Electromagnetic Nuclear Physics Overview

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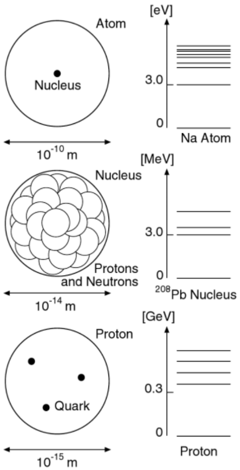
EM Nuclear Physics Overview

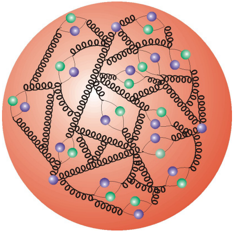
... summarize the current experimental situation, and highlight opportunities for progress with high-current electron beams in the 10-500 MeV energy range.

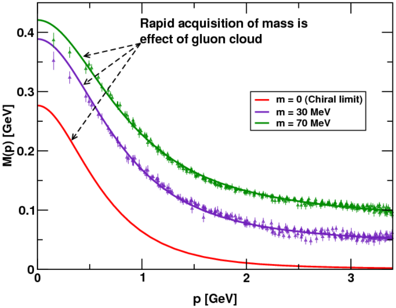
- 10-500 MeV range covers:
  - E ~Few 100 MeV - nucleon properties, lowest resonances
  - $E > \pi$ - π at threshold
  - $E \sim$ Few - 10s MeV - Nuclear excitations
- Both real and virtual γ interactions have been critical in our understanding of the strong nuclear force
- Broadly FF, neutron, isovector, and polarization observables are popular experimental areas



Nucleon Structure

- Protons and neutrons are the “ground state” of QCD
- $E < 500$ MeV probes non-perturbative structures
- Important to consider elastic processes (static structure), polarizabilities, and intermediate state properties

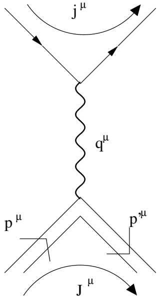




Form Factors for Nucleons

Scattering matrix element, $M \sim \frac{j_\mu J^\mu}{Q^2}$
Generalizing to spin 1/2 with arbitrary structure, one-photon exchange, using parity conservation, current conservation the current parameterized by two form factors

$$J^\mu = e\bar{u}(p')\left[F_1(q^2)\gamma^\nu + i\frac{\kappa}{2M}q_\nu\sigma^{\mu\nu}F_2(q^2)\right]u(p)$$



Form Factors

- Dirac - F_1, chirality non-flip
- Pauli - F_2, chirality flip

Sachs Form Factors

Replace with Sachs Form Factors

$$G_E = F_1 - \kappa\tau F_2$$
$$G_M = F_1 + \kappa F_2$$

Limit as $Q^2 \to 0$

$$G_E^p(Q^2=0) = 1, \qquad G_M^p(Q^2=0) = \mu_p = 2.79$$
$$G_E^n(Q^2=0) = 0, \qquad G_M^n(Q^2=0) = \mu_n = -1.91$$
$$-6\frac{dG_{EM}}{dQ^2}\bigg|_{Q^2\to 0} = \langle r_{EM}^2\rangle$$

Rosenbluth Formula

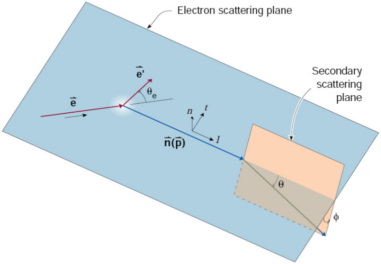
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right], \tau = \frac{Q^2}{4M^2}$$

G_E/G_M through Spin Observables

- Akhiezer and Rekalo (1968) - Polarization offers access to G_E/G_M
- Typically have fewer systematic contributions from nuclear structure and radiative effects

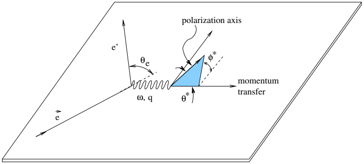
Polarization Transfer, $\vec{e}N, e'\vec{N}'$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan\theta_e/2}{2M}$$



Polarized Beam/Target $\vec{e}\vec{N}, e'N'$

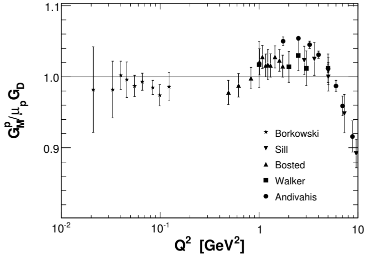
$$A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

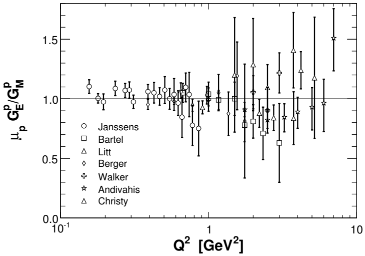


Proton Results

- G_M^p generally follow dipole - exponential distribution

$$G_D = \frac{1}{\left(1 + Q^2/(0.71\ \mathrm{GeV}^2)\right)^2}$$





- JLab, Jones *et al.*, G_E^p different from G_M^n using polarization
  - Neglect of hard two-photon exchange can cause systematic errors in extraction
  - Results testing this are now being produced

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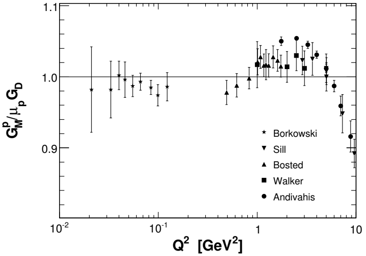

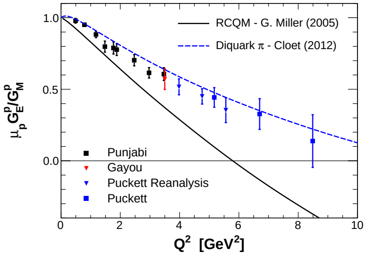

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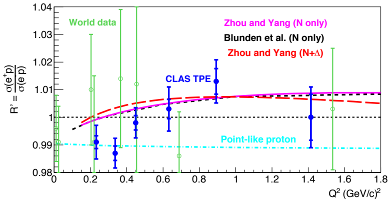
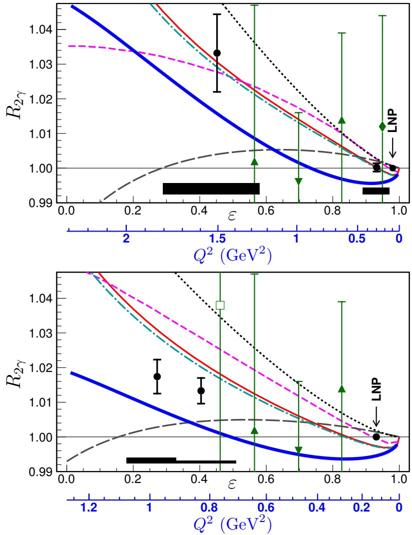
Two-photon Exchange Results - CLAS, VEPP-III

- Results from CLAS and VEPP-III with e^+/e^- available
- Kinematic coverage over broad ϵ and Q^2 up to $\sim 1.5\ \mathrm{GeV}^2$
- Both show definite effects of exchange and agreement with reconciliation



D. Adikaram et al

Phys. Rev. Lett. 114, 062003

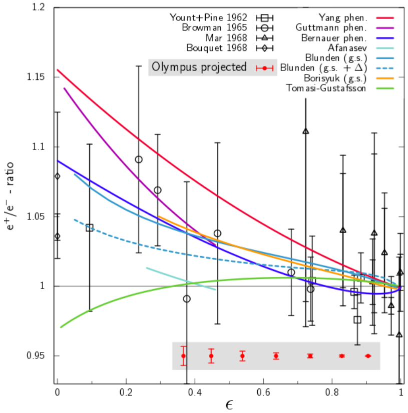


I.A. Rachek et al

Phys. Rev. Lett. 114, 062005

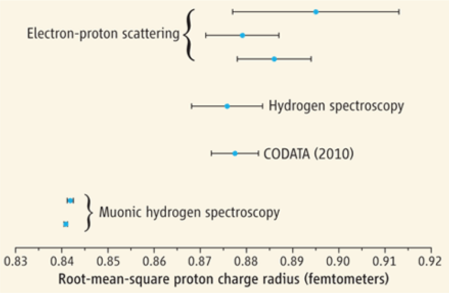
OLYMPUS at DESY - Milner et al

- e^+/e^- ratio
- Will provide data up to $Q^2 = 2.2$ GeV^2 at 1% level
- Higher Q^2 in addition with other data will provide stronger constraints
- Ended running in 2013 - Under analysis with hope for results at the end of 2015



Discrepancy with Muonic Hydrogen Lamb Shift

- Lamb shift breaks degeneracy in $2S_{1/2}$ and $2P_{1/2}$ - Hyperfine splitting, is sensitive to $\sqrt{\langle r_p^2 \rangle}$
- μ-hydrogen more sensitive due to smaller Bohr radius, increases as m^3, $m_\mu / m_e \sim 200$



H.S. Margolis, *Science* **339**, 405 (2013)

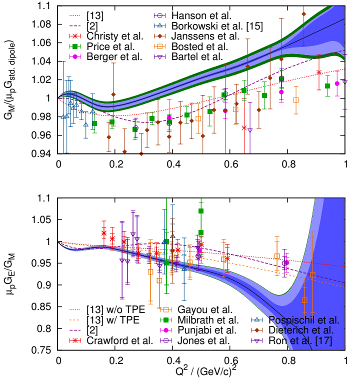
- $e(p, e')$ and spectroscopy agree
- $\mu - \mathrm{H}_2$ off by more than 6σ!
- Missing QED effects? Proton distorting?
- New coupling to just μ^-? Tie to $g_\mu - 2$ problem?

Theory and experiment review: Pohl *et al.* Annu. Rev. Nucl. Part. Sci 2013. 63: 175-204

Mainz low Q^2 G_E^p results

J.C. Bernauer *et al.* PRL 105, 242001 (2010) Rosen. Sep.

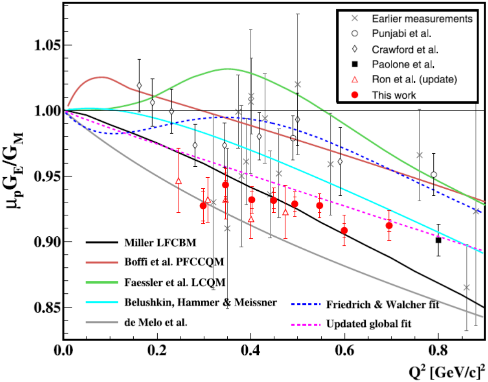
- Rosenbluth separation of over 1400 cross sections from Mainz, Q^2 up to 1 GeV^2
- Results have some systematic discrepancies with previous experiments - normalization errors
- Includes two photon effects, proton radiative effects not large

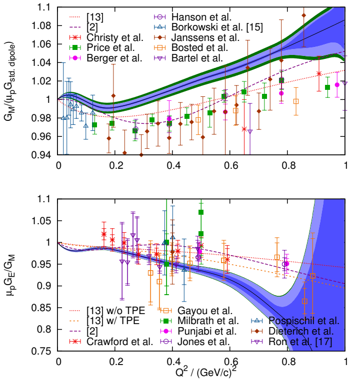


- $\langle r_E^2 \rangle^{1/2} = 0.879 \pm 0.008$ fm, consistent
- $\langle r_M^2 \rangle^{1/2} = 0.777 \pm 0.016$ fm, smaller by about 0.1 fm!
- $\langle r_M^2 \rangle^{1/2} = 0.85 \pm 0.03$ fm from other global fit (Zhan et al.)

Latest low Q^2 G_E^p results

X. Zhan *et al.* Phys. Lett. B 705, 59 (2011) Pol. Trans.





- Discrepancy with other data, but G_E^p slope values are in agreement with Bernauer
- Bernauer magnetic radius from new unseen "wiggle"
- JLab data from $0.01 - 0.08\ \mathrm{GeV}^2$ with polarized target under analysis.

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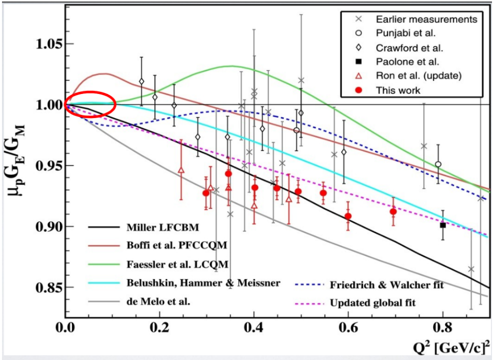

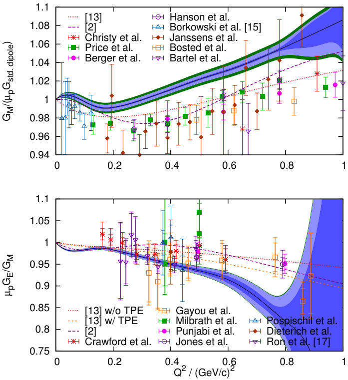

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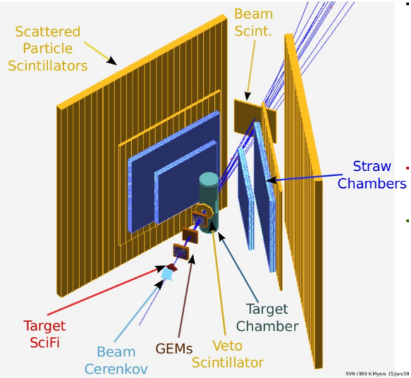
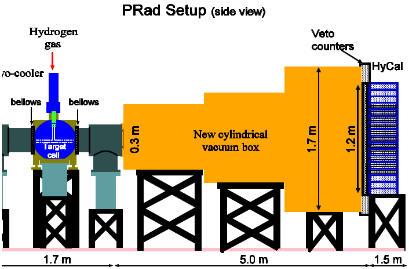
New Charge Radius Measurements

MUSE at PSI



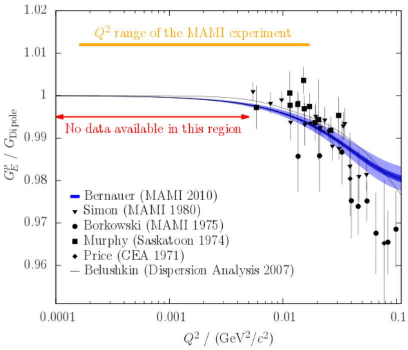
- Gilman et al.
- Elastic μ^- and μ^+
- $Q^2 = 0.002 - 0.07$ GeV^2

PRad

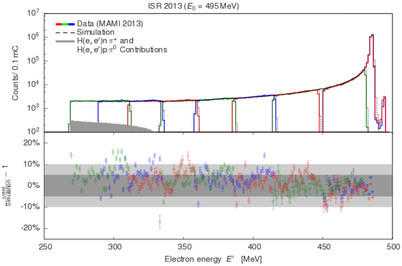


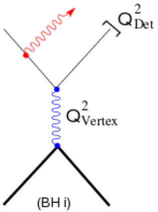
- Gasparian et al.
- Very low Q^2 e^-
- $Q^2 = 2 \times 10^{-4} - 0.14$ GeV^2
- No magnetic elements - high precision calorimeter

Precision Radius Measurements - Under Analysis

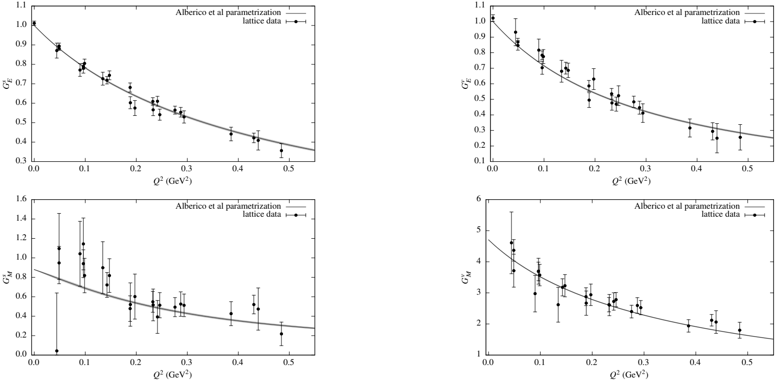


- Data taken at Mainz will use initial state radiation reaches to effectively low Q^2
- Will extend to $Q^2 \sim 10^{-4}$ GeV^2
- Under analysis - preliminary results in weeks?





Scalar | Vector

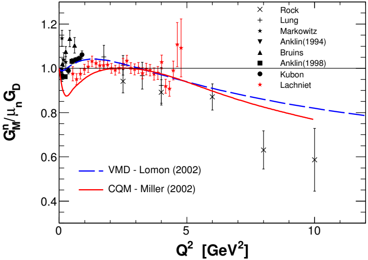


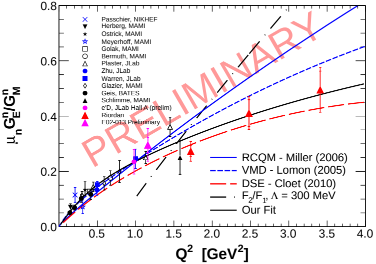
- $m_\pi = 149\ \mathrm{MeV}$, Q^2 to 0.5 GeV^2
- Can't differentiate between two proton radii results (though quoted errors are about the difference)

Green et al. arXiv:1404.4029 [hep-lat]

Neutron Status

- Neutron form factor data is challenging: No free neutron targets and G_E^n is small
- Data has been consistant at low Q^2
- Medium Q^2 polarization data has one high point which has been suggested to be looked at

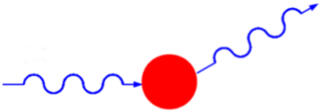


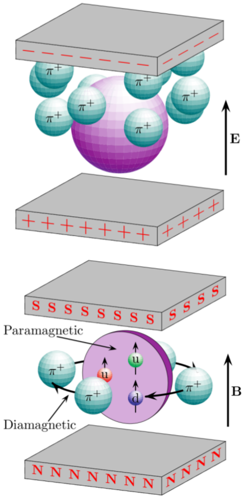


- Neutron MS radius done from thermal neutron scattering on electrons
- $\langle r_n^2 \rangle$ = -0.1161 fm

Nucleon Polarizabilities

- Polarizabilities with real photons also probe fundamental properties
- Six indepdentent scattering amplitudes
  - Lowest order probe $\vec{E}$ and $\vec{B}$ responses
  - Four higher order spin observables $(\vec{\gamma}\vec{p}, \gamma p)$ give spin polarizabilities
- Several basic sum rules to be comprehensively tested





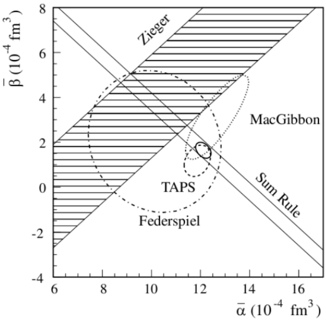
Proton Scalar Polarizabilities

- Best data from 55-156 MeV w/ TAPS at MAMI

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\Big|_{\mathrm{Born}} - \omega\omega' \left(\frac{\omega'}{\omega}\right)^2 \frac{e^2}{m} \times \left[\frac{\alpha+\beta}{2}(1+\cos\theta)^2 + \frac{\alpha-\beta}{2}(1-\cos\theta)^2\right]$$

- Baldin-Lapidus sum rule:

$$\alpha + \beta = \frac{1}{2\pi}\int_{\omega_0}^{\infty} \frac{\sigma_{\mathrm{tot}}(\omega)}{\omega^2} d\omega$$



de Leon et al., Eur.Phys.J. A10 (2001) 207

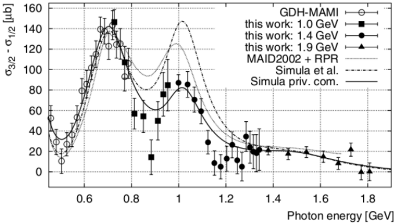
Global results:

$$\alpha = [12.1 \pm 0.3(\mathrm{stat}) \pm 0.4(\mathrm{sys}) \pm 0.3(\mathrm{mod})] \times 10^{-4}\mathrm{fm}^3$$
$$\beta = [1.6 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{sys}) \pm 0.4(\mathrm{mod})] \times 10^{-4}\mathrm{fm}^3$$

Proton Spin Polarizabilities

$$H_{\text{eff}}^{(3)} = -4\pi\left[\frac{1}{2}\vec{\sigma}\cdot\left(\vec{E}\times\dot{\vec{E}}\right)+\frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot\left(\vec{H}\times\dot{\vec{H}}\right)\right.$$
$$\left.-\gamma_{M1E2}E_{ij}\sigma_i H_j+\gamma_{E1M2}H_{ij}\sigma_i E_j\right]$$

- Four terms at $H^{(3)}$
- Requires several spin observables for complete determination
- γ_0 can come from DR

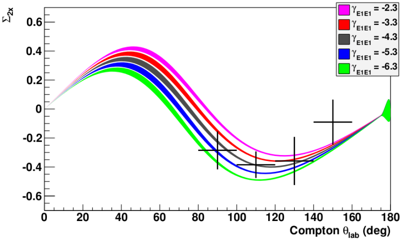


Forward and backward polarizabilities:

$$\gamma_0 = -\gamma_{E1E1}-\gamma_{E1M2}-\gamma_{M1E2}-\gamma_{M1M1} = -\frac{1}{4\pi}\int_{\omega_0}^{\infty}\frac{\sigma_{3/2}-\sigma_{1/2}}{\omega^3}d\omega$$
$$\gamma_\pi = -\gamma_{E1E1}-\gamma_{E1M2}+\gamma_{M1E2}+\gamma_{M1M1}$$

Proton Spin Polarizabilities

- Combination of LEGS and recent Mainz data with polarized beam/target determines polarizabilities
- Dominated by statistical uncertainties - much room for improvement with large statistics



	$O(\epsilon^3)$	$O(p^4)_a$	$O(p^4)_b$	K matrix	HDPV	DPV	L_χ	HBχPT	BχPT	Experiment
γ_{E1E1}	−1.9	−5.4	1.3	−4.8	−4.3	−3.8	−3.7	-1.1 ± 1.8 (theory)	−3.3	-3.5 ± 1.2
γ_{M1M1}	0.4	1.4	3.3	3.5	2.9	2.9	2.5	2.2 ± 0.5(stat) ± 0.7(theory)	3.0	3.16 ± 0.85
γ_{E1M2}	0.7	1.0	0.2	−1.8	−0.02	0.5	1.2	-0.4 ± 0.4 (theory)	0.2	-0.7 ± 1.2
γ_{M1E2}	1.9	1.0	1.8	1.1	2.2	1.6	1.2	1.9 ± 0.4 (theory)	1.1	1.99 ± 0.29
γ_0	−1.1	1.9	−3.9	2.0	−0.8	−1.1	−1.2	−2.6	−1.0	$-1.01 \pm 0.08 \pm 0.10$ [3,4]
γ_π	3.5	6.8	6.1	11.2	9.4	7.8	6.1	5.6	7.2	8.0 ± 1.8 [5]

P.P. Martel et al, PRL 114, 112501 (2015)

Neutron Polarizabilities

- Neutron much less well determined especially outside of DR
- Analysis primarily done in γd reactions, potentially ^{3}He

$$\begin{aligned}\alpha^n &= 12.5 \pm 1.8(\mathrm{stat})^{+1.1}_{-0.6}(\mathrm{sys}) \pm 1.1(\mathrm{model}) \times 10^{-4}\mathrm{fm}^3 \\ \beta^n &= 2.7 \pm 1.8(\mathrm{stat})^{+0.6}_{-1.1}(\mathrm{sys}) \pm 1.1(\mathrm{model}) \times 10^{-4}\mathrm{fm}^3\end{aligned}$$

Levchuk MI, L'vov AI. Nucl. Phys. A 674:449 (2000)
Kossert K, et al. Eur. Phys. J. A 16:259 (2003)

- Provides test of HBχPT with relations between p and n polarizabilities

$$\alpha^p = \alpha^n, \beta^p = \beta^n = \alpha/10$$
$$\gamma_0^p = \gamma_0^n = \frac{8}{10}\frac{1}{\pi m_\pi}\alpha$$

$$\gamma_\pi^p = -\gamma_0^p\left[\frac{12}{g_A} - 1\right]$$
$$\gamma_\pi^n = -\gamma_0^p\left[\frac{12}{g_A} + 1\right]$$

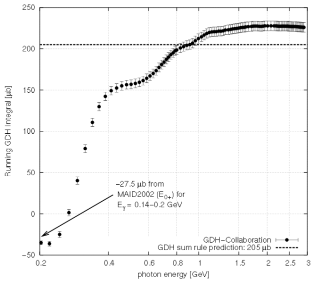
GDH Sum Rule

- GDH sum rule one of the best known and tested dispersion relations in NP

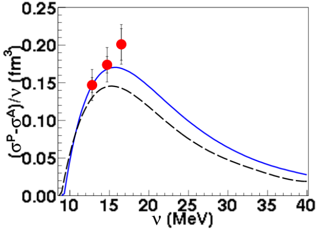
$$\int_{\omega_0}^{\infty} \frac{\sigma_{3/2} - \sigma_{1/2}}{\omega} d\omega = \frac{2\pi^2\alpha}{m^2}\kappa^2$$

- Proton tested to ~8% level
- Neutron remains a challenge with very little data! Low energy and nuclear binding effects are an issue
- Polarized ^{3}He efforts at facilities like HIγS offer opportunities for data and testing 3 body calculations

Helbing, Prog. Part. Nucl. Phys. 57 (2006) 405



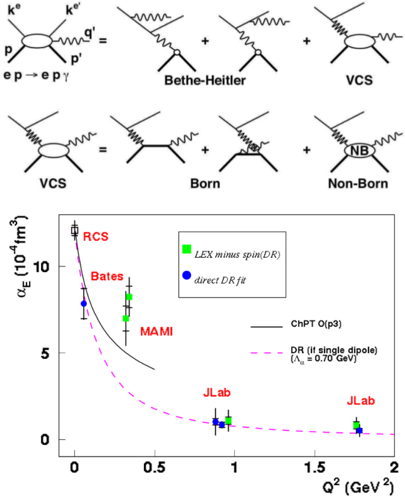
Recent ^{3}He Result:



Laskaris et al, arXiv:1506.00332

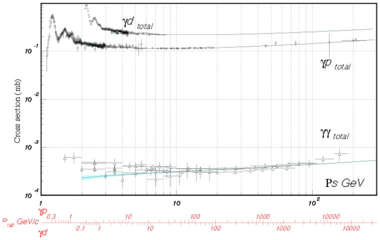
VCS below $\pi\pi$ Threshold

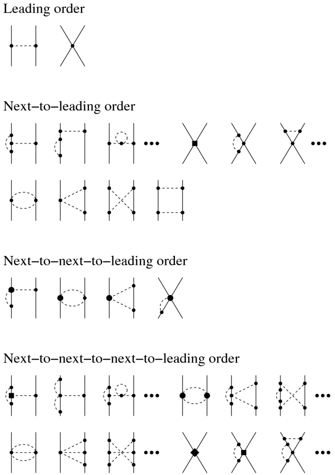
- Virtual Compton scattering has 6 independent generalized polarizabilities
- Scattering below threshold can also test χPT and DR formalisms past threshold
- Tests low energy non-perturbative dynamics of nucleon system
- Similar work to be done for polarizabilities with full beam/target polarization states



Pion Production

- Limited to Δ resonance below 500 MeV
- πN coupling critical for chiral effective theories, isospin symmetry, etc.
- Couplings are some of the best studied properties, but still room for improvement (e.g. γn)
- New opportunities with high current (e.g. virtual photon tagging)

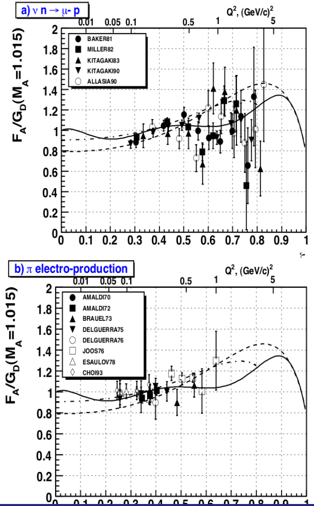




Charged Pion Production Near Threshold

- $\pi^{\pm}$ at threshold sensitive to G_A using chiral theories
- Assume dipole form with g_A constrained
- Complementary to $\nu n \to \mu p$ scattering
- Both methods generally in agreement with latest χ corrections

$$G_A = \frac{g_A}{1 + Q^2/M_A^2}$$

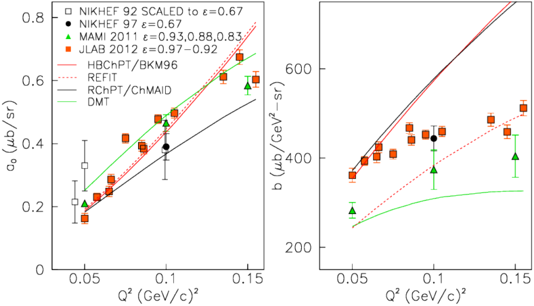


Experiment $\nu_\mu d \to \mu^-\ p\ p_s$	QE events	Q^2 range GeV/c^2	M_A (published)	ΔM_A FF	$M_A^{updated}$ GeV/c^2
$Mann_{73}$	166	$.05 - 1.6$	$0.95 \pm .12$		
$Barish_{77}$	500	$.05 - 1.6$	$0.95 \pm .09$	$-.026$	
$Miller_{82,77,73}$	1737	$.05 - 2.5$	$1.00 \pm .05$	$-.030$	$0.970 \pm .05$
$Baker_{81}$	1138	$.06 - 3.0$	$1.07 \pm .06$	$-.028$	$1.042 \pm .06$
$Kitagaki_{83}$	362	$.11 - 3.0$	$1.05^{+.12}_{-.16}$	$-.025$	$1.025^{+.12}_{-.16}$
$Kitagaki_{90}$	2544	$.10 - 3.0$	$1.070^{+.040}_{-.045}$	$-.036$	$1.034^{+.040}_{-.045}$
$Allasia_{90}$	552	.1-3.75	$1.080 \pm .08$	$-.080$	$1.00 \pm .08$
Av. ν_μd	5780	above			$1.014 \pm .026$
π *electrprod.*					$1.014 \pm .016$
$\overline{\nu}_\mu H \to \mu^-\ n$	13	0-1.0	0.9 ± 0.35	$-.070$	$0.83 \pm .35$
$\overline{\nu}_\mu H \to \mu^-\ n$	13	0-1.0	σ_{QE}		$1.04 \pm .40$
Average − all					$1.014 \pm .014$

- π^0 production at threshold offers strong tests for χPT
- Coupling vanishes in the chiral limit and $p_\pi \to 0$
- Recent results with unpolarized and spin observables from JLab and MAMI and have agreement with low Q^2 theories, but differences at high Q^2

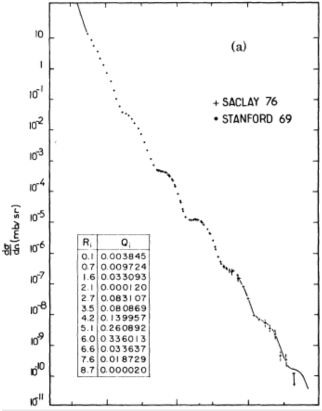
$$A_0^{T+L} = a_0 + b|p_\pi^*|^2$$

- *b* coefficient parameterizes *p*-wave multipoles

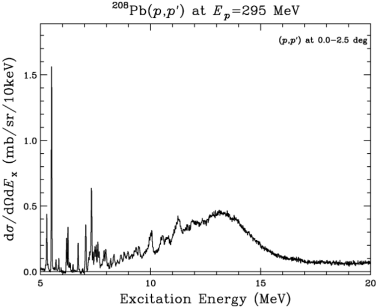


Hornidge et al. PRL 111, 062004 (MAMI)
Chirapatpimol et al. PRL. 114, 192503 (JLab)

Nuclear Properties through EM Probes

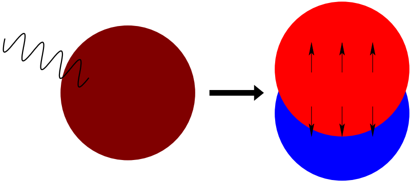


- Nuclear structure and low lying excited states have been done for decades
- Gives some of the best data we have in enumerating these states
- Possibility for studying some reaction channels (backwards) that have a photon in the final state

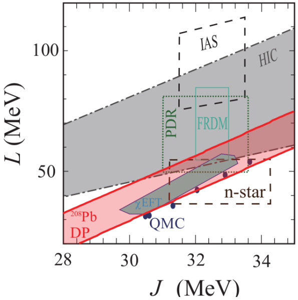


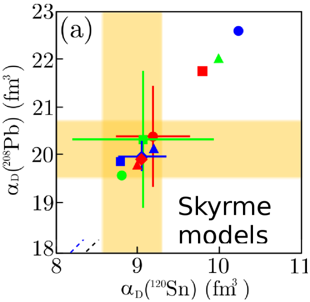
- Dipole polarizability offers constraints on symmetry energy density dependence

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{\mathrm{abs}}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{B(E1)}{\omega} d\omega$$



- Ties into programs of neutron star studies, PREX/CREX
- Tamii EPJ A (2014) 50:28 ^{208}Pb
- Hashimoto arXiv:1503.08321 ^{120}Sn

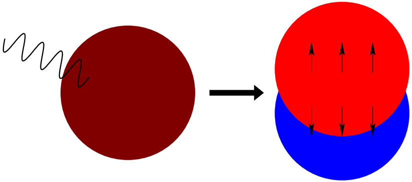




Nuclear Properties - Dipole Polarizabilities

- Dipole polarizability offers constraints on symmetry energy density dependence

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{\rm abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{B(E1)}{\omega} d\omega$$



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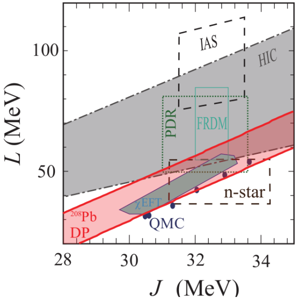
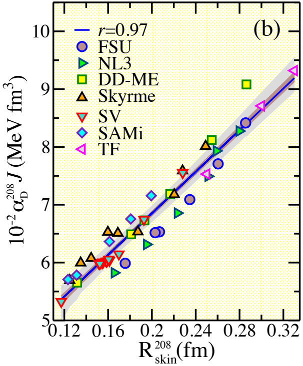
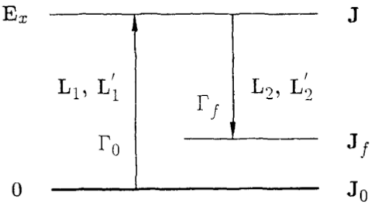
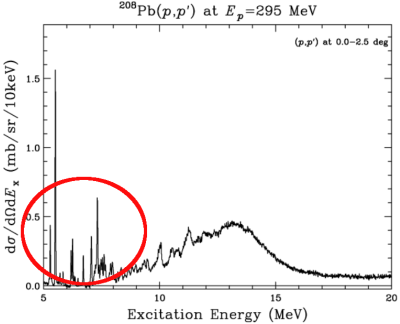




Nuclear Properties - Nuclear Resonance Fluorescense

- NRF gives access to $\gamma A \rightarrow \gamma A$ processes
- Monochromatic beams from Compton backscattering can test very low lying < 10 MeV states to very high resolution
- Used at HIγS to identify state E and J^{π} in ^{138}Ba, ^{88}Sr, ^{92}Sr and ^{94}Mo and others, EM branching ratios, etc.





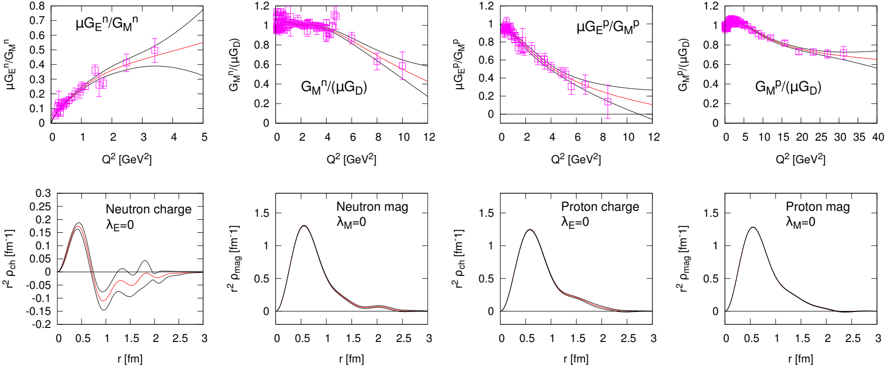
Summary

- Electromagnetic nuclear physics is an incredibly powerful and far-reaching tool for studying the strong nuclear force
- The Proton Radius Puzzle is one of the biggest problems in particle physics and is imperative to explore
- Many fundamental properties of the nucleon still remain to be measured to great precision, especially where polarization observables are necessary and for the proton
- New low energy, non-perturbative physics still remains an important area for exploration

BACKUP

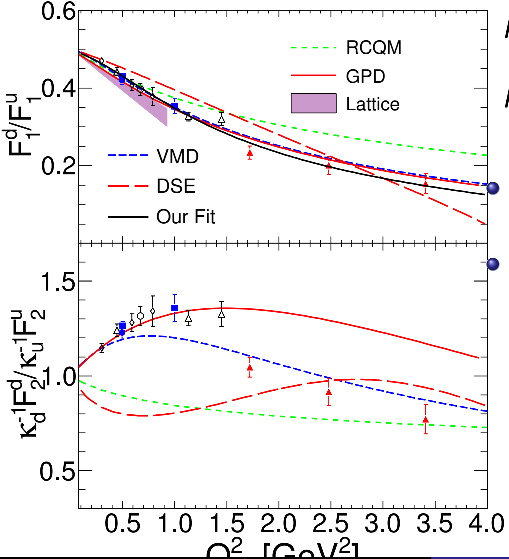
Revisiting Kelly

Latest data fit with complete basis set:



- Focusing more on high Q^2 data uncertainty

Low Q^2 Dirac/Pauli



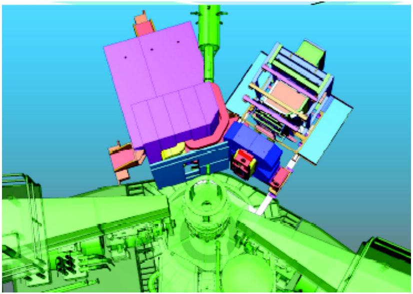
$$F^p_{1,2} = \frac{2}{3}F^u_{1,2} - \frac{1}{3}F^d_{1,2}$$

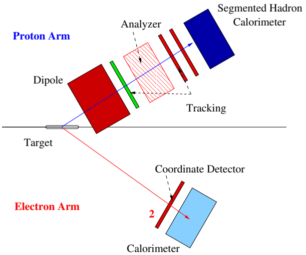
$$F^n_{1,2} = -\frac{1}{3}F^u_{1,2} + \frac{2}{3}F^d_{1,2}$$

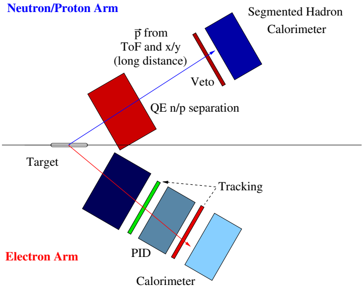
- F_1 predictions have pretty good consistency with data
- F_2 is wildly off
  - Hard to accurately predict nucleon magnetic moments from first principles
  - F_2 contains quark "structure" - is zero (up to radiative corrections) for pointlike

Motivation

- Super Bigbite builds on large acceptance/moderate resolution experience
- Measures *ratios* to control systematics
- G_E^p/G_M^p, G_M^n/G_M^p, G_E^n/G_M^n

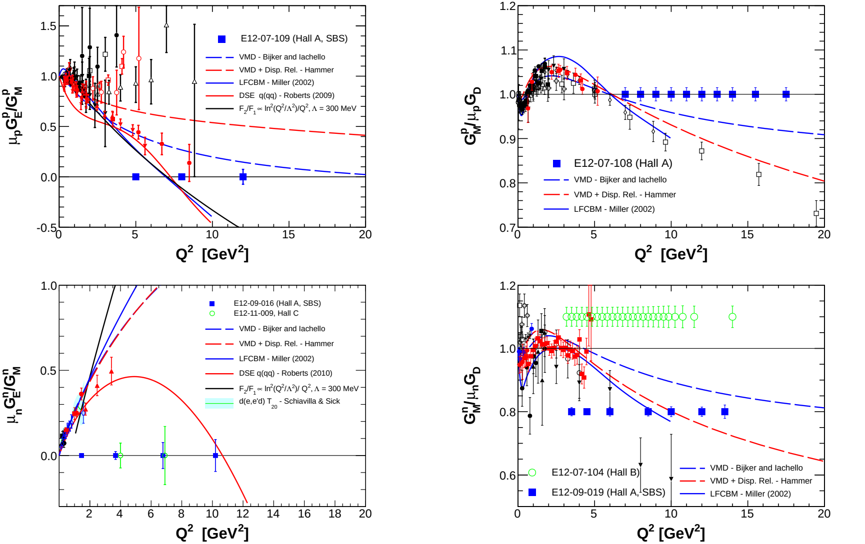




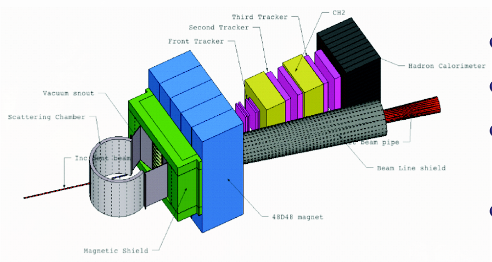


FFs with 12 GeV CEBAF

High Q^2 measurements of all four nucleon form factors planned

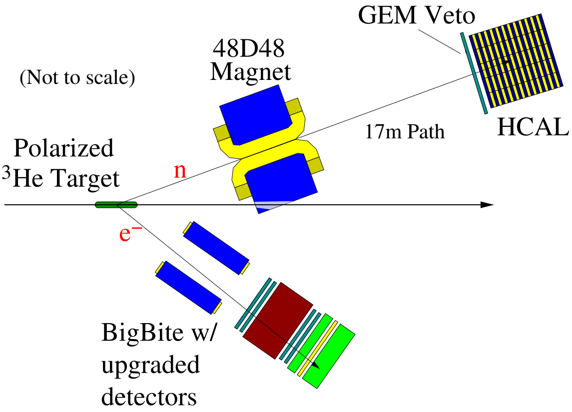


- Recoil polarimetry through two CH_2 analyzers
- e^- detected in ECal with coordinate detector
- Q^2 up to 12 GeV^2



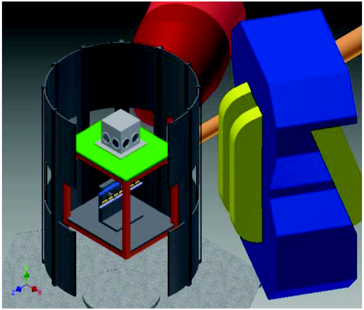
- 75 μA on 40 cm target
- θ_h down to 17°
- Background rates up to 150 kHz/cm^2
- ECal radiation damage serious issue

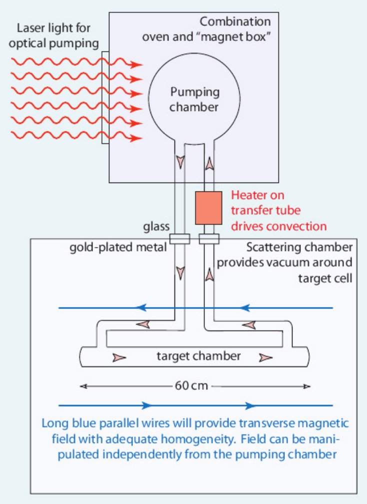
High Q^2 G_E^n Experimental Layout



- Upgraded Bigbite detector stack for higher rates, better PID
- Hadron calorimeter at 17 m, need 0.5 ns ToF
- 48D48 deflects protons
- New addition of Cherenkov and GEMs for π^- rejection and high rate tracking

Polarized ^{3}He Target

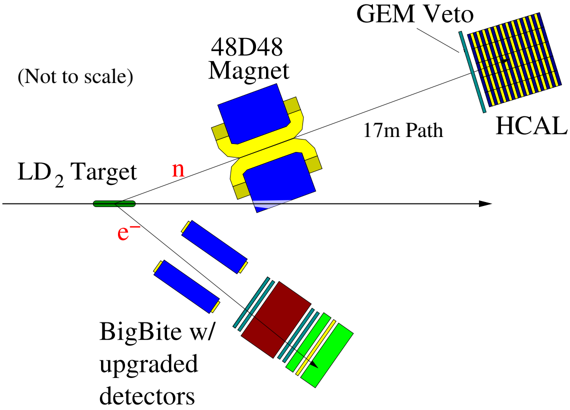




- Upgraded $^3\mathrm{He}$ cell allows for $I = 8 \rightarrow 60\ \mu\mathrm{A}$, $l = 40 \rightarrow 55\ \mathrm{cm}$
- Convection and metal cell ends allow for higher sustained $\vec{P}$ ($\sim 60\%$)

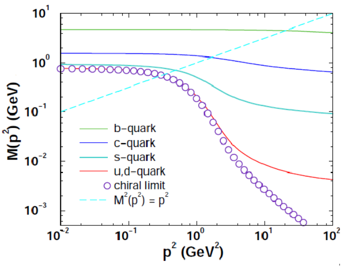
G_M^n Setup

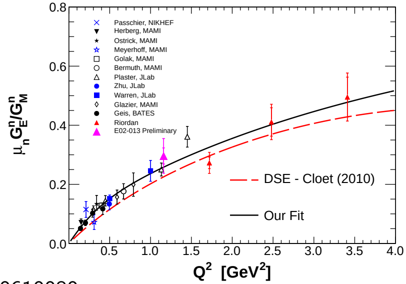
- 7 Q^2 points ranging from 3.5 GeV^2 to 13.5 GeV^2
- Setup similar to G_E^n with LD_2 target



DSE/Fadeev q(qq) Calculations

- Model based on QCD's Dyson-Schwinger equations to describe dressed quark propagator
- Fadeev amplitudes describe three-quark states
- Few free parameters tuned to reproduce nucleon properties such as masses

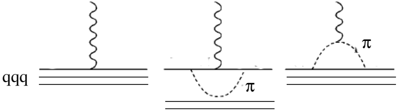


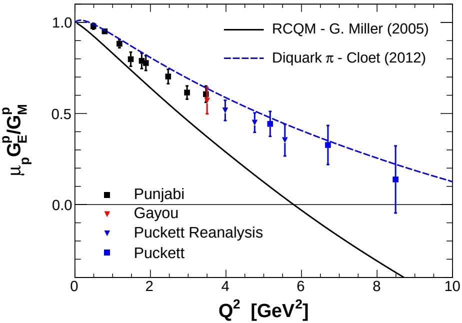


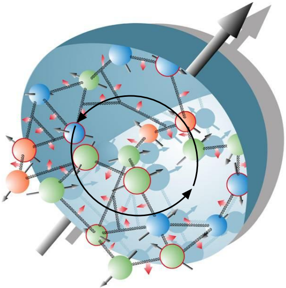
- Bhagwat et. al. arXiv:nucl-th/0610080
- Cloët et. al. arXiv:nucl-th/0804.3118

Constituent Quark Light-Front Cloudy Bag Model

- Construct model of 3 massive quarks or quark/diquark, include pion cloud:







- G_E^p suppression at higher Q^2 due to inclusion of quark orbital angular momentum
- Know only 1/3 of the spin of the proton is carried by the quark *spins*, reproduced with di-quark DOF