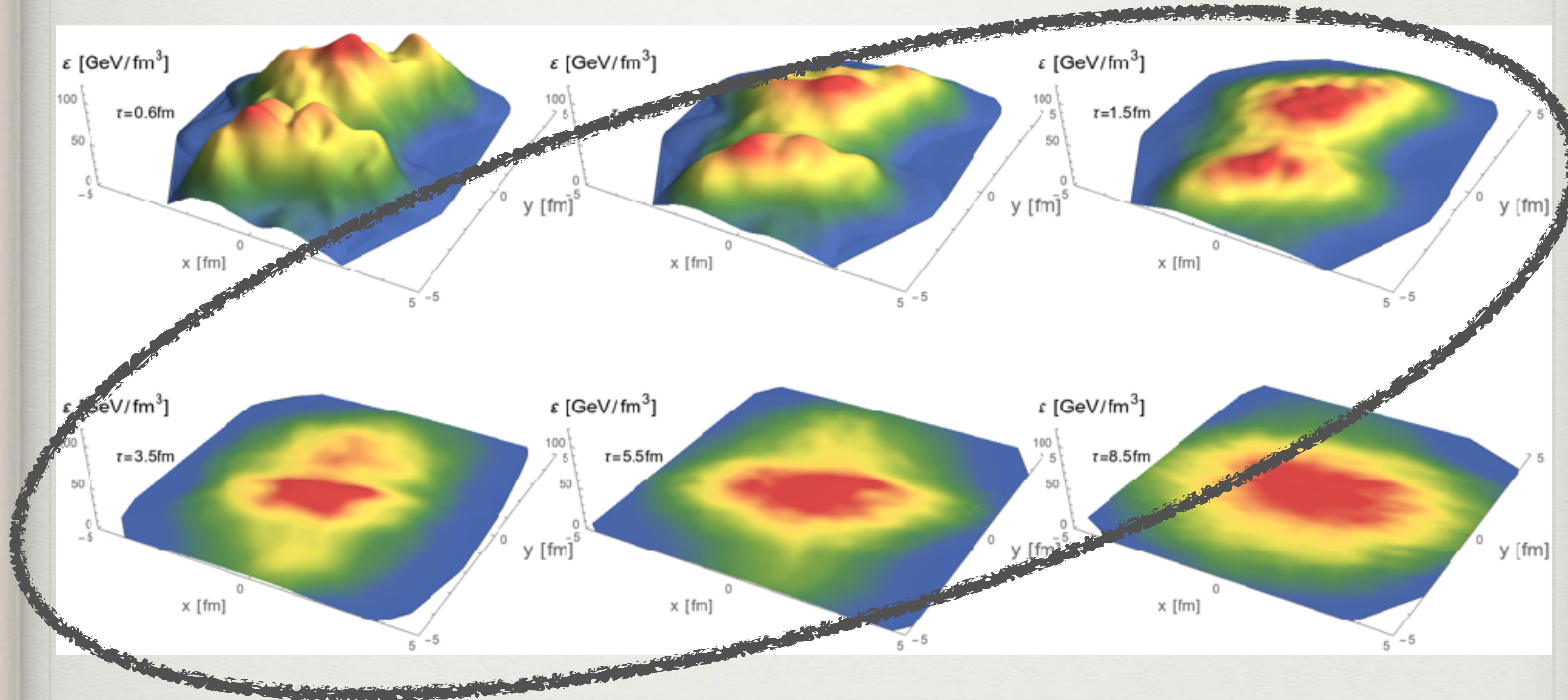
- Trento like IP-Glasma
  Moreland, Bernhard, Bass Phys.Rev. C92 (2015) no.1, 011901
  Hydro: Alba et al, Phys.Rev. D96 (2017) no.3, 034517

- 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 $T_{FO} = 120\ MeV$
- PDG05

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

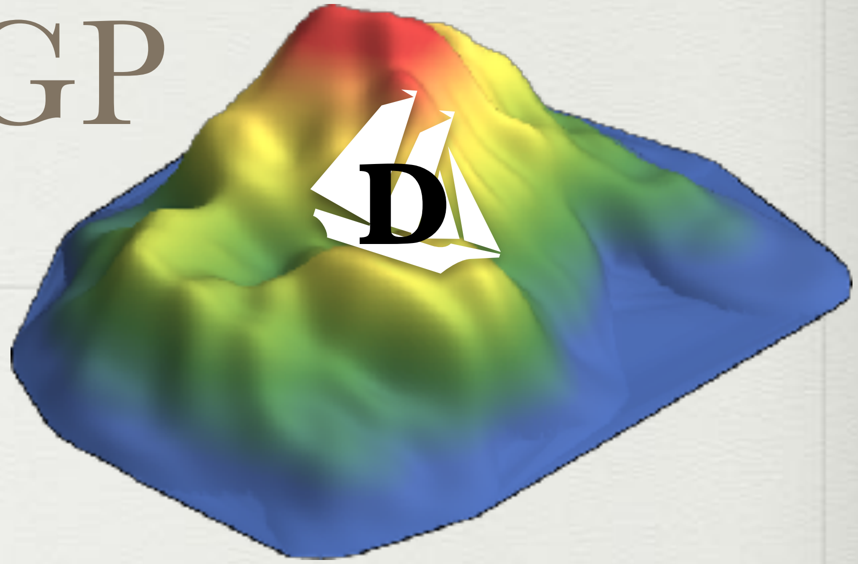
Trento

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 $T_{FO} = 150\ MeV$
- 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

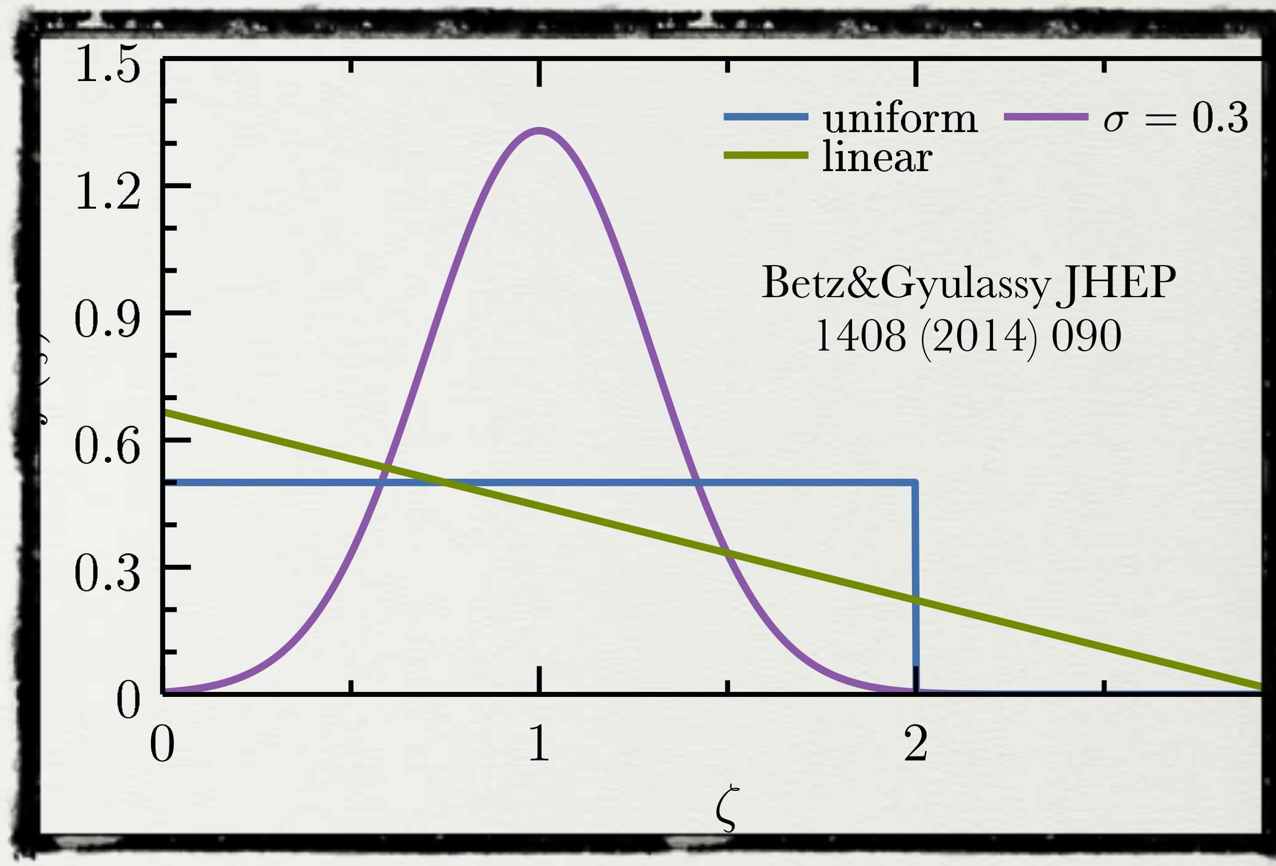
$f(\zeta) = 0.5$ For $0 \leq \zeta \leq 2$

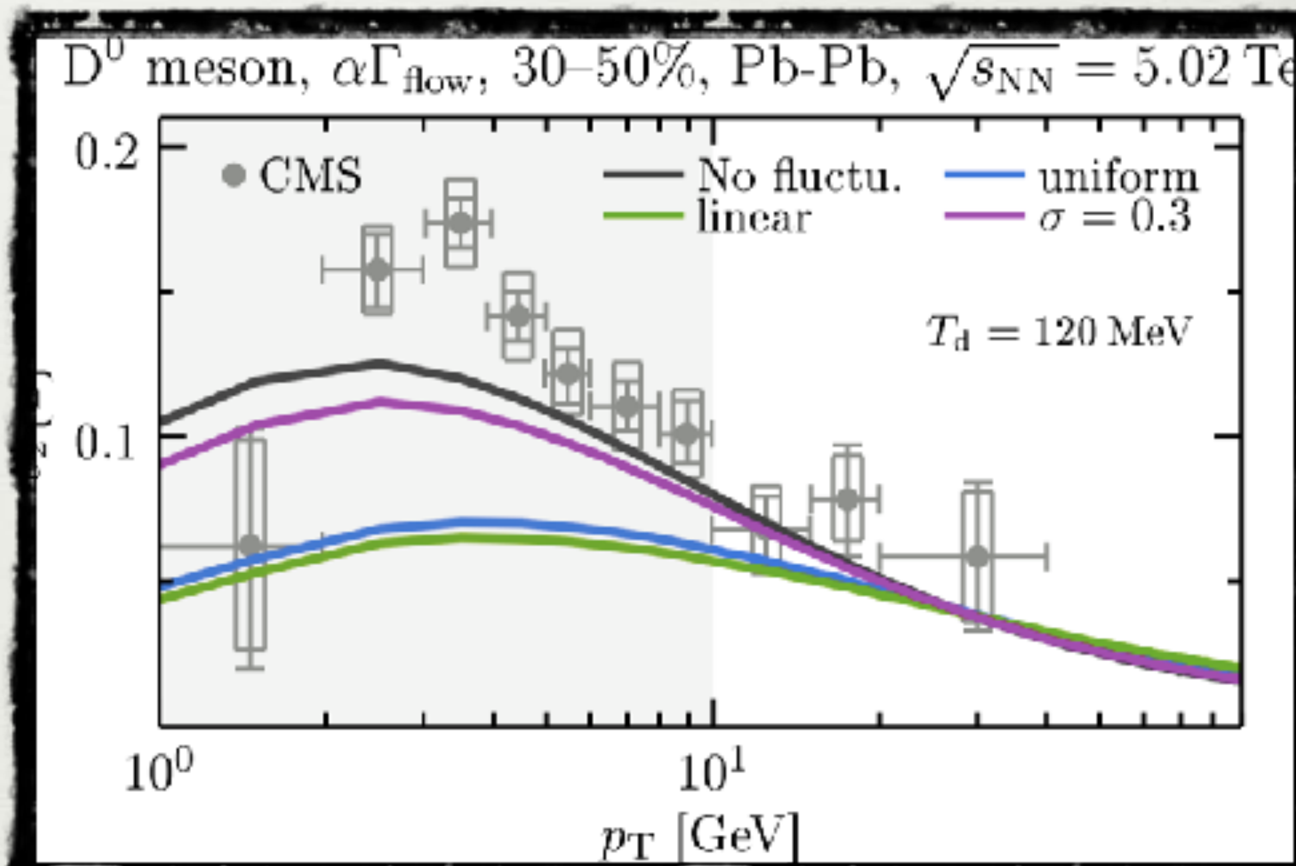
Linear

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

for

$0 \leq \zeta \leq 3$





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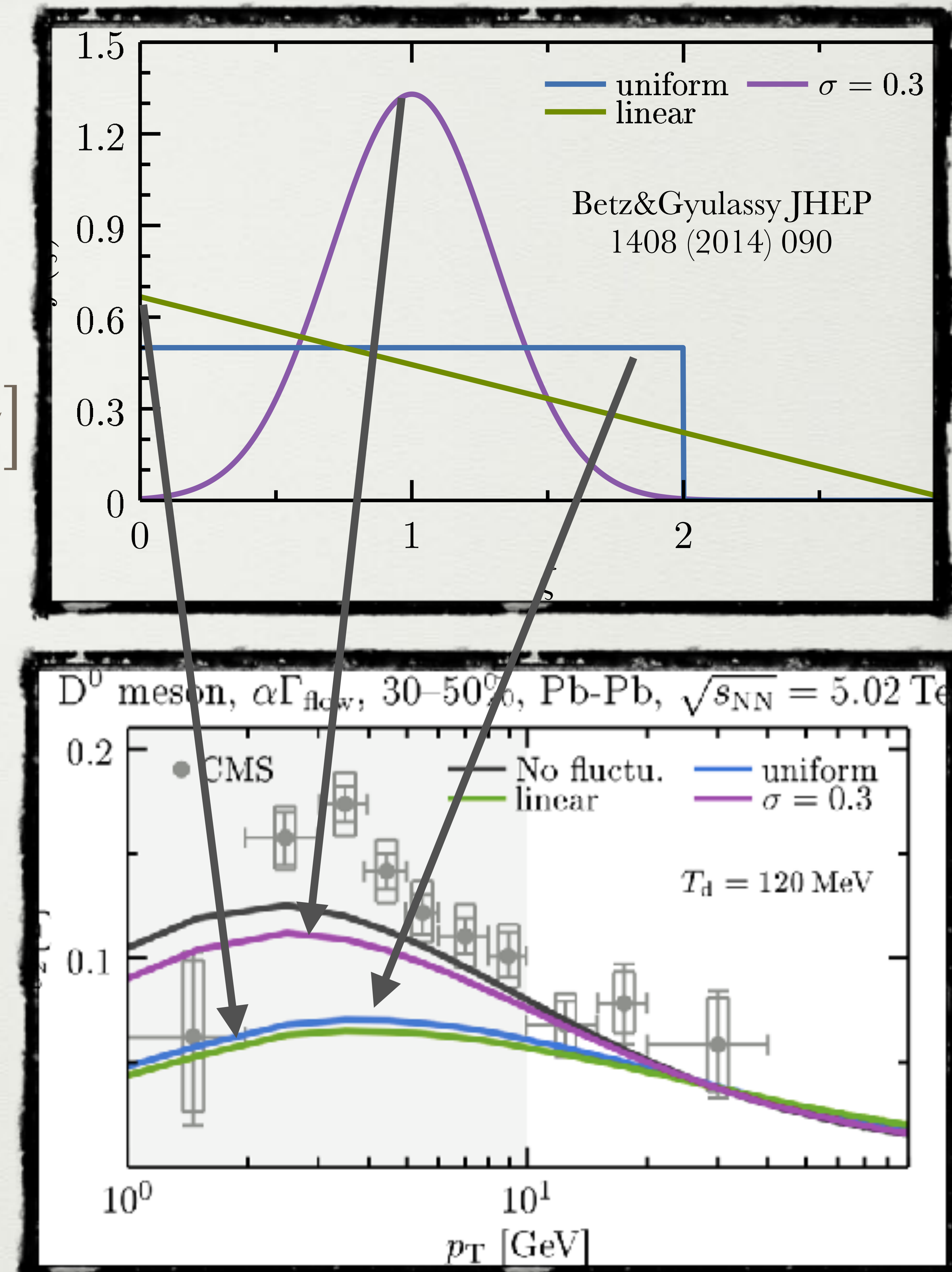
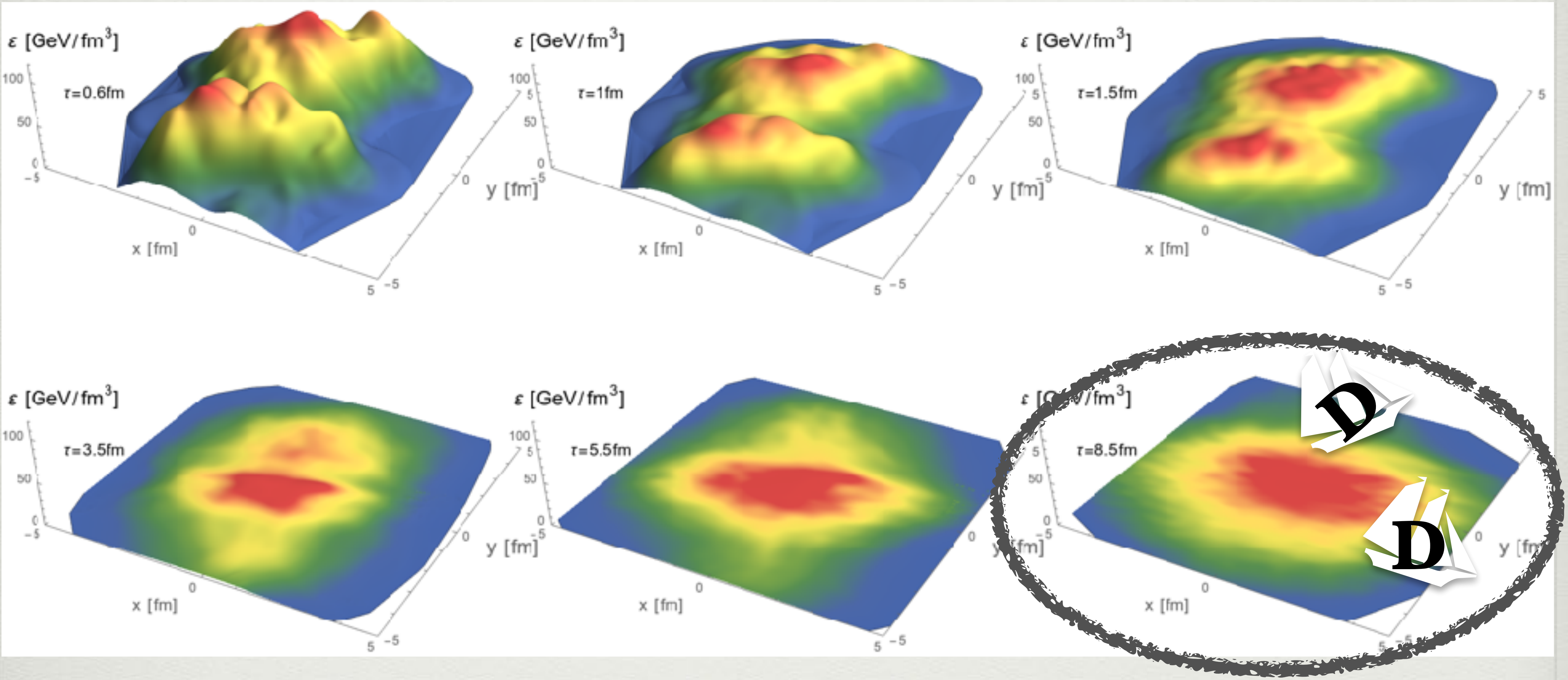


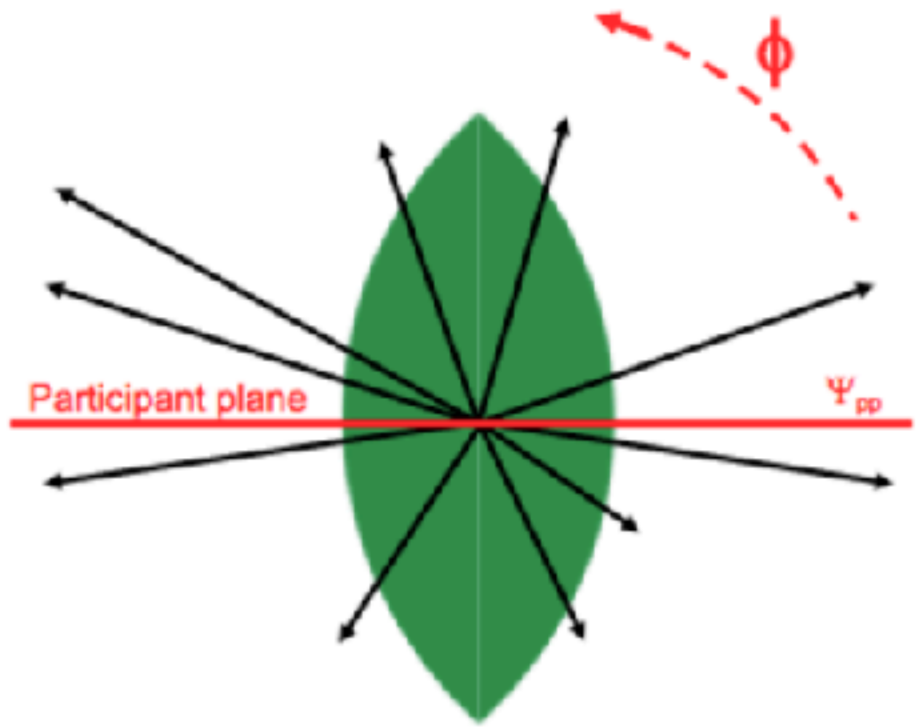
Hydro particlization: Cooper-Frye+decays
Heavy quark fragmentation: Petersen fragmentation function+light/heavy quark coalescence



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

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

Rapidity gap to suppress non-flow

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

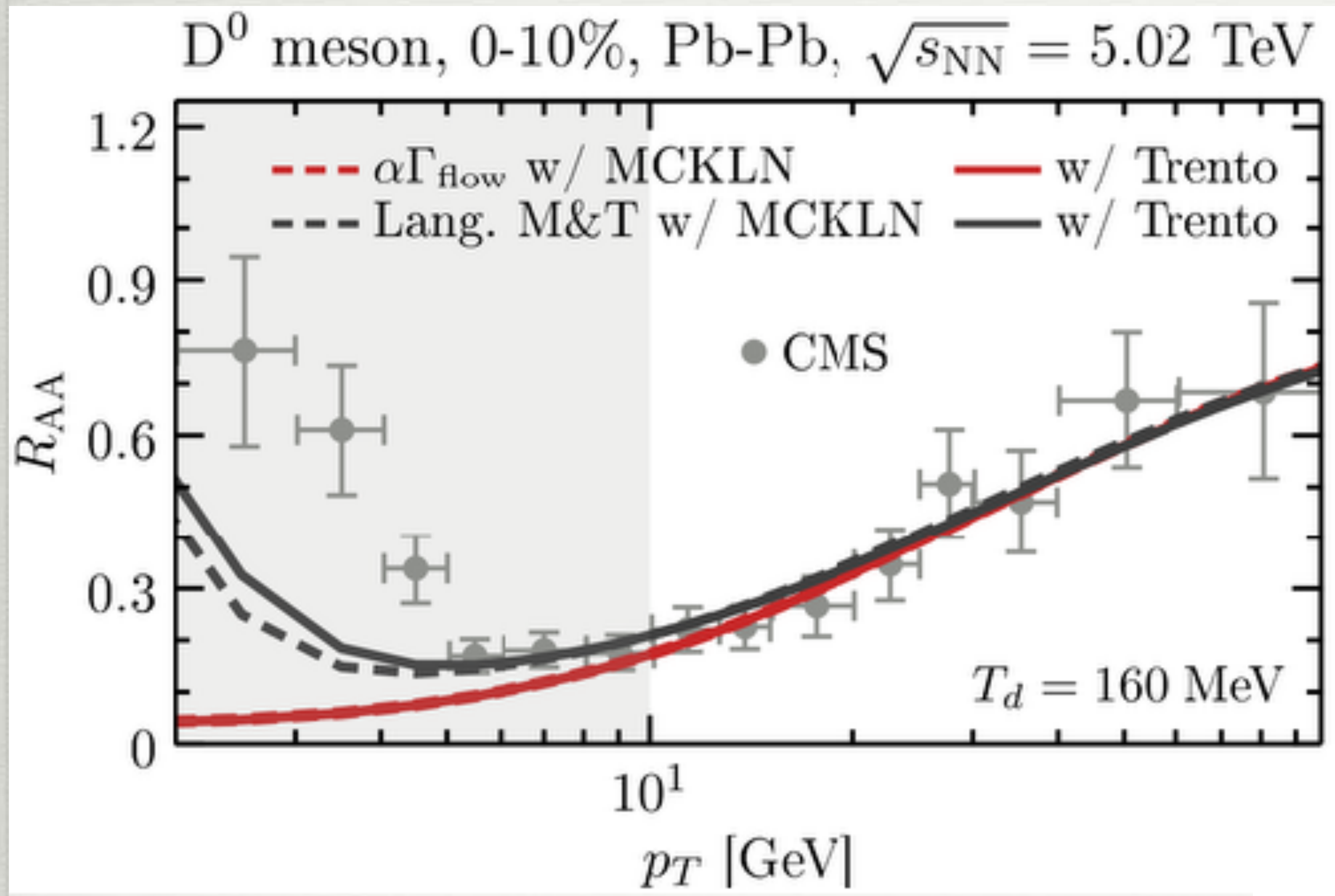
- Calculated in 0.5% centrality bins
- $\langle \cdots \rangle \to$ multiplicity weighing
- 0.5% rebinned into 5% or 10%

[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

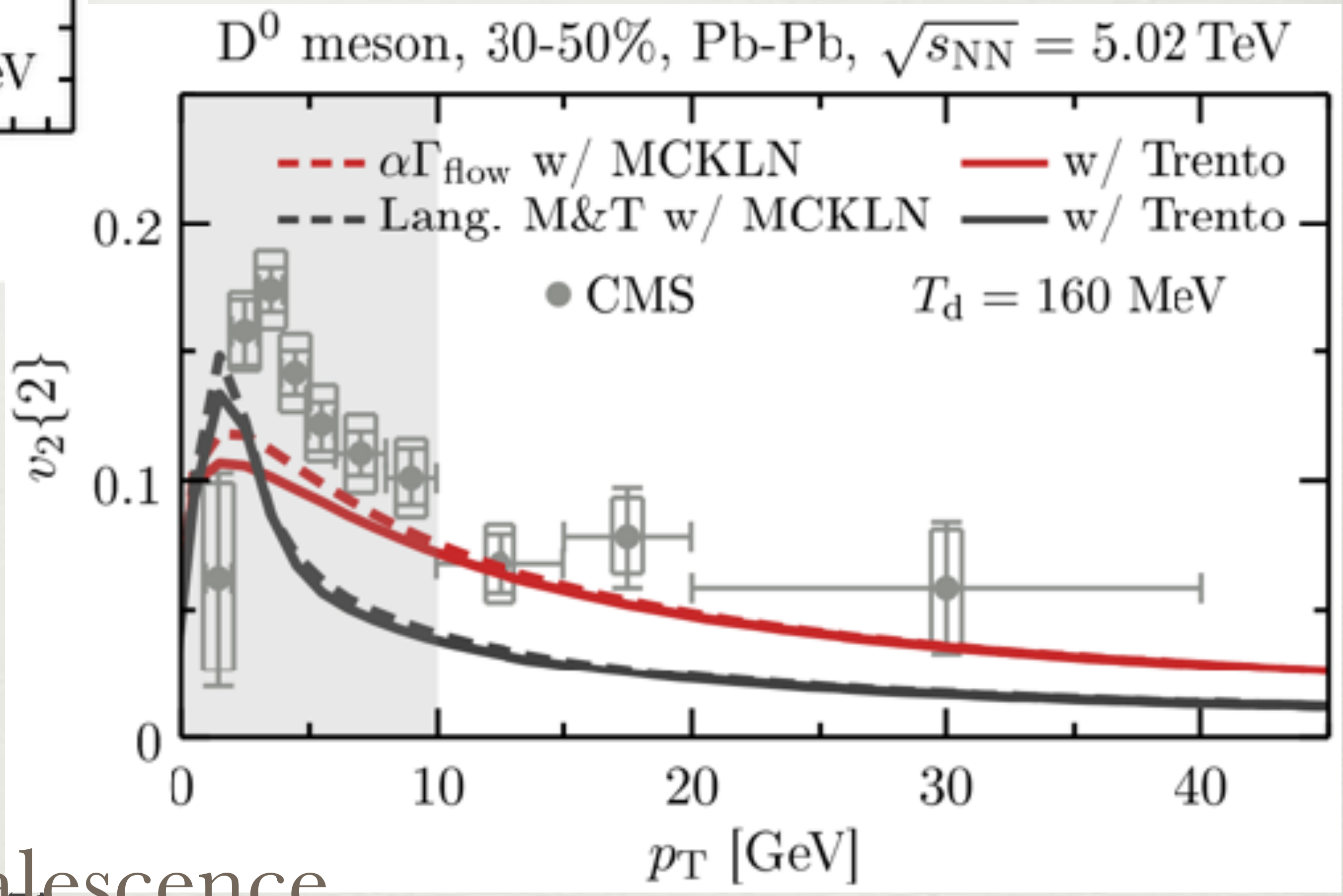
Can D mesons “see” the difference between initial conditions?

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

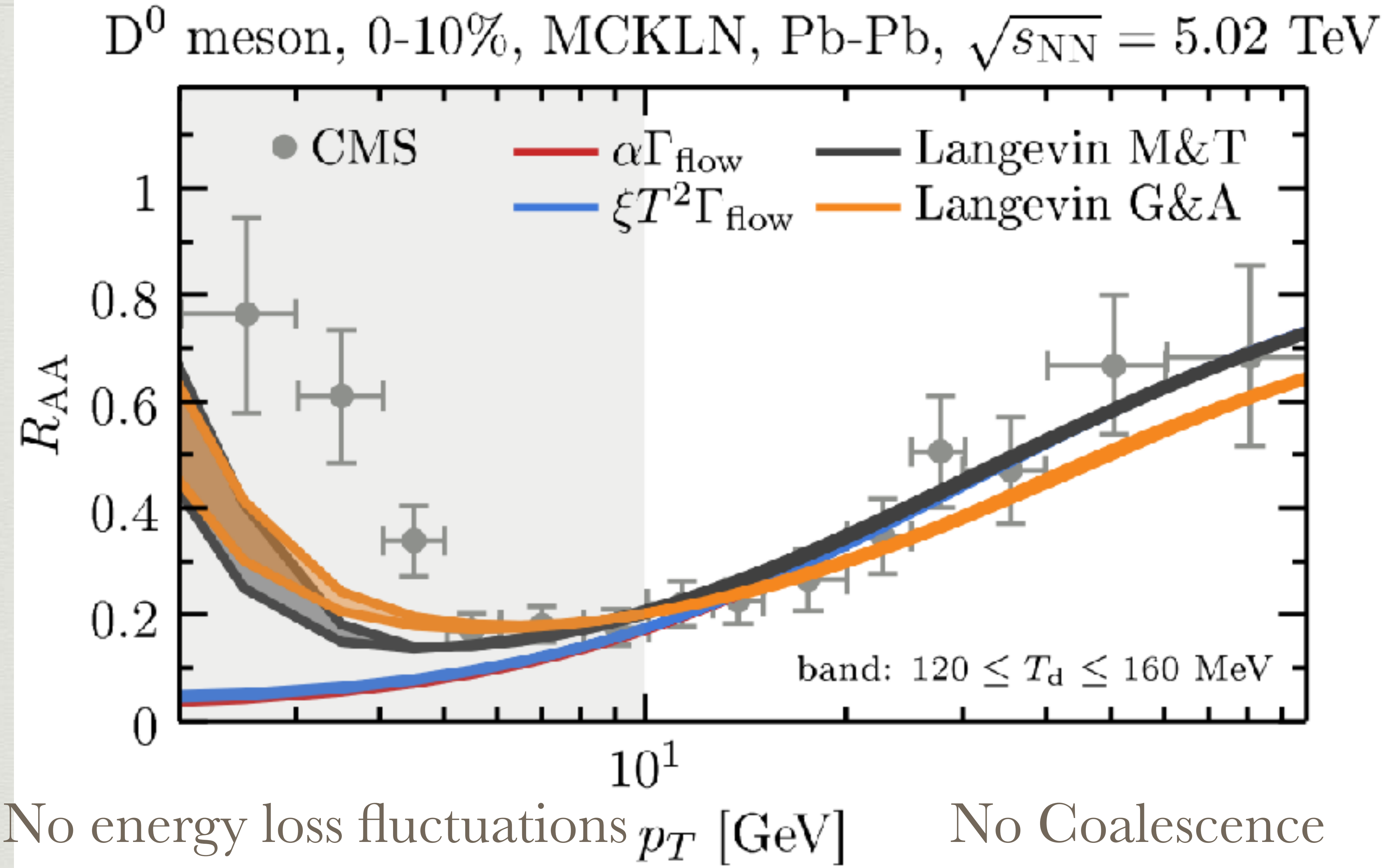
Initial temperature

- Both mckln and TRENTO start at $\tau_0 = 0.6\ fm$
- Mckln initial temperature less (outdated EOS) from Trento, Trento gives smaller v_2
- Connection between τ_0 and v_2 but T_0 also matters, EOS must be correct!

See also:
Andres et al, arXiv:1902.03231
S. Shi arXiv:1808.05461
Ke et al, arXiv:1810.08177

How do energy loss models compare to Langevin?

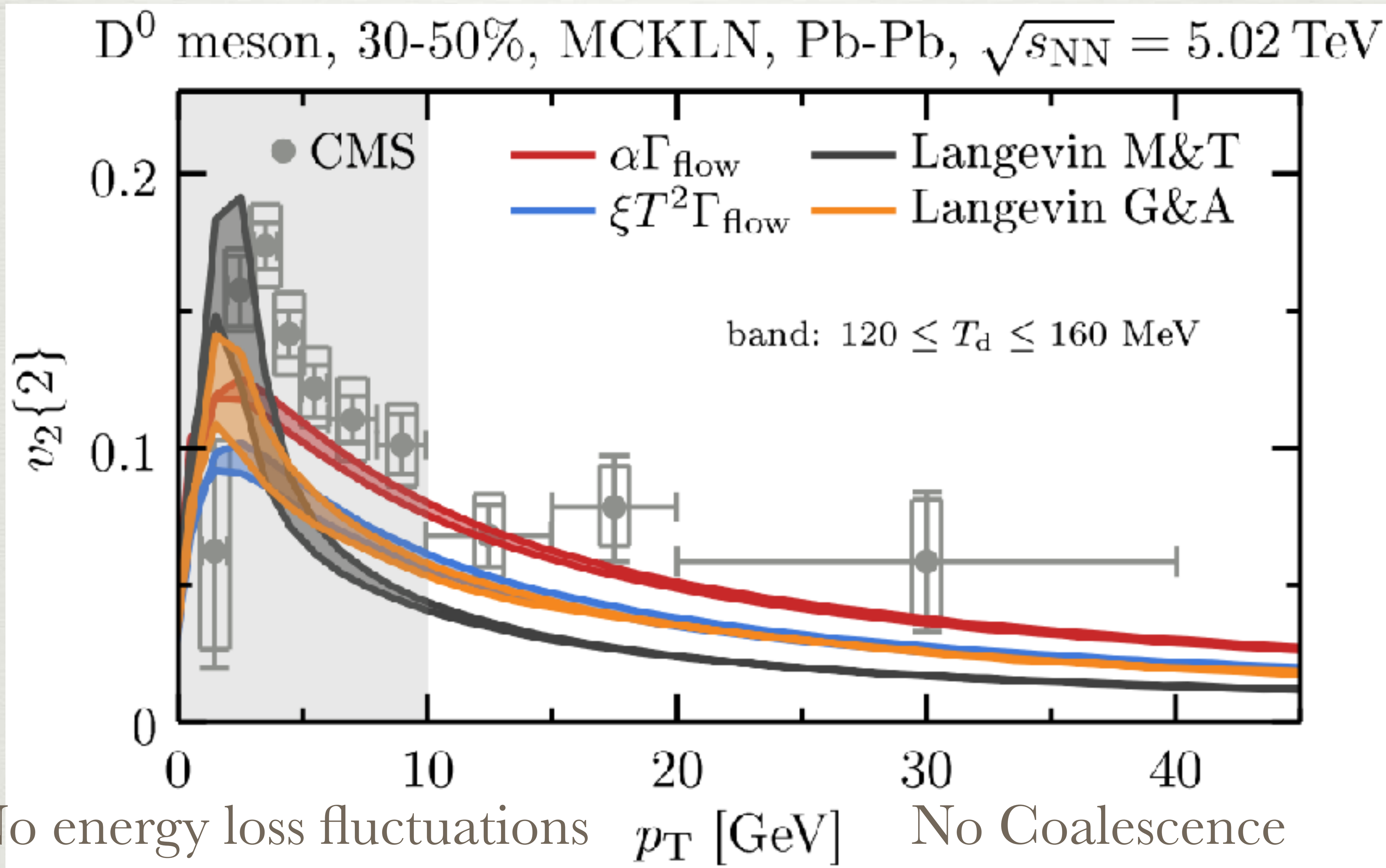
Energy loss vs. Langevin



No energy loss fluctuations

No Coalescence

Energy loss vs. Langevin



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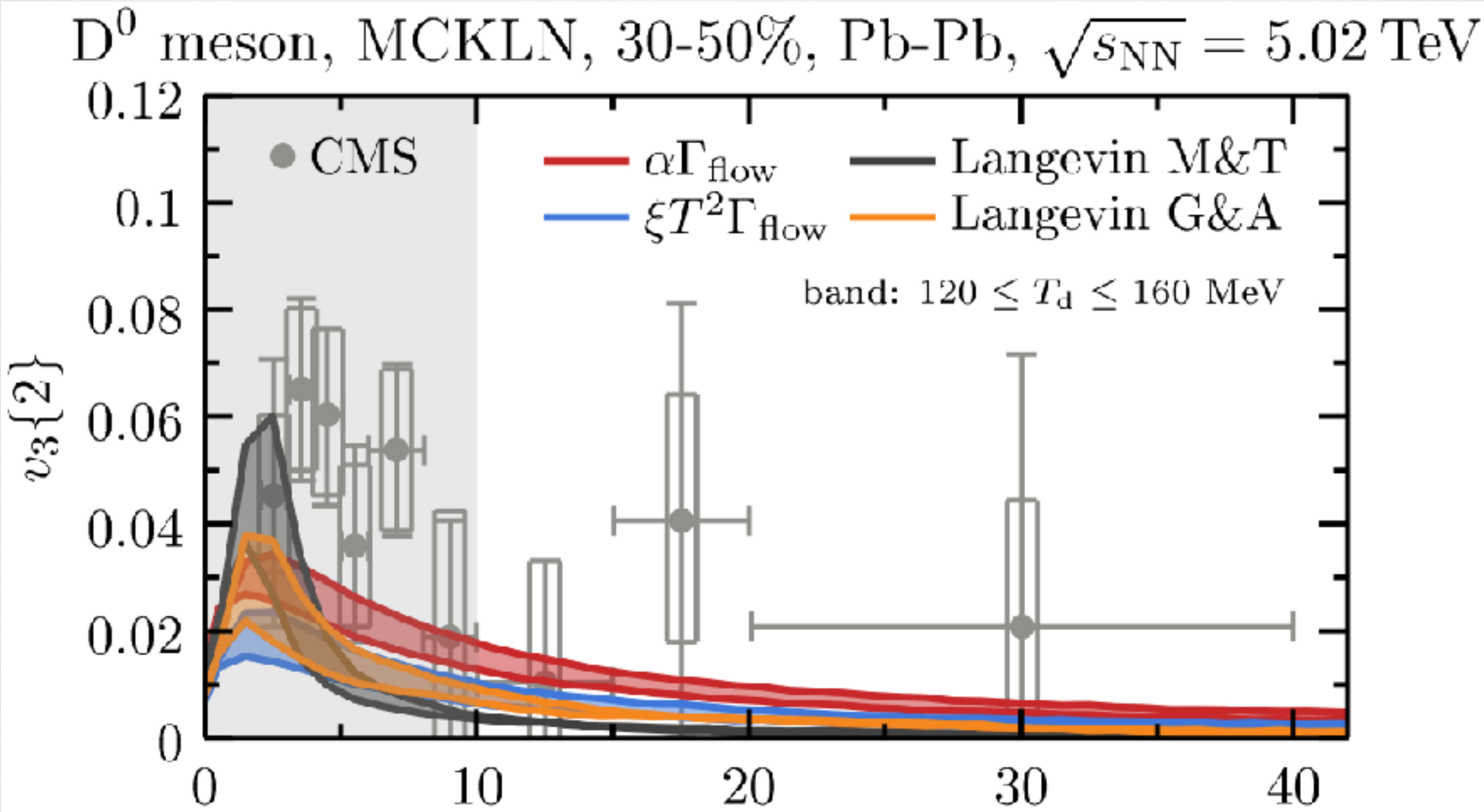
No Coalescence

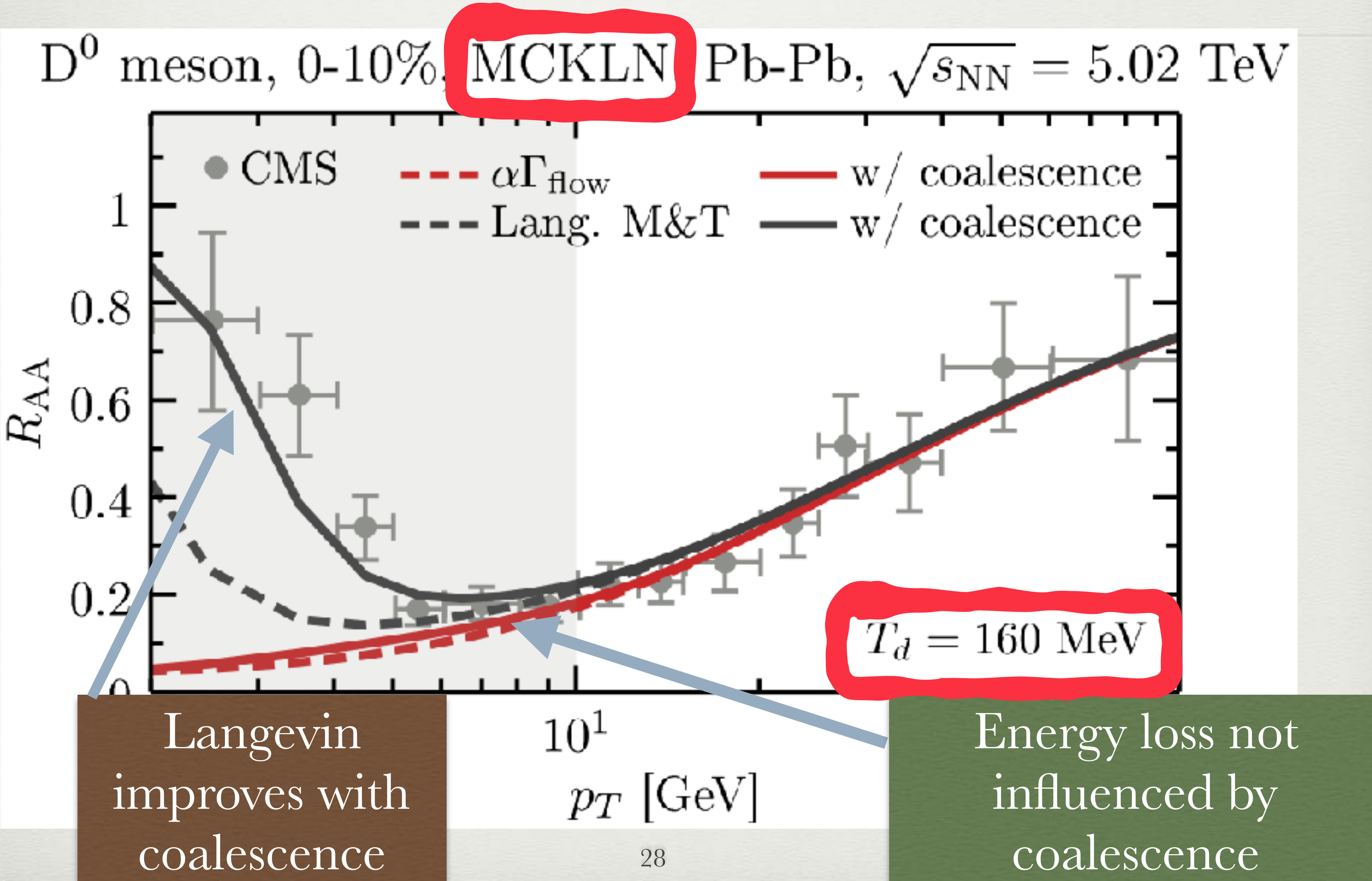
Energy loss vs. Langevin



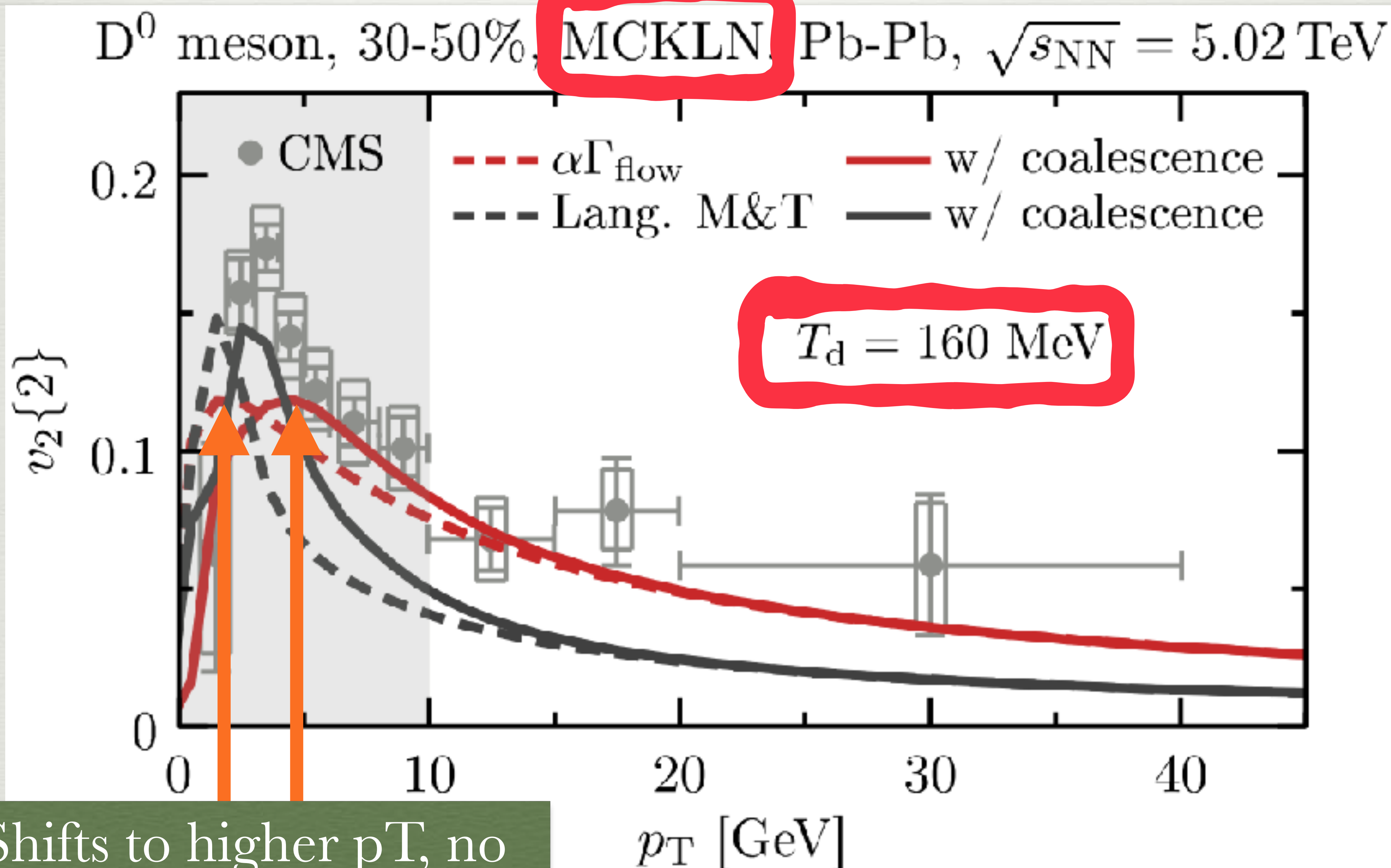
No energy loss fluctuations   No Coalescence

What roles does coalescence play?

Influence of coalescence on R_{AA}



Azimuthal anisotropies and coalescence



Shifts to higher pT, no change in magnitude

Best fit

- **pT<5 GeV:** Langevin (Moore & Teaney) +coalescence
- **pT>5 GeV:** Constant Energy loss+Gaussian Energy Loss fluctuations+coalescence

SYSTEM SIZE

PROPOSAL FOR COLLISIONS

$^{40}Ar^{40}Ar$ $^{16}O^{16}O$

arXiv:1812.06772

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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

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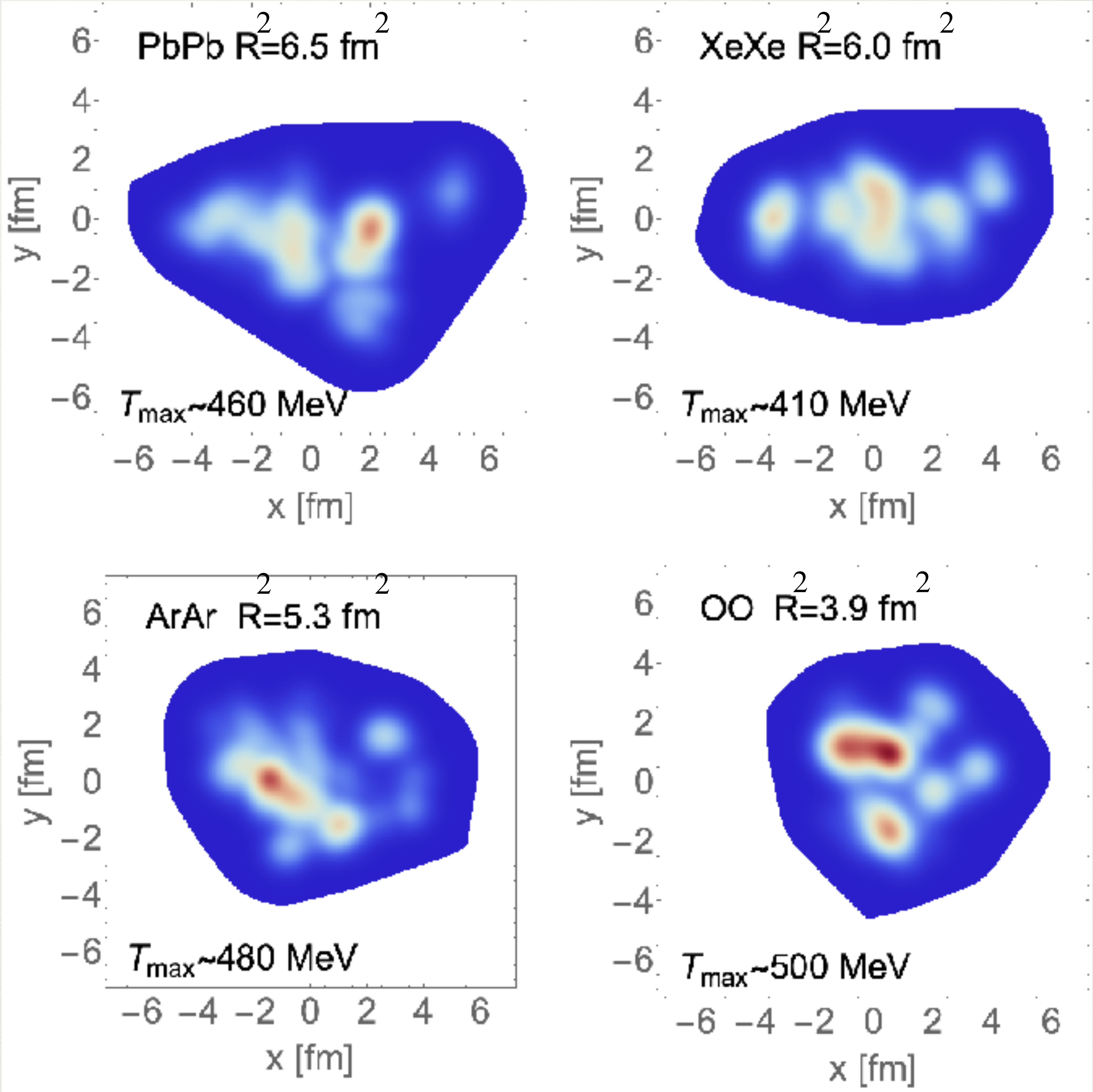
TYPICAL EVENTS

PbPb and XeXe events larger, more elliptical.

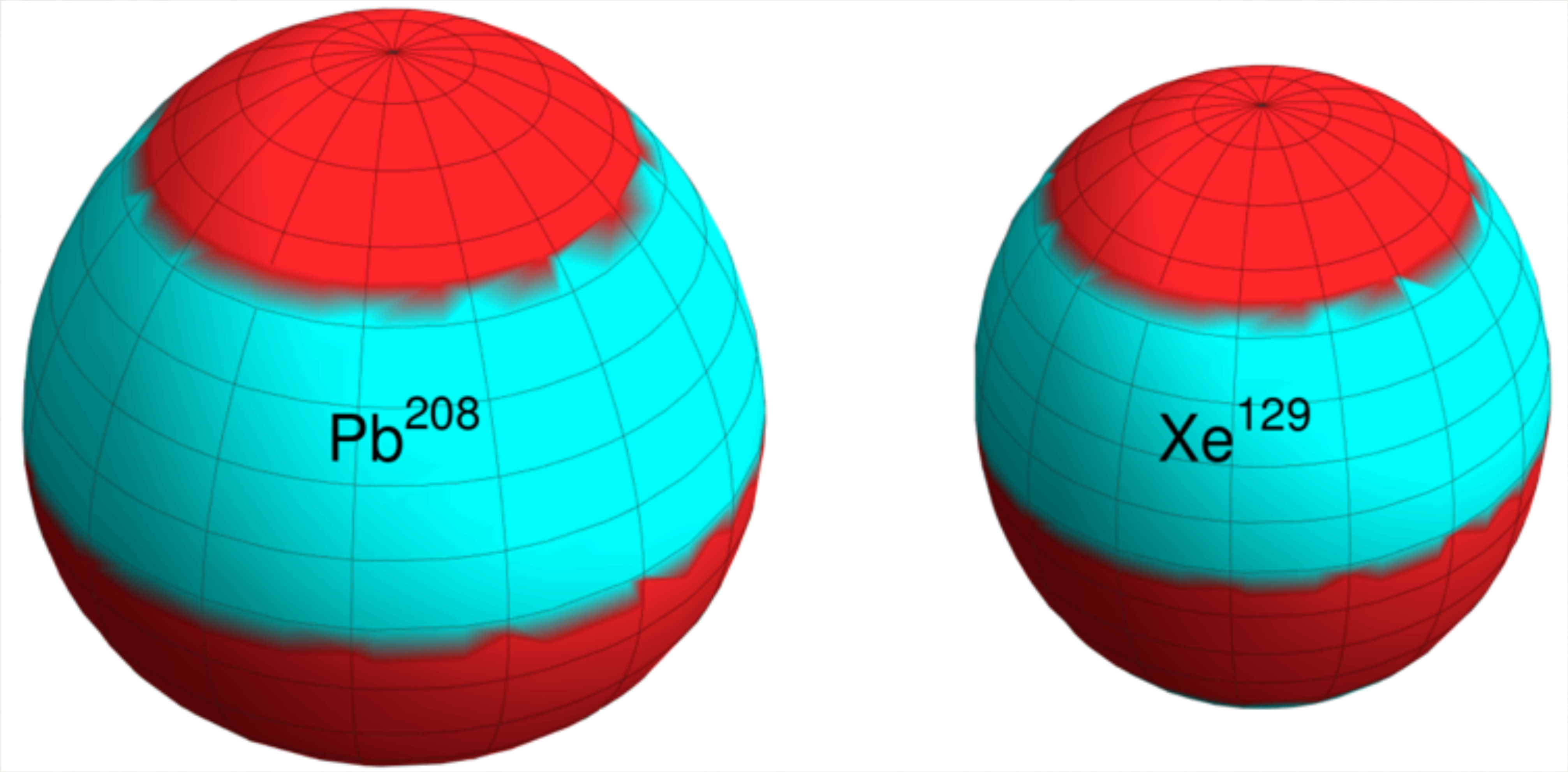
ArAr and OO smaller and rounder.

Small systems are hotter



Sievert, JNH, arXiv:1901.01319

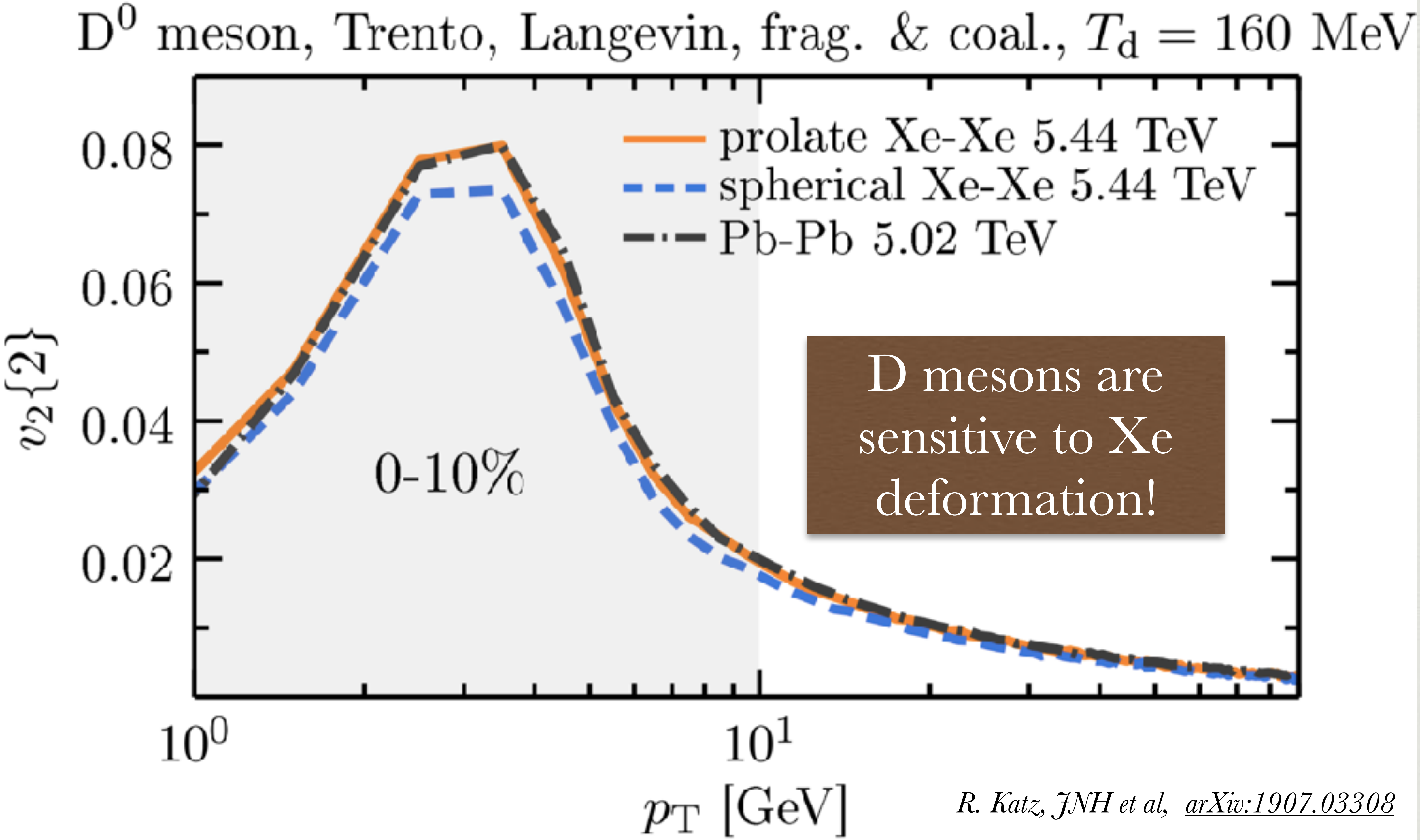
Comparing are best fit PbPb to XeXe collisions



Sensitivity to deformed Xe nucleus?

Giacalone, JNH et al, Phys.Rev. C97 (2018) no.3, 034904; ALICE Phys.Lett. B784 (2018) 82-95; CMS Phys.Rev. C100 (2019) no. 4, 044902; ATLAS Phys.Rev. C101 (2020) no.2, 024906

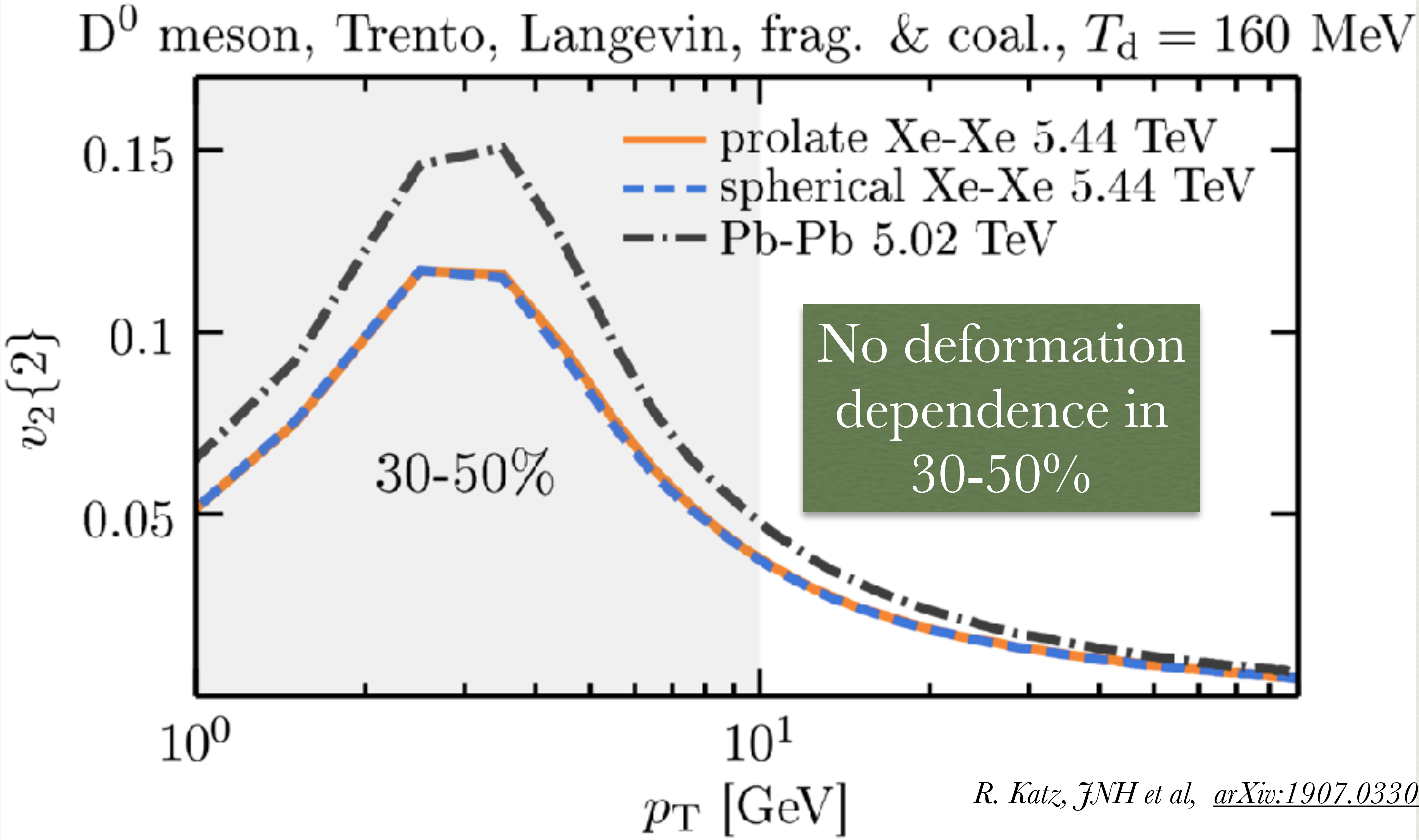
D mesons in XeXe collisions



D mesons are sensitive to Xe deformation!

R. Katz, JNH et al, arXiv:1907.03308

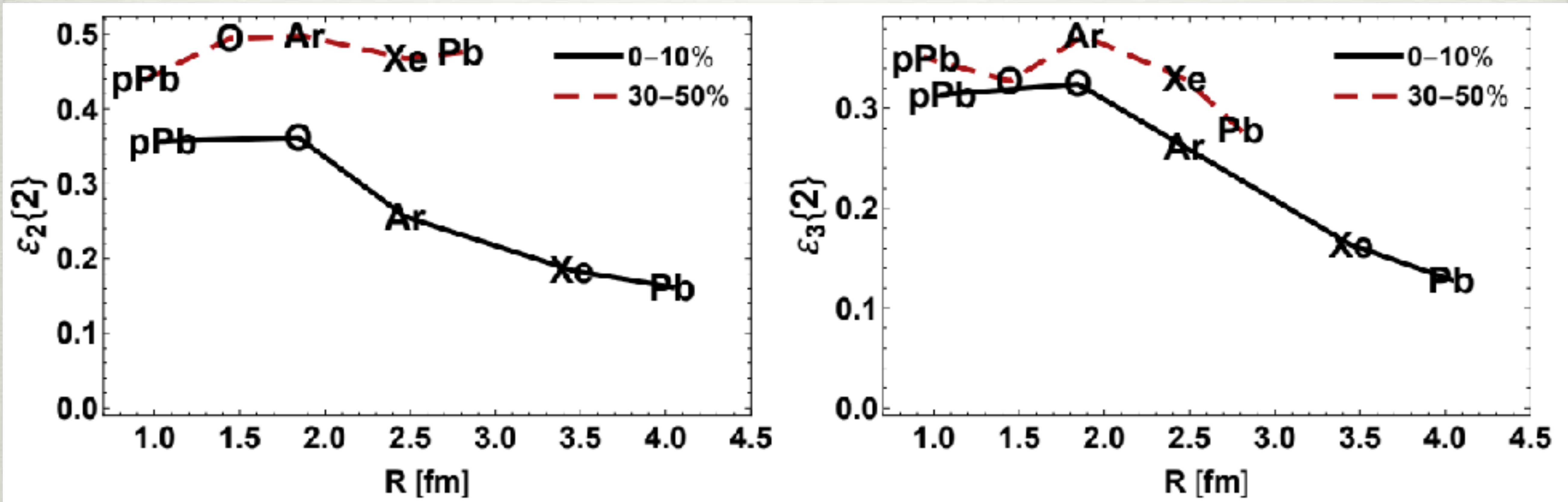
D meson v2 suppressed in "small" system



R. Katz, JNH et al, *arXiv:1907.03308*

Different methods to compare system size

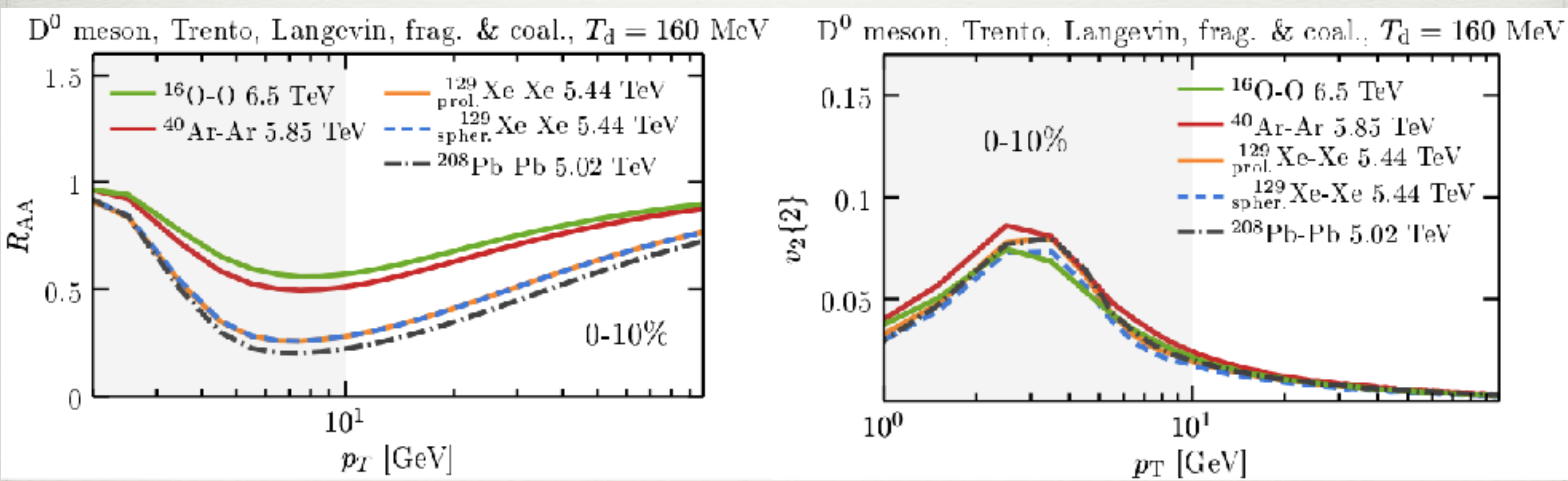
R. Katz, JNH et al, arXiv:1907.03308



- Comparing Central collisions: as system sized ⇓ system is more elliptical
- Comparing mid-central collisions: as system sized ⇓ system , shape is nearly constant

Central collisions

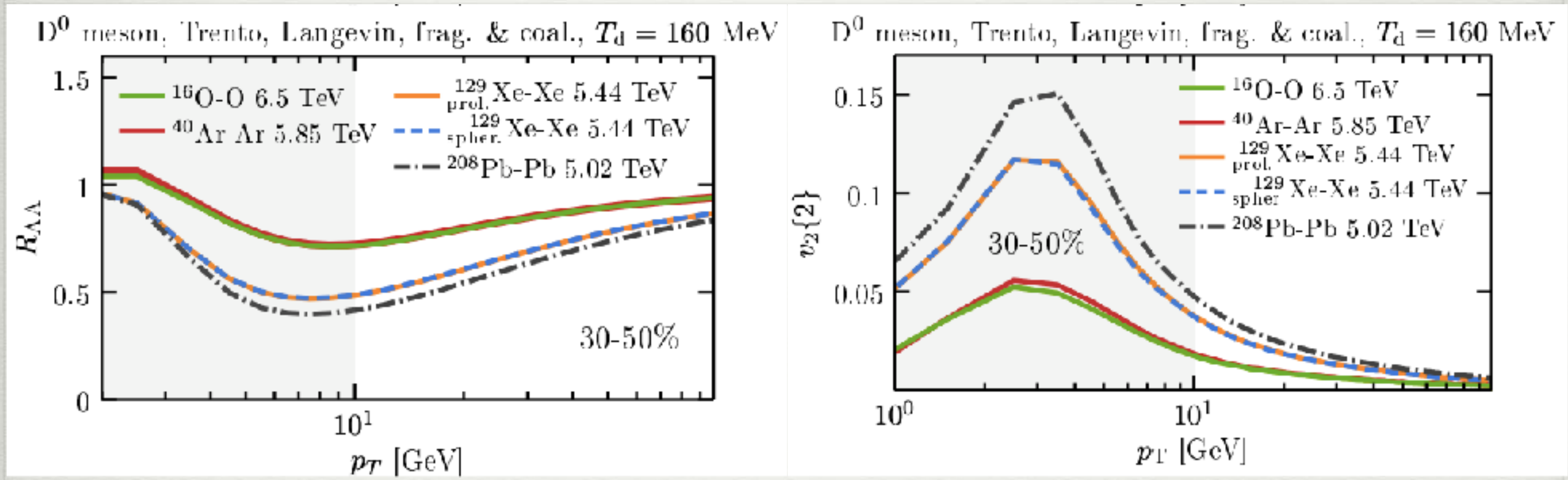
R. Katz, JNH et al, *arXiv:1907.03308*



- $R_{AA} \to 1$ as the system size decreases
- $v_2 \sim$ *const* as the system size decreases (compensating effect of ⇑ in eccentricities with ⇓ system size)
- v_3 ⇓ with ⇓ system size (see paper)

Mid-Central collisions

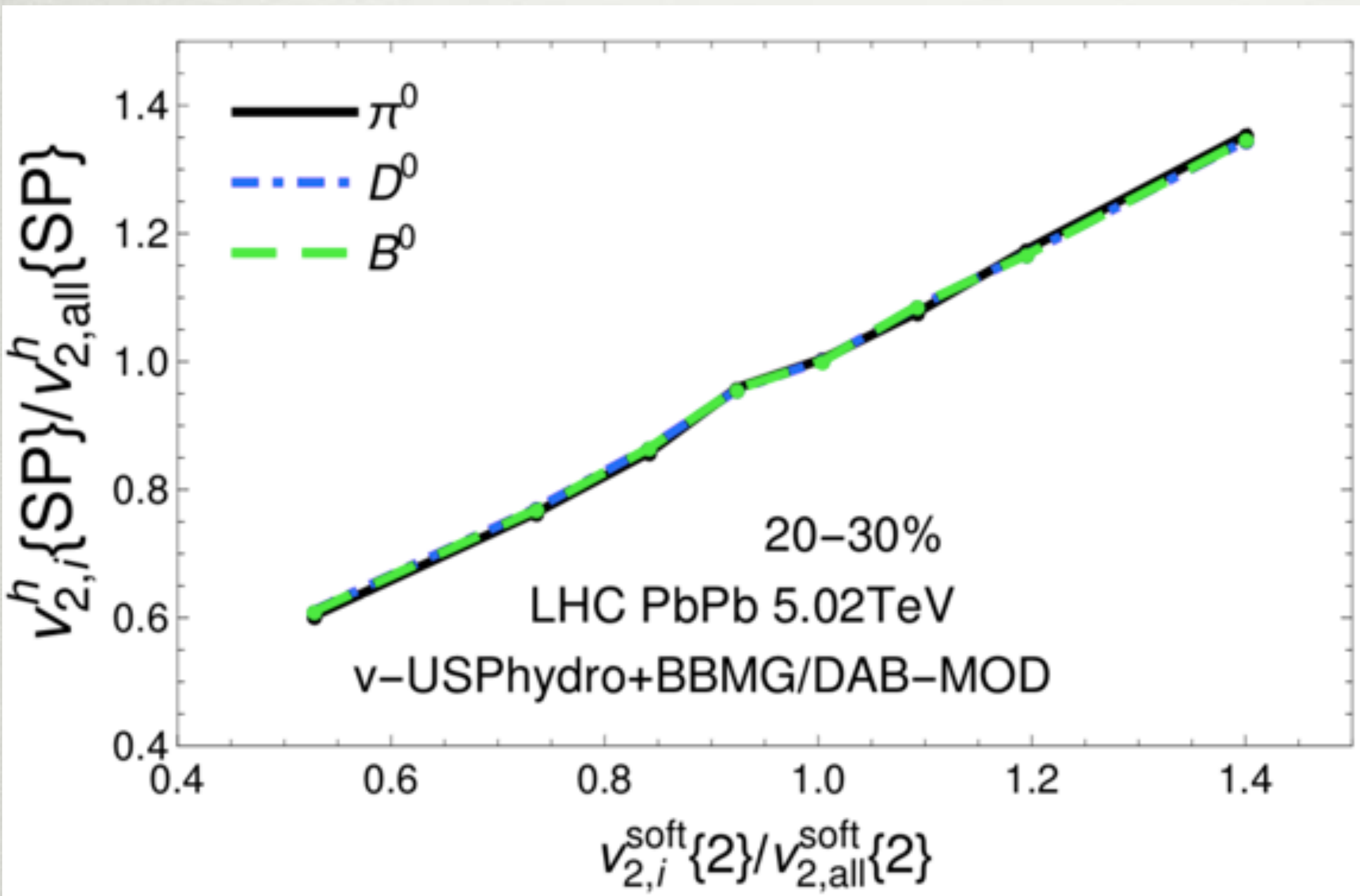
R. Katz, JNH et al, arXiv:1907.03308



- $R_{AA} \rightarrow 1$ as the system size decreases
- v_2 and $v_3 \Downarrow$ with $\Downarrow$ system size (eccentricities ~ const.)

Motivation 3:

SHEE: Soft-Hard Event Engineering



Consequences:

Soft-Hard correlations: Gossiax Nucl.Phys. A967 (2017) 672-675

Constraining soft first, then calculate hard: S. Shi et al arXiv:1808.05461

Constraining τ_0 Andres et al arXiv:1902.03231

Flow within E loss models Brewer et al JHEP 1802 (2018) 015

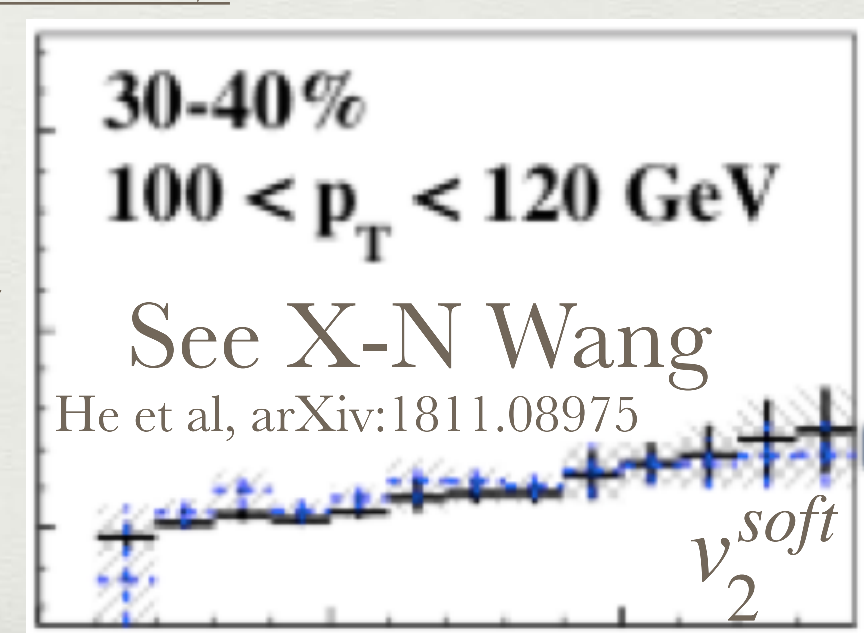
Constraining ε_0 Djordjevic arXiv:1903.06829

SHEE: JNH et al Phys.Rev.Lett. 116 (2016) no.25, 252301; Phys.Rev. C95 (2017) no.4, 044901

Heavy: Prado et al (JNH) Phys.Rev. C96 (2017) no.6, 064903

ALICE D meson SHEE: arXiv:1809.09371

v_2^{jet}



See X-N Wang

He et al, arXiv:1811.08975

v_2^{soft}

Multi particle cumulants

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

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

If there are no difference between soft and hard fluctuations

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

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

v2 fluctuations of D mesons

R. Katz, JNH et al, arXiv:1906.10768

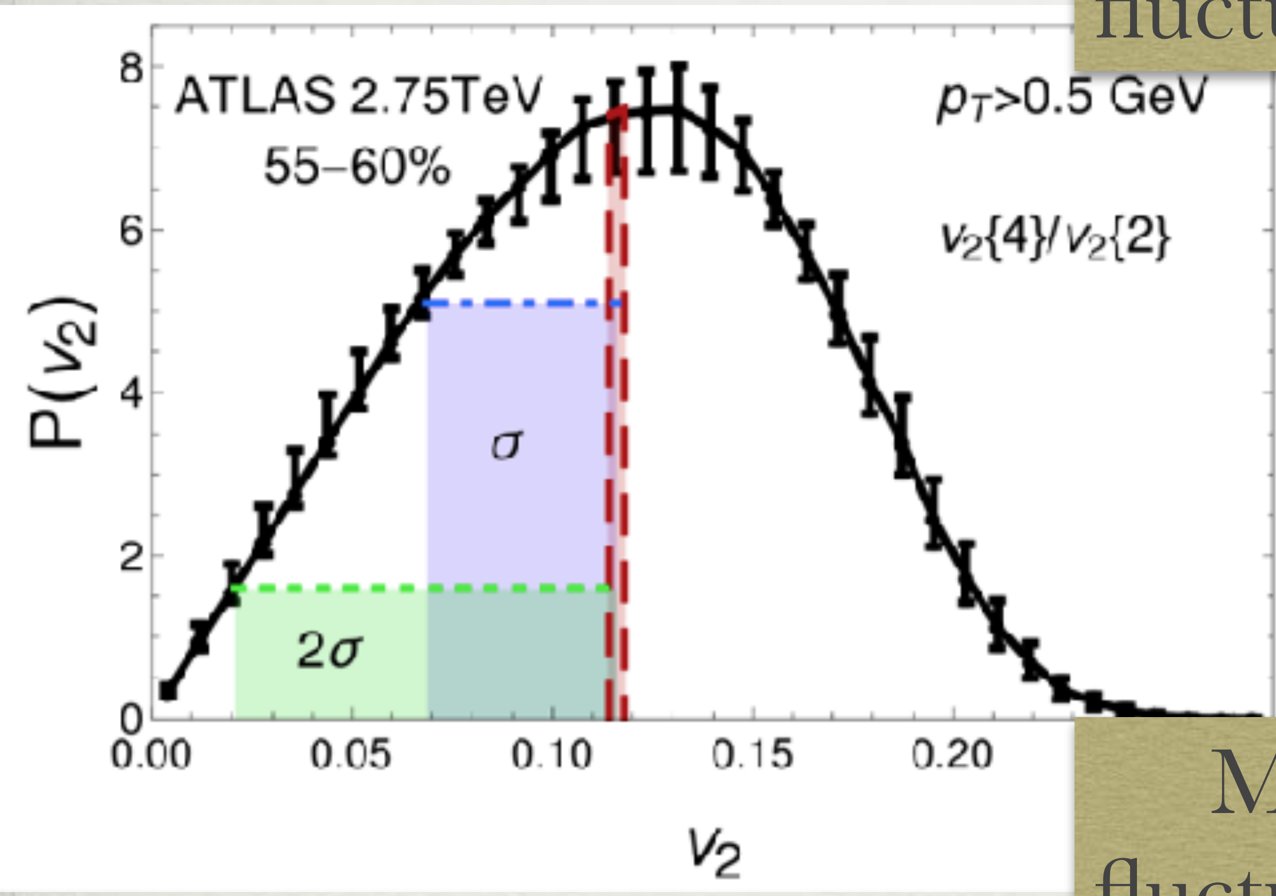
Soft sector: fluctuations in elliptical flow primarily drive by initial conditions

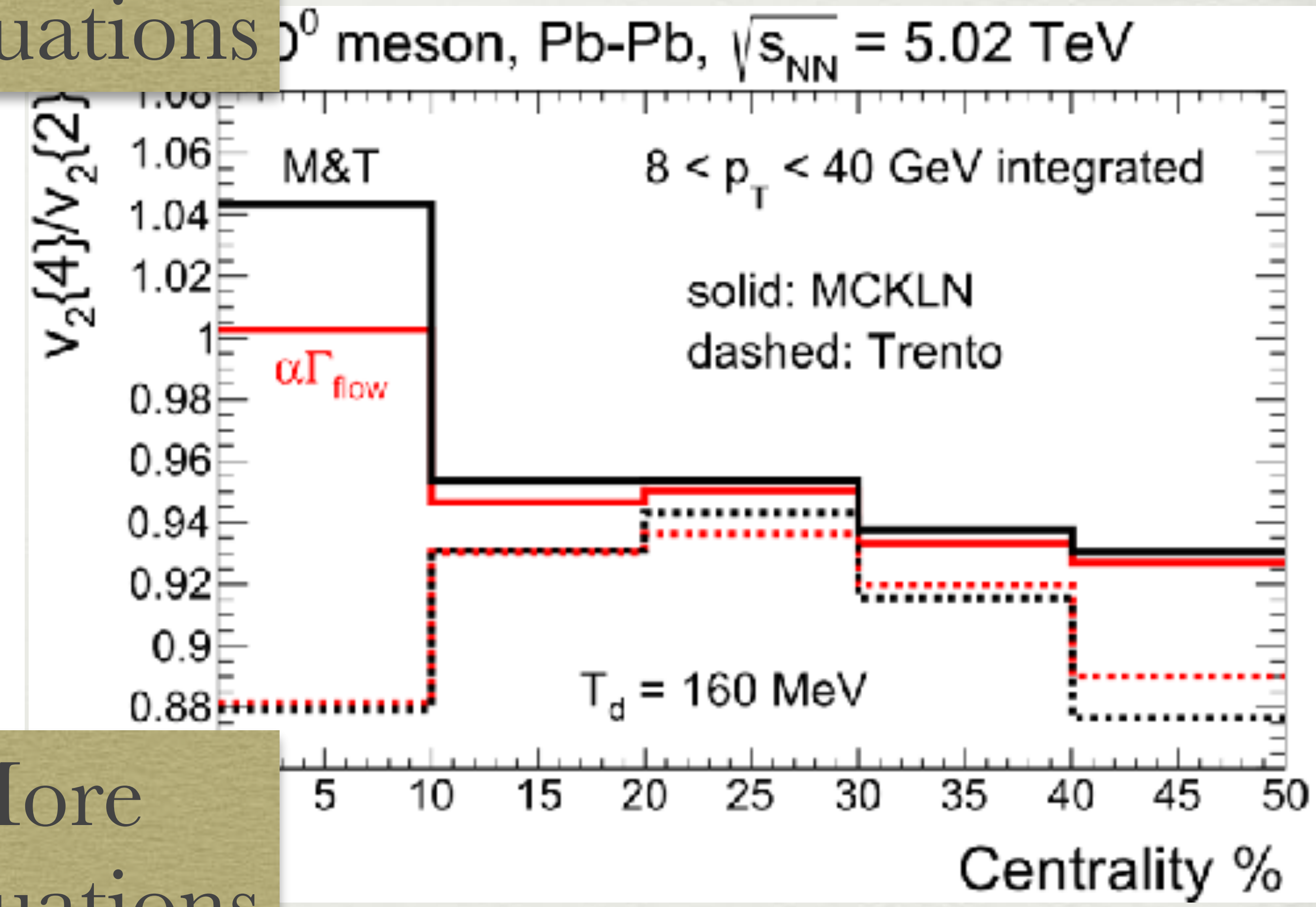
Heavy sector: still driven by initial conditions

Very different behavior [...]licted for central collisions

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

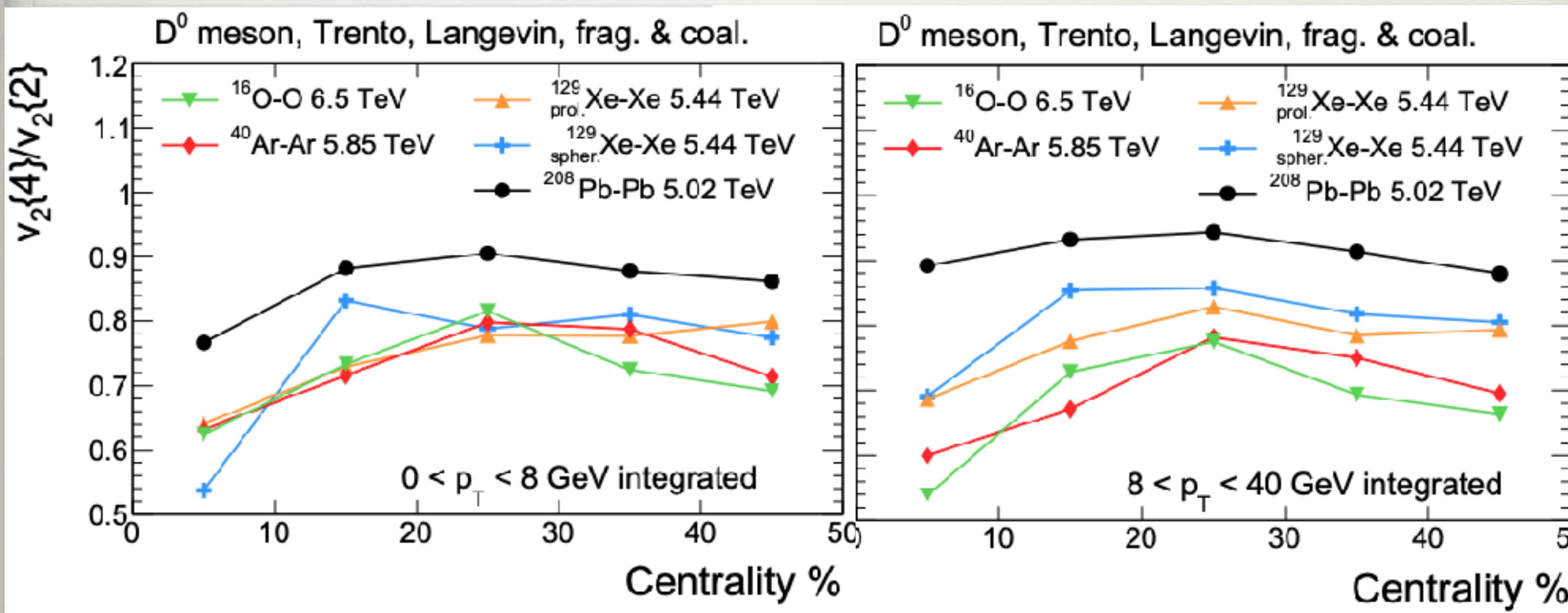
Less fluctuations





More fluctuations

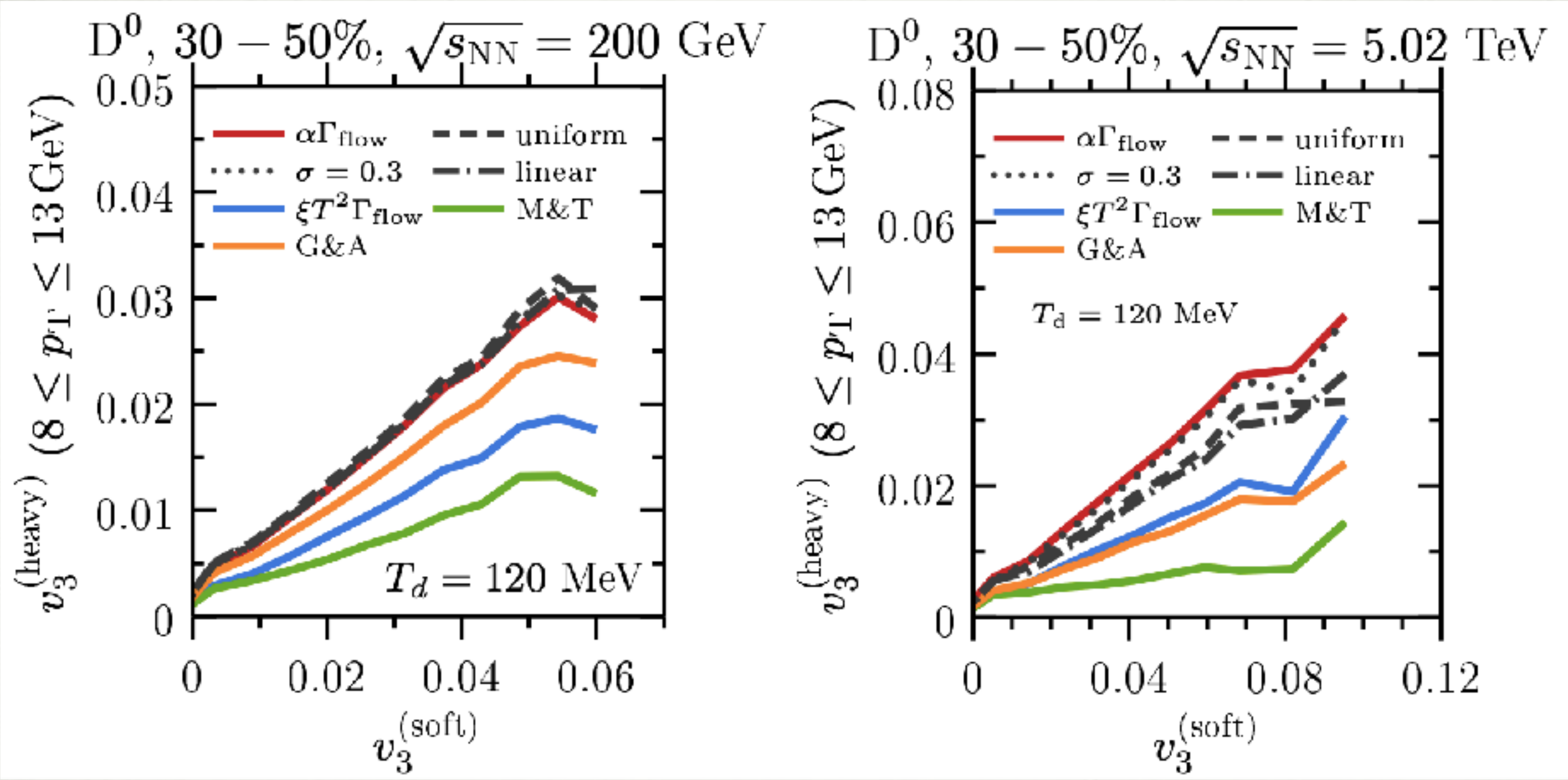
System size effects in fluctuations



Fluctuations at high p_T more sensitive to system size

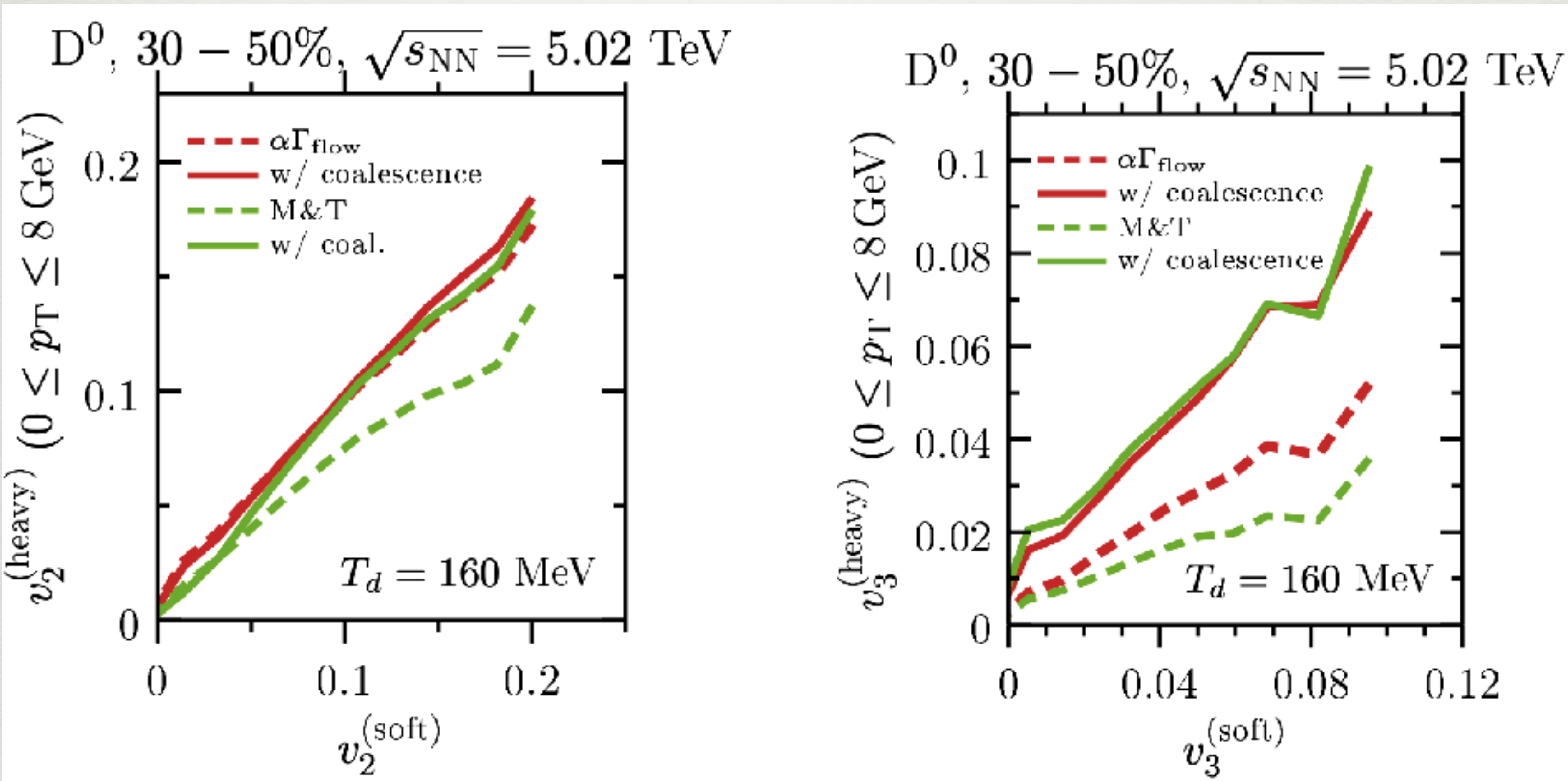
Soft Hard engineering at $p_T > 8$ GeV

R. Katz, JNH et al, arXiv:1906.10768



Sensitive to energy loss description and fluctuations

Soft-Hard Event Engineering at $0 < p_T[GeV] < 8$



Effect swamped by coalescence

R. Katz, JNH et al, arXiv:1906.10768

CONCLUSIONS

Conclusions and Outlook

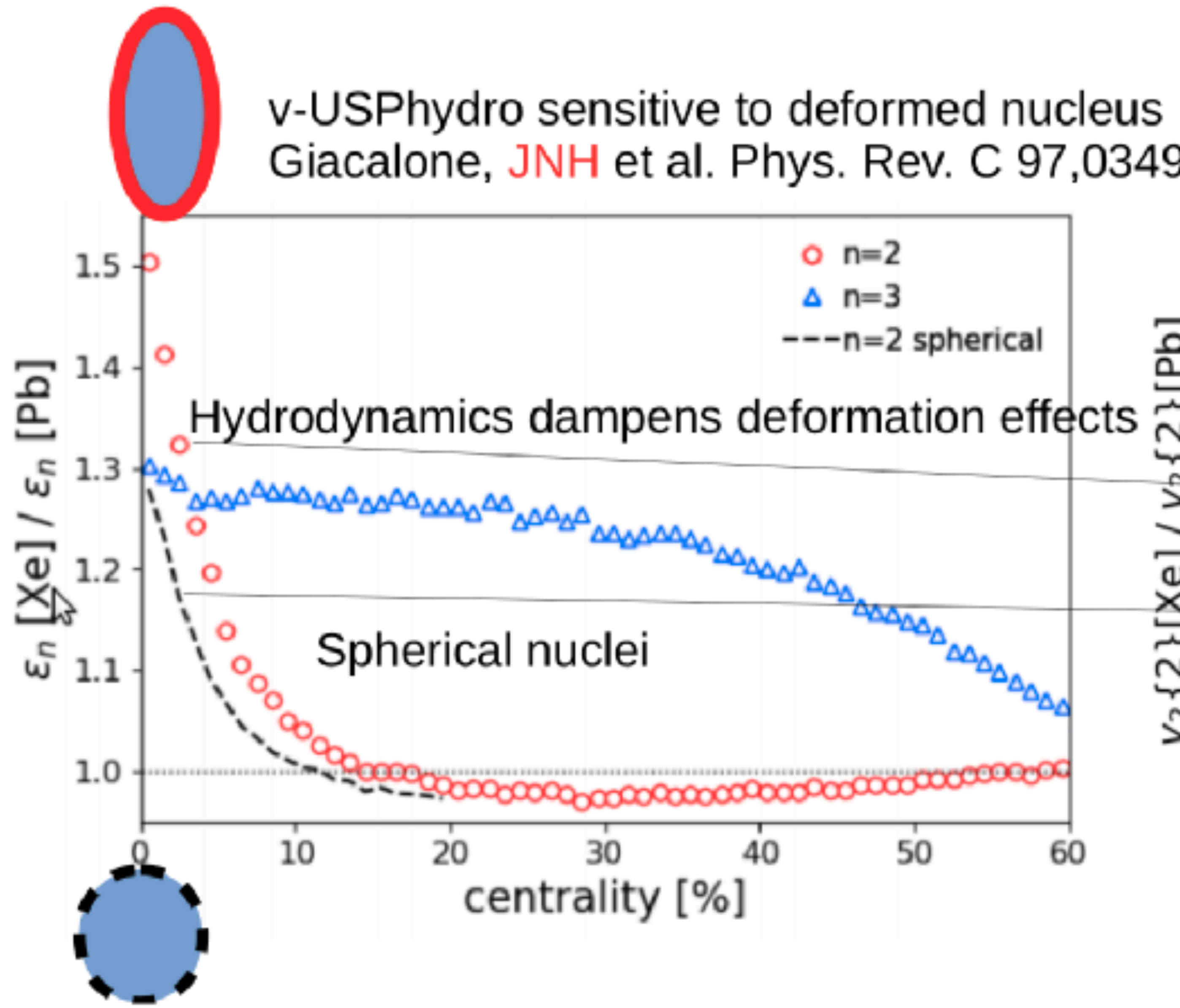
- DAB-MOD is a modular heavy flavor code that can compare energy loss vs. Langevin directly with the same hydrodynamic backgrounds
    - Langevin works best at low pT and Energy loss at high pT
- Comparing PbPb, XeXe, ArAr, OO collisions:
    - D mesons sensitive to deformed nucleus
    - v2 of D mesons ~const in 0-10% and sensitive to system size in 30-50%
- More RHIC/sPHENIX results to come.

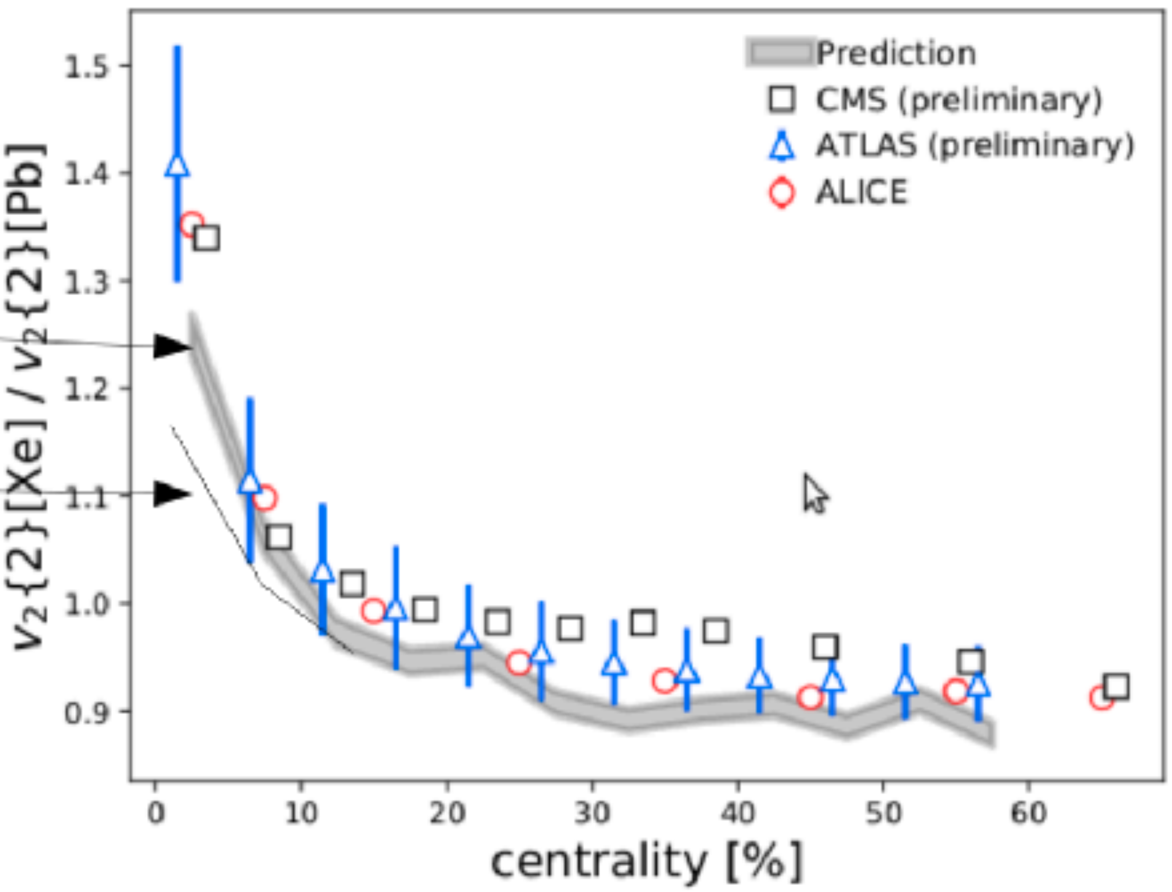
Happy Birthday, John!

BACKUP

XE DEFORMATION MEASURED

v-USPhydro sensitive to deformed nucleus
Giacalone, JNH et al. Phys. Rev. C 97,034904 (2018)



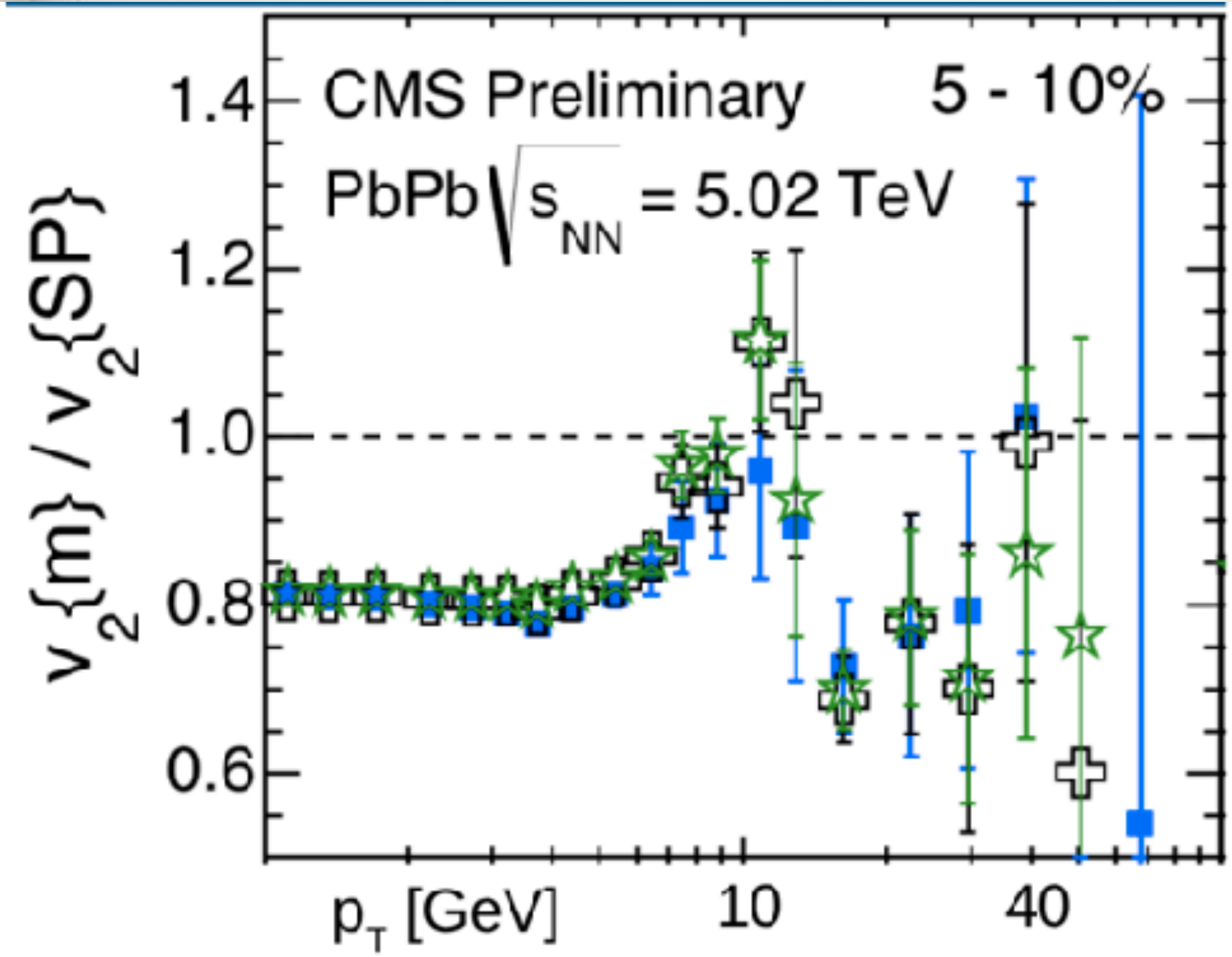


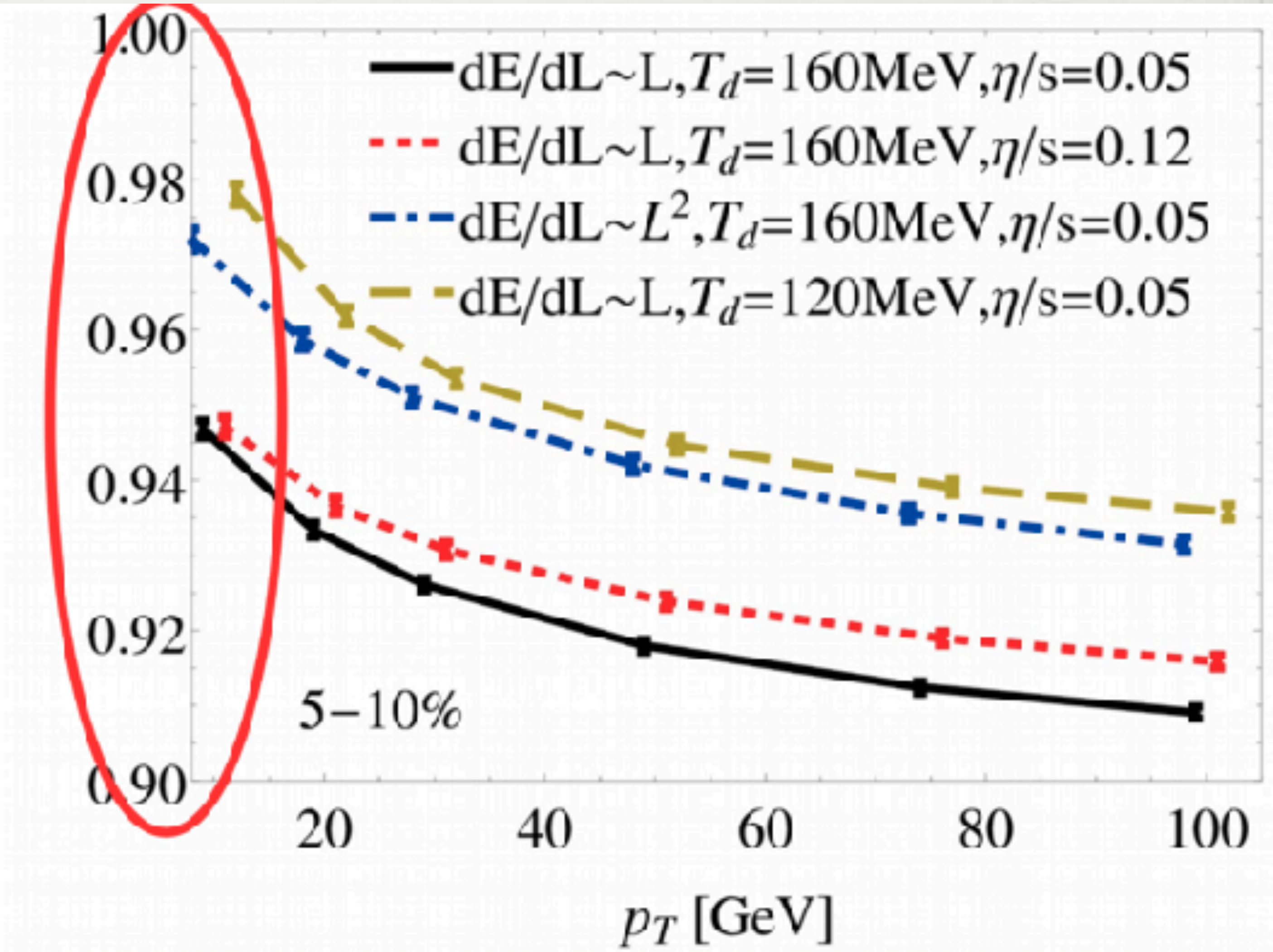
Fragmentation & Coalescence

- Create D mesons at decoupling temperature $T_d \geq T_{FO}$
- Fraction of heavy quarks z from Peterson frag. function

$$f(z) \propto \left[z \left(1 - 1/z - \epsilon_Q/(1-z) \right) \right]$$

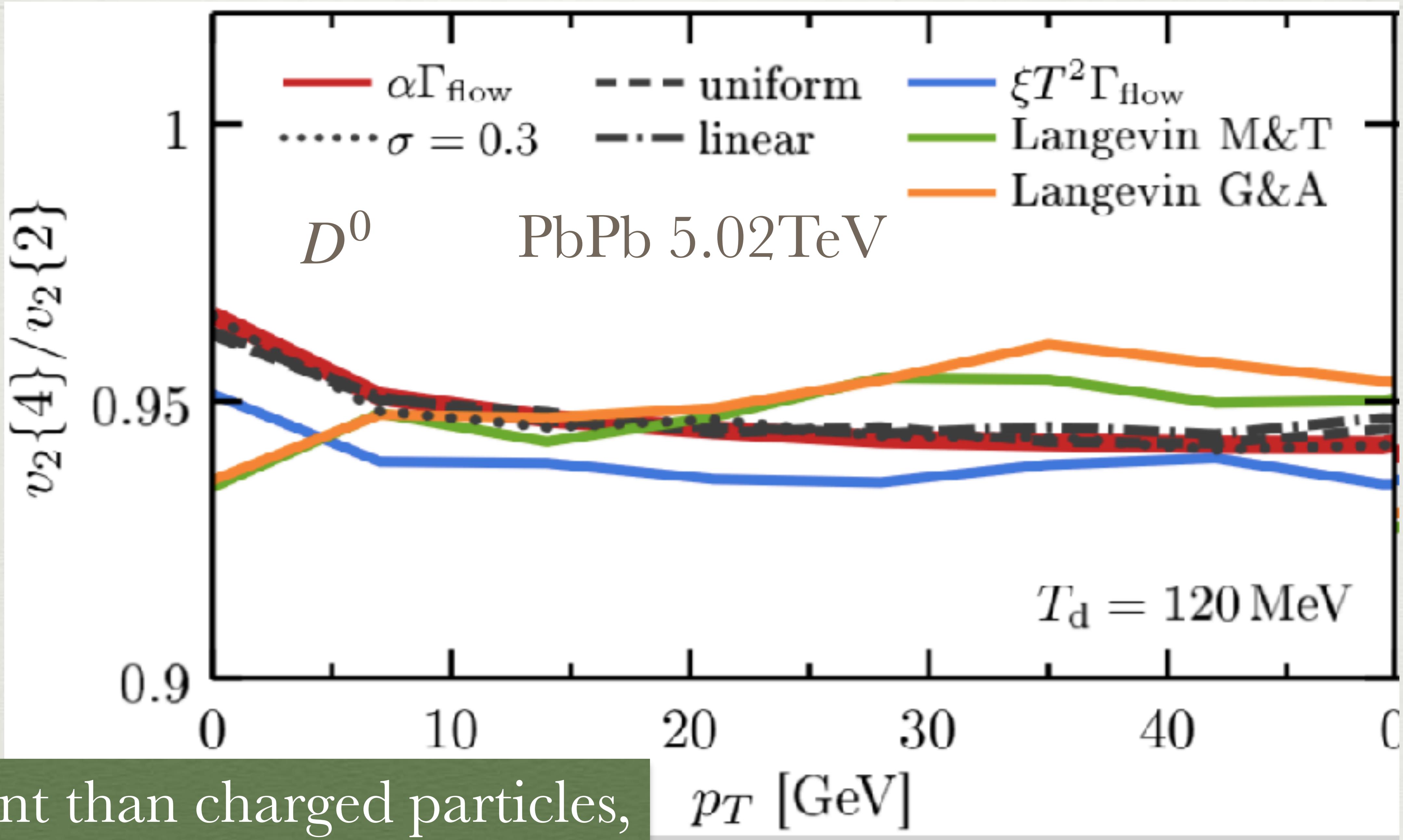
-





p_T dependence of $v_2\{4\}/v_2\{2\}$ from soft vs. hard fluctuations

pT dependence of fluctuations



Different than charged particles, heavy flavor requires physics beyond just hydro across all pT

Multiparticle cumulants

Reconstructing the v_n distribution with cumulants

$$
\begin{aligned}
v_n\{2\}^2 &= \langle v_n^2 \rangle, \\
v_n\{4\}^4 &= 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle, \\
v_n\{6\}^6 &= \frac{1}{4}\left[\langle v_n^6 \rangle - 9\langle v_n^2 \rangle\langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3\right], \\
v_n\{8\}^8 &= \frac{1}{33}\left[144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2\langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2\right. \\
&+ \left. 16\langle v_n^2 \rangle\langle v_n^6 \rangle - \langle v_n^8 \rangle\right],
\end{aligned}
$$

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)

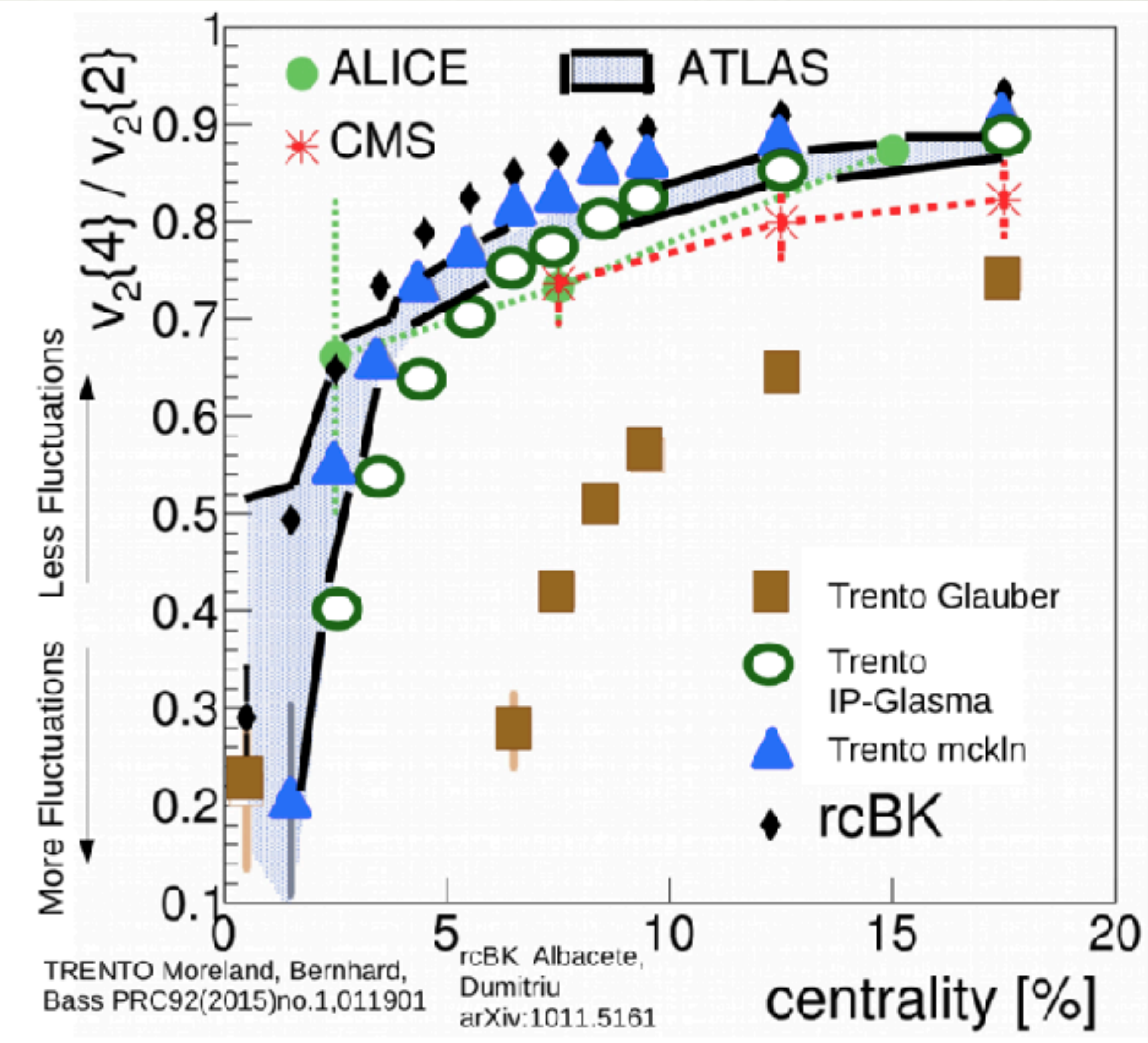
$$\frac{\langle v_n^{soft}\, v_n^{hard}(p_T) \cos\left(n\left[\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle}{\sqrt{\left\langle \left(v_n^{soft}\right)^2 \right\rangle}}$$

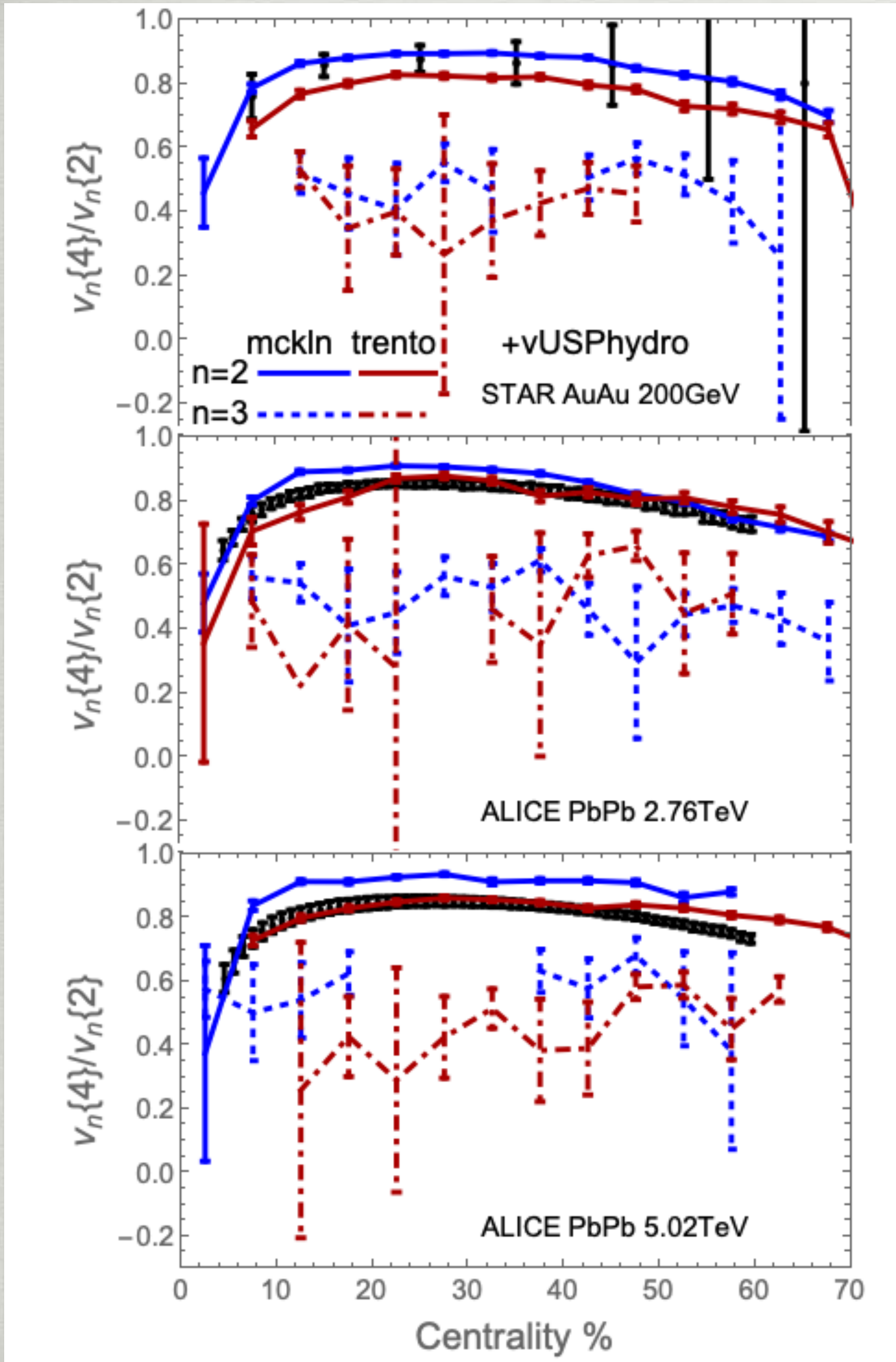
$v_2\{4\}(p_T)$ Four particle correlation (three soft, one hard)

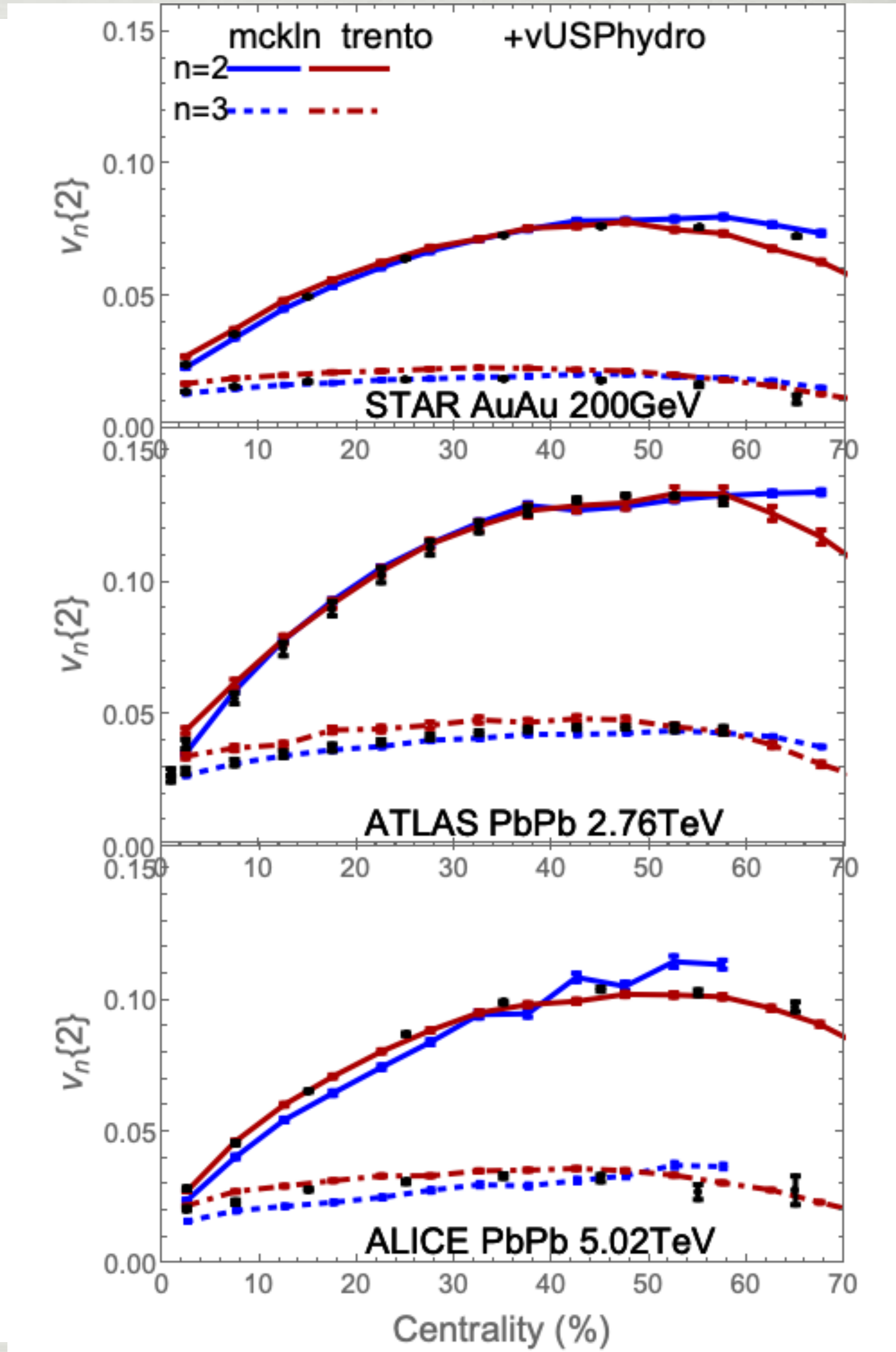
$$\frac{2\langle |v_n^{soft}|^2\rangle \langle v_n^{soft}\, v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle - \langle (v_n^{soft})^3\, v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle}{(v_n^{soft}\{4\})^{3/4}}$$

Constraints on initial conditions

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




mckln trento +vUSPhydro
n=2
n=3
STAR AuAu 200GeV
ALICE PbPb 2.76TeV
ALICE PbPb 5.02TeV
$v_n\{4\}/v_n\{2\}$
Centrality %


mckln trento +vUSPhydro
n=2
n=3
STAR AuAu 200GeV
ATLAS PbPb 2.76TeV
ALICE PbPb 5.02TeV
$v_n\{2\}$
Centrality (%)

Transport Coefficients