Determination of the neutron skin of ^{208}Pb from ultrarelativistic nuclear collisions

Govert Nijs

September 6, 2023

Based on:

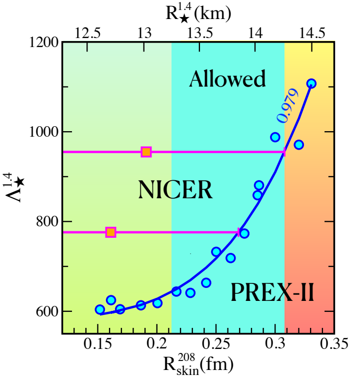
- Giacalone, GN, van der Schee, 2305.00015

Neutron skin

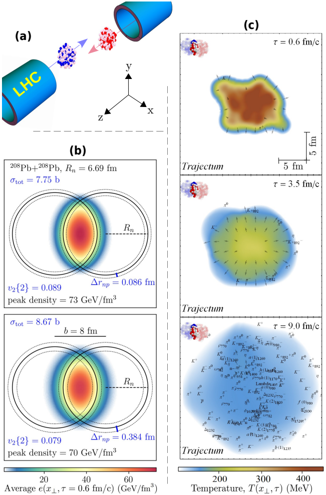
- In a ^{208}Pb nucleus, neutrons sit further from the center than protons.
  - This is quantified by the *neutron skin*:

$$\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2},$$

    i.e. the *difference* in RMS radii of the neutron and proton distributions.
- Heavy nuclei and neutron stars are sensitive to the same nuclear interactions.
  - A constraint on Δr_{np} translates directly into a constraint on the radius of a $1.4 M_\odot$ neutron star.
  - We can learn something about the low T, high μ_B region even at LHC energies!



How to measure neutron skin?

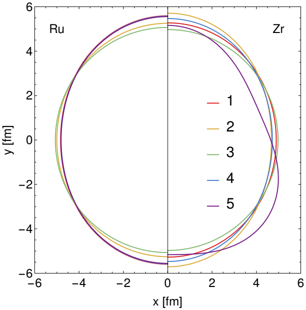


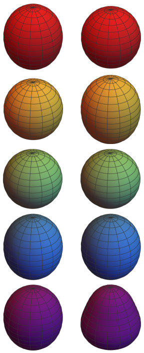
- To measure the neutron skin, we need the distributions of protons and neutrons inside the nucleus.
  - The proton distribution distribution is well-known from electron scattering.
- Several different methods are in use for the neutron distribution:
  - Polarized electron scattering off ^{208}Pb (PREX).
  - Photon tomography of ^{197}Au (STAR).
- Heavy ion collisions provide a completely orthogonal method.
  - Sensitive to the total matter distribution inside the nucleus.
  - Purely gluonic measurement.

[Giacalone, GN, van der Schee, 2305.00015; STAR, 2204.01625; PREX, 2102.10767]

Effects of nuclear structure on soft observables

- The STAR isobar run sparked great interest in nuclear structure in heavy ion collisions.
    - Originally intended to measure the chiral magnetic effect.
- Differences in the shapes of ${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr lead to differences in soft observables.
    - We can distinguish several possibilities for the shapes of ${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr, with model 5 giving the best agreement.
    - Isobar nature of ${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr leads to robust ratios insensitive to details of hydrodynamics.





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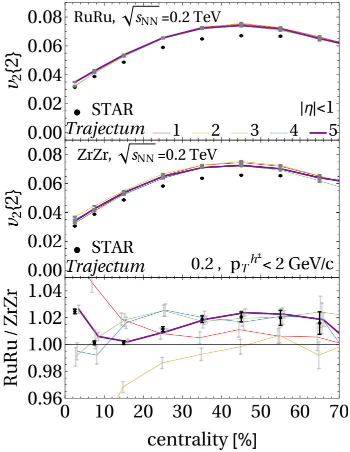

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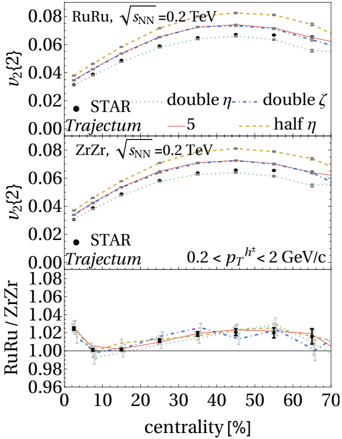
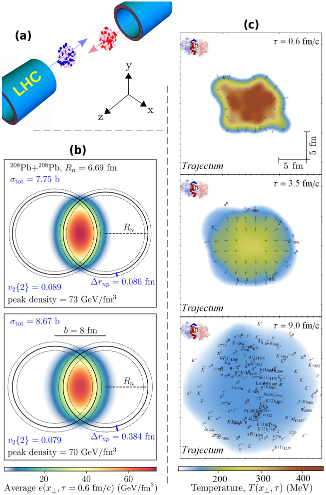


Can we see nuclear structure without isobars?

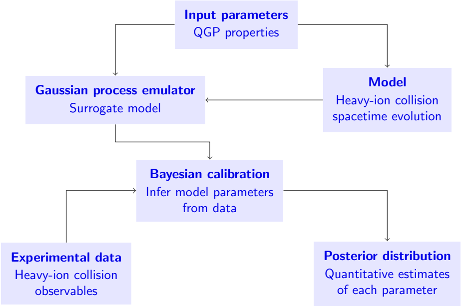


- The isobar run was particularly sensitive to nuclear structure, because other effects approximately cancel in the ratio.
- PbPb collisions at LHC energies however are not paired with anything close in mass.
- Extraction of the ^{208}Pb neutron skin from PbPb collisions alone will need to distinguish nuclear structure effects from the various model parameters.
    - Need Bayesian analysis to perform a systematic fit to take into account such correlations.

[GN, van der Schee, 2112.13771; STAR, 2109.00131]

Bayesian analysis workflow

- In principle, Bayesian analysis is simply a fit to data.
- In practice the process is more complicated:
  - Generate a large number of randomly chosen parameter sets called *design points*.
  - Run the model for each one to obtain the prior.
  - Train the emulator.
  - Run the MCMC to obtain the posterior.
- The posterior then is a list of likely parameter sets.



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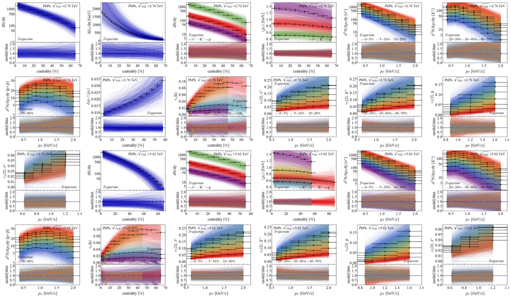

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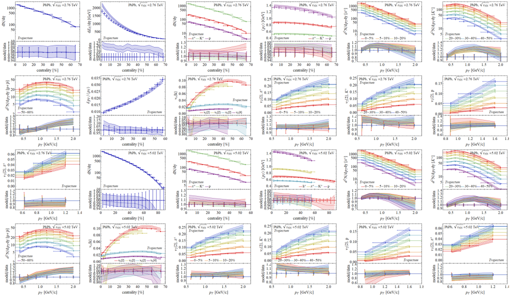

[GN, van der Schee, 2304.06191; Giacalone, GN, van der Schee, 2305.00015]

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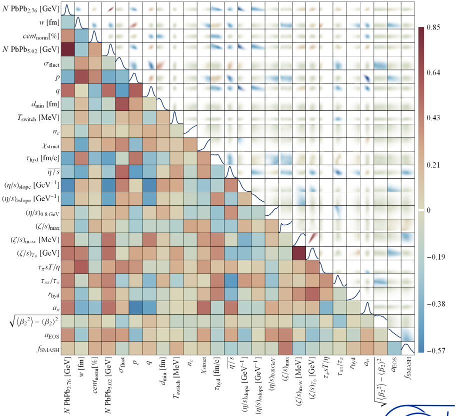
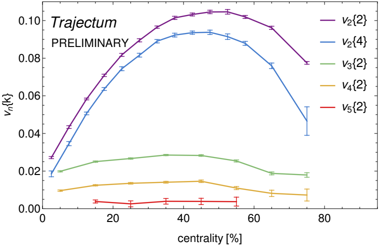


Model used: *Trajectum*

- New heavy ion code developed in Utrecht/MIT/CERN.
  - *Trajectum* is the old Roman name for Utrecht.
- Contains initial stage, hydrodynamics and freeze-out, as well as an analysis suite.
- Easy to use, example parameter files distributed alongside the source code.
- Fast, fully parallelized.
  - Figure (20k oversampled PbPb events at 2.76 TeV) computes on a laptop in 21h.
  - Bayesian analysis requires $\mathcal{O}(1000)$ similar calculations to this one.
- Publicly available at `sites.google.com/view/govertnijs/trajectum/`.



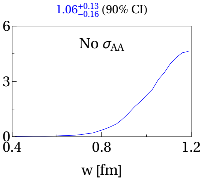
Data used: 670 individual data points

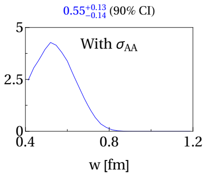
✓: data used 🕓: data exists ✗: data does not exist	PbPb 2.76 TeV incl.	PbPb 2.76 TeV $\pi^\pm$	PbPb 2.76 TeV $K^\pm$	PbPb 2.76 TeV p	PbPb 5.02 TeV incl.	PbPb 5.02 TeV $\pi^\pm$	PbPb 5.02 TeV $K^\pm$	PbPb 5.02 TeV p	pPb 5.02 TeV incl.
σ	✗	✗	✗	✗	✓	✗	✗	✗	✓
dN/dy	✓	✓	✓	✓	✓	✓	✓	✓	🕓
$\langle p_T \rangle$	✗	✓	✓	✓	✓	✓	✓	✓	🕓
$dE_T/d\eta$	✓	✗	✗	✗	✗	✗	✗	✗	✗
$\delta p_T/\langle p_T \rangle$	✓	✗	✗	✗	✗	✗	✗	✗	✗
$v_{2,3,4}\{2\}$	✓	🕓	🕓	🕓	✓	✗	✗	✗	🕓
$v_2\{4\}$	✓	✗	✗	✗	✓	✗	✗	✗	🕓
$d^2N/dp_T dy$	✗	✓	✓	✓	✗	✓	✓	✓	✗
$v_2\{2\}(p_T)$	✗	✓	✓	✓	✗	✓	✓	✓	✗
$v_3\{2\}(p_T)$	✗	✓	🕓	🕓	✗	✓	🕓	🕓	✗
$NSC(2,3)$	🕓	✗	✗	✗	✓	✗	✗	✗	✗
$NSC(2,4)$	🕓	✗	✗	✗	✓	✗	✗	✗	✗
$\rho(v_2\{2\}^2, \langle p_T \rangle)$	✗	✗	✗	✗	✓	✗	✗	✗	✗

[Giacalone, GN, van der Schee, 2305.00015]

Fitting to the pPb and PbPb cross sections

- In the TRENTo model, the nucleon size is described by the Gaussian radius w.
- Previous analyses favored $w \approx 1$ fm.
    - This leads to a 3σ discrepancy in σ_{PbPb}.
- Fitting to the pPb and PbPb cross sections lowers w to 0.6 fm.
    - σ_{PbPb} discrepancy is reduced to 1σ.
    - Many other observables fit slightly worse.
- Smaller width is now compatible with our knowledge of the gluonic structure of the proton at low x.





	σ_{PbPb}[b]	$\sigma_{p\mathrm{Pb}}$[b]
with σ_{AA}	8.02 ± 0.19	2.20 ± 0.06
without σ_{AA}	8.95 ± 0.36	2.48 ± 0.10
ALICE/CMS	7.67 ± 0.24	2.06 ± 0.08

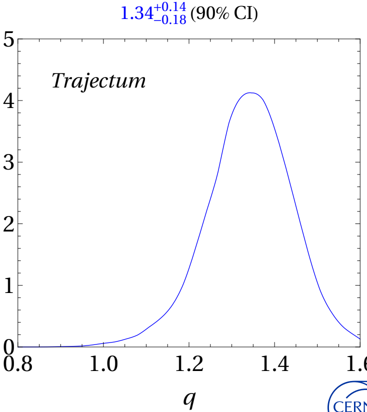
[GN, van der Schee, 2206.13522; ALICE, 2204.10148; CMS, 1509.03893; Caldwell, Kowalski, *Phys. Rev. C* **81** (2010) 025203]

Energy deposition in the initial state

- Nuclear thickness functions $\mathcal{T}_{A/B}$ deposit matter into the initial state energy density $\mathcal{T}$ as follows:

$$\mathcal{T} \propto \left(\frac{\mathcal{T}_A^p + \mathcal{T}_B^p}{2}\right)^{q/p} \overset{p\to 0}{=} (\mathcal{T}_A \mathcal{T}_B)^{q/2}.$$

- Previous analyses implicitly set $q = 1$.
- The fit to experimental data favors $q \approx 4/3$.
  - Previous default $q = 1$ is disfavored.
  - Binary scaling $q = 2$ is ruled out.
  - $q = 4/3$ indicates that $\sqrt{\mathcal{T}_A \mathcal{T}_B}$ behaves like an entropy density.



The Woods-Saxon distribution

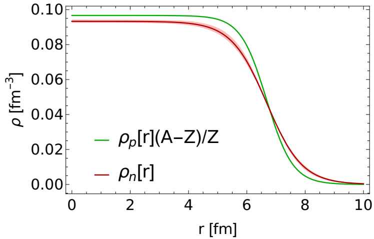
- Nucleon positions are drawn from a Woods-Saxon distribution:

$$\rho_{\mathrm{WS}}(r) \propto \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}.$$

  - We fix R for both protons and neutrons.
  - We fix a for protons, while varying a_n as a parameter.

- Neutron skin $\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$ strongly depends on a_n:

$$\langle r^2 \rangle_{\mathrm{WS}} = \frac{12a^2\,\mathrm{Li}_5\left(-e^{R/a}\right)}{\mathrm{Li}_3\left(-e^{R/a}\right)}.$$



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R [fm]	6.68	6.69
a [fm]	0.447	a_n

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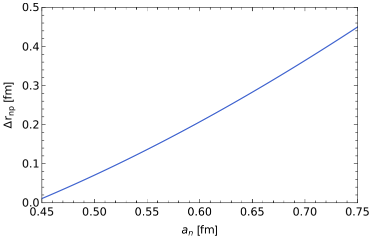

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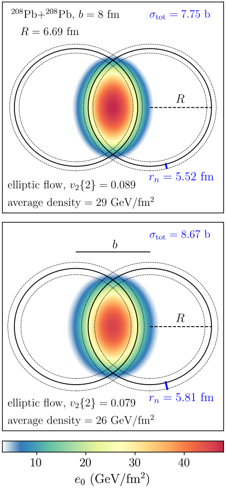
Do we have observables sensitive to a_n?

- Initial geometry is sensitive to a_n. Larger nuclei lead to:
  - Larger hadronic PbPb cross-section,
  - Larger initial QGP size,
  - Smaller initial QGP eccentricity.
- Final state observables are in turn sensitive to initial geometry. Larger Δr_{np} leads to:
  - Larger hadronic PbPb cross-section,
  - Smaller charged particle yield,
  - Smaller mean transverse momentum,
  - Smaller elliptic flow.



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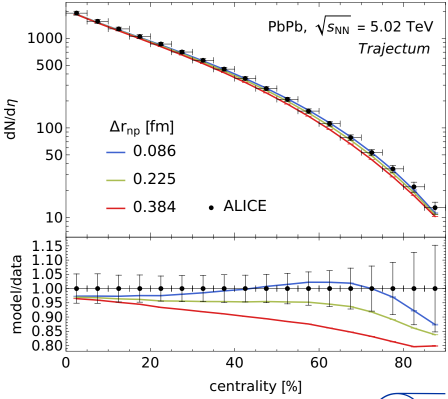

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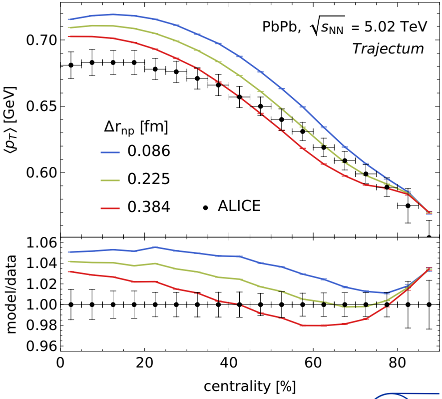

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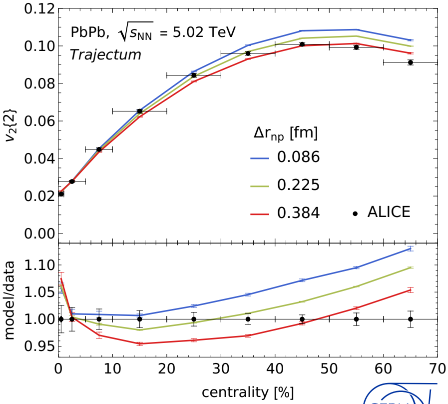
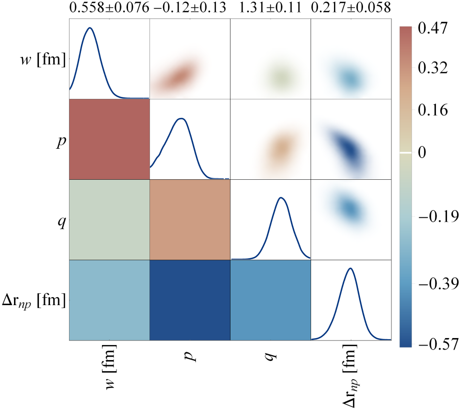


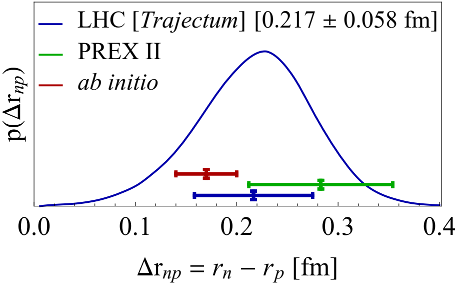
What does a_n correlate with?

- a_n is not the only parameter affecting the initial geometry, leading to correlations. a_n:
  - anticorrelates with p,
  - mildly anticorrelates with both w and q.
- Correlations highlight the importance of global analysis.
- Parameters are not degenerate, allowing us to extract a_n, and with it, Δr_{np}.



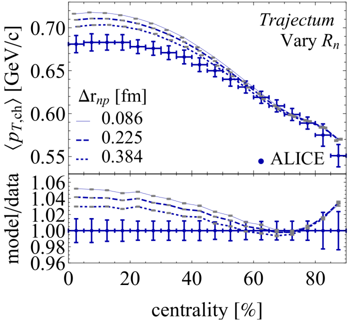
Bayesian analysis result using LHC data

- Resulting posterior for Δr_{np} is compatible with PREX II and ab initio nuclear theory.
- Slightly stronger constraint than PREX II ($\Delta r_{np} = 0.283 \pm 0.071$).
- Result is in principle improvable with better Bayesian analyses.
  - May be hard to do in practice.
  - The current analysis already took 2M CPUh.



Future improvements

- We kept R_n fixed in the present analysis.
  - Bayesian analysis increases in difficulty with more parameters.
  - A priori it was not clear that this approach would work.
  - Decided to include only a_n in the first analysis.
- What can be expected from varying R_n in a future Bayesian analysis?
  - When varying R_n, as R_n grows, σ_{PbPb} increases and $\langle p_T \rangle$ decreases.
  - Smallness of of σ_{PbPb} prefers smaller R_n, possibly leading to a smaller estimate of Δr_{np}.
  - In this case bulk viscosity would need to increase to compensate for $\langle p_T \rangle$.



Conclusions & Outlook

Conclusions:

- Bayesian analysis can extract a value for the neutron skin of ^{208}Pb from LHC data.
- Value obtained ($\Delta r_{np} = 0.217 \pm 0.058\,\mathrm{fm}$) is compatible with ab initio nuclear theory and with PREX II.
- Precision obtained is comparable with PREX II.

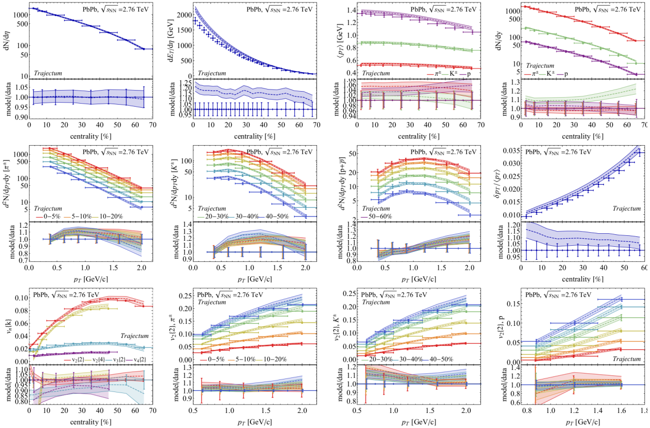
Outlook:

- A future analysis will vary R_n as a parameter alongside a_n, removing a potential source of bias.
- One could attempt to spend more CPUh for a more precise estimate.

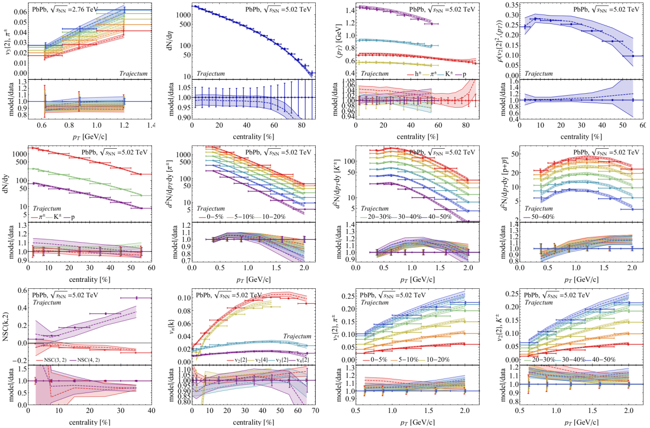
Bayesian analysis details

- 3000 design points.
- 18k events per design point.
- Every 15th design point has 10$\times$ more statistics, enabling to emulate ‘hard’ observables such as $SC(n, m)$ and $\rho(v_2\{2\}^2, \langle p_T \rangle)$.

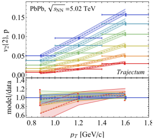
Posterior observables (1/3)

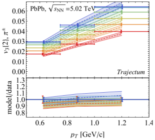


Posterior observables (2/3)



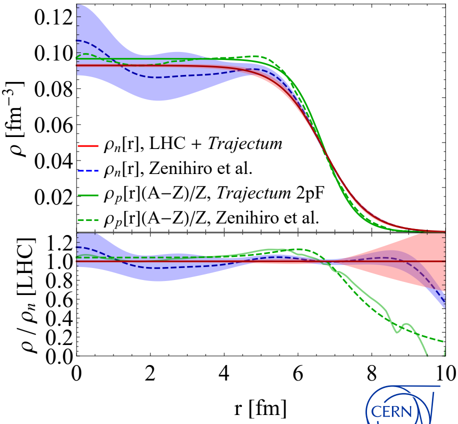
Posterior observables (3/3)





Comparison with polarized proton scattering

- We show the proton/neutron density as a function of radius as measured using polarized proton scattering.
- Our result agrees within error bars.
- We do not see the features found in the central region due to our use of a Woods-Saxon parameterization.



TRENTo initial conditions

- Nucleons A and B become *wounded* with probability

$$P_{\text{wounded}} = 1 - \exp\left(-\sigma_{gg} \int d\mathbf{x}\, \rho_A(\mathbf{x})\rho_B(\mathbf{x})\right), \quad \rho_A \propto \exp\left(\frac{-|\mathbf{x}-\mathbf{x}_A|^2}{2w^2}\right).$$

- Each wounded nucleon desposits energy into its nucleus's *thickness function* $\mathcal{T}_{A/B}$:

$$\mathcal{T}_{A/B} = \sum_{i \in \text{wounded A/B}} \gamma \exp(-|\mathbf{x}-\mathbf{x}_i|^2/2w^2),$$

  with γ drawn from a gamma distribution with mean 1 and standard deviation σ_{fluct}.
- Actual formulas slightly modified because each nucleon has n_c constituents.