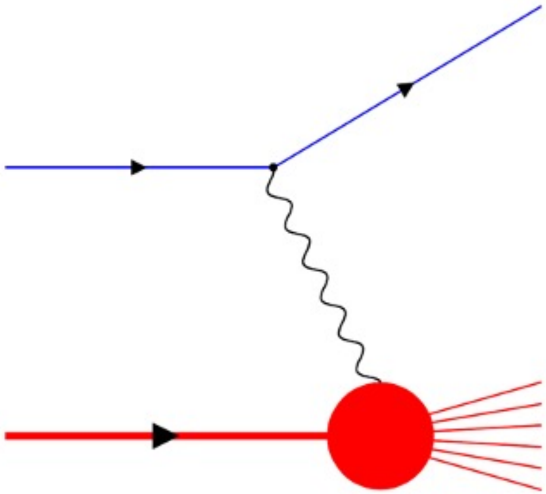
Probing the isobaric Ru and Zr nuclear structure with the diffractive photoproduction of ρ^0 mesons

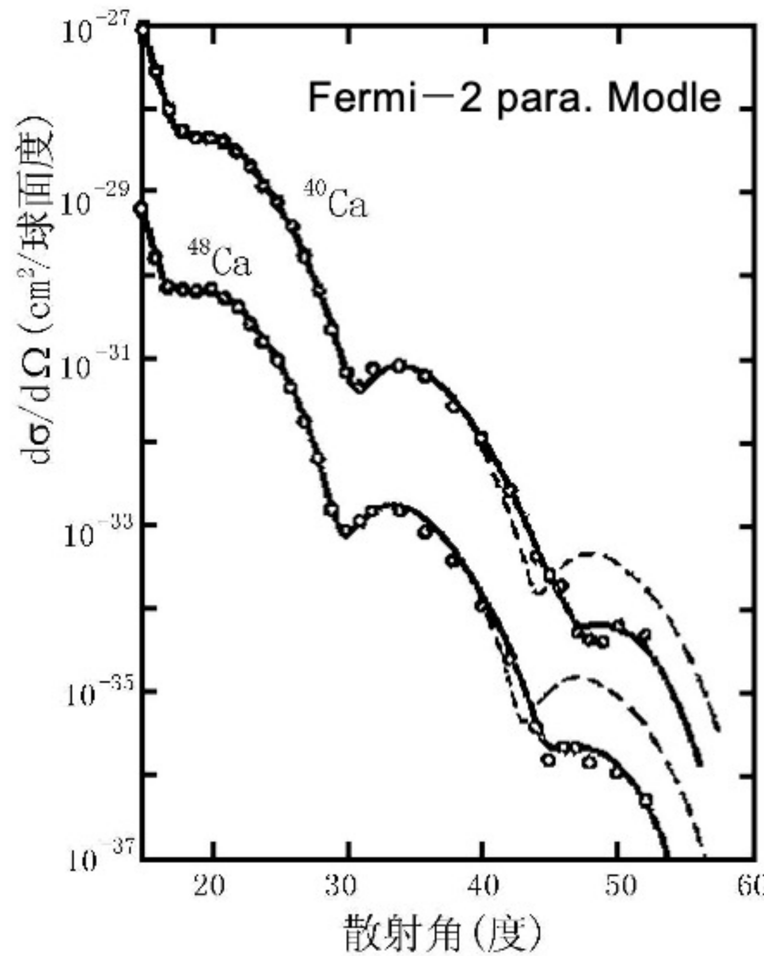
Jie Zhao

Apr. 14, 2024

Charge radius

R. Hofstadter, Rev. Mod. Phys. 28 214-254 (1956)





$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{point}\left|F(\vec{q})\right|^2 \qquad F(\vec{q})=\int d\vec{r}^{\,3}\,e^{i\vec{q}.\vec{r}}\rho(\vec{r})$$

$$F(q^2)=\int d\vec{r}^{\,3}\rho(r)e^{i\vec{q}.\vec{r}}\xrightarrow{qR<<1}1-\frac{1}{6}q^2\int drd\Omega r^4\rho(r)\ +\cdots$$

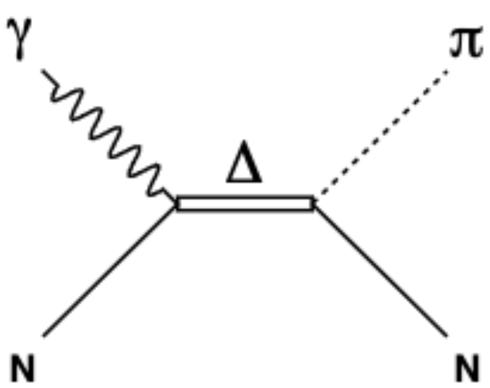
$$\cdots\cdots\cdots=1-\frac{1}{6}q^2\left\langle r^2\right\rangle+\cdots$$

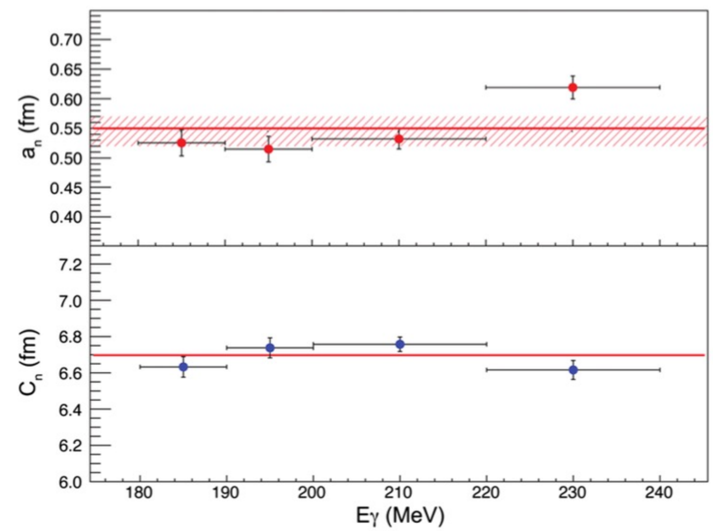
G.F. Chew, et.al, Phys. Rev. 106, 1345 (1957); R.A. Schrack, et.al, Phys. Rev. 127, 1772 (1962);

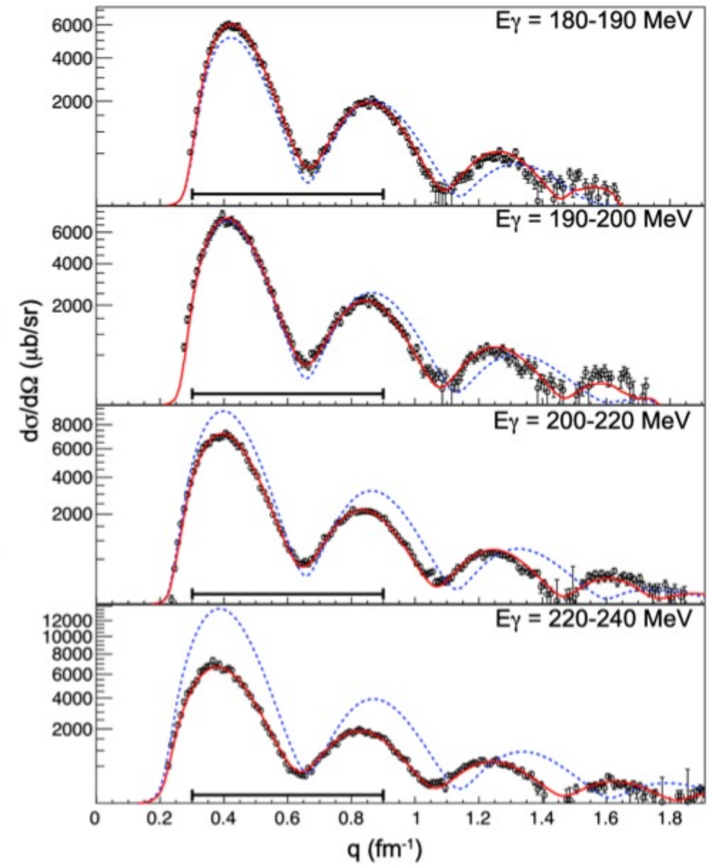
- Electron scattering measures the form factor, charge radius

Mass radius

$$\gamma + A(gs) \rightarrow A(gs) + \pi^0$$







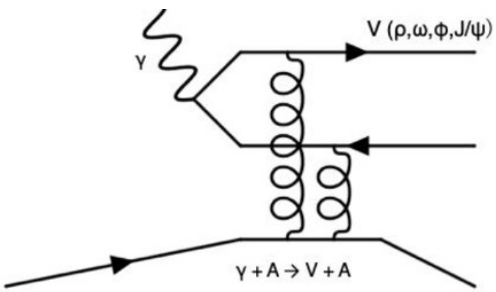
$$A(\gamma p \rightarrow \pi^0 p) = A(\gamma n \rightarrow \pi^0 n)$$

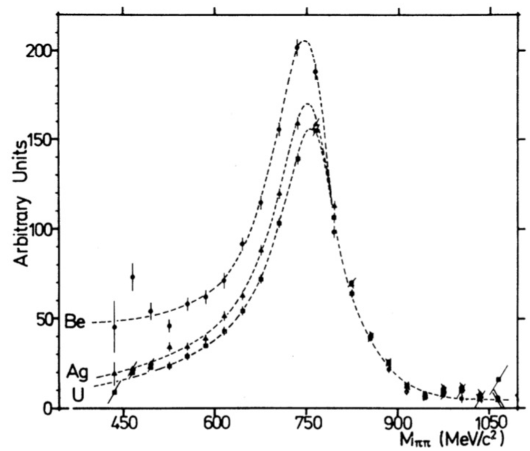
G.F. Chew, et.al, Phys. Rev. 106, 1345 (1957); R.A. Schrack, et.al, Phys. Rev. 127, 1772 (1962); C.M. Tarbert, et.al, Phys. Rev. Lett. 112, 242502 (2014)

- Electron scattering measures the form factor, charge radius
- Photoproduction of π^0 meson: Δ(1232), the mass radius (1960s)

Strong-Interaction Nuclear Radii

$$\gamma + (Z, A) \rightarrow \rho + (Z, A)$$





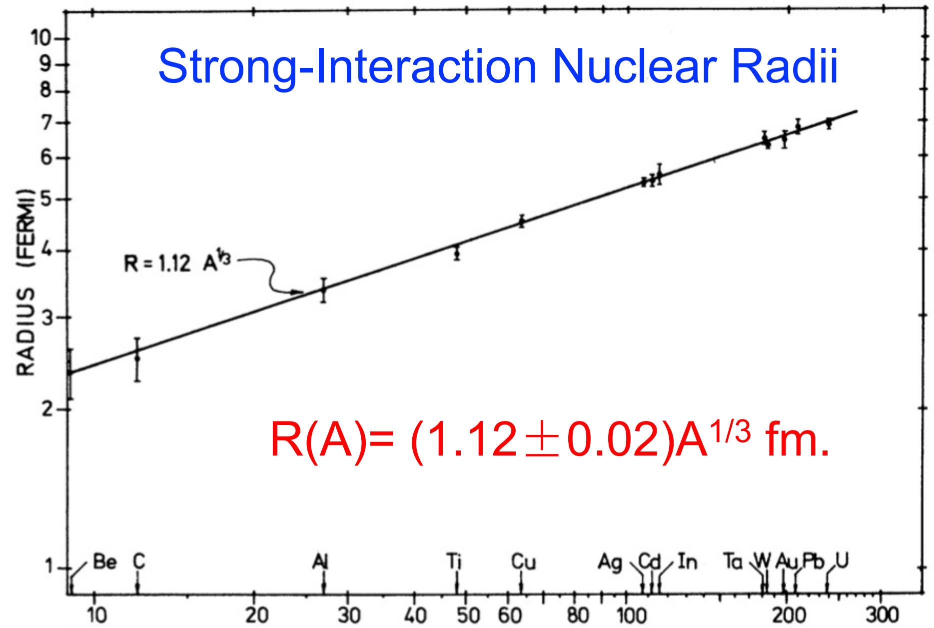
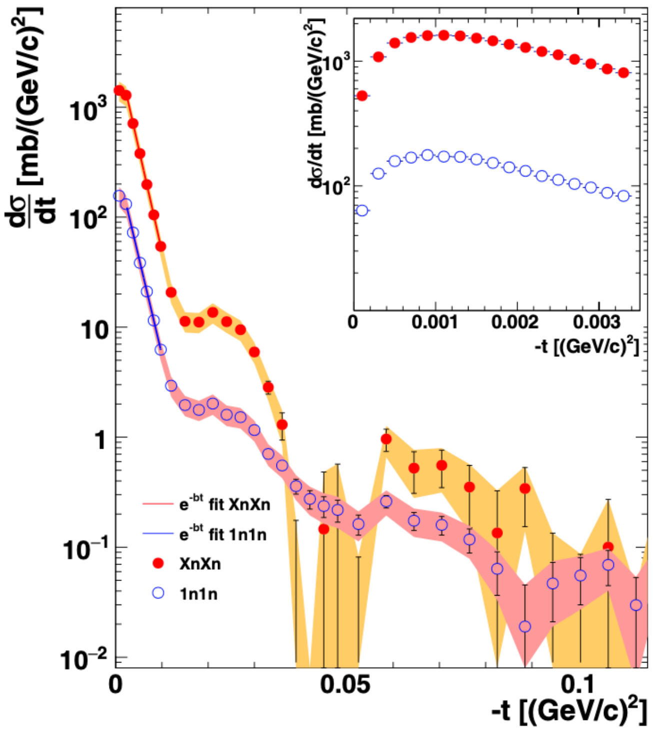


FIG. 1. Results on $R(A)$ and the best fit with $R = r_0 A^{1/3}$.

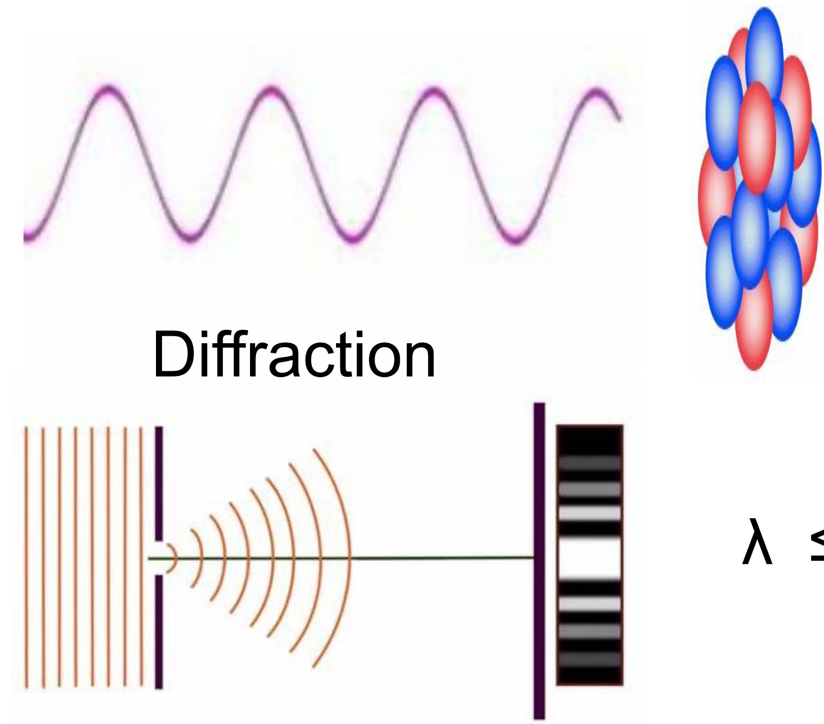
G.F. Chew, et.al, Phys. Rev. 106, 1345 (1957); R.A. Schrack, et.al, Phys. Rev. 127, 1772 (1962);
C.M. Tarbert, et.al, Phys. Rev. Lett. 112, 242502 (2014)
F. Bulos, et.al, Phys. Rev. Lett. 22, 490 (1969); L.J. Lanzerotti, et.al, Phys. Rev. 166, 1365 (1968)
H. Alvensleben et.al, Phys. Rev. Lett. 24, 786 and 792 (1970)

- Electron scattering measures the form factor, charge radius
- Photoproduction of π^0 meson: Δ(1232), the mass radius (1960s)
- Photoproduction of ρ^0 meson: "Determination of Strong-Interaction Nuclear Radii" (1970s)

Diffractive ρ^0 meson production



STAR, PRC 96, 054904 (2017)
STAR, PRL 89, 272302 (2002)
Spencer, et.al, PRC 60, 014903, (1999)



$\lambda \leq L$

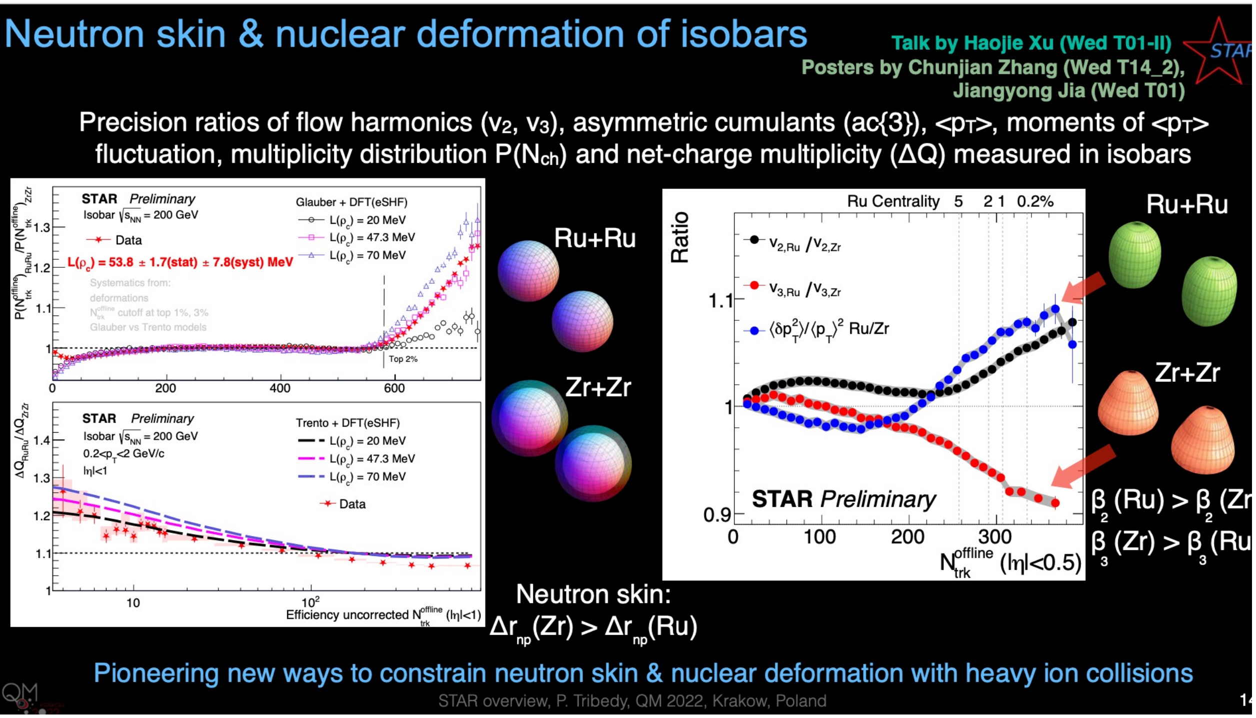
F. Bulos, et.al, Phys. Rev. Lett. 22, 490 (1969)
H. Alvensleben et.al, Phys. Rev. Lett. 24, 786 and 792 (1970)
H. Mäntysaari, F. Salazar, B. Schenke, arXiv:2207.03712

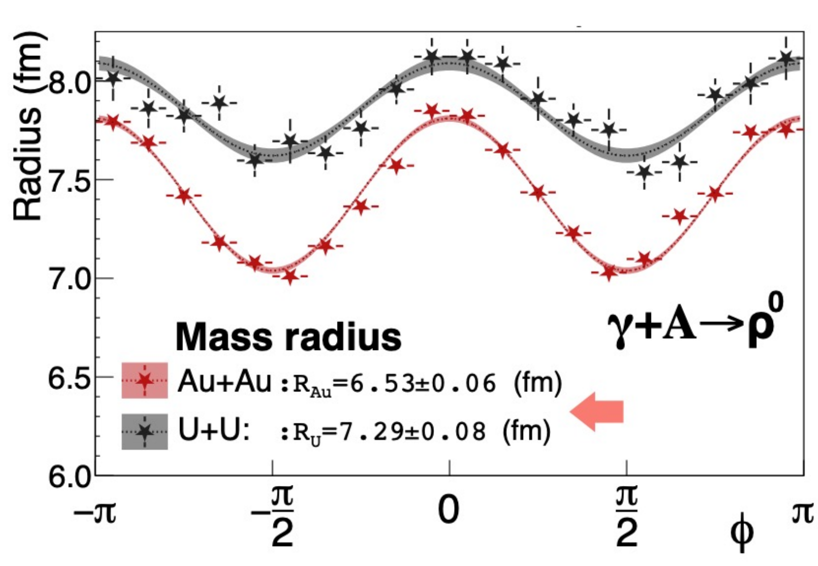
- Diffraction pattern (minima) of the coherent ρ^0 production are sensitive to the nuclear size.
- "The slopes of the diffraction patterns measure directly the nuclear density distribution. For example, at t -> 0, the diffraction pattern behaves as e^{at} where a is a measure of the nuclear size."
- Can used to study the nuclear structure of the isobar Ru and Zr

Isobaric Ru and Zr nuclear structure

STAR, Phys. Rev. C 105 (2022), 014901
T. Prithwish (for STAR), QM2022

STAR, Sci. Adv. 9 (2023) 1





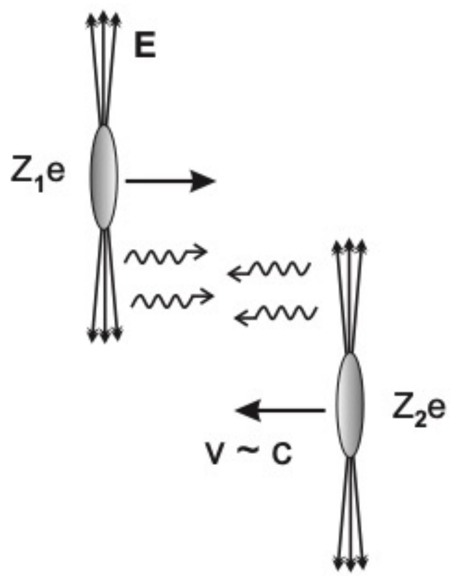
Tomography of ultra-relativistic nuclei with polarized photon-gluon collisions.

➢ The γ-A interaction may help to understand the structure of the isobar Ru and Zr nuclei ?

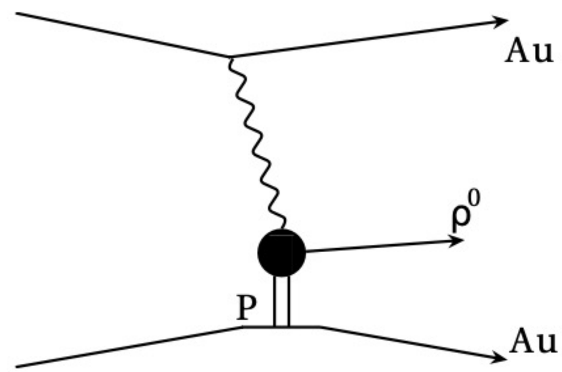
Spencer, et.al, PRC 60, 014903, (1999); STAR, PRL 89, 272302 (2002), PRC 96, 054904 (2017)

γ-A interaction from UPC

C.A. Bertulani, S.R. Klein, J. Nystrand
Ann. Rev. Nucl. Part. Sci. 55 (2005) 271



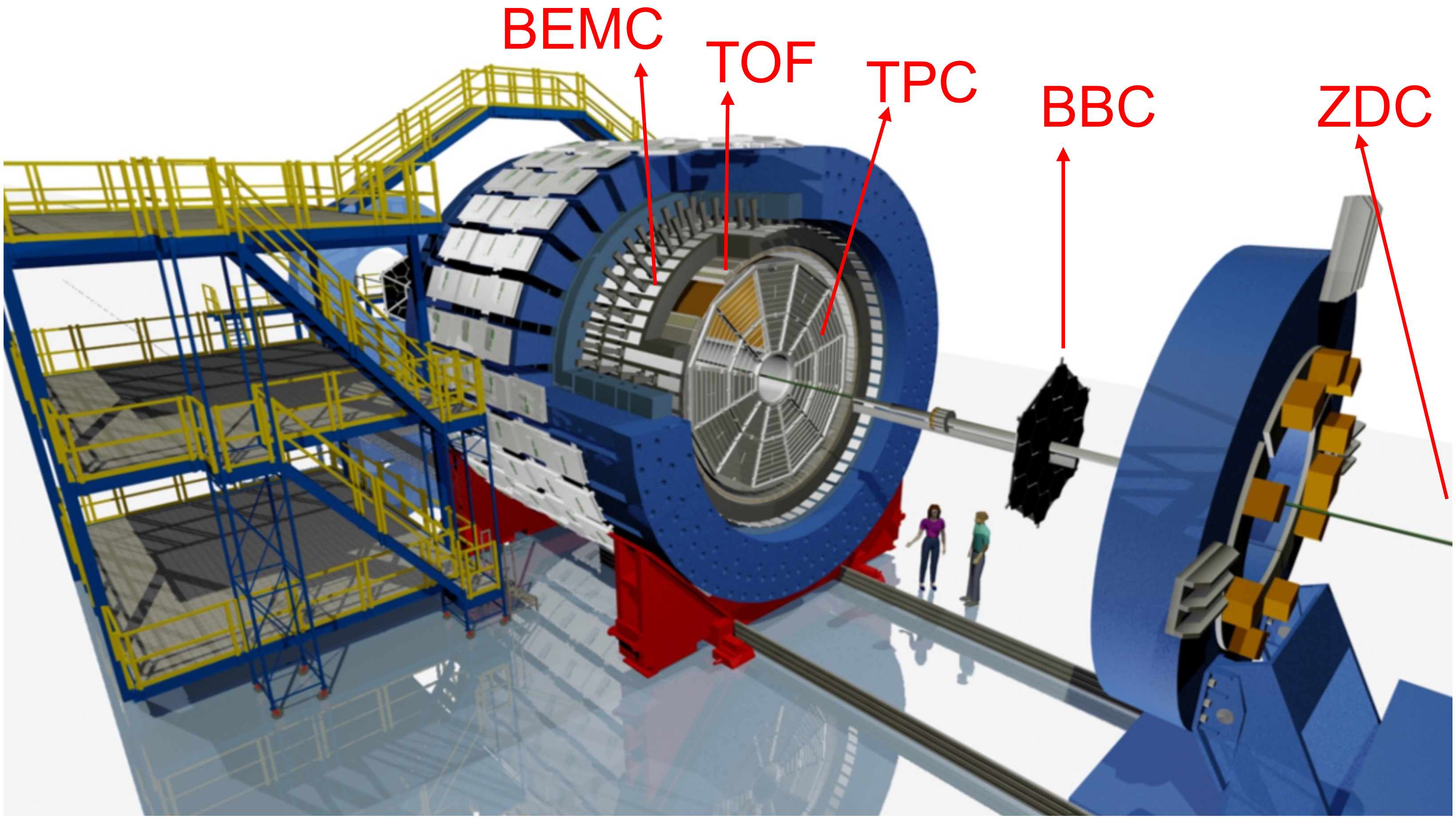
STAR, PRL 89, 272302 (2002)



Soft-Pomeron (gluons) exchange

- Ultra-peripheral heavy-ion collisions (UPC) ($b>2R_0$)
- Electromagnetic field as quasi-real photons (EPA)
- ρ^0 meson production through the soft-pomeron (gluons) exchange, sensitive to the Strong-Interaction Nuclear Radius

STAR detector



- Time Projection Chamber: tracking and particle identification within $|\eta|<1$
- Time Of Flight: multiplicity trigger, particle identification and pile-up track removal
- Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
- Beam-Beam Counters: scintillator counters within $2.1<|\eta|<5.2$, forward veto
- Zero Degree Calorimeters: detection of very forward neutrons, $|\eta| > 6.6$

Datasets

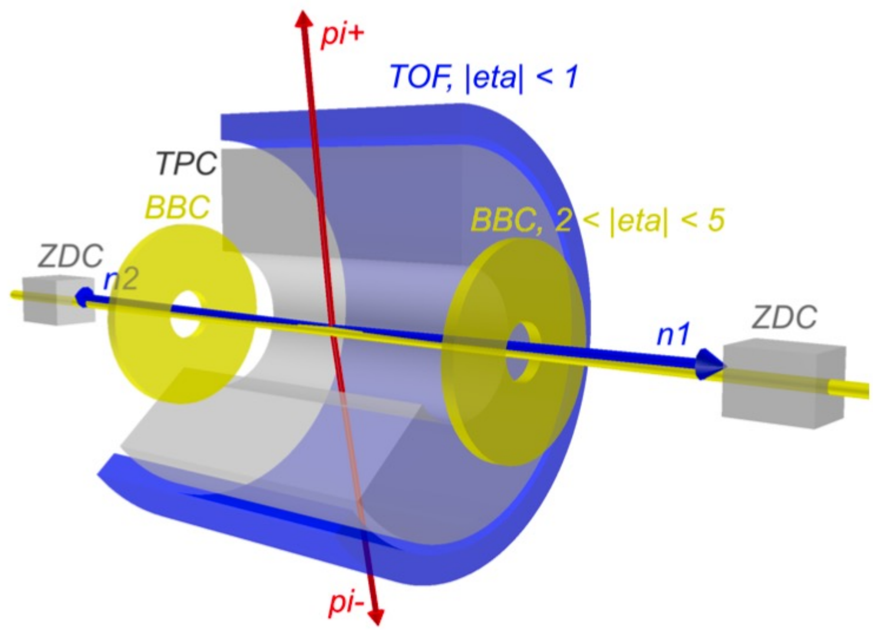
System	Year	Trigger (ID)	|Vz|	Vr
Ru+Ru	2018	UPC-Jpsi	<100cm	<2cm
Zr+Zr	2018	UPC-Jpsi	<100cm	<2cm

Track cuts: (primary track)

nHitFit>15, $|\eta|<1$, dca<3cm

pT>0.2 && <4 GeV/c

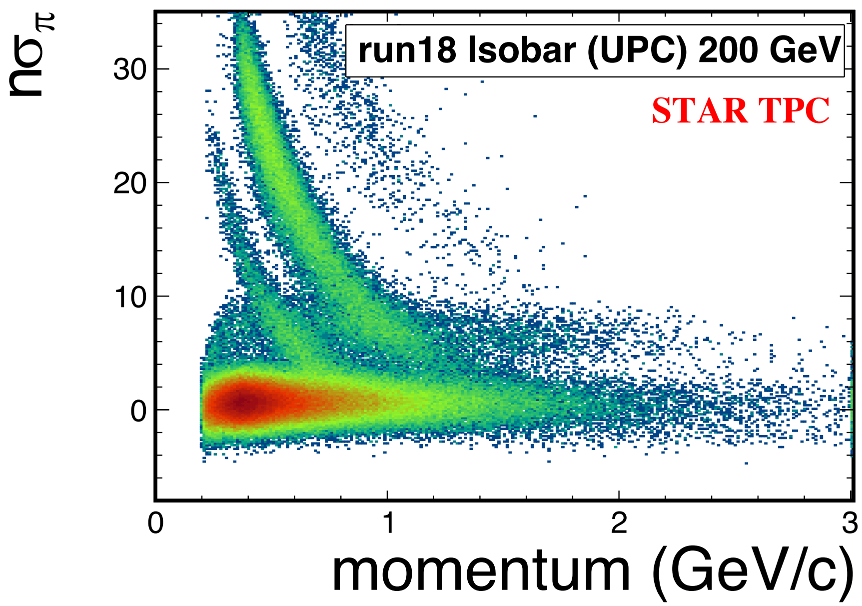
TOF matched>0

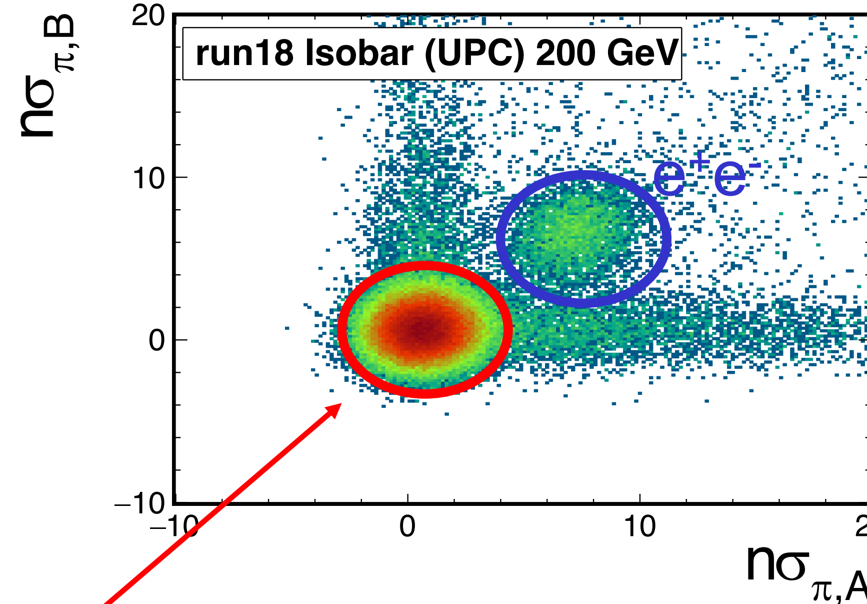


plot from Jaroslav Adam

- Events are selected with number of primary tracks = 2
- Track pair not matched to the BEMC topo. clusters with (E_0>0.5)

PID: remove the e^+e^- contamination



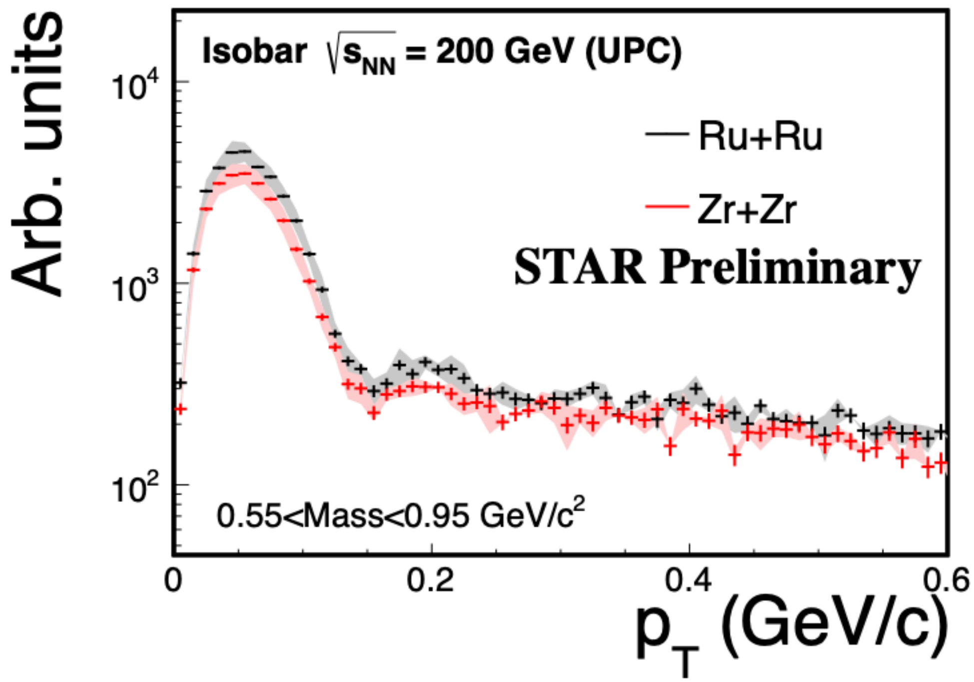


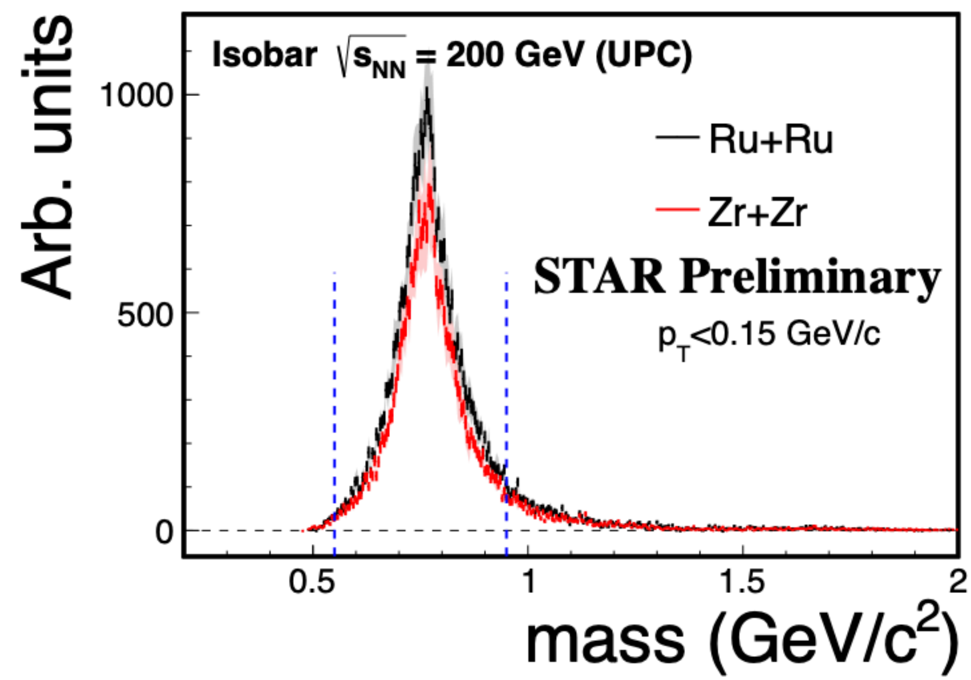
STAR, PRL 127, 052302 (2021)

ALICE, JHEP. 2015, 95 (2015)

- $\sigma_{\pi,A}{}^2 + \sigma_{\pi,B}{}^2 < 16$,
  remove the e^+e^- contamination from $\gamma+\gamma$ interaction

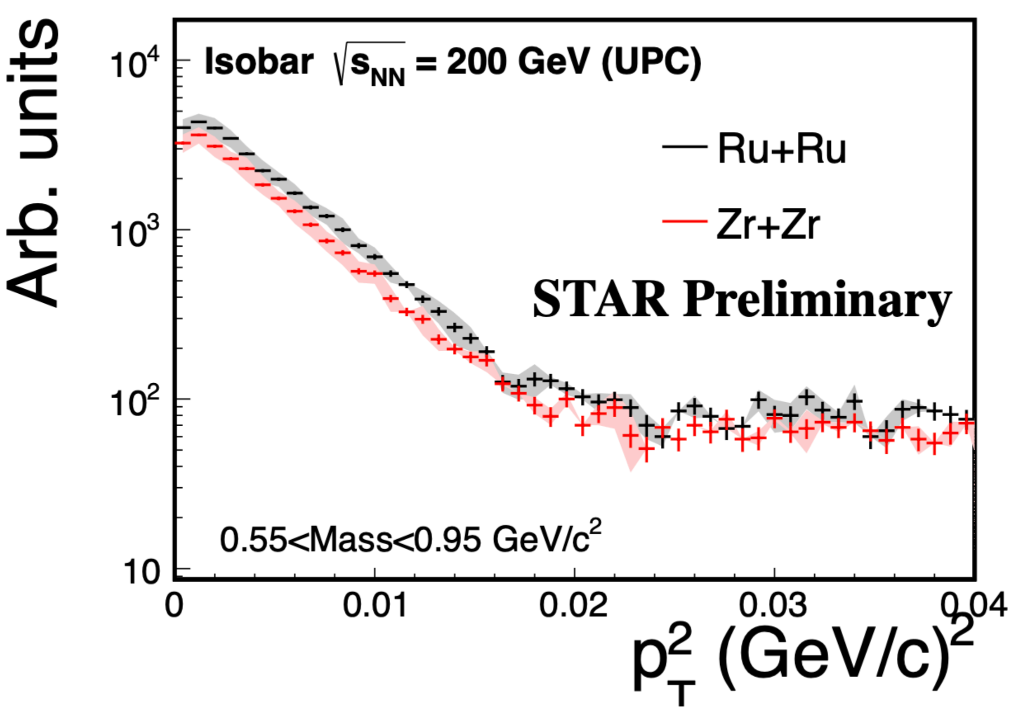
Diffractive photoproduction of ρ^0 in isobar

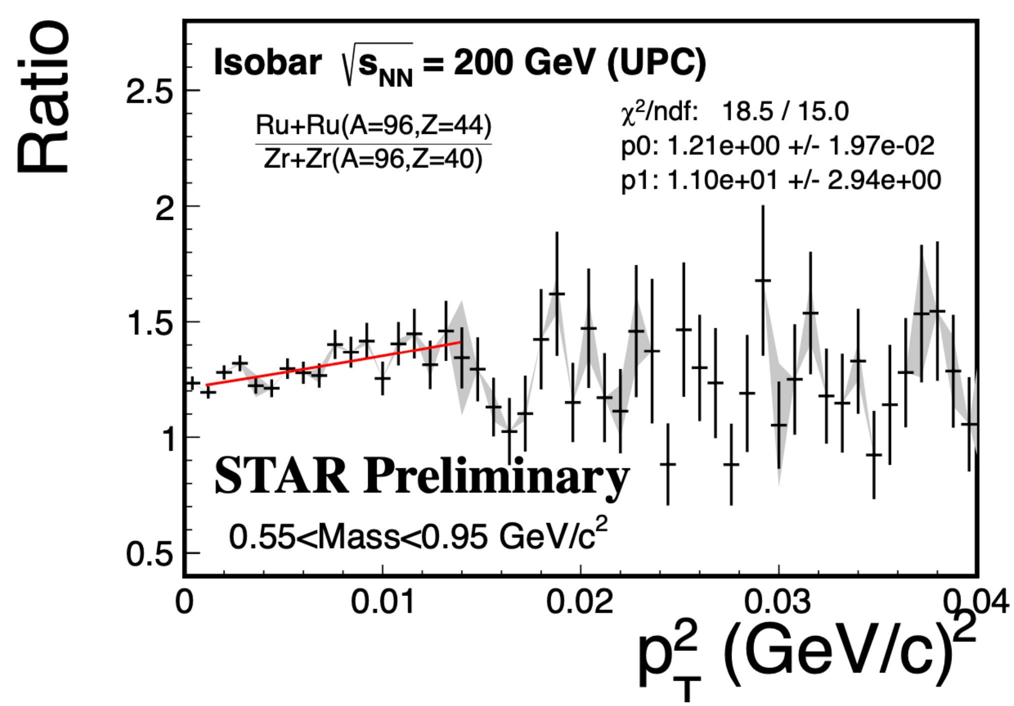




- Systematic uncertainty sources:
  dca: 1.0, 2.0 (3.0) cm; nHitsFit: 20 (15); $|V_Z|$: 50 (100) cm
- Total systemic uncertainty : RMS(σ (dca)) $\otimes$ σ(nHit) $\otimes$ σ(Vz)
- Diffraction pattern (minima) of the coherent ρ^0 production

Ru and Zr nuclear structure





$A{*}e^{-b{*}t}$, $(t \simeq -p_T^2)$

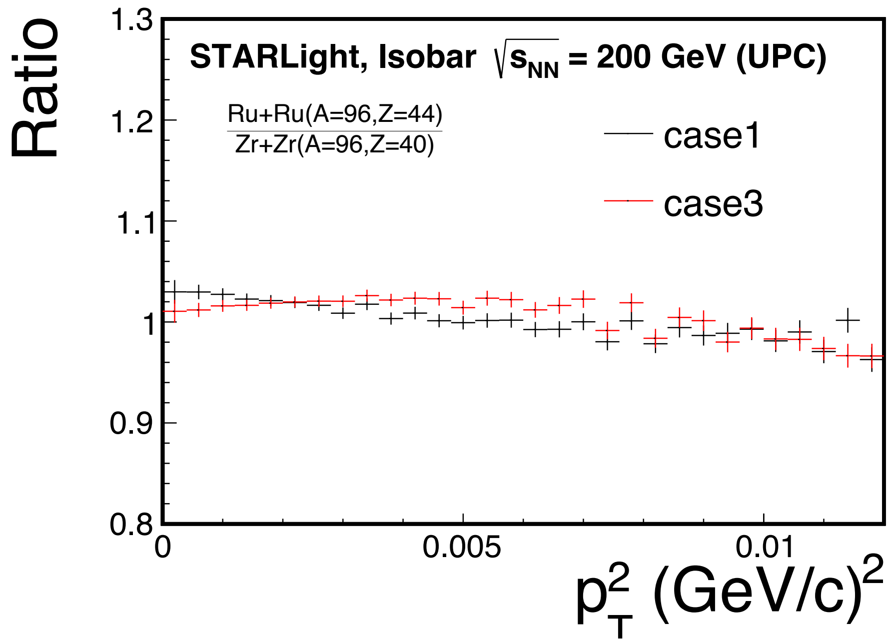
- Indication of larger Zr size than Ru from the γ-A interaction. The slope of the dN/dt ratio is 11.0+/- 2.9 +/- 0.3 (~3σ sigma effect)
- Interference and deformation effects need to be considered

STARLight simulation

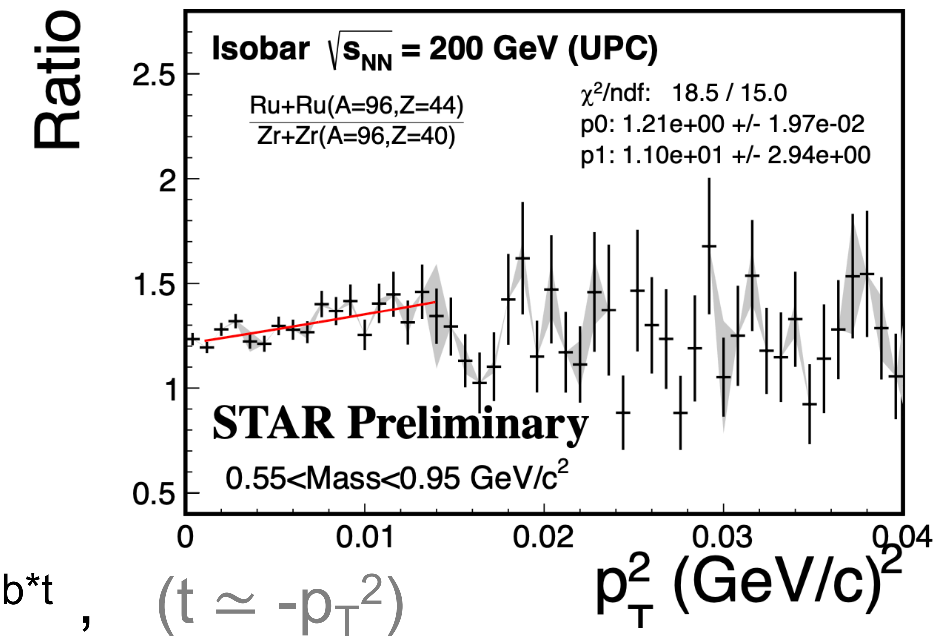
Spencer, et.al, Comput.Phys.Commun. 212 (2017) 258　　STAR, Phys.Rev.C 105 (2022), 014901

TABLE II. The Woods-Saxon parameters used in the Glauber simulations for the centrality determination.

Nucleus	Case-1 [83]			Case-2 [83]			Case-3 [113]		
	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0



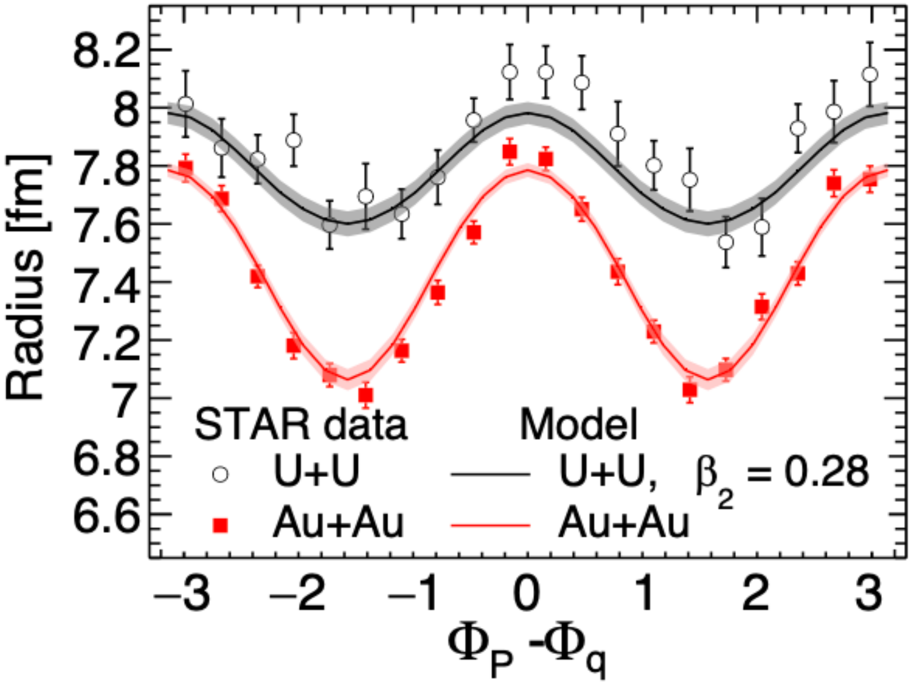
$A*e^{-b*t}$, $(t \simeq -p_T^2)$

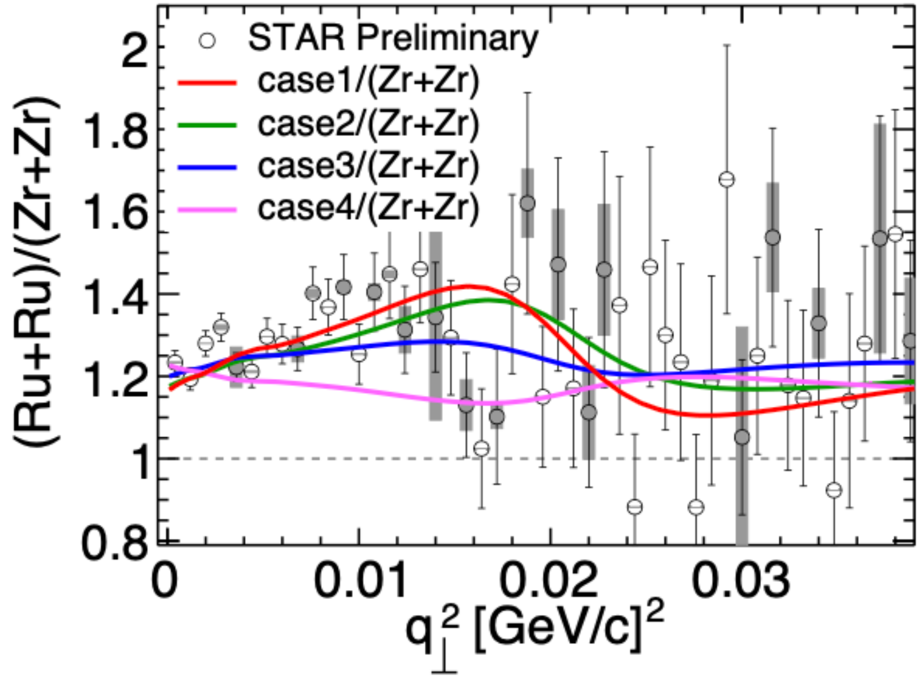


- STARLight simulation with case 1 shows negative slope of the ratio, where Ru size is larger than Zr.
- Case 3: simulation shows positive, which indicates larger Zr size.
- Case 3 agrees better with data, but still large difference (slope ~1.7)

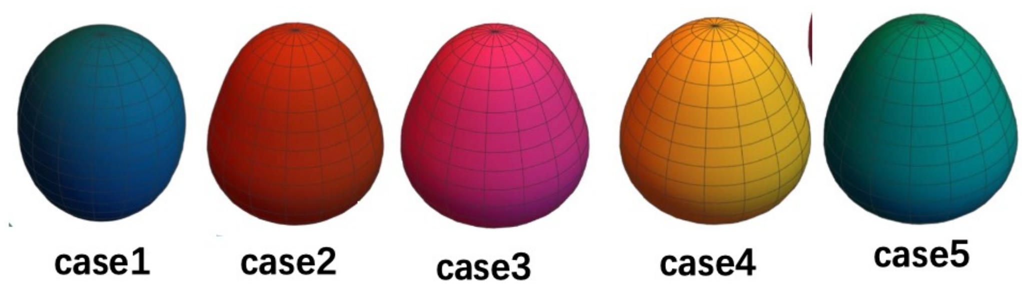
Ru and Zr nuclear structure

W. Zhao QM2023





system	R_0 [fm]	a_0 [fm]	β_2	β_3	β_4
case1 (Ru+Ru)	5.09	0.46	0.16	0.0	0.0
case2 (Ru+Ru)	5.09	0.46	0.16	0.20	0.0
case3 (Ru+Ru)	5.09	0.46	0.06	0.20	0.0
case4 (Ru+Ru)	5.09	0.52	0.06	0.20	0.0
case5 (Zr+Zr)	5.02	0.52	0.06	0.20	0.0



- The vector meson produc2on in isobar UPCs is sensitive to the nuclear structures
- “By eyes”, the ``full’’ Ru/Zr (case1/case5) is closest to data

Summary

- Diffractive photoproduction of ρ^0 mesons in isobar
- Indication of larger Zr size than Ru from the γ-A, the slope of the dN/dt ratio is 11.0+/- 2.9 +/- 0.3 (~3σ effect)
- Comparison with simulation also indicates larger Zr size
- Interference and deformation effects need to be considered using model calculations