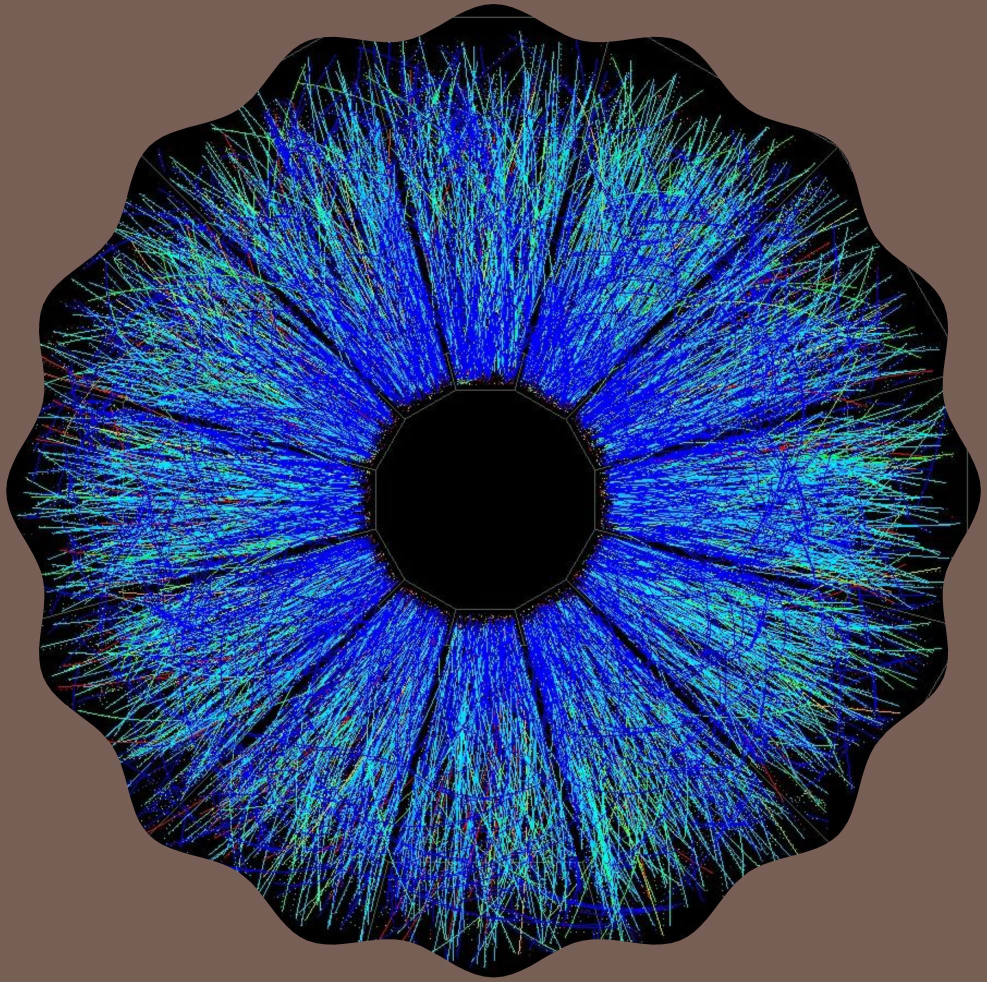


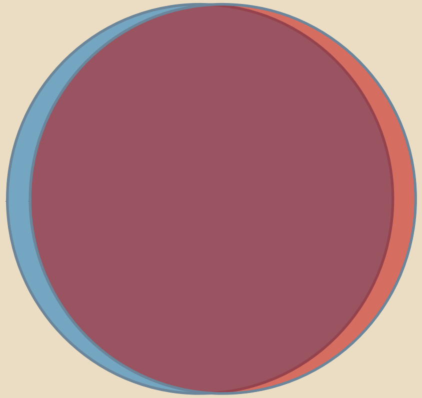
SKANDA RAO, MATTHEW LUZUM
MATTHEW SIEVERT, JACQUELYN NORONHA-HOSTLER
PHYS.REV.C 102 (2020) 5, 054905
ARXIV: 2007.00780 [NUCL-TH]

OCTUPOLE DEFORMATION OF ^{208}Pb DOES NOT RESOLVE THE ULTRA-CENTRAL $v_2 - to - v_3$ PUZZLE

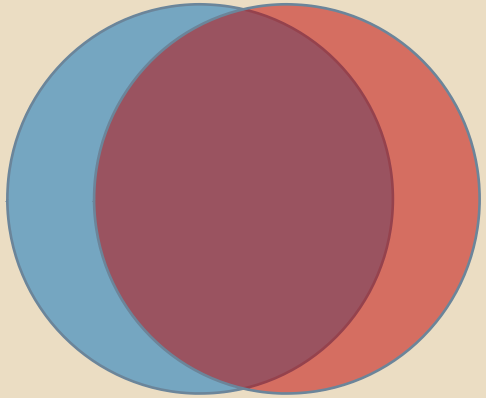
PATRICK CARZON, UIUC
INT 2/20/2023
INTERSECTION OF NUCLEAR STRUCTURE AND HIGH-ENERGY NUCLEAR COLLISIONS

Optical Glauber: Initial Condition

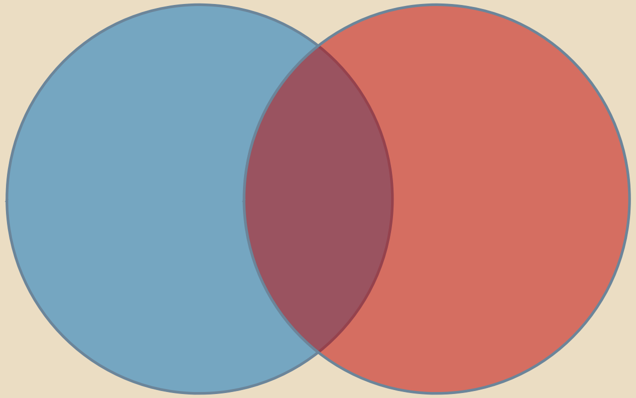
1^{st} −order: Nucleus is a Sphere



Central
(0-10%)



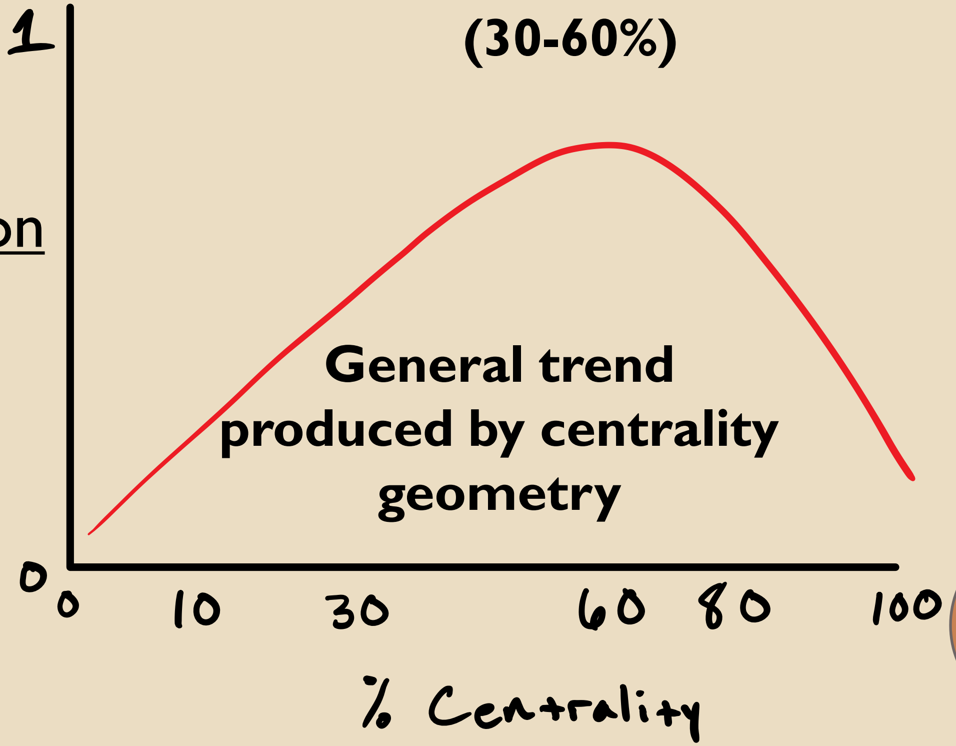
Mid-Central
(30-60%)



Peripheral
(80-100%)

2-Particle Correlation

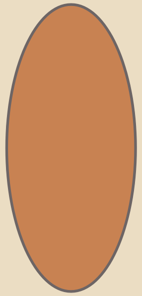
$$\epsilon_n\{2\} = \sqrt{\langle \epsilon_n^2 \rangle}$$



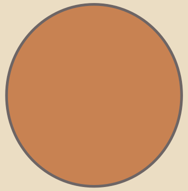
General trend produced by centrality geometry

Fourier Series of Initial State

$$E_n = \epsilon_n e^{in\phi_n}$$



$$\epsilon_2 = 1$$

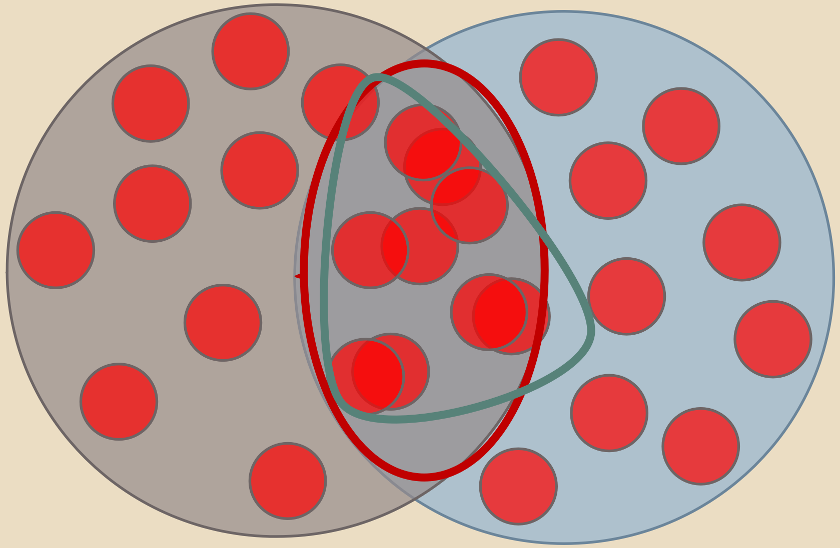


$$\epsilon_2 = 0$$

No Triangularity!

Monte Carlo Glauber: Initial Condition

2^{nd} −order: Nucleon Fluctuations



<u>Including Nucleon Fluctuations</u>

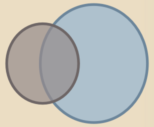
Enhance Ellipticity

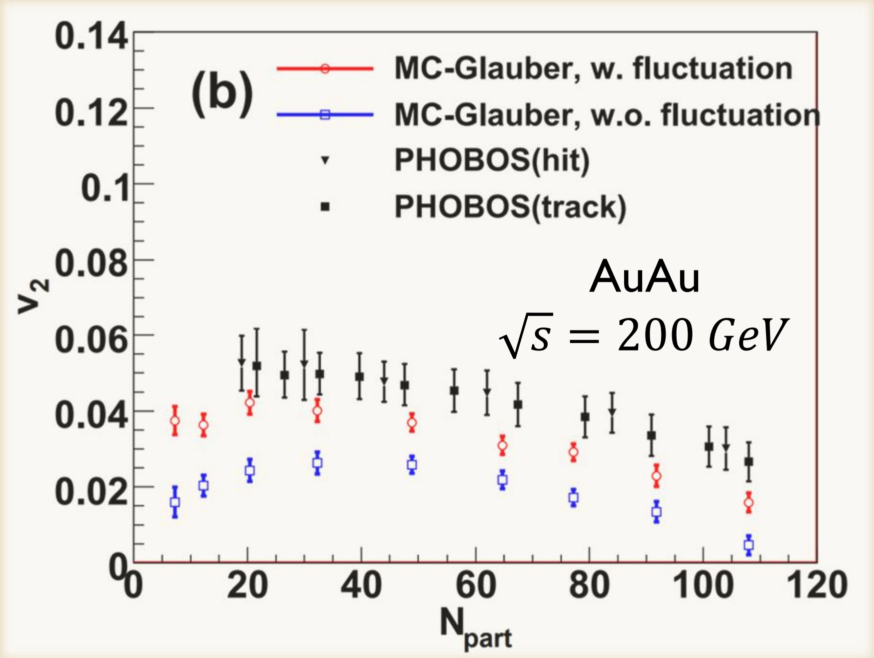
~10% effect on N_{part}

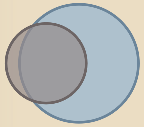
Introduces Significant Triangularity, $\varepsilon_3 > 0$

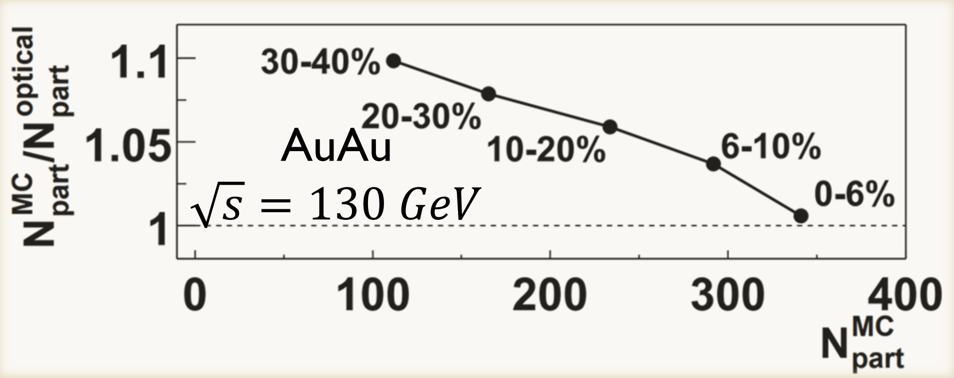
Better agreement with experiment but still significant shortfalls

T. Hirano, Y. Nara
Phys.Rev.C 79 (2009), 064904, arxiv:0904.4080 [nucl-th]





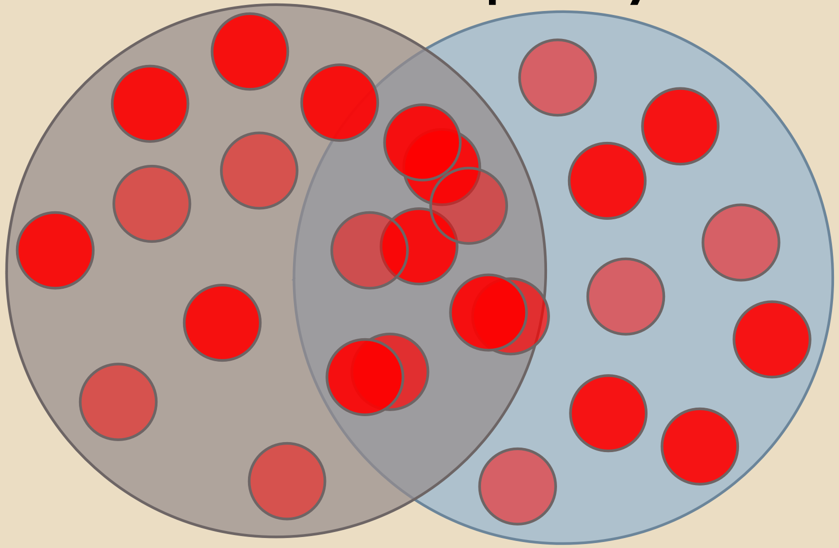




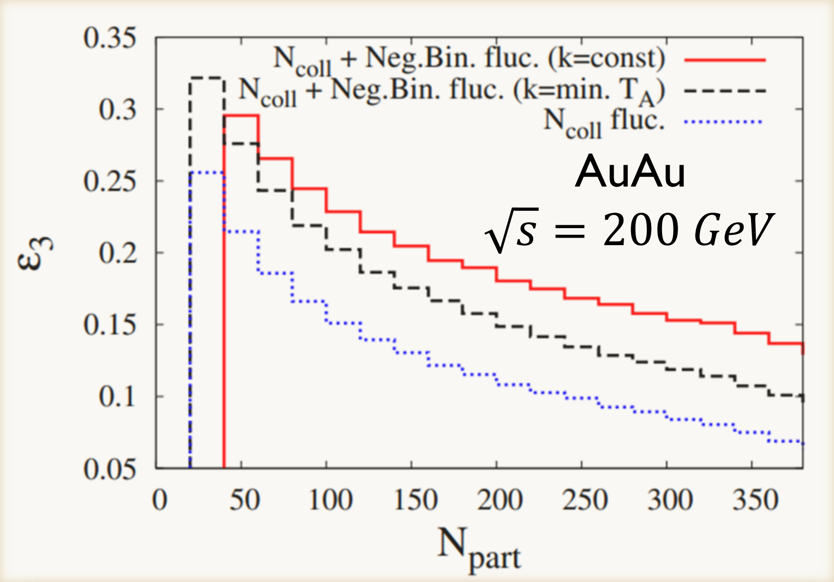
M. L. Miller, K. Reygers, S. J. Sanders, P. Steinberg
Ann.Rev.Nucl.Part.Sci. 57 (2007), 205-243
arxiv:0701025 [nucl-ex]

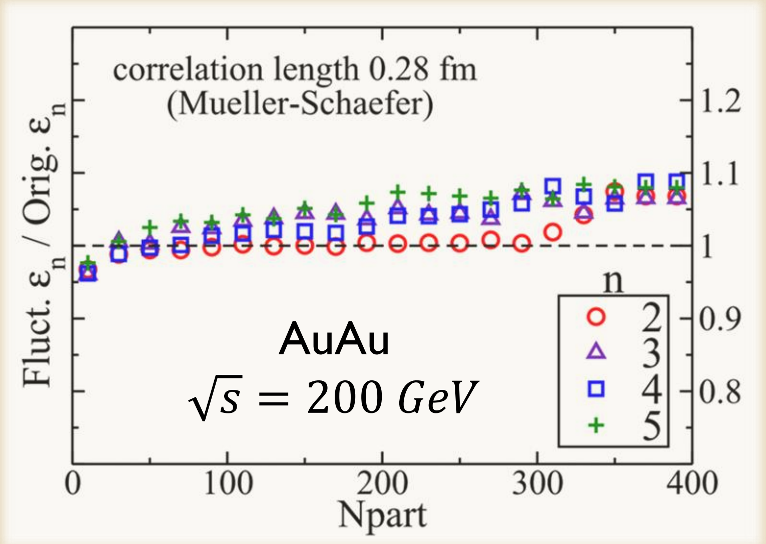
Modern Glauber: Initial Condition

3^{rd} −order: Multiplicity Fluctuations



A. Dumitru and Y. Nara
Phys.Rev.C 85 (2012), 034907, arxiv: 1201.6382 [nucl-th]





J.S. Moreland, Z. Qiu, U.W. Heinz
Nucl.Phys.A 904-905 (2013), 815c-818c, arxiv: 1210.5508 [nucl-th]

Including Multiplicity Fluctuations

Emulates Quantum Fluctuations of Gluons

Enhances Triangularity

~10% effect on all Central Geometry

Theoretical models now fit data very well, except for the most extreme regimes

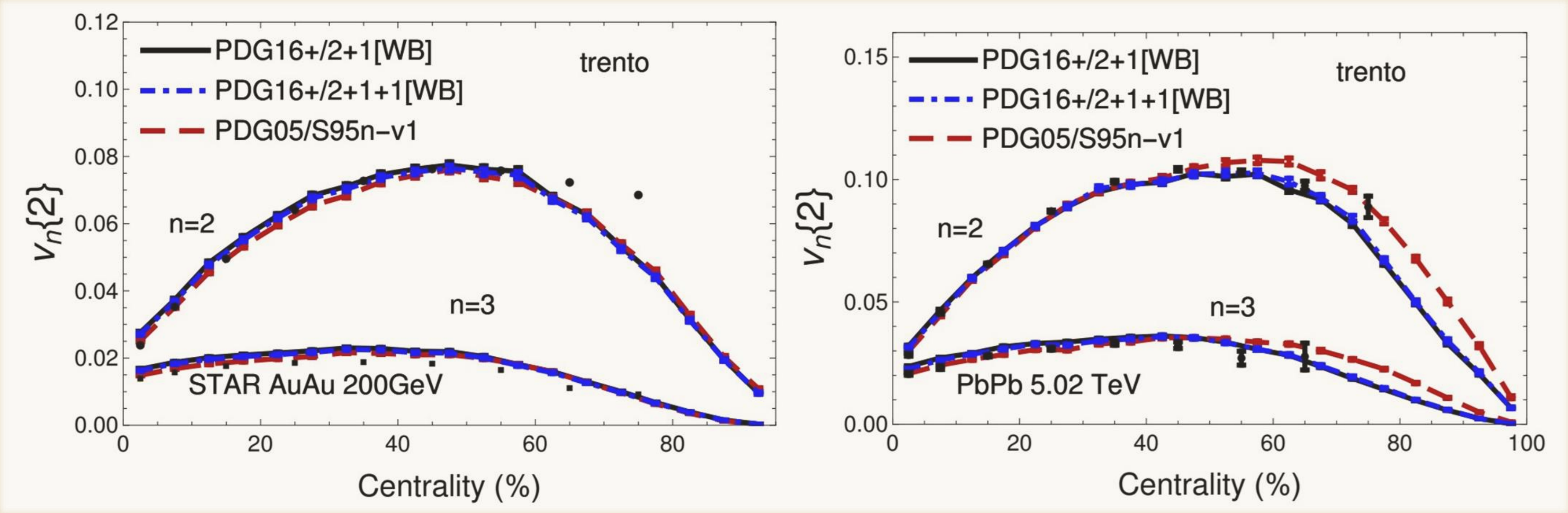
Trento: Initial Condition

Includes

Model Agnostic Construction
Monte Carlo Structure
Nucleon Fluctuations
Multiplicity Fluctuations

Trento can match experimental data despite different choices for evolution

Initial State appears to have a linear scaling relationship with the final state (falls apart > 60% Centrality)



P. Alba, V. Mantovani Sarti, J. Noronha, J. Noronha-Hostler, P. Parotto, I. Portillo Vazquez, and C. Ratti
Phys.Rev. C98 (2018), 034909, arXiv:1711.05207 [nucl-th]

Ultra-Central Weirdness

Ultra-central $^{208}Pb^{208}Pb$

Theory orders $v_2 > v_3$

Experiment shows $v_2 \sim v_3$

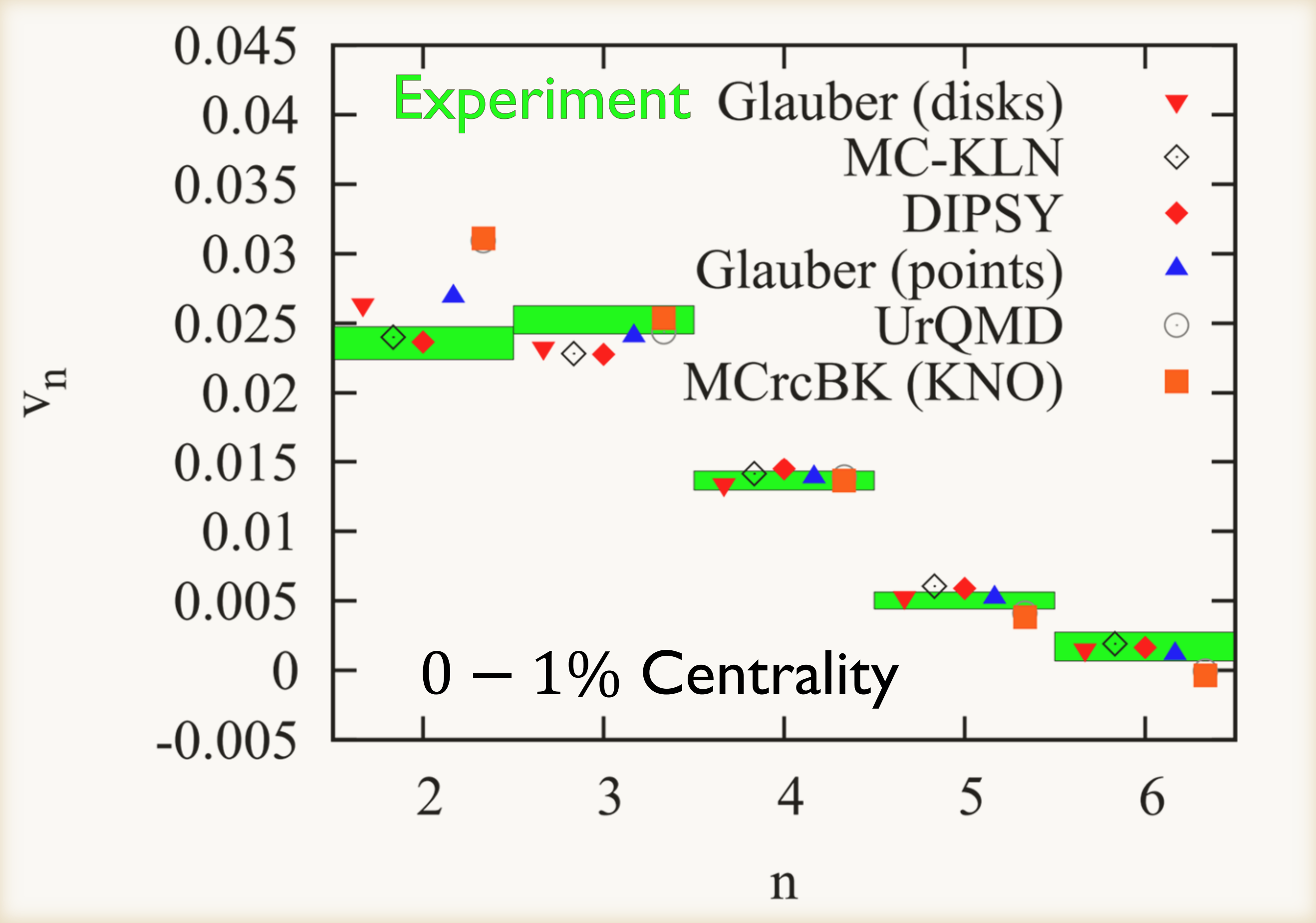
M. Luzum, J-Y. Ollitraulta arXiv:1210.6010 [nucl-th]

P. Alba, V. Mantovani Sarti, J. Noronha, J. Noronha-Hostler, P. Parotto, I. Portillo Vazquez, and C. Ratti arXiv:1711.05207 [nucl-th]

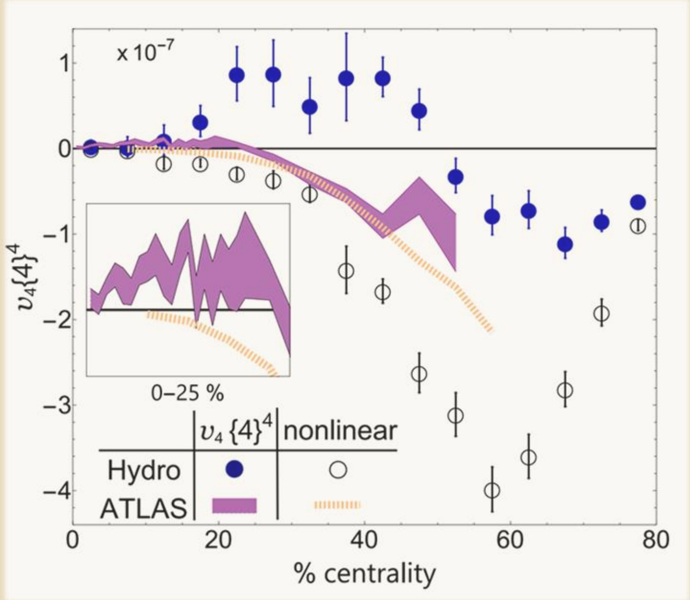
F. Gelis, G. Giacalone, P. Guerrero-Rodríguez, C. Marquet, J-Y. Ollitrault arXiv:1907.10948 [nucl-th]

Chun Shen, Zhi Qiu, and Ulrich Heinz arXiv:1502.04636 [nucl-th]

J-B. Rosea, J-F. Paqueta, G. S. Denicola, M. Luzuma, B. Schenkec, S. Jeona, C. Galea arXiv:1408.0024 [nucl-th]



M. Luzum, J-Y. Ollitrault
Nucl.Phys.A 904-905 (2013), 377c-380c
arxiv: 1210.6010 [nucl-th]



G. Giacalone, L. Yan, J. Noronha-Hostler, J.-Y. Ollitrault
J.Phys.Conf.Ser. 779 (2017) 1, 012064
arxive: 1608.06022 [nucl-th]

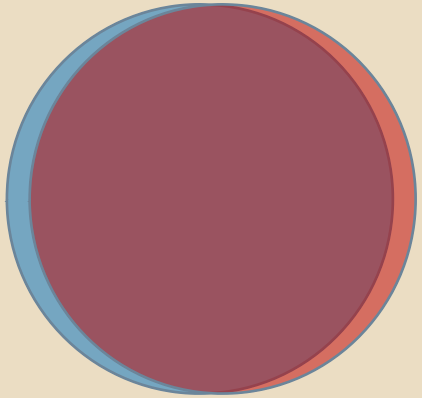
Train of Logic

Why do hydrodynamic models get $v_2 > v_3$?

Final State
Flow Harmonics - $v_n = \kappa_n \epsilon_n$ - Initial State
Geometry

Linear Response Coefficients
Contain information about viscosity

Initial State



Ultra-Central
$\epsilon_2 \approx \epsilon_3 \approx 0$

Event-by-event fluctuations lead to

$\epsilon_2 \approx \epsilon_3 \neq 0$

Viscosity orders response coefficients as

$\kappa_2 > \kappa_3$

Which leads to

$v_2 > v_3$

To offset viscosity effects we need

$\epsilon_2 < \epsilon_3$

Response across system size: M. Sievert and J. Noronha-Hostler, *Phys. Rev. C*100, (2019) 2, 024904
M. Bleicheret al., J. Phys. G25, 1859 (1999), arXiv:hep-ph/9909407
T. Nunes da Silva, D. Dobrigkeit Chinellato, R. Der-radi De Souza, M. Hippert, M. Luzum, J. Noronha, andJ. Takahashi, MDPI Proc.10, 5 (2019), arXiv:1811.05048[nucl-th]
H. Marrochio, J. Noronha, G. S. Denicol, M. Luzum,S. Jeon, and C. Gale, Phys. Rev. C91, 014903 (2015),arXiv:1307.6130 [nucl-th]
G. Denicol, S. Jeon, and C. Gale, Phys. Rev. C90,024912 (2014), arXiv:1403.0962 [nucl-th]
J. Adamet al.(ALICE), Phys. Rev. Lett.117, 182301(2016), arXiv:1604.07663 [nucl-ex]
G. Giacalone, L. Yan, J. Noronha-Hostler, and J.-Y. Olli-trault, Phys. Rev. C94, 014906 (2016), arXiv:1605.08303[nucl-th]

Nuclear Deformation

L.M. Robledo, G.F. Bertsch
Phys.Rev.C 84 (2011), 054302
arxiv: 1107.3581 [nucl-th]

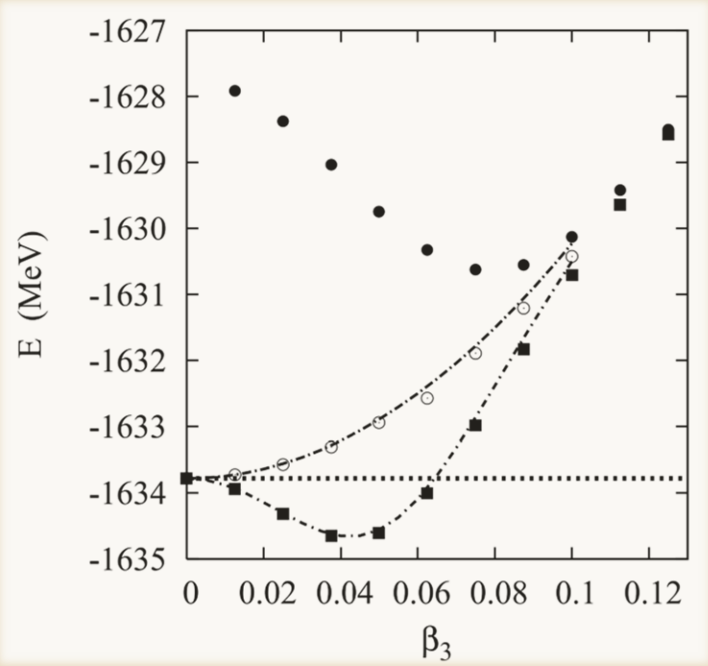
Optimizing Triangularity

$$\rho(r,\theta) = \rho_0 \left[1 + e^{\frac{r-R(\theta)}{a}}\right]^{-1}$$

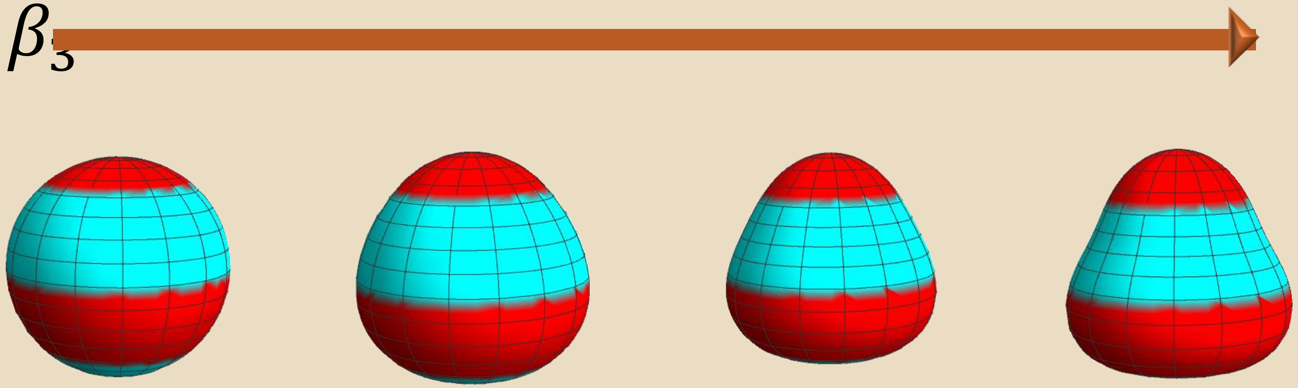
Woods-Saxon Distribution

$$R(\theta) = R(1 + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta) + \cdots)$$

Radius Expansion



$\beta_3 \approx 0.0375$ and $\beta_3 \approx 0.075$ have preferable energy configurations



Other Ultra-Central Collisions

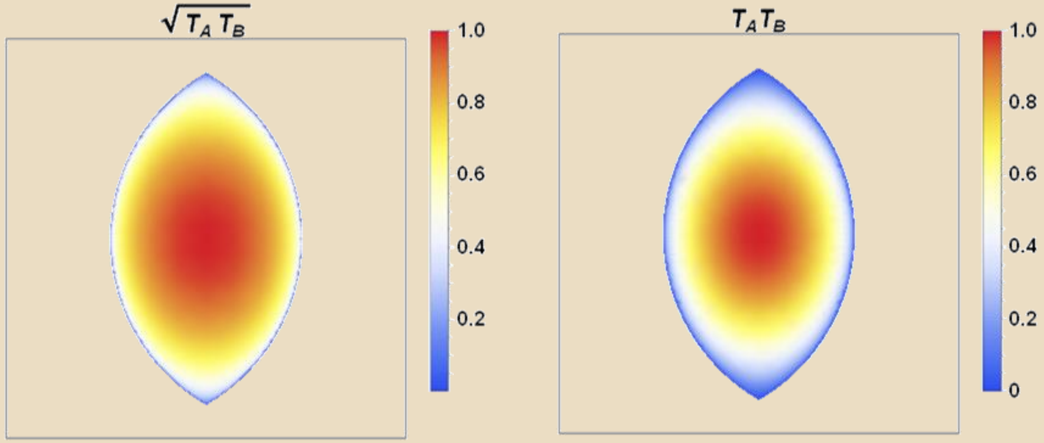
(^{129}Xe, ^{238}U) have been analyzed

Phys. Rev.C97, 034904 (2018),arXiv:1711.08499 [nucl-th]
Phys. Lett.B784, 82 (2018),arXiv:1805.01832 [nucl-ex]
Phys. Lett.B788, 166 (2019),arXiv:1805.04399 [nucl-ex]
C. Collaboration (CMS), (2018)
T. A. collaboration (ATLAS), CERN (CERN, Geneva,2018)
Phys. Rev. Lett.115,222301 (2015), arXiv:1505.07812 [nucl-ex]
Phys.Rev.C92, 044903 (2015), arXiv:1507.03910 [nucl-th]
Phys.Rev.C95, 064907 (2017), arXiv:1609.01949 [nucl-th]
Phys. Rev.C99, 024910 (2019),arXiv:1811.03959 [nucl-th]

Models

Trento
- Bayesian Analysis showed the best reduced thickness is given by $T_R = \sqrt{T_A T_B}^{*}$
- Theory based models (CGC) produce the relation $T_R = T_A T_B{}^{\dagger}$ (In backup slides)

- **v-USPhydro (Parameter Set 1)**
  - EOS (WB21/PDG16+), state of the art
  - Hadronic After Burner, direct decays only but full particle list
  - $\frac{\eta}{s} = const, \frac{\zeta}{s} = 0$



- **MUSIC (Parameter Set 11)**
  - EOS (s95p-v1.2), outdated
  - Hadronic After Burner (UrQMD), transport but not all resonances
  - $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$, from Bayesian Analysis

* **TRENTO:** J. S. Moreland et al, Phys. Rev.C92, 011901 (2015), 1412.4708
J. E. Bernhard et al, Phys. Rev.C94, 024907(2016), 1605.03954
† $T_A T_B$ **scaling:** J. L. Nagle and W.A. Zajc,[arXiv:1808.01276[hep-th]]
T. Lappi, Phys. Lett. B643, 11 (2006), arXiv:hepph/0606207 [hep-ph]
G. Chen et al, [arXiv:1507.03524 [nucl-th]]
P. Romatschke and U. Romatschke, [arXiv:1712.05815 [nucl-th]]

v-USPhydro: J. Noronha-Hostler et al, Phys. Rev. C88, 044916 (2013),arXiv:1305.1981 [nucl-th]
J. Noronha-Hostler et al, Phys.Rev. C90, 034907 (2014), arXiv:1406.3333 [nucl-th]
EOS data comparison: P. Alba et al, Phys. Rev. C98, 034909 (2018), arXiv:1711.05207 [nuclth]
PDG16+: P. Alba et al., Phys. Rev. D96, 034517 (2017), arXiv:1702.01113 [hep-lat]

MUSIC: B. Schenke et al, Phys. Rev. C82,014903 (2010), arXiv:1004.1408 [hep-ph]
B. Schenke et al, Phys. Rev. Lett.106,042301 (2011), arXiv:1009.3244 [hep-ph]
EOS: P. Huovinen and P. Petreczky, Nucl. Phys. A 837, 26 (2010), arXiv:0912.2541 [hep-ph]
UrQMD: S. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998), arXiv:nucl-th/9803035
M. Bleicher et al., J. Phys. G 25, 1859 (1999), arXiv:hepph/9909407

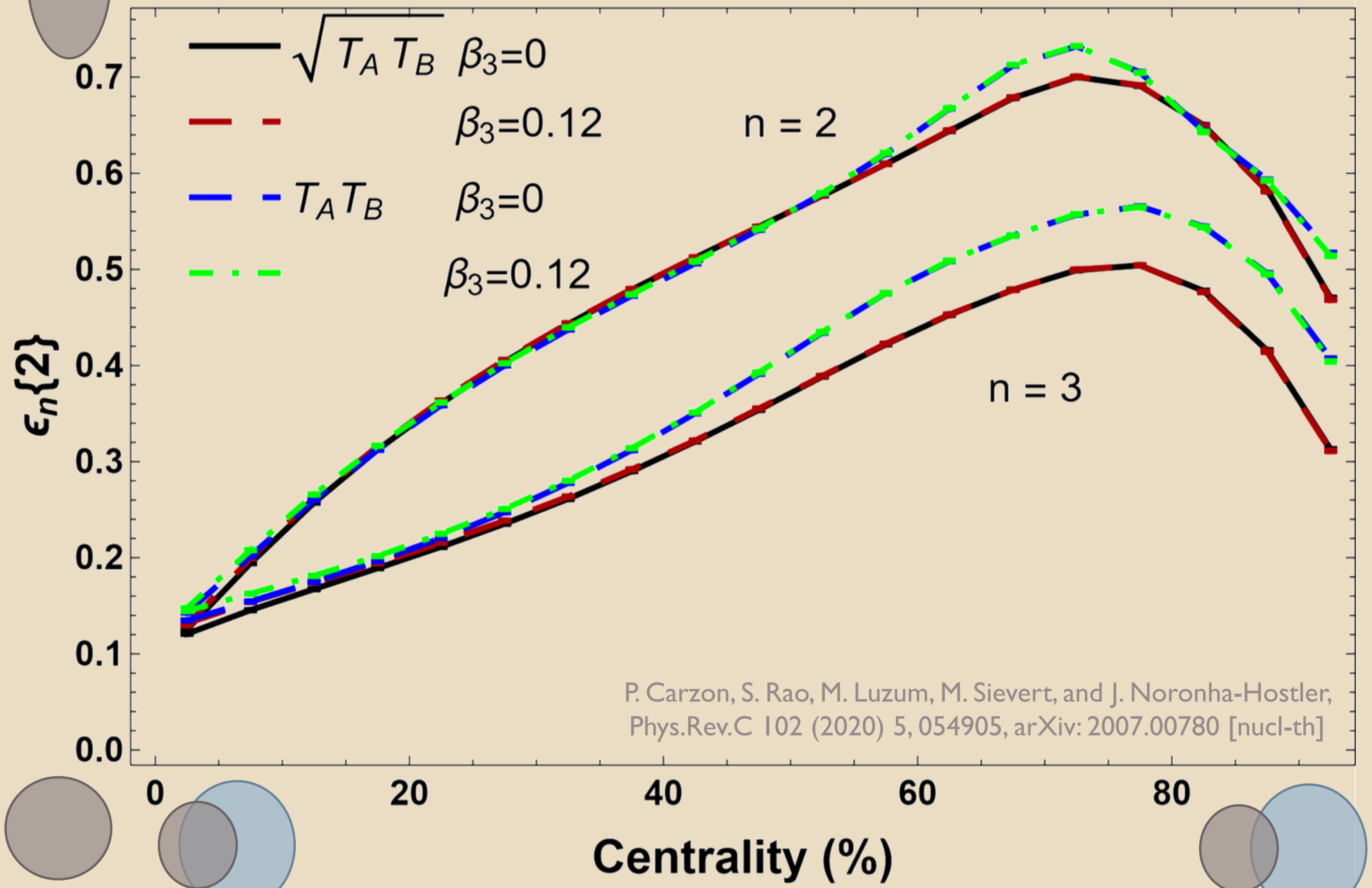
Eccentricities: Definitions

$$\epsilon_n\{2\} = \sqrt{\langle \epsilon_n^2 \rangle}$$

Two-Particle Correlation

No substantial difference seen when including maximum considered β_3, except at Ultra-Central

$T_A T_B$ is in backup slides



P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, Phys.Rev.C 102 (2020) 5, 054905, arXiv: 2007.00780 [nucl-th]

Elliptic/Triangular Ratios

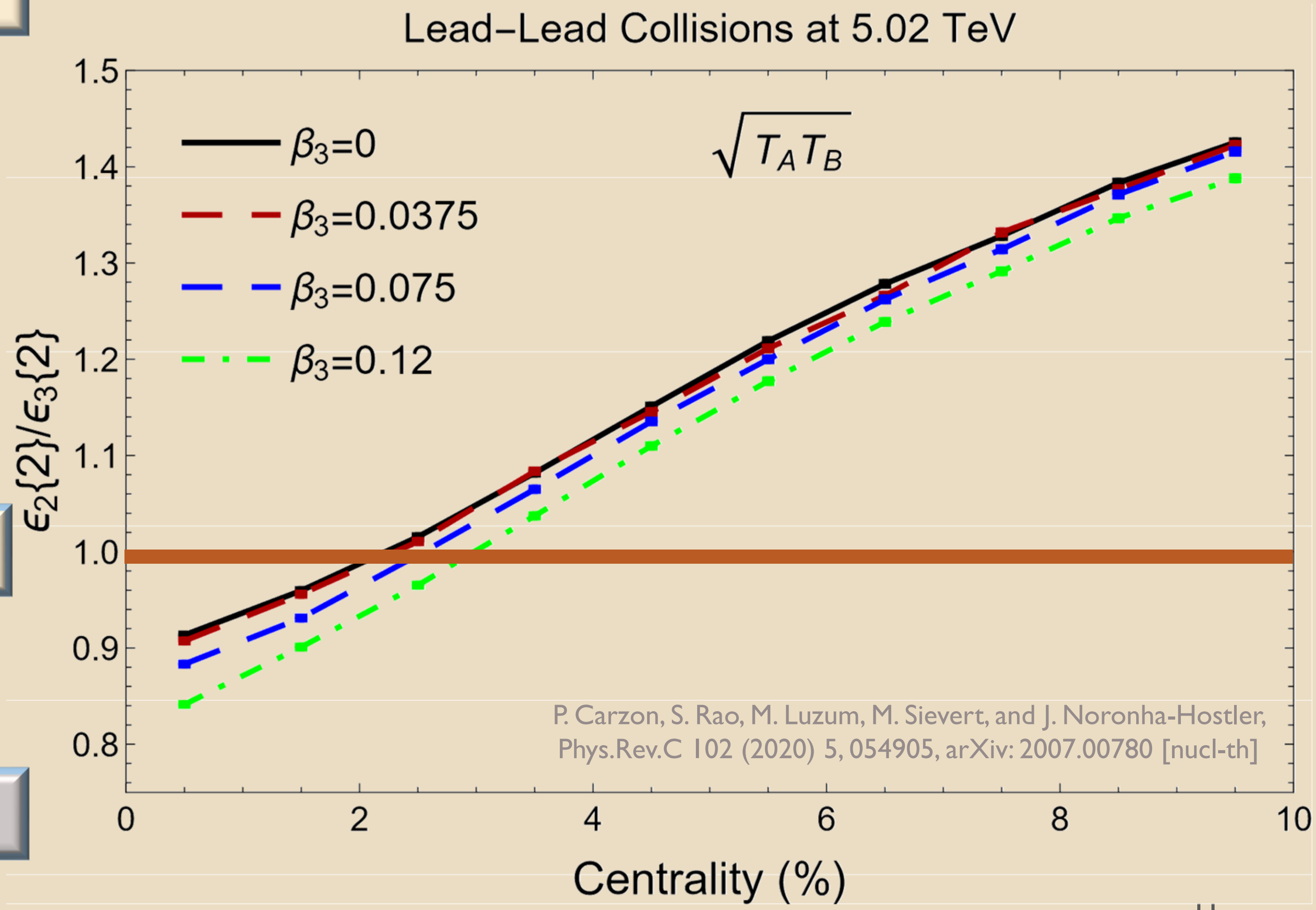
$\epsilon_3 > \epsilon_2 \rightarrow v_3 \sim v_2$

$\epsilon_3 < \epsilon_2$

$$\frac{v_2\{2\}}{v_3\{2\}} \approx \frac{\kappa_2 \epsilon_2\{2\}}{\kappa_3 \epsilon_3\{2\}}$$

$\epsilon_3 \sim \epsilon_2$

$\epsilon_3 > \epsilon_2$

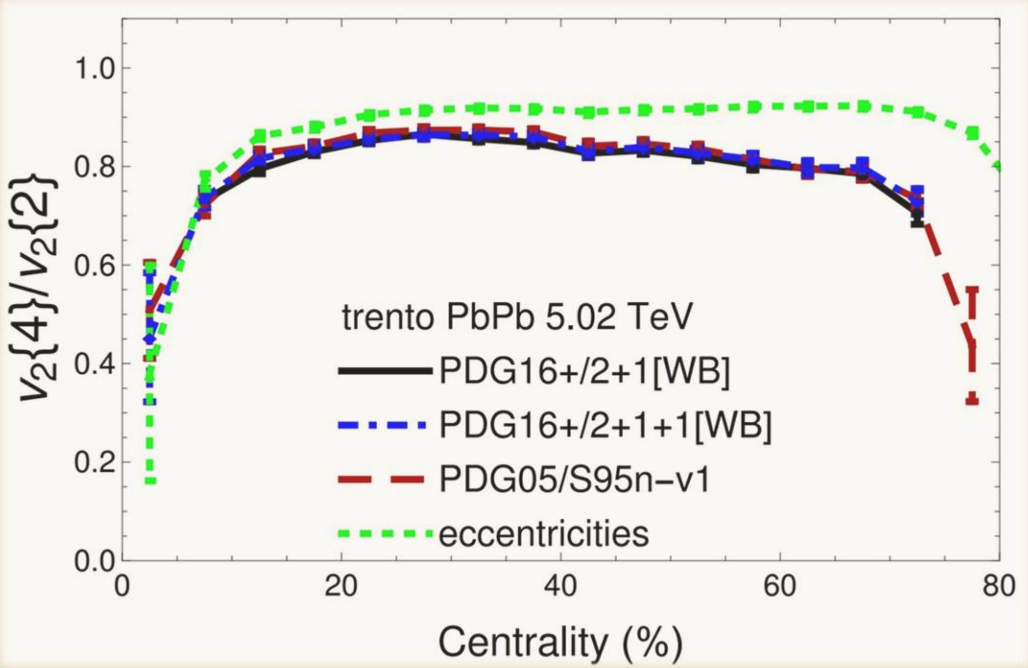


P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, Phys.Rev.C 102 (2020) 5, 054905, arXiv: 2007.00780 [nucl-th]

Canceling Medium Effects

Mostly linear response cancels out across different models that have varying viscosity

Less Fluctuations



More Fluctuations

P. Alba, V. Mantovani Sarti, J. Noronha, J. Noronha-Hostler, P. Parotto, I. Portillo Vazquez, and C. Ratti
Phys.Rev. C98 (2018), 034909, arXiv:1711.05207 [nucl-th]

Initial State

$$E_n = \epsilon_n e^{in\phi_n}$$

$$V_n \approx \kappa_n E_n$$

Mostly linear response

Final State

$$V_n = v_n e^{in\phi_n}$$

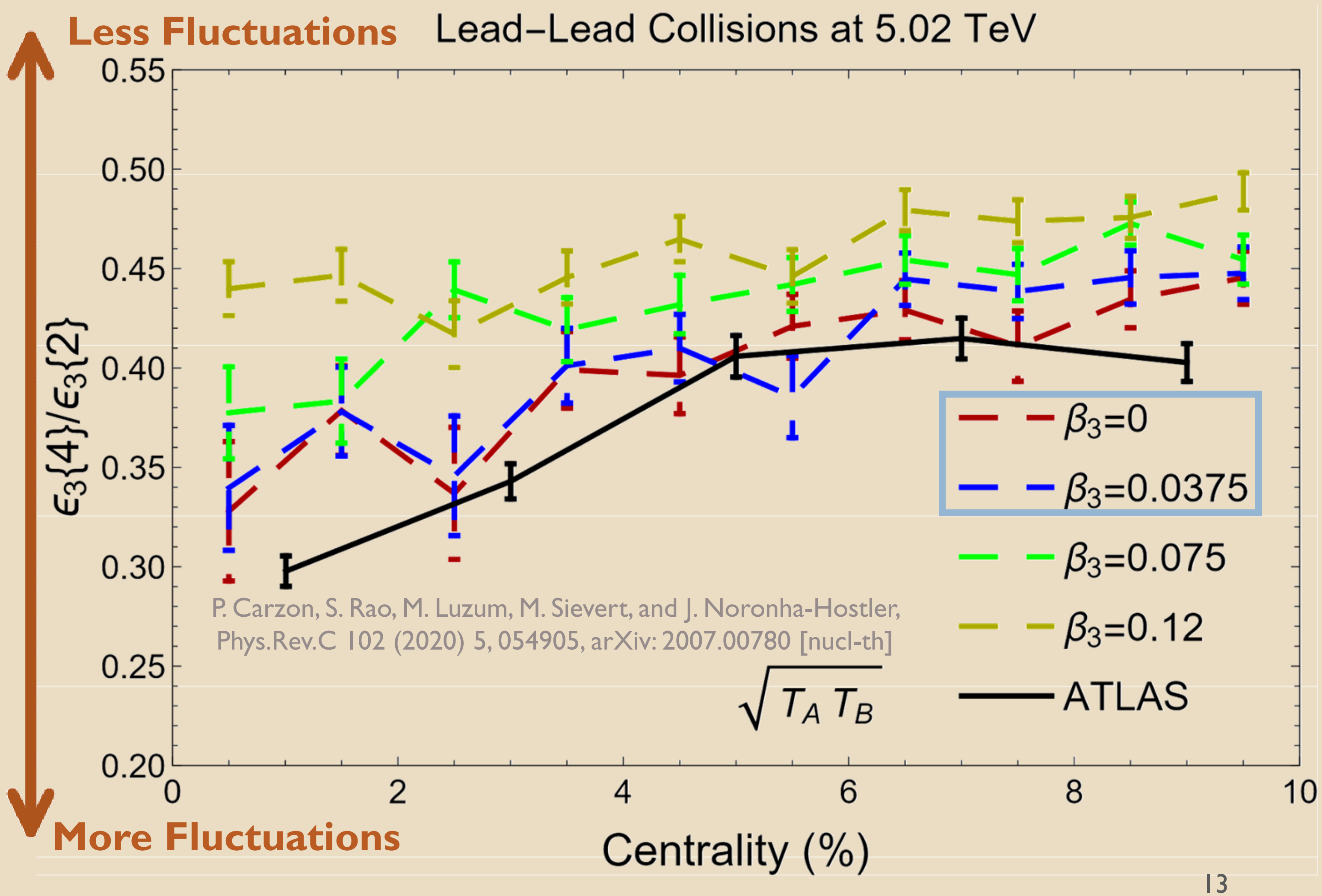
$$\frac{v_n\{4\}}{v_n\{2\}} \approx \frac{\kappa_n \epsilon_n\{4\}}{\kappa_n \epsilon_n\{2\}}$$

Teaney et al, PRC 83, 064904 (2011), PRC 86, 044908 (2012);
Qiu et al, PRC 84, 024911 (2011);
Gardim et al, Noronha-Hostler et al,
Phys.Rev. C93 (2016) no.1, 014909
Giacalone et al, **Phys.Rev. C95 (2017) no.5, 054910**

4-Particle/2-Particle Ratios

$\beta_3 \leq 0.0375$

$$\frac{v_3\{4\}}{v_3\{2\}} \approx \frac{\kappa_3 \epsilon_3\{4\}}{\kappa_3 \epsilon_3\{2\}}$$

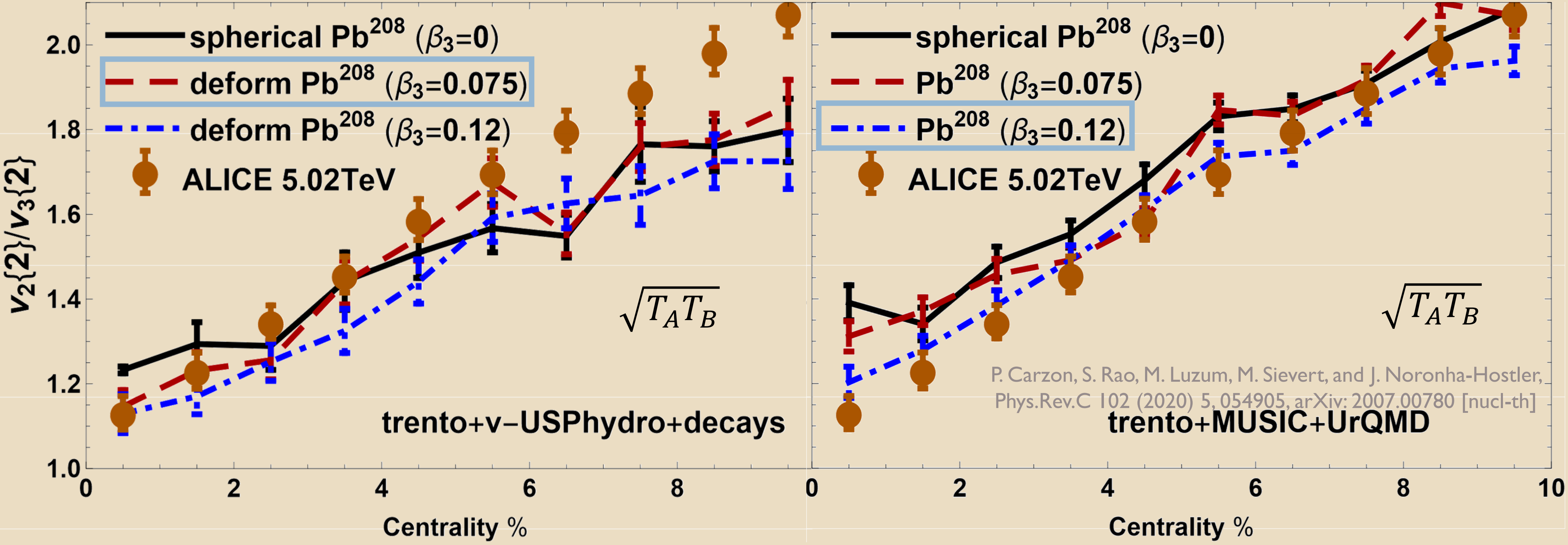


P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, Phys.Rev.C 102 (2020) 5, 054905, arXiv: 2007.00780 [nucl-th]

ATLAS Data: G. Aad et al. (ATLAS), Eur. Phys. J. C74, 3157 (2014), arXiv:1408.4342 [hep-ex]

Flow Harmonic Ratio Elliptic/Triangular

$$\kappa_2 > \kappa_3 \rightarrow v_2 > v_3$$



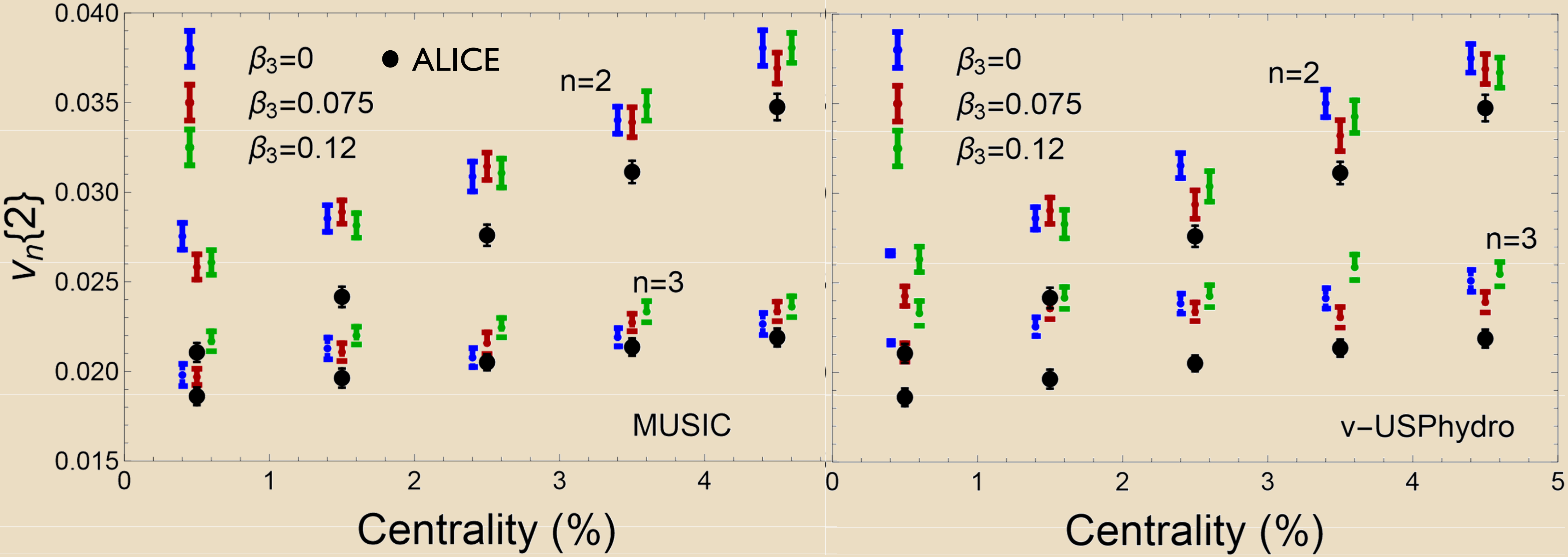
P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, Phys.Rev.C 102 (2020) 5, 054905, arXiv: 2007.00780 [nucl-th]

ALICE Data: S. Acharya et al. (ALICE), Phys. Rev. Lett. 123, 142301 (2019), arXiv:1903.01790 [nucl-ex]
S. Acharya et al. (ALICE), JHEP 07, 103 (2018), arXiv:1804.02944 [nucl-ex]

Flow Harmonics

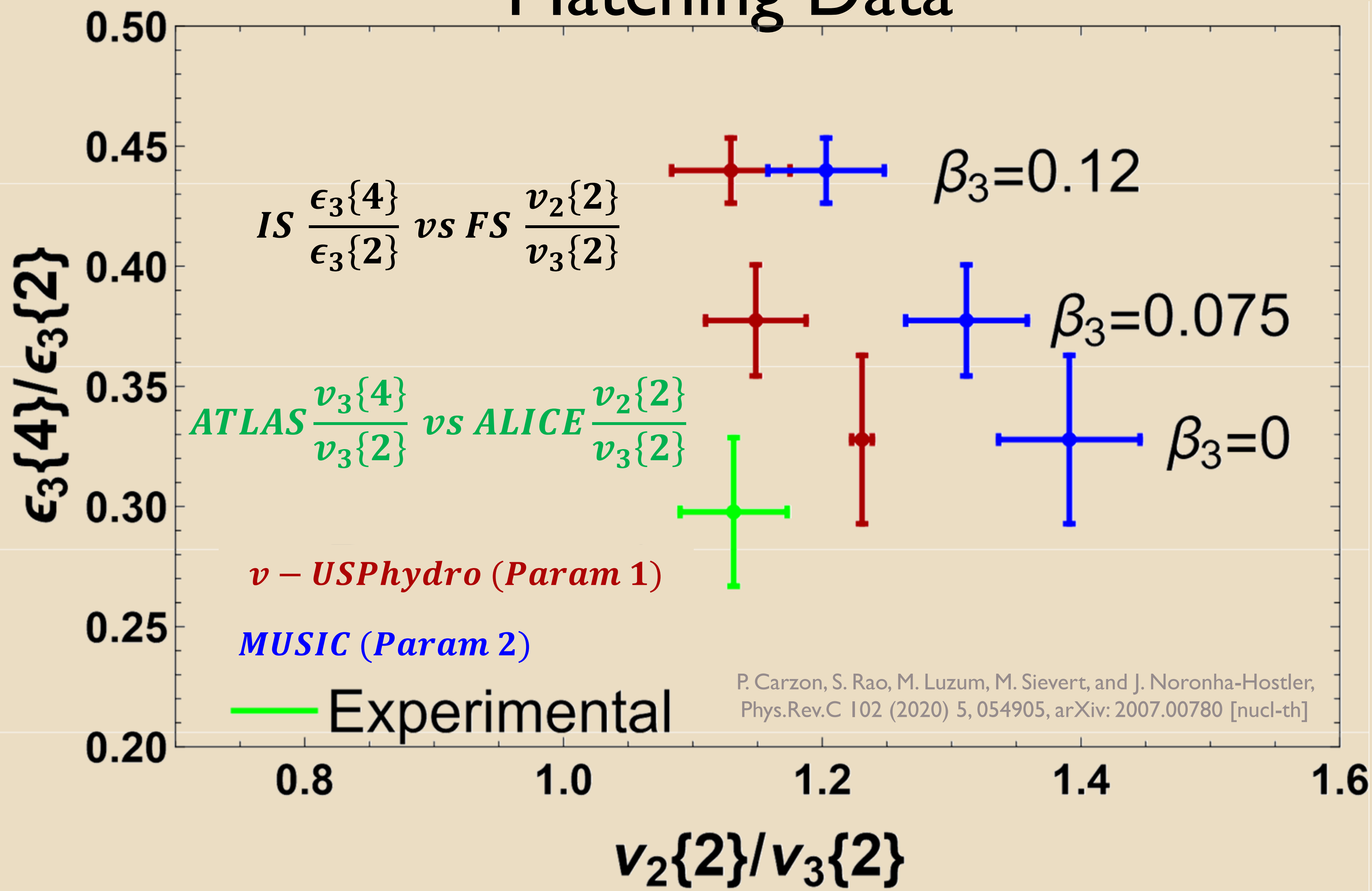
Irregular behavior with respect to β_3

P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, Phys.Rev.C 102 (2020) 5, 054905, arXiv: 2007.00780 [nucl-th]



ALICE Data: S. Acharya et al. (ALICE), Phys. Rev. Lett. 123, 142301 (2019), arXiv:1903.01790 [nucl-ex]
S. Acharya et al. (ALICE), JHEP 07, 103 (2018), arXiv:1804.02944 [nucl-ex]

Matching Data



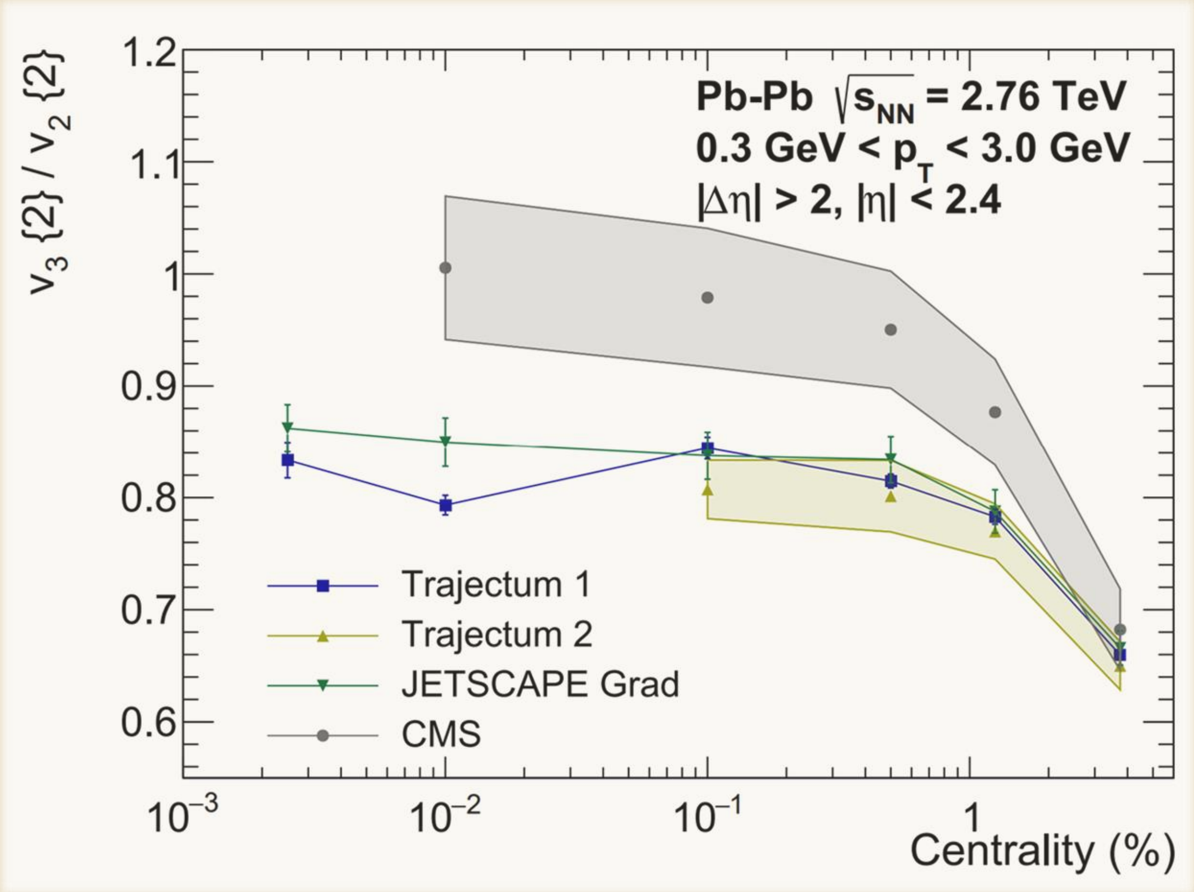
P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, Phys.Rev.C 102 (2020) 5, 054905, arXiv: 2007.00780 [nucl-th]

ATLAS Data: G. Aad et al. (ATLAS), Eur. Phys. J. C74, 3157 (2014), arXiv:1408.4342 [hep-ex]
ALICE Data: S. Acharya et al. (ALICE), Phys. Rev. Lett. 123, 142301 (2019), arXiv:1903.01790 [nucl-ex]
S. Acharya et al. (ALICE), JHEP 07, 103 (2018), arXiv:1804.02944 [nucl-ex]

Current Status

A recent review, utilizing Bayesian models, showed the $v_2 - to - v_3$ puzzle is still unsolved

Can Nuclear Structure help with the solution to this puzzle?



A.V. Giannini, M. N. Ferreira, M. Hippert, D. D. Chinellato, G. S. Denicol, M. Luzum, J. Noronha, T. Nunes da Silva, J. Takahashi arXiv:2203.17011 [nucl-th]

Conclusions

- v_2-to-v_3 puzzle in ultracenteral ${}^{208}Pb{}^{208}Pb$ is conflict between theory, $v_2 > v_3$, and experiment, $v_2{\sim}v_3$

- Solution requires $\epsilon_2 < \epsilon_3$ because viscosity suppresses ϵ_3

- Increasing β_3 deformation gives better agreement in $v_2\{2\}/v_3\{2\}$, but makes observable $\epsilon_3\{4\}/\epsilon_3\{2\}$ worse

- Solution must address $v_2\{2\}/v_3\{2\}$ and $v_3\{4\}/v_3\{2\}$ because they play off each other in non-trivial ways

- The $v_2 - to - v_3$ puzzle remains unsolved and a possible source of new physics

Previous Work

Extracting the shear viscosity
in ultra-centr
M. Luzum, J-Y. Ollitr
- Attempted to solve the puz
MC-KLN and its Glauber imp

Effect of the QCD equation of state and strange hadronic resonances on multiparticle correlations in heavy ion collisions

P. Alba, V. Mantovani Sarti, J. Noronha, J. Noronha-Hostler, P. Parotto, I. Portillo Vazquez, and C. Ratti arXiv:1711.05207 [nucl-th]

- Looked at the effect different EOS (S95n-v1, 2+1 and 2+1+1 flavor EOS) have on v_2 to v_3 puzzle
- Closest match to data with 2+1 EOS but still 15% difference

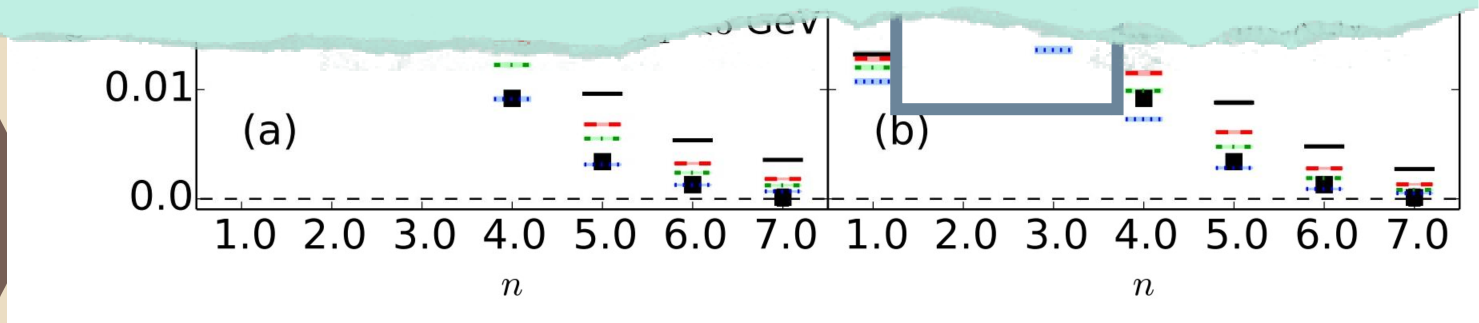
Prin
F. Gelis, G. Giacalone,
- Attempted magma

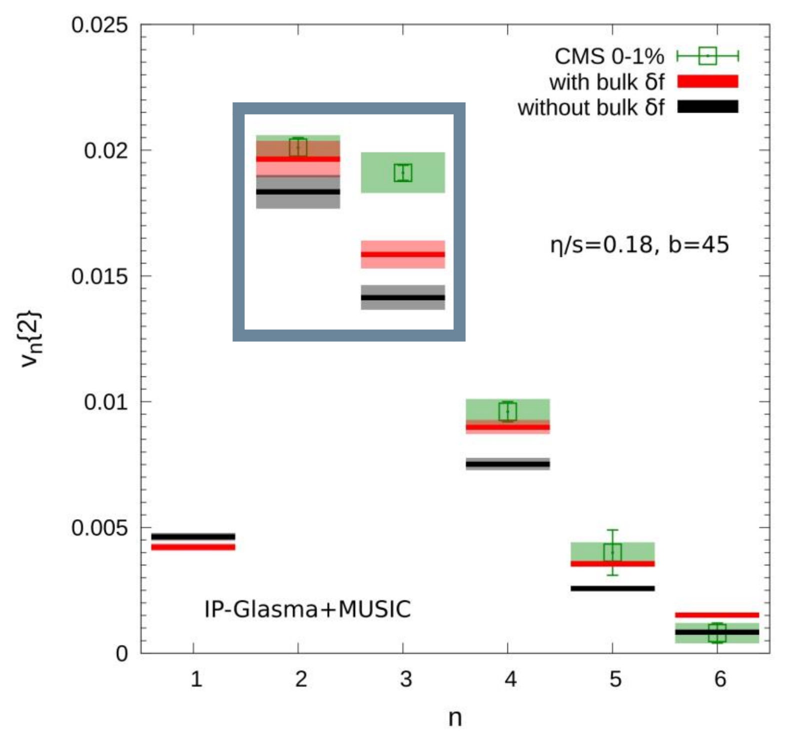
Shape and flow
C
- Attempted Glauber and MC
- Could not resolve puzzle

Extracting the bulk viscosity of the quark-gluon plasma

J-B. Rosea, J-F. Paqueta, G. S. Denicola, M. Luzuma, B. Schenkec, S. Jeona, C. Galea arXiv:1408.0024 [nucl-th]

- ICs: IP-Glasma
- Looked at effects of bulk viscosity, has effect but not enough to resolve puzzle on its own

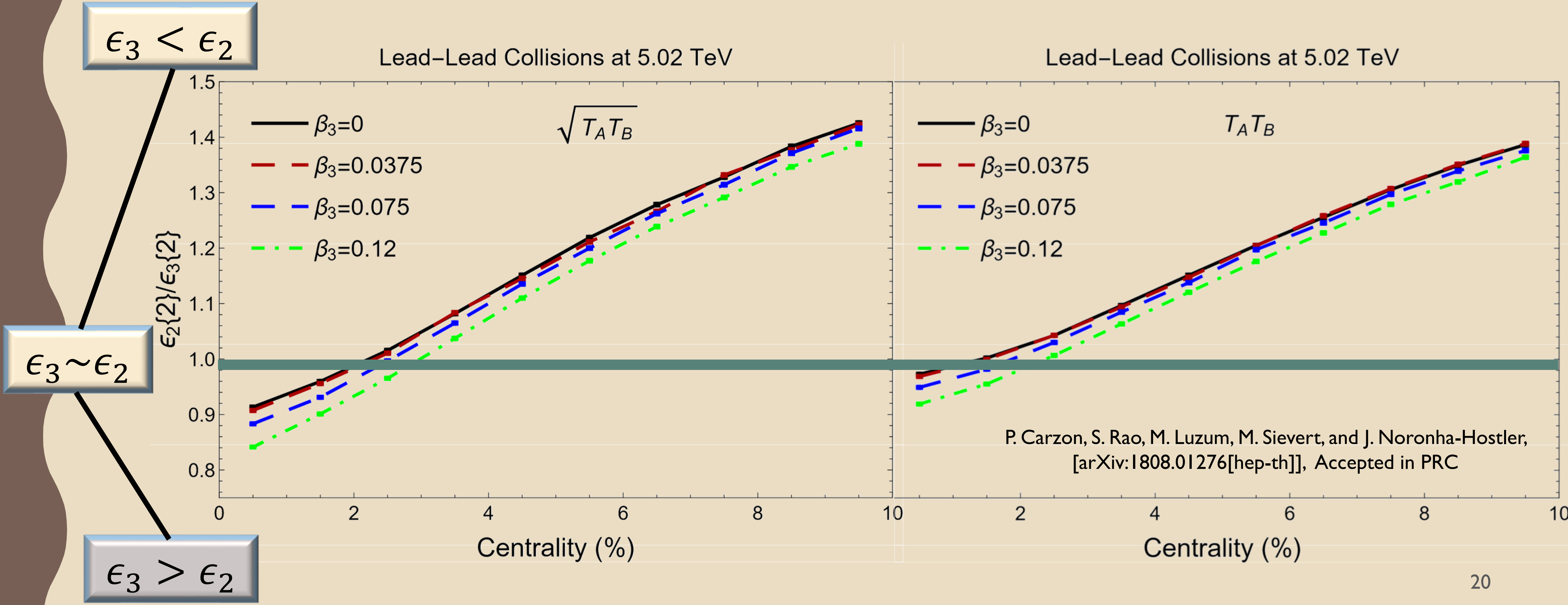




Elliptic/Triangular Ratios

$$\frac{v_2\{2\}}{v_3\{2\}} \approx \frac{\kappa_2 \epsilon_2\{2\}}{\kappa_3 \epsilon_3\{2\}}$$

$\epsilon_3 > \epsilon_2 \rightarrow v_3 \sim v_2$



$\epsilon_3 < \epsilon_2$

$\epsilon_3 \sim \epsilon_2$

$\epsilon_3 > \epsilon_2$

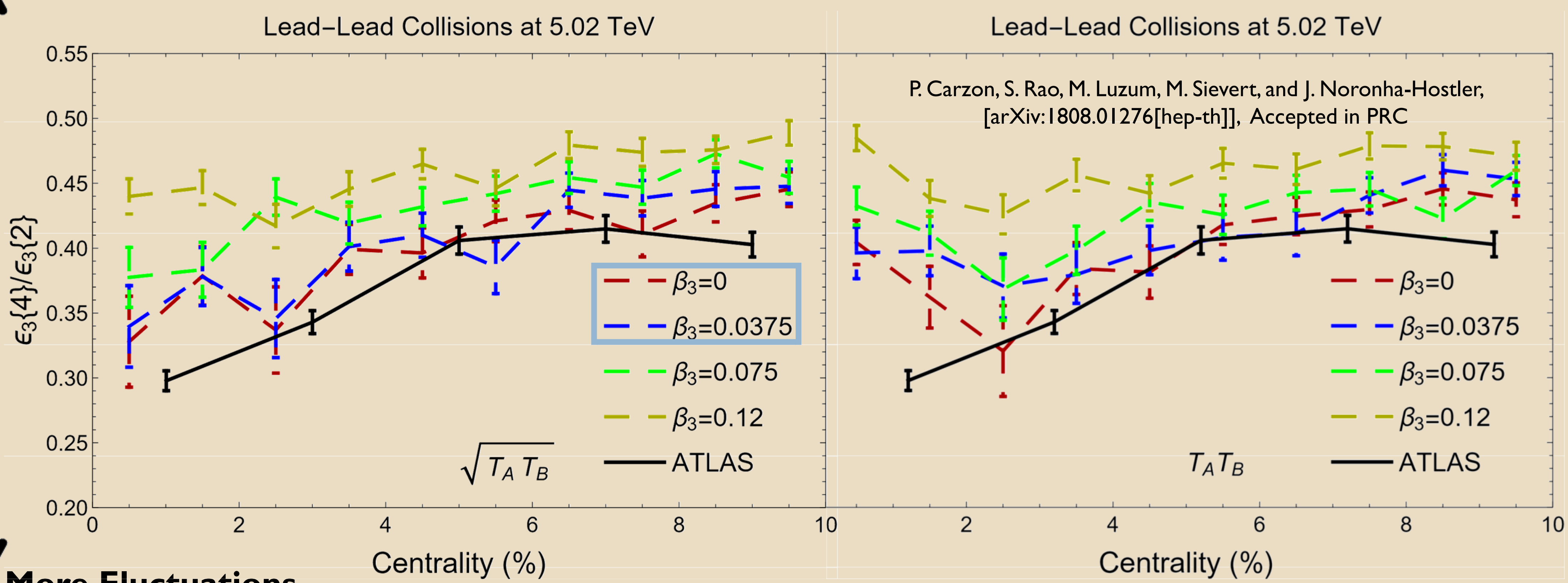
P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, [arXiv:1808.01276[hep-th]], Accepted in PRC

4-Particle/2-Particle Ratios

$$\frac{v_3\{4\}}{v_3\{2\}} \approx \frac{\kappa_3 \epsilon_3\{4\}}{\kappa_3 \epsilon_3\{2\}}$$

$$\boxed{\beta_3 \leq 0.0375}$$

Less Fluctuations



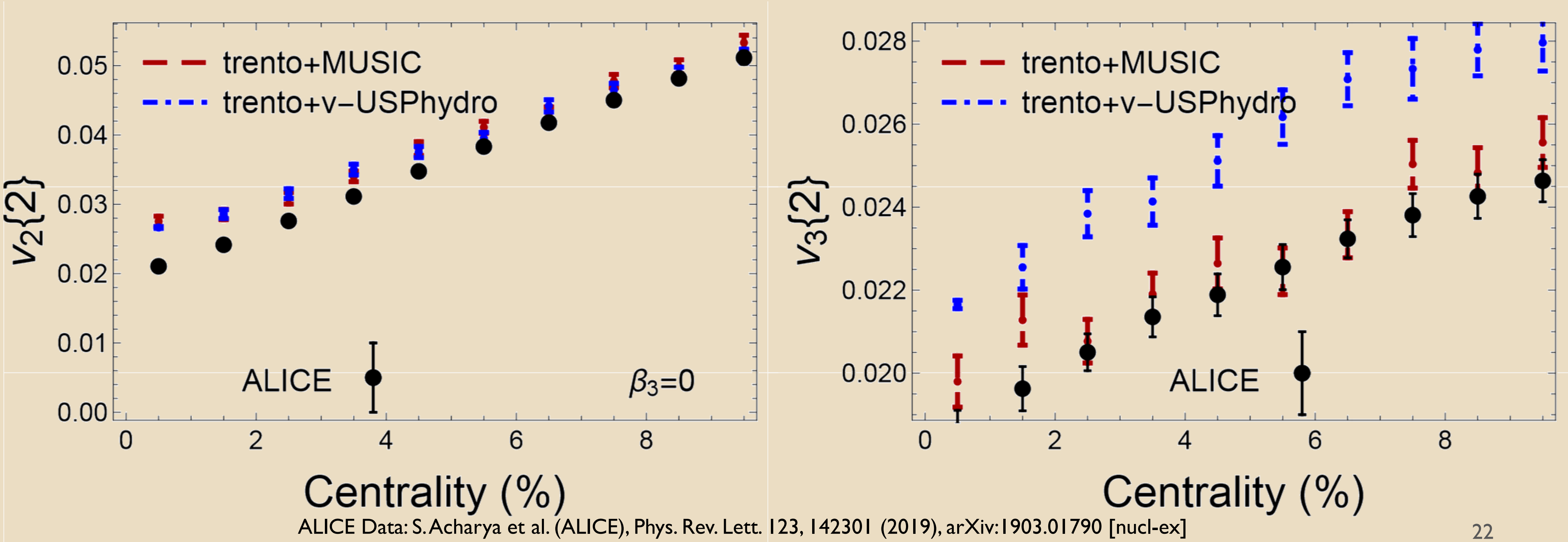
P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler, [arXiv:1808.01276[hep-th]], Accepted in PRC

More Fluctuations

ATLAS Data: G. Aad et al. (ATLAS), Eur. Phys. J. C74, 3157 (2014), arXiv:1408.4342 [hep-ex]

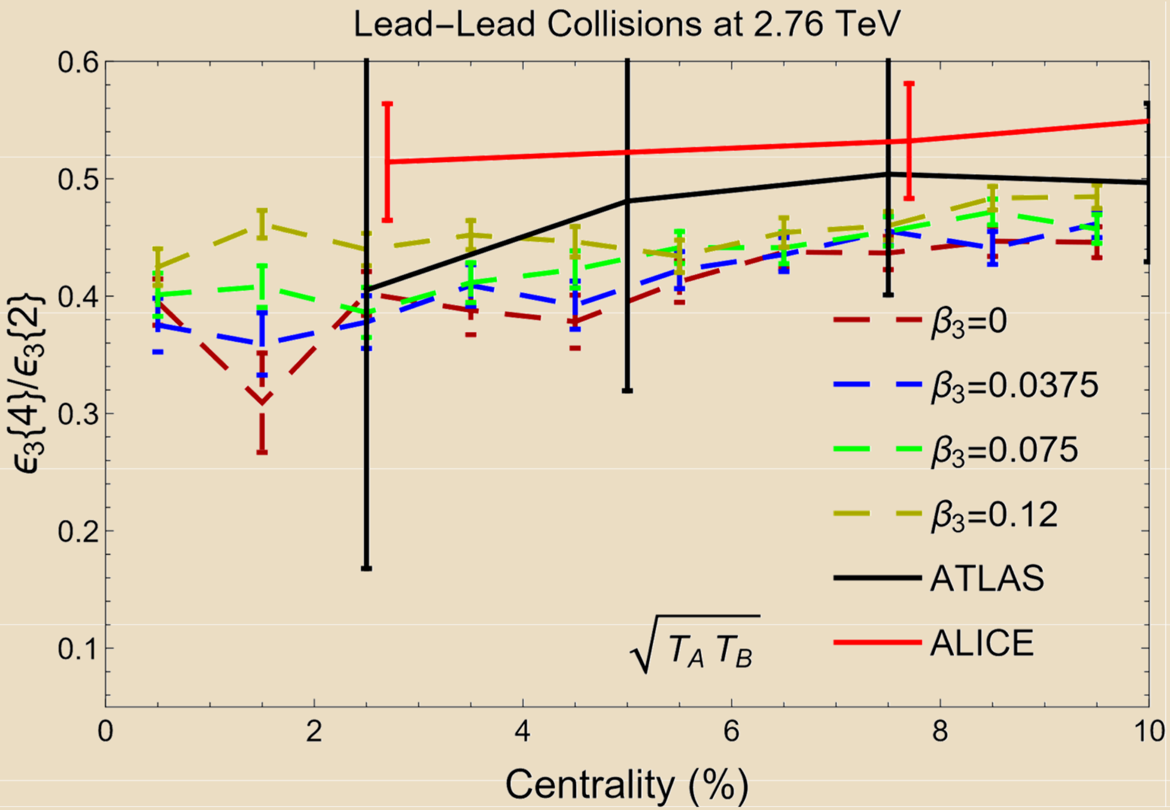
Flow Harmonics

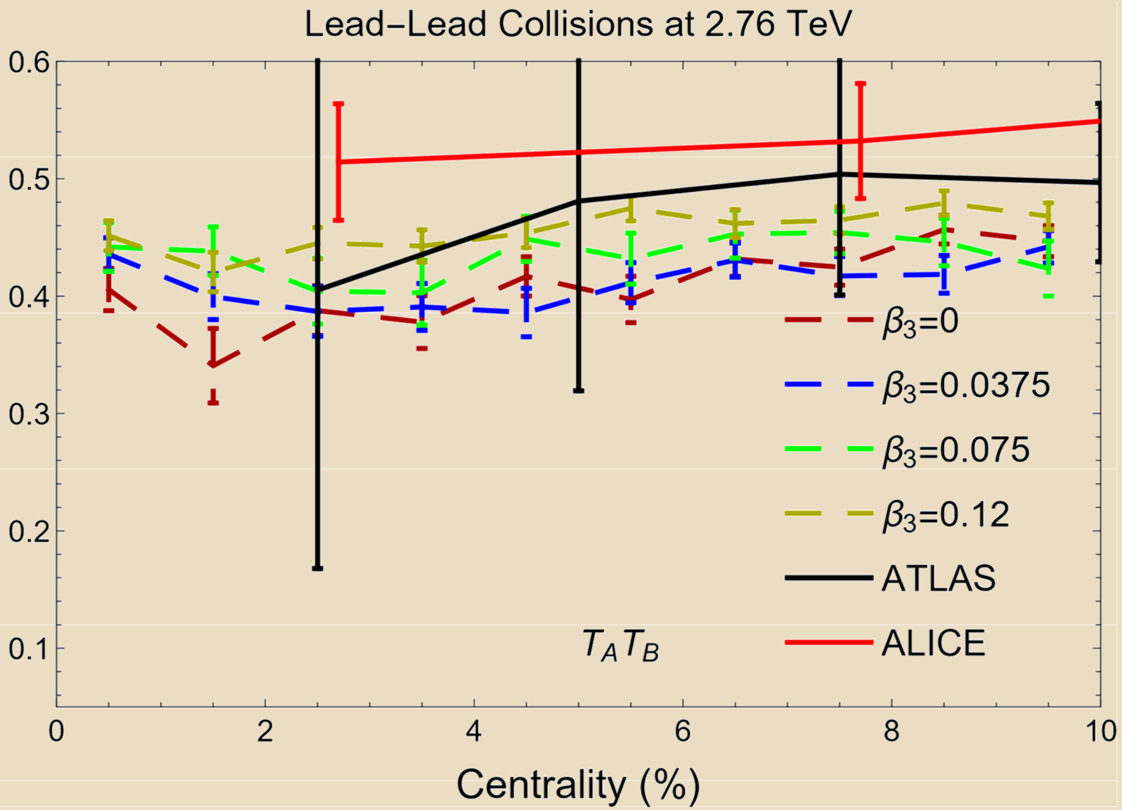
Since both v_2 and v_3 are overestimated, the ratio will look good



ALICE Data: S. Acharya et al. (ALICE), Phys. Rev. Lett. 123, 142301 (2019), arXiv:1903.01790 [nucl-ex]
S. Acharya et al. (ALICE), JHEP 07, 103 (2018), arXiv:1804.02944 [nucl-ex]

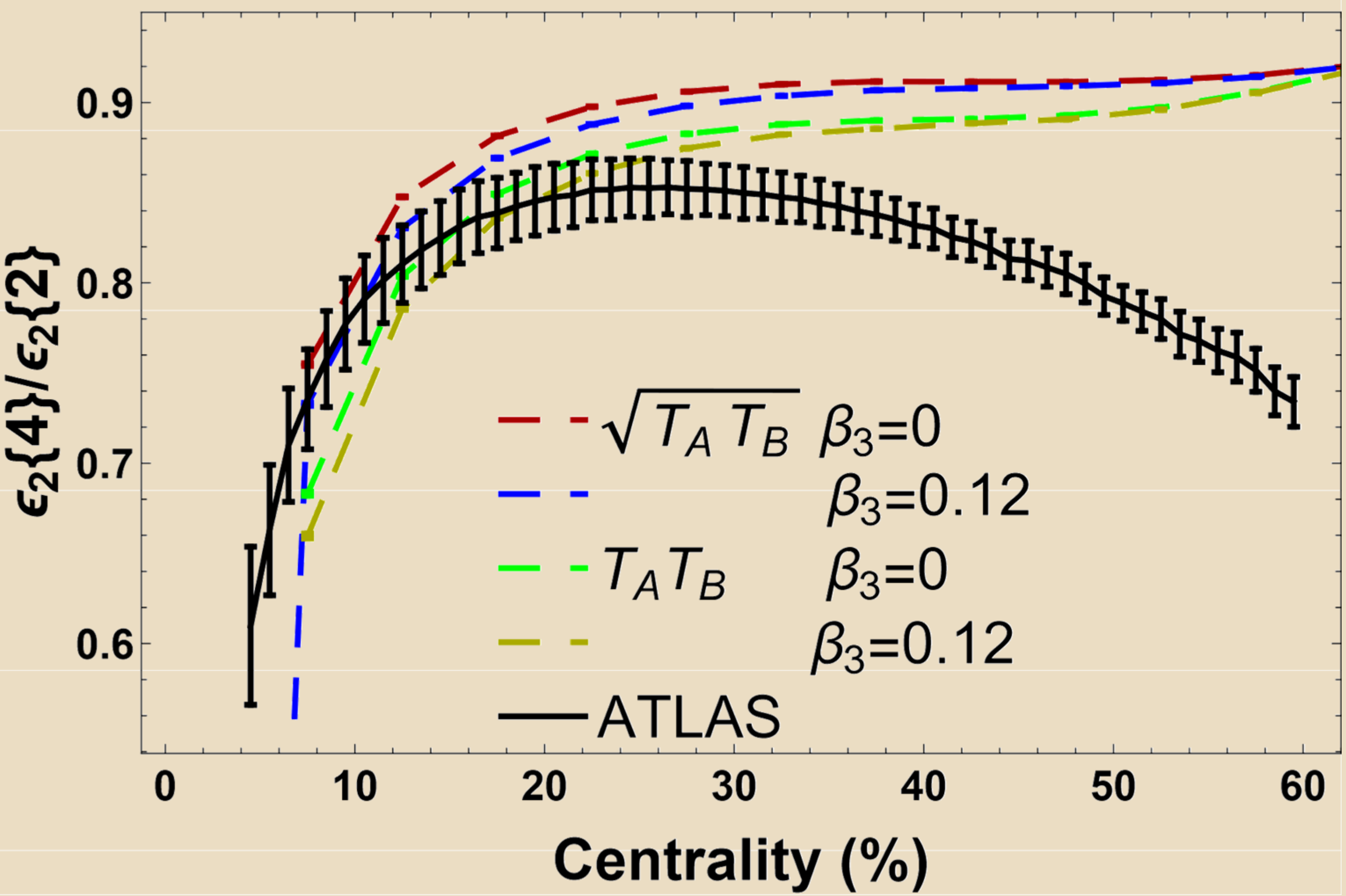
4-Particle/2-Particle Ratios





4-Particle/2-Particle Ratios

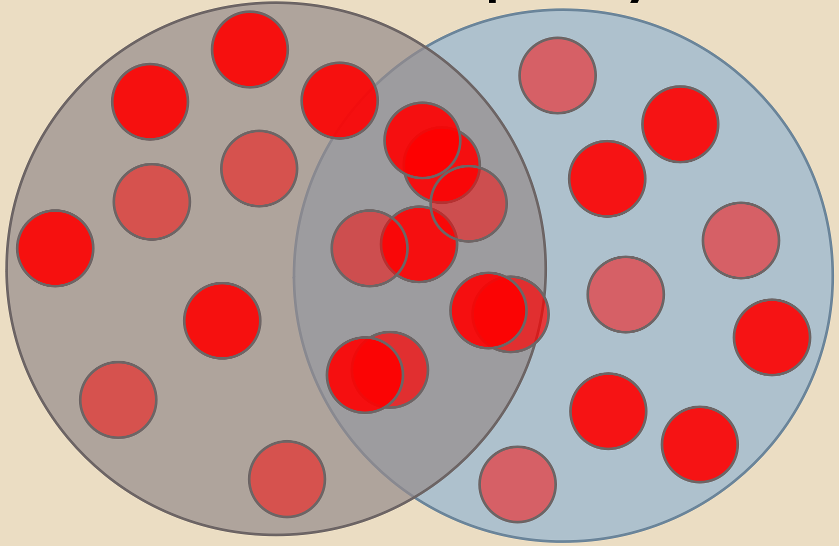
Do I need this for the story?

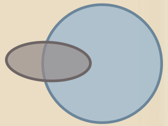


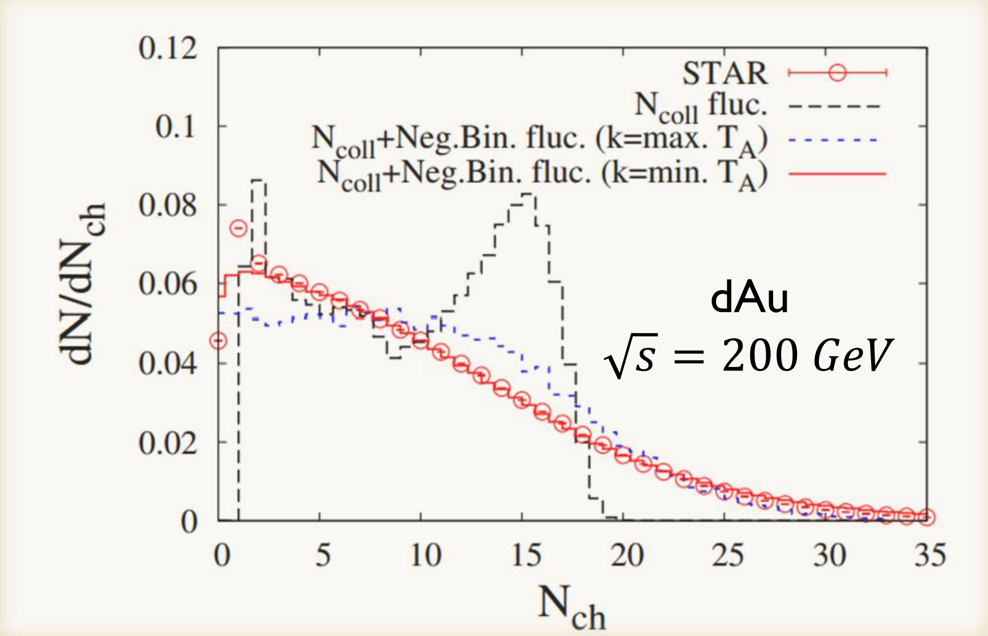
Multiplicity Fluctuations

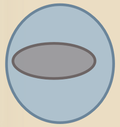
A. Dumitru and Y. Nara
Phys.Rev.C 85 (2012), 034907
1201.6382 [nucl-th]

3^{rd} −order: Multiplicity Fluctuations

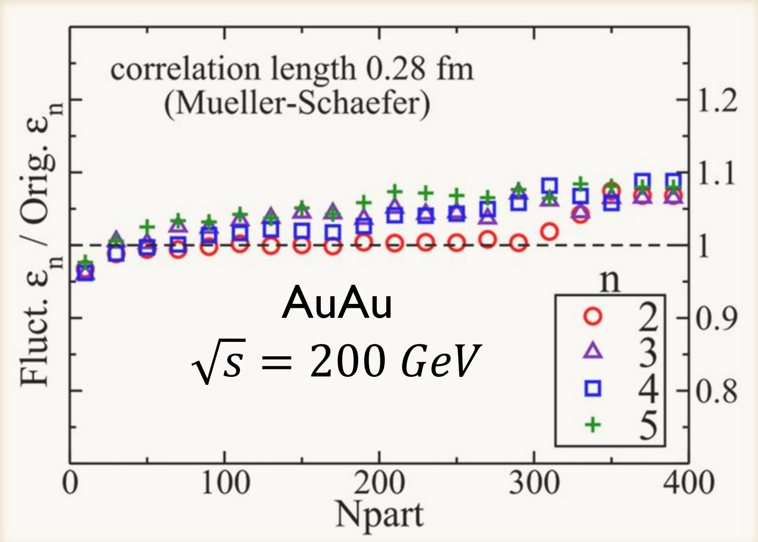


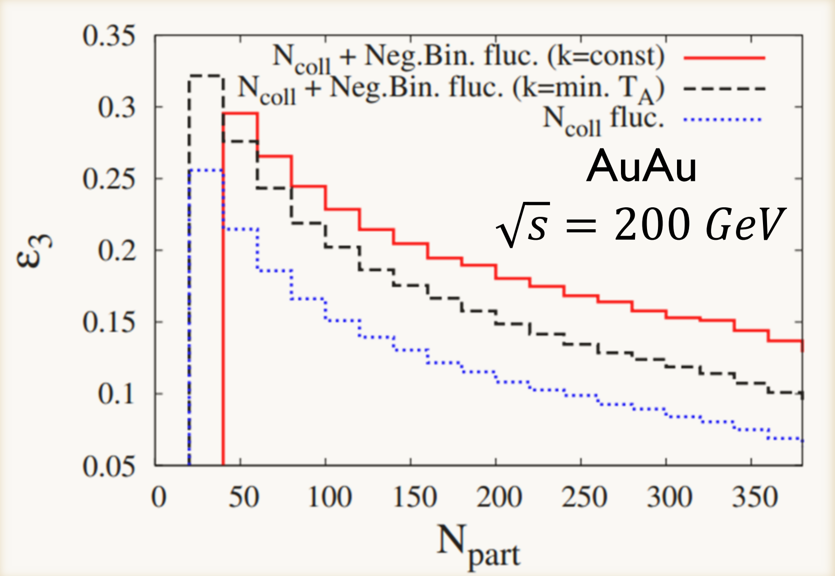






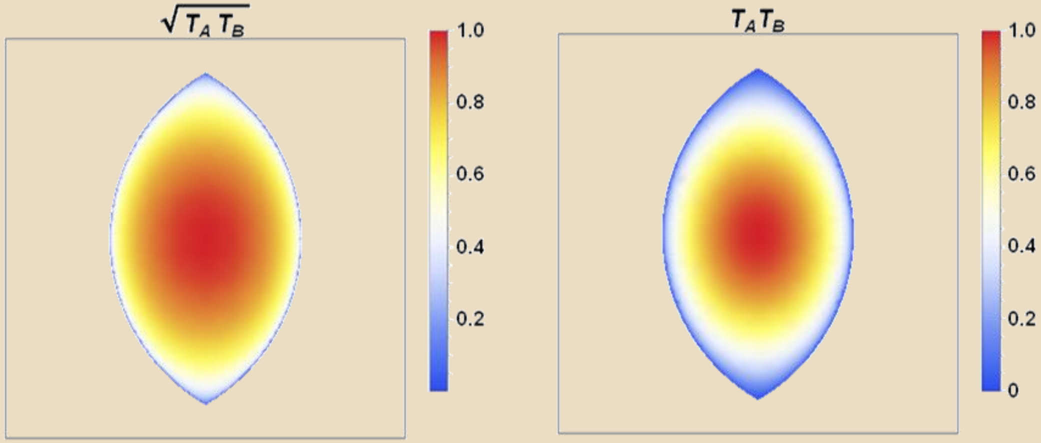
J.S. Moreland, Z. Qiu, U.W. Heinz
Nucl.Phys.A 904-905 (2013), 815c-818c
1210.5508 [nucl-th]





Models

Trento
- Bayesian Analysis showed the best reduced thickness is given by $T_R = \sqrt{T_A T_B}^*$
- Theory based models (CGC) produce the relation $T_R = T_A T_B{}^\dagger$ (not included in Bayesian)



- **v-USPhydro (Parameter Set 1)**
  - EOS (WB21/PDG16+), state of the art
  - Hadronic After Burner, direct decays only but full particle list
  - $\frac{\eta}{s} = const, \frac{\zeta}{s} = 0$

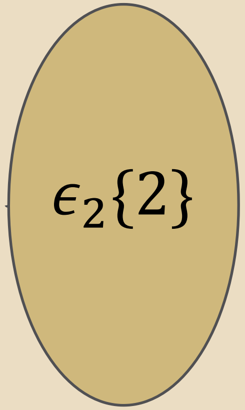
- **MUSIC (Parameter Set 11)**
  - EOS (s95p-v1.2), outdated
  - Hadronic After Burner (UrQMD), transport but not all resonances
  - $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$, from Bayesian Analysis

* **TRENTO:** J. S. Moreland et al, Phys. Rev.C92, 011901 (2015), 1412.4708
J. E. Bernhard et al, Phys. Rev.C94, 024907(2016), 1605.03954
† $T_A T_B$ **scaling:** J. L. Nagle and W.A. Zajc,[arXiv:1808.01276[hep-th]]
T. Lappi, Phys. Lett. B643, 11 (2006), arXiv:hepph/0606207 [hep-ph]
G. Chen et al, [arXiv:1507.03524 [nucl-th]]
P. Romatschke and U. Romatschke, [arXiv:1712.05815 [nucl-th]]
v-USPhydro: J. Noronha-Hostler et al, Phys. Rev. C88, 044916 (2013),arXiv:1305.1981 [nucl-th]
J. Noronha-Hostler et al, Phys.Rev. C90, 034907 (2014), arXiv:1406.3333 [nucl-th]
EOS data comparison: P. Alba et al, Phys. Rev. C98, 034909 (2018), arXiv:1711.05207 [nuclth]
PDG16+: P. Alba et al., Phys. Rev. D96, 034517 (2017), arXiv:1702.01113 [hep-lat]
MUSIC: B. Schenke et al, Phys. Rev. C82,014903 (2010), arXiv:1004.1408 [hep-ph]
B. Schenke et al, Phys. Rev. Lett.106,042301 (2011), arXiv:1009.3244 [hep-ph]
EOS: P. Huovinen and P. Petreczky, Nucl. Phys. A 837, 26 (2010), arXiv:0912.2541 [hep-ph]
UrQMD: S. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998), arXiv:nucl-th/9803035
M. Bleicher et al., J. Phys. G 25, 1859 (1999), arXiv:hepph/9909407

Geometry Observables

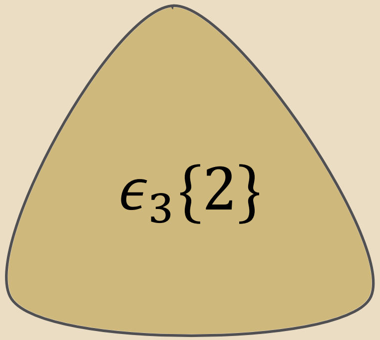
Fourier Series of Initial State

$$E_n = \epsilon_n e^{in\phi_n}$$



2-Particle Correlation

$$\epsilon_n\{2\} = \sqrt{\langle \epsilon_n^2 \rangle}$$



4-Particle Correlation

$$\epsilon_n\{4\} = \sqrt[4]{2\langle \epsilon_n^2 \rangle^2 - \langle \epsilon_n^4 \rangle}$$

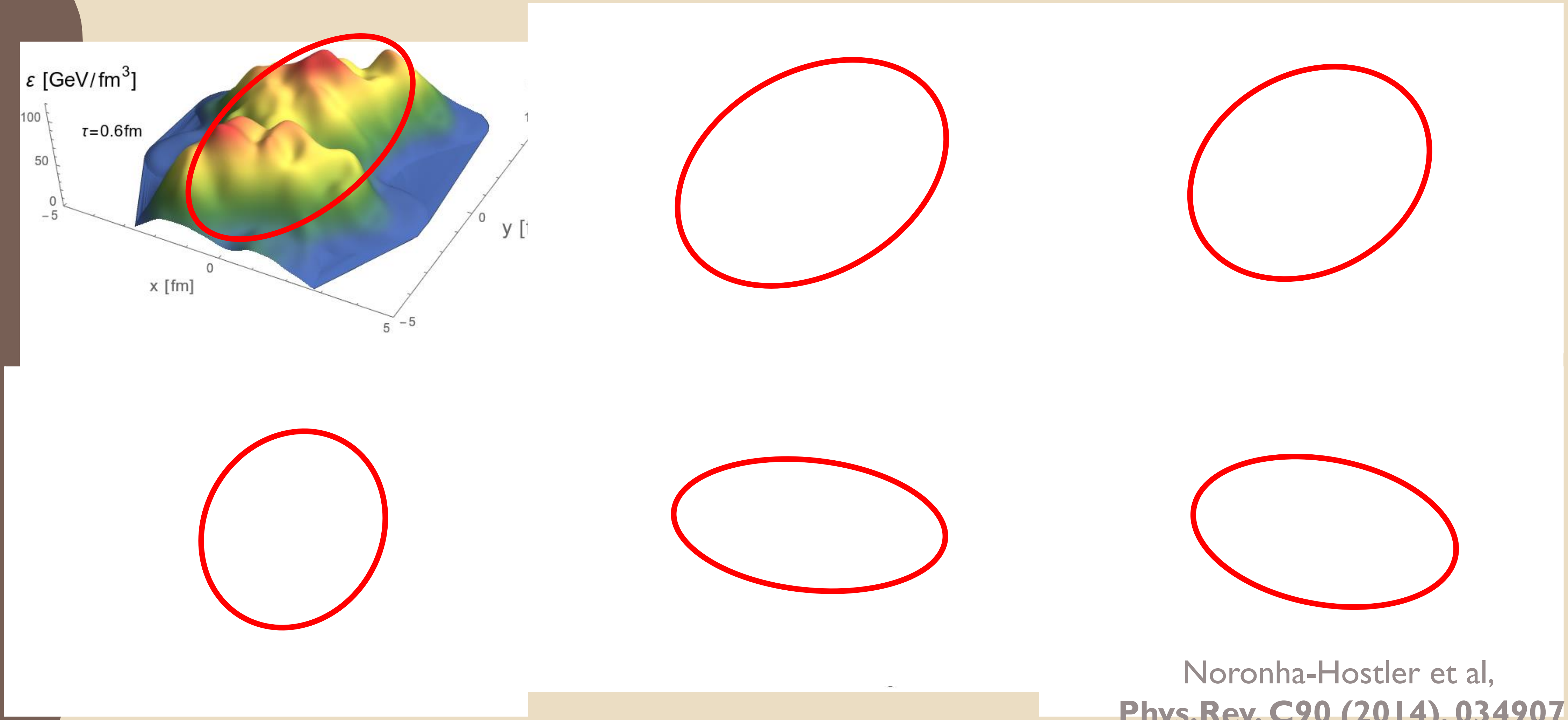
Fluctuations of Geometry Eccentricities

Less

More

$$\frac{\epsilon_n\{4\}}{\epsilon_n\{2\}} = \sqrt[4]{1 - \frac{Var(\epsilon_n^2)}{\langle \epsilon_n^2 \rangle^2}}$$

Hydrodynamic Evolution



Noronha-Hostler et al,

Phys.Rev. C90 (2014), 034907