

# Fixing the Nuclear Charge Density with Finite Nucleons

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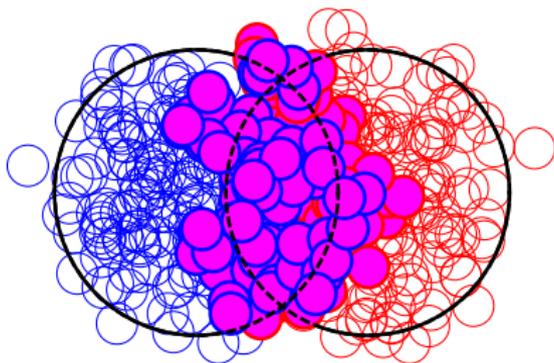
January 14, 2021



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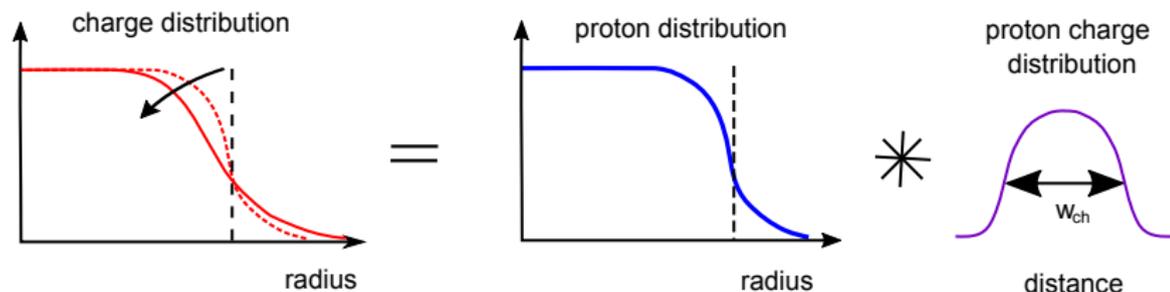
# Motivation

- Nucleon positions within nuclei *fluctuate*.
- Often sampled from a *Woods-Saxon distribution*.
- Nuclear *charge distribution*, extracted from  $e^-N$  scattering.
- Charge distribution  $\Rightarrow$  proton distribution  $\Rightarrow$  nucleon distribution.



# Nuclear charge density

- Protons are finite-sized: *charge distribution*  $\neq$  *proton distribution*.
- The former is a *convolution*:

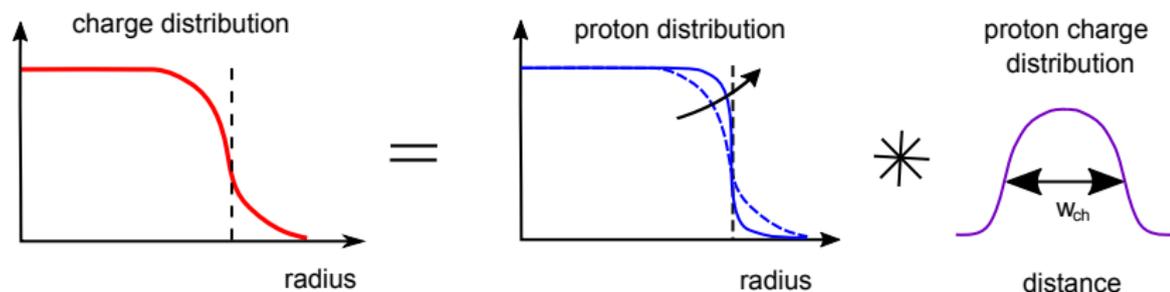


$$\rho_{ch}^{(w_{ch})}(\mathbf{r}) = \int d^3r_n \rho_p(\mathbf{r}_n) \rho_{ch}^{(p)}(\mathbf{r} - \mathbf{r}_n)$$

W. Broniowski, M. Rybczynski and P. Bozek, *Comput. Phys. Commun.* **180** (2009)  
 T. Hirano and Y. Nara, *Phys. Rev. C* **79** (2009),  
 C. Shen et al. *Comput. Phys. Commun.* **199** (2016)

# Fixing the Nuclear Charge Density

- Proton size changes nuclear charge density.
- Correct for the effect by changing the nucleon distribution:



$$\rho_{ch}(\mathbf{r}) = \int d^3 r_n \rho_p^{(w_{ch})}(\mathbf{r}_n) \rho_{ch}^{(p)}(\mathbf{r} - \mathbf{r}_n)$$

- *Unfolding* problem.

W. Broniowski, M. Rybczynski and P. Bozek, *Comput. Phys. Commun.* **180** (2009)  
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# Proton Radius

- Here: fix charge density by changing nucleon distribution.
- Effects on nucleon distribution, centrality classification and event-by-event fluctuations, for Gaussian protons.
- Vary nucleon Gaussian width  $w$ , r.m.s. radius  $R = \sqrt{3}w$ .

Low-Energy E.M.<sup>1</sup>



Duke Bayesian<sup>2</sup>



JETSCAPE Bayesian<sup>3</sup>



<sup>1</sup>A. Antognini *et al.*, Science **339** (2013),  $w_{\text{ch}} = 0.486$  fm

<sup>2</sup>J. E. Bernhard, arXiv:1804.06469 [nucl-th],  $w = 0.956$  fm

<sup>3</sup>D. Everett *et al.* (JETSCAPE), arXiv:2011.01430 [hep-ph],  $w = 0.8 - 1.2$  fm

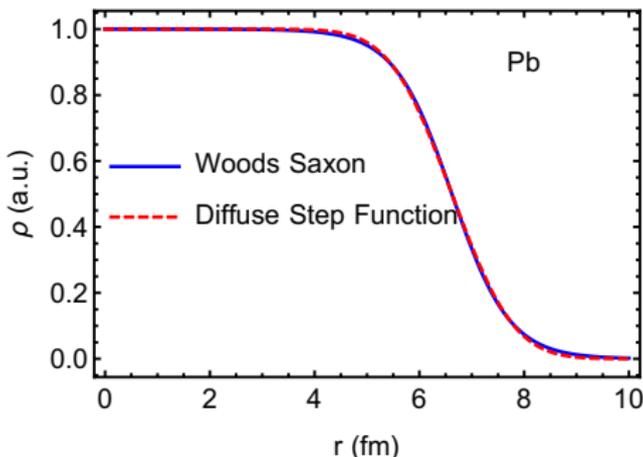
# Distribution of Nucleons

## Method: Diffuse Step Function

- *Strategy*: employ distributions for which unfolding is analytical.
- Ex.: Convolution of step function with a Gaussian:

$$\rho(r) \approx \tilde{\Theta}_{\tilde{R}}^{\tilde{a}}(r) = \int d^3r' \Theta(\tilde{R} - r') \exp\left(-\frac{|\mathbf{r} - \mathbf{r}'|^2}{2\tilde{a}^2}\right)$$

- For Woods-Saxon, find  $\tilde{R}(R, a)$  and  $\tilde{a}(R, a)$ .

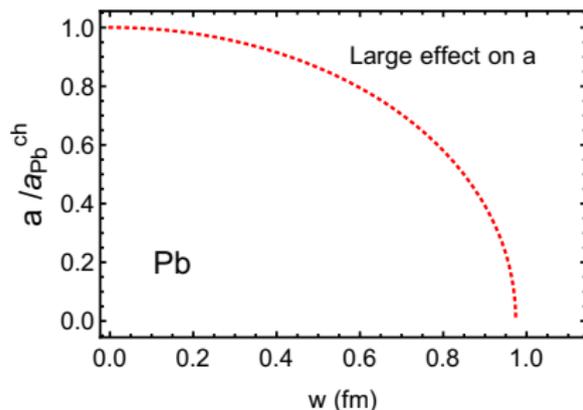
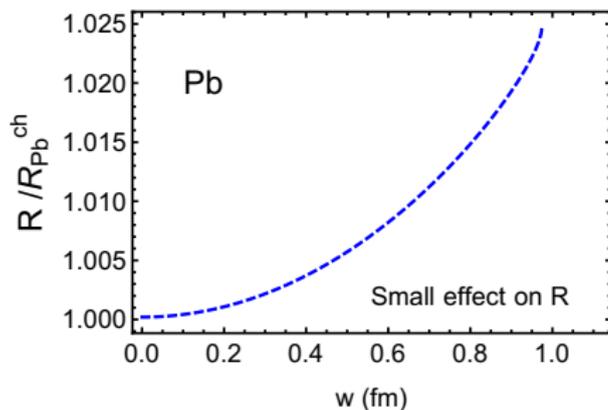


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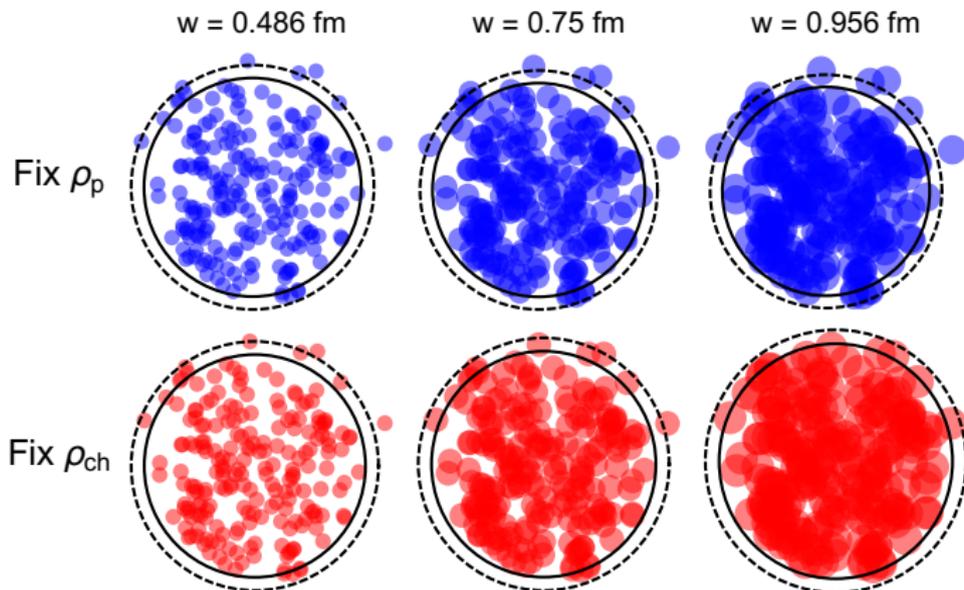
$$\rho(r) \approx \tilde{\Theta}_{\tilde{R}}^{\tilde{a}}(r) = \int d^3r' \Theta(\tilde{R} - r') \exp\left(-\frac{|\mathbf{r} - \mathbf{r}'|^2}{2\tilde{a}^2}\right)$$

- Folding/unfolding with proton charge profile:  $\tilde{a}^2 \rightarrow \tilde{a}^2 \pm w^2$



# Sampling Nucleons

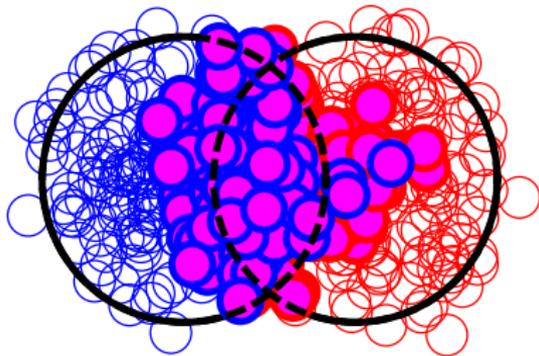
- Increasing the nucleon size **increases the nuclear radius**.
- Fixing the charge distribution **makes the nucleus' edge smoother**.



# Nucleus-Nucleus Collisions

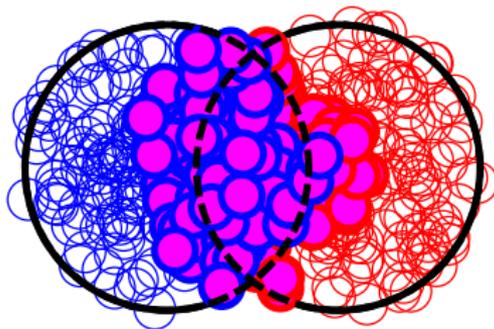
- Fixed proton distribution
- *Broader* ICs

$w = 0.956$  fm



- Fixed charge distribution
- *More compact* ICs

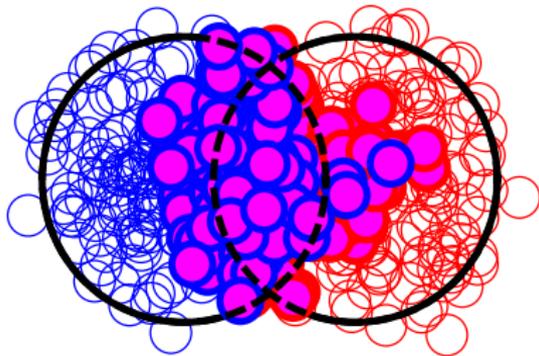
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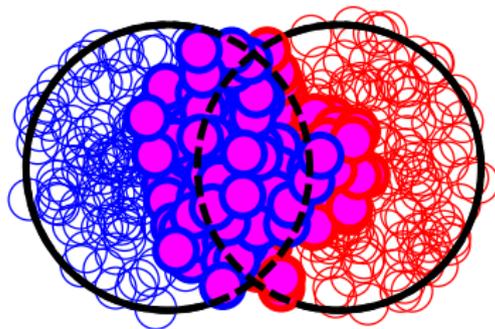
# Nucleus-Nucleus Collisions

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- Fixed charge distribution
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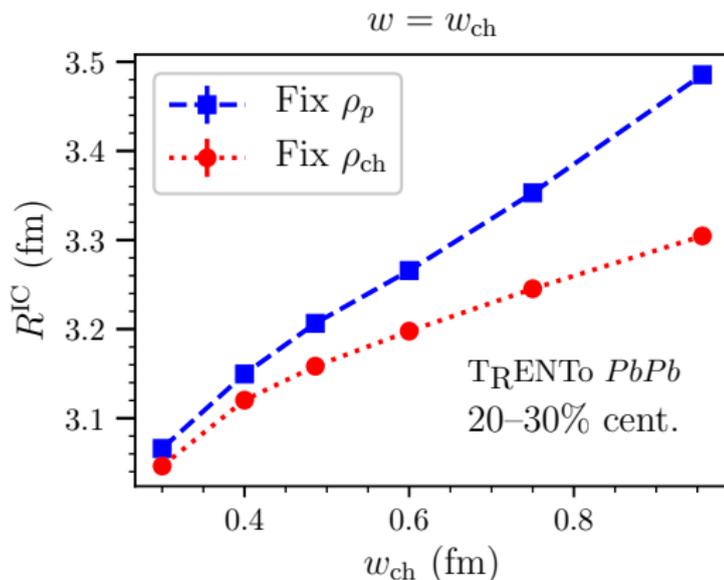


Affects centrality classification, system size and fluctuations.

# Centrality and System Size

## Transverse Size

- Transverse r.m.s. size,  $R^{\text{IC}}$ , decreases by up to 7%.
- Should affect spectra and mean  $p_T$ .
- Bias in extracted viscosities?

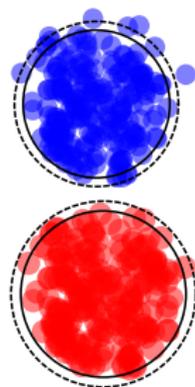
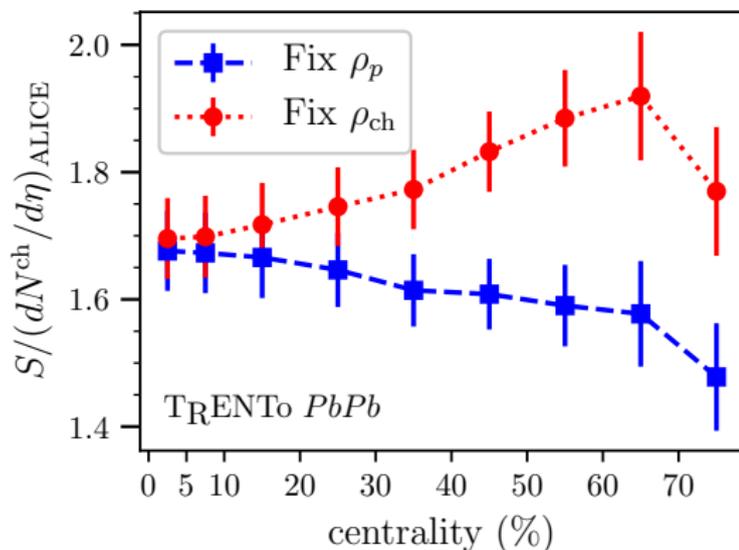


- Results using TRENTo for  $Pb + Pb$  @ 2.76 TeV.

# Centrality Distribution

- Collision probability  $\Rightarrow$  cross section  $\Rightarrow$  centrality.
- Duke Bayesian value  $w = 0.956$  fm.

$$w = w_{\text{ch}} = 0.956 \text{ fm}$$



K. Aamodt *et al.* (ALICE), PRL **106** (2011)

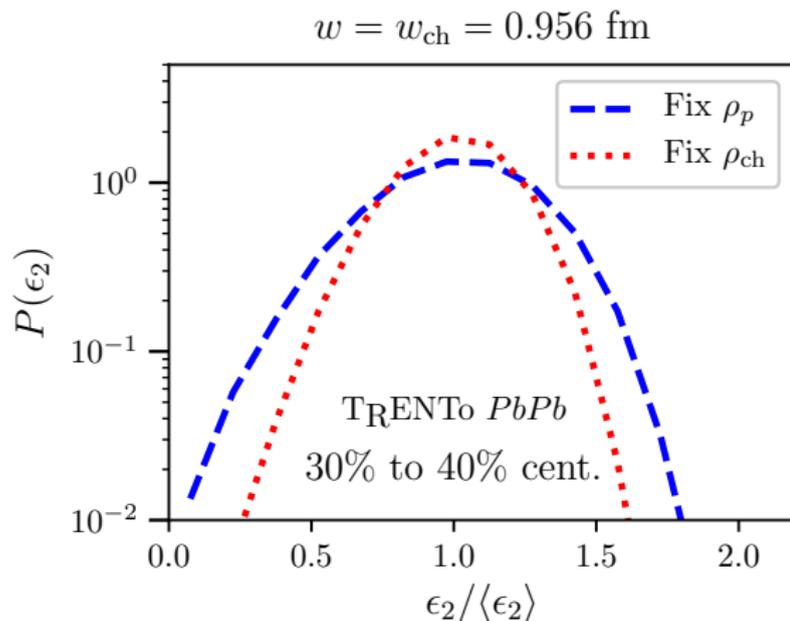
J. E. Bernhard, arXiv:1804.06469 [nucl-th]

J. S. Moreland, J. E. Bernhard and S. A. Bass, PRC **92** (2015)

# Event-by-Event Fluctuations

# Eccentricity Fluctuations

- Smoother, more compact ICs  $\Rightarrow$  less fluctuations.
- Duke Bayesian value  $w = 0.956$  fm.

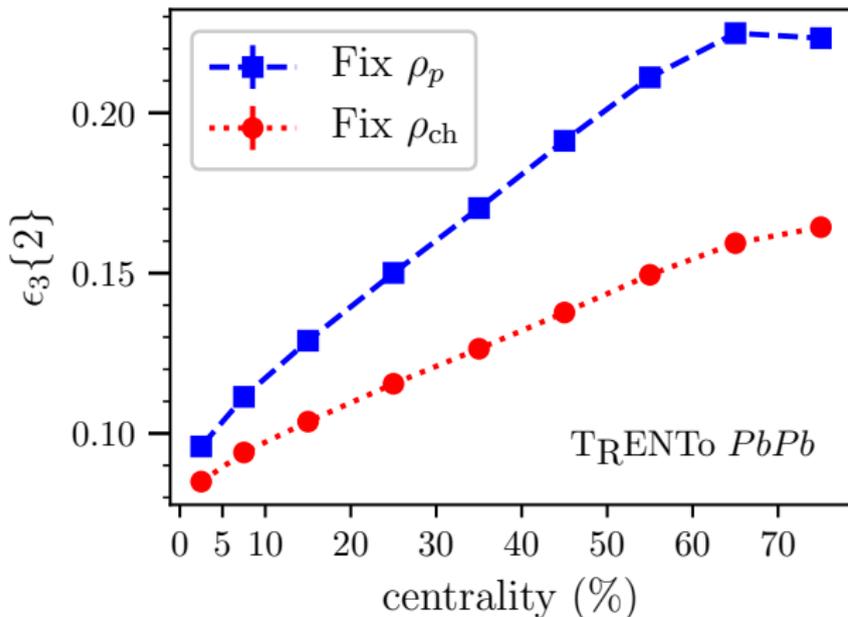


- $\epsilon_2\{4\}/\epsilon_2\{2\}$  increases by up to 15%.

# Triangular Eccentricity

- Smoother, more compact ICs  $\Rightarrow$  less fluctuations.

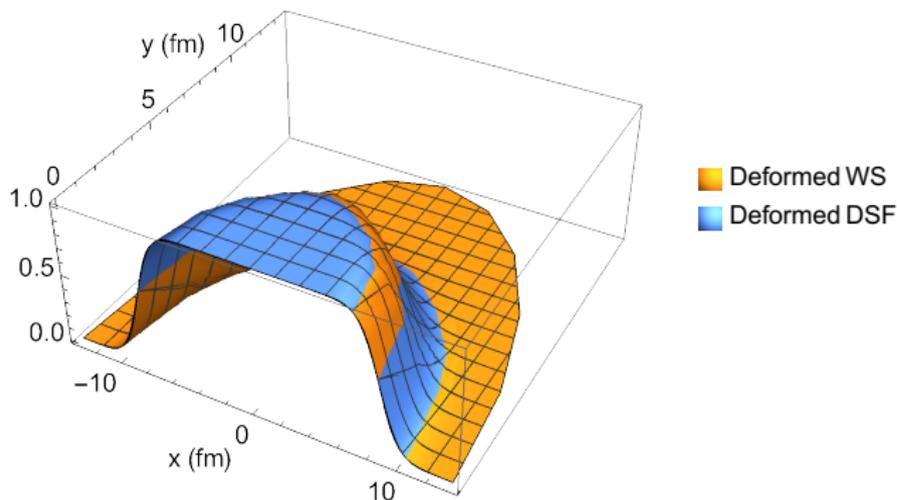
$$w = w_{\text{ch}} = 0.956 \text{ fm}$$



- Suppression of  $\epsilon_3$  by up to 30%
- Consequences for triangular flow.

Deformed Nuclei –  $^{238}\text{U}$  (Preliminary)

- Deformed nuclei:  $\tilde{R}(\theta)/\tilde{R}(0) \approx R(\theta)/R(0)$   
 $^{238}\text{U}$



- Similar accuracy as non-deformed DSF.

H. Masui, B. Mohanty and N. Xu, PLB **679** (2009)  
J. S. Moreland, J. E. Bernhard and S. A. Bass, PRC **92** (2015)

# Conclusions and Outlook

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- **Charge** distribution  $\neq$  **proton** distribution  
 $\Rightarrow$  Must be taken into account.
- Different **surface diffusivity** for finite protons
- Effects for centrality, fluctuations, flow harmonics

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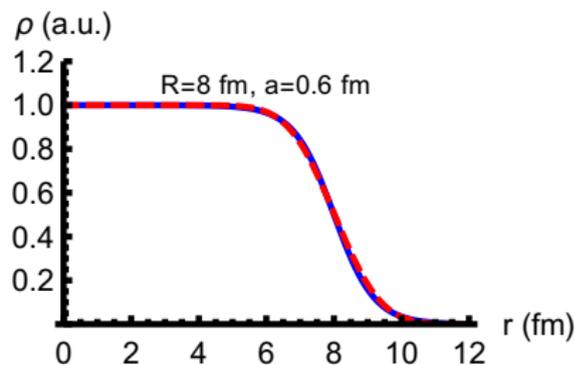
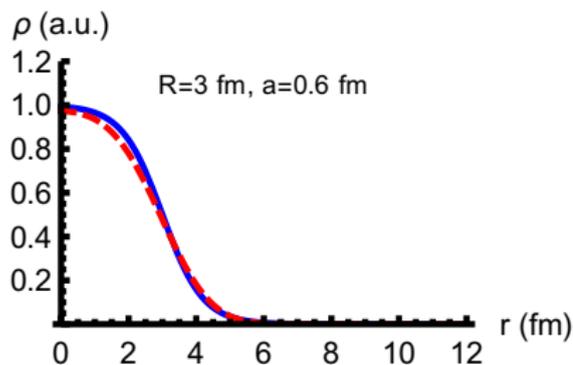
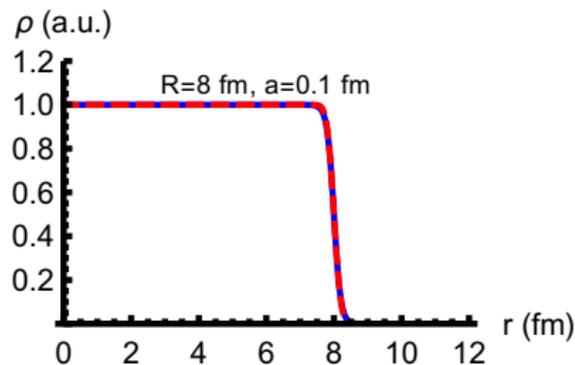
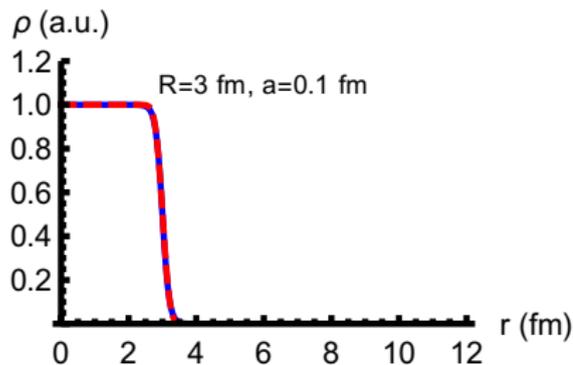
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     $\Rightarrow$  Must be taken into account.
- Different **surface diffusivity** for finite protons
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## Outlook:

- Study broader impact on hydrodynamic simulations.
- Effects on **smaller collision systems**.
- Generalizations: other Ansätze, numerical unfolding...

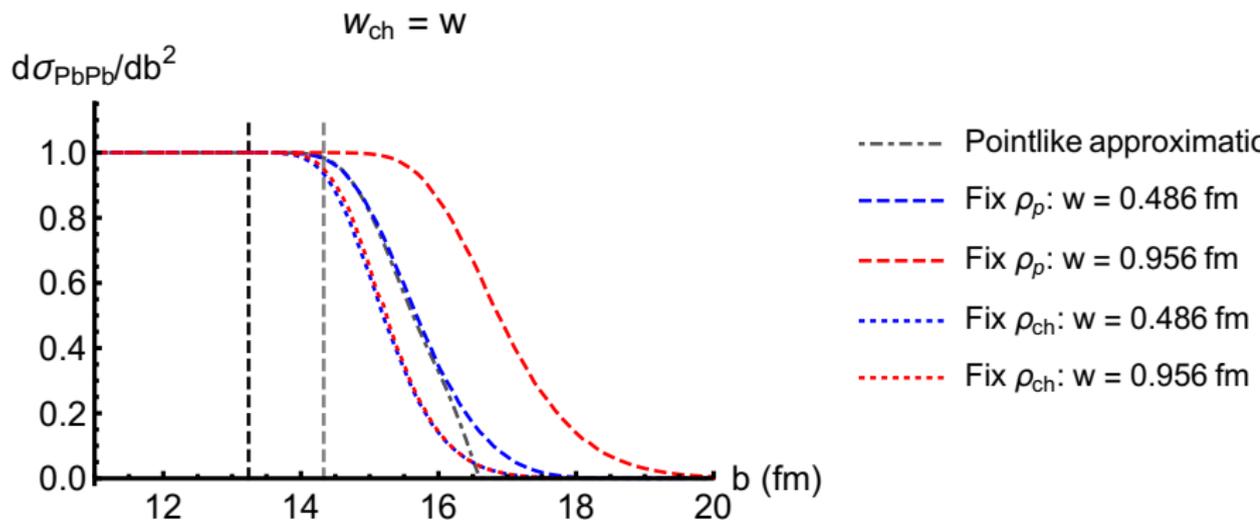
Backup slides...

# Woods-Saxon vs. Diffuse Step Function



# Nucleus-Nucleus Cross-Sections

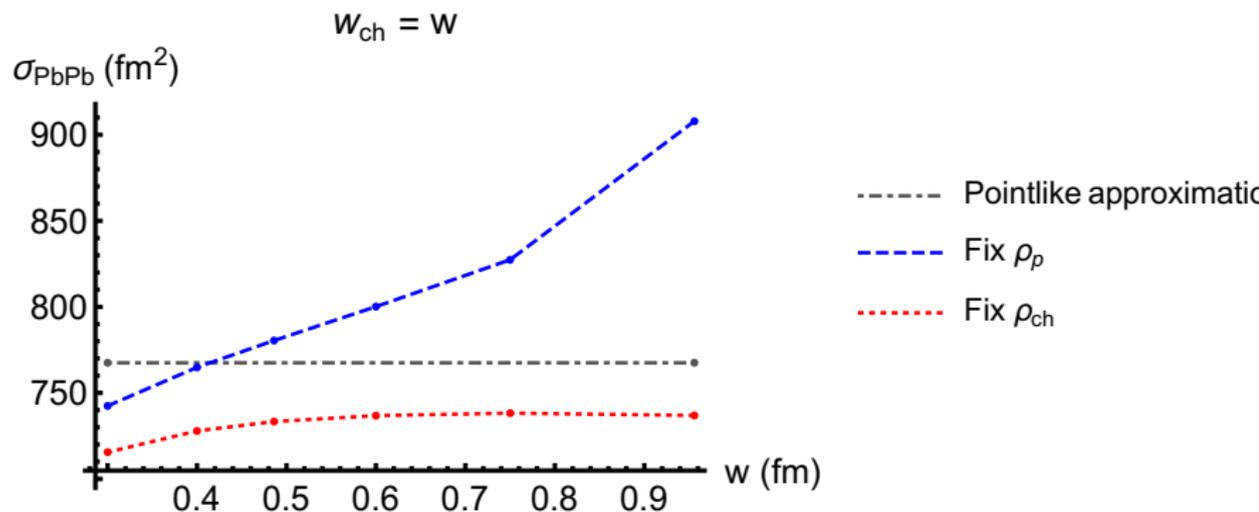
- Non-negligible effects for peripheral nucleon-nucleon collisions
- Affects nucleus-nucleus cross section



- Nucleon-nucleon cross section  $\sigma_{NN} = 6.28 \text{ fm}^2$ .

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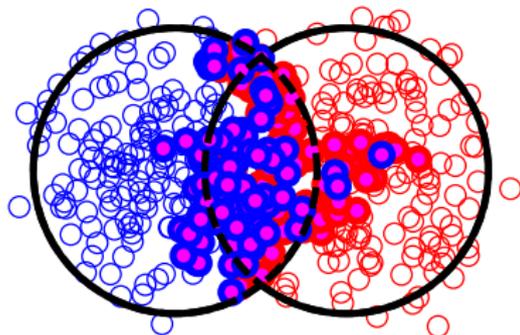


- Nucleon-nucleon cross section  $\sigma_{NN} = 6.28 \text{ fm}^2$ .

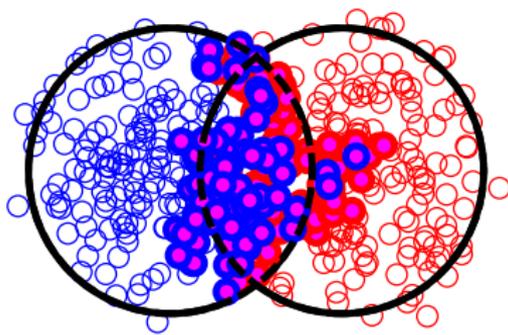
# Full Initial Conditions

- Fixed proton distribution
- *More extended ICs* for larger  $w$
- Fixed charge distribution
- *Smoother ICs* for larger  $w_{\text{ch}}$

$w = 0.486$  fm



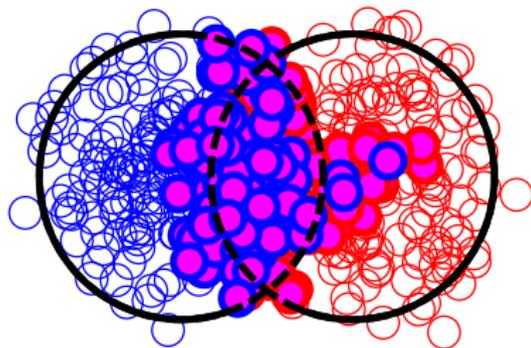
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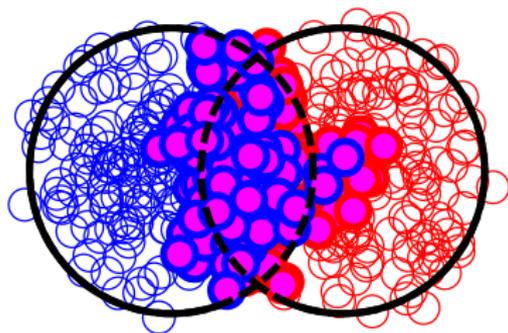
# Full Initial Conditions

- Fixed proton distribution
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- *Smoother ICs* for larger  $w_{\text{ch}}$

$w = 0.75 \text{ fm}$



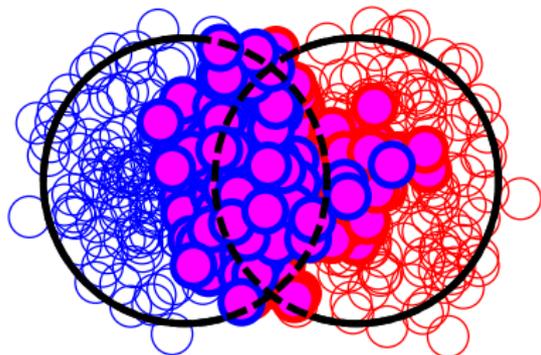
$w = 0.75 \text{ fm}$



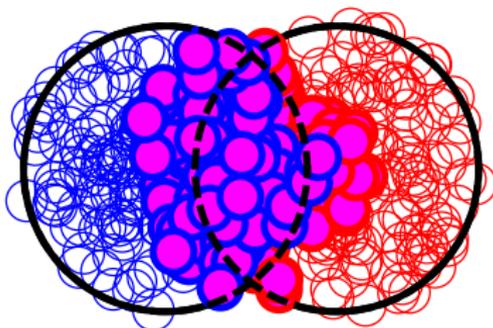
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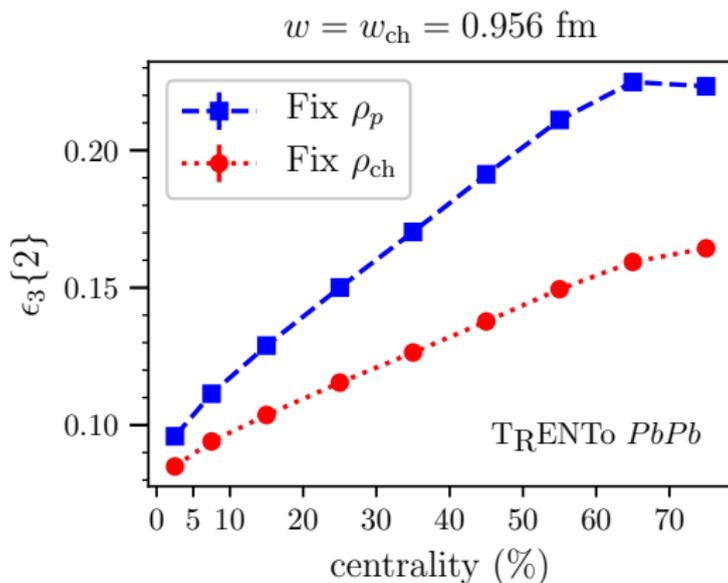


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# Triangular Eccentricity

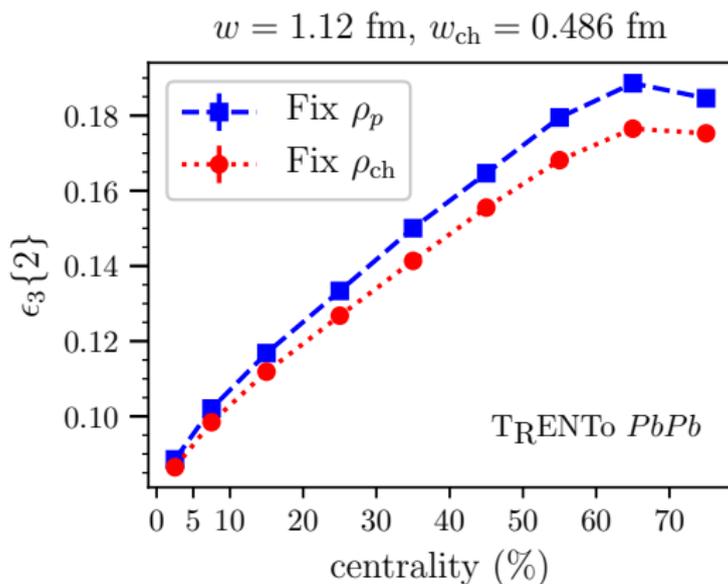
- Smoother, more compact ICs  $\Rightarrow$  less fluctuations.
- Suppression of  $\epsilon_3$ , triangular flow.



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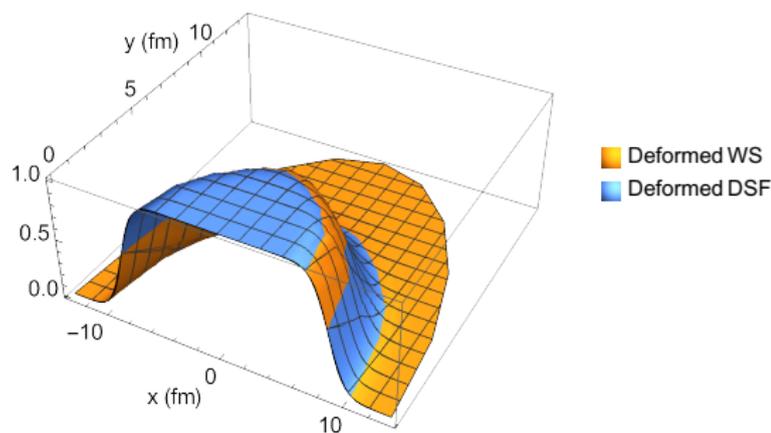
- Smoother, more compact ICs  $\Rightarrow$  less fluctuations.
- Suppression of  $\epsilon_3$ , triangular flow.
- Effects even for low-energy E.M. radius  $w_{\text{ch}} = 0.486$  fm

A. Antognini *et al.*, Science **339** (2013),  $w_{\text{ch}} = 0.486$  fm



## Deformed Nuclei (Preliminary)

- $\tilde{R}(\theta) \approx \tilde{R}(1 + \beta_2 Y_{20} + \beta_4 Y_{40})$
  - $R = 6.81$ ;  $a = 0.6$ ;  $\beta_2 = 0.280$ ,  $\beta_4 = 0.093$
- $^{238}\text{U}$

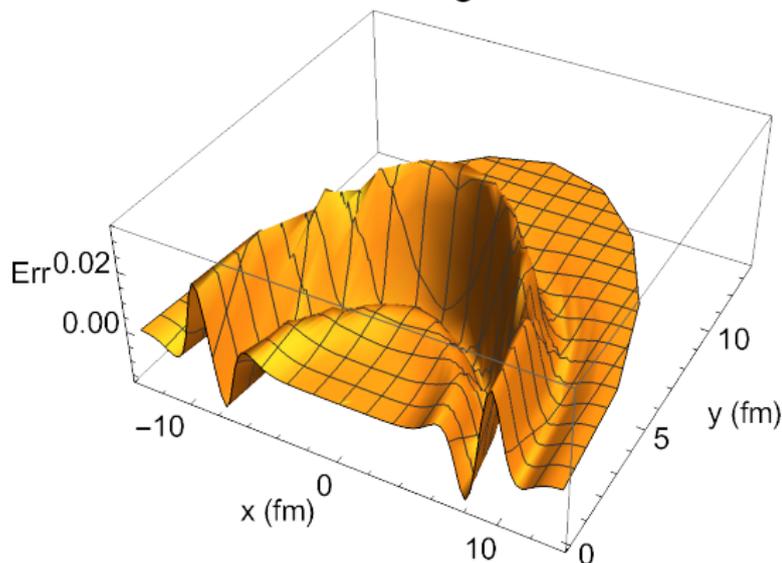


- Similar accuracy as non-deformed DSF.

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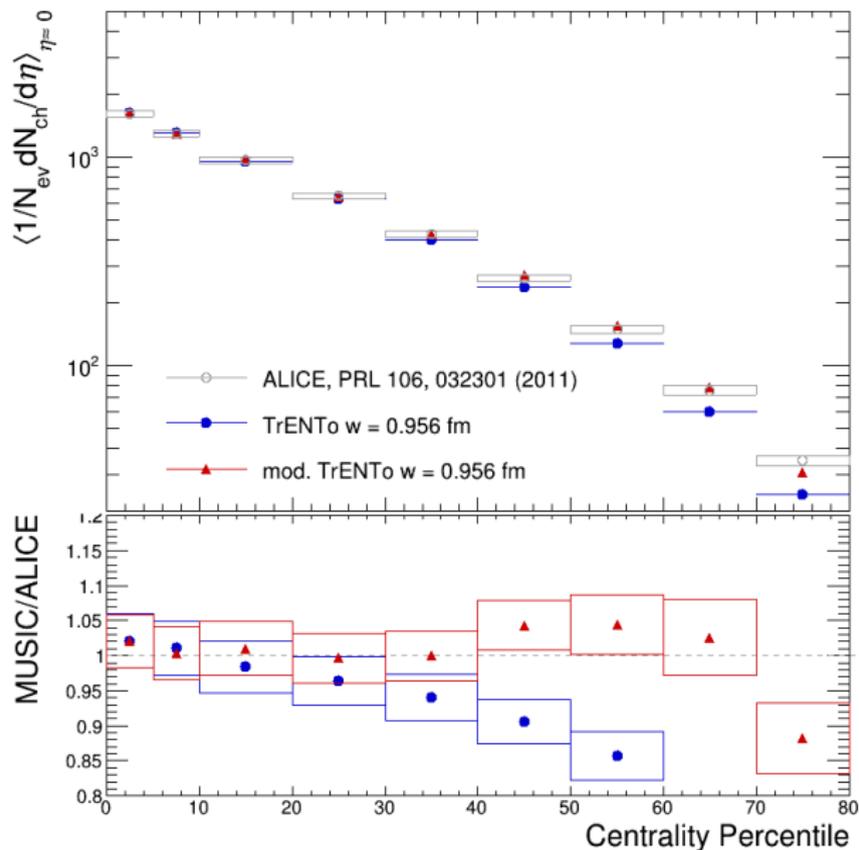
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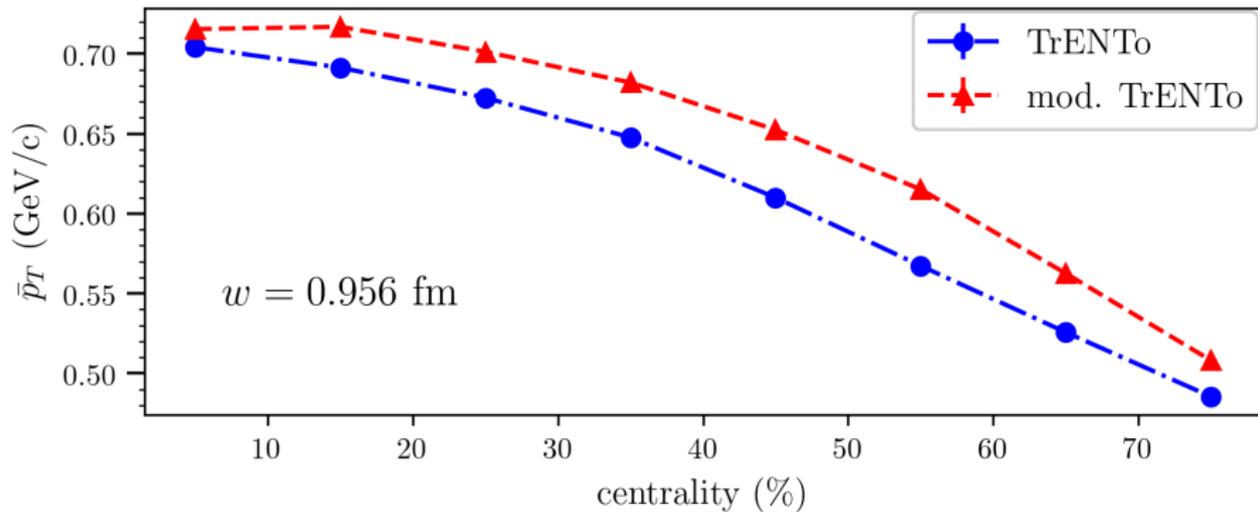
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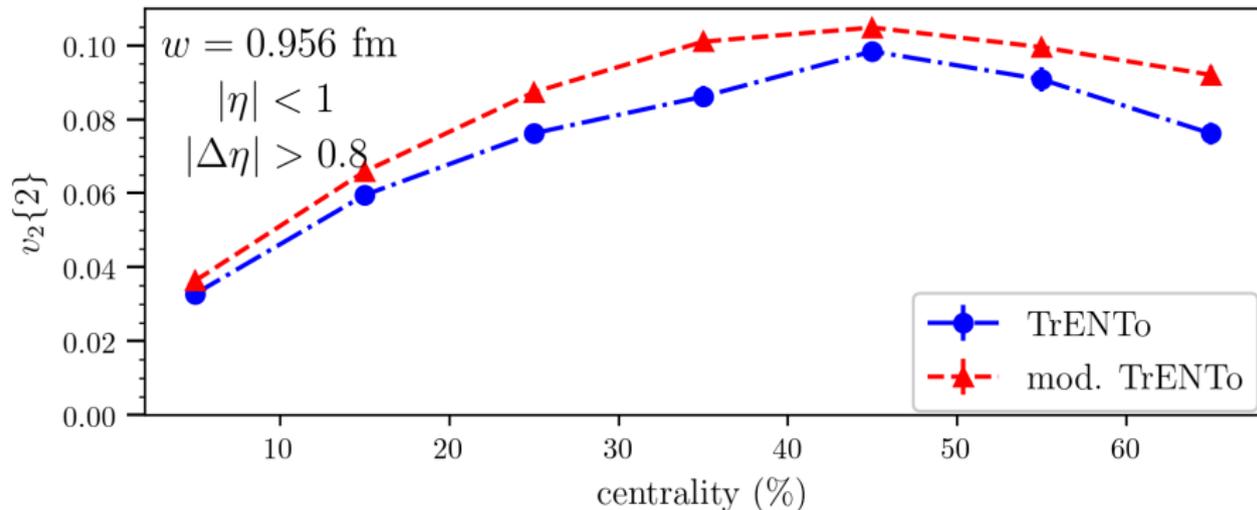
# Preliminary Hydro Results



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