REVISITING THE DISCOVERY POTENTIAL OF THE ISOBAR RUN AT RHIC

Alba Soto-Ontoso

[Jan Hammelmann, ASO, Massimiliano Alvioli, Hannah Elfner, Mark Strikman, arXiv:1908.10231]

JLAB Theory Seminar

Remote, 22nd June, 2020

BROOKHAVEN NATIONAL LABORATORY

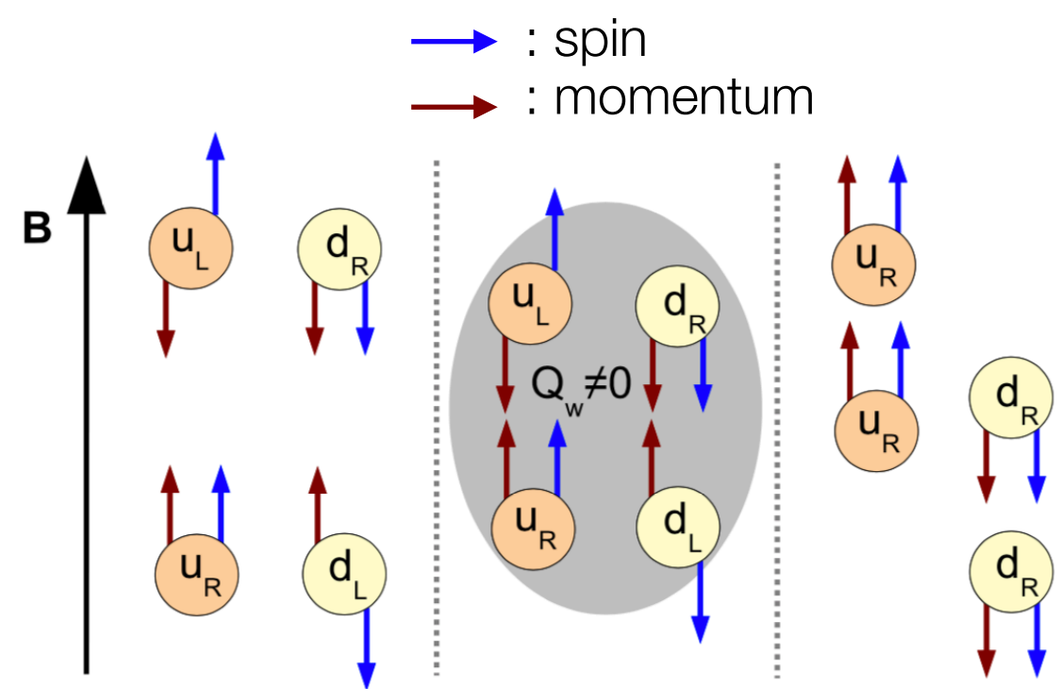
Center for Frontiers in Nuclear Science

The Chiral Magnetic Effect in a nutshell

QCD axial anomaly in the massless limit

$$\partial_\mu j_5^\mu = -\frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

$$\vec{j} \propto \mu_5 \vec{B}$$

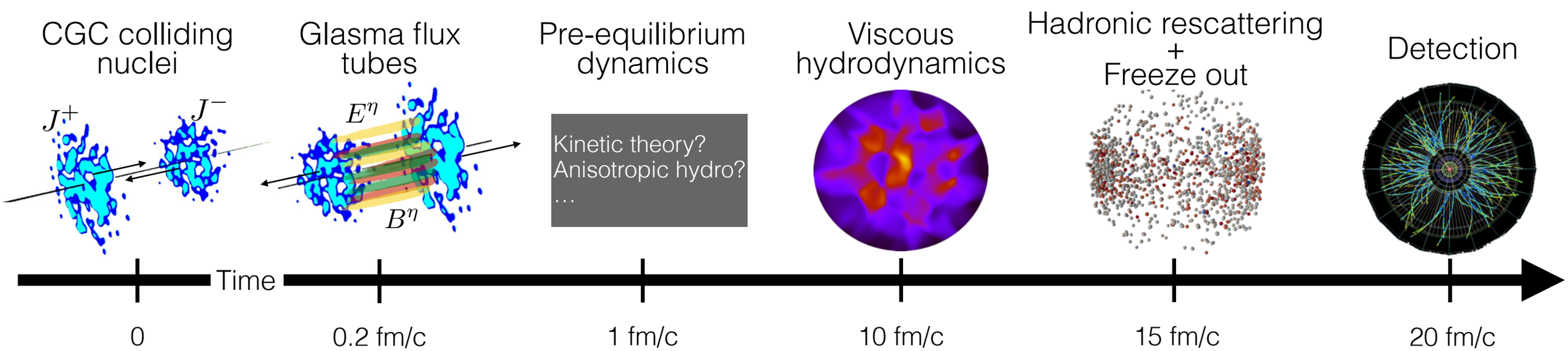


[D. Kharzeev, R.Pisarski, M.H.G Tytgat PRL 81, 512 (1998)]
[K.Fukushima, D.Kharzeev, H. Warringa PRD78 (2008) 074033]

Ingredients

1) Chiral fermions 2) $F\tilde{F} \neq 0$ 3) Strong magnetic field

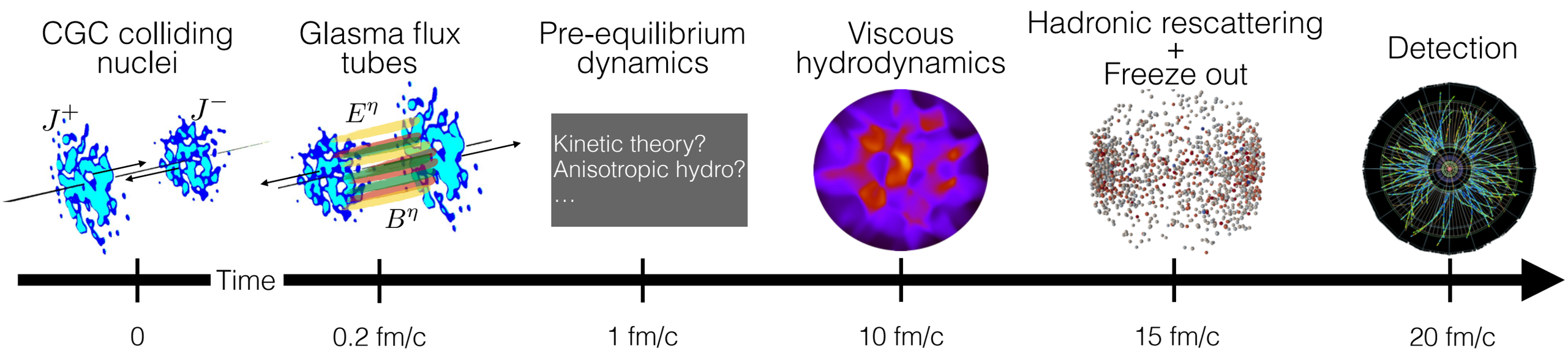
The Chiral Magnetic Effect via HICs



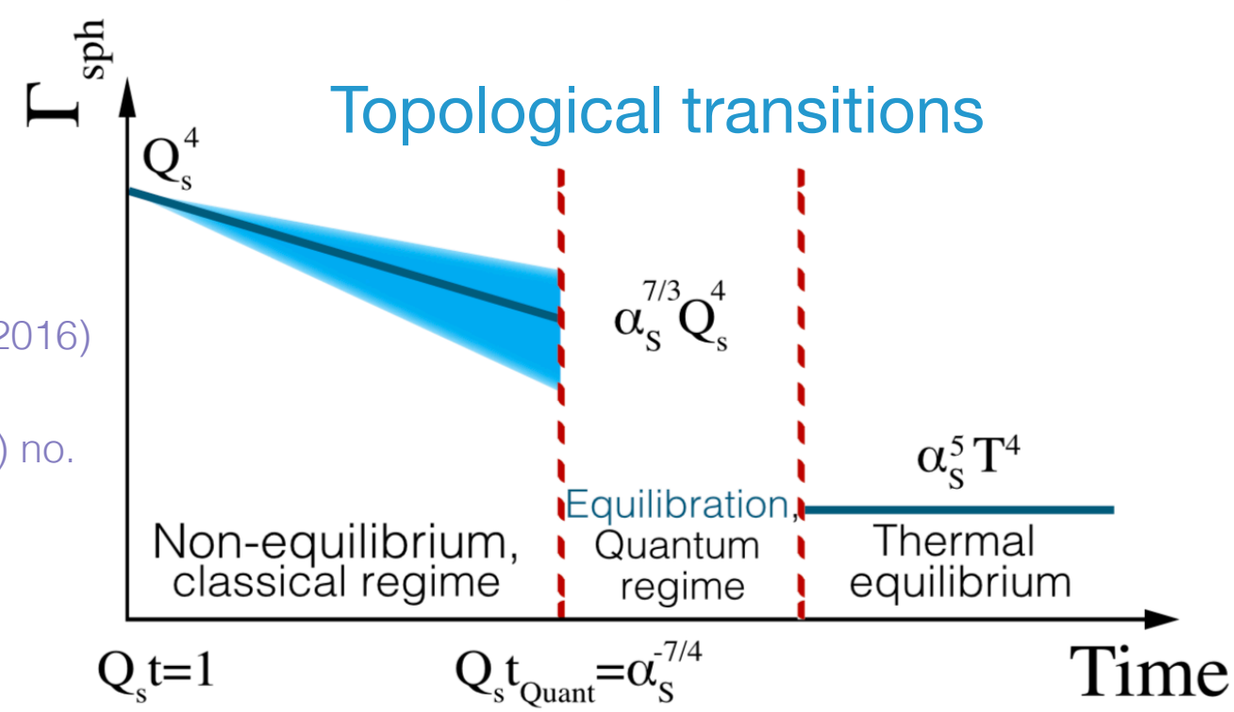
☑ Chiral symmetry restoration in the QGP phase T_c~156 MeV

[HotQCD Collab. PLB795 (2019) 15-21]

The Chiral Magnetic Effect via HICs



- ☑ Chiral symmetry restoration in the QGP phase
- ☑ Sources of $F\tilde{F} \neq 0$:

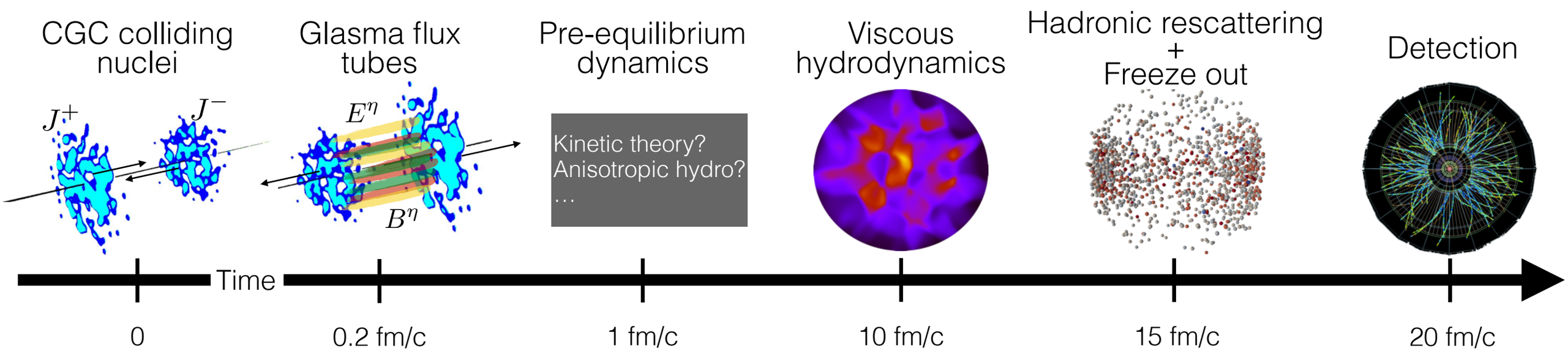


[G.D.Moore, M. Tassler, JHEP 02, 105 (2011)]

[M.Mace, S. Schlichting, R. Venugopalan PRD 93 (2016) no.7, 074036]

[N.Mueller, S. Schlichting, S.Sharma PRL117 (2016) no. 14, 14230]

The Chiral Magnetic Effect via HICs

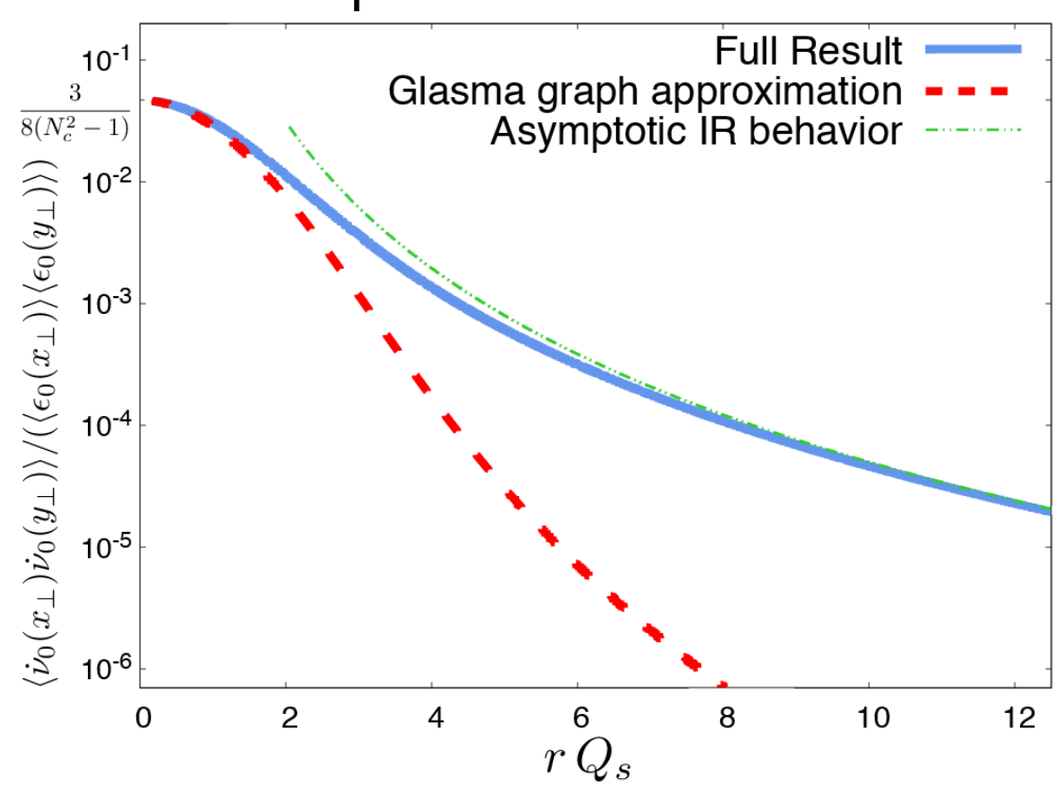


- ☑ Chiral symmetry restoration in the QGP phase
- ☑ Sources of $F\tilde{F} \neq 0$

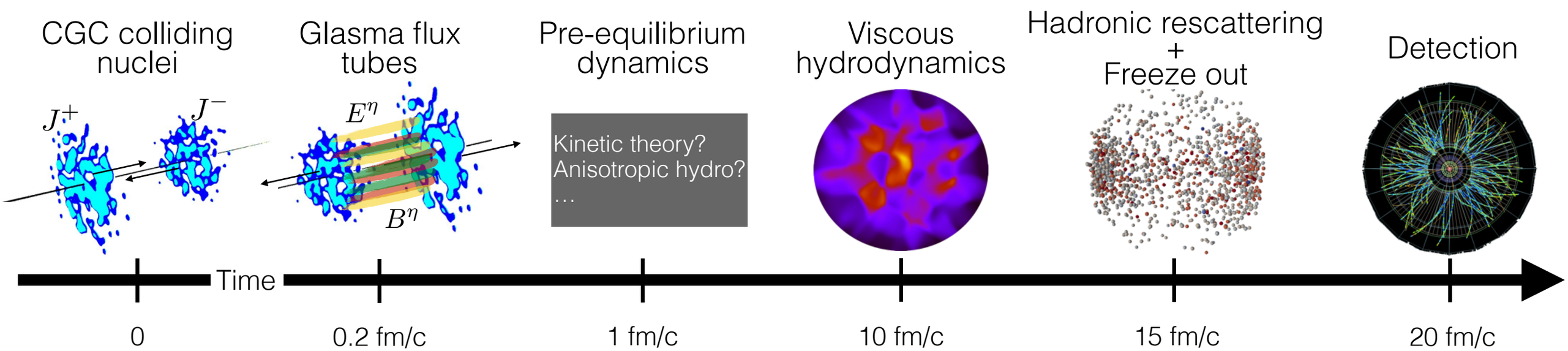
Axial charge fluctuations in the Glasma

[T. Lappi, S. Schlichting, PRD 97, 034034 (2018)]

[P. Guerrero-Rodriguez, JHEP 1908 (2019) 026]



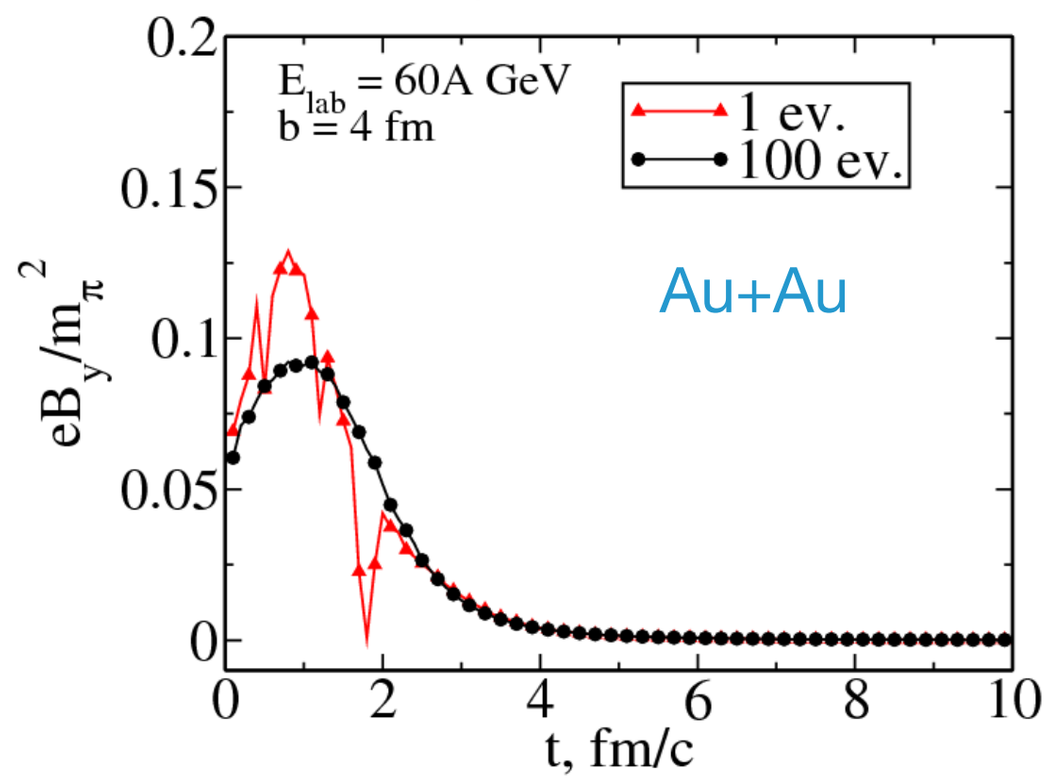
The Chiral Magnetic Effect via HICs



- ☑ Chiral symmetry restoration in the QGP phase
- ☑ Several sources of $F\tilde{F} \neq 0$
- ☑ Strong magnetic field

[Skokov et al. Int.J.Mod.Phys. A24 (2009) 5925-5932]

$$\vec{j} \propto \mu_5 \vec{B}$$

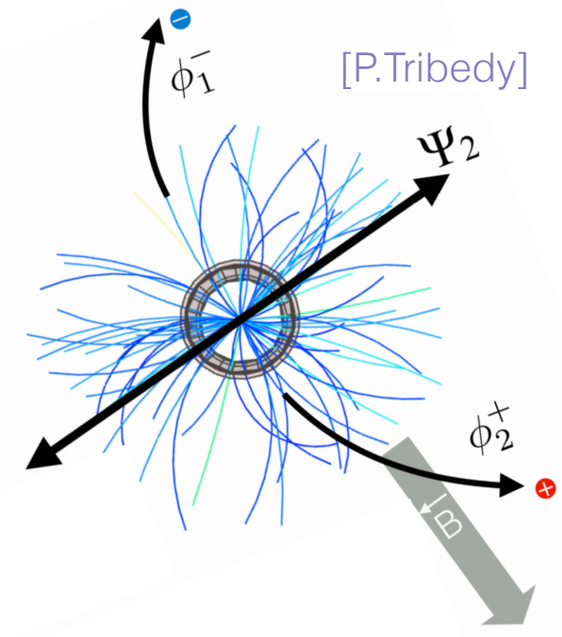


Experimental determination of the CME

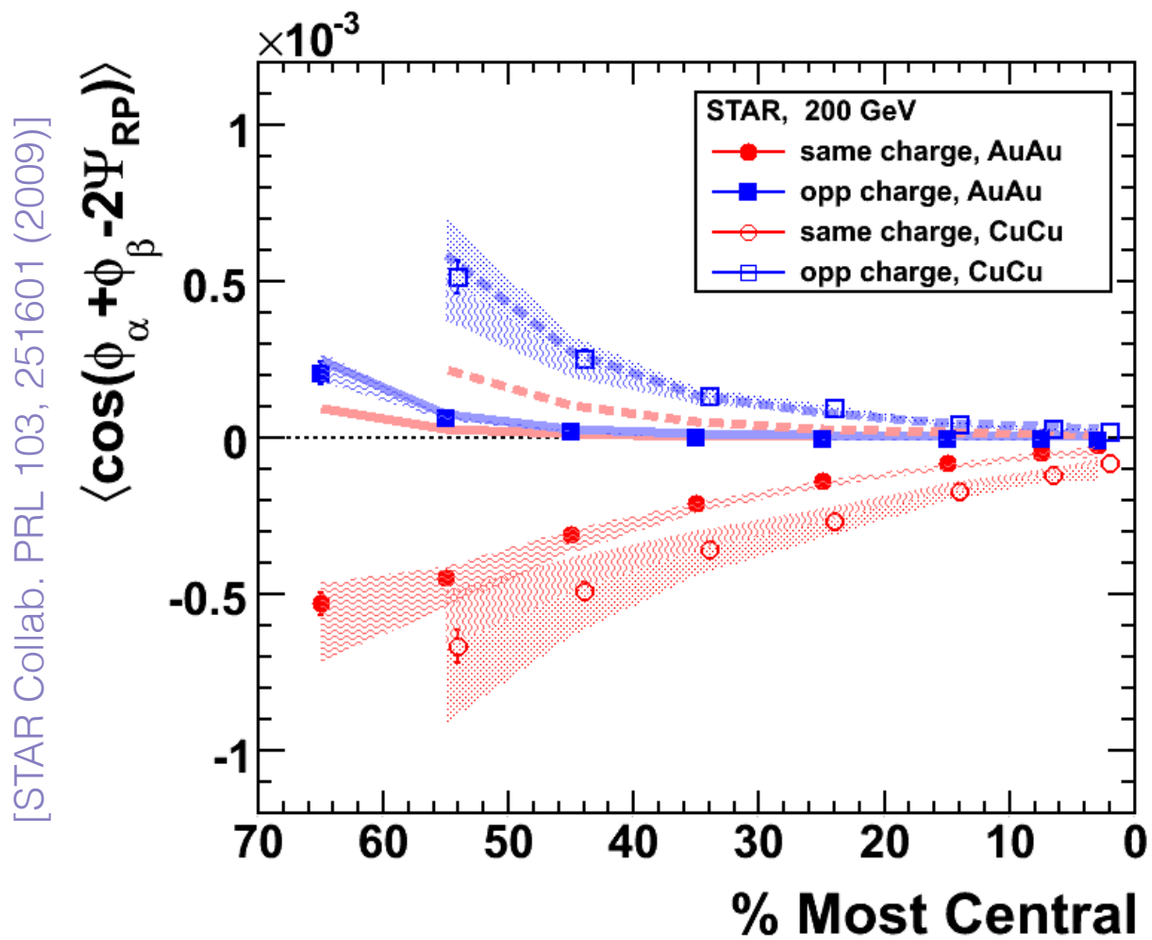
Charge-dependent azimuthal correlations

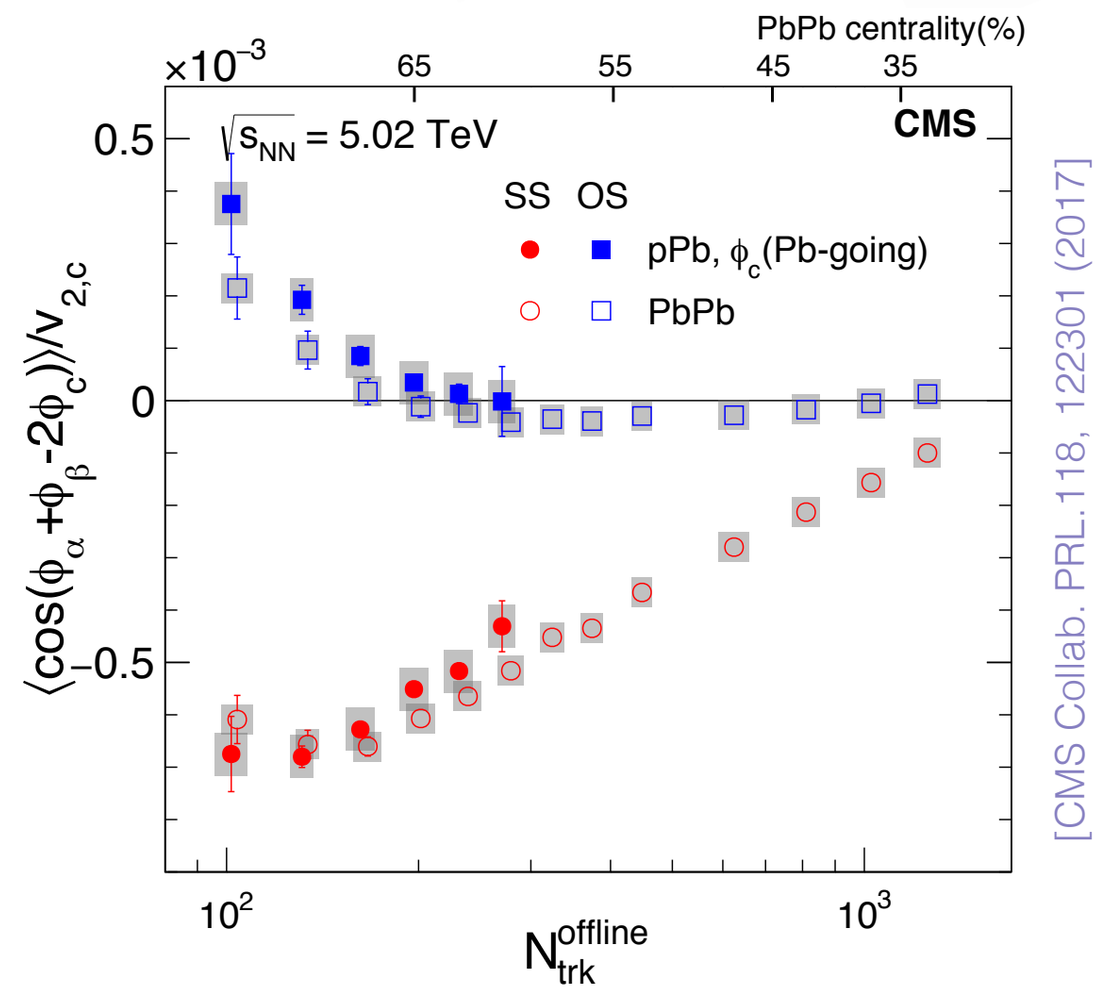
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle, \alpha, \beta \in \{+, -\}$$

[S.Voloshin PRC 70, 057901 (2004)]



CME prediction: $\gamma_{++,--} < 0, \gamma_{+-} > 0$





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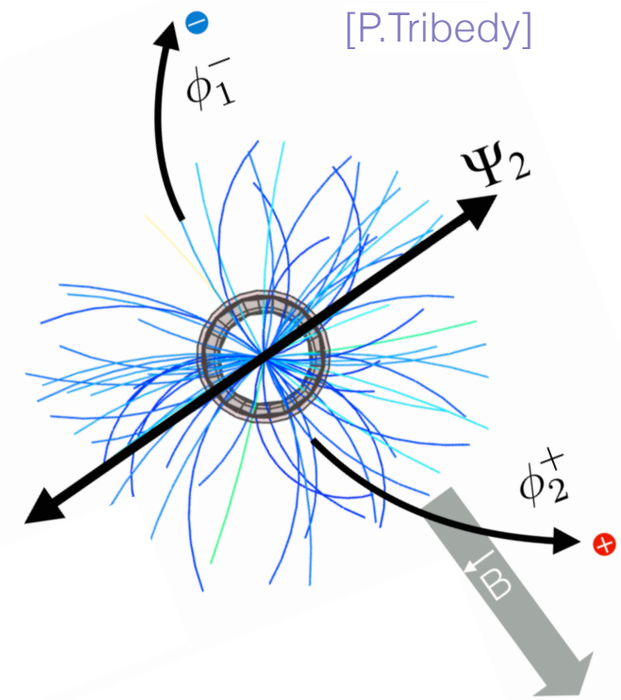

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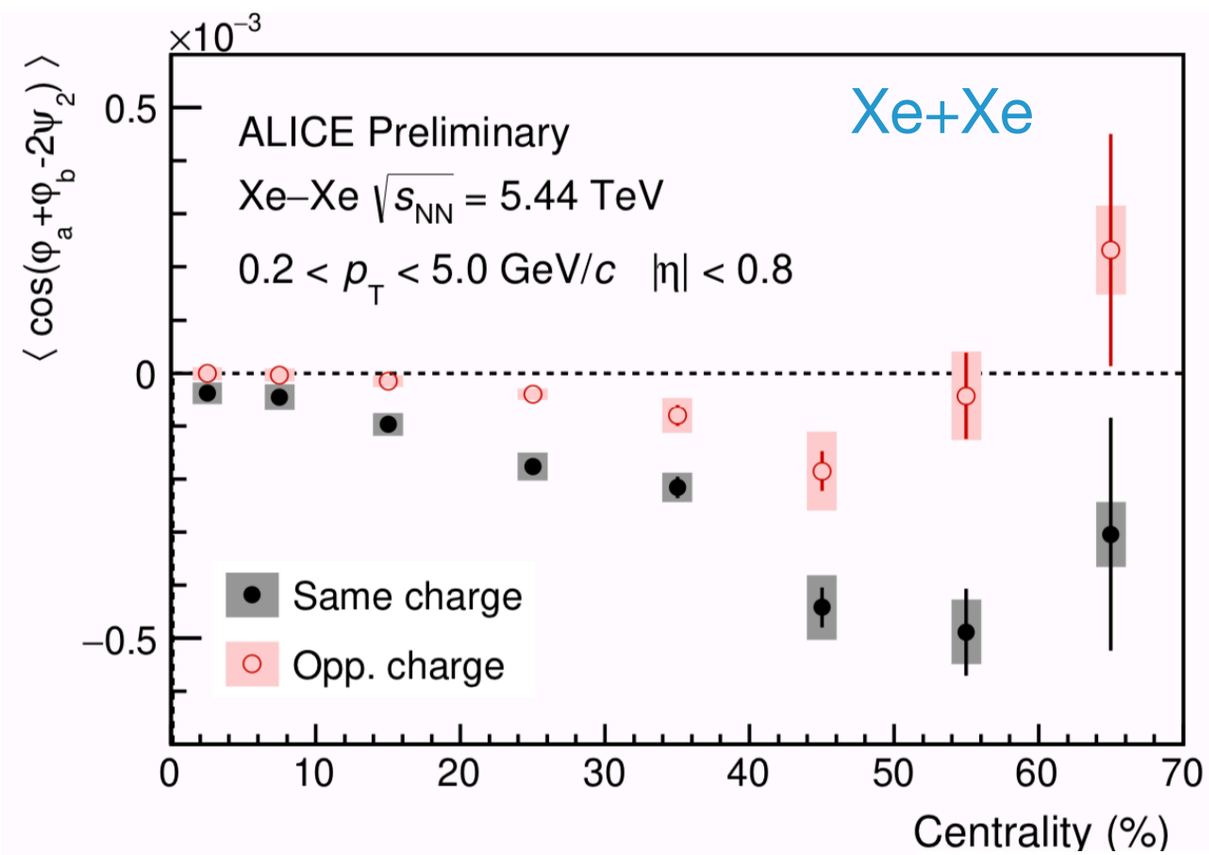
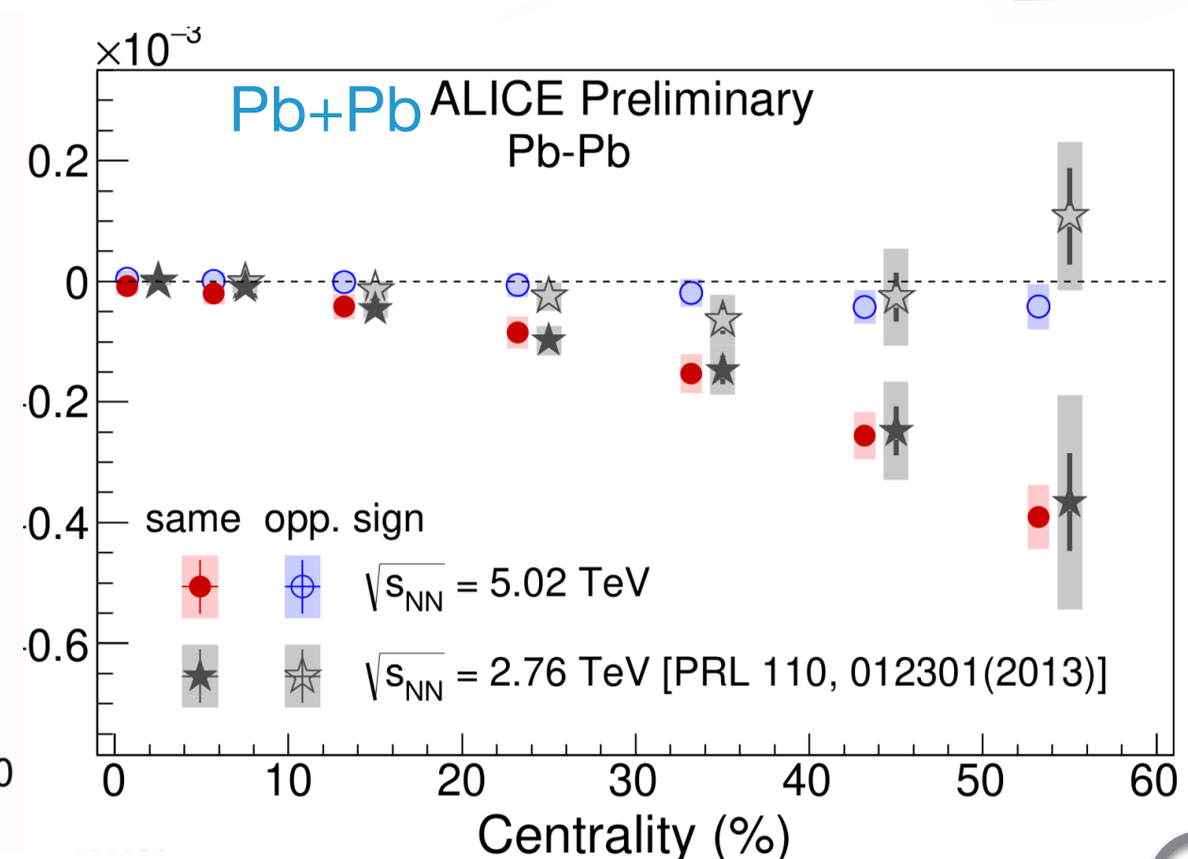


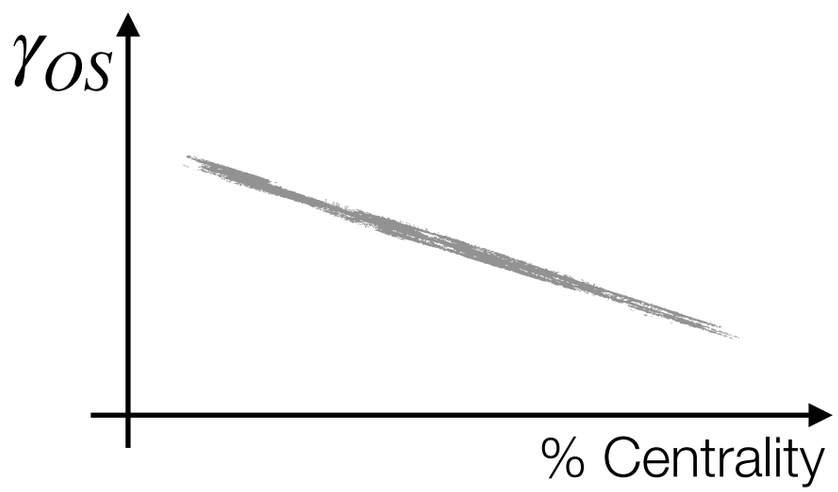


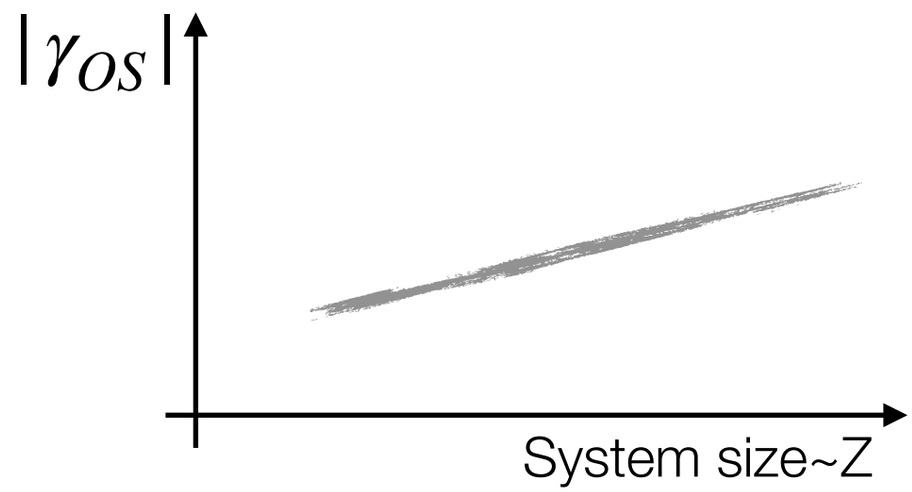
[S.Aziz for the ALICE Collab. QM'19]

Experimental determination of the CME

Contributions to the experimental measurement:

- CME driven: $\gamma_{\alpha\beta} \propto \langle B^2 \cos(2(\Psi_B - \Psi_2))\rangle$





- Background: $\gamma_{\alpha\beta} \propto v_2$
  - Local charge conservation, momentum conservation, resonance decays…

e.g.[S.Schlichting, S.Pratt PRC 83 (2011) 014913] STAR'09 data explained without CME

Two ways out

- New observables beyond $\gamma_{\alpha\beta}$ have been proposed.

  e.g. [M. Magdy et al. PRC 97, 061901 (2018)]

- Isobar run at RHIC

"We have specifically investigated the case for colliding nuclear isobars (nuclei with the same mass but different charge) and find the case compelling. We recommend that a program of nuclear isobar collisions to isolate the chiral magnetic effect from background sources be placed as a high priority item in the strategy for completing the RHIC mission."

– Chiral Magnetic Effect Task Force Report

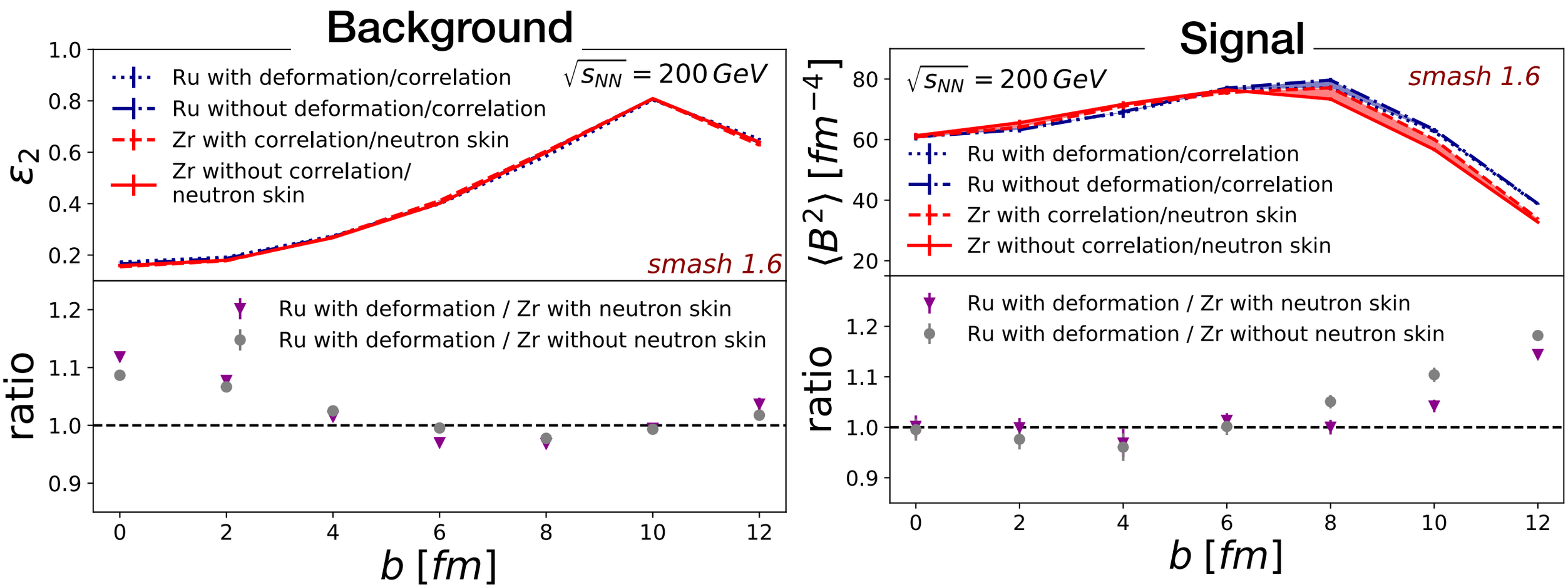
[Chin.Phys. C41 (2017) no.7, 072001]

$_{44}Ru^{96} + {}_{44}Ru^{96}$ vs. $_{40}Zr^{96} + {}_{40}Zr^{96}$ @200GeV

Change signal (B), keeping background (v_2) fixed

Goal of this talk + sneak peek

Check the impact of $_{44}Ru^{96}$ and $_{40}Zr^{96}$ nuclear structure on the hypothesis *"Change signal (B), keeping background (v_2) fixed"*



Woods-Saxon parameters for isobars

Traditionally nucleons sampled from a Woods-Saxon distribution

$$\rho(r,\theta) = \frac{\rho_0}{e^{(r-R'(\theta,\phi))/d} + 1}$$

where $R'(\theta) = R_0(1 + \beta_2 Y_2^0(\theta))$

$_{44}Ru^{96}$

$R_0 = 5.08$ fm

$d = 0.46$ fm

Option 1: $\beta_2 = 0.158$

[Prytichenko et al. Atom Data Nucl. Data Tabl. 107 1, (2016)]

Option 2: $\beta_2 \sim 0$

[Moller et al. Atom Data Nucl. Data Tabl. 59 185, (1995)]

$_{40}Zr^{96}$

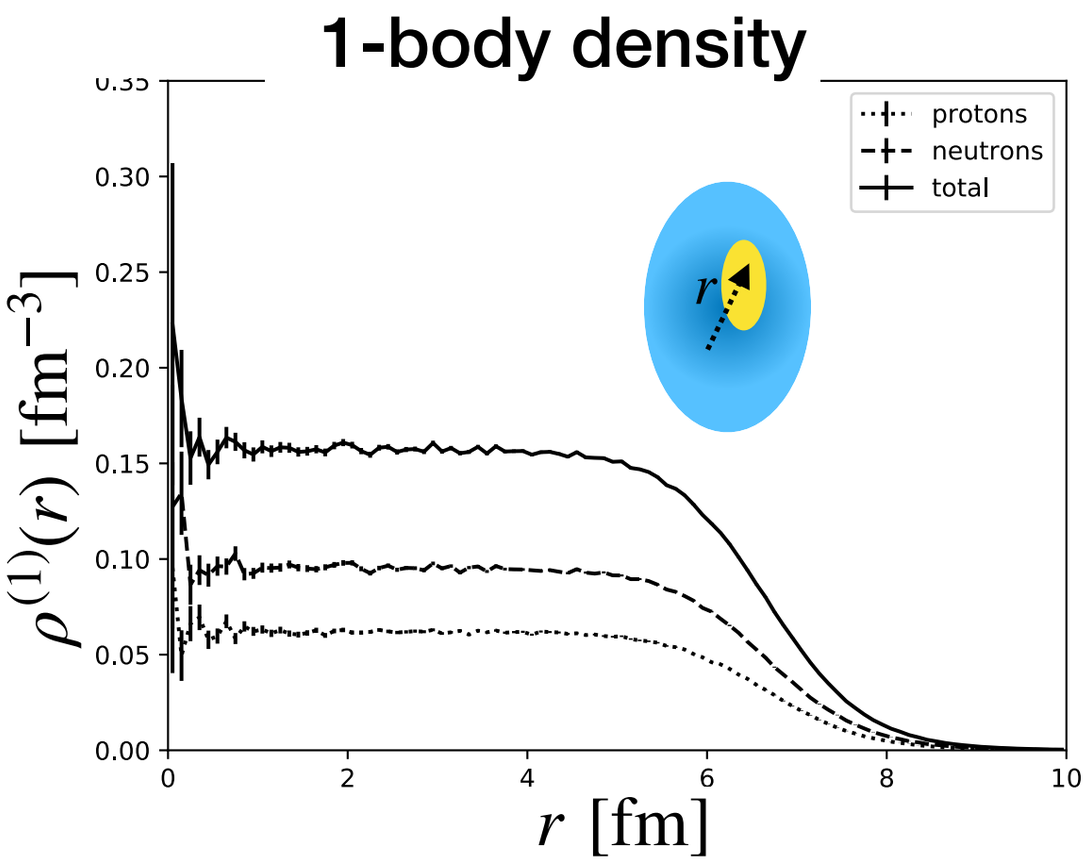
$R_0 = 5.02$ fm

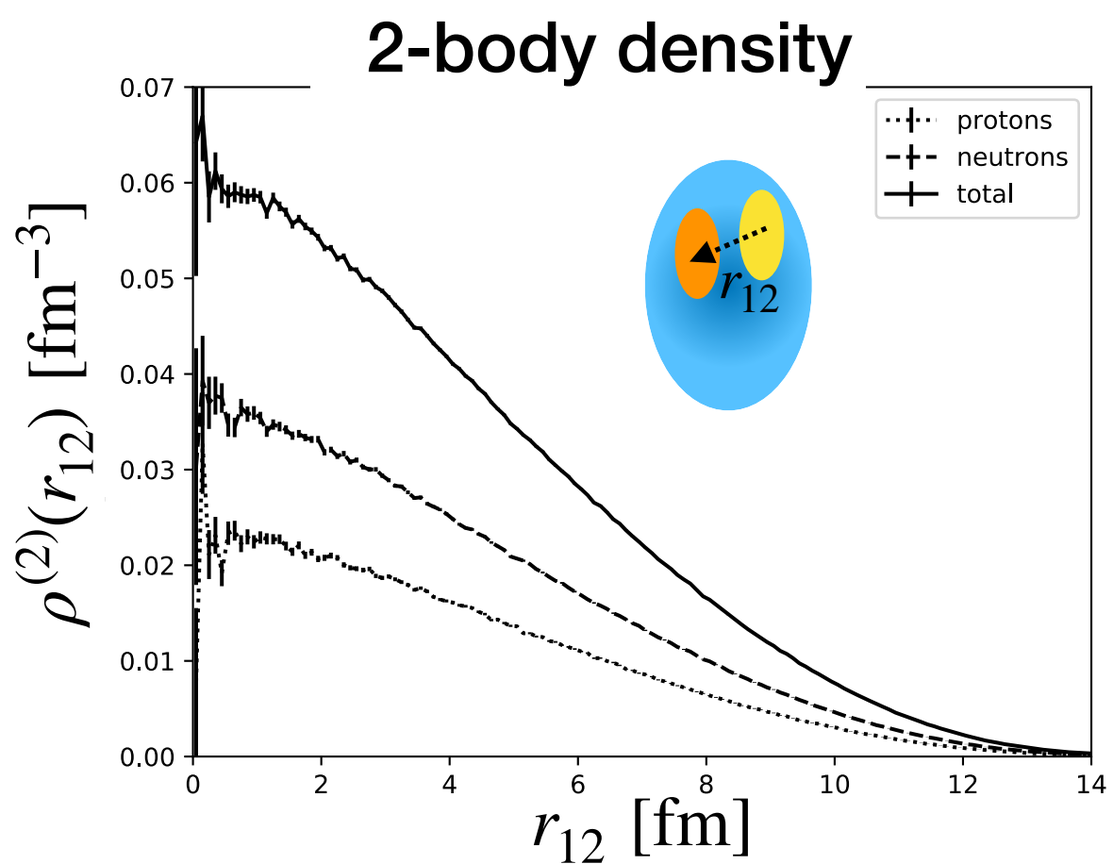
$d = 0.46$ fm

$\beta_2 \sim 0$

$\beta_2 = 0.217$

Beyond Woods-Saxon distribution



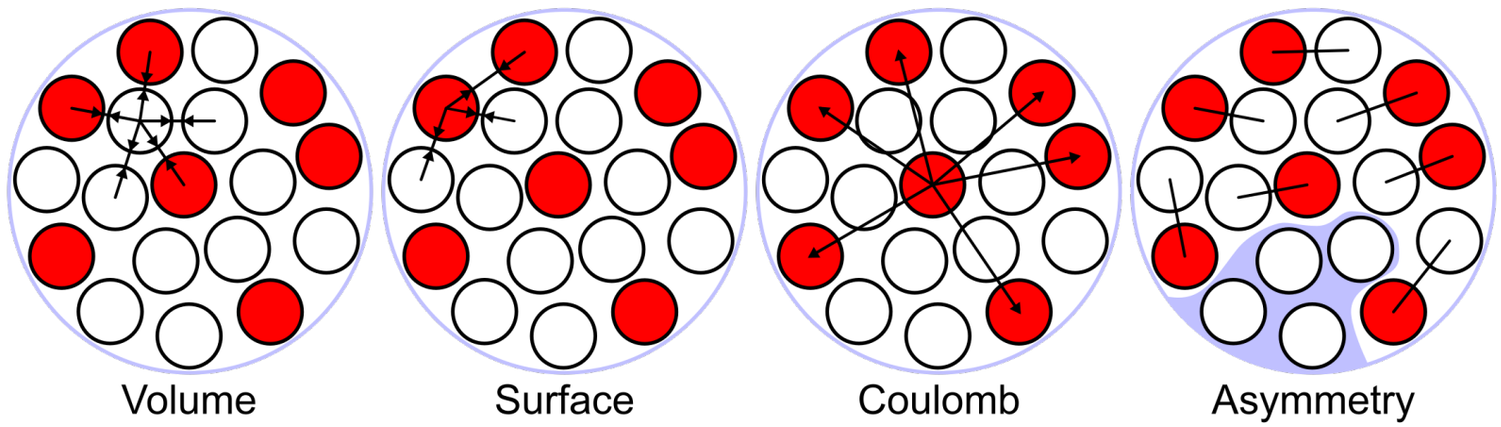


❌ No distinction between protons and neutrons

❌ Nucleons are considered independent of each other

Neutron skin within the liquid drop model

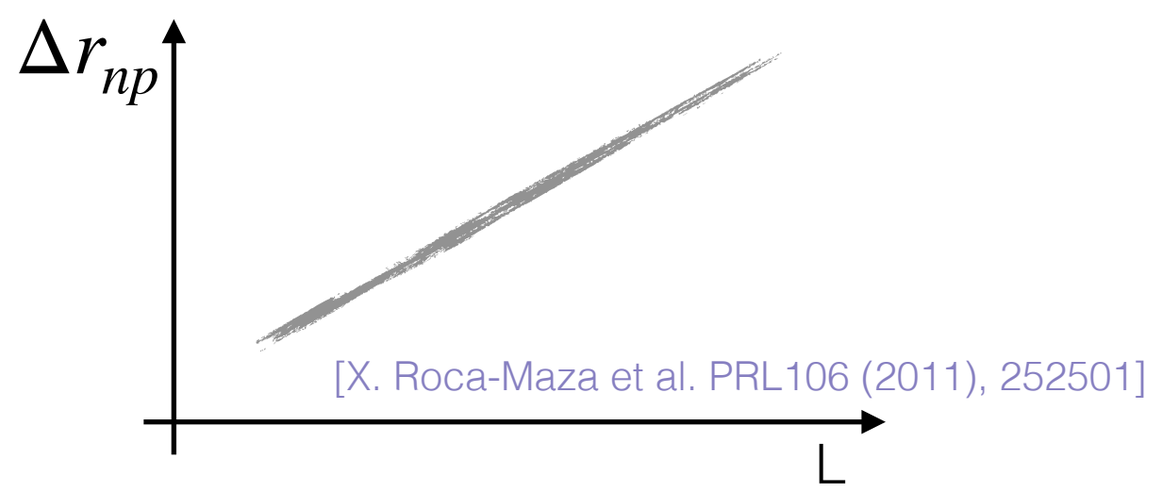
$$B(Z,N) = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_A (N-Z)^2/A + \ldots$$



[Wikipedia]

Neutron-rich nuclei: where to locate extra-neutrons?
Surface or core?

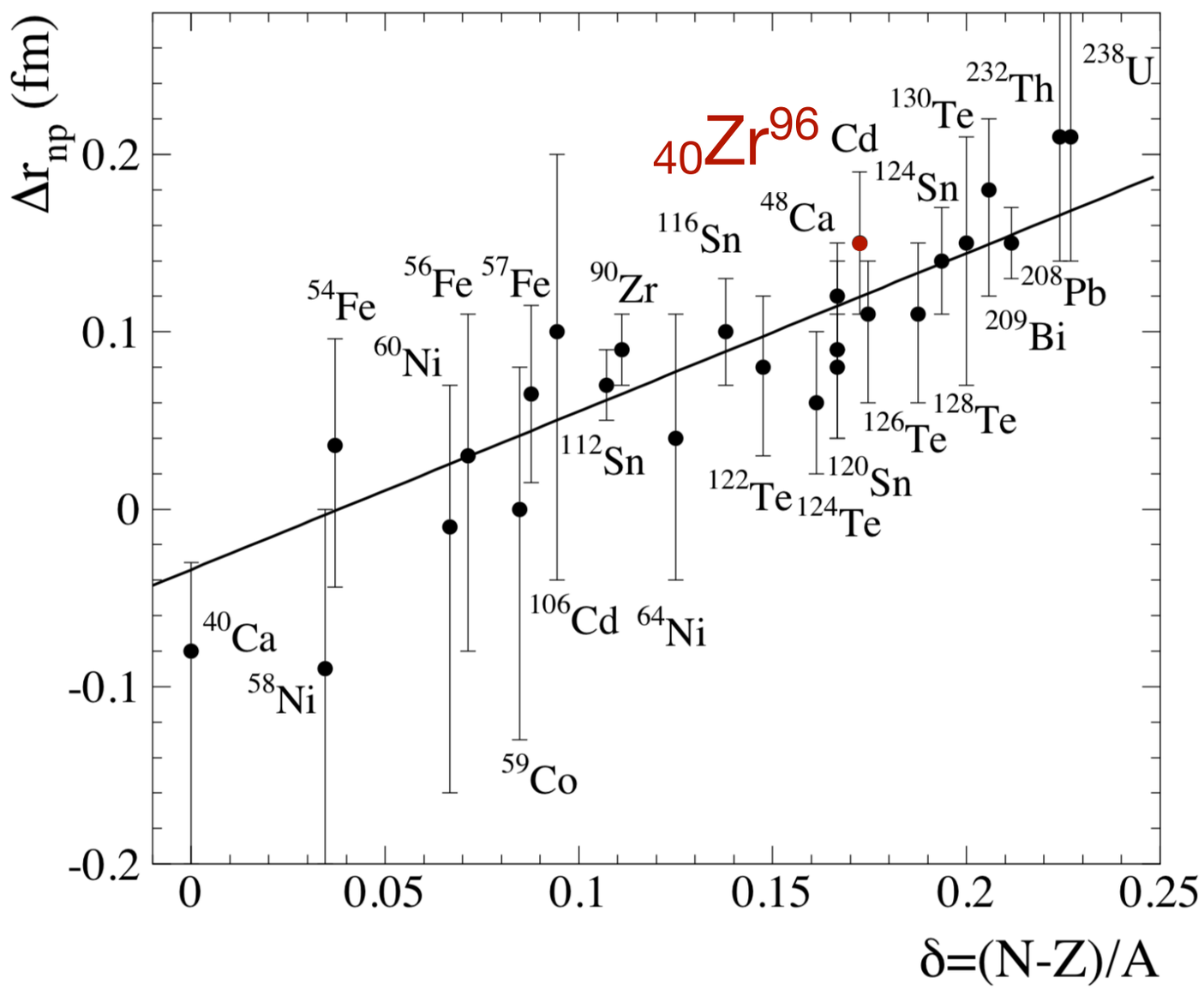
Neutron-skin thickness: surface tension vs stiffness of the symmetry energy (L)



[X. Roca-Maza et al. PRL106 (2011), 252501]

Neutron skin: experimental data

$$\rho(r) = \frac{Z}{A}\rho_p(r) + \frac{N}{A}\rho_n(r) \Longrightarrow \boxed{\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}}$$

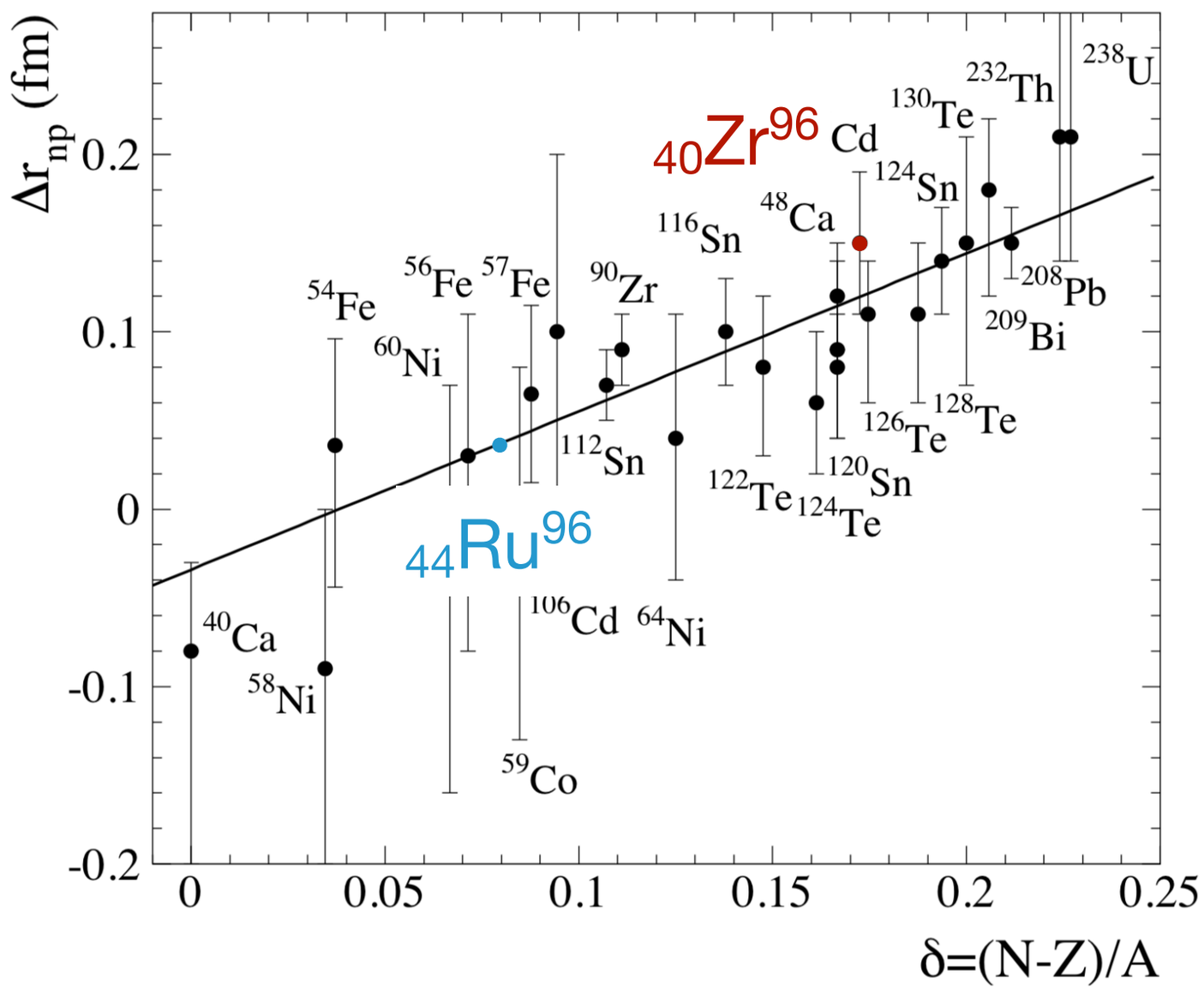


[LEAR Collab. Int Jour of Mod Phys E 13 (2004) 343]

- ^{96}Zr: 0.12 ± 0.03 fm
- ^{48}Ca: $0.14 - 0.2$ fm
  [Birkhan et al. PRL 118, 252501 (2017)]
  +CREX
- ^{208}Pb: 0.33 ± 0.17 fm
  [PREX Collab. PRL 108, 112502 (2012)]

Neutron skin: experimental data

$$\rho(r) = \frac{Z}{A}\rho_p(r) + \frac{N}{A}\rho_n(r) \Longrightarrow \boxed{\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}}$$



[LEAR Collab. Int Jour of Mod Phys E 13 (2004) 343]

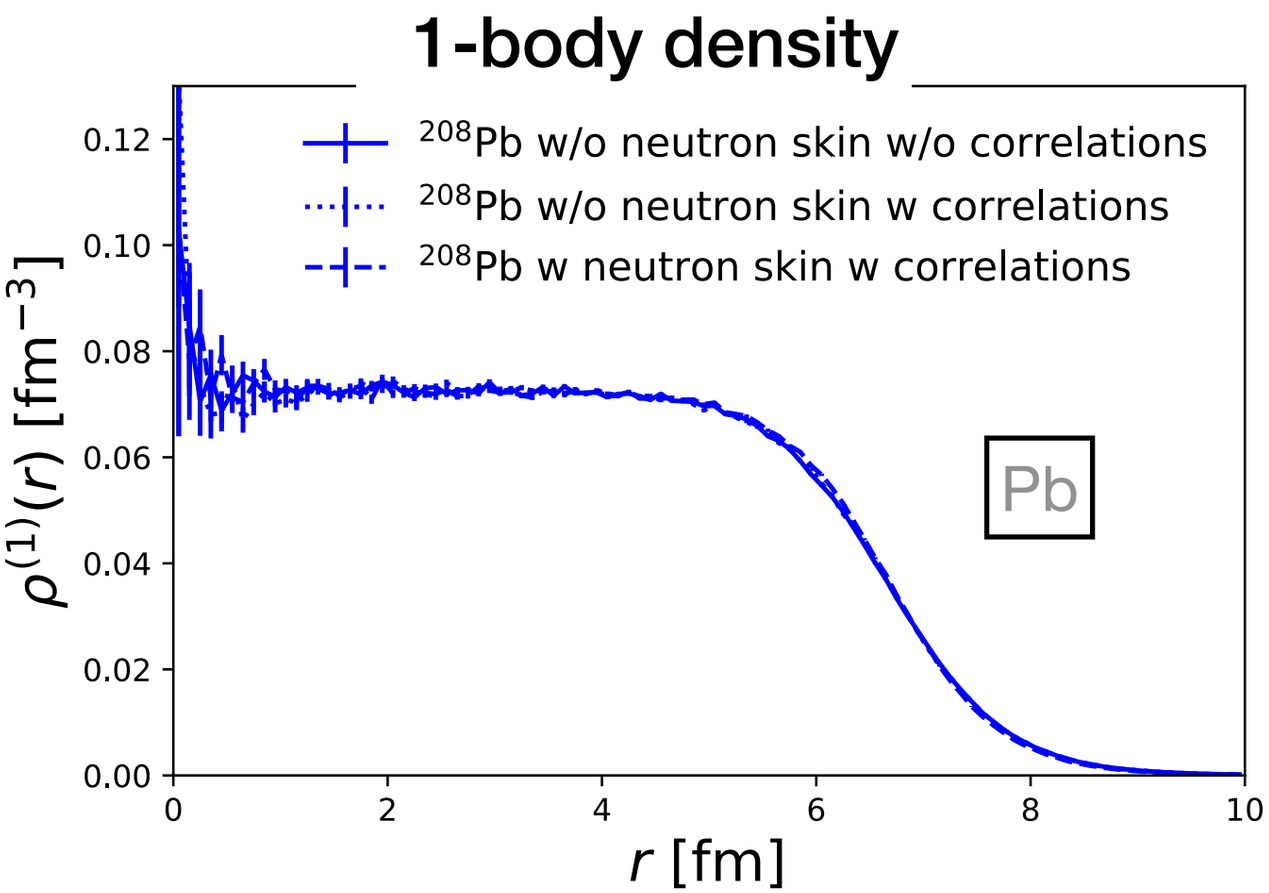
- ^{96}Zr: 0.12 ± 0.03 fm
- ^{96}Ru: $0.04 \pm ?$ fm

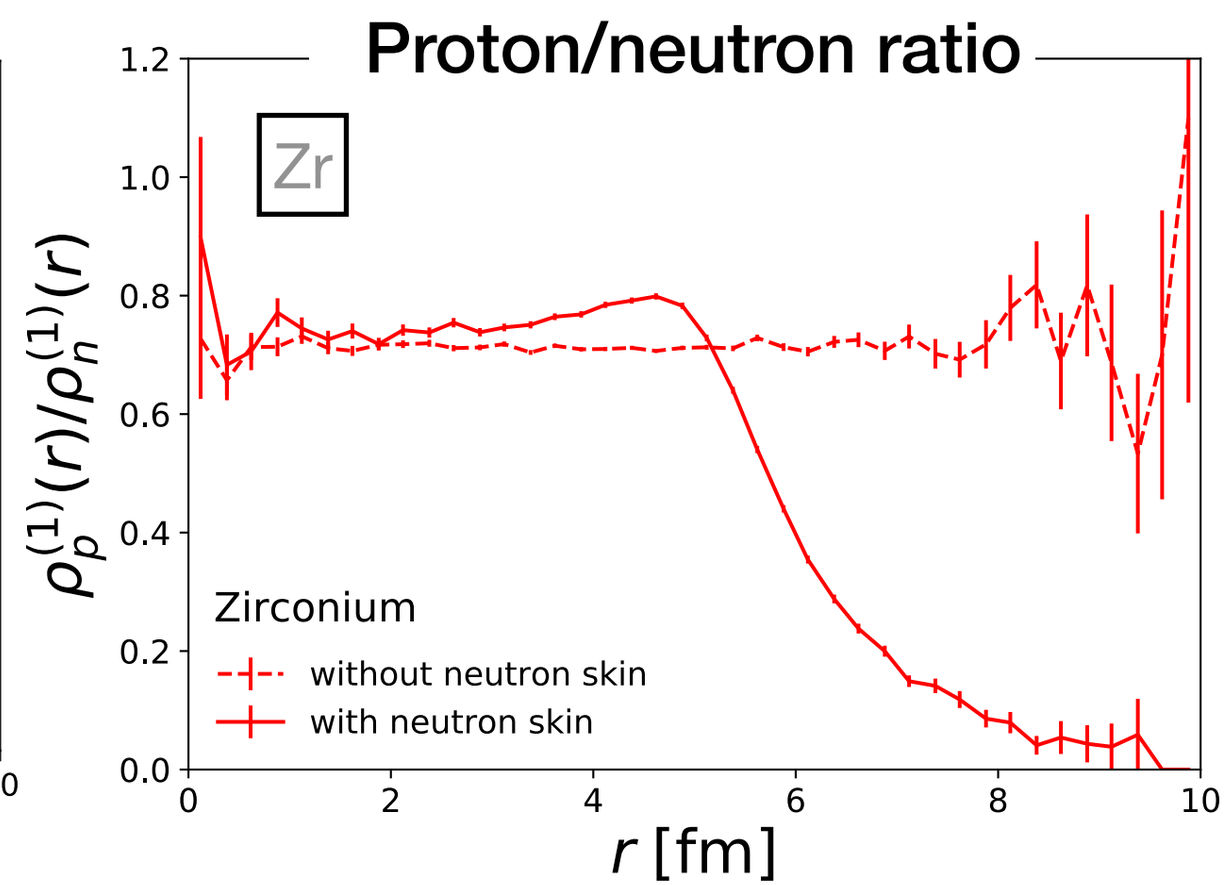
$\boxed{\Delta r_{np} = 0 \text{ for } {}_{44}\text{Ru}^{96}}$

Neutron skin: implementation for $_{40}Zr^{96}$

Neutron-halo type i.e. Δr_{np} translates into $d_n > d_p$

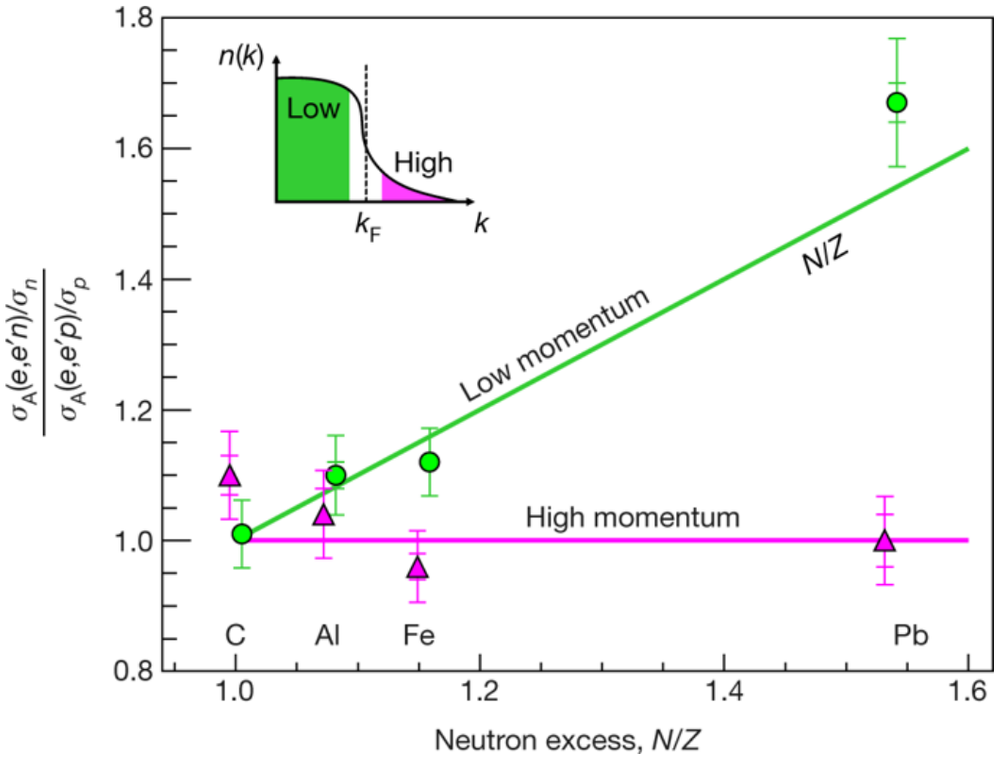
$_{40}Zr^{96}$	
Protons	Neutrons
$R_0 = 5.08$ fm	$R_0 = 5.08$ fm
$d = 0.34$ fm	$d = 0.46$ fm



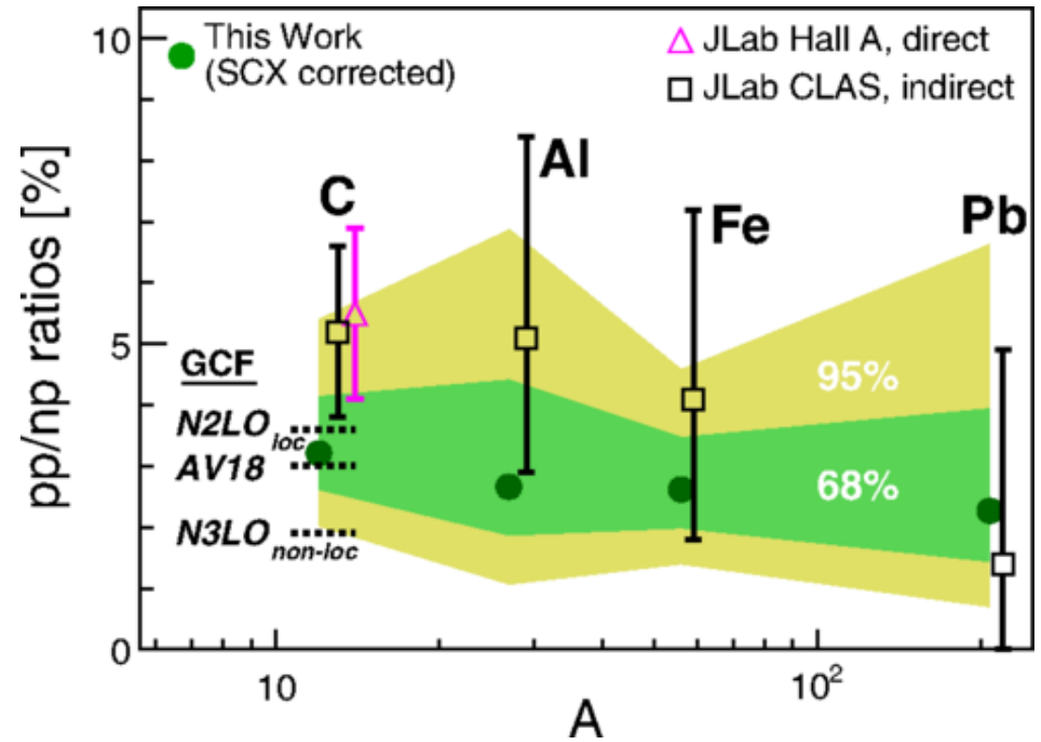


@LHC: [Helenius et al. EPJC 77 (2017), 148]
[Loizides et al. PRC 97 (2018)] [Alvioli et al. arXiv:1811.10078]

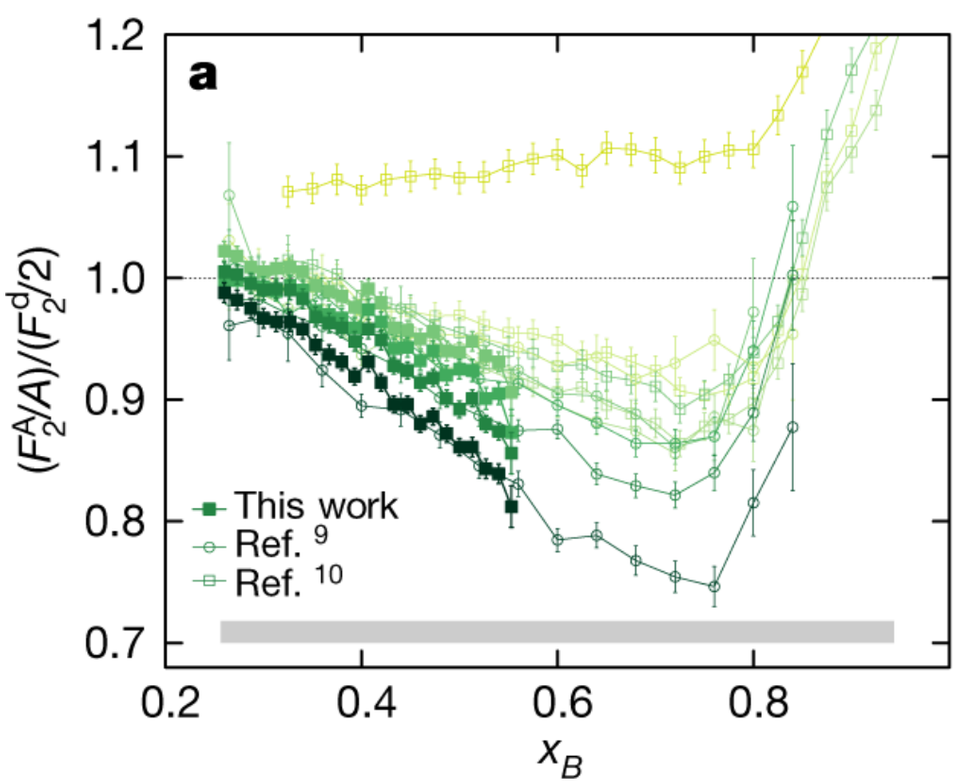
Short-range nucleon-nucleon correlations

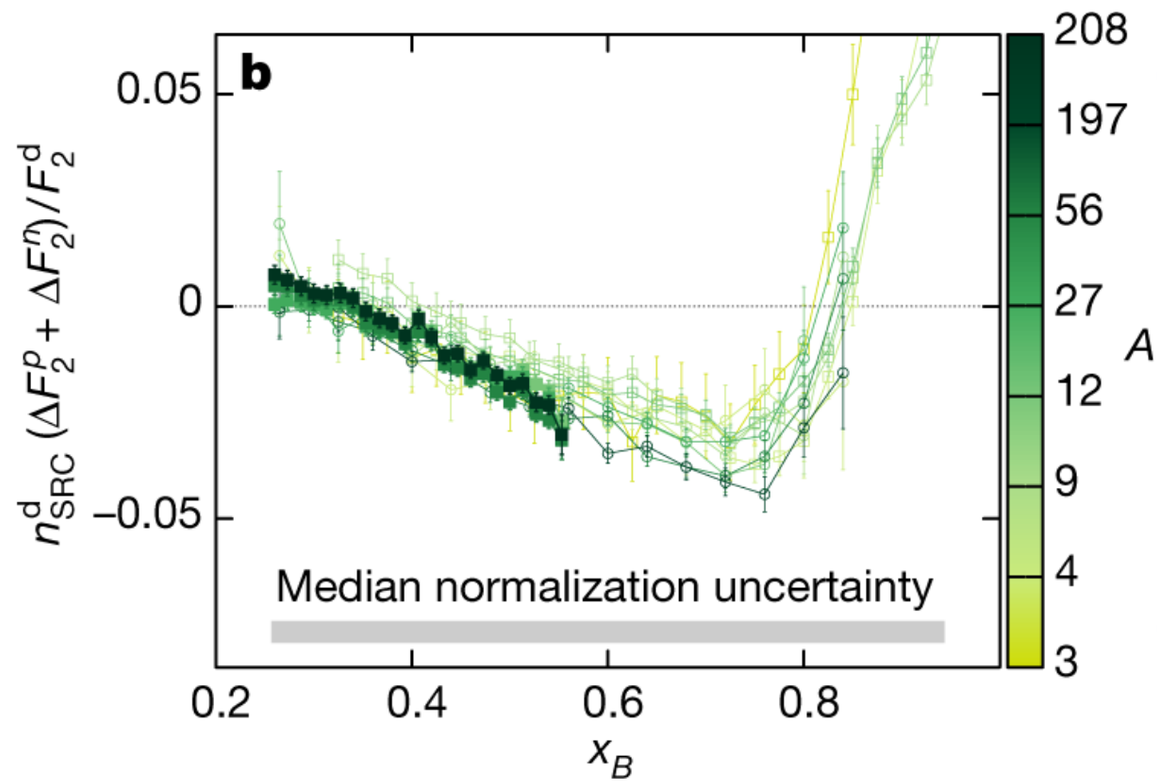


[CLAS Collab Nature 560,2018]



[CLAS Collab PRL 122, 172502 (2019)]





[CLAS Collab Nature 566,2019]

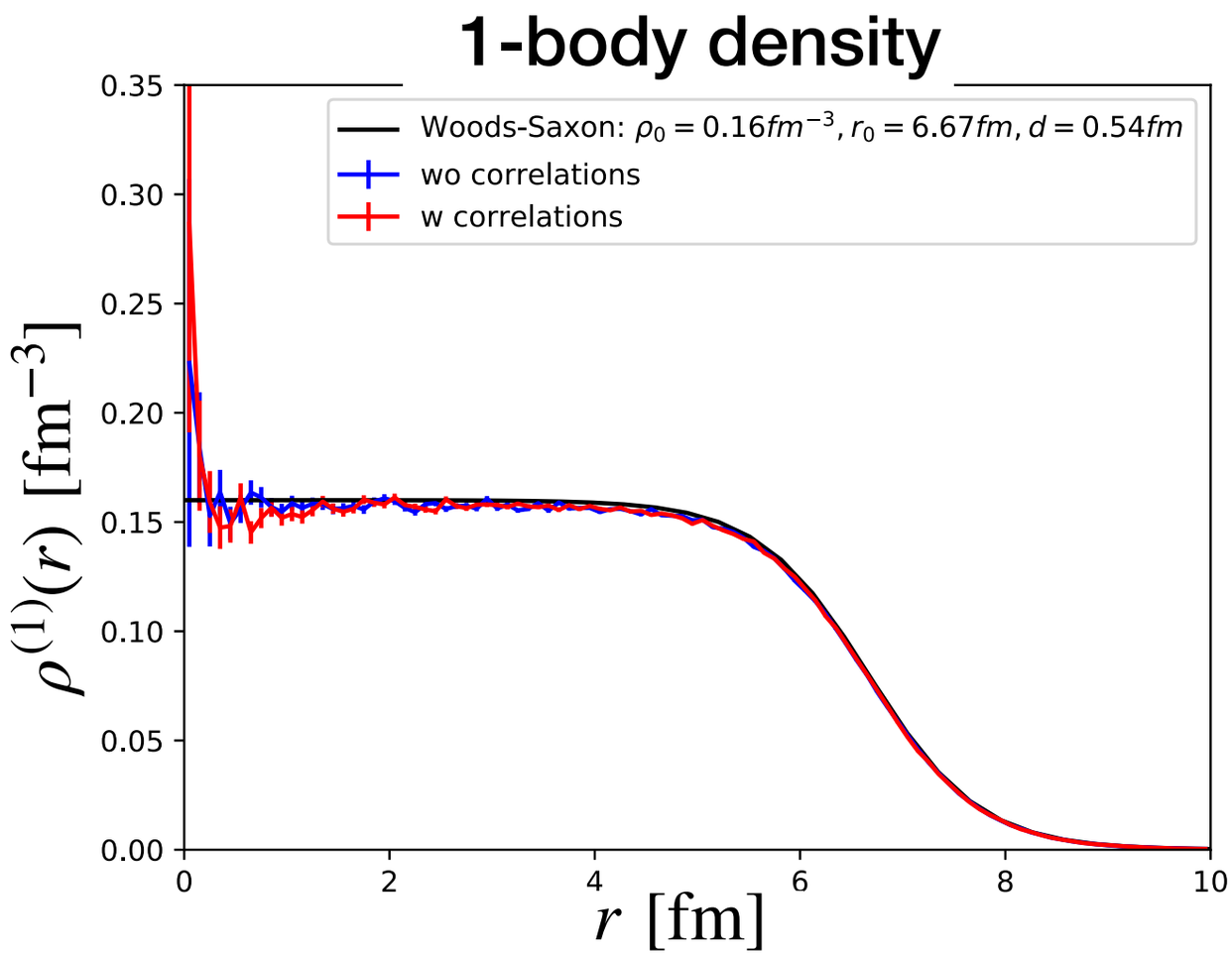
Short-range nucleon-nucleon correlations

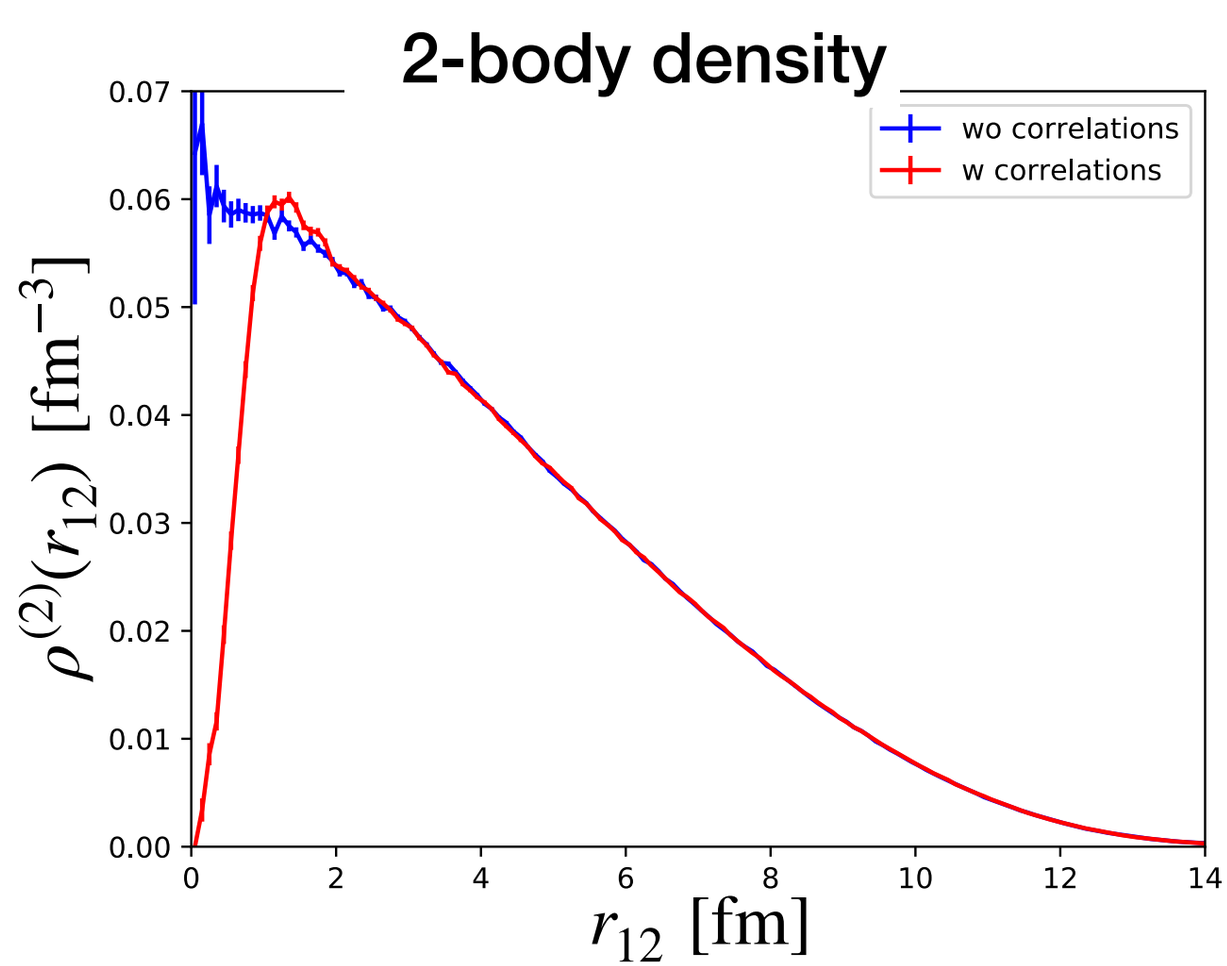
Metropolis Monte Carlo generator of nuclear configurations using
[Alvioli et al. PLB 680 (2009]

$$\Psi_0(x_1, x_2, \ldots, x_A) = \hat{F}(x_1, x_2, \ldots, x_A)\phi_0(x_1, x_2, \ldots, x_A)$$

Correlation operator

Mean-field wave function
==Woods-Saxon





Other studies in heavy-ion collisions: [http://inspirehep.net/author/profile/M.Alvioli.1]

Nuclear configurations for isobar run

[Jan Hammelmann, ASO, Massimiliano Alvioli, Hannah Elfner, Mark Strikman, arXiv:1908.10231]

	$_{44}Ru^{96}$	$_{40}Zr^{96}$
Deformation	✓	
Neutron skin		✓
NN SRC	✓	✓

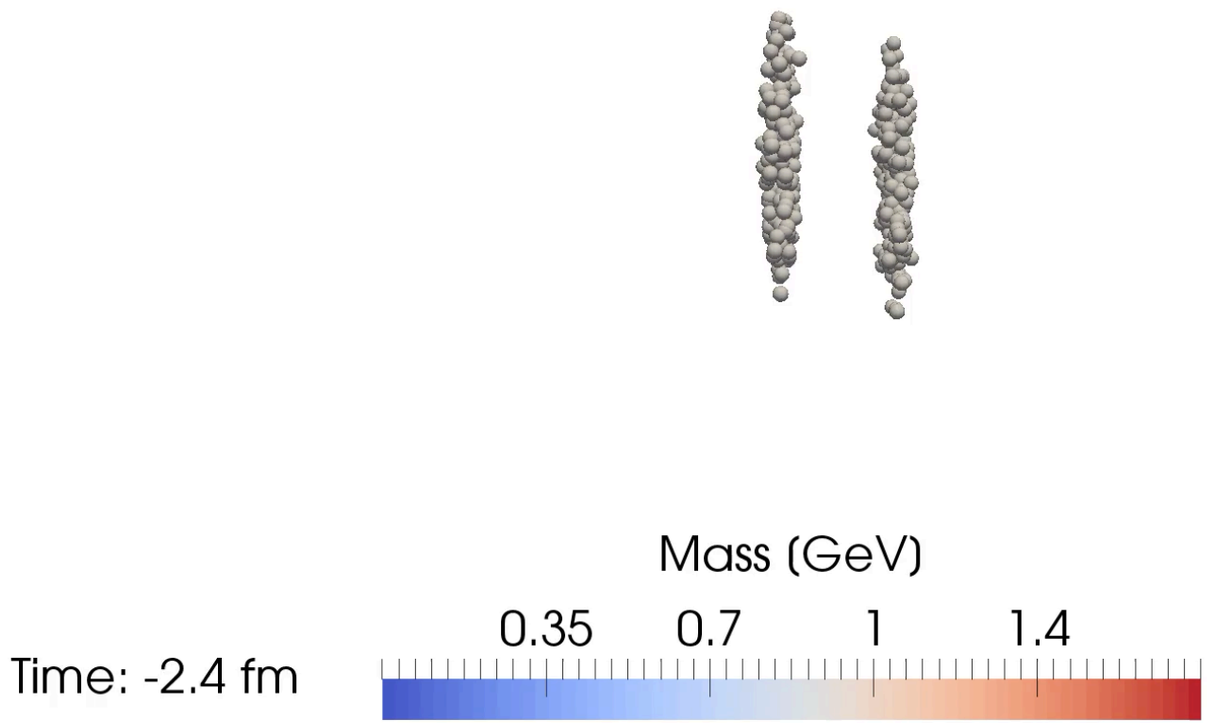
To be compared with “default” Woods-Saxon distribution

Role of deformation and neutron-skin on eccentricity and magnetic field strength

SMASH as a tool [Weil et al. PRC 94 (2016) no.5, 054905]

Relativistic hadronic transport approach available at

https://smash-transport.github.io



smash

^{208}Pb + ^{208}Pb @17.3 GeV By J.Mohs

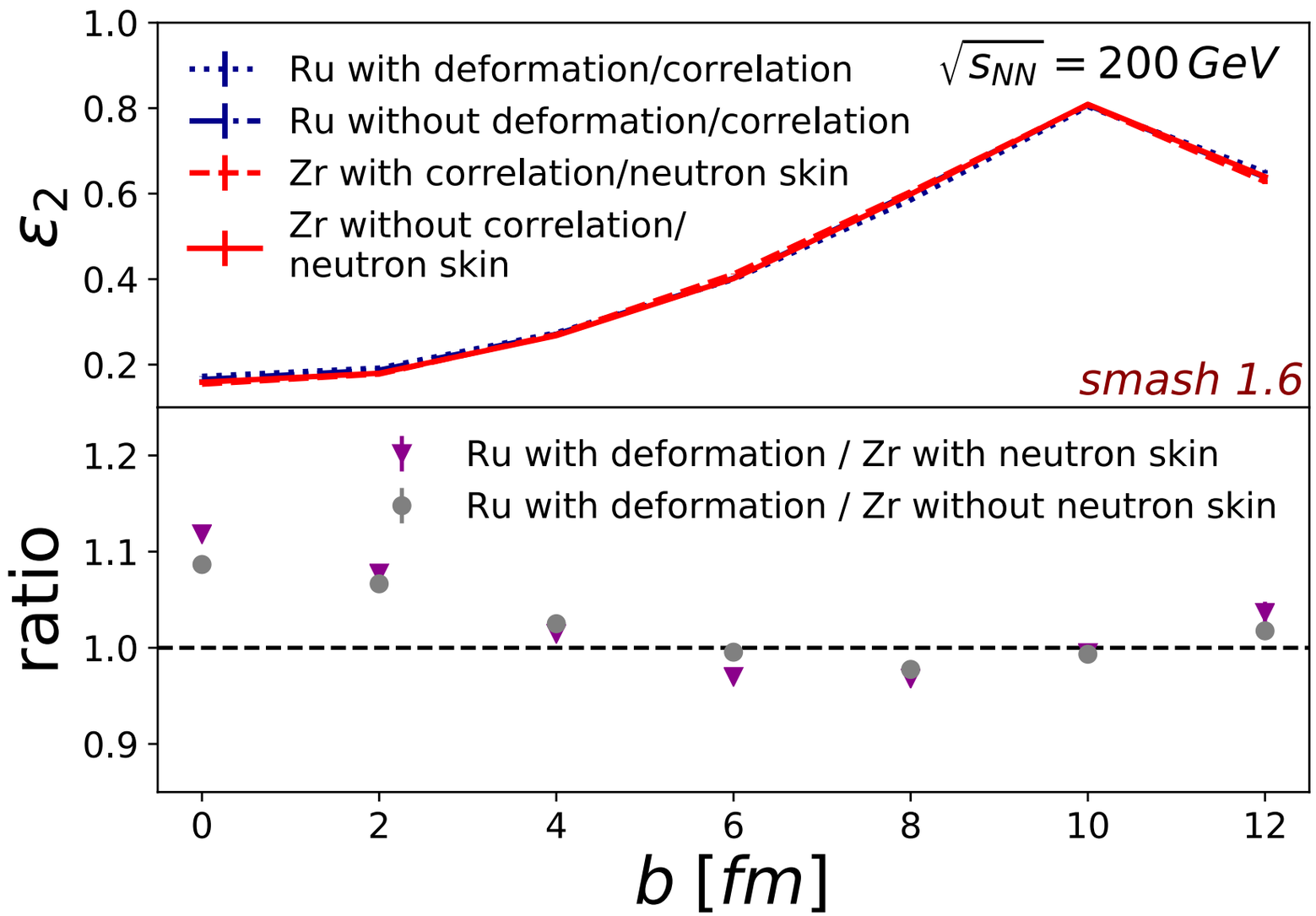
Binary hadron-hadron interactions proceed via string excitation and decay à la PYTHIA 8 [Mohs et al. arXiv:1909.05586]

Eccentricity as a proxy for v_2

Participant eccentricity at the maximum overlap time $t = R/\sqrt{\gamma^2 - 1}$

$_{44}Ru^{96}$

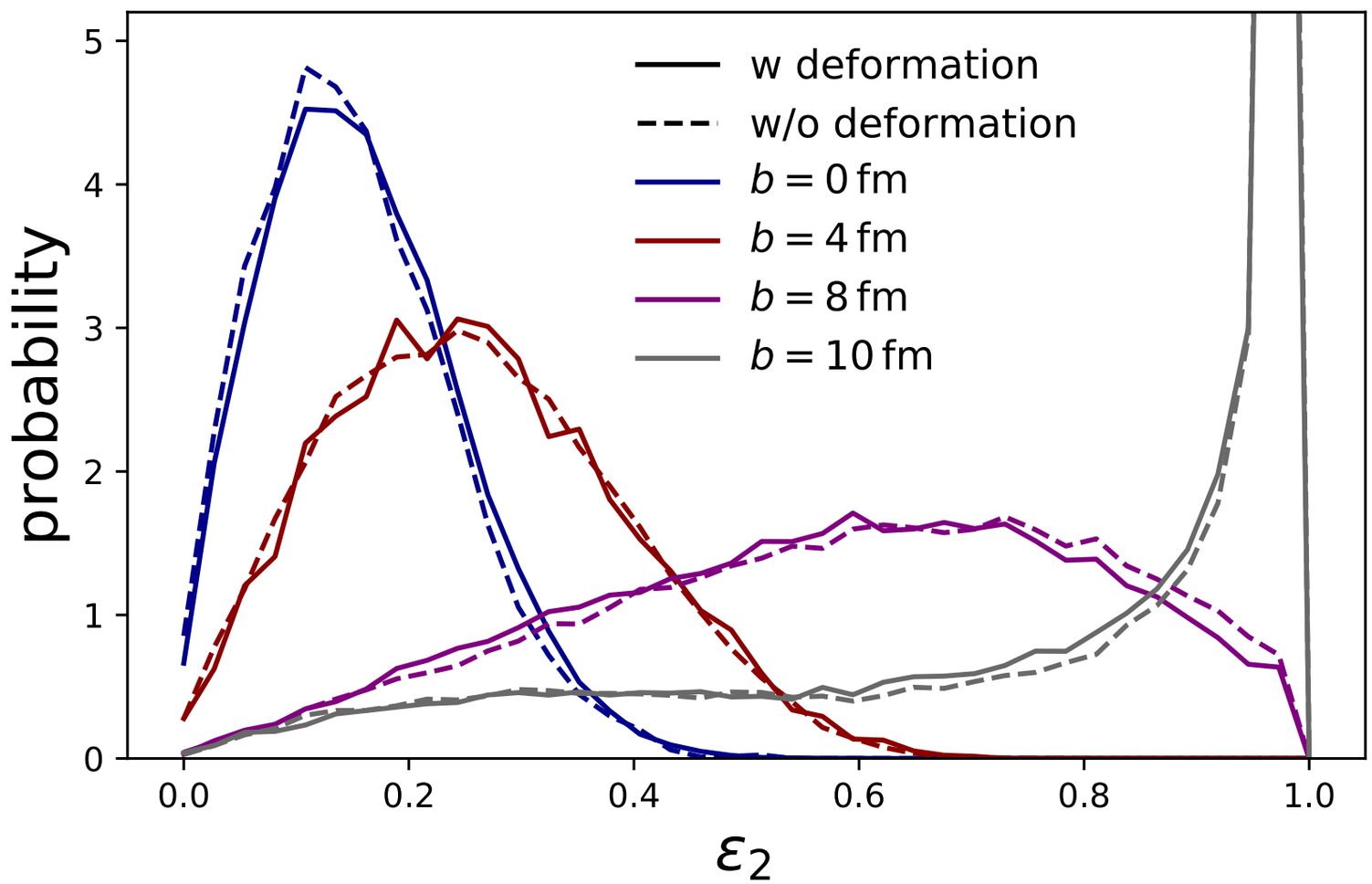
$_{40}Zr^{96}$



Up to 10% difference on background contribution among the isobars in ultra-central collisions

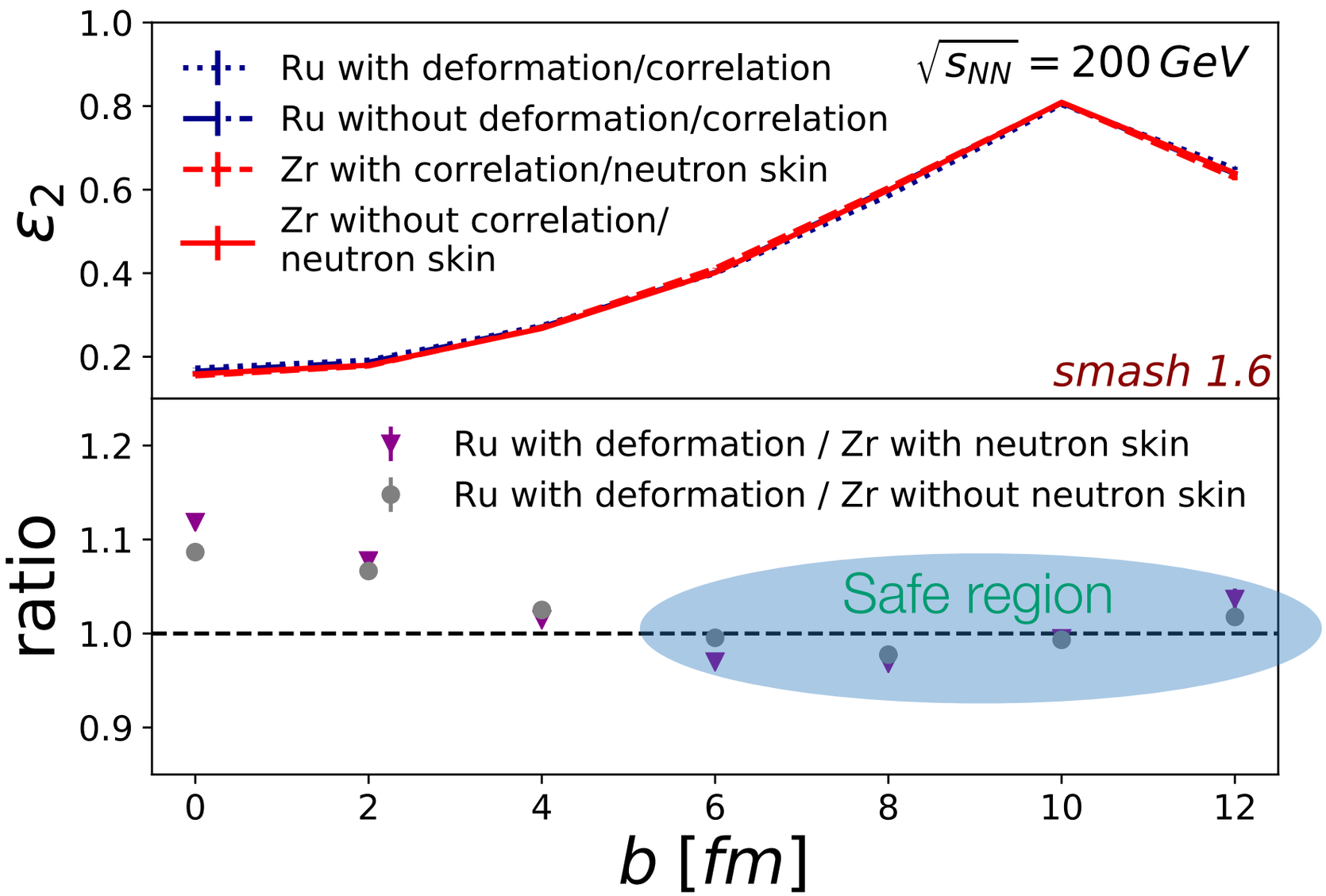
Eccentricity probability distribution

Normalized such that the integral is one



Neat enhancement in ultra-central collisions due to deformation

"…, keeping background (v_2) fixed"

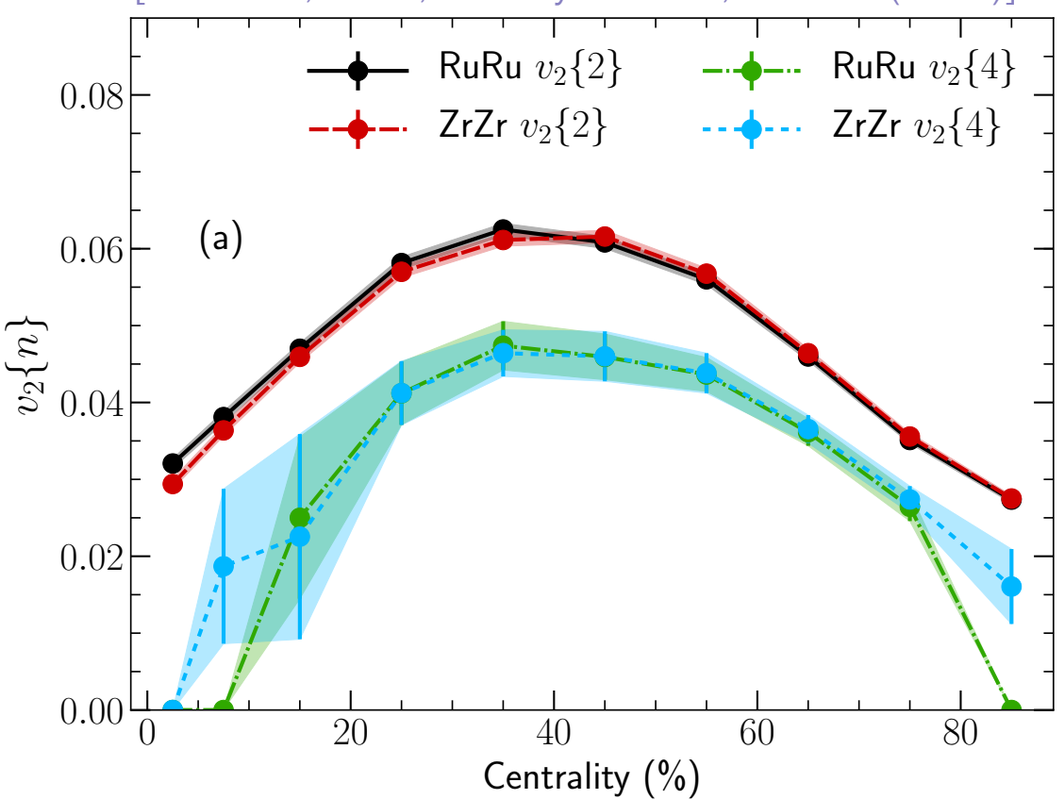


Same background from mid-to-peripheral collisions

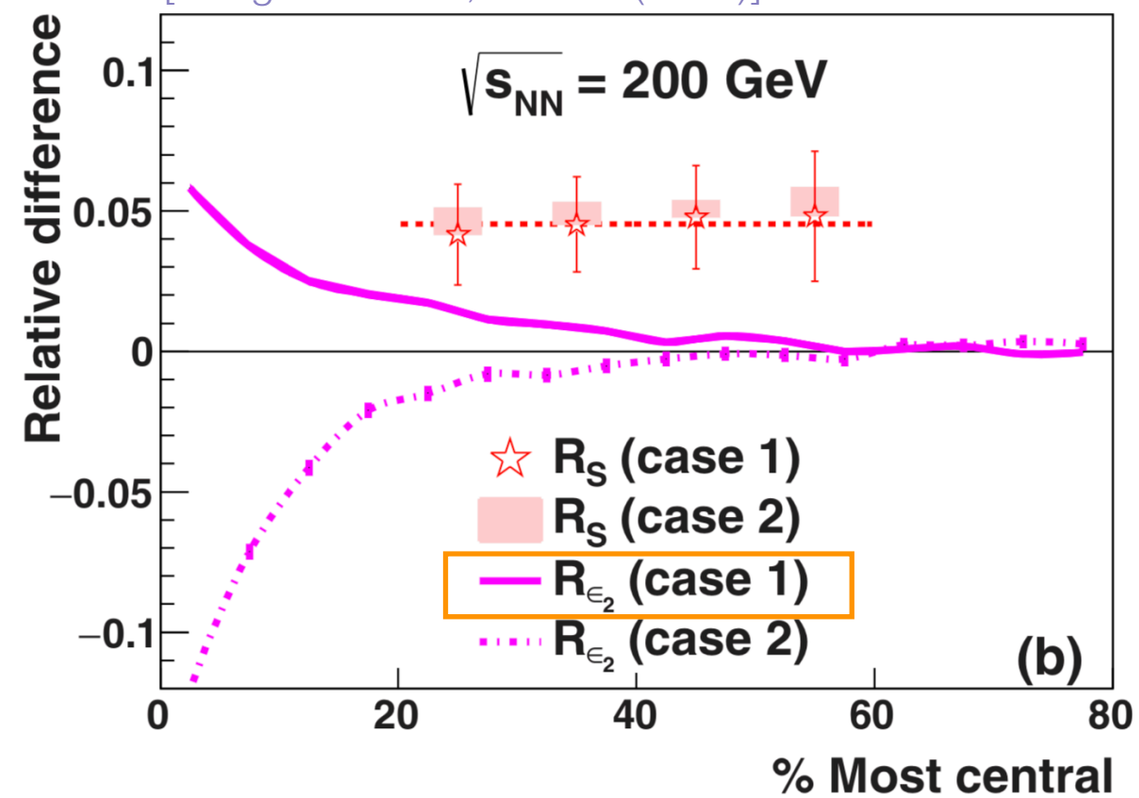
Check with the literature

Our result is in agreement with other models

[Schenke, Shen, Tribedy PRC 99, 044908 (2019)]



[Deng et al. PRC, 041901 (2016)]



Not sufficient to select the same centrality bin in both event samples to ensure identical background

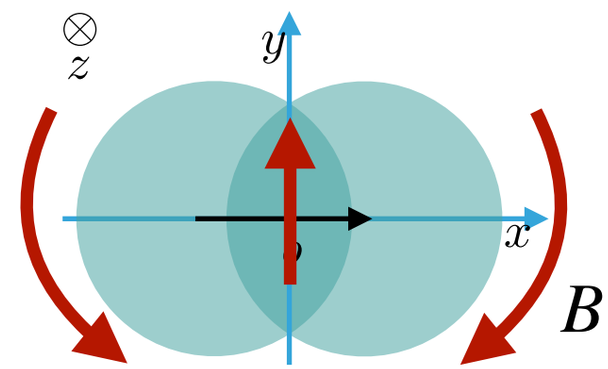
Magnetic field

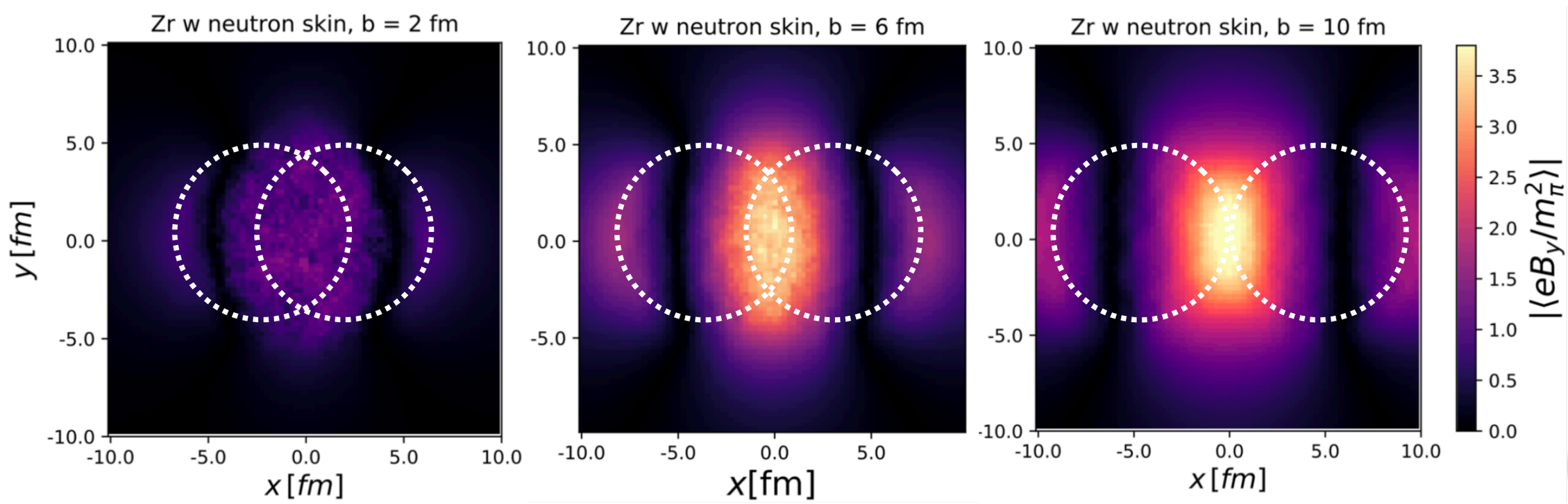
[Wiechert, Annalen der Physik, vol. 309, 4, pp.667-68 (1901)]
[Lienard, L'éclairage électrique 16, 5-14 (1898)]

Event-by-event calculation via Lienard-Wiechert retarded potentials

$$e\vec{B}(t,\vec{r}) = \alpha_{\mathrm{EM}} \sum_n \frac{(1-v_n^2)(\vec{v}_n \otimes \vec{R}_n)}{R_n^3[1-(\vec{R}_n \otimes \vec{v}_n)/R_n^3]^{3/2}}$$

- $\sum_n$: charged particles
- $\vec{R}_n(t) = \vec{r} - \vec{r}_n(t)$: observation point
- $\vec{v}_n$: velocity



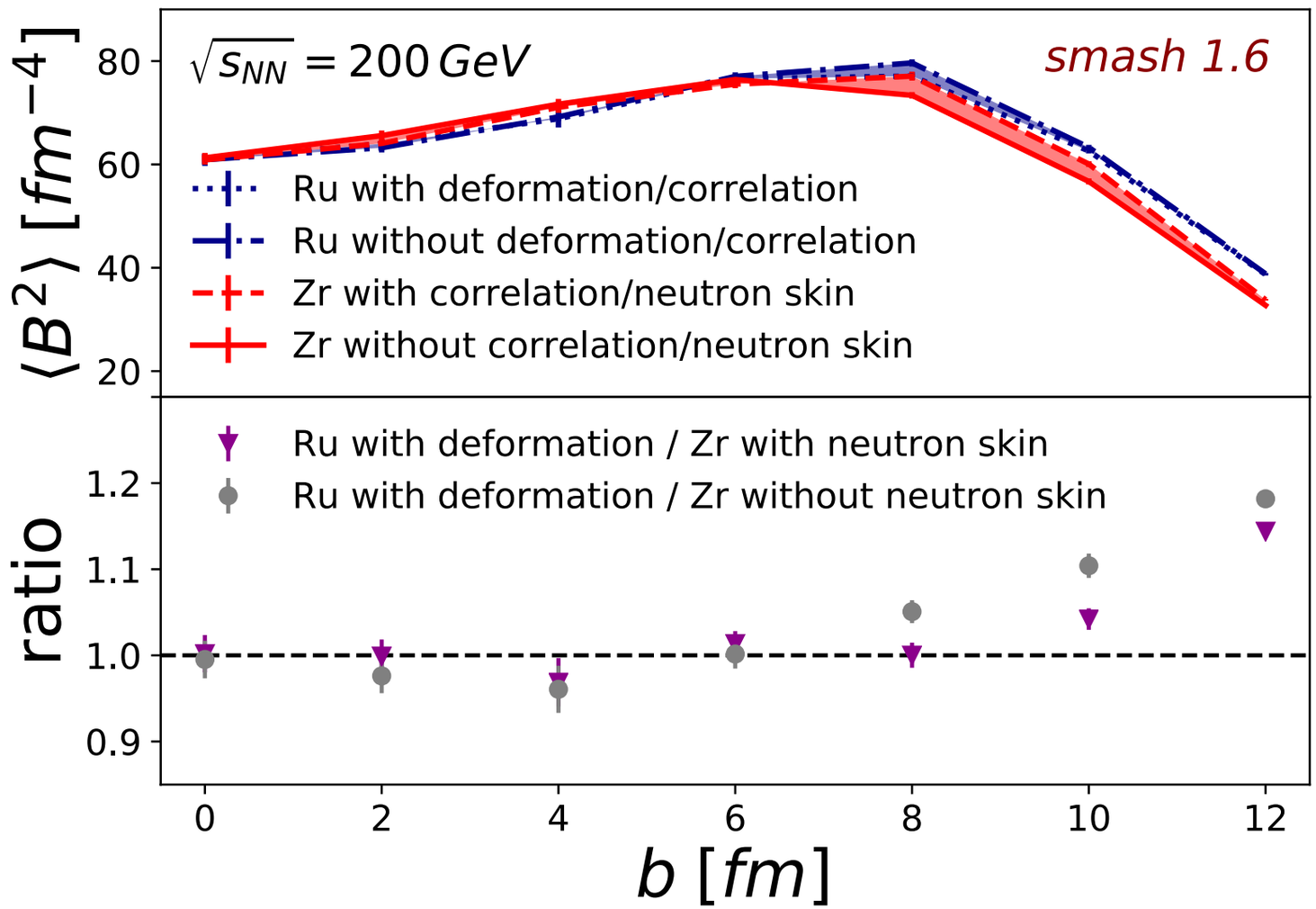


Magnetic field strength

Magnetic field strength computed at the center of the collision

$_{44}Ru^{96}$

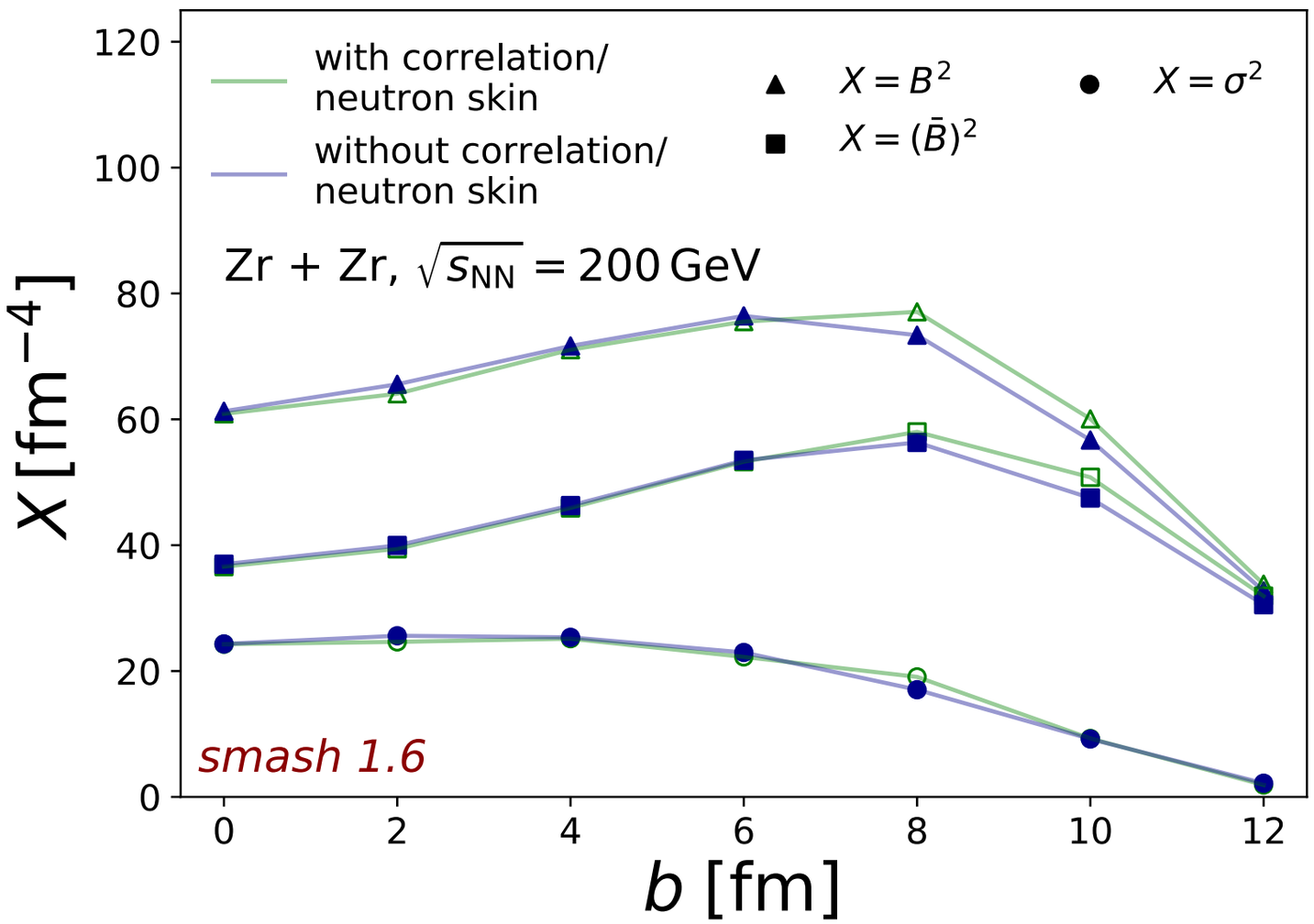
$_{40}Zr^{96}$



Concentration of protons in the nucleus core leads to a higher magnetic field in peripheral collisions

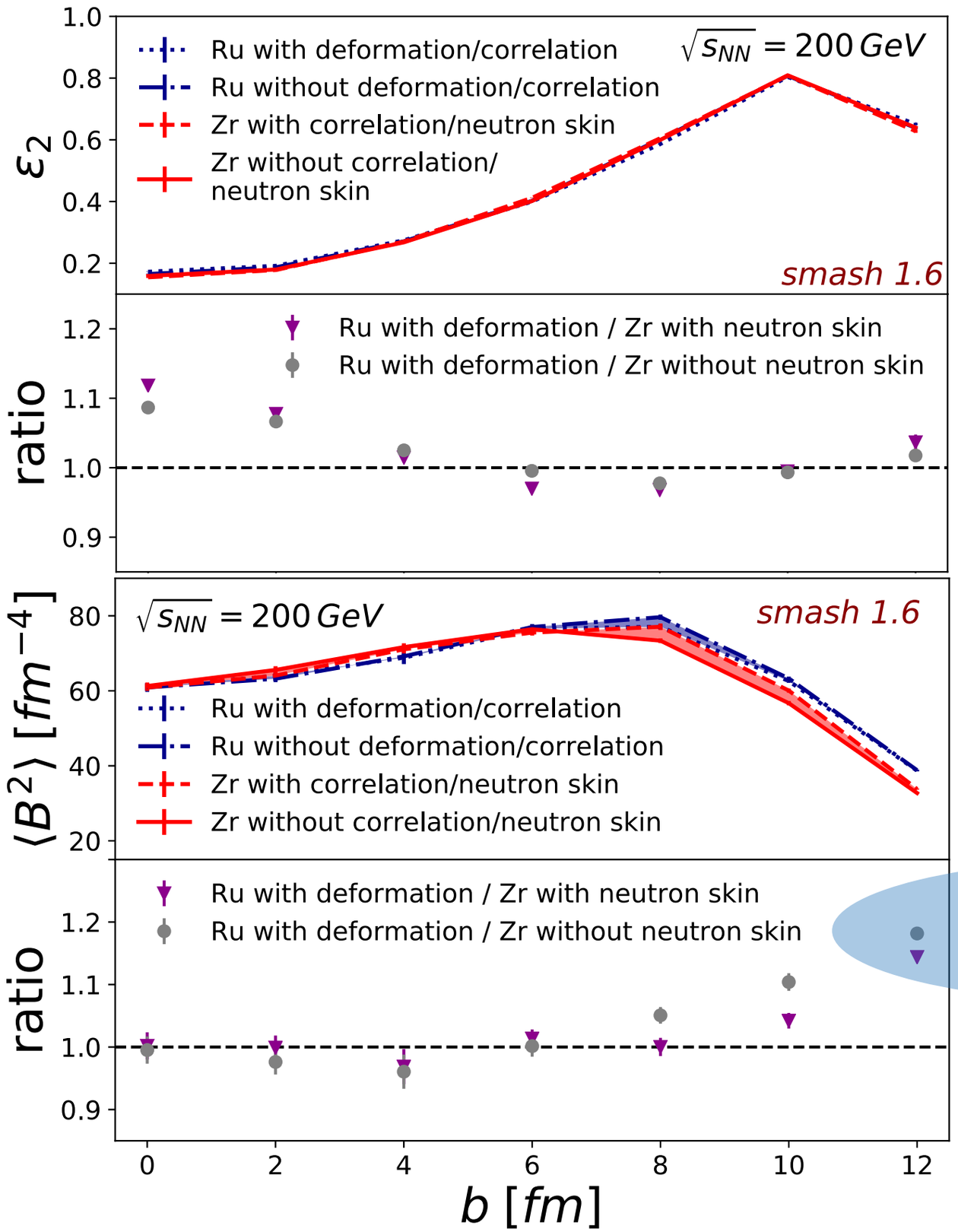
Origin of the enhancement

$$B^2 = \langle B \rangle^2 + \sigma^2$$



Not an effect of a larger degree of fluctuations

“Change signal (B), keeping background (v_2) fixed”



Safe region