

# New Constraints of QCD Matter from Bayesian Parameter Estimation with LHC Data

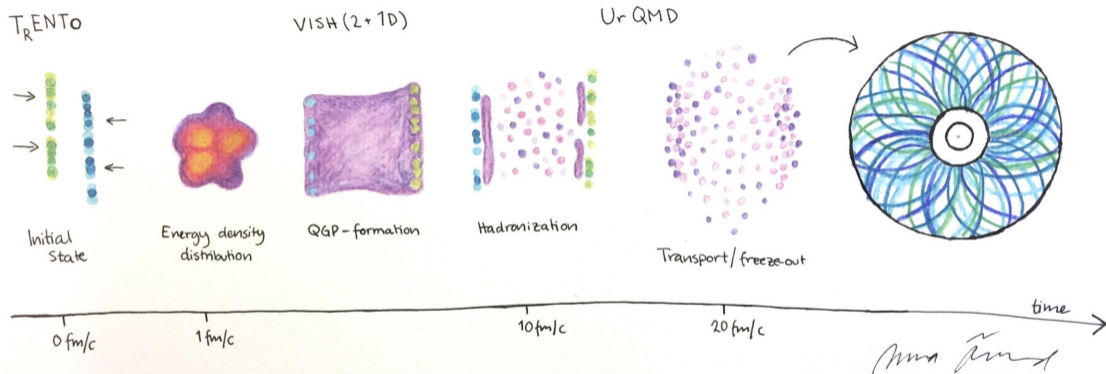
Dong Jo Kim<sup>1</sup>, Jasper Parkkila<sup>2</sup>, Anna Onnerstad<sup>1</sup>, C. Mordasini<sup>1</sup>, S. F. Taghavi<sup>3</sup>, A. Bilandzic<sup>3</sup>  
Based on PRC 104 (2021) 054904, arXiv:2111.08145

1. University of Jyväskylä, Finland
2. CERN, Switzerland
3. Technische Universität München, Germany

Friday 22<sup>nd</sup> July, 2022

Workshop on Particle Correlation and Femtoscopy, East Lansing, Michigan, USA

# THE DIFFERENT STAGES OF HEAVY-ION COLLISIONS



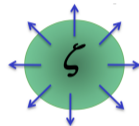
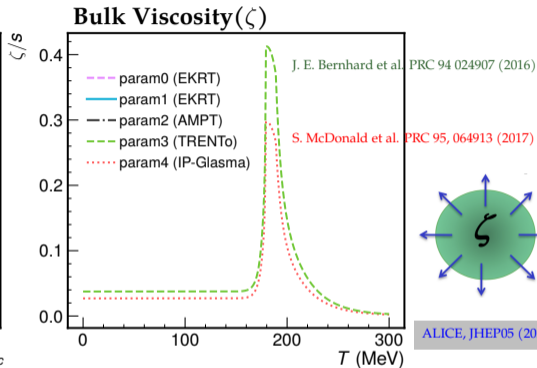
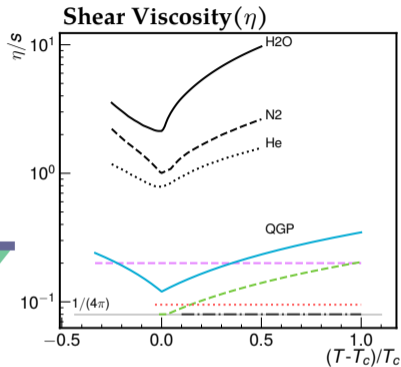
$$T^{\mu\nu} = e u^\mu u^\nu - (P + \Pi) \Delta_{\mu\nu} + \pi^{\mu\nu}, \quad \delta_\mu T^{\mu\nu} = 0$$

## LATEST MAP PARAMETERS, JYVASKYLA (2022)

Table: Input parameter ranges for the initial condition and hydrodynamic models.

Parameter	Description	Range	MAP
$N(2.76 \text{ TeV})$	Overall normalization (2.76 TeV)	[11.152, 18.960]	14.373
$N(5.02 \text{ TeV})$	Overall normalization (5.02 TeV)	[16.542, 25]	21.044
$p$	Entropy deposition parameter	[0.0042, 0.0098]	0.0056
$\sigma_k$	Std. dev. of nucleon multiplicity fluctuations	[0.5518, 1.2852]	1.0468
$d_{\text{min}}^3$	Minimum volume per nucleon	[0.889 <sup>3</sup> , 1.524 <sup>3</sup> ]	1.2367 <sup>3</sup>
$\tau_{\text{fs}}$	Free-streaming time	[0.03, 1.5]	0.71
$T_c$	Temperature of const. $\eta/s(T)$ , $T < T_c$	[0.135, 0.165]	0.141
$\eta/s(T_c)$	Minimum $\eta/s(T)$	[0, 0.2]	0.093
$(\eta/s)_{\text{slope}}$	Slope of $\eta/s(T)$ above $T_c$	[0, 4]	0.8024
$(\eta/s)_{\text{curve}}$	Curvature of $\eta/s(T)$ above $T_c$	[-1.3, 1]	0.1568
$(\zeta/s)_{\text{peak}}$	Temperature of $\zeta/s(T)$ maximum	[0.15, 0.2]	0.1889
$(\zeta/s)_{\text{max}}$	Maximum $\zeta/s(T)$	[0, 0.1]	0.01844
$(\zeta/s)_{\text{width}}$	Width of $\zeta/s(T)$ peak	[0, 0.1]	0.04252
$T_{\text{switch}}$	Switching / particlization temperature	[0.135, 0.165]	0.1595

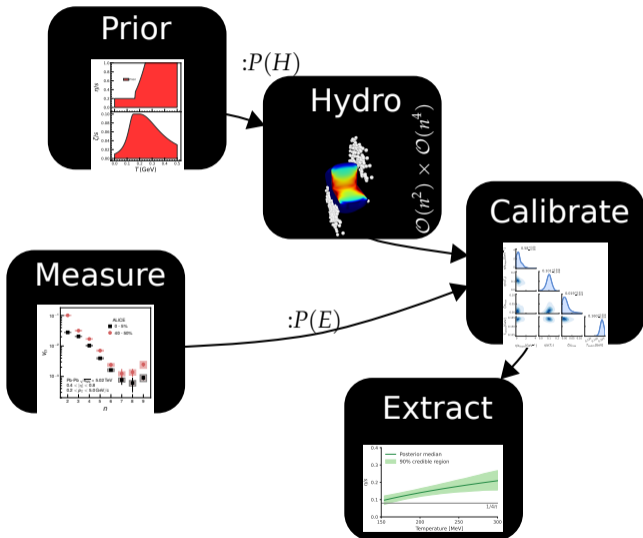
# TRANSPORT PROPERTIES IN HEAVY-ION COLLISIONS



ALICE, JHEP05 (2020) 085

$$(\eta/s)(T) = (\eta/s)(T_c) + (\eta/s)_{\text{slope}}(T - T_c) \left( \frac{T}{T_c} \right)^{(\eta/s)_{\text{curve}}}, \quad (\zeta/s)(T) = \frac{(\zeta/s)_{\text{max}}}{1 + \left( \frac{T - (\zeta/s)_{T_{\text{peak}}}}{(\zeta/s)_{\text{width}}} \right)^2}$$

## BAYESIAN PARAMETER ESTIMATION



Bayes' theorem:

$$P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E)}$$

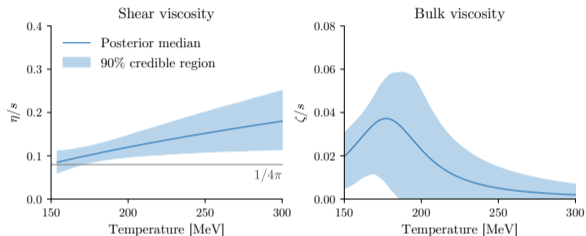
$$P(E) = \sum_{i=1}^n P(E|H_i)P(H_i)$$

- Find optimal set of model parameters that best reproduce the experimental data
- Utilize constraints, such as flow observables, to help narrow down the  $\eta/s(T)$  and such.

Testing a single set of parameters requires  $\mathcal{O}(10^4)$  hydro events, and evaluating eight different parameters five times each requires  $5^8 \times 10^4 \approx 10^9$  hydro events.

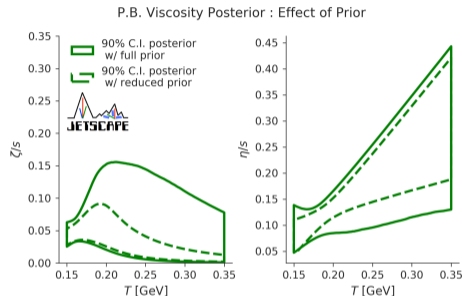
**That's roughly  $10^5$  CPU years!**

## BAYESIAN PARAMETER ESTIMATION: PREVIOUS WORK

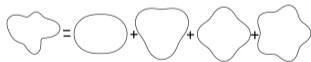
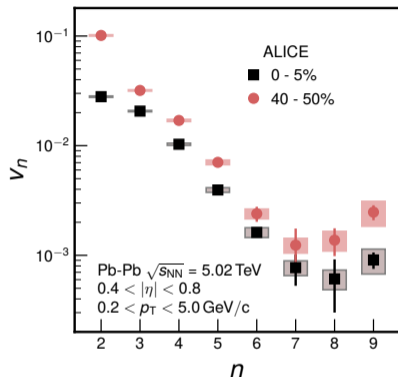
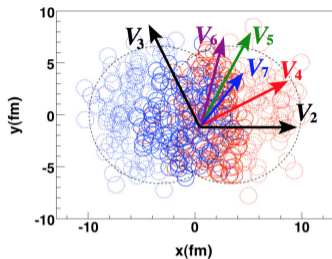
Duke T<sub>R</sub>ENTo+VISH(2+1D)+UrQMDSteffen A. Bass *et al.*, Nature Physics (2019)

- Low to moderate temperature dependence on  $\eta/s(T)$
- Moderate magnitude of  $\zeta/s(T)$  ( $\sim 0.1 \times$  w.r.t lattice QCD(PRL. **94**, 072305 (2005)))
- Large uncertainty for both  $\eta/s(T)$  and  $\zeta/s(T)$ .
- Subsequent studies with still limited observables:
  - J. Auvinen *et al.* PRC. **102**, 044911 (2020)
  - G. Nijs *et al.* PRL. **126**, 202301 (2021)

Uncertainties need to and can be further improved.

Only low-order harmonic  $v_n$  was used, including a limited set of mostly 2.76 TeV observables.JETSCAPE T<sub>R</sub>ENTo+MUSIC+SMASHJETSCAPE Collaboration, PRC **103** (2021) 054904

# HIGHER FLOW HARMONICS AND FLOW FLUCTUATION

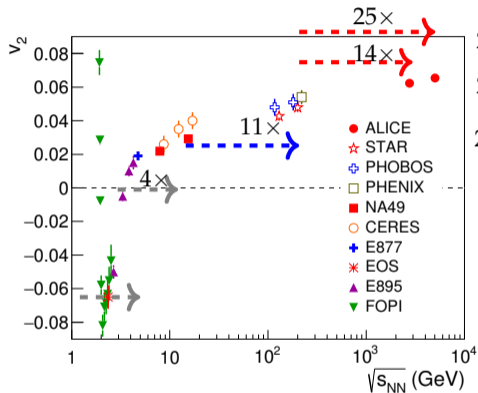


$$P(\varphi) \propto \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

$$V_n \equiv v_n \{\psi_n\} e^{in(\psi_n - \phi)}$$

- Sensitive to initial state geometry and properties of the expanding QGP (viscosity( $\eta/s$ ), equation of state)

# $v_2$ VS $\sqrt{s_{NN}}$ AND FLOW POWER SPECTRUM



2015 LHC 5.02TeV CERN

2010 LHC 2.76TeV CERN

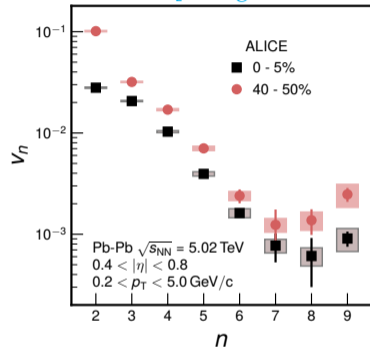
2000 RHIC 200GeV USA

90s SPS 17GeV CERN

80s AGS 4GeV USA

ALICE, Phys. Rev. Lett. 105 (2010) 252302

2020, cerncourier [Going with the flow]

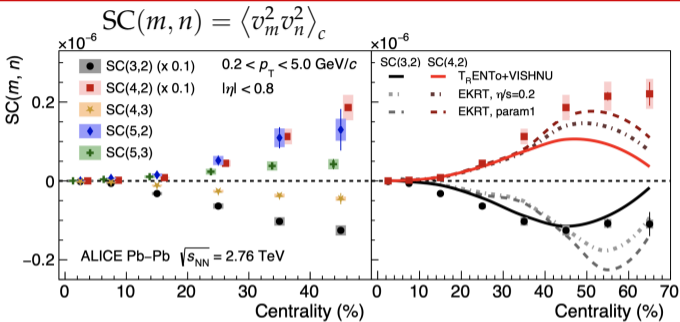


ALICE, JHEP05 (2020) 085

**Measured the largest flow  $v_2$  in 2010!**  
**Measured the largest harmonic order flow (up to  $v_9$ ) so far, 2020**



# HIGH PRECISION FLOW RESULTS AND NEW DEVELOPMENTS- SYMMETRIC CUMULANTS



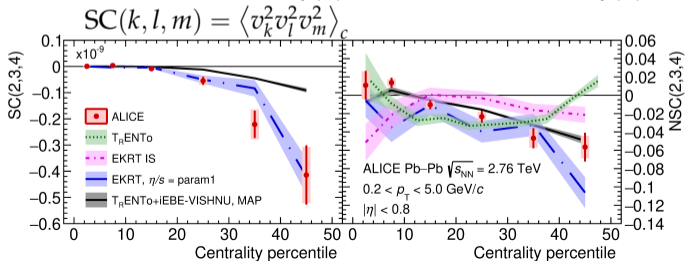
ALICE, Phys. Rev. Lett. 117 (2016) 182301

ALICE, Phys. Rev. C 97 no. 2, (2018) 024906

- Accessing the temperature dependence of  $\eta/s(T)$

ALICE, Phys. Rev. Lett. 127 (2021) 092302

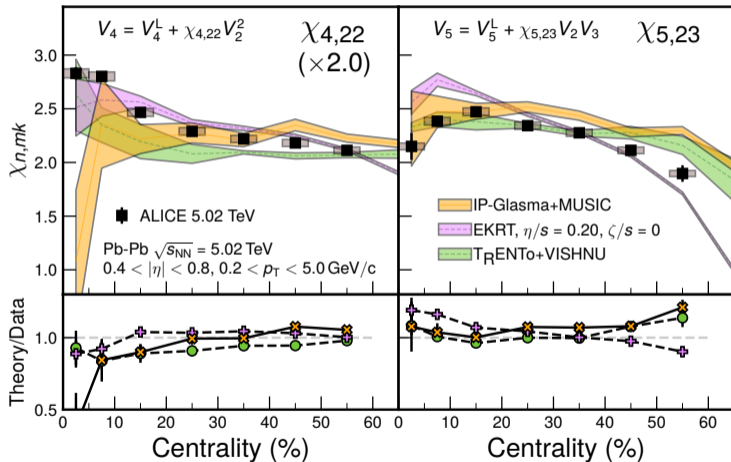
- $\eta/s(T)$  and accessing  $\zeta/s(T)$



- Very challenging measurements because of their required high precisions (i.e  $10^{-6}$  SC( $m, n$ ),  $10^{-12}$  for SC( $k, l, m$ )) and difficulties in correcting experimental biases.

- Symmetric Cumulants(Standard Candle)

## IMPROVING RESULTS WITH HIGHER HARMONICS AND MORE PRECISION - NON-LINEAR FLOW MODES



ALICE, JHEP05 085 (2020)

- Higher order  $v_n$ 's ( $n > 3$ ) were studied  $\rightarrow$  non-linear dependence on lower orders
- Characterised by the non-linear flow mode coefficients,  $\chi_{n,mk}$
- Better sensitivity to  $\eta/s(T)$ .

## OUR ARSENAL OF OBSERVABLES - STOCHASTIC APPROACH

- Together various flow observables cover the sensitivity for all components of transport properties.

Name	Symbol	Measure	Sensitivity-stochastic approach
Flow coefficients	$v_n$	System expansion and anisotropy of the flow	Average $\langle \eta/s \rangle$ and $\zeta/s(T)$ peak
(Normalized) Symmetric cumulants	(N)SC( $k, l, m$ )	Correlation between magnitudes of flow harmonics	$\eta/s(T)$ temperature dependence
Non-linear flow mode coefficients	$\chi_{n,mk}$	Quantification of the non-linear response	$\eta/s(T)$ at the freeze-out
Symmetry-plane correlations	$\rho_{n,mk}$	Correlations between the directions of flow harmonics	$\eta/s(T)$

Thanks to excellent ALICE papers over years:

- Phys.Rev.Lett. 117 (2016) 182301, Phys.Lett. B773 (2017) 68, Phys.Rev. C 97 (2018) 024906, JHEP05 (2020) 085, Phys.Lett. B818 (2021) 136354, Phys.Rev.Lett. 127 (2021) 092302 - [flow](#)
- Phys.Rev.Lett. 106 (2011) 032301, Phys.Rev.C 88 (2013) 044910, Phys.Lett. B772 (2017) 567-577, Phys.Rev.C 101, 044907 (2020) - [N<sub>ch</sub> and  \$\langle p\_T \rangle\$](#)

## OUR ARSENAL OF OBSERVABLES

## Duke (2019)

## 2.76 TeV

- PID<sup>1</sup> mult. and  $N_{\text{ch}}$
- Transverse energy  $E_T$
- PID<sup>1</sup>  $\langle p_T \rangle$
- $\delta p_T / \langle p_T \rangle$
- $v_2$  to  $v_4$

## 5.02 TeV

- $N_{\text{ch}}$
- $v_2$  to  $v_4$

## [1] Jyvaskyla (2021)

## 5.02 TeV

- PID<sup>2</sup> mult. and  $N_{\text{ch}}$
- $v_2$  to  $v_7$
- NSC(3,2) to NSC(4,3)
- PID<sup>1</sup>  $\langle p_T \rangle$
- $\chi_{4,22}$  to  $\chi_{6,mk}$

## [2] Jyvaskyla (2022)

## 2.76 TeV

- $N_{\text{ch}}$
- NSC(3,2), NSC(4,2)
- NSC(2,3,4), NSC(2,3,5)
- PID<sup>1</sup>  $\langle p_T \rangle$
- $v_2$  to  $v_4$
- $\chi_{4,22}$  to  $\chi_{6,mk}$
- $\rho_{4,22}$  to  $\rho_{6,mk}$

## 5.02 TeV

- PID<sup>2</sup> mult. and  $N_{\text{ch}}$
- NSC(3,2) to NSC(4,3)
- PID  $\langle p_T \rangle$
- $v_2$  to  $v_7$
- $\chi_{4,22}$  to  $\chi_{6,mk}$
- $\rho_{4,22}$  to  $\rho_{6,mk}$

All reference data based on ALICE measurements.

Red: Missing from other group (Duke etc)

Blue: New since our PRC.

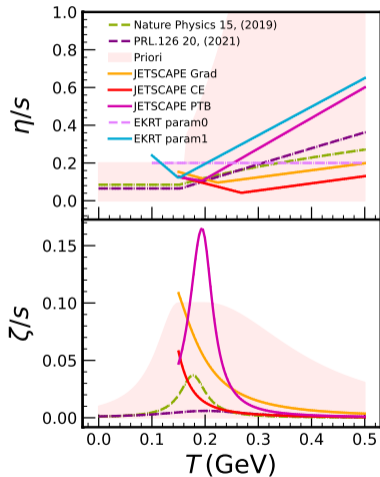
Orange: Not used in our studies.

<sup>1</sup> $\pi^\pm, K^\pm$  and  $p^\pm$   
<sup>2</sup> $p^\pm$

[1]. J.E. Parkkila, A. Onnerstad, D.J. Kim, PRC **104** (2021) 054904

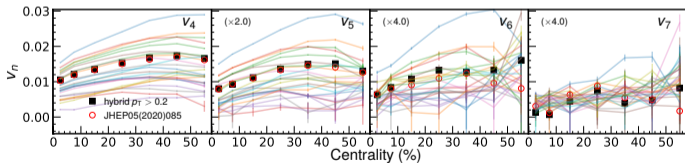
[2]. J.E. Parkkila, A. Onnerstad, S.F. Taghavi, C. Mordasini, A. Bilandzic, D.J. Kim, arXiv:2111.08145

## ANALYSIS STEPS AND PRIORI

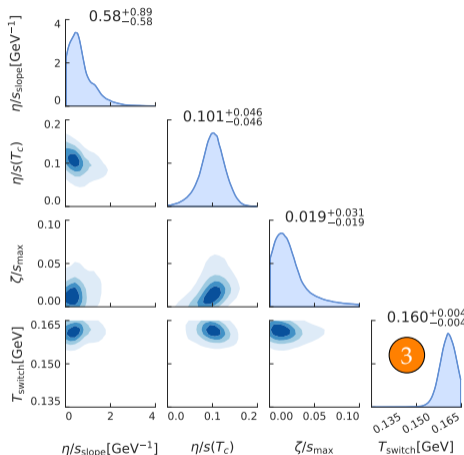
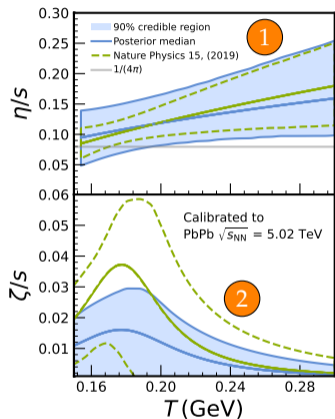


PRC 104 (2021) 054904

- 1 Choose prior parameter range based on results from 2019
- 2 Run hydro  $T_{\text{RENT}} + \text{VISH}(2+1\text{D}) + \text{UrQMD}$  for 500 parameterizations, 3-5 million events ( $\times 100$  previous).
- 3 Calculate observables using our experimental framework
- 4 Train emulator and setup/run Bayesian analysis



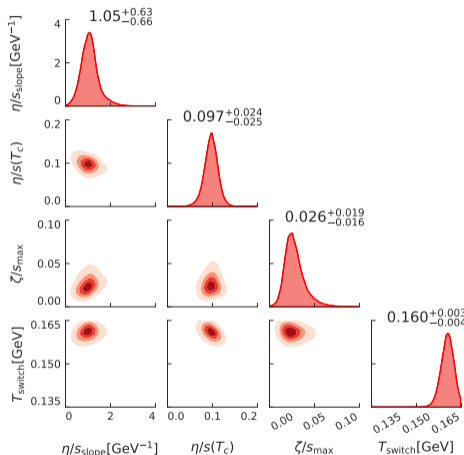
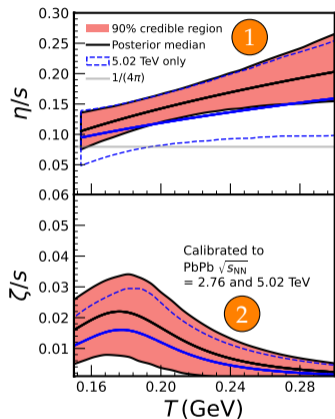
## RESULTS: JYVASKYLÄ (2021) (5.02 TEV ONLY) – HIGHER STATISTICS RUN



- 1 Similar  $\eta/s(T)$  to Duke (2019)
- 2 Lower  $\zeta/s(T)$  – much lower to previous calculations
- 3 Higher switching temperature  $T_{\text{switch}}$  (vs. Duke 152 MeV)

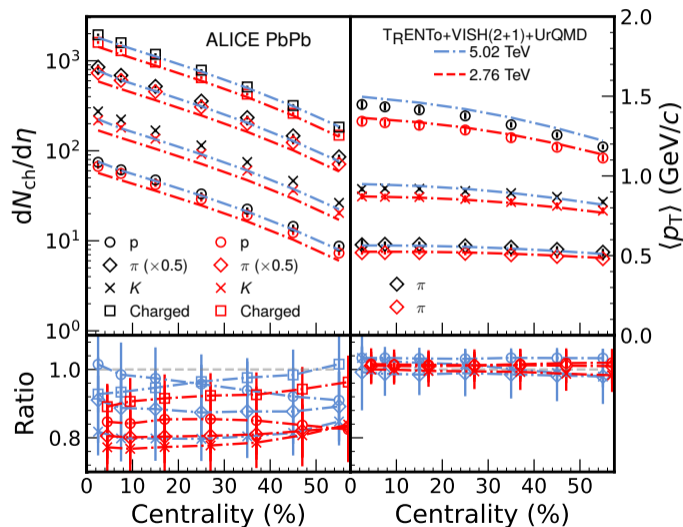
- Additional observables have reduced  $\zeta/s(T)$ .
- However, one collision energy only limits the potential of the additions.

# RESULT: JYVASKYLA (2022) – COMBINED COLLISION ENERGY ANALYSIS (2.76 + 5.02 TeV)



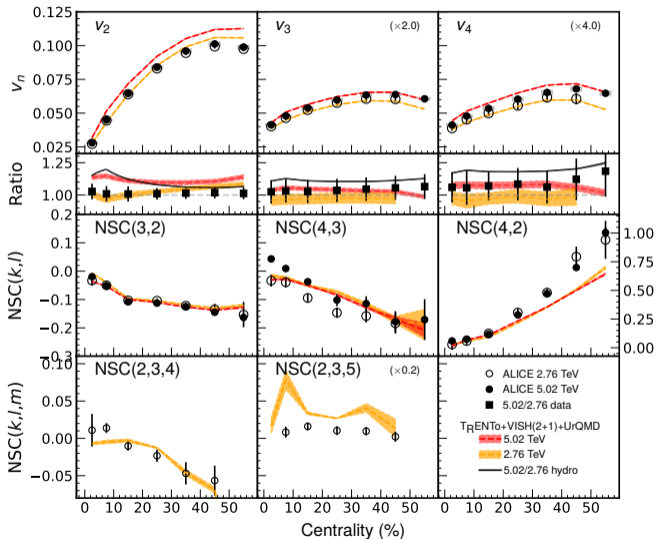
- 1 Significantly improved  $\eta/s(T)$  uncertainty
- 2 Non-zero  $\zeta/s(T)$
- 3 Overall better convergence for parameter components

Together with two collision energies and added observables, the uncertainty has reduced!

PID MULTIPLICITY AND  $\langle p_T \rangle$ 

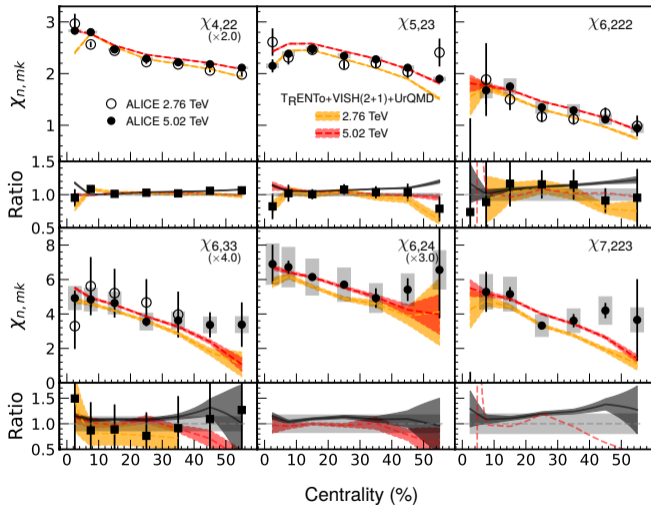
- Agreement for charged particle yield in 2.76 TeV and 5.02 TeV
- 10–20% difference for PID multiplicity
- Qualitative agreement for  $\langle p_T \rangle_{\pi,K}$



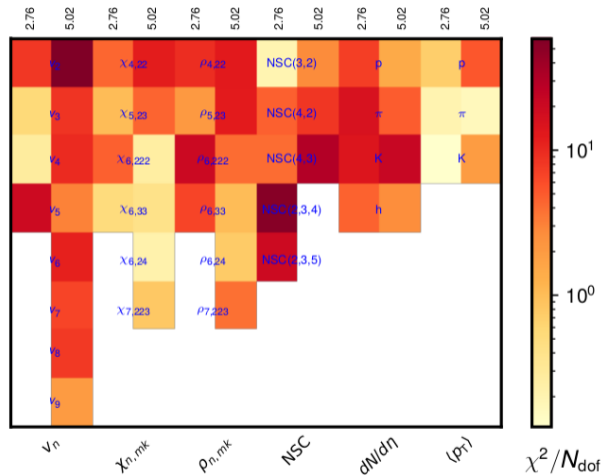
$v_n$  AND SYMMETRIC CUMULANTS

- Good agreement for 2.76 TeV  $v_n$ , overestimated  $v_2$  for 5.02 TeV by  $\sim 10\%$
- Magnitude and centrality dependence of NSC well captured. Further improved estimate for NSC(4,2).
- Good agreement for NSC(2,3,4). NSC(2,3,5) overestimated.

## NON-LINEAR FLOW COEFFICIENTS

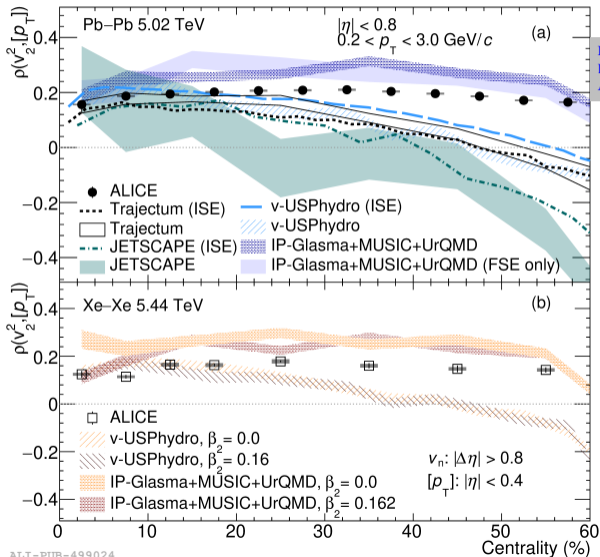


- Qualitative agreement in both beam energies for all mode coupling coefficients.
- See arXiv:2111.08145 for all graphs.

REMAINING CONCERNS?  $\chi^2$ -TEST

- Higher energy description worse for all observables except for:
  - $v_5$
  - $\chi_{6,222}$
  - charged particle multiplicity
- Concerns
  - overestimated  $v_n$  for 5.02 TeV by  $\sim 10\%$
  - still underestimated NSC(4,2)
  - overestimated NSC(2,3,5)
  - PID multiplicity (especially  $\pi^\pm$ )
- Why?
  - Reduction of the uncertainties is understood?

## REMAINING CONCERNS?



P. Bozek, R. Samanta, Phys. Rev. C 102, 034905  
 B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905  
 ALICE, arXiv:2111.06106

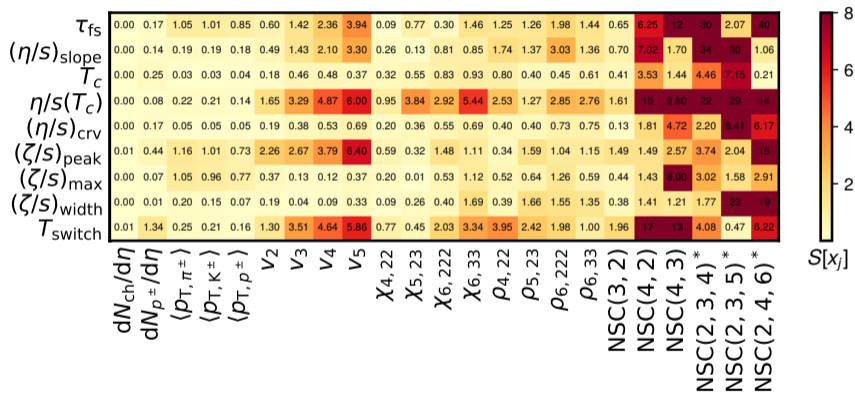
$$\rho(v_2^2, [p_T]) = \frac{\langle \delta v_2^2 \delta [p_T] \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta [p_T])^2 \rangle}}, \quad (1)$$

- Correlation between  $[p_T]$  and  $v_2$ :
  - can be used to differentiate initial state models
  - More peripheral  $\rightarrow$  best described by models with IP-Glasma
  - strong centrality dependence on the models with Trento
- Why?
  - Sensitive to  $p_T$  interval...
  - and pseudorapidity range...
  - and even the multiplicity estimator

SQM22, V. Vislavicius

## SENSITIVITY OF THE OBSERVABLES TO PARAMETERS

Sensitivity of the observables:  $S[x_j] = \Delta/\delta.$ , where  $\Delta = \frac{|\hat{O}(\vec{x}') - \hat{O}(\vec{x})|}{|\hat{O}(\vec{x})|}$ .



- $NSC(m,n)$  and  $NSC(k,l,m)$  are among the most sensitive observables followed by  $v_n$  and  $\chi_{n,mk}$ .
- The precision measurements of observables, reflecting mostly non-linear responses, are crucial.

## SUMMARY

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### Success:

- Higher harmonic orders and non-linear flow observables → better constraints.
- Improved the overall uncertainty by  $\times 2$  by combining two beam energy data.
- As a bonus, sensitivities of the observables are now quantified  
→ precision measurements of observables, reflecting non-linear hydrodynamic responses.

### Challenges:

- 10% difference for  $v_2$  (5.02 TeV)
- NSC description improved except for NSC(4,2)
- Remaining discrepancy for PID multiplicity (especially  $\pi^\pm$ )
- Improving the initial state model, with dynamical collision model or subnucleon structure à la IP-Glasma, might help us to improve the results.

# OUTLOOK

## Experiments

- RHIC data (AuAu collisions) - Energy and system size dependence
- LHC pPb and pp data - System size dependence
- Use new observables
  - Higher order ( $n > 5$ ) Symmetric cumulants
  - Improved Symmetric Plane Correlation (SPC) : independent from flow magnitude correlations and Asymmetric Cumulants (AC) [ALICE, ICHEP2022](#)

## Theory

- Improving the initial conditions with
  - EKRT
  - IP+Glasma
- Testing hydro limit with small systems?
- Role of the small system?

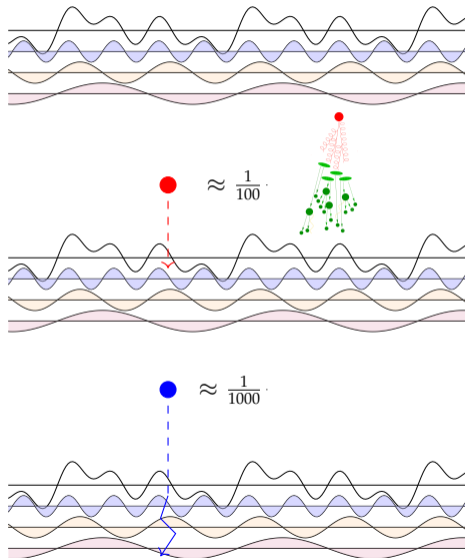
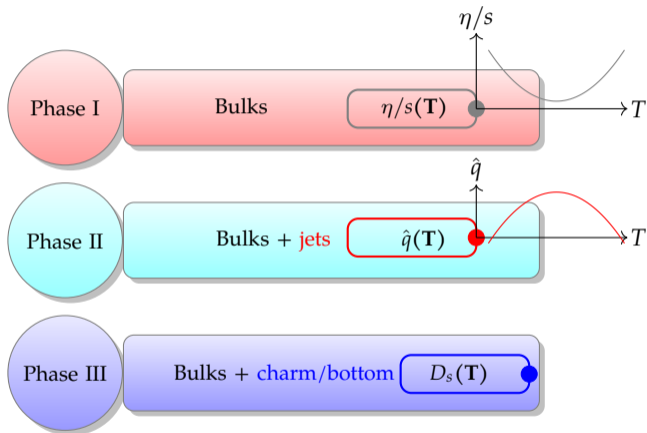
# Thank you for your attention!

## Acknowledgments:

- CSC for providing the ~24 million CPU hours
- Harri Niemi, Kari Eskola, Jonah E. Bernhard, J. Scott Moreland and Steffen A. Bass for their useful comments



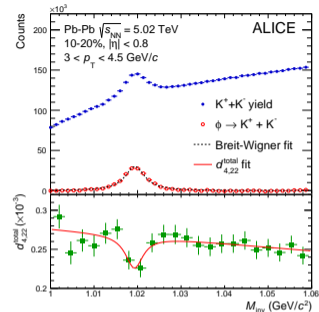
## TRANSPORT PROPERTIES



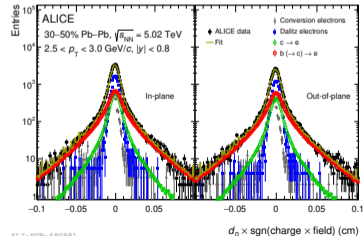
## HEAVY FLAVOUR OBSERVABLES

$$\begin{aligned}
 SC(m, n) &\equiv \langle \langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle \rangle_c \\
 &= \langle \langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle \rangle \\
 &\quad - \langle \langle \cos[m(\varphi_1 - \varphi_3)] \rangle \rangle \langle \langle \cos[n(\varphi_2 - \varphi_4)] \rangle \rangle \\
 &= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle
 \end{aligned}$$

- Replace  $\varphi_1$  or  $\varphi_2$  with HF candidates
- Invariant mass or DCA approach
- compared to all tracks

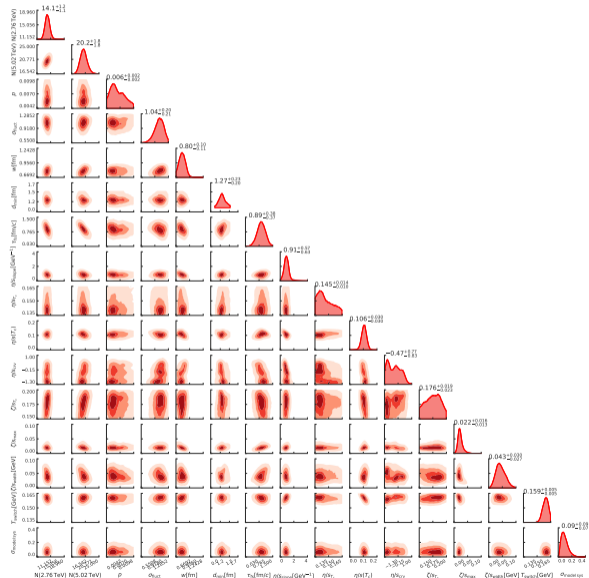


ALICE, JHEP06 (2020) 147

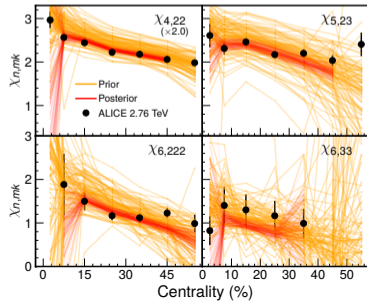
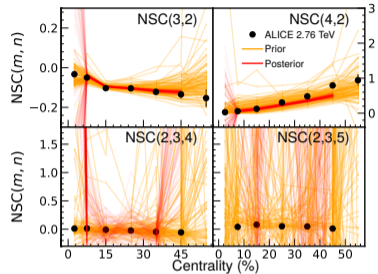
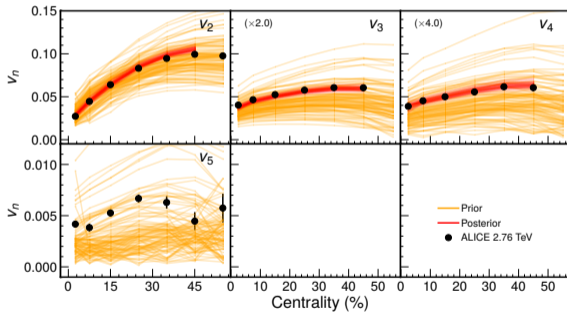


ALICE, Phys. Rev. Lett. 126 (2021) 162001

## MARGINAL AND JOINT MARGINAL PARTS OF THE POSTER DISTRIBUTION



## DESIGN PARAMETRIZATIONS



# CONCERNS ON THE HIGHER ORDER HARMONICS

