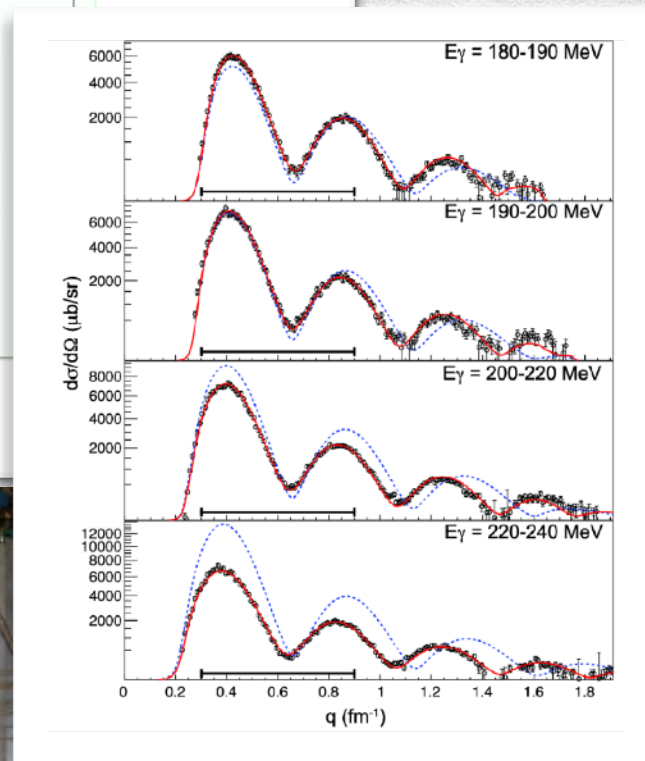
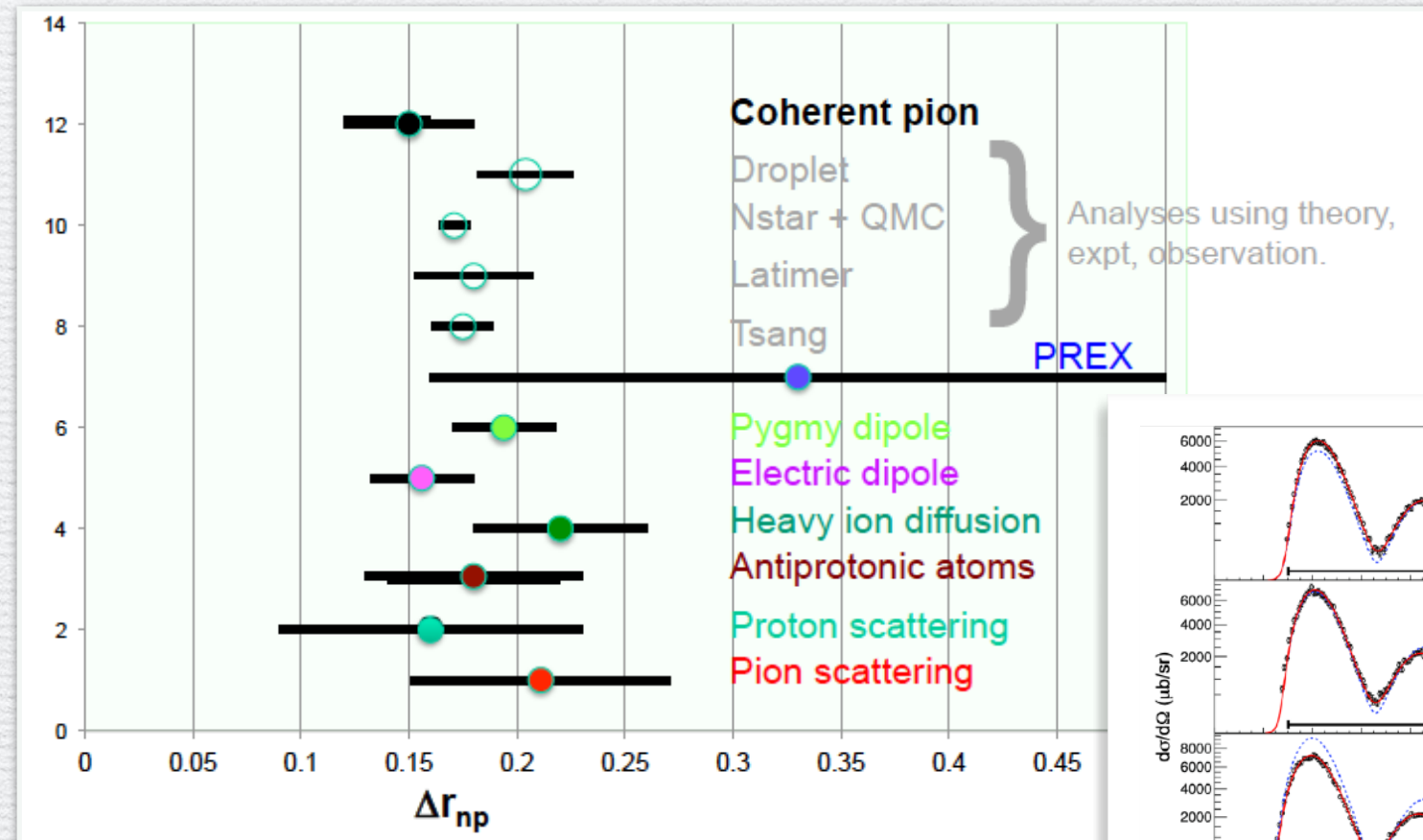
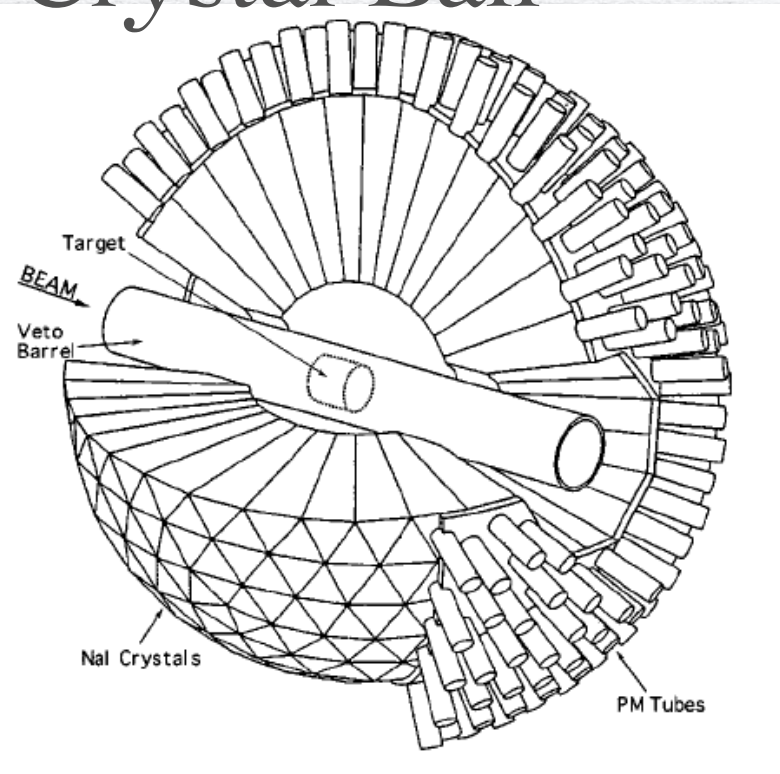


Neutron Skin of ^{208}Pb from Coherent Pion Photoproduction

C.M. Tarbert et al., Phys. Rev. Lett. **112**, 242502 (2014)

Crystal Ball



B-mode
polarization
in CMB

RCNP核理1aグループ勉強会 2015.7.22 by A. Tamii

$\Delta E_\gamma \sim 2 \text{ MeV}$
 $10^8 \gamma \text{ sec}^{-1}$

Neutron Skins of Nuclei: from laboratory to stars

Introductory Workshop

May 4-7, 2015 at MITP, Mainz

	4 May	5 May	6 May	7 May
9:00-10:30	Welcome and Introduction – Chuck	Pygmy (45) Aumann <i>Discussion</i>	Schwenk (45) + <i>Discussion</i>	Wrap-up – Jorge
10:30-11:00	Coffee Break	Coffee Break	Coffee Break	Coffee Break
11:00-12:30	PREX (45)- Kumar <i>Discussion</i>	p-scattering (45) – Egelhof <i>Discussion</i>	Hagen (45) + <i>Discussion</i>	<i>Discussion and homework assignments</i>
12:30-14:00	Lunch	Lunch	Lunch	Lunch
14:00-15:30	EDP (45) – Tamii <i>Discussion</i>	Gandolfi (45) + <i>Discussion</i>	Li (45) + <i>Discussion</i>	
15:30-16:00	Coffee Break	Coffee Break	Coffee Break	
16:00 – 17:30	Pi0 (45) – Watts <i>Discussion</i>	<i>Chuck Colloquium</i>	Roca-Maza (45) + <i>Discussion</i>	
17:30-18:30	<i>Contingency</i>		<i>Contingency</i>	



Organized by
Concettina Sfienti



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17:30-18:30	Contingency		Contingency	



Big-debates were held for each of the experiments!

MITP Conference on Neutron Skin, 17-27 May, 2015

Two Approaches for the Neutron Skin Thickness

Probing the matter/neutron/weak-charge distribution

Takes the difference from the charge (or p) distribution $\rightarrow \Delta R_{np}$

- Less / no model dependence
- Data must be highly accurate

$$\frac{\sigma(\Delta R_{np})}{R_p} \sim \frac{0.02 \text{ fm}}{5.45 \text{ fm}} \sim 4 \times 10^{-3}$$

PREX

p elastic scattering

coherent π production

→ Probing the difference between the p/n distribution

- Requires theoretical models
- Data can be less accurate

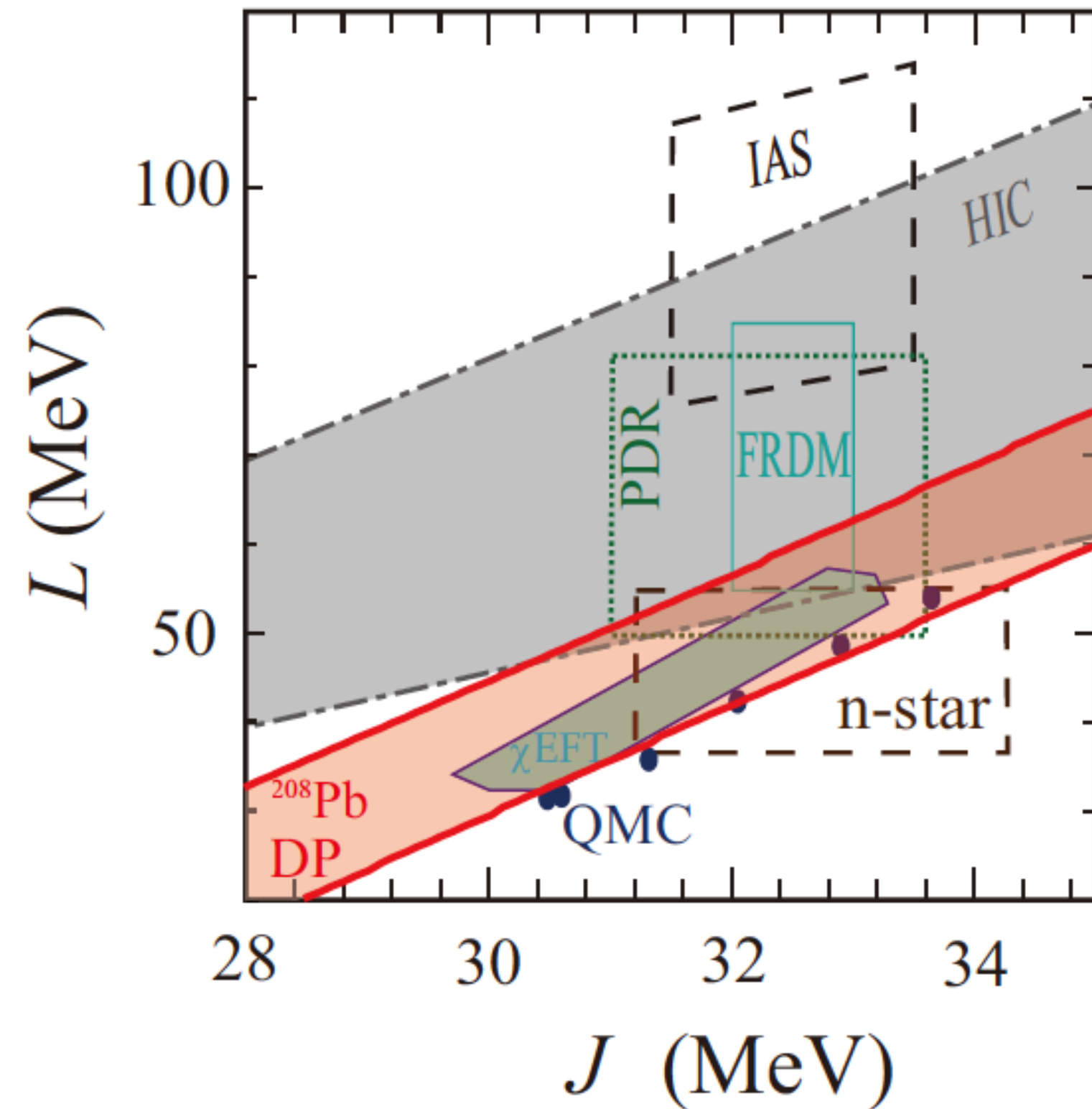
$$\frac{\sigma(\Delta R_{np})}{\Delta R_{np}} \sim \frac{0.02 \text{ fm}}{0.2 \text{ fm}} \sim 10^{-1}$$

Dipole Polarizability

PDR

GDR

Constraints on J and L



AT et al., EPJA**50**, 28 (2014).

M.B. Tsang *et al.*, PRC**86**, 015803 (2012)

C.J. Horowitz et al., JPG**41**, 093001 (2014)

DP: Dipole Polarizability

HIC: Heavy Ion Collision

PDR: Pygmy Dipole Resonance

IAS: Isobaric Analogue State

FRDM: Finite Range Droplet

Model (nuclear mass analysis)

n-star: Neutron Star Observation

cEFT: Chiral Effective Field Theory

QMC: S. Gandolfi, EPJA**50**, 10(2014).

I. Tews et al., PRL**110**, 032504 (2013)



Neutron Skin of ^{208}Pb from Coherent Pion Photoproduction

C. M. Tarbert,¹ D. P. Watts,^{1,*} D. I. Glazier,¹ P. Aguar,² J. Ahrens,² J. R. M. Annand,³ H. J. Arends,² R. Beck,^{2,4} V. Bekrenev,⁵ B. Boillat,⁶ A. Braghieri,⁷ D. Branford,¹ W. J. Briscoe,⁸ J. Brudvik,⁹ S. Cherepnya,¹⁰ R. Codling,³ E. J. Downie,³ K. Foehl,¹ P. Grabmayr,¹¹ R. Gregor,¹² E. Heid,² D. Hornidge,¹³ O. Jahn,² V. L. Kashevarov,¹⁰ A. Knezevic,¹⁴ R. Kondratiev,¹⁵ M. Korolija,¹⁴ M. Kotulla,⁶ D. Krambrich,^{2,4} B. Krusche,⁶ M. Lang,^{2,4} V. Lisin,¹⁵ K. Livingston,³ S. Lugert,¹² I. J. D. MacGregor,³ D. M. Manley,¹⁶ M. Martinez,² J. C. McGeorge,³ D. Mekterovic,¹⁴ V. Metag,¹² B. M. K. Nefkens,⁹ A. Nikolaev,^{2,4} R. Novotny,¹² R. O. Owens,³ P. Pedroni,⁷ A. Polonski,¹⁵ S. N. Prakhov,⁹ J. W. Price,⁹ G. Rosner,³ M. Rost,² T. Rostomyan,⁷ S. Schadmand,¹² S. Schumann,^{2,4} D. Sober,¹⁷ A. Starostin,⁹ I. Supek,¹⁴ A. Thomas,² M. Unverzagt,^{2,4} Th. Walcher,² L. Zana,¹ and F. Zehr⁶
(Crystal Ball at MAMI and A2 Collaboration)

Abstract

Information on the size and shape of the neutron skin on ^{208}Pb is extracted from coherent pion photoproduction cross sections measured using the Crystal Ball detector together with the Glasgow tagger at the MAMI electron beam facility. On exploitation of an interpolated fit of a theoretical model to the measured cross sections, the half-height radius and diffuseness of the neutron distribution are found to be $c_n = 6.70 \pm 0.03(\text{stat.})$ fm and $a_n = 0.55 \pm 0.01(\text{stat.})_{-0.03}^{+0.02}(\text{sys.})$ fm, respectively, corresponding to a neutron skin thickness $\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})_{-0.03}^{+0.01}(\text{sys.})$ fm. The results give the first successful extraction of a neutron skin thickness with an electromagnetic probe and indicate that the skin of ^{208}Pb has a halo character. The measurement provides valuable new constraints on both the structure of nuclei and the equation of state for neutron-rich matter.

Structure of the Paper

Neutron Skin of ^{208}Pb from Coherent Pion Photoproduction

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(Received 2 February 2014; published 18 June 2014)

Information on the size and shape of the neutron skin on ^{208}Pb is extracted from coherent pion photoproduction cross sections measured using the Crystal Ball detector together with the Glasgow tagger at the MAMI electron beam facility. On exploitation of an interpolated fit of a theoretical model to the measured cross sections, the half-height radius and diffuseness of the neutron distribution are found to be $c_n = 6.70 \pm 0.03(\text{stat.}) \pm 0.55 \pm 0.01(\text{stat.})_{-0.02}^{+0.01}(\text{sys.})$ fm, respectively, corresponding to a neutron skin thickness $\Delta r_{\text{np}} = 0.15 \pm 0.03(\text{stat.})_{-0.02}^{+0.01}(\text{sys.})$ fm. The results give the first successful extraction of a neutron skin thickness with an electromagnetic probe and indicate that the skin of ^{208}Pb has a halo character. The measurement provides valuable new constraints on both the structure of nuclei and the equation of state for neutron-rich matter.

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PACS numbers: 25.20.Lj, 21.65.Cd, 21.65.Ef, 27.80.+w

Obtaining an accurate determination of the character of the neutron distribution in nuclei has proven elusive despite decades of study. This has been a long-standing and serious shortcoming in our understanding of nuclear structure. The difference between the neutron and proton distributions is often expressed as the neutron skin thickness (Δr_{np}), a fine scale in the difference between the mean square radii of the neutron and proton distributions. This convention was adopted as many previous measurements had little or no sensitivity to the diffuseness of the density distributions, excluding analysis based on the more familiar half-height radius and diffuseness of

a two-parameter Fermi distribution [1]. State-of-the-art nuclear theories predict Δr_{np} values for ^{208}Pb that range from 0.05 to 0.35 fm [2], despite all being constrained by the same nuclear data. Recently, it was pointed out that the magnitude of Δr_{np} in heavy nuclei shows a tight, model-independent relation with its density dependence of the symmetry energy of nuclear matter [3]. The sign and the amount of the neutron skin thus depends on the potential to give important new information on neutron star structure and cooling mechanisms [5–9], searches for physics beyond the standard model [10,11], the nature of three-body forces in nuclei [12,13],

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the extraordinary statistical accuracy in the maxima, an additional 3% error was assigned to each cross section value to ensure that the important information in the first minimum was given sufficient weight in the fit. The fitted theoretical cross sections are shown together with the experimental data for all measured q in Fig. 2. Excellent fits are obtained in the fitted q range with χ^2 per degree of freedom of ~ 1 . Outside this fitted range the model still gives a very good description of the experimental data with discrepancies only evident at high q , probably due to the inability of the 2PF parameterization to describe the fine details of the distribution. A normalization parameter was included in the fit and was found to vary only within $\pm 5\%$ of unity. Figure 2 also shows model predictions when the π^0 -nucleus interaction is not included in the calculation. For the three lower E_γ bins, the effect of the π^0 -nucleus interaction is modest in the fitted q range. For the highest bin, the differences are significantly larger, probably due to the increase in the π^0 absorption cross section for q

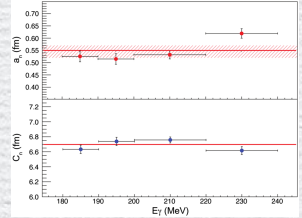


FIG. 3 (color online). The best fit for diffuseness (upper) and half-height radius (lower) for the neutron distribution for each E_γ bin. The horizontal lines show the average over E_γ , and the shaded band shows the estimated systematic error (see text).

framework from Ref. [47], where the theoretical model predictions are fitted with a 2PF function. The difference between the diffuseness parameters for neutrons and protons is plotted vs the difference in half-height radii. The present result clearly shows that the diffuseness of the neutron distribution in ^{208}Pb is in the range of theoretical predictions and is significantly greater than that for the protons. This is an important result, as conclusive experimental evidence for the difference in the diffuseness of the nuclear density distributions has been lacking [48]. A pure “skin” effect would have a $c_n - c_p$ value close to zero, so this new result indicates that the neutron skin of ^{208}Pb has a halo character.

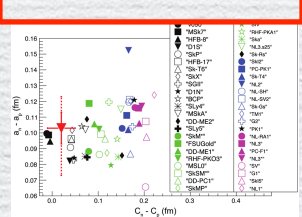


FIG. 4 (color online). The quantity $(c_n - c_p)$ plotted versus $(c_n + c_p)$ for ^{208}Pb . The red inverted triangle shows the present result with statistical and systematic errors shown by solid and dashed lines, respectively. The symbols show the predictions from the various nuclear structure calculations, obtained from Ref. [47].

collective nuclear excitations [14–17], and flows in heavy-ion collisions [18,19].

The potential impact of obtaining an accurate determination of Δr_{np} has led to much theoretical and experimental interest in recent years. Many studies have focused on ^{208}Pb , which has a relatively well-understood structure due to the closed proton ($Z = 82$) and neutron ($N = 126$) shells. A goal of a ± 0.05 fm accuracy in Δr_{np} is quoted [2] as the requirement to constrain the equation of state sufficiently to remove the current major ambiguities. A recent review of the experimental attempts to measure Δr_{np} in ^{208}Pb is given by Tsang *et al.* [12]. Recent analysis of proton [20] and pion [21] scattering data gave $\Delta r_{\text{np}} = 0.211 \pm 0.06$ fm and $\Delta r_{\text{np}} = 0.16 \pm 0.07$ fm, respectively. Studies of the annihilation of antiprotons on the nuclear surface [22,23] gave $\Delta r_{\text{np}} = 0.18 \pm 0.04(\text{expt.}) \pm 0.05(\text{theor.})$ fm. Isospin diffusion in heavy-ion collisions gave $\Delta r_{\text{np}} = 0.22 \pm 0.04$ fm [24]. Measurements of pygmy dipole resonances and electric dipole polarizabilities of nuclei [15,17,25] gave Δr_{np} values ranging from 0.156 to 0.194 fm with quoted accuracies as small as ± 0.024 fm, although the model dependence is still debated [26] and an accuracy of ± 0.05 fm is taken in Ref. [12].

Experiments with electromagnetic probes [27–29] have systematic errors different from those with the strongly interacting probes described above and have the advantage of probing the full nuclear volume. However, there have been no successful measurements of the neutron distribution. A measurement using an electron probe has very recently been obtained in parity-violating electron scattering on nuclei, utilizing the preferential coupling of the exchanged weak boson to neutrons. A first measurement at a single momentum transfer gave $\Delta r_{\text{np}} = 0.33 \pm 0.17$ fm in ^{208}Pb [30].

The latter also has the coherent photoproduction of π^0 mesons from ^{208}Pb as an accurate probe of the nuclear shape, which has sufficient sensitivity to detect and characterize the neutron skin. In the coherent reaction, the target nucleus is left in its ground state, which ensures that all the nucleons contribute coherently to the reaction amplitude. For our data at incident photon energies 180–240 MeV, where Δ excitation is the dominant mechanism, the amplitudes for neutron and proton Δ excitation are expected to be identical [29]. The coherent (γ, π^0) cross section, the ratio of the neutron to proton cross section, is expected to be identical [29]. The coherent π^0 production from ^{208}Pb has been used to study the neutron skin, interpretation of the (γ, π^0) reaction being advantageous as it is not complicated by initial state interactions. However, final state interactions between π^0 and nucleus are significant; they produce both a shift in the pion emission angle and a modification of the outgoing flux, which must be accurately treated in the theoretical calculation of the (γ, π^0) cross section if reliable nuclear shape information is to be

obtained. The π^0 -nucleus interaction varies with energy, and the validity of its treatment can, therefore, be assessed from the consistency of the nuclear shape parameters obtained from (γ, π^0) angular distributions at different incident photon energies. The analysis below presents data for the E_γ range of 180–240 MeV. Data have also been obtained from the threshold up to 180 MeV, but extensions to the theoretical calculation are required before these data can be used, to allow for different photon couplings to neutrons and protons. Above $E_\gamma = 240$ MeV the extracted shape parameters become unreliable, probably as a result of the rapid increase in the π^0 -nucleus interaction in the Δ resonance region.

Previous (γ, π^0) measurements for ^{208}Pb [27,29] either did not use isotopically pure targets or did not achieve the precision needed to study the neutron skin, mainly because they used π^0 detection systems with limited angular coverage resulting in a small detection efficiency with too large a dependence on pion energy and angle to give definitive results. In the present experiment, these problems are almost completely removed by utilizing a large solid-angle photon detector, the Crystal Ball (CB) [31], in conjunction with the Glasgow photon tagger [32] and the MAMI electron microtron [33]. The experimental setup is described in detail in Ref. [34]. The tagged photon beam had a resolution of ~ 2 MeV full width and an intensity of $\sim 2 \times 10^5 \text{ s}^{-1} \text{ MeV}^{-1}$. The tagged photons were incident on a 0.52 ± 0.01 mm thick isotopically enriched (99.5%) ^{208}Pb target placed at the center of the CB detector. The CB is a 672 element NaI detector covering 94% of $4\pi \text{ sr}$. A central detector system provided charged particle identification [35] and track information [36] and allowed the target position to be determined within ~ 0.5 mm.

The coherent photoproduction of π^0 mesons from ^{208}Pb has been used to study the neutron skin, interpretation of the (γ, π^0) reaction being advantageous as it is not complicated by initial state interactions. However, final state interactions between π^0 and nucleus are significant; they produce both a shift in the pion emission angle and a modification of the outgoing flux, which must be accurately treated in the theoretical calculation of the (γ, π^0) cross section if reliable nuclear shape information is to be

$$\Delta E_{\text{eff}}^{\pi^0} = E_\gamma^{\pi^0} - E_{\text{th}}^{\pi^0}. \quad (1)$$

$E_{\text{th}}^{\pi^0}$ is the energy of the pion in the center-of-mass (c.m.) frame of the incident photon and nucleus at rest, calculated using the incident photon energy assuming coherent π^0 production from a ^{208}Pb nucleus. $E_{\text{th}}^{\pi^0}$ is the detected π^0 energy in the c.m. frame. For a coherent reaction, $\Delta E_{\text{eff}}^{\pi^0}$ should be close to zero. Example spectra for $\Delta E_{\text{eff}}^{\pi^0}$ are shown in Fig. 1. In the first maximum of the π^0 angular distribution, the coherent process dominates and allows the determination of the width of the coherent peak. The measured $E_{\text{eff}}^{\pi^0}$ resolution ranged from 2 MeV near threshold to 9 MeV at $E_\gamma = 240$ MeV, in excellent agreement with a Geant4 [37] (G4) simulation. Near the diffraction minima a background arising from one or more non-coherent processes is evident. An additional Gaussian term

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difference between the two transforms only rises to 0.3% at $q = 0.9 \text{ fm}^{-1}$.

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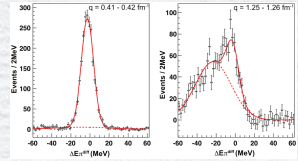


FIG. 1 (color online). The fits to the spectrum of $\Delta E_{\text{eff}}^{\pi^0}$ for $E_\gamma = 200$ MeV for a momentum transfer near the first diffraction maximum (left) and the first diffraction minimum (right).

in the fit gave a good description of the background, which exhibited an E_γ and θ_γ dependence consistent with a simple Monte Carlo model of quasifree π^0 production. The area of the Gaussian fitted to the coherent peak is taken as a measure of the coherent yield.

To obtain cross sections, the yield was corrected for the π^0 detection efficiency. This is calculated by analyzing pseudodata from a G4 simulation of the detector apparatus using the same analysis procedure as for the real data. The detection efficiency shows no sharp dependence on pion angle and was typically around 40%, a factor of over 30 improvement on previous measurements. The yield was also corrected for the photon tagging efficiency ($\sim 40\%$), with the procedure described in Ref. [38]. The contribution of pions not originating from the ^{208}Pb target was found to be less than $\sim 1\%$ in additional runs with the target removed and was subtracted from the yield.

The differential cross sections are analyzed in terms of the momentum transfer q , defined as $\mathbf{q} = \mathbf{P}_\gamma - \mathbf{P}_\pi$ where \mathbf{P}_γ is the incident photon momentum and \mathbf{P}_π is the measured pion momentum. The differential cross sections as a function of momentum transfer are presented in Fig. 2 for E_γ bins from 180 to 240 MeV. For this E_γ region, pion photoproduction from Δ excitation is the dominant mechanism. The maximum photon energy restricts the data to regions of pion momentum where the model of Ref. [42] predicts that FS1 effects are fairly small. In order to extract information about the nucleon distribution in ^{208}Pb , the measured (γ, π^0) cross sections are compared with predictions from the model of Drechsel *et al.* [42], which represents Δ photoproduction using a unitary isobar model and includes a self-energy term for Δ propagation effects in the nucleus. The π^0 -nucleus interaction is treated using a complex optical potential [1], whose parameters are fixed by fits to pion-nucleus scattering data. The model gave good agreement with coherent data from a range of nuclei [43]. In the (γ, π^0) model the nucleon density distribution $\rho(r)$ is parametrized as a single

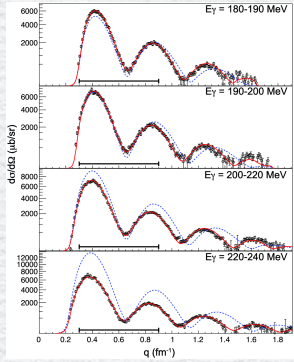


FIG. 2 (color online). Differential cross sections for the reaction $^{208}\text{Pb}(\gamma, \pi^0)^{208}\text{Pb}$ (black circles) for the E_γ regions indicated. The y axis employs a square-root scale to improve the clarity. The red solid line shows the interpolated fit of the theoretical model to the data. The q range of the fit is indicated by the horizontal bar. The dashed blue line shows the model predictions without including the π^0 -nucleus interaction.

parametrized two-parameter Fermi distribution (2PF) [44] with half-height radius c and diffuseness a . For the present analysis, different proton and neutron distributions, each separately parametrized by a 2PF distribution, are needed to describe the nuclear shape $\rho(r) = (Z/A) \rho_p(r) + (N/A) \rho_n(r)$. Then, in order to put $\rho(r)$ into the (γ, π^0) code it is fitted by a single 2PF distribution [44]. The parameters for $\rho_p(r)$ are well determined by electron scattering [45], viz., $c_p = 0.447$ fm and $a_p = 6.680$ fm. The values used have been corrected for the finite size of the proton to give the point charge distribution that is relevant for pion photoproduction [22]. For the neutron distribution parameters, a grid of 35 points covering the ranges $c_n = 6.28$ to 7.07 fm and $a_n = 0.35$ to 0.65 fm was selected and the (γ, π^0) cross section was calculated at each point. These cross sections were smeared with the experimental q resolution $\sigma_q = 0.02$ – 0.03 fm^{-1} depending on E_γ , as determined from the G4 simulation. A two-dimensional interpolation between the 35 smeared cross sections was then used to fit the (γ, π^0) cross sections in Fig. 2 in the region $q = 0.3$ to 0.9 fm^{-1} and, thus, extract the best fit values a_n and c_n for the neutron distribution for each photon energy bin. Because of

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difference between the two transforms only rises to 0.3% at $q = 0.9 \text{ fm}^{-1}$.

[45] M. Warda, X. Viñas, X. Roca-Maza, and M. Centelles, *Phys. Rev. C* **81**, 054309 (2010).

[46] R. W. Hasse and W. D. Myers, *Geometrical Relationships of Macroscopic Nuclear Physics* (Springer-Verlag, Heidelberg, 1988).

[47] M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, *Phys. Rev. C* **80**, 024316 (2009).

[48] M. Warda, X. Viñas, X. Roca-Maza, and M. Centelles, *Phys. Rev. C* **80**, 024316 (2009).

[49] M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, *Phys. Rev. C* **80**, 024316 (2009).

[50] M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, *Phys. Rev. C* **80**, 024316 (2009).

[51] M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, *Phys. Rev. C* **80**, 024316 (2009).

[52] M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, *Phys. Rev. C* **80**, 024316 (2009).

[53]

Introductions: Neutron Skin Thickness

Neutron distribution in nuclei

Neutron skin thickness (Δr_{np})

$$\Delta r_{np} \equiv \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p} \quad \text{difference of the root mean square radii of } n \text{ and } p$$

➡ no sensitivity to the diffuseness of the density distributions

Predictions of “state of the art” nuclear theories

$$\Delta r_{np} = 0.05 - 0.35 \text{ fm}$$

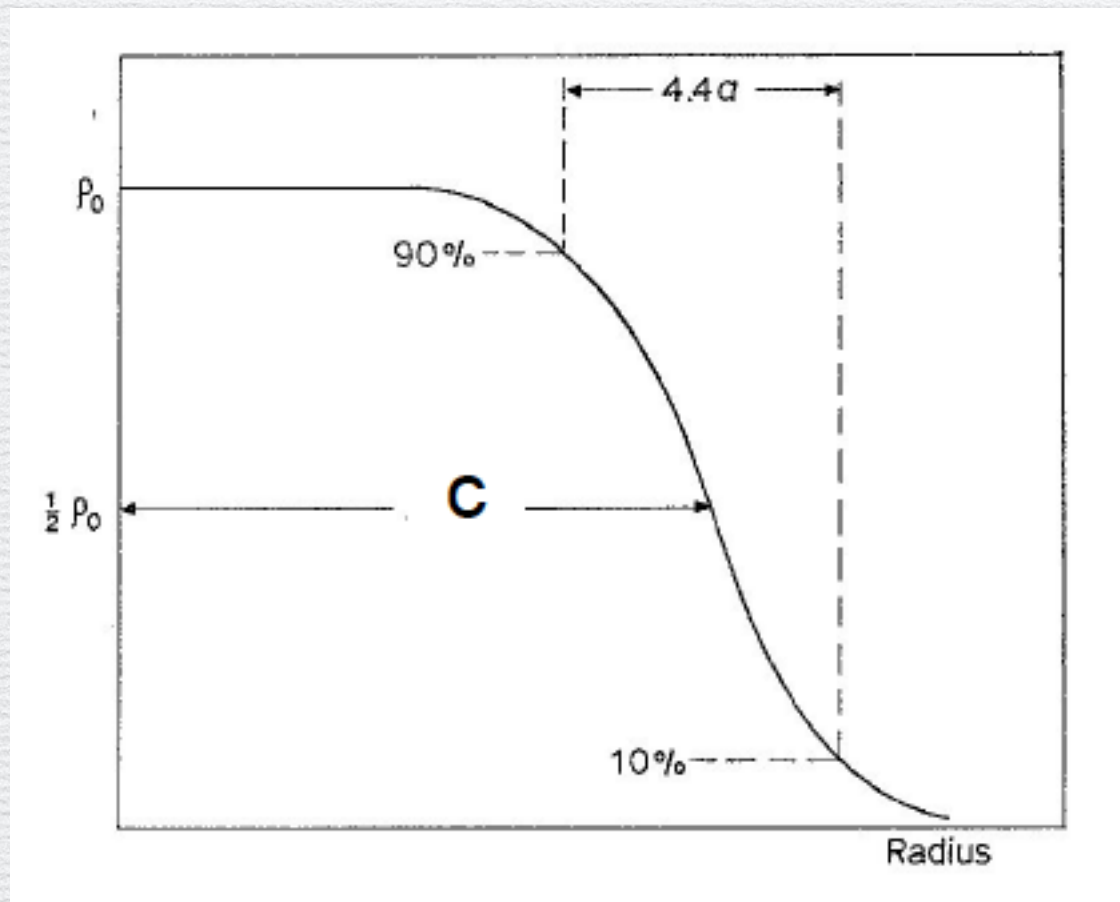
➡ density dependence of the symmetry energy

- Neutron star structure/cooling mechanism [5-9]
- Physics beyond the standard model [10,11]
- Three-body forces in nuclei [12,13]
- Collective nuclear excitations [14-17]
- Flows in heavy-ion collision [18-19]

Introductions: Neutron Skin Thickness

Neutron distribution in nuclei

two parameter Fermi (2PF) distribution



$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r - c}{a}\right)}$$

Introductions: The case of ^{208}Pb

A goal of 0.05 fm accuracy is quoted [2] to constrain the EoS sufficiently to remove the current major ambiguities

[2] R. J. Furnstahl, NPA706, 85 (2002).

Taken from [12] M. B. Tsang et al., PRC86, 015803 (2012).

proton scattering $\Delta r_{np} = 0.211 \pm 0.06 \text{ fm}$ [20]

pion scattering $\Delta r_{np} = 0.16 \pm 0.07 \text{ fm}$ [21]

anti-proton annihilation $\Delta r_{np} = 0.18 \pm 0.04_{\text{exp.}} \pm 0.05_{\text{theor.}} \text{ fm}$ [22,23]

Isospin-diffusion heavy ion collision $\Delta r_{np} = 0.22 \pm 0.04 \text{ fm}$ [24]

pygmy dipole $\Delta r_{np} = 0.156 - 0.194 \text{ fm}$ [15,17,25]

dipole polarizability with quoted accuracy of $\pm 0.024 \text{ fm}$
although the model dependency is still debated
and the accuracy of $\pm 0.05 \text{ fm}$ is taken

^{208}Pb DP $\Delta r_{np} = 0.156 - 0.021 + 0.025 \text{ fm}$ [17]

$\Delta r_{np} = 0.168 \pm 0.022 \text{ fm}$ J. Piekarewicz et al., PRC85, 041302(R) (2012)

$\Delta R_{np} = 0.165 \pm (0.009)_{\text{expt}} \pm (0.013)_{\text{theor}} \pm (0.021)_{\text{est}} \text{ fm}$ Roca-Maza et al., PRC88, 024316(2013)

Neutron Density (Proton Scattering)

V.E. Starodubsky et al., PRC18, 2641(1994)

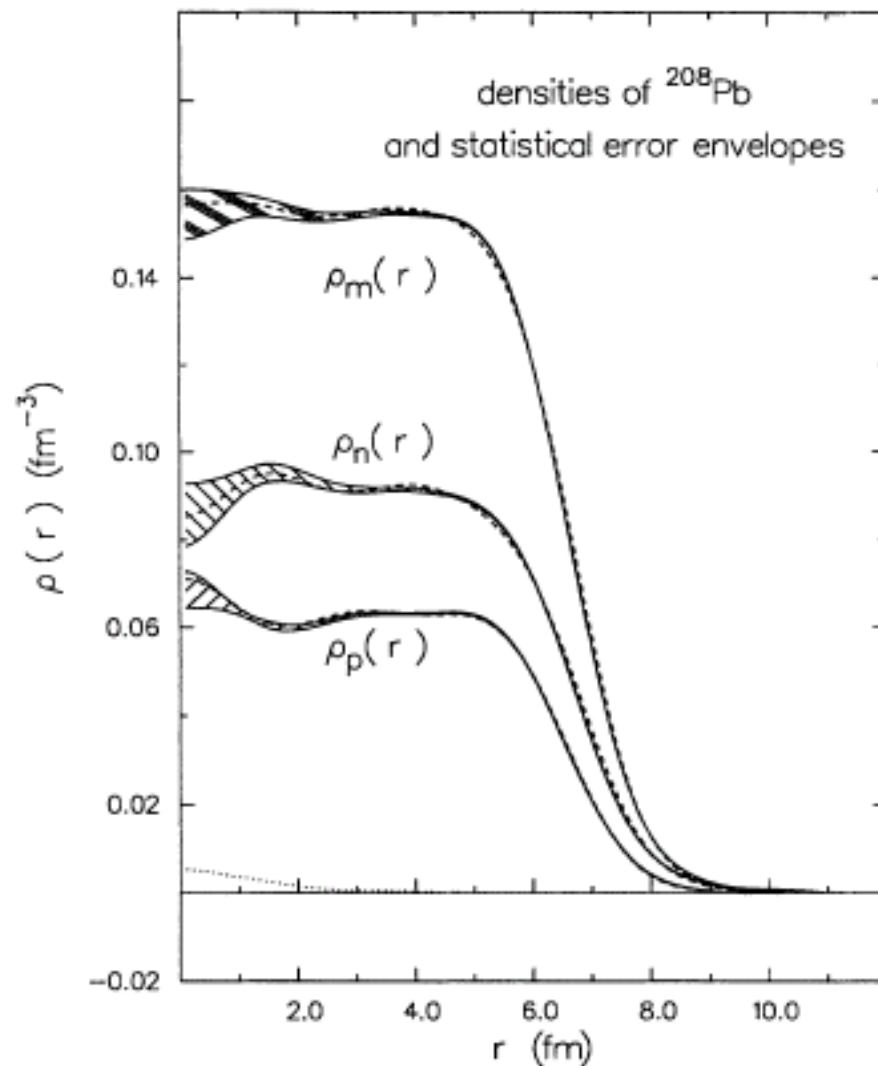
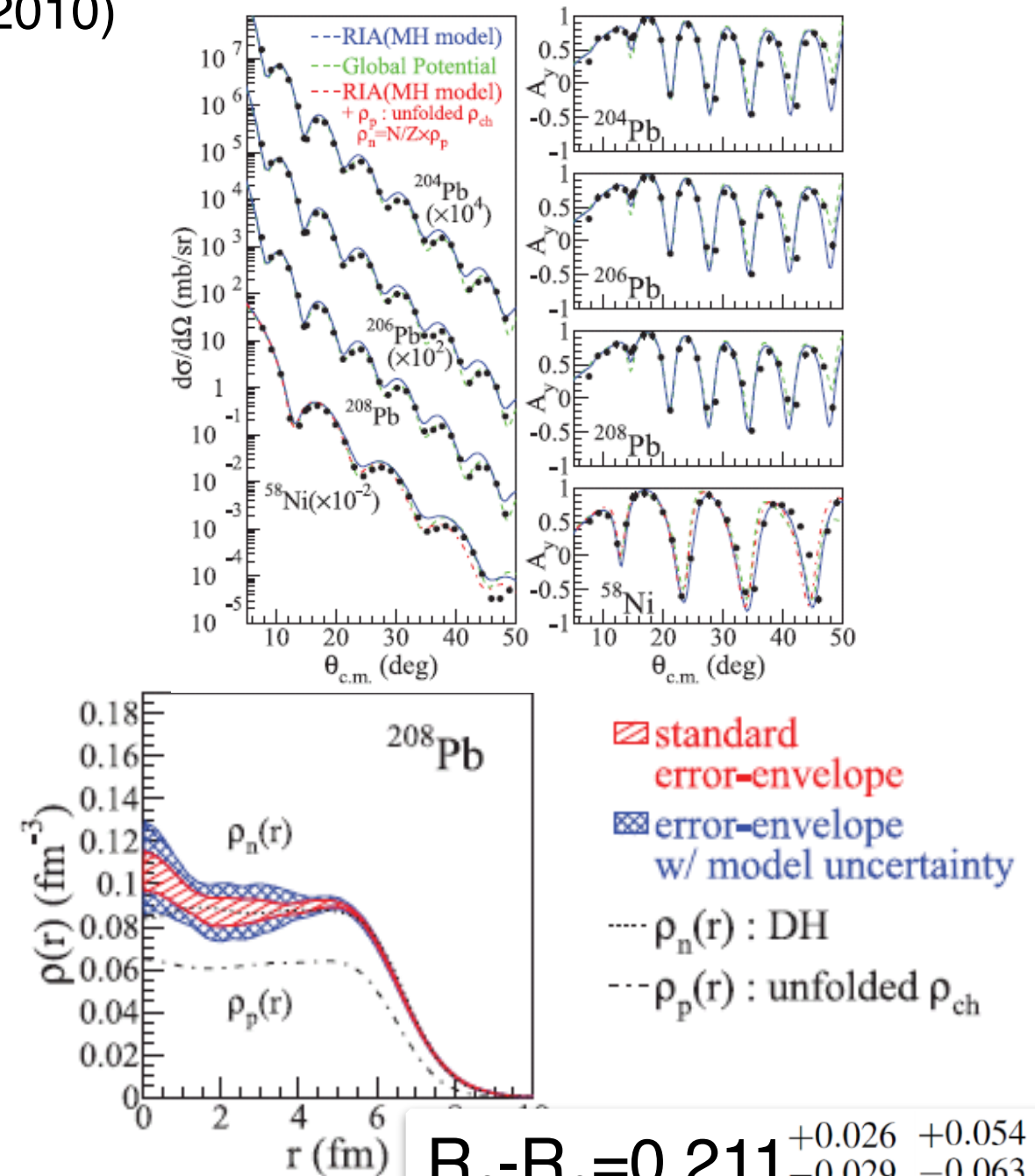


FIG. 6. Extracted neutron and matter densities for ^{208}Pb lying in the middle of the corresponding statistical error bands (the hatched areas). The HF proton, neutron, and matter densities are depicted by the dashed lines. The proton density obtained by unfolding the charge density of Ref. [43] is also shown with its statistical error envelope. The dotted line at the bottom is for the statistical error band obtained with the SOG method of Ref. [23].

$$R_{\text{ch}}=5.503(2), R_p=5.458, R_n=5.655(42) \text{ fm}$$

$$R_n-R_p=0.197(42) \text{ fm}$$

[22] J. Zenihiro et al., PRC82, 044611 (2010)



$$R_n-R_p=0.211^{+0.026}_{-0.029} \text{ } ^{+0.054}_{-0.063} \text{ fm}$$

Nucleus	r_{ch}	r_p^{unfold}	r_n	δr_n^{std}	δr_n^{mdl}
^{204}Pb	5.479(2)	5.420(2)	5.598	$+0.029$ -0.020	$+0.047$ -0.059
^{206}Pb	5.490(2)	5.433(2)	5.613	$+0.026$ -0.026	$+0.048$ -0.064
^{208}Pb	5.503(2)	5.442(2)	5.653	$+0.026$ -0.029	$+0.054$ -0.063

Dipole Polarizability (α_D)

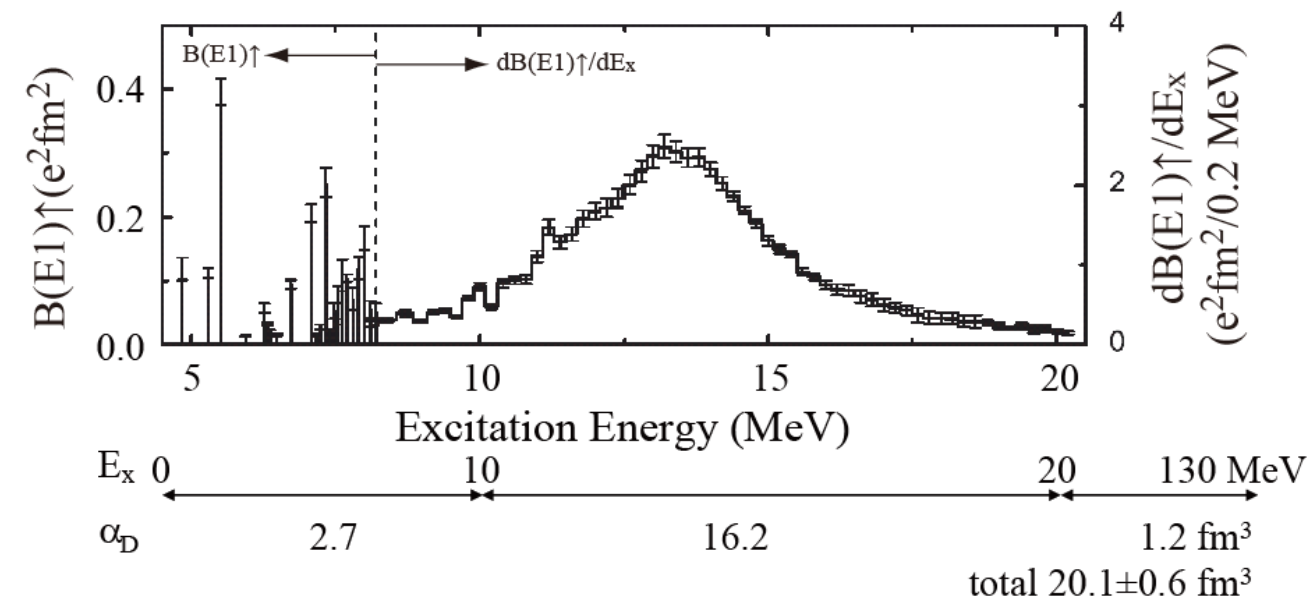
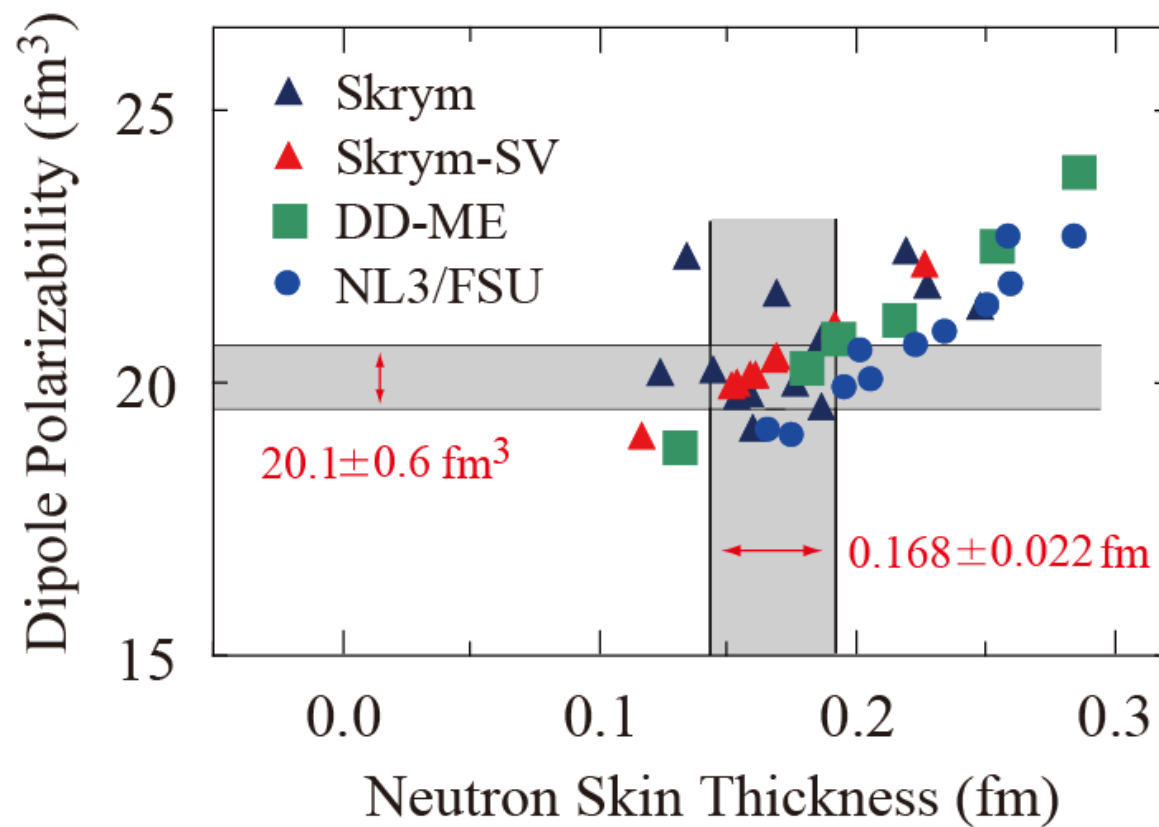
Dipole Polarizability is strongly correlated with $R_n - R_p$ [17]

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

$$R_n - R_p = 0.168 \pm 0.022 \text{ fm for } ^{208}\text{Pb}$$

Determination of α_D by an Electro-Magnetic Probe

including model uncertainty.



AT et al. PRL107,062502(2011) [27]

J. Piekarewicz et al., PRC85, 041302(2012)

A detailed illustration of a Tyrannosaurus Rex head and upper body. The dinosaur is shown in profile, facing right, with its mouth wide open, revealing sharp, white teeth. Its skin is textured and colored in shades of brown, tan, and grey. The background is a solid dark blue.

A_{PV} from interference

(1) in PWBA

(²⁰⁸Pb)

interference between
EM and weak
interactions

Fourier transform of the weak charge density

F_{ch} : charge form factor

The diagram illustrates the difference between Right-Handed (R) and Left-Handed (L) coordinate systems. In both, a green circle represents a cross-section. A vertical line passes through its center. A vector originates from the center, pointing upwards and to the left, forming an angle θ with the vertical. Below the circle, a green dot labeled 'e' is shown with an upward-pointing arrow. In the 'R' (Right-Handed) system, a curved arrow indicates a counter-clockwise rotation around the vertical axis. In the 'L' (Left-Handed) system, a curved arrow indicates a clockwise rotation around the vertical axis.

helicity

Weak Charge

J-F. Rajotte, arxiv:1110.2218v1

TABLE I: Electroweak Couplings of u and d Quarks and Nucleons as Function of the Weak Mixing Angle θ_W

Particles	EM Charge	Weak Charge
u	$+\frac{2}{3}$	$1 - \frac{8}{3} \sin^2 \theta_W$
d	$-\frac{1}{3}$	$-1 + \frac{4}{3} \sin^2 \theta_W$
$p(uud)$	$+1$	$1 - 4 \sin^2 \theta_W$
$n(udd)$	0	-1

in the standard model

~ 0.08

0.0721

-0.9878



with radiative
correction

θ_W : Weinberg Angle or Weak Mixing Angle

$\sin^2 \theta_W = 0.23116(12)$ c.f. PDG 2012

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Weak charge distribution is primarily
determined by the neutron distribution

BUT weak interaction is VERY weak...

APV ~ 656 ppb $= 0.000000656$

Standard Model

TABLE 13.1

Weak Isospin and Hypercharge Quantum Numbers of Leptons and Quarks

Lepton	T	T^3	Q	Y
ν_e	$\frac{1}{2}$	$\frac{1}{2}$	0	-1
e_L^-	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1
e_R^-	0	0	-1	-2

Quark	T	T^3	Q	Y
u_L	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$
d_L	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$
u_R	0	0	$\frac{2}{3}$	$\frac{4}{3}$
d_R	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$

$$Q = T^3 + \frac{Y}{2}$$

$$j_\mu^{em} = J_\mu^3 + \frac{1}{2}j_\mu^Y.$$

$$-i g (J^i)^\mu W_\mu^i - i \frac{g'}{2} (j^Y)^\mu B_\mu.$$

charged fields

$$W_\mu^\pm = \sqrt{\frac{1}{2}} (W_\mu^1 \mp i W_\mu^2)$$

neutral fields (mass eigenstates)

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \quad (\text{massless}),$$

$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W \quad (\text{massive}),$$

\Rightarrow Electro-Magnetic Field

Electro-weak neutral current interaction

$$-i g J_\mu^3 (W^3)^\mu - i \frac{g'}{2} j_\mu^Y B^\mu$$

$$= -i \left(g \sin \theta_W J_\mu^3 + g' \cos \theta_W \frac{j_\mu^Y}{2} \right) A^\mu$$

$$\Rightarrow -i e j_\mu^{em} A^\mu$$

$$-i \left(g \cos \theta_W J_\mu^3 - g' \sin \theta_W \frac{j_\mu^Y}{2} \right) Z^\mu.$$

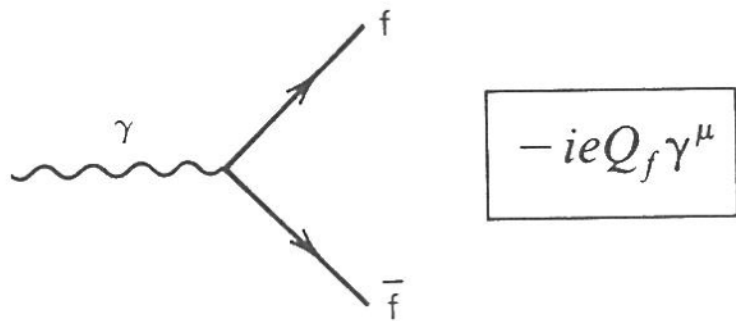
$$\Rightarrow -i \frac{g}{\cos \theta_W} J_\mu^{NC} Z^\mu$$

$$g \sin \theta_W = g' \cos \theta_W = e$$

$$J_\mu^{NC} \equiv J_\mu^3 - \sin^2 \theta_W j_\mu^{em}$$

Electro-magnetic interaction

$$-i e (j^{em})^\mu A_\mu = -i e (\bar{\psi} \gamma^\mu Q \psi) A_\mu$$

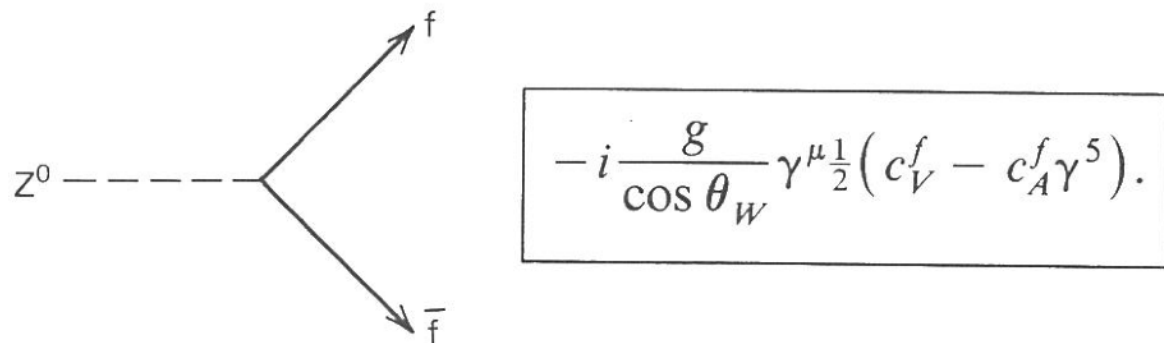


Vector coupling

Electro-weak neutral current interaction

$$-i \frac{g}{\cos \theta_W} \left(J_\mu^3 - \sin^2 \theta_W j_\mu^{em} \right) Z^\mu =$$

$$-i \frac{g}{\cos \theta_W} \bar{\psi}_f \gamma^\mu \left[\frac{1}{2} (1 - \gamma^5) T^3 - \sin^2 \theta_W Q \right] \psi_f Z_\mu$$



Vector coupling

V-A coupling

produces parity-violation

=L-helicity projection operator

TAI
The $Z \rightarrow f\bar{f}$ Vertex Factors, (13.41), in the Standard Model (with $\sin^2 \theta_W = 0.234$)

f	Q_f	c_A^f	c_V^f
ν_e, ν_μ, \dots	0	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, \dots	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2 \sin^2 \theta_W \approx -0.03$
u, c, ...	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3} \sin^2 \theta_W \approx 0.19$
d, s, ...	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W \approx -0.34$

Result

$$R_n = 5.78^{+0.16}_{-0.18}$$

$$R_n - R_p = 0.33^{+0.16}_{-0.18} \text{ fm}$$

In abstract

“provides the first electroweak observation of the neutron skin”

In summary

“A future run is planned which will reduce the quoted uncertainty by a factor of 3 [43], to discriminate between models and allow predictions relevant for the description of neutron stars and parity violation in atomic systems.”

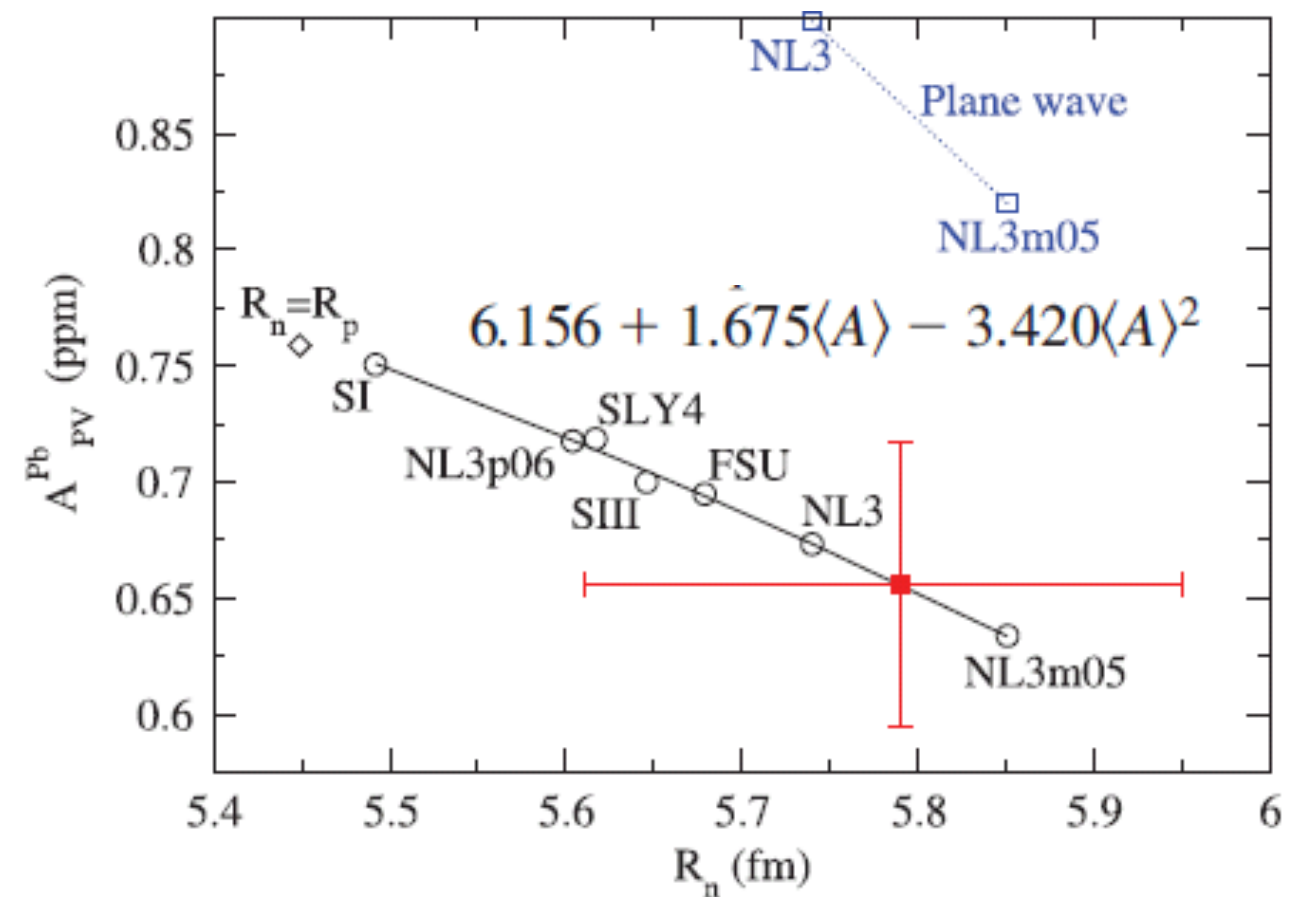


FIG. 1 (color). Result of this experiment (red square) vs neutron point radius R_n in ^{208}Pb . Distorted-wave calculations for seven mean-field neutron densities are circles while the diamond marks the expectation for $R_n = R_p$ [39]. References: NL3m05, NL3, and NL3p06 from [11], FSU from [12], SIII from [13], SLY4 from [14], SI from [15]. The blue squares show plane wave impulse approximation results.

No discussion on the impact of the result?

Is this analysis really model independent?

Introductions: The case of ^{208}Pb

Experiments with electromagnetic probes [27-29]

no successful measurement on neutron density distribution

Electroweak probe: parity-violating electron scattering PREX [30]

$$\Delta r_{np} = 0.33 \pm 0.17 \text{ fm}$$

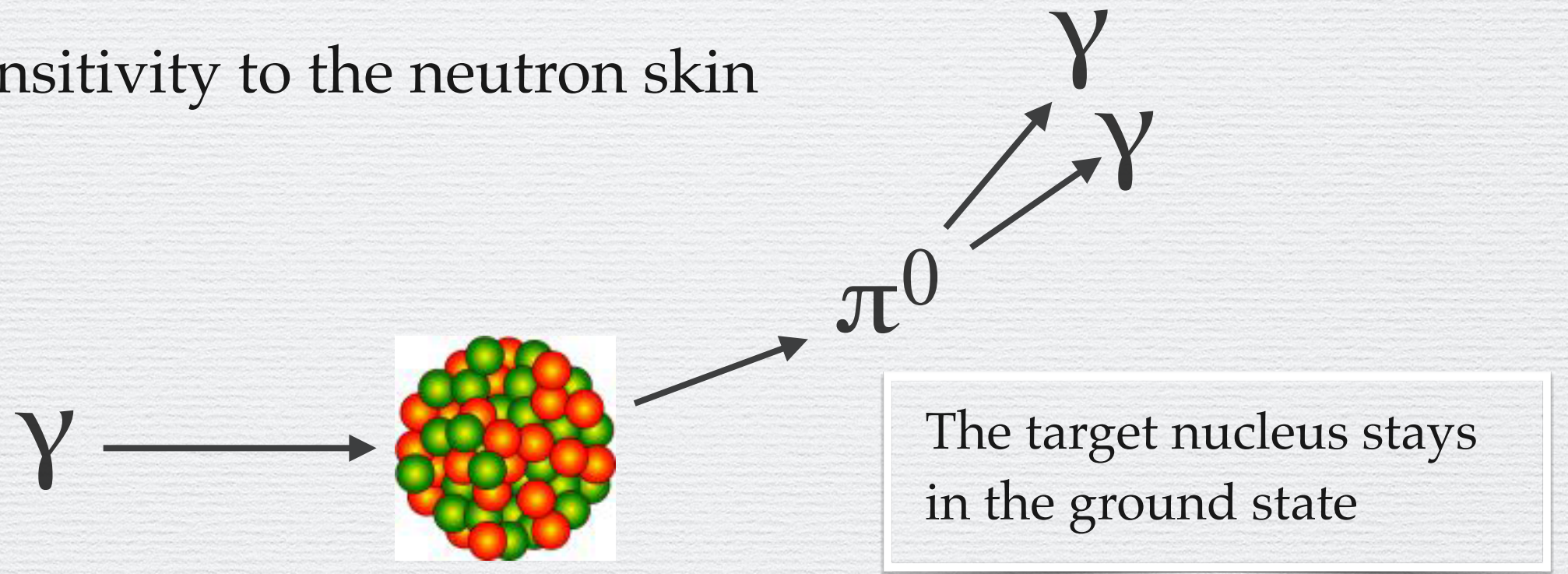


Coherent π^0 Photo-production:

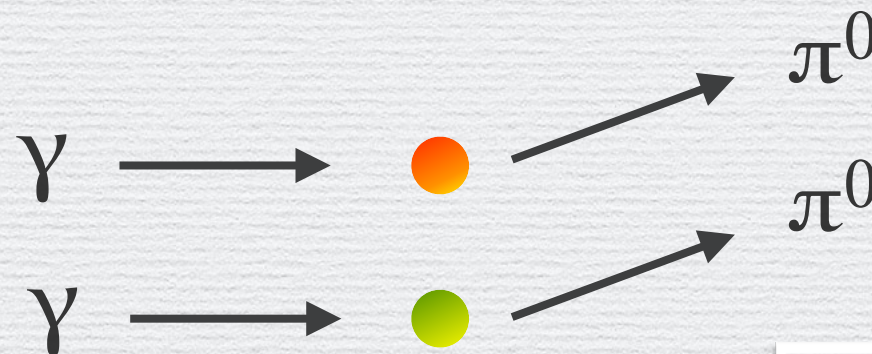
- Electro-magnetic probe
- Sufficient sensitivity to the neutron skin

Coherent π^0 Photoproduction

- Electro-magnetic probe
- Sufficient sensitivity to the neutron skin



elementary
processes



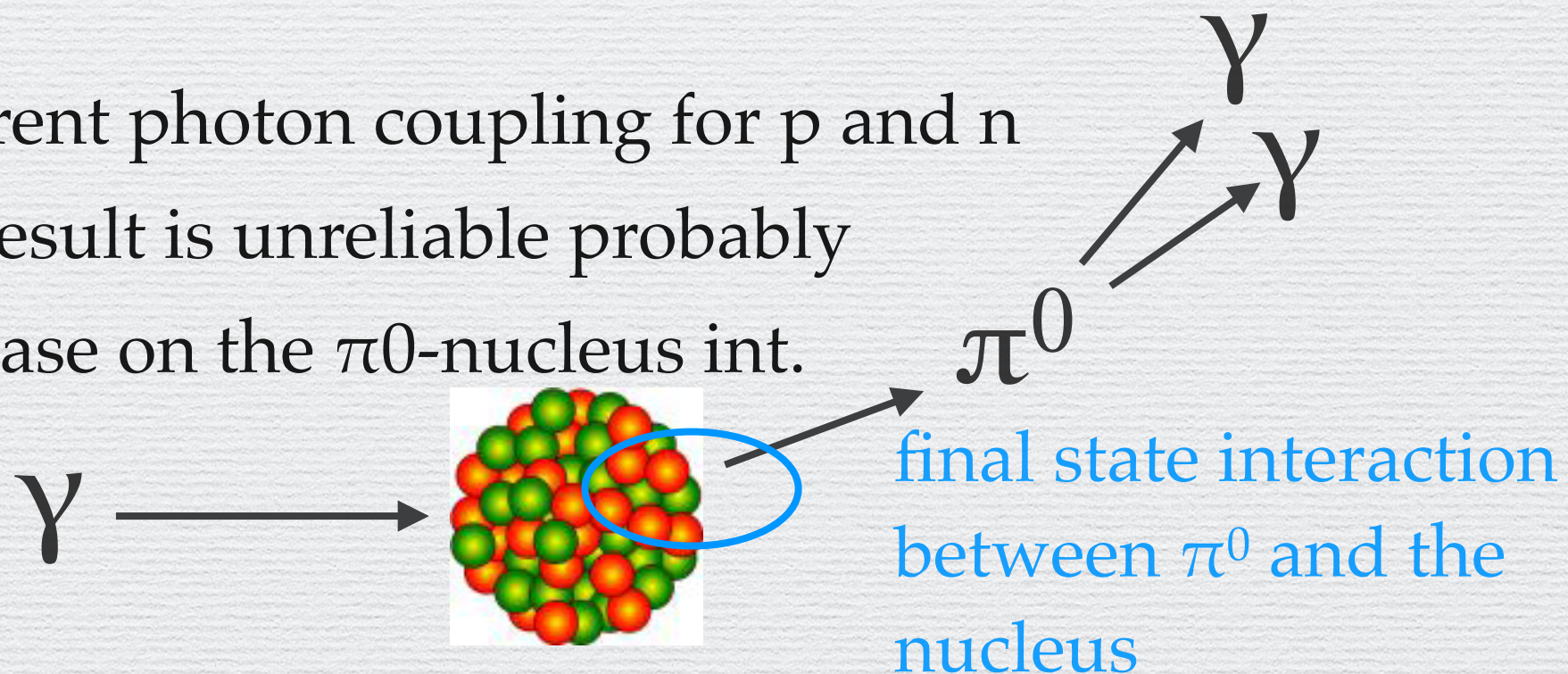
Δ excitation is the dominant
process at 180-240 MeV

neutron and proton Δ excitations
are expected to be identical

All the nucleons contribute coherently to the reaction amplitude

Coherent π^0 Photoproduction

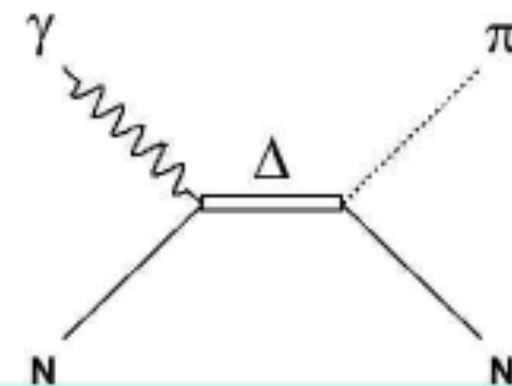
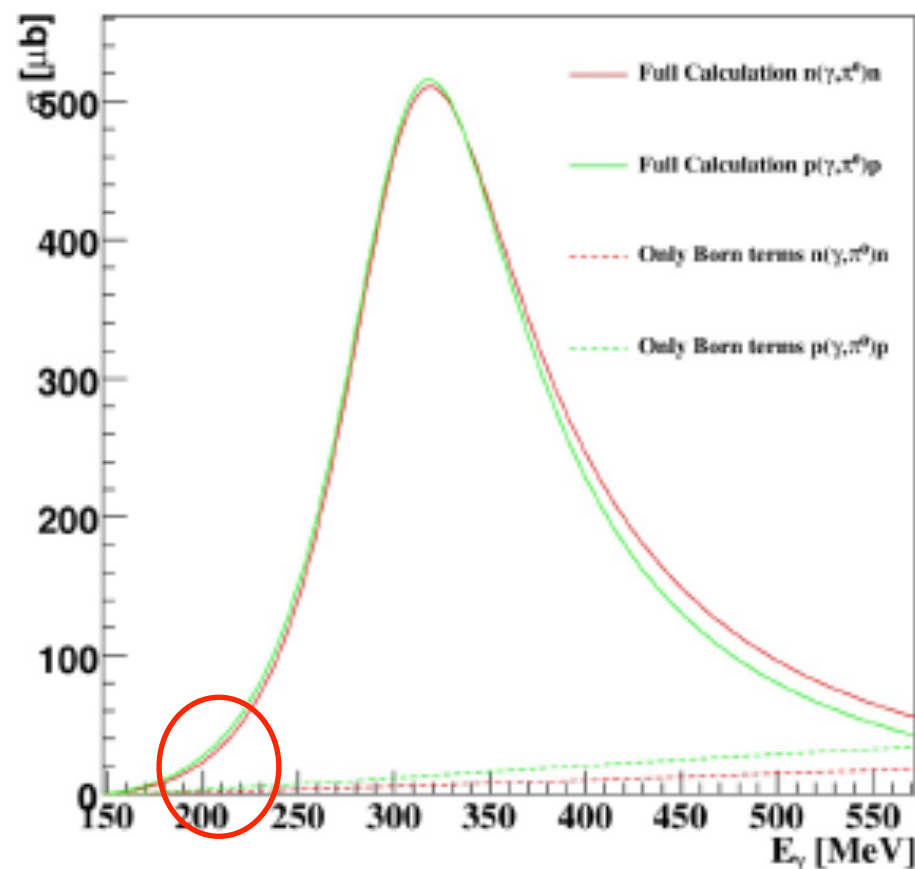
- The initial state interaction is electromagnetic and is simple
- The final state interaction between π^0 and nucleus is significant.
 - shift in the angle and modification in the flux
 - theoretical calculation
- The π^0 -nucleus interaction is energy dependent.
 - consistency of the density distribution at different energies
- Below 180 MeV, different photon coupling for p and n
- Above 240 MeV, the result is unreliable probably due to the rapid increase on the π^0 -nucleus int.



Coherent π^0 Photoproduction

π^0 photoproduction - amplitude

- Basic production amplitude \sim equal for protons and neutrons in Δ region
- PWA (MAID, SAID) - close agreement $E_\gamma > 180$ MeV for p,n cross sections
→ M1 well established multipole
- Electromagnetic probe of the matter distribution!



Isospin structure of amplitude

$$A(\gamma p \rightarrow \pi^0 p) = \sqrt{2/3} A^{V3} + \sqrt{1/3} (A^{V1} - A^{IS})$$

$$A(\gamma n \rightarrow \pi^0 n) = \sqrt{2/3} A^{V3} + \sqrt{1/3} (A^{V1} + A^{IS})$$

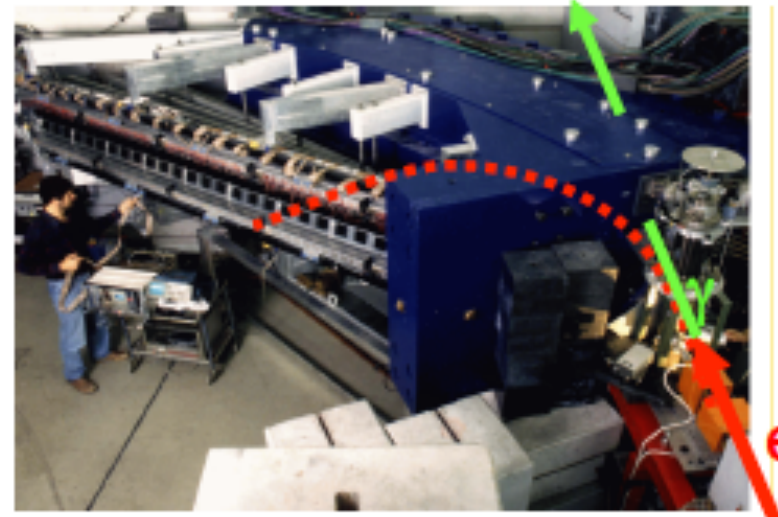
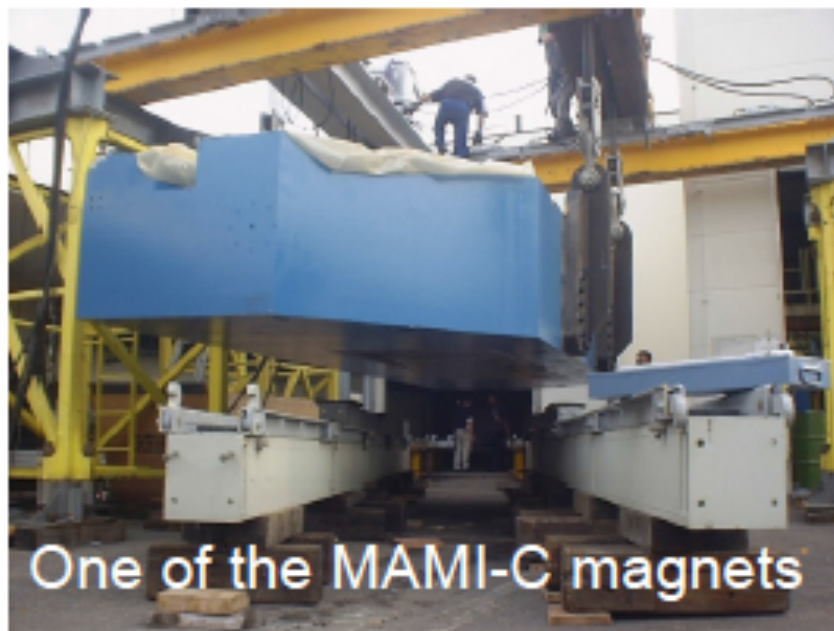
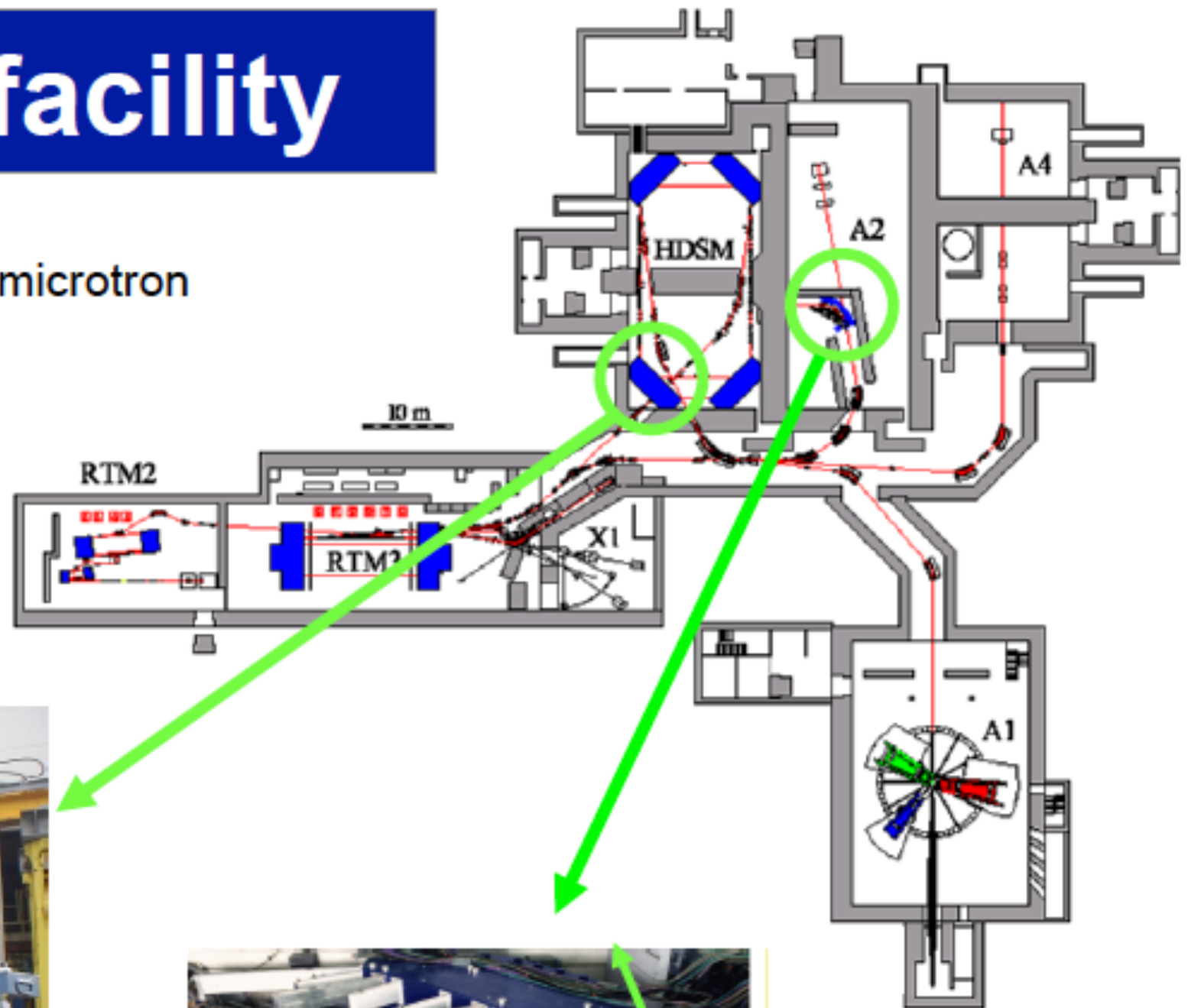
Δ has $I=3/2$ → A^{V3} only

EM couplings identical for p,n

Experiment

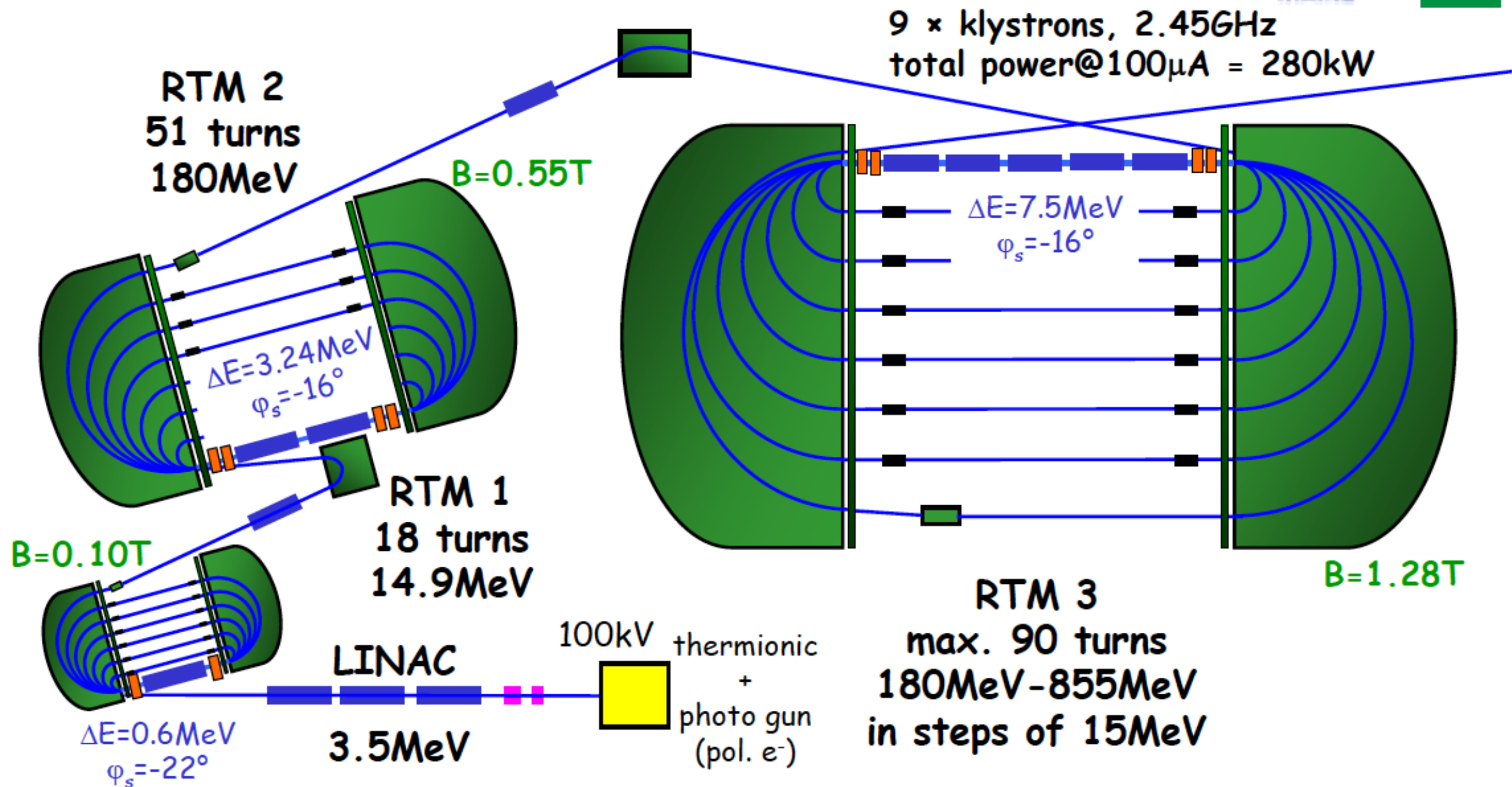
The MAMI facility

- 100% duty factor electron microtron
- MAMI-C 1.5 GeV upgrade
(MAMI-B 0.85 GeV)



Experiment

The Mainz Microtron MAMI, scheme



beam parameters: 100μA max cw current (86kW beam power)

injector linac:

$$\sigma E = 1.2 \text{ keV } (3 \cdot 10^{-4})$$

$$\varepsilon_{x,n} = 0.05 \cdot 10^{-6} \text{ m rad}$$

RTM 1:

$$\sigma E = 1.2 \text{ keV } (8 \cdot 10^{-5})$$

$$\varepsilon_{x,n} = 0.07 \cdot 10^{-6} \text{ m rad}$$

RTM 2:

$$\sigma E = 2.8 \text{ keV } (1.5 \cdot 10^{-5})$$

$$\varepsilon_{x,n} = 0.25 \cdot 10^{-6} \text{ m rad}$$

*) RTM 3:

$$\sigma E = 13 \text{ keV } (1.5 \cdot 10^{-5})$$

$$\varepsilon_{x,n} = 13 \cdot 10^{-6} \text{ m rad}$$

$$\varepsilon_{x,abs} = 8 \cdot 10^{-9} \text{ m rad}$$

*) Increase in energy spread and emittance due to sr-effects

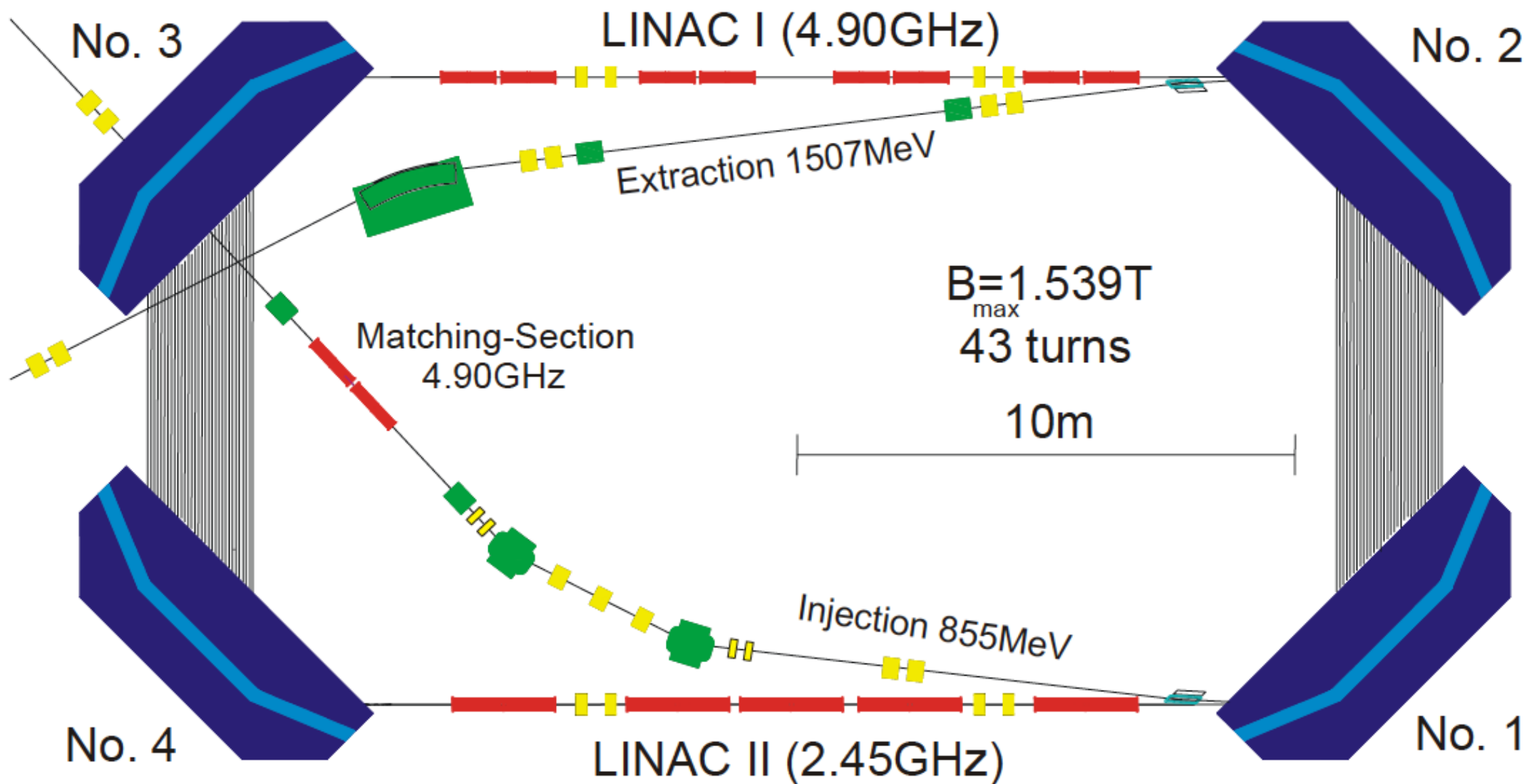
Experiment

RTM3



Experiment

The Harmonic Double Sided Microtron (HDSM) for MAMI C



Best adaptation to the inherent stable and reliable RTM principle

Experiment

MAMI electron microtron [33]

Table 1
Main parameters of the HDSM

<i>General</i>		
Injection energy (MeV)	854.9	
Max. extraction energy ^a	1508.5	
Number of recirculations	43	
Length of linac straights (m)	17.359	
Distance between 1 and linac 2 (m)	12.599	
n_0 (see Eq. (9))	1057	
<i>HF-system</i>	Linac 1	Linac 2
Operational frequency (GHz)	4.899064	2.449532
Linac amplitude (MV)	9.05	9.30
Synchronous phase at second turn	0.6°	-35.0°
Synchronous phase at last turn	-26.8°	-50.5°
Linac length (electrical) (m)	8.567	10.097
Number of sections	8	5
Number of klystrons	4	5
Rf-power per unit length (kW/m)	14.0	11.8
Beam loading at 100 μ A (kW)	37.0	28.4
Total rf-power (kW)	305.00	
Total power consumption (including matching double section) (kW)	1050	
<i>Magnet system</i>		
Max. magnetic flux density (T)	1.5388	
Min. magnetic flux density (T)	0.939	
Min. gap distance (mm)	85	
Max. gap distance	140	
Iron mass (ton)	1044	
Copper mass (ton)	30	
Dipole current (A)	213	
Dipole voltage (V)	320	
Number of correction dipoles	$2 \times 4 \times 43 + 8 = 352$	
Number of quadrupoles	14	
Total power consumption (kW)	310	
<i>Beam parameters</i>		
Energy spread (1σ) at 1.5 GeV (keV)	30 at 0.855 GeV	110 ^a at 1.5 GeV
Horizontal emittance (norm., 1σ) ($\pi \times 10^{-6}$ m)	13	27 ^a
Vertical emittance (norm., 1σ) ($\pi \times 10^{-6}$ m)	1.2	1.2 ^a

^a From SYTRACE simulations.

ABSTRACT

At the Institut für Kernphysik of Mainz University a harmonic double-sided microtron (HDSM) has been built to extend the experimental capabilities for nuclear and particle physics experiments to higher excitation energies. This novel microtron variant accelerates the 0.855 GeV continuous wave (cw) electron beam of the established three-staged race track microtron (RTM) cascade MAMI B up to 1.5 GeV. It consists of two normal conducting linear accelerators (linacs) through which the electrons are guided up to 43 times by a pair of 90°-bending magnets at each end. For beam dynamical reasons the linacs operate at the harmonic frequencies of 4.90 and 2.45 GHz. The extended facility is called MAMI C.

The relatively strong vertical defocussing due to the 45°-pole face rotations (Fig. 1) at both the entrance and exit of the segment-shaped bending magnets is compensated for all recirculations by a suitable field decay in the magnets towards higher orbits. As a consequence, the energy gain of the electrons has to decrease with increasing turn number to maintain coherent acceleration. This occurs by an appropriate phase slip of the electron bunches downwards the rf-waves during the acceleration process.

In this paper the functional principle and the beam dynamical concept of the double-sided microtron (DSM) as well as the design and development of its main components are described. Finally, the results of first beam measurements taken after starting up in December 2006 are discussed.

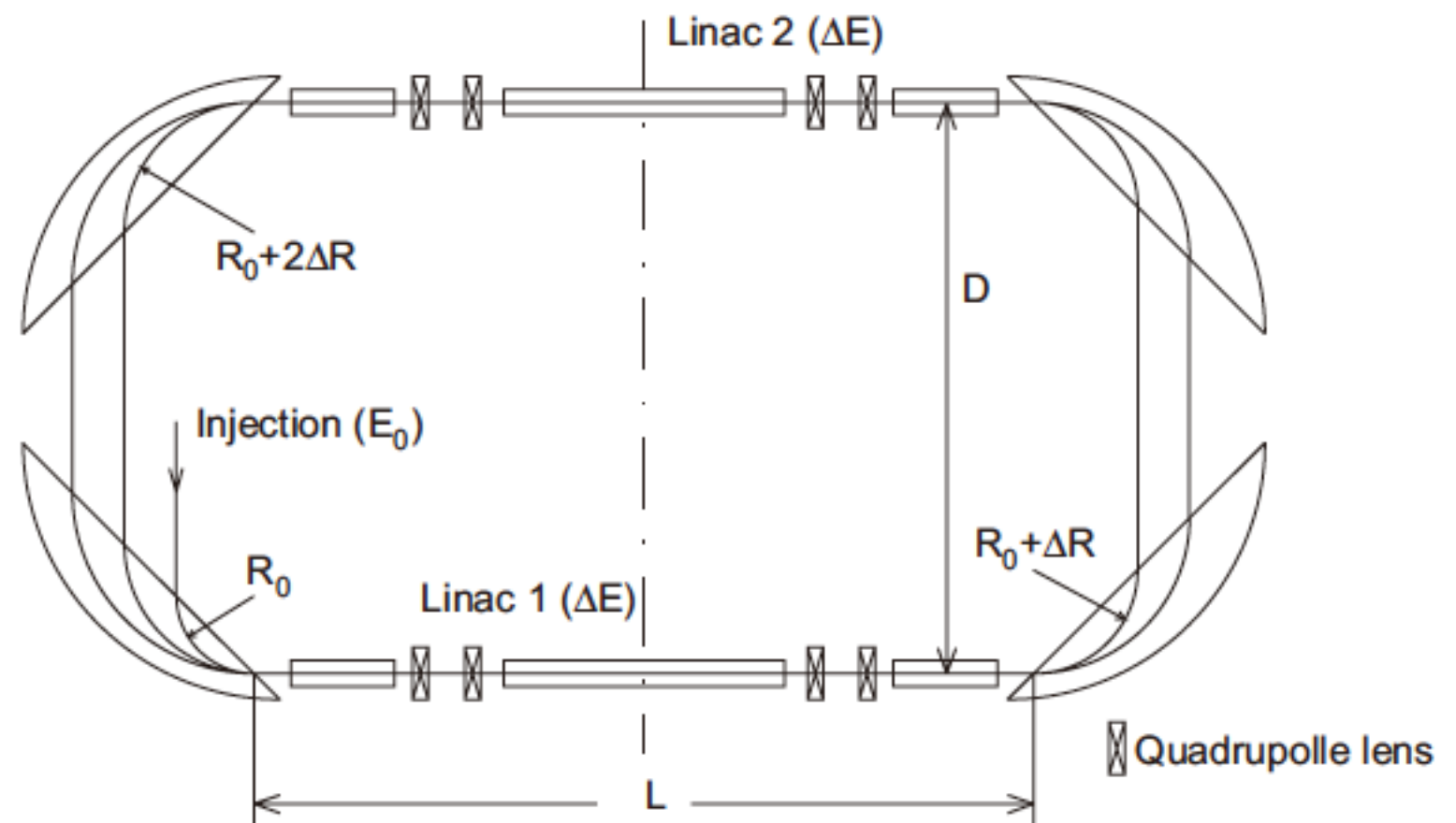


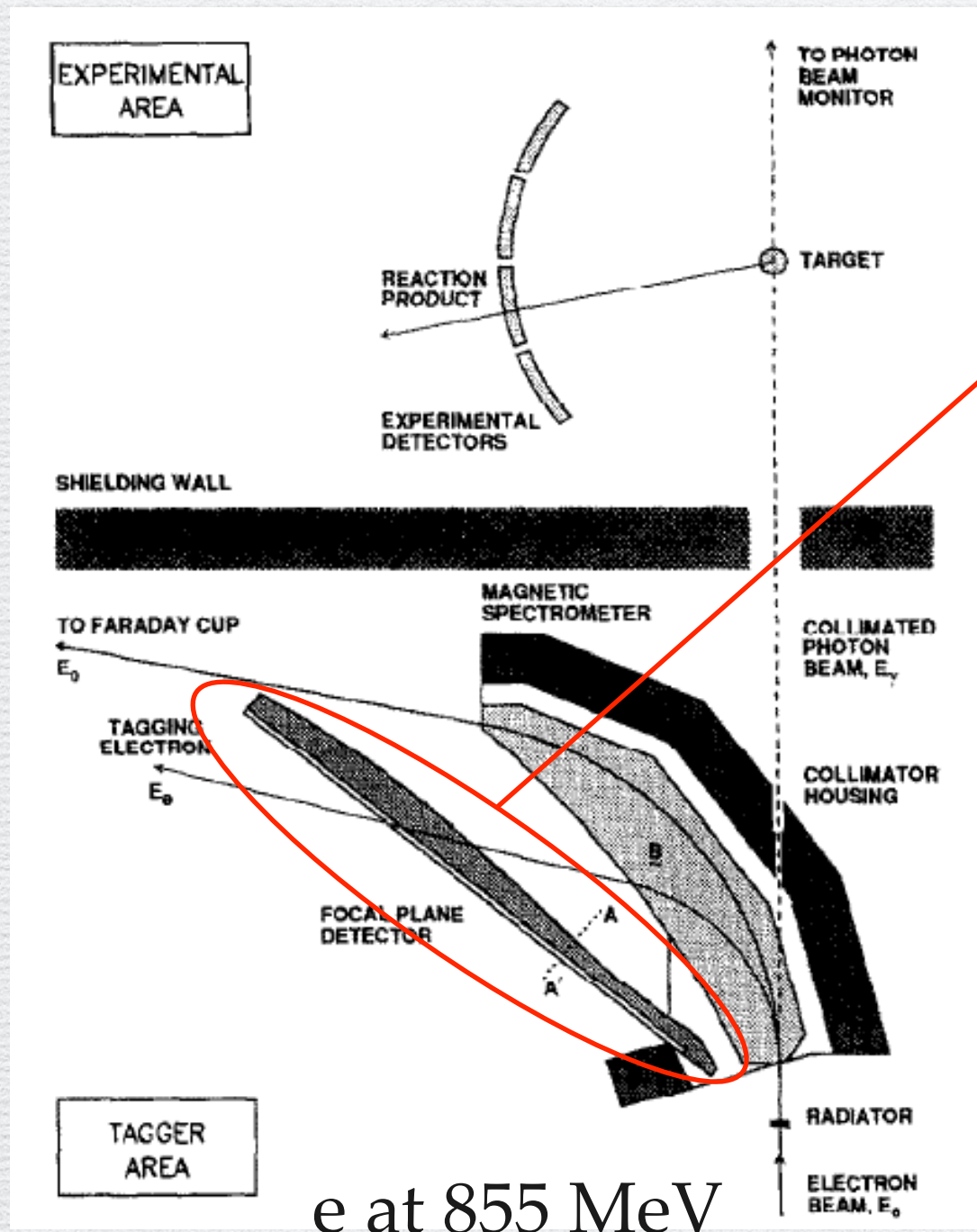
Fig. 1. Scheme of the double-sided microtron.

Experiment

Glasgow Photon Tagger [32]

2 MeV (FWHM)

$2 \times 10^5 \gamma \text{ sec}^{-1} \text{ MeV}^{-1}$



e at 855 MeV

plastic scintillators (2 mm^t)

353 channels

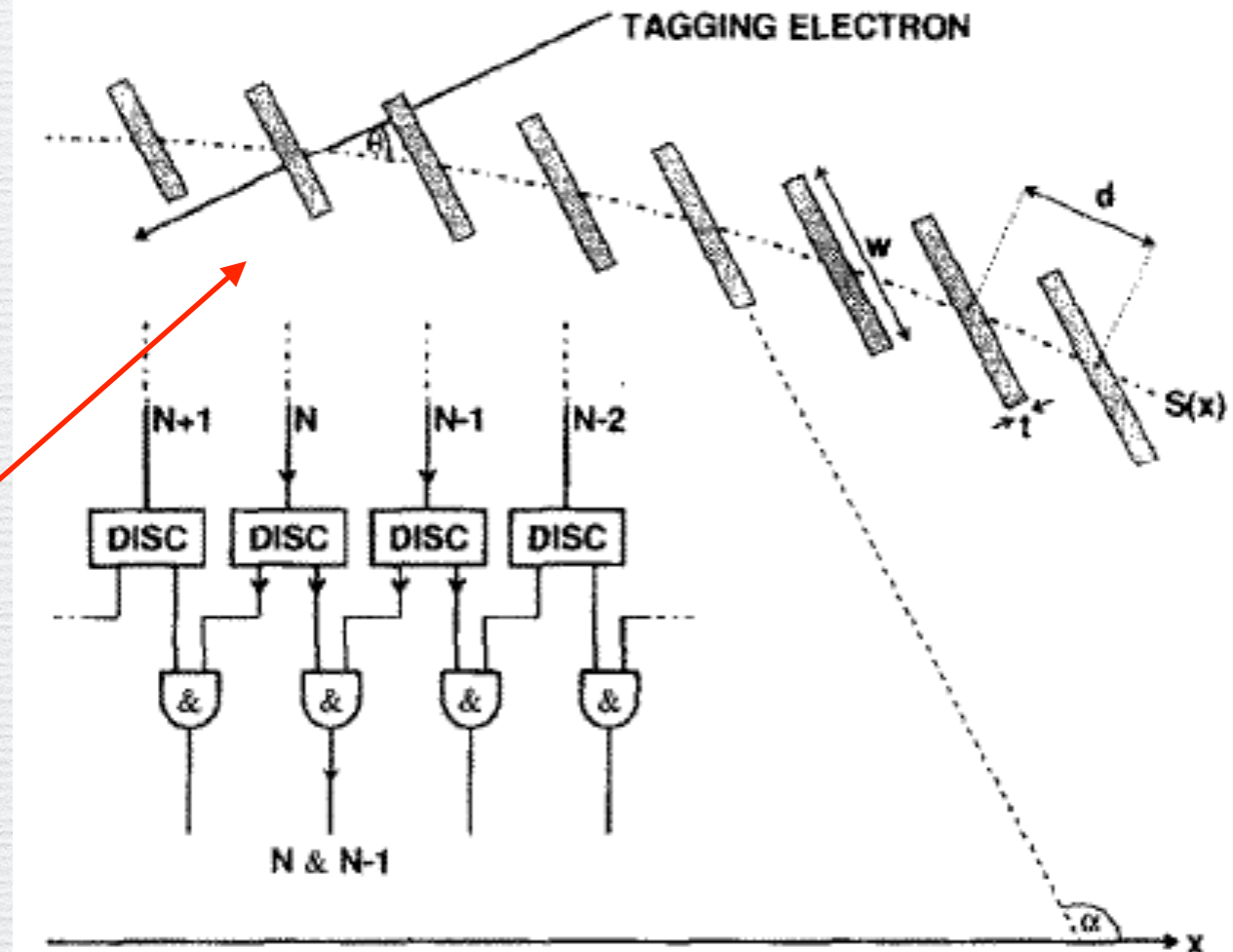


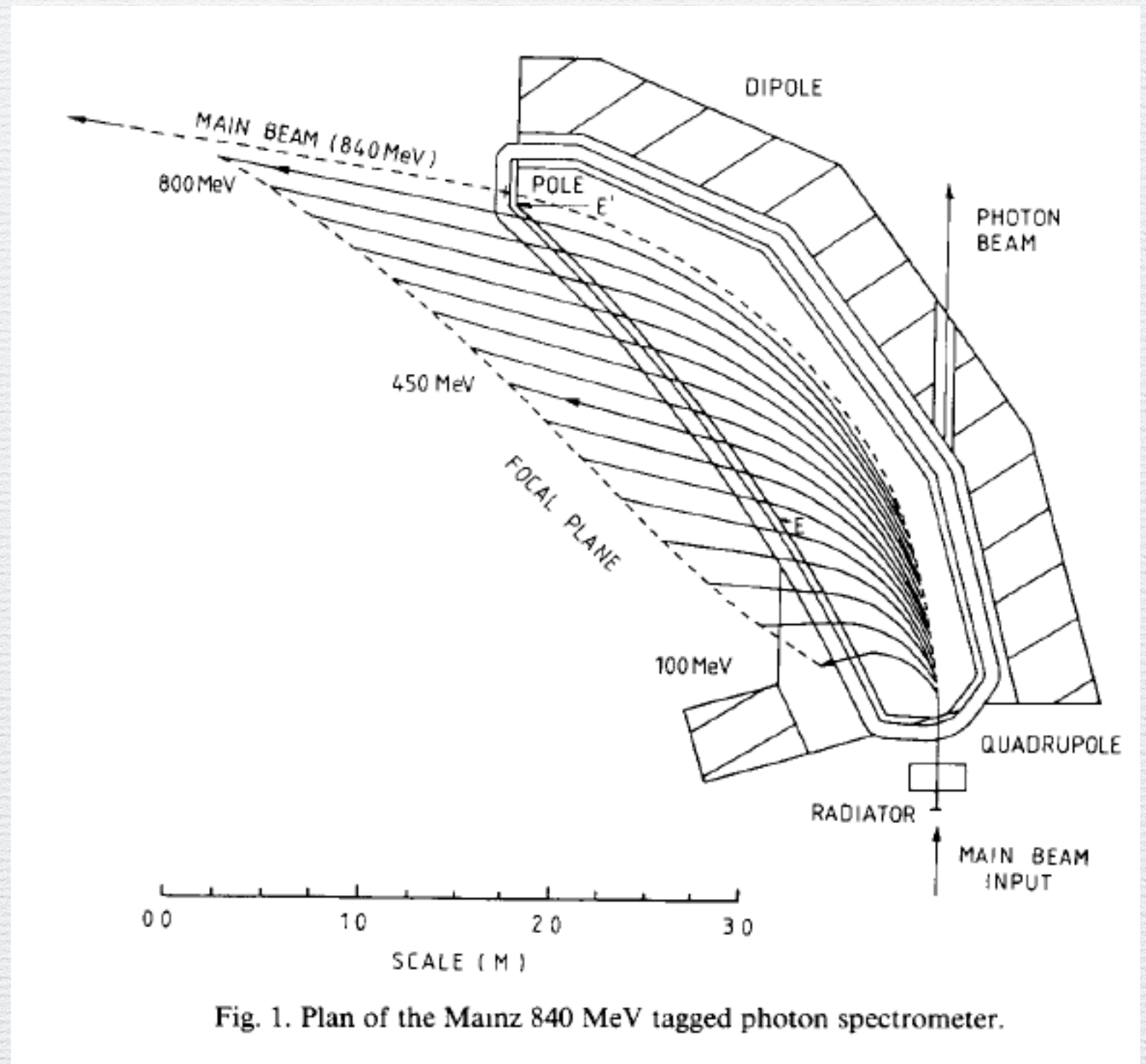
Fig. 3. Schematic view of the scintillator arrangement along the curve $S(x)$ which lies parallel to the true focal plane. The scintillators are set normal to the electron trajectories (θ) with widths (w) chosen to achieve slightly more than a half-overlap with each neighbour. The scintillator thickness ($t = 2 \text{ mm}$) and separation ($d = 13 \text{ mm}$) is the same for all elements. Also shown schematically is the coincidence requirement between adjacent channels.

Experiment

Glasgow Photon Tagger [32]

2 MeV (FWHM)

$2 \times 10^5 \gamma \text{ sec}^{-1} \text{ MeV}^{-1}$



Experiment

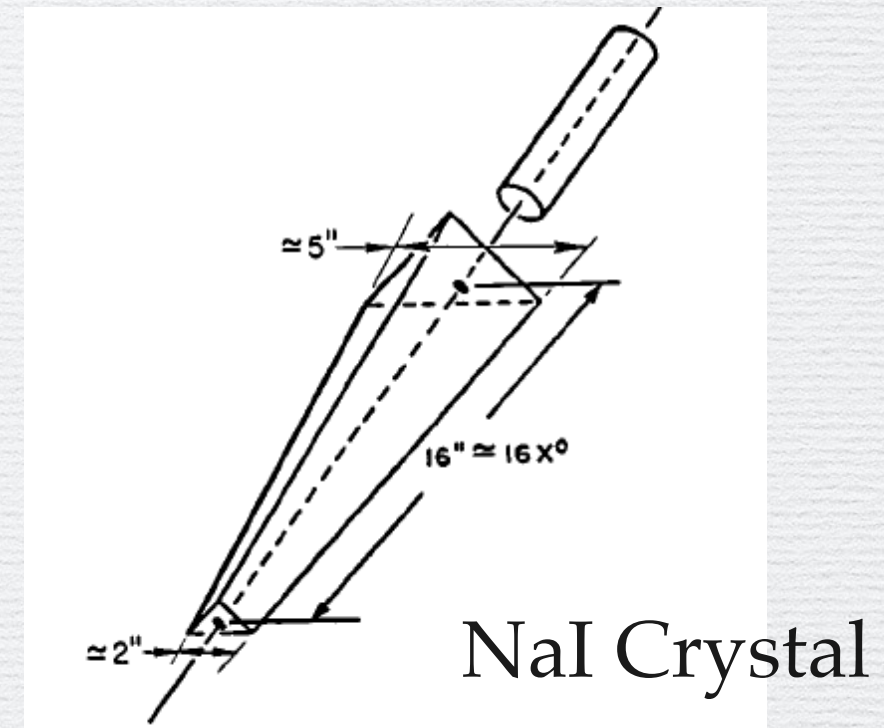
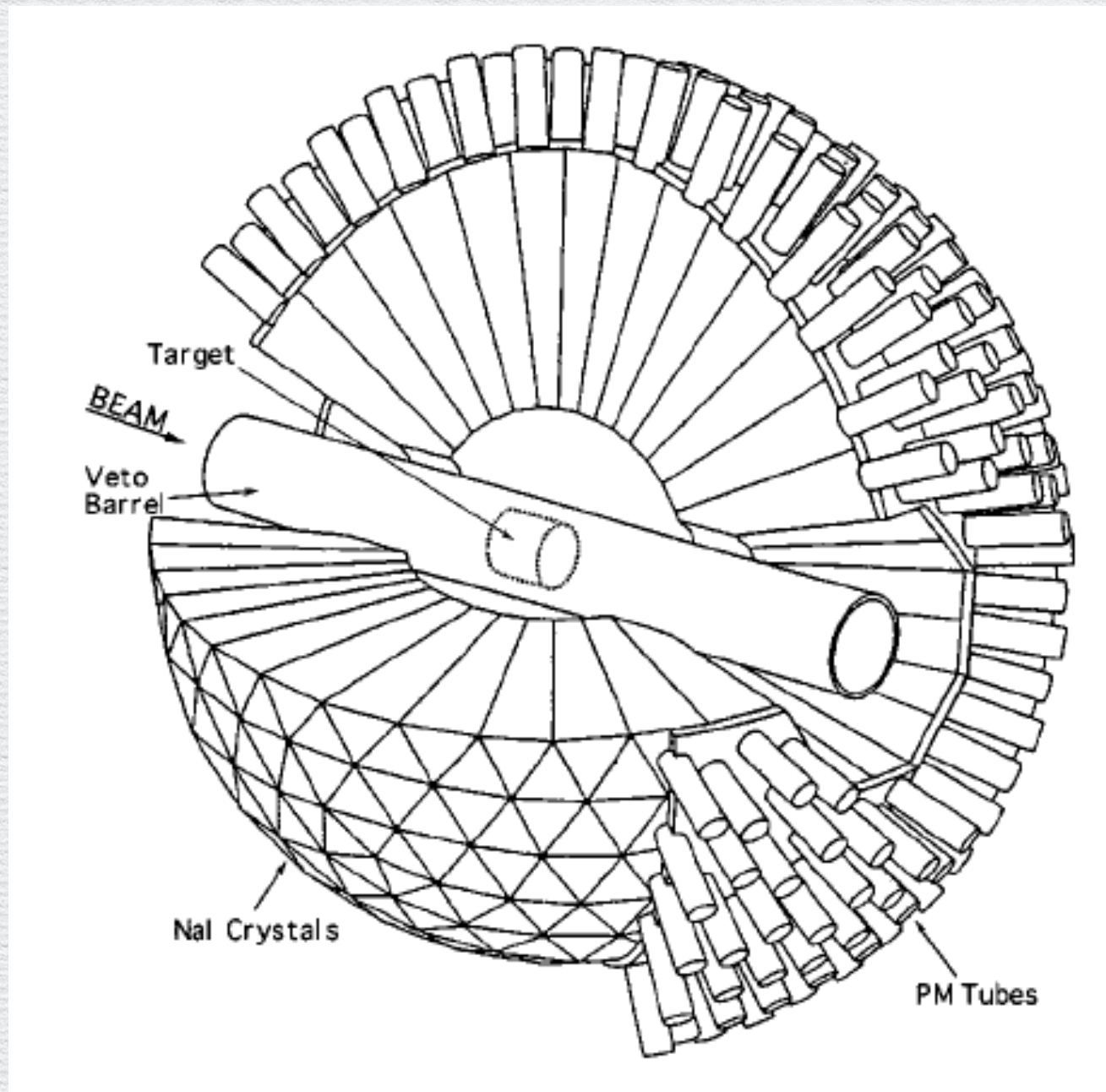
Target:

^{208}Pb 99.5%, 0.52 ± 0.01 mm thick (~ 590 mg/cm²)

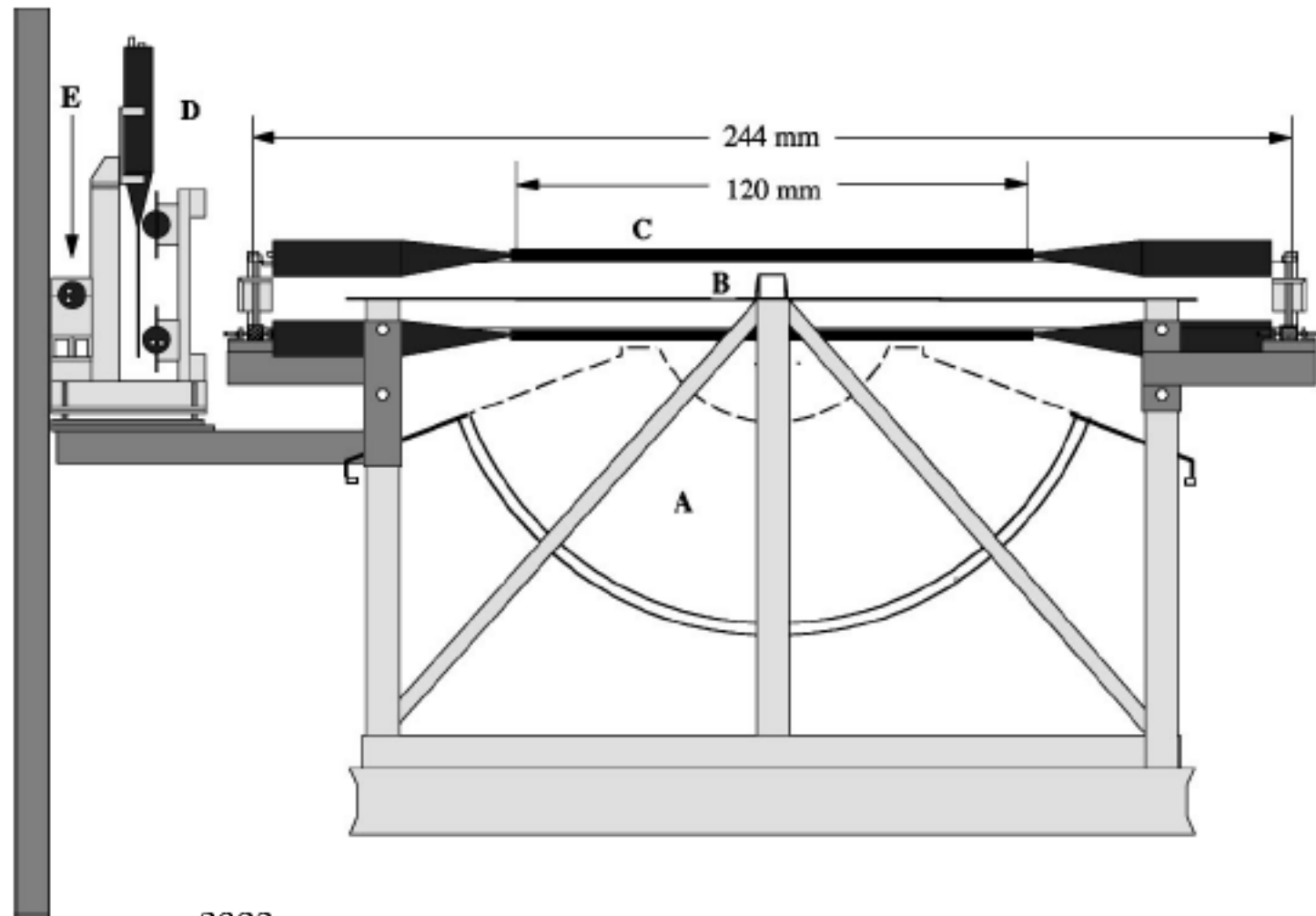
η

Experiment

Crystal Ball (CB) [31]



- inner radius = 25.3 cm
- outer radius = 66.0 cm
- icosahedron:
20 triangles \rightarrow 4 triangles \rightarrow 9 triangles:
692 out of 720
- wrapped with reflective paper and aluminized mylar



- four veto scintillators
5mm thick and 120cm long
- 0.76 mm stainless steel
- maintained at temperature $20 \pm 1^\circ\text{C}$

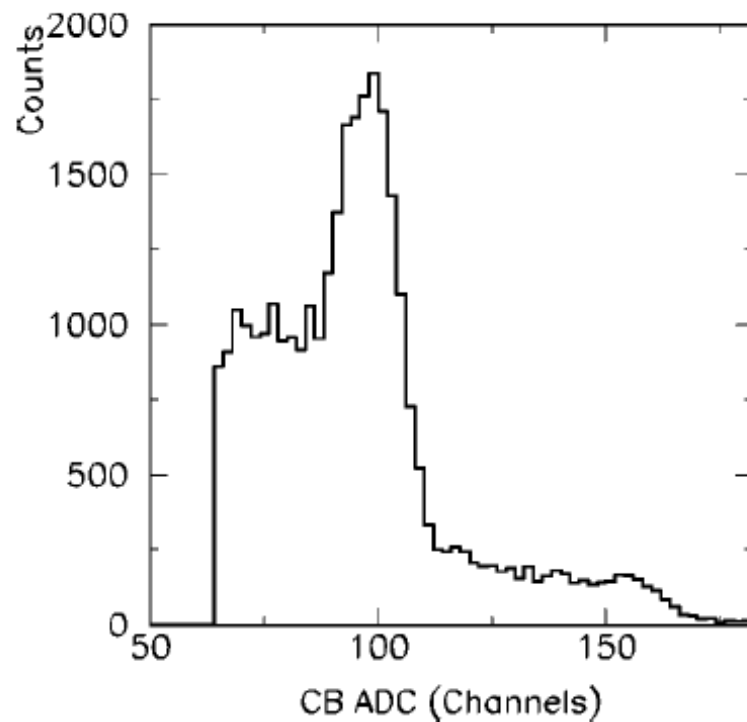


FIG. 7. Typical ^{60}Co spectrum of a CB crystal.

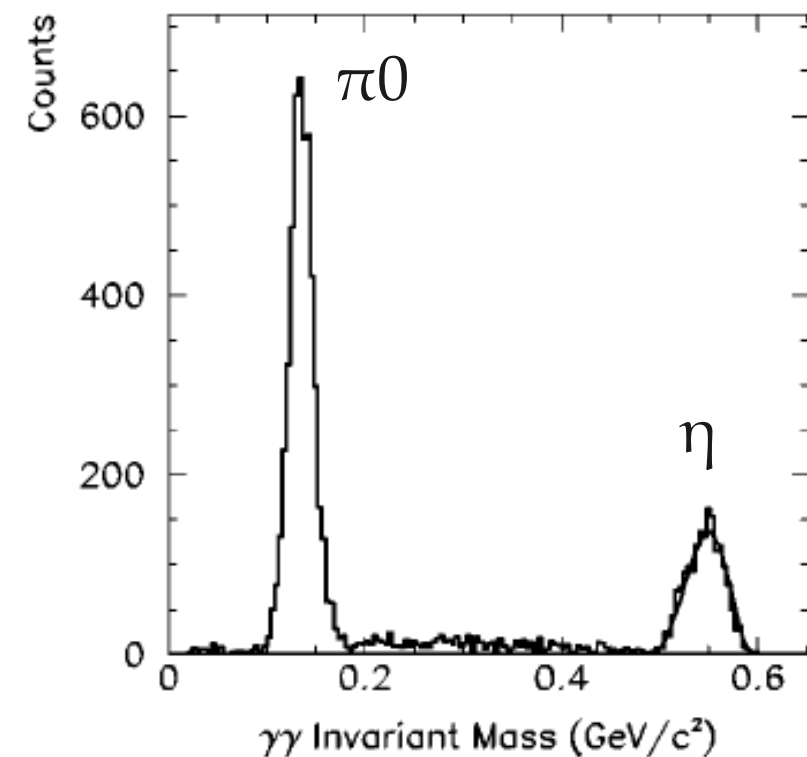
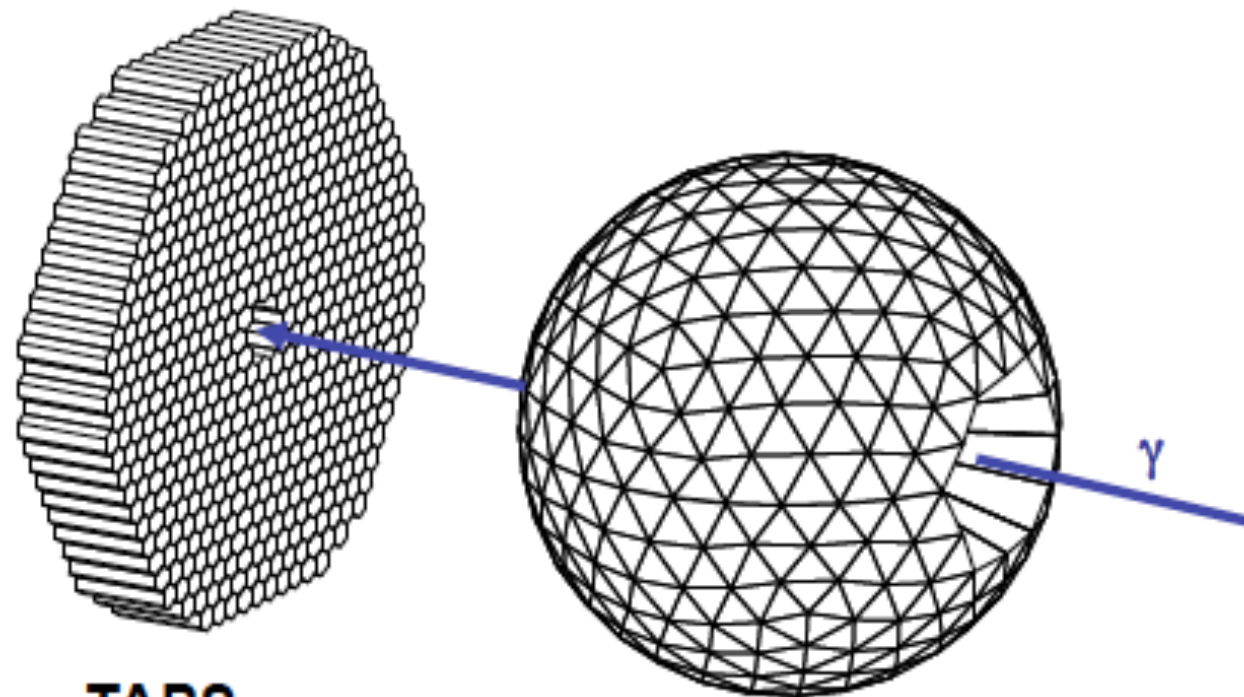
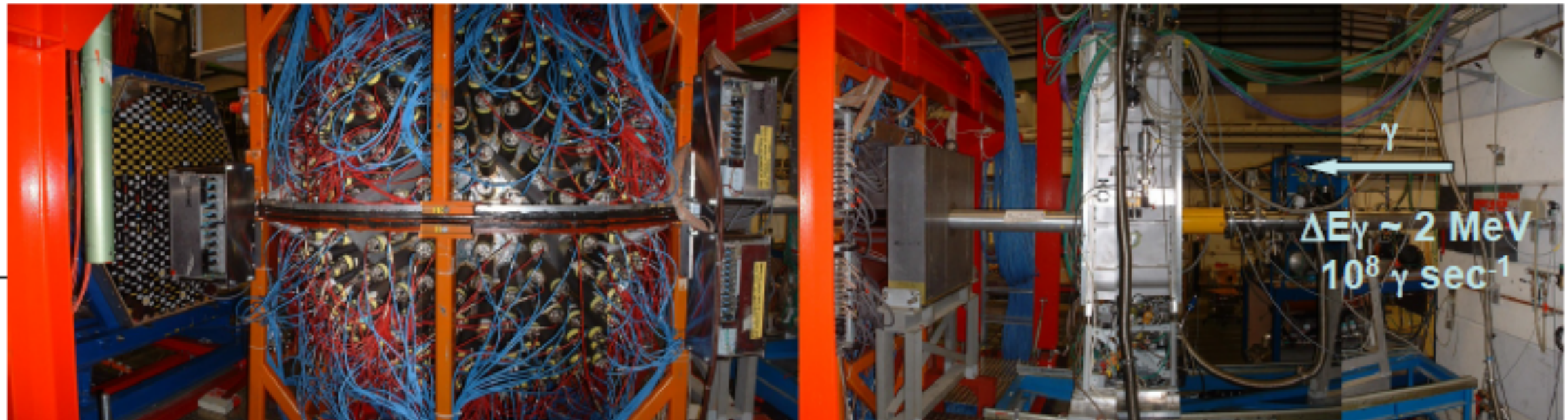


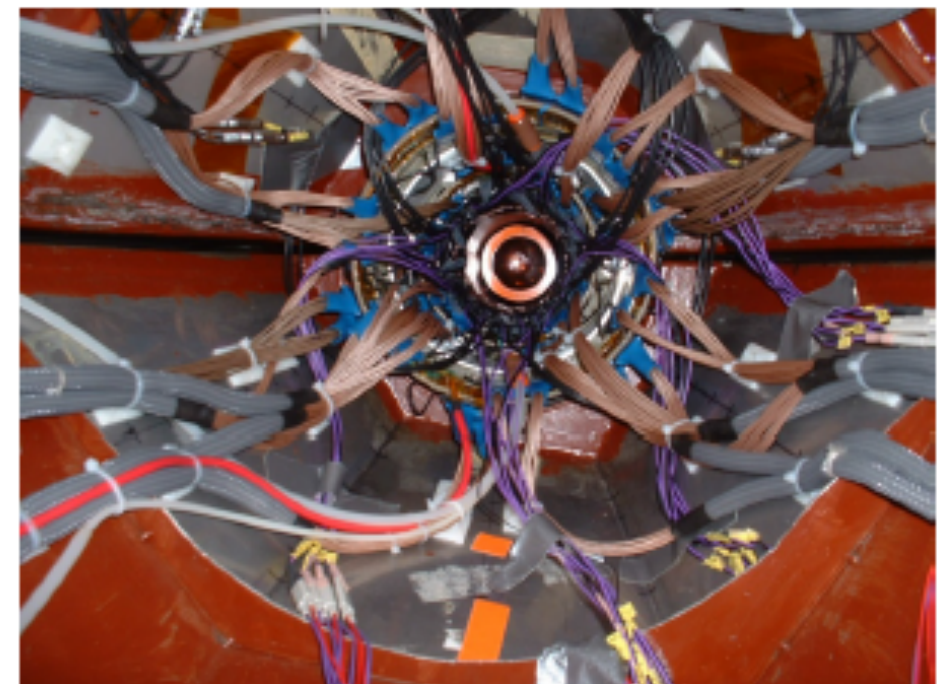
FIG. 11. The invariant mass of two photons in $K^- p \rightarrow \gamma\gamma\Lambda$ obtained with the high-momentum beam. The normalized empty target spectrum has been subtracted. The results of the Monte Carlo simulation are shown by the smooth solid line. The first peak is due to $K^- p \rightarrow \pi^0\Lambda$ and the second one to $K^- p \rightarrow \eta\Lambda$.

Crystal Ball at MAMI



TAPS
528 BaF_2 crystals

Crystal Ball
672 NaI crystals

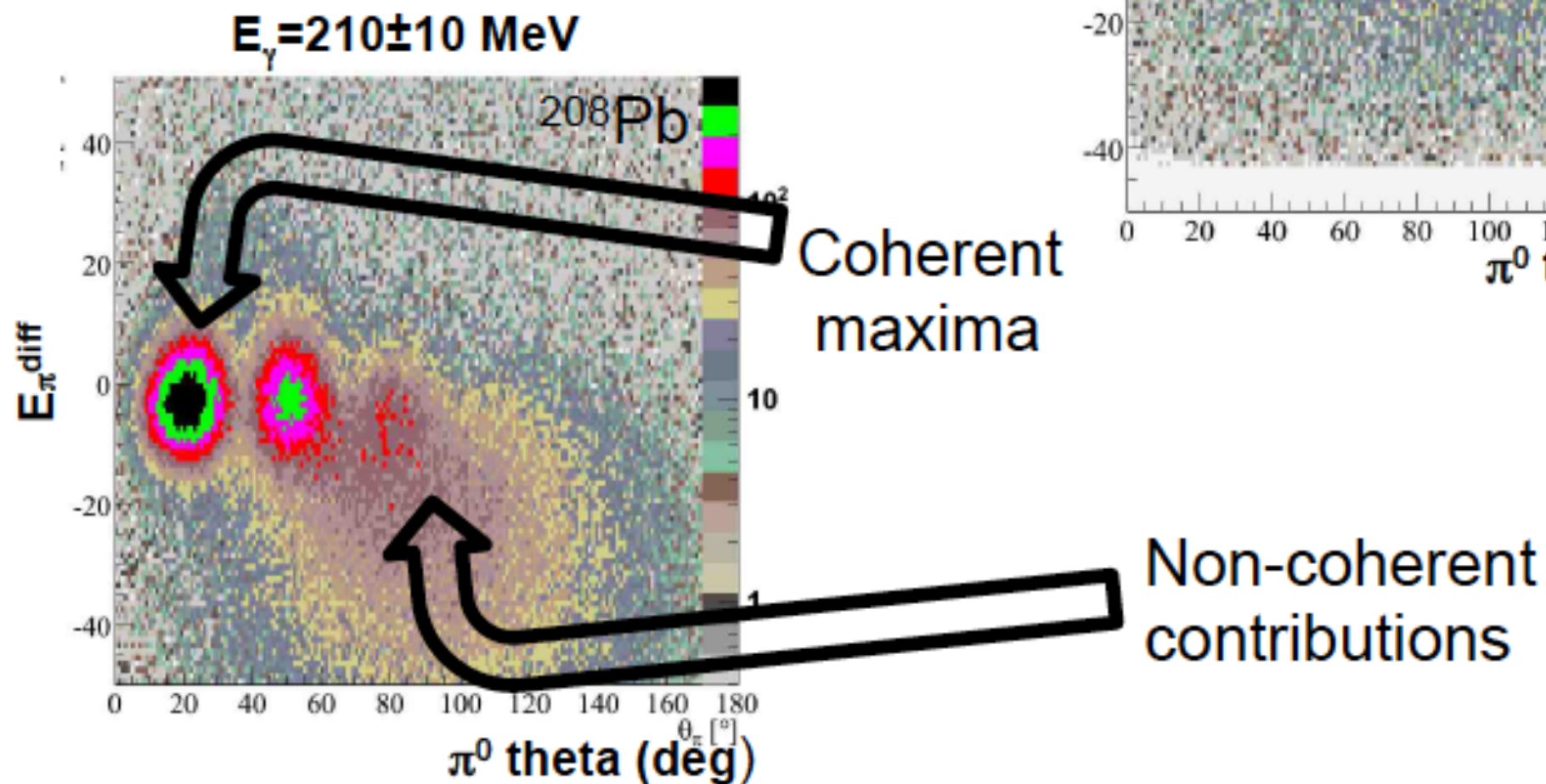
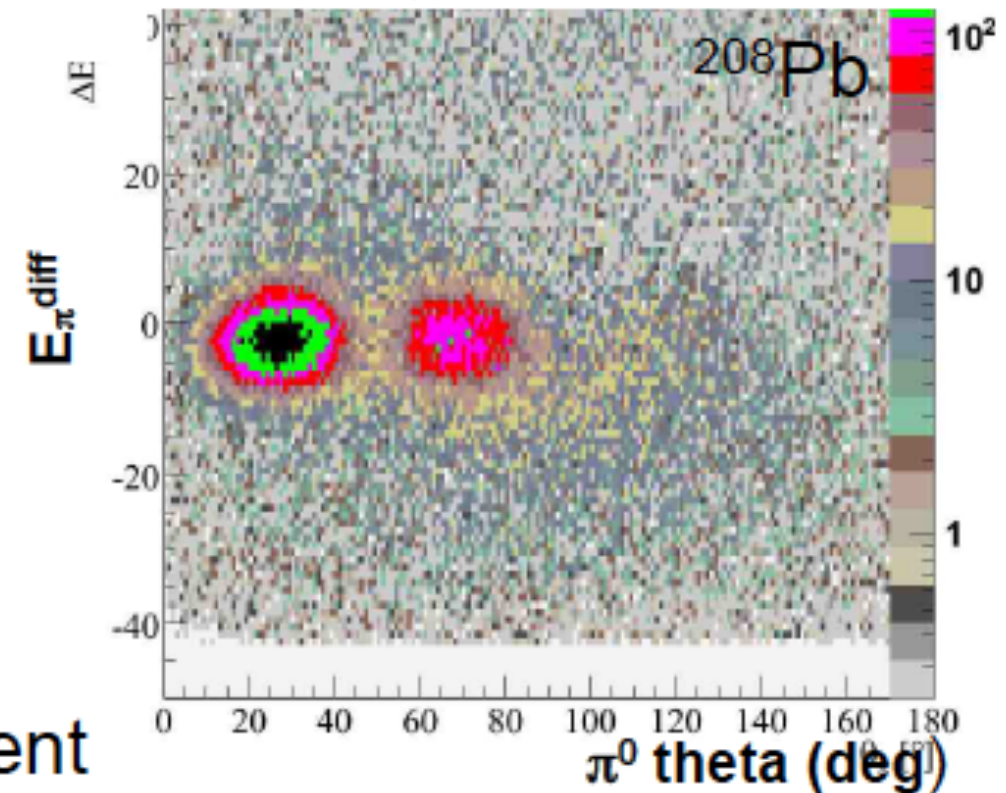


Analysis

Coherent pion photoproduction - analysis

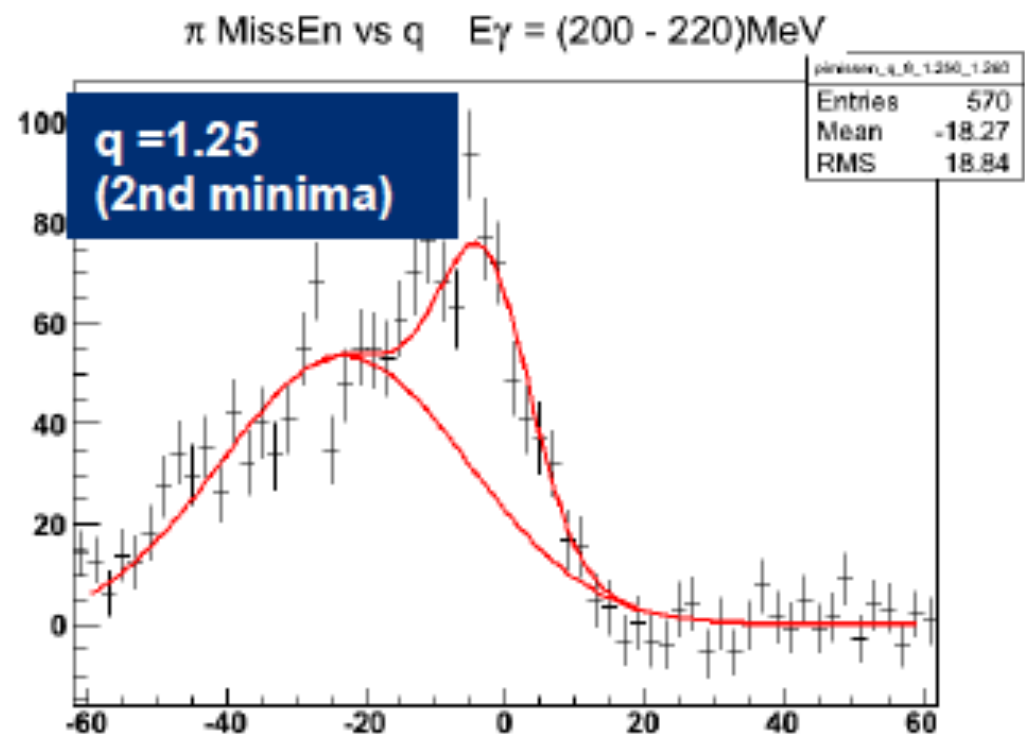
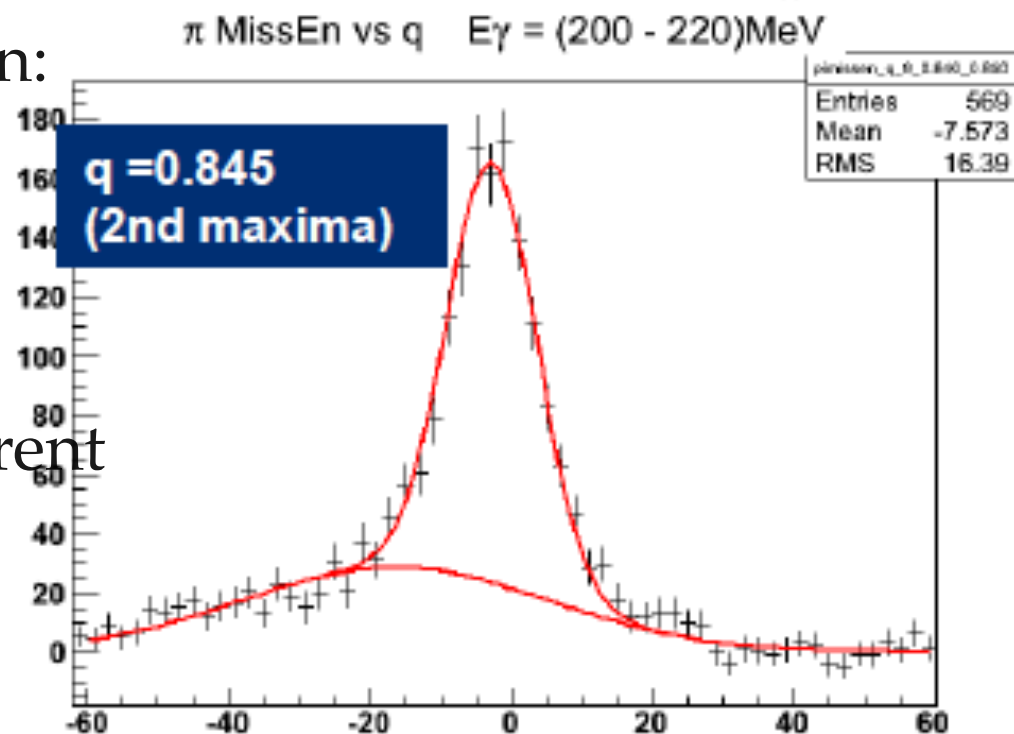
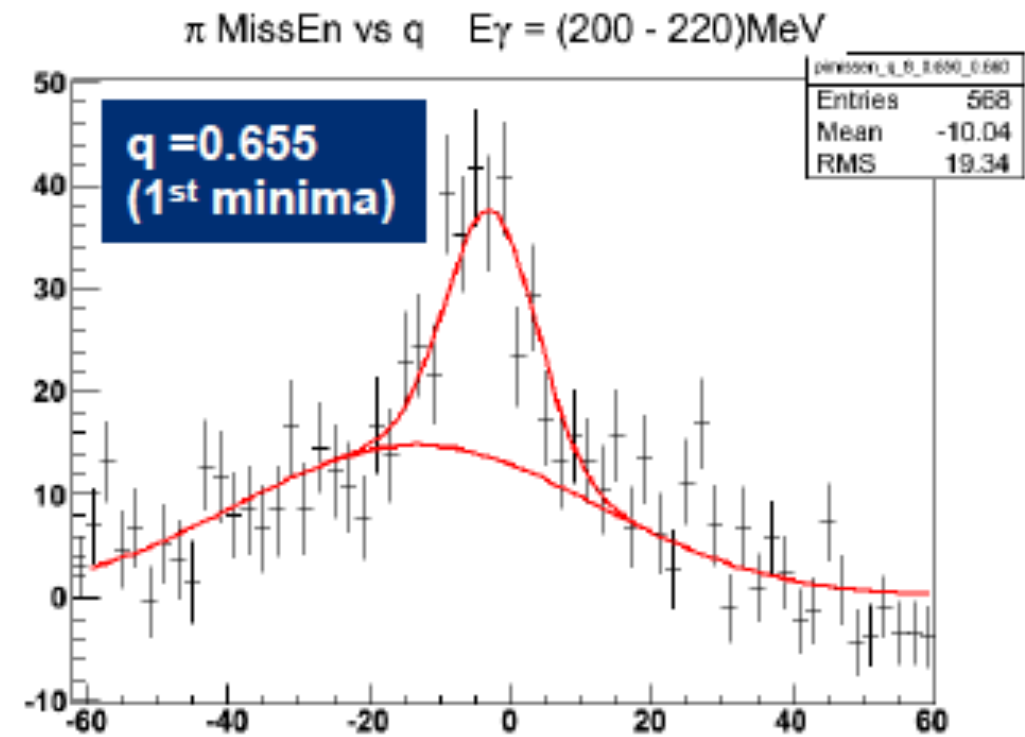
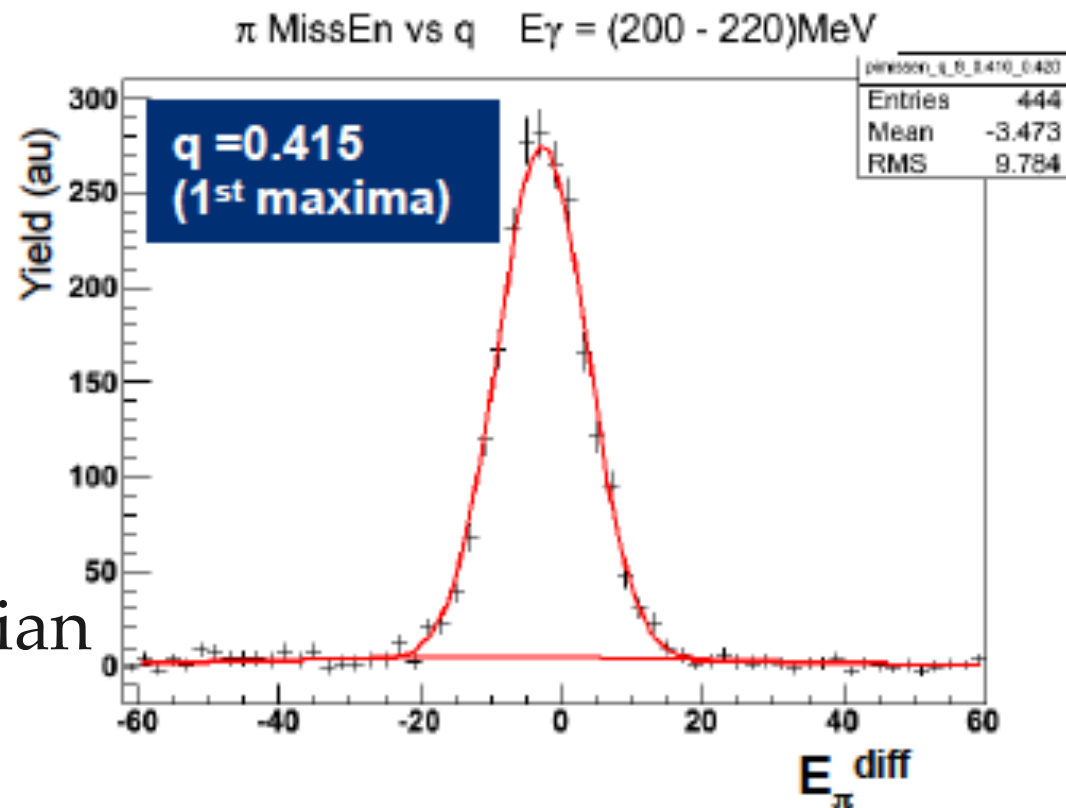
$$E_{\pi}^{\text{diff}} = E_{\pi}^{\text{calc}} - E_{\pi}^{\text{det}}$$

$E_{\gamma} = 175 \pm 5$ MeV



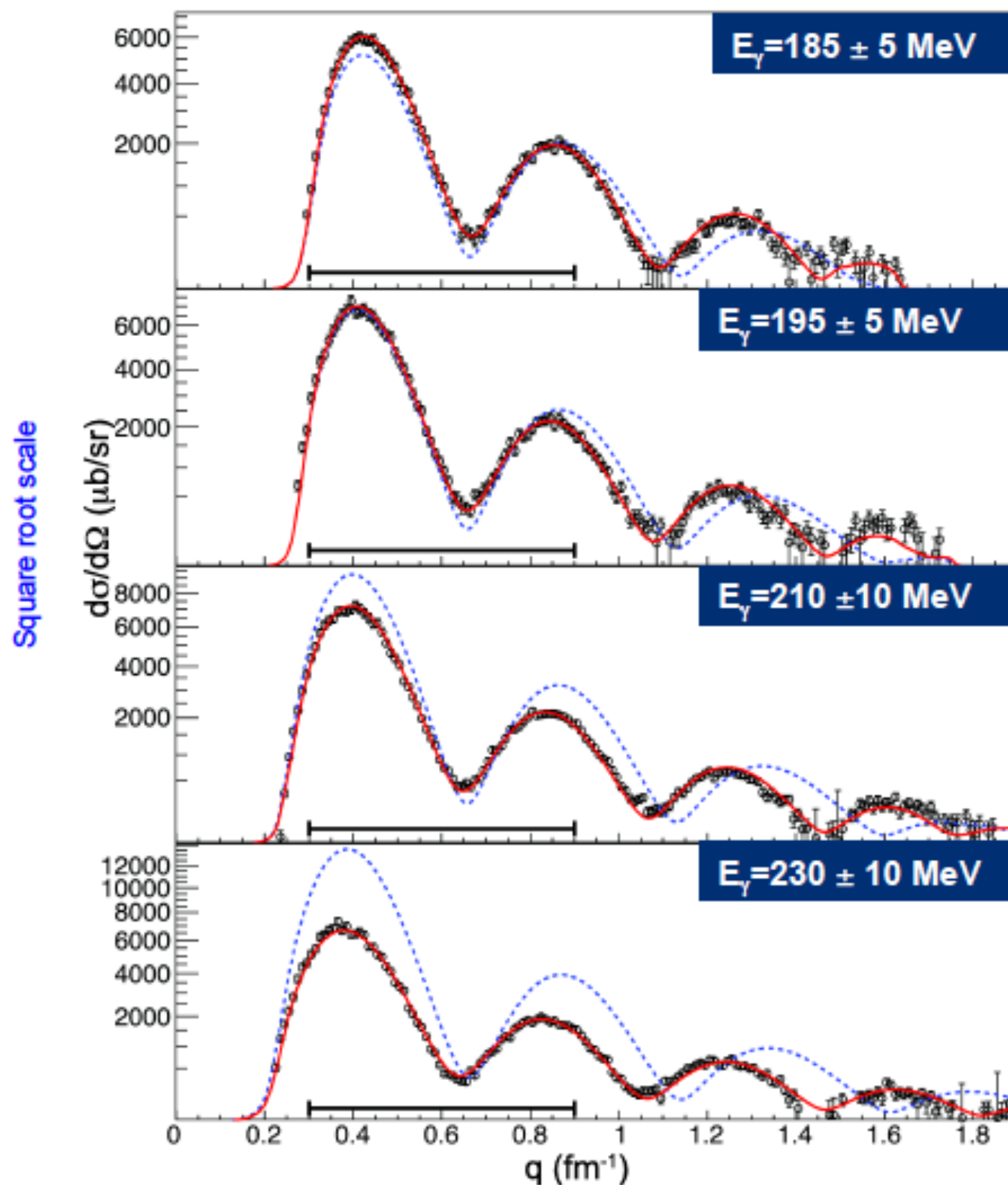
Analysis

Extraction of coherent yield : $E_\gamma = 210 \pm 10$ MeV



Analysis

Momentum transfer distributions



-- PWIA calculation
- Full calculation

Drechsel et. al. NPA 660 (1999)

Fitting procedure

Calculate grid $c_n = 6.28 - 7.07 \text{ fm}$
 $a_n = 0.35 - 0.65 \text{ fm}$

Predictions smeared by q resolution

Interpolated fit to experimental data
($q = 0.3 - 0.9$)

Free param. : norm, c_n , a_n ,
Fixed param. : $c_p = 6.68$ $a_p = 0.447$
(PRC 78 014211 (2011))

Low E_γ limit: Δ dominates
High E_γ limit: π FSI not too large
(p -wave interactions set in)

Analysis

pion photo-production on a nucleon

[42] D. Drechsel, et al., NPA645, 145 (1999).

Unitary Isobar Model

We have developed a new operator for pion photo- and electroproduction for applications to reactions on nuclei at photon equivalent energies up to 1 GeV. The model contains Born terms, vector mesons and nucleon resonances up to the third resonance region ($P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $F_{15}(1680)$, and $D_{33}(1700)$).

For the Born terms we propose an energy dependent superposition of pseudovector and pseudoscalar πNN couplings. This procedure describes the correct energy dependence of the non-resonant multipoles for photon *lab* energies up to $E_\gamma = 1$ GeV, in particular

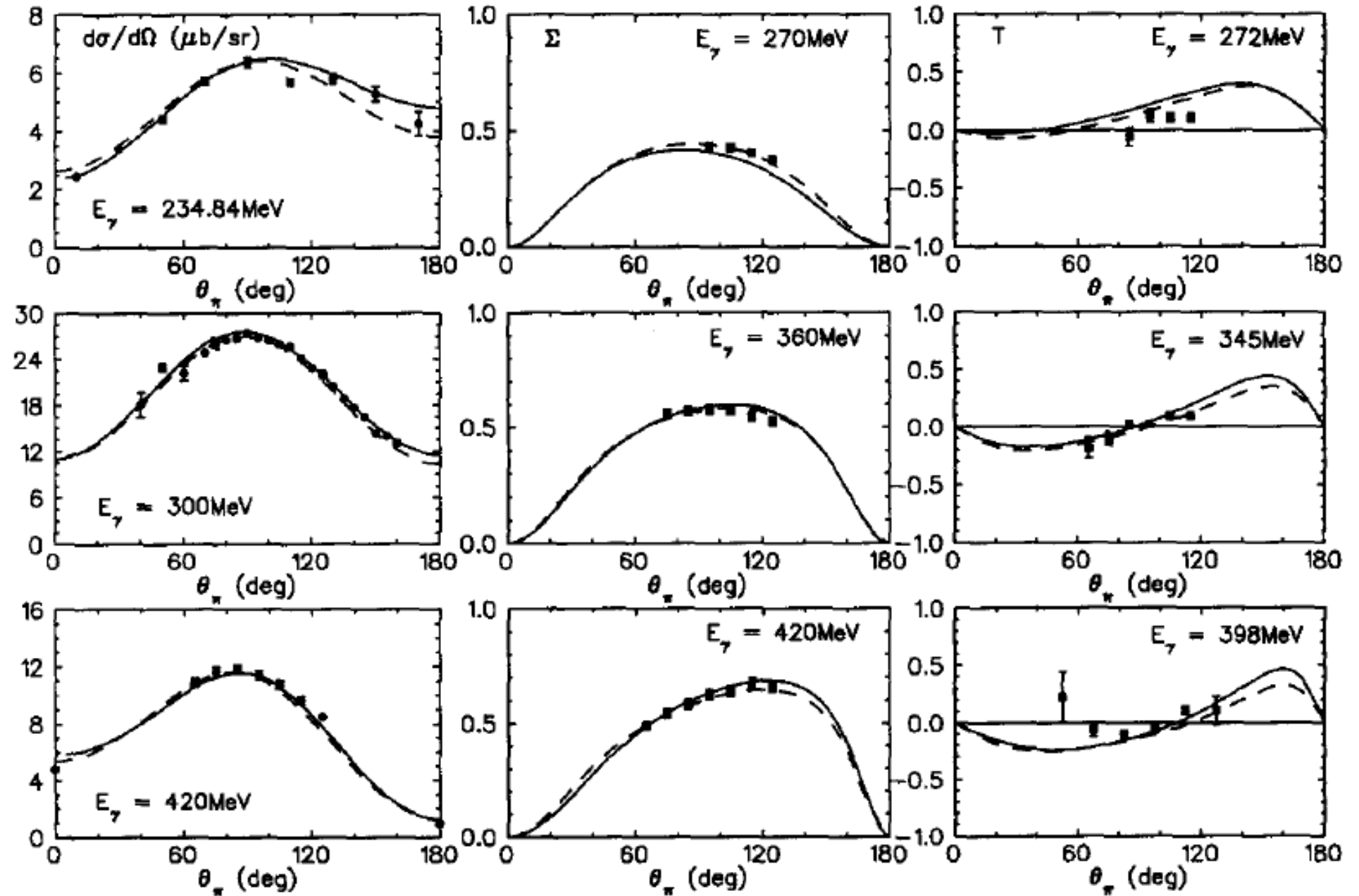


Fig. 8. The same as in Fig. 7 for $p(\gamma, \pi^0)p$. Experimental data from Refs. [28,29].

Analysis

pion nucleus optical potential

[42] D. Drechsel, et al., NPA645, 145 (1999).

A first-plus-second-order pion-nucleus optical potential constructed by fitting the phenomenological q^2 -dependent term to the $\pi^{+-} - {}^{12}\text{C}$ total and differential cross sections

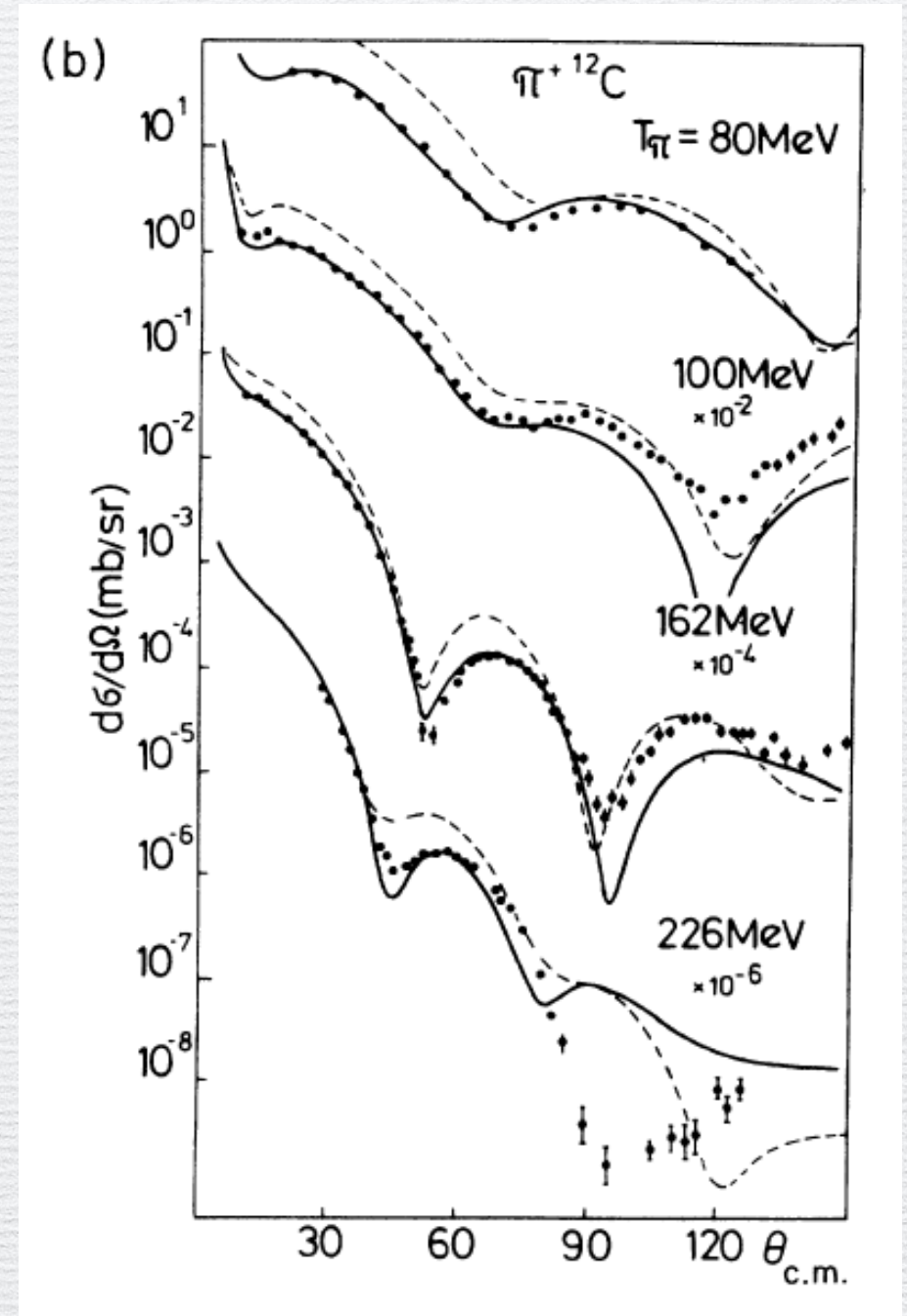


FIG. 2. Comparison of theoretical calculations with the data for π scattering from ${}^{12}\text{C}$. The dashed curves represent the results for $V^{(1)}$ and the solid curves include the effects of $V^{(2)}$ with B_0 and C_0 taken from Table I, while the dashed-double-dotted line is obtained with $V^{(2)}$ calculated for mesoatomic values (Ref. 19) $B_0 = -0.043(1-i)$ and $C_0 = -0.10(1-i)$. Data are from the following references: (a) $T_\pi = 14$ MeV (Ref. 22), 20 MeV (Ref. 23), 30 MeV (\blacklozenge Ref. 24; \blacksquare Ref. 26), 40 MeV (Ref. 25), 50 MeV (Ref. 24), 65 MeV (\blacklozenge Ref. 28), 67.5 MeV (\blacklozenge Ref. 27); (b) $T_\pi = 80$ MeV (Ref. 28), 100 MeV (Ref. 29), 162 and 226 MeV (Ref. 30); (c) $120 \leq T_\pi \leq 200$ MeV (Ref. 31), 226 MeV (\blacklozenge Ref. 30; \blacksquare Ref. 31).

Analysis

pion photo-production on nuclei

[43] B. Krusche et al., PLB526, 287(2002)

Self-energy term in the Δ propagation fitted to the ^4He data.

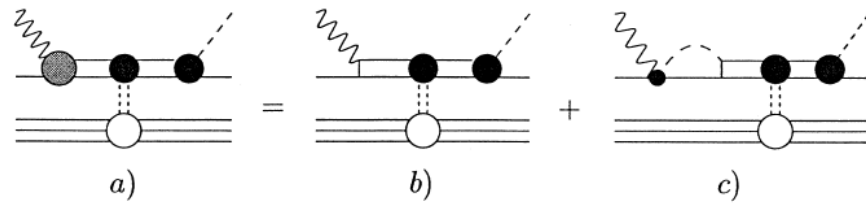


Fig.1. Two main mechanisms of the Δ isobar excitation and corresponding medium effects: (b) direct excitation with the bare $\gamma N \Delta$ vertex; (c) vertex renormalization mechanism where the Δ isobar is excited from pions produced by non-resonant background.

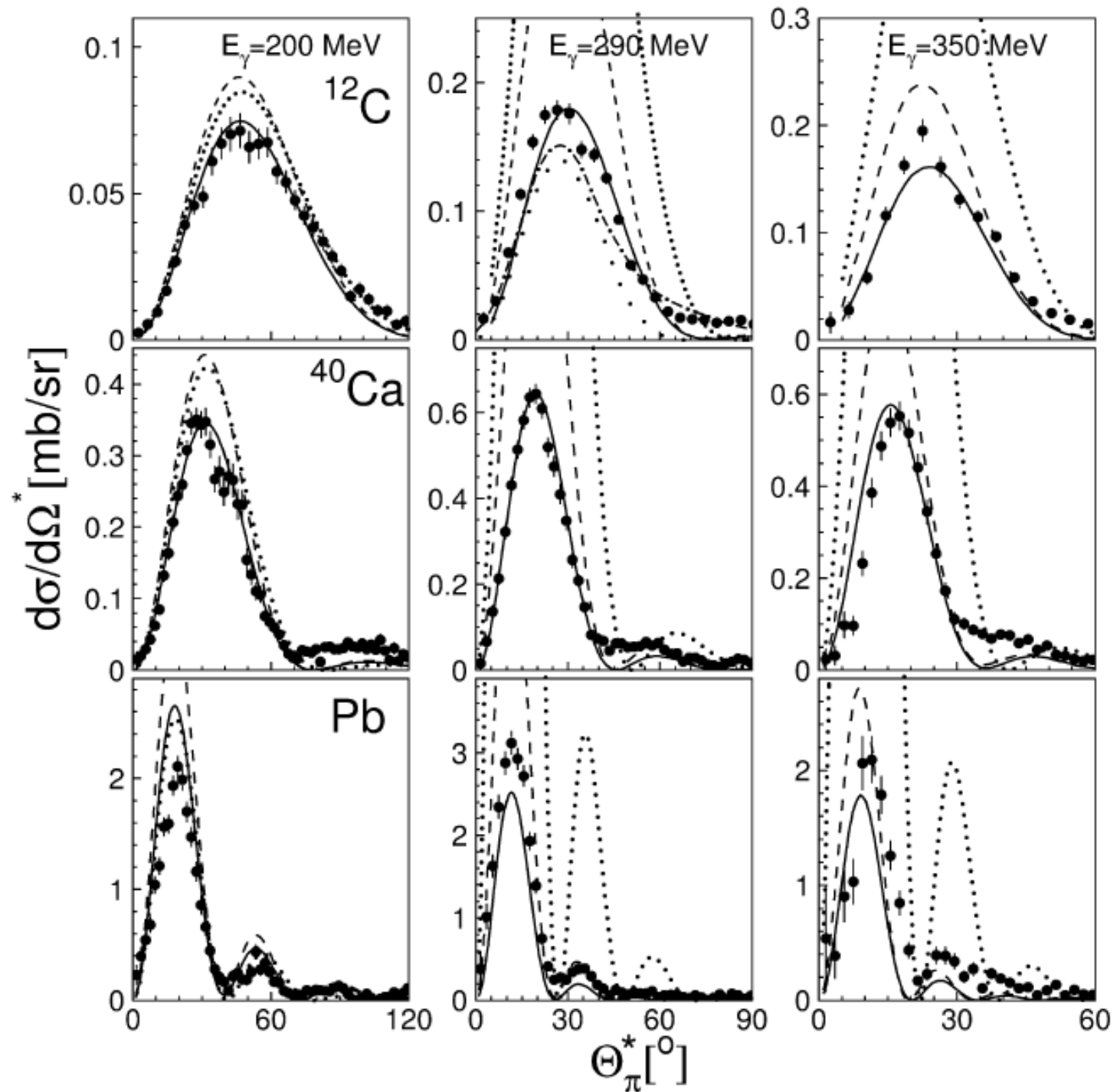


Fig. 4. Differential cross sections for $^{12}\text{C}(\gamma, \pi^0)^{12}\text{C}$, $^{40}\text{Ca}(\gamma, \pi^0)^{40}\text{Ca}$, and $\text{Pb}(\gamma, \pi^0)\text{Pb}$ compared to the predictions from Drechsel et al. [15]. Dotted lines: PWIA, dashed lines: DWIA, full lines: DWIA with Δ -self energy fitted to ^4He cross sections. For the carbon data at 290 MeV the predictions from Ref. [13] for the coherent reaction (wide space dotted) and coherent plus incoherent excitation of low lying states (dash-dotted) are also shown.

Analysis

Density Distribution

$$\rho_p(r) \quad [45]$$

$$c_p = 6.680 \text{ fm} \quad a_p = 0.447 \text{ fm}$$

→ converted to point charge distribution
incorporating the proton finite size

$$\rho_n(r)$$

calculated in the 35 grids ranging

$$c_p = 6.28 - 7.07 \text{ fm} \quad a_p = 0.35 - 0.65 \text{ fm}$$

$$\rho(r) = \frac{Z}{A} \rho_p(r) + \frac{N}{A} \rho_n(r)$$

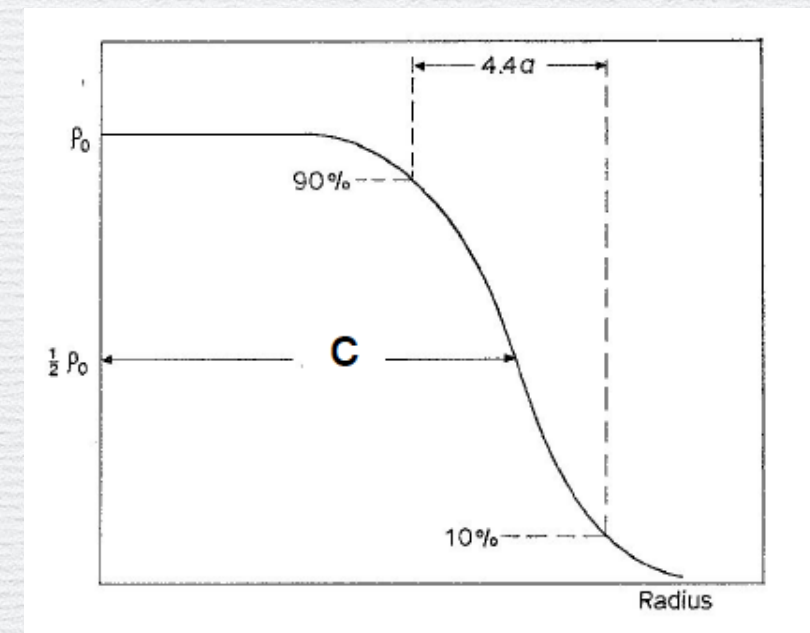
fitted with a single 2PF distribution

→ DWIA calculation

smeared with experimental q resolution of $0.02\text{-}0.03 \text{ fm}^{-1}$,
3% error is added to the c.s. data

Fitted to the data in $q=0.3\text{-}0.9$.
Interpolated in the ρ_n grids.

two parameter Fermi (2PF) distribution



$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-c}{a}\right)}$$

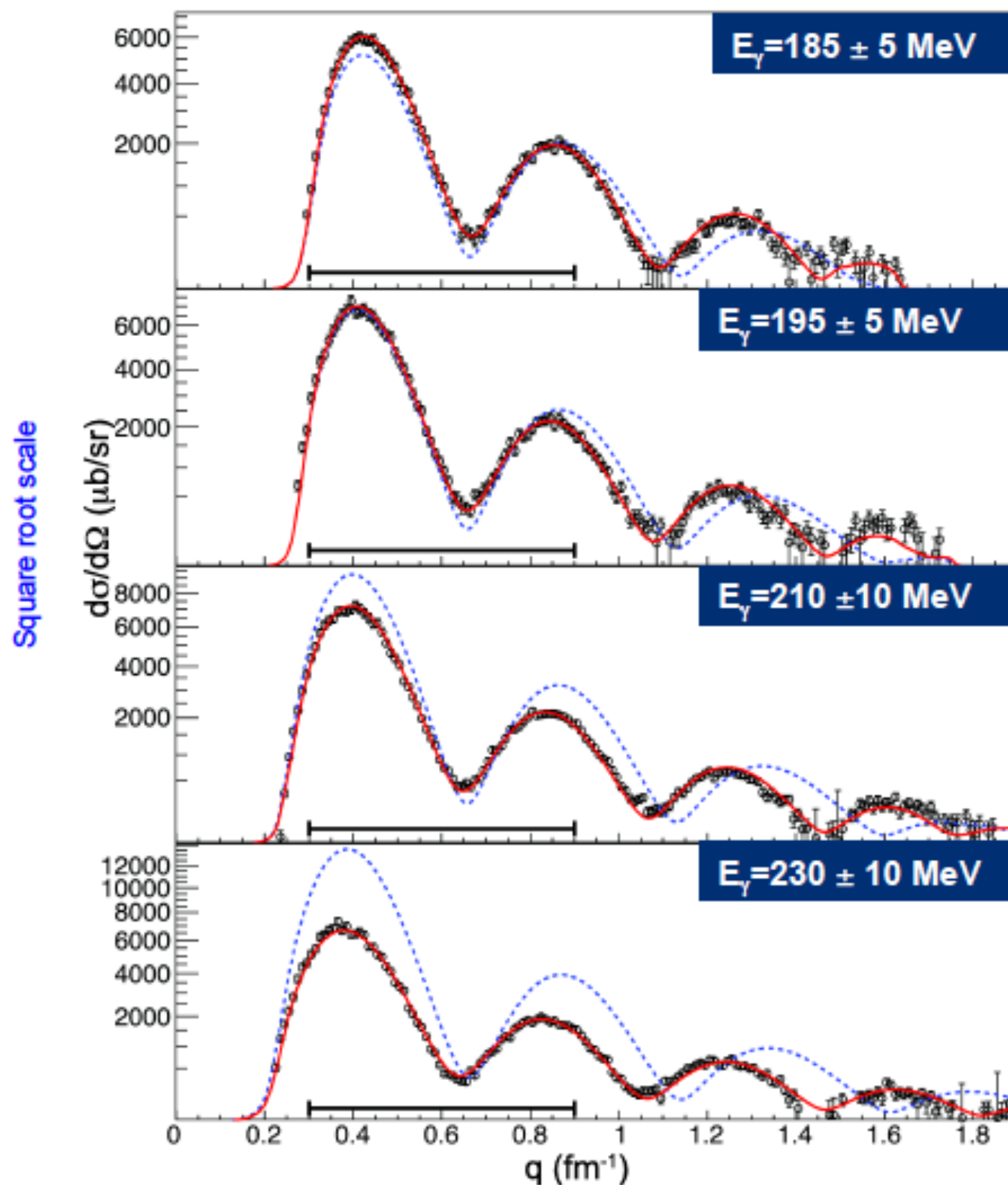
- discrepancy at high- q , probably due to inability of 2PF for describing the details of the density distribution
- discrepancy at high- E , probably due to the rapid increase of the π^0 absorption c.s. in the Δ resonance energy

Analysis

[44] To check the validity of approximating $\rho(r)$ by a single 2PF distribution, the Fourier transforms of $\rho(r)$ and the fitted 2PF distribution were compared. In the momentum range up to $q = 0.9 \text{ fm}^{-1}$, over which the (γ, π^0) cross section was fitted to extract information about $\rho_n(r)$, the fractional difference between the two transforms only rises to 0.3% at $q = 0.9 \text{ fm}^{-1}$.

Analysis

Momentum transfer distributions



-- PWIA calculation
-- Full calculation

Drechsel et. al. NPA 660 (1999)

Fitting procedure

Calculate grid $c_n = 6.28 - 7.07 \text{ fm}$
 $a_n = 0.35 - 0.65 \text{ fm}$

Predictions smeared by q resolution

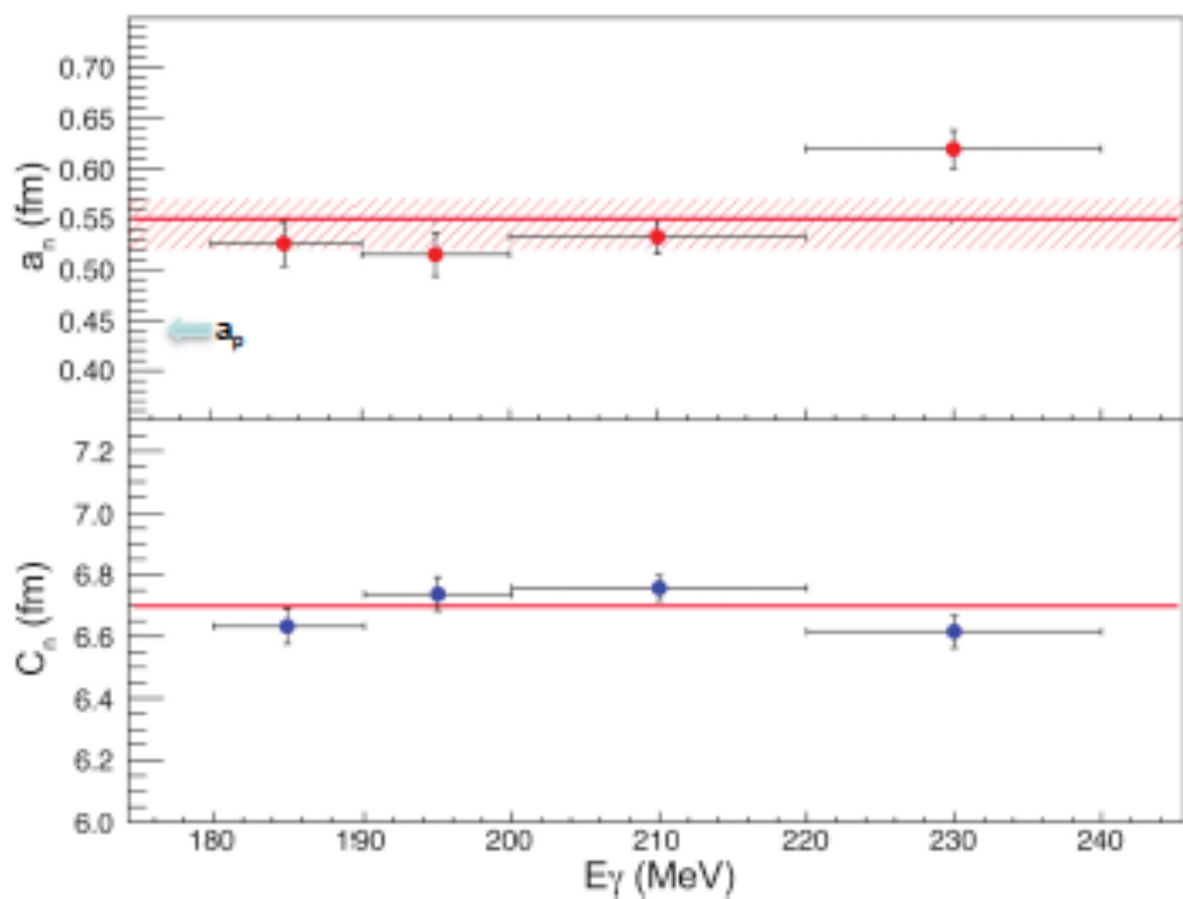
Interpolated fit to experimental data
($q = 0.3 - 0.9$)

Free param. : norm, c_n , a_n ,
Fixed param. : $c_p = 6.68$ $a_p = 0.447$
(PRC 78 014211 (2011))

Low E_γ limit: Δ dominates
High E_γ limit: π FSI not too large
(p -wave interactions set in)

Results

The extracted skin properties



$$a_n = 0.55 \pm 0.01(stat.)^{+0.02}_{-0.03}(sys.)$$

$$c_n = 6.70 \pm 0.03(stat.)fm$$

$$\Delta r_{np} = 0.15 \pm 0.03(stat.)^{+0.01}_{-0.03}(sys.)$$

- Systematics:

- Normalisation parameter within $\pm 5\%$ of unity for all bins
- E_γ dependences – a_n high E_γ bin 3.5σ away from average
- Vary yield fitting procedure
- 10% variation relative p,n amplitudes in the model (mainly affects diffuseness)
- Different fit ranges

Results

Systematic Error

- Analysis using only the first minimum
→ consistent result in the half-height radius ←How consistent?
- Variation of the relative weighting of the p and n amplitudes by 10%
→ change of 0.02 fm in the diffuseness and negligible effect on the half-height radius
- Variation in the modeling of the background
→ systematic error of 0.01 fm in the diffuseness ←How is the error in radius?

How is error in the reaction model?

Results

Half-height radius: $6.70 \pm 0.03(\text{stat.})$ fm

←How is the systematic error?

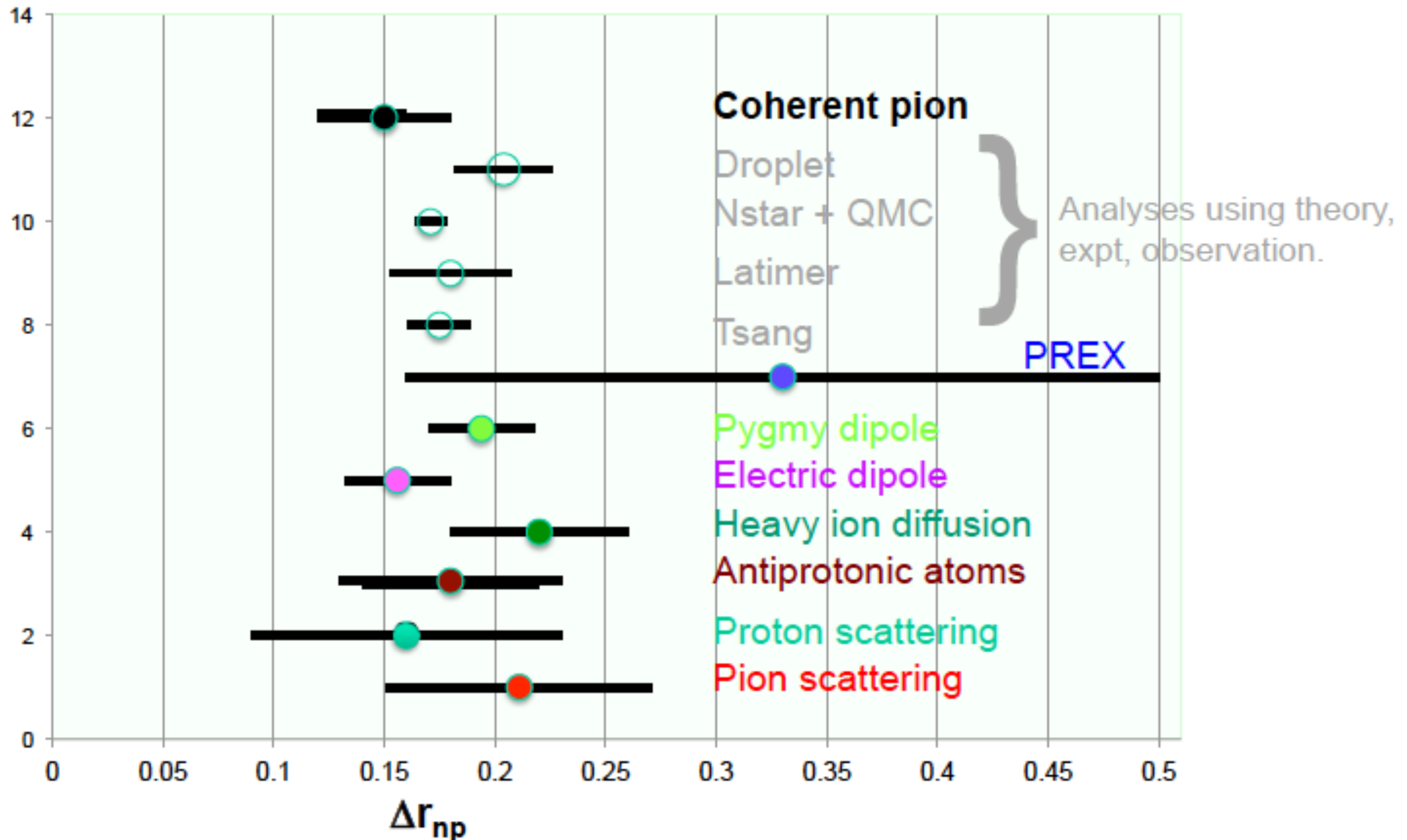
Isn't the fluctuation in Fig.3 much larger?

Diffuseness: $0.55 \pm 0.01(\text{stat.}) + 0.02 - 0.03(\text{sys.})$ fm

→ $\Delta r_{np} = 0.15 \pm 0.03(\text{stat.}) + 0.01 - 0.03(\text{sys.})$ fm

Results

Comparison with previous measurements

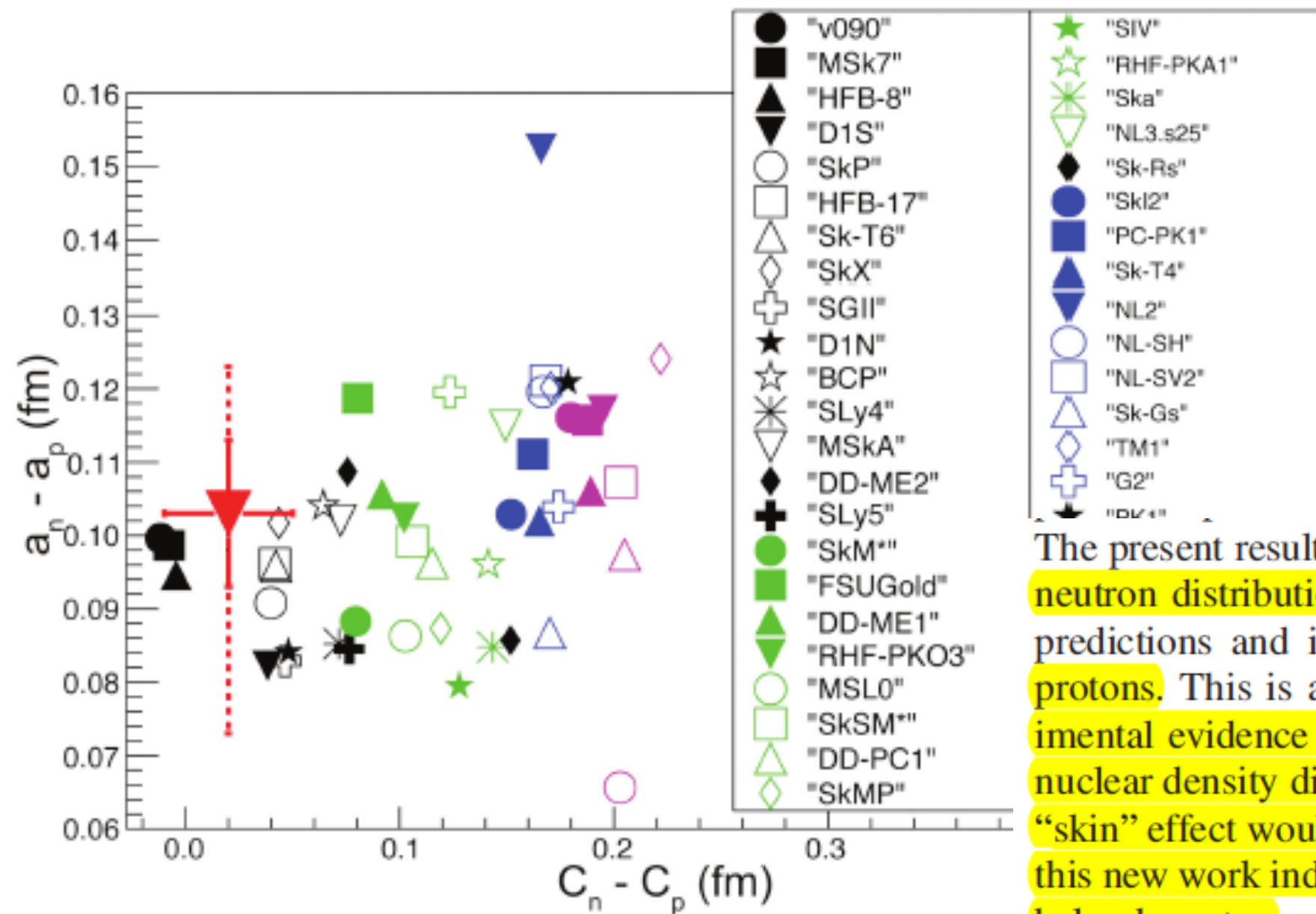


- New result in general agreement with other methods

Discussions

Comparison with theory

Slide by D.P. Watts

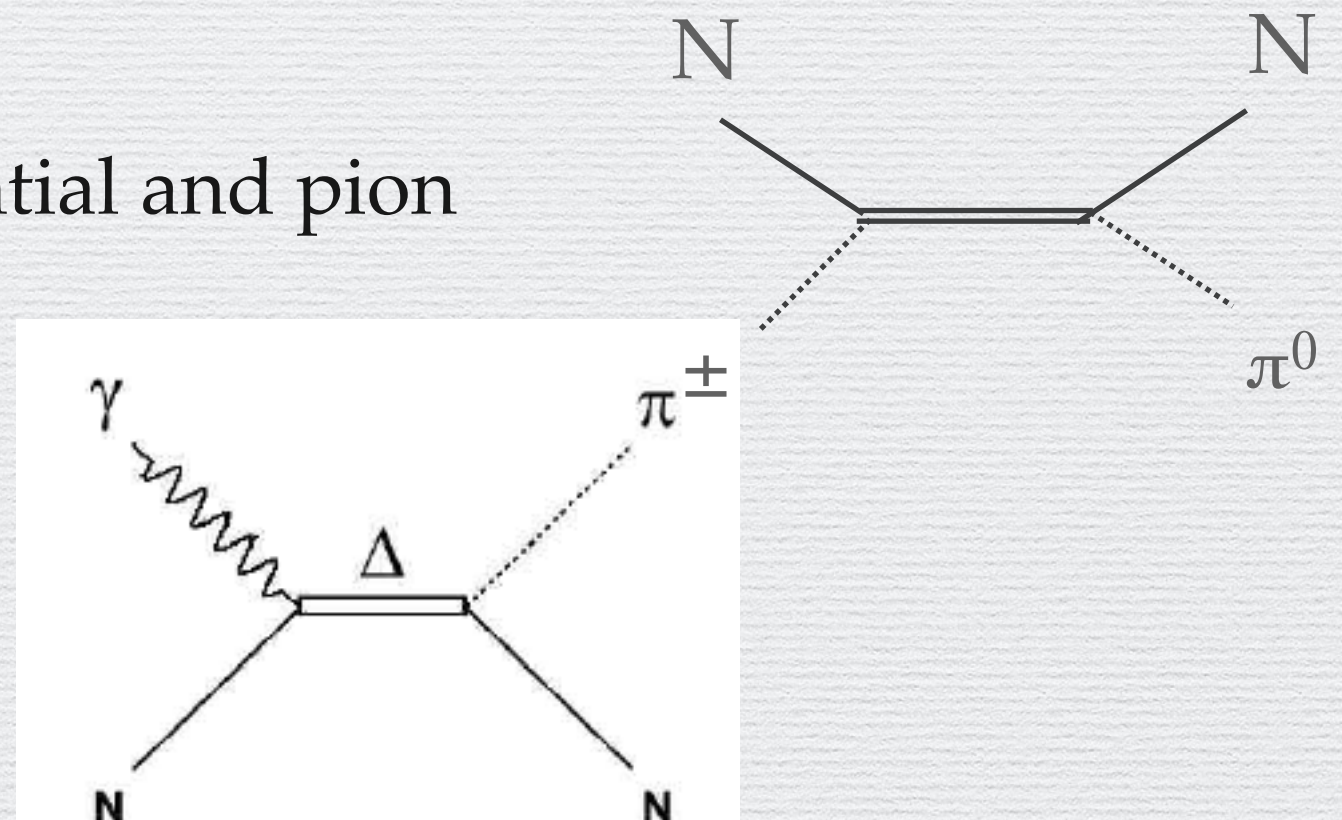


The present result clearly shows that the diffuseness of the neutron distribution in ^{208}Pb is in the range of theoretical predictions and is significantly greater than that for the protons. This is an important result, as conclusive experimental evidence for a difference in the diffuseness of the nuclear density distributions has been lacking [48]. A pure "skin" effect would have an $a_n - a_p$ value close to zero, so this new work indicates that the neutron skin of ^{208}Pb has a halo character.

Conclusive evidence that the neutron diffuseness is larger than the proton diffuseness \rightarrow Halo?

Critical Discussions

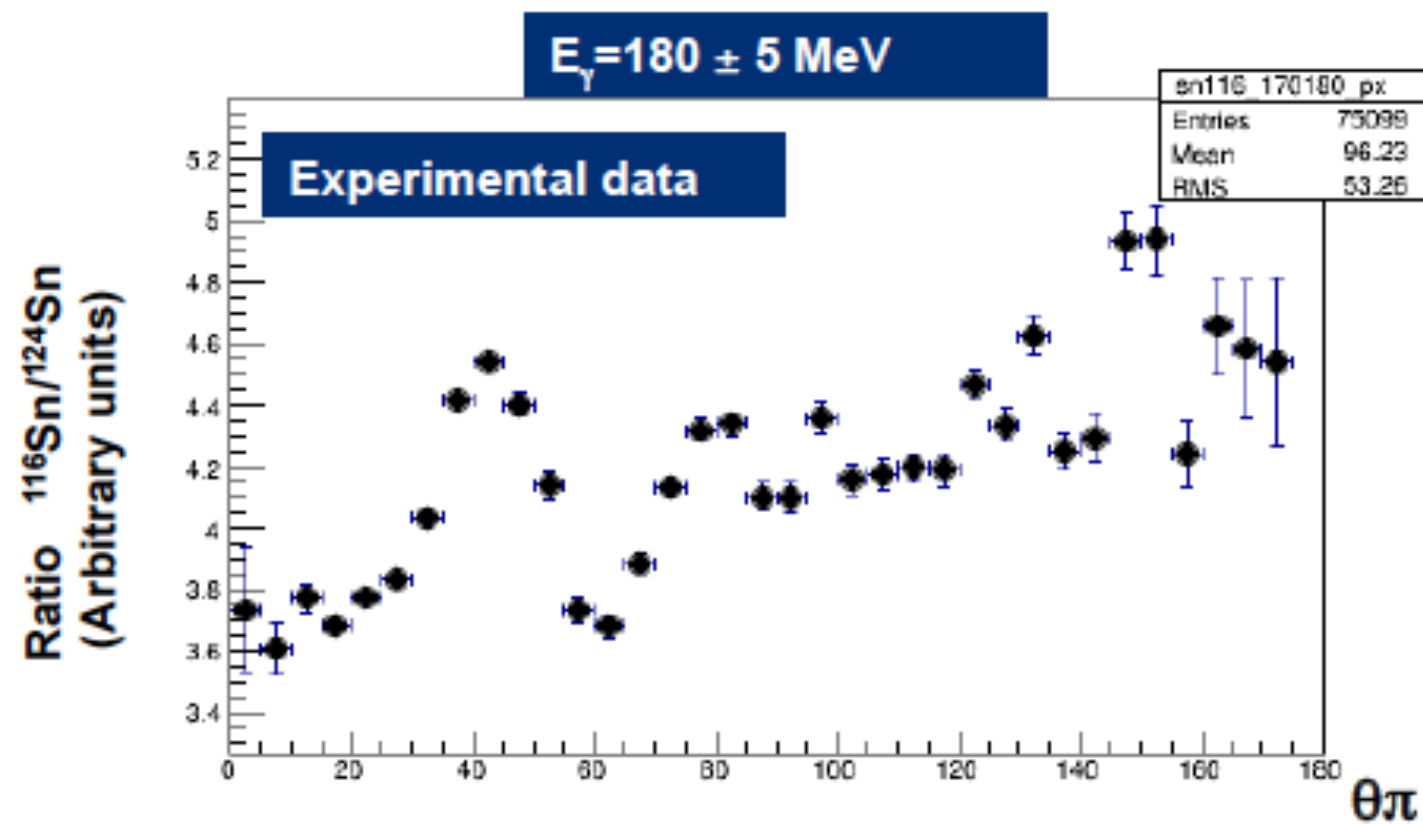
- Why only at 180-240 MeV?
- Why only at $q=0.3-0.9 \text{ fm}^{-1}$?
- How large is the model dependence of π^0 -nucleus interaction?
- How is the assumption of the “single” two parameter Fermi distribution good enough?
- Pion charge-exchange contribution?
- Medium modification of the delta resonance? Pion production on the multiple nucleons?
- Uncertainty of the optical potential and pion propagation in medium?



Discussions

Future plans

- Data under analysis for ^{116}Sn , ^{120}Sn , ^{124}Sn & ^{56}Ni
- Plans for ^{48}Ca , ^{40}Ca in future
- Discussions on Xenon isotopic chain



- Very early stage analysis

Summary

In summary, a measurement of the coherent photo-production of π^0 mesons from ^{208}Pb has provided the first determination of a nuclear matter form factor with an electromagnetic probe. The existence of a neutron skin on the surface of the ^{208}Pb nucleus is confirmed with a thickness $\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})_{-0.03}^{+0.01}(\text{sys.})$ fm. The method is sensitive enough to extract the shape of the neutron distribution, which is found to be $\sim 20\%$ more diffuse than the charge distribution. This new determination of the neutron skin properties discriminates against some of the modern nuclear theories in common use and will be a valuable new constraint on the equation of state for neutron-rich matter and neutron stars.