Bulk observables in the sPHENIX era and the legacy of RHIC

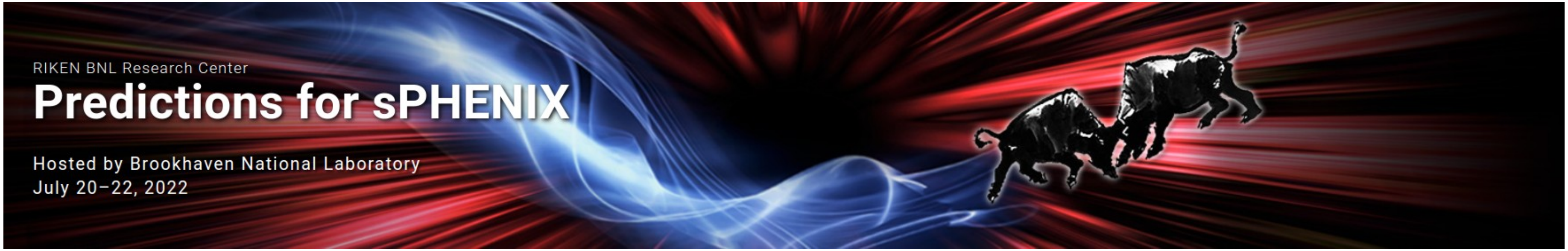
by

GIULIANO GIACALONE

22nd July, 2022

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

IsoQuant
SFB1225



OUTLINE

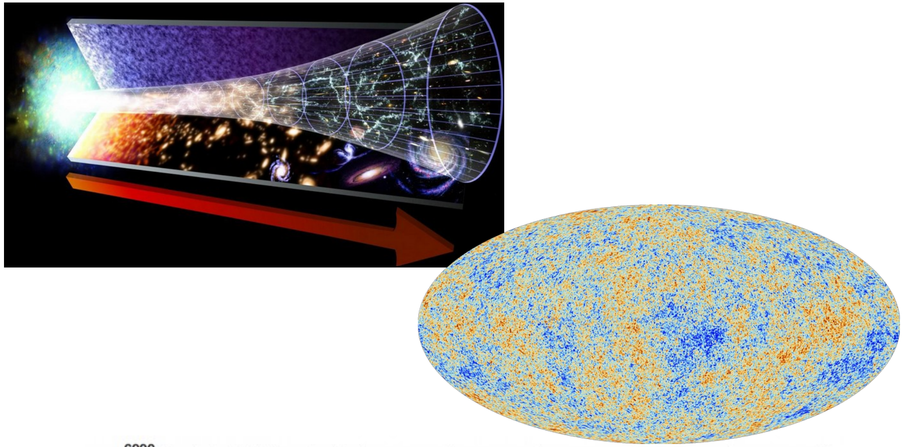
- Milestones in Au-Au collisions.
  - Non-Gaussian elliptic flow fluctuations.
  - Primordial non-Gaussianities in Au-Au.

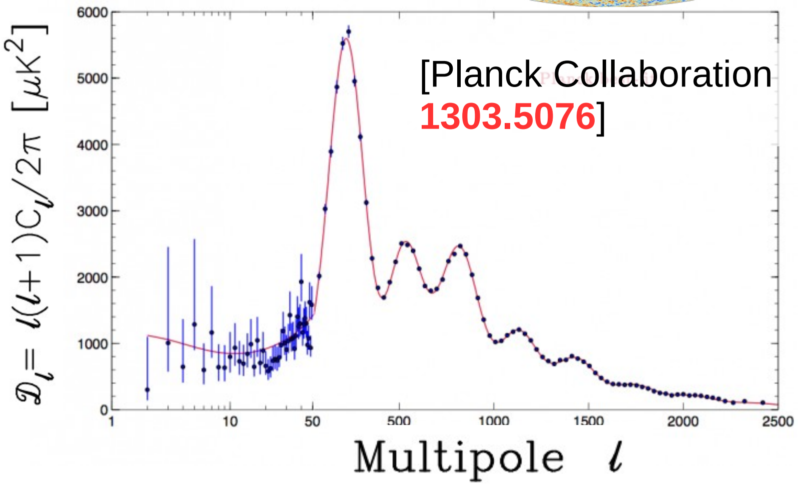
- Missing results in pA collisions.
  - non-Gaussianity and nonlinear hydrodynamic response in small systems.

- Science cases for a short run of ^{208}Pb collisions at RHIC.
  - Refined understanding of Au-Au initial conditions.
  - Neutron skin mesurements.

- Conclusion.

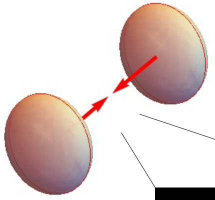
The Big Bang

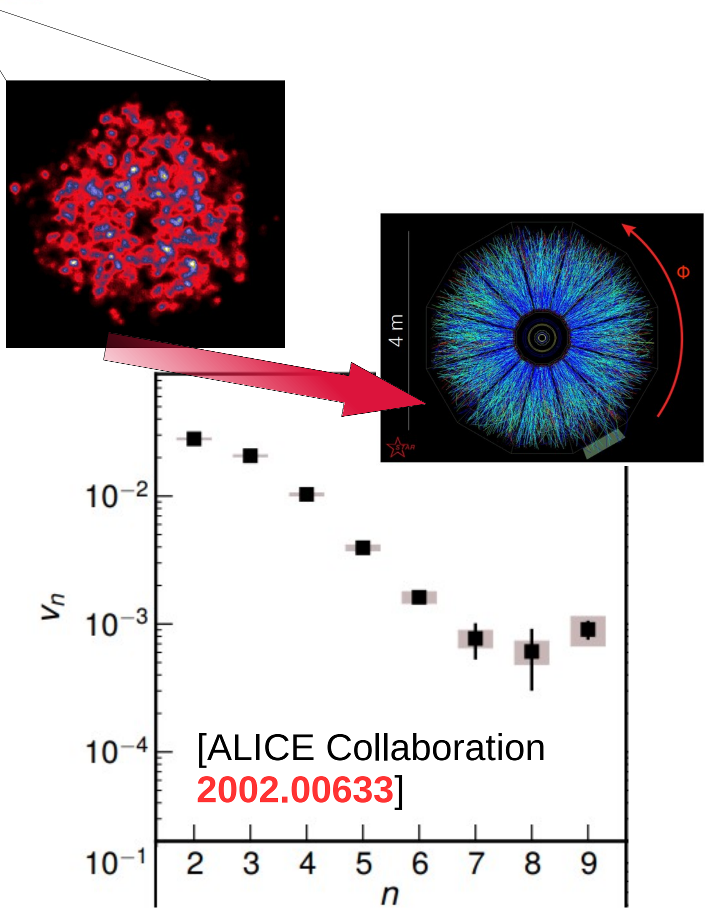




[Planck Collaboration 1303.5076]

The Little Bang(s)





[ALICE Collaboration 2002.00633]

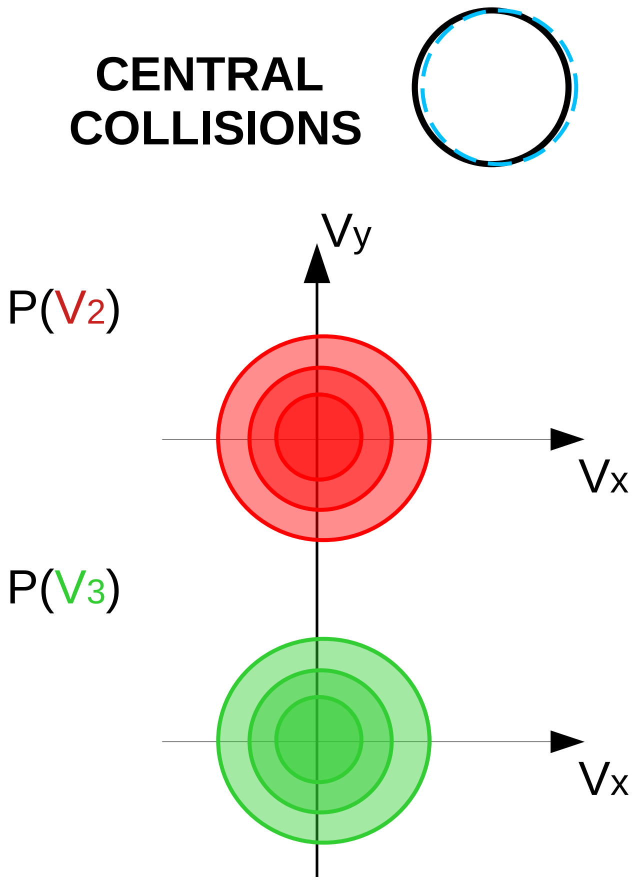
Physics of primordial fluctuations. Where do we stand at RHIC, and sPHENIX impact?

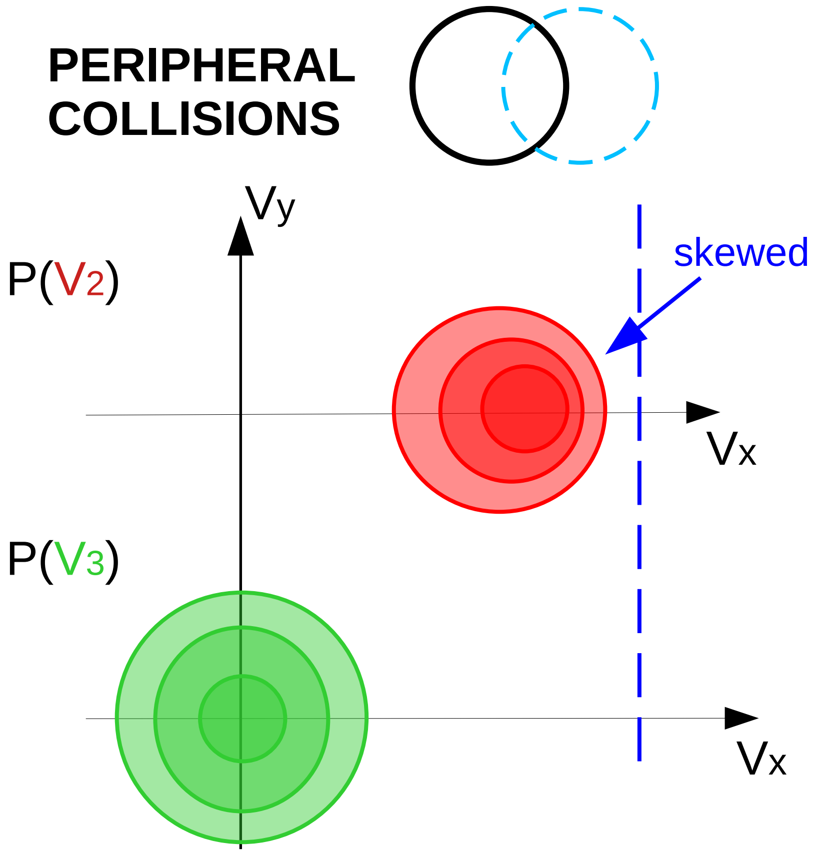
Milestones in Au-Au collisions.

We measure distributions of Fourier coefficients $V_n = (V_x, V_y)$ at fixed multiplicity.

Take **x** aligned with the impact parameter.

Two features: mean value along **x** (V_2), fluctuation around the mean value (V_3 or central V_2).





Physics of the reaction plane flow (mean value)

Distributions of Vn = (Vx, Vy) specified by cumulants.

[Giacalone et al, PRC **95**, 1, 014913 (2017)]
[Bhalerao, Giacalone, Ollitrault, PRC **99**, 1, 014907 (2019)]

$$\ln\left\langle e^{k_x v_x + k_y v_y}\right\rangle = \sum_{n_x,n_y} \frac{k_x^{n_x}}{n_x!}\frac{k_y^{n_y}}{n_y!}\kappa_{n_x,n_y}$$

With:

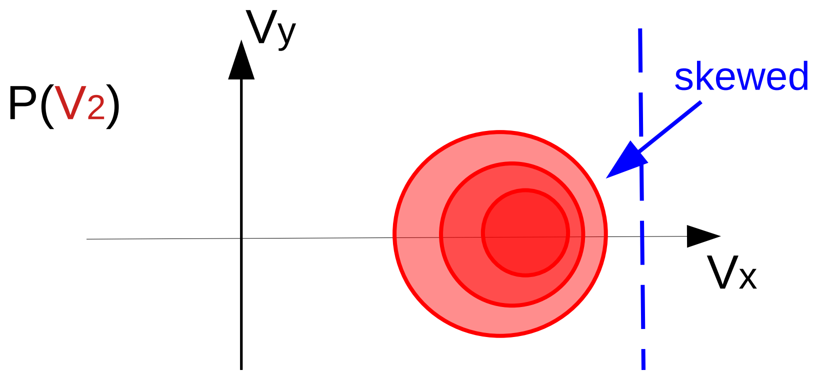
$\kappa_{10} = \langle v_x \rangle$ **MEAN**

$\kappa_{20} = \left\langle (v_x - \langle v_x \rangle)^2 \right\rangle$ **VARIANCE**

$\kappa_{30} = \left\langle (v_x - \langle v_x \rangle)^3 \right\rangle$ **SKEWNESS**

$\kappa_{40} = \left\langle (v_x - \langle v_x \rangle)^4 \right\rangle - 3\kappa_{20}^2$ **KURTOSIS**

PERIPHERAL COLLISIONS



Generic relations for peripheral collisions (κ_{10}>0 is dominant effect):

$$v_2\{2\}^2 - v_2\{4\}^2 = 2\kappa_{20}$$

$$v_2\{4\}^3 - v_2\{6\}^3 = -\kappa_{30}$$

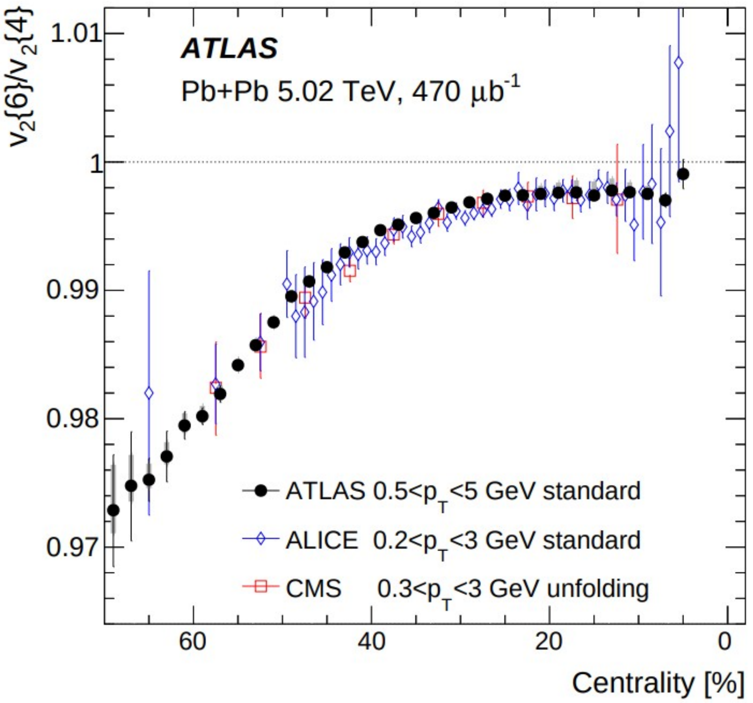
$$v_2\{4\}^4 - 12v_2\{6\}^4 + 11v_2\{8\}^4 = -\frac{8}{3}\kappa_{40}$$

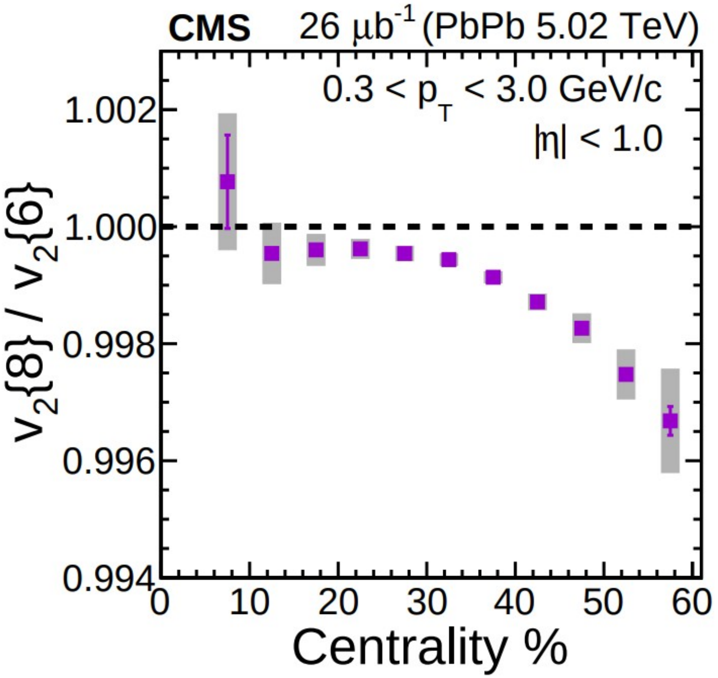
Splitting of higher-order cumulants gives access to non-Gaussianity in the reaction plane.
[not yet observed at RHIC]

Physics of the reaction plane flow (mean value)

Non-Gaussianity in Pb+Pb collisions @LHC.

[ATLAS Collaboration, JHEP 01 (2020) 051]
[CMS Collaboration, PLB **789** (2019) 643-665]
[ALICE Collaboration, JHEP 07 (2018) 103]

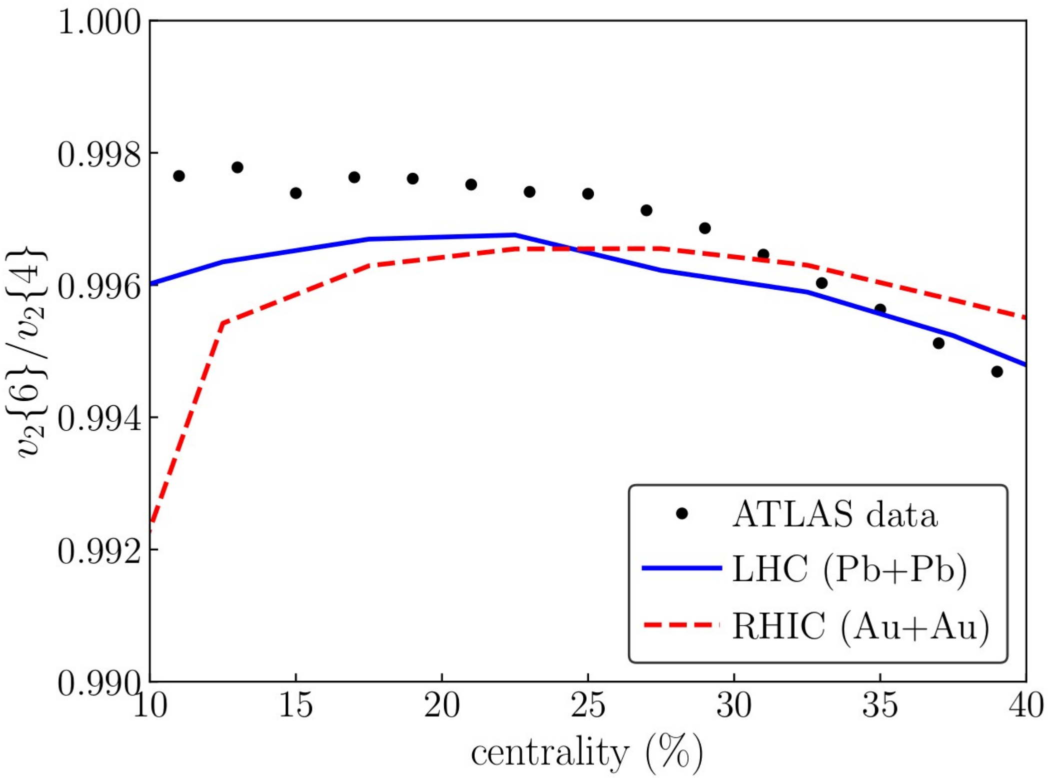




Basic physics but outside current model precision.
Important for legacy of data sets and future model building.

Physics of the reaction plane flow (mean value)

PREDICTION FOR sPHENIX? TRENTo model (only differences are A and σ_{NN}).



$dS/dy \sim (T_A T_B)^{1/2}$

nucleon size = 0.5fm

$$\frac{v_2\{6\}}{v_2\{4\}} \sim \frac{\varepsilon_2\{6\}}{\varepsilon_2\{4\}}$$

Significant deviations from this prediction may imply effects from sub-nucleon structure, error on neutron skins, hydrodynamic response.

Primordial non-Gaussianities (fluctuations)

Distributions of Vn = (Vx, Vy) specified by cumulants.

$$\ln \left\langle e^{k_x v_x + k_y v_y} \right\rangle = \sum_{n_x, n_y} \frac{k_x^{n_x}}{n_x!} \frac{k_y^{n_y}}{n_y!} \kappa_{n_x, n_y}$$

With:

$$\kappa_{10} = \langle v_x \rangle,$$ **MEAN**

$$\kappa_{20} = \left\langle (v_x - \langle v_x \rangle)^2 \right\rangle$$ **VARIANCE**

$$\kappa_{30} = \left\langle (v_x - \langle v_x \rangle)^3 \right\rangle$$ **SKEWNESS**

$$\kappa_{40} = \left\langle (v_x - \langle v_x \rangle)^4 \right\rangle - 3\kappa_{20}^2$$

$$\kappa_{22} = \left\langle (v_x - \langle v_x \rangle)^2 v_y^2 \right\rangle - \kappa_{20}\kappa_{02}$$

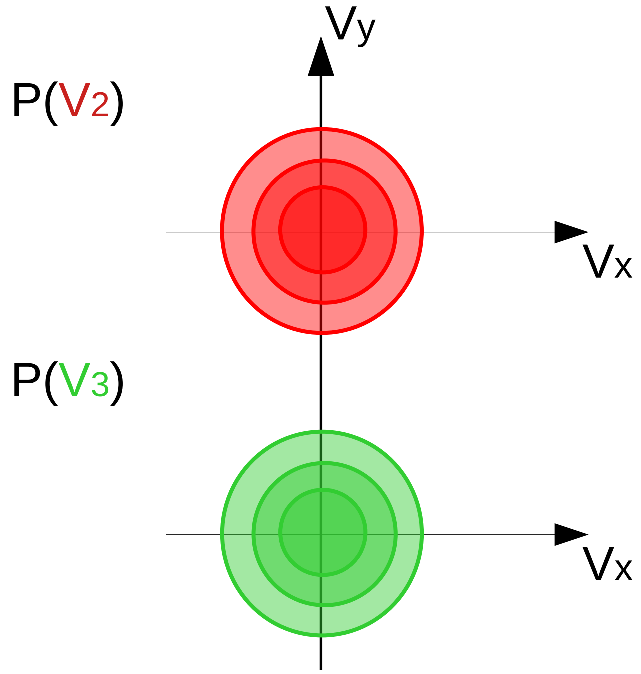
KURTOSIS

When all mean values are zero:

$$v_n\{4\}^4 = -(\kappa_{40} + 2\kappa_{22} + \kappa_{04})$$

[Abbasi et al., PRC **98** (2018) 2, 024906]
[Bhalerao, Giacalone, Ollitrault, PRC **99** (2019) 1, 014907]

CENTRAL COLLISIONS

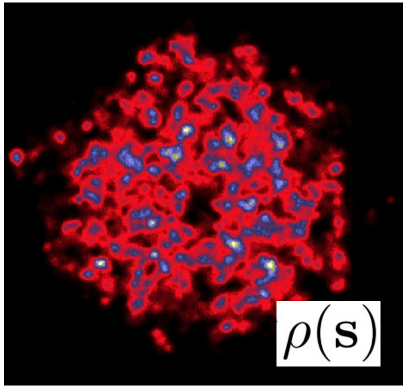


Higher-order cumulants
=
genuine non-Gaussianities

Primordial non-Gaussianities (fluctuations)

Origin of non-Gaussianity. First-principles ingredient is fluctuating energy density field.

$$\rho(\mathbf{s}) = \langle \rho(\mathbf{s}) \rangle + \delta\rho(\mathbf{s}) \qquad \langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2) \rangle \qquad \langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2)\delta\rho(\mathbf{s}_3) \rangle \quad \text{etc.}$$



Relation with final-state observables:

primordial fluctuations

$$\langle \rho(\mathbf{s}) \rangle, \ \langle \rho(\mathbf{s}_1)\rho(\mathbf{s}_2) \rangle$$

nonlinear →

$$\varepsilon_n \equiv \frac{\int_{\mathbf{s}} \mathbf{s}^n \rho(\mathbf{s})}{\int_{\mathbf{s}} |\mathbf{s}|^n \rho(\mathbf{s})}$$

primordial anisotropy

$$\langle \varepsilon_n \rangle, \ \langle \varepsilon_n \varepsilon_n^* \rangle$$

linear →

$$v_n = k_n \varepsilon_n$$

observable anisotropy

$$\langle e^{in(\phi_1 - \phi_2)} \rangle$$

IDEA: Linearize expressions with respect to the fluctuation, $\delta\rho(\mathbf{s})$.

[Blaizot, Broniowski, Ollitrault, PLB **738** (2014) 166-171]
[Floerchinger, Wiedemann, PLB **728** (2014) 407-411]

Primordial non-Gaussianities (fluctuations)

[Bhalerao, Giacalone, Ollitrault, PRC **100** (2019) 1, 014909]

Fourth-order cumulant:

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

Originates from multi-point correlation functions.

$$c_n\{4\} = c_n\{4\}_K + c_n\{4\}_S + c_n\{4\}_V$$

KURTOSIS

$$\langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2)\delta\rho(\mathbf{s}_3)\delta\rho(\mathbf{s}_4)\rangle_c$$

SKEWNESS

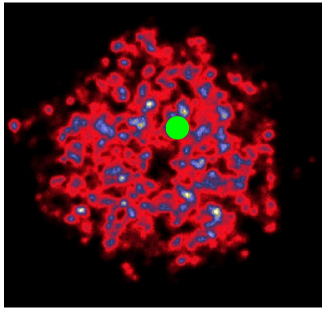
$$\langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2)\delta\rho(\mathbf{s}_3)\rangle$$

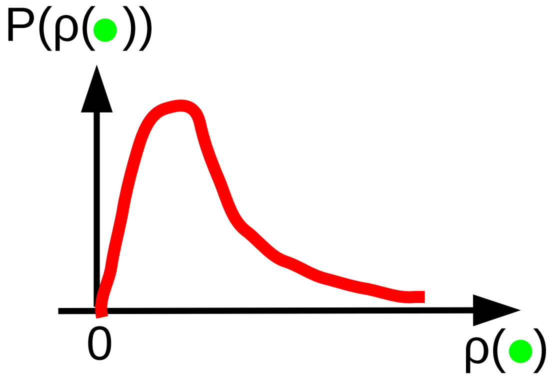
VARIANCE

$$\langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2)\rangle$$

skewness term is the most important.
Experimentally $c_3\{4\}<0$.
Consequence of positivity of energy!

ρ(x,y)





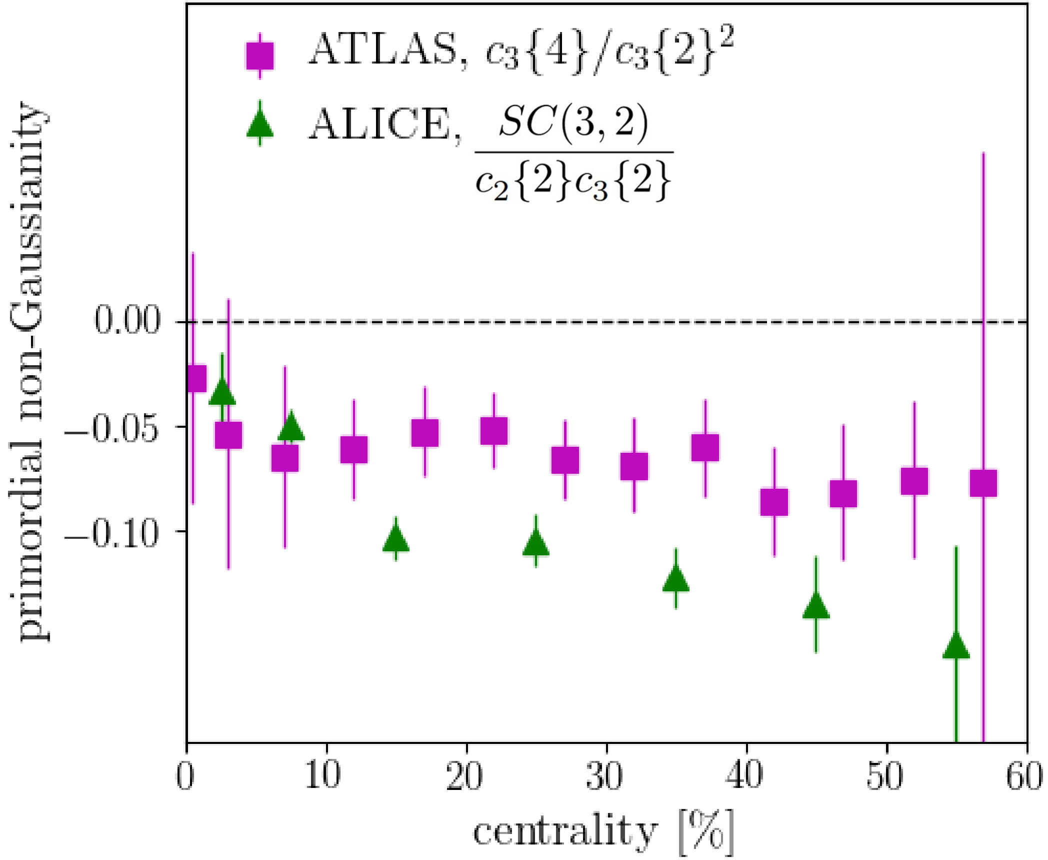
Primordial non-Gaussianities (fluctuations)

[Bhalerao, Giacalone, Ollitrault, PRC **100** (2019) 1, 014909]

Universal behavior of
non-Gaussian fluctuations.

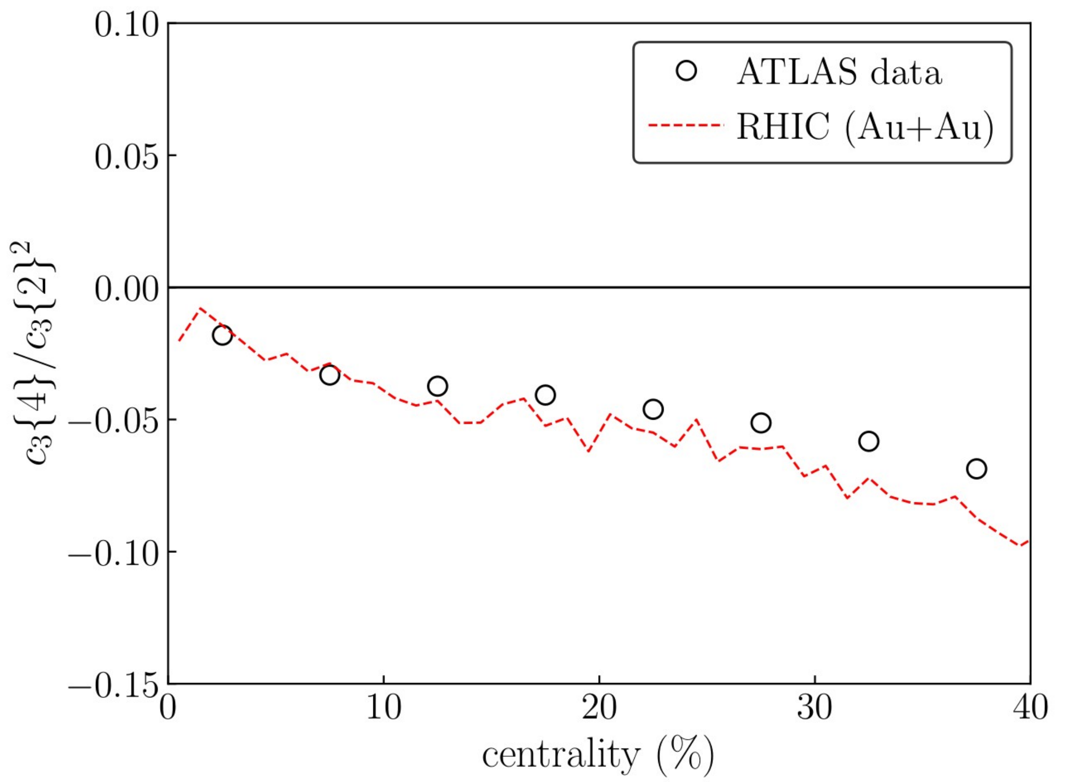
However SC(3,2) is strongly
impacted by reaction plane flow.

$c_3\{4\}$ is the cleanest probe.
No precise data from RHIC.



Primordial non-Gaussianities (fluctuations)

PREDICTION FOR sPHENIX? TRENTo model (only differences are A and σ_{NN}).

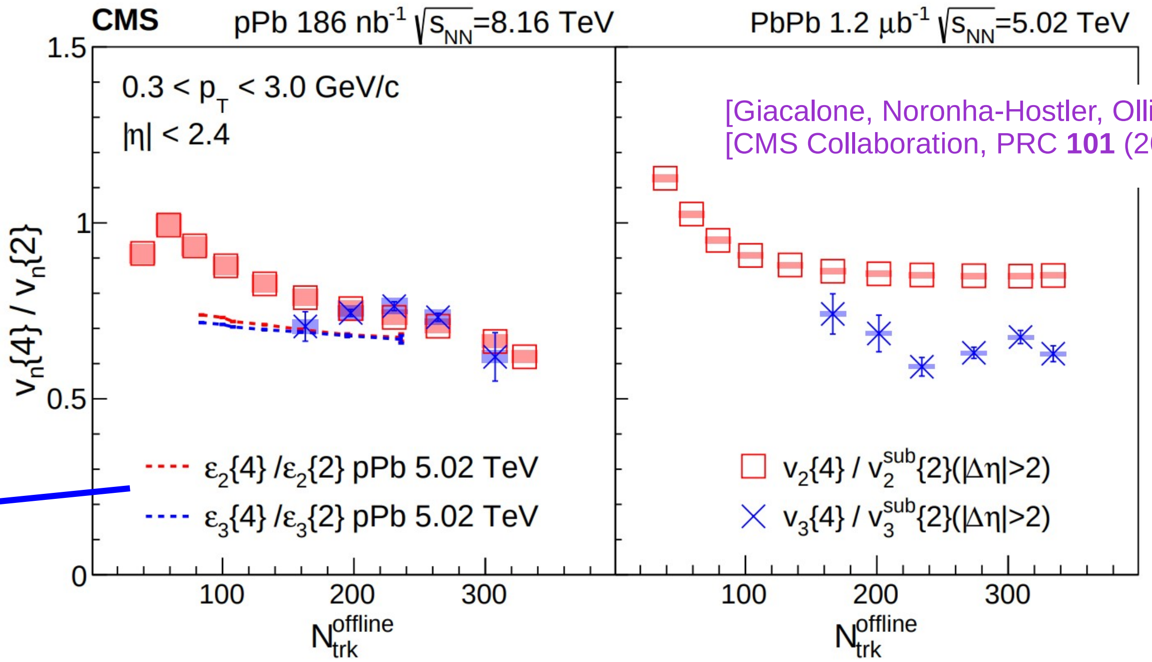


$$\frac{\varepsilon_3\{4\}}{\varepsilon_3\{2\}} \sim \frac{v_3\{4\}}{v_3\{2\}}$$

Once more, basic physics. Outside current hydro precision.
Important for legacy of data sets and future model building.

Missing results in p-Au collisions.

Breakthrough observations from LHC. Great insight on origin of flow. Theory is not there yet.



[Giacalone, Noronha-Hostler, Ollitrault, **PRC 95** (2017) 5, 054910]
[CMS Collaboration, PRC **101** (2020) 1, 014912]

old TRENTo model

Having these measurements is crucial for legacy of data sets.

However, for lower multiplicities (sPHENIX), η gaps are required.
Feasibility study is mandatory.

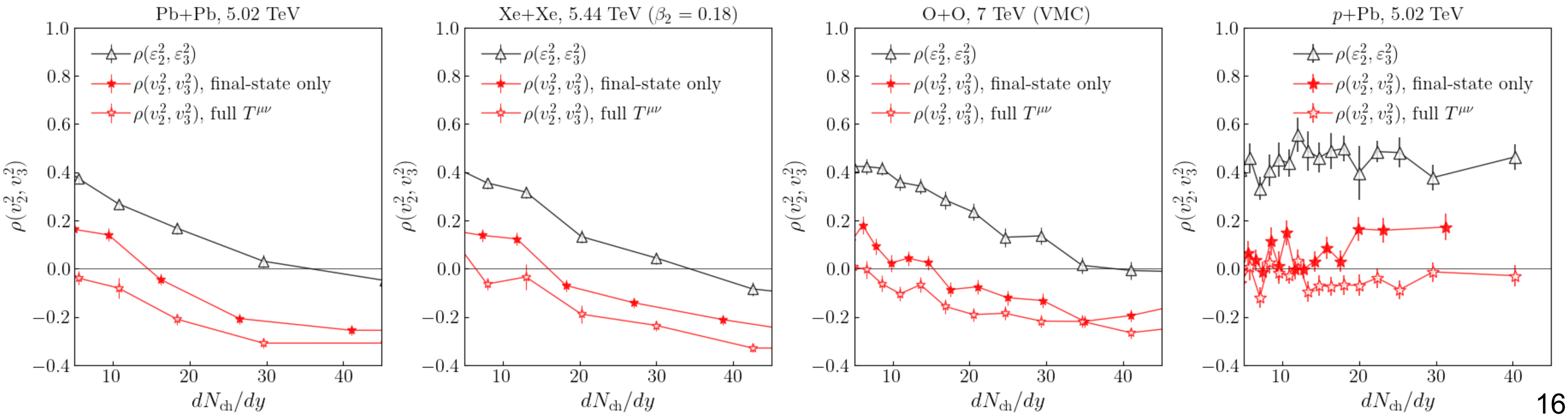
Insights from flow harmonics correlations, e.g., $\rho(v_2^2, v_3^2) = \langle (v_2)^2 (v_3)^2 \rangle - \langle (v_2)^2 \rangle \langle (v_3)^2 \rangle$

At small multiplicities, experimental data indicates: $\rho(v_2^2, v_3^2) < 0$

Hydrodynamic results: Negative sign coming from nonlinear response effects.

[Giacalone, Schenke, Shen, in preparation]

My expectation for sPHENIX: It will be negative. Probe of nonlinear regime.
Role of pre-flow?



Science cases for ^{208}Pb collisions at RHIC.

From sPHENIX Beam Use Proposal:

opportunity in 2027. The upgrades enable a doubling of the Au+Au data set to 30 nb^{-1} or equivalently 200 billion Au+Au events. These events will serve as a permanent archive of Au+Au data, to be mined for any future analysis once RHIC is no longer running heavy ions. There

Potential alternatives to exploit Au-Au data set?

From Beam Use Request (STAR):
possibilities from a short ^{208}Pb+^{208}Pb run
(few 100M MB collisions, no impact on Au-Au program)

RHIC legacy?

Precision phenomenology of Au-Au collisions.

With 100B events, measurements will be more precise than theoretical predictions.

In future, models may however become competitive in terms of stat precision.

But can we really make precision physics?

In short: not really.

Problem(s): At some point we crash into the boundary of our knowledge of the colliding ions (deformations, neutron distributions).

Way out? comparing two systems close in size.

Precision phenomenology of Au-Au collisions.

[STAR collaboration, PRC **105** (2022) 1, 014901]
Courtesy Chunjian Zhang

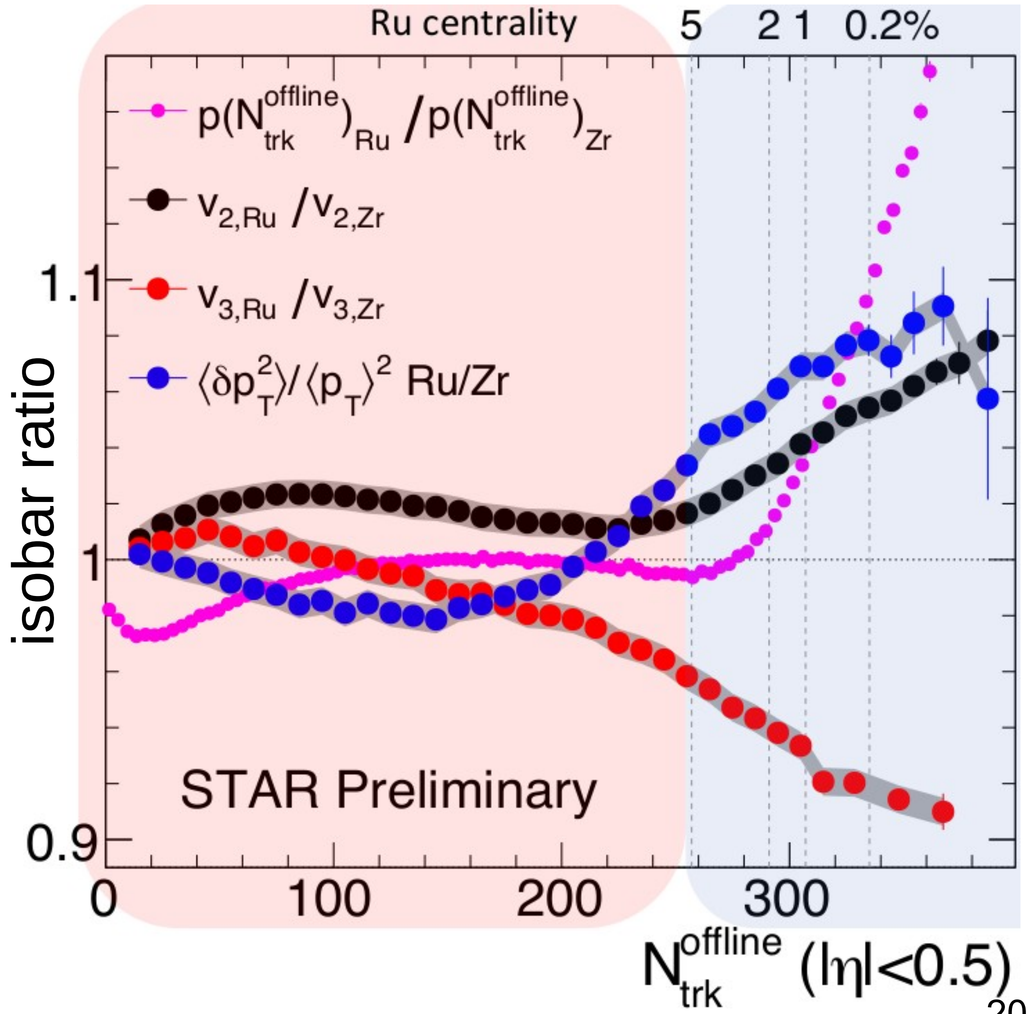
Hard lesson from isobar collisions in 2021.

Assume we had 96Zr without 96Ru.

We would have to fix a 10% correction in $v_3\{2\}$ via model/transport parameters...

Precise (<5%) understanding possible only **when two systems are available**.

MAIN IDEA:
Make the same plot but Au/Pb.
Only way to assess these problems!



Precision phenomenology of Au-Au collisions.

$$\rho_n = \frac{\langle\langle v_n^2 \delta p_{\mathrm{T}} \rangle\rangle}{\sqrt{\left(\langle v_n^4 \rangle - \langle v_n^2 \rangle^2\right)\sqrt{\langle\langle \delta p_{\mathrm{T}} \delta p_{\mathrm{T}} \rangle\rangle}}}$$

Example: Triaxiality of nuclei.

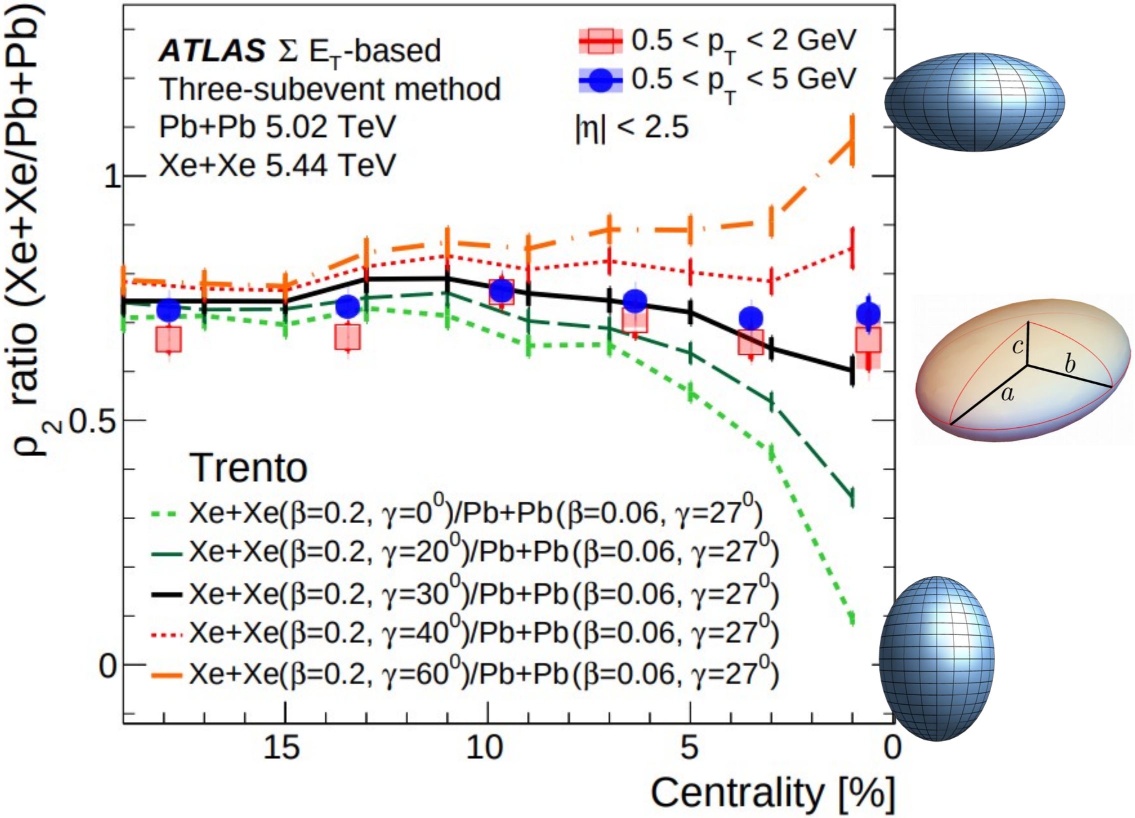
Pb-Pb vs. Xe-Xe collisions.

Low-energy theory predicts that ^{129}Xe is triaxial.

[Bally et al., PRL **128** (2022) 8, 082301]

Confirmed at LHC via comparison with ^{208}Pb+^{208}Pb collisions.

[ATLAS Collaboration, arXiv:2205.00039]



Brings confidence about initial conditions.
It would be very difficult to reach the same conclusion if we had only ^{129}Xe collisions!

Precision phenomenology of Au-Au collisions.

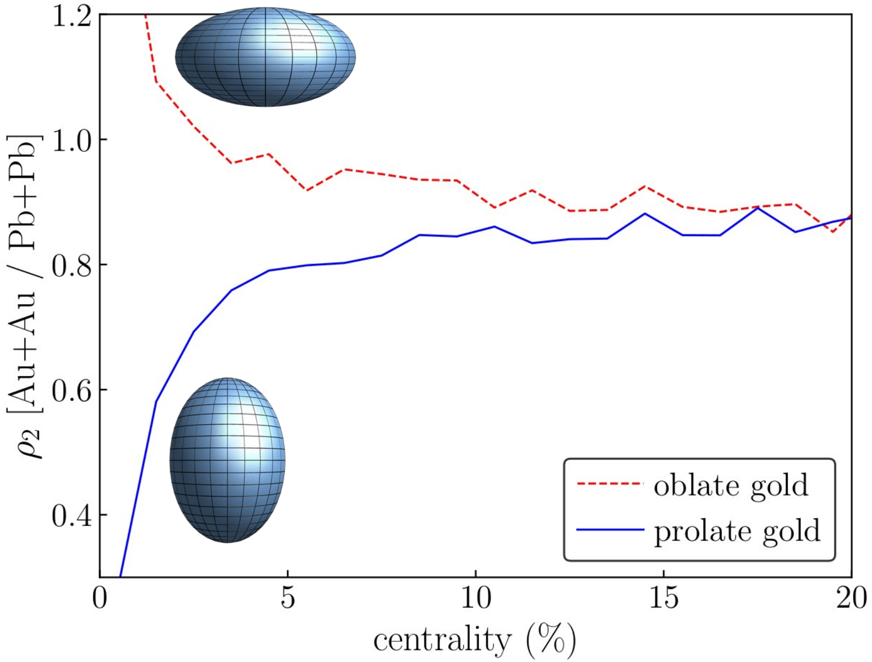
Problem is, ^{197}Au is a bit like 129Xe. We need to assess the triaxiality.

Preliminary low-energy results indicate some triaxiality for gold-197.

[work in preparation]

PREDICTION FOR sPHENIX?
Pb-Pb vs. Au-Au

Experiment can determine the triaxiality.



Consistency of high- and low-energy phenomena for improved initial conditions.
Only possible via ^{208}Pb+^{208}Pb!

Neutron skin physics at RHIC.

Astrophysics-motivated. Equation of state of nuclear matter:

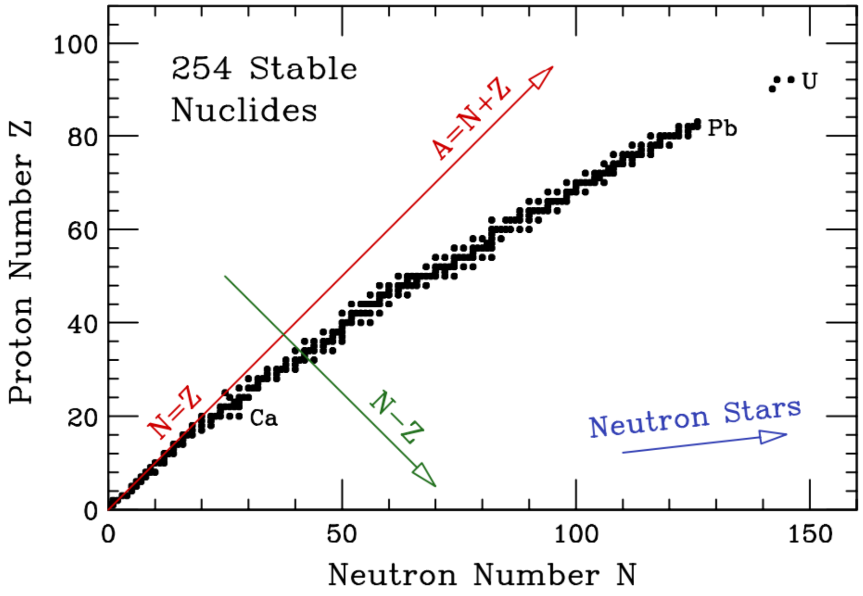
$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + \mathcal{O}(\dots^4)$$

symmetric matter (a)symmetry energy $\rho = \rho_n + \rho_p$

Symmetry energy is usually Taylor expanded around saturation density

$$S(\rho) = S(\rho_0) + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \dots$$

[From P. Danielewicz,
RBRC Workshop Jan 2022]



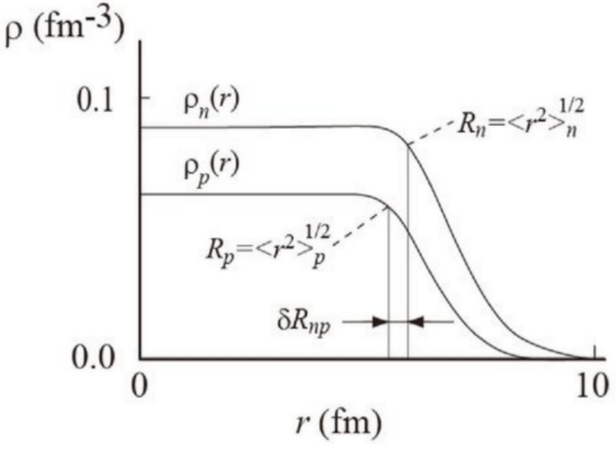
Symmetry energy is about the 'cost' of making system more neutron rich at a given density.

Slope parameter, L, determines the stiffness of the EoS.

Determines structure of neutron rich systems, from nuclei to neutron stars.

Neutron skin physics at RHIC.

The neutron skin in atomic nuclei, Δr_{np}, is proportional to the slope L of symmetry energy.

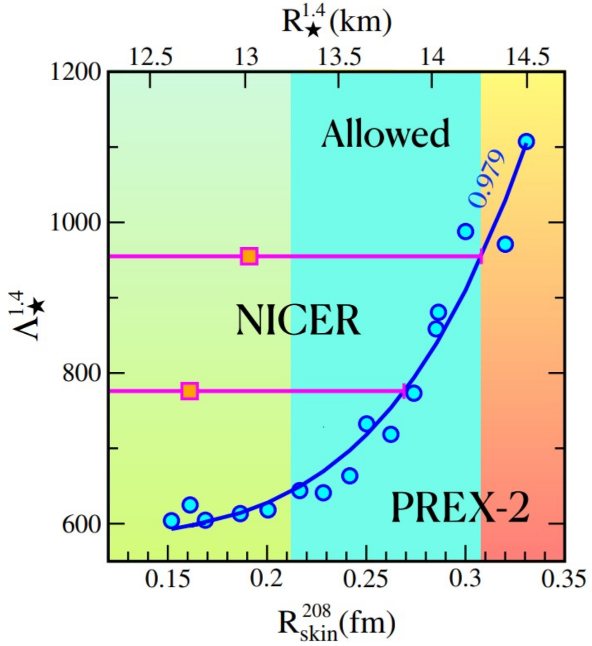


Accurate measurement of Δr_{np} of ^{208}Pb from neutral weak form factor at JLab (PREX-II experiment):

$$\Delta r_{np} = 0.283 \pm 0.071 \text{ fm}$$

$$L = (106 \pm 37) \text{ MeV}$$

[PREX-II experiment, PRL **126** (2021) 17, 172502]



Stiffer EoS than expected.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]

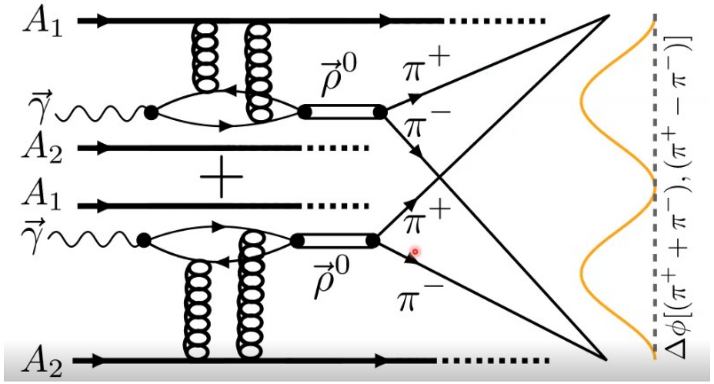
From GW170817

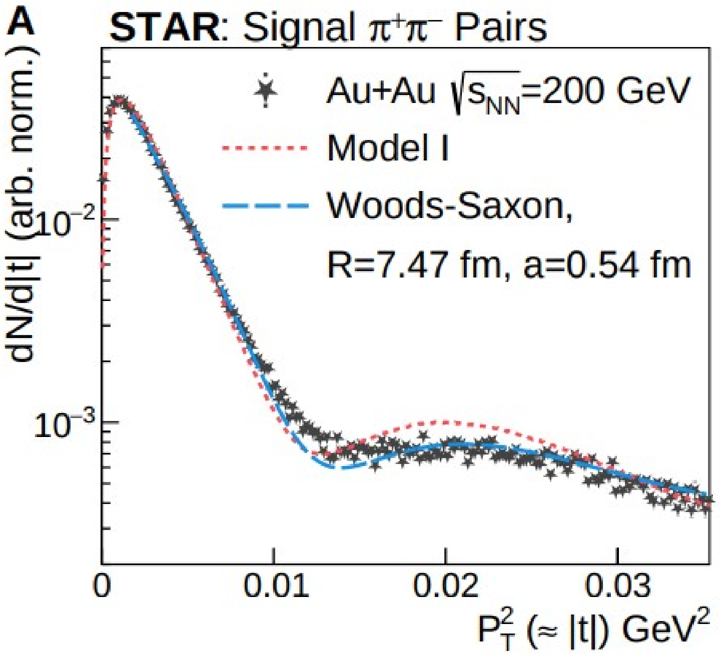
of $\Lambda_{1.4} \lesssim 580$ [44], we eagerly await the next generation of terrestrial experiments and astronomical observations to verify whether the tension remains. If so, the softening of the EOS at intermediate densities, together with the subsequent stiffening at high densities required to support massive neutron stars, may be indicative of a phase transition in the stellar core [42].

Can we get an independent estimate at RHIC?

Neutron skin physics at RHIC.

Ultra-peripheral collisions.





$$f(t) = A_c |\mathcal{F}[\rho_A(r; R, a)](|t|)|^2 + \frac{A_i/Q_0^2}{(1 + |t|/Q_0^2)^2}$$

FT of gluon density (Woods-Saxon)

[STAR Collaboration, arXiv:2204.01625]

neutron skins:

$$0.44 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.}) \text{ fm for } {}^{238}U$$

$$0.17 \pm 0.03(\text{stat.}) \pm 0.08(\text{syst.}) \text{ fm for } {}^{197}Au$$

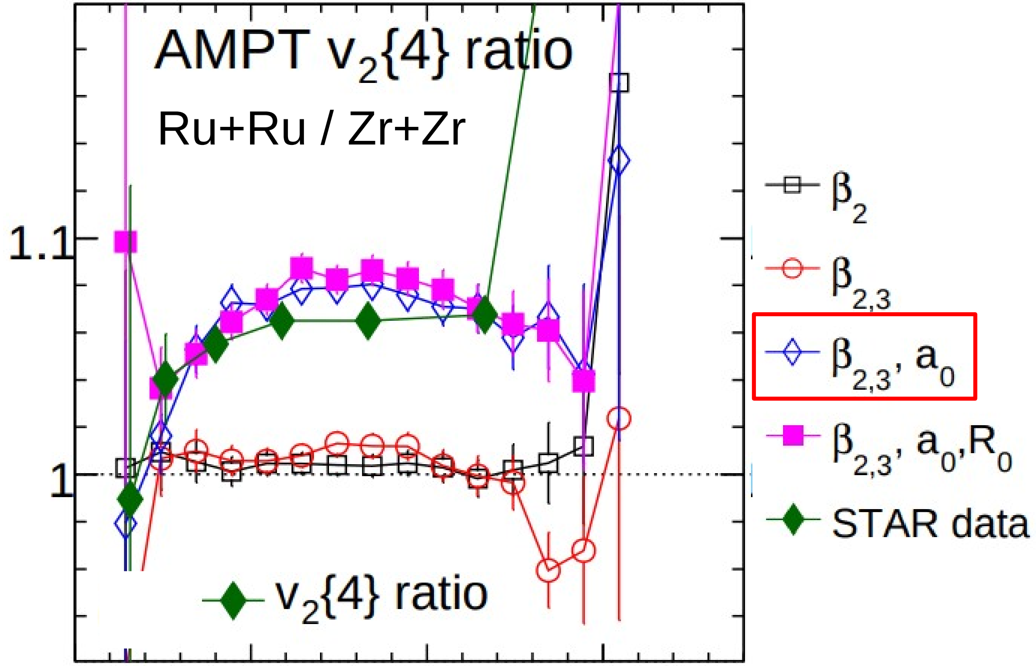
Neutron skin physics at RHIC.

[Jia, Giacalone, Zhang, arXiv:2206.10449]

Lesson from isobar collisions.

Neutron skin difference
Δr_{np} (^{208}Pb) - Δr_{np} (^{197}Au)
from variation of $v_2\{4\}$.

For all practical purposes,
^{197}Au and ^{208}Pb are isobars.



The plan:

1 - Estimate neutron skin of ^{208}Pb from UPCs.

2 - Estimate neutron skin difference Δr_{np} (^{208}Pb) - Δr_{np} (^{197}Au) from UPCs.

3 - Estimate neutron skin difference Δr_{np} (^{208}Pb) - Δr_{np} (^{197}Au) from ratio of $v_2\{4\}$.

4 – Check for consistency… if consistent, it is a breakthrough.

CONCLUSION

- sPHENIX and high-statistics data sets will leave a crucial imprint in the legacy of the RHIC machine.

- **A-A collisions:** precision measurements of non-Gaussian v_2 fluctuations ($v_2\{6,8\}$) and primordial non-Gaussianities ($v_3\{4\}$).

- **p-A collisions:** measurements of cumulants are crucial to understand the origin of flow.
  Feasibility is however not guaranteed.

- Unique opportunities from ^{208}Pb collisions at RHIC not to be neglected.

  1. Improved understanding of Au-Au (relevant for sPHENIX goals).

  2. Neutron skin estimates are useful for the whole nuclear physics community.

  (3. Last chance to improve connection with LHC)

THANK YOU!

Intersection of nuclear structure and high-energy nuclear collisions

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

Organizers:
Giuliano Giacalone (Heidelberg)
Jiangyong Jia (Stony Brook & BNL)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Jaki Noronha-Hostler (Urbana-Champaign)
Fuqiang Wang (Purdue)