Neutron skins from coherent pion photoproduction

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MAINZER MIKROTRON

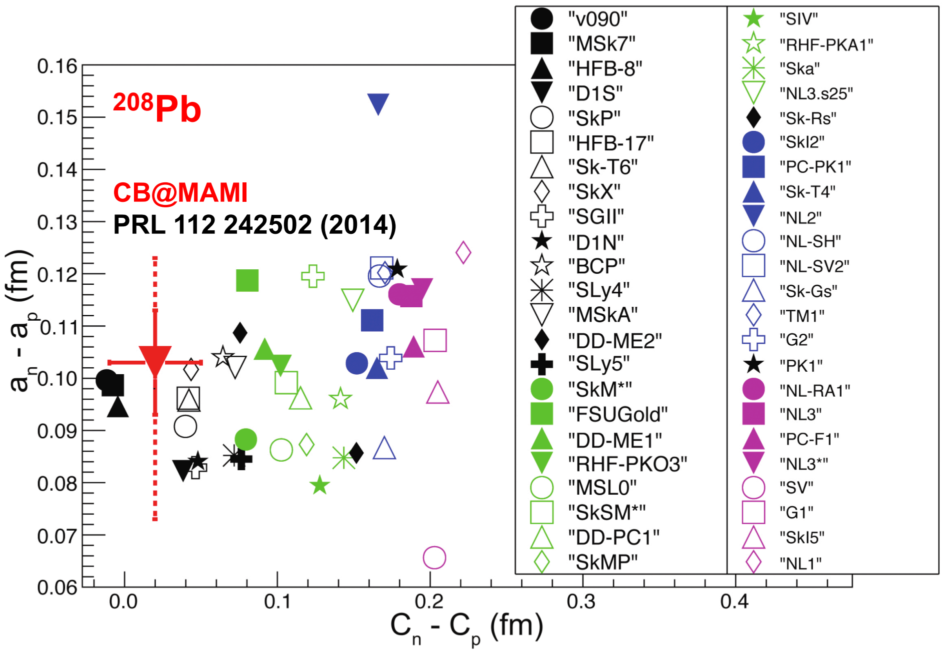
Talk Outline

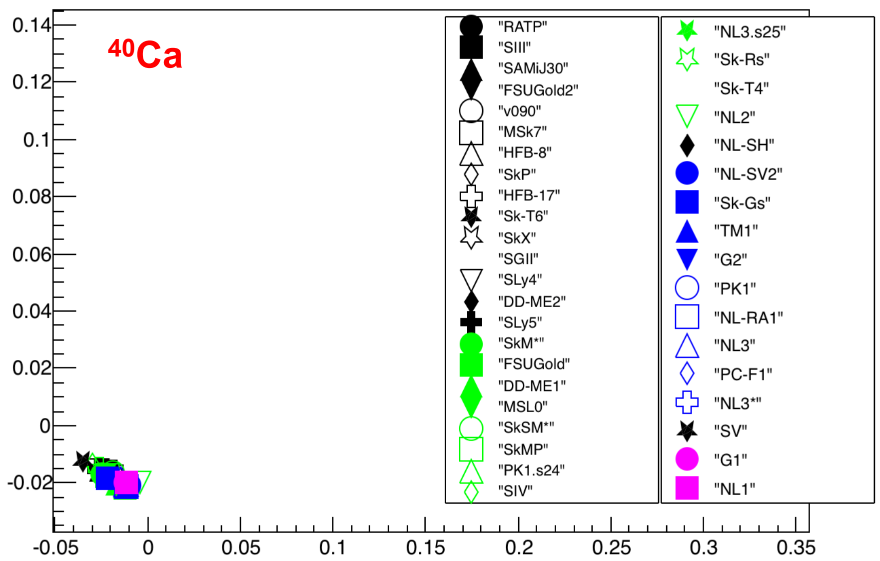
- Why measure neutron skins?
- Basics of coherent π^0 photoproduction process
- Measurement apparatus - The Crystal Ball at MAMI
- Results for ^{208}Pb; preliminary analysis for ^{40}Ca, $^{116-124}$Sn
- Discussion of systematics
- Other future future work relevant to EOS
  – the intriguing d* resonance

Neutron distributions in nuclei

- Motivation: Neutron distributions in nuclei established with poorer accuracy than the proton distributions.

- Modern nuclear theories – divergent predictions of properties of the neutron distribution in heavy (asymmetric) nuclei. Largely due to uncertainty in L



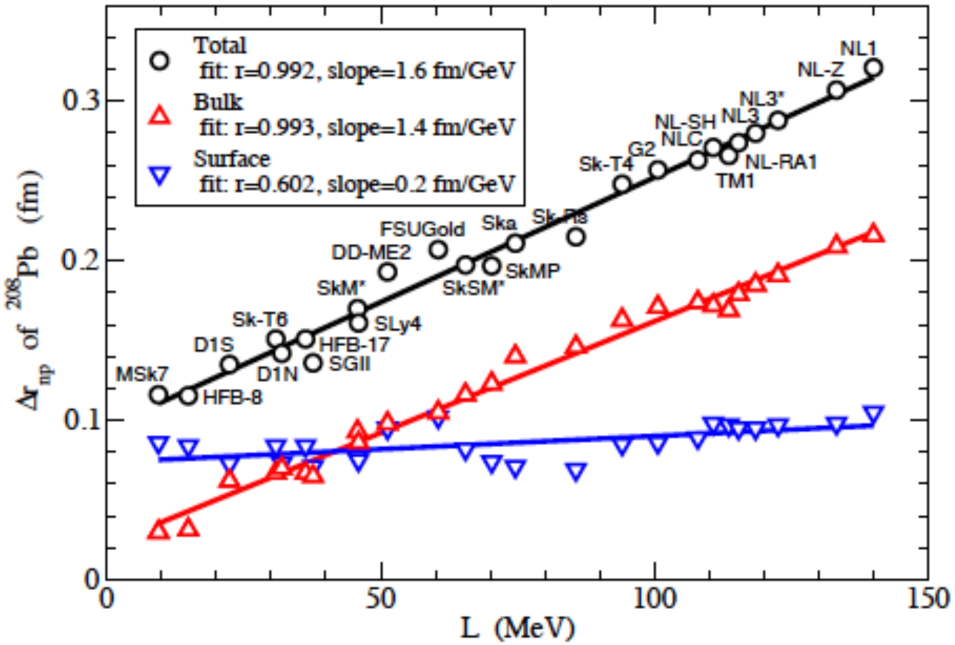


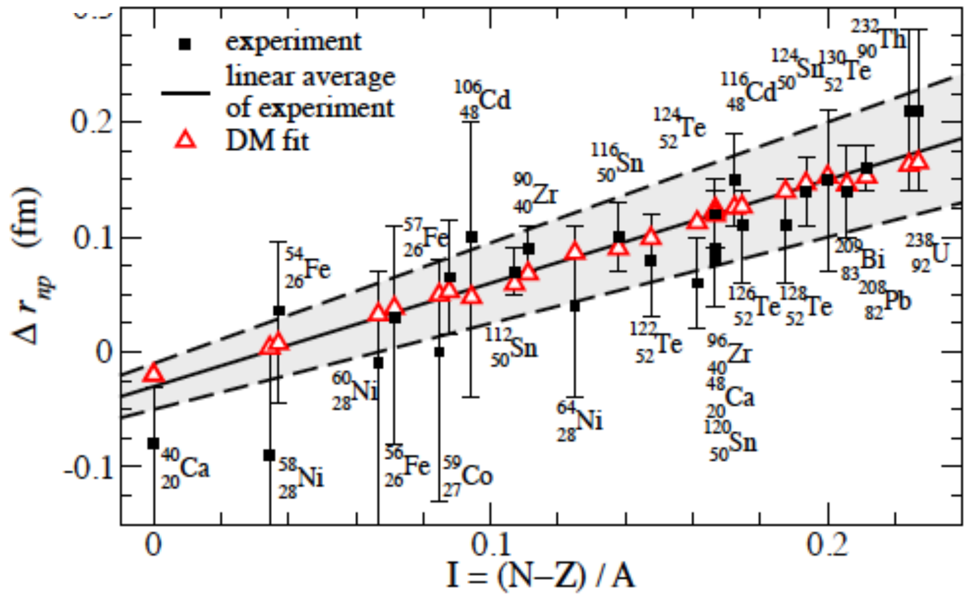
2PF analysis of nuclear model predictions - analytic relationship between a,c and $\langle r^2 \rangle$

Centelles et. al. (Barcelona)

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

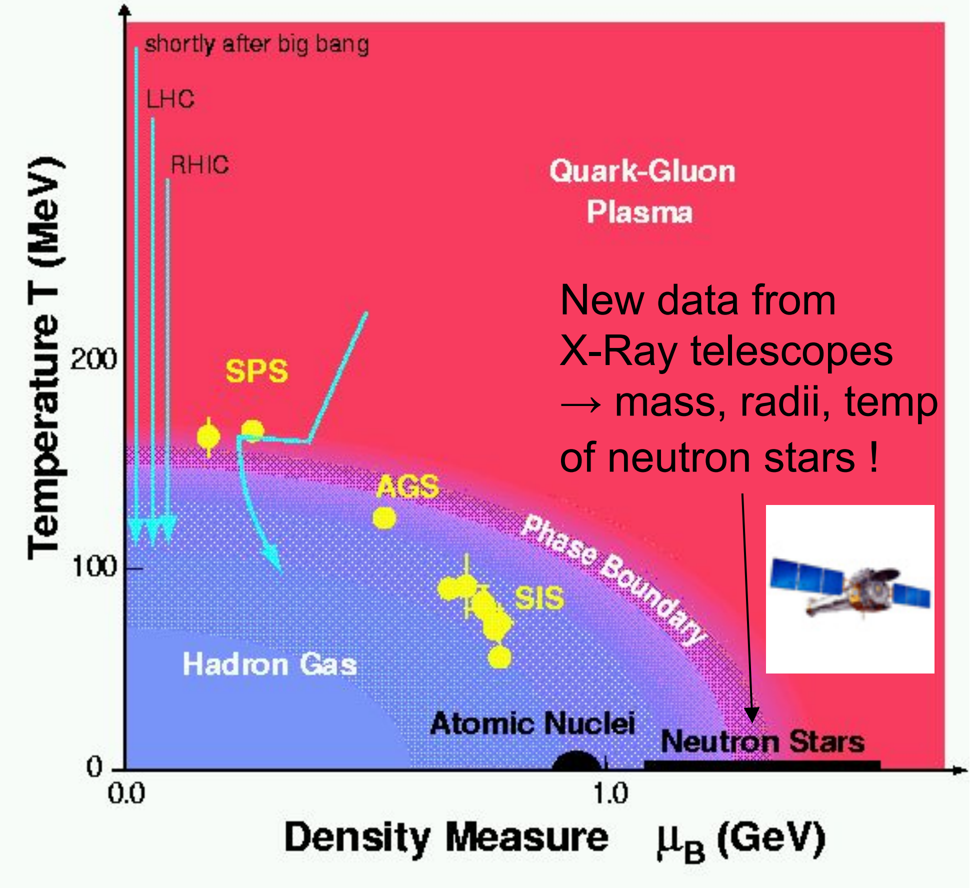
Correlation of the neutron skin and the EOS





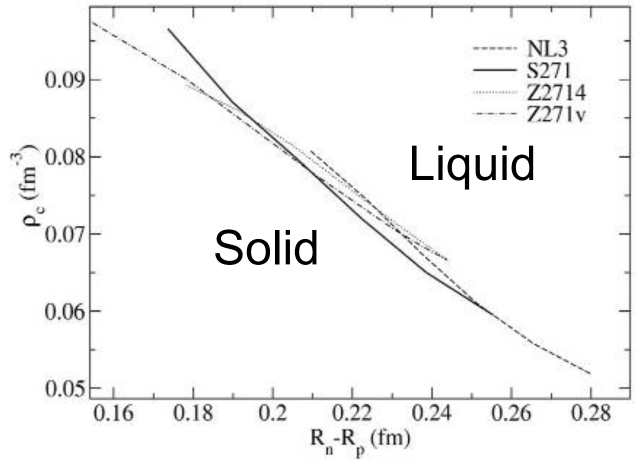
Centelles, Roca-Maza, Vinas and Warda
(Barcelona, Lupin)

Neutron skins and neutron stars

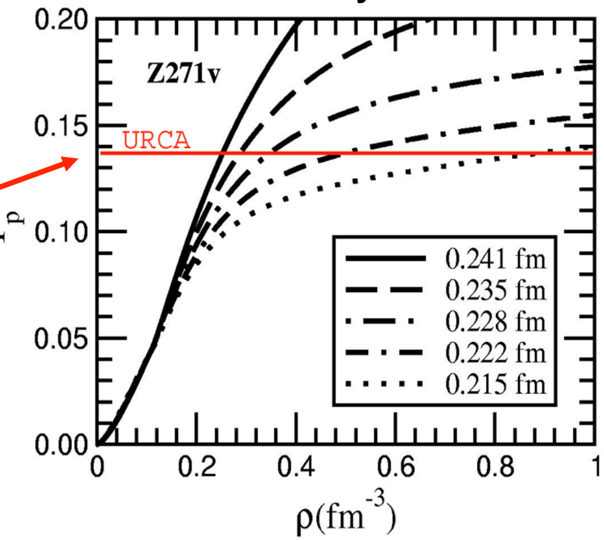


Rutel et al, PRL 95 122501 (2005)
Horowitz, PRL 86 5647 (2001)
Horowitz, PRC 062802 (2001)
Carriere, Astrophysical Journal 593 (2003)
Tsuruta, Astrophysical Journal Lett. 571 (2002)

Thick neutron skin
→ Low transition density in neutron star



Proton fraction as a function of density in neutron star



Direct URCA Cooling

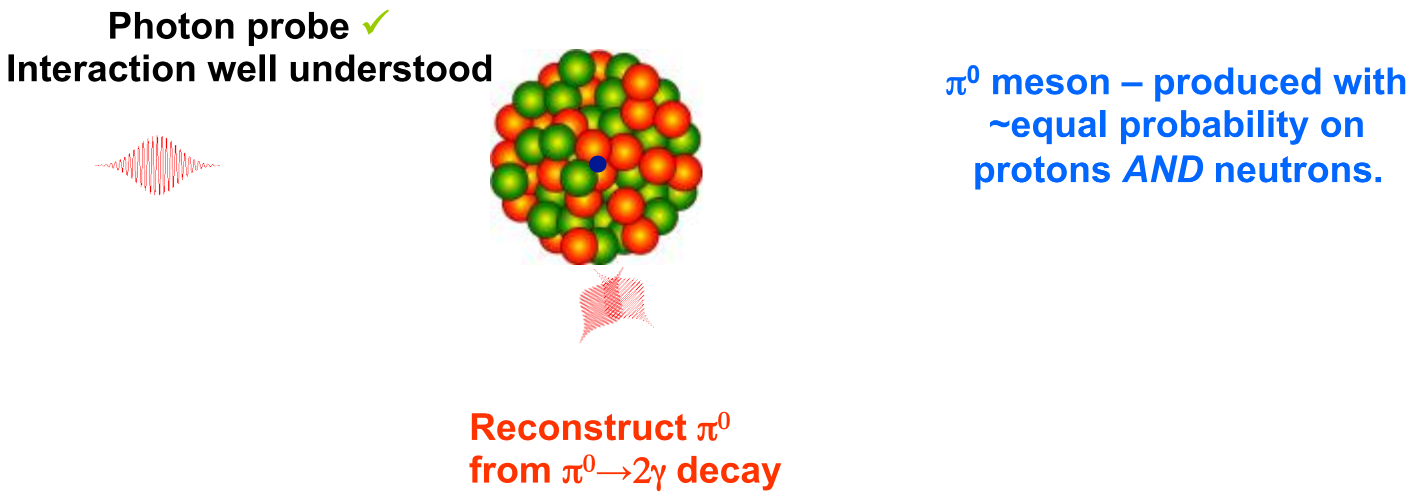
$n \rightarrow p + e^- + \overline{\nu}$

$e^- + p \rightarrow n + \nu$

Constrains gravitational wave emission from neutron stars – Frequency and damping modes!! PRC 80 025801 (2009)

Description of the Coherent pion photoproduction method for measuring neutron skins

Coherent pion photoproduction in PWIA



- Angular distribution of π^0 → PWIA contains the matter form factor

$$d\sigma/d\Omega(\text{PWIA}) = (s/m_N^2)\, A^2\, (q_\pi^*/2k_\gamma)\, F_2(E_\gamma^*, \theta_\pi^*)^2\, |F_m(q)|^2 \sin^2\theta_\pi^*$$

s – square of total energy of γ-N pair [MeV^2]

q – Momentum transfer [MeV/c]

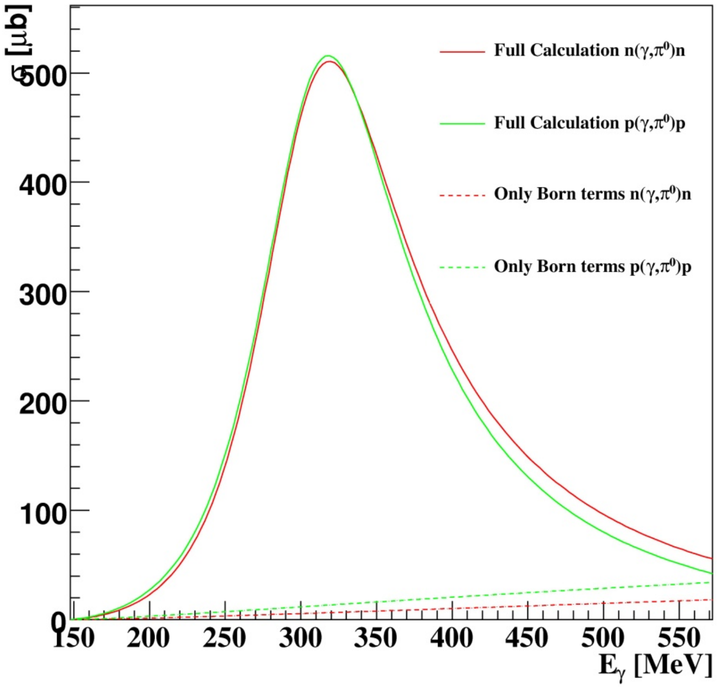
F_2 - spin independent amplitude (unitary isobar analysis of pion photoproduction from the nucleon)

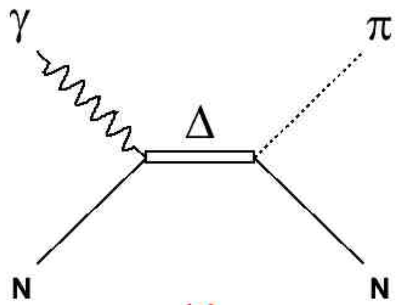
$|F_m(q)|^2$ – Matter form factor

* denotes the quantities are measured in the γ-N CM system

Details of the theoretical model : Production amplitude

- Model uses the MAID parametrisation of the amplitudes
- Amplitude ~ equal for protons and neutrons in the region of the Δ
- Different PWA converge in the Delta region ➔ M1 well established multipole





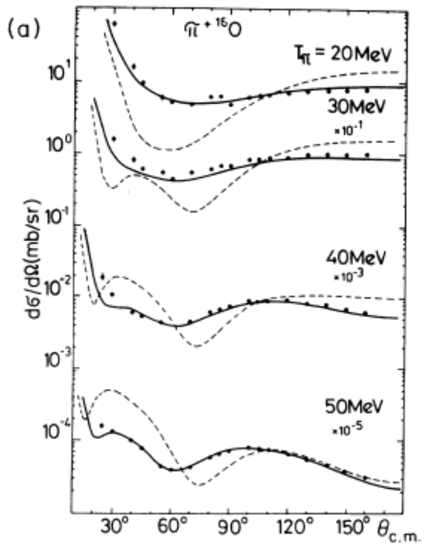
Isospin structure of amplitude

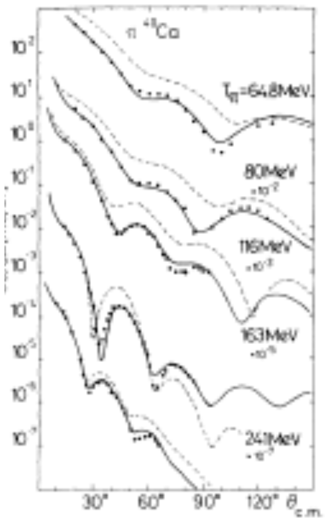
$A(\gamma p \rightarrow \pi^0 p) = \sqrt{2/3}\, A^{V3} + \sqrt{1/3}(A^{VI} - A^{IS})$
$A(\gamma n \rightarrow \pi^0 n) = \sqrt{2/3}\, A^{V3} + \sqrt{1/3}(A^{VI} + A^{IS})$

Δ has I=3/2 ➔ A^{V3} **only**
EM couplings identical for p,n

Details of the theoretical model : π-nucleus interaction

- Second order pion-nucleus optical potential evaluated in momentum space
- Good description of available total and elastic differential pion scattering on nuclei - fitted in range T_{π}=20 - 250 MeV
- Includes a Δ self energy term – respecting unitarity





Δ – self energy

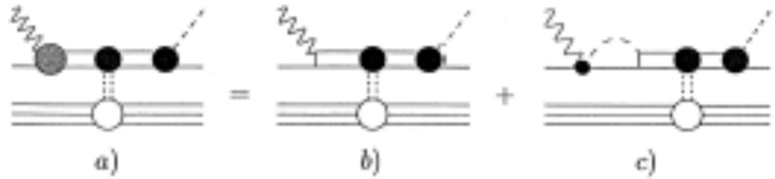
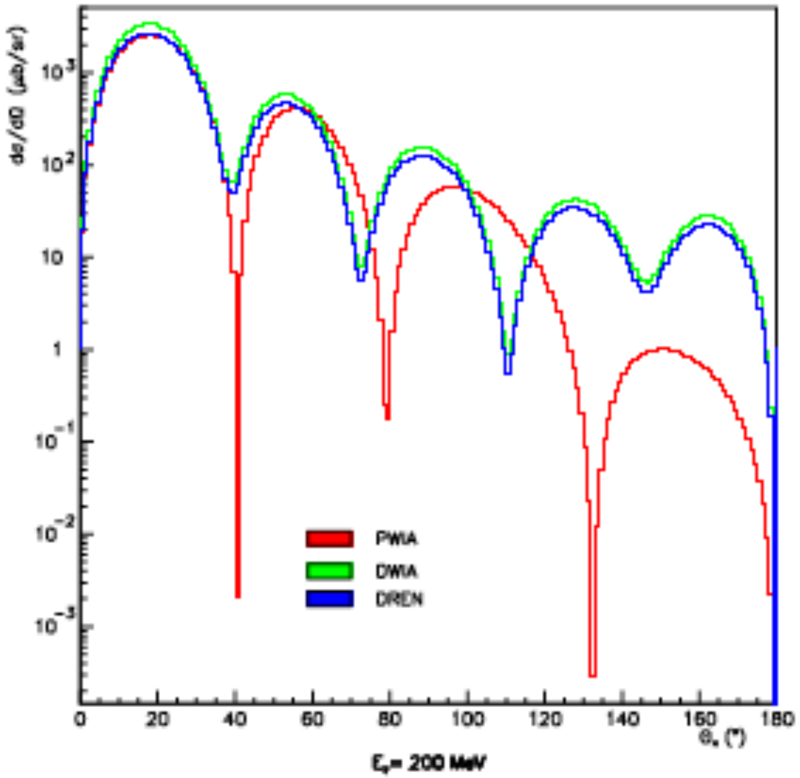


Figure 2.7: Diagram (a) is the sum of (b) and (c), the two main mechanisms contributing to the excitation of the Δ and the corresponding medium effects. (b) direct excitation of the isobar, (c) the Δ is excited via pion rescattering. Diagram from [8].

Details of the theoretical model: Relative π-nucleus interactions

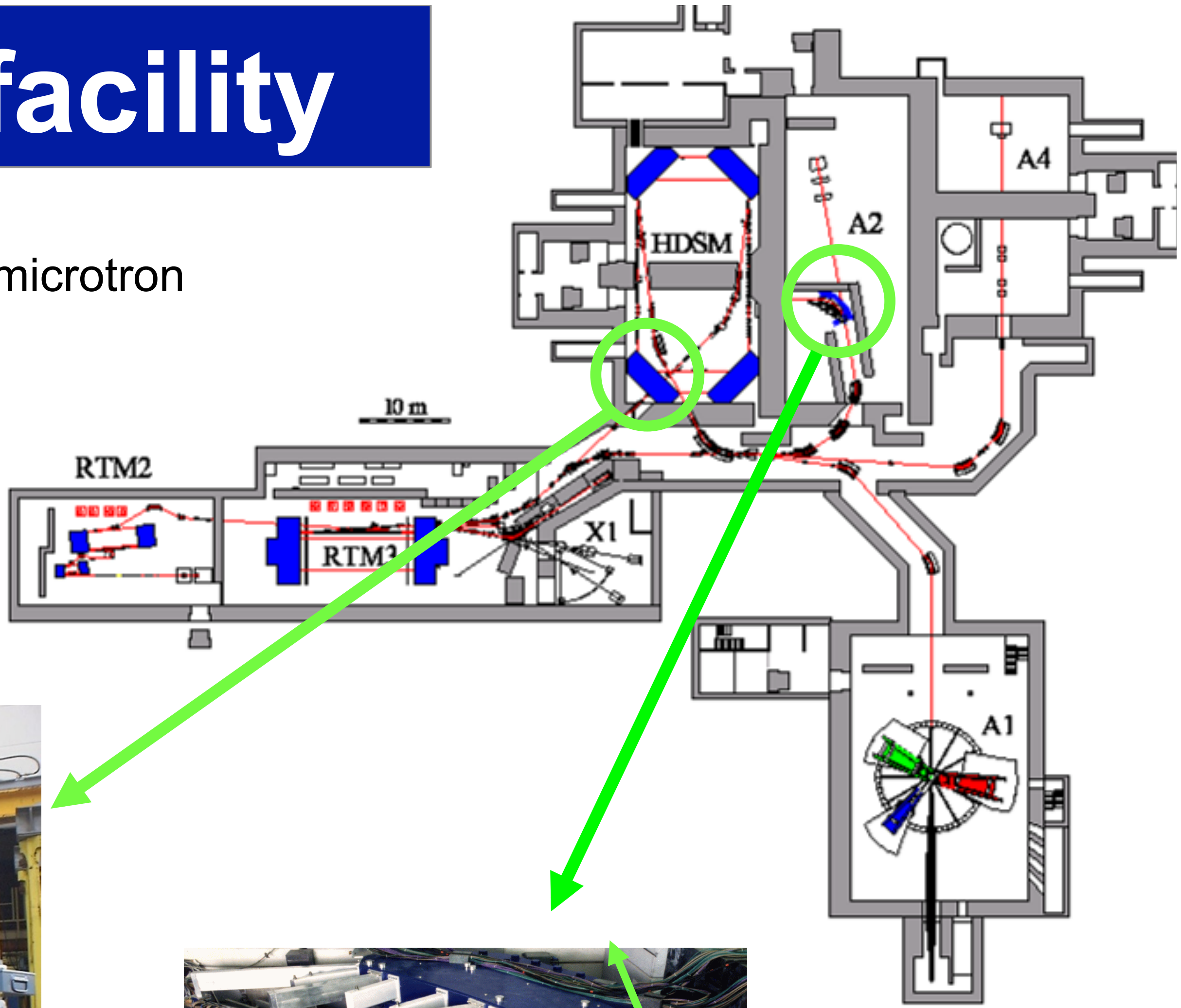


- Δ-self energy produces a rather uniform reduction for all θ_π (or q)
- q-shifts – dominantly from the optical potential

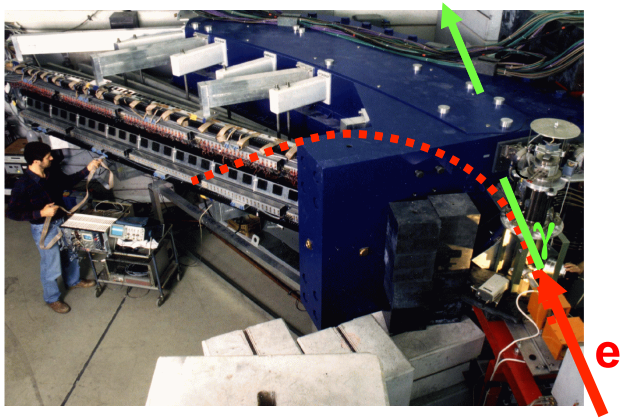
Details of the experiment & analysis

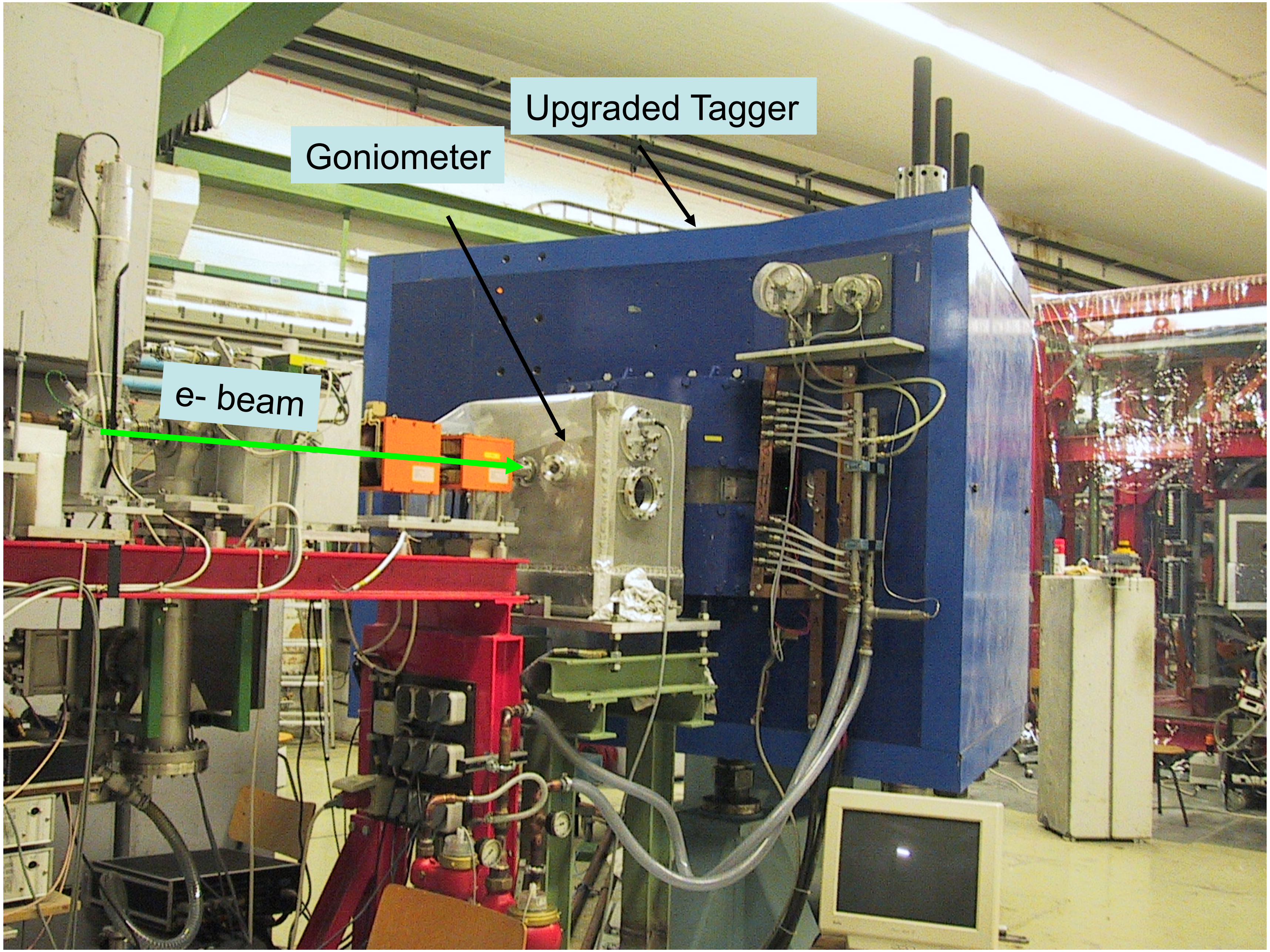
The MAMI facility

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



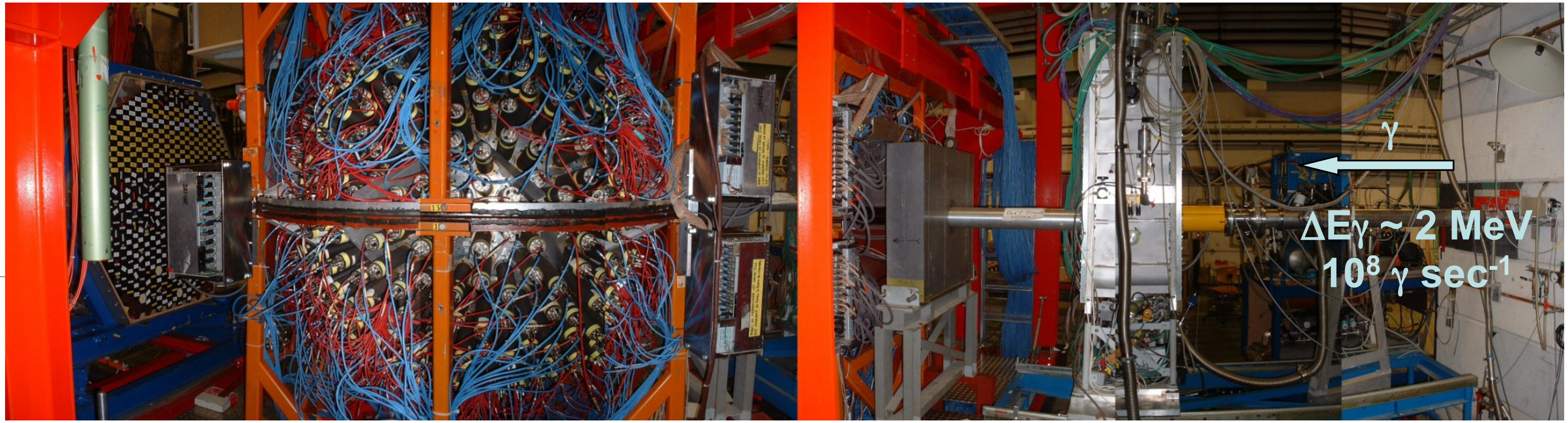

One of the MAMI-C magnets

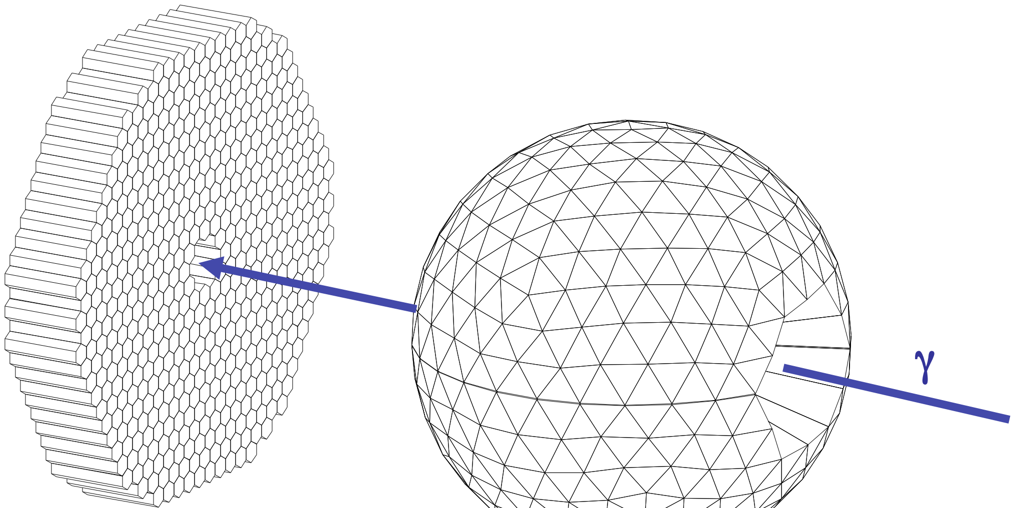



Upgraded Tagger
Goniometer
e- beam

Crystal Ball arrives at Frankfurt

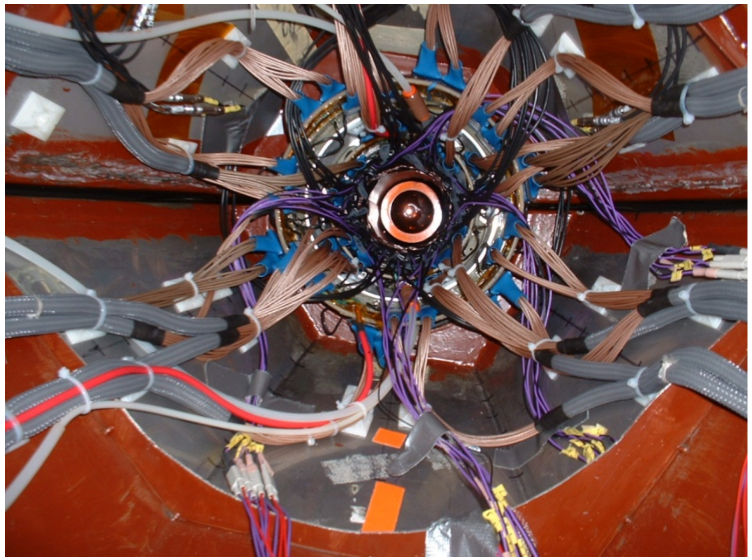
Crystal Ball at MAMI





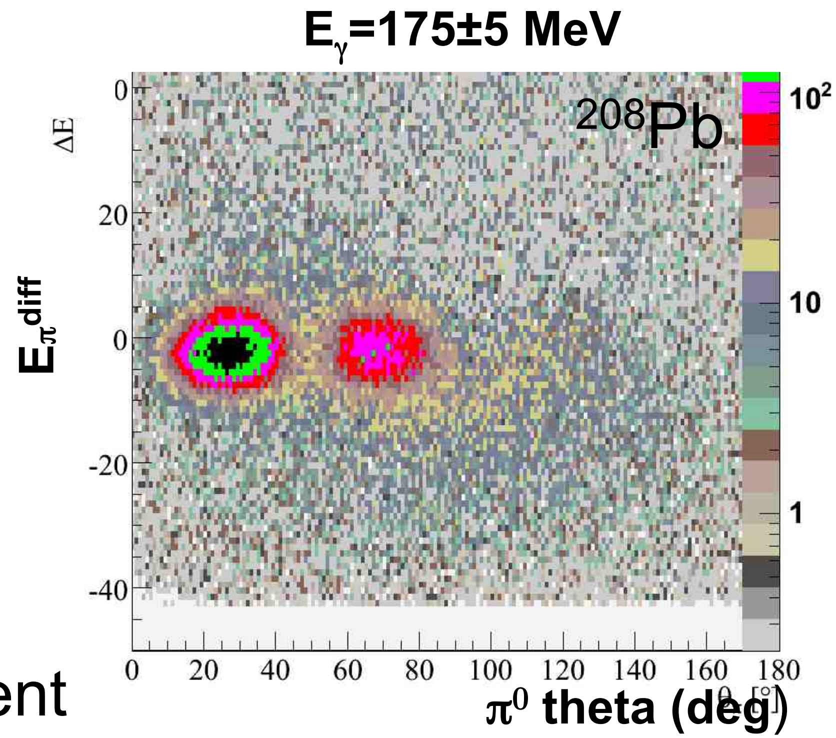
TAPS
528 BaF_2 crystals

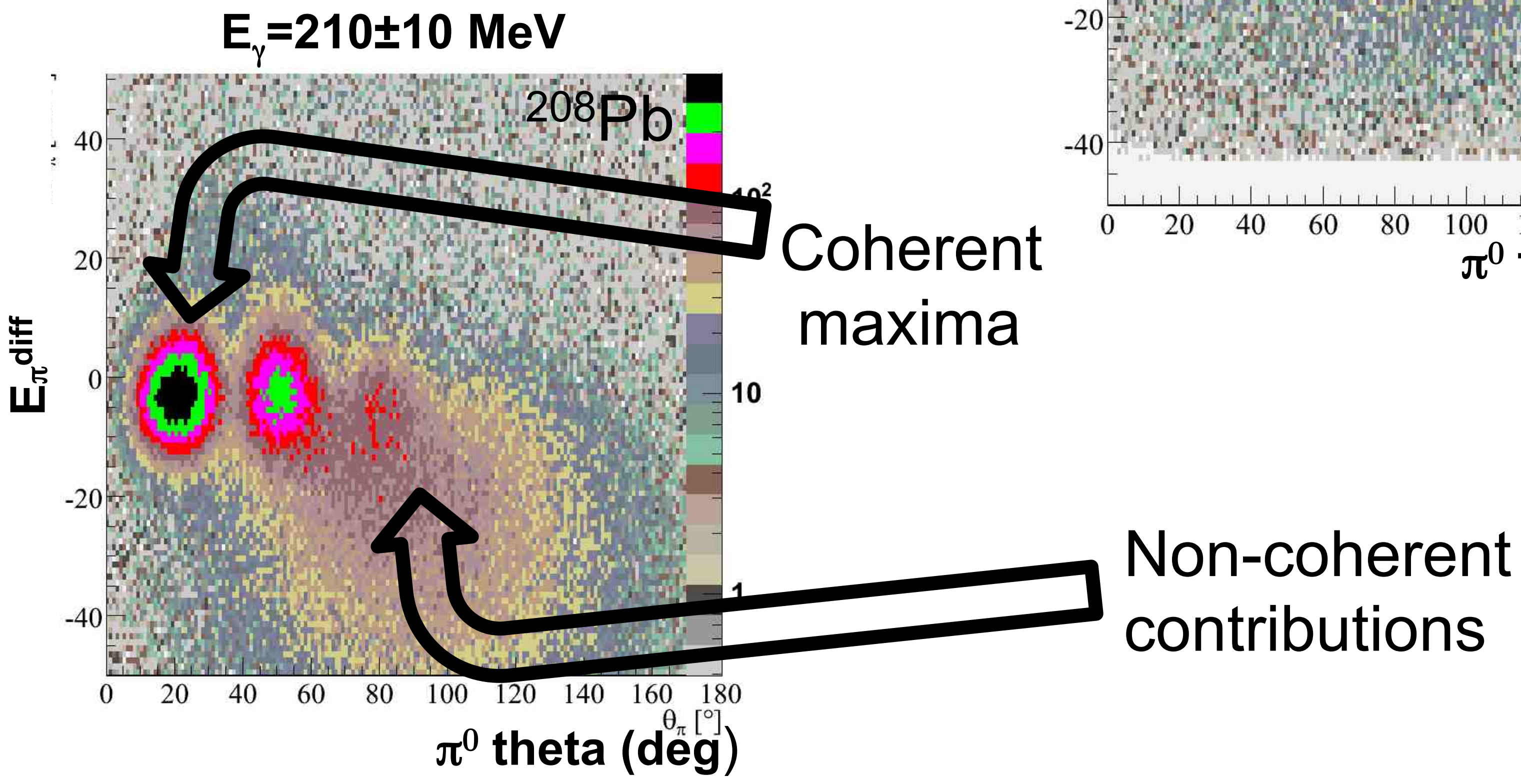
Crystal Ball
672 NaI crystals



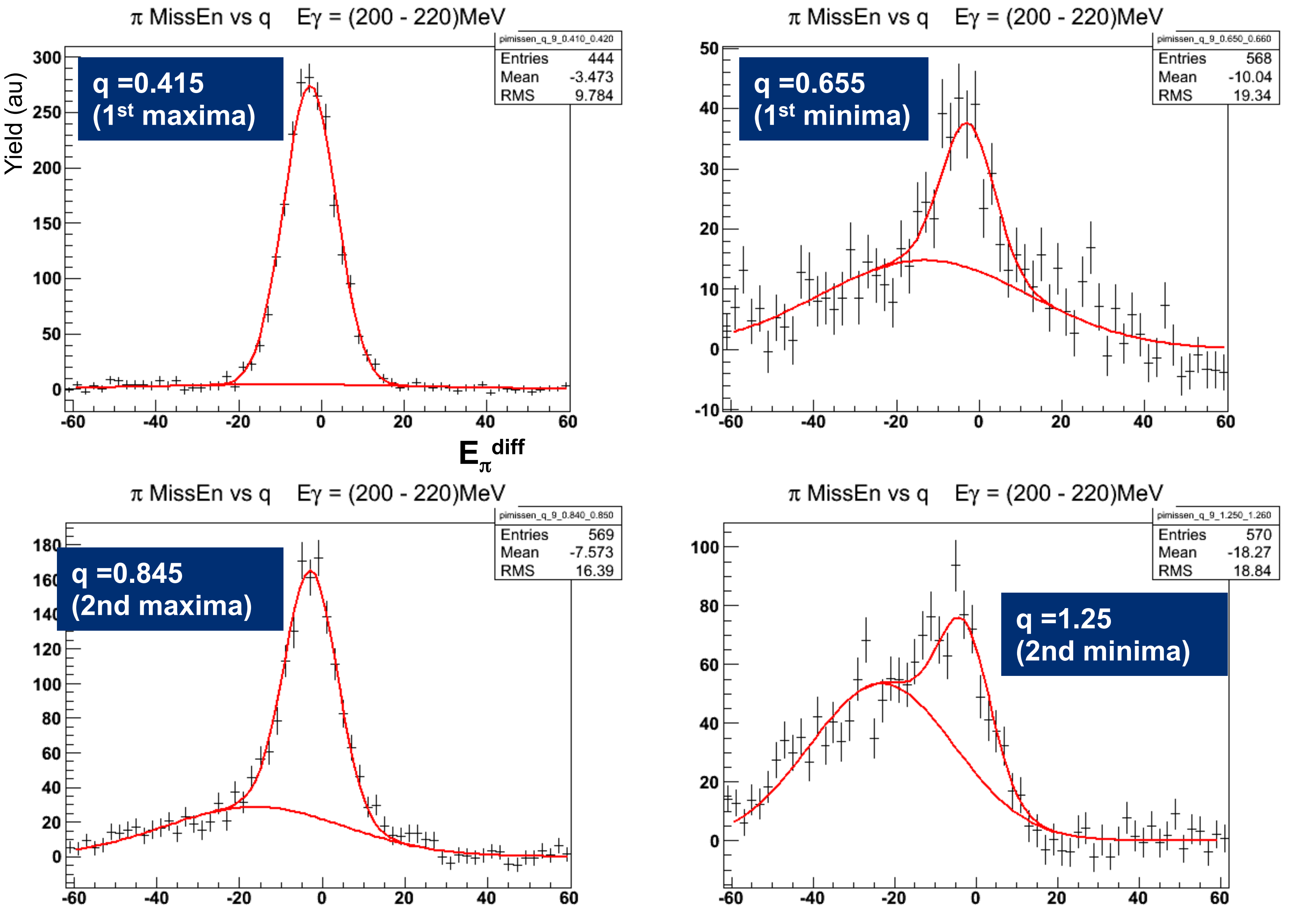
Coherent pion photoproduction - analysis

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

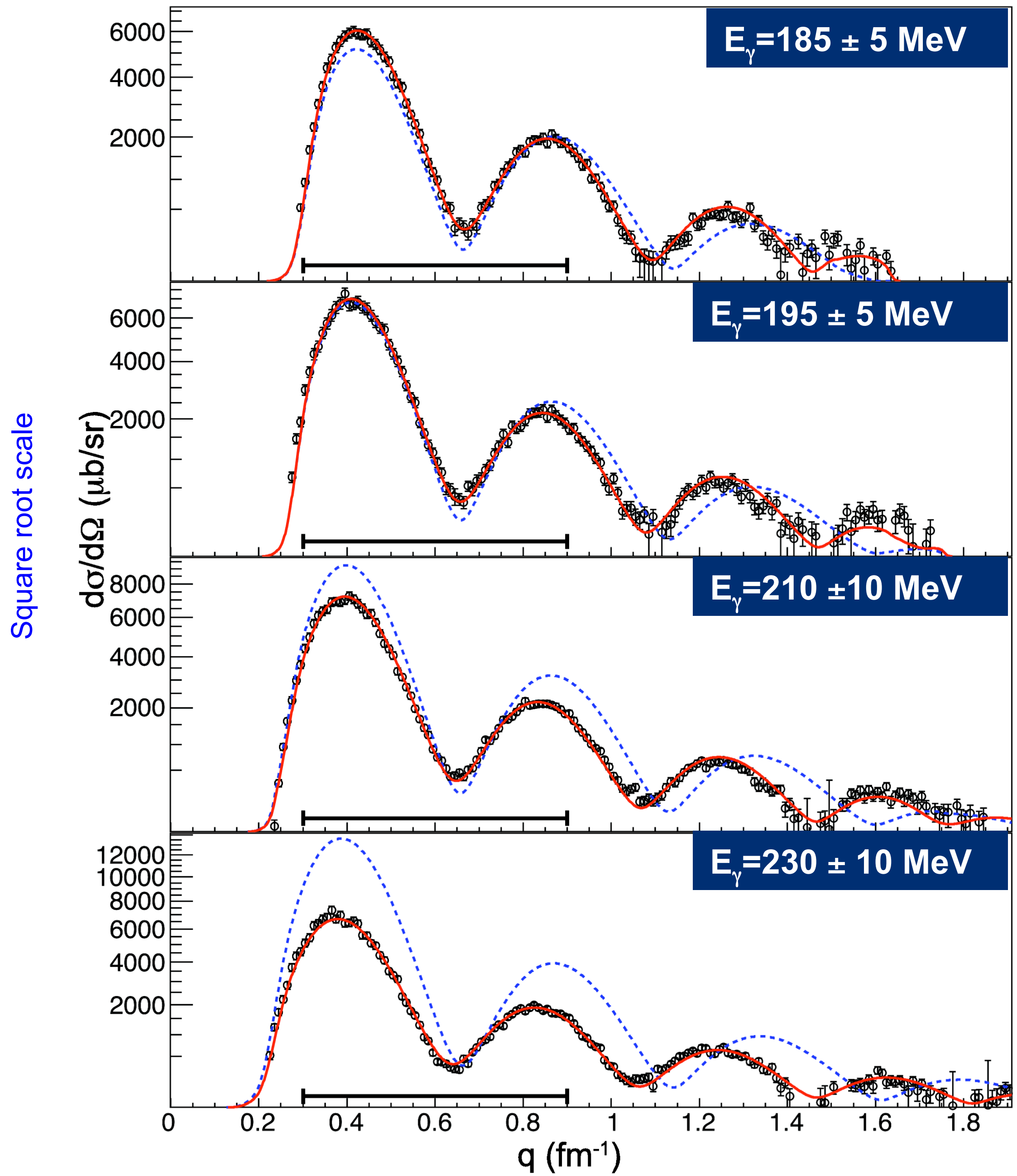




Extraction of coherent yield : E_γ=210±10 MeV



Momentum transfer distributions



-- PWIA calculation

− Full calculation

Drechsel, Kamalov, Tiator et. al. NPA 660 (1999)

Fitting procedure

Calculate grid c_n=6.28-7.07 fm

a_n=0.35-0.65 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

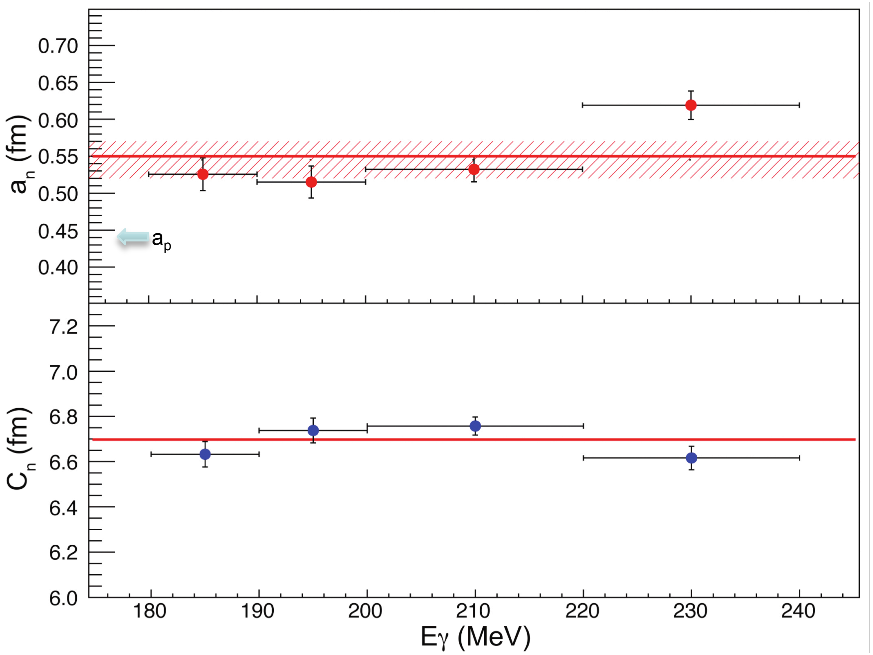
(PRC 76 014211 (2011))

Low E_γ limit: Δ dominates, model valid

High E_γ limit: π FSI not too large

(*p*-wave interactions set in)

The extracted skin properties



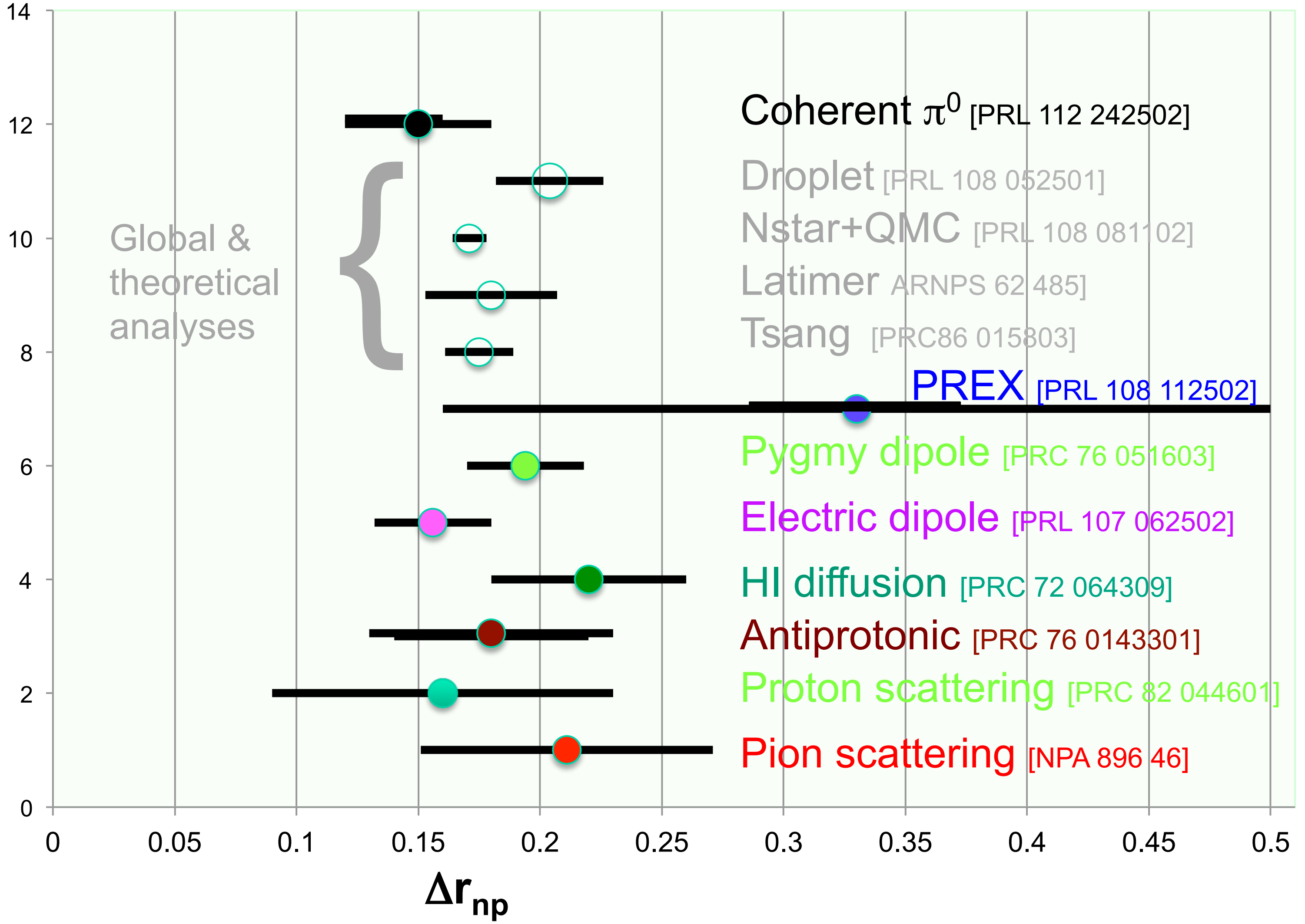
$$a_n = 0.55 \pm 0.01(stat.)^{+0.02}_{-0.03}(sys.)$$

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

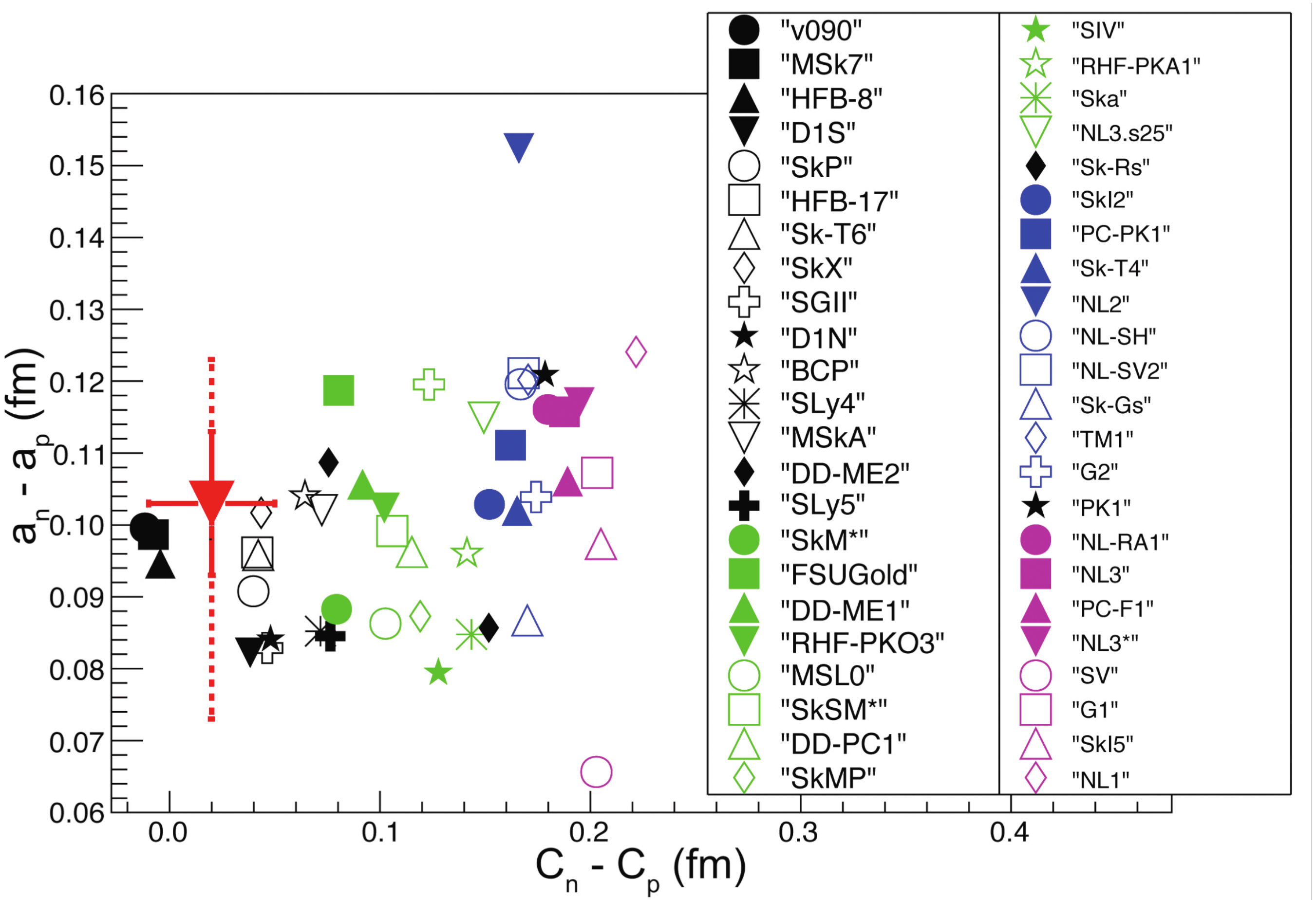
$$\Delta r_{np} = 0.15 \pm 0.03(stat.)^{+0.01}_{-0.03}(sys.)$$

- π absorption FSI increases rapidly in last bin – diffuseness is sensitive to heights of maxima.
- Evaluate diffuseness with and without the high bin to estimate error

Comparison with previous measurements



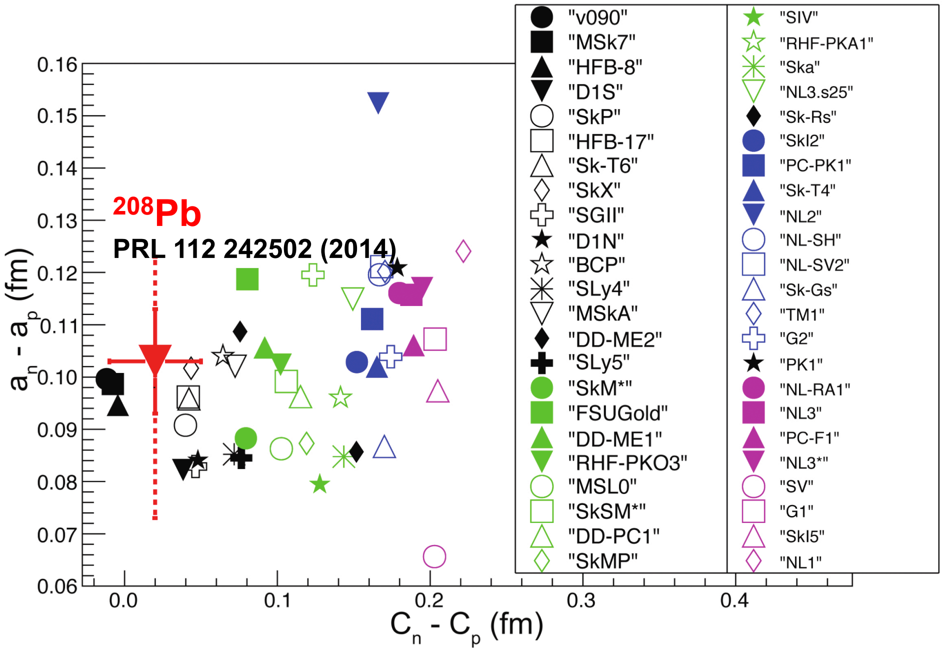
^{208}Pb Comparison with theory

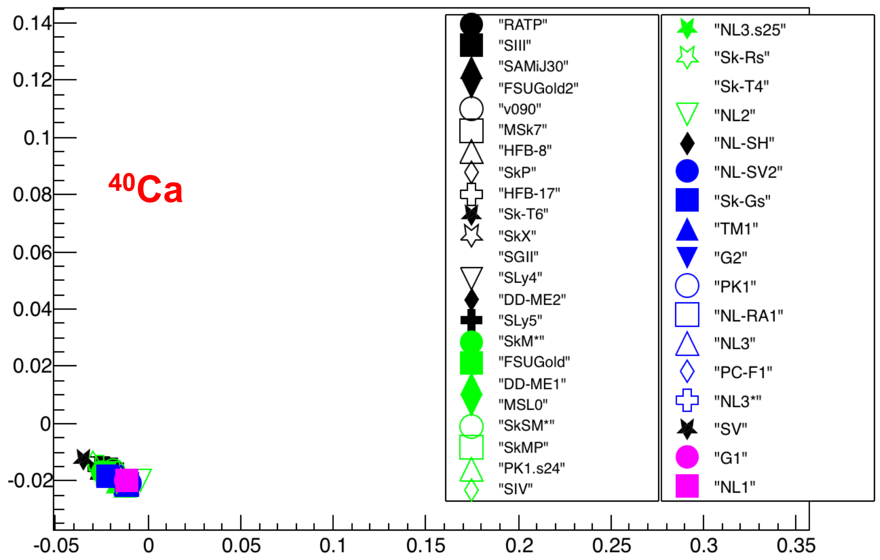


PRL 112 242502 (2014)

^{40}Ca – a well known nucleus

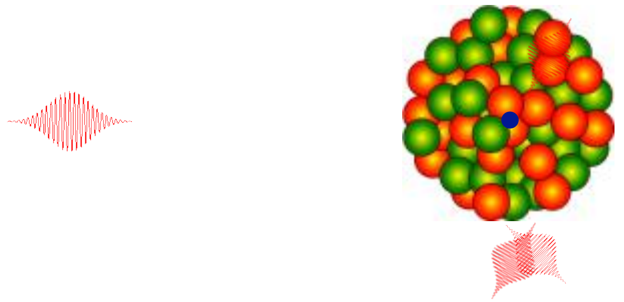
- ^{40}Ca shows agreement between theories – symmetric nucleus
  - A good test of any method for extracting neutron skins
- All theories predict a **negative** neutron skin



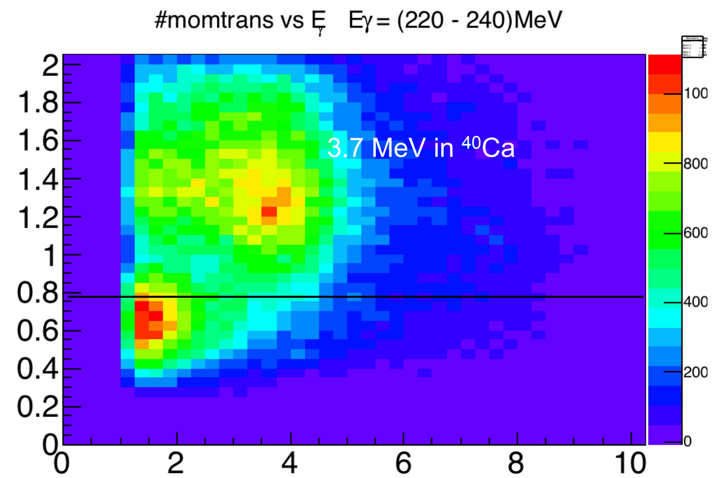


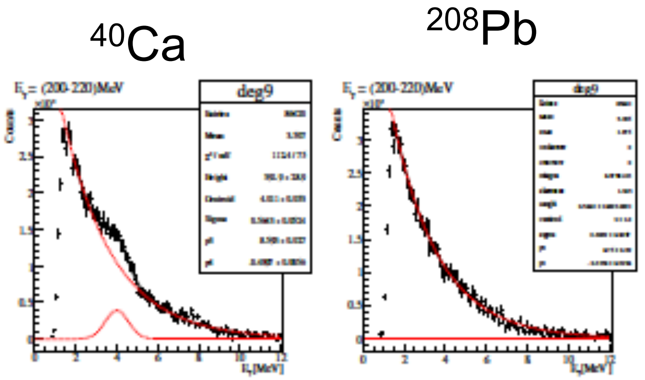
$^{40}Ca(\gamma,\pi^0)^{40}Ca$ – Unpicking the coherent contribution

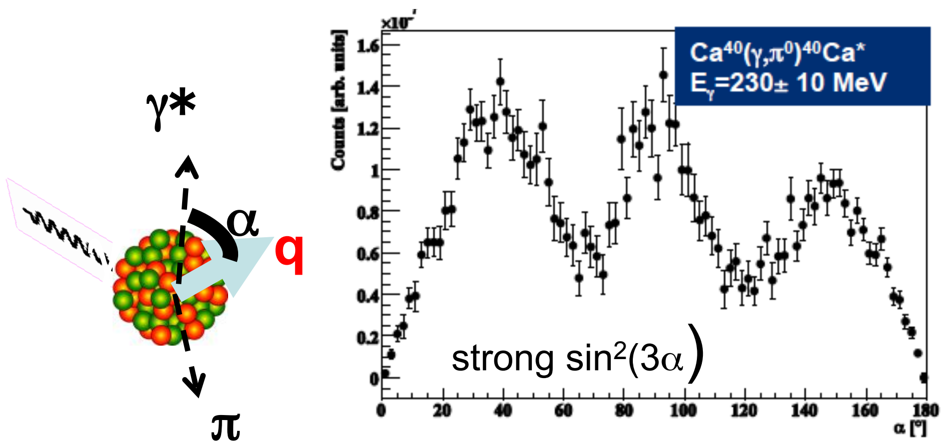
Low energy **nuclear** decay photon !



Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay

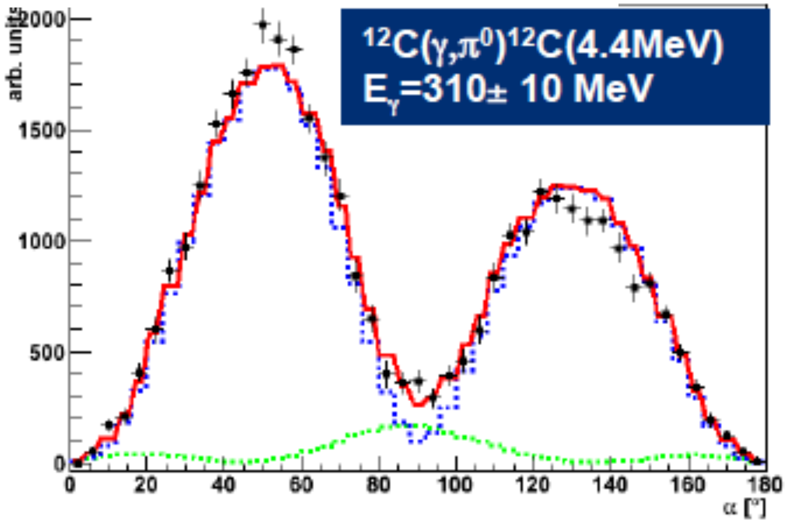






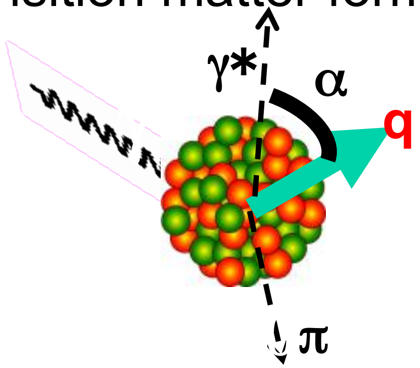
Gamma-ray spectroscopy with the CB

PRL 100, 132301 (2008)



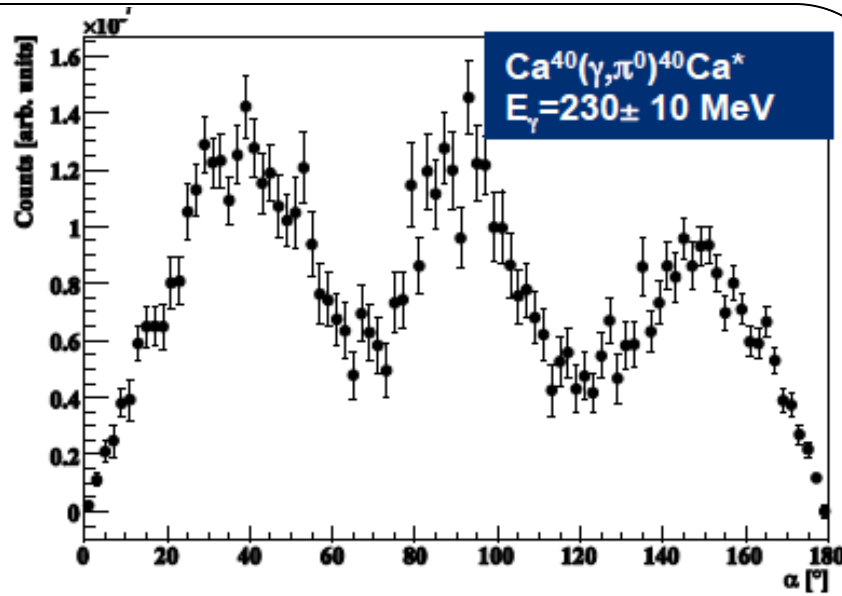
- $\sin^2(2\alpha)$ – dominant 2^+ to 0^+;

-> information on
transition matter form factor



^{40}Ca: Fit to 3.7 MeV gaussian

Determination/subtraction of inelastic contribution may be possible ?
-> work in progress

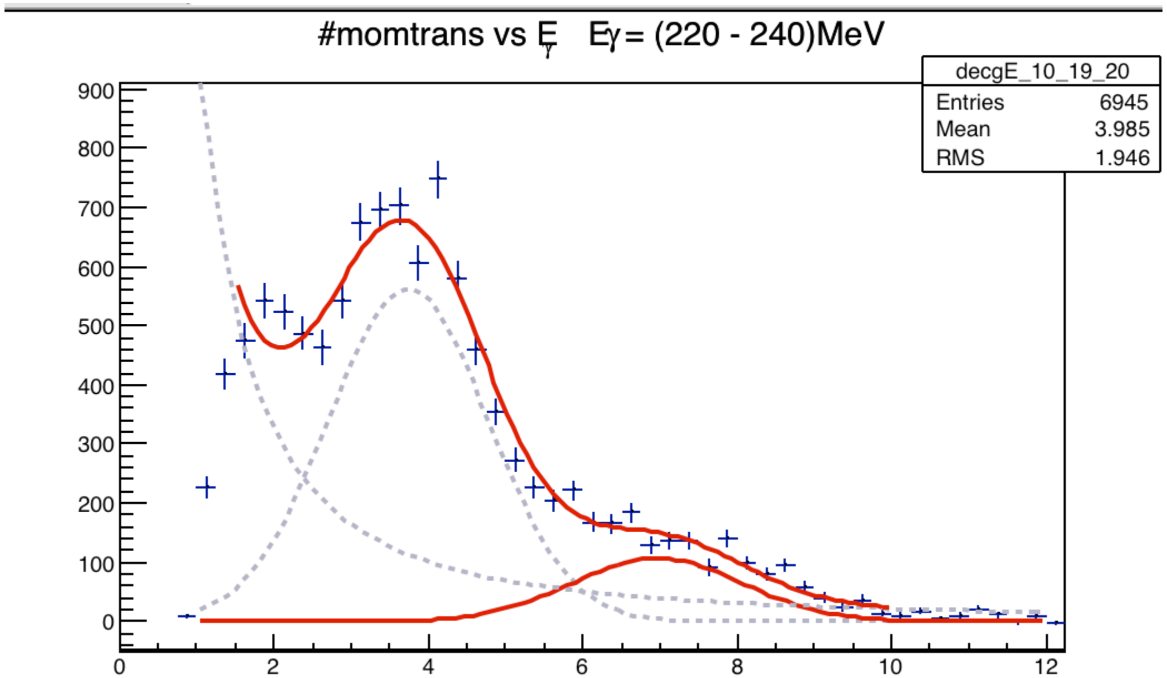


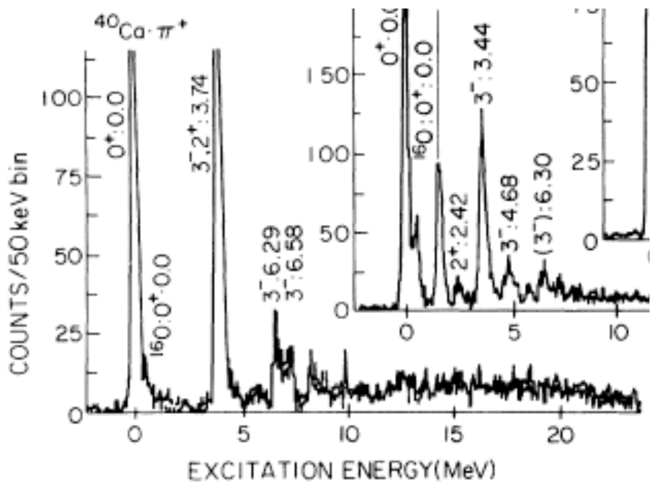
^{40}Ca(γ,π^0)^{40}Ca – Unpicking the coherent contribution

- Fit nuclear decay photon spectrum with
  - Exponential background (split off photons from π^0)
  - Gaussian at 3.7 MeV
  - Gaussian at 7 MeV

- Use to guide missing energy fits?
- Subtract off inelastic before fitting?

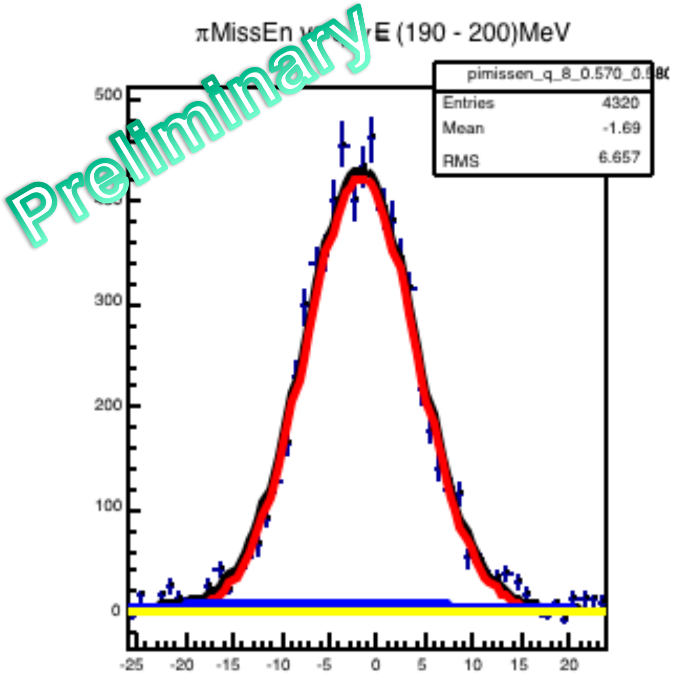
} Work in progress



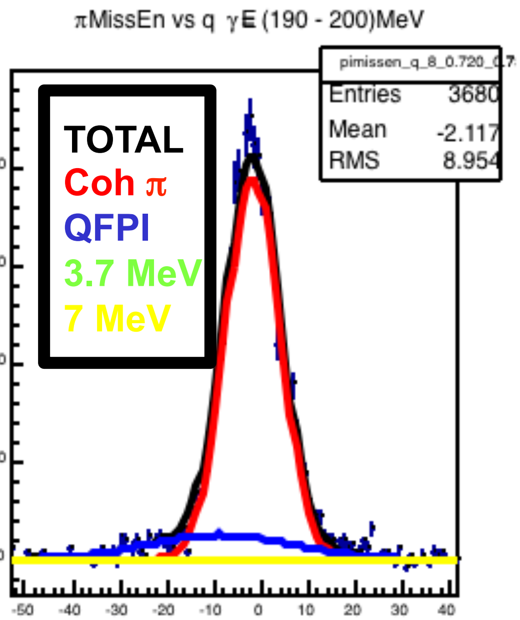


$^{40}Ca(\gamma,\pi^0)^{40}Ca$ – Missing energy fits

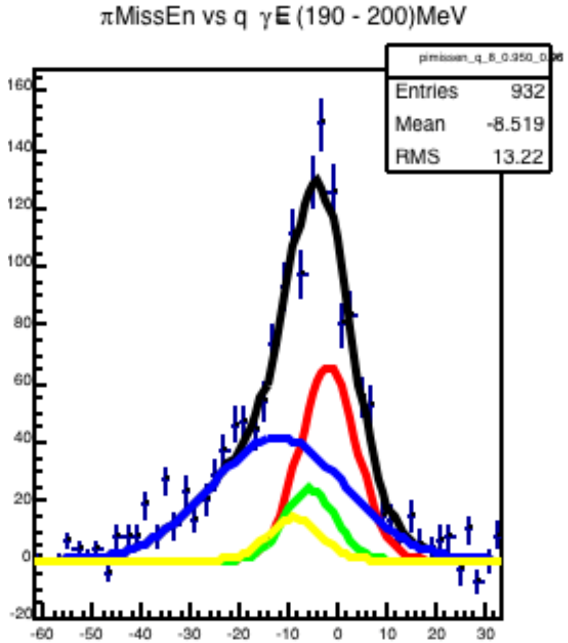
- First simple approximation – fit additional gaussians at 3.7 and 7 MeV
- Width of gaussians same as coherent signal



Fit near coherent maxima
-> Dominated by coherent

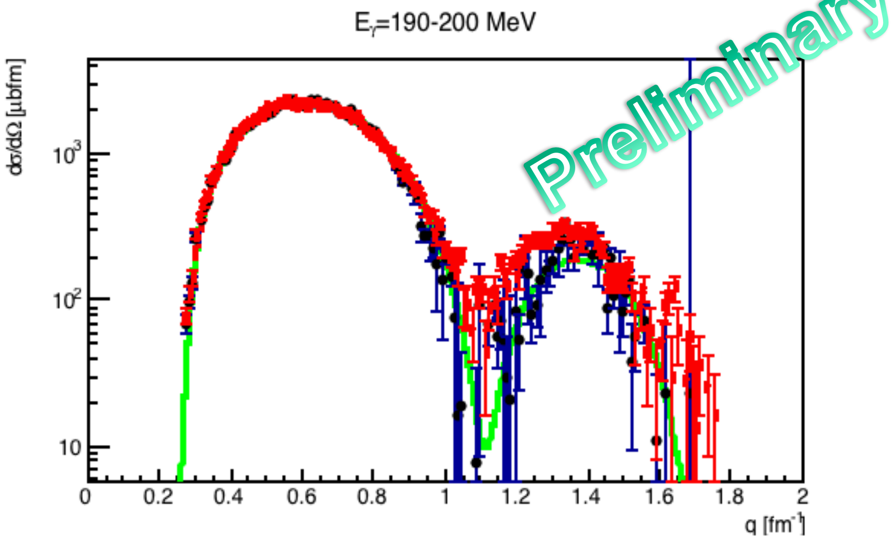


Fit at $q=0.8\ fm^{-1}$
-> small QFPI background



Fit at larger q
-> more significant
inelastic contributions

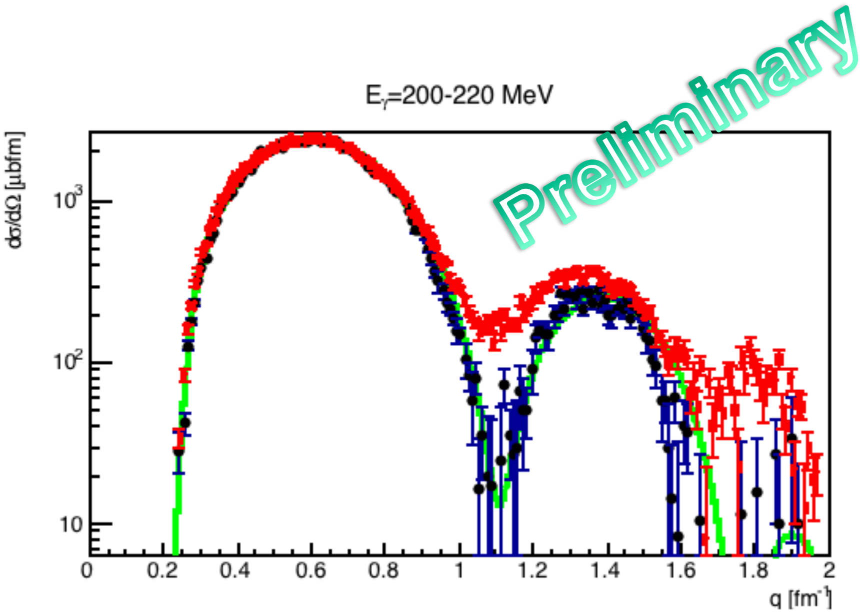
$^{40}Ca(\gamma,\pi^0)^{40}Ca$ – Example Fits to extract skin

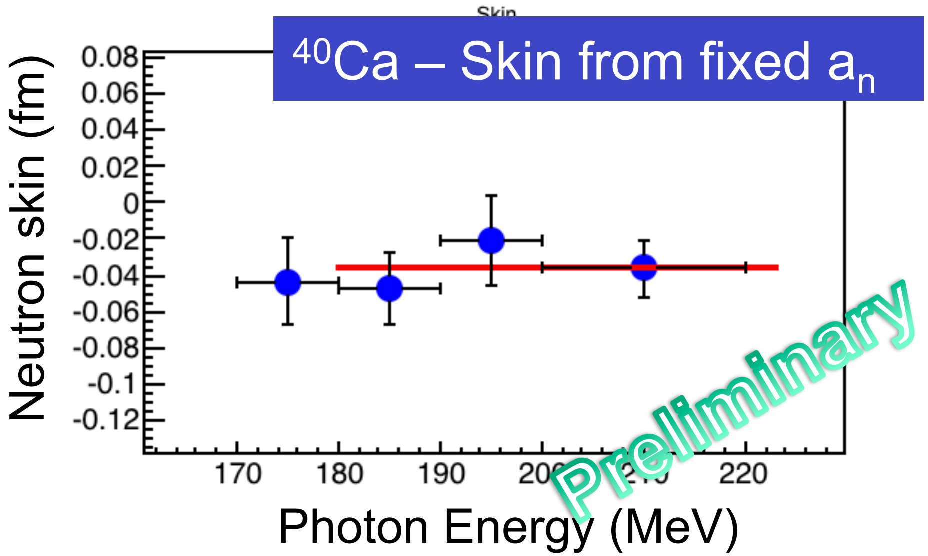


- COH + QFPI
- COH+QFPI + 3⁻(3.74) + 7MeV

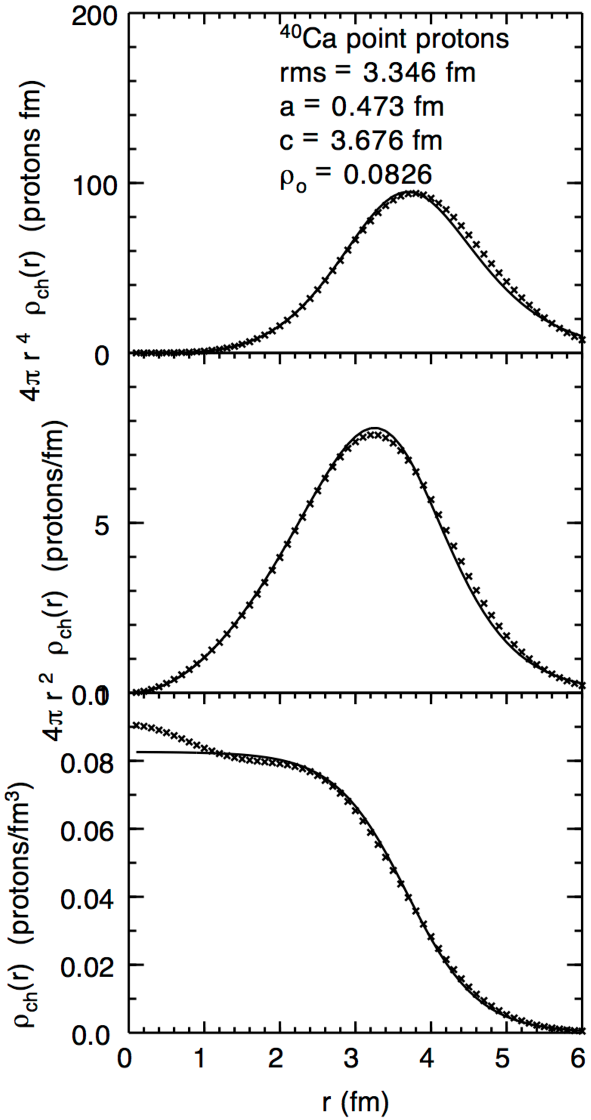
— Fit to data (q<0.7 fm⁻¹only)

c_p = 3.676 fm a_p=0.473fm (Brown, MSU)
a_n=0.453 (from theory))





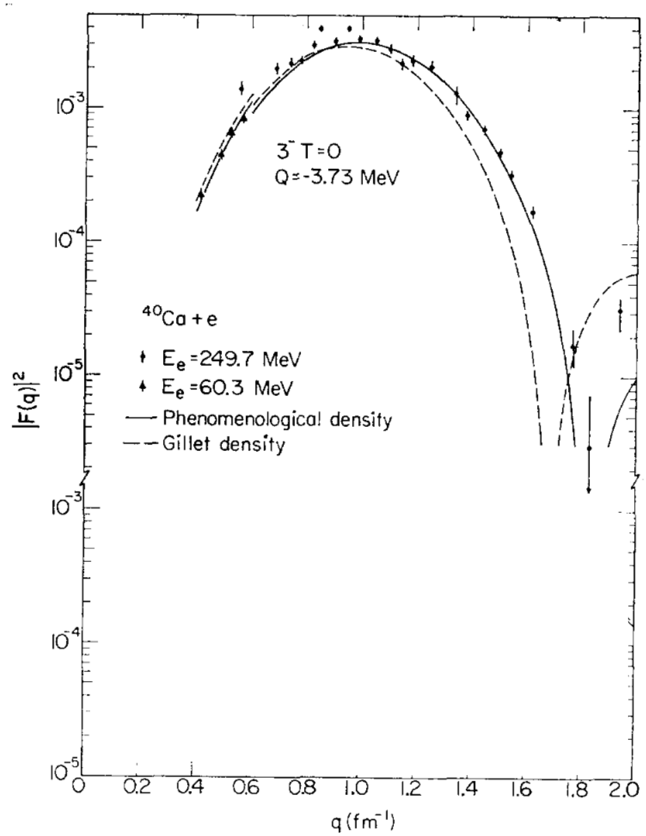
Point charge distribution



Extraction carried out by Alex Brown (MSU)

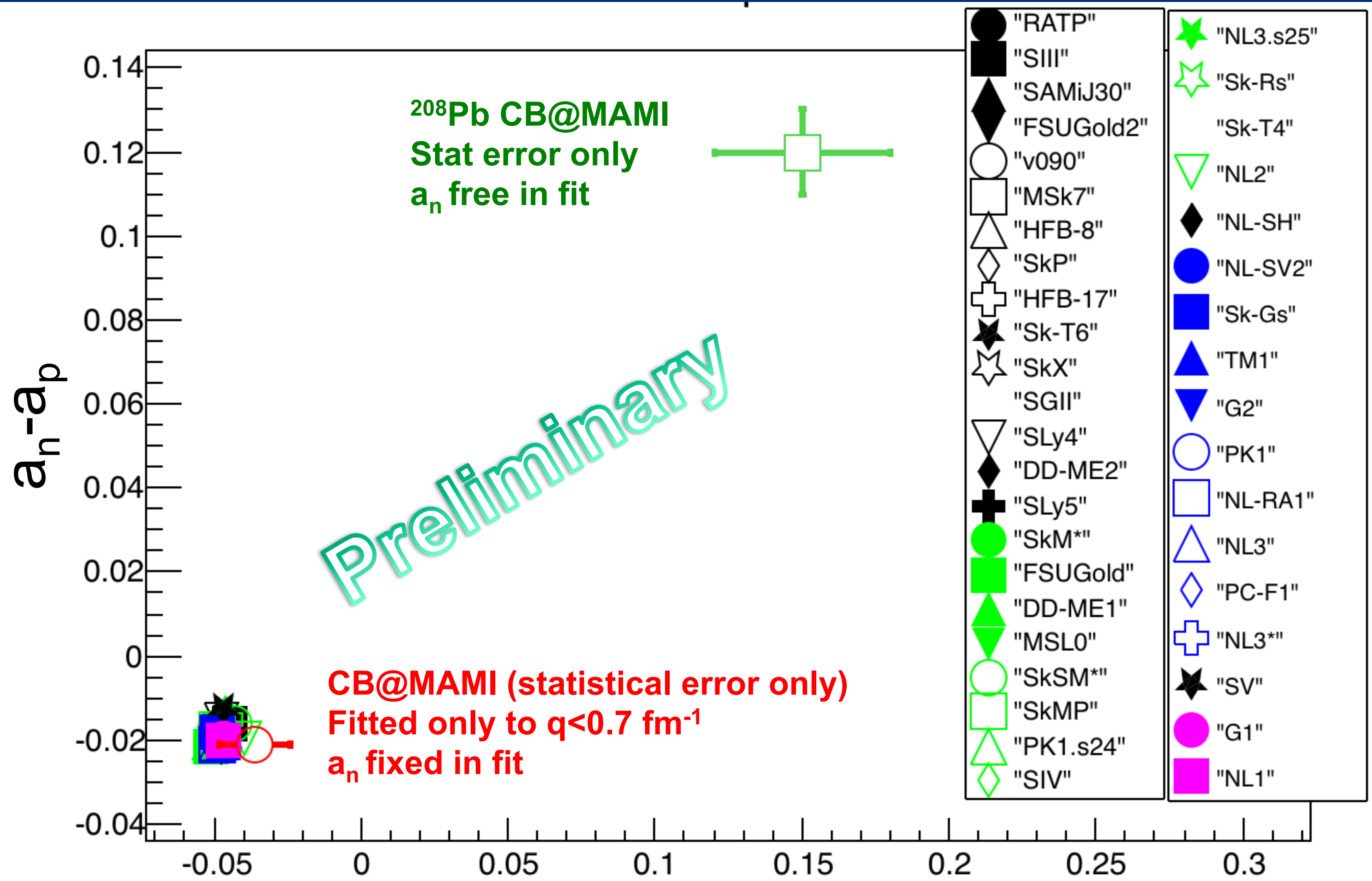
Transition form factor to 3- state

e, p SCATTERING 51



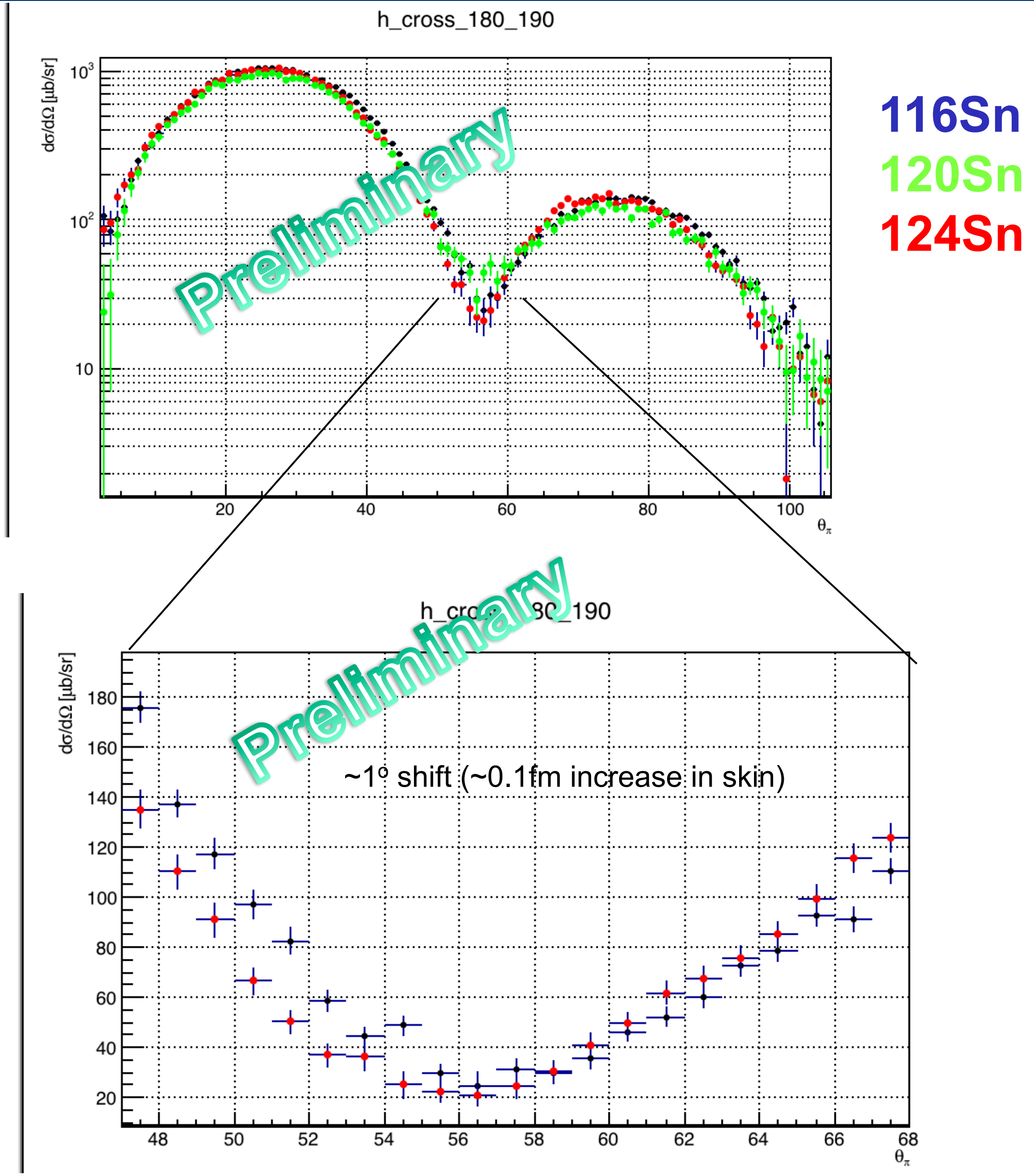
g. 1. Electron scattering form factor for 3^- $T = 0$ ($Q = -3.73$ MeV) and 5^- $T = 0$ ($Q = -4.48$ MeV) levels in ^{40}Ca.

Comparison of ^{40}Ca skin with theory



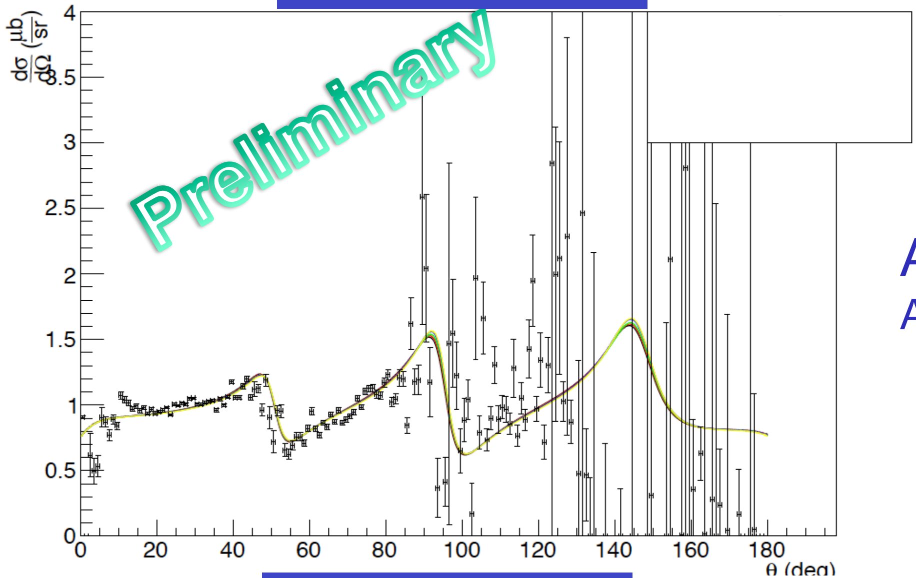
- Ab initio calculations for ^{40}Ca(Hagen) Δr_{np} = -0.0400 to -0.0461 fm

Tin isotopes: Preliminary cross sections



Tin isotopes: Cross section ratios $^{124}Sn/^{116}Sn$

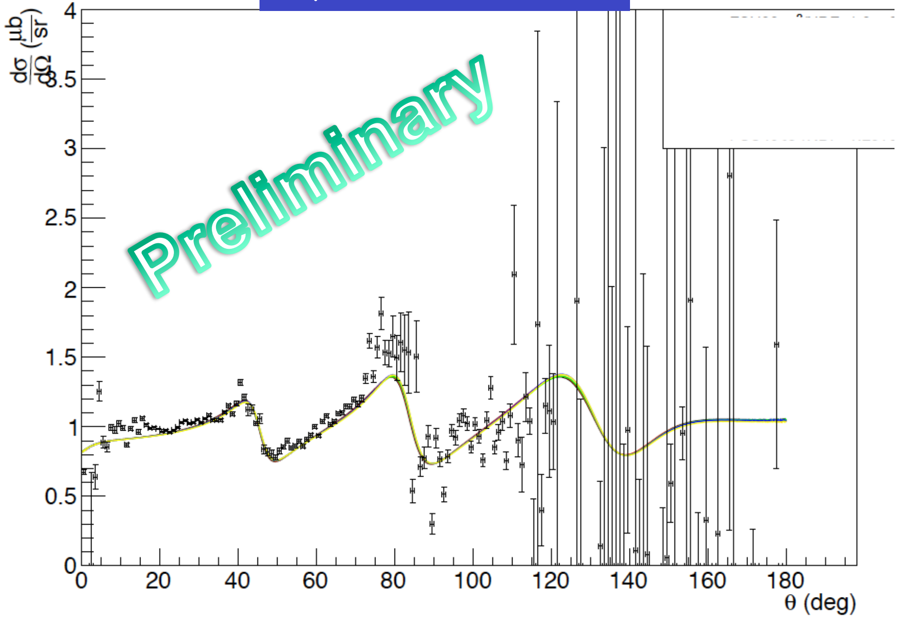
Eγ=180-190 MeV



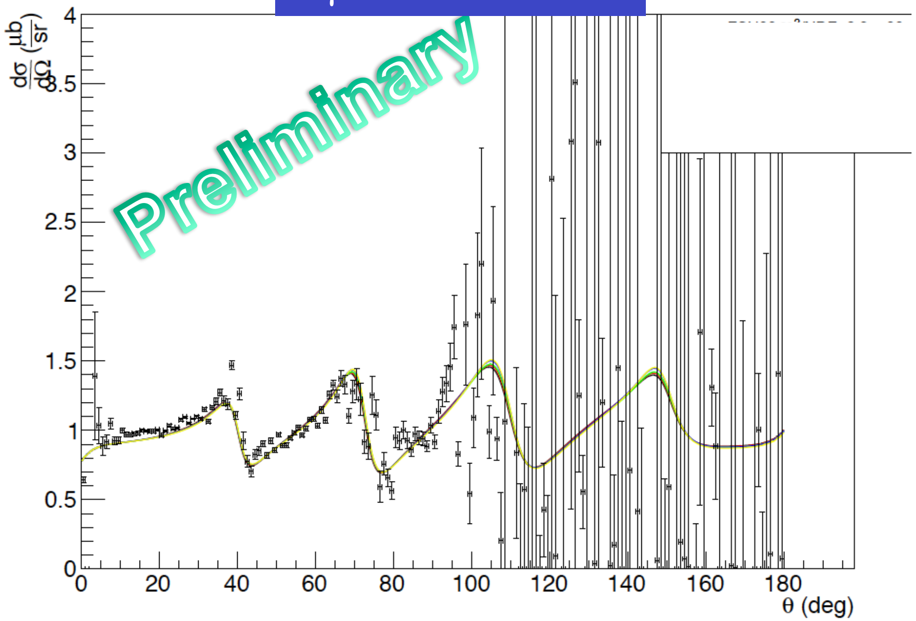
Analysis of D. Glowa (Edinburgh)

Also Parallel analysis by Ferretti (Mainz)

Eγ=190-200 MeV



Eγ=200-220 MeV

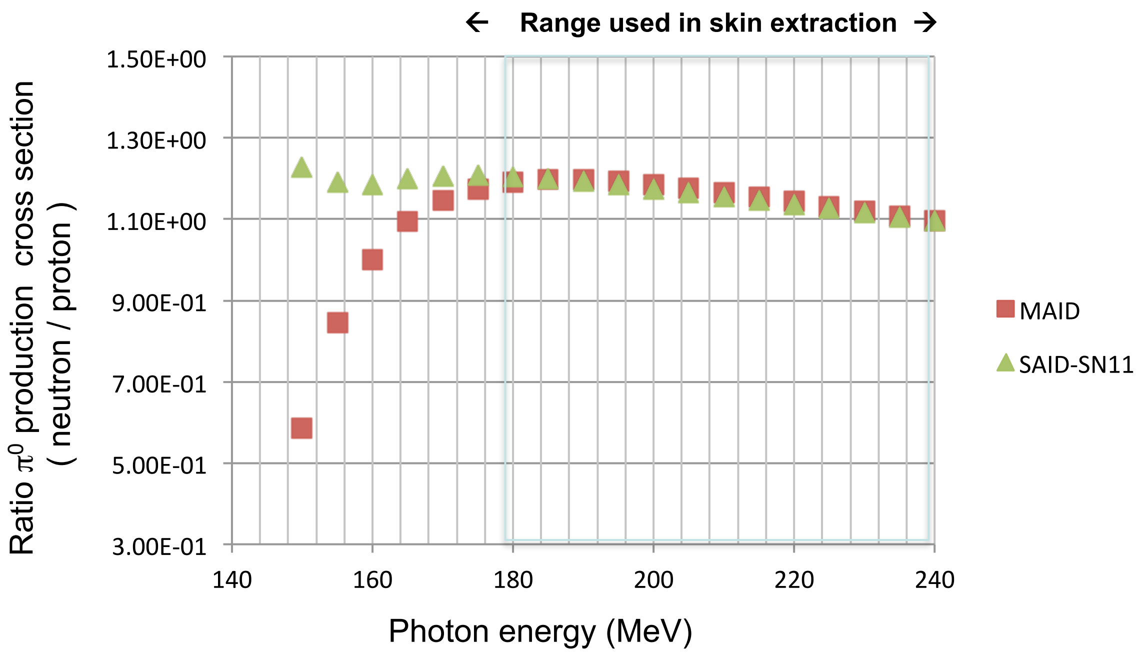


Discussion of potential systematics

Systematics: Photocoupling

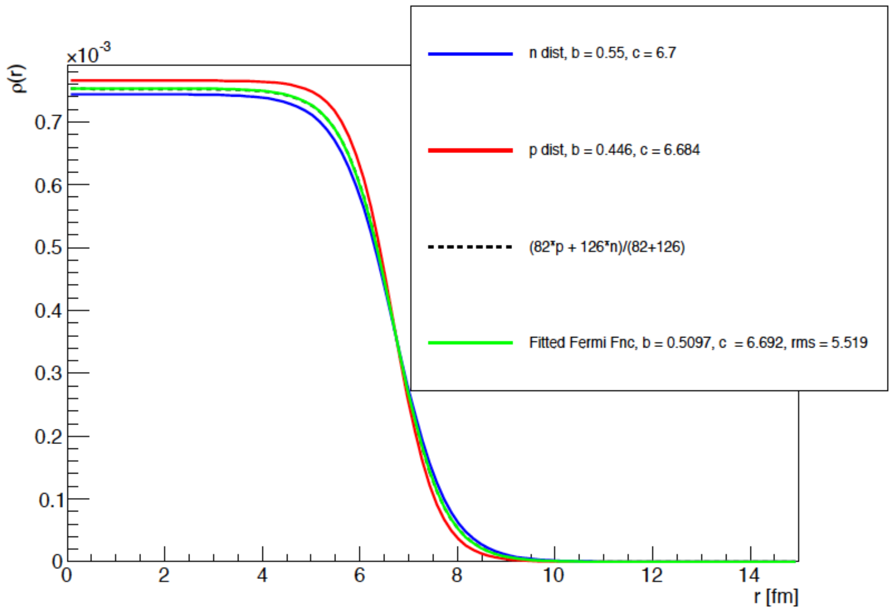
Pion photoproduction amplitude:

Where the Δ dominates - various PWA of meson photoproduction data agree



Maximum variation between PWA models ~5% in fitted region

10% change in weighting of amplitudes



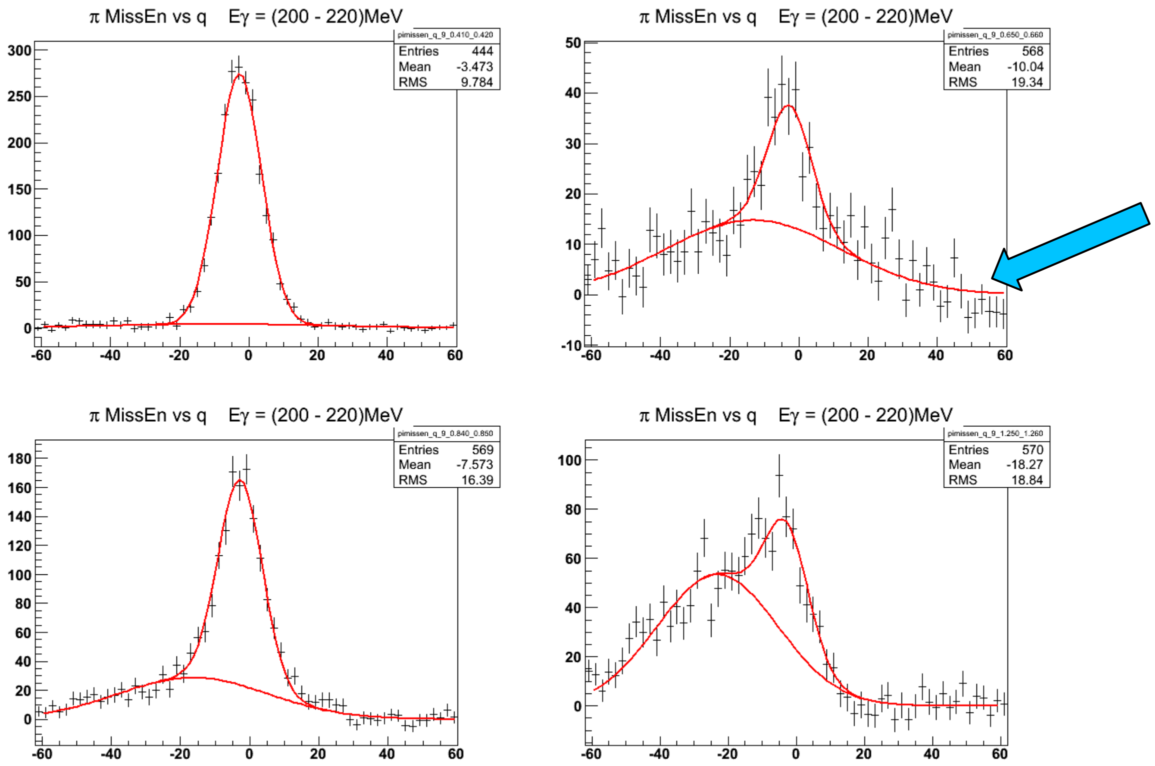
Estimate systematic effect of
+-5% error in relative pn coupling

Give different weighting to
proton/neutron distribution
→ Refit with 2PF

Only significantly affects diffuseness

$\Delta c \sim 0.02$ fm

Extraction of coherent yield : E_γ=210±10 MeV



$$\Delta E_\pi^{\text{diff.}} = E_\pi^{c.m.} - E_\pi^{\text{det}}.$$

Width of coherent peak independent of q

Peak properties well established from data near the coherent maximum

Investigated effect of using different background functions (polynomials of different order)

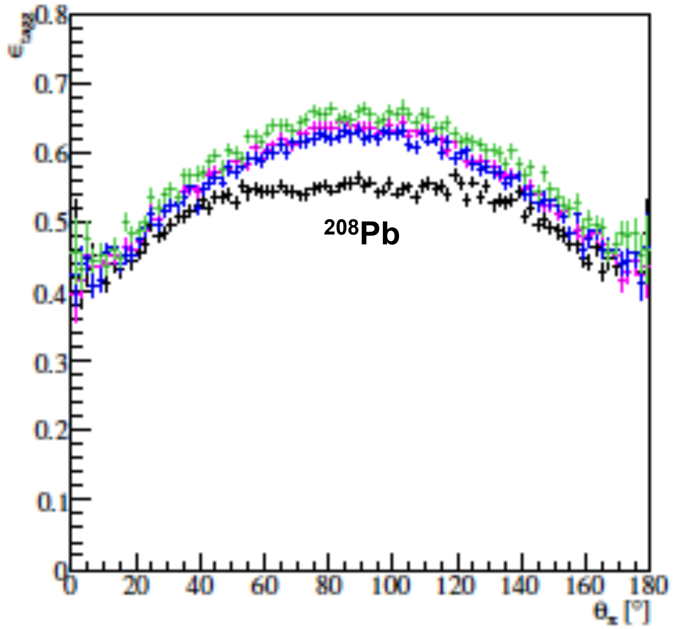
small effects on 2nd maxima height -> affect extracted diffuseness

Δc=0.01 fm

$E_\pi^{c.m.}$ – energy of pion in cm frame of photon and nucleus at rest calculated using photon energy and assuming coherent production

E_π^{det} – detected pion energy in c.m. frame

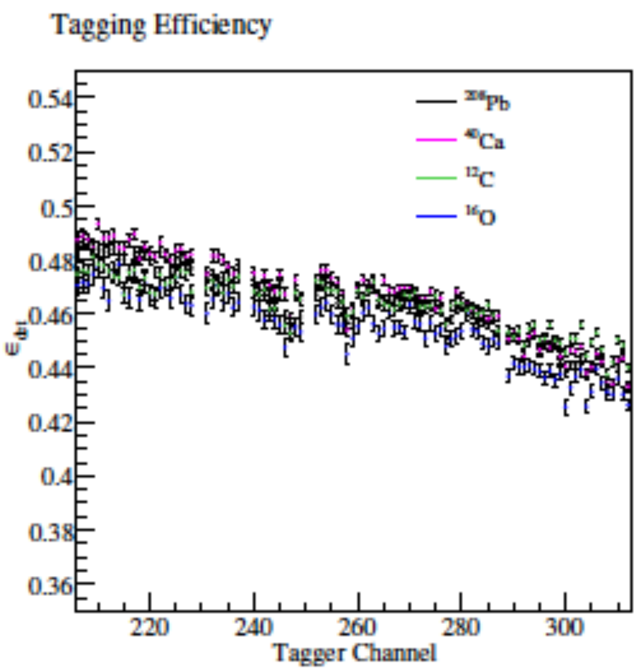
Pion detection efficiency



- The π^0 detection efficiency varies from ~42-52% over the fitted region
- Mainz π^0 data gives good agreement with previous measurements
- The fit of the theory to the data only uses the shape of the distribution - includes an overall normalisation of model to data
- From the fits this varies by +-5%
- Can get estimate of any residual systematics from comparison of neutron skin using minima alone (very restricted q,θ_π range) with full form factor

Tagging efficiency

- Tagging efficiency: Probability that an e^- hit in tagger FP ➔ γ @ target
- Measured in dedicated runs using a Pb glass detector ε_γ ~100%
- Varies from ~0.44 to 0.48 over full range of tagger
- ➔ Skin extraction in small Eγ bins & overall normalisation allowed in the fit



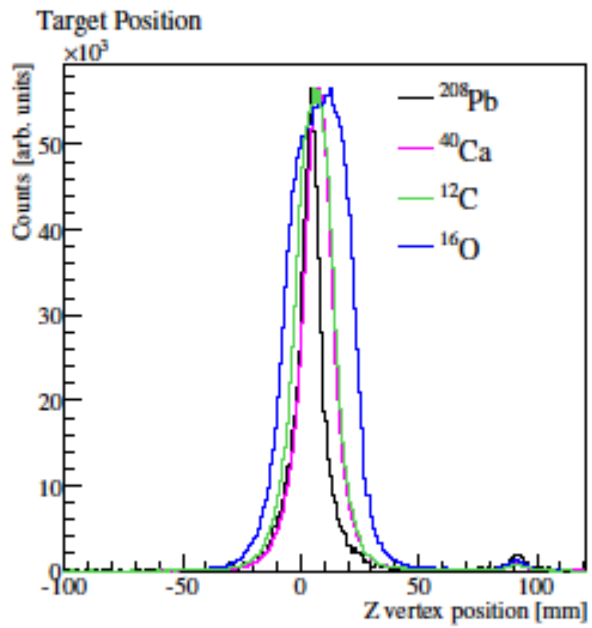
Target density

- Target thickness measured to accuracy of ~2%
- Systematic error would produce an overall normalisation in the measured cross sections
- Accounted for by allowing an overall normalisation in the fit of theory to data

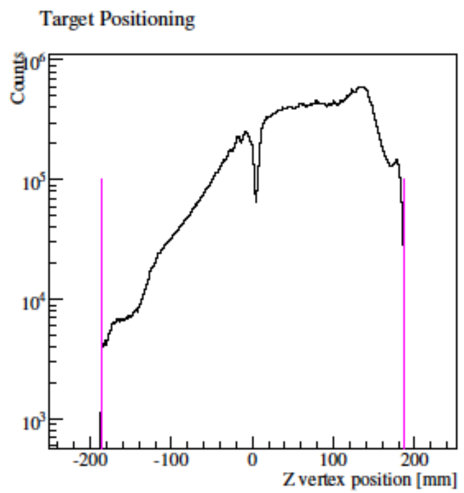
target	Thickness	Atomic mass	surface density
^{208}Pb >99.8% (Isoflex)	0.52±0.01 mm	207.977	0.8369 g/cm^2

Target position & pion angle

- $\theta_{\pi 0}$ - weak sensitivity to changes in target position (centroid of photon shower at ~40 cm)
- **1cm** shift in target -> **1° in** $\theta_{\pi 0}$ **-> 0.1fm** in Δr_{np}
- Target position (MWPC) <~1/2mm
  $\delta(\Delta r_{np})$<~0.005fm



- **Systematic checks**
  MWPC mounted centrally relative to ref. points on CB
  Charged particle data:
  Correlation of θ_{CB} and θ_{MWPC}
  Symmetry of MWPC z intercept around z=0 for CB hits
  No stat. significant shift in E_{miss} or Δr_{np} with $\theta_{\pi 0}$ / q
  Lighter A: known skin, same apparatus/procedure.



(a) MWPC intersection point for charg
particles detected in the CB.

- $\theta_{\pi 0}$(G4) – $\theta_{\pi 0}$(gen): average consistent with zero over fitted range (ptp statistics ~0.02°).

Summary of estimated systematic errors

Systematic	Estimated error
Coherent peak fitting - diff background forms	± 0.01 (diffuseness)
High E_γ bin shows 3σ variation in diffuseness	- 0.025 (diffuseness)
10% change in p,n coupling	± 0.02 (diffuseness)
π^0 Detection efficiency, tagging efficiency, target density	Free normalisation allowed in fit (agreement to +-5%)
π^0 angle reconstruction:	< ~0.005 (c_n)

- The skin is extracted via a model - systematics can be investigated by:
  → Comparing agreement between model and data in the fitted and unfitted regions
  → Restricting the q range for the skin extraction (e.g minima only, high q only)
  → Analysis on lighter targets where the skin is known (theoretically at least!)

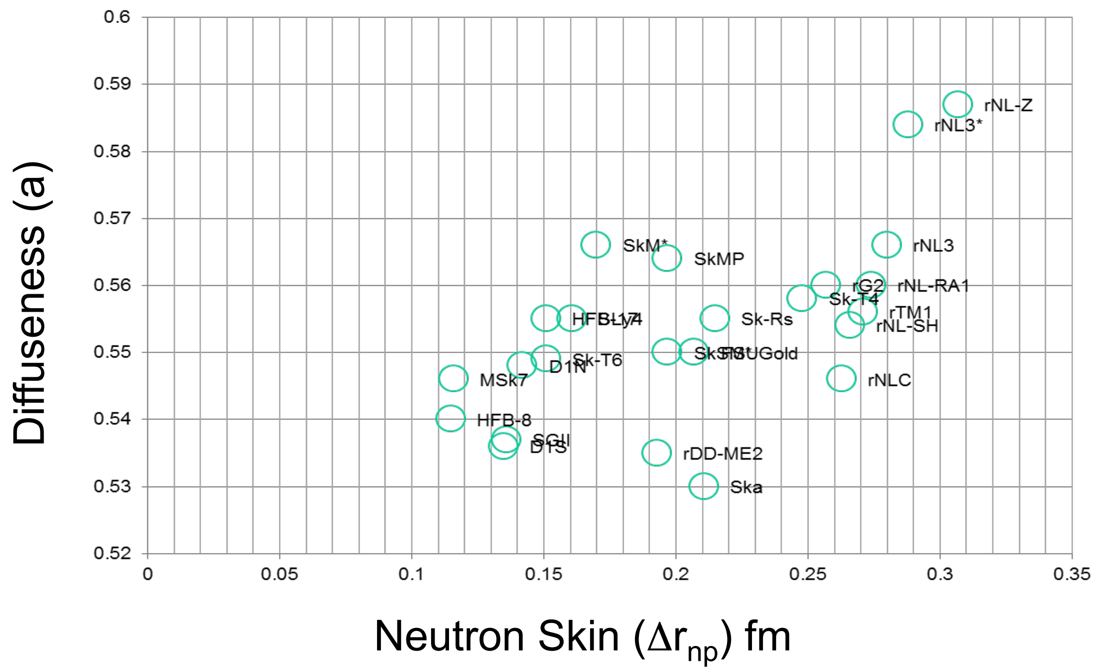
Exploring systematics: First minima fits

- The full fit has sensitivity to the half radii **and** diffuseness

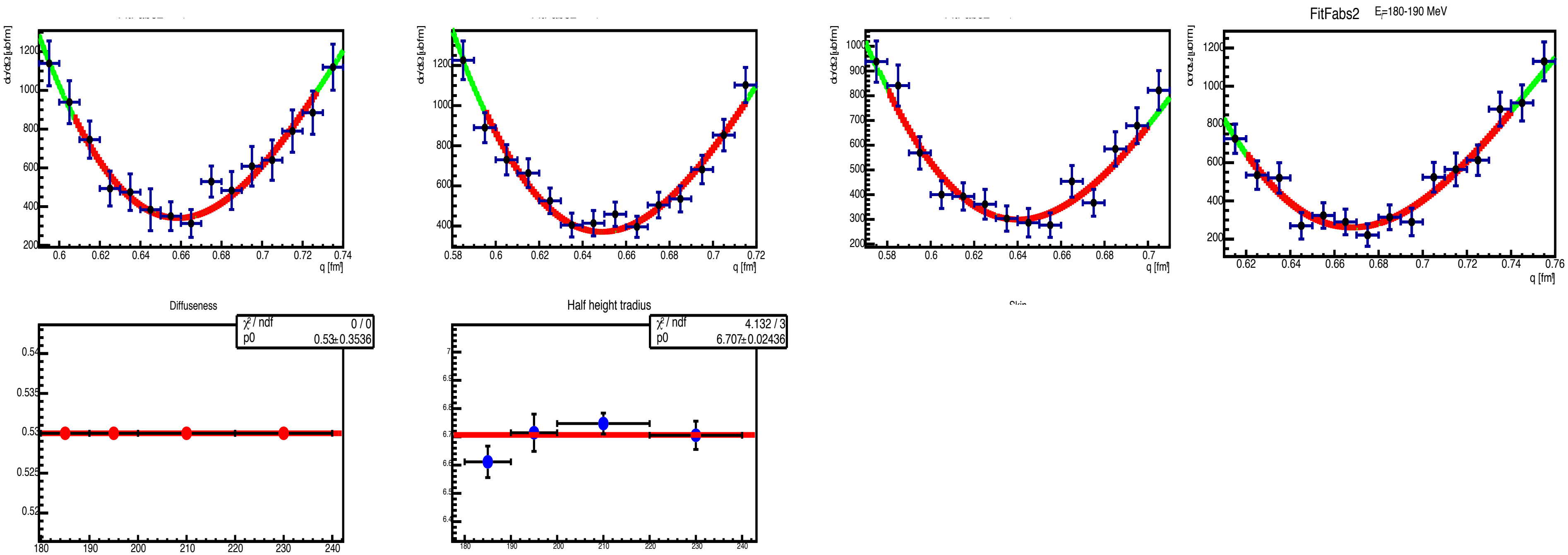
- Fitting minima alone gives sensitivity to the radius only

  ▶ Therefore have to assume a diffuseness rather than extracting this from the fit to the data (take range predicted by nuclear theories)

  ▶ Less sensitivive to imaginary part of π-A optical potential (absorptive part). A good test of their treatment in the model



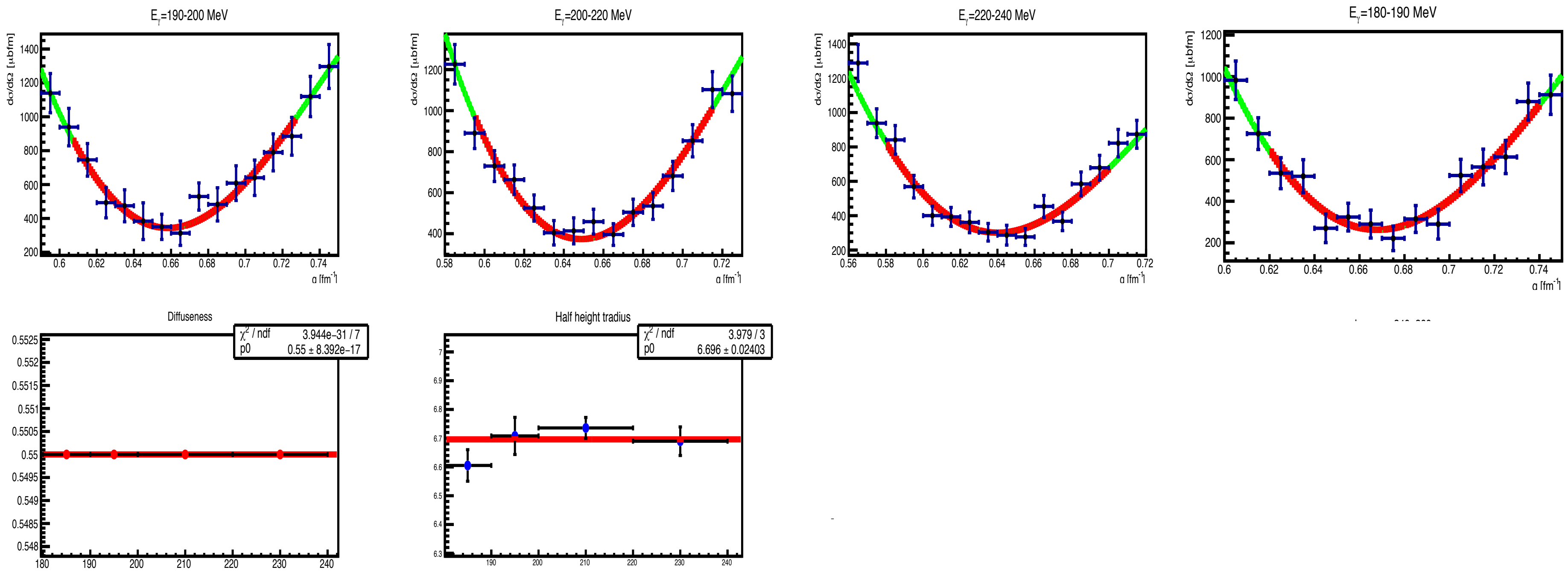
1^{st} minima fits: $a_n = 0.53$



$r_{np}(a_n=0.53) = 0.12\pm0.02(stat)$

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

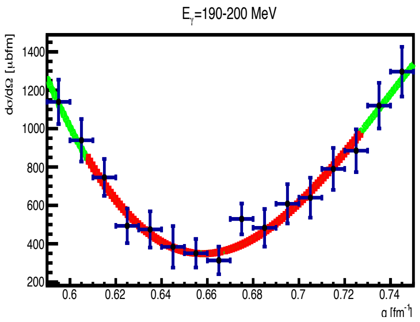
1st minima fits: $a_n = 0.55$

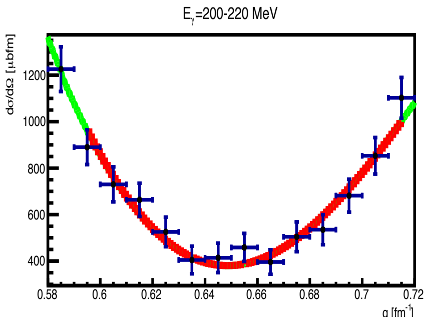


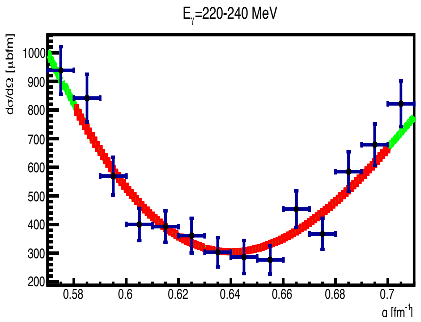
$r_{np}(a_n=0.55) = 0.14\pm0.02(\text{stat})$

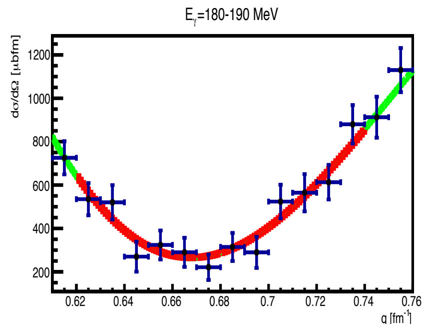
$$\Delta r_{np} = 0.15 \pm 0.03(stat.)^{+0.01}_{-0.03}(sys.)$$

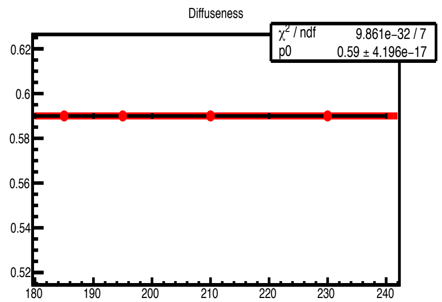
1st minima fits: $a_n = 0.59$

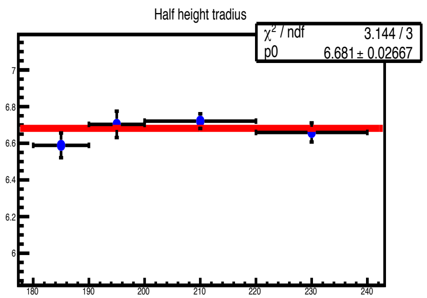








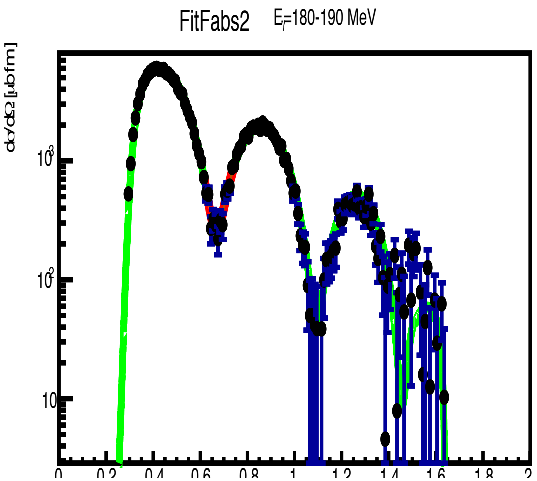


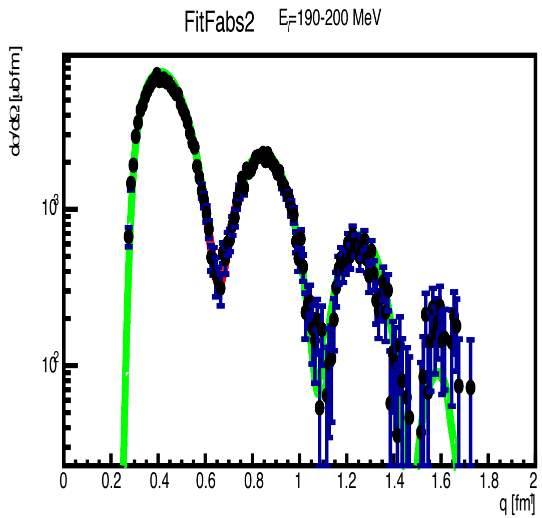


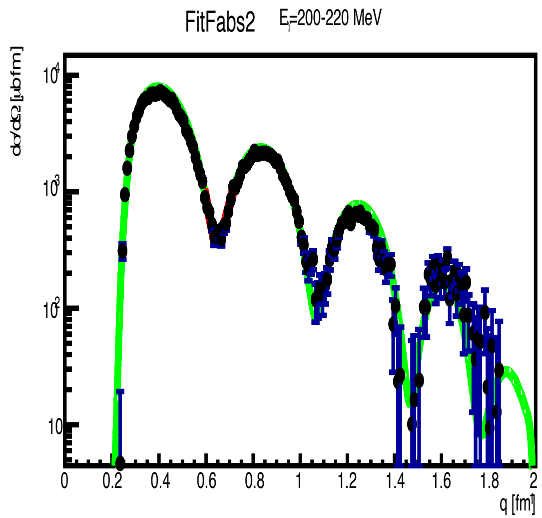
$r_{np}(a_n=0.59) = 0.18\pm0.02(\text{stat})$

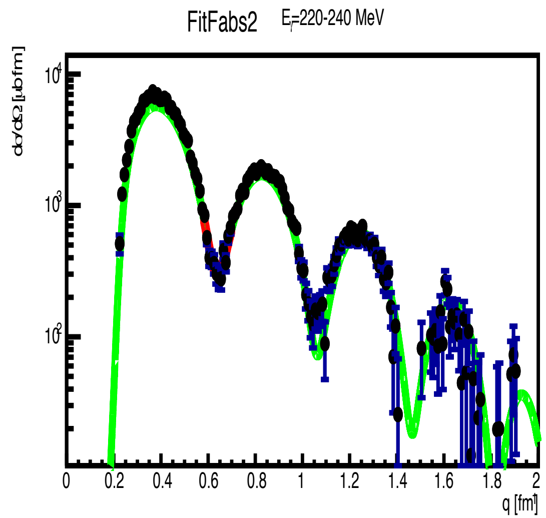
$$\Delta r_{np} = 0.15 \pm 0.03(stat.)^{+0.01}_{-0.03}(sys.)$$

Full prediction: a_n = 0.55: Fitted 1st minima only









- When fitting only in 1st minimum still get good description of rest of FF

Systematic errors: Other q ranges

r_{np}(2nd minima) = 0.18±0.02(stat)

r_{np}(Fit over 3rd minima) = 0.18±0.02(stat)

- Extracted skin shows consistency over different q ranges within statistical uncertainties
- Minima only fits - more sensitive to treatment of real part of π-A optical potential (q-shift)
- Analysis gives a constraint on magnitude of any q-dependent model uncertainties

Reproduction of features outside fitted range – 3rd maxima

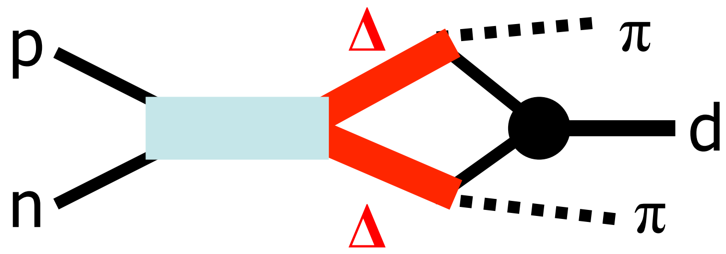
Eg bin	3rd max from model	3rd max from gauss fit to data	Shift between PWA and full model	Diff between data and model	% accuracy of shift
180	1.263	1.260	0.07	0.003	4.4%
190	1.255	1.247	0.095	0.008	8.4%
210	1.245	1.239	0.1	0.006	6.0%
230	1.245	1.231	0.125	0.014	11%

- For low E_γ bin in the first minima: shift between PWA- full model is 0.01 fm^{-1}
- This is ~OOM smaller than shift for 3rd maxima and comparable to the shift expected for a 0.1fm change in neutron skin
- Assuming same accuracy (~10%) in PWA-Full model shifts at low q
  → ~0.01 fm systematic in the skin

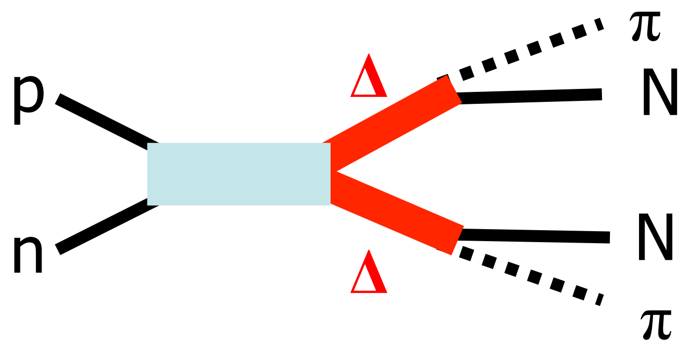
Other work at Edinburgh relevant to the EOS

Proton-neutron scattering – Recent data fro CELSIUS@WASA

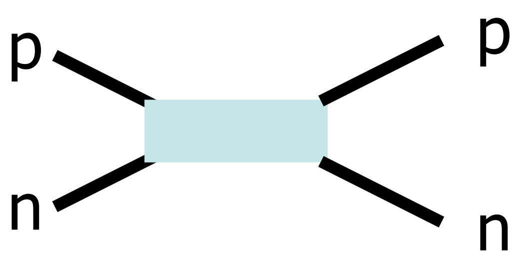
- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi\pi$



- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow NN\pi\pi$

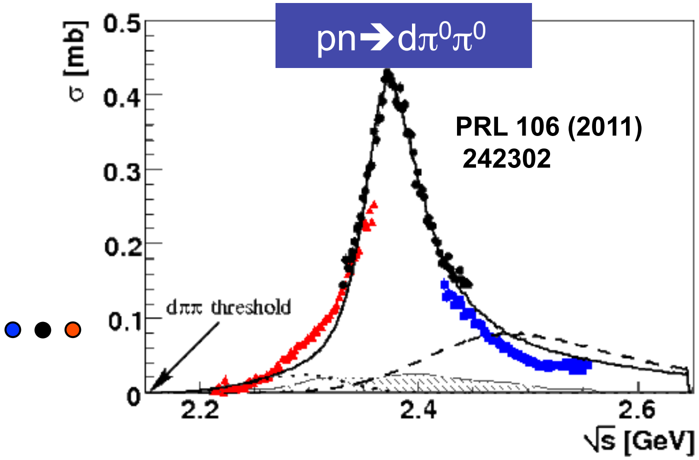


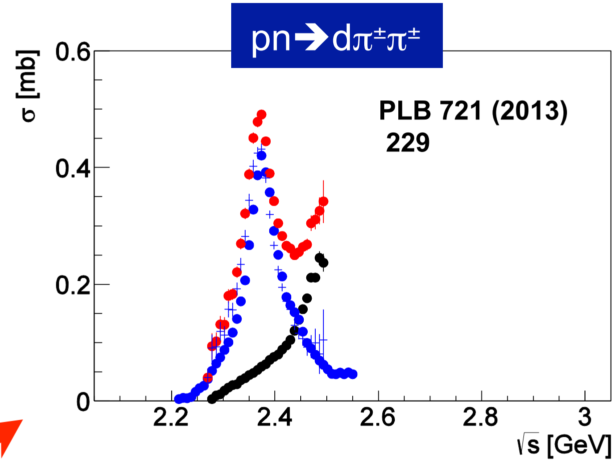
- $pn \rightarrow d^* \rightarrow pn$



M. Bashkanov (ERF Edinburgh '15) et. al.

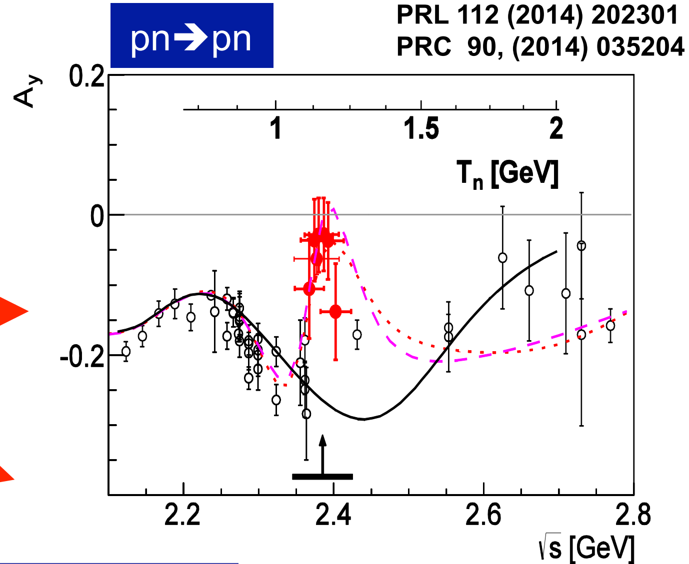
d* evidence in p-n scattering

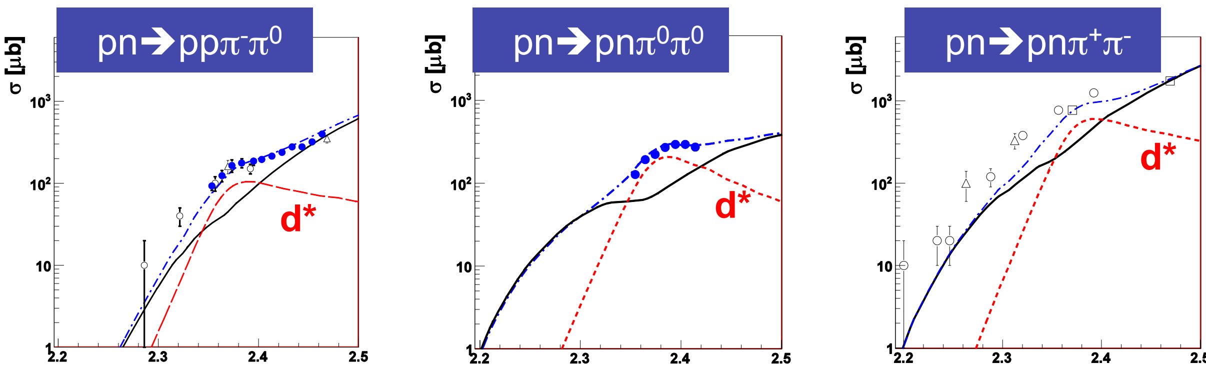




WASA data

pn → d*(2380)





PRC 88 (2013) 055208
PLB 743 (2015) 325

PWA including new polarized np data

PRL 112, 202301, (2014)
PRC 90, 035204 , (2014)

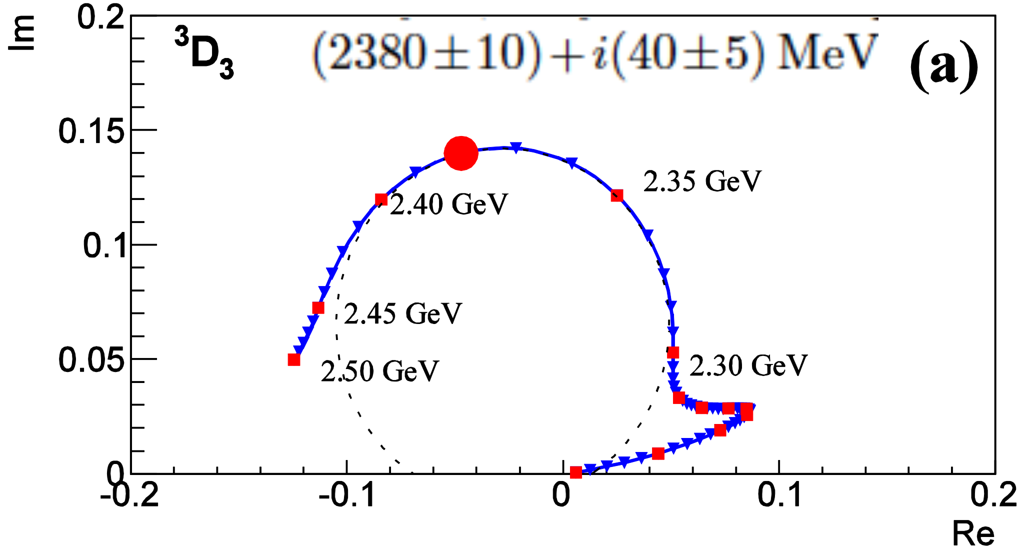
- Strong resonance signature for d* in $^3D_3$ wave

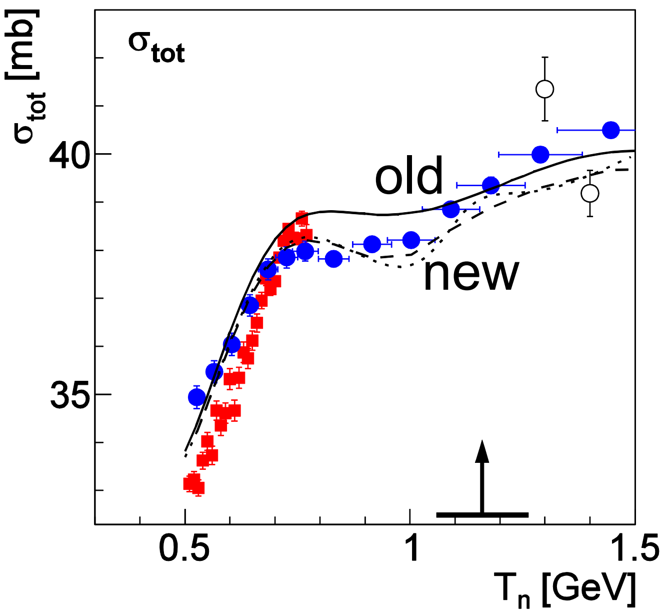
I(J^p) = 0(3$^+$)

d*(2380)

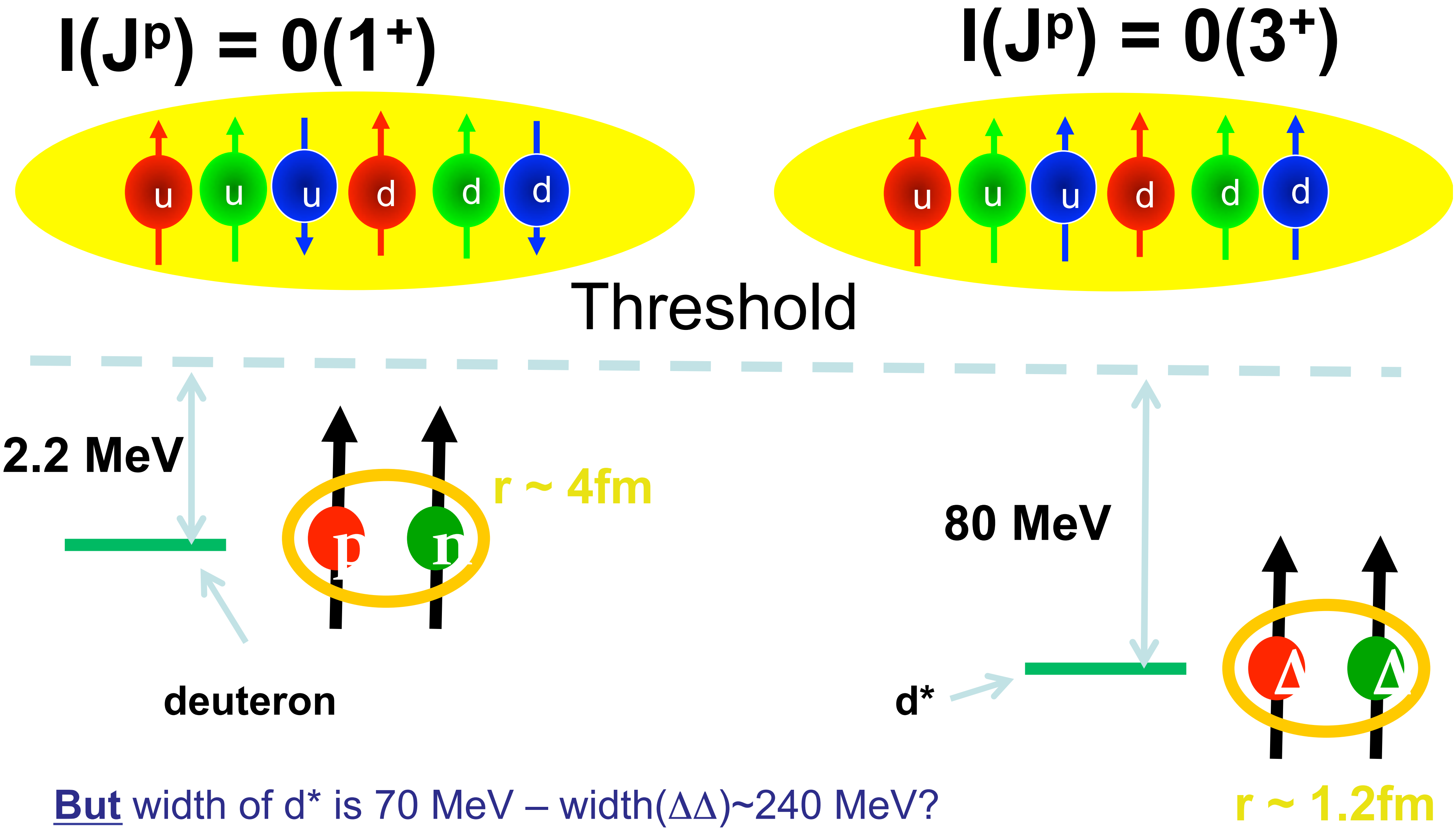
- Gives an explanation for (previous) inability for PWA to describe total np cross section !

ΔΔ decay ~ 90%
pn decay ~10%
(ang. mom. barrier, double spin-flip)





What is the d* - Deltaron hypothesis



But width of d* is 70 MeV – width(ΔΔ)~240 MeV?
& strong decay open (NNππ, NΔπ) ?

What is the d* - Hexaquark ?

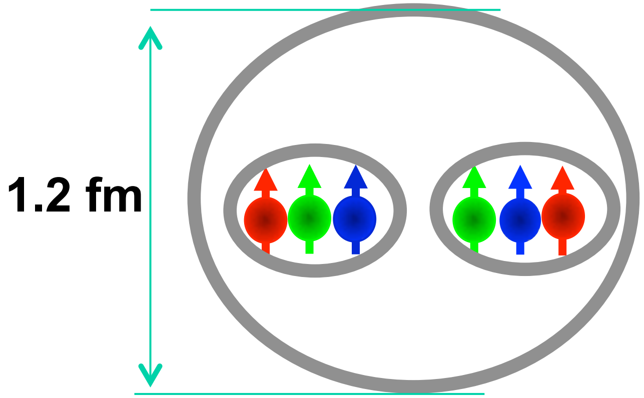
- Any quark model with confinement at large distances and one gluon exchange **inevitably** predicts a d* with numbers (I)J^P=(0)3^+

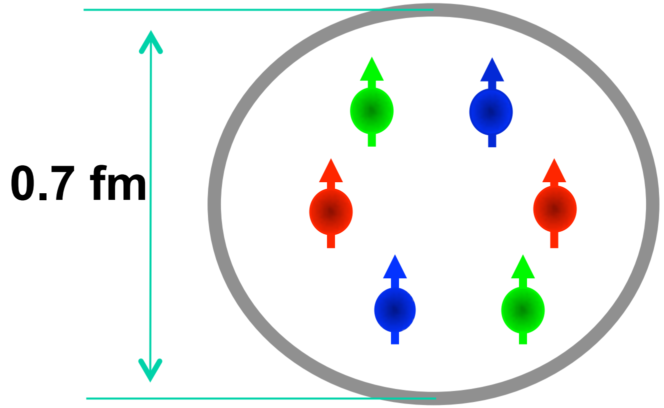
  T Goldman et. al. Phys. Rev. C 39, 1889 (1989)

- Recent microscopic coupled channel chiral quark model **ΔΔ + hidden colour**

  F. Huang et al, Chin.Phys. C39 (2015) 7, 071001

F. J. Dyson and N. H. Xuong, Phys. Rev. Lett. **13**, 815 (1964).
M. Oka and K. Yazaki, Phys. Lett. B **90**, 41 (1980).
Z. Y. Zhang *et al.*, Nucl. Phys. A **625**, 59 (1997).
X. Q. Yuan *et al.*, Phys. Rev. C **60**, 045203 (1999).
Q. B. Li *et al.*, Nucl. Phys. A **683**, 487 (2001).
L. R. Dai *et al.*, Nucl. Phys. A **727**, 321 (2003).
A. M. Kusainov *et al.*, Phys. Rev. C **44**, 2343 (1991).
L. Ya. Glozman, V. G. Neudatchin, and I. T. Obukhovsky, Phys. Rev. C **48**, 389 (1993).
Fl. Stancu, S. Pepin, and L. Ya. Glozman, Phys. Rev. C **56**, 2779 (1997).
M. Bashkanov, S.J. Brodsky, and H. Clement, Phys. Lett. B **727**, 438 (2013).
H. X. Huang *et al.*, Phys. Rev. C **89**, 034001 (2014).





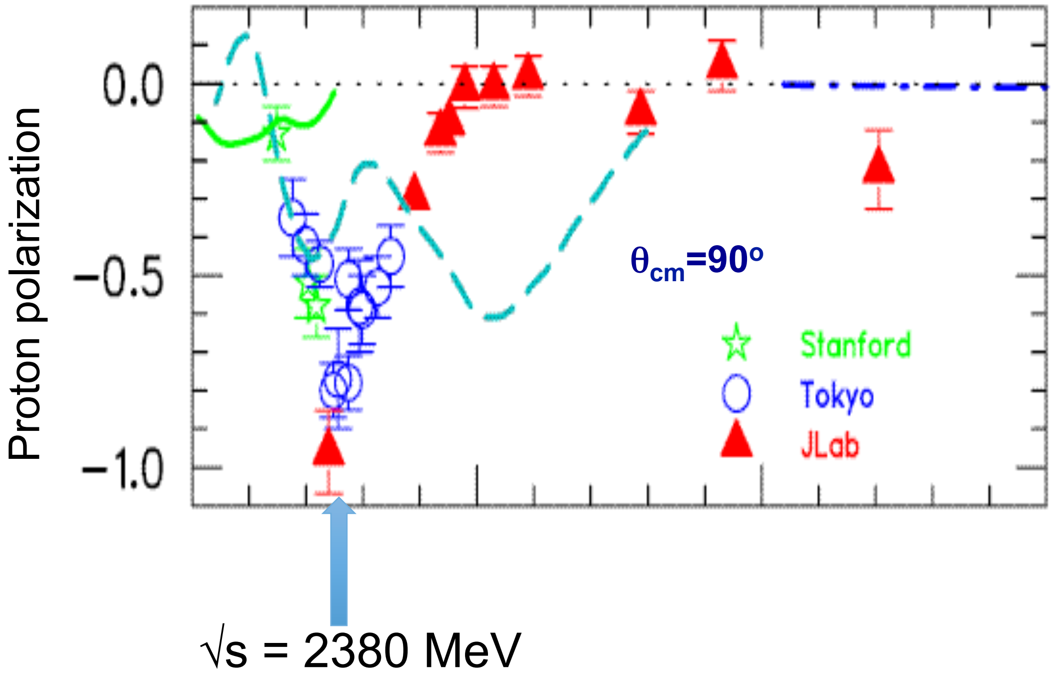
Identifying the d*

- Need EM probe to elucidate d* structure
- 1st stage: -> What is the coupling to EM probe - γ
  -> Edinburgh nucleon polarimeter@MAMI
- 2nd stage: Look at electroproduction (Q^2 dependence)?
  -> CLAS12@JLAB (+polarimeter,..)

EM coupling to the d* - D(γ,pn)

- Expect mirror behaviour for neutron polarisation - if due to a 3^{+} state

- What about other polarisation observables e.g. polarised γ, .. ?

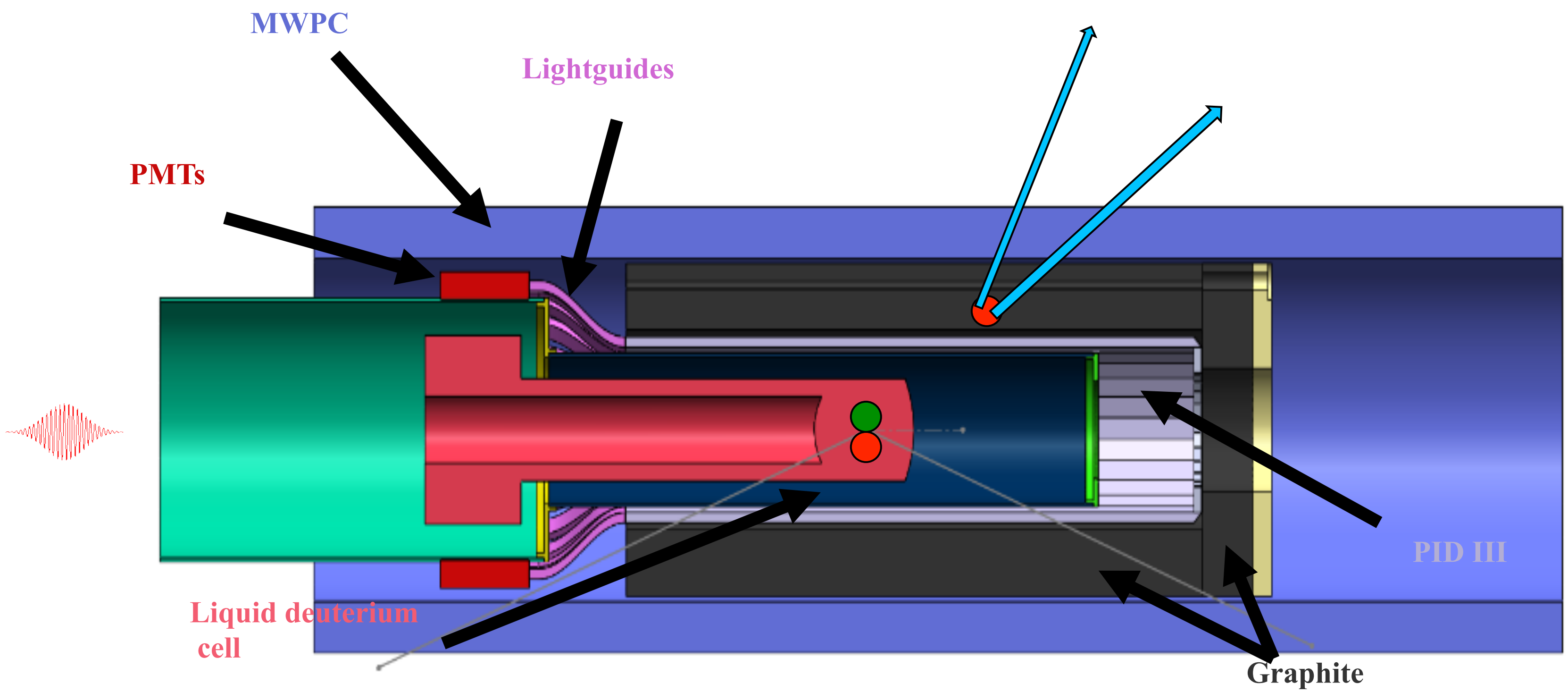


- Proton polarisation approaches 100% at d* mass !

Edinburgh nucleon polarimeter phase 2

Runs late summer 2016

Sikora, DPW, Glazier et. al. PRL112 022501 (2014)



$$n(\theta,\phi) = n_o(\theta)\{1+A(\theta)[P_y\cos(\phi)-P_x\sin(\phi)]$$

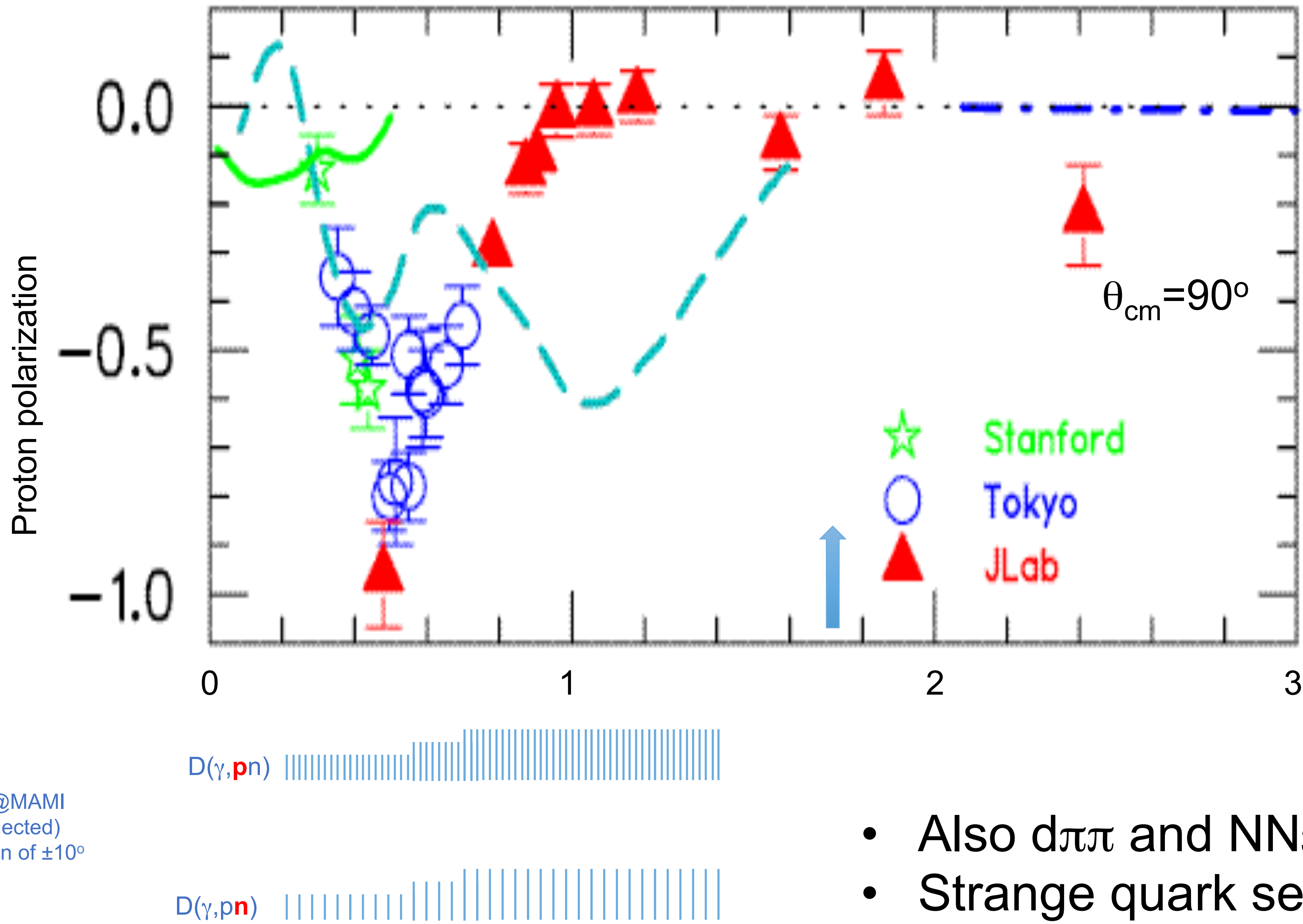
Number of nucleons scattered In the direction θ, ϕ

Polar angle distribution for unpolarised nucleons

Analysing power of scatterer

x and y (transverse) components of nucleon polarisation

Expected accuracy for D(γ,pn)



CB@MAMI
(projected)
θ_p bin of ±10°

- Also dππ and NNππ
- Strange quark sector

Summary

- Coherent π photoproduction is a promising method for measuring neutron skins

  -> Distortion effects relatively small, no ISI, amplitude well established

- Experimental systematics in extracting the coherent pi cross section with CB estimated to be small -> symmetric CB calorimeter, tracking, ..

- Skin extraction uses a theoretical model – significant systematics do not reveal themselves in studies of q dependence, Eγ dependence, T_{π} dependence and A dependence (Pb and Ca),

- Experiments take ~ 2-3 days per target – offering the possibility to map many nuclei

The END

Thanks for your attention !