Symmetry Plane Correlations in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$ with ALICE at the LHC

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Technical University of Munich

15th of November 2021, IMPRS Recruiting Workshop

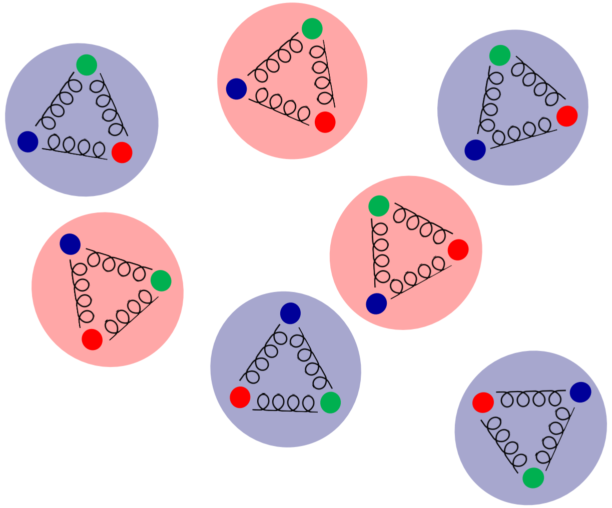
Study of an extreme state of matter

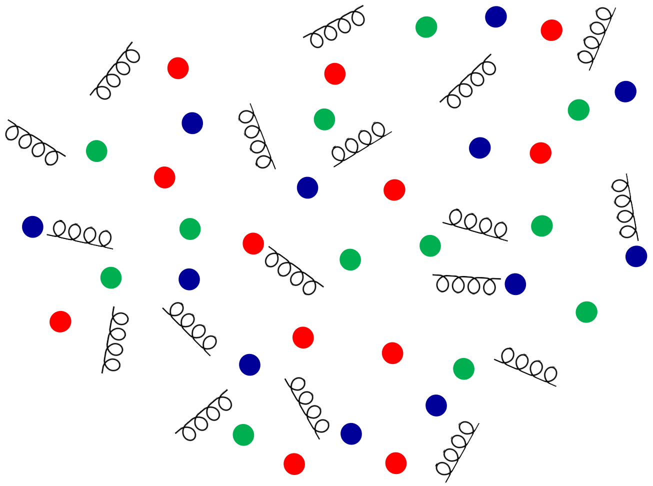
- Existence of Quark-Gluon Plasma (QGP) at extreme temperatures
- Important for

  → the evolution of the Early Universe

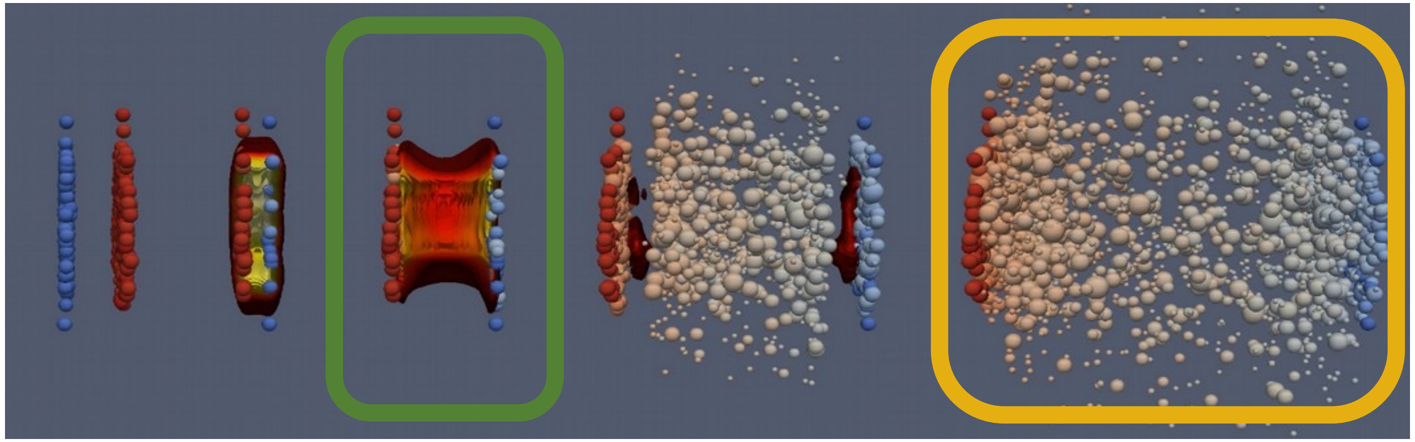
  → the general understanding of the strong interaction

Study of an extreme state of matter

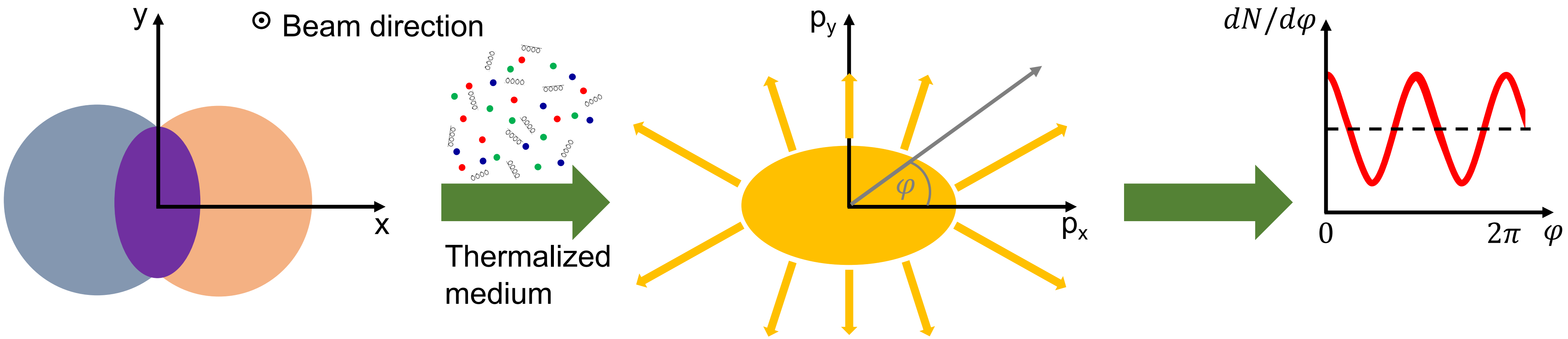




- Study of the QGP in heavy-ion collisions, e.g. Pb-Pb at the LHC
- Collectivity of produced particles introduced by QGP

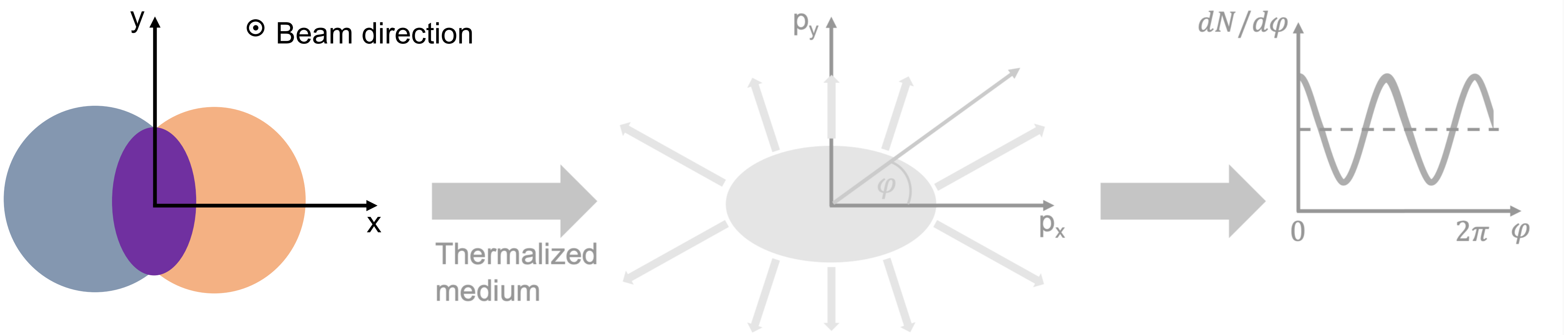


Anisotropic Flow

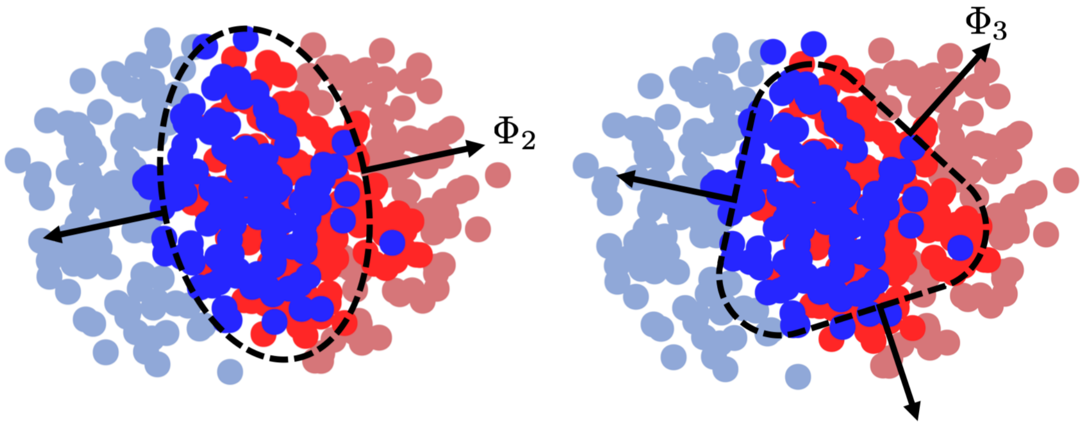


Anisotropic Flow: Transition from anisotropy in coordinate space to anisotropy in momentum space via thermalized medium

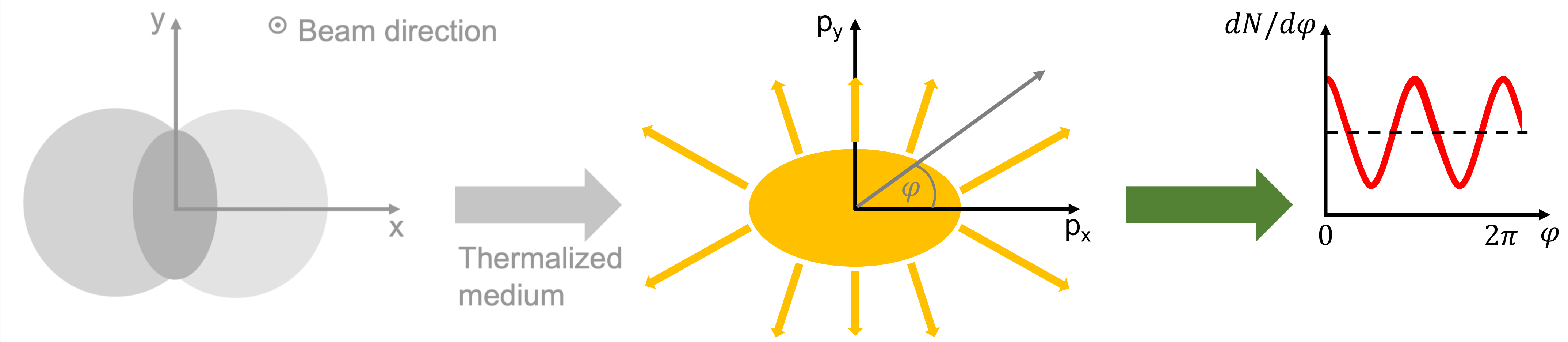
From initial state



- **Initial state** (coordinate space) characterised by $C_n = c_n e^{in\Phi_n}$



From initial state to final state



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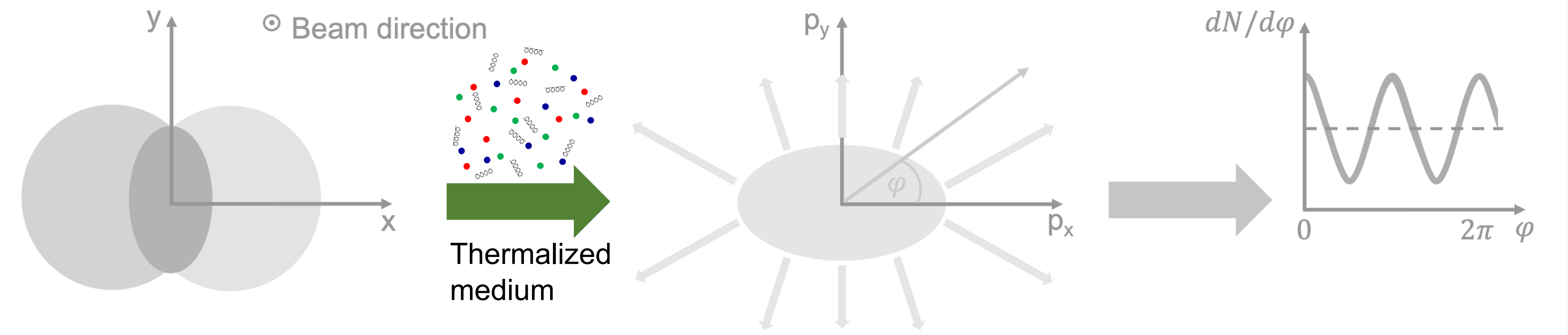
From initial state to final state – The QGP response



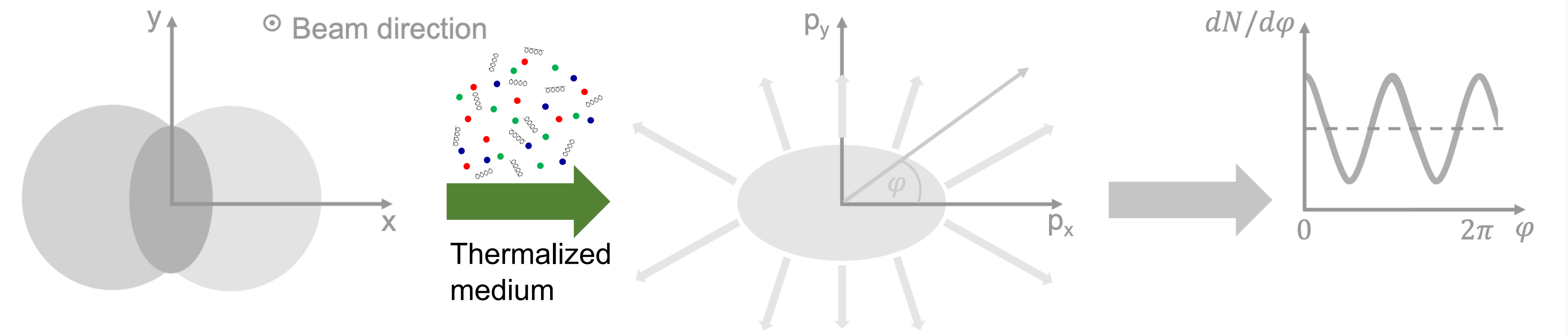
- **Initial state** (coordinate space) characterised by $C_n = c_n e^{in\Phi_n}$
- **Final state** (momentum space) characterised by $V_n = v_n e^{in\Psi_n}$

- **Linear** and **non-linear response**, e.g.:

$$v_4 e^{i4\Psi_4} = \omega_4 c_4 e^{i4\phi_4} + \omega_{422} c_2^2 e^{i4\phi_2} + \cdots$$

Li Yan, Chinese Physics C, 42(4), 042001, 2018.

From initial state to final state – The QGP response



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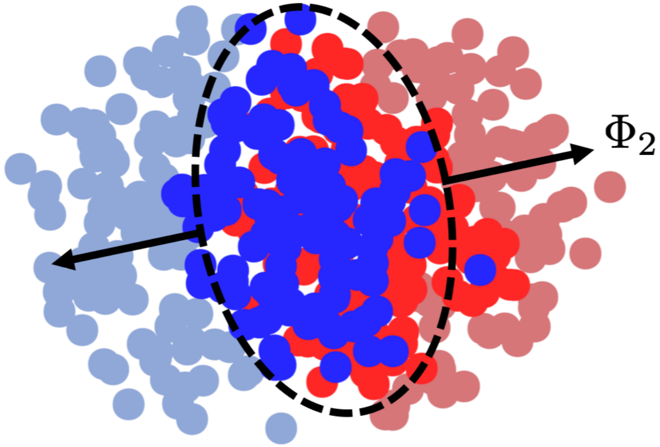
Symmetry Plane Correlations (SPC)

- **Final state**: Measurement of single symmetry planes not possible

  → Use Symmetry Plane Correlations, e.g. $\langle\cos[4(\Psi_4 - \Psi_2)]\rangle$

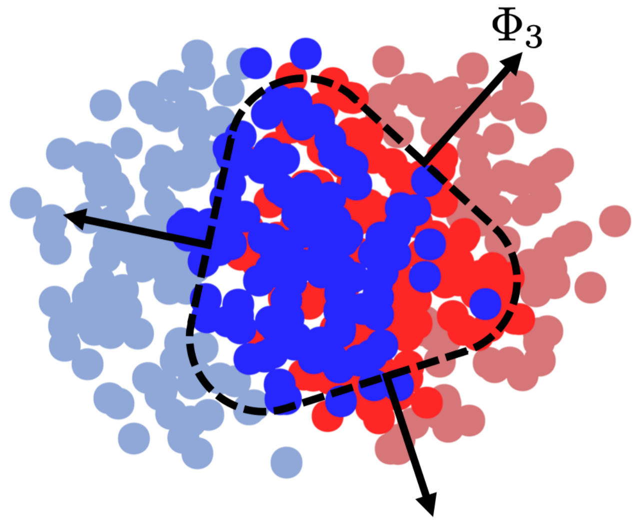


- Comparison of SPC in the initial and final state is sensitive to linear and non-linear response, e.g.

$\omega_{422} = 0$ $\quad\langle\cos[4(\Psi_4 - \Psi_2)]\rangle = \langle\cos[4(\Phi_4 - \Phi_2)]\rangle$

$\omega_{422} \neq 0$ $\quad\langle\cos[4(\Psi_4 - \Psi_2)]\rangle \neq \langle\cos[4(\Phi_4 - \Phi_2)]\rangle$

→ Imprint of the hydrodynamic evolution of the system



New experimental technique for SPC

- Previous work: **Scalar Product (SP)-Method**

  STAR Collaboration. PRC 66, 034904, 2002
  R. S. Bhalerao, J.-Y. Ollitrault, S. Pal. PRC 88, 024909, 2013

- Example:

$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle_{\mathrm{SP}} = \frac{\langle v_2^2 v_4 \cos[4(\Psi_4 - \Psi_2)] \rangle}{\sqrt{\langle v_2^4 \rangle \langle v_4^2 \rangle}}$$

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- Problem:

$$\langle v_2^4 v_4^2 \rangle \neq \langle v_2^4 \rangle \langle v_4^2 \rangle$$

- New technique for SPC must be developed!

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- New technique for SPC must be developed!

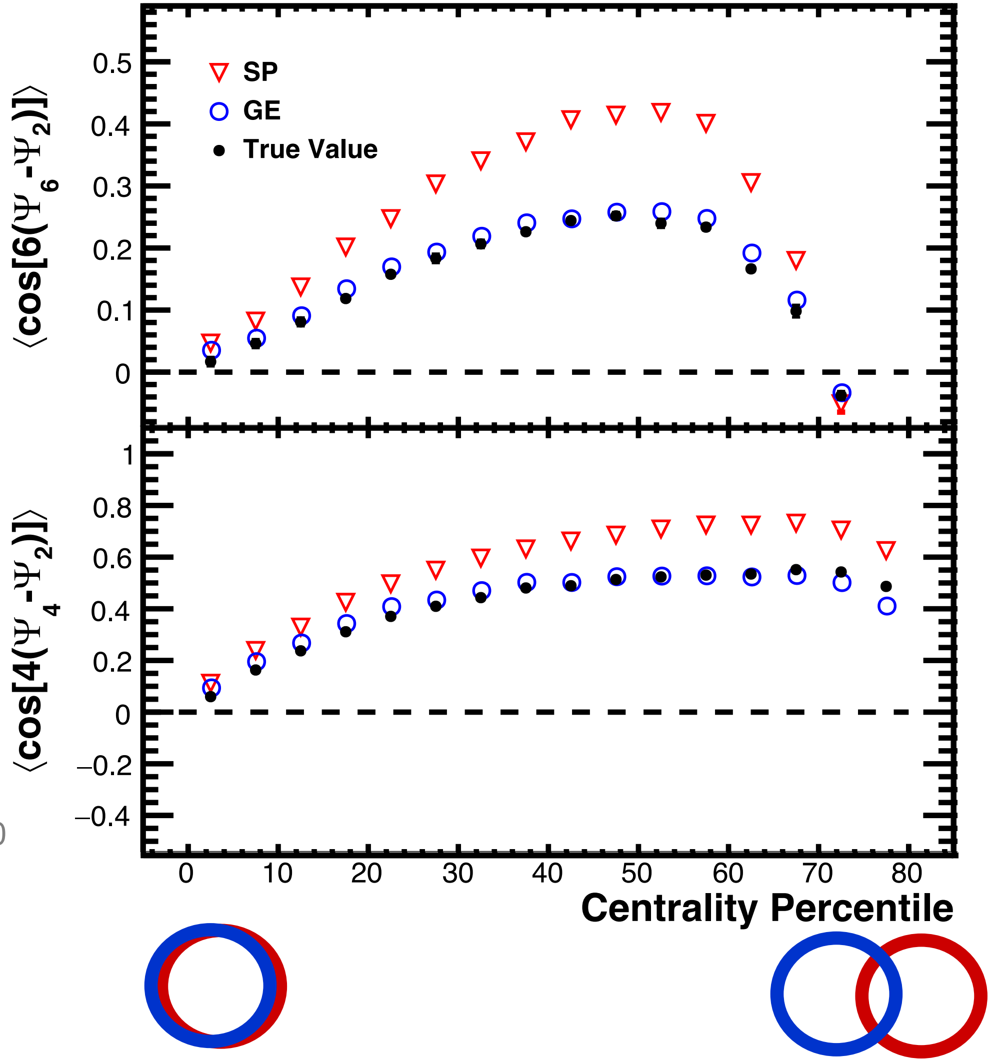
- New: **Gaussian Estimator (GE)**
- Modelling of multi-harmonic flow fluctuations with 2D Gaussian
- Example:

$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle_{\mathrm{GE}} = \sqrt{\frac{\pi}{4}} \frac{\langle v_2^2 v_4 \cos[4(\Psi_4 - \Psi_2)] \rangle}{\sqrt{\langle v_2^4 v_4^2 \rangle}}$$

- Details see:
  A. Bilandzic, **ML**, S. F. Taghavi:
  "New estimator for symmetry plane correlations in anisotropic flow analyses"
  PRC **102**, 024910 – 2020

Gaussian Estimator for SPC

- Comparison of GE to SP and "true" value in iEBE-VISHNU (Pb-Pb $\sqrt{s_{NN}} = 2.76\ \mathrm{TeV}$)
- Clear improvement over existing SP-method
- GE reproduces the "true" value of SPC extremely well in central to mid-central collisions!

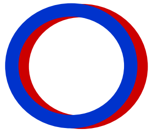


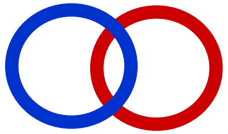
A. Bilandzic, ML, S. F. Taghavi: "New estimator for symmetry plane correlations in anisotropic flow analyses", PRC 102, 024910 – 2020

First experimental results with GE

ATLAS results from: ATLAS Collaboration, Phys. Rev. C 90, 024905, 2014.

Unpublished Result





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No initial anisotropy in coordinate space

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[redacted]

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Correlated symmetry planes

- Correlation from initial state?
- Impact of non-linear response?

Correlations between ψ_2 and ψ_4

- Comparison of state-of-the-art model T_RENTo + iEBE-VISHNU

J. E. Bernhard, J. S. Moreland, and S. A. Bass, “Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma,” Nature Phys. 15 no. 11, (2019) 1113–1117.

$$\omega_{422} = 0 \quad \langle \cos[4(\Psi_4 - \Psi_2)] \rangle = \langle \cos[4(\Phi_4 - \Phi_2)] \rangle$$

$$\omega_{422} \neq 0 \quad \langle \cos[4(\Psi_4 - \Psi_2)] \rangle \neq \langle \cos[4(\Phi_4 - \Phi_2)] \rangle$$

[redacted]

Unpublished Result

Correlations between ψ_2, ψ_3 and ψ_5

- Probing of linear and non-linear response of ψ_5 to ψ_2 and ψ_3
- Linear response dominates in the model
- Model describes the data extremely well

[redacted]

Unpublished Result

Correlations between four symmetry planes

- First experimental extraction of SPC between 4 planes
- Proof of feasibility for higher order SPC
- Large difference between data and models for higher order flow

→ Data presents great opportunity for model tuning

Unpublished Result

Summary

- GE estimates SPC more accurately than other existing methods
- First experimental results from ALICE using the GE (in total 9 different combinations)

  → Currently under preparation for paper proposal

Further Work:

- First cumulant to probe the correlations between SPC, see

  A. Bilandzic, **ML**, C. Mordasini, S. F. Taghavi: *“Multivariate cumulants in flow analyses: The Next Generation”*, arXiv 2101.05619

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[redacted]

Unpublished Result

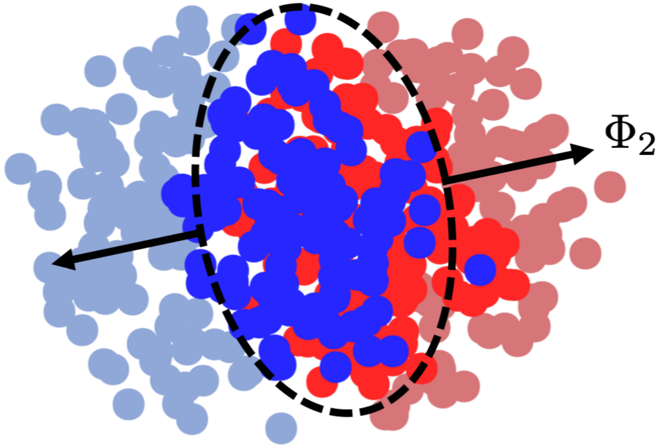
THANK YOU!

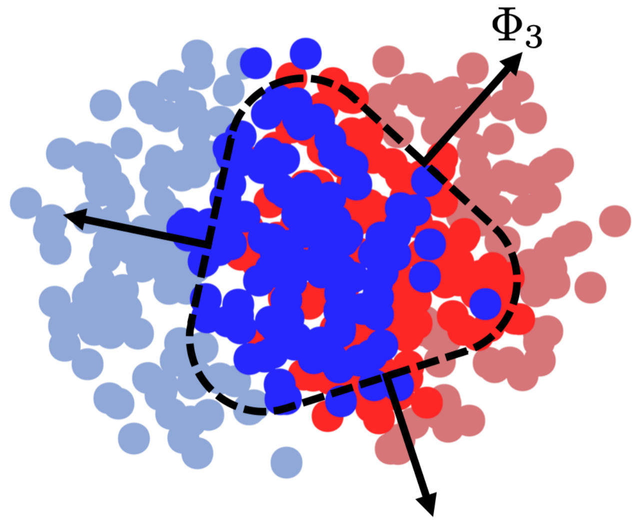
Backup

Symmetry Plane Correlations (SPC)

- **Initial state**: Higher order participant planes from fluctuations
- **Final state**: Measurement of single symmetry planes not possible

  → Use Symmetry Plane Correlations, e.g. $\langle\cos[4(\Psi_4 - \Psi_2)]\rangle$





- Comparison of SPC in the initial and final state is sensitive to linear and non-linear response, e.g.

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→ Imprint of the hydrodynamic evolution of the system

Scalar Product Method

- Previous work: **Scalar Product (SP)-Method**

$$\langle \cos(c_1\Psi_1 + 2c_2\Psi_2 + \ldots + lc_l\Psi_l)\rangle = \frac{\langle v_1^{c_1} v_2^{c_2} \ldots v_l^{c_l} \cos(c_1\Psi_1 + 2c_2\Psi_2 + \ldots + lc_l\Psi_l)\rangle}{\sqrt{\langle v_1^{2c_1}\rangle \langle v_2^{2c_2}\rangle \ldots \langle v_l^{2c_l}\rangle}}$$

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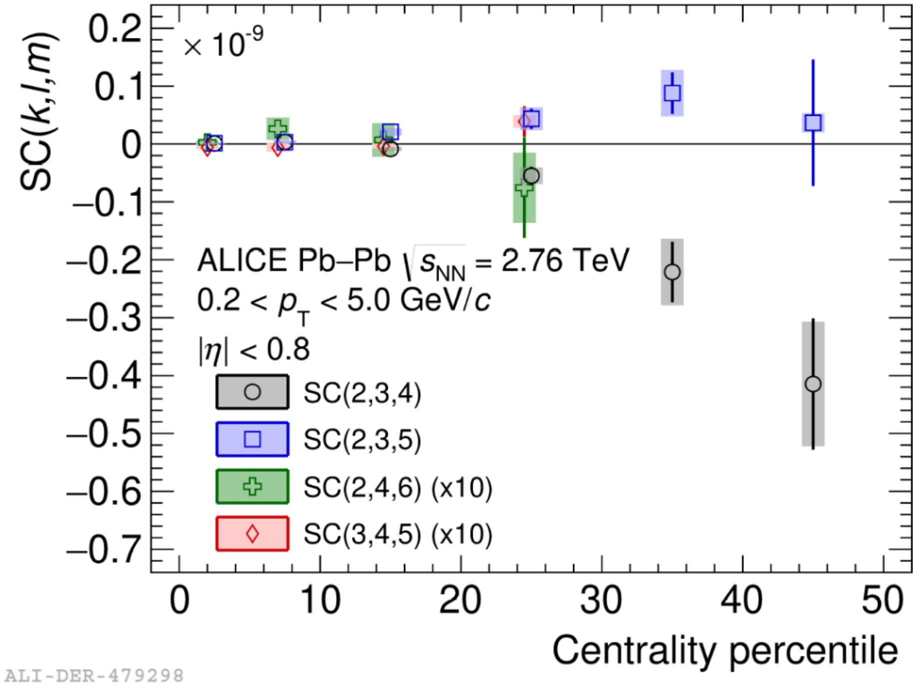
- Problem:

$$\langle v_n^2 v_m^2\rangle \neq \langle v_n^2\rangle\langle v_m^2\rangle$$

$$\langle v_k^2 v_l^2 v_m^2\rangle \neq \langle v_k^2\rangle\langle v_l^2\rangle\langle v_m^2\rangle$$

New technique for SPC must be developed!



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

Everything is Gaussian if you are brave enough

- **Starting point**: Modelling of multi-harmonic flow fluctuations
  $\mathcal{R}_x = v_{n_1}^{a_1} \cdots v_{n_k}^{a_k} \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k})$ and $\mathcal{R}_y = v_{n_1}^{a_1} \cdots v_{n_k}^{a_k} \sin(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k})$
  with a 2D Gaussian
- Use this 2D Gaussian to calculate $\langle \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle$

  → **Gaussian Estimator (GE):**

$$\langle \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle_{\mathrm{GE}} = \sqrt{\frac{\pi}{4}} \frac{\langle v_{n_1}^{a_1} \cdots v_{n_k}^{a_k} \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle}{\sqrt{\langle v_{n_1}^{2a_1} \cdots v_{n_k}^{2a_k} \rangle}}$$

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Gaussian Estimator for SPC

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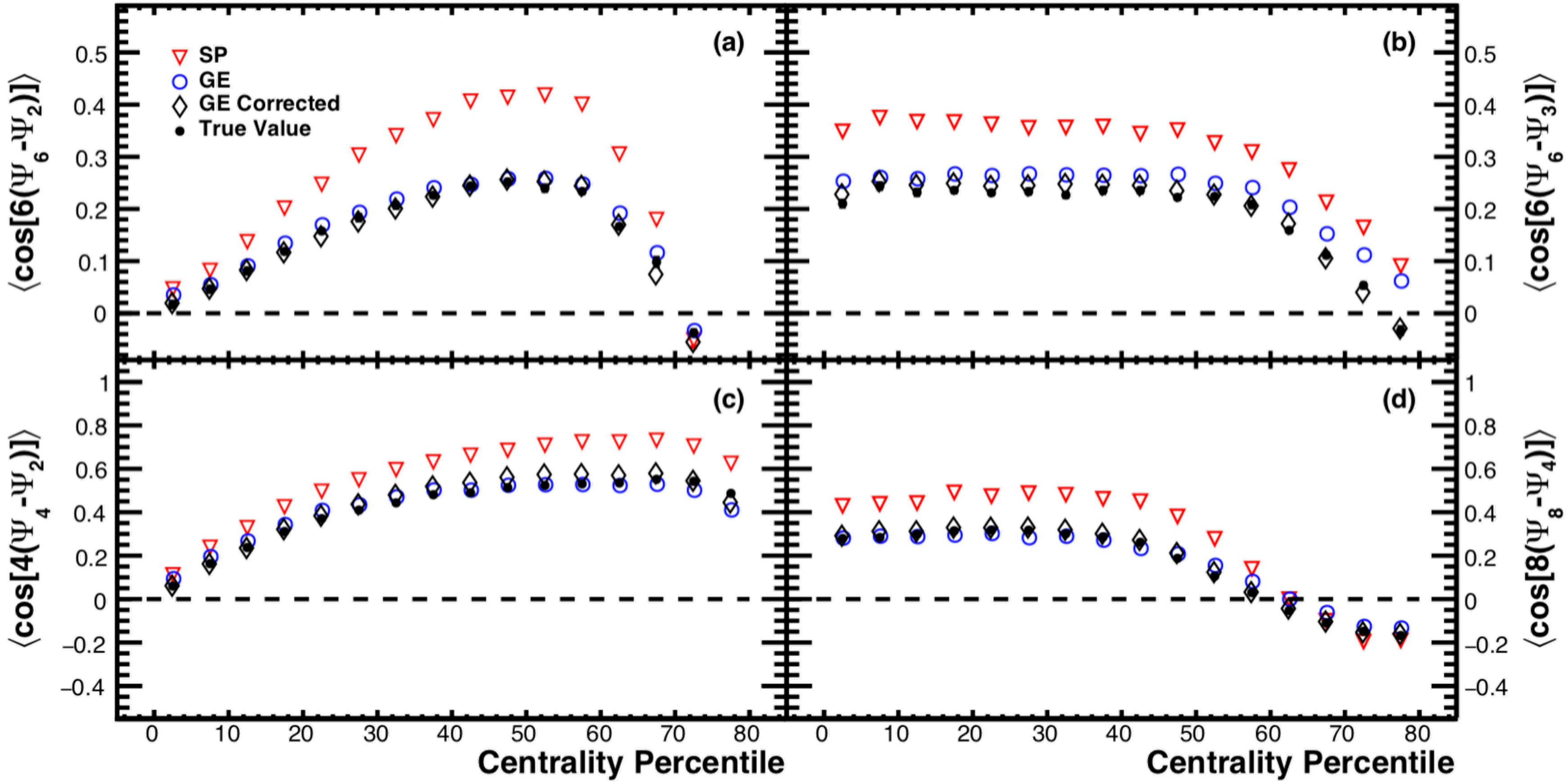
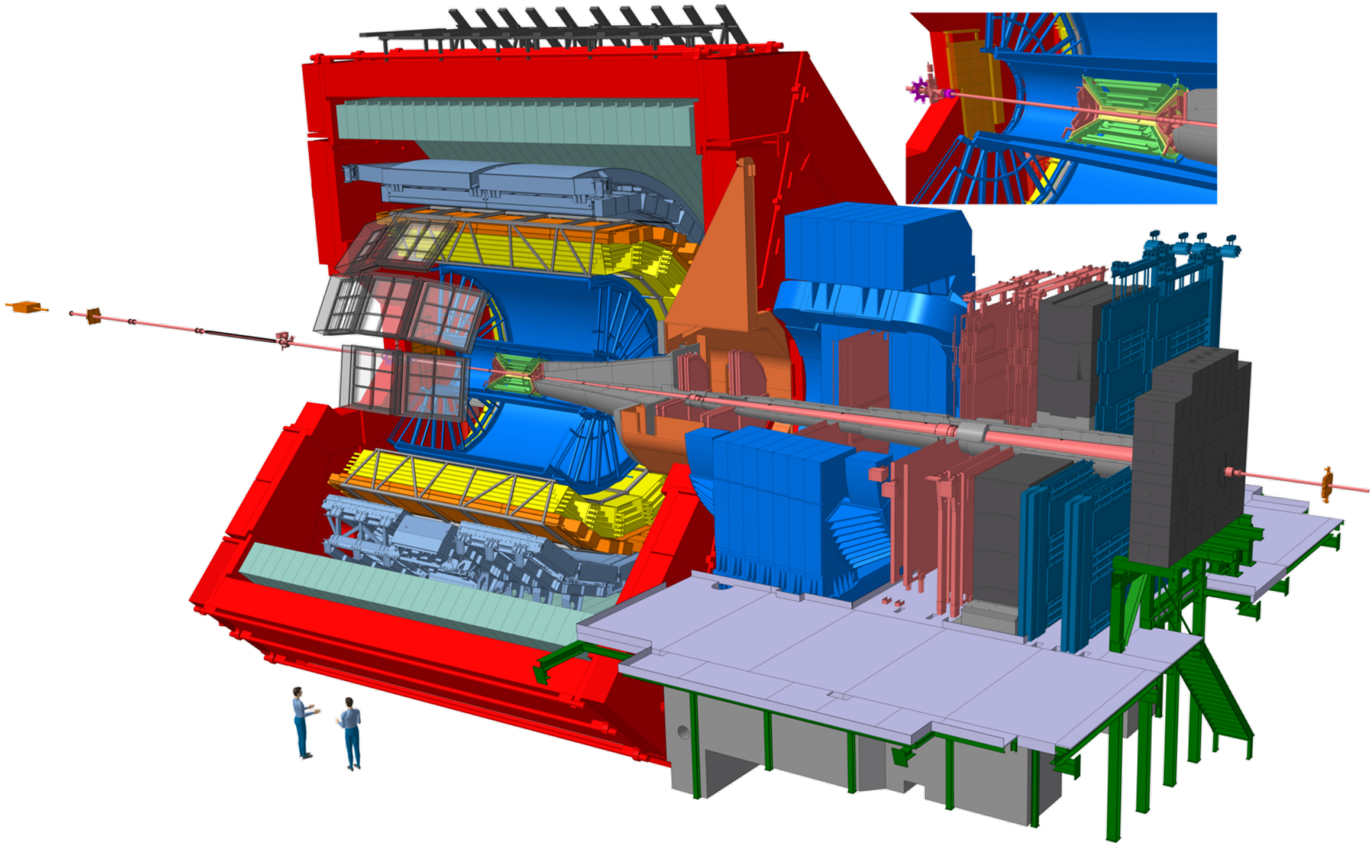


ALICE - A Large Ion Collider Experiment

- Dedicated heavy ion experiment at the LHC
- **I**nner **T**racking **S**ystem
  - Used for PV determination
  - SPD clusters for centrality determination
- **T**ime **P**rojection **C**hamber
  - Used as the main detector
    for track reconstruction ($\varphi, p_{T,}$ ...)



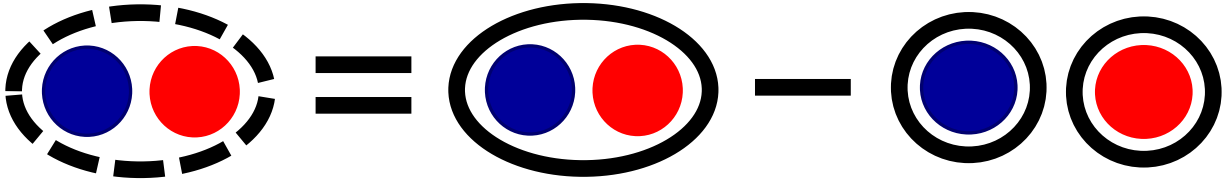
A. Tauro, "ALICE Schematics" (2017), CERN CDS

Is this all we can do with Symmetry Planes?

Answer: No, there is more

Cumulants

- Cumulants probe the **genuine** correlation between variables
- Example: Lowest order, two-variate cumulant



$$\kappa_{1,1} = \langle X_1 X_2 \rangle - \langle X_1 \rangle \langle X_2 \rangle$$

- Cumulants in flow analyses, e.g. symmetric cumulants:

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

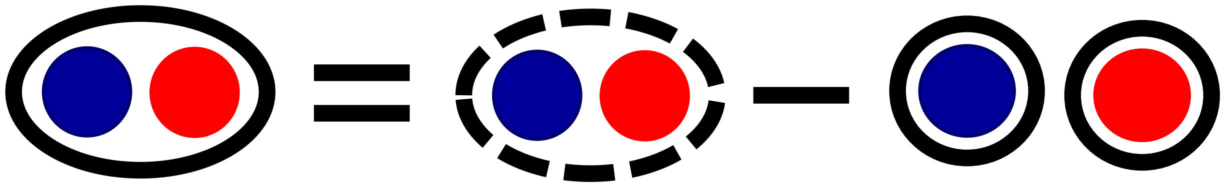
Cumulant of Symmetry Plane Correlation (CSC)

- Approach: Use SPC as the statistical observables in the cumulant expansion

$$X_1 = e^{ib(\Psi_c - \Psi_d)}$$

$$X_2 = e^{ik(\Psi_l - \Psi_m)}$$

- Example:

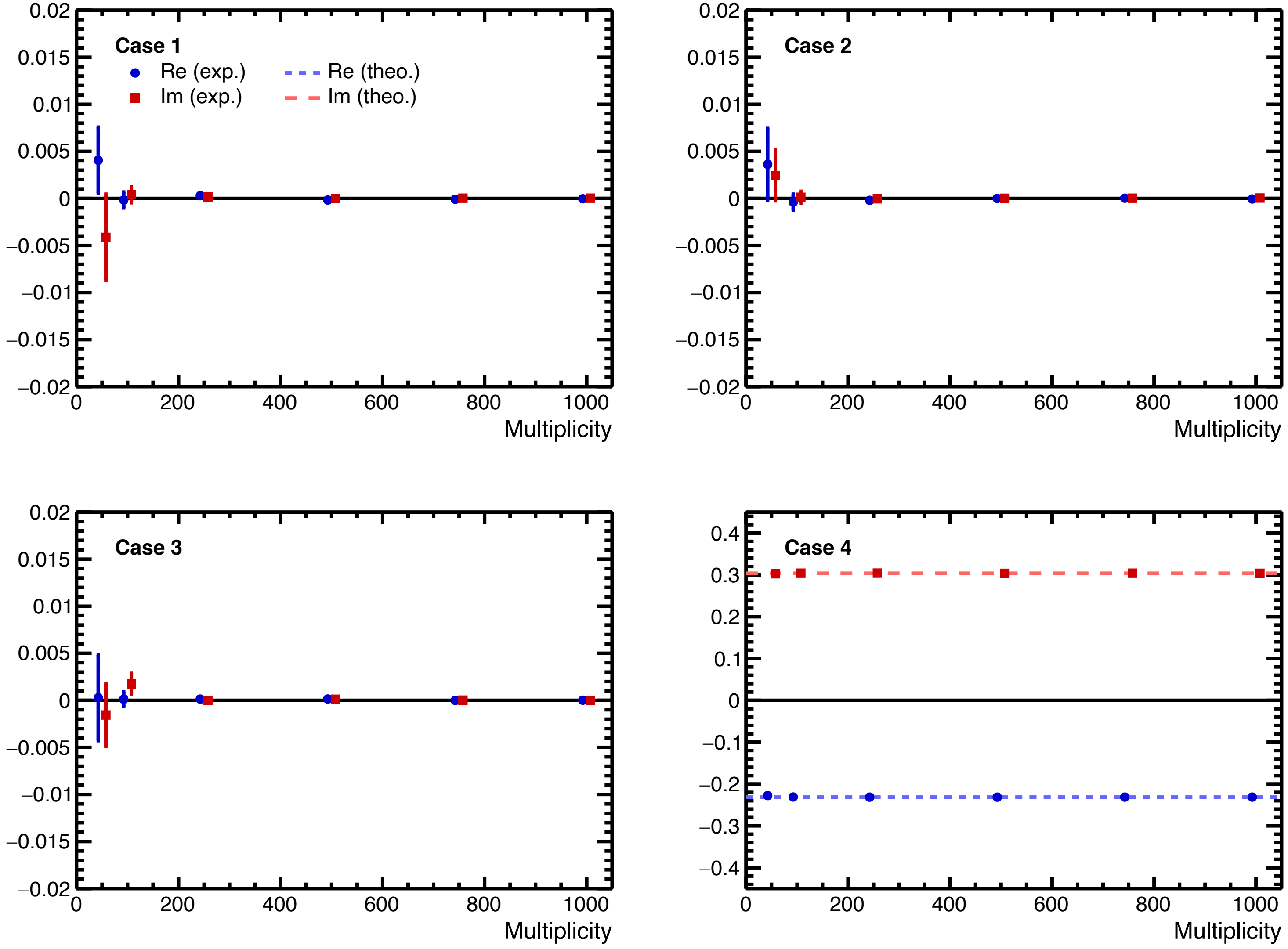


$$\mathrm{CSC}\left(4\delta_{4,2},\, 6\delta_{6,3}\right) = \left\langle e^{i(4(\Psi_4-\Psi_2)+6(\Psi_6-\Psi_3))} \right\rangle - \left\langle e^{i4(\Psi_4-\Psi_2)} \right\rangle \left\langle e^{i6(\Psi_6-\Psi_3)} \right\rangle$$

- Interpretation:
  - SPC as static pictures
  - CSC as dynamic picture for the evolution of SPC relative to each other
- Details see: A. Bilandzic, **ML**, C. Mordasini, S. F. Taghavi: *“Multivariate cumulants in flow analyses: The Next Generation”*, arXiv 2101.05619

Toy Monte Carlo Studies

- Study of CSC in a controlled environment with known input
- Cases 1-3: uncorrelated SPC → CSC yields zero
- Case 4: genuine correlation between the two SPC → non-zero value



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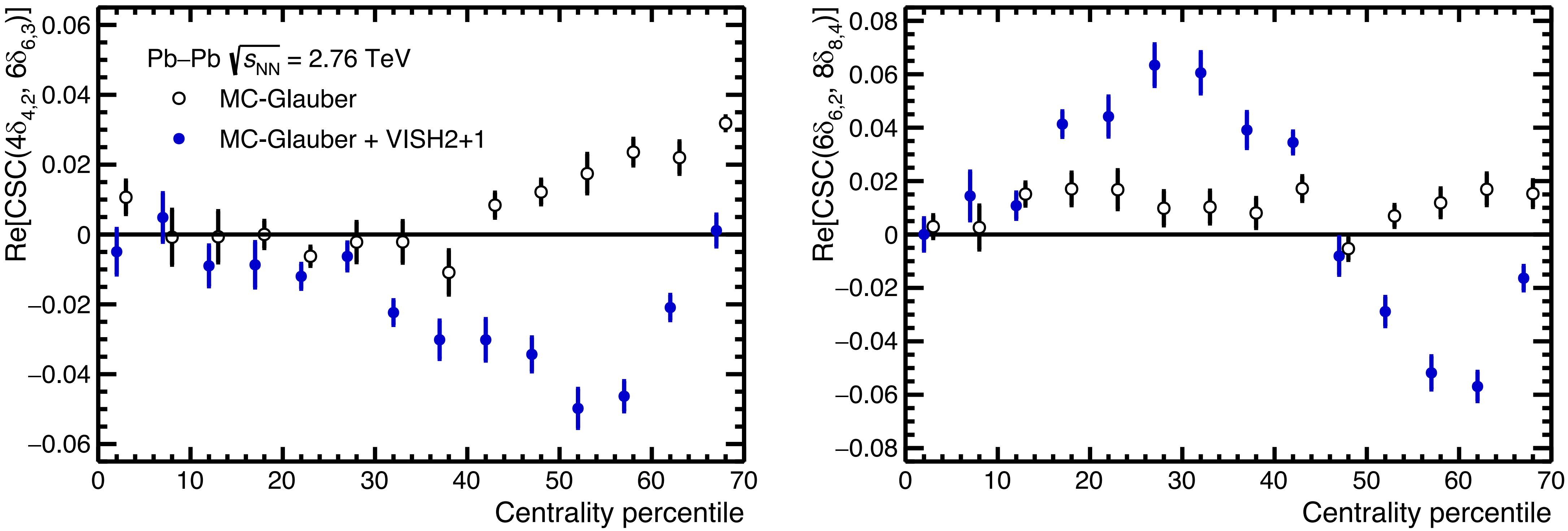
First model predictions for CSC

A. Bilandzic, ML, C. Mordasini, S. F. Taghavi: "New estimator for symmetry plane correlations in anisotropic flow analyses", arXiv 2101.05619



- Non-trivial signal in the initial and final state
- Indication that symmetry plane correlations are (anti-) correlated to each other