Alternative Method for Measuring the Radius of the Deuteron

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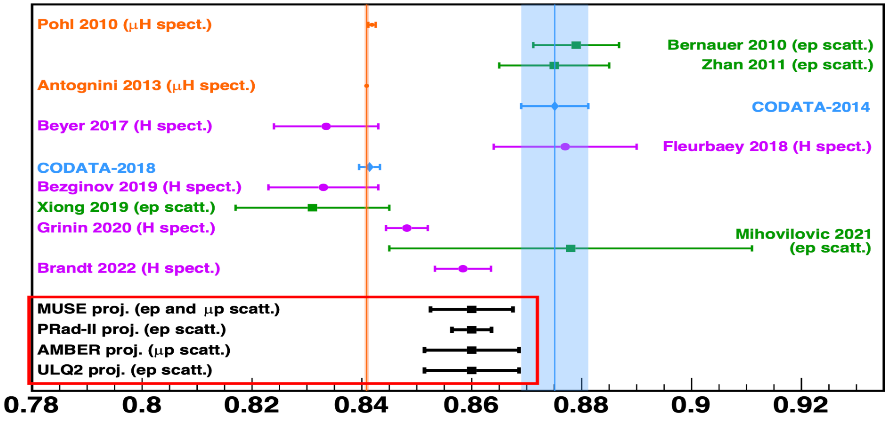
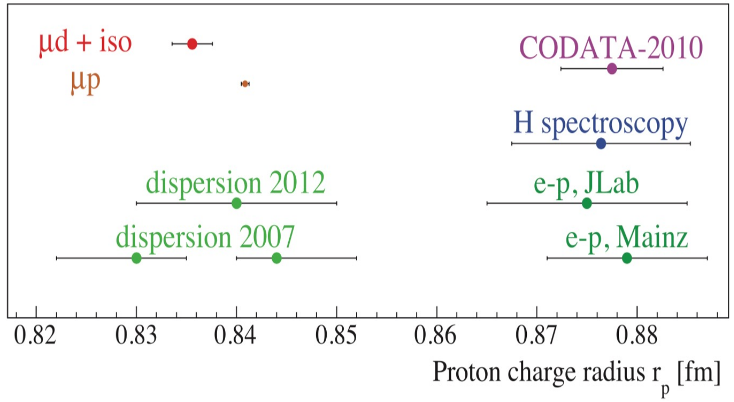
Spectroscopic vs e-Scattering Measurement of Radii

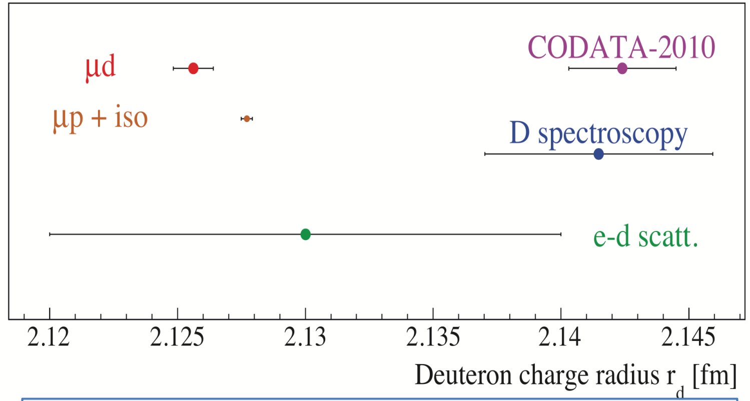
Radii	e-Spectroscopic	mu-Spectroscopic	e-Scattering
Proton	0.8775(51)fm	0.84087(39)fm	0.879(8)fm
Deuteron	2.1415(45)fm	2.12562(13)fm	2.13(12)fm
^4He	3 body problem	1.67824(13)fm	1.681(4)fm



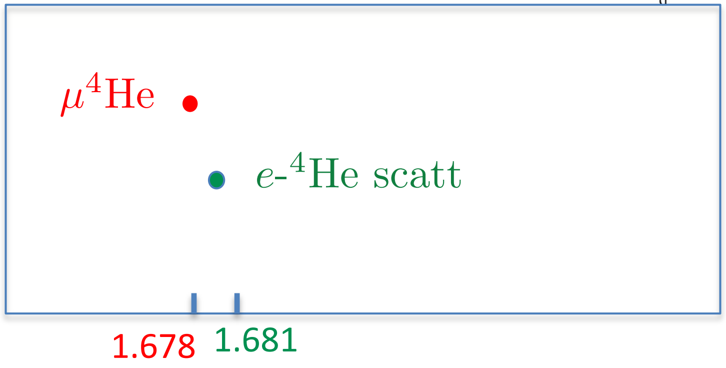
A.Gasparian, yesterday



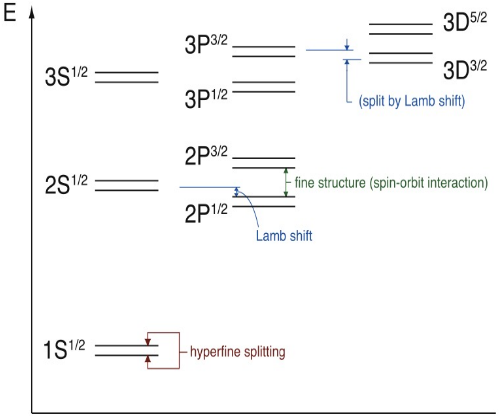
R.Pohl, Nature, 2010

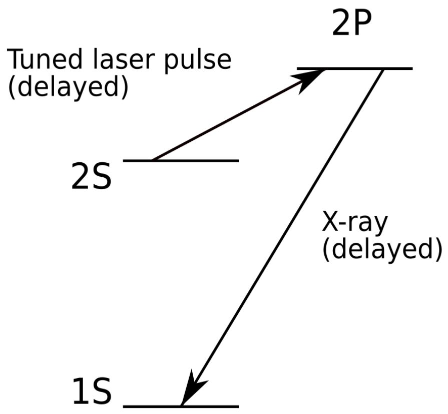


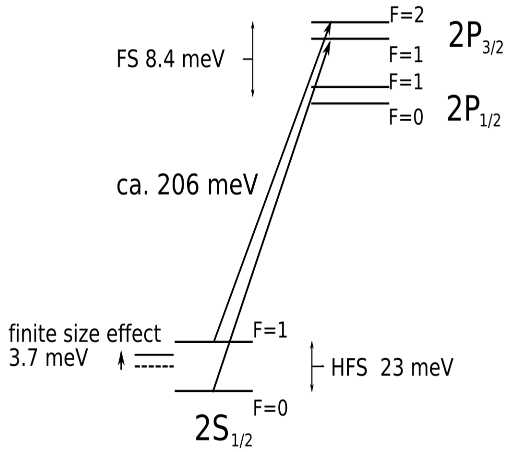
R.Pohl, Science, 2016



J.Krauth, Nature, 2021

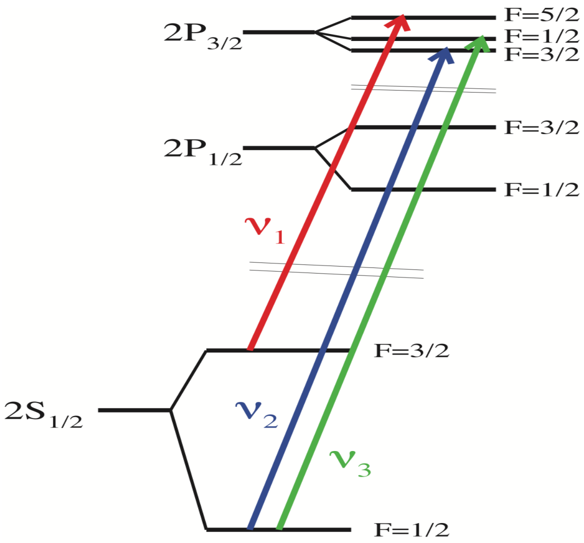




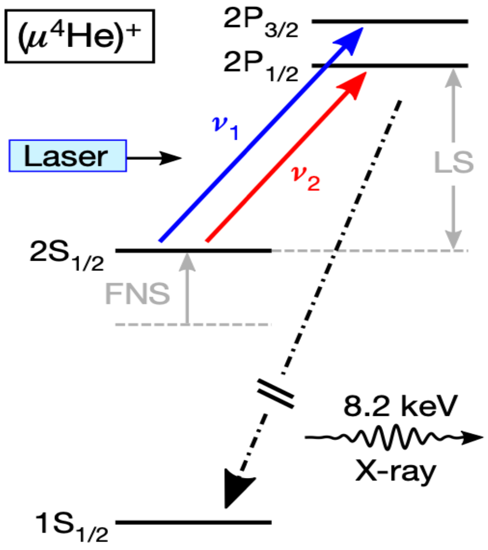


H

C.Carlson, PPNP, 2015

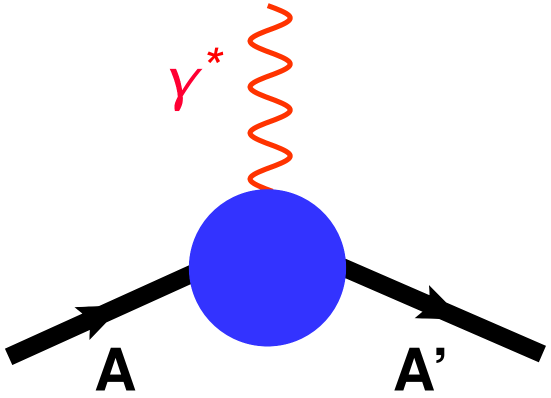


D



^{4}He

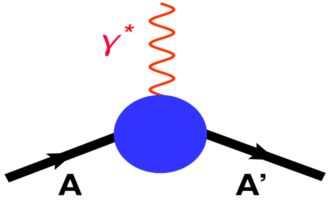
$$\mathbf{e}+\mathbf{A}\rightarrow \mathbf{e}' + \mathbf{A}'$$

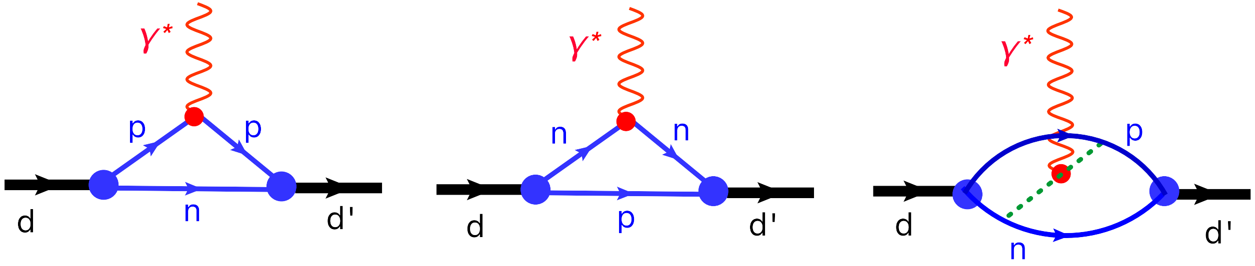


$$R_{ch}^2 = -6\frac{dG_{ch}(Q^2)}{dQ^2}\Big|_{Q^2\rightarrow 0}$$

$$e + A \to e' + A'$$

New Method





$$T_{eA}(Q^2) = ZT_{ep}(Q^2)S_A(\tfrac{q}{2}) + (A-Z)T_{en}(Q^2)S_A(\tfrac{q}{2}) + T_{MEC} + T_{Rel}$$

$$Q^2 \to 0$$

$$r^2_{A,ch} = Zr^2_{A,m} + Zr^2_{p,ch} + (A-Z)r^2_{n,ch} + r^2_{MEC} + r^2_{Rel}$$

$$e + d \rightarrow e' + d'$$

$$r^2_{d,ch} = r^2_{d,m} + r^2_{p,ch} + r^2_{n,ch} + r^2_{MEC} + \frac{3}{4}\frac{1}{m_p^2}$$

Klarsfeld, et al, Nuclear Physics A456, 1986

This relation was used to evaluate the matter radius

Instead we try to evaluate deuteron charge radius using

$r_{d,m} = 1.973 fm$ EFT

$r_{p,ch} = 0.879 fm$ ep-scatt

$r^2_{n,ch} = -0.106 fm^2$

$r^2_{MEC} = 0.0034 fm$

$r_{d,ch} = 2.135 fm$ **2.13(12)fm** ed - scattering

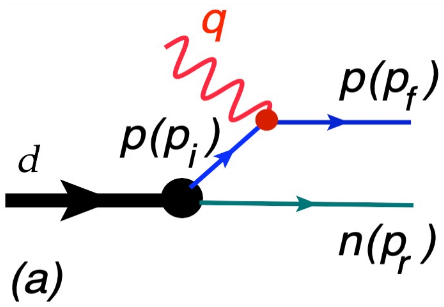
Alternative Method

Empirical Evaluation of Deuteron Matter Radius

Consider Deuteron Electrodisintegration process

$$\mathrm{e} + \mathrm{d} \rightarrow \mathrm{e}' + \mathrm{p} + \mathrm{n}$$

Within Plane Wave Impulse Approximation



$$\sigma_{ed} = K\sigma_{ep}(Q^2)(U^2(k) + W^2(k))$$

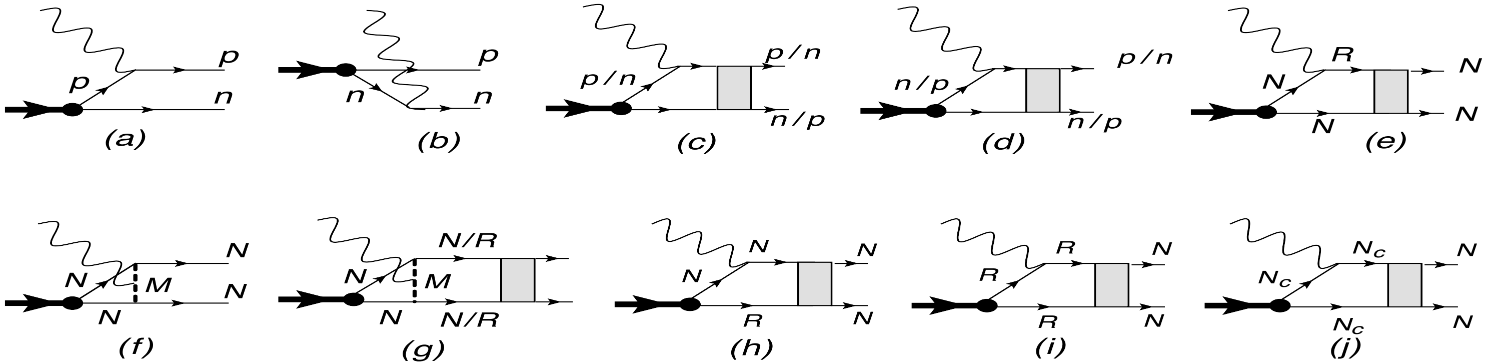
$$\vec{k} = \vec{p}_{miss}$$

$$\frac{u(r)}{r} = \frac{1}{(2\pi)^{\frac{3}{2}}} \int U(k) j_0(kr) d^3k$$

$$\frac{w(r)}{r} = \frac{1}{(2\pi)^{\frac{3}{2}}} \int W(k) j_2(kr) d^3k$$

$$r^2_{d,m} = \frac{1}{4} \int r^2(u(r)^2 + w(r)^2) dr$$

Reality is more complicated



GEA

M.Sargsian, PRC,2010

$$\langle s_f, s_r \mid A^\mu \mid s_d\rangle = \langle s_f, s_r \mid A_0^\mu \mid s_d\rangle + \langle s_f, s_r \mid A_1^\mu \mid s_d\rangle + \langle s_f, s_r \mid A_{1,chex}^\mu \mid s_d\rangle + \langle s_f, s_r \mid A_{1,R}^\mu \mid s_d\rangle, \quad (2)$$

$$\langle s_f, s_r \mid A_0^\mu \mid s_d\rangle = \sqrt{2}\sqrt{(2\pi)^3 2E_r} \times \sum_{s_i} J_N^\mu(s_f, p_f; s_i, p_i)\Psi_d^{s_d}(s_i, p_i, s_r, p_r),$$

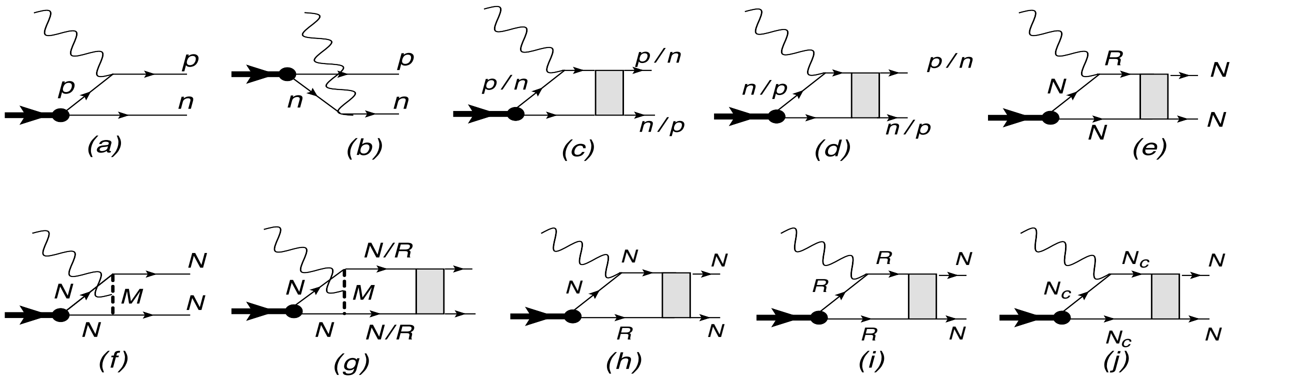
$$\langle s_f, s_r \mid A_1^\mu \mid s_d\rangle = -\int \frac{d^4 p_r'}{i(2\pi)^4} \times \frac{\bar{u}(p_f, s_f)\bar{u}(p_r, s_r)F_{NN}[\not{p}_r' + m][\not{p}_d - \not{p}_r' + \not{q} + m]}{(p_d - p_r' + q)^2 - m^2 + i\epsilon} \times \frac{\Gamma_{\gamma^* N}[\not{p}_d - \not{p}_r' + m]\Gamma_{DNN}\chi^{s_d}}{((p_d - p_r')^2 - m^2 + i\epsilon)(p_r'^2 - m^2 + i\epsilon)}, \quad (11)$$

Non PWIA Contributions

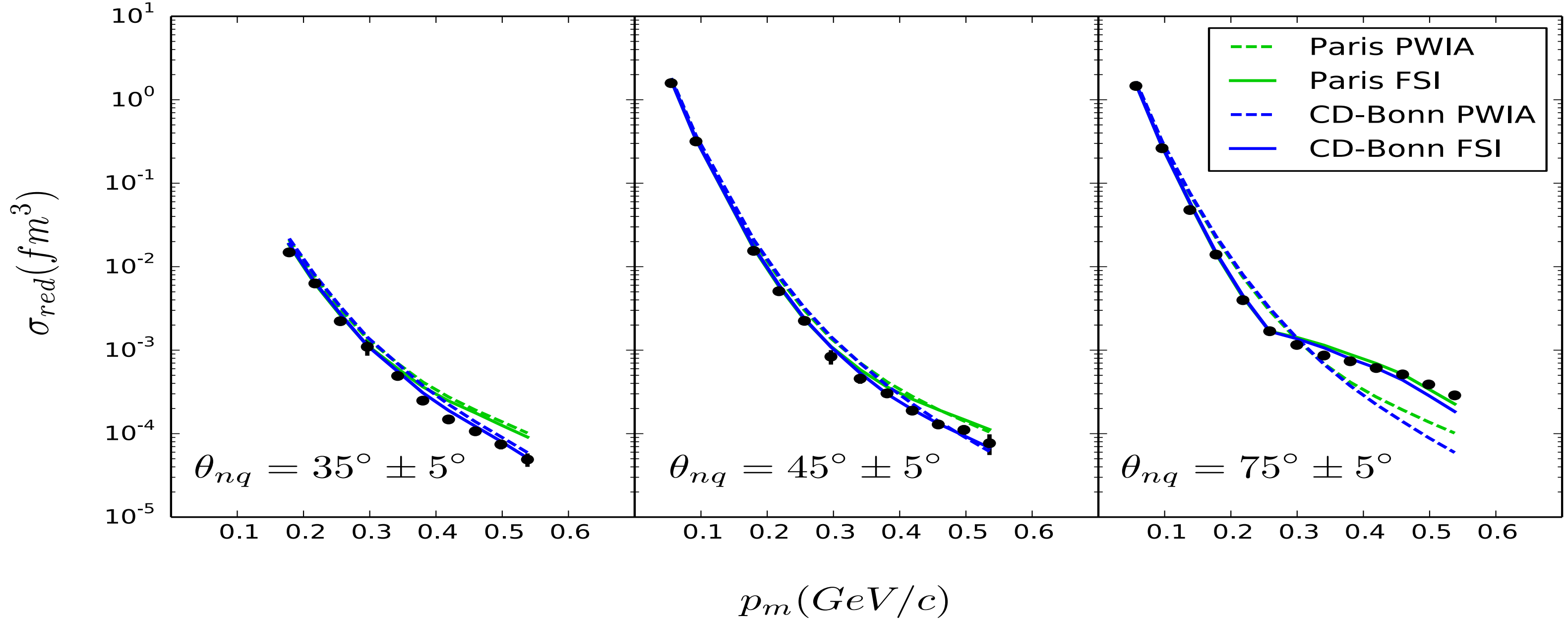
$$\langle s_f, s_r \mid A_1^\mu \mid s_d \rangle = -\int \frac{d^4 p_r'}{i(2\pi)^4}$$
$$\times \frac{\bar{u}(p_f, s_f)\bar{u}(p_r, s_r) F_{NN} [\not{p}_r' + m][\not{p}_d - \not{p}_r' + \not{q} + m]}{(p_d - p_r' + q)^2 - m^2 + i\epsilon}$$
$$\times \frac{\Gamma_{\gamma^* N}[\not{p}_d - \not{p}_r' + m]\Gamma_{DNN}\chi^{s_d}}{((p_d - p_r')^2 - m^2 + i\epsilon)(p_r'^2 - m^2 + i\epsilon)}, \qquad (11)$$

$$\langle s_f, s_r \mid A_1^\mu \mid s_d \rangle = \frac{i\sqrt{2}(2\pi)^{\frac{3}{2}}}{4} \sum_{s_f', s_r', s_i} \int \frac{d^2 p_r'}{(2\pi)^2} \frac{\sqrt{2\tilde{E}_r'}\sqrt{s(s-4m^2)}}{2\tilde{E}_r' |q|} \langle p_f, s_f; p_r, s_r \mid f^{NN,on}(t,s) \mid \tilde{p}_r', s_r'; \tilde{p}_f', s_f' \rangle$$
$$\times J_N^\mu(s_f', p_f'; s_i, \tilde{p}_i') \cdot \Psi_d^{s_d}(s_i, \tilde{p}_i', s_r', \tilde{p}_r')$$
$$-\frac{\sqrt{2}(2\pi)^{\frac{3}{2}}}{2} \sum_{s_f', s_r', s_i} \mathcal{P} \int \frac{dp_{r,z}'}{2\pi} \int \frac{d^2 p_r'}{(2\pi)^2} \frac{\sqrt{2E_r'}\sqrt{s(s-4m^2)}}{2E_r' |\mathbf{q}|} \frac{\langle p_f, s_f; p_r, s_r \mid f^{NN,off}(t,s) \mid p_r', s_r'; p_f', s_f' \rangle}{p_{r,z}' - \tilde{p}_{r,z}'}$$
$$\times J_N^\mu(s_f', p_f'; s_i, p_i') \cdot \Psi_d^{s_d}(s_i, p_i', s_r', p_r'), \qquad (13)$$

Reality is more complicated



Q^2 = 3.5 Gev^2



W.Boeglin, et al, PRL 2011

Jlab Experiment

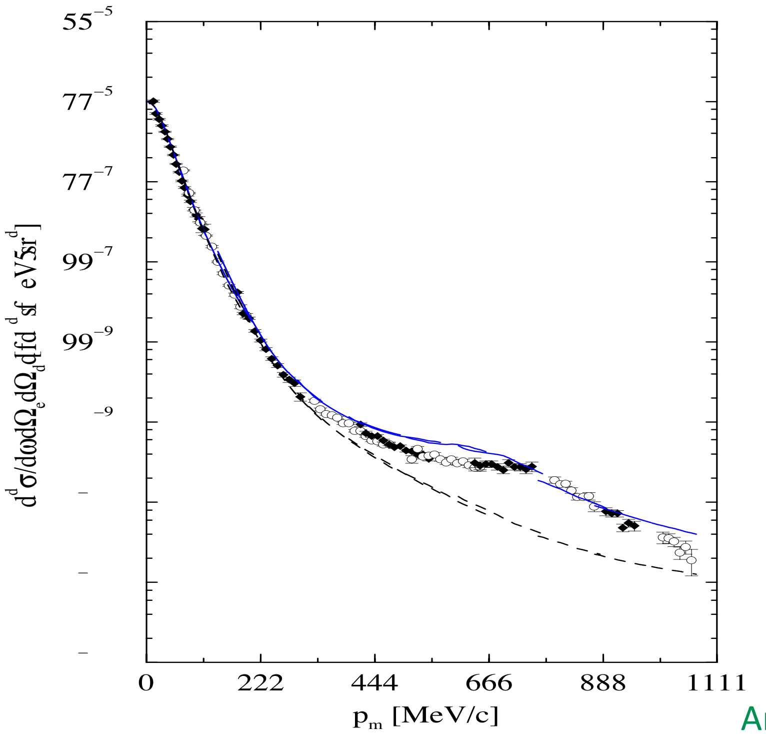
Anomalous Distribution at Very Small Missing Momenta

$$e + d \rightarrow e' + p + n$$

W.Boeglin et al Phys.Rev.C 78 (2008) 054001

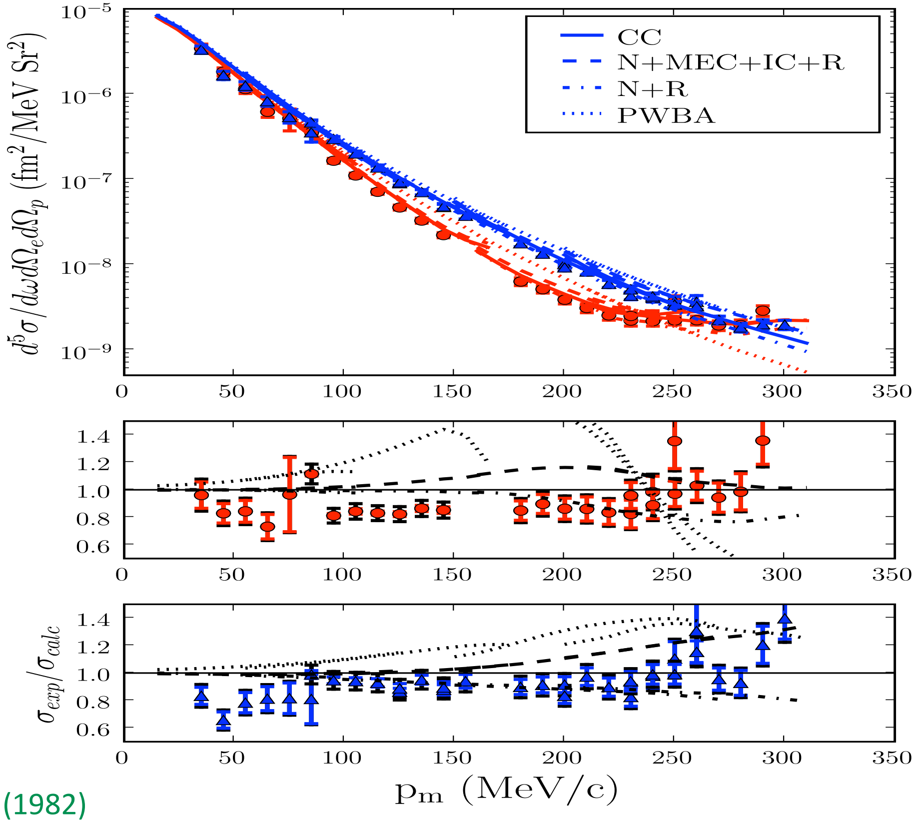
Mainz experiment

Mainz Measurement at $Q^2 = 0.33\mathrm{GeV}^2$



Arenhoevel

Nucl.Phys.A 384 (1982)

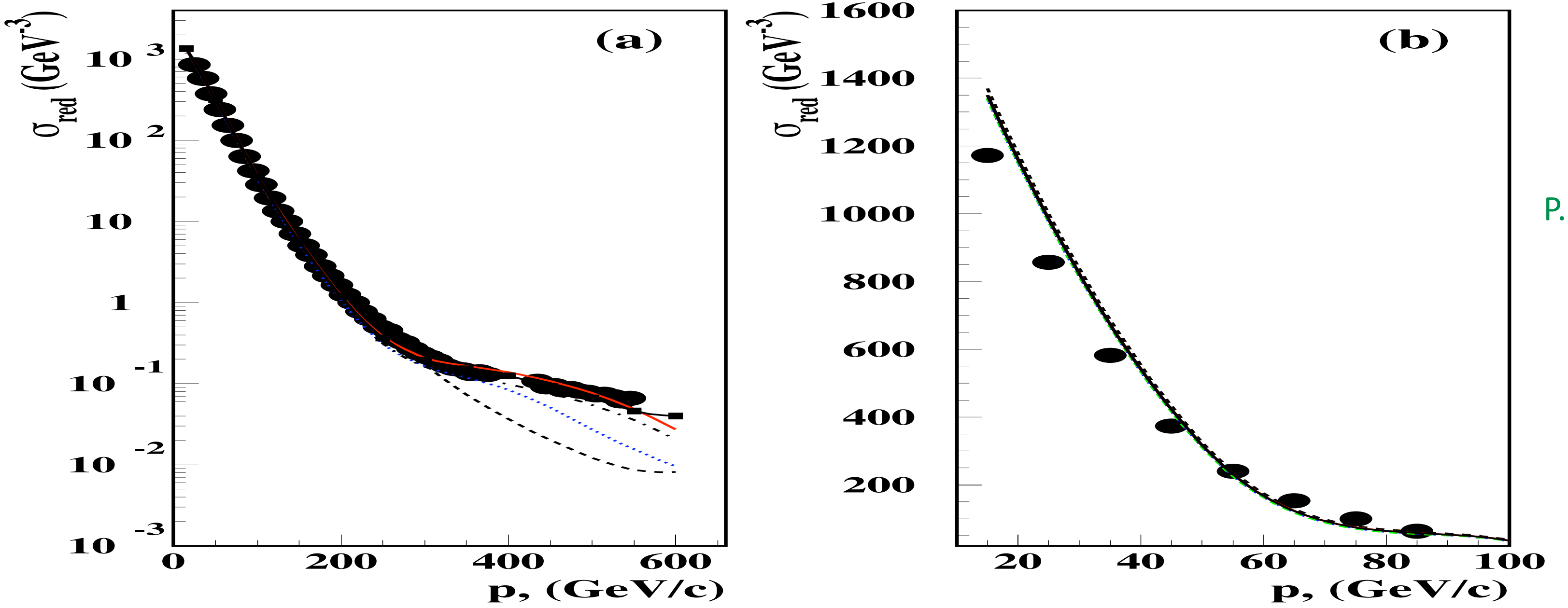


Anomalous Distribution at Very Small Missing Momenta

$$\mathrm{e} + \mathrm{d} \to \mathrm{e}' + \mathrm{p} + \mathrm{n}$$

JLab Measurement at $Q^2 = 0.66\mathrm{GeV}^2$

M.Sargsian, *Phys.Rev.C* 82 (2010) 014612



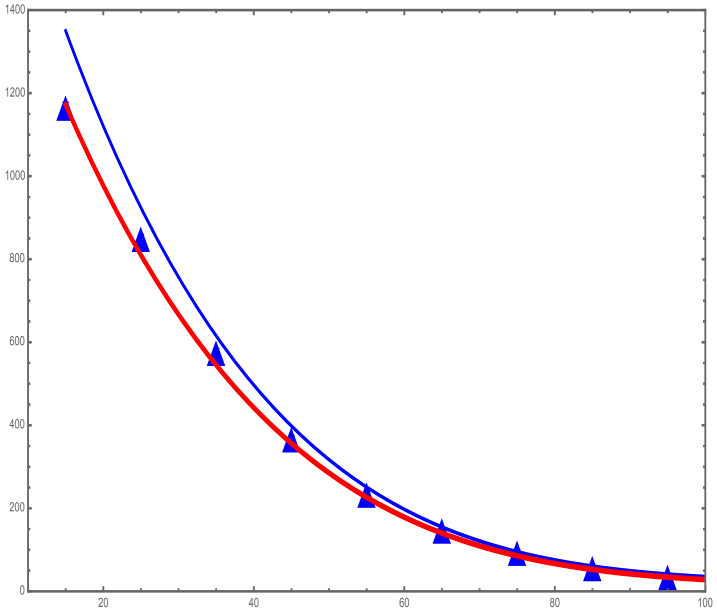
P.Ulmer, et al, PRL 2002

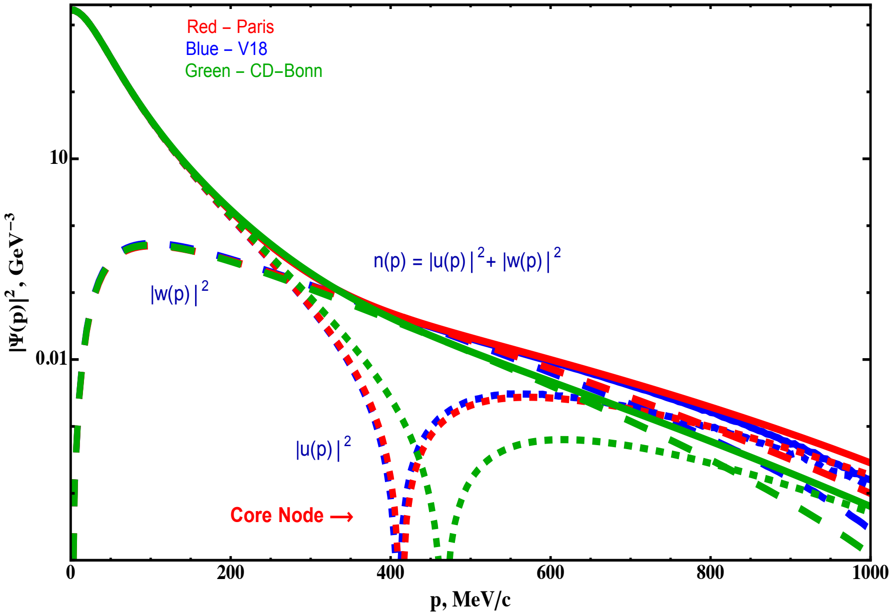
JLab experiment

Fitting Deuteron Wave Function to the data

$$e + d \rightarrow e' + p + n$$

JLab Measurement at $Q^2 = 0.66 \mathrm{GeV}^2$





$$r_{d,m} = 1.957 Fm$$

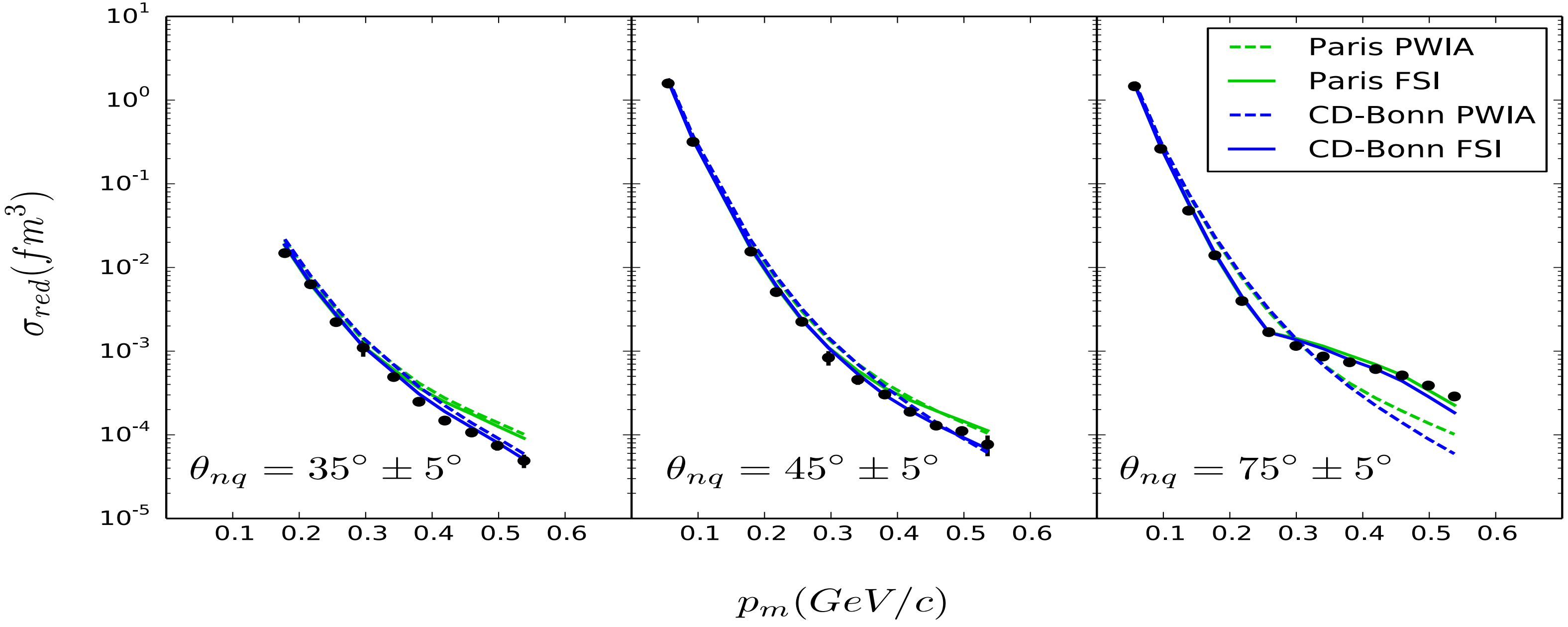
Only S-state needs to be modified

$$r_{d,m} = 1.957 fm$$
$$r_{p,ch} = 0.879 fm$$
$$r^2_{n,ch} = -0.106 fm^2$$
$$r^2_{MEC} = 0.0034 fm$$

$$r_{d,ch} = 2.121 fm$$ **2.12562(13)fm** μd - spectrometry

Alternative Method

$Q^2 = 3.5$ Gev^2



W.Boeglin, et al, PRL 2011

Jlab Experiment

Conclusion/Outlook

- ``Alternative” method is suggested to evaluate charge radius of the deuteron

- ed – scattering results can be reconciled with ep scattering better than ed spectroscopy

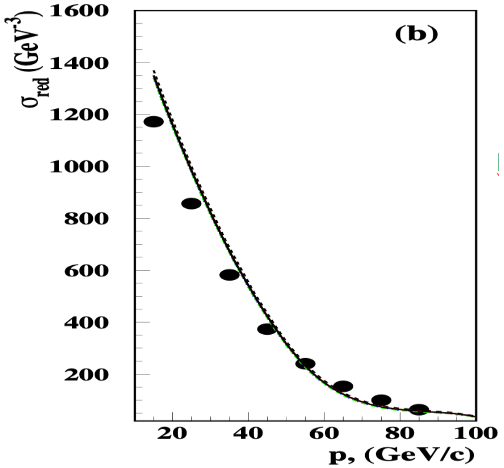
- the same may be true for ^{4}He nucleus

- Initial analysis indicates that the deuteron matter radius may be smaller

- it may indicate that BSM effects may be related to electron spectroscopy rather than to muon spectroscopy

- careful analysis of deuteron break-up reaction at small missing momenta may be needed (*this will require new experiments with short beam time*)

- as well as reliable measurement of neutron charge radius square and MEC



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The primary goal of the conference is to continue the advancement of the field of the future Electro Collider (EIC) physics which was granted Critical Decision 3A (CD-3A) by the U.S. Department of En