Ultra-Peripheral Collisions as a Nuclear-Structure Interferometer with Interpretable Multitask Deep Learning

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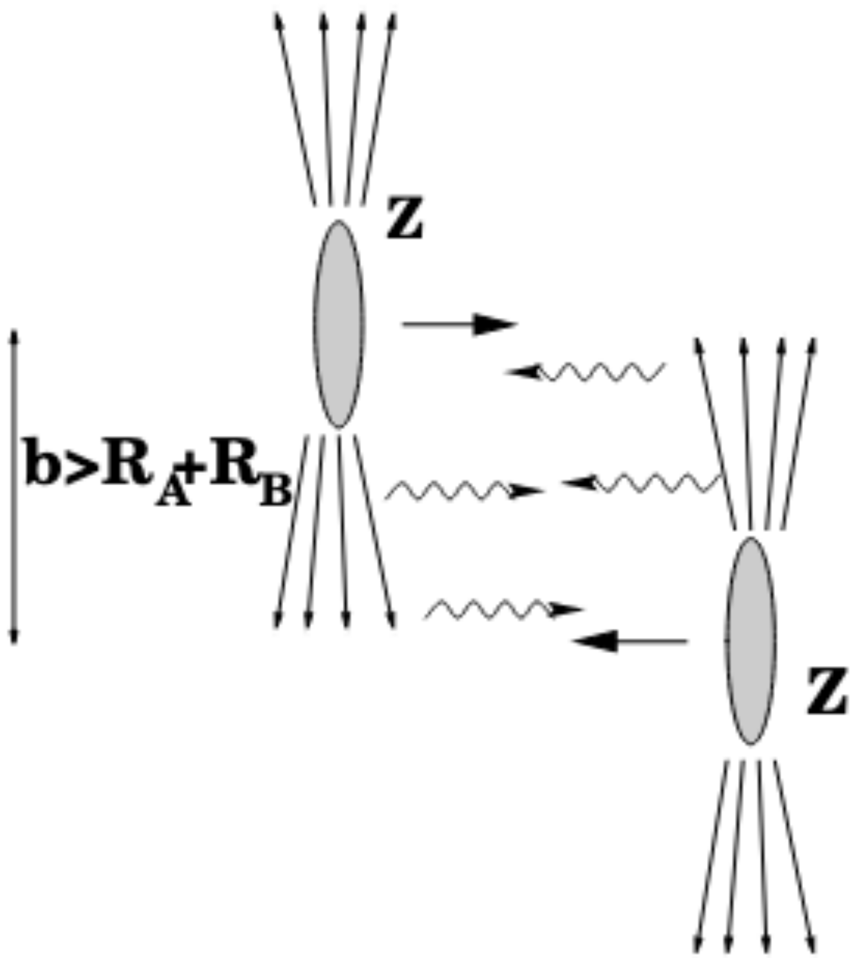
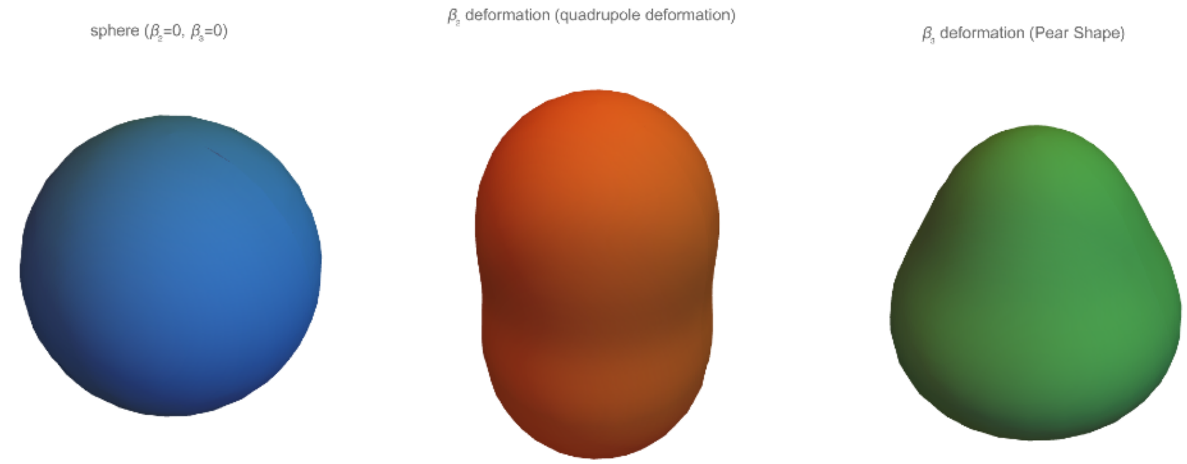
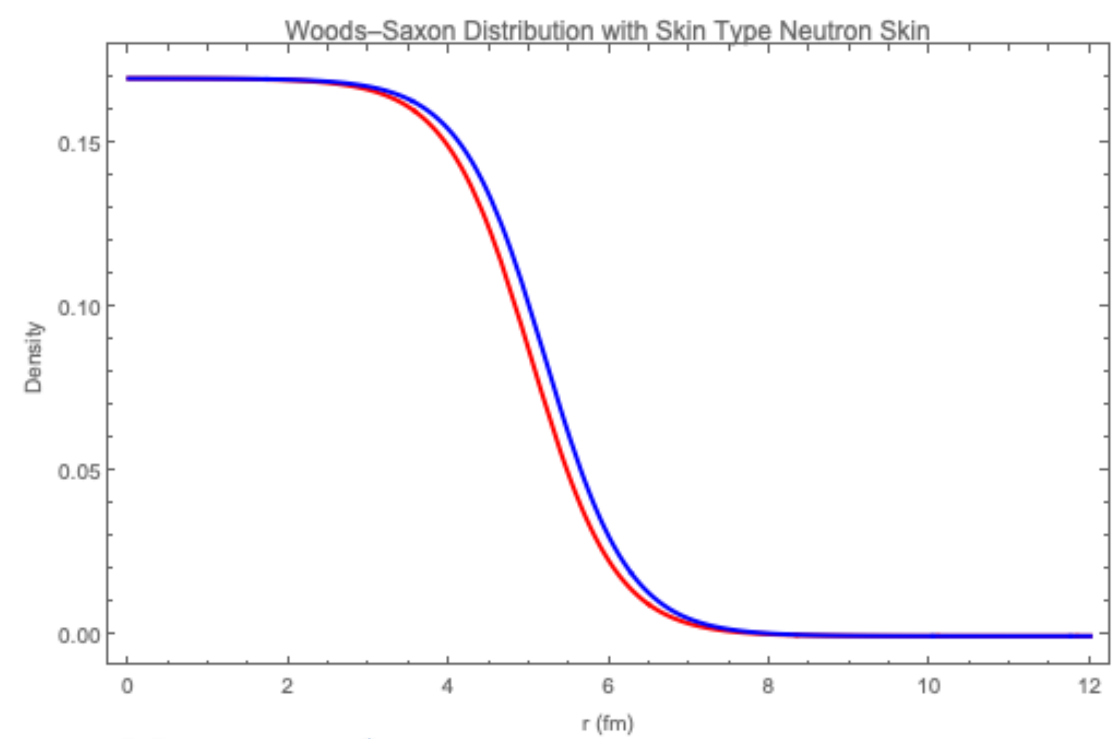
Research Background

Probing Nuclear Structure via UPCs and AI-Guided Strategy







UPC coherent production →sensitive to nuclear structure

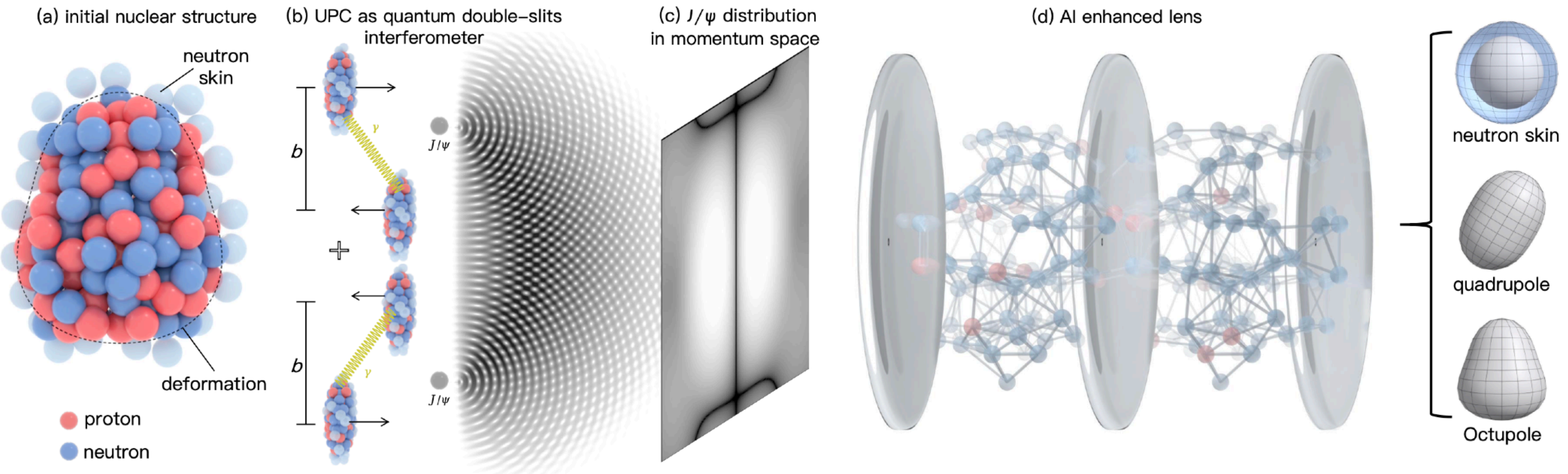
Retrieving these parameters from final state → "Inverse Problem"

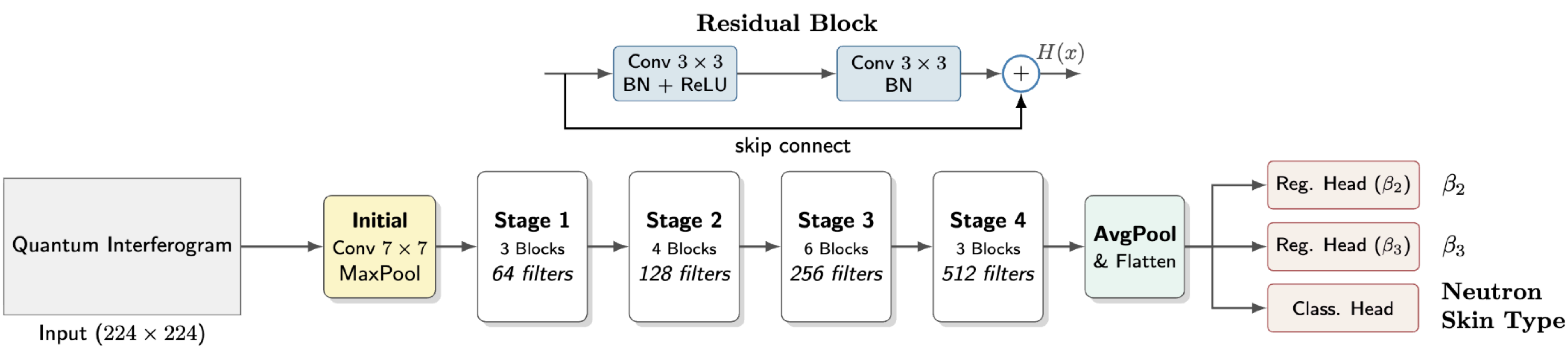
Deep Learning → decouple these parameters,

Design interpretable observables → bridge AI "Black Box" and physics

Workflow

Inferring Nuclear Structure from (p_x, p_y) Distributions





Simulation of UPC Photonuclear Processes

VMD+Glauber

density of nucleus (WS)

$$\rho_A(r) = \frac{\rho^0}{1 + exp[(r - R_{ws})/d]}$$

nuclear electromagnetic form

$$F(\vec{q}) = \int d^3\vec{r}\rho(\vec{r})e^{-\vec{q}\cdot\vec{r}}$$

nuclear thickness function

$$T'(\vec{r}) = \int_{-\infty}^{+\infty} dz\rho(\sqrt{\vec{r}^2 + z^2})e^{iq_L z}$$

photon flux

$$\frac{d^3N_\gamma(\omega_\gamma, \vec{x}_\perp)}{d\omega_\gamma d\vec{x}_\perp} = \frac{4Z^2\alpha}{\omega_\gamma}\left|\int \frac{d^2\vec{k}_{\gamma\perp}}{(2\pi)^2}\vec{k}_{\gamma\perp}\frac{F_\gamma(\vec{k}_\gamma)}{|\vec{k}_\gamma|^2}e^{i\vec{x}_\perp\cdot\vec{k}_{\gamma\perp}}\right|^2$$

Where $\vec{k}_\gamma = (\vec{k}_{\gamma\perp}, \frac{\omega_\gamma}{\gamma_c})$; $\omega_\gamma = M_{J/\psi}e^{\pm y}/2$

scattering amplitude

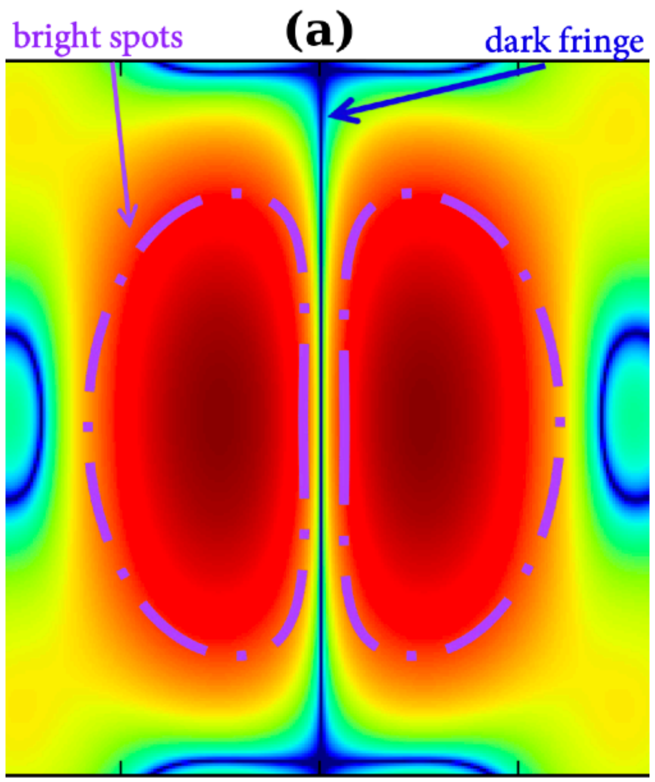
$$\Gamma_{\gamma A\to J/\psi A}(\vec{r}) = \frac{f_{\gamma p\to J/\psi N}(0)}{\sigma_{J/\psi N}} \times 2 \times [1 - exp(-\frac{\sigma_{J/\psi N}}{2} \times T'(\vec{r}))]$$

the amplitudes for J/ψ

$$A(y, \vec{r}, \pm\frac{\vec{b}}{2}) = \Gamma_{\gamma A\to J/\psi A}(\vec{r} \pm \frac{\vec{b}}{2}) \times \sqrt{\frac{d^2N_\gamma(\vec{r} \pm \frac{\vec{b}}{2})}{d^2r}}$$

probability distribution of J/ψ in momentum space

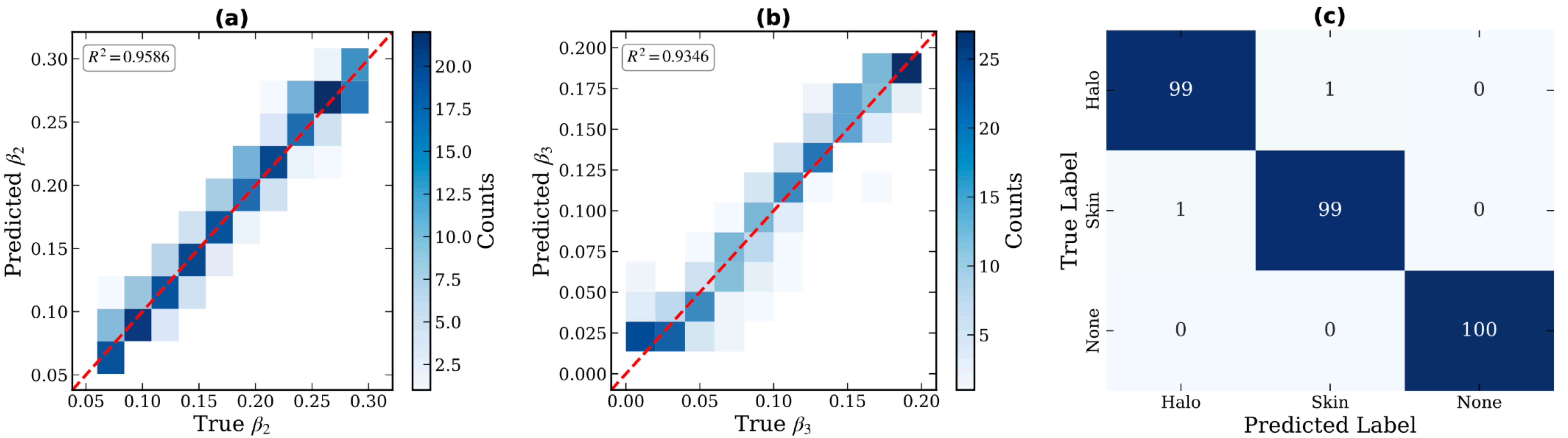
$$\frac{d^2P}{dp_xdp_y} = \frac{1}{2\pi}\left|\int d^2r\left[A_1(y, \vec{r}, -\frac{\vec{b}}{2}) - A_2(y, \vec{r}, +\frac{\vec{b}}{2})\right]e^{i\vec{p}\cdot\vec{r}}\right|^2$$



Zha et al. Physical Review C, 2019, 99(6): 061901.

Model Performance

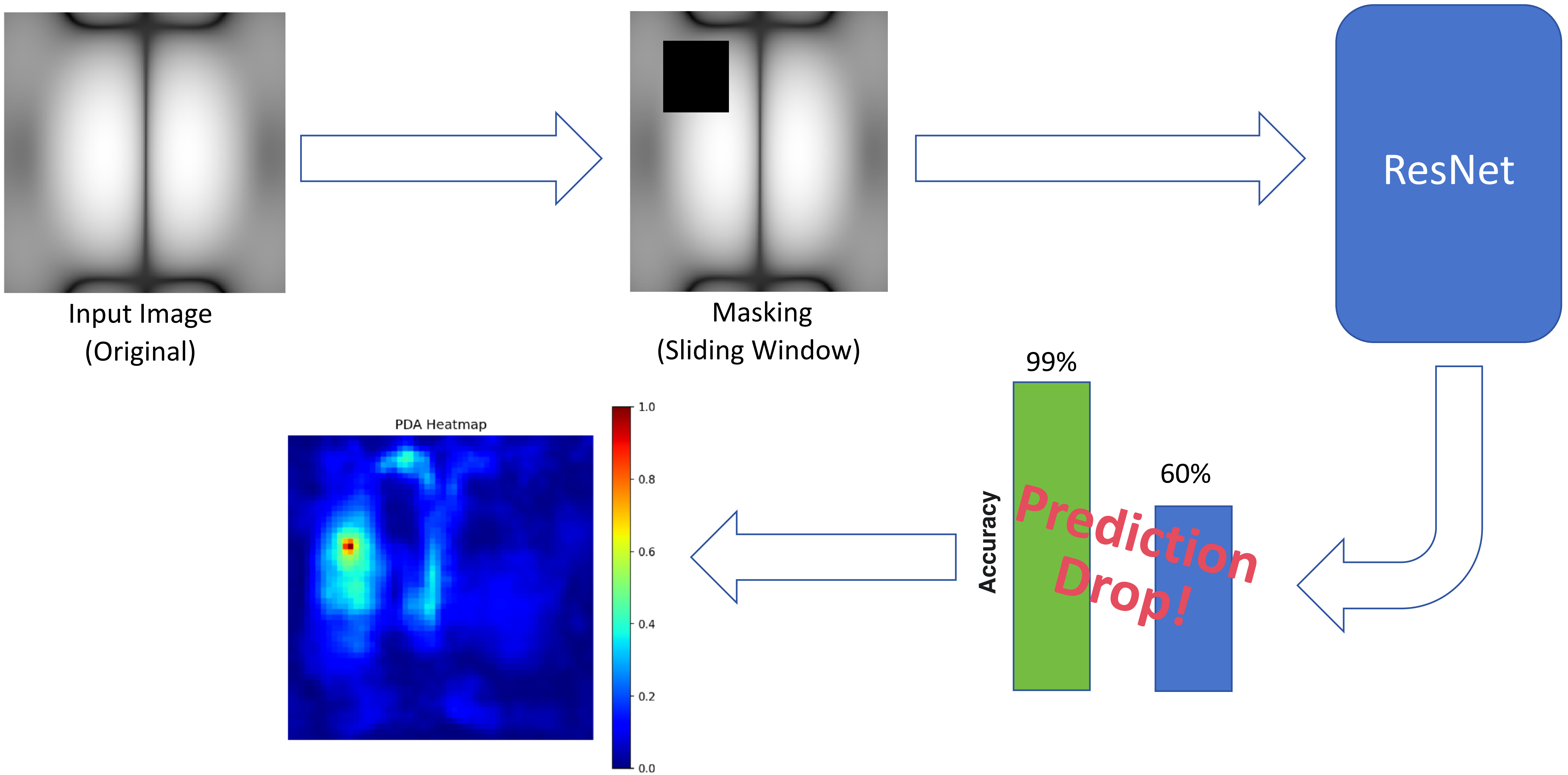
Prediction Accuracy of the ResNet Model



The model successfully handles multi-task learning, achieving high accuracy in simultaneously predicting deformation and neutron skin, even in the presence of incoherent noises.

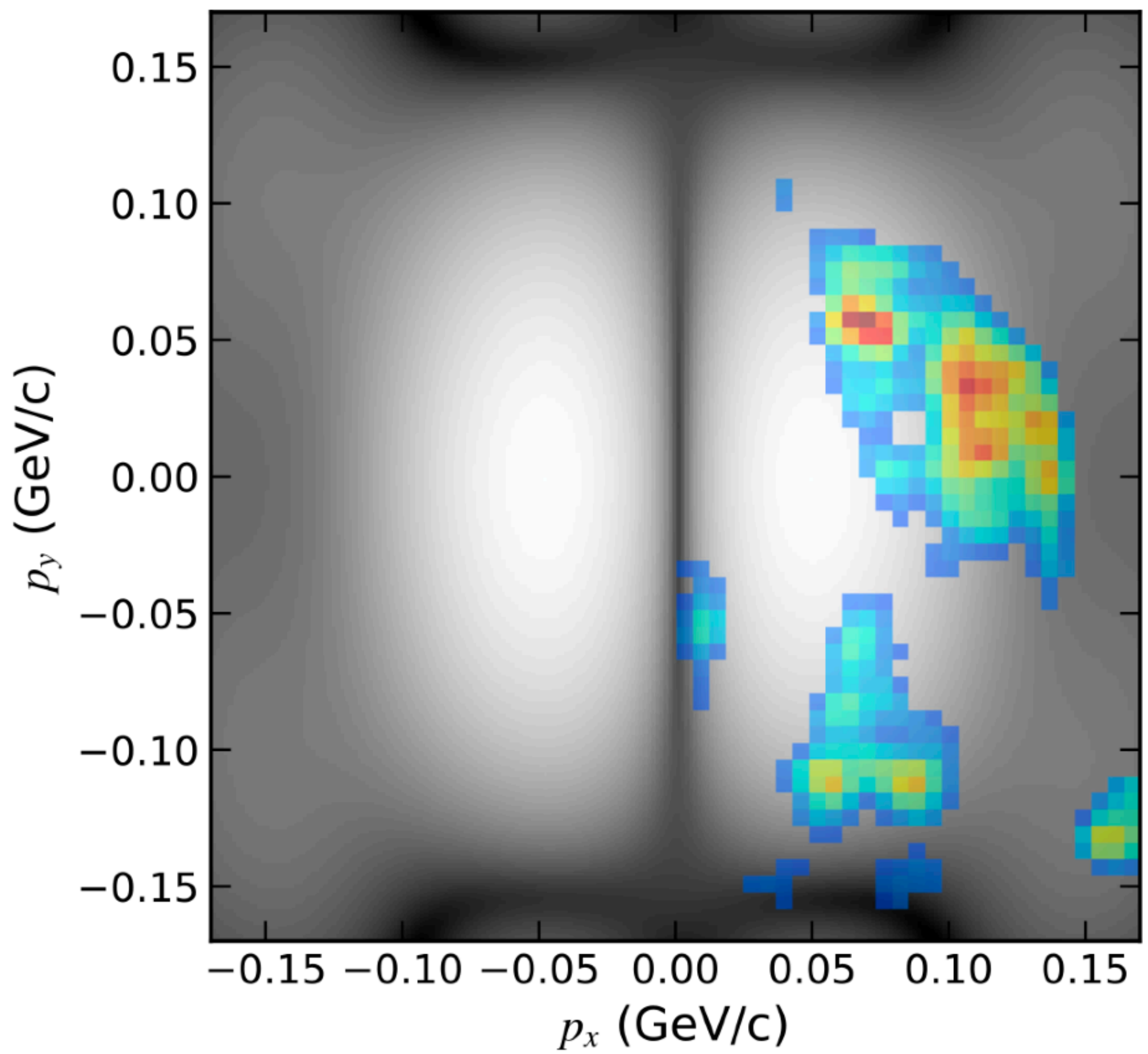
Interpretability Method

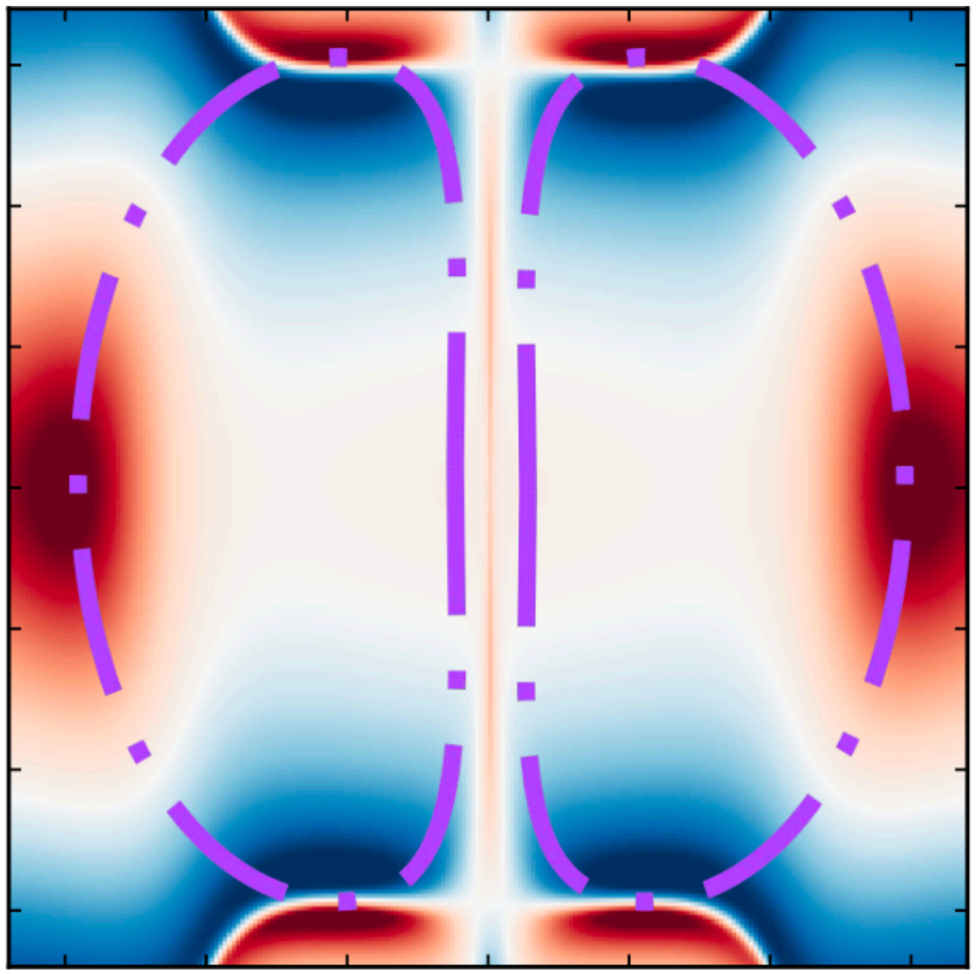
Prediction Difference Analysis (PDA)



Interpretability Analysis

Neutron Skin Effect

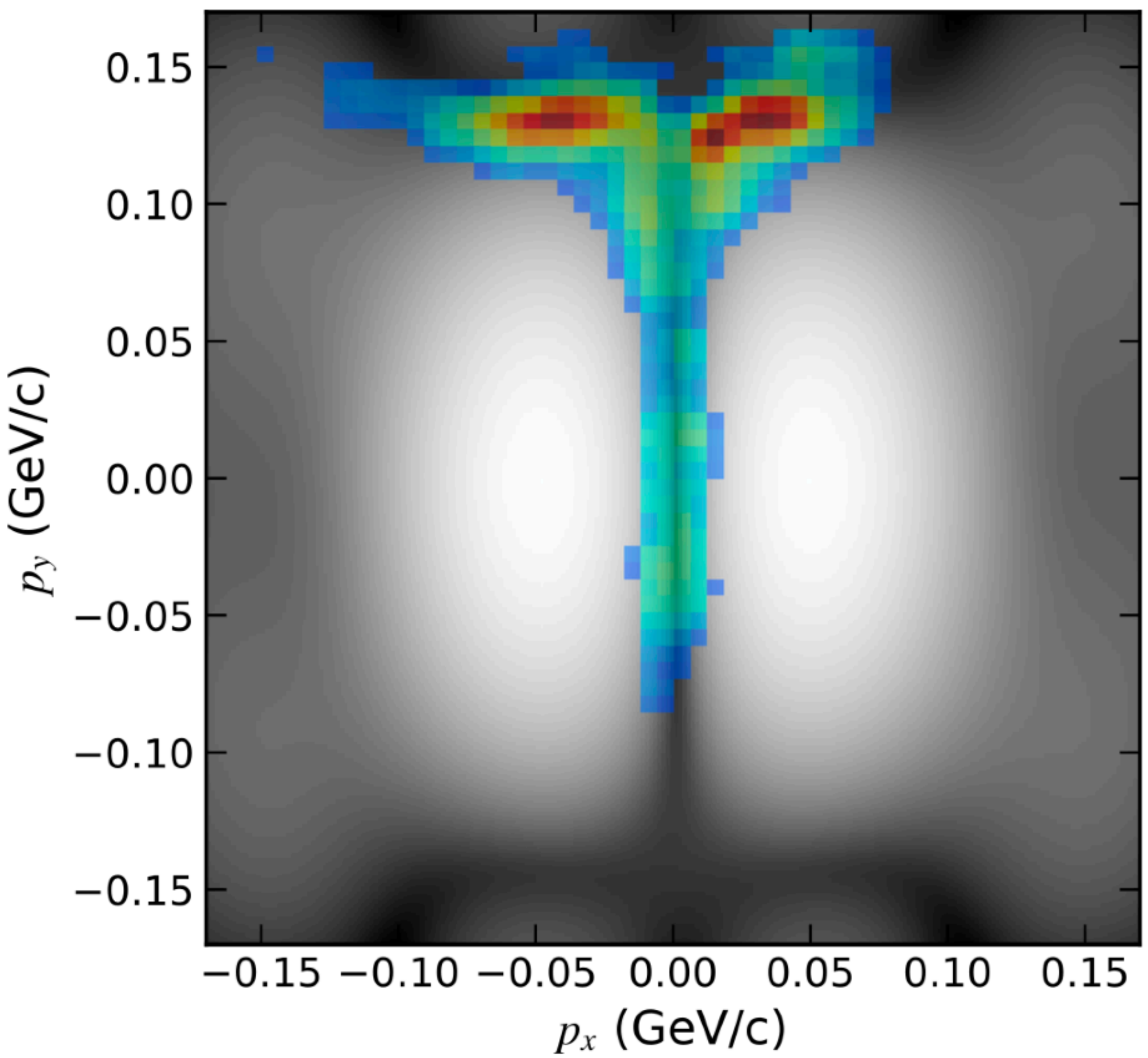


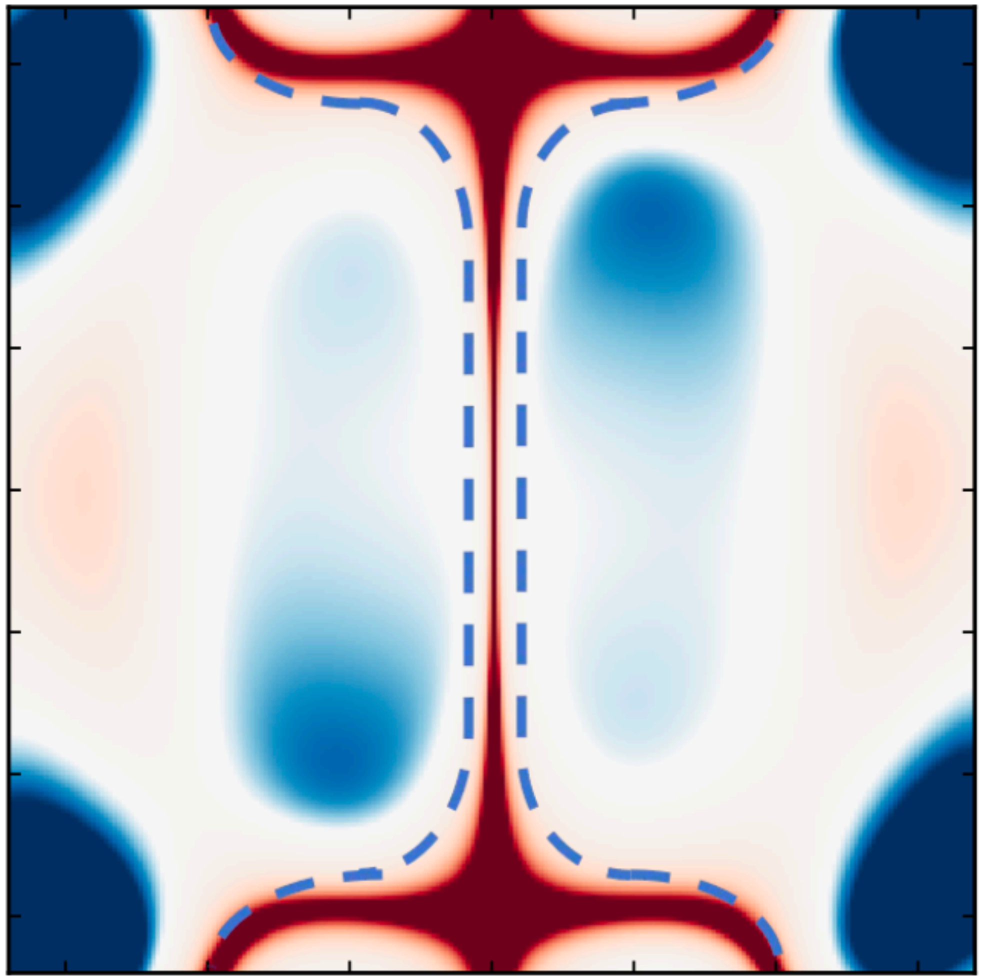


For neutron-skin classification, model focuses on **bright spots.**

Interpretability Analysis

Deformation





For (β2,β3), the model focuses on the **dark fringes.**

Physical Mechanism

Optical Analogy for Neutron Skin

$$\frac{d^2P}{dp_x dp_y} = \left| \mathscr{F}^{-1}\left\{A_1(\vec{r} - \frac{\vec{b}}{2})\right\} - \mathscr{F}^{-1}\left\{A_2(\vec{r} + \frac{\vec{b}}{2})\right\} \right|^2$$

$$= \left| \mathscr{F}^{-1}\left\{A_1(\vec{r})\right\} e^{i\vec{p}\cdot\frac{\vec{b}}{2}} - \mathscr{F}^{-1}\left\{A_2(\vec{r})\right\} e^{-i\vec{p}\cdot\frac{\vec{b}}{2}} \right|^2$$

Interference term
(Impact parameter b)

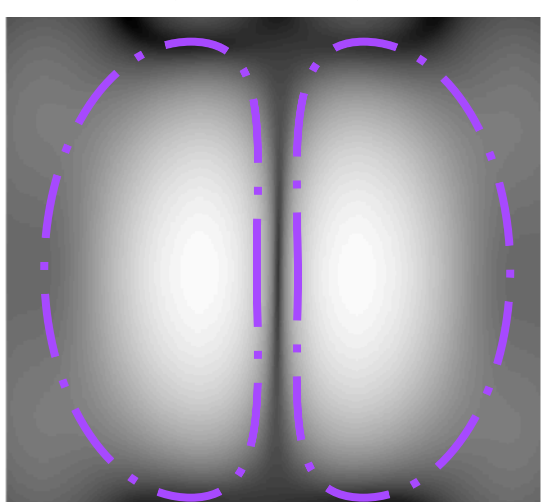
$$\vec{p} \cdot \vec{b} = 2n\pi$$

The two nuclei are an identical sphere: $A_1 = A_2 = A$

$$\frac{d^2P}{dp_x dp_y} = |\mathscr{F}^{-1}\{A(\vec{r})\}\ (e^{i\vec{p}\cdot\frac{\vec{b}}{2}} - e^{-i\vec{p}\cdot\frac{\vec{b}}{2}})|^2 = 4\underbrace{|\mathscr{F}^{-1}\{A(\vec{r})\}|^2}\overbrace{sin^2(\vec{p}\cdot\frac{\vec{b}}{2})}$$

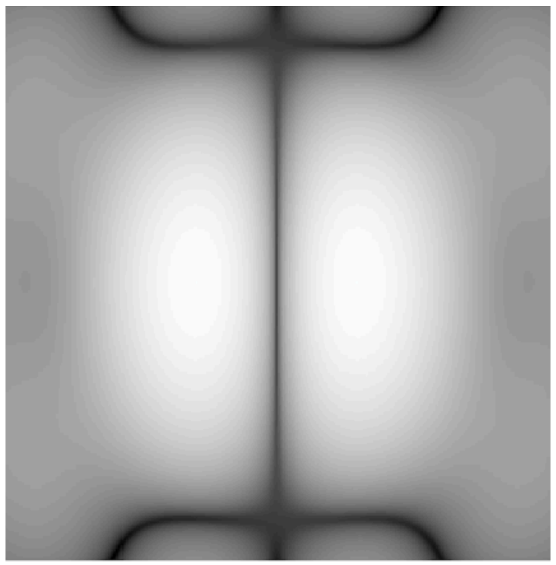
Diffraction term
(Structure info)

input example

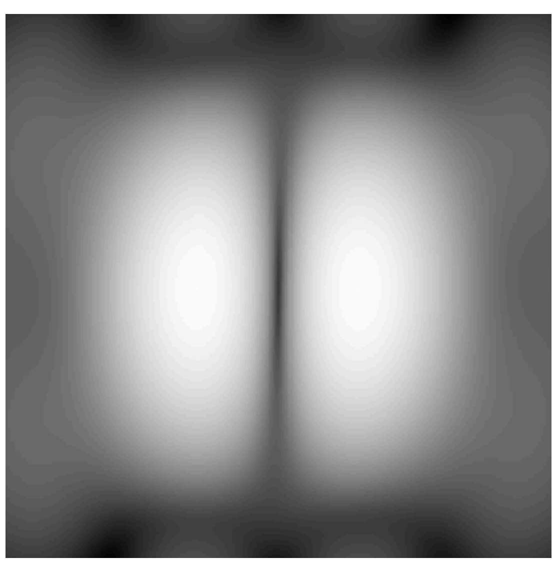


Physical Mechanism

Optical Analogy for Nuclear Deformation



Small deformation:
Sharp fringes



Large deformation:
Smeared fringes
(Phase averaging effect)

$$\frac{d^2P}{dp_x dp_y} = \left| \mathcal{F}^{-1}\{A_1(\vec{r})\} e^{i\vec{p}\cdot\frac{\vec{b}}{2}} - \mathcal{F}^{-1}\{A_2(\vec{r})\} e^{-i\vec{p}\cdot\frac{\vec{b}}{2}} \right|^2$$

$$= F_1^2 + F_2^2 - F_1 F_2^* e^{i\overrightarrow{p}\cdot\overrightarrow{b}} - F_1^* F_2 e^{-i\overrightarrow{p}\cdot\overrightarrow{b}}$$

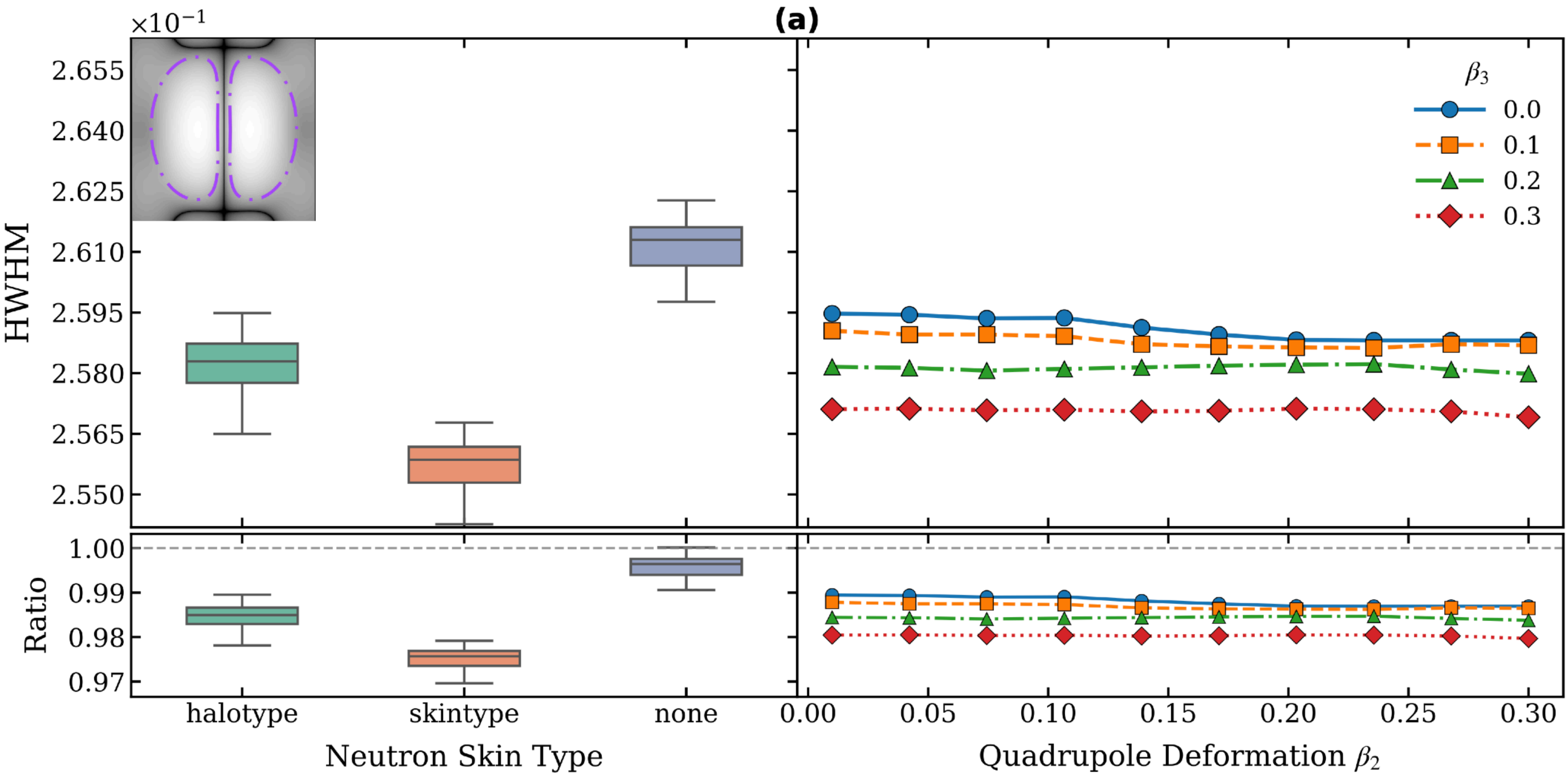
$$= F_1^2 + F_2^2 - |F_1 F_2| \left(e^{i(\overrightarrow{p}\cdot\overrightarrow{b}+\Delta\phi)} + e^{-i(\overrightarrow{p}\cdot\overrightarrow{b}+\Delta\phi)} \right)$$

$$= F_1^2 + F_2^2 - 2|F_1 F_2| cos(\overrightarrow{p}\cdot\overrightarrow{b} + \Delta\phi)$$

The location of the interference dark fringes shifts from $\overrightarrow{p}\cdot\overrightarrow{b} = 2n\pi$ in the spherical nucleus to $\overrightarrow{p}\cdot\overrightarrow{b} = 2n\pi - \Delta\phi$.

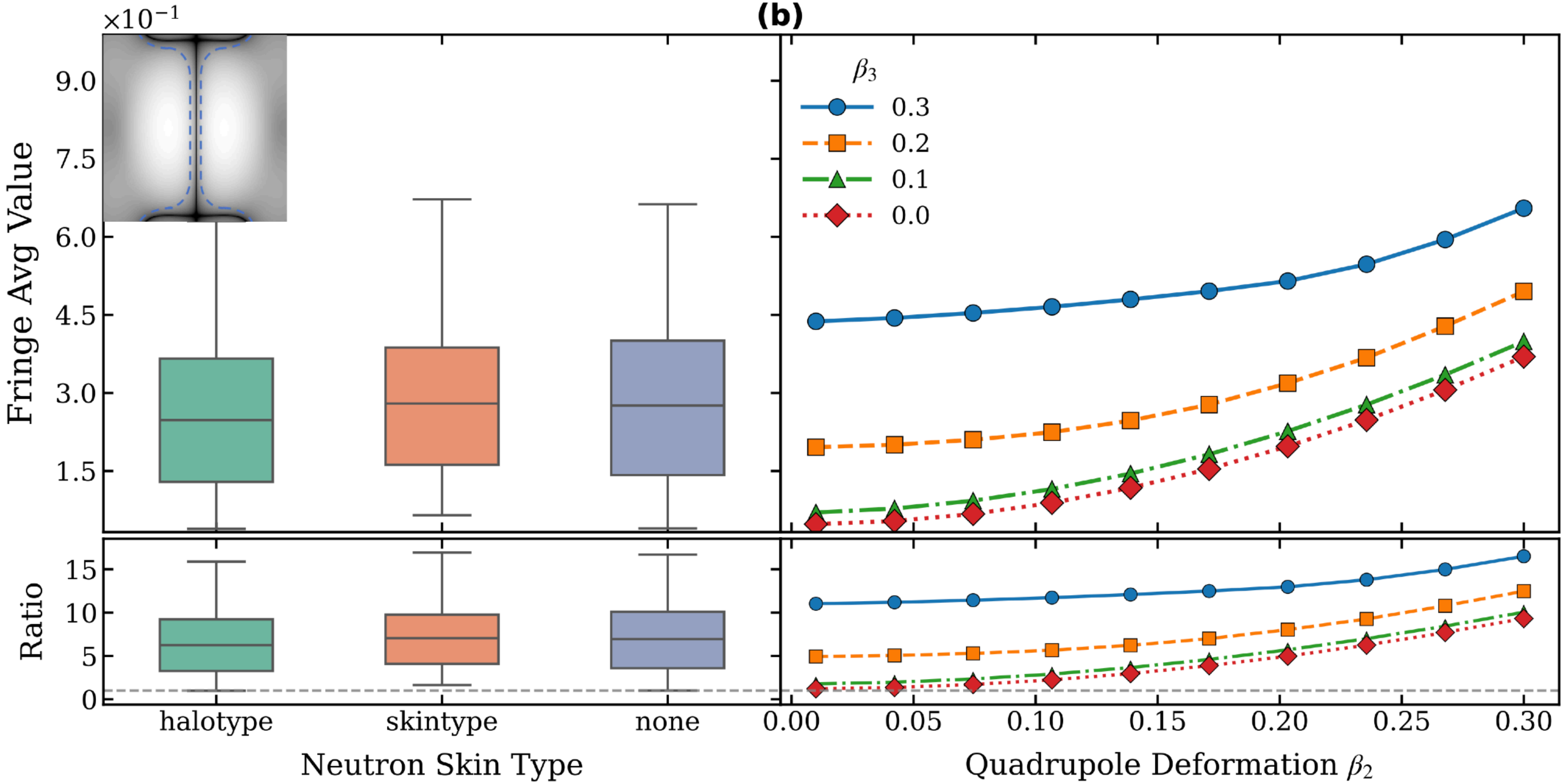
Proposed Observables Guided by Deep Learning

Neutron Skin Effect



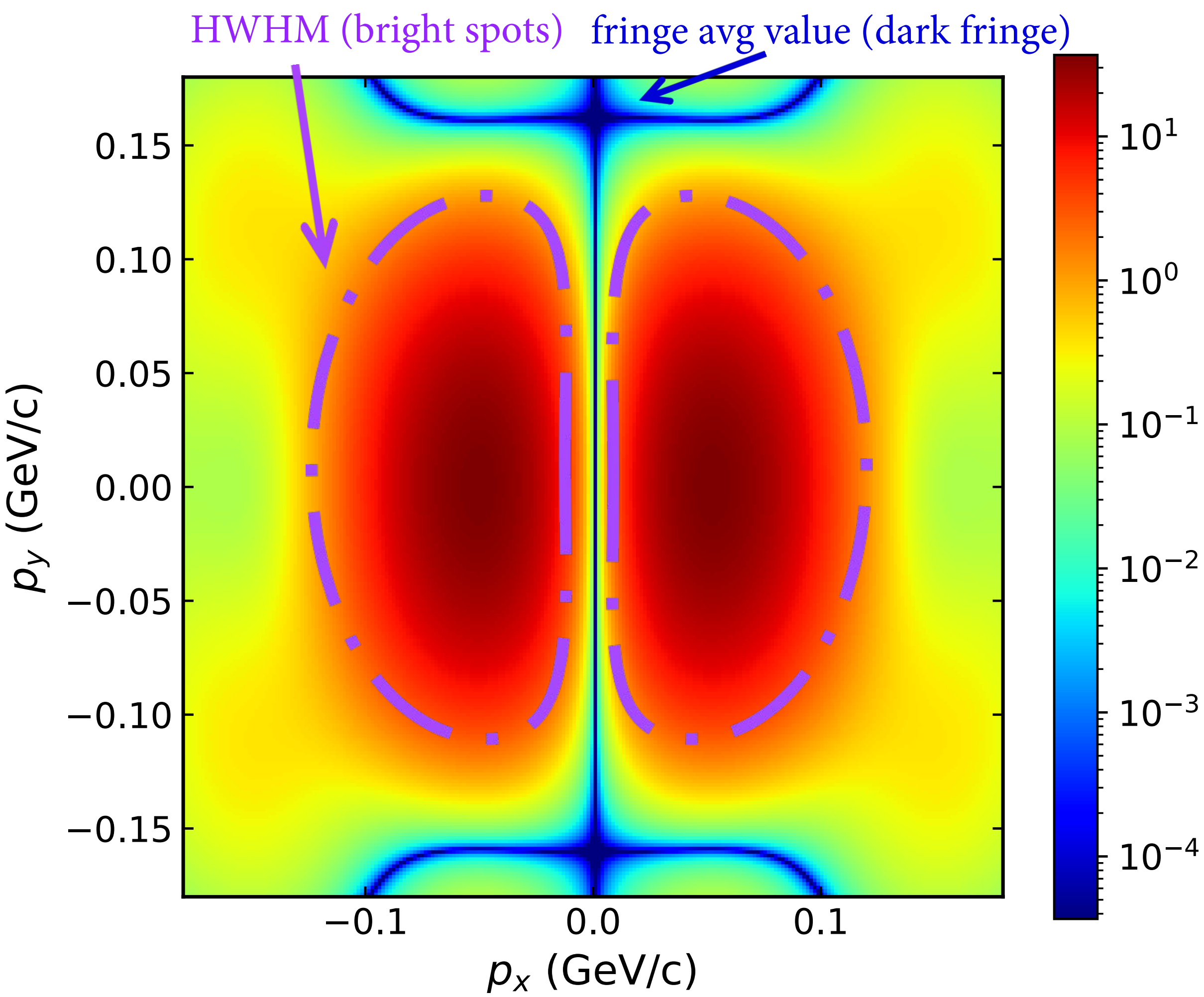
Proposed Observables Guided by Deep Learning

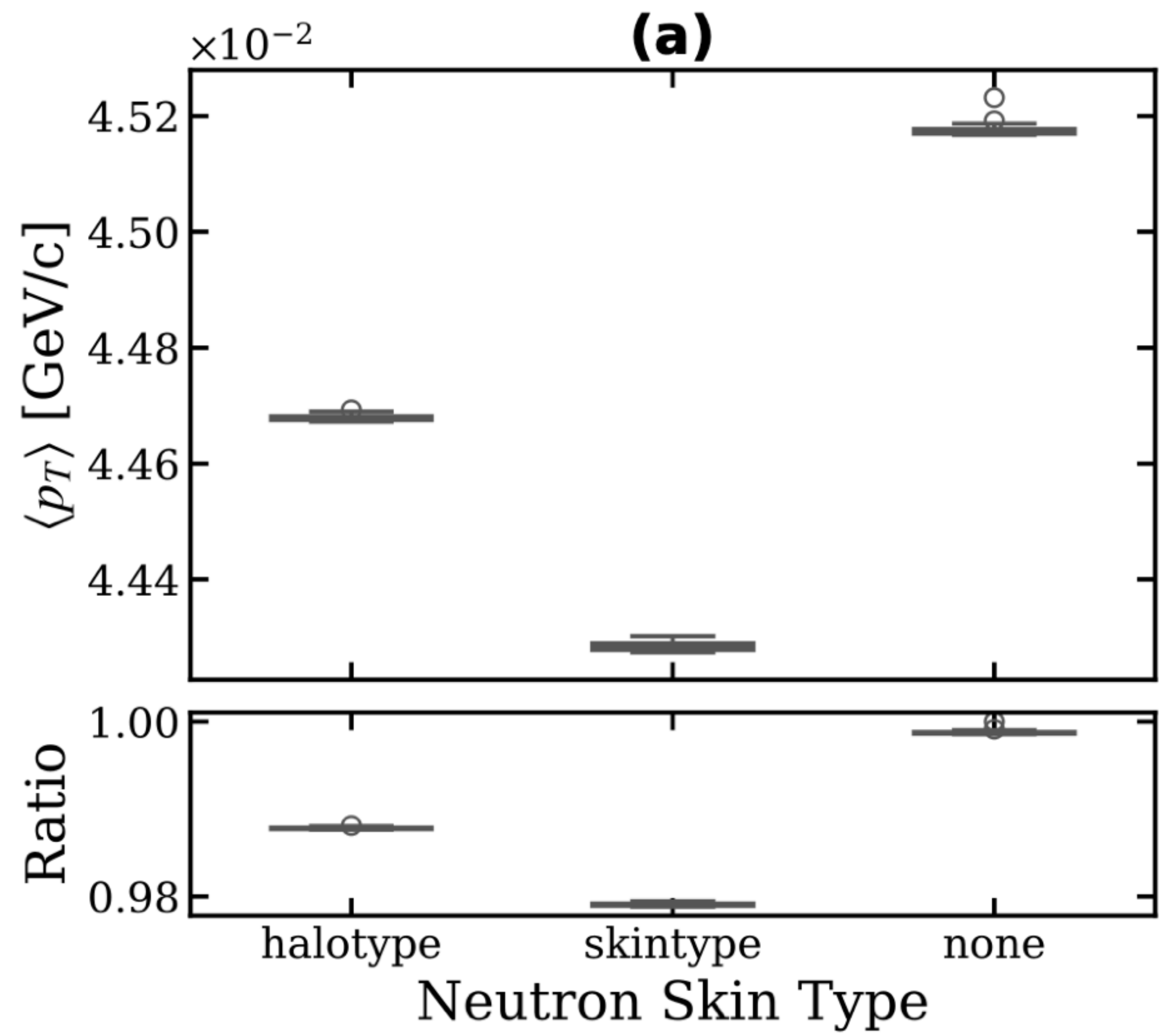
Deformation



Connection to Traditional Observables

mean pT





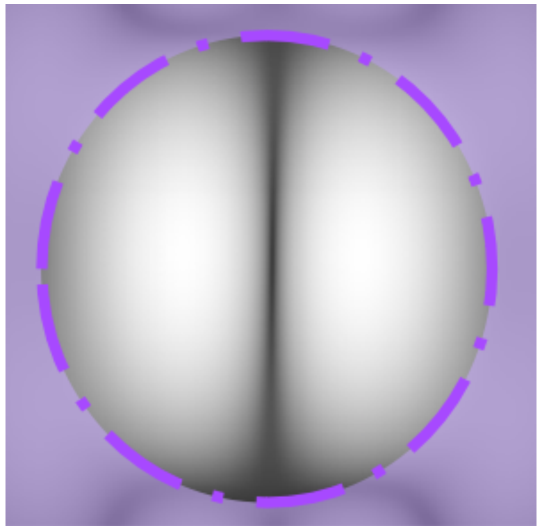
HWHM ⇒ Mean p_T

A larger HWHM (broader central spot) → momentum distribution extends to higher p_T

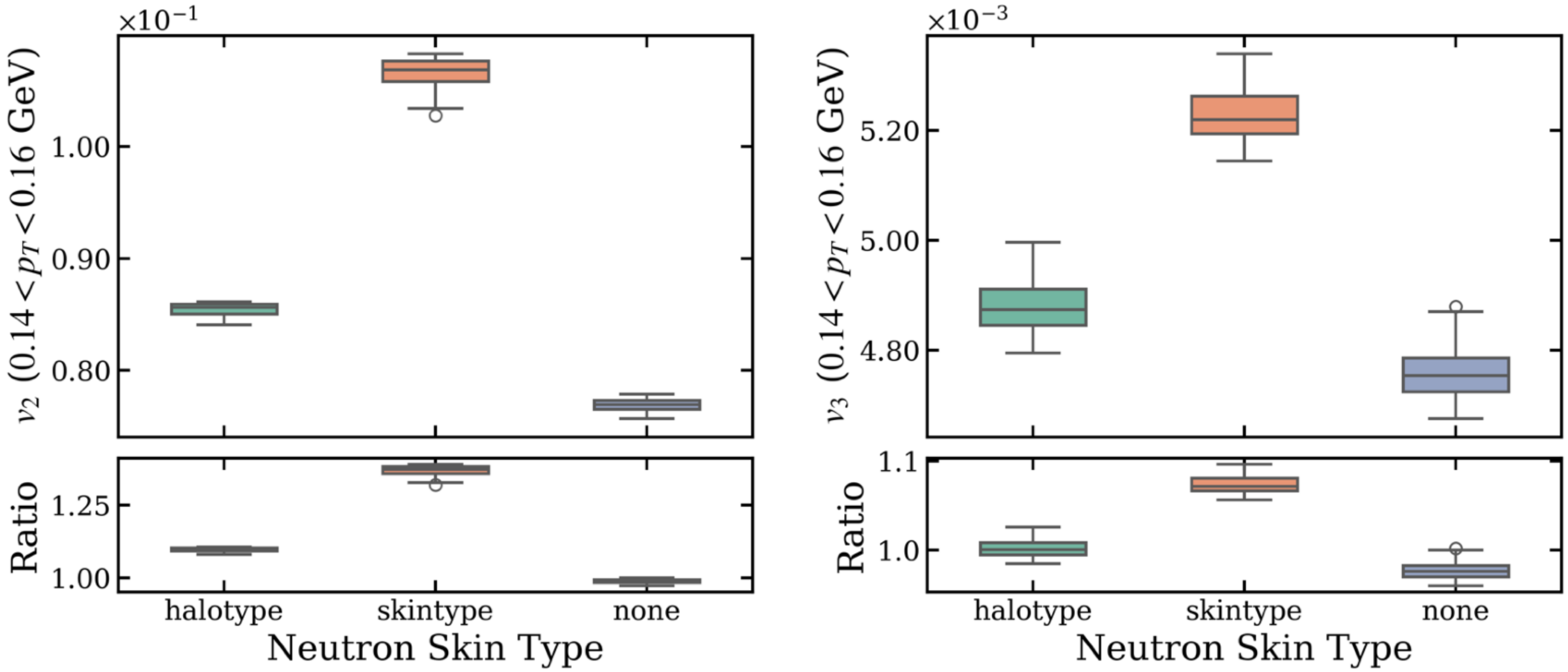
Result: larger HWHM to higher mean p_T

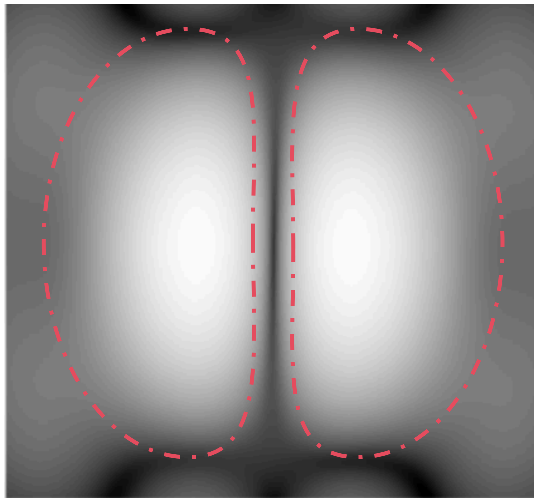
Connection to Traditional Observables

flow



0.14GeV<pt<0.16GeV



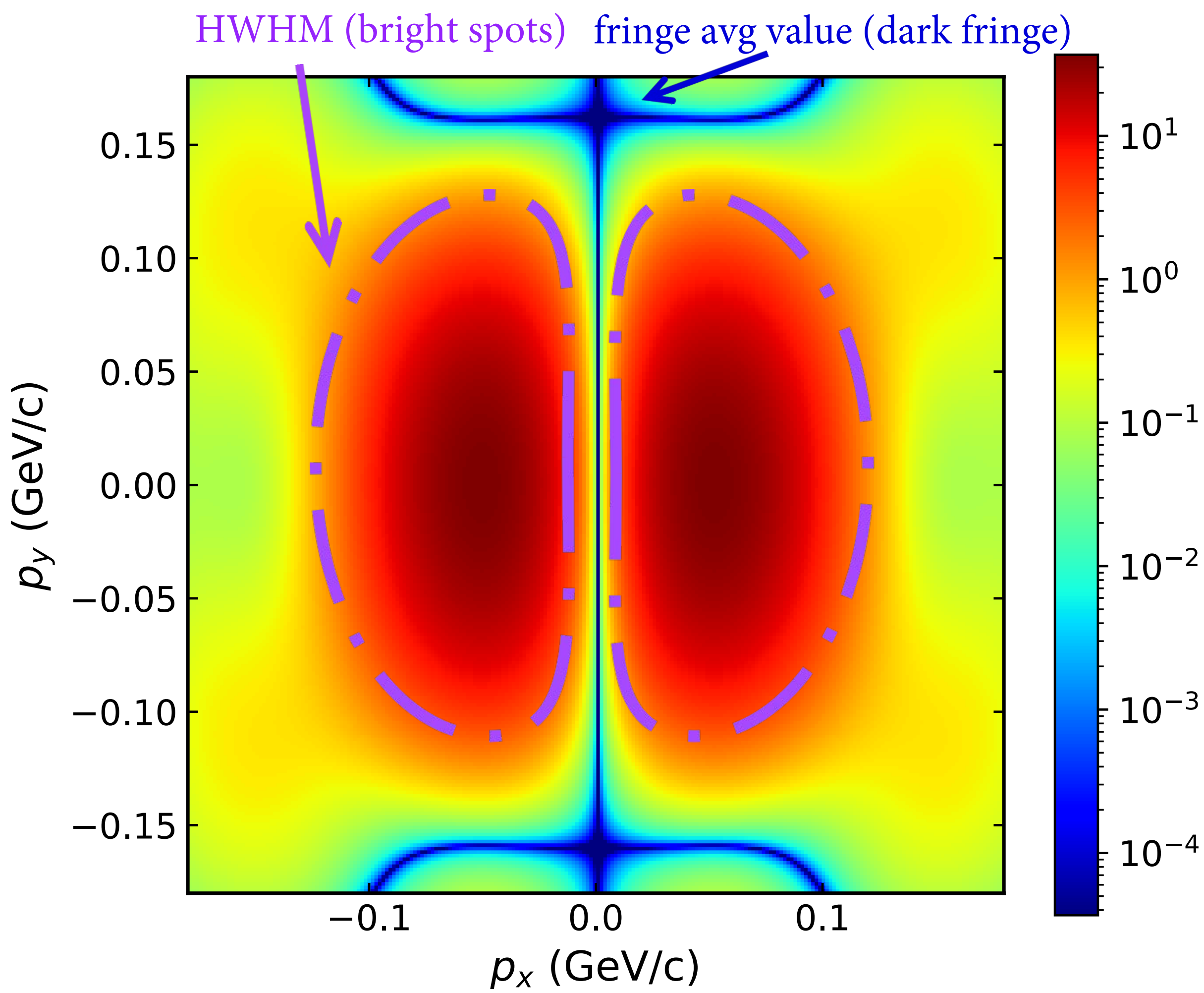


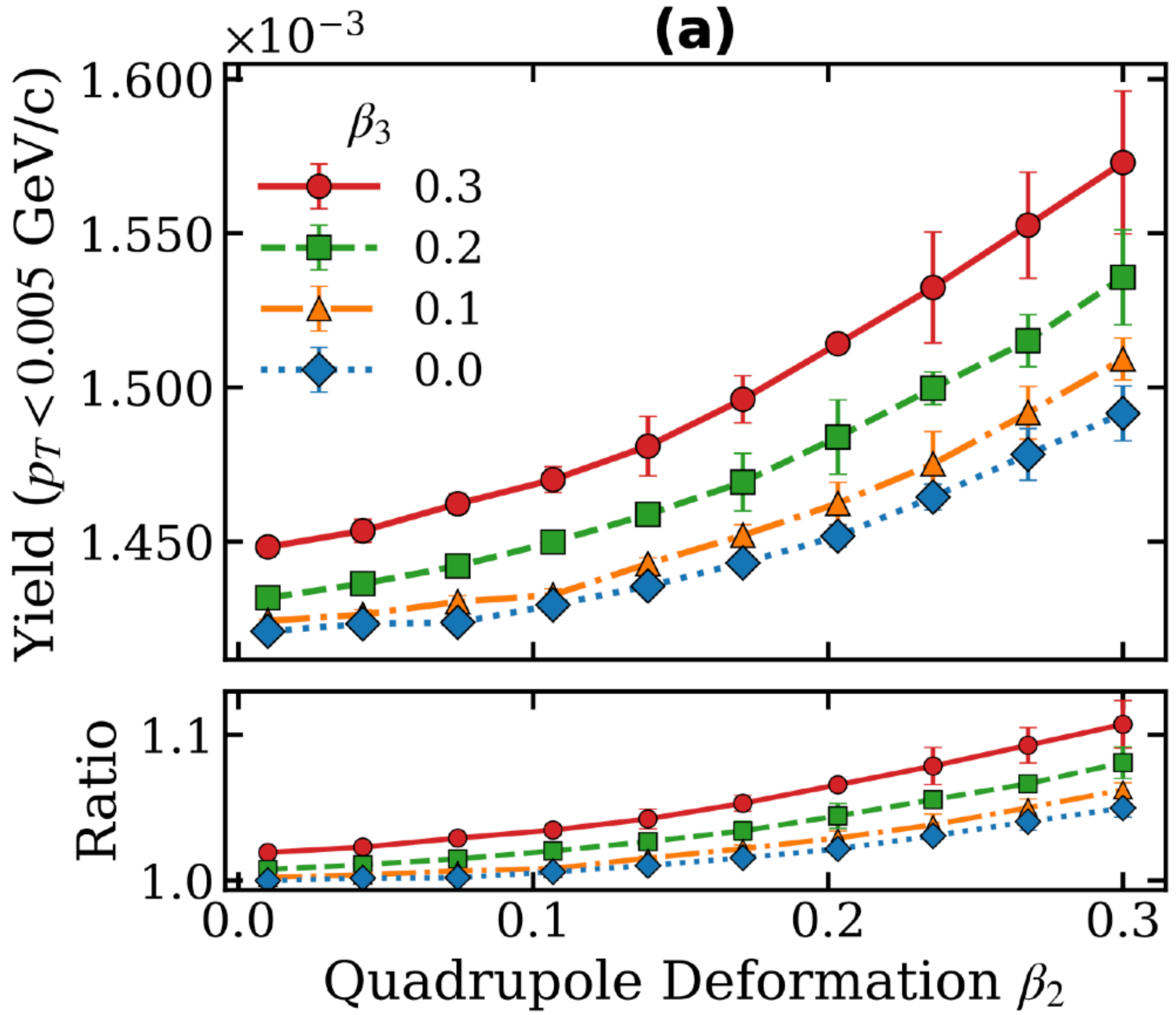
Butterfly shaped region affected by neutron skin

Neutron skin affects the butterfly shaped region and thus the v2 v3 in this high pT region.

Connection to Traditional Observables

low pT yield





Fringe Intensity ⇒ Low p_T Ratio & v_n

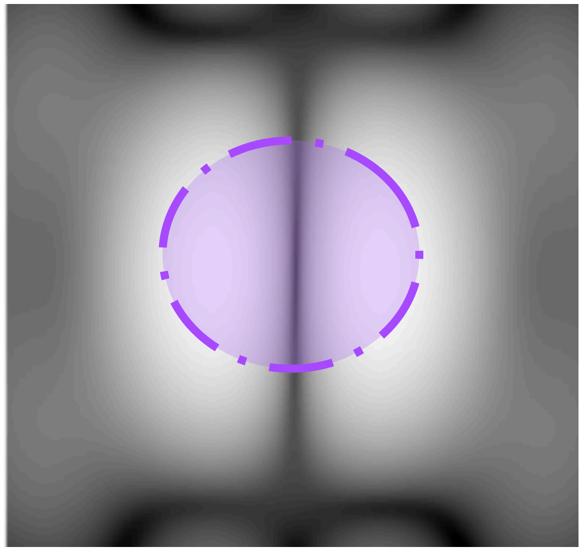
Fringe Intensity measures the "depth" and the clarity of interference minima.

Result: lower Fringe Intensity → low p_T yield in the dark fringe region

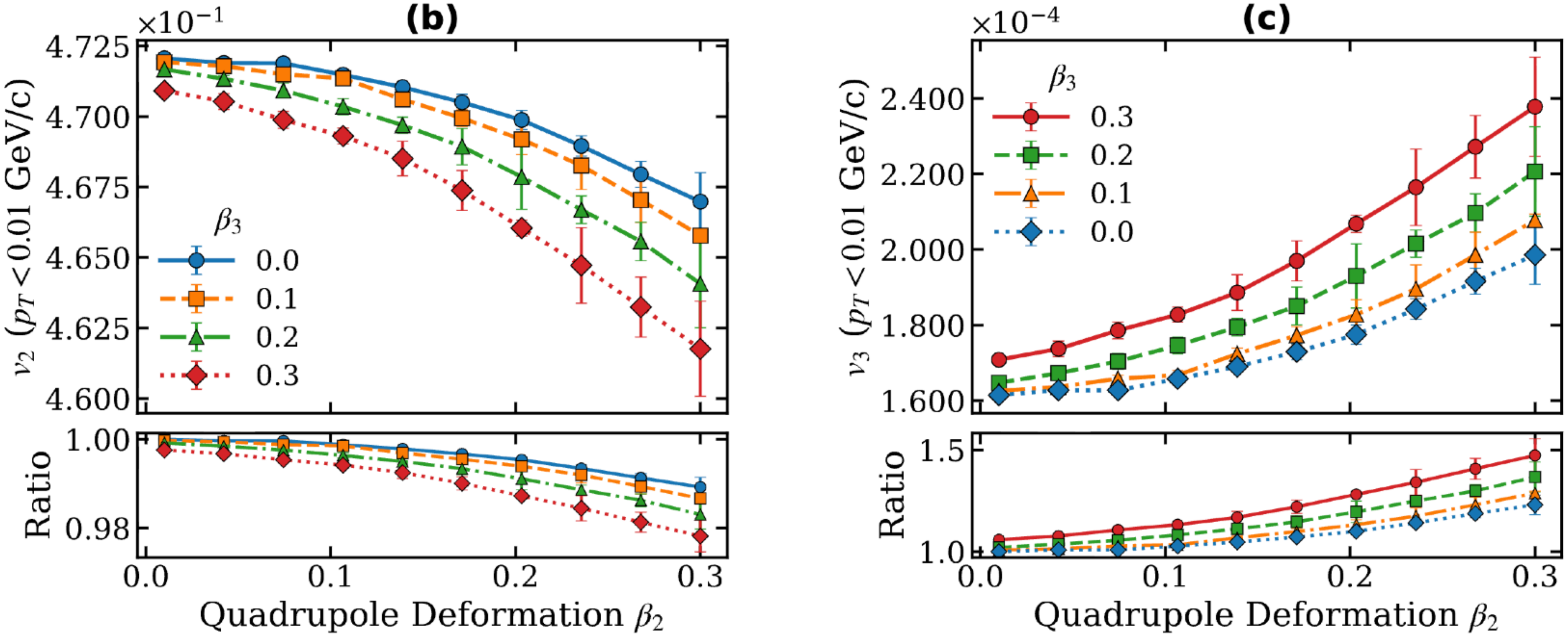
or → azimuthal anisotropy (v_2, v_3) caused by fringe smearing (detailed in the next slides).

Connection to Traditional Observables

flow



pt<0.05GeV



This region is characterized by smeared dark fringes .
Low pT flow harmonics serve as sensitive probes for deformation parameters.

Conclusion & Outlook

- UPC as an AI-assisted nuclear-structure interferometer
- Robust despite realistic incoherent backgrounds
- Attention → bright spots (skin) & dark fringes (deformation)
- AI-inspired observables: $\langle p_t \rangle$, low-p_t ratio, v_2, v_3
- Future: coherent ρ^0 UPC, nuclear clustering, etc.

Thanks you!