THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON DC

Manifestations of Neutron Spin Polarizabilities in Compton Scattering on d and He-3

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Supported by US-DOE

Focus

- Neutron Spin Polarizabilities
- Neutron- particularly challenging
- Polarizabilities- EM properties- Compton Scattering
  - Polarization observables in Compton Scattering on d and He-3
- Chiral Perturbation Theory (χPT)- pions and nucleons- $\omega \sim m_\pi$

Polarizabilities

LO:

$$H = \frac{(\vec{p} - e\vec{A})^2}{2m} + e\phi$$

$$\mathrm{Amp} = -\frac{Z^2 e^2}{M}\hat{\epsilon}\cdot\hat{\epsilon}'$$

NLO:

$$H_{eff} = -\frac{1}{2}4\pi\alpha_E\vec{E}^2 - \frac{1}{2}4\pi\beta_M\vec{H}^2$$

$$\vec{p} = -\frac{\delta H_{eff}}{\delta\vec{E}} = 4\pi\alpha_E\vec{E}; \quad \vec{\mu} = -\frac{\delta H_{eff}}{\delta\vec{H}} = 4\pi\beta_M\vec{H}$$

$$\mathrm{Amp} = \hat{\epsilon}\cdot\hat{\epsilon}'\left(-\frac{Z^2e^2}{M} + \omega\omega'\,4\pi\bar{\alpha}_E\right) + \hat{\epsilon}\times\hat{k}\cdot\hat{\epsilon}'\times\hat{k}'\,\omega\omega' 4\pi\bar{\beta}_M + \mathcal{O}(\omega^4)$$

NNLO:

$$H^{(3)}_{eff} = -\frac{1}{2}4\pi(\gamma^p_{E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma^p_{M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} - 2\gamma^p_{E2}E_{ij}\sigma_i H_j + 2\gamma^p_{M2}H_{ij}\sigma_i E_j)$$

where

$$E_{ij} = \frac{1}{2}(\nabla_i E_j + \nabla_j E_i), \quad H_{ij} = \frac{1}{2}(\nabla_i H_j + \nabla_j H_i)$$

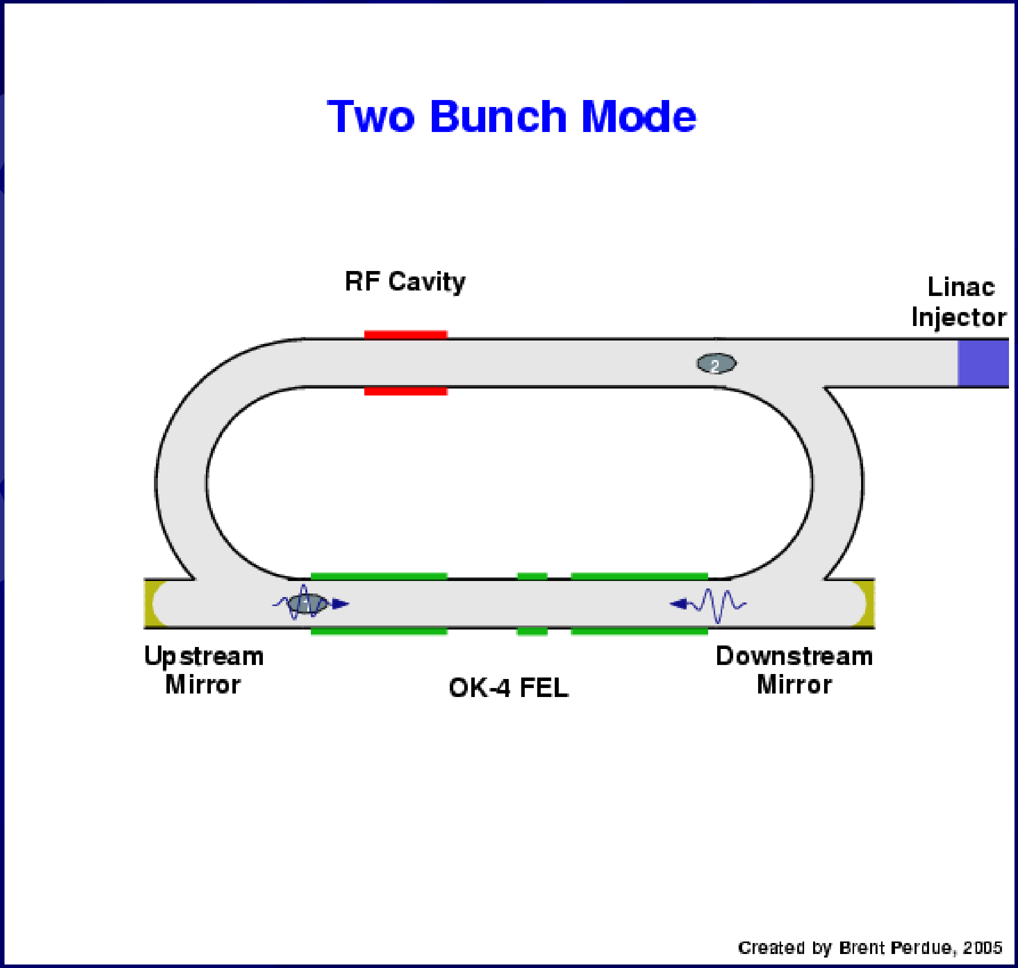
State of affairs

- Proton
  - Proton EM polarizabilities are well established.

$$\alpha_p = (12.0 \pm 0.7) \times 10^{-4}\ fm^3 \qquad \beta_p = (1.6 \pm 0.6) \times 10^{-4}\ fm^3$$

  - Spin polarizabilities less known (only γ_0 and γ_π)
- Neutron still remains elusive
  - Even electric and magnetic polarizabilities not known to desired accuracy
  - Spin polarizabilities less known (only γ_0 and γ_π)
  - Problems:
    - Neutron charge = 0
    - Lifetime ~887 secs
- Experiments @ HIγS

HIγS @ TUNL



- Circularly polarized photons
- 10^8 γ/sec

Thus, we study

Compton Scattering

on

Light Nuclei (d & He-3)

at

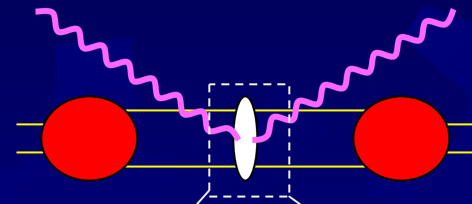
Low Energies ($E \sim m_\pi$)

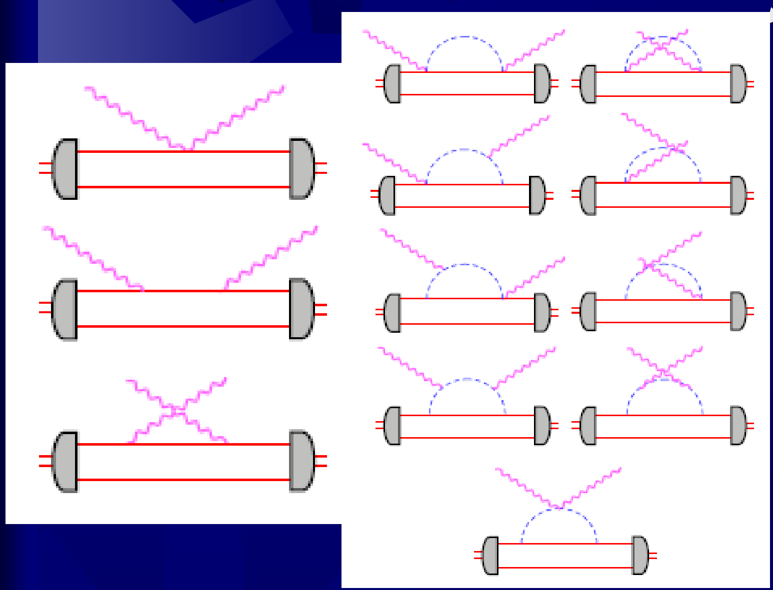
using

HBχPT(upto $O(Q^3)$)

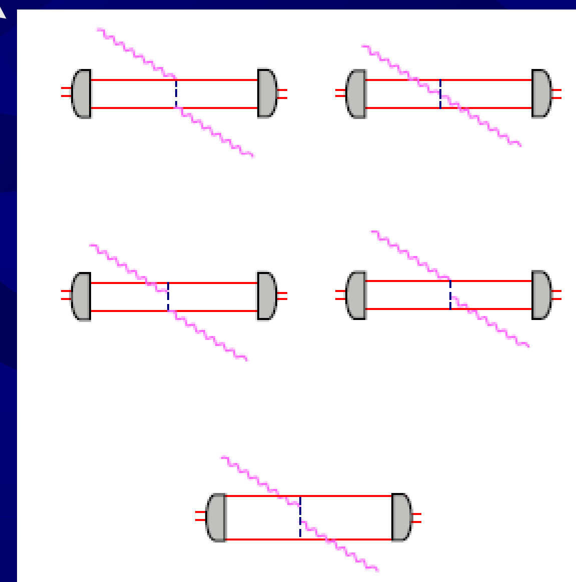
$\gamma d \rightarrow \gamma d$

DC, D.Phillips
(PRC 71, 044002)





$$T^{1B}_{\gamma NN} + T^{2B}_{\gamma NN}$$
$$\downarrow$$
$$T_{\gamma NN}$$

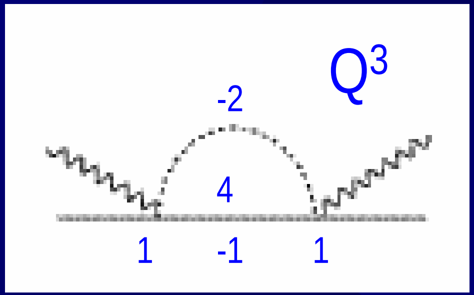


$$A \propto \int \frac{d^3p\, d^3p'}{(2\pi)^6} \left\langle \Psi'_d \left| T_{\gamma NN} \right| \Psi_d \right\rangle$$

&

$$\frac{d\sigma}{d\Omega} \propto \left| A \right|^2$$

The scattering amplitude



- $T_{\gamma NN}$ has a chiral expansion.
  - Naïve dimensional analysis-
    - Q^n for a vertex with n powers of p or m_π
    - Q^{-2} for pion propagator ($1/(p^2-m_\pi^2)$)
    - Q^{-1} for nucleon propagator ($1/(E-p^2/2M)$)
    - Q^4 for loop (loop integral)
    - Q^3 for a two-body diagram ($\delta^3(p_2'-p_2)$ absent)

- The wavefunctions are derived from potential model or chiral potential.

How do the polarizabilites enter into the calculations?

- At $O(Q^3)$ the calculations are predictive.

$$T^{1B} = \sum_{i=1}^{6} A_i t_i$$

$$A_1 = -\frac{Z^2}{M} + (\alpha + \beta\cos\theta)\omega^2 + (\Delta\alpha + \Delta\beta\cos\theta)\omega^2$$

$$A_2 = \frac{Z^2}{M}\omega + \beta\omega^2 + \Delta\beta\omega^2$$

$$A_3 = \frac{\omega}{2M^2}[Z(Z+2\kappa) - (Z+\kappa)\cos\theta] + A_3^{\pi^0} + \omega^3(\gamma_1 - (\gamma_2 + 2\gamma_4)\cos\theta)$$
$$+\omega^3(\Delta\gamma_1 - (\Delta\gamma_2 + 2\Delta\gamma_4)\cos\theta)$$

$$A_4 = -\frac{(Z+\kappa)^2\omega}{2M^2} + \omega^3\gamma_2 + \omega^3\Delta\gamma_2$$

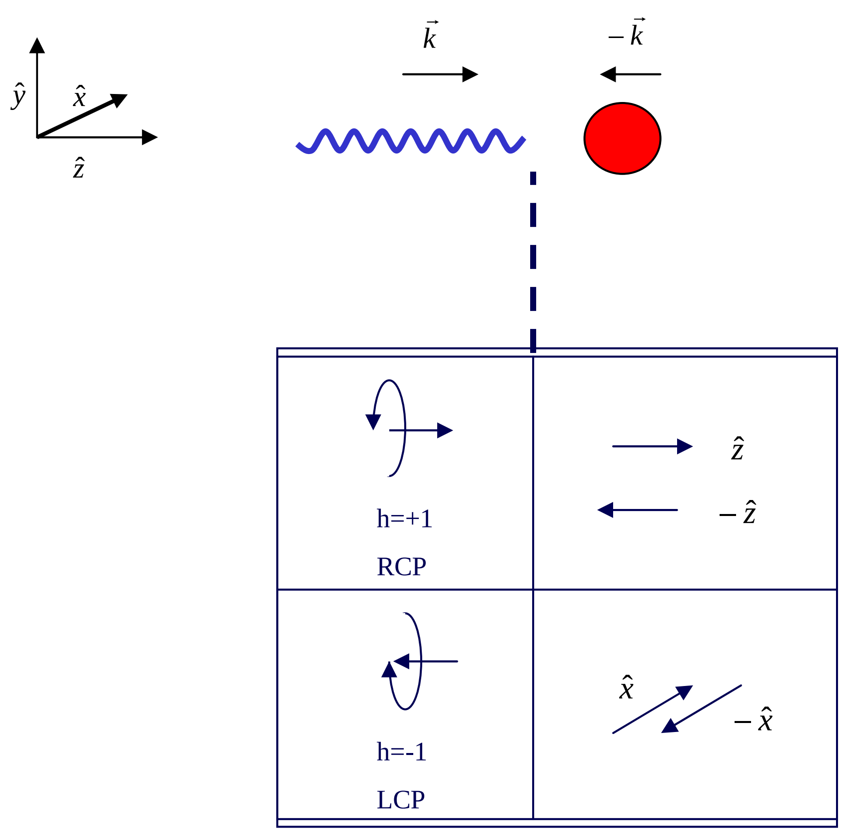
$$A_5 = \frac{(Z+\kappa)^2\omega}{2M^2} + A_5^{\pi^0} + \omega^3\gamma_4 + \omega^3\Delta\gamma_4$$

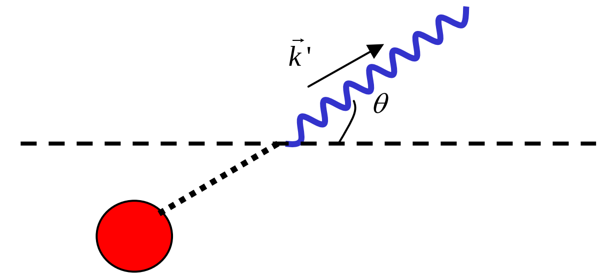
$$A_6 = -\frac{Z(Z+\kappa)\omega}{2M^2} + A_6^{\pi^0} + \omega^3\gamma_3 + \omega^3\Delta\gamma_3$$

$$\alpha_p = \alpha_n = 12.2\times10^{-4}\ fm^3$$
$$\beta_p = \beta_n = 1.2\times10^{-4}\ fm^3$$
$$\gamma_{1p} = \gamma_{1n} = 4.4\times10^{-4}\ fm^4$$
$$\gamma_{2p} = \gamma_{2n} = 2.2\times10^{-4}\ fm^4$$
$$\gamma_{3p} = \gamma_{3n} = 1.1\times10^{-4}\ fm^4$$
$$\gamma_{4p} = \gamma_{4n} = -1.1\times10^{-4}\ fm^4$$

BKM, PRL 67 1515

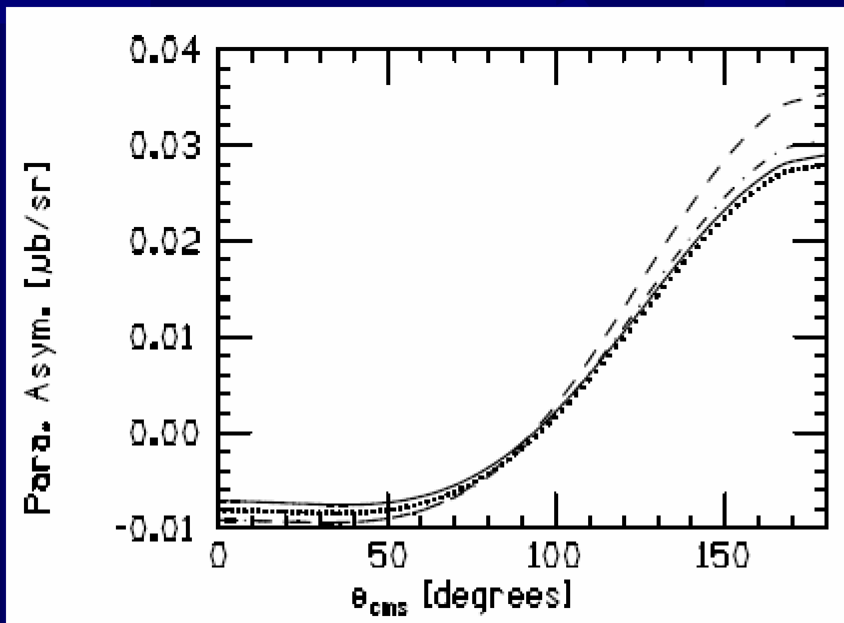
Observable (Double Polarization Asymmetries, Δ_z & Δ_x)

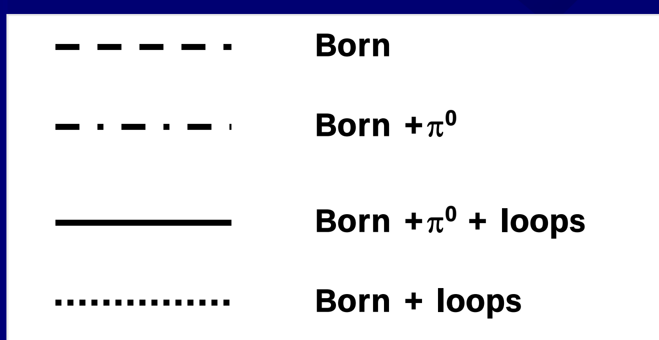




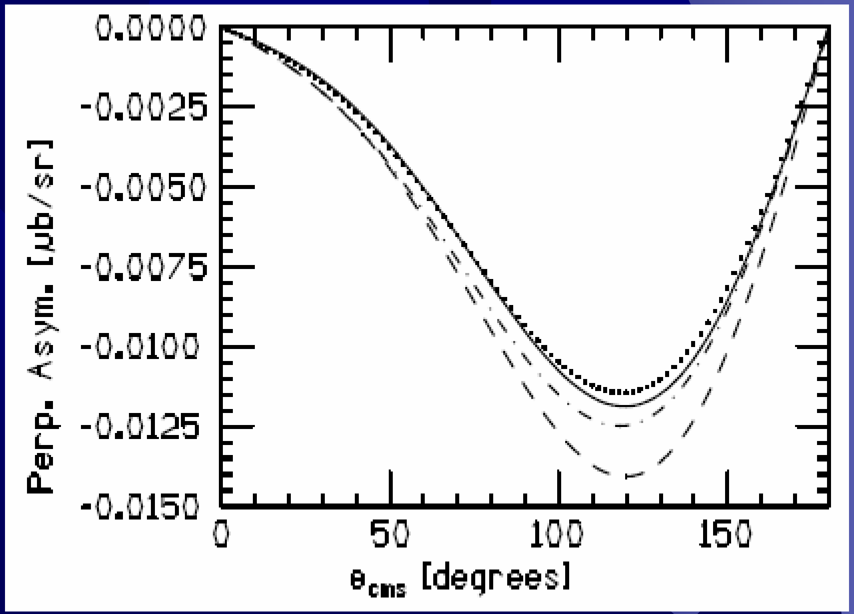
$$\left[\Delta_z = \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\downarrow}\right]_{h=\pm 1}$$

$$\left[\Delta_x = \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\rightarrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\leftarrow}\right]_{h=\pm 1}$$

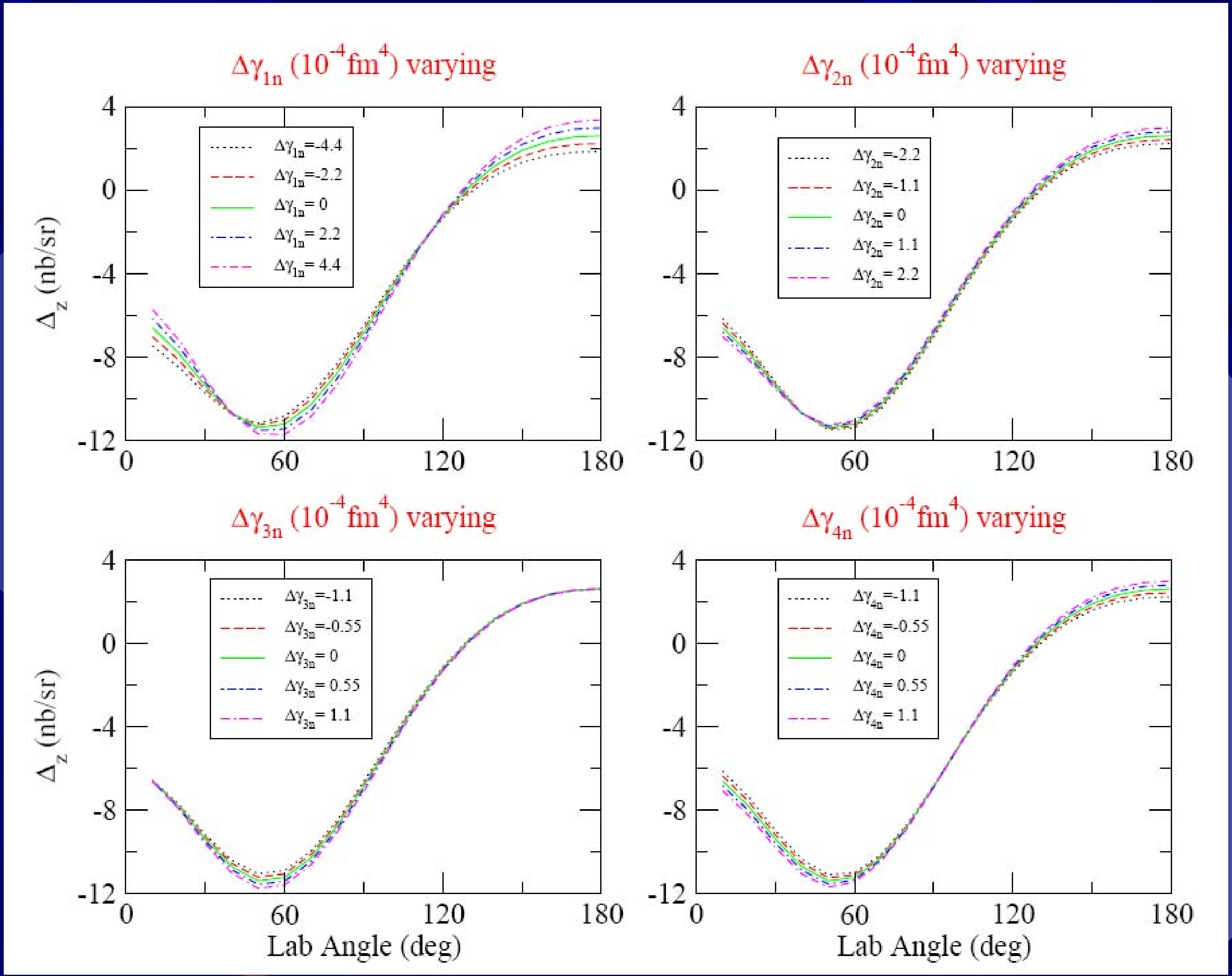




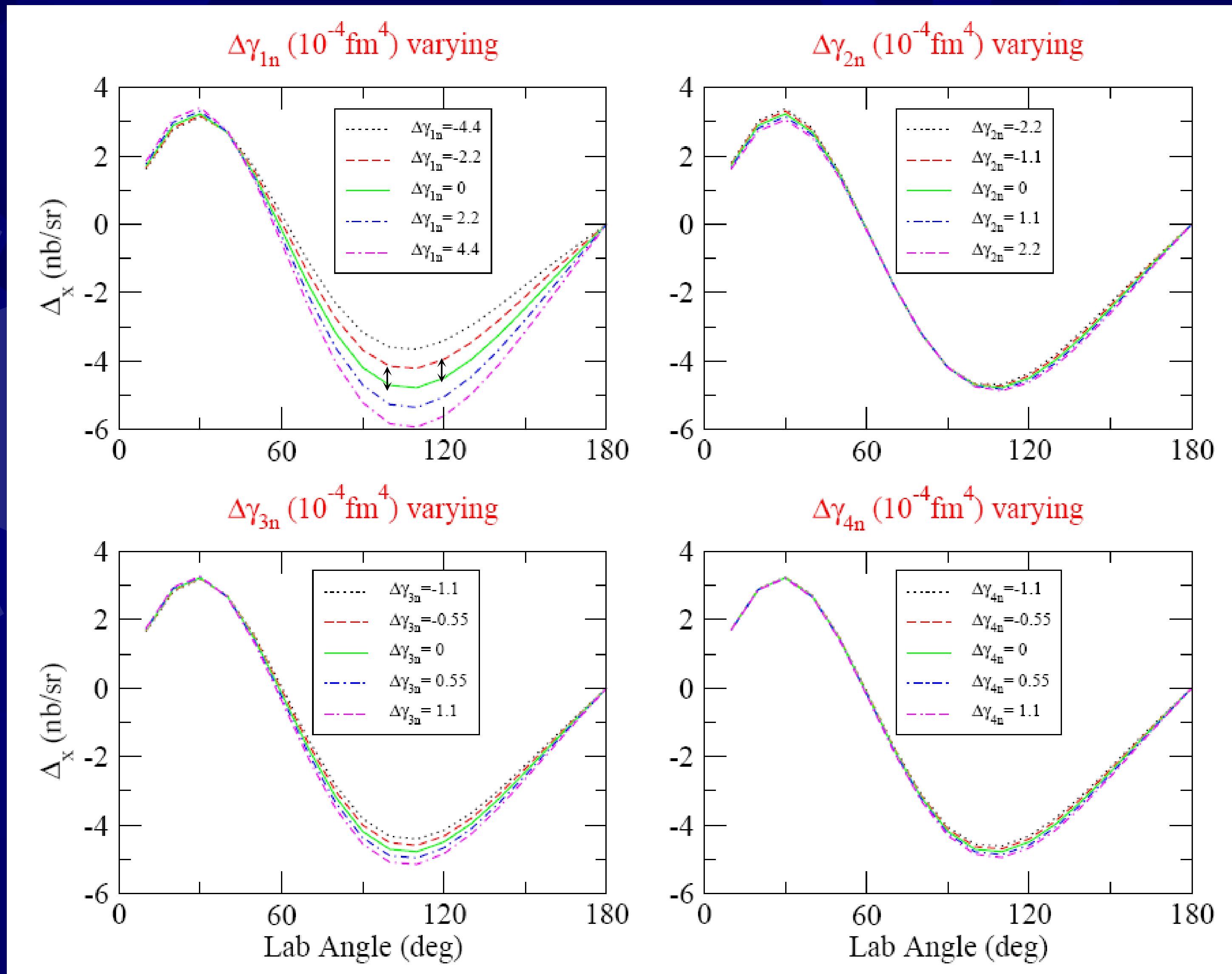
V. Bernard, N. Kaiser, Ulf-G. Meissner,
Int. J. of Mod. Phys. E4, 193



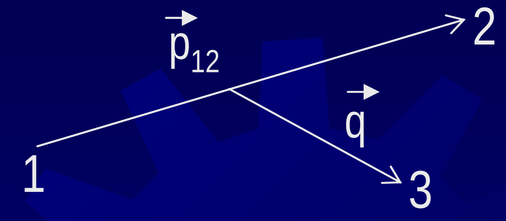
Effect of varying γ's on Δ_z at 135 MeV (lab)

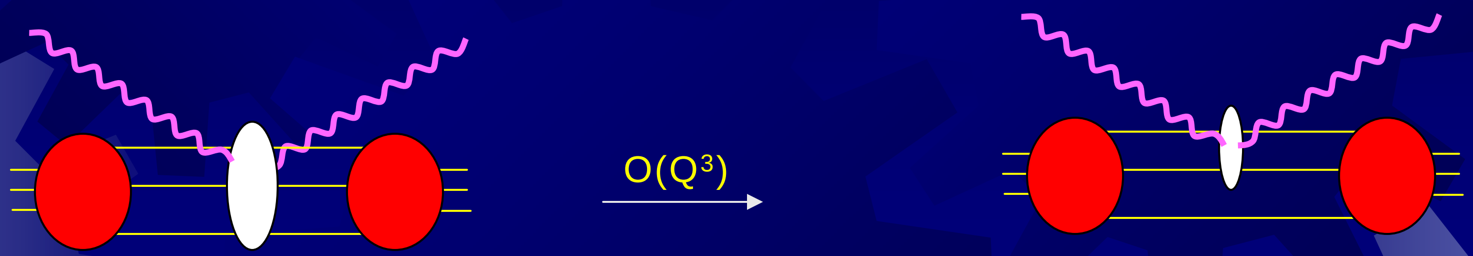


Effect of varying γ's on Δ_x at 135 MeV (lab)



$\gamma\,{}^3He \to \gamma\,{}^3He$





$$\int d^3p_{12}\,d^3p'_{12}\,d^3q\,d^3q'\langle\Psi'_{He}|\hat{O}|\Psi_{He}\rangle \xrightarrow{O(Q^3)} \int d^3p_{12}\,d^3p'_{12}\,d^3q\langle\Psi'_{He}|\hat{O}|\Psi_{He}\rangle$$

$$|\Psi_{He}\rangle \equiv |p_{12}\,q\,\alpha\rangle = |p_{12}\,q\,\alpha_J\rangle|\alpha_T\rangle$$

$$|\alpha_J\rangle = \left|(l_{12}s_{12})j_{12}m_{12};\left(l_3\,\frac{1}{2}\right)j_3m_3;(j_{12}\,j_3)JM\right\rangle$$

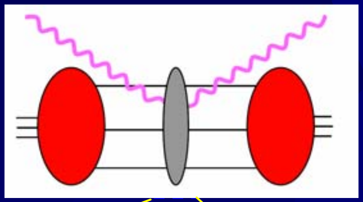
$$|\alpha_T\rangle = \left|\left(t_{12}\,\frac{1}{2}\right)TM_T\right\rangle$$

Wfns from A. Nogga

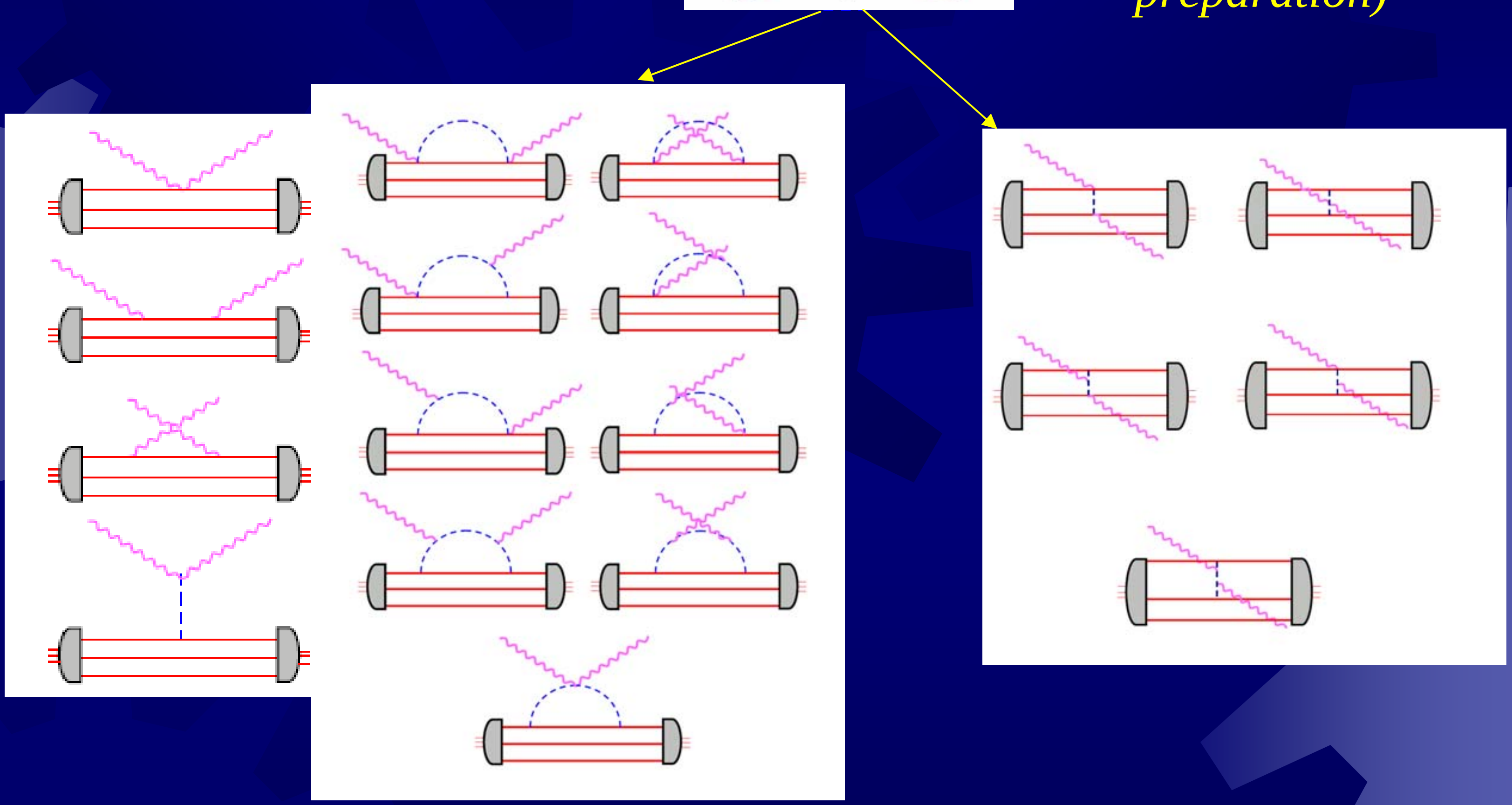
DC, A. Nogga, D. Phillips (submitted to PRL)

Anatomy of the Calculation

$$\gamma\,{}^{3}He \rightarrow \gamma\,{}^{3}He$$

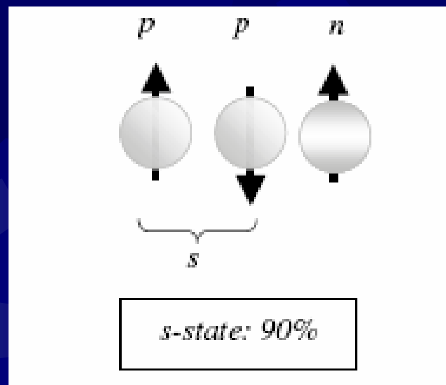


DC, D. Phillips, A. Nogga (in preparation)



$$T = T^{1B} + T^{2B}$$

Polarized He-3 is interesting!

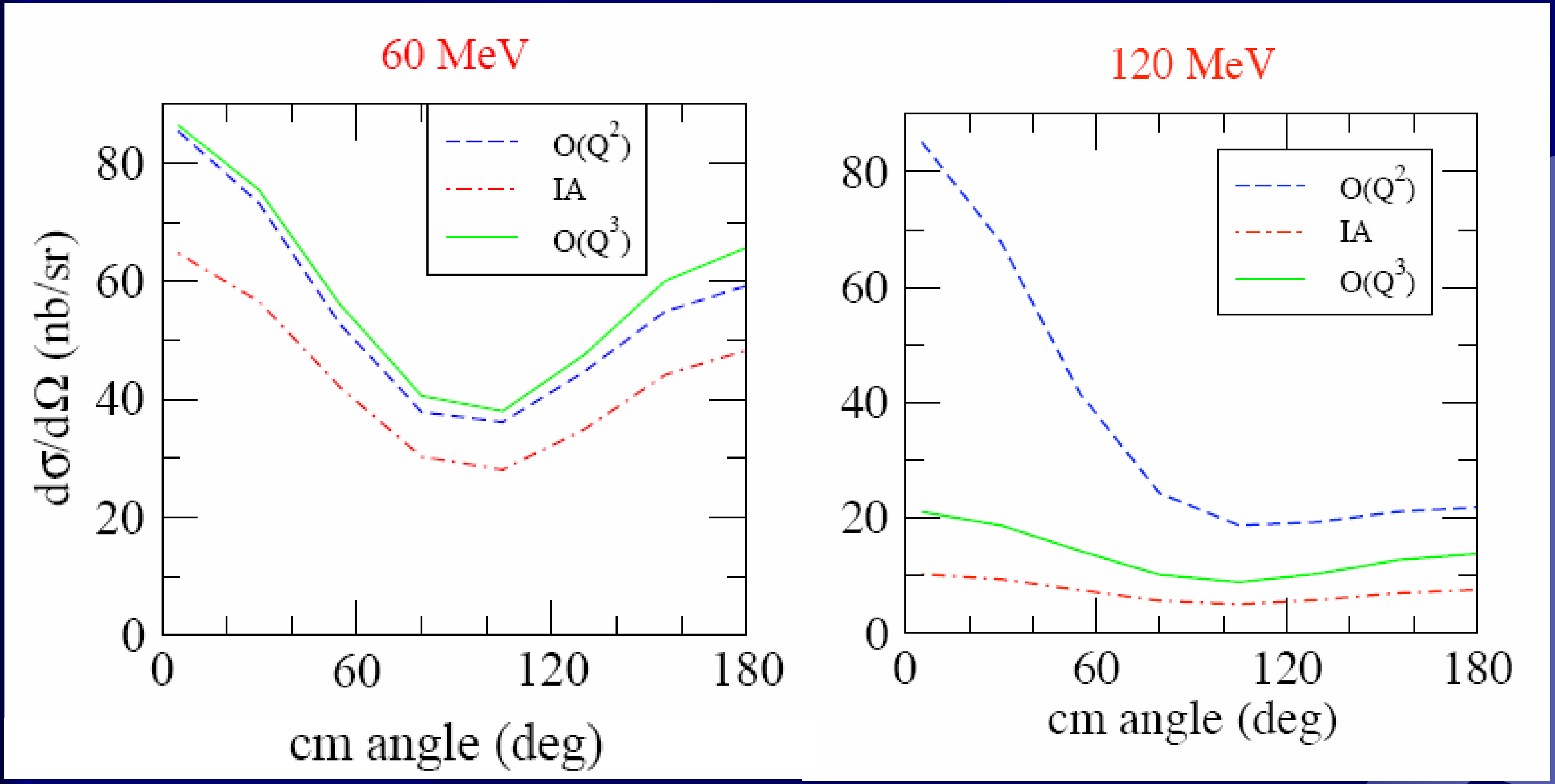


$$T_{\gamma^3He} = \sum_{i=1}^{6} A_i t_i ,$$

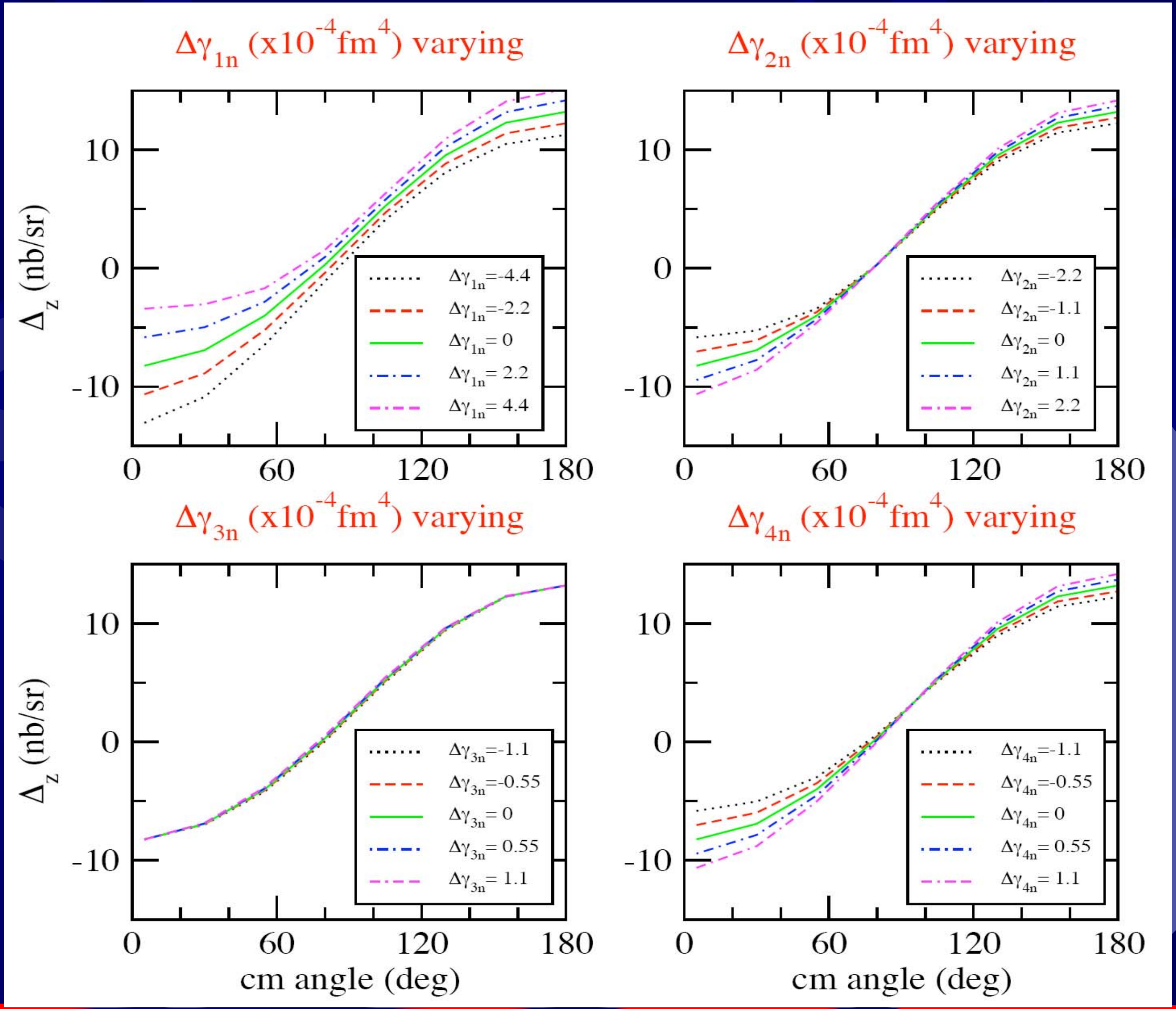
$$A_i \equiv A_i^{1B} + A_i^{2B}$$

- To the extent that polarized He-3 behaves as an "effective" neutron, contributions from $A_i^{2B}(i=3..6)$ are negligible
- $A_i^{1B} \sim A_i^{1B}\,(O(Q^3)) + \Delta A_i^{1B}$
  - $\Delta A_i^{1B} \sim \Delta A_i^{1B}(n)$

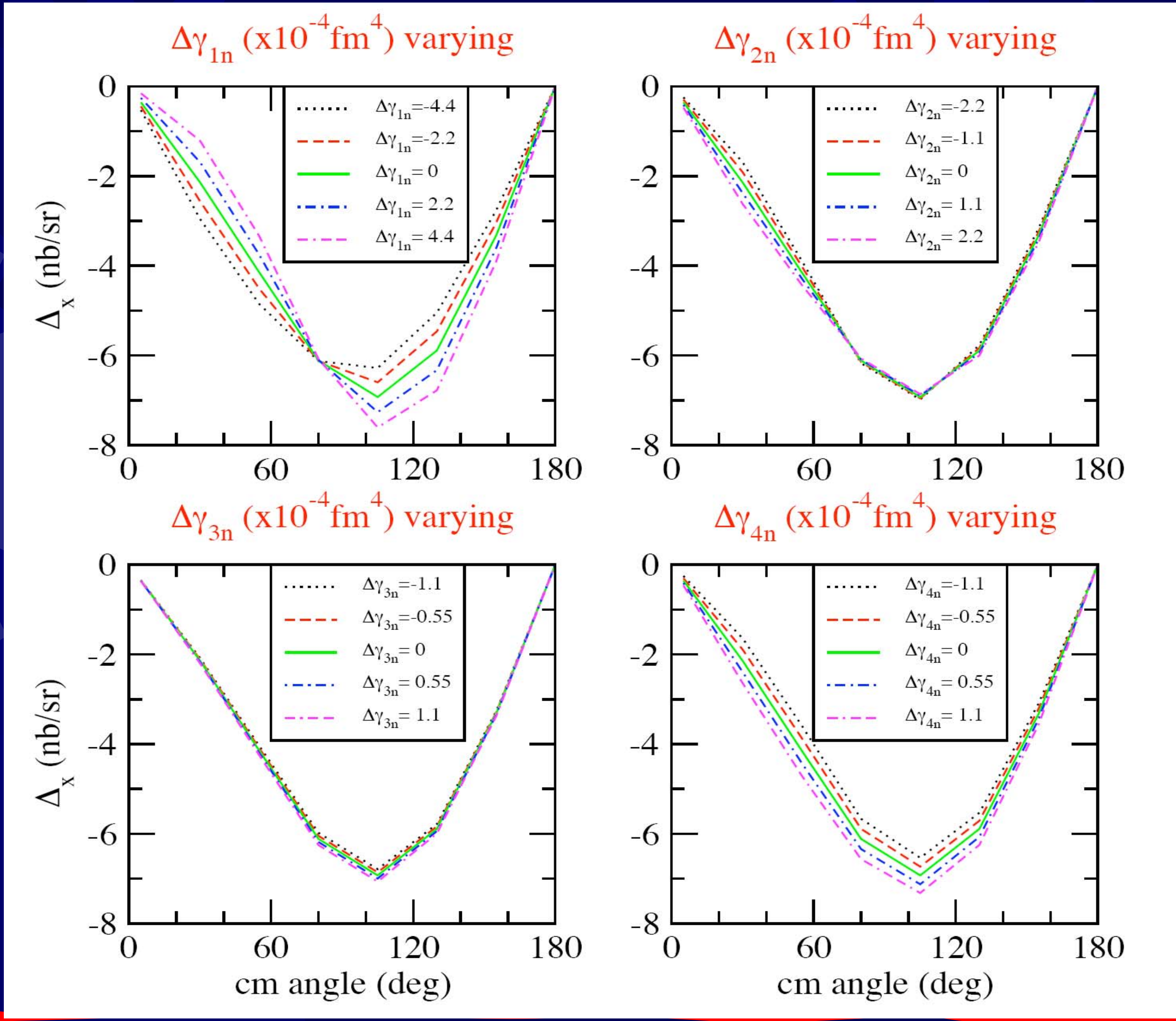
Comparison of dcs at different orders



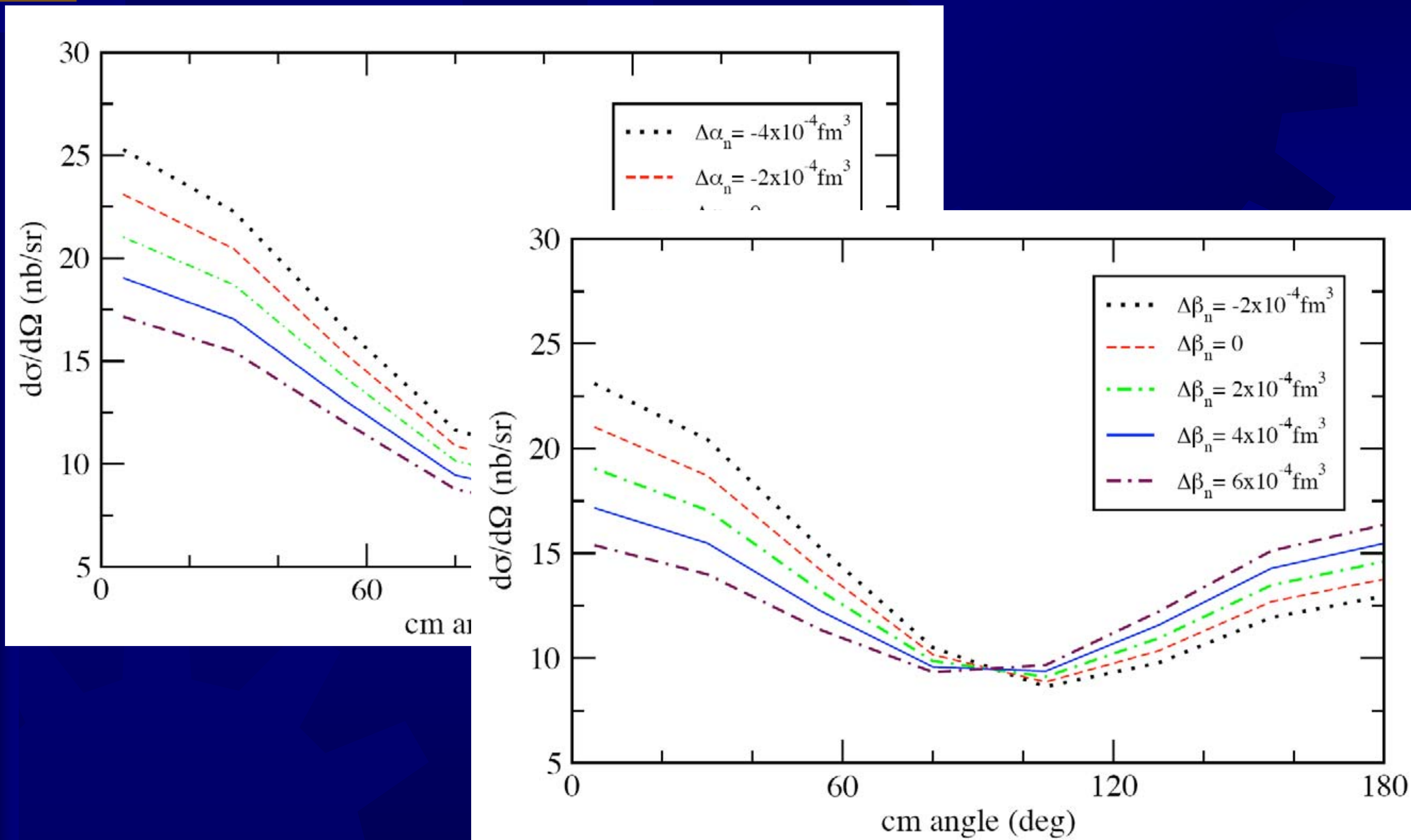
Δ_z vs cm angle at 120 MeV



Δ_x vs cm angle at 120 MeV



DCS vs cm angle at 120MeV (Effect of α_n and β_n)



Not so Simple!

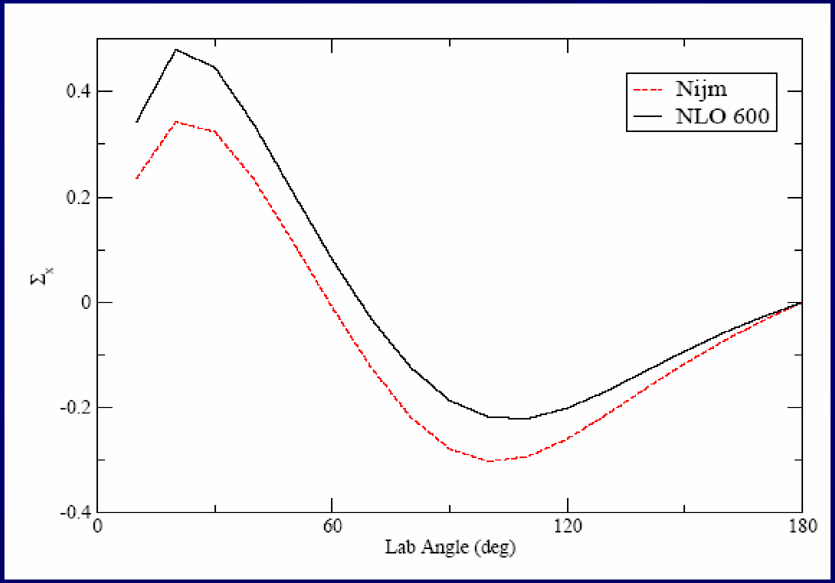
- Proton Spin polarizabilities not well known
  - Experiment scheduled at HIγS (R. Miskimen)
  - Measure double polarization observables for Compton scattering on proton.
- Neutron electric and magnetic polarizabilities not accurately known
  - Unpolarized Compton scattering experiment on d at MAXLab (Lund).

Theoretical Ambiguities

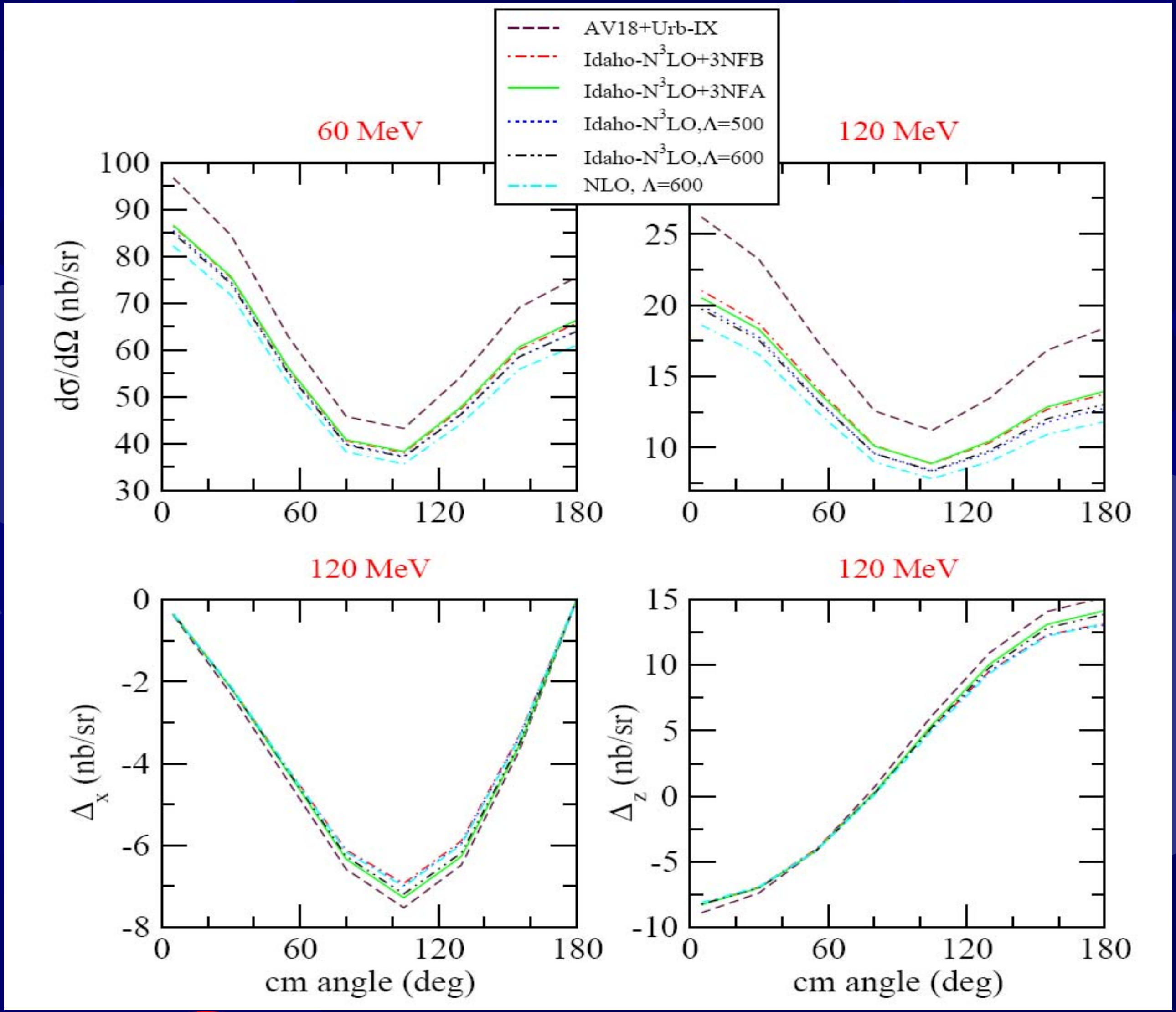
- Boost corrections (really small)
  - Included in d calculations.
  - Effect studied for He-3 calculations.
- Recoil corrections
  - Included in d calculations.
  - Effect studied for He-3.
- Wavefunction dependence
  - Studied for both d and He-3.
- Effect of the Delta
  - Collaborated with R. Hildebrandt for polarized γd
  - Needs to be done for γHe-3

Wavefunction Dependence

- For polarized γd calculation

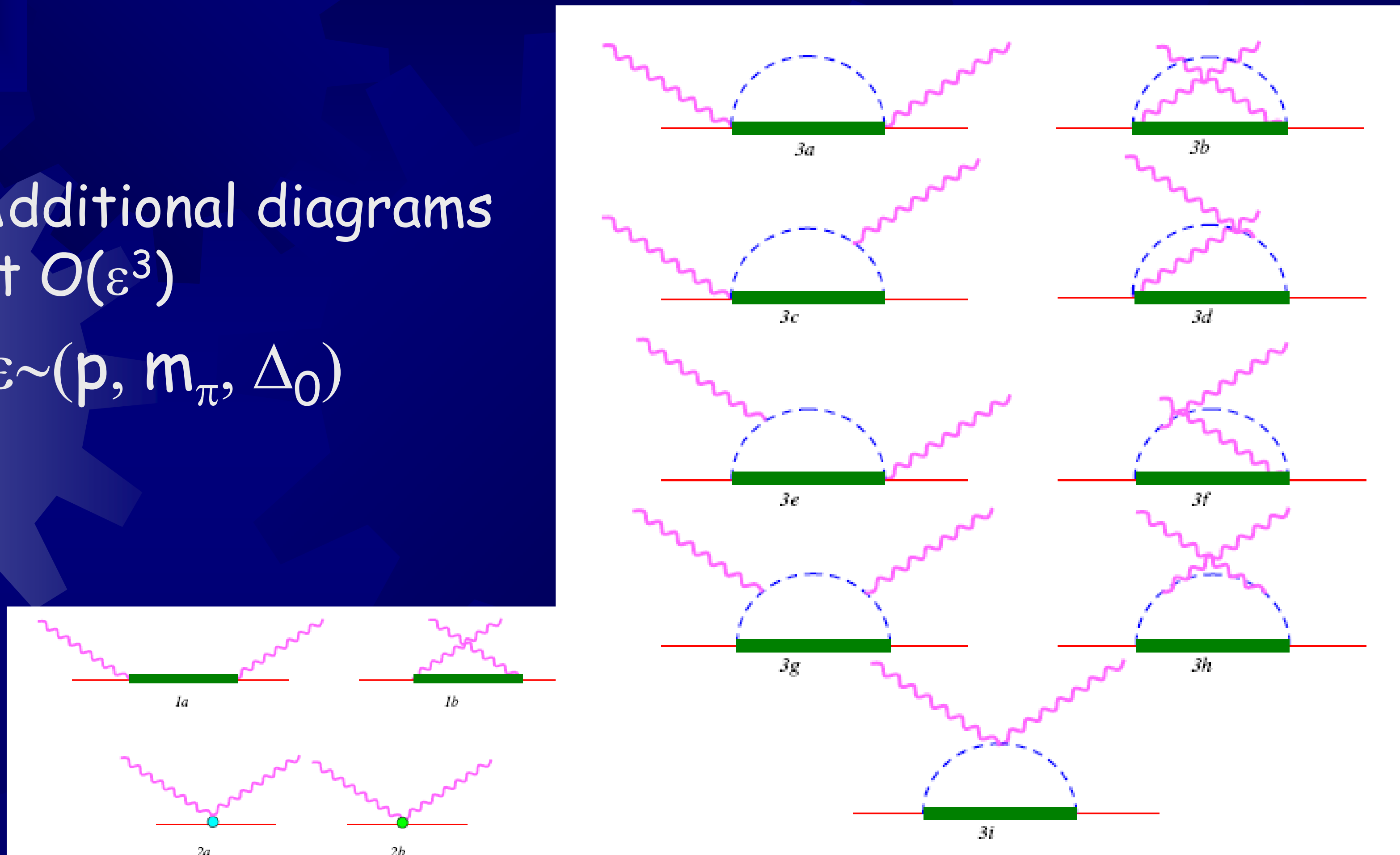


Wavefunction Dependence (γHe-3)



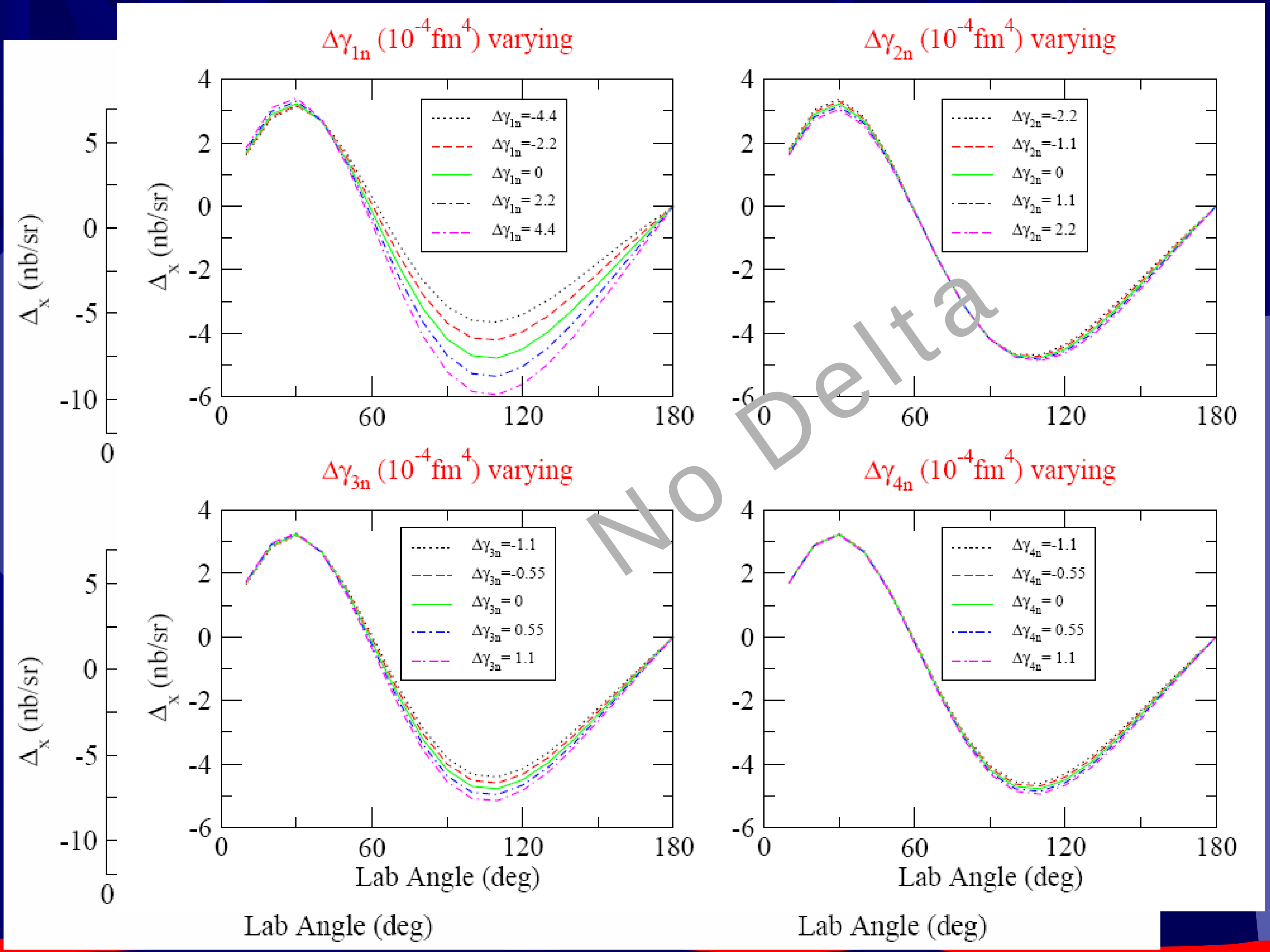
Effect of the Delta (R. Hildebrandt)

- Additional diagrams at $O(\varepsilon^3)$
- $\varepsilon \sim (p, m_\pi, \Delta_0)$

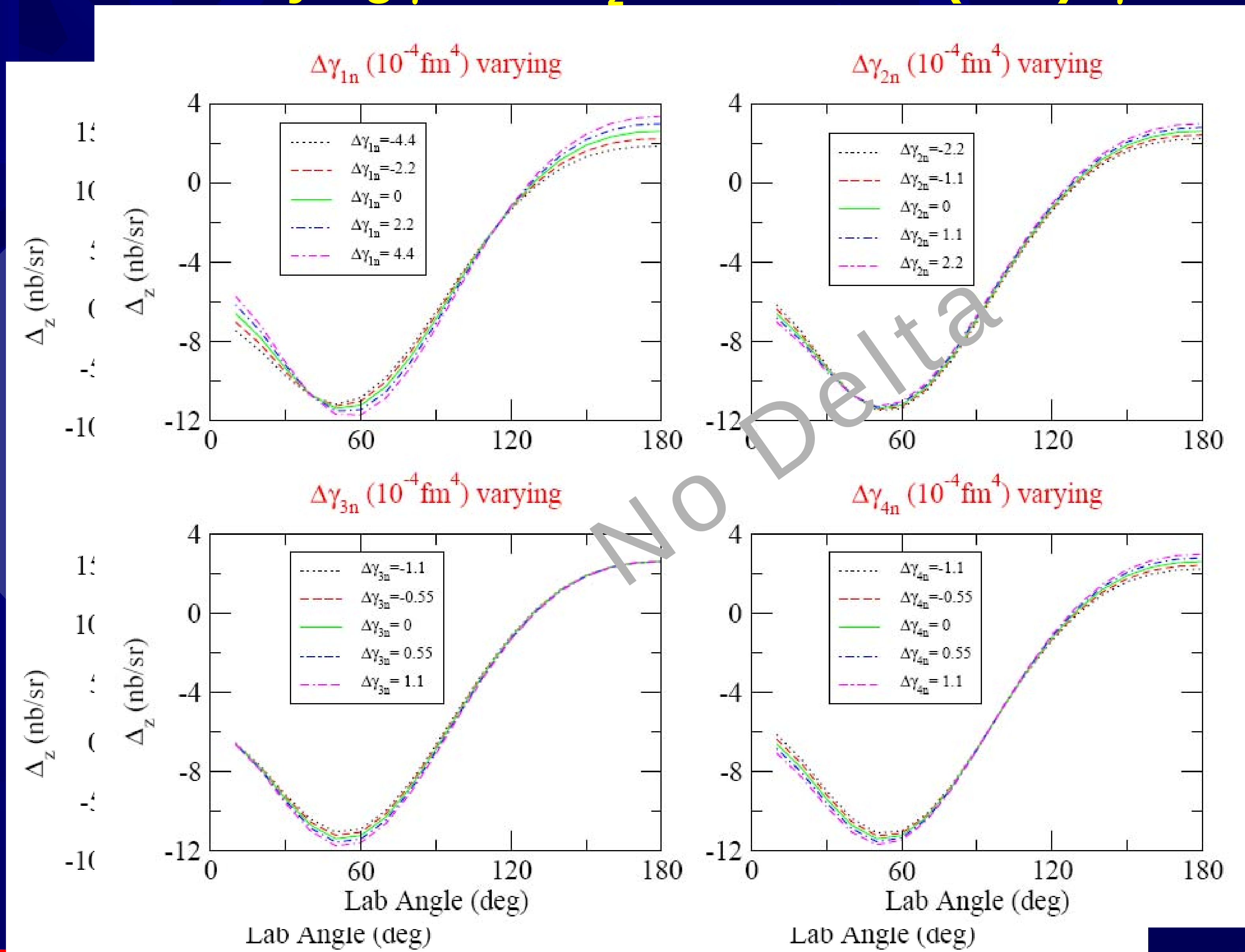


DC, R. Hildebrandt (in preparation)

Effect of varying γ's on Δ_x at 135 MeV (lab): γd



Effect of varying γ's on Δ_z at 135 MeV (lab): γd



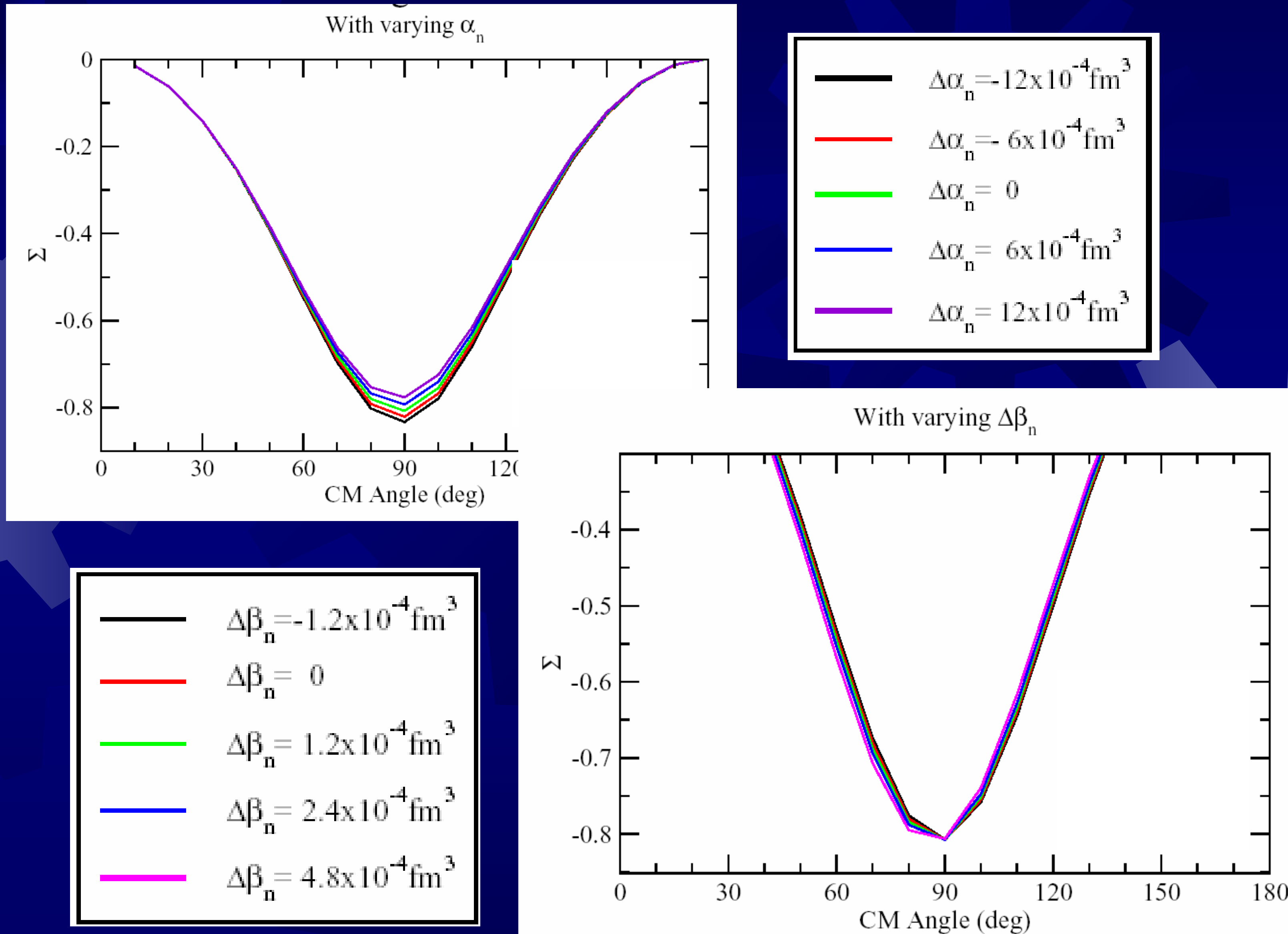
Summary

- Elastic scattering – "promising" avenue to extract polarizabilities.
- We have taken the first step with γHe-3 and polarized γd calculations.
- $$\gamma d \rightarrow \gamma d$$
  - Double pol. Observables are sensitive to combination of neutron spin polarizabilities.
- $$\gamma\, {}^{3}He \rightarrow \gamma\, {}^{3}He$$
  - Double pol. Observables are quite sensitive to combinations of neutron spin polarizabilities.
  - dcs is sensitive to α_n and β_n and can be used to extract them if needed.

Outlook

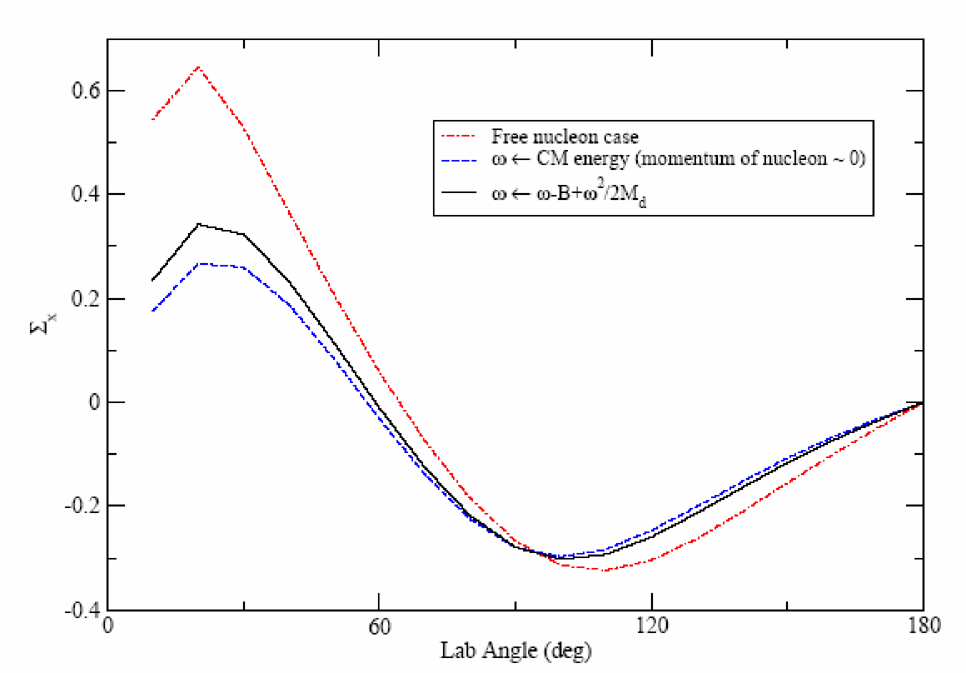
- More needs to be done both in theory and experiment.
  - Proton spin polarizabilities should be measured first (HIγS - scheduled).
  - α_n & β_n should be pinned down (Lund – unpolarized γd experiments).
  - Neutron spin polarizabilities through polarized γd and γHe-3 (HIγS - scheduled).
  - Theory: Delta-ful, $O(Q^4)$ calculations
  - Effort required to reduce theoretical uncertainties.

Thank You!



With varying α_n
Σ
0
-0.2
-0.4
-0.6
-0.8
0
30
60
90
120
CM Angle (deg)
$\Delta\alpha_n$=-12x10^{-4}fm^3
$\Delta\alpha_n$=- 6x10^{-4}fm^3
$\Delta\alpha_n$= 0
$\Delta\alpha_n$= 6x10^{-4}fm^3
$\Delta\alpha_n$= 12x10^{-4}fm^3
With varying $\Delta\beta_n$
Σ
-0.4
-0.5
-0.6
-0.7
-0.8
0
30
60
90
120
150
180
CM Angle (deg)
$\Delta\beta_n$=-1.2x10^{-4}fm^3
$\Delta\beta_n$= 0
$\Delta\beta_n$= 1.2x10^{-4}fm^3
$\Delta\beta_n$= 2.4x10^{-4}fm^3
$\Delta\beta_n$= 4.8x10^{-4}fm^3

$$
\begin{aligned}
\gamma_{E1E1} &= -\gamma_1 - \gamma_3, \\
\gamma_{M1M1} &= \gamma_4, \\
\gamma_{M1E2} &= \gamma_2 + \gamma_4, \\
\gamma_{E1M2} &= \gamma_3.
\end{aligned}
$$


Free nucleon case
ω ← CM energy (momentum of nucleon ~ 0)
ω ← ω-B+ω²/2M_d
0.6
0.4
0.2
0
-0.2
-0.4
Σ_x
0
60
120
180
Lab Angle (deg)