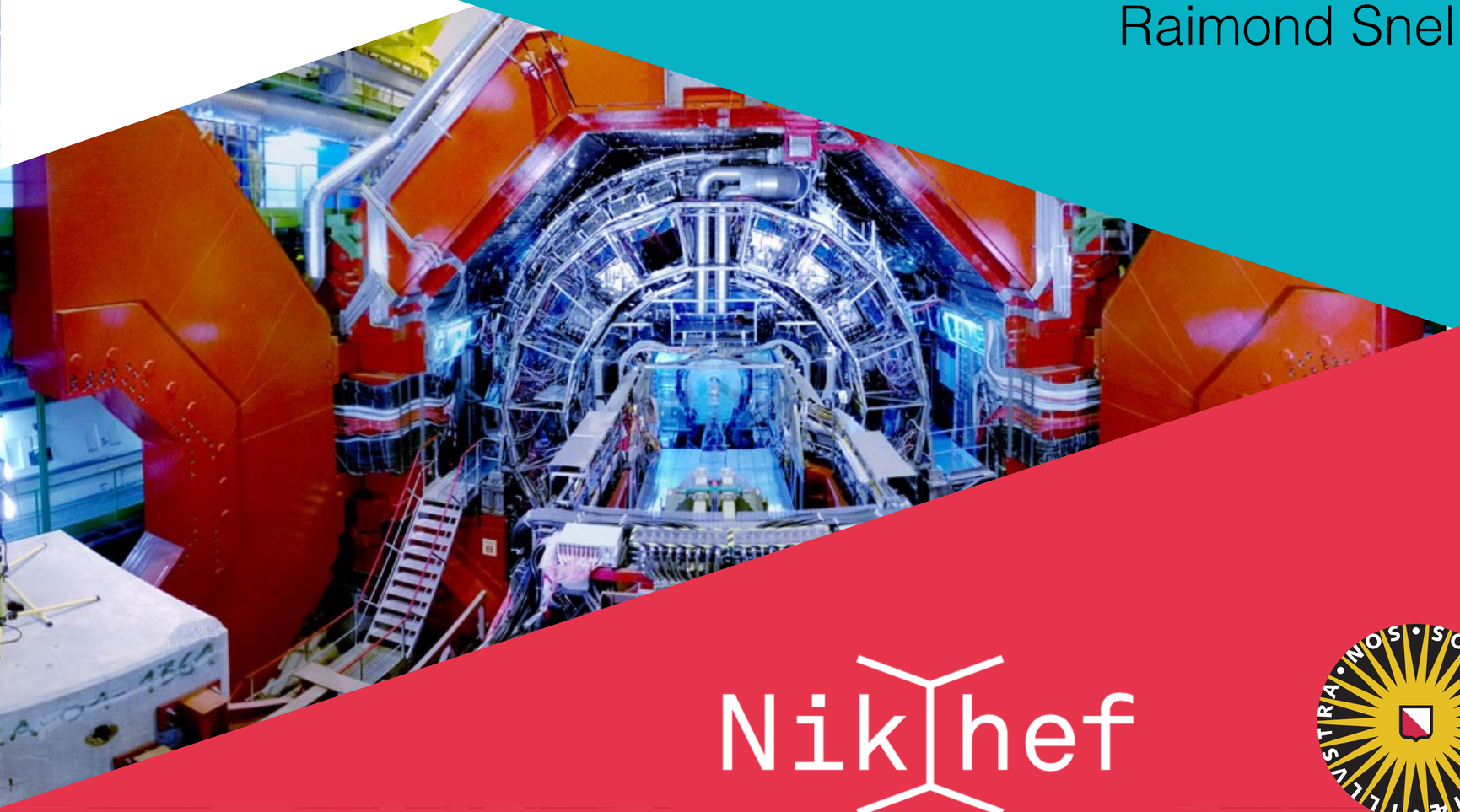
Energy Dependence and Fluctuations of Anisotropic Flow

Raimond Snellings

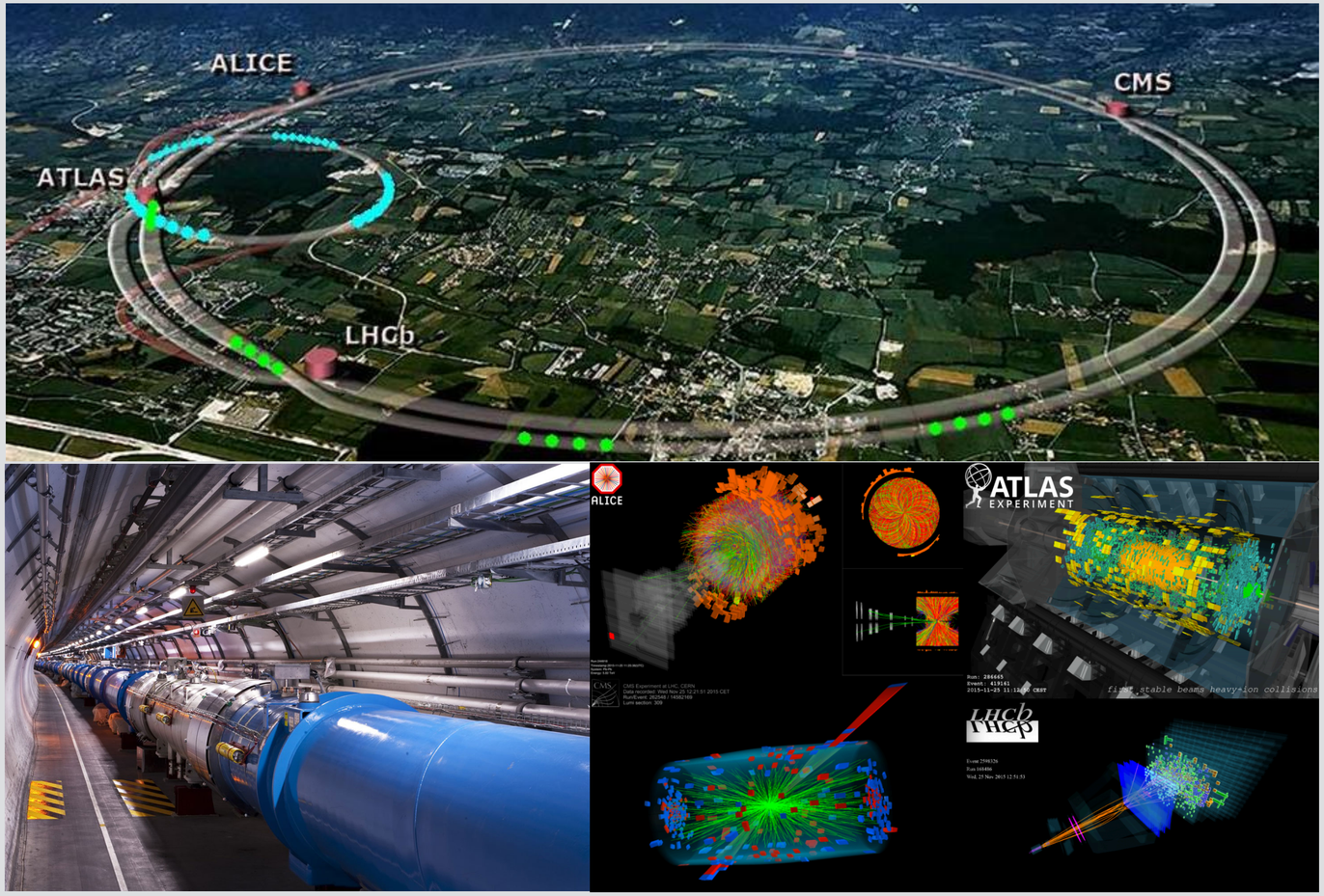


Nikhef

Universiteit Utrecht

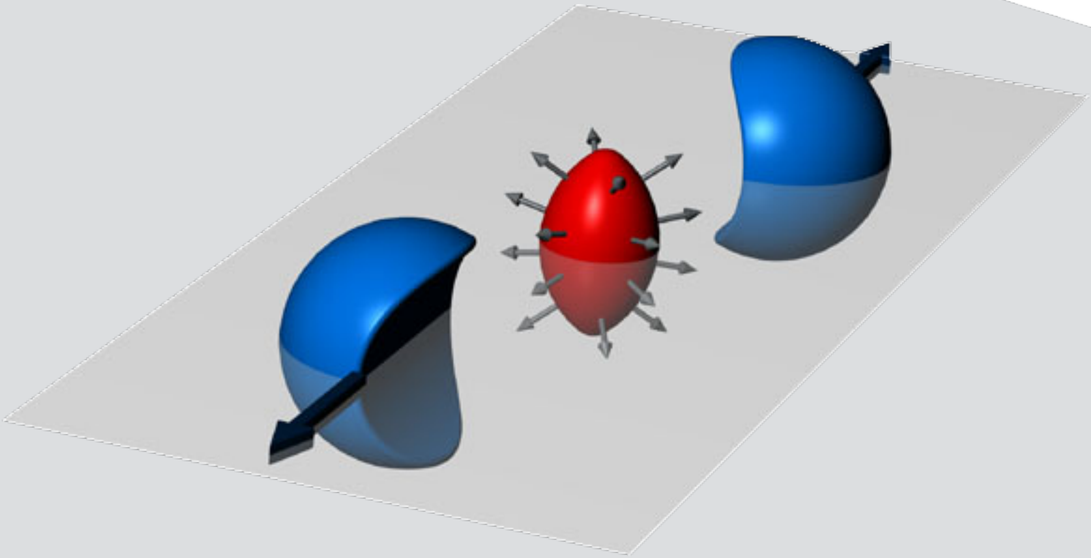
Heavy-Ion Collisions at the LHC

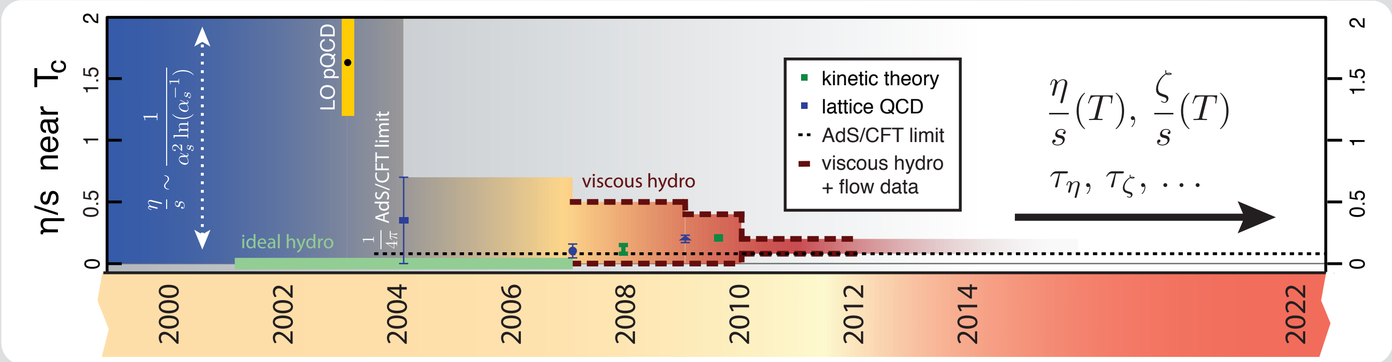
- What happens to matter when you heat and compress it to extreme magnitudes which existed in the primordial universe?
  - Lattice QCD predicts a phase transition to a quark-gluon-plasma at an energy density of about 1 GeV/fm^3 and at a temperature of about 10^{12} K
    - Temperatures 10^5 larger than the core of the sun
    - Magnetic fields of order 10^{18} Gauss (strongest magnetic fields known of order 10^8 in the lab and 10^{15} in nature (magnetar))



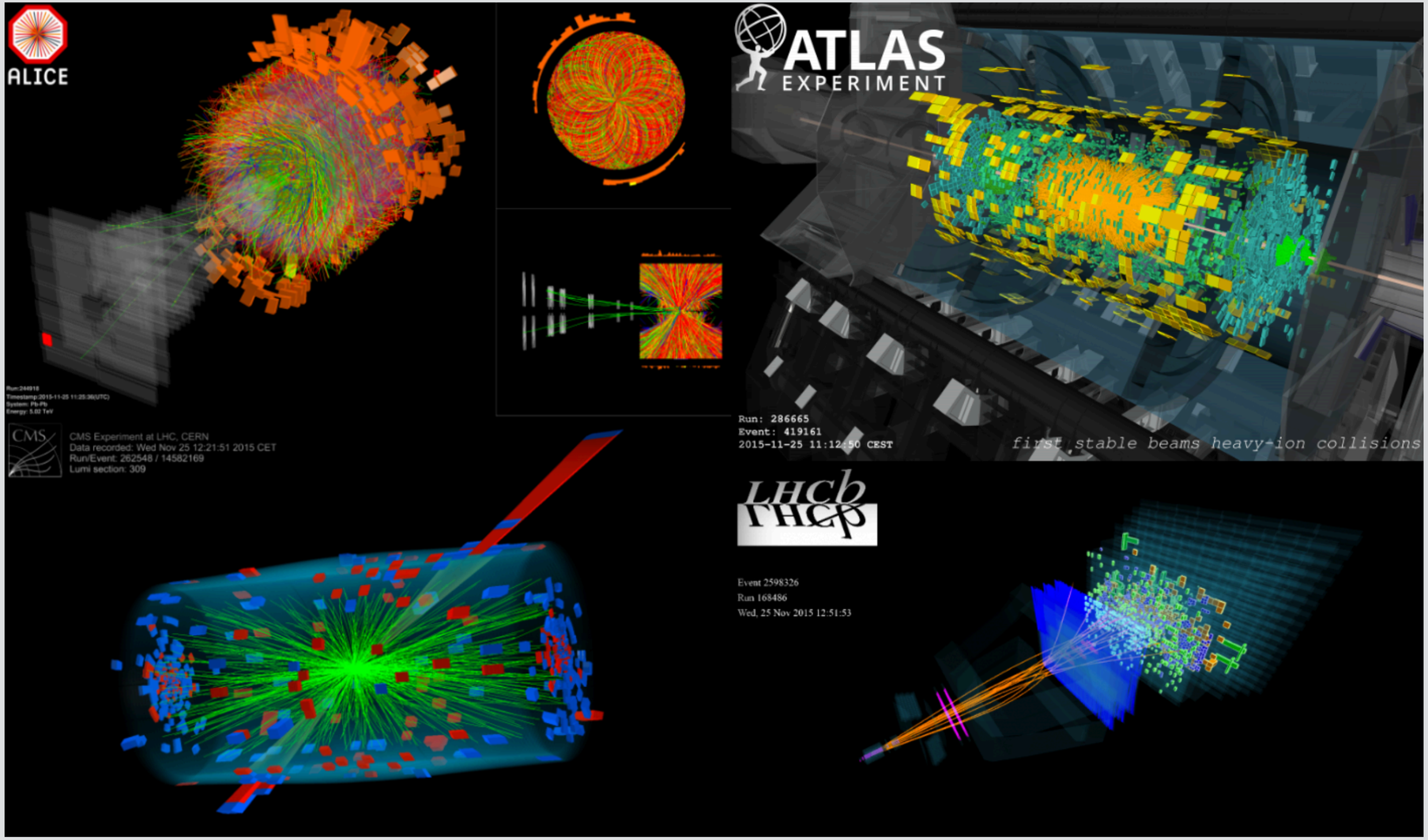
Anisotropic Flow

- QCD in the strong coupling regime is complicated to calculate from first principles, pQCD only useful or small fraction of observables
- Measure properties of this hot and dense matter with respect to simpler systems p-p and p-A
- **Use geometry as a control parameter**
  - **Anisotropic flow**
  - Can we constrain the transport parameters?
  - Can we constrain the initial conditions?



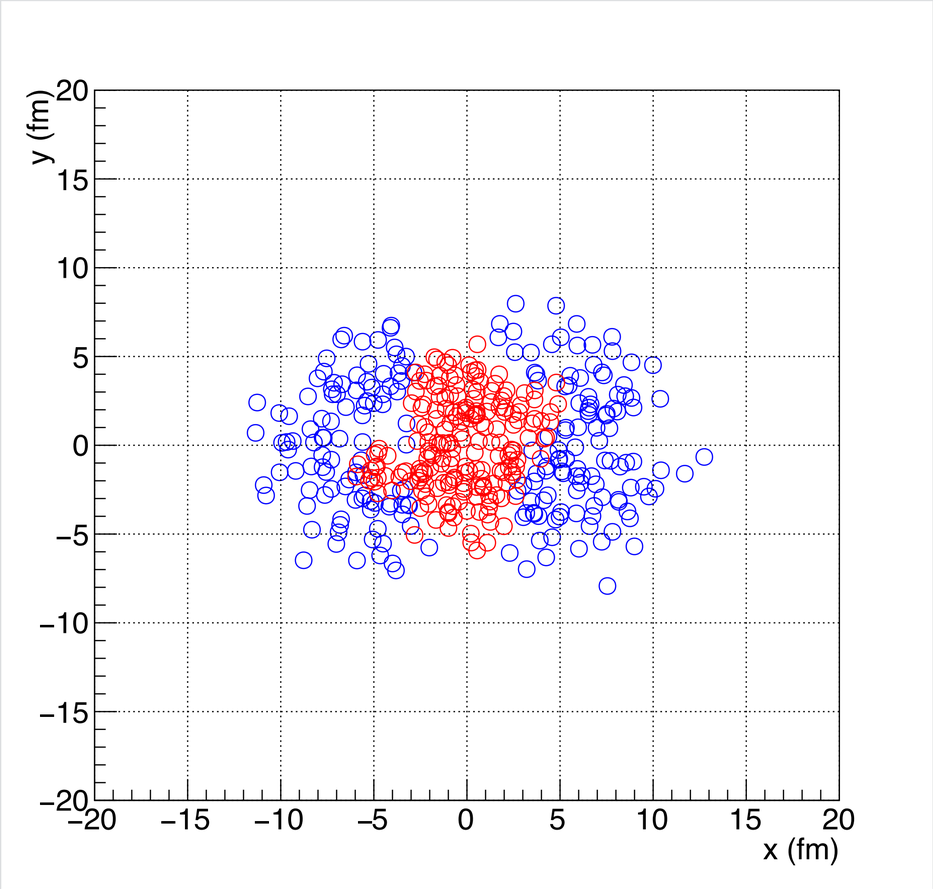


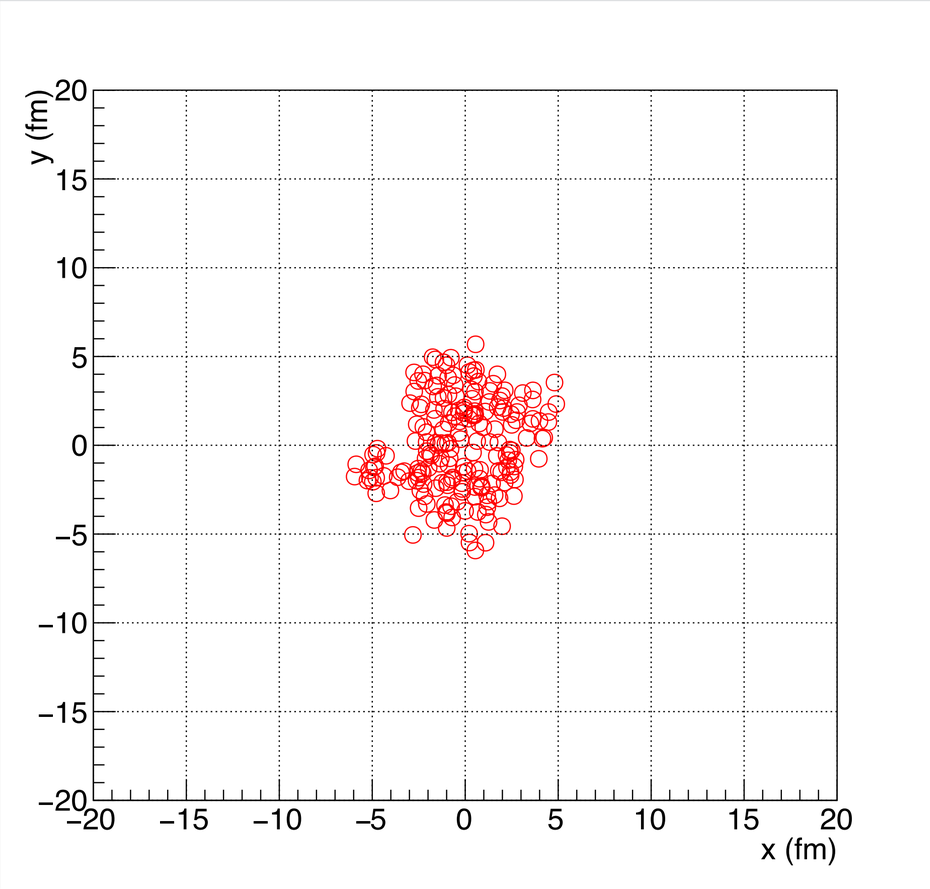
A Single Collision



A Single Collision (coordinate space)

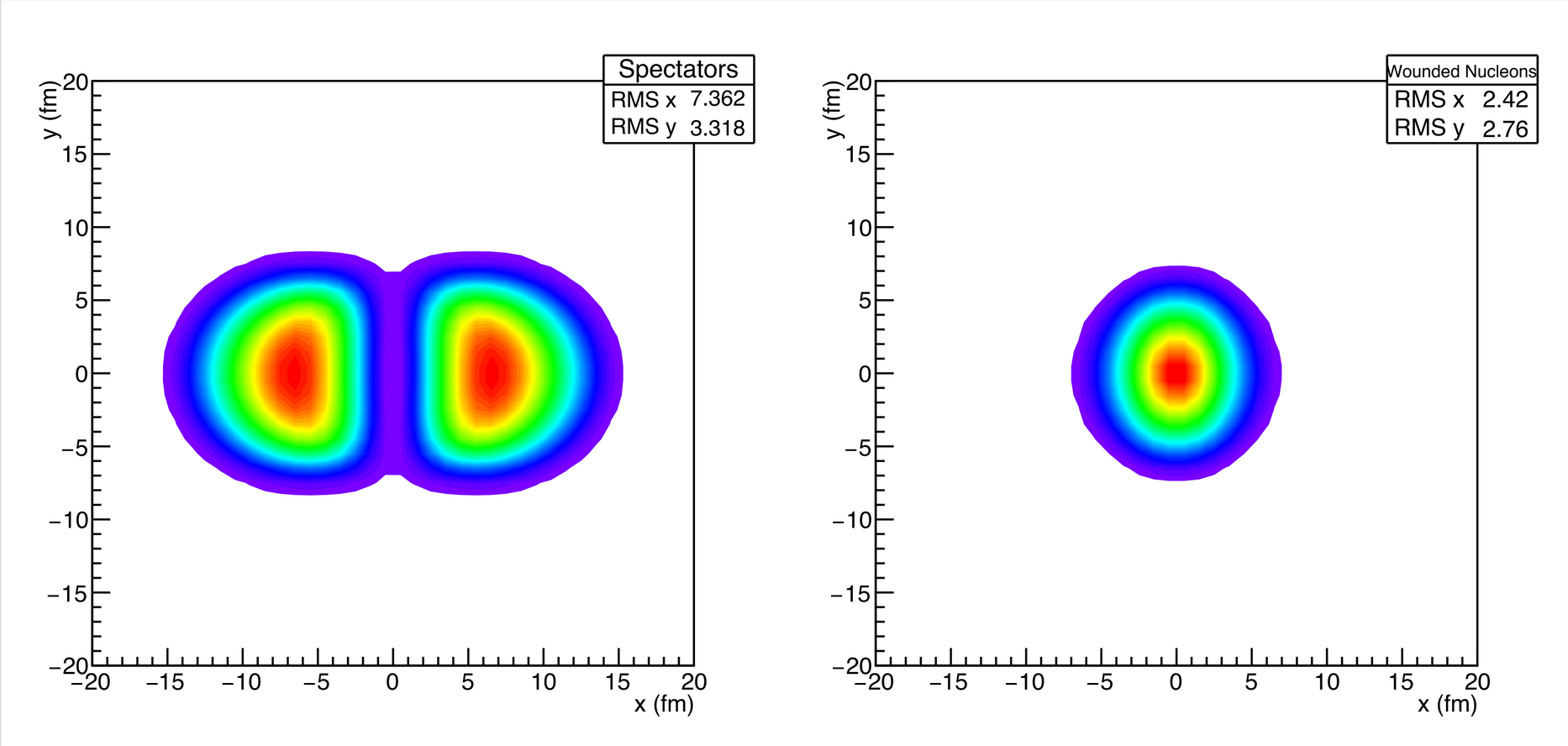
Simple Glauber Model Monte Carlo





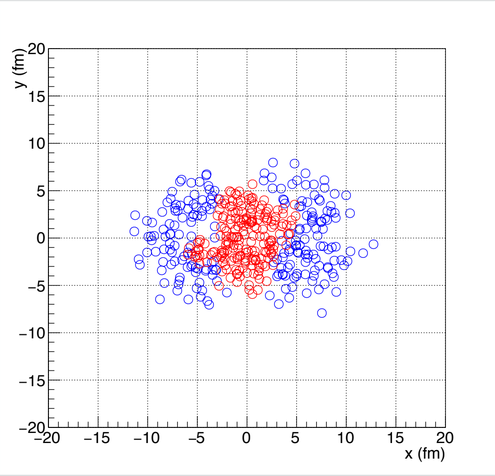
Many Collisions versus the Reaction Plane

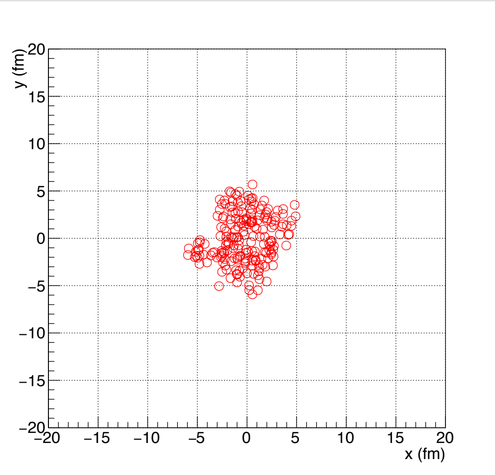
Simple Glauber Model Monte Carlo

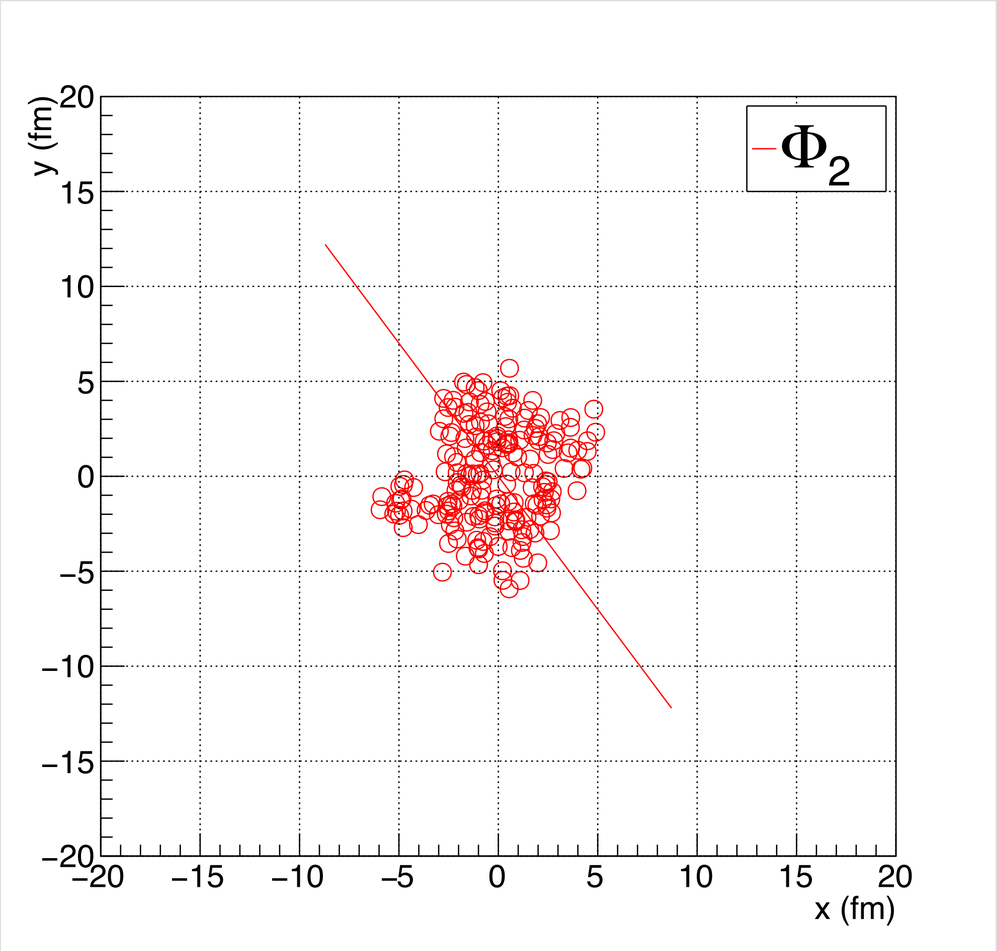


Plane(s) of Symmetry (coordinate space)

Simple Glauber Model Monte Carlo

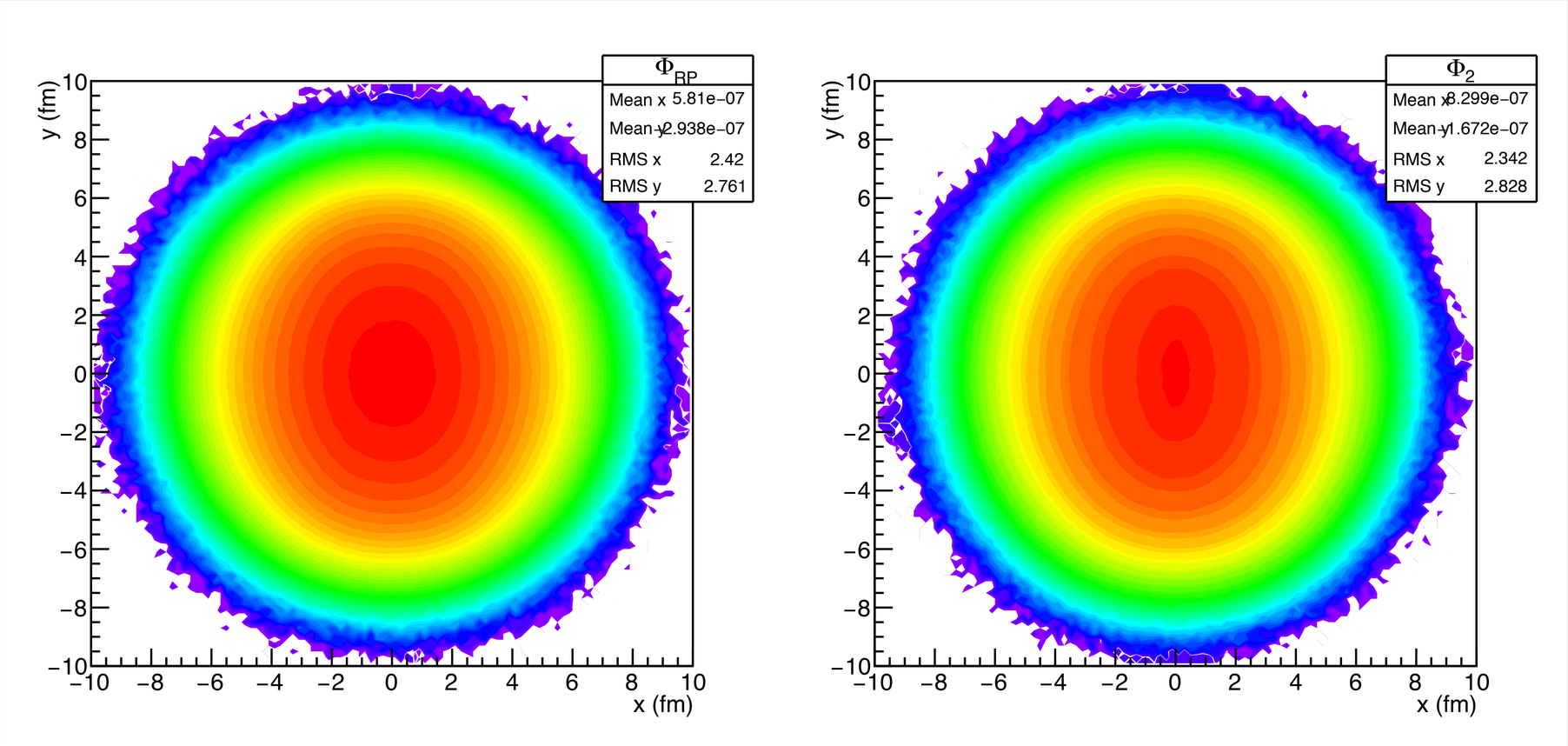






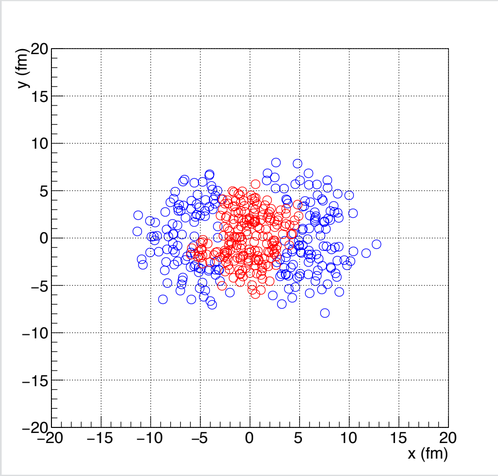
Plane(s) of Symmetry (coordinate space)

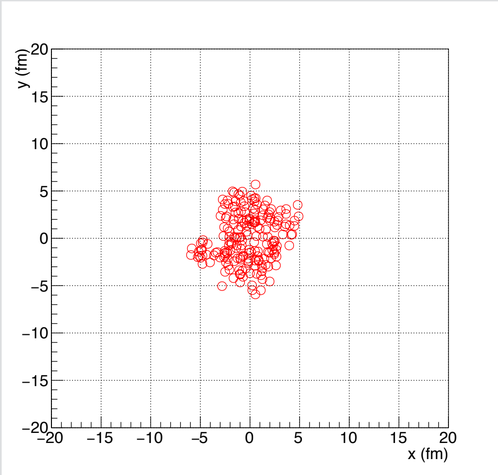
Simple Glauber Model Monte Carlo

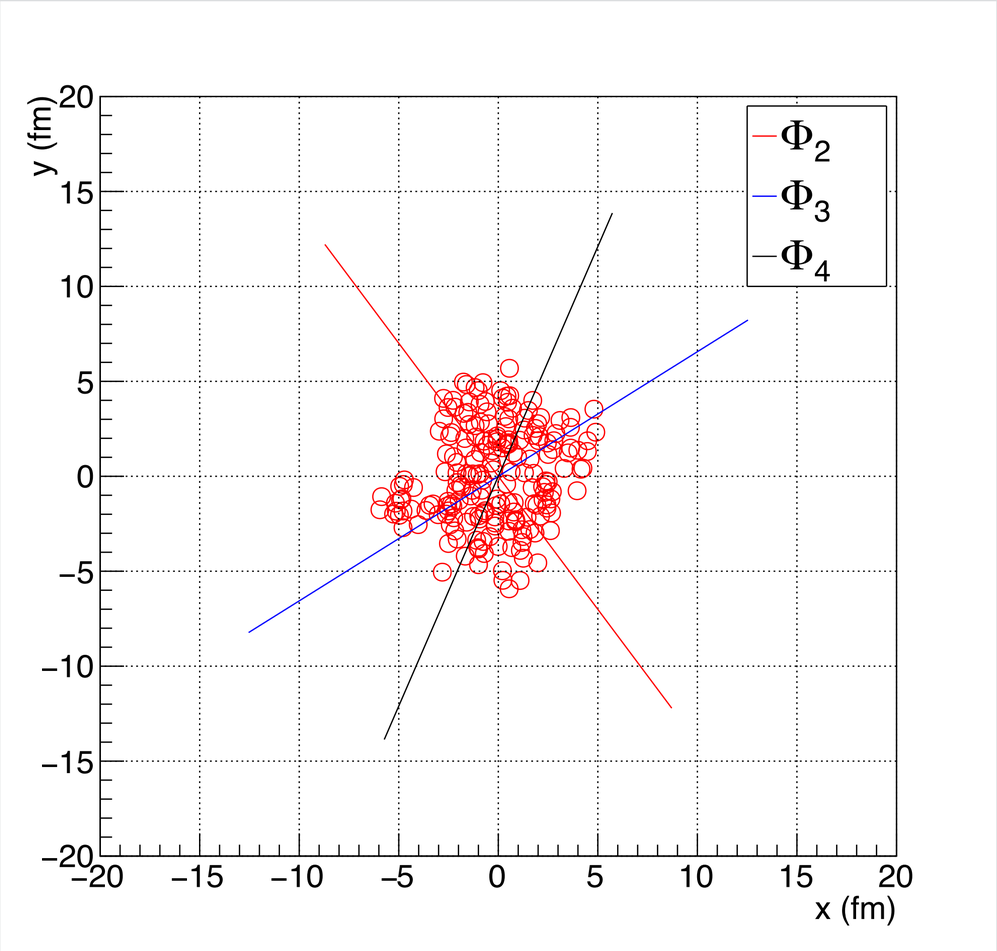


Plane(s) of Symmetry (coordinate space)

Simple Glauber Model Monte Carlo

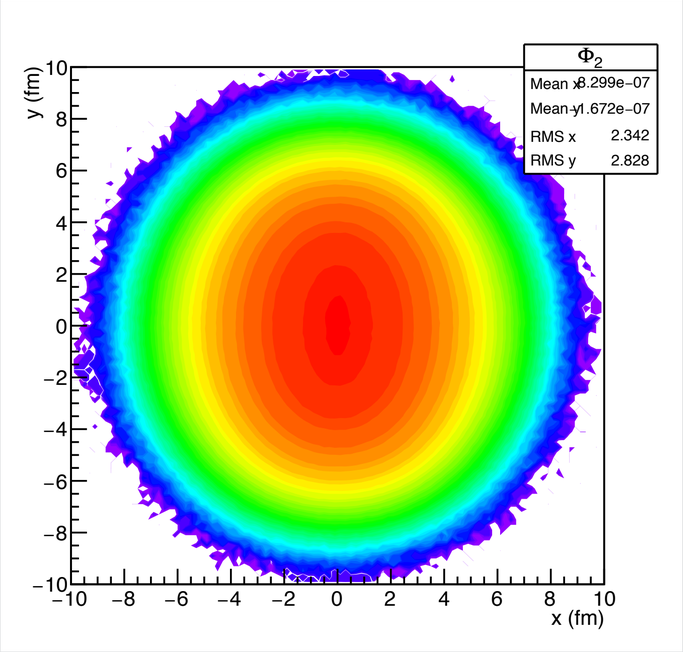


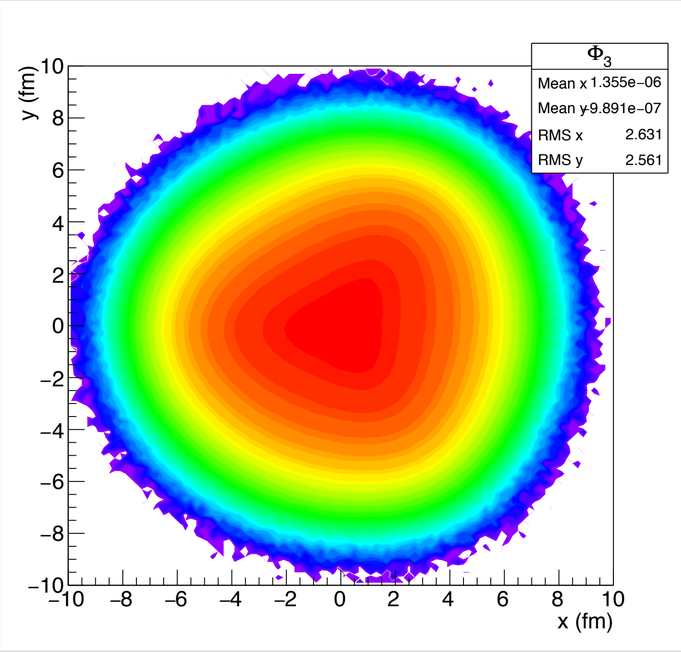


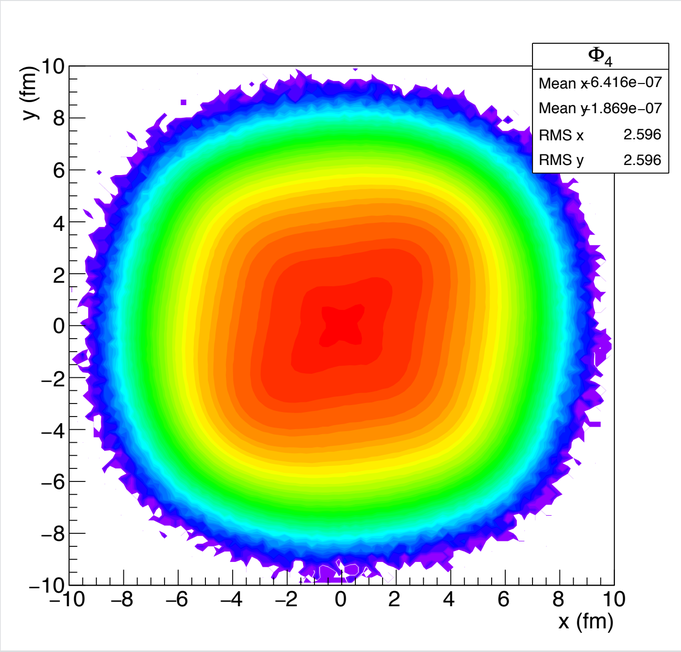


Plane(s) of Symmetry (coordinate space)

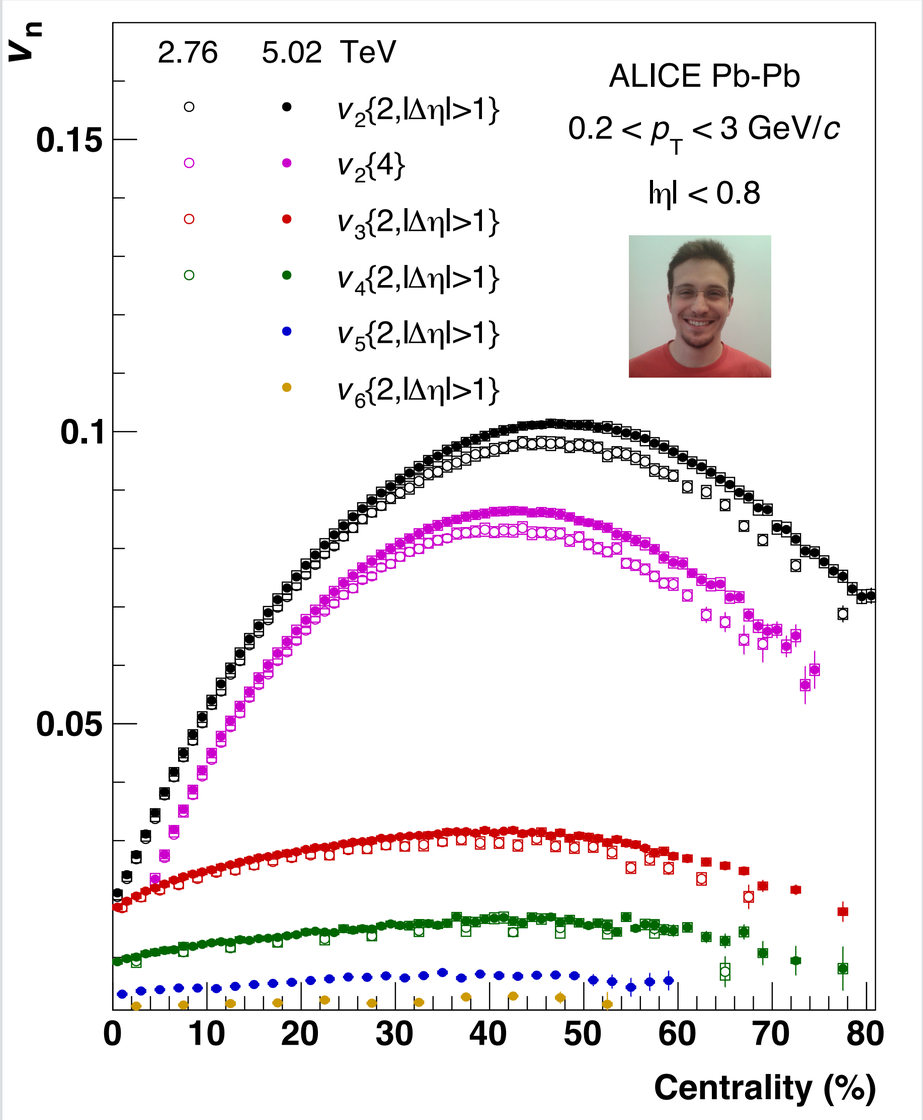
Simple Glauber Model Monte Carlo







Anisotropic Flow (momentum space)

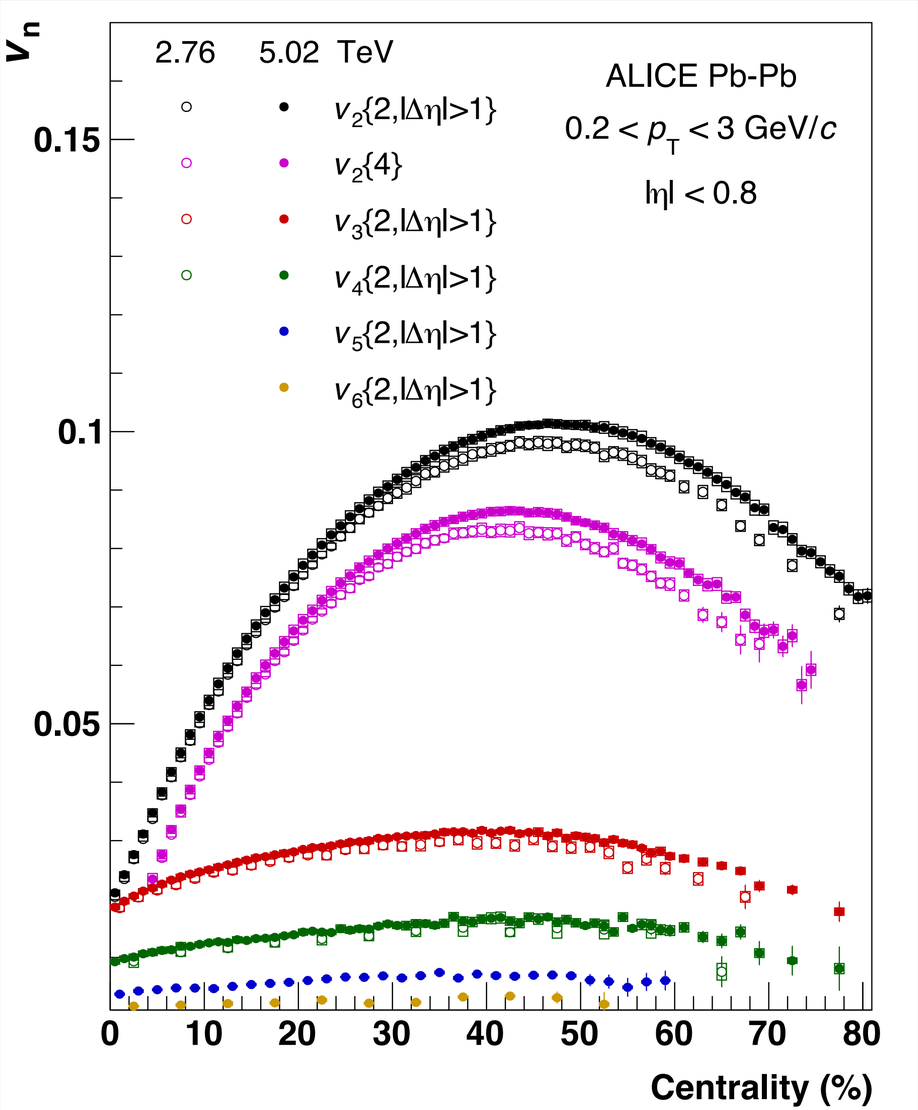


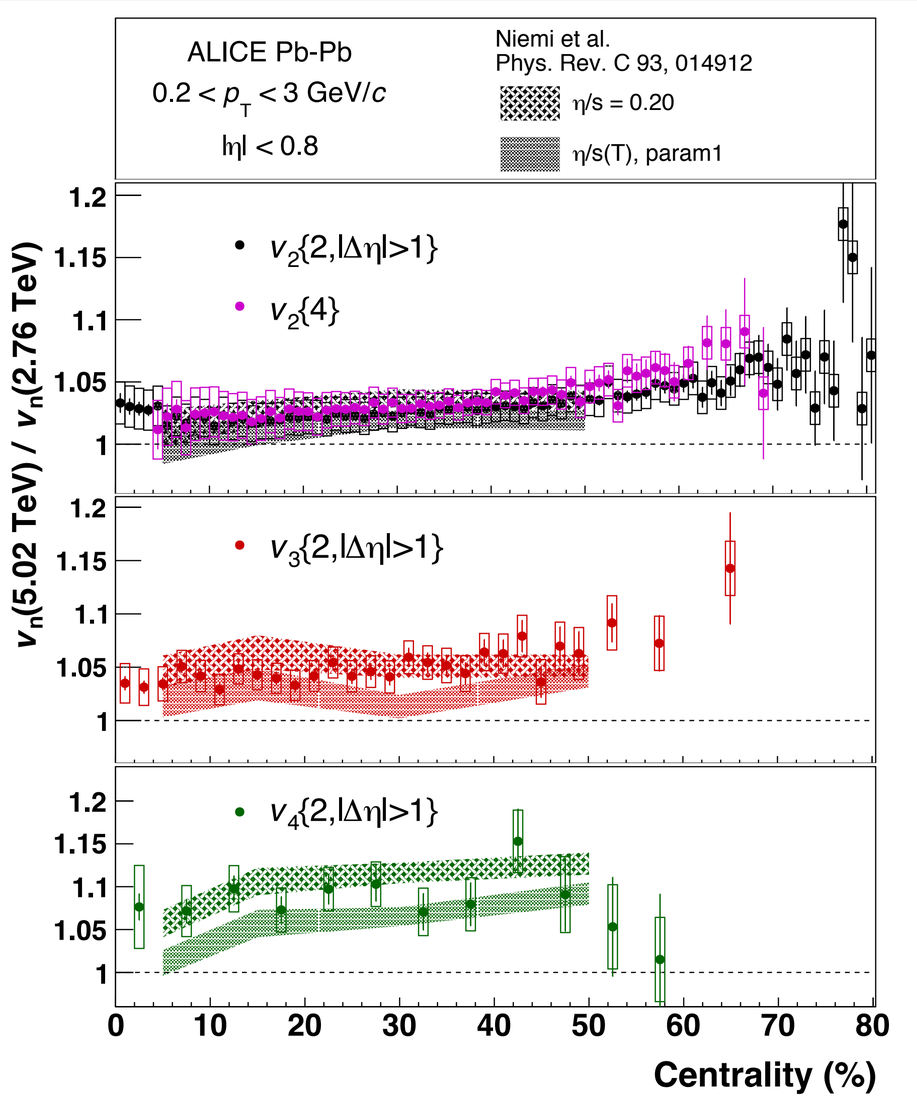
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \Psi_n)\right],$$

- Use geometry as a control parameter
- If the constituents interact they convert the coordinate space asymmetries into momentum space asymmetries
- The v_n coefficients provide information about the initial state anisotropies, the transport parameters and the EoS, and can be used to constrain them
  - Many parameters to constrain, need many different observables
- The energy dependence can be used to constrain the temperature dependance of these parameters on which the v_n depend the most
- Detailed measurements can constrain the p.d.f. of the v_n

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow

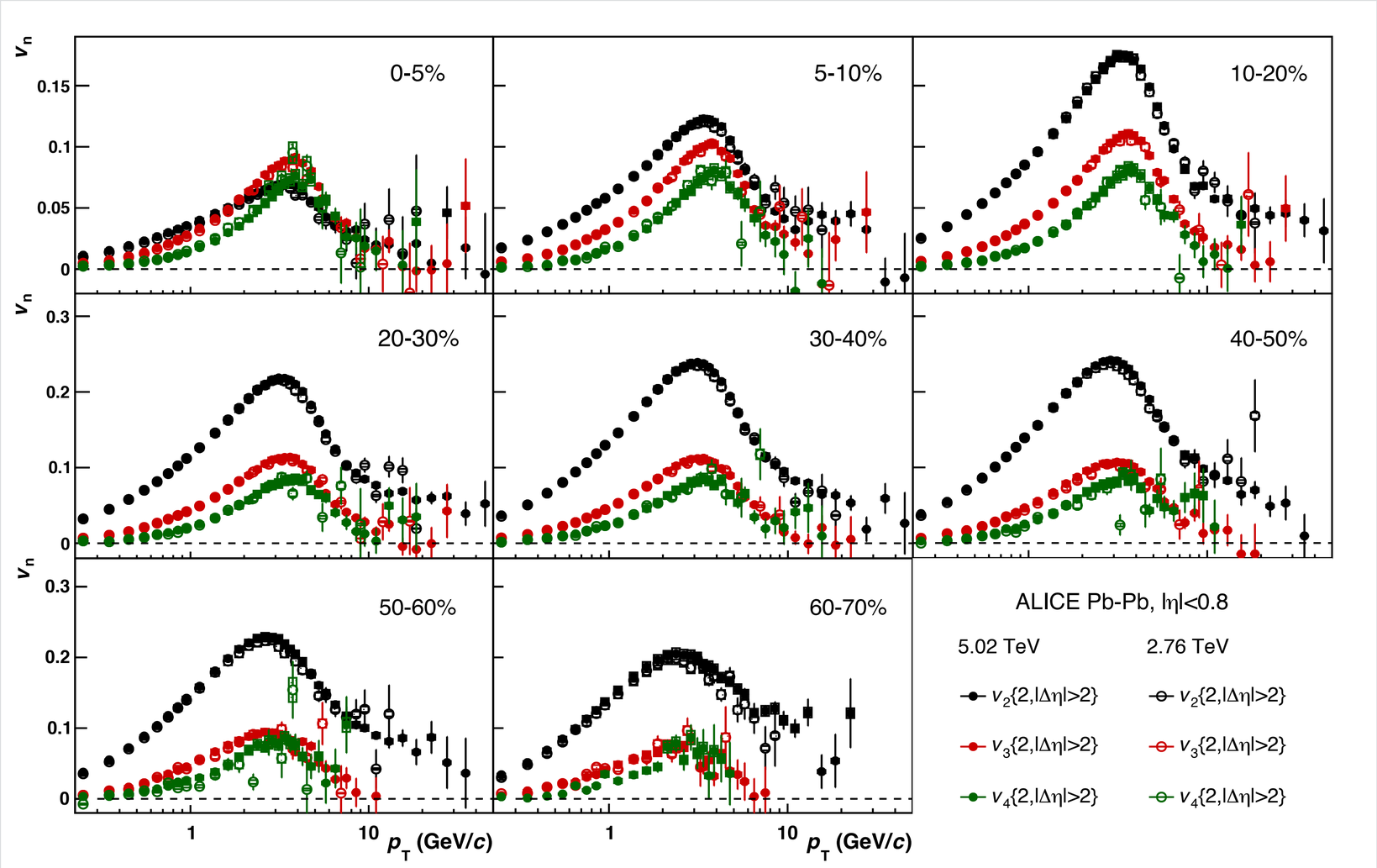




- The difference between $v_2\{2\}$ and $v_2\{4\}$ depends on the v_2 event-by-event fluctuations (later in this talk)
- A small increase between 2-10% for the v_n is observed from 2.76 to 5.02 TeV
- The two parameterisations of eta/s which describe the data might indicate no or a small dependence on temperature

arXiv:1804.02944 [nucl-ex] 9 April 2018

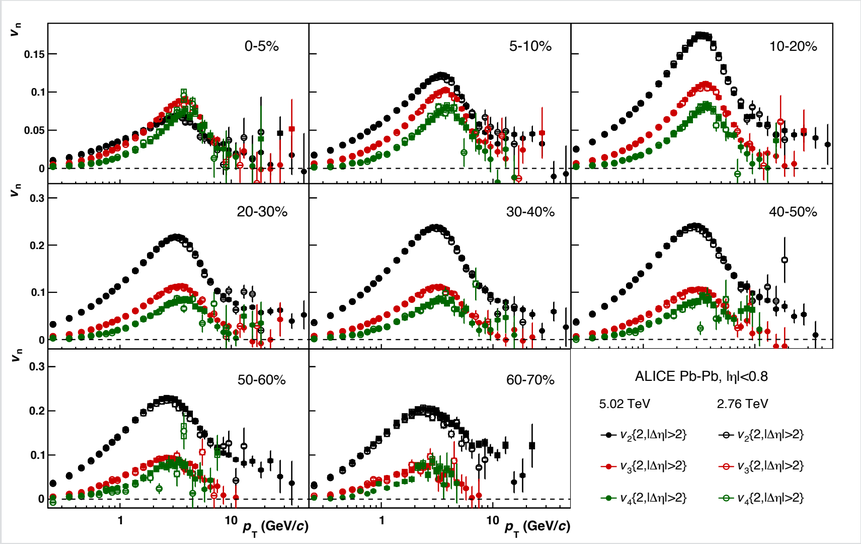
Anisotropic Flow

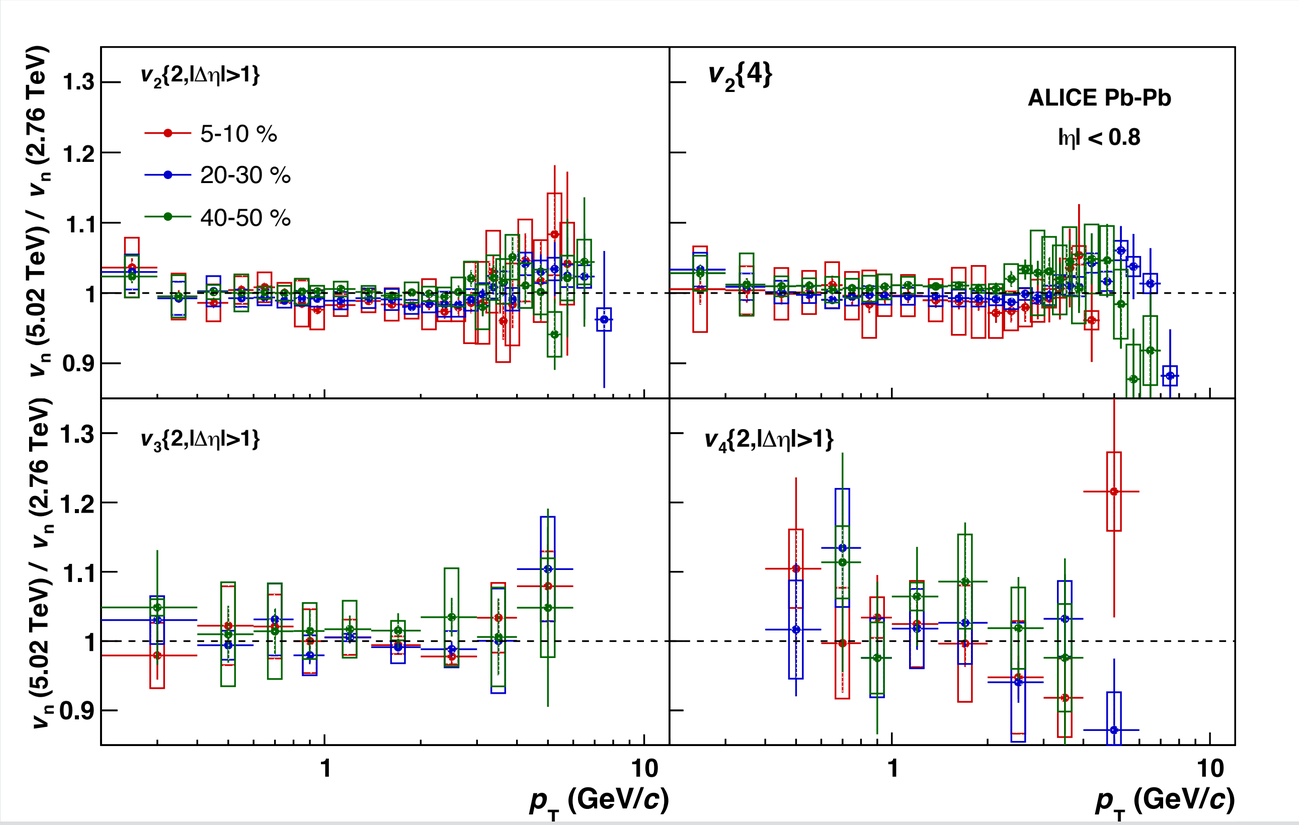


- The dependence of v_n on transverse momentum provides more differential information
- At low transverse momentum the data can be interpreted in a "hydrodynamical" picture while at high-p_t the dominant mechanism is though to be path length dependent energy loss of high energetic partons
- The v_2 coefficients dominates over all transverse momenta except for the most central collisions
- The v_2 is significant up to the highest transverse momenta

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow

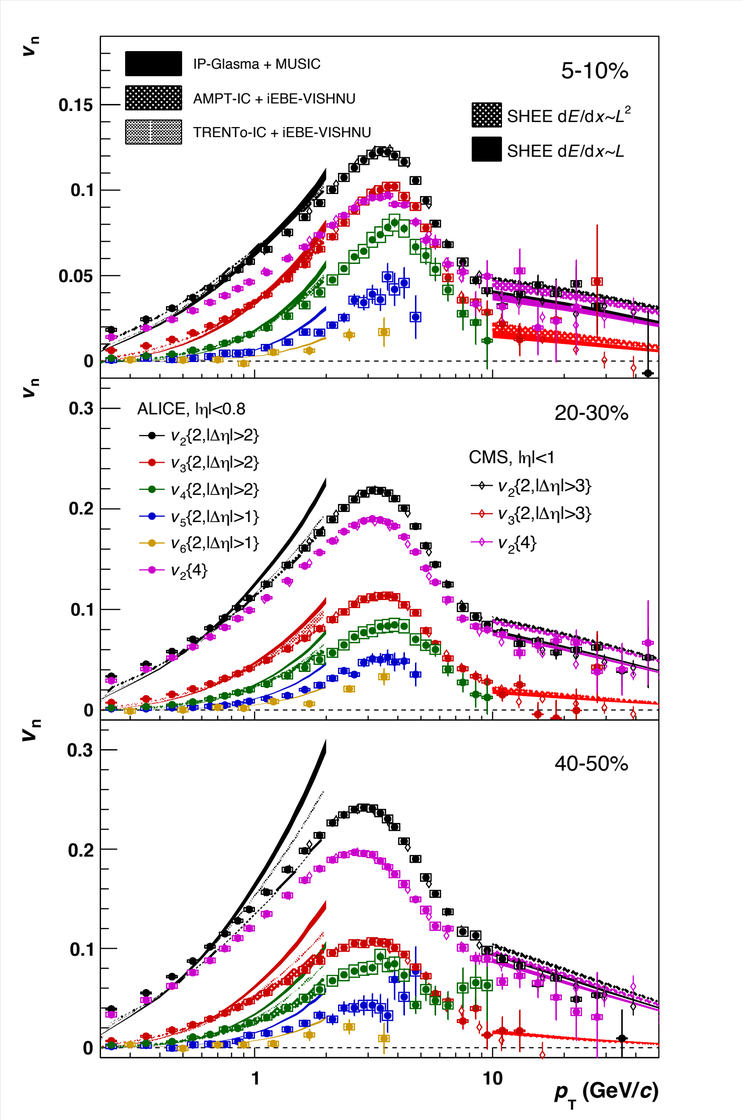




- The ratios between v_n at 5.02 and 2.76 TeV are consistent with unity
  - The increase in integrated v_n due to increase in $\langle p_t \rangle$ (due to radial flow in hydro picture)
- Also consistent with almost no change of eta/s between the two beam energies

arXiv:1804.02944 [nucl-ex] 9 April 2018

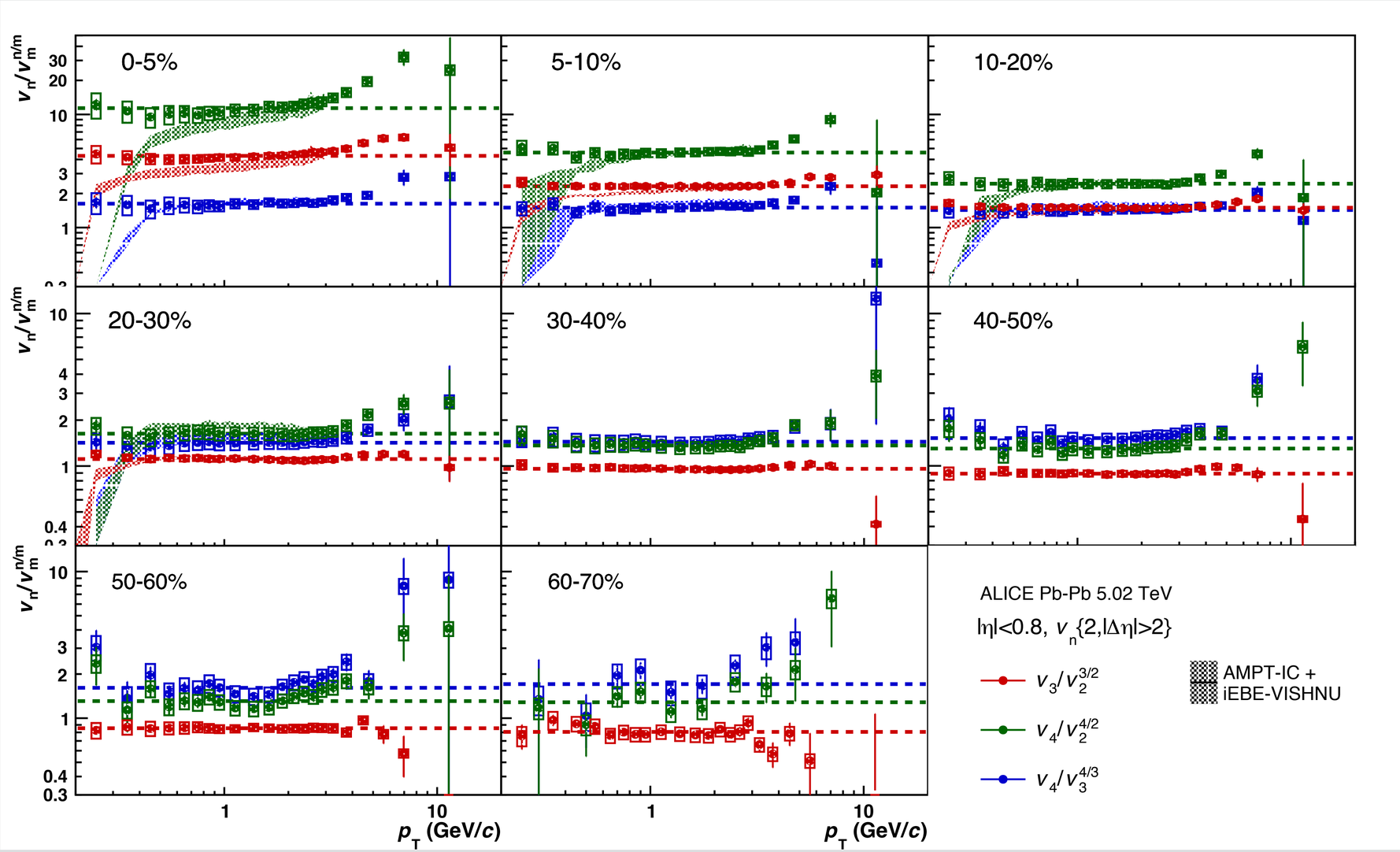
Anisotropic Flow; compared to models



- Models use IP-Glasma, AMPT-IC or TRENTo initial conditions and all use UrQMD for the hadronic phase
  - All models qualitatively describe the low pt data while AMPT-EC + iEBE-VISHNU does best in details (artefact?)
- At large p_t the azimuthal asymmetries are though to be due to path length dependent parton energy loss
  - The model compared to the data uses an event-by-event hydro description (v-USPhydro) and jet quenching model (BBMG)
  - Tested is a linear dE/dx ~L and quadratic energy loss
    - The v_2 at large p_t is compatible with linear energy loss

arXiv:1804.02944 [nucl-ex] 9 April 2018

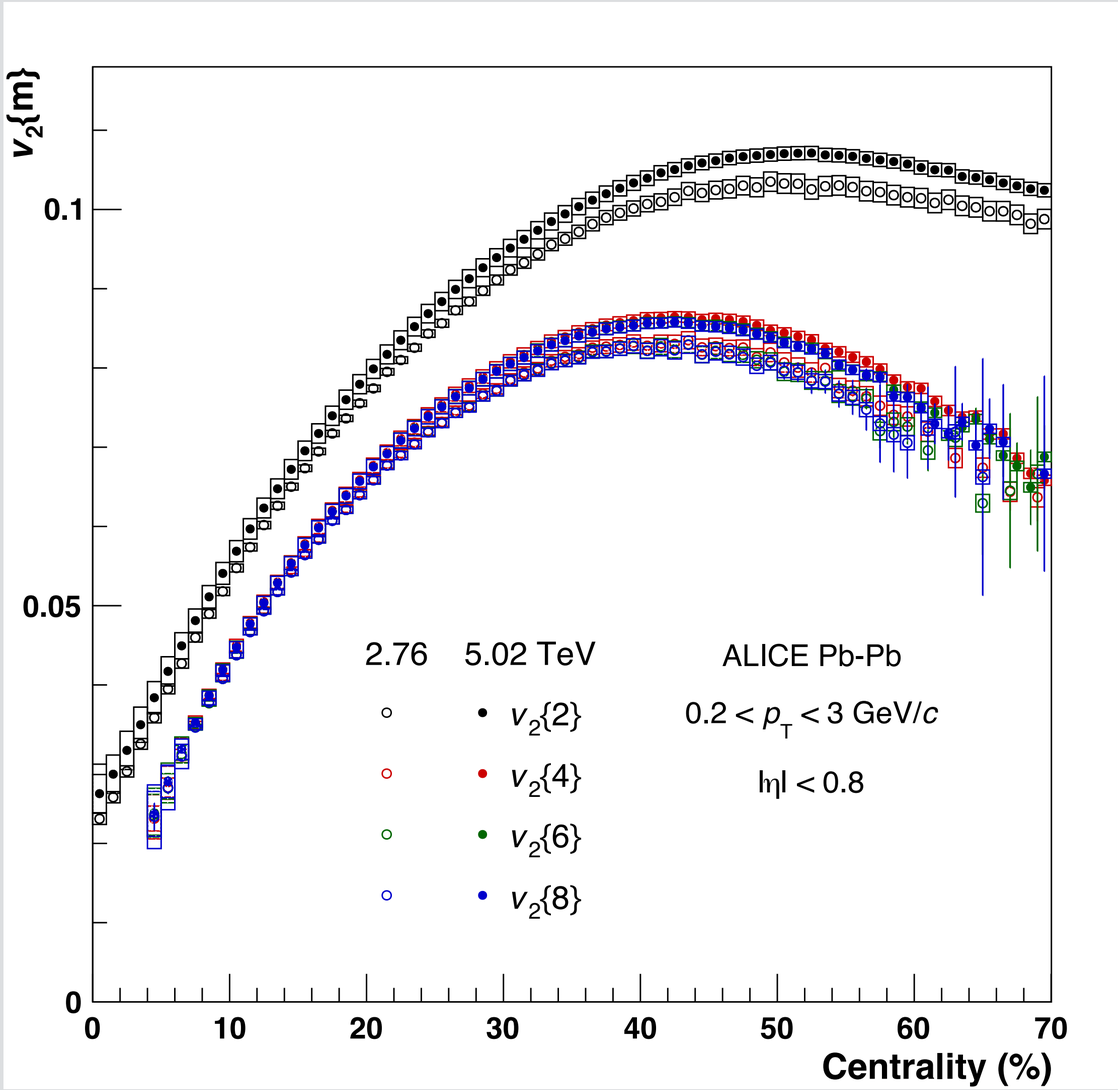
Anisotropic Flow; the shape of v_n



- The dependence of v_n on transverse momentum follows the previous observed power law scaling of $v_n^{1/n} \sim v_m^{1/m}$
- The scaling works over a surprisingly large momentum range particularly for v_3 compared to v_2
- The scaling does not exist in ideal hydro however seems to hold reasonably well for viscous hydro calculations shown

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations



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

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

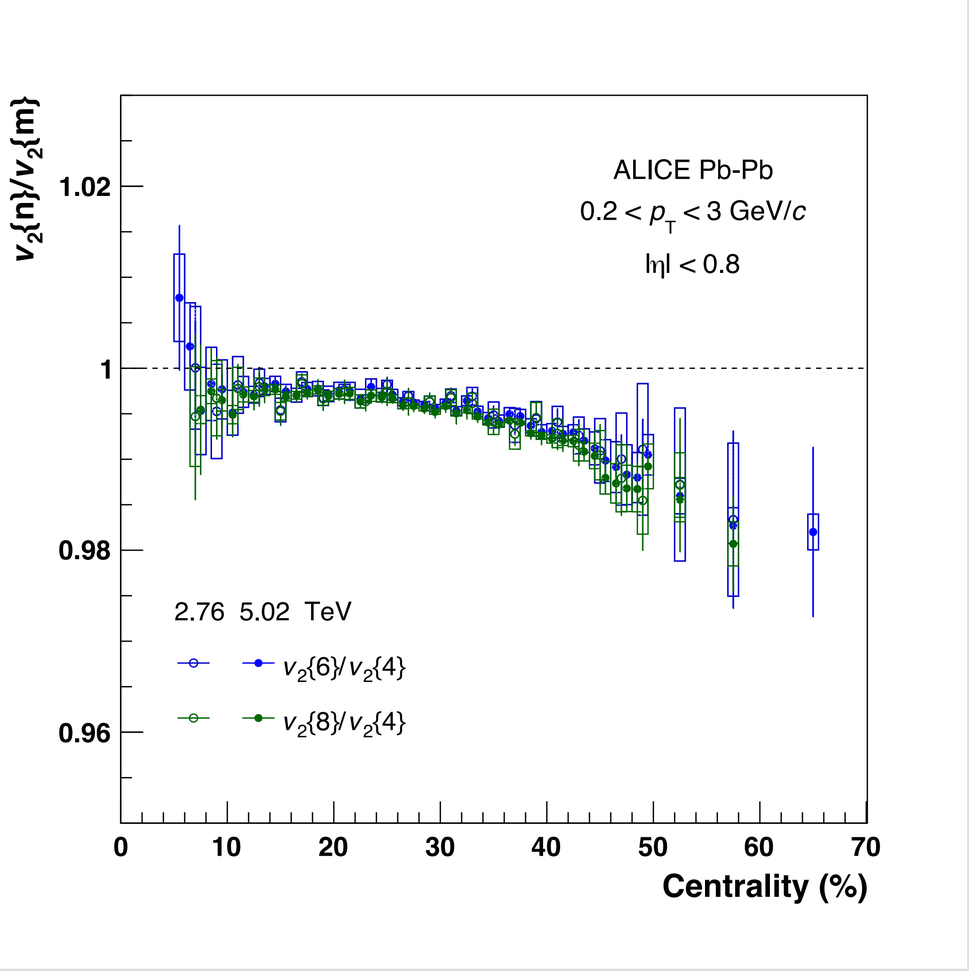
$$v_n\{6\} = \sqrt[6]{\langle v_n^6 \rangle - 9\langle v_n^2 \rangle \langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3},$$

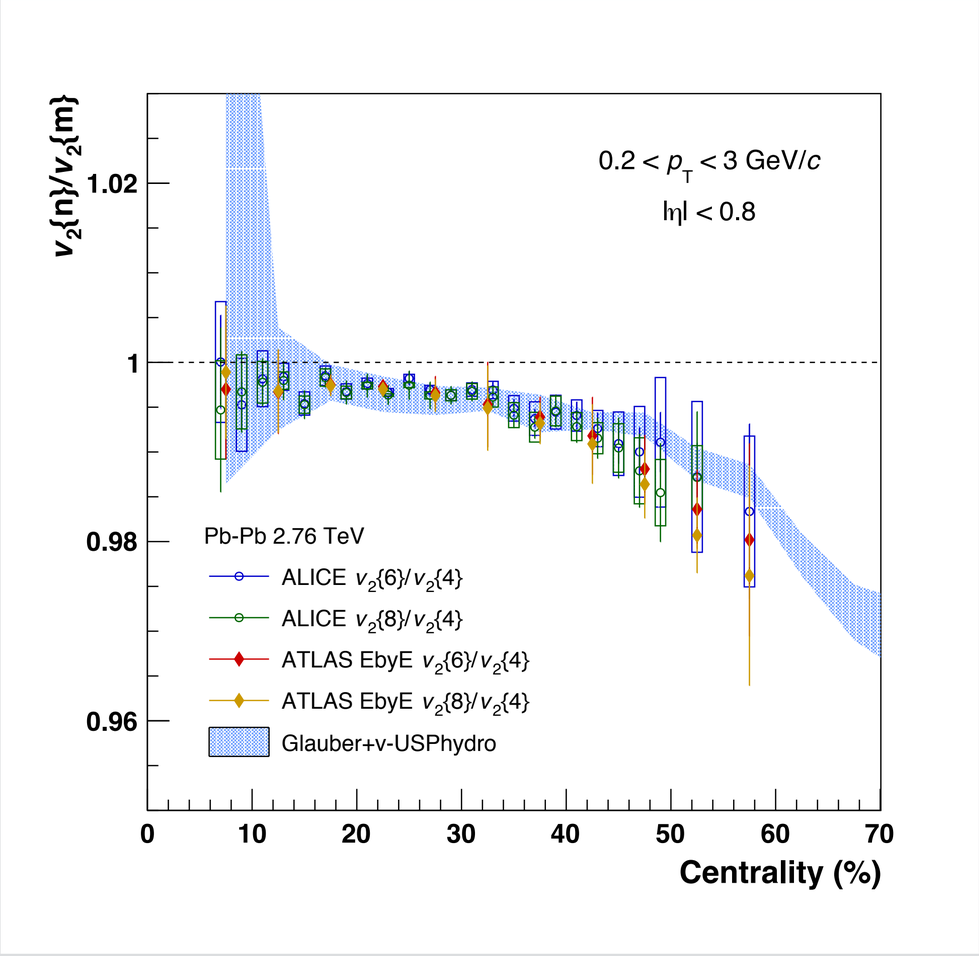
$$v_n\{8\} = \sqrt[8]{\langle v_n^8 \rangle - 16\langle v_n^2 \rangle \langle v_n^6 \rangle - 18\langle v_n^4 \rangle^2 + 144\langle v_n^2 \rangle^2 \langle v_n^4 \rangle - 144\langle v_n^2 \rangle^4}.$$

The different estimates of v_2 are sensitive to the moments of the v_2 distribution, if $v_2\{4\}=v_2\{6\}=v_2\{8\}$ then the distribution is a Bessel-Gaussian p.d.f.

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations





A fine splitting is observed which is centrality dependent showing the non Bessel Gaussian contribution

The splitting does not depend on the p_t range used and collision energy

The results agree well with model calculations as well as with ATLAS results based on a different technique

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations

$$\gamma_1 = \frac{\langle (v_n\{\mathrm{RP}\} - \langle v_n\{\mathrm{RP}\}\rangle)^3\rangle}{\langle (v_n\{\mathrm{RP}\} - \langle v_n\{\mathrm{RP}\}\rangle)^2\rangle^{3/2}},$$

The standardised skewness

$$\gamma_1^{\mathrm{exp}} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}.$$

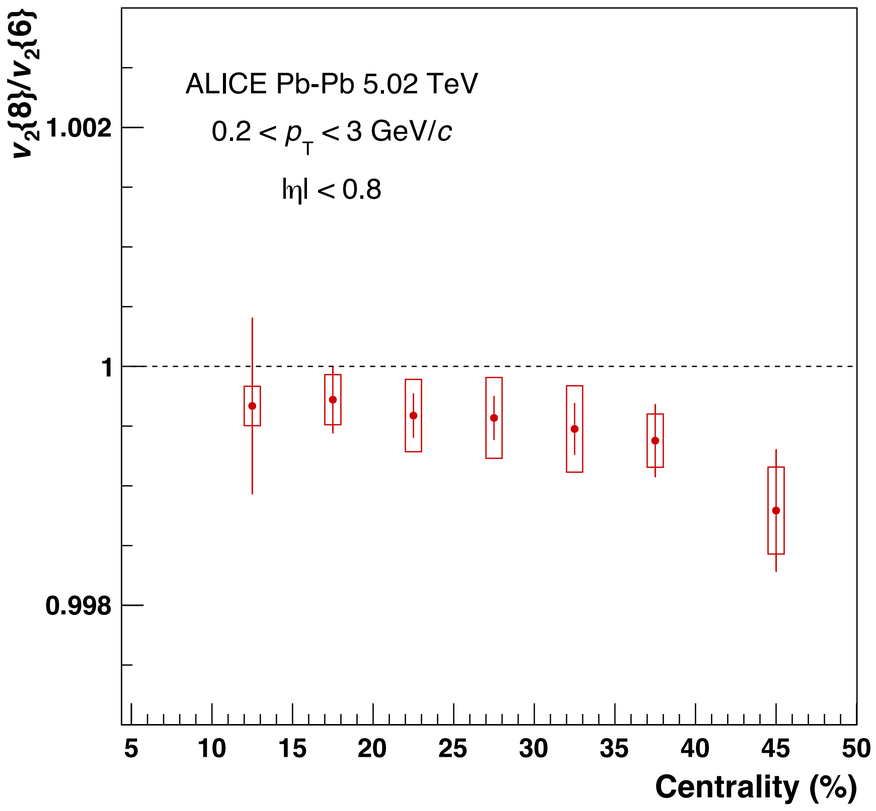
The standardised skewness can estimated using the multi-particle cumulants

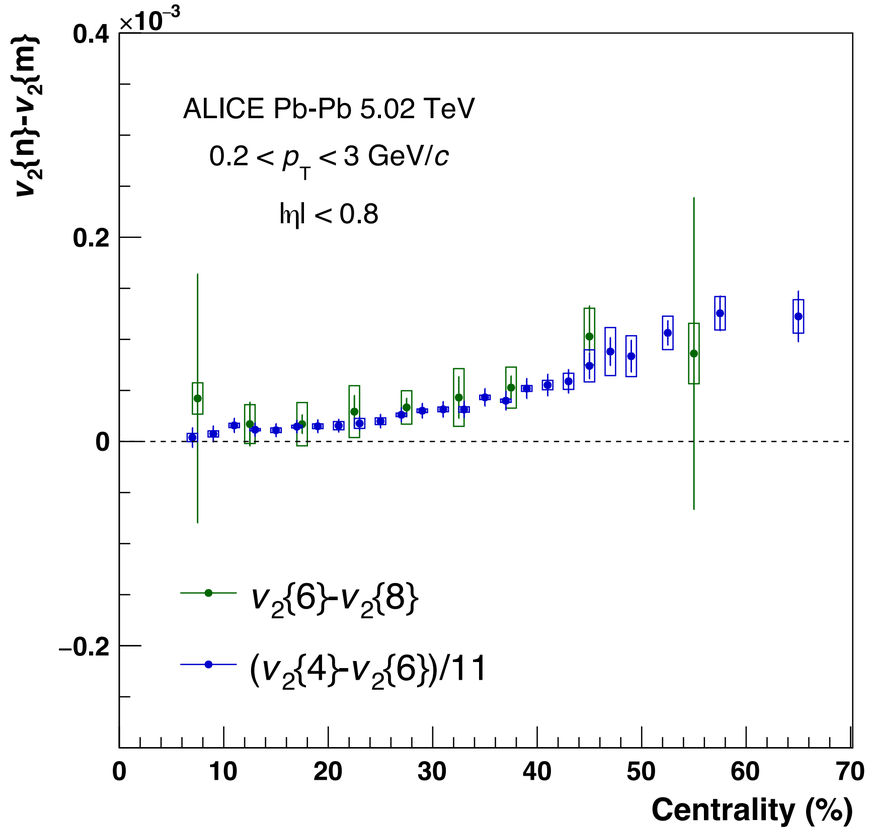
$$v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\}).$$

The experimental estimate depends on the fact that the higher order moments, e.g. kurtosis are small

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations





A fine splitting is observed between v2{8} and v2{6}

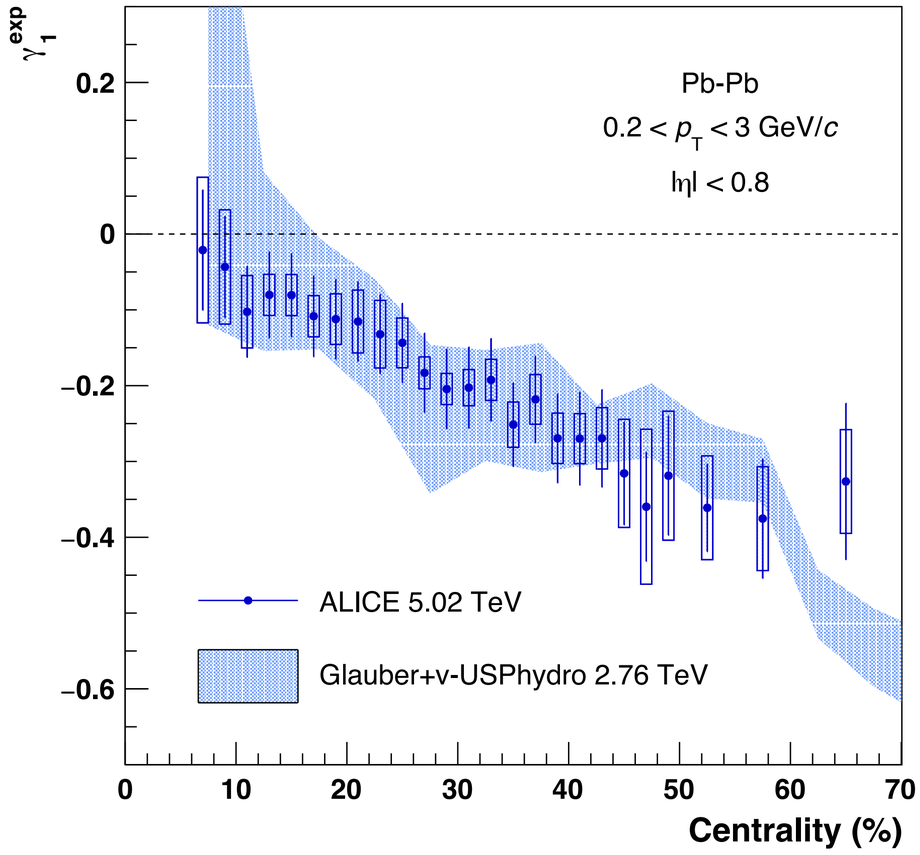
Can be contributed to the skewness of the distribution

Higher order contributions are constrained in the equality

$$v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\}).$$

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations



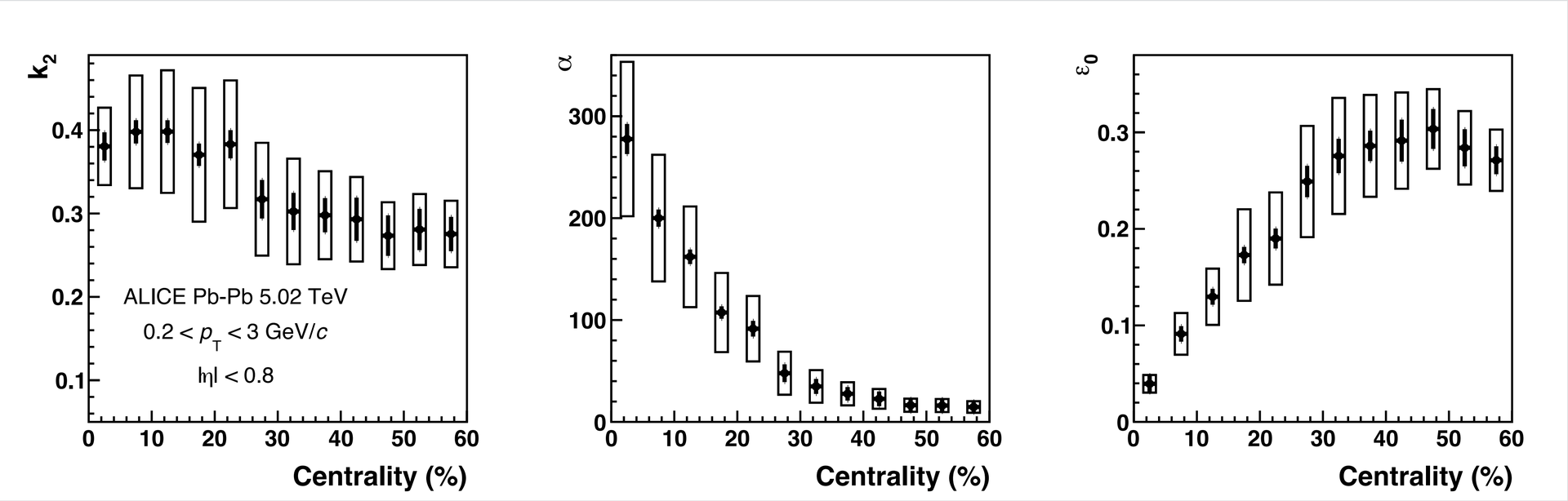
$$\gamma_1^{\mathrm{exp}} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}.$$

- A negative skewness is observed as expected due to the constrains on ε_2 between 0-1
- The skewness agrees well with model calculations and increases towards peripheral collisions due to the constraint of 1

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations

$$P(\varepsilon_2) = \frac{1}{k_2} 2\,\alpha\,\varepsilon_2\,(1-\varepsilon_2^2)^{\alpha-1}\,(1-\varepsilon_0^2)^{\alpha+1/2}\,\frac{1}{\pi}\int_0^{\pi}(1-\varepsilon_2\varepsilon_0\cos\varphi)^{-2\alpha-1}\,d\varphi,$$

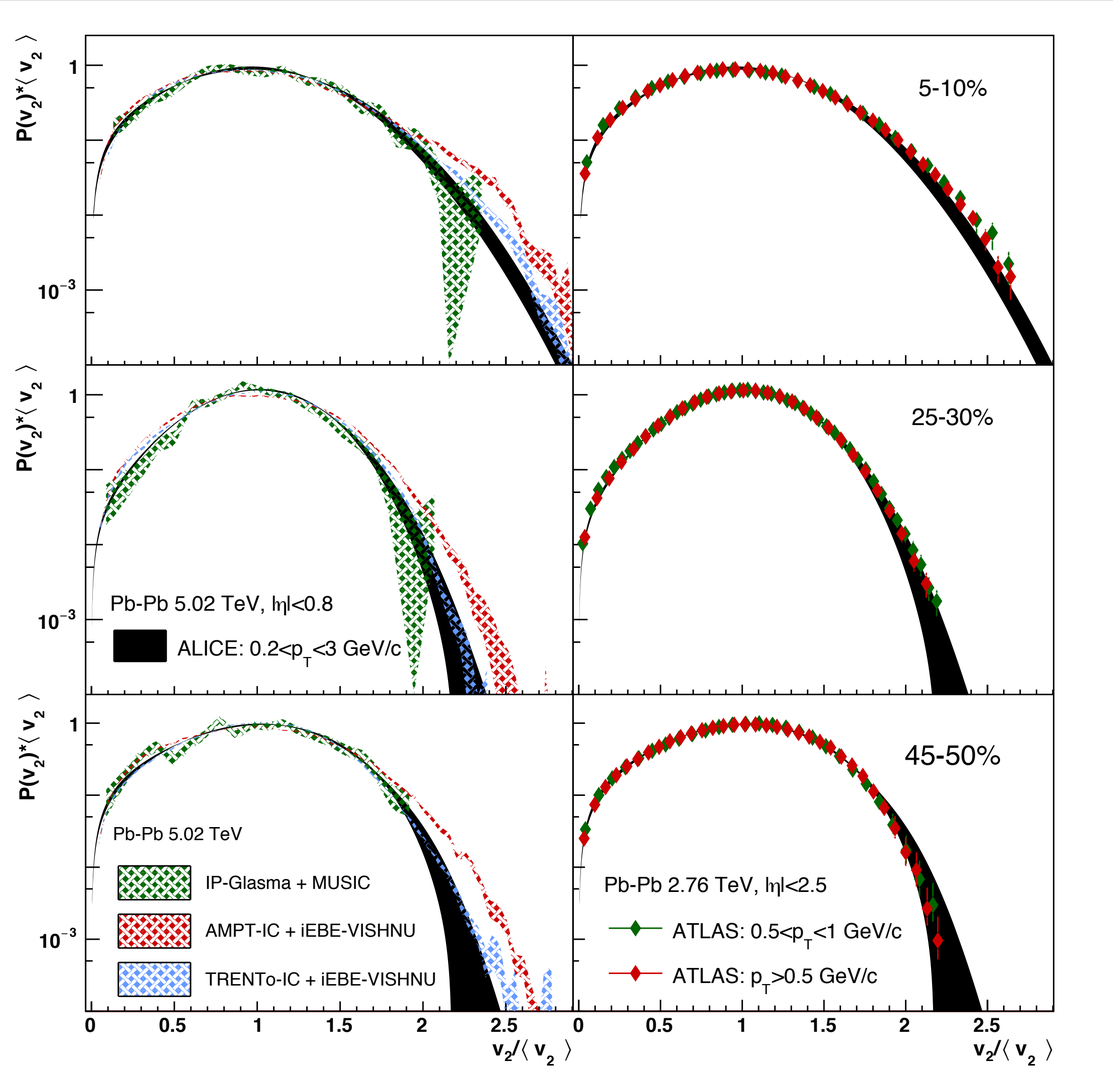


The elliptic power distribution can be used to describe the underlying p.d.f. of ε_2

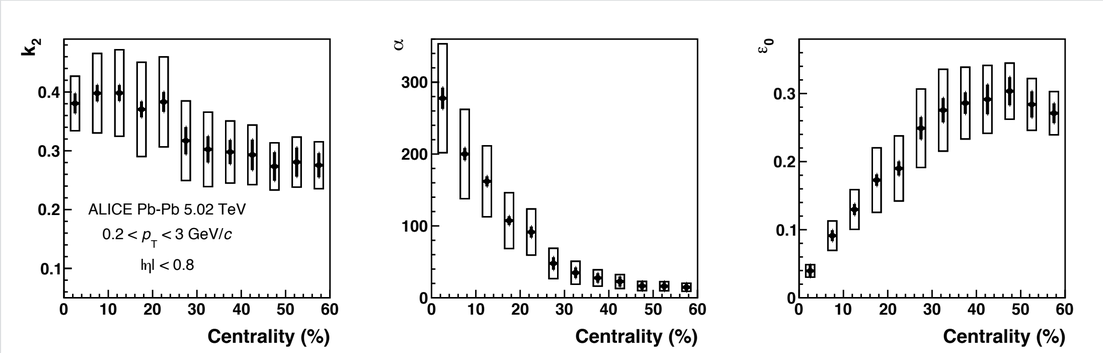
The parameter α qualifies the magnitude of the flow fluctuations, ε_0 the mean eccentricity in the reaction plane and k_2 the proportionality between ε_2 and v_2; $v_2 = k_2\,\varepsilon_2$

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow p.d.f.



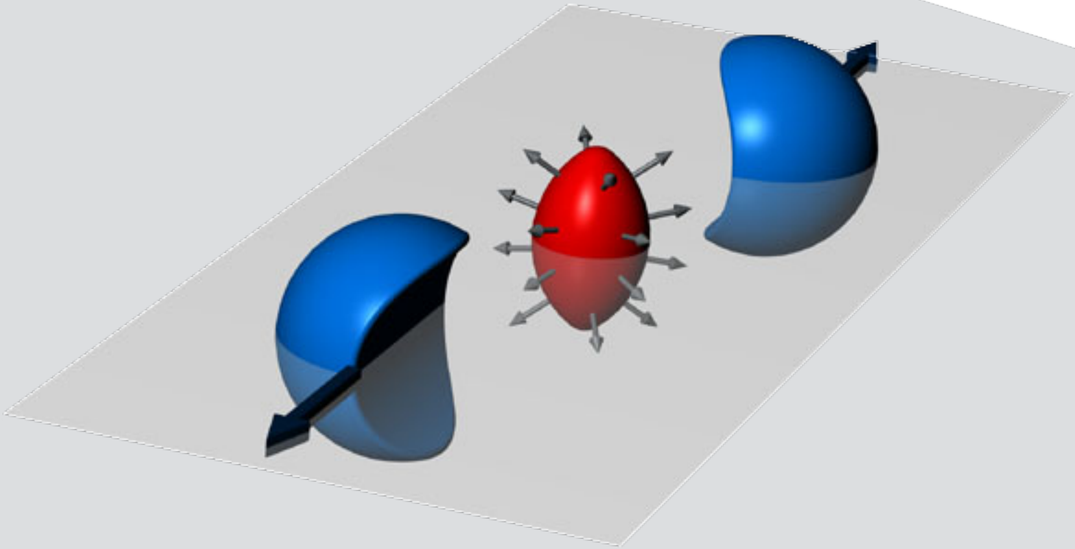
$$P(\varepsilon_2) = \frac{1}{k_2} 2\,\alpha\,\varepsilon_2\,(1-\varepsilon_2^2)^{\alpha-1}\,(1-\varepsilon_0^2)^{\alpha+1/2}\,\frac{1}{\pi}\int_0^{\pi}(1-\varepsilon_2\varepsilon_0\cos\varphi)^{-2\alpha-1}\,d\varphi,$$

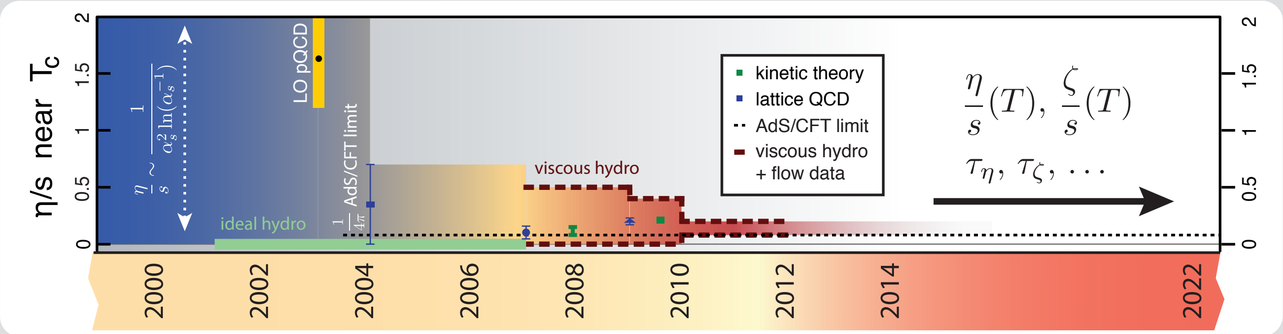


arXiv:1804.02944 [nucl-ex] 9 April 2018

Summary

- Anisotropic flow is precisely measured at the LHC as function of collision energy using multi-particle cumulants
- The measurements show that the system created behaves as an almost perfect liquid and constrain the path length dependence of parton energy loss
- The underlying p.d.f. of v_2 can be determined and used to constrain the initial conditions





Gracias!