Compton Scattering from ^{3,4}He using an Active Target

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Collaboration
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University of Glasgow

Obtaining the Nucleon Scalar Polarisabilities

- Differential cross section for Real Compton Scattering (RCS) on the nucleon sensitive to α and β

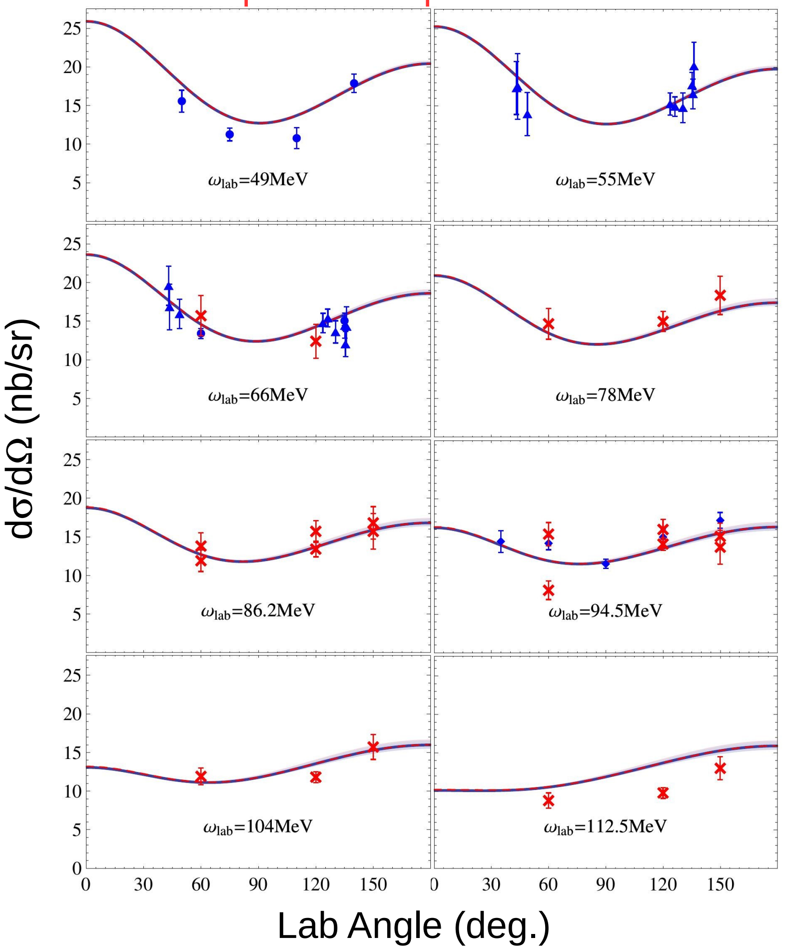
$$\sigma(\omega,\theta) = \sigma_{Born}(\omega,\theta) - \omega\omega'(\frac{\omega'}{\omega})^2\frac{e^2}{m}\left\{\frac{\alpha+\beta}{2}(1+\cos\theta)^2 + \frac{\alpha-\beta}{2}(1-\cos\theta)^2\right\}$$

+ higher order terms

- Higher order terms contain spin polarisabilities
  See talk Mainz Compton programme: E.J. Downie, Friday.
- To date most of the measurements are on the proton
  Free proton target, relatively straightforward interpretation of data
- **Neutron data very sparse by comparison**
- α_n from EM scattering of thermal n from E-field of heavy nucleus
  ...uncertainties open to question
- Bulk of neutron polarisability info. comes from Compton on ^{2}H target
- Either quasi-free ^{2}H(γ,γ'n) scattering
  Or coherent ^{2}H(γ,γ)
  Interpretation more complicated than in proton case.
- Other light nuclei possible "neutron targets"...^{3}He, ^{4}He, ^{6}Li

New MAX-lab Measurements of ^{2}H(γ,γ)

× L.S. Myers et al., PRL 113 (2014),262506
Full description: accepted PRC



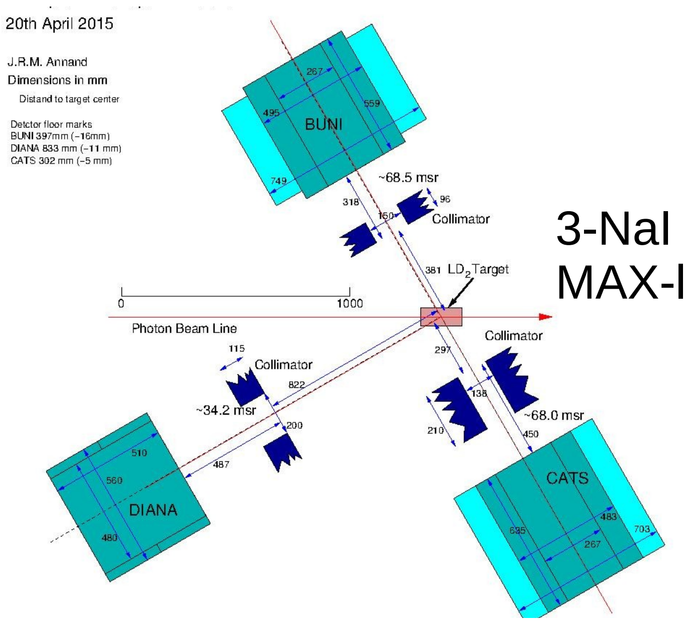
● M.A. Lucas, PhD Thesis, Uni. Illinois, 1994.
◆ D.L. Hornidge et al. PRL84(2000),2334
▲ M. Lundin et al. PRL90(2003),192501

$$\alpha_n = 11.1 \pm 1.8(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \pm 0.8(\mathrm{th})$$
$$\beta_n = 4.1 \mp 1.8(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \mp 0.8(\mathrm{th}),$$

BSR = Baldin Sum Rule

With new MAX-lab data

$$\alpha_n = 11.55 \pm 1.25(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \pm 0.8(\mathrm{th})$$
$$\beta_n = 3.65 \mp 1.25(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \mp 0.8(\mathrm{th}).$$



3-NaI setup
MAX-lab

- Isoscalar polarisabilities. Subtract proton contribution to obtain neutron value
- Benefit from Thompson term in cross section
- Need very good γ' energy resolution to separate non-coherent from coherent

$$\alpha_p = 10.65 \pm 0.35(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \pm 0.3(\mathrm{th})$$
$$\beta_p = 3.15 \mp 0.35(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \mp 0.3(\mathrm{th}),$$

Proton Values
J.A. McGovern et al, EPJ A49(2013),12

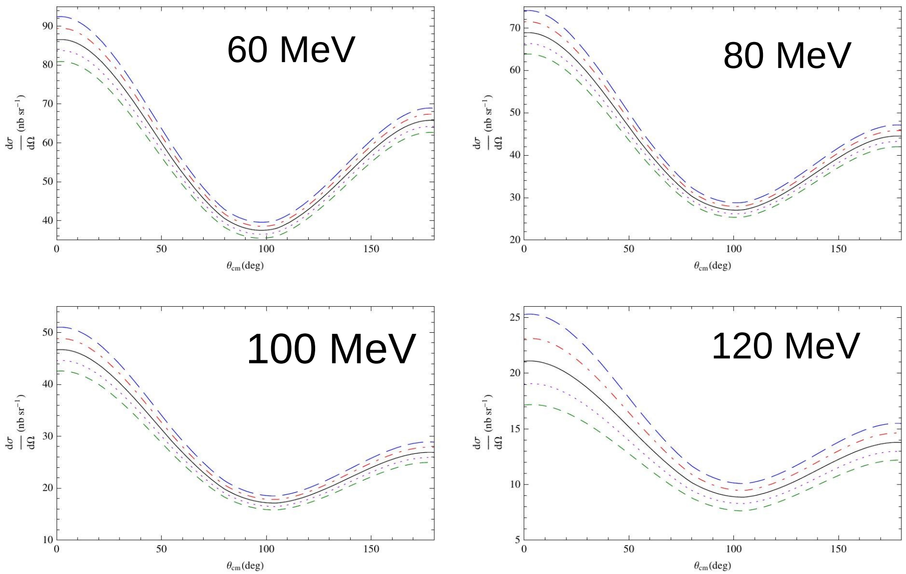
Alternative Neutron Target ^{3}He (or ^{4}He...)

- Advantages of Z = 2 compared to Z = 1
  Larger cross section...scales ~Z at ω ~ 120 MeV
  Larger sensitivity to polarisabilities (interference Thompson term)
- Binding energy of ^{3,4}He higher than ^{2}H...can separate coherent elastic events with poorer energy resolution compared to ^{2}H experiment
- **He scintillates: can be used in a high-rate active target.**
  Experiment A2-01/13
  "Compton Scattering on the He Isotopes with an Active Target"
- Theoretical treatment becomes more complicated as number of nucleons increases
  HBχPT treatment of Compton scattering on ^{3}He: *D.Shulka, A. Nogga & D. Phillips Nucl. Phys, A819 (2009),98*
  Further development (Griesshammer, Phillips and Strandberg)
- As yet no χEFT calculation of ^{4}He (or ^{6}Li)
- ^{4}He would give a different isospin combination
- ^{6}Li(γ,γ)...HIGS data up to 60 MeV, MAX-lab data 60 – 100 MeV

Theoretical Calculations $^3He(\gamma,\gamma)^3He$

D.Shulka, A. Nogga & D. Phillips
Nucl. Phys, A819 (2009),98

Sensitivity to α_n



Full $\mathcal{O}(e^2Q)$ calculation

long-dash $\Delta\alpha_n = -4 \times 10^{-4}\ fm^3$

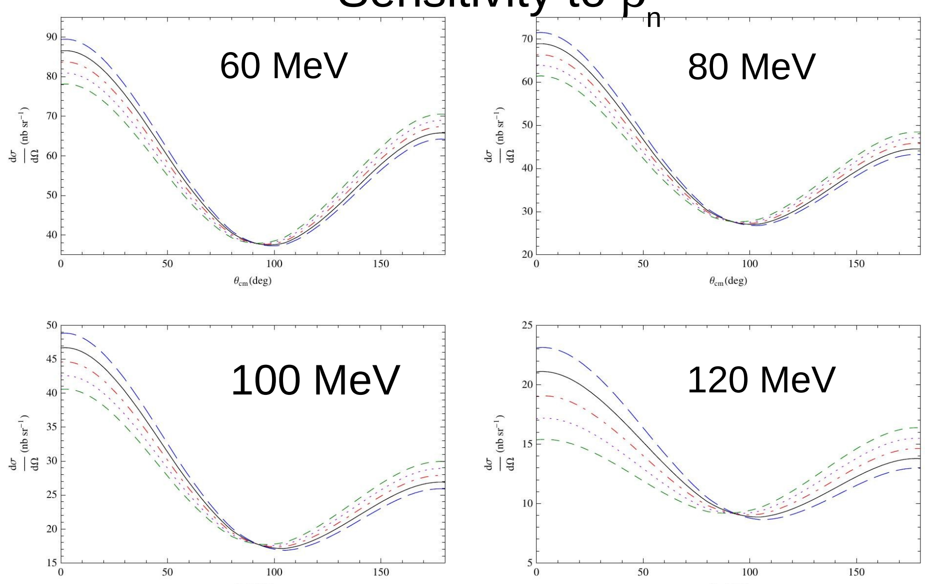
dot-dash $\Delta\alpha_n = -2 \times 10^{-4}\ fm^3$

dotted $\Delta\alpha_n = +2 \times 10^{-4}\ fm^3$

dash $\Delta\alpha_n = +4 \times 10^{-4}\ fm^3$

- Calculation @ ω = 60,80,100,120 MeV HBχPT NLO, $\omega < m_\pi$
- Δ contributions not considered
- Sensitivity of $\sigma(\theta)$ to α_n and β_n increasing with increasing E_γ
- $\sigma(\theta)$ insensitive to β_n at $\theta_\gamma \sim 90^o$

Sensitivity to β_n



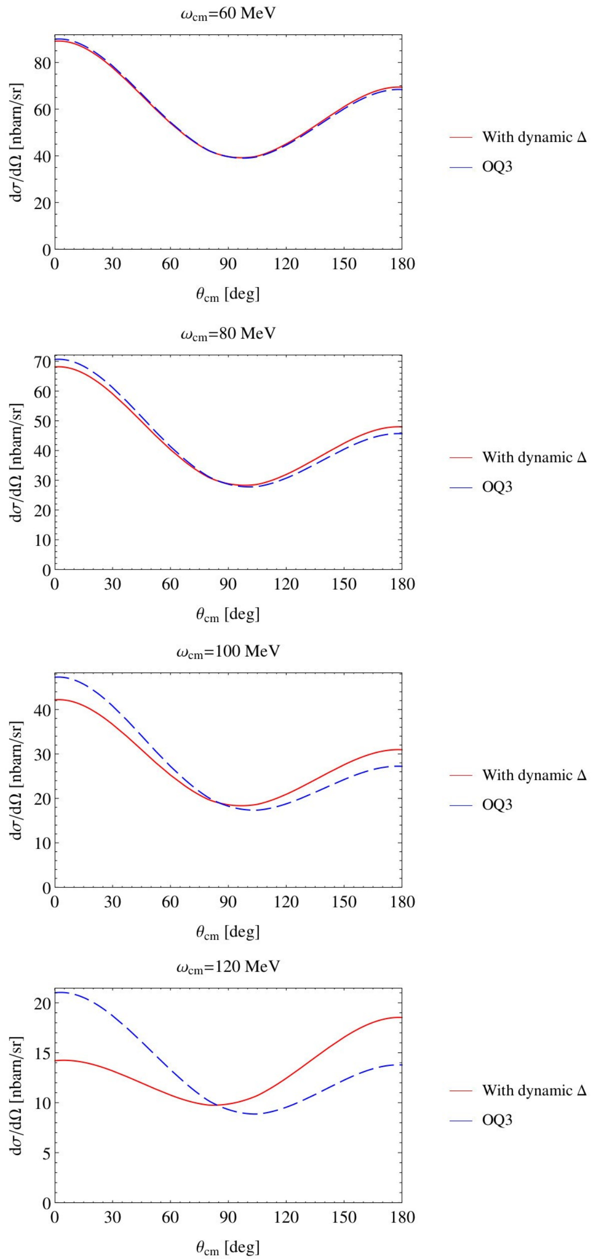
long-dash $\Delta\beta_n = -2 \times 10^{-4}\ fm^3$

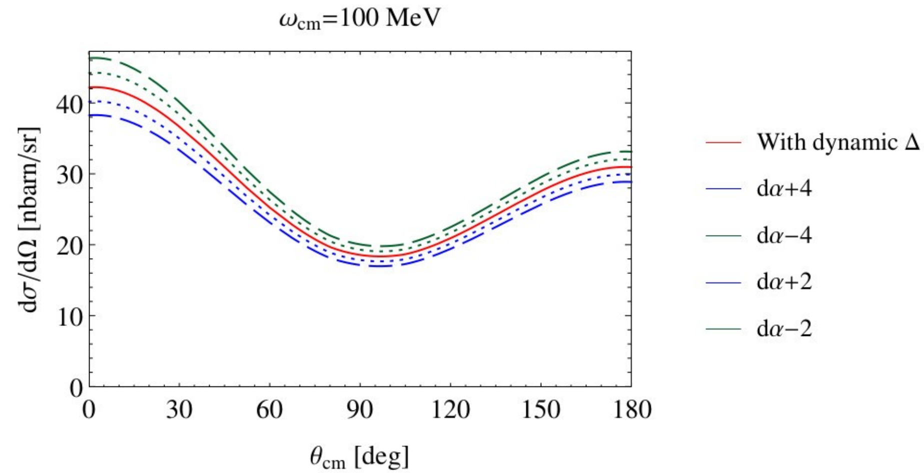
dot-dash $\Delta\beta_n = +2 \times 10^{-4}\ fm^3$

dotted $\Delta\beta_n = +4 \times 10^{-4}\ fm^3$

dash $\Delta\beta_n = +6 \times 10^{-4}\ fm^3$

Recent Development of ^{3}He(γ,γ) χEFT Theory





H. Griesshammer, D. Phillips and B. Strandberg
Extension of Shukla at al. to include dynamical
Δ terms

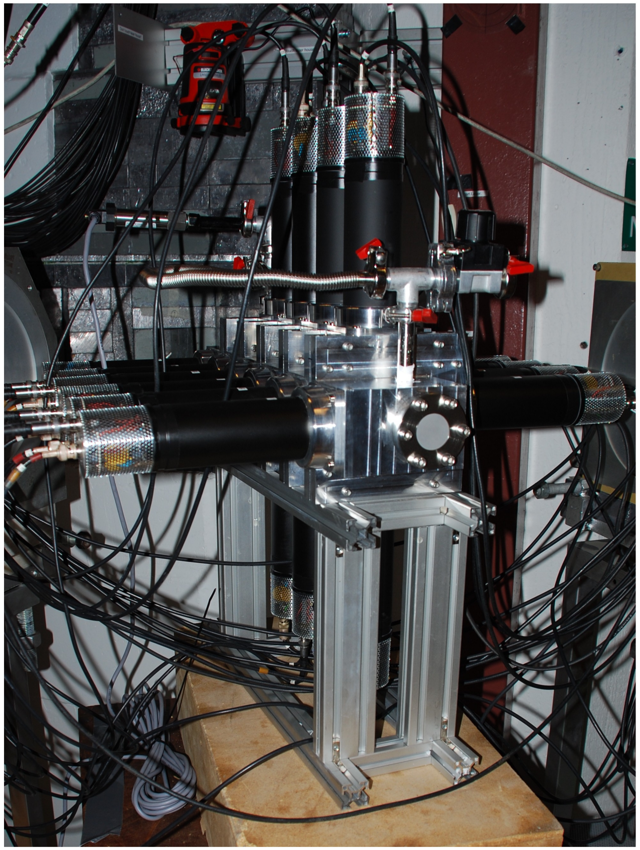
- Extend calculation beyond pion threshold?
- Sensitivity to polarisability increases with energy
- Theoretical interpretation more complicated above π threshold
- Opening of π^0 channel can obscure Compton experimental signal

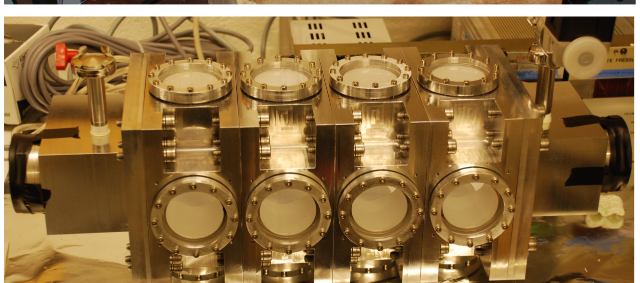
See also at CD2015
χEFT Treatment of Compton Scattering on ^{1}H, ^{2}H, ^{3}He…
See talks J. McGovern, H. Griesshammer

The Mk2 He ActiveTarget @ MAX-lab

Tagged Photon measurement ^{4}He Breakup

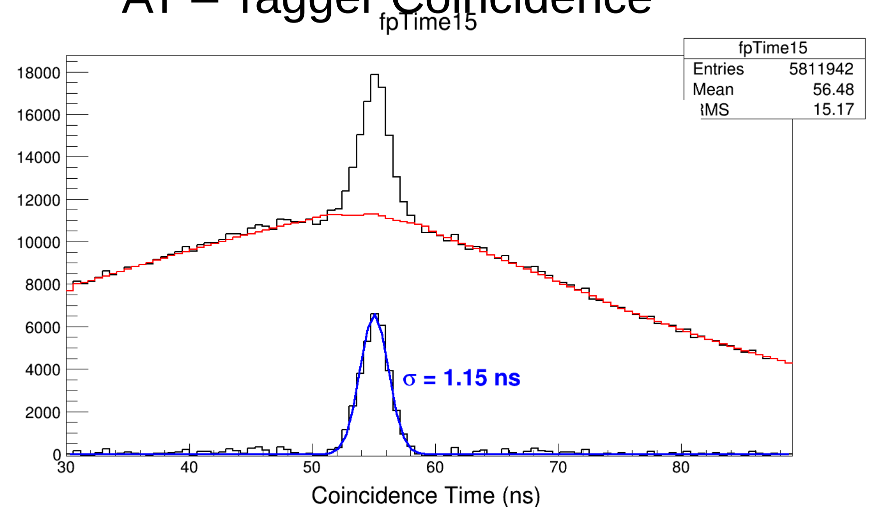
The Active Target @ MAX-lab

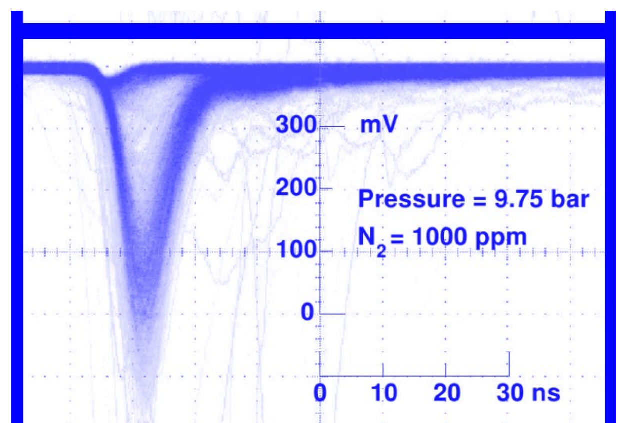




- The Active Target is a detector of charged reaction products
- He gas scintillator: pressure 20 bar

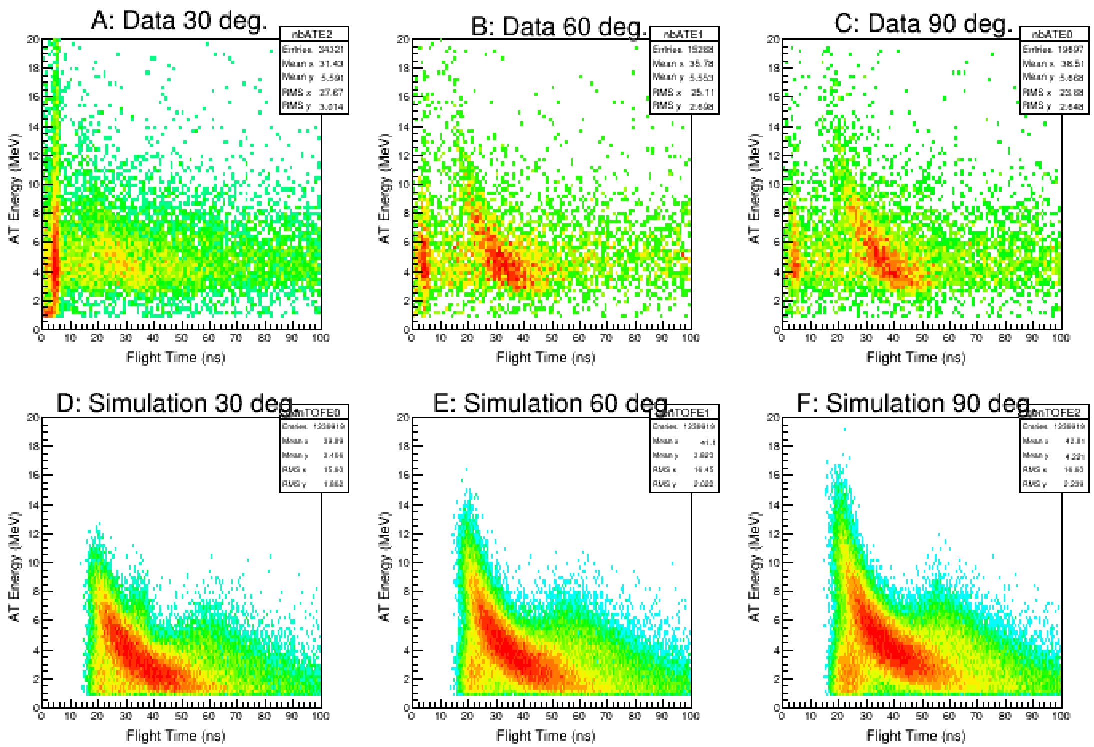
AT – Tagger Coincidence

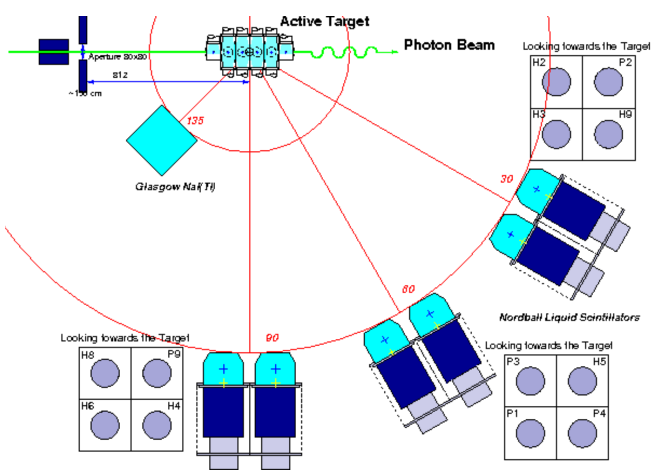




- Fast scintillation signal
- High rate capability
- Full intensity γ beam
- Good timing resolution
- Clean coincidence with photon tagger

Comparison Measured AT energy response to MC Simulation

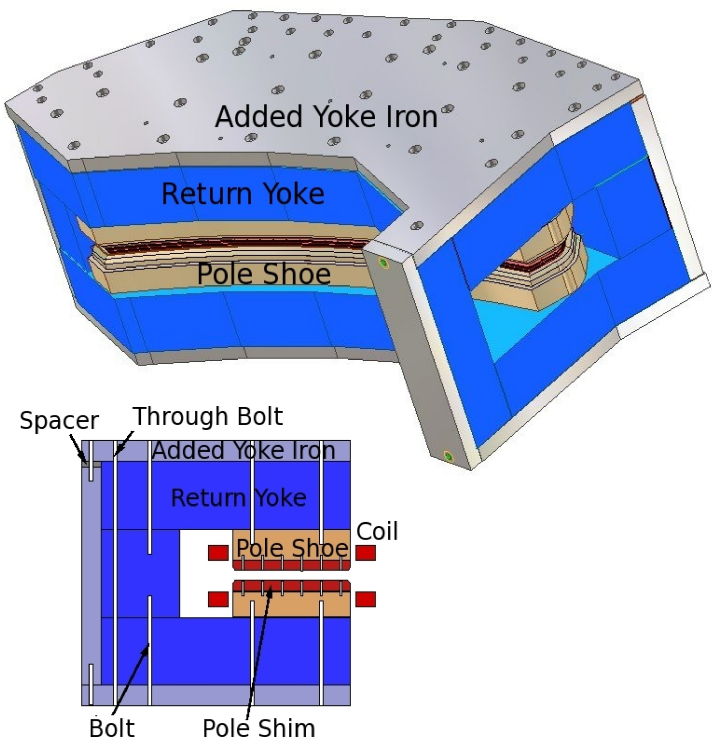




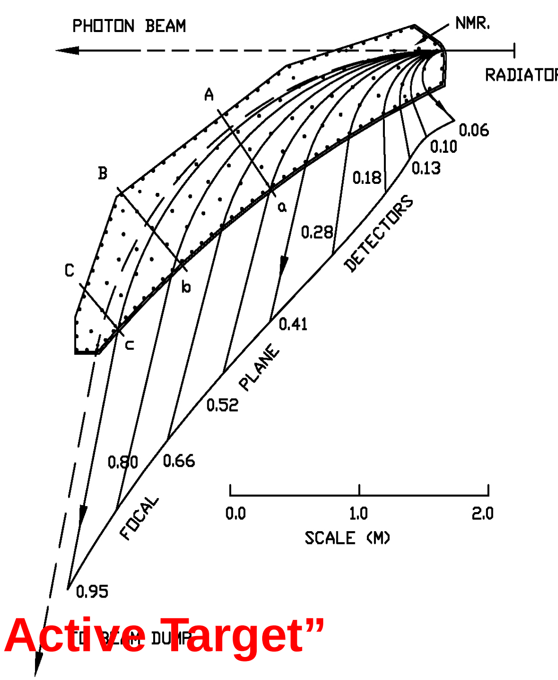
- $^4He(\gamma,n)$ measured at MAX-lab
  Active Target +
  Nordball Time-of-Flight Array
  Tagged photon beam
  E_γ = 10 - 65 MeV
- Correlation of AT total energy with TOF in external liquid scintillators
  θ_n = 30, 60, 90 deg.
- The prominent "banana" is from $^4He(\gamma,n\ ^3He)$
- Correlations between AT & external counters well reproduced by Geant-4 MC simulation
- He is a linear scintillator: light output depends on energy only

A New ^{3,4}He Compton Experiment at Mainz

The Glasgow/Mainz Photon Tagger

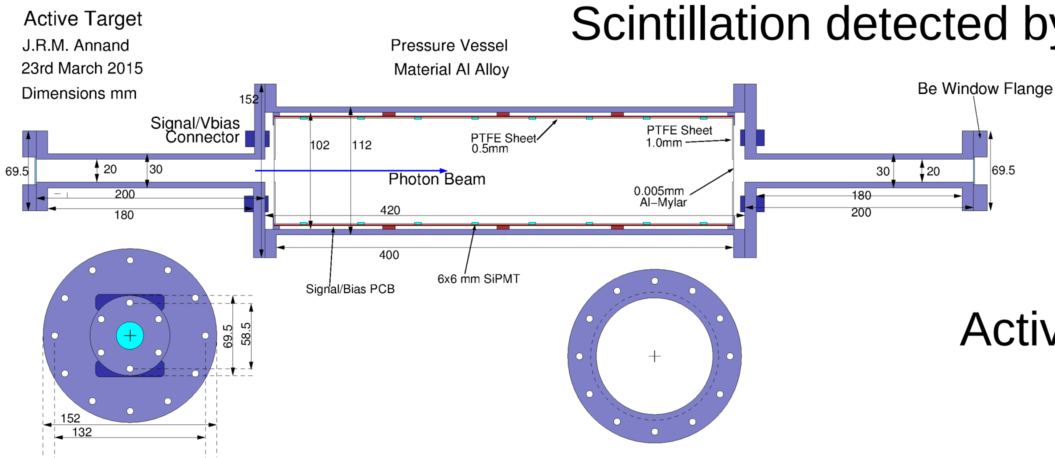


- Electron beam energy 180 – 1604 MeV, CW operation.
- Broad band (5 – 95% of E_0) Glasgow/Mainz photon tagging spectrometer
- In operation since ~1990, upgraded 2007
- Tagged photon rate: 2.5 MHz per 10 MeV wide bin of photon energy
- Plan to increase tagged beam intensity by a factor 5-10...new high-rate focal plane detector

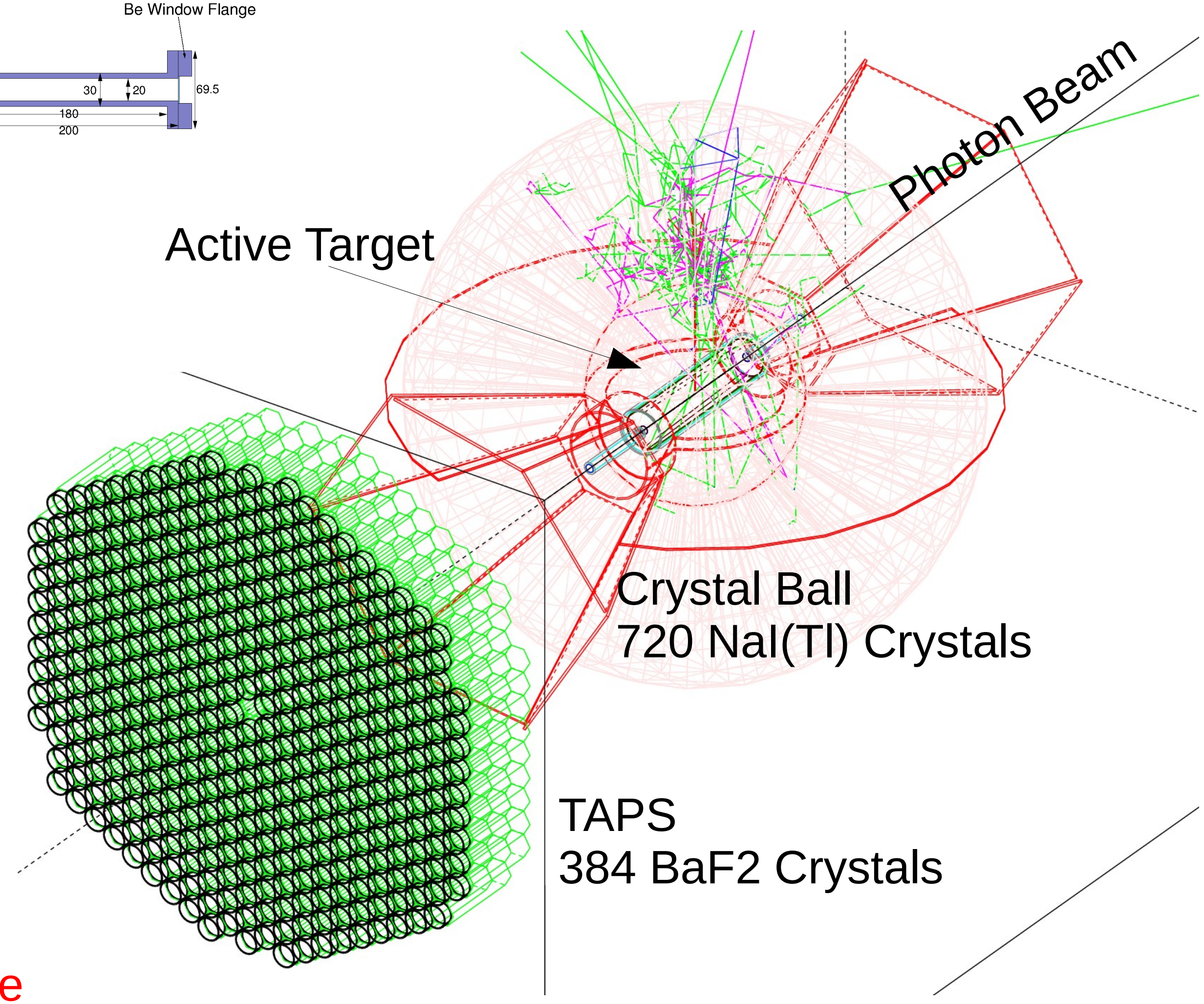


- Use active target to detect ^{3}He ions
  Target Thickness ^{3}He: 0.075 g/cm2
- Crystal Ball & TAPS 4π calorimeter to detect scattered photons
- Measure range ω = 80 – 200 MeV
  Experiment A2-01/13
  “Compton Scattering on the He Isotopes with an Active Target”

Mk3 He Active Target for Mainz



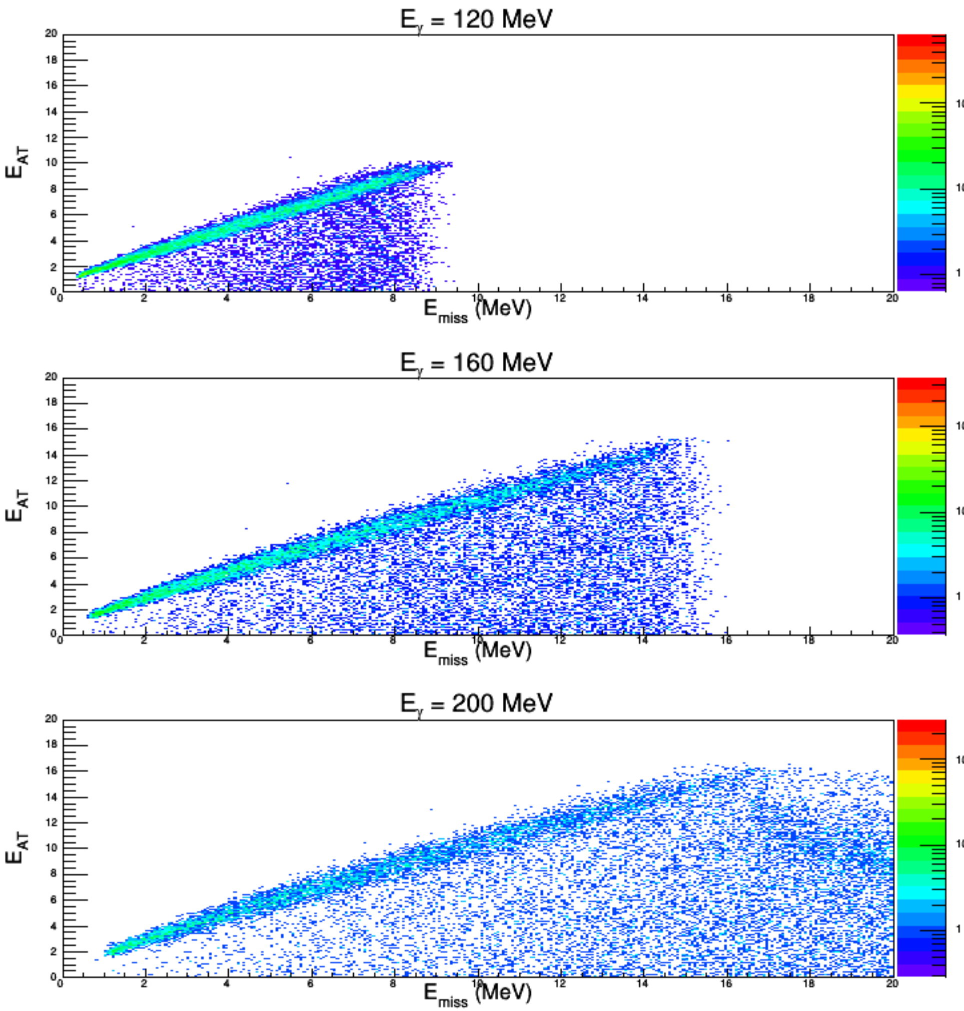
Scintillation detected by 64 SiPMT situated inside pressure vessel



- Measure $\gamma + {}^3\mathrm{He} \rightarrow \gamma + {}^3\mathrm{He}$)
- ^{3}He detected in AT
- γ' detected by CB or TAPS
- Coherent Compton cross section small
- How clean is the Compton signal?

- Simulate the combined response of the AT + CB/TAPS for:
  i. Coherent Compton scattering ^{3}He
  ii. Quasi-free $\gamma + {}^3\mathrm{He} \rightarrow \gamma NX$
  iii. $\gamma + {}^3\mathrm{He} \rightarrow ppn$ ... neutron (could mimic γ in CB)
  iv. Coherent and QF π^0 production

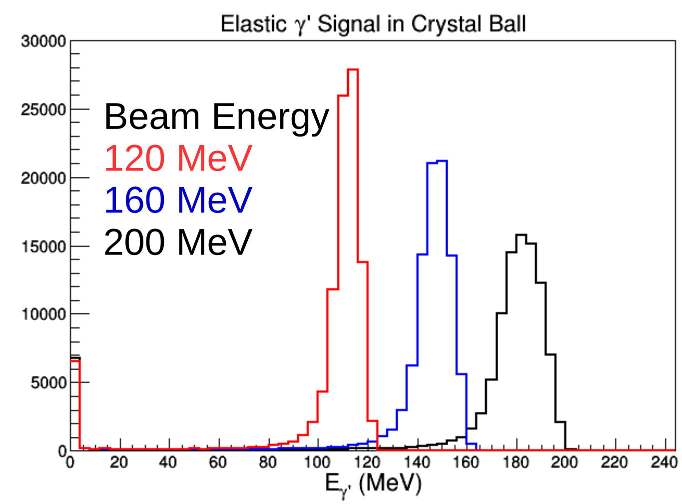
The Simulated ^{3}He(γ,γ) Signal



Compare measured AT kinetic energy with missing energy obtained from 4-momenta of initial γ, target ^{3}He and final γ'

$$E_{miss} = (\mathbf{P}_{\gamma} + \mathbf{P}_{targ} - \mathbf{P}_{\gamma'}) \rightarrow E - M_{3He}$$

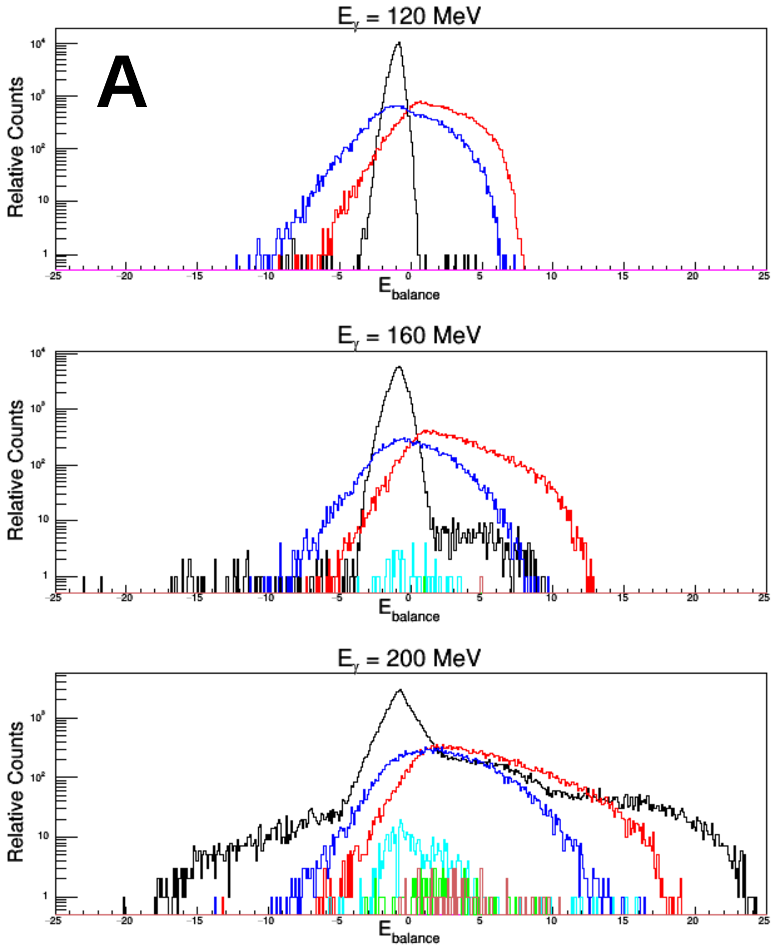
Select Compton signal by cut on elastic scattering energy region in Crystal Ball or TAPS



Simulated ^{3}He(γ,γ) Signal and Background

$E_{balance} = E_{miss} - E_{AT}$

A



$\gamma + ^3He \rightarrow \gamma + ^3He$

$\gamma + ^3He \rightarrow \gamma + n + p + p$

$\gamma + ^3He \rightarrow \gamma + p + d$

$\gamma + ^3He \rightarrow p + p + n$

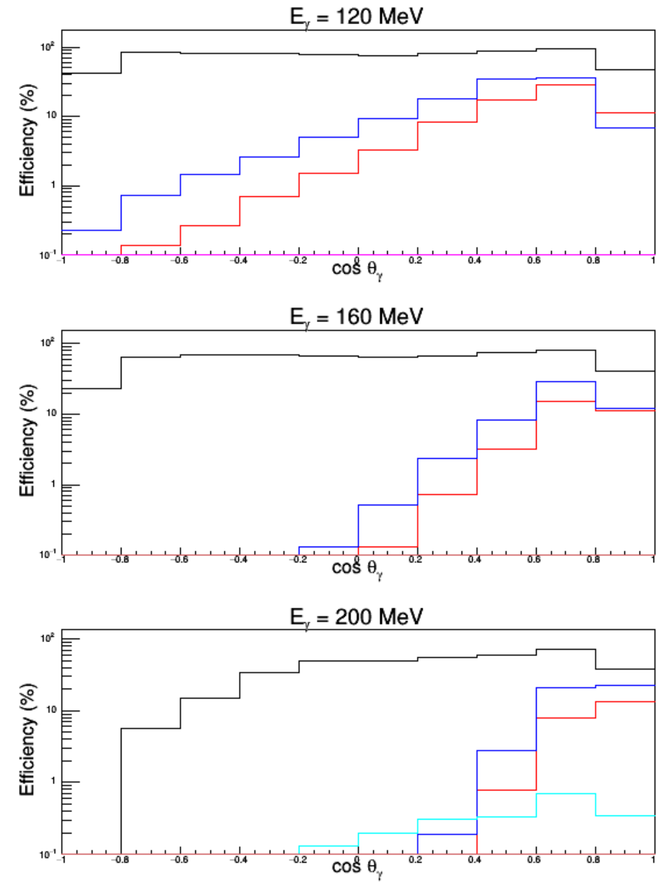
$\gamma + ^3He \rightarrow \pi^0 + ^3He$

$\gamma + ^3He \rightarrow \pi^0 + n + p + p$

$\gamma + ^3He \rightarrow \pi^0 + p + d$

Events generated
For these reaction
channels

B



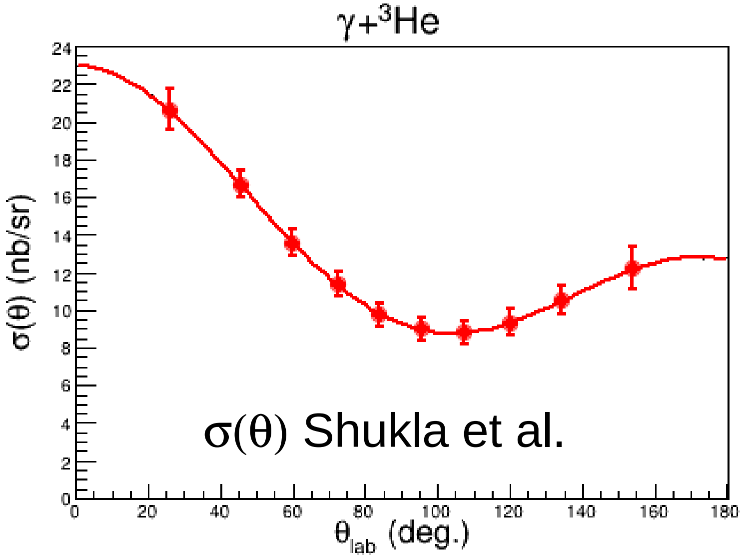
A: AT $E_{balance}$ signal for various reaction channels,

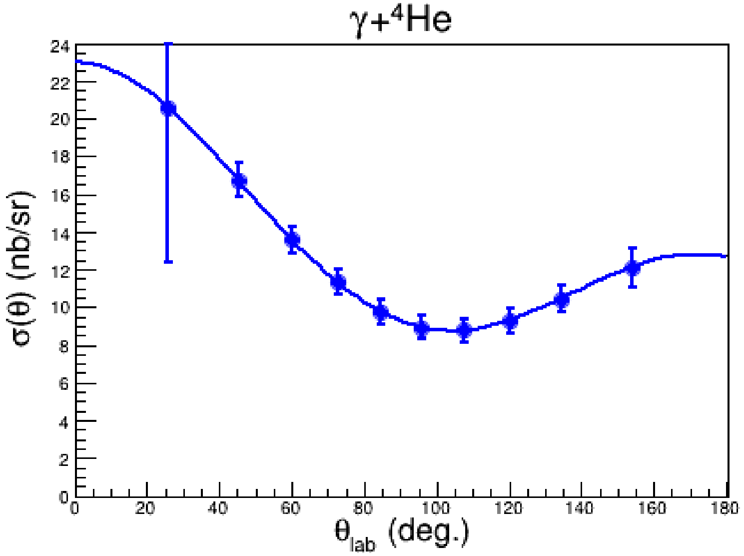
Elastic γ' energy range selected

B: Detection efficiency of corresponding reaction channels after
selection coherent $E_{balance}$ peak and T_{AT} > 1.0 MeV

Projected Statistical Uncertainty ω = 120 MeV

Projected uncertainties ω = 115 – 125 MeV





Uncertainties

- 200 hrs of beam
- Statistical 4-7% most angles at current beam intensity
- Statistical uncertainties factor ~2 smaller with increased beam intensity
- Systematic uncertainties beam flux, target thickness ~3%
- Systematic uncertainty QF Compton subtraction: to be determined

Analyze data in 10-MeV wide bins covering ω = 80 – 200 MeV
In total ~ 100 data points

Degree of Constraint on α^n,β^n

Estimate of α^n,β^n based on χEFT fit to γ+d$\rightarrow\gamma$+d *(Griesshammer et al.)*
Units 10^{-4} fm^{3,} with Baldin Sum Rule constraint

$$\alpha_n = 11.55 \pm 1.25(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \pm 0.8(\mathrm{th})$$
$$\beta_n = 3.65 \mp 1.25(\mathrm{stat}) \pm 0.2(\mathrm{BSR}) \mp 0.8(\mathrm{th}).$$

29 + 23 new coherent deuteron Compton scattering points

Factors affecting accuracy of extracted α^n,β^n from $\gamma+^3$He$\rightarrow\gamma+^3$He

- Absolute normalisation of differential cross section
  Target thickness, photon flux
  Uncertainty ~3%
- Uncertainty from background subtraction (mainly at forward angle)
  To be determined
- Fit to differential cross section $\sigma(\omega,\theta)$
  Statistical uncertainties 2 - 4% at ω = 120 MeV (with FPD upgrade)
  Data at 80, 90, 100, 110, 120, 150, 160, 170, 180, 190, 200.... MeV
  ~100 ^{3}He data points
  GOAL
  Reduce statistical uncertainty in extraction of α,β by a factor 2
  Theoretical interpretation uncertainty to be determined
- ^{4}He expect similar “stat” uncertainty
  χEFT analysis not developed
- Useful extra from Σ asymmetry ? Used to separate α^p,β^p
  $\sigma_{perp} - \sigma_{para} : \alpha$ $\quad$ $\cos^2(\theta).\sigma_{perp} - \sigma_{para} : \beta$

Summary

- The AT will be used at Mainz in conjunction with CB/TAPS to measure Compton scattering on He isotopes
  Experiment A2-01/13
  "Compton Scattering on the He Isotopes with an Active Target"
- Geant-4 simulations of AT + CB/TAPS suggest that clean separation of coherent Compton from background processes is possible
- 9-10 angle-point Compton differential cross section 10 MeV bin ω ($\delta\sigma(\theta)$ ~ 4 – 7%) possible in ~200 hr. Reduce statistical uncertainties by factor ~2 with new high rate tagger
- Targeted statistical uncertainty in neutron scalar polarisabilities reduced by factor ~2
- Extend χPT calculations on ^{3}He(γ,γ):
  George Washington, Ohio U., Manchester and Glasgow
- AT also suitable for coherent π^0 measurements on He isotopes...
  Mainz LOI A2-03 Hornidge et al. S-wave nπ^0 amplitude χPT

Thanks for your attention

Signal for Coherent π^0 Production

Coherent π^0 Signal

Compare AT energy with that obtained from π^0 4-momentum

$T_{miss} = (\mathbf{P}_{\gamma} + \mathbf{P}_{targ} - \mathbf{P}_{\pi 0}) \rightarrow T$

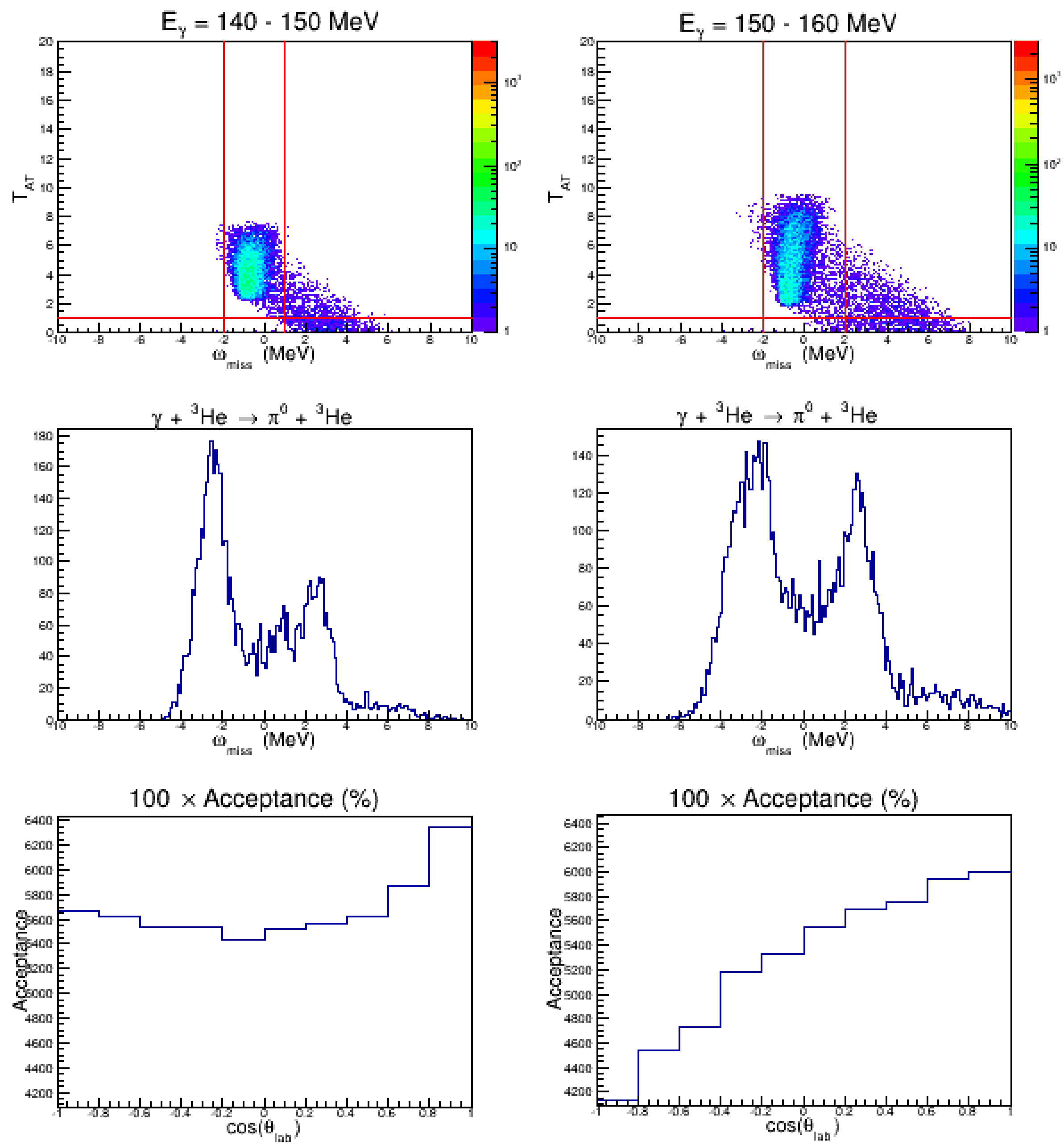
$\omega_{miss} = T_{miss} - T_{AT}$

Select coherent π^0 signal by cut on:

$-2 < \omega_{miss} < 1$ MeV

$T_{AT} > 1$ MeV

$M_{\pi 0}$ 2-γ in CB/TAPS



Backup Slides

Nucleon Compton Scattering

H.W. Griesshammer et al., Prog.P.N.Phys. 67,841 (2012)
χEFT analyses of proton and neutron data

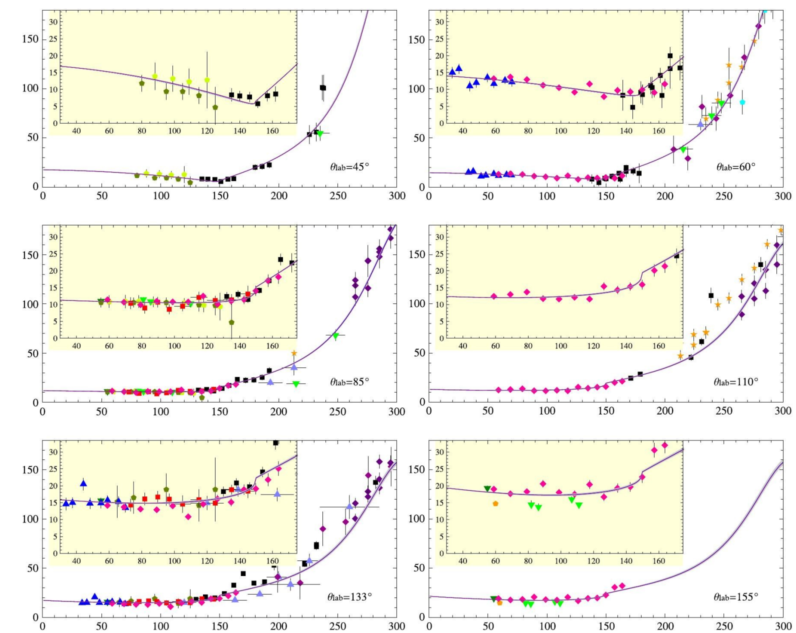
Relative wealth of ^{1}H(γ,γ) differential cross section data, largely from Mainz.
Recent χEFT analysis
McGovern et al. EPJ A49(2013),12

$$\alpha_p = 10.65 \pm 0.35(\text{stat}) \pm 0.2(\text{BSR}) \pm 0.3(\text{th})$$
$$\beta_p = 3.15 \mp 0.35(\text{stat}) \pm 0.2(\text{BSR}) \mp 0.3(\text{th}),$$

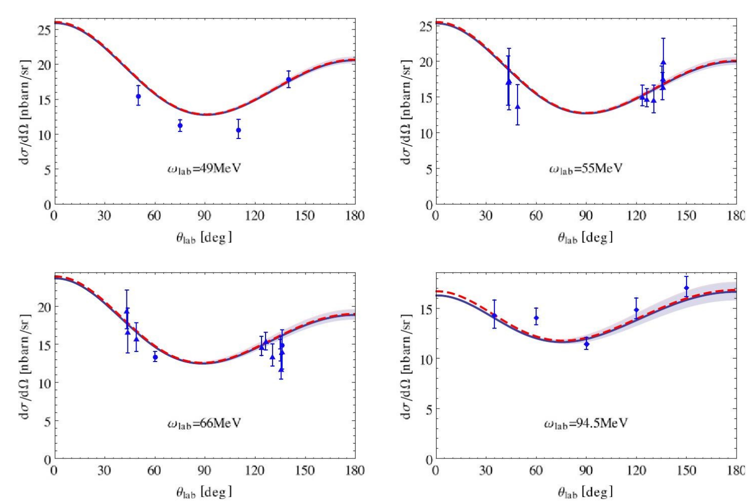
(BSR = Baldin Sum Rule)
Mainz work continues: proton spin polarisabilities

No free neutron target...use ^{2}H, ^{3}He...
Limited data set for ^{2}H(γ,γ)
(Illinois, MAX-lab, SAL)
Neutron scalar polarisabilities poorly determined relative to proton
Neutron-proton differences relatively small...and potentially very interesting
But...we are a long way from quantifying these differences

^{1}H(γ,γ)



^{2}H(γ,γ)



Neutron Compton Scallering

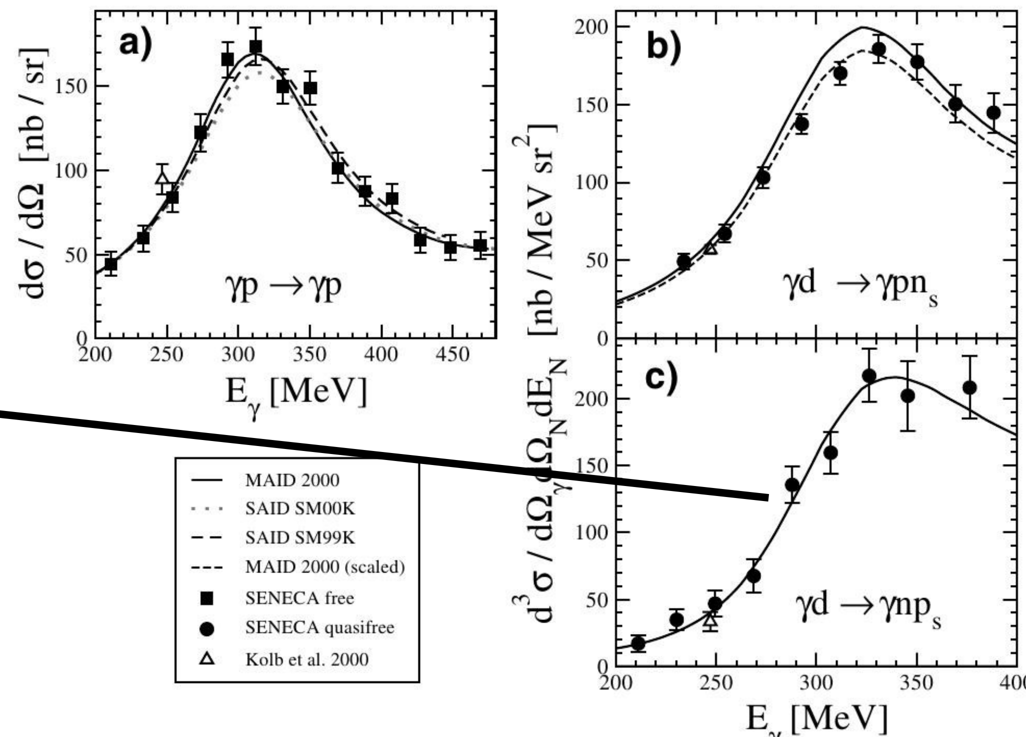
- Quasi free d(γ,γ'n)p measured at Mainz and SAL: determine α – β
- Proton: interference between Thompson term in Born amplitude & non-Born amplitude containing the polarizabilities.
- Neutron: Thomson amplitude vanishes
- Mainz experiment 200 – 400 MeV

$$\alpha_n = 12.5 \pm 1.8(\mathrm{stat})^{+1.1}_{-0.6}(\mathrm{sys}) \pm 1.1(\mathrm{th})$$
$$\beta_n = 2.7 \mp 1.8(\mathrm{stat})^{+0.6}_{-1.1}(\mathrm{sys}) \mp 1.1(\mathrm{th}),$$

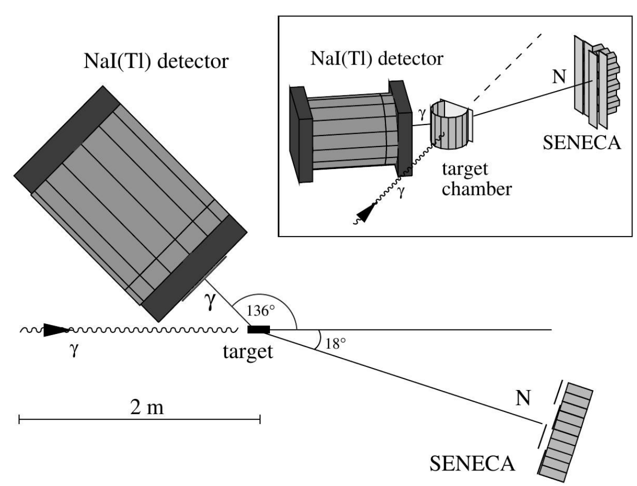
- Theoretical uncertainty may be underestimated

- Alternative: coherent ^{2}H(γ,γ')^{2}H
- Isospin averaged polarisabilities. Subtract proton contribution
- Benefit from Thompson term in cross section
- Need very good γ' energy resolution to separate non-coherent
- Up to now all “neutron” Compton measurements on ^{2}H

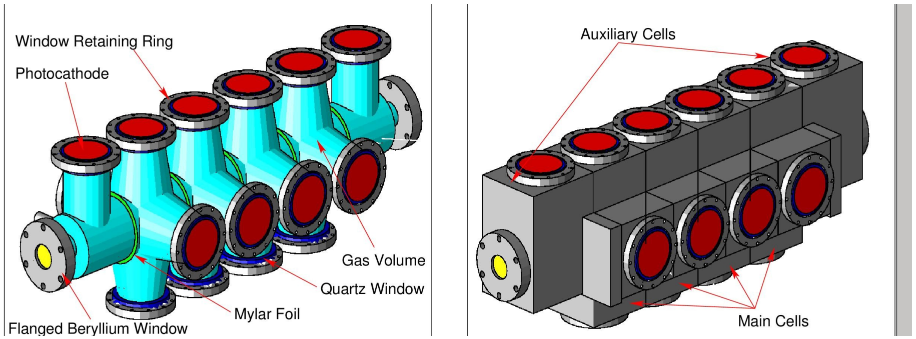
K.Kossert et al., PRL88, 162301 (2002)

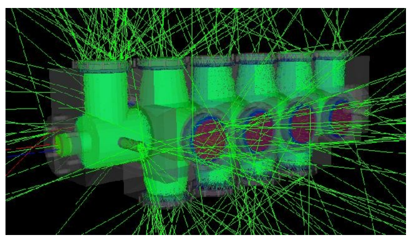


SAL Data: N. R. Kolb et al., PRL85(2000), 1388.

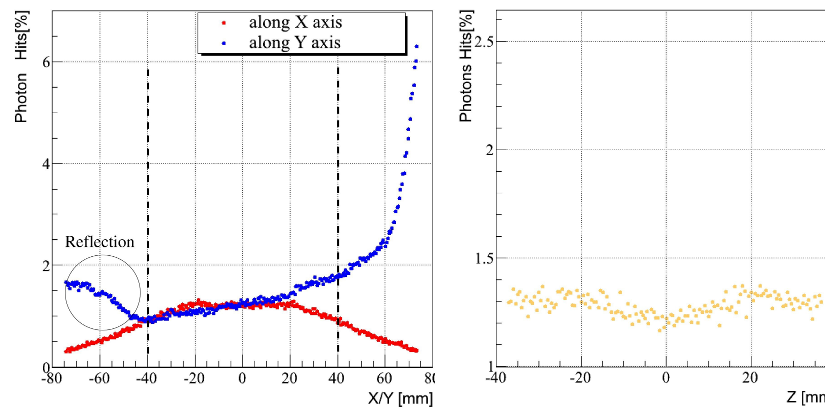


An Active Target for γ+He→γ+He

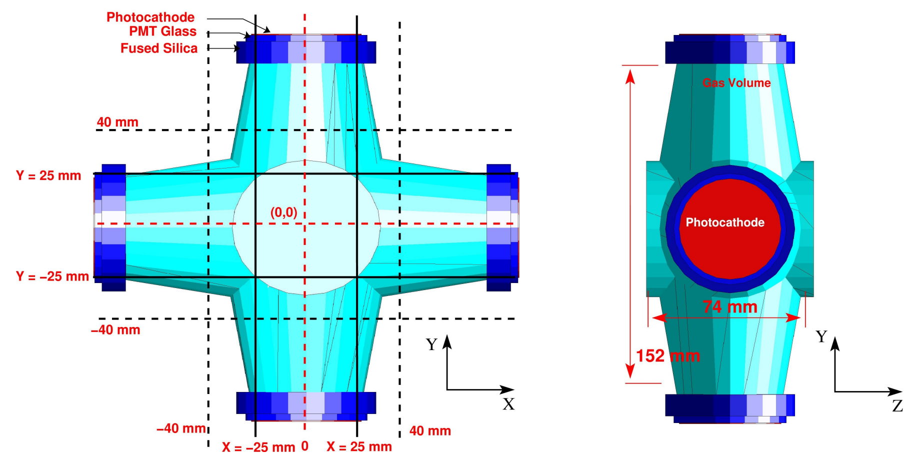




Monte Carlo Simulation
Scintillation light transport
Position dependence of signal
Fold with calculated energy loss



He target is also detector of
Photo reaction products
Low energy recoil He ions detected
Coincidence with CB & TAPS



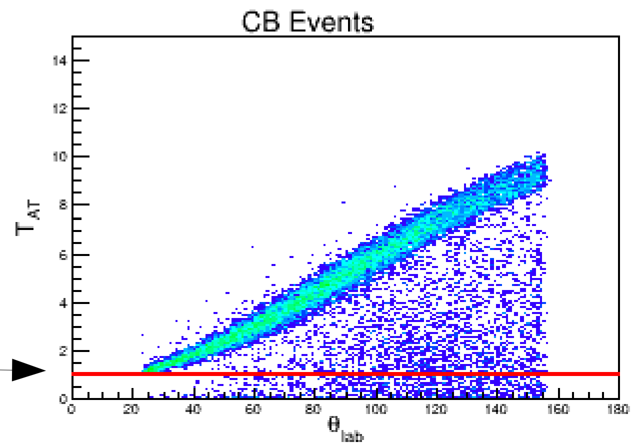
Compton Cross Section Measurement at Mainz

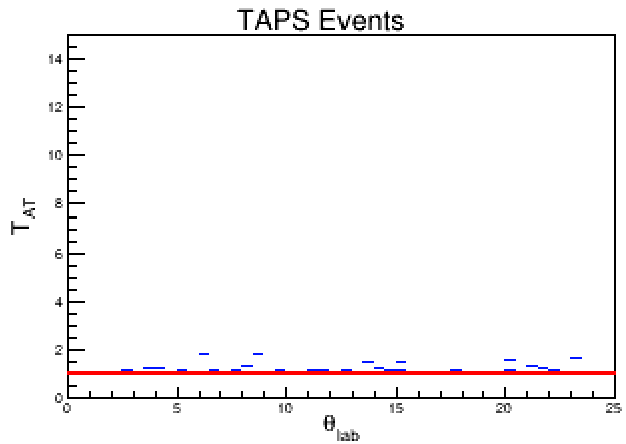
- 855 MeV electron beam, ω = 46 - 795 MeV, $\delta\omega$ ~ 2 MeV
  1 MHz rate per tagger channel @ 120 MeV,
  50% tagging efficiency (4mm collimator)
  Incident photon rate 0.25 x 10^6 per MeV
- Active Target (AT) sits directly in beam at centre of CB
  Remove PID and MWPC
  AT insensitive to electrons generated by photon beam
  and to low energy background in general
- 4π electromagnetic calorimeter CB + TAPS
  Good angle and energy resolution
- AT makes primary trigger (good timing). ~ 10 kHz rate
  Coincidence rate < 1 kHz
  Demand ≥1 cluster coincidence with CB or TAPS
- Record Compton, π^0, η photoproduction.
  Best AT signal where recoiling He ion stops in target gas

Experimental Acceptance ^{3}He(γ,γ)

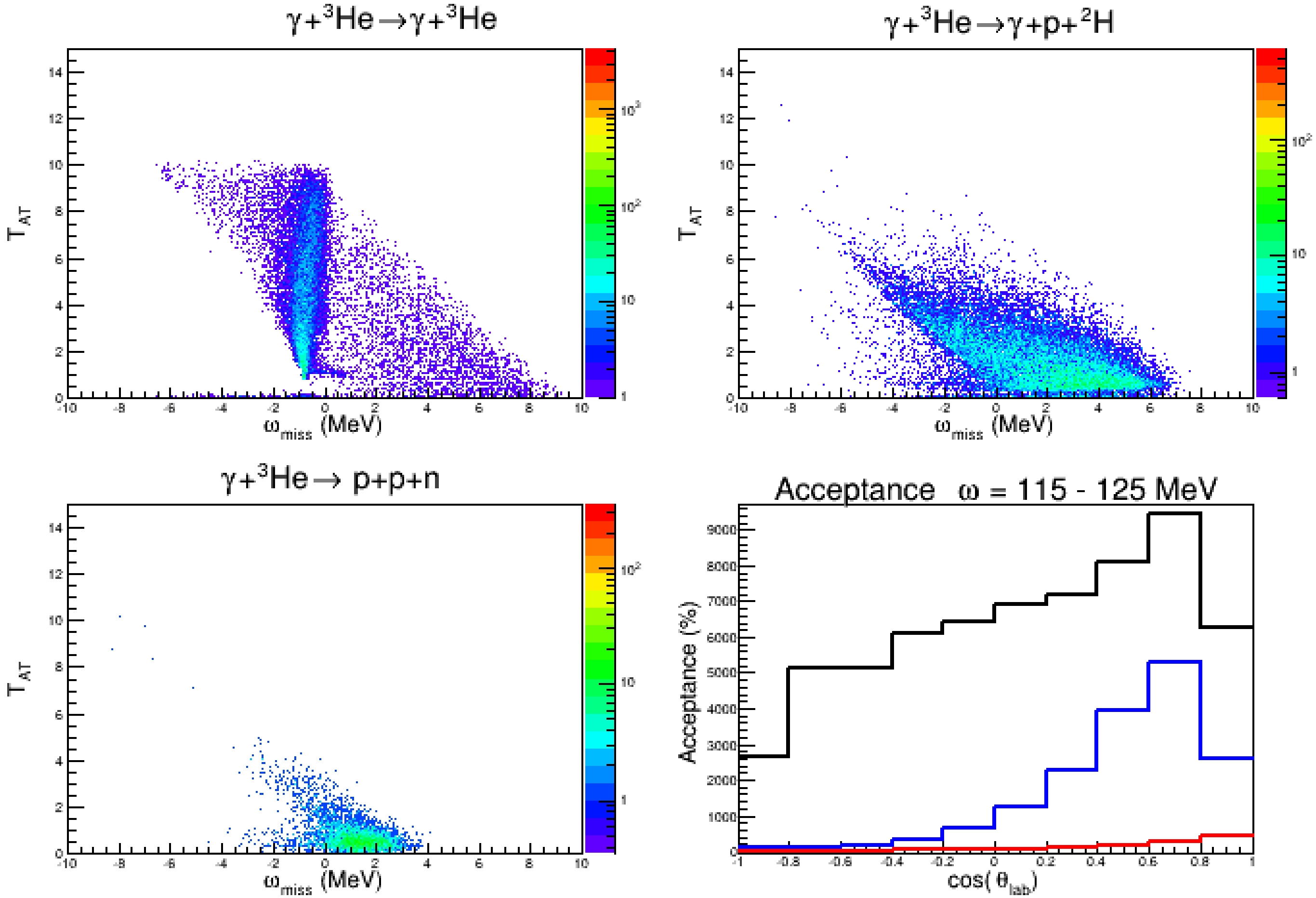
E_γ = 115 - 125 MeV

- Around 70% of started ^{3}He Compton events registered within the coherent-elastic region by the AT-CB combination
- Acceptance has some angle dependence
- Small AT signal amplitude at $\theta_\gamma < 20^o$
- Potential background contamination any channel which produces neutral
- Below π^0 threshold quasi-free Compton is the main source of background
- Breakup channels (producing neutron)
  -higher cross section
  -neutron efficiency 20-30% CB
  -neutron pulse height in CB or TAPS
  much lower than scattered photon



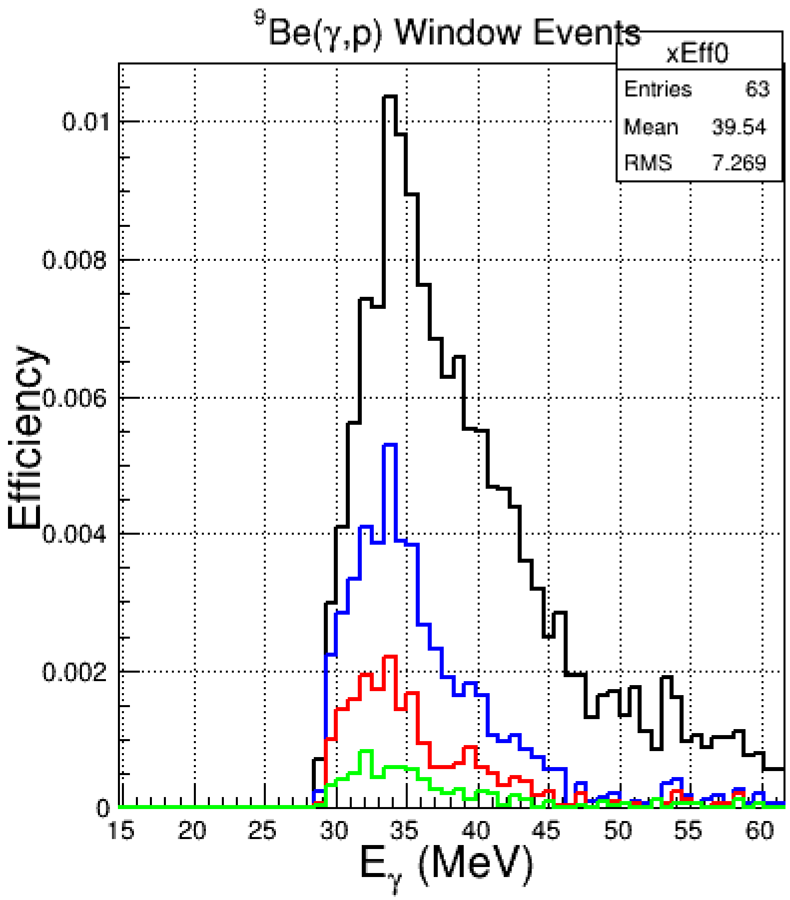


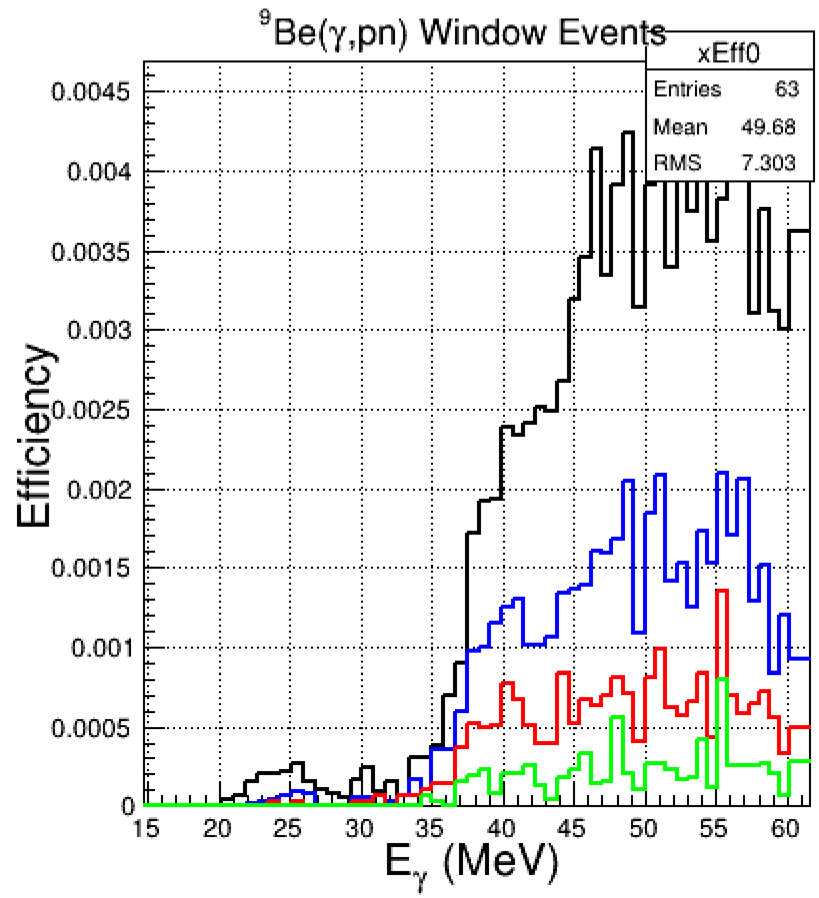
ω = 115-125 MeV



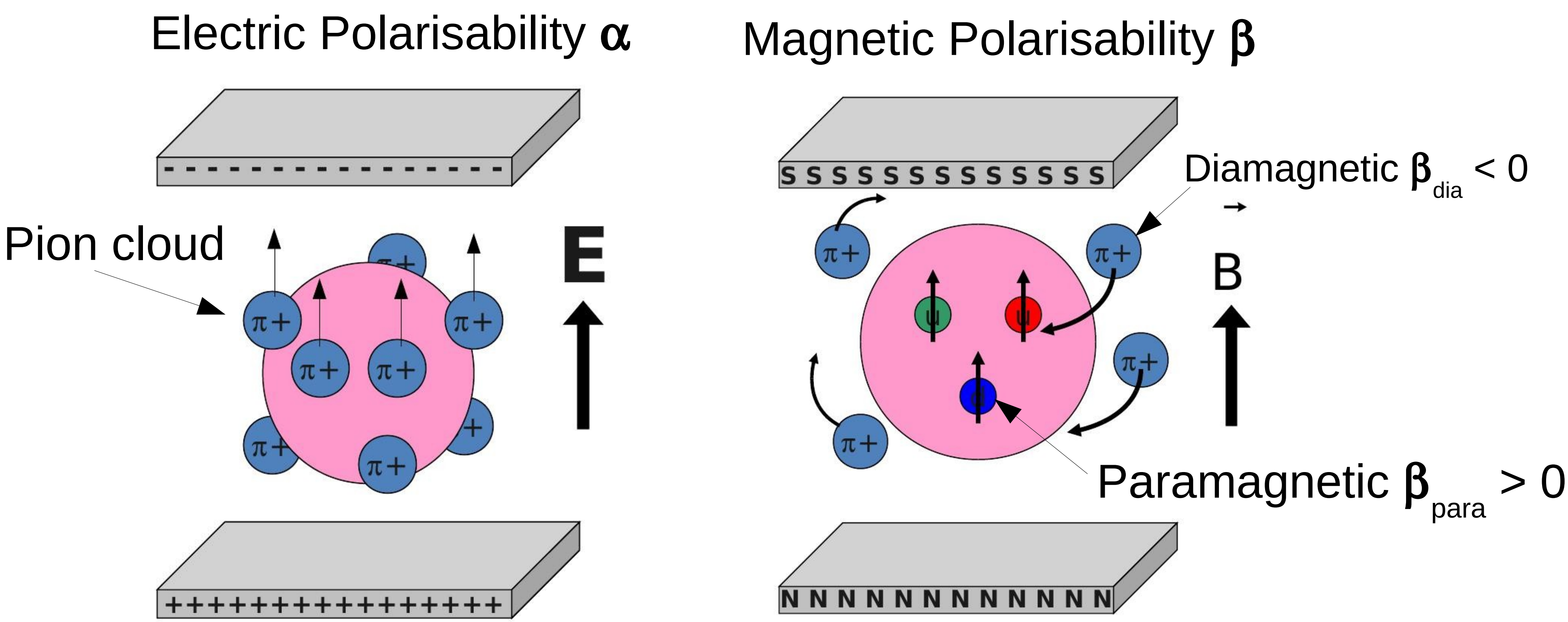
$\gamma+^3He \to \gamma+^3He$
$\gamma+^3He \to \gamma+p+^2H$
$\gamma+^3He \to p+p+n$
Acceptance ω = 115 - 125 MeV
T_{AT}
ω_{miss} (MeV)
Acceptance (%)
cos(θ_{lab})

Be Window Effects
PRELIMINARY





Nucleon Scalar Polarisabilities



- Nucleon is pretty "stiff"
  Polarisabilities come in units of 10^{-4} fm^3
- How to access: nucleon Compton Scattering
  incident real photon
  $\omega \sim 100 - 200$ MeV