Dan Watts, Claire Tarbert

University of Edinburgh

Crystal Ball@MAMI
Collaboration

Neutral pion photoproduction

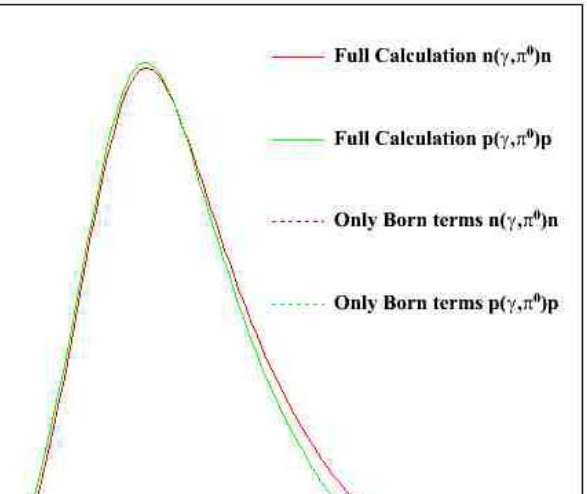
- Basic Amplitude
- Nuclear case - Coherent, Incoherent

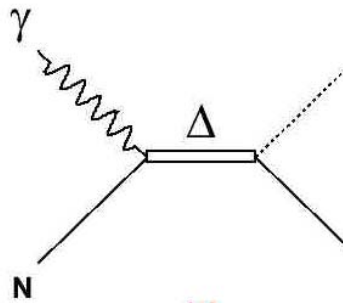
Matter form factor, transition matter form factor

Crystal Ball/TAPS at MAMI

New data on Coherent and incoherent reactions

minated by $\Delta(1232)$ production

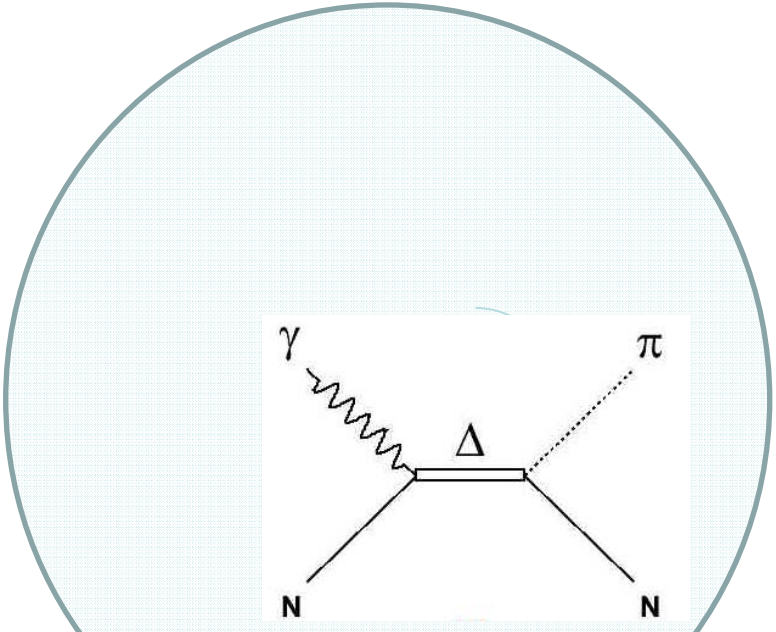




Isospin structure of amplit

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

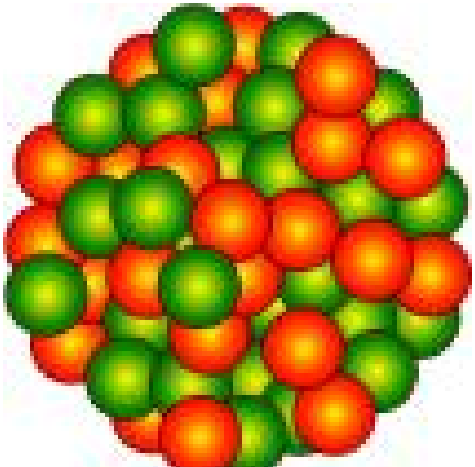
matter transition form factor
EM probe

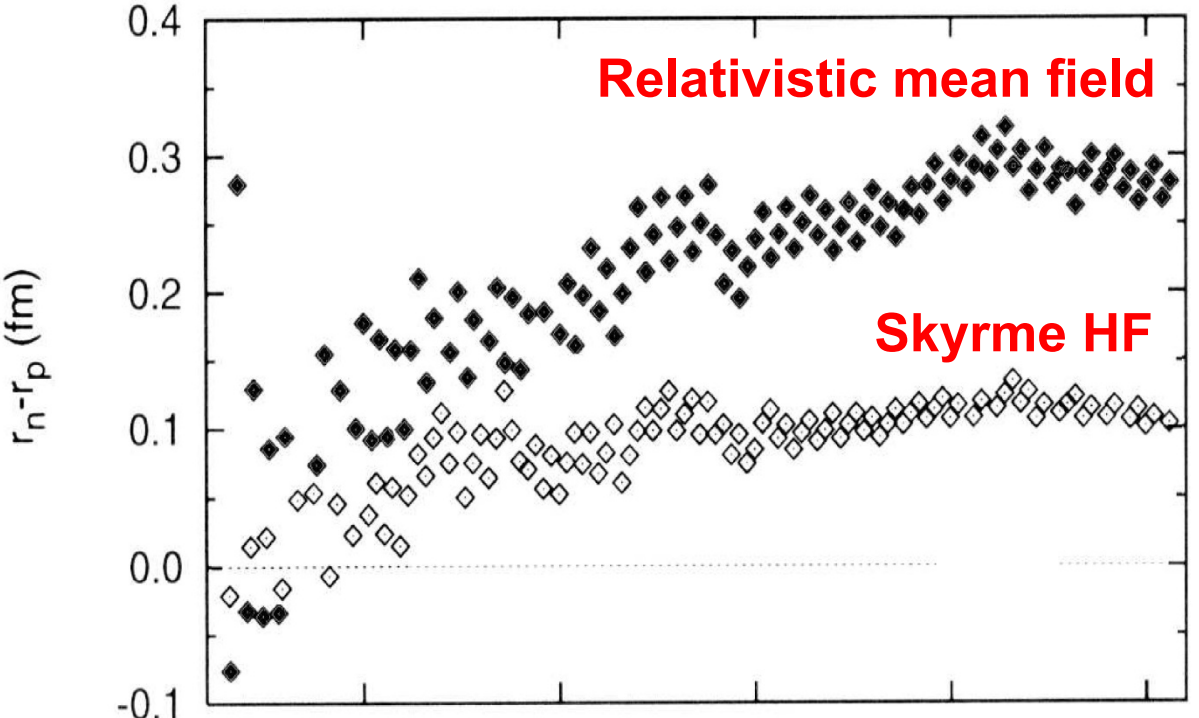


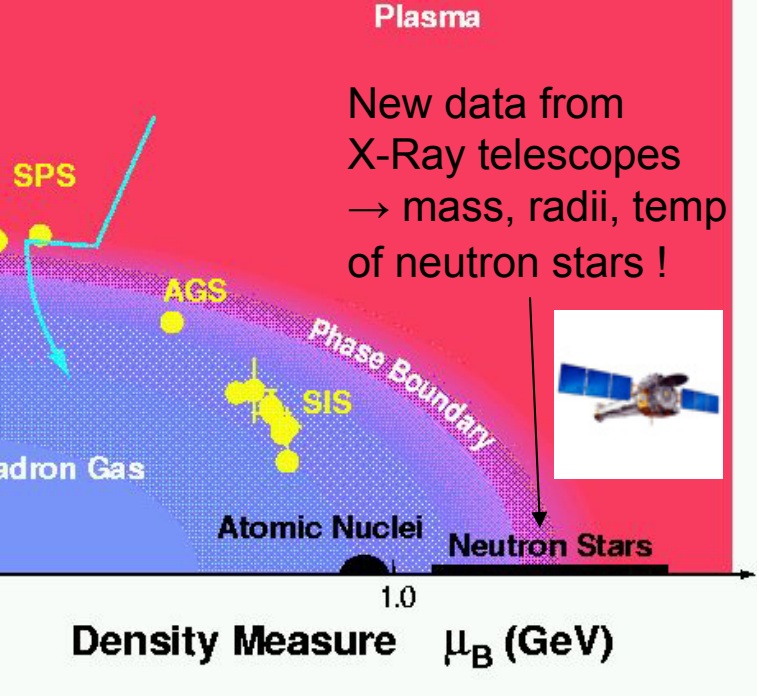
"Clean" test of π^0-n
interaction & effe
medium on Δ–prop

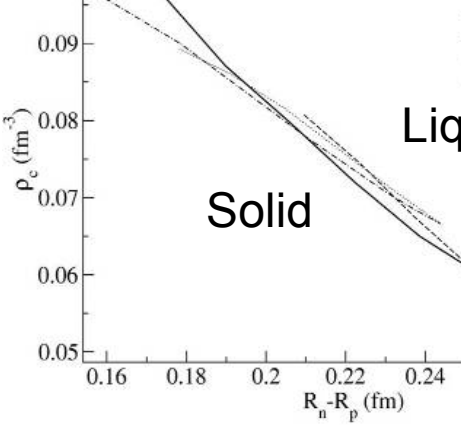
...knowledge of the shape of stable nuclei is presently incomplete

...Pb RMS charge radius known to < 0.001 fm
RMS neutron radius only known to ~0.2 fm !! Horowitz et al. PRC63 (
Piekarewicz et al. NPA

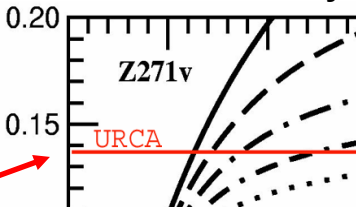



Relativistic mean field
Skyrme HF
r_n-r_p (fm)
0.4
0.3
0.2
0.1
0.0
-0.1

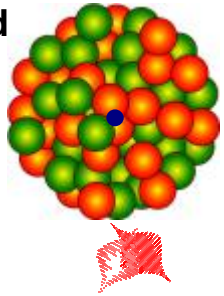




Proton fracti
function of density i



well understood



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

Select reactions which leave nucleus in ground state

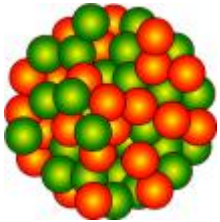
Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay

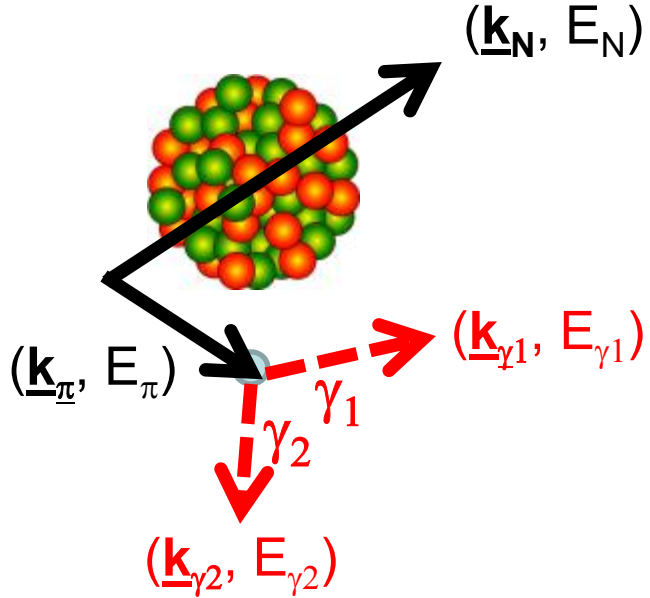
ar distribution of π^0 → PWIA contains the matter form factor

$$(\text{PWIA}) = (s/m_N^2)\, A^2\, (q_{cm}^*/2k)\, F_2(E_{\pi^0}^*, \theta_{\pi^0}^*)^2\, |F_{nl}(q)|^2\, si$$

Eγ)

(0, E)

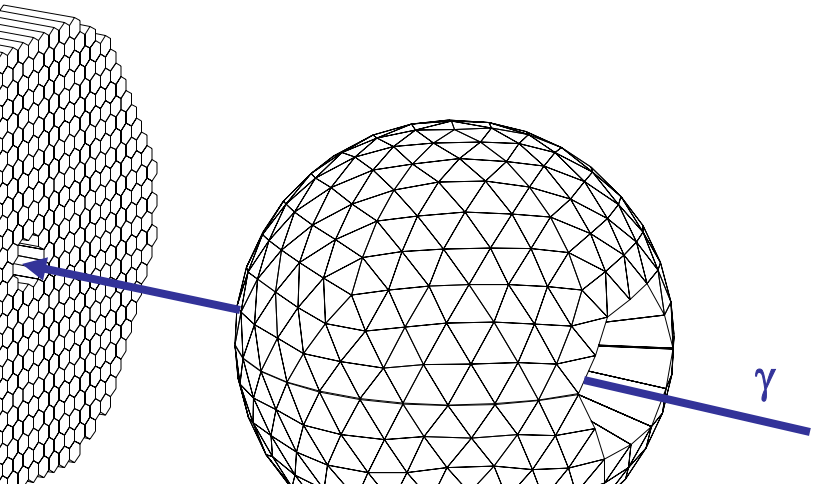




$= E_\pi(E_\gamma) - E_\pi(\gamma_1,\gamma_2)$

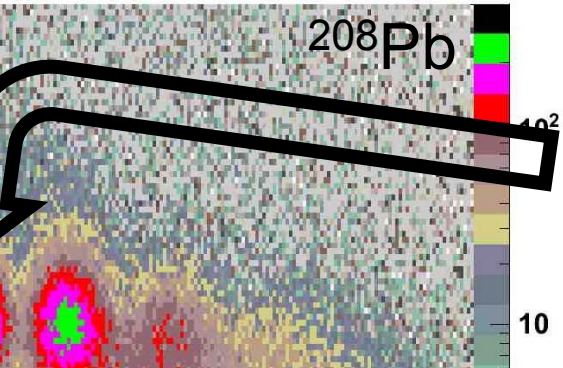
Best previous measurements → segmente


ΔEγ ~
10^8 ~

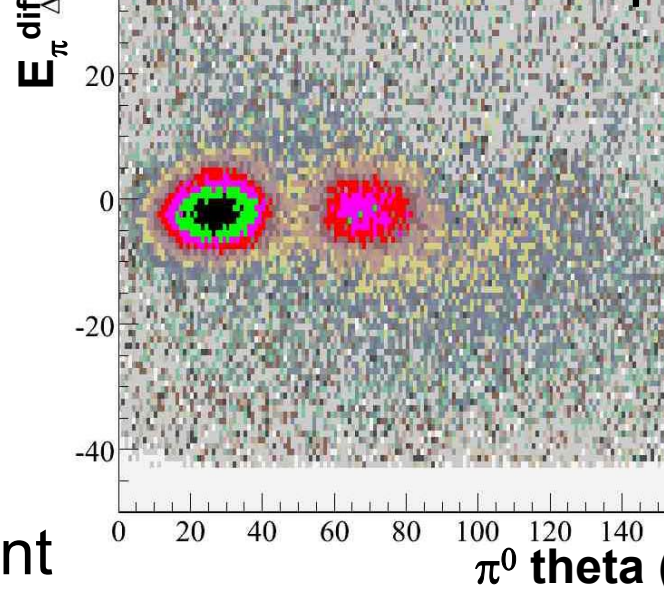

γ

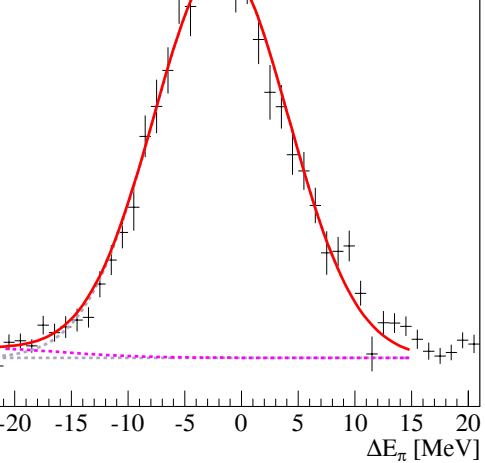

Target Position
×10^3
[arb. units]
50

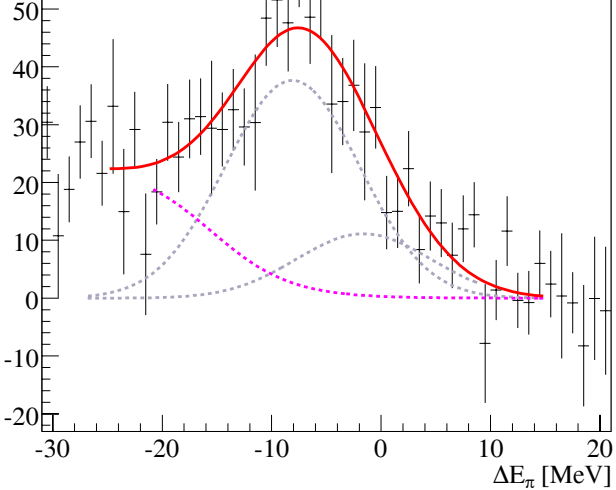
E_γ=210±10 MeV



Coherent maxima

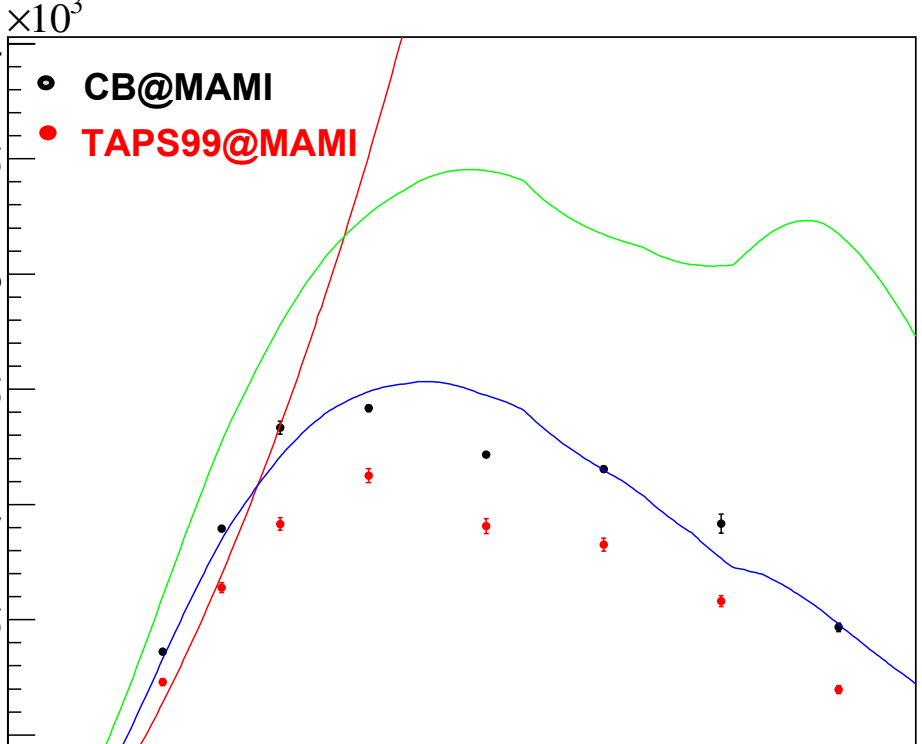






ent → Gaussian with $\sigma(E_\pi)$ extracted from coherent maximum

red step function at A(γ,π^0N)A-1 threshold



PWIA

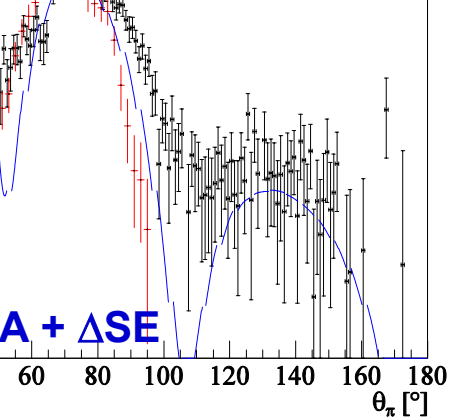
DWIA

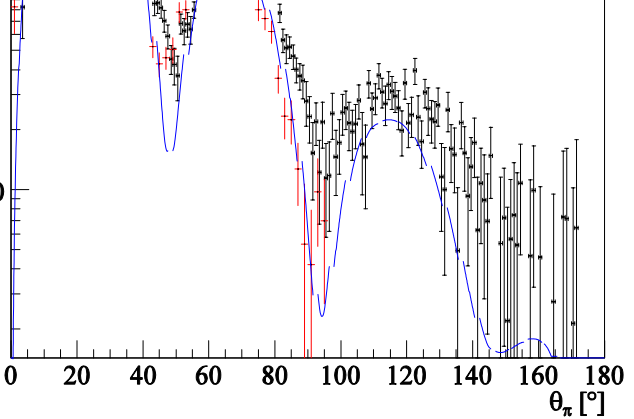
DWIA+Δ self e

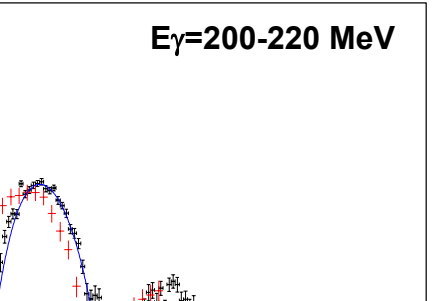
Theoretical predi

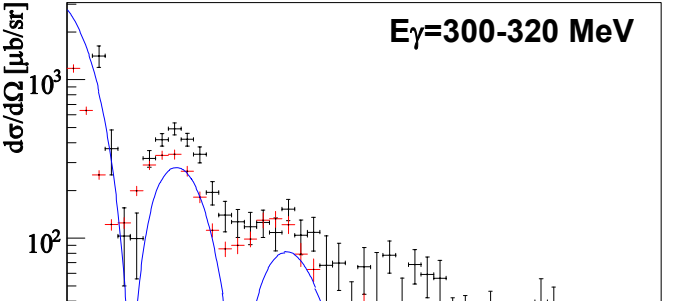
Dreschel, Tiator, Kamal
& Yang - NPA 660 (199

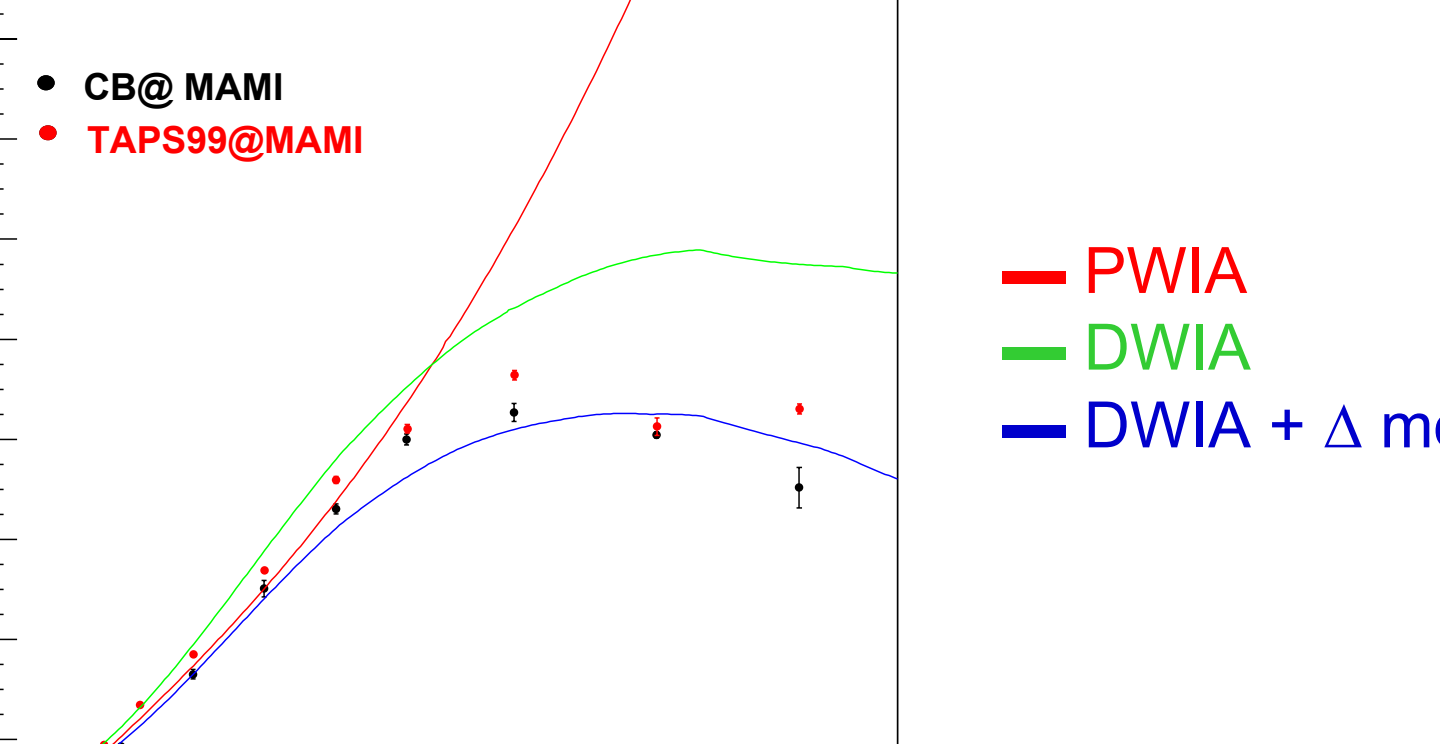
π^0 production amplitu
from Unitary Isobar M

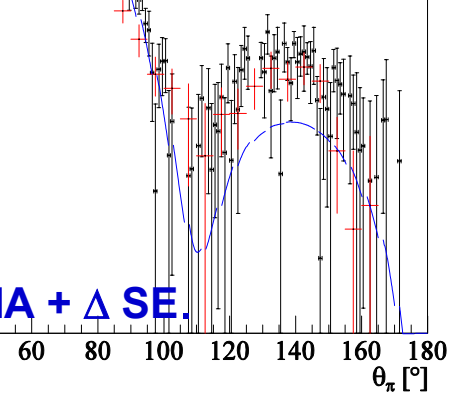

A + ΔSE
60 80 100 120 140 160 180
θπ [°]

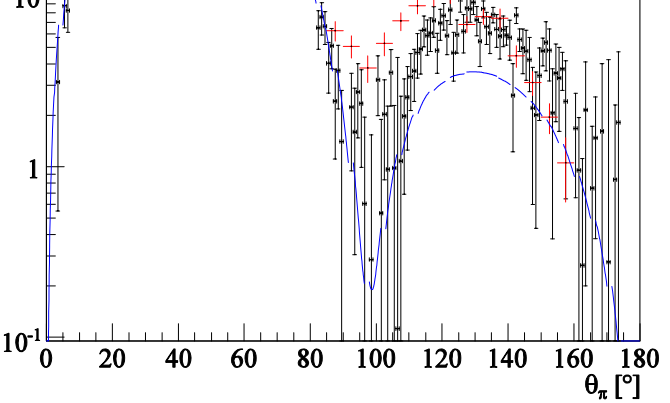

10
0 20 40 60 80 100 120 140 160 180
θπ [°]

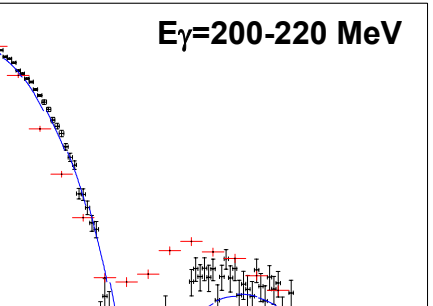

Eγ=200-220 MeV

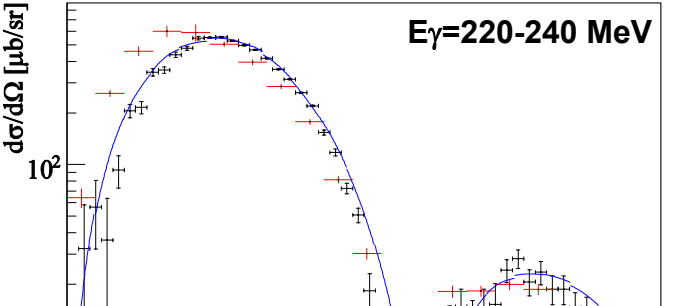

Eγ=300-320 MeV
dσ/dΩ [μb/sr]
10³
10²

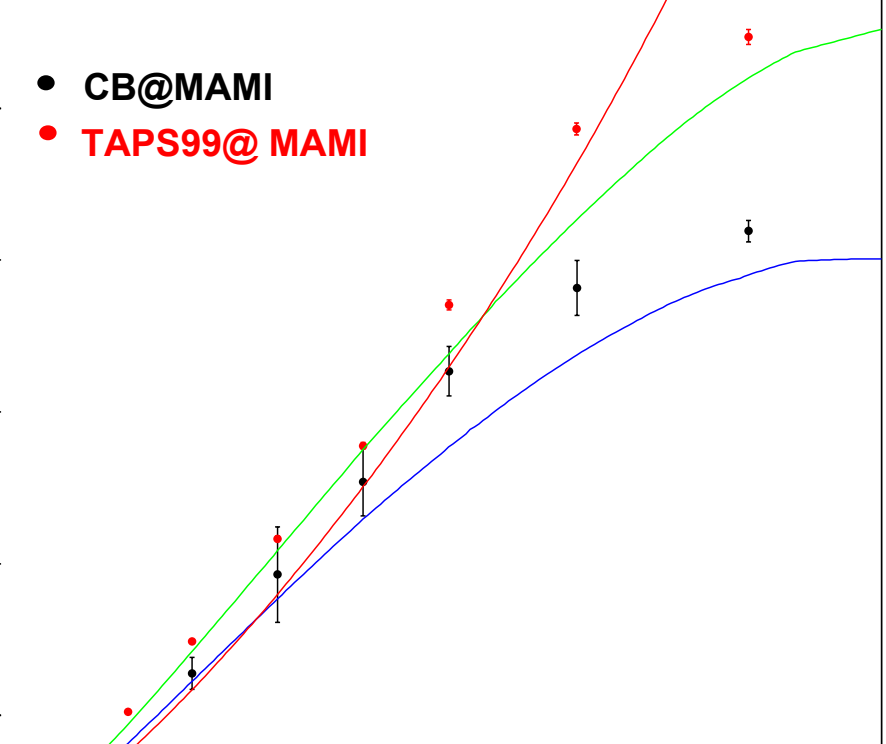

CB@ MAMI
TAPS99@MAMI
PWIA
DWIA
DWIA + Δ m


A + Δ SE.
60
80
100
120
140
160
180
θπ [°]


10
1
10-1
0
20
40
60
80
100
120
140
160
180
θπ [°]


Eγ=200-220 MeV


Eγ=220-240 MeV
dσ/dΩ [μb/sr]
10²



PWIA

DWIA

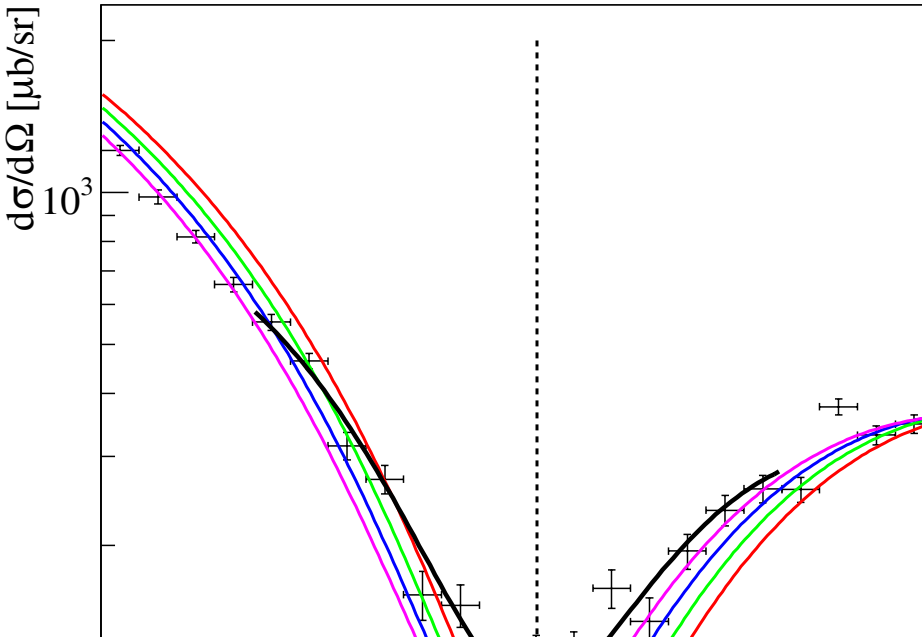
DWIA + Δ m

Extract matter form factor from PWIA expression

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

Obtain corrected $|F_m(q)|^2$ - use ratio DWIA/PWIA f
heory

Eγ = (200-220)MeV

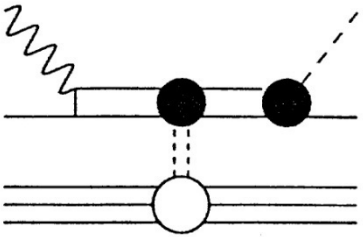


lo neutron skin
.1 fm skin
.2 fm skin
.3 fm skin

umes diffuseness
ne for proton and

th an electromagnetic probe.

so allows test of more specific Δ-nucleus interaction
ompared to coherent



b)

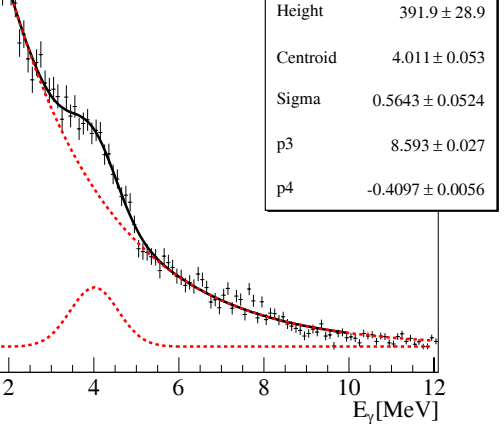
e.g. Δ-N interactions important

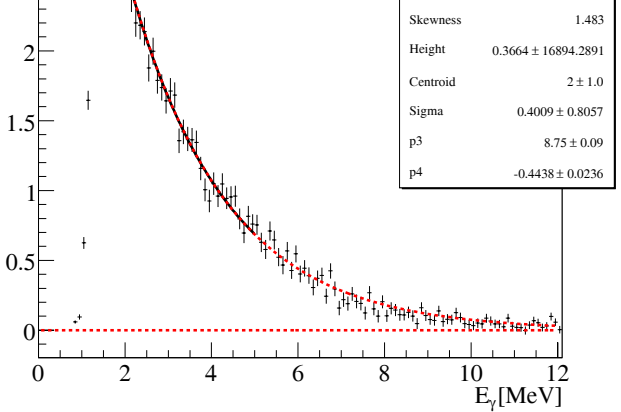
ficult to extract strength using E_π^{diff}

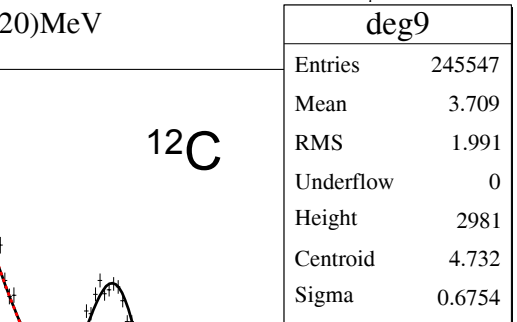
rginally “resolvable” for lowest E_γ bins

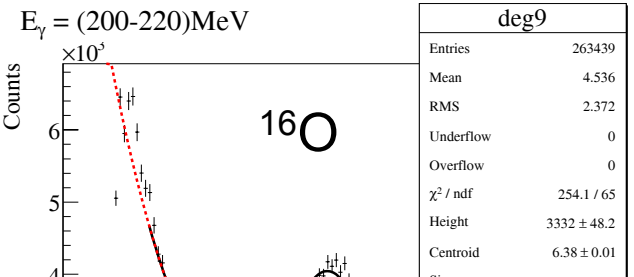
Detect nuclear decay photon *in the same detector a*
π^0 decay photons

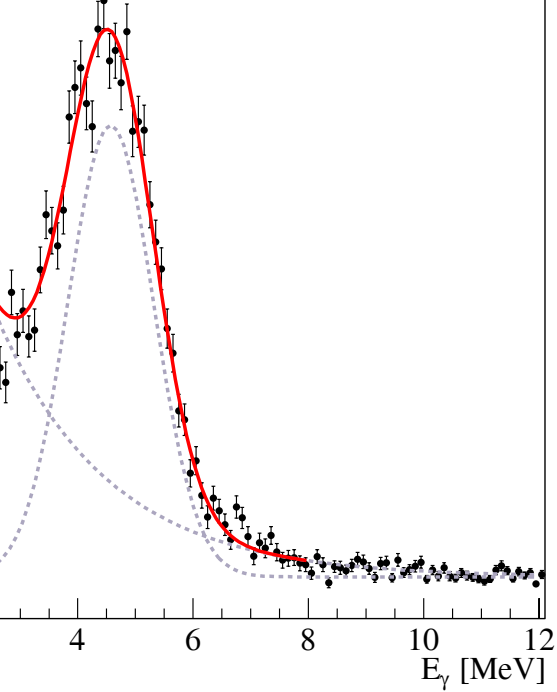
ens up access to incoherent reaction to discrete
clear states and up to higher π energies

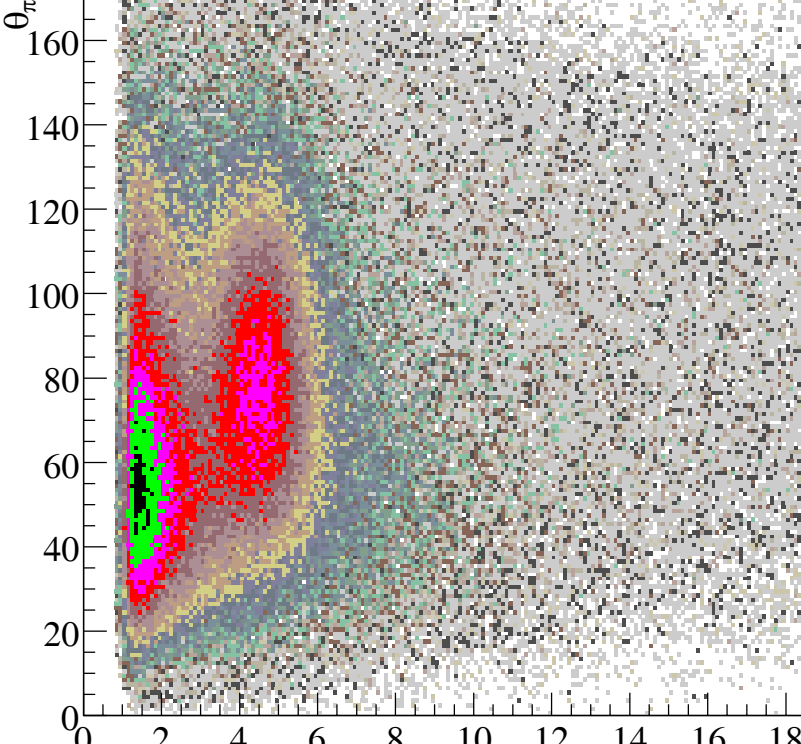

Height 391.9 ± 28.9
Centroid 4.011 ± 0.053
Sigma 0.5643 ± 0.0524
p3 8.593 ± 0.027
p4 -0.4097 ± 0.0056
2
4
6
8
10
12
E_γ[MeV]

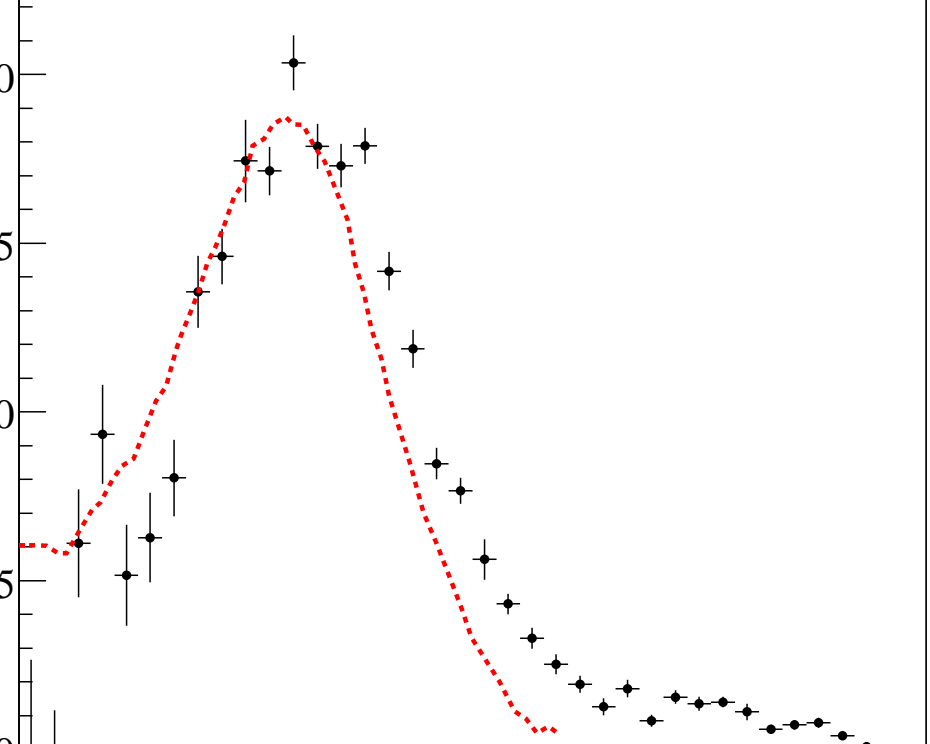

Skewness 1.483
Height 0.3664 ± 16894.2891
Centroid 2 ± 1.0
Sigma 0.4009 ± 0.8057
p3 8.75 ± 0.09
p4 -0.4438 ± 0.0236
0
0.5
1
1.5
2
0
2
4
6
8
10
12
E_γ[MeV]


20)MeV
^{12}C
deg9
Entries 245547
Mean 3.709
RMS 1.991
Underflow 0
Height 2981
Centroid 4.732
Sigma 0.6754


E_γ = (200-220)MeV
^{16}O
deg9
Entries 263439
Mean 4.536
RMS 2.372
Underflow 0
Overflow 0
χ^2 / ndf 254.1 / 65
Height 3332 ± 48.2
Centroid 6.38 ± 0.01
Counts
$\times 10^3$
6
5
4


4
6
8
10
12
E_γ [MeV]


θ_π
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18



Takaki Δ-hole
NPA 443 p570 (19

Nuclear wavefunctions
configuration coefficie
extracted from e- scat

oherent process extracted with a new level of accu

ata set of sufficient quality to extract information on
atter form factor

uclear decay photon analysis allows determination
coherent production -> study in it's own right and u
improve coherent extraction

rtment of Physics and Astronomy, University of Glasgow, Glasgow, UK

l W.Briscoe George Washington University, Washington, USA

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

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

sche and F.Zehr, Institut fur Physik University of Basel, Basel, Ch

jelm, M. Kotulla, K. Makonoyi, R.Novotny, M. Thiel and D. Trnka II. Phys. Institut, University of

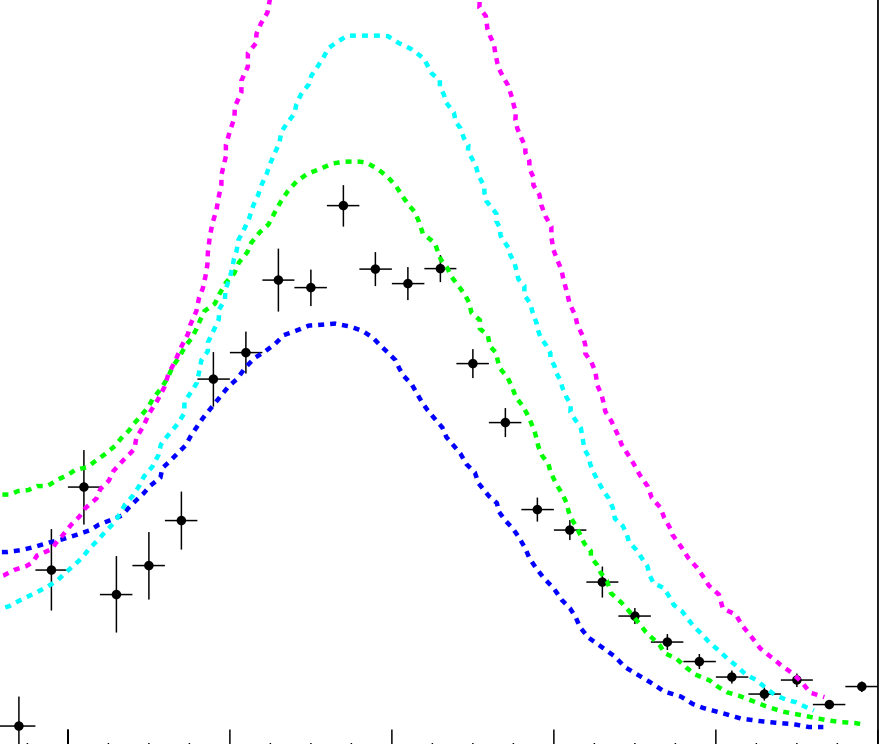
oehl, D. Glazier, T. Jude, C.Tarbert and D.P.Watts, School of Physics, Univ. of Edinburgh, Edin

ratiev and A.Polonski Institute for Nuclear Research, Moscow, Russia

ornia State University, Dominguez hills, CA, USA

unt Allison University, Sackville, Canada

d T. Hehl Physikalisches Institut Universitat Tubingen, Tubingen, Germany



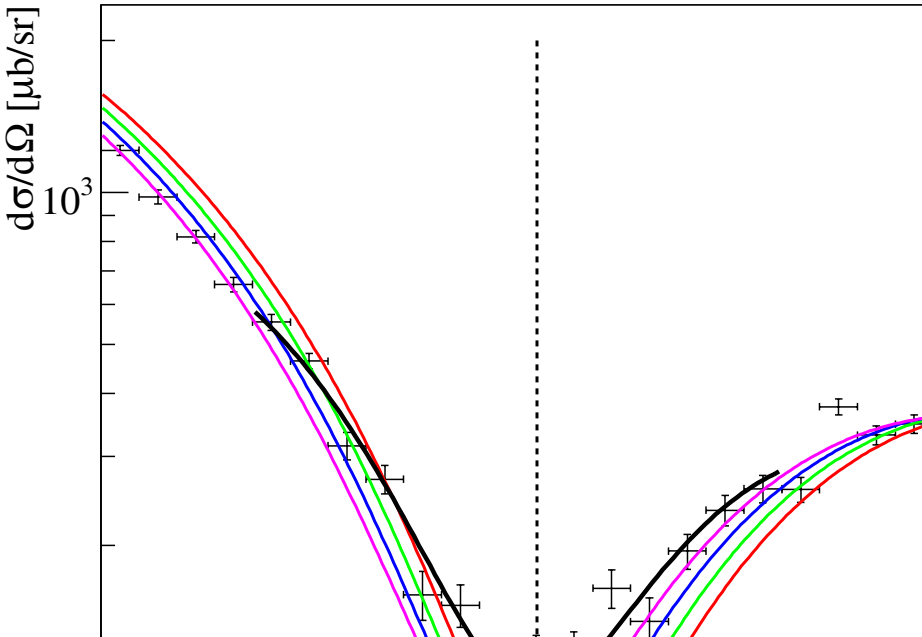
DWIA

+ Many body production

+ Intermediate coh. pi pr

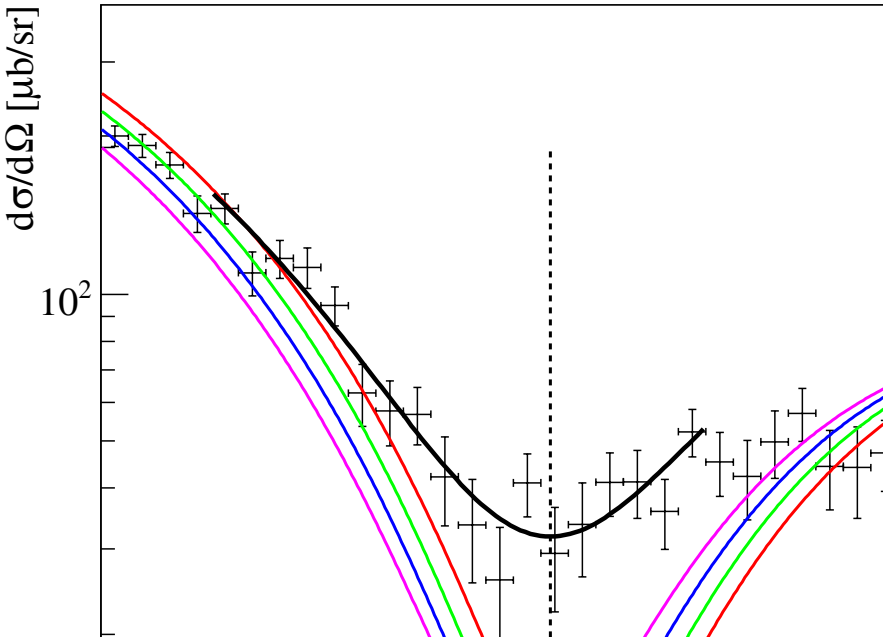
+ ΔN interaction

Eγ = (200-220)MeV

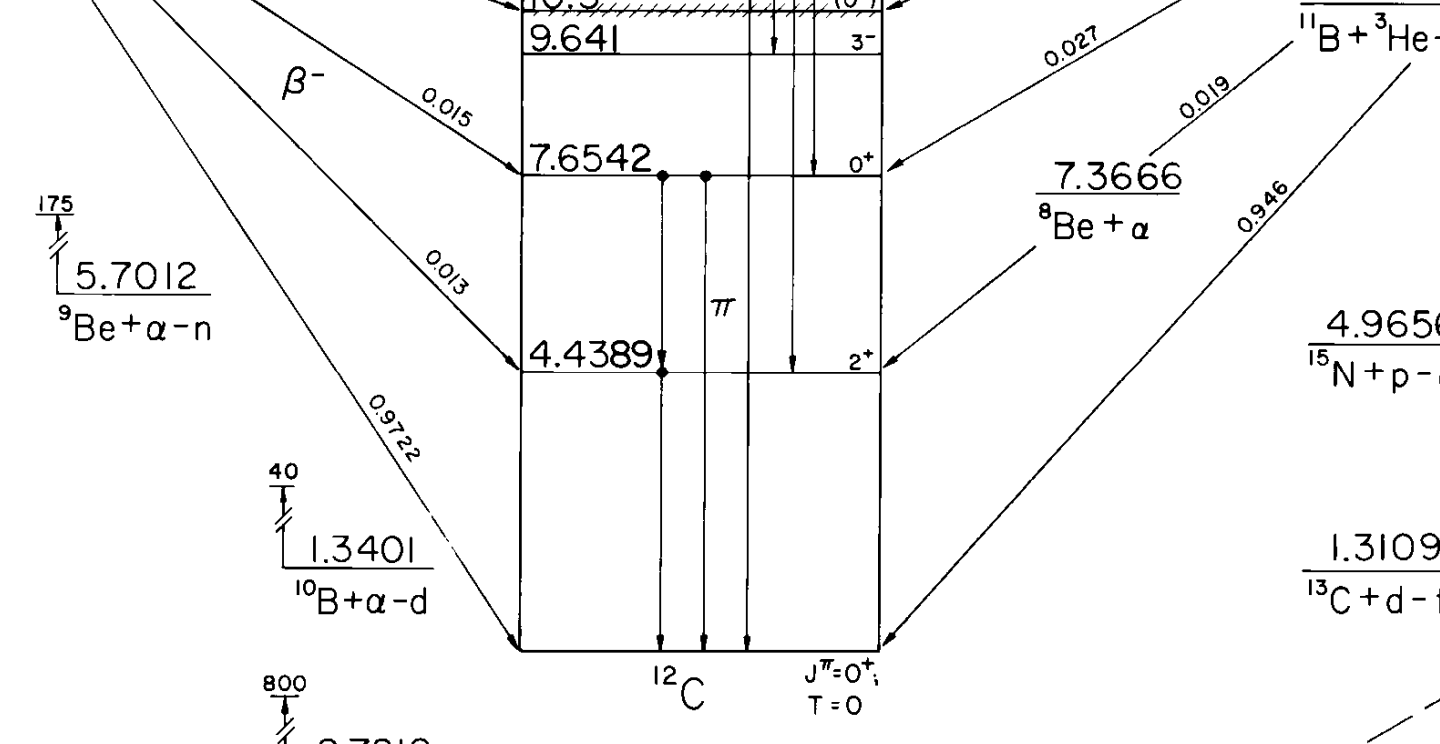


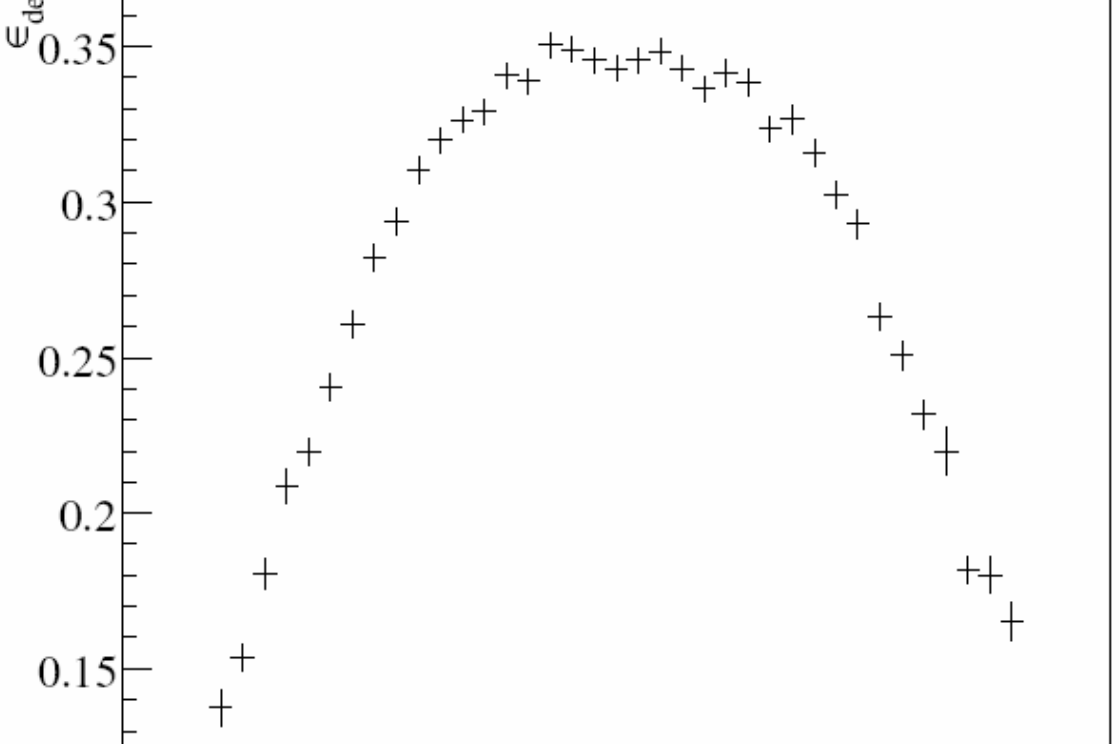
No neutron skin
0.1 fm skin
0.2 fm skin
0.3 fm skin

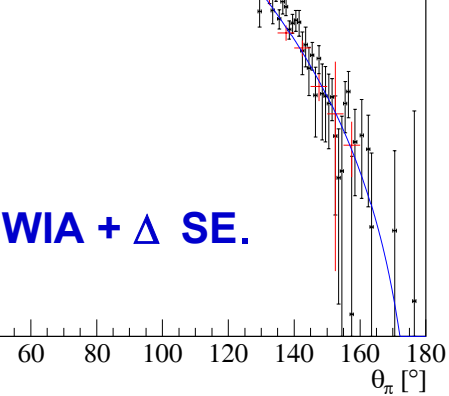
Eγ = (160-170)MeV

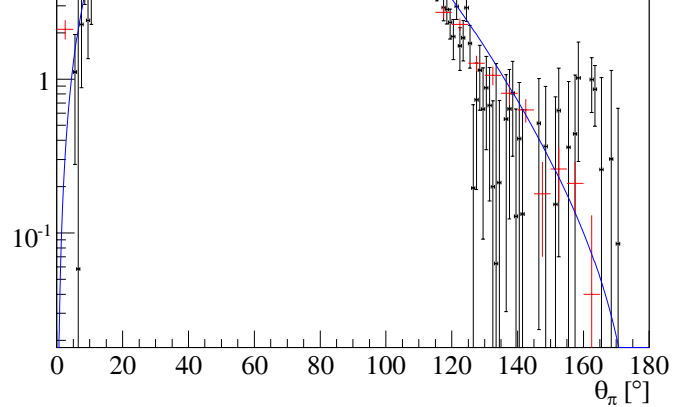


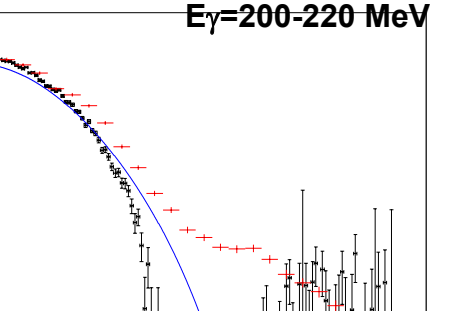
No neutron skin
0.1 fm skin
0.2 fm skin
0.3 fm skin

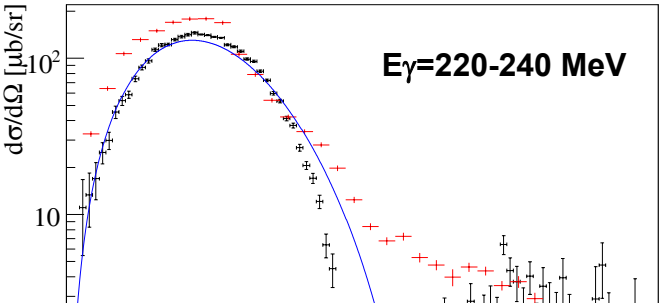

9.641
3⁻
7.6542
0⁺
4.4389
2⁺
β⁻
0.015
0.013
0.9722
0.027
0.019
0.946
π
175
5.7012
⁹Be+α-n
40
1.3401
¹⁰B+α-d
800
7.3666
⁸Be + α
¹¹B + ³He
4.965
¹⁵N + p -
1.3109
¹³C + d -
¹²C
J^π=0⁺;
T=0


ϵ_{det}
0.35
0.3
0.25
0.2
0.15


WIA + Δ SE.
60
80
100
120
140
160
180
θπ [°]

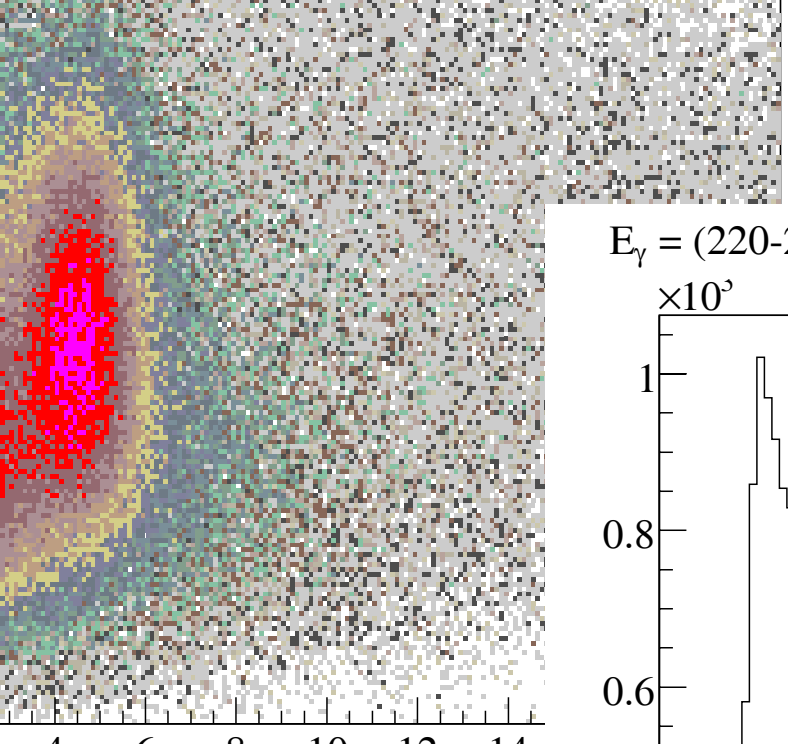

1
10-1
0
20
40
60
80
100
120
140
160
180
θπ [°]

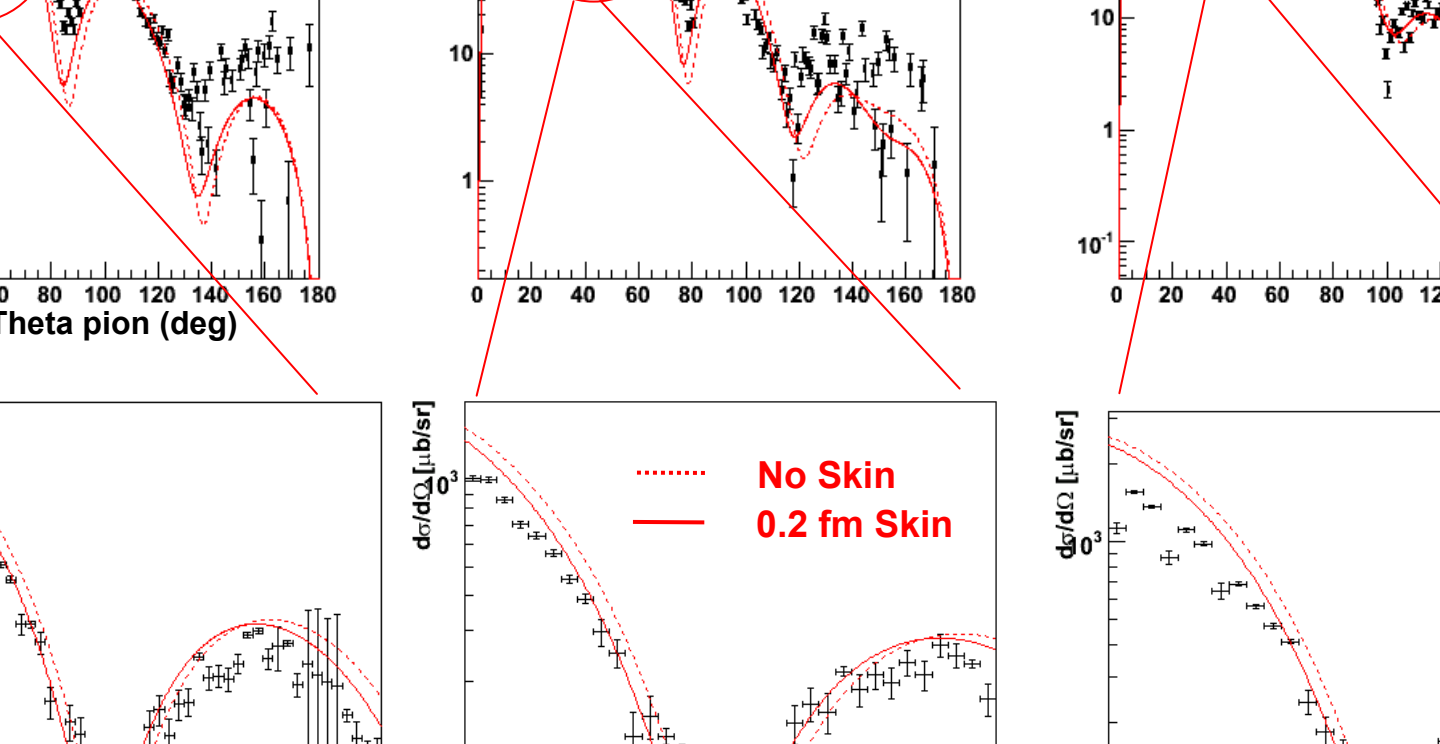

Eγ=200-220 MeV


dσ/dΩ [μb/sr]
10²
10
Eγ=220-240 MeV

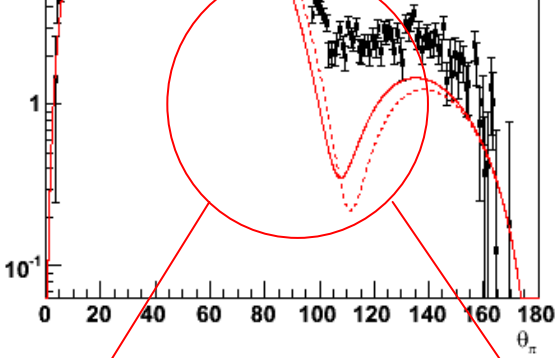
θ_π = (128-132)°

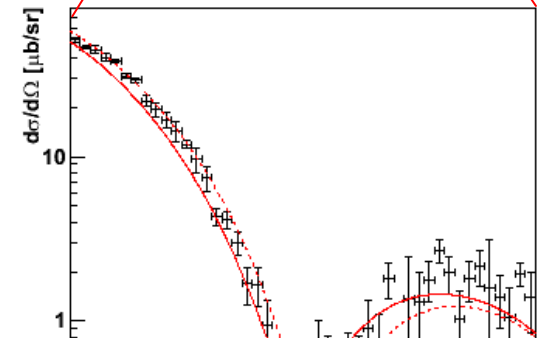
E_γ = (220-240)MeV θ_π = (35-40)°

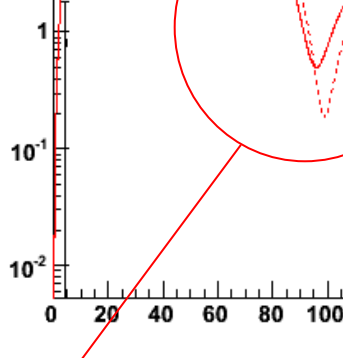


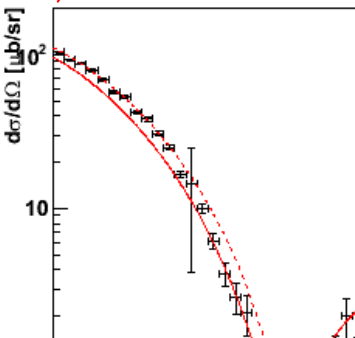

No Skin
0.2 fm Skin
dσ/dΩ [μb/sr]
Theta pion (deg)

vident in
r Decay
spectra
up by CB!!





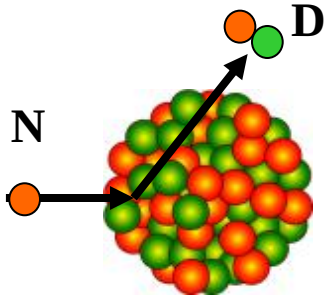


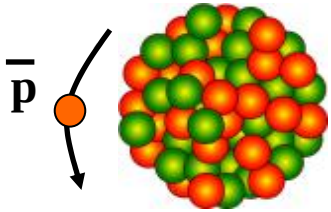


inal analysis by Hoffman for all data (0.3 -
eV). Δr_{np} (^{208}Pb) = -0.02 →0.5 fm

kup reactions.

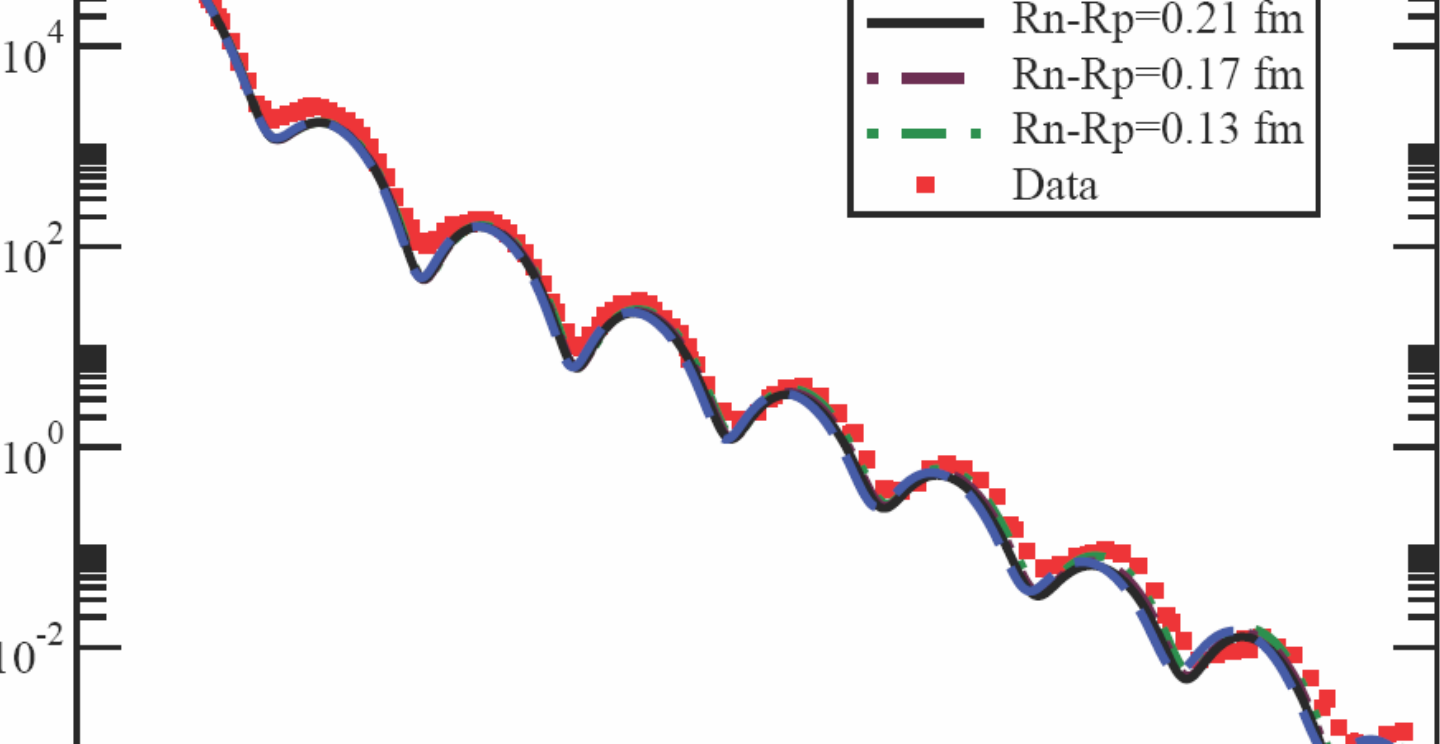
cent analysis of p and n pickup gave
~0.5fm for ^{208}Pb

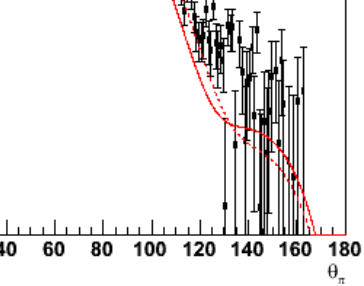


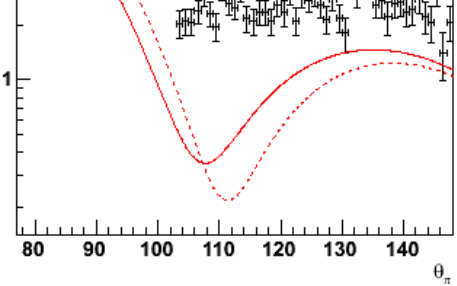


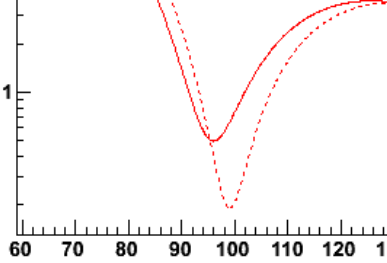
tiprotonic atoms

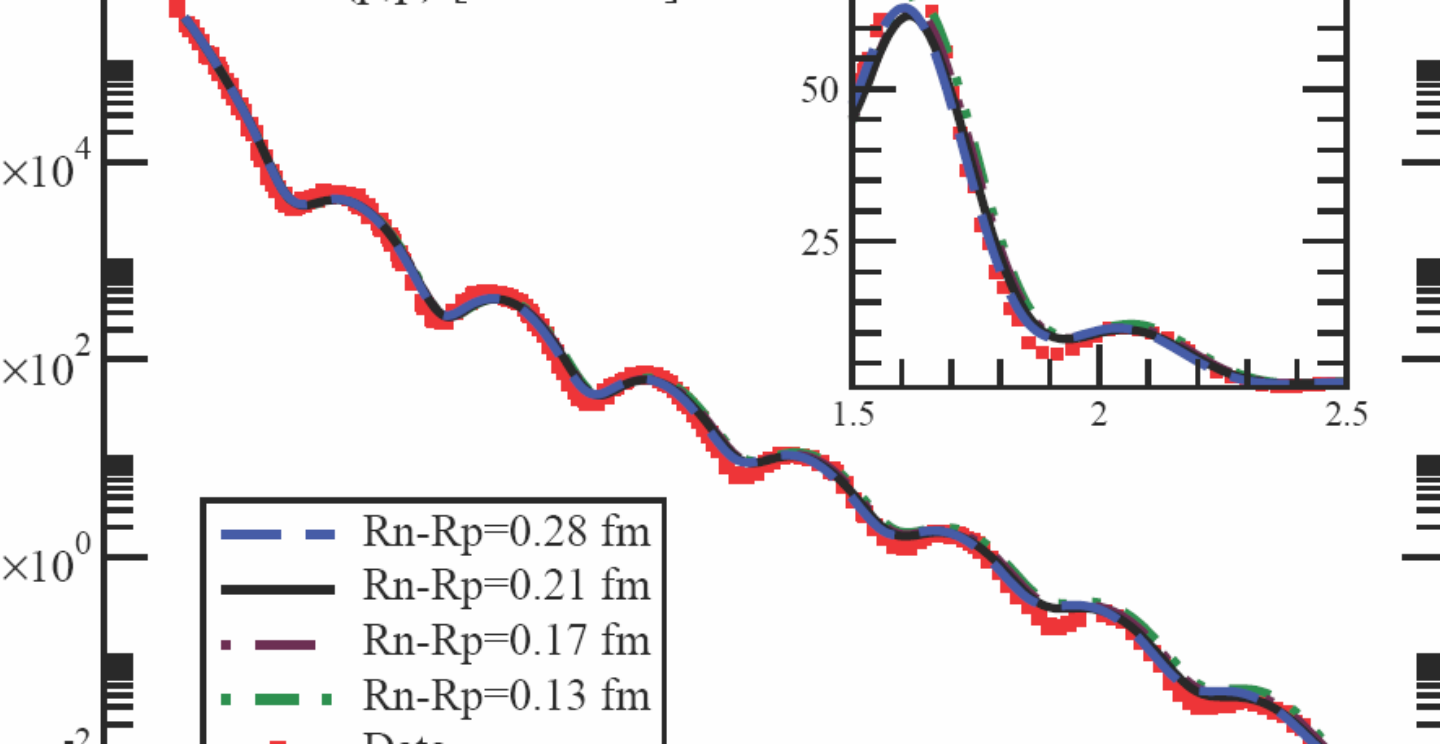
~0.15fm for ^{208}Pb

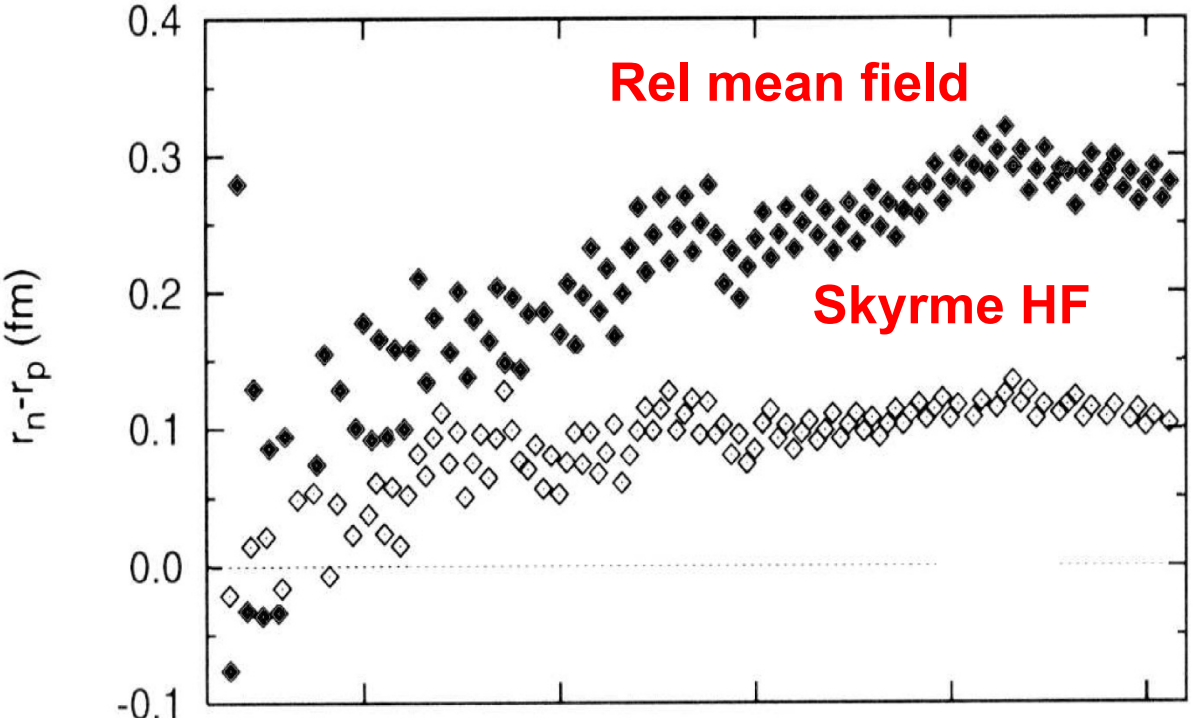

Rn-Rp=0.21 fm
Rn-Rp=0.17 fm
Rn-Rp=0.13 fm
Data
10^4
10^2
10^0
10^-2

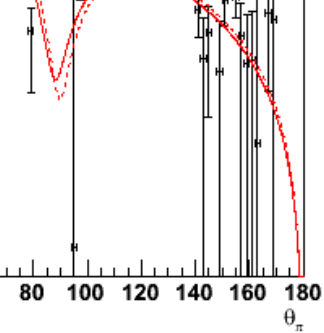

40 60 80 100 120 140 160 180
θ_π

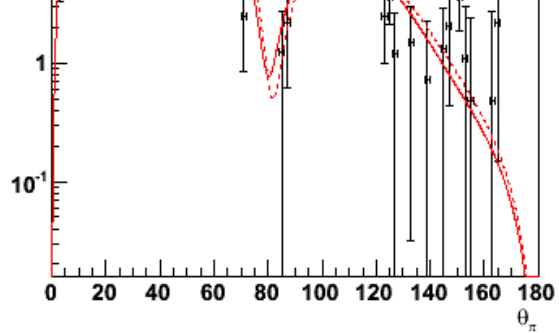

1
80 90 100 110 120 130 140
θ_π

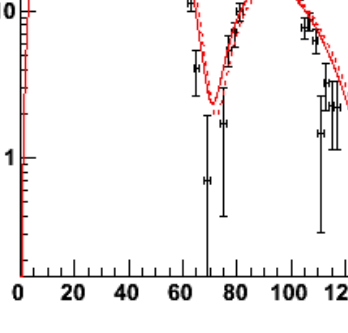

1
60 70 80 90 100 110 120 1


×10^4
×10^2
×10^0
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


Rel mean field
Skyrme HF
r_n-r_p (fm)
0.4
0.3
0.2
0.1
0.0
-0.1

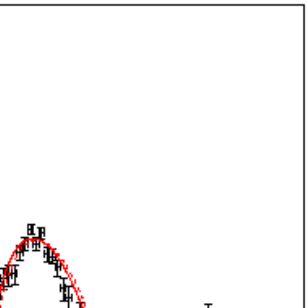


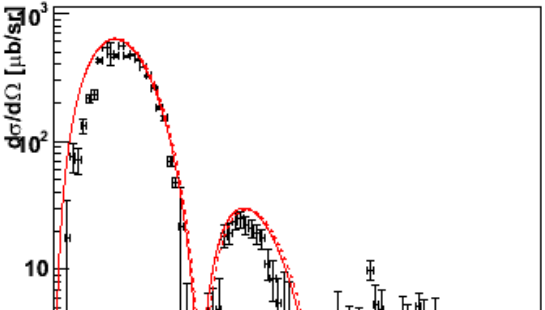


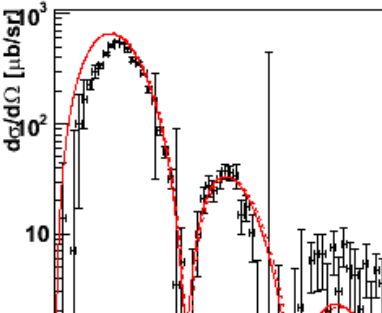


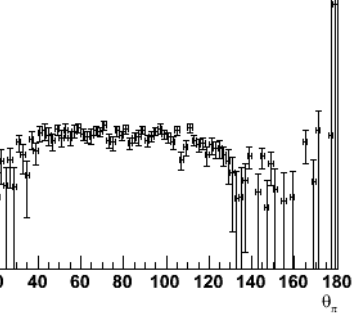
h_cross_240_260

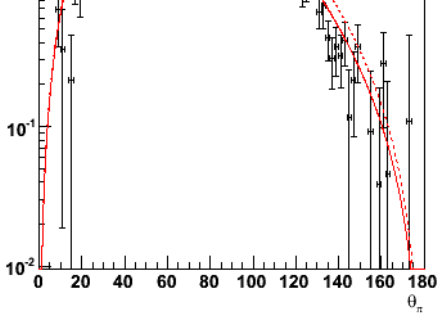
h_cross_260_280

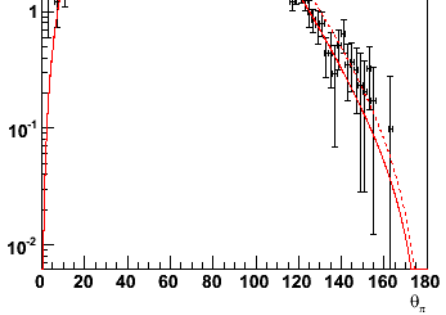




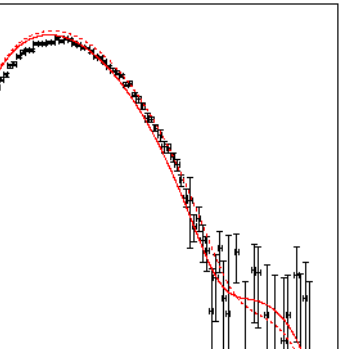




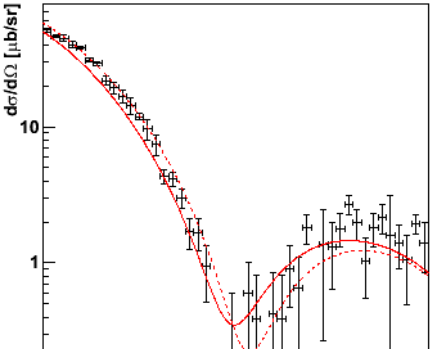




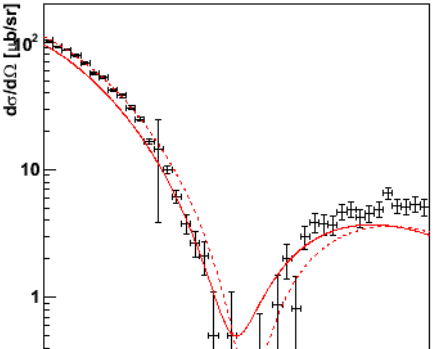
_150_160

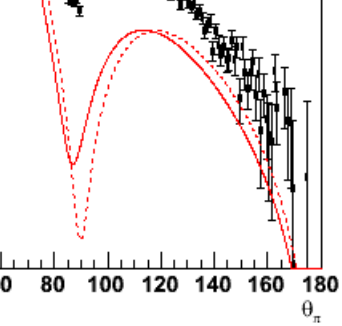


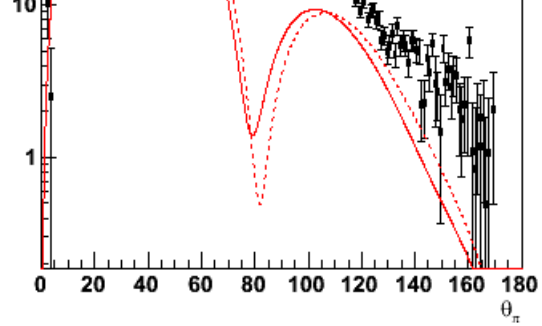
h_cross_160_170

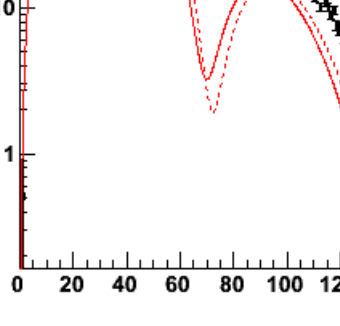


h_cross_170_180



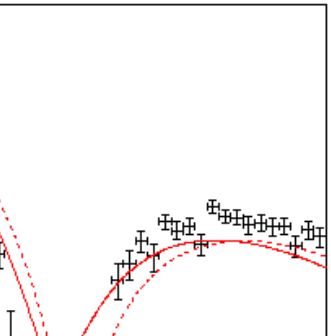


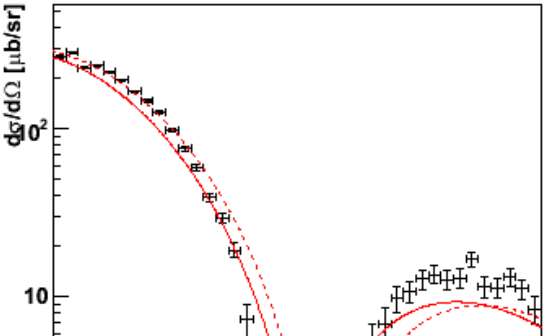


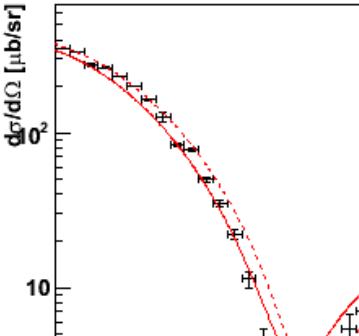


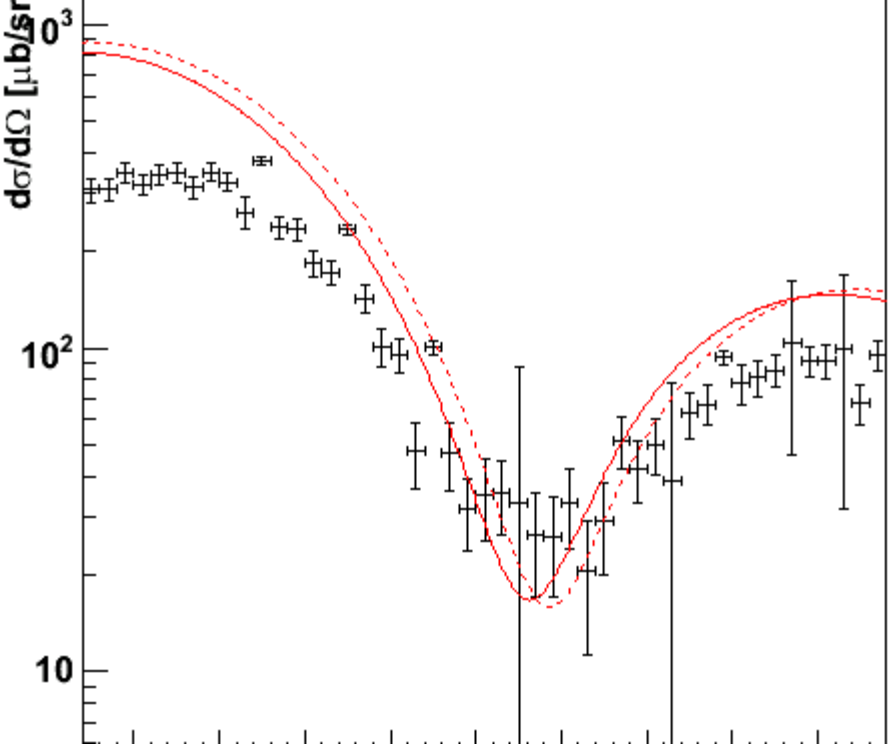
h_cross_190_200

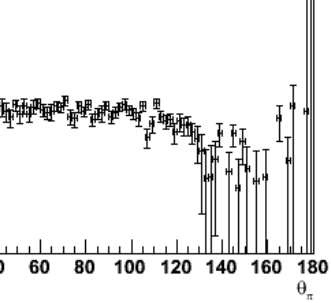
h_cross_200_220

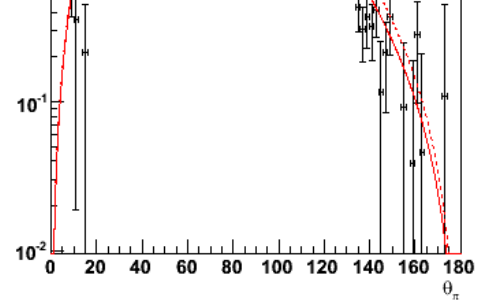


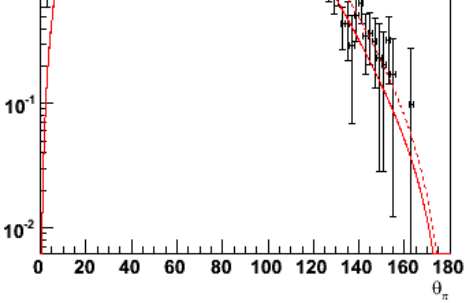




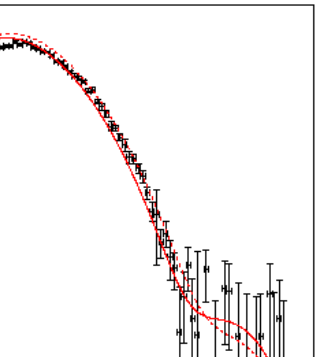

dσ/dΩ [μb/sr]
10³
10²
10



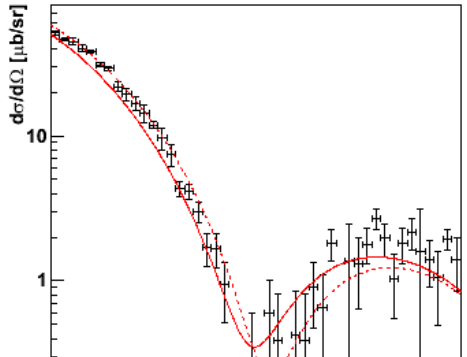




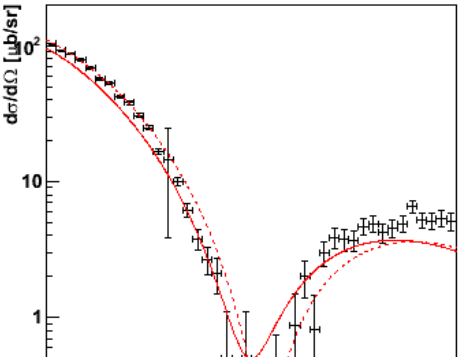
_160



h_cross_160_170



h_cross_170_180

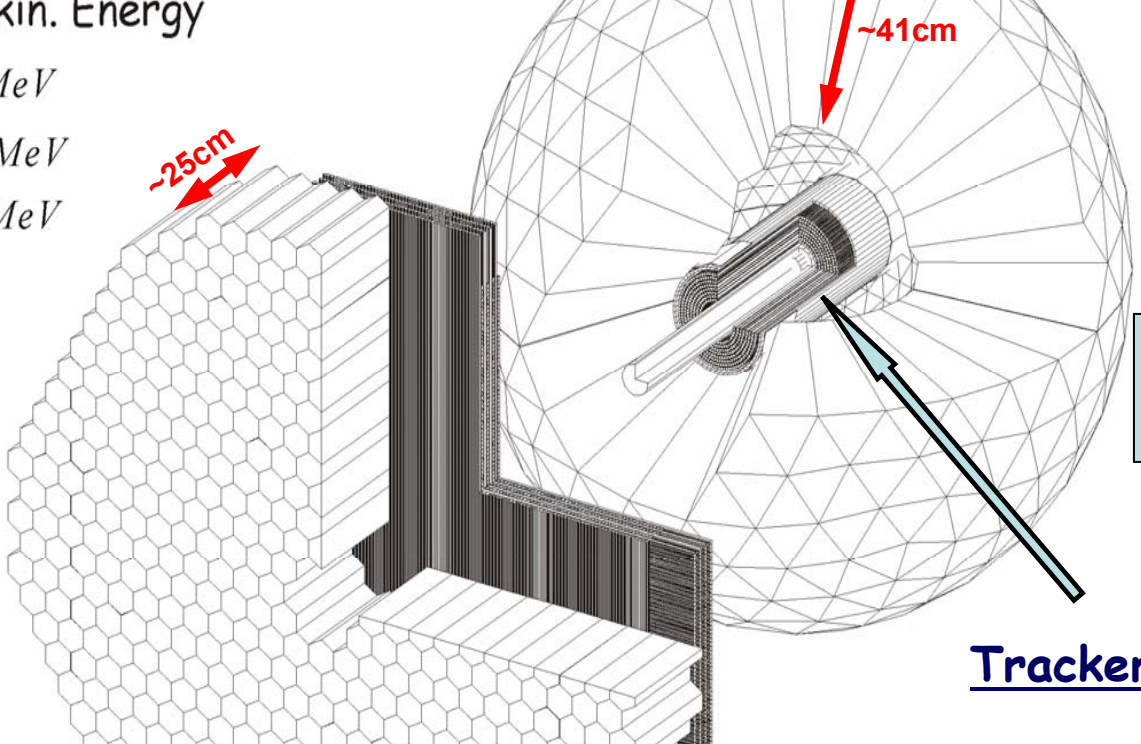


um kin. Energy

80 *MeV*

280 *MeV*

360 *MeV*



maximum ki

$\mu^{\pm}$: 233 *M*

$\pi^{\pm}$: 240 *M*

$K^{\pm}$: 341 *M*

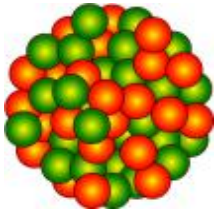
p : 425 *M*

$\sigma/E\gamma = 1.7\% /$

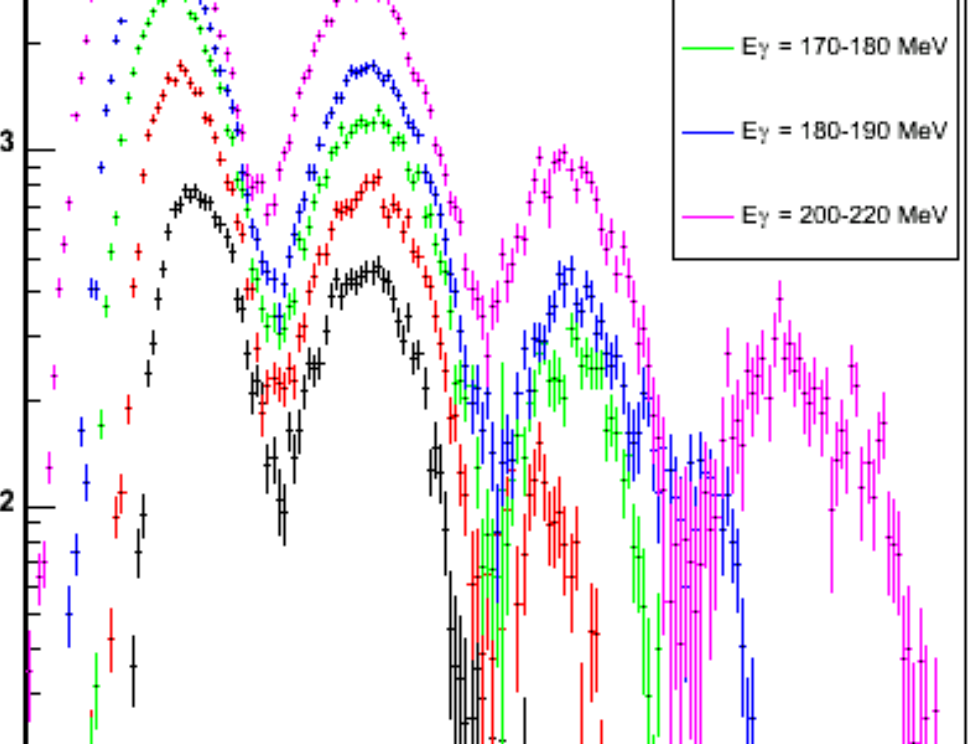
$\sigma_\theta = 2\text{–}3^\circ$

$\sigma_\phi = 2^\circ / \sin\theta$

Tracker & Partic

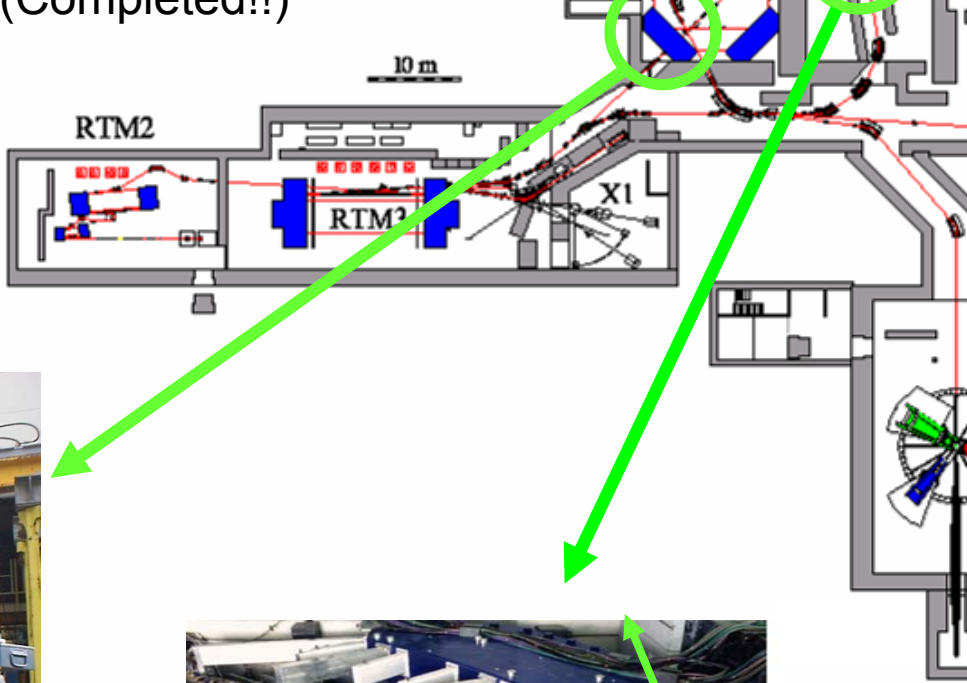


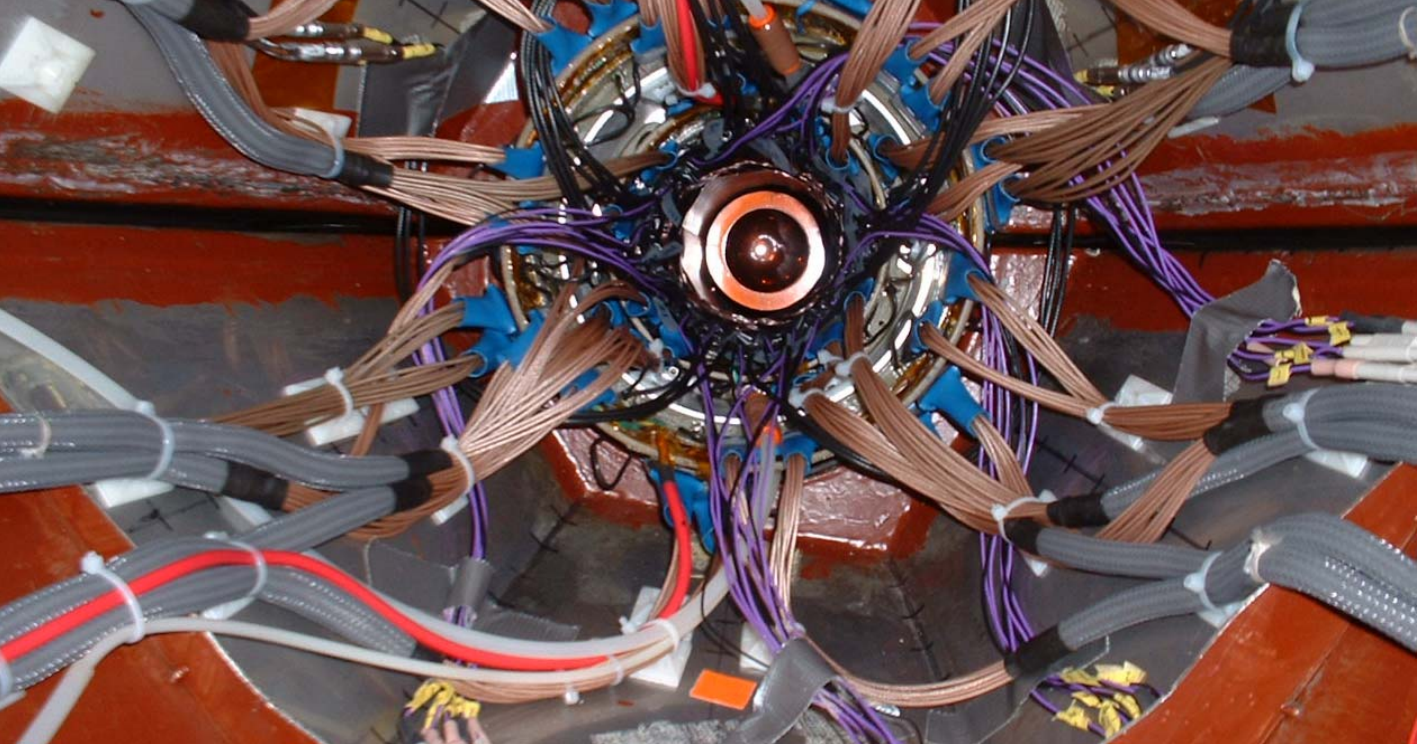
$$\Omega \sim A^2(q/k_\gamma)P_3^{\,2}|F_m(q)|^2\sin^2\theta_\pi$$

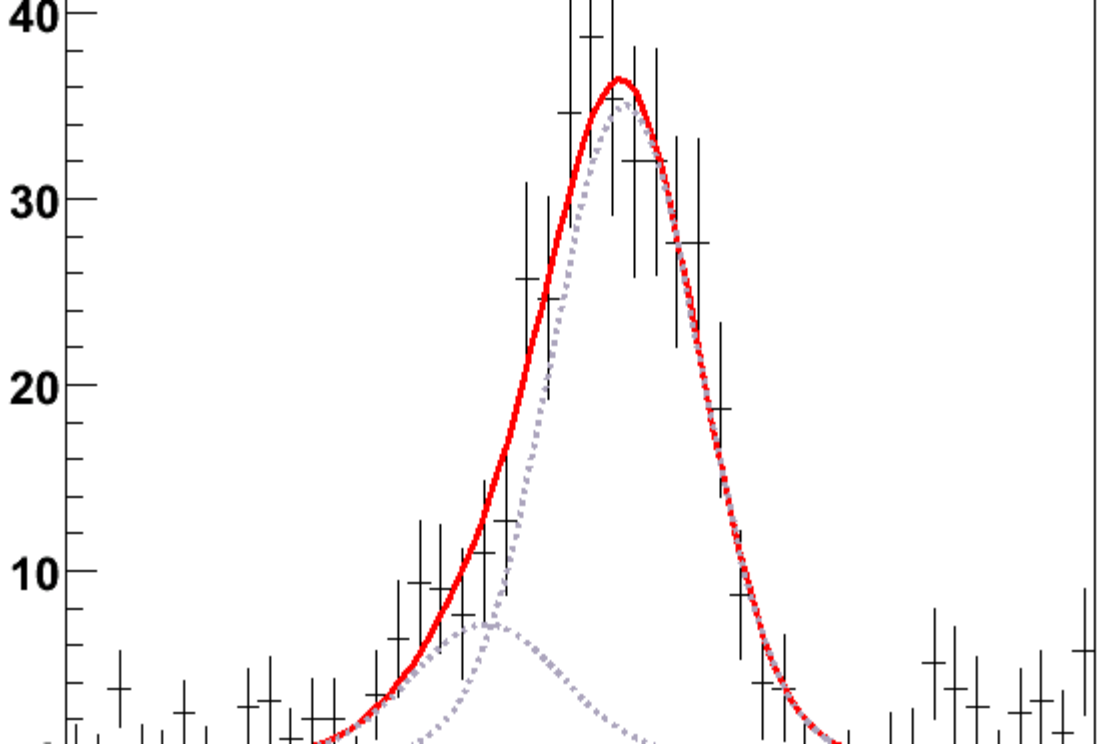

Eγ = 170-180 MeV
Eγ = 180-190 MeV
Eγ = 200-220 MeV
3
2

MI-C 1.5 GeV upgrade (Completed!!)

MI-B 0.85 GeV)






40
30
20
10

d, R.Codling, E.Downie, J. Kellie, K.Livingston, J.McGeorge, I.J.D.MacGregor, R. Owens D.Proto
partment of Physics and Astronomy, University of Glasgow, Glasgow, UK

nd W.Briscoe George Washington University, Washington, USA

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

S.Kruglov, A.Koulbardis, and N.Kozlenko Petersburg Nuclear Physics Institute, Gatchina, Russi

rusche and F.Zehr, Institut fur Physik University of Basel, Basel, Ch

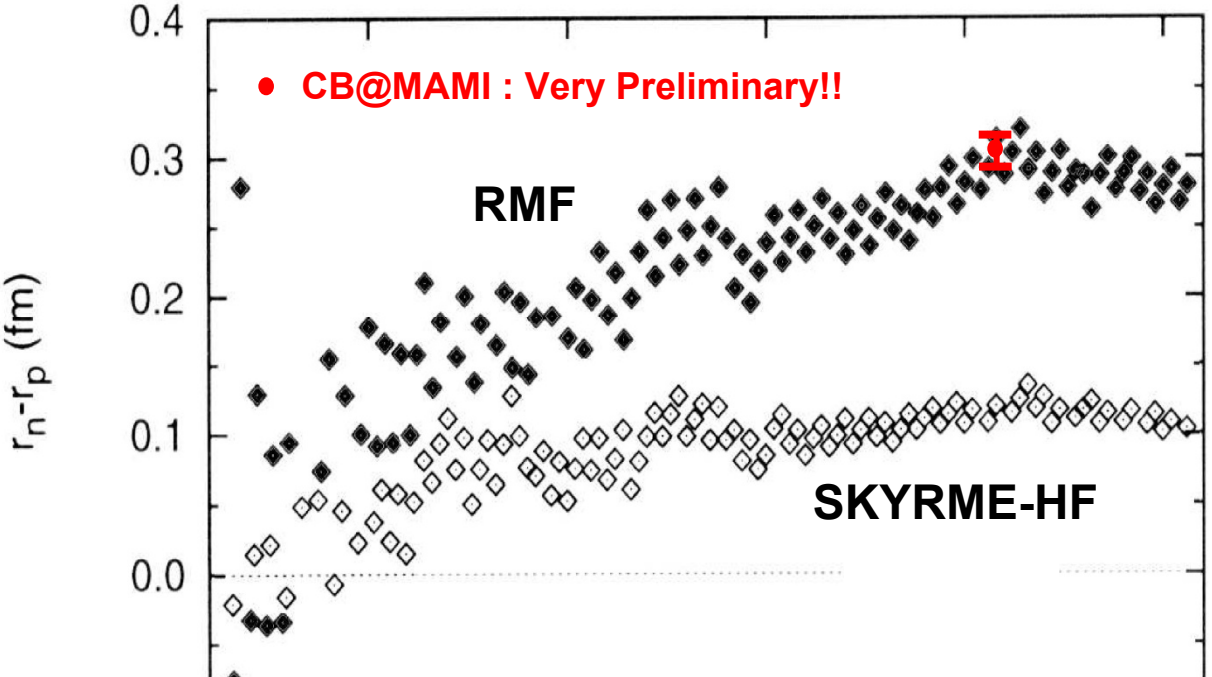
Hjelm, M. Kotulla, K. Makonoyi, R.Novotny, M. Thiel and D. Trnka II. Phys. Institut, University

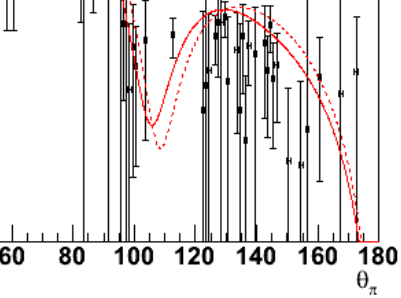
K.Foehl, D. Glazier, T. Jude, C.Tarbert and D.P.Watts, School of Physics, Univ. of Edinburgh, Ed

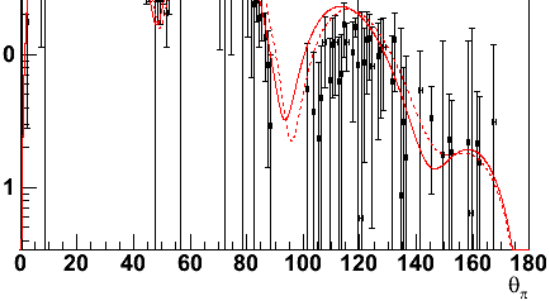
ndratiev and A.Polonski Institute for Nuclear Research, Moscow, Russia

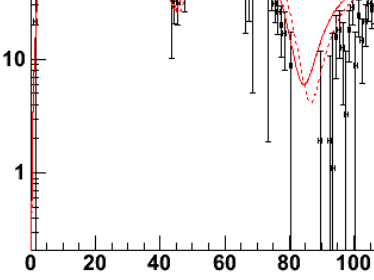
lifornia State University, Dominguez hills, CA, USA

lount Allison University, Sackville, Canada

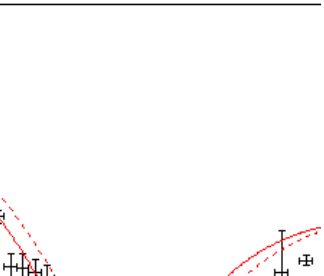

0.4
0.3
0.2
0.1
0.0
r_n-r_p (fm)
• CB@MAMI : Very Preliminary!!
RMF
SKYRME-HF



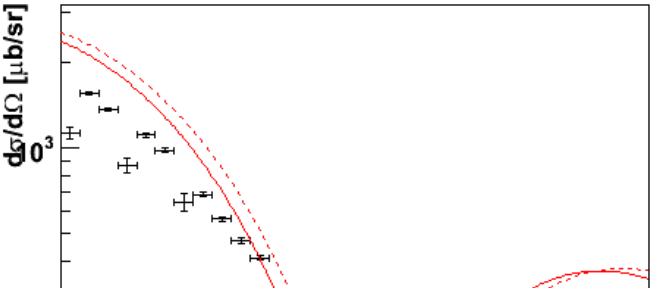




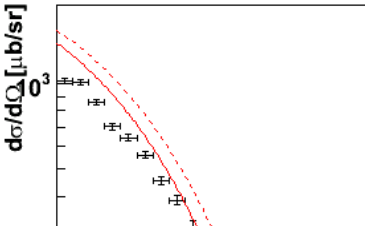
70

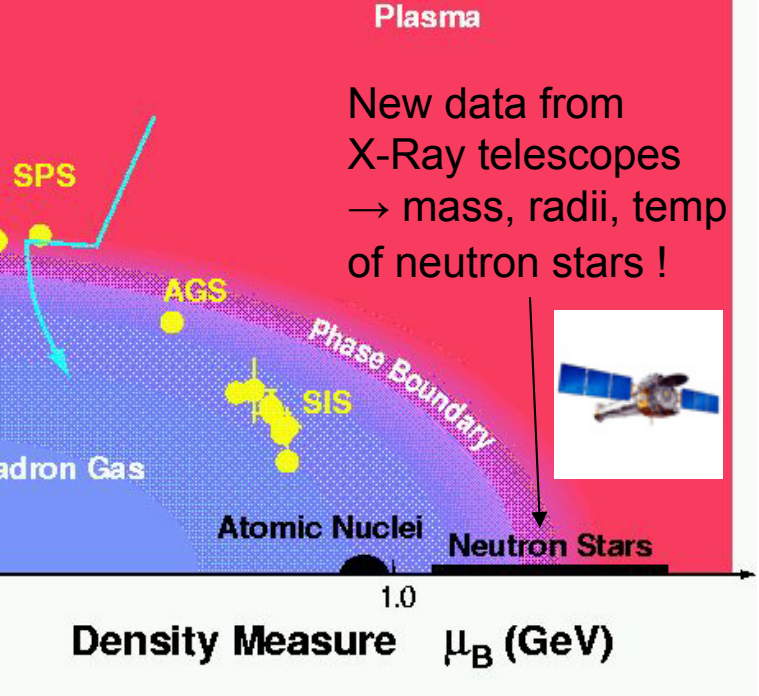


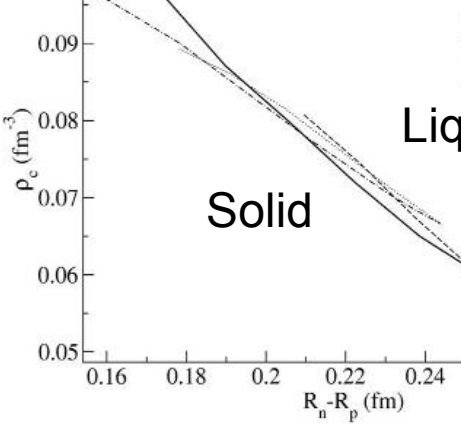
h_cross_200_220



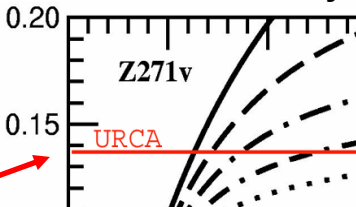
h_cross_190_200







Proton fracti
function of density i

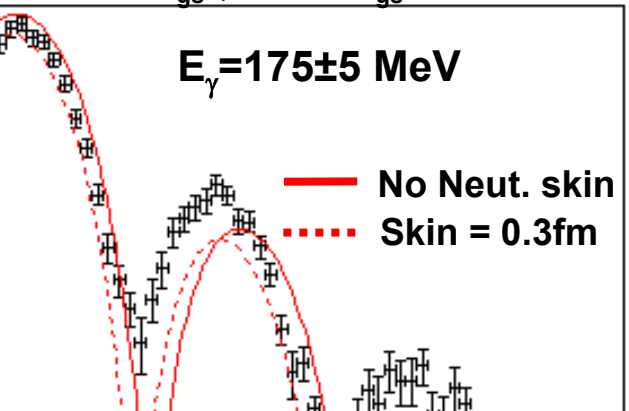


iffraction patterns for ^{208}Pb
ange of lighter nuclei

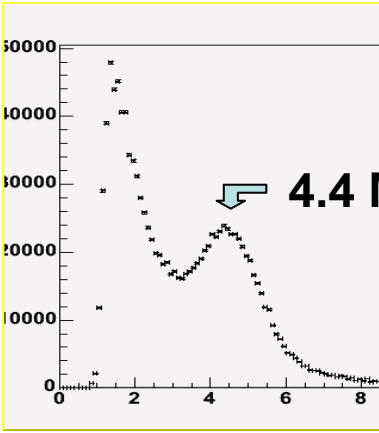
Also see coincident I
Nuclear Decay Pho

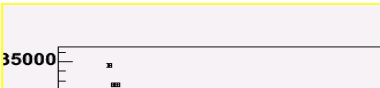
$$\sim A^2(q/k_\gamma)P_3{}^2|F_m(q)|^2\sin^2\theta_\pi$$

$^{208}Pb_{gs}(\gamma,\pi^0)^{208}Pb_{gs}$



Data analysis
Of C. Tarbert





d, R.Codling, E.Downie, D.Glazier, J. Kellie, K.Livingston, J.McGeorge, I.J.D.MacGregor, R. Owe
scu and G.Rosner Department of Physics and Astronomy, University of Glasgow, Glasgow, UK

nd W.Briscoe George Washington University, Washington, USA

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

S.Kruglov, A.Koulbardis, and N.Kozlenko Petersburg Nuclear Physics Institute, Gatchina, Russi

rusche and F.Zehr, Institut fur Physik University of Basel, Basel, Ch

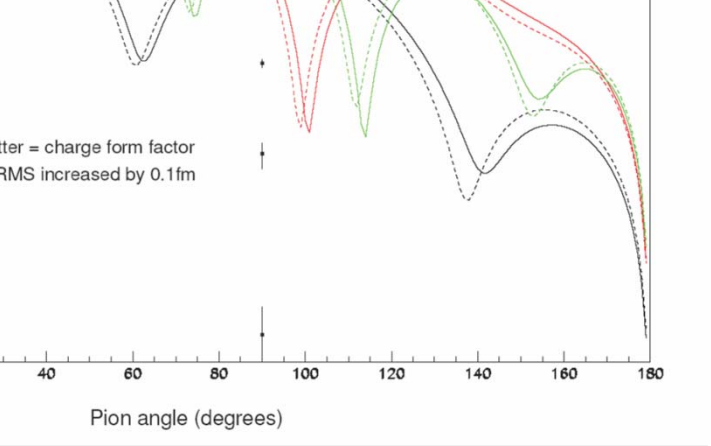
Hjelm, M. Kotulla, K. Makonoyi, R.Novotny, M. Thiel and D. Trnka II. Phys. Institut, University

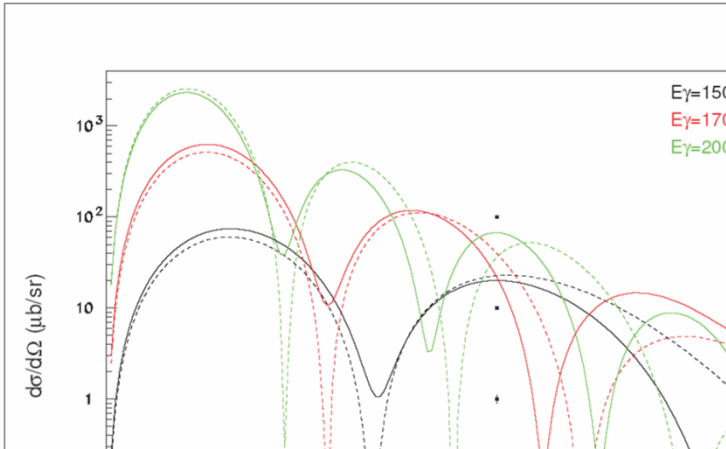
K.Foehl, C.M.Tarbert and D.P.Watts School of Physics, University of Edinburgh, Edinburgh, UK

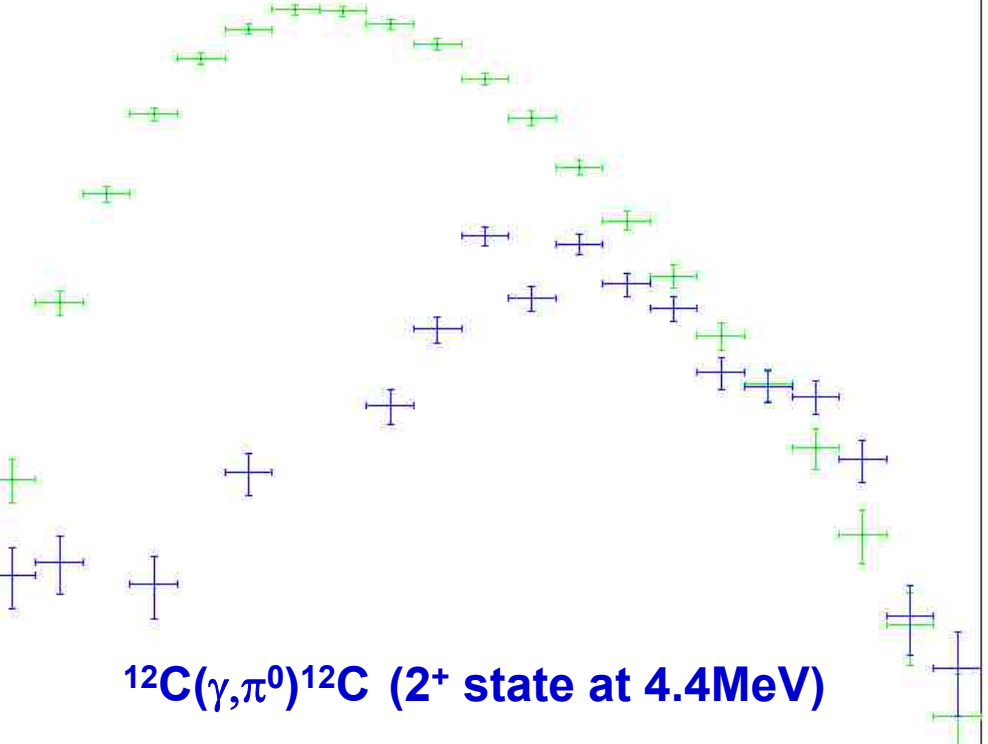
ndratiev and A.Polonski Institute for Nuclear Research, Moscow, Russia

lifornia State University, Dominguez hills, CA, USA

lount Allison University, Sackville, Canada


tter = charge form factor
RMS increased by 0.1fm
40
60
80
100
120
140
160
180
Pion angle (degrees)


Eγ=150
Eγ=170
Eγ=200
10³
10²
10
1
dσ/dΩ (μb/sr)



$^{12}C(\gamma,\pi^0)^{12}C$ (2^+ state at 4.4MeV)