Studies of three-particle correlations and reaction-plane correlators from STAR

Prithwish Tribedy

(for the STAR Collaboration)

BROOKHAVEN NATIONAL LABORATORY

XLVI International Symposium on Multiparticle Dynamics (ISMD2016)

Jeju island, South Korea August 29 – September 2, 2016

STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

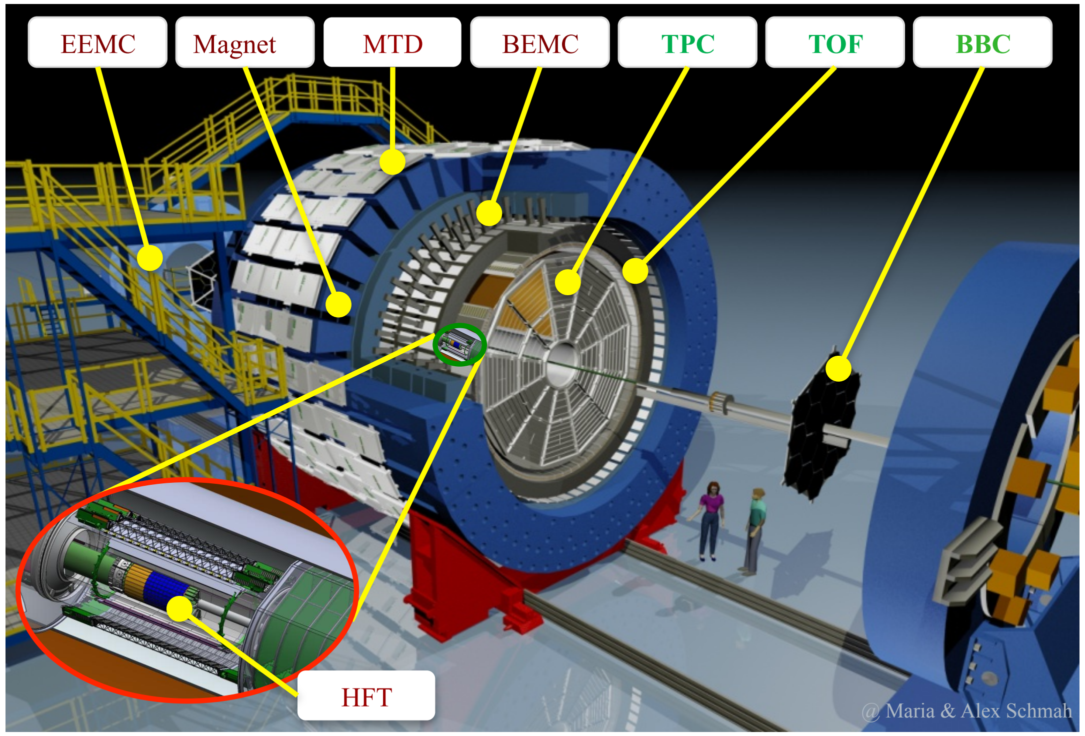
- Introduction
- Measurement of 3-particle correlations from STAR
- Comparison to models & possible interpretations

Goal is to :

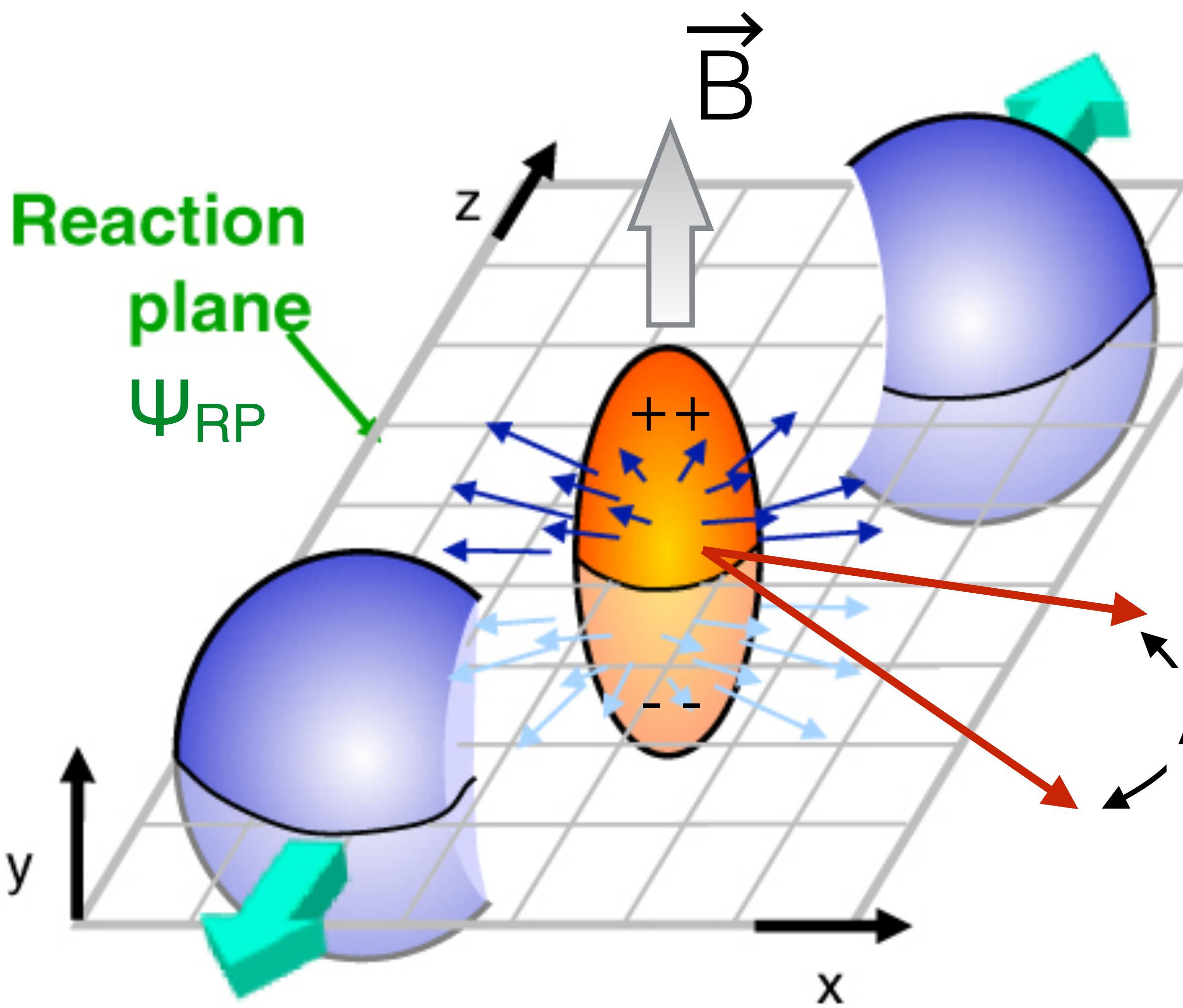
Map out 3D structure of HIC

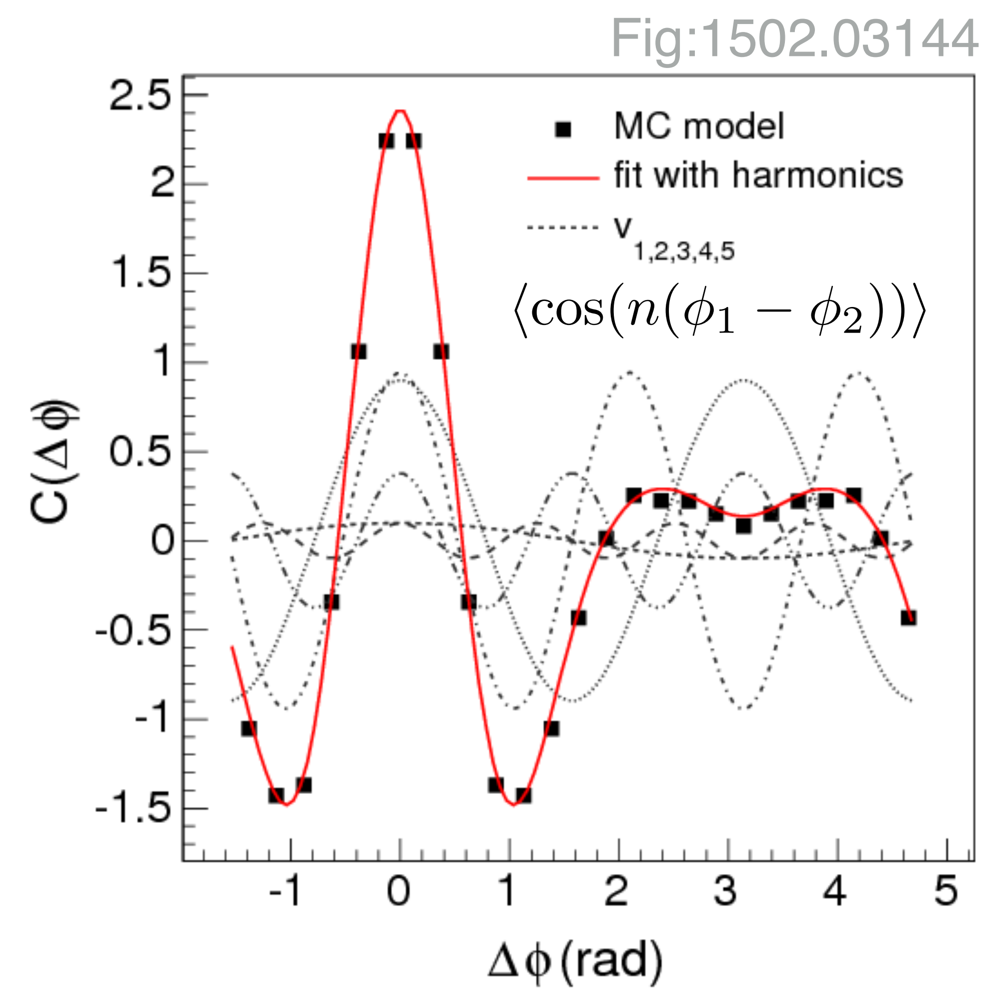
Constrain η/s with more precision

Provide baseline for CME



Azimuthal correlations in Relativistic Heavy Ion collisions





Conventional measurement → two-particle correlations : $\langle\cos(n(\phi_1-\phi_2))\rangle$

This measurement → three-particle correlations : $\langle\cos(m\phi_1+n\phi_2-(m+n)\phi_3)\rangle$

Definition of the observables

- General (3-particle) correlator :

$$C_{m,n,m+n} = \langle\langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3)\rangle\rangle$$

- Connection to event-plane correlator (based on flow interpretation)

$$C_{m,n,m+n} = \langle v_m v_n v_{m+n} \cos(m\Psi_m + n\Psi_n - (m+n)\Psi_{m+n})\rangle$$

Different harmonic of $C_{m,n,m+n}$ → sensitive to different physics

$C_{112} = \langle \cos((\phi_1^{\pm} + \phi_2^{\mp} - 2\phi_3))\rangle$ → charge separation w.r.to event plane driven by chiral magnetic effect

Why study three-particle correlations ?

Teany, Yan 1010.1876
Bhalerao, Luzum, Ollitrault 1106.4940
Heinz, Qiu 1208.1200
ATLAS 1408.4342

- Two particle correlation w.r.to RP :
  More freedom to map out both transverse and longitudinal structure of the fireball

- Connection to flow harmonic & event-plane correlations :
  Non-linear hydrodynamic response more sensitive to viscosity

- Baseline for Chiral Magnetic Effects (CME) :
  Essential to understand components driven by initial-state, magnetohydrodynamics

Going beyond conventional measurements of flow harmonics

Motivation-I (3D structure of HIC)

Initial-state fluctuations

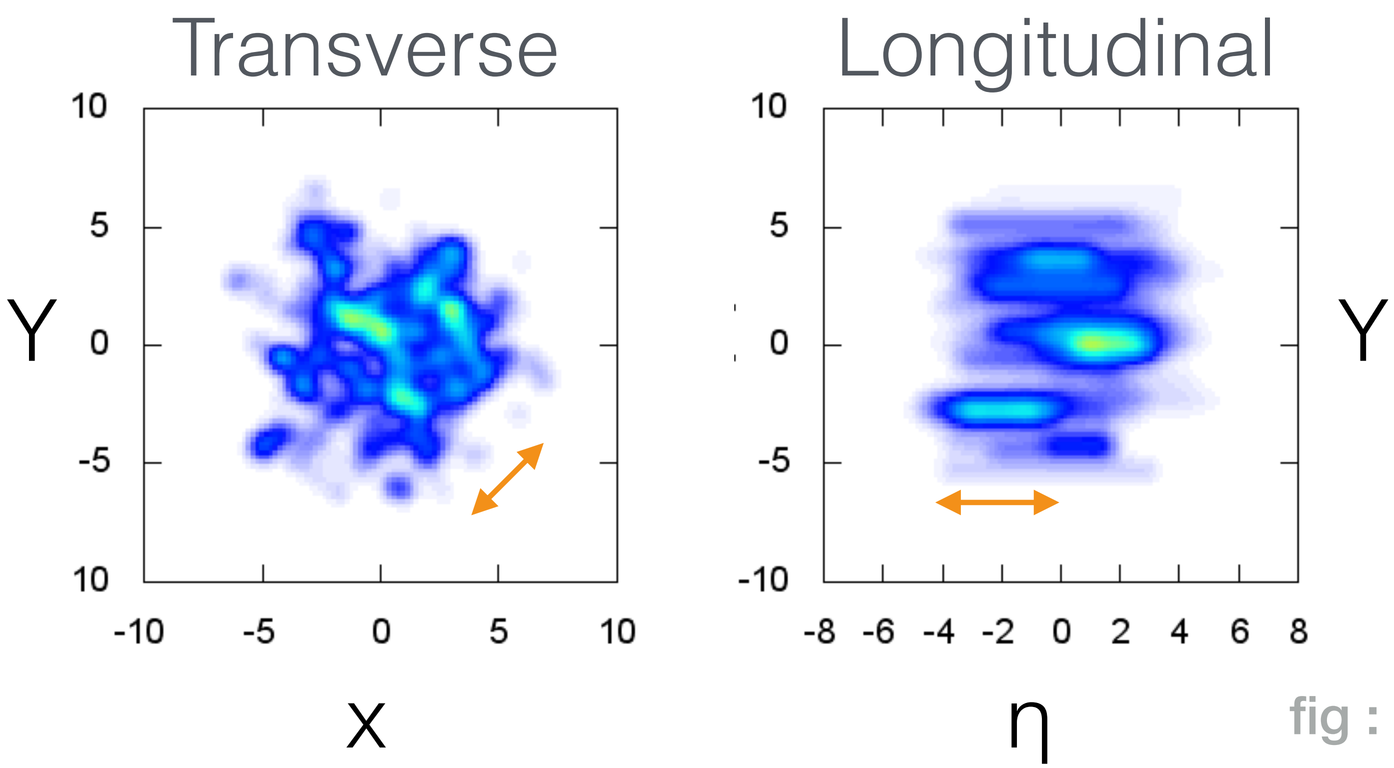
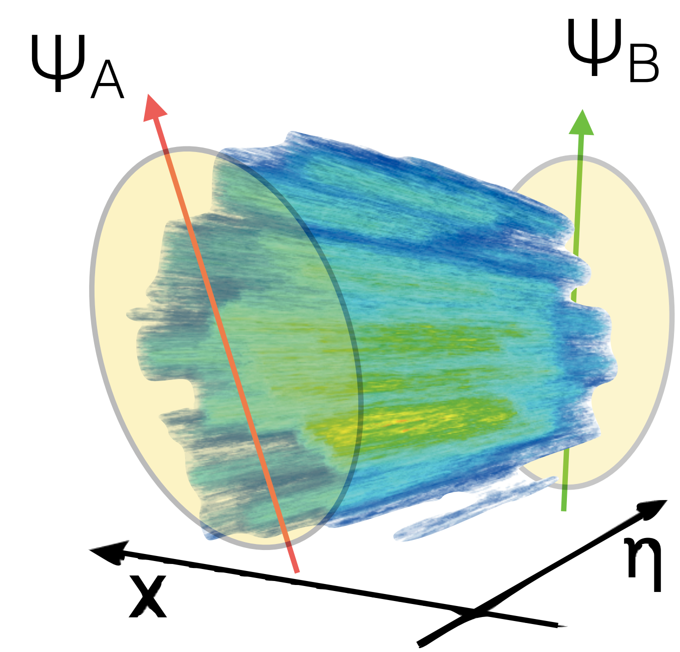


fig : Schenke QM'15

fig : 1605.07158



Bozek *et al* 1011.3354
Jia *et al* 1403.6077
Pang *et al* 1511.04131

Breaking of **boost-invariance** → due to longitudinal fluctuations

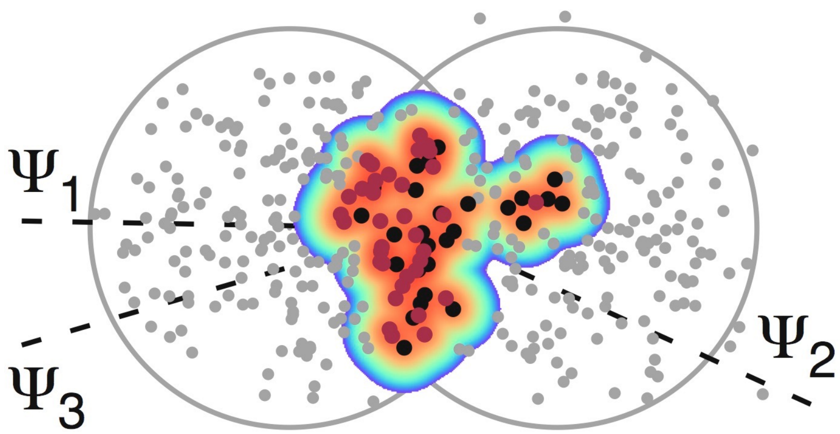
These effects → referred as **twist**, **torque**, event-plane **decorrelation**

3D initial state → can be probed by $C_{m,n,m+n}$ & its Δη dependence

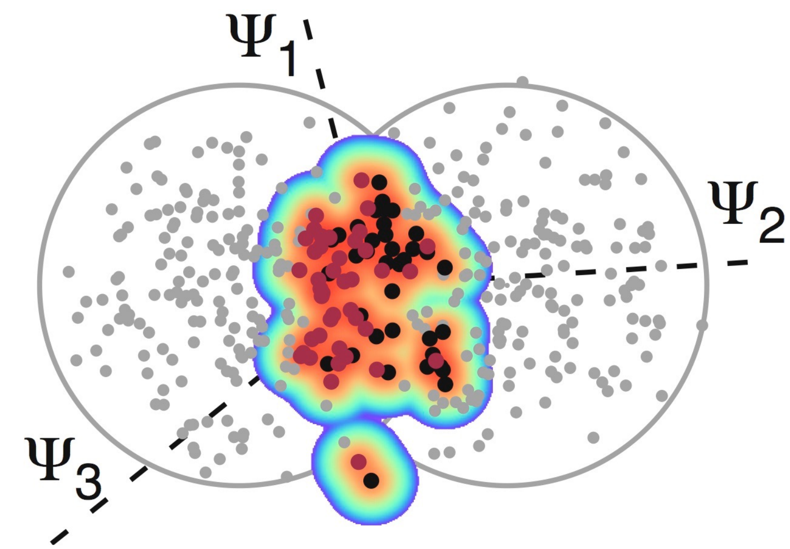
Motivation-I (3D structure of HIC)

v_3 is driven by both geometry + fluctuation

Teany, Yan 1010.1876



In-plane fluctuations



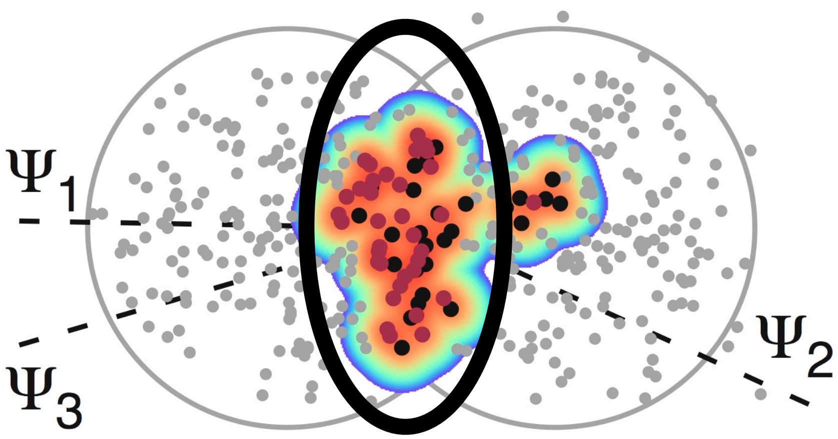
Out-of-plane fluctuations

v_1 drives v_3 in mid-central collisions $\rightarrow$ can be probed by C_{123}

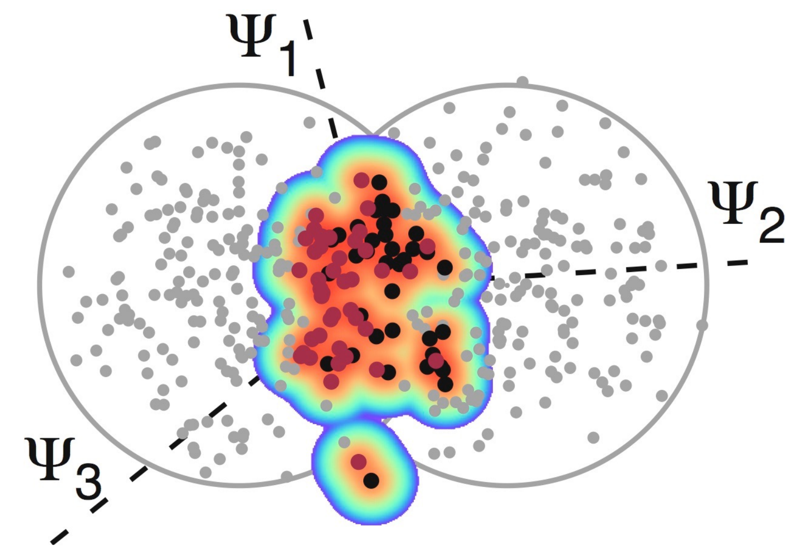
Motivation-I (3D structure of HIC)

v_3 is driven by both geometry + fluctuation

Teany, Yan 1010.1876



In-plane fluctuations



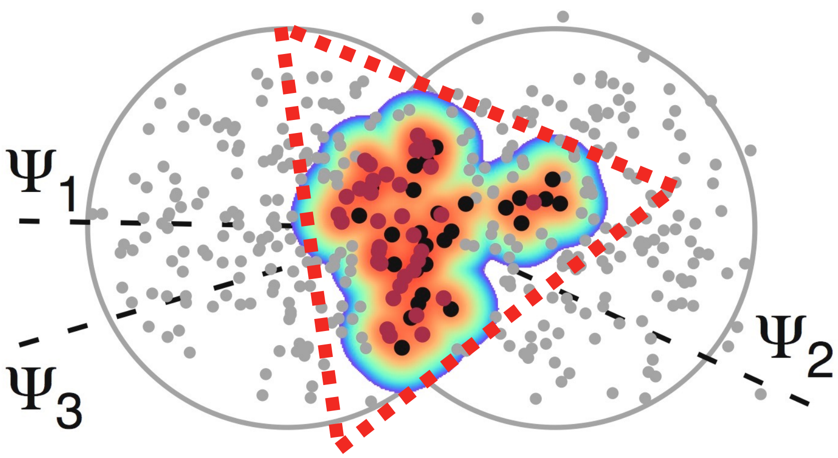
Out-of-plane fluctuations

v_1 drives v_3 in mid-central collisions → can be probed by C_{123}

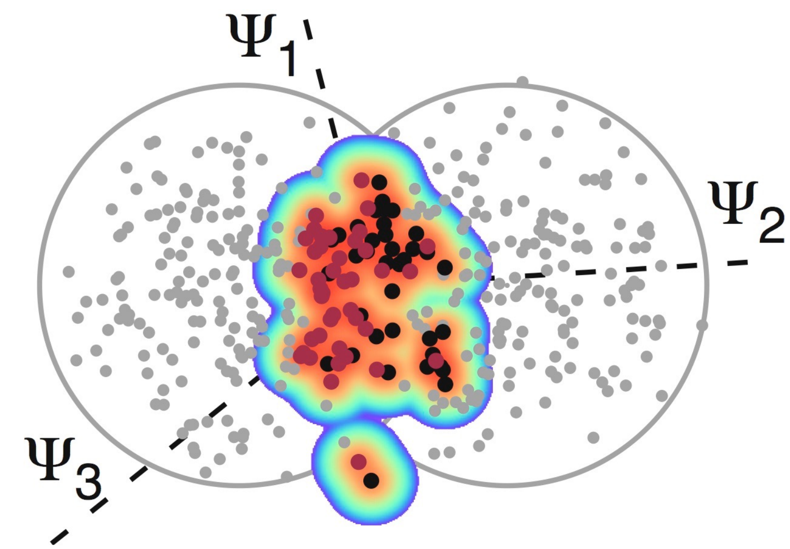
Motivation-I (3D structure of HIC)

v_3 is driven by both geometry + fluctuation

Teany, Yan 1010.1876



In-plane fluctuations



Out-of-plane fluctuations

v_1 drives v_3 in mid-central collisions → can be probed by C_{123}

Motivation-II (Non-linear hydro response)

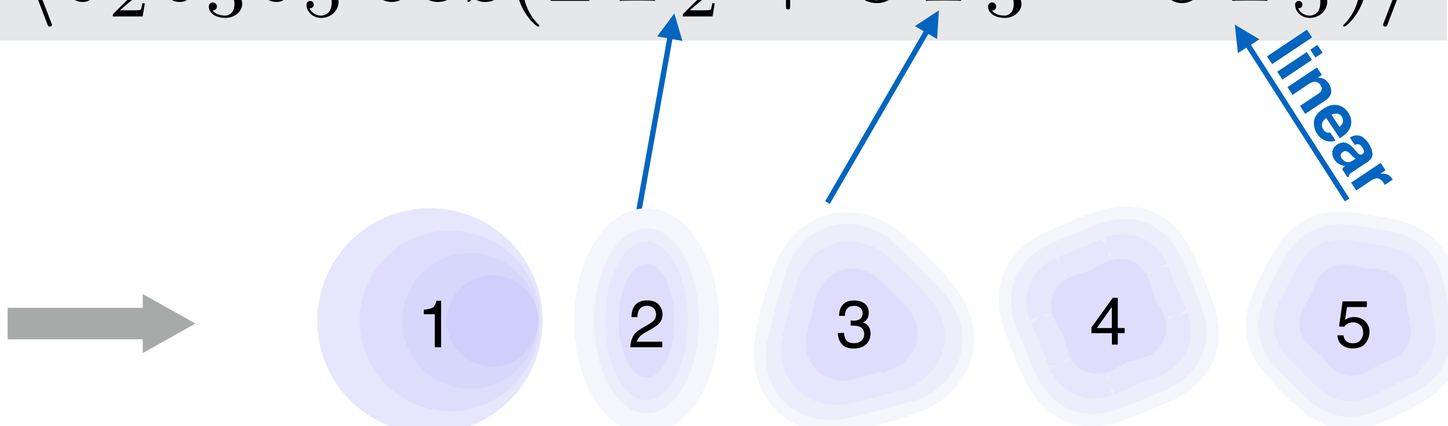
Teany, Yan 1010.1876
Heinz, Qiu 1208.1200

Better probe for transport properties of QGP

- More sensitivity due to **non-linear** hydro response

$$C_{235} = \langle v_2 v_3 v_5 \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5) \rangle$$

Initial geometry



Motivation-II (Non-linear hydro response)

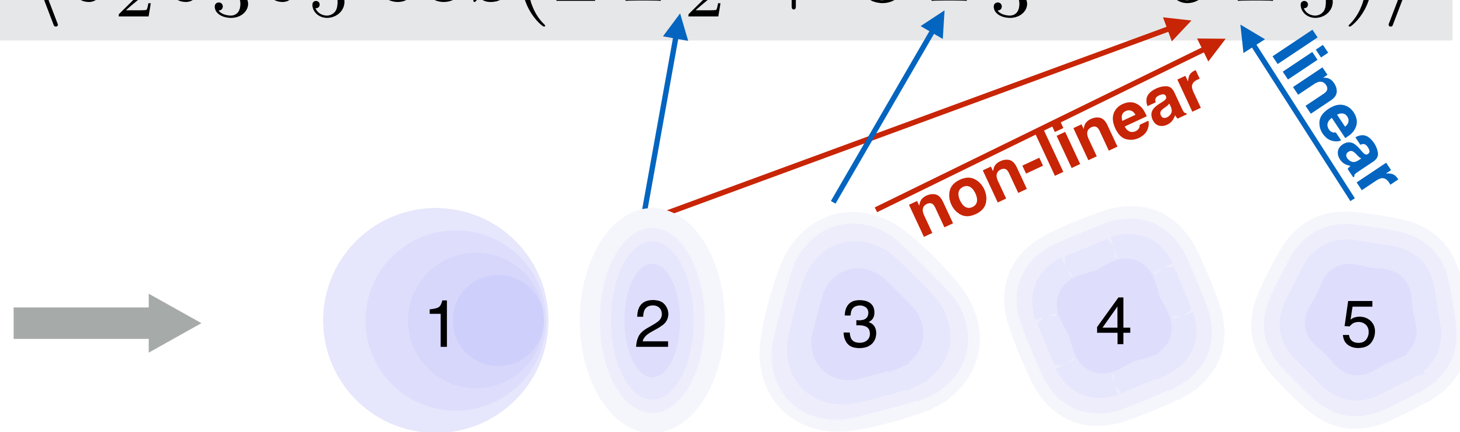
Teany, Yan 1010.1876
Heinz, Qiu 1208.1200

Better probe for transport properties of QGP

- More sensitivity due to **non-linear** hydro response

$$C_{235} = \langle v_2 v_3 v_5 \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5)\rangle$$

Initial geometry



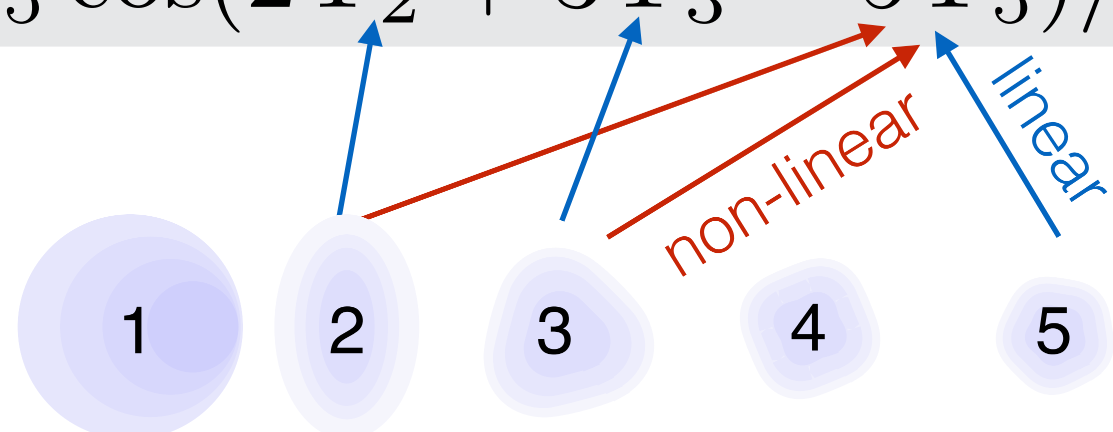
Motivation-II (Non-linear hydro response)

Better probe for transport properties of QGP

Teany, Yan 1010.1876
Heinz, Qiu 1208.1200

- More sensitivity due to **non-linear** hydro response

$$C_{235} = \langle v_2 v_3 v_5 \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5)\rangle$$



Initial geometry →

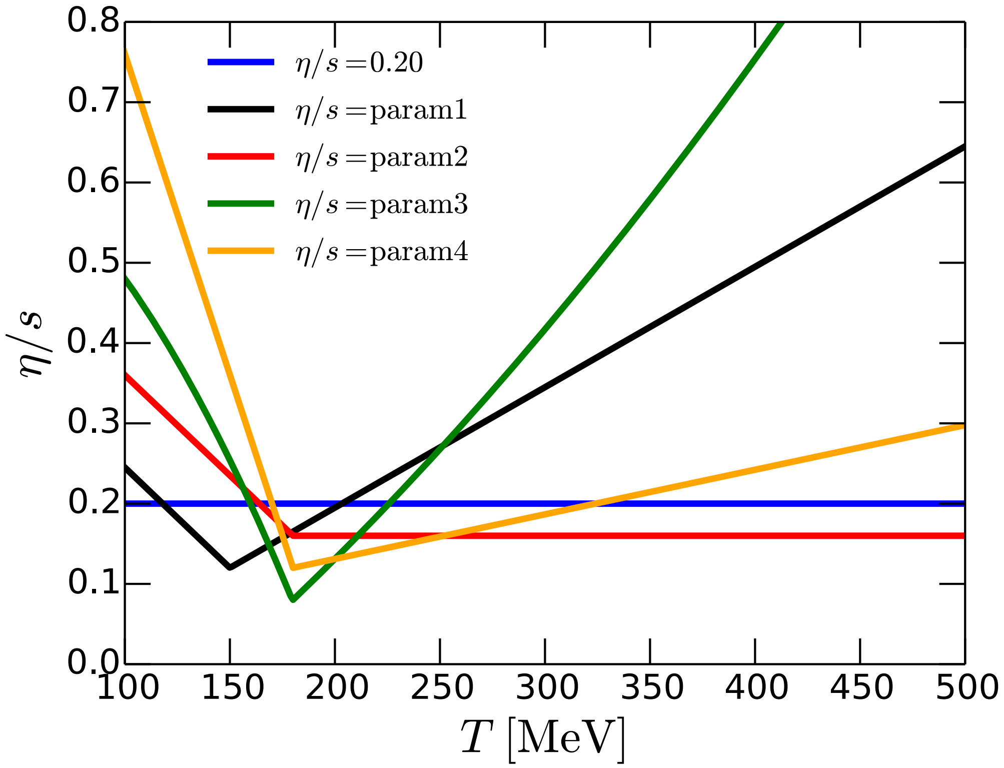
Effect of Viscosity → less-damping more-damping

$\Psi_5 \rightarrow$ more correlated to Ψ_2 & Ψ_3 due to viscous damping

Non-linear response → can be probed by sign change of $C_{m,n,m+n}$

Motivation-III (Towards constraining η/s(T))

Niemi *et al*
1505.02677



Viscosity has temperature dependence

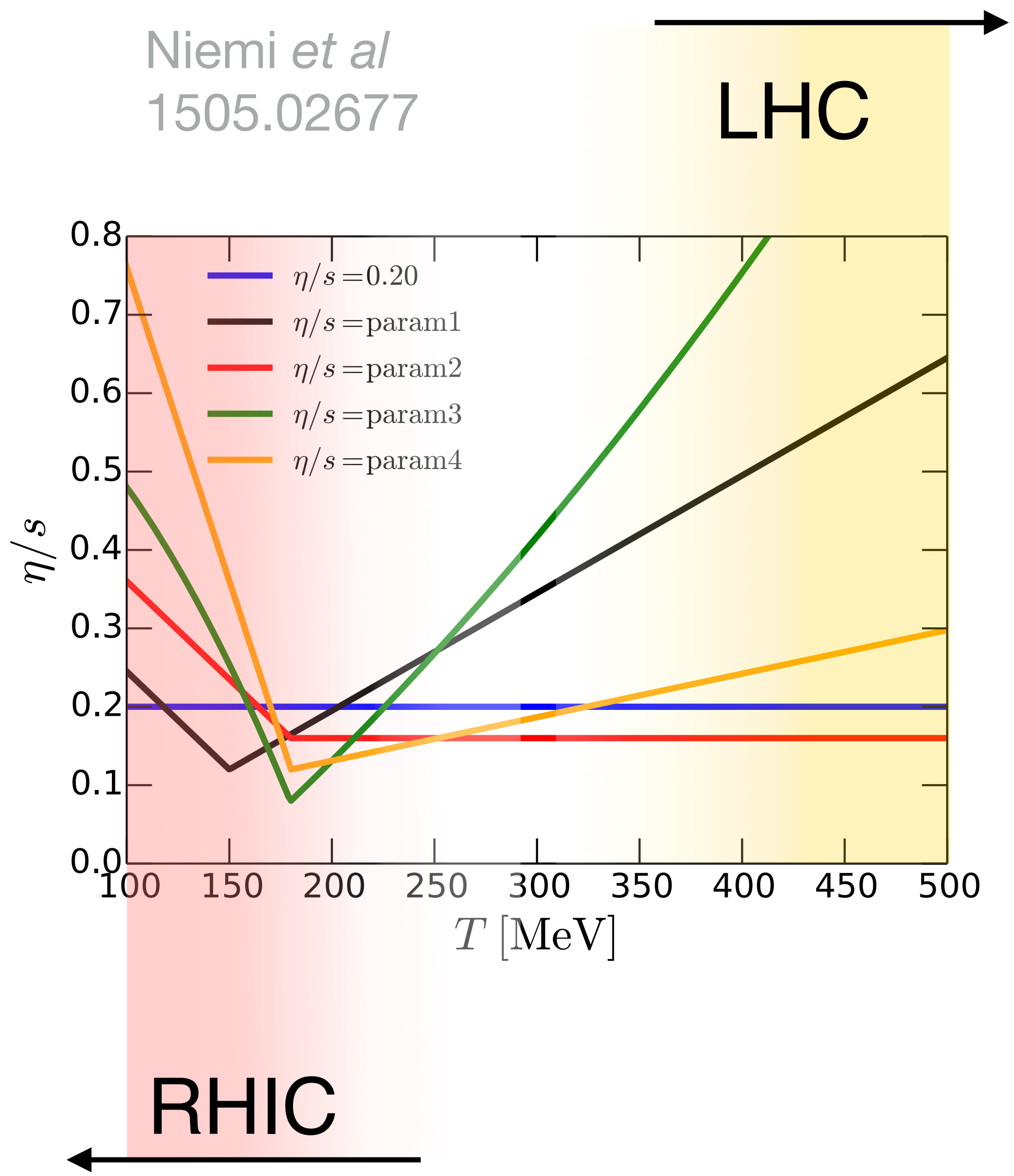
η/s (T) → not yet fully constrained

Models assume parametrization

Niemi et al 1101.2442
Lacey et al 1305.3341
Niemi et al 1505.02677
Denicol et al 1512.01538

Motivation-III (Towards constraining η/s(T))

Niemi *et al*
1505.02677



Viscosity has temperature dependence

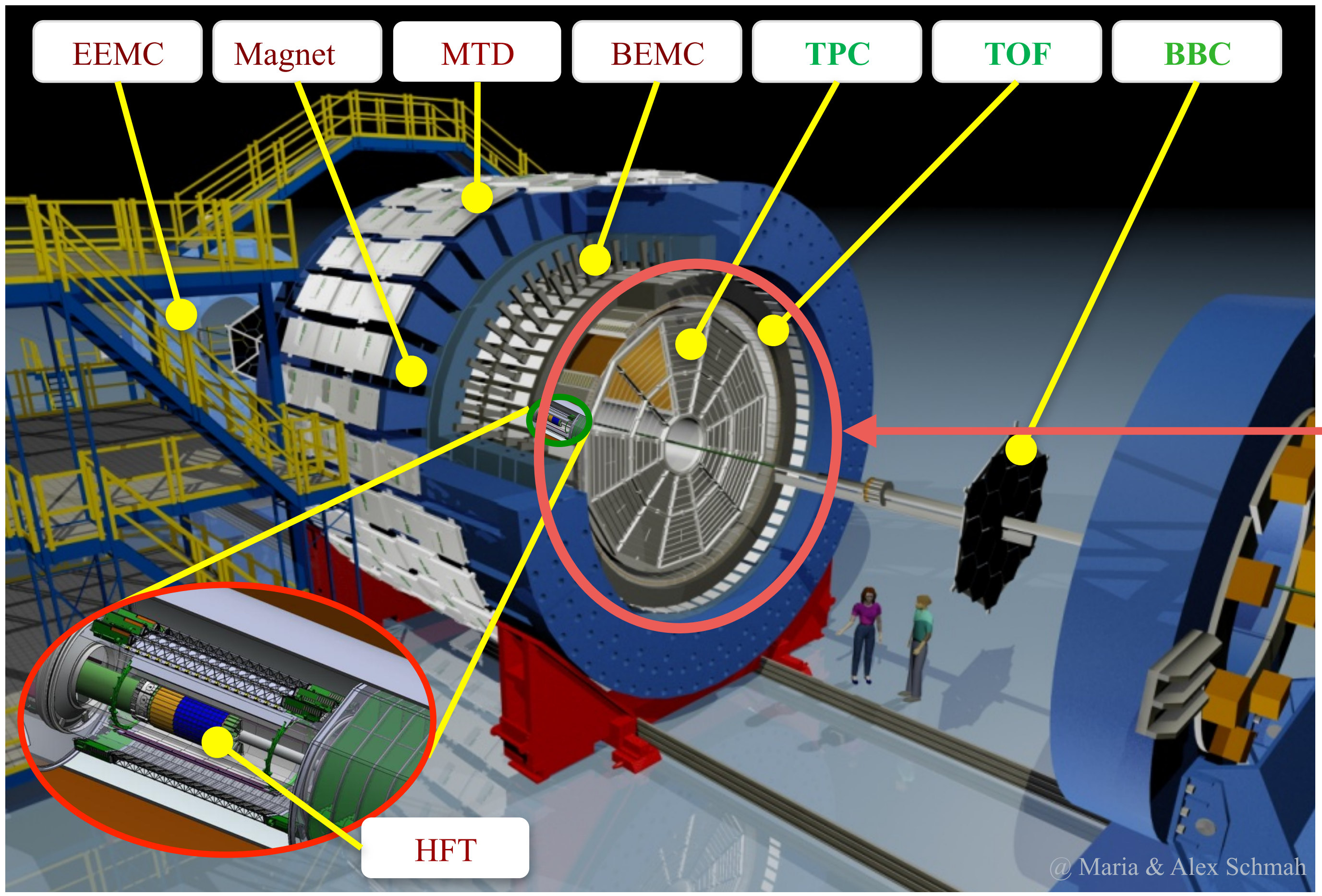
η/s (T) → not yet fully constrained

Models assume parametrization

Measurements at RHIC are essential to constrain η/s (T) at low temperatures

Niemi et al 1101.2442
Lacey et al 1305.3341
Niemi et al 1505.02677
Denicol et al 1512.01538

STAR detector system



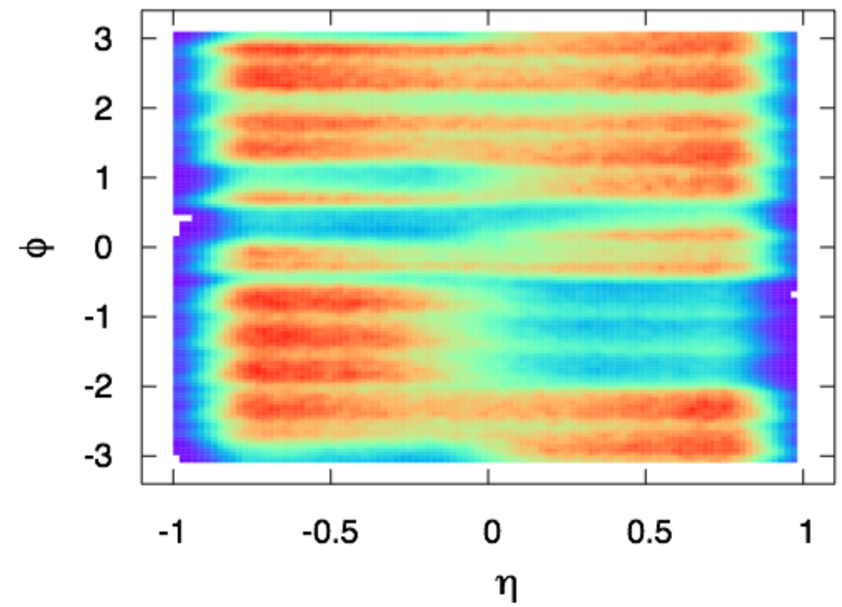
This analysis uses inclusive charged particles detected by the Time-Projection Chamber

Data sets used are from year 2004, 2010-12, & 2014 :
Au+Au collisions at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 27, 19.6, 14.5, 11.5, 7.7 GeV

Details of the cuts & methods

- **Centrality selection:** Uncorrected multiplicity in $|\eta|<0.5$
- **Acceptance cuts:** $0<\phi<2\pi$, $|\eta|<1$, $p_T > 0.2$ GeV/c

TPC acceptance/weight
(used in this analysis)

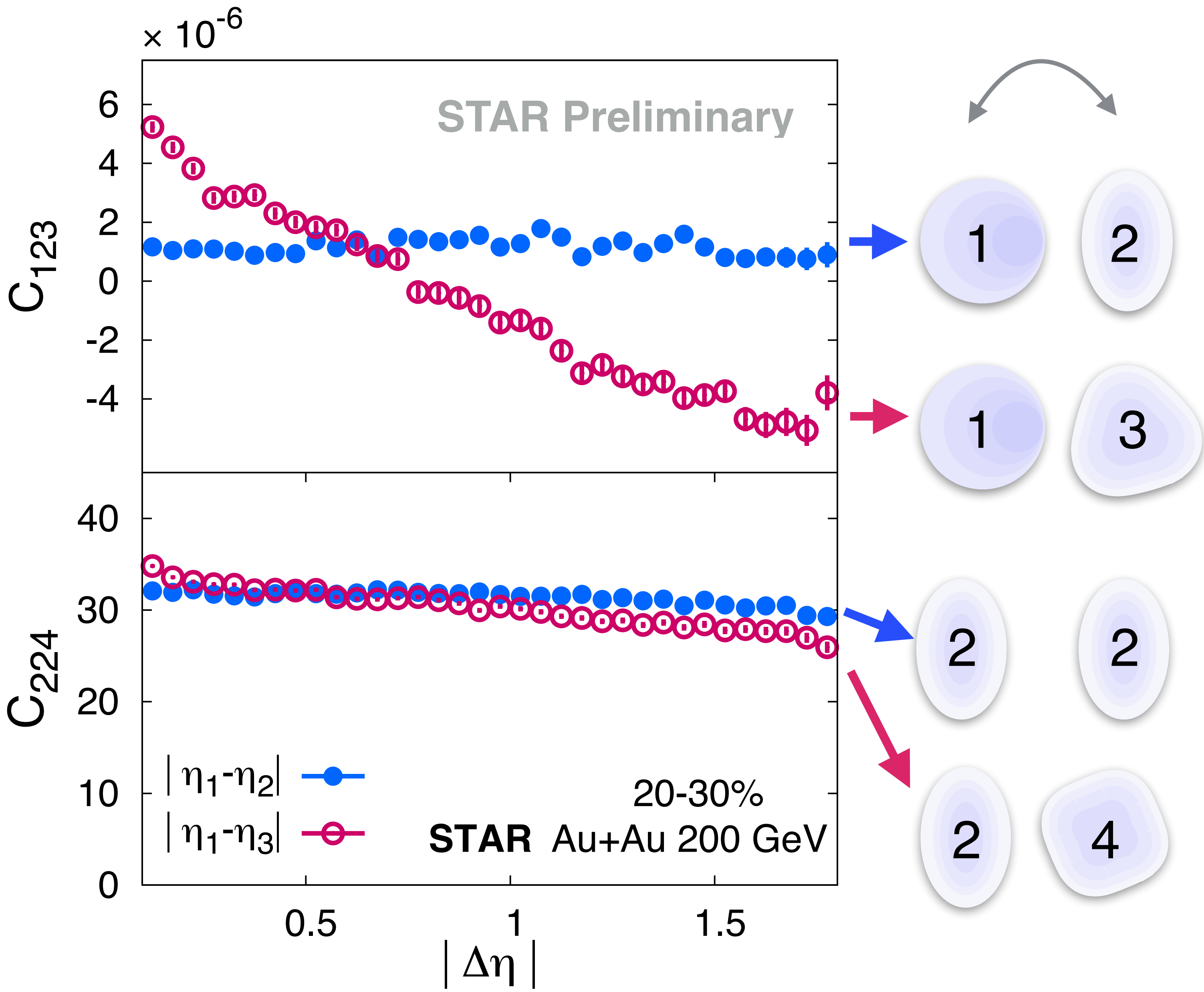


We use Q-Cumulant method & estimate :

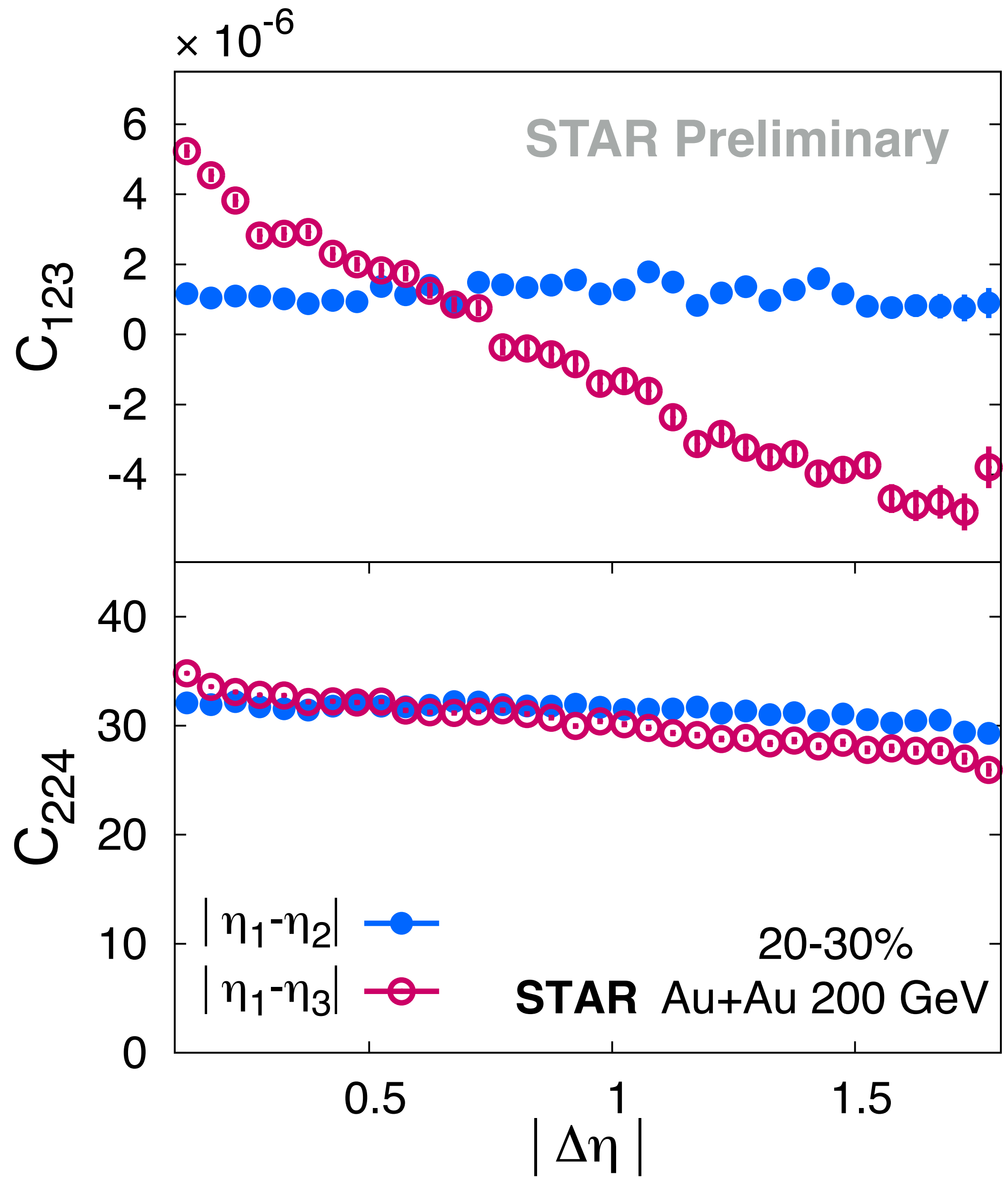
$$C_{m,n,m+n} = \left\langle \frac{\sum\limits_{i,j,k} \omega_i \omega_j \omega_k \cos(m\phi_i + n\phi_i - (m+n)\phi_k)}{\sum\limits_{i,j,k} \omega_i \omega_j \omega_k} \right\rangle$$

$\omega_{i,j,k} \rightarrow$ Weight estimated in bins of sagitta, η-ϕ of tracks

Results : Δη dependence of $C_{m,n,m+n}$

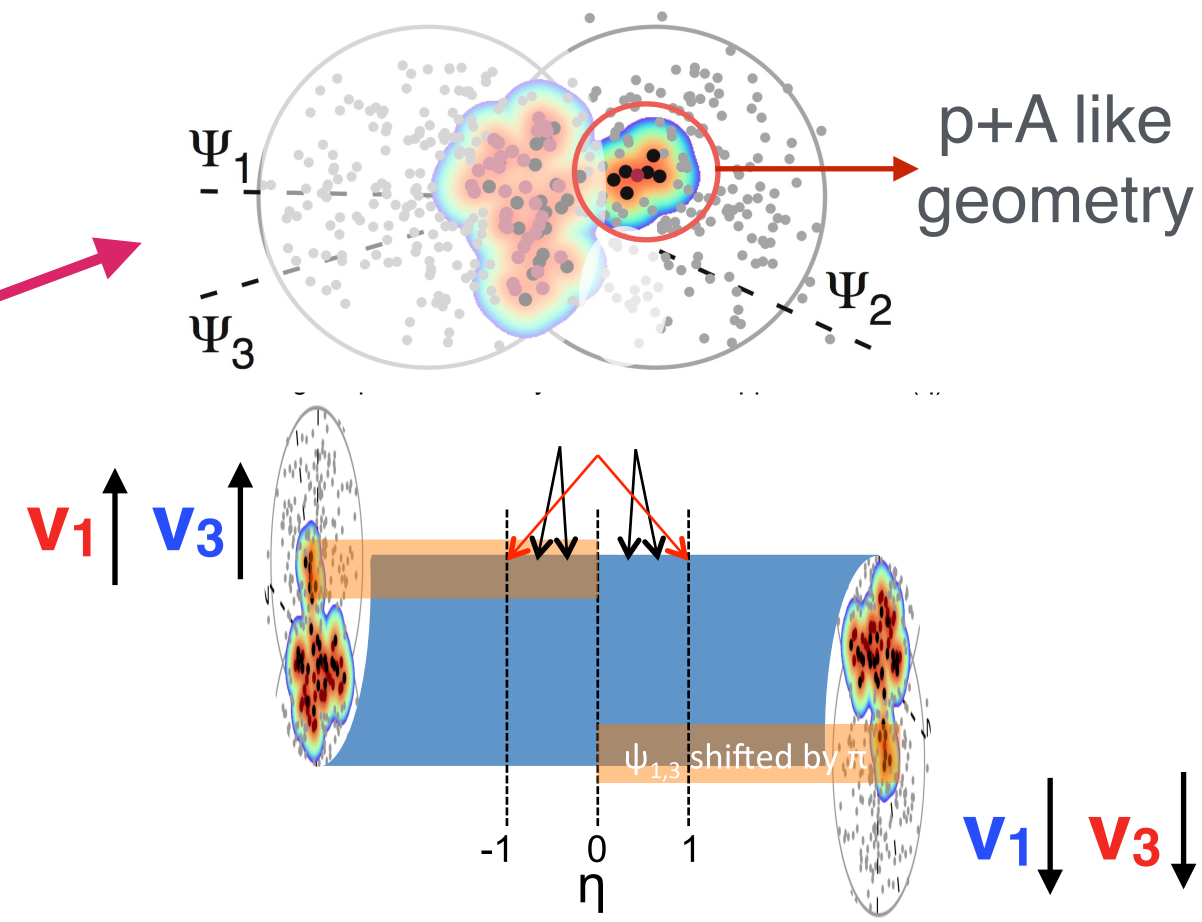


Results : Δη dependence of $C_{m,n,m+n}$

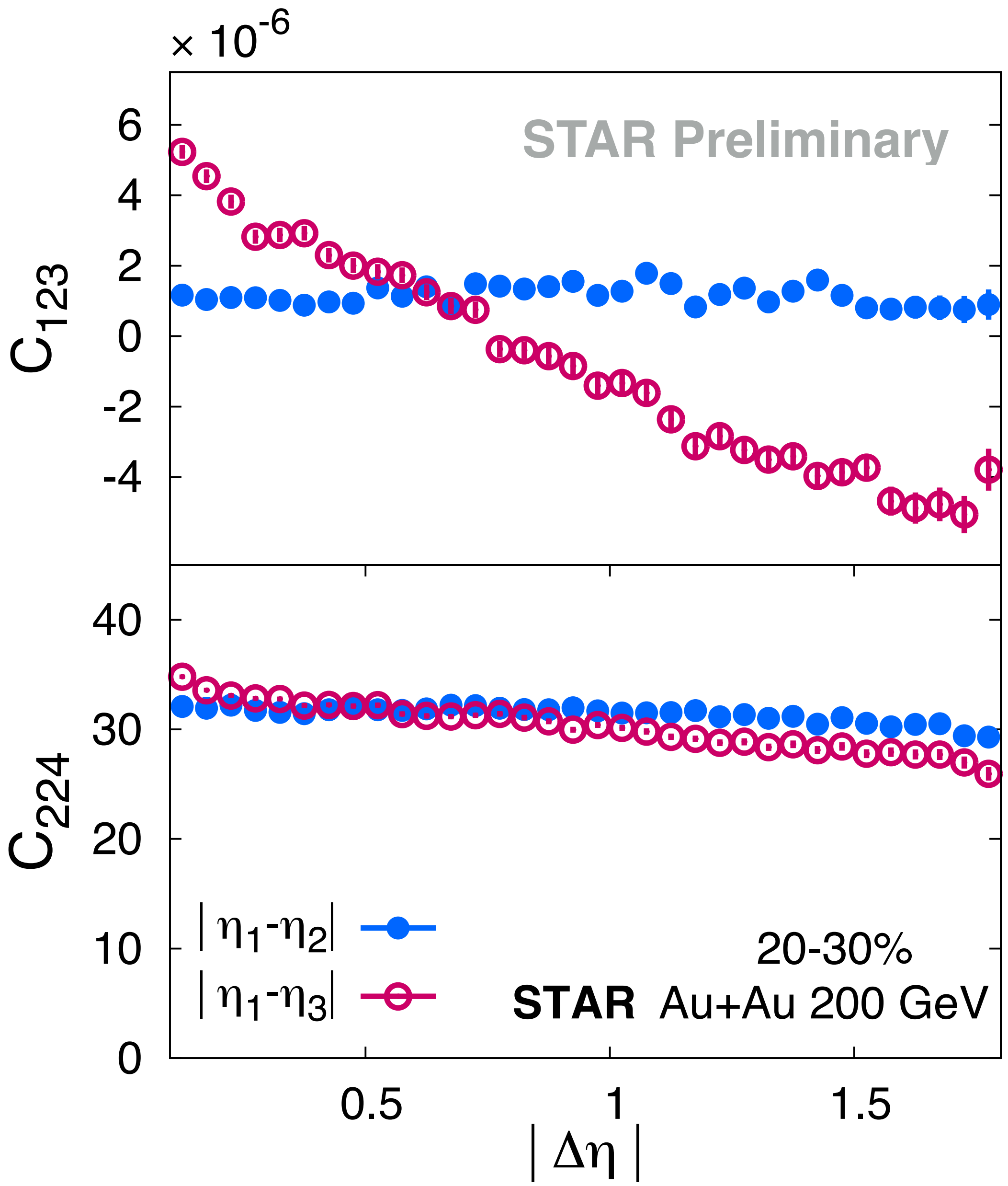


Possible scenario:

fluctuations → η-asymmetry, Δη dependence

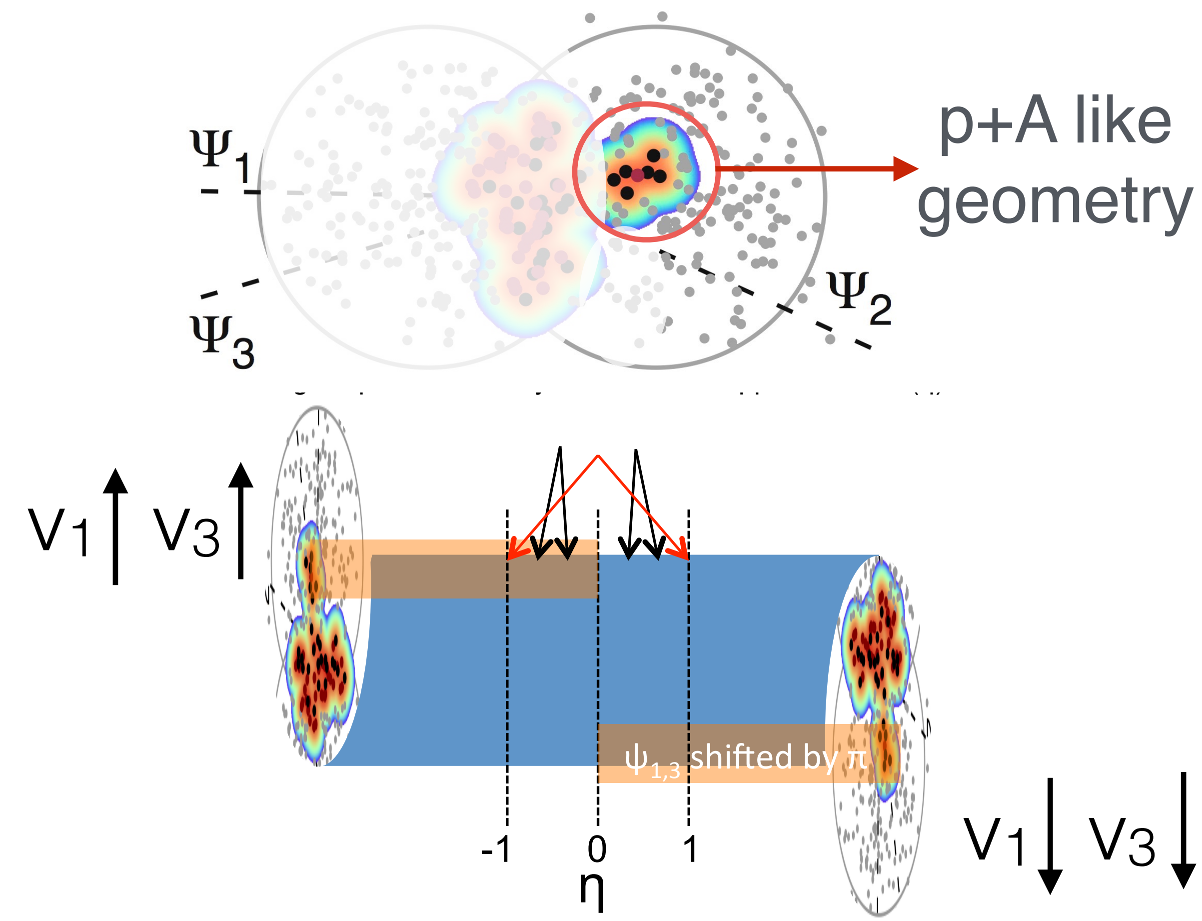


Results : Δη dependence of $C_{m,n,m+n}$



Possible scenario:

fluctuations → η-asymmetry, Δη dependence



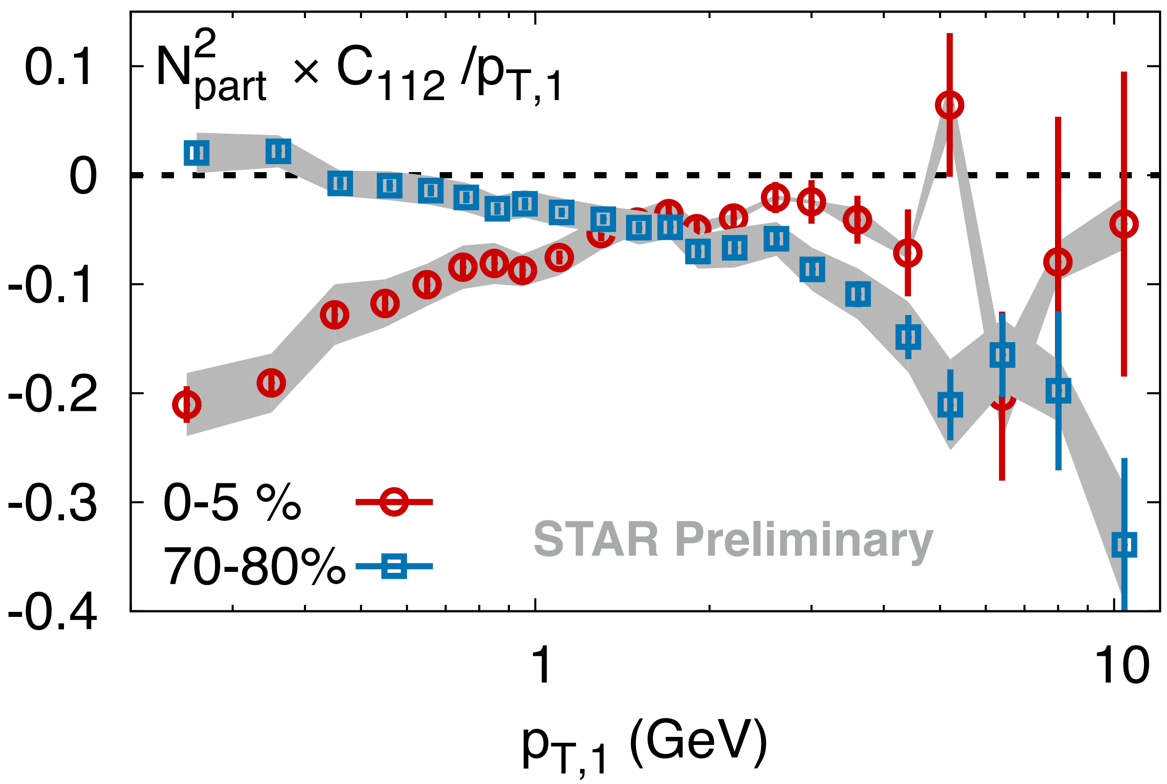
Jet correlated to Ψ_2 plane may also lead to Δη dependence

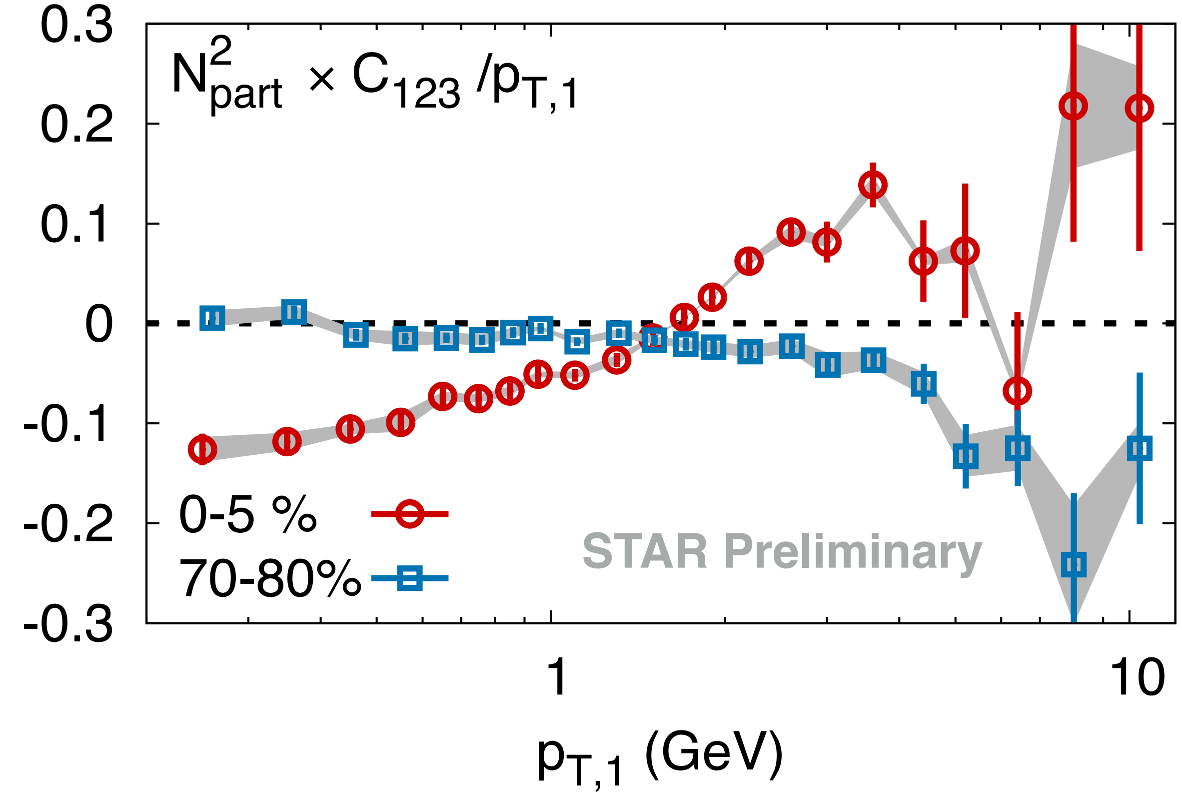
Strong Δη dependence of C_{123} → due to η asymmetric of v_1

C_{224} → weak dependence, best for comparison to 2D hydro models

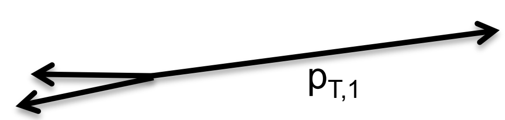
Measurement of p_T dependence of $C_{m,n,m+n}$

Different p_T regime → sensitivity to different physics





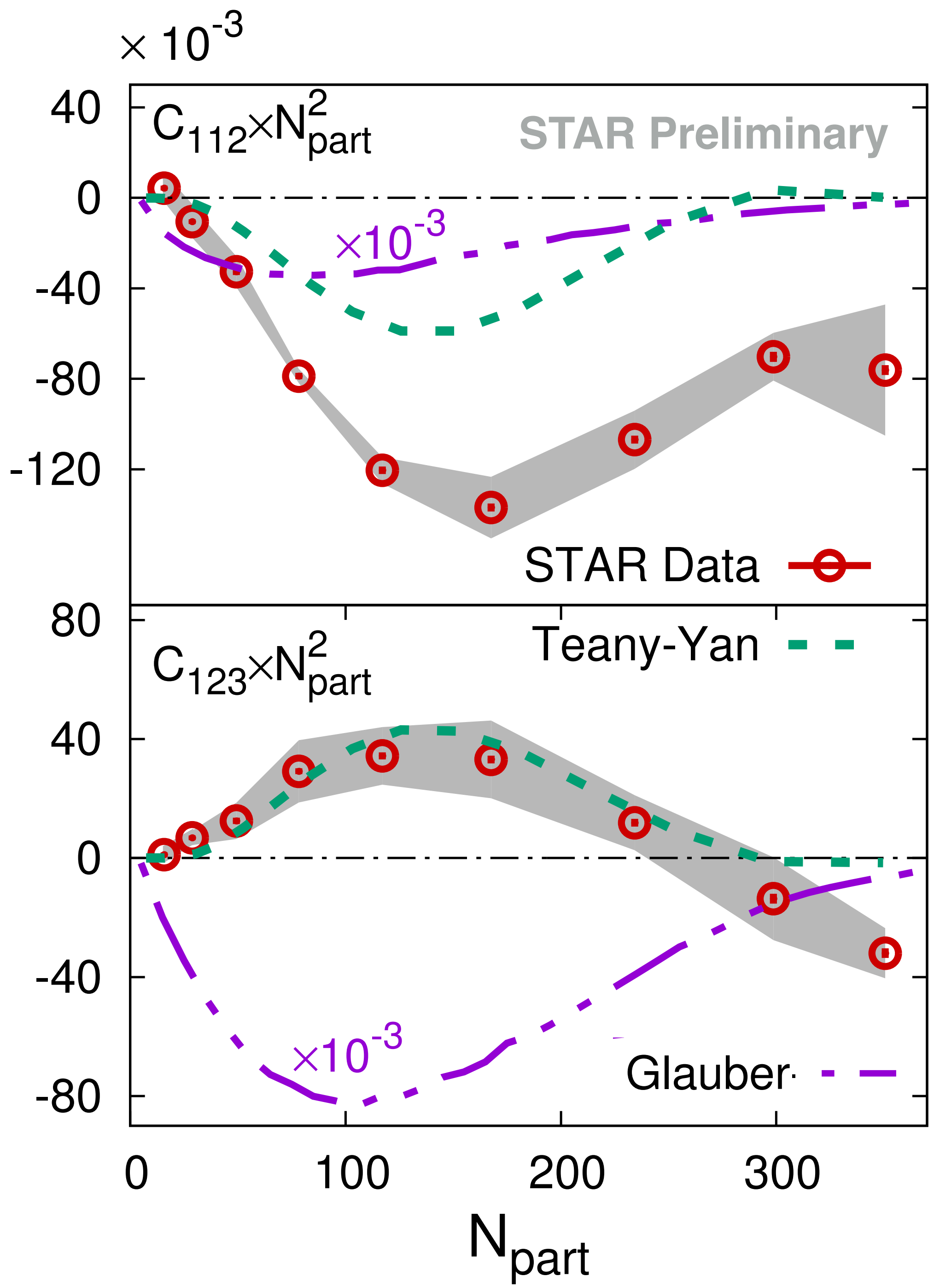
High p_T & peripheral events → momentum conservation from jets



C_{112}, C_{123} → (-)

Correlations in central events look completely different from peripheral

Centrality dependence of $C_{m,n,m+n}$

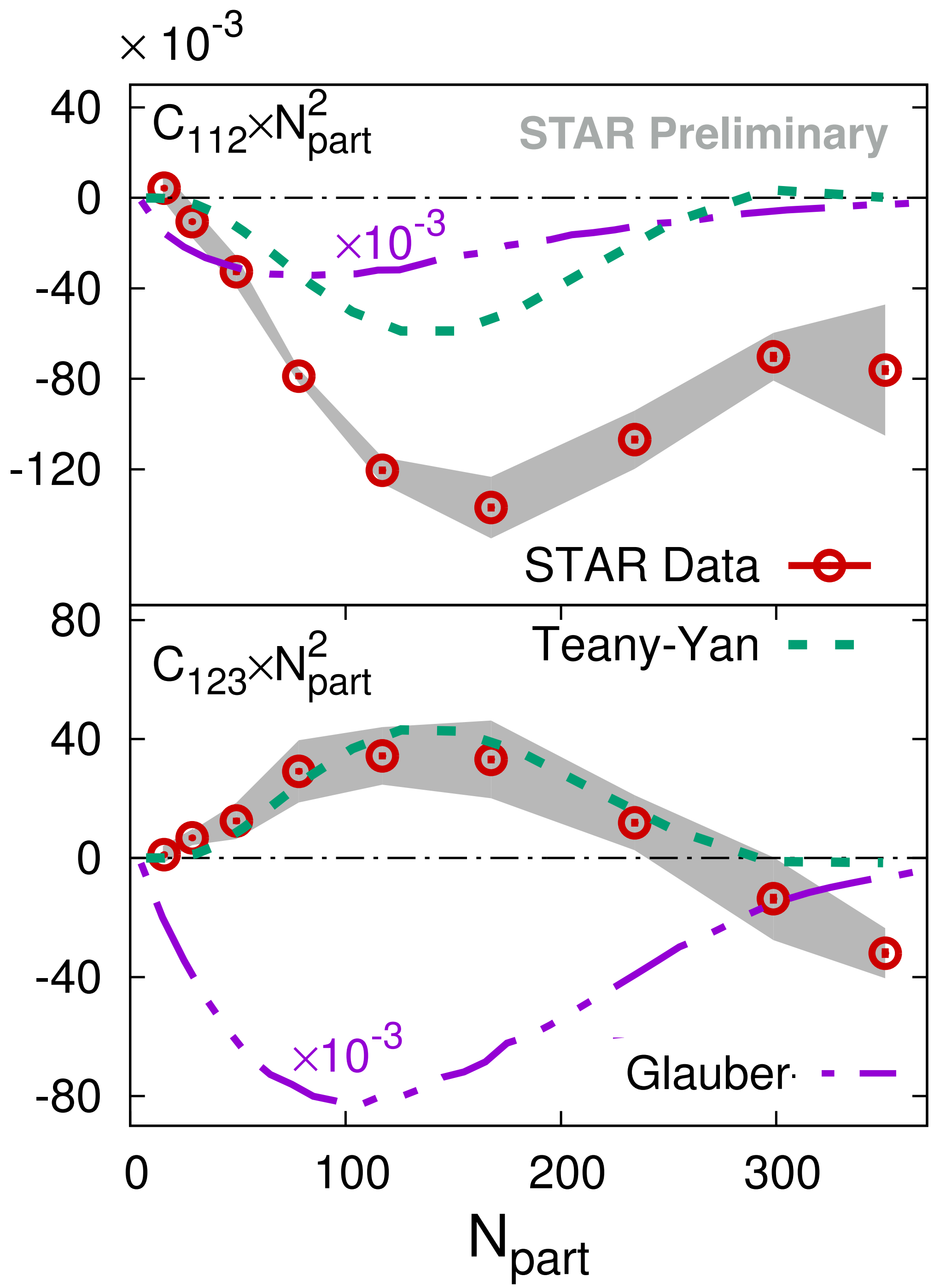


C_{112} :

- Measures baseline for CME
- Non-zero correlations for central collisions in contrast to the models

Magnitude follows initial state but sign depends on final state effects

Centrality dependence of $C_{m,n,m+n}$



C_{112} :

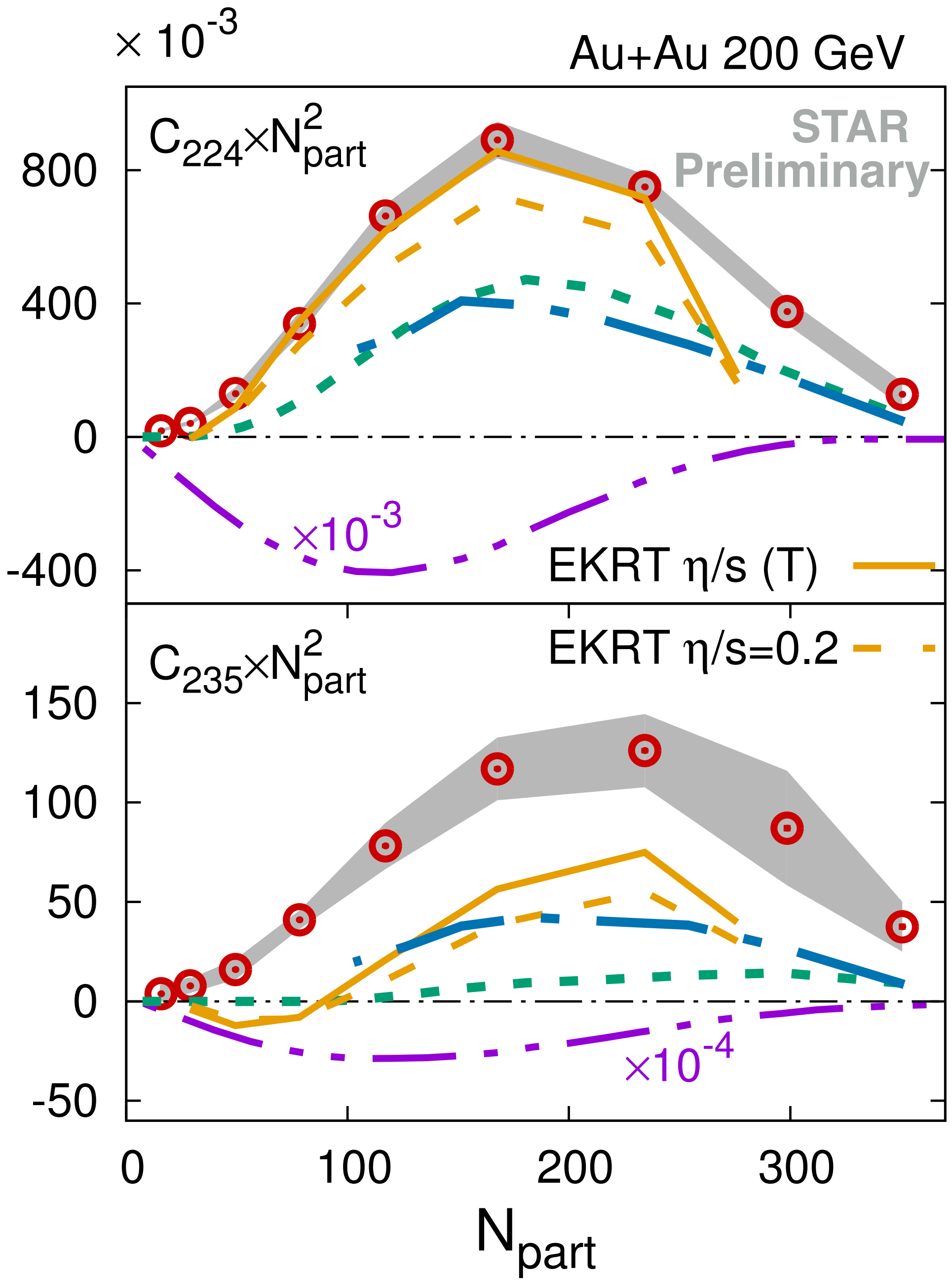
- Measures baseline for CME
- Non-zero correlations for central collisions in contrast to the models

C_{123} :

- Indicates v_1 drives v_3 (in mid-central collisions) as predicted by Teaney & Yan
- Non zero (negative) for central collisions

Magnitude follows initial state but sign depends on final state effects

Centrality dependence of higher order $C_{m,n,m+n}$



Sign change from Glauber expectations

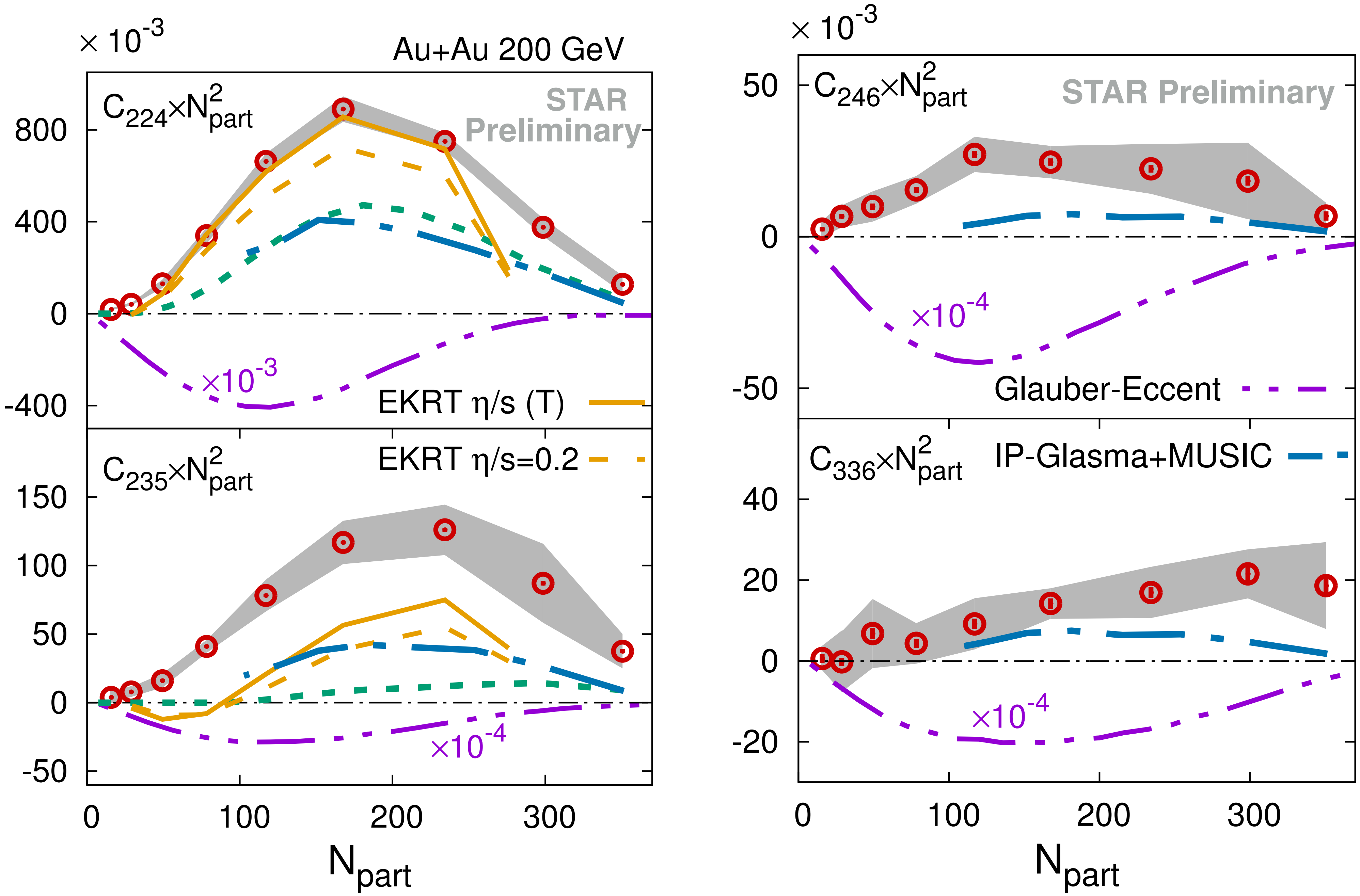
↓

non-linear hydro response

Indication of strong non-linear hydro response, sensitivity to η/s(T)

2+1D hydro models describe trends but under predicts the data

Centrality dependence of higher order $C_{m,n,m+n}$



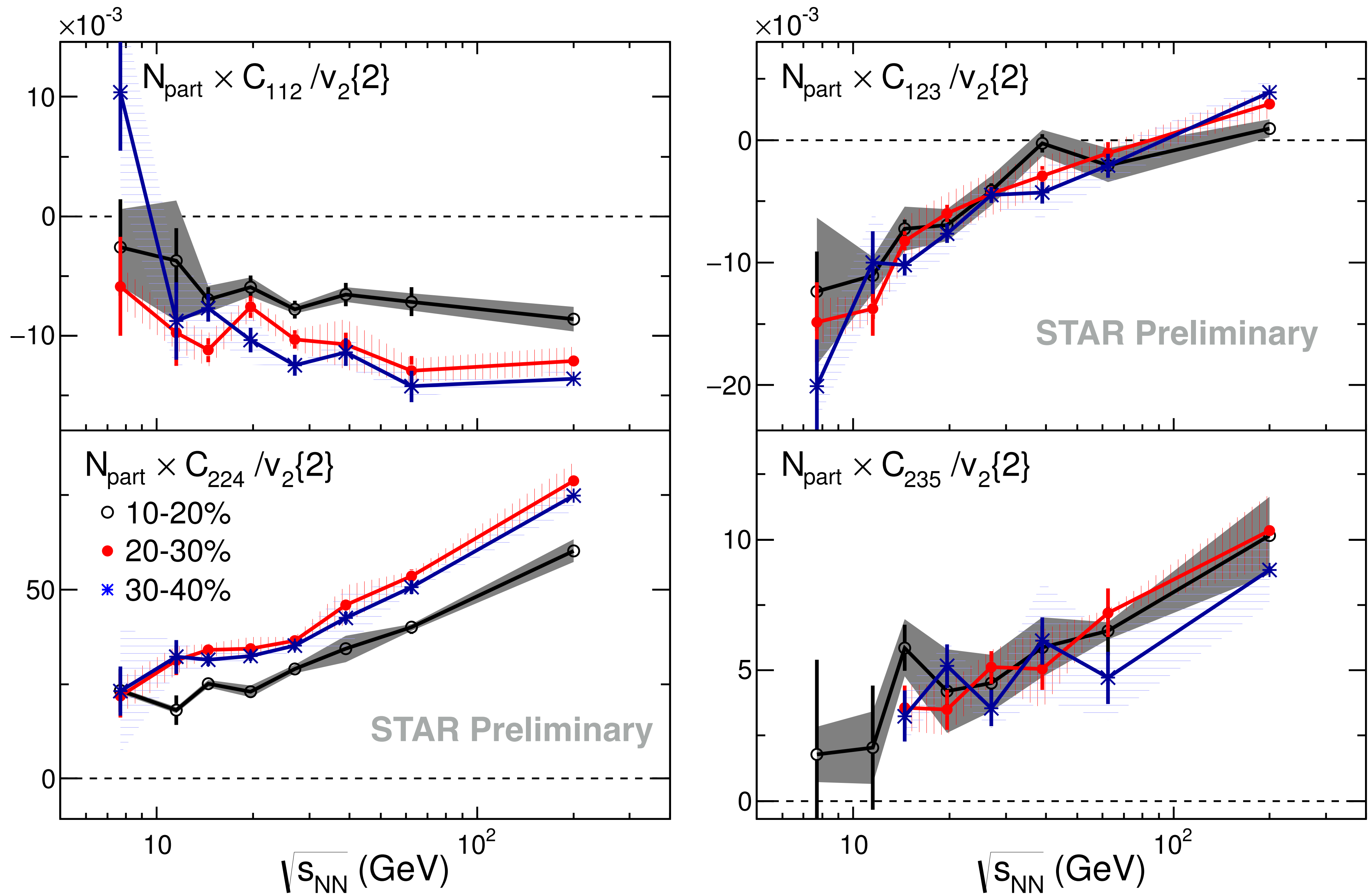
Sign change from Glauber expectations

non-linear hydro response

Indication of strong non-linear hydro response, sensitivity to η/s(T)

2+1D hydro models describe trends but under predicts the data

Energy dependence of $C_{m,n,m+n}$



Monotonic dependence with C_{123} changing sign

Results will improve modeling of heavy ion collisions at low energy

Tomography of particle flow

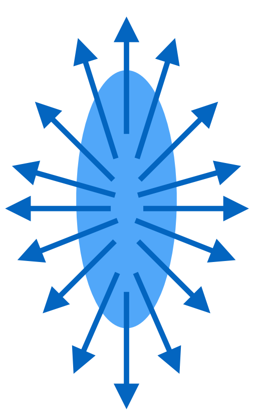
Combining all results together can give us a picture of collisions

$$\langle\cos(1\phi_1 + 1\phi_3 - 2\phi_2)\rangle/v_2 \approx \langle\cos(1\phi'_1 + 1\phi'_2)\rangle$$
$$\langle\cos(1\phi_1 + 2\phi_3 - 3\phi_2)\rangle/v_2 \approx \langle\cos(1\phi'_1 - 3\phi'_2)\rangle$$
$$\langle\cos(2\phi_1 + 2\phi_3 - 4\phi_2)\rangle/v_2 \approx \langle\cos(2\phi'_1 - 4\phi'_2)\rangle$$
$$\langle\cos(2\phi_3 + 3\phi_1 - 5\phi_2)\rangle/v_2 \approx \langle\cos(3\phi'_1 - 5\phi'_2)\rangle$$

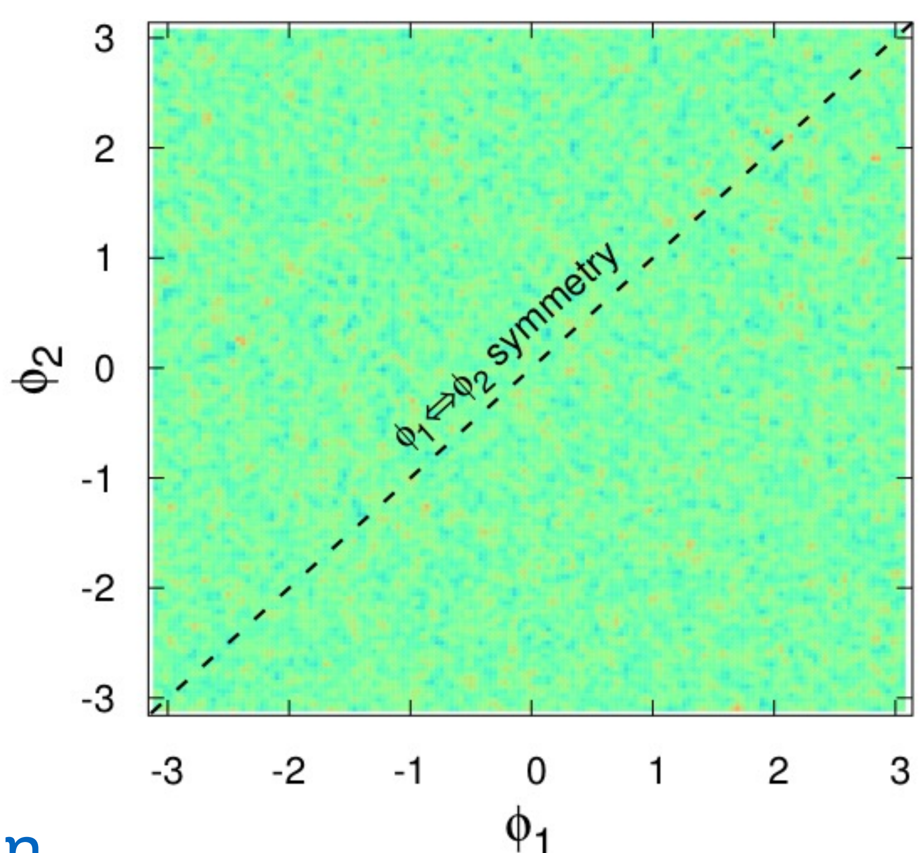
	$(\phi'_1,\ \phi'_2)$ [rad]				
	$(0,\ 0)$	$(0,\ \pi)$	$(\frac{\pi}{2}, \frac{\pi}{2})$	$(\frac{\pi}{2}, -\frac{\pi}{2})$	$\pm(\frac{\pi}{3},\ \frac{2\pi}{3})$
$C_{1,1,2}/v_2$	+1	-1	-1	+1	-1
$C_{1,2,3}/v_2$	+1	-1	-1	+1	$+\frac{1}{2}$
$C_{2,2,4}/v_2$	+1	+1	-1	-1	+1
$C_{2,3,5}/v_2$	+1	-1	-1	+1	$+\frac{1}{2}$

Signs of $C_{m,n,m+n}$ restrict allowed values of angles w.r.t Ψ_2

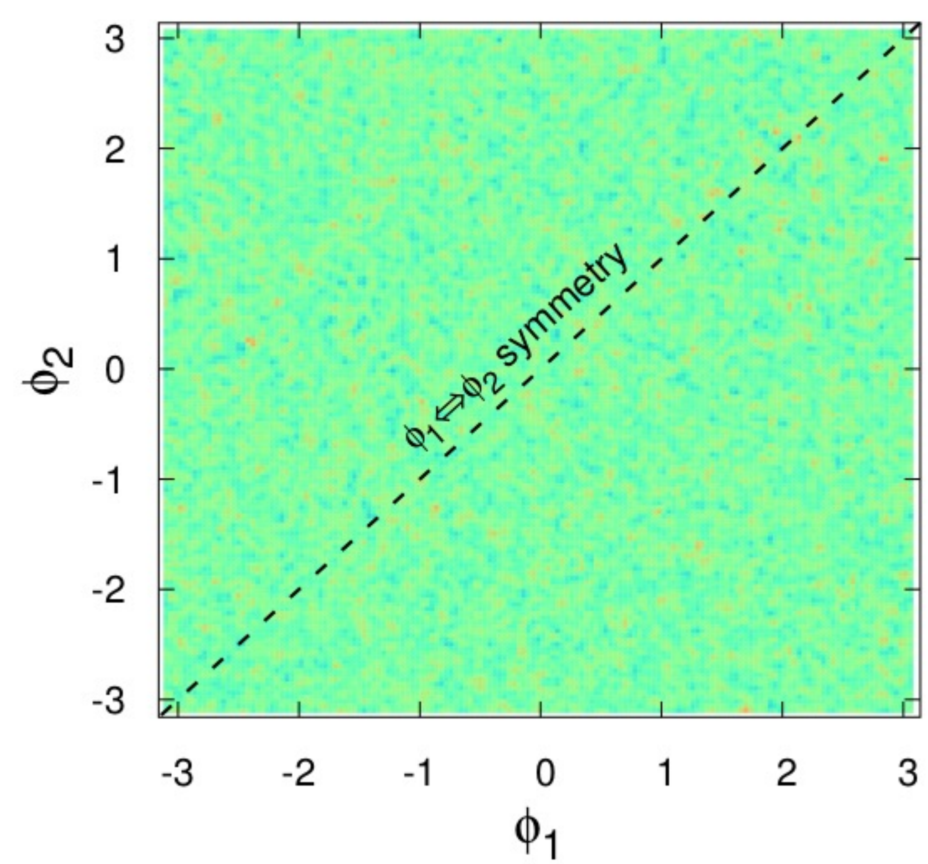
P. Sorensen
WWND’14

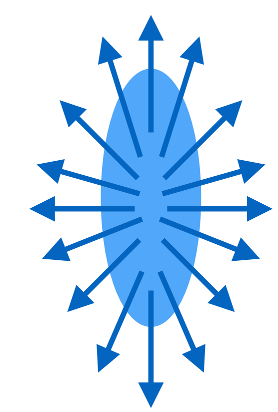


No restriction



No restriction





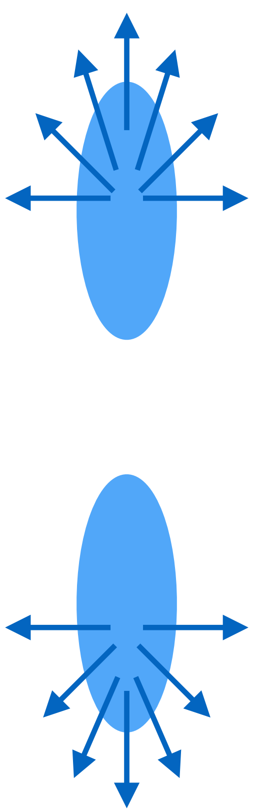
small $\Delta\eta$

large $\Delta\eta$

Tomography of particle flow

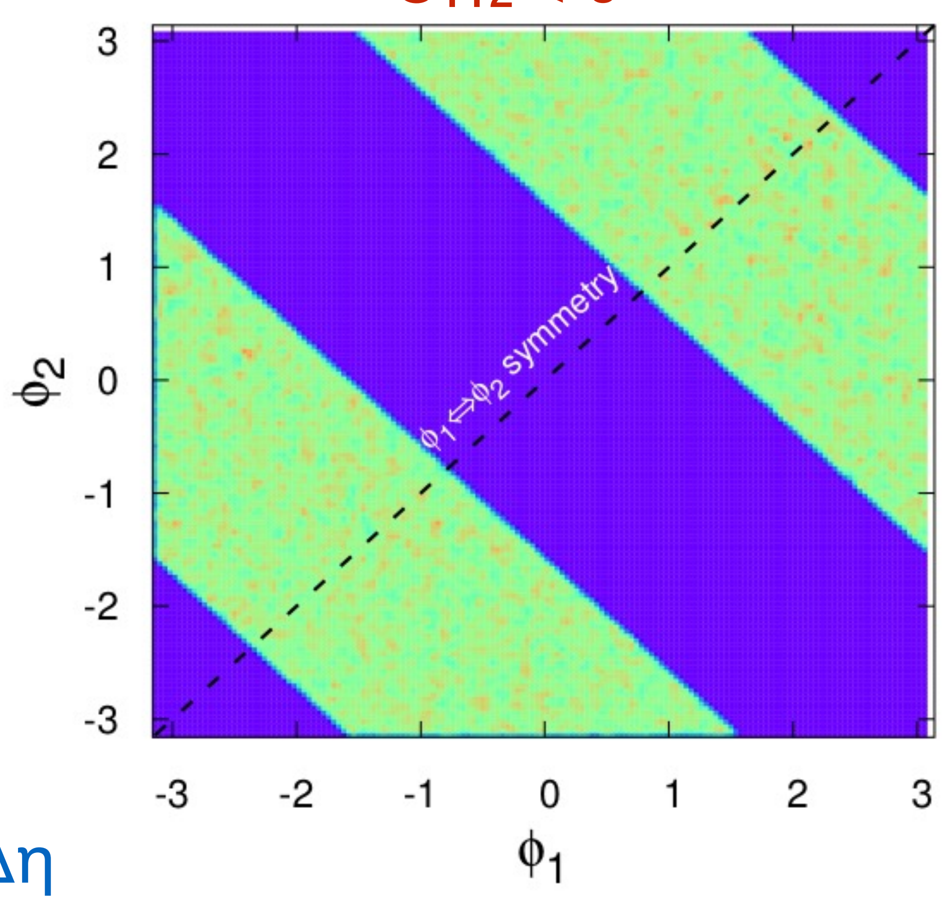
Combining all results together can give us a picture of collisions

$$\langle\cos(1\phi_1 + 1\phi_3 - 2\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1' + 1\phi_2')\rangle$$
$$\langle\cos(1\phi_1 + 2\phi_3 - 3\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1' - 3\phi_2')\rangle$$
$$\langle\cos(2\phi_1 + 2\phi_3 - 4\phi_2)\rangle/v_2 \approx \langle\cos(2\phi_1' - 4\phi_2')\rangle$$
$$\langle\cos(2\phi_3 + 3\phi_1 - 5\phi_2)\rangle/v_2 \approx \langle\cos(3\phi_1' - 5\phi_2')\rangle$$

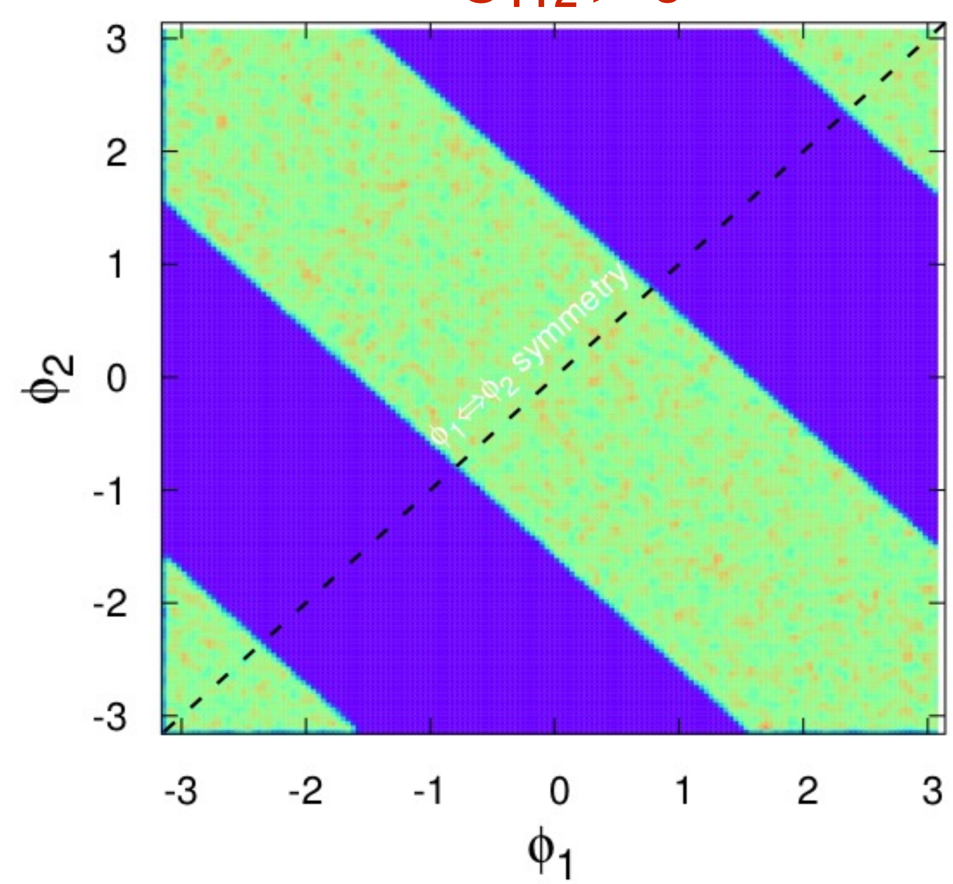


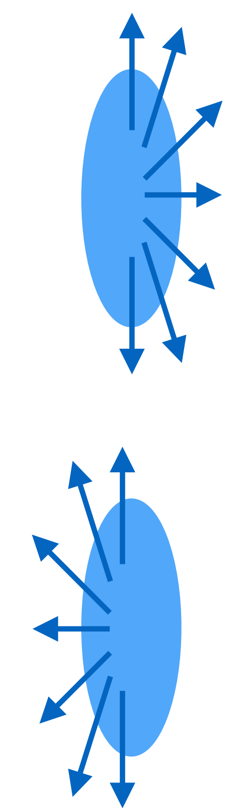
small Δη

$C_{112} < 0$



$C_{112} > 0$



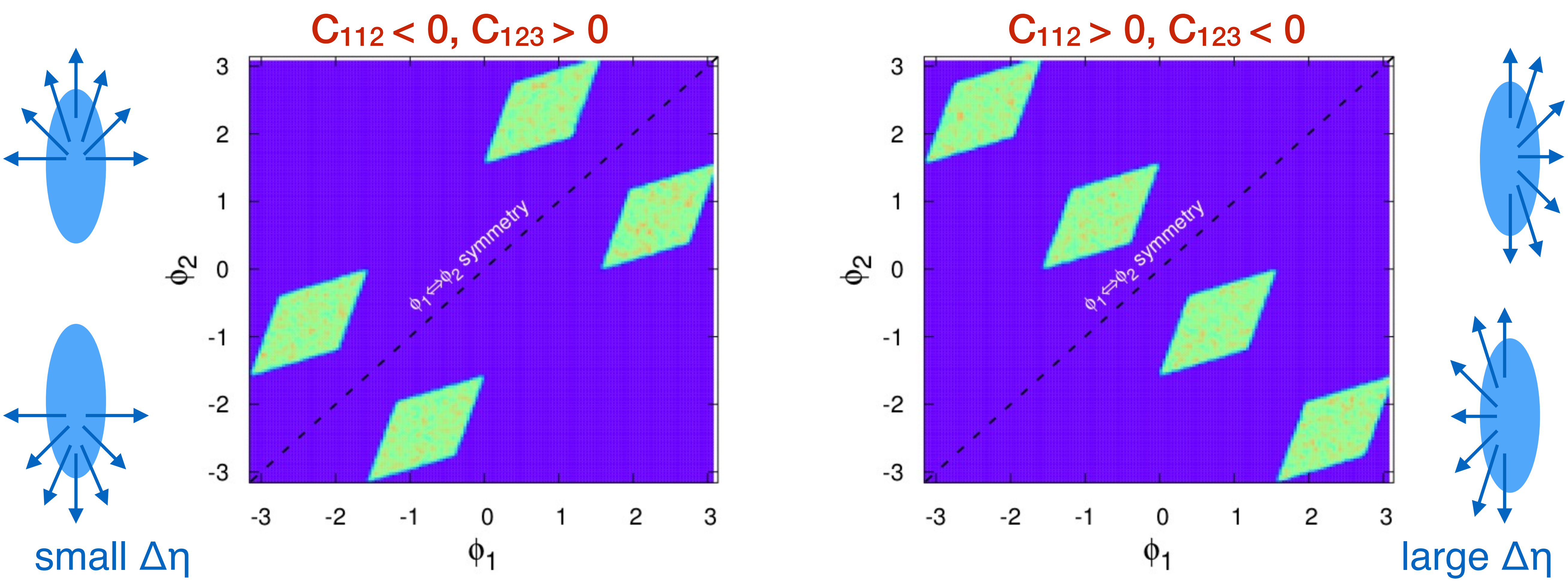


large Δη

Tomography of particle flow

Combining all results together can give us a picture of collisions

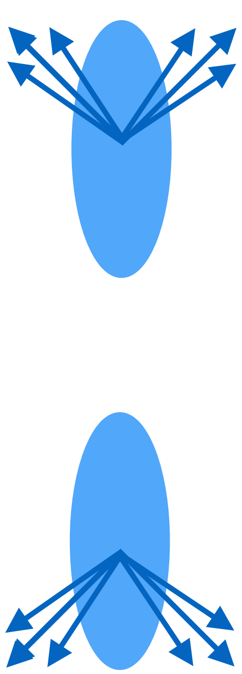
$$\langle\cos(1\phi_1 + 1\phi_3 - 2\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1' + 1\phi_2')\rangle$$
$$\langle\cos(1\phi_1 + 2\phi_3 - 3\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1' - 3\phi_2')\rangle$$
$$\langle\cos(2\phi_1 + 2\phi_3 - 4\phi_2)\rangle/v_2 \approx \langle\cos(2\phi_1' - 4\phi_2')\rangle$$
$$\langle\cos(2\phi_3 + 3\phi_1 - 5\phi_2)\rangle/v_2 \approx \langle\cos(3\phi_1' - 5\phi_2')\rangle$$



Tomography of particle flow

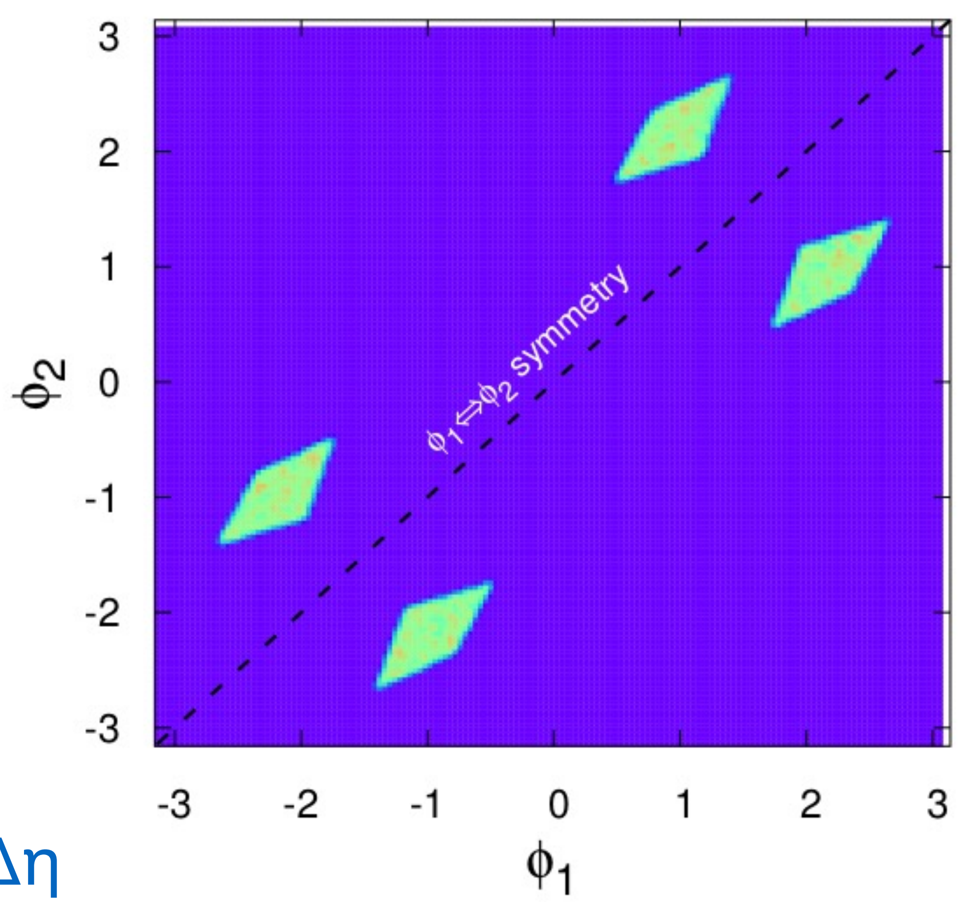
Combining all results together can give us a picture of collisions

$$\langle\cos(1\phi_1 + 1\phi_3 - 2\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1' + 1\phi_2')\rangle$$
$$\langle\cos(1\phi_1 + 2\phi_3 - 3\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1' - 3\phi_2')\rangle$$
$$\langle\cos(2\phi_1 + 2\phi_3 - 4\phi_2)\rangle/v_2 \approx \langle\cos(2\phi_1' - 4\phi_2')\rangle$$
$$\langle\cos(2\phi_3 + 3\phi_1 - 5\phi_2)\rangle/v_2 \approx \langle\cos(3\phi_1' - 5\phi_2')\rangle$$

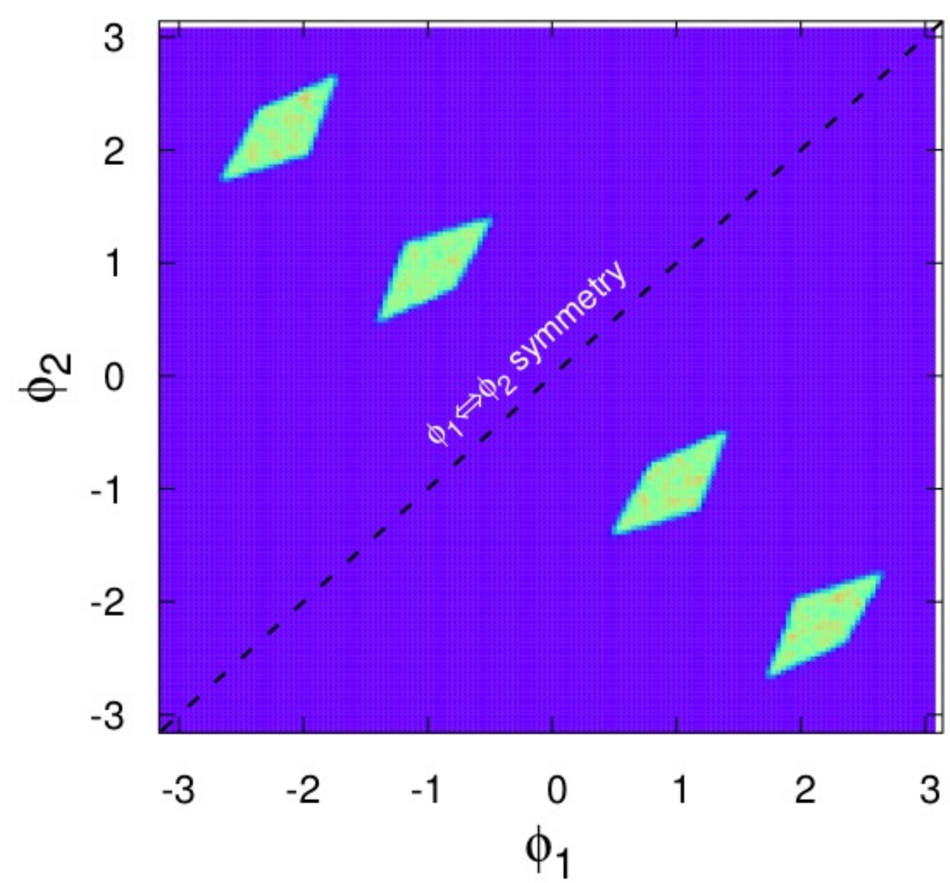


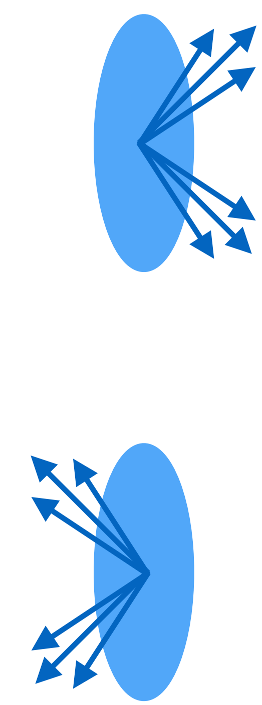
small Δη

$C_{112}<0$, $C_{123}>0$, $C_{224}>0$



$C_{112}>0$, $C_{123}<0$, $C_{224}>0$



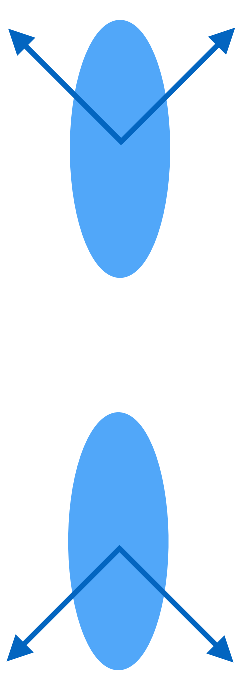


large Δη

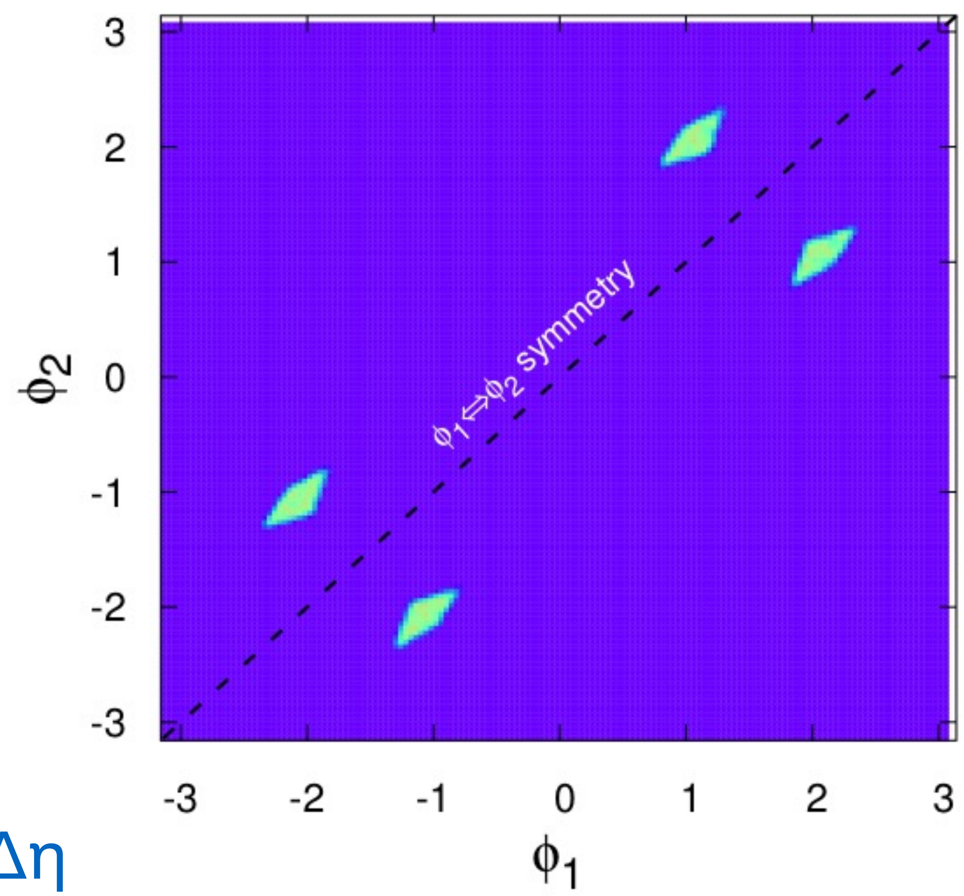
Tomography of particle flow

Combining all results together can give us a picture of collisions

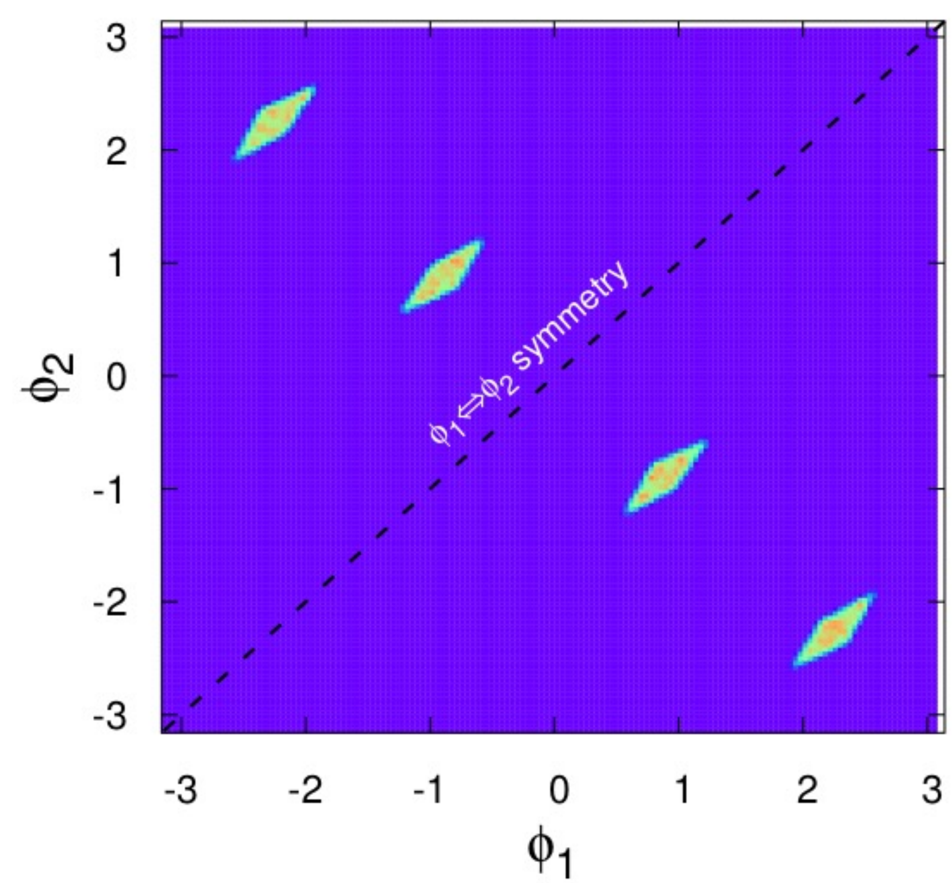
$$\langle\cos(1\phi_1+1\phi_3-2\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1'+1\phi_2')\rangle$$
$$\langle\cos(1\phi_1+2\phi_3-3\phi_2)\rangle/v_2 \approx \langle\cos(1\phi_1'-3\phi_2')\rangle$$
$$\langle\cos(2\phi_1+2\phi_3-4\phi_2)\rangle/v_2 \approx \langle\cos(2\phi_1'-4\phi_2')\rangle$$
$$\langle\cos(2\phi_3+3\phi_1-5\phi_2)\rangle/v_2 \approx \langle\cos(3\phi_1'-5\phi_2')\rangle$$

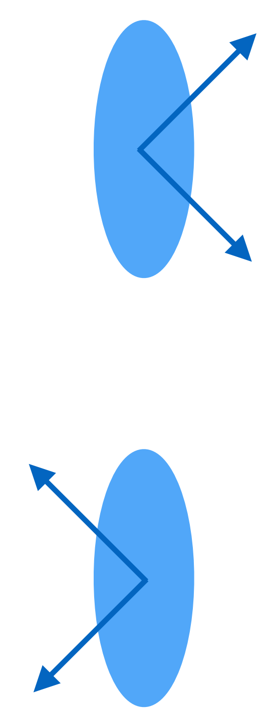


$C_{112}<0, C_{123}>0, C_{224}>0, C_{235}>0$



$C_{112}>0, C_{123}<0, C_{224}>0, C_{235}>0$





small Δη

large Δη

Summary

Measurement of charge inclusive three particle correlations :

- Goes beyond conventional measurements of flow
- Potential for constraining η/s (T)
- Indicates presence of non-linear hydrodynamic response
- Constrains modeling of 3D-initial state and hydro evolution

Outlook

PID, charge dependence of $C_{m,n,m+n}$

Measurement of $C_{m,n,m+n}$ over wider rapidity range with STAR upgrade

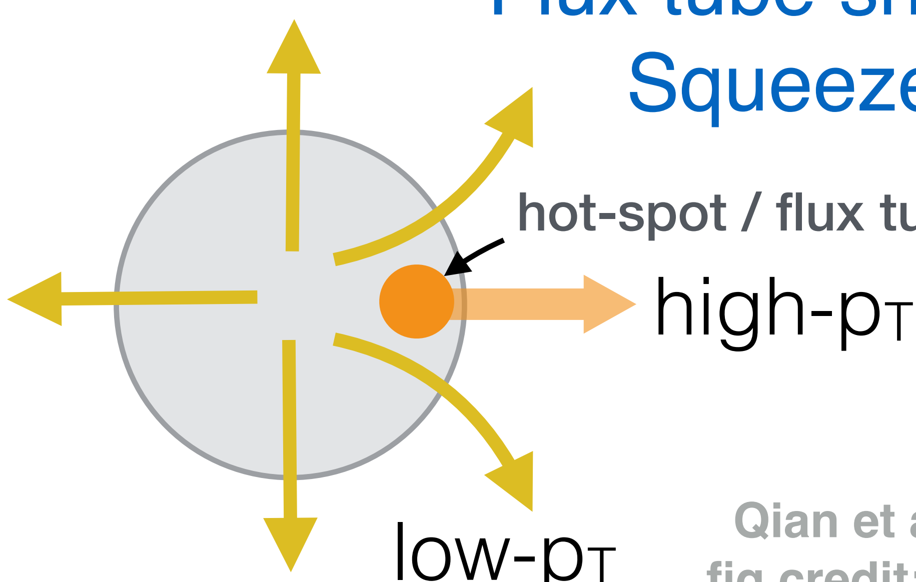
Backup

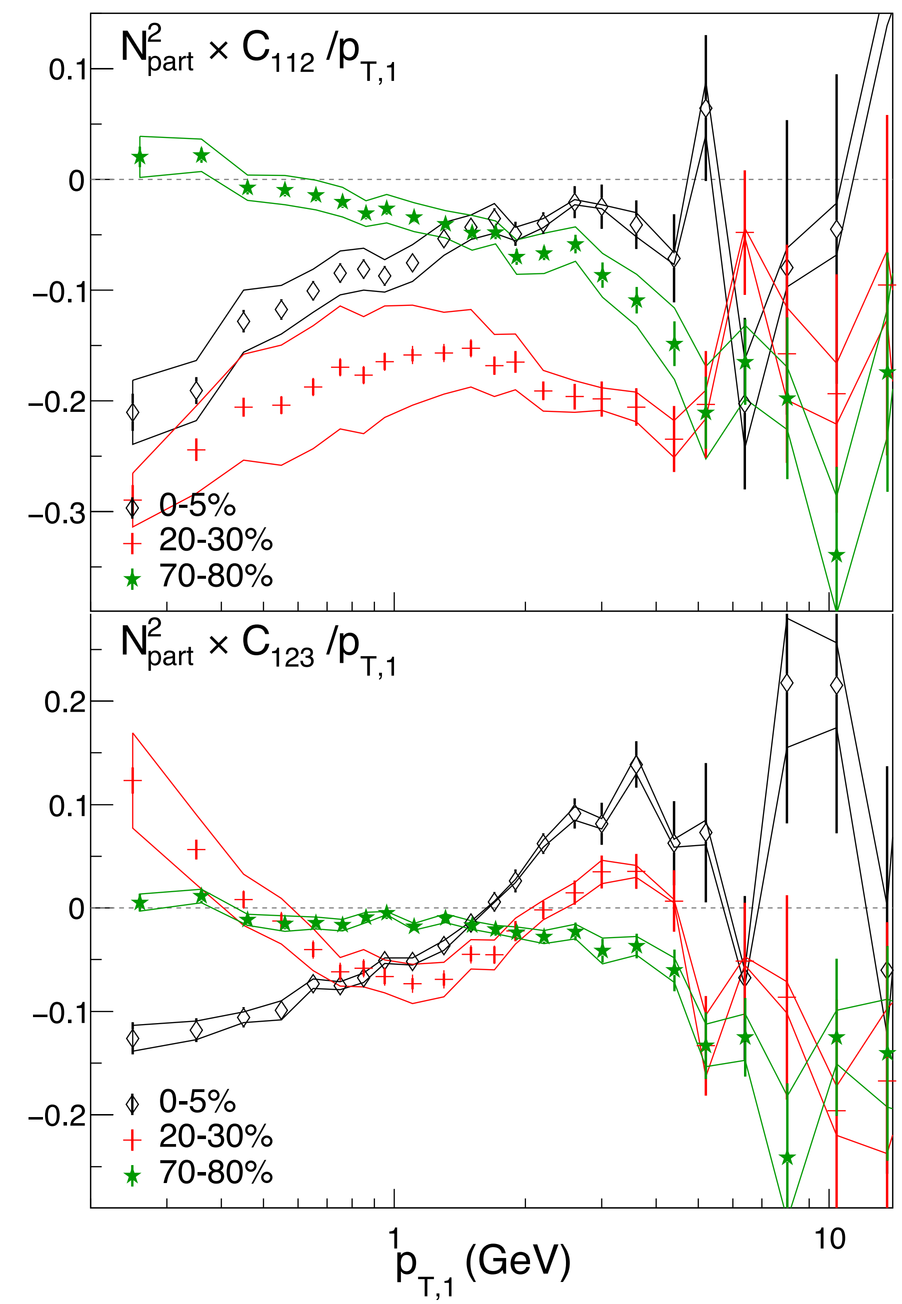
Motivation-IV (Insights beyond flow-I)

p_T dependence of $C_{m,n,m+n}$

Momentum conservation

Flux tube shadowing
Squeeze-out





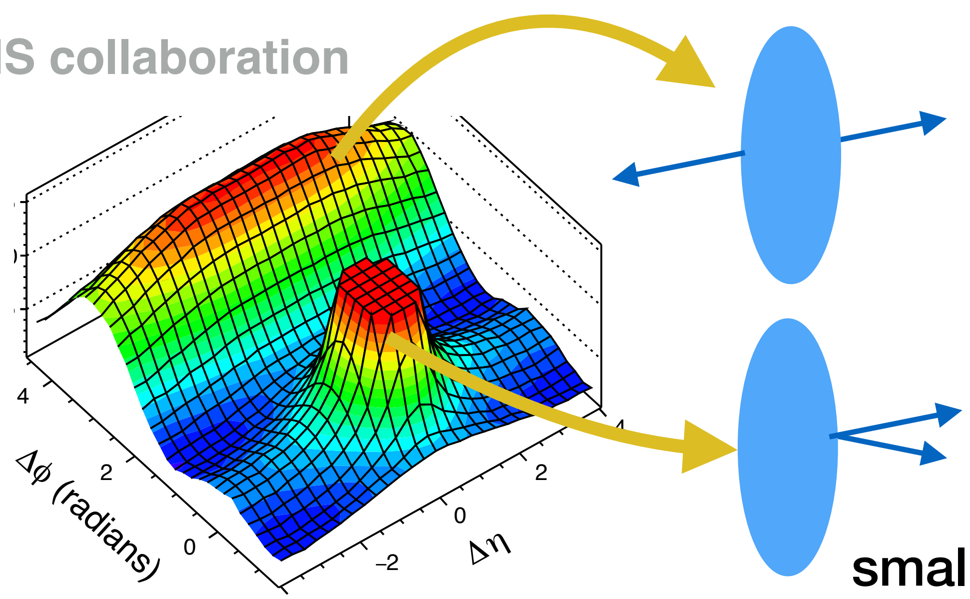
Qian et al 1305.4673
fig credit: R. Longacre

Motivation-IV (Insights beyond flow-II)

Δη dependence of $C_{m,n,m+n}$

Jets/mini-jets correlated to reaction plane

fig : CMS collaboration



large $\Delta\eta_{13}$ → forced to be back-to-back

C_{123} ~ cos(-3π), cos(π) → (-1)

C_{224} ~ cos(-4π), cos(2π) → (+1)

C_{123} ~ (cos(0),cos(-2π)) → (+1)

C_{224} ~ (cos(0),cos(-2π)) → (+1)

small $\Delta\eta_{13}$ → no constrain, more probable to be same-sided