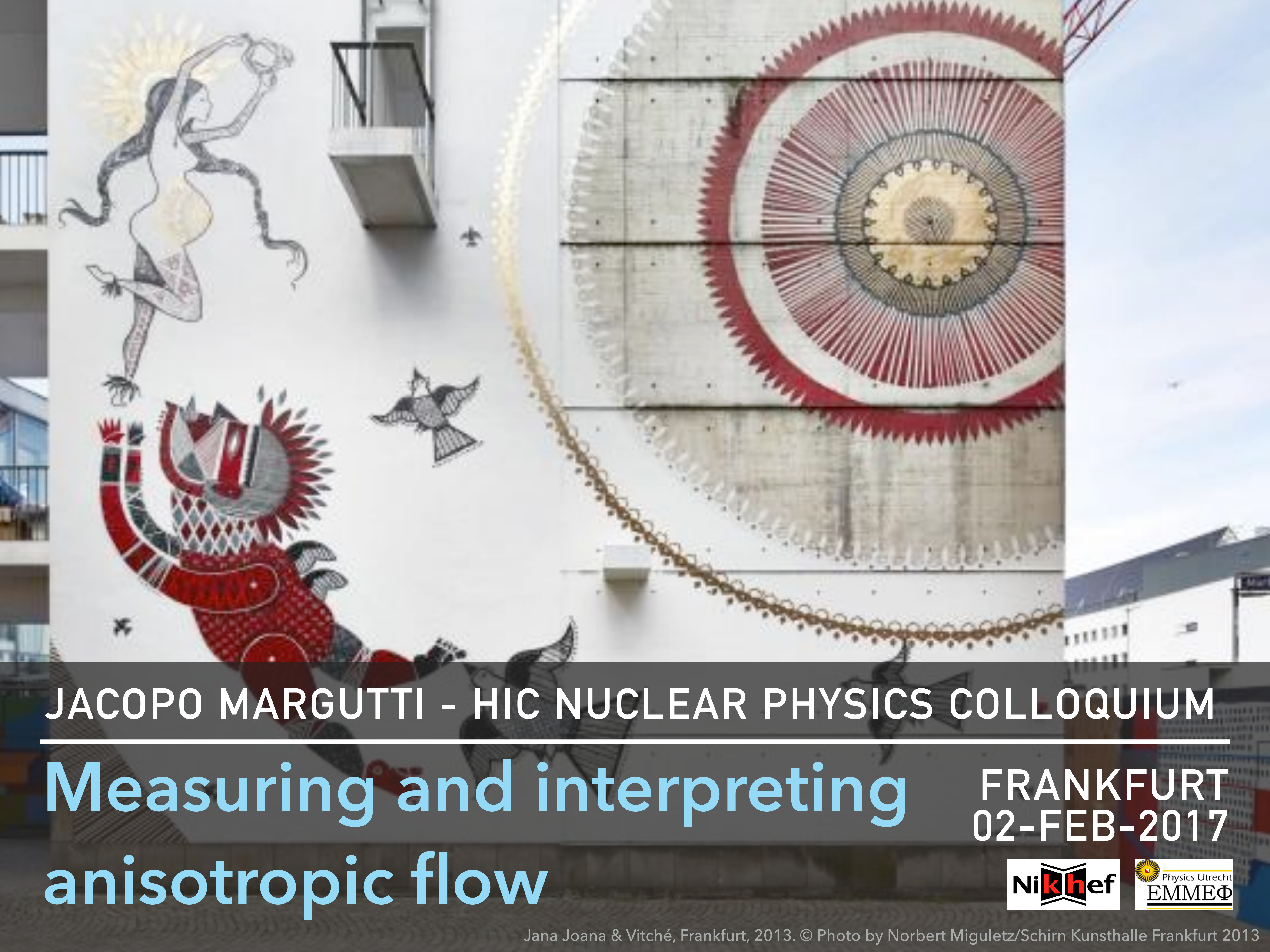


JACOPO MARGUTTI - HIC NUCLEAR PHYSICS COLLOQUIUM

Measuring and interpreting anisotropic flow

FRANKFURT
02-FEB-2017

Nikhef

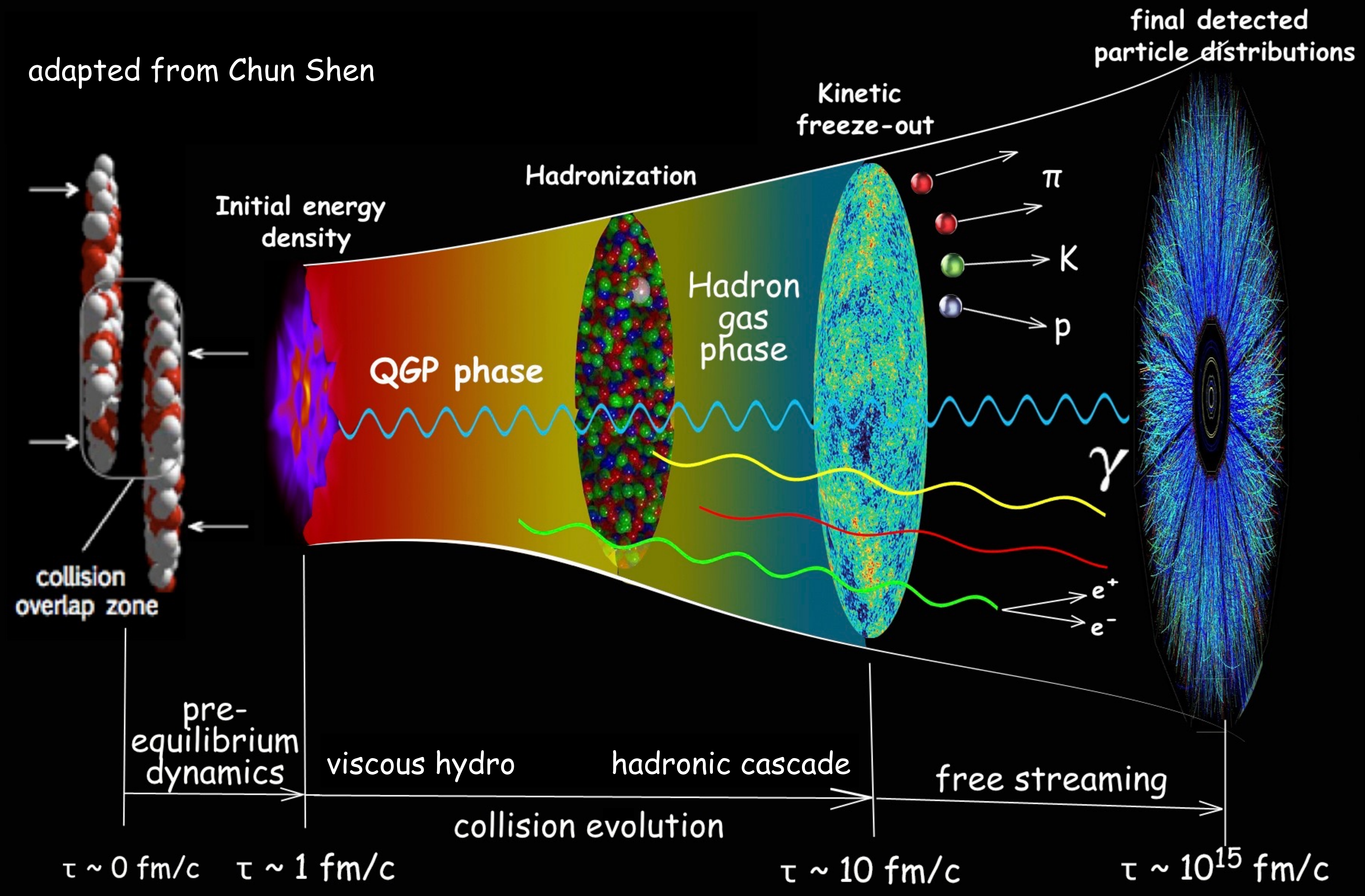
Physics Utrecht
EMMEΦ

Jana Joana & Vitché, Frankfurt, 2013. © Photo by Norbert Miguletz/Schirn Kunsthalle Frankfurt 2013

Outline

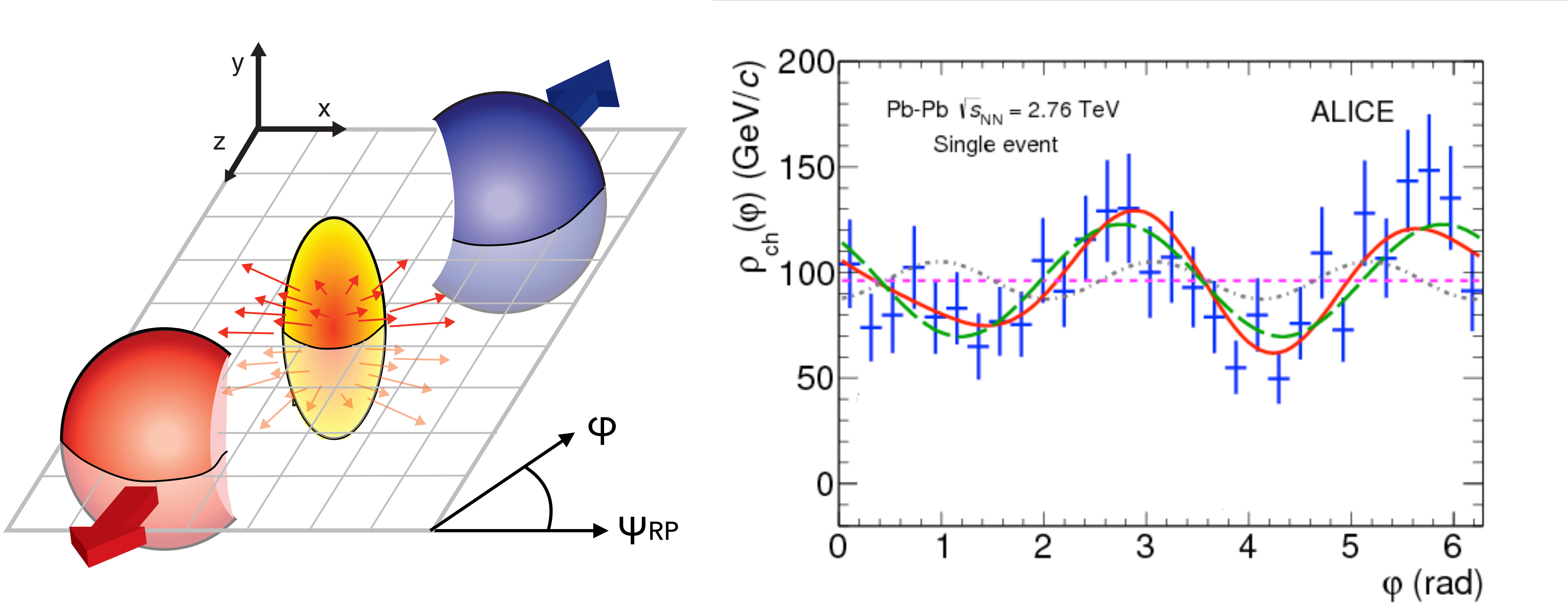
- Intro: what is flow
- Why should you care?
- How do we measure it?
- What have we learned so far?
- Where do we go from here?

Heavy-ion collisions



What is flow?

Anisotropic Flow: anisotropies in the azimuthal distribution of particles in momentum space.



ALICE, Phys. Lett. B 753 (2016)

Why does it flow?

It is commonly interpreted as the result of the hydrodynamic behaviour of strongly-interacting QCD matter:

- strongly-interacting non-spherical system
  –> anisotropic pressure –> anisotropic flow

Spatial anisotropies of the initial system are due to:

- event-by-event fluctuations
- impact parameter

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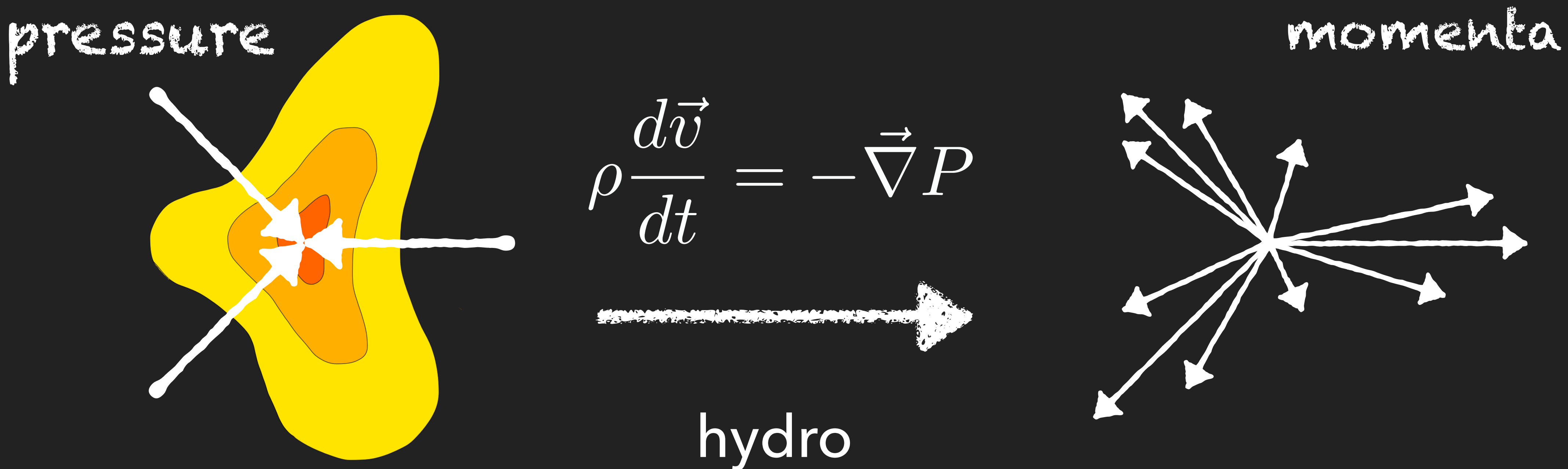

$$\rho \frac{d\vec{v}}{dt} = -\vec{\nabla} P$$

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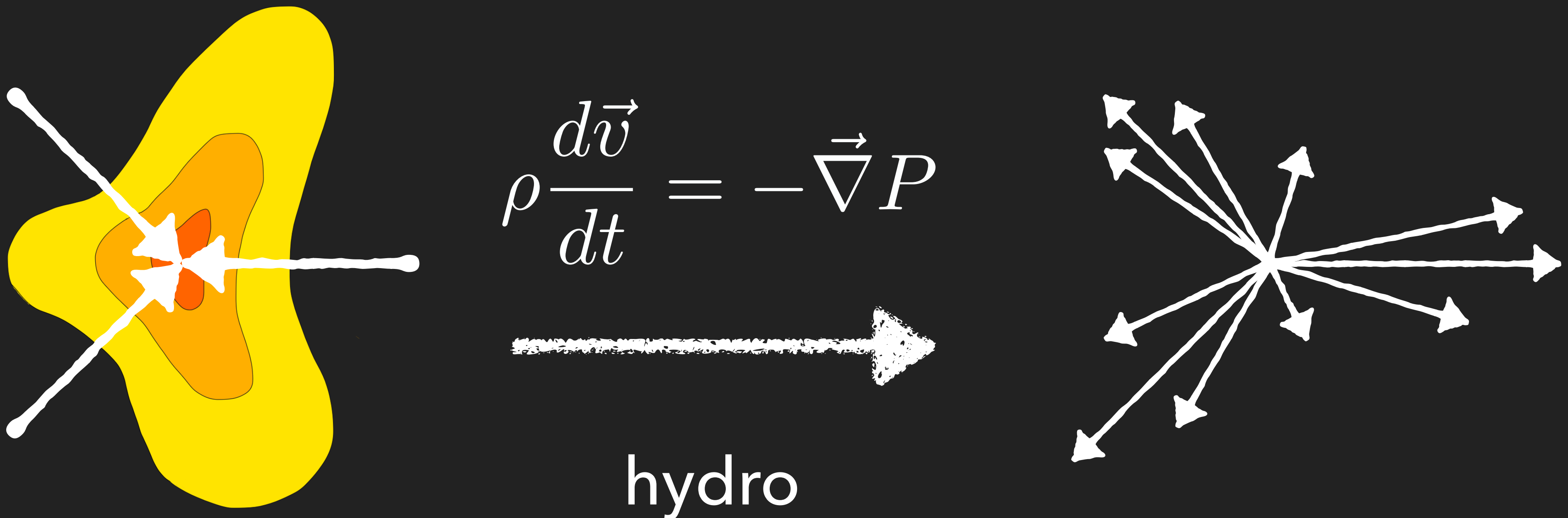

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hydro

spatial anisotropies

momentum anisotropies

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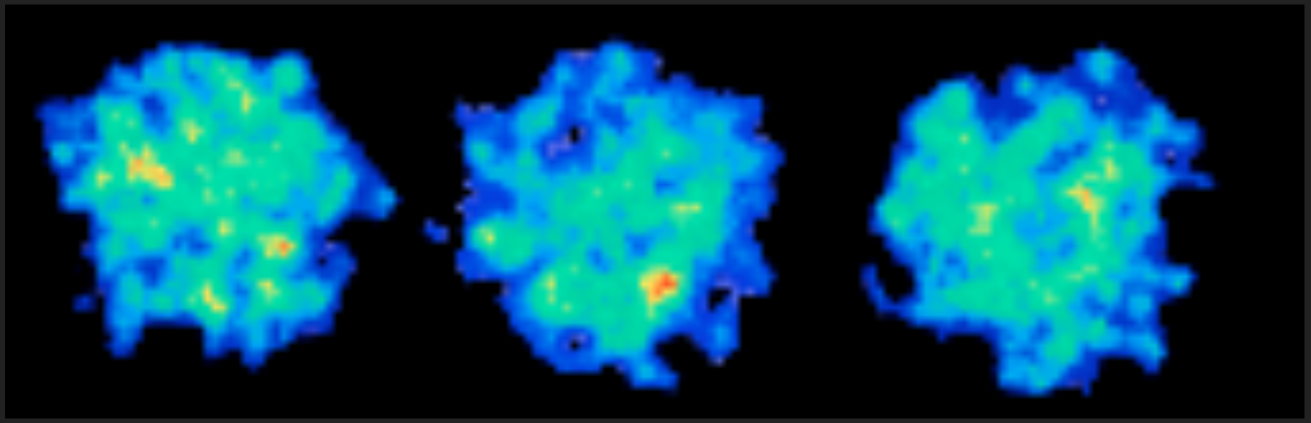

from B.Schenke

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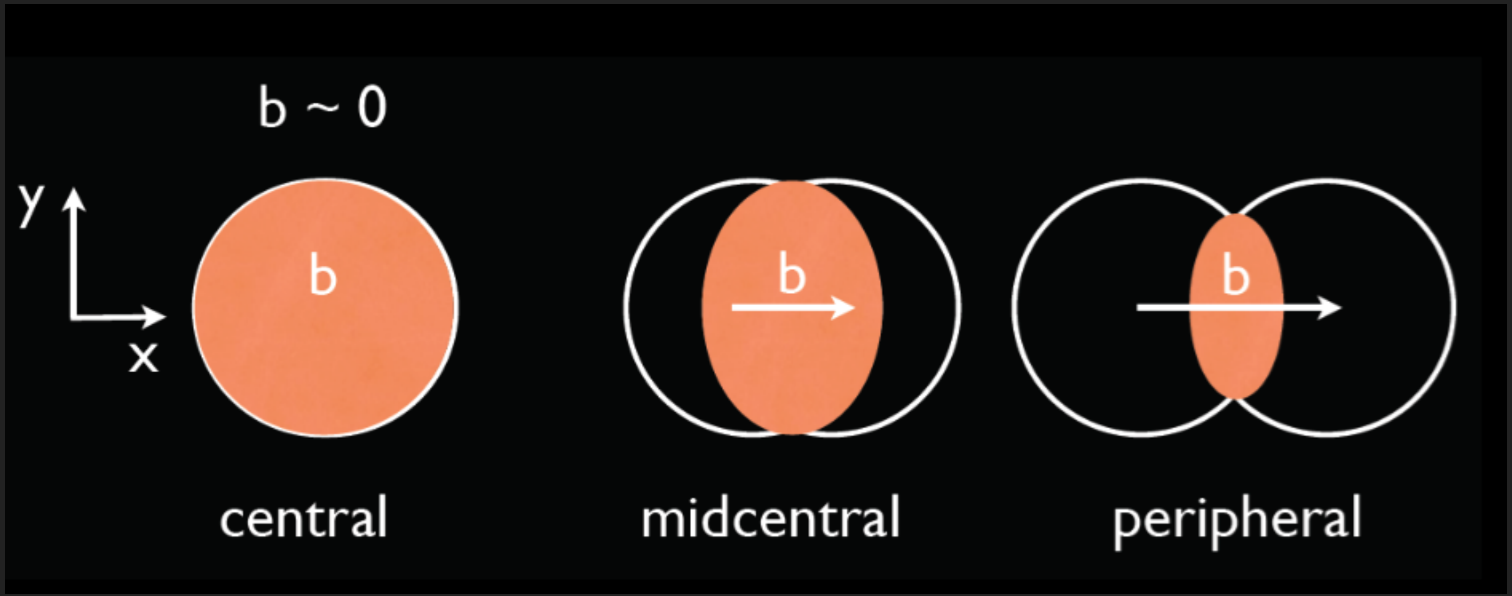
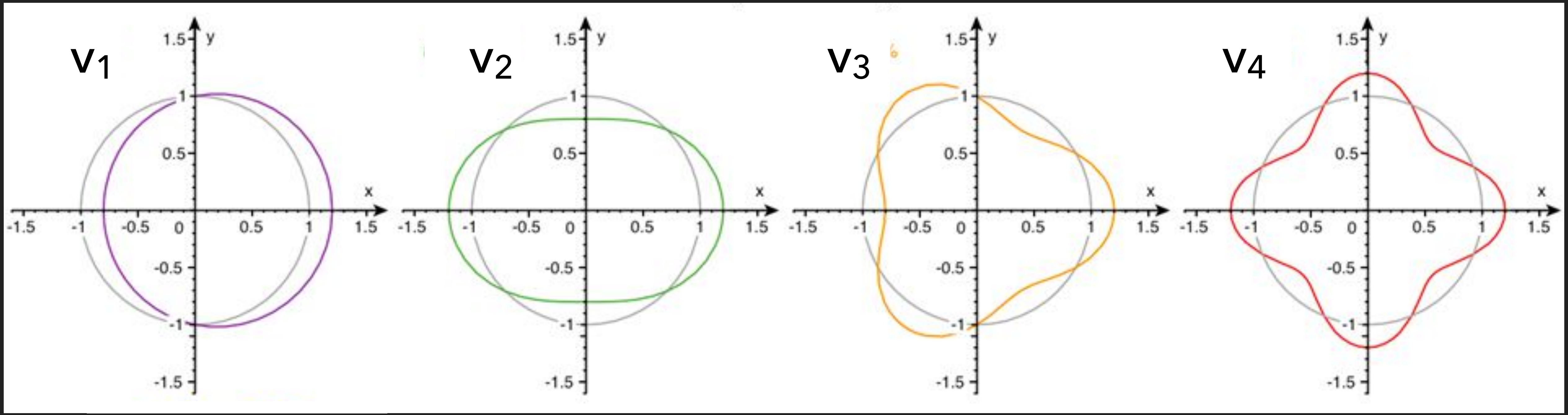


in HI collisions, strong elliptical anisotropy, depending on centrality / impact parameter.

How do we quantify it?

Flow is quantified in terms of Fourier coefficients:

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



directed flow

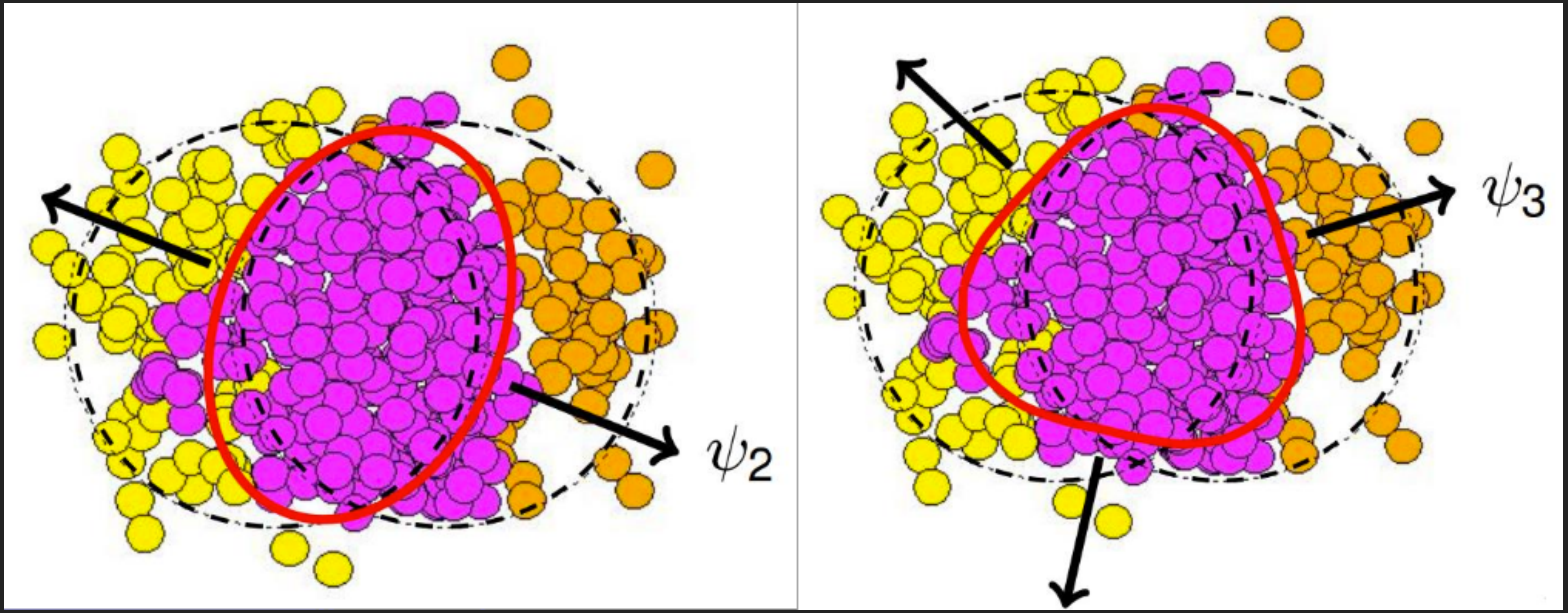
elliptic flow

triangular flow

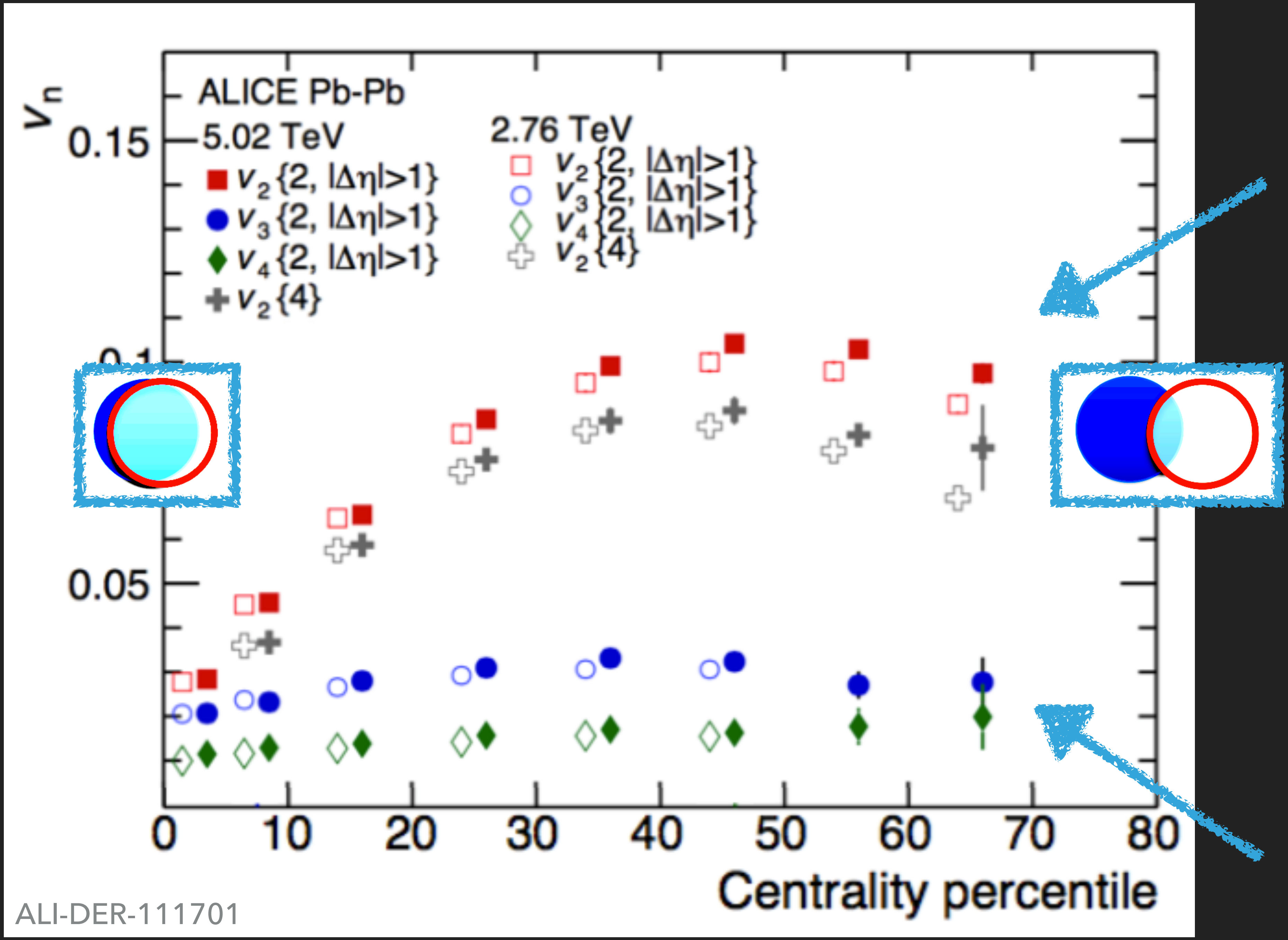
Symmetry planes

There's not only the reaction plane:

Fluctuating initial conditions → Each harmonic (v_n) develops along its corresponding symmetry plane ($\psi_n \neq \psi_{RP}$)



a First Look



impact parameter dominated

fluctuations dominated

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a Realistic Medium

Whatever information you want to extract about the QGP from experimental data requires a realistic modelling of a Heavy-Ion collision:

- Energy loss: jets, heavy flavour
- Charmonia
- Strangeness production
- Photons / dileptons

Most of what we know so far has been inferred from soft hadron observables: p_T spectra, flow

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Flow can be measured with a variety of techniques:

- 2-particle correlation function (Δη,Δφ)
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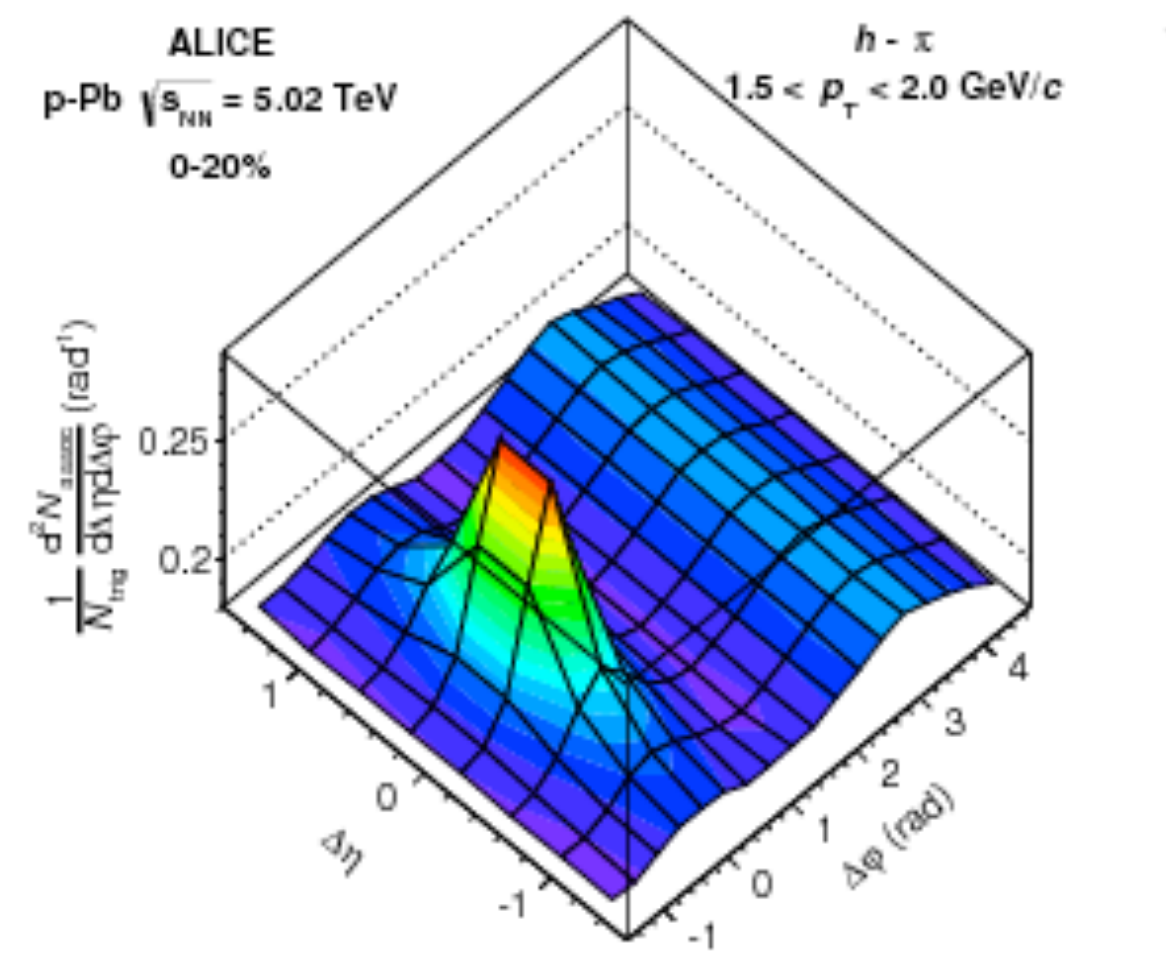

ALICE, Phys. Lett. B 726 (2013)

$$S(\Delta\varphi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2 N}{d\Delta\varphi d\Delta\eta}$$

- Flow
- Jets (near-side and away-side)

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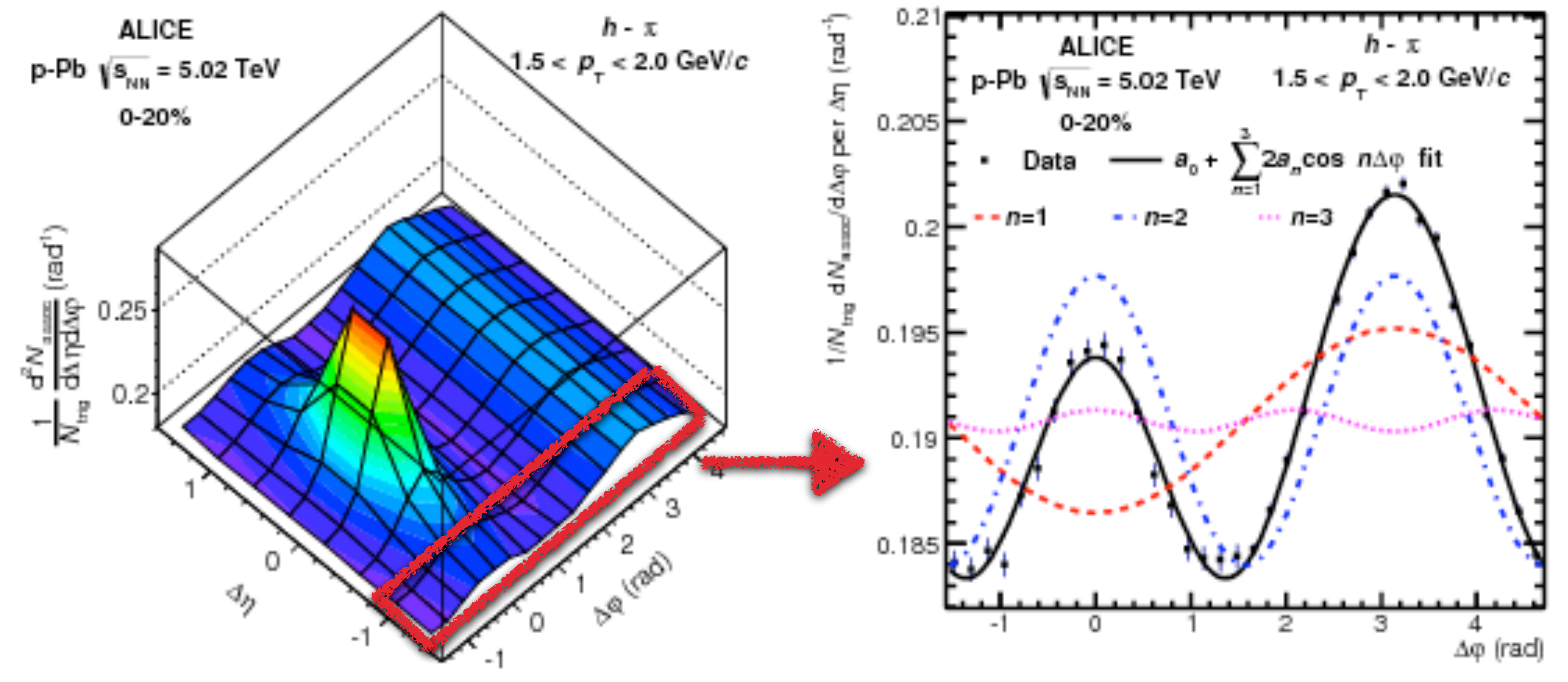

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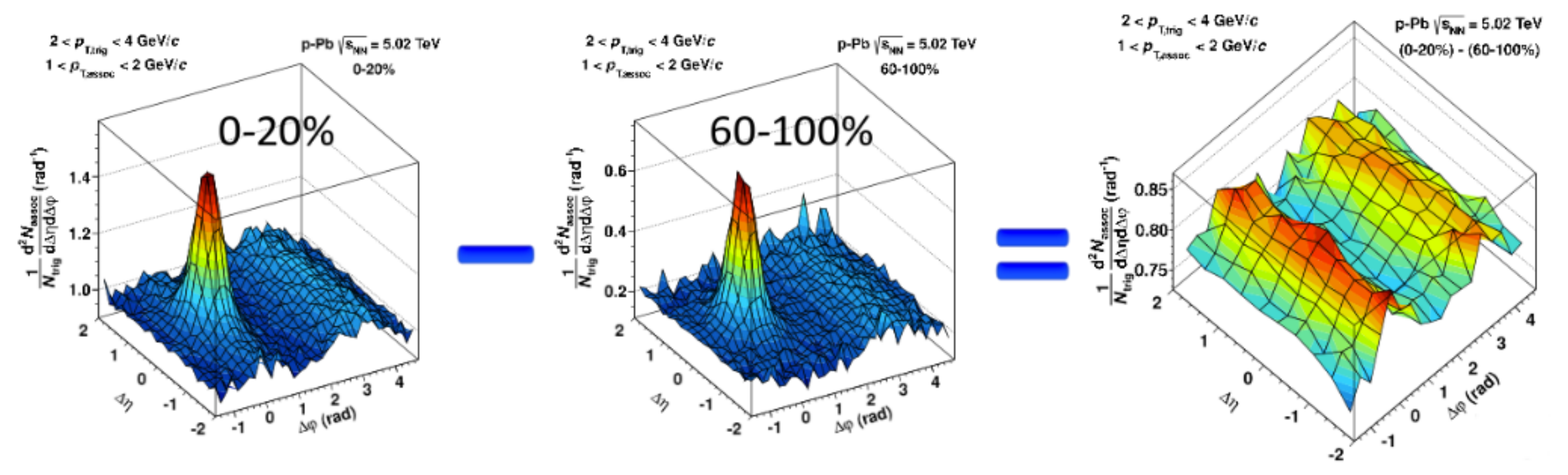
"the Double Ridge"



ALICE, Phys. Lett. B 719 (2013)

How do we measure it?

Flow can be measured with a variety of techniques:

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- Scalar Product / Event Plane methods

correlate tracks with an event plane (ψ_{EP})
reconstructed with an independent detector:

$$v_n\{\mathrm{EP}\} = \frac{1}{R}\langle\cos(n(\phi - \Psi_{\mathrm{EP}}))\rangle$$

N.B. *conceptually, it's again a 2-particle correlation*

How do we measure it?

Flow can be measured with a variety of techniques:

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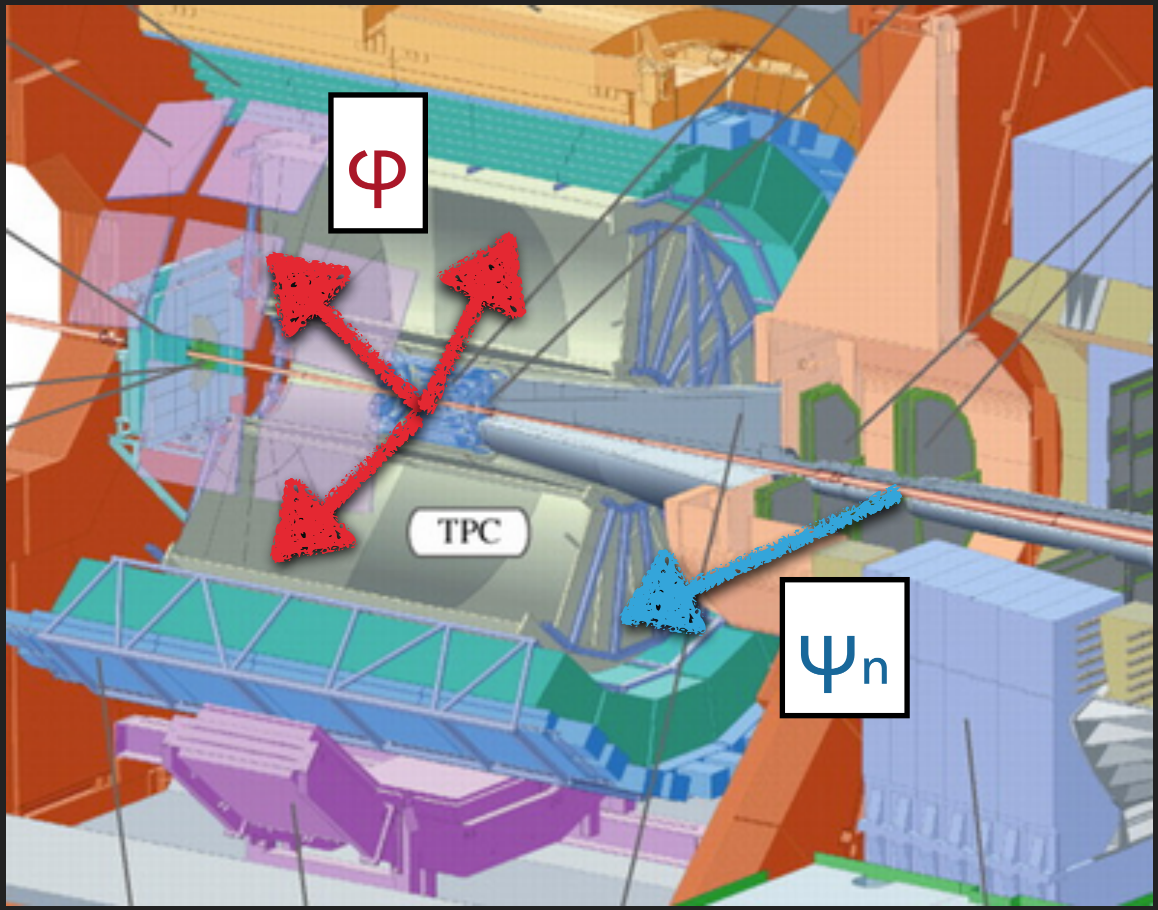
can be used to correlate reconstructed tracks with event planes from forward detectors (scintillators/ calorimeters)

ALICE



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    - Provide additional information on flow fluctuations
    - Analytically suppress background

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Multi-particle cumulants

Possible to measure different **cumulants** of the underlying flow:

2-particle: $\langle\langle 2\rangle\rangle = \langle\langle e^{in(\varphi_1-\varphi_2)}\rangle\rangle = \langle v_n^2\rangle$

4-particle: $\langle\langle 4\rangle\rangle = \langle\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\rangle\rangle = \langle v_n^4\rangle$

$$v_n\{2\} = \sqrt{\langle v_n^2\rangle}$$

$$v_n\{4\} = \sqrt[4]{2\langle v_n^2\rangle^2 - \langle v_n^4\rangle}$$

by definition:

$v_n\{4\} = v_n\{2\} = \langle v_n\rangle$ if v_n is constant

$v_n\{4\} \neq v_n\{2\} \neq \langle v_n\rangle$ if v_n **fluctuates**

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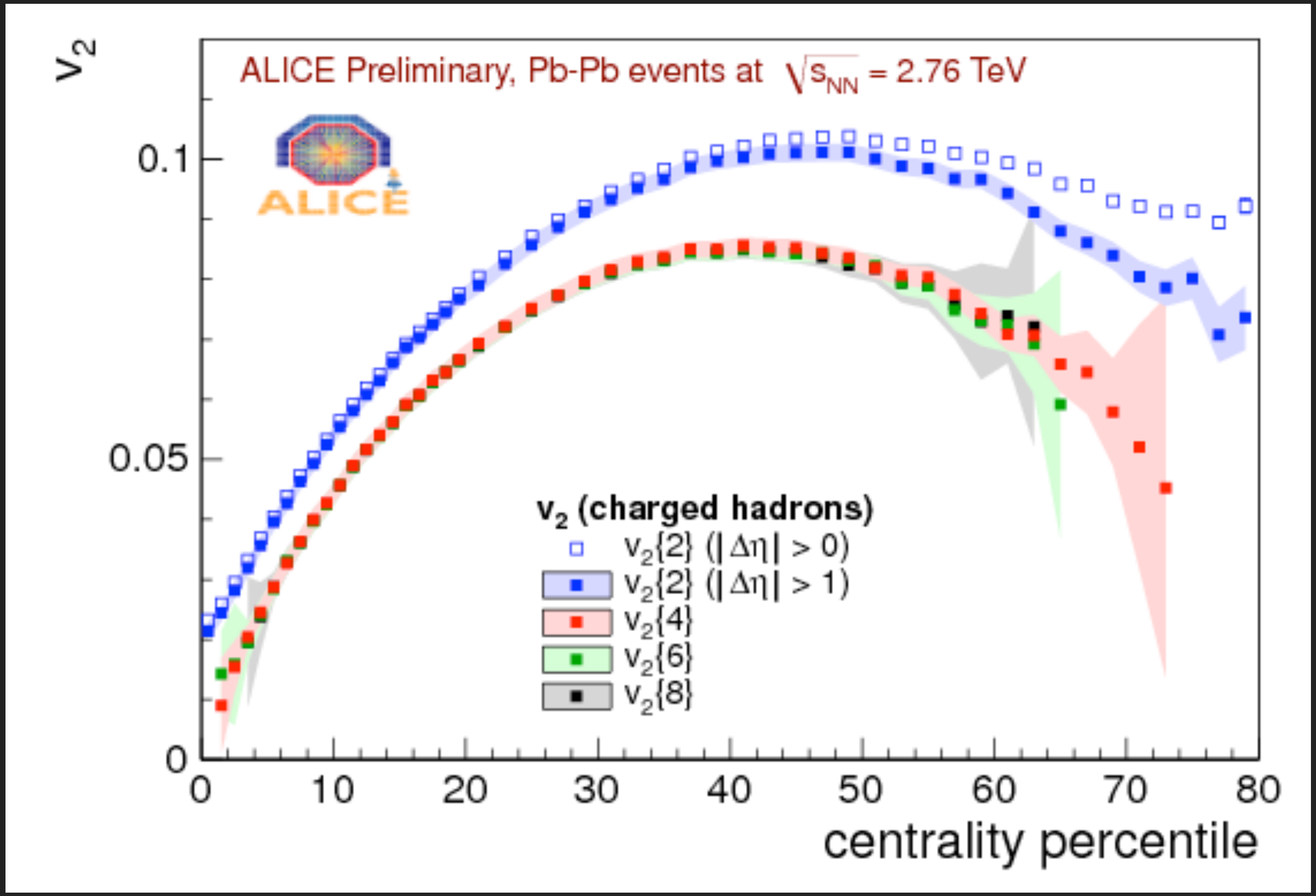


ALICE, QM '11

$v_2\{2\} \neq v_2\{4\}$

flow fluctuations!

Up to order σ^2:

$$v_2\{2\} = \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$

$$v_2\{4\} = v_2\{6\} = \ldots v_2\{n\} = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$

the Flow Hypothesis

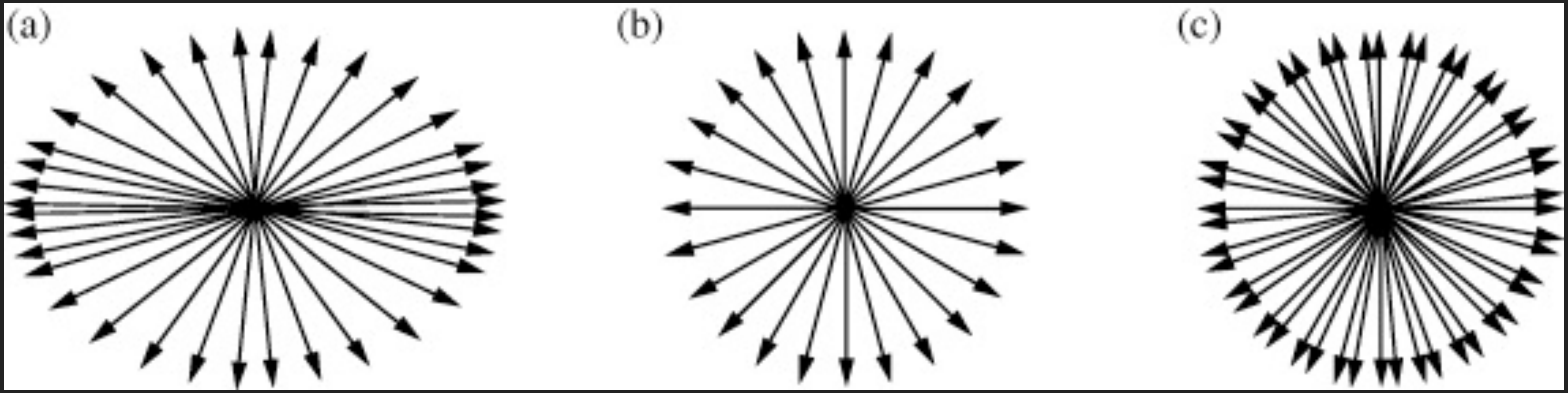
2- and multi-particle correlations are based on one simple assumption (*a.k.a. the flow hypothesis*)

$$\left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle = \left\langle e^{in(\varphi_1-\Psi_n-(\varphi_2-\Psi_n))}\right\rangle \overset{*}{=}$$

$$= \left\langle e^{in(\varphi_1-\Psi_n)}\right\rangle\left\langle e^{in(\varphi_2-\Psi_n)}\right\rangle = \left\langle v_n^2\right\rangle$$

** Correlations among produced particles are induced only by correlation of each particle with the event planes.*

Non-flow



$v_2>0$, $v_2\{2\}>0$ $v_2=0$, $v_2\{2\}=0$ $v_2=0$, $v_2\{2\}>0$

short-range correlations (jets, resonances) unrelated to the reaction plane enter into multi-particle correlations:

$$v_2\{2\} = \sqrt{\langle\langle e^{i2(\varphi_1-\varphi_2)}\rangle\rangle} = \sqrt{\langle v_n^2 + \delta_2\rangle}$$

e.g. for two-body decays: $\delta_2 \propto 1/M$

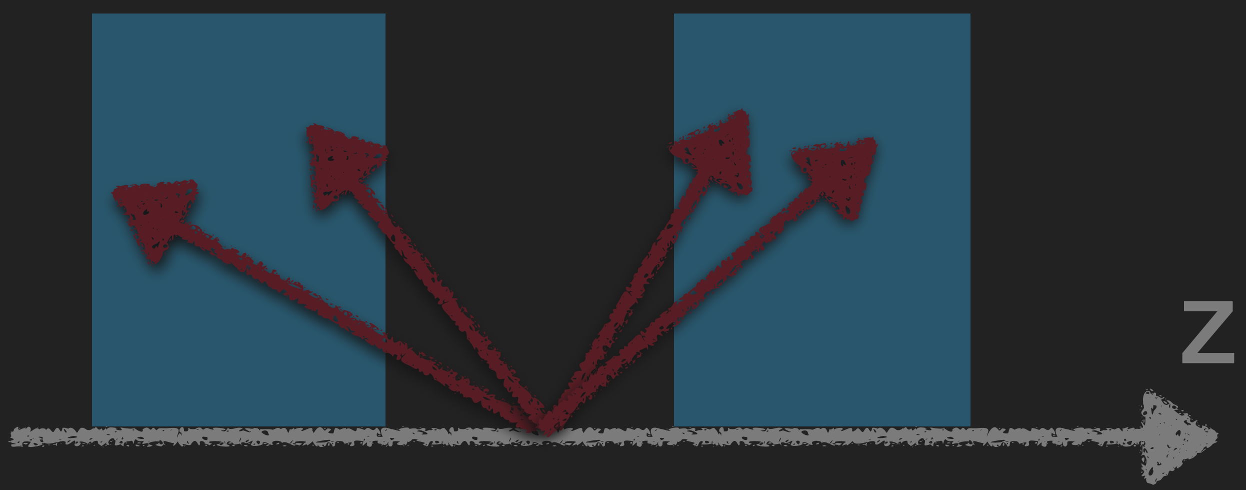
Non-flow

but are suppressed in higher order cumulants:

$$
\begin{aligned}
v_2\{4\} &= \sqrt[4]{2\,\langle\langle e^{i2(\varphi_1-\varphi_2)}\rangle\rangle^2 - \langle\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\rangle\rangle} \\
&= \sqrt[4]{2\,\langle v_2^2+\delta_2\rangle^2 - \langle v_2^4+\delta_4+4v_2^2\delta_2+2\delta_2^2\rangle} \\
&= \sqrt[4]{\langle v_2^4-\delta_4\rangle}
\end{aligned}
$$

$$\delta_4 \propto 1/M^3$$

and/or by imposing a large gap in rapidity (Δη>1):



the advantage of using forward detectors!

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$$= \sqrt[4]{2\,\langle v_2^2 + \delta_2\rangle^2 - \langle v_2^4 + \delta_4 + 4v_2^2\delta_2 + 2\delta_2^2\rangle}$$

$$= \sqrt[4]{\langle v_2^4 - \delta_4\rangle}$$

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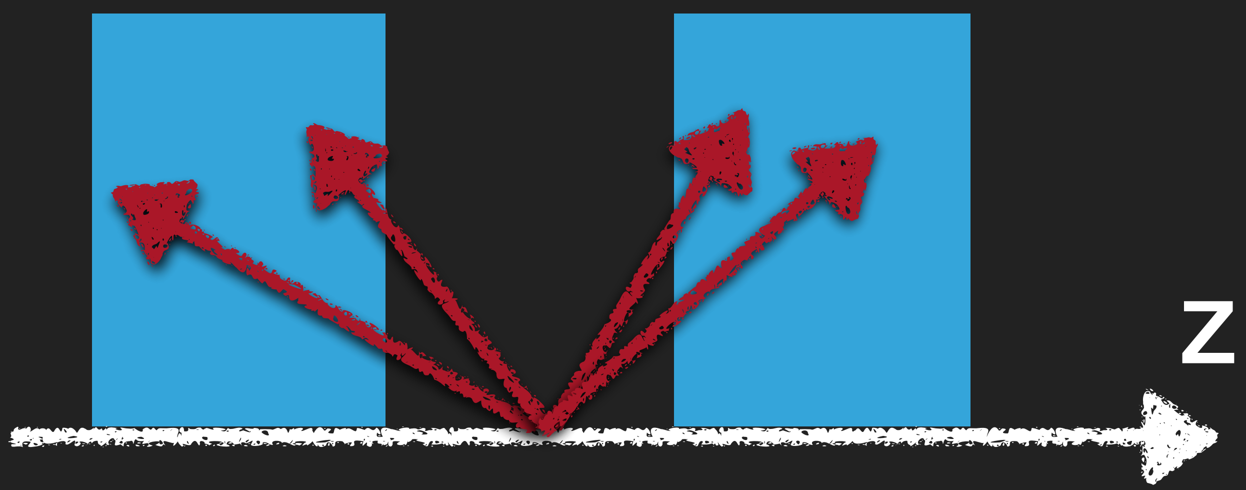


the advantage of using forward detectors!

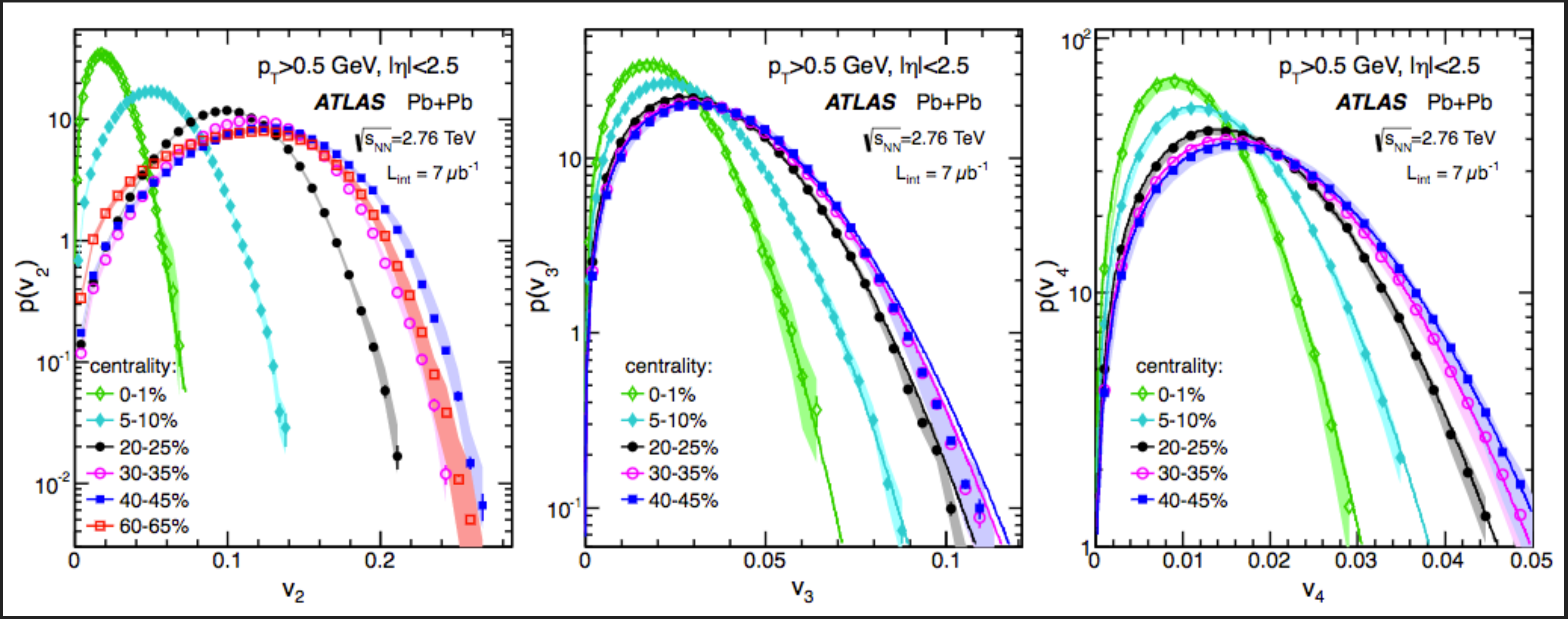
Flow tutti-frutti

Many different observables measurable (and measured) around flow:

- Centrality dependence
- p_T and η dependence
- Identified particles, resonances
- Flow fluctuations (also event-by-event)
- Event planes: p_T and η dependence
- Correlations between harmonics
- Event-Shape-Engineering

Flow fluctuations

Possible to reconstruct the complete v_n pdf:



ATLAS, JHEP 1311, 183 (2013)

Fairly well parametrised by a power law distribution:

$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$

L.Yan, J.Y. Ollitrault PRL 112, 082301 (2014)

Correlations between harmonics

Correlations between flow harmonics (*a.k.a. symmetric cumulants*):

$$\mathrm{SC}(m,n) = \frac{\langle\langle e^{i(m\phi_1+n\phi_2-m\phi_3-n\phi_4)}\rangle\rangle - \langle\langle e^{im(\phi_1-\phi_2)}\rangle\rangle\,\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle}{\langle\langle e^{im(\phi_1-\phi_2)}\rangle\rangle\,\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle}$$

$$\approx \frac{\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\,\langle v_n^2\rangle}{\langle v_m^2\rangle\,\langle v_n^2\rangle}\cos^2(c_n\Psi_n - c_m\Psi_m)$$

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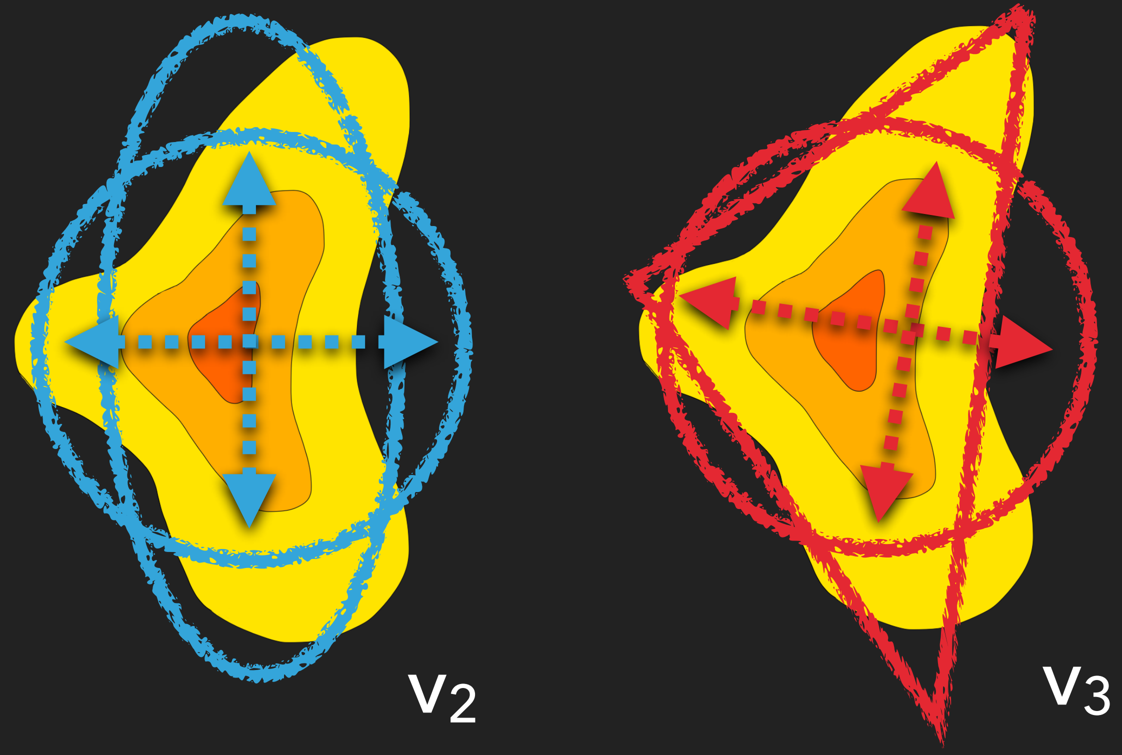
correlation between

flow fluctuations



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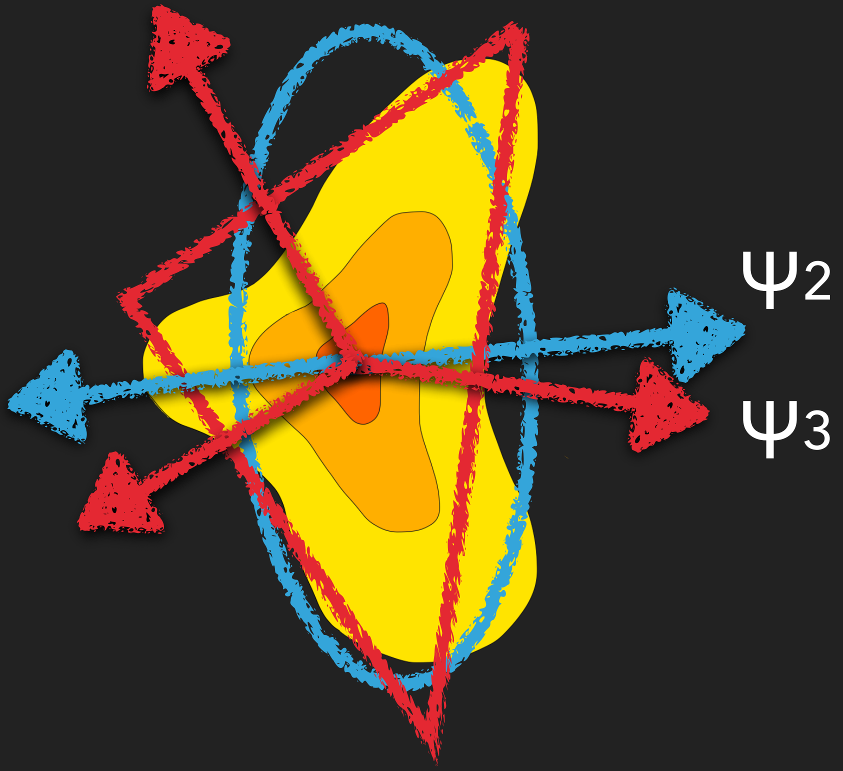
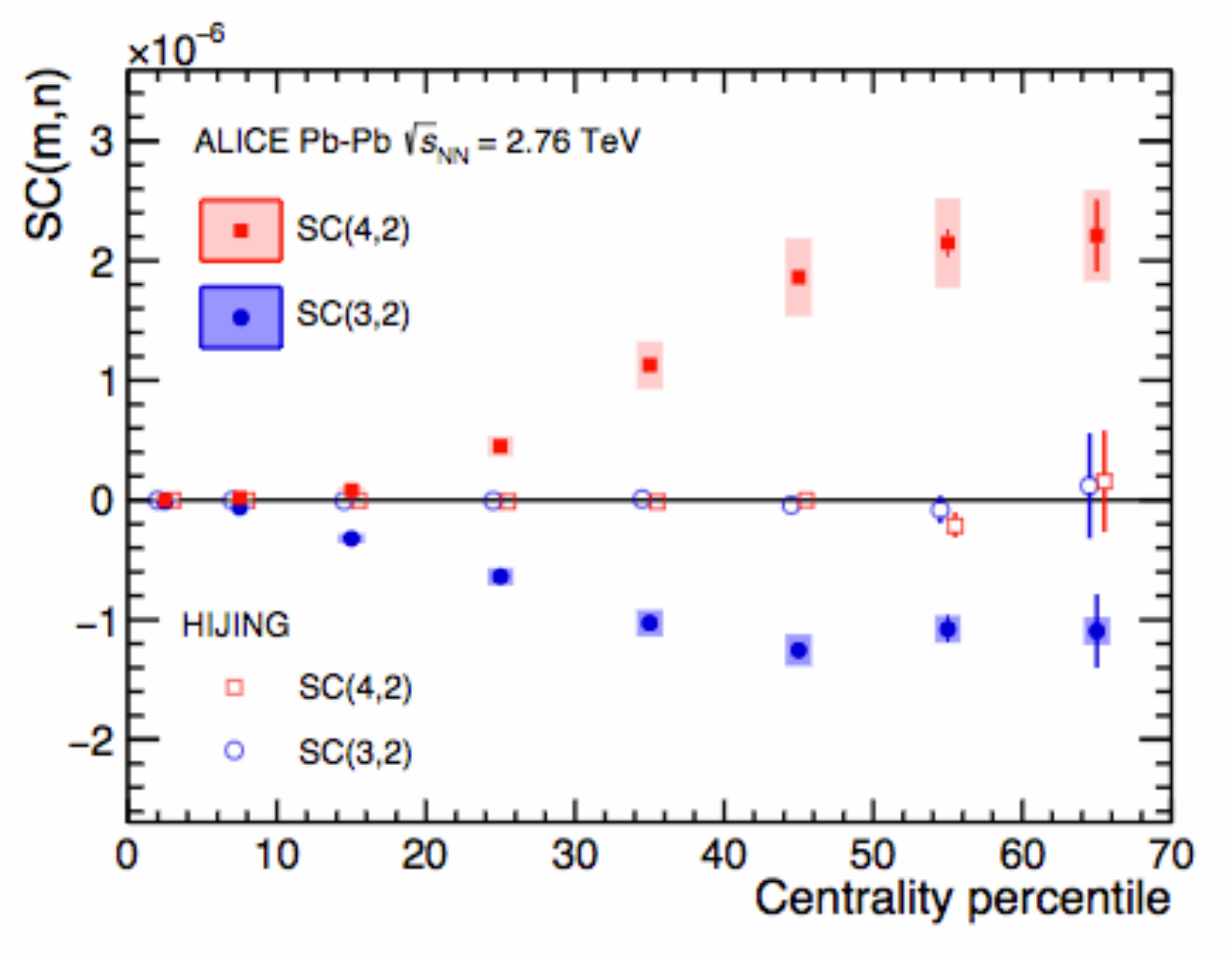


correlation between event planes

Correlations between harmonics

Correlations between flow harmonics (*a.k.a. symmetric cumulants*):



v_2 and v_4: correlated

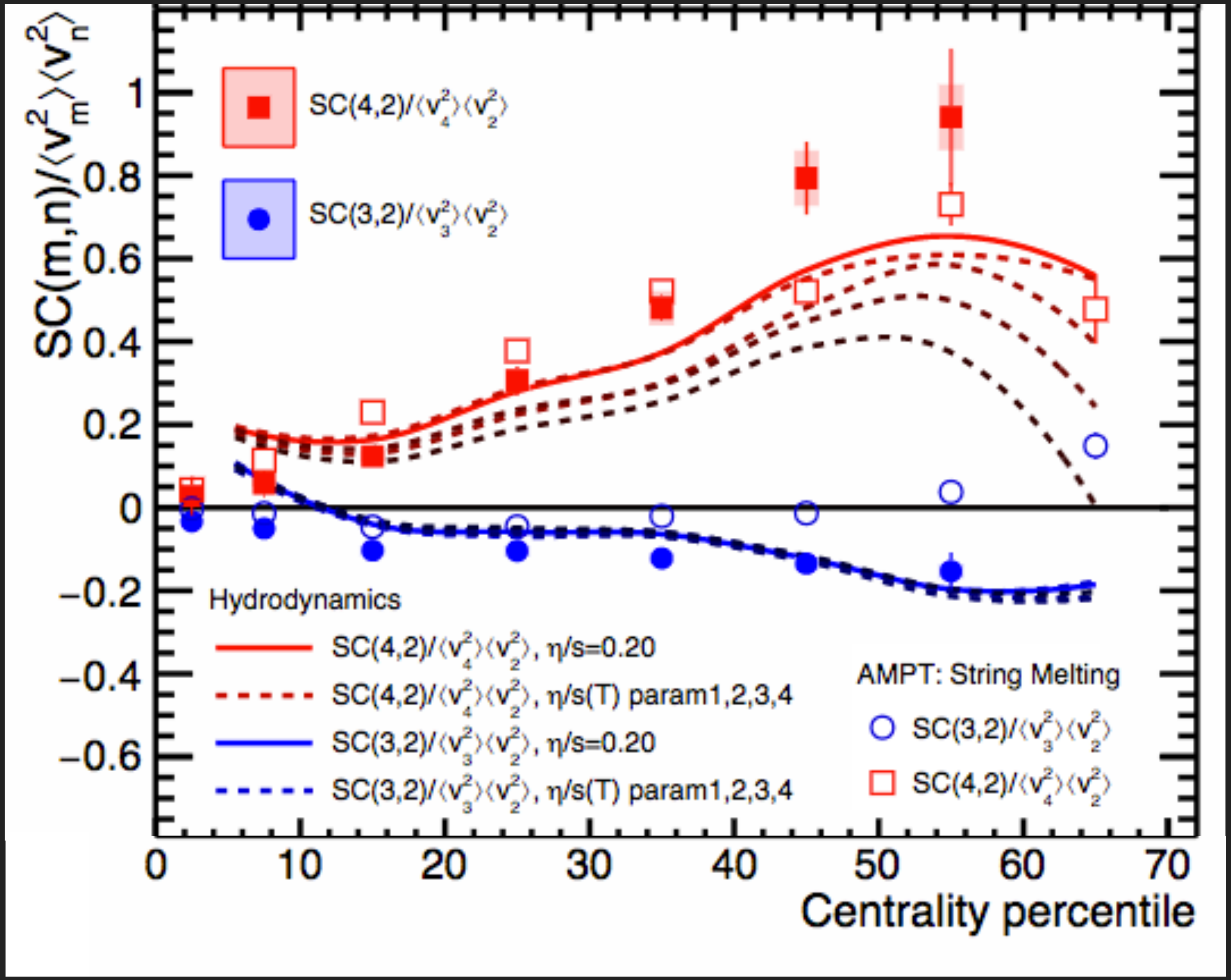
v_2 and v_3: anticorrelated

ALICE, PRL 117, 182301 (2016)

Correlations between harmonics

Correlations between flow harmonics (*a.k.a. symmetric cumulants*):

Show great potential to decouple different model parameters!



ALICE, PRL 117, 182301 (2016)

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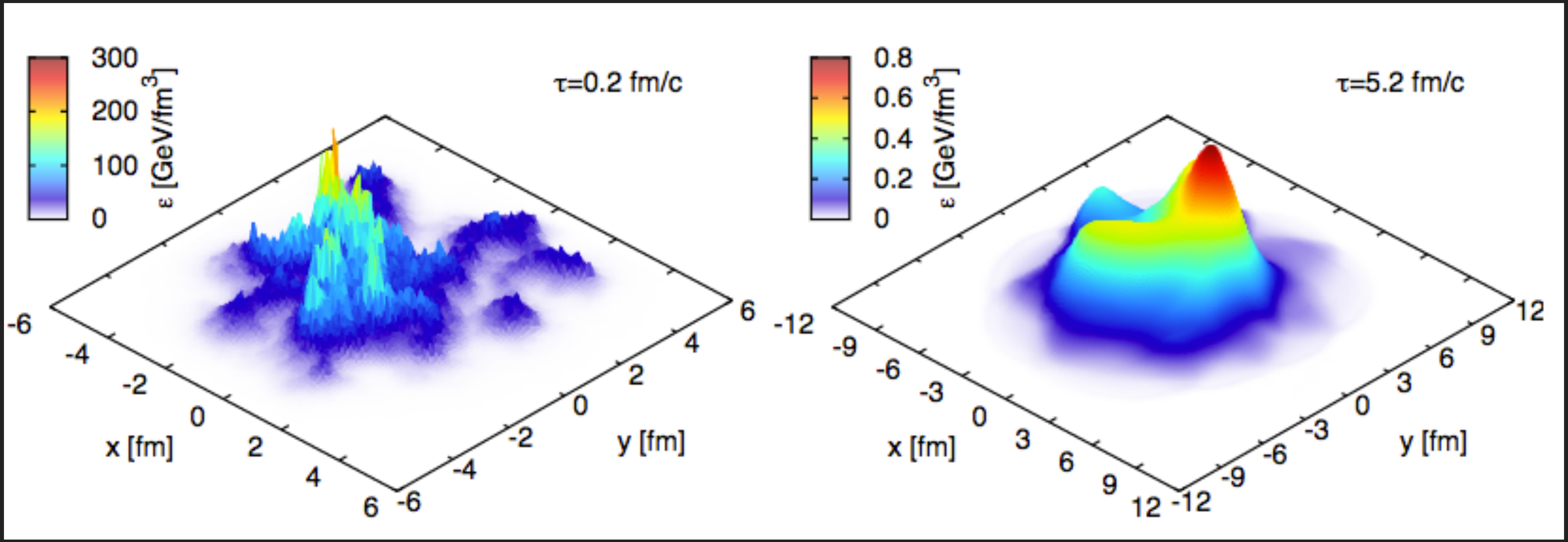
the Paradigm

The sizeable values of flow coefficients, up to high harmonics, have been successfully explained by:

fluctuating initial conditions + hydro-like collective expansion



U.Heinz and R.Snellings, Annu. Rev. Nucl. Part. Sci. 63 (2013)

the Paradigm

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Implications:

- yes, we create a strongly coupled system
- it quickly expands before hadronizing
- doing so, it behaves like a fluid with very low viscosity
  - initial spatial anisotropies translate into momentum ones

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which initial conditions?

which collectivity?

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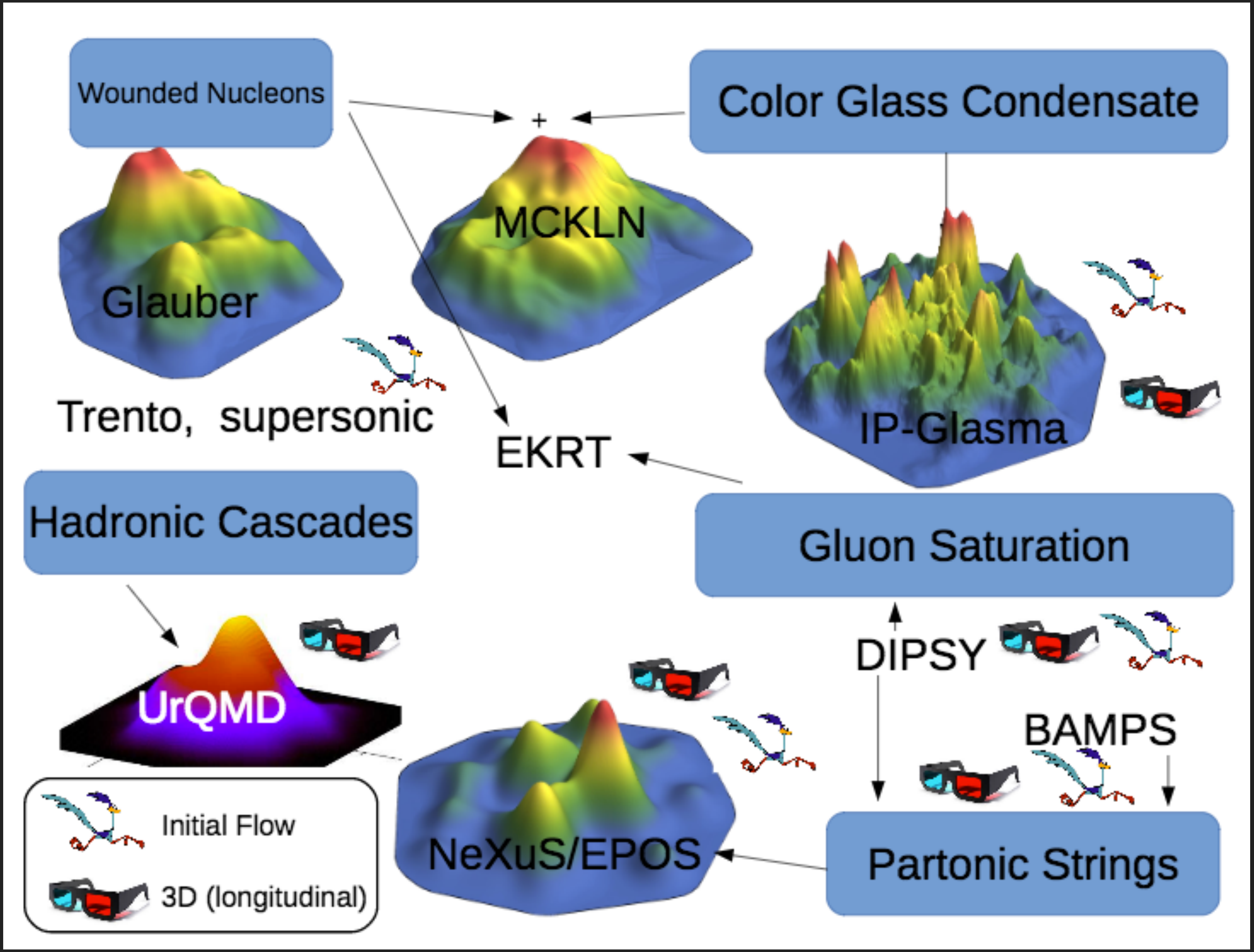
which Initial Conditions?



from J. Noronha-Hostler at Hot Quarks 2016

which Initial Conditions?

The observed v_n always come from an interplay of initial and final state effects: *not straightforward to decouple them!*

which Initial Conditions?

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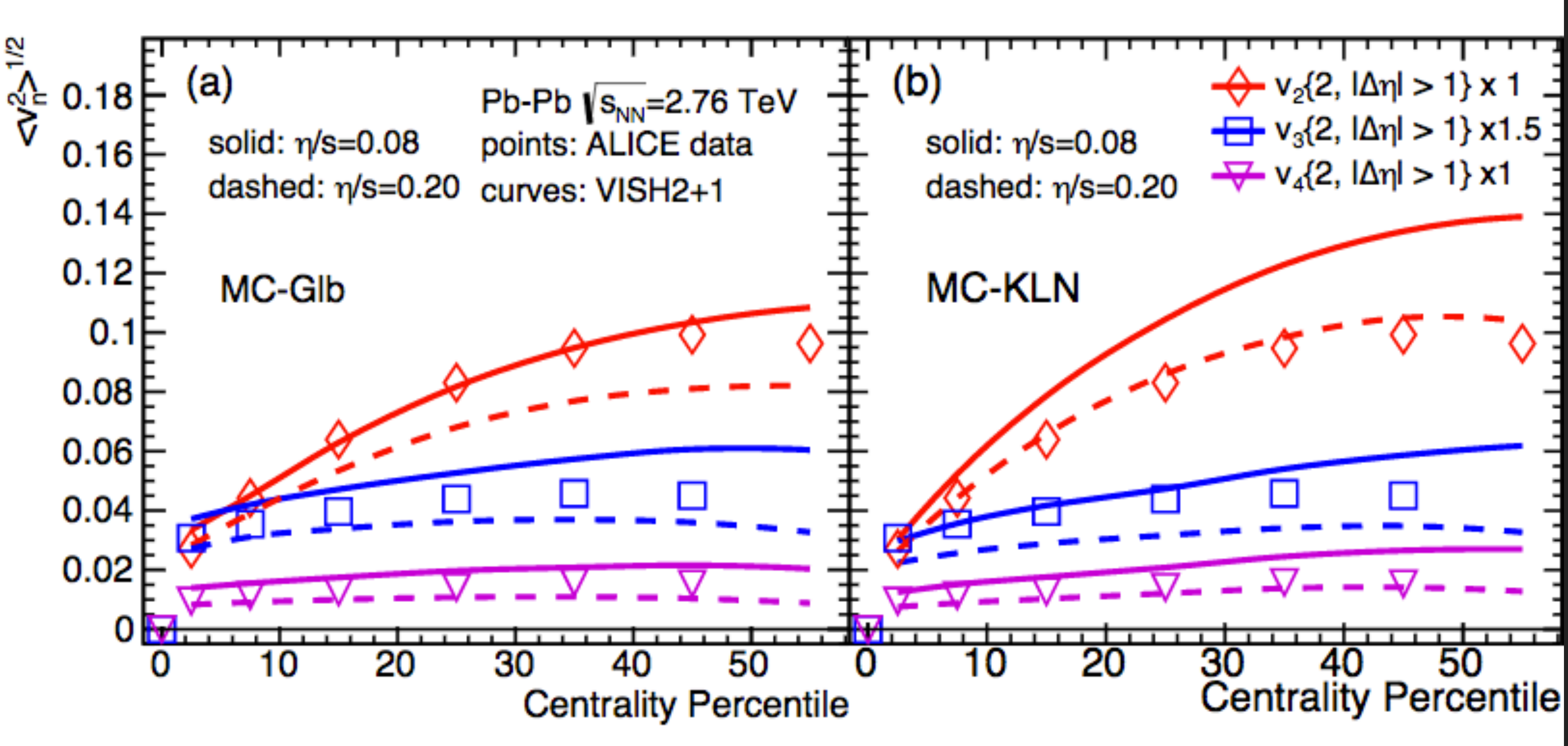
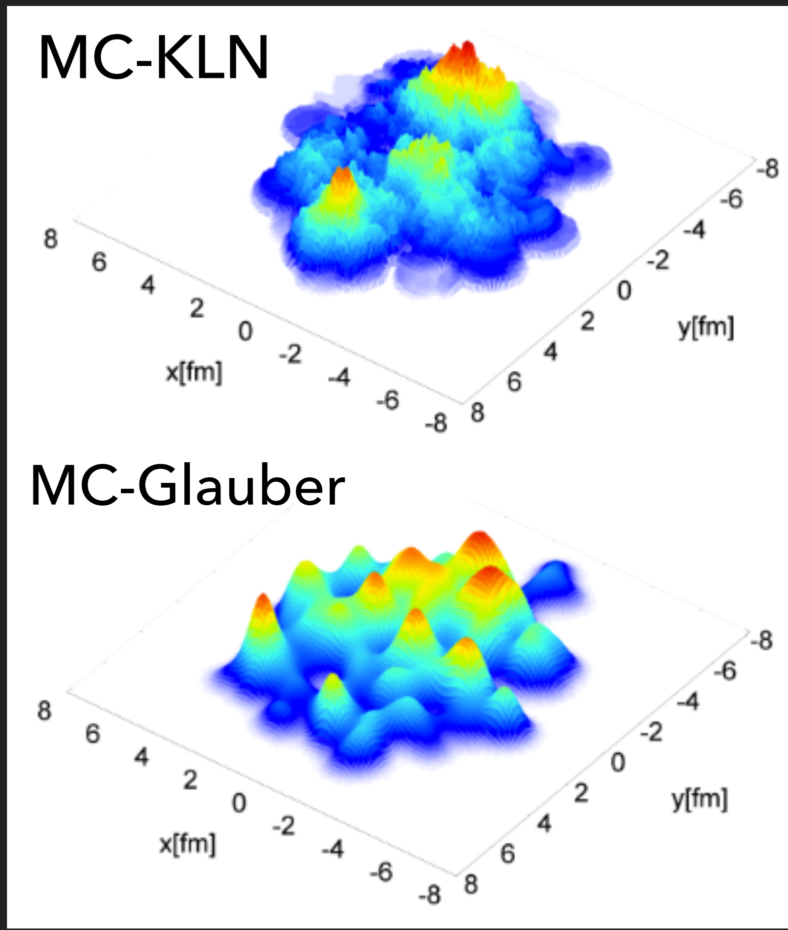
e.g. $< v_n >$: lumpy IC + high viscosity ≃ smooth IC + low viscosity



X. Zhu et al., arXiv:1608.05305

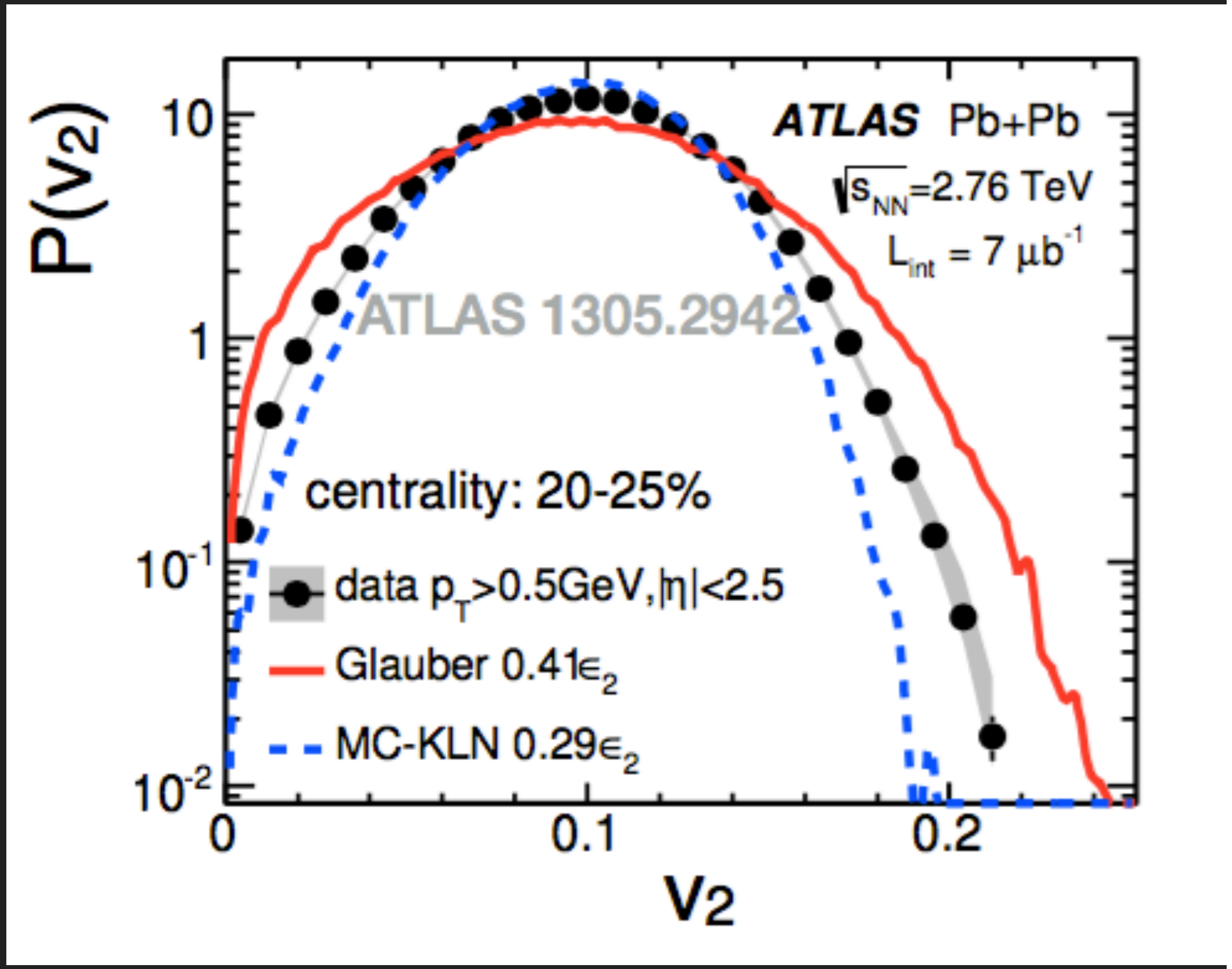


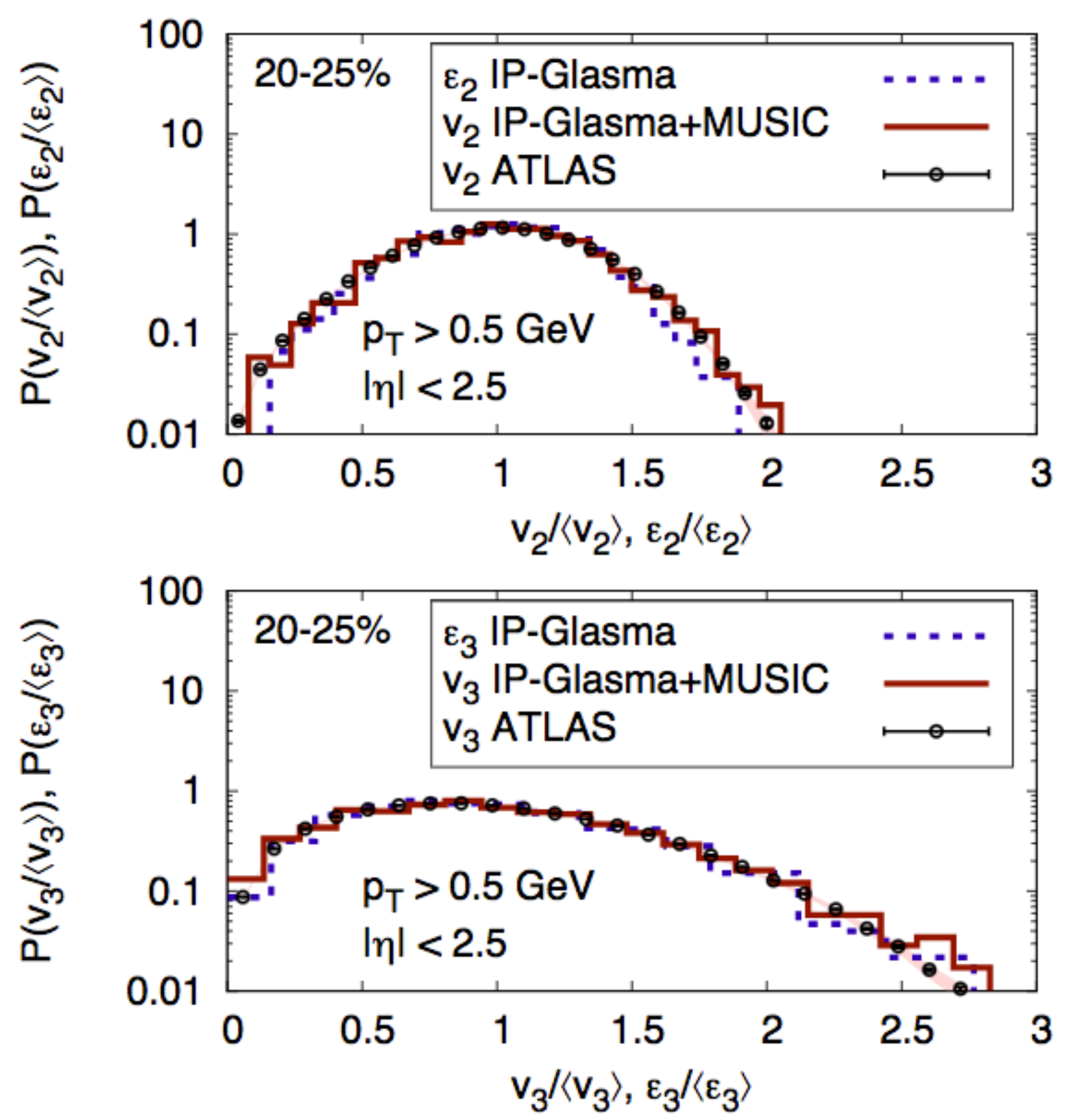
B. Schenke et al., PRL 108 (2012)

which Initial Conditions?

… but looking at the full flow pdf does favour one: IP-Glasma

C. Gale et al., arXiv:1210.5144



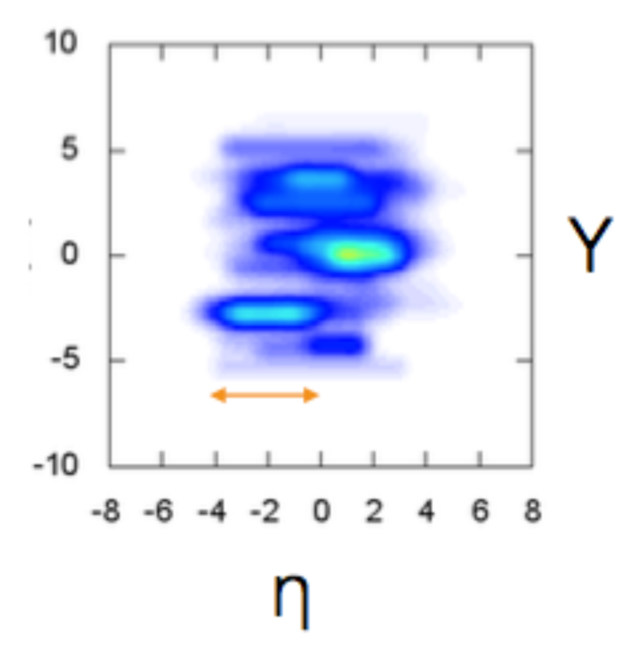


which Initial Conditions?

What about the longitudinal structure? (default: boost invariance)

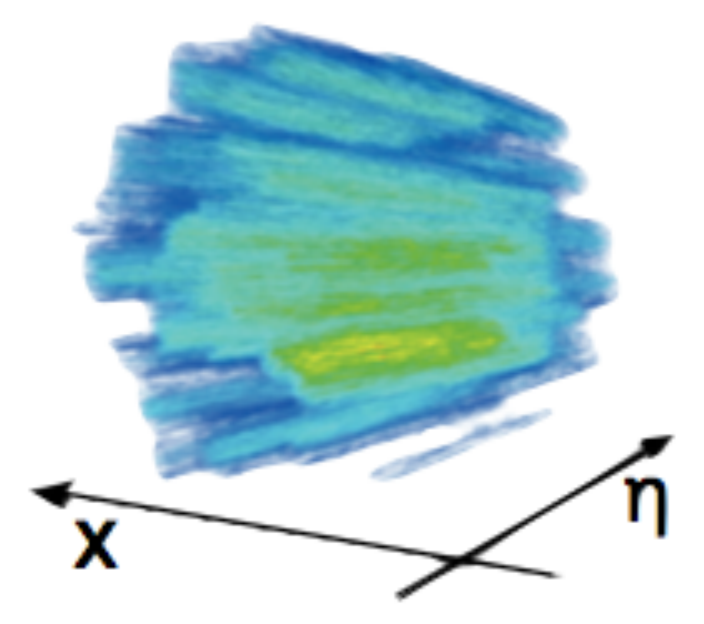
- Required to describe forward-backward asymmetric phenomena (directed flow, twist/torque/event plane decorrelations…)
- More important at lower energies!

3D-Glauber



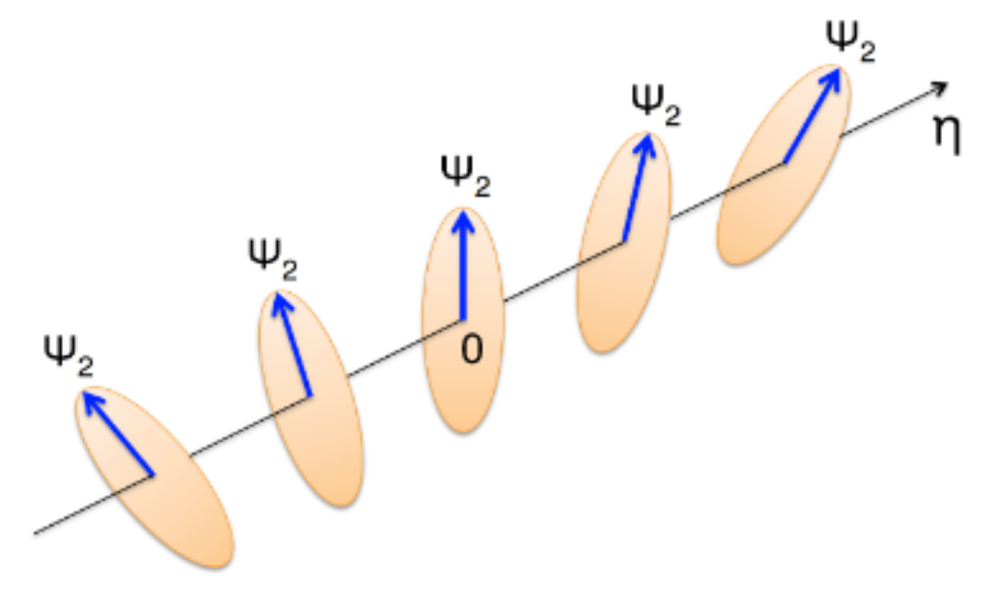
Monnai, Schenke PLB 752 (2016)

3D-Glasma



Schenke, Schlichting PRC 94 (2016)

the twist



which Collectivity?

Do the final momentum correlations come only from the hydro-like evolution of the system? Where does the “collectivity” come from?

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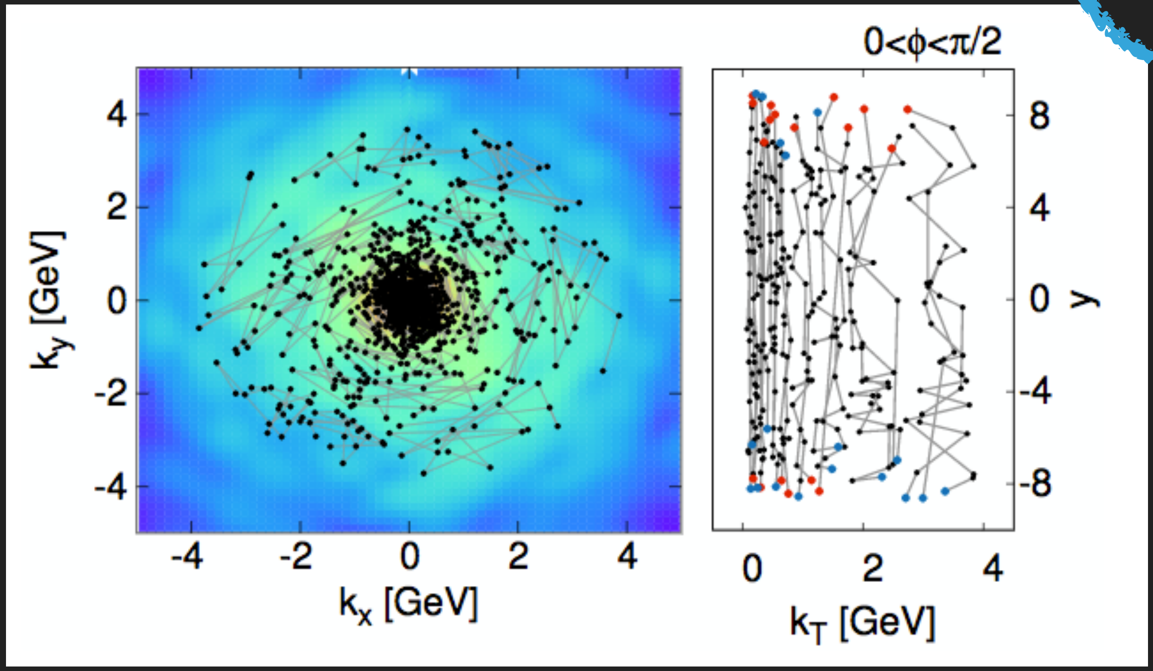
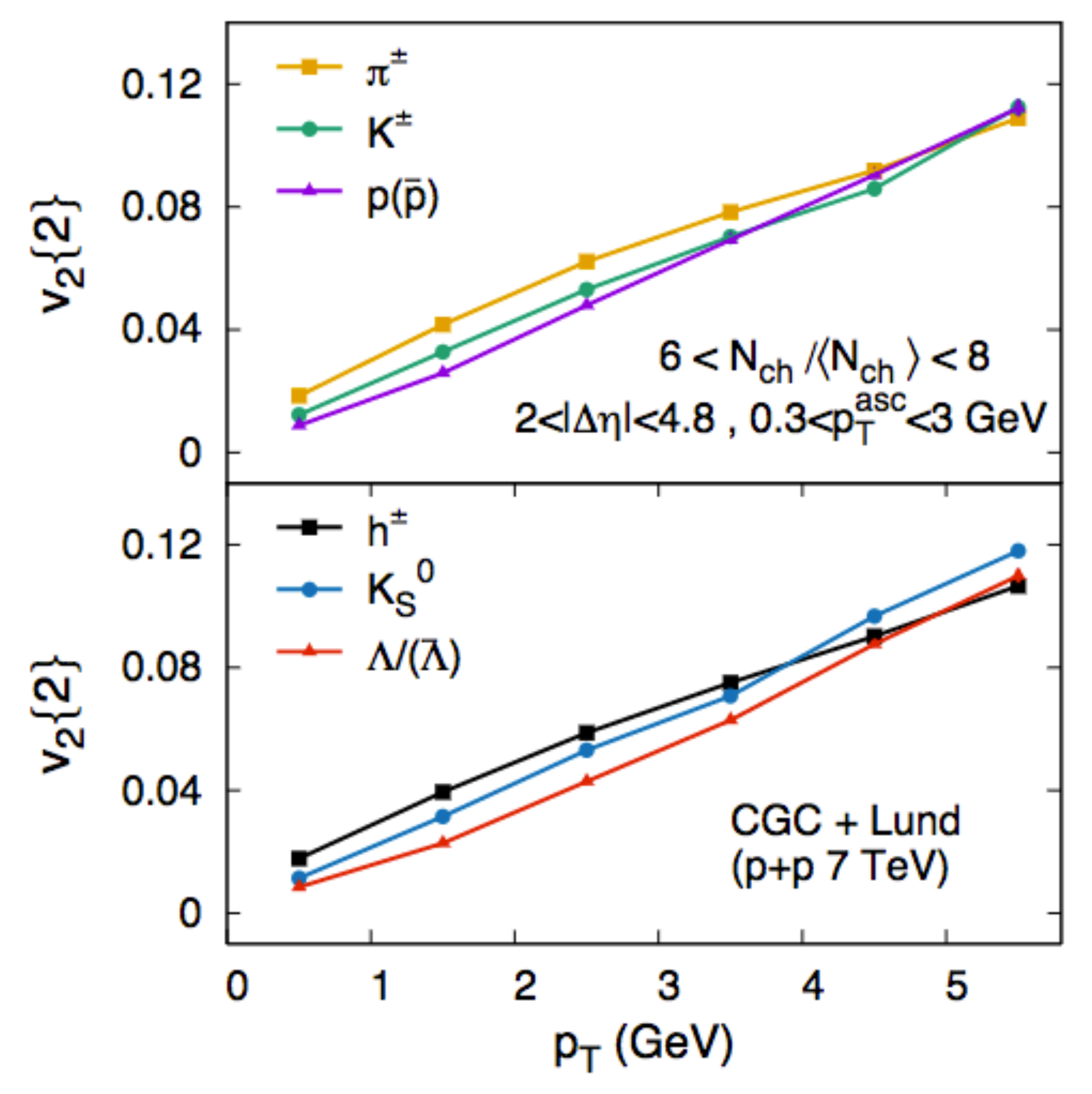
flow + mass ordering

CGC + Lund

p-p



B.Schenke et al, PRL 117, 162301 (2016)



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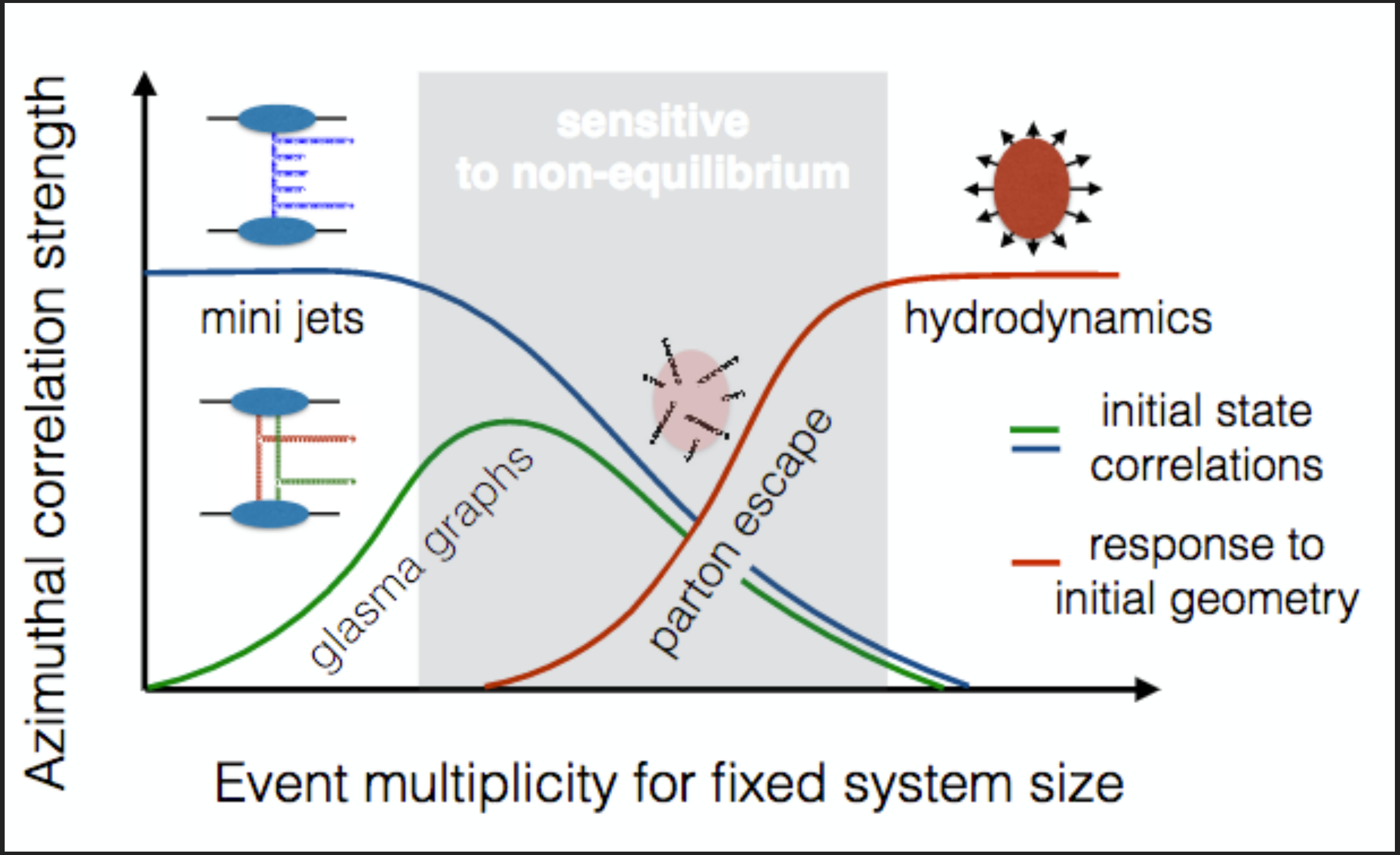

Schlichting, Tribedy arXiv:1611.00329

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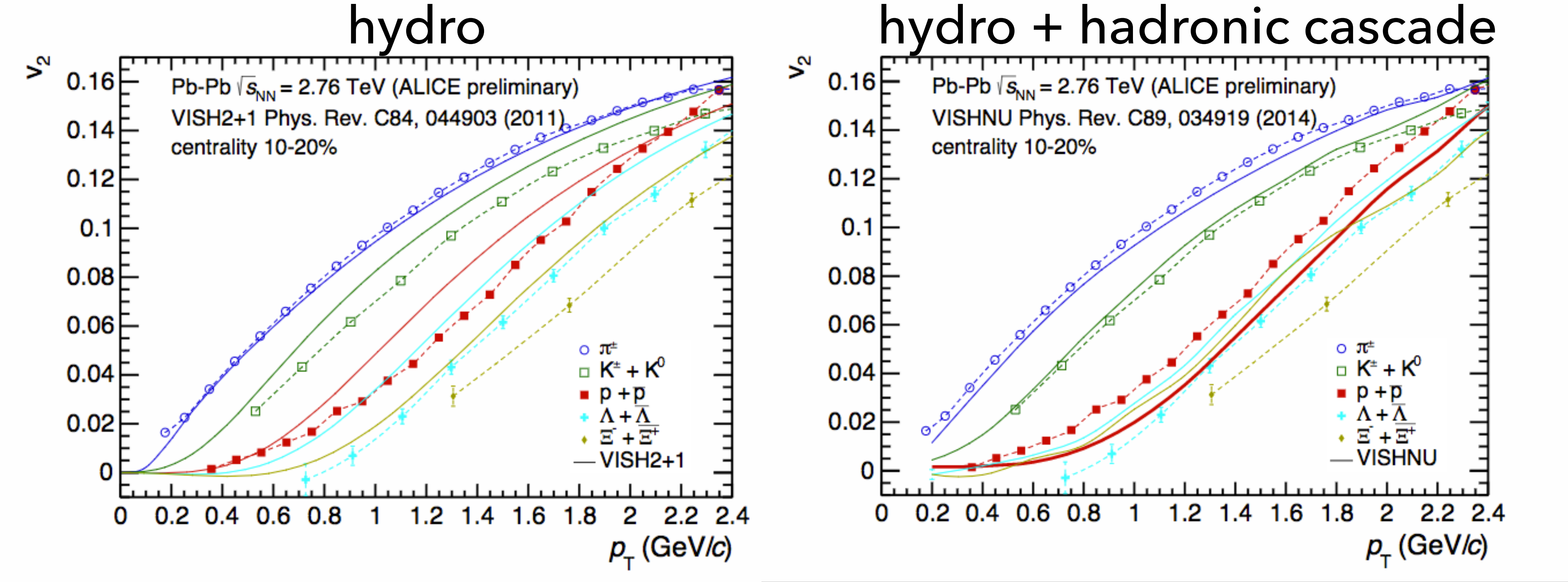

ALICE, JHEP 06 (2015)

Outline

- Intro: what is flow
- Why should you care?
- How do we measure it?
- What have we learned so far?
- Where do we go from here?

a Convoluted Problem

- Flow is a key observable for characterising the collective proprieties and the evolution of the medium
- However, it develops during different phases (initial state, QGP, hadronic phase): *highly convoluted problem!*
- The problem: how to decouple these?
  - New observables (e.g. symmetric cumulants)
  - New approaches from theory

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New Observables

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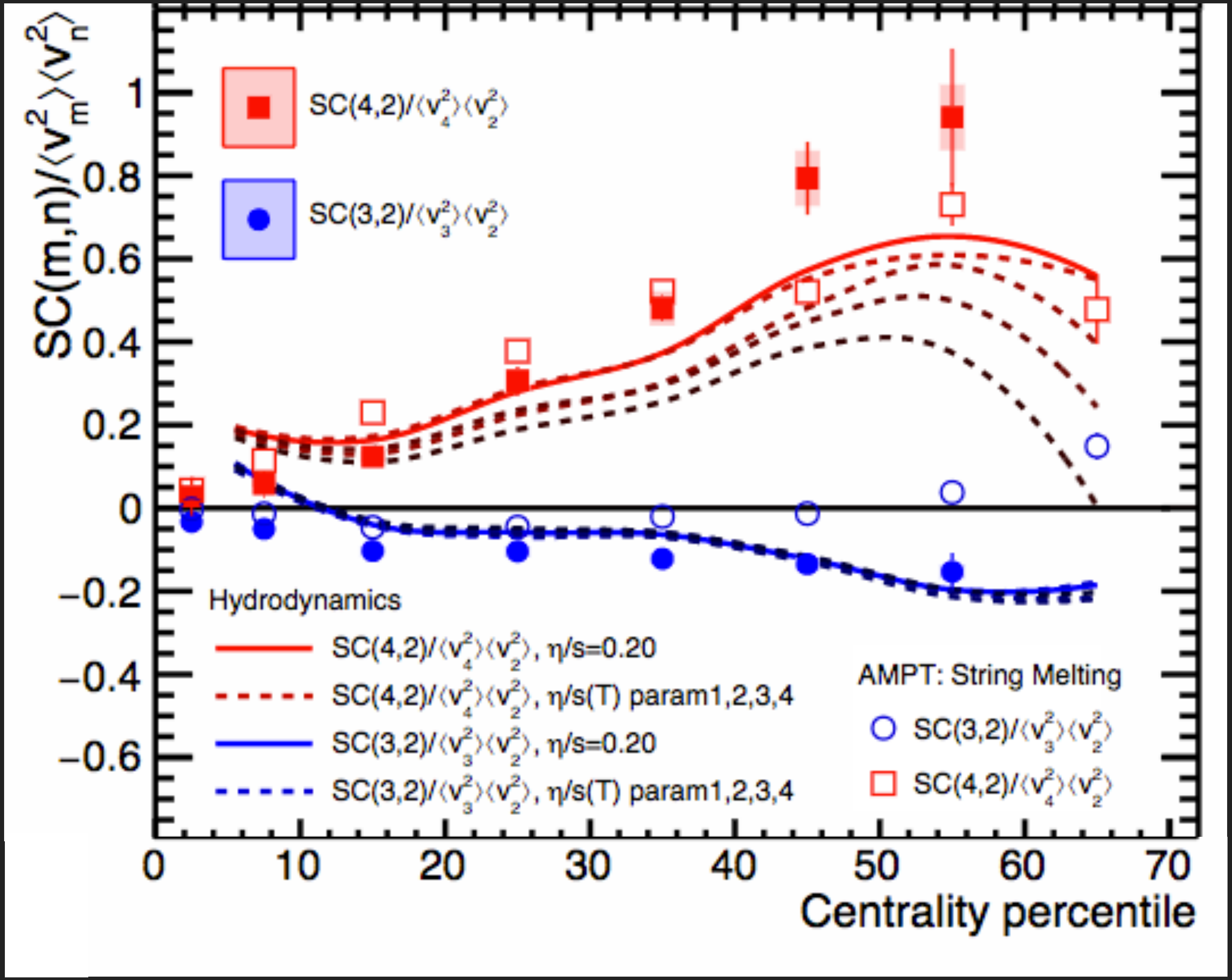

ALICE, PRL 117, 182301 (2016)

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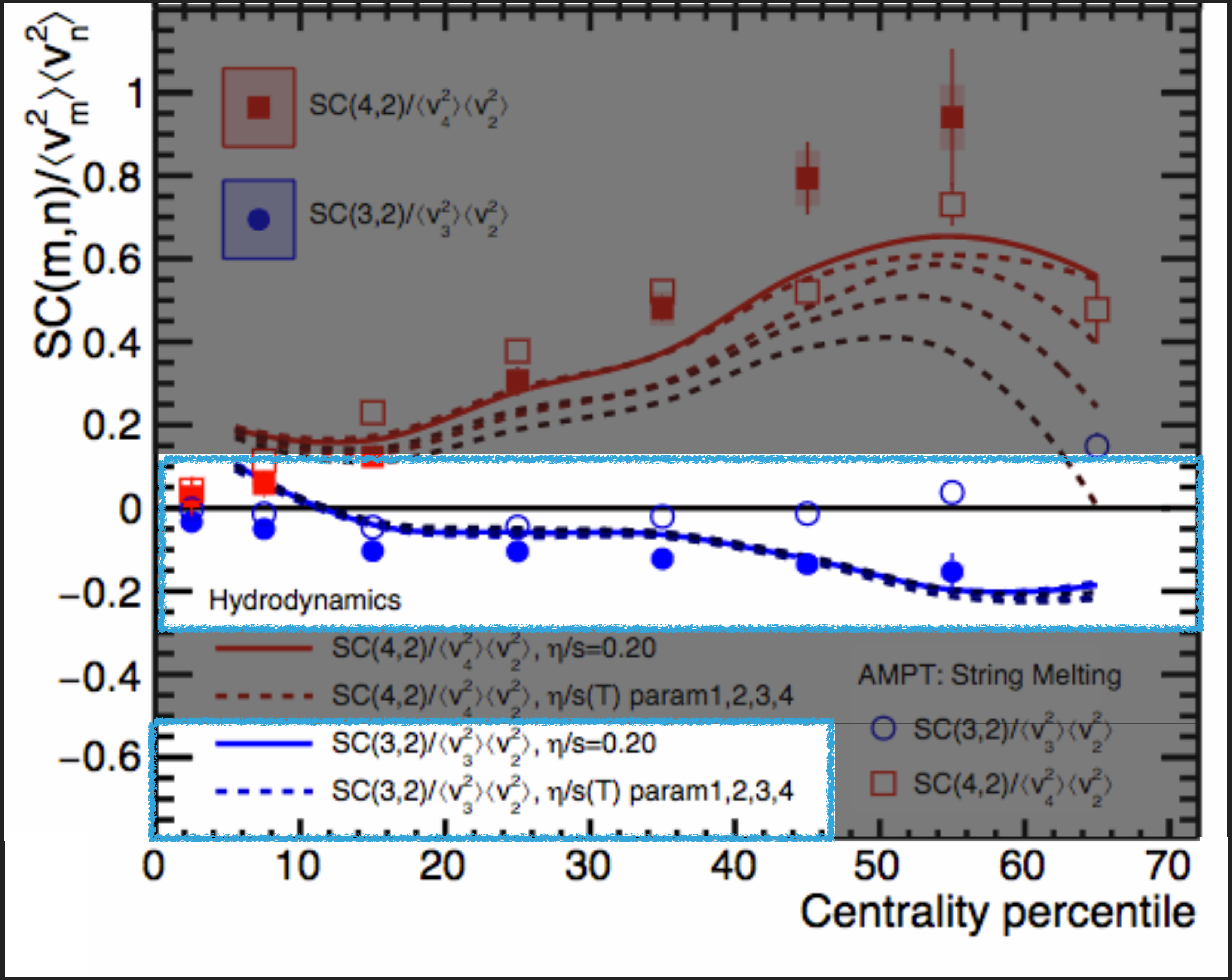

SC(3,2): set by initial conditions

ALICE, PRL 117, 182301 (2016)

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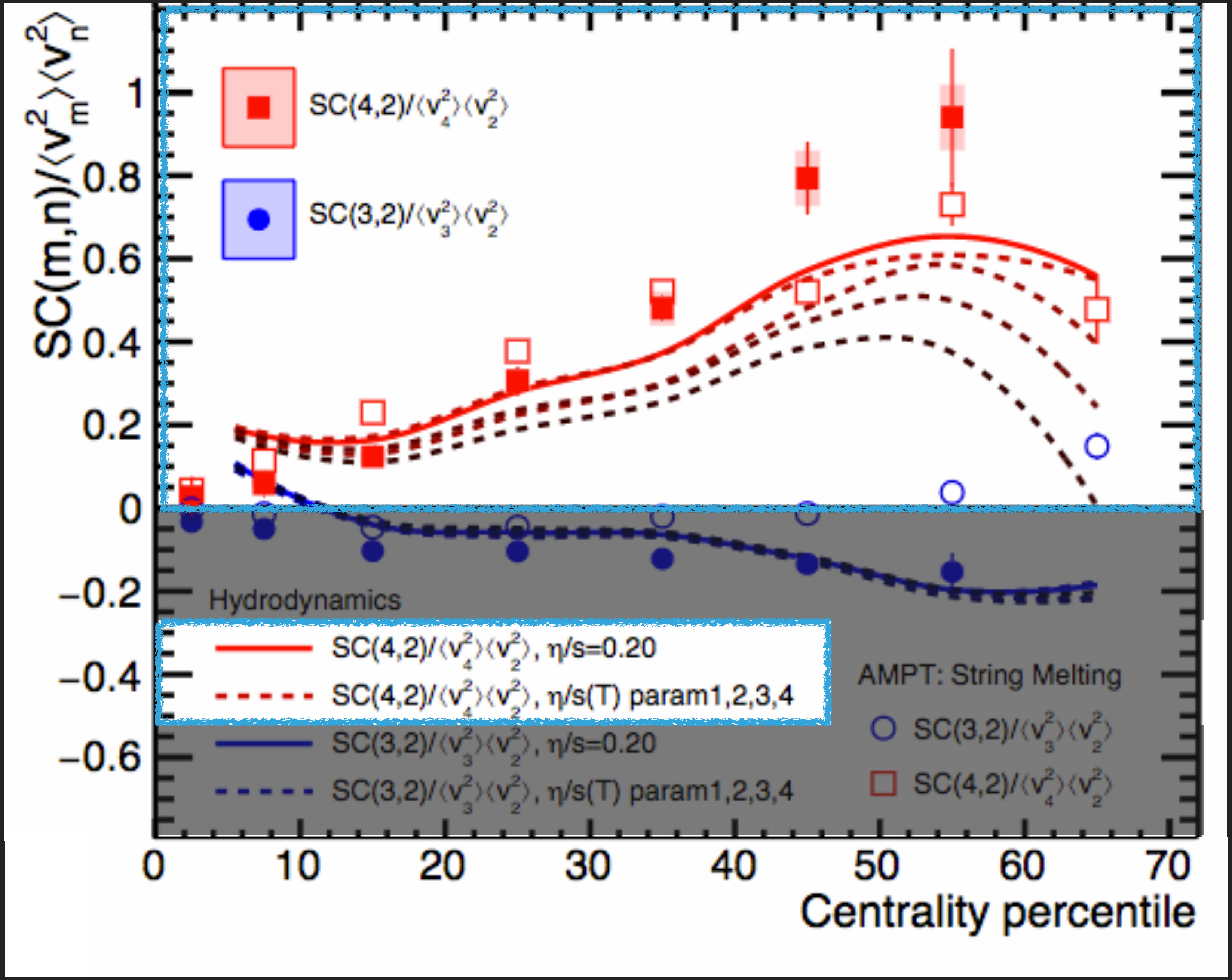


SC(4,2): set by hydro phase

ALICE, PRL 117, 182301 (2016)

New Approaches

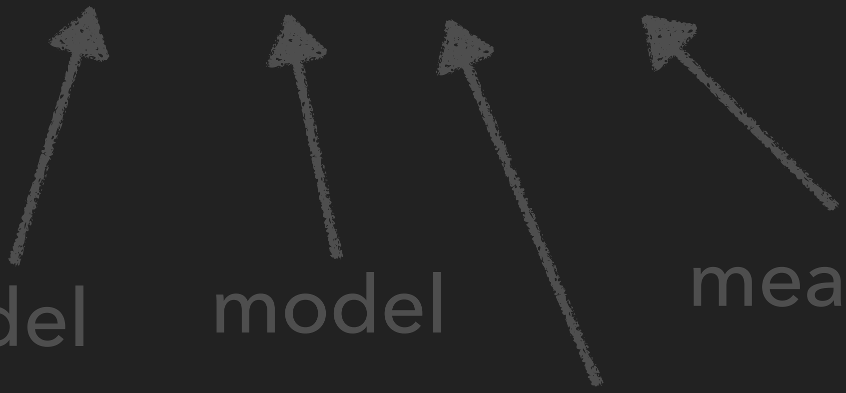
Applying Bayesian parameter estimation to relativistic heavy-ion collisions: simultaneous characterization of the initial state and quark-gluon plasma medium

J. Bernhard et al., Phys. Rev. C 94, 024907 (2016)

Using Bayesian methods to perform multi-parameter model-to-data comparison:

posterior likelihood prior

$$P(x_*|X,Y,y_{\rm exp}) \propto P(X,Y,y_{\rm exp}|x_*)P(x_*)$$



model parameter

model

computed obs.

measured obs.

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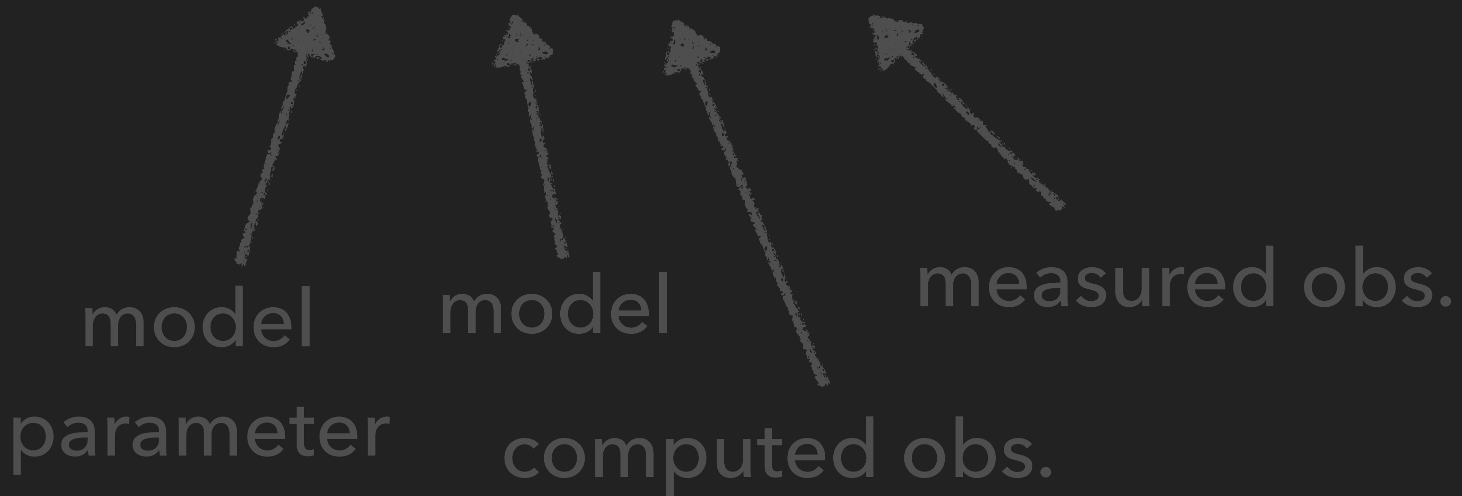
$$\overset{\text{posterior}}{P(x_*|X,Y,y_{\text{exp}})} \propto \overset{\text{likelihood}}{P(X,Y,y_{\text{exp}}|x_*)}\,\overset{\text{prior}}{P(x_*)}$$



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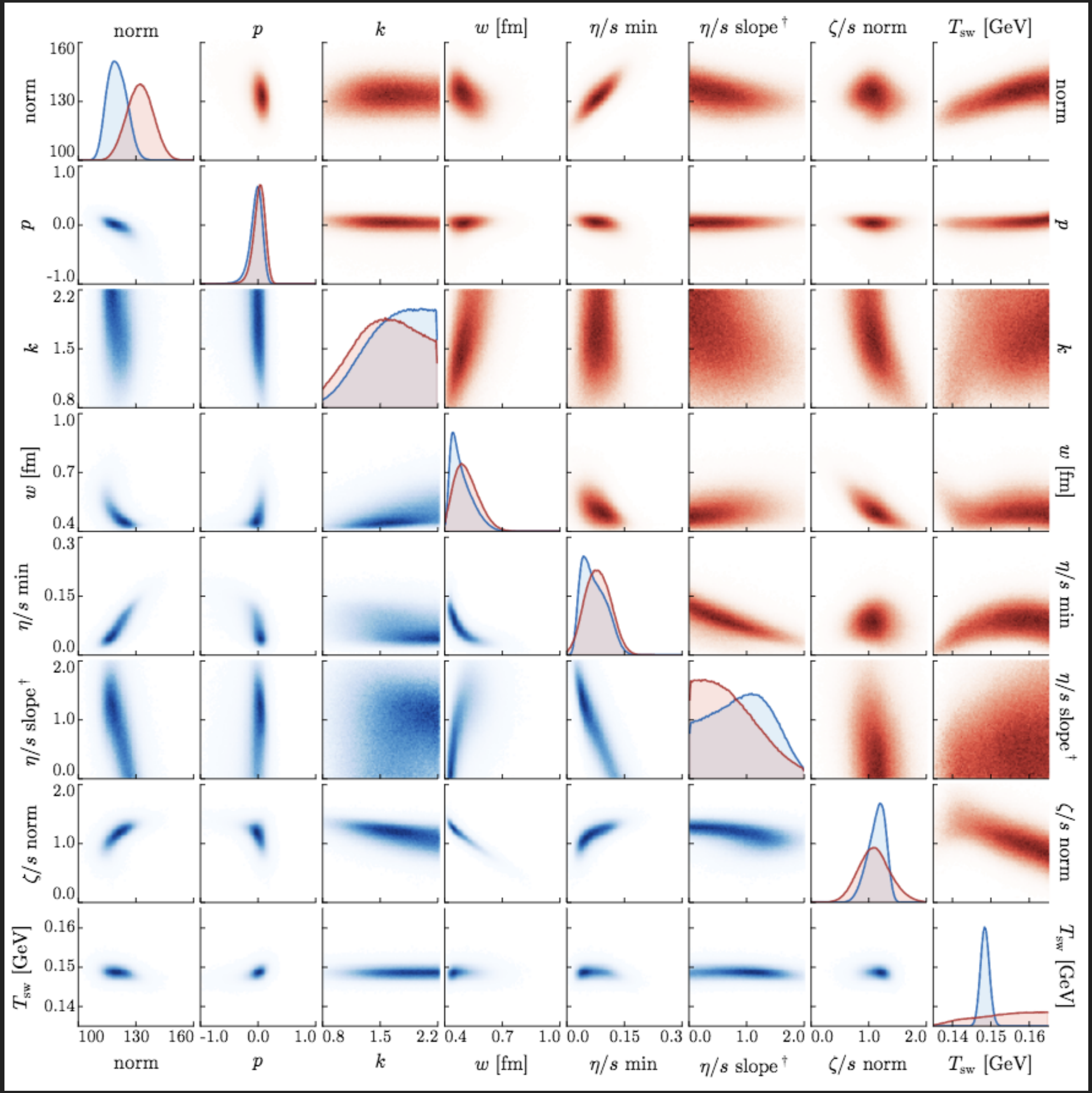
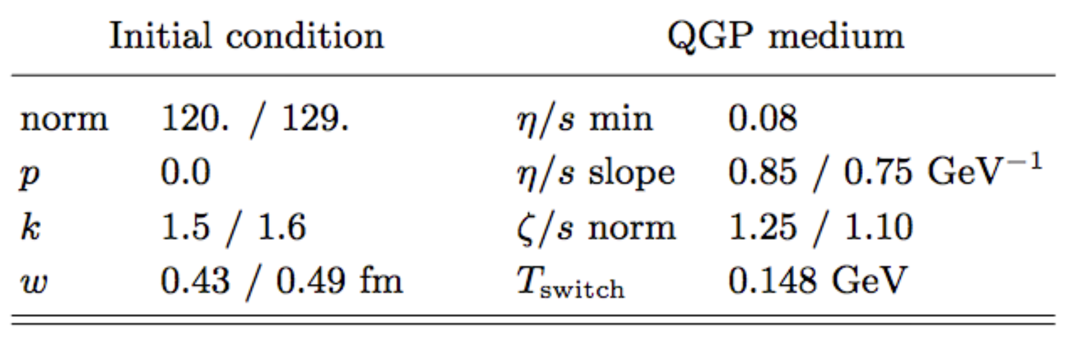


simultaneous parameter optimisation of initial state and hydro phase:



Initial condition		QGP medium	
norm	120. / 129.	η/s min	0.08
p	0.0	η/s slope	0.85 / 0.75 GeV^{-1}
k	1.5 / 1.6	ζ/s norm	1.25 / 1.10
w	0.43 / 0.49 fm	T_{switch}	0.148 GeV

one Final Plea

We need more and more synergy between experimentalists and theoreticians: *fast, efficient, frequent exchange of ideas*.

If we want things to move forward, don't be afraid and go open source:

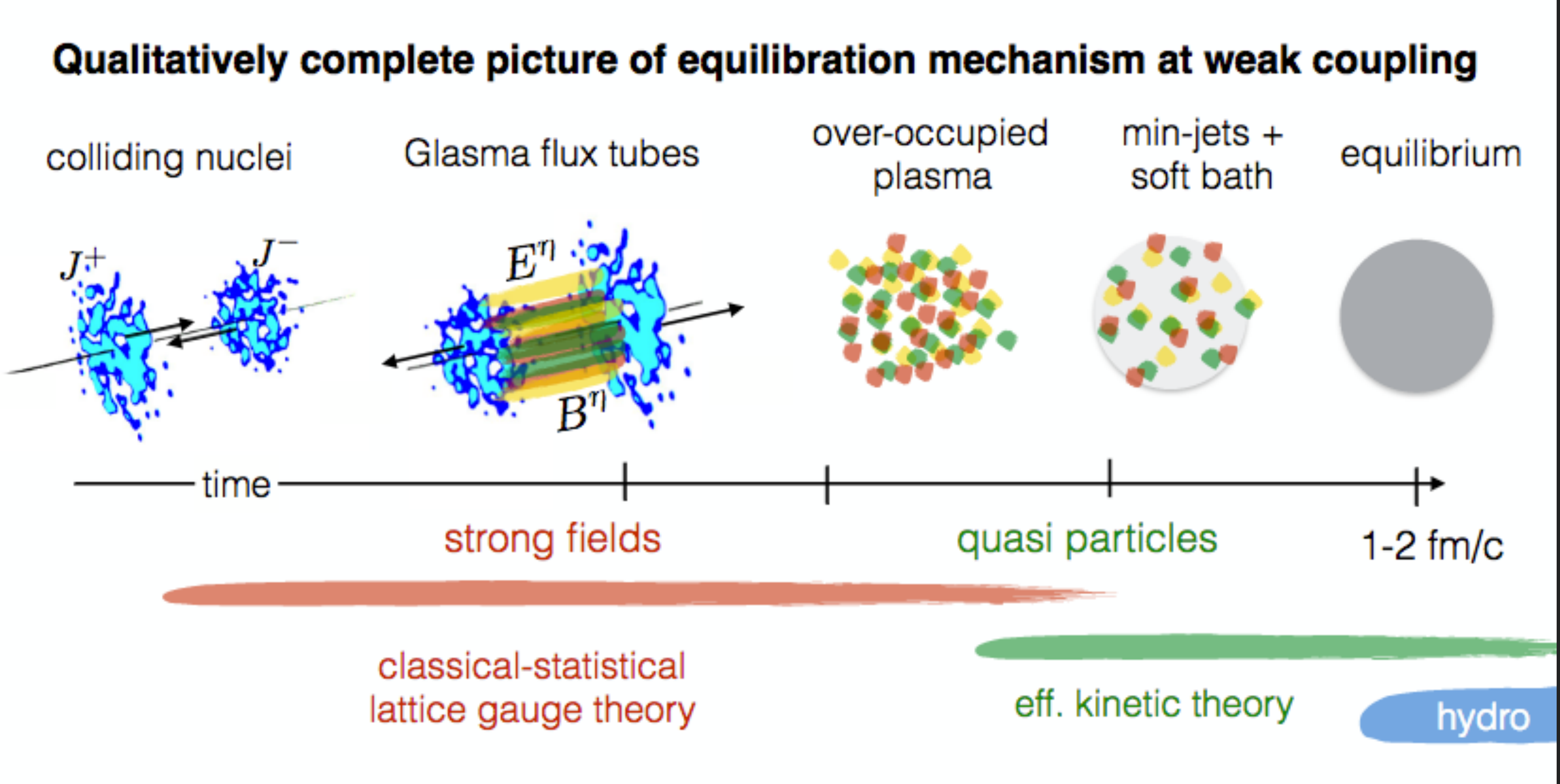
- Github
- Rivet


I WANT YOU
TO GO OPEN SOURCE
NEAREST SOFTWARE RESPOSITORY

THANKS FOR THE ATTENTION!

BACKUP

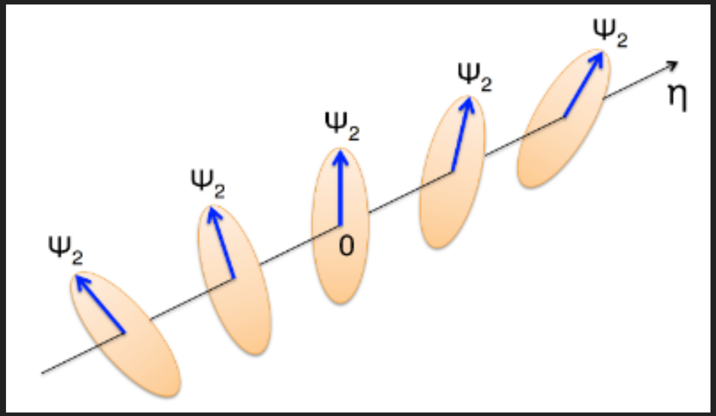
Pre-Equilibrium Dynamics

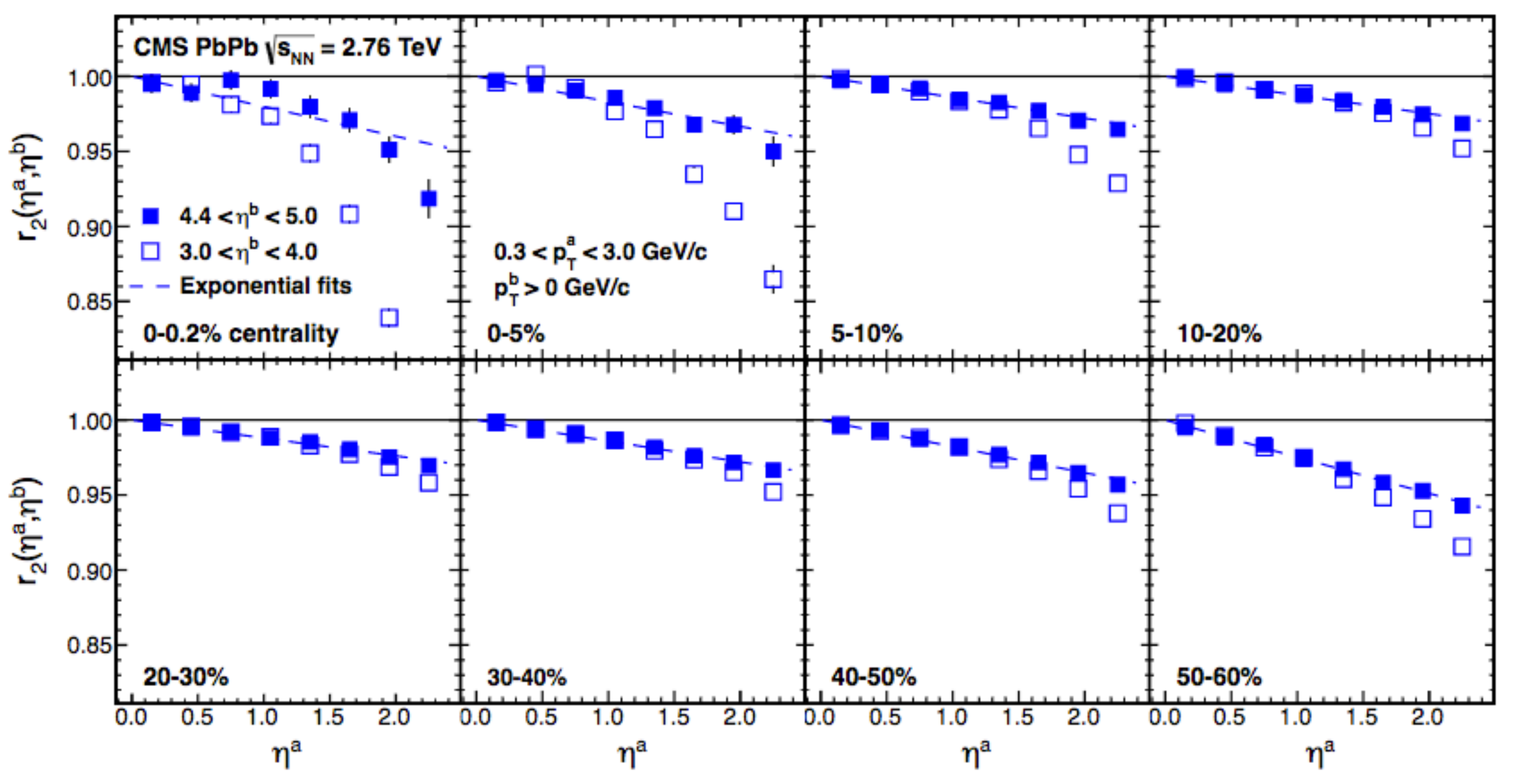


from Soeren Schlichting at "Exploring the QCD Phase Diagram through Energy Scans" 2016

Twist and Shake

$$r_n(\eta_a, \eta_b) = \frac{\langle\langle \cos[n(\phi(-\eta_a) - \phi(\eta_b))]\rangle\rangle}{\langle\langle \cos[n(\phi(\eta_a) - \phi(\eta_b))]\rangle\rangle}$$





CMS, Phys. Rev. C 92 (2015) 034911