Coherent and incoherent π^0 photoproduction at MAMI

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For the Crystal Ball at MAMI and A2 Collaboration

Meson 2008

SUPA

THE UNIVERSITY OF EDINBURGH

Mainzer Mikrotron
MAMI

mami
MAINZER MIKROTRON

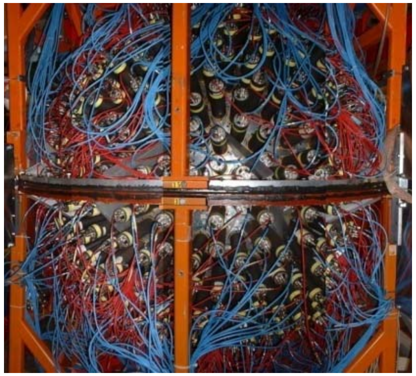
Talk Outline

• Physics motivation for accurate π^0 photoproduction measurements

Coherent – Accurate Matter form factors
Neutron skins of stable nuclei (neutron stars)
Incoherent - Transition matter form factors

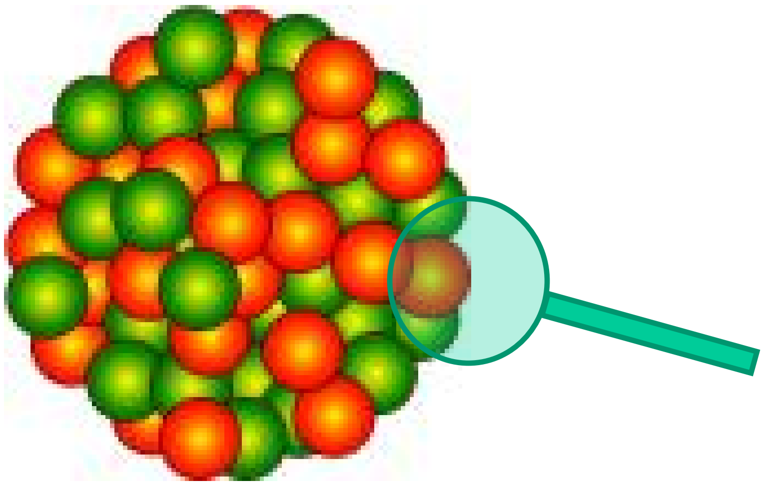
• The Crystal Ball at MAMI

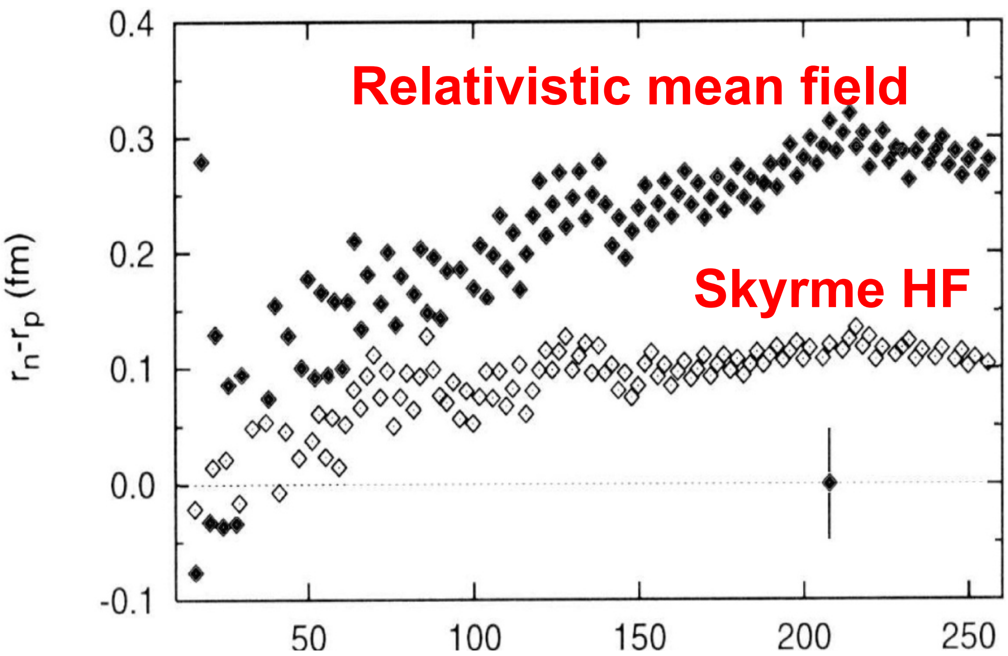
• Forward look



Why measure the matter form factor?

- Our knowledge of the shape of stable nuclei is presently incomplete

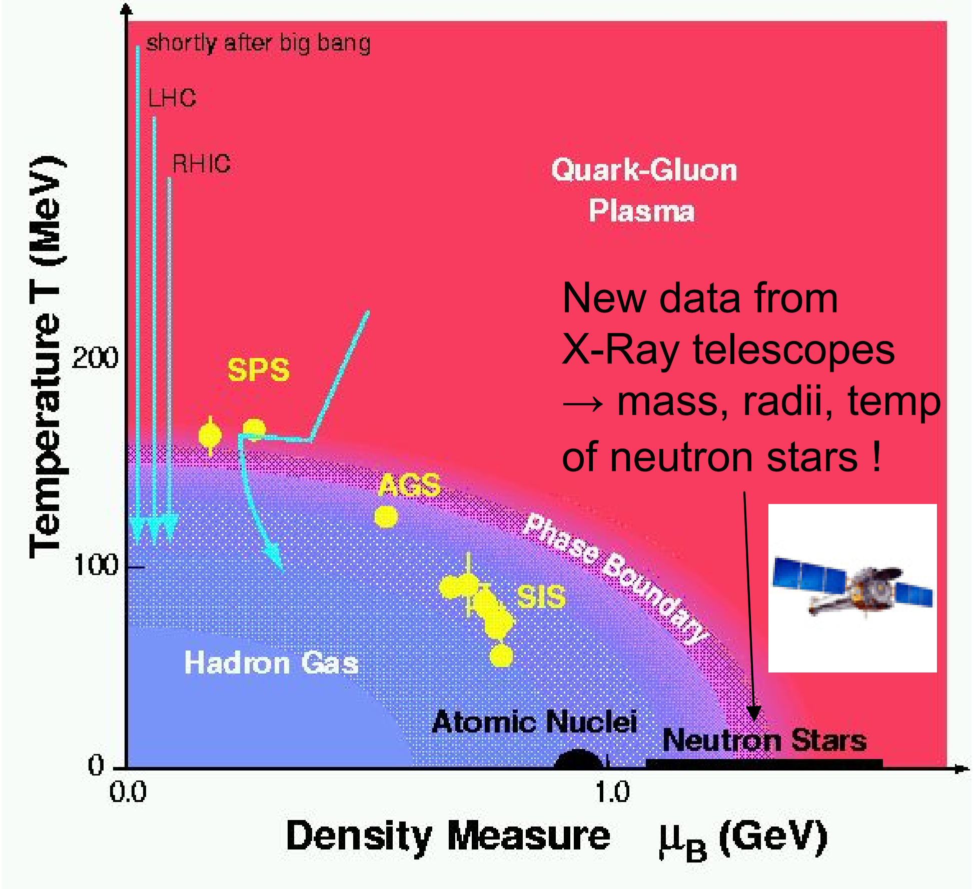




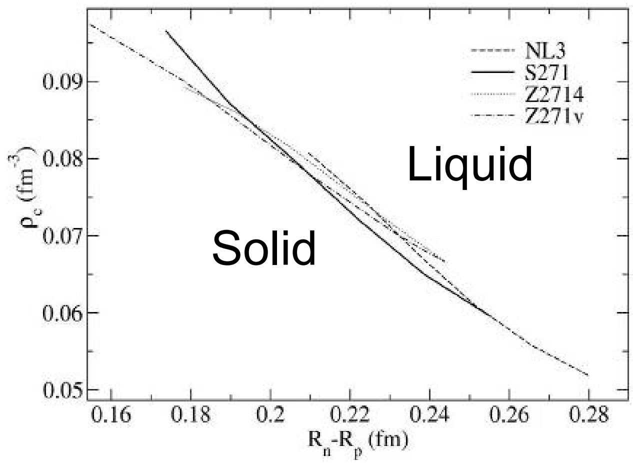
e.g. ^{208}Pb RMS charge radius accuracy < 0.001 fm
RMS neutron radius accuracy ~0.2 fm !!

Horowitz et al. PRC63 025501 (2001)
Piekarewicz et al. NPA 778 (2006)

Matter form factor and neutron stars



Thick neutron skin
→ Low transition density in neutron star

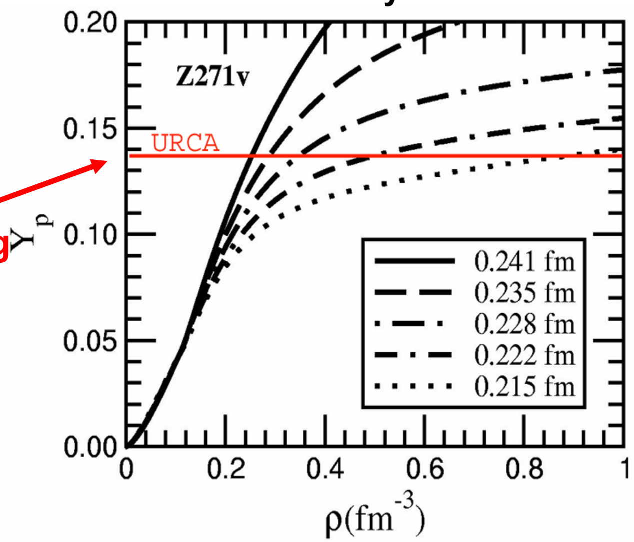


Proton fraction as a function of density in neutron star

Direct URCA Cooling

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

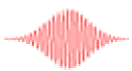
$e^- + p \rightarrow n + \nu$

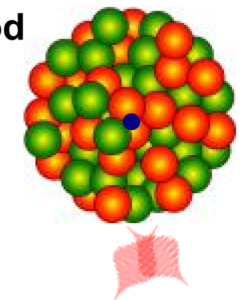


Rutel et al, PRL 95 122501 (2005)
Horowitz, PRL 86 5647 (2001)
Horowitz, PRC 062802 (2001)
Carriere, Astrophysical Journal 593 (2003)
Tsuruta, Asttrophysical Journal Lett. 571 (2002)

Coherent pion photoproduction

Photon probe ✓
Interaction well understood





π^0 meson – produced with ~equal probability on protons *AND* neutrons.

Select reactions which leave nucleus in ground state

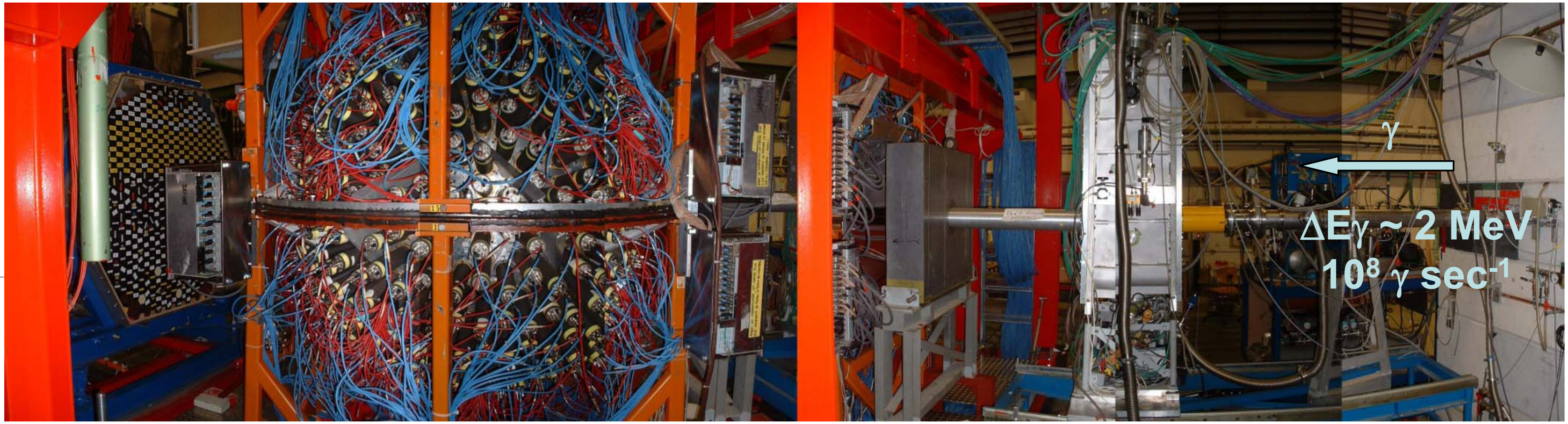
Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay

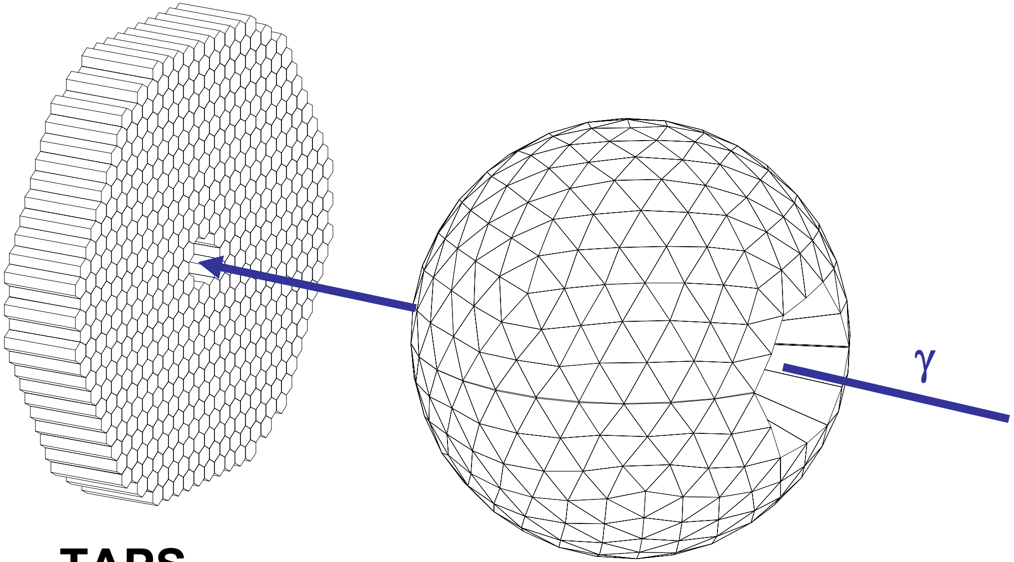
- Angular distribution of π^0 $\rightarrow$ PWIA contains the matter form factor

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

- π^0 final state interactions - use latest complex optical potentials tuned to π-A scattering data. Corrections modest at low pion momenta

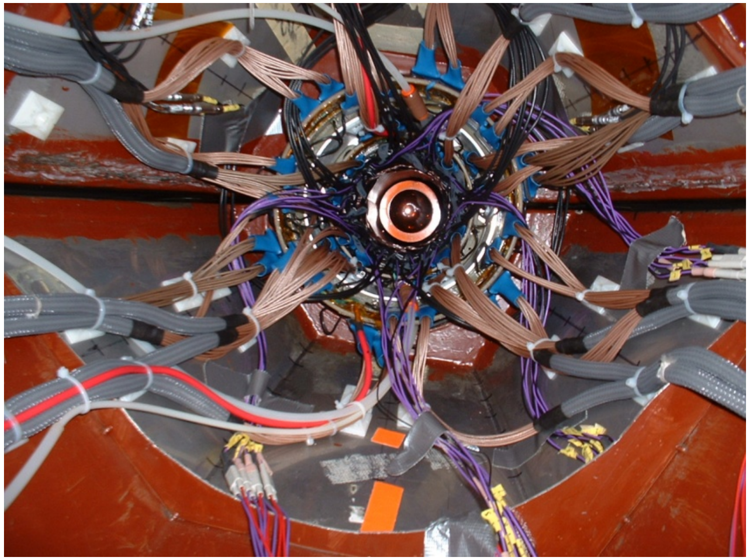
Coherent pion photoproduction





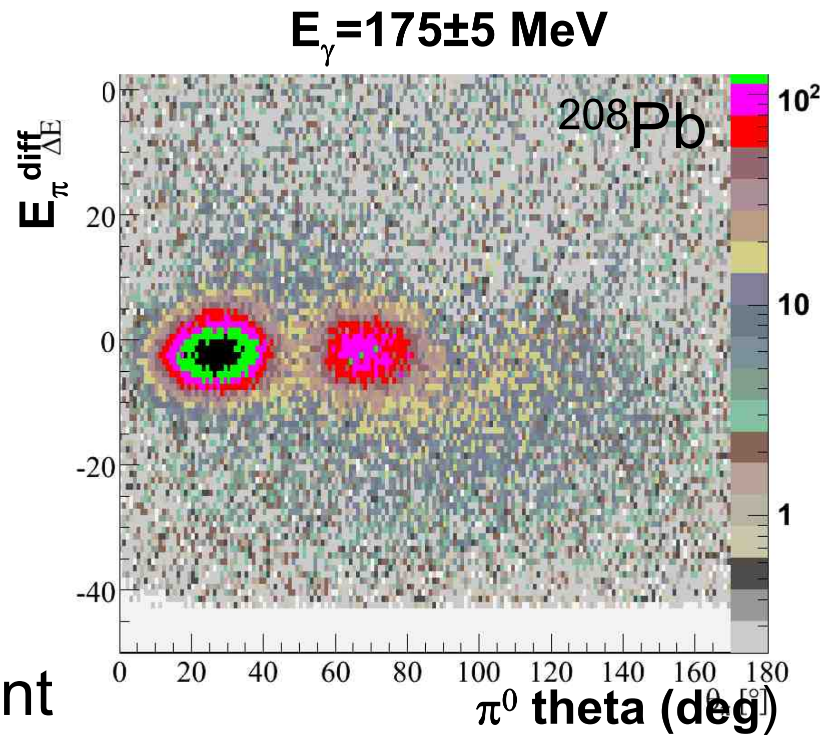
TAPS
528 BaF_2 crystals

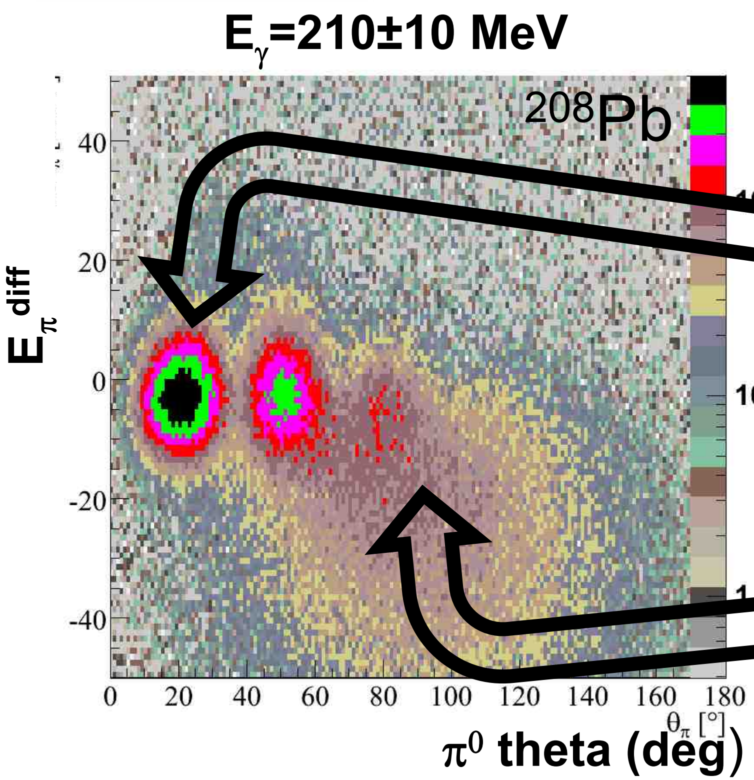
Crystal Ball
672 NaI crystals



Outline of analysis

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

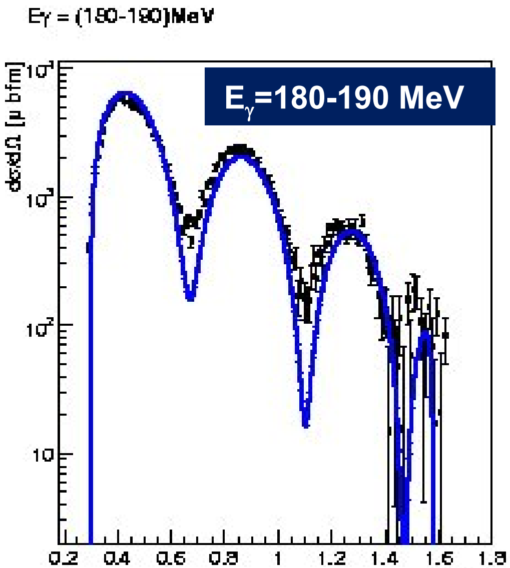


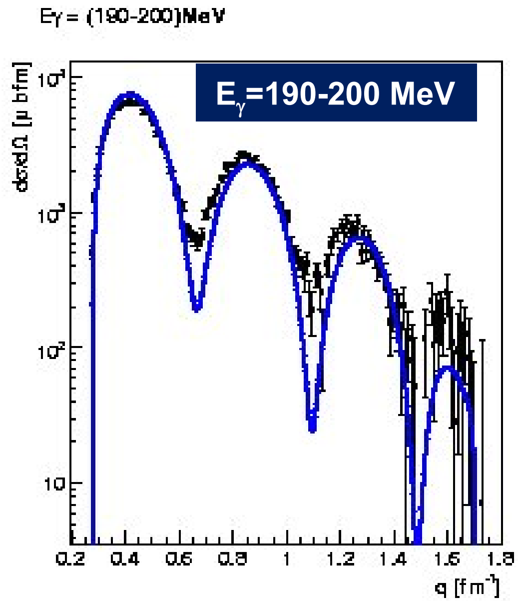


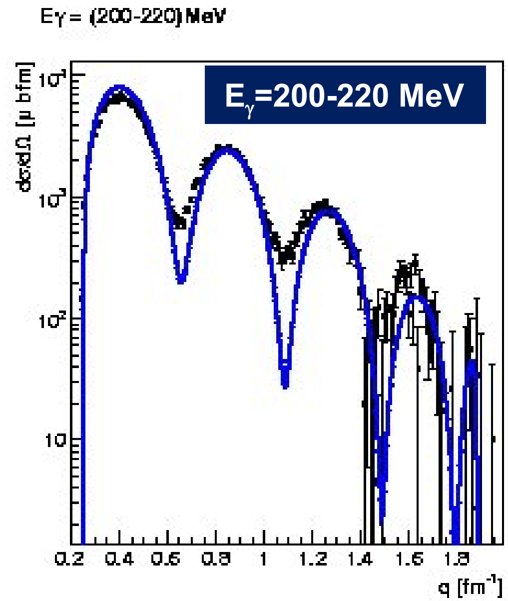
Coherent maxima

Non-coherent contributions

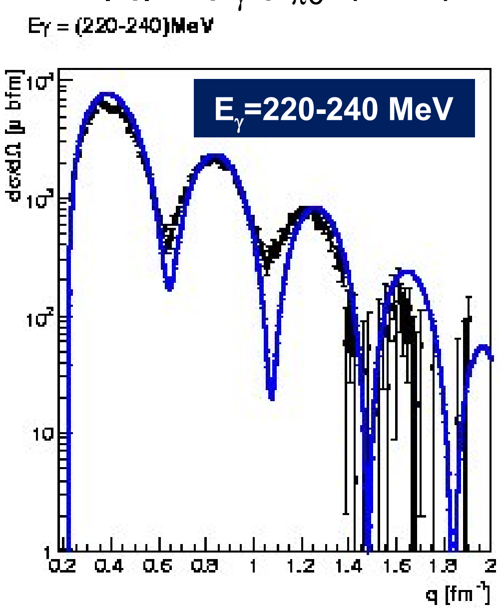
^{208}Pb : Momentum transfer distributions

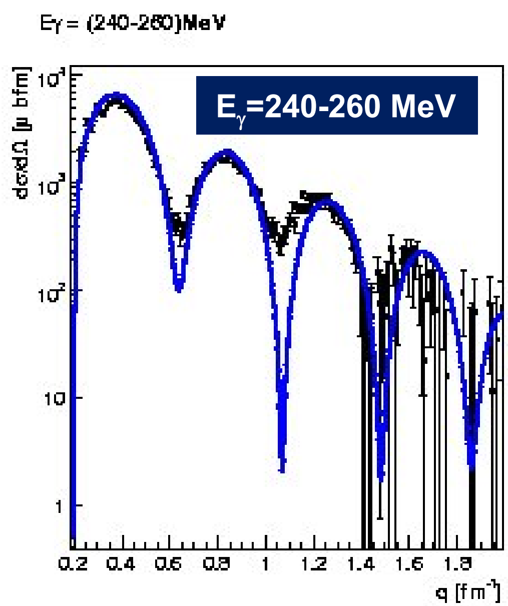






$|q| = p_\gamma - p_{\pi 0}$ (fm^{-1})





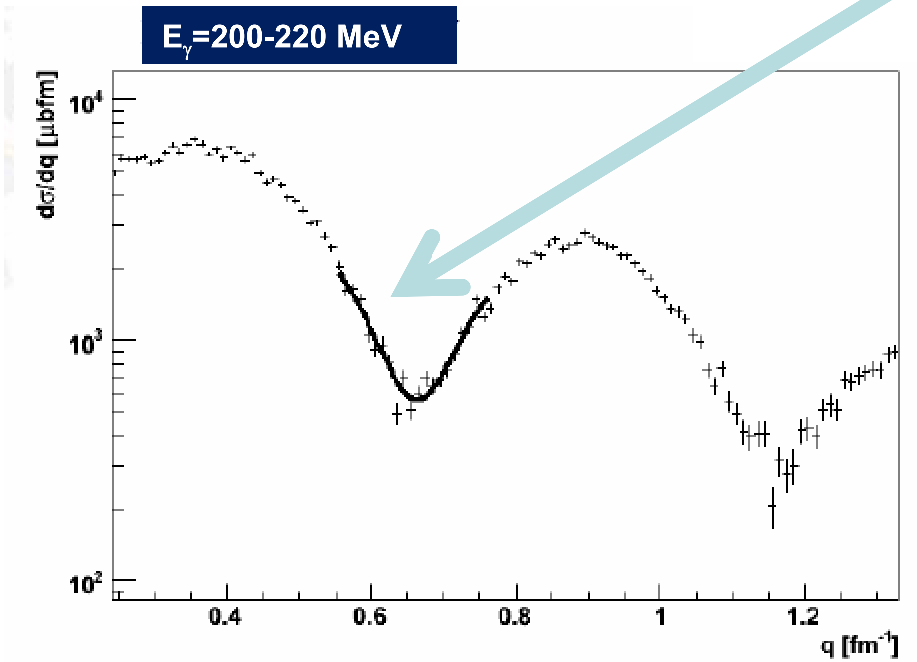
— Unitary isobar model (γ,π) with complex optical potential

Dreschel NPA 660 (1999)

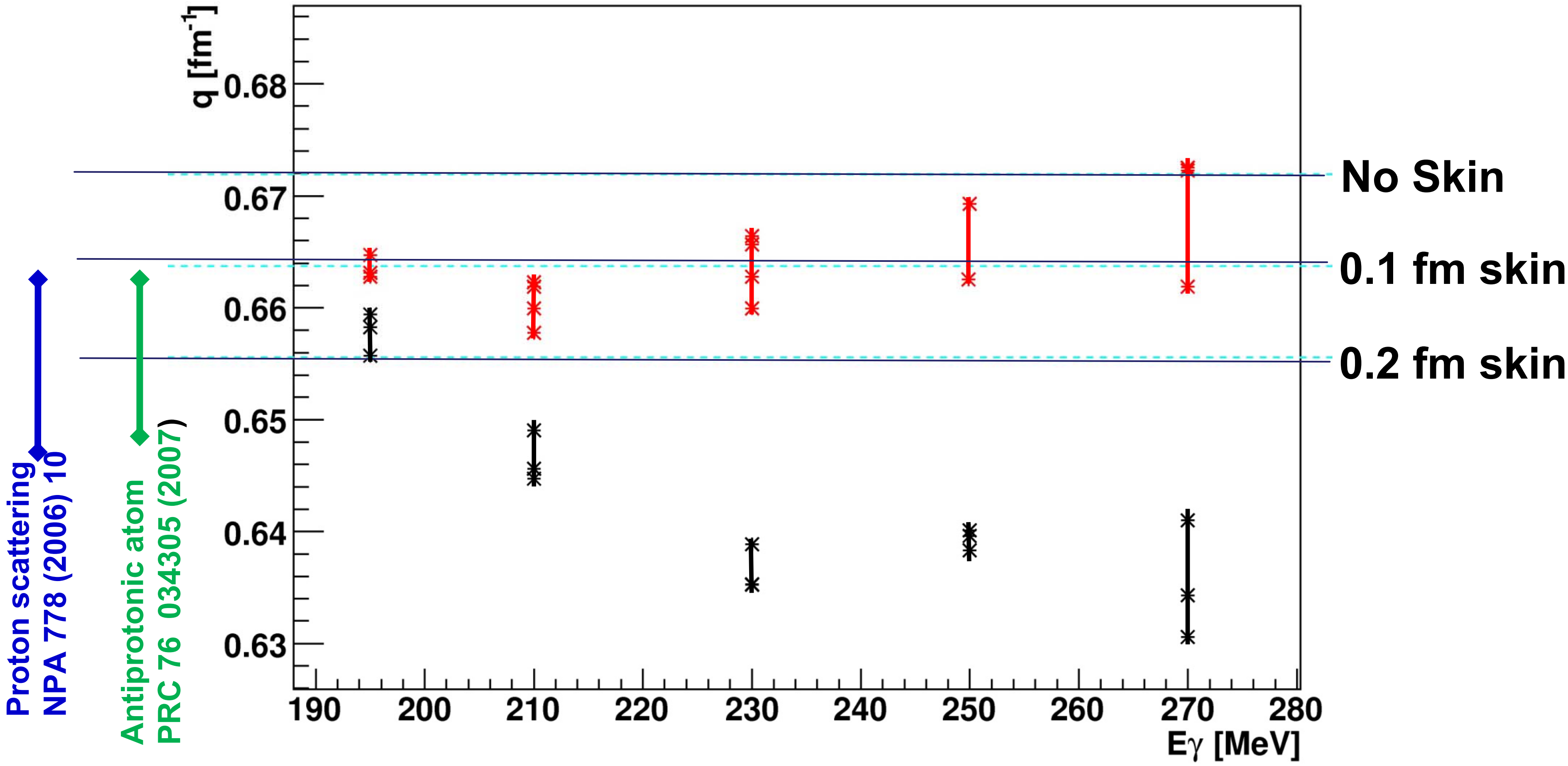
^{208}Pb: Simple correction for distortion

- Full "model independent" analysis planned

- For first preliminary assessment
  1) Carry out simple correction of q shift using the theory
  2) Analyse corrected minima - fit with Bessel fn.

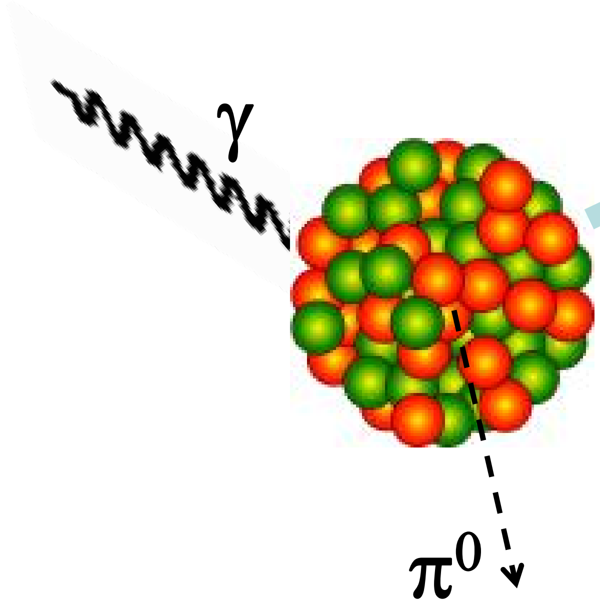


^{208}Pb neutron skin – preliminary assessment



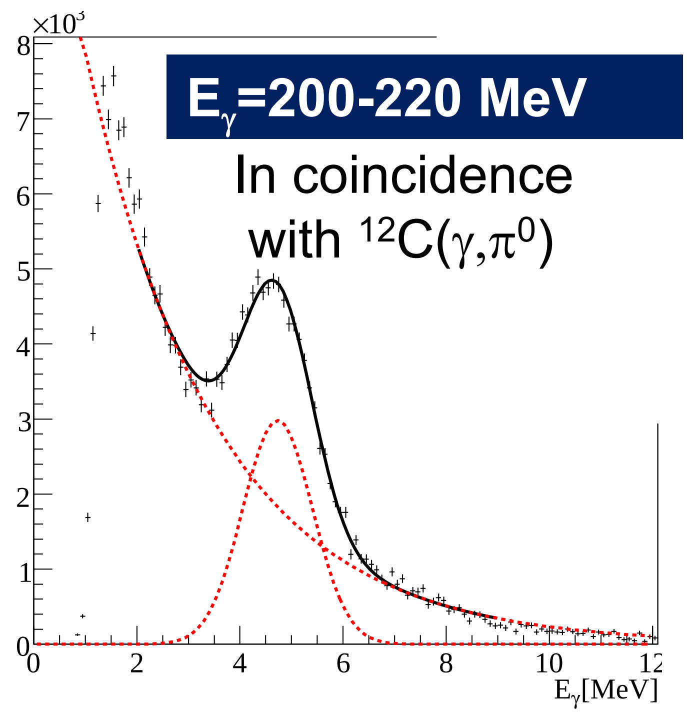
- See effects of a neutron skin of ~0.1 fm !! (preliminary)
- More detailed analysis in progress to reduce and assess systematics
- Future measurement - skin development across isotopic chain?

Incoherent nuclear π^0 photoproduction

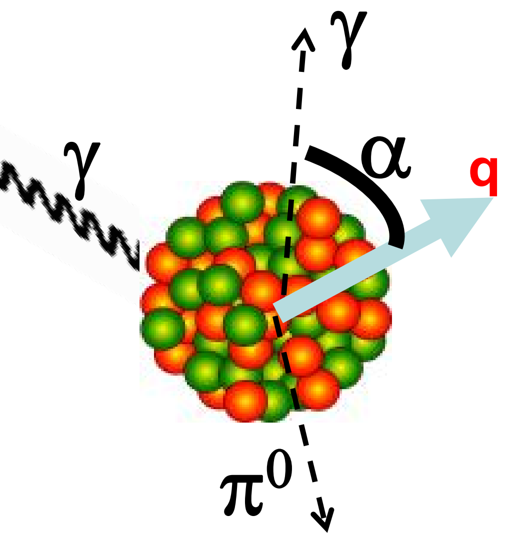


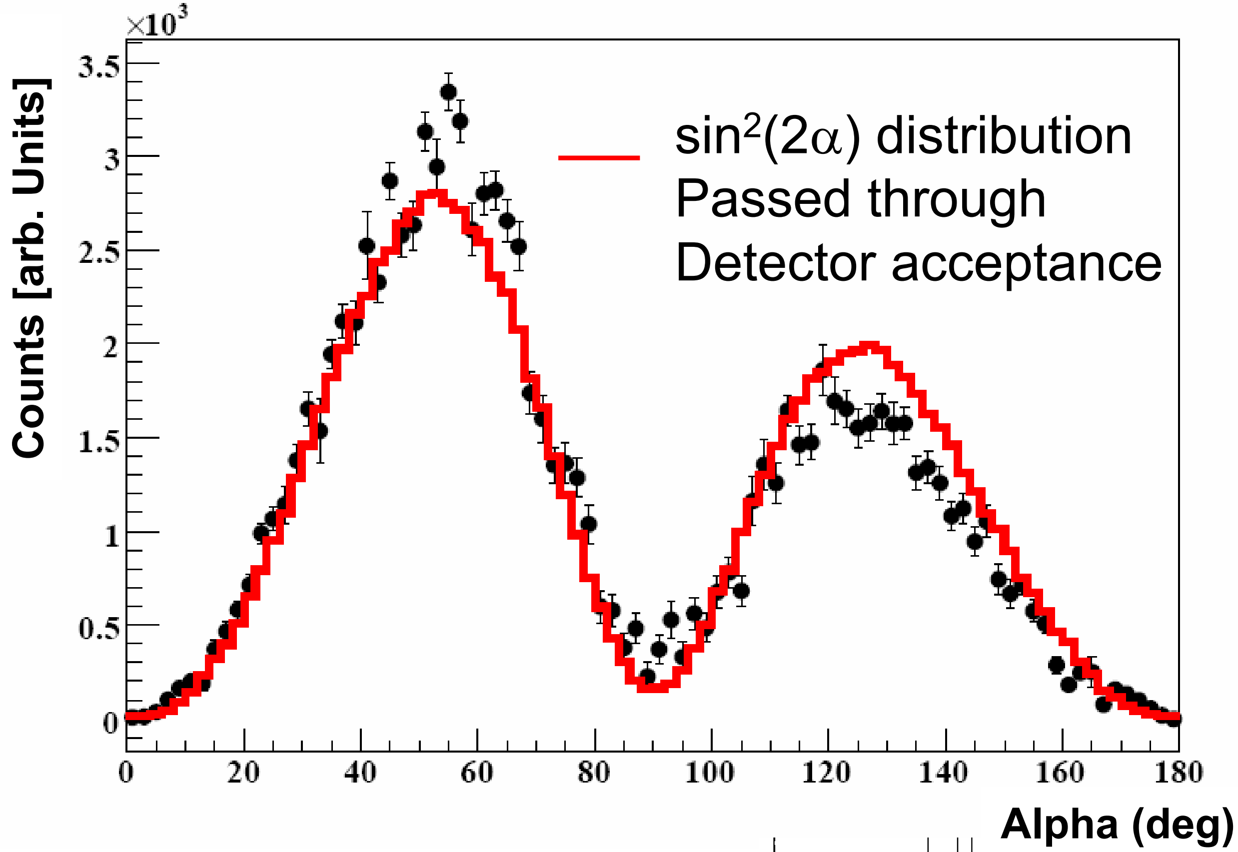
- Measurement of neutral pion production to a discrete excited nuclear state has proven elusive for many decades

- → Detect nuclear decay photon *in the same detector* as the π^0 decay photons

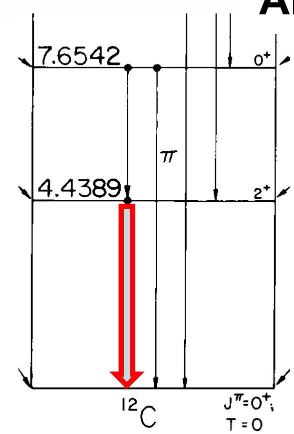


Alignment of recoiling ^{12}C nucleus

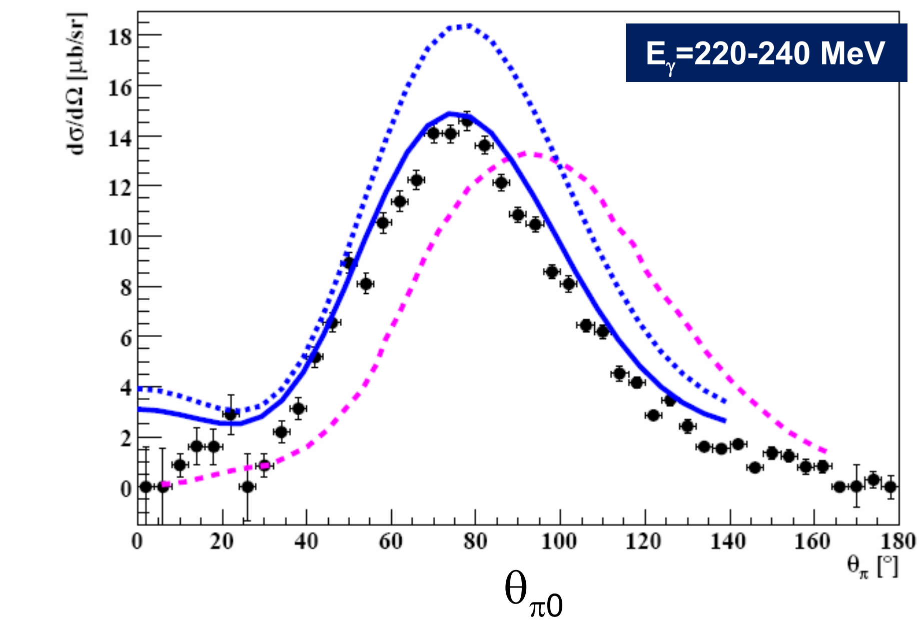




- Strong $\sin^2(2\alpha)$ distribution for 4.4 MeV photons
- 2^+ to 0^+ transition from aligned residual nucleus
- Degree of alignment - new experimental observable!!



Incoherent nuclear π^0 photoproduction



Takaki Δ-hole model (NPA 443 p570 (1985))
— Full calculation
--- Without Δ-N interaction

----- Tryasuchev (Phys At.Nuc. 70 827 (2007)

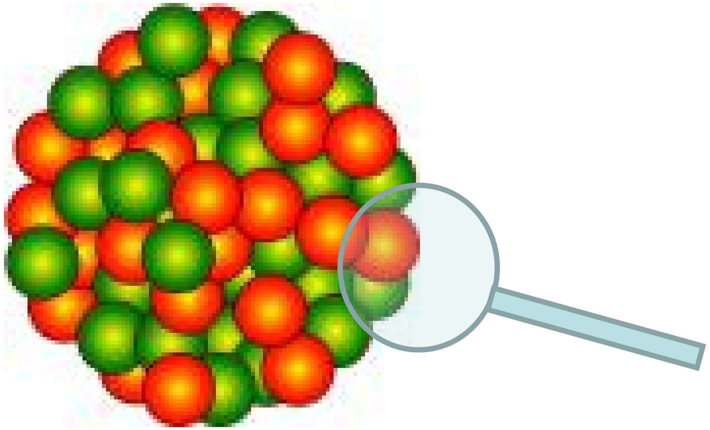
Next steps for decay γ work:

- ^{16}O, ^{40}Ca
- Neutron rich nuclei - multiproton knockout
- Hypernuclei?

CM Tarbert, DP Watts et. al., Phys. Rev. Lett (2008)

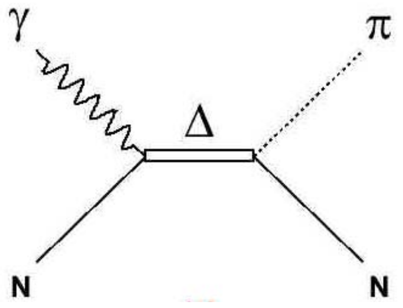
Summary

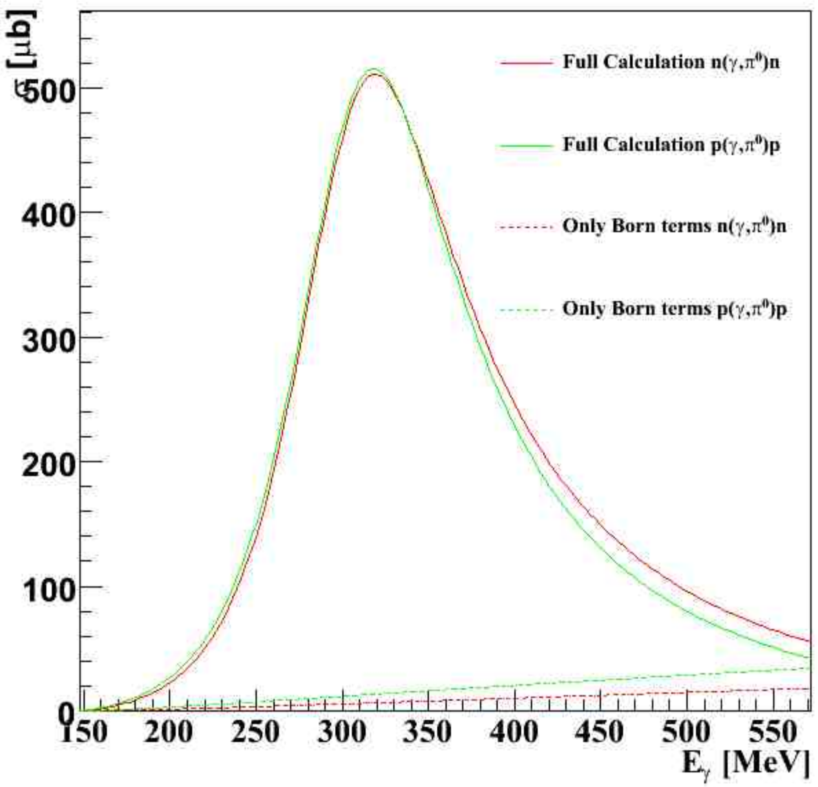
- New high quality π^0 photoproduction data will give valuable and timely constraints on the structure of the nucleus and neutron stars



π^0 photoproduction amplitude

- Basic production amplitude ~ equal for protons and neutrons
- Dominated by $\Delta(1232)$ production



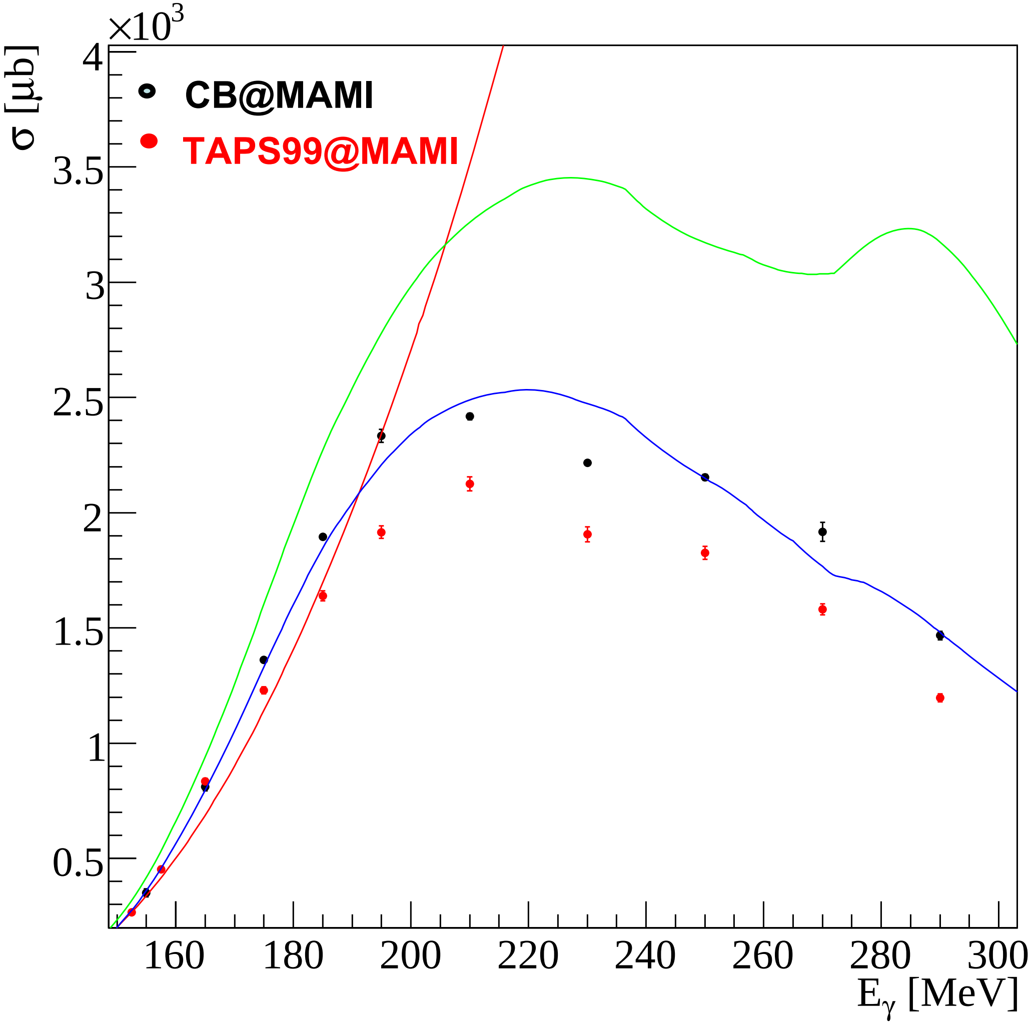


Isospin structure of amplitude

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

Δ has I=3/2 -- A^{V3} only

^{208}Pb: Total coherent cross sections



— PWIA

— DWIA

— DWIA+Δ self energy.

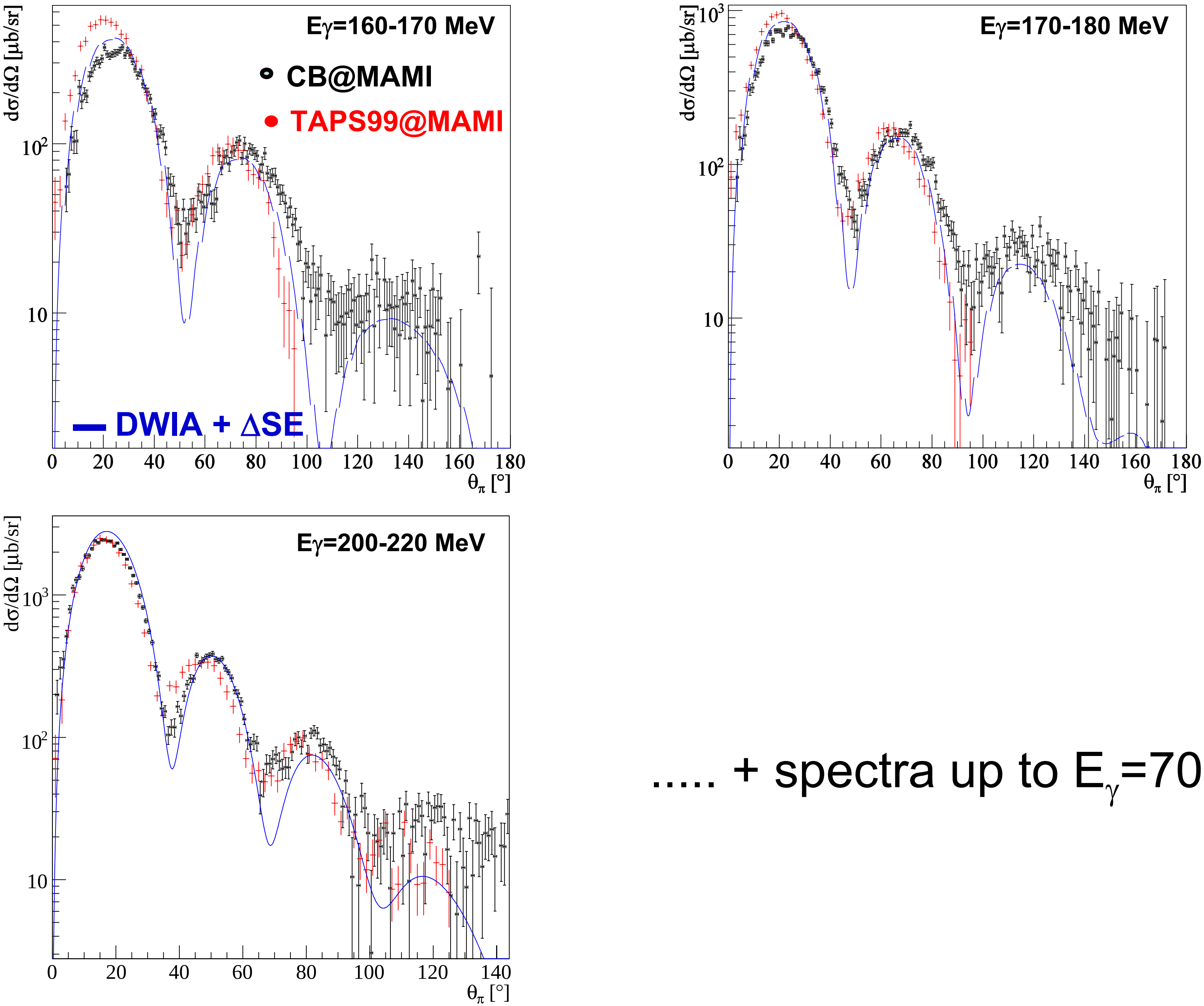
Theoretical prediction

Dreschel, Tiator, Kamalov & Yang - NPA 660 (1999)

π^0 production amplitude from Unitary Isobar Model

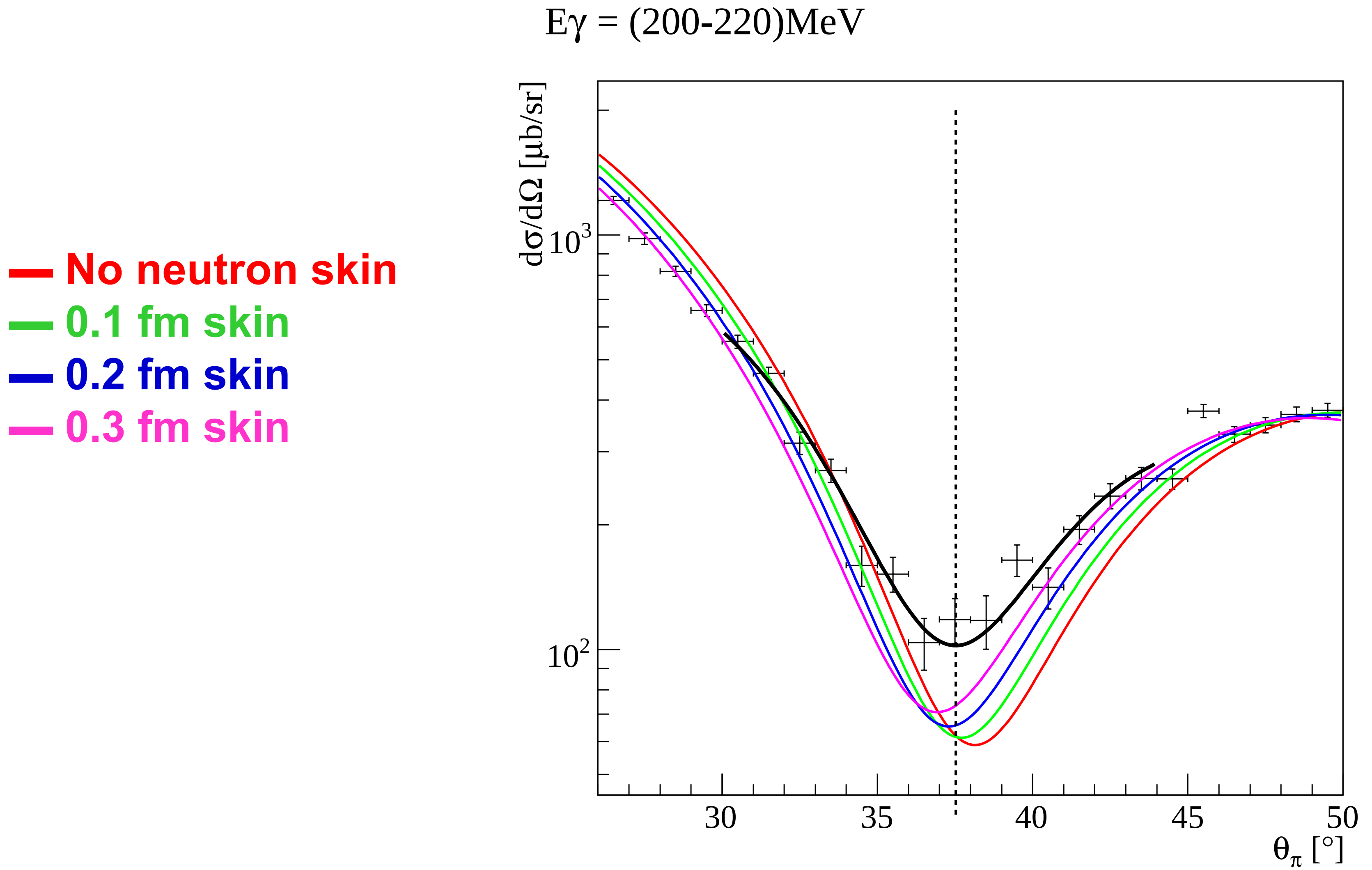
π^0 interaction treated with momentum space optical potential supplemented with Δ self-energy

^{208}Pb: π^0 angular distributions

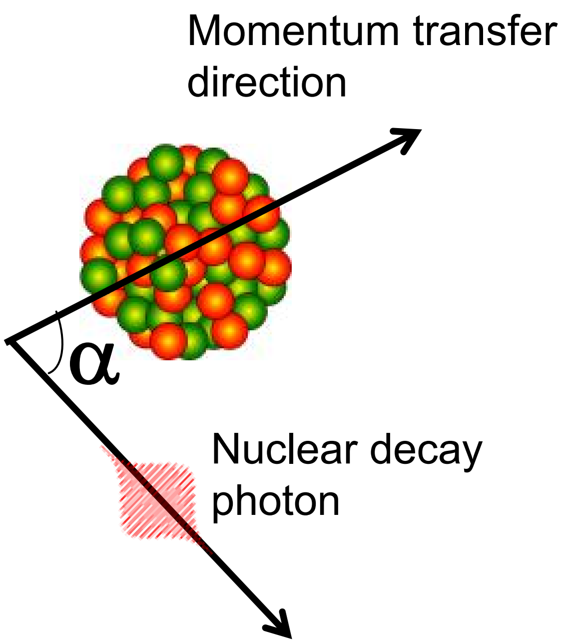


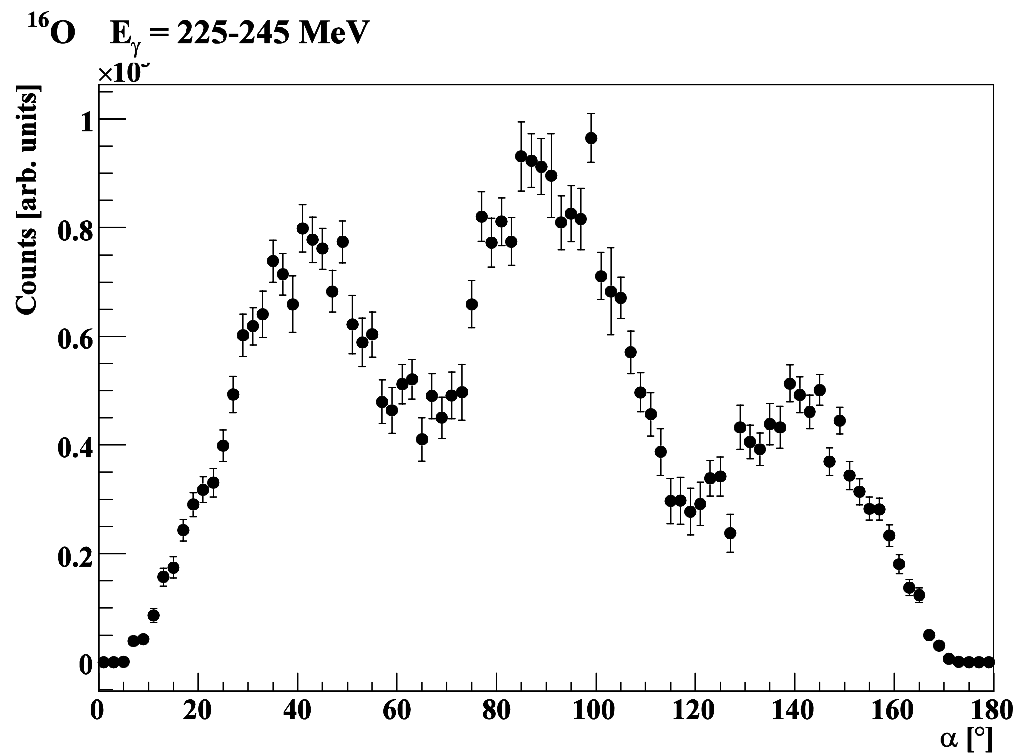
..... + spectra up to E_γ=700 MeV

^{208}Pb: Preliminary assessment of Neutron skin

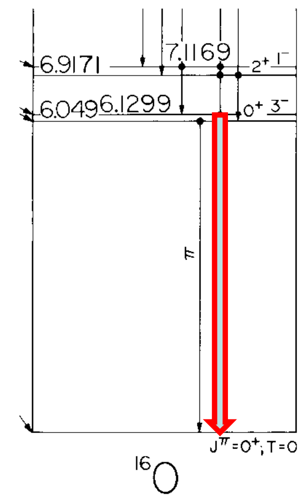


Alignment of recoiling ^{16}O nucleus

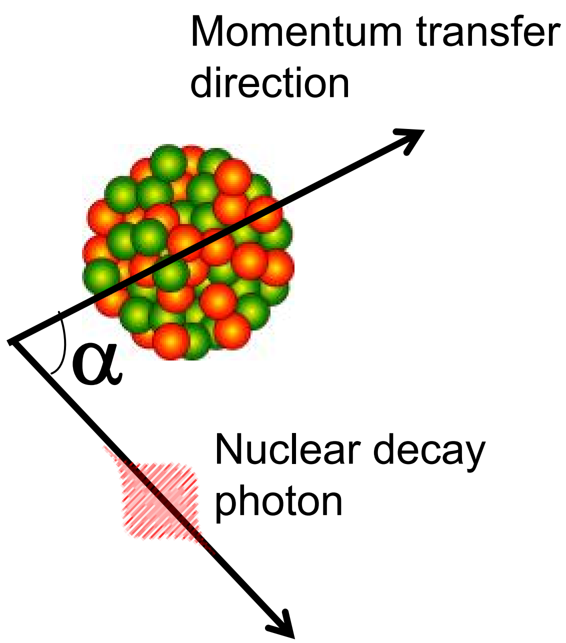


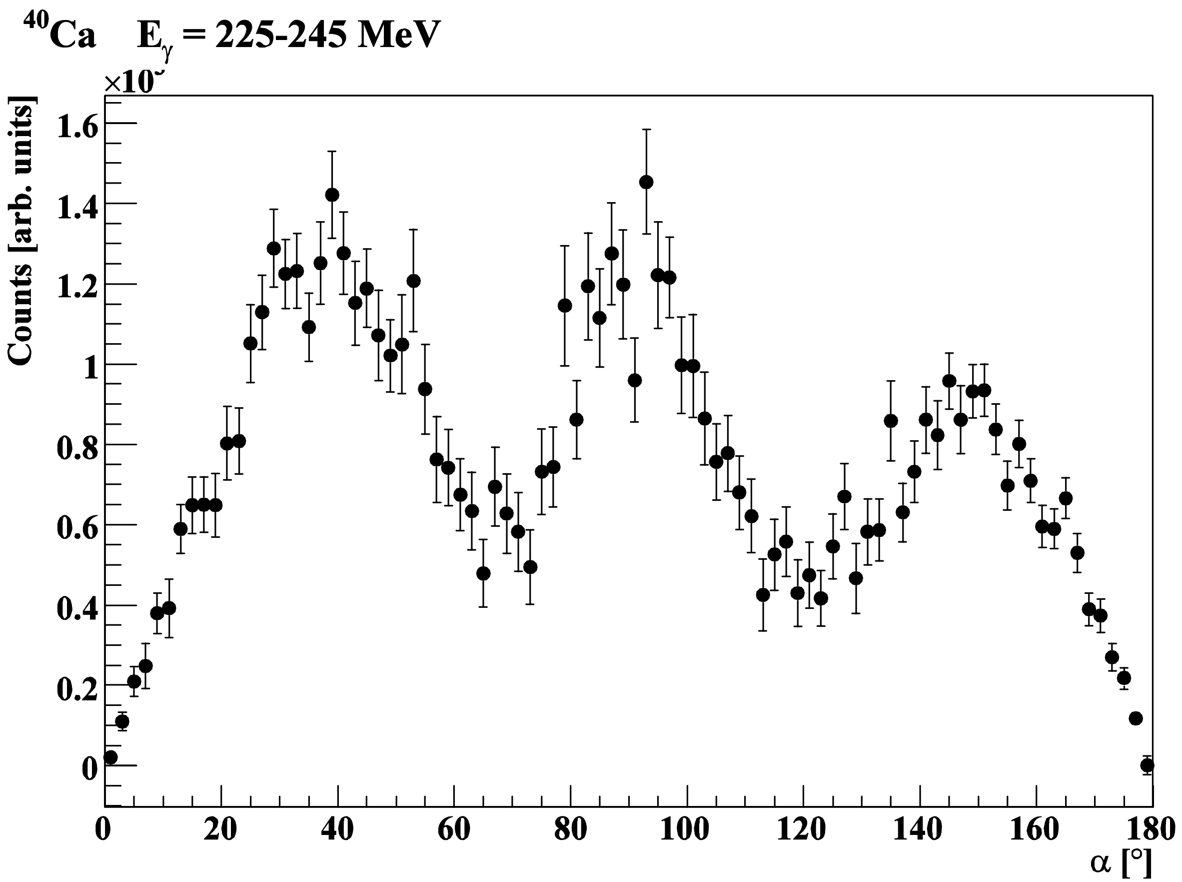


- Strong $\sin^2(3\alpha)$ component
- Expected from 3^- to 0^+ transition



Alignment of recoiling ^{40}Ca nucleus



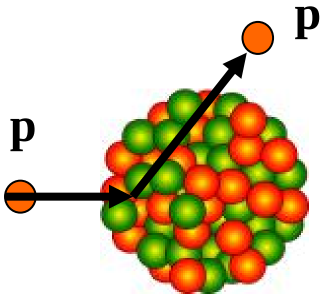


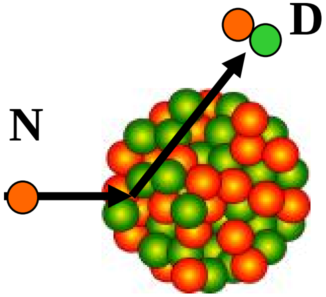
- Strong $\sin^2(3\alpha)$ component
- Expected from 3^- to 0^+ transition

Neutron Skins - present situation

- **Proton scattering**

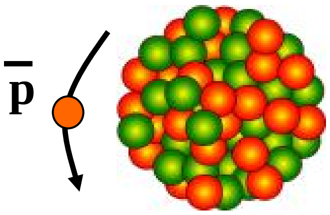
  Seminal analysis by Hoffman for all data (0.3 - 1 GeV). Δr_{np} (^{208}Pb) = -0.02 →0.5 fm





- **Pickup reactions.**

  Recent analysis of p and n pickup gave Δr_{np}~0.5fm for ^{208}Pb

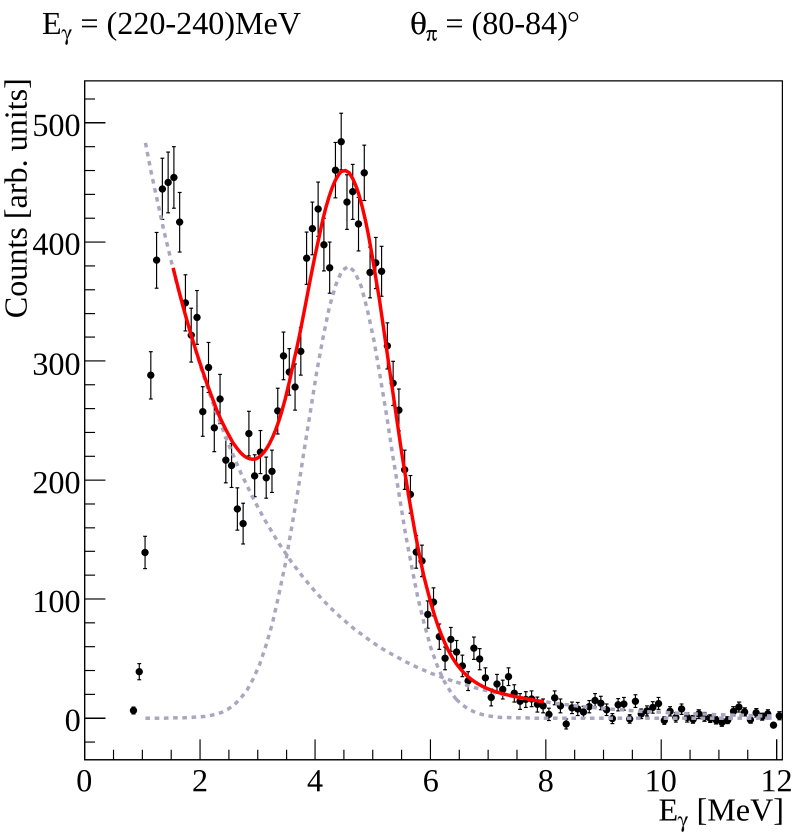


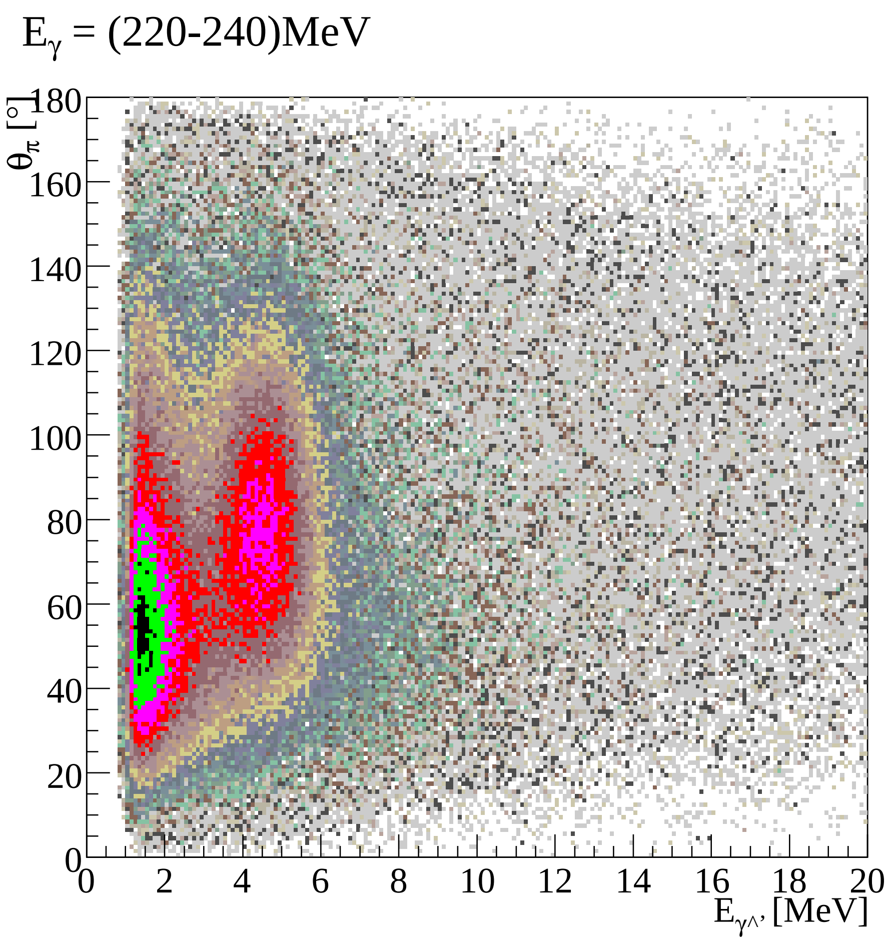
- **Antiprotonic atoms**

  Δr_{np} ~ 0.

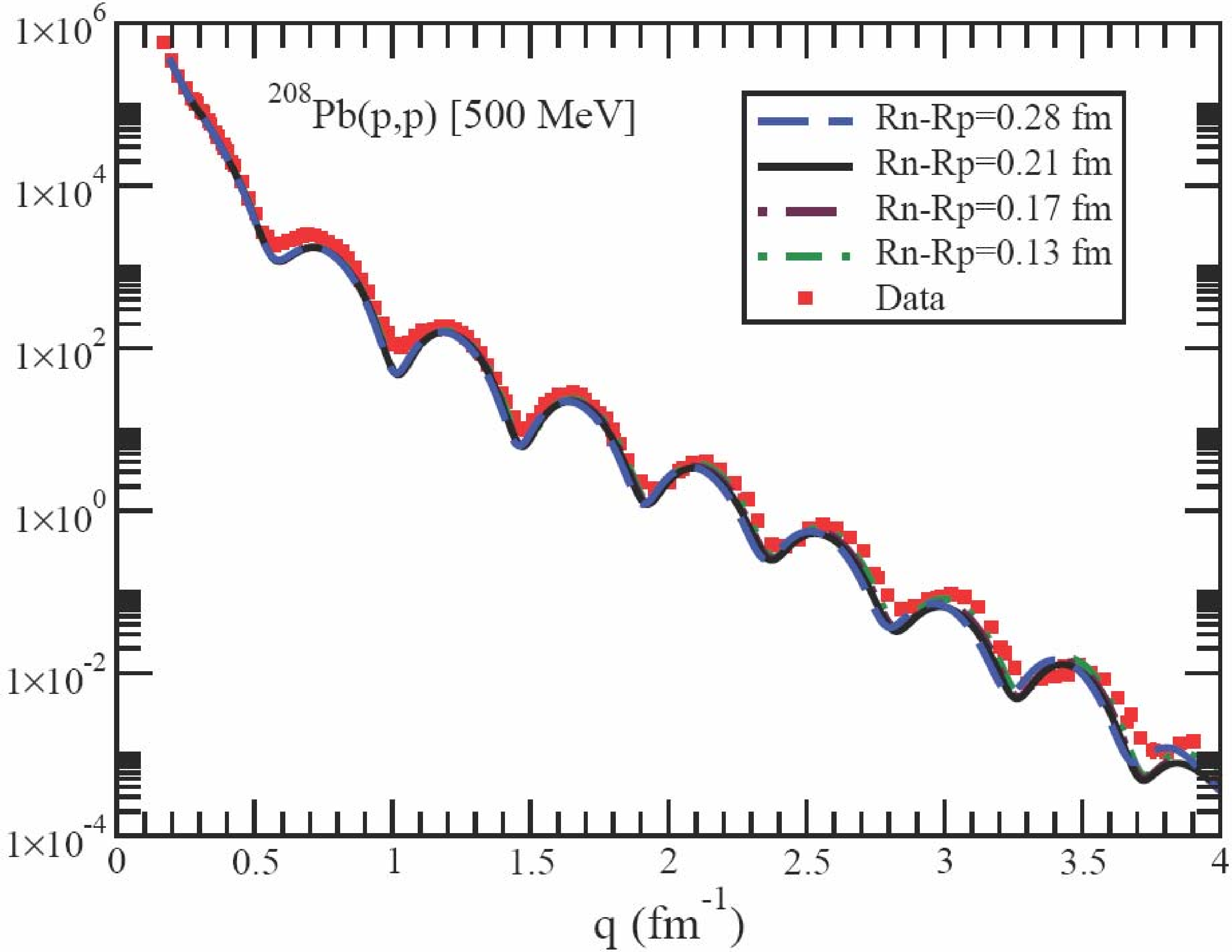
Coherent pion photoproduction

Nuclear decay photons ^{12}C

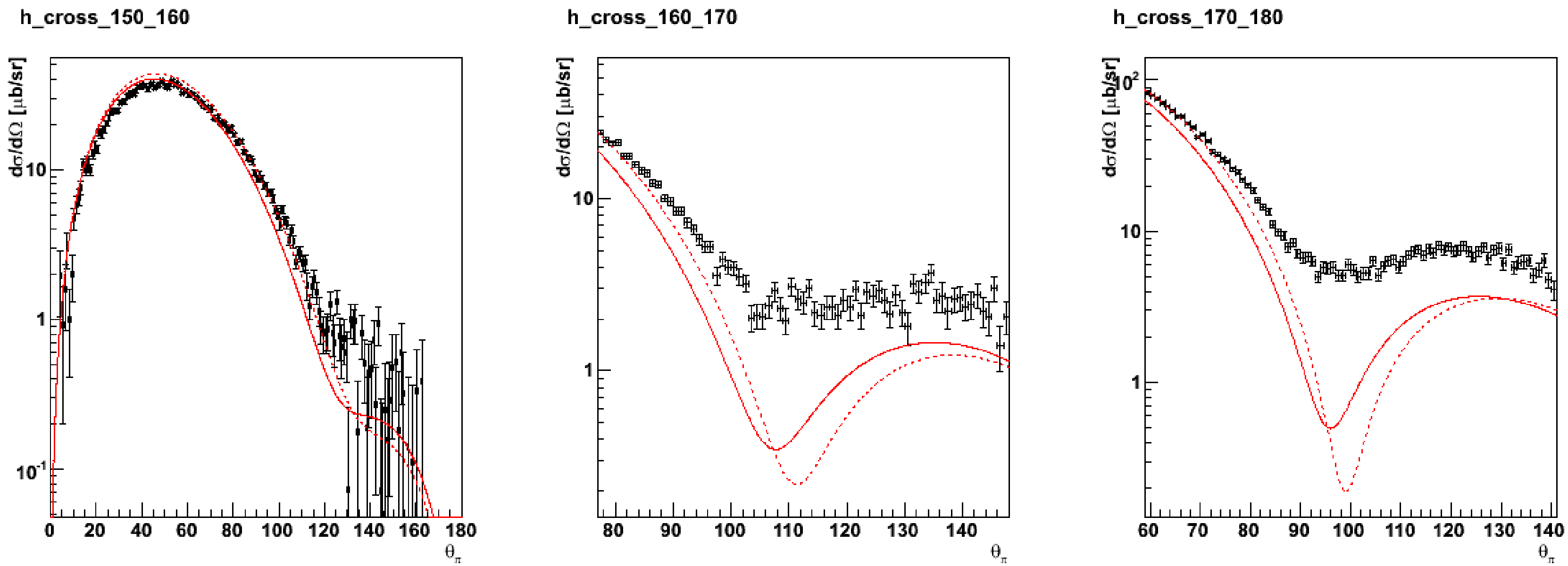


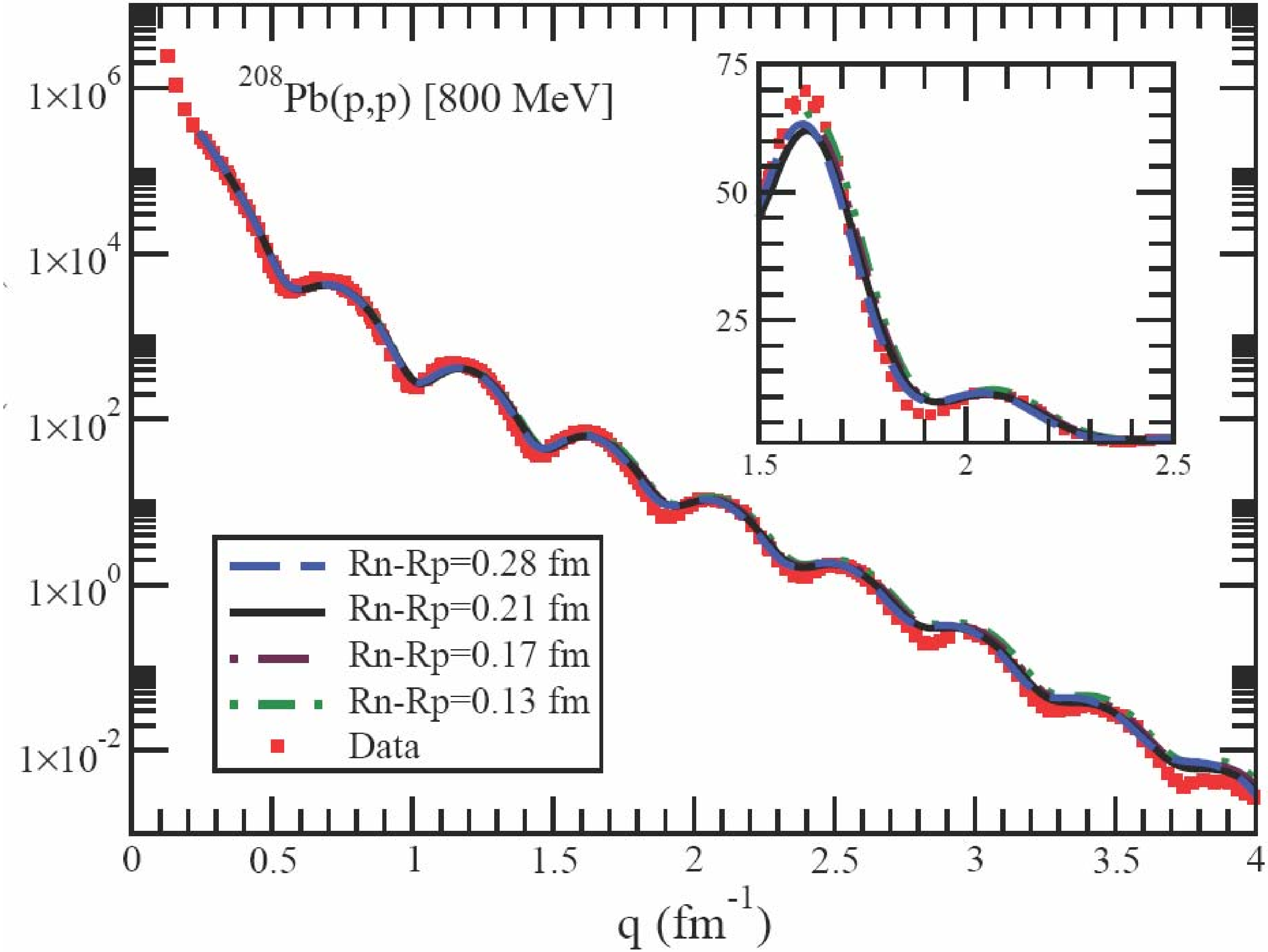


Background predominantly from split-off clusters from pi0 detection



^{208}Pb(p,p) [500 MeV]
Rn-Rp=0.28 fm
Rn-Rp=0.21 fm
Rn-Rp=0.17 fm
Rn-Rp=0.13 fm
Data
1×10^6
1×10^4
1×10^2
1×10^0
1×10^{-2}
1×10^{-4}
0
0.5
1
1.5
2
2.5
3
3.5
4
q (fm^{-1})


h_cross_150_160
h_cross_160_170
h_cross_170_180
dσ/dΩ [μb/sr]
θ_π



^{208}Pb(p,p) [800 MeV]
Rn-Rp=0.28 fm
Rn-Rp=0.21 fm
Rn-Rp=0.17 fm
Rn-Rp=0.13 fm
Data
q (fm^{-1})
1×10^{6}
1×10^{4}
1×10^{2}
1×10^{0}
1×10^{-2}
0
0.5
1
1.5
2
2.5
3
3.5
4
75
50
25
1.5
2
2.5

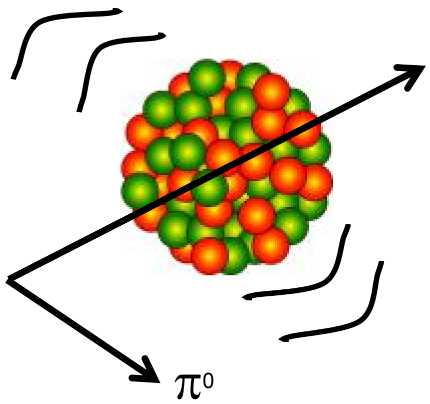
Coherent π^0 - next steps

- Plot data as function of momentum transfer (q)
- Use ratio DWIA/PWIA from theory (passed through detector acceptance)

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

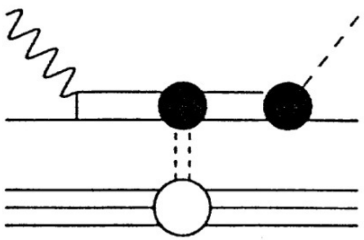
- $|F_m(q)|^2 \rightarrow$ 16 independent determinations in range $E\gamma=150\text{-}220$ MeV
- Accuracy r_n (rms) < 0.05fm

Incoherent π^0 photoproduction



1) 1st measurement of transition matter form factor with an EM probe!

2) New precision test of the Δ-N interaction

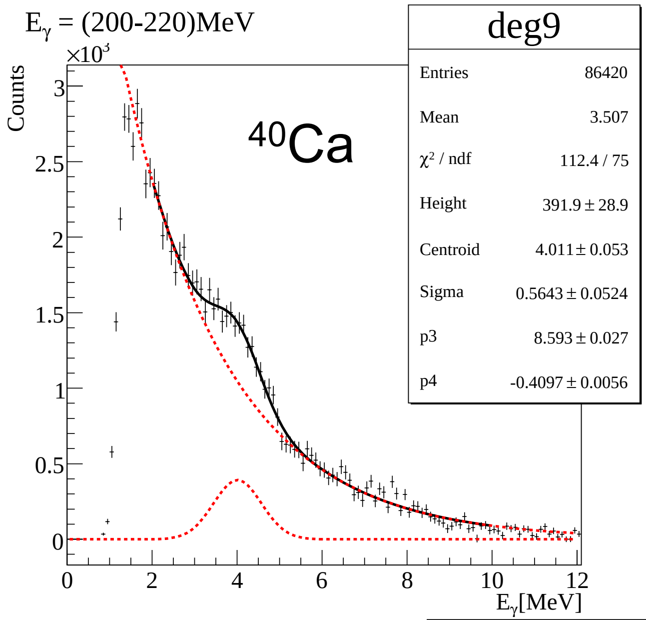


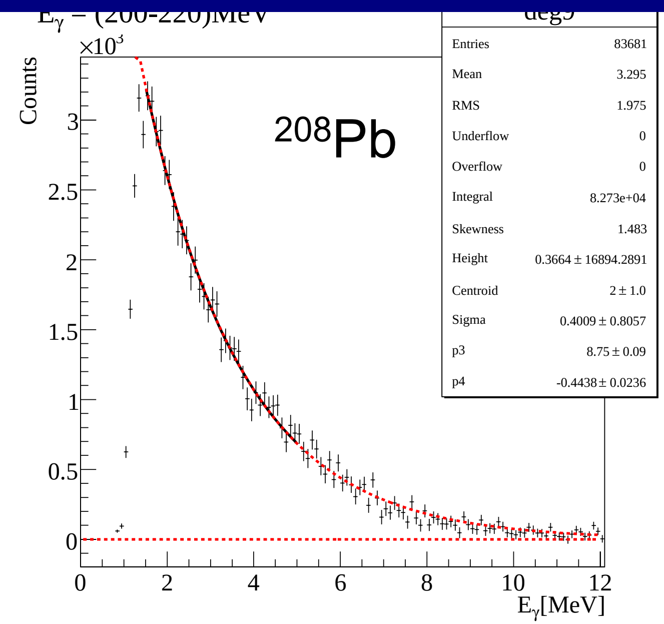
b)

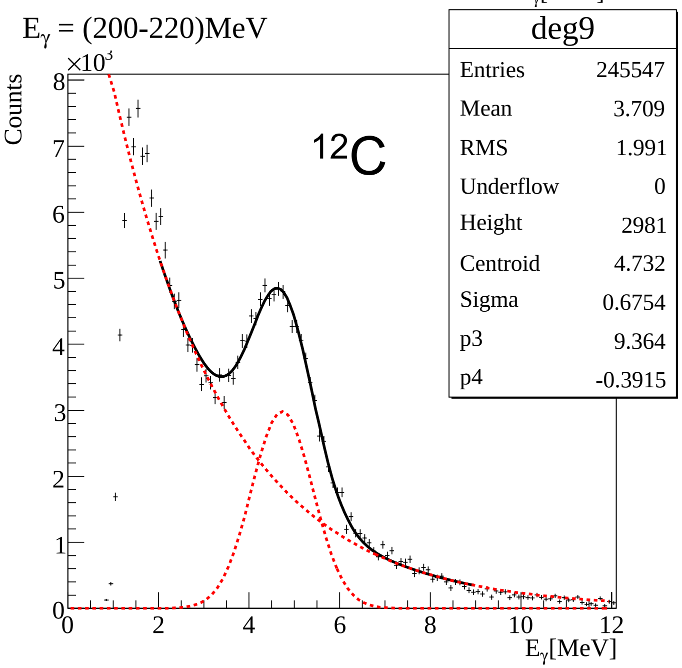
• Cannot extract incoherent strength with attainable resolution of γ and π^0

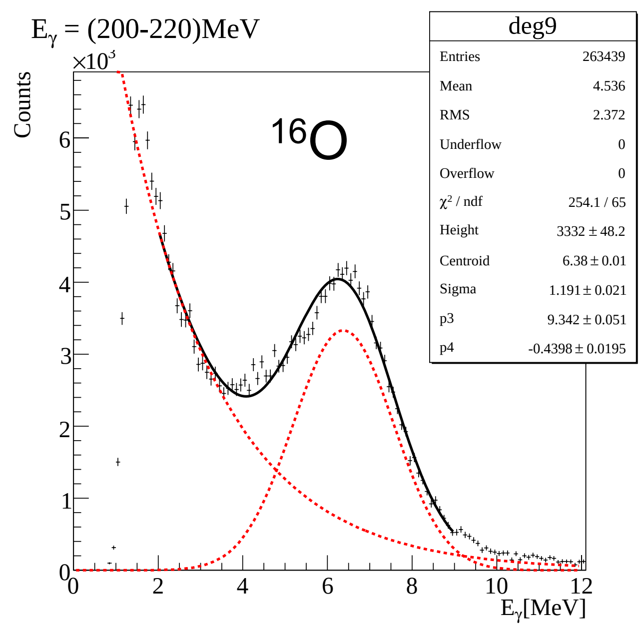
• $\rightarrow$ Detect nuclear decay photon *in the same detector* as the π^0 decay photons

Nuclear decay photons !!

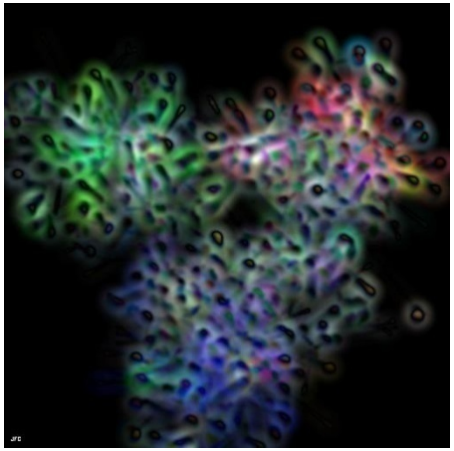








Excitation spectrum of nucleon



- Nucleon: 3 light quarks existing in a sea of virtual gluons and $q\bar{q}$ pairs

- Excitation spectrum → fundamental information on interactions/dynamics of constituents.
  Underpins understanding of the NN force

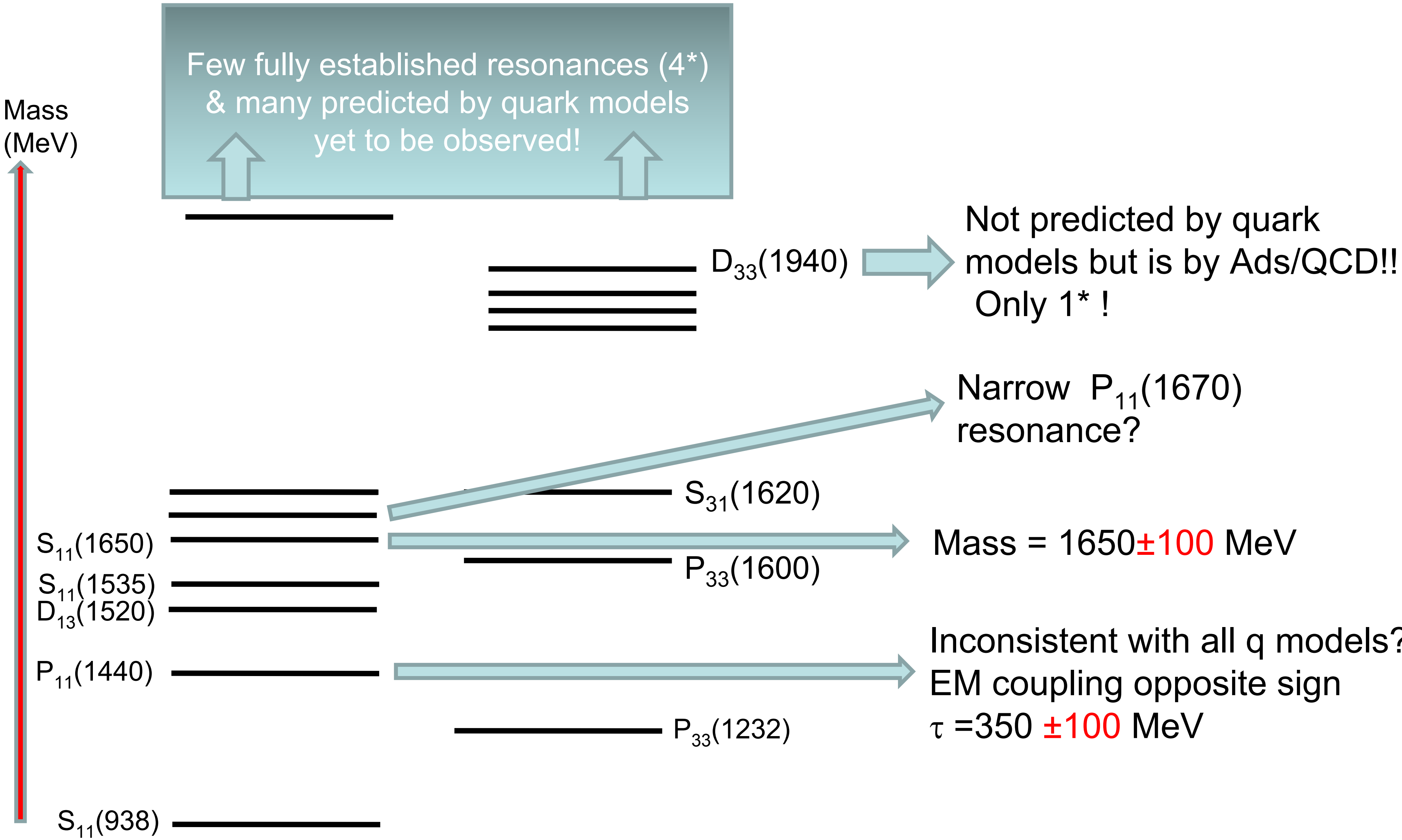
- Predicted by various theories using different approaches)

  Constituent quark models (e.g. Capstick & Roberts, FSU)

  Lattice QCD (fast developing) (e.g. Jefferson Lab, Morningstar)

  Conformal holographic dual of QCD (e.g. Brodsky, SLAC)

- But ... Experimental determination of spectrum is poor



Few fully established resonances (4*)
& many predicted by quark models
yet to be observed!
Mass
(MeV)
D33(1940)
Not predicted by quark
models but is by Ads/QCD!!
Only 1* !
Narrow P11(1670)
resonance?
S31(1620)
S11(1650)
Mass = 1650±100 MeV
P33(1600)
S11(1535)
D13(1520)
Inconsistent with all q models?
EM coupling opposite sign
τ =350 ±100 MeV
P11(1440)
P33(1232)
S11(938)

Polarisation observables

- σ just *one of 16 observables* in pseudo scalar meson photoproduction
- Complete measurement requires 8 well chosen observables
- Only possible with double polarisation measurements

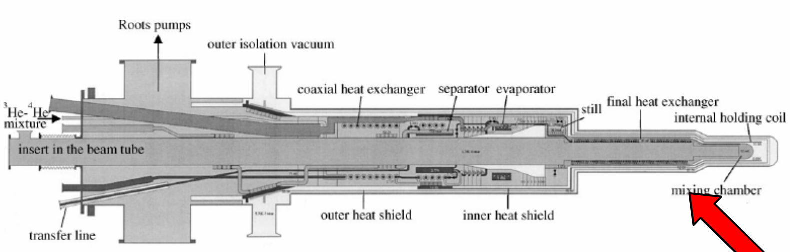
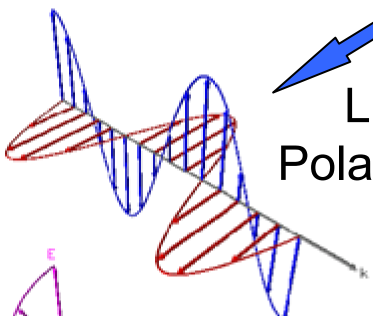


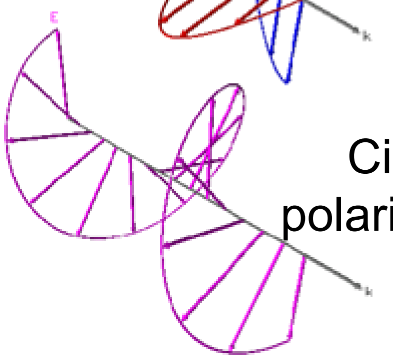
Fig. 4. Schematic diagram of the dilution refrigerator.

Longitudinally polarised proton target ✓
Transversely polarised ✓

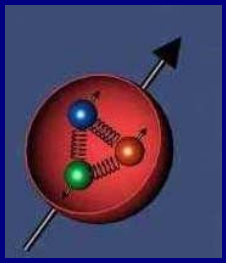
$$\gamma + N \rightarrow N + m$$



Linear Polarisation ✓



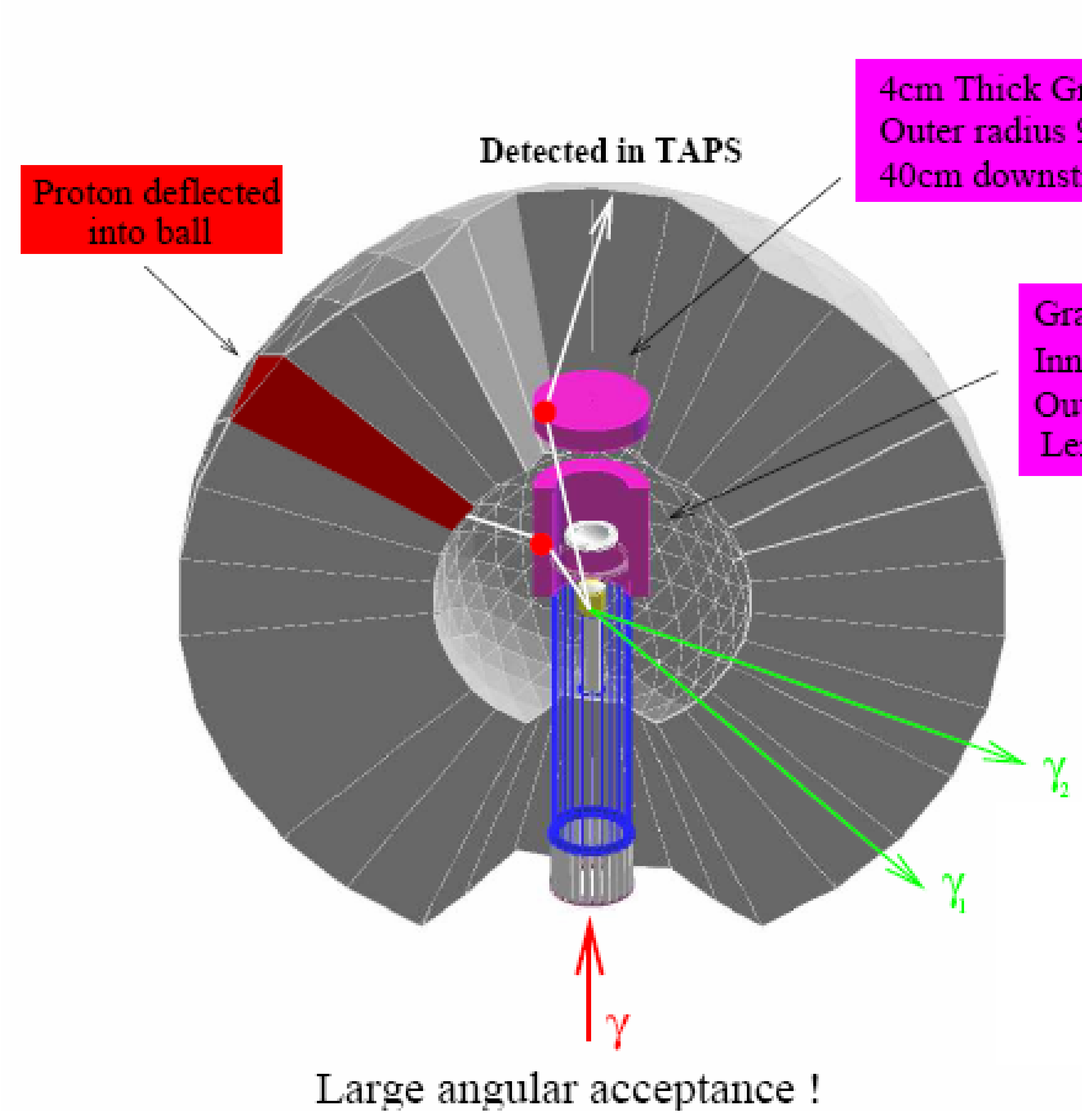
Circular polarisation ✓

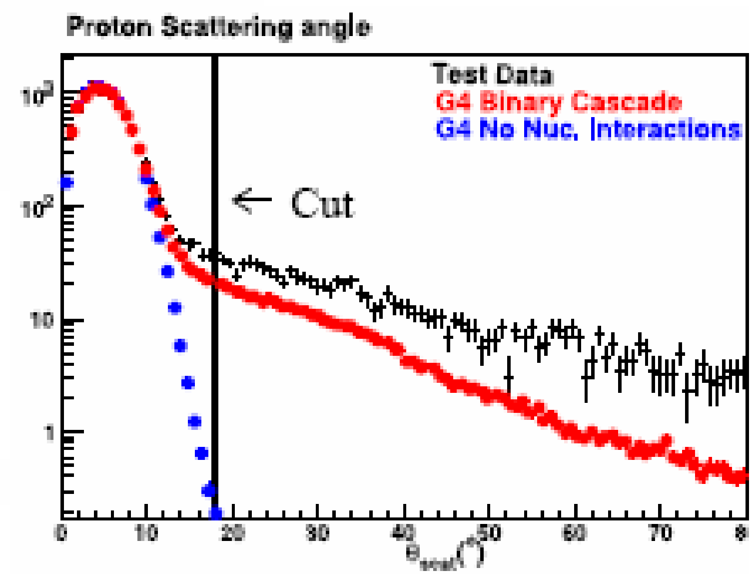


Recoil polarimeter – Provide 4 additional observables to enable the <u>first complete measurement</u>

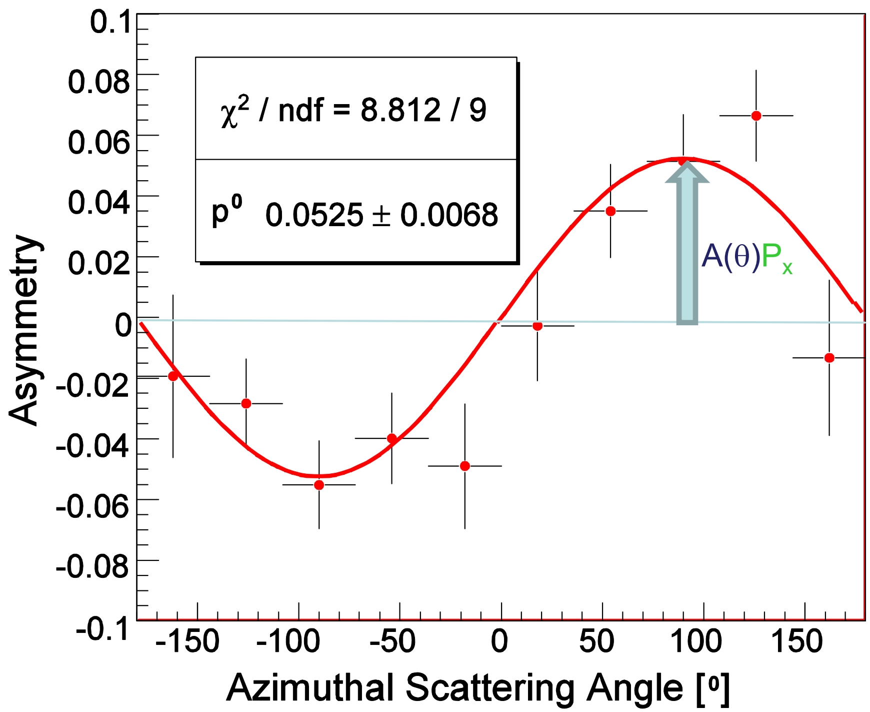
Fully constrain the reaction amplitudes

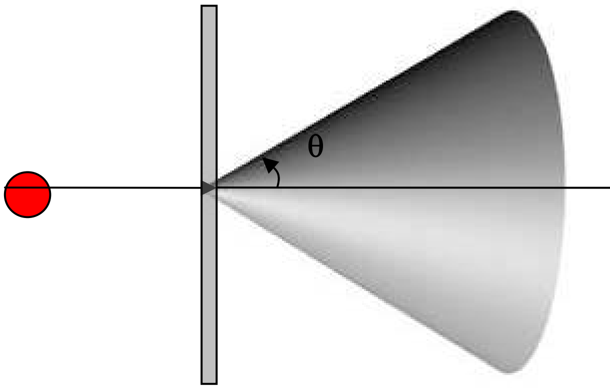
The Edinburgh nucleon polarimeter – test prototype





Results from 1st test of polarimeter





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

Number of nucleons scattered In the direction θ, ϕ

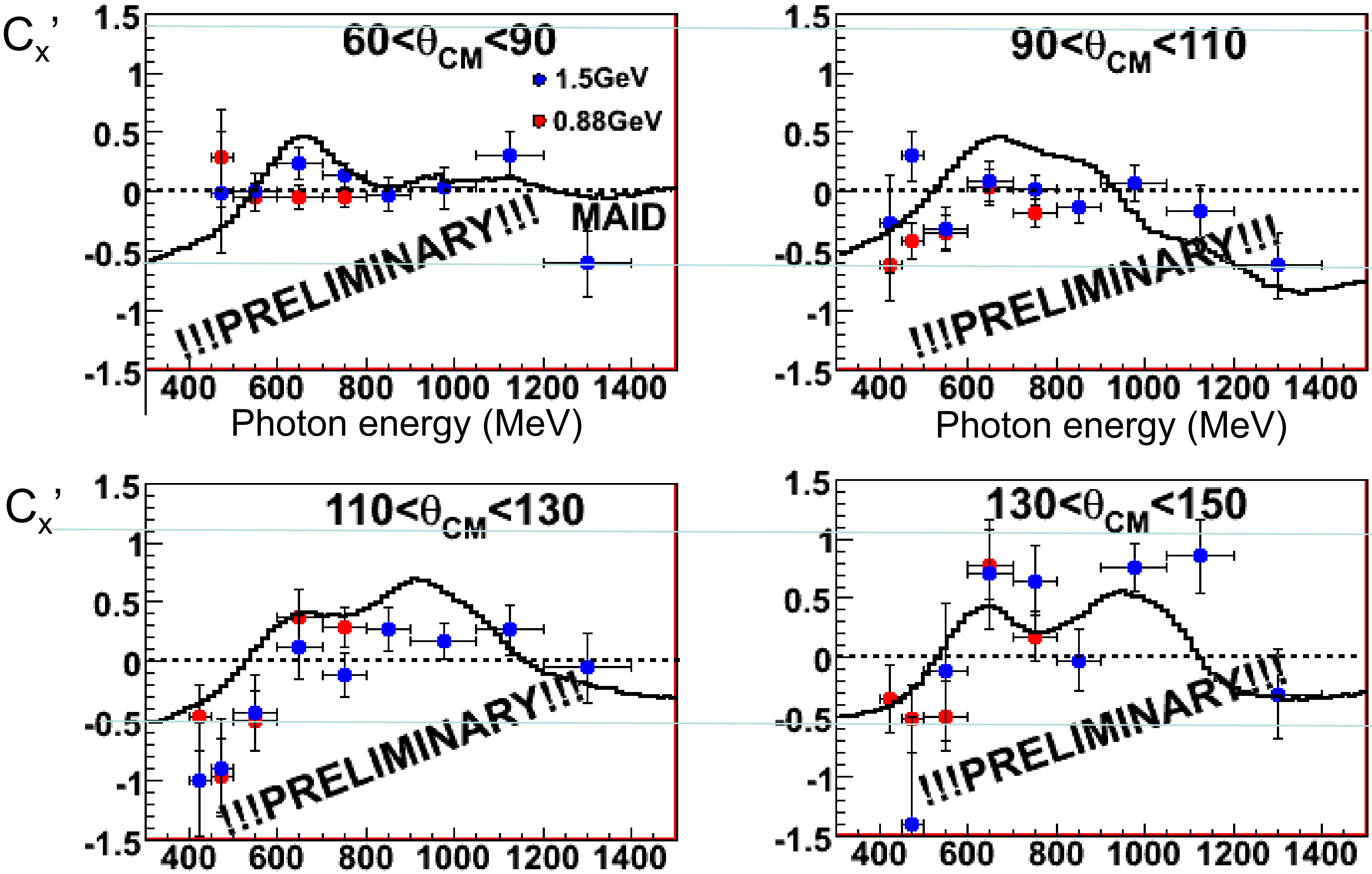
Polar angle distribution for unpolarised nucleons

Analysing power of scatterer

x and y (transverse) components of nucleon polarisation

Analysis of test data – p(γ,π^0)p $C_{x'}$

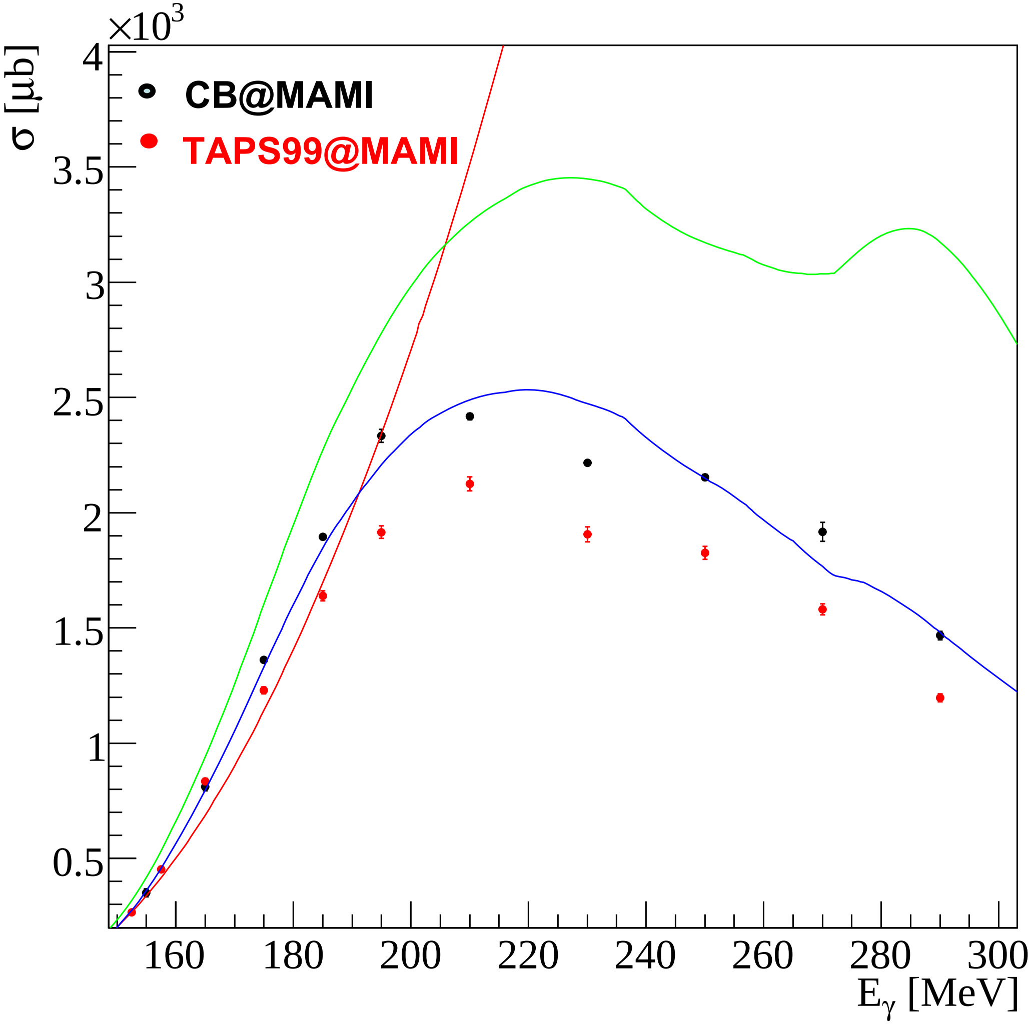
- First measurement of beam helicity transfer in resonance region
- 1000 hour production beamtime later this year



The way forward – First “Complete measurement”

Observable	Polarisation of γ	target	recoil	
1. $\{d\sigma/d\Omega\}/\mathcal{N}$				$=\lvert b_1\rvert^2+\lvert b_2\rvert^2+\lvert b_3\rvert^2+\lvert b_4\rvert^2$
Single polarization				
2. P			↑	$=\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$
3. Σ	→			$=\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$
4. T		→		$=\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$
Double polarizaton				
Beam-target				
5. E	●	●		$=2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
6. F	●	→		$=2\,\mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$
7. G	→	●		$=2\,\mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$
8. H	→	→		$=-2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
Beam-recoil				
9. C_x	●		→	$=-2\,\mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$
10. C_y	●		●	$=2\,\mathrm{Re}(b_1 b_4^* + b_2 b_3^*)$
11. O_x	→		→	$=2\,\mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$
12. O_z	→		●	$=2\,\mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$
Target-recoil				
13. T_x		→	→	$=2\,\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$
14. T_z		→	●	$=2\,\mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$
15. L_x		●	→	$=-2\,\mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$
16. L_z		●	●	$=2\,\mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$

^{208}Pb: Total coherent cross sections



PWIA

DWIA

DWIA+Δ self energy.

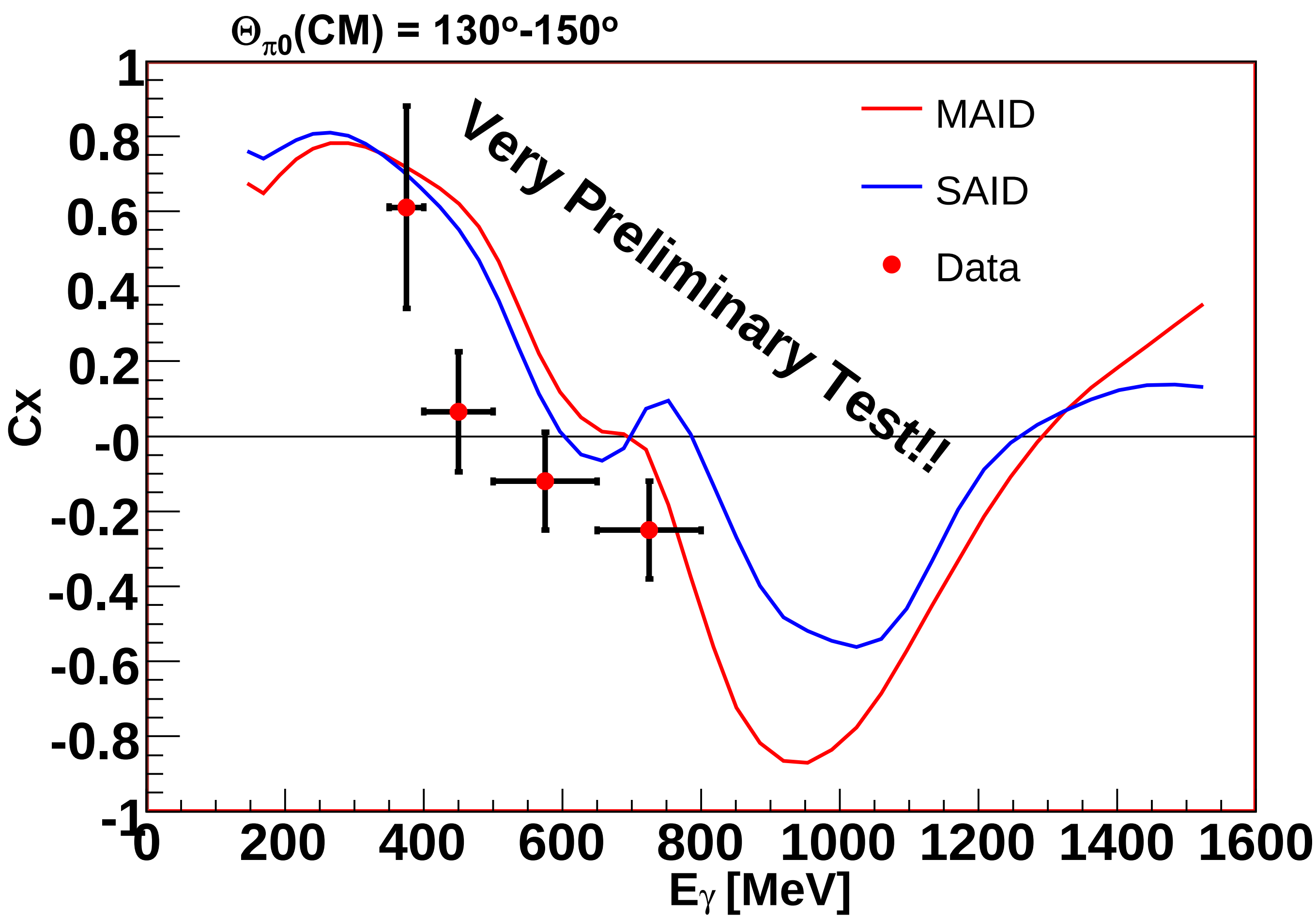
Theoretical prediction

Dreschel, Tiator, Kamalov & Yang - NPA 660 (1999)

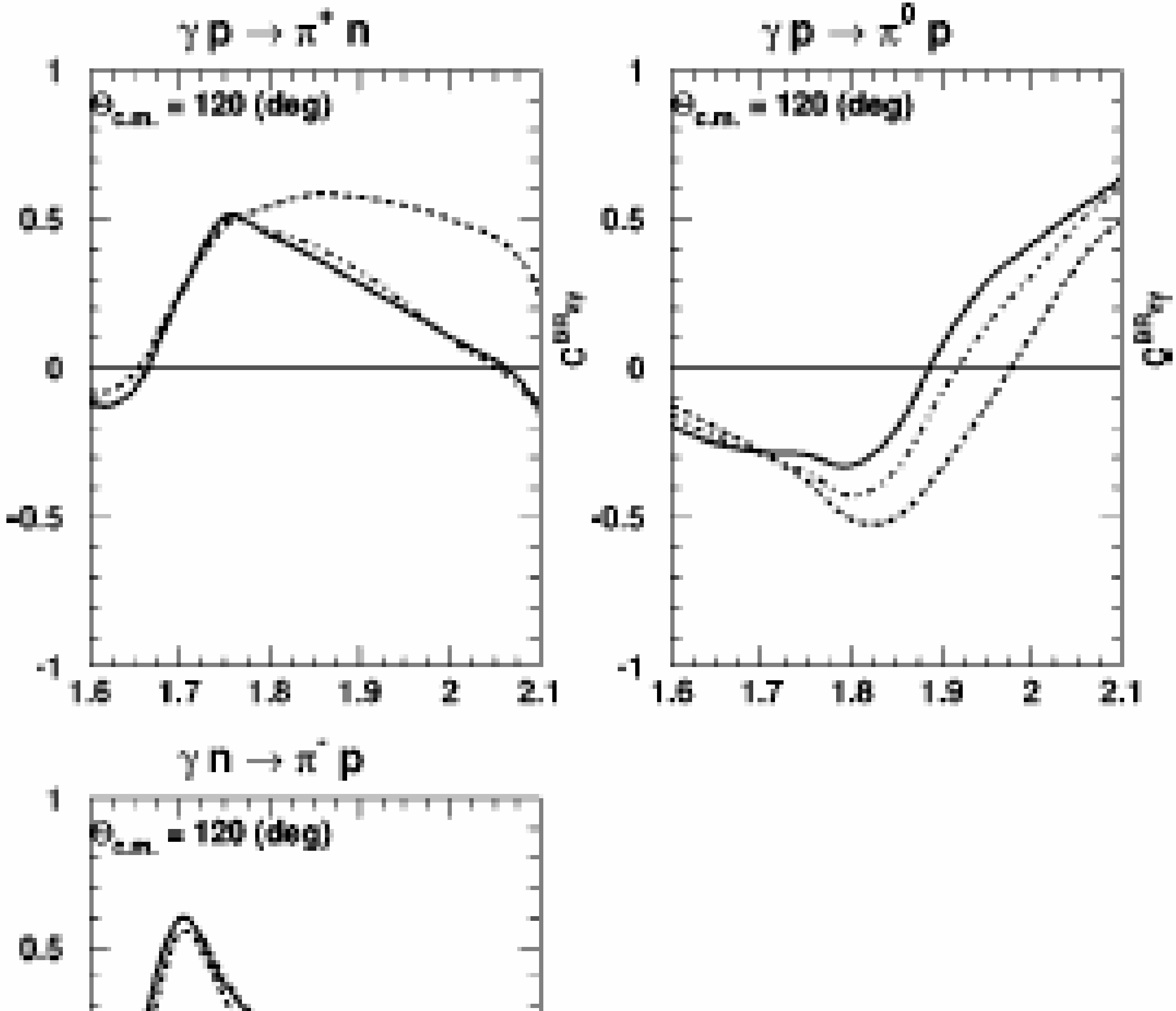
π^0 production amplitude from Unitary Isobar Model

π^0 interaction treated with momentum space optical potential supplemented with Δ self-energy

Preliminary (!!) extraction of C_x in $p(\gamma,\pi^0)p$



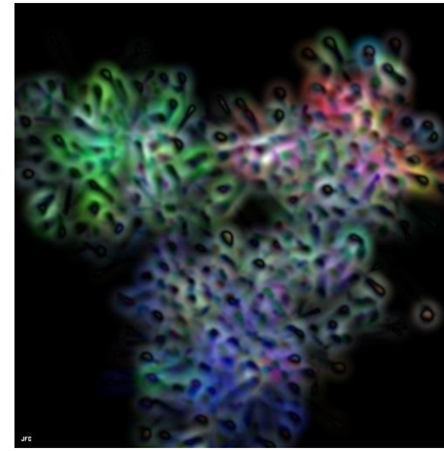
- C_x – Polarisation transfer from helicity polarised beam to recoil N
- 1000 hour beamtime scheduled in 2007 !!



γ p → π⁺ n
Θc.m. = 120 (deg)
γ p → π⁰ p
Θc.m. = 120 (deg)
γ n → π⁻ p
Θc.m. = 120 (deg)
1
0.5
0
-0.5
-1
1.6
1.7
1.8
1.9
2
2.1

Excitation spectrum of nucleon

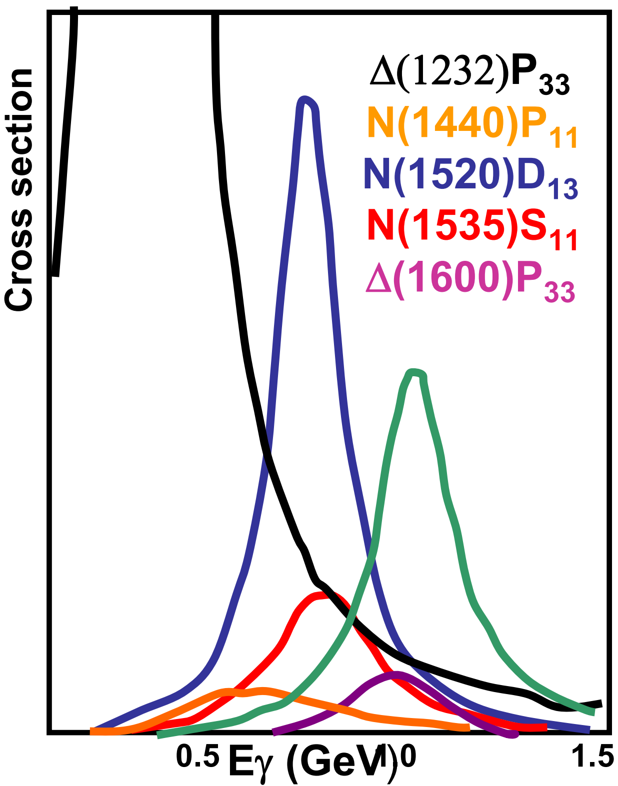
- Primary motivation of the new EM beam facilities
  → better establish the nucleon excitation spectrum

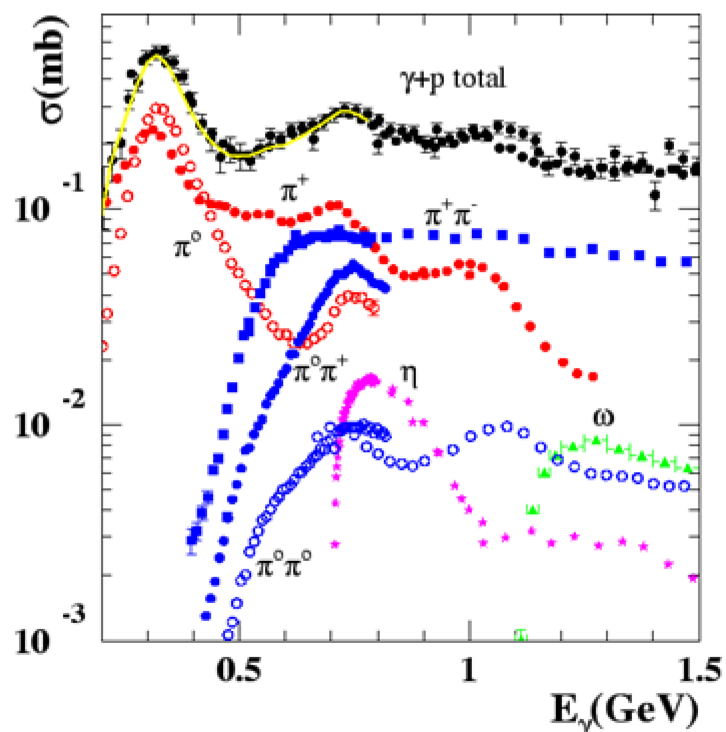


- Meson photoproduction reactions on nucleon targets

$$\gamma + \mathbf{N} \rightarrow \mathbf{N^*} \rightarrow N + \pi$$

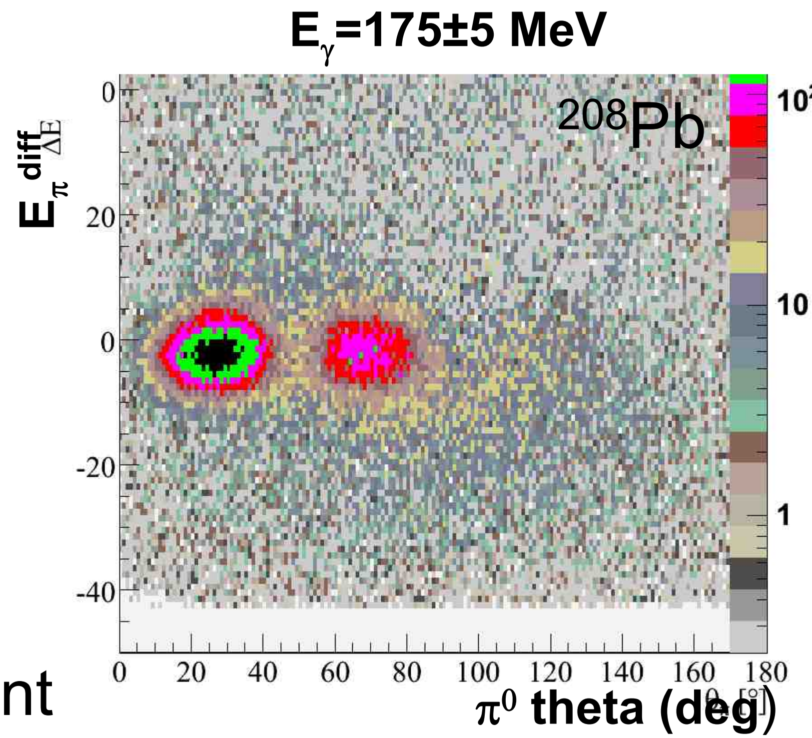
- τ small → resonances are broad ($\Delta E \Delta\tau \sim \hbar$)

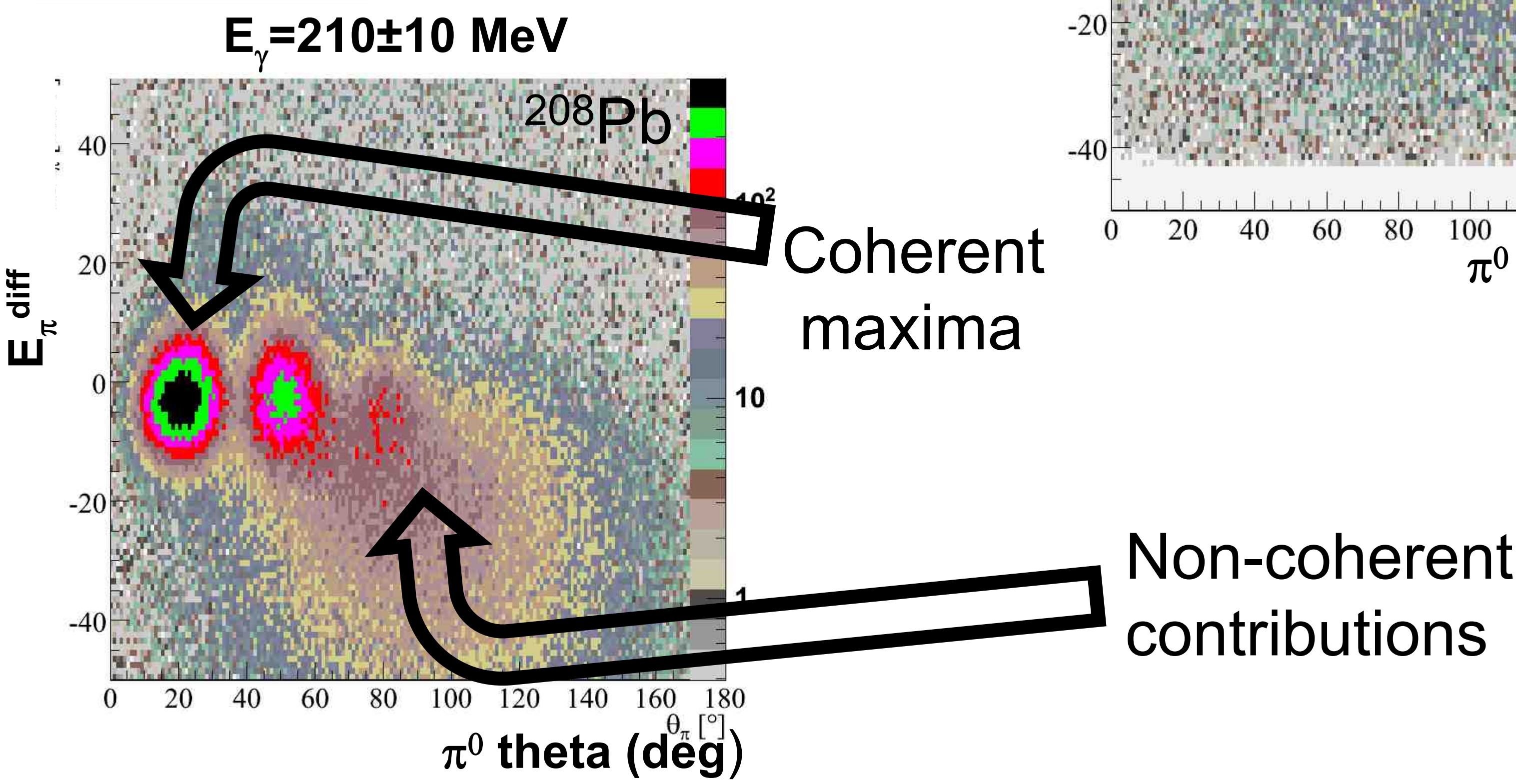




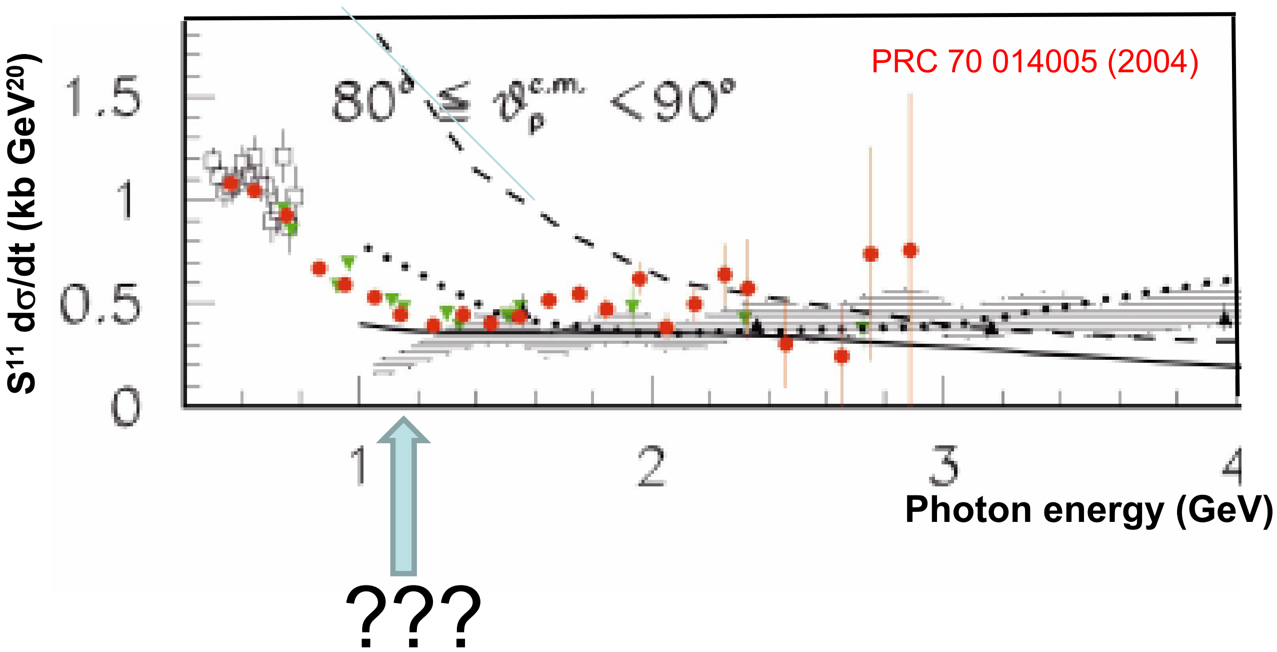
Coherent pion photoproduction - analysis

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





Onset of quark degrees of freedom in the Deuteron



- pQCD quark prediction: σ will scale with s^{-11} $\rightarrow$ D(γ,pn) at 1GeV ??
- More sensitivity → Polarisation transfer (=0 for pQCD - hadron helicity conservation)
- Edinburgh polarimeter - first measurement through "transition"
- Also test new generation of baryon-meson models, quark gluon string models ...

J.Brudvik, J. Goetz, B.M.K.Nefkens, S.N.Prakhov, A.Starostin, I. Saurez, University of California, Los Angeles, CA, USA

J.Ahrens, H.J.Arends, D.Drechsel, D.Krambrich, M.Rost, S.Scherer, A.Thomas, L.Tiator, D. von Harrach and Th.Walcher Institut fur Kernphysik, University of Mainz, Germany

R. Beck, M. Lang, A. Nikolaev, S. Schumann, M. Unverzagt, Helmholtz-Institut fur strahlen und Kernphysik, Universitat Bonn,

S.Altieri, A.Braghieri, P.Pedroni, A.Panzeri and T.Pinelli INFN Sezione di Pavia and DFNT University of Pavia, Italy

J.R.M.Annand, R.Codling, E.Downie, J. Kellie, K.Livingston, J.McGeorge, I.J.D.MacGregor, R. Owens D.Protopopescu and G.Rosner Department of Physics and Astronomy, University of Glasgow, Glasgow, UK

C.Bennhold and W.Briscoe George Washington University, Washington, USA

S.Cherepnya, L.Fil'kov, and V.Kashevarow Lebedev Physical Institute, Moscow, Russia

V.Bekrenev, S.Kruglov, A.Koulbardis, and N.Kozlenko Petersburg Nuclear Physics Institute, Gatchina, Russia

B.Boillat, B.Krusche and F.Zehr, Institut fur Physik University of Basel, Basel, Ch

P. Drexler, F. Hjelm, M. Kotulla, K. Makonoyi, R.Novotny, M. Thiel and D. Trnka II. Phys. Institut, University of Giessen, Germany

D.Branford, K.Foehl, D. Glazier, T. Jude, C.Tarbert and D.P.Watts, School of Physics, Univ. of Edinburgh, Edinburgh, UK

V.Lisin, R.Kondratiev and A.Polonski Institute for Nuclear Research, Moscow, Russia

J.W. Price California State University, Dominguez hills, CA, USA

D.Hornidge Mount Allison University, Sackville, Canada

P. Grabmayr and T. Hehl Physikalisches Institut Universitat Tubingen, Tubingen, Germany

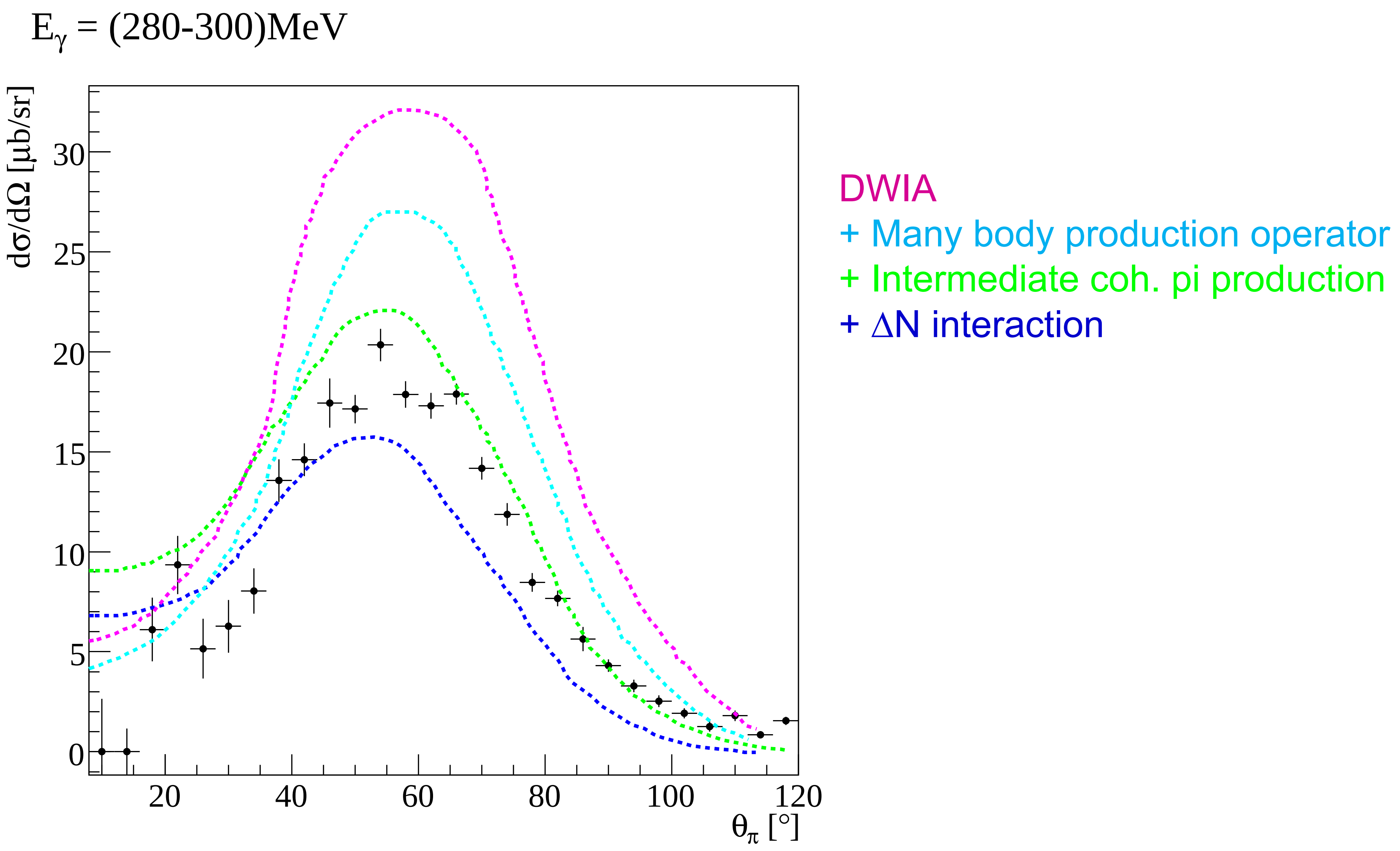
D.M. Manley Kent State University, Kent, USA

M. Korolija and I. Supek Rudjer Boskovic Institute, Zagreb, Croatia

D. Sober, Catholic University, Washington DC

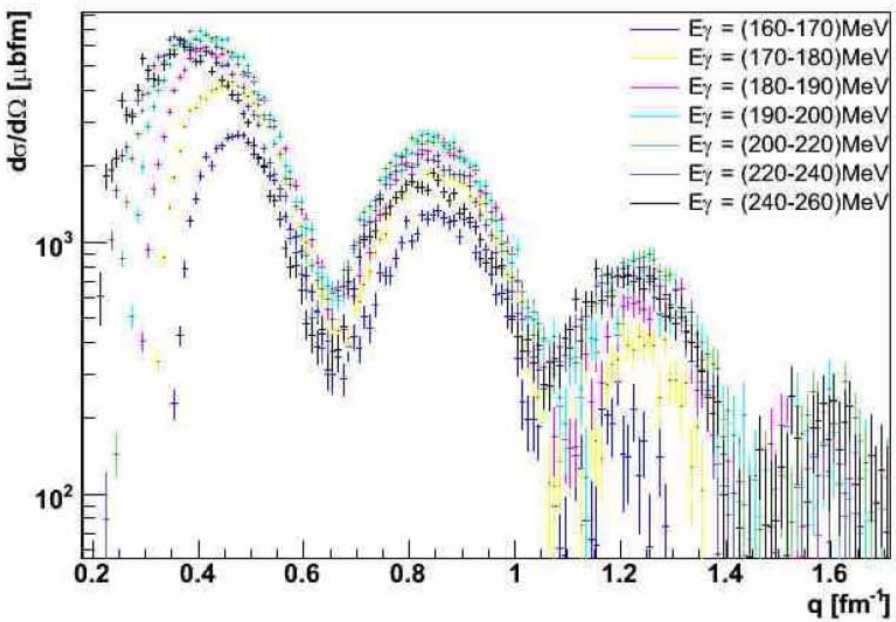
M. Vanderhaeghen, College of William and Mary, Williamsburg, USA

CB@MAMI



Eγ = (280-300)MeV
dσ/dΩ [μb/sr]
θπ [°]
0
5
10
15
20
25
30
20
40
60
80
100
120
DWIA
+ Many body production operator
+ Intermediate coh. pi production
+ ΔN interaction

^{208}Pb : Momentum transfer distributions

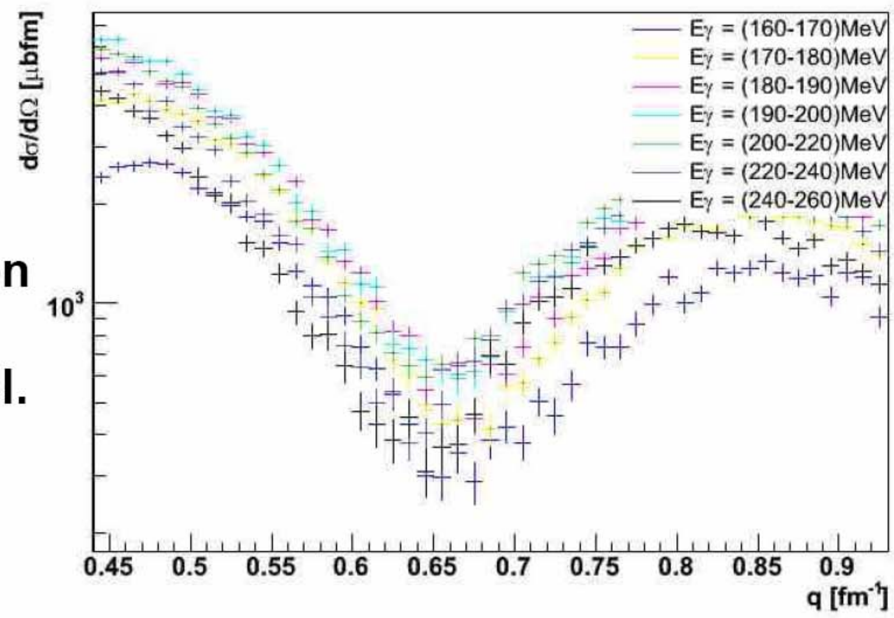


Without FSI cross section could be descibed by PWIA.

FSI has effect of:

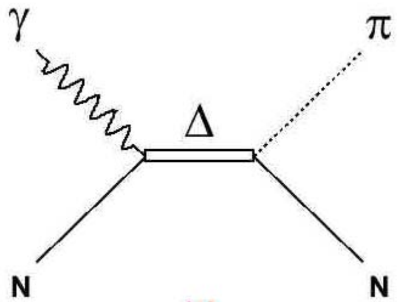
1. Changing momentum of outgoing pion as it leaves the nucleus (shift in q).

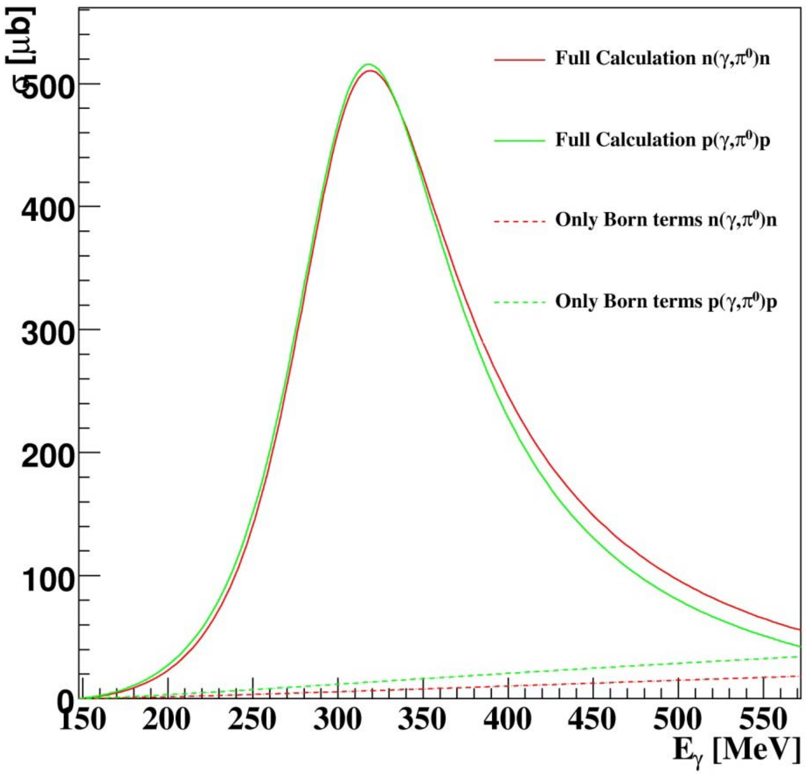
2. Loss of strength with another channel.



π^0 photoproduction - amplitude

- Basic production amplitude ~ equal for protons and neutrons
- Dominated by $\Delta(1232)$ production



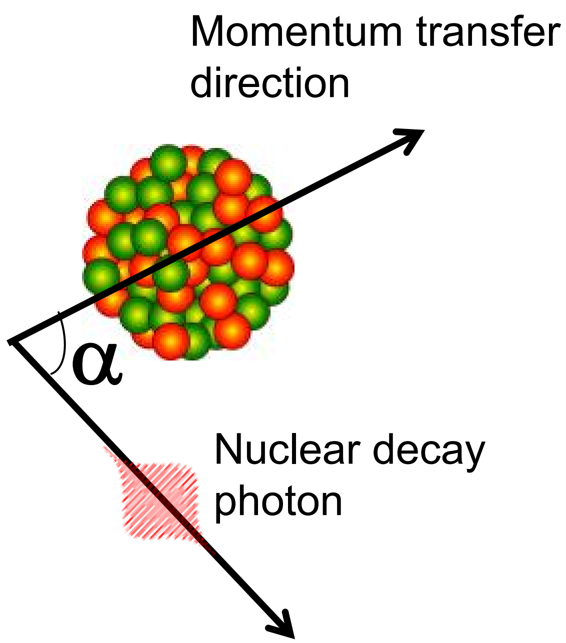


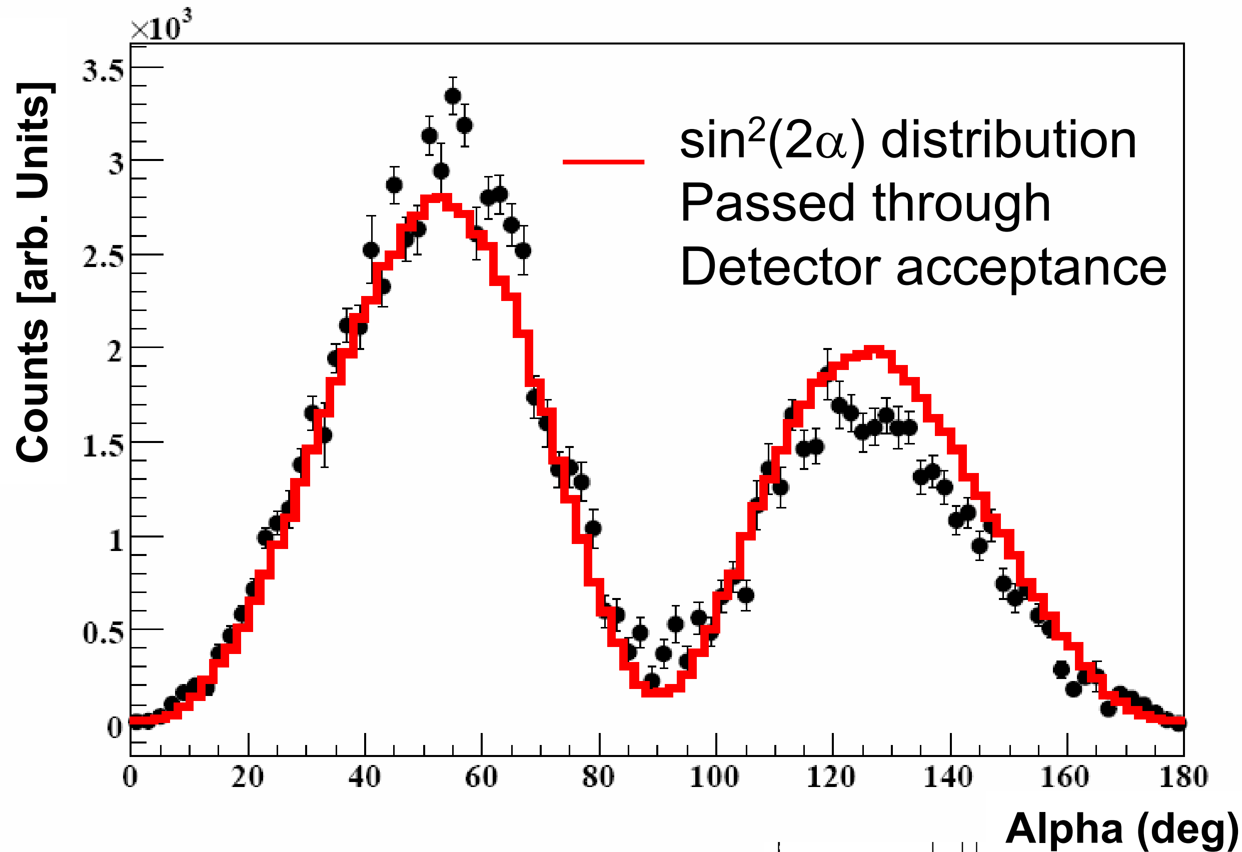
Isospin structure of amplitude

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

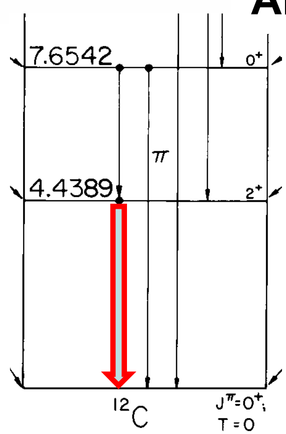
Δ has I=3/2 -- A^{V3} only

Alignment of recoiling ^{12}C nucleus

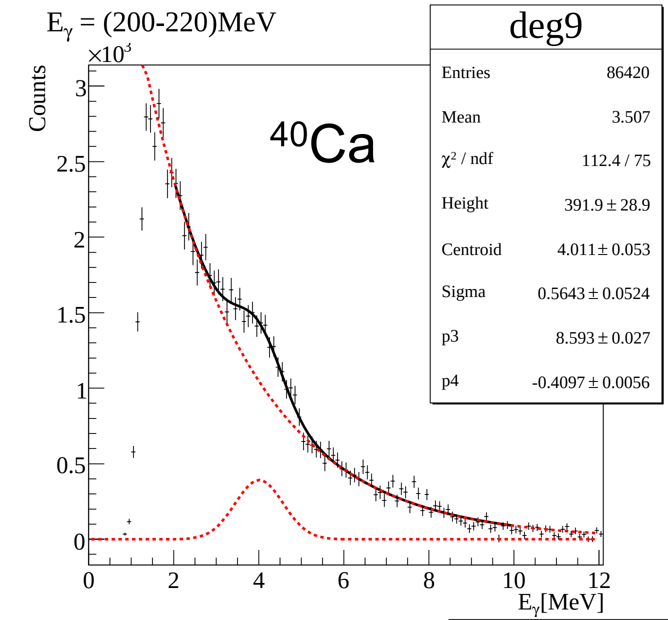


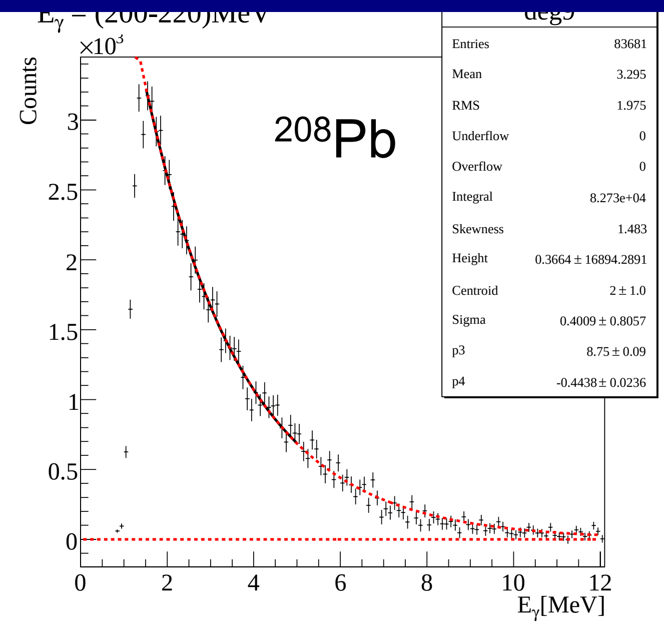


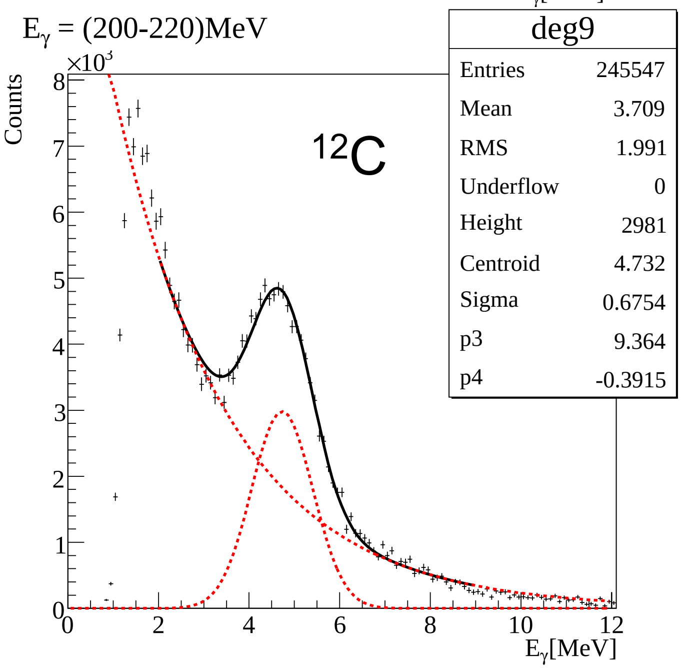
- Strong $\sin^2(2\alpha)$ distribution for 4.4 MeV photons
- 2^+ to 0^+ transition from aligned residual nucleus
- Degree of alignment - new experimental observable!!

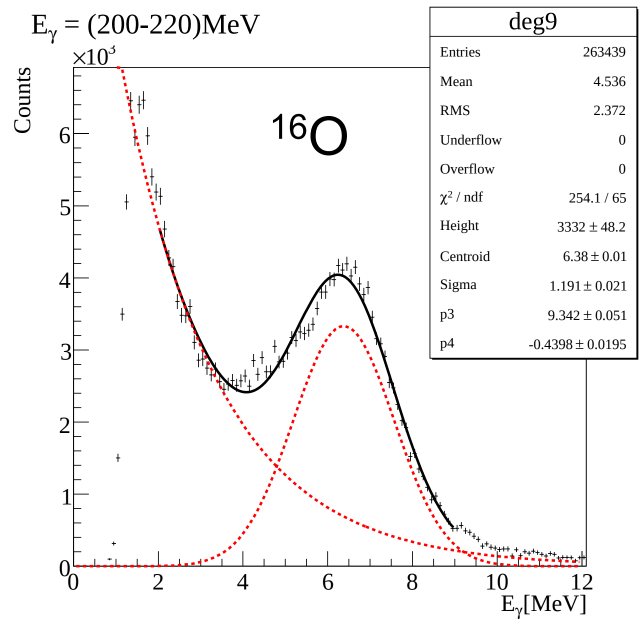


Nuclear decay photons in the Crystal Ball !!

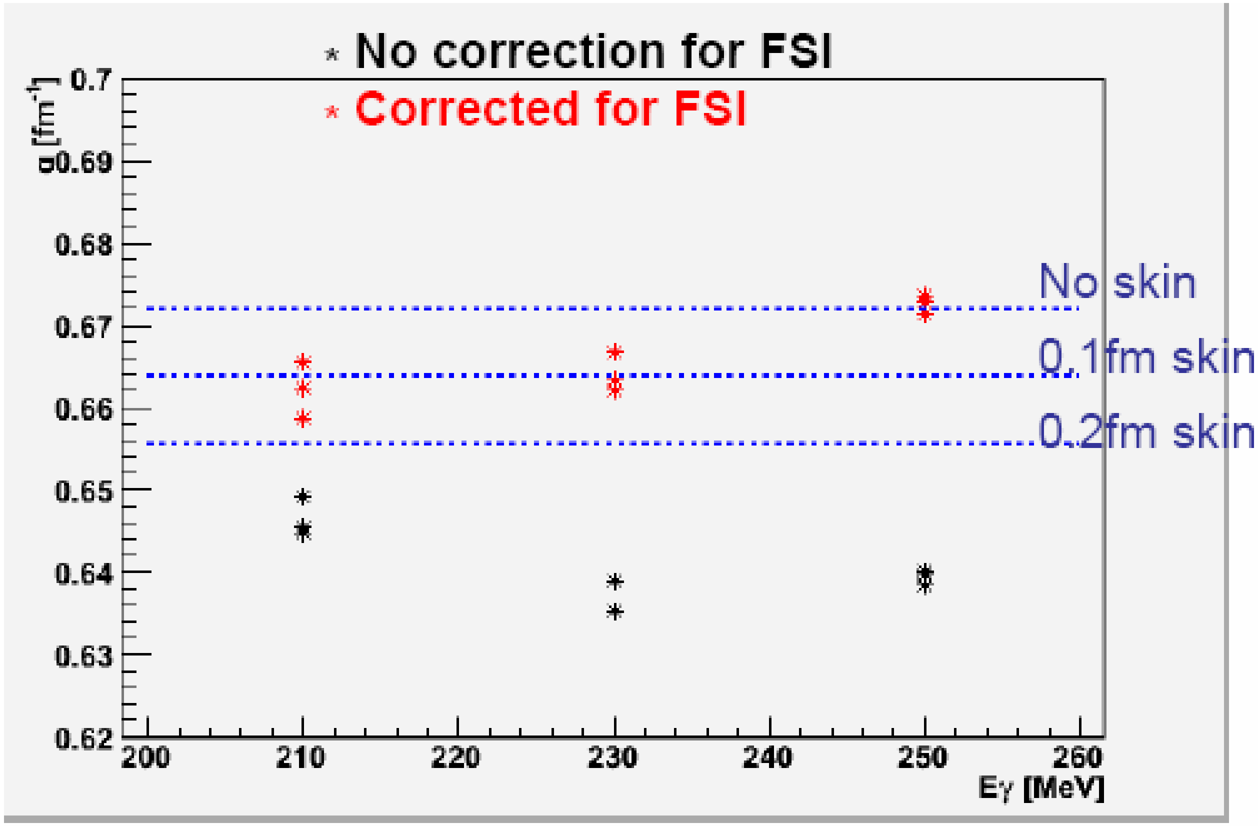








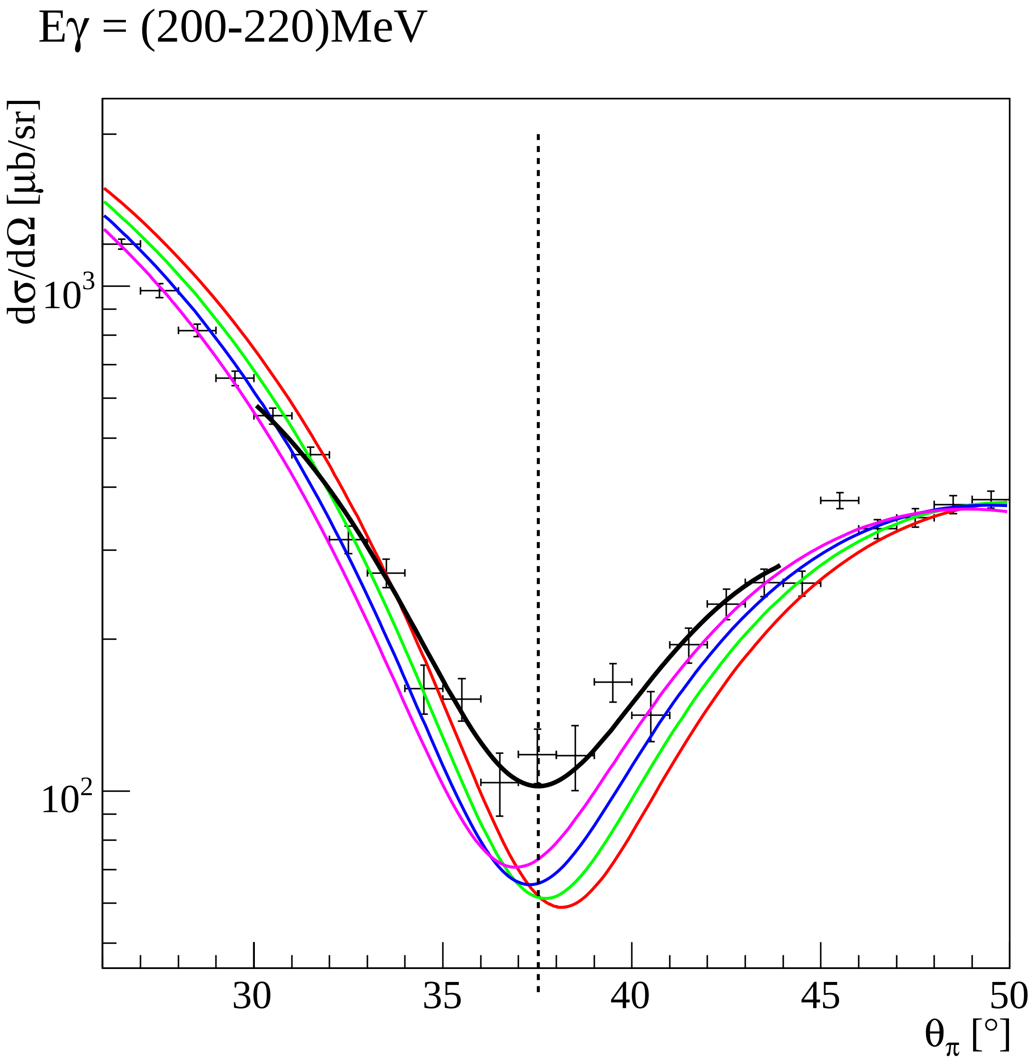
^{208}Pb neutron skin – preliminary assessment



- See effects of a neutron skin of 0.1-0.15 fm !! (preliminary)
- More detailed analysis in progress to reduce and assess systematics
- Future measurement - skin development across isotopic chain?

^{208}Pb: Preliminary evaluation of Neutron skin effects

- No neutron skin
- 0.1 fm skin
- 0.2 fm skin
- 0.3 fm skin

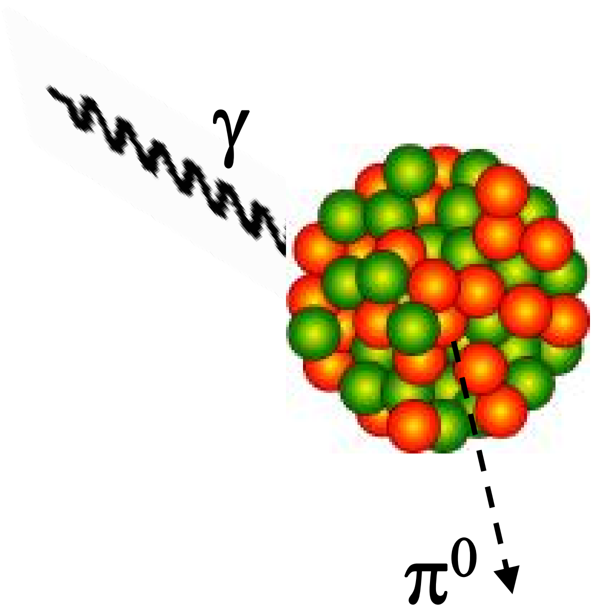


π^0 photoproduction as a nuclear probe

- Gives information on the matter distribution ***with EM probe***
- π^0 production ~ identical probability from protons & neutrons

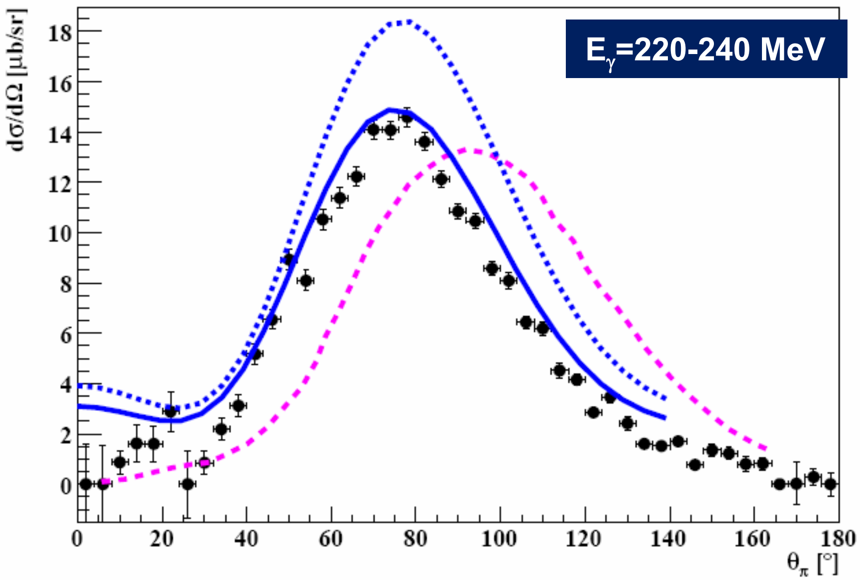
Access matter form factor and matter transition form factors

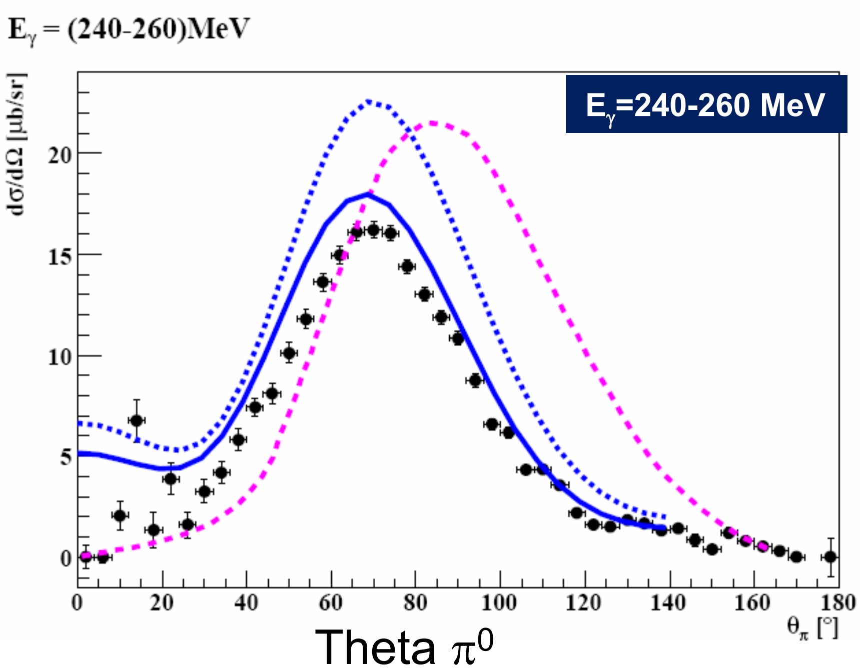
Precision test of our understanding of the Δ–nucleon interaction



Test specific aspects of the pion production amplitude

Transition matter form factors



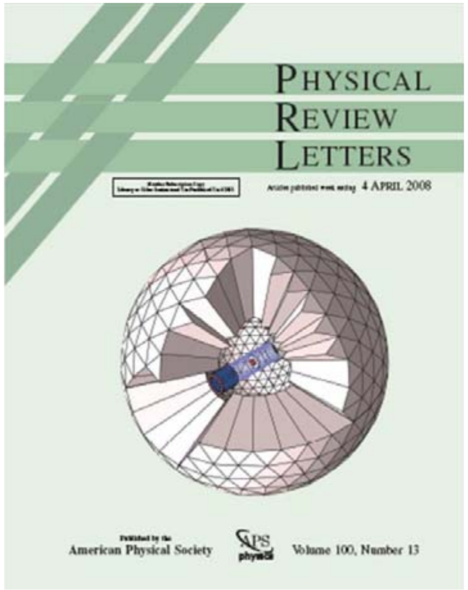


Takaki Δ-hole model (NPA 443 p570 (1985))

— Full calculation

--- Without Δ-N interaction

— Tryasuchev (Phs At. Nuc. 70 827 (2007))

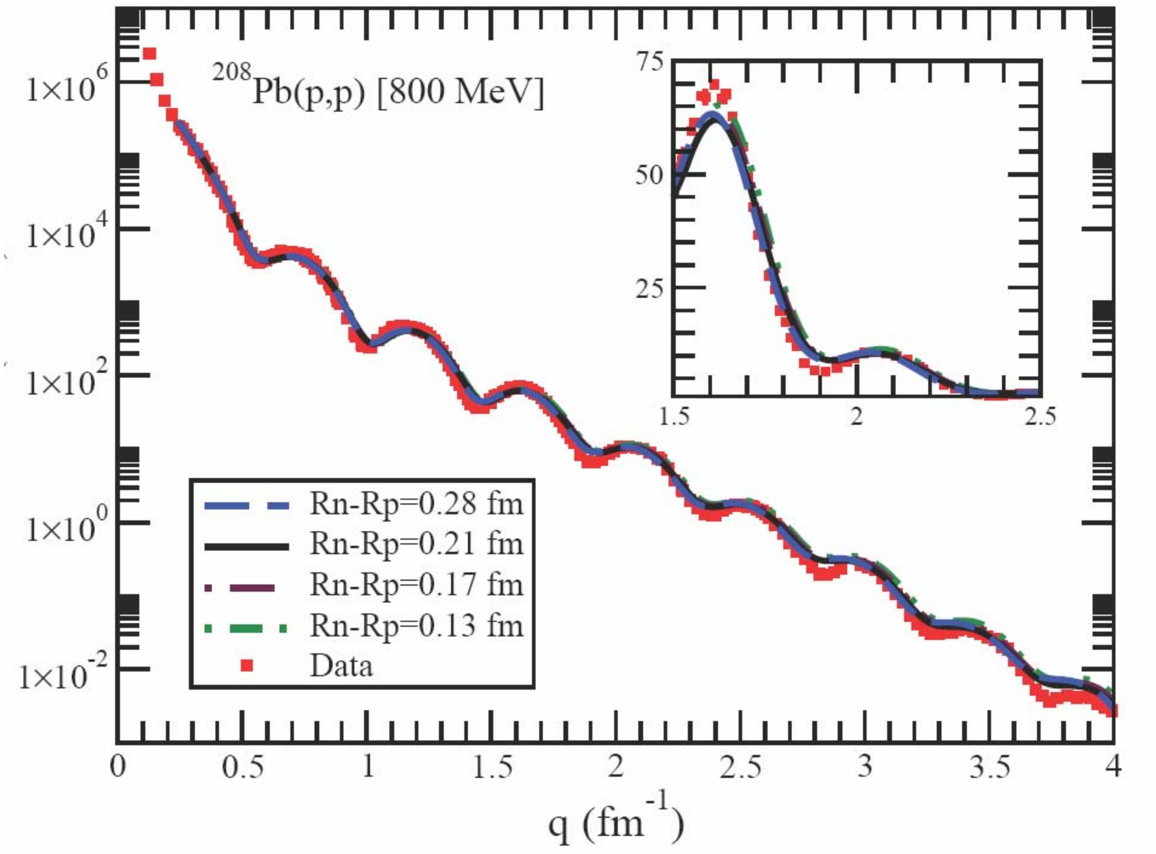


CM Tarbert, DP Watts et. al., Phys. Rev. Lett (2008)

Coherent π^0 analysis - next steps

- “Model independent” extraction of matter form factor as done for elastic electron scattering
- Parameterise $\rho(r)$ - sum of bessel functions
- Fit theoretical predictions to data to extract coefficients
- Active collaboration with people involved in charge distribution measurements

Why is neutron radius hard to establish?



"Insensitivity of the elastic proton–nucleus reaction to the neutron radius of ^{208}Pb"

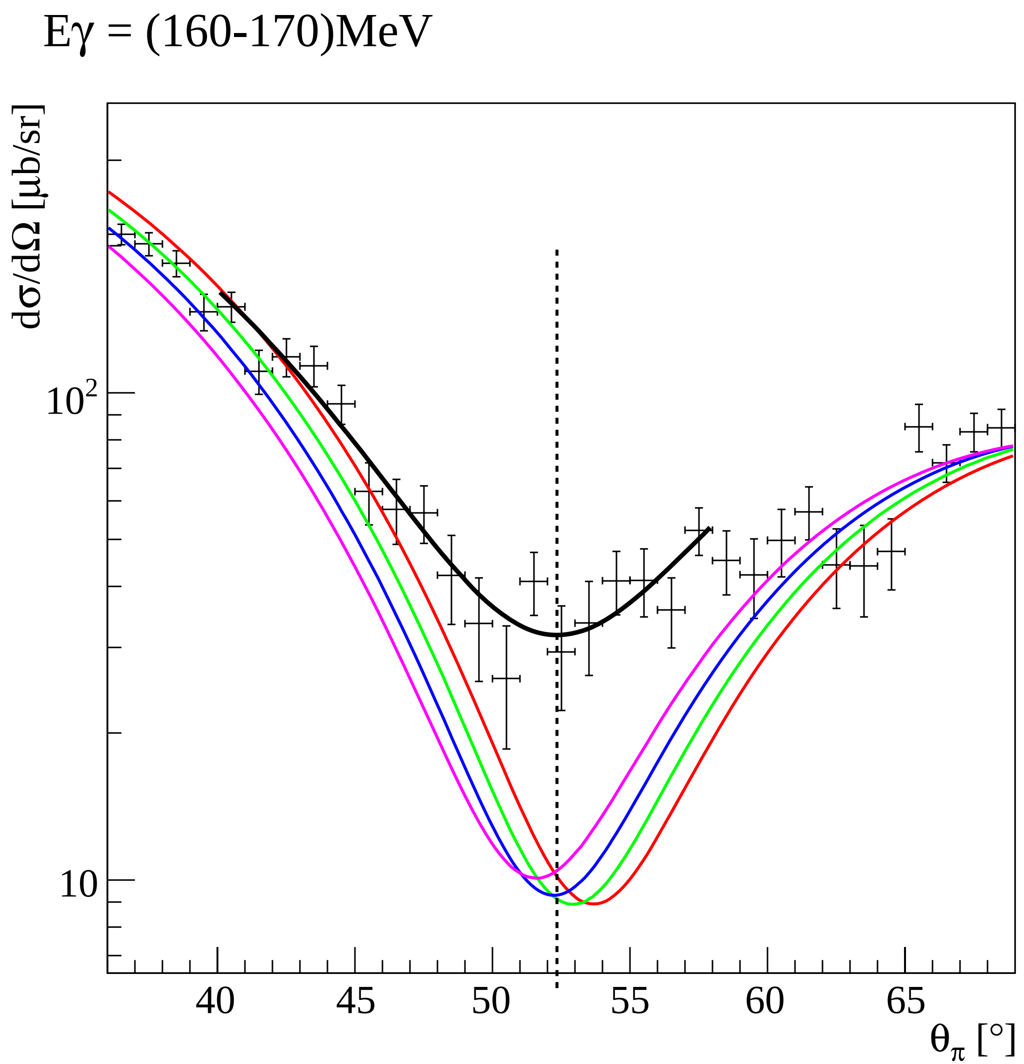
Piekarewicz and Pieper

NPA 778 10 (2006)

Maybe mention antiproton stuff?

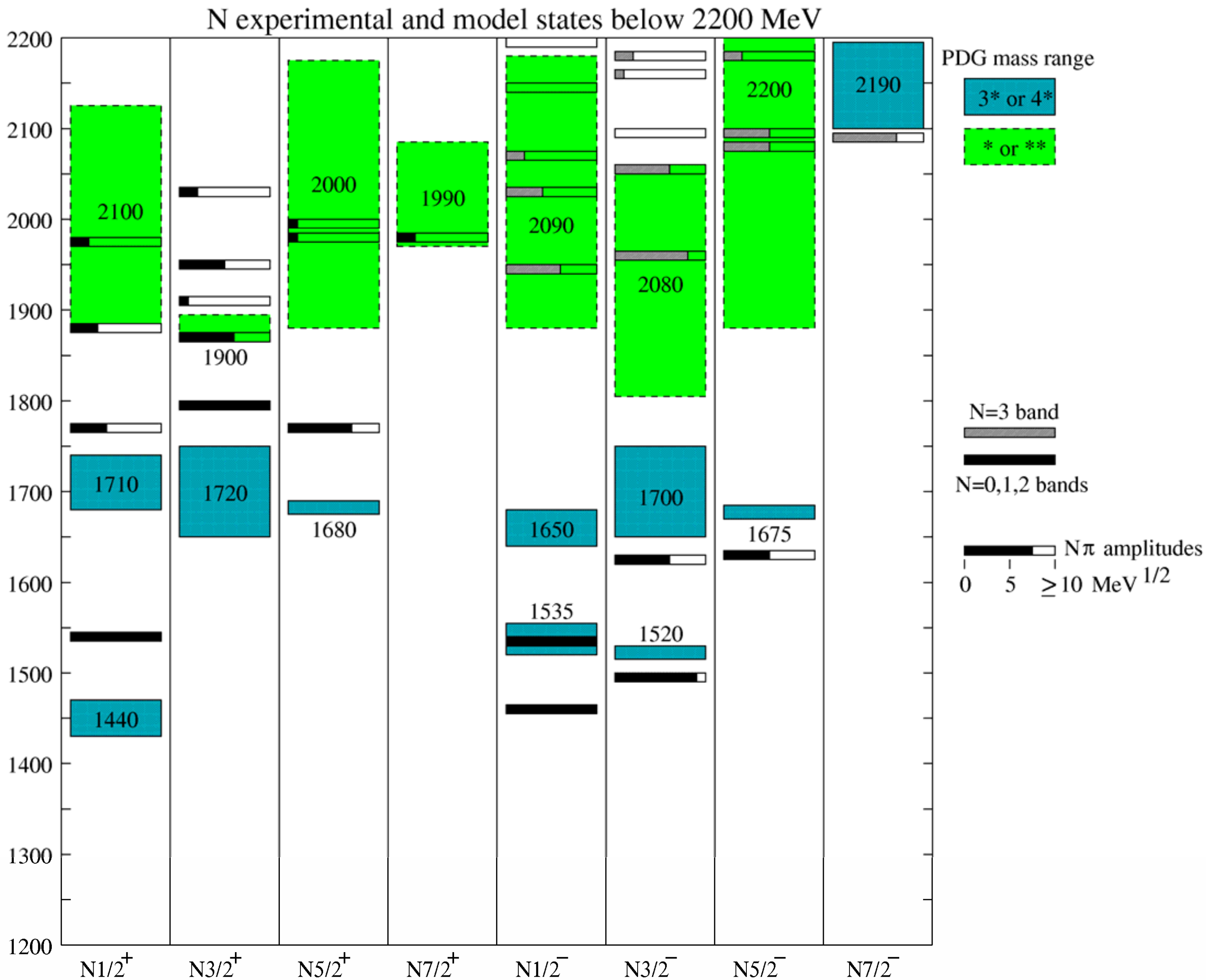
^{208}Pb: Preliminary evaluation of Neutron skin effects

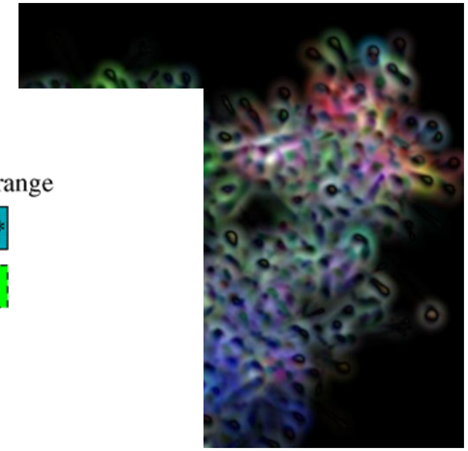
- No neutron skin
- 0.1 fm skin
- 0.2 fm skin
- 0.3 fm skin



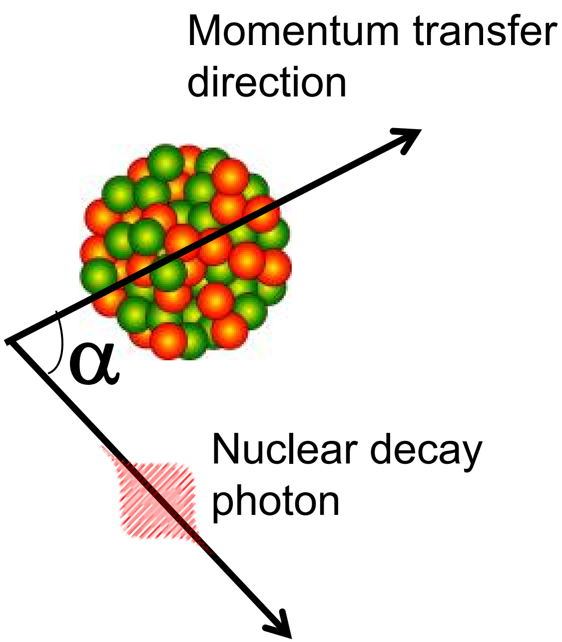
Excitation spectrum of nucleon

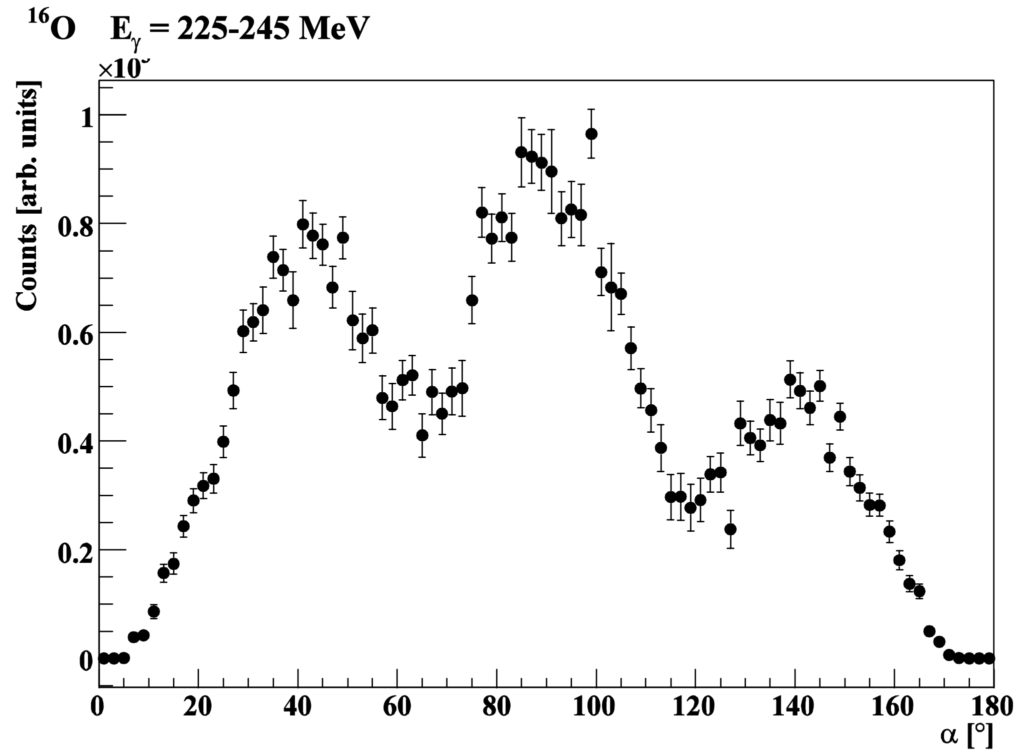
- Structure of nucleon fundamental – gives important information on nature of quark confinement



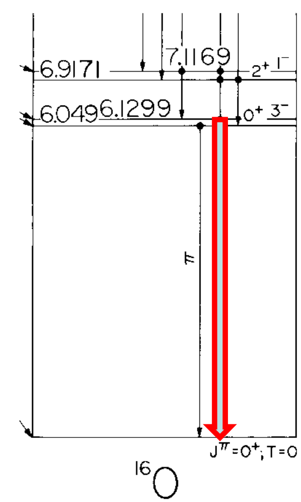


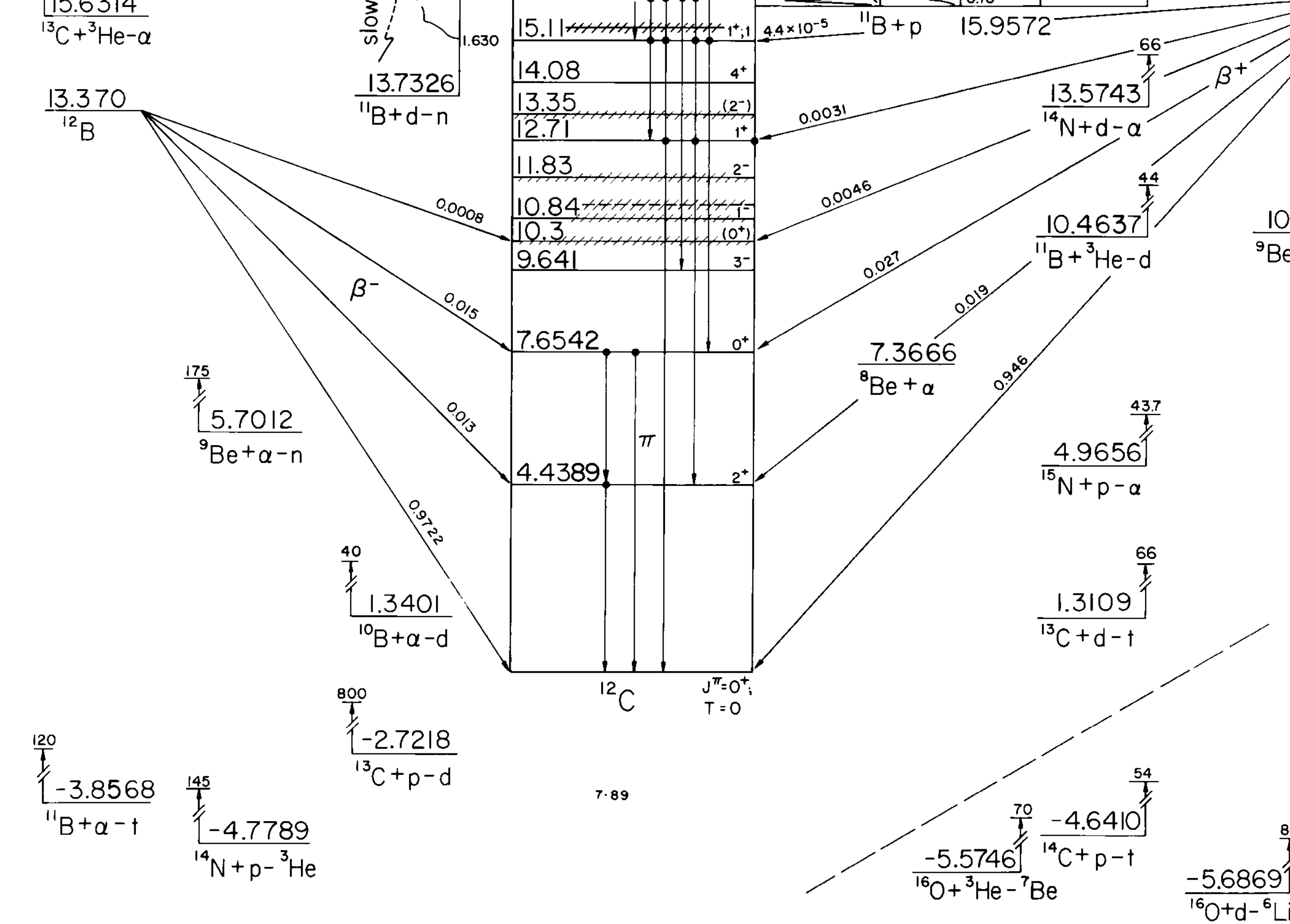
Alignment of recoiling ^{16}O nucleus





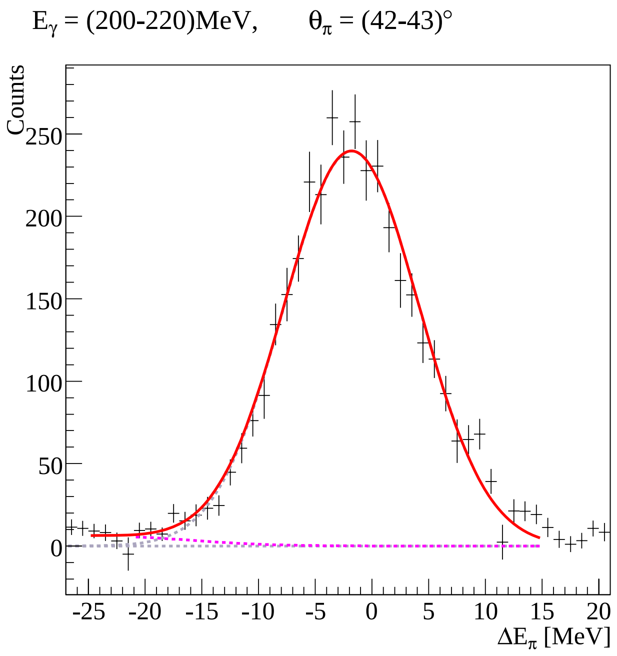
- Strong $\sin^2(3\alpha)$ component
- Expected from 3^- to 0^+ transition

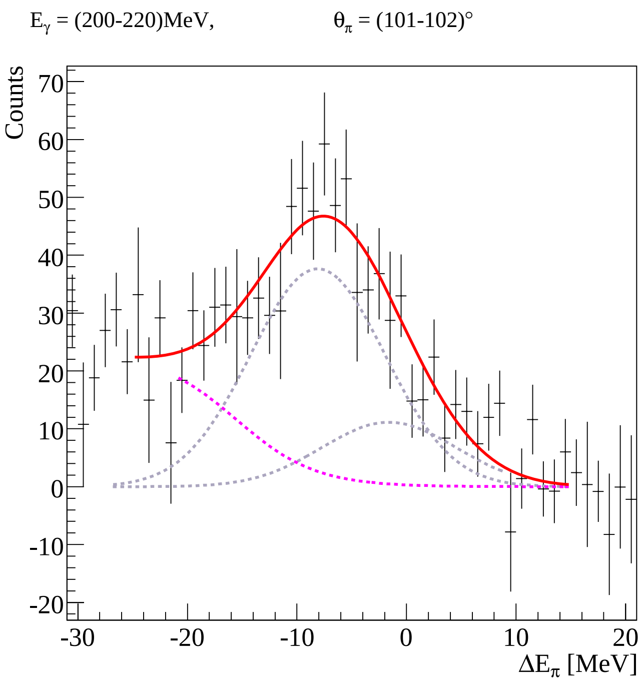




15.6314
13C+3He-α
slow
1.630
13.7326
11B+d-n
13.370
12B
β−
0.0008
0.015
0.013
0.9722
175
5.7012
9Be+α-n
40
1.3401
10B+α-d
800
-2.7218
13C+p-d
120
-3.8568
11B+α-t
145
-4.7789
14N+p-3He
15.11
1+;1
14.08
4+
13.35
(2−)
12.71
1+
11.83
2−
10.84
1−
10.3
(0+)
9.641
3−
7.6542
0+
π
4.4389
2+
12C
Jπ=0+;
T=0
7·89
4.4×10−5
11B+p
15.9572
66
β+
13.5743
14N+d-α
0.0031
0.0046
0.027
44
10.4637
11B+3He-d
0.019
7.3666
8Be+α
0.946
43.7
4.9656
15N+p-α
66
1.3109
13C+d-t
54
-4.6410
14C+p-t
70
-5.5746
16O+3He-7Be
-5.6869
16O+d-6Li
9Be

Fitting the pion energy difference Spectra





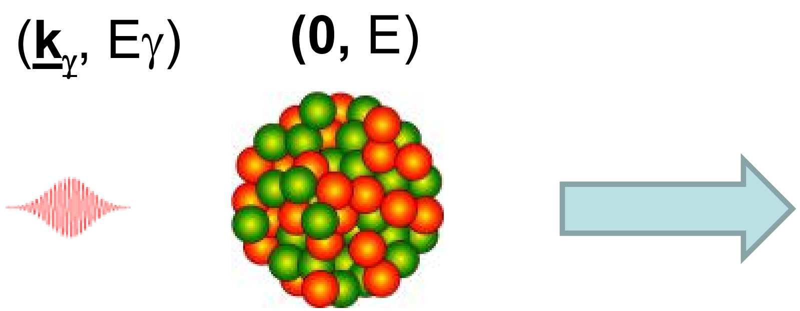
Coherent → Gaussian with $\sigma(E_\pi)$ extracted from coherent maximum)

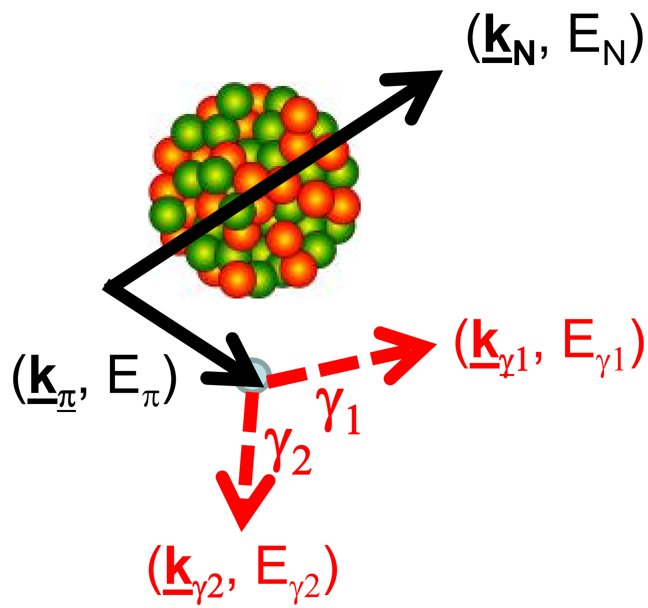
Smeared step function at $A(\gamma,\pi^0N)A\text{-}1$ threshold

For light nuclei with well separated 1st excited state(s)
Include second gaussian centered at appropriate energy

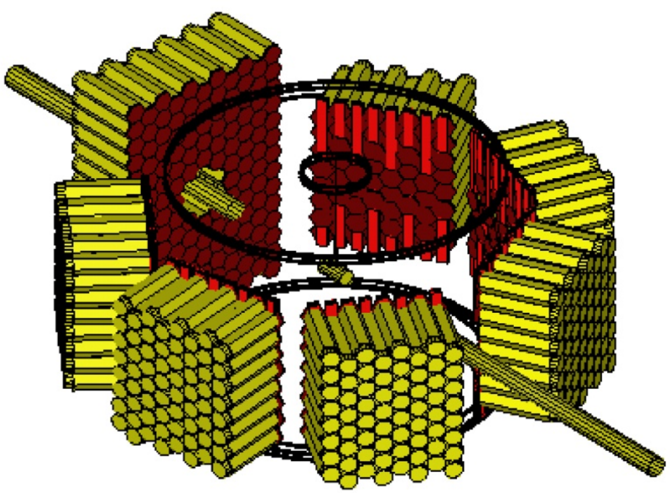
How do we get the Coherent part?

- One technique is to use energy difference analysis





$$E_\pi^{diff} = E_\pi(E_\gamma) - E_\pi(\gamma_1,\gamma_2)$$



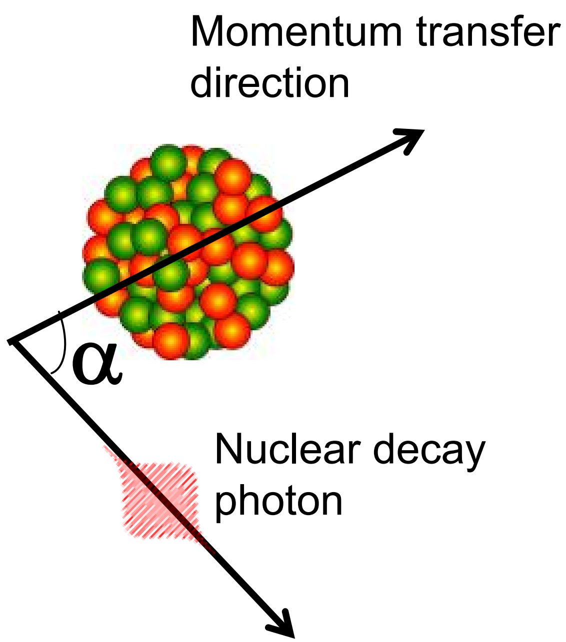
Best previous measurements → segmented arrays

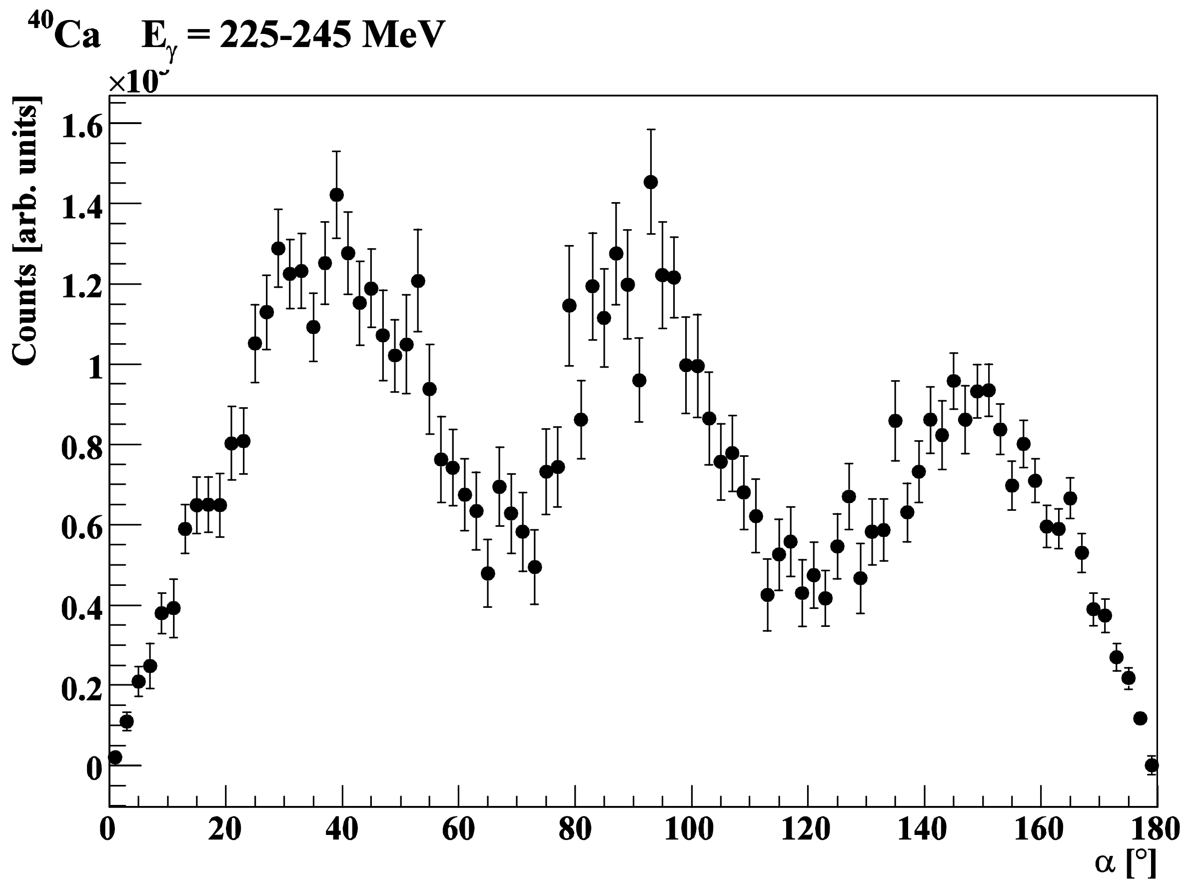
Reliable coherent extraction limited due to sharply θ_π dependent systematic effects in $E\pi$ determination

The excitation spectrum of the nucleon

- Coherent process extracted with a new level of accuracy
- Data set of sufficient quality to extract information on matter form factor
- Nuclear decay photon analysis allows determination of incoherent production -> study in it’s own right and use to improve coherent extraction

Alignment of recoiling ^{40}Ca nucleus

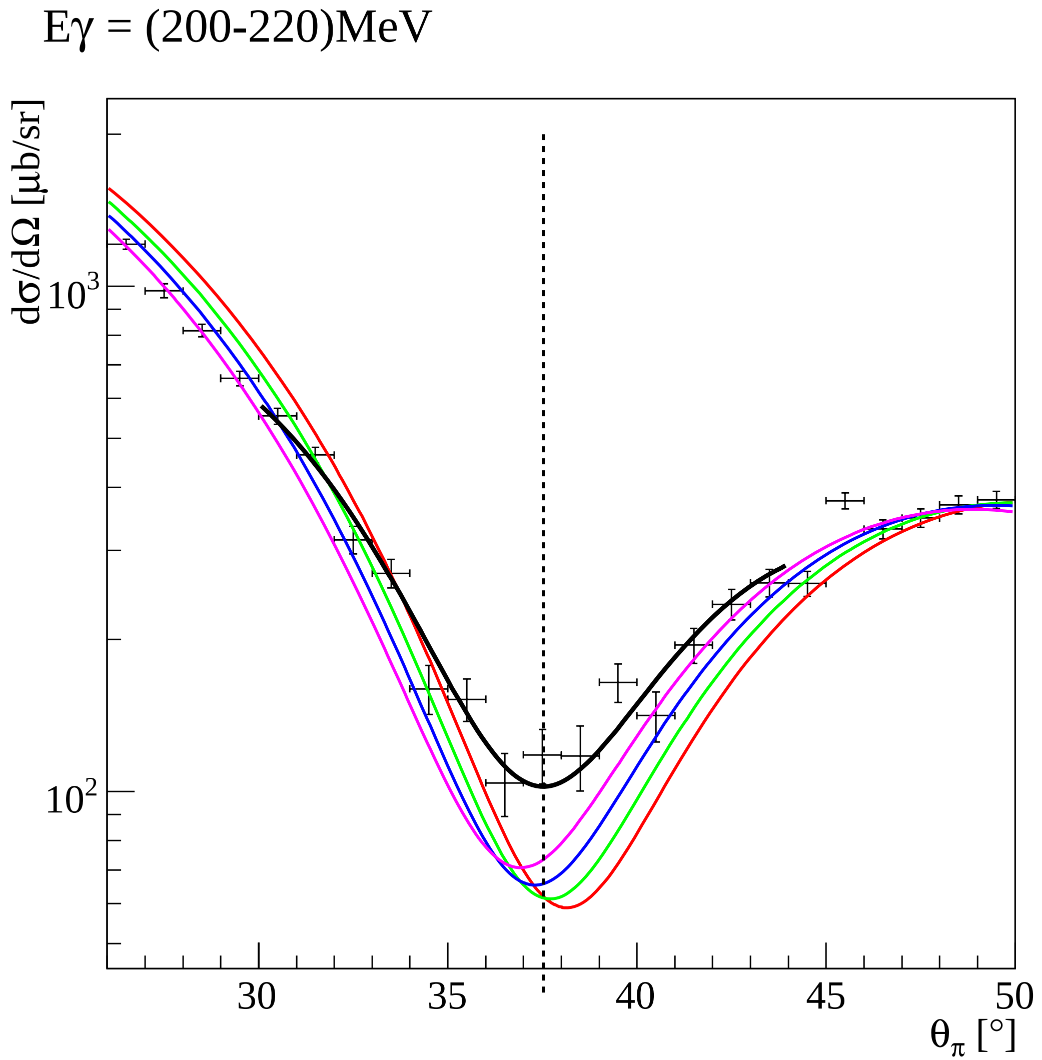




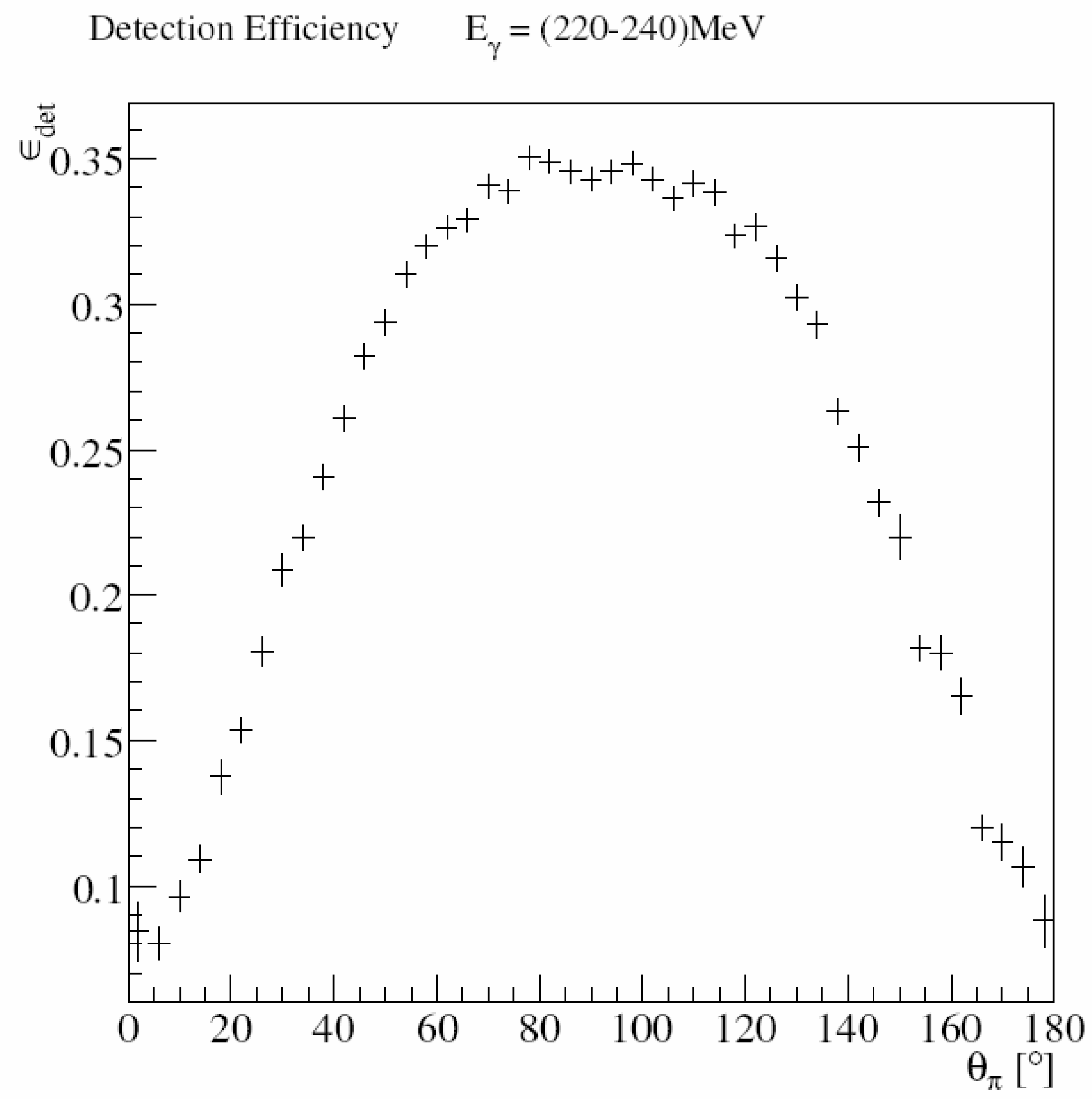
- Strong $\sin^2(3\alpha)$ component
- Expected from 3^- to 0^+ transition

^{208}Pb: Preliminary assessment of Neutron skin

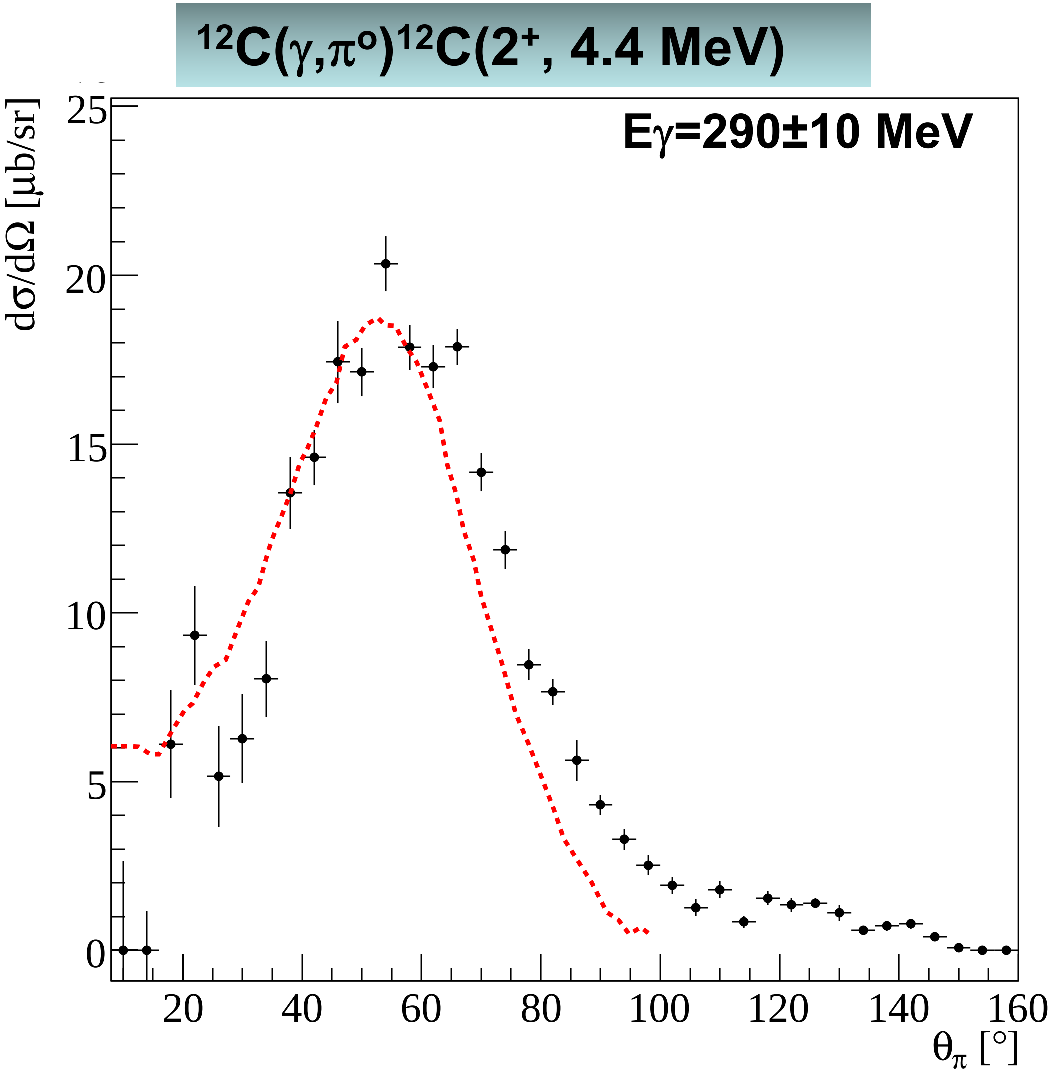
- No neutron skin
- 0.1 fm skin
- 0.2 fm skin
- 0.3 fm skin



Combined p0 and decay g detection efficiency



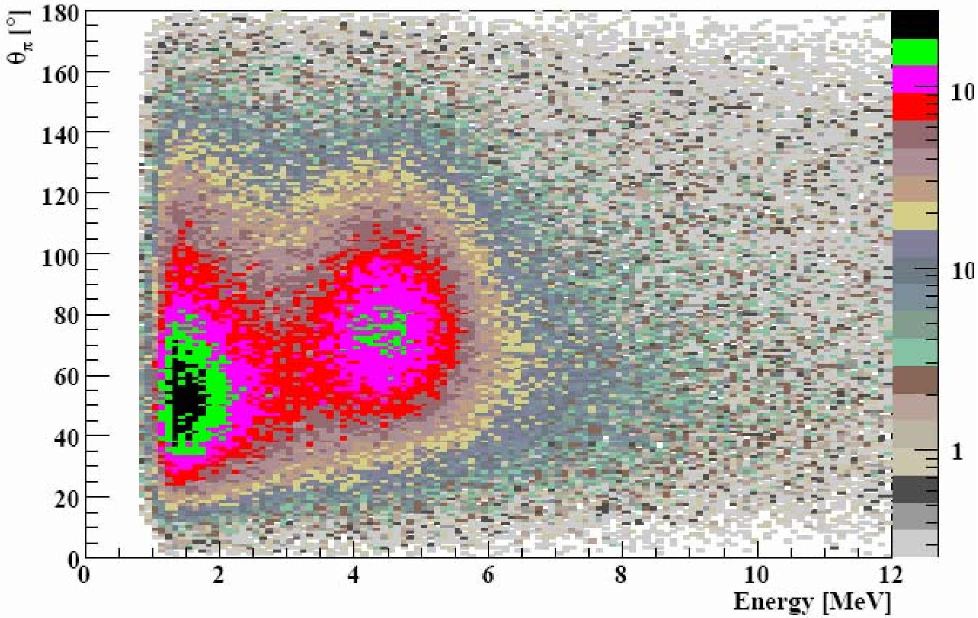
Incoherent nuclear pion photoproduction



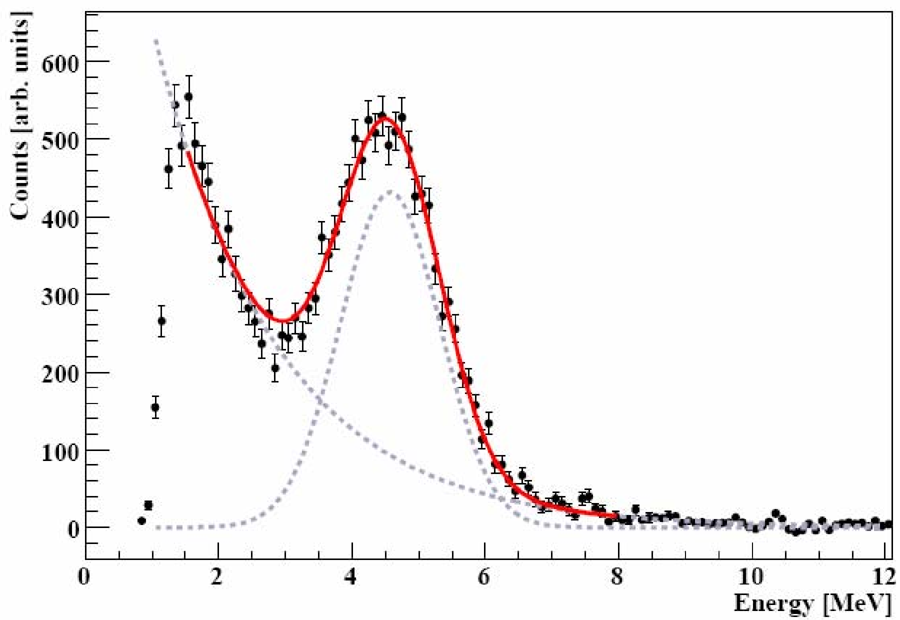
— Takaki Δ-hole model
NPA 443 p570 (1985)

Nuclear wavefunctions have configuration coefficients extracted from e- scattering

- $d\sigma/d\Omega$ corrected for both π^0 and nuclear decay γ detection efficiency
- First determination of incoherent photoproduction

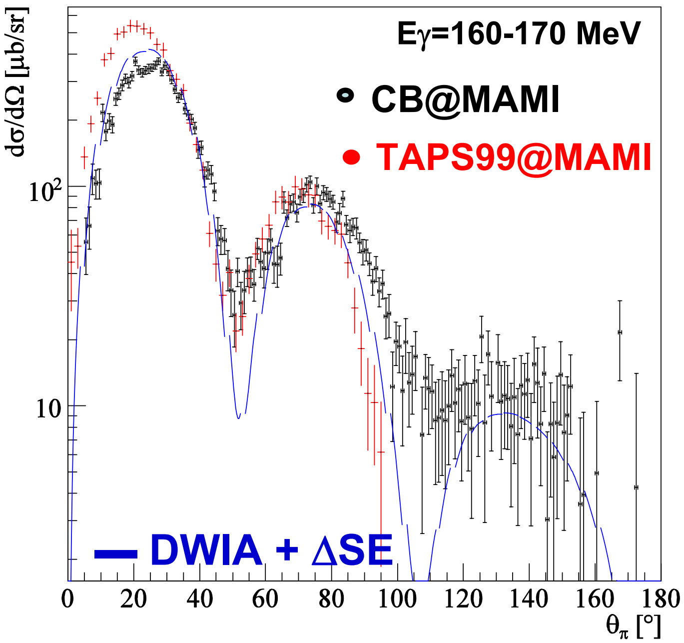


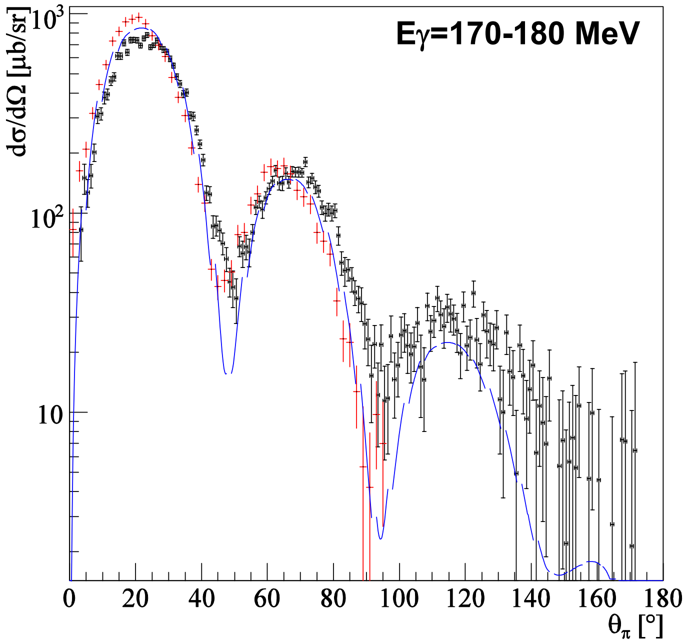
θπ [°]
Energy [MeV]

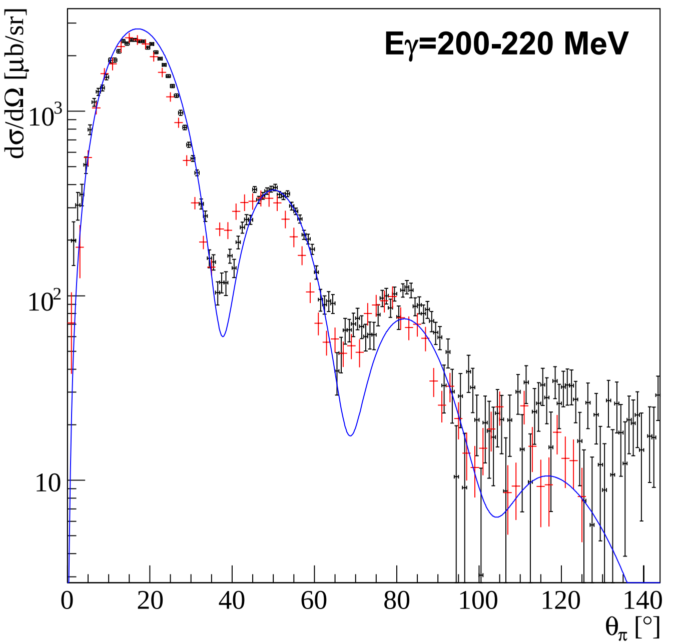


Counts [arb. units]
Energy [MeV]

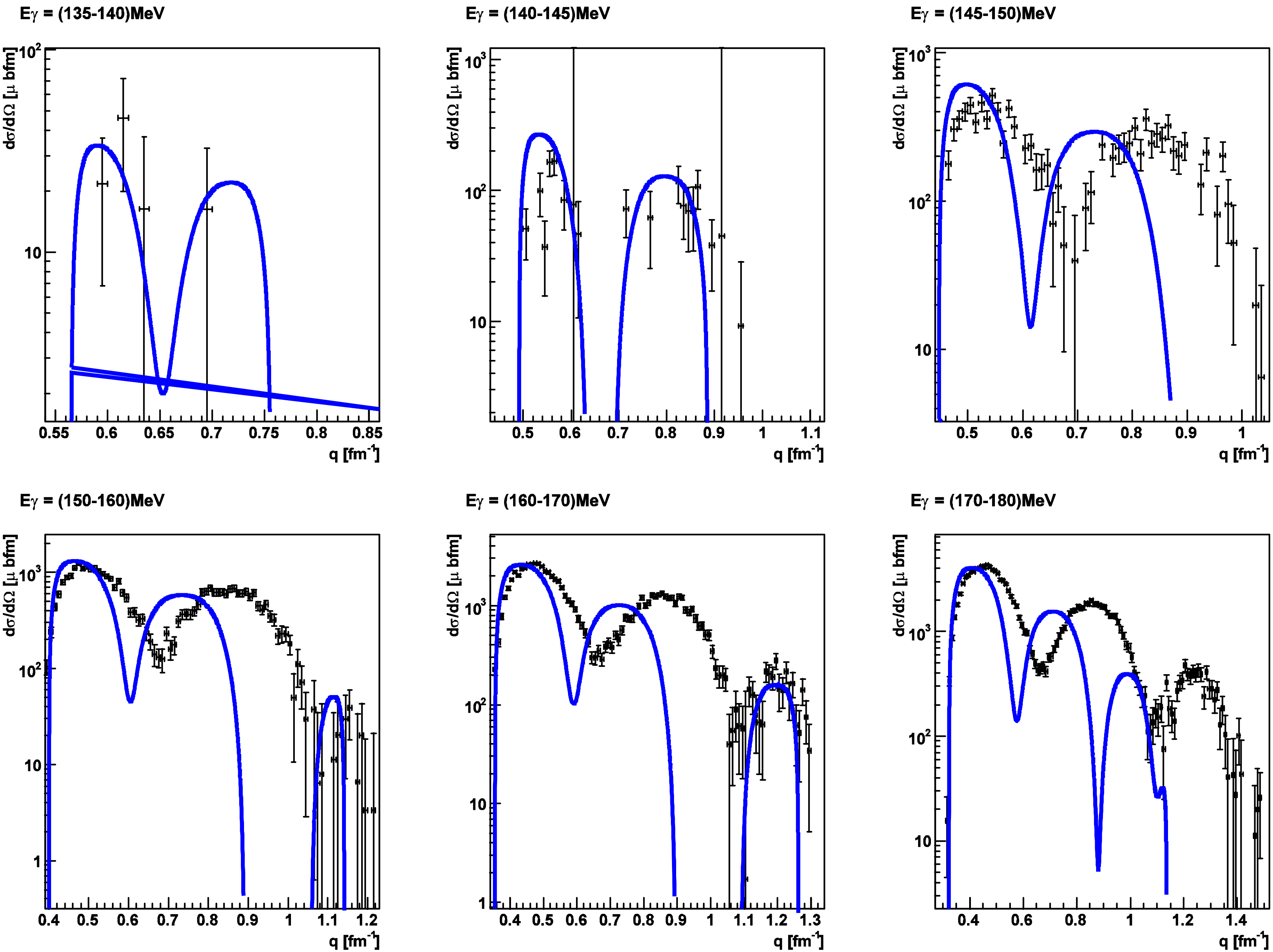
^{208}Pb: π^0 angular distributions





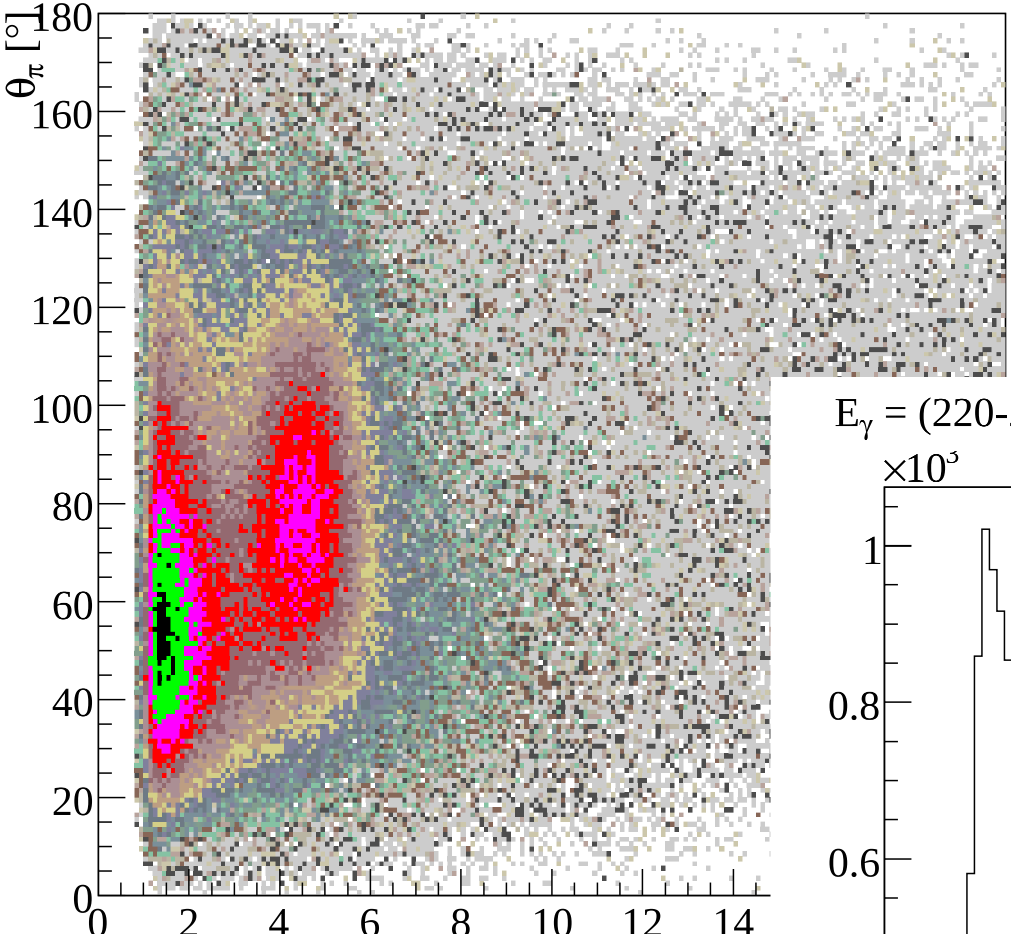


..... + spectra up to E_γ=700 MeV


Eγ = (135-140)MeV
Eγ = (140-145)MeV
Eγ = (145-150)MeV
Eγ = (150-160)MeV
Eγ = (160-170)MeV
Eγ = (170-180)MeV
dσ/dΩ [μ bfm]
q [fm-1]

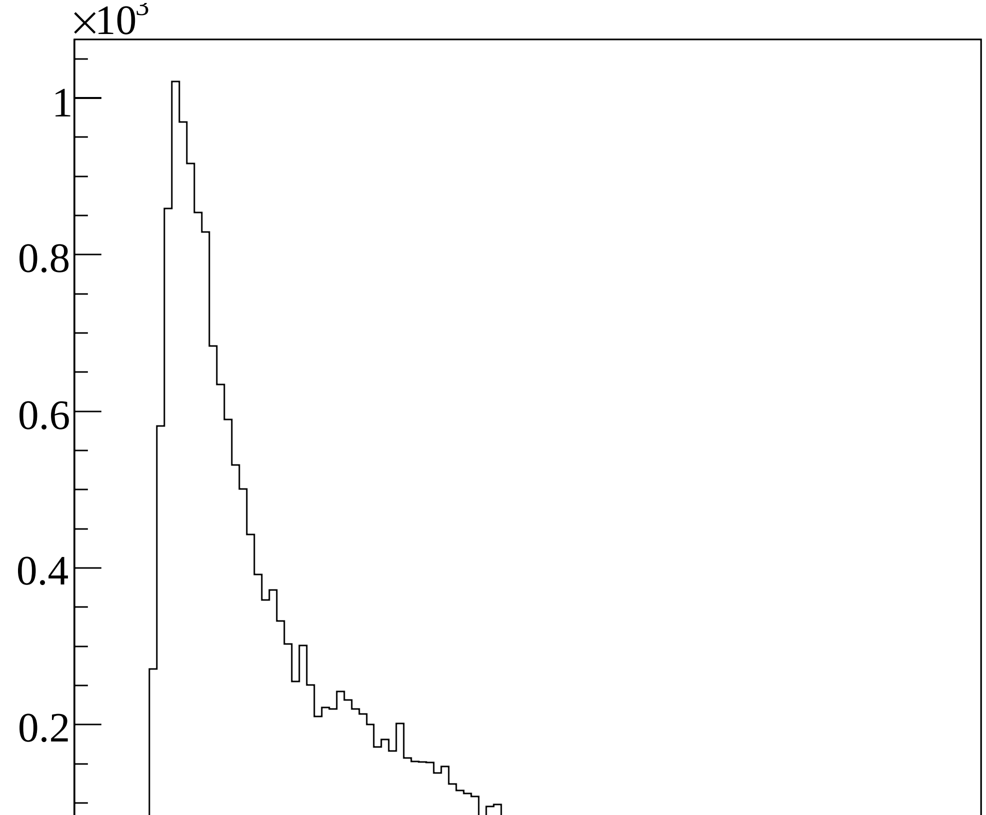
E_γ = (220-240)MeV

= (20-24)°

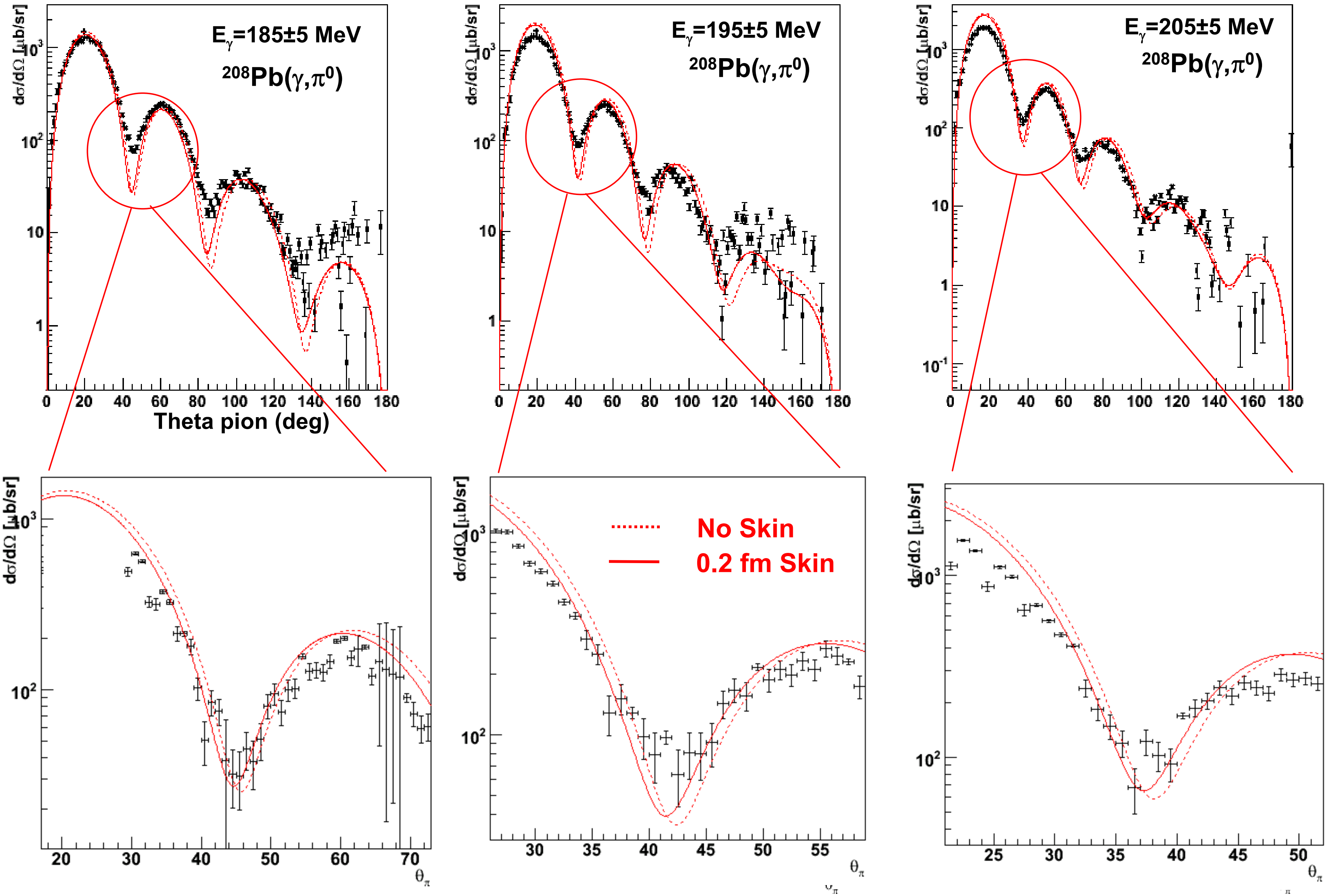


θ_π = (128-132)°

E_γ = (220-240)MeV θ_π = (35-40)°



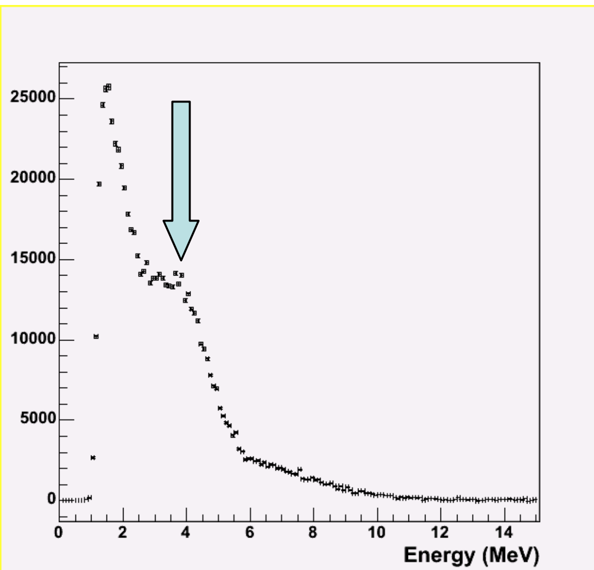
θ_π = (100-105)°

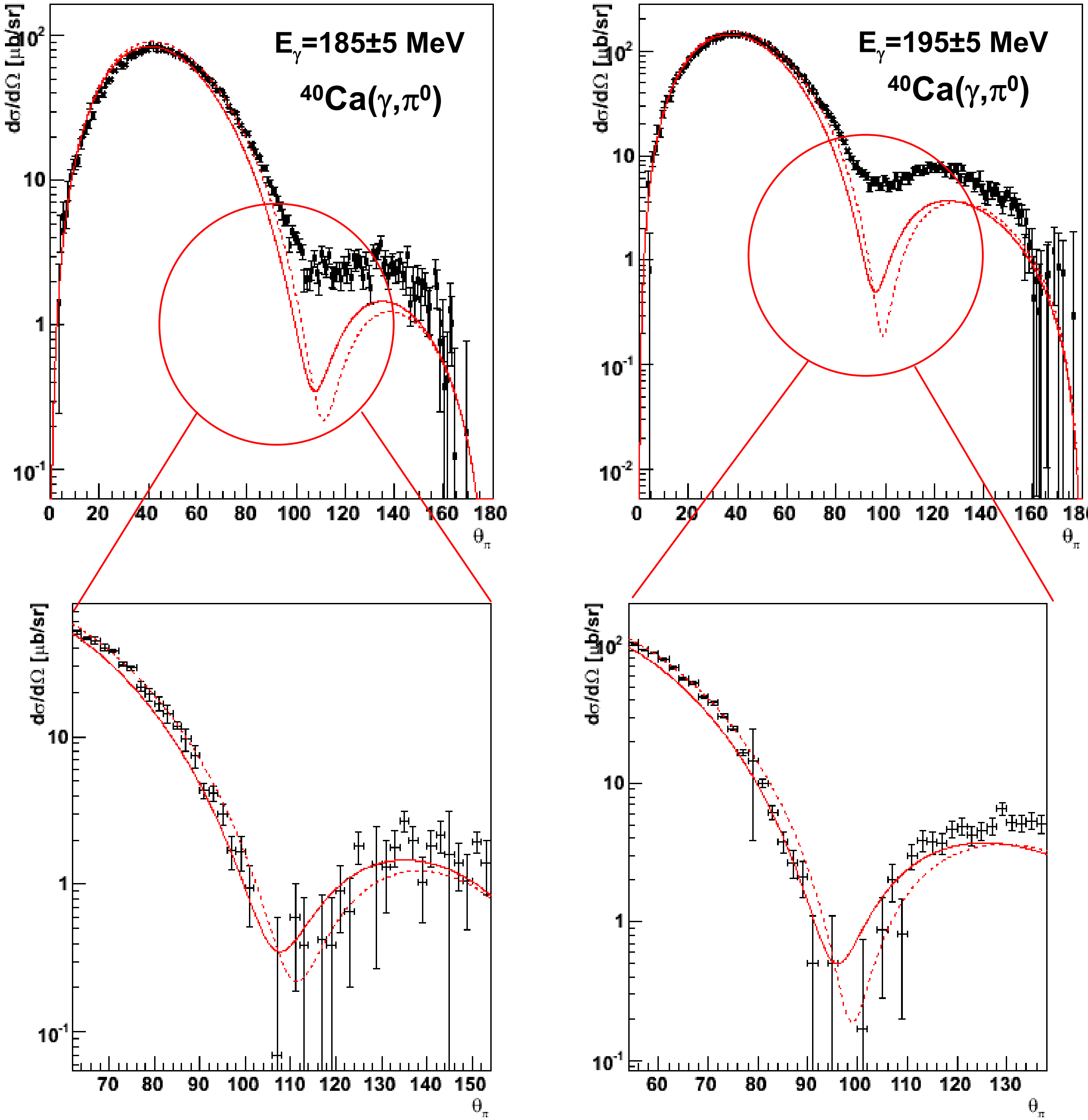


Eγ=185±5 MeV
208Pb(γ,π0)
Eγ=195±5 MeV
208Pb(γ,π0)
Eγ=205±5 MeV
208Pb(γ,π0)
dσ/dΩ [μb/sr]
Theta pion (deg)
θπ
No Skin
0.2 fm Skin

^{40}Ca shows large Incoherent contamination At larger π^0 angles

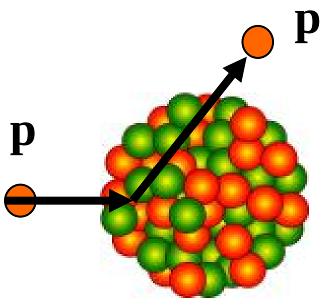
Also evident in Nuclear Decay photon spectra Picked up by CB!!



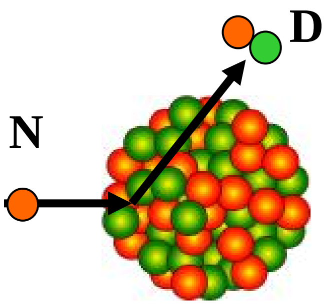


Neutron Skins - present situation

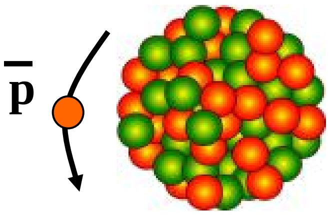
- **Proton scattering**
  Seminal analysis by Hoffman for all data (0.3 - 1 GeV). Δr_{np} (^{208}Pb) = -0.02 →0.5 fm



- **Pickup reactions.**
  Recent analysis of p and n pickup gave Δr_{np}~0.5fm for ^{208}Pb

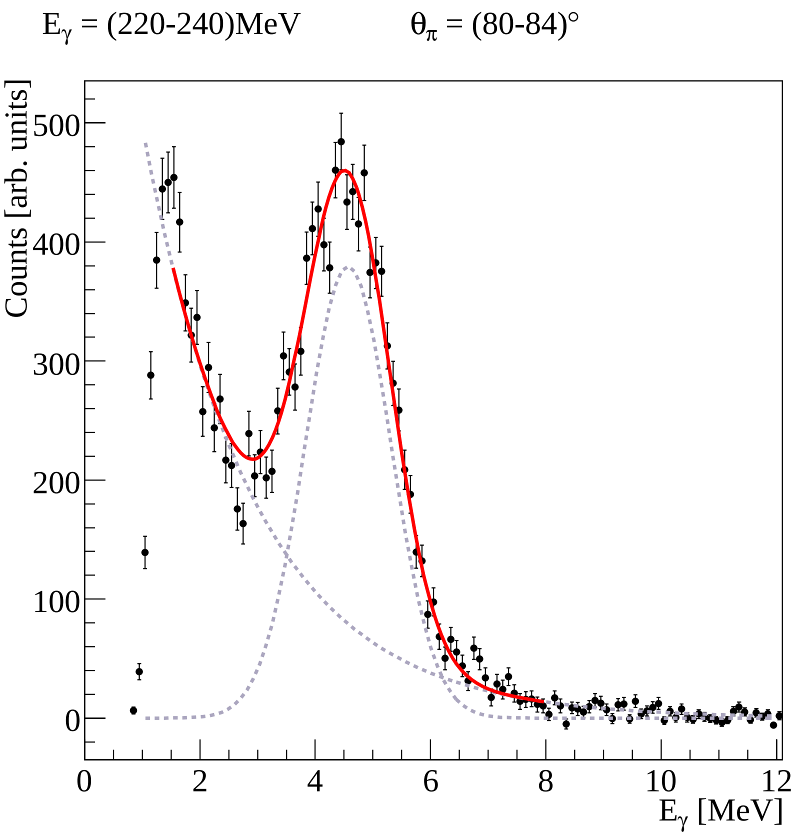


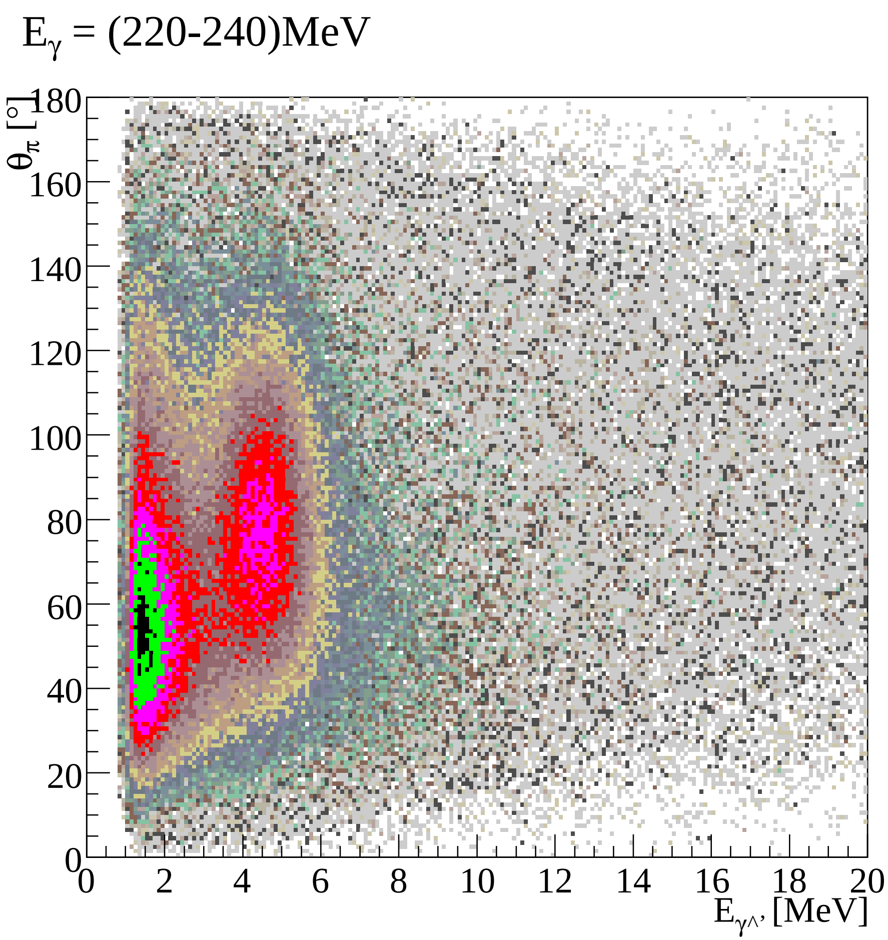
- **Antiprotonic atoms**
  Δr_{np} ~ 0.15fm for ^{208}Pb.



→ **Coherent pion photoproduction**

Nuclear decay photons ^{12}C





Background predominantly from split-off clusters from pi0 detection

Talk Outline

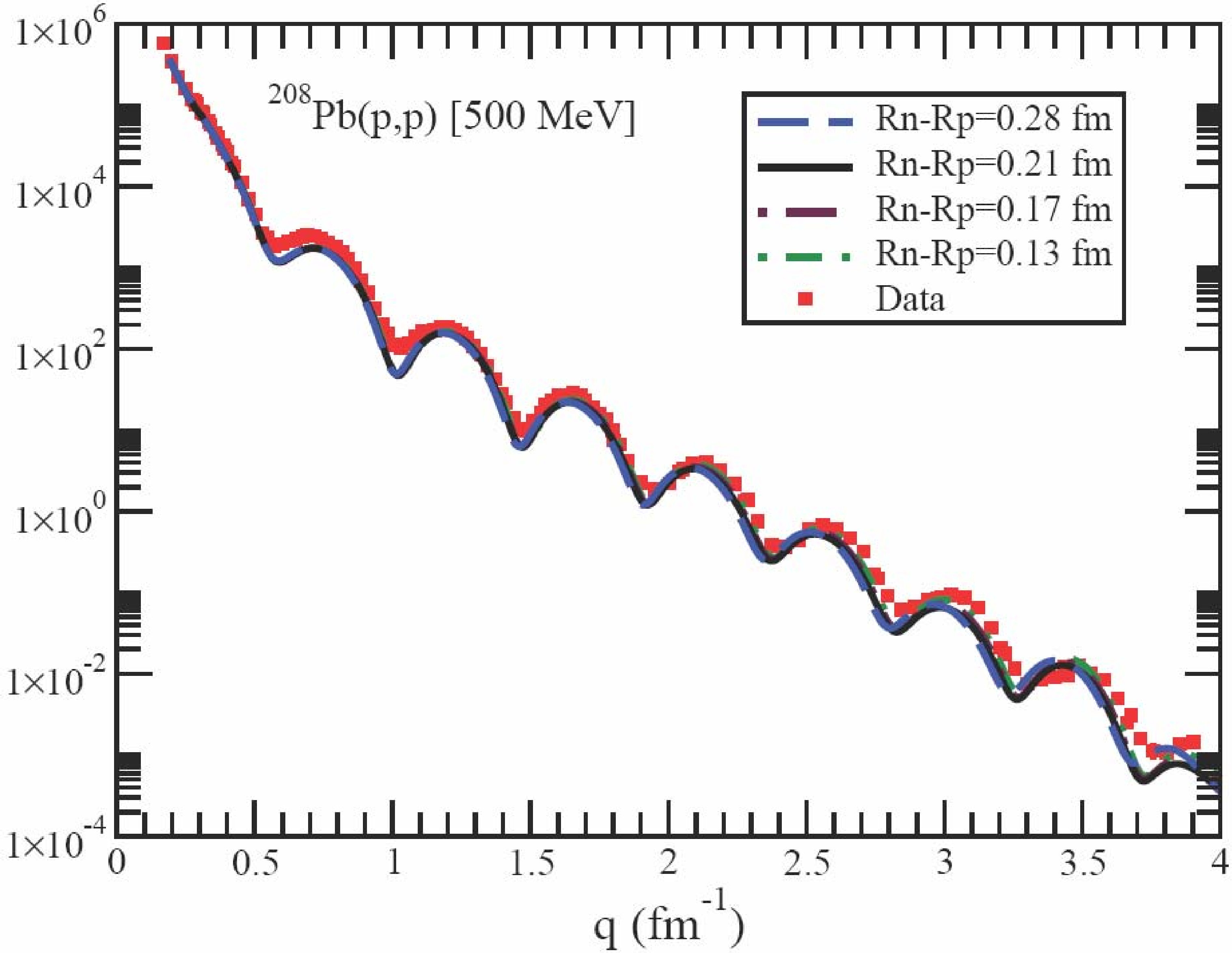
- CrystalBall@MAMI

- π^0 photoproduction from nuclei

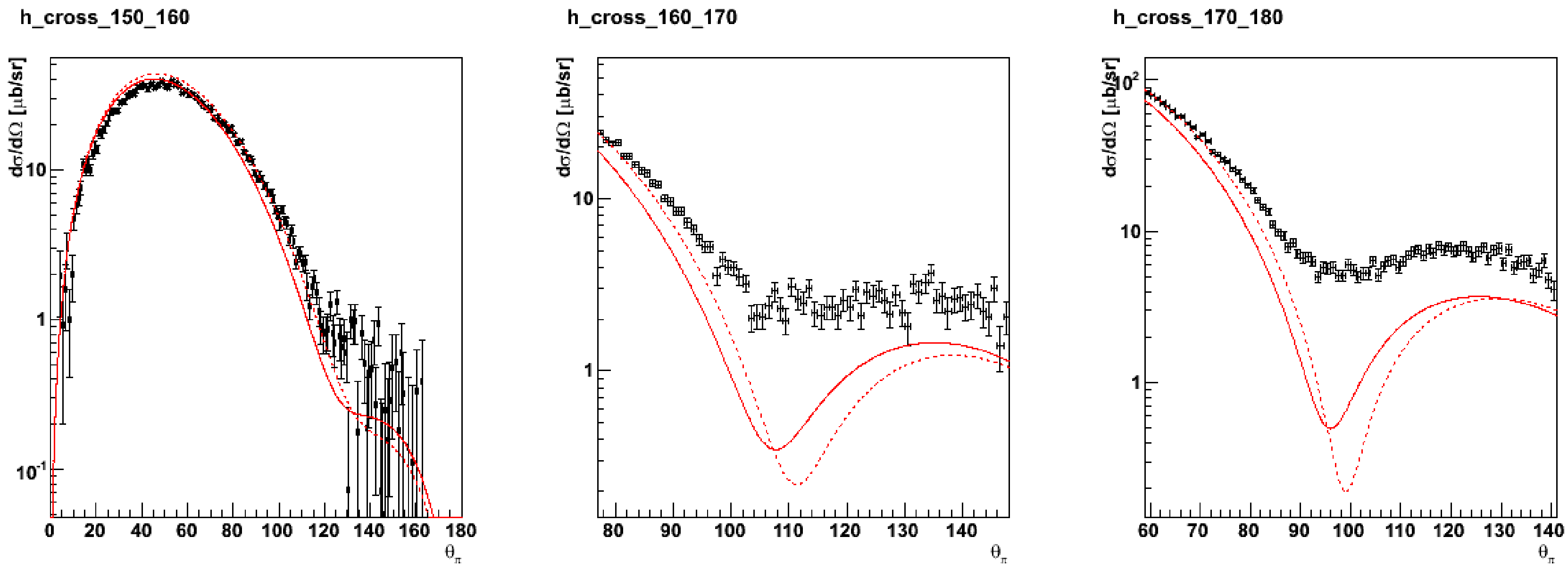
  - **Coherent** → **Matter form factors**
  - **Incoherent** → **Transition matter FFs**

- The new Edinburgh nucleon polarimeter

  - **π photoproduction from nucleon** → **Nucl. excitation spectrum**
  - **Deuterium disintegration** → **onset of quark d.o.f.**



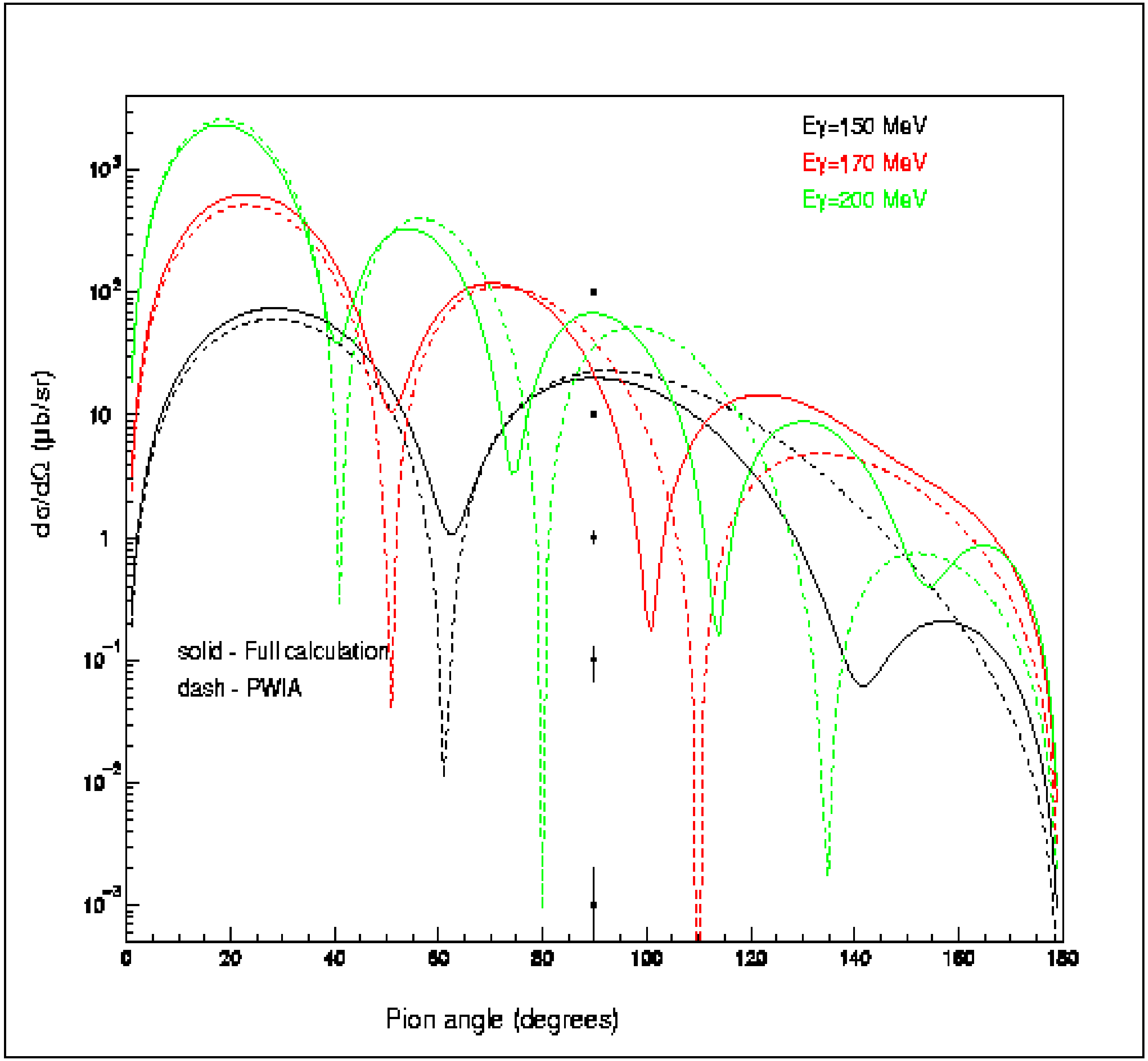
^{208}Pb(p,p) [500 MeV]
Rn-Rp=0.28 fm
Rn-Rp=0.21 fm
Rn-Rp=0.17 fm
Rn-Rp=0.13 fm
Data
1×10^{6}
1×10^{4}
1×10^{2}
1×10^{0}
1×10^{-2}
1×10^{-4}
0
0.5
1
1.5
2
2.5
3
3.5
4
q (fm^{-1})

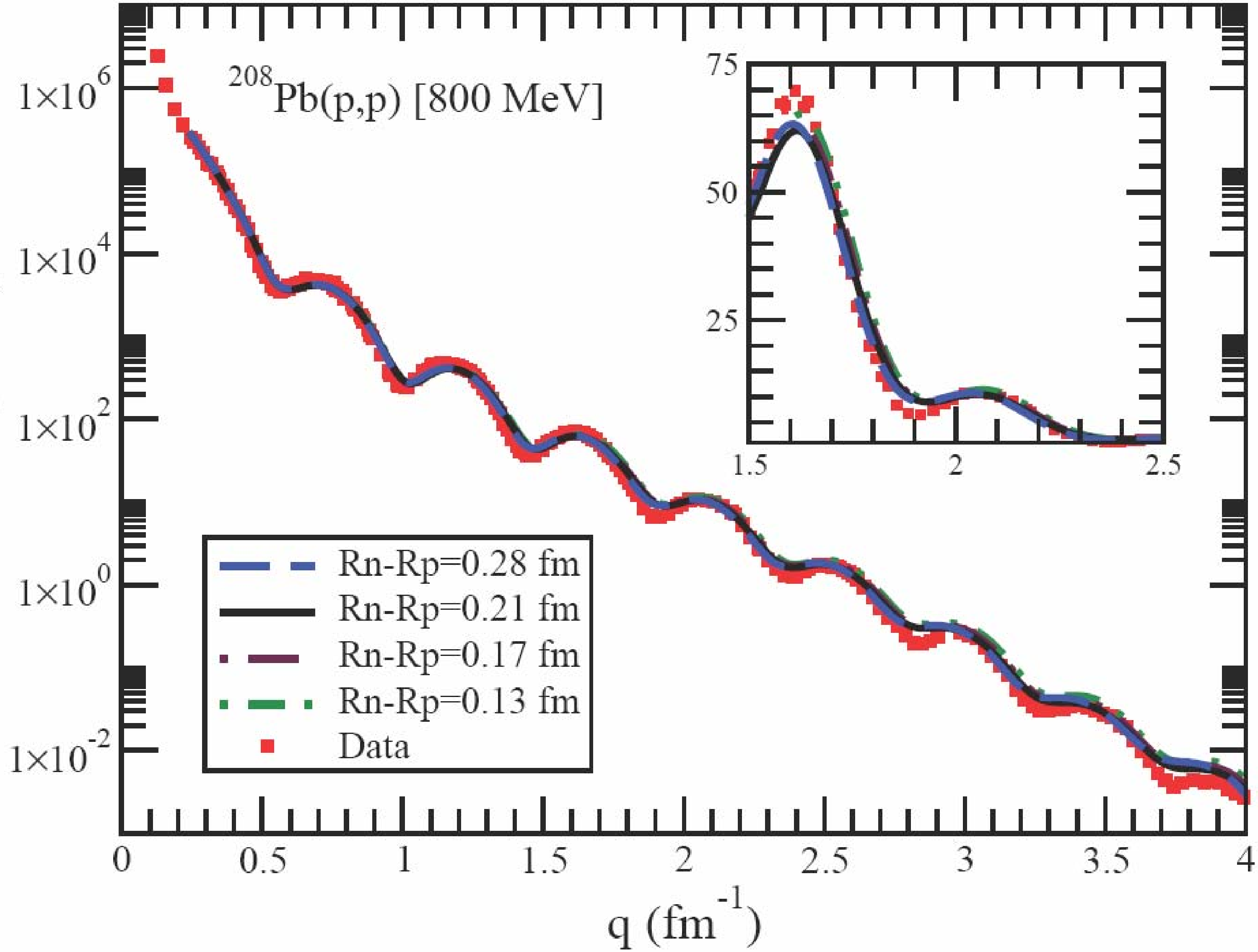


h_cross_150_160
dσ/dΩ [μb/sr]
θ_π
h_cross_160_170
dσ/dΩ [μb/sr]
θ_π
h_cross_170_180
dσ/dΩ [μb/sr]
θ_π

Pion – Nucleus interactions

- Diffraction pattern distorted due to π-A interactions (FSI)
- Optical potential constructed from p amplitude in **p** space
- Intermediate Δ also included (impo higher P_{π})
- Accurately describes wealth of A(π,
- If Δ(FSI) ~ 10% $(0.07)\times(\pm 2^{o})\times 0.1 = \pm 0.014$ fm
- Each **q** occurs for different **P**π at di incident **E**γ – check predicted FSI effe

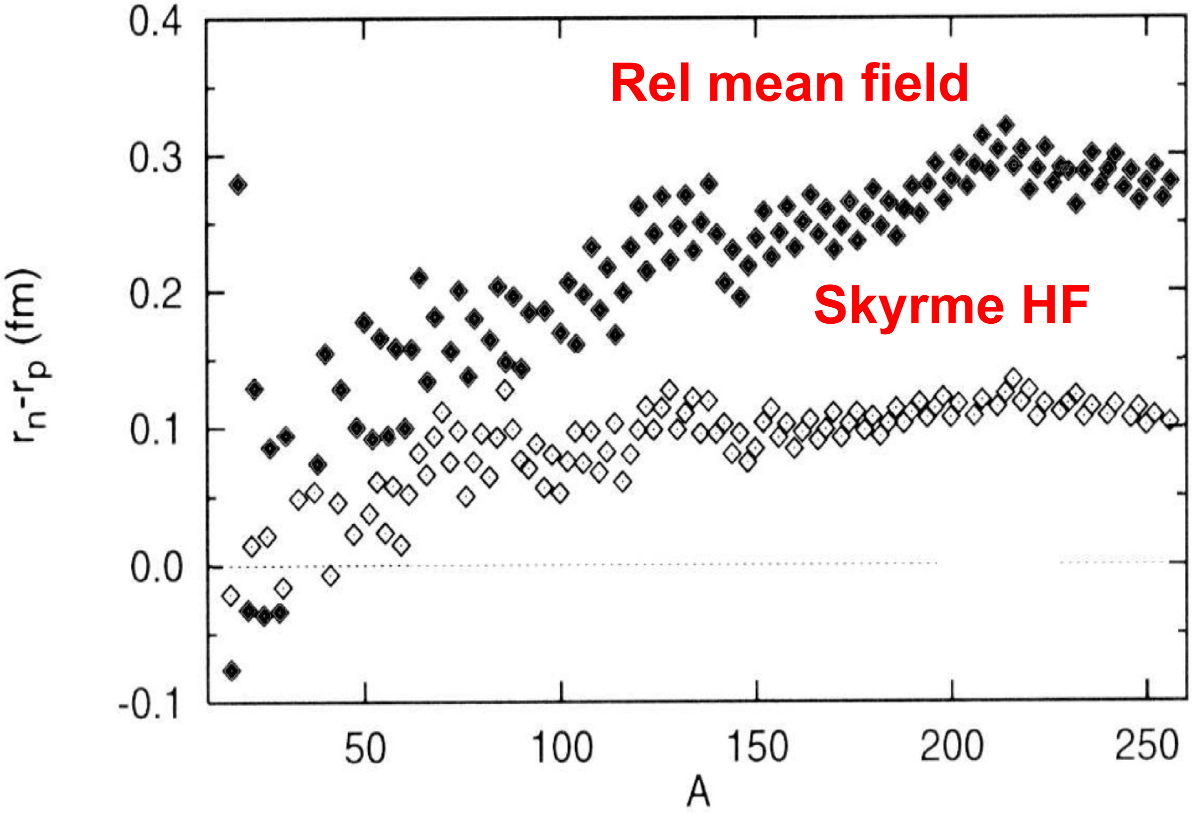




^{208}Pb(p,p) [800 MeV]
1×10^{6}
1×10^{4}
1×10^{2}
1×10^{0}
1×10^{-2}
75
50
25
1.5
2
2.5
Rn-Rp=0.28 fm
Rn-Rp=0.21 fm
Rn-Rp=0.17 fm
Rn-Rp=0.13 fm
Data
0
0.5
1
1.5
2
2.5
3
3.5
4
q (fm^{-1})

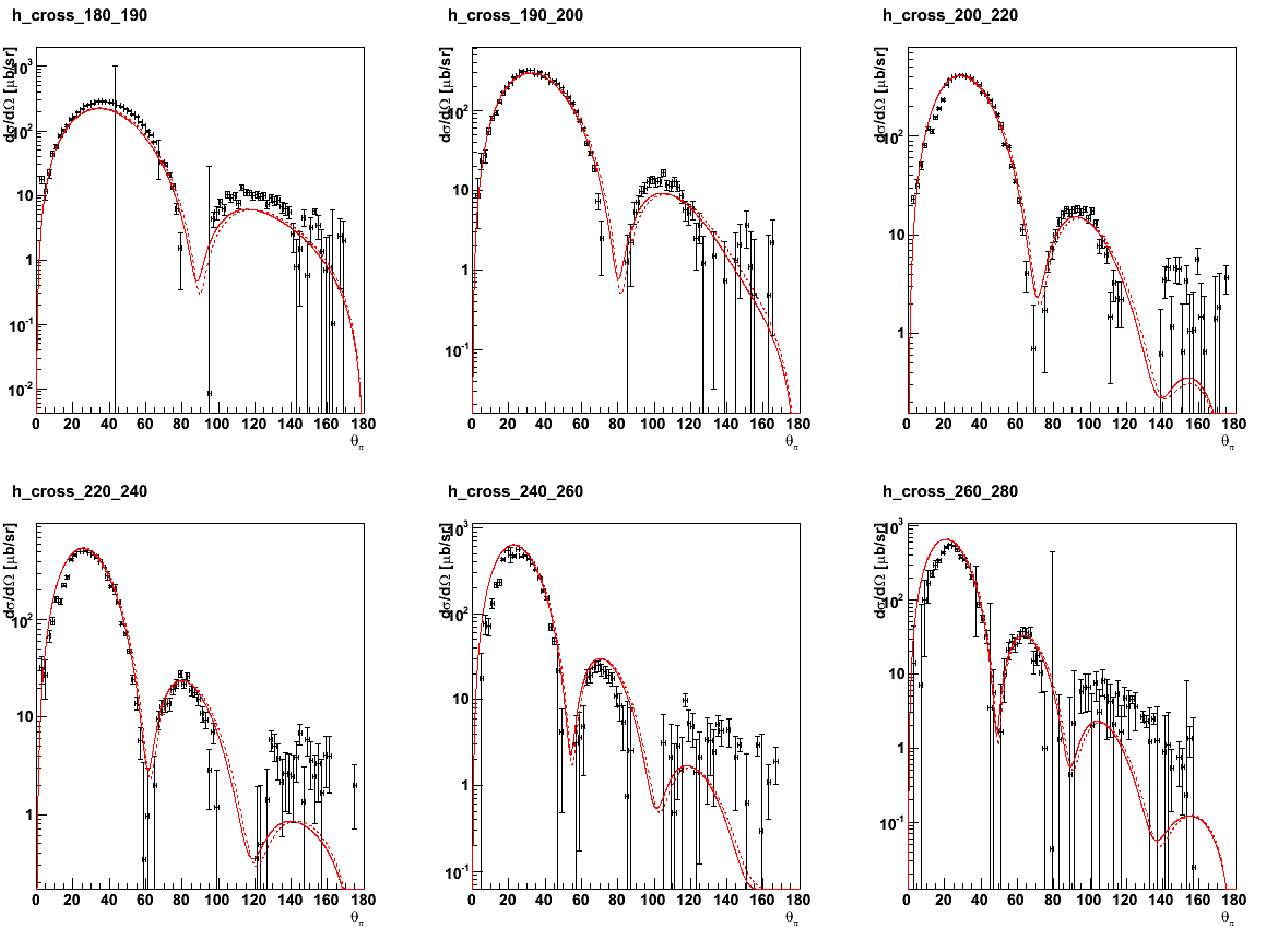
Neutron Skins - why are they interesting?

1) Fundamental quantity of Nuclear physics



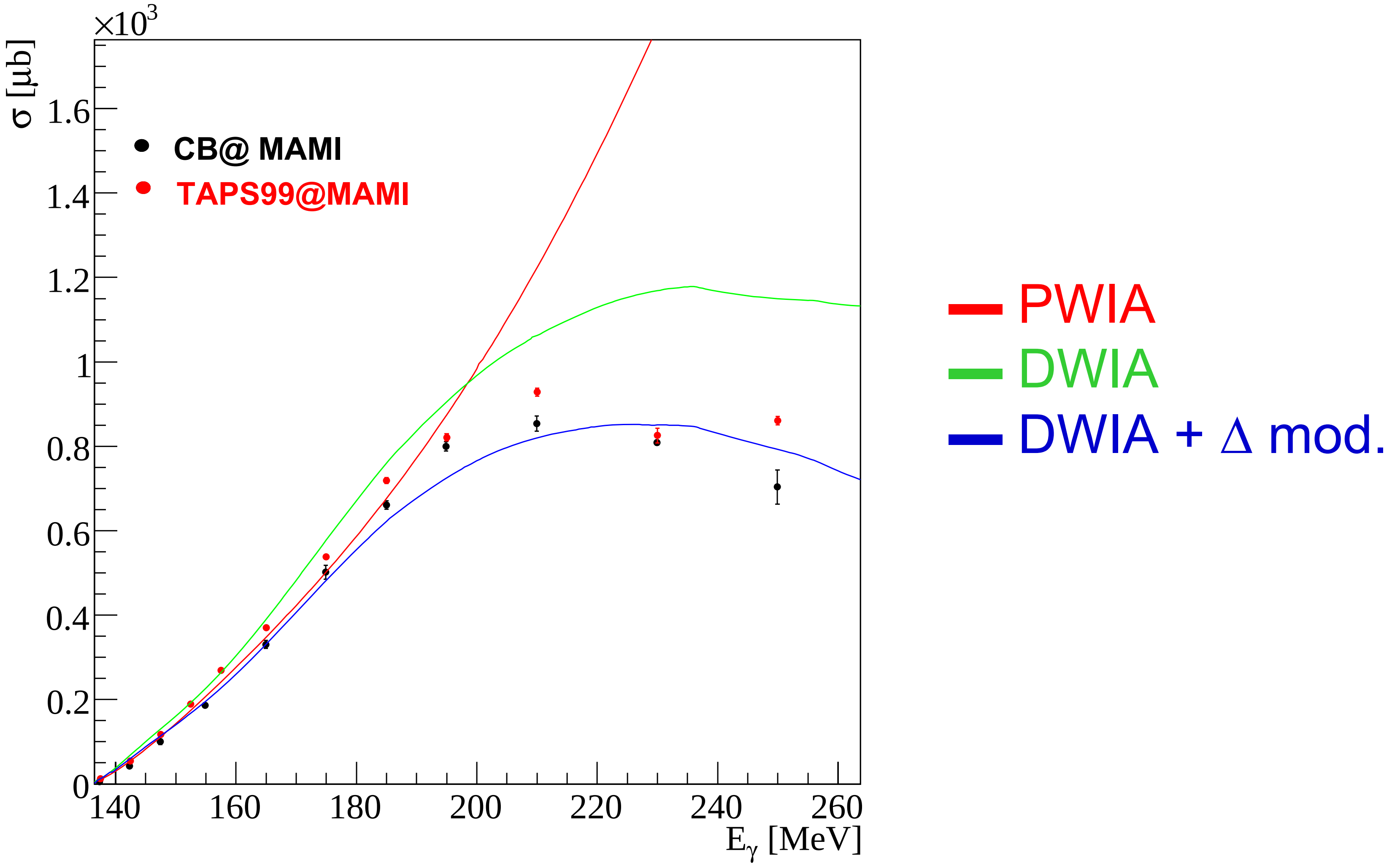
RMS charge radius known to < 0.0001 fm
RMS neutron radius known to ~0.2 fm !!

Horowitz et al. PRC63 025501 (2001)

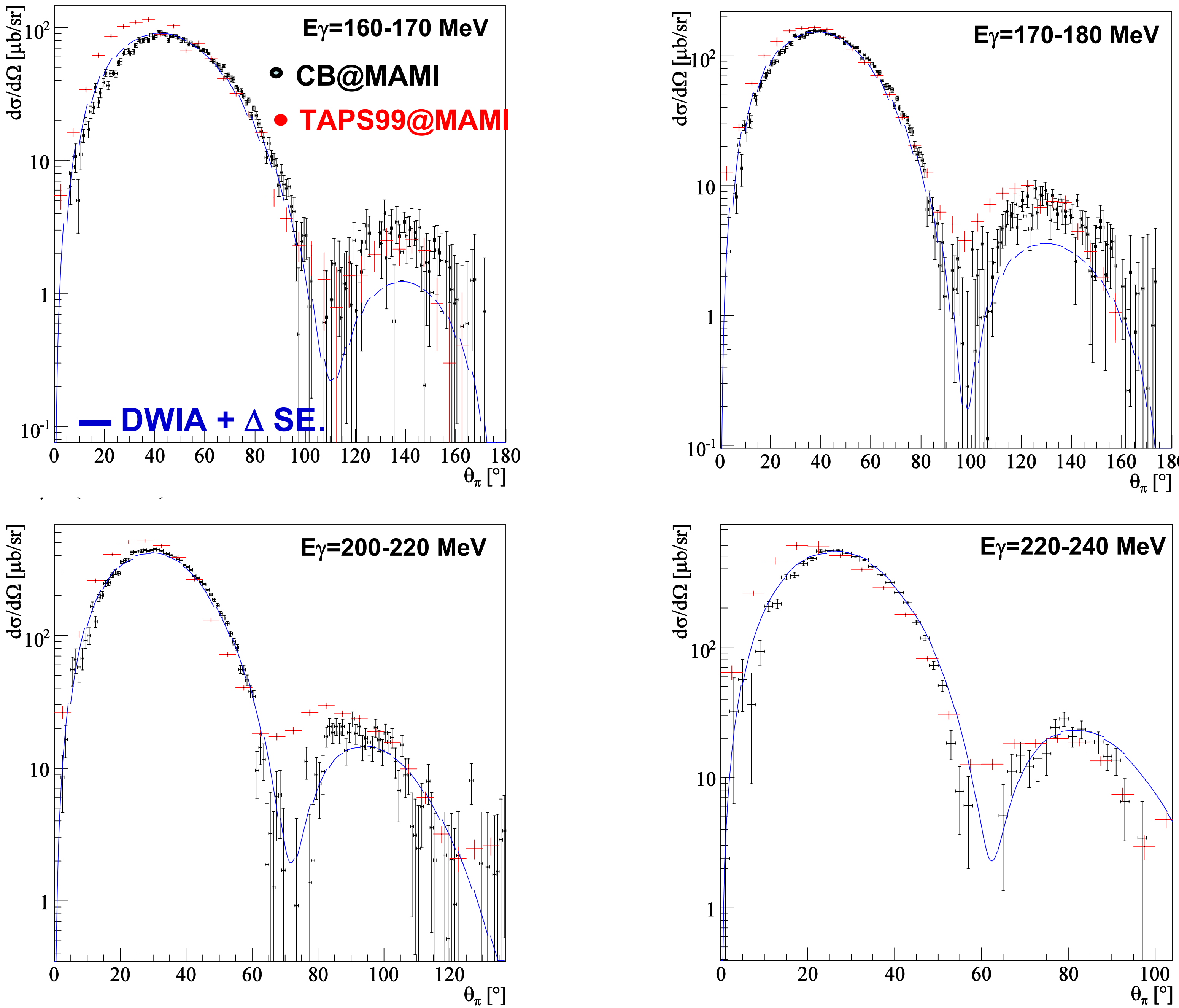


h_cross_180_190
h_cross_190_200
h_cross_200_220
h_cross_220_240
h_cross_240_260
h_cross_260_280
dσ/dΩ [μb/sr]
θ_π

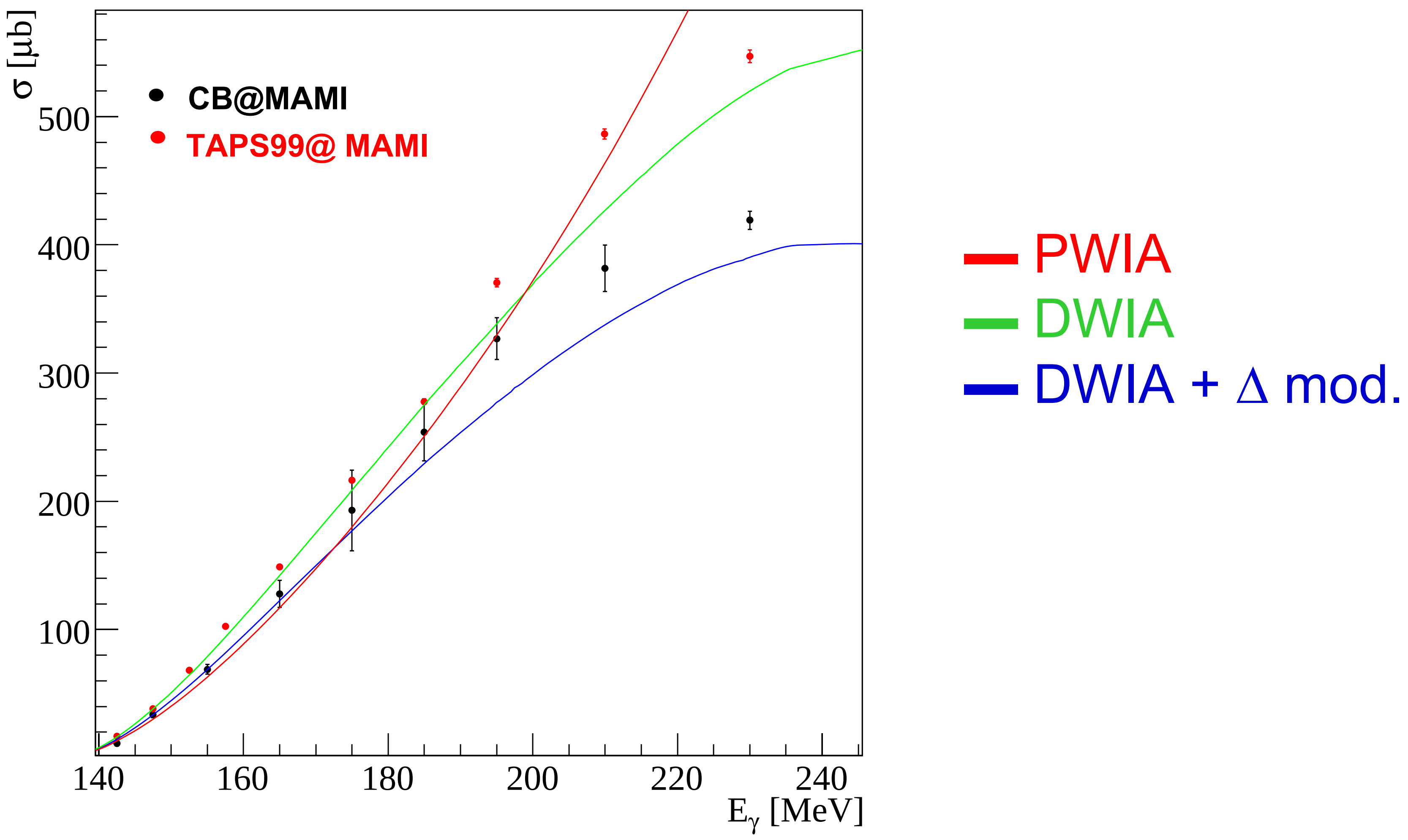
^{40}Ca: Total coherent cross sections

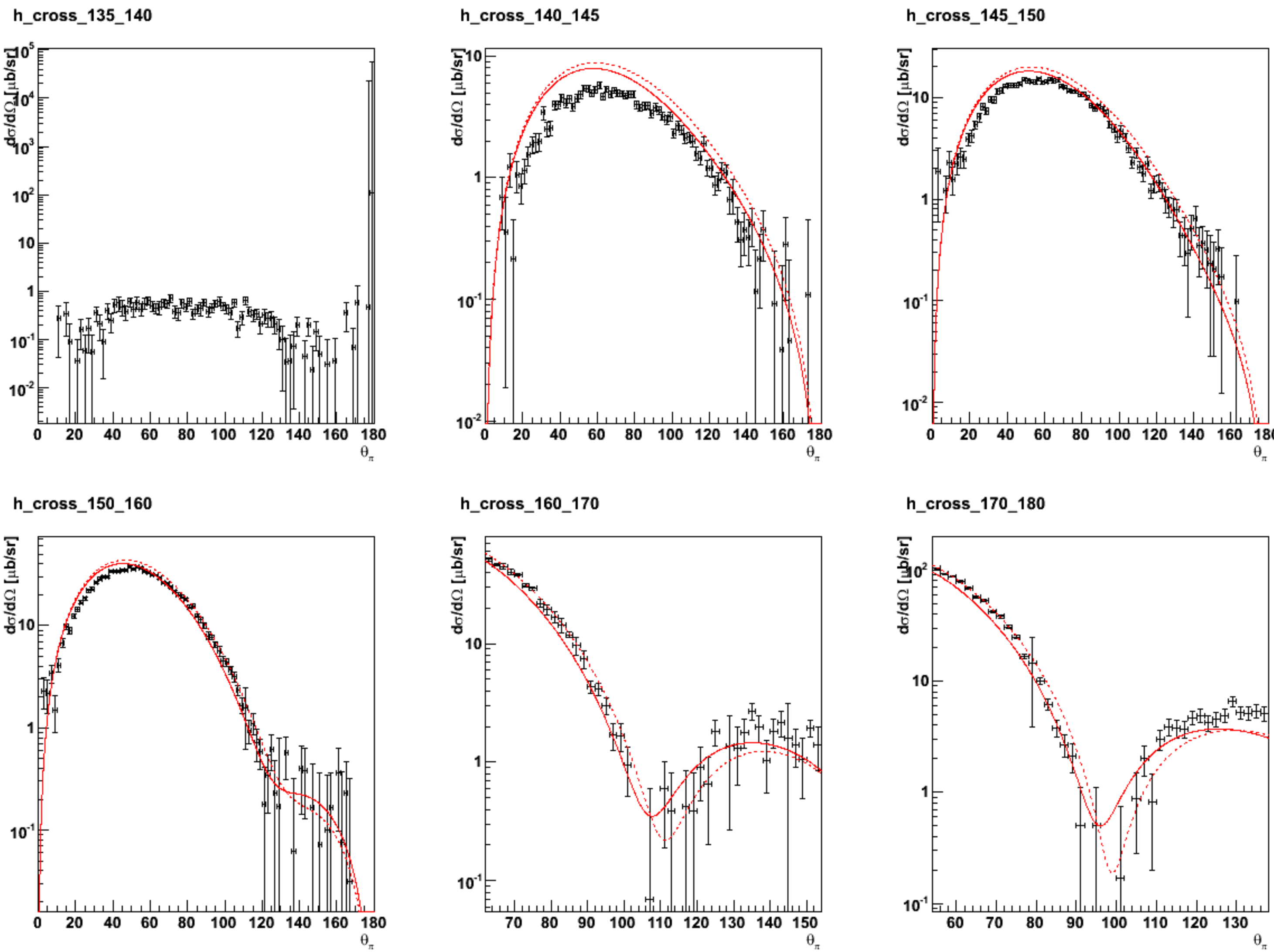


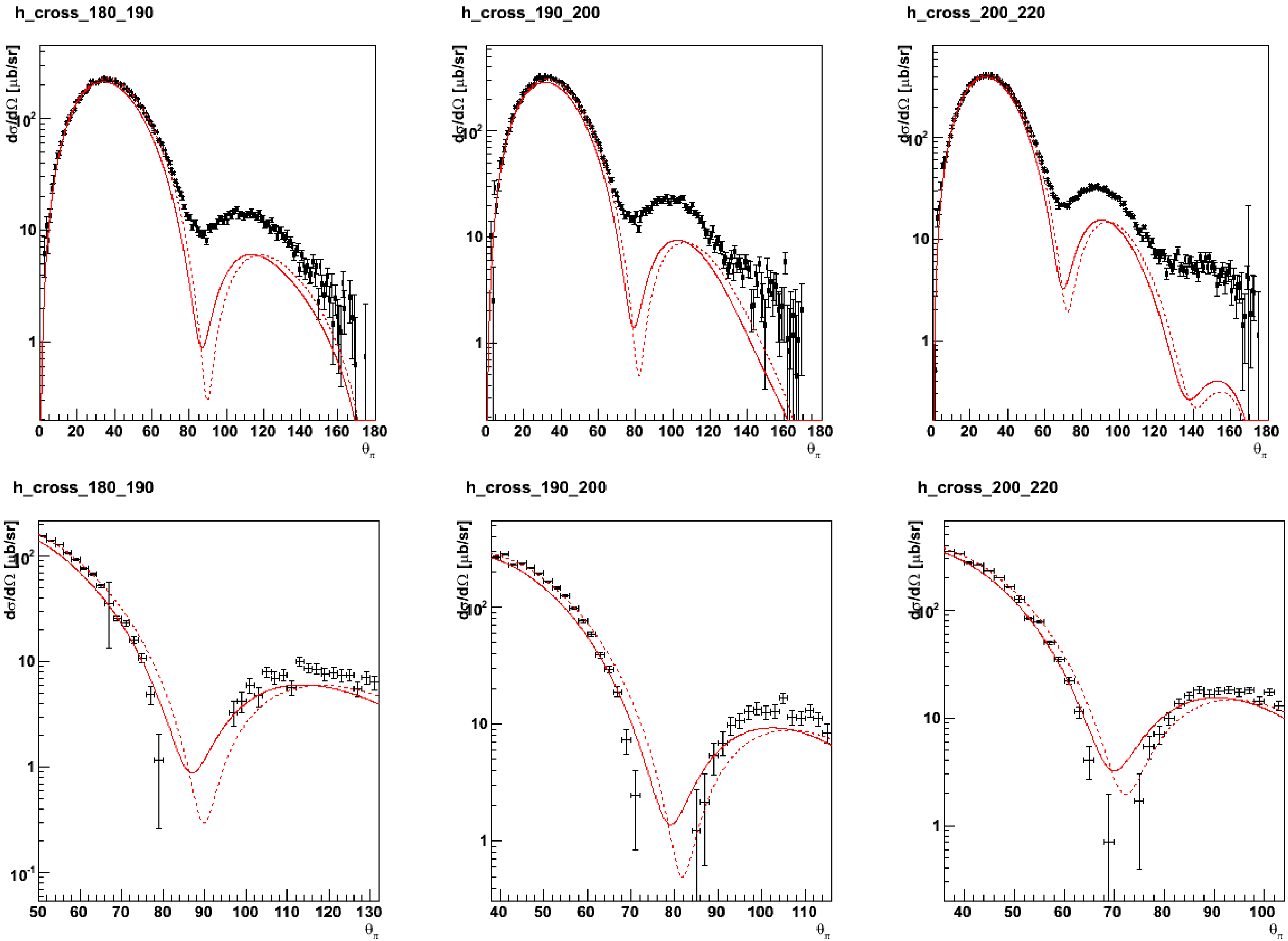
^{40}Ca: π^0 angular distributions



^{12}C: Total coherent cross sections

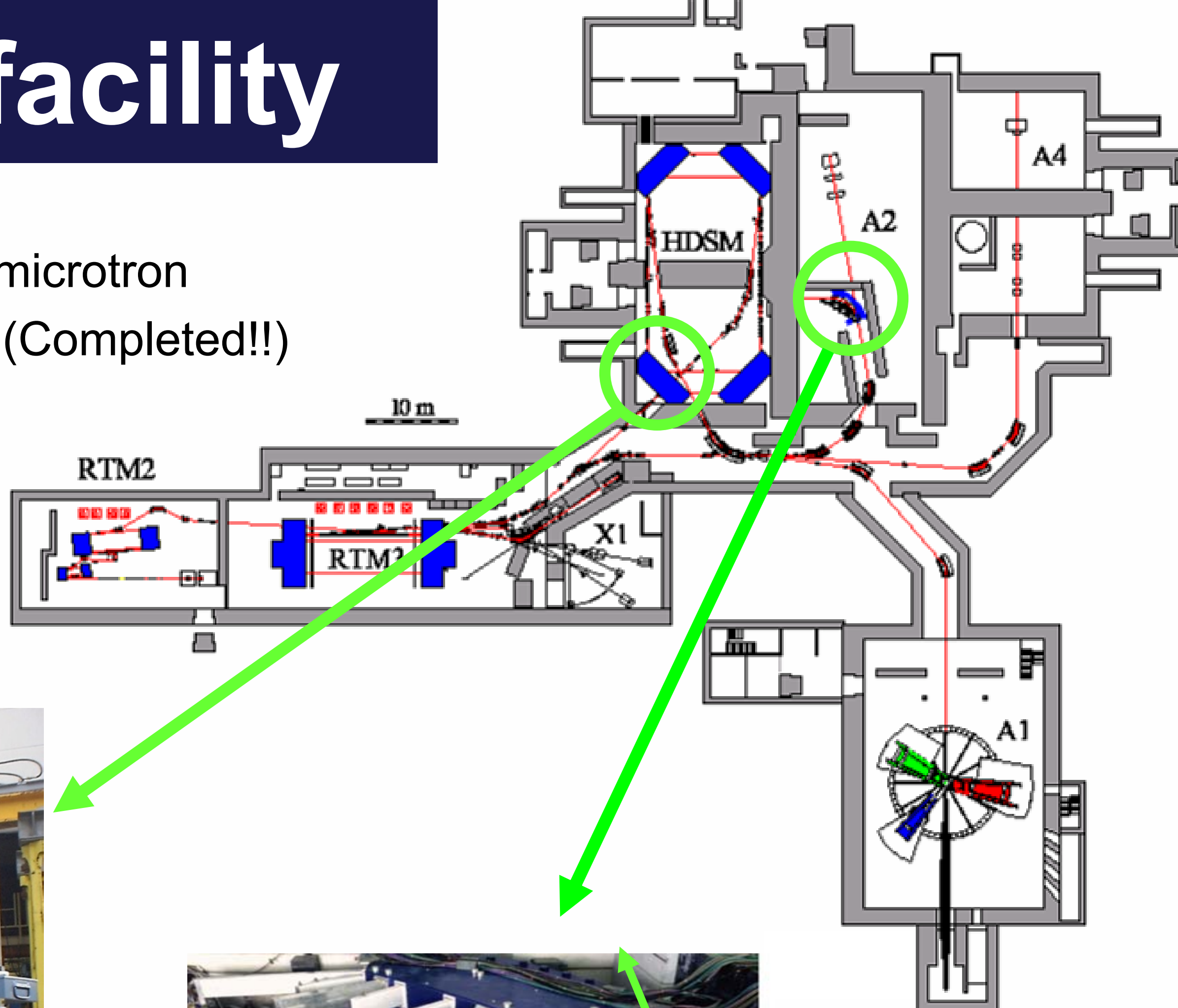


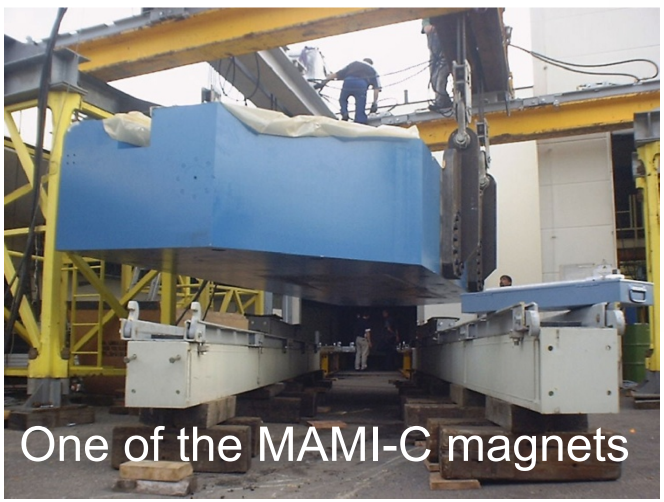

h_cross_135_140
h_cross_140_145
h_cross_145_150
h_cross_150_160
h_cross_160_170
h_cross_170_180
dσ/dΩ [μb/sr]
θ_π

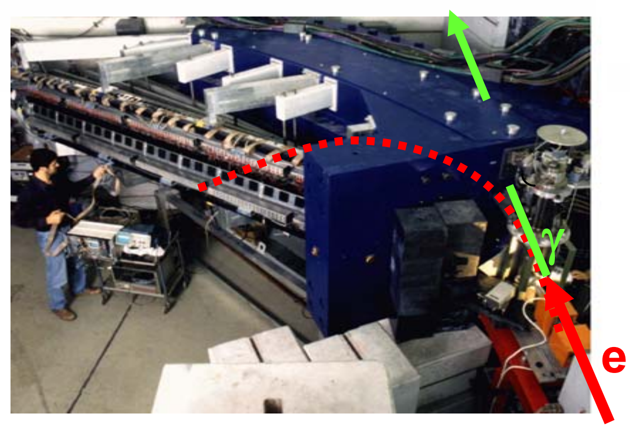

h_cross_180_190
h_cross_190_200
h_cross_200_220
h_cross_180_190
h_cross_190_200
h_cross_200_220
dσ/dΩ [μb/sr]
θ_π

The MAMI facility

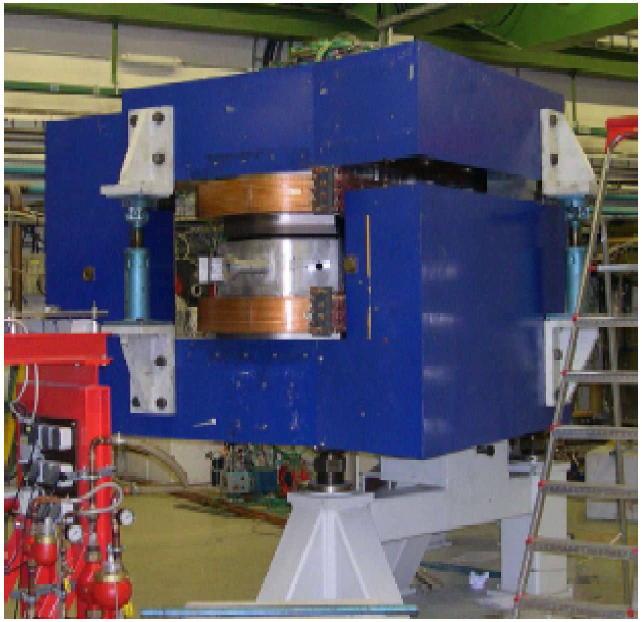
- 100% duty factor electron microtron
- MAMI-C 1.5 GeV upgrade (Completed!!)
  (MAMI-B 0.85 GeV)



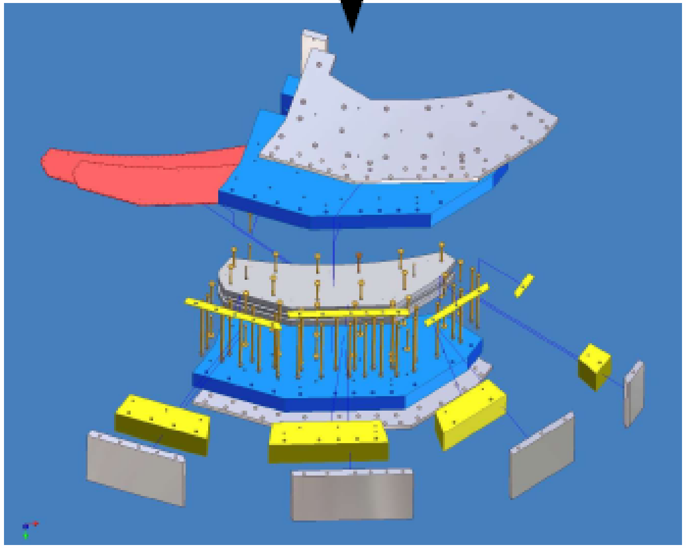

One of the MAMI-C magnets

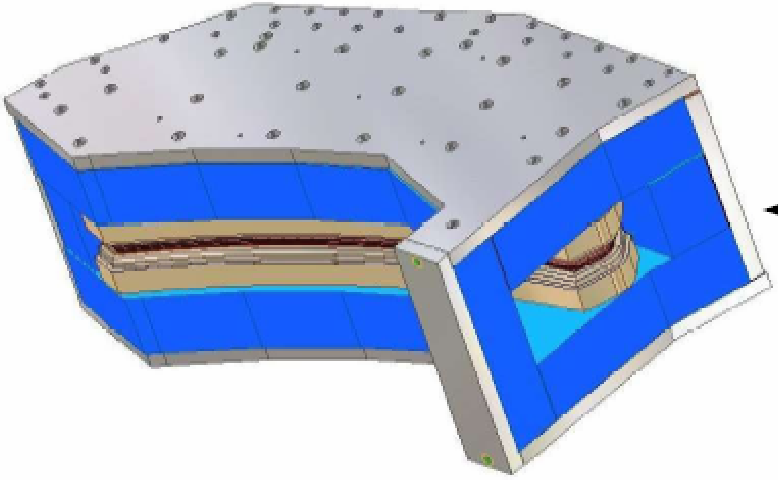


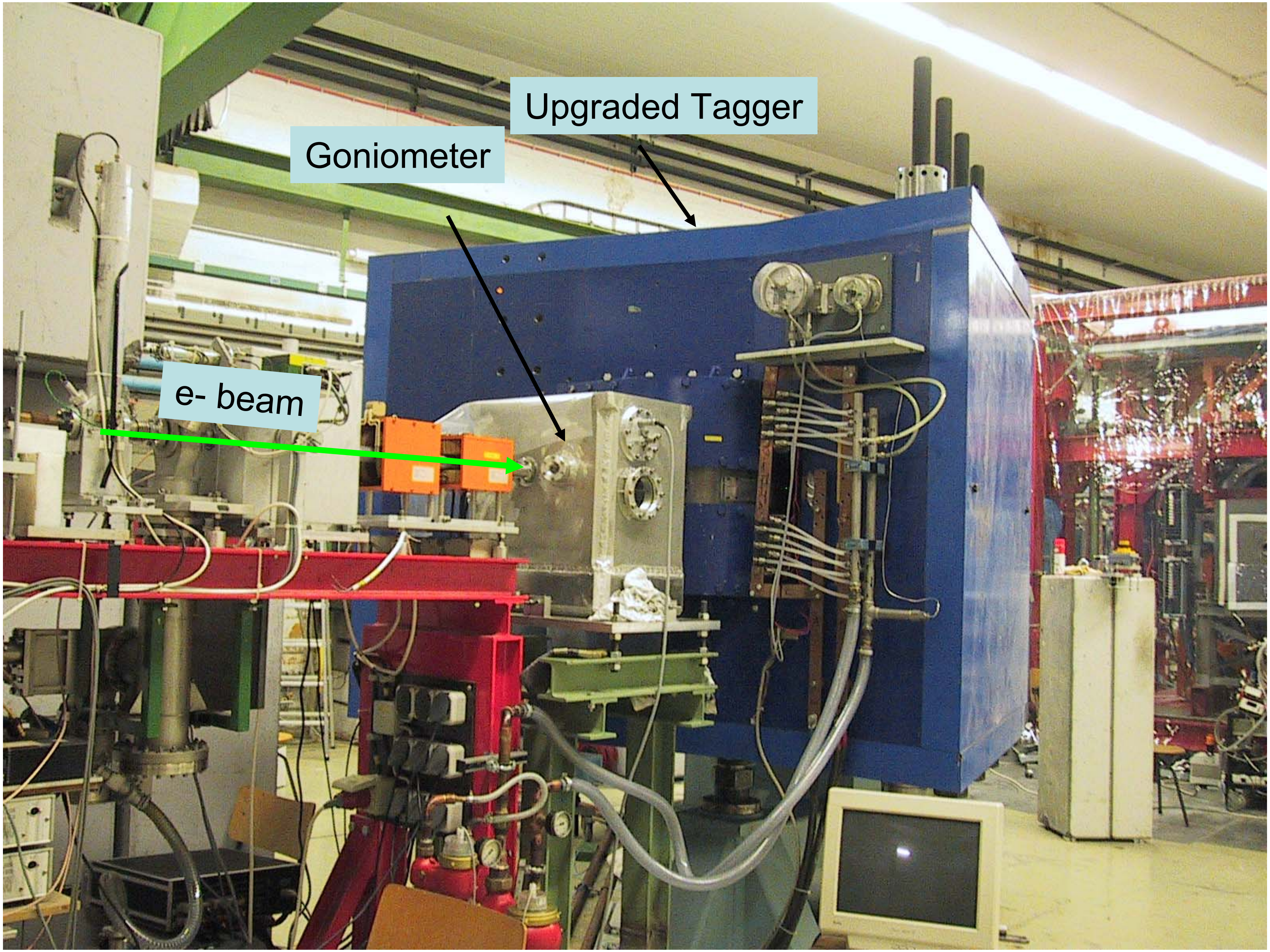
Photon Tagger upgrade



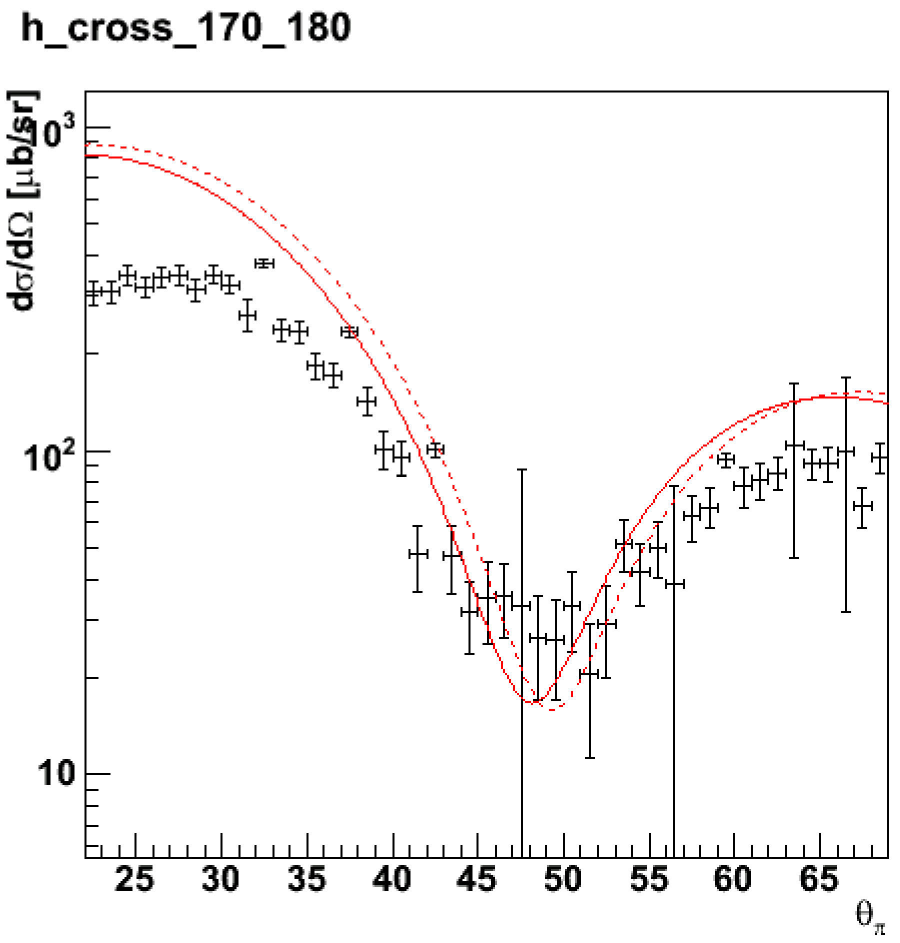
+



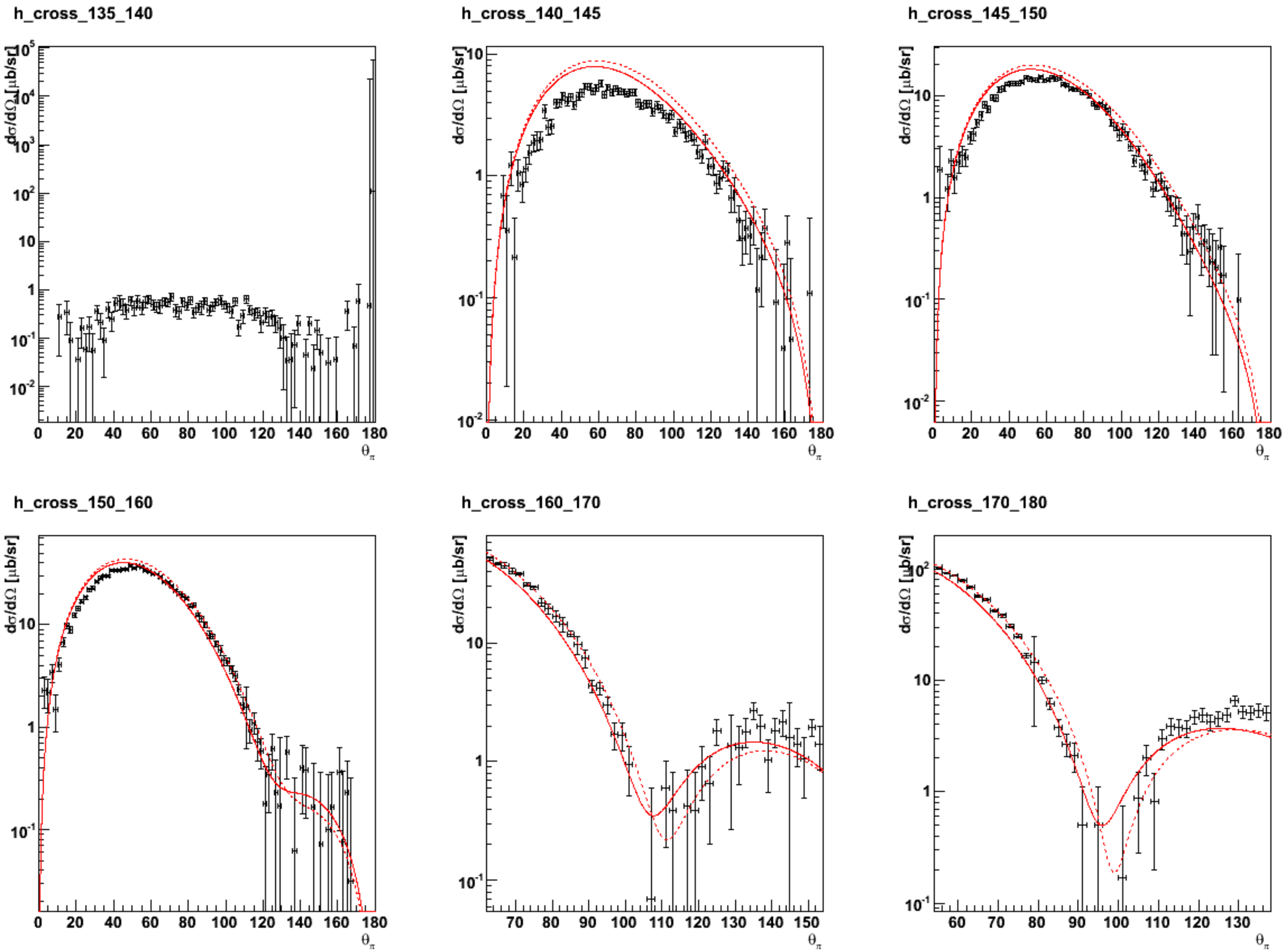



Upgraded Tagger
Goniometer
e- beam

Crystal Ball arrives at Frankfurt



h_cross_170_180
dσ/dΩ [μb/sr]
10³
10²
10
25
30
35
40
45
50
55
60
65
θ_π


h_cross_135_140
h_cross_140_145
h_cross_145_150
h_cross_150_160
h_cross_160_170
h_cross_170_180
dσ/dΩ [μb/sr]
θ_π

Setup at MAMI

TAPS:

510 BaF_2-detectors
maximum kin. Energy

$\pi^{\pm}: 180\ MeV$

$K^{\pm}: 280\ MeV$

$p: 360\ MeV$

Crystal Ball:

672 NaI-detectors
maximum kin. energy

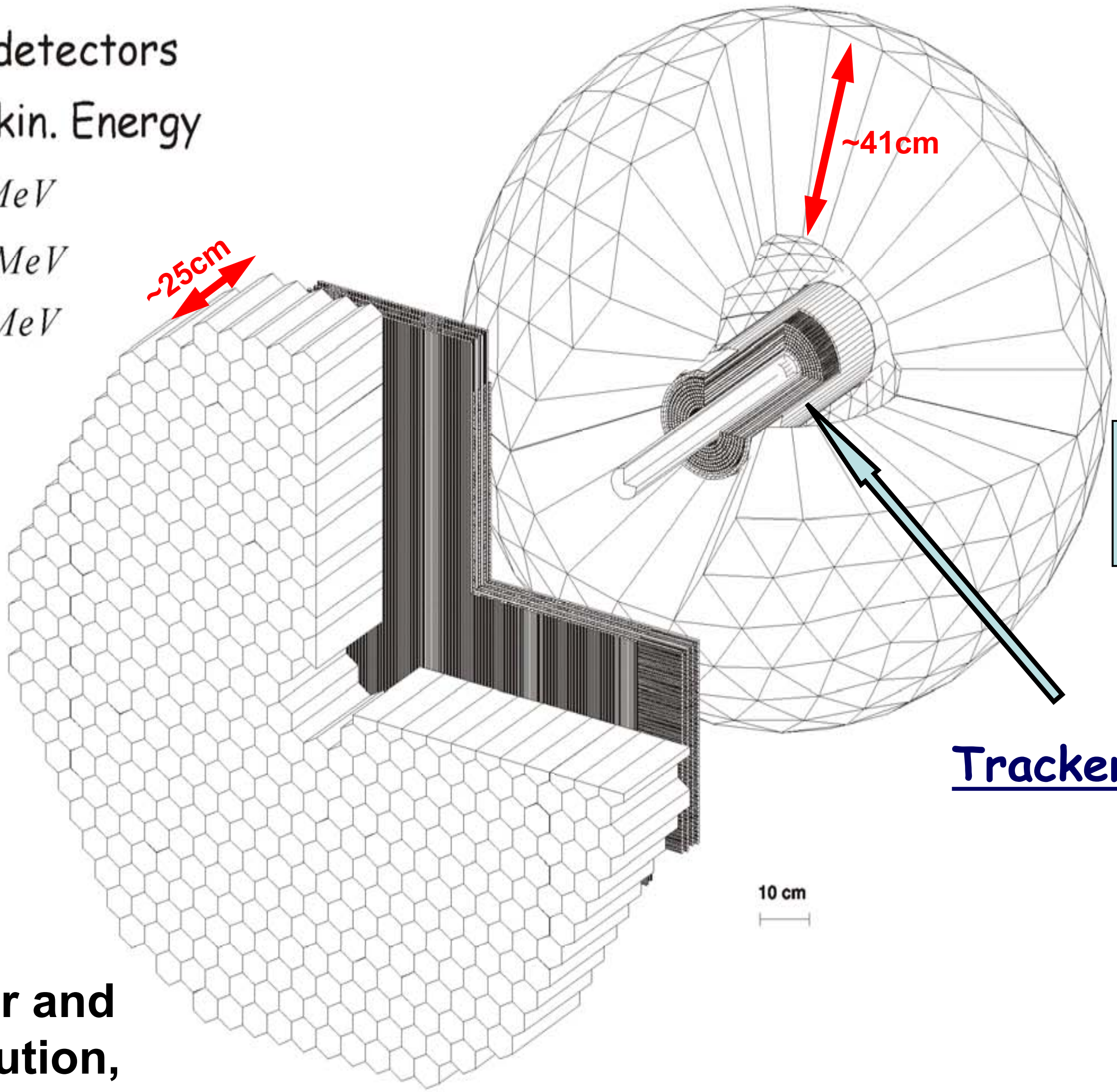
$\mu^{\pm}: 233\ MeV$

$\pi^{\pm}: 240\ MeV$

$K^{\pm}: 341\ MeV$

$p: 425\ MeV$

$\sigma/E\gamma = 1.7\% / E_{\gamma}(\mathrm{GeV})^{0.4}$
$\sigma_{\theta} = 2\text{–}3^{\circ}$
$\sigma_{\phi} = 2^{\circ} / \sin\theta$

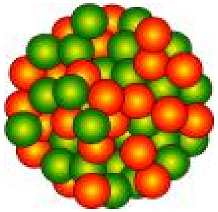


Tracker & Particle-ID

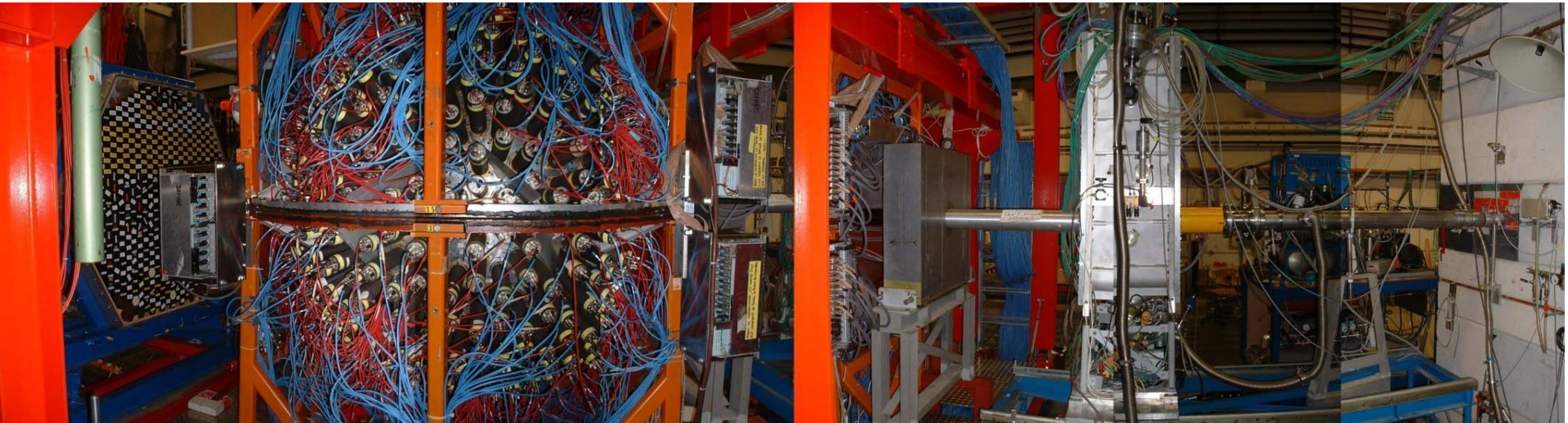
Good angular and energy resolution, close to 4π acceptance

Crystal Ball arrives at Frankfurt

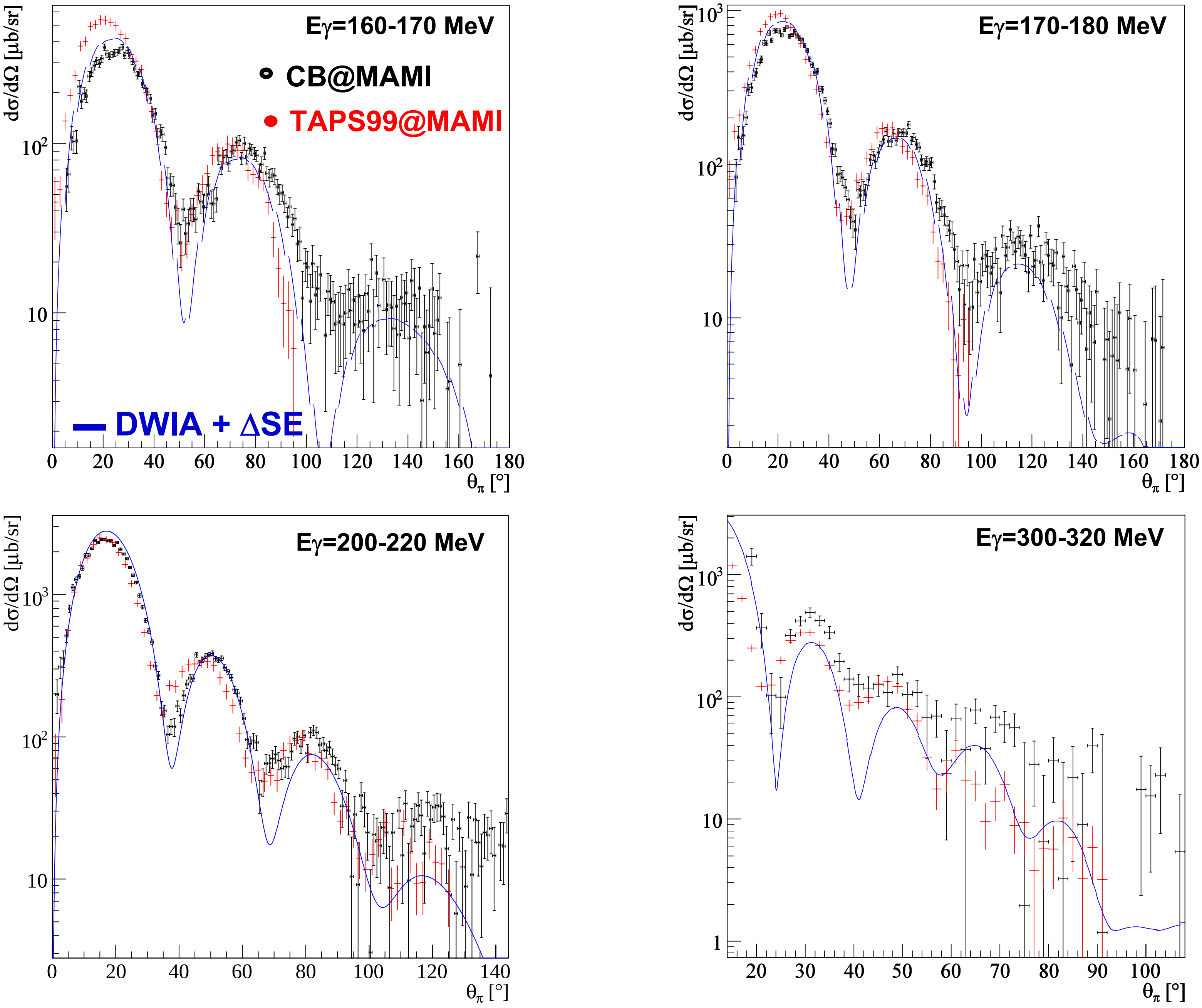
$A_{gs}(\gamma,\pi^0)A_{gs}$ coherent π^0 photoproduction

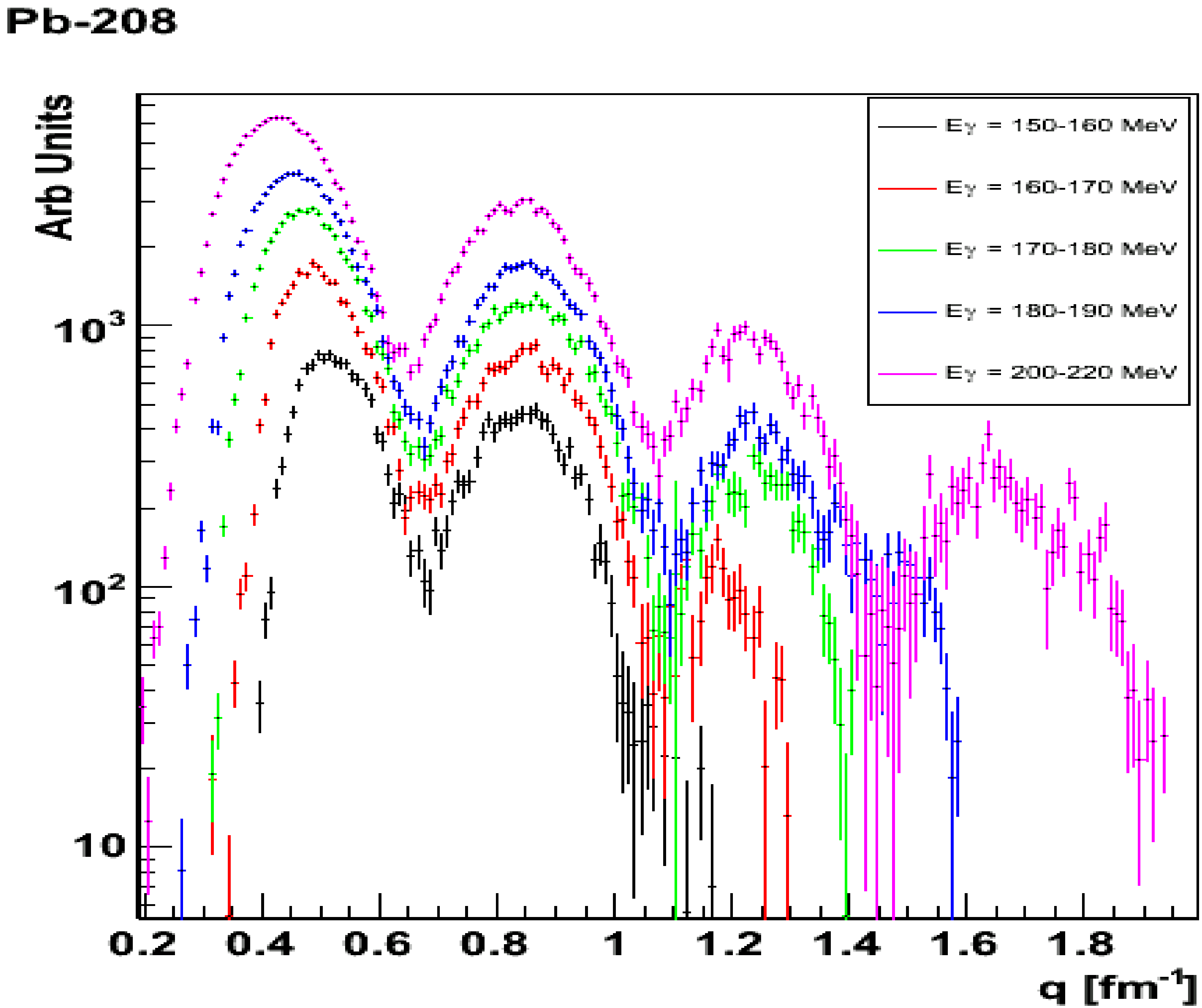


$$d\sigma/d\Omega \sim A^2(q/k_\gamma)P_3{}^2|F_m(q)|^2\sin^2\theta_\pi$$



^{208}Pb: π^0 angular distributions





Pb-208
Arb Units
10³
10²
10
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
q [fm⁻¹]
Eγ = 150-160 MeV
Eγ = 160-170 MeV
Eγ = 170-180 MeV
Eγ = 180-190 MeV
Eγ = 200-220 MeV

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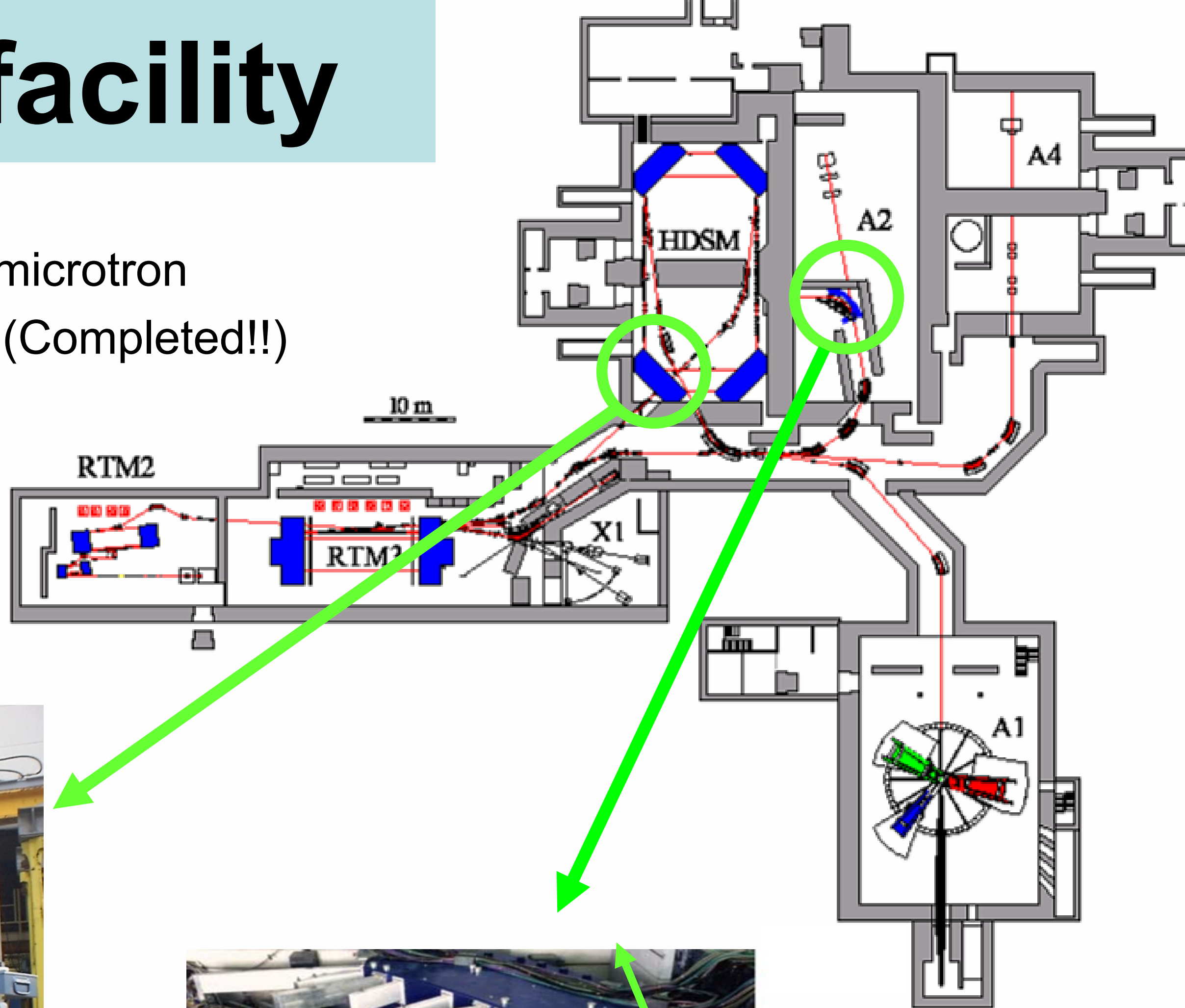

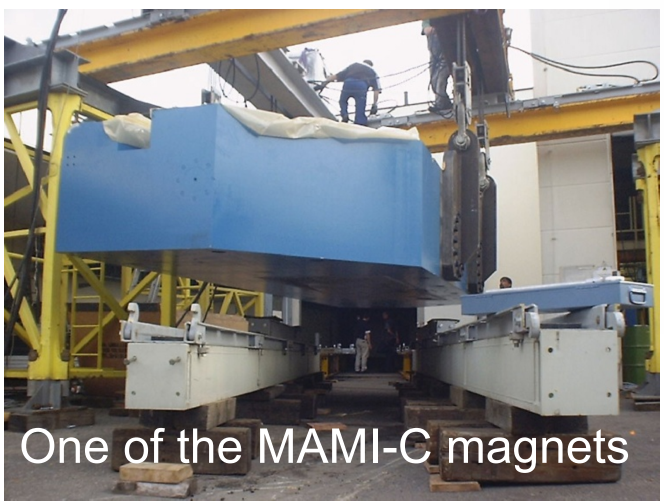
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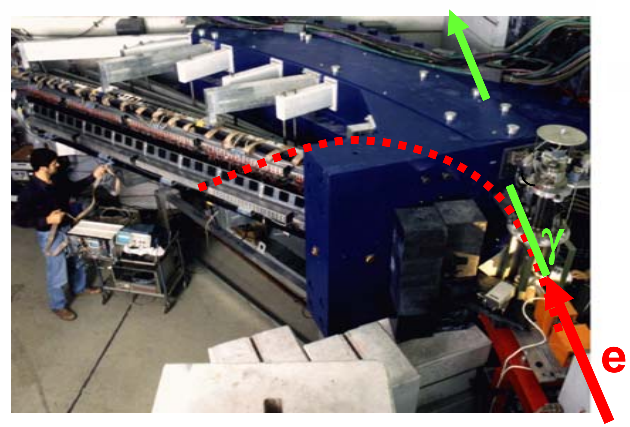
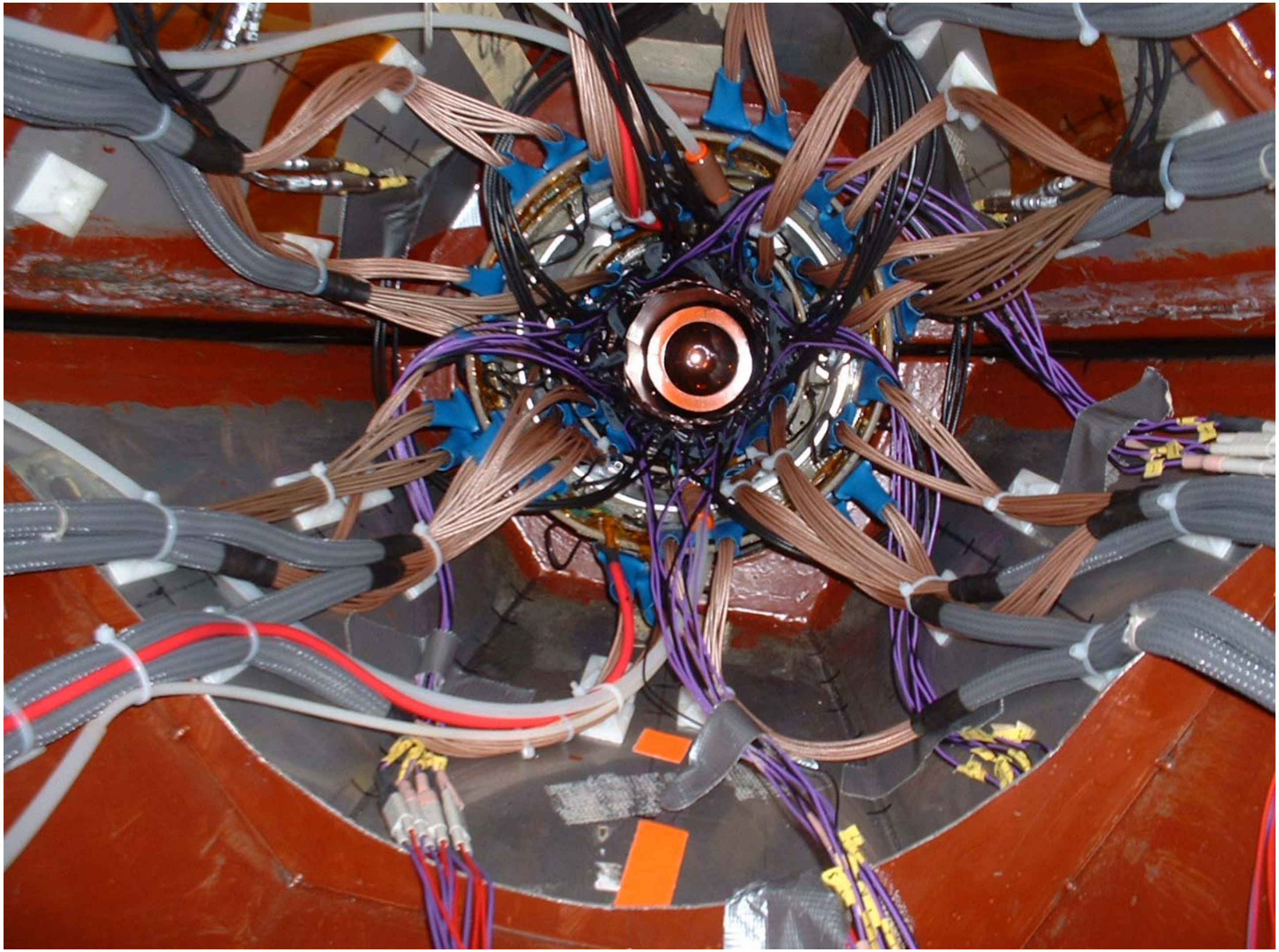
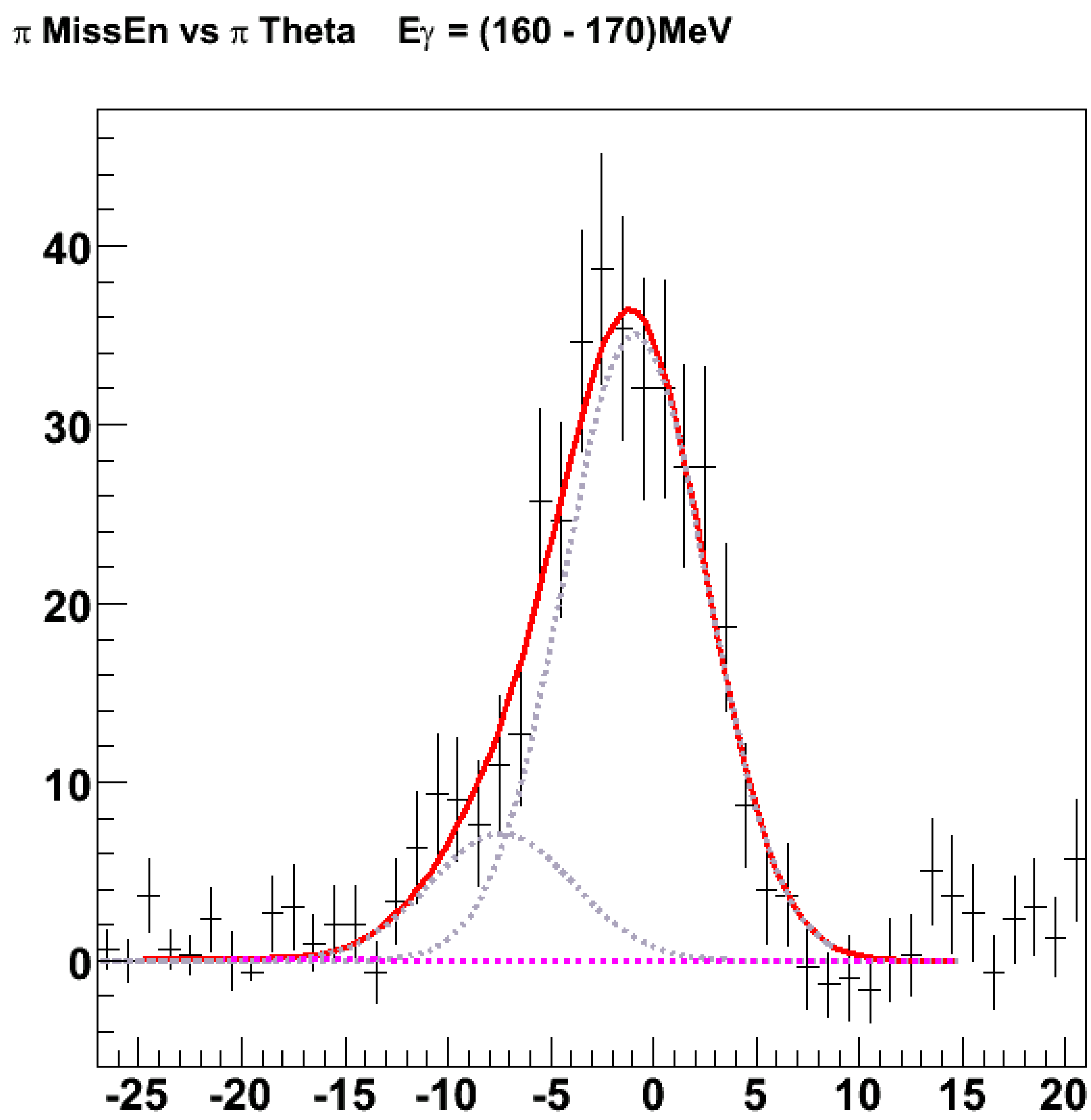


MAINZER MIKROTRON

MWPC & Particle-ID in situ





π MissEn vs π Theta   Eγ = (160 - 170)MeV
40
30
20
10
0
-25
-20
-15
-10
-5
0
5
10
15
20

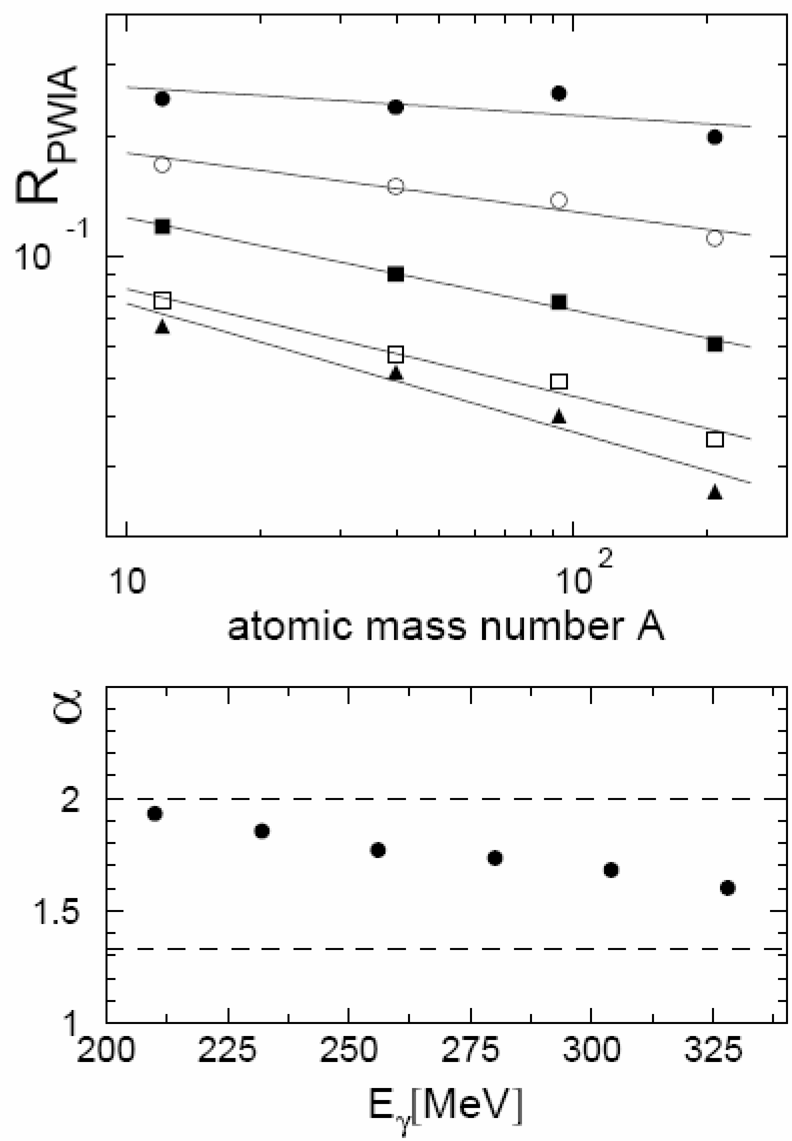
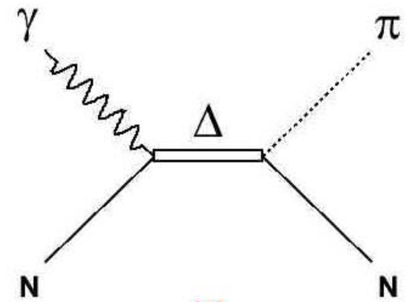
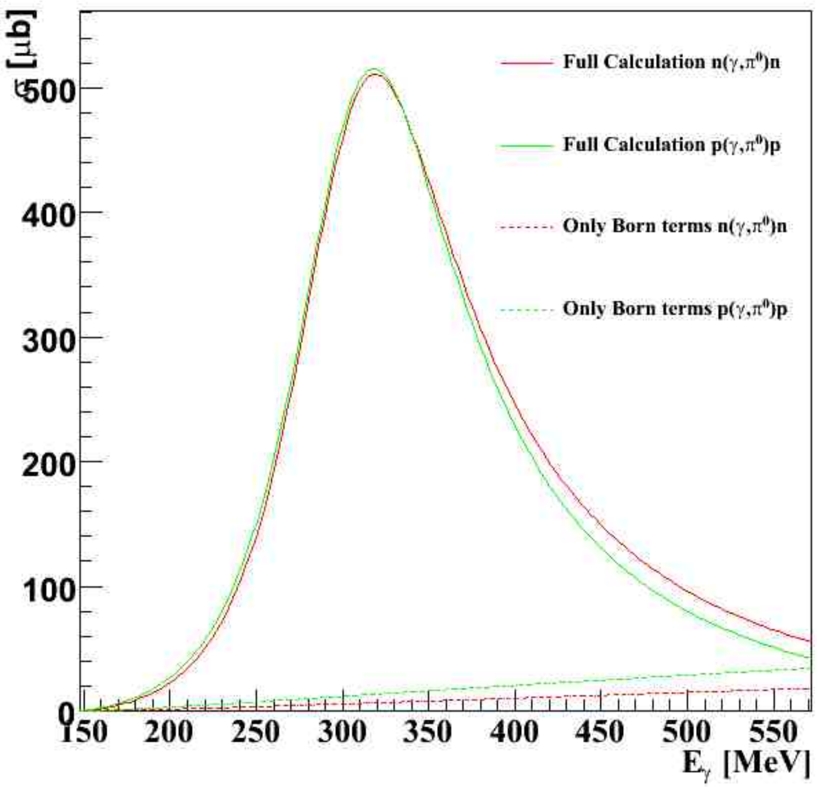


Fig. 3. Upper part: A-dependence of R_{PWIA} at $q = 0.5q_1$ for incident photon energies of 210, 230, 255, 280, and 305 MeV (from top to bottom). Lower part: fitted coefficients α of the mass dependence.

π^0 photoproduction amplitude

- Basic production amplitude ~ equal for protons and neutrons
- Dominated by $\Delta(1232)$ production





Isospin structure of amplitude

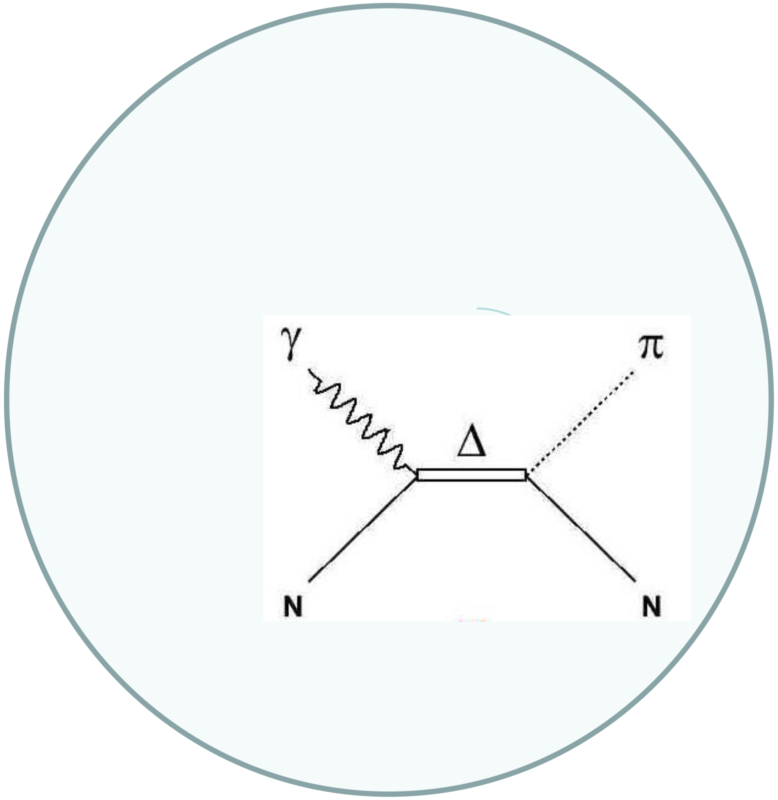
$$A(\gamma p\rightarrow\pi^0 p) = \sqrt{2/3}\, A^{V3} + \sqrt{1/3}(A^{IV} - A^{IS})$$
$$A(\gamma n\rightarrow\pi^0 n) = \sqrt{2/3}\, A^{V3} + \sqrt{1/3}(A^{IV} + A^{IS})$$

Δ has I=3/2 -- A^{V3} only

π^0 production in the nucleus

Access matter form factor
and matter transition form factor
with EM probe

"Clean" test of π^0-nucleus interaction & effect of medium on Δ–properties



Test more specific aspects of the basic production amplitude

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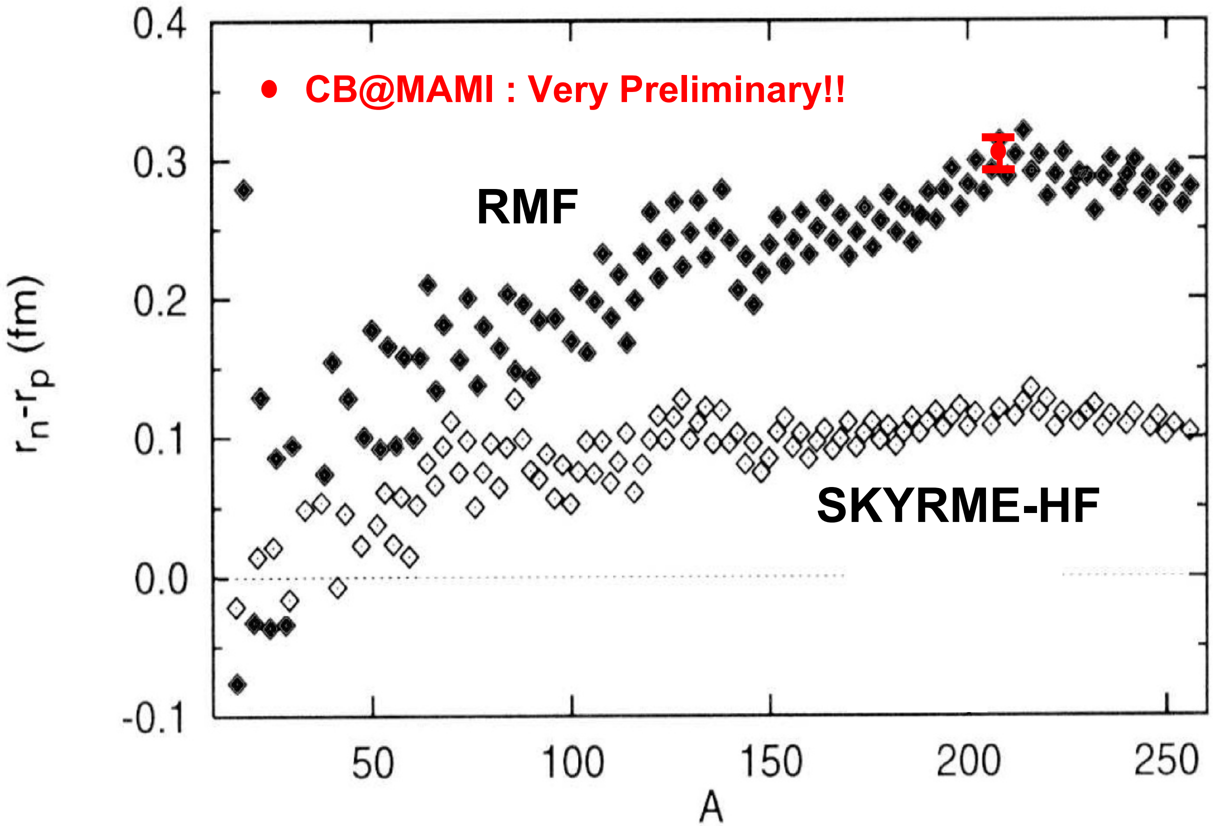
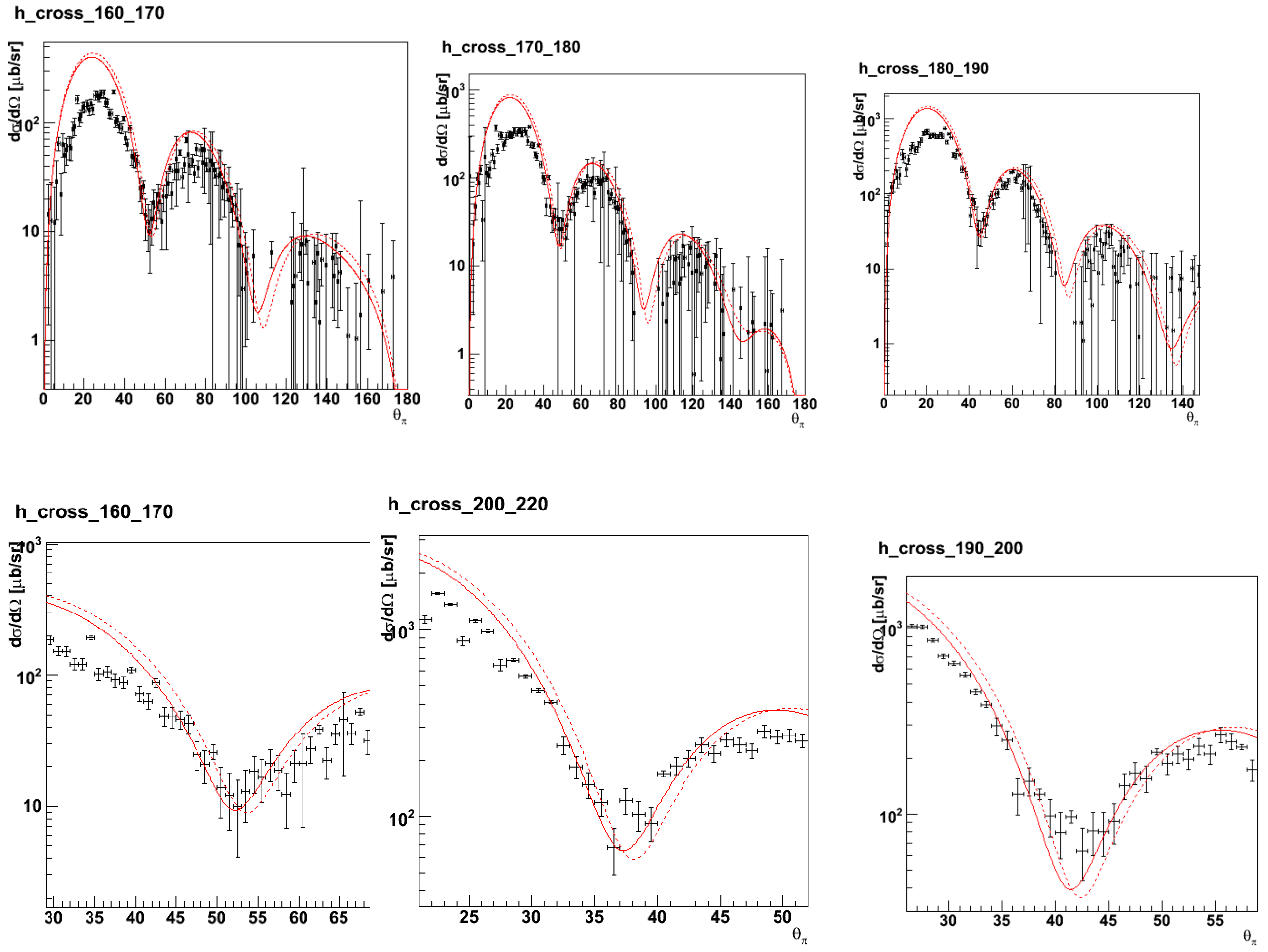
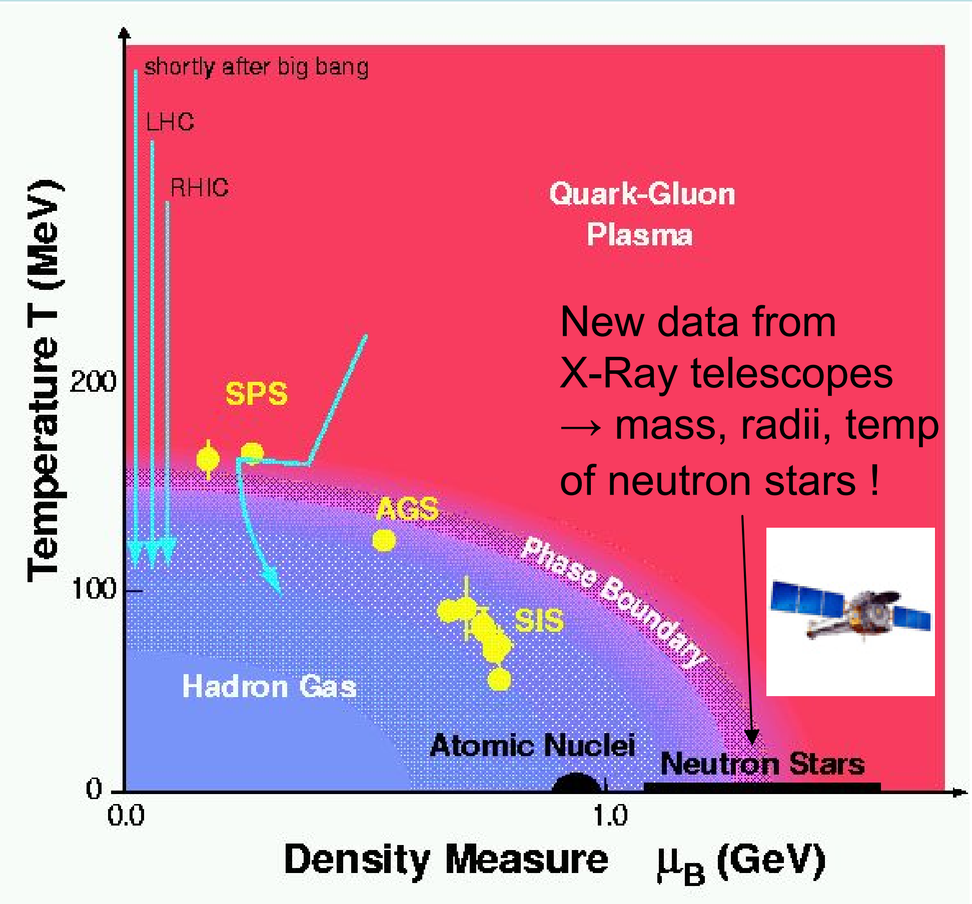
Neutron skins & Nuclear theories

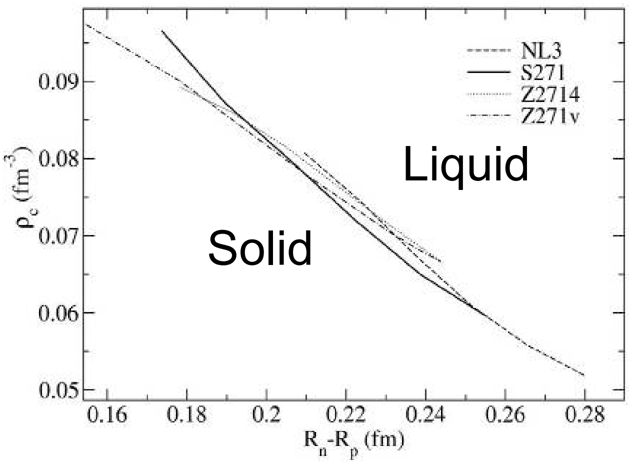



h_cross_160_170
dσ/dΩ [μb/sr]
θπ
h_cross_170_180
dσ/dΩ [μb/sr]
θπ
h_cross_180_190
dσ/dΩ [μb/sr]
θπ
h_cross_160_170
dσ/dΩ [μb/sr]
h_cross_200_220
dσ/dΩ [μb/sr]
θπ
h_cross_190_200
dσ/dΩ [μb/sr]
θπ

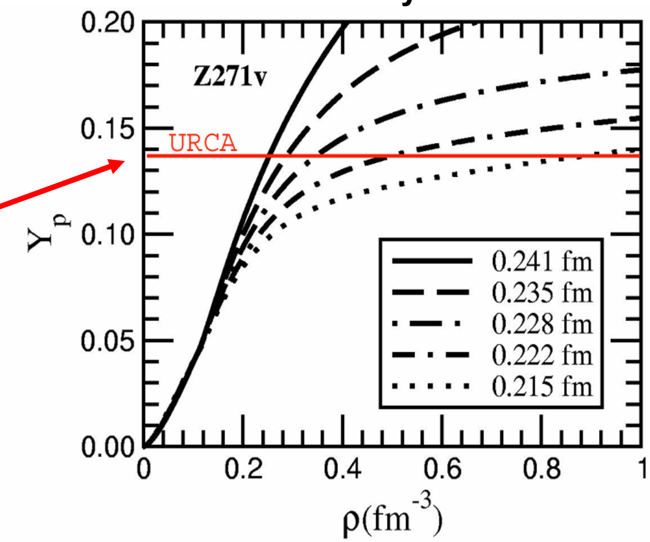
^{208}Pb Neutron skin and Neutron stars



Thick neutron skin
→ Low transition density in neutron star



Proton fraction as a
function of density in neutron star



URCA Cooling

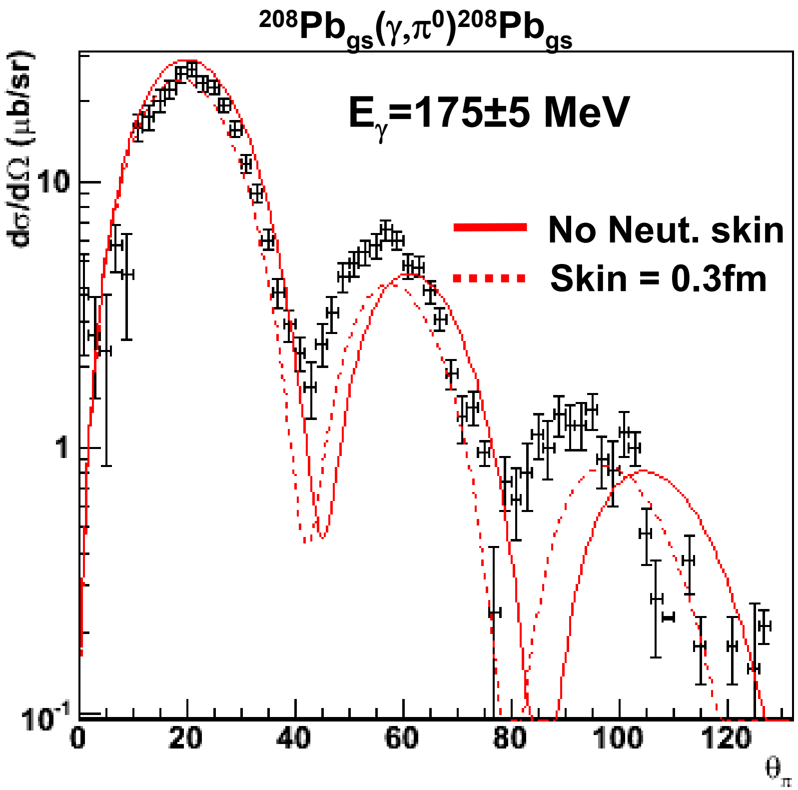
$n \rightarrow p + e^- + \bar{\nu}$

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

Preliminary analyses: Neutron skin determination from $A_{gs}(\gamma,\pi^0)A_{gs}$ coherent π^0 photoproduction

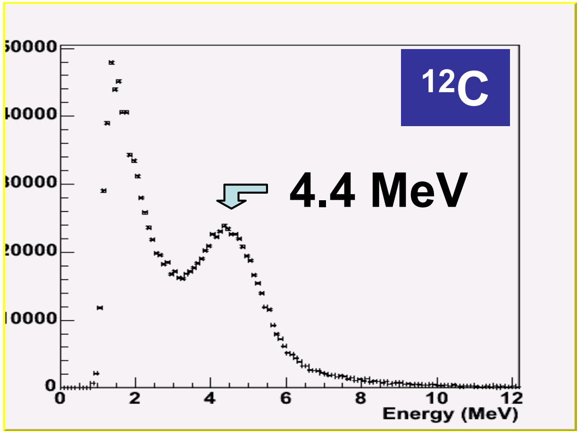
- Clear diffraction patterns for ^{208}Pb and a range of lighter nuclei

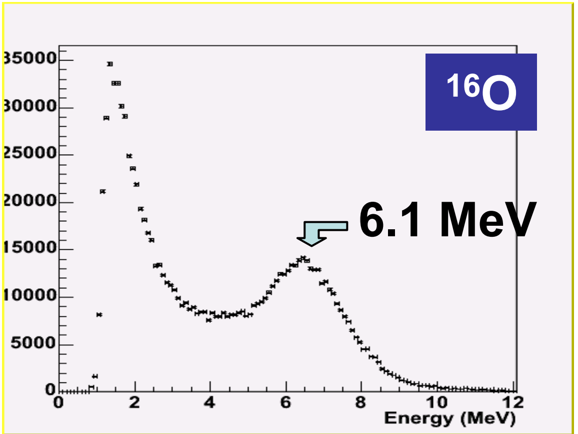
$$d\sigma/d\Omega \sim A^2(q/k_\gamma)P_3{}^2|F_m(q)|^2\sin^2\theta_\pi$$



Also see coincident low energy ***Nuclear Decay Photons !!***

Data analysis
Of C. Tarbert





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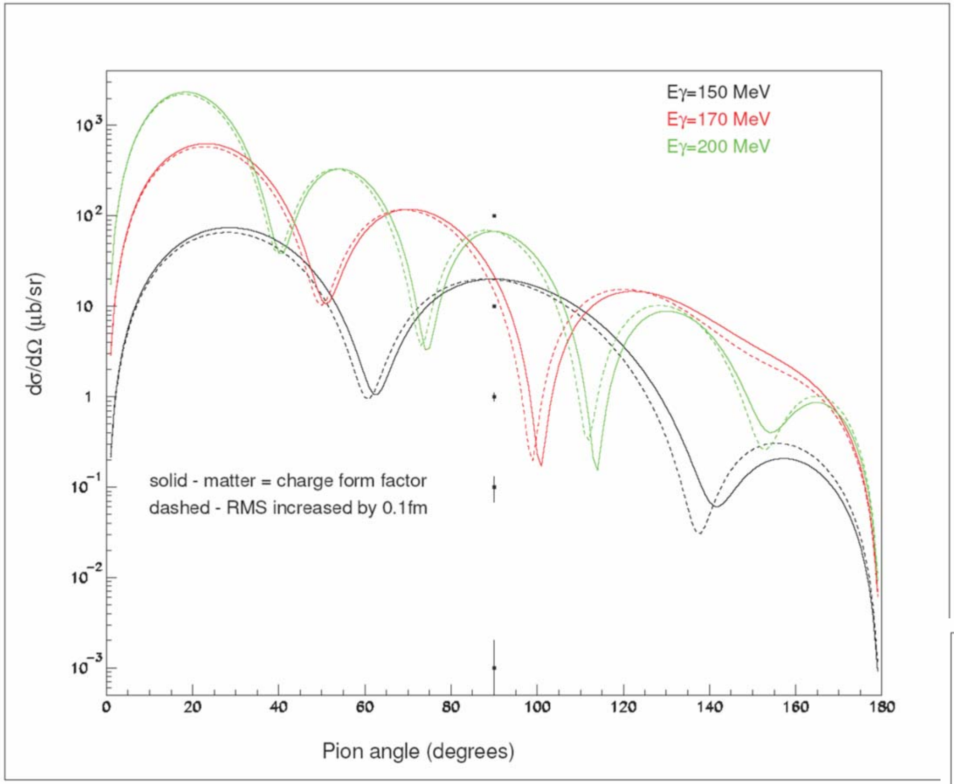
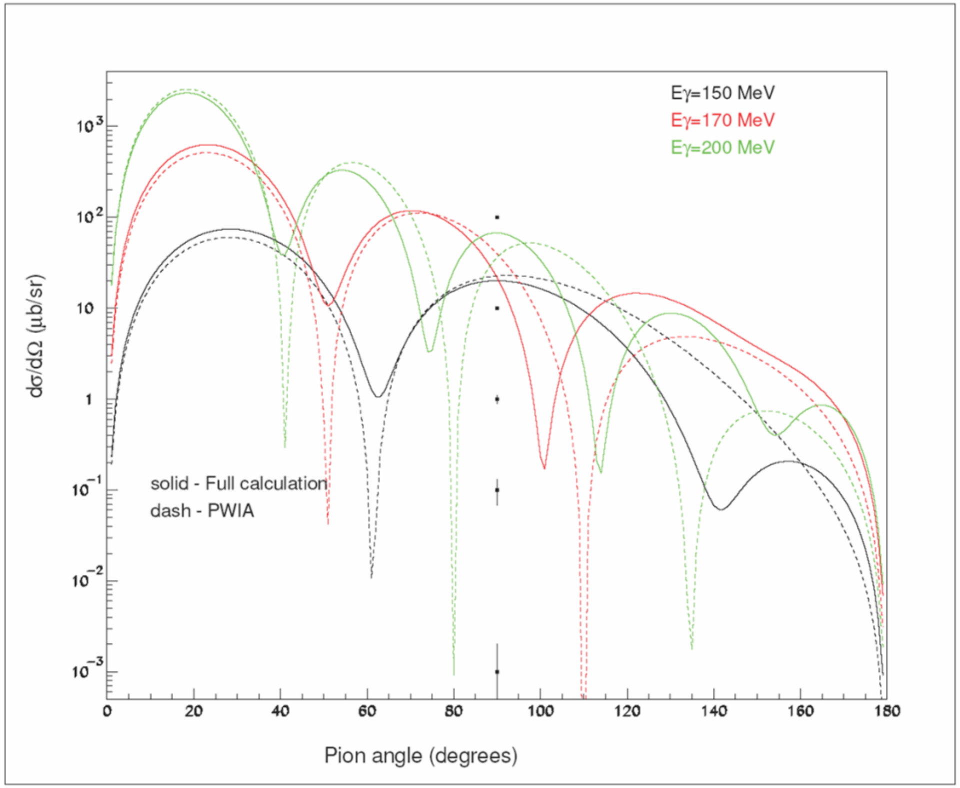
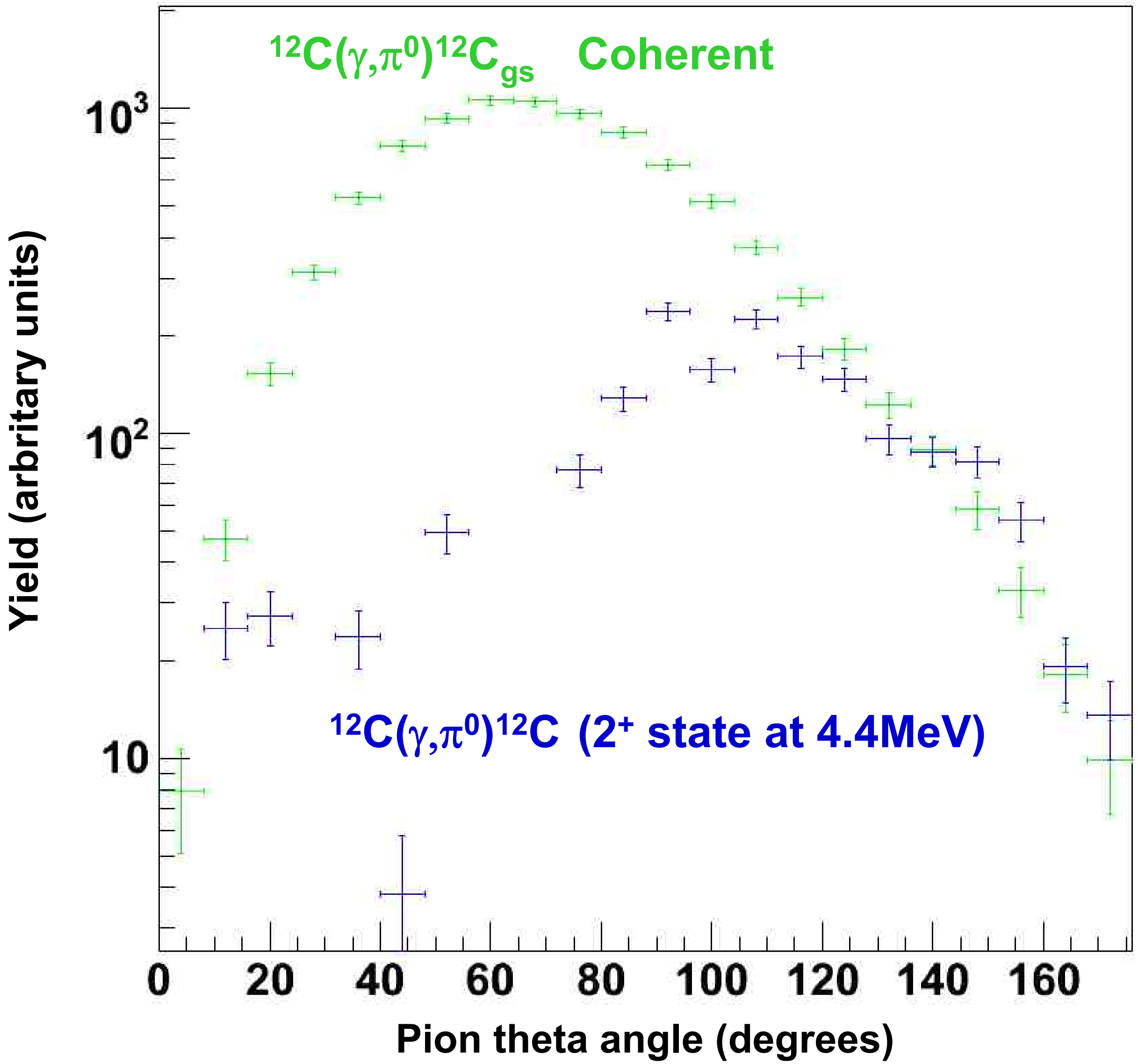
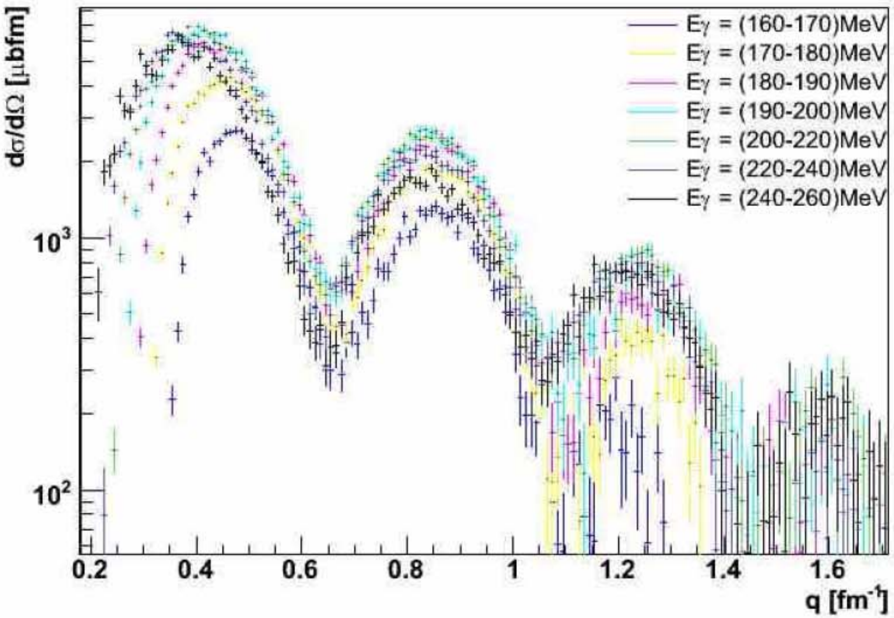

Eγ=150 MeV
Eγ=170 MeV
Eγ=200 MeV
solid - matter = charge form factor
dashed - RMS increased by 0.1fm
dσ/dΩ (μb/sr)
Pion angle (degrees)


Eγ=150 MeV
Eγ=170 MeV
Eγ=200 MeV
solid - Full calculation
dash - PWIA
dσ/dΩ (μb/sr)
Pion angle (degrees)

Preliminary analyses: Incoherent π^0



^{208}Pb : Momentum transfer distributions



Without FSI cross section could be descibed by PWIA.

FSI has effect of:

1. Changing momentum of outgoing pion as it leaves the nucleus (shift in q).

2. Loss of strength with another channel.