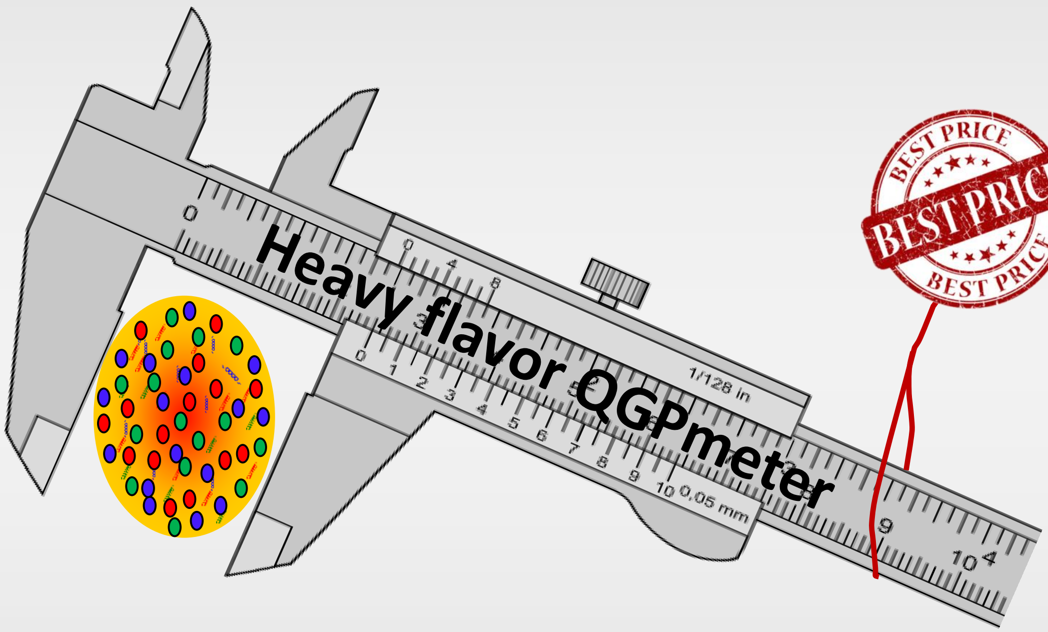
Sensitivity of heavy flavor to system size, structure and initial conditions



Roland Katz (SUBATECH, France)

Project developed at the University of São Paulo (Brazil)

with C. Prado, J. Noronha-Hostler, A. Suaide, J. Noronha

Subatech

SQM 2019 – Bari Italy – 11/06/2019

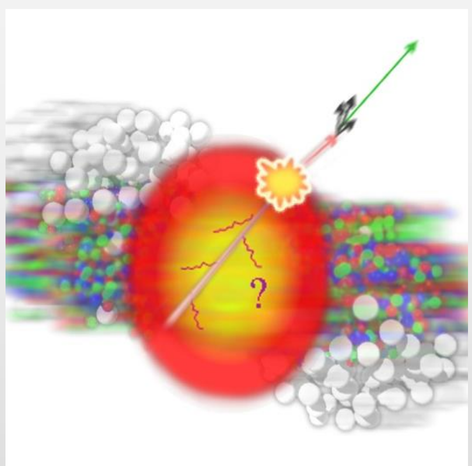
IFUSP Instituto de Física da USP

Heavy quark probes

- ✓ **Only produced before the hot medium**
- ✓ **Do not flow hydrodynamically**
- ✓ **But still strongly couple to the medium**

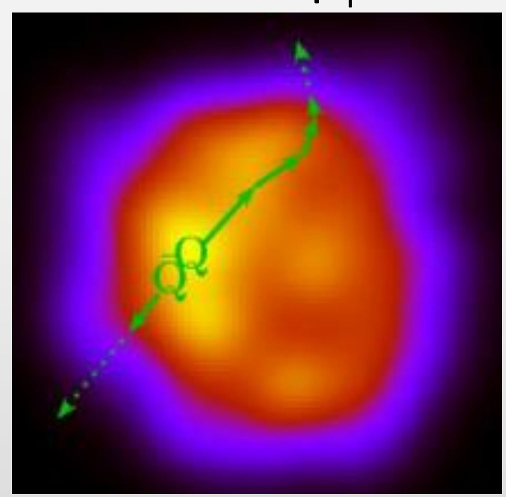
=> ideal to perform a « tomography » at any p_T of the medium

At high p_T



Heavy flavor quenching

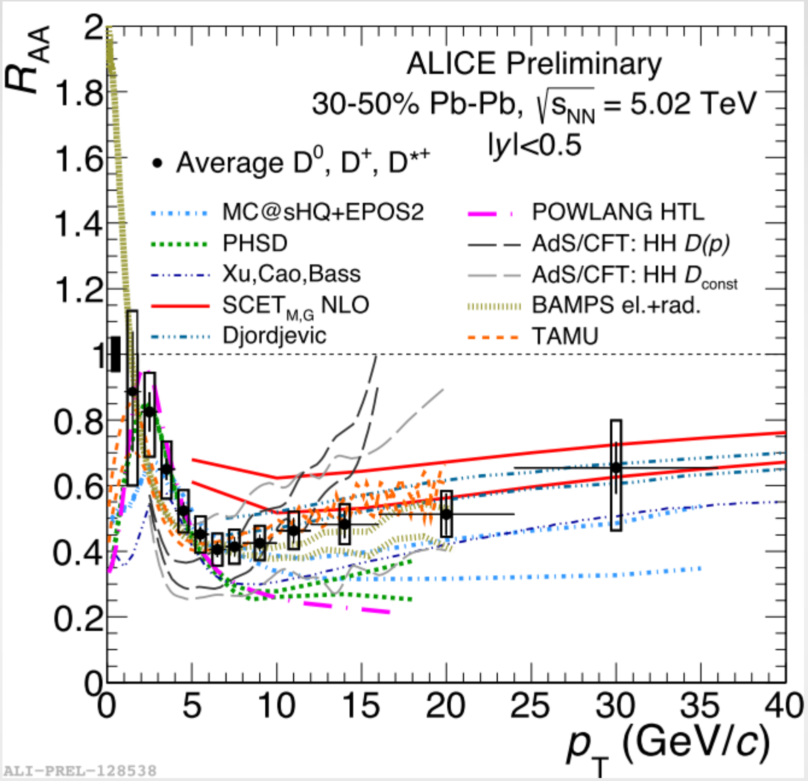
At low p_T

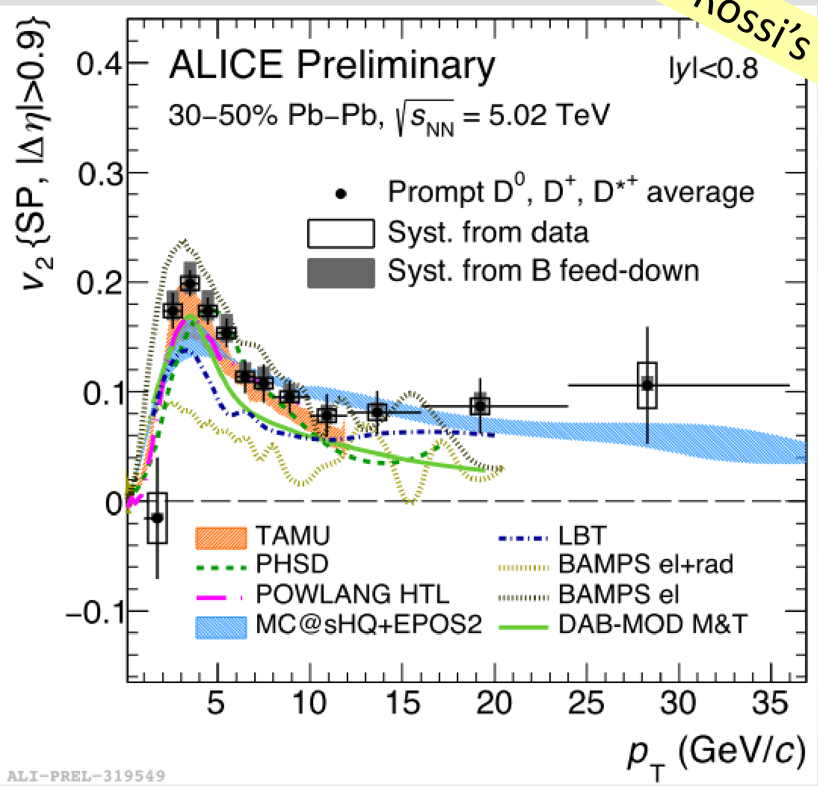


Heavy flavor diffusion

Models vs. Data: Pb-Pb

A. Rossi's talk



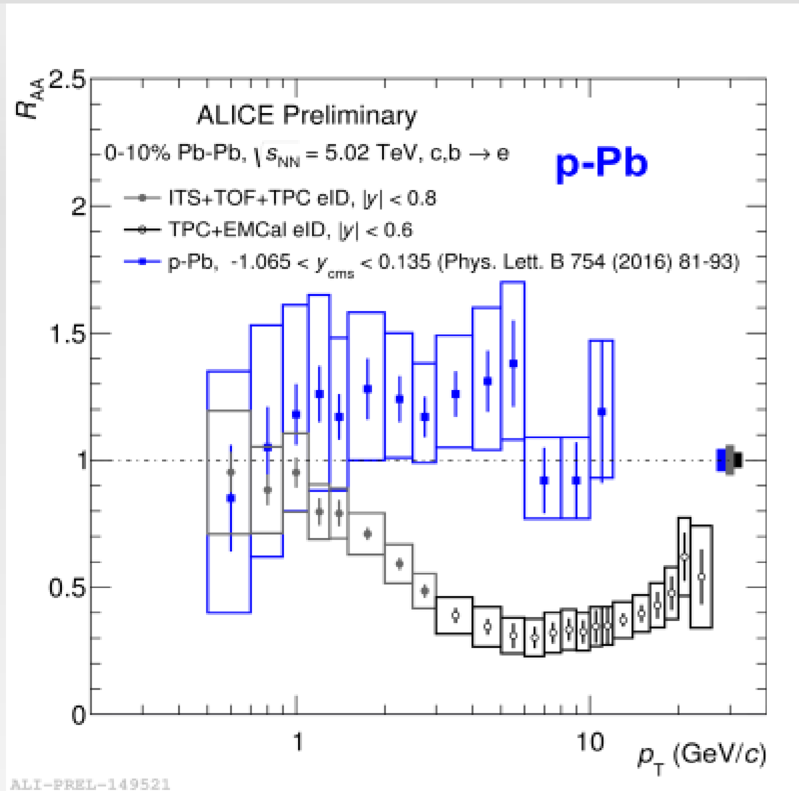


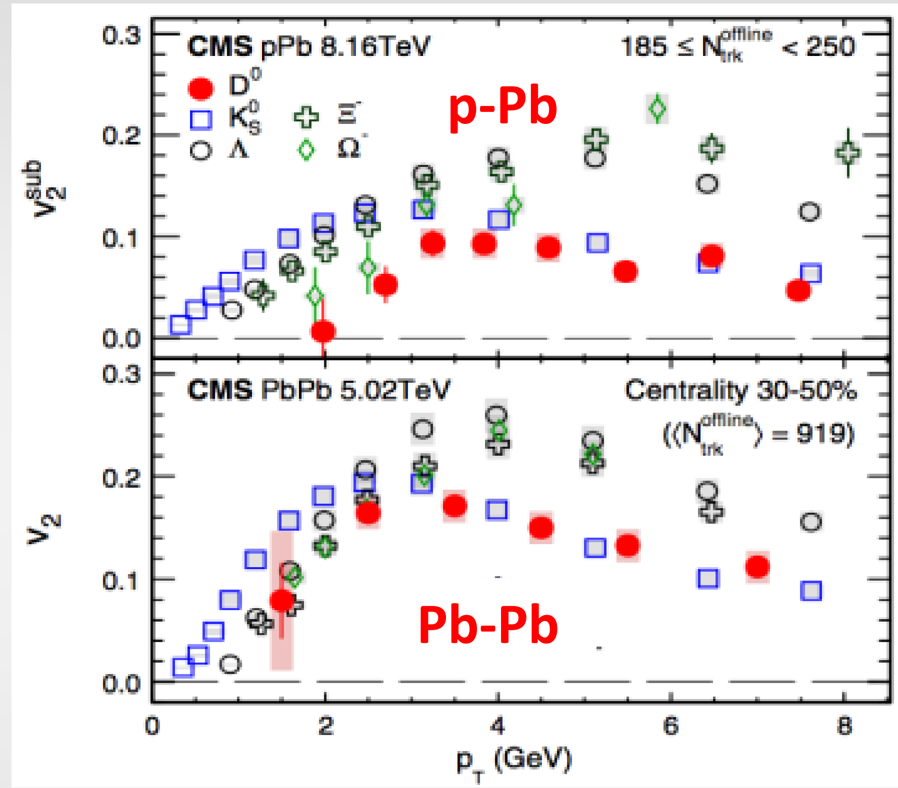
- Difficulty to describe both R_{AA} and v_2

- Difficulty to distinguish between models

Motivation 1 : What makes theory match data ?

Models vs. Data: small systems





- R_{AA} ~ 1 but significant v_2 !

<u>Motivation 2:</u> D^0 scaling with system size and structure ?

Is the common framework still valid in smaller systems ?

DAB-MOD: motivations

Effects of various ingredients

R_{AA} and v_n
with cumulant method
+ explore new observables

What makes theory match data ?

"D And B mesons - modular code"
to study open heavy flavours

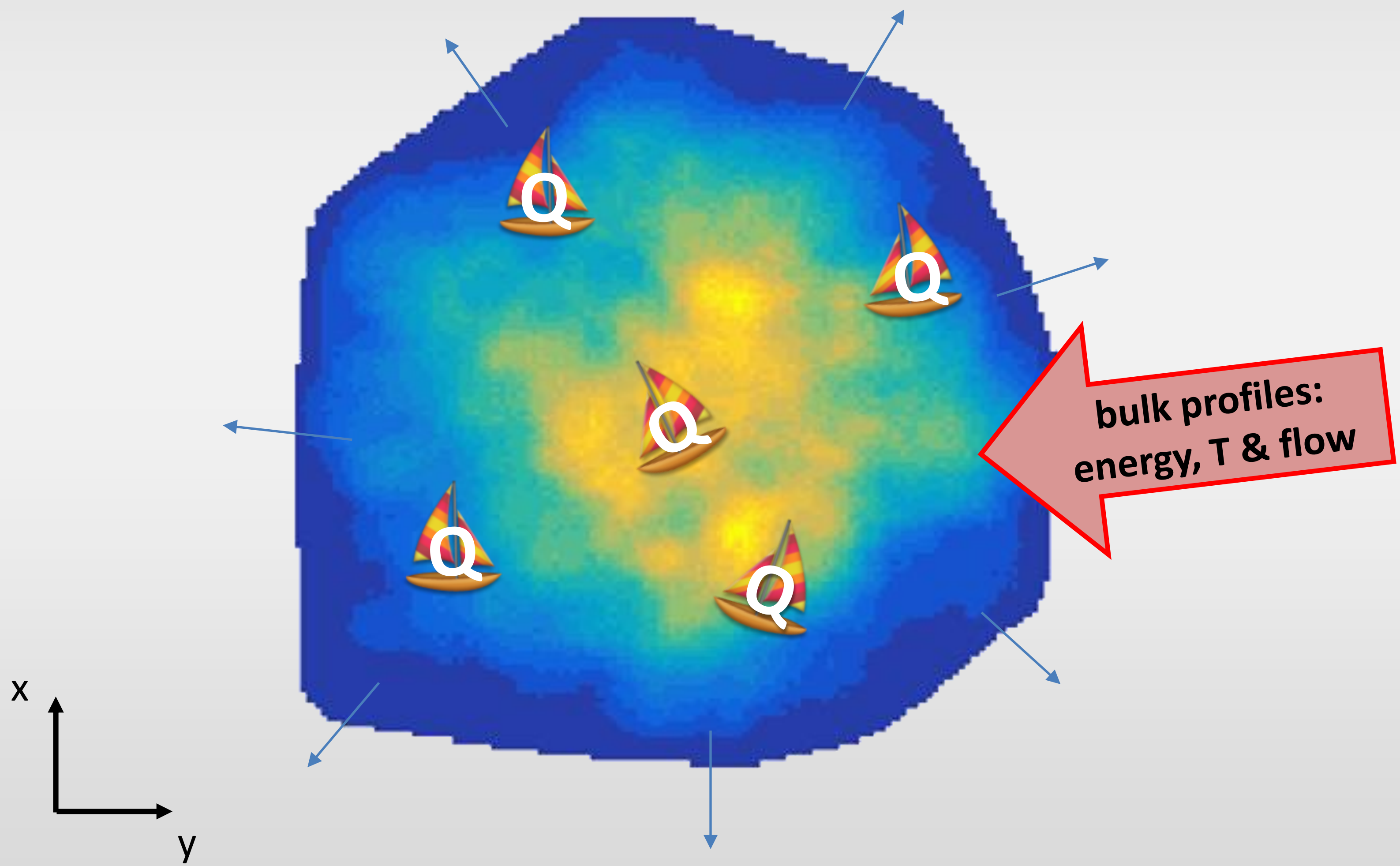
D^0 scaling with system size & structure ?

Effect of
event-shape engineering
(initial fluctuations and geometries)

Explore various colliding systems toward p-A collisions

DAB-MOD: basics

Heavy quarks evolve on the top of 2d+1 bulk profiles

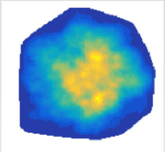


DAB-MOD: bulk profiles

Initial fluctuations

- "**MCKLN**": implementation of a Color Glass Condensate k_T-factorization model

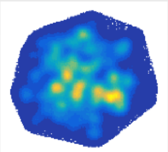
MCKLN



or

- **Trento**: tuned to IP-Glasma. Has larger initial T. At LHC run 2 Trento generally works best

TRENTO



Expansion

- Using **v-USPhydro**: a **2d+1 event-by-event relativistic viscous hydro** Viscosity set to $\eta/s = 0.05$
- With MCKLN: Equation of state S95n-v1 ≠ Trento: EOS2+1 from lQCD

Final stages

- **Cooper-Frye** freeze-out with viscous corrections

t

~1000 profiles per 10% centrality range

Describes data in the soft sector => hydro parameters are fixed

Refs: IC: arXiv:0707.0249, arXiv:1412.4708, arXiv:1711.08499; hydro: arXiv:1305.1981, arXiv:1508.02455, arXiv:1307.6130, arXiv:0707.0249

DAB-MOD: heavy quarks

Initial conditions

- **Large oversampling** of the HQs (statistics)
- Spatial -> following initial bulk densities; p_T -> **FONLL spectra**
- **No shadowing or cold nuclear matter** effects

Transport

- **Parametric Energy loss models** $\frac{dE}{dx} = -f(T,p,x)\,\Gamma_{\text{flow}}$

  Where Γ_{flow} : takes into account the boosts

  Parametrizations $f(T,p,x) = \alpha$ or $f(T,p,x) = \xi T^2$ -> R_{AA} trends ok

or

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

  Two different parametrizations:
  - "**M&T**": from Moore and Teaney, QCD+HTL model $D \propto 1/(2\pi T)$
  - "**G&A**" : from Gossiaux and Aichelin, QCD+HTL model with running coupling and optimized propagator.

Refs: arXiv:1404.6378, arXiv:1609.05171, arXiv:0412346, arXiv:0802.2525

DAB-MOD: heavy quarks

Hadronization

- **Decoupling T**: 120 < T_d < 160 MeV -> hadronization uncertainties
- **Fragmentation**: Peterson function $f(z) \propto [z(1 - 1/z - \epsilon_Q/(1-z))]^{-1}$ to obtain the fraction z of the HQ E_Q+p_Q taken by the hadron E_H+p_H

with or without

- **Light-heavy quark coalescence**
  - Inspired by Dover et al.: instantaneous projection of states
  - Coalescence proba. function of $\vec{p_Q}$, $\overrightarrow{\text{local flow}}$ & angle between
  - To better fit the observed heavy hadron ratios, we included:
    1) thermal factors "exp[-($m_{excited}$-m_{ground})/T_d]" => not only spin but also mass hierarchy between energy states of a hadron type
    2) baryon factor (~1.6): enhance the baryon/meson ratios (to compensate missing dynamics)

Final stages

- **No final hadronic re-scattering**

t

Refs: arXiv:1804.09083v1, Radhakrishnan's talk at QM 2018, arXiv:1505.01413

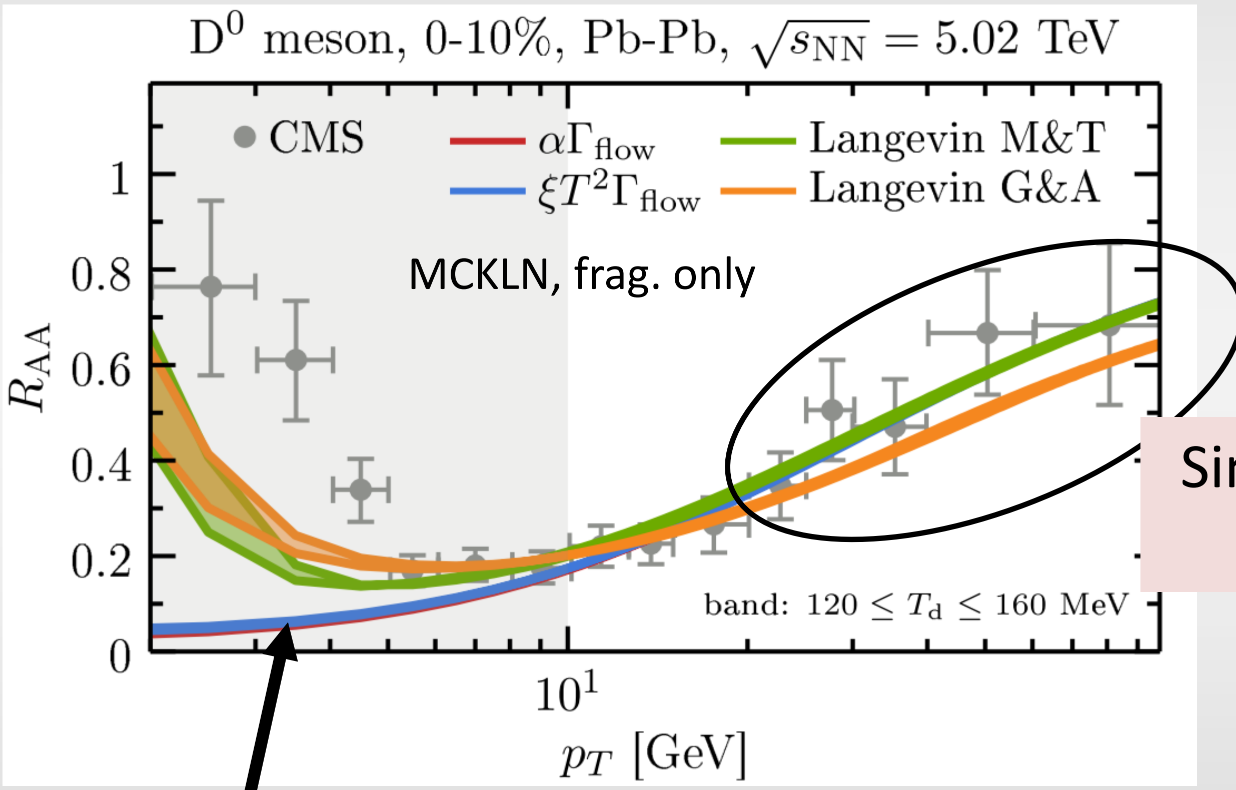
D^0 in Pb-Pb: sensitivity to ingredients and some “new” observables

What makes theory match data ?

For more details: Hard Probes 2018 poster and flash talk or paper out soon

Transport models ? R_{AA}

Note: Each **transport model has one parameter -> fixed with 0-10% high-p_T R_{AA}**



Similar trends at high p_T

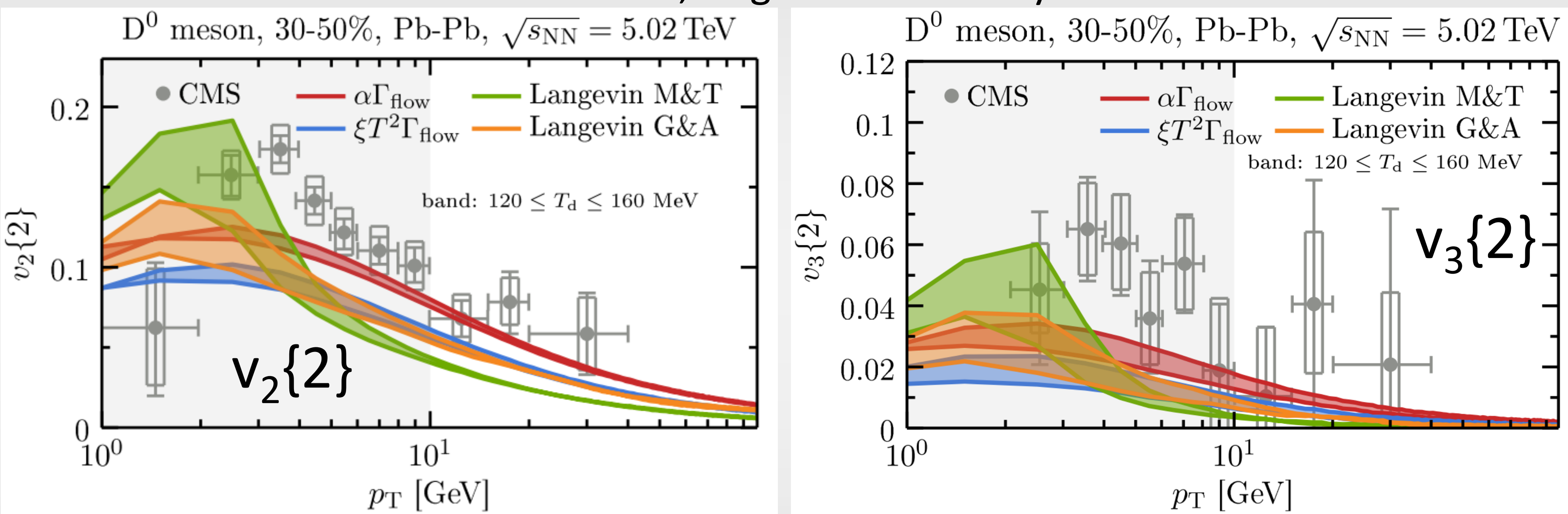
Energy loss: very wrong at low p_T

Ref data: arXiv:1708.04962

Transport models ? v_n

<u>Note:</u> cumulant $v_n\{k\}(p_T)$ -> correlation of 1 hard particle of p_T to k-1 soft particles

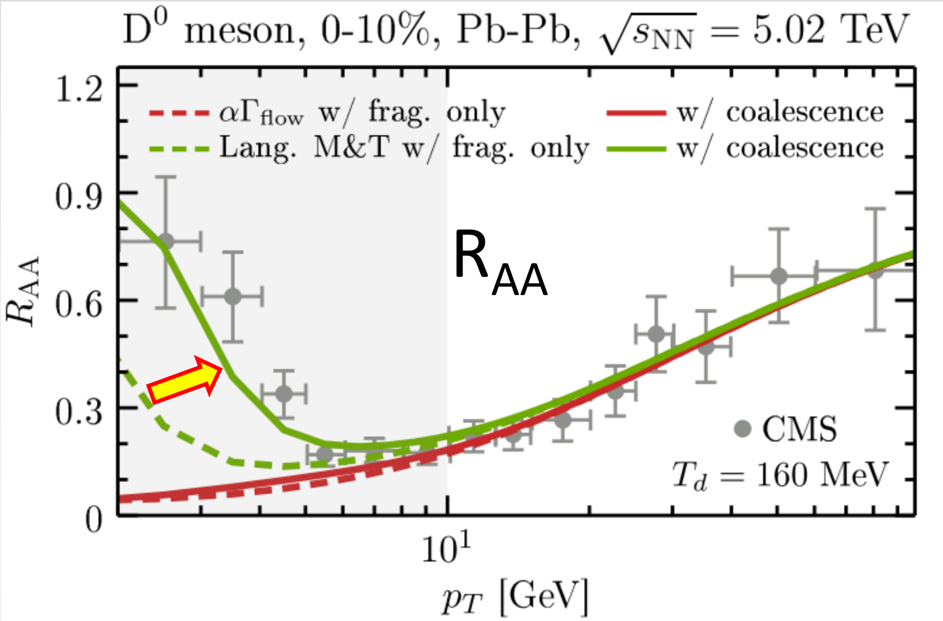
MCKLN, fragmentation only

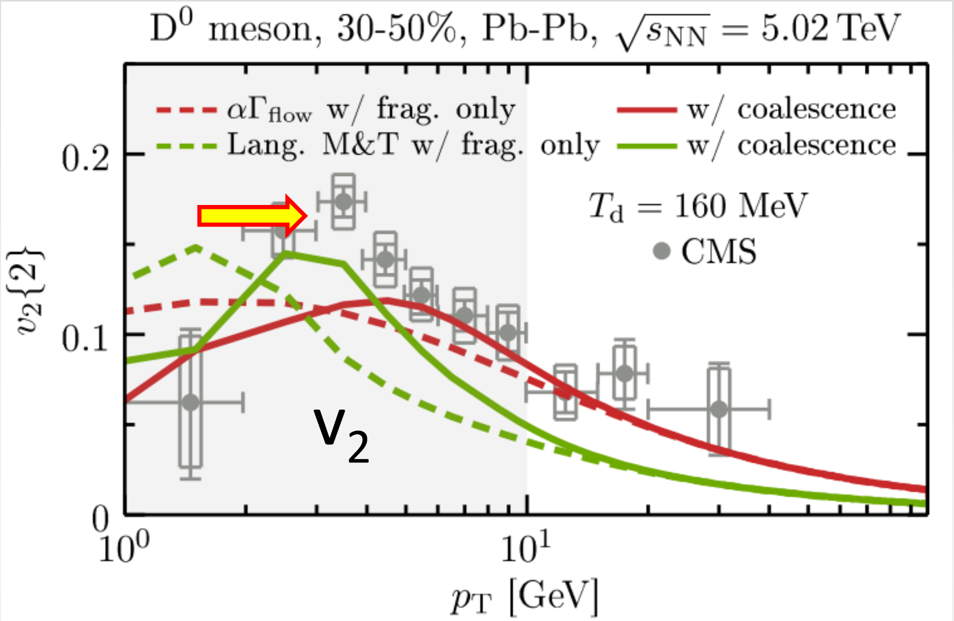


Langevin M&T: best at low-p_T ≠ const Energy loss: best at high-p_T
Globally underestimate the v_n

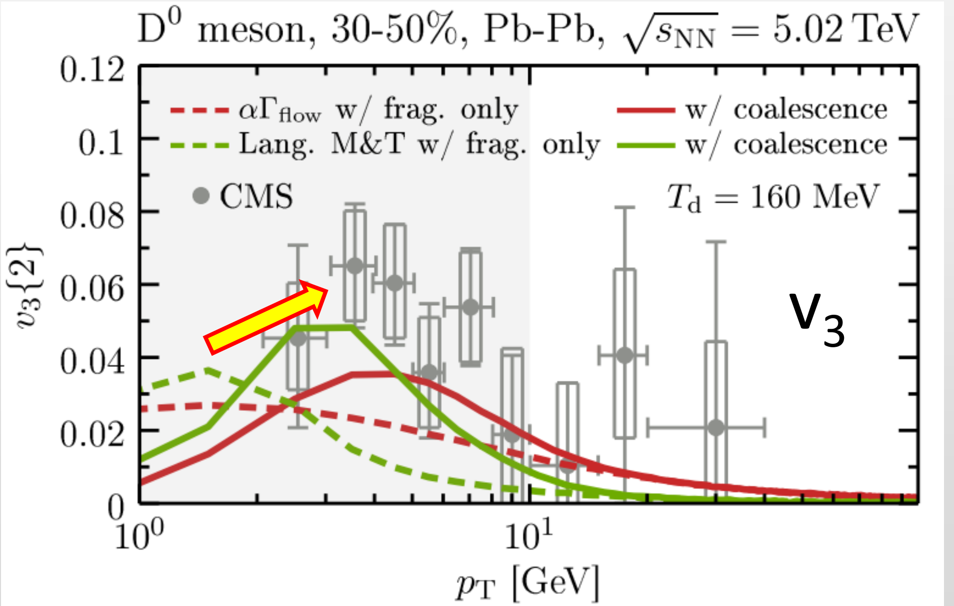
Ref data: arXiv:1708.03497

Coalescence ?





MCKLN

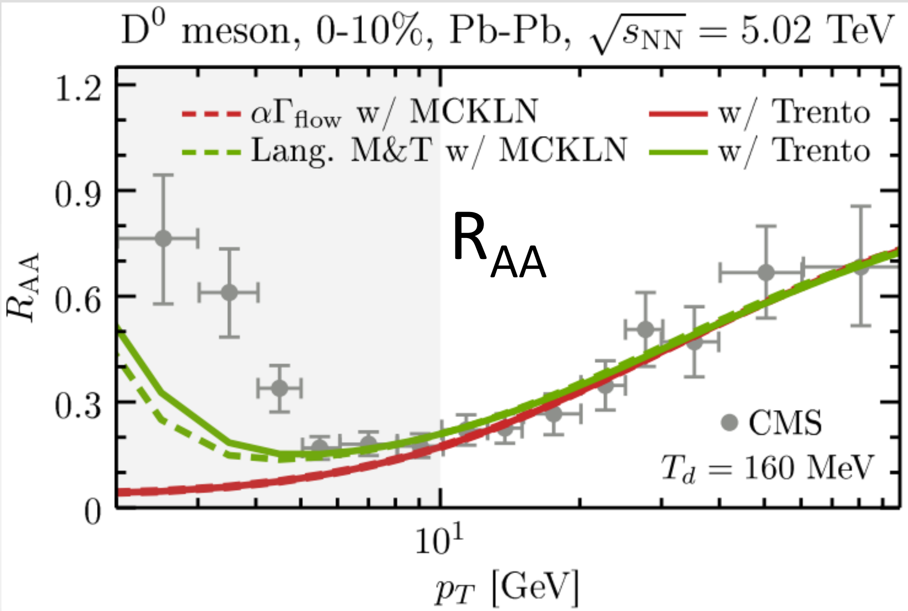


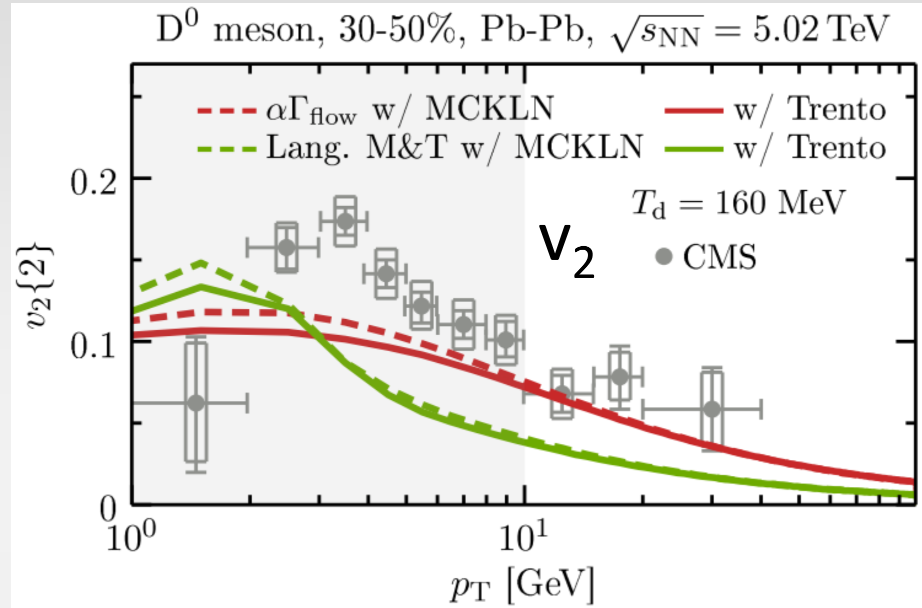
Low-p_T “lump” shifts:
very necessary
(but not enough)

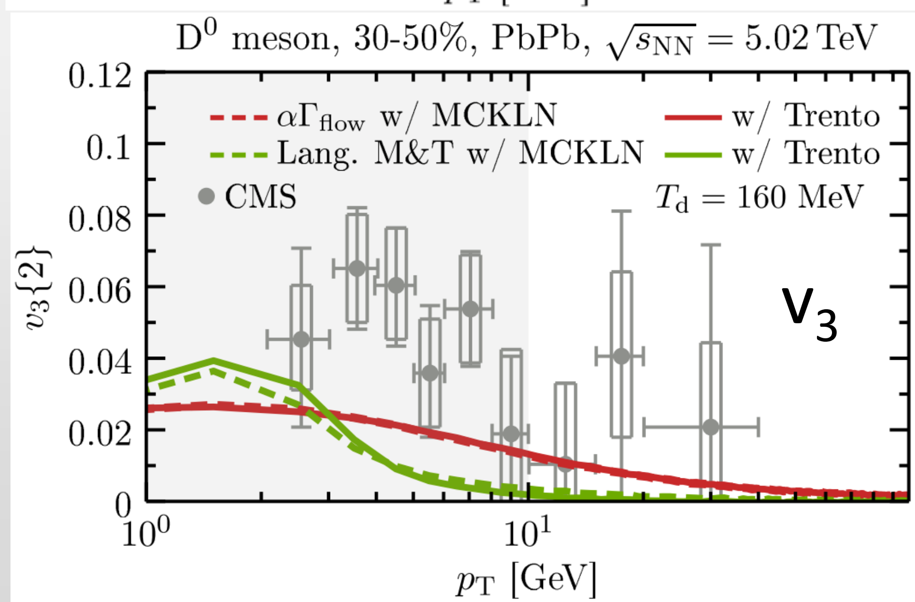
Ref data: arXiv:1708.04962, arXiv:1708.03497

MCKLN vs. Trento initial conditions ?

Fragmentation only





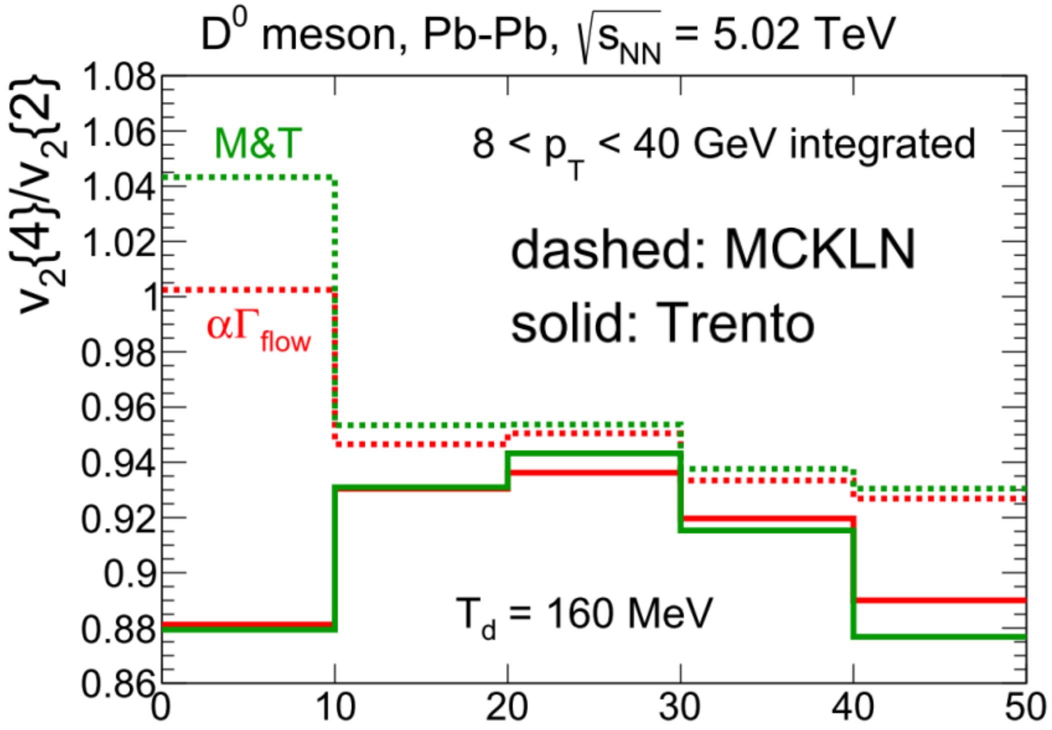


- Small effects on R_{AA} and v_n
- Trento: low-p_T v_2 ↘ (v_3 ↗)

(MCKLN $\varepsilon_2 \geq$ Trento ε_2)

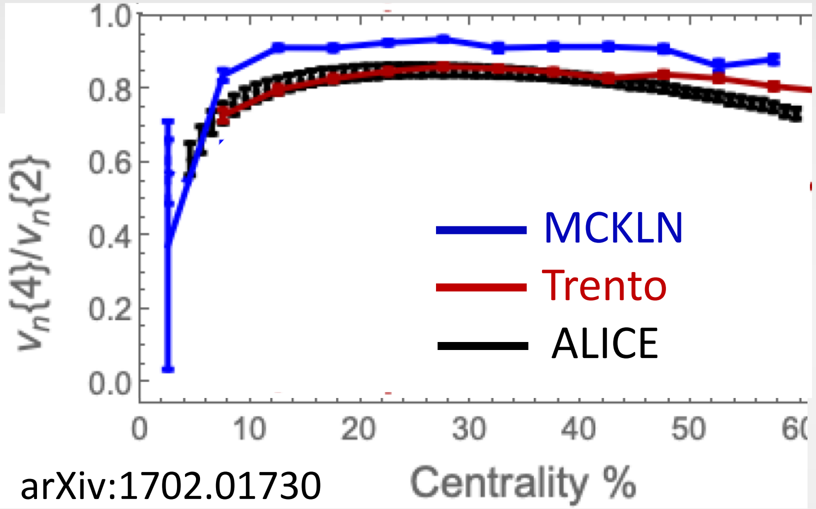
⚠ NOT the same EOS and transport model parameters

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



Fragmentation only

SOFT SECTOR Pb-Pb 5.02 TeV

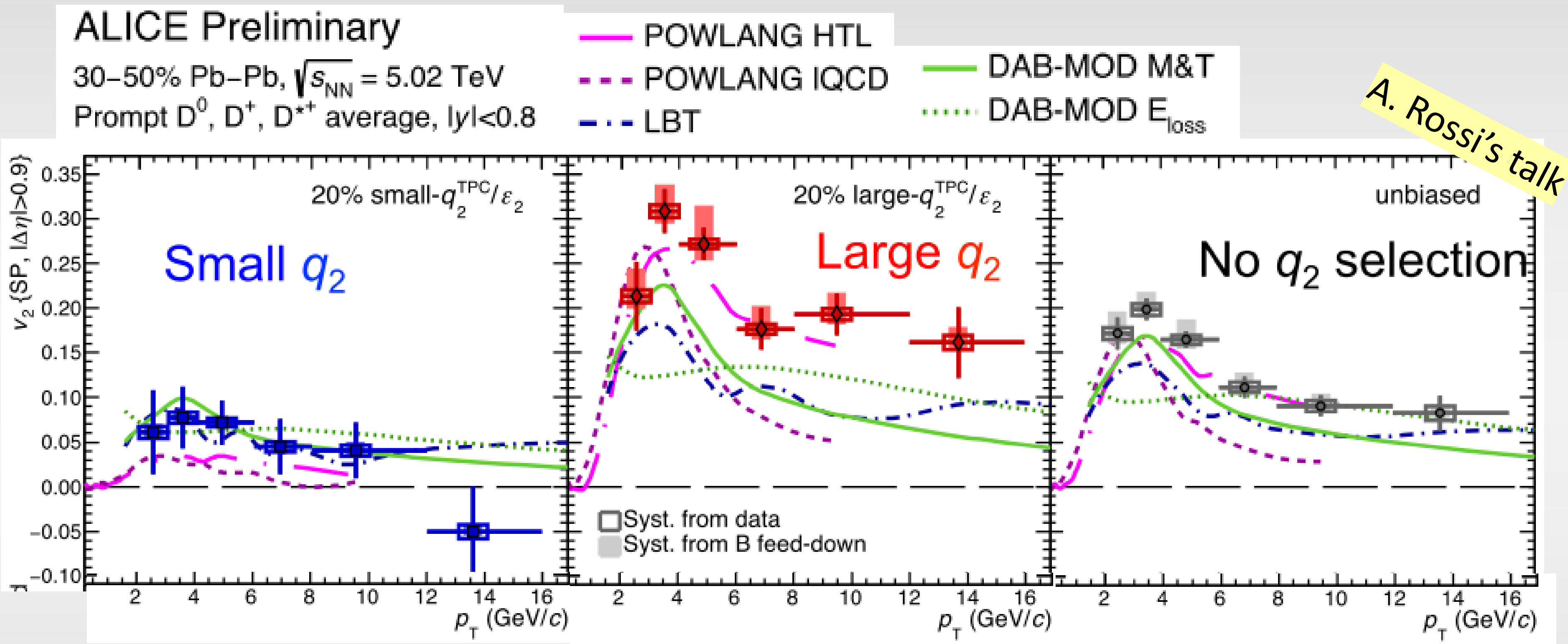


arXiv:1702.01730

At LHC run 2:
Trento is favored by soft data

- Small dependence on transport model and most kinetics/features
- **Strong dependence of the ratio trend on initial fluctuations**
- MCKLN: heavy vs. soft -> different behaviour in most central collisions

Soft-heavy flow correlations



- Clear linear correlations between heavy quark and soft flows

- With data: ok but **discrepancy at large q_2**

Ref. data: arXiv:1809.09371

D^0 in smaller systems: Pb-Pb^{208} vs. Xe-Xe^{129} vs. Ar-Ar^{40} vs. O-O^{16}

D^0 scaling with system size & structure ?

Proposal for Ar-Ar and O-O collisions
for a LHC system size scan

arXiv:1812.06772

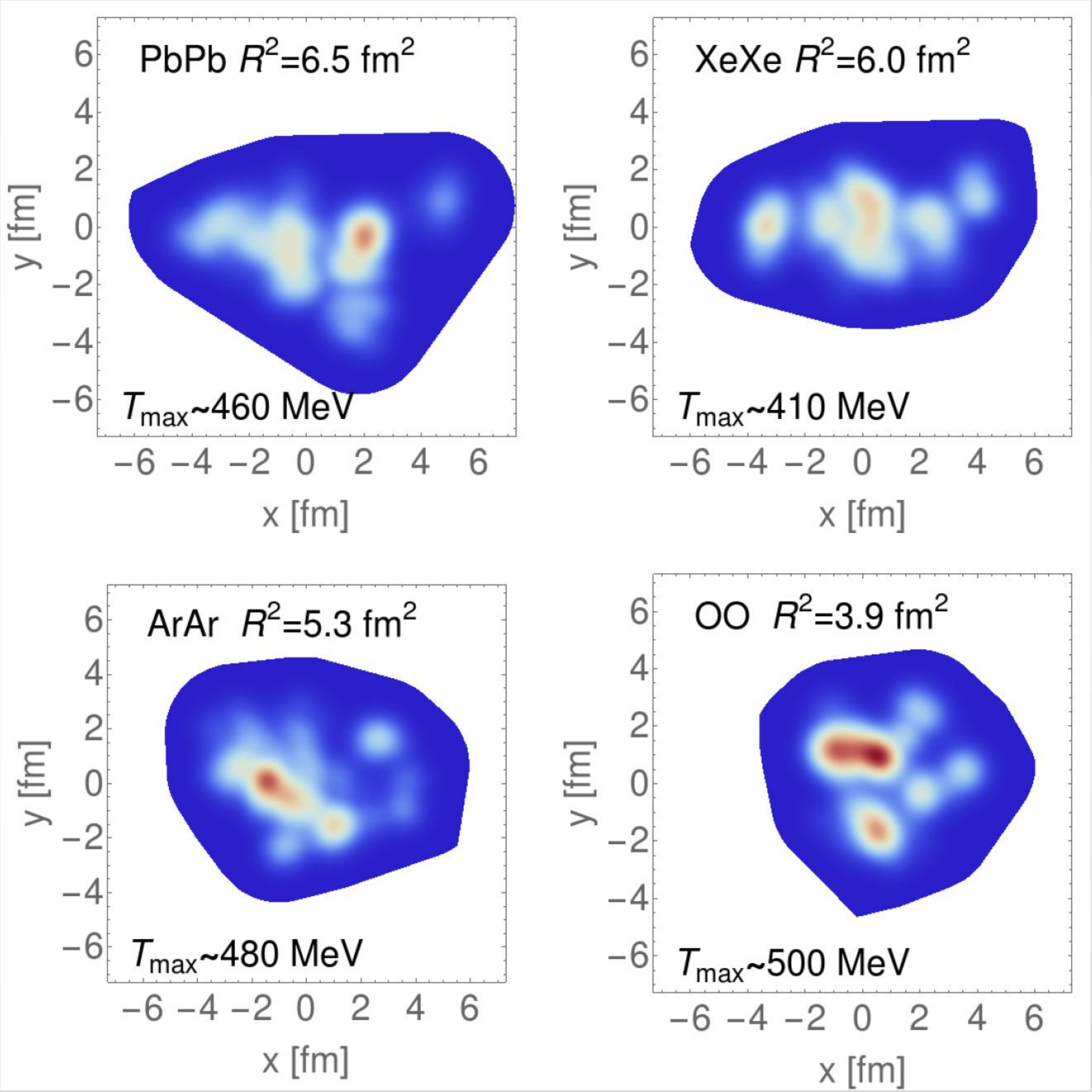
CERN-LPCC-2018-07
December 18, 2018

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

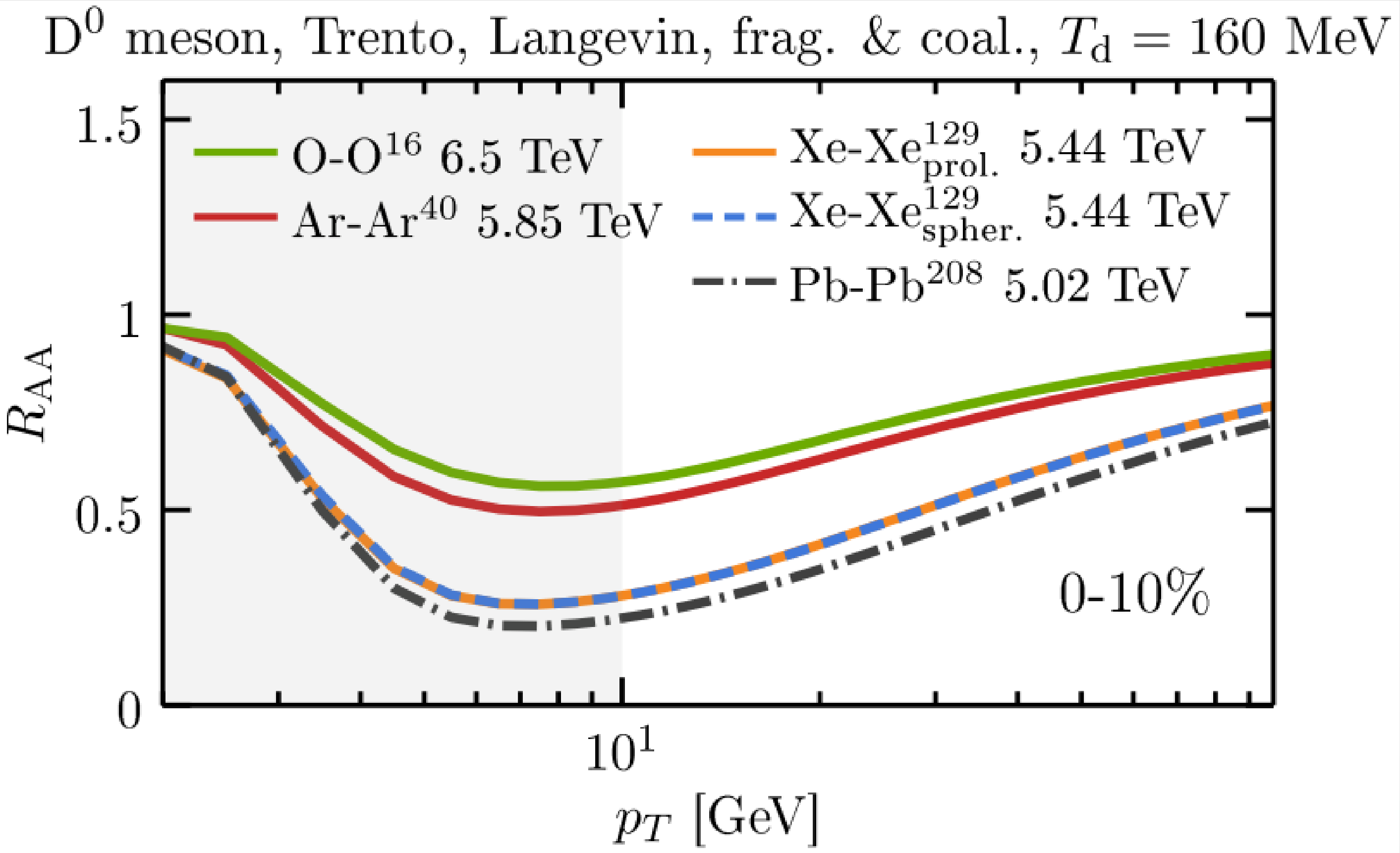
Typical soft events

Ar-Ar and O-O
smaller,
hotter and
more eccentric
in central collisions



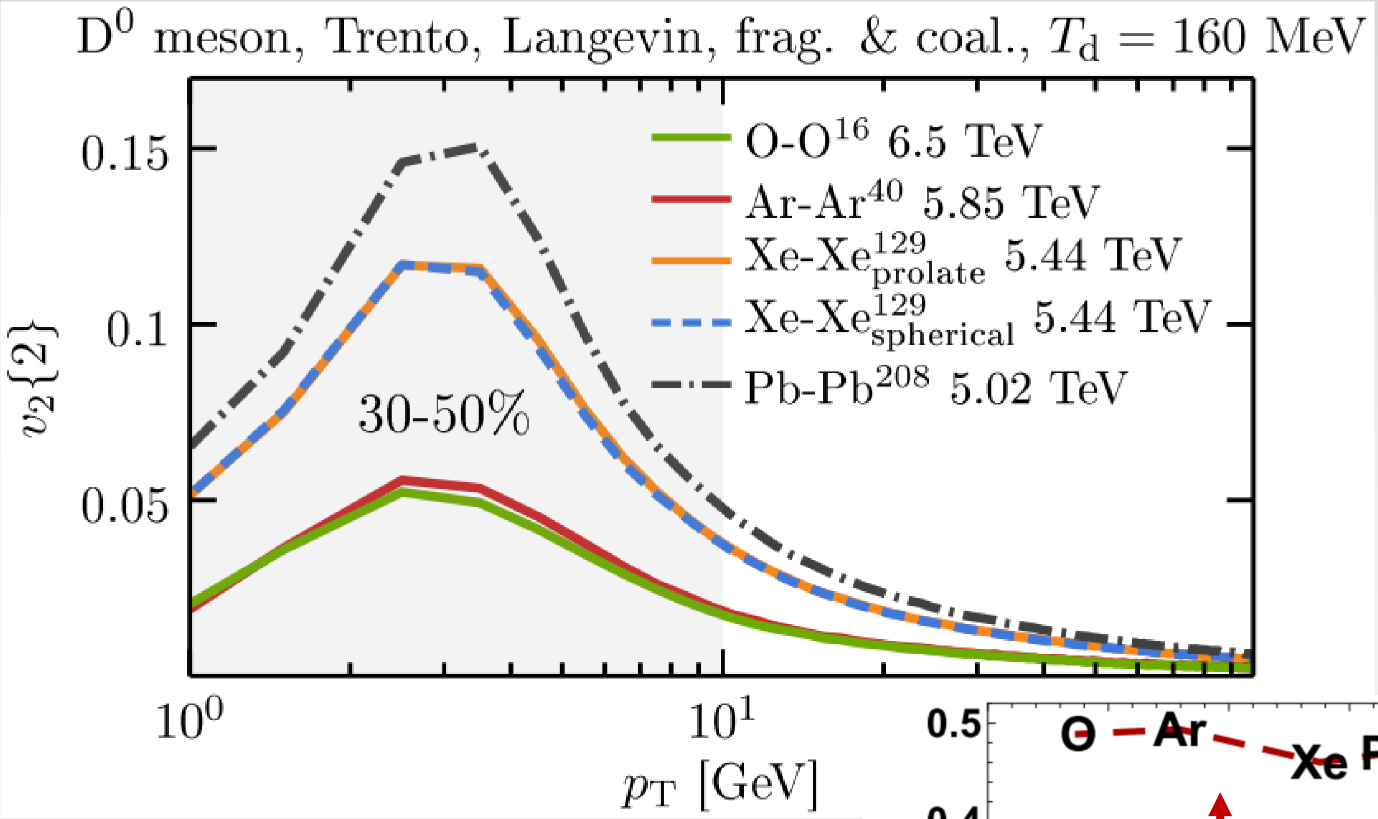
See M. Sievert and J. Noronha-Hostler arXiv:1901.01319 for the soft part

System size scan: R_{AA}

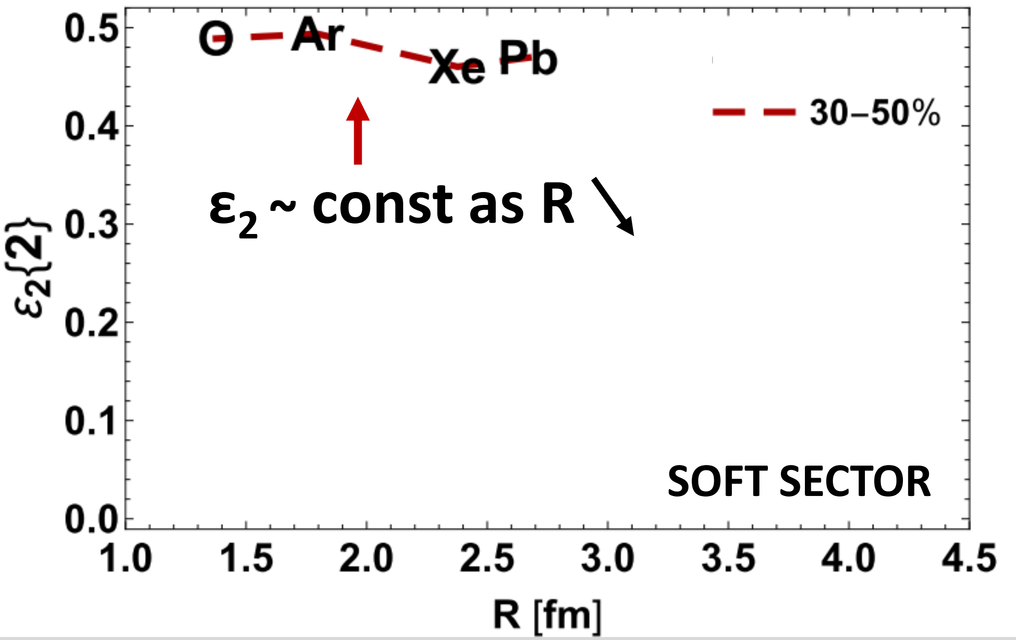


R_{AA} → 1 gradually as system size decreases

=> heavy quarks lose less energy as the path length decreases

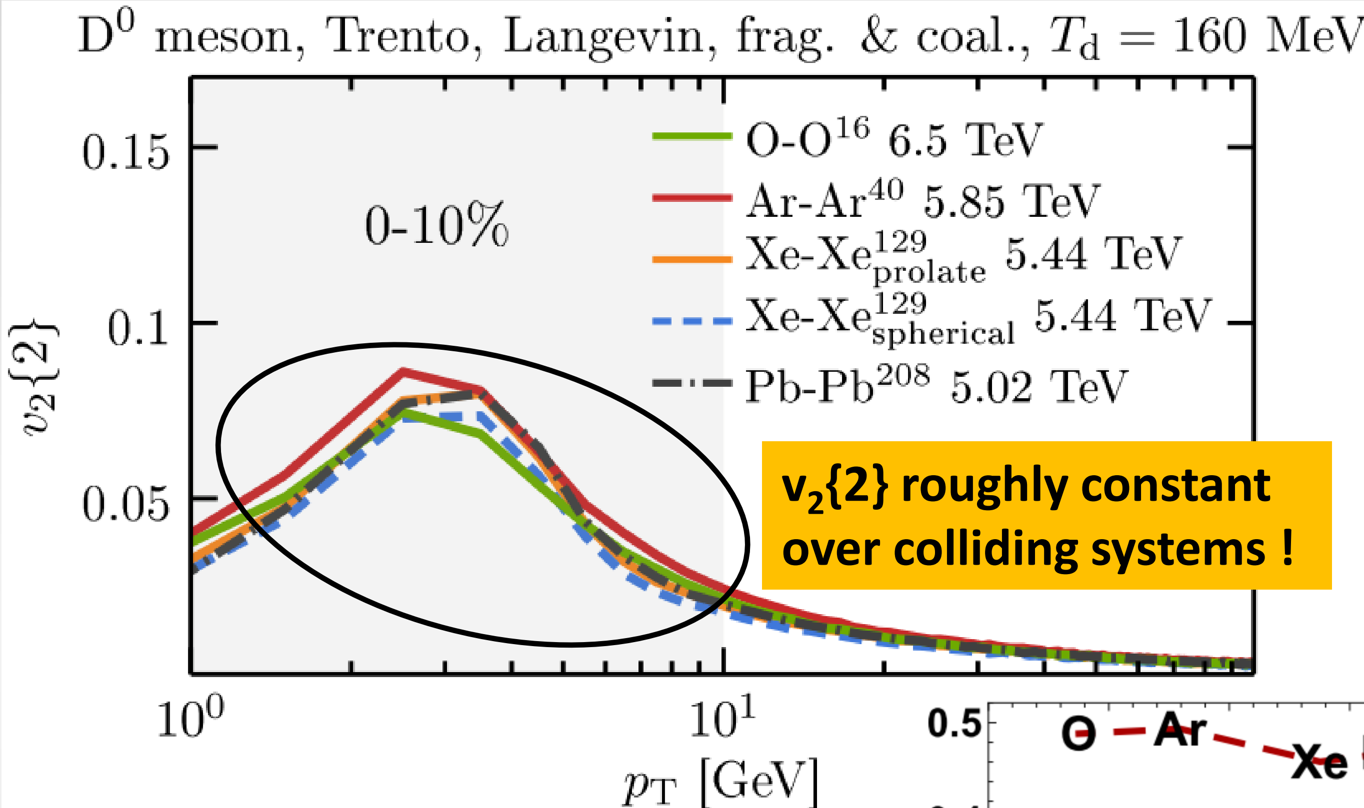


System size scan: v_2 30-50 %

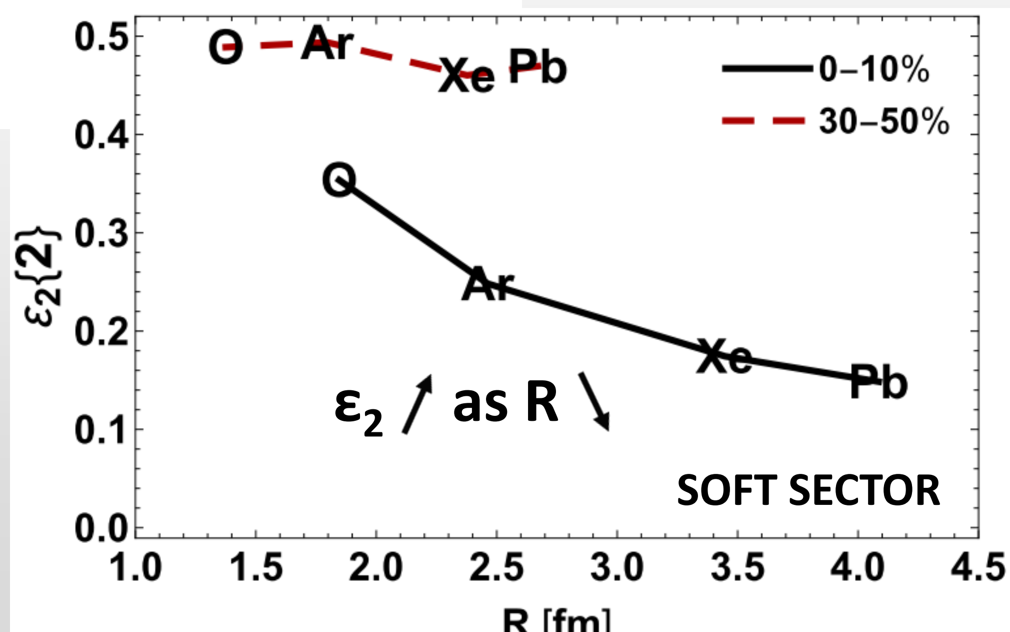


Whereas $\varepsilon_2 \sim$ const, system size plays an important role for $v_2\{2\}$!

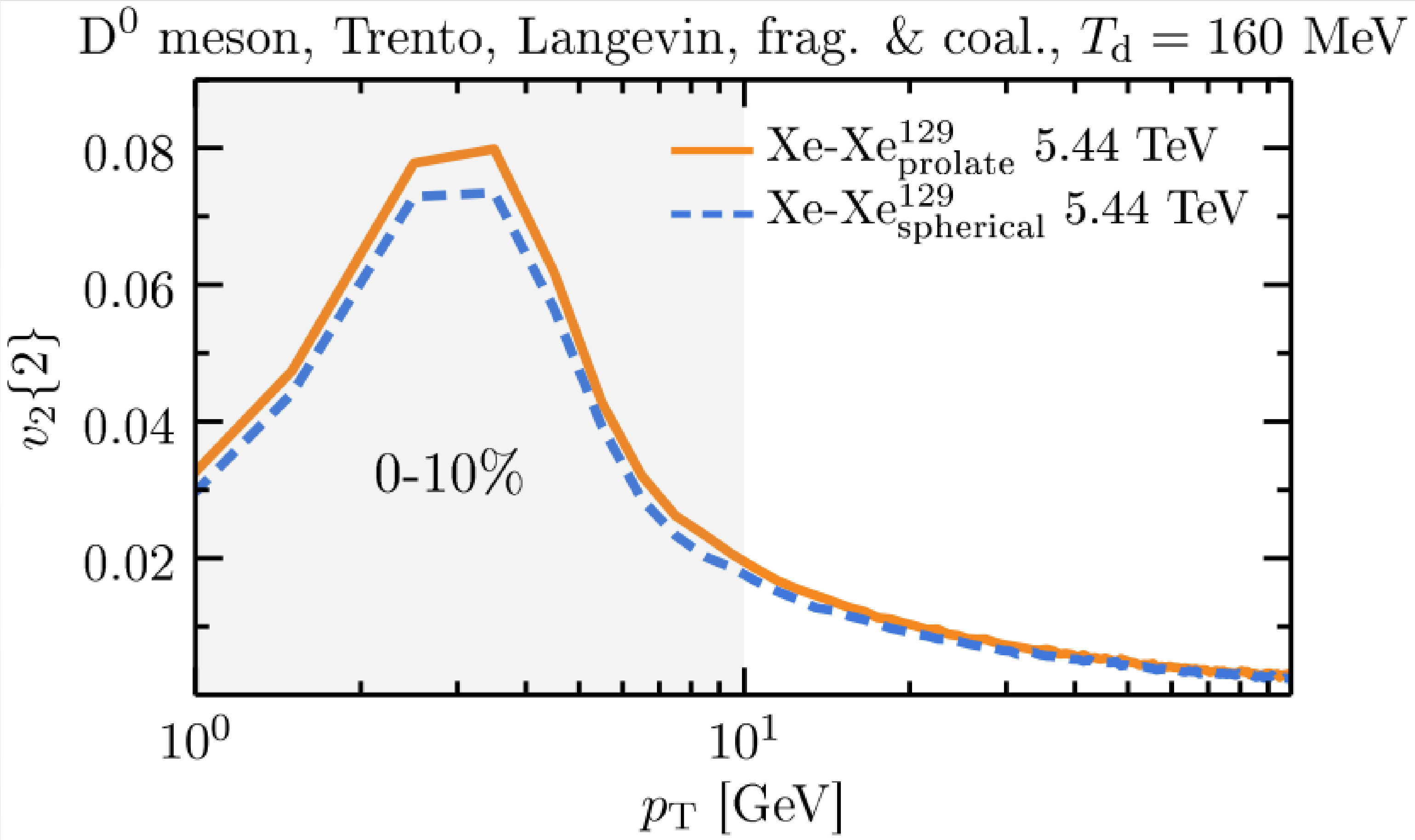
System size scan: v_2 0-10 %



- Balance between v_2 suppression from R ↘ and enhancement from ε_2 ↗
- Larger v_2 of Ar-Ar and O-O in 0-10 % than in 30-50%

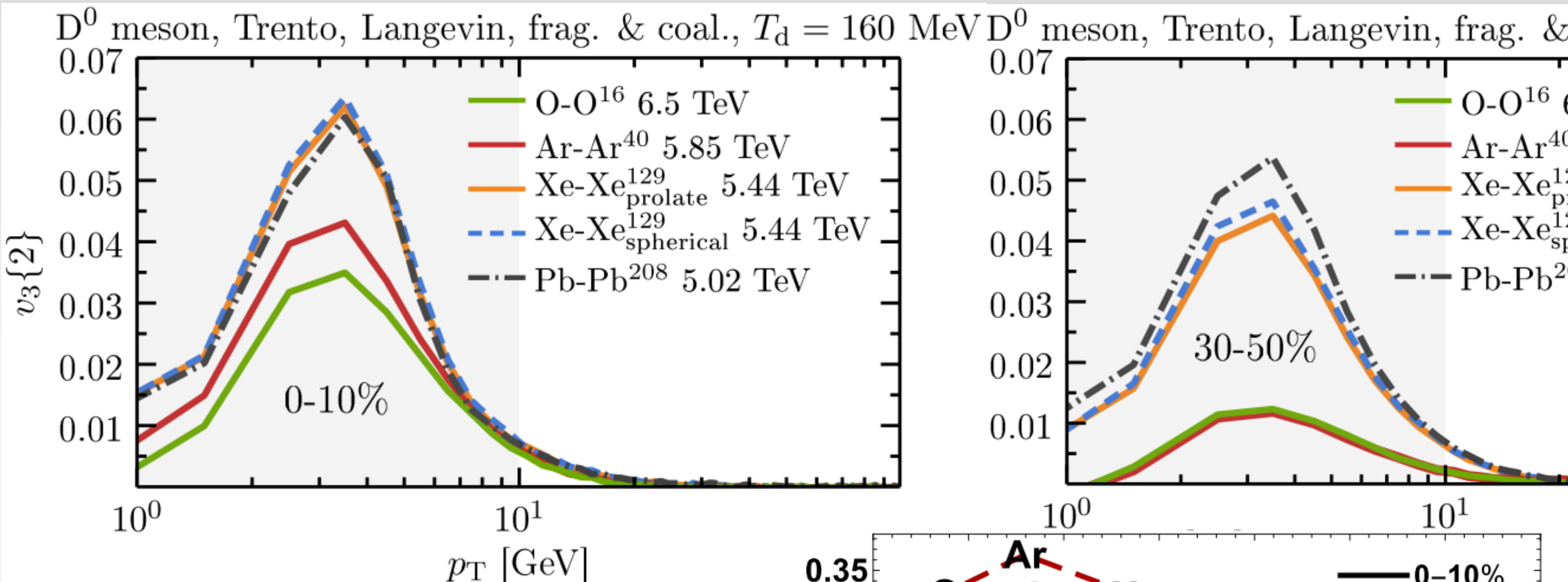


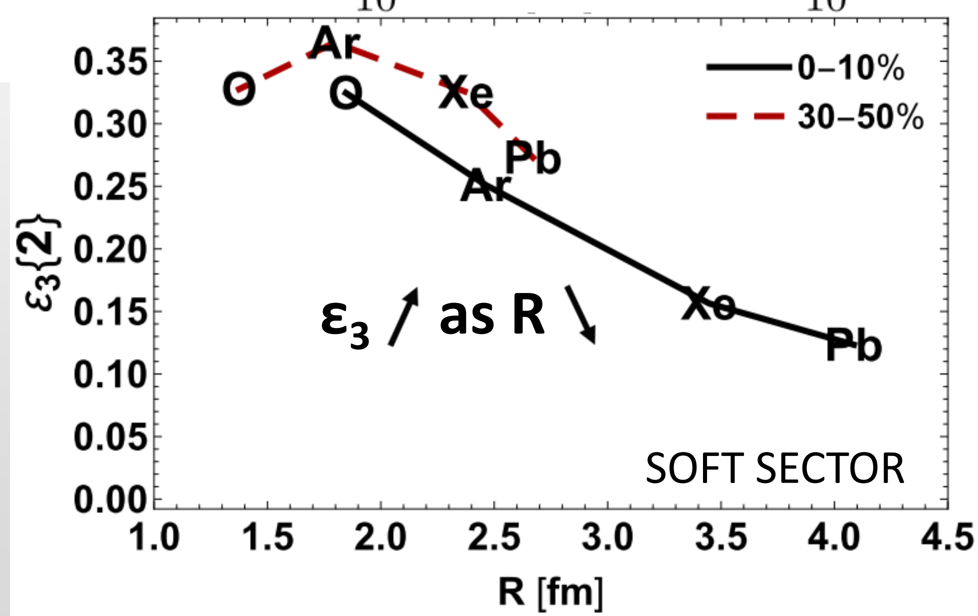
System size scan: v_2



D^0 $v_2\{2\}$ sensitive to deformed Xe^{129} nucleus in central collisions

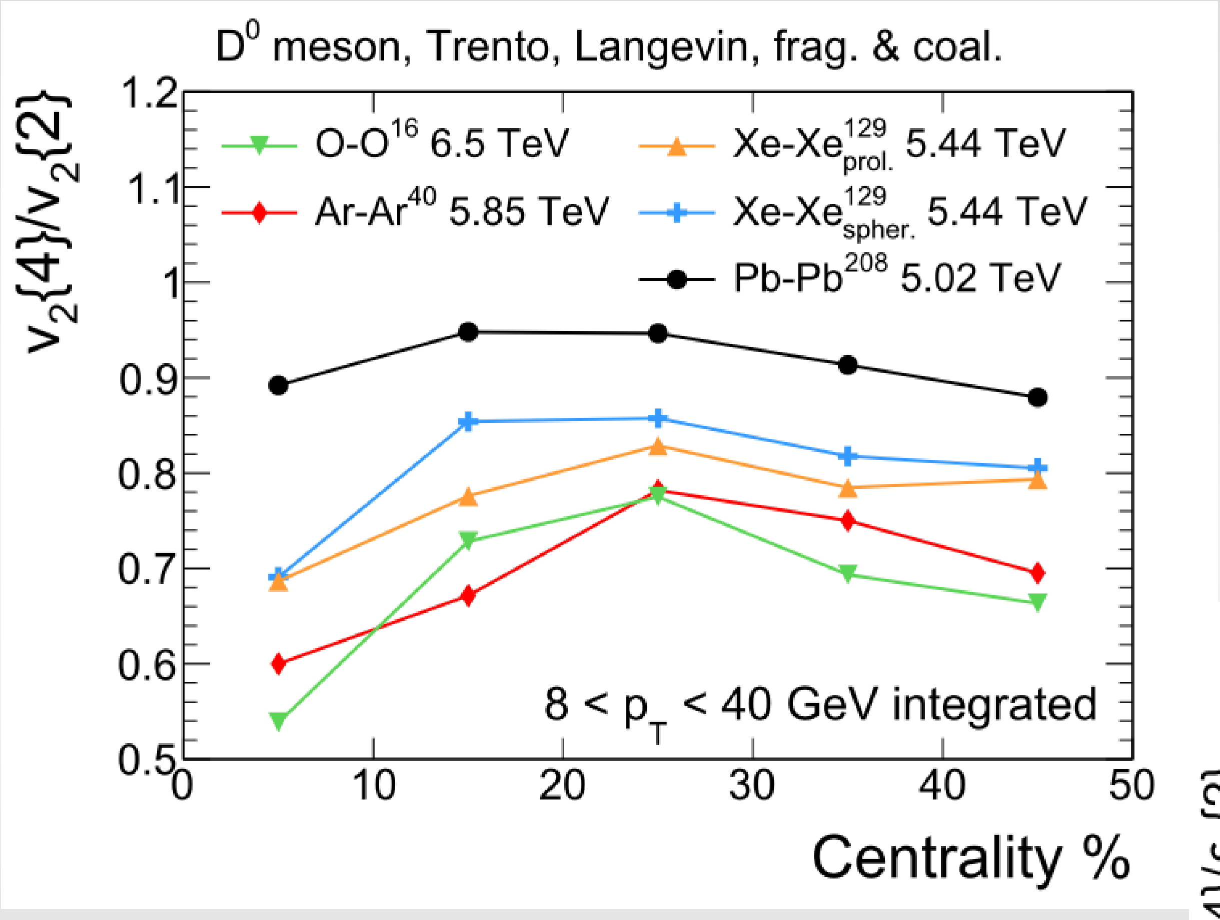
System size scan: v_3





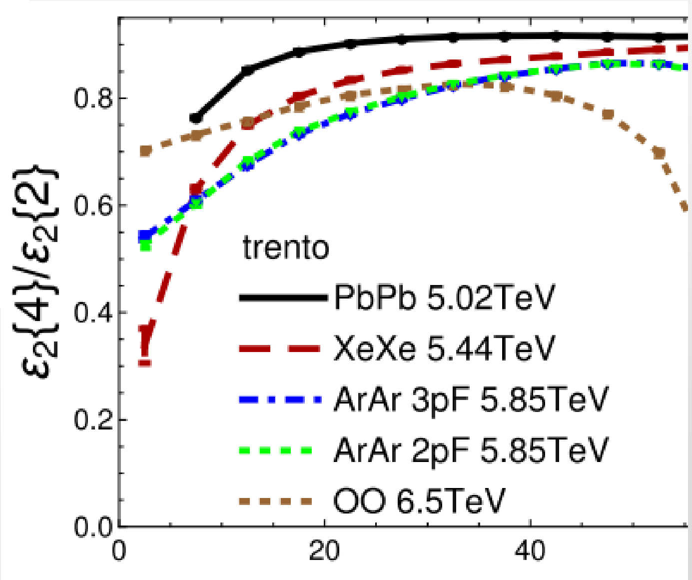
- More suppressed in small systems, even with ε_3 ↗
- At the ≠ of Pb-Pb, in smaller systems no ~ universality with centrality: $v_3^{0\text{-}10\%} >> v_3^{30\text{-}50\%}$

System size scan: $v_2\{4\}/v_2\{2\}$



At high p_T:
strong dependence on system size of the average value

SOFT SECTOR



arXiv: 1901.01319

v2{4}/v2{2} ↘ with size ↘
~ in line with eccentricity calculations

Conclusion 1/2

- « Multi-scale » behaviour:
  Langevin better at low-p_T, energy loss at high-p_T
- Coalescence required but not sufficient to fit low-p_T data
- T_RENTo vs. MCKLN: small effect on common observables
- $v_2\{4\}/v_2\{2\}$ ratio: small dependences on most kinetics, but
  - trend depends on initial fluctuations
  - average value on colliding system size
- Clear linear correlations of the soft and heavy "flows"

Conclusion of D^0 in smaller systems

- First predictions for the D meson observables for the potential system size scan at the LHC
- $R_{AA} \rightarrow 1$ gradually as systems size decreases
- $v_n\{2\}$ arise from interplay between shrinking of path length in small systems and the enhancement of eccentricities in central small systems
- $v_2\{2\}$ ~ const over colliding systems in 0-10% !
  -> balance between these effects
- $v_3\{2\}$ more sensitive to system size despite variation of ε_3

p-Pb: large enough ε_2 to overcome system size shrinking ?

Thank you !

Personal website: rolandkatz.com

Back up

Open heavy flavors

== Many models/simulations on the market ==

PHSD, POWLANG, MC@sHQ+EPOS , BAMPS, TAMU, UrQMD, LBT...

→ **mostly based on Langevin or Boltzmann HF dynamic, with different parametrizations of the diffusion coefficients:**

derived from pQCD models, from lattice QCD, AdS-CFT...

→ **mostly run with/on the top of the bulk dynamic:**

Boltzmann, quasi-particles, averaged or event-by-event (viscous) hydro...

→ **include different ingredients for the initial and final stages:**

shadowing, multiparticle interactions, pre-equilibrium scatterings, fragmentation, recombination, final hadronic rescatterings...

DAB-MOD: heavy quarks

Initial conditions

- **Large oversampling** of the HQs (statistics)
- Spatial -> following initial bulk densities; p_T -> **FONLL spectra**
- **No shadowing or cold nuclear matter** effects

Transport

- **Parametric Energy loss models** $\frac{dE}{}= - f(T, p, x)\,\Gamma_{\text{fl}}$

Where]

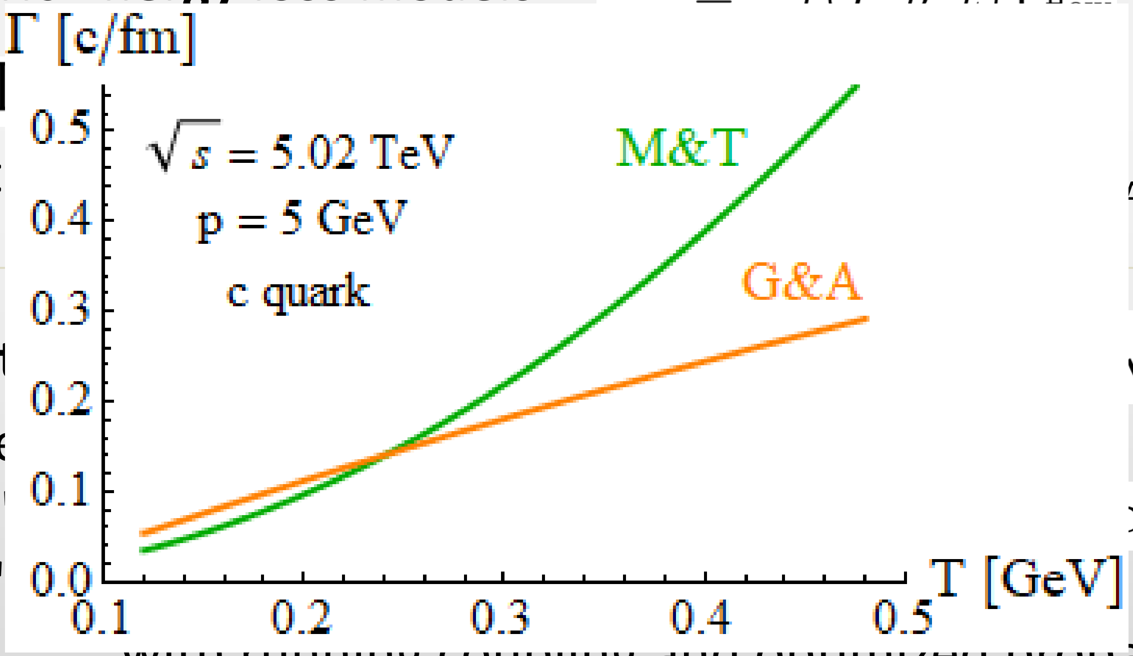
Paramet … $_{AA}$ trends ok

- **Relativist** … $\sqrt{\kappa}\rho_i$

Two diffe…

- "**M&T**" … x $1/(2\pi T)$
- "**G&A**" …

with running coupling and optimized propagator.



Refs: arXiv:1404.6378, arXiv:1609.05171, arXiv:0412346, arXiv:0802.2525

Coalescence

Approximate values at low p_t	Experimental [82, 88, 112–114]	"basic" coalescence	w/ extra element (1)	w/ extra elements (1) & (2)
direct $c \to D^0$	in pp: 0.17	0.06	0.10	0.083
prompt $c \to D^0$	in pp: 0.55	0.36	0.32	0.26
D^+/D^0	0.47	0.32	0.45	0.45
D^{*+}/D^0	0.45	0.5	0.4	0.4
D_s^+/D^0	0.35	0.31	0.34	0.34
D_s^+/D^+	0.75	0.99	0.76	0.76
Λ_c^+/D^0	1.5	0.74	0.94	1.5

Miscellaneous

Free parameters ?

Each **transport model has one -> fixed with 0-10% high-p_T R_{AA}** at T_d = 120 and 160 MeV

The cumulant method ?

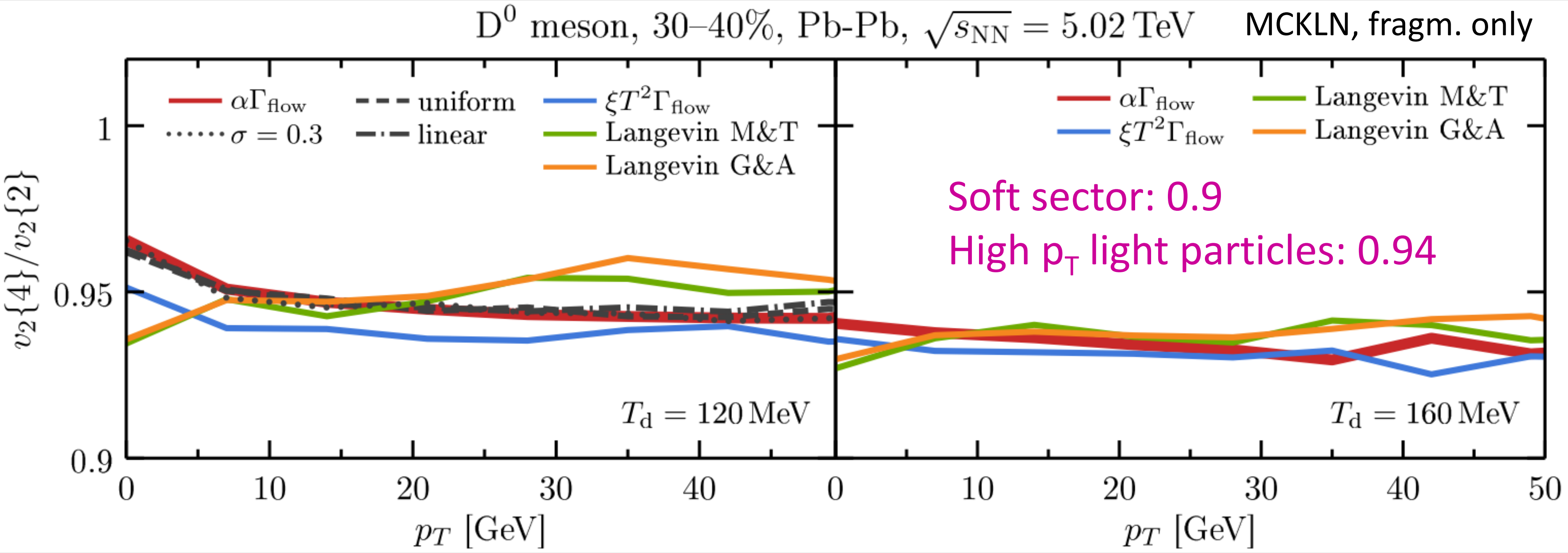
- Based on multiparticle azimuthal correlations => **unambiguous measurement** of the azimuthal anisotropies ≠ Event Plane method (see e.g. Luzum and Ollitrault arXiv: 1209.2323 for more details).
- **Removes non-flow contributions** for cumulant orders > 2
- **$v_n\{k\}(p_T)$: correlation of 1 heavy probe of p_T to k-1 bulk particles**
- In practice: scalar product method, e.g for 2nd order cumulant:

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

+ some multplicity weightings

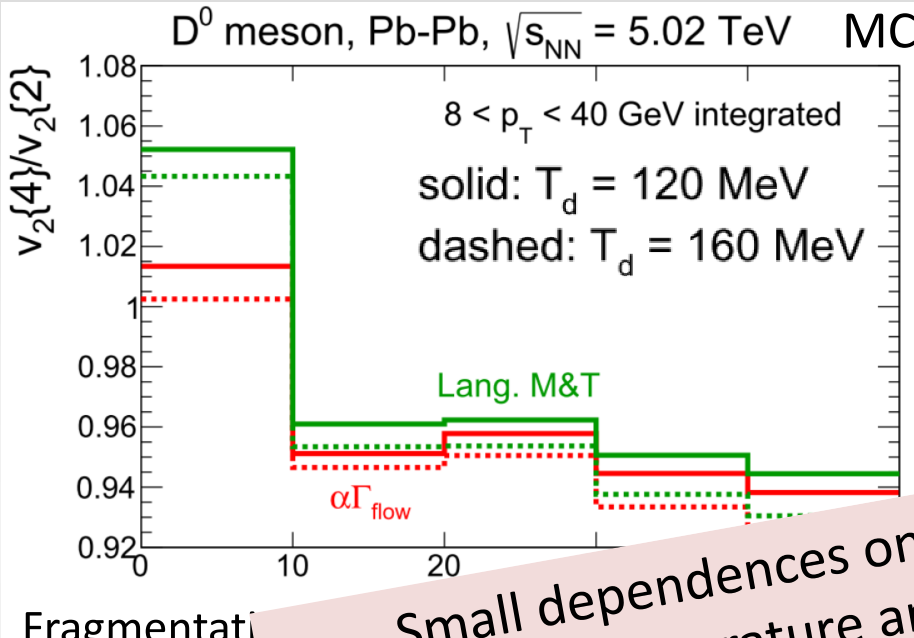
$v_2\{4\}/v_2\{2\}$: p_T

In the soft sector: related to the variance of the flow distribution over events, so mainly to the initial fluctuations.
In the hard sector: deviate from soft value if other sources of fluctuations.

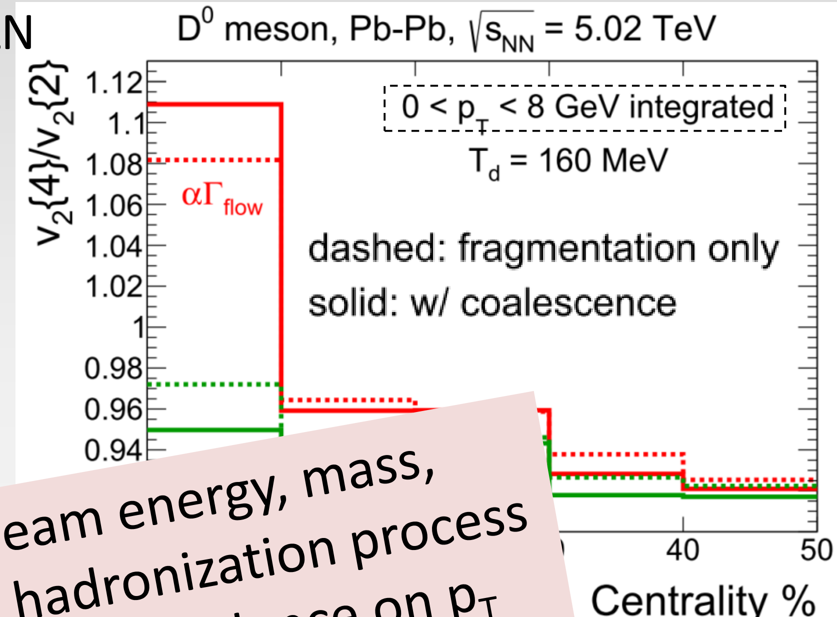


- In 30-40%: v2{4}/v2{2} ~ 0.94 for the high p_T and heavy sectors ≠ soft
- In 30-40%: small depedences on models and p_T

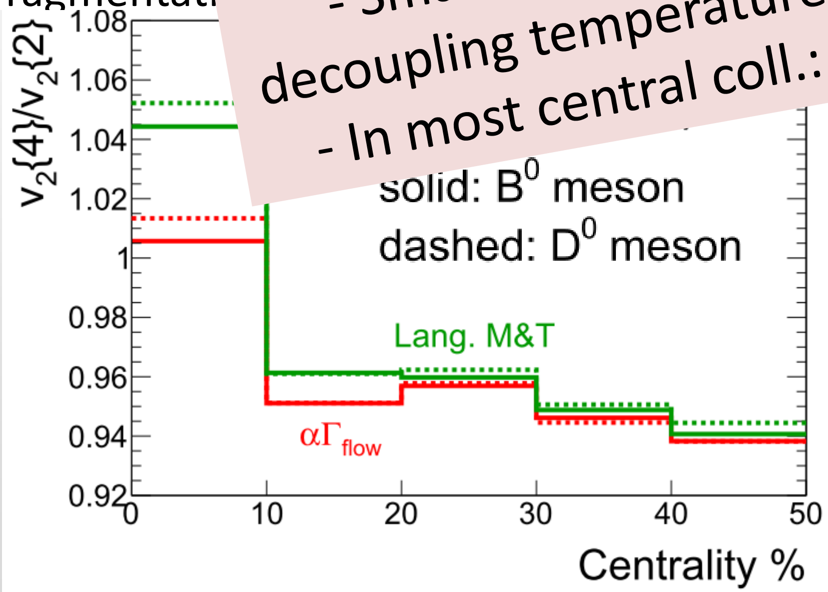
$v_2\{4\}/v_2\{2\}$: other dependences ?

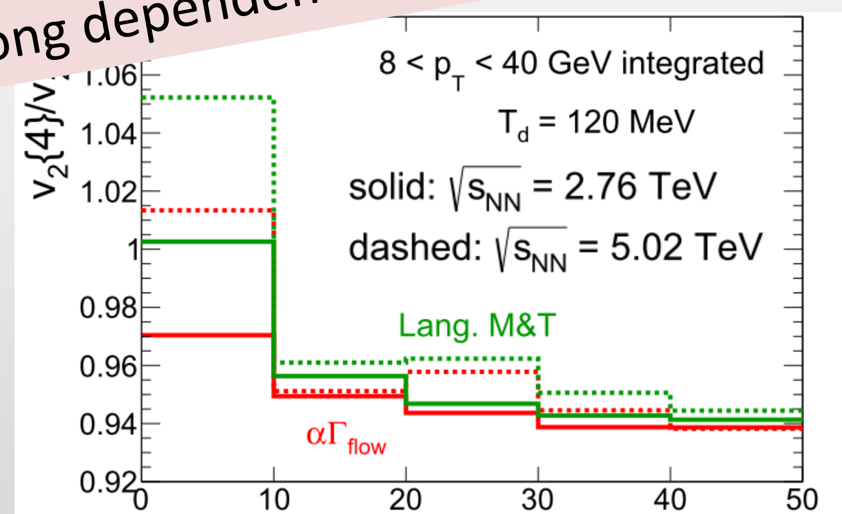


MCKLN



Fragmentation only

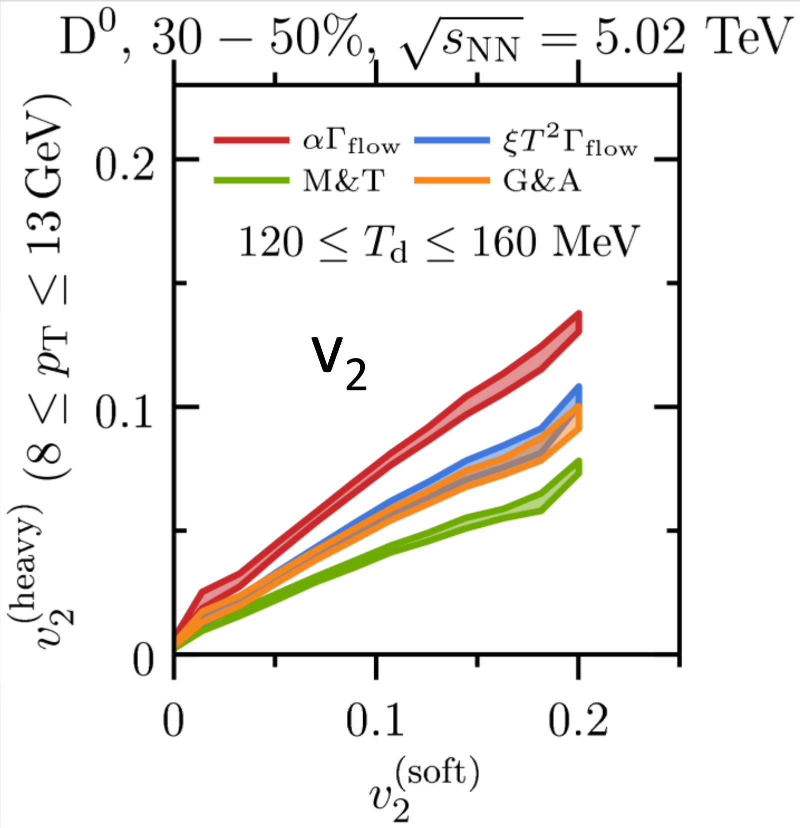


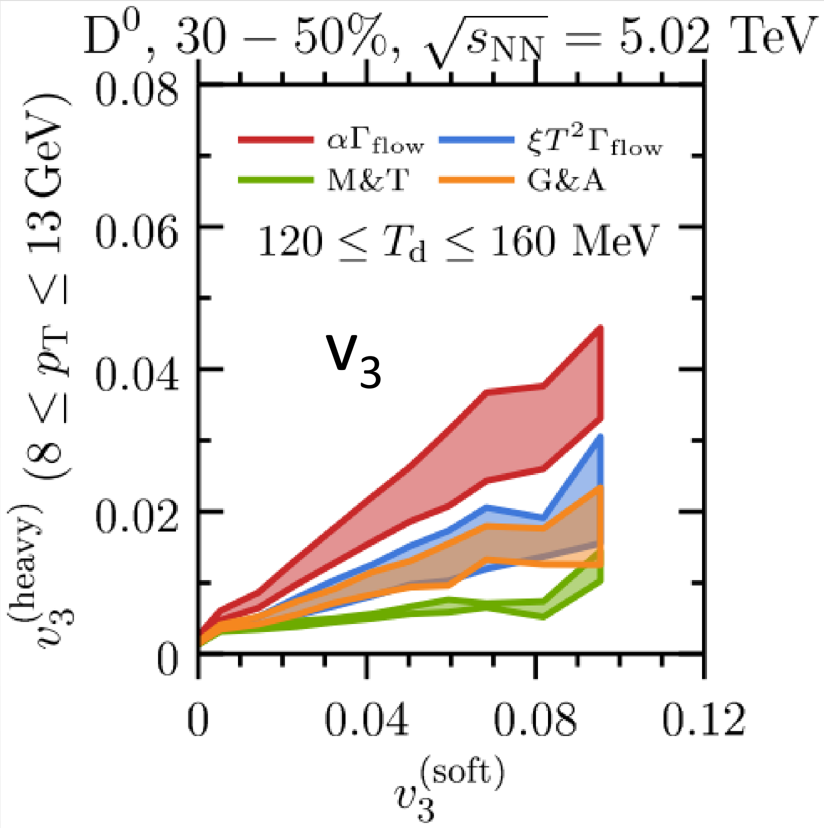


Fragmentation only

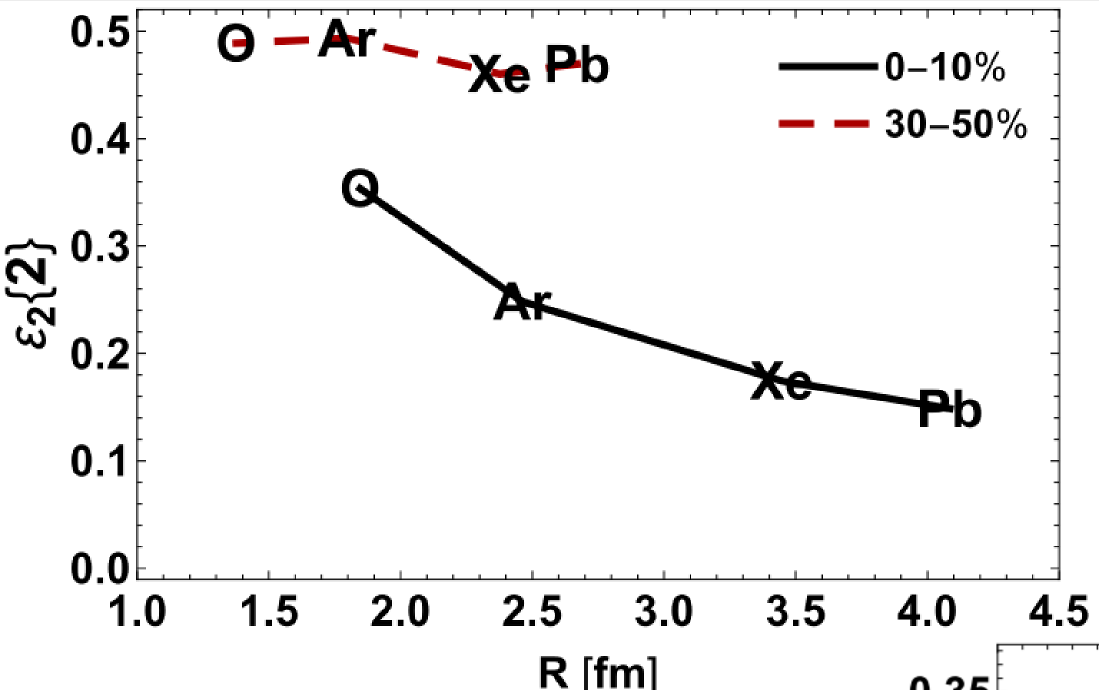
- Small dependences on beam energy, mass, decoupling temperature and hadronization process
- In most central coll.: strong dependence on p_T

Soft-heavy flow correlations

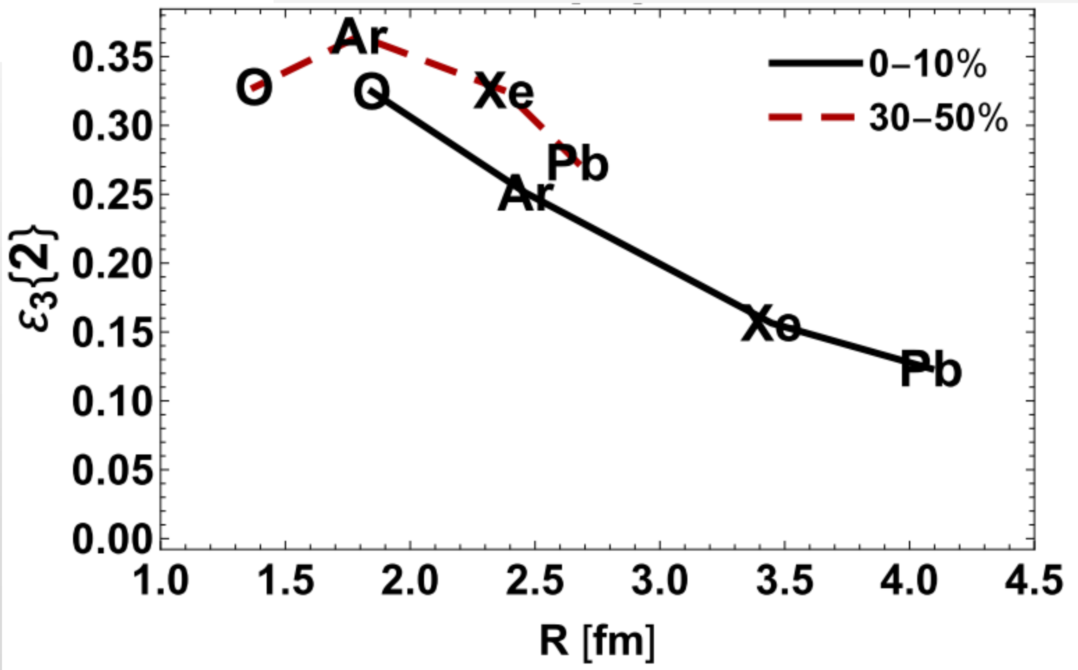




Clear linear correlations between
heavy quark anisotropies and soft flows
=> bulk fluctuations affect the distribution of hard path lengths

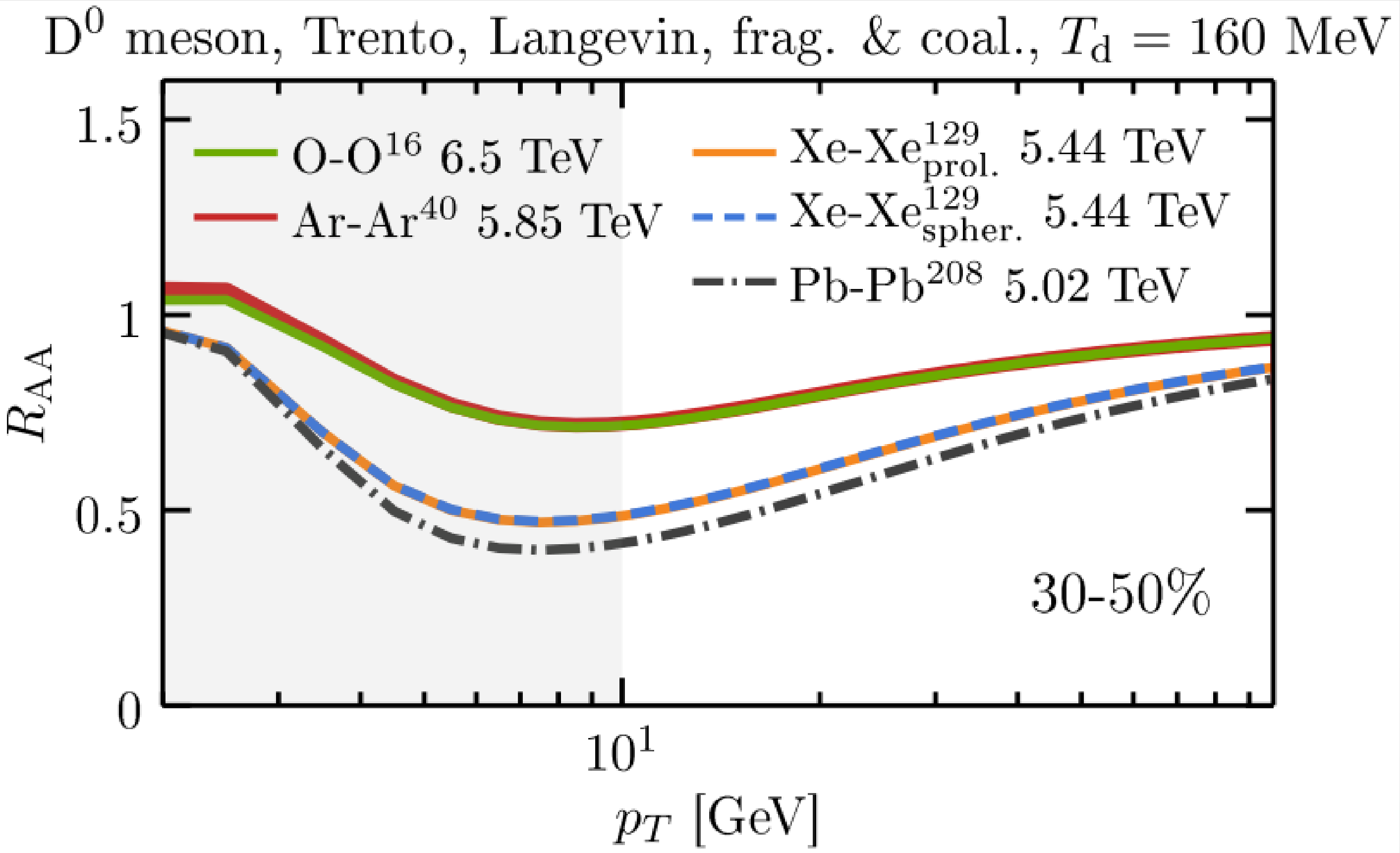


Central collisions:
significant different system sizes
and significantly different
eccentricities.
Thus, the results in central
collisions have two varying effects.

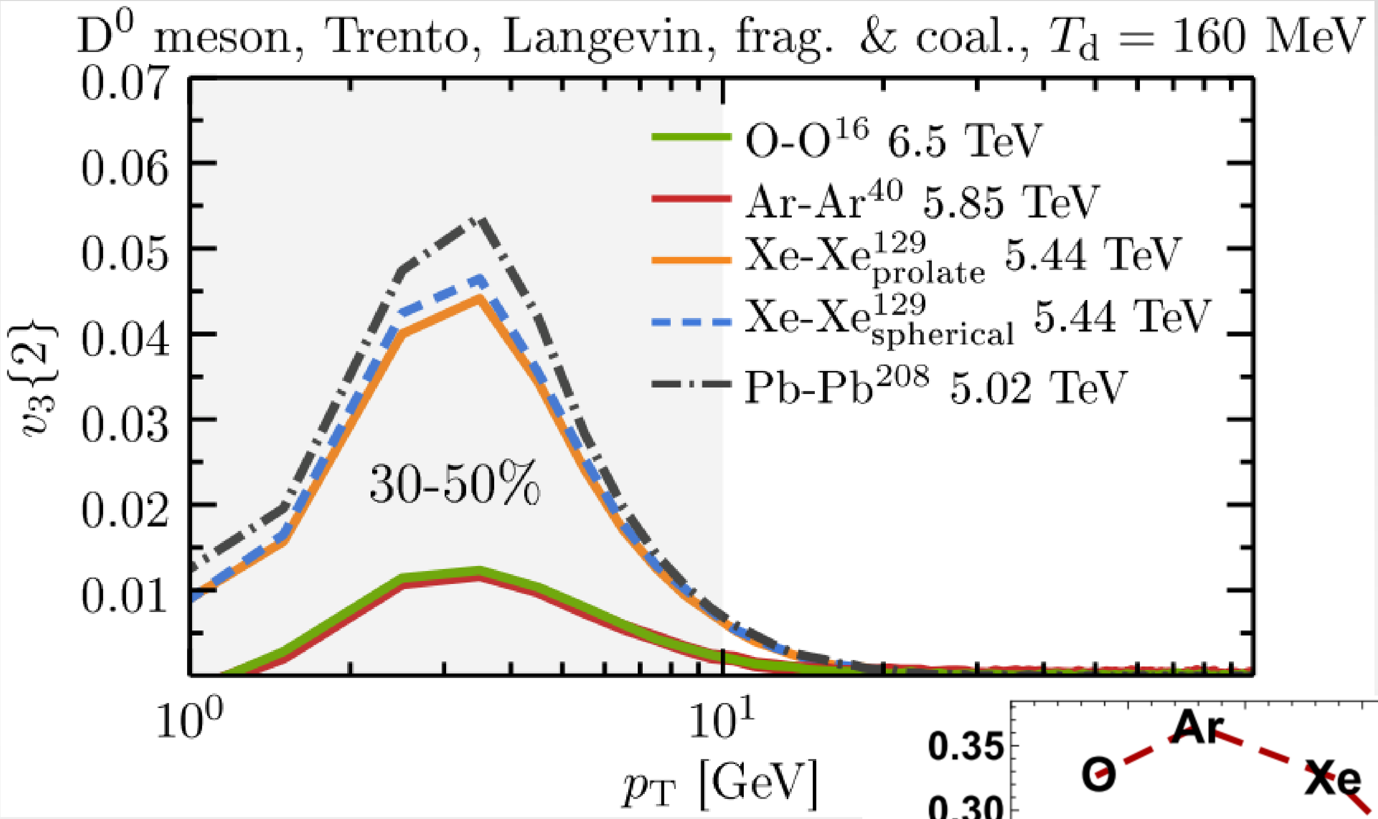


In contrast, mid-central collisions:
roughly equivalent eccentricities
and only vary the system
size -> give us a better insight
into system size effects.

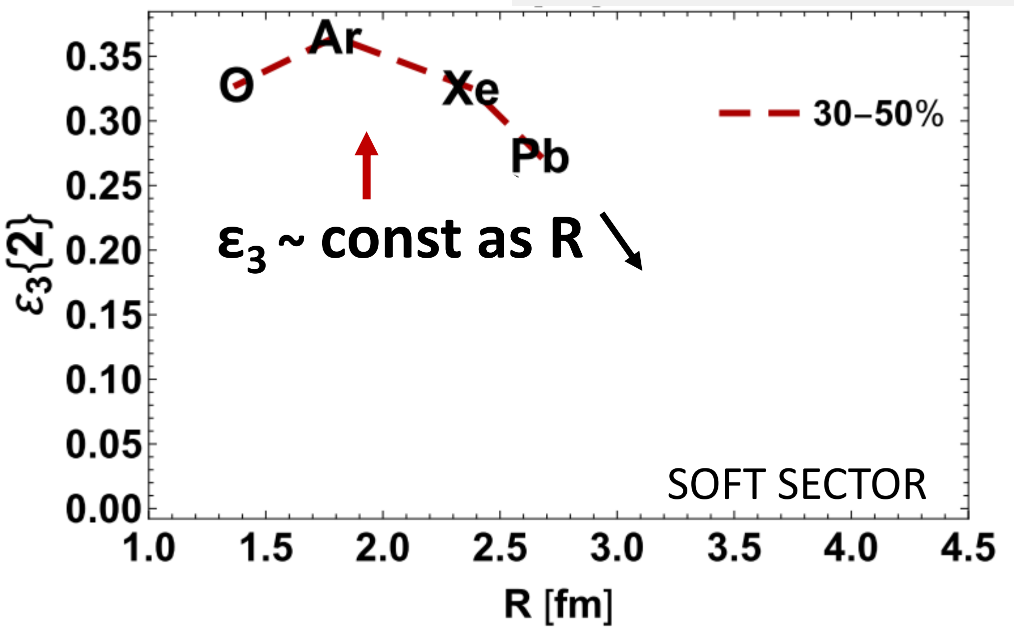
System size scan: R_{AA}



- 30-50% centralities are less sensitive to system size effects
- R_{AA} not sensitive to any effects of a deformed nucleus

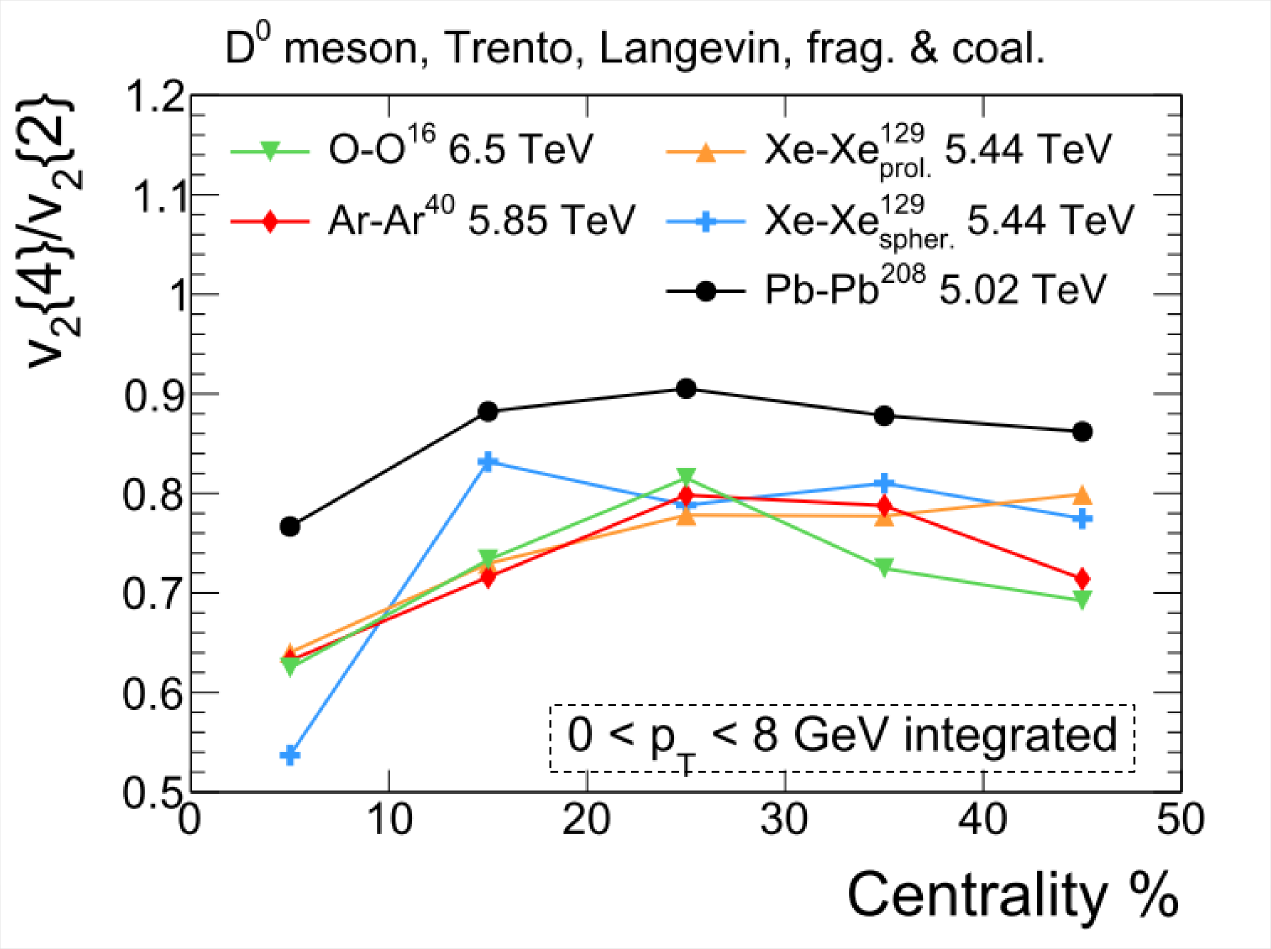


System size scan: v_3 30-50 %



Like for the v_2:
- Whereas $\varepsilon_3 \sim$ const, system size plays an important role for $v_3\{2\}$
- $v_3\{2\}$ of O-O ≈ $v_3\{2\}$ of Ar-Ar

System size scan: $v_2\{4\}/v_2\{2\}$



Lower p_T: less sensitivity to system size

Future

- Extended coalescence at Td=120 MeV and for bottom.
- Langevin with radiative component to improve high-p_T
- p-Pb collisions
- Hadronic re-scattering and shadowing
- 3d+1 hydro and rapidity dependences
- Effect of heavy quark propagation on the medium (back-reaction)