Success and challenges of flow harmonic analysis in LHC collisions from large to small systems

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XVth Quark Confinement and the Hadron Spectrum

XVth Quark Confinement and the Hadron Spectrum Conference

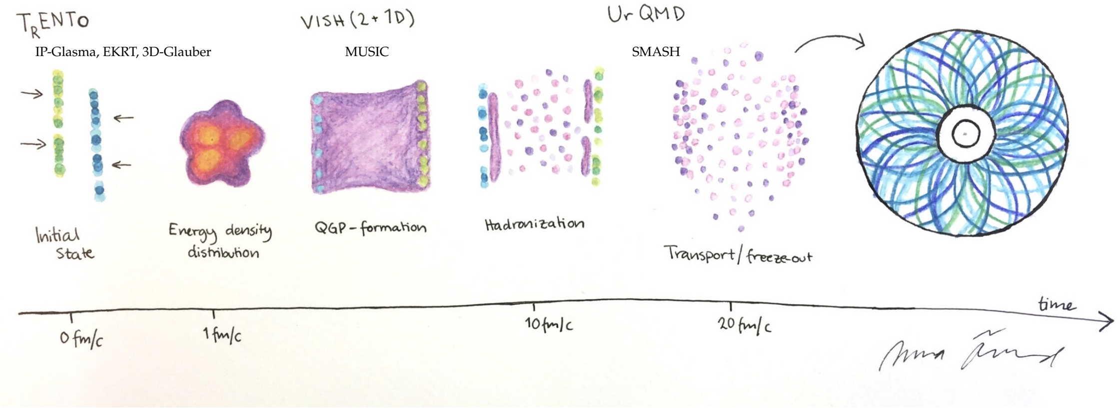
2022 - University of Stavanger

UNIVERSITY OF JYVÄSKYLÄ

CoE QM

HELSINKI INSTITUTE OF PHYSICS

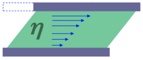
A Standard Model of Heavy-Ion collisions



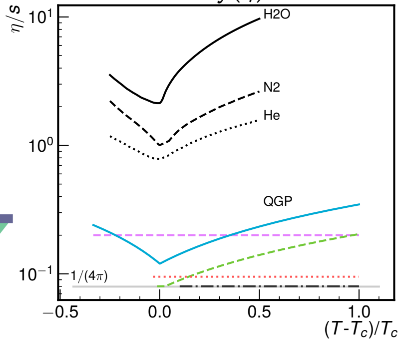
Credits to Anna Onnerstad

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

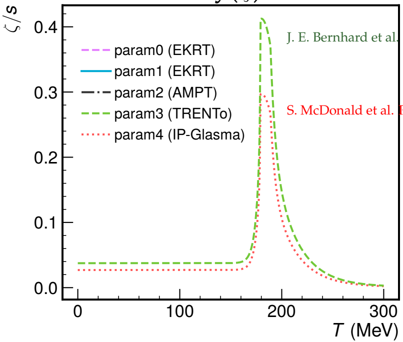
Transport properties in Heavy-ion collisions



Shear Viscosity(η)

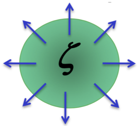


Bulk Viscosity(ζ)



J. E. Bernhard et al. PRC 94 024907 (2016)

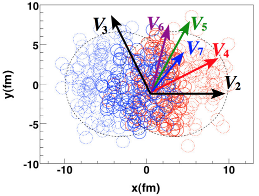
S. McDonald et al. PRC 95, 064913 (2017)

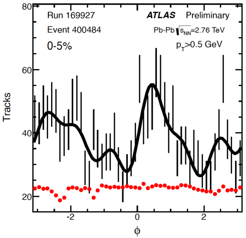


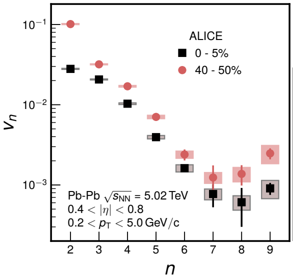
ALICE, JHEP05 (2020) 085

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

Higher Flow Harmonics Seen by All Experiments



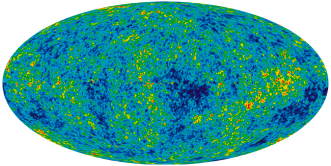


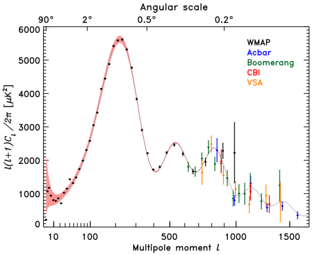


ALICE, JHEP05 (2020) 085

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

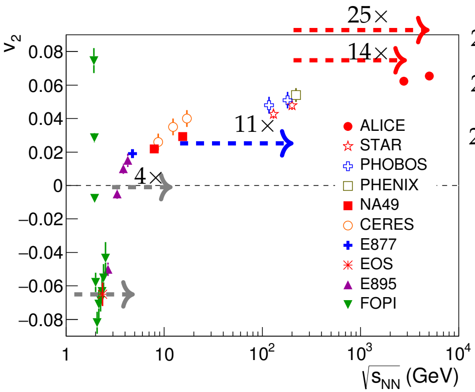
$$V_n \equiv v_n\{\psi_n\} e^{in(\psi_n - \phi)}$$





- Sensitive to initial state geometry and properties of the expanding QGP (viscosity (η/s), equation of state)
- Like measurements of early universe sound harmonics

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



2015 LHC 5.02TeV CERN

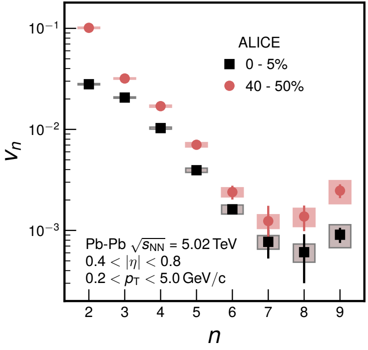
2010 LHC 2.76TeV CERN

2000 RHIC 200GeV USA

90s SPS 17GeV CERN

80s AGS 4GeV USA

2020, cerncourier[Going with the flow]



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

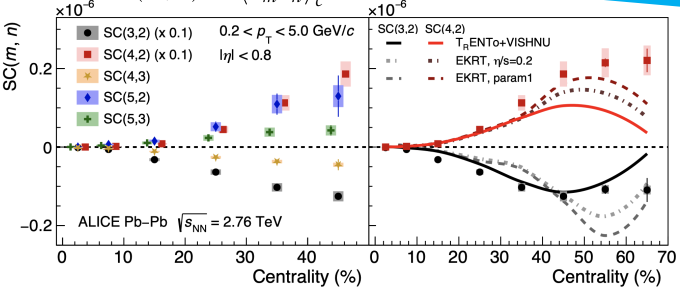
ALICE, JHEP05 (2020) 085

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

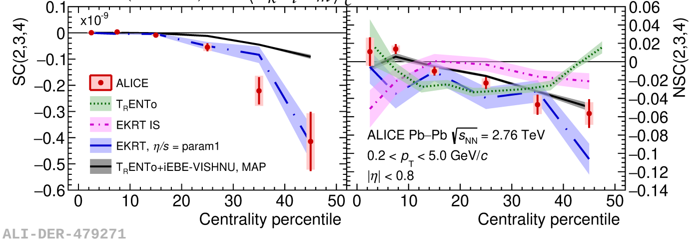
High precision flow results and New developments- Symmetric Cumulants

$$SC(m,n) = \langle v_m^2 v_n^2 \rangle_c$$

C. Mordasini's talk



$$SC(k,l,m) = \langle v_k^2 v_l^2 v_m^2 \rangle_c$$



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

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

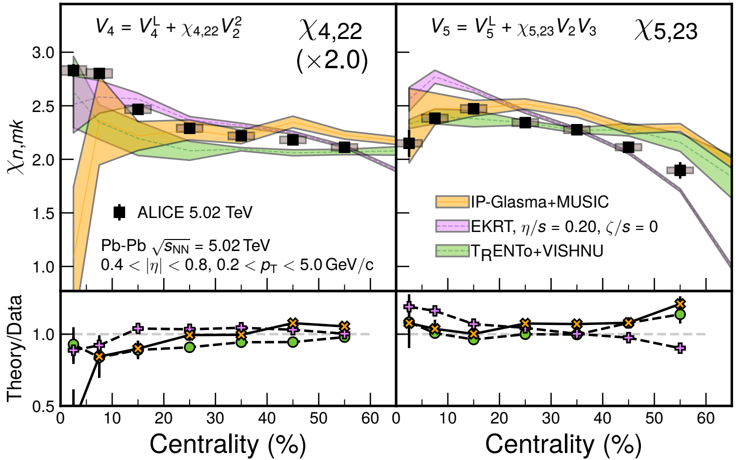
- Accessing the temperature dependence of $\eta/s(T)$

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)

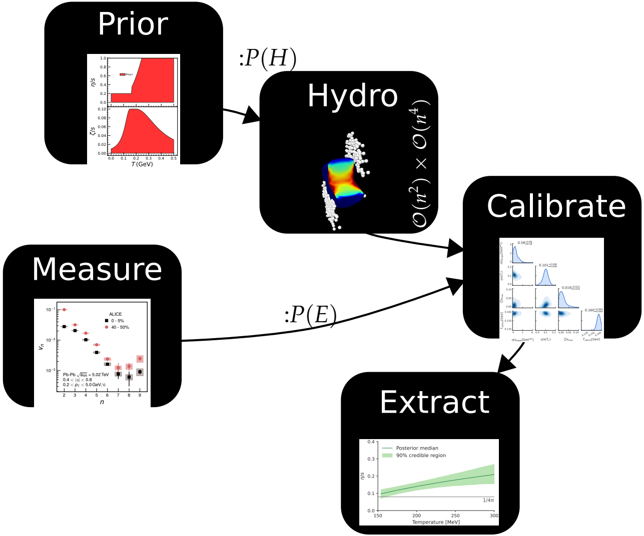
Improving results with higher harmonics and more precision - Non-linear flow modes



ALICE, JHEP05 **085** (2020)

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

Bayesian parameter estimation



Bayes' theorem:

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

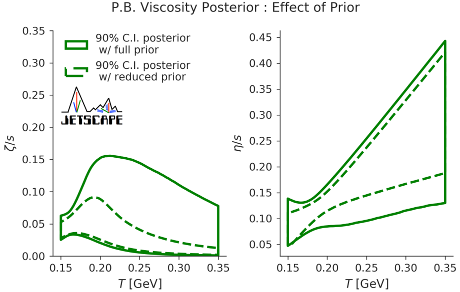
$$, P(E) = \sum_{i=1}^{n} P(E|H_i)P(H_i)$$

- 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!

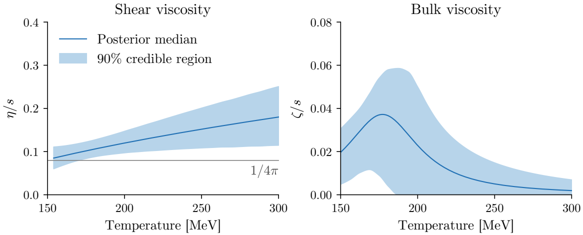
Bayesian parameter estimation I

JETSCAPE T$_R$ENTo+MUSIC+SMASH



JETSCAPE Collaboration, PRC **103** (2021) 054904

Duke T$_R$ENTo+VISH(2+1D)+UrQMD

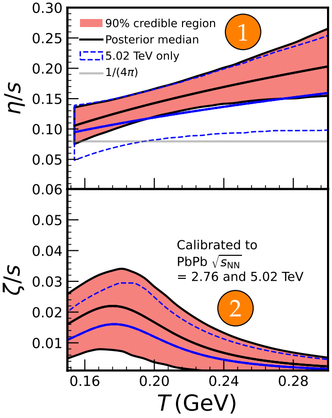


Steffen A. Bass *et. al*, Nature Physics (2019)

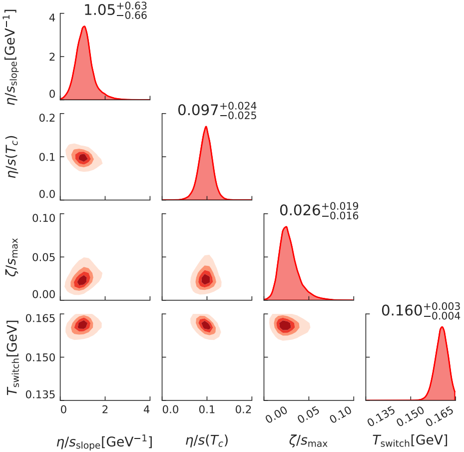
- Low to moderate temperature dependence on $\eta/s(T)$
- Moderate magnitude of $\zeta/s(T)$ ($\sim 0.1\times$ w.r.t lattice QCD(PRL. **94**, 072305 (2005))
- Large uncertainty for both $\eta/s(T)$ and $\zeta/s(T)$.
- Subsequent studies with still limited observables:
  - J. Auvinen *et al.* PRC. **102**,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

Result: Jyvaskyla (2022) – combined collision energy analysis (2.76 + 5.02 TeV)



PRC 104 (2021) 054904, arXiv:2111.08145



S. F. Taghavi's talk

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!

Sensitivity of the observables to parameters

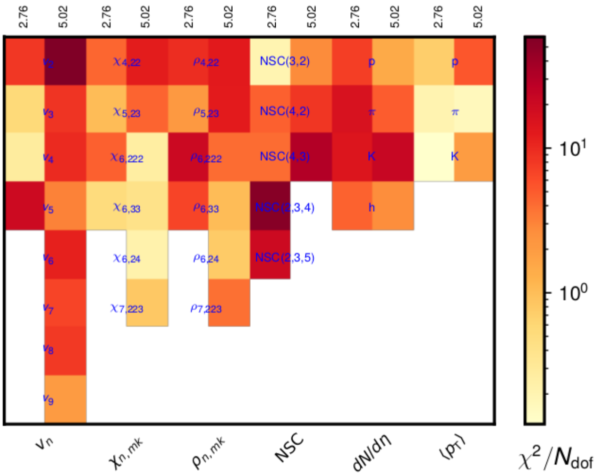
Sensitivity of the observables: $S[x_j] = \Delta/\delta.$, where $\Delta = \frac{|\hat{O}(\vec{x}')-\hat{O}(\vec{x})|}{|\hat{O}(\vec{x})|}$.

	$dN_{ch}/d\eta$	$dN_{p^\pm}/d\eta$	$\langle p_{T,\pi^\pm}\rangle$	$\langle p_{T,K^\pm}\rangle$	$\langle p_{T,p^\pm}\rangle$	v_2	v_3	v_4	v_5	$\chi_{4,22}$	$\chi_{5,23}$	$\chi_{6,222}$	$\chi_{6,33}$	$\rho_{4,22}$	$\rho_{5,23}$	$\rho_{6,222}$	$\rho_{6,33}$	NSC(3, 2)	NSC(4, 2)	NSC(4, 3)	NSC(2, 3, 4)*	NSC(2, 3, 5)*	NSC(2, 4, 6)*
τ_{fs}	0.00	0.17	1.05	1.01	0.85	0.60	1.42	2.36	3.94	0.09	0.77	0.30	1.46	1.25	1.26	1.98	1.44	0.65	6.25	12	30	2.07	40
$(\eta/s)_{slope}$	0.00	0.14	0.19	0.19	0.18	0.49	1.43	2.10	3.30	0.26	0.13	0.81	0.85	1.74	1.37	3.03	1.36	0.70	7.02	1.70	34	30	1.06
T_c	0.00	0.25	0.03	0.03	0.04	0.18	0.46	0.48	0.37	0.32	0.55	0.83	0.93	0.80	0.40	0.45	0.61	0.41	3.53	1.44	4.46	7.15	0.21
$\eta/s(T_c)$	0.00	0.08	0.22	0.21	0.14	1.65	3.29	4.87	6.00	0.95	3.84	2.92	5.44	2.53	1.27	2.85	2.76	1.61	15	9.80	22	29	14
$(\eta/s)_{crv}$	0.00	0.17	0.05	0.05	0.05	0.19	0.38	0.53	0.69	0.20	0.36	0.55	0.69	0.40	0.40	0.73	0.75	0.13	1.81	4.72	2.20	8.41	6.17
$(\zeta/s)_{peak}$	0.01	0.44	1.16	1.01	0.73	2.26	2.67	3.79	6.40	0.59	0.32	1.48	1.11	0.34	1.59	1.04	1.15	1.49	1.49	2.57	3.74	2.04	15
$(\zeta/s)_{max}$	0.00	0.07	1.05	0.96	0.77	0.37	0.13	0.12	0.37	0.20	0.01	0.53	1.12	0.52	0.64	1.26	0.59	0.44	1.43	8.00	3.02	1.58	2.91
$(\zeta/s)_{width}$	0.00	0.01	0.20	0.15	0.07	0.19	0.04	0.09	0.33	0.09	0.26	0.40	1.69	0.39	1.66	1.55	1.35	0.38	1.41	1.21	1.77	23	19
T_{switch}	0.01	1.34	0.25	0.21	0.16	1.30	3.51	4.64	5.86	0.77	0.45	2.03	3.34	3.95	2.42	1.98	1.00	1.96	17	13	4.08	0.47	6.22

$S[x_j]$

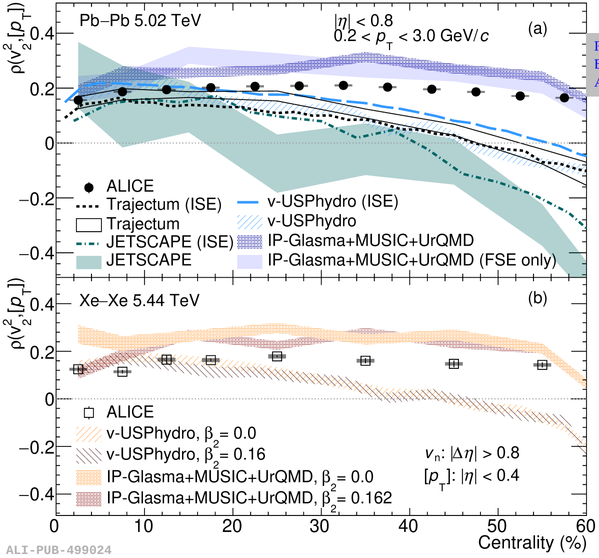
- $N_{p^\pm}/d\eta$ is sensitive to T_{switch} and $\langle p_T\rangle$ is sensitive to τ_{fs}.
- NSC(m,n) and NSC(k,l,m) are among the most sensitive observables followed by v_n and $\chi_{n,mk}$.
- The precision measurements of observables, reflecting mostly non-linear responses, are crucial.

Remaining Concerns? χ^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: Indication - shortage of TRENTo model



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

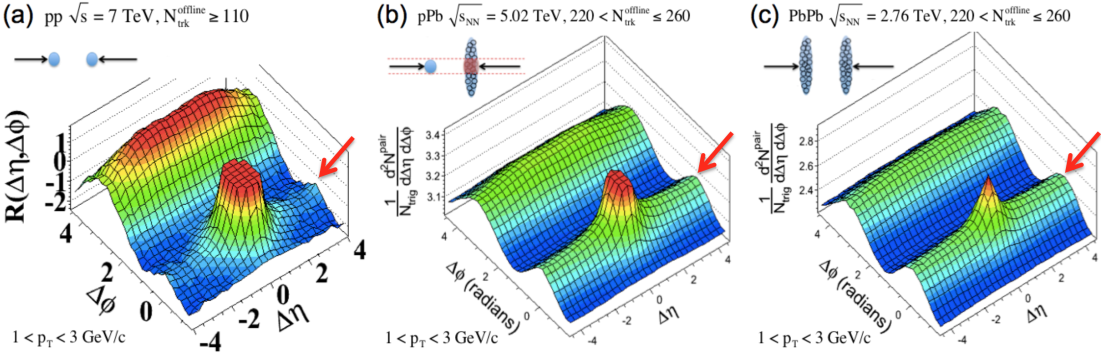
W.van.der.Schee's poster

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

- Correlation between $[p_T]$ and v_2:
  - can be used to differentiate initial state models
  - More peripheral → 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

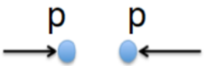
Collectivity in small systems

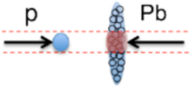


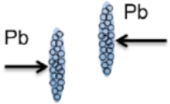
CMS, JHEP09(2010)091

- 2-particle correlations measured as a function of $\Delta\eta$ and $\Delta\varphi$
- Structure that is long range in $\Delta\eta$ and generally shows two bumps in $\Delta\varphi \to$ **double-ridge**
- **Double-ridge** comes from dominant $\cos(2\Delta\varphi)$ contribution due to the mostly elliptic shape of the collision overlap zone
- In large systems, this is due to medium response to the initial transverse geometry (well described by hydrodynamics)

Small Sytems : Challenges







Experimental Challenges

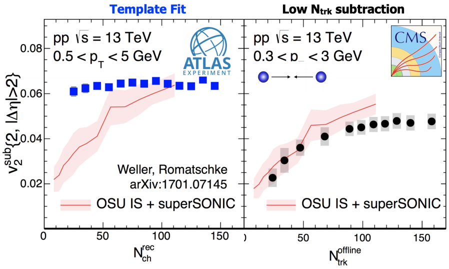
- No clear evidence of jet quenching yet in pPb.
- Possible to observe thermal photons?
  C. Gale et. al, PRC 105, 014909 (2022)
- Possible to discriminate flow and non-flow or suppress non-flow? A. Önnerstad's poster

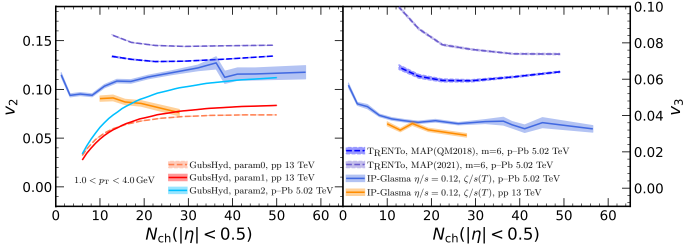
Theoretical Challenges

- but smaller volume and shorter lived...
- applicability of fluid dynamics (too large $Kn = \lambda/L$ for pPb even with small QGP $\eta/s = 0.08$)? H. Niemi, D. H. Rischke et. al, PRC 98, 024912 (2018)
- better understanding gluonic hot spots in the proton S. Demirci's poster

Flow extraction Methods and theory status in small systems?

S. F. Taghavi's talk





- Flow extraction in small systems with different methods leads to different results, can we find the correct method?

A. Önnerstad's poster

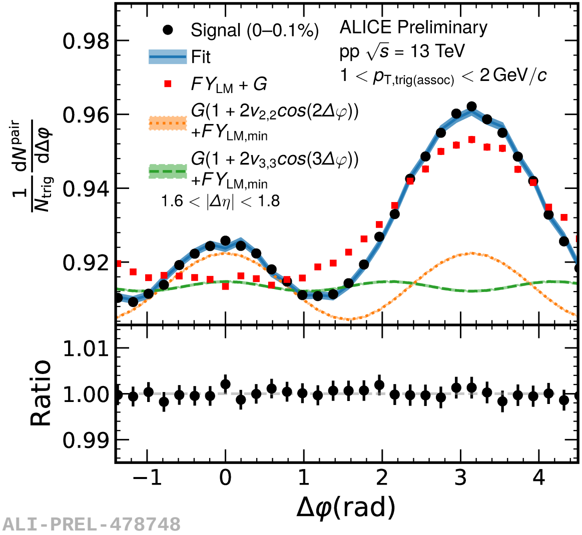
- Viscosity effect is clearly seen in the hydro calculations from N_{ch} dependence
- However, magnitutes and N_{ch} dependence are very different between the models which describe the PbPb data rather well.
- Can we set the lower limit of event multiplicity on flow signal both for pp and p–Pb?

Long-range $\Delta\varphi$ correlations and flow extraction

A. Önnerstad's poster

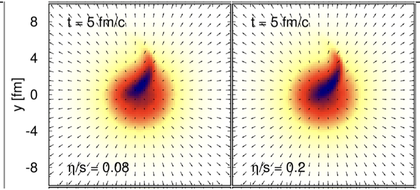
$$Y(\Delta\varphi) = G(1 + 2v_{2,2}\cos(2\Delta\varphi) + 2v_{3,3}\cos(3\Delta\varphi)) + FY_{\mathrm{LM}}(\Delta\varphi)$$

- Subtract the remaining away-side jet contribution in high multiplicity event relative to the low multiplicity term
- F: Ratio of away-side jet fragments in high-multiplicity to low-multiplicity events (60–100%), $F = 1.304 \pm 0.018$
- Assumptions
  - No ridge or flow in the LM-template
  - No away-side jet modifications (quenching) in HM events relative to the LM-template



The method was verified and gives proper collective flow results in small systems!

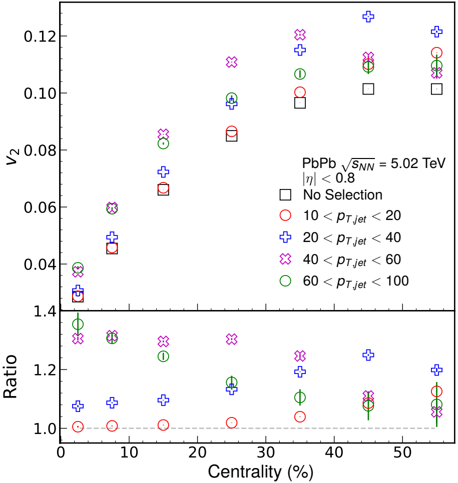
Mach Cone searches

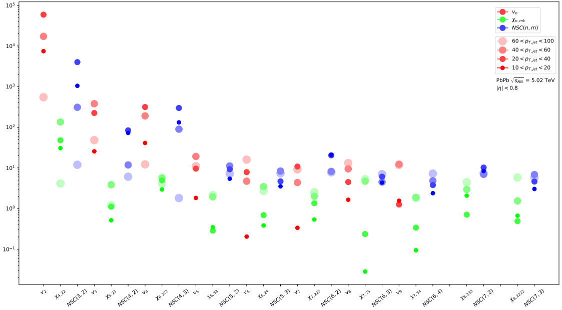
char	large	small (tiniest substance in nature)
fig		
v_{medium}	≈ 0	$\approx 0.65 \times c$
v_{jet}	$\approx$ 5km/hour	$\approx$ 20-200 GeV/c
viscosity/entropy	>>1	$\approx 1/4\pi (\approx 0.08)$, perfect fluid
substance	H_2O	gluons and quarks
scale	$\approx$ cm	$\approx$ 1fm (0.0000000000010 cm)

- There has been no evidence of the mach signal so far.
- The modification of the away side jets turned out to be odd harmonic flow signal, ALICE Phys. Rev. Lett. 107, 032301 (2011) .
- Radial flow influnces the shape of the signal as well as hard scattering points(random in the collison zone) (Phys. Rev. C 90, 024904, Phys. Rev. C 93, 054907 (2016)) $\rightarrow$ need new way?

The modification of v_2 in the presence of jets $\rightarrow$ evidence of Mach signal?

M. Virta's poster





- Clear deviation on v_2, up to 40% difference w.r.t No Selection
- The deviation is quantified for various flow observables.

Summary

Success:

- Higher harmonic orders and non-linear flow observables $\rightarrow$ better constraints.
- Improved the overall uncertainty by $\times$ 2 by combining two beam energy data.
- Sensitivity analysis
  $\rightarrow$ precision measurements of observables, reflecting non-linear hydrodynamic responses.
- Flow signals in small systems, improving the measurements(exp) as well as sub-nucleon structure(theory)

Challenges:

- Large systems
  - 10% difference for v_2 (5.02 TeV) and $\rho(v_2^2, [p_T])$
  - still lacking for NSC(4,2)
  - Remaining discrepancy for PID multiplicity (especially $\pi^{\pm}$) ...
- Small systems
  - Better understanding on flow extraction method
  - Need more insights from theory

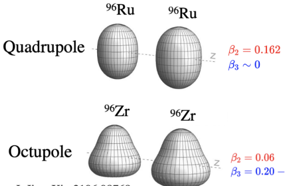
Outlook

Experiments

- RHIC data (AuAu collisions) - Energy and system size dependence
- LHC pPb and pp data - System size dependence but with improved method
  A. Önnerstad's poster
- Use new observables
  - Higher order ($n > 5$) Symmetric cumulants
  - Improved Symmetric Plane Correlation (SPC) : independent from flow magnitude correlations and Asymmetric Cumulants (AC) C. Mordasini's talk
- Soft-Hard interation M. Virta's poster
- What about isobar runs in LHC? (WCPF2022, J, Jia)

Theory

- Improving the initial conditions with
  - EKRT, IP+Glasma
  - or nucleon size W.van.der.Schee's poster
  - better understading of proton S. Demirci's poster
- Testing hydro limit of small systems?
- Role of the small system for further

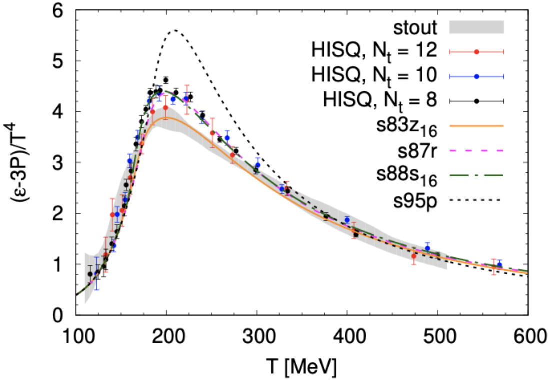


J. Jia, aXiv:2106.08768

Questions to think about during this conference?

Effect of EoS to Bayesian analysis

- Uncertainties from the equation of state?

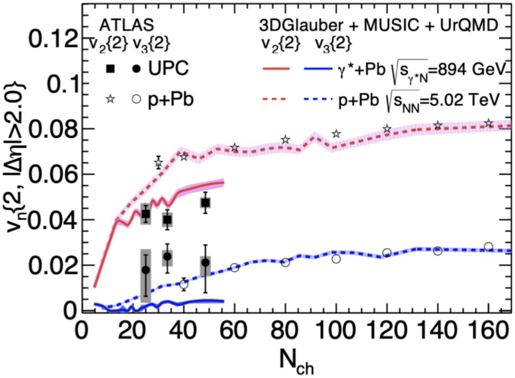


P. Huovinen, P. Petreczky, Nucl.Phys.A837:26-53,2010

PoS(Confinement2018)135

Zero flow at zero multiplicity?

- What does it mean by seeing non-zero flow at zero multiplicity?

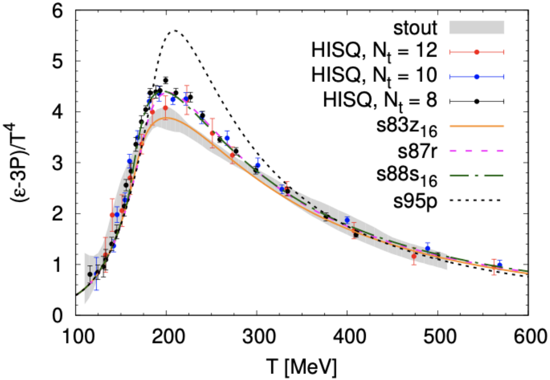


W. Zhao, C. Shen, B. Schenke, arXiv:2203.06094

Two Questions to think about during this conference?

Effect of EoS to Bayesian analysis

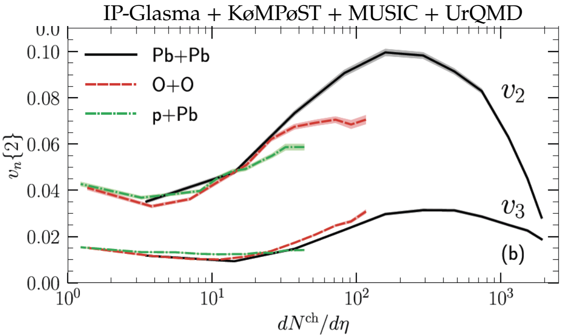
- Uncertainties from the equation of state?



P. Huovinen, P. Petreczky, Nucl.Phys.A837:26-53,2010

Zero flow at zero multiplicity?

- What does it mean by seeing non-zero flow at zero multiplicity?



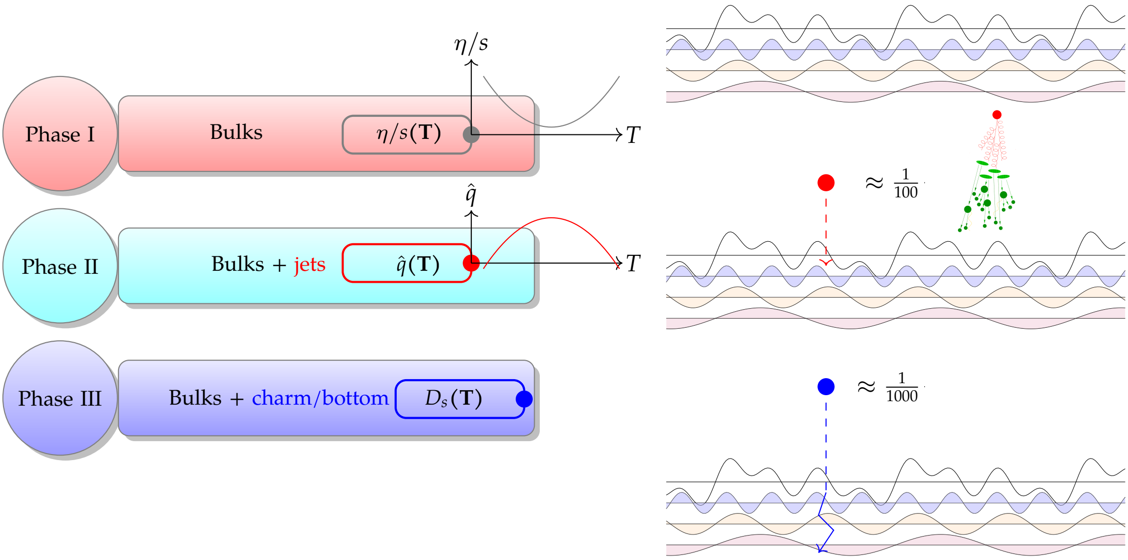
B. Schenke et. al, PRC, 105, 014909 (2022)

PoS(Confinement2018)135

Thanks

Thank you for your attention!

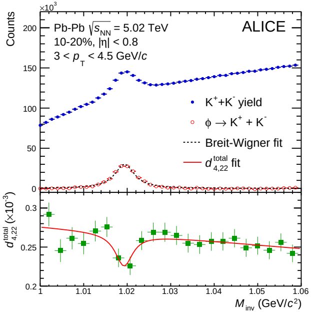
Transport properties



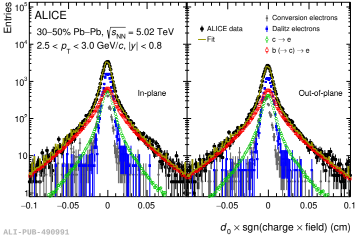
Heavy flavour obsrvables

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

- Replace φ_1 or φ_2 with HF candidates
- Invariant mass or DCA approach
- compared to all tracks



ALICE, JHEP06 (2020) 147



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