Challenges of Flow Harmonic Analysis in LHC Collisions from Large to Small Systems

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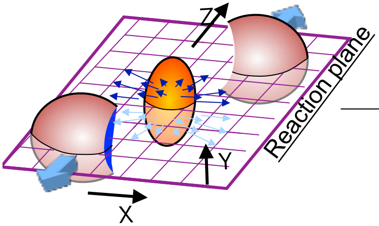
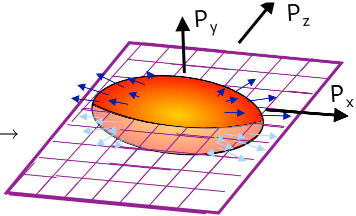
Anistotropic Flow

Initial geometry fluctuations → Transport $\delta_\mu T^{\mu\nu} = 0$ → final-state particles





$$\varepsilon_n e^{in\Phi_n} \equiv -\frac{\langle r^n e^{in(\phi-\Phi_n)}\rangle}{\langle r^n\rangle}, n \geq 2.$$

(theory only - initial state models)

$$\frac{dN}{d\phi} \propto \frac{1}{2\pi}\sum_{n=-\infty}^{\infty} \underbrace{\langle e^{in\phi}\rangle}_{V_n = v_n e^{in\psi_n}} e^{-in\phi},$$

(experiments, theory - hydro+hadronization models)

- Collectivity as a probe to the properties of the medium – transport properties such as $\eta/s(T)$, $\zeta/s(T)$

Symmetric and Asymmetric Cumulants

- Symmetric Cumulants measure genuine correlations between two different harmonics m and n

$$\textbf{SC: } \left\langle v_m^2 v_n^2 \right\rangle - \left\langle v_m^2 \right\rangle \left\langle v_n^2 \right\rangle$$

- By normalizing we get the magnitudes of the genuine correlations

Normalized Symmetric Cumulant (NSC):

$$NSC(m,n) = \frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

- Generalized symmetric cumulants with different moments - additional information!(Skewness,Kurtosis)

$$\textbf{AC: } \left\langle v_m^4 v_n^2 \right\rangle_c, \left\langle v_m^6 v_n^2 \right\rangle_c, \ldots$$

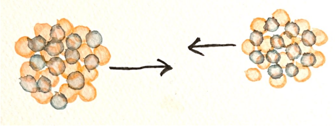
$$\begin{aligned} \mathrm{AC}_{2,1}(\mathrm{m,n}) &\equiv \langle (v_m^2)^2 vn_n^2 \rangle_c = \langle v_m^4 v_n^2 \rangle_c \\ &= \langle v_m^4 v_n^2 \rangle - \langle v_m^4 \rangle \langle v_n^2 \rangle \\ &\text{- } 2 \langle v_m^2 v_n^2 \rangle \langle v_m^2 \rangle + 2 \langle v_m^2 \rangle^2 \langle v_n^2 \rangle \end{aligned}$$

Normalized Asymmetric Cumulant (NAC):

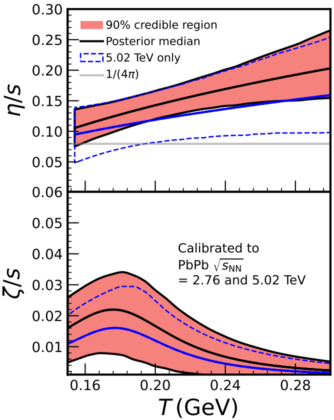
$$NAC_{2,1}(m,n) = \frac{AC_{2,1}(m,n)}{\langle v_m^2 \rangle^2 \langle v_n^2 \rangle}$$

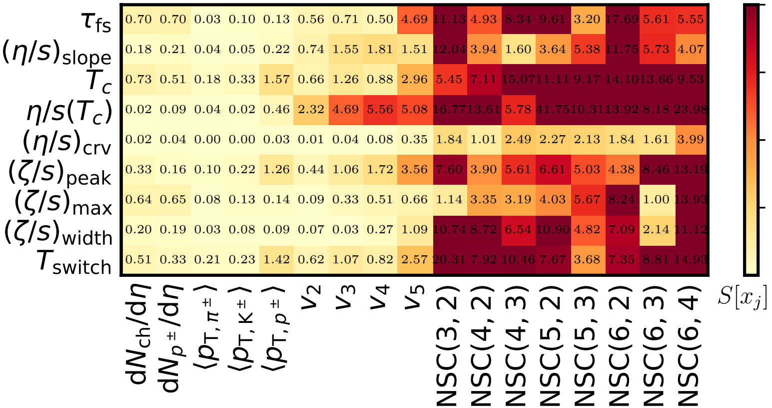
- (A)Symmetric Cumulants will only be presented for large systems

Challenges in Large Systems



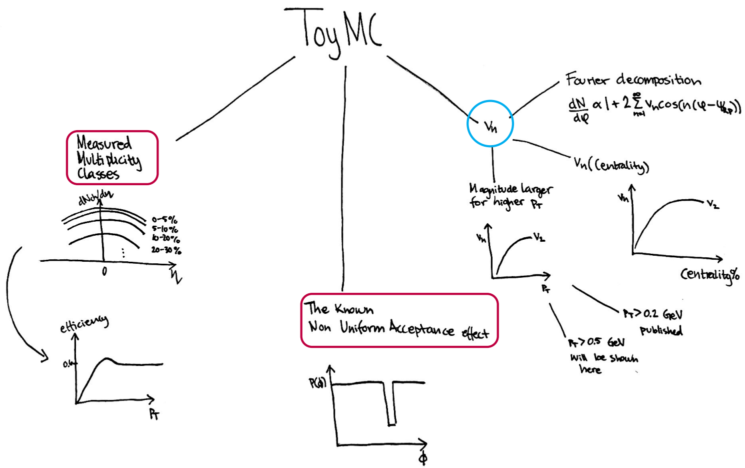
Sensitivity - Bayesian approach





- Higher order flow observables are very sensitive to QGP parameters and helped to reduce the uncertainty of model parameters → getting closer to pin down the transport properties of QGP.

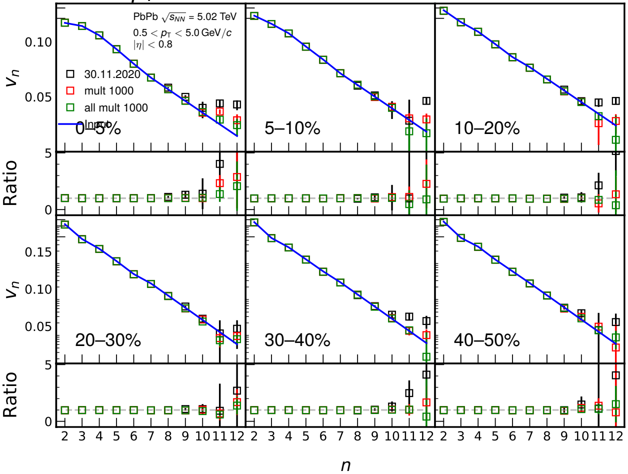
Verifying the experimental biases on the higher order flow harmonic measurements



- Inputs shown in the sketch:
  - v_n information (True)
  - Multiplicity classes (Detector effect)
  - Non Uniform Acceptance (Detector effect)
- Event by event fluctuations for multiplicity and v_n not regarded in ToyMC.

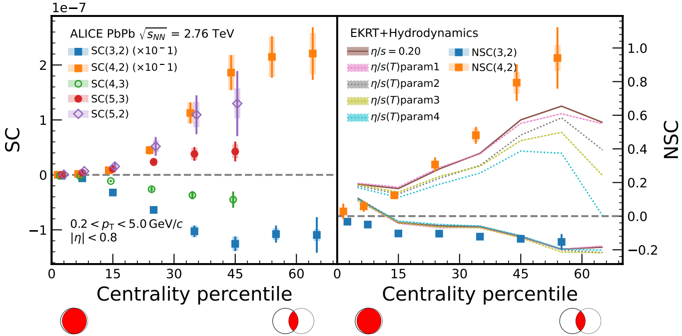
Can we go higher than n=9?

$0.5 < p_T < 5.0$ GeV



- Input v_n spectra from JHEP05 (2020) 085 and exponential fit for $n > 8$.
- Well recovered for n=10 for all centrality classes, but not for $n > 10$
- Why?
  - Increased the multiplicity $N_{ch} \times$ 1000
  - $N_{ch} \times$ 1000 + $\times$ 10 statistics
- With larger multiplicity and more events → Converges to the input!

High precision flow results - Symmetric Cumulants



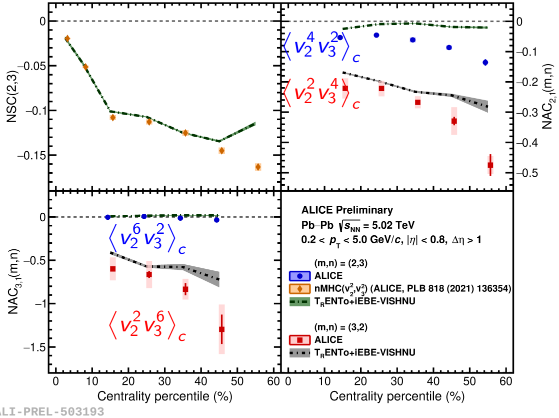
- Accessing the temperature dependence of $\eta/s(T)$

ALICE, Phys. Rev. Lett. 117 (2016) 182301, Editors' Suggestion

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

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

High precision flow results - Asymmetric Cumulants A First Look in Data

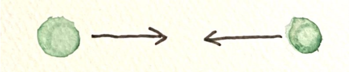


- Tension between data and model predictions for $NAC_{2,1}(2,3)$ and $NAC_{3,1}(2,3) \rightarrow$ Constraints on the initial state
- Information on the model description of the fluctuations and correlations of v_n

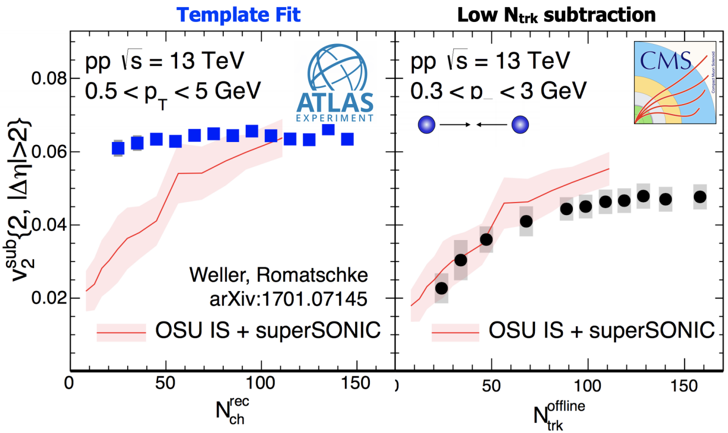
Challanges:

- Even higher precision required depending on which AC observable, e.g. $AC_{3,1}(2,3) \approx 10^{-12}$.
- Improve the Systematic errors

Challenges in small systems



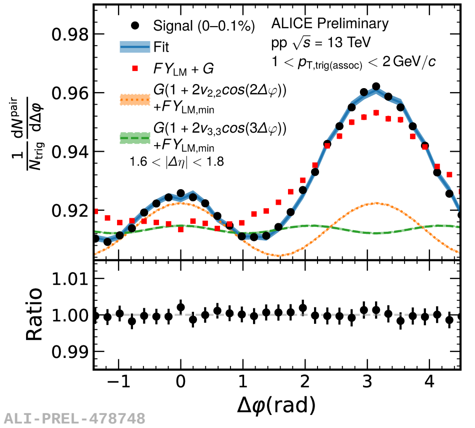
Signs of collective behaviour in small systems



- Cumulants and Two-Particle Correlations previously used → jet contributions are not fully removed.
- Multiplicity definition and Jet acceptance are different between experiments → how to compare?

Improved Flow Extraction Method

Low multiplicity template fit method

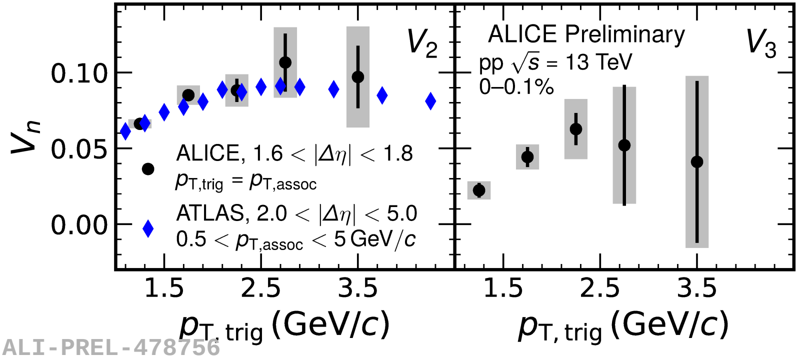


More details here!

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

- Assumptions
  - No ridge or flow in the LM-template
  - No away-side jet modifications (quenching) in HM events relative to the LM-template
- 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%), $F = 1.304 \pm 0.018$ → **The effect is 30% for 0-0.1% multiplicity in pp 13 TeV, hence must be considered.**

Verifying Low Multiplicity Template Fit



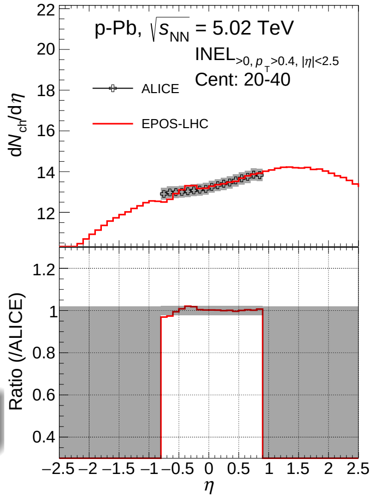
- Comparable with ATLAS result
- Note that multiplicity class for ATLAS is classified with central particles ($|\eta| < 2.5$, $p_T > 0.4$ GeV/c), $N_{Mult}^{ATLAS} > 60$
- Not an apple to apple comparison

Multiplicity Mapping Between Experiments

Exp.	ALICE	ATLAS
Mult. Class (%)	$N_{\mathrm{ch}}(\lvert\eta\rvert < 0.5)$	$N^{rec}_{\mathrm{ch,ATLAS}}$ ($p_{\mathrm{T}} > 0.4$, $\lvert\eta\rvert < 2.5$)
0–0.1	31.33	84.07 (80.33)
1–5	20.02	50.10(48.83)
5–20	13.99	33.70(29.15)
20–60	7.2	16.11(14.12)
60–100	N/A	5.23

- The EPOS LHC is scaled to the measurements.
- Addition p_T cut applied to have the same kinematic cut as ATLAS.
- MAP between ATLAS and ALICE

- **Different experimental multiplicity definitions can be compared by using the measured $dN/d\eta$ distributions.**



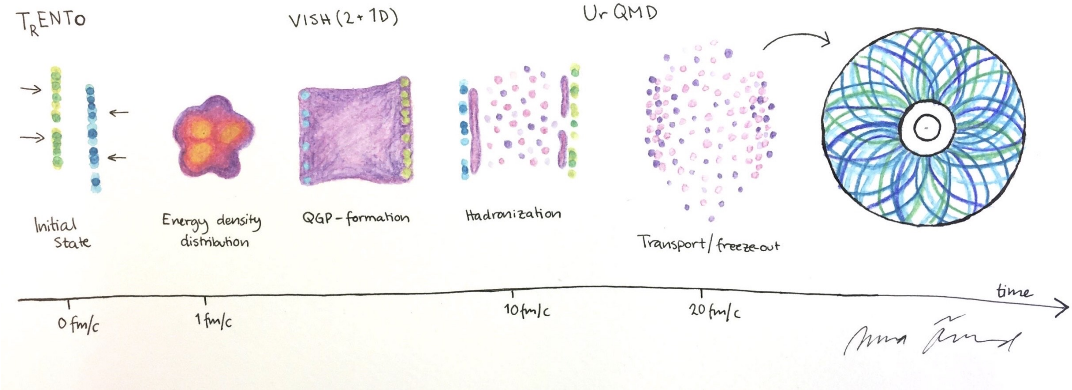
Summary

Large Systems:

- Both observables presented require high precision measurements → large statistics needed.
- Another challenge is how to improve systematic uncertainties.

Small Systems:

- Jet contributions are not fully removed → solved with *low multiplicity template fit method*.



Thank you for your attention!