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

KNOXVILLE JET WORKSHOP 2019

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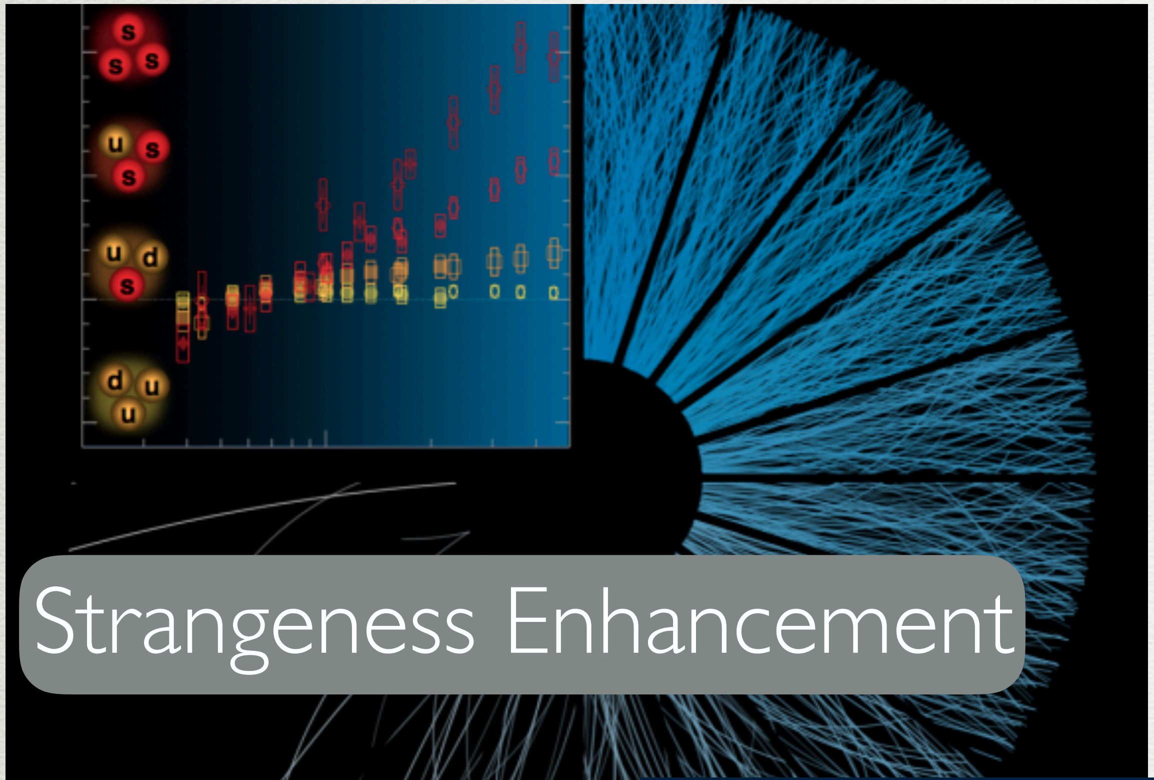
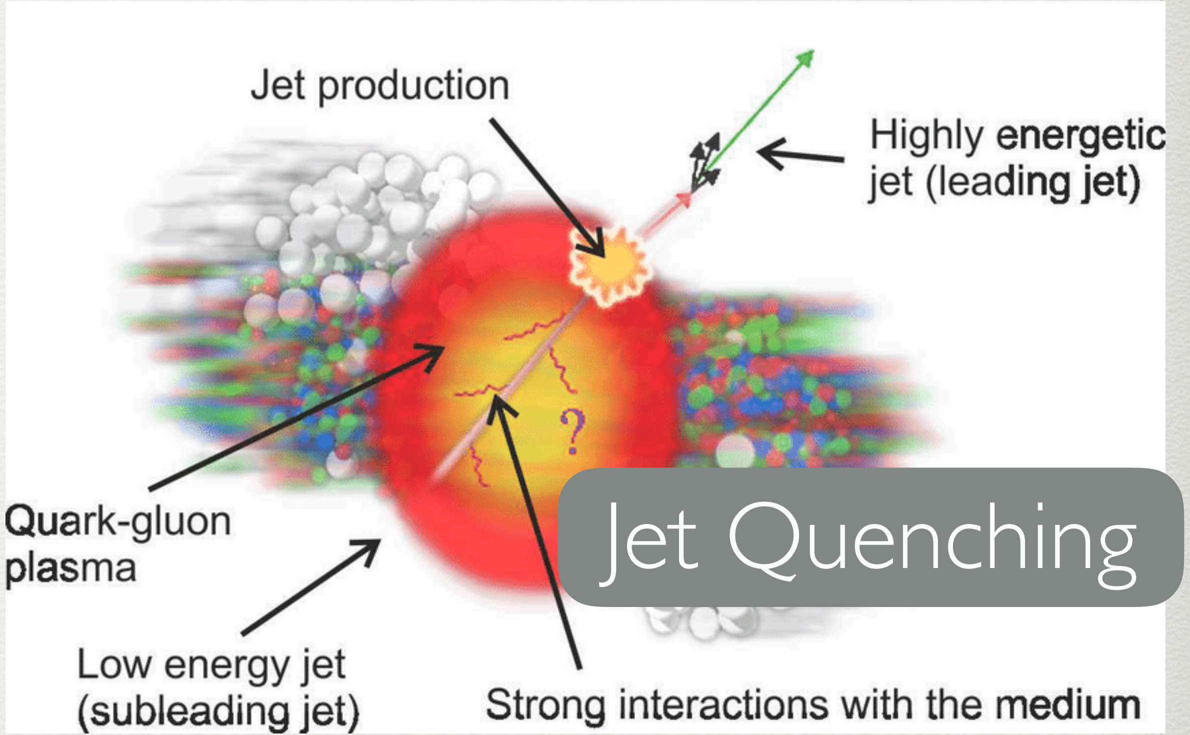
Collaborators: **Roland Katz, Caio A.G. Prado**, Alexandre A.P. Suaide, Marcelo G. Munhoz arXiv:1812.08009 & to appear shortly

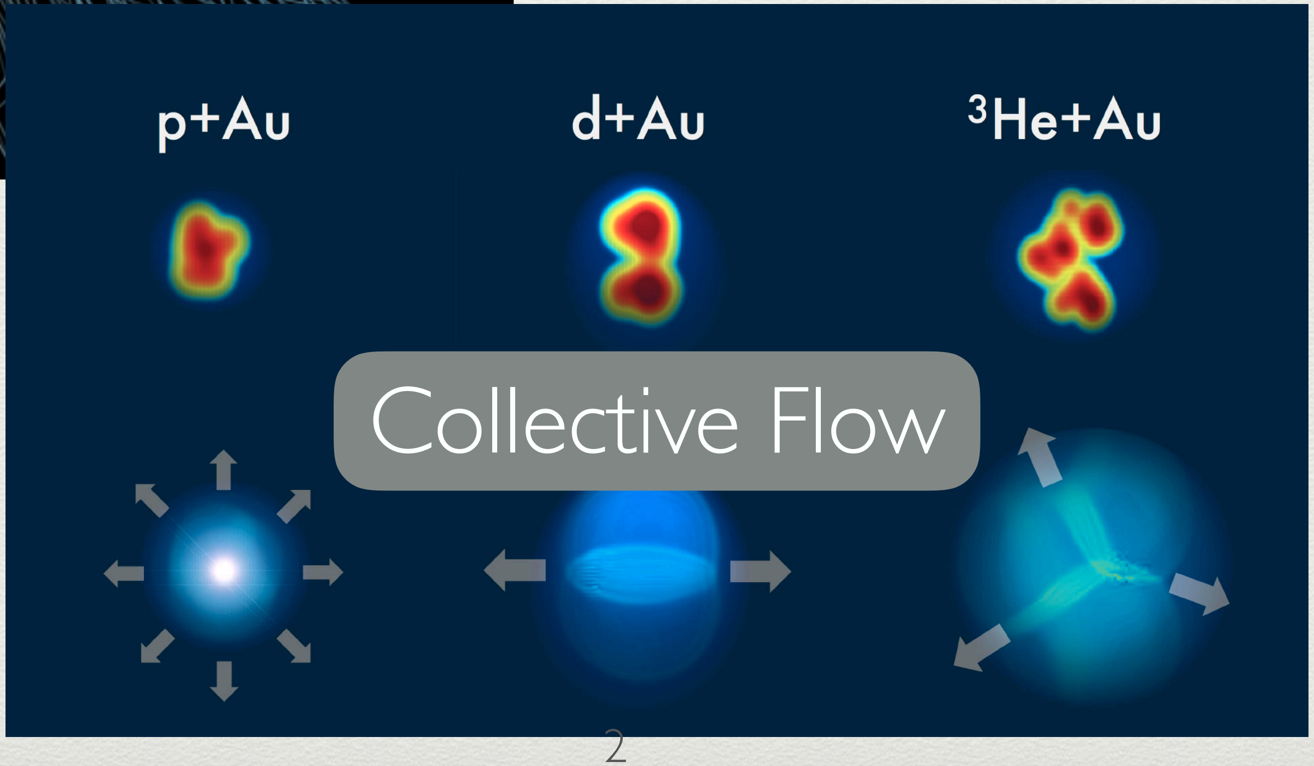
SIGNALS OF THE QGP



Strangeness Enhancement

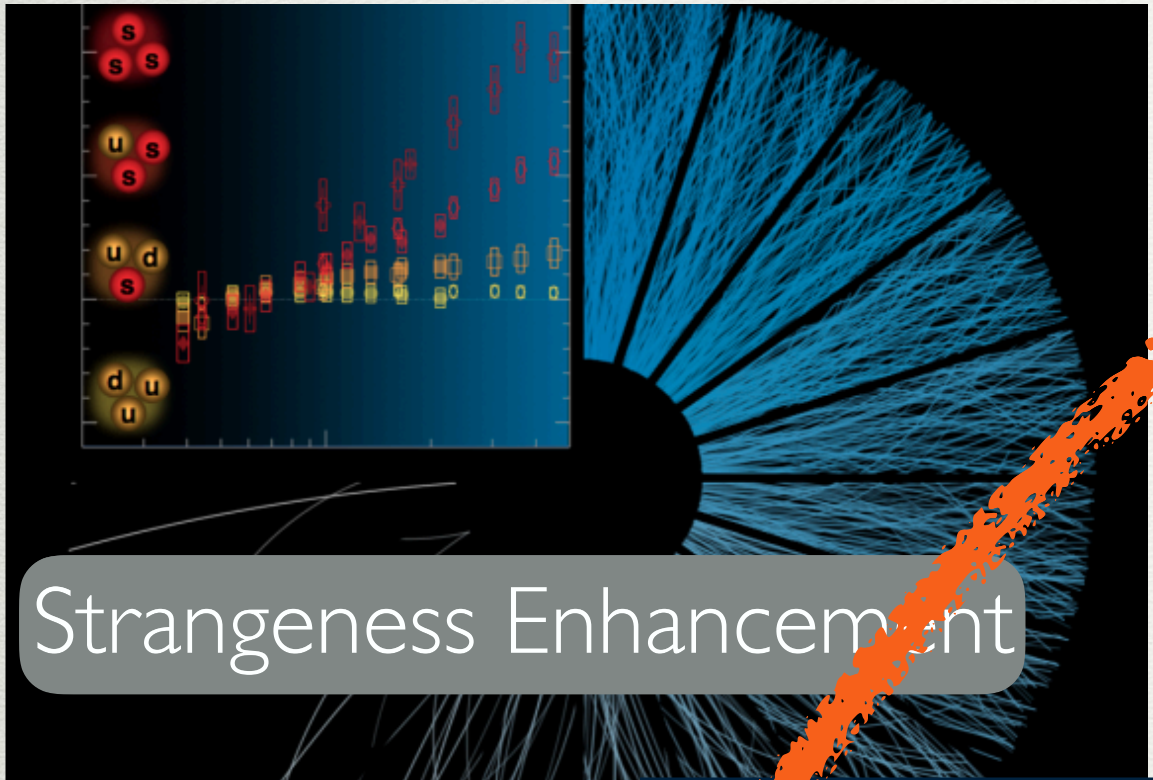


Jet Quenching

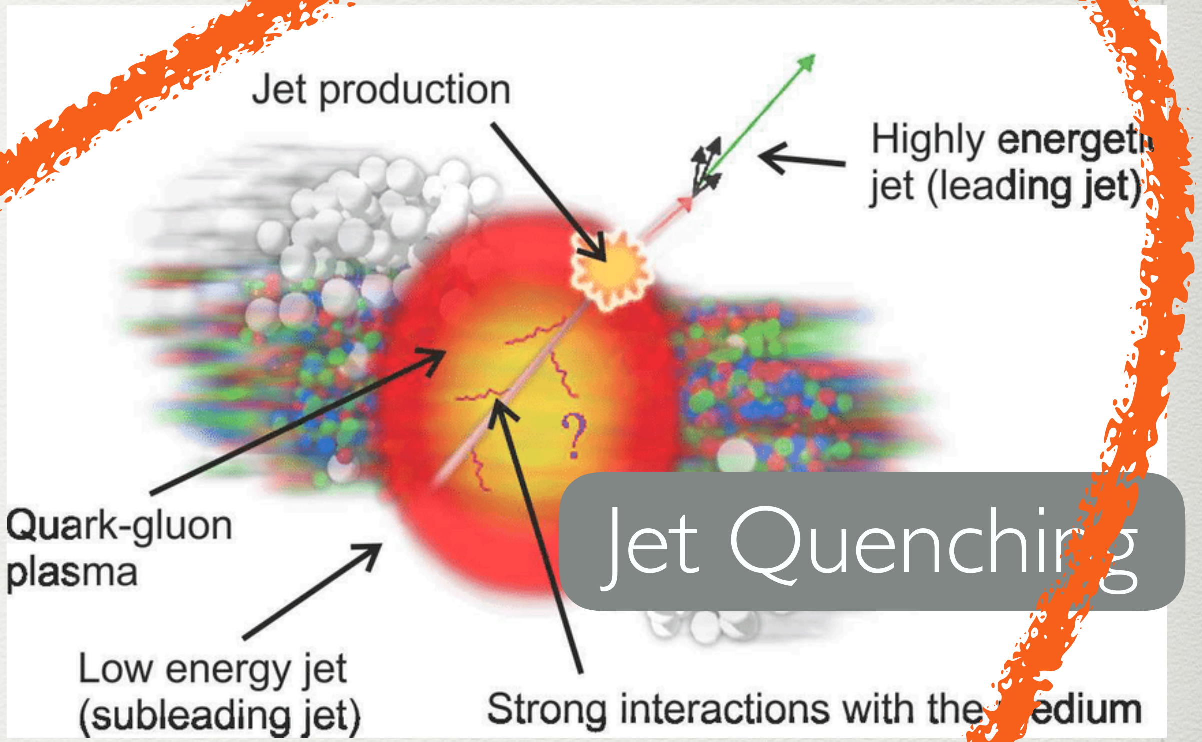


Collective Flow

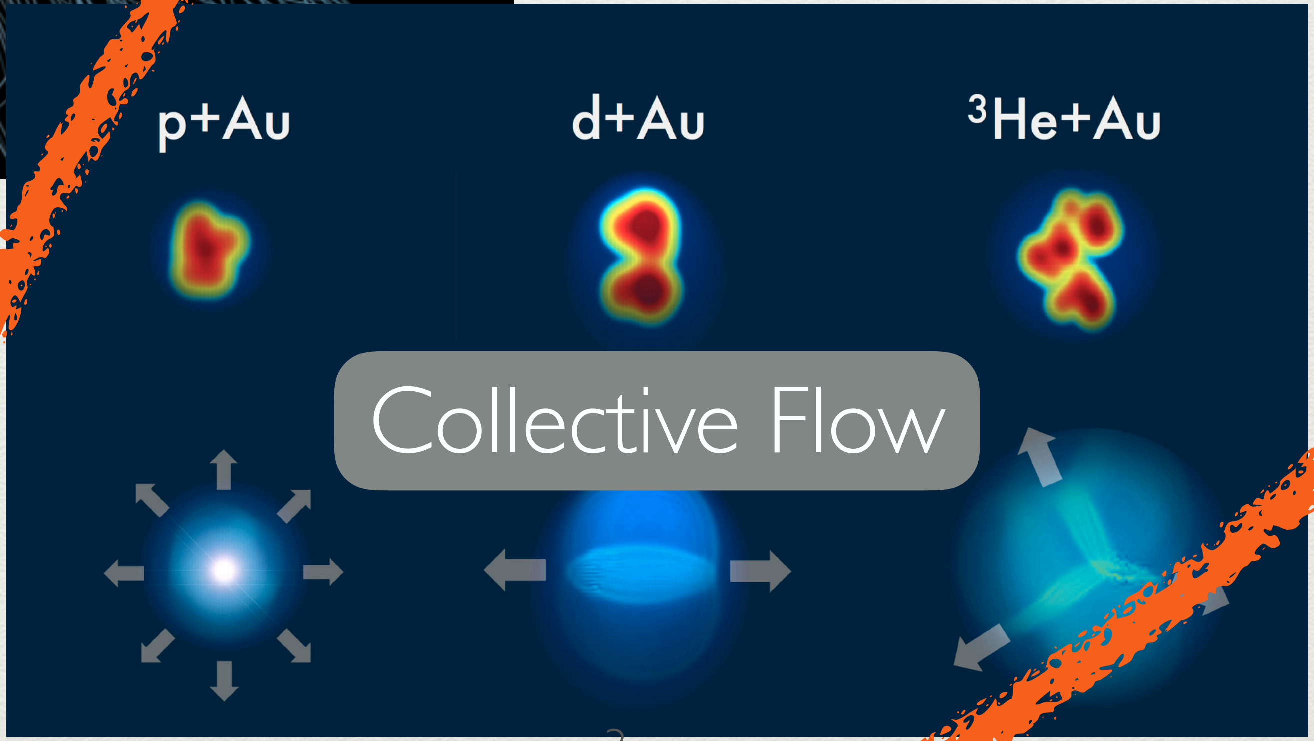
SIGNALS OF THE QGP



Strangeness Enhancement



Jet Quenching



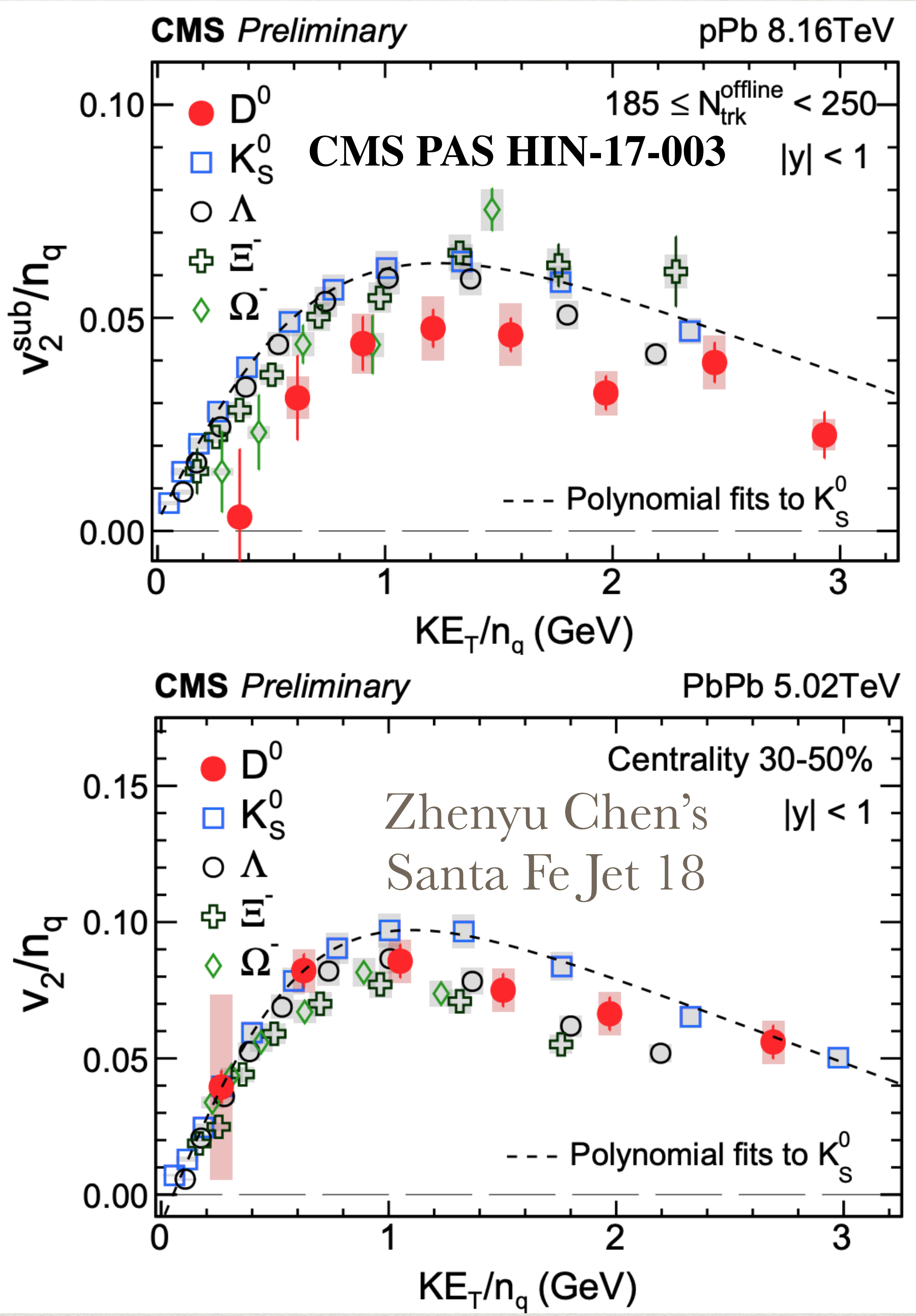
Collective Flow

Motivation 1:

D meson scaling with system size

Can we understand system size dependence of energy loss?

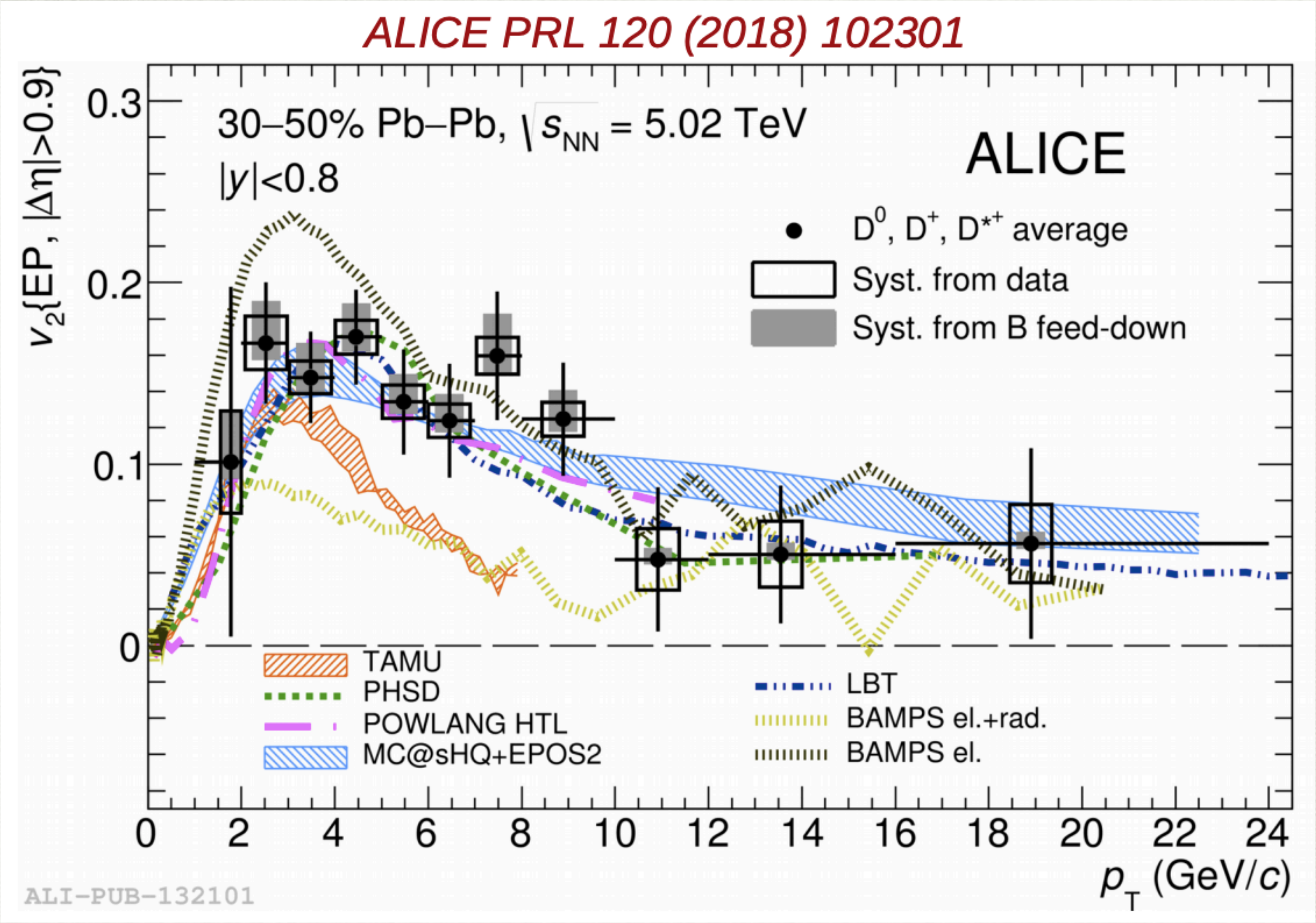
Comparisons between soft and hard sector?



CMS PAS HIN-17-003

Zhenyu Chen's Santa Fe Jet 18

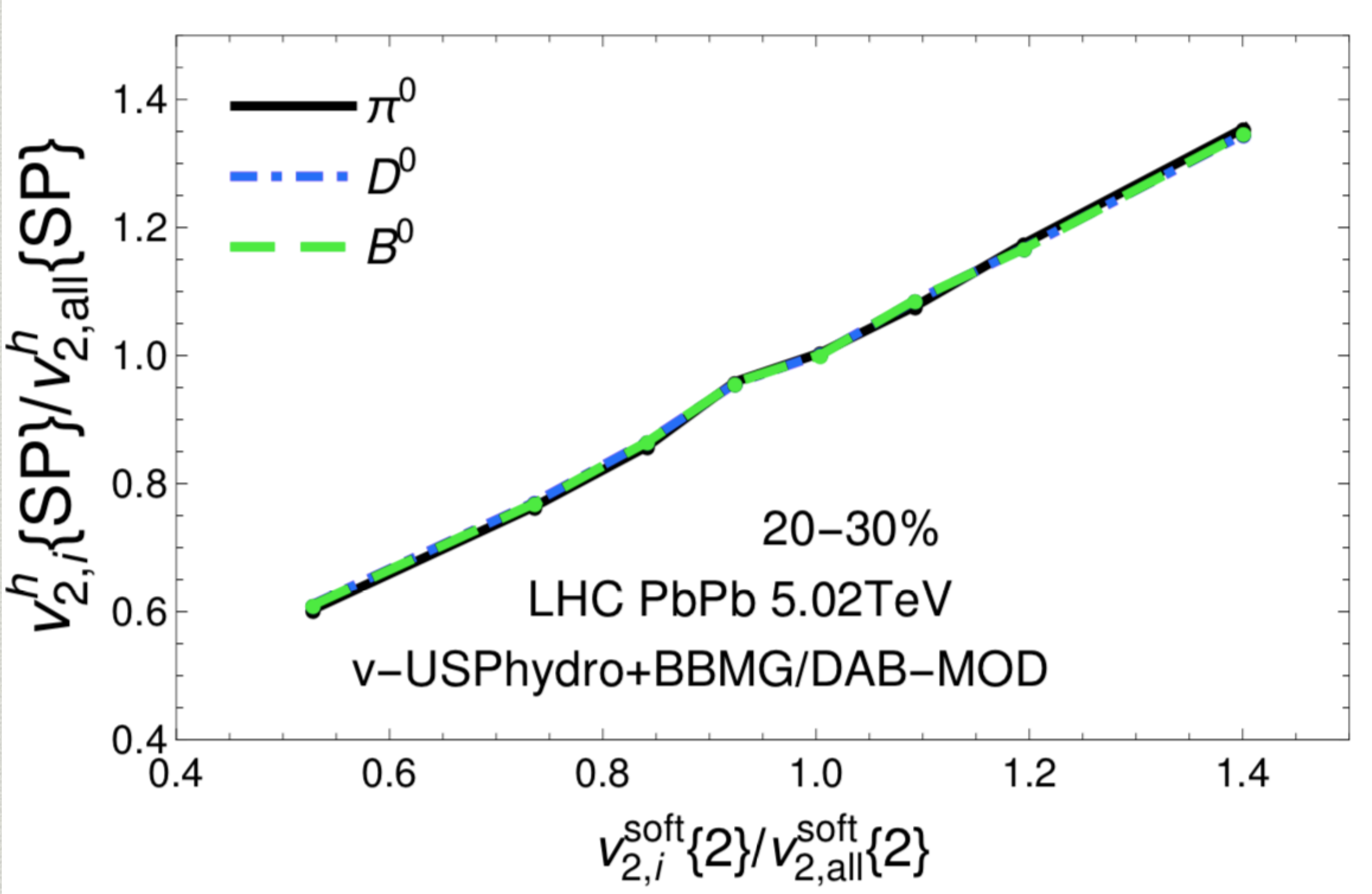
Motivation 2:
What makes theory match data?



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

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

Motivation 3:
SHEE: Soft-Hard Event Engineering



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

Consequences:

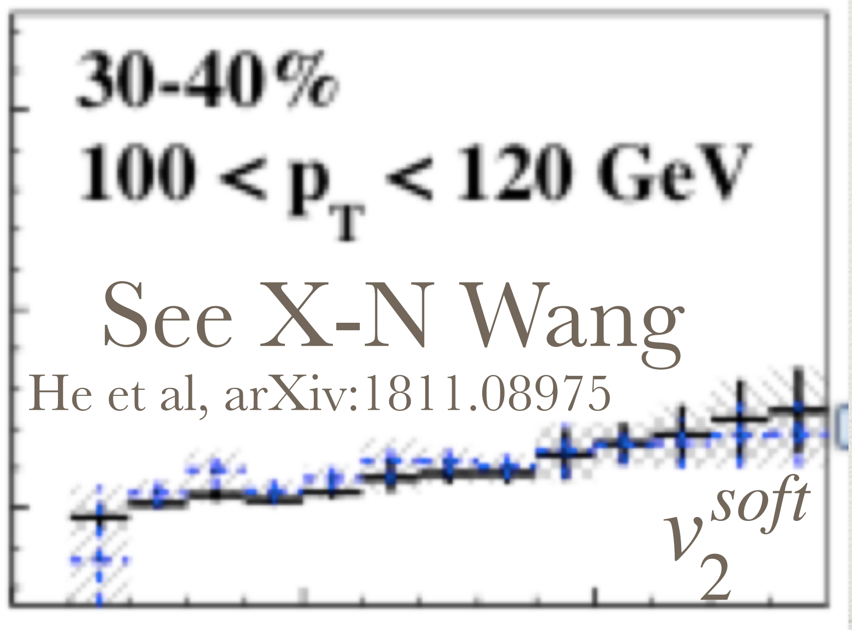
Soft-Hard correlations: Gossiax Nucl.Phys. A967 (2017) 672-675

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



See X-N Wang

He et al, arXiv:1811.08975

MODEL

DAB-MOD

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

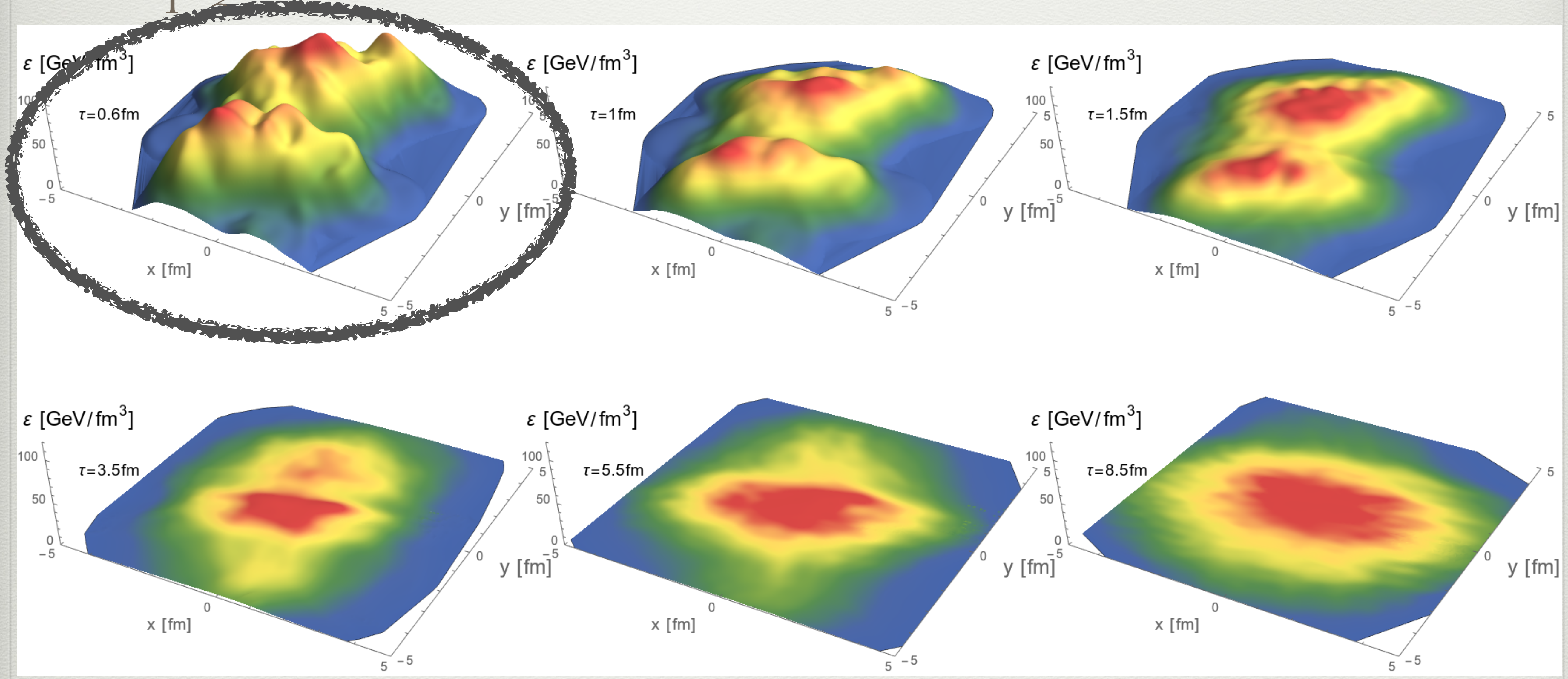
- Heavy flavor (D and B mesons) package that allows for a variety of parameterized energy loss models or *relativistic Langevin models*.
- *Coalescence*

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

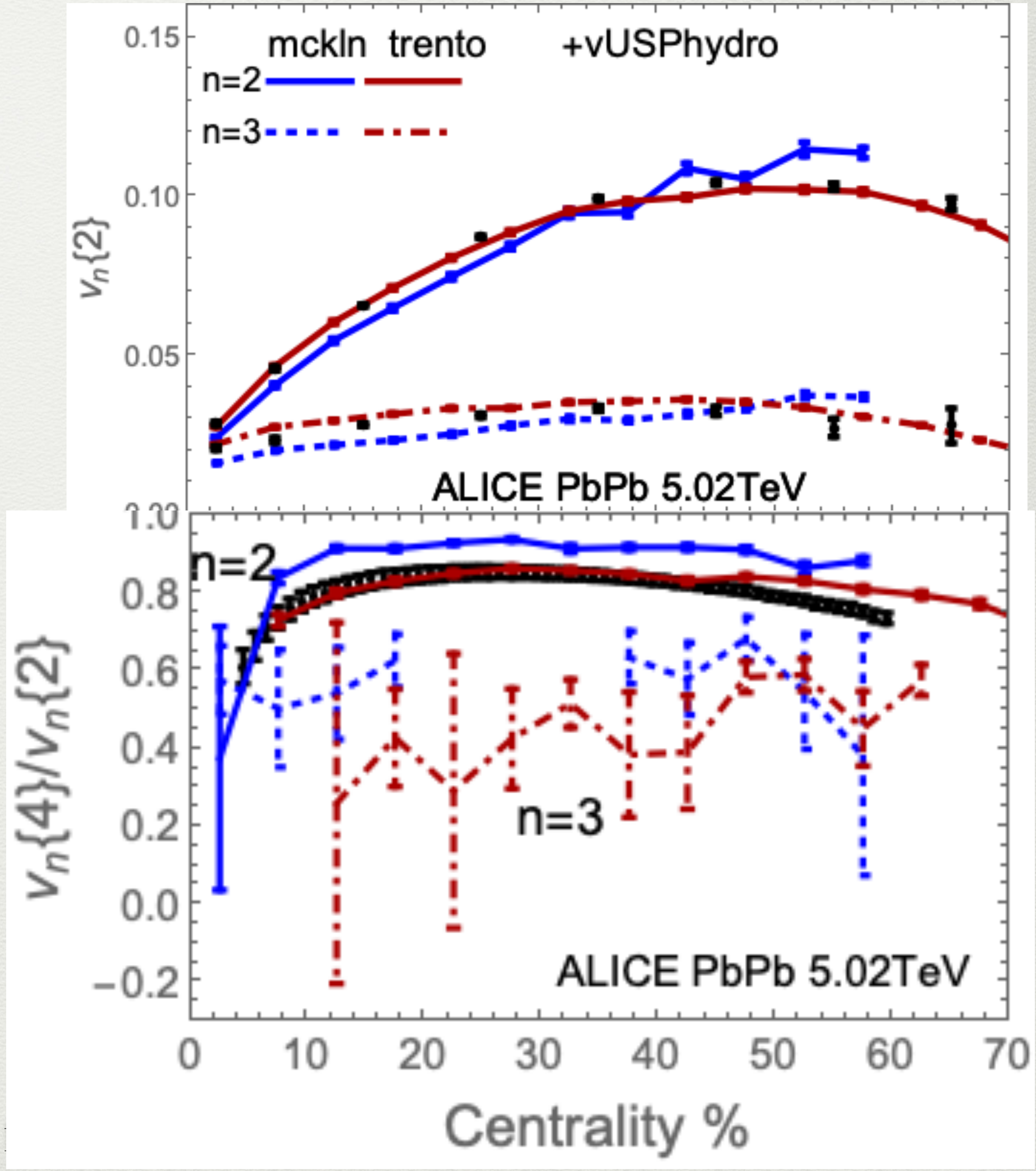
  Hydro: Alba et al, Phys.Rev. D96 (2017) no.3, 034517

- mckln

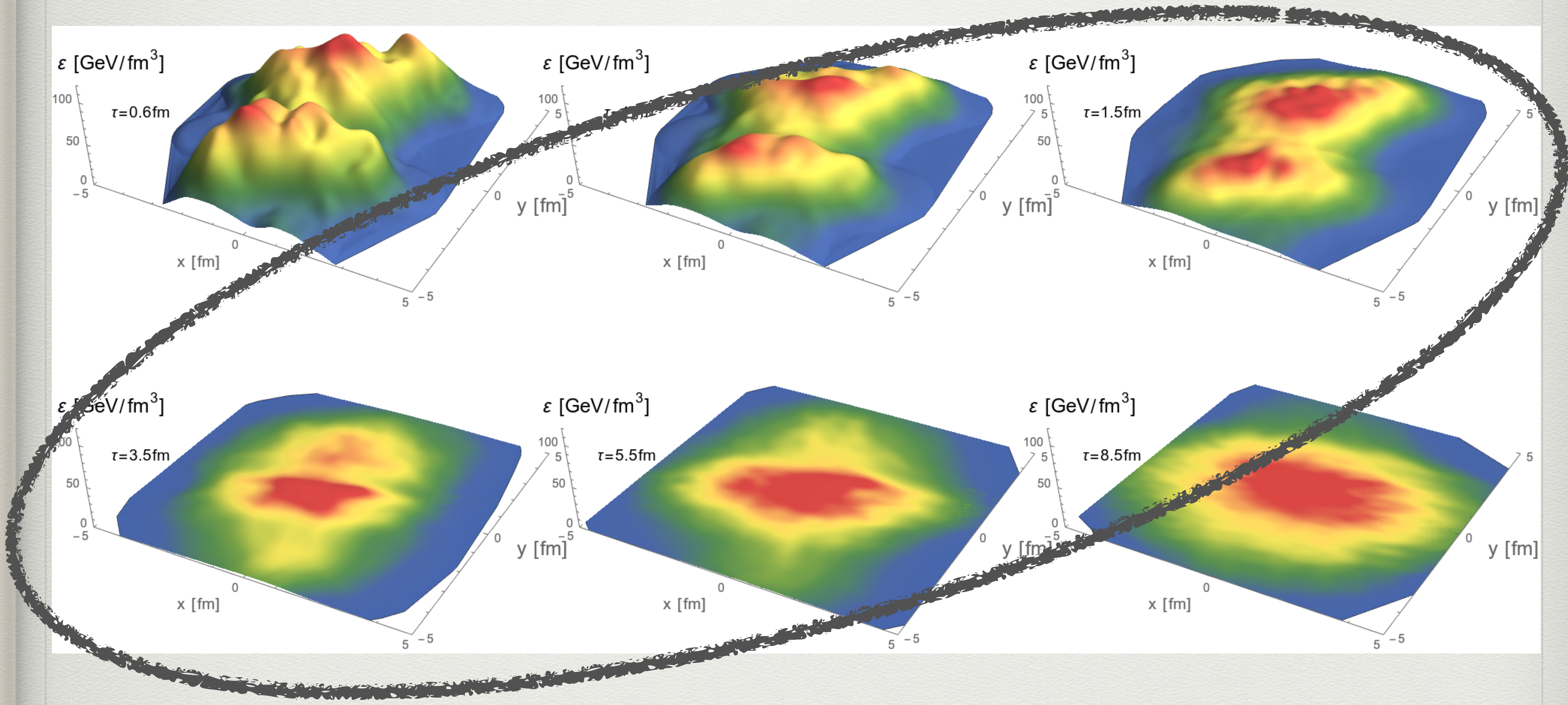
  Drescher et al, Phys. Rev. C74, 044905 (2006); Phys. Rev. C76, 041903 (2007); Phys. Rev. C75, 034905 (2007)

  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

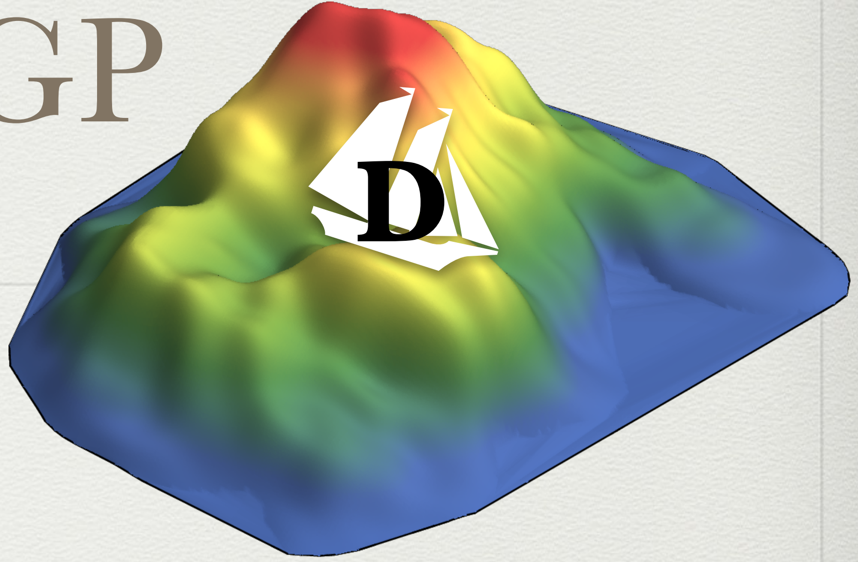
Alba et al, Phys.Rev. D96 (2017) no.3, 034517

- 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)

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

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

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

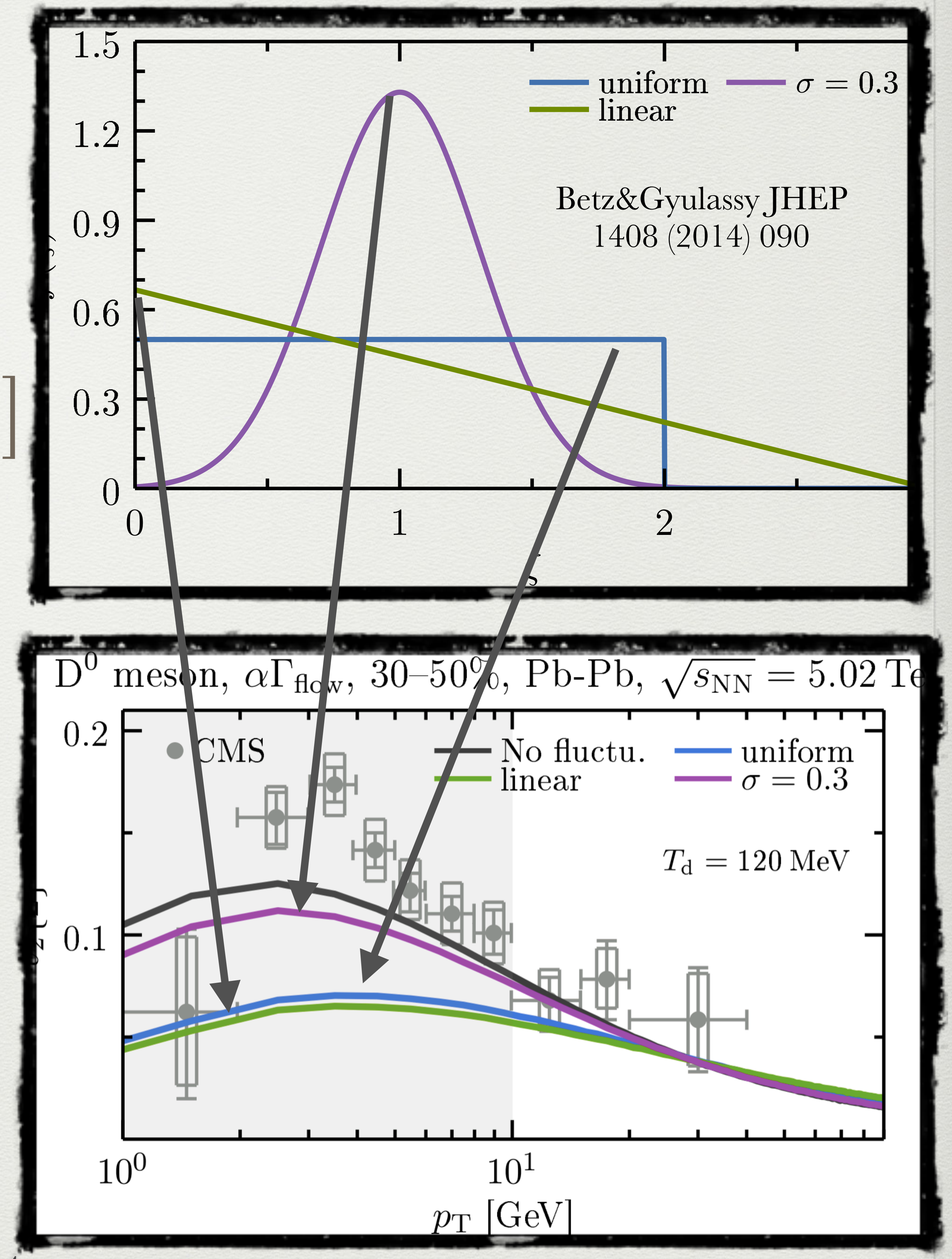
$f(\zeta) = 0.5$ For $0 \leq \zeta \leq 2$

Linear

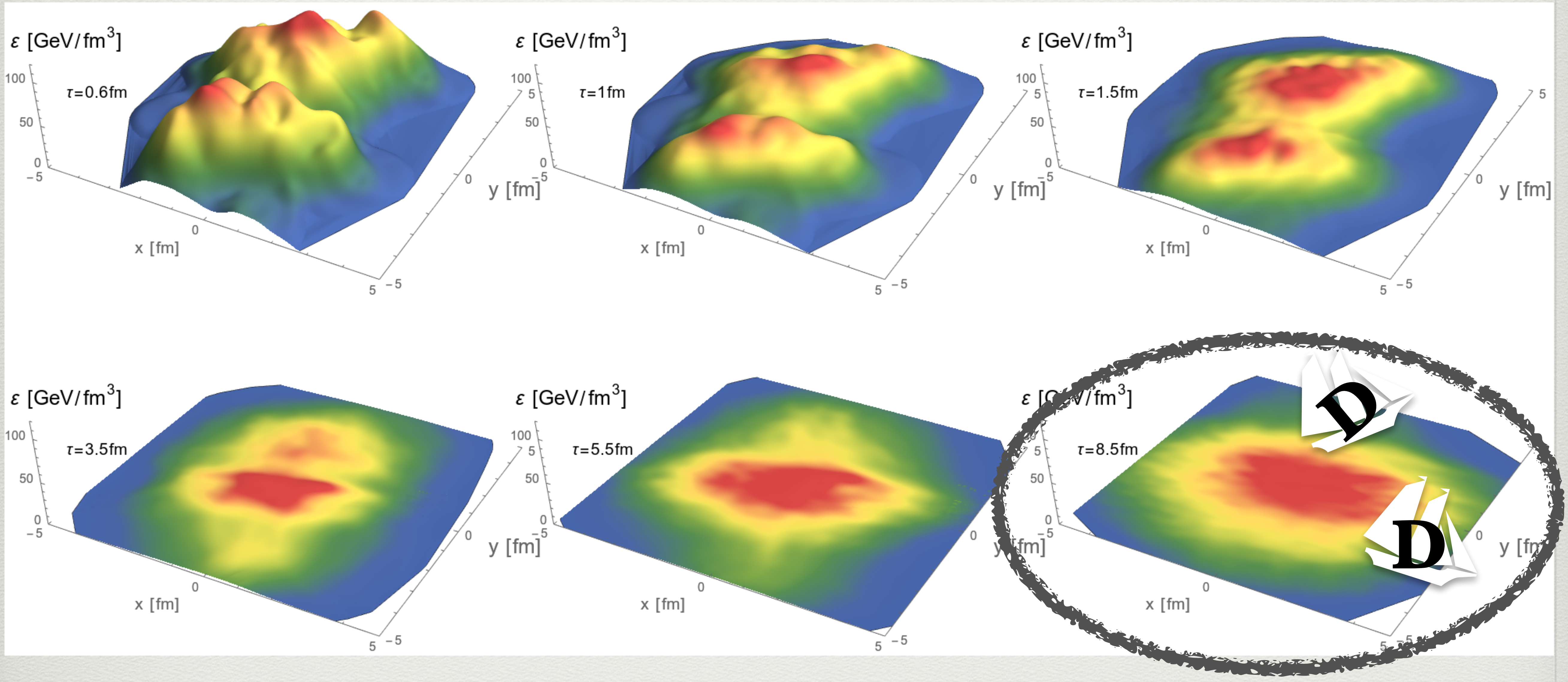
$$f(\zeta) = 2/3 - (2/9)\zeta$$

for

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



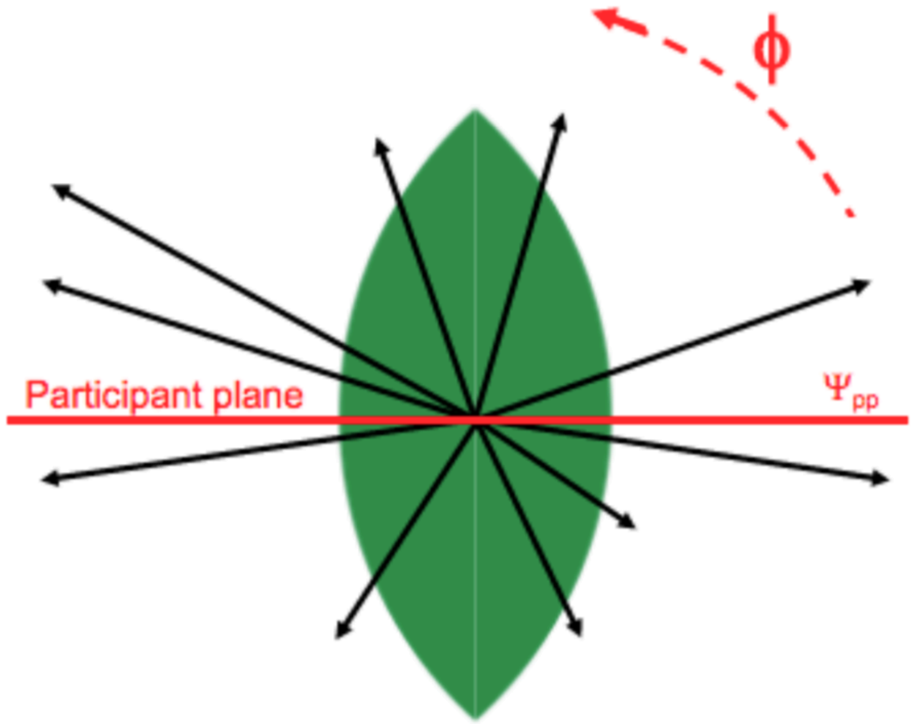
Hydro particlization: Cooper-Frye+decays
Heavy quark fragmentation: Petersen fragmentation function+light/heavy quark coalescence



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
- $\langle \cdots \rangle \rightarrow$ 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

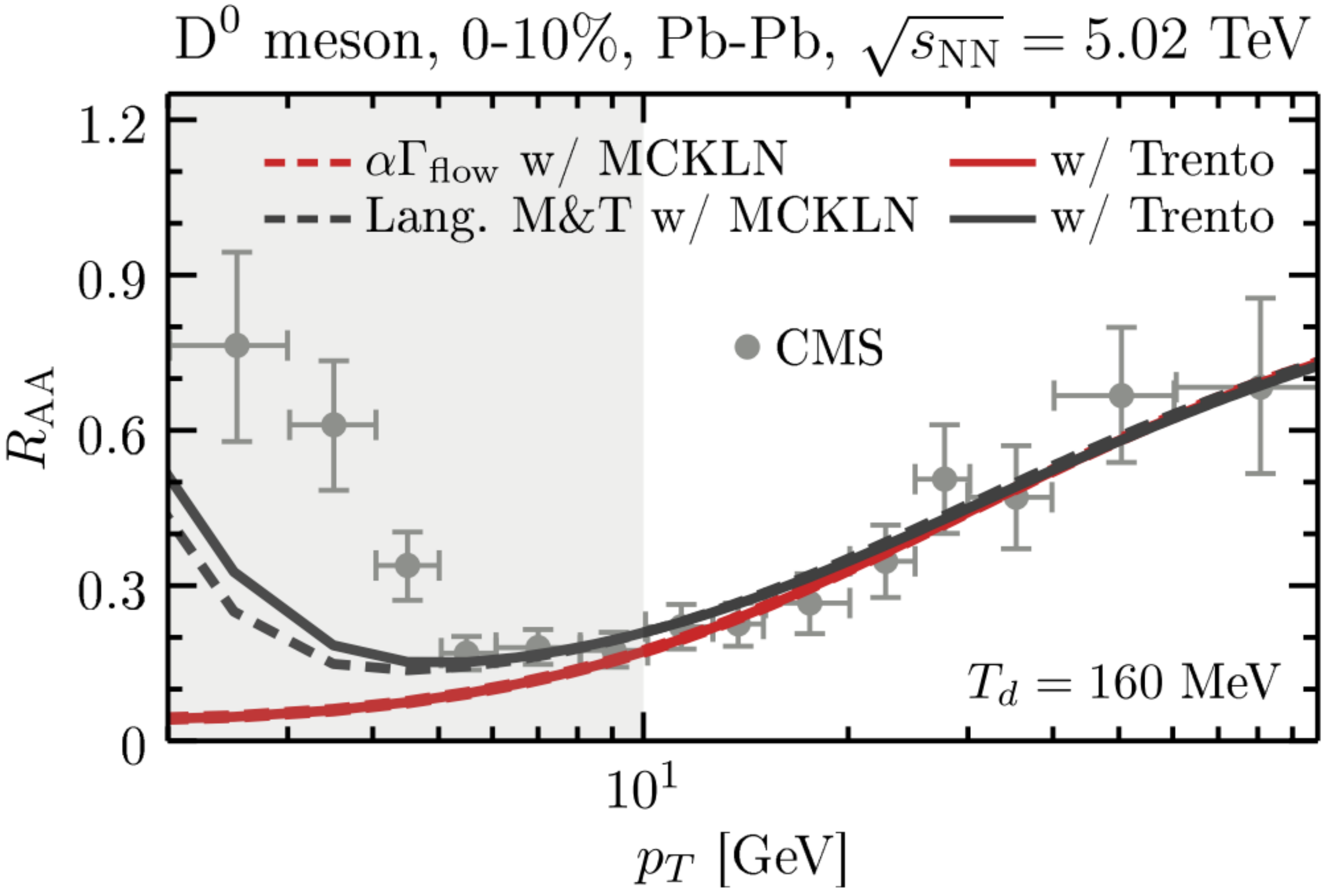
[2] Bilandzic et al, PRC83(2011)044913; PRC89(2014)no.6,064904

[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?

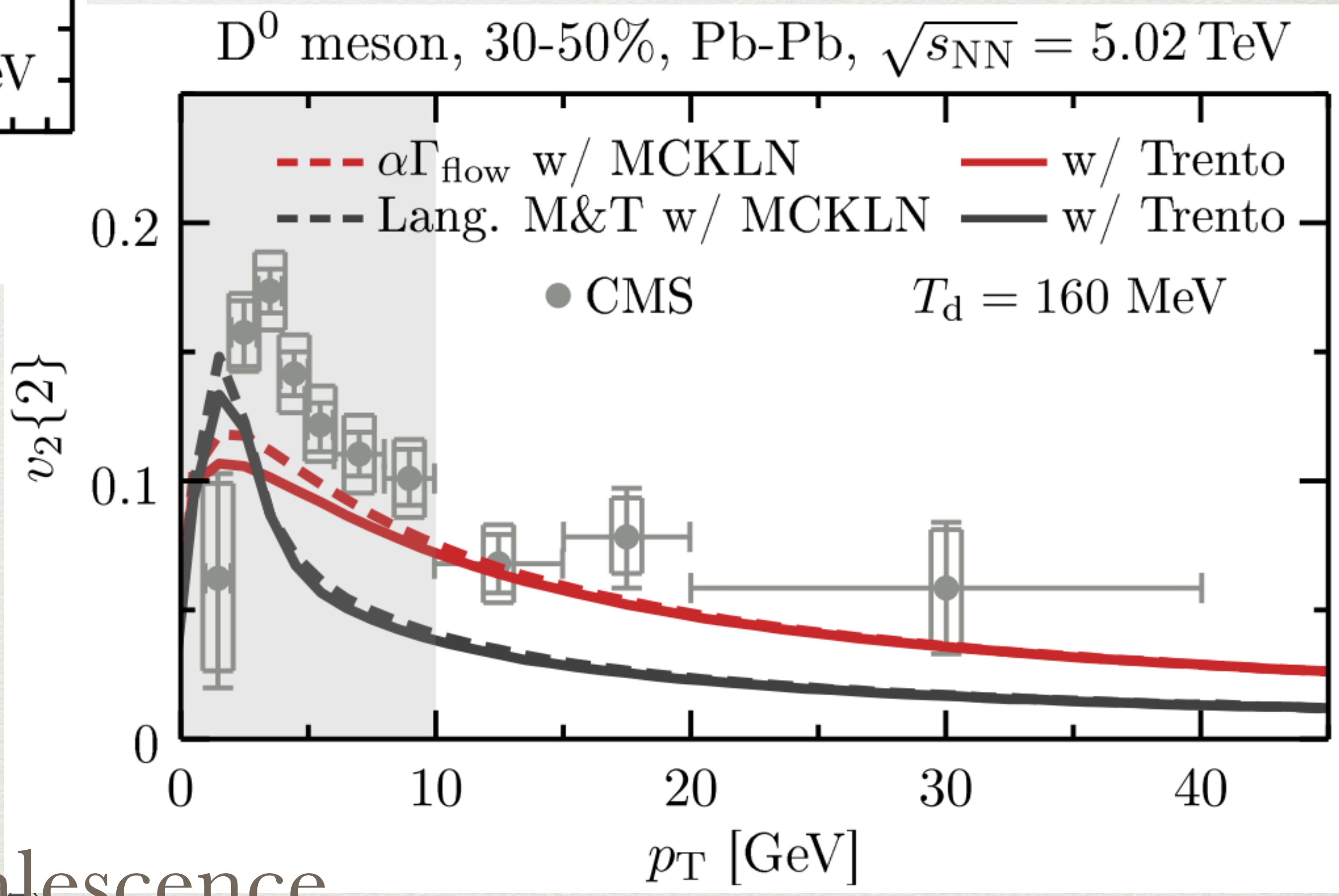
D MESONS*: MCKLN VS TRENTO



$v_2\{2\}$

Elliptical flow sensitive to initial conditions below

$p_T < 10\ GeV$



R_{AA}

Nuclear modification factor robust regardless of initial conditions

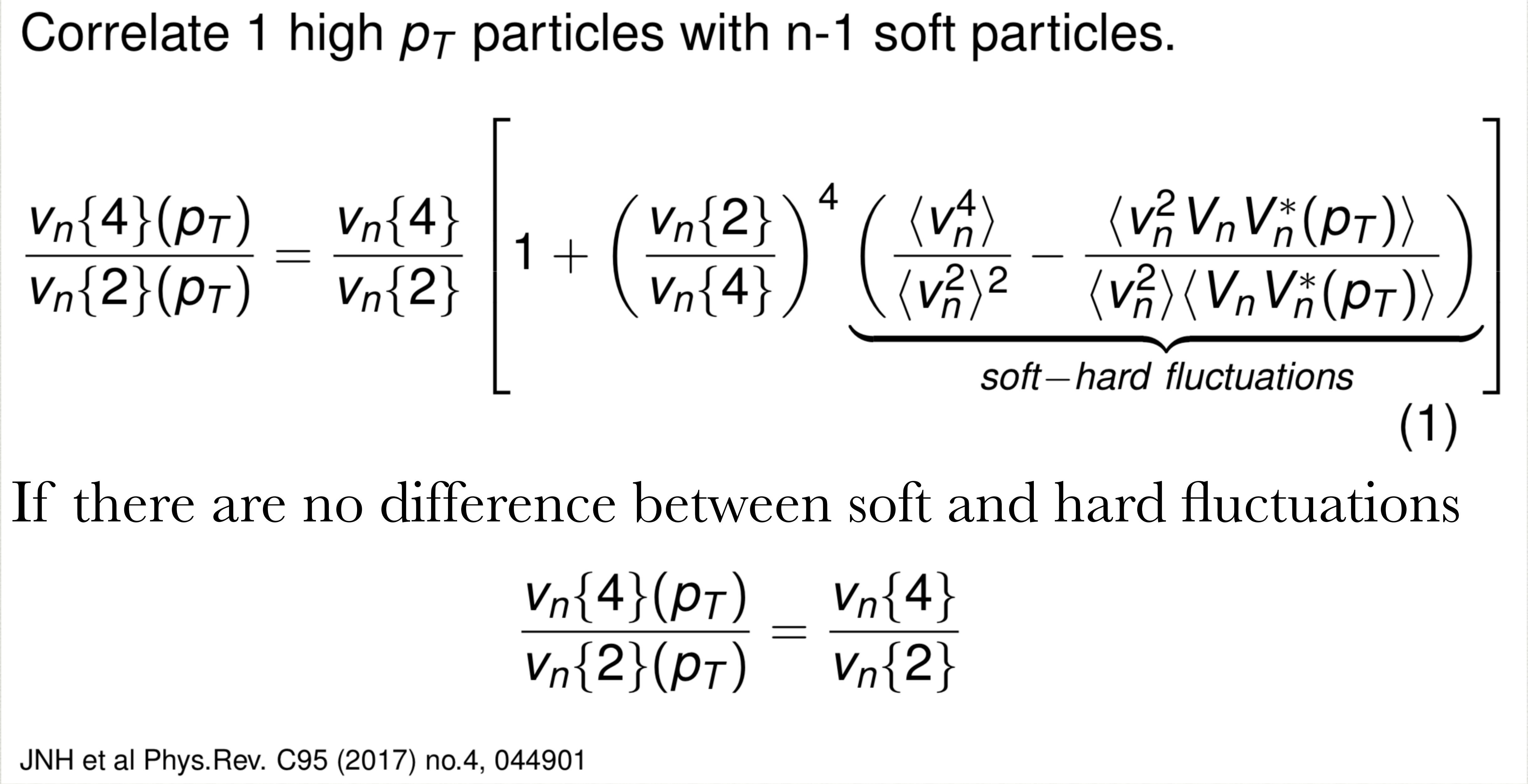
* no coalescence

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

Multi particle cumulants



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

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

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

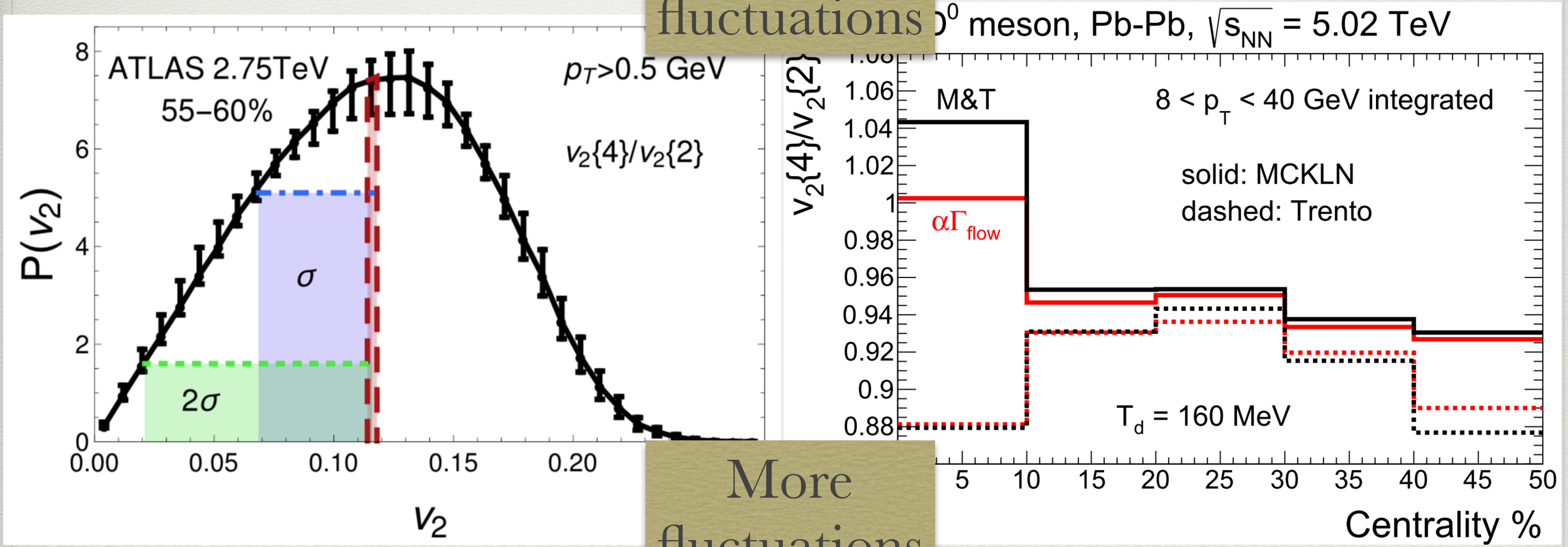
Soft sector: fluctuations in elliptical flow primarily drive by initial conditions

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

Heavy sector: still driven by initial conditions

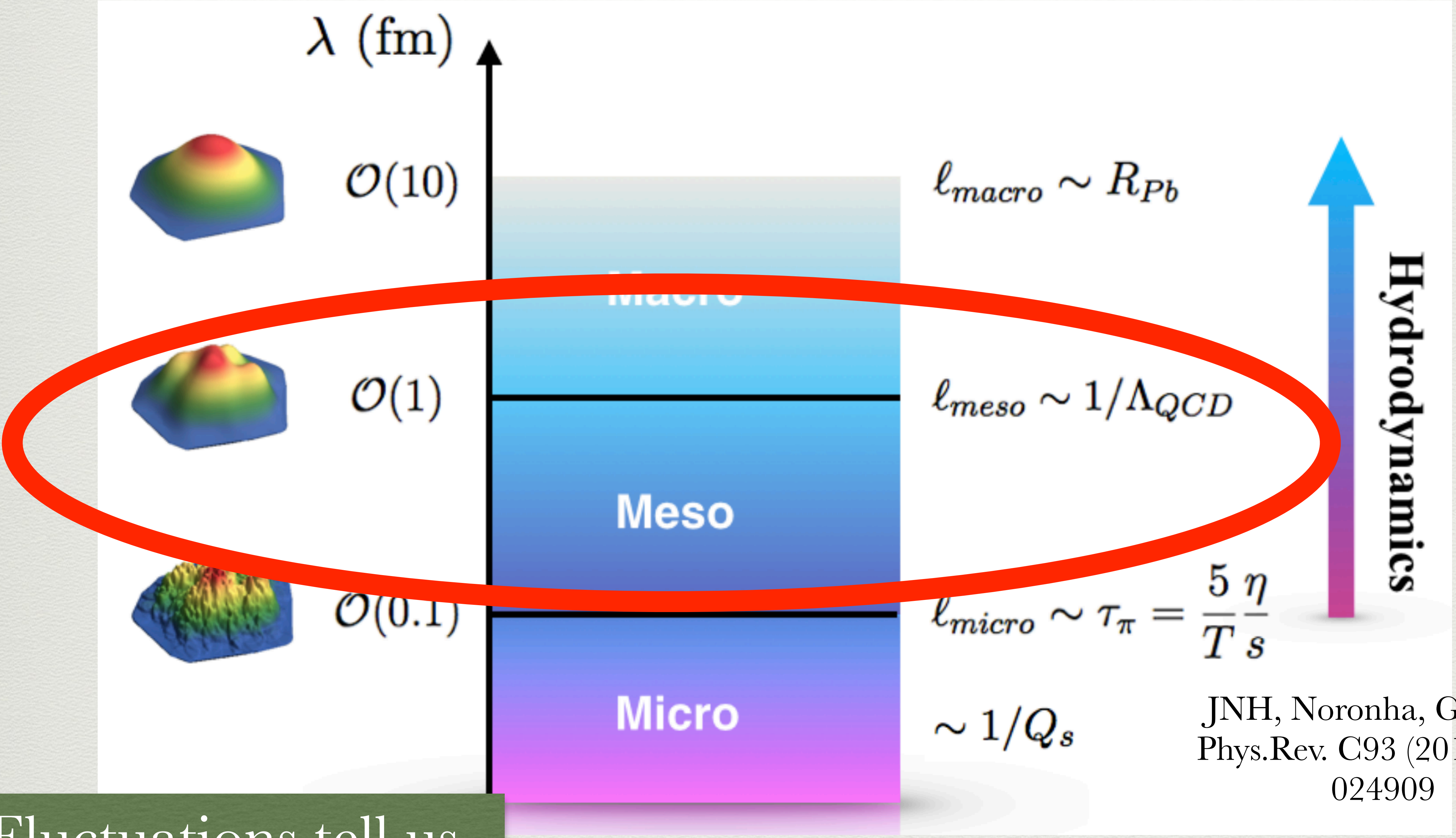
Very different behavior icted for central collisions

Less fluctuations



More fluctuations

Scales probed by initial conditions

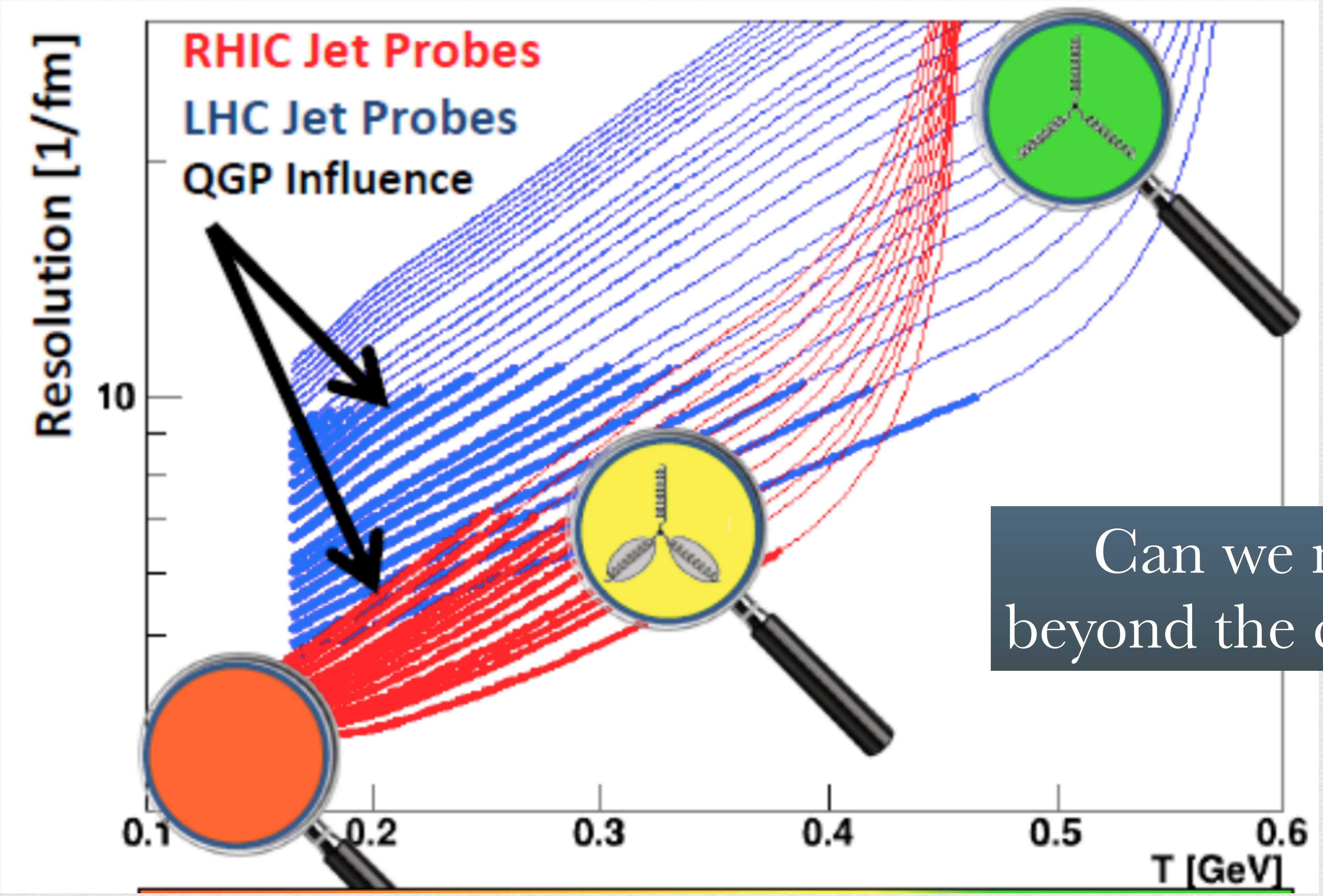


JNH, Noronha, Gyulassy
Phys.Rev. C93 (2016) no.2, 024909

Fluctuations tell us about the meso scale

Can we learn about Qsat?

Can we constrain small scale structure?



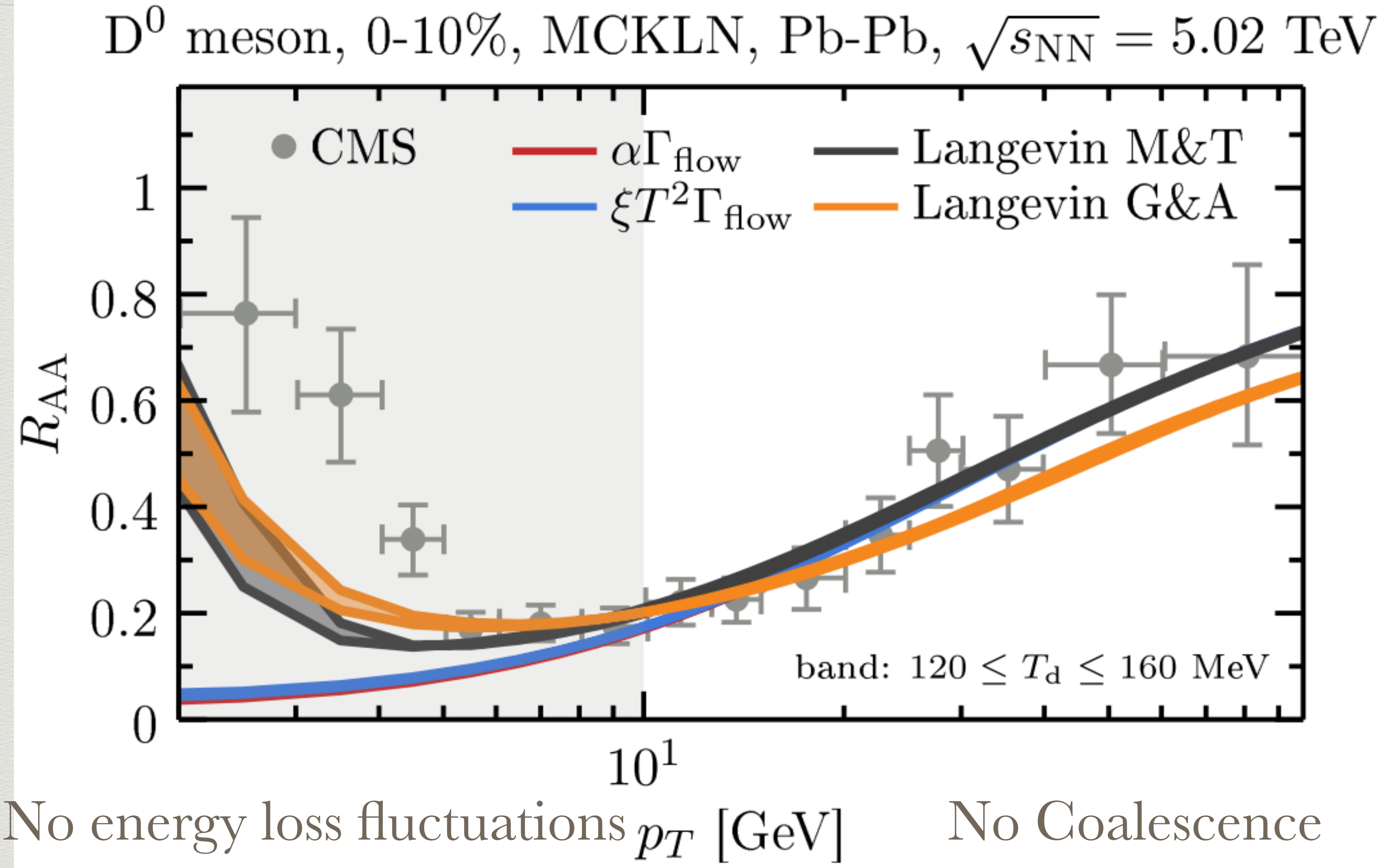
Can we move beyond the cartoon?

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?

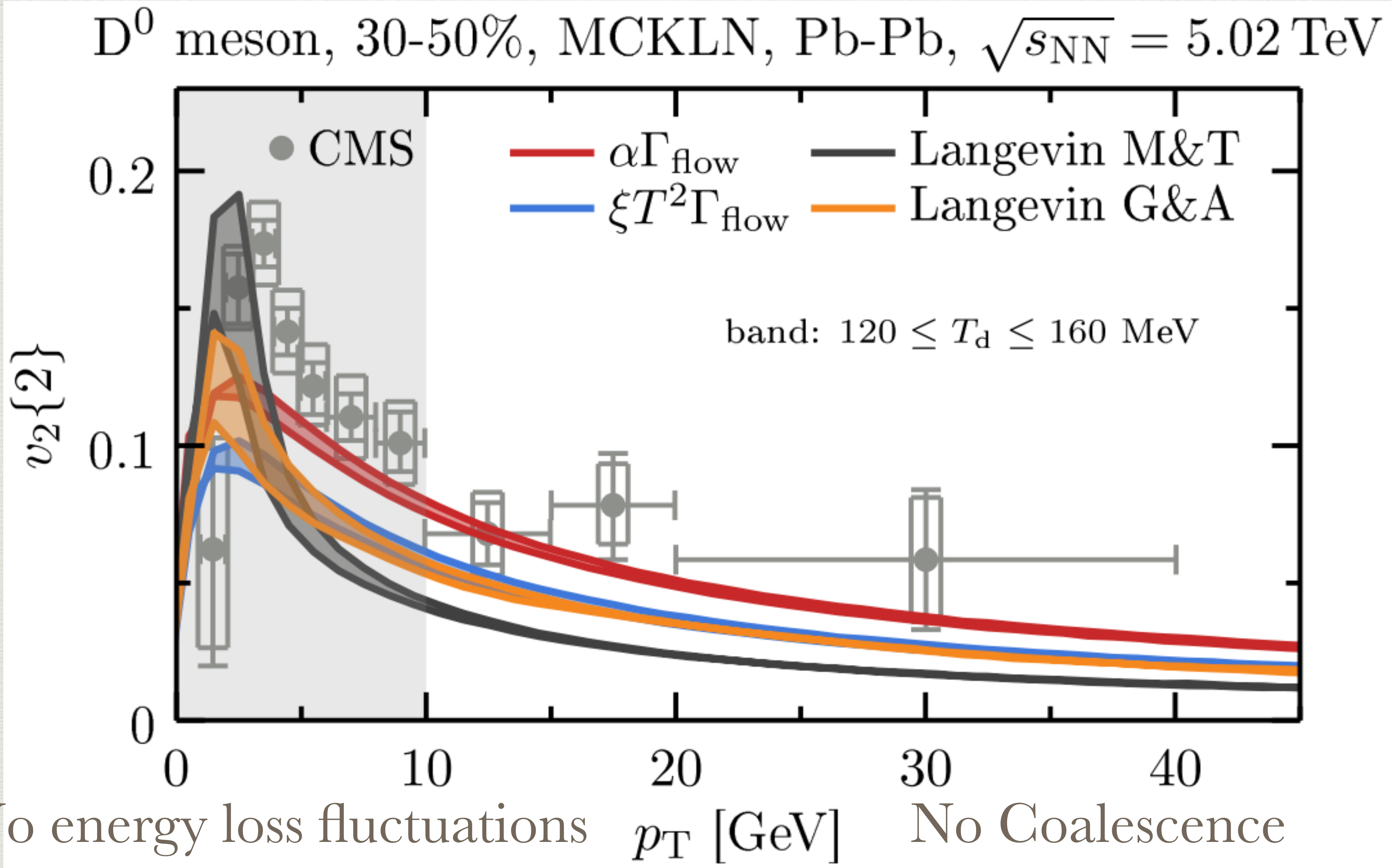
Energy loss vs. Langevin



No energy loss fluctuations

No Coalescence

Energy loss vs. Langevin



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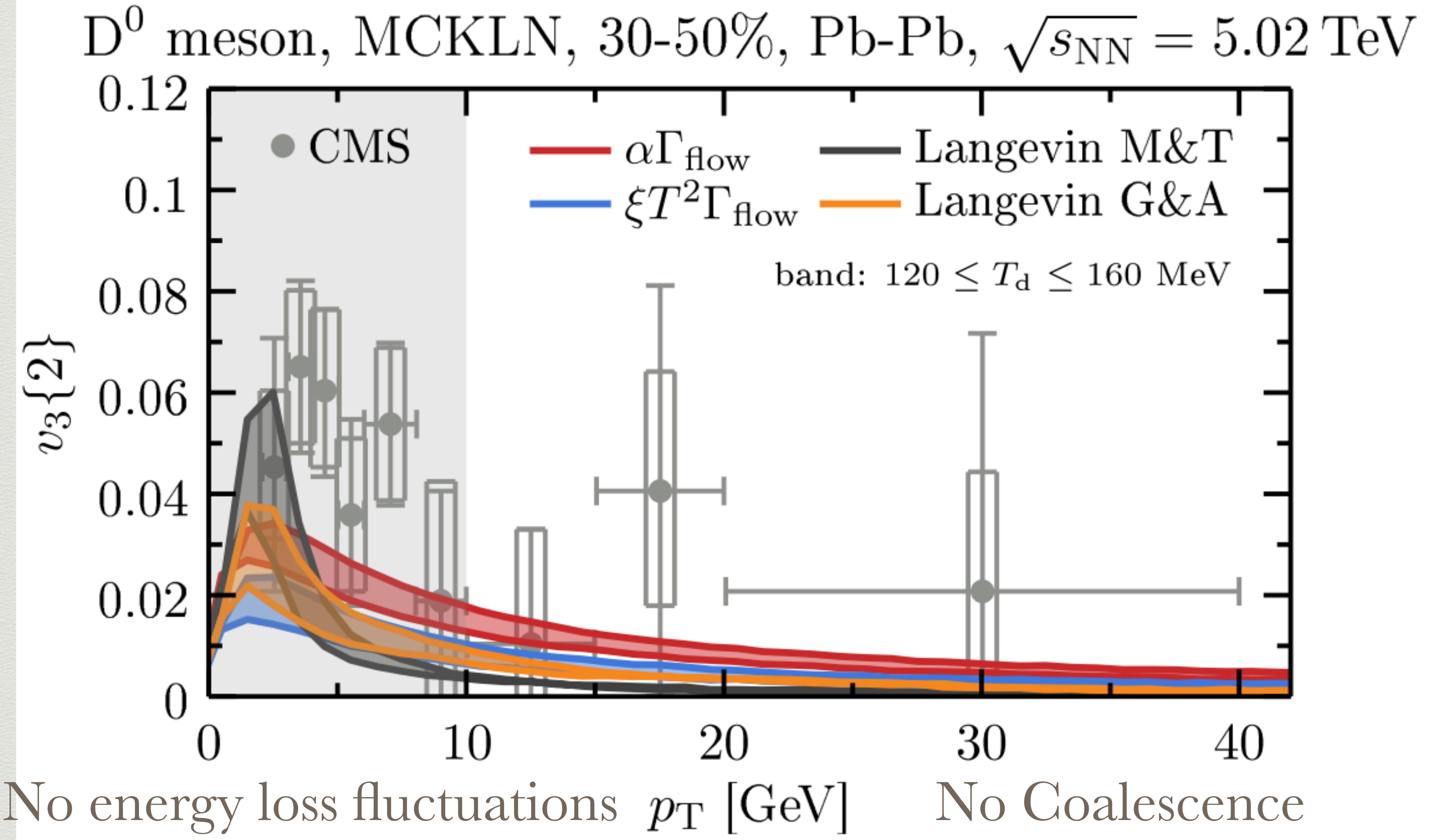
Energy loss vs. Langevin



No energy loss fluctuations

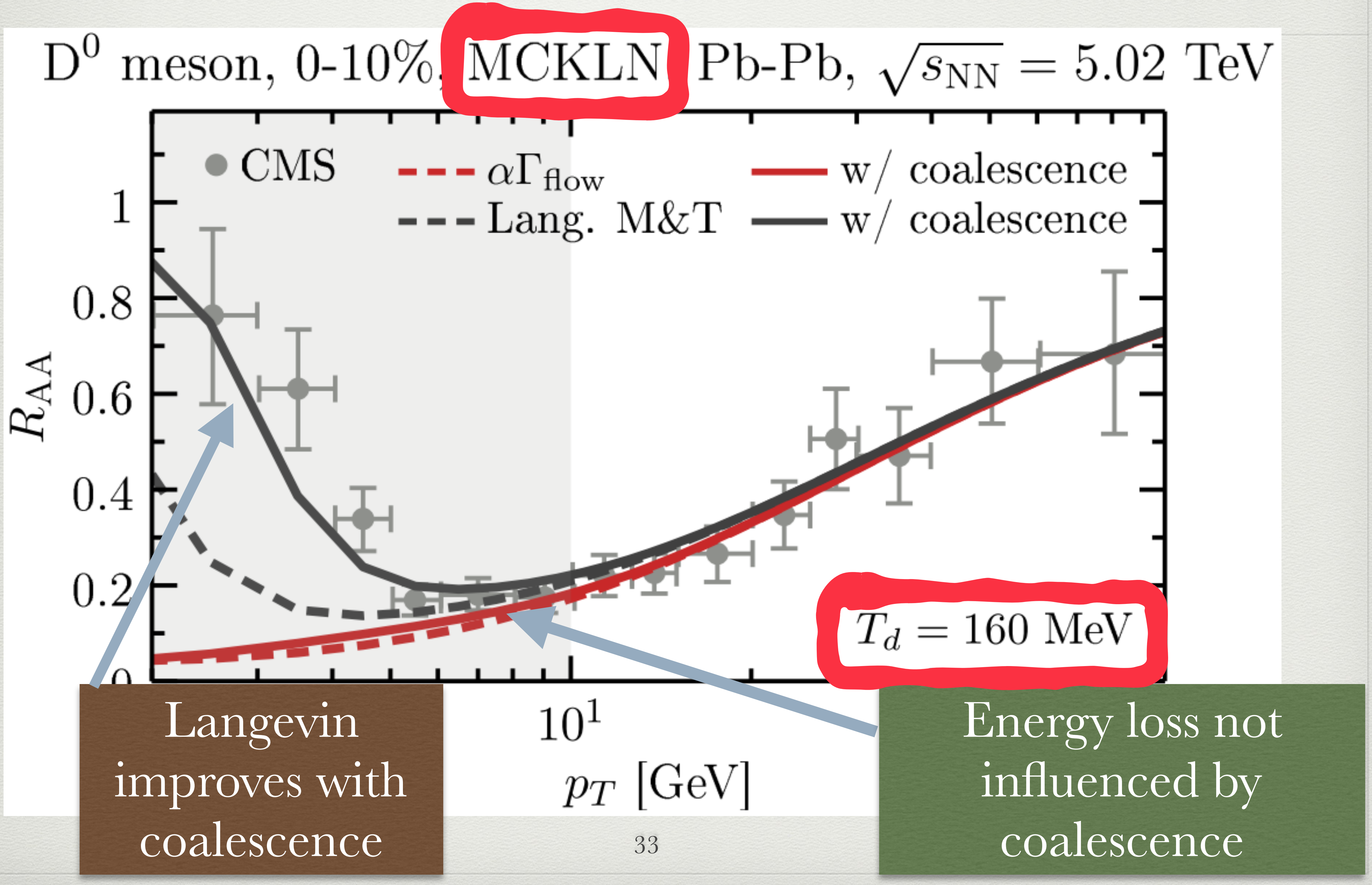
No Coalescence

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?

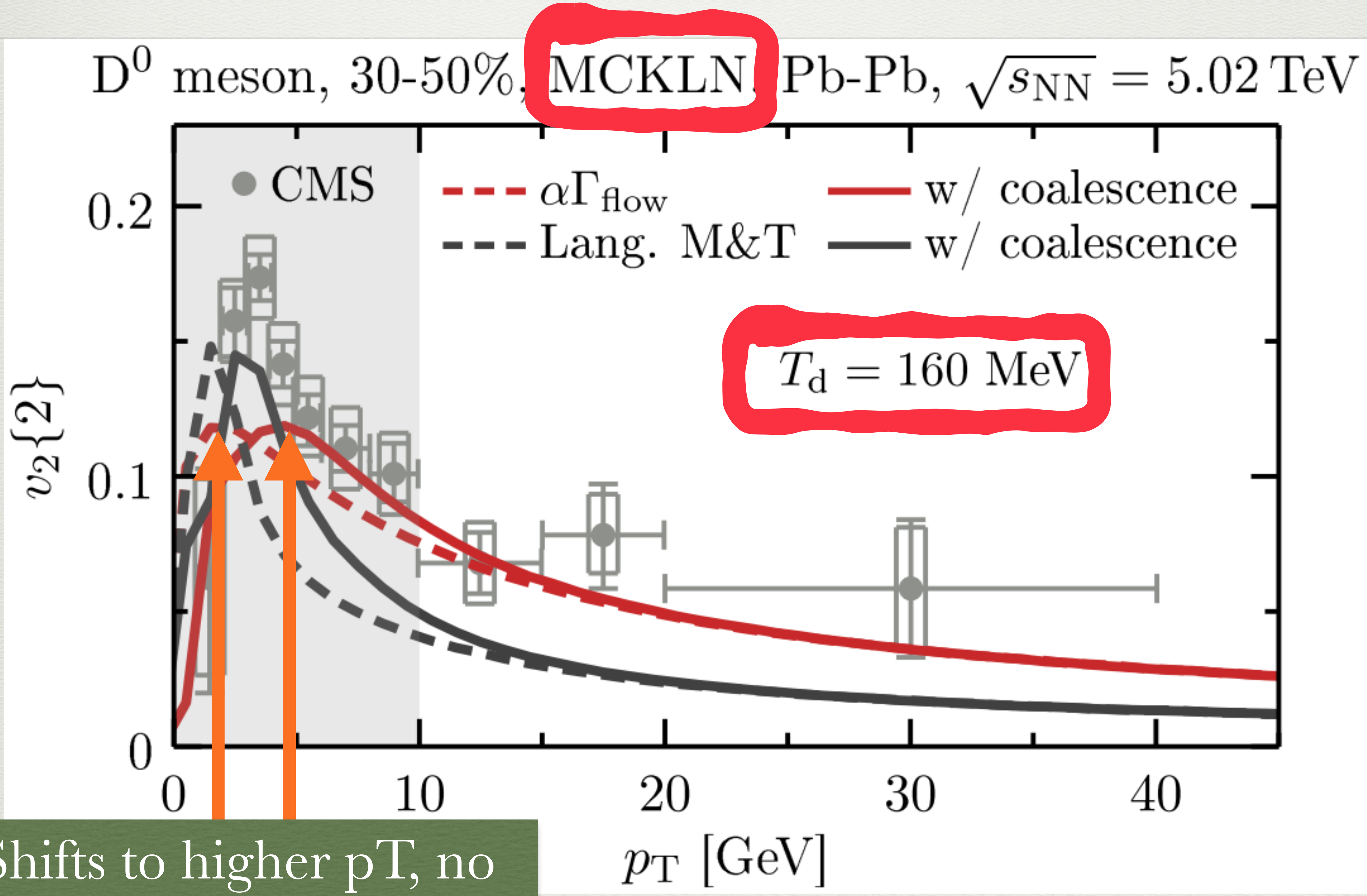
Influence of coalescence on R_{AA}



Langevin improves with coalescence

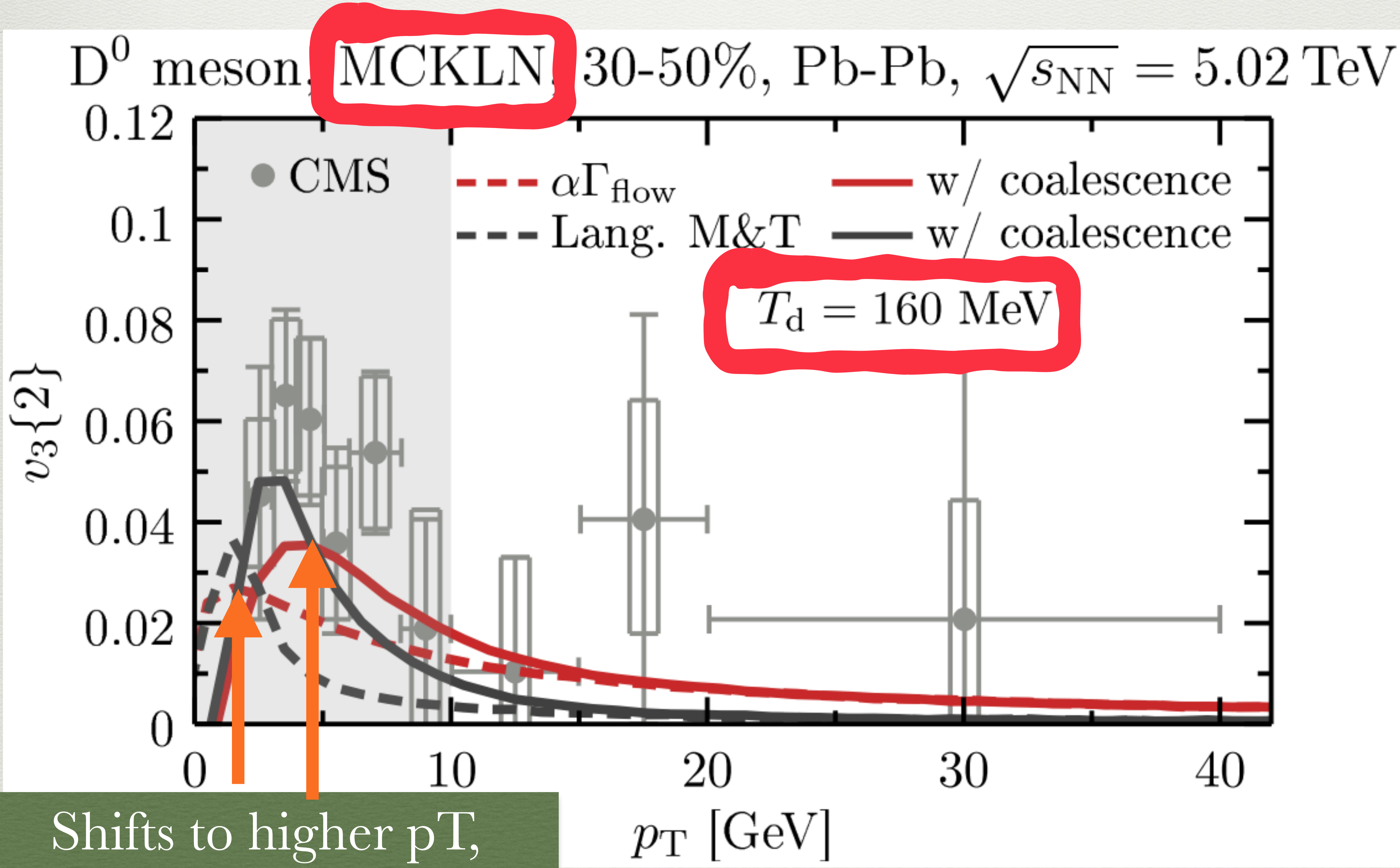
Energy loss not influenced by coalescence

Azimuthal anisotropies and coalescence



Shifts to higher pT, no change in magnitude

Azimuthal anisotropies and coalescence



Shifts to higher pT, 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

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

SYSTEM SIZE

PROPOSAL FOR COLLISIONS

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

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

Hydro already worked well with XeXe collisions

Giacalone, JNH, Phys.Rev. C97 (2018) no.3, 03

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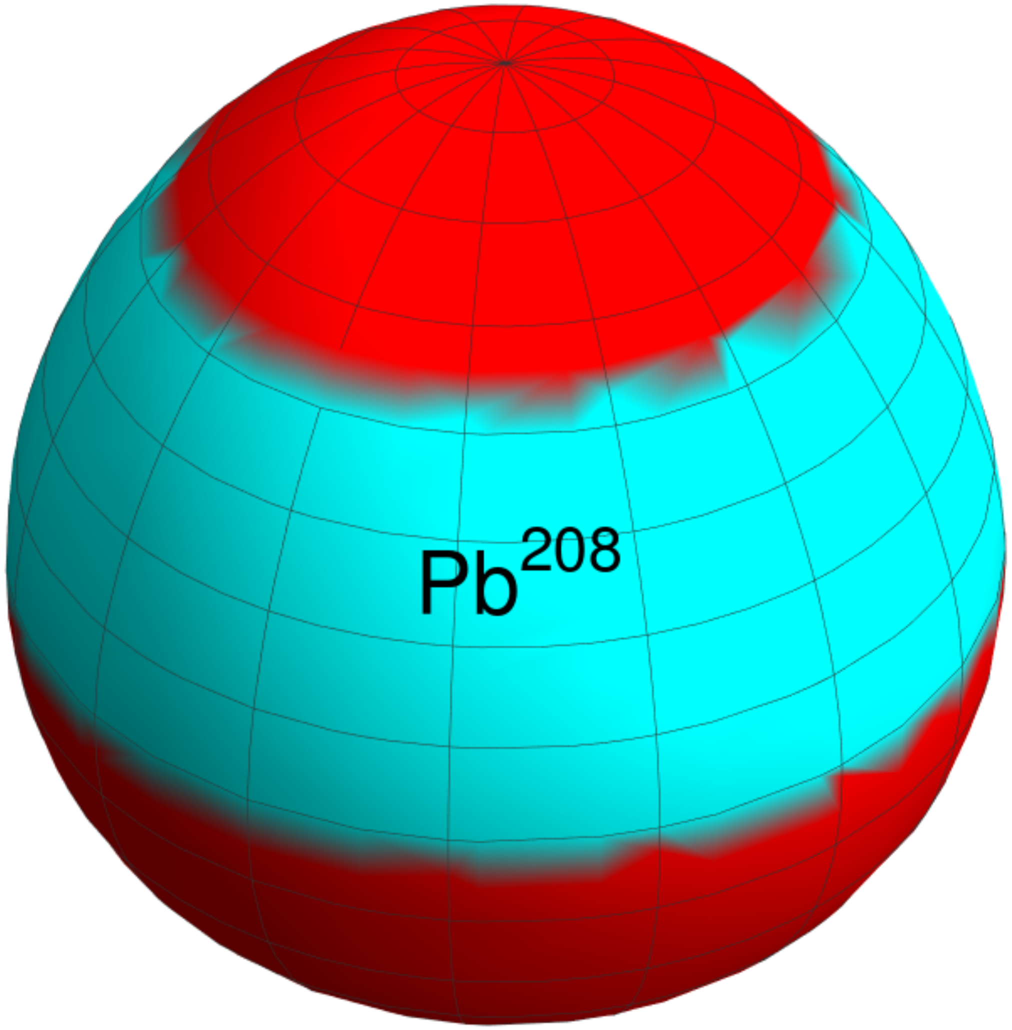
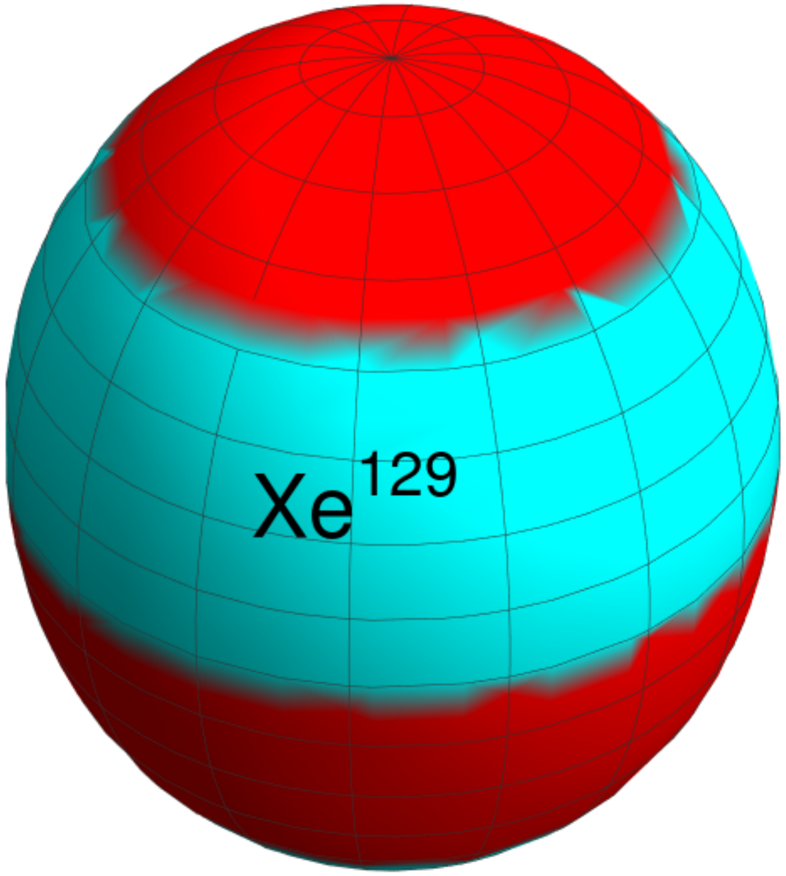
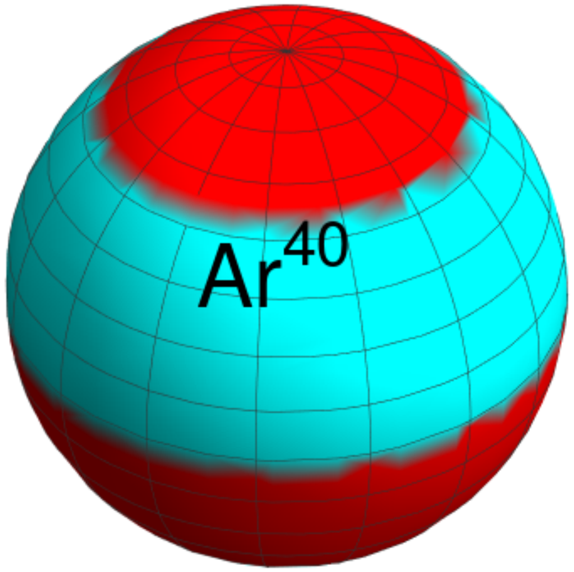
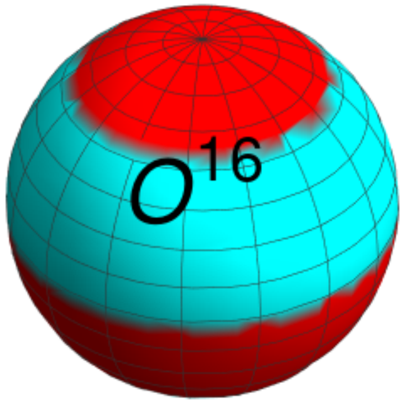


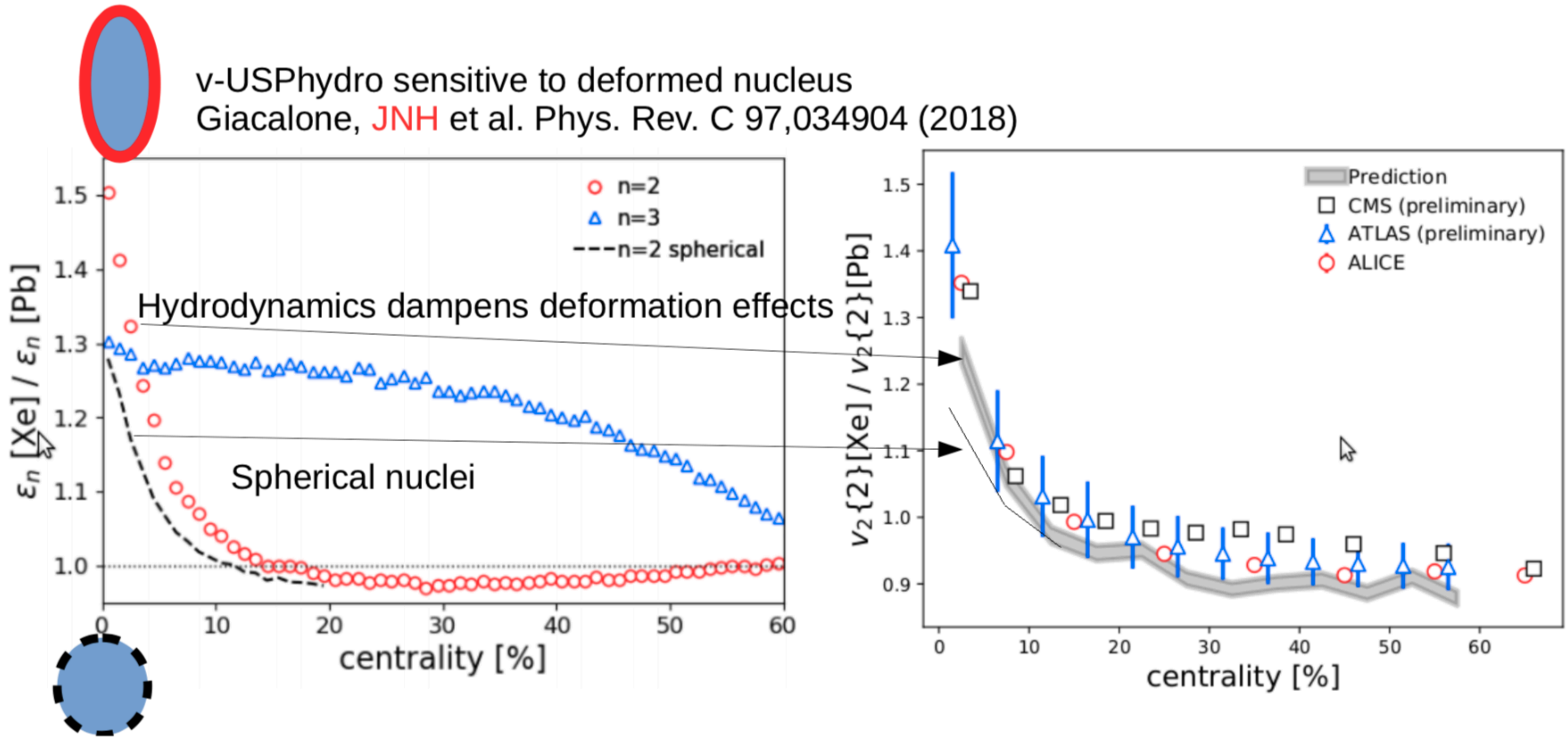


LHC system size scan





XE DEFORMATION MEASURED



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

Hydrodynamics dampens deformation effects

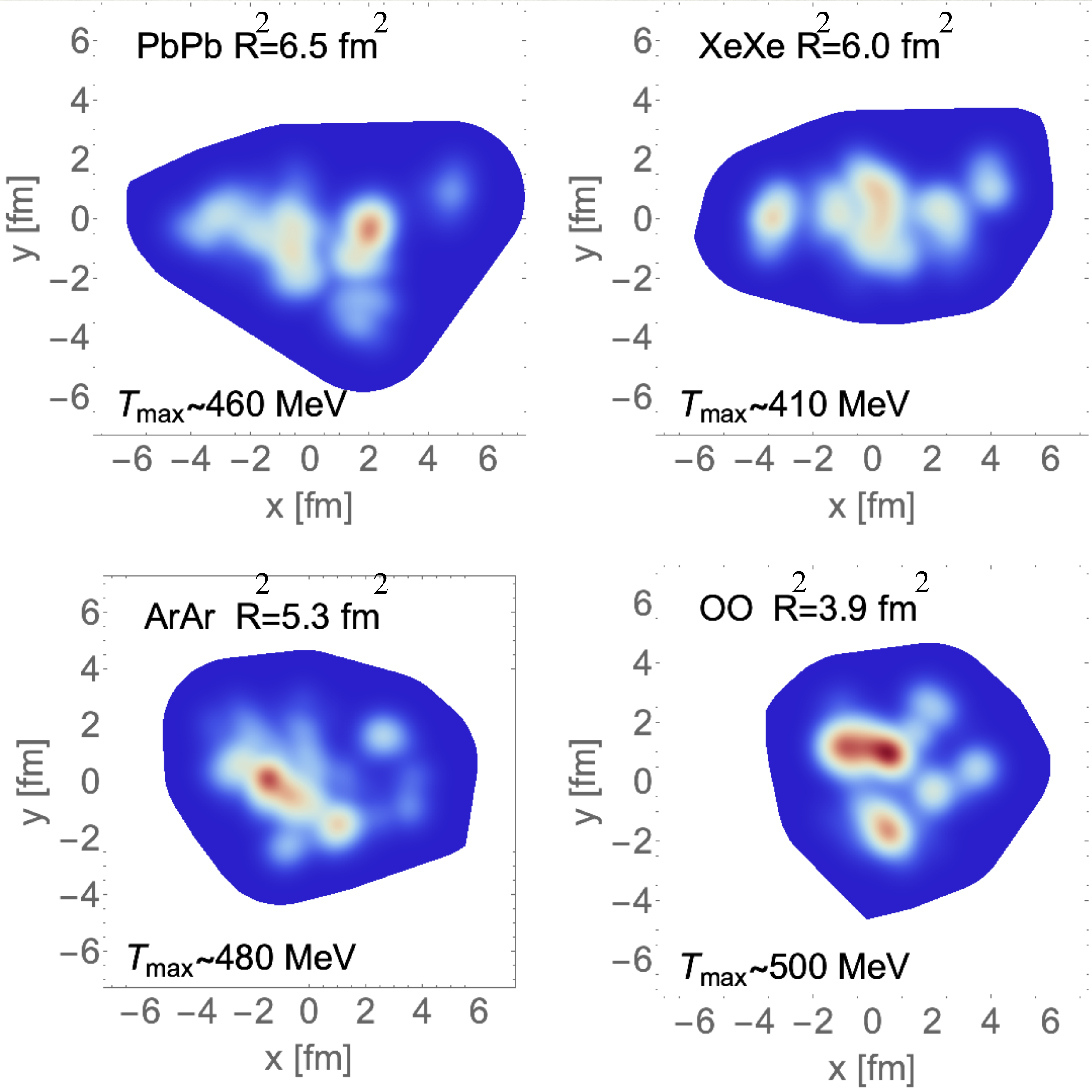
Spherical nuclei

TYPICAL EVENTS

PbPb and XeXe events larger, more elliptical.

ArAr and OO smaller and rounder.

Small systems are hotter

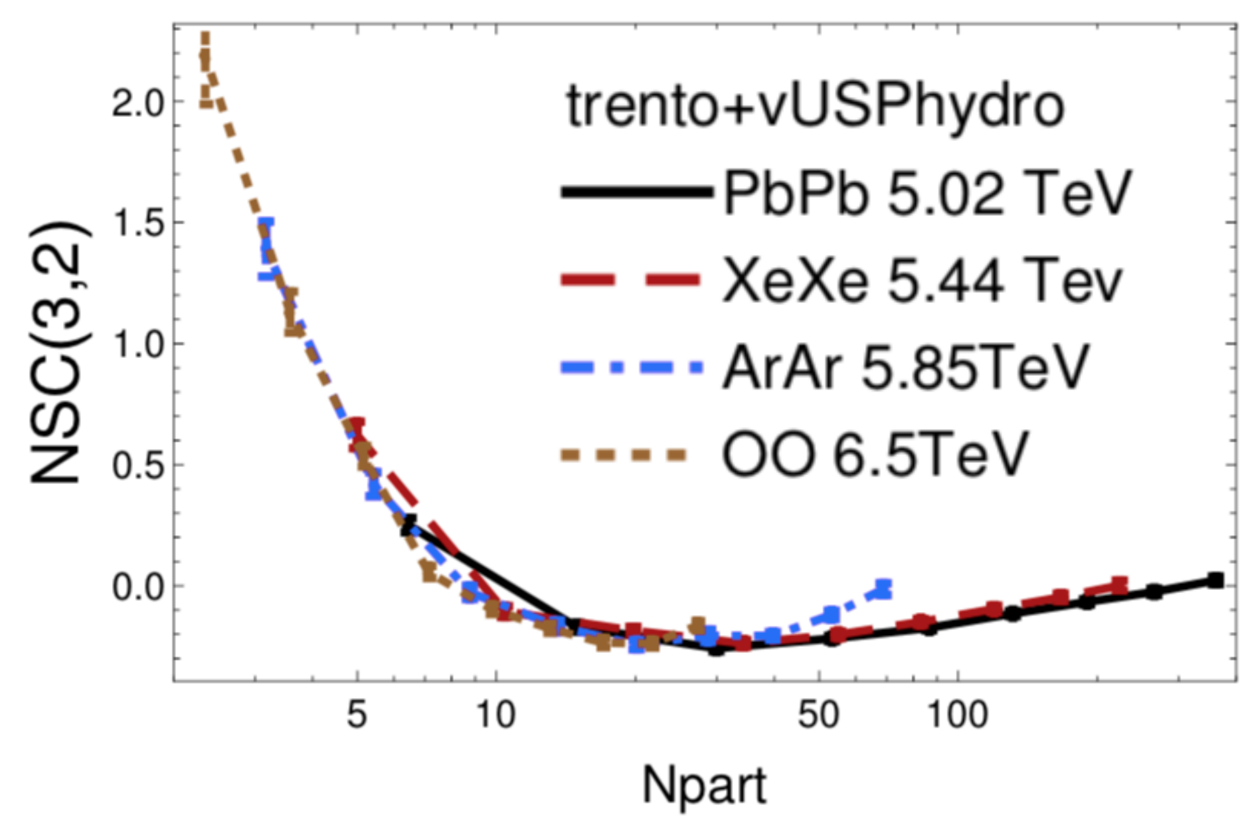


Sievert, JNH, arXiv:1901.01319

SOFT SECTOR: UNIVERSAL SCALING VS. HIERARCHY

Sievert, JNH, arXiv:1901.01319

Universal Scaling

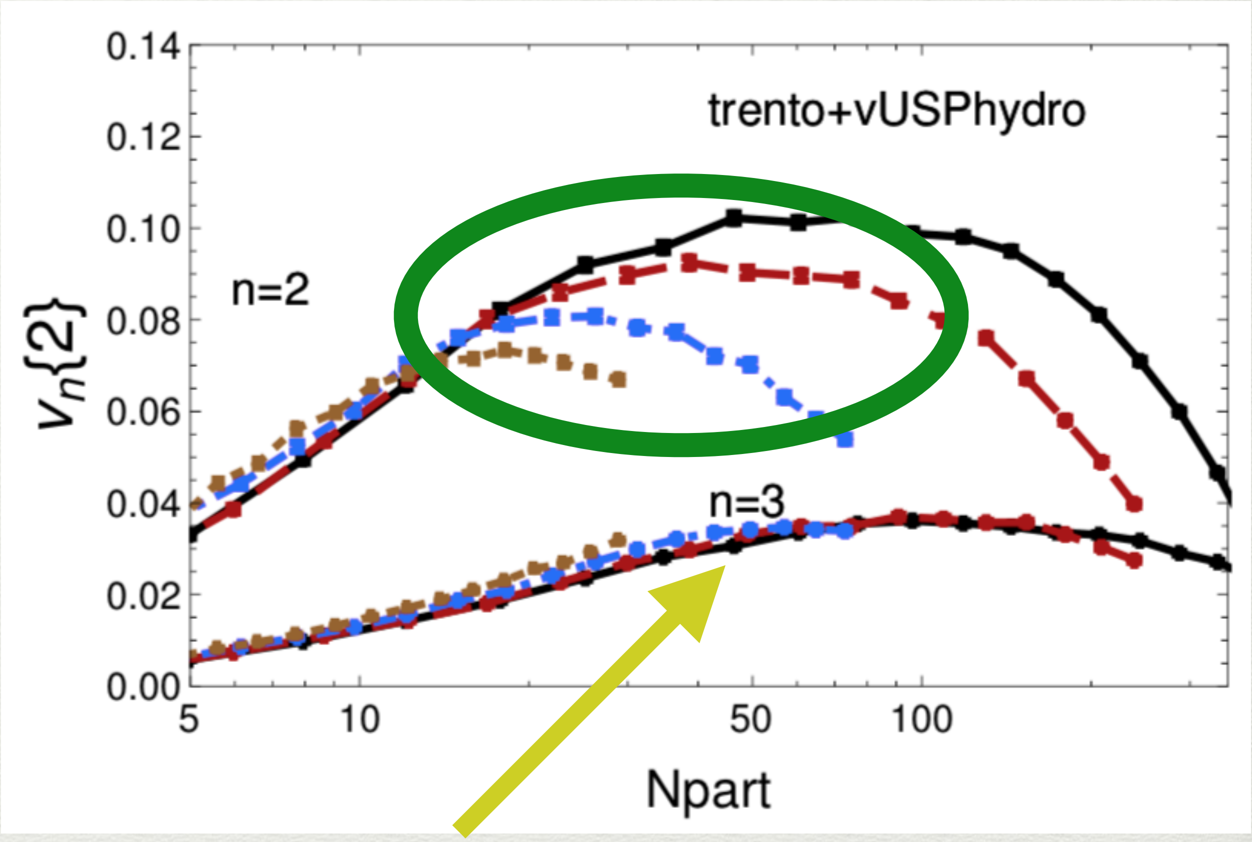


$v_3\{2\}$

$NSC(m,n)$

$$\frac{v_3\{4\}}{v_3\{2\}}$$

Size Hierarchy



$\langle p_T \rangle$

$v_2\{2\}$

Event plane correlations

$$\frac{v_2\{4\}}{v_2\{2\}}$$

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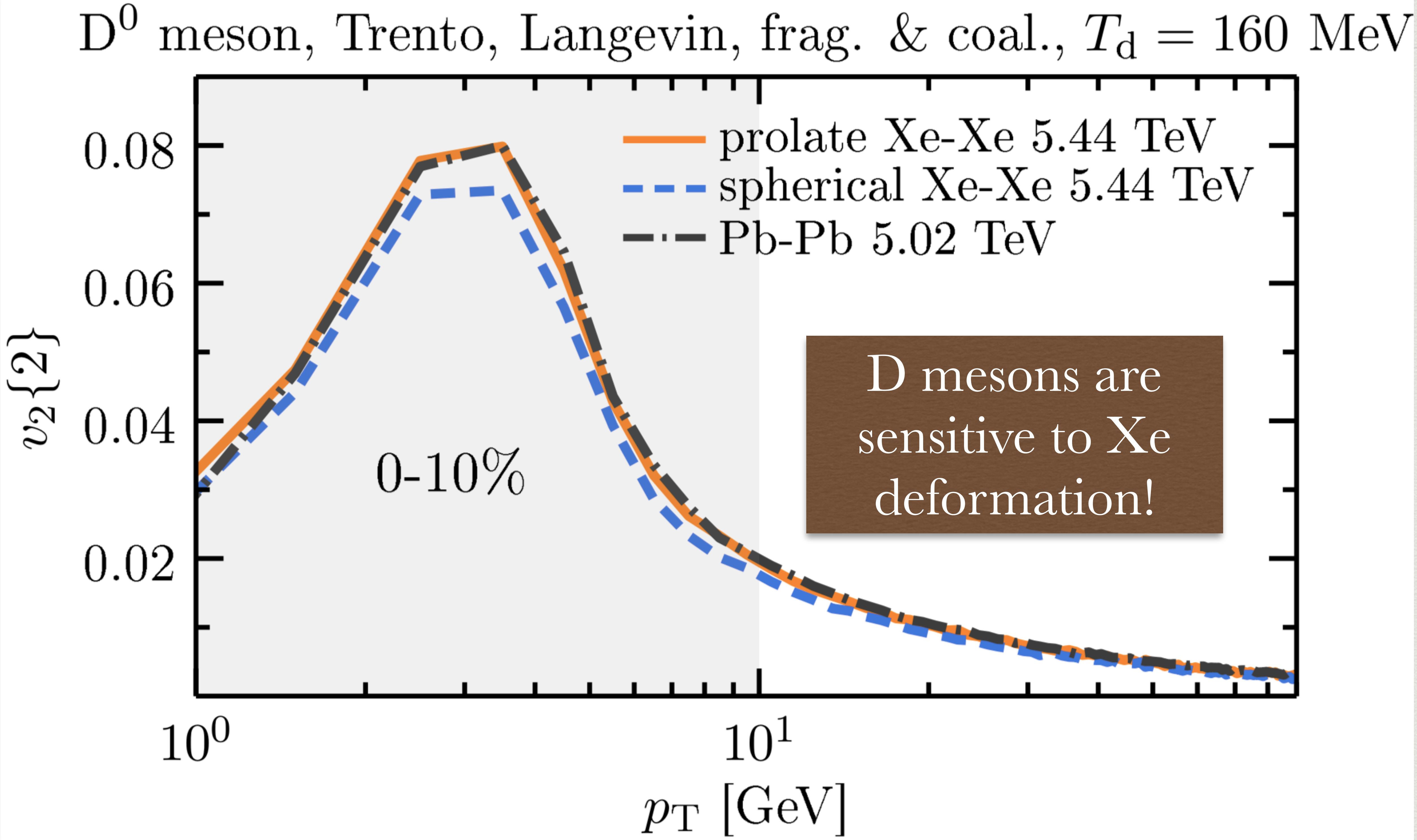
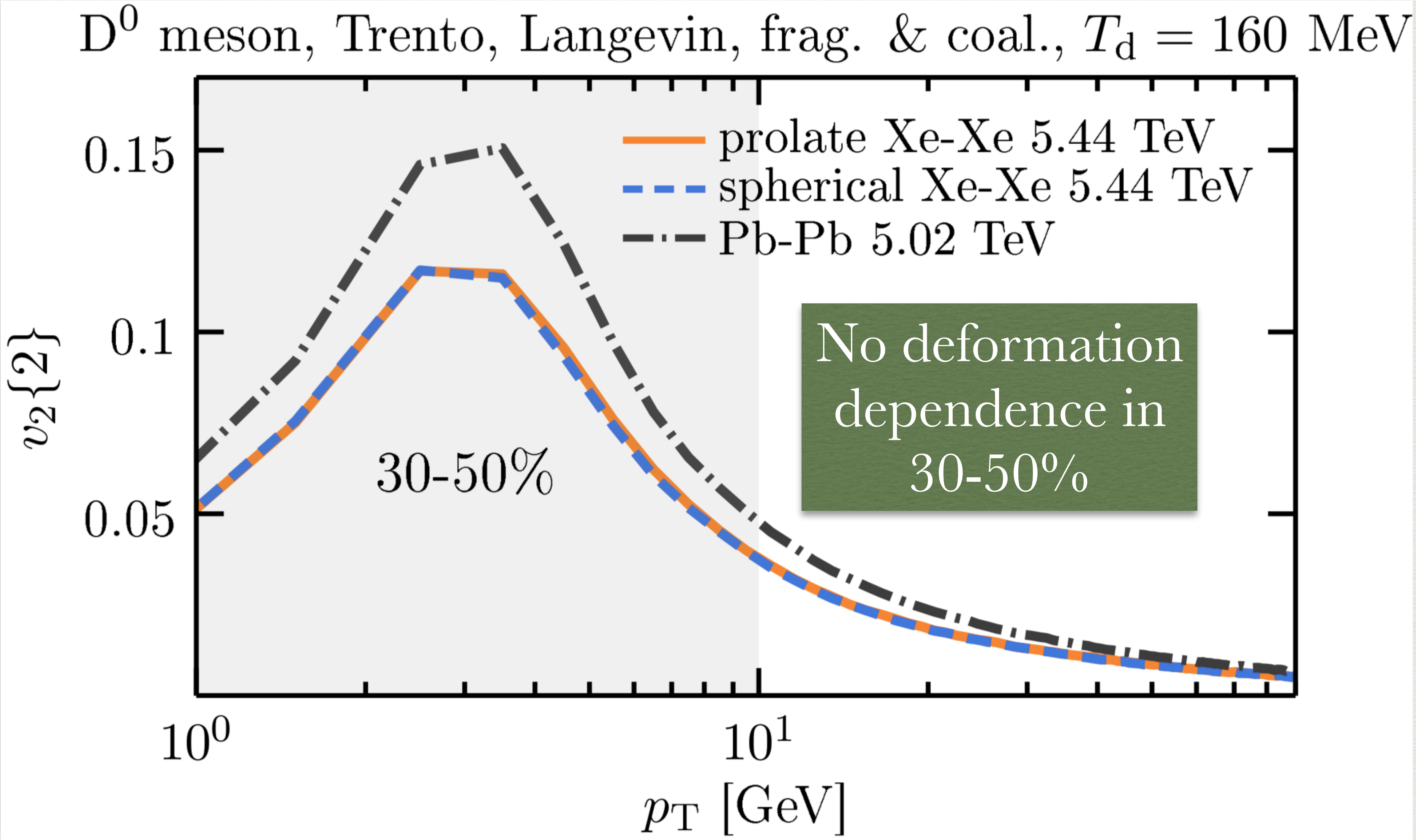
Comparing are best fit PbPb to XeXe collisions

D mesons in XeXe collisions



D mesons are sensitive to Xe deformation!

D meson v2 suppressed in "small" system

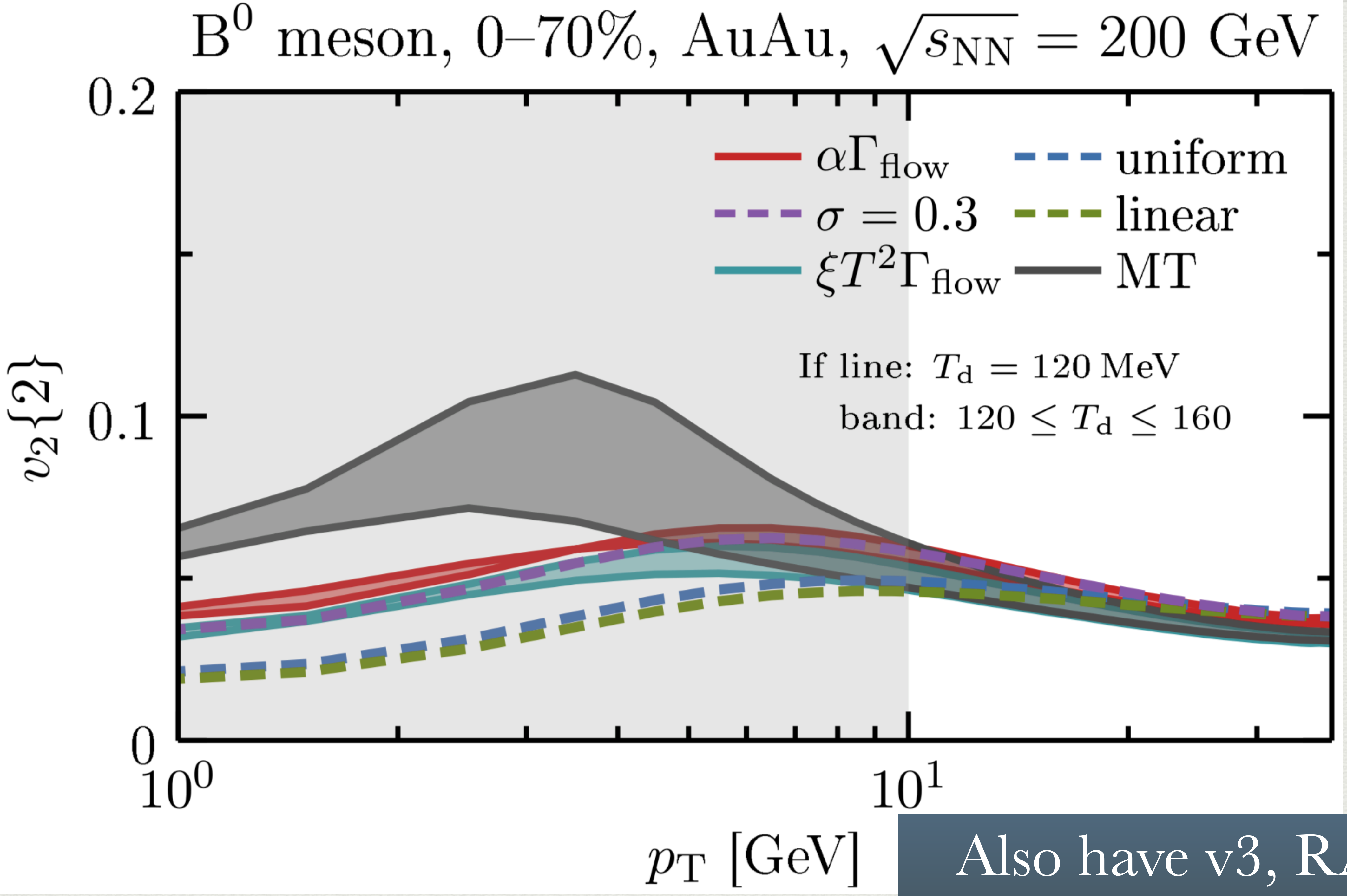


No deformation dependence in 30-50%

RHIC

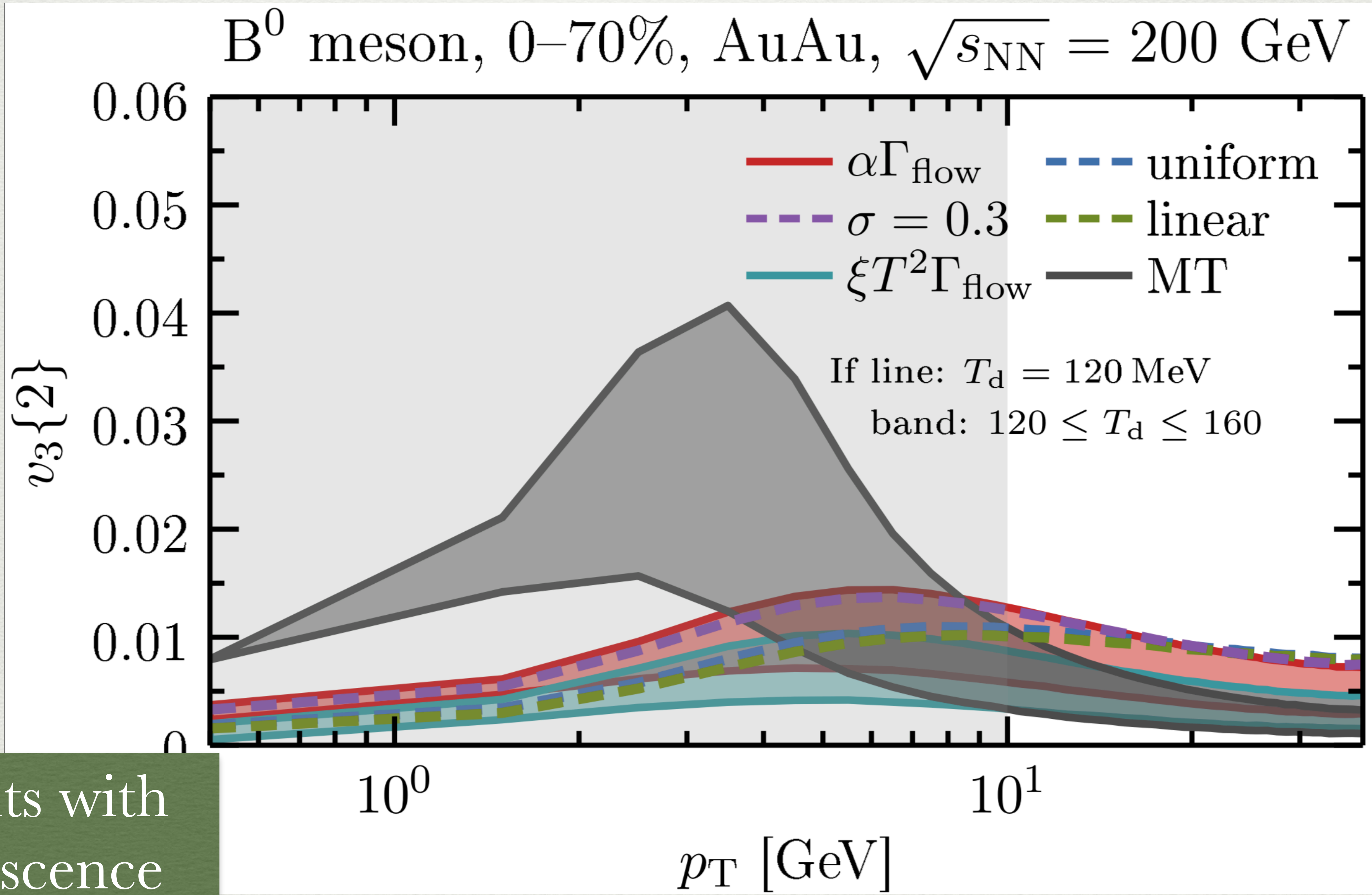
See Xin Dong (STAR/sPHENIX) and Kazuya Nagashima’s (PHENIX) talks on Monday

sPHENIX predictions (B v2{2})



Also have v3, RAA, muons, and electrons

sPHENIX predictions (B v3{2})



Results with coalescence coming soon

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 to XeXe collisions:
    - D mesons sensitive to deformed nucleus
    - v2 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.

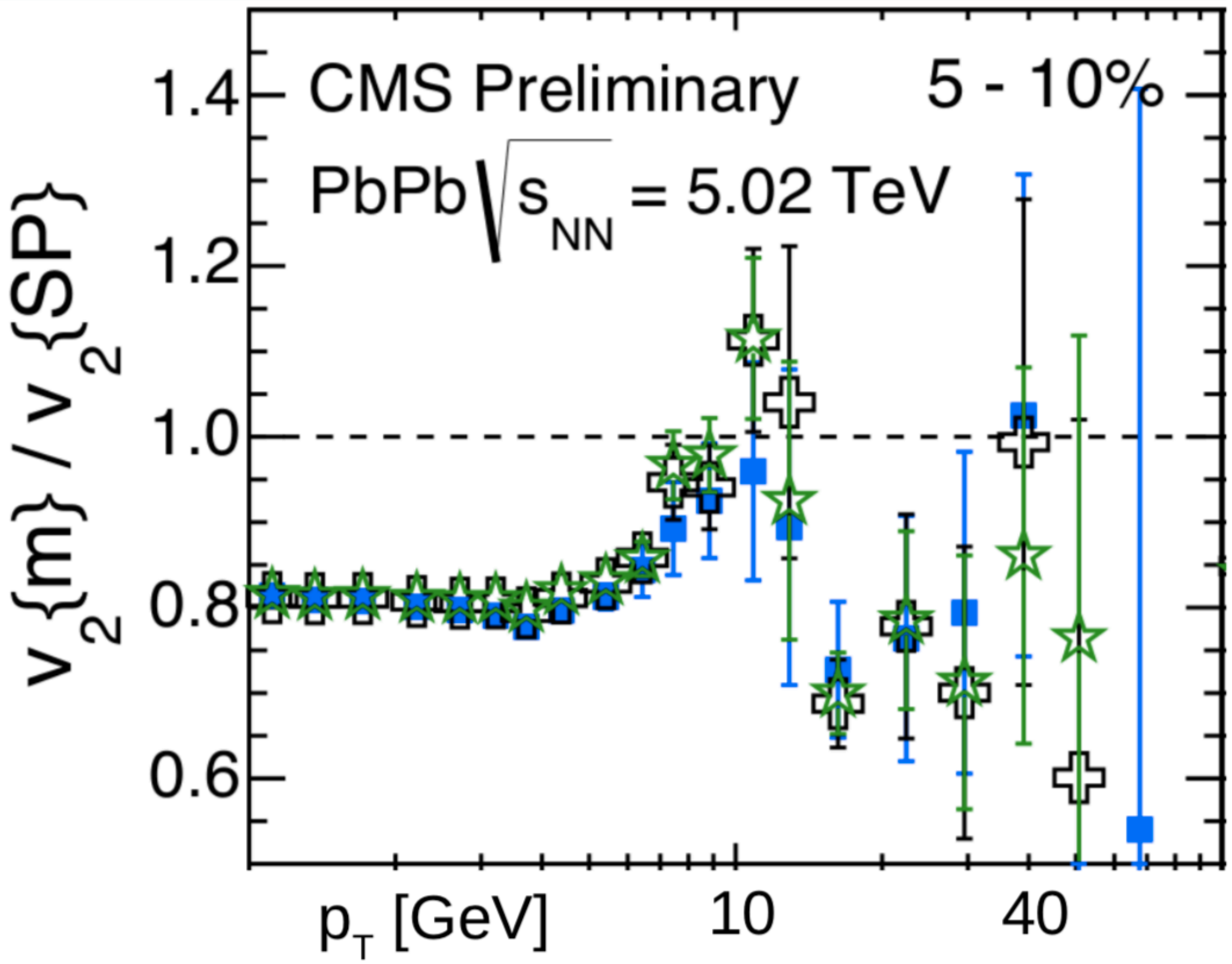
BACKUP

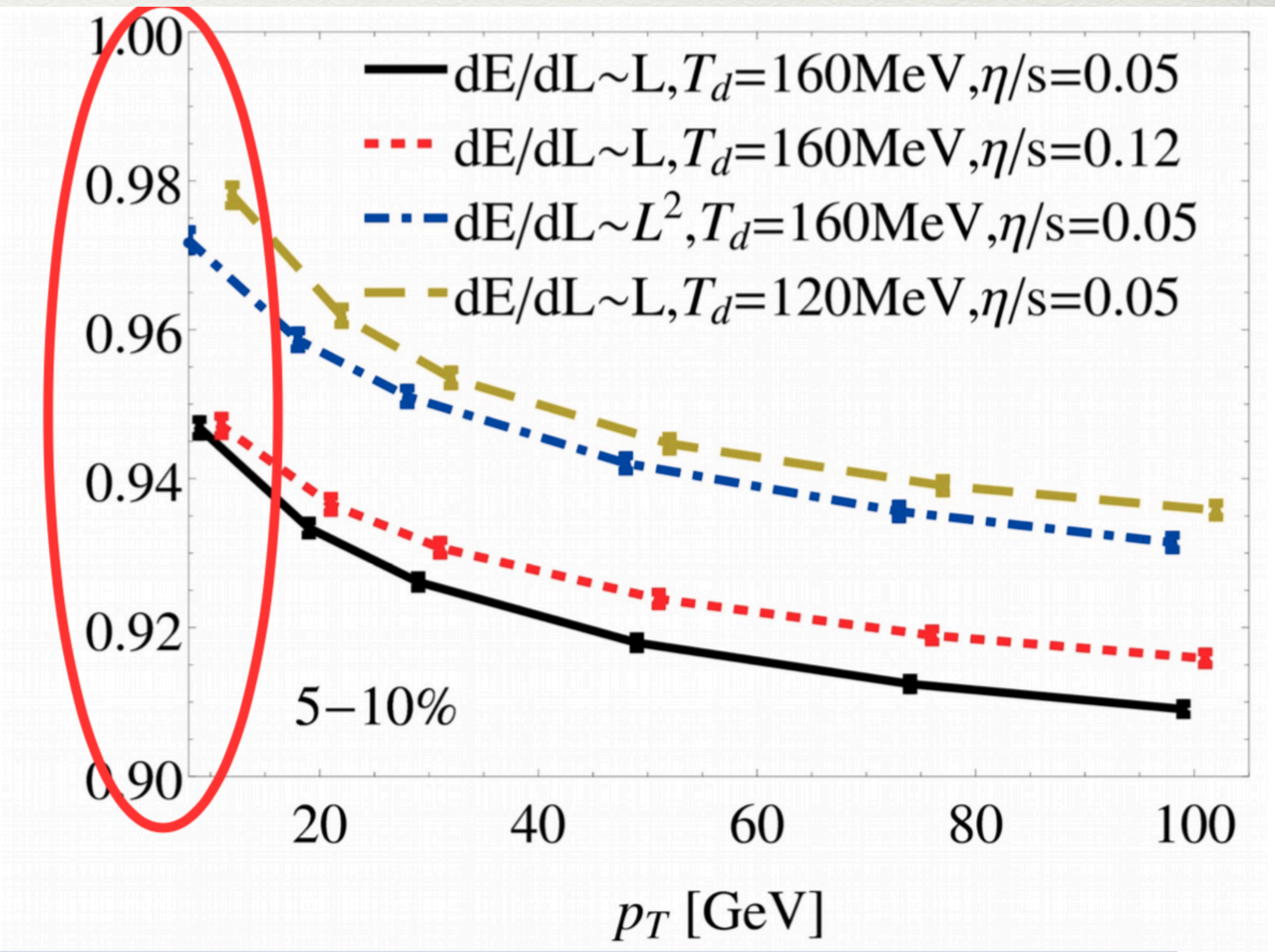
Fragmentation & Coalescence

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

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

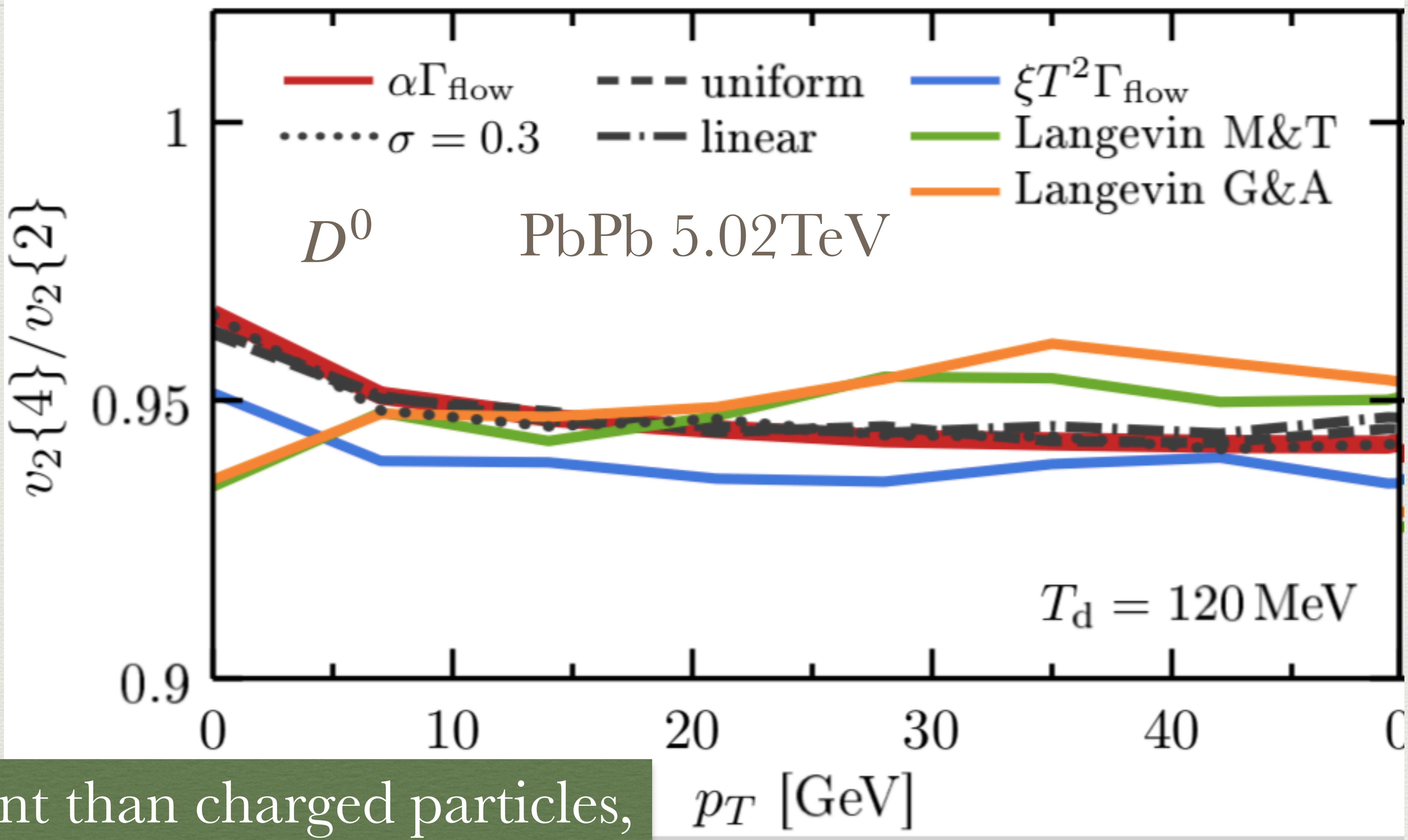
-





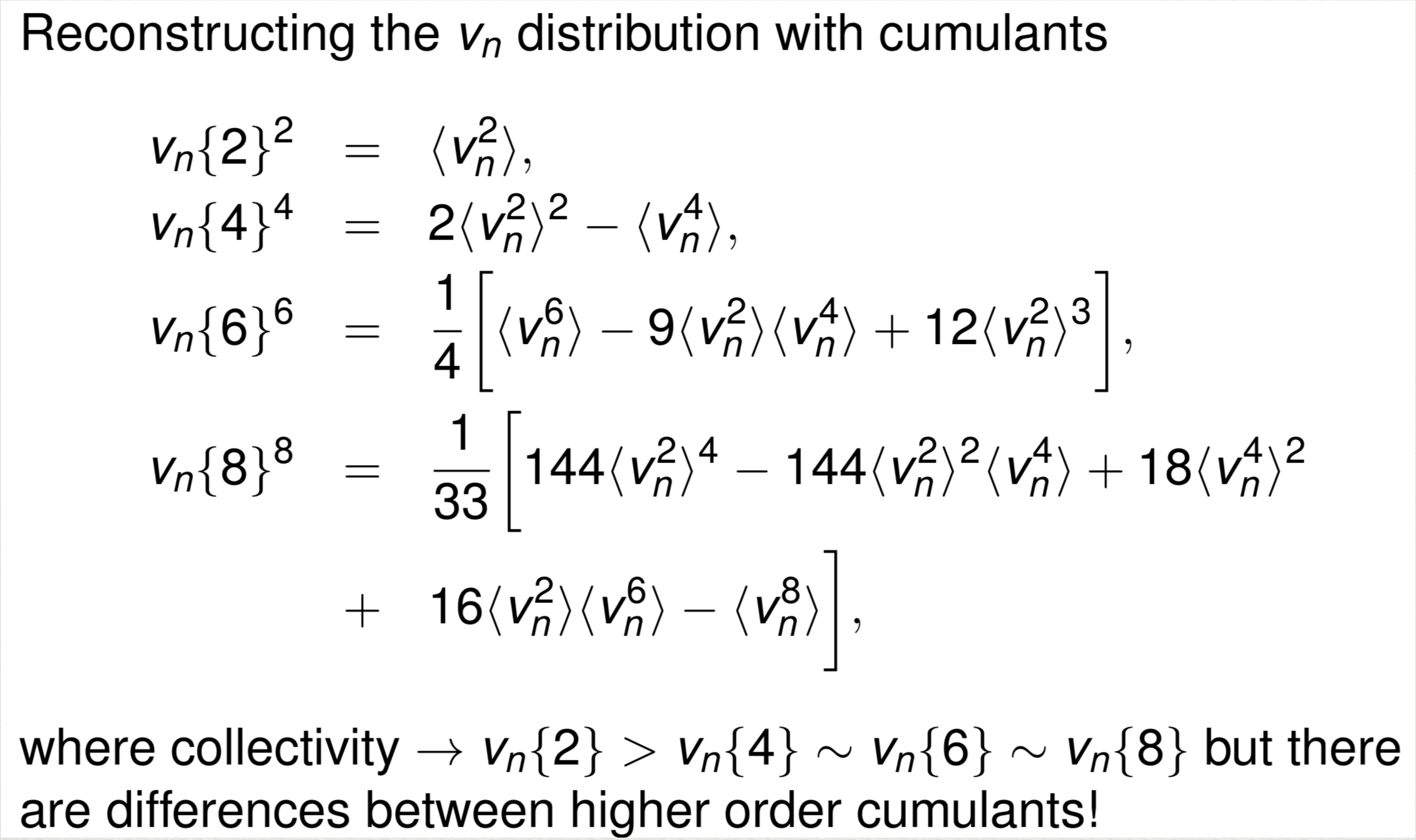
p_T dependence of $v_2\{4\}/v_2\{2\}$ from soft vs. hard fluctuations

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

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

where collectivity → $v_n\{2\} > v_n\{4\} \sim v_n\{6\} \sim v_n\{8\}$ 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)

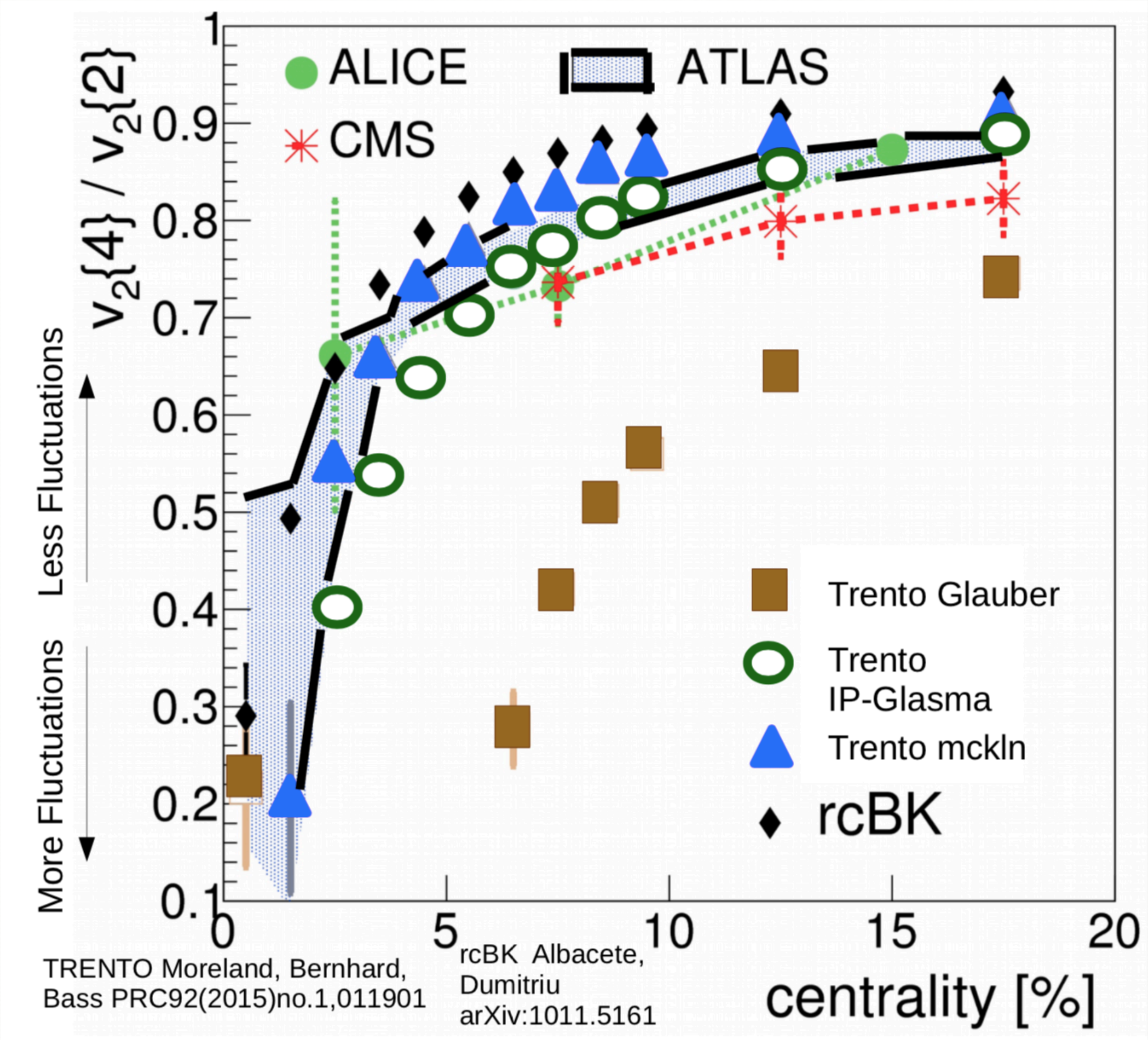
$$\frac{\langle v_n^{soft}\, v_n^{hard}(p_T) \cos\left(n\left[\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle}{\sqrt{\left\langle\left(v_n^{soft}\right)^2\right\rangle}}$$

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

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

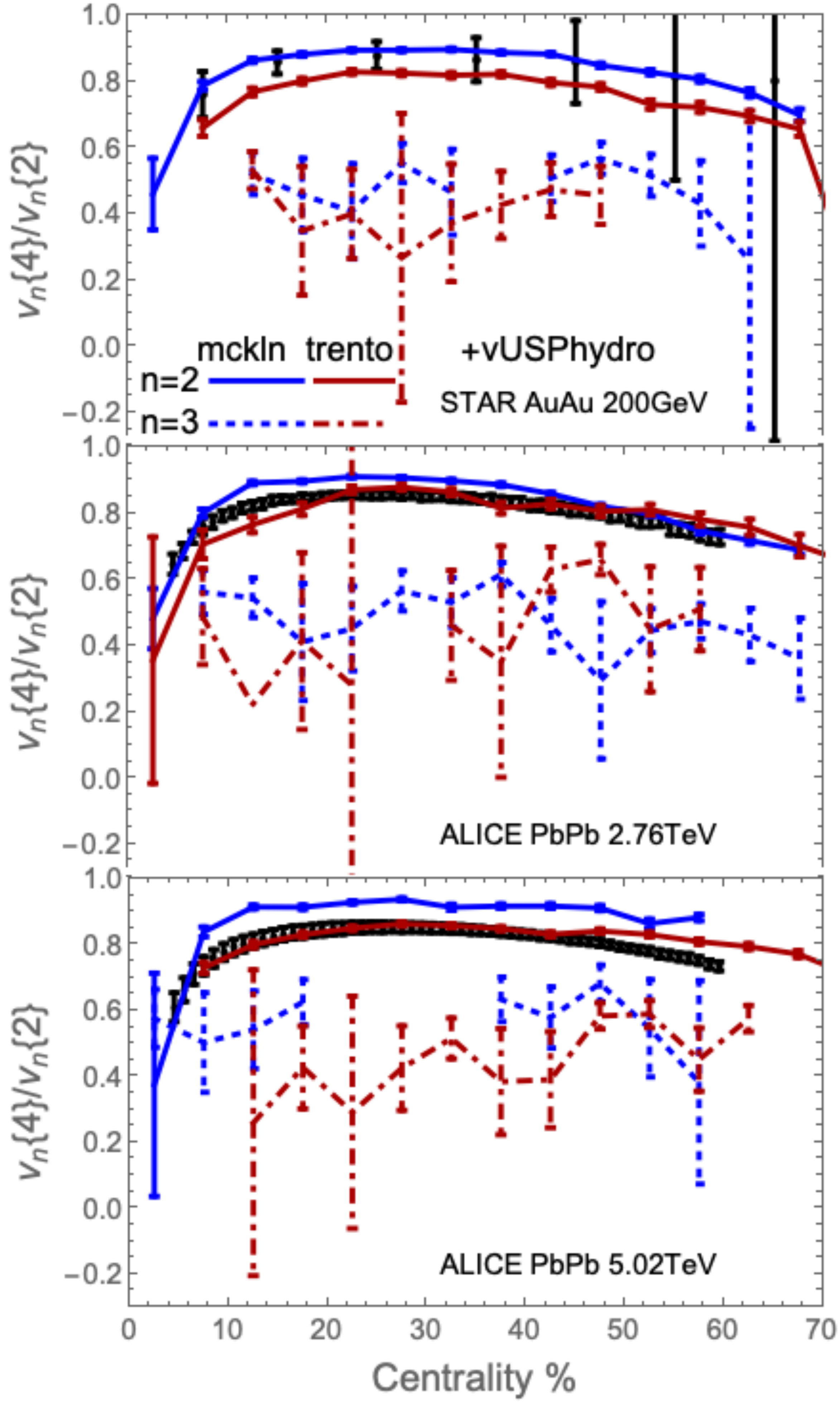
Constraints on initial conditions

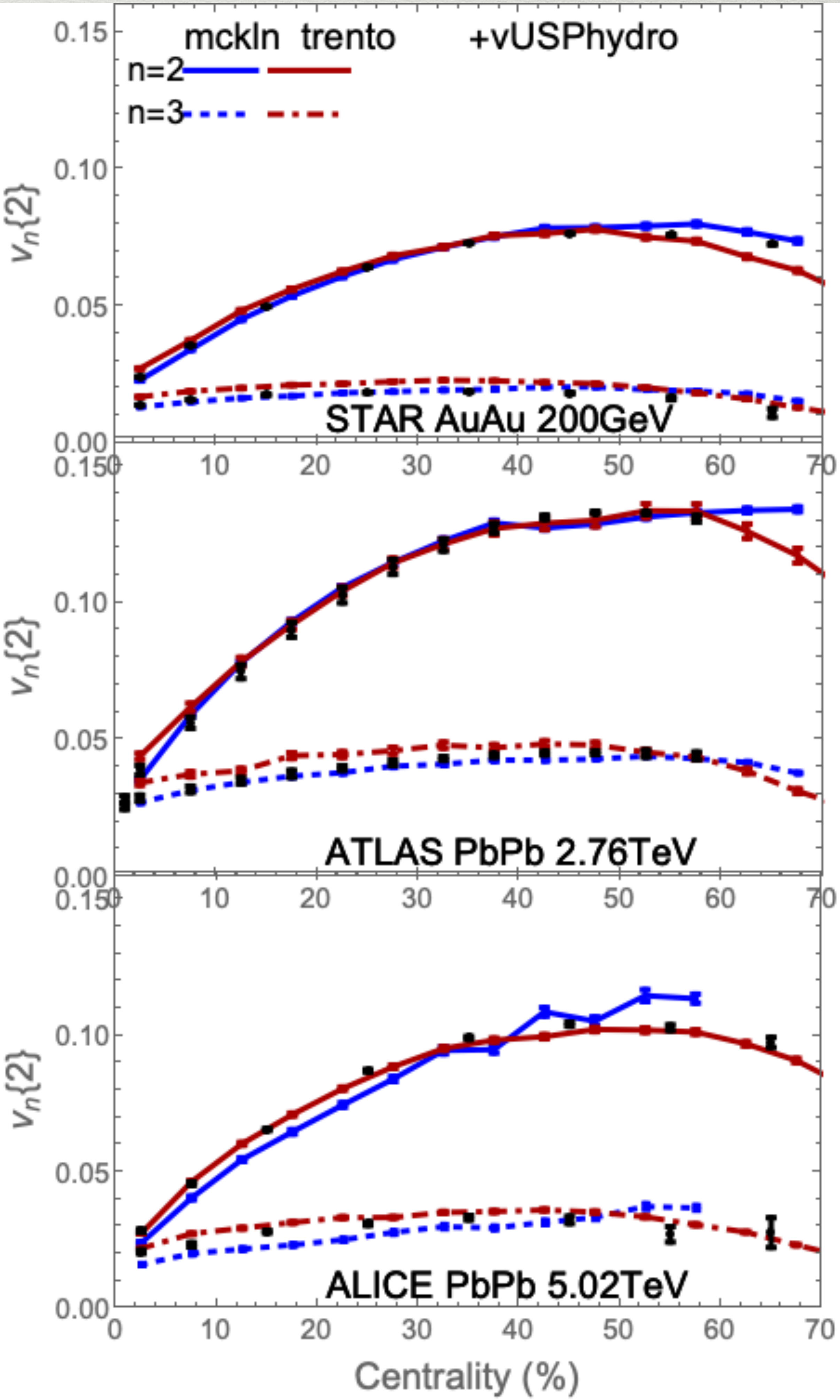
Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910



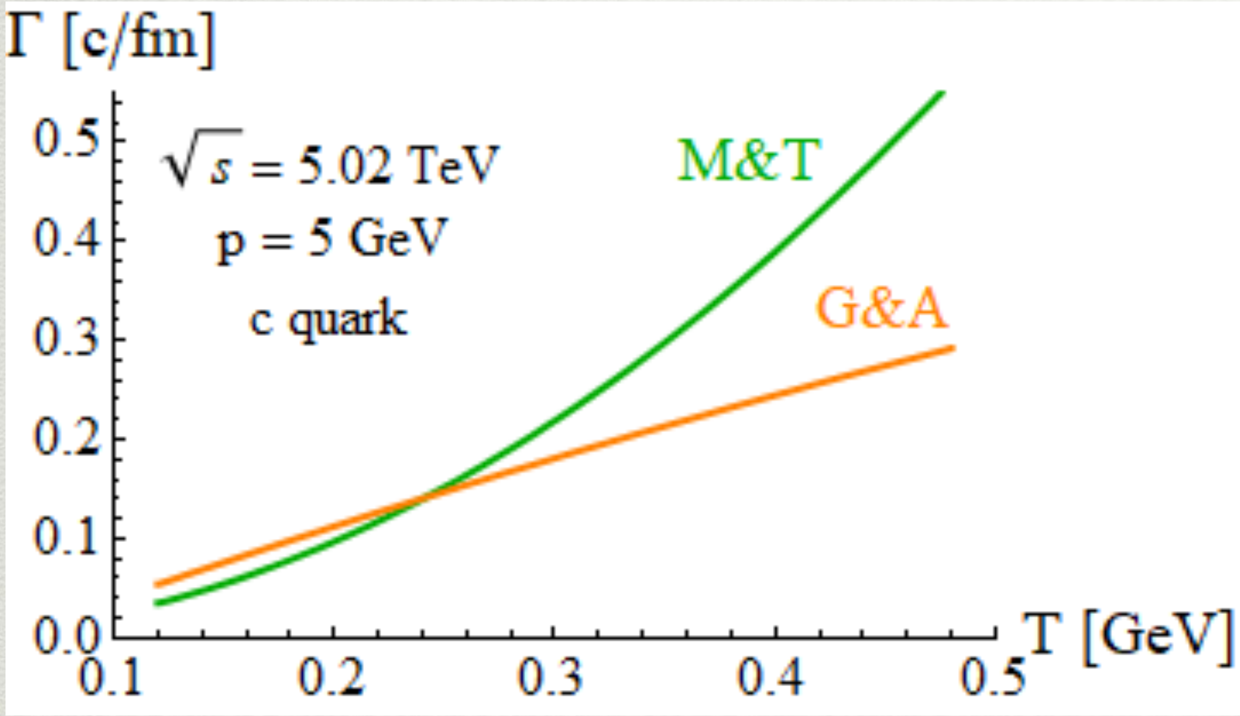
TRENTO Moreland, Bernhard, Bass PRC92(2015)no.1,011901

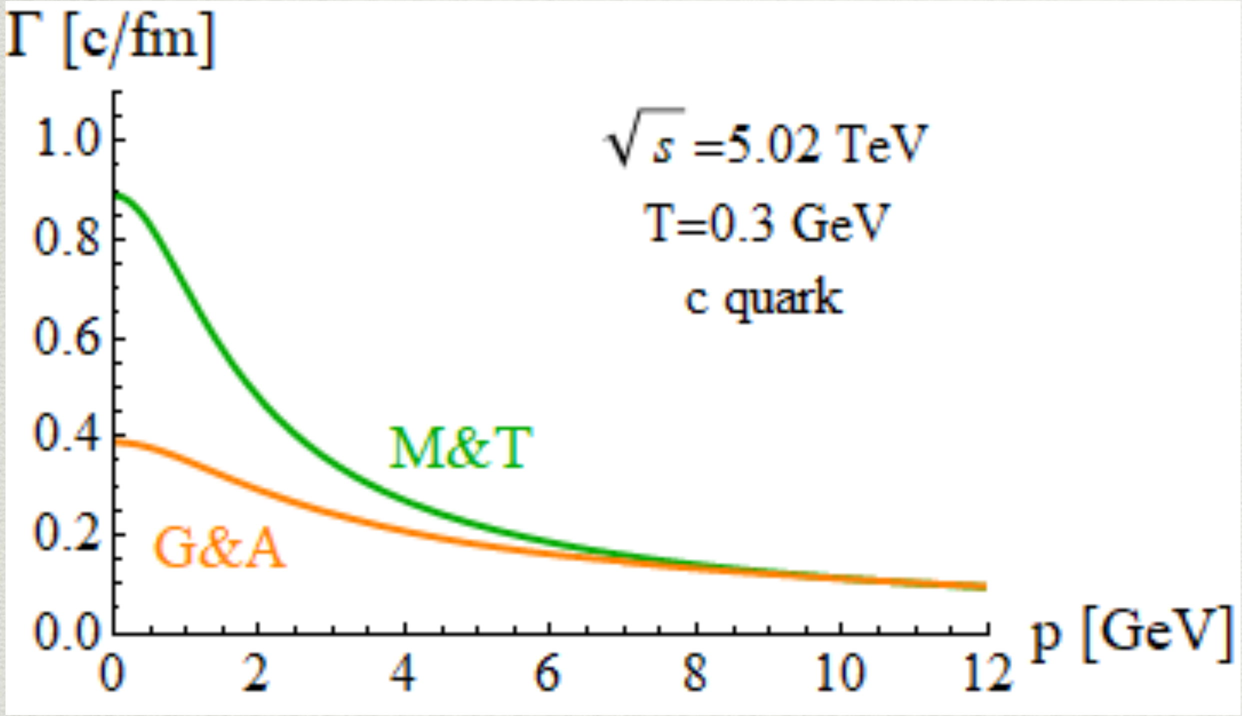
rcBK Albacete, Dumitriu arXiv:1011.5161

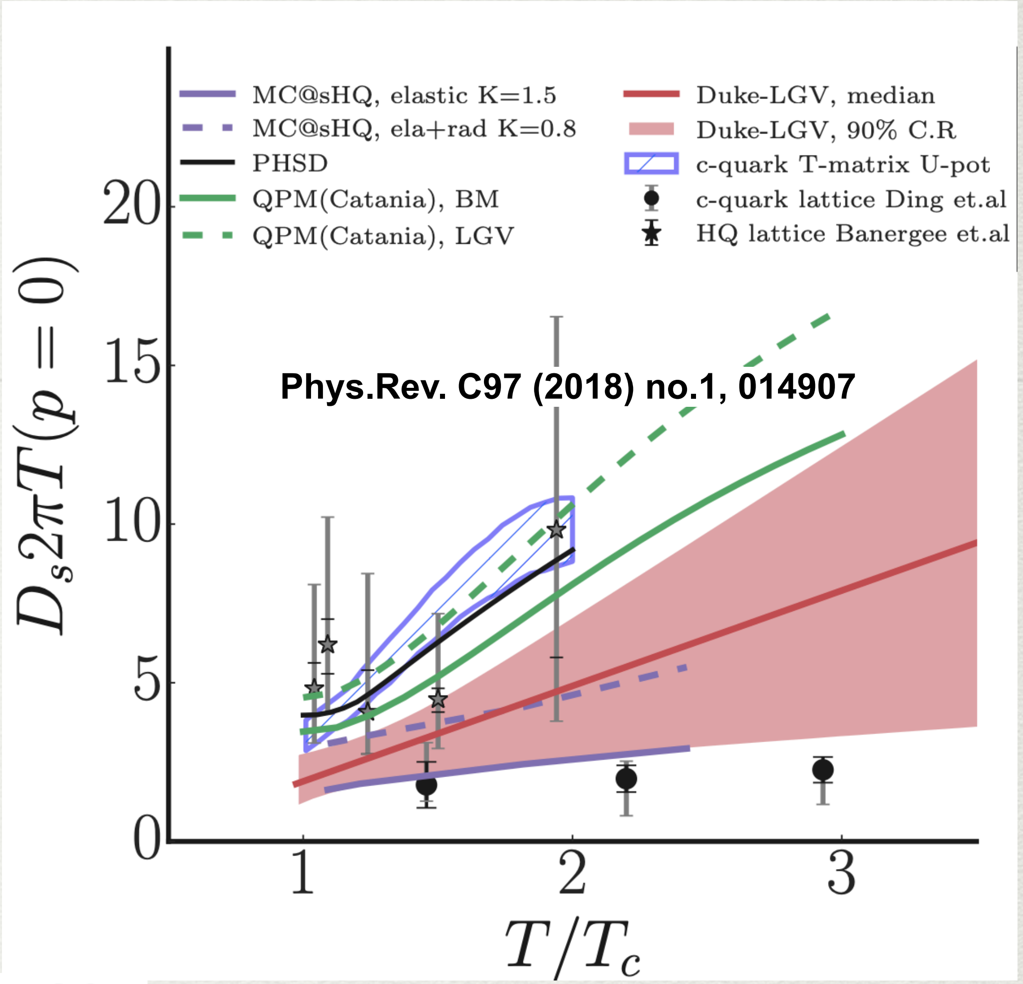

mckln trento +vUSPhydro
n=2
n=3
STAR AuAu 200GeV
ALICE PbPb 2.76TeV
ALICE PbPb 5.02TeV
$v_n\{4\}/v_n\{2\}$
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
10
20
30
40
50
60
70
Centrality %


mckln trento +vUSPhydro
n=2
n=3
STAR AuAu 200GeV
ATLAS PbPb 2.76TeV
ALICE PbPb 5.02TeV
$v_n\{2\}$
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Centrality (%)

Transport Coefficients







Phys.Rev. C97 (2018) no.1, 014907