A GUIDE TO UNDERSTAND

COLLECTIVITY IN SMALL SYSTEMS

KATARINA KRIZKOVA GAJDOSOVA

18.01.2019

OUTLINE

- Heavy-ion collisions
- Flow
- Collectivity in heavy-ion collisions

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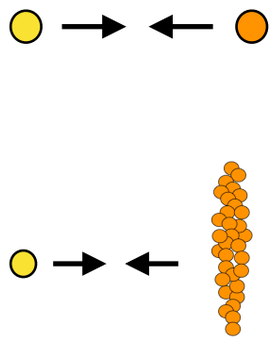
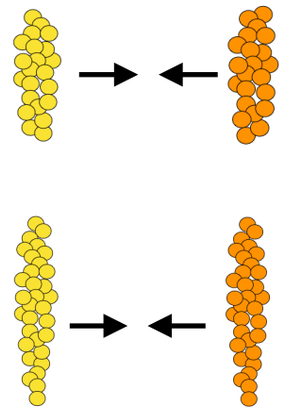
- Flow
- Collectivity in heavy-ion collisions
- Small collision systems



small systems

1+1 nucleon

1+208 nucleons



large systems

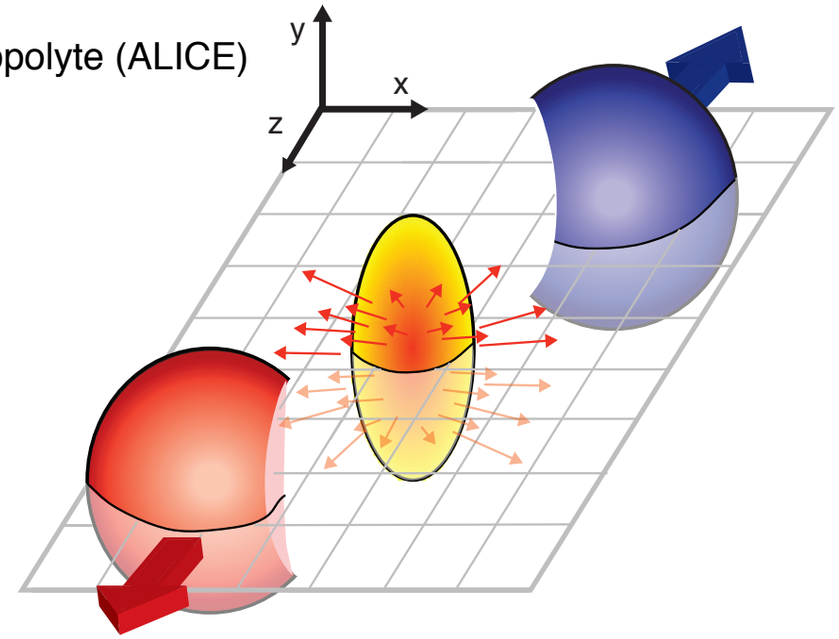
129+129 nucleons

208+208 nucleons

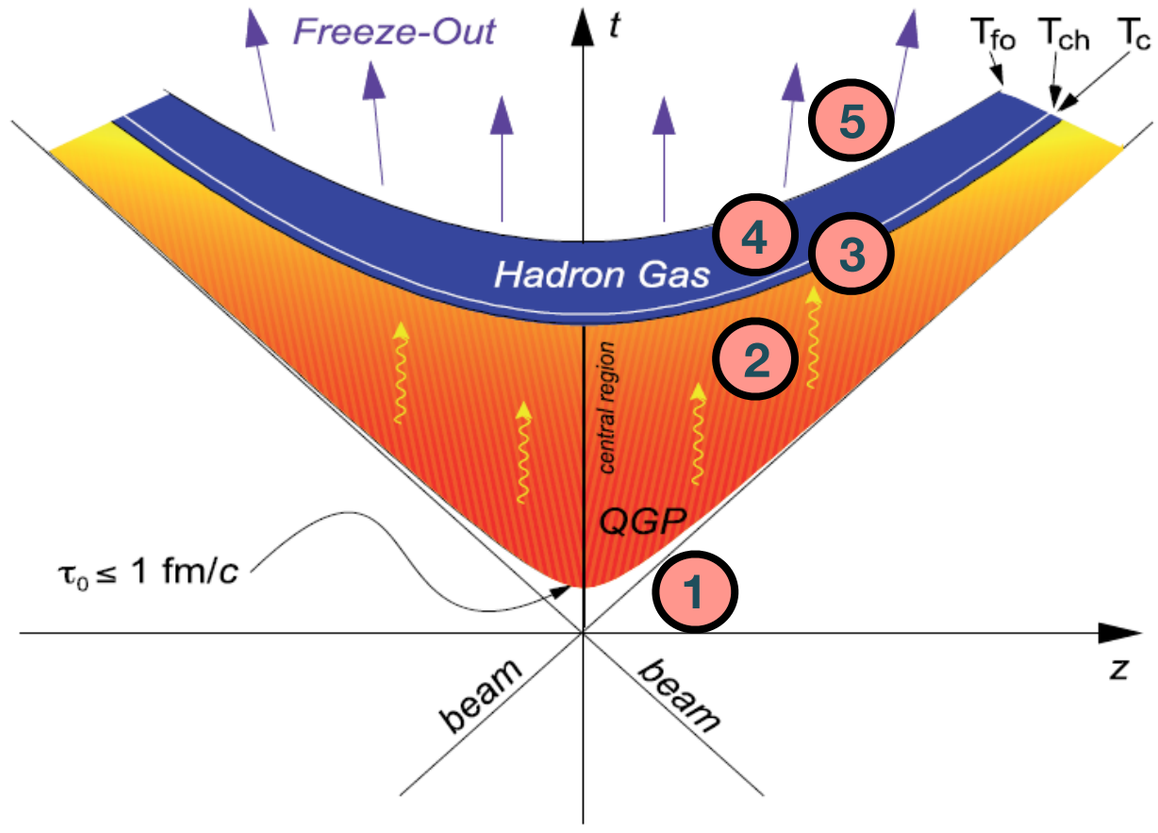
- Collisions:
  - pp
  - p-Pb
  - Xe-Xe
  - Pb-Pb

HEAVY-ION COLLISION

credits: Boris Hippolyte (ALICE)

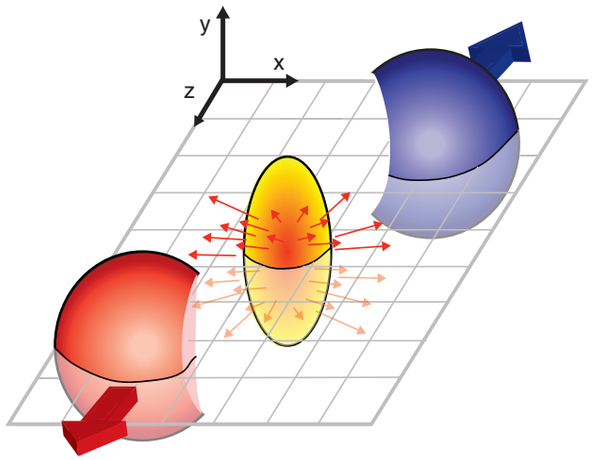


5. Freeze-out
4. Hadron gas
3. Phase transition
2. **Quark-Gluon Plasma**
1. Pre-equilibrium phase

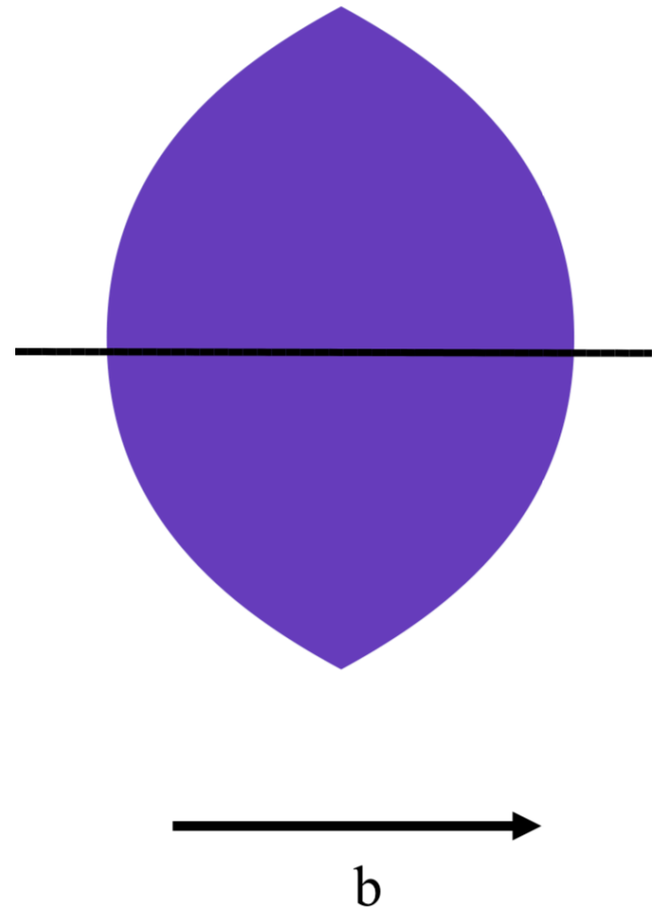


arXiv: 0807.1610 [nucl-ex]

EVOLUTION OF A HEAVY-ION COLLISION



A. Superposition of independent pp collisions



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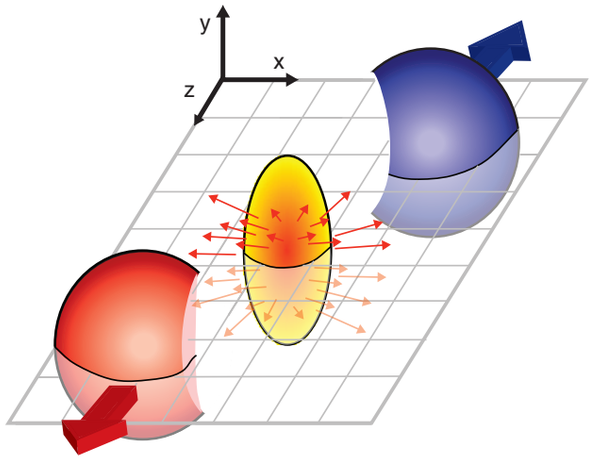

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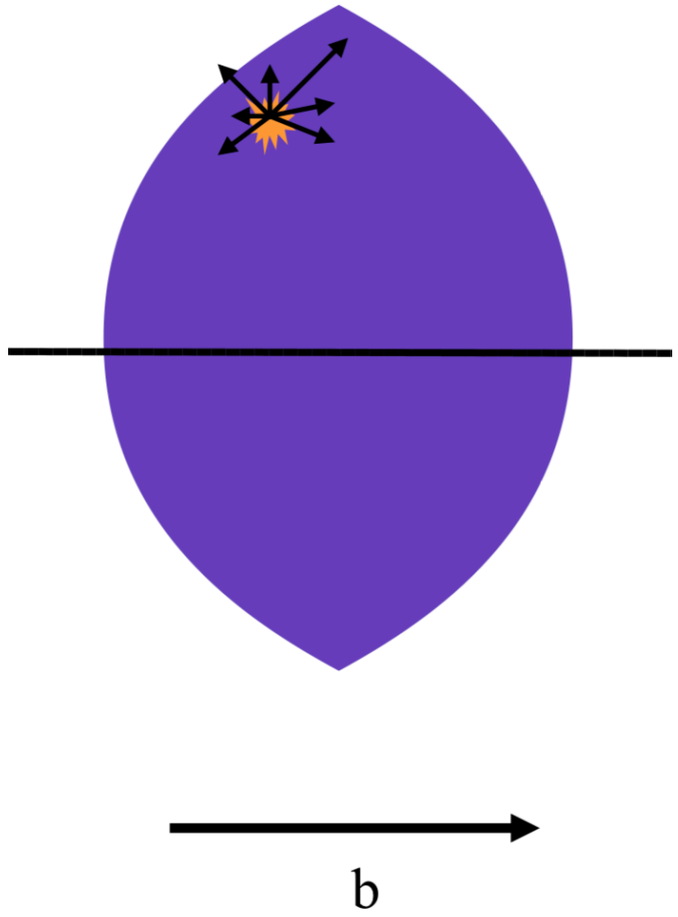

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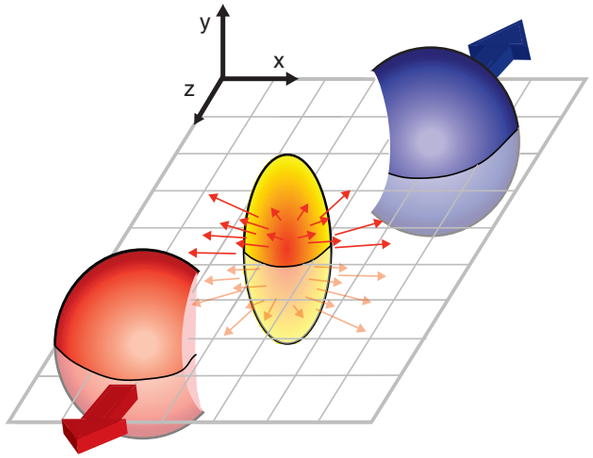

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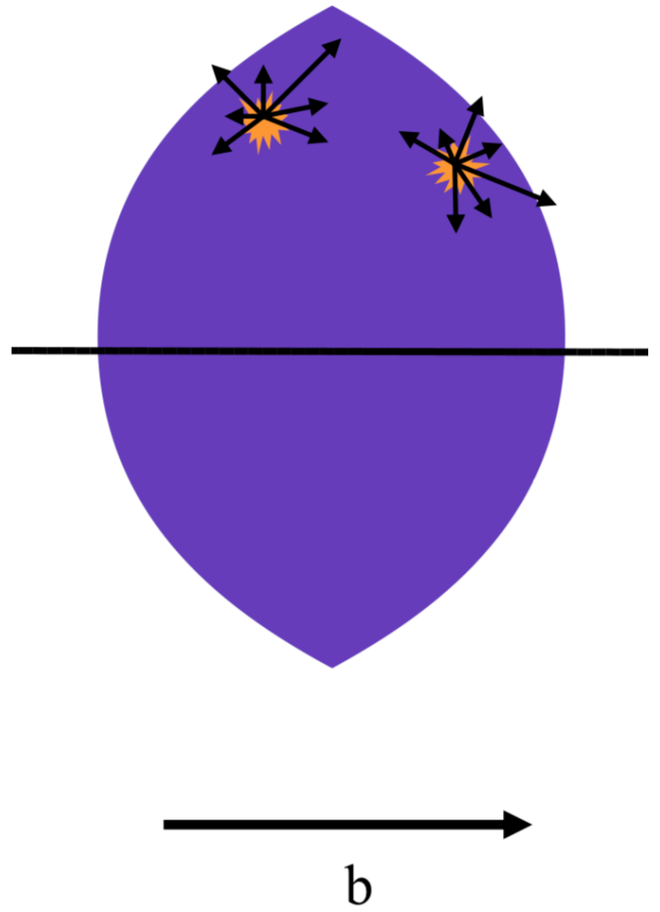

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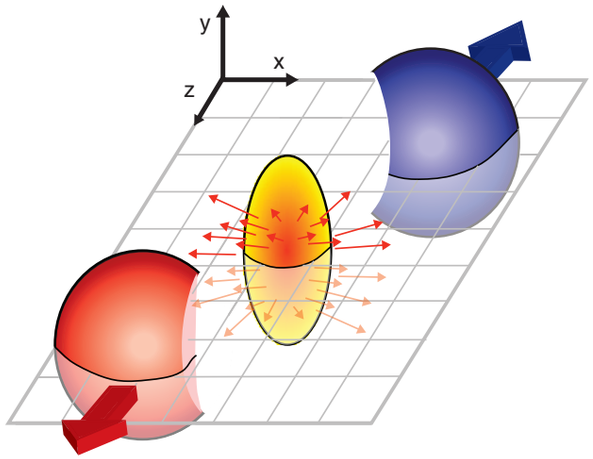

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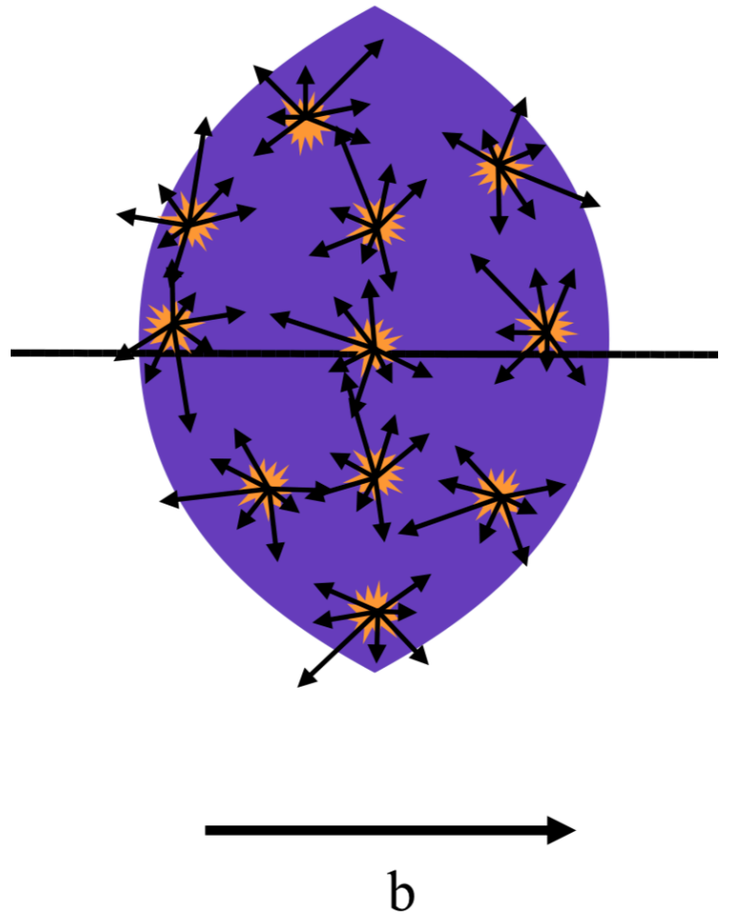

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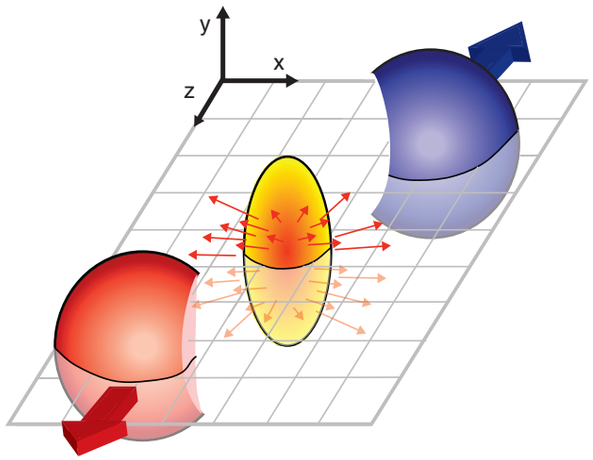

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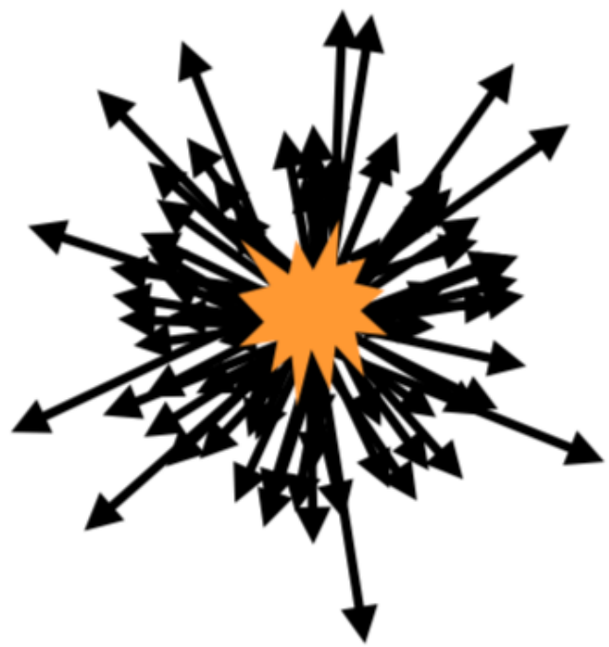

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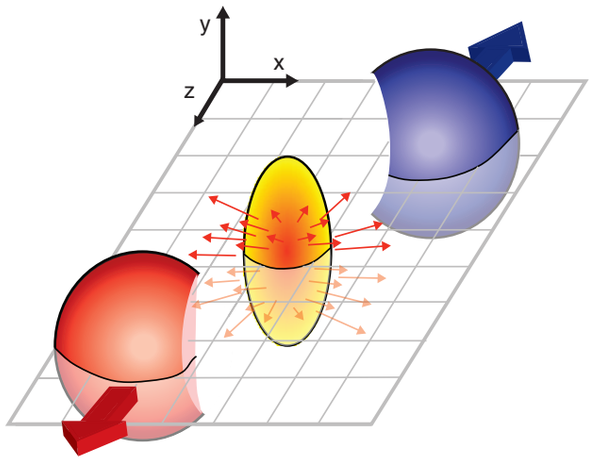

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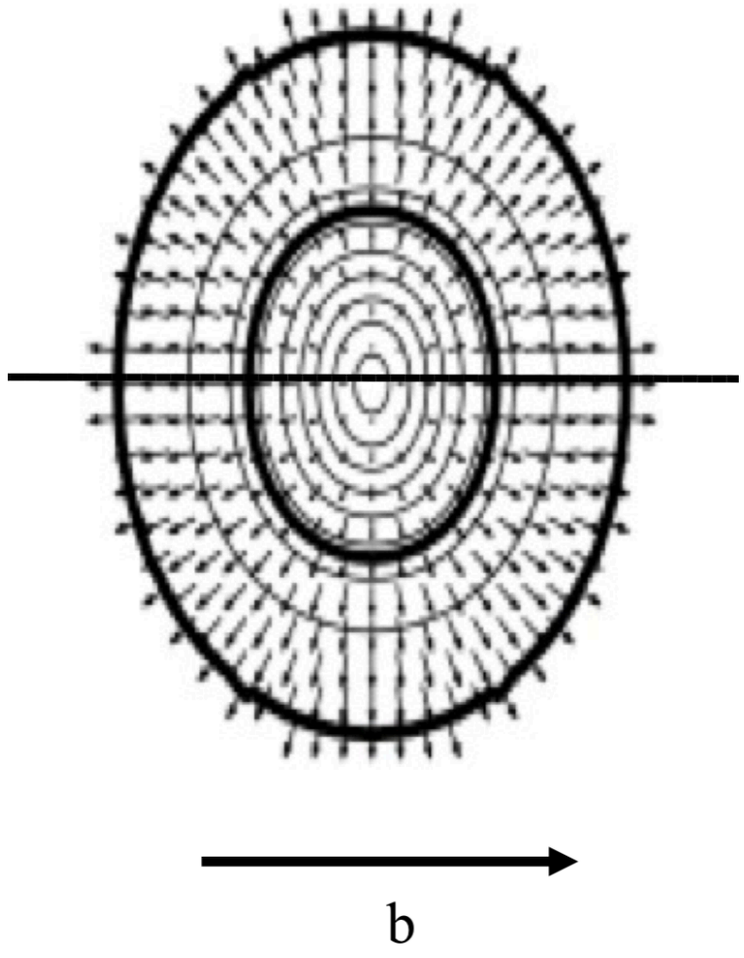
B. Evolution as a bulk



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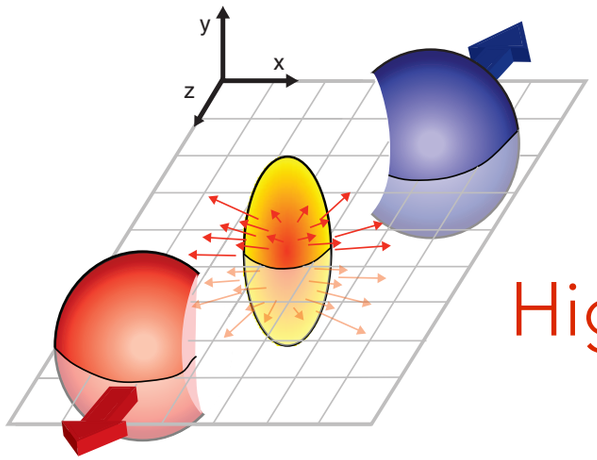

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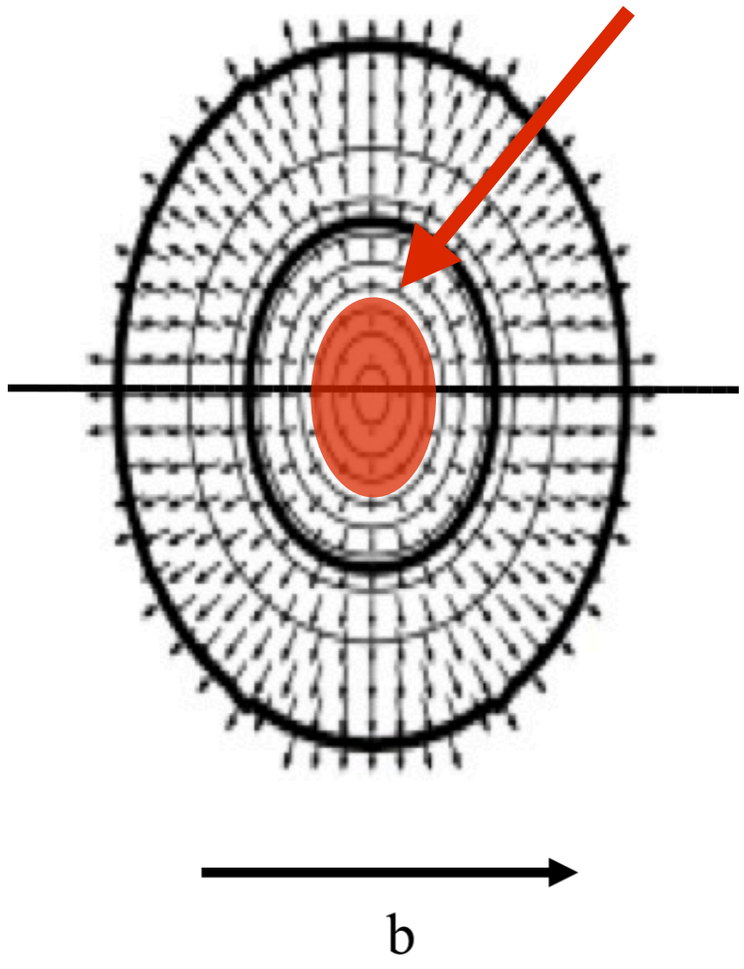
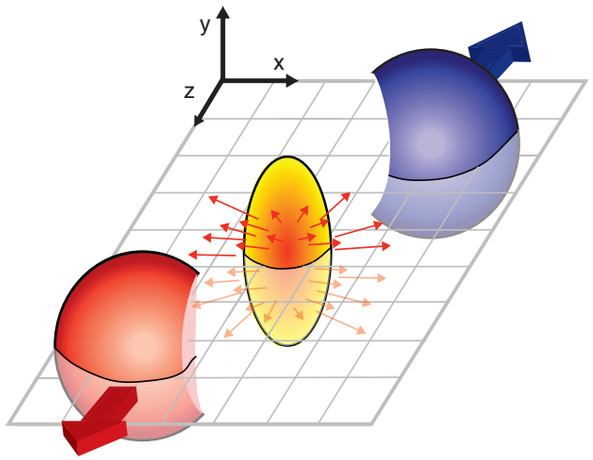
High pressure at the centre



"Zero" pressure around

Credits: Mike Lisa

EVOLUTION OF A HEAVY-ION COLLISION



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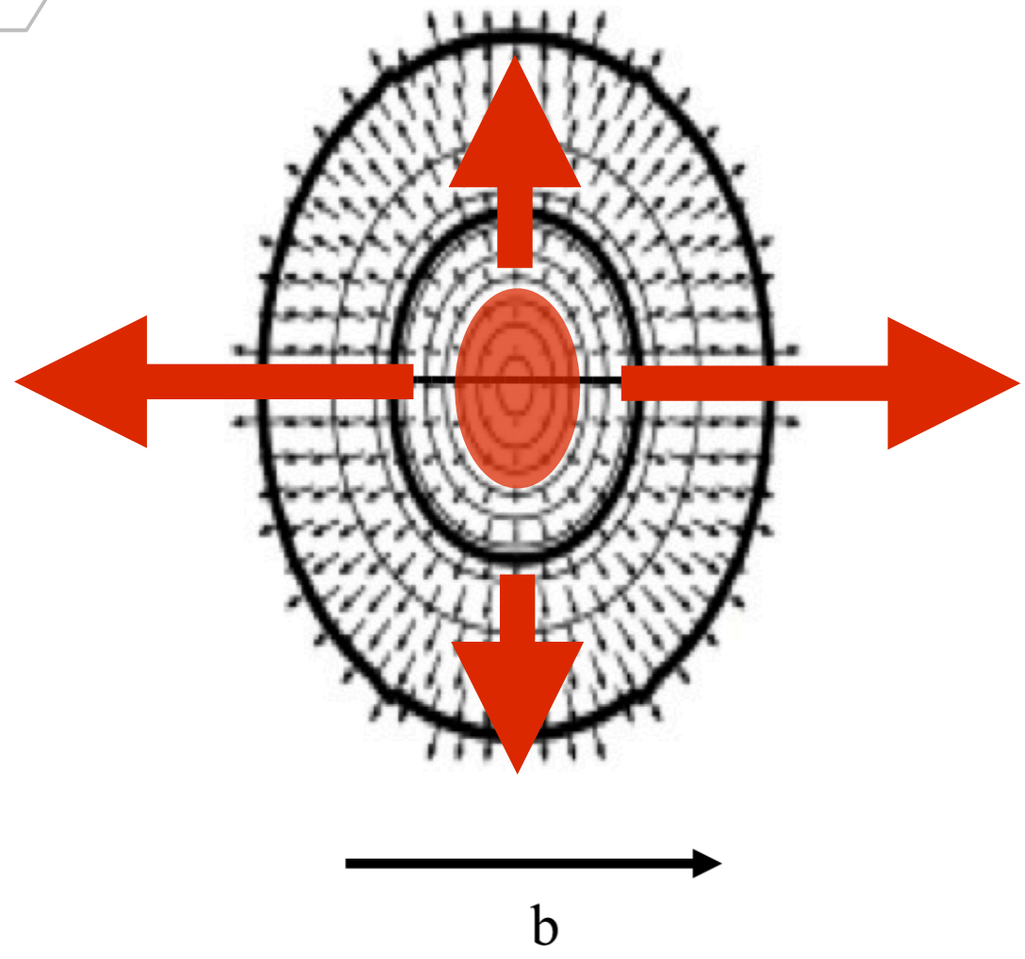

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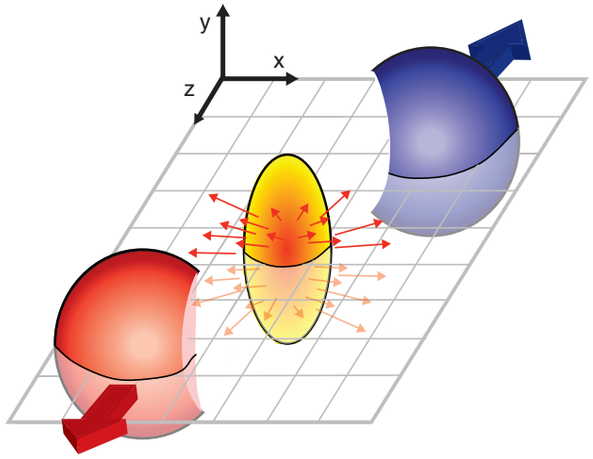

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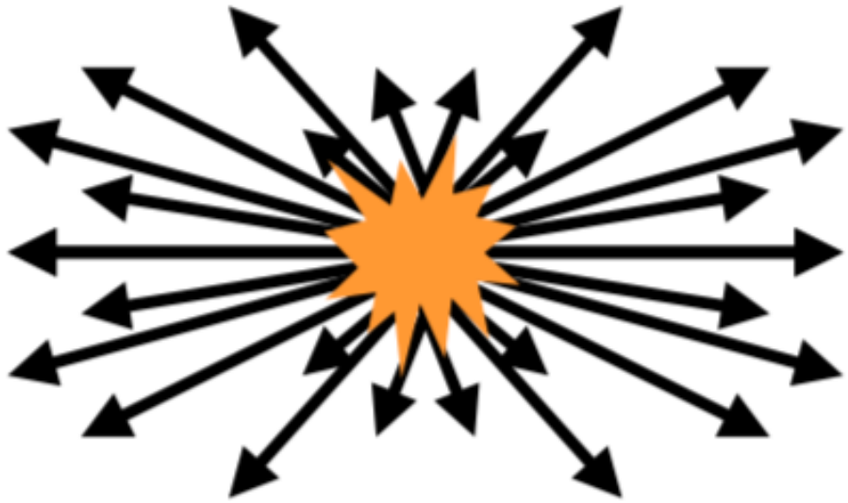

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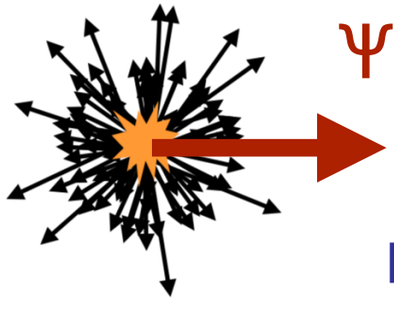

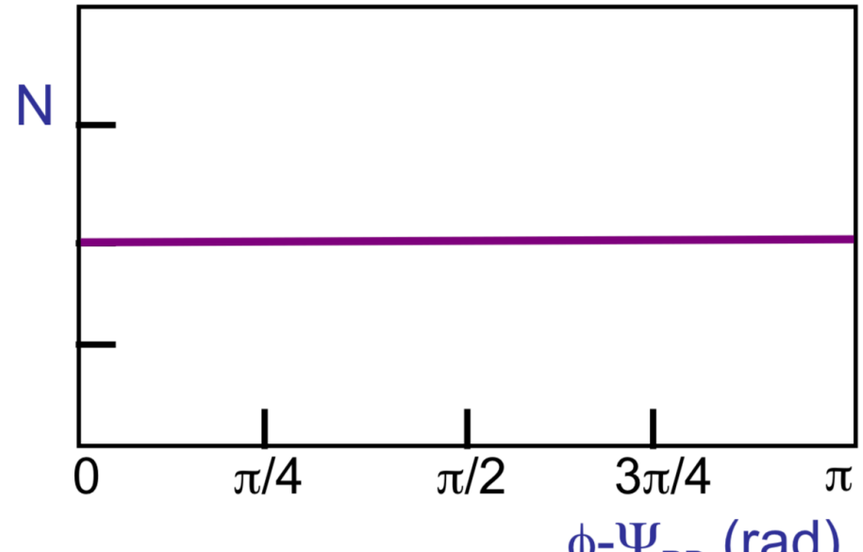

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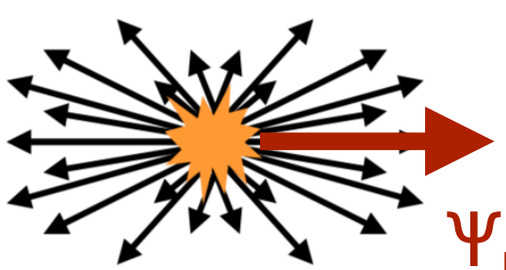
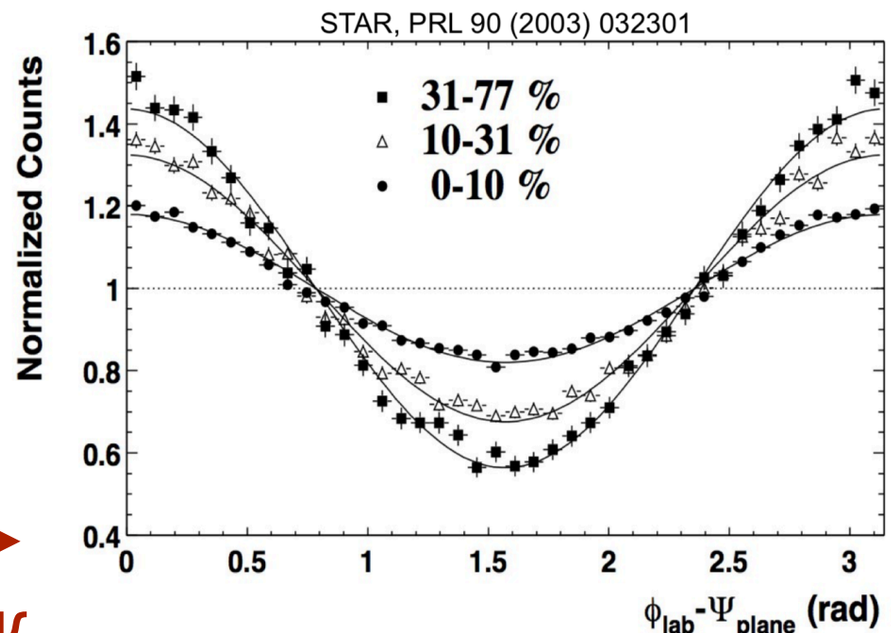
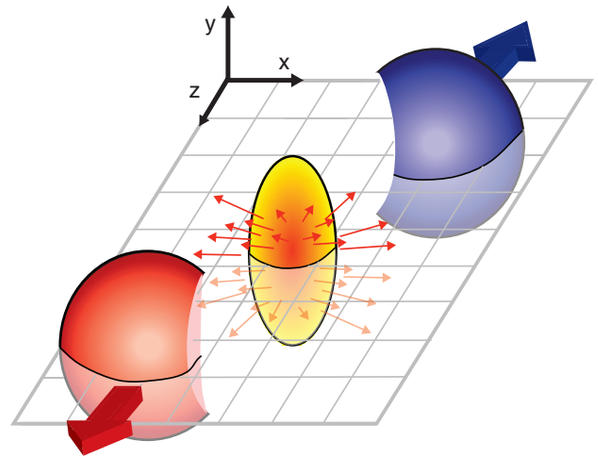


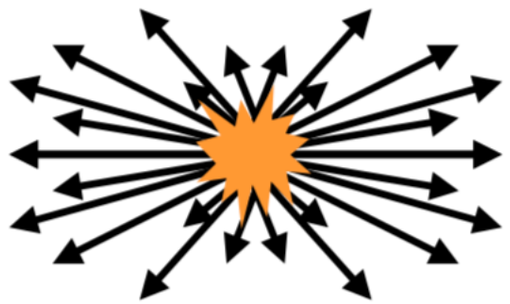


Credits: Mike Lisa

- QGP transforms initial spatial anisotropy to the anisotropy of final emitted particles



- The system expands collectively
  - Global collectivity



- Investigation of anisotropy of the distribution of emitted particles provides information about the evolution of HI collision

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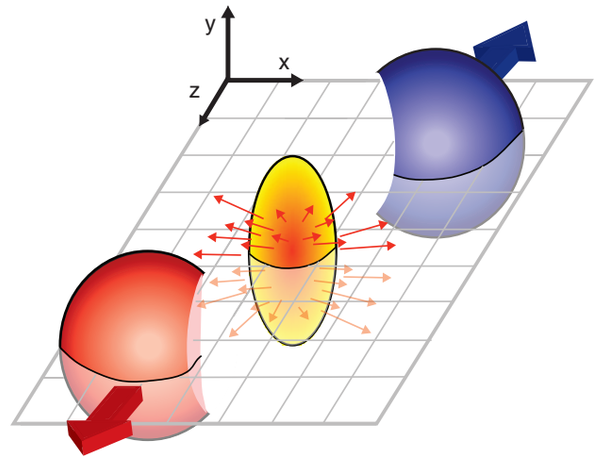

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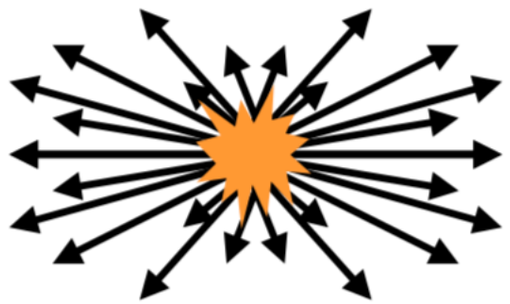


- Investigation of anisotropy of the distribution of emitted particles provides information about the evolution of HI collision -> HOW?

HOW TO QUANTIFY PARTICLE ANISOTROPY

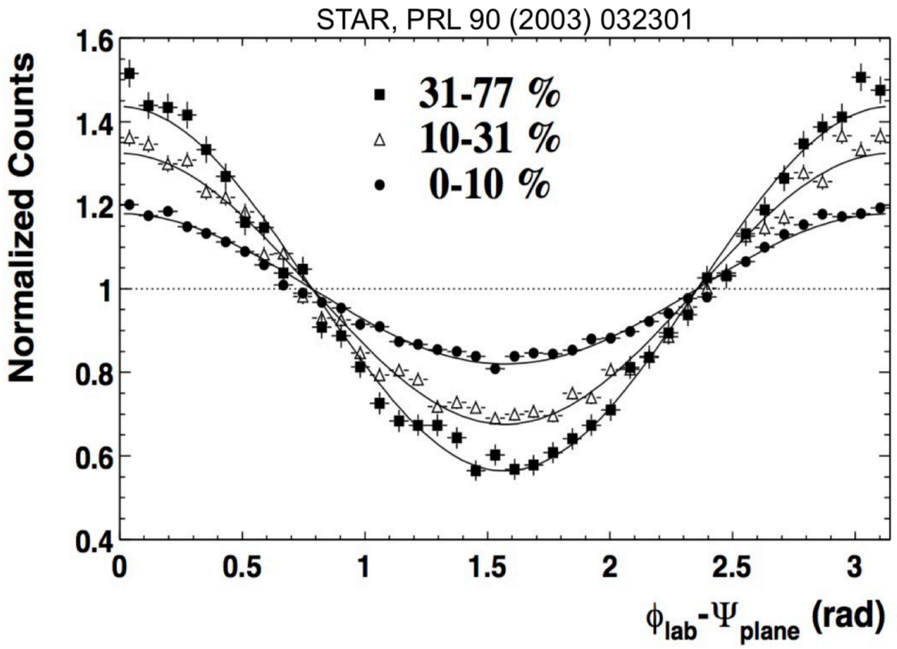
- Distribution of emitted particles in azimuth expanded in Fourier series

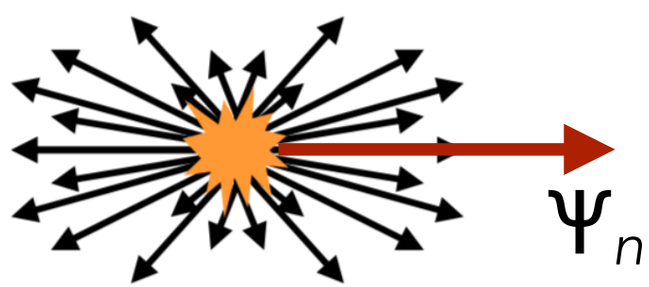
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

flow coefficient:

participant plane

$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$





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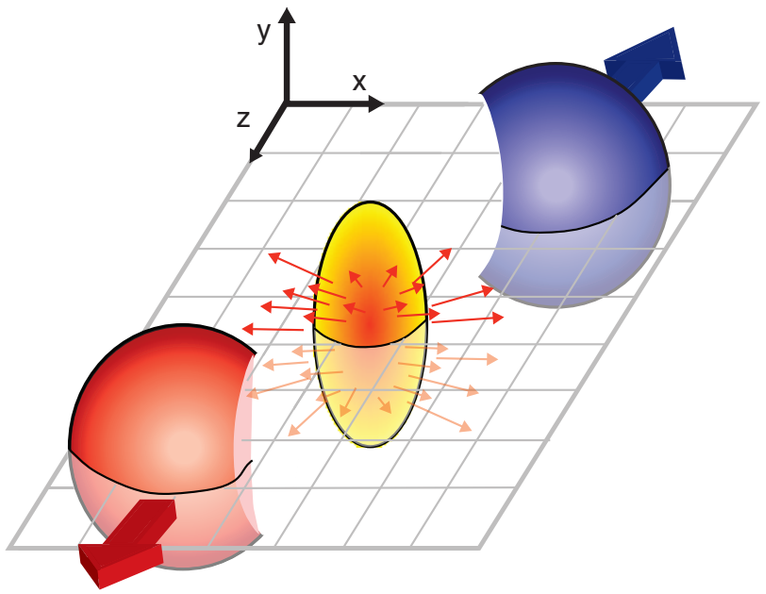

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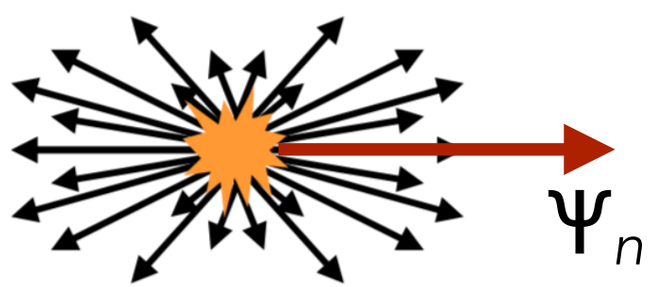

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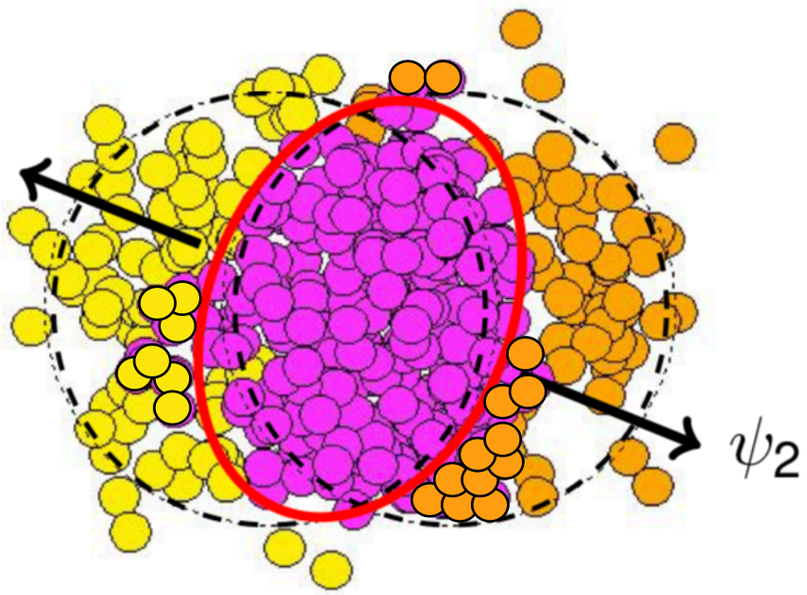

flow coefficient:

$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

participant plane

Elliptic initial overlap geometry $\boldsymbol{\varepsilon}_2$ -> Large elliptic flow v_2

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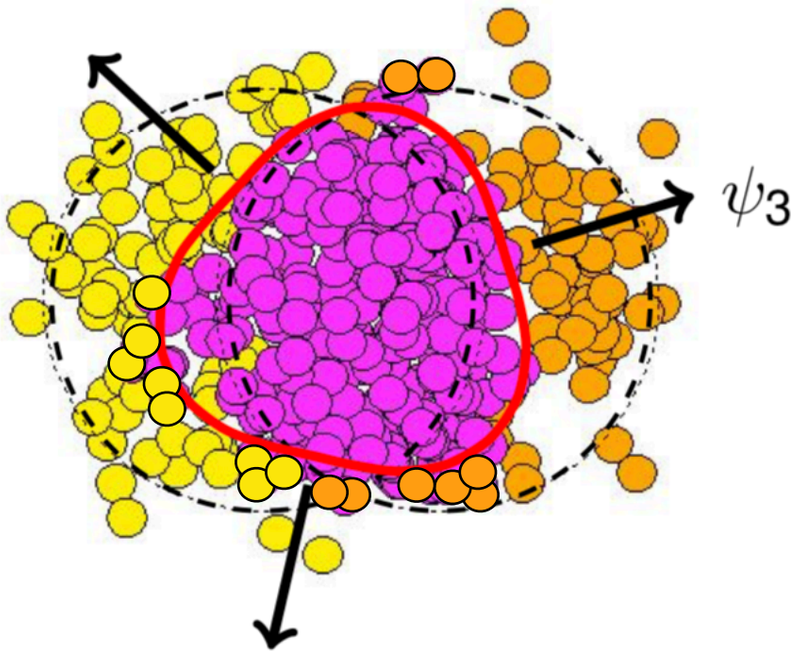

flow coefficient:

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participant plane

Triangular initial overlap geometry ε_3 -> Large triangular flow v_3

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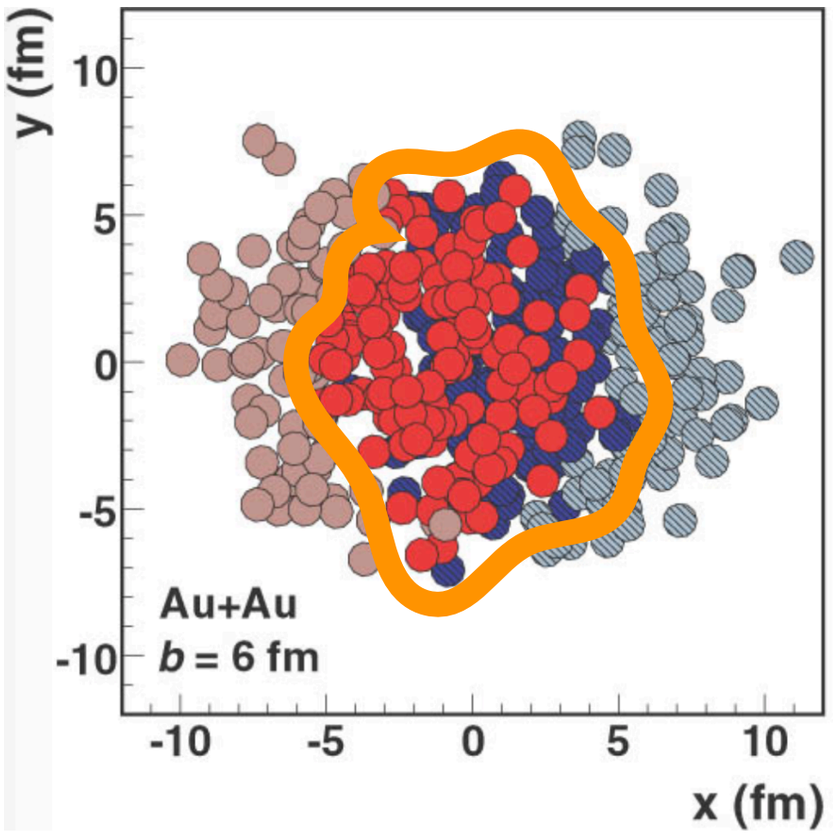

flow coefficient:

v_n

participant plane

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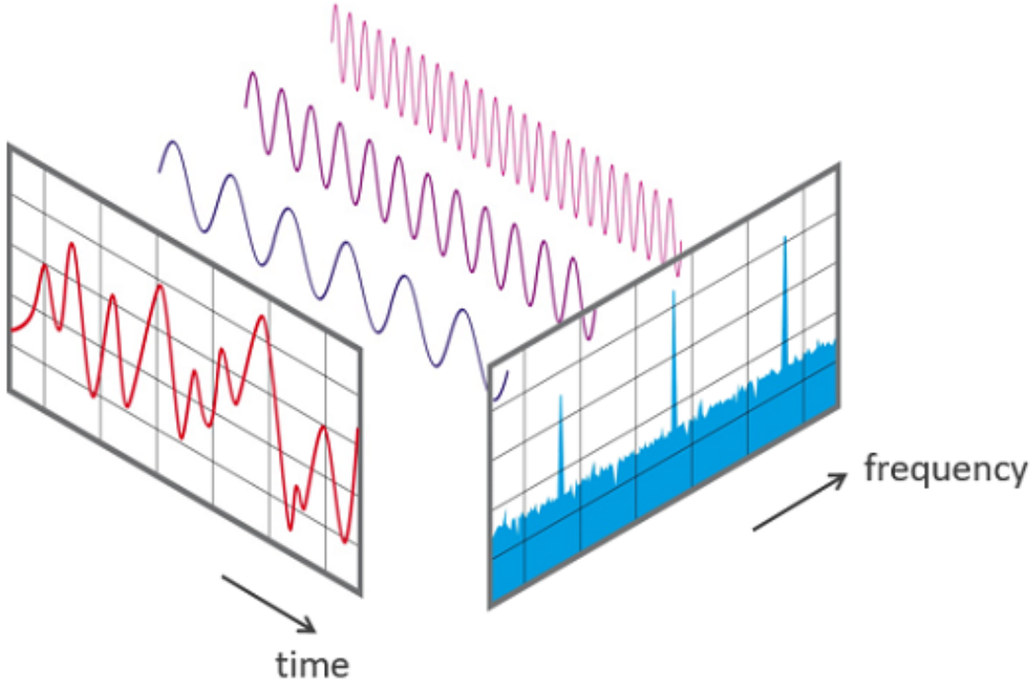
Real collision contains several harmonic modes -> superposition of v_2, v_3, v_4, …

ANALOGY TO FLOW COEFFICIENTS

- Electronic signal contains several types of waves
  - Superposition of the basic harmonic modes



wikipedia, https://en.wikipedia.org/wiki/Fast_Fourier_transform#/media/File:FFT-Time-Frequency-View.png

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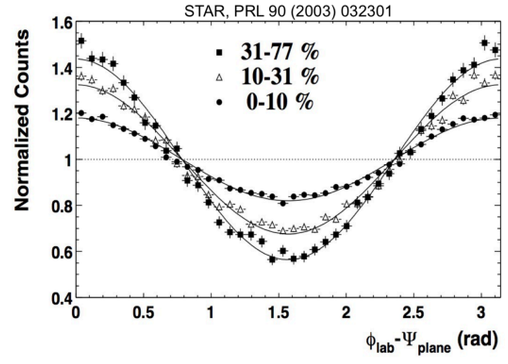
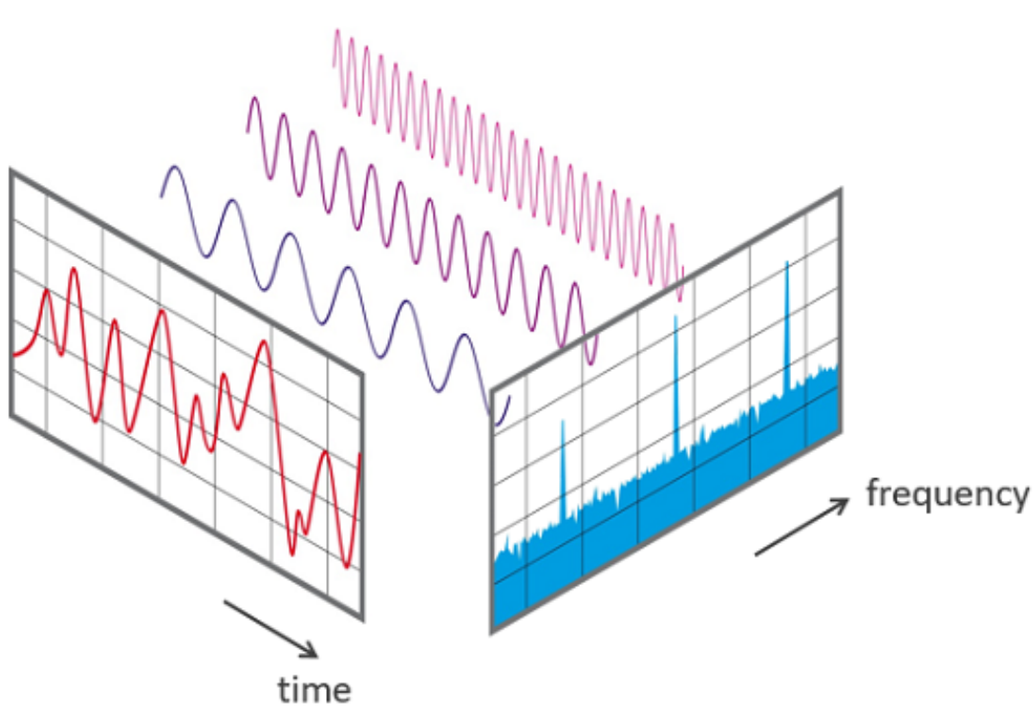


PRL 107, 032301 (2011)



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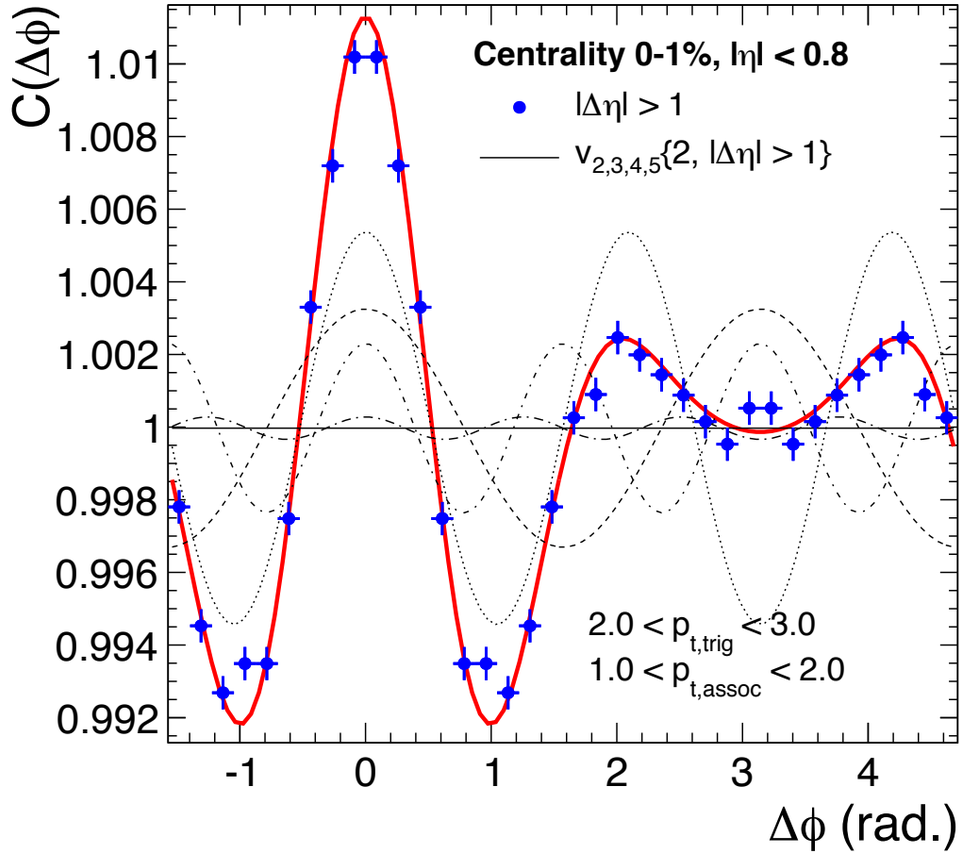

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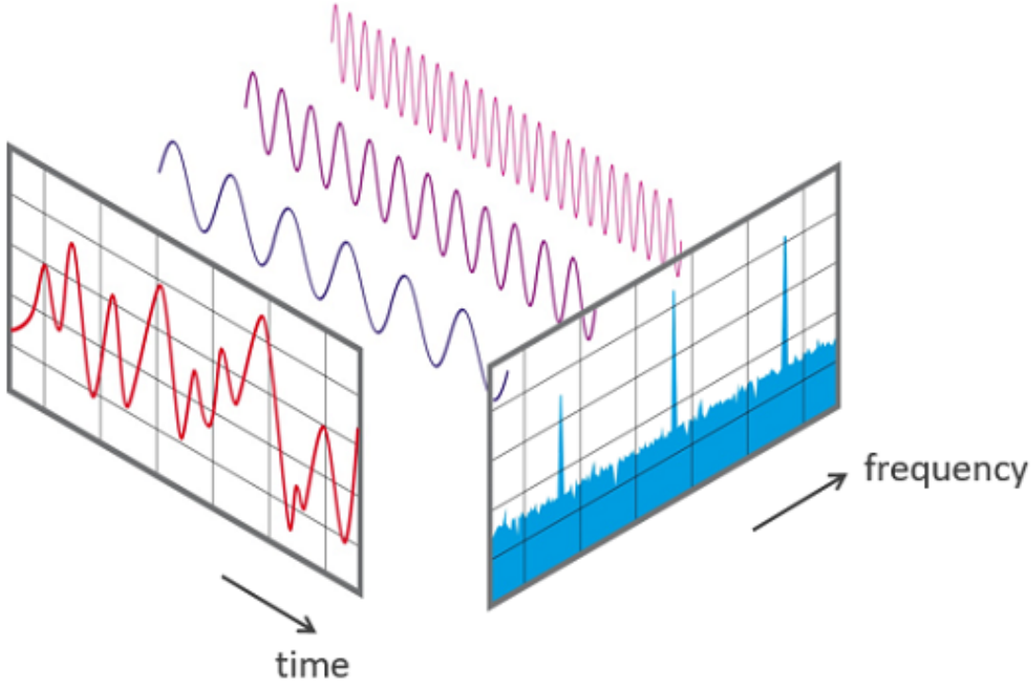
  - Fourier transform to frequency domain: amplitude shows the abundance of the basic harmonic modes within the signal



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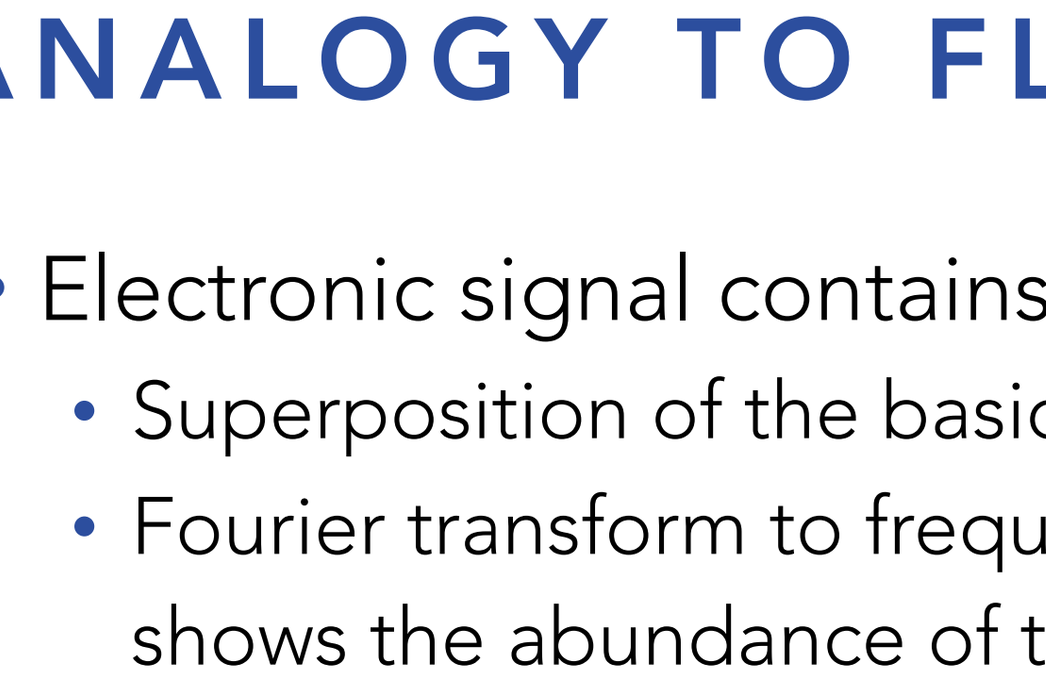

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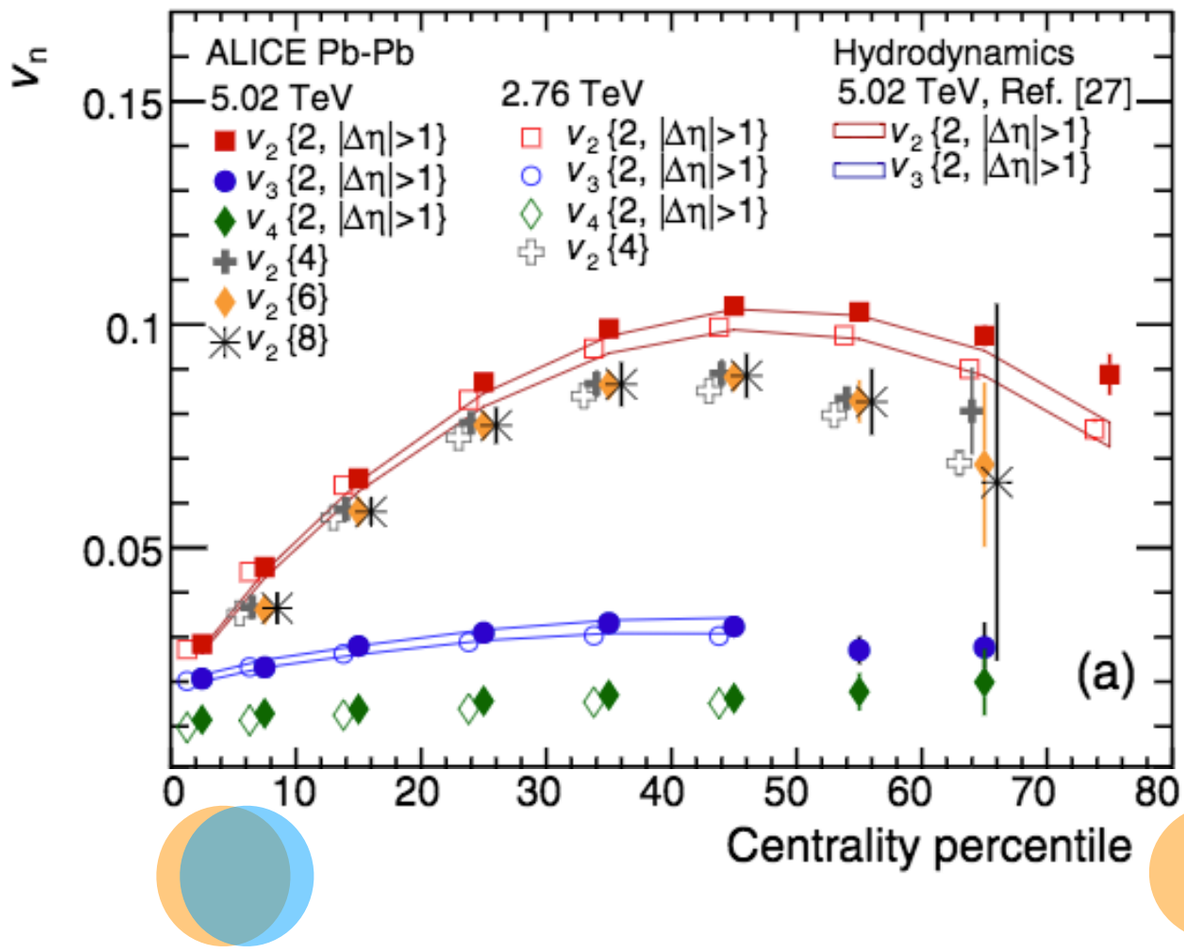
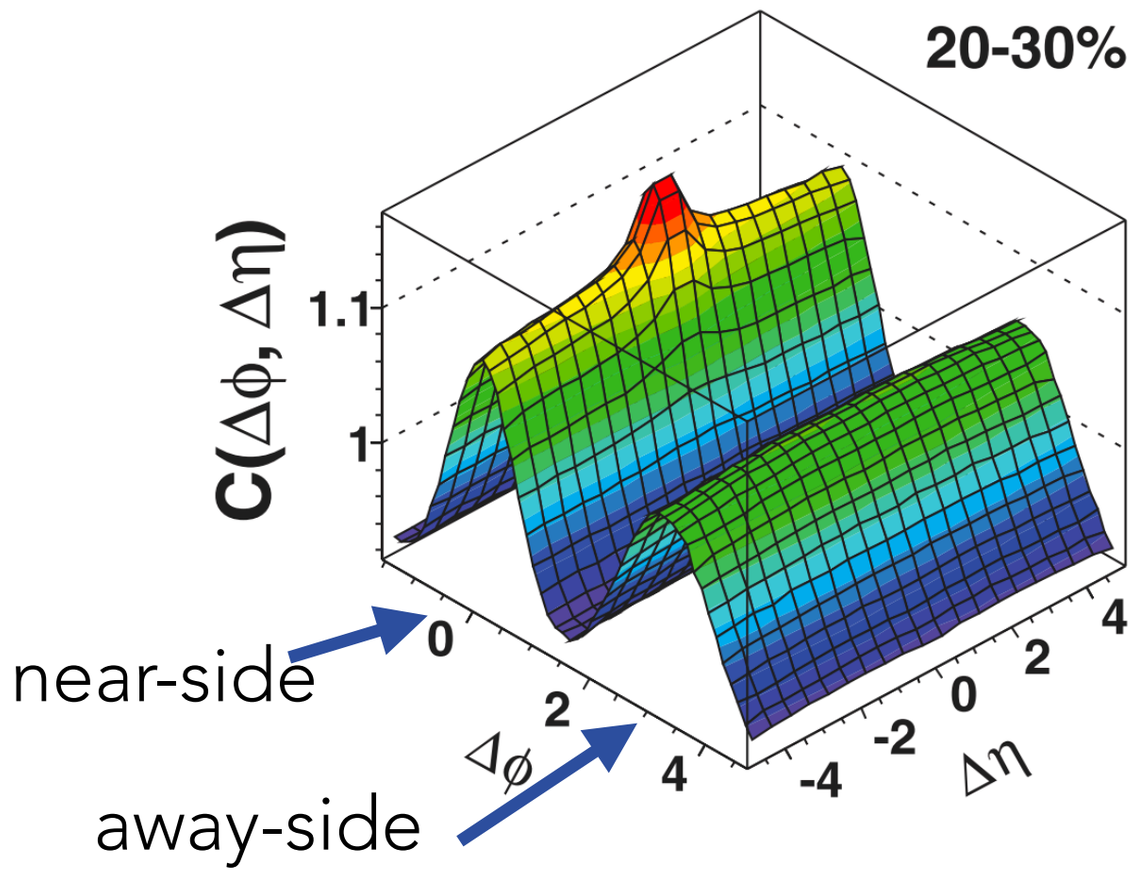
PRL 116, 132302 (2016)



HOW TO MEASURE FLOW

- Two-particle correlation function between particles with (φ_1, η_1) and (φ_2, η_2)

ATLAS, PRC 86, 014907 (2012)



$$\Delta\varphi = \varphi_1 - \varphi_2 \qquad \Delta\eta = \eta_1 - \eta_2$$

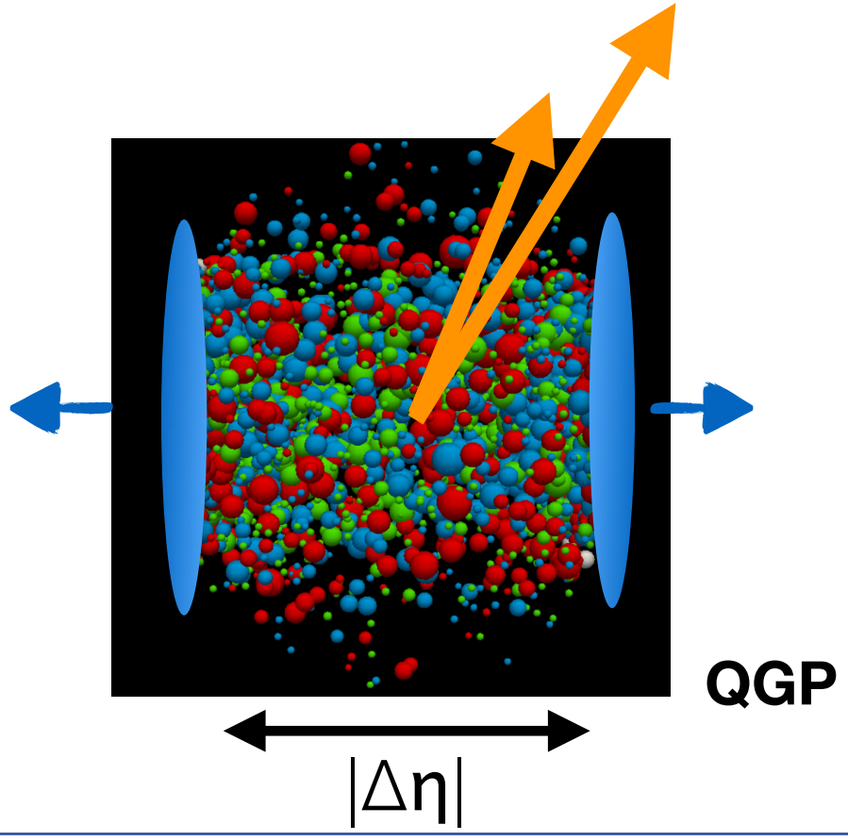
short range $\Delta\eta \approx 0$

long range $\Delta\eta \gg 0$

HOW TO MEASURE FLOW

- Two-particle correlation function between particles with (φ_1, η_1) and (φ_2, η_2)

- Jet peak: high-p_T resonances or jets



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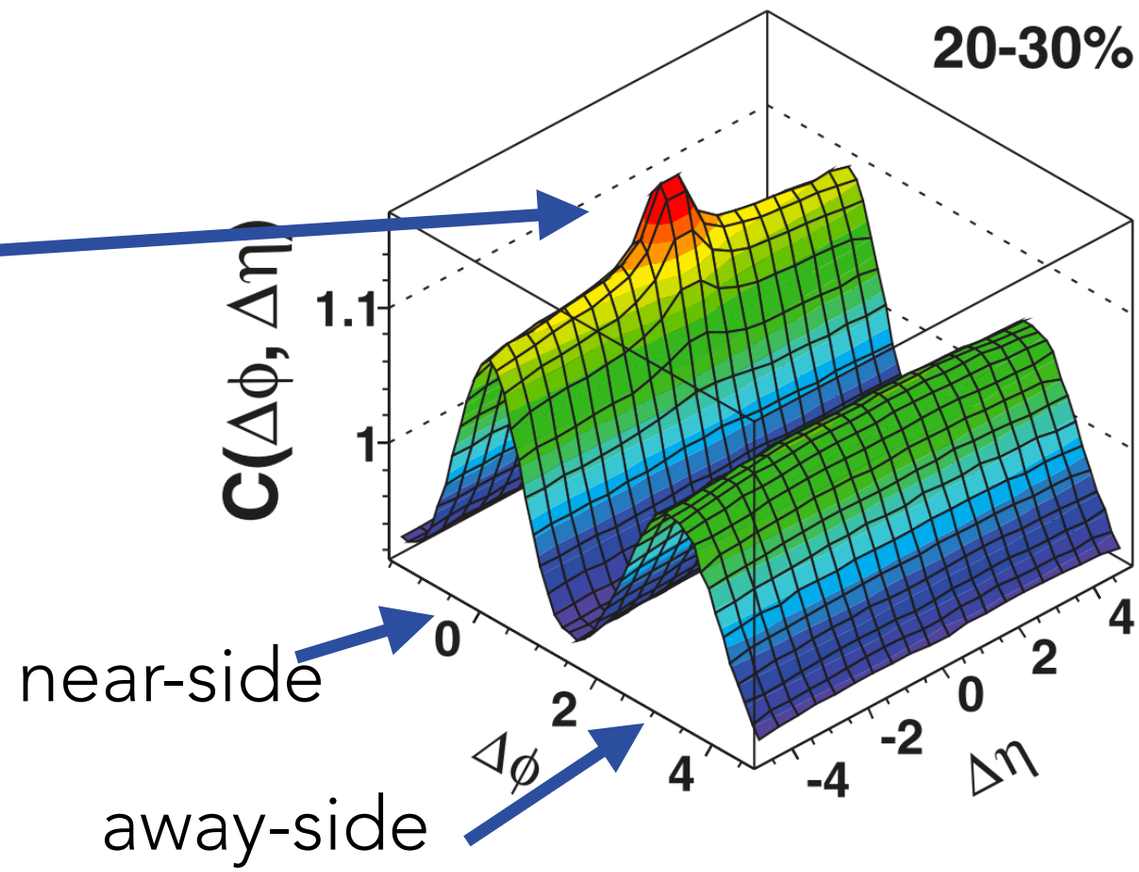

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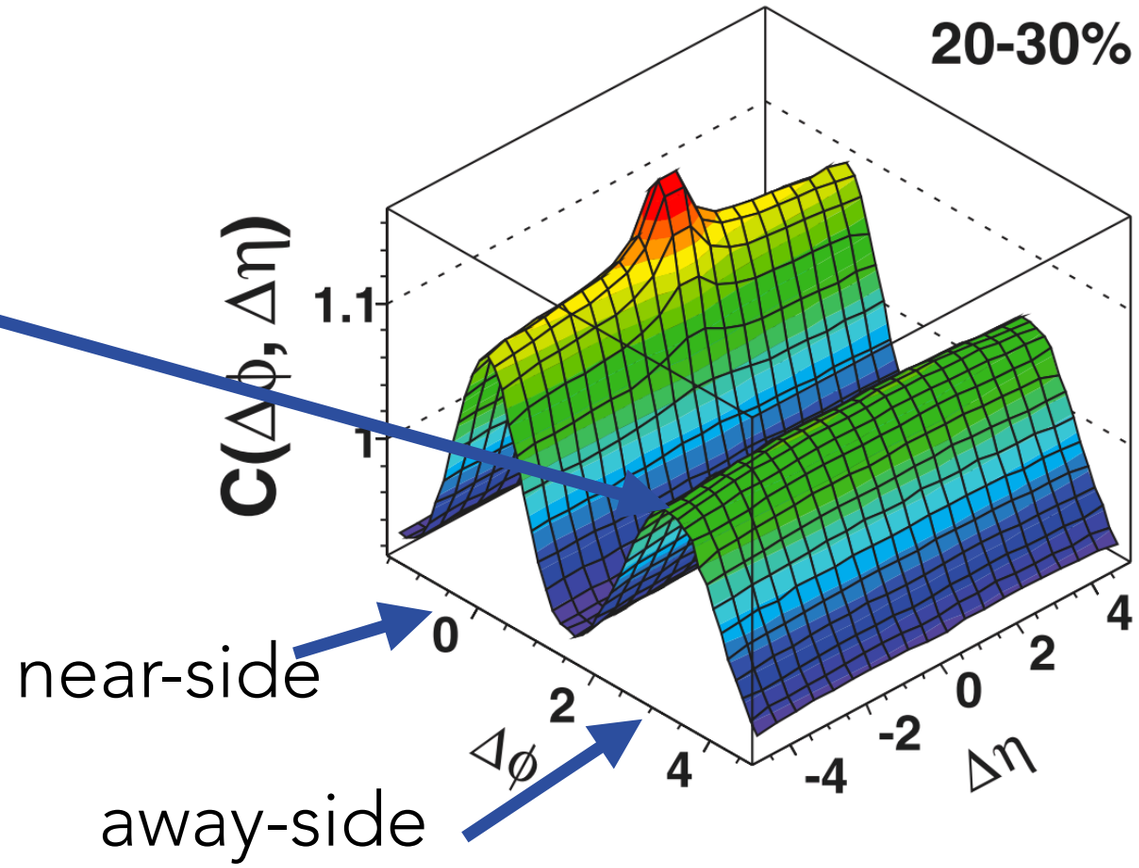
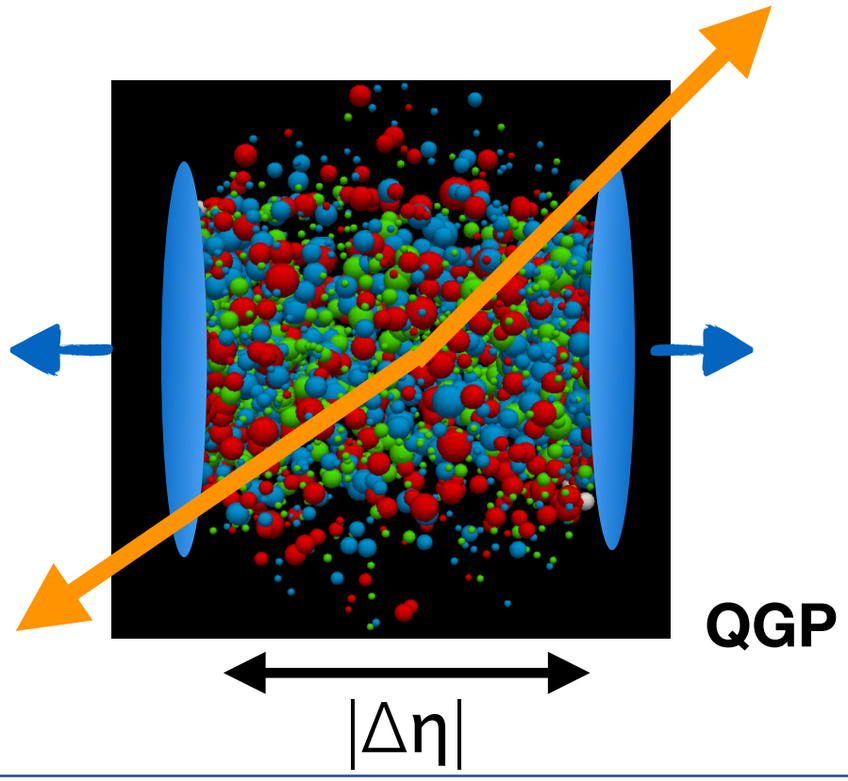
HOW TO MEASURE FLOW

- Two-particle correlation function between particles with (φ_1, η_1) and (φ_2, η_2)
- Away-side ridge: low p_T resonances or correlations between particles from the two cones of a jet

ATLAS, PRC 86, 014907 (2012)





$$\Delta\varphi = \varphi_1 - \varphi_2 \qquad \Delta\eta = \eta_1 - \eta_2$$

short range $\Delta\eta \approx 0$

long range $\Delta\eta \gg 0$

HOW TO MEASURE FLOW

- Two-particle correlation function between particles with (φ_1, η_1) and (φ_2, η_2)
- Away-side ridge: low p_T resonances or correlations between particles from the two cones of a jet

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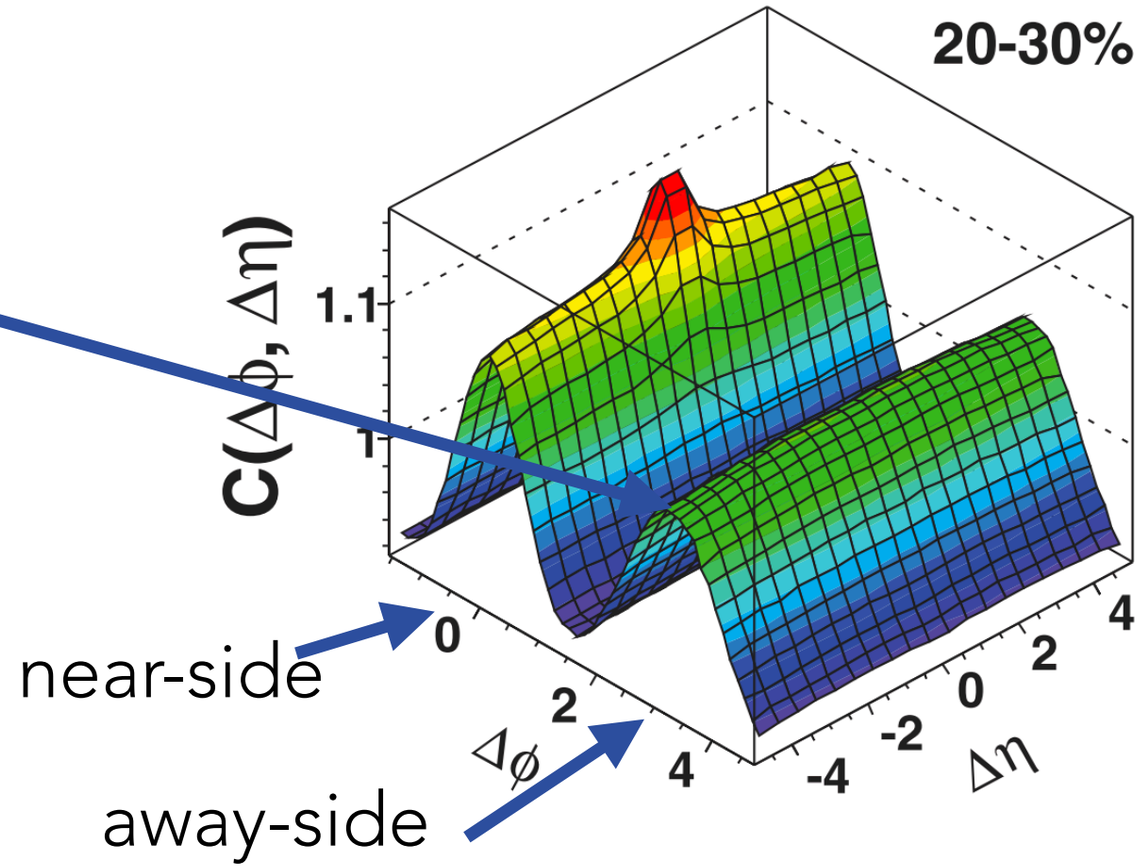

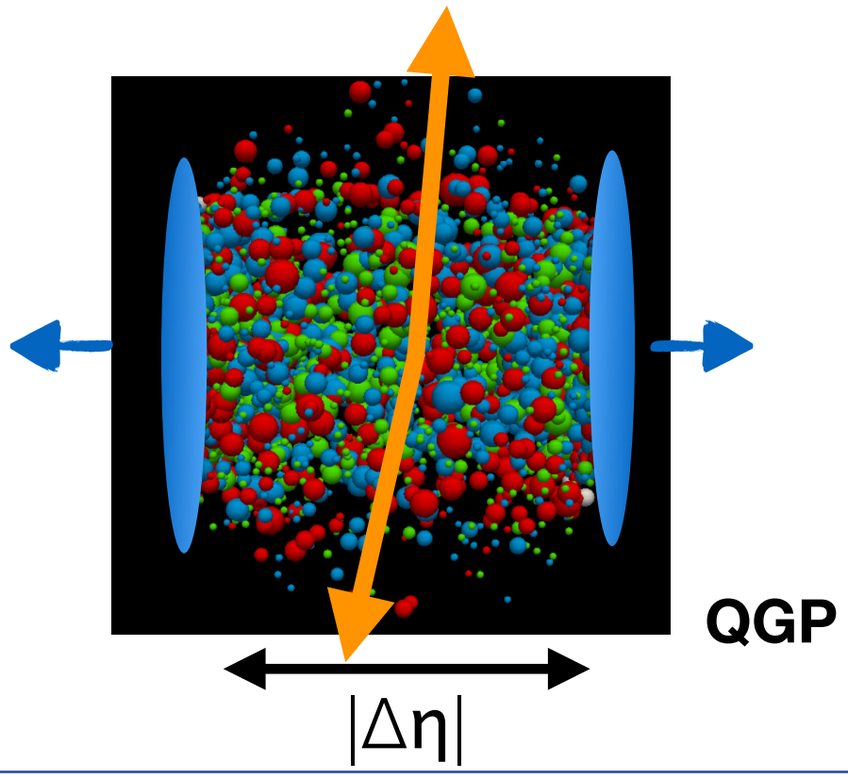

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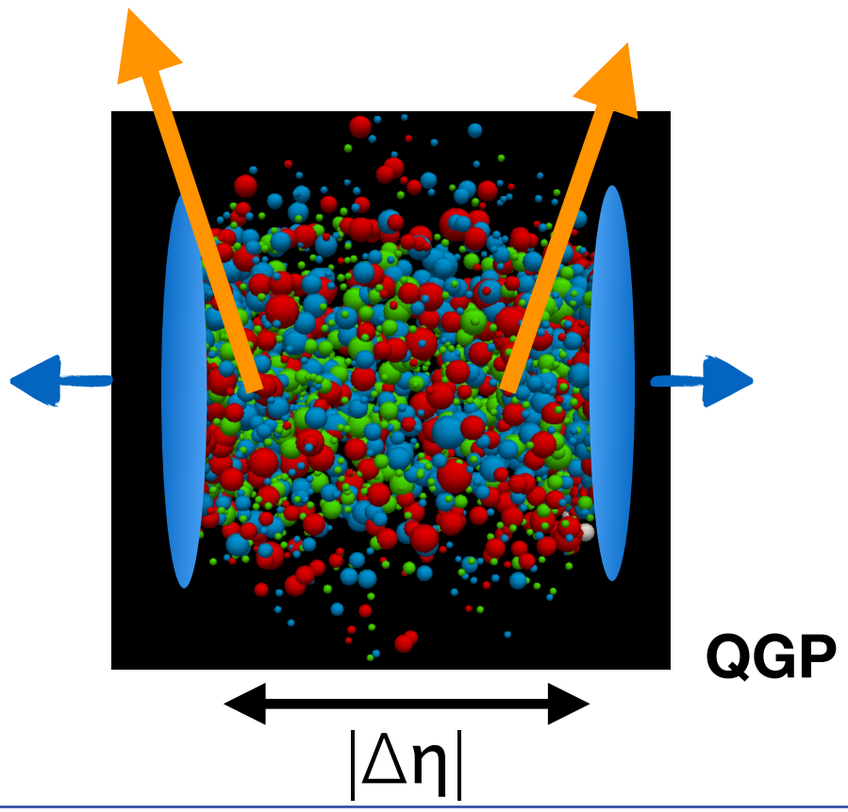
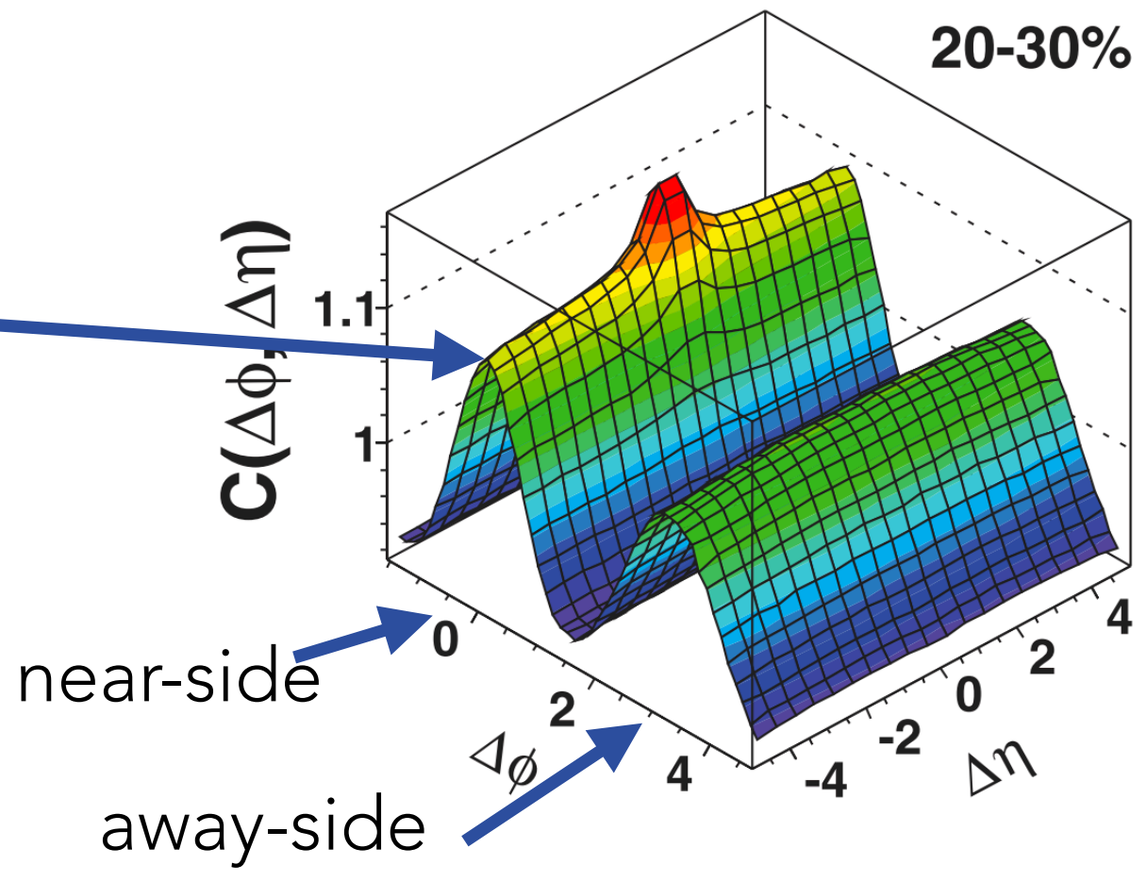


ATLAS, PRC 86, 014907 (2012)



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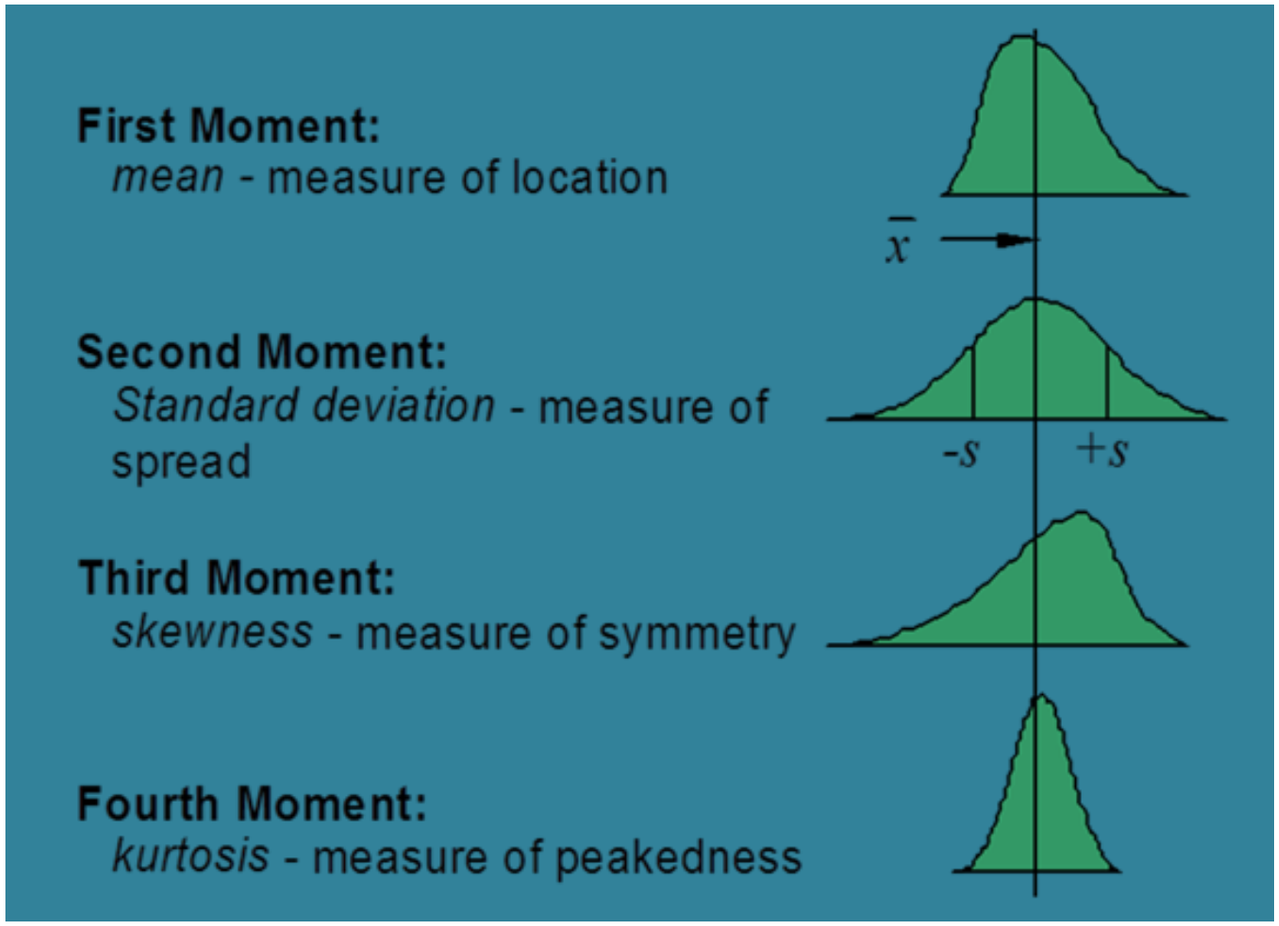
HOW TO MEASURE FLOW

- *m*-particle cumulants



- Moments of a distribution:
- Cumulants are similar (derived from moments)

- We measure cumulants of the flow distribution

HOW TO MEASURE FLOW

How to get flow coefficients (using cumulants)

1. multi-particle correlations
2. multi-particle cumulants
3. flow coefficients

HOW TO MEASURE FLOW

How to get flow coefficients (using cumulants)

1. multi-particle correlations

$$\langle\langle 2 \rangle\rangle = \langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle = \langle v_n^2 \rangle$$

average over particles in an event

average over all events

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average over all events

$$\langle\langle 4\rangle\rangle = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle = \langle v_n^4\rangle$$

- 4-particle correlation contains contribution from:

$$\langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle = \langle\langle 2\rangle\rangle^2$$
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HOW TO MEASURE FLOW

How to get flow coefficients (using cumulants)

1. multi-particle correlations
2. multi-particle cumulants

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

genuine 4-particle correlation

HOW TO MEASURE FLOW

How to get flow coefficients (using cumulants)

1. multi-particle correlations
2. multi-particle cumulants
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$$\sqrt{c_n\{2\}} = \sqrt{\langle\langle 2\rangle\rangle} \approx v_n \rightarrow \boxed{v_n\{2\}}$$

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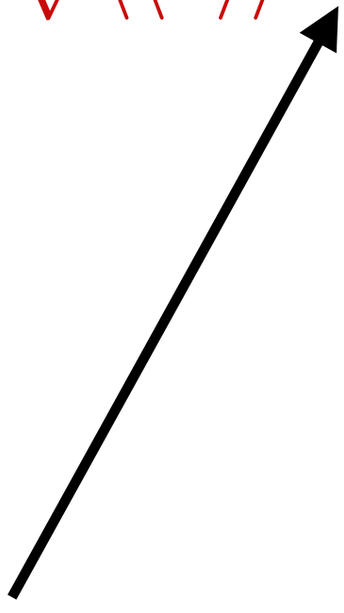

Equality is in ideal case of a delta function of v_n

HOW TO MEASURE FLOW

How to get flow coefficients (using cumulants)

1. multi-particle correlations
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$$\sqrt{c_n\{2\}} = \sqrt{\langle\langle 2\rangle\rangle} \approx v_n \rightarrow \boxed{v_n\{2\}}$$

$$\sqrt[4]{-c_n\{4\}} = \sqrt[4]{-\langle\langle 4\rangle\rangle + 2\cdot\langle\langle 2\rangle\rangle^2}$$

$$= \sqrt[4]{-v_n^4 + 2\cdot v_n^2} \approx v_n \rightarrow \boxed{v_n\{4\}}$$

Equality is in ideal case of a delta function of v_n

HOW TO MEASURE FLOW

How to get flow coefficients (using cumulants)

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$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[6]{1/4 \cdot c_n\{6\}}$$

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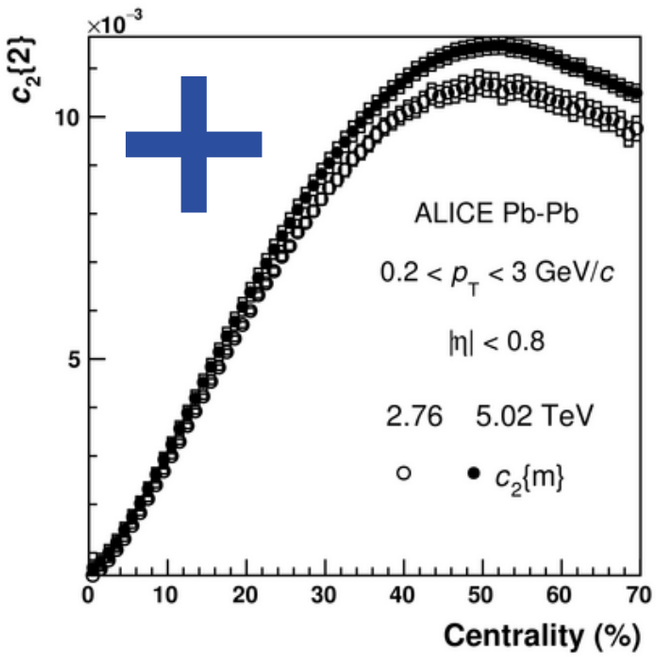
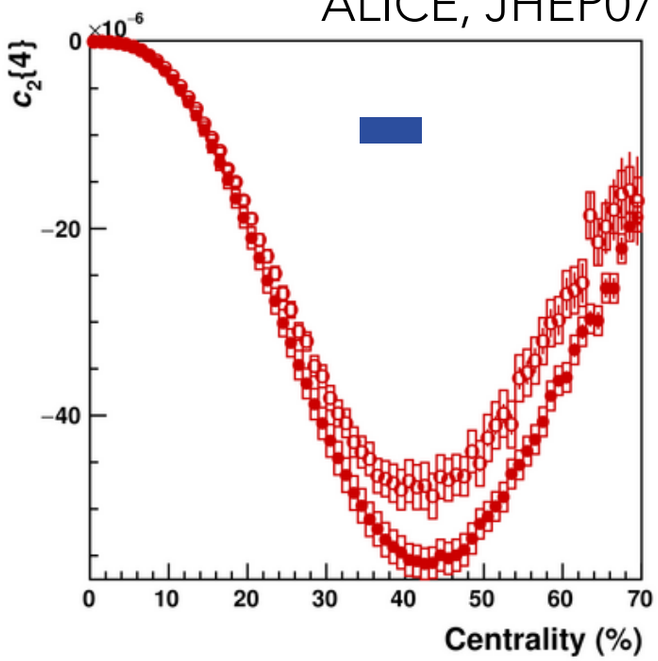
MEASUREMENTS OF FLOW
USING M-PARTICLE CUMULANTS

ALICE, JHEP07 (2018) 103





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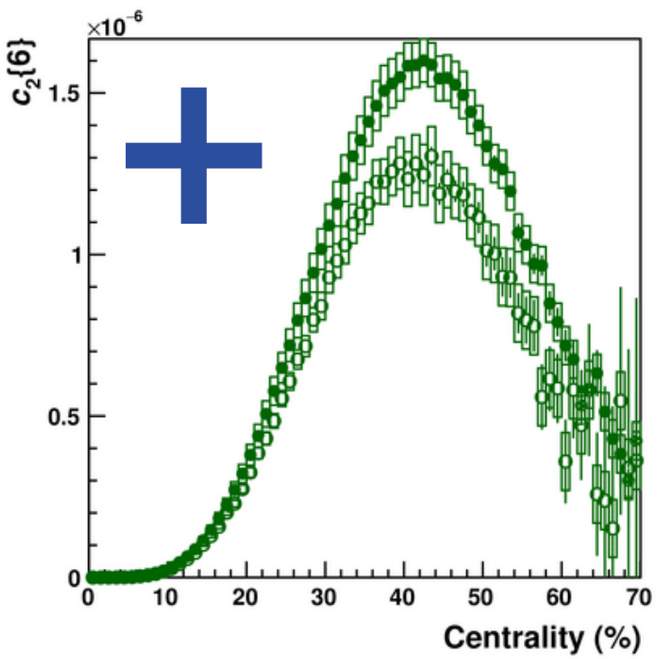

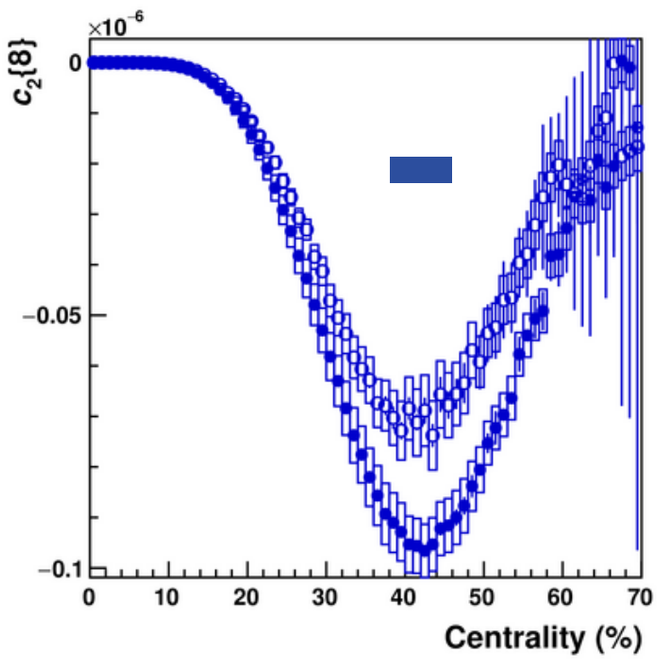

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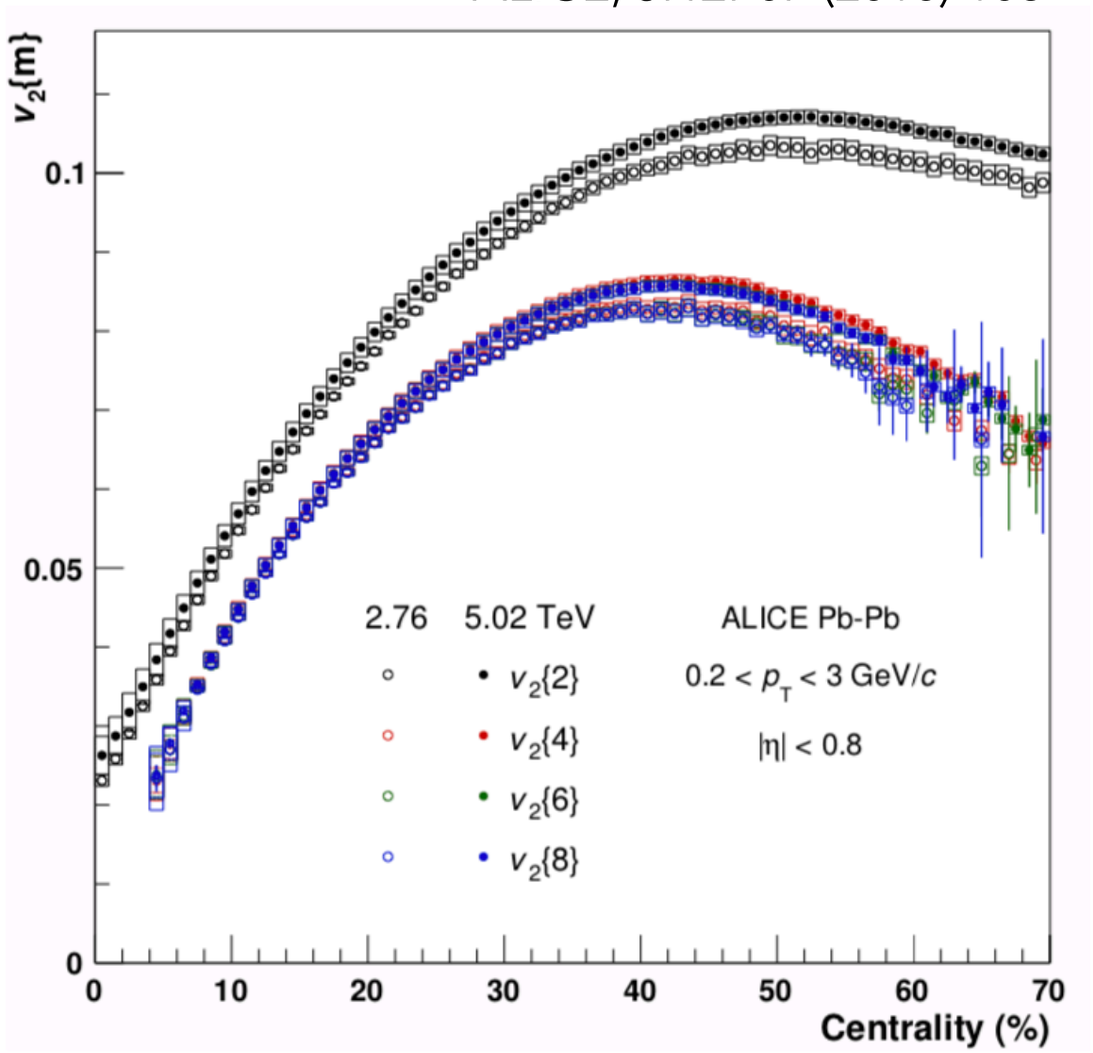
ALICE, JHEP07 (2018) 103



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MEASUREMENTS OF FLOW
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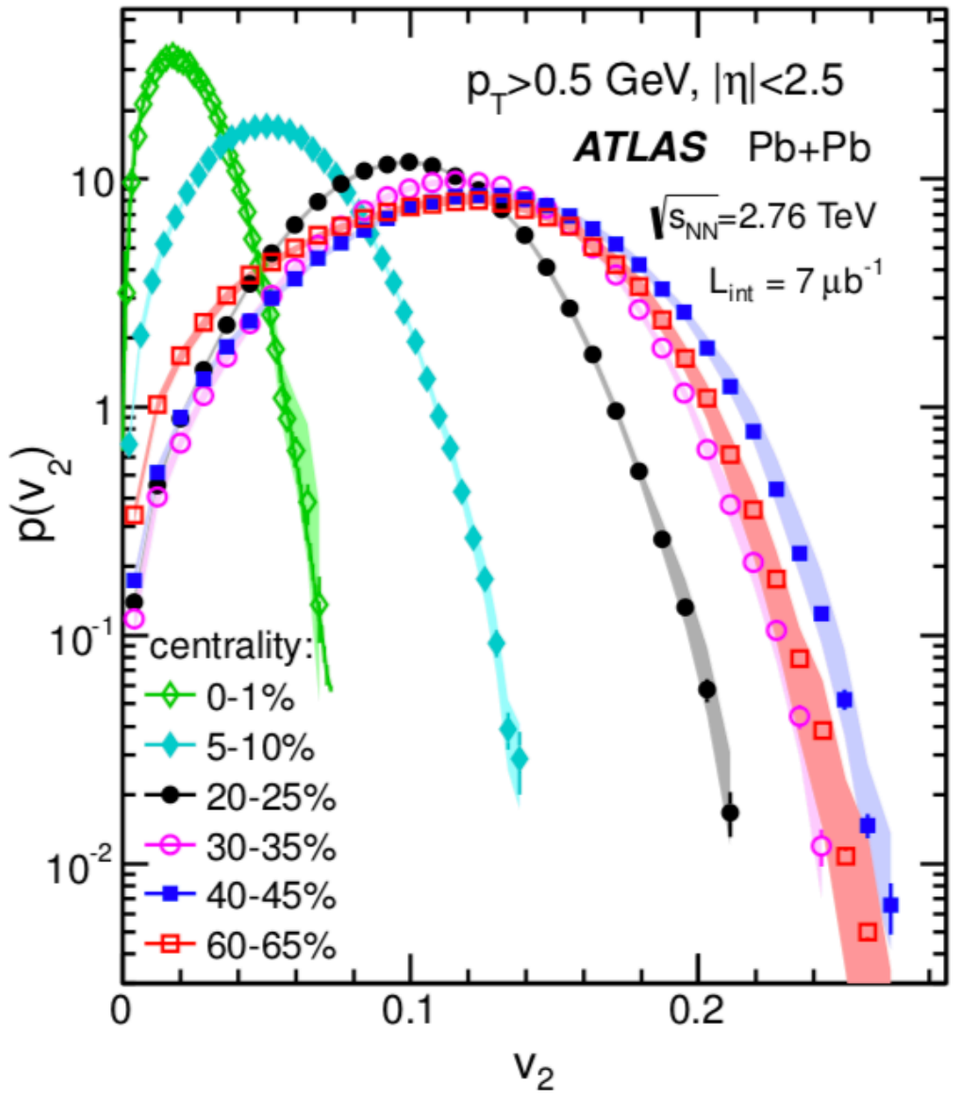
ATLAS, JHEP11 (2013) 183



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"DEFINITION" OF COLLECTIVITY

- Based on a collective system (heavy-ion collisions) we define:
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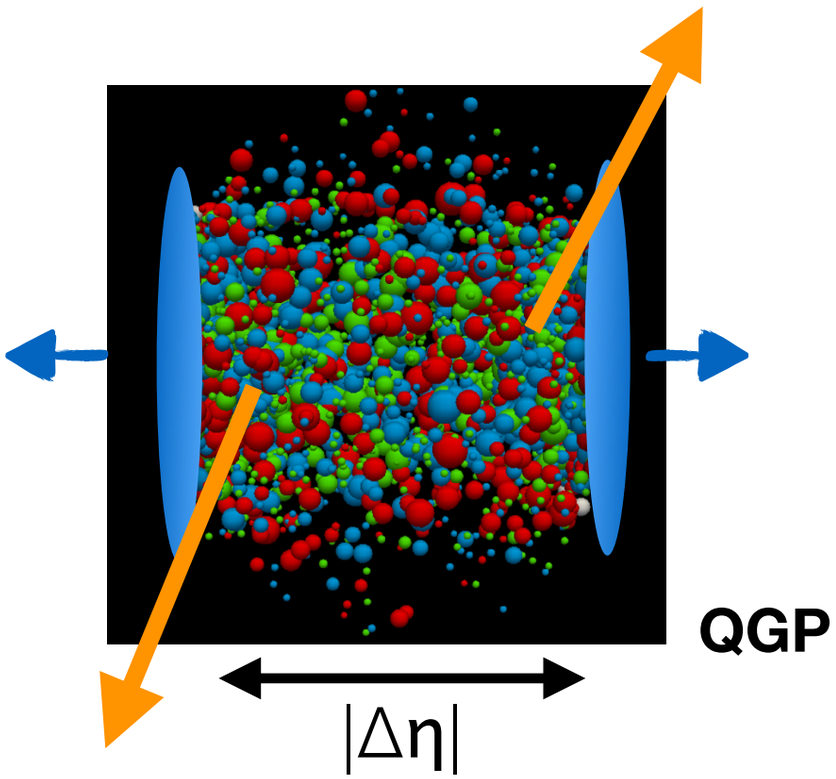
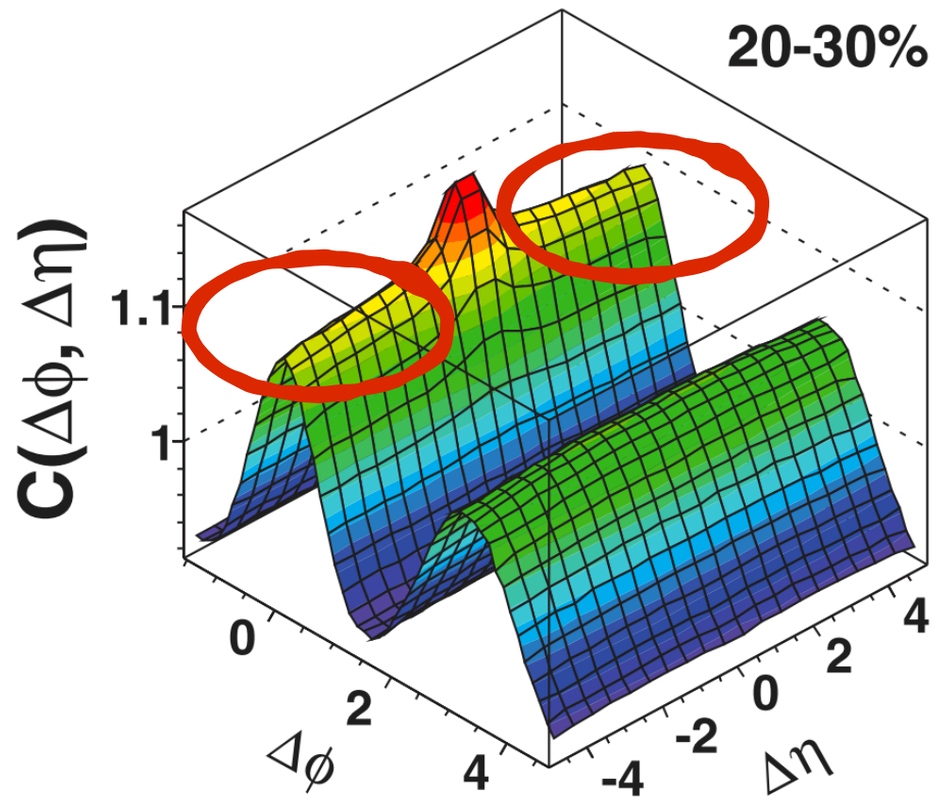


ATLAS, PRC 86, 014907 (2012)



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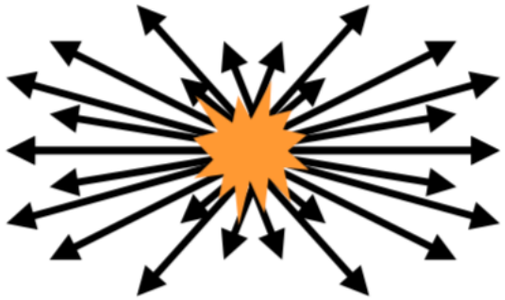
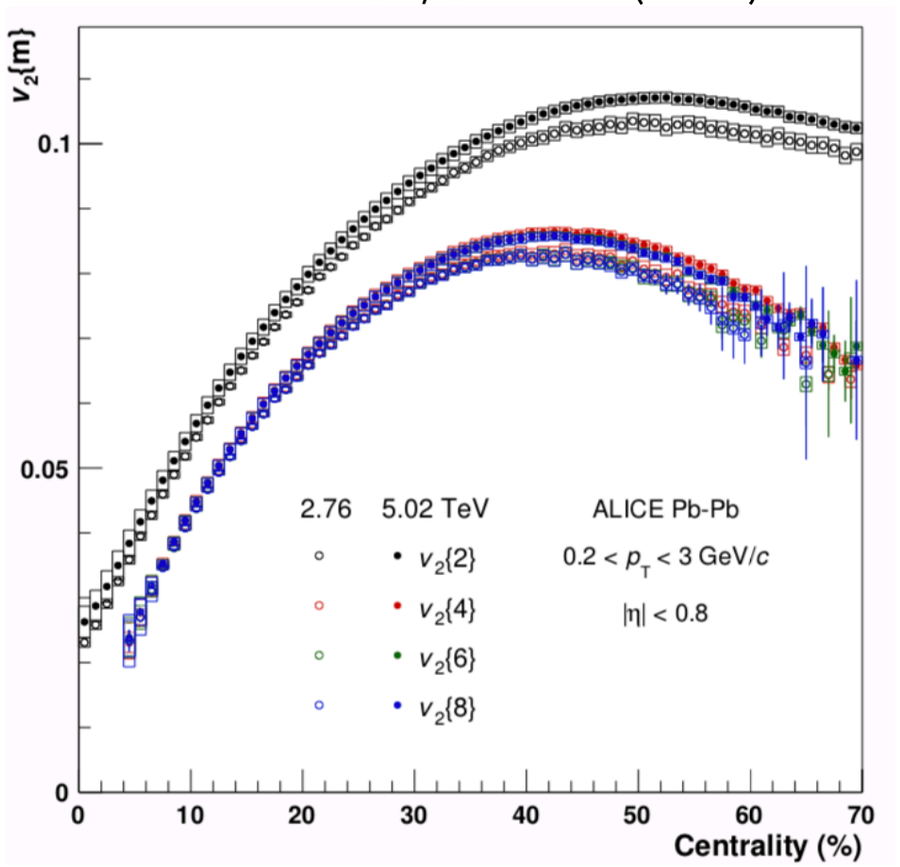


All particles originate from a common source

ALICE, JHEP07 (2018) 103

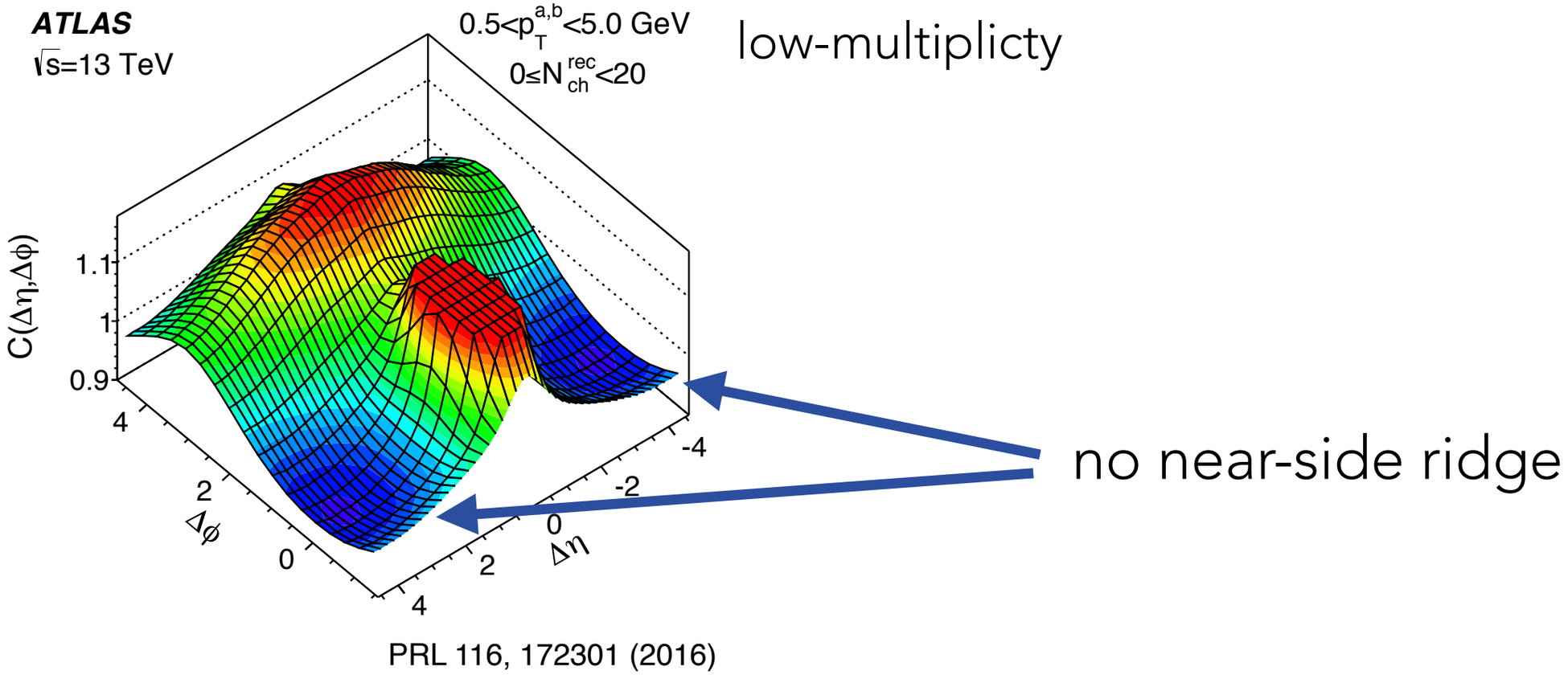


"correct" sign of cumulants

$$v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$$

SMALL COLLISION SYSTEMS

- Original understanding:
  - No QGP is formed in small systems
  - pp collisions: reference for measurements from HI collisions
  - p-Pb collisions: Cold Nuclear Matter effects



PRL 116, 172301 (2016)

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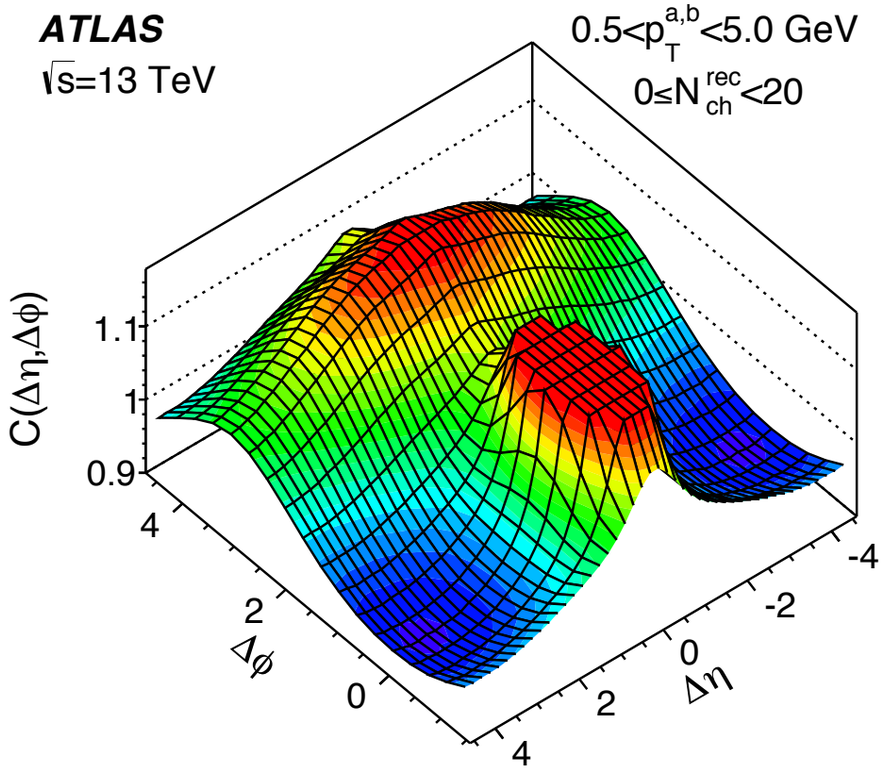

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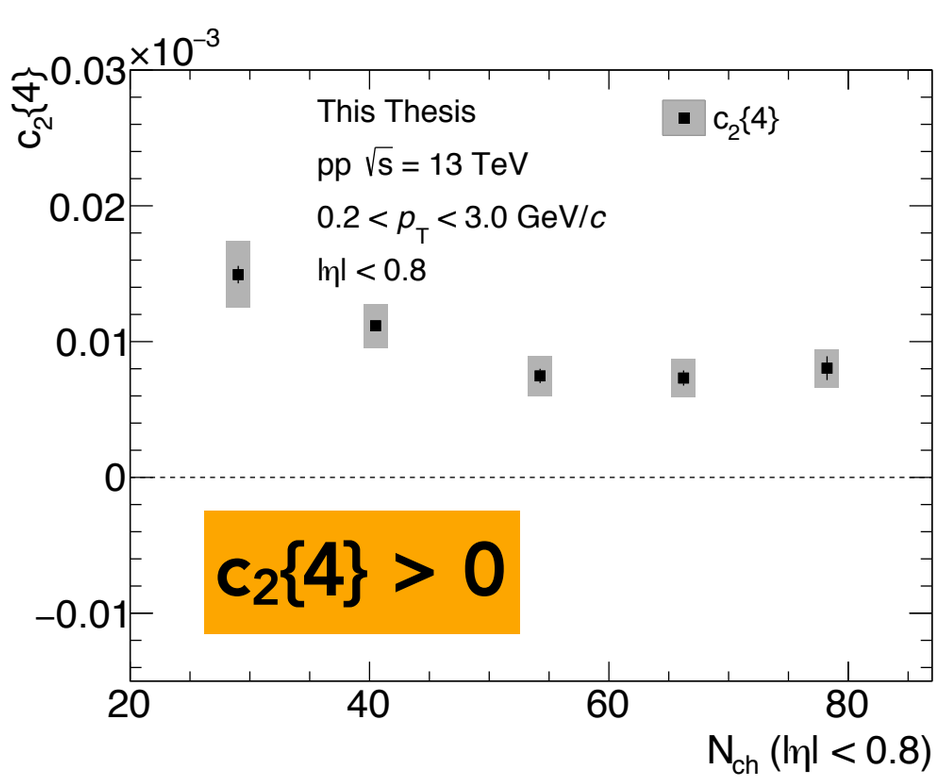

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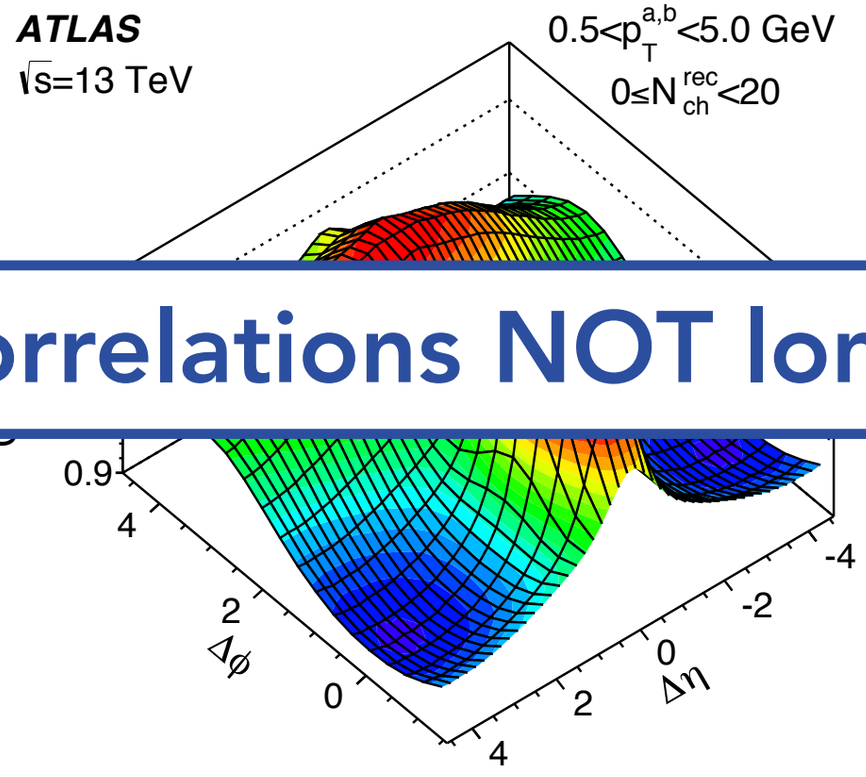

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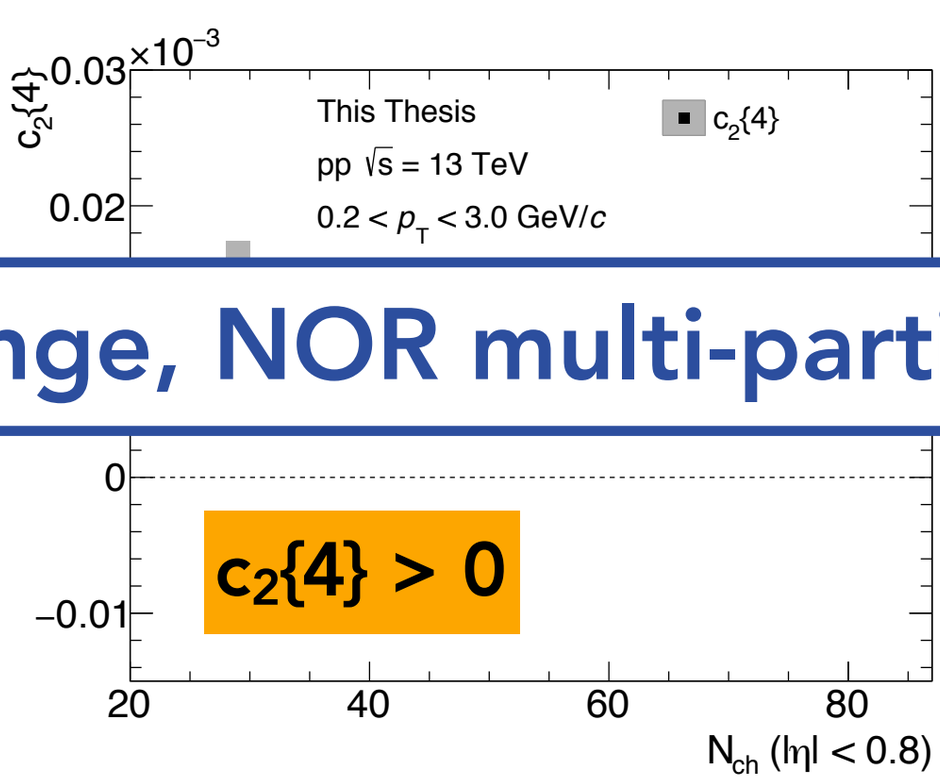
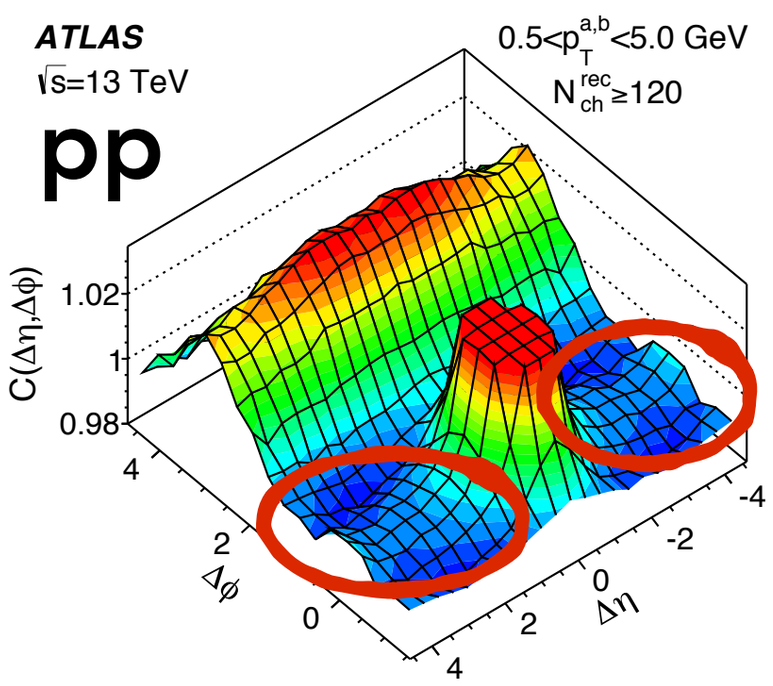


correlations NOT long-range, NOR multi-particle

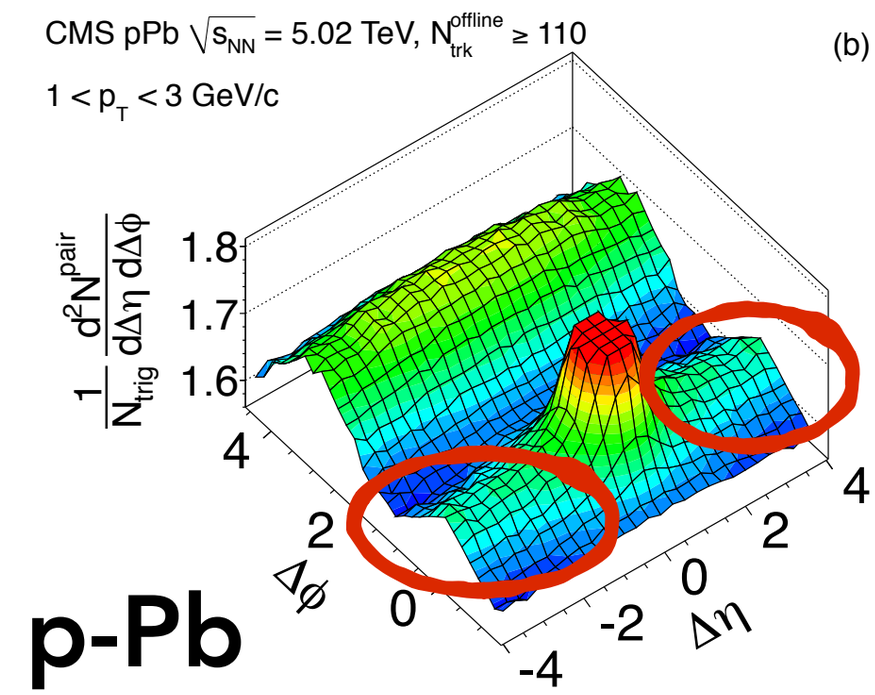
SMALL COLLISION SYSTEMS

- Surprise:
  - near-side ridge is observed at high-multiplicity pp and p-Pb collisions

high-multiplicity collisions



ATLAS, PRL 116, 172301 (2016)



ATLAS, PLB 718, 795 (2013)

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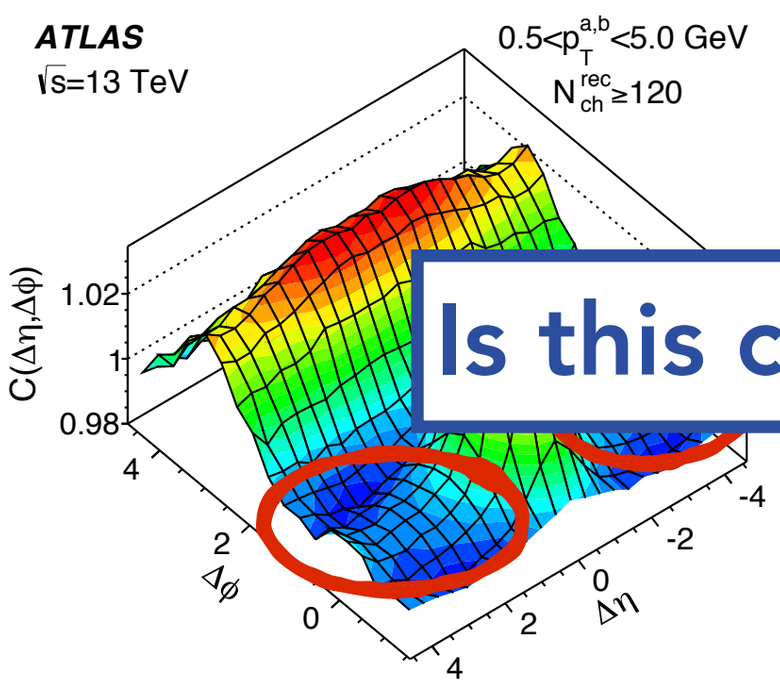
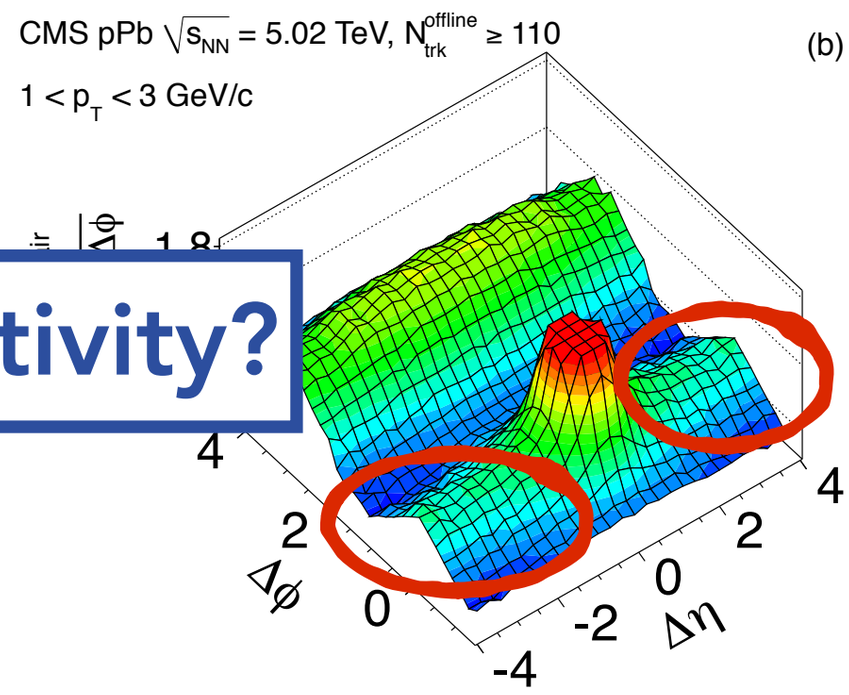


ATLAS, PRL 116, 172301 (2016)



ATLAS, PLB 718, 795 (2013)

Is this collectivity?

4-PARTICLE CUMULANT

- REMINDER: **Collectivity** = long-range multi-particle correlations
- What about multi-particle cumulants (m>2) ?

4-PARTICLE CUMULANT

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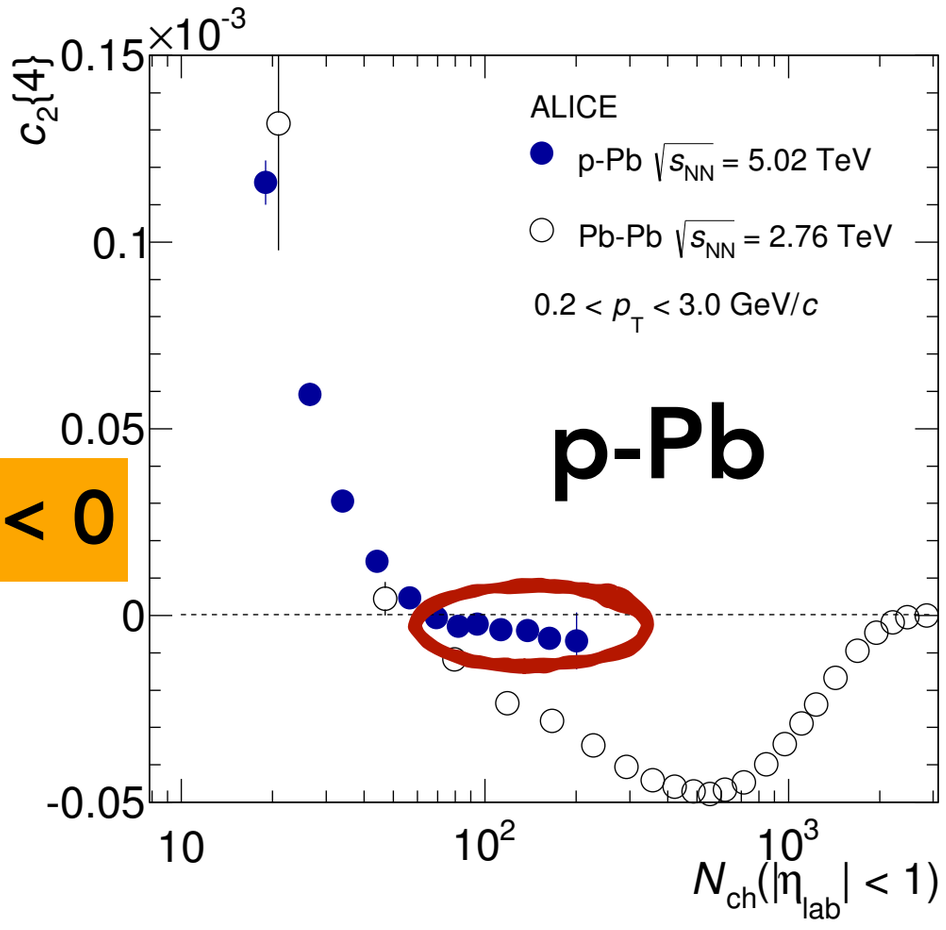

$c_2\{4\} < 0$

- Hint of collectivity in p-Pb collisions

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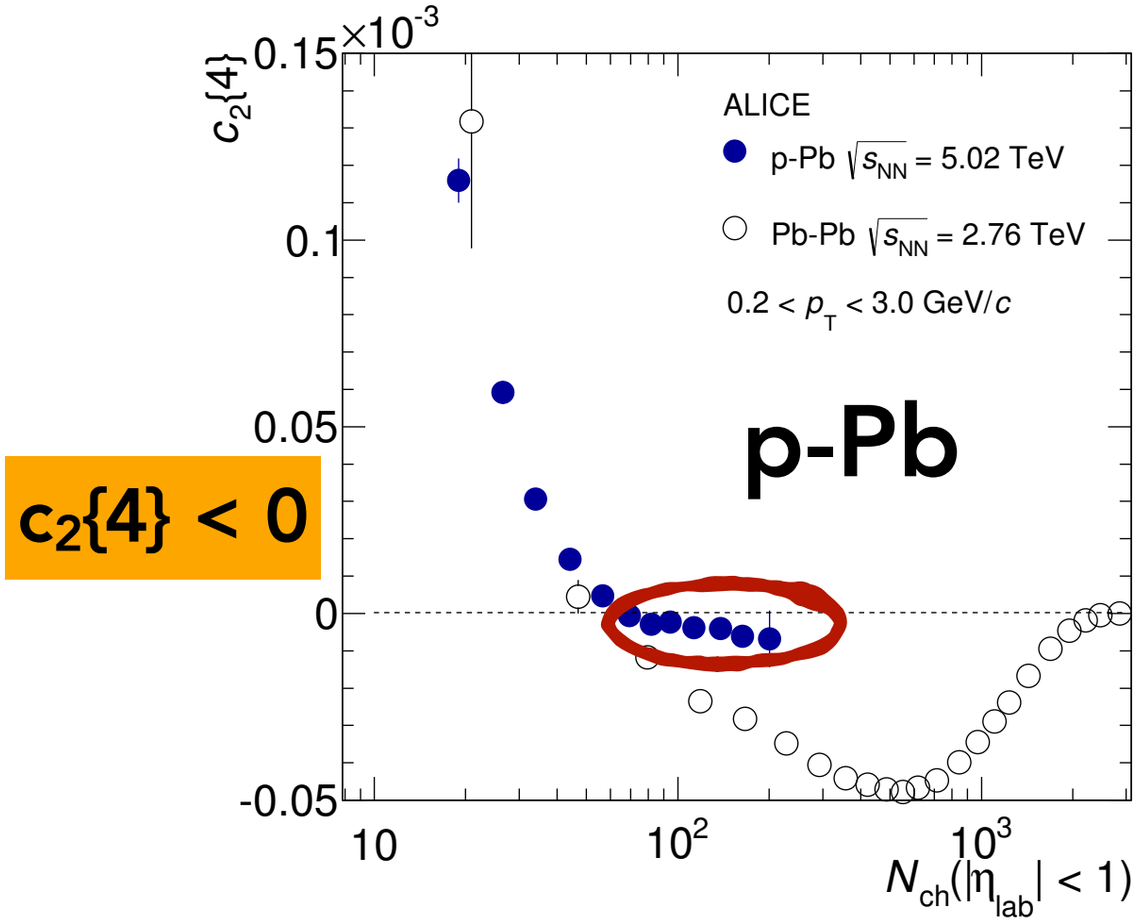
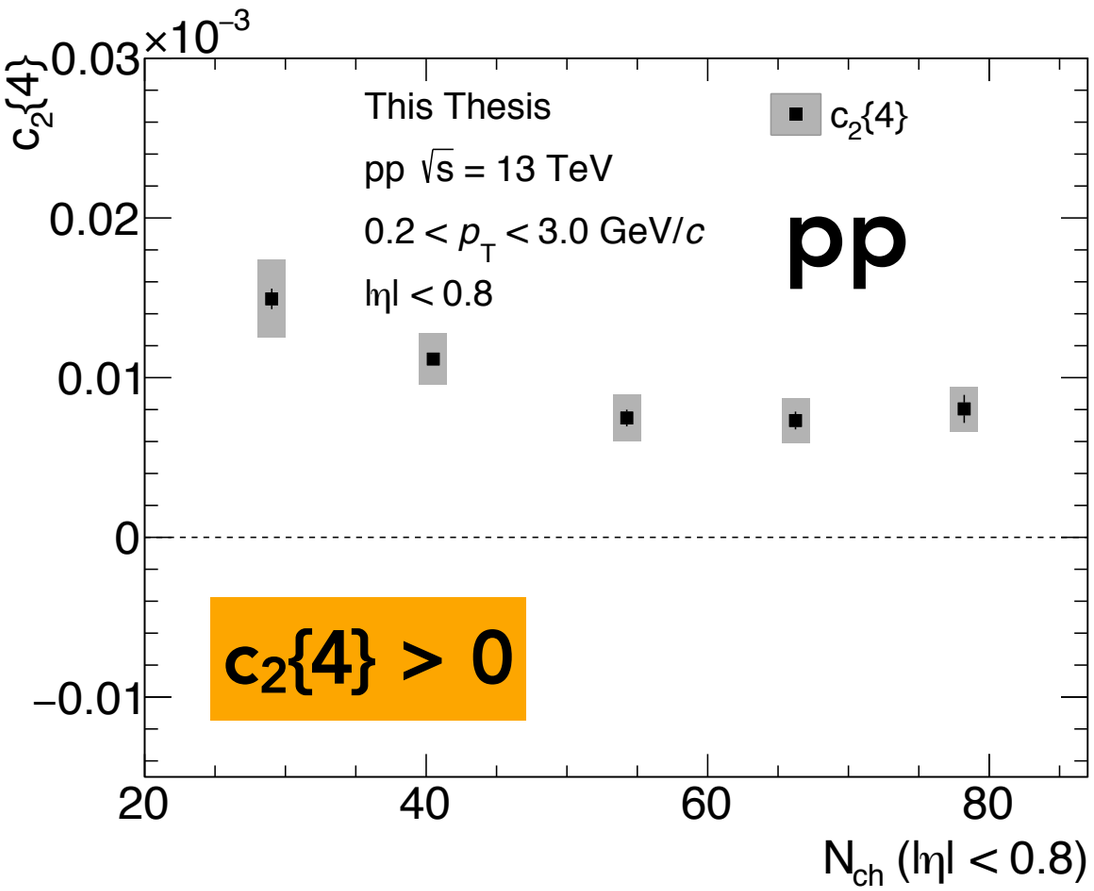


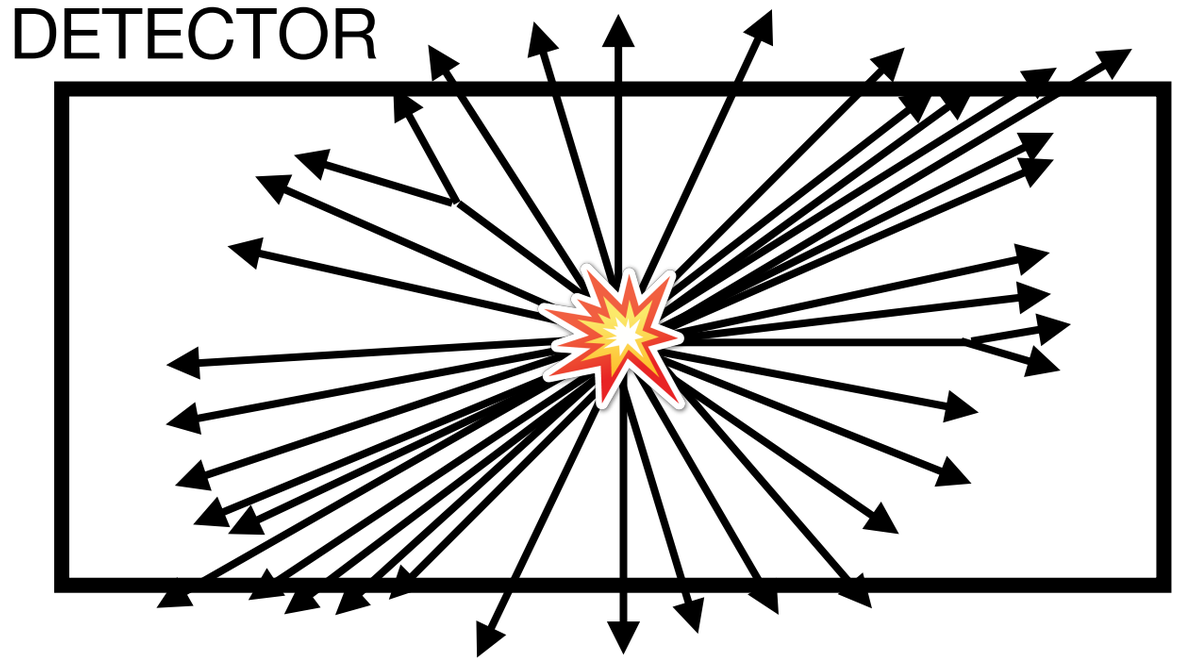


- Hint of collectivity in p-Pb collisions

$c_2\{4\} < 0 \Rightarrow$ collectivity

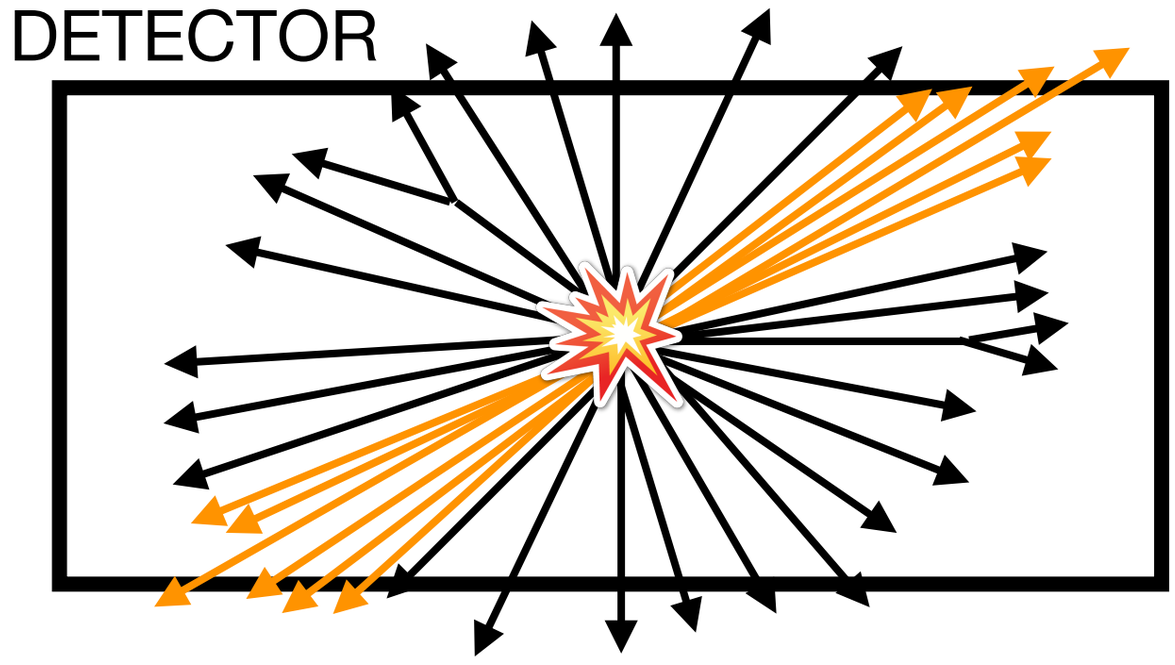
$c_2\{4\} > 0 \not\Rightarrow$ collectivity

NON-FLOW EFFECTS



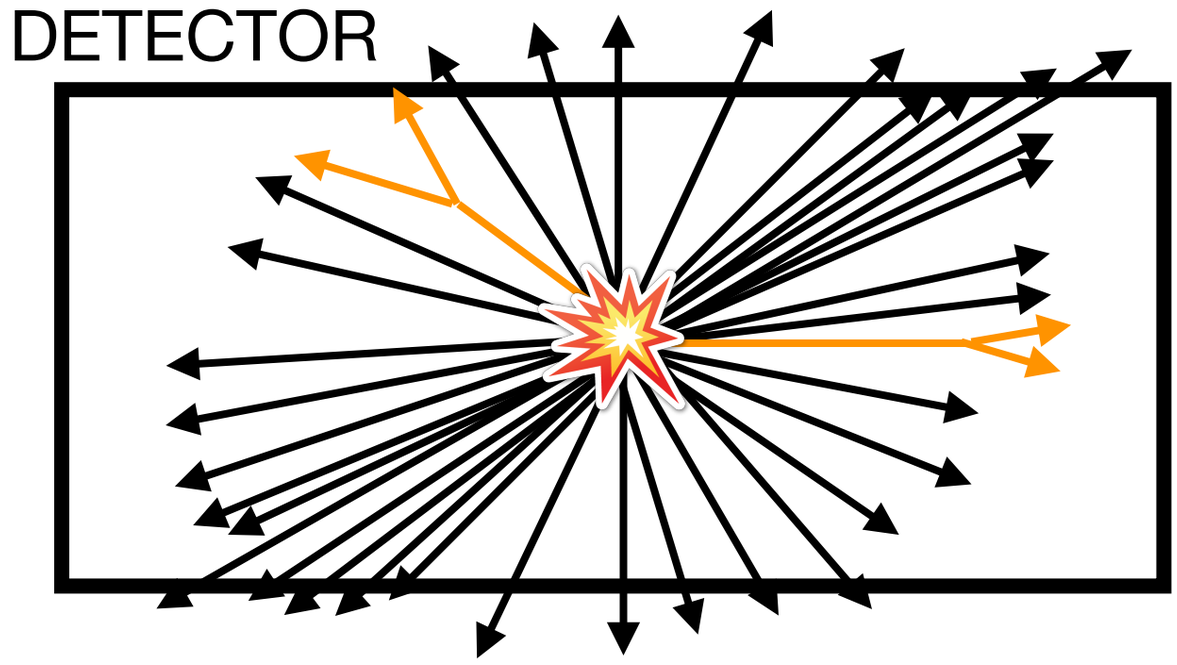
- Correlations not associated with the global symmetry plane Ψ_n

NON-FLOW EFFECTS



- Correlations not associated with the global symmetry plane Ψ_n
- Jets: correlations between particles within a jet cone
  correlations between particles from opposite cones

NON-FLOW EFFECTS

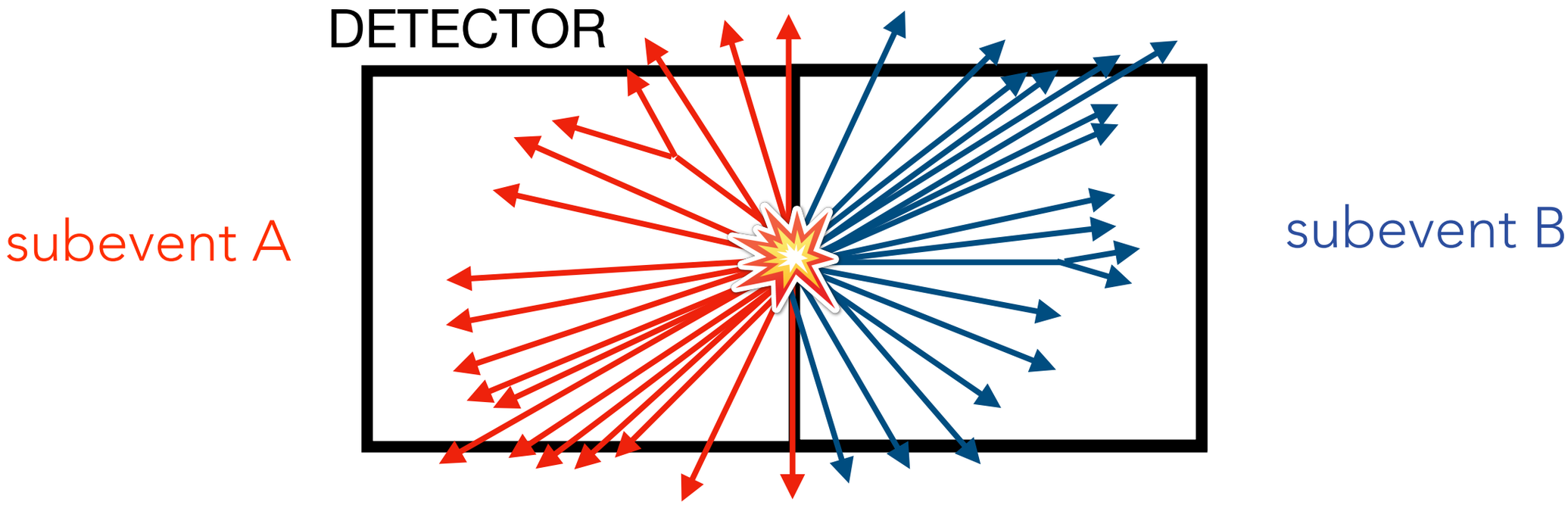


- Correlations not associated with the global symmetry plane Ψ_n
- Jets: correlations between particles within a jet cone
  correlations between particles from opposite cones
- Resonance decays: correlations between the decay products

NON-FLOW EFFECTS

- Subevent method: suppresses such non-flow effects
  - Spatial separation between particles that are being correlated

NON-FLOW EFFECTS



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- 2-subevent method:
  - Suppresses resonance decays and correlations within a jet cone

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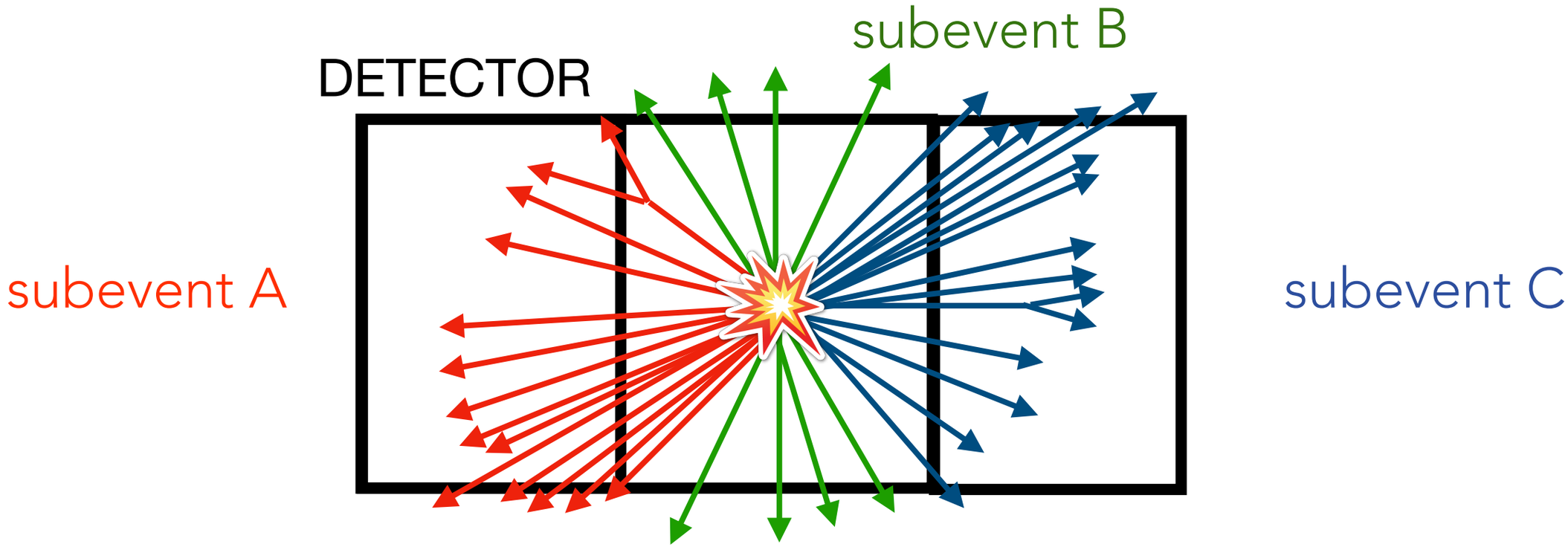

- Subevent method: suppresses such non-flow effects
  - Spatial separation between particles that are being correlated
- 2-subevent method:
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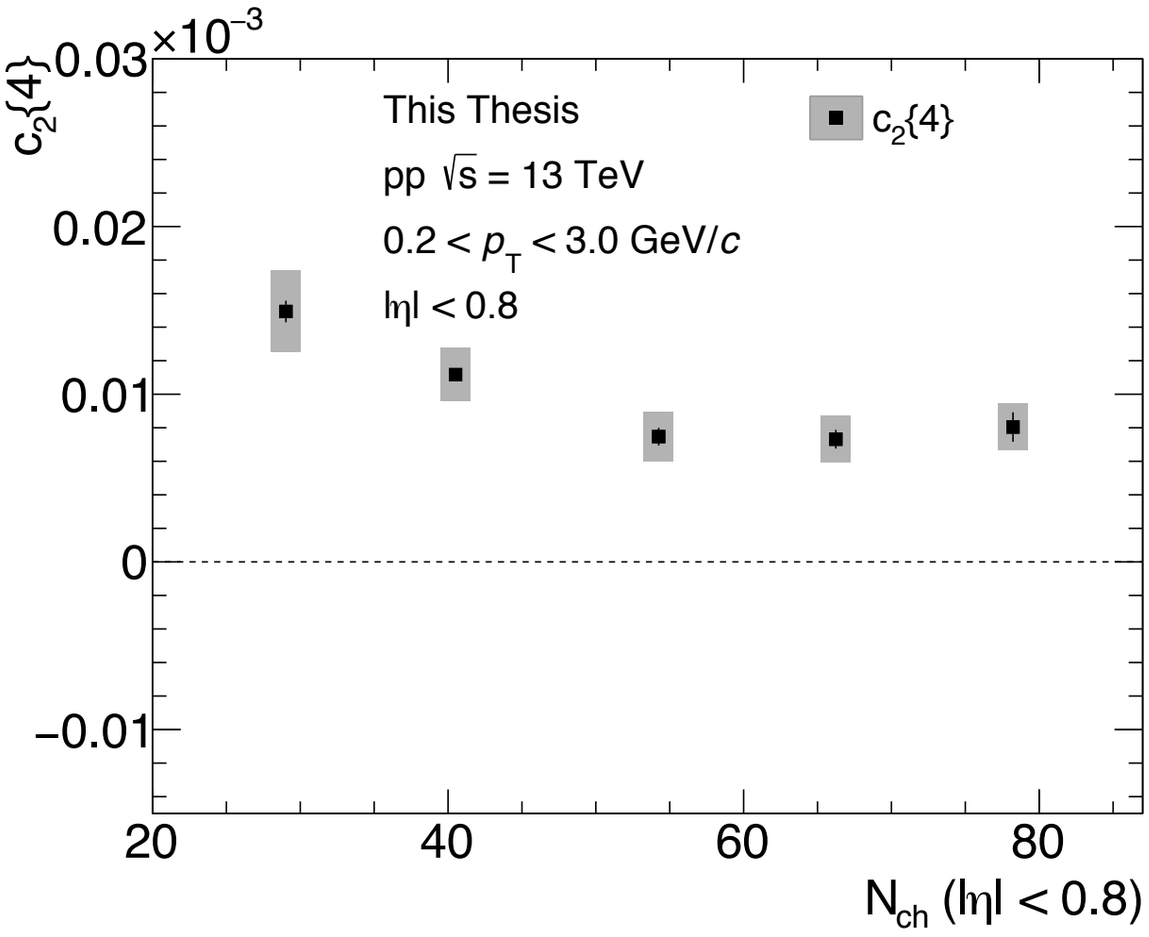
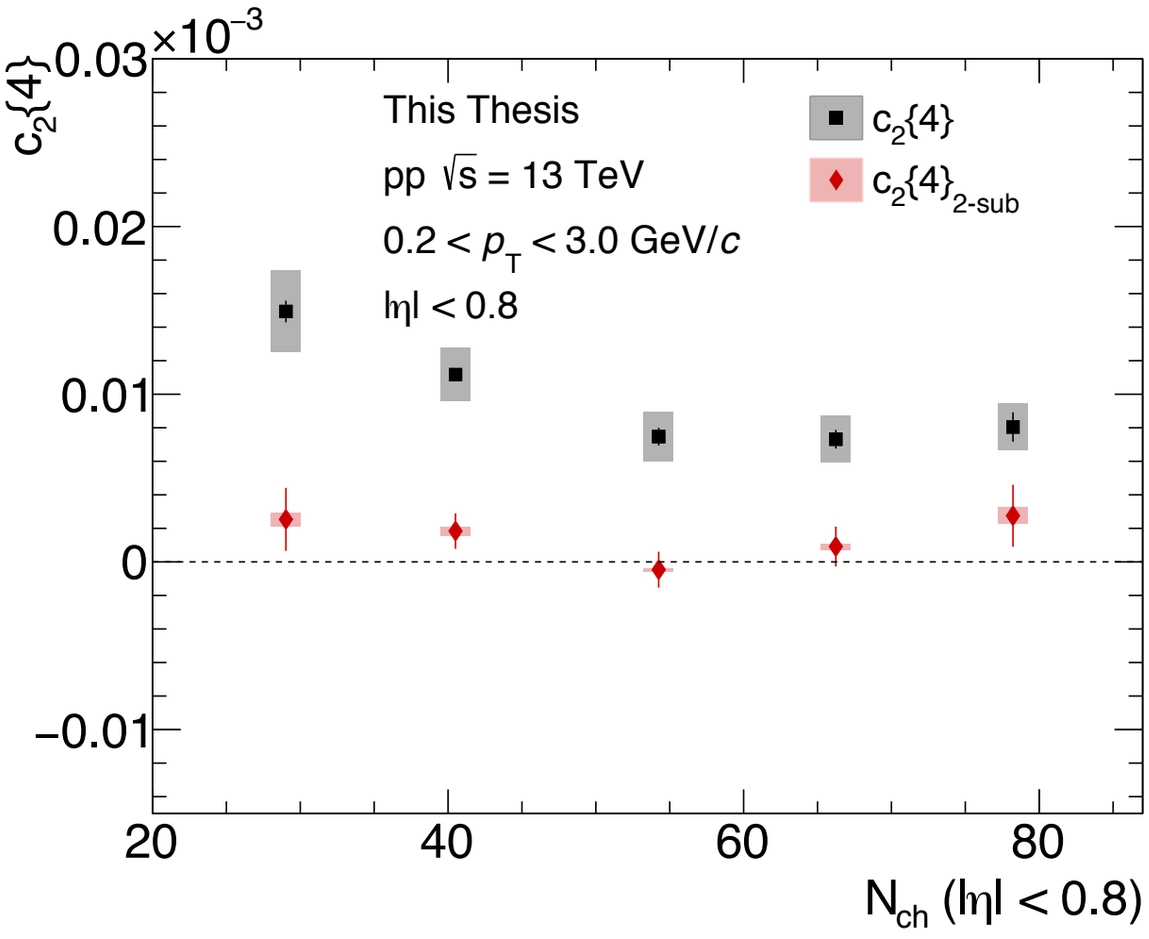
- 3-subevent method:
  - In addition suppresses correlations between jet cones

4-PARTICLE CUMULANT IN PP COLLISIONS

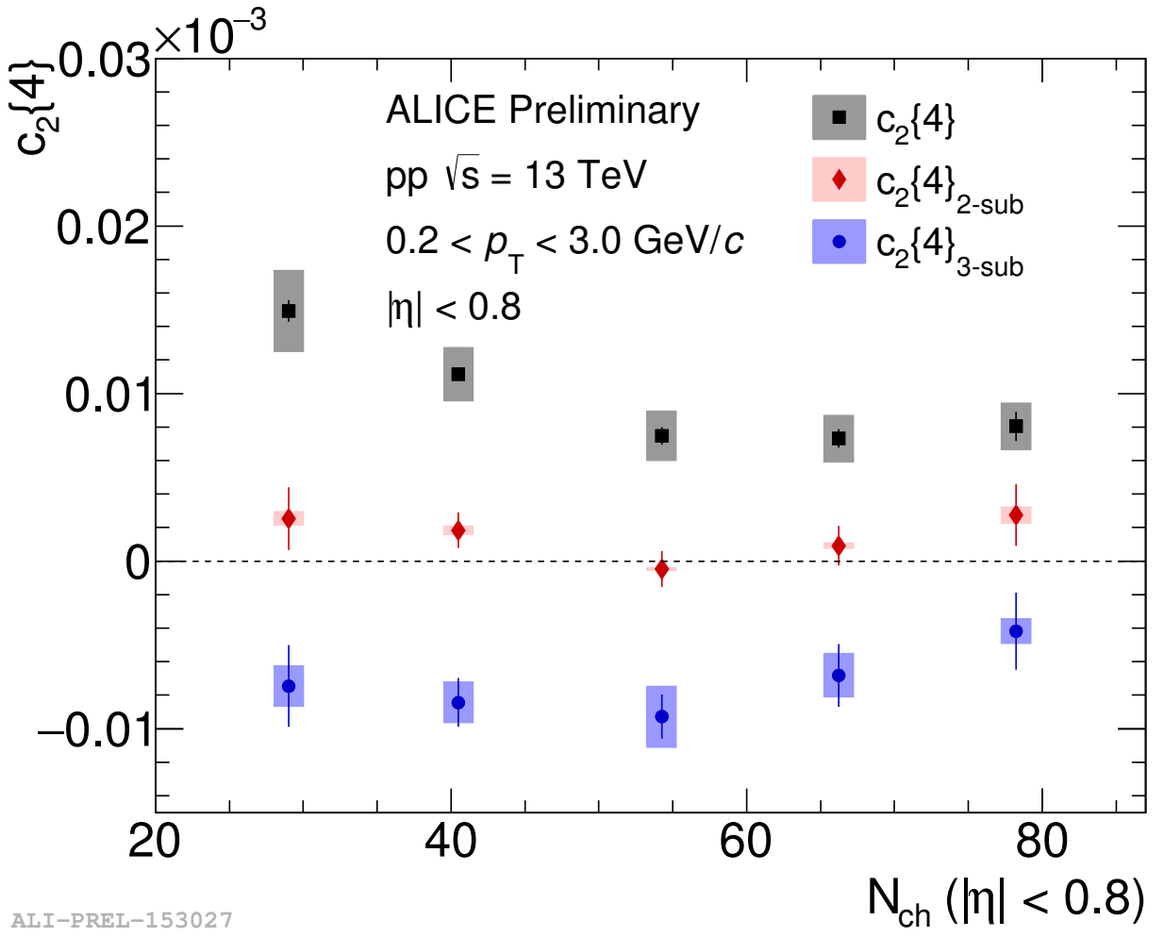


4-PARTICLE CUMULANT IN PP COLLISIONS



4-PARTICLE CUMULANT IN PP COLLISIONS

- Negative $c_2\{4\}$!
- Indication of collectivity also in pp collisions



WHAT NOW?

- The presence of collectivity doesn’t necessarily mean presence of the QGP
- Next step: Investigation of the origin of collectivity in small systems by comparison to models