

Probing ^{48}Ca neutron skin measurement capabilities at the LHC

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24. September 2026

In collaboration with: You Zhou, Giuliano Giacalone, Pepijn Demol, and more
EMMI Workshop: Light-ion Collisions 2026



European Research Council

Established by the European Commission

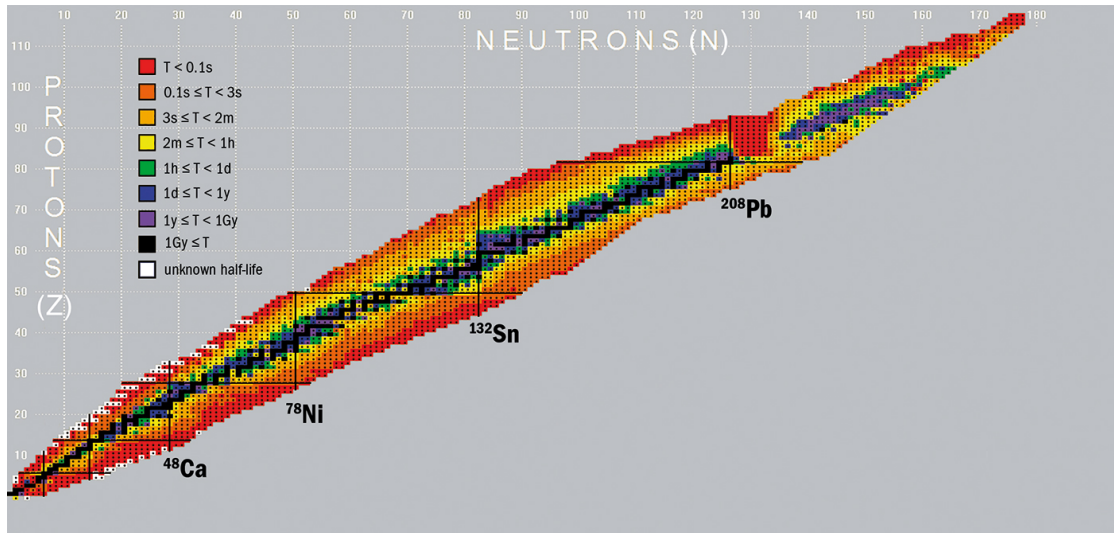
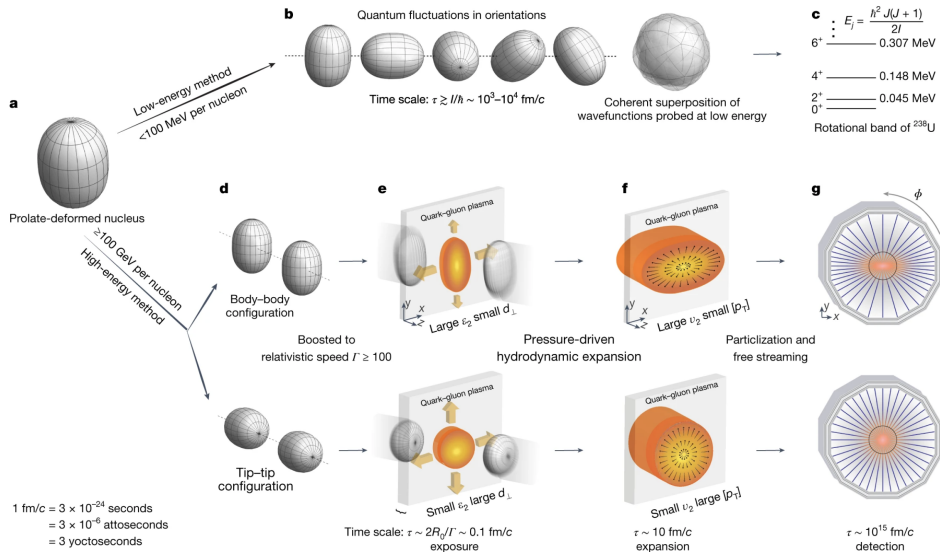


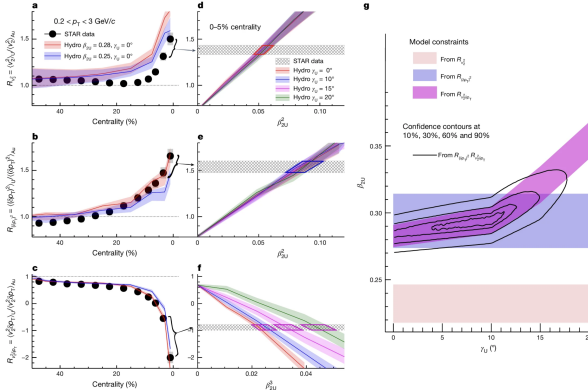
Figure from CERN Courier: <https://cerncourier.com/a/exploring-nuclei-at-the-limits/>

NUCLEAR STRUCTURE IN ULTRA-RELATIVISTIC COLLISIONS

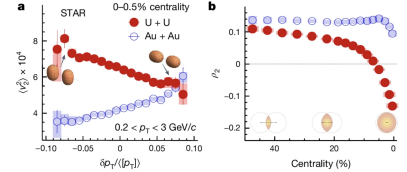


<https://www.nature.com/articles/s41586-024-08097-2/figures/1>

STAR Collaboration studied the nuclear structure of ^{238}U with transverse momentum observables at RHIC

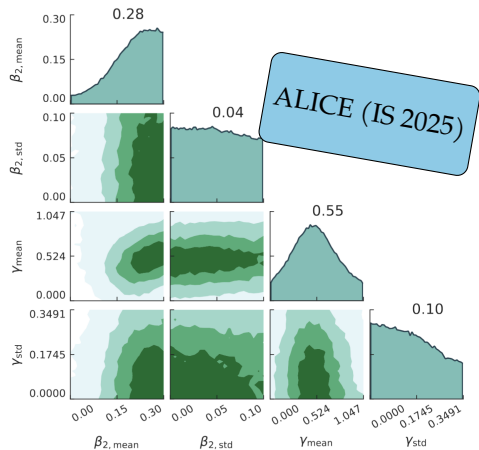


STAR, *Nature* 635 (2024) 8037, 67-72

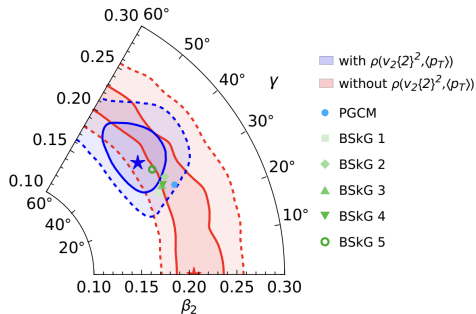


- Utilise transverse momentum correlations in central UU and Au–Au collisions
- Observable ratios to reduce the final-state effects

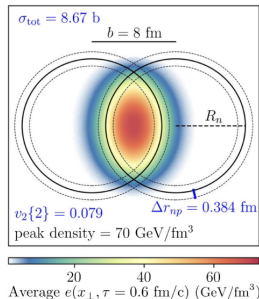
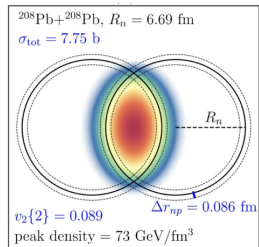
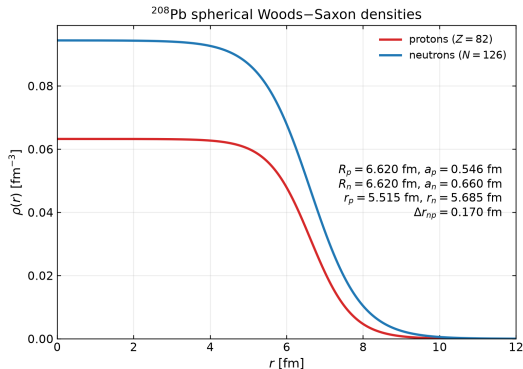
Ultra-relativistic heavy-ion collisions have been used to probe the structure of nuclei



Trajectum, *arXiv* 2606.03993

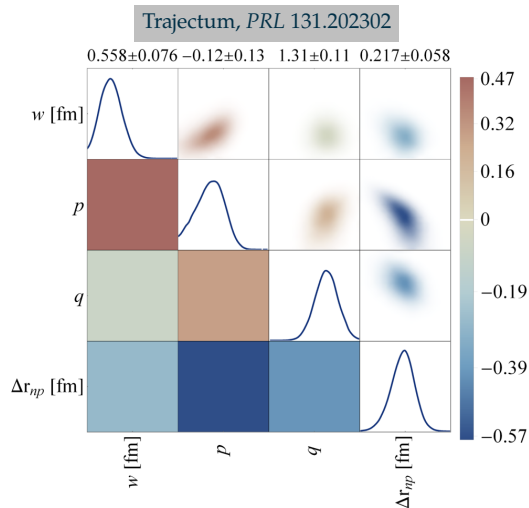
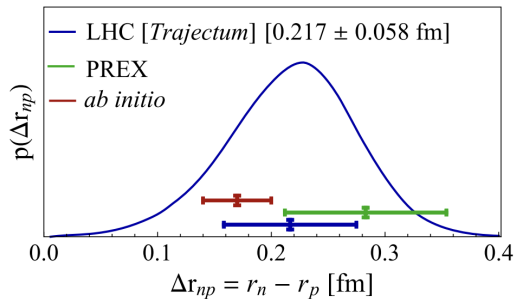


- Neutron-rich nuclei are expected to show larger densities of neutrons at the surface
- This is characterised as a difference in the root-mean-square radii between protons and neutrons

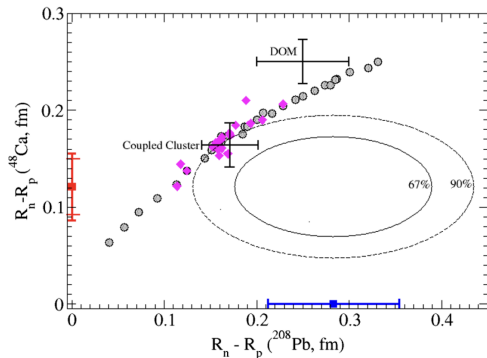


Trajectum, PRL 131.202302

- The Trajectum collaboration extracted the neutron skin of ^{208}Pb with Bayesian inference
- Utilising various heavy-ion collision observables such as $\langle p_T \rangle$ and flow harmonics
- PREX, *PRL* 126.172502 ^{208}Pb neutron skin is 0.283



- The CREX collaboration measured the ^{48}Ca neutron skin with parity-violating electron scattering
- CREX ^{48}Ca neutron skin is 0.121



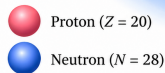
CREX, PRL 129.042501

^{48}Ca

$Z = 20$

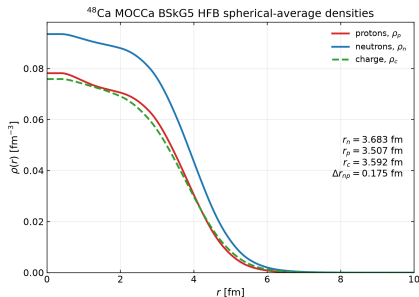
$N = 28$

Neutron skin
(excess neutrons
extending further out)



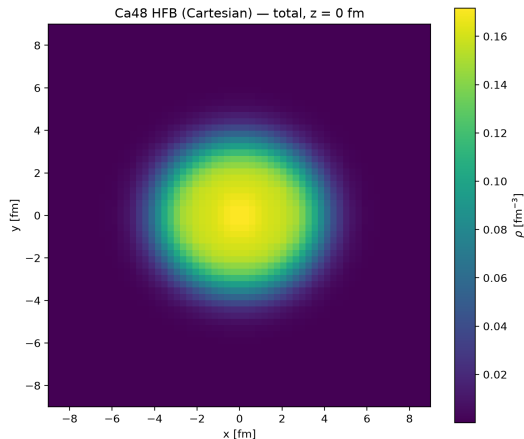
HOW TO PROBE ^{48}Ca NEUTRON SKIN IN HIC?

- 1 Sample nucleons positions (Woods-Saxon or first principle densities)
- 2 Evaluate initial energy/entropy distribution (Trento model)
- 3 Carry out hydro simulation (VISH 2+1D)
- 4 Calculate and compare final-state observables



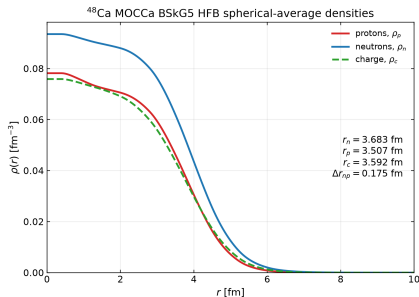
Plotted with calculations provided by Pepijn Demol and Wouter Ryssens based on

W. Ryssens, *et. al EPJA* 58 (2022) 12, 246



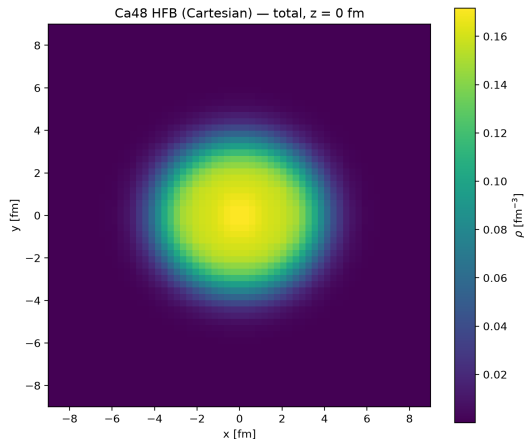
HOW TO PROBE ^{48}Ca NEUTRON SKIN IN HIC?

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- 2 Evaluate initial energy/entropy distribution (Trento model) **initial-state observables**
- 3 Carry out hydro simulation (VISH 2+1D)
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Plotted with calculations provided by Pepijn Demol and Wouter Ryssens based on

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- Use BSkG5 mean-field densities by Pepijn
- Compare with WS fit of the same densities
- Probe whether WS R_n or a_n is more sensitive to the neutron skin effect

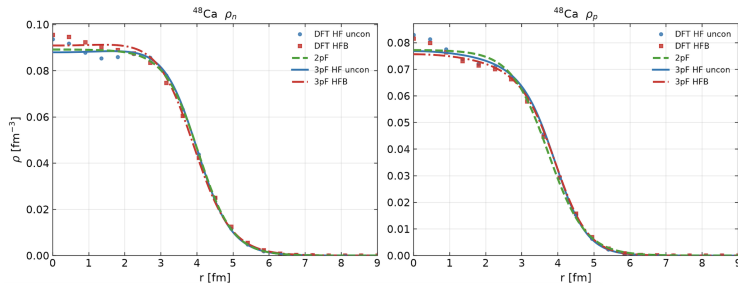
$$\rho_{\text{WS}} = \rho_0 \frac{1 + w \frac{r^2}{R_n^2}}{1 + e^{\frac{r-R_n}{a_n}}}$$

Neutron skins

- DFT HF = 0.167
- DFT HFB = 0.178
- 3pF HF = 0.164
- 3pF HFB = 0.160

Two density profiles used:

- 1 Unconstrained Hartree-Fock (spherical)
- 2 Constrained Hartree-Fock-Bogoliubov (triaxial deformation)

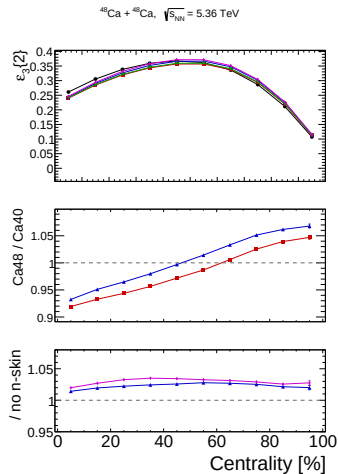
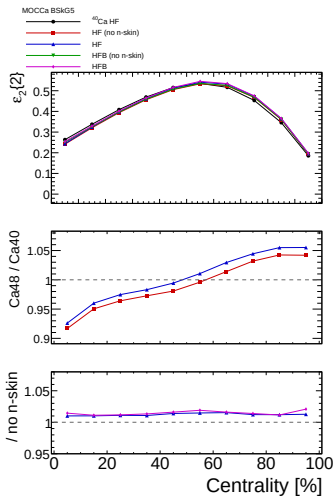


WHAT IS SEEN IN THE INITIAL STATE?

- Using mean-field densities
 - Unconstrained HF
 - Constrained HFB
- Different trends between ^{40}Ca and ^{48}Ca
- The effect of neutron skin is minimal in ε_2 but becomes stronger in ε_3

Neutron skins

- DFT HF = 0.167
- DFT HFB = 0.178



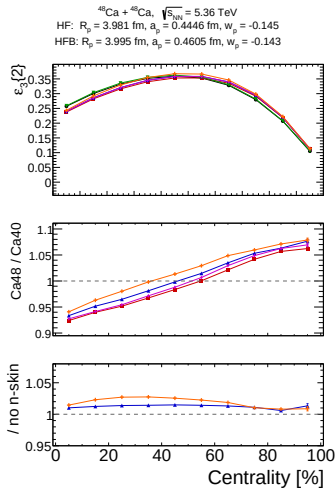
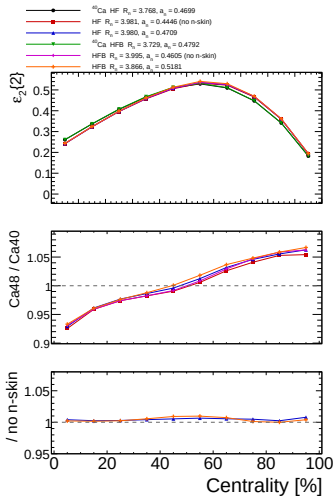
- Using 3-parameter WS fit

$$\rho_{WS} = \rho_0 \frac{1 + w \frac{r^2}{R_n^2}}{1 + e^{\frac{r-R_n}{a_n}}}$$

- With the fits HFB fit has larger change of diffuseness between proton and neutrons
- Diffuseness seem to play more important role in neutron skin

Neutron skins

- 3pF HF = 0.164
- 3pF HFB = 0.160

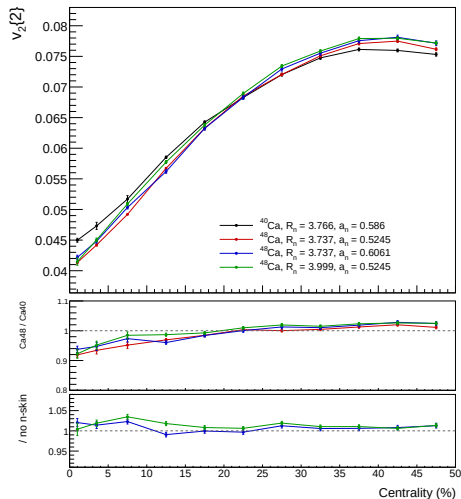


Employ full hydro simulation
Trento + VISH (2+1D) + UrQMD
Use 3pF charge density from

H. De Vries, *et. al Atom.Data Nucl.Data Tabl.* 36 (1987) 495-536

$$\rho_{WS} = \rho_0 \frac{1 + w \frac{r^2}{R_n^2}}{1 + e^{\frac{r-R_n}{a_n}}}$$

- Neutron skin of 0.171 is obtained by varying R_n and a_n separately
- Stronger dependence in observables is seen when varying a_n
- Diffuseness **plays** more important role in neutron skin

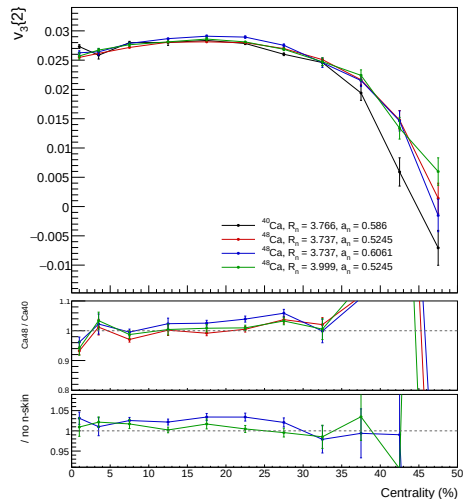


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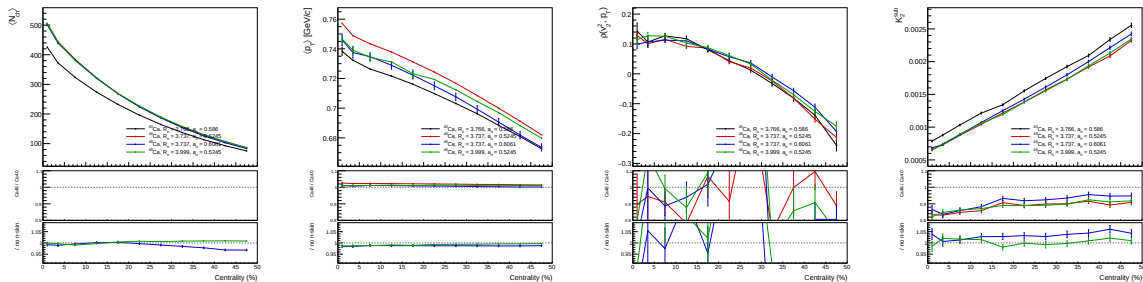
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$$\rho_{WS} = \rho_0 \frac{1 + w \frac{r^2}{R_n^2}}{1 + e^{\frac{r-R_n}{a_n}}}$$

- Neutron skin of 0.171 is obtained by varying R_n and a_n separately
- Stronger dependence in observables is seen when varying a_n
- Diffuseness **plays** more important role in neutron skin



- Many more observables can be included to get better sensitivity to the neutron skin
- Current results with 15M simulated collisions are not enough for higher-order observables
- Note: 10 h of Ne–Ne data gave 400 M minimum bias events at ALICE

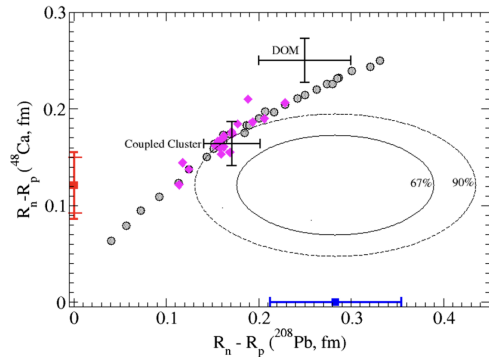


RED Graph: no neutron skin

BLUE Graph: neutron skin

GREEN Graph: neutron skin

- With a few fills of ^{40}Ca and ^{48}Ca , one can probe the neutron skin effect at the LHC
- A few per cent difference between with and without neutron skin can be picked up by Bayesian analyses
- Enhance the effect of neutron skin and reduce systematic uncertainties with ratios to ^{40}Ca
- Together with ^{208}Pb data, one can really probe the discrepancy between PREX and CREX measurements



THANK YOU!

BACKUP

