The Axial Form Factor of the Proton

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The Axial Form Factor of the Proton: Physics Highlights

$$G_A^p\left(Q^2\right)=\frac{1}{2}\left[-G_A^u\left(Q^2\right)+G_A^d\left(Q^2\right)+G_A^s\left(Q^2\right)\right]$$

G_A^p is a fundamental proton matrix element, as are the vector form factors (G_E^p, G_M^p). The vector form factors are most easily measured in electron-nucleon scattering, while the axial form factor is most easily measured in neutrino-nucleon scattering. The full axial form factor can be measured in neutral-current neutrino elastic scattering, e.g. $\nu p \rightarrow \nu p$ or $\bar{\nu} p \rightarrow \bar{\nu} p$. The up-down part ($-G_A^u+G_A^d$) can also be separately measured in charged-current scattering, e.g. $\nu n \rightarrow \mu p$ or $\bar{\nu} p \rightarrow \mu n$. Then the strangeness contribution, G_A^s, can be isolated, which in turn determines the full strangeness contribution to the proton spin: $\Delta S = G_A^s\left(Q^2=0\right)$.

Measurement of the strangeness contribution to the axial form factor is critical to our studies of nucleon substructure. It is also vital for searches for heavy dark matter particles [Ellis, Olive, & Savage, PhysRevD.77.065026].

The Axial Form Factor of the Proton: Current Status

$(-G_A^u + G_A^d)$ measured in charged-current scattering, e.g. $\nu n \rightarrow \mu p$ or $\bar{\nu} p \rightarrow \mu n$

Many measurements over the last 40 years, with high statistics in recent experiments [K2K, T2K, MiniBooNE, SciBooNE, MINERvA]. Many recent reviews: see especially Formaggio & Zeller, Rev. Mod. Phys. 84, 1307 (2012).

G_A^p measured in neutral-current neutrino elastic scattering, e.g. $\nu p \rightarrow \nu p$ or $\bar{\nu} p \rightarrow \bar{\nu} p$

Only a handful of measurements, and no data for $Q^2 < 0.45$ GeV^2. [BNL E734, MiniBooNE] As a result, we have only scarce data on the strangeness contribution.

Combining data from neutrino-nucleon and electron-nucleon experiments, the strangeness contribution to the vector and axial form factors has been determined for several points in the range $0.45 < Q^2 < 1.0$ GeV^2. [Pate, McKee, & Papavassiliou, PhysRevC.78.015207]

Additional $\nu p \rightarrow \nu p$ data are needed for $Q^2 < 0.45$ GeV^2 to establish the strangeness contribution to the proton spin, ΔS.

[While the polarized parton distribution function $\Delta S(x)$ has been determined in polarized leptonic deep-inelastic scattering for $x > 0.005$, the full integral value ΔS has not. See, for example, Chang & Peng, arXiv:1406.1260.]

The Axial Form Factor of the Proton: Future Prospects

MicroBooNE is a large (2.3 × 2.6 × 10.4 m^3, 86-ton active volume) liquid argon time-projection chamber at Fermilab, positioned in the Booster Neutrino Beam (E_ν~ 1 GeV). Neutrino-nucleon cross section measurements are among the priority physics goals for this experiment that will begin taking data early in 2015. <u>It is ideally suited for measurement of neutral-current events as it can identify very low energy (down to ~40 MeV) isolated proton tracks.</u>

Yes, argon is a ***nucleus***. To obtain neutrino-***nucleon*** cross sections from these data it will be necessary to understand the nuclear physics. Much is already known from electron- and neutrino-scattering experiments on other nuclei. There is an approved (A-) experiment at Jefferson Lab to measure the proton spectral function of argon [Benhar, Mariani, Jen, Day, Higinbotham, arxiv:1406.4080]. There is a considerable theoretical effort to understand the necessary physics [Martini et al., PhysRevC.84.055502; Ruiz Simo et al., PhysRevD.90.033012; Meucci et al., PhysRevD.88.013006; Lalakulich et al., PhysRevC.86.014614; and many more].

A simulation of the neutral-current and charged-current events at MicroBooNE, combined with electron-nucleon data, shows it is possible to determine the strangeness contribution to the axial form factor in the range $0.1 < Q^2 < 1.0$ GeV^2 and determine ΔS to better than ±0.05 [Pate & Trujillo, arxiv:1308.5694].

<u>The Long Range Plan needs to recognize the importance of the opportunity to explore nucleon and nuclear substructure with medium-energy neutrino beams.</u> In these 3 slides I have only been able to give you a small glimpse.

Understanding $q\bar{q}$ Creation

Mac Mestayer

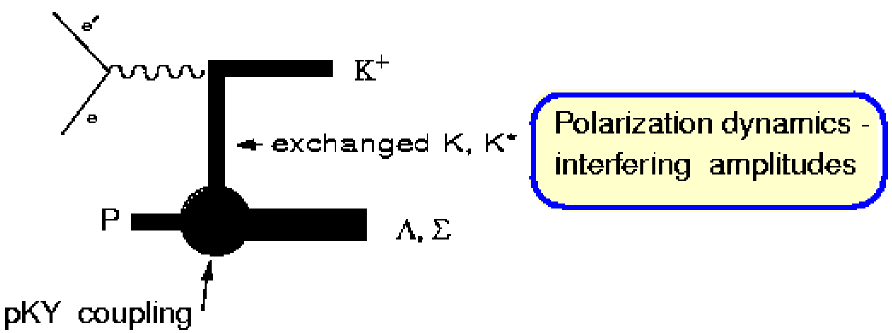
Does the quark model work for exclusive production?
- compared to an hadronic current approach.

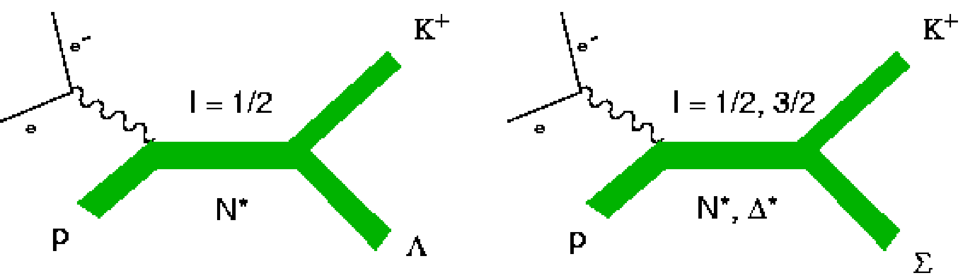
What are 'constituent quarks'?

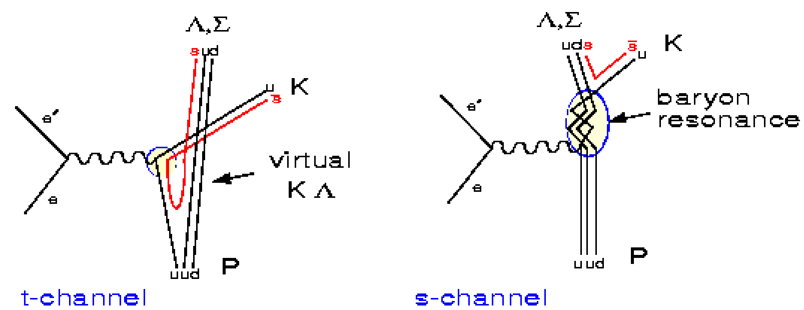
What is the 'flux-tube'?

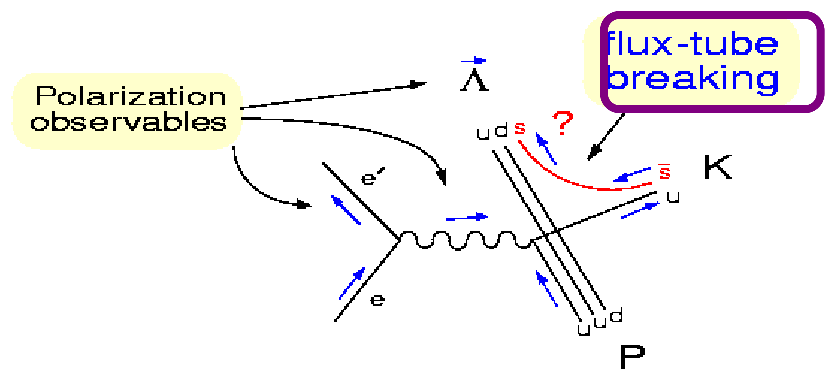
How do $q\bar{q}$ pairs 'break' or 'neutralize' the color force-field?
What is the flavor dependence?
What is the angular momentum structure?

How to describe exclusive production ? hadrons or quarks ?









- Currents are mesons, baryons
- Not “elementary”
- Mature field; but many parameters

- Currents are constituent quarks
- Not “elementary” either !
- Successes in meson decays; not as much work on production

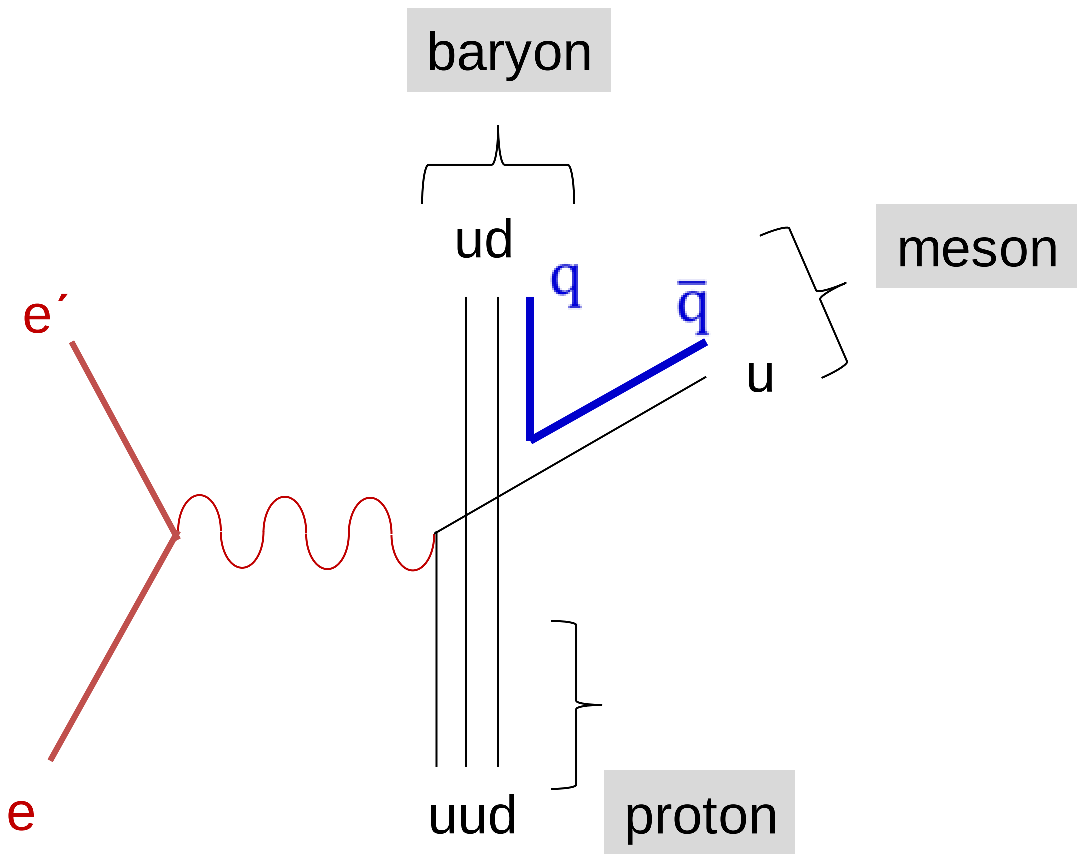
“Strangeness Suppression in $q\bar{q}$ Creation Observed in Exclusive Production” *

Mac Mestayer, Kijun Park & CLAS Collaboration

- What did we measure ?
  - ratio of electro-production cross-sections for 2-body (baryon-meson) final states: $K^+\Lambda$, π^+n and π^0p
  - ratio of processes in which only one $q\bar{q}$ pair is produced
  - in a quark model picture, the ratios are proportional to the relative production rates of $s\bar{s}$, $d\bar{d}$, or $u\bar{u}$
- What was the physics conclusion?
  - that $s\bar{s}$ production is suppressed relative to $d\bar{d}$ and $u\bar{u}$
  - suppression factor may be universal

* accepted for publication in Phys. Rev. Lett.

Exclusive Baryon Meson Production
- quark model picture



$q\bar{q}$	Final State
$u\bar{u}$	π^0 p
$d\bar{d}$	π^+ n
$s\bar{s}$	$K^+ \Lambda$

Strangeness Suppression Results

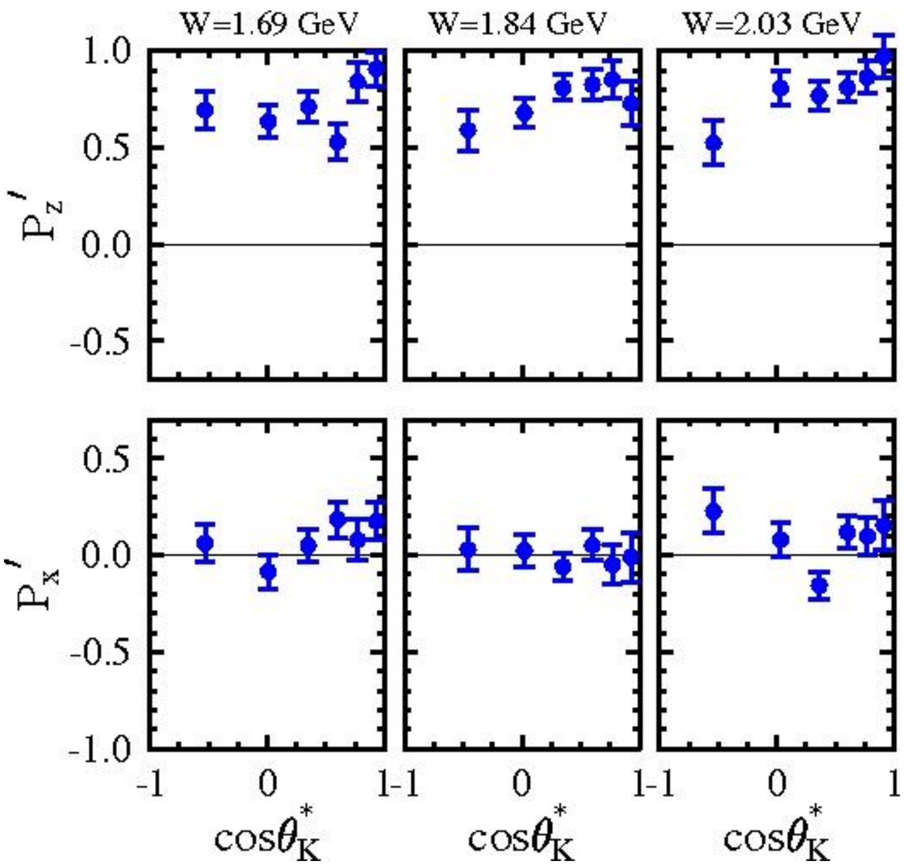
Experimental Ratio Used	$s\bar{s}/d\bar{d}$
$\Lambda K^+/n\pi^+$	0.19 +/- 0.03
$\Lambda K^+/p\pi^0$ "a"	0.22 +/- 0.07
$\Lambda K^+/p\pi^0$ "b"	0.28 +/- 0.07

"a" → assume $u\bar{u}/d\bar{d} = 0.74$ "b" → assume $u\bar{u}/d\bar{d} = 1$

Strangeness suppression is ~same in the exclusive limit as it is at the Z mass → suggests that it is a **universal phenomenon** ?

- what are the dynamics ?

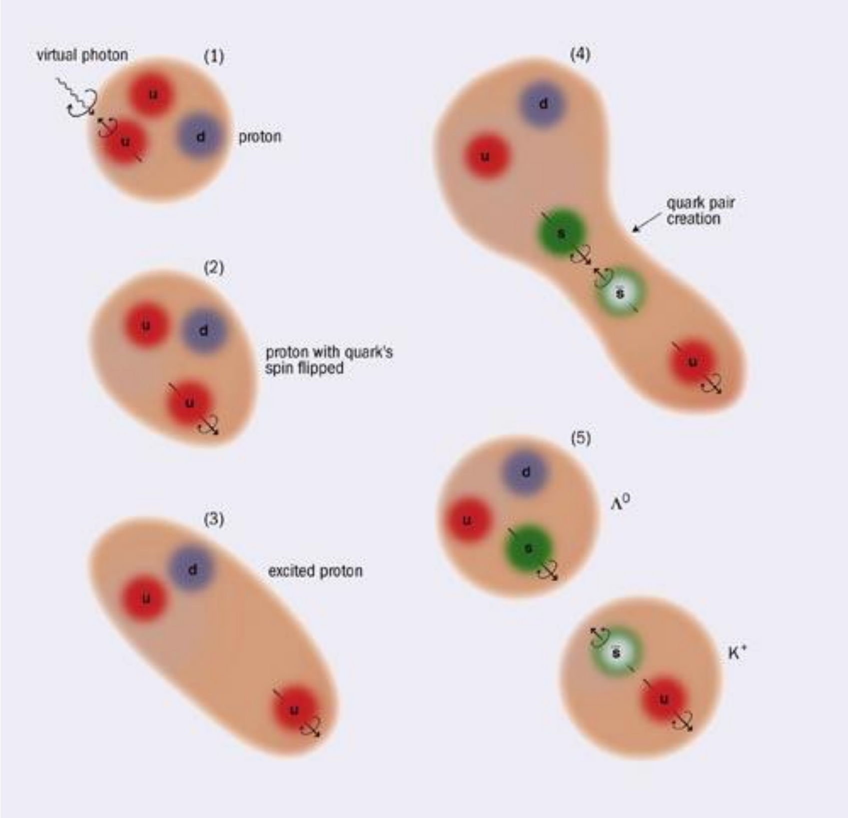
Polarization Transfer in $\vec{e}p \to K^+\vec{\Lambda}$ *



Polarization transfer to Λ is **very large**

* Phys.Rev.Lett. 90 (2003) 131804

Λ – polarization and $q\bar{q}$ Spin State



CERN Cour. June, 2003 *
CERN Cour. September, 2007 **

Simple quark reaction process:

Two-step process

- polarized γ → polarized u-quark
- scalar K^+ → polarized $\bar{s}$ quark
- observed Λ polarization

  → $s\bar{s}$ in spin-0 state

Not consistent with $^3P_0$??

* "Jlab results put new spin on the vacuum"

** "Polarized hyperons probe dynamics of quark spin"

Conclusions and Future Studies

- Can simple quark dynamics explain low-energy phenomena ?
  is $q\bar{q}$ creation a universal phenomenon ?
  - early evidence says yes to both
- Is $u\bar{u} = d\bar{d}$? (our data show 0.74 +/- 0.18)
  - study ratio of $\pi^0 p$ / $\pi^+ n$ from D_2 target
- Can theory explain the dynamics of $q\bar{q}$ creation?
  - what role does angular momentum play ? *
  - study Λ transferred polarization in $K^*\Lambda$ final states
- What other experiments can we do ?

* "On the Mechanism of Open-Flavor Strong Decays", E.S. Ackleh, T. Barnes, E.S. Swanson, Phys.Rev.D54 (1996) 6811-6829

Analysis in brief:

- Detect electron and charged hadron (π^+, p, or K^+)
- Bin: Q^2, W, $\cos\theta$, ϕ
- Identify neutral hadron (n, π^0 or Λ) by missing mass
  - fit (sig. + bkgd.), subtract bkgd., count within cuts
- Corrections to yield
  - efficiency/acceptance, phase-space
- Fit corrected ϕ distribution: ($a + b\cos\phi + c\cos2\phi$)
- Ratio of constant terms: $K^+\Lambda/\pi^+n$, π^0p/π^+n, $K^+\Lambda/\pi^0p$

LUND Model of Hadronization (for electro-production)

- Virtual photon 'knocks' a quark out of the proton
- Quark recoils from the remainder di-quark;
- stretching a 'flux-tube' between them
  - energy density ~ 1 GeV/fermi
- A $q\bar{q}$ pair tunnels out of the potential energy well
- Probability $\approx e^{-\pi m^2/k}$
  - m is the quark mass; k is the flux-tube energy density
- Ratio of $s\bar{s}$: $d\bar{d}$: $u\bar{u}$ $\approx$ 0.3 : 1 : 1

12 GeV Upgrade
Future Science at Jefferson Lab

J/ψ Near Threshold Production with SoLID

Zhiwen Zhao (ODU/Jlab)
Kawtar Hafidi (ANL),*Zein-Eddine Meziani* (Temple)
Xin Qian (BNL), *Nikos Sparveris* (Temple)

SoLID Collaboration

Jefferson Lab
EXPLORING THE NATURE OF MATTER

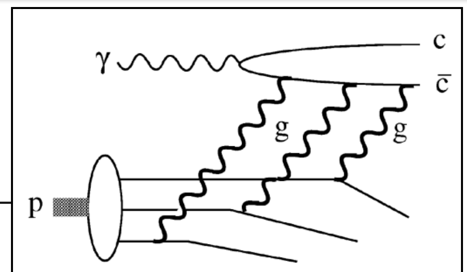
OLD DOMINION UNIVERSITY
IDEA FUSION

J/ψ as a Unique Probe of Strong Color Field in Nucleon

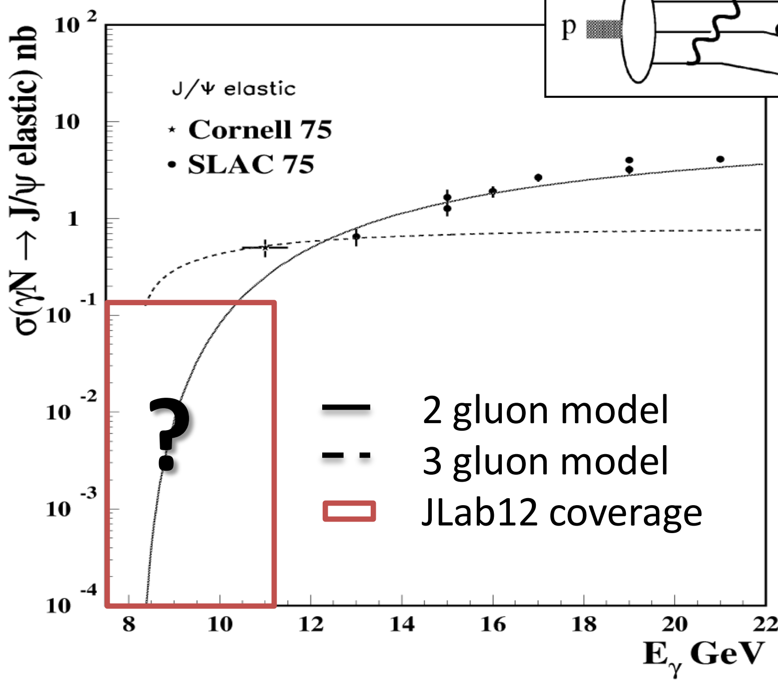
- **Probes strong gluonic interaction between two color neutral objects J/ψ and nucleon near threshold**
- **Models relate J/ψ production near threshold to trace anomaly and proton mass budget**

(D. Kharzeev et al Eur.Phys.J. C9 459 (1999), A. Sibirtsev et al. Phys. Rev., D71:076005 (2005))

Multiple gluon exchange may cause enhancement near threshold

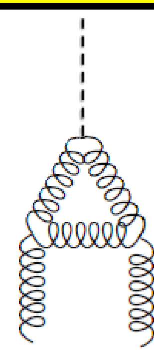


Trace anomaly of QCD energy momentum tensor plays an essential part in proton mass budget

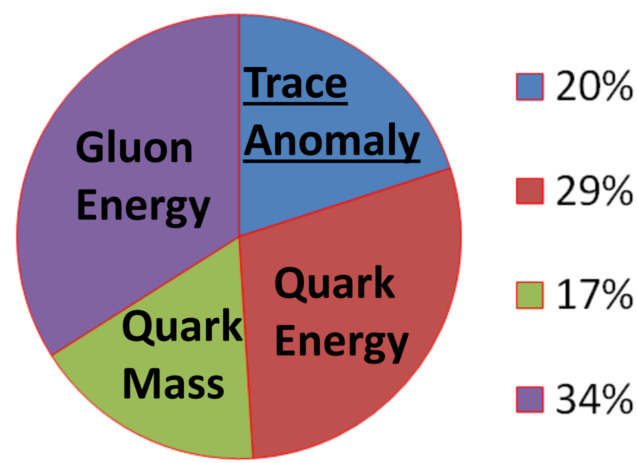


S.J. Brodsky et al. Phys.Lett.B 498 23 (2001)

$$G^{\alpha\beta\gamma}G^{\gamma}_{\alpha\beta}$$

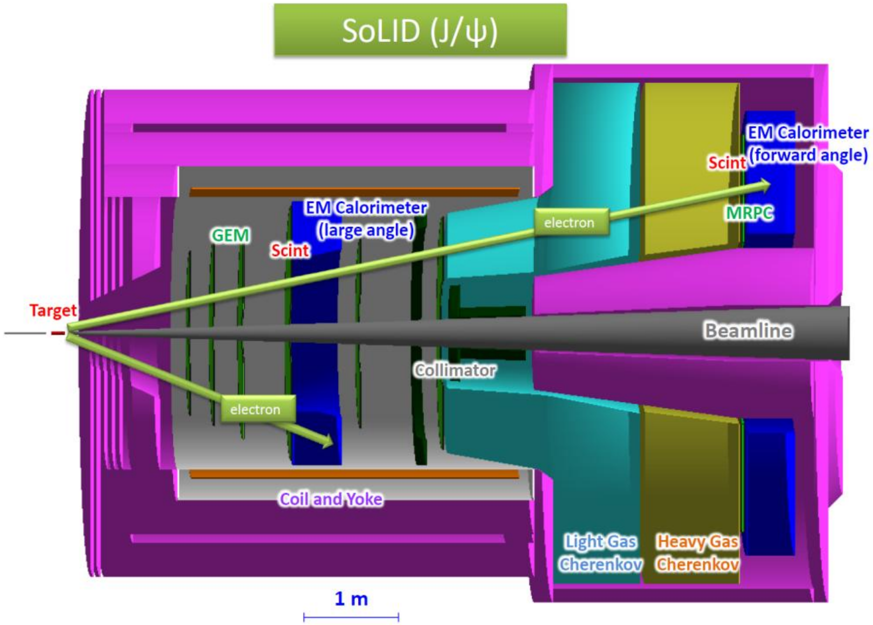


Proton Mass Budget

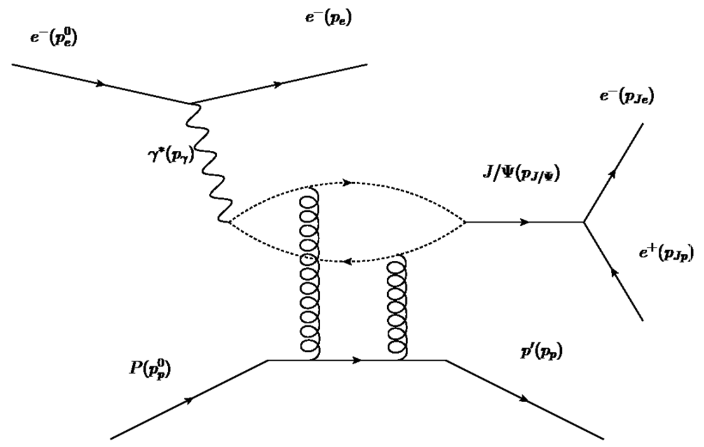


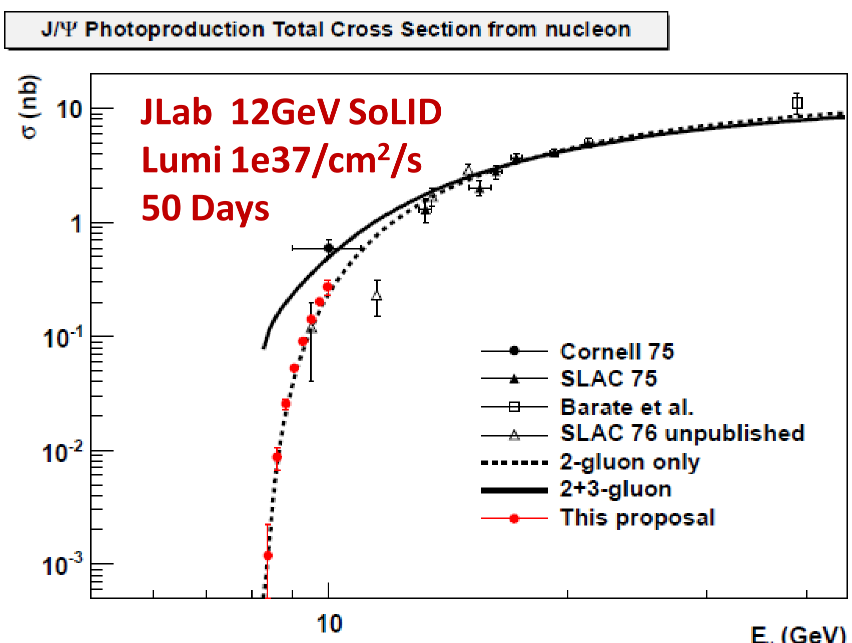
X. Ji PRL 74 1071 (1995)

J/ψ Near Threshold Production with SoLID



$$\gamma^* + N \rightarrow N + J/\psi$$





- <u>high luminosity & large acceptance</u> capability of SoLID enables a unique "precision" measurement near threshold
- Search for possible enhancement
- Study multiple gluons exchange
- Shed light on the low energy J/ψ-nucleon interaction (color Van der Waals force)
- Shed light on the trace anomaly, an important piece in the proton mass budget

Trace Anomaly and Proton Mass Budget

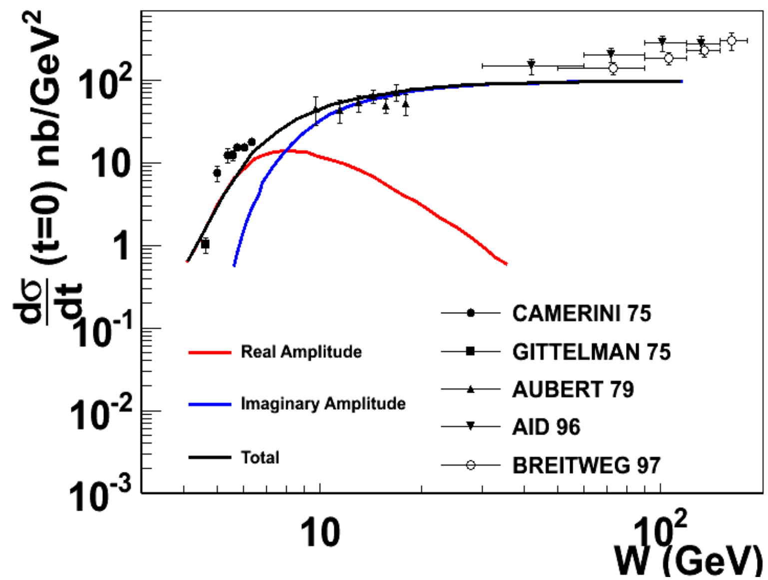
Backup

D. Kharzeev. Quarkonium interactions in QCD, 1995

D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)=\frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$



$$H_{QCD}=H_q+H_m+Hg+H_a$$

$$H_a=\int d^3x\,\frac{9\alpha_s}{16\pi}\left(\mathbf{E}^2+\mathbf{B}^2\right)$$

$$H_q=\int d^3x\;\psi^\dagger\left(-i\mathbf{D}\cdot\alpha\right)\psi$$

$$H_m=\int d^3x\;\bar\psi m\psi$$

$$H_g=\int d^3x\;\frac{1}{2}\left(\mathbf{E^2}+\mathbf{B^2}\right)$$

$$H_a=\int d^3x\;\frac{9\alpha_s}{16\pi}\left(\mathbf{E^2}-\mathbf{B^2}\right)$$

$$\mathcal{T}_{AB}=2\sqrt{M_AM_B}\,\alpha_{AB}\langle N|\frac{1}{2}\vec{E}^a\cdot\vec{E}^a|N\rangle,$$

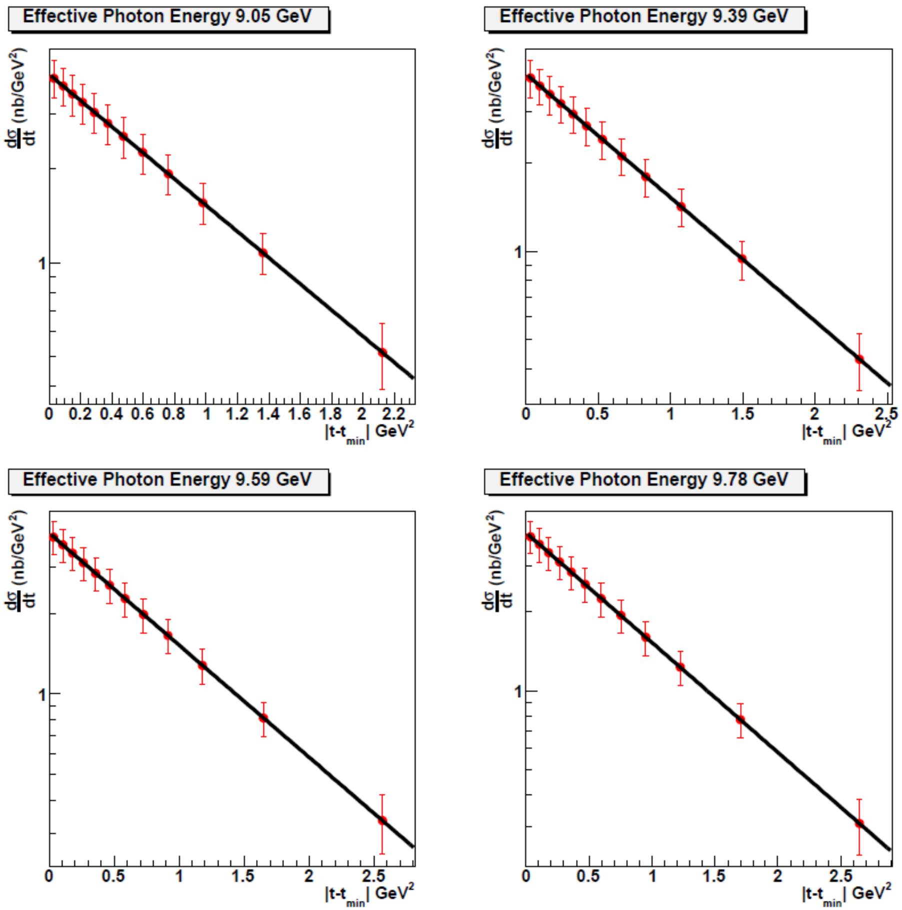
$$\langle N|\frac{1}{2}\vec{E}^a\cdot\vec{E}^a|N\rangle\geq\frac{8\pi^2}{b}2m_N^2,$$

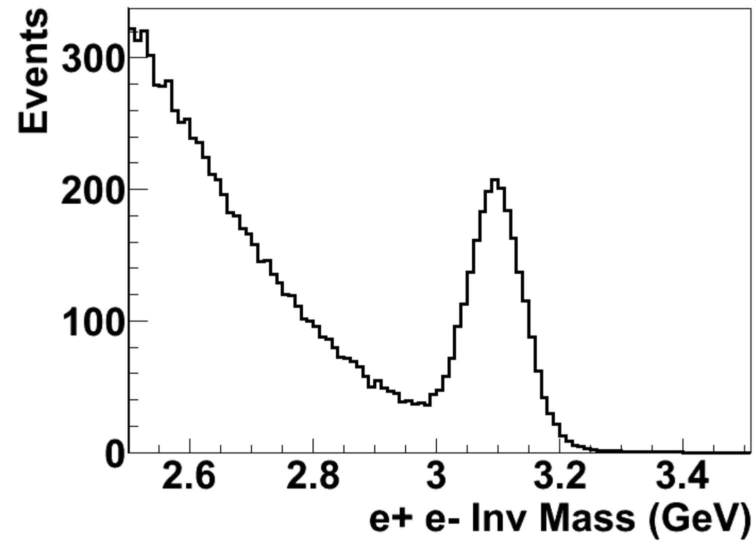
X. Ji PRL 74 1071 (1995)

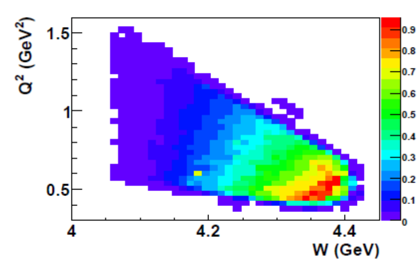
A. Sibirtsev et al. Phys. Rev., D71:076005 (2005)

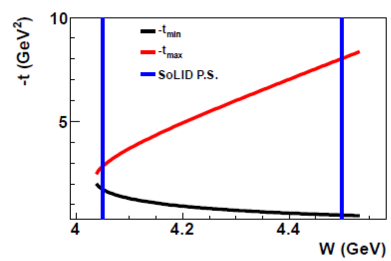
SoLID J/ψ Exp Details

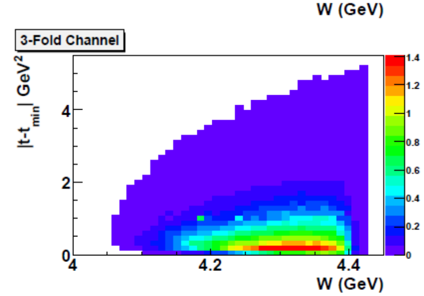
Backup

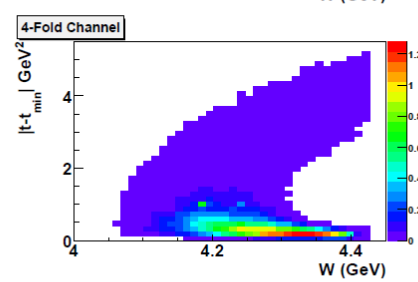










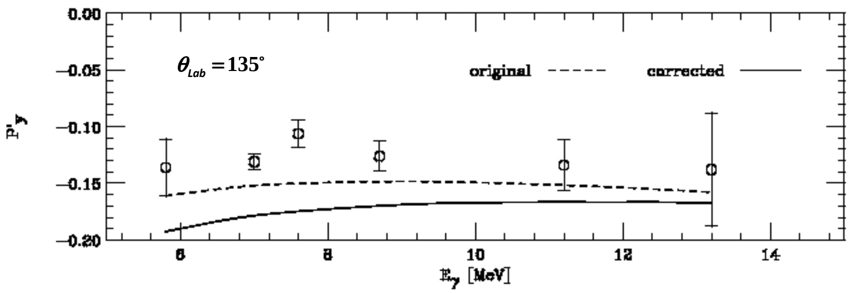


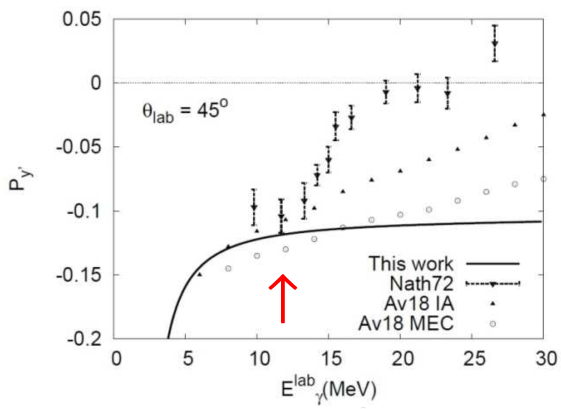
$$E_\gamma^{eff} = \frac{W^2 - M_p^2}{2M_p}$$

Problems with the Two-Nucleon System?

To quote Chadwick and Goldhaber (1934), *"... its [the deuteron's] properties are as important in nuclear theory as the hydrogen atom is in atomic theory."*

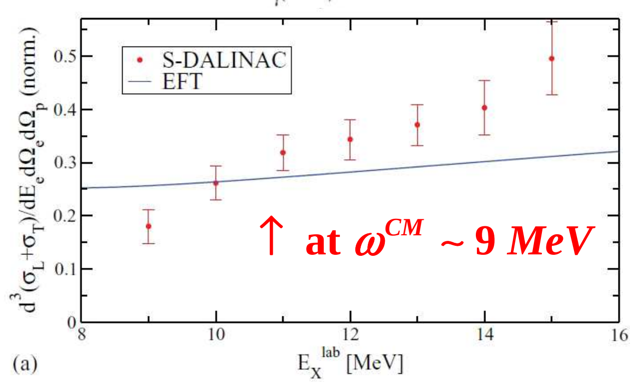
$$\frac{d\sigma}{d\Omega} \propto 1 + a_2 P_2 + a_4 P_4$$





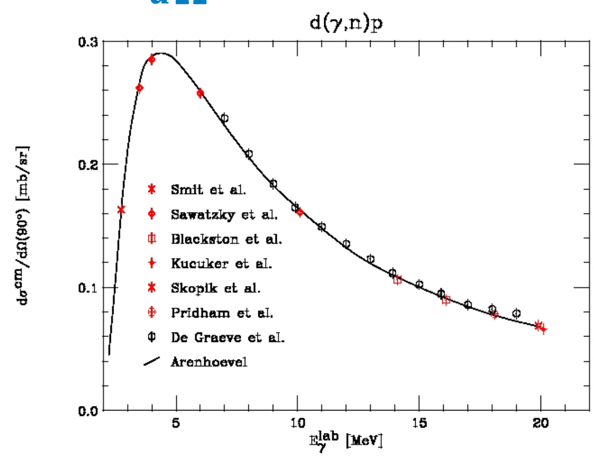
↑

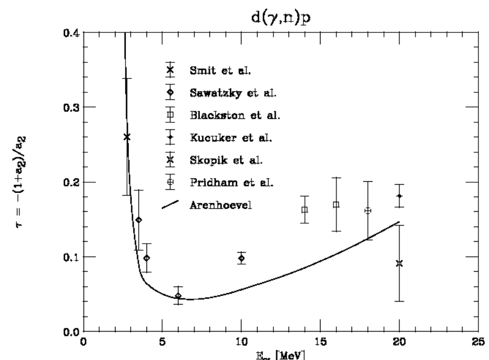
← $d(\gamma,\vec{n})$



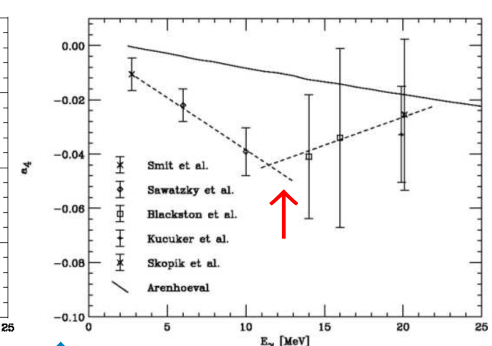
← $d(e,e'p)$

$[\theta_p = 180°]$





a_2



↑

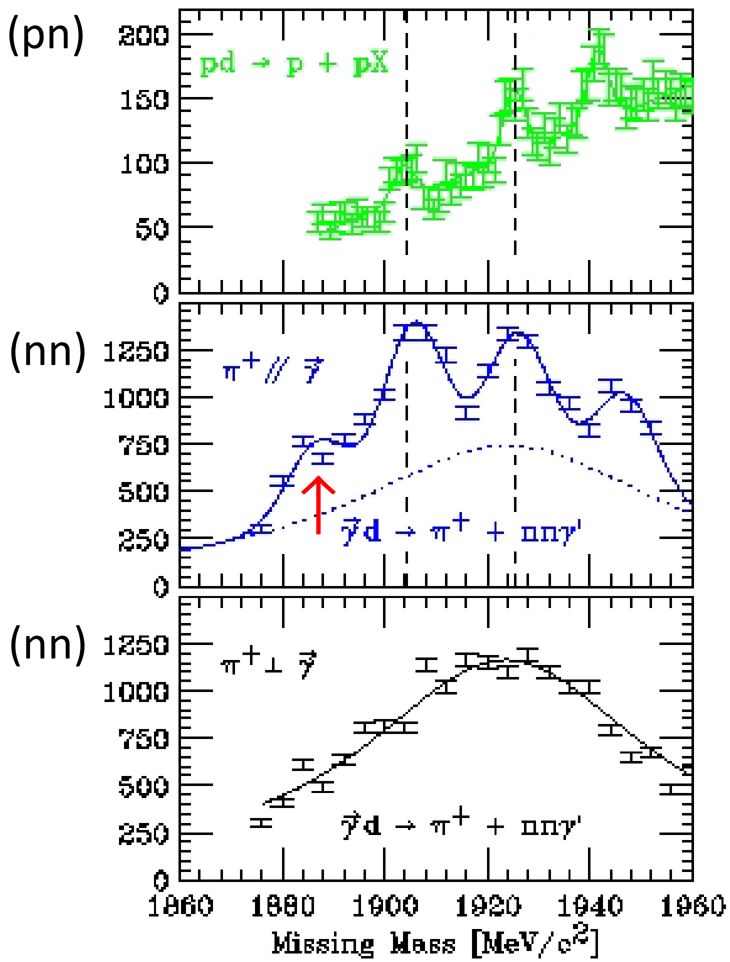
a_4

$d(\vec{\gamma},n)$

Blaine Norum, Univ of Virginia – LRP 13 Sept. 2014

Serious problem exists:

- Absolutely warrants examination!
- Explanation? (6q)?

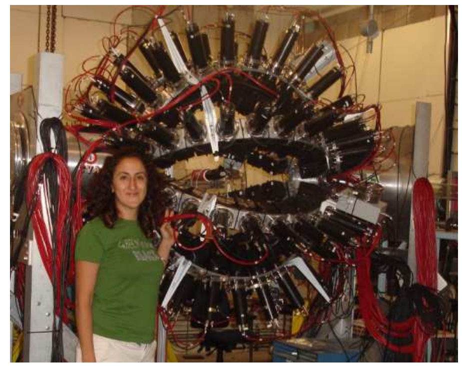


↑ **at ω^{CM} ~ 9 *MeV***

Current activities at HI$\vec{\gamma}$S: $d(\vec{\gamma},n)$, $\vec{d}(\vec{\gamma},n)$, $d(\vec{\gamma},\vec{n})$

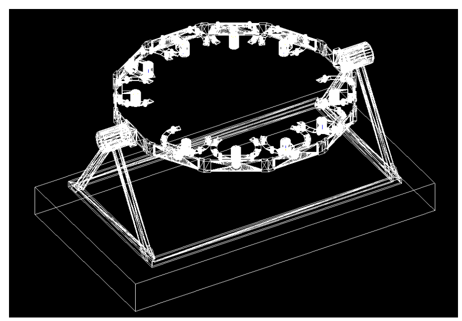
Planned activities at HI$\vec{\gamma}$S: $d(\vec{\gamma},\gamma')pn$, $^{3,4}He(\vec{\gamma},n)$, $^{3,4}He(\vec{\gamma},\vec{n})$

Conditionally approved at MAMI: $d(\vec{\gamma},\pi^+\gamma')$, $d(\vec{\gamma},\pi^0\gamma')$, $d(e,e'\pi^+\gamma')$



Blowfish – 88 cell neutron detector array

HIFROST – polarized hydrogen/deuterium target



Ten (later 20?) cell neutron polarimeter array

<u>Takeaways:</u>

- Much work to be done
- Much greater focus required at HI$\vec{\gamma}$S and elsewhere
- If we can't understand the deuteron … ???

Chiral Dynamics: 2 Photons and Few Nucleons

H. W. Grießhammer (apologise for no-show due to virus)

Institute for Nuclear Studies, George Washington University

Compton Scattering $\gamma X \to \gamma X$ Tests Low-Energy QCD

cf. Phillips, Howell, Ahmed, Tiburzi,...

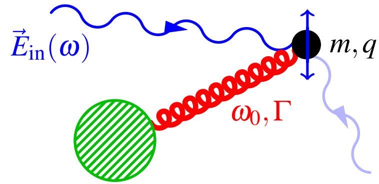
Phillips, Howell: Polarisabilities: scales, symmetries & mechanisms of interactions with & among constituents:

Clean, perturbative probe of χiral symmetry of pion-cloud

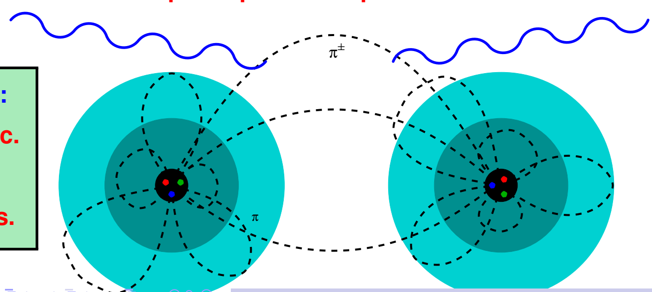
iso-spin breaking, $\Delta(1232)$ properties,

spin-constituents: nucleonic bi-refringence (Faraday effect).

Lattice-QCD gears up for results.



$$\mathcal{L}_{\text{pol}} = 2\pi \Big[\underbrace{\alpha_{E1}(\omega)\vec{E}^2 + \beta_{M1}(\omega)\vec{B}^2}_{\text{electric, magnetic scalar dipole}} + \underbrace{\gamma_{E1E1}(\omega)\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \gamma_{M1M1}(\omega)\vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}}) + \dots}_{\text{spin-dependent dipole}} \Big]$$



Neutron polarisabilities from few-nucleon targets:

Subtract binding model-independently, systematic.

$+$ Understanding of charged-pion NN force.

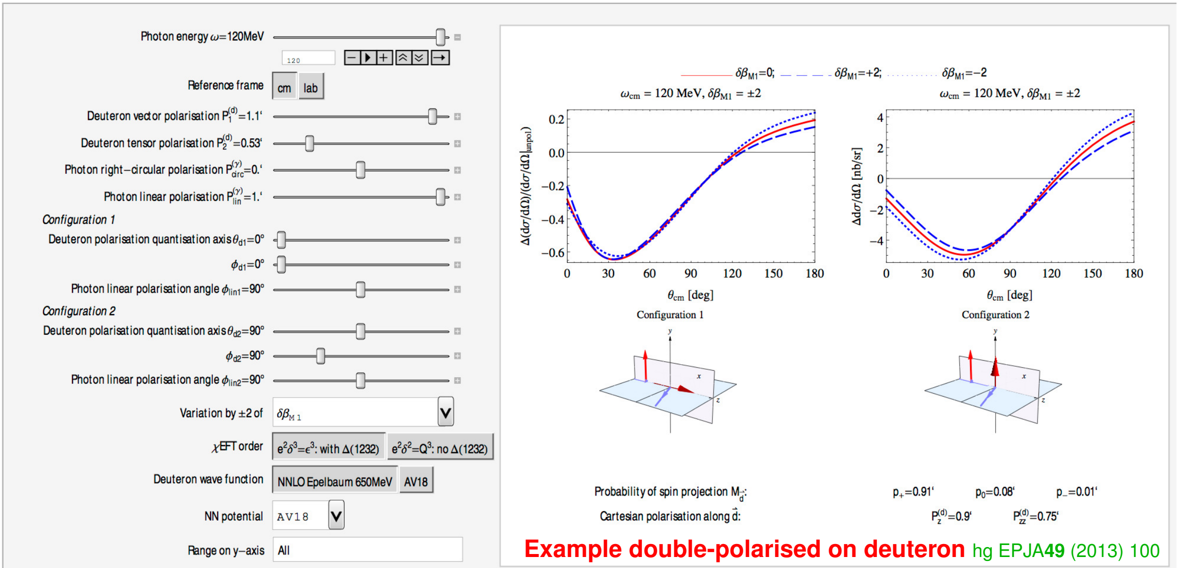
$\Longrightarrow \chi$EFT for $A = 0-6$ for reliable uncertainties.

Guide, Support, Analyse, Predict Polarised Experiments

Unpol./linear/circular beam on scalar/vector/tensor target $\Longrightarrow$ 23 indep. deuteron observables

Constraints: rates, detector settings, partial beam/target polarisations, Sum rules,. . .

HIγS, MAMI: Exp. & theory collaborate on *observables with biggest impact* using *mathematica* notebooks.



$\Delta\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega}\Big|_{\rm unpol}\times[0+0.78\,T^{\rm lin}_{1,-1}-0.78\,T_{1,1}+0.78\,T^{\rm lin}_{1,1}-0.32\,T^{\rm lin}_{2,-2}+0.8\,T_{2,0}-0.8\,T^{\rm lin}_{2,0}+0.32\,T_{2,2}-0.32\,T^{\rm lin}_{2,2}]$

Spin-polarisabilities to 20%: 80 to 200 MeV, 100% polarised: $\lesssim 10^7\,\dfrac{\text{photons}}{\text{s MeV}}\times 1000$ hrs per observable.

χEFT Goals for Compton/Polarisabilities:

- **Comprehensive, unified picture into resonance region:**
  p: done; deuteron: done for $\omega \lesssim m_\pi$; ^{3}He: only $\omega \sim [80-120]$ MeV
- **Connect lattice-QCD and experiment with competitive errors.**
- **Continue close collaboration with US experimenters at HIγS, MAMI.**

Compton@χEFT Collaboration: hg, McGovern (U. Manchester), Phillips (Ohio U.), ...

Deliverables: Extractions with Reproducible Error Estimates

– Identify proton-neutron difference: isospin breaking of pion cloud, μH,...

– Extract spin-polarisabilities to $\lesssim 20\%$ accuracy.

Intensity & Precision Frontier: *"At present, single and double polarised data is sorely missing."* Theory letter [arXiv:1409.1512]

Experiment: $\frac{d\sigma}{d\Omega} \propto$ (target-charge)$^{2\text{ to }1}$ $\Longrightarrow$ more & easier targets, better signals

Theory: Reliable extraction needs accurate description of binding & levels: **computational resources for $A \geq 3$.**

Find *sweet-spot* between competing forces: ^{3}He, ^{4}He, ^{6}Li (HIγS data!): *Find Most Cost-Effective!*

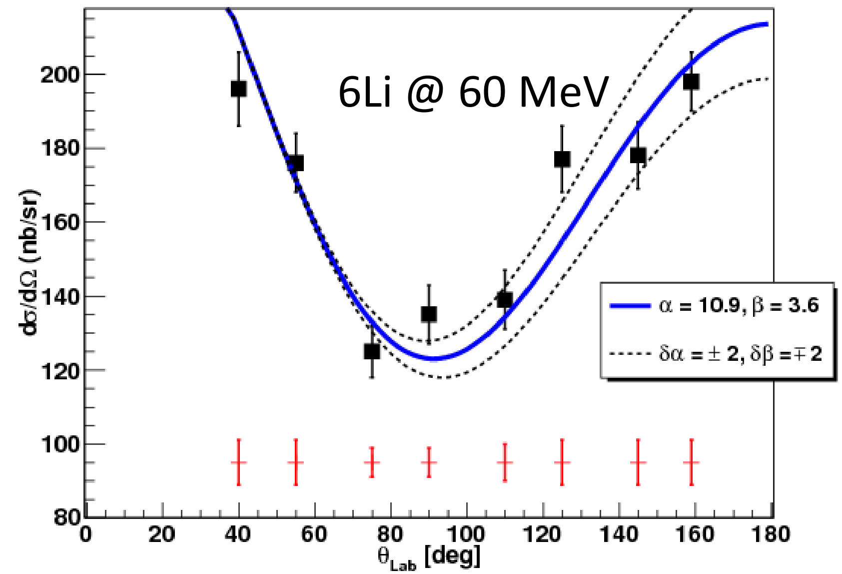
χEFT for few-N systems provides important answers with quantifiable errors (Compton is one example).

Compton Scattering at HIGS – EM Polarizabilities

Mohammad Ahmed, North Carolina Central University & TUNL

[From the Last LRP, QCD and the Structure of Hadrons, p 29]

Polarizabilities. Another important property of the nucleon is its electromagnetic polarizability—the ability of its internal constituents to orient themselves in response to external electric and magnetic fields. The most direct method of determining such polarizabilities is Compton scattering, the direct scattering of a photon from the nucleon. This provides stringent tests of calculations that link the effective low-energy description of nucleons to QCD. As with the nucleon electromagnetic distributions, the formalism to describe the polarizabilities can be extended to probe differing distance scales, using the technique of virtual Compton scattering. Collectively, the results indicate that the nucleon's paramagnetic (or intrinsic) polarizability is of opposite sign to its diamagnetic (or induced) response. The next generation of such experiments will be carried out at the HIγS facility.



- ^{6}**Li at 60 MeV**, L. S. Myers, et al., **Phys. Rev. C 86**, 044614 (2012), ^{6}**Li at 86 MeV,** L. S. Myers, et al., **Phys. Rev. C 90, 027603 (2014)**

Duke U (H. Gao, H. R. Weller, C. R. Howell), GWU (W. Briscoe, E. Downie, G. Feldman, H. Griesshammer), UMass(R. Miskimen), UVa(B. Norum, D. Crabb), UKy(M. Kovash), JMU(S. Whisant),USask (R. Pywell), MTA(D. Hornidge)

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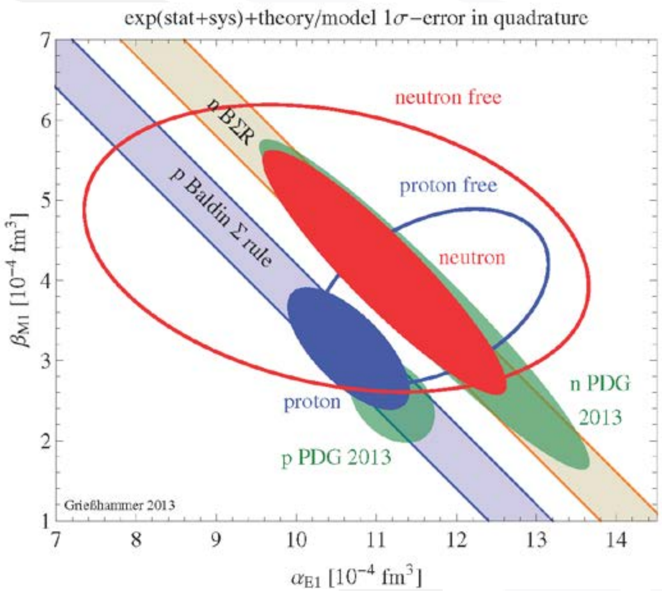
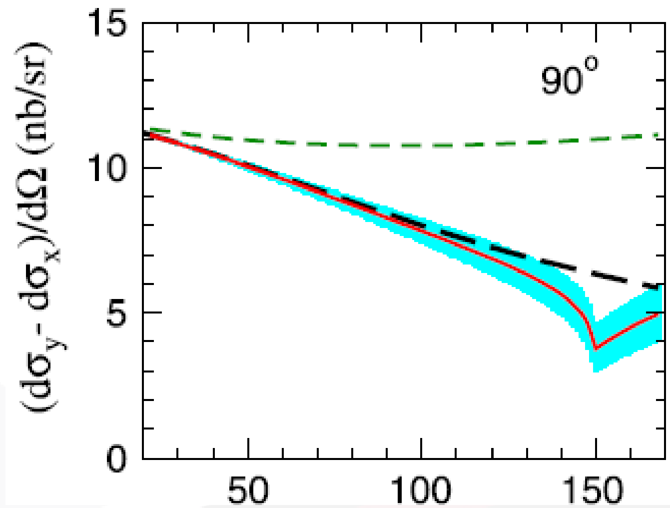
EM Polarizabilities Extractions & Errors

- EFT Extractions (Neutron) – HWG, JAM, DRP, GF, PPNP, 67 (2012) 841-897
- (Proton) – JAM, DRP, HWG, EJP, A 49 (2013) 12



Eur. Phys. J. C (2010) 65: 195–209
DOI 10.1140/epjc/s10052-009-1183-z

BχPT with Δ



I. The experiments at HIGS will make *model independent* measurements of the electromagnetic polarizabilities for the proton (bring the blue open circle at the same level of errors as the filled ellipse), and

II. reduce the error in the neutron magnetic polarizability (filled red ellipse) to one-half of its current value.

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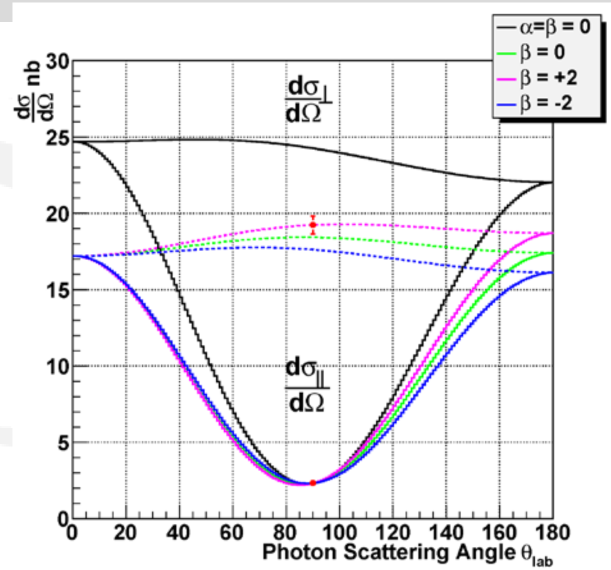
Dissecting deuteron Compton scattering I: The observables with polarised initial states, Harald Griesshammer, Eur. Phys. J. A (2013) 49: 100

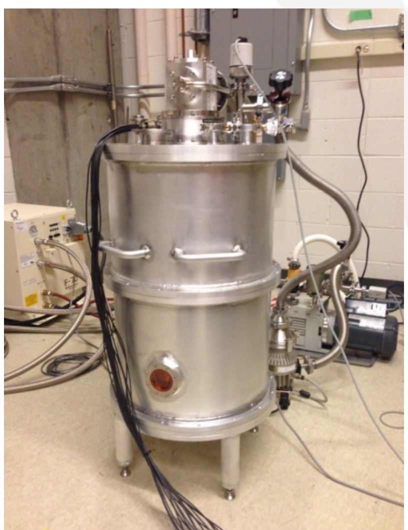
Making use of polarization sensitivity in Linear Polairzed CS

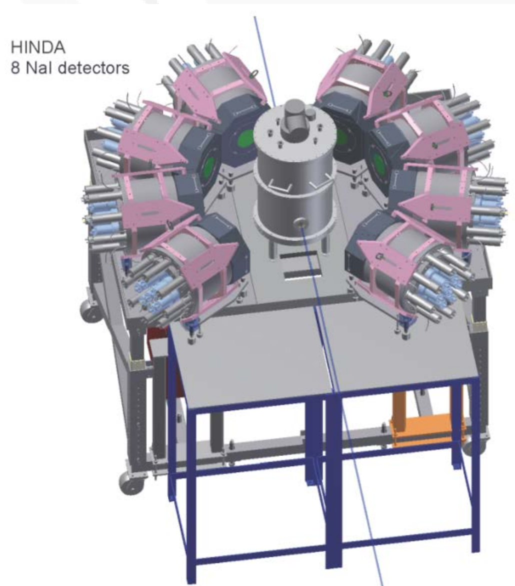
Proton: First such series of measurements of alpha and beta separately using linearly polarized gamma rays (HIGS and MAMI)

Quantity	Polarization	$E\gamma$	% Err
α_p	Linear	85 MeV	2.5 %
β_p	Linear	85 MeV	<10%

Neutron: The 65 and 100 MeV measurements will reduce the error in βn from ~ 50% to ~20 %







Scattered photons attenuated < 5%

- Cryo-Cooler
- Cooling Power: 1.5 W @ 4.2 K
- Base T = 3.5 K
- L = 20 cm, V = 0.24 Lit
- D/H/cm^2 = 10^{24}

- HIGS NaI Detector Array, (HINDA), 8-large NaI Core detectors with active shields

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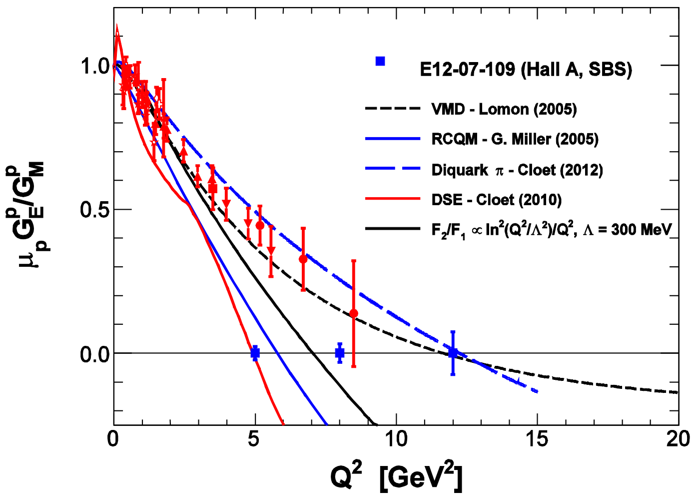
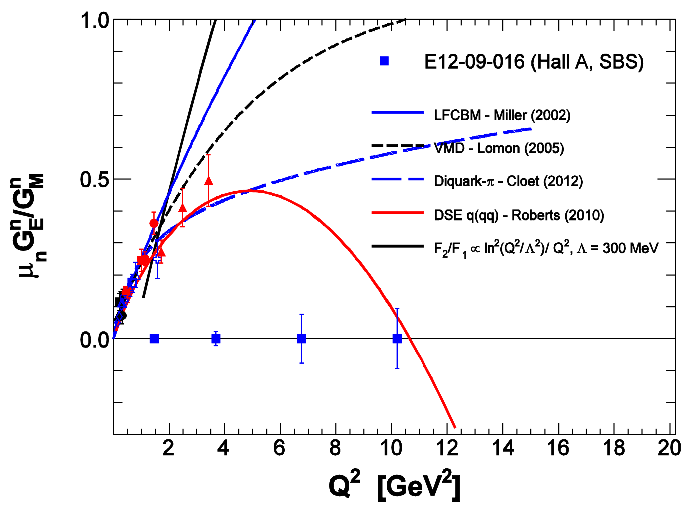
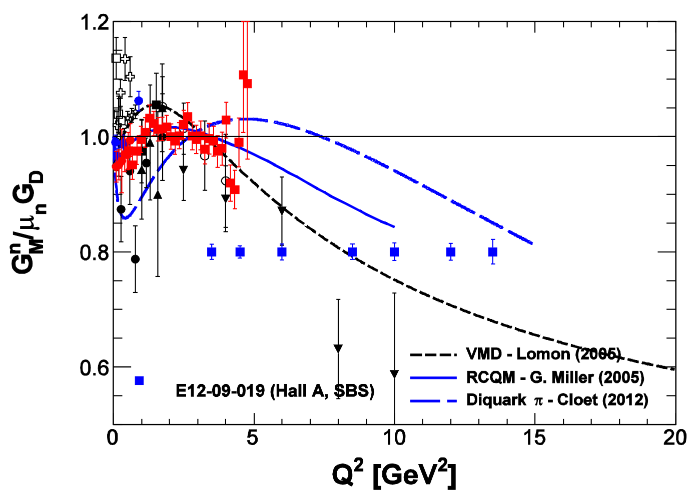
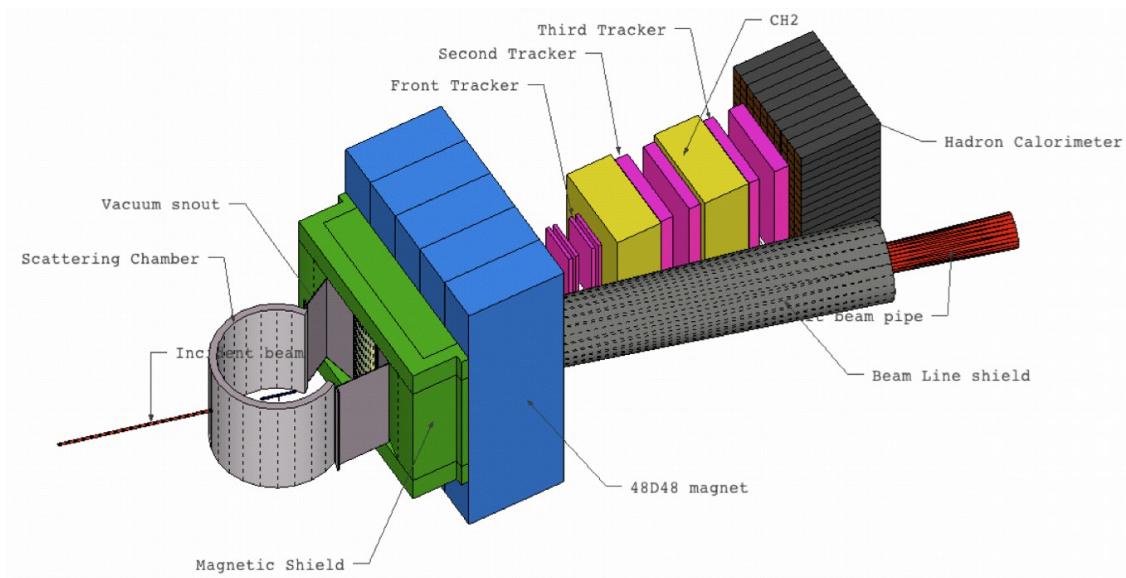
Super Bigbite Program at Jefferson Lab

High Momentum Transfer Nucleon Form Factors

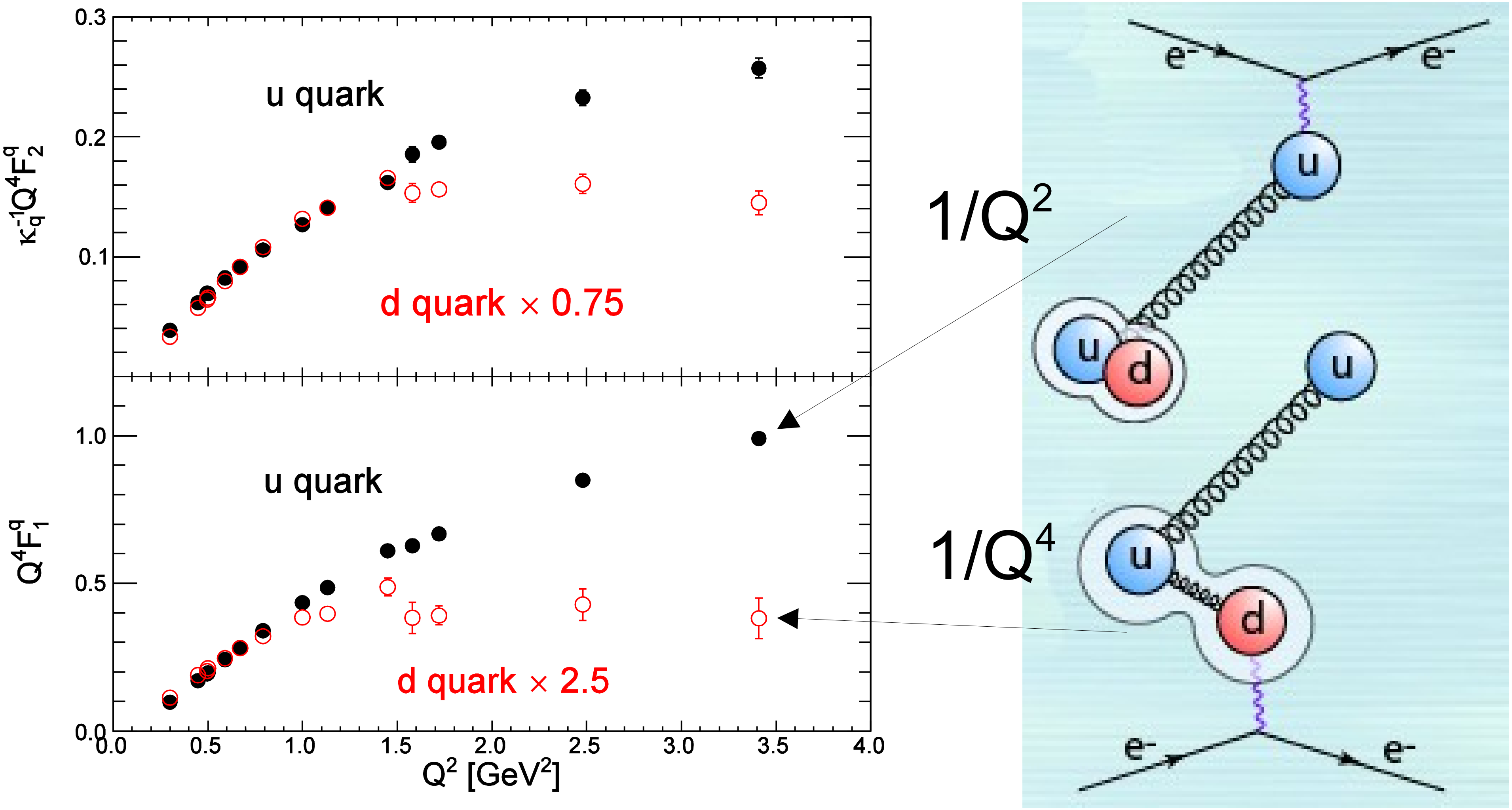








- DOE Project in JLab Hall A begun in 2013
- Measurements expected to begin as early as 2017
- All form factors will be completed to
- Q^2 = 10 GeV^2 with high precision
- Allows for flavor decomposition and QCD model tests



- Flavor decomposition of nucleon FFs reveal new features
- How and when Q2 scaling occurs is an important question for QCD