Flow fluctuations

WORK IN PROGRESS

Katarína Křížková Gajdošová
Czech Technical University in Prague

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

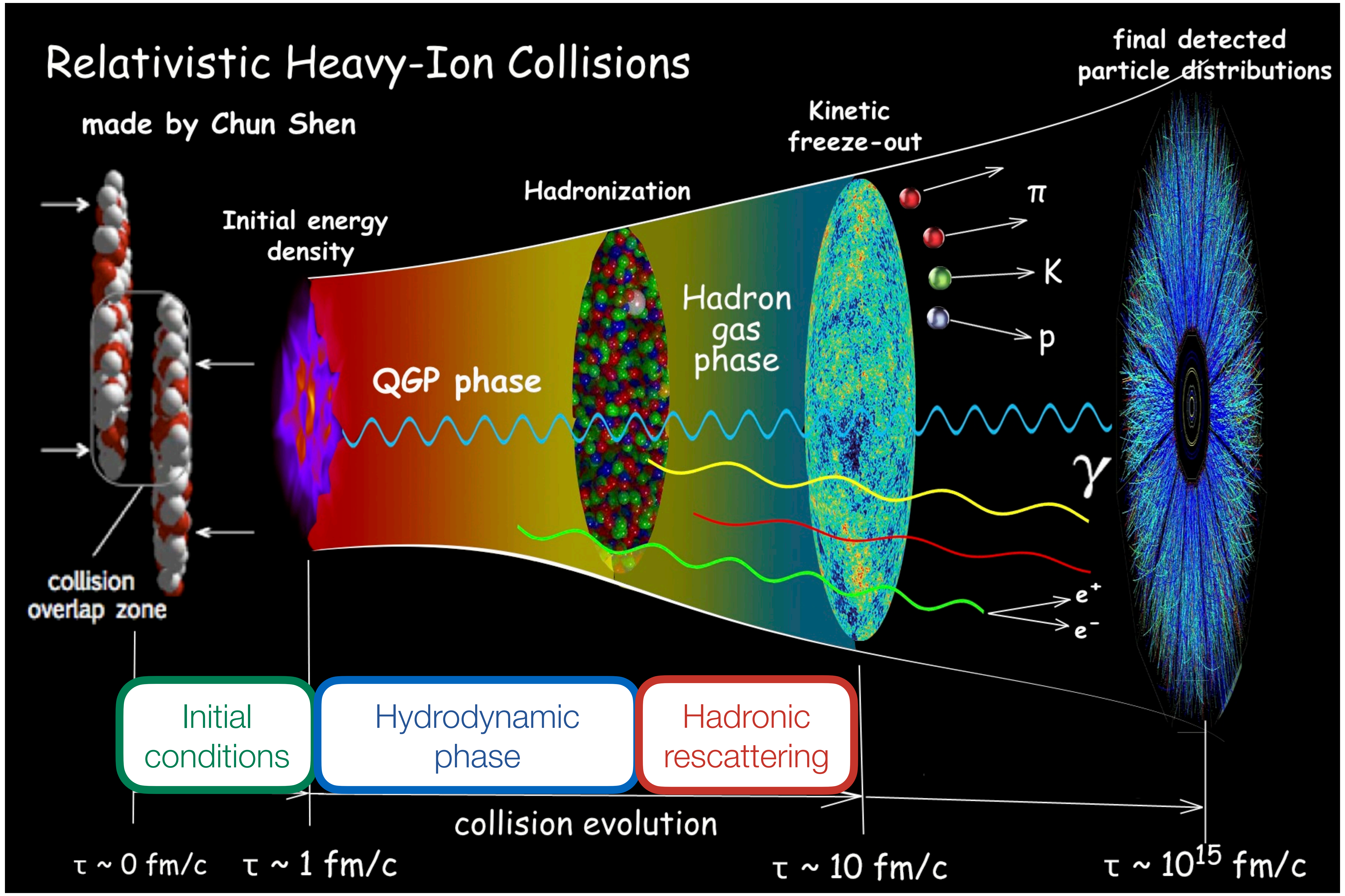
4th miniworkshop difrakce a ultraperiferalnich srazek
14th September 2021

Supported by the Ministry of Education, Youth and Sports of the Czech Republic under grant
„International Mobility of Researchers MSCA IF III at CTU in Prague“
CZ.02.2.69/0.0/0.0/16 027/0008465

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

Creating the hot and dense QCD medium



time [fm/c]

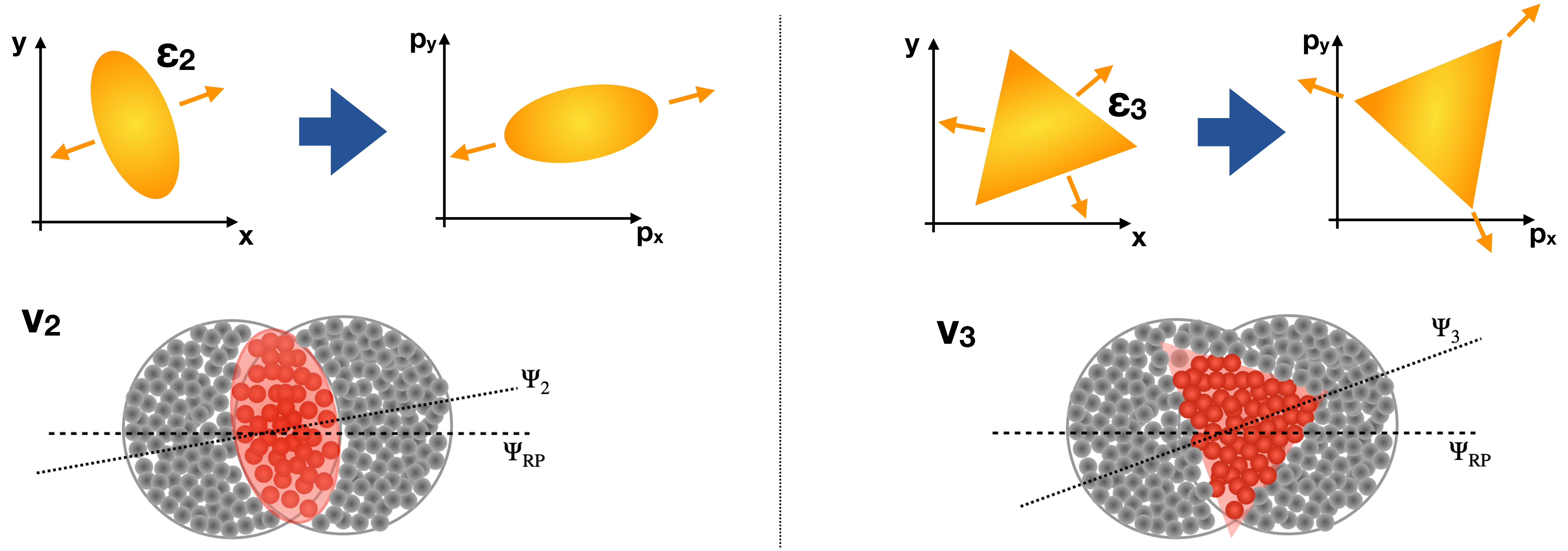
- Lattice QCD predicts a phase transition from a hadron gas to a strongly interacting deconfined medium, **quark-gluon plasma (QGP)**
  - We are interested in studying the emergent phenomena of this QCD medium, and knowing its properties
- Relativistic heavy-ion collisions allow us to reach the necessary conditions to recreate this medium
  - Medium expands and cools down
  - Phase transition from QGP to hadron gas
  - Further interactions in the hadronic phase until freeze-out
  - Detection of final particles
- Comparison to phenomenological models

Anisotropic flow

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

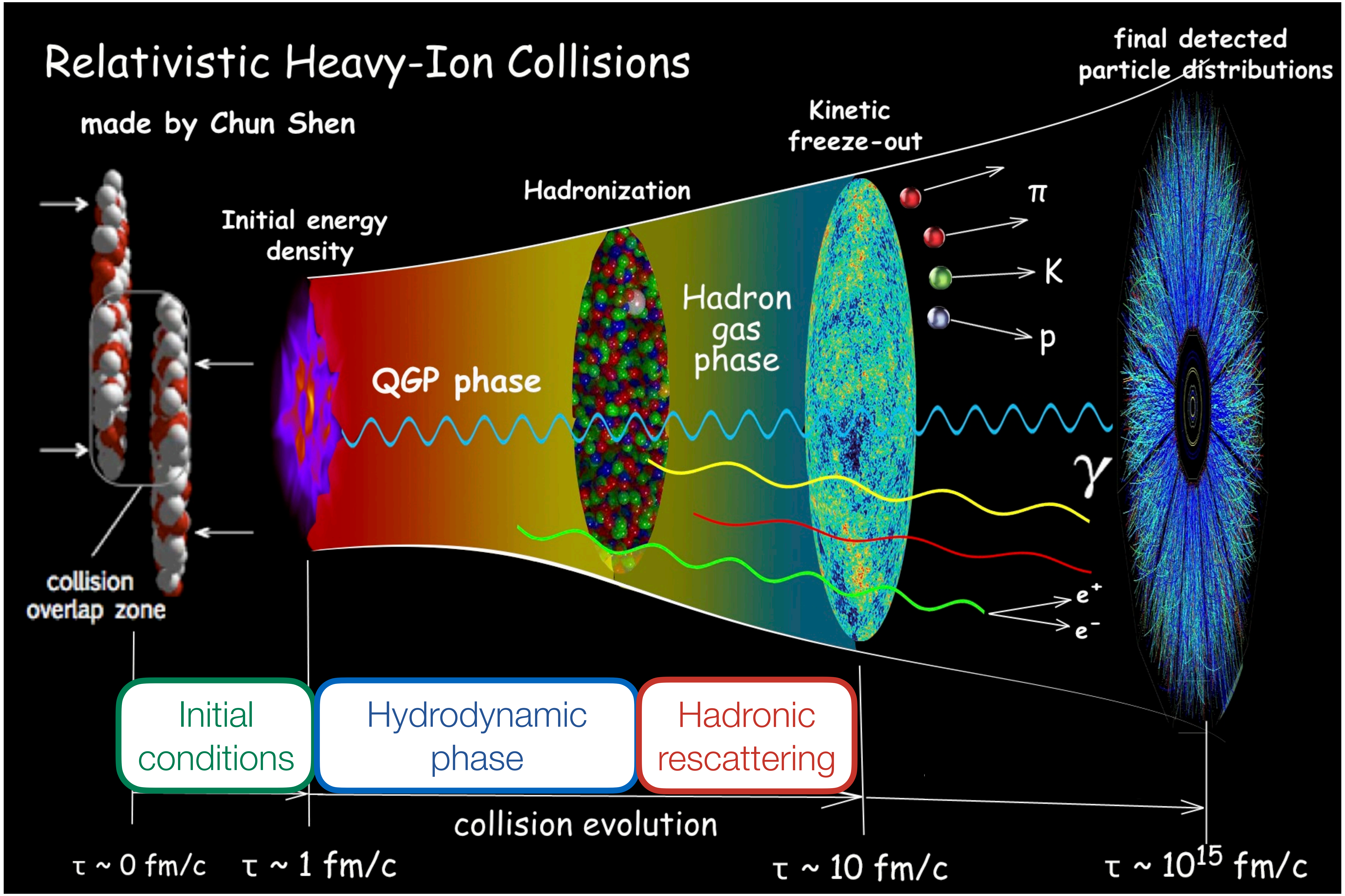
Initial spatial anisotropy is transferred via interactions in the medium to momentum anisotropy of outgoing particles

$$v_n \propto \epsilon_n, \quad n \leq 3$$



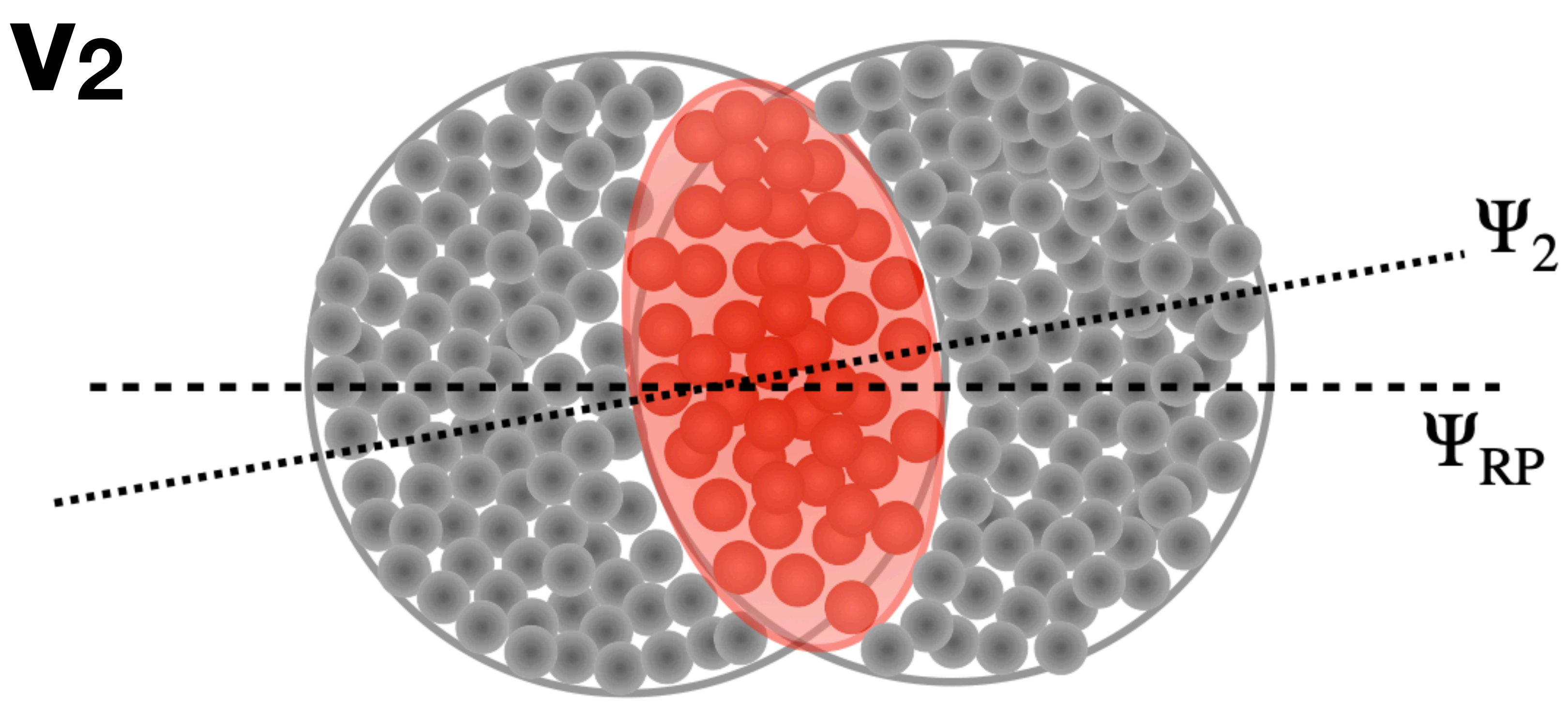
Modelling of heavy-ion collisions

initial eccentricity

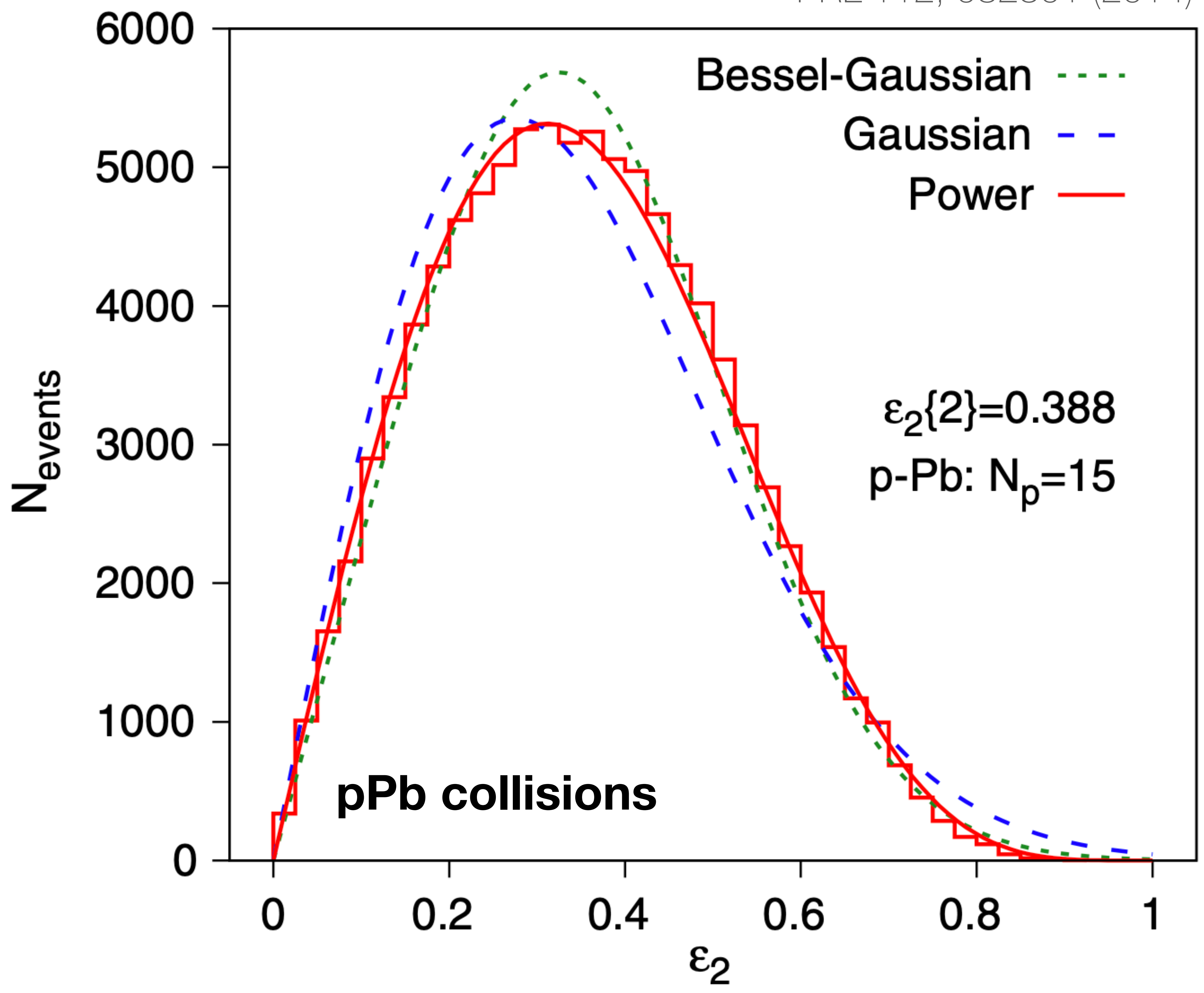


anisotropic flow

Eccentricity distribution

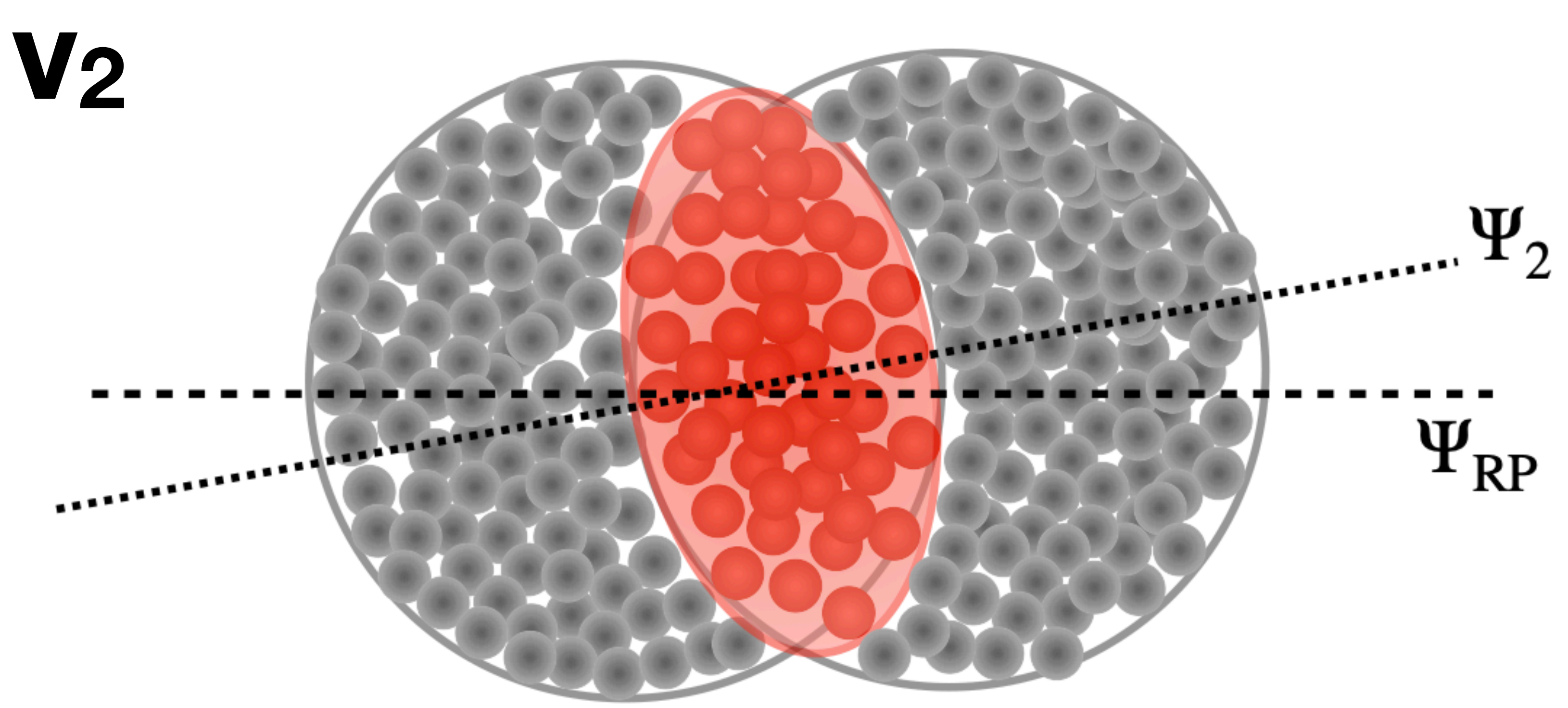


PRL 112, 082301 (2014)

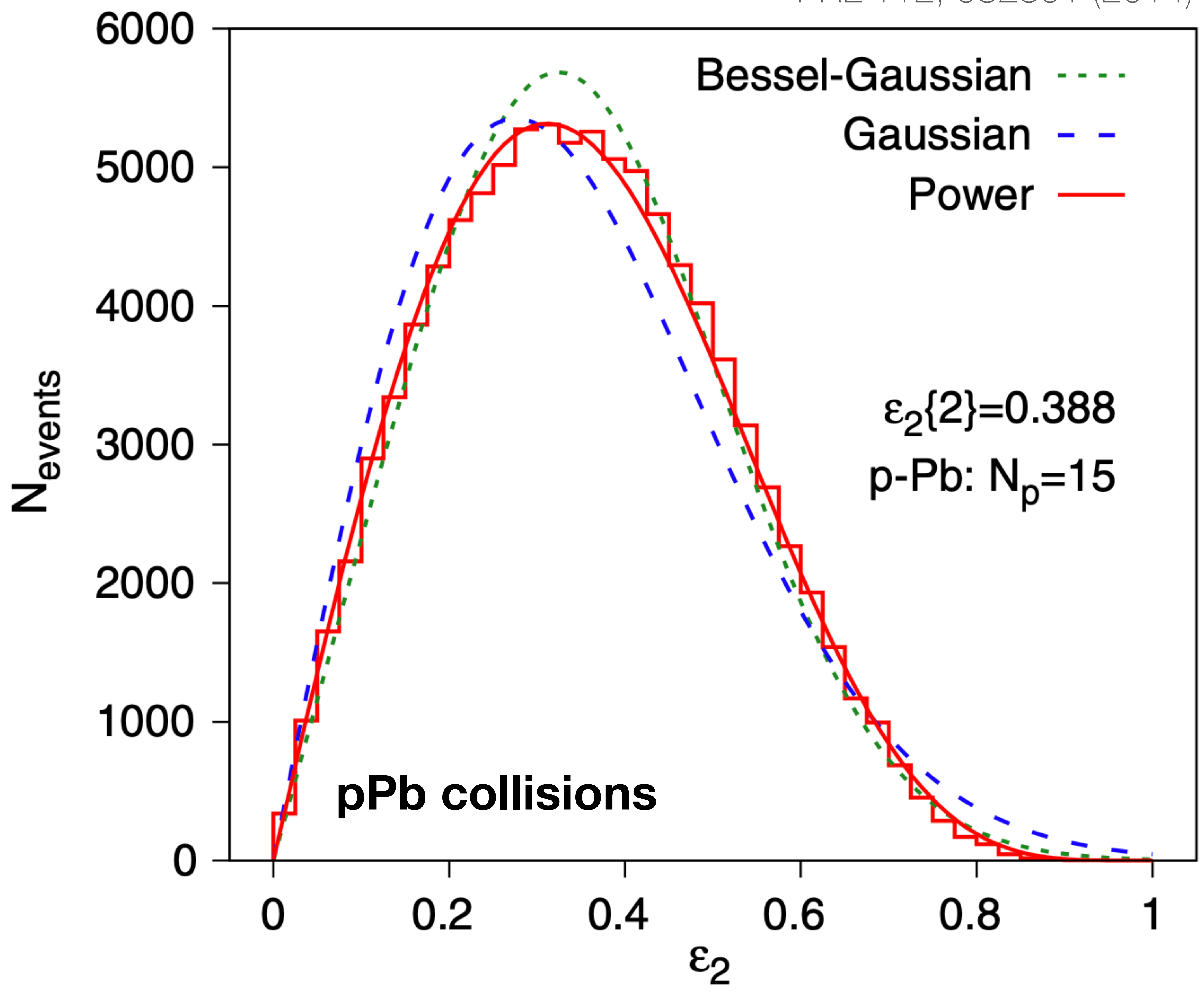


- Event-by-event fluctuations in the initial geometry -> initial eccentricity nc
- Parametrizations of the p.d.f.
  1. Gaussian
  2. Bessel-Gaussian - more suitable for fluctuations of ε_2 in PbPb
  3. Power law - more suitable for fluctuation-driven eccentricities (small systems, or ε_3

Eccentricity distribution



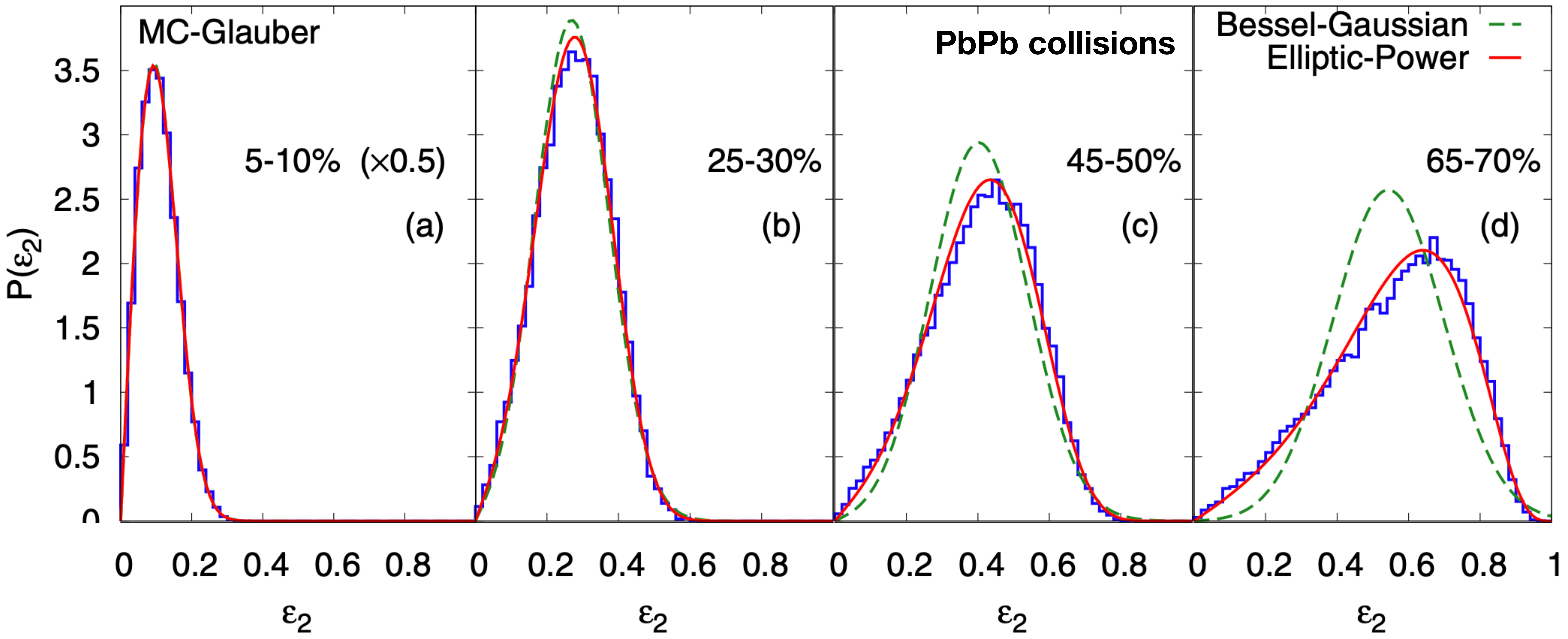
PRL 112, 082301 (2014)



- Event-by-event fluctuations in the initial geometry -> initial eccentricity nc
- Parametrizations of the p.d.f.
  1. Gaussian
  2. Bessel-Gaussian - more suitable for fluctuations of ε_2 in PbPb
  3. Power law - more suitable for fluctuation-driven eccentricities (small systems, or ε_3
  4. Elliptic Power - general parametrization including cases 2) and 3)

Elliptic power distribution

PRC 90, 024903 (2014)



- Elliptic power distribution governed by two parameters
  - Ellipticity ε_0 (for $\varepsilon_0 = 0$, symmetric distribution)
  - Power α (magnitude of fluctuations; smaller α -> larger fluctuations

$$p(\varepsilon_x,\varepsilon_y) = \frac{\alpha}{\pi}\left(1-\varepsilon_0^2\right)^{\alpha+\frac{1}{2}} \frac{\left(1-\varepsilon_x^2-\varepsilon_y^2\right)^{\alpha-1}}{\left(1-\varepsilon_0\varepsilon_x\right)^{2\alpha+1}}$$

How to ...?

- **How to experimentally access the P(ε_n) ?**
- Lower order flow coefficients are linearly related to initial eccentricities
  - By measuring the P(v_n), we can get to know about the fluctuations in the initial state

$$v_n \propto \epsilon_n, \quad n \leq 3$$

How to ...?

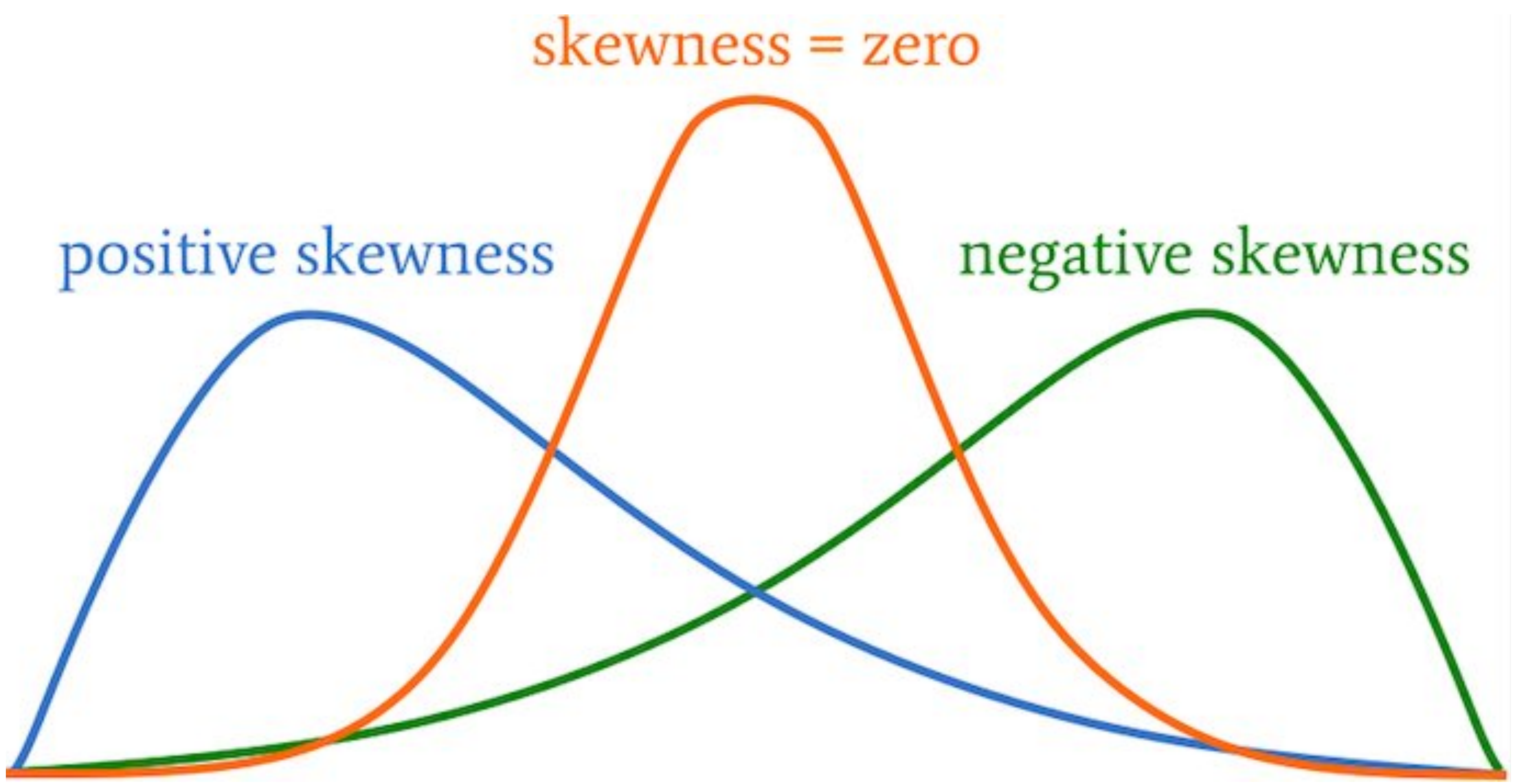
- **How to experimentally access the P(εn) ?**

- Lower order flow coefficients are linearly related to initial eccentricities
  - By measuring the $P(v_n)$, we can get to know about the fluctuations in the initial state

$$v_n \propto \epsilon_n, \quad n \leq 3$$

- **How to experimentally characterize a distribution?**

1. Measure the distribution directly
2. Measure its moments/cumulants



- First moment → mean
- Second moment → variance
- Third moment → skewness
- Fourth moment → kurtosis

- Cumulants - related to moments

How to ...?

- **How to experimentally access the P(ε_n) ?**
- Lower order flow coefficients are linearly related to initial eccentricities
  - By measuring the P(v_n), we can get to know about the fluctuations in the initial state

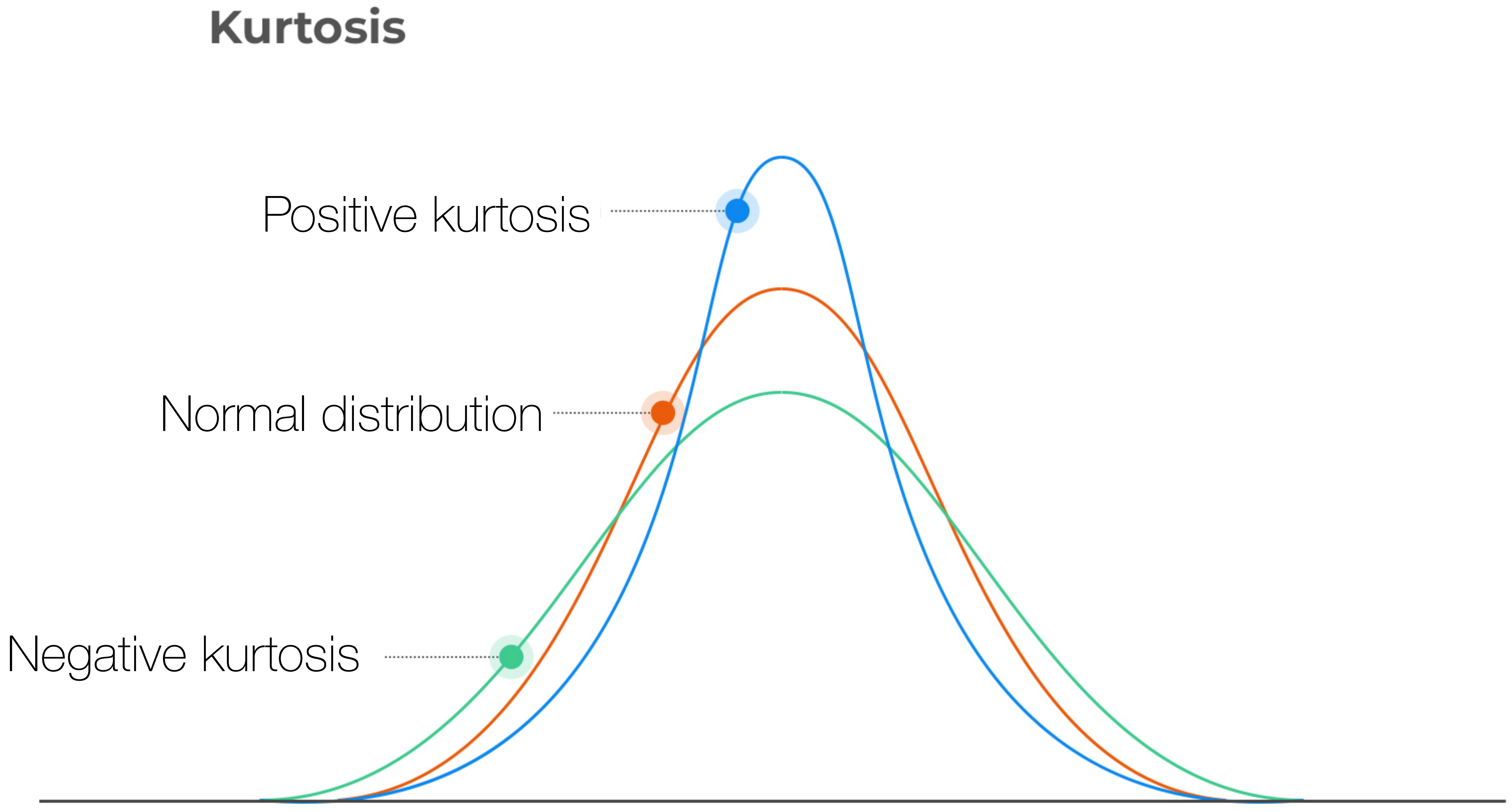
$$v_n \propto \epsilon_n, \quad n \leq 3$$

- **How to experimentally characterize a distribution?**

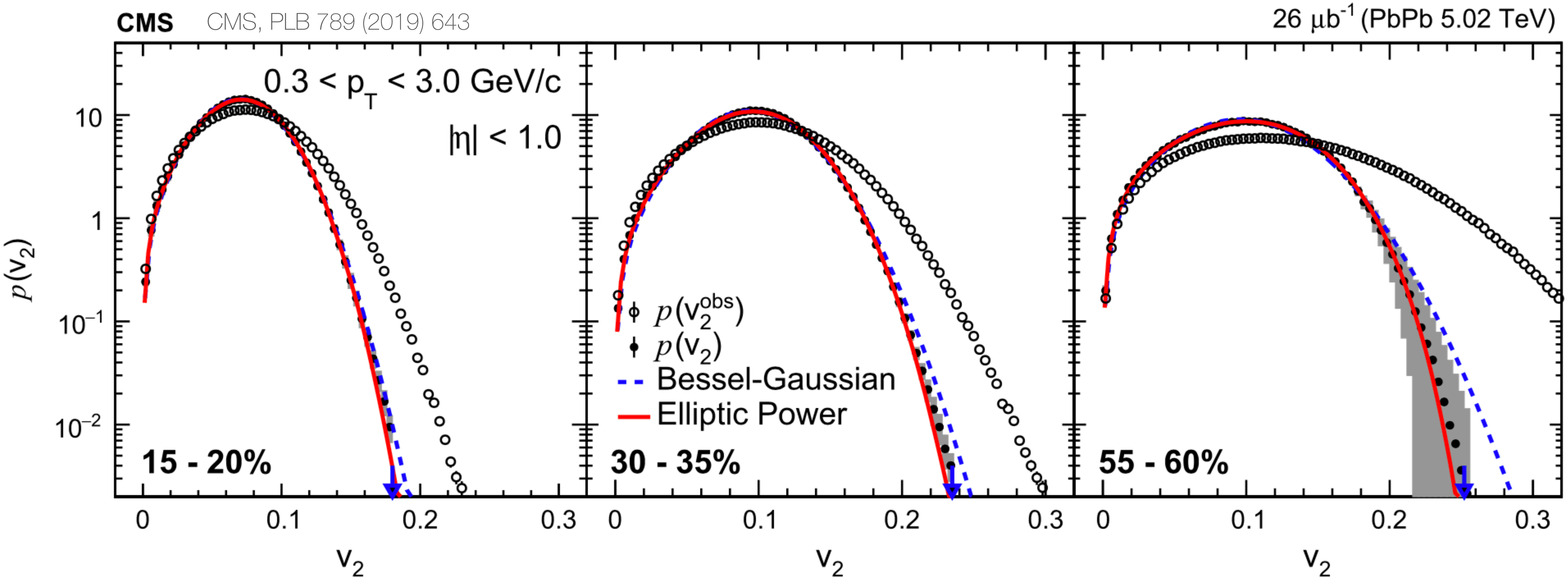
1. Measure the distribution directly
2. Measure its moments/cumulants

- First moment → mean
- Second moment → variance
- Third moment → skewness
- Fourth moment → kurtosis

- Cumulants - related to moments



How to distinguish between parametrizations



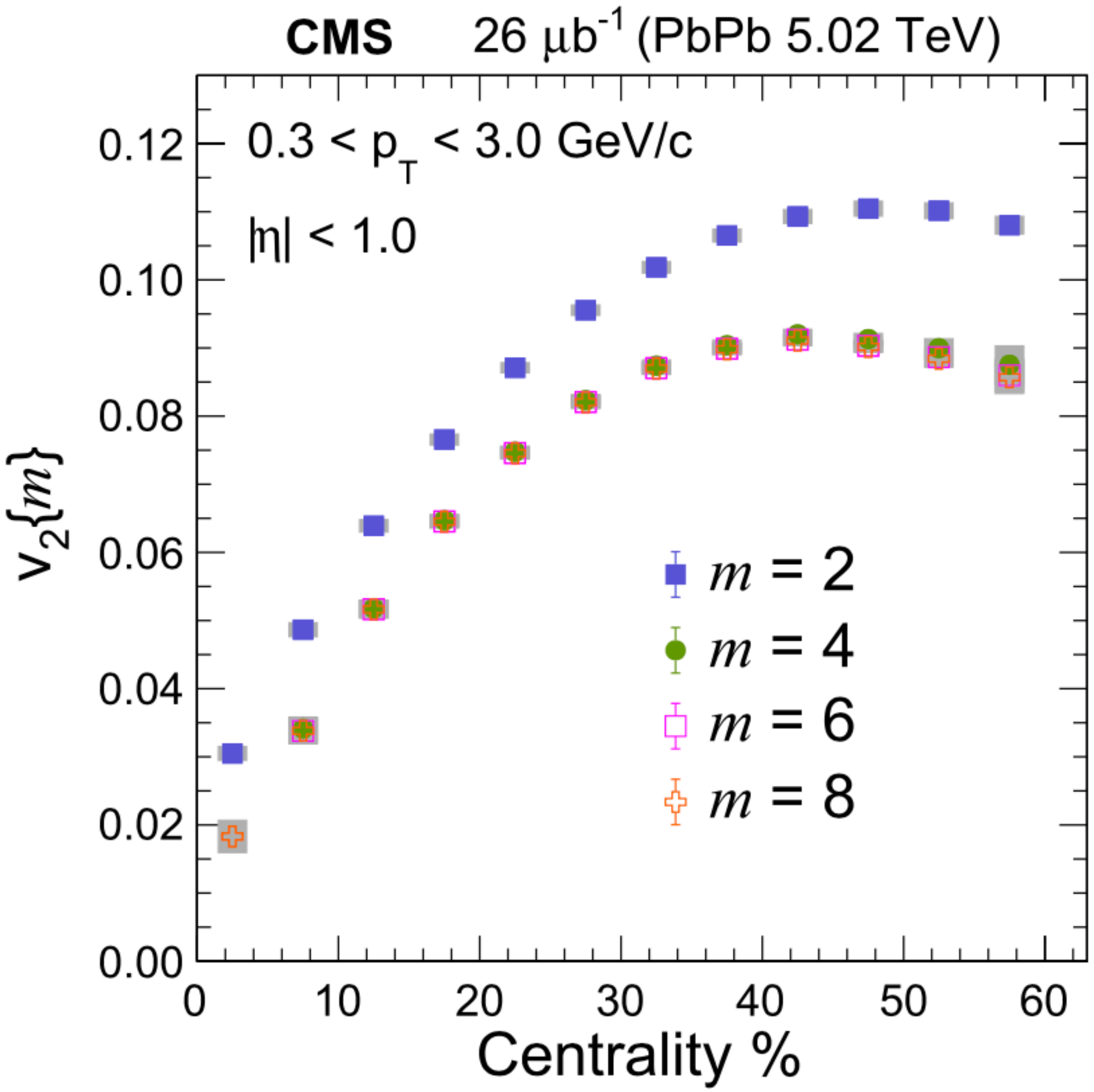
- Fitting the measured $P(v_n)$ distributions
  - Bessel-Gaussian is good approximation semicentral collisions (ellipticity dominates)
  - Elliptic power works for all centralities

How to distinguish between parametrizations

- Measuring ratios of v_n obtained from multiparticle cumulants

$$v_n\{m\}$$

m = order of particle correlation



CMS, PLB 789 (2019) 643

- **Gaussian parametrization**
  - Higher order cumulants equal to 0

$$v_2\{2\} > v_2\{4\} = v_2\{6\} = v_2\{8\} = 0$$

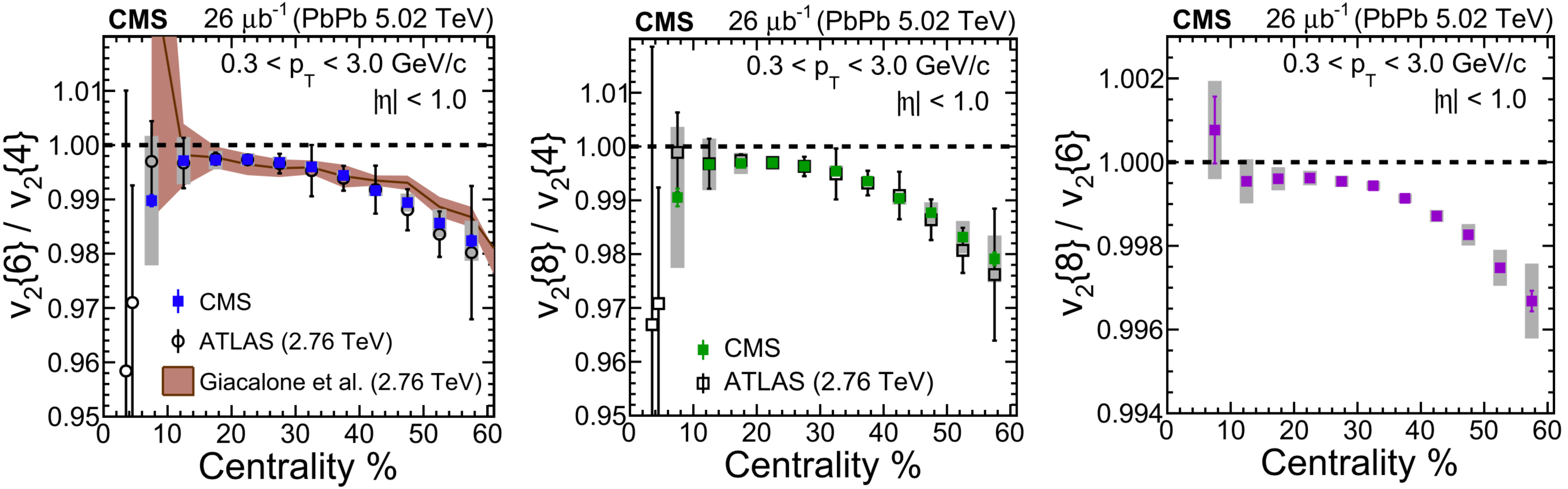
- **Bessel-Gaussian parametrization**
  - Higher order cumulants are degenerate

$$v_2\{2\} > v_2\{4\} = v_2\{6\} = v_2\{8\}$$

- **Elliptic power parametrization**
  - Differences between higher order cumulants
  - Differences at small scales
  - Can probe details of the distributions

$$v_2\{2\} > v_2\{4\} > v_2\{6\} > v_2\{8\}$$

How to distinguish between parametrizations



CMS, PLB 789 (2019) 643

- Ratios of $v_2\{m\}$ deviate from unity, especially in peripheral collisions
  - Non-Bessel-Gaussian fluctuations

$$v_2\{2\} > v_2\{4\} > v_2\{6\} > v_2\{8\} \Rightarrow \frac{v_2\{6\}}{v_2\{4\}} < 1 \qquad \frac{v_2\{8\}}{v_2\{4\}} < 1 \qquad \frac{v_2\{8\}}{v_2\{6\}} < 1$$

Moments of $P(v_n)$

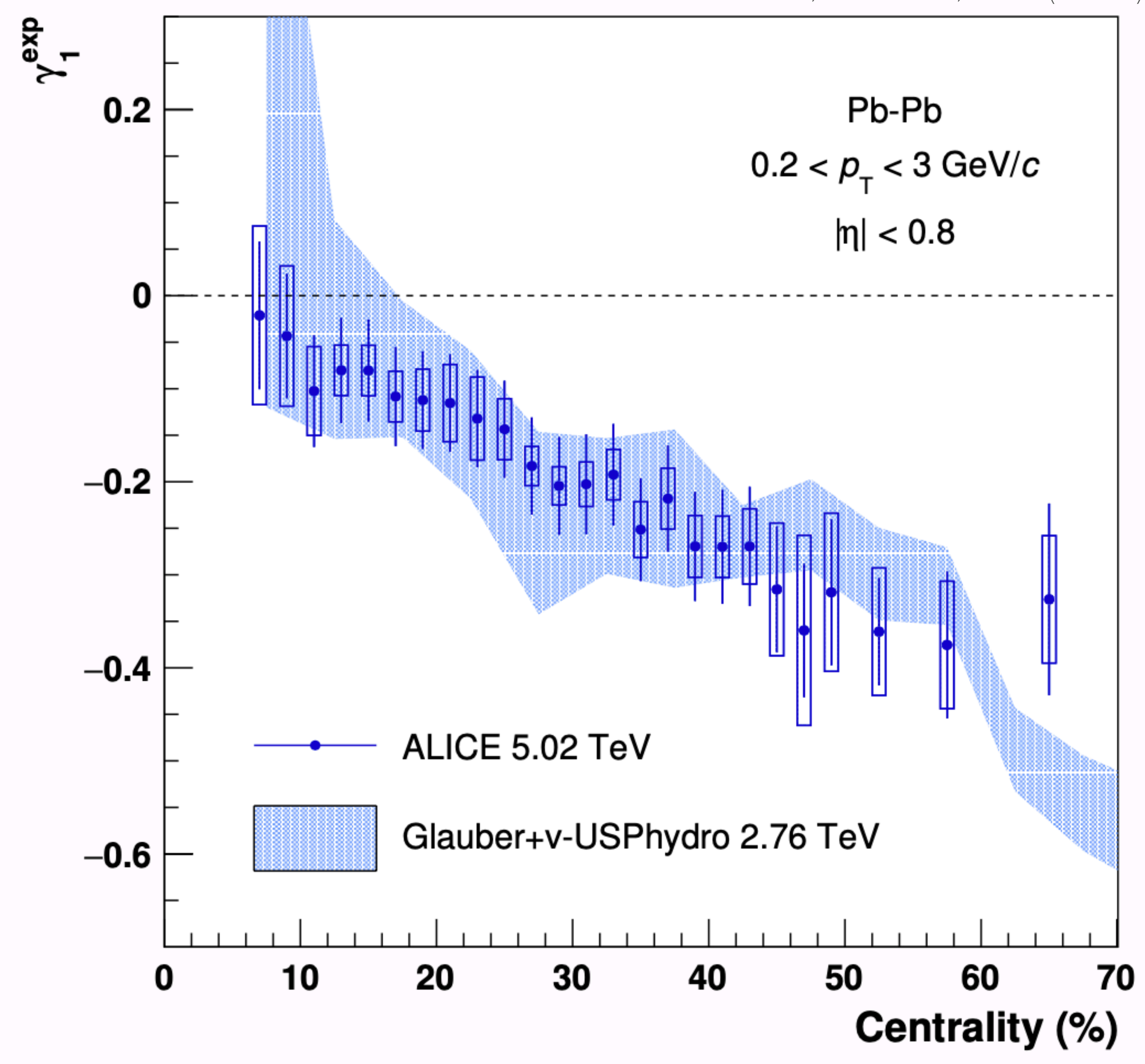
- The v_n distribution was found to be **left-skewed**
- Compatible with hydrodynamic calculations

$$\gamma_1^{\rm expt} \equiv -2^{3/2} \frac{v_2\{4\}^3 - v_2\{6\}^3}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}$$

- **Kurtosis not measured so far**
  - Need for precise measurement of $v_2\{8\}$

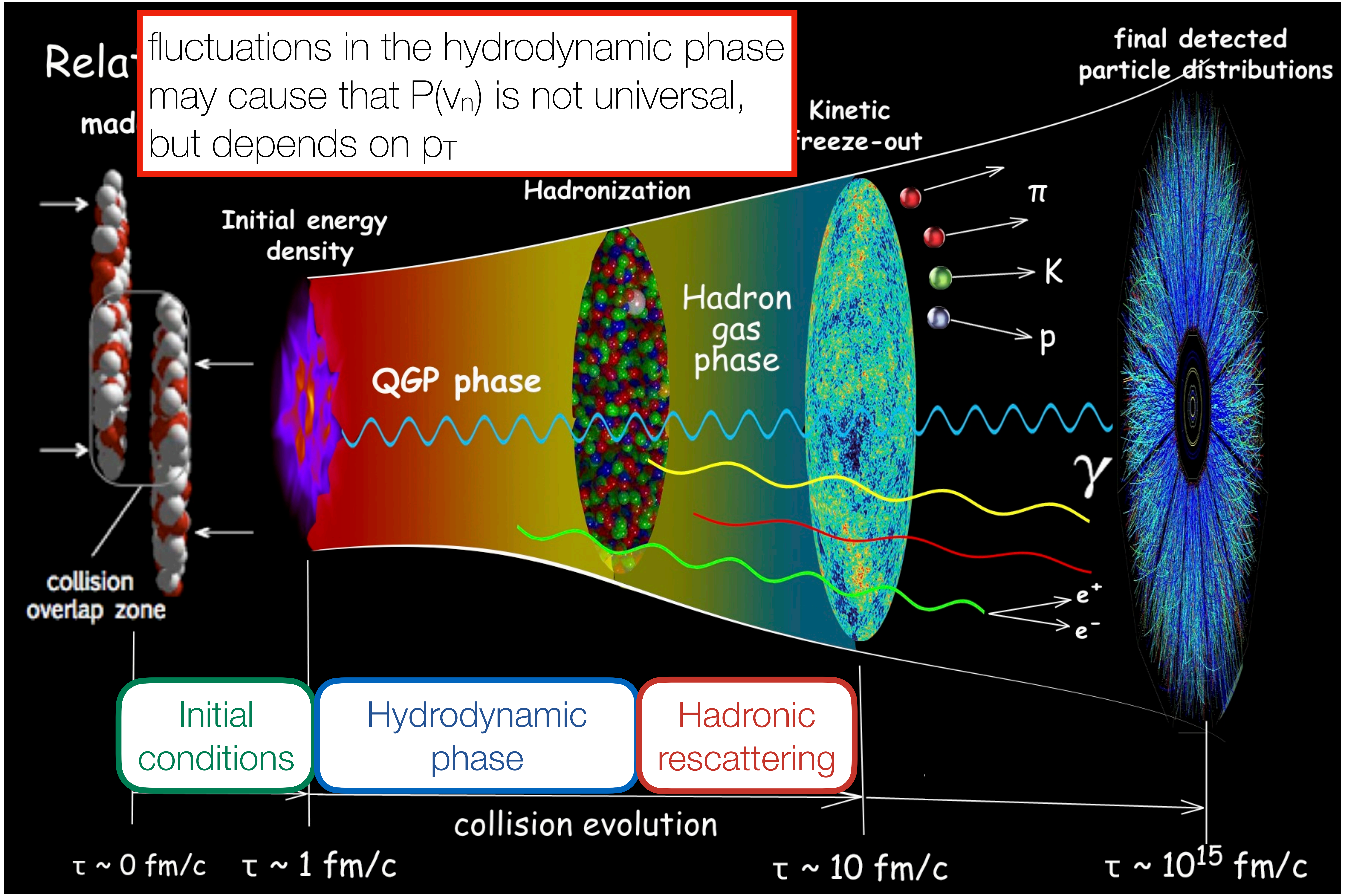
$$\gamma_2^{\rm expt} \equiv -\frac{3}{2} \frac{v_2\{4\}^4 - 12 v_2\{6\}^4 + 11 v_2\{8\}^4}{(v_2\{2\}^2 - v_2\{4\}^2)^2}$$

ALICE, JHEP07, 103 (2018)



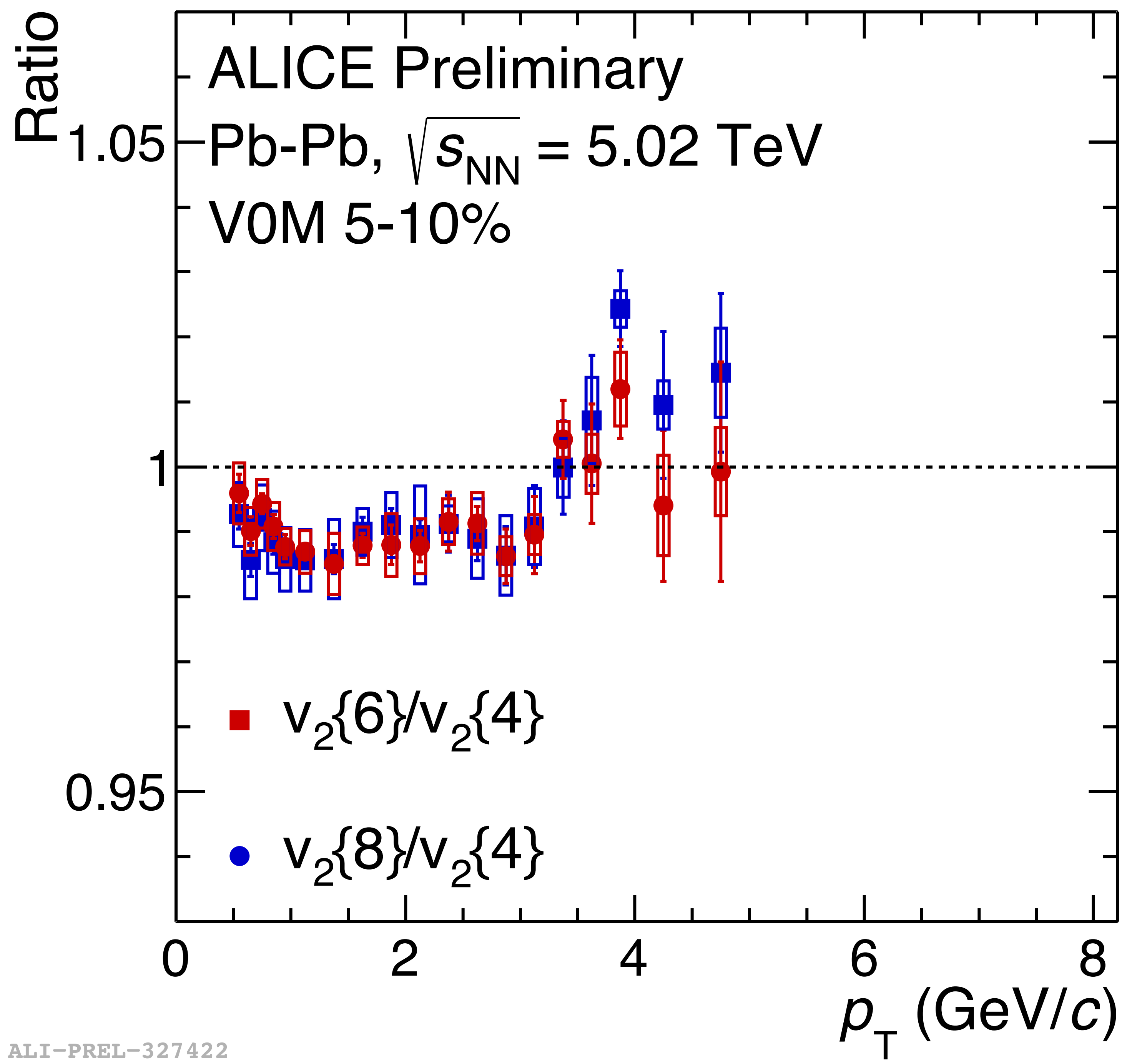
Modelling of heavy-ion collisions

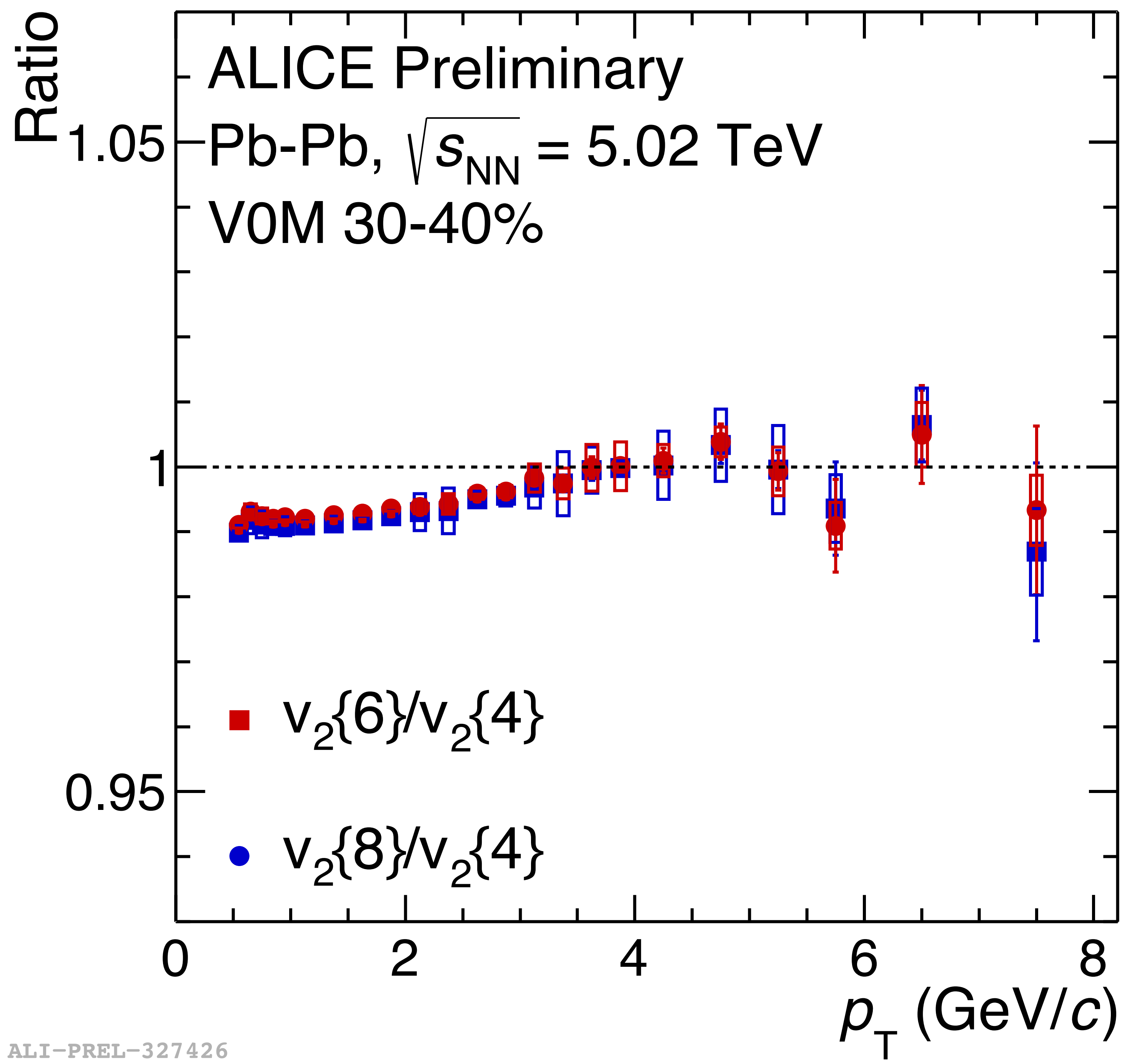
initial eccentricity

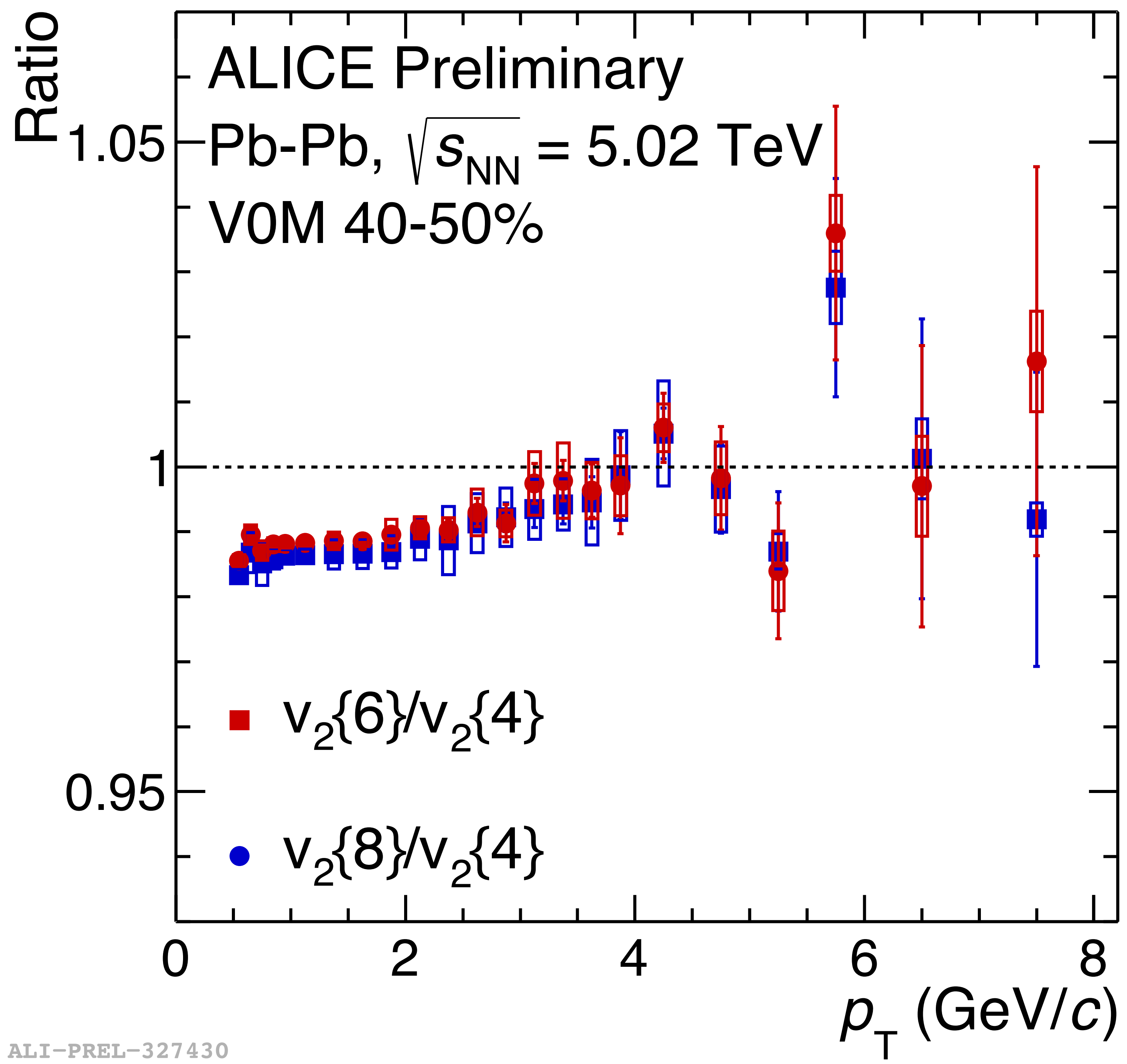


anisotropic flow

Ratios of multiparticle cumulants







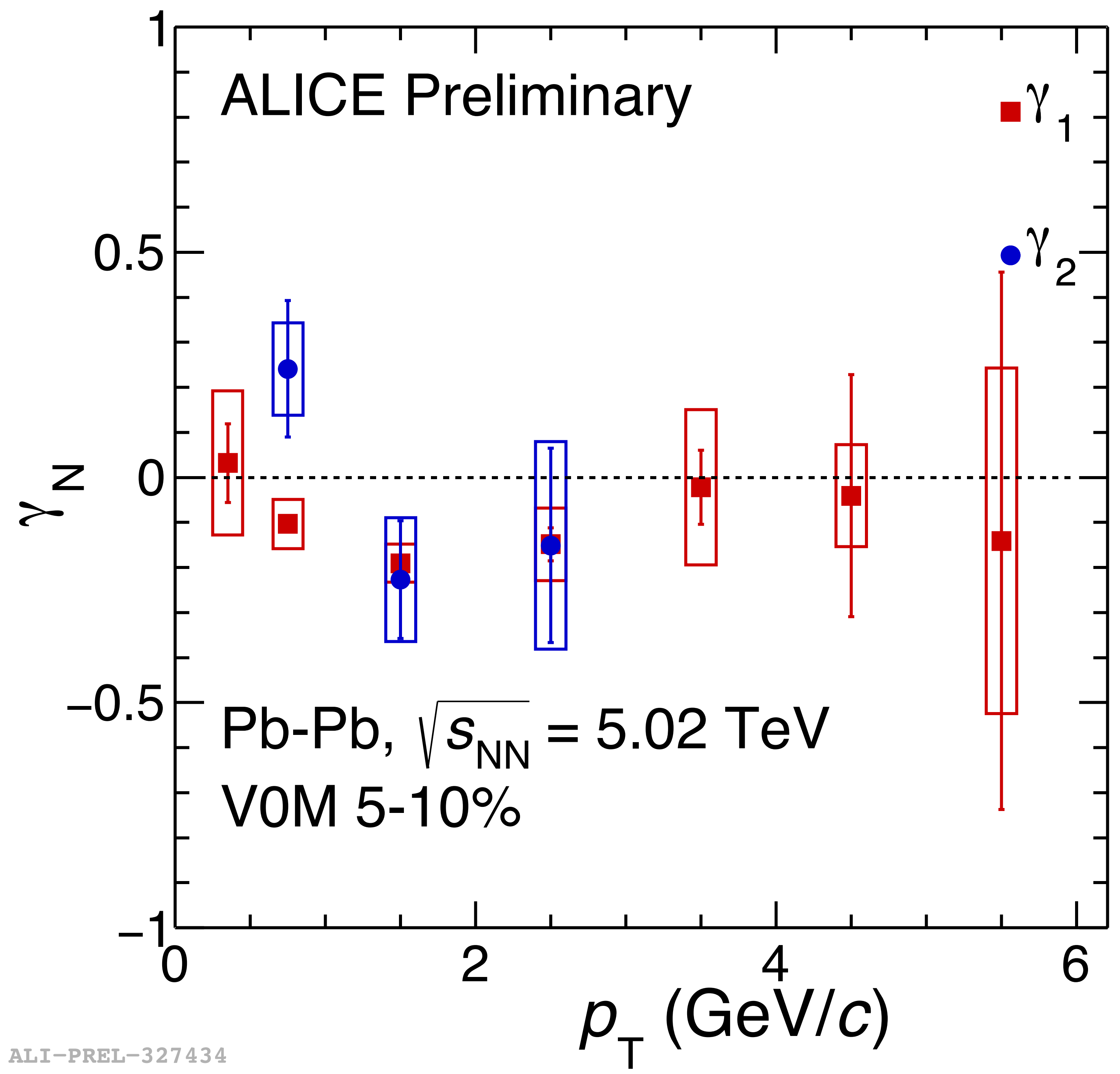
p_T < 3 GeV/c

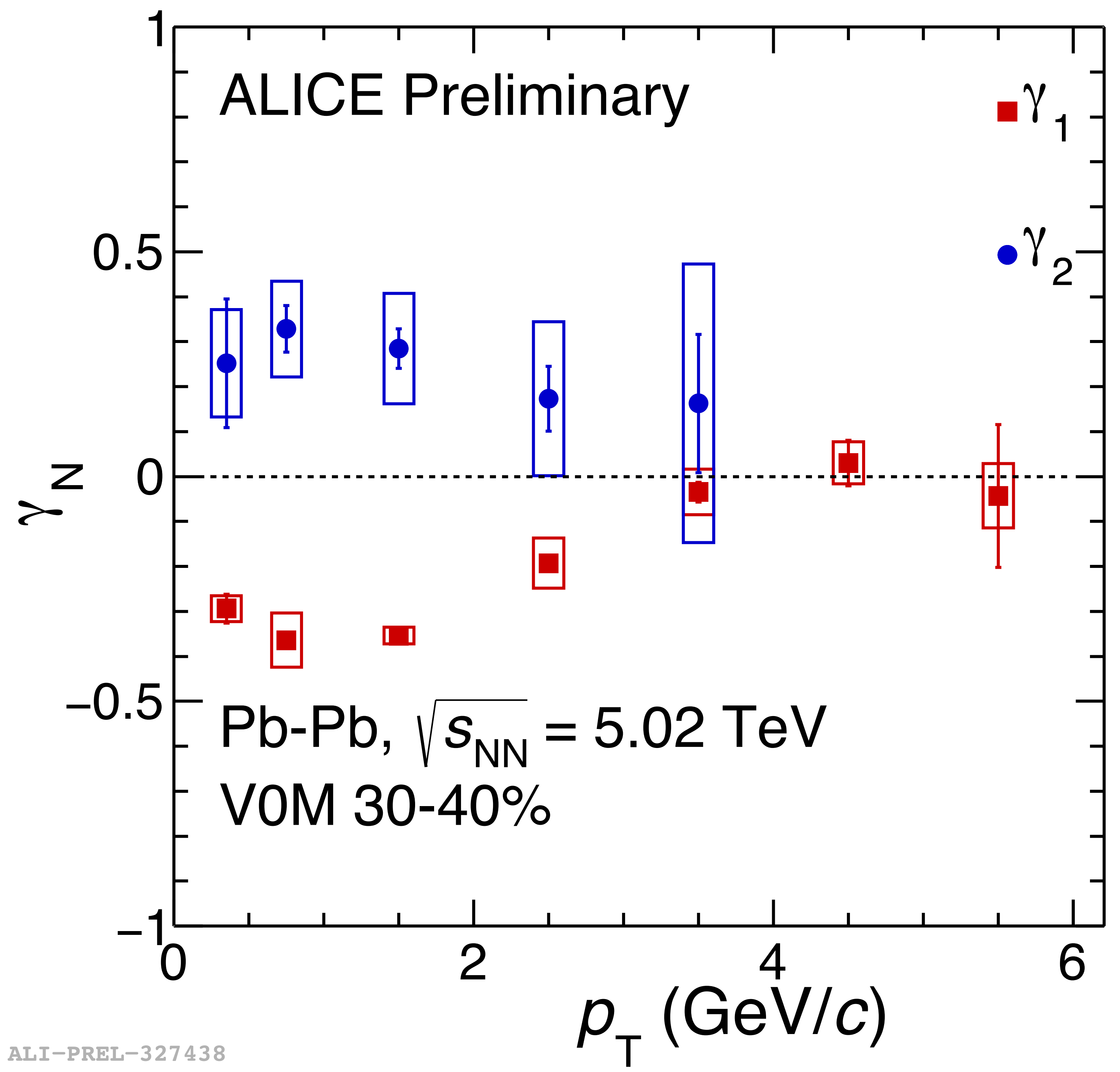
- Ratios < 1
  - Non-Bessel-Gaussian type of fluctuations
- Dependence on transverse momentum
  - Influence from fluctuations in the hydrodynamic phase

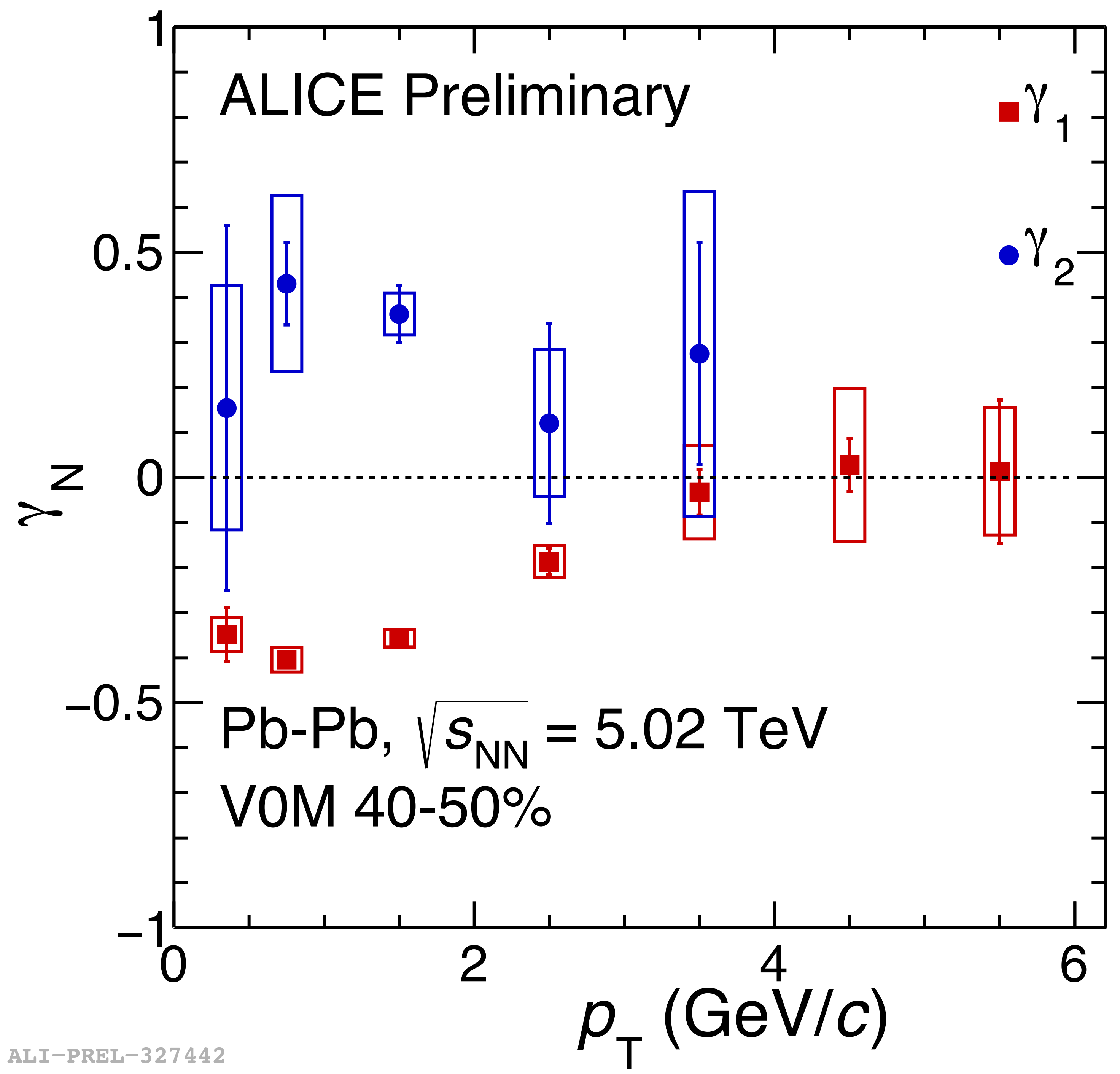
p_T > 3 GeV/c

- Ratios = 1
  - Degenerate high order cumulants → Bessel-Gaussian type of fluctuations even in peripheral collisions
  - Note: we are not in a hydrodynamic regime anymore, the flow harmonics originate more from the path length dependence of parton energy loss

Skewness and kurtosis







p_T < 3 GeV/c

- Negative skewness
  - Compatible with non-Bessel-Gaussian type of fluctuations

p_T > 3 GeV/c

- Zero skewness
  - Compatible with Bessel-Gaussian type of fluctuations

First ever measurement of kurtosis

Summary

Measurements of flow fluctuations provide information about fluctuations in the initial state

The parametrization of flow (eccentricity) fluctuations are non-Bessel-Gaussian.

Observed p_T dependence points to influence by hydrodynamic fluctuations

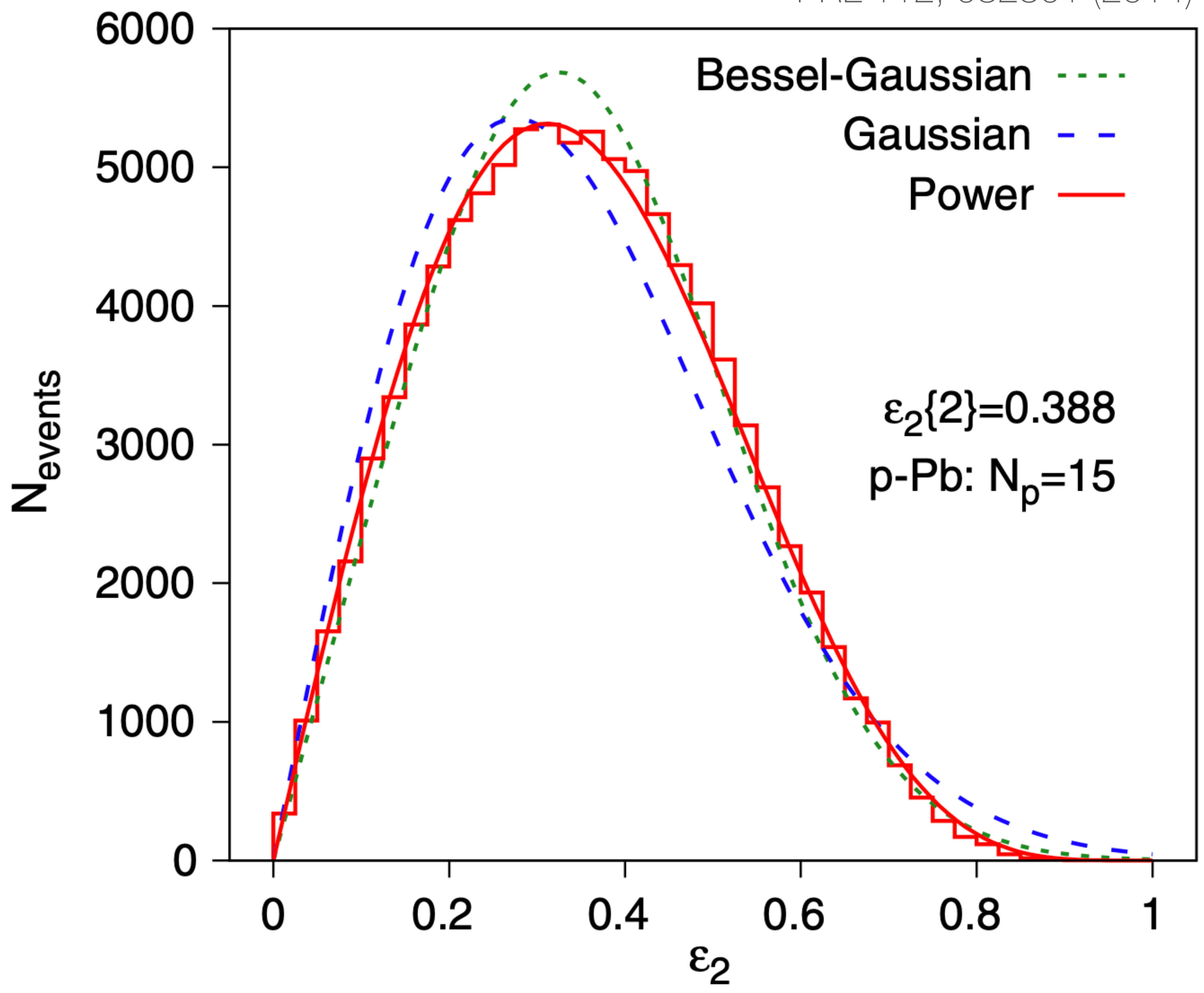
Our differential measurements of flow fluctuations provide new constraints to theoretical calculations.

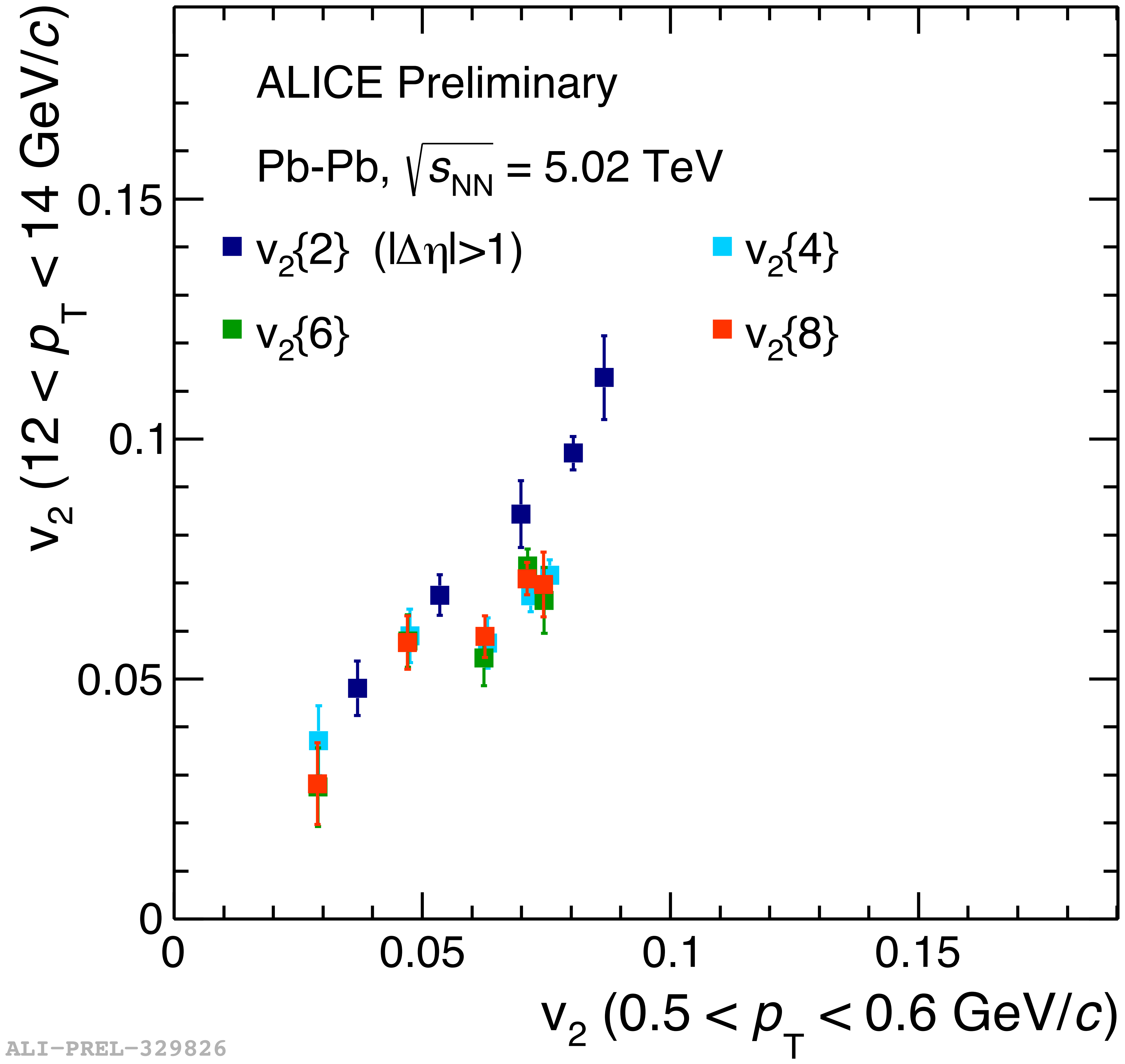
Backup

Eccentricity distribution

- Event-by-event fluctuations in the initial geometry -> initial eccentricity not a delta function
- Parametrizations of the p.d.f.
  1. Gaussian
$$P(\varepsilon) = \frac{2\varepsilon}{\sigma^2}\exp\left(-\frac{\varepsilon^2}{\sigma^2}\right)$$
  2. Bessel-Gaussian - more suitable for fluctuations of ε_2
$$P(\varepsilon) = \frac{2\varepsilon}{\sigma^2} I_0\left(\frac{2\varepsilon\bar{\varepsilon}}{\sigma^2}\right)\exp\left(-\frac{\varepsilon^2+\bar{\varepsilon}^2}{\sigma^2}\right)$$
  3. Power law - more suitable for fluctuation-driven eccentricities
$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$
  4. Elliptic Power - general parametrization including cases 2) and 3)
$$p(\varepsilon_x,\varepsilon_y) = \frac{\alpha}{\pi}(1-\varepsilon_0^2)^{\alpha+\frac{1}{2}}\frac{(1-\varepsilon_x^2-\varepsilon_y^2)^{\alpha-1}}{(1-\varepsilon_0\varepsilon_x)^{2\alpha+1}}$$

PRL 112, 082301 (2014)





- Correlation of soft and hard v_2 (low and high p_T)
- Shows that at high p_T we indeed have parton energy loss that depends on the initial eccentricity
- Both flow and parton energy loss are correlated with initial ellipticity
  - But we saw that the p_T dependence of fluctuations is different at the two regimes