Probing the Structure of the O-16 Nucleus in High-Energy Ultra-Peripheral Collisions

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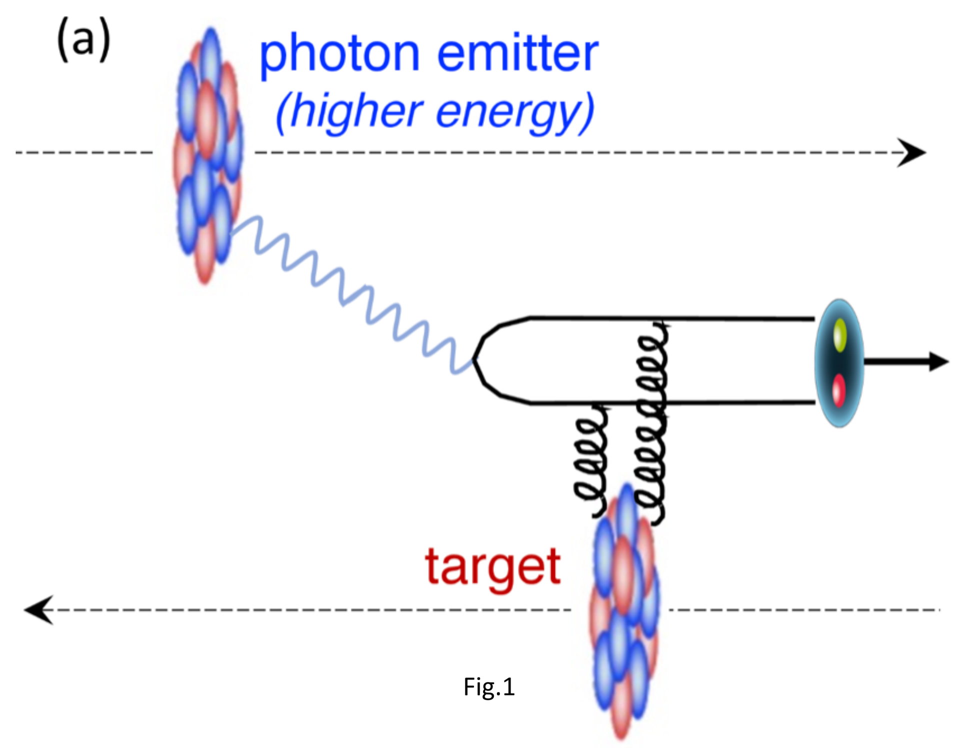
1 Abstract

Ultraperipheral oxygen-oxygen collisions provide a clean electromagnetic probe of nuclear geometry. A photon emitted by one ion fluctuates into a quark-antiquark pair and scatters from the other ion, producing a vector meson. Coherent events encode the ensemble-averaged transverse density, whereas incoherent events respond to event-by-event fluctuations. We compare a smooth Woods-Saxon model with a four-alpha-cluster model, compute thickness functions and form factors, and fit their predicted |t| spectra to the supplied collider data. Both descriptions reproduce the measured spectrum with nearly identical reduced chi-squared values. A superposition fit is Woods-Saxon dominated, but the current |t| spectrum plot does not robustly exclude alpha clustering. More precise low-|t| measurements and reduced background are needed to expose geometry-sensitive differences.

2 Ultra-Peripheral Collisions (UPC)



- **Photon flux:** fast nuclei carry a cloud of photons.
- **Vector mesons:** an emitted photon fluctuates into a quark–antiquark pair → a ρ^0 meson that scatters off the other nucleus.
- **Coherent** — scatters off the whole nucleus → the average shape (key to O-16 structure).
- **Incoherent** — scatters off one nucleon → the lumpiness (alpha-cluster is lumpier than Woods–Saxon).

Works cited

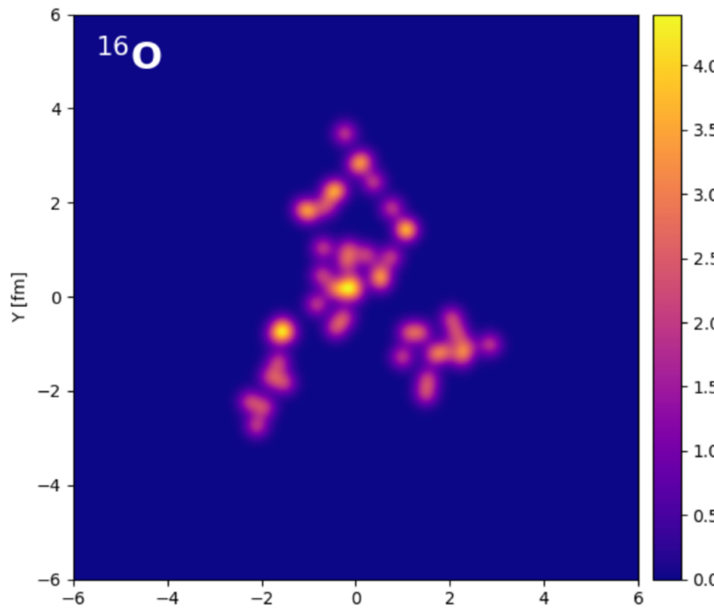
Fig.1: https://cms-results.web.cern.ch/cms-results/public-results/publications/HIN-22-002/CMS-HIN-22-002_Figure_001.png Source: cms-results.web.cern.ch

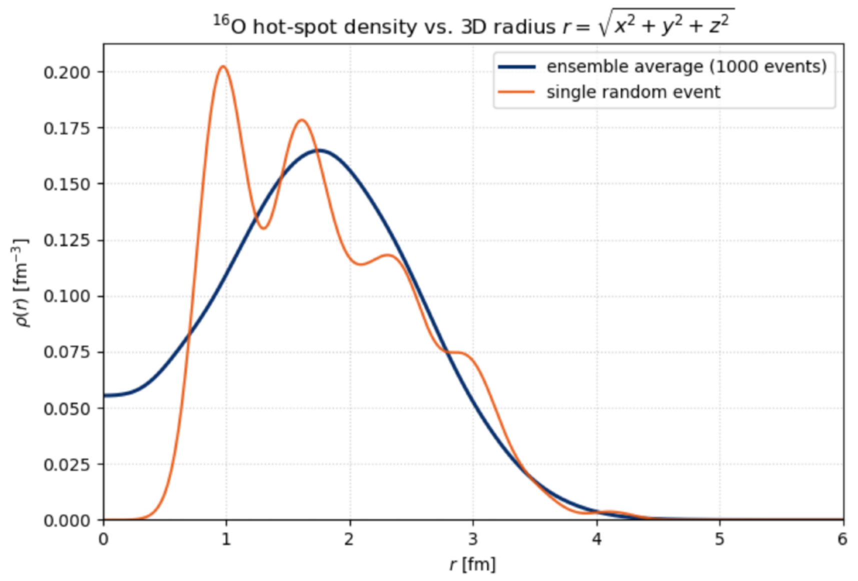
Fig.2: Effect of α-clusters on particle production in O–O and p–O collisions at LHC energies, Deependra Sharma, Arpit Singh etc. 25 Mar 2025

3 1. Alpha-Cluster Model vs. 2. Woods–Saxon (ws) Model:

Not spherical. **O-16** = 4 alpha (He-4) clusters on a tetrahedron: 4 clusters × 4 nucleons × 3 hot spots = 48 hot spots.

A **hot spot** is a small Gaussian lump of matter inside a nucleon (sub-nucleon structure). Positions are sampled from nested Gaussians; the width σ (= s in the code) sets the hot-spot size. \mu are centers of hotspots, which are sampled from gaussian.





Right: hot-spot density vs magnitude of radius — one event is lumpy, the 1000-event average is smooth >> key to form factor.

Left: transverse density map T(X,Y) of one event; bright spots are the individual hot spots

The Alpha Cluster Equation: $$\rho(x,y,z) = \sum_{i=1}^{48} \frac{1}{3(2\pi\sigma^2)^{\frac{3}{2}}} \exp\left\{-\frac{1}{2}\left[\frac{(x-\mu_{x_i})^2+(y-\mu_{y_i})^2+(z-\mu_{z_i})^2}{\sigma^2}\right]\right\}$$

2. WS Model:

Spherically symmetric: nucleons drawn from a smooth radial density ρ(r).

R = 2.608 fm	half-density radius	
a = 0.513 fm	surface diffuseness	
w = −0.051	central-shape parameter	

WS Equation: $$\rho(r) = \rho_0 \cdot \frac{1+w(r/R)^2}{1+\exp\left(\frac{r-R}{a}\right)}$$

Left: 16 nucleons sampled from the round Woods–Saxon density — no clustering. Right: thickness T_b(r) = density integrated along the beam (z); peaks at r = 0 (0.845 fm^{-2}) and fades by ~5 fm.

T_b(s) = ∫ ρ(s, z) dz

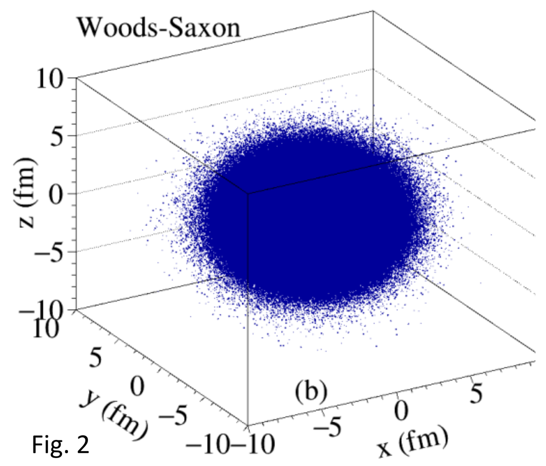
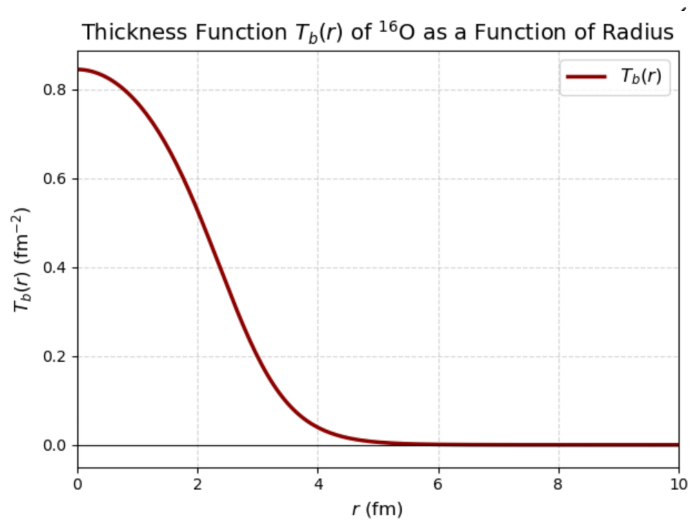


Fig. 2



4 Form Factors & Cross Sections

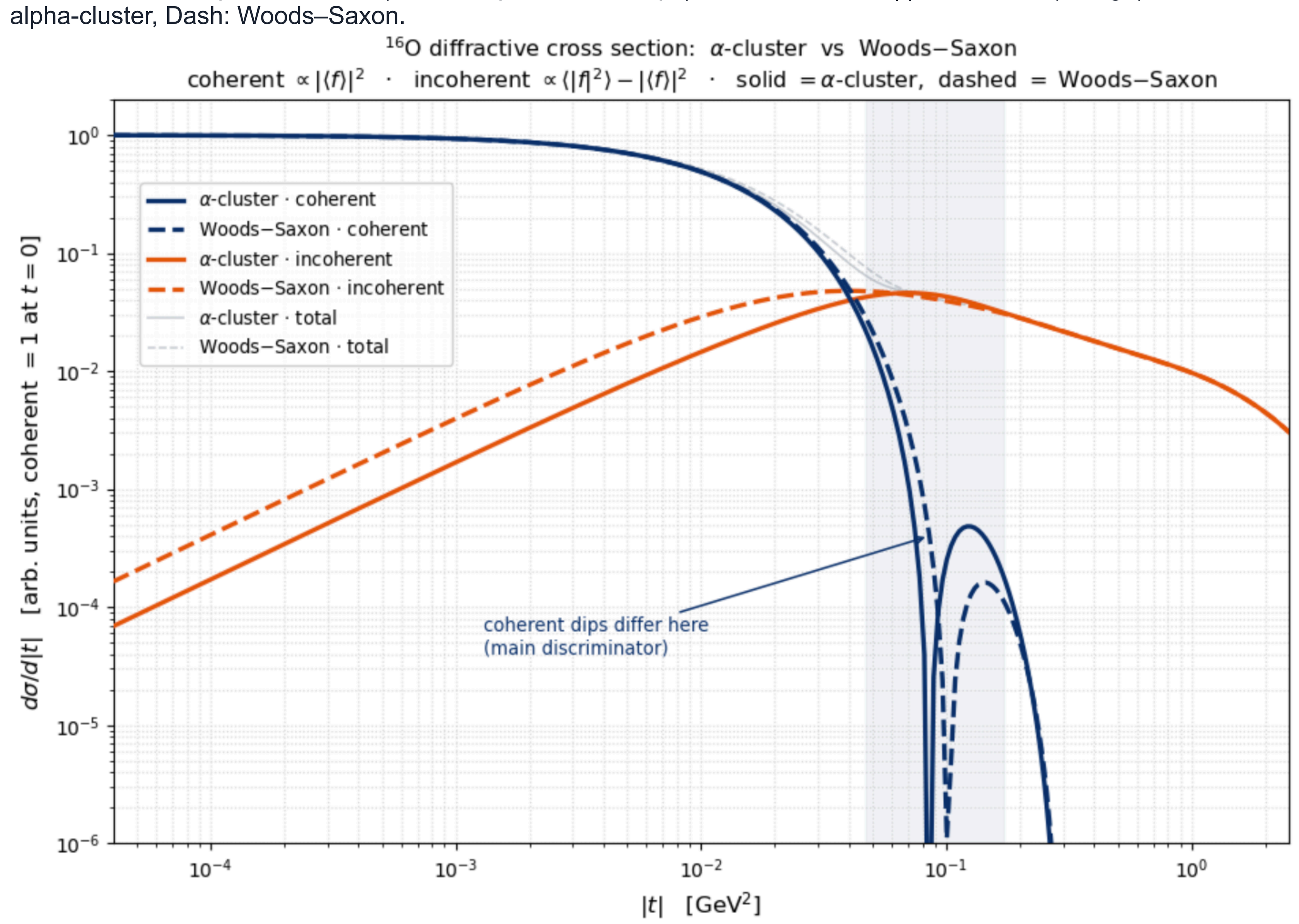
The form factors >> Fourier transform of the density — each hot spot adds a phase e^{iqr}; the angular average makes it real.

$$f(\mathbf{q}) = \int \rho(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}\, d^3r \qquad \langle e^{i\mathbf{q}\cdot\mathbf{r}}\rangle = \frac{\sin(|q|\cdot|r|)}{|q|\cdot|r|} = j_0(|q|\cdot|r|)$$

The cross sections >> It's not a derivative, physically it's the probability probing the real matters. Cross section is correlated to form factor with following expressions:

$$\frac{d\sigma_{coh}}{d|t|} \propto |\langle f\rangle|^2 \qquad \frac{d\sigma_{incoh}}{d|t|} \propto \langle|f|^2\rangle - |\langle f\rangle|^2$$

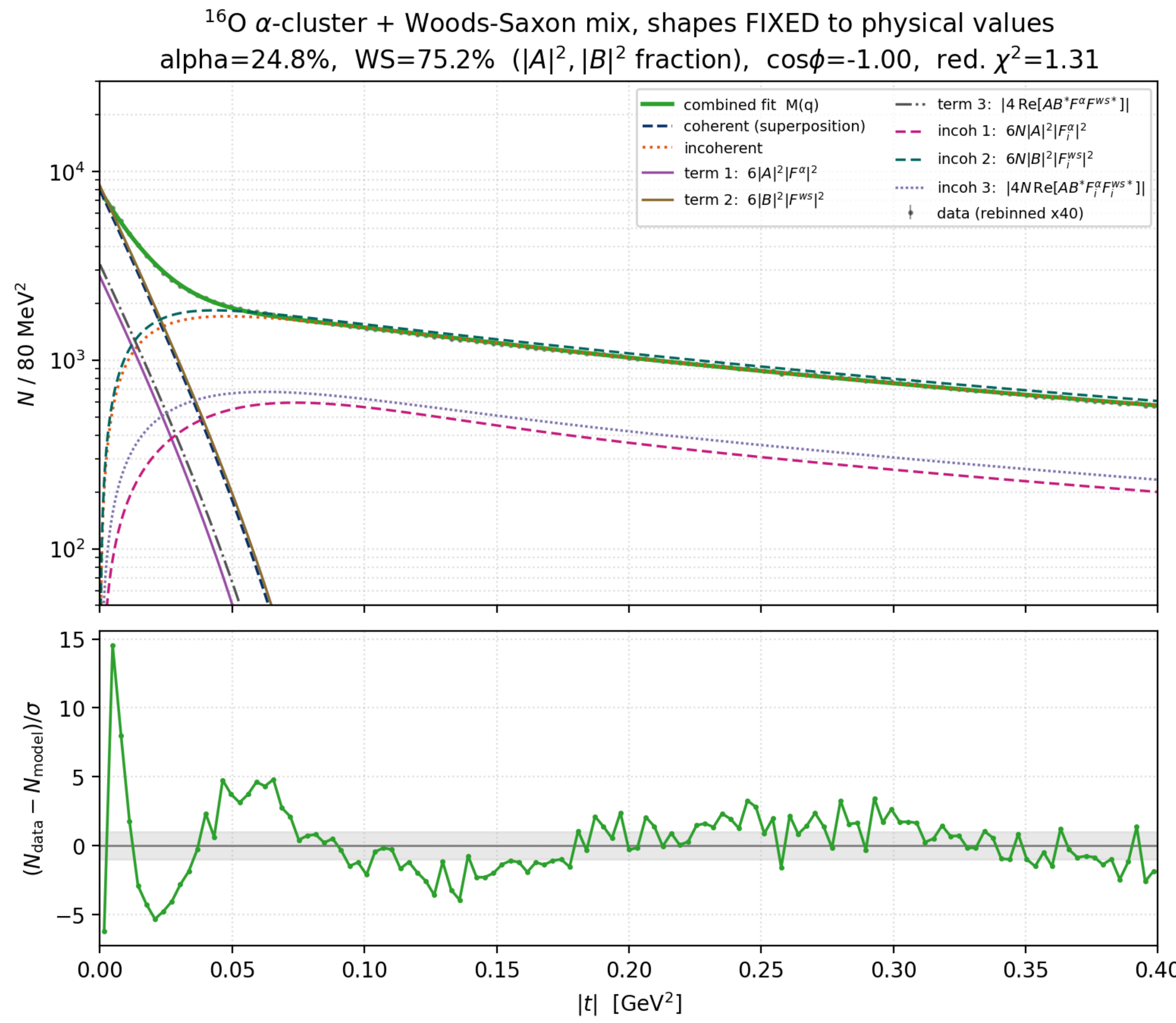
Therefore, we can plot: Coherent (blue, steep, diffractive dips) dominates at low |t|; incoherent (orange) takes over at high |t|. |t| = (ħcq)². Solid: alpha-cluster, Dash: Woods–Saxon.



By uncertainty principal, higher |t| >> higher resolution. The coherent part: q_{1st dip} *R_o rms ~ constant >> the first dip roughly determines the rms radius of O16. Higher resolution >> the position space lumpier >> in momentum space, the more higher frequency waves (higher |t|) will be needed to fit the position space. However, the position space still follows a general trend >> general trend of momentum space also decreasing.

The incoherent part >> the variance of the events. Higher resolution >> variance between events will increase, especially alpha cluster model. However, our model ends up with 48 hotspots >> variance has a peak >> decrease gradually (with very flat slope).

5 Combined Fit: α + WS



Top: combined fit for both ws and alpha, shapes fixed to physical values (green). Bottom: residuals for alpha and Woods Saxon combined fit.

Below is the fit function (derived from quantum state). The two amplitudes — **A** (real) weights alpha, **B** (complex) weights Woods–Saxon:

$$\begin{aligned} &6\cdot|A|^2|F^{\alpha}_{coh}|^2 \\ &+6\cdot|B|^2|F^{ws}_{coh}|^2 \\ &+4\cdot\mathbf{Re}[AB^*F^{\alpha}_{coh}F^{ws^*}_{coh}] \\ &+N_{incoh}(6\cdot|A|^2|F^{\alpha}_{incoh}|^2 \\ &+6\cdot|B|^2|F^{ws}_{incoh}|^2 \\ &+4\cdot\mathbf{Re}[AB^*F^{\alpha}_{incoh}F^{ws^*}_{incoh}]) \end{aligned}$$

with |A|^2, |B|^2 are the percentage contributions.

Each term in the fit function is also shown in the plot.

The angle \phi is the phase difference between A and B.

6 Key Result

|B|² ≈ 75% (Woods–Saxon). **|A|² ≈ 25%** (alpha-cluster).

|A|^2 = 0.248 +/- 0.0054 (24.8 %), |B|^2 = 0.752 +/- 0.0054 (75.2 %), reduced χ² = 1.31. Woods–Saxon dominates the **O-16** mixture.

7 Key Fit Parameters (combined fit)

Symbol	Meaning	α	WS
s	hot-spot size σ (fm)	0.237	
σ_hot	nucleon spread (fm)	0.405	
σ_nuc (α) | R (ws)	cluster σ | half density radius (fm)	0.98	2.608
m (α) | a (ws)	cluster dist to origin (fm) | diffuseness	2.10	0.513
O-16 RMS	matter radius (fm)	2.82	2.85
χ²	fit quality	1.31	

8 The Conclusion

Results:
- Built both Woods–Saxon and alpha-cluster models and fit them to LHCb / STAR ρ^0 data.
- Both fit well; Woods–Saxon has the slightly smaller χ² and dominates the mixture (~86%).
- But low-energy nuclear theory predicts a superposition of alpha-cluster-dominated with a mixture with woods saxon.

Challenge:
- Both models fit the data almost identically (< 1σ apart across |t|), so the alpha / WS difference is hard to measure and therefore computer failed to measure the combined fit at first. Only by fixing each model to physical shapes with some proper constants can the fraction be measured.

Future efforts:
- Refine the combined alpha + WS fit and its normalization.
- Find a more precise mechanism to truly separate the models.
- Reduce experimental background to sharpen the distinction.

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