# Bayesian analysis meets ultra-central collisions: assessing the anisotropic flow puzzle

arXiv:2203.17011
Submitted to PRL

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[The ExTrEMe collaboration]
Experiment and Theory in Extreme Matter

UNICAMP

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Workshop

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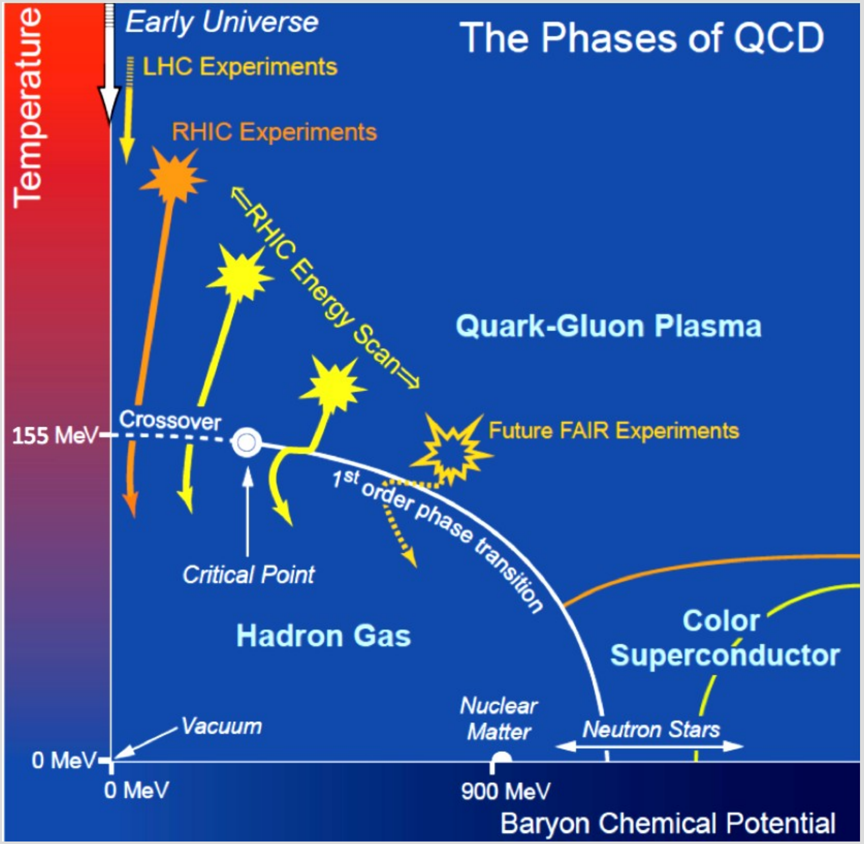
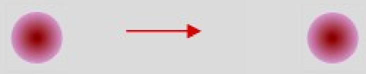
Grants: 2017/05685-2 & 2021/04924-9

# Nuclear matter under extreme conditions

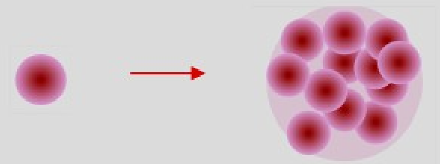



arXiv:1501.06477

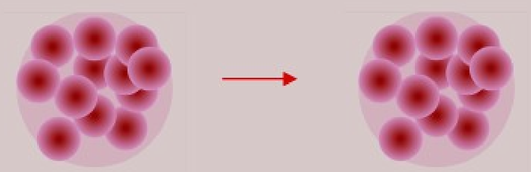
proton-proton collisions ["reference" data]



proton-nucleus collisions ["control" experiment]



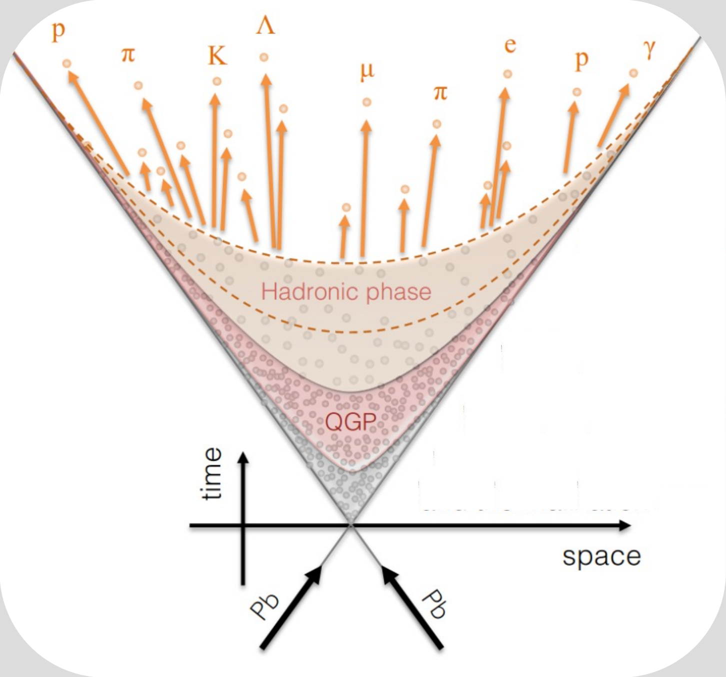
nucleus-nucleus collisions: create & characterize the QGP



Ex: lead-lead collisions = heavy-ion collisions

# Ultra-relativistic heavy-ion collisions

Currently best understood via multi-stage hybrid hydrodynamic simulations




Observed particles

Final state dynamics [transport equations – UrQMD, SMASH]

"Particlization" [out-of-equilibrium corrections]

Hydrodynamical evolution [$\partial_\mu T^{\mu\nu} = 0$ + transport coefficients + EOS]

Pre-equilibrium phase [free-streaming, effective kinetic theory]

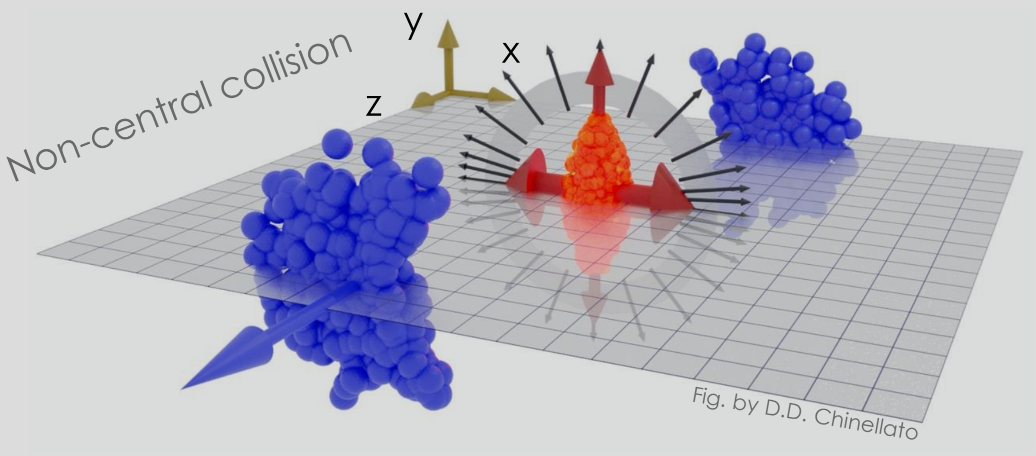
Initial conditions [MC-Glauber, MC-KLN, IP-Glasma, TRENTo, ...]

Simulations **fail to explain** anisotropic flow data @ ultra-central collisions **since** ~ 2012 – 2013

CMS PAS HIN-12-011, Luzum, Ollitrault, NPA 904-905 377c (2013); S. Chatrchyan et al. [CMS], JHEP 02, 088 (2014); M. Aaboud et al. [ATLAS], JHEP 01, 051 (2020)

# Anisotropic flow @ non-central & ultra-central regimes

[0-1% of the total cross-section]




Initial state eccentricities + **collision geometry**

Pressure is largest in the direction of shortest axis

Spatial anisotropies → momentum anisotropies

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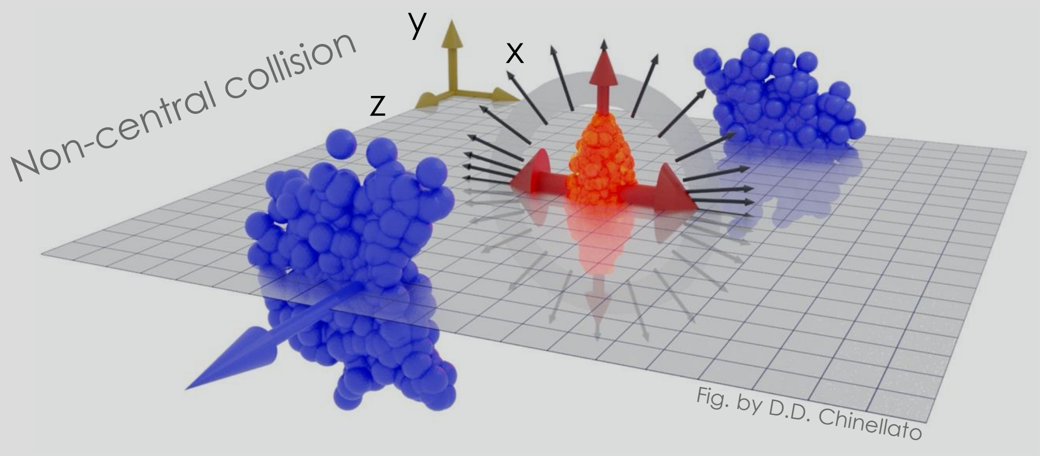


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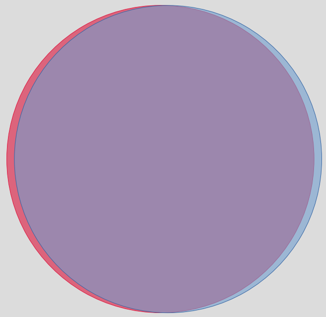

Nearly vanishing impact parameter

**Collision geometry is fixed**
(on avg. spherically symmetric for non-deformed nuclei)

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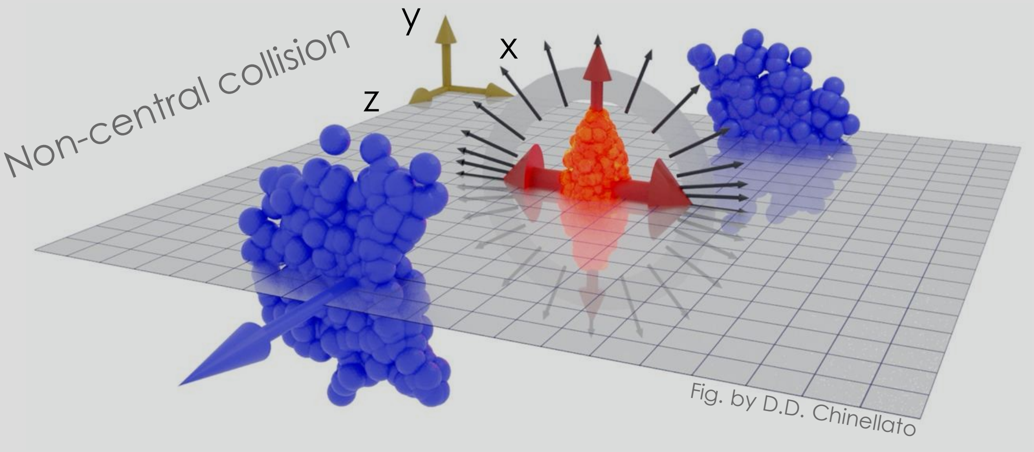


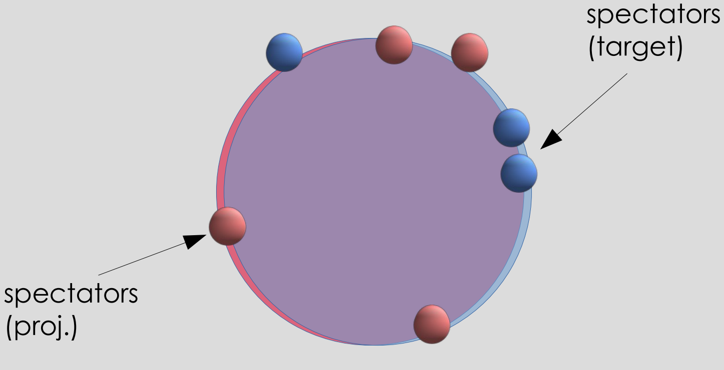


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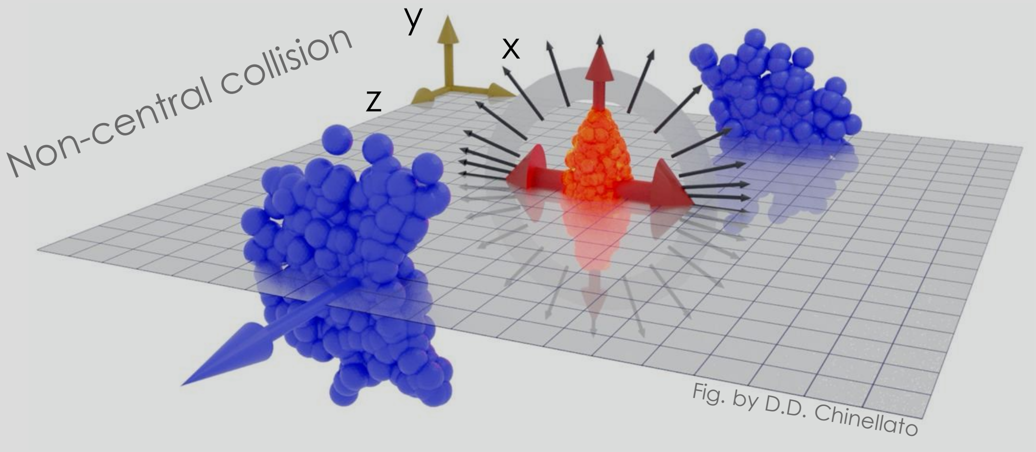


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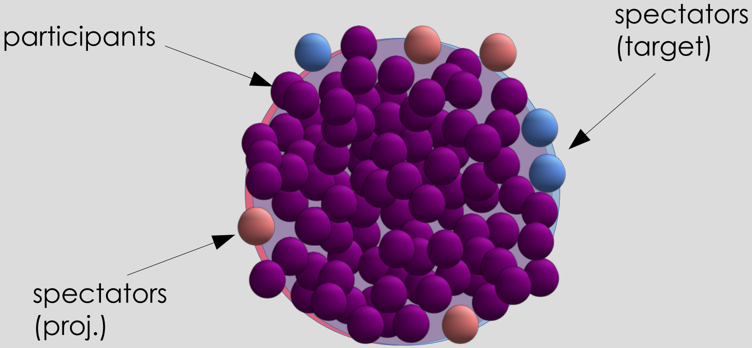
Spatial anisotropies → momentum anisotropies




Nearly vanishing impact parameter

**Collision geometry is fixed**
(on avg. spherically symmetric for non-deformed nuclei)

**Dominated by initial state eccentricities**

Spatial anisotropies → momentum anisotropies

# Characterizing the anisotropic flow

Poskanzer, Voloshin, PRC58, 1671-1678 (1998)
Bilandzic, Snellings, Voloshin, PRC83, 044913 (2011)
+ many others

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T d_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{\rm RP}))\right)$$

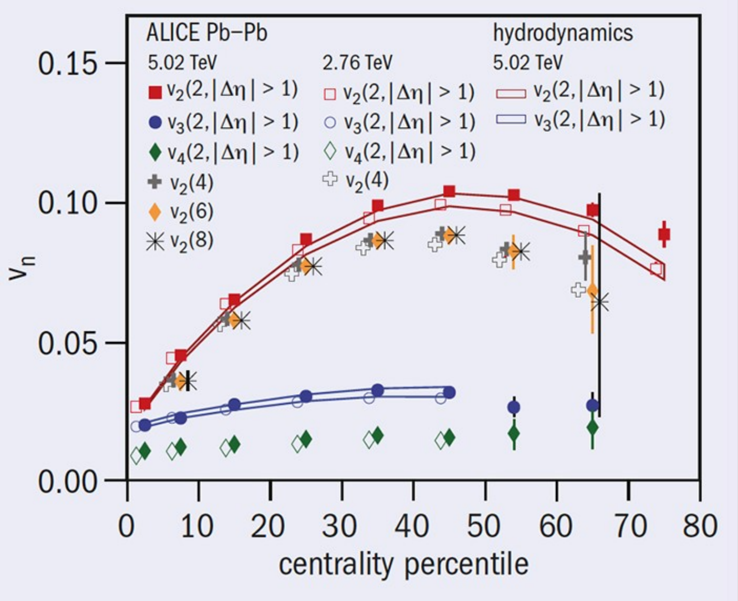
$\phi$ : azimuthal angle of produced particle

$\Psi_{\rm RP}$ : "reaction plane" angle; angle between beam direction and the impact parameter vector [not exp. accessible!]

Move to multi-particle correlations

$$v_n = \langle \cos[n(\phi - \Psi_{\rm RP})] \rangle \quad \rightarrow \quad v_n = \langle \cos[n(\phi_1 - \phi_2)] \rangle$$

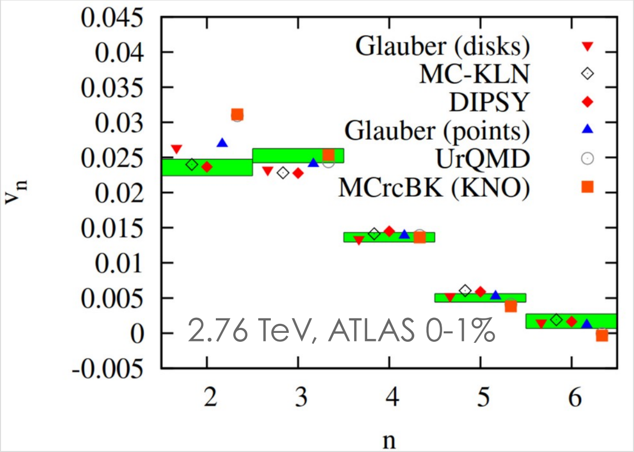
$v_n \equiv v_n(p_T, \Delta\eta)$ : integrate over pt, get centrality dependence



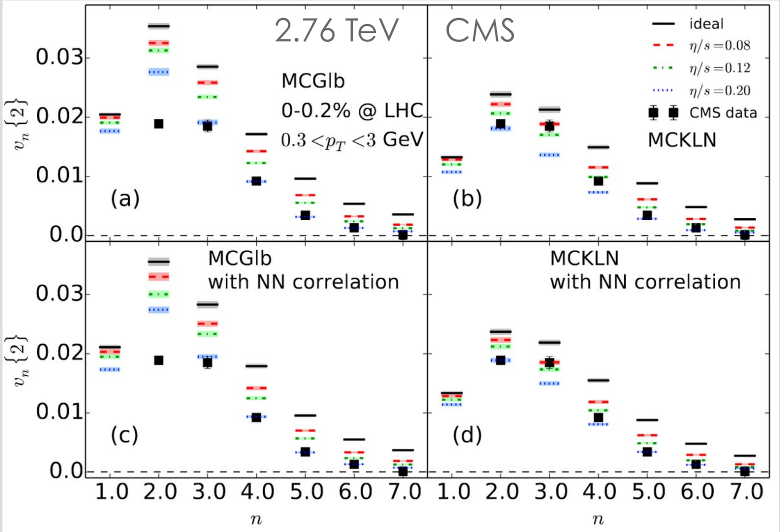

https://cerncourier.com/a/anisotropic-flow-in-run-2/
ALICE, PRL 116, no.13, 132302 (2016)

[0-1% of the total cross-section]

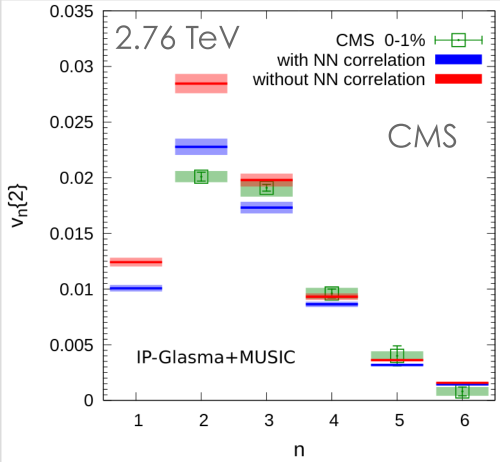
# Description of ultra-central flow data: a 10-year old puzzle



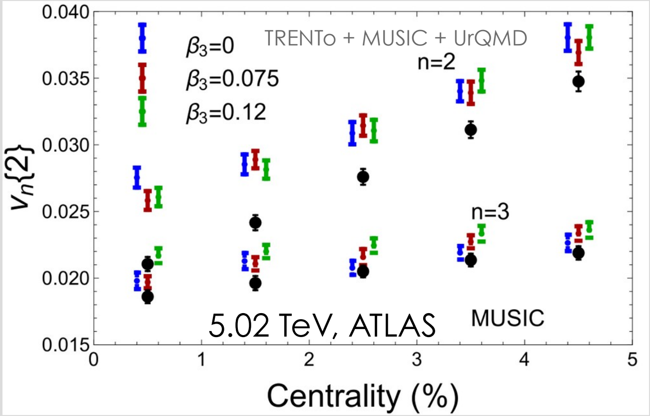

Luzum, Ollitrault, NPA 904-905 377c (2013)




Shen, Qiu, Heinz, PRC92, no.1, 014901 (2015)




Denicol, Gale, Jeon, Paquet, Schenke, arXiv:1406.7792 [nucl-th]




Carzon,Rao,Luzum,Sievert,Noronha-Hostler,PRC102, no.5, 054905 (2020)

Overall feature of simulations:

– overproduction of elliptic flow
– underproduction of triangular flow
– both

[0-1% of the total cross-section]

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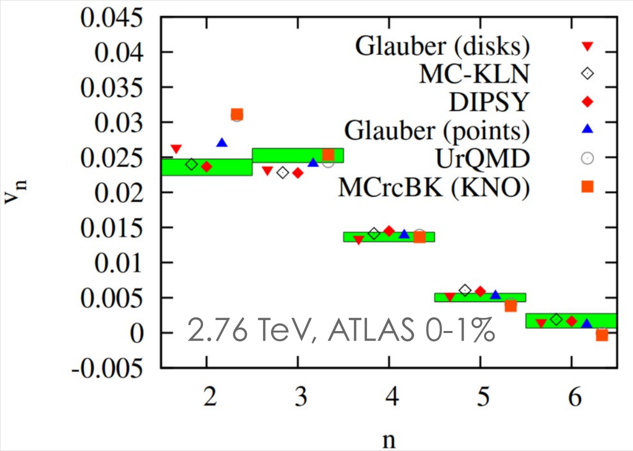
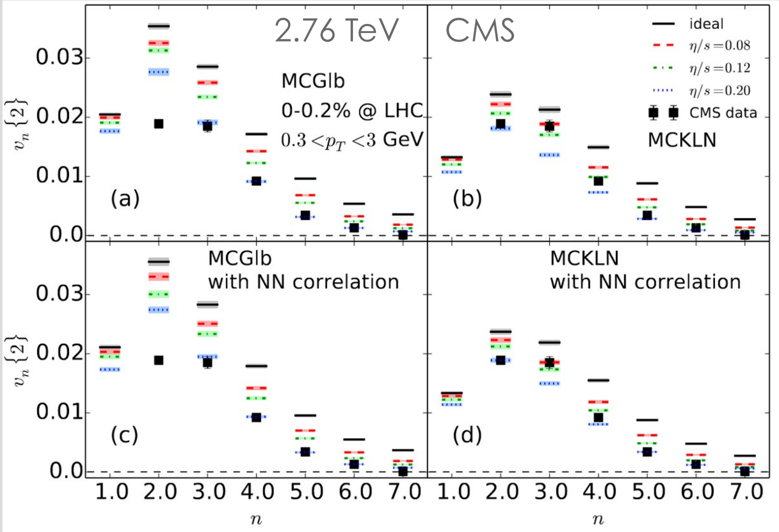
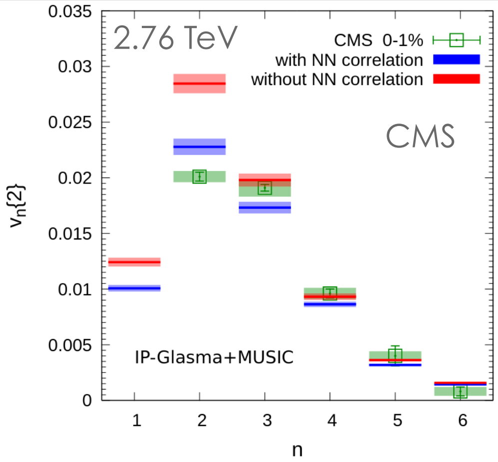


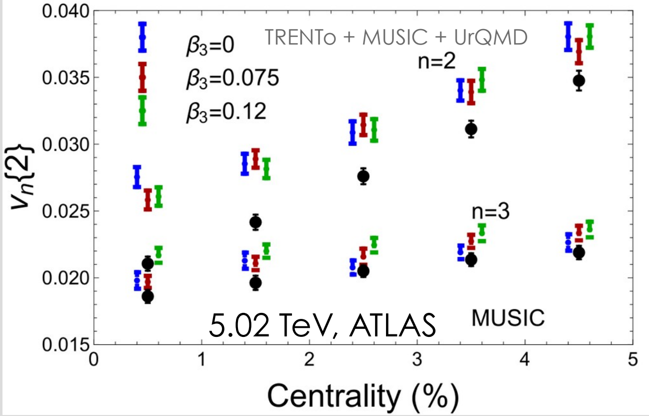

Luzum, Ollitrault, NPA 904-905 377c (2013)




Shen, Qiu, Heinz, PRC92, no.1, 014901 (2015)




Denicol, Gale, Jeon, Paquet, Schenke, arXiv:1406.7792 [nucl-th]



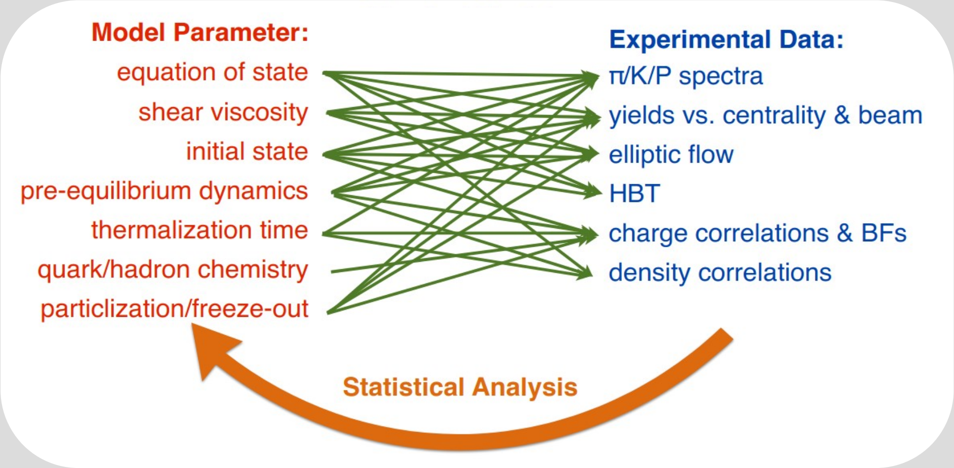

Carzon,Rao,Luzum,Sievert,Noronha-Hostler,PRC102, no.5, 054905 (2020)

New constraints from Bayesian analysis available since then

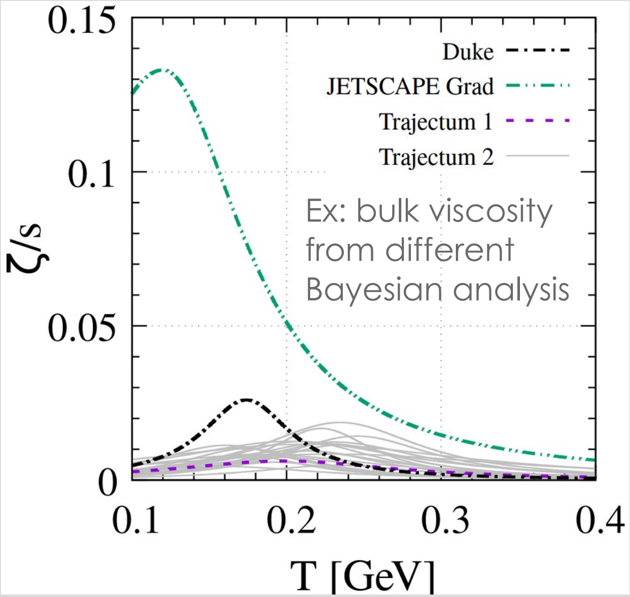
Goal: **determine whether modern Bayesian-tuned models have the same pathology as previous models for ultra-central collisions**

# Systematic parameter estimation: “Bayesian era”

Systematic data-to-model statistical analysis as tool for constraining potentially large parameter space of hybrid hydrodynamic simulations




Adapted from: Shen, Yan, Nucl. Sci. Tech. **31**, no.12, 122




All data considered come from typical centralities

[0 – 5% centrality bin is the narrower bin included]

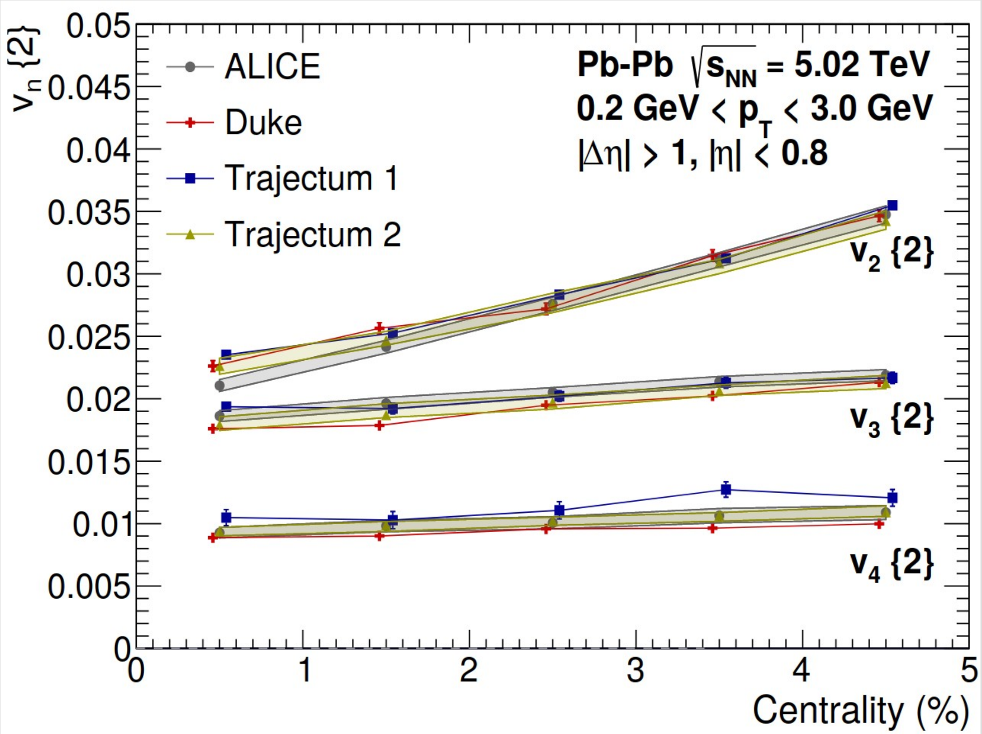
# Selected Bayesian analysis & non-ultra-central data

**Duke:**
p+Pb @ 5.02 TeV
Pb+Pb @ 5.02 TeV
Moreland, Bernhard, Bass, PRC 101, no.2, 024911(2020)
**Run using MAP values**

**JETSCAPE Grad:**
Pb+Pb @ 2.76 TeV
Au+Au @ 0.2 TeV
Everett et al.[JETSCAPE], PRL 126, no.24, 242301 (2021) Phys. Rev. C 103, no.5, 054904 (2021)
**Run using MAP values**

**"Trajectum 1":**
Pb+Pb @ 2.76 TeV & 5.02 TeV
p+Pb @ 5.02 TeV
Nijs, van der Schee, Gürsoy, Snellings, PRC 103, no.5, 054909 (2021); Phys. Rev. Lett. 126, no.20, 202301 (2021)
**Run using MAP values**

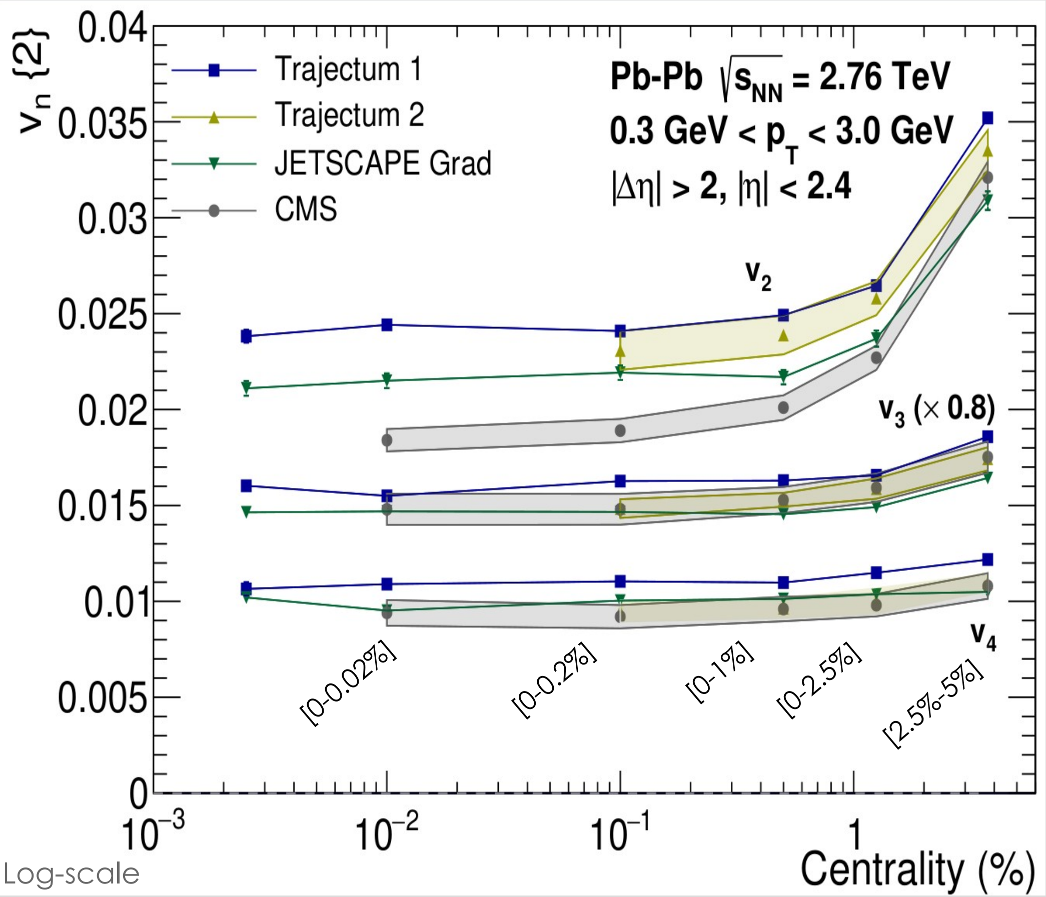
**"Trajectum 2":**
Same Pb+Pb data from Trajectum 1
G. Nijs and W. van der Schee, arXiv:2110.13153
**Run using 20 random posterior samples**




**Good overall agreement w/ non-ultra-central data** for anisotropic flow coefficient + **hint of deviations for ≲ 1% - 2%**

# Bayesian analysis meets ultra-central anisotropic flow data

[0-1% of the total cross-section]




Measured $v_2\{2\}$ **decreases** with centrality while **simulations become ~ constant!**

**Similar behavior** found in older calculations before "Bayesian era"

# Bayesian analysis meets ultra-central anisotropic flow data

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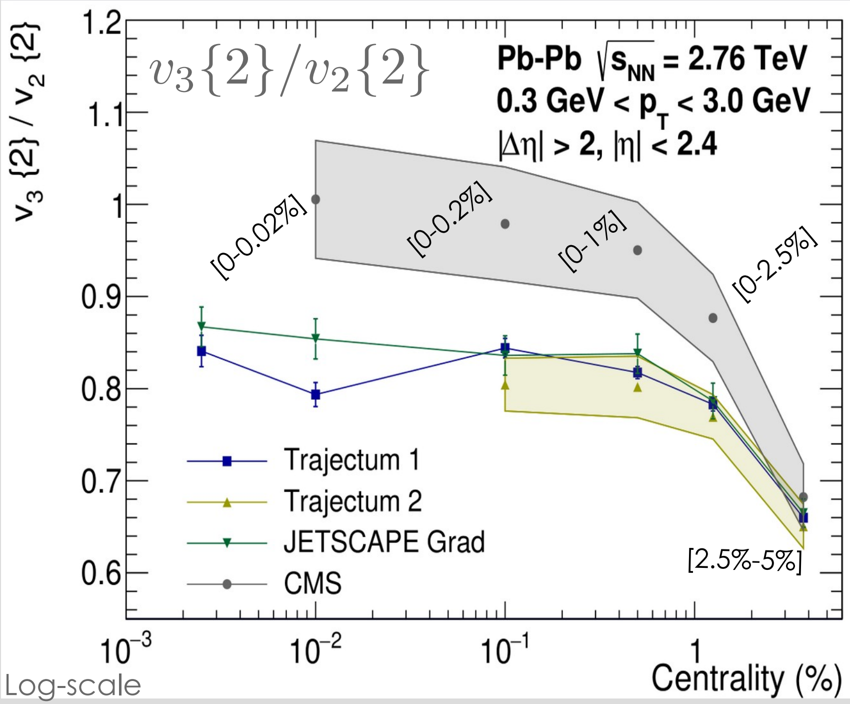


All Bayesian constrained models tested fail in the same way even after including the full posterior predictive distribution [Trajectum 2]

[Assumed uncorrelated errors for CMS points]

# Bayesian analysis meets ultra-central anisotropic flow data

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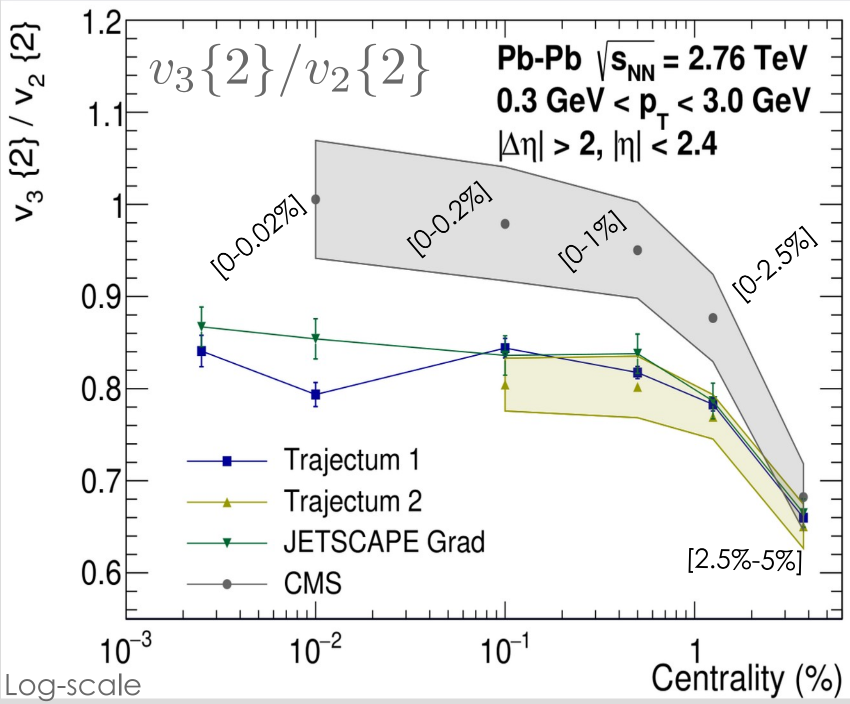


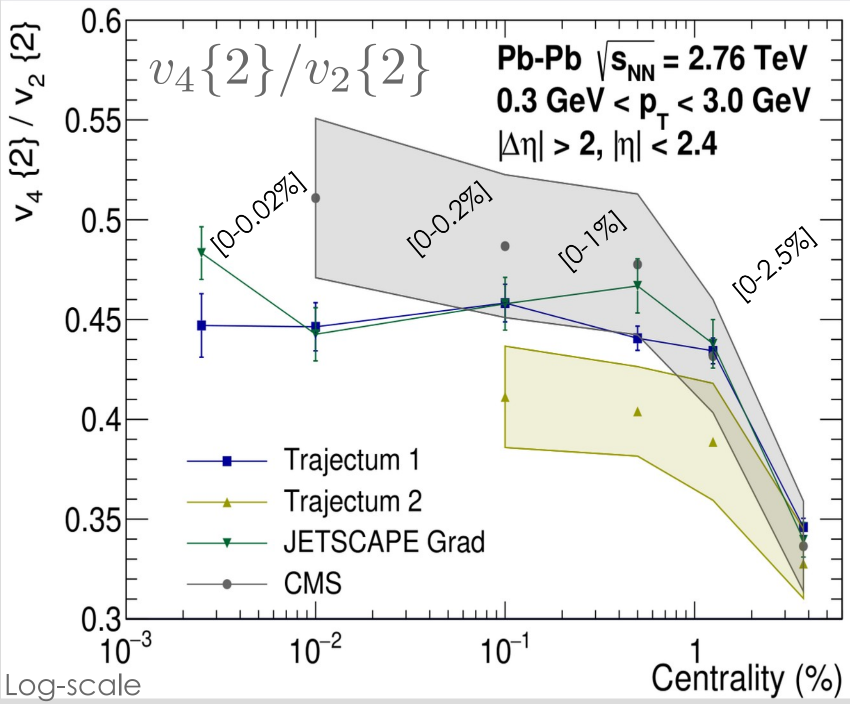


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[Assumed uncorrelated errors for CMS points]

Overall trend is better but wrong centrality dependence for most central bins

[Assumed uncorrelated errors for CMS points]

# Bayesian analysis meets ultra-central anisotropic flow data

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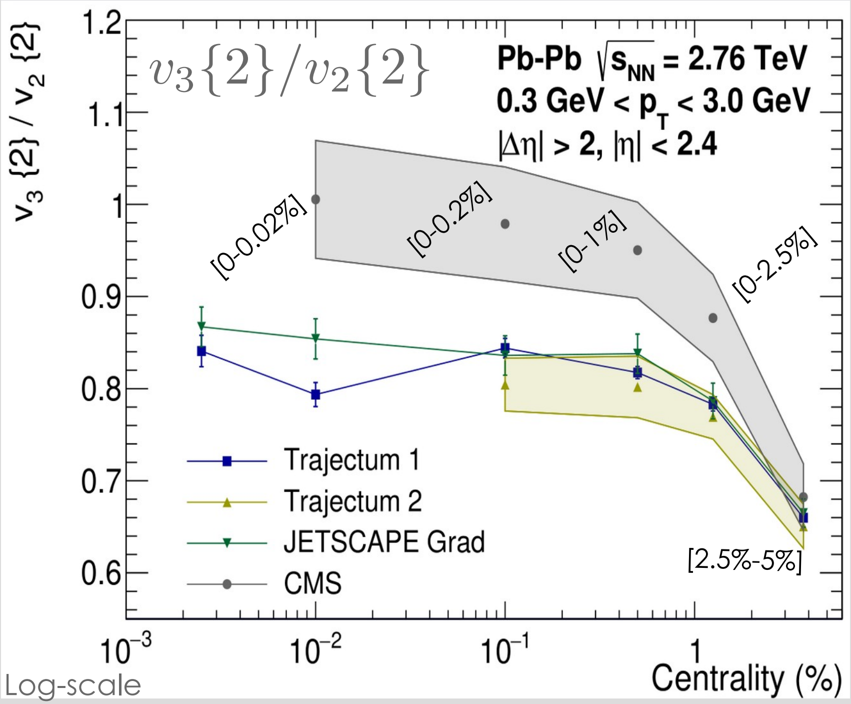
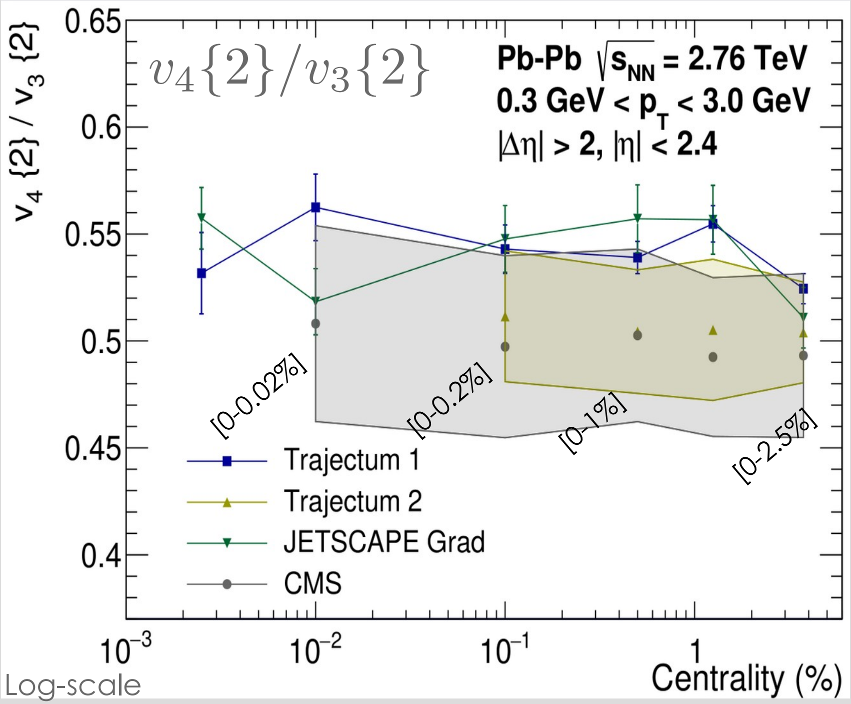



All Bayesian constrained models tested fail in the same way even after including the full posterior predictive distribution [Trajectum 2]

[Assumed uncorrelated errors for CMS points]

**No $v_2$ involved**: better overall agreement for centrality dependence (still, wrong magnitude for Trajectum 1 and JETSCAPE Grad)

[Assumed uncorrelated errors for CMS points]

# Conclusions

Ultra-central flow puzzle: still an open problem!

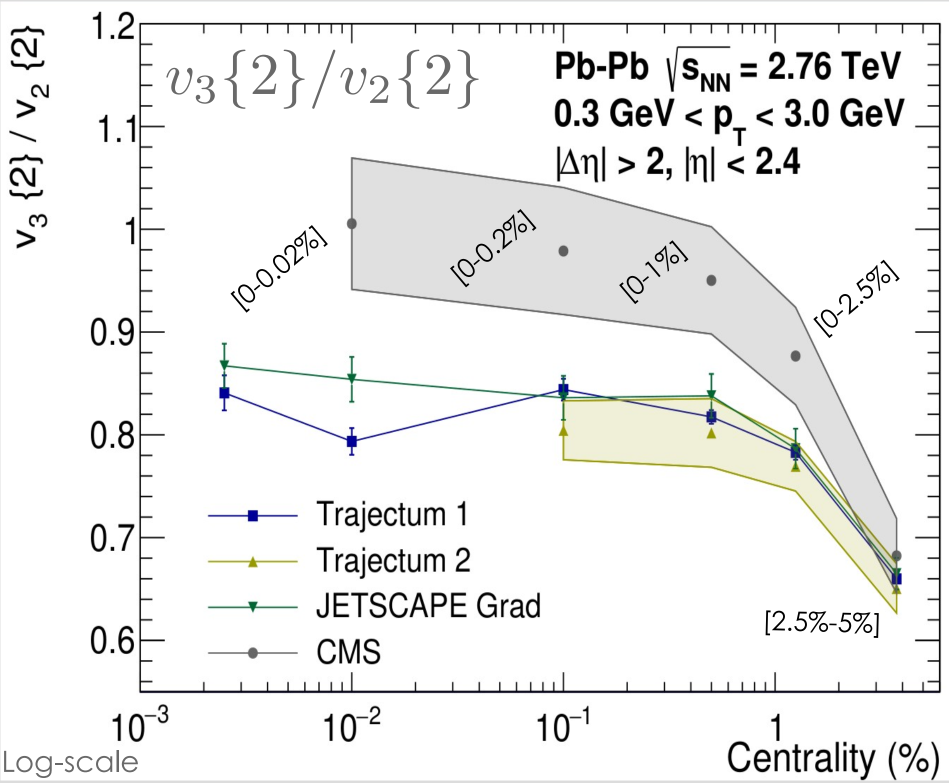
Unlikely to be solved by another round of fine-tuning of input parameters!

Understanding this puzzle:

Potential physics insight;

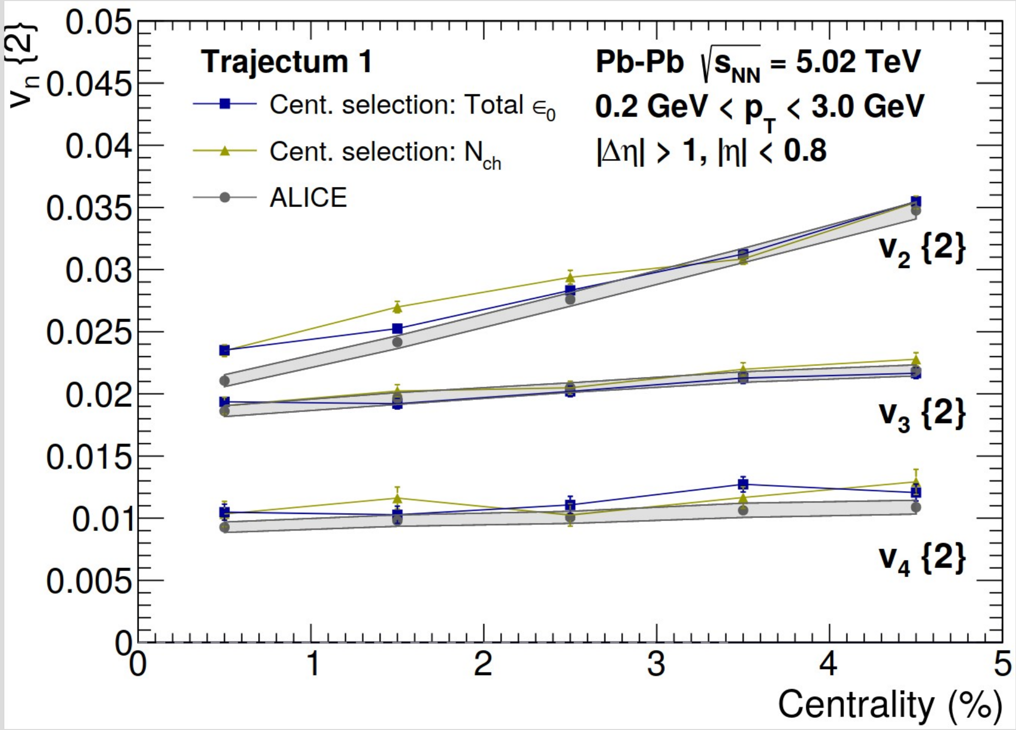
**More confidence** in simulation results;

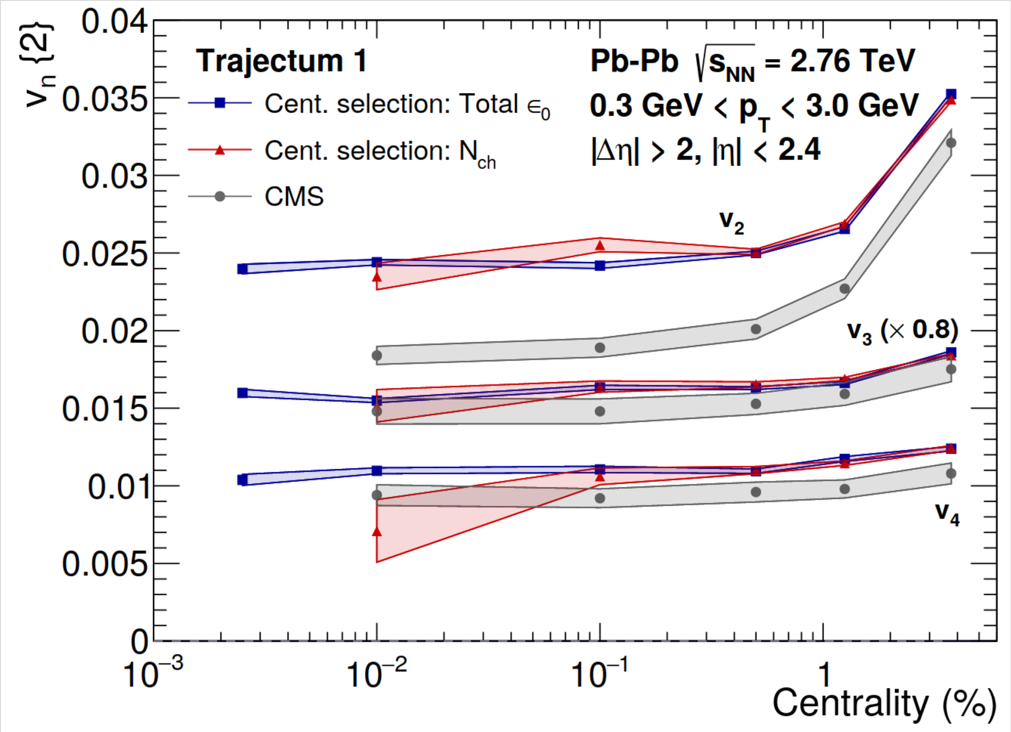
**Better precise determinations** of system properties in future Bayesian analyses.



# Backup slides

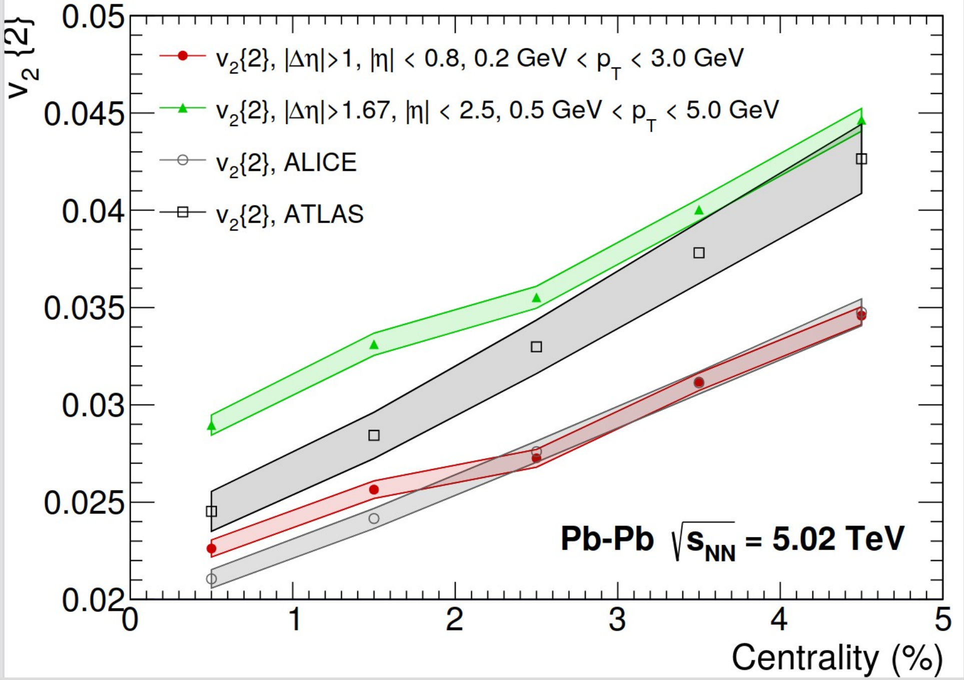
# Effect of centrality selection: Total initial energy vs $N_{ch}$

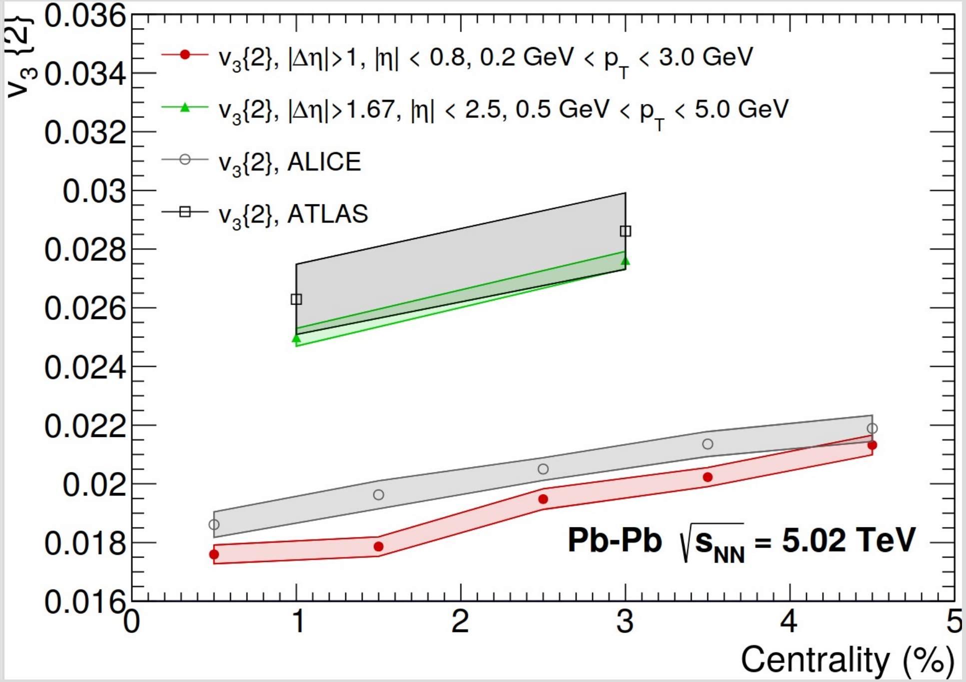



No significant changes if selecting centrality via final multiplicity

# Other comparisons to anisotropic flow @ 5.02 TeV



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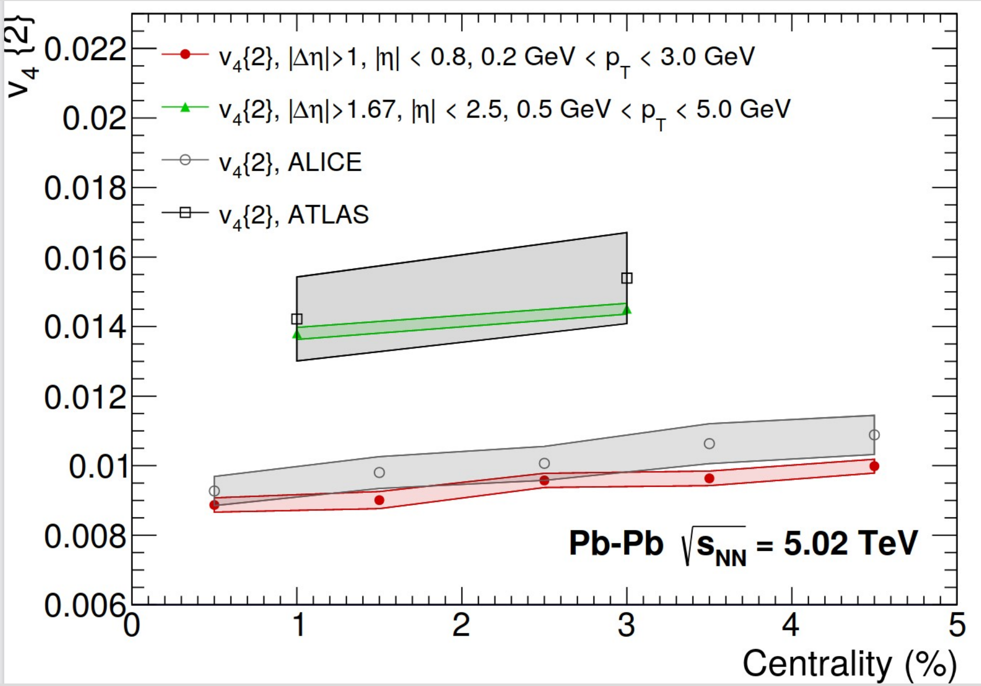

# Shear and bulk viscosities from Bayesian analysis