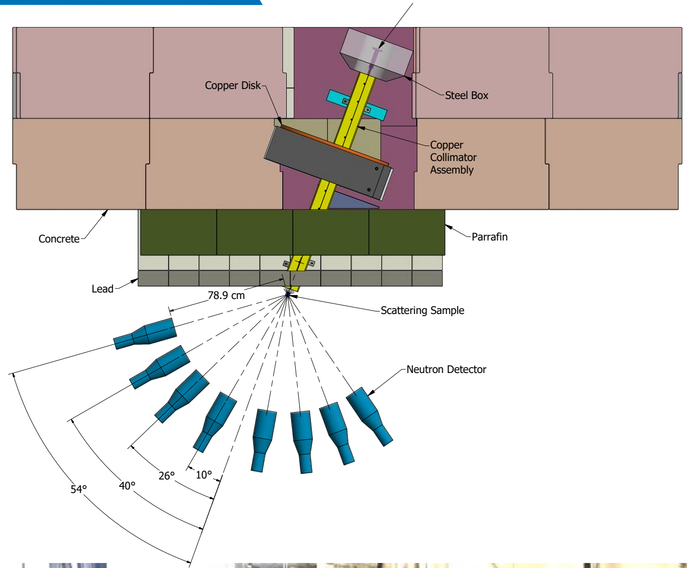
Probing the Neutron-Neutron Interaction and the Structure of the Neutron at Low Energies

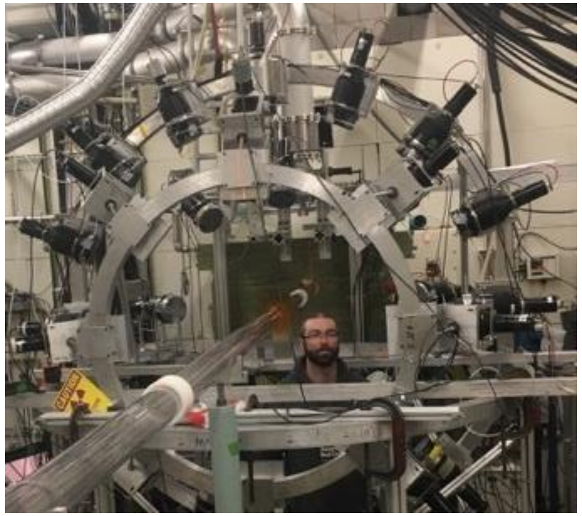
TUNL

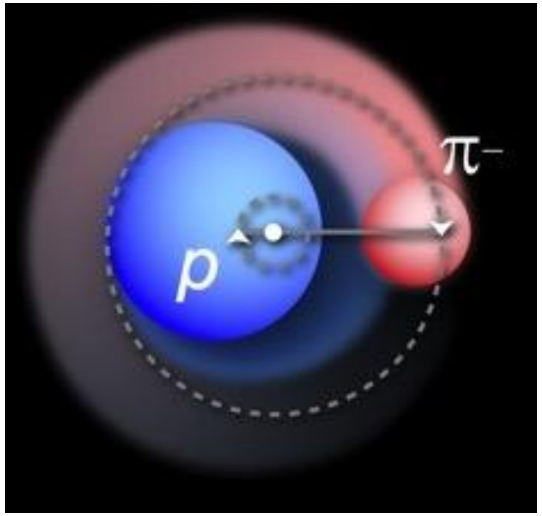


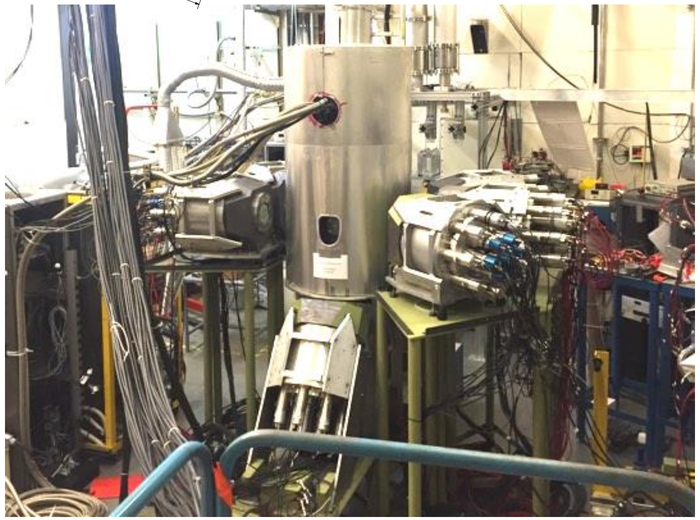
Program Components:

- Nucleon structure in terms of collective degrees of freedom: Compton scattering at $E_{\gamma} > 60$ MeV
- Investigation of the strong nuclear force in the context of few-nucleon systems: *photodisintegration and neutron-induced breakup of few-nucleon systems*

By: Calvin R. Howell, Duke University







Duke UNIVERSITY | NC Central UNIVERSITY | NC STATE UNIVERSITY | THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

LEQCD: HIGS collaborations involving TUNL faculty

Researchers from 16 institutions: 12 USA + 4 international

A. Compton Scattering Collaboration

1) **Duke:** H. Gao, C. Howell, W. Tornow, Y. Wu
2) **NCCU:** M. Ahmed, B. Crowe, D. Markoff
3) **UNC-CH:** H. Karwowski
4) **GWU:** E. Downie, J. Feldman, H. Griesshammer
5) **James Madison Univ.:** A. Banu and S. Whisnant
6) **MontClair State Univ**., Kent Leung
7) **Mount Alison Uni**, David Hornidge
8) **North Georgia State Univ.:** M. Spraker
9) **Ohio Univ.:** D. Phillips
10) **Univ. Kentucky:** M. Kovash
11) **Univ. Manchester:** J.A. McGovern
12) **Univ. New Hampshire:** R. Miskimen
13) **Univ. Saskatchewan:** R. Pywell

B. Few-Nucleon Systems

1) **Duke:** H. Gao, C. Howell, W. Tornow, Y. Wu
2) **NCCU:** M. Ahmed, B. Crowe, D. Markoff
3) **UNC-CH:** H. Karwowski
4) **Jagiellonian Univ.:** H. Witała
5) **Univ. Rochester:** C.J. Forrest, M. Sharpe, M. Wittman
6) **Vilnius Univ., Lithuania:** A. Deltuva

Current Graduate Students:
- Mitchell Lewis, GWU
- Zhuoqi Liu, GWU
- Ethan Mancil, Duke U.
- Courtney Martin, Duke U.
- Ricardo Mendez, Duke U.
- Nicholas Walton, Duke U.
- Jingyi Zhou, Duke U.

Current Postdocs and Research Scientists:
- Forrest Friesen, Duke
- Danula Godagama, GWU

Note: Theory collaborators underlined

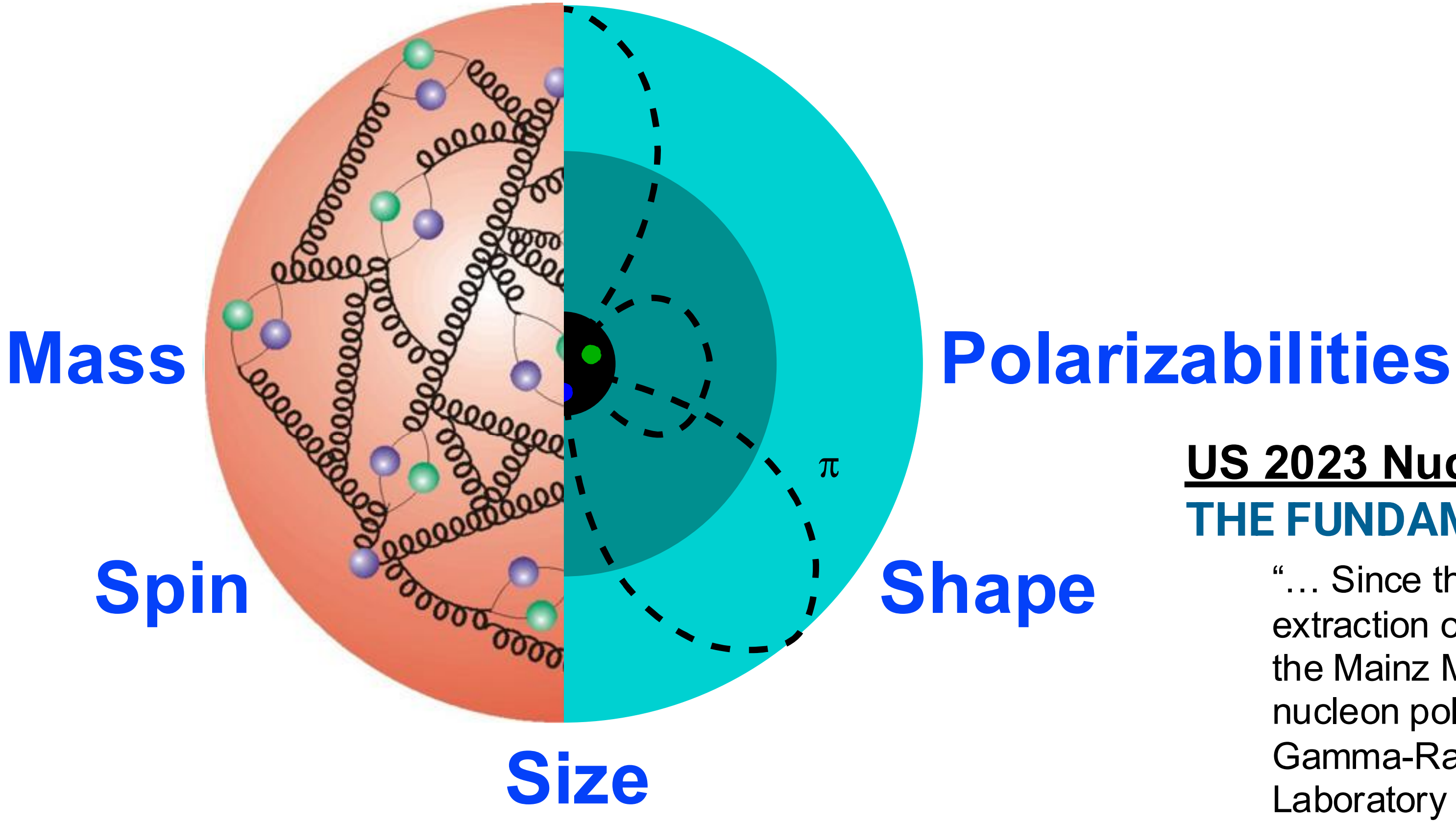
Low-Energy Nucleon Structure: Polarizabilities

High Energies

How do the macroscopic properties of the proton emerge from the dynamics of the quark & gluon constituents?

Low Energies

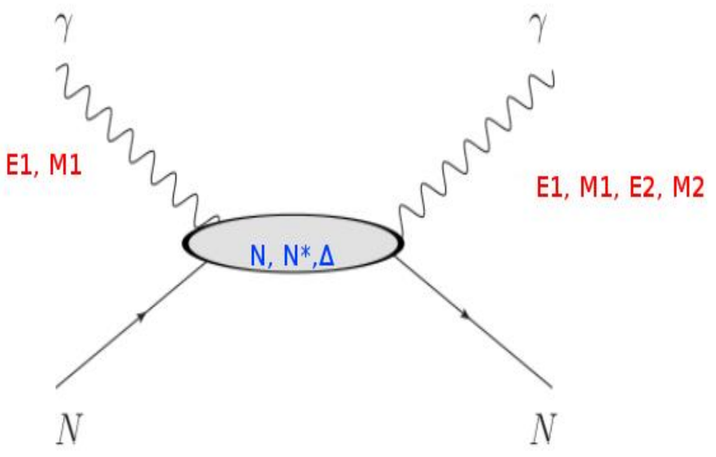
How does the proton size and EM polarizabilities emerge from the low-energy effective degrees of freedom?



US 2023 Nuclear Science LRP:

THE FUNDAMENTAL STRUCTURE OF VISIBLE MATTER

"… Since the last Long Range Plan, we have seen the first extraction of the proton spin polarizabilities from measurements at the Mainz Microtron (MAMI) accelerator and results on various nucleon polarizabilities from Jefferson Lab and the High Intensity Gamma-Ray Source (HIGS) at Triangle Universities Nuclear Laboratory (TUNL). *These measurements test theoretical predictions using lattice QCD and chiral effective field theory, a low-energy description of QCD."*



$$\frac{d\sigma}{d\Omega} = \Phi^2 |T|^2$$

$$T(\omega,z) = A_1(\omega,z)\,\vec{\epsilon}'^* \cdot \vec{\epsilon} + A_2(\omega,z)\,\vec{\epsilon}'^* \cdot \hat{\vec{k}}\,\vec{\epsilon} \cdot \hat{\vec{k}}'$$
$$+ i\,A_3(\omega,z)\,\vec{\sigma} \cdot (\vec{\epsilon}'^* \times \vec{\epsilon}) + i\,A_4(\omega,z)\,\vec{\sigma} \cdot \left(\hat{\vec{k}}' \times \hat{\vec{k}}\right) \vec{\epsilon}'^* \cdot \vec{\epsilon}$$
$$+ i\,A_5(\omega,z)\,\vec{\sigma} \cdot \left[\left(\vec{\epsilon}'^* \times \hat{\vec{k}}\right) \vec{\epsilon} \cdot \hat{\vec{k}}' - \left(\vec{\epsilon} \times \hat{\vec{k}}'\right) \vec{\epsilon}'^* \cdot \hat{\vec{k}}\right]$$
$$+ i\,A_6(\omega,z)\,\vec{\sigma} \cdot \left[\left(\vec{\epsilon}'^* \times \hat{\vec{k}}'\right) \vec{\epsilon} \cdot \hat{\vec{k}}' - \left(\vec{\epsilon} \times \hat{\vec{k}}\right) \vec{\epsilon}'^* \cdot \hat{\vec{k}}\right]$$

At low energies, e.g., ω < 300 MeV

- Dynamical structure response: contained in the non-pole parts of the amplitudes
- 6 dynamical response functions (or **polarizabilities**):
  - 2 spin independent (**α_{E1} and β_{M1}**)
  - 4 spin dependent (**γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, γ_{M1E2}**)

Separate A's into pole and non-pole parts

$$A_i(\omega,z) = A_i^{Born}(\omega,z) + \bar{A}_i(\omega,z)$$

(l = 1)

$$\bar{A}_1(\omega,\,z) = \frac{4\pi\,W}{M}\,[\alpha_{E1}(\omega) + z\,\beta_{M1}(\omega)]\,\omega^2 + \mathcal{O}(l=2),$$

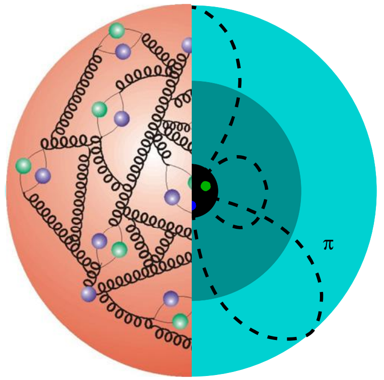
$$\bar{A}_2(\omega,\,z) = -\frac{4\pi\,W}{M}\,\beta_{M1}(\omega)\,\omega^2 + \mathcal{O}(l=2),$$

$$\bar{A}_3(\omega,\,z) = -\frac{4\pi\,W}{M}\Big[\gamma_{E1E1}(\omega) + z\,\gamma_{M1M1}(\omega) + \gamma_{E1M2}(\omega) + z\,\gamma_{M1E2}(\omega)\Big]\,\omega^3 + \mathcal{O}(l=2),$$

$$\bar{A}_4(\omega,\,z) = \frac{4\pi\,W}{M}\Big[-\gamma_{M1M1}(\omega) + \gamma_{M1E2}(\omega)\Big]\,\omega^3 + \mathcal{O}(l=2),$$

$$\bar{A}_5(\omega,\,z) = \frac{4\pi\,W}{M}\,\gamma_{M1M1}(\omega)\,\omega^3 + \mathcal{O}(l=2),$$

$$\bar{A}_6(\omega,\,z) = \frac{4\pi\,W}{M}\,\gamma_{E1M2}(\omega)\,\omega^3 + \mathcal{O}(l=2).$$



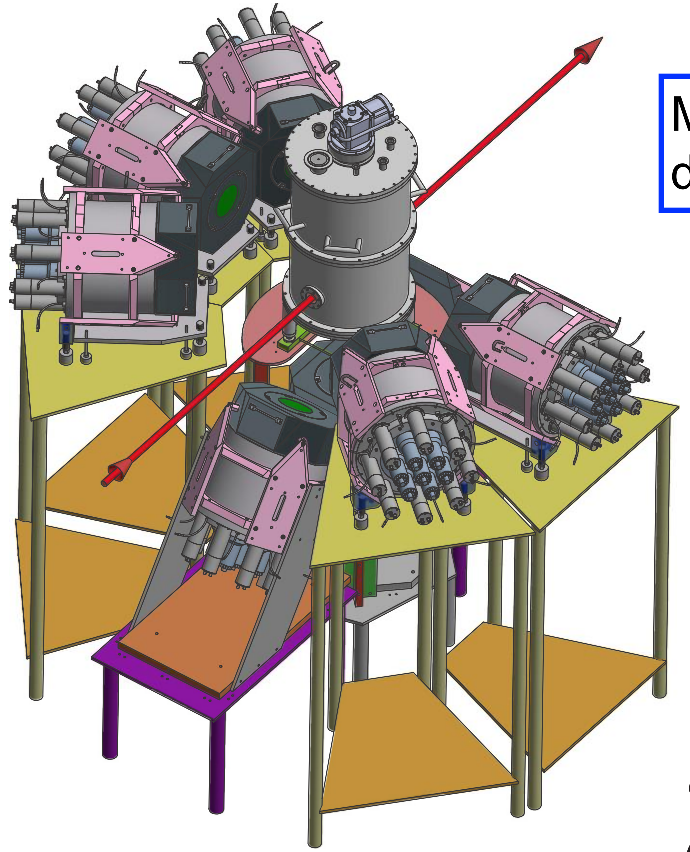
R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 329 (2004).

HIGS: Proton scalar polarizabilities, dσ/dΩ and Σ_3 measurements

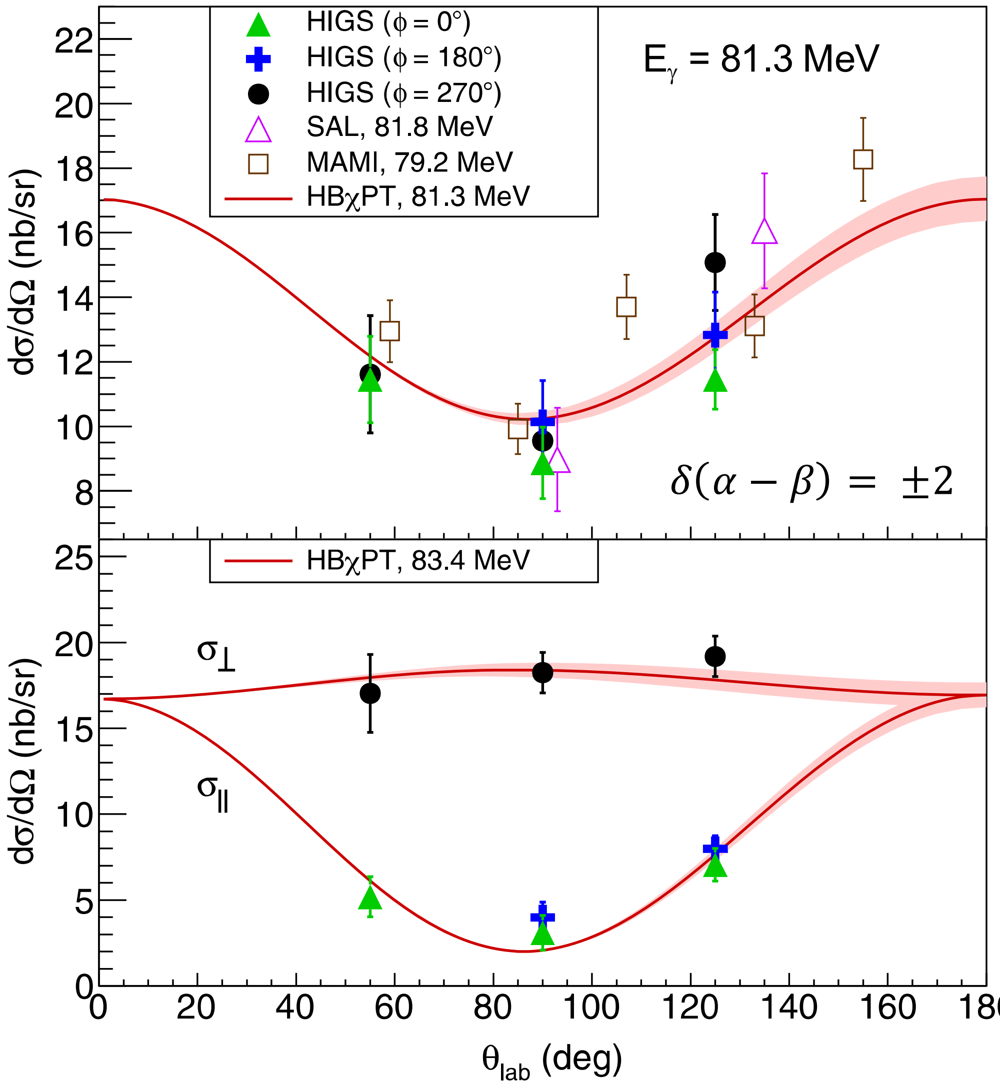
PHYSICAL REVIEW LETTERS **128,** 132502 (2022)

Proton Compton Scattering from Linearly Polarized Gamma Rays

X. Li,[1,2,*] M. W. Ahmed,[2,3] A. Banu,[4] C. Bartram,[2,5] B. Crowe,[2,3] E. J. Downie,[6] M. Emamian,[2] G. Feldman,[6] H. Gao,[1,2] D. Godagama,[7] H. W. Grießhammer,[6,1] C. R. Howell,[1,2] H. J. Karwowski,[2,5] D. P. Kendellen,[1,2] M. A. Kovash,[7] K. K. H. Leung,[1,2,8] D. M. Markoff,[2,3] J. A. McGovern,[9] S. Mikhailov,[2] R. E. Pywell,[10] M. H. Sikora,[6,2] J. A. Silano,[2,5] R. S. Sosa,[3] M. C. Spraker,[11] G. Swift,[2] P. Wallace,[2] H. R. Weller,[1,2] C. S. Whisnant,[4] Y. K. Wu,[1,2] and Z. W. Zhao[1,2]



Measure dσ(θ)/dΩ → Analyze χEFT → α_N, β_N



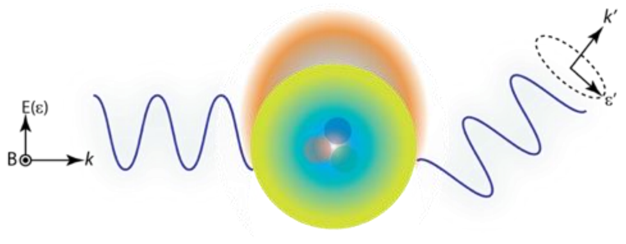
$$\alpha_{E1}^{p} = 13.8 \pm 1.2_{\text{stat}} \pm 0.1_{\text{BSR}} \pm 0.3_{\text{theo}},$$

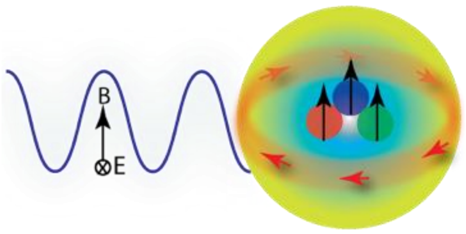
$$\beta_{M1}^{p} = 0.2 \mp 1.2_{\text{stat}} \pm 0.1_{\text{BSR}} \mp 0.3_{\text{theo}},$$

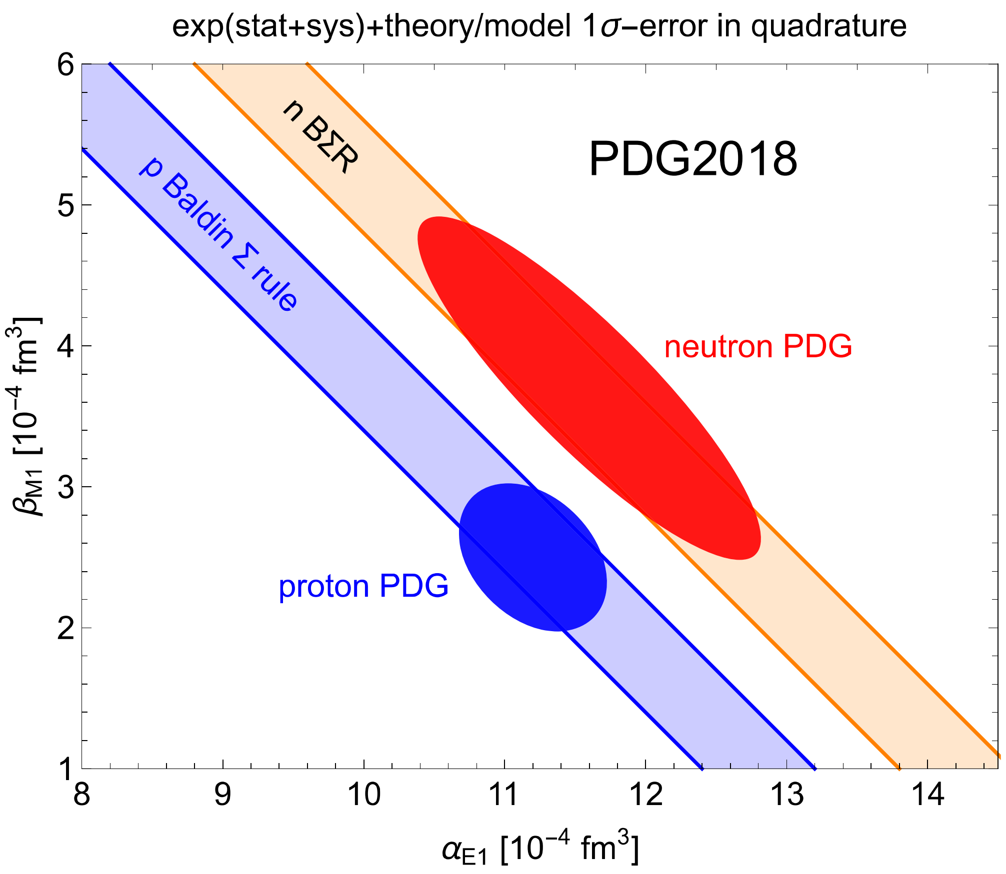
$$\bar{A}_1(\omega,\, z) = \frac{4\pi\, W}{M}\, [\alpha_{E1}(\omega) + z\, \beta_{M1}(\omega)]\; \omega^2 + \mathcal{O}(l=2),$$

$$\bar{A}_2(\omega,\, z) = -\frac{4\pi\, W}{M}\, \beta_{M1}(\omega)\, \omega^2 + \mathcal{O}(l=2),$$

- α_{E1}: charged pion-cloud dynamics
- β_{M1}: diamagnetic pion charge current dynamics
  + diamagnetic constituent quarks







Baldin sum rule

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2}\int_{\nu_0}^{\infty} \frac{\sigma_T}{\nu^2}\, d\nu$$

Baldin sum rule

$$\alpha_{E1}^{(p)} + \beta_{M1}^{(p)} = 13.8 \pm 0.4$$

$$\alpha_{E1}^{(n)} + \beta_{M1}^{(n)} = 15.2 \pm 0.4$$

$$\alpha_{E1}^{(p)} = 11.2 \pm 0.4 \quad \beta_{M1}^{(p)} = 2.5 \pm 0.4$$

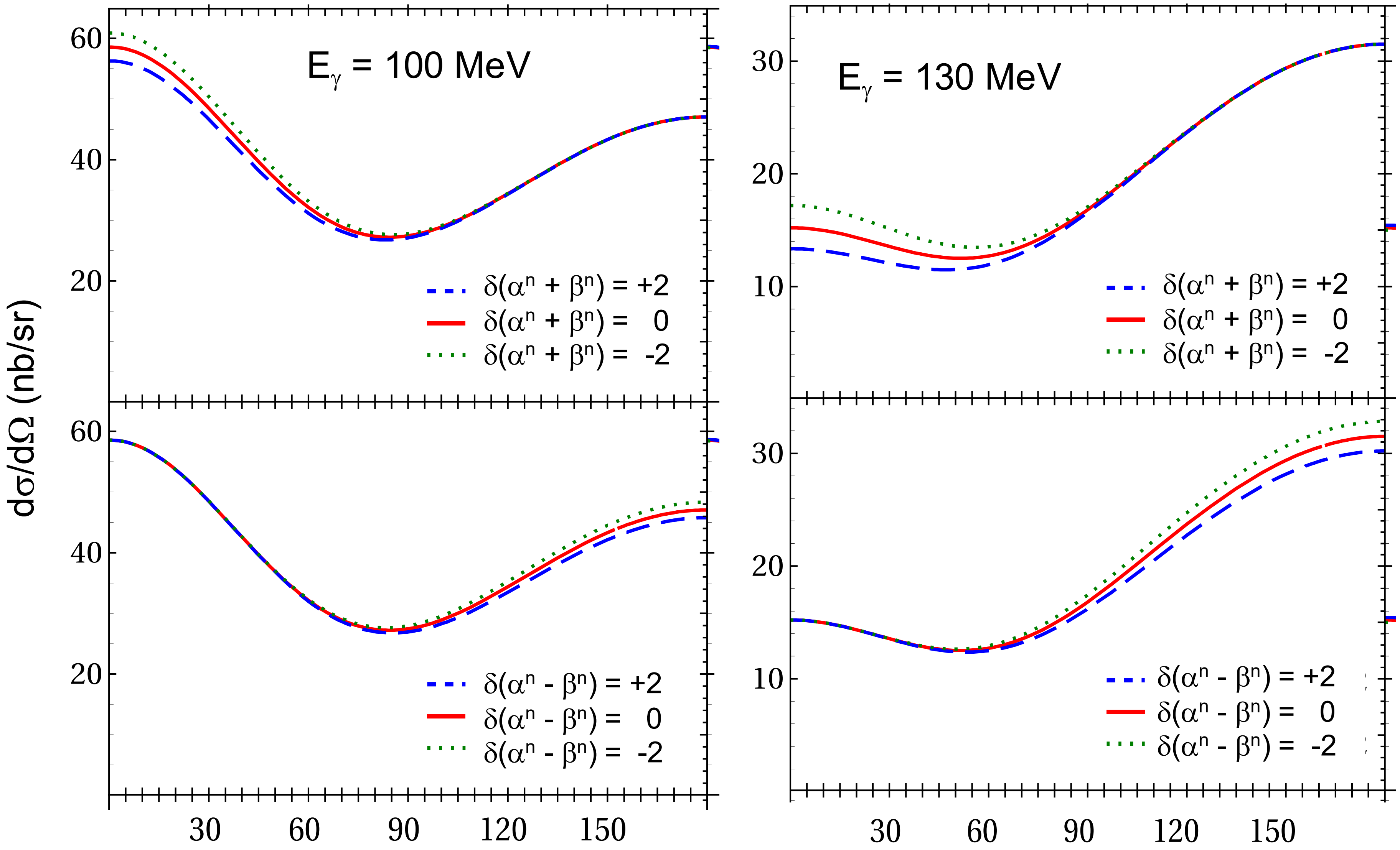
$$\alpha_{E1}^{(n)} = 11.8 \pm 1.1 \quad \beta_{M1}^{(n)} = 3.7 \pm 1.2$$

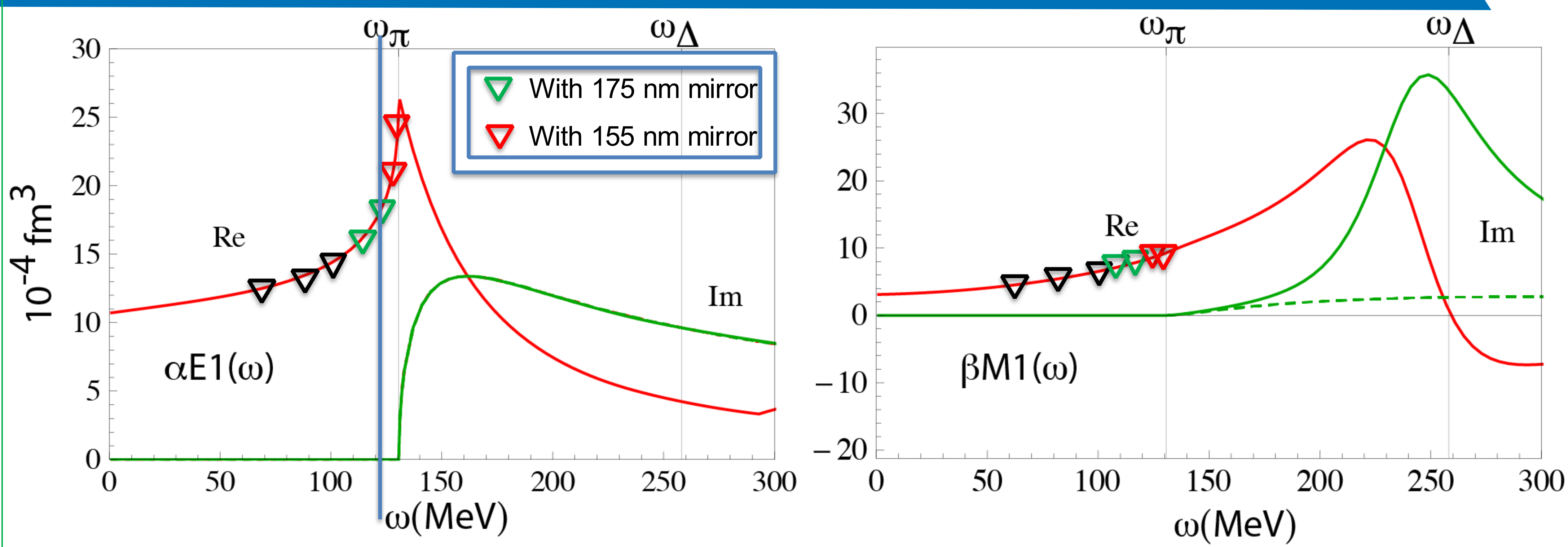
R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 293 (2004).

HIGS Compton Scattering: ^{3}He as target for neutron

χEFT calculations by H. Griesshammer, GWU

Potential: Nogga-IdahoN3LO+3NIb





- **Reduce uncertainty in neutron α and β by a factor of 2**
  - Liquid ^{2}H target at E_γ = 61 MeV; done spring - summer 2022
  - Liquid ^{3}He target at E_γ = 60 and 100 MeV; done summer 2024
  - Liquid ^{4}He target at E_γ = 87 and100 MeV; done summer 2025
  - Liquid ^{3}He target at E_γ = 87 MeV
  - Liquid ^{2}H target at E_γ = 87 MeV
  - Liquid ^{3}He and ^{4}He targets at E_γ = 120 MeV (need 175-nm mirrors)
- **High precision measurement of proton α and β**
  - Liquid H target at E_γ = 87, 100 MeV, = 120 MeV (need 175-nm mirrors)

What's next

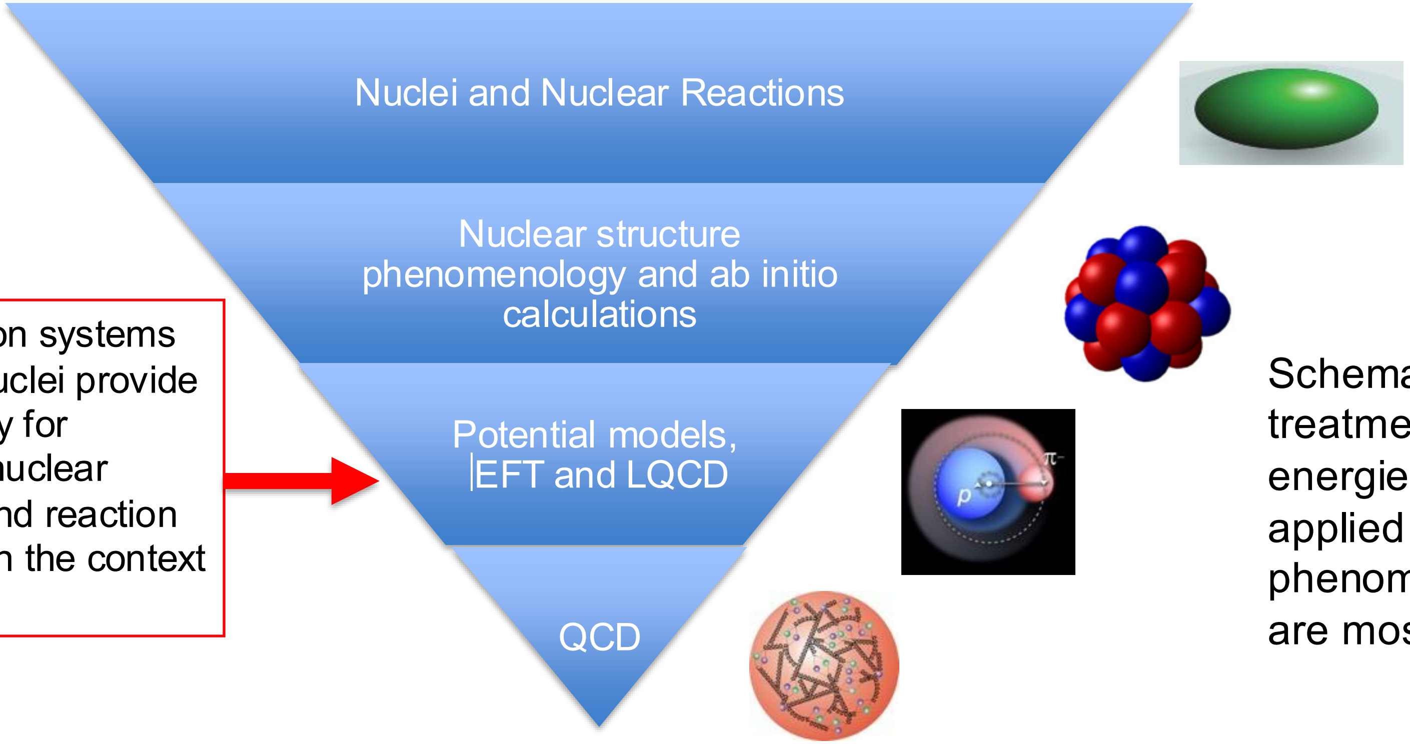
TUNL

US 2023 Nuclear Science LRP: WHAT IS THE NATURE OF THE NUCLEAR FORCE?

"Ultimately, an accurate description of the nuclear force is needed for a precise and predictive theory of nuclei ... A challenge for the forthcoming decade is to make these lattice calculations accurate enough that they provide meaningful constraints and to connect them, via effective field theories, to microscopic calculations of nuclear structure and reactions, thus enabling predictions more firmly grounded in QCD."

Hierarchy of theoretical treatments of nuclear systems

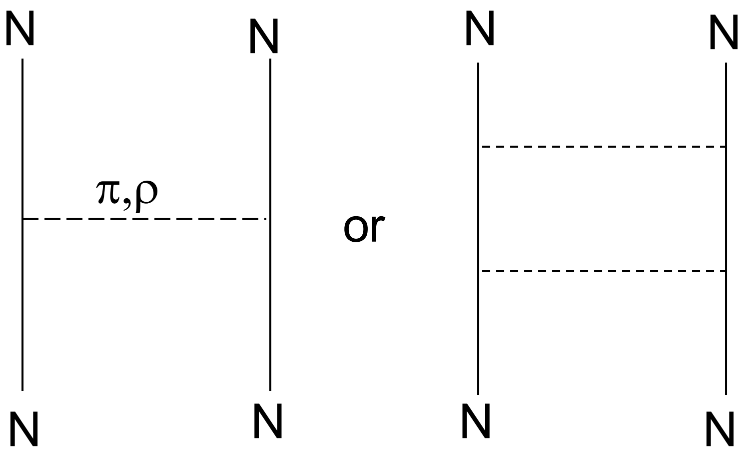
Few nucleon systems and light nuclei provide a laboratory for analyzing nuclear structure and reaction dynamics in the context of QCD.



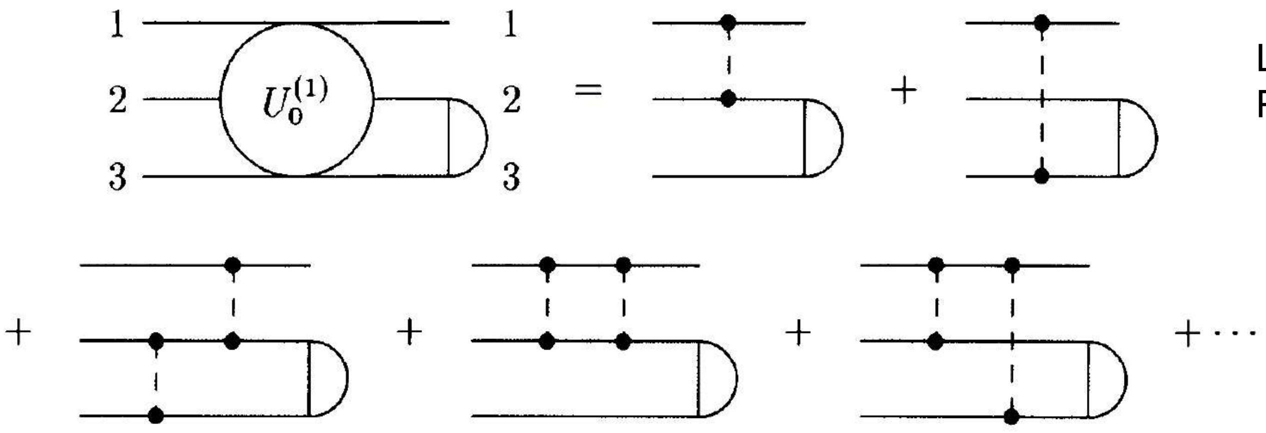
Schematic diagram for coherent theoretical treatment of nuclear systems starting from high energies where perturbative QCD can be applied going to low-energy nuclear phenomena where mean-field potential models are most efficient.

Nucleon-nucleon Interaction

proton-proton
neutron-proton
neutron-neutron



Three-nucleon System



- **Formulism** for solution to the 3-body system developed by:

L. D. Faddeev, Zh. Eksp. Teor. Fiz. **39**, 1459 (1960) [Sov. Phys. JETP **12**, 1014 (1961)].

- **Rigorous 3N calculations** by:

W. Glöckle, H. Witała, D. Huber, H. Kamada, J. Golak, Phys. Reports **274**, 107 (1996).

Nucleon-Nucleon Interaction - charge dependence

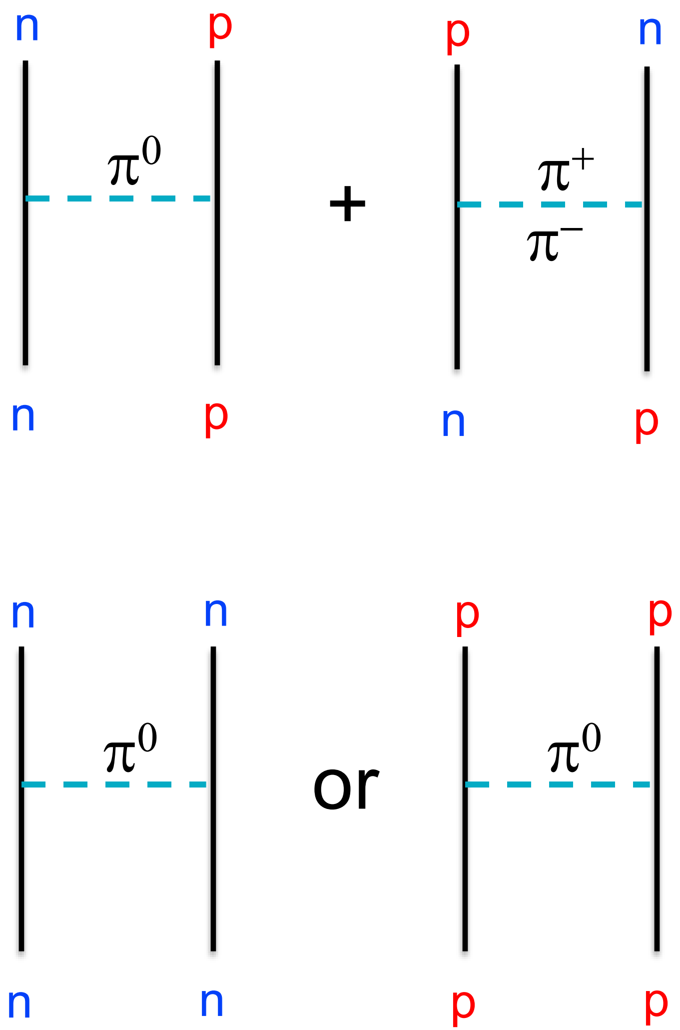
On-shell phase equivalent NN potential models, e.g.,

Bonn, R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. 149, **1** (1987)

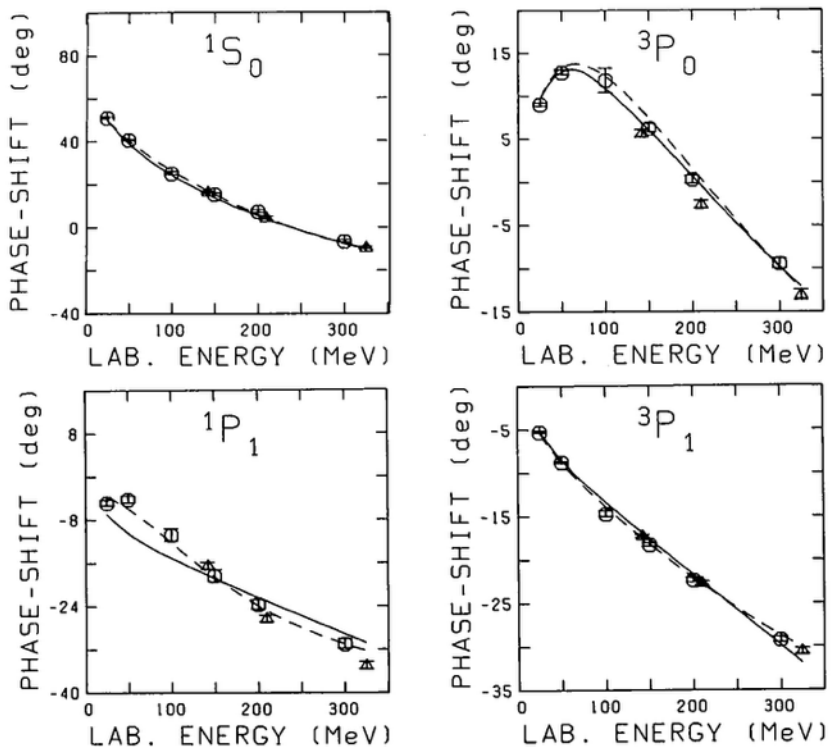
Paris, M. Lacombe et a!., Phys. Rev. C **21**, 861 (1980).

AV14, R.B. Wiringa, R.A. Smith, T.L. Ainsworth, Phys. Rev. C 29, 1207 (1984).

AV18, R.B. Wiringa, V.G.J. Stoks and R. Schiavilla, Phys. Rev.C **51** (1995) 38



R. Machleidt, K. Holinde and Ch. Elster, Phys. Rep. 149, 1 (1987).

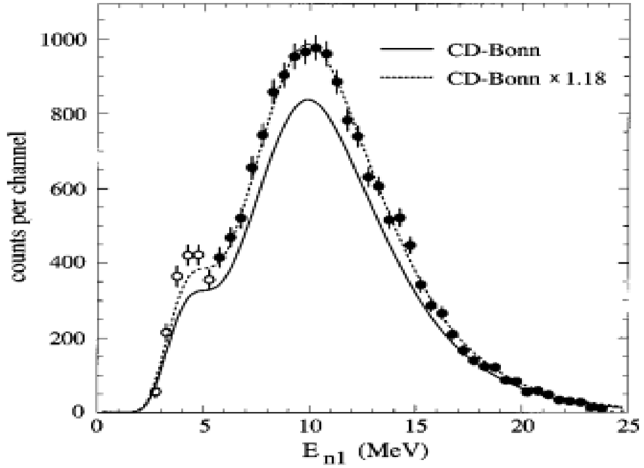


$$\nabla V = V_{nn}^N - V_{pp}^N$$

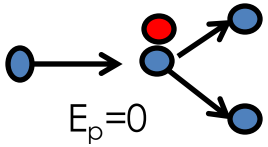
Due to u-d mass difference
and
Difference in EM interactions

nn QFS → Implications

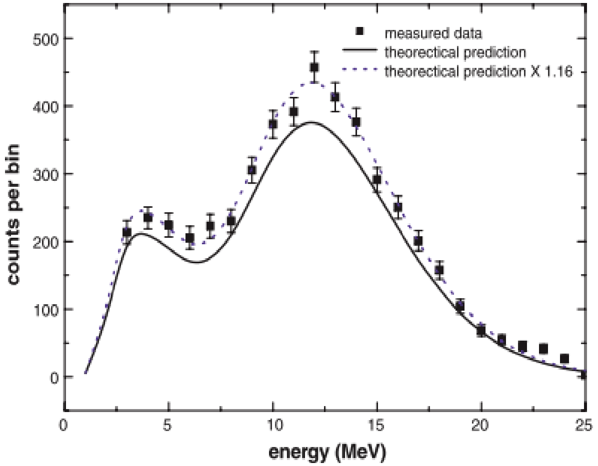
A. Siepe et al., Phys. Rev. C **65,** 034010 (2002).
Univ. Bonn, E_n=26 MeV

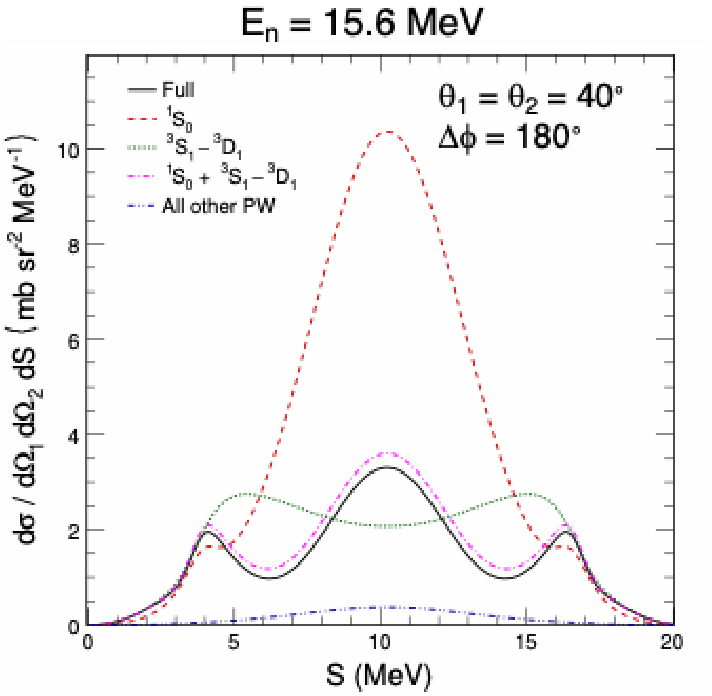


nd breakup
nn QFS



X.C. Ruan et al., Phys. Rev. C **75,** 057001 (2007).
CIAE, E_n=25 MeV

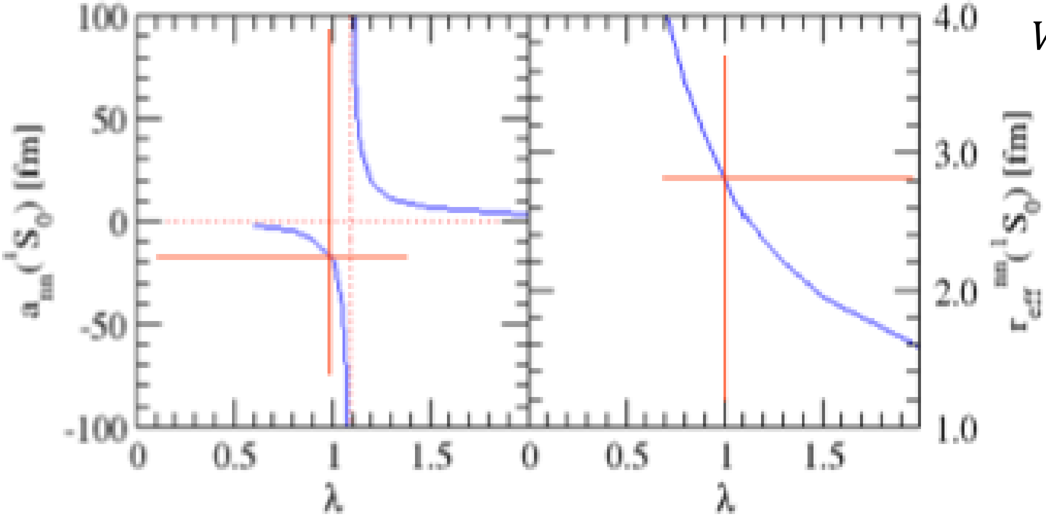




Must increase the strength of accepted value of the nn $^1S_0$ interaction to fit data by λ = x 1.08

r_{eff} = 2.41 fm

H. Witala and W. Glockle, PRC 83, 034004 (2011)



$$V_{nn}(^1S_0) = \lambda\, V_{CDBonn}(^1S_0)$$

CD Bonn (λ=1.0)
a_{nn} = -18.8 fm
r_{eff} = 2.82 fm

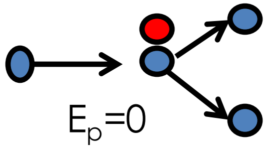
nn QFS → Current Few-Nucleon Program

nd breakup

nn QFS

A. Siepe et al., Phys. Rev. C **65,** 034010 (2002).

Univ. Bonn, E_n=26 MeV



X.C. Ruan et al., Phys. Rev. C **75,** 057001 (2007).

CIAE, E_n=25 MeV

H. Witala and W. Glockle, Phys. Rev. C **83**, 034004 (2011)

Must increase the accepted nn $^1S_0$ strength to fit data by λ = x 1.08

Accepted: r_{eff} = 2.75 fm vs. r_{eff} = 2.41 fm: fit to nn QFS data

- **Implication:** Large CSB in NN force
- **Conjecture:** (1) reported uncertainties in data are too small, (2) long-range 3NI not included in the models, and/or (3) large CSB in NN force

Two-pronged approach

Neutron beam at tandem lab

Measure nn-QFS

γ beam at HIγS

np and nn FSI via

(1) γ+ ^{3}He → n + p + p

(2) γ+ ^{3}H → n + n + p

Determination of the Effective Range Parameters: a_{nn} and r_{nn}

S-wave (L = 0) scattering

$$\sigma_{NN} = \tfrac{1}{4}\,\sigma_s + \tfrac{3}{4}\,\sigma_t$$

$$\sigma_{nn} = \tfrac{1}{4}\,\sigma_s + \tfrac{3}{4}\,\sigma_t = \tfrac{1}{4}\,\sigma_s \qquad (\sigma_t = 0)$$

$$\sigma_s = \frac{4\pi}{(1/a_{nn} - k^2 r_{nn}/2)^2 + k^2}$$

nn Final State Interaction (FSI)

$$k \to 0$$

$$\sigma_s = 4\pi a_{nn}^2$$

$$\sigma_{nn} = \pi a_{nn}^2$$

$$\frac{\Delta a}{a} = \frac{1}{2}\frac{\Delta\sigma}{\sigma}$$

$$\frac{\Delta\sigma}{\sigma} = 2\frac{\Delta a}{a} = 2\left(\frac{0.5}{18}\right) = 0.055$$

nn Quasi-Free Scattering (QFS)

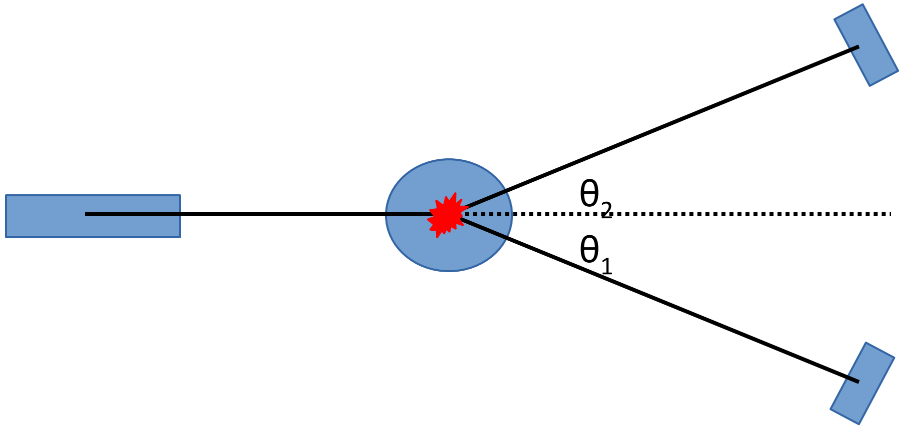
$$k^2 \gg \left|\frac{2}{a_{nn} r_{nn}}\right| \;\rightarrow\; k \gg 39\ MeV/c$$

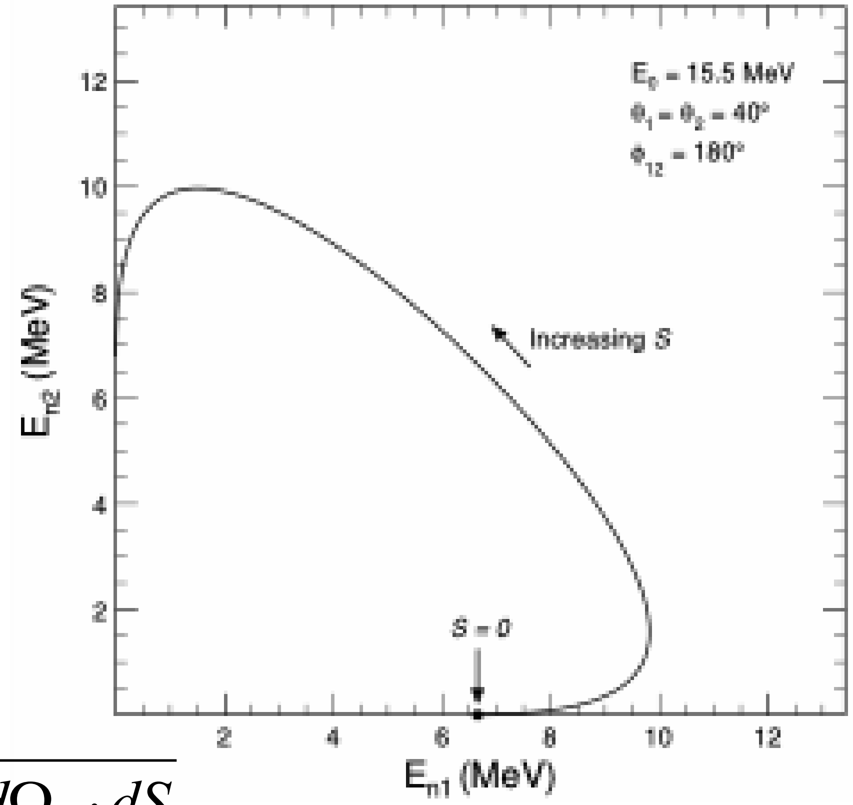
$$\sigma_s = \frac{4\pi}{k^2\left(\frac{1}{4}k^2 r_{nn}^2 + 1\right)}$$

Accepted values:
a_{nn} = -18.6 fm
r_{nn} = 2.75 fm

Cross-section Measurement of nn QFS in nd breakup

Breakup: n + d → n_1 + n_2 + p





$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{Y_{bu}}{N_n \cdot N_d \cdot \varepsilon(E_1)\cdot\varepsilon(E_2)\cdot\alpha(E_0)\cdot\alpha(E_1)\cdot\alpha(E_2)\cdot d\Omega_1 \cdot d\Omega_2 \cdot dS}$$

Elastic scattering: n + d → n + d

absolute luminosity determined in situ via nd elastic scattering

$$N_n \cdot N_d = \frac{Y_{el}}{\frac{d\sigma}{d\Omega}\cdot\varepsilon(E_{el})\cdot\alpha(E_0)\cdot\alpha(E_{el})\cdot d\Omega}$$

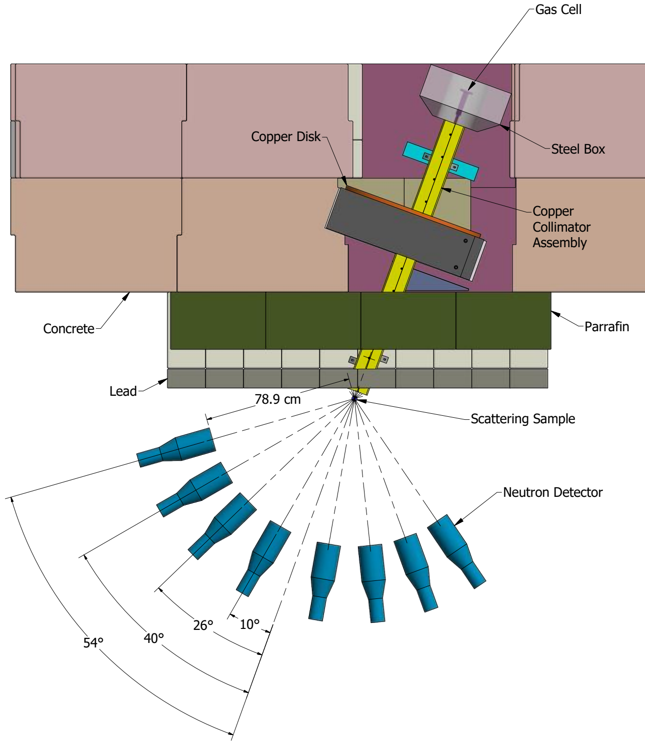
nn QFS in *nd* breakup: Experiment setup and example data

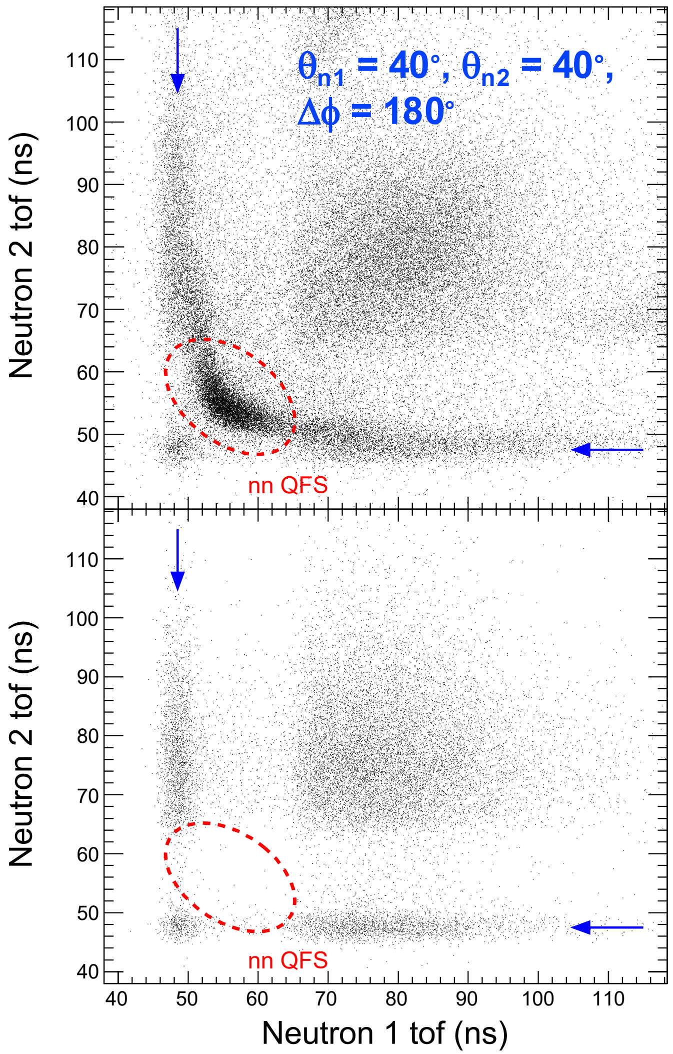
R.C. Malone *et al.*, PLB 835, 137557 (2022)

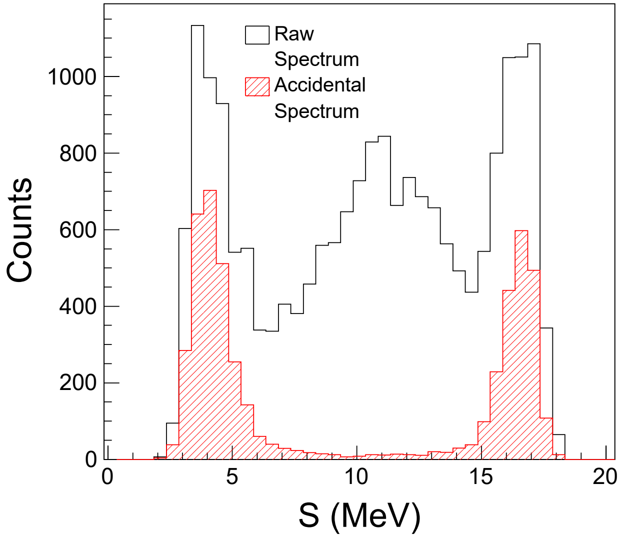
$$n + {}^{2}H \rightarrow n + n + p$$

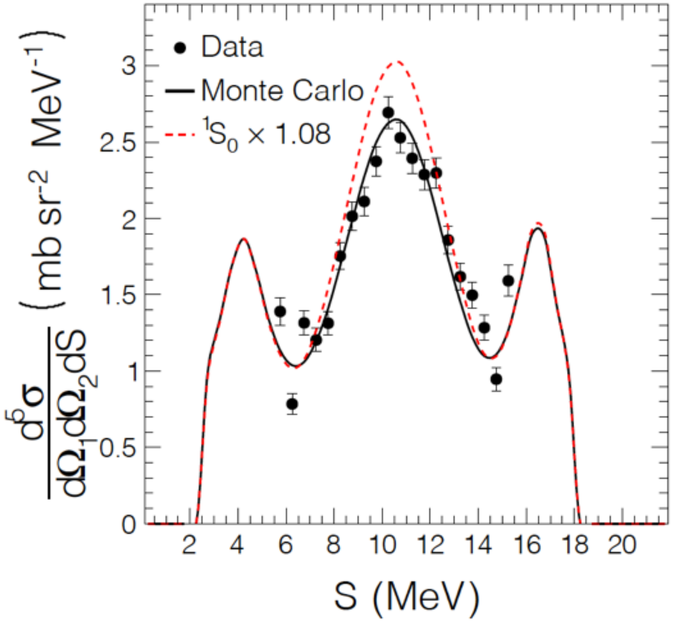
E_n = 15.6 MeV

Neutron Source: d + d → n + ^{3}He, Q=+3.3 MeV









Partial Results

Physics Letters B 835 (2022) 137557

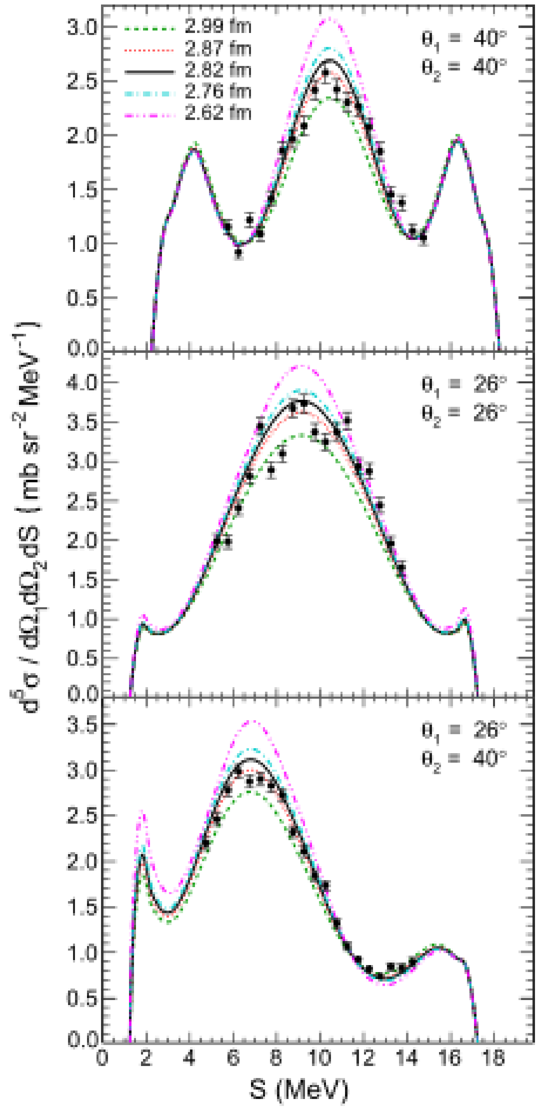
Measurement of the $^1S_0$ neutron-neutron effective range in neutron-deuteron breakup

R.C. Malone [a,b,*], A.S. Crowell [a,b], L.C. Cumberbatch [a,b], B.A. Fallin [a,b,1], F.Q.L. Friesen [a,b], C.R. Howell [a,b], C.R. Malone [a,b,1], D.R. Ticehurst [a,b], W. Tornow [a,b], D.M. Markoff [a,c], B.J. Crowe [a,c], H. Witała [d]

[a] Triangle Universities Nuclear Laboratory, Durham, NC, United States of America
[b] Department of Physics, Duke University, Durham, NC, United States of America
[c] Department of Mathematics and Physics, North Carolina Central University, Durham, NC, United States of America
[d] M. Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland

Configuration	$r_{nn} \pm \sigma_{stat} \pm \sigma_{sys}$ (fm)
$\theta_1 = 40°$ $\theta_2 = 40°$	$2.85 \pm 0.02 \pm 0.09$
$\theta_1 = 26°$ $\theta_2 = 26°$	$2.85 \pm 0.02 \pm 0.11$
$\theta_1 = 26°$ $\theta_2 = 40°$	$2.87 \pm 0.01 \pm 0.10$
CD Bonn Average	$2.86 \pm 0.01 \pm 0.10$
N^{4}LO$^+$ Average	$2.87 \pm 0.01 \pm 0.10$

STAY TUNED – MORE RESULTS TO COME IN PAPER REPORTING ANALYSIS OF THE COMPLETE DATA SET!



Thank you