Compton Scattering from the Deuteron and the Polarizability of the Neutron

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- Introduction to nucleon polarizability
- Measuring neutron polarizability
  - Low-energy neutron scattering
  - Quasi-free Compton scattering
  - Elastic Compton scattering
- New experiment at Lund

Introduction

- polarizability – measure of induced dipole moment in external field

electric

$$D = \alpha E$$

$$\Delta\varepsilon = -d \cdot E - \tfrac{1}{2}\alpha |E|^2$$

magnetic

$$M = \beta B$$

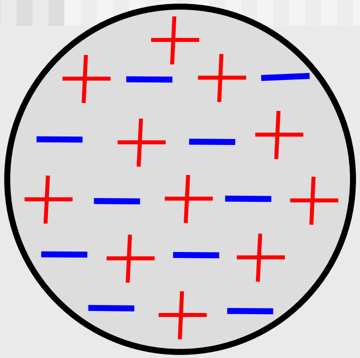
$$\Delta\varepsilon = -\mu \cdot B - \tfrac{1}{2}\beta |B|^2$$

q, μ	$\Rightarrow\Rightarrow\Rightarrow\Rightarrow$	**1st order response**
α, β	$\Rightarrow\Rightarrow\Rightarrow\Rightarrow$	**2nd order response**

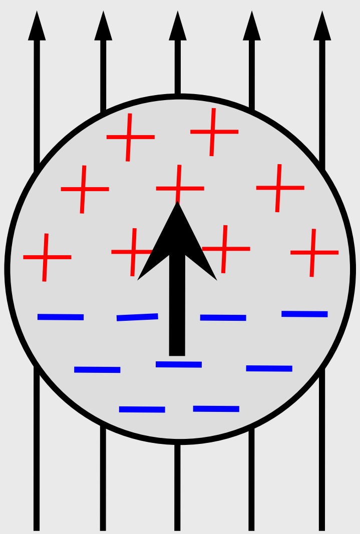
(lowest order response of *internal* structure)

- for the free nucleon:
  - fundamental structure constants
  - proton is decent now, but neutron needs work

electric polarizability: separation of charge

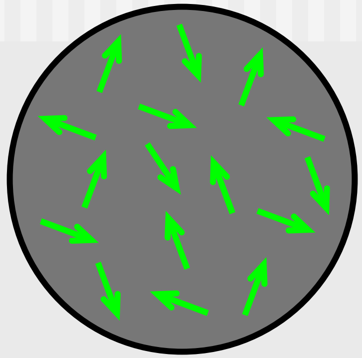


$D = 0$

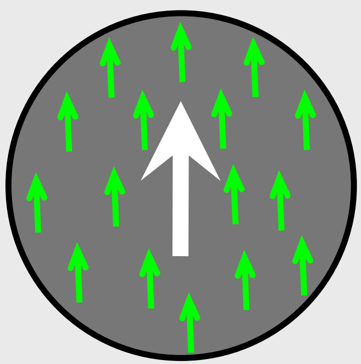


$D = \alpha E$

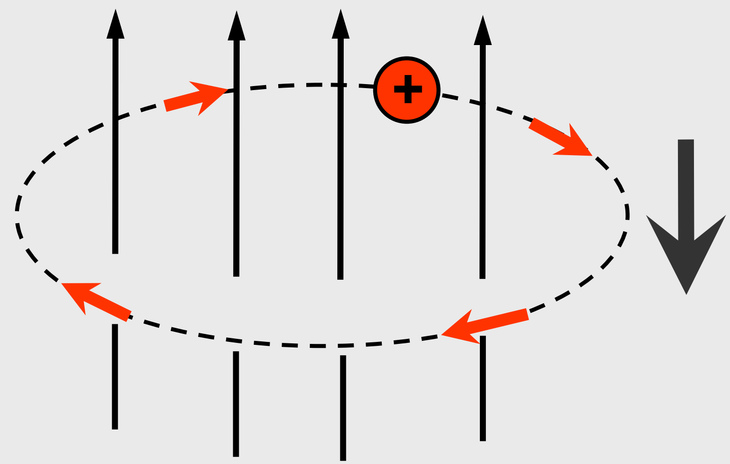
paramagnetic polarizability: moments align with *B*



$M = 0$



$M = \beta_{para} B$



$M = \beta_{dia} B$

diamagnetic polarizability: induced current opposes *B*

Measuring Nucleon Polarizability

- **Proton**
  - Compton scattering

$$\sigma_p(\omega) \approx r_0^2 - 2\, r_0\, \alpha_p\, \omega^2$$

- **Neutron**
  - difficulties
    - no free neutron targets
    - neutron is uncharged (no Thomson scattering)

$$\sigma_n(\omega) \approx \alpha_n^2\, \omega^4$$

  - techniques
    - neutron scattering by heavy nucleus
    - quasi-free Compton scattering: $D(\gamma,\gamma' n)p$
    - elastic Compton scattering: $D(\gamma,\gamma)D$

Classical Compton Scattering

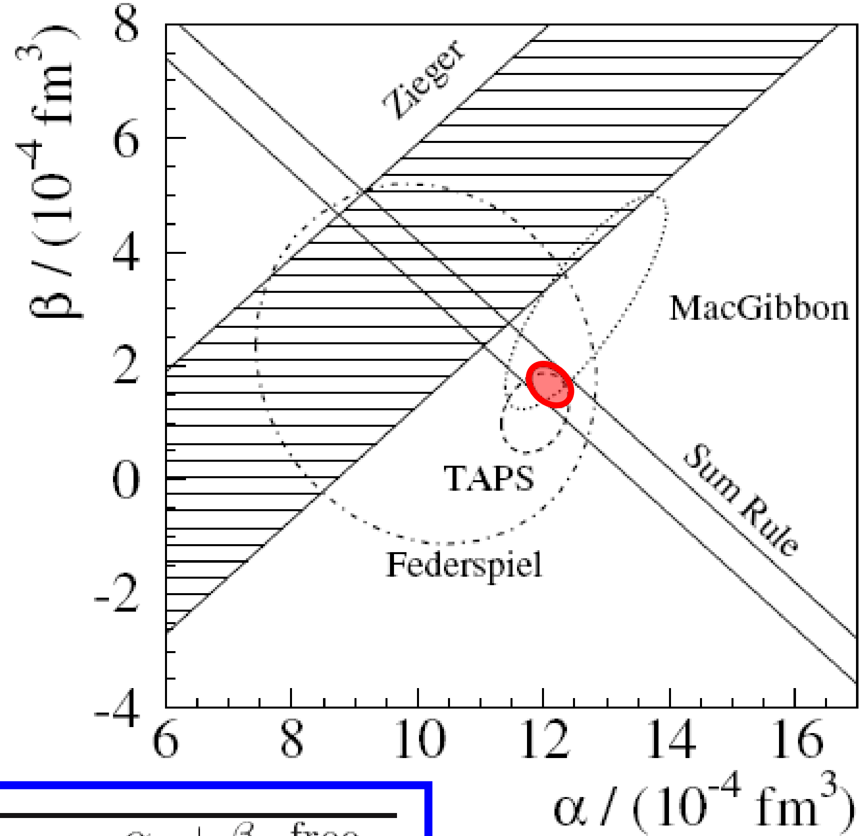
$$\sigma_p(\omega) = r_0^2 \left| 1 - \frac{2\omega^2}{\omega_p^2 - \omega^2 - i\omega\Gamma_p} \right|^2$$

$$\approx r_0^2 \left| 1 - \frac{2\omega^2}{\omega_p^2} \right|^2 \approx r_0^2 \left[1 - \frac{4\omega^2}{\omega_p^2} + \cdots \right] \approx r_0^2 - 2r_0\, \alpha_p\, \omega^2 + \cdots$$

$$\sigma_n(\omega) \approx r_0^2 \left| \frac{-2\omega^2}{\omega_n^2} \right|^2 \approx \alpha_n^2\, \omega^4$$

approximation holds at energies $\omega \ll \omega_{p,n}$

Proton Polarizability



Data		$\alpha_p + \beta_p$ fixed	$\alpha_p + \beta_p$ free
TAPS	α_p	$12.1 \pm 0.4 \mp 1.0$	$11.9 \pm 0.5 \mp 1.3$
Olmos de Leon	β_p	$1.6 \pm 0.4 \pm 0.8$	$1.2 \pm 0.7 \pm 0.3$
MacGibbon	α_p	$11.9 \pm 0.5 \mp 0.8$	$12.6 \pm 1.2 \mp 1.3$
[4]	β_p	$1.9 \pm 0.5 \pm 0.8$	$3.0 \pm 1.8 \pm 0.1$
Federspiel	α_p	$10.8 \pm 2.2 \mp 1.3$	$10.1 \pm 2.6 \mp 2.0$
[3]	β_p	$3.0 \pm 2.2 \pm 1.3$	$2.0 \pm 3.3 \pm 0.3$
Zieger	$\alpha_p - \beta_p$	$6.4 \pm 2.3 \pm 1.9$	
[6]			
Global	α_p	$12.1 \pm 0.3 \mp 0.4$	$11.9 \pm 0.5 \mp 0.5$
fit	β_p	$1.6 \pm 0.4 \pm 0.4$	$1.5 \pm 0.6 \pm 0.2$

Olmos de Leon EPJ 01

Neutron Polarizability Experiments

Alexandrov (Dubna – 1986)
Koester (Munich – 1986)
Schmiedmayer (Vienna/Harwell – 1986)
Koester (Munich – 1988)
Schmiedmayer (Vienna/ORNL – 1991)
Koester (Munich – 1995)
Enik (Dubna – 1997)
Laptev (Gatchina – 2002)

n scattering

$\alpha_n = 12.6 \pm 1.5(\text{stat}) \pm 2.0(\text{syst})$

Rose (Gottingen/Mainz – 1990)
Kolb (SAL – 2000)
Kossert (Mainz – 2003)

$D(\gamma,\gamma' n)p$

$\alpha_n = 12.5 \pm 1.8(\text{stat})\,^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model})$

$\beta_n = 2.7 \mp 1.8(\text{stat})\,^{+0.6}_{-1.1}(\text{syst}) \mp 1.1(\text{model})$

Neutron Scattering

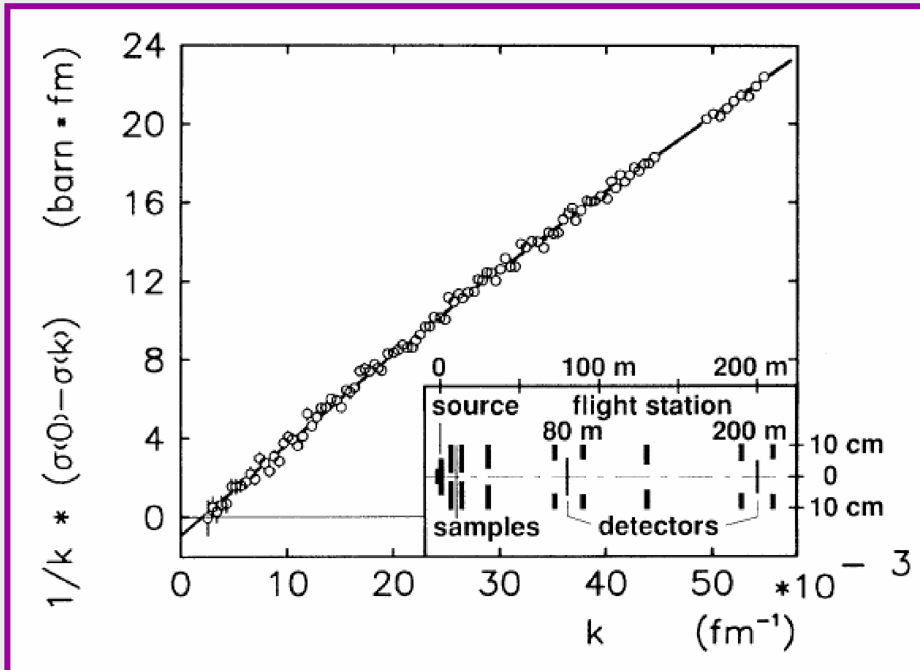
- near heavy nucleus: $E \sim 10^{21}$ V/m
  - interaction potential: $V = -\frac{1}{2}\alpha_n E^2 = -\frac{1}{2}\alpha_n (Ze)^2/r^4$
- scattering cross section includes:
  - **effect of α_n ($\sim k$)**
  - neutron-nucleus potential scattering
  - resonance scattering
  - spin-orbit (Schwinger) scatt.
  - neutron-electron interaction

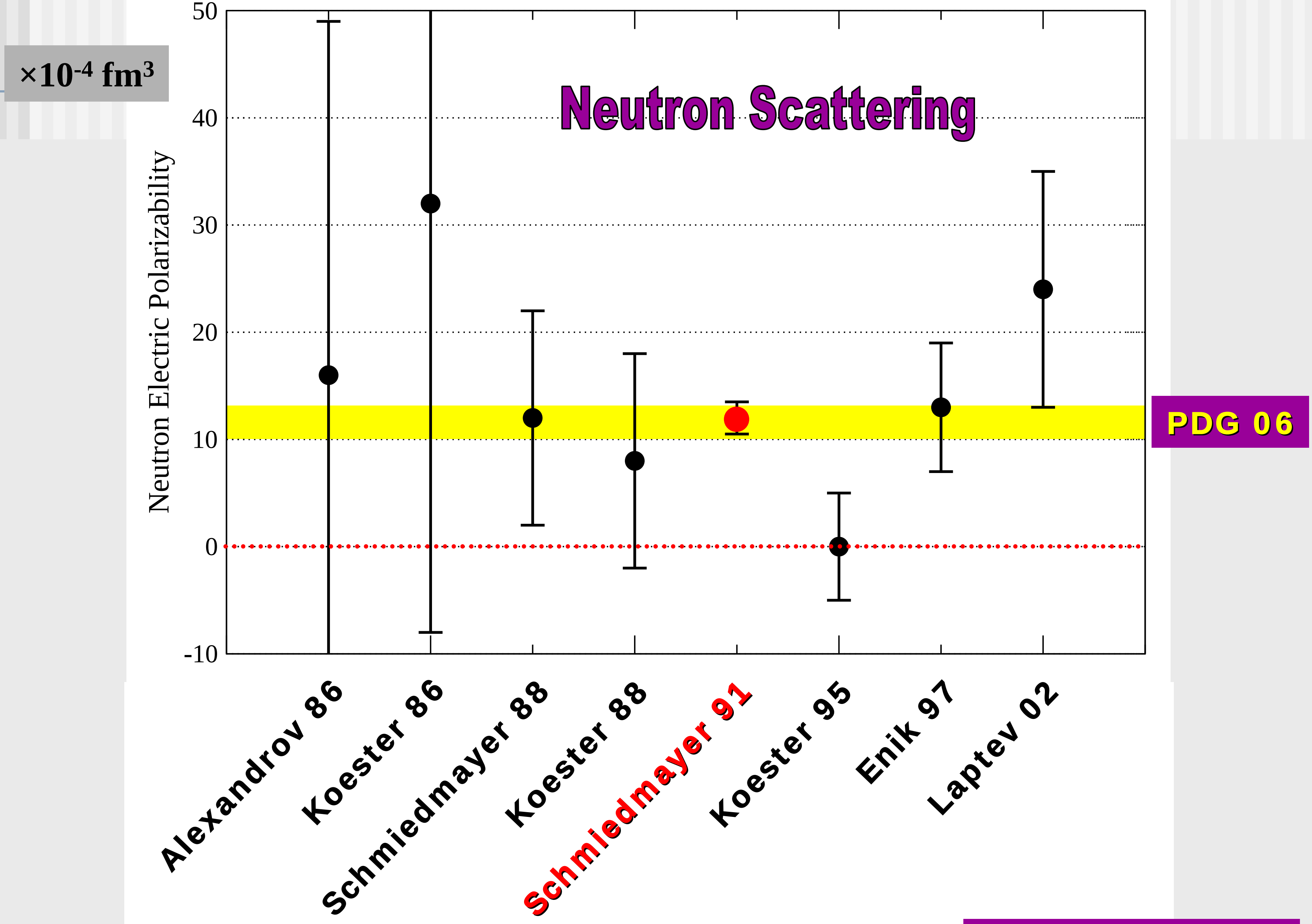
$$\sigma_s(k) = \sigma_s(0) + ak + bk^2 + ck^4$$

(E_n < 50 keV)

$$\alpha_n = 12.6 \pm 1.5(\text{stat}) \pm 2.0(\text{syst})$$

Schmiedmayer PRL 1991



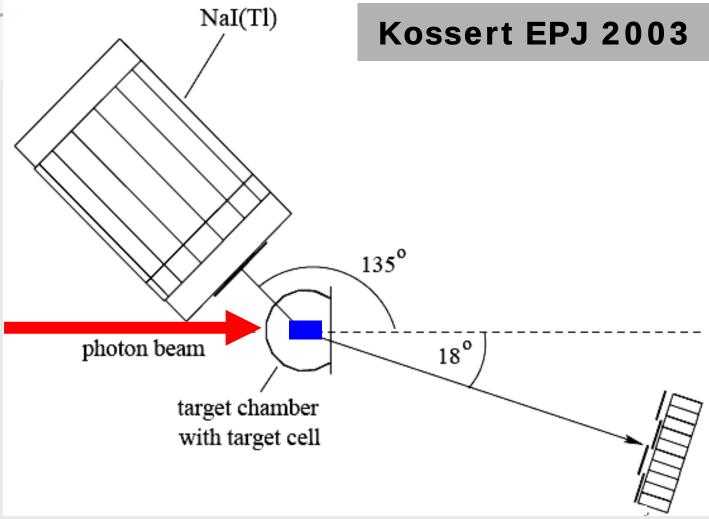


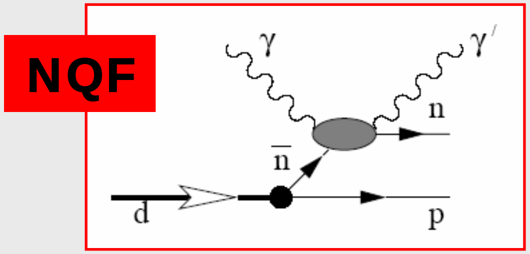
PDG $\alpha_n = 11.6 \pm 1.5$

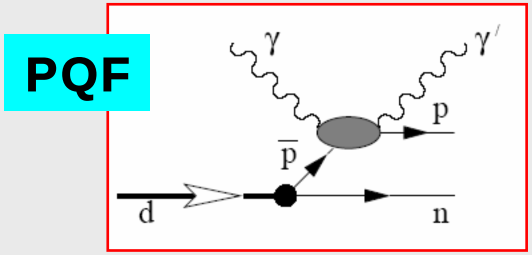
Quasi-Free Compton Scattering

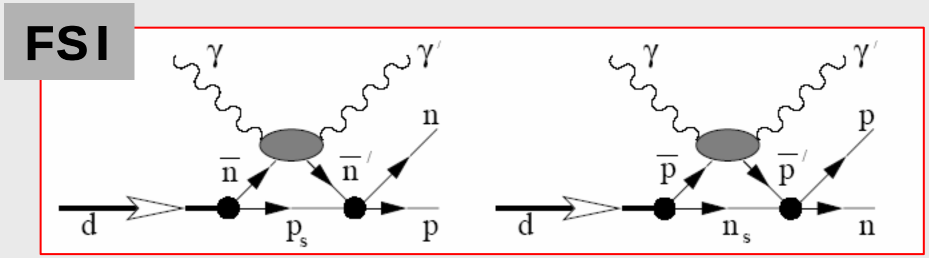
- $D(\gamma,\gamma' n)p$
  - detect scattered photon at back angle with a forward neutron

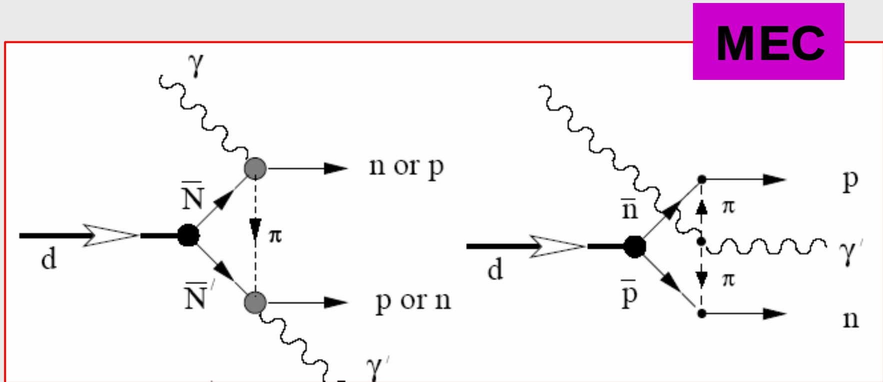
- analysis: diagrammatic approach of Levchuk/L'vov

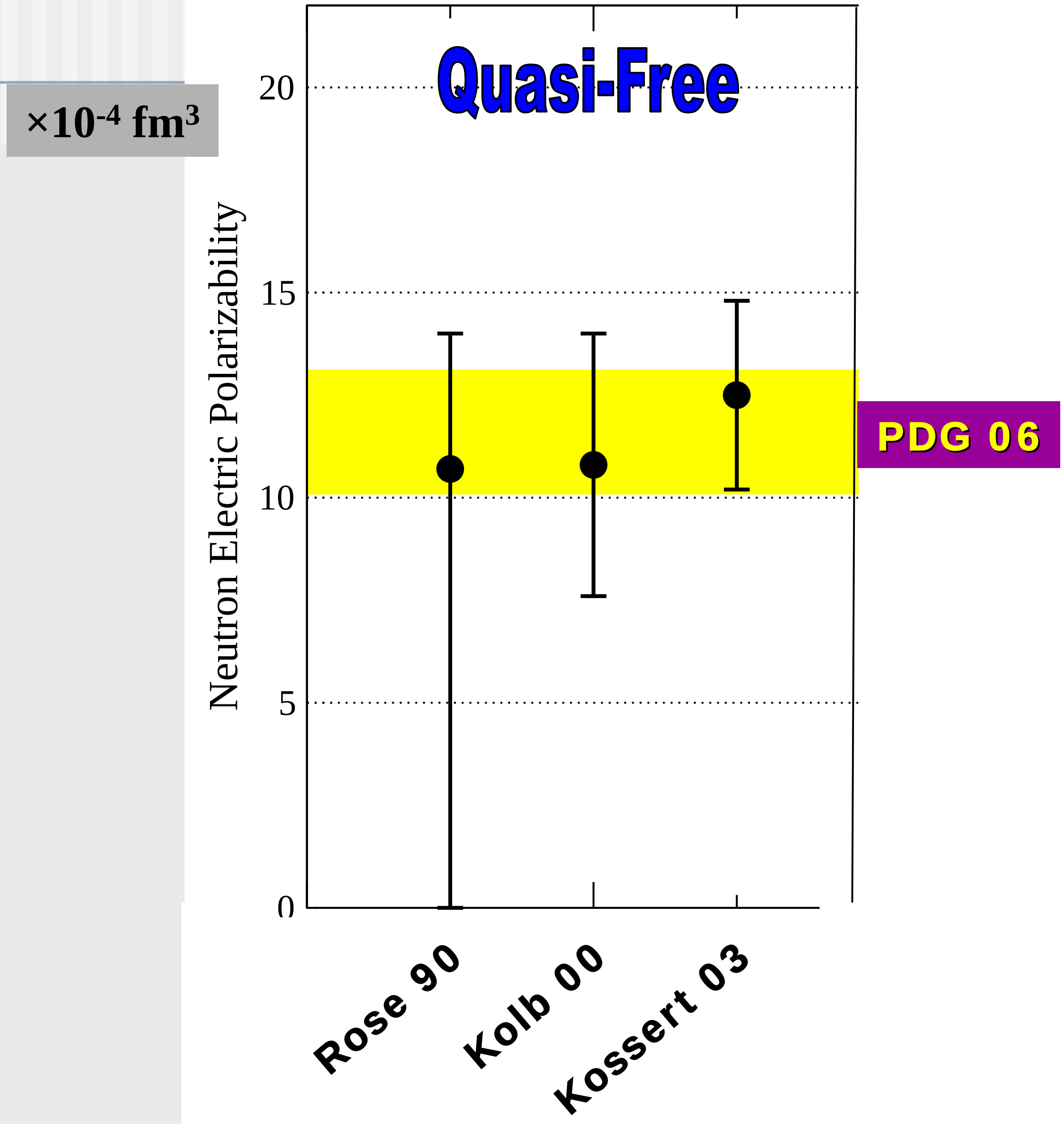






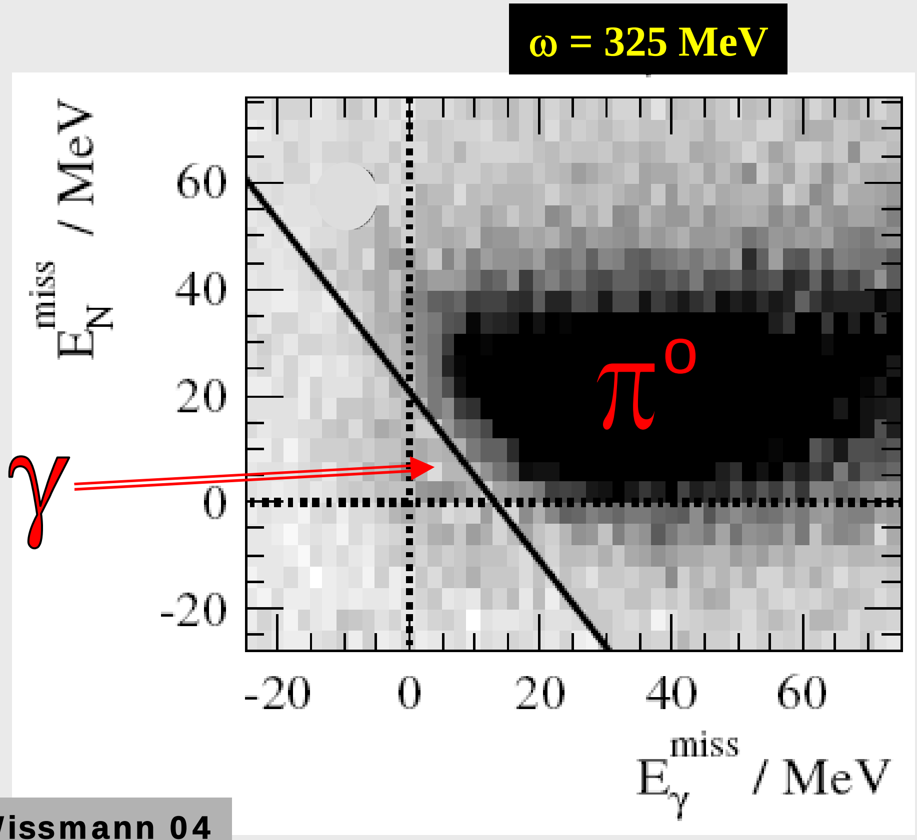




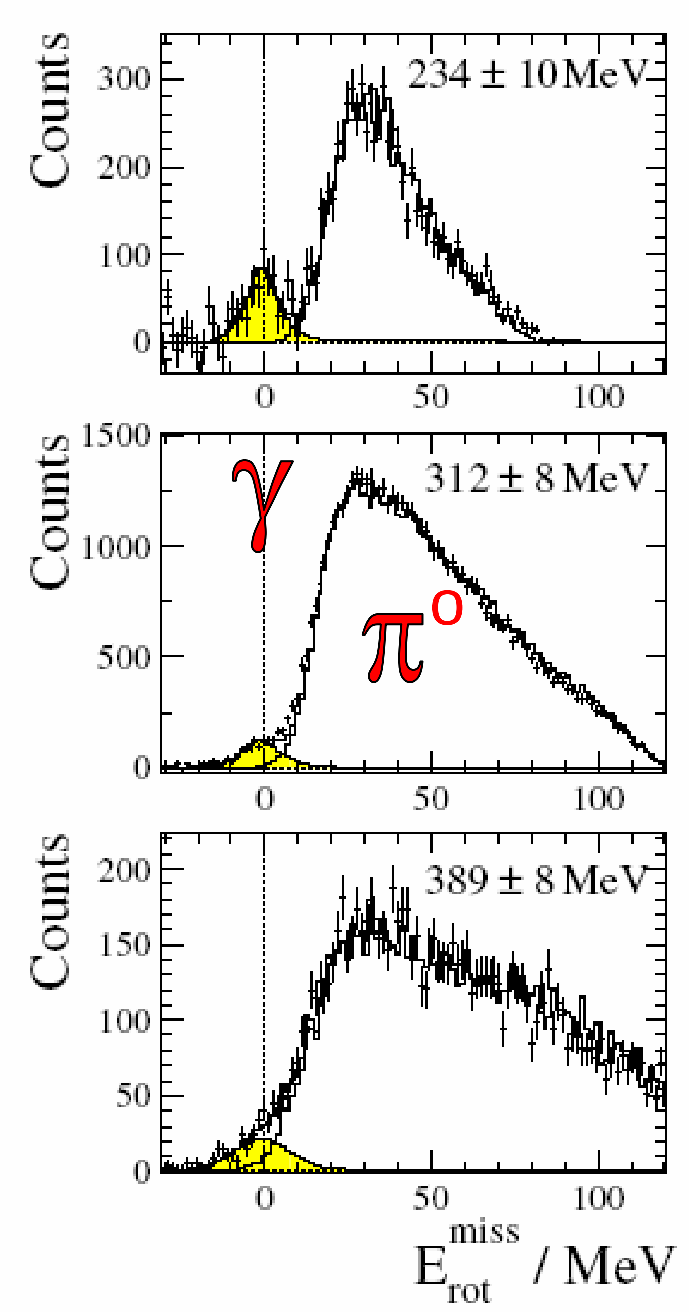

×10-4 fm3
Quasi-Free
Neutron Electric Polarizability
20
15
10
5
0
PDG 06
Rose 90
Kolb 00
Kossert 03

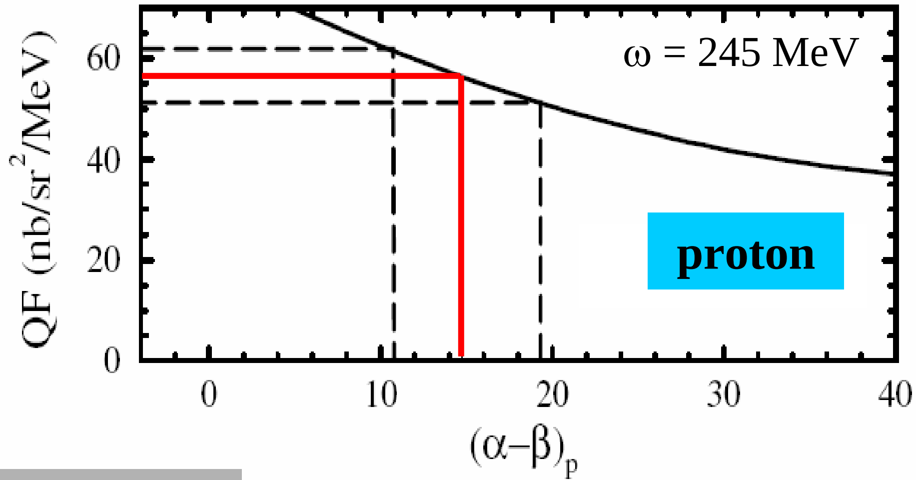
Finding QF Events

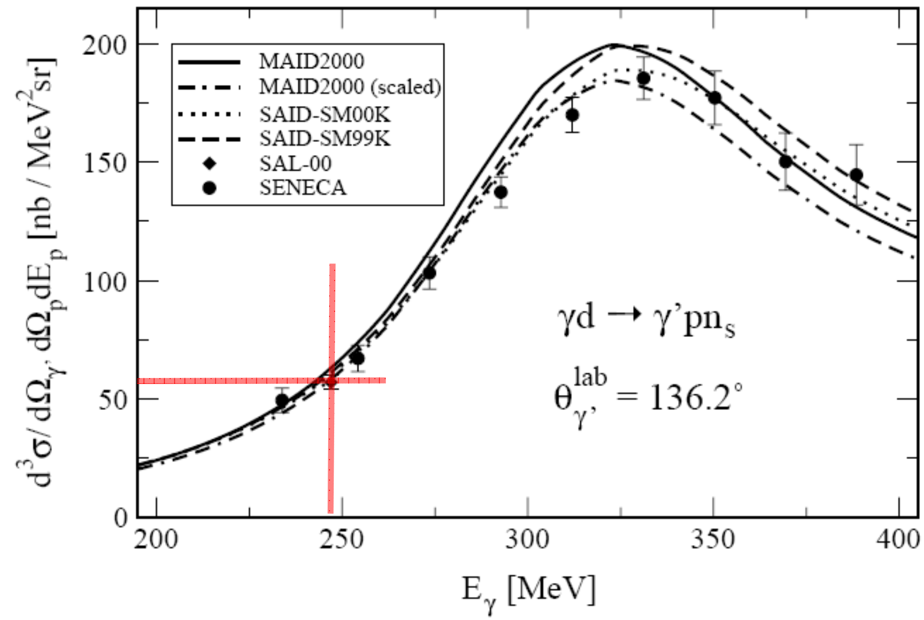
Kossert EPJ 2003



Wissmann 04





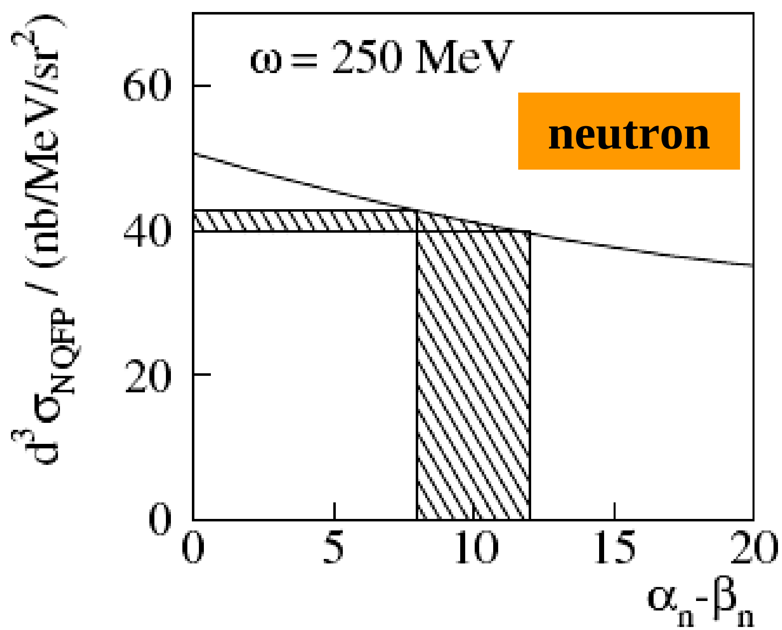


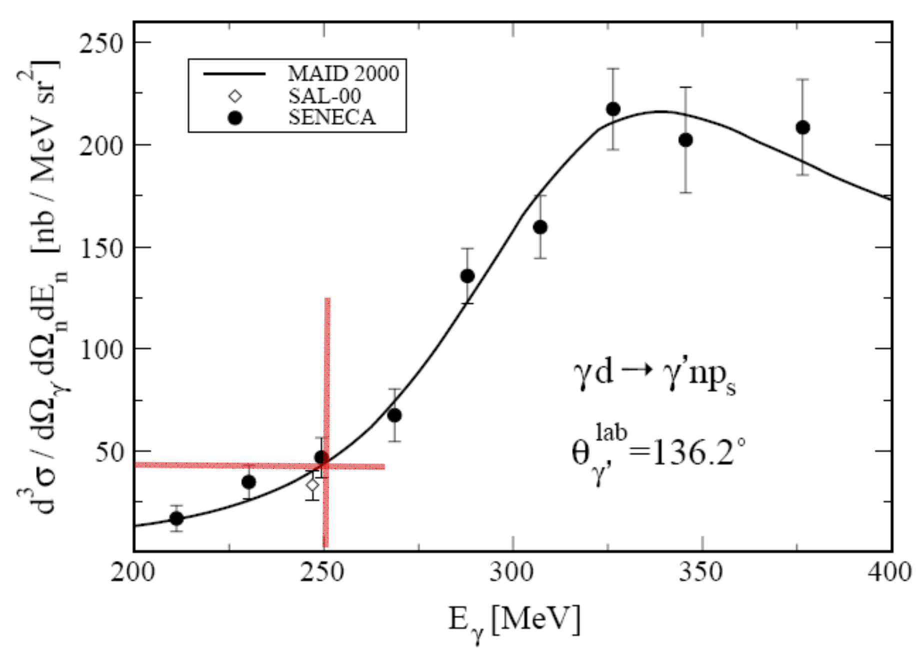
Kolb PRL 00

$$(\alpha-\beta)_p = 14.7^{+4.6}_{-4.0}$$

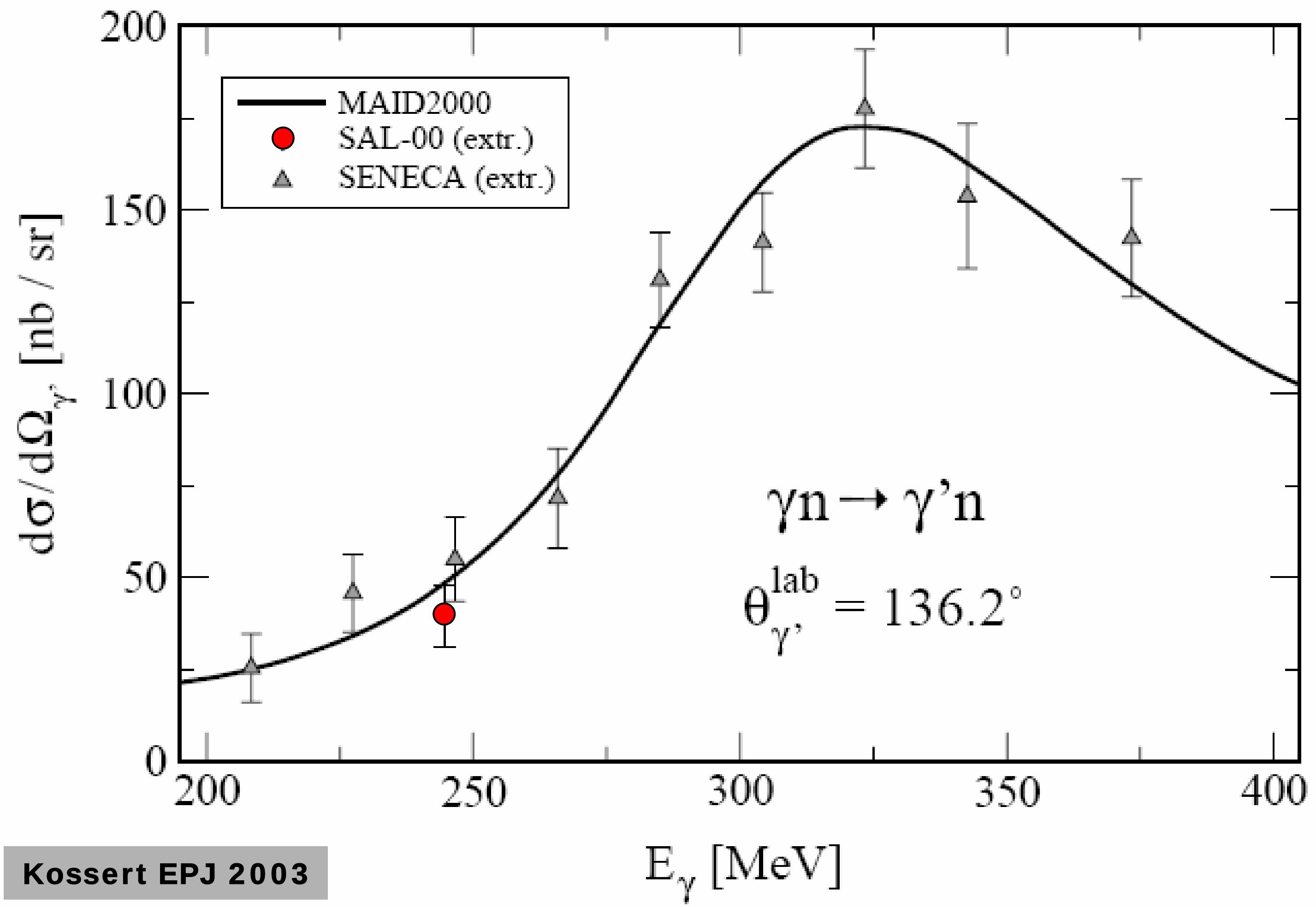
Wissmann 04

$$(\alpha-\beta)_n \approx 9.8$$





Quasi-Free Compton Scattering



Kossert EPJ 2003

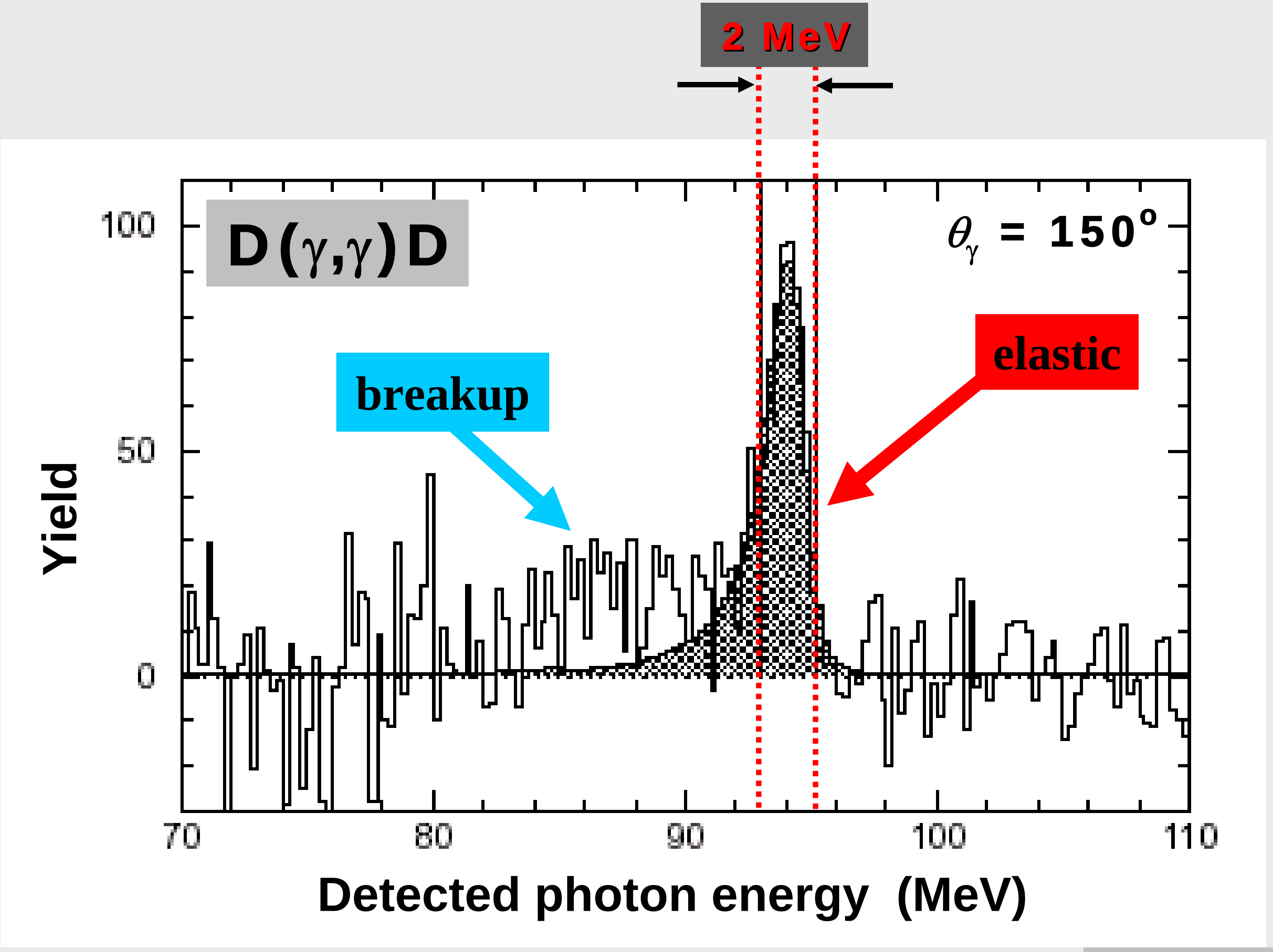
$$\alpha_n = 12.5 \pm 1.8(\text{stat})\ ^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model})$$

$$\beta_n = 2.7 \mp 1.8(\text{stat})\ ^{+0.6}_{-1.1}(\text{syst}) \mp 1.1(\text{model})$$

Elastic Compton Scattering on D

- Motivation
  - ***sum*** of proton and neutron polarizabilities
  - $\sigma_D(\omega) \approx r_0^2 - 2\, r_0\, \boldsymbol{(\alpha_p + \alpha_n)}\, \omega^2$
- Requirements
  - must separate ***elastic*** from *breakup*!
    - ✓ monoenergetic (tagged) photons
    - ✓ high-resolution photon detector ($\Delta E/E$ < 2% at 100 MeV)
- Data
  - Lucas – Illinois (1994) E_γ = 49, 69 MeV
  - Hornidge – SAL (2000) E_γ = 85-105 MeV
  - Lundin – Lund (2003) E_γ = 55, 66 MeV
- Theory
  - diagrammatic approach (Levchuk/L'vov)
  - EFT (Hildebrandt, Griesshammer, Hemmert, Phillips,...)

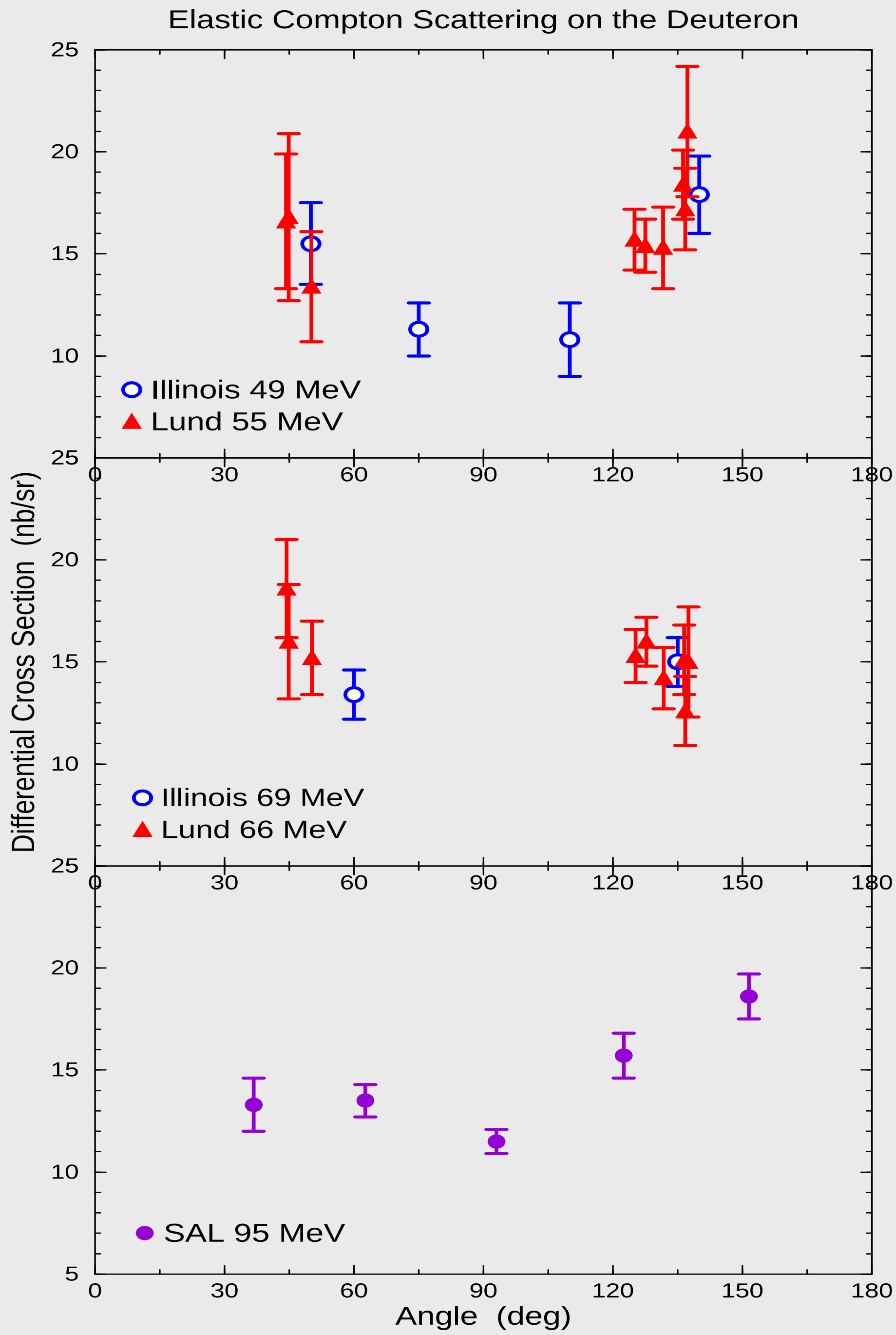
Photon Energy Spectrum



Hornidge PRL 2000

World Data Set

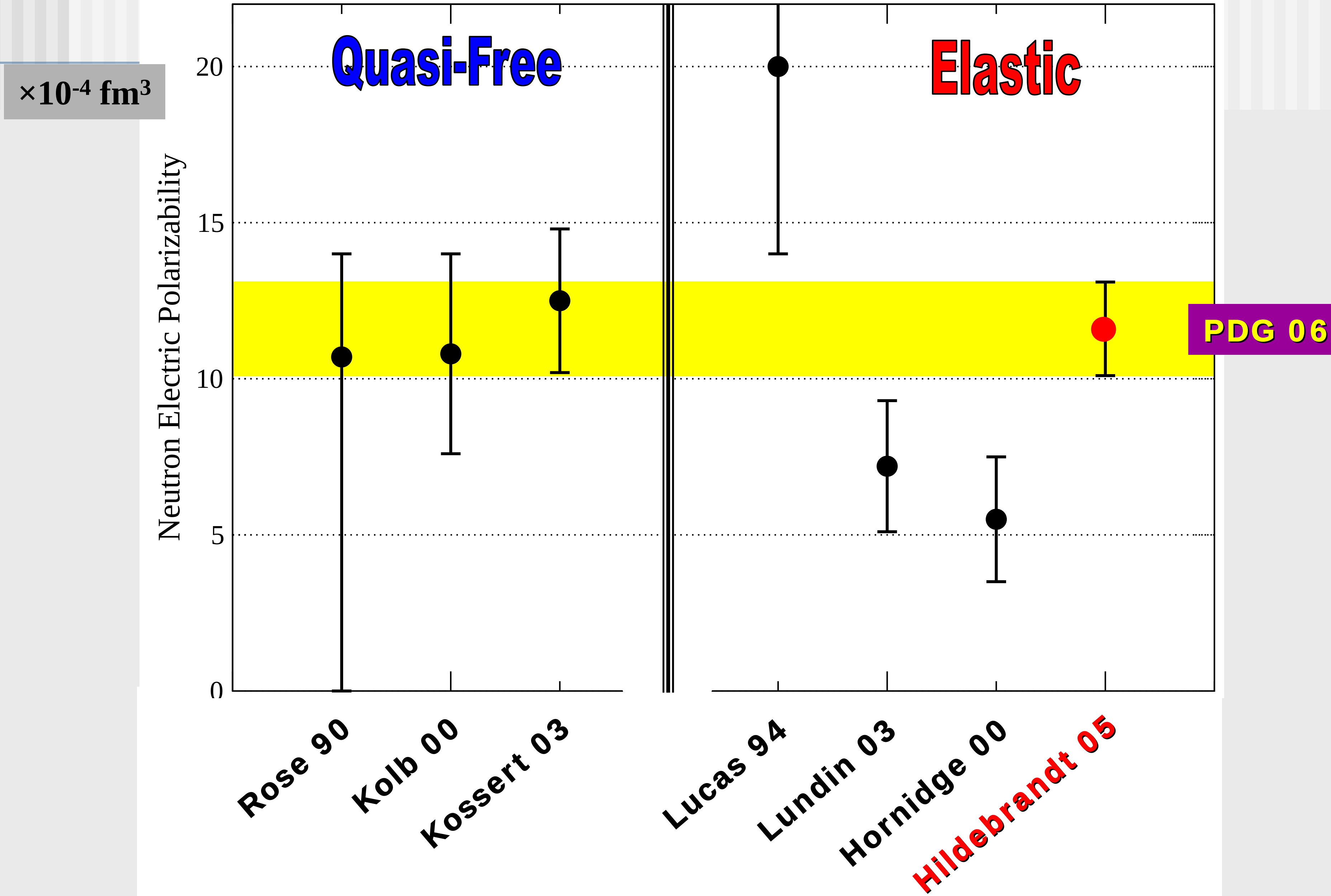
- **Lucas – Illinois (1994)**
  E_{γ} = 49, 69 MeV
- **Hornidge – SAL (2000)**
  E_{γ} = 85-105 MeV
- **Lundin – Lund (2003)**
  E_{γ} = 55, 66 MeV



Elastic Data “Issues”

- energy width of bins is too large
- statistics rarely less than 7%
- sparse coverage in energy and angle

	Energy Range	Energy Bin Width	Statistical	Systematic
Hornidge	85-105	20	5.2-9.8%	4.8-6.4%
Lundin	55, 66	10, 10	7.5-24.4%	6.5-14.3%
Lucas	49, 69	6.5, 7.7	4.2-12.6%	3.6-4.0%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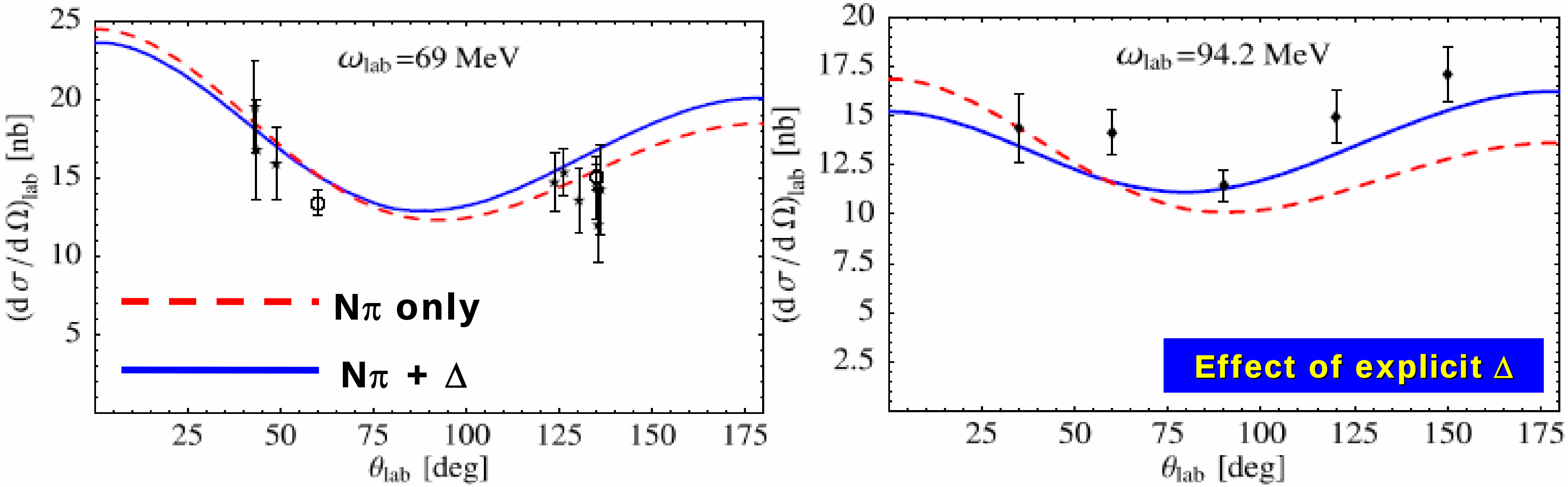
PDG 06
Rose 90
Kolb 00
Kossert 03
Lucas 94
Lundin 03
Hornidge 00
Hildebrandt 05

Hildebrandt EFT Calculations

- Improvements over previous calculations
  - EFT with nucleons, pions and also explicit $\Delta(1232)$
    - treat Δ by power-counting rules of Small Scale Expansion
    - strong paramagnetic M1 coupling of photon to $N \rightarrow \Delta$ transition
  - two-nucleon Green's function method (gauge invariance)
  - deuteron wave functions from latest NN potentials
  - Siegert's theorem for photon coupling (static limit)
- Successes of the present theory
  - good description of data over all energies (49-95 MeV)
    - simultaneously fits "low" and "high" energy regimes
    - reproduces back-angle behavior at 95 MeV
  - recovery of Thomson (static) limit as $E \rightarrow 0$
  - very little dependence on deuteron wave function
  - consistent theory can extend to 110-120 MeV (future data)

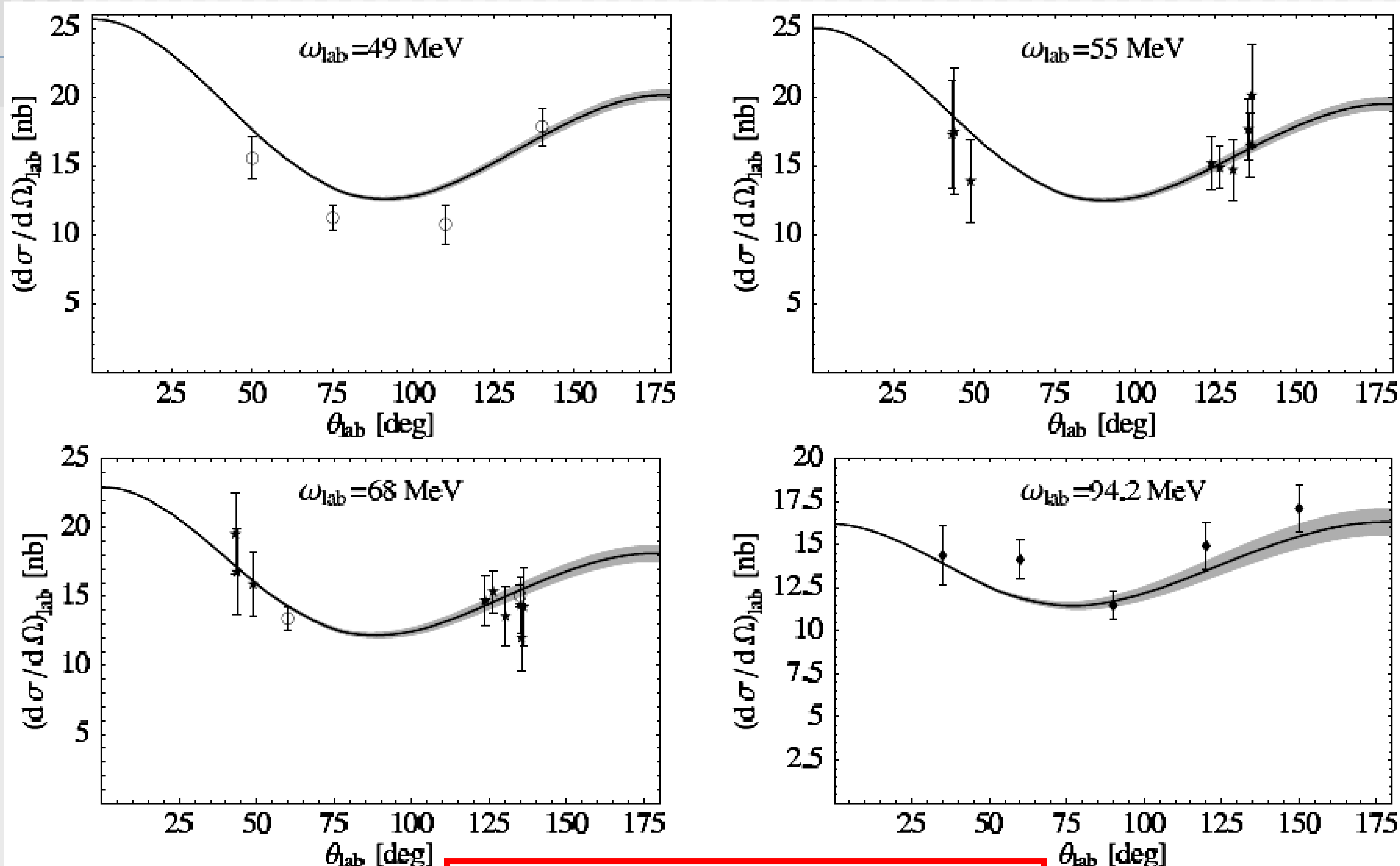
Hildebrandt EFT Calculations



Hildebrandt NPA 2004

- adding the Δ raises back-angle cross section
  - contributes M1 strength
  - without it, β comes out anomalously large
- reduced effect at lower energies

Hildebrandt EFT Calculations



$$\alpha_E^n\Big|_{\text{Baldin}} = (11.6 \pm 1.5\,(\text{stat}) \pm 0.6\,(\text{Baldin}))$$

$$\beta_M^n\Big|_{\text{Baldin}} = (3.6 \mp 1.5\,(\text{stat}) \pm 0.6\,(\text{Baldin}))\cdot$$

Hildebrandt Ph.D. thesis 2005

Summary of Neutron Results

- Neutron scattering
  - Schmiedmayer (91)

$$\alpha_n = 12.6 \pm 1.5(\text{stat}) \pm 2.0(\text{syst})$$

- Quasi-free Compton scattering
  - Kossert (03)

$$\alpha_n = 12.5 \pm 1.8(\text{stat}) \,{}^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model})$$

$$\beta_n = 2.7 \mp 1.8(\text{stat}) \,{}^{+0.6}_{-1.1}(\text{syst}) \mp 1.1(\text{model})$$

- Elastic Compton scattering
  - data from Lucas (94), Hornidge (00), Lundin (03)
  - global fit by Hildebrandt (05)

$$\alpha_n = 11.6 \pm 1.5\ (\text{stat}) \pm 0.6\ (\text{Baldin})$$

$$\beta_n = 3.6 \mp 1.5\ (\text{stat}) \mp 0.6\ (\text{Baldin})$$

We can do better . . .

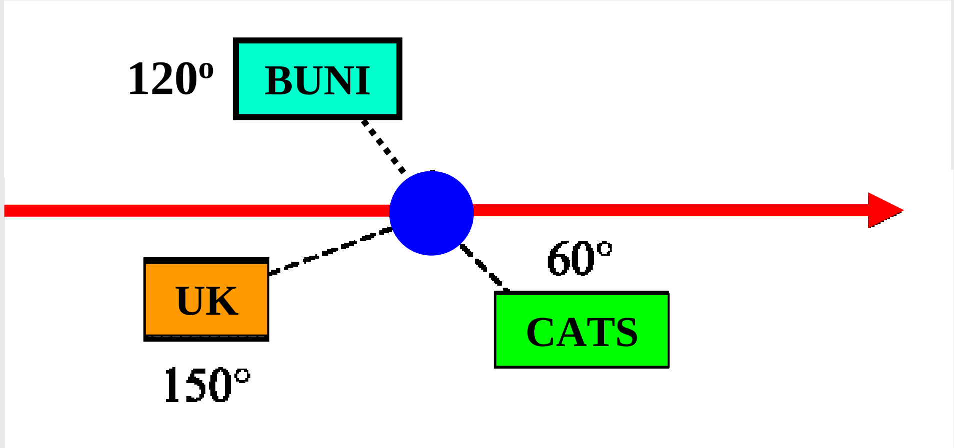
Elastic Compton Scattering from Deuterium at E_γ = 60-115 MeV

Compton@MAX-Lab Collaboration

- George Washington University
  - Jerry Feldman
  - Daniel Mittelberger (undergrad)
- Lund University
  - Bent Schroder
  - Lennart Isaksson
  - Kevin Fissum
  - Mattias Andersson
  - Magnus Lundin
  - Kurt Hansen
- University of Illinois
  - Alan Nathan
  - Luke Myers
- University of Kentucky
  - Mike Kovash
- Duke University
  - Henry Weller
  - Seth Henshaw
  - Sean Stave
- University of Glasgow
  - John Annand

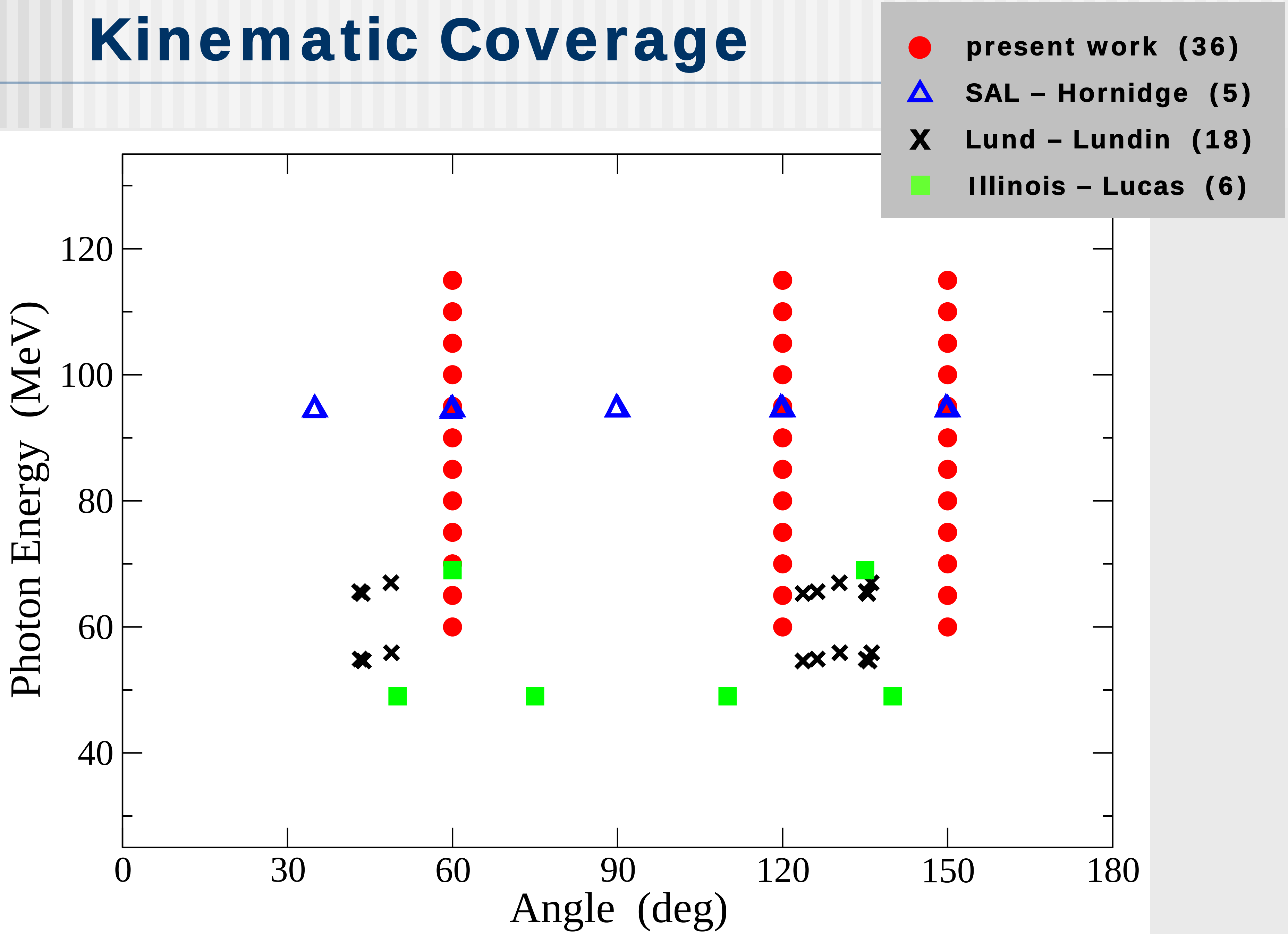
Experiment at Lund

- energies: **E_γ = 60-115 MeV using tagged photons**
  - two tagger settings: 115-95 and 97-60 MeV
  - bin data in 5 MeV energy bins (with 5% statistics)
- angles: **θ_γ = 60°, 120°, 150°**
  - with 3 NaI detectors simultaneously
- detectors: 3 large-volume (50 cm × 50 cm) NaI's
  - excellent photon energy resolution ($\Delta E_\gamma / E_\gamma$ ~ 2%)



BUNI: Boston Univ.
CATS: Mainz Univ.
UK: Univ. of Kentucky

Kinematic Coverage



Polarizability Uncertainty

- Calculate error bar for α-β based on statistics (3.1%)
  - each entry represents error for one energy/angle point
  - error decreases at back angles and at higher energy

Energy		60	65	70	75	80	85	90
Angle		$\Delta(\alpha$-$\beta)$	$\Delta(\alpha$-$\beta)$	$\Delta(\alpha$-$\beta)$	$\Delta(\alpha$-$\beta)$	$\Delta(\alpha$-$\beta)$	$\Delta(\alpha$-$\beta)$	$\Delta(\alpha$-$\beta)$
60°		30.1	25.9	22.5	19.7	17.4	15.4	13.7
90°		7.6	6.7	6.0	5.4	5.0	4.6	4.3
150°		3.8	3.4	3.1	2.8	2.6	2.4	2.3

Overall uncertainty $\Delta(\alpha$-$\beta)$ = 0.96

21 data pts

proton: $\alpha_p - \beta_p = 10.5 \pm 0.9(\text{stat.} + \text{syst.}) \pm 0.7(\text{mod.})$

Polarizability Uncertainty

- Compare several angle configurations
  - one vs. two sets of angles
  - statistics varying from 3% (good) to 10% (bad)

Statistics		3%	5%	10%
Angles		$\Delta(\alpha-\beta)$	$\Delta(\alpha-\beta)$	$\Delta(\alpha-\beta)$
60, 90, 150		0.93	1.57	3.11
60, 135, 150		0.77	1.28	2.56
45, 60, 90, 120, 150		0.75	1.25	2.49

for central value of $\alpha-\beta$ = **20.2**

proton: $\alpha_p - \beta_p = 10.5 \pm 0.9(\text{stat.} + \text{syst.}) \pm 0.7(\text{mod.})$

Summary

- Present situation for the neutron is not satisfactory
  - neutron scattering results are questionable
  - only one precise quasi-free Compton result
  - elastic Compton data are sparse, with large error bars

- New elastic Compton scattering program (Lund)
  - expand data set in energy and angular coverage
  - improve energy resolution per data point (ΔE_{γ} = 5 MeV)
  - confirm 100 MeV data
  - first data at 70-90 MeV
  - **determine neutron polarizabilities to match proton precision**
  - **production runs in Nov. 2007 and June 2008 (now!)**