Assessing the ultracentral flow puzzle in hydrodynamic modeling of heavy-ion collisions

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Andre V. Giannini

Universidade Federal da Grande Dourados – UFGD
Instituto de Física "Gleb Wataghin" – Universidade Estadual de Campinas

M.N. Ferreira, M. Hippert, D. D. Chinellato, G. S. Denicol,

M. Luzum, J. Noronha, T. N. da Silva and J. Takahashi

[ExTrEMe collaboration]
Experiment and Theory in Extreme Matter

Universidade Federal da Grande Dourados

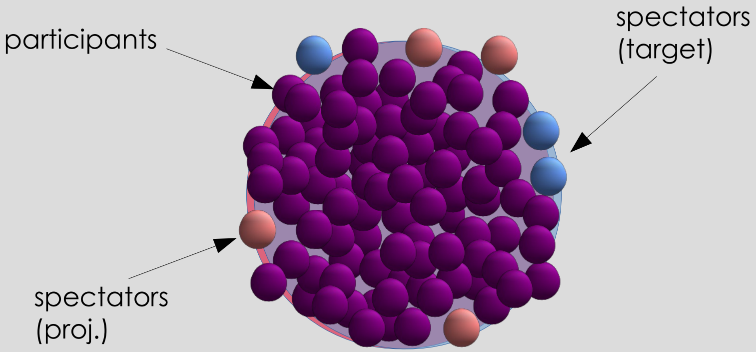
UNICAMP

ISMD 2023 – 21/08/23 – 25/08/23
[remote participation]

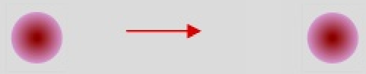
FAPESP
SÃO PAULO RESEARCH FOUNDATION

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

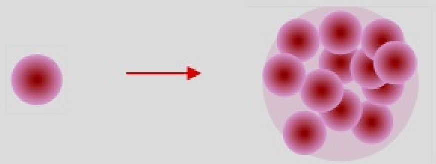
Nuclear matter under extreme conditions



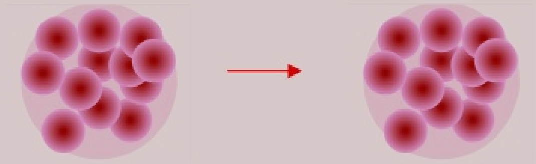
proton-proton collisions ["reference" data]



proton-nucleus collisions ["control" experiment]



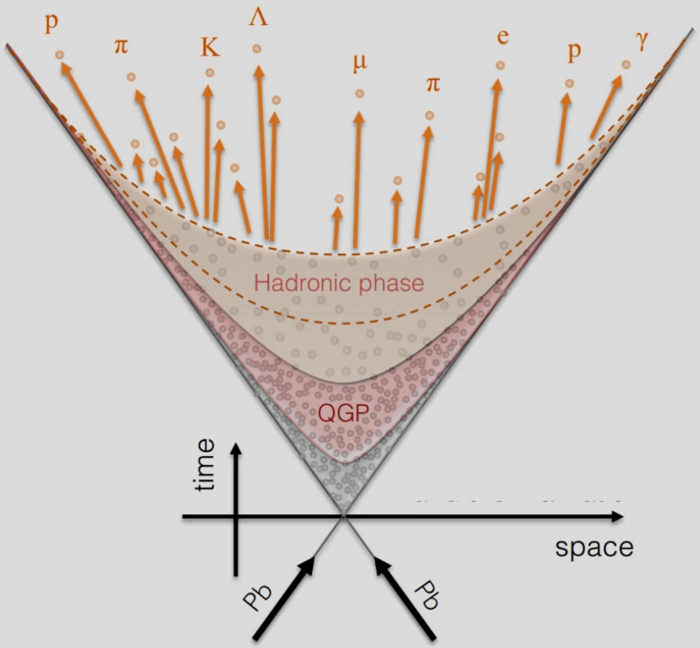
nucleus-nucleus collisions: create & characterize the QGP



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]

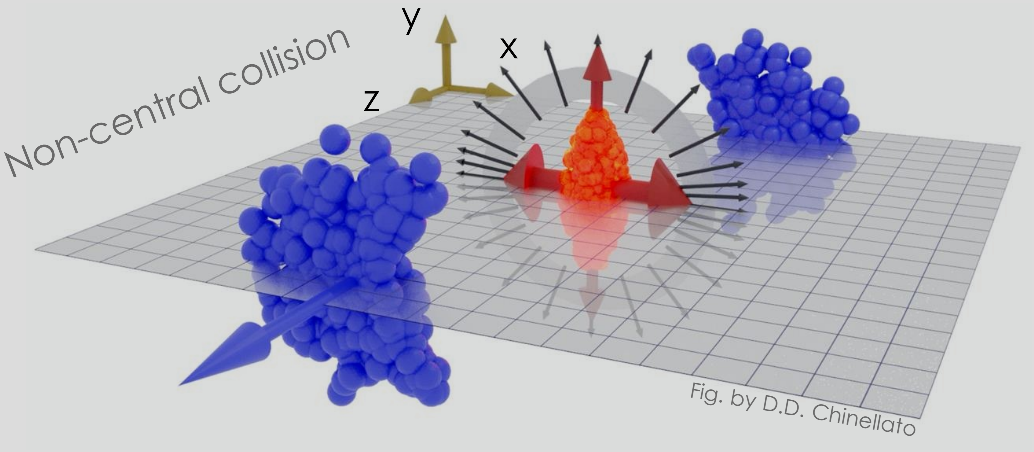
Initial conditions [MC-Glauber, MC-KLN, IP-Glasma, TRENTo, …]

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

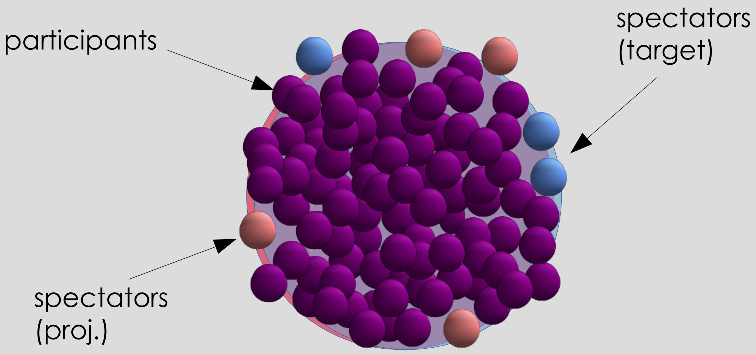
[0-1% of the total cross-section]



Initial state eccentricities + **collision geometry**

Pressure is largest in the direction of shortest axis

Spatial anisotropies → momentum anisotropies



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

Ollitrault,PRD 46, 229-245 (1992)
Poskanzer, Voloshin, PRC 58, 1671-1678 (1998)
Bilandzic, Snellings, Voloshin, PRC 83, 044913 (2011)
+ many others

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

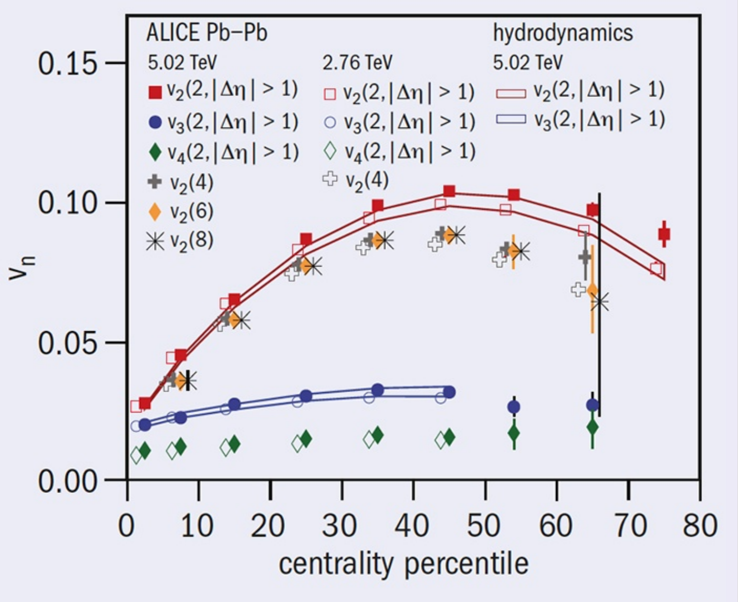
ϕ : azimuthal angle of produced particle

Ψ_{RP} : “reaction plane” angle; angle between beam direction and the impact parameter vector [not exp. accessible!]

Move to multi-particle correlations

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

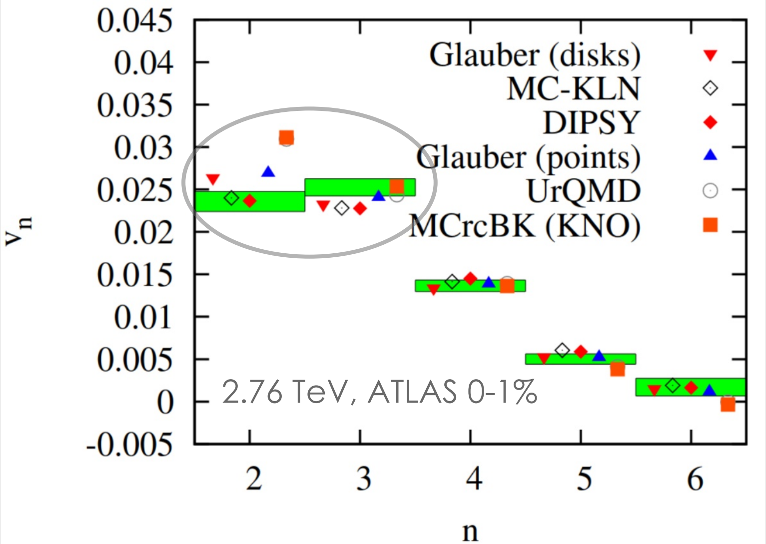
$v_n \equiv v_n(p_T, \Delta\eta)$: integrate over pt, get centrality dependence →



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)

Overall behavior is reproduced by several simulations in the last decade

Overall feature of simulations:

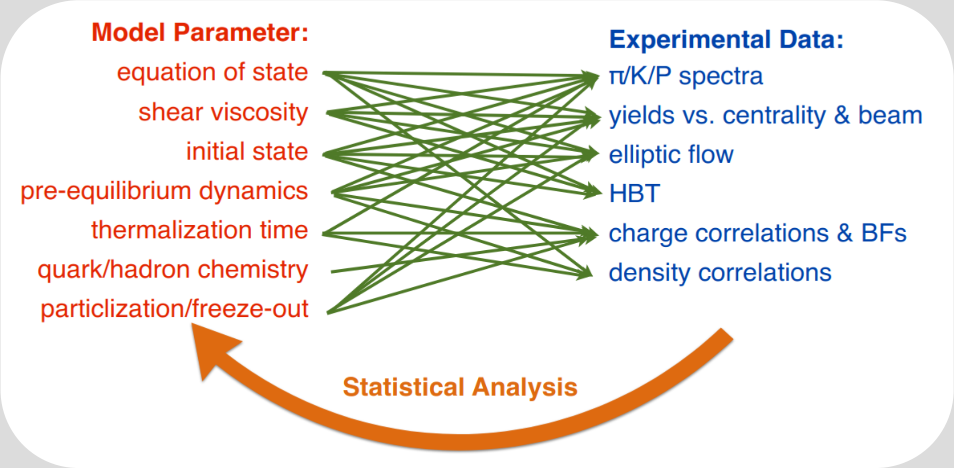
– overprediction of elliptic flow
– underprediction of triangular flow

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”

Ke, Moreland, Bernhard, Bass, PRC 96, no.4, 044912 (2017); Bernhard, Moreland, Bass, Nature Phys. 15, no.11, 1113-1117 (2019); Moreland, Bernhard, Bass, PRC 101, no.2, 024911(2020); Everett et al.[JETSCAPE], PRL 126, no.24, 242301 (2021) PRC 103, no.5, 054904 (2021); Nijs, van der Schee, Gürsoy, Snellings, PRC 103, no.5, 054909 (2021); PRL 126, no.20, 202301 (2021); Parkkila, Onnerstad, Kim, PRC 104, no.5, 054904 (2021); G. Nijs, van der Schee, PRC 106 (2022) 4, 044903; Parkkila, Onnerstad, Taghavi, Mordasini, Bilandzic, Virta, Kim, PLB 835, 137485 (2022); Liyanage, Sürer, Plumlee, Wild, Heinz, arXiv:2302.14184; Soeder, Ke, Paquet, Bass, arXiv:2306.08665 [nucl-th]; Heffernan, Gale, Jeon, Paquet, arXiv:2306.09619 [nucl-th]



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

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

Each analysis is unique an may lead to e.g.: different temperature dependence for the transport coefficients

All **data** considered come **from typical centralities**
[0 – 5% centrality bin is the narrower bin included]

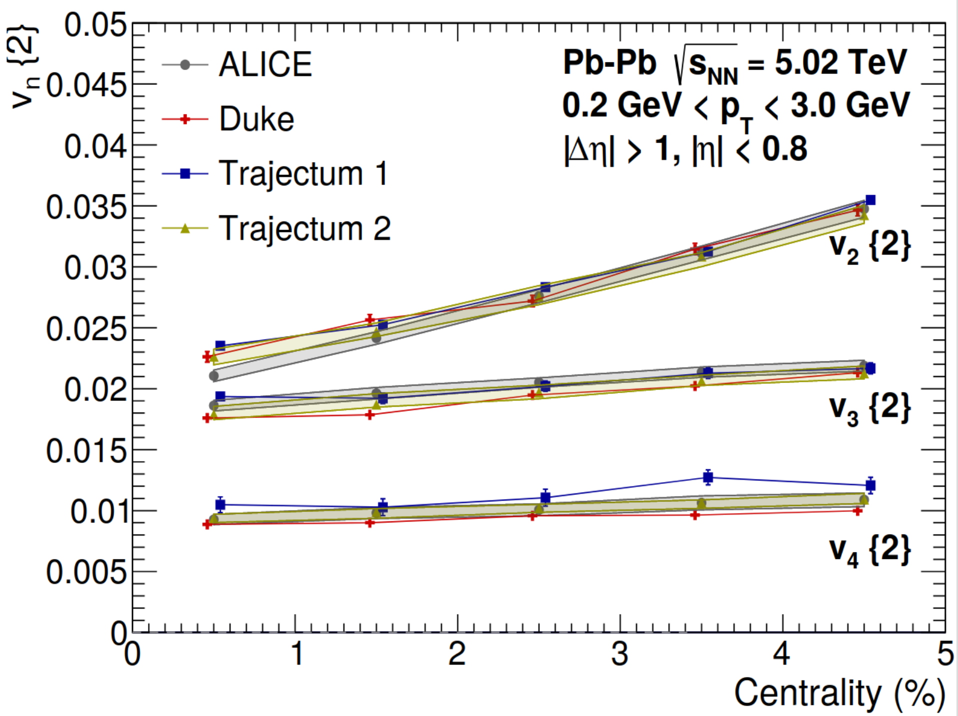
Selected Bayesian constrained models (BCM) & non-ultra-central data

Duke:
p+Pb @ 5.02 TeV
Pb+Pb @ 5.02 TeV
Moreland, Bernhard, Bass, PRC 101, no.2, 024911(2020)
Maximum A Posteriori [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)
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)
MAP values

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

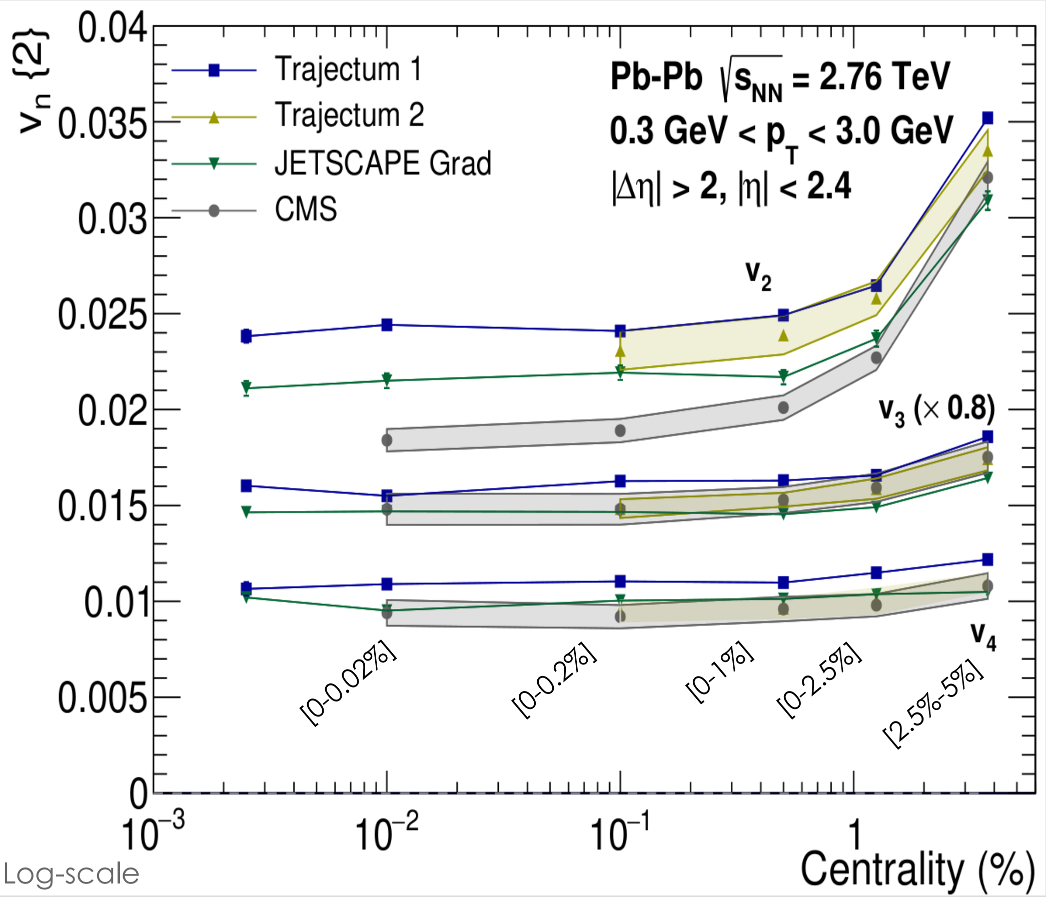


Good overall agreement w/ non-ultra-central data for anisotropic flow coefficient + **hint of deviations for ≲ 1% - 2%**

[0-1%] N_σ = 1.91 (Trajectum 2) N_σ = 3.62 (Trajectum 1)

BCM meet ultra-central anisotropic flow data

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



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

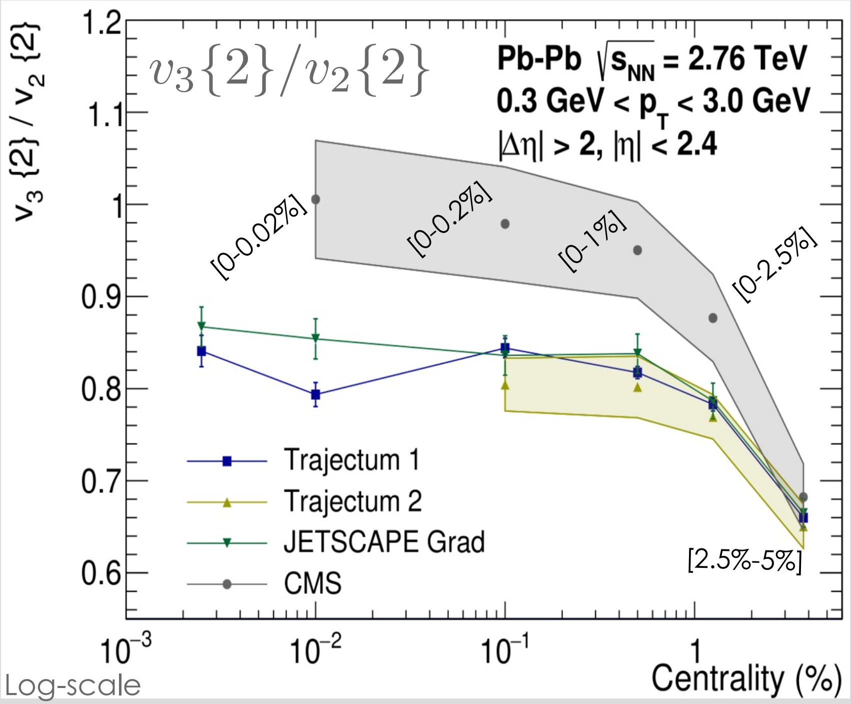
[0-0.02%] N_σ = 4.44 (JETSCAPE Grad)

N_σ = 9.38 (Trajectum 1)

Similar behavior found in older calculations before "Bayesian era"

BCM meet ultra-central anisotropic flow data

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



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]

Ratio $v_4\{2\}/v_2\{2\}$ [backup slides]

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

Ratio $v_4\{2\}/v_3\{2\}$ [backup slides]

No v_2 involved: better overall agreement for centrality dependence

Conclusions

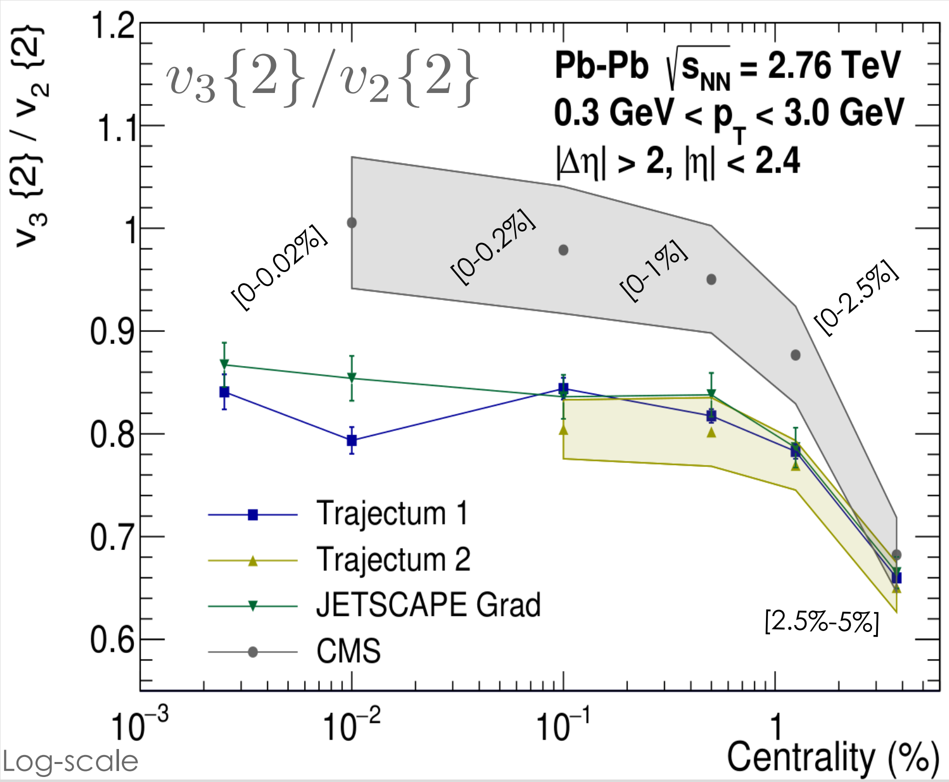
Ultra-central flow puzzle: still an open problem!

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

Solving this puzzle:

New elements are likely needed in the standard modeling of heavy-ion collisions;

Better precise determinations of system properties in future Bayesian analyses.

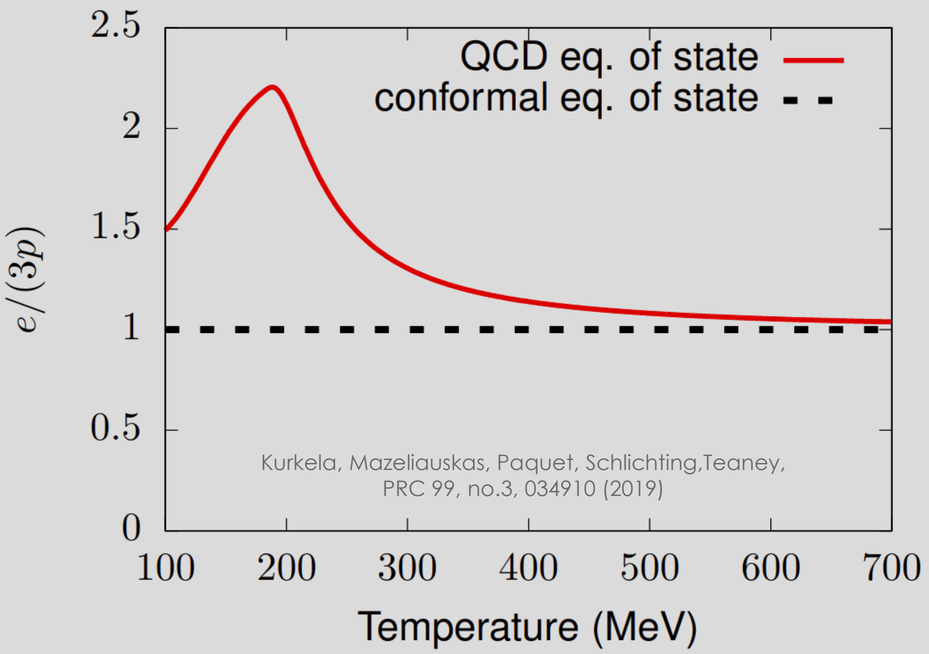


Advances on pre-equilibrium modeling

$$p_\mu \partial_\mu f(x,p) = C[f]$$

$C[f] = 0$ free-streaming

$C[f] = -C_{2\leftrightarrow 2}[f] - C_{2\leftrightarrow 1}[f]$ EKT



$$T^{\mu\nu}_{EKT} = eu^\mu e^\nu + p_{\text{conformal}}(\epsilon)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\neq$$

$$T^{\mu\nu}_{hydro} = eu^\mu e^\nu + p_{QCD}(\epsilon)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Discontinuity @ energy-momentum tensor

Recently explored in:
Extreme collab. PRC 103, 054906 (2021); PRC 107, no.4, 044901 (2023)

Advances on pre-equilibrium modeling

Lead by M.N.Ferreira

Breaking of the conformal invariance with a thermal mass @ Boltzmann equation:

Jeon, Yaffe,PRD 53, 5799-5809 (1996); Debbasch, van Leeuwen, Physica A: Statistical Mechanics and its Applications 388, 1818 (2009)

$$p_\mu \partial_\mu f(x,p) + \frac{1}{2}\partial_i M^2(T)\partial^i_{(\mathbf{p})} f(x,p) = C[f]$$

$$p = \sqrt{\mathbf{p}^2 + M^2(T)}$$

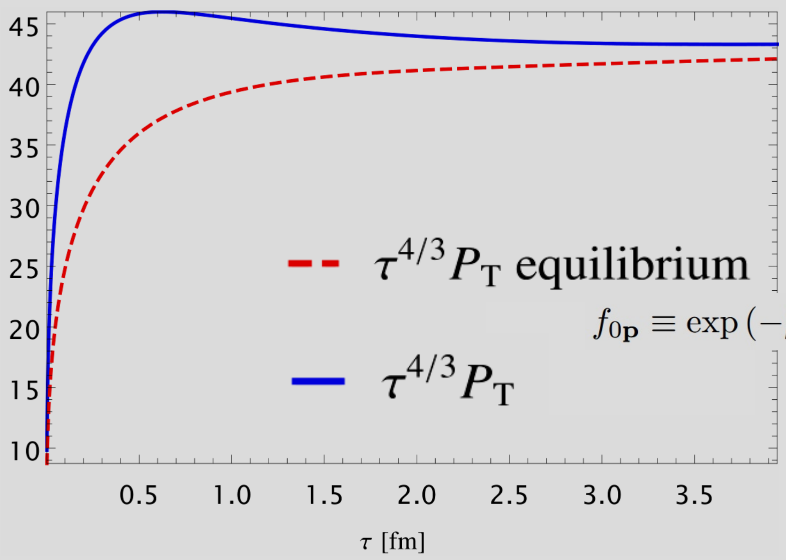
$$f(x,\mathbf{p}) = f_{BG} + \delta f$$

$$B(x) = B_{BG} + \delta B$$

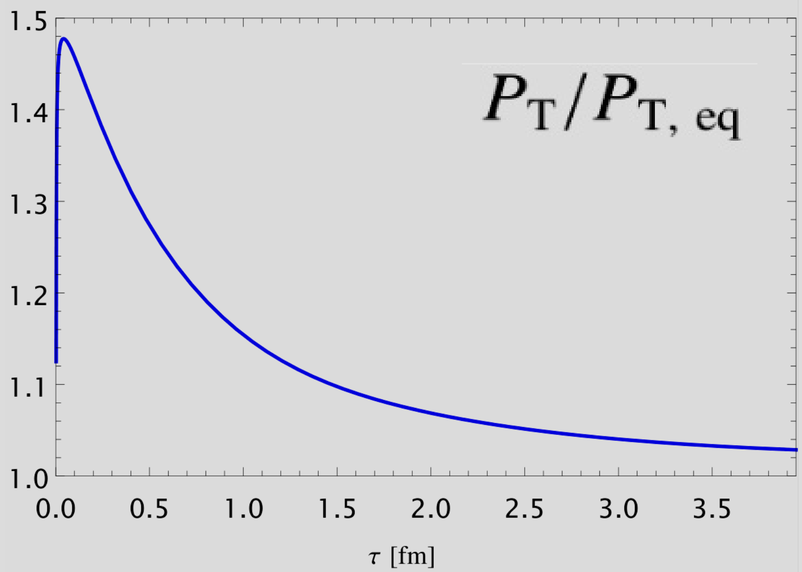
System equilibrates to a non-conformal state! Here: Wuppertal-Budapest EOS

Borsanyi, Endrodi, Fodor, Jakovac, Katz, Krieg, Ratti, Szabo, JHEP 11, 077 (2010)

Opens up opportunity to remove discontinuity @ energy-momentum tensor

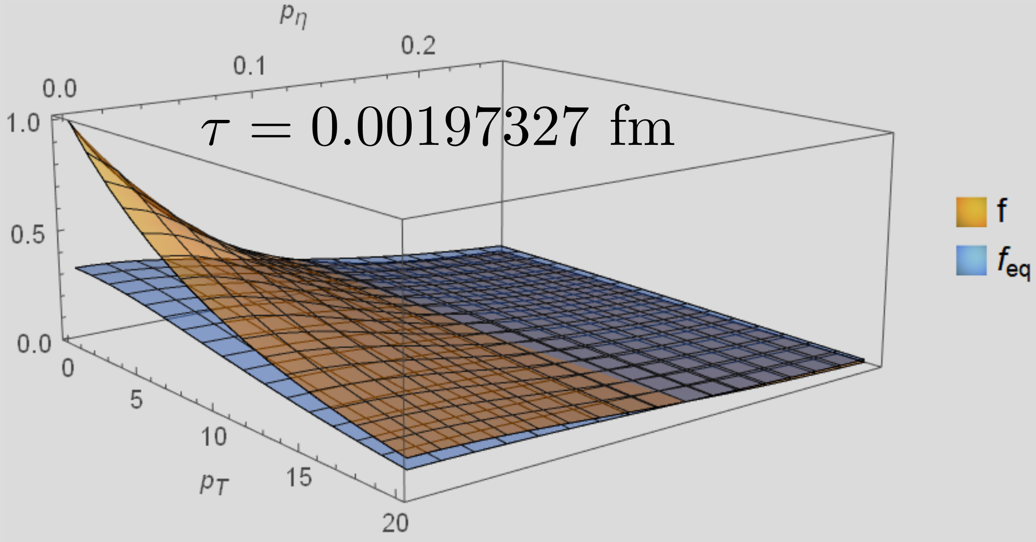


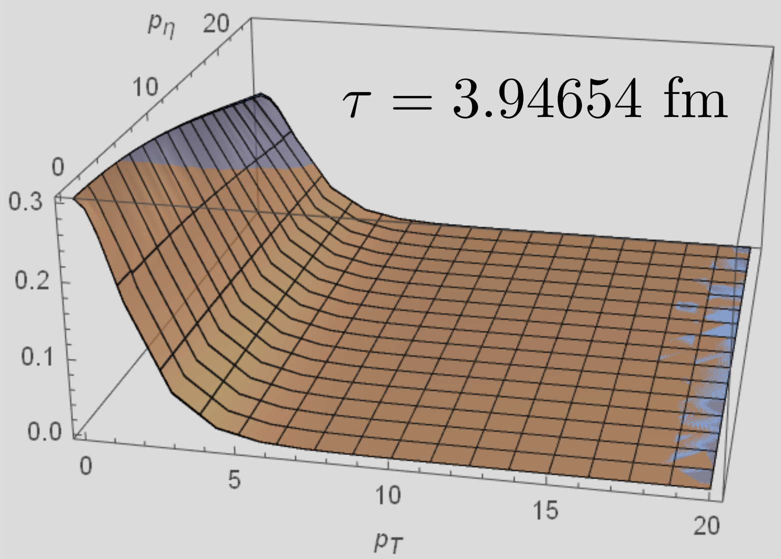
$$f_{0\mathbf{p}} \equiv \exp\left(-\beta u_\mu p^\mu\right)$$



Evolution of the background – early & late times

Lead by
M.N.Ferreira





Background: isotropic in transverse plane and symmetric in η (Bjorken symmetry)

Deviations from equilibrium distribution at early times
while evolving towards the equilibrium distribution at late times

Perturbations around the background ongoing! Stay tuned for new results!

Backup slides

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

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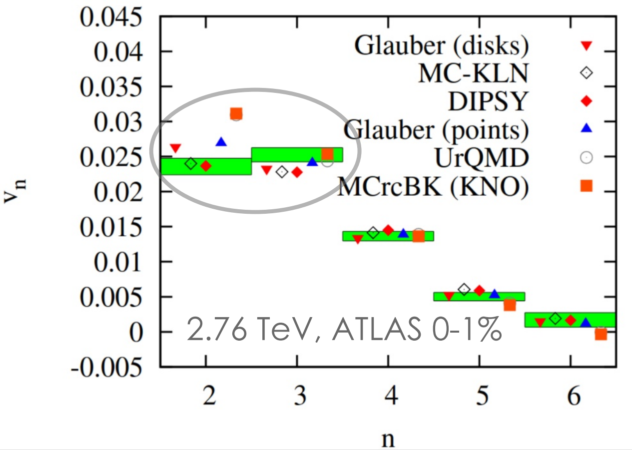
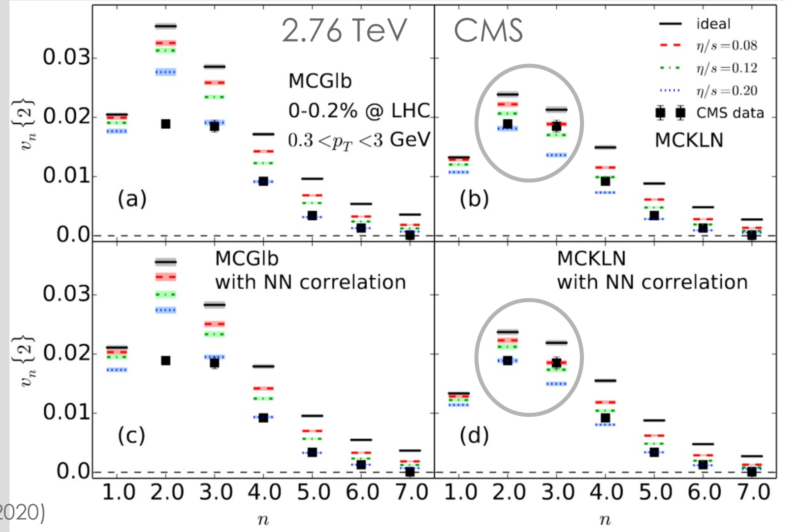
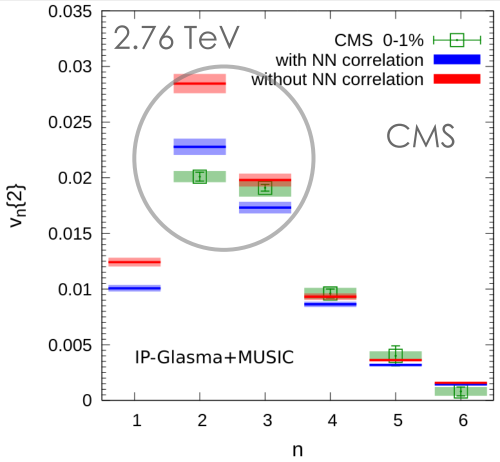


Luzum, Ollitrault, NPA 904-905 377c (2013)

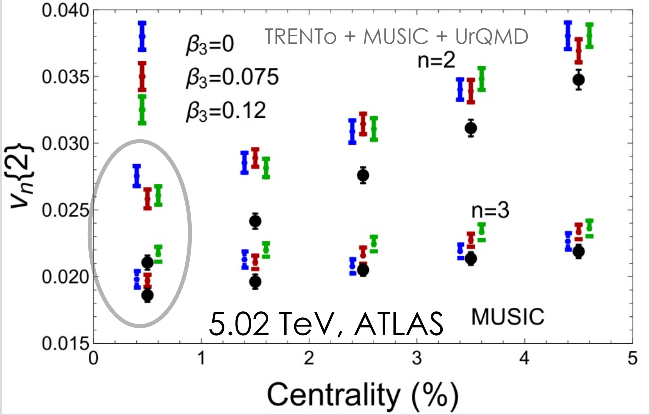


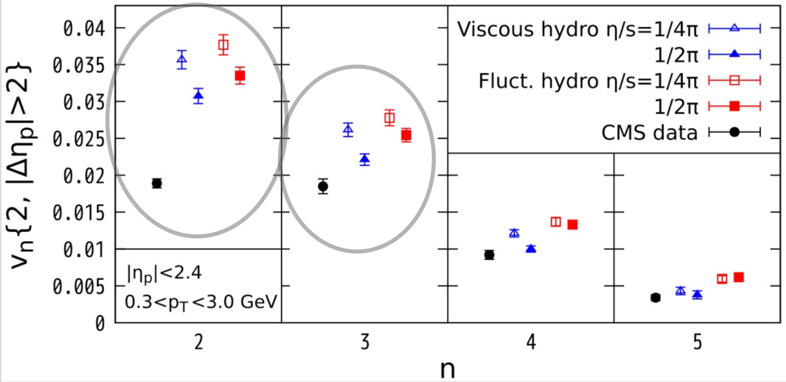
Shen, Qiu, Heinz, PRC92, no.1, 014901 (2015)



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

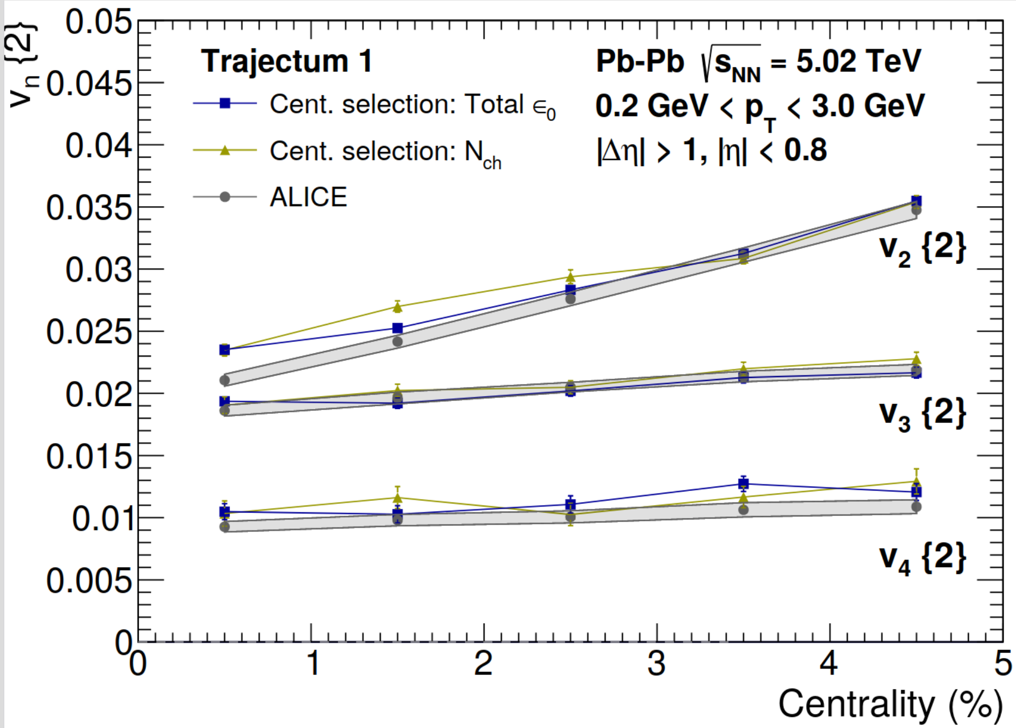
Carzon,Rao,Luzum,Sievert,Noronha-Hostler,PRC102, no.5, 054905 (2020)

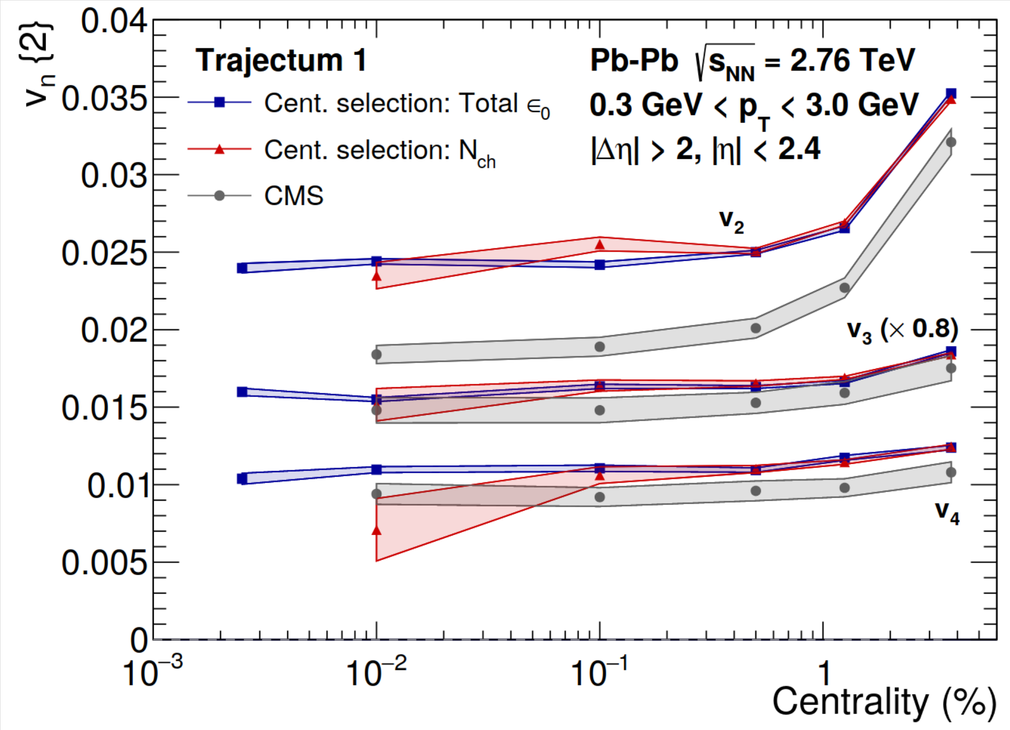




Kuroki, Sakai,Murase,Hirano,PLB 842 (2023) 137958

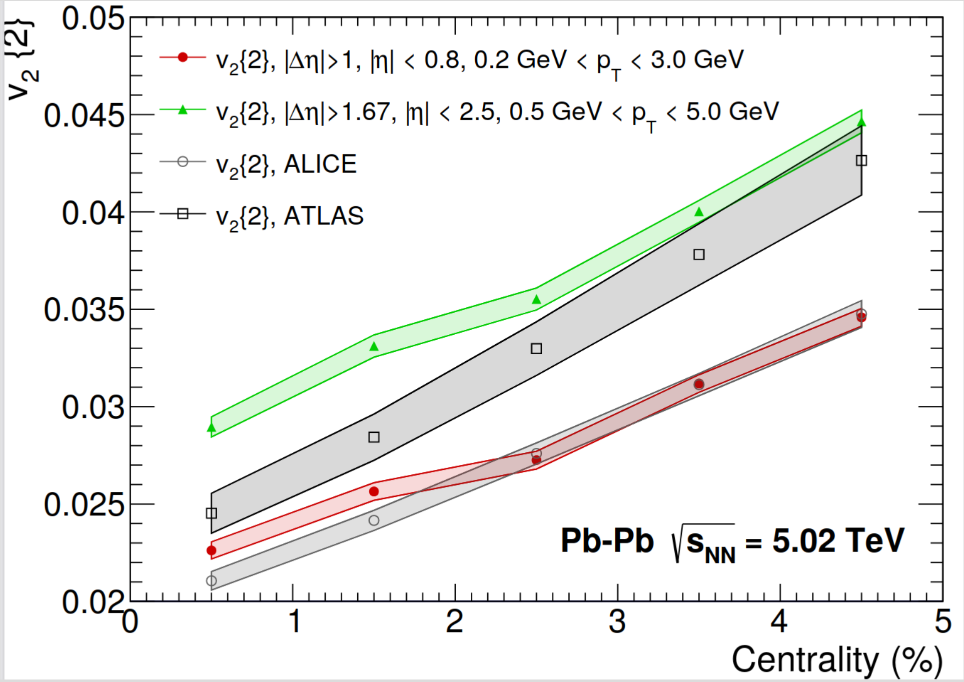
Effect of centrality selection: Total initial energy vs N_{ch}

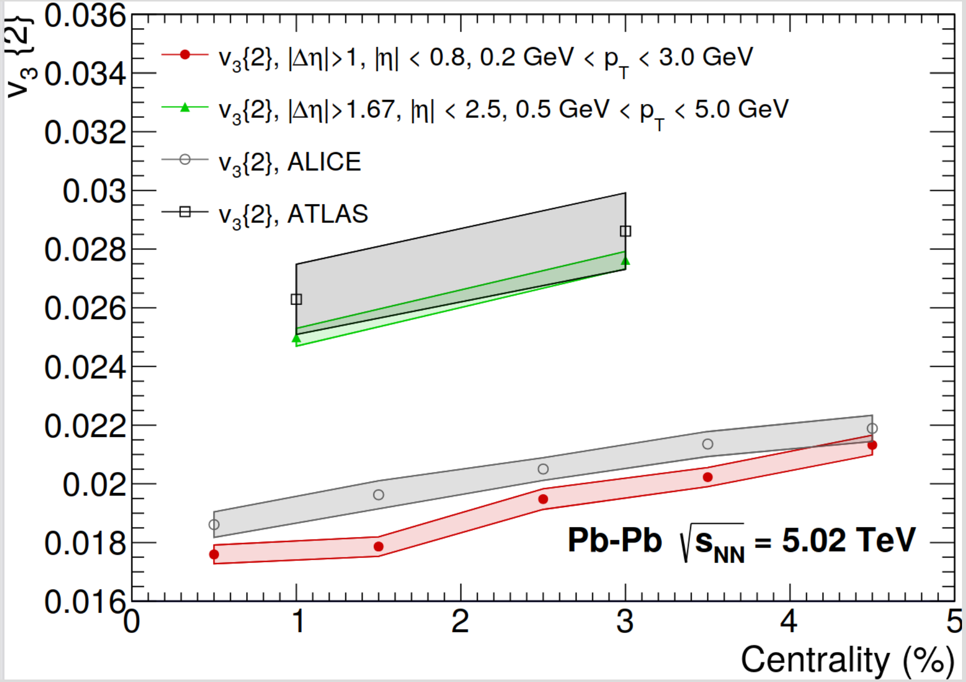




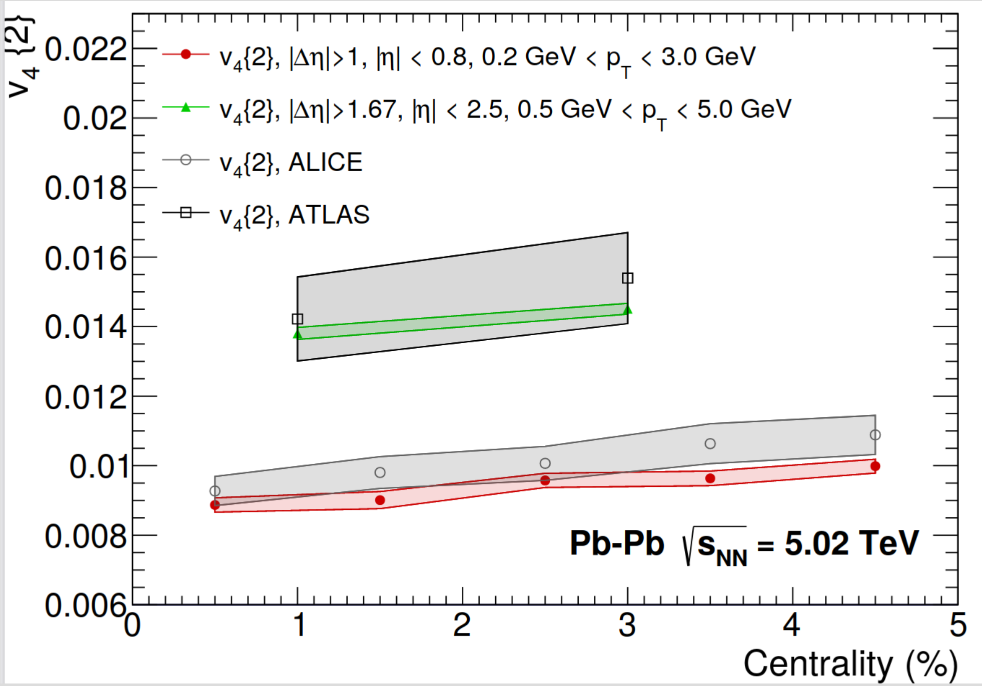
No significant changes if selecting centrality via final multiplicity

Other comparisons to anisotropic flow @ 5.02 TeV

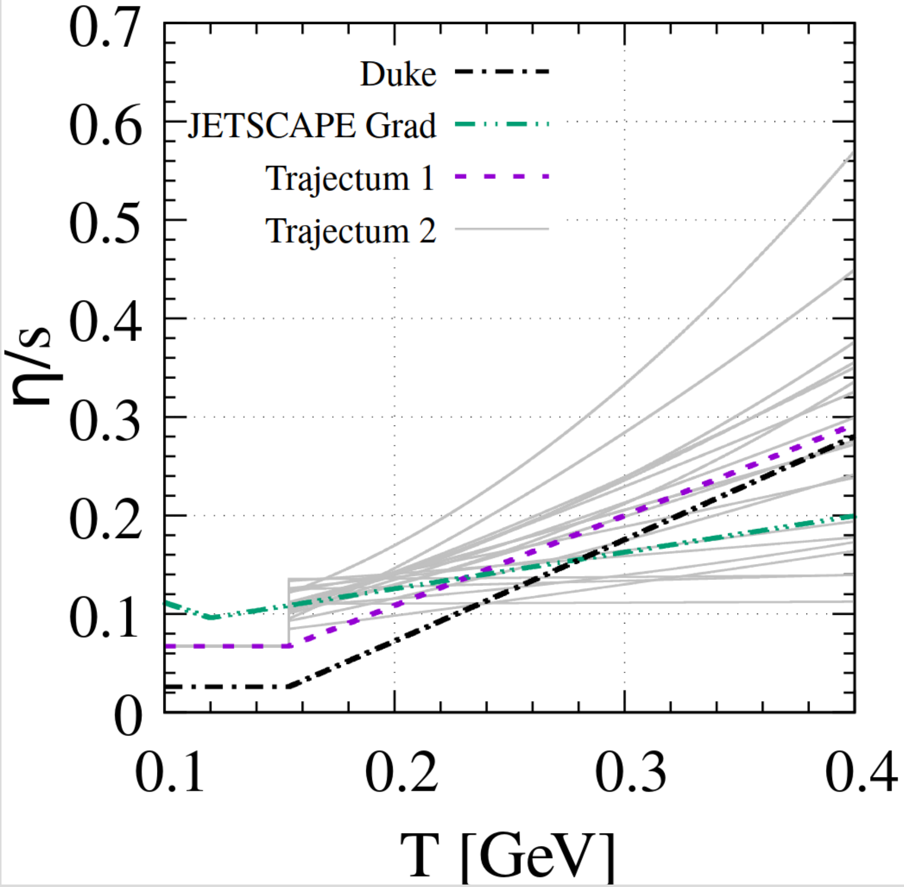


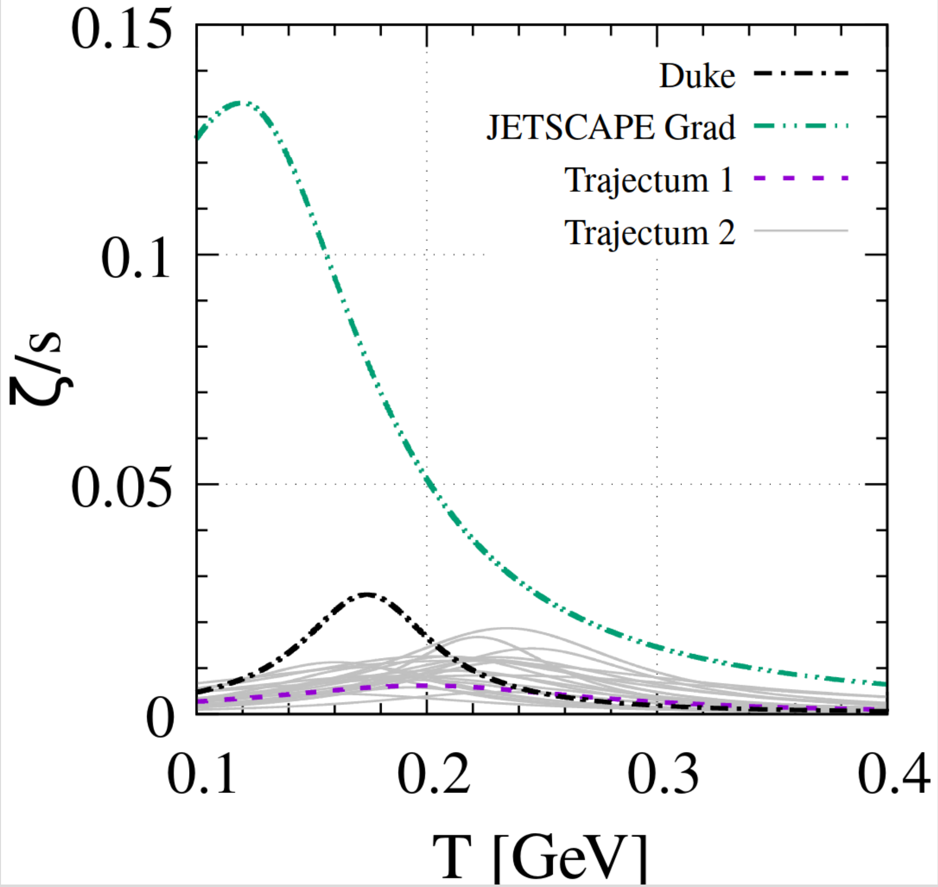


Other comparisons to anisotropic flow @ 5.02 TeV



Shear and bulk viscosities from Bayesian analysis





Non-conformal pre-equilibrium

$$p^\mu \partial_\mu f(x,\mathbf{p}) + \frac{1}{2}\partial_i M^2(T)\partial^i_{(\mathbf{p})} f(x,\mathbf{p}) = C[f]\,, \qquad p^0 = \sqrt{\mathbf{p}^2 + M^2(T)}$$

Collision kernel: Relaxation Time Approximation

$$C[f] = -\frac{E_\mathbf{p}}{\tau_R}\left\{ f(x,\mathbf{p}) - f_{\rm eq}(x,\mathbf{p})\left[1 + \frac{\left[\left\langle E_\mathbf{p}^2/\tau_R\right\rangle - \left\langle E_\mathbf{p}^2/\tau_R\right\rangle_{\rm eq}\right]E_\mathbf{p}}{\left\langle E_\mathbf{p}^3/\tau_R\right\rangle_{\rm eq}} + \frac{\left[\left\langle E_\mathbf{p} p^{\langle\mu\rangle}/\tau_R\right\rangle - \left\langle E_\mathbf{p} p^{\langle\mu\rangle}/\tau_R\right\rangle_{\rm eq}\right]p_{\langle\mu\rangle}}{\frac{1}{3}\left\langle \Delta^{\alpha\beta}p_\alpha p_\beta E_\mathbf{p}/\tau_R\right\rangle_{\rm eq}}\right]\right\},$$

$$\tau_R = t_R\left(\frac{E_\mathbf{p}}{T}\right)^\gamma$$

$$\mathrm{t}_R = 0.5\ GeV^{-1}$$
$$\gamma = 0.5$$

Non-conformal pre-equilibrium

$$p^\mu \partial_\mu f(x,\mathbf{p}) + \frac{1}{2}\partial_i M^2(T)\partial^i_{(\mathbf{p})} f(x,\mathbf{p}) = C[f]\,, \qquad p^0 = \sqrt{\mathbf{p}^2 + M^2(T)}$$

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = \langle p^\mu p^\nu \rangle + g^{\mu\nu} B$$

$$\partial_\mu B = -\frac{1}{2}\partial_\mu M^2(T)\,\langle 1 \rangle \qquad \langle \ldots \rangle = \int dP(\ldots) f(x,\mathbf{p})$$

$$\left\langle E_\mathbf{p}^2 \right\rangle = \left\langle E_\mathbf{p}^2 \right\rangle_{\mathrm{eq}}$$

quasi-Landau matching condition