Probing Effect of Nuclear Shape Coexistence in Heavy-Ion Collisions using Glauber Model

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Introduction

- Nuclear geometry parametrized by Woods-Saxon distribution,

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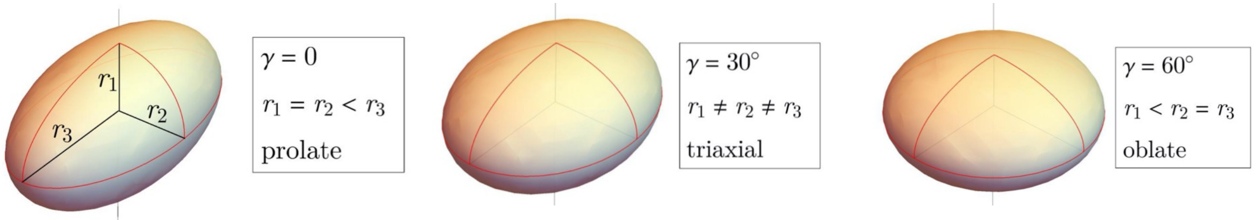
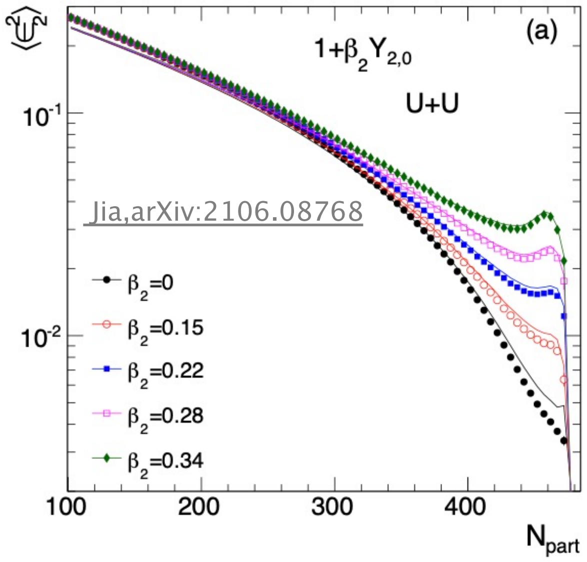
$$\rho(r) = \frac{\rho_0}{[1 + exp(r - R(\theta, \phi))/a]}$$

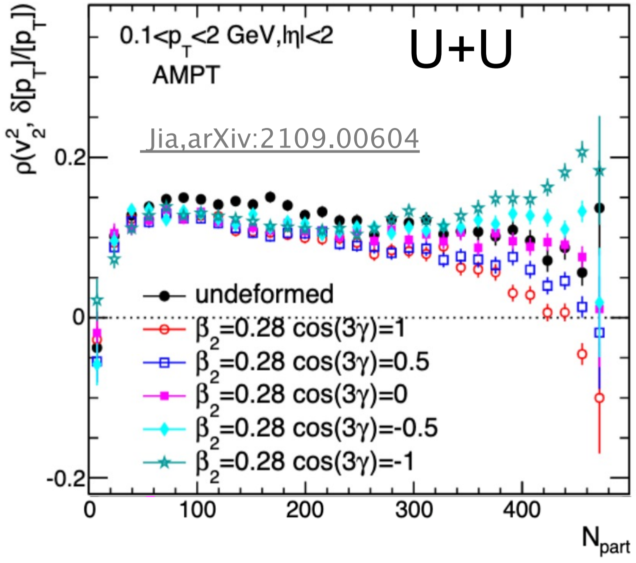
$$R(\theta, \phi) = R_0(1 + \beta(cos\gamma Y_{20}(\theta, \phi) + sin\gamma Y_{22}(\theta, \phi)))$$



$$\beta = \frac{4\pi}{3ZeR_0^2}\sqrt{B(E2)\uparrow}$$

- ➢ Deformation parameters generally estimated from spectroscopic measurements.
- ➢ **Nuclear geometric deformation impacts shape and size of overlap area in initial state.**





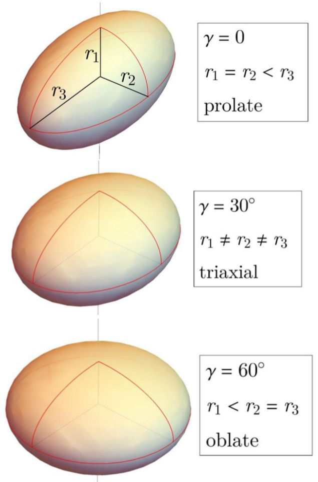
$$\langle\varepsilon_2^2\rangle = a + b\beta^2 \qquad \langle v_2^2 \delta p_T\rangle \sim a_3 - b_3\ cos(3\gamma)\beta^3$$

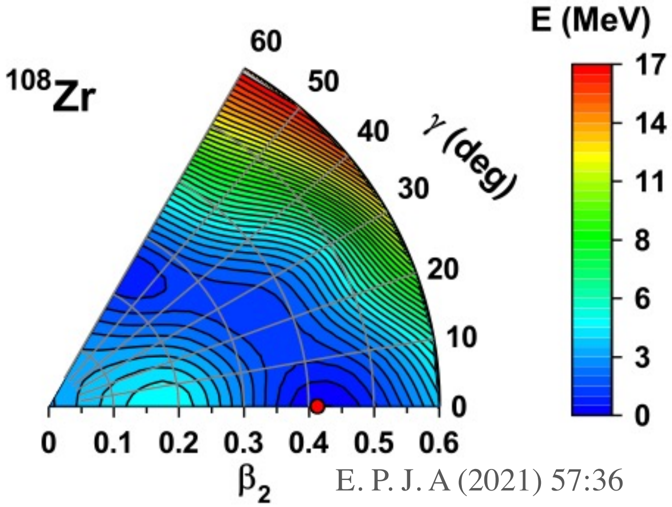
- Deformation effects gets transferred via hydrodynamics from Initial state to Final state observables.
- 2-particle correlations show β^2 dependence, 3-particle correlations show β^3 dependence.
- Nuclear Shape coexistence is a fundamental property of nucleus where it displays a wide range of β values at lower energies.

➢ **How does fluctuations in β arising from shape coexistence manifest in heavy ion collisions?**

Methodology

Goal: Study effect of β and σ_β on initial state fluctuations (eg: $\langle \varepsilon_2^2 \rangle$, C_2) in heavy ion collisions using Glauber model.





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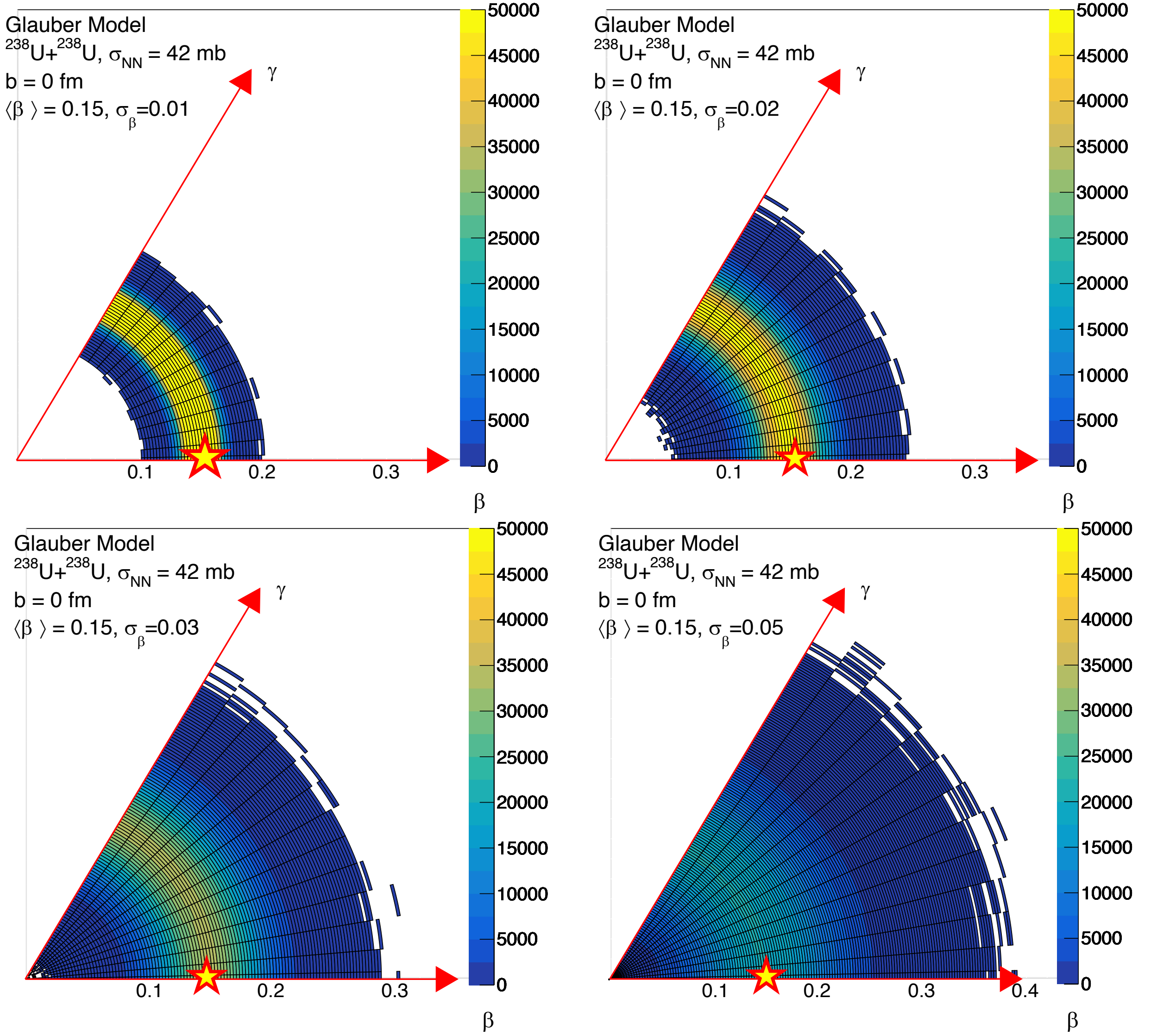
$$R(\theta,\phi) = R_0(1 + \beta(cos\gamma Y_{20}(\theta,\phi) + sin\gamma Y_{22}(\theta,\phi)))$$



☆: γ = 0, β = 0.15

✓ Simulate ^{238}U+ ^{238}U collisions using Glauber Model with at a given γ and allow and β, σ_β to fluctuate on an event-by-event basis.

✓ In our study, generated events with b = 0 fm.

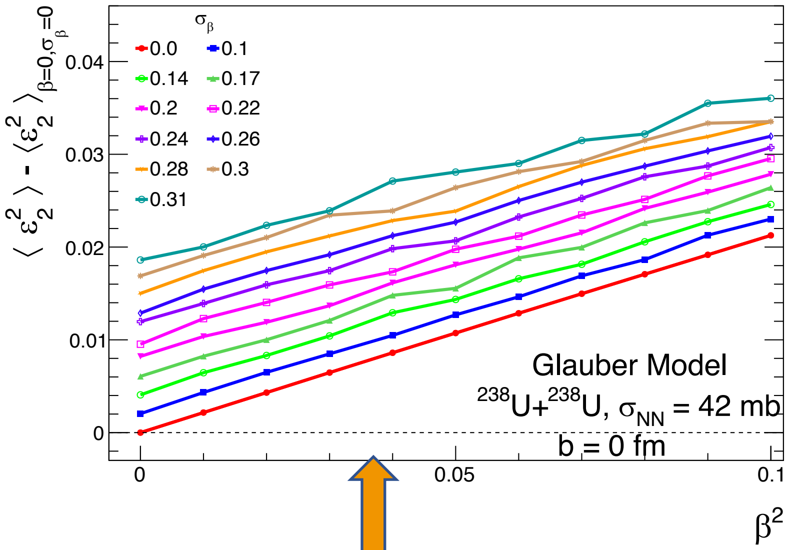
- 11 β^2 values chosen : 0,0.01,0.02…..0.1.
- 11 σ_β^2 values chosen : 0,0.01,0.02…..0.1.
- Default γ=0^0

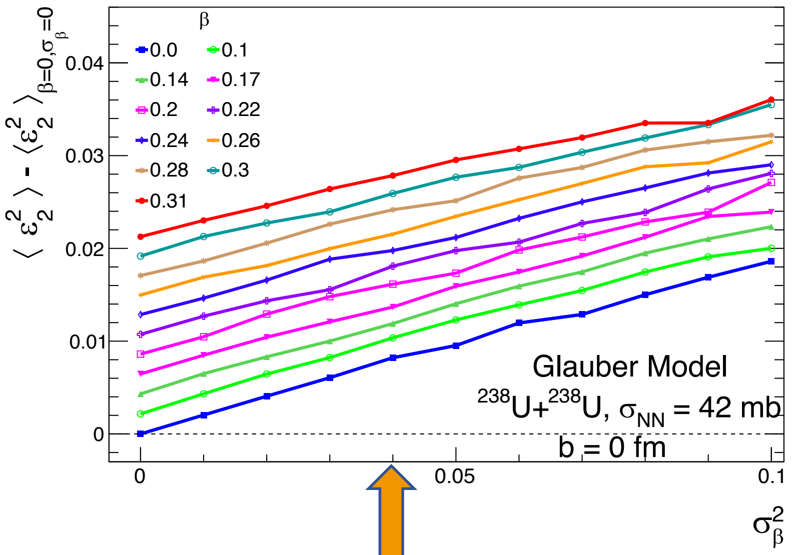
$\langle \varepsilon_2^2 \rangle$ dependence on $(\boldsymbol{\beta}, \boldsymbol{\sigma_\beta})$

➢ $\langle \varepsilon_2^2 \rangle$ being a 2-particle correlator is expected to have largest dependence on β^2

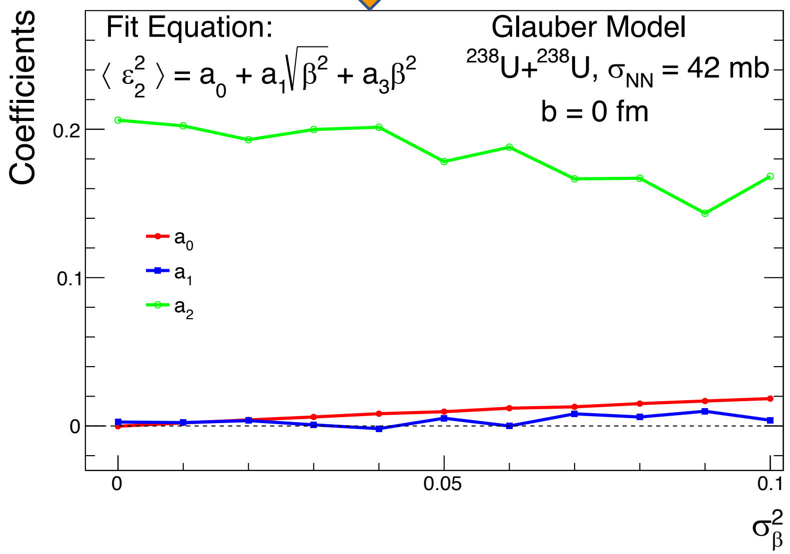
$$\langle \varepsilon_2^2 \rangle = a + b\beta^2$$

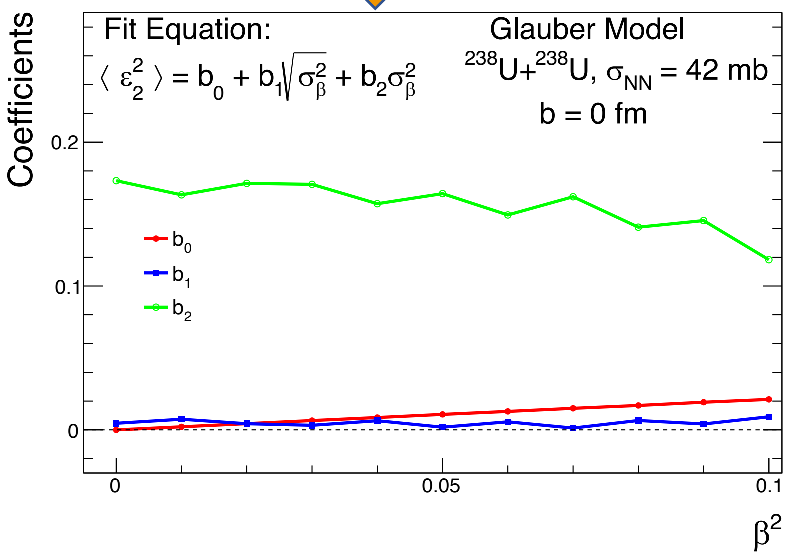
Jia,arXiv:2106.08768





1. dependance is quadratic in both β and σ_β .
2. Negligible dependence of $\langle \varepsilon_2^2 \rangle$ on linear order of β or σ_β





3. A slow decrease of the coefficient for quadratic term is observed with increasing β and σ_β.

$$\langle \varepsilon_2^2 \rangle = a + b\beta^2 + c\sigma_\beta^2$$

Where b ~ 0.2 and c~0.15

C_2 $\left(\left\langle\left(\delta d_\perp / \langle d_\perp \rangle\right)^2\right\rangle\right)$ dependence on (β, σ_β)

- c_2 being a 2-particle correlator is expected to have largest dependence on β^2

$$c_2 = a + b\beta^2$$

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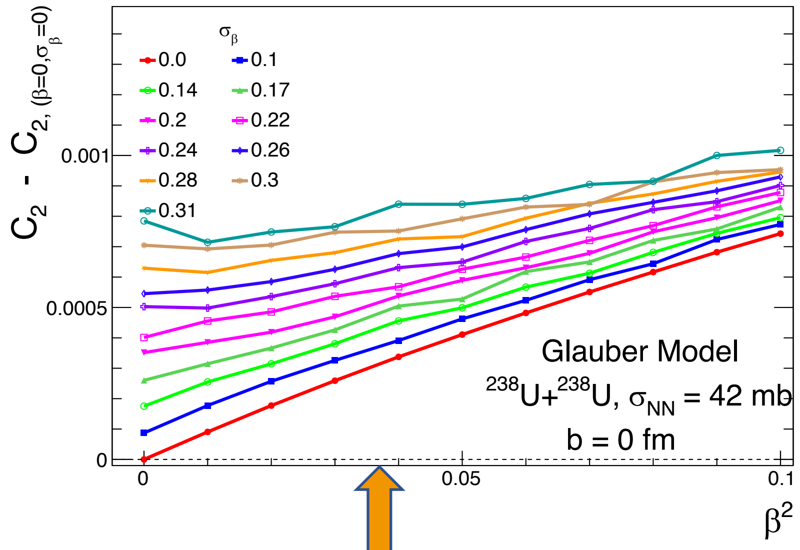
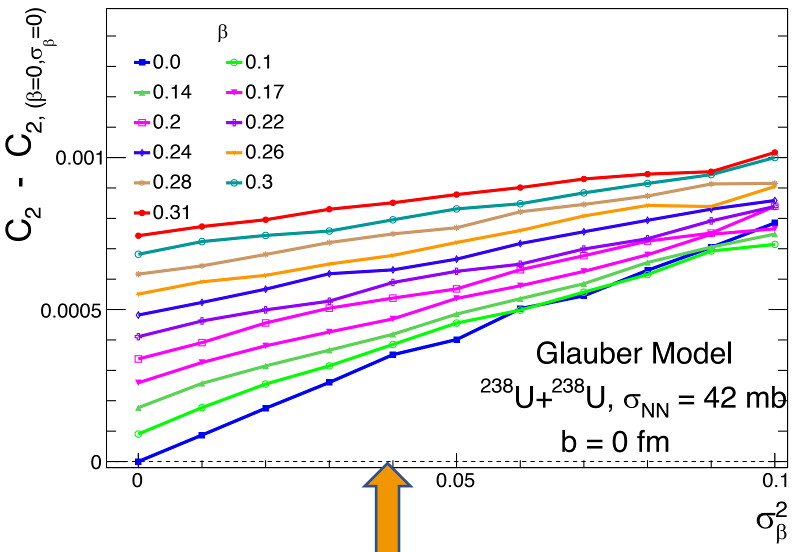
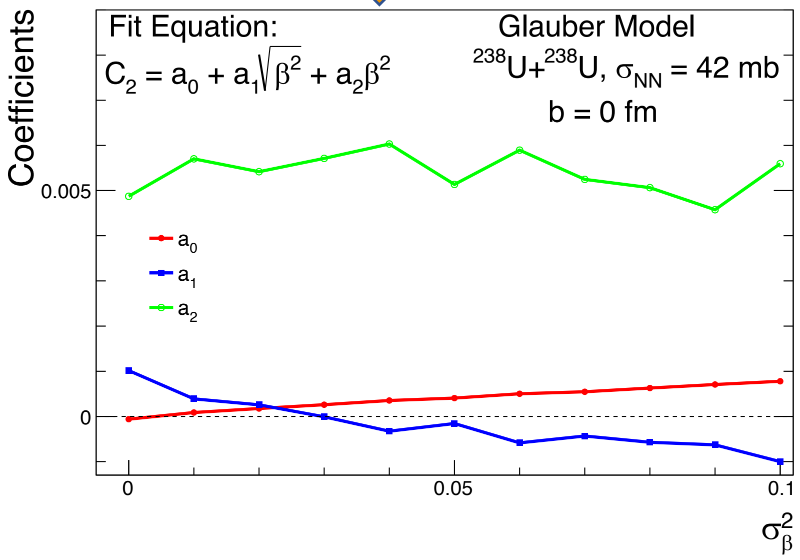
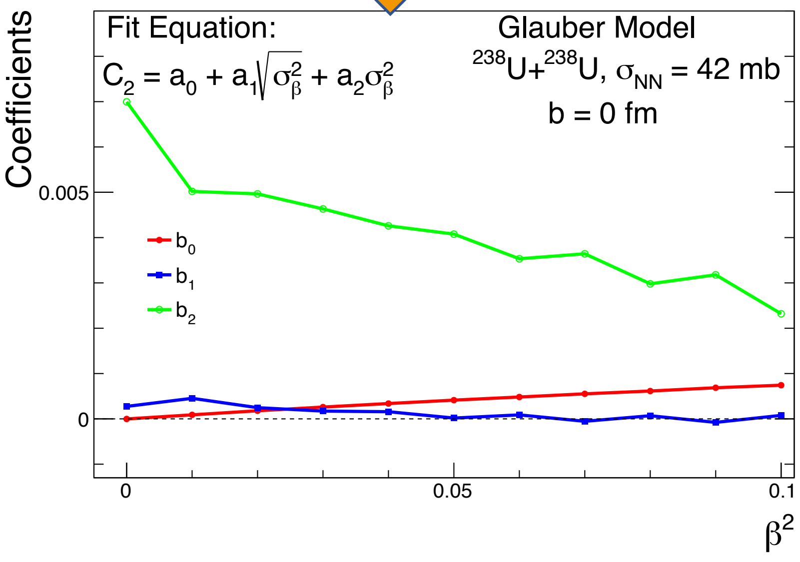




1. dependance is quadratic in both β and σ_β .
2. Dependence of c_2 on linear order of β or σ_β is very small.



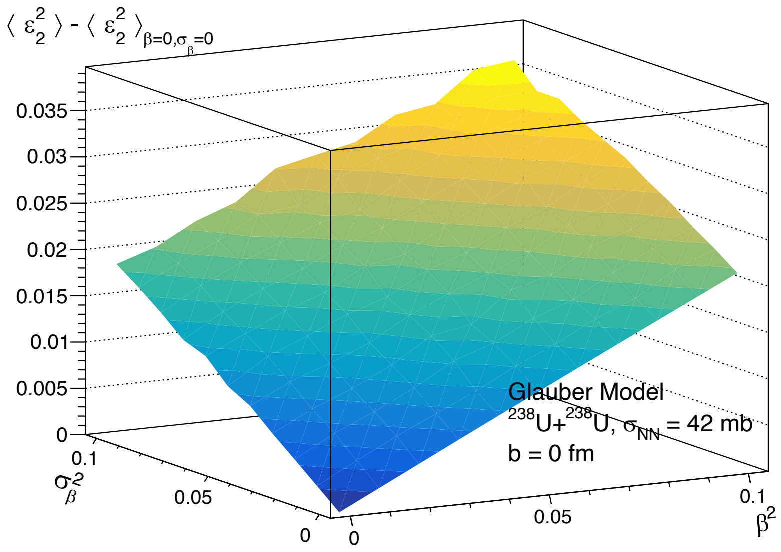


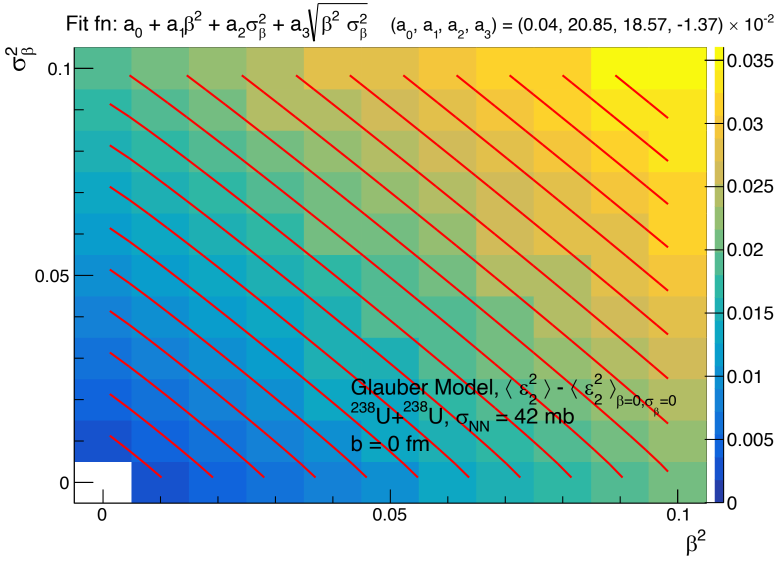
3. A small residual dependence for the coefficient of linear order is observed with β. The same is negligible for σ_β.

$$\langle c_2 \rangle \approx a + b\beta^2 + c\sigma_\beta^2$$

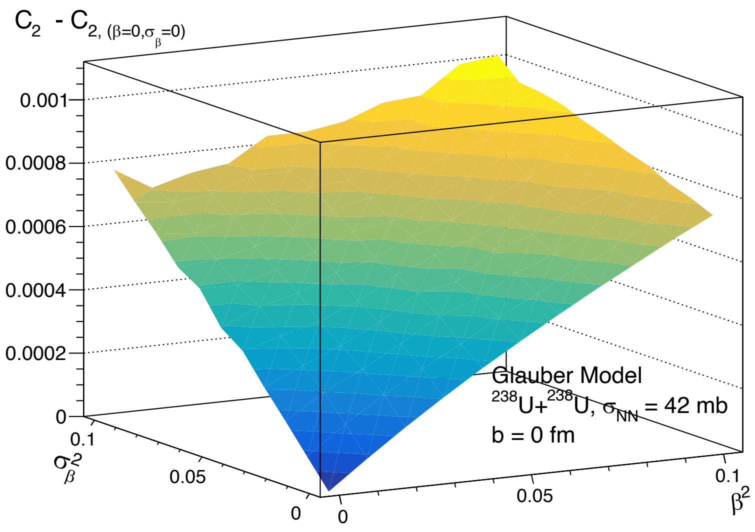
Where b ~ 0.005 and c~0.0045

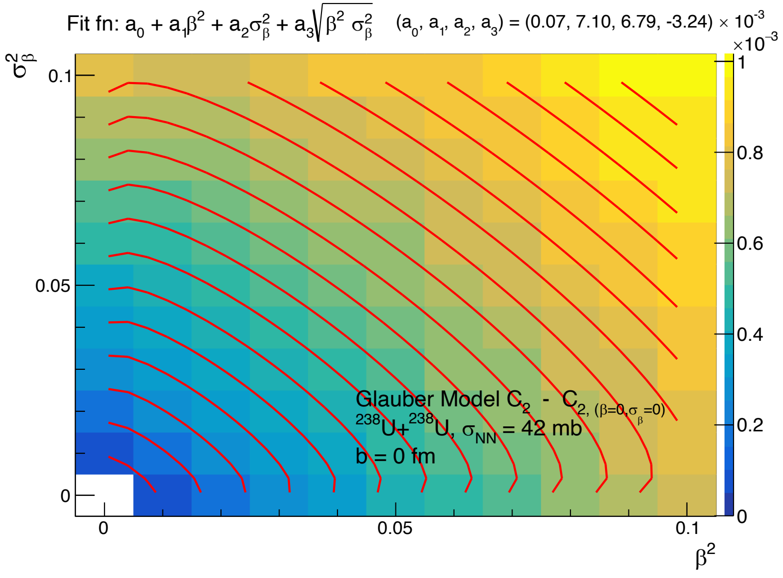
$2D$-Simultaneous fits for 2-Particle correlations





For $\langle \varepsilon_2^2 \rangle$: $a_0 = 0.04\times10^{-2}, a_1 = 20.85\times10^{-2}, a_2 = 18.57\times10^{-2}, \ a_3 = -1.37\times10^{-2}$





For c_2 : $a_0 = 0.07\times10^{-3}, a_1 = 7.1\times10^{-3}, a_2 = 6.79\times10^{-3}, \ a_3 = -3.24\times10^{-3}$

- Homogenous second order polynomial in (β, σ_β) used for fitting.

$$f = a_0 + a_1\beta^2 + a_2\sigma_\beta^2 + a_3\sqrt{(\beta^2\sigma_\beta^2)}$$

- dependence is almost independently quadratic for $< \varepsilon_2^2 >$.
- Coefficient of cross term an order of magnitude smaller than that of the quadratic terms.
- The quadratic coefficients consistent with 1-D fits shown previously.
- The residuals are within 1% of the eccentricity values for almost the entire range : good fit in the entire range of sampled values.

Conclusion and Outlook

- Glauber MC Model was used to investigate effect of shape coexistence in nuclear geometry on 2-particle correlations in $^{238}U + ^{238}U$ Collisions.
- Shape coexistence is observed to have clear effect on 2-particle correlations $\langle \varepsilon_2^2 \rangle$ and c_2.

$$\langle \varepsilon_2^2 \rangle = a + b\beta^2 + c\sigma_\beta^2$$

Where $a \sim 0$, b $\sim$ 0.2 and c$\sim$0.15

$$\langle c_2 \rangle \approx a + b\beta^2 + c\sigma_\beta^2$$

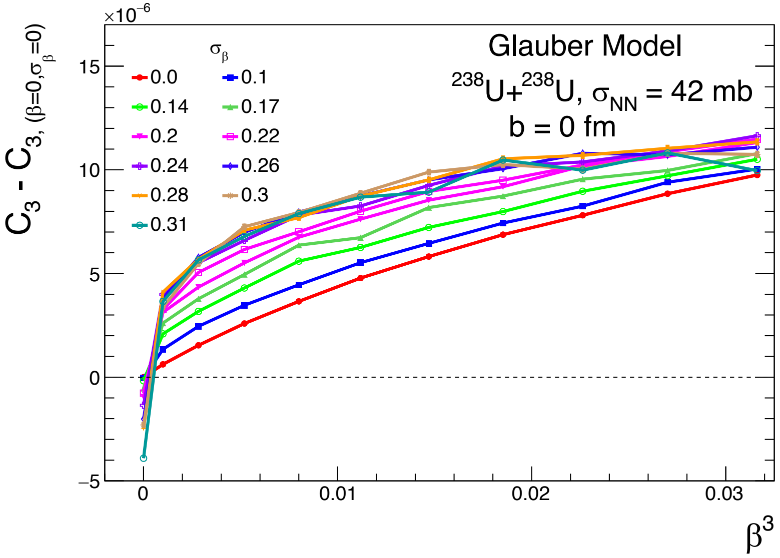
Where $a \sim 0$, b $\sim$ 0.005 and c$\sim$0.0045

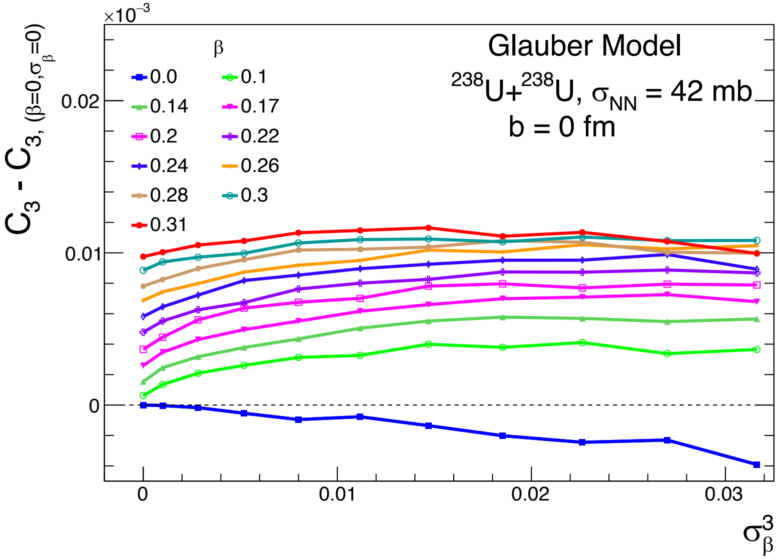
- Both 1-D and 2-D simultaneous fits give consistent coefficients for dependence of 2-Particle correlations on β and σ_β.
- Multi-particle correlations in heavy ion collisions are clearly sensitive to shape coexistence effects and provides a unique method to extract this sensitive property of nuclear structure.

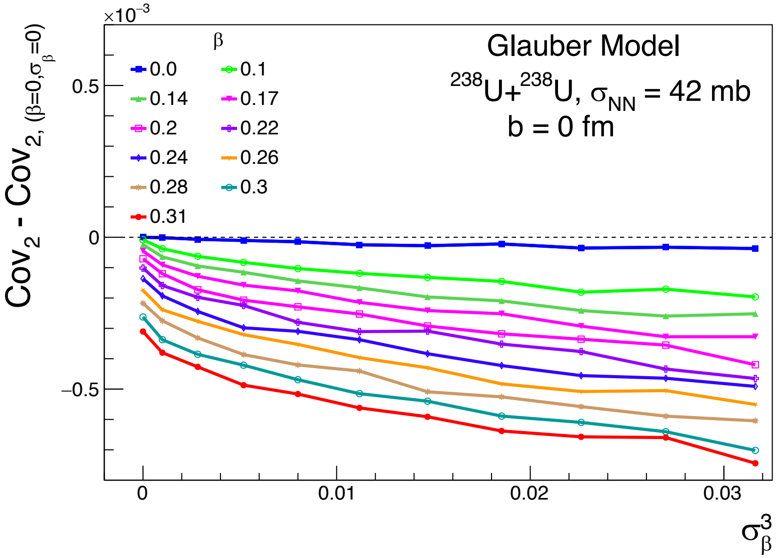
BACKUP

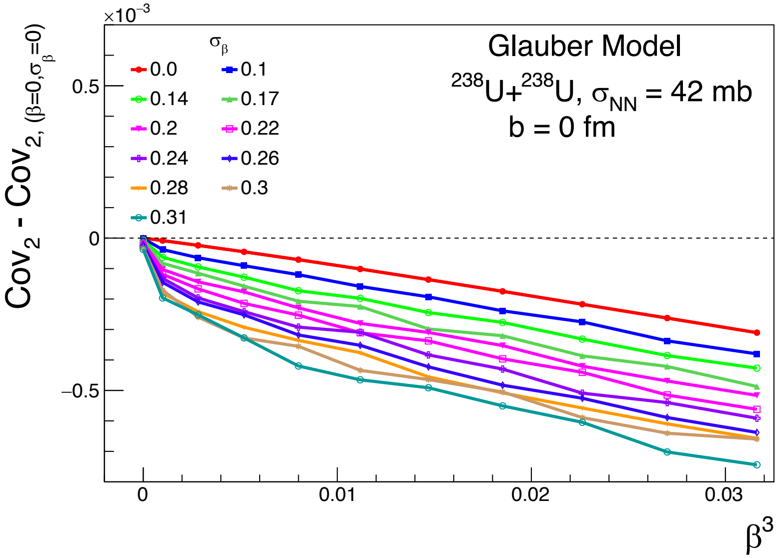
dependence of c_3 and cov_2 on (β, σ_β)

➢ For $\gamma = 0^0$, c_3 and cov_2 being 3-particle correlators is expected to have largest dependence on β^3









$$c_3 = \langle (\delta d_\perp / d_\perp)^3 \rangle \approx a + b\cos(3\gamma)\beta^3$$

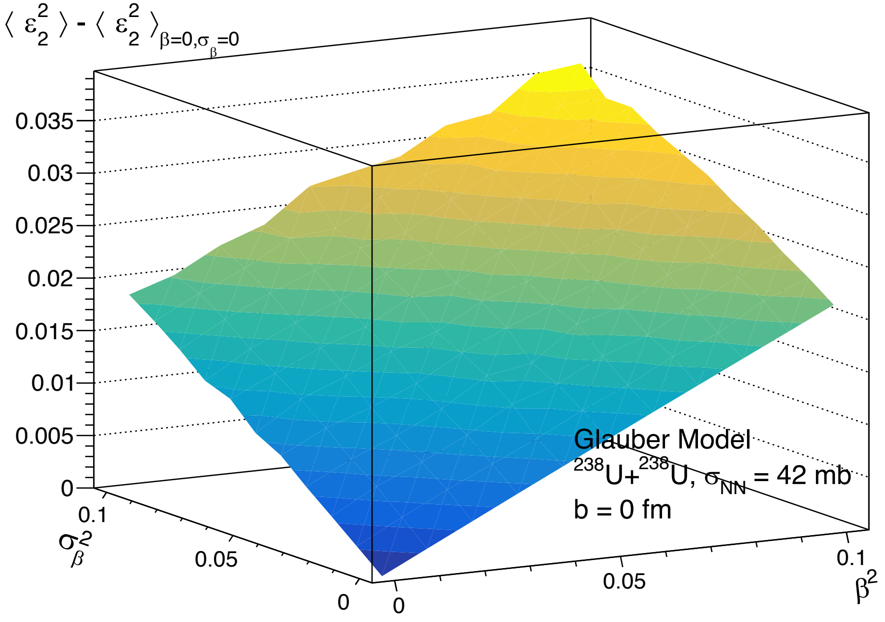
$$cov_2 = \langle \varepsilon_2^2 \delta d_\perp \rangle \approx a - b\cos(3\gamma)\beta^3$$

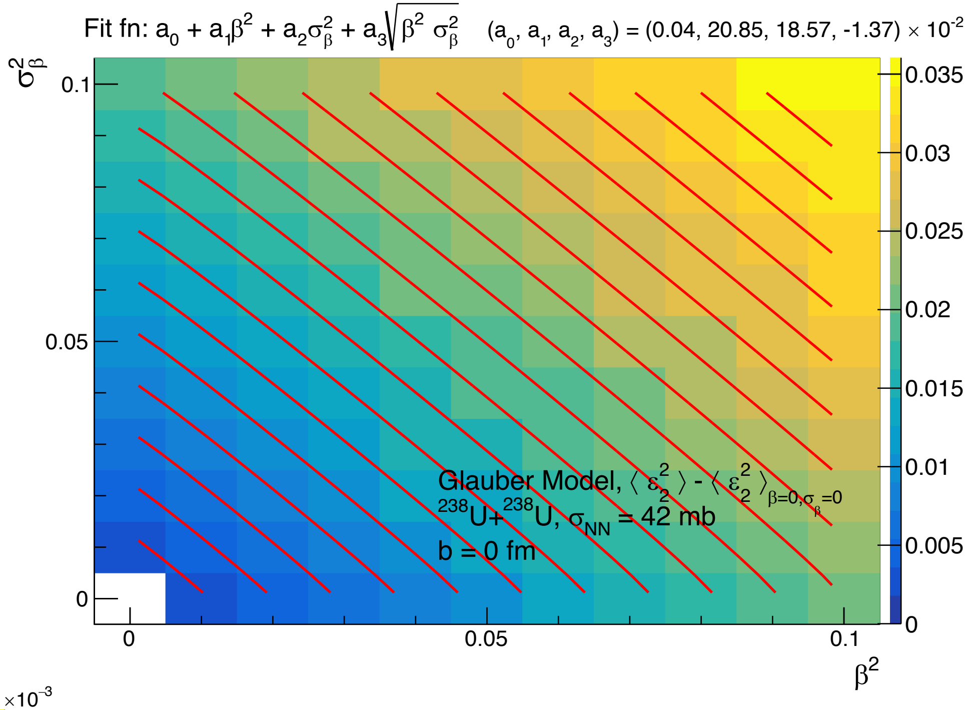
1. With increasing β^3, c_3 increases and cov_2 decreases as expected, almost linearly.

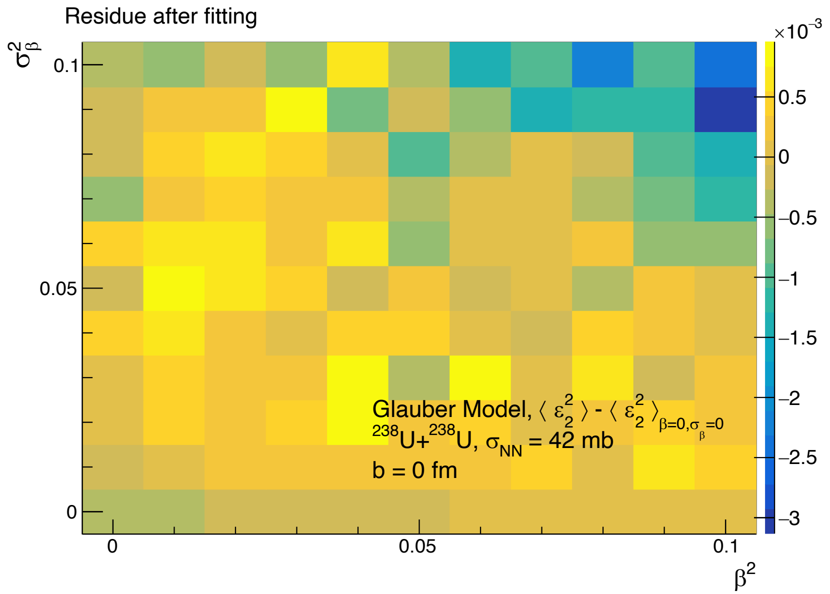
2. With increasing $\sigma_\beta{}^3$, c_3 increases and cov_2 decreases as expected, almost linearly., dependence weaker than that of β^3.

3. For $\beta = 0$ case, having a large σ_β inverses the trend for c_3 .
   This probably arises from the dependency on σ_β , which could have different coefficients for c_3 (eg: negative)and cov_2 (eg: posititve).
   Further study required for exact dependency on σ_β

$2D$-Simultaneous fits for $\langle \varepsilon_2^2 \rangle$







$2D$-Simultaneous fits for c_2