Hall C Users Meeting, JLab, Feb. 21-22, 2014

E12-11-009
The Neutron Electric Form Factor at Q^2 up to 7 $(GeV/c)^2$ from the Reaction $^2H(\vec{e},e'\vec{n})^1H$ via Recoil Polarimetry

E12-11-009 (G_{En}) Update

Michael Kohl

Hampton University, Hampton, VA 23668
Jefferson Laboratory, Newport News, VA 23606

HAMPTON UNIVERSITY
The Standard of Excellence, An Education for Life

Jefferson Lab

G^n_E in absence of a free neutron target

- Form factors are fundamental quantities describing spatial structure
- Knowledge of G_{En} still limited to $Q^2 = 3.4\ (GeV/c)^2$
- No free neutron target → elastic and quasi-elastic scattering
- Nuclear corrections (FSI, MEC, …)
- Use interference to amplify smallness of G^n_E

G_Q from $A+T_{20}$ / $^2H(e,e'd)$
$G^n_E G^p_E$ interference
Schiavilla+Sick

$^3\vec{He}(\vec{e},e'n)$ quasielastic
Polarized Helium-3
$G^n_E G^n_M$ interference
MAMI A3, A1, Hall A

$^2H(e,e'd)$ elastic, $A(Q^2)$
$G^n_E G^p_E$ interference
Galster, Platchkov, …

G^n_E

$^2\vec{H}(\vec{e},e'n)$ quasielastic
Vector-polarized deuterium
$G^n_E G^n_M$ interference
Nikhef, Bates/BLAST, Hall C

$^2H(\vec{e},e'\vec{n})$ quasielastic
Neutron recoil polarization
$G^n_E G^n_M$ interference
Bates, MAMI A3, A1, Hall C

Neutron electric form factor G^n_E

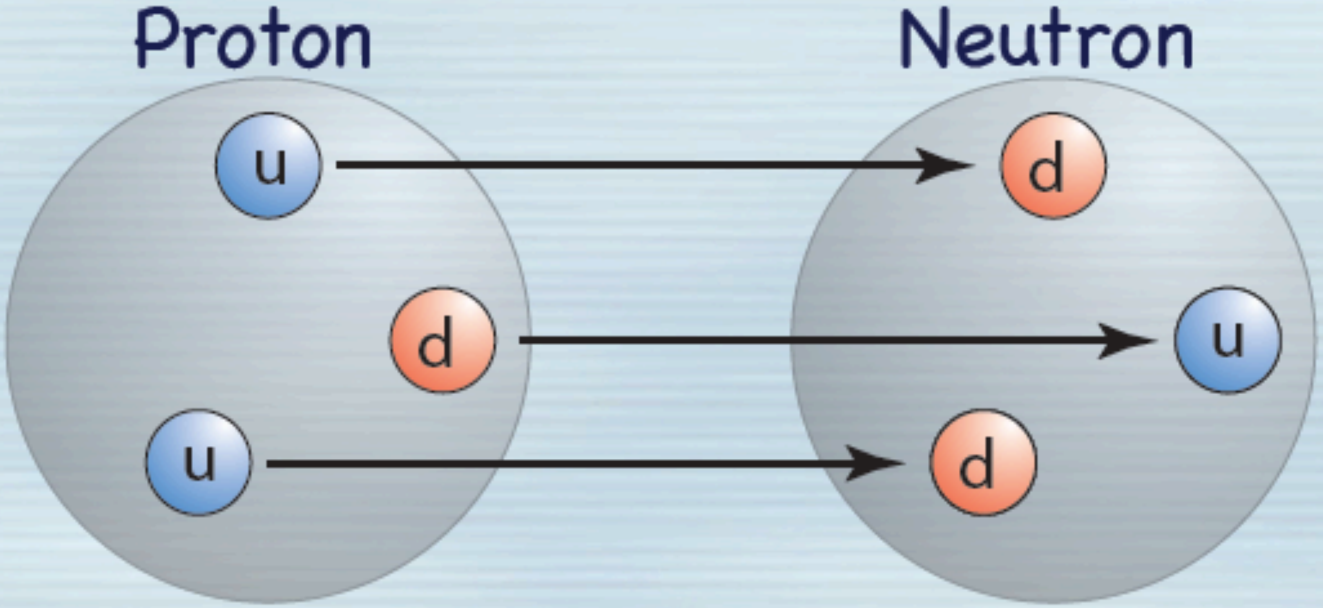
- **Measurements of G_{En} in high Q^2 range provide important insight**
  - **Complete set of form factors in region with small pion cloud contributions**
  - **Extraction of isoscalar and isovector form factors**
  - **Flavor decomposition of up, down quark contributions (neglect strange quarks)** *[Cates (2011) ; Qattan and Arrington et al. (2012)]*
  - **Model-independent extraction of neutron infinite-momentum frame [IMF] transverse charge density** *[Miller (2007) ; Venkat et al. (2010)]*
  - **Important comparisons to QCD-based calculations**
    - **Lattice QCD: isovector form factor (G_{Ep}-G_{En}) cancels disconnected diagrams**
    - **Region of interest for Dyson-Schwinger Equation calculations**

- **Polarized $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)$ (E12-09-016) will extend G_{En} to $Q^2 = 10\ (\mathrm{GeV}/c)^2$**
  - **Systematics limited**
  - **Significant systematics due to larger proton backgrounds, worse inelastic/ quasielastic separation, beam and target polarization uncertainty**

- **Recoil polarization in $^2\mathrm{H}(\vec{e},e'\vec{n})$ (E12-11-009) will provide complementary data with smaller (and very different) systematics up to $Q^2 = 7\ (\mathrm{GeV}/c)^2$**
  - **Statistics limited**
  - **Cleaner, better control of systematics**
  - **Nuclear corrections smaller than in ^{3}He**

Flavor decomposition

By assuming charge symmetry, we can combine form-factor data from protons and neutrons to gain insight into the tranverse structure of the nucleon's constituents.

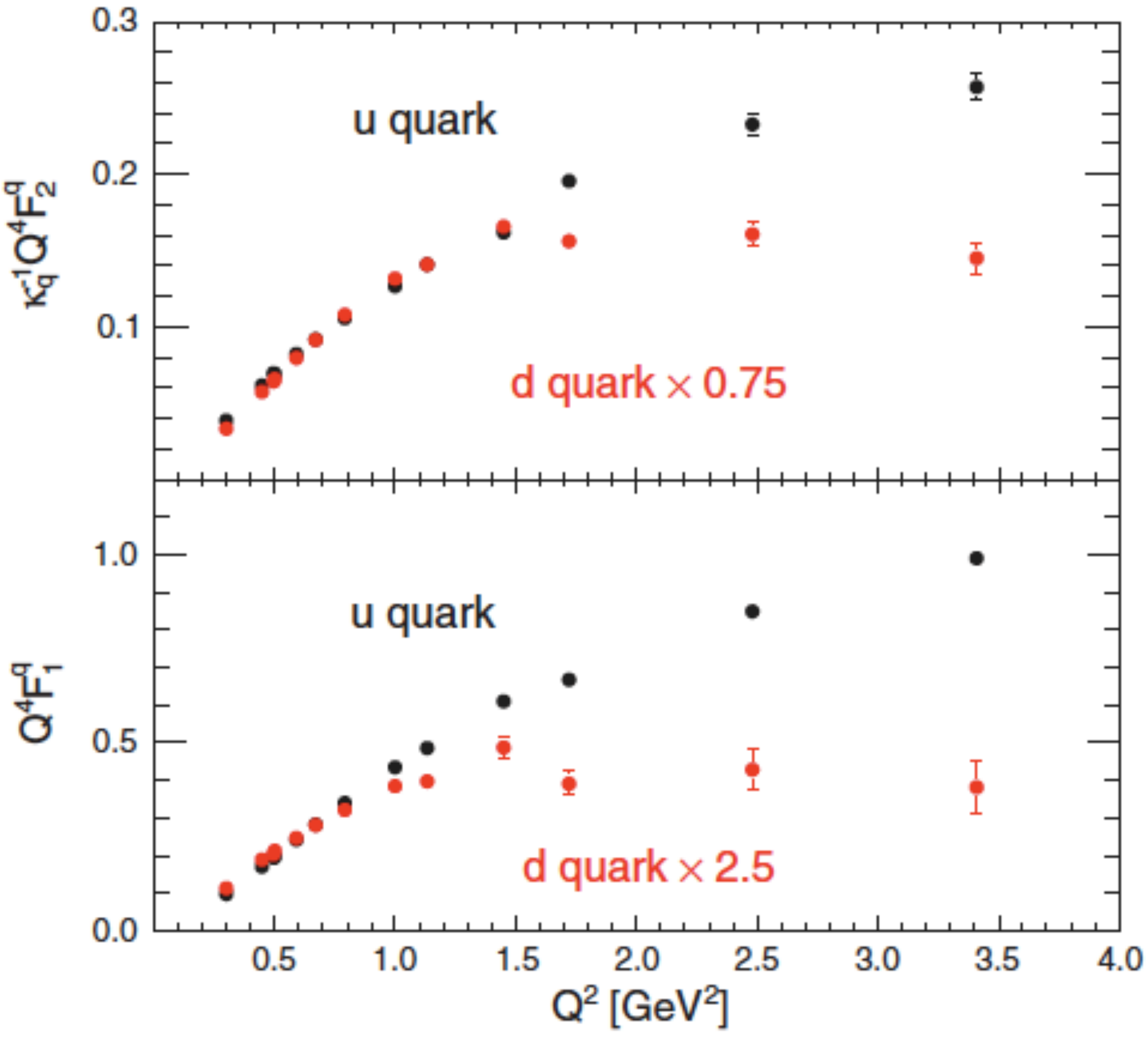


$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

G. Cates et al., PRL 106 (2011) 252003

I.A. Qattan and J. Arrington, PRC86 (2012) 065210

Flavor decomposition and scaling



u-quark

d-quark

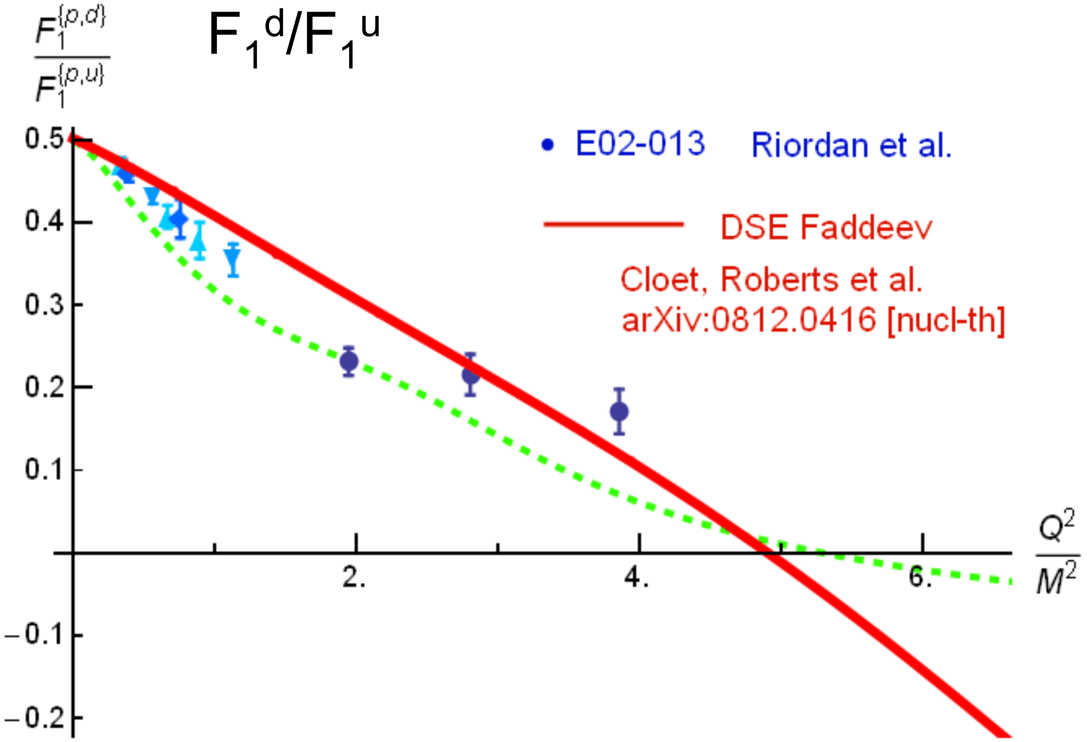
Reduction of
d over u can be
related to diquark
correlations in
DSE approach

Flavor decomposition and scaling

- **Separate u, d in comprehensive analysis of nucleon form factors**

→ Study non point-like scalar, axial-vector diquark correlations

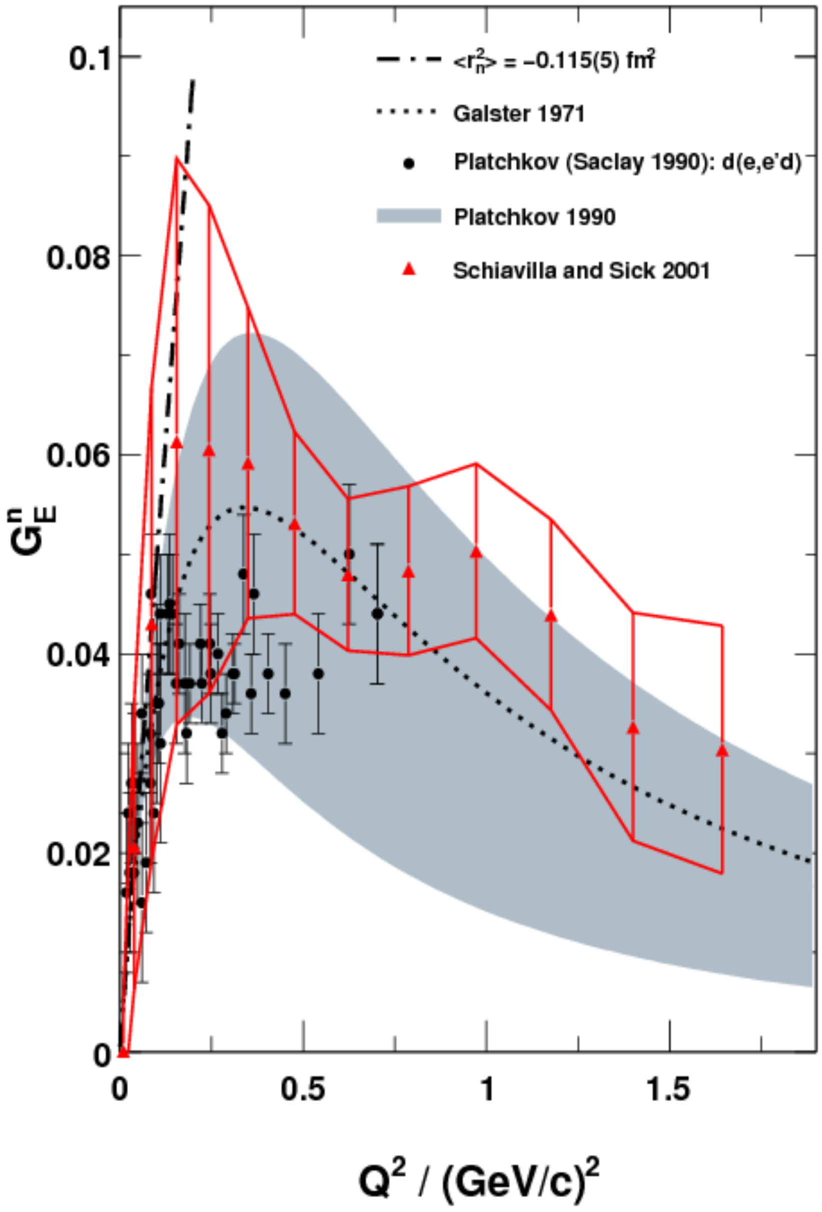
- **Singly-represented *d*-quark is most likely to be struck in association with *1*$^+$ diquark & these form factor contributions are soft**
- ***u*-quark is predominantly linked with harder *0*$^+$ diquark contributions**



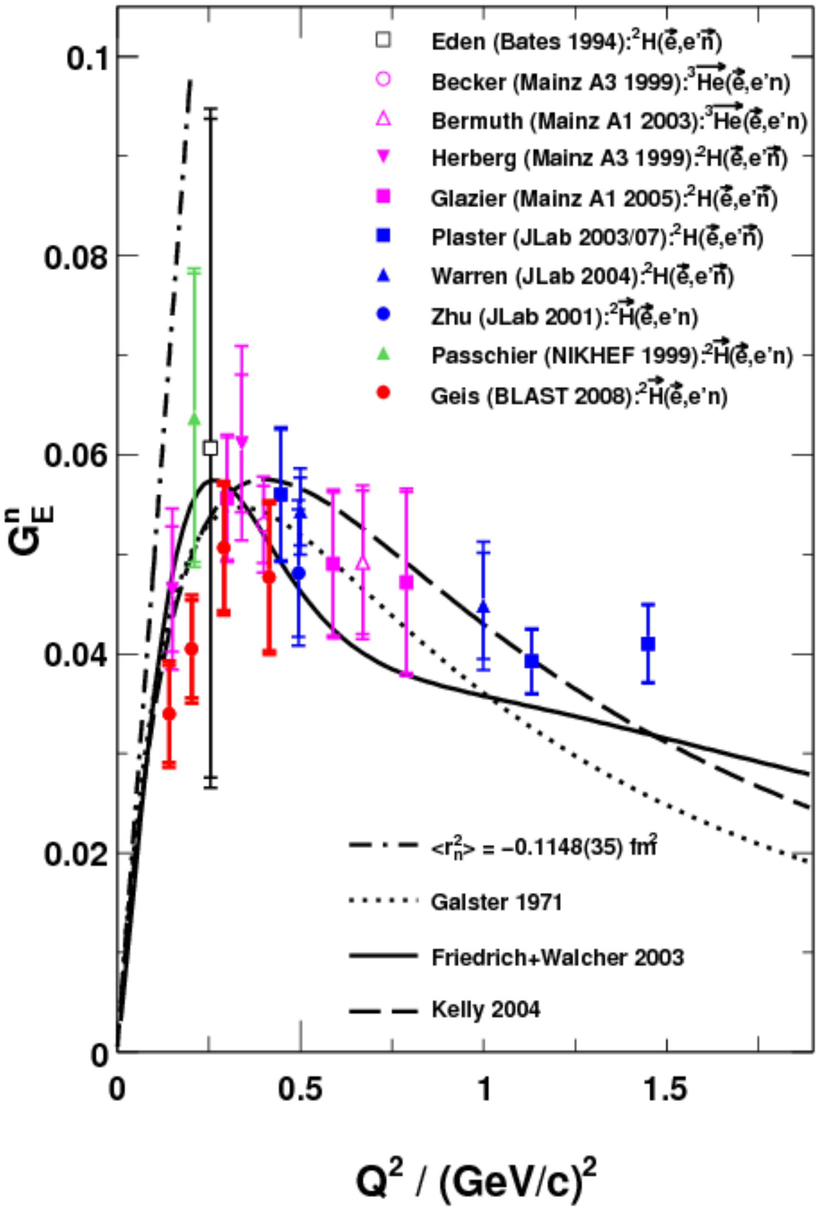
- **Follows that**
  - ***d*-quark Dirac form factor is softer than that of *u*-quark**
  - **F_1^d/F_1^u passes through zero**
  - **Location of zero depends on relative probability $1^+/0^+$ diquarks in proton**
- **Same physics explains $d_v(x)/u_v(x)$ at $x \sim 1$**

Neutron electric form factor G^n_E

ed elastic data



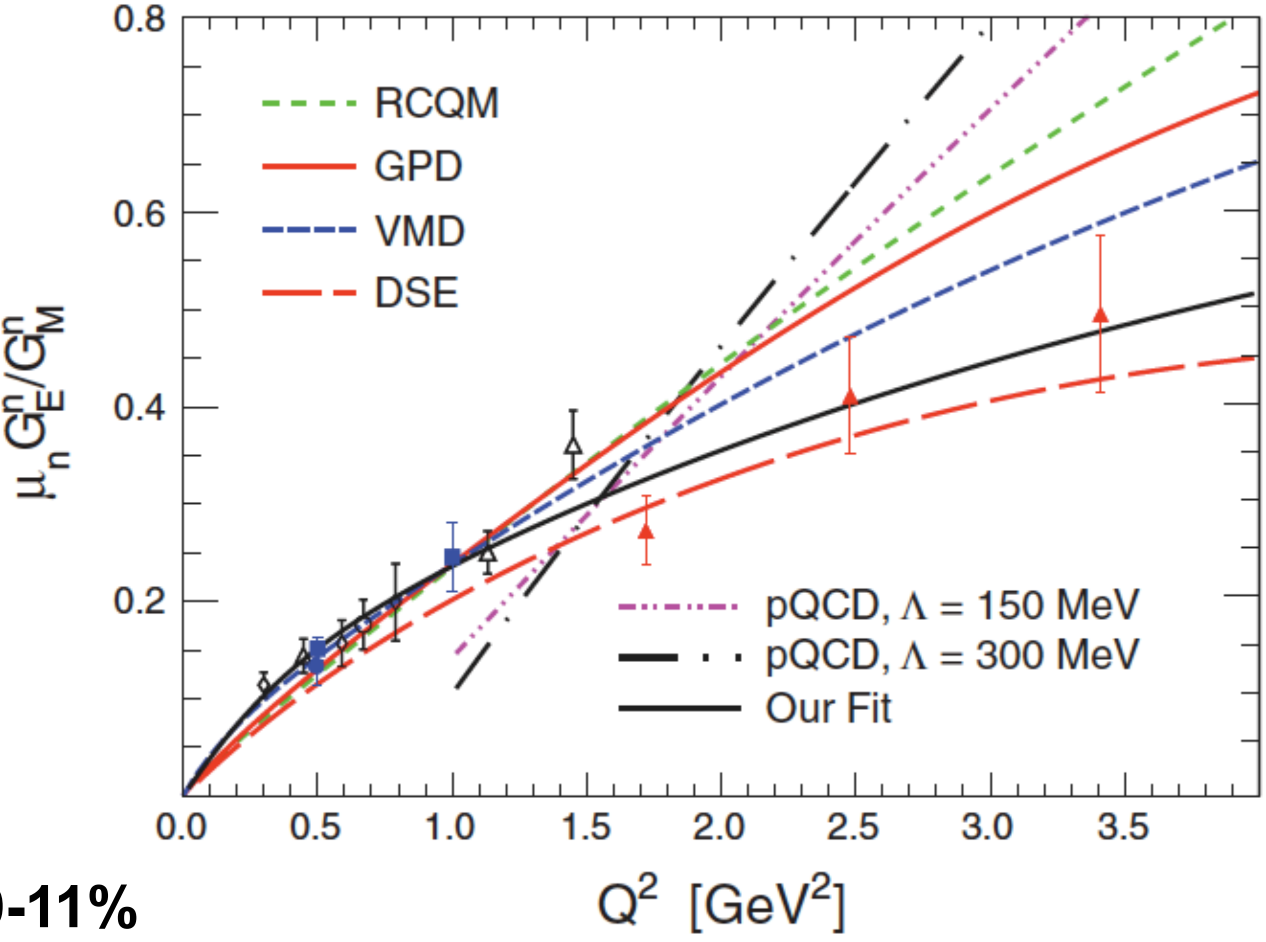
Status in 2008



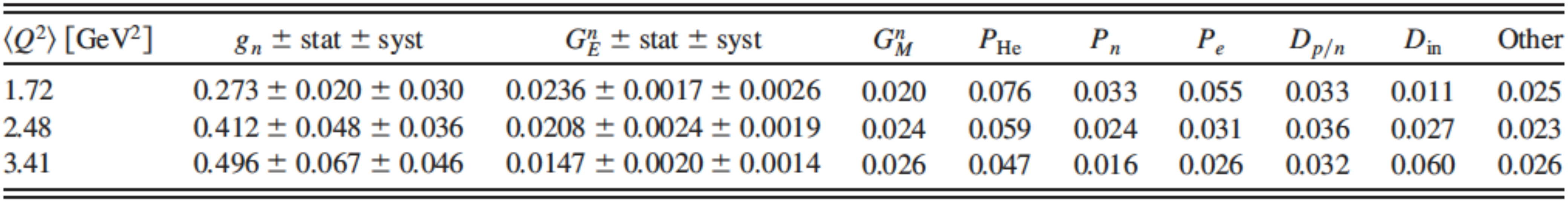
High Q^2 measurement of G^n_E

Hall A / E02-013, S. Riordan et al., PRL105 (2010) 262302

Polarized He-3, Q^2=1.2, 1.7, 2.5, 3.5 $(\mathrm{GeV/c})^2$



Sys. errors: 9-11%

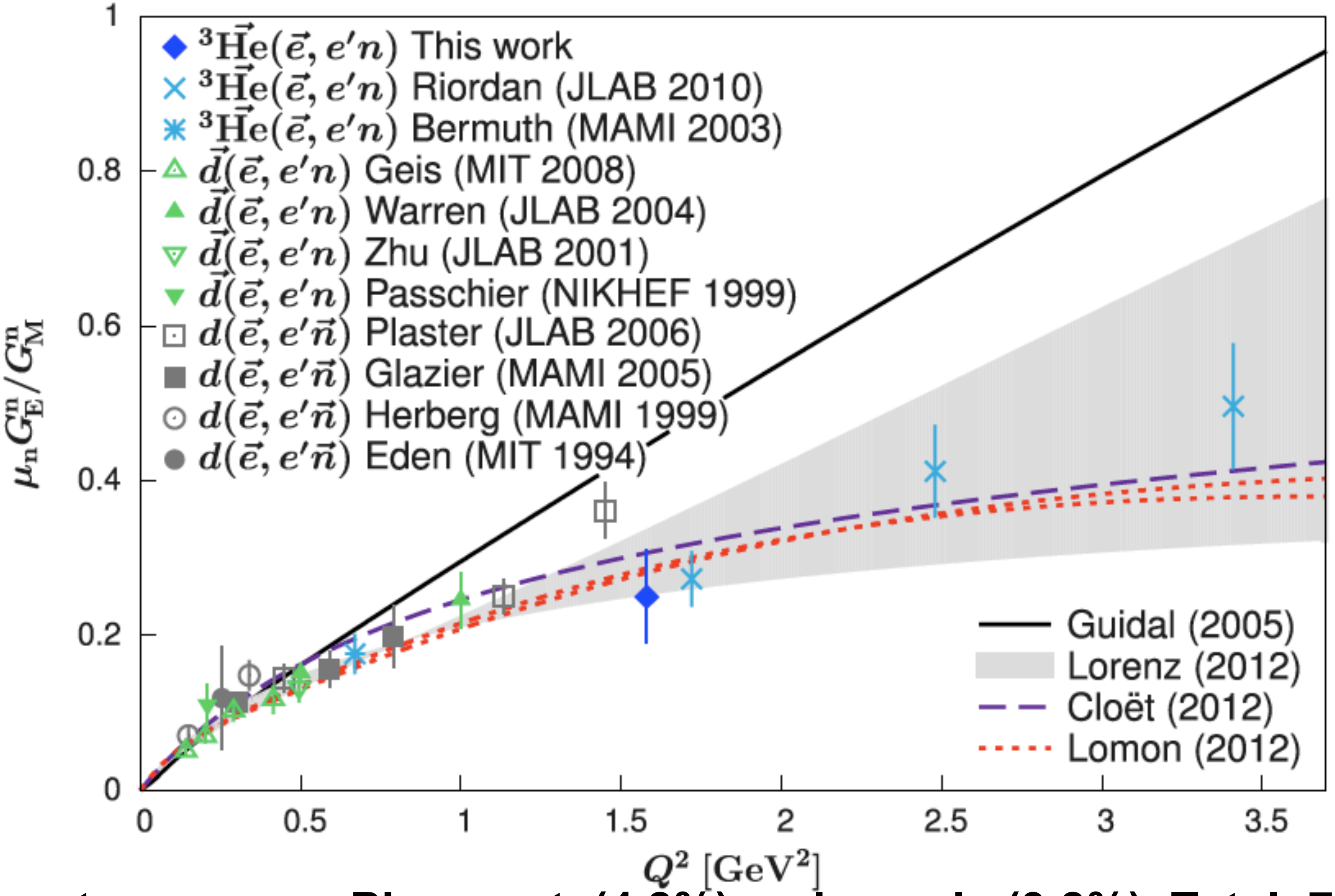


$\langle Q^2\rangle$ [GeV^2]	g_n ± stat ± syst	G^n_E ± stat ± syst	G^n_M	P_{He}	P_n	P_e	$D_{p/n}$	D_{in}	Other
1.72	0.273 ± 0.020 ± 0.030	0.0236 ± 0.0017 ± 0.0026	0.020	0.076	0.033	0.055	0.033	0.011	0.025
2.48	0.412 ± 0.048 ± 0.036	0.0208 ± 0.0024 ± 0.0019	0.024	0.059	0.024	0.031	0.036	0.027	0.023
3.41	0.496 ± 0.067 ± 0.046	0.0147 ± 0.0020 ± 0.0014	0.026	0.047	0.016	0.026	0.032	0.060	0.026

New measurement of G_{En} from Mainz

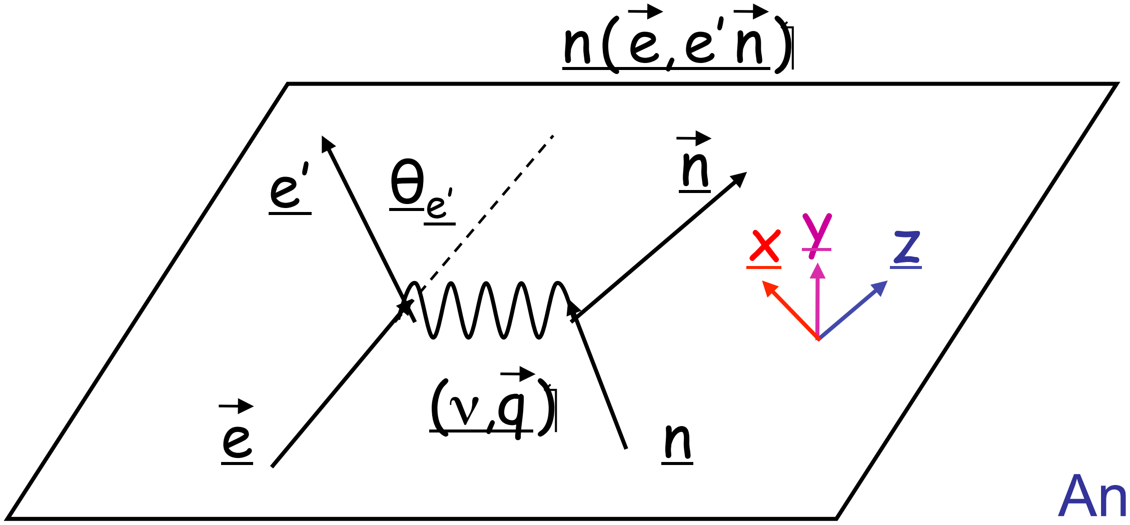
A1 Collaboration, B.S. Schlimme et al., PRL111 (2013) 132504

Polarized He-3, Q^2=1.58 $(GeV/c)^2$



Largest sys. error: Pion cont. (4.8%), spin angle (3.8%), Total=7%
PWIA correction (-3.6%), FSI found negligible

Recoil polarization technique



electron scattering plane

Recoil polarization

$$P_x = -P_e K_t G_{En} G_{Mn}$$

$$P_z = P_e K_\ell G_{Mn}^2$$

Analyzed by second scattering in polarimeter with analyzing power A_Y

Ratio Technique:
Measure P_x and P_z

$$\longrightarrow \frac{P_x}{P_z} = -\frac{K_t}{K_\ell}\frac{G_{En}}{G_{Mn}} \longrightarrow$$

small systematics
$A_Y(q)$ and P_e cancel

- **Electrons detected in SHMS**
- **Neutron spin precessing in dipole magnet**
- **Neutron detected, polarization analyzed in neutron polarimeter**
- **Two linear combinations of P_x and P_z (two precession angles)**

E12-11-009 (GEn) collaboration

G_{En} via neutron recoil polarization in deuteron electrodisintegration
R. Madey, S. Kowalski, B. Anderson

6-GeV era proposals

PR-89-005, replaced by E93-038: Q^2 = 0.45, 1.13, and 1.45 $(GeV/c)^2$
R. Madey, PRL91 (2003) 122002; B. Plaster, PRC73 (2006) 025205

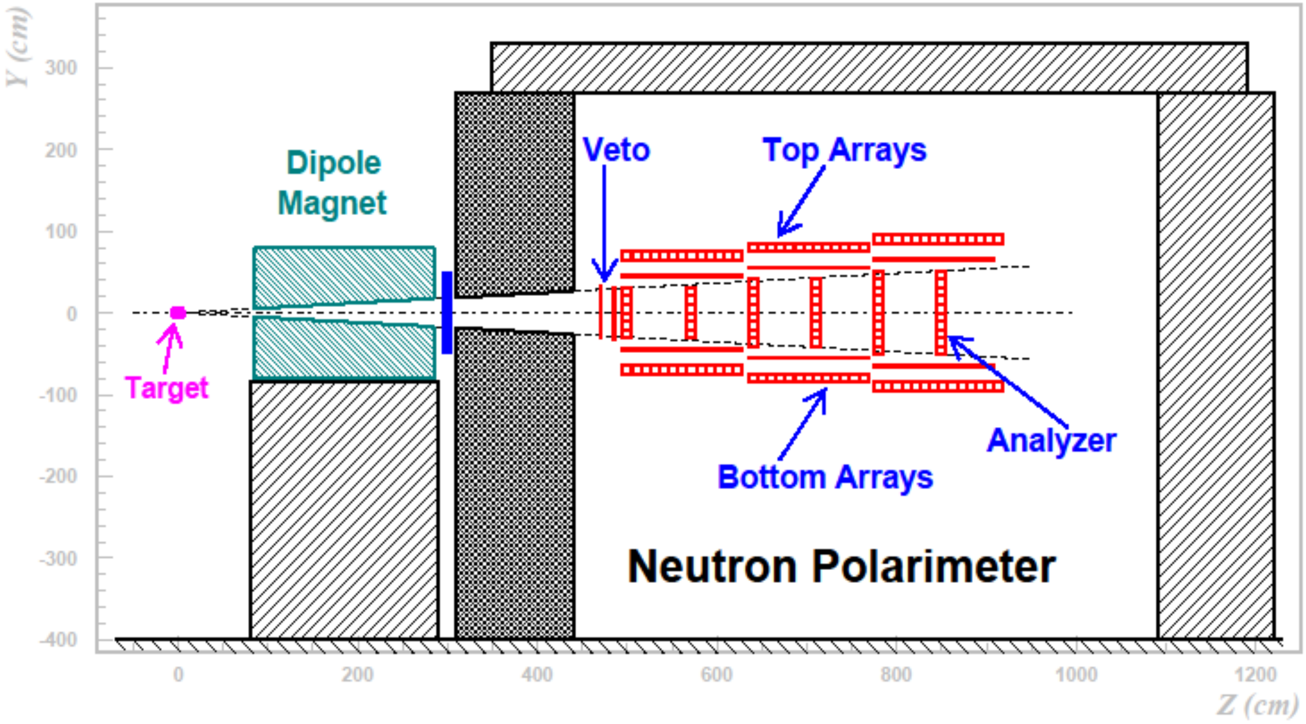
PR-01-106 (PAC20), PR-02-009 (PAC 21): Q^2=2.4 $(GeV/c)^2$
PR-04-003 (PAC25): Q^2 up to 4 $(GeV/c)^2$
PR-04-110 (PAC26): Q^2 = 4.3 $(GeV/c)^2$

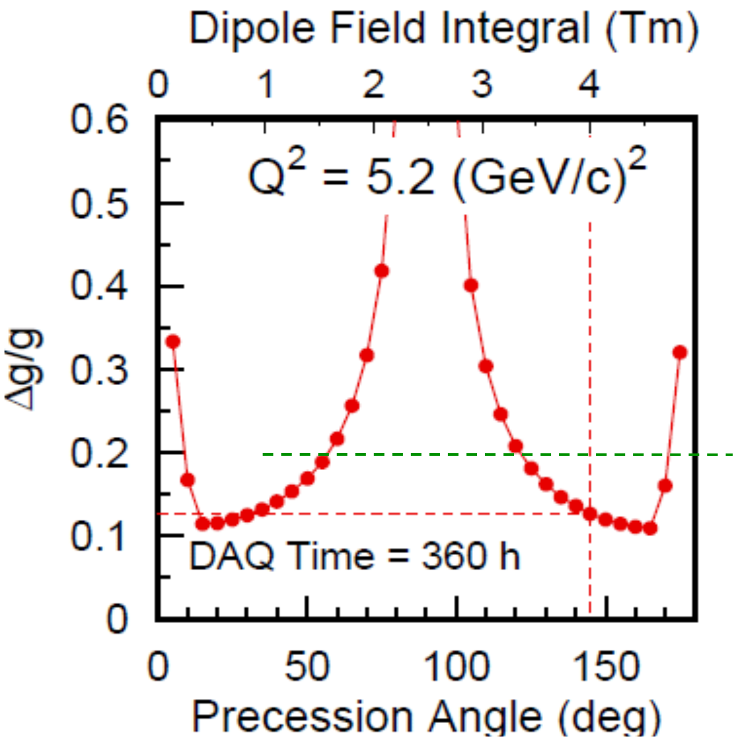
12-GeV era proposals

PR-09-006 (PAC34, Jan 2009): Q^2 up to 7 $(GeV/c)^2$
PR12-11-009 update proposed at PAC37 (Jan. 2011)

Collaboration in process of being restructured
Charter in preparation
Reduced list of spokespeople – currently active (the next generation):
J. Arrington, M.K., B. Sawatzky, A. Semenov
New distribution of responsibilities

Precession magnet





where, $g \equiv G_E/G_M$

- Field serves two functions
  - precess the neutron spin to maximize detected asym (low *or* high field OK, but 'medium' == no good)
  - suppress charged backgrounds from target (*need high-field*)
- Optimal B·dl : 4.3 T·m
  - Search for magnet solution with at least 4.0 T·m

Magnet search

Need 4 Tm field integral

1) Charybdis, used in previous experiment E93-038 (GEn)
   available
   operated at 530 A / 2.15 Tm
   measured and calculated field maps exist

2) Identified 48D48 from BNL (same model as SBS)

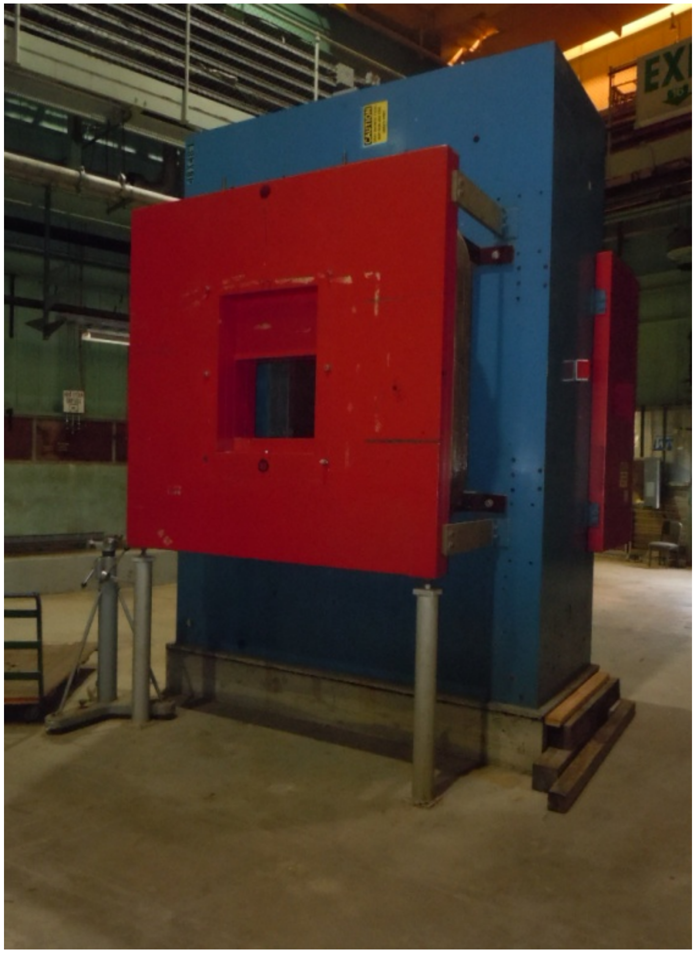
- Stack both magnets to achieve > 4.0 Tm
- Increase distance of polarimeter from ~3 to ~5 m
  Detailed CAD in preparation
- Impact on FOM to be investigated

BNL 48D48 Magnet(s)

- Same magnet model as for SBS in Hall A
- Yoke pieces for two magnets onsite for SBS, a third set at BNL
- One coil pack onsite and could be used (has been verified)
- No expensive modifications of coil packs as for SBS necessary
- No modifications to yokes necessary; need to build stand
- Power supplies:
  - SBS has ordered its own, available if not running in parallel
  - Hall C: either use QTOR, or one of the Moller PS
- Existing TOSCA model used for SBS study (R. Wines): 2.5 Tm @ 2000 A with pole shims;
- Limit to 2.2 Tm @ 2000 A / 220V, consistent with resistance of coil pack, 2.0 Tm probably safe

BNL 48D48 Magnet(s)

- Magnet assembled with the iron slabs vertical as shown
- Booster coils are installed (not to be used for GEn)
- Provisions for lifting machined into the top of the slabs



Dimensions of iron:
146.5” tall
110” wide
48” deep
gap (3’’ pol ext.)

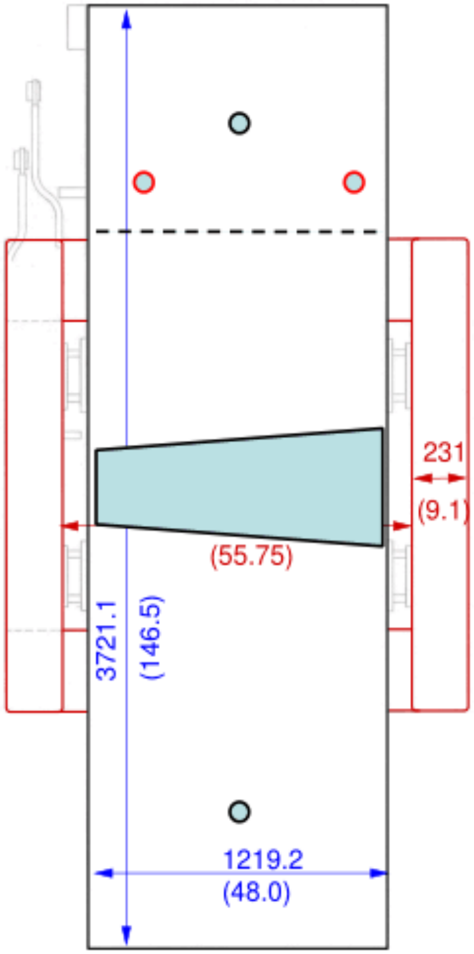
Front

Rear

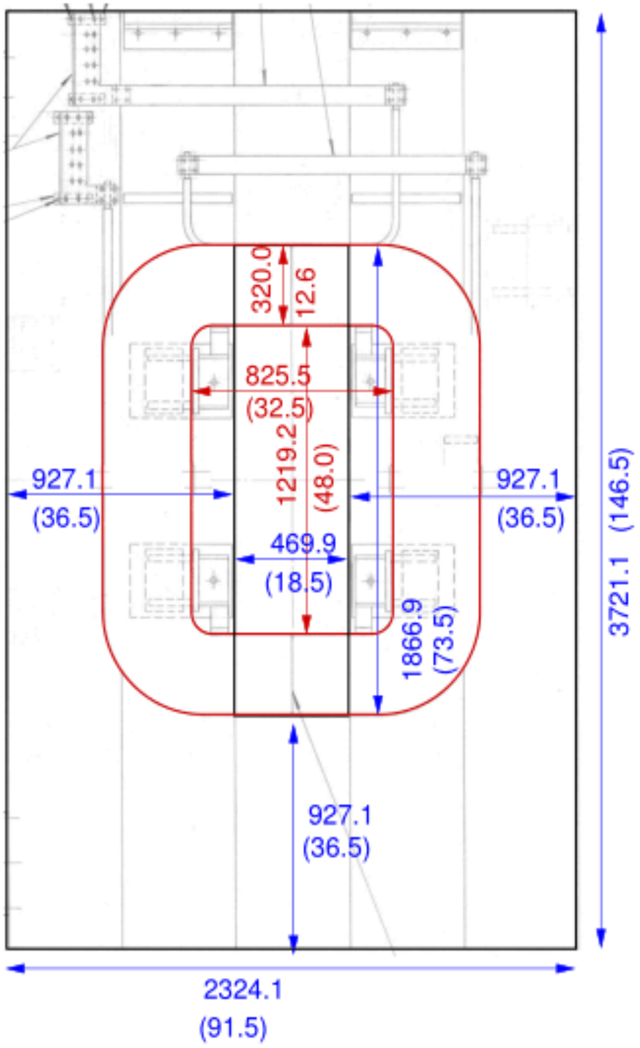
Slide from Whit Seay

BNL 48D48 Magnet(s)

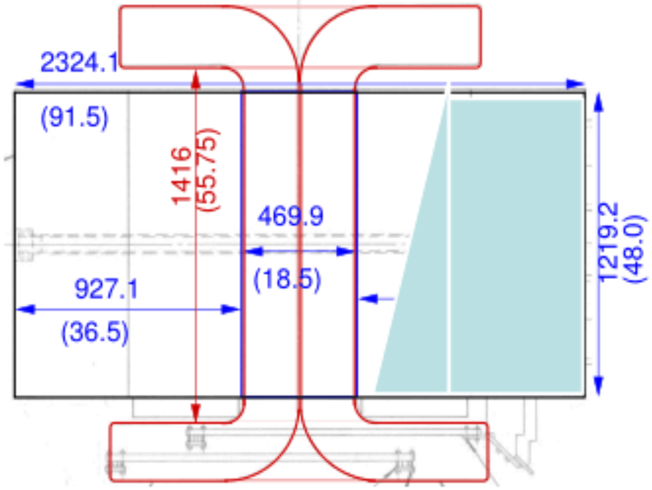
SIDE



FRONT

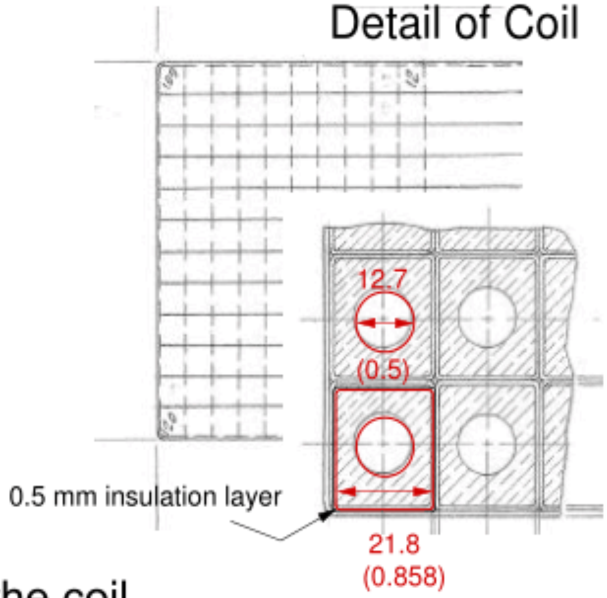


TOP



IRON YOKE 74.6 tons

Detail of Coil

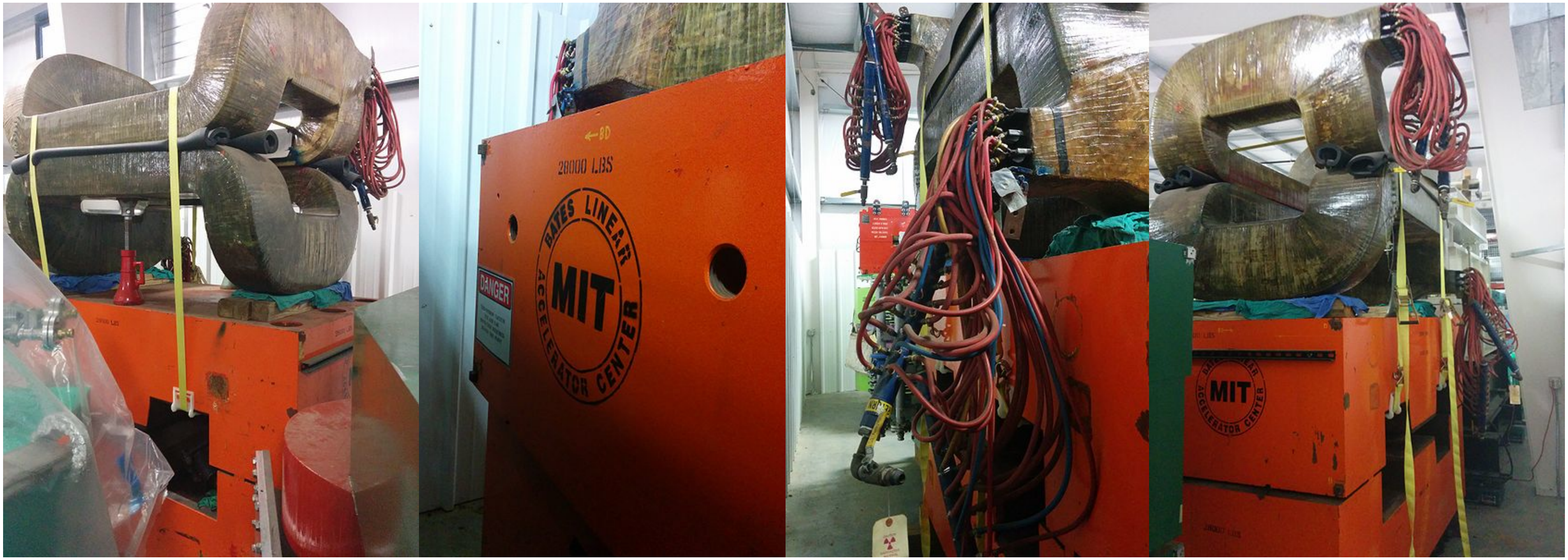


120 turns in the coil

Resistance 0.072 Ohm

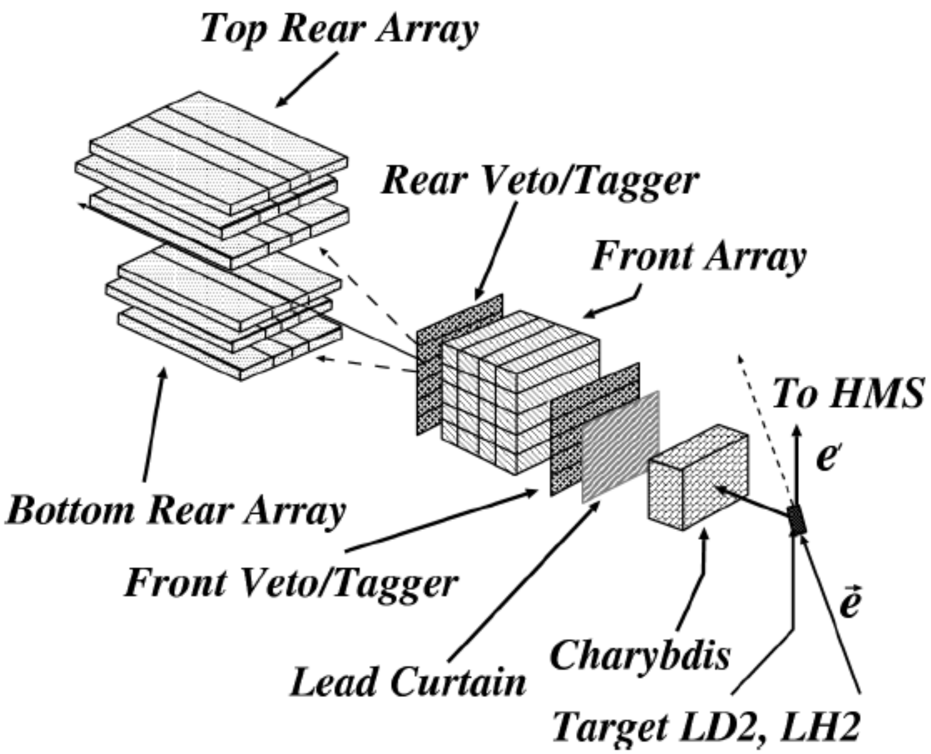
Conductor has 3.5 cm^2

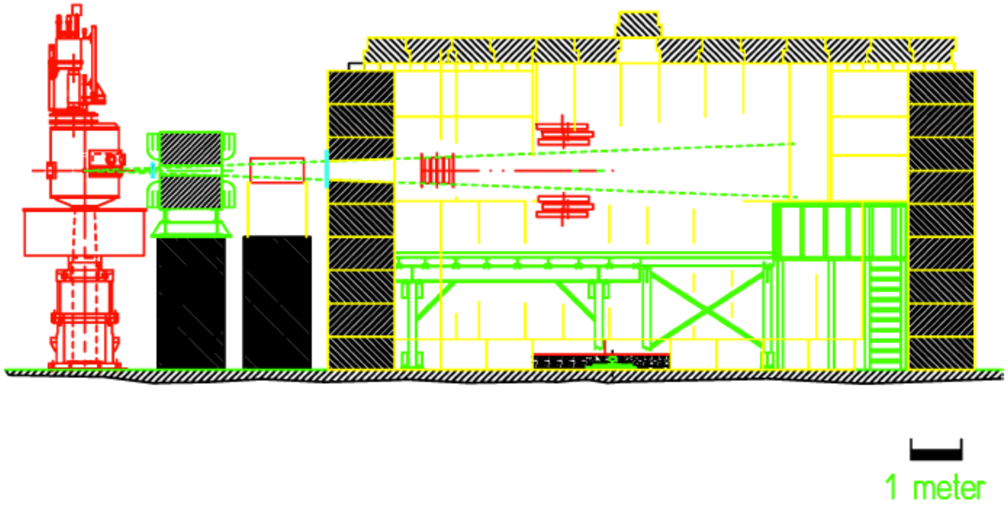
Charybdis (from E93-038)



Onsite, NW corner of ESB (JLab)
Yoke, coil packs, and water manifolds appear to be in good shape
E93-038: max B·dl of 2.15 T·m @ 590 A @ 150 V, operated at 530 A
Power supply: SOS-D1, Moller Quad, BigBite
Weight: 38 tons; Outer measures 1.5 m tall, 2.3 m wide, and 1.7 m long
Aperture 8.25’’ high × 0.56 m wide,1.22 m gap length

Polarimeter: History / E93-038





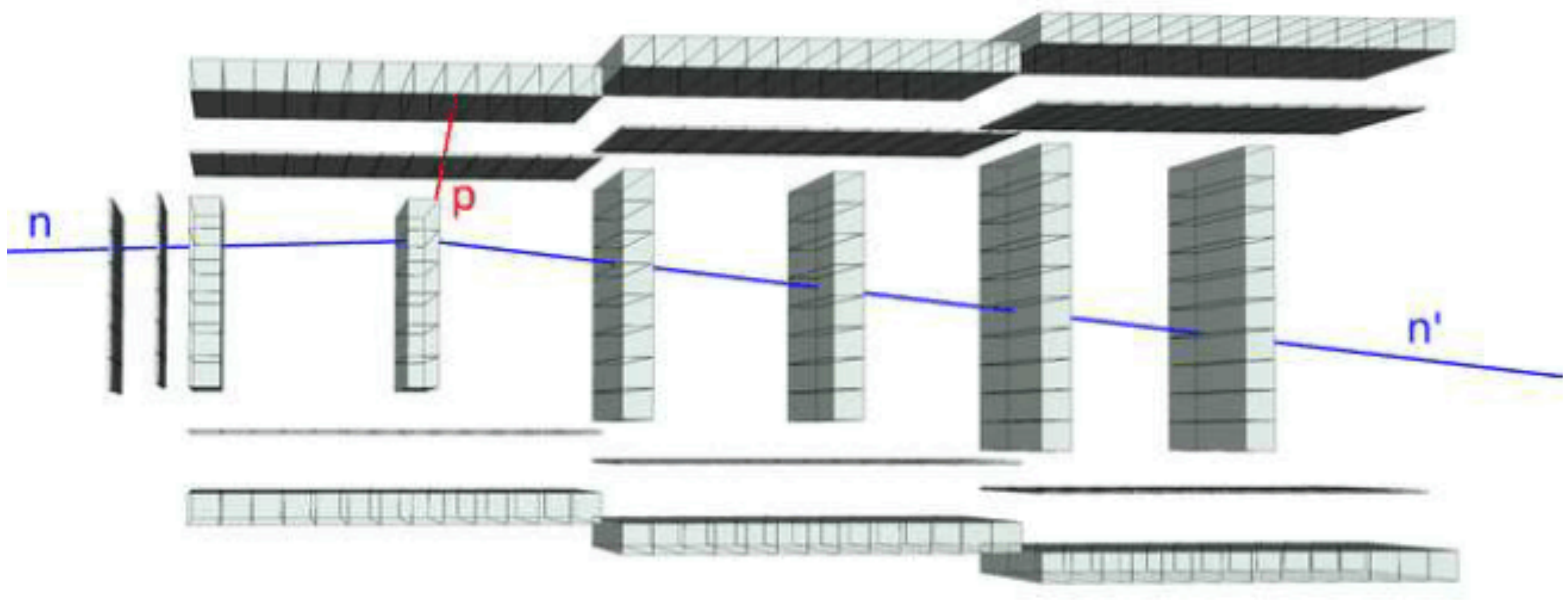
- Beam charge asymmetry, polarimeter efficiency and A_y cancel in "super-ratio" and ratio of asymmetries
- Operation at high luminosity: front array segmented, rear array shielded from direct view of target; detectors located in the bunker

- PROBLEM : NOT suitable for measurements at higher Q^2
- Difficult to reach small scattering angles (max of Ay at high energies)
- Relatively small efficiency

- Solution proposed for 2004 proposal (viz., bigger front array & converters in the rear array) not sufficient

New neutron polarimeter

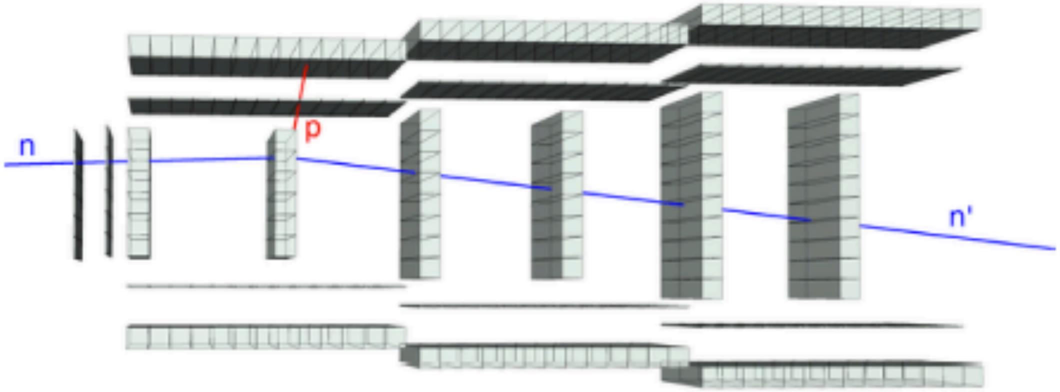
- Design and further improvements by A. Semenov / Regina
- Scintillator R&D by Will Tireman / Northern Michigan U.
- Planning for MRI proposal in 2015 (HU, NCA&T, SUNO, NMU)



PAC37 version

Polarimeter: PAC37 version

PAC37 : Detection of Recoil Protons Instead of Scattered Neutrons

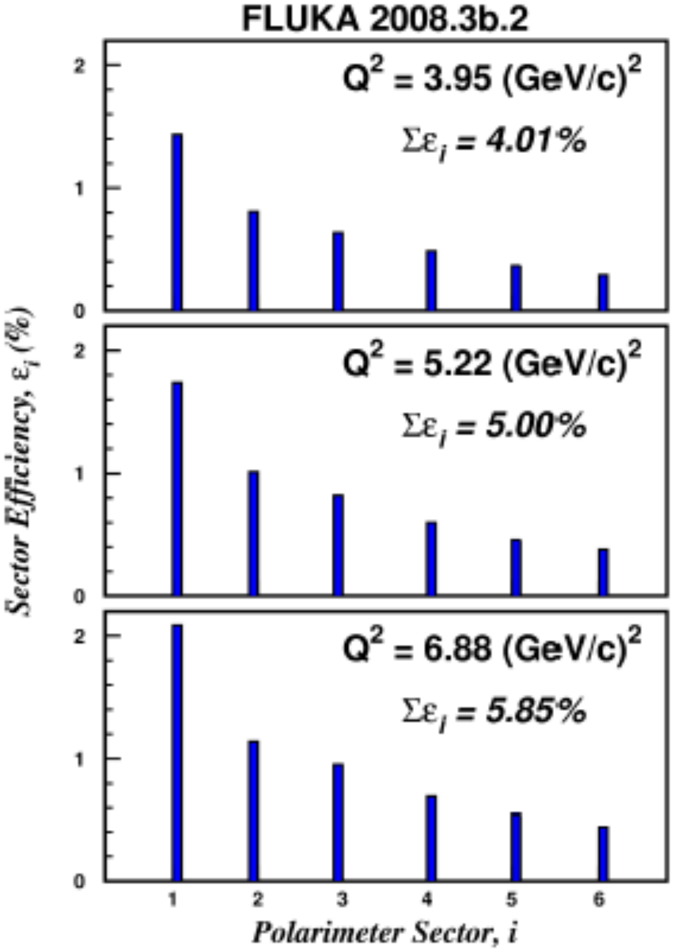


* Easy detection of 300-500 MeV protons via TOF and dE-E techniques

* Comfortable access to the small scattering angles of neutrons

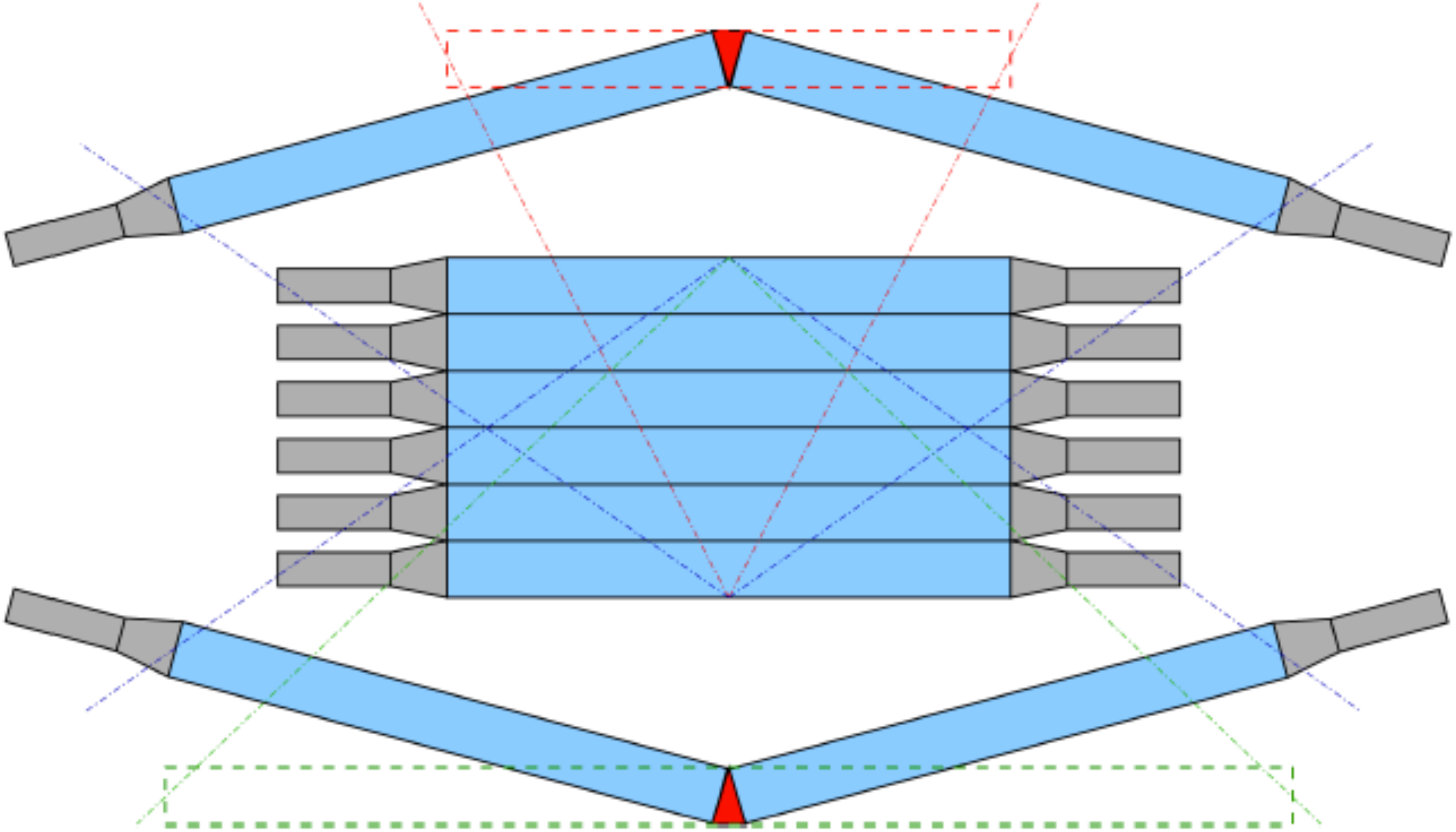
* Segmented and distributed analyzer (easy escape of protons and control on double-scattered neutrons)

* Issues:
- No full coverage of top/bottom acceptance
- 5th and 6th Sections (too small efficiency with too many detectors)



Improving the acceptance … Plan A

Plan A: Let's Glue Detectors in Top/Bottom Arrays

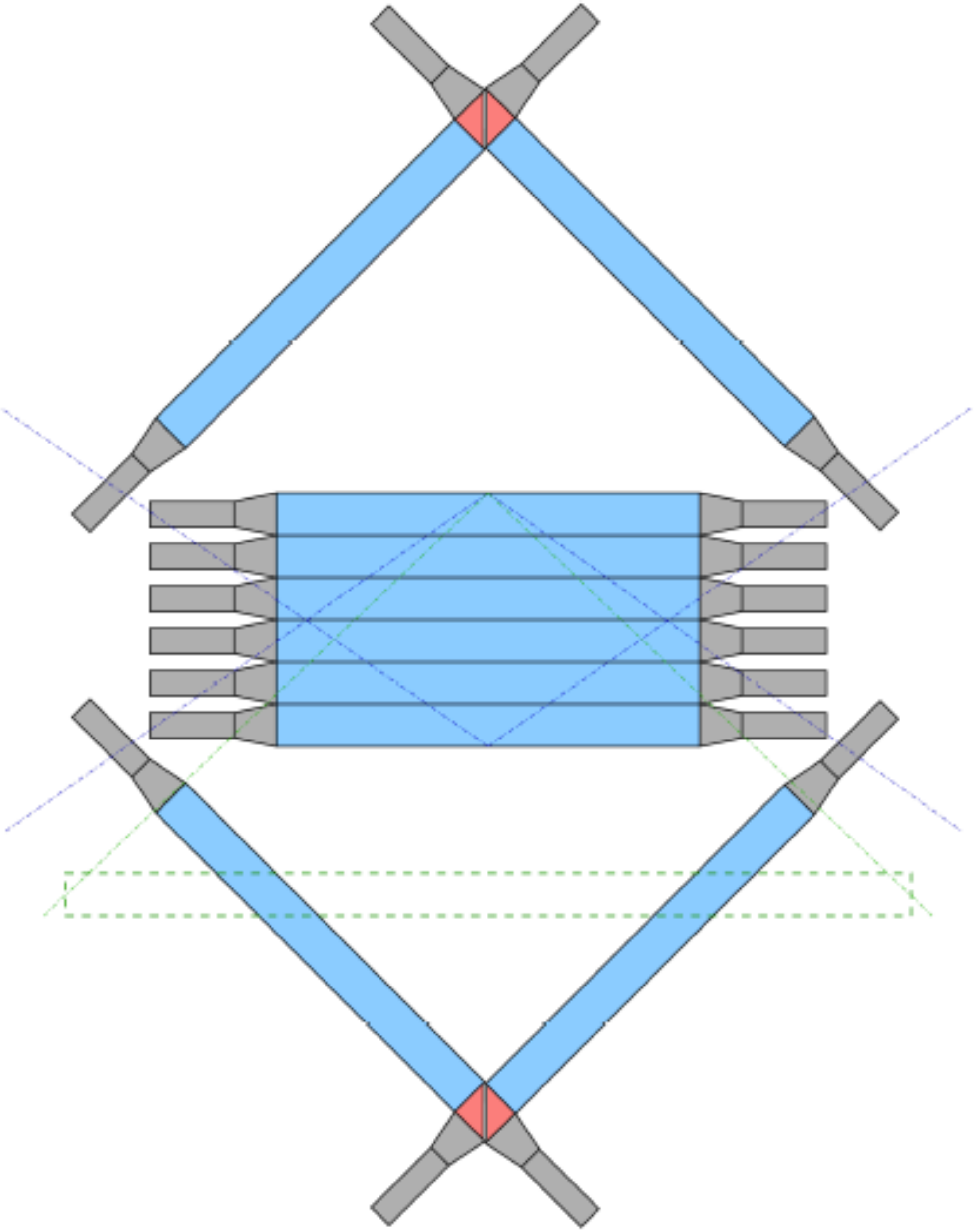


Pros: Maximal acceptance & minimal number of electronics channels

Cons: Low granularity & possible handling problems

Improving the acceptance … Plan B

Preferable Plan B: Let's Keep Top/Bottom Detectors Separated



Light collection is 90-deg rotated on one side (using prism shown in red) to achieve high packing in top/bottom arrays

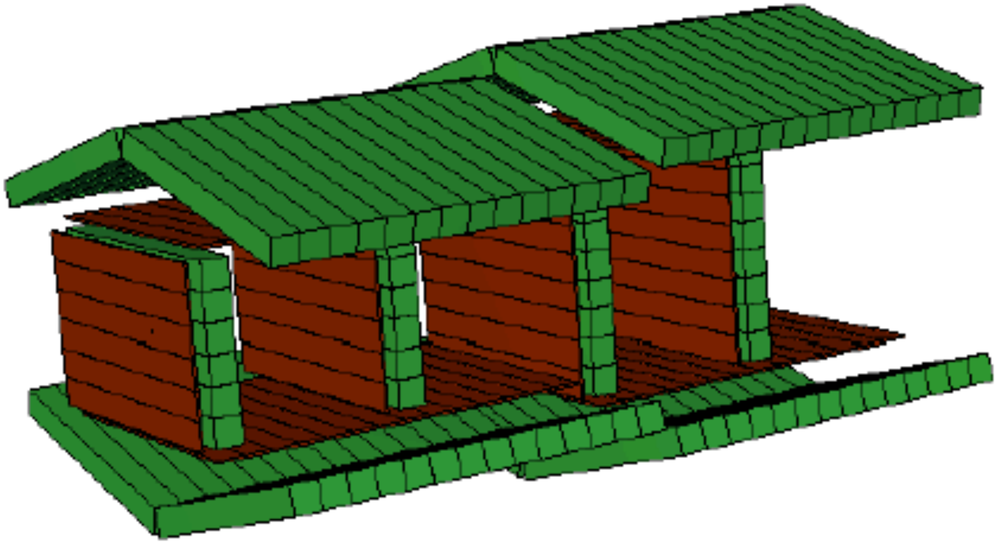
Pros:

- Better granularity
- Easier handling of detectors
- Bigger path for TOF
- 160-cm detectors allow achieve very good acceptance coverage

Cons:

- Bigger number of electronics channels

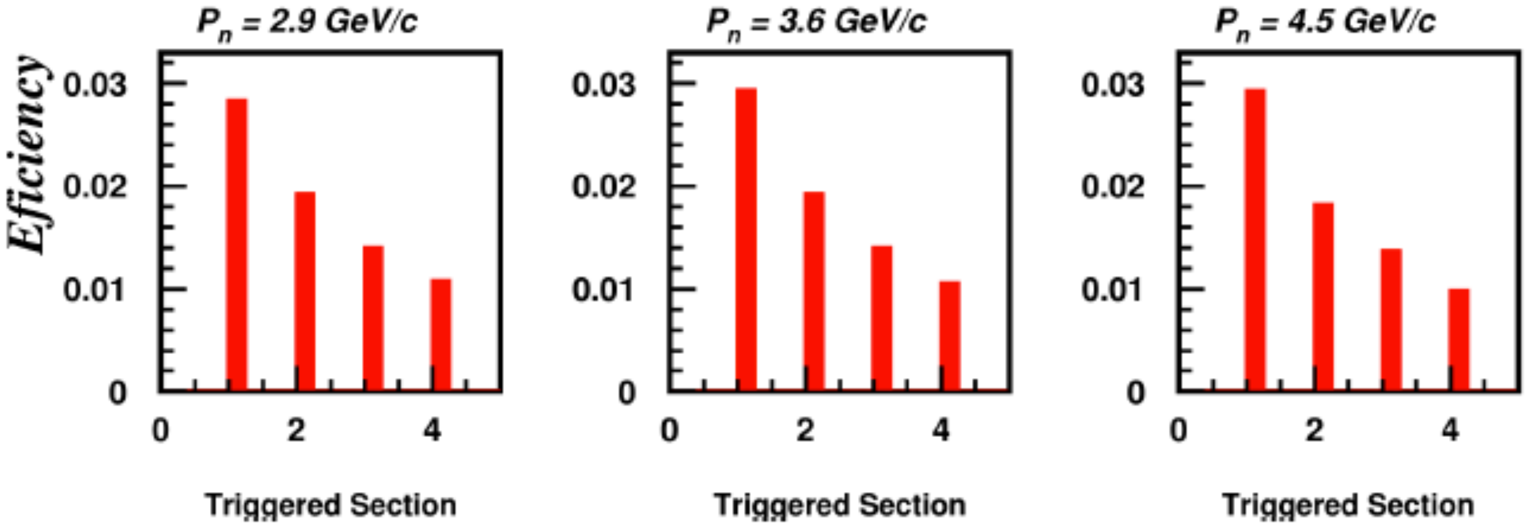
Updated neutron polarimeter



Simulation:

Fluka 2011.2.9 + MCEEP-generated flux of neutrons

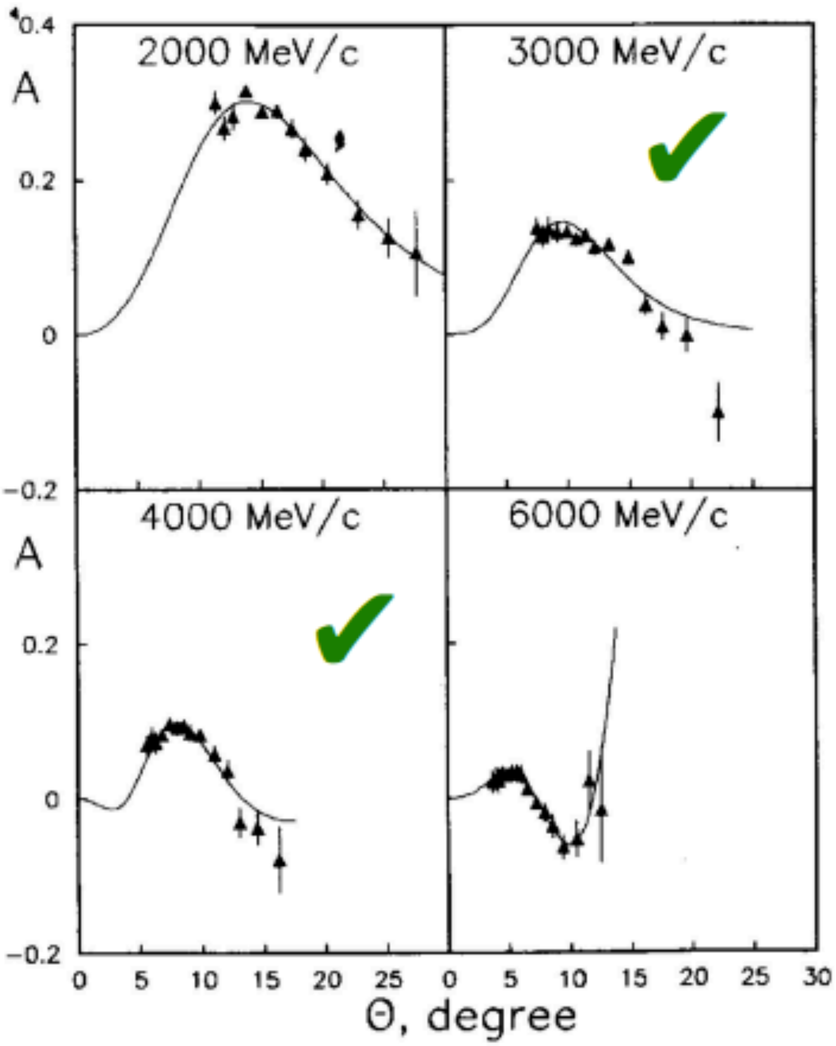
Visible increase of polarimeter efficiency even with only 4 sections in the polarimeter



A. Semenov

Optimal use of analyzing power

Control on Scattering Angle to Maximize Ay for Elastic and QE *np*



V.P. Ladygin, JINR preprint E13-99-123

*** Non-zero analyzing power is located at small scattering angles of neutrons (with possible flip at higher angles)**

*** Control of the neutron scattering angle with accuracy of 1.5-2 degrees requires the control of recoil proton scattering angle with accuracy of 5-6 degrees; that requires 10-15-cm z-position resolution in the top/bottom arrays. Our polarimeter provides ±5-7 cm (with 10-cm bars)**

OK

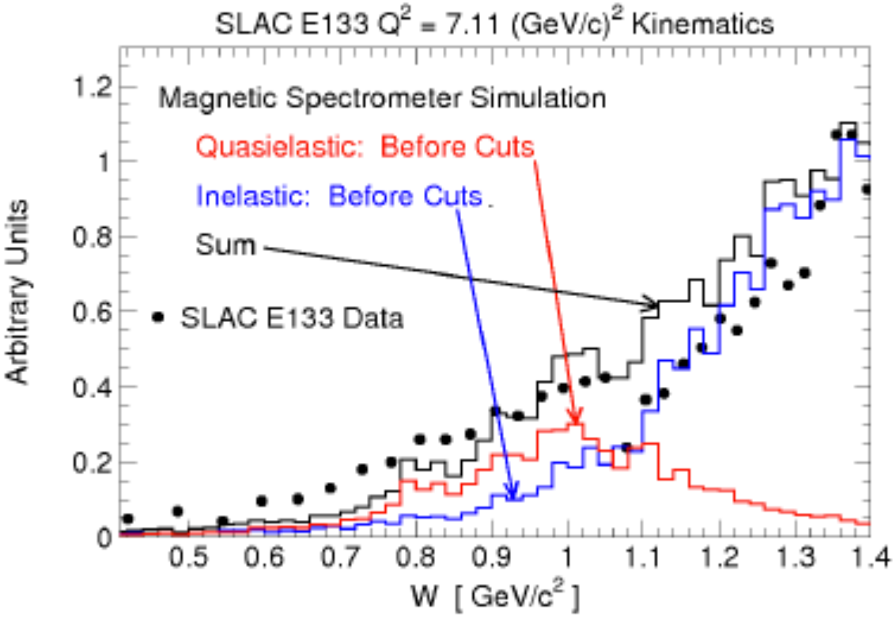
A. Semenov

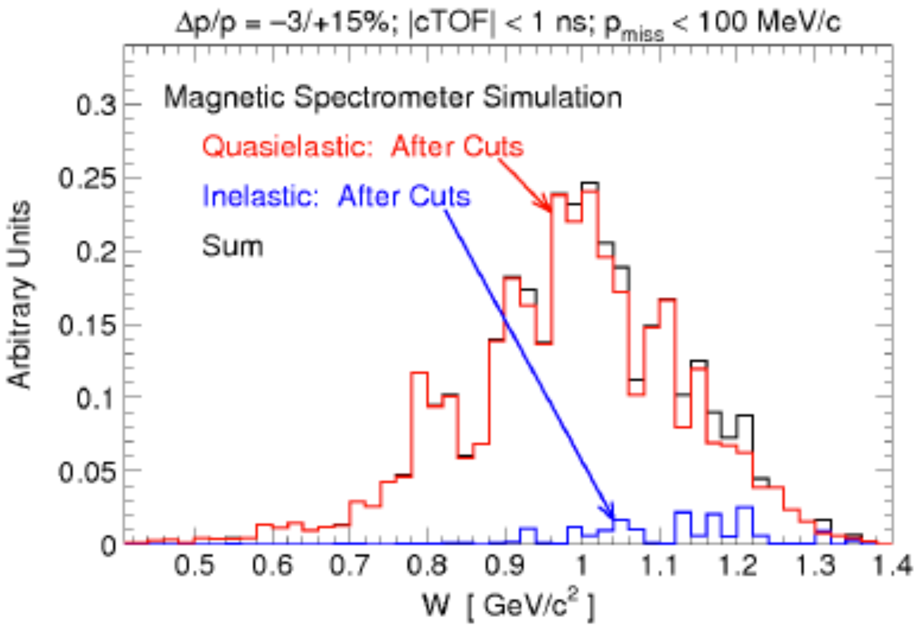
Good timing for clean QE event selection

Time Resolution of Analyzer: Selection of Quasielastic *en*

Cut on the SHMS-NPOL Analyzer time difference is an important part of selection of e-n quasielatic scattering events in the target.

High mean-time resolution (as better as possible, but definitely better than 1 ns) is desired for neutron bars in the polarimeter analyzer.

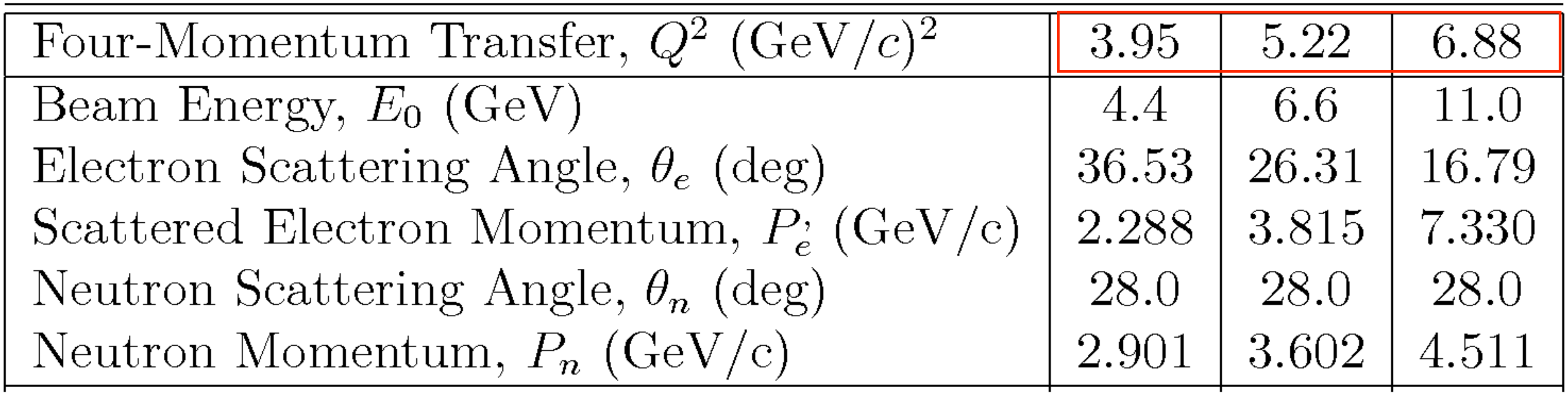




A. Semenov

Kinematics, beam request (PAC37)

80 μA beam, 80% polarization, 40-cm LD_2 target



Four-Momentum Transfer, Q^2 $(\mathrm{GeV}/c)^2$	3.95	5.22	6.88
Beam Energy, E_0 (GeV)	4.4	6.6	11.0
Electron Scattering Angle, θ_e (deg)	36.53	26.31	16.79
Scattered Electron Momentum, $P_e^{\prime}$ (GeV/c)	2.288	3.815	7.330
Neutron Scattering Angle, θ_n (deg)	28.0	28.0	28.0
Neutron Momentum, P_n (GeV/c)	2.901	3.602	4.511

Requested: 60 days

Statistical uncertainty [assumes BLAST fit]:	10.1%	12.7%	16.3%
Systematic uncertainty:	2.5-3% for all settings		
Beam Time on LD2 [days]	10	15	30
Beam Time (LH2, Dummy, other) [days]	1	1.5	2.5

60d production + 7d checkout with beam for 67 total PAC days

Three Q^2 values, starting near high end of 6 GeV data and extending significantly into the region of the 12 GeV ^{3}He measurement

Approved by (PAC37), requested (PAC41)

80 µA beam, 80% polarization, 40-cm LD_2 target

Four-Momentum Transfer, Q^2 $(\mathrm{GeV}/c)^2$	3.95	~~5.22~~	6.88
Beam Energy, E_0 (GeV)	4.4	~~6.6~~	11.0
Electron Scattering Angle, θ_e (deg)	36.53	~~26.31~~	16.79
Scattered Electron Momentum, P_e' (GeV/c)	2.288	~~3.815~~	7.330
Neutron Scattering Angle, θ_n (deg)	28.0	~~28.0~~	28.0
Neutron Momentum, P_n (GeV/c)	2.901	~~3.602~~	4.511

Approved: 50 days, only two settings

Statistical uncertainty [assumes BLAST fit]:	10.1%	~~12.7%~~	16.3%
Systematic uncertainty:	2.5-3% for all settings		
Beam Time on LD2 [days]	10	~~15~~	**36**
Beam Time (LH2, Dummy, other) [days]	1	~~1.5~~	2.5

50d production + 7d checkout with beam for 57 total PAC days

PAC concerned about low statistics, and cuts beamtime(!)

Only two Q^2 values, starting near high end of 6 GeV data, drop one point and add time to improve statistics at high Q^2

Funding and timeline

Cost for magnet: < 100 k$ (cost has reduced substantially)

Planning to submit MRI request in January 2015 for the neutron polarimeter (~300 k$)

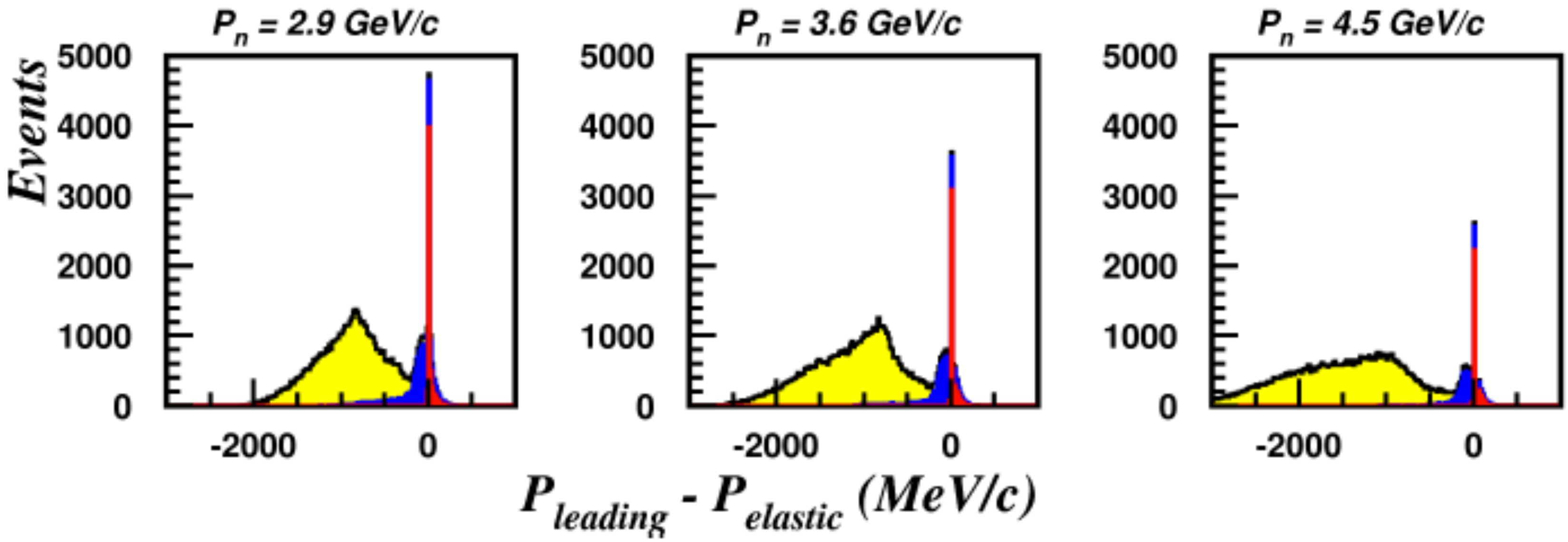
PIs:
M.K. (Hampton University)
Abdellah Ahmidouch (North Carolina A&T)
Mostafa Elaasar (Southern University at New Orleans)
Will Tireman (North Michigan University)
…

Polarimeter design 2014-2015
Polarimeter construction and testing 2015-2018
Installation and running of E12-11-009 (GEn) in ~2018-2019

Backup

Require clean separation for maximal FOM

Maximal FOM: Separation of Inelastic Events from Elastic and QE



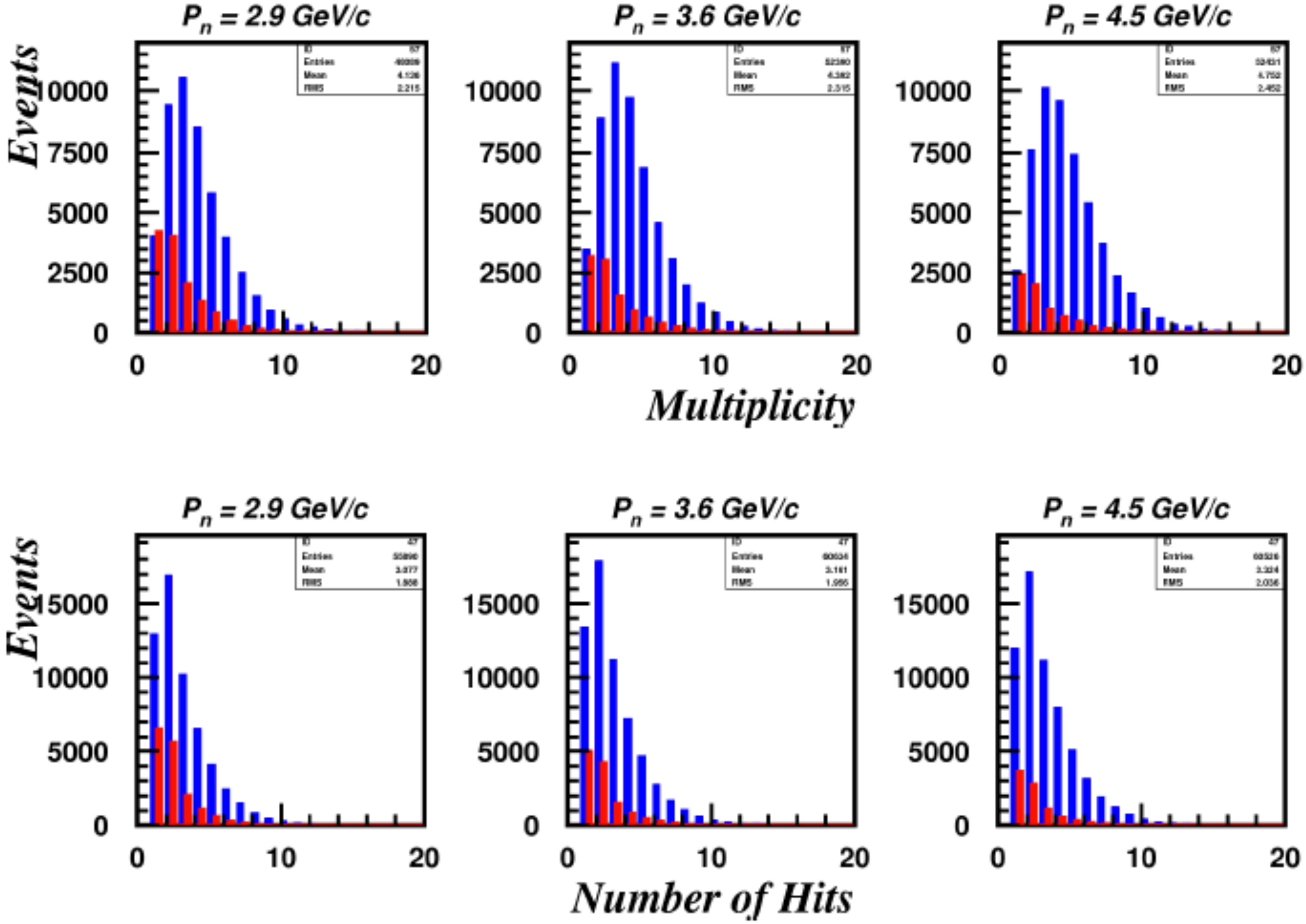
- Elastic
- Quasielastic: Nucleons as secondary particles
- Inelastic: Other secondary particles (mostly pions) accompany the nucleons (shown in Yellow)

Reconstruction of scattering event kinematics is highly desired. (Viz., we need PID and position/angle resolution.)

A. Semenov

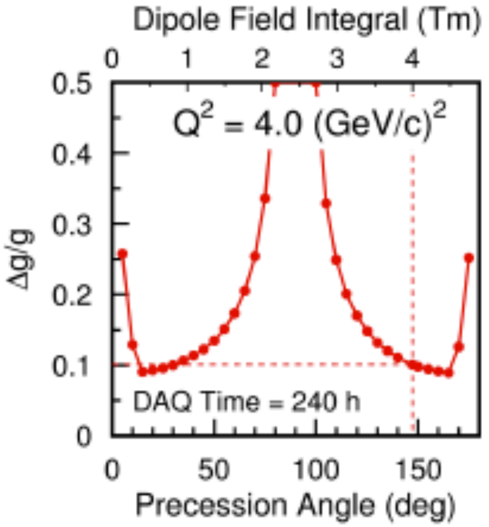
Multiplicity study

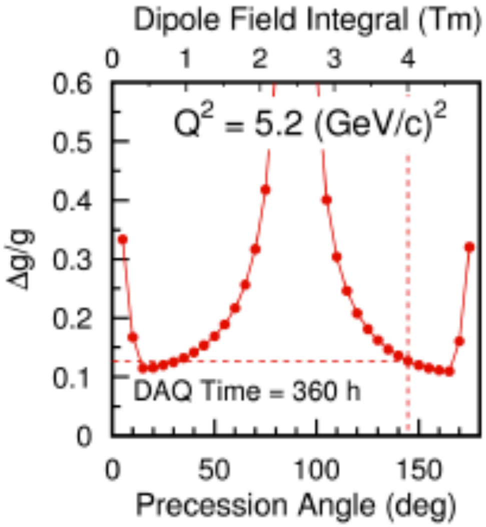
First Step: Analysis of Multiplicity

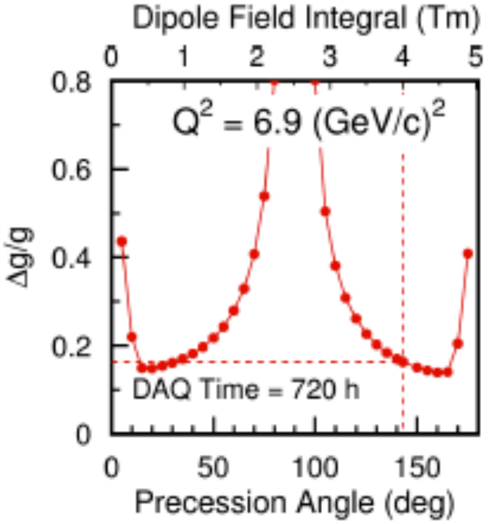


A. Semenov

Spin precession in dipole







* Precession on χ degrees provides access to the same polarization vector projection as precession on (180-χ) deg.

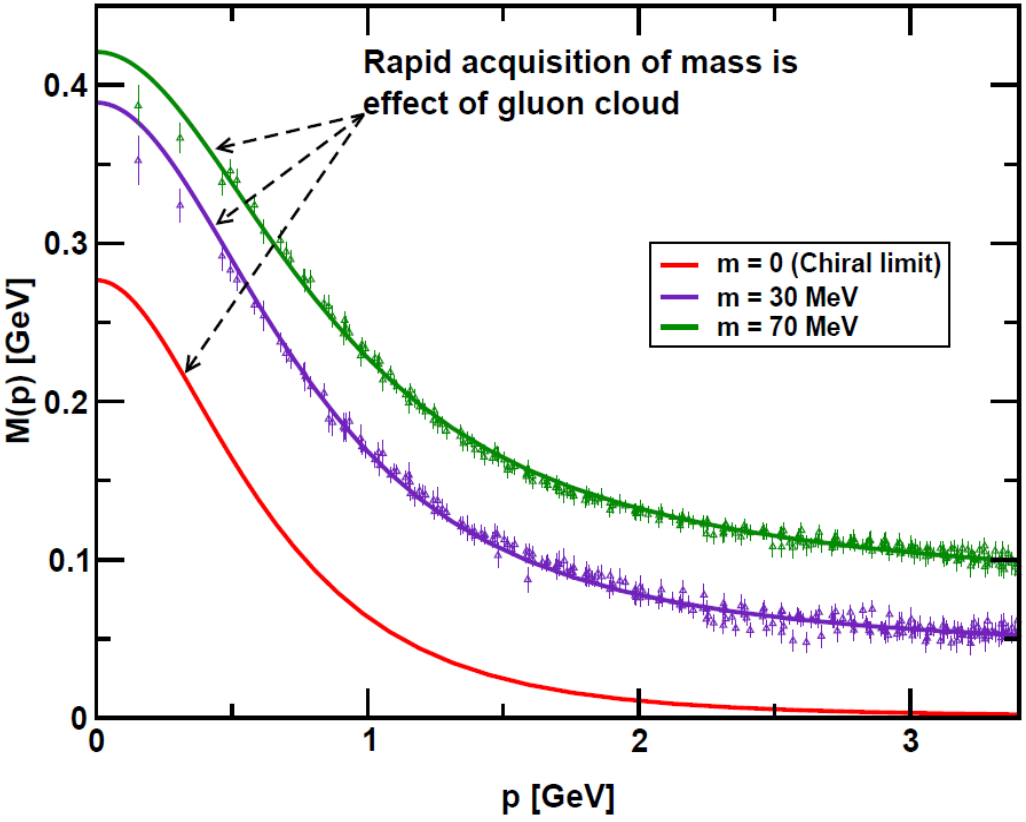
*** However the high-magnetic-field precession is required to remove the charged particles (including high-energy protons from QE e-p scattering) from NPOL acceptance.**
VERY IMPORTANT for vetoes dead time!!!

*** Problem: one dipole has not enough field integral; two dipoles take more space along the beam.**

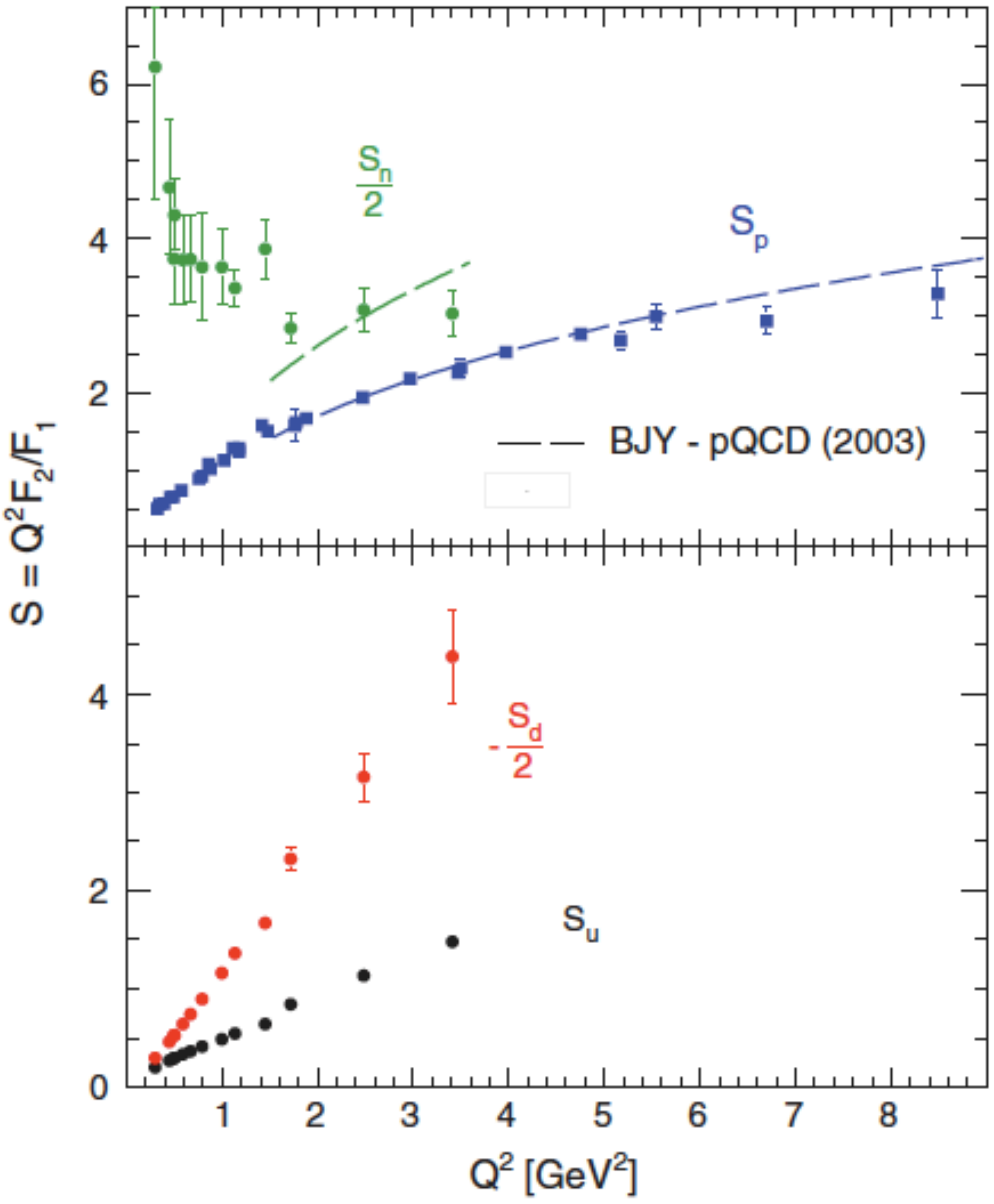
A. Semenov

Transition from bare to dressed quarks

- **Dressed quark mass function M(p)**
  - **Curves: Dyson-Schwinger calc.**
  - **Points: unquenched Lattice QCD**
- **High energy interactions sensitive to ‘undressed’ quarks, m ≈ m_{bare}**
- **Low energy interactions sensitive to fully dressed constituent quarks**
- **Form factor measurements going to higher Q^2 probe transition region between these two limits**



Flavor decomposition and scaling



Neutron

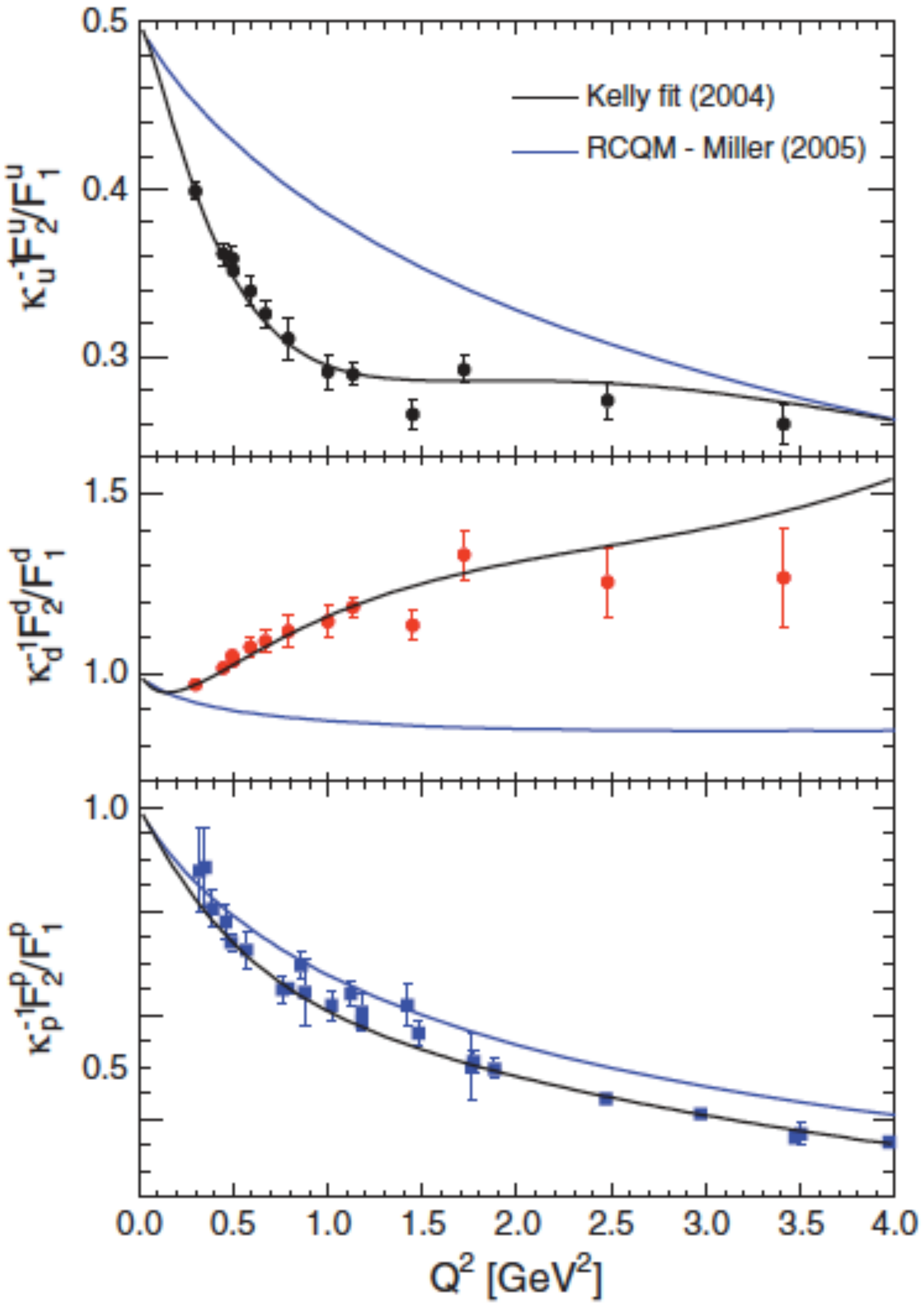
Proton

d-quark

u-quark

u and d quark contributions to Q^2F_2/F_1 scale linear with Q^2

Flavor decomposition and scaling



u-quark

d-quark

u and d quark contributions to F_2/F_1 become ~constant for $Q^2 > 1$ (GeV/c)^2