Fixing the Nuclear Charge Density with Finite Nucleons

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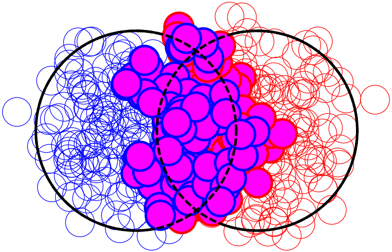
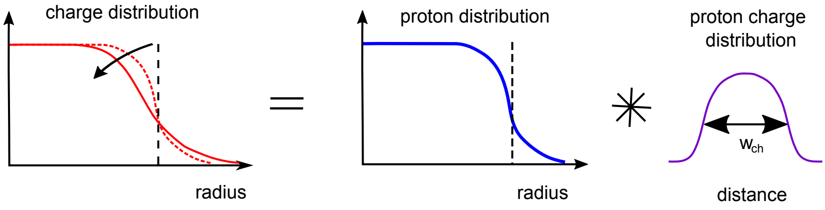
Motivation

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



Nuclear charge density

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



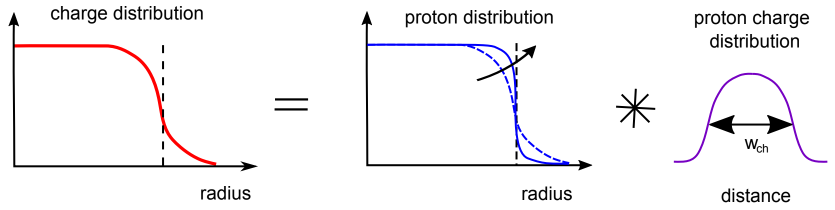
$$\rho_{\mathrm{ch}}^{(w_{\mathrm{ch}})}(\boldsymbol{r}) = \int d^3 r_n \, \boldsymbol{\rho}_{\mathrm{p}}(\boldsymbol{r}_n) \, \rho_{\mathrm{ch}}^{(p)}(\boldsymbol{r} - \boldsymbol{r}_n)$$

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:



$$\boldsymbol{\rho}_{\rm ch}(\boldsymbol{r}) = \int d^3 r_n \, \rho_{\rm p}^{(w_{\rm ch})}(\boldsymbol{r}_n) \, \rho_{\rm ch}^{(p)}(\boldsymbol{r} - \boldsymbol{r}_n)$$

- *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 proton distribution.
- Effects on proton distribution, centrality classification and event-by-event fluctuations, for Gaussian protons.
- Vary nucleon Gaussian width w, r.m.s. radius $R = \sqrt{3}w$.

[1] A. Antognini *et al.*, Science **339** (2013), $w_{\text{ch}} = 0.486$ fm
[2] J. E. Bernhard, arXiv:1804.06469 [nucl-th], $w = 0.956$ fm
[3] D. Everett *et al.* (JETSCAPE), arXiv:2011.01430 [hep-ph], $w = 0.8 - 1.2$ fm

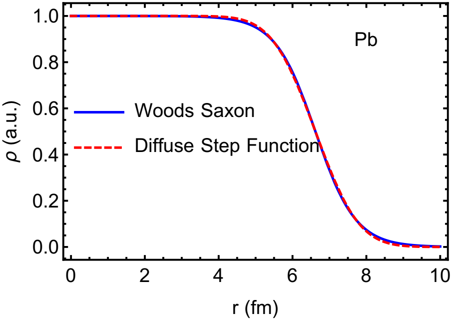
Fixing the Woods-Saxon Distribution

Method: Diffuse Step Function

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

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

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



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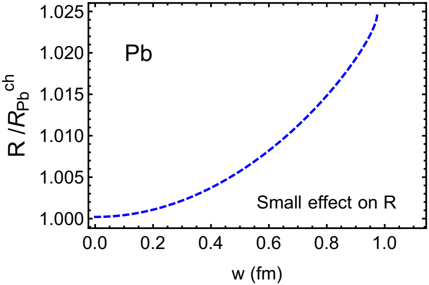
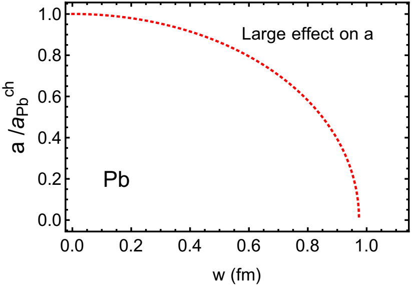
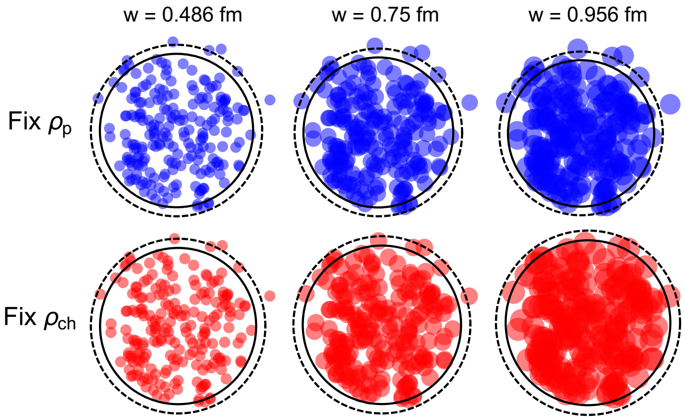
- Folding/unfolding with proton charge profile: $\tilde{a}^2 \to \tilde{a}^2 \pm w^2$





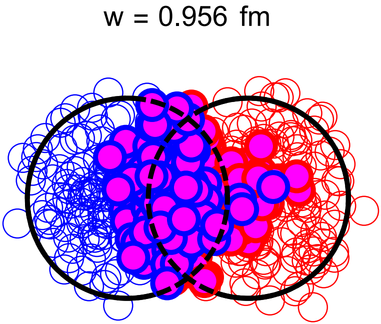
Sampling Nucleons

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

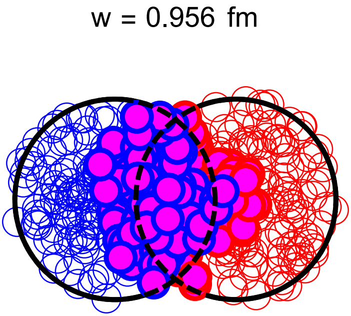


Nucleus-Nucleus Collisions

- Fixed proton distribution
- *Broader* ICs



- Fixed charge distribution
- *More compact* ICs



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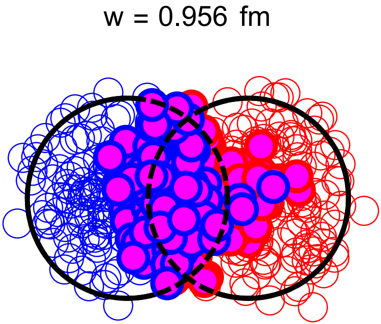
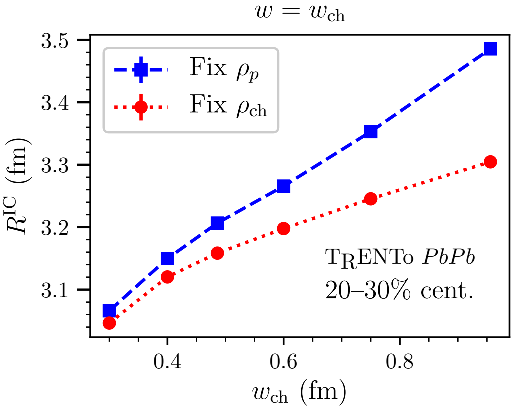


Affects centrality classification, system size and fluctuations.

Centrality and System Size

Transverse Size

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

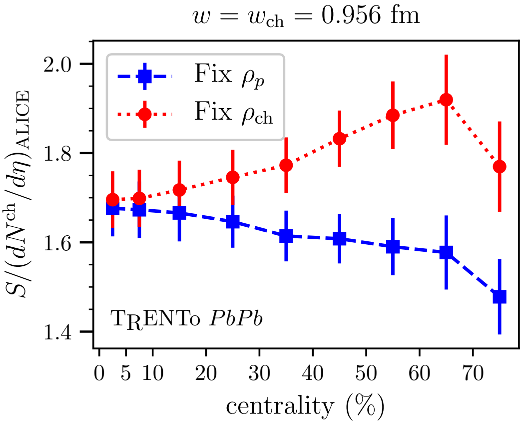


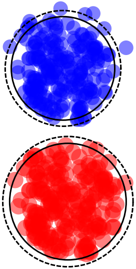
- Results using TRENTo for $Pb + Pb$ @ 2.76 TeV.

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

Centrality Distribution

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





K. Aamodt *et al.* (ALICE), PRL **106** (2011)
J. E. Bernhard, arXiv:1804.06469 [nucl-th]
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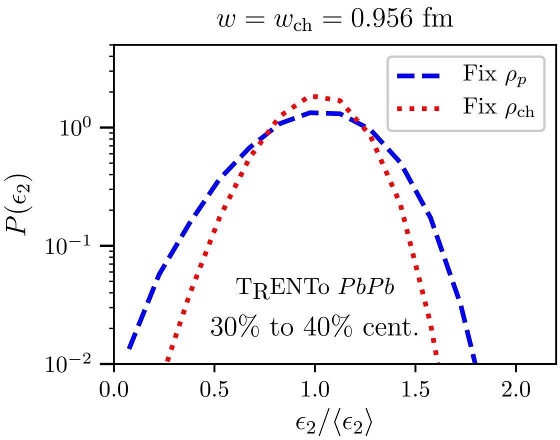
Event-by-Event Fluctuations

Eccentricity Fluctuations

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

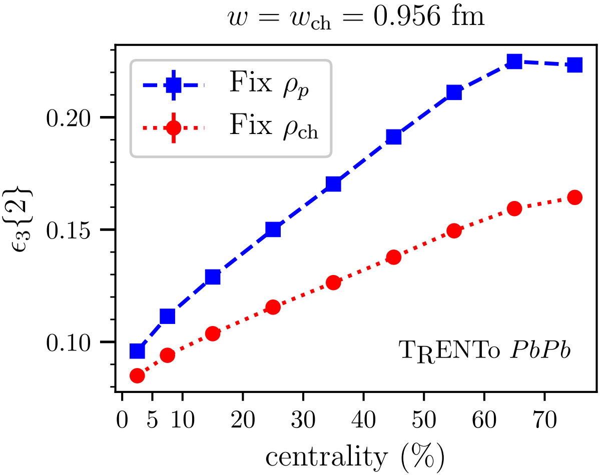


- $\epsilon_2\{4\}/\epsilon_2\{2\}$ increases by up to 15%.

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

Triangular Eccentricity

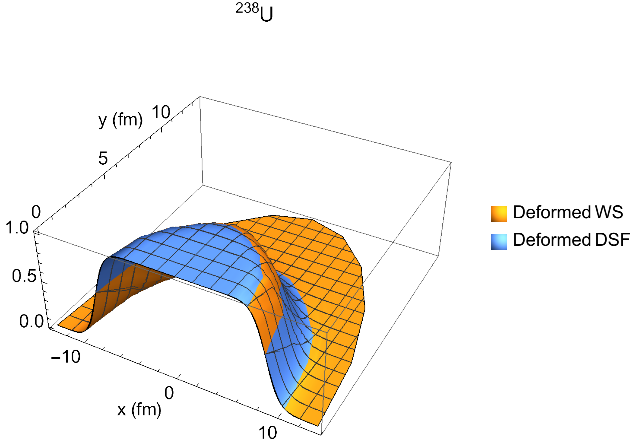
- Smoother, more compact ICs ⇒ less fluctuations.



- Suppression of ϵ_3 by up to 30%
- Consequences for triangular flow.

Deformed Nuclei – ^{238}U (Preliminary)

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



- 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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- **Charge** distribution $\neq$ **proton** distribution
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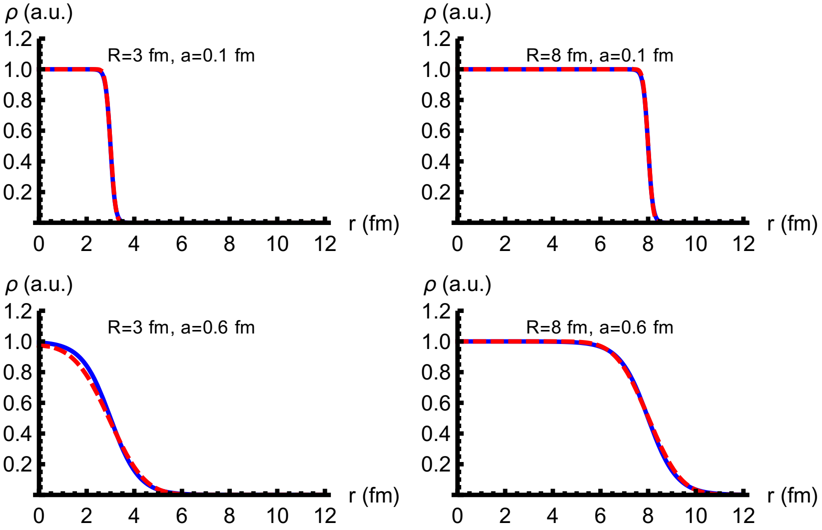
- Effects for centrality, fluctuations, flow harmonics

Outlook:

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

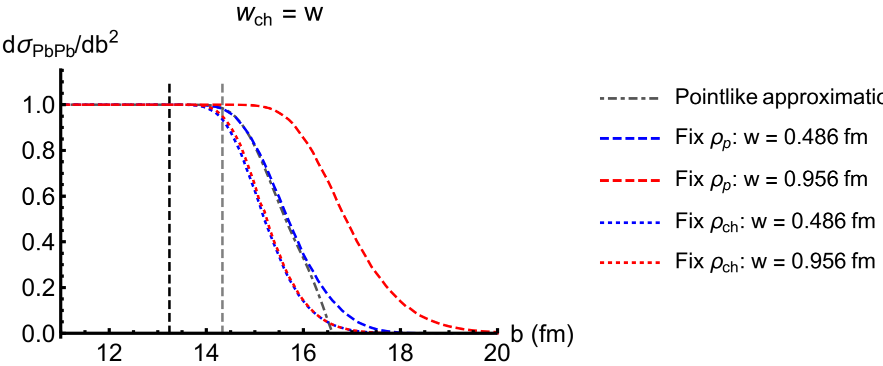
Backup slides...

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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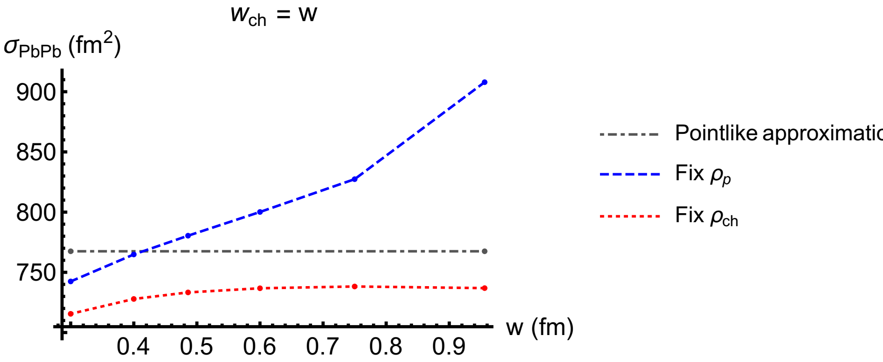

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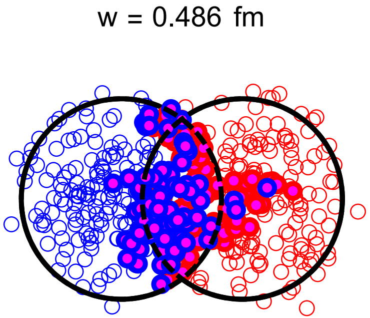
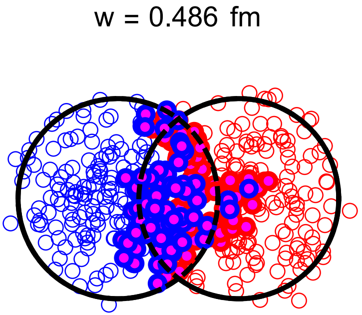
Full Initial Conditions

- Fixed proton distribution
- *More extended* ICs for larger w



- Fixed charge distribution
- *Smoother* ICs for larger w_{ch}



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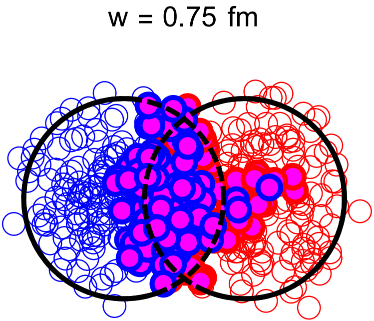

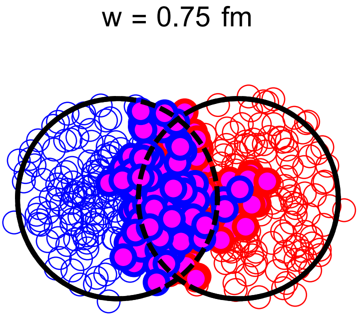

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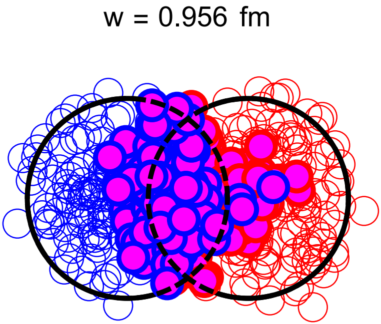

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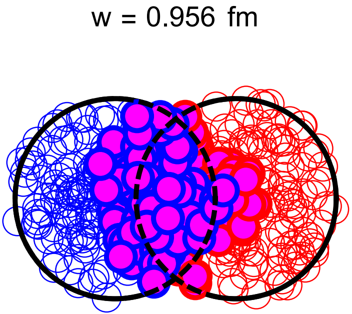
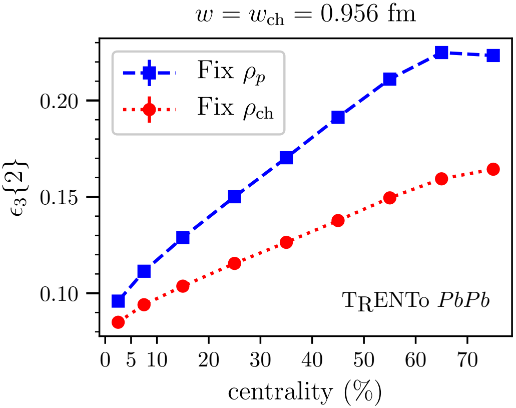


Triangular Eccentricity

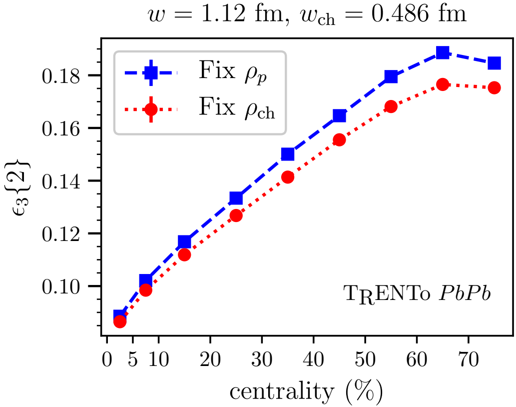
- Smoother, more compact ICs ⇒ less fluctuations.
- Suppression of ϵ_3, triangular flow.



Triangular Eccentricity

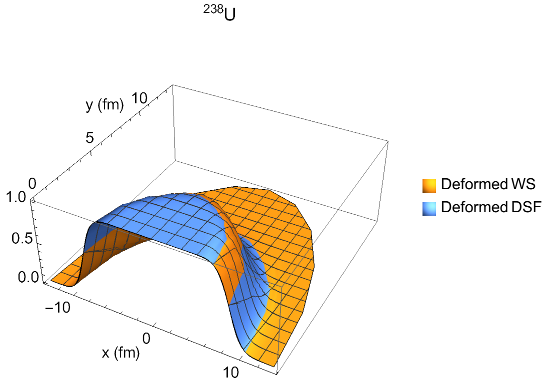
- Smoother, more compact ICs $\Rightarrow$ less fluctuations.
- Suppression of ϵ_3, triangular flow.
- Effects even for low-energy E.M. radius $w_{\rm ch} = 0.486$ fm

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



Deformed Nuclei (Preliminary)

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



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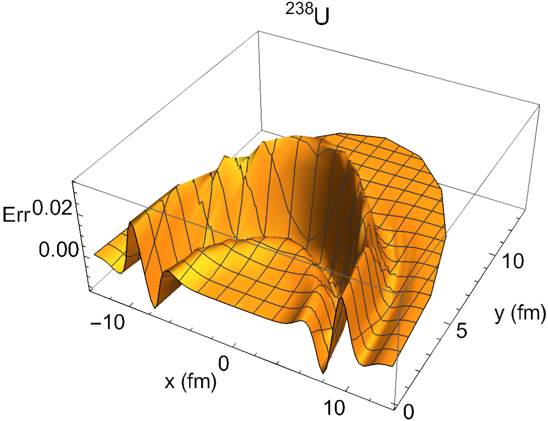

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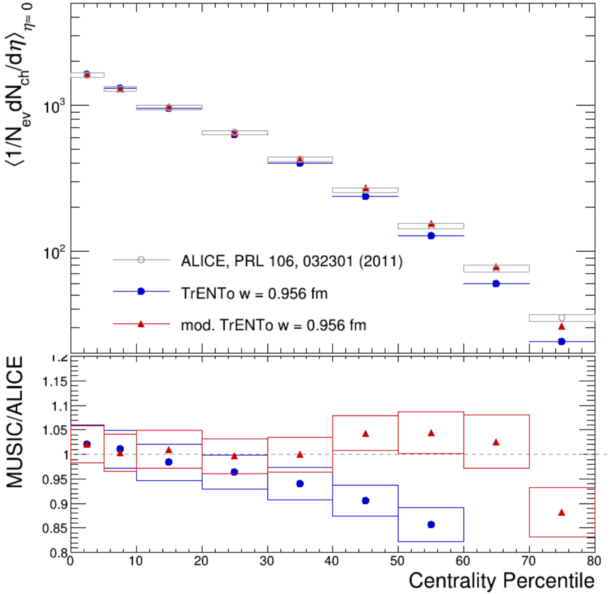
Preliminary Hydro Results



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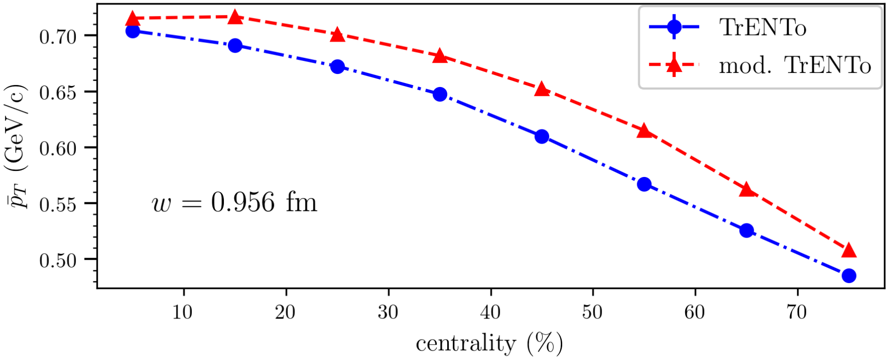

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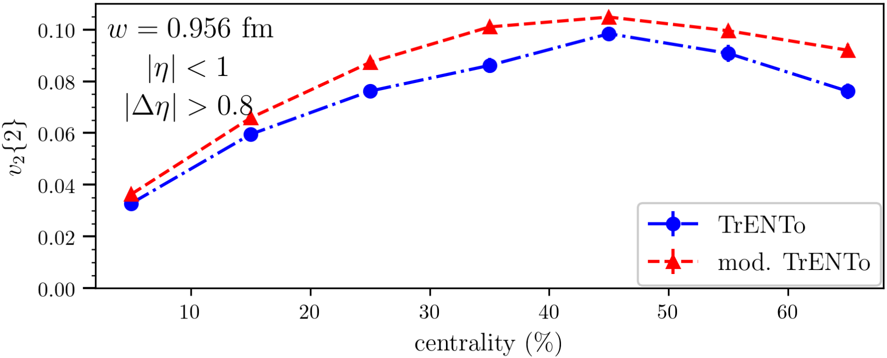

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