The SBS Form Factor Program

- Initial SBS goal: measure three out of four of the elastic nucleon form factors
- Measurements of both GMn and GEn are now complete
- Upcoming measurements include GEp … but also GMn-RP, K_{LL} and more …
- With MOLLER coming soon, we hope to see SBS move to Hall C

Gordon D. Cates
Hall A Collaboration meeting:
January 16, 2024

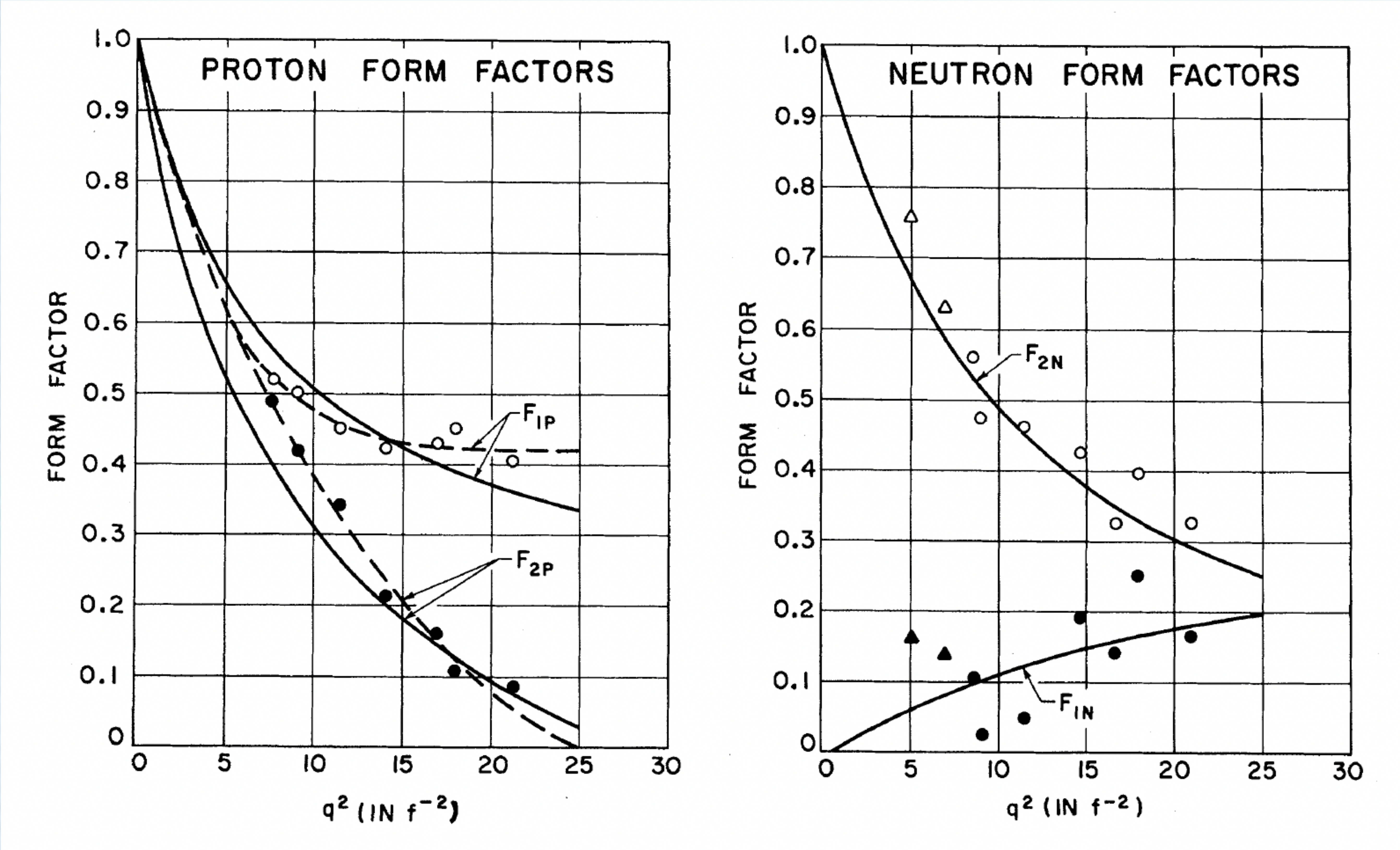
History of Elastic Nucleon Form Factors

Somehow I'm reminded of the
movie Godfather III
when Al Pacino says:
"Just when I thought I was out,
they pull me back in … "

Ok … maybe not a perfect parallel - but historically, nucleon form factors keep coming back in their importance for understanding the structure of hadronic matter

Hofstadter directly measured of the size of the proton and neutron

1961



"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

The very first experiment at SLAC: Looking for the "nucleon core" in elastic scattering

One expectation was that at sufficiently high Q^2 , a rapid drop off would occur in the elastic form factor indicating some kind of core to the nucleon

As Dick Taylor said in his Nobel Prize address, quoting Richard Wilson of Harvard, they found that

"The peach has no pit."

PROPOSALS FOR INITIAL ELECTRON SCATTERING EXPERIMENTS USING THE SLAC SPECTROMETER FACILITIES

Submitted

By

SLAC-MIT-CIT Collaboration

January 1966

4a. Electron-Proton Elastic Scattering

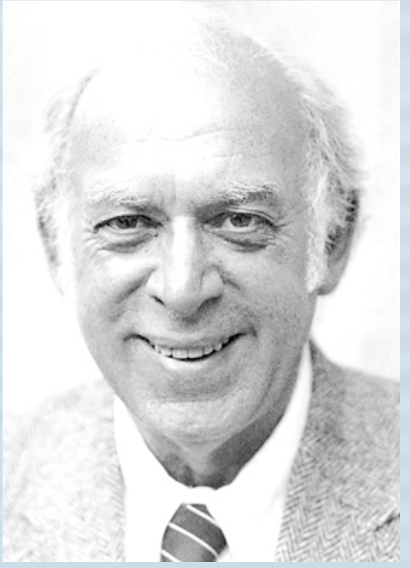
Summary

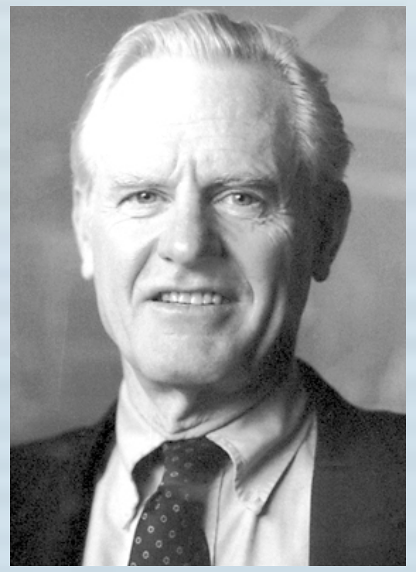
form factors. It is useful to list some of the questions of interest that can be investigated by extending the measurements to higher q^2:

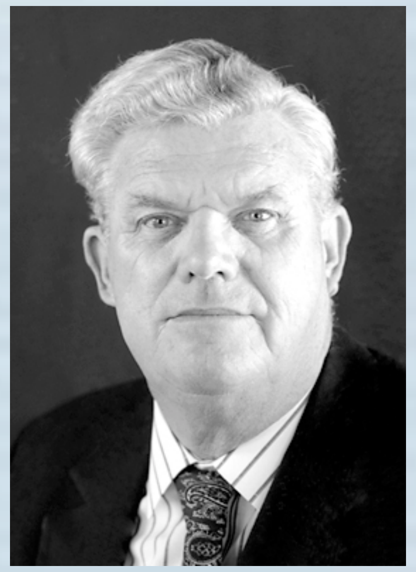
(1) Existence of a nucleon core.

(2) Validity of the pole description of nucleon form factors.

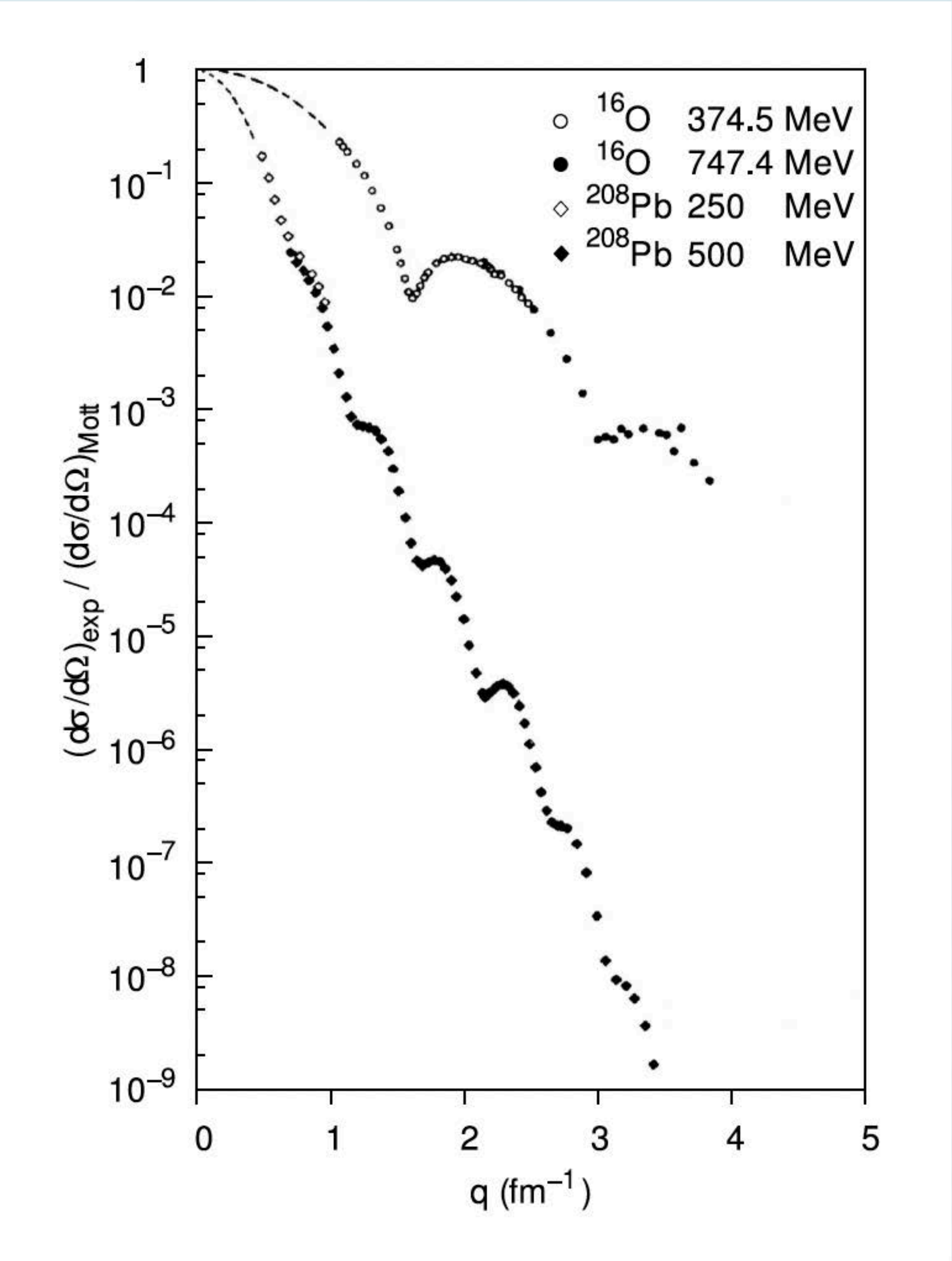
This finding set the stage for the inelastic scattering measurements that led to the discovery of quarks

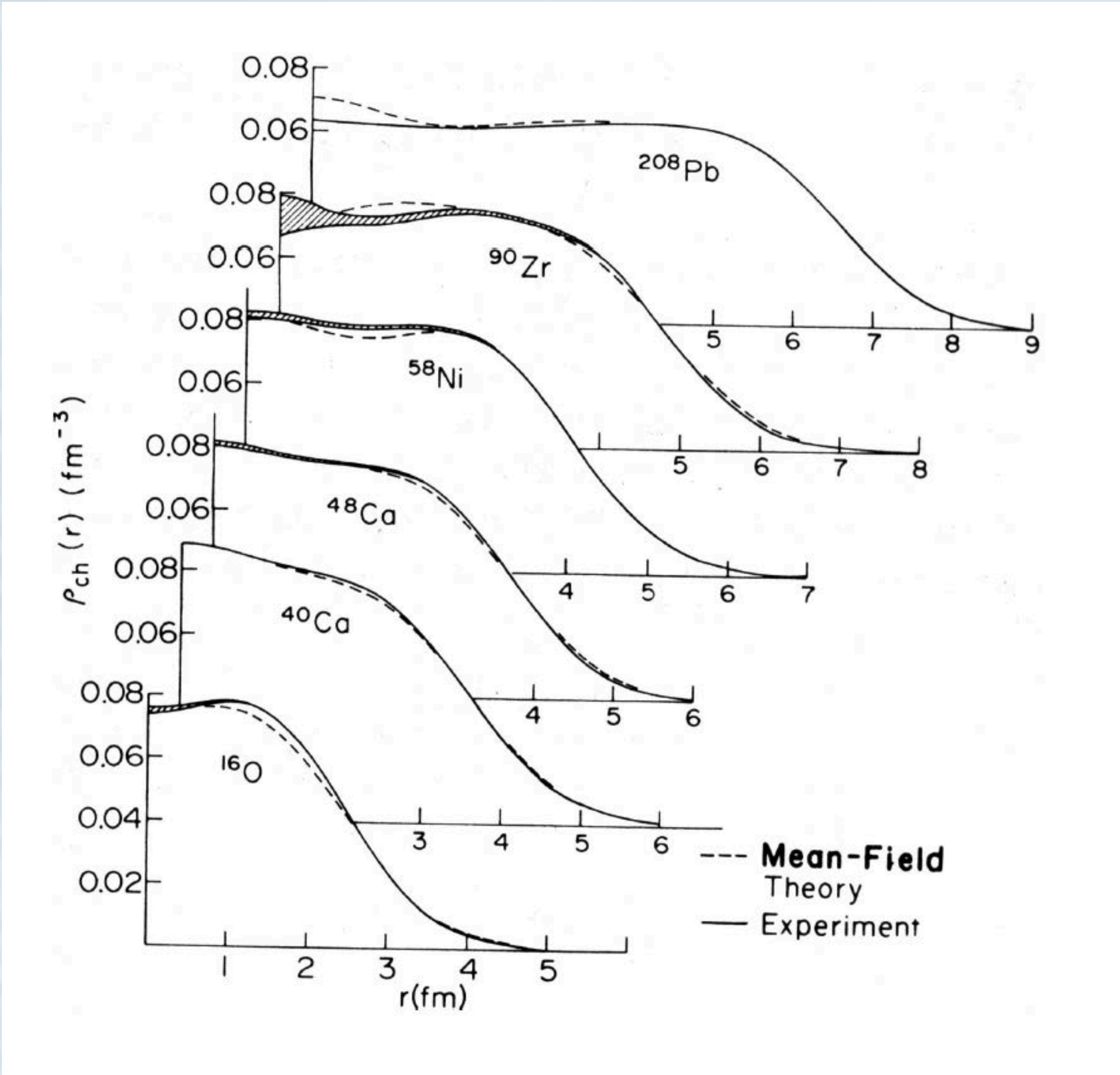




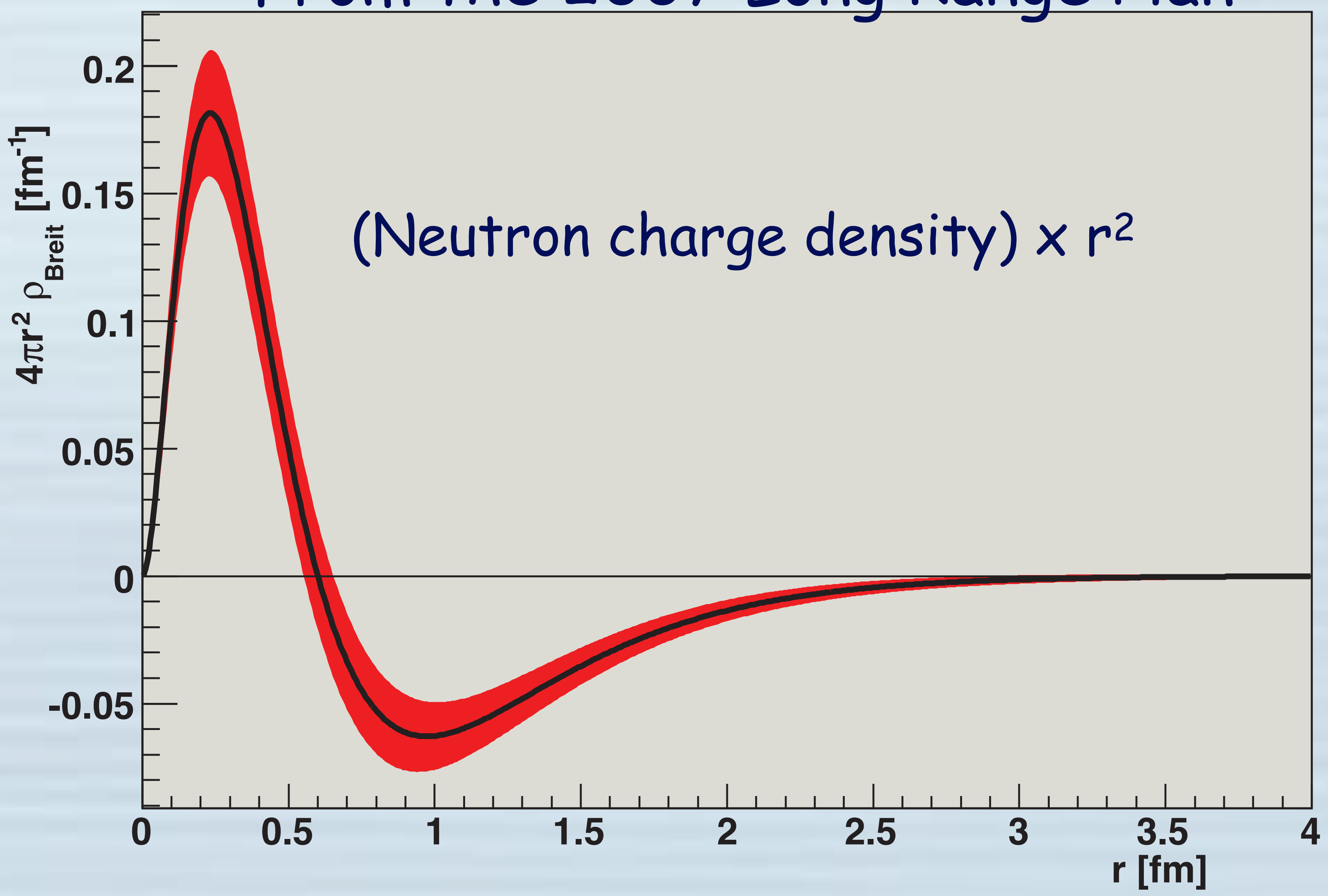


Form factors - at least of the nucleon - became somewhat less topical, although very productive



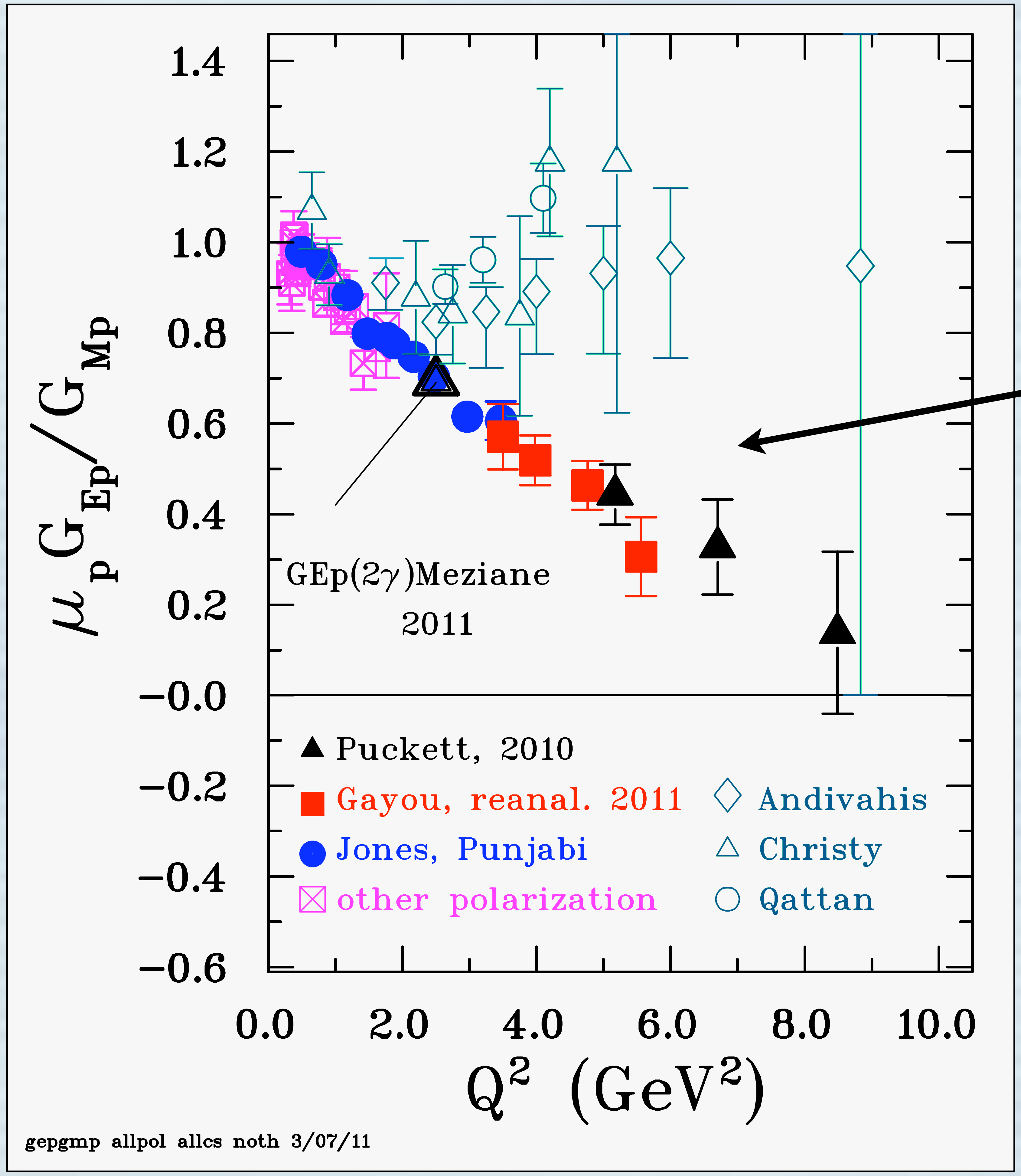


From the 2007 Long Range Plan



until ……

Double polarization techniques brought them right back ... with the discovery of the high Q^2 behavior of $\mu_p G_E^p/G_M^p$



Data from both Rosenbluth separations and the double-polarization technique.

Resulted in the 2017 Bonner Prize in Nuclear Physics being awarded to to Charles Perdrisat of William and Mary

Explanations for the Q^2 behavior of G_E^p/G_M^p have typically relied upon the role of quark orbital angular momentum.

In part, nucleon form factors are so important because they provide an exceptionally clean probe:

The hadronic current:

$$\mathcal{J}^{\mu}_{\text{hadronic}} = e\overline{N}(p')\left[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}F_2(Q^2)\right]N(p)$$

Dirac FF (F_1) Pauli FF (F_2)

The Sachs FFs:

$$G_{E} = F_1 - \tau F_2 \quad \text{and} \quad G_{M} = F_1 + F_2$$

where

$$\tau = \mathrm{Q}^2/4\mathrm{M}^2_{\text{nucleon}}$$

The form factors still provide one of the most important constraints for GPDs

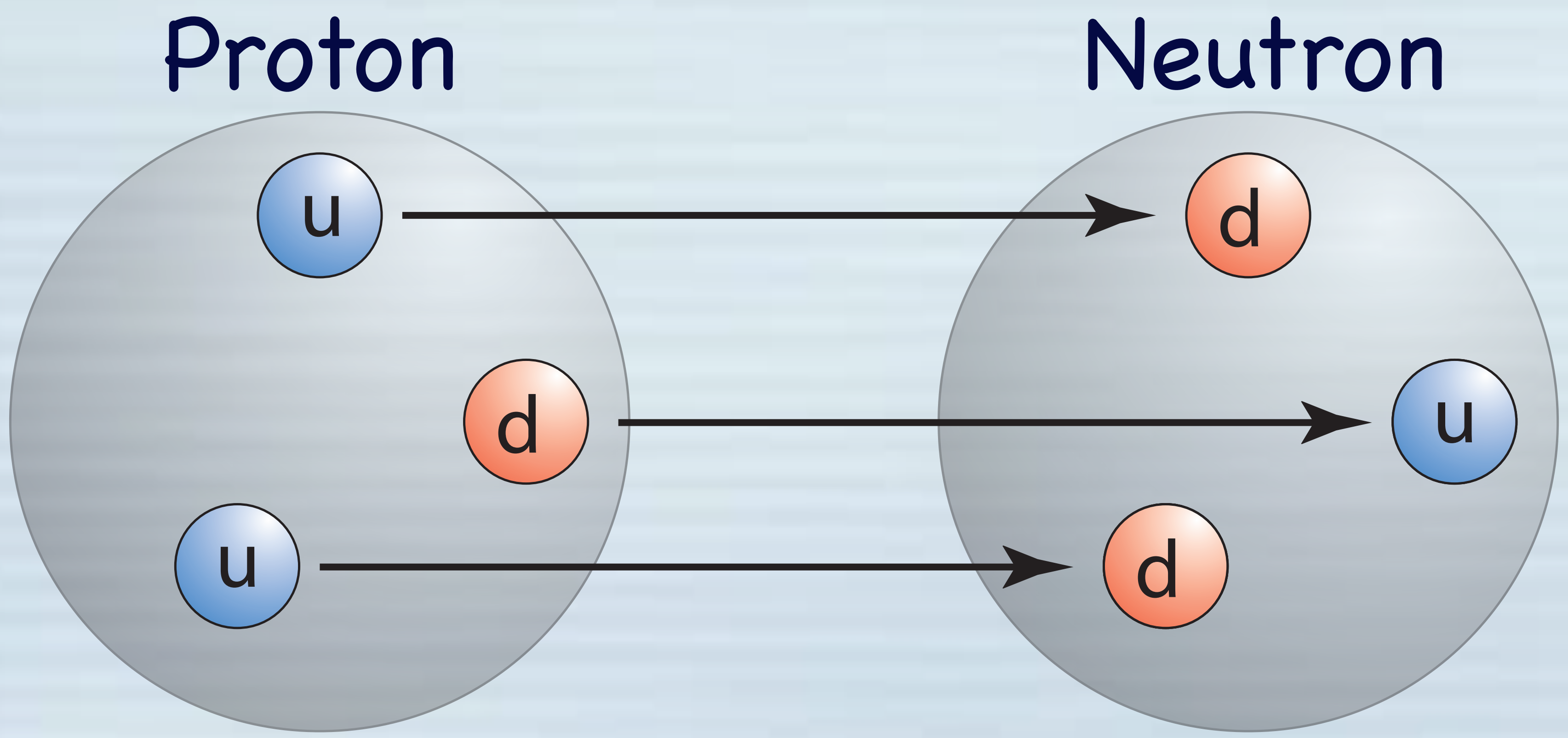
$$\int_{-1}^{+1} dx H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} dx E^q(x,\xi,Q^2) = F_2^q(Q^2)$$

Among other things, FFs thus play a role in determining the angular momentum of the quarks using Ji's Sum Rule:

$$J^q = \frac{1}{2}\int_{-1}^{1} x\, dx\, \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

FFs thus play a an important role in the entire GPD program, one of the signature goals of the 12 GeV upgrade

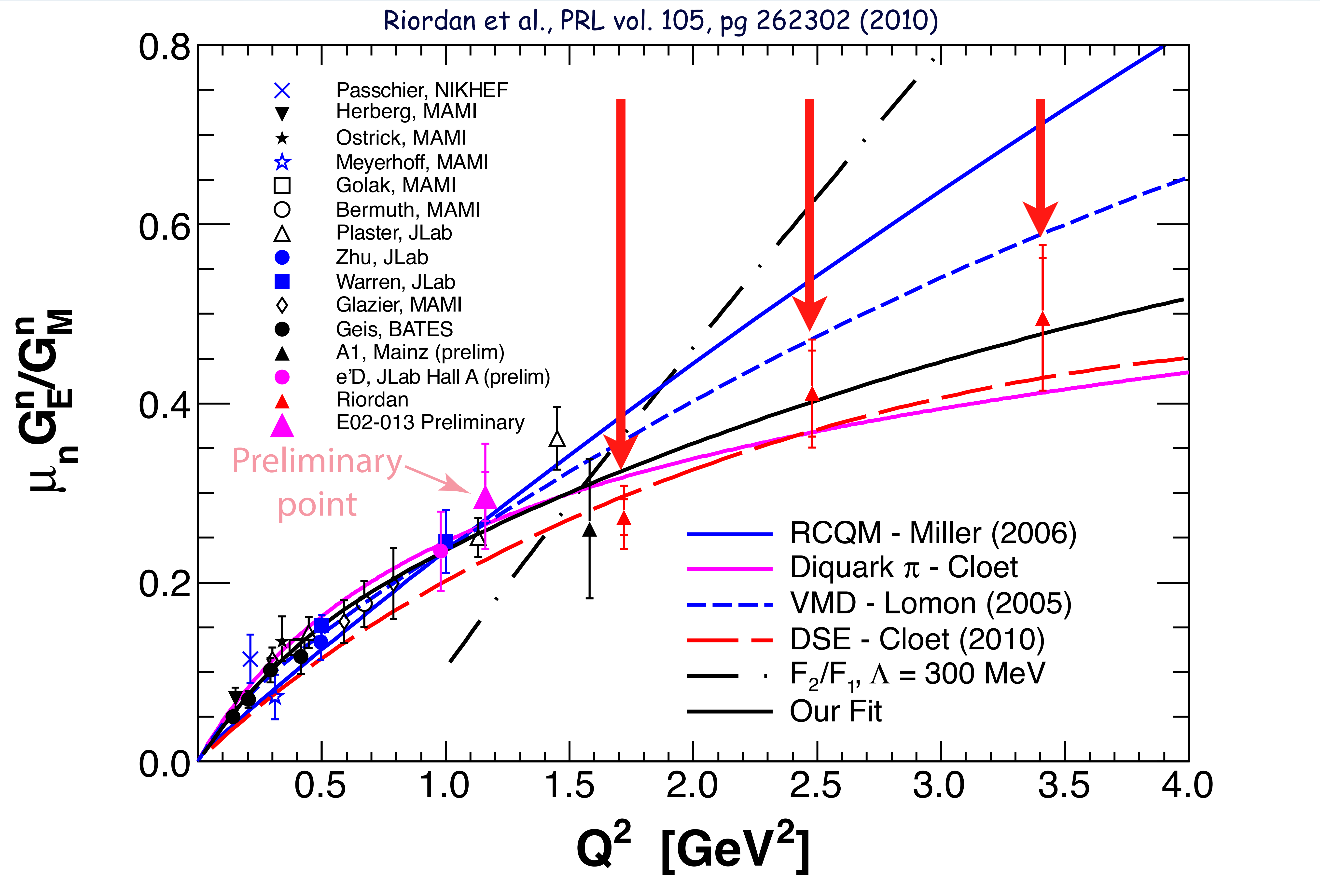
With detailed knowledge of both proton and neutron form factors, the individual contributions of the up- and down-quarks can be extracted



For the Dirac form factors (and similarly for the Pauli form factors):

up quark: $F_1^u = 2F_1^p + F_1^n$ down quark: $F_1^d = 2F_1^n + F_1^p$

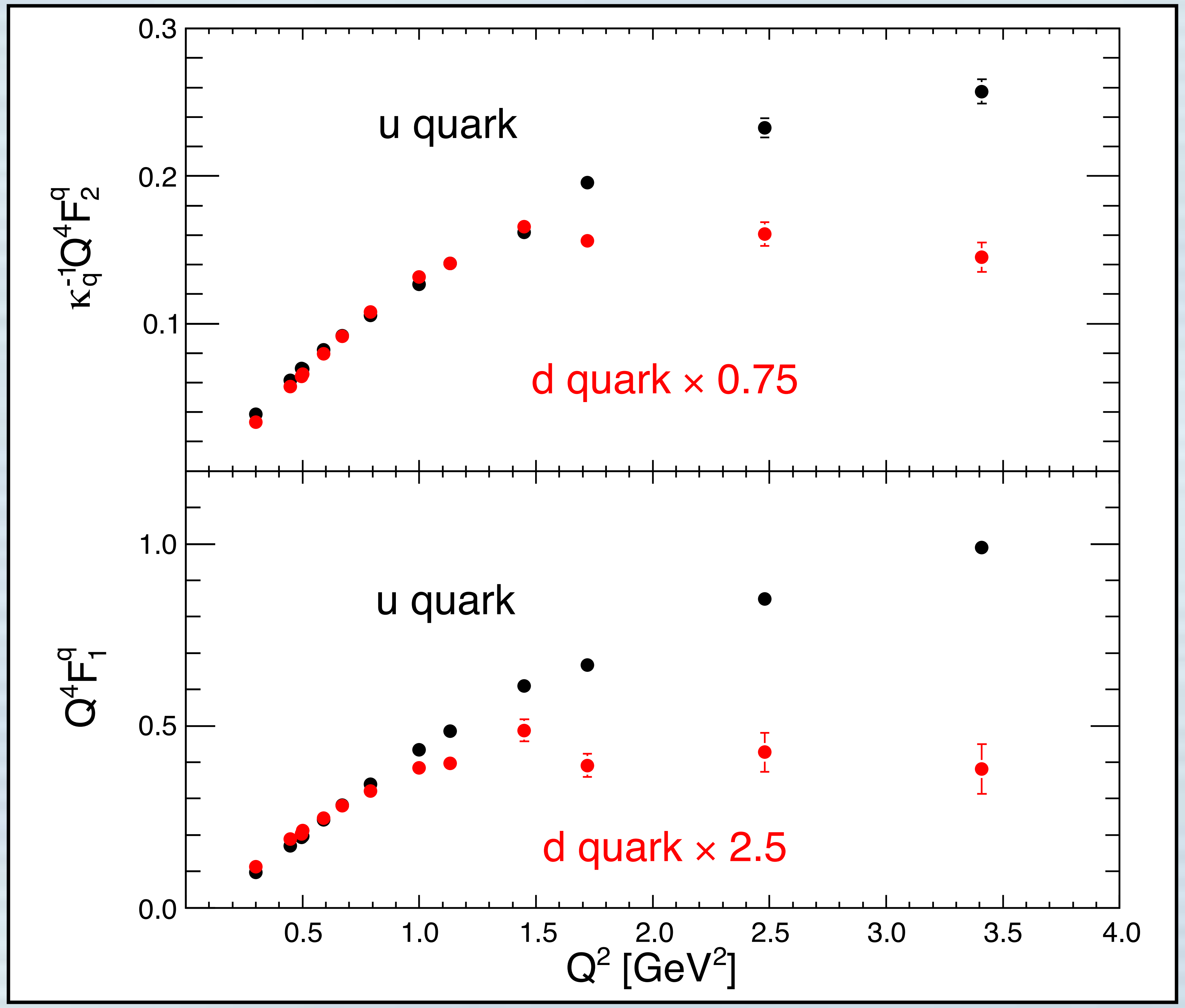
Data from the first Hall A polarized ^3He experiment (E02-013) extended knowledge of G_E^n to high Q^2



The BigBite G_E^n experiment provided the first test of theories developed to explain the surprising proton results, although clearly, higher Q^2 would be desirable

The behavior of the u- and d-quark form factors are quite distinct from on another

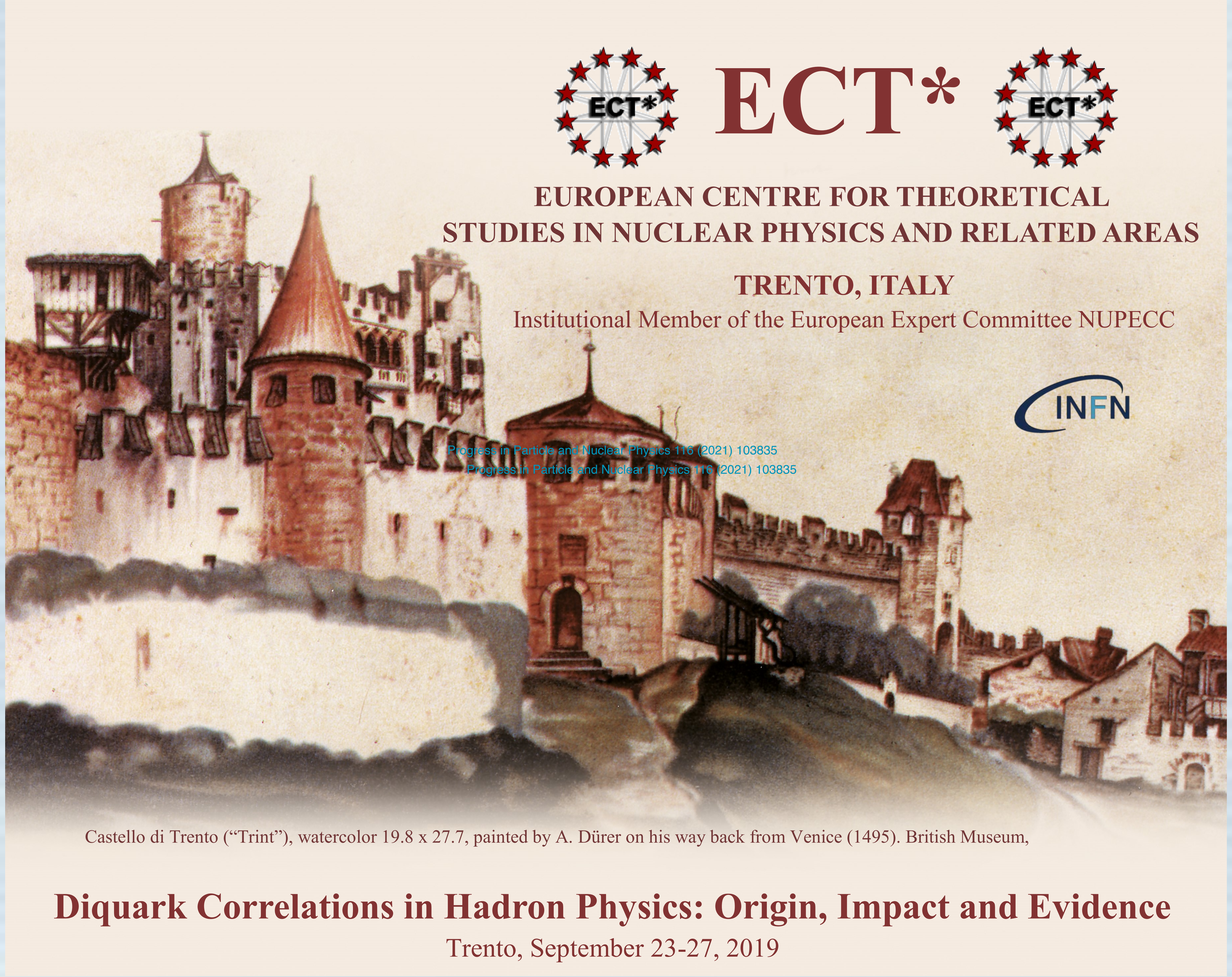
Cates, de Jager, Riordan and Wojtsekhowski, PRL vol. 106, pg 252003 (2011)



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

Many of the theoretical models that reproduce the above trends indicate the importance of diquark correlations.

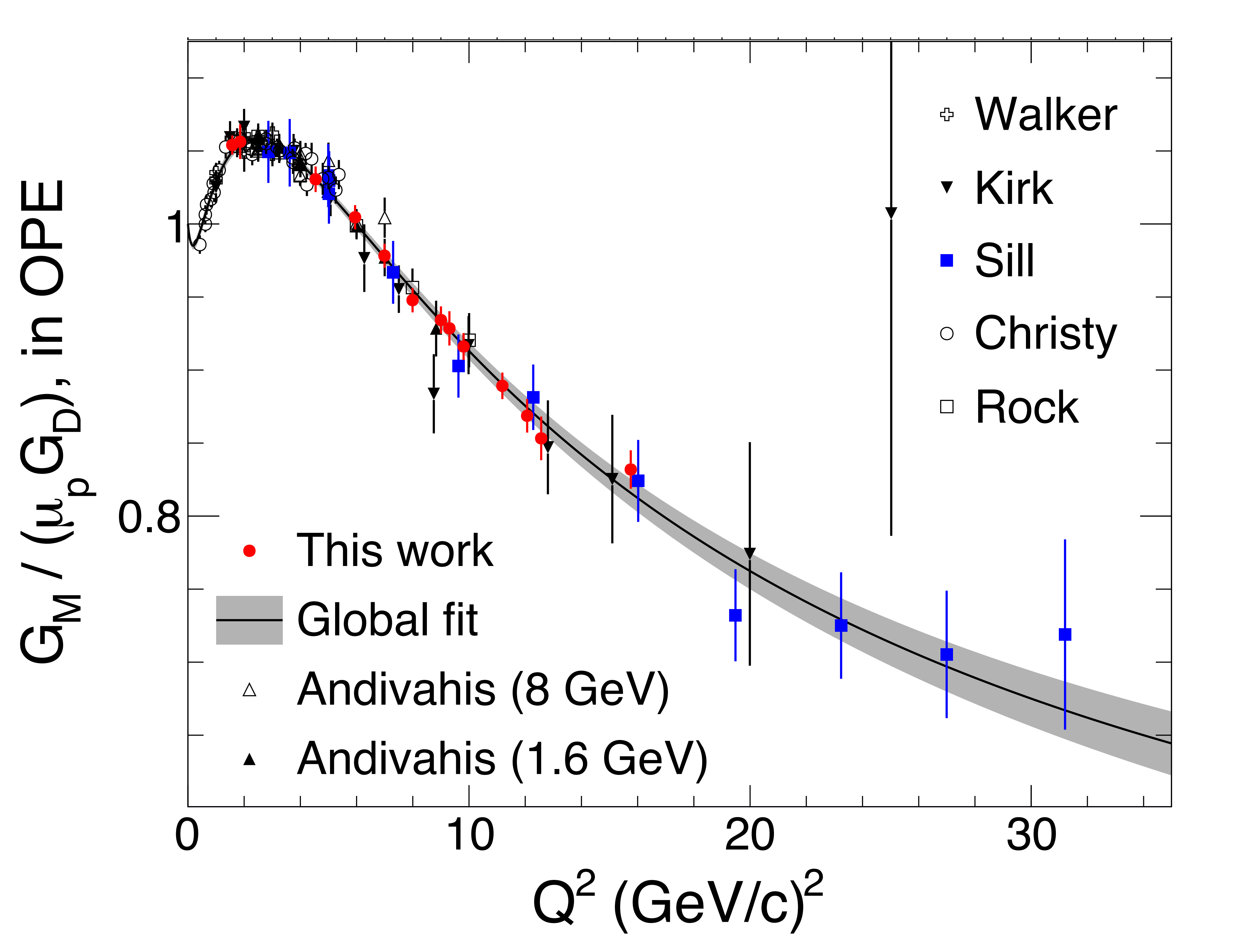
Workshop on diquarks at ECT* in Trento
(September 2019)

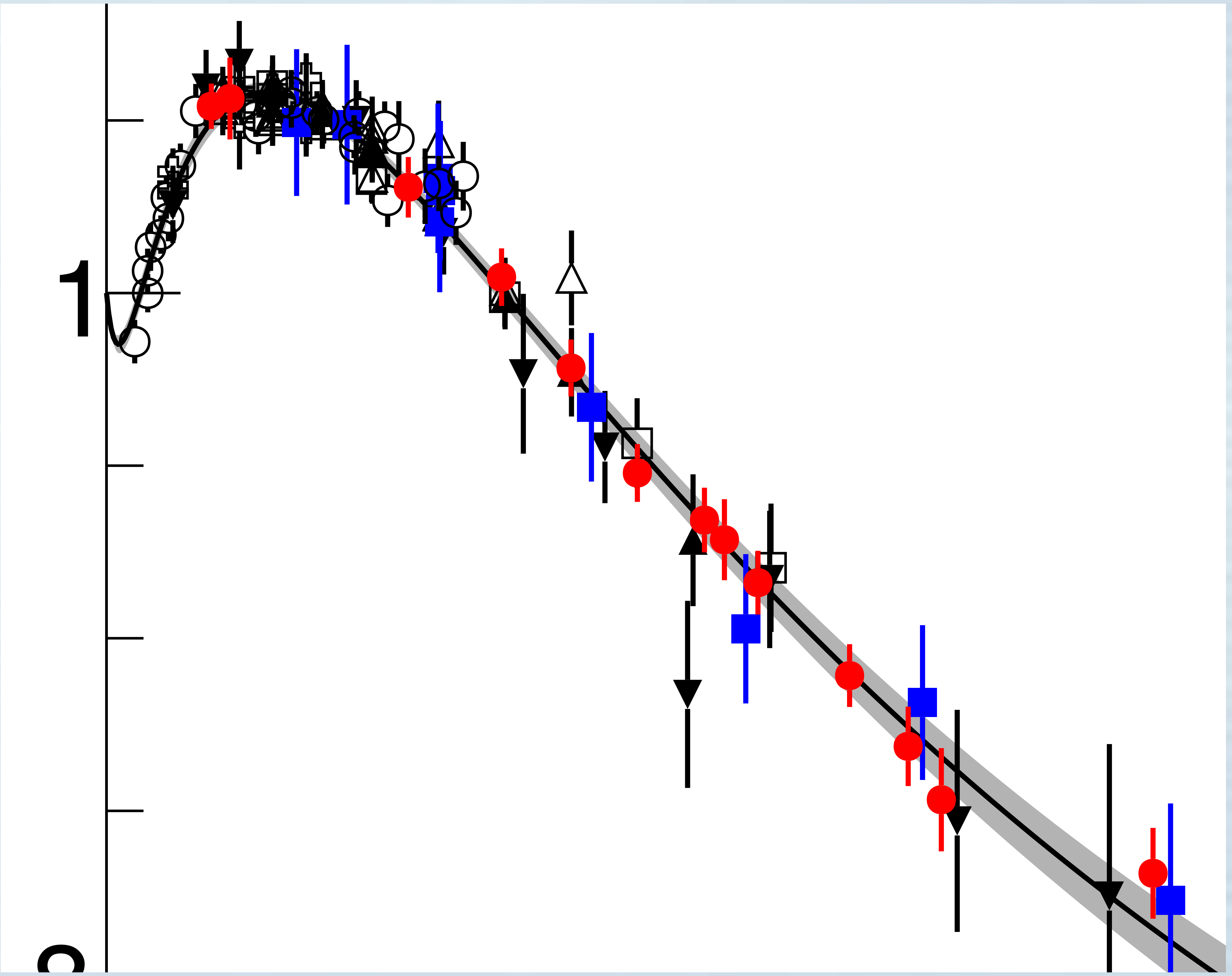


Review article grew out of the workshop: "Diquark Correlations in Hadron Physics: Origin, Impact and Evidence", Progress in Particle and Nuclear Physics 116 (2021) 103835".

Nucleon form factors in the JLab 12 GeV era

Precise new extraction of the proton's magnetic form factor up to $Q^2 = 15.75\ GeV^2$





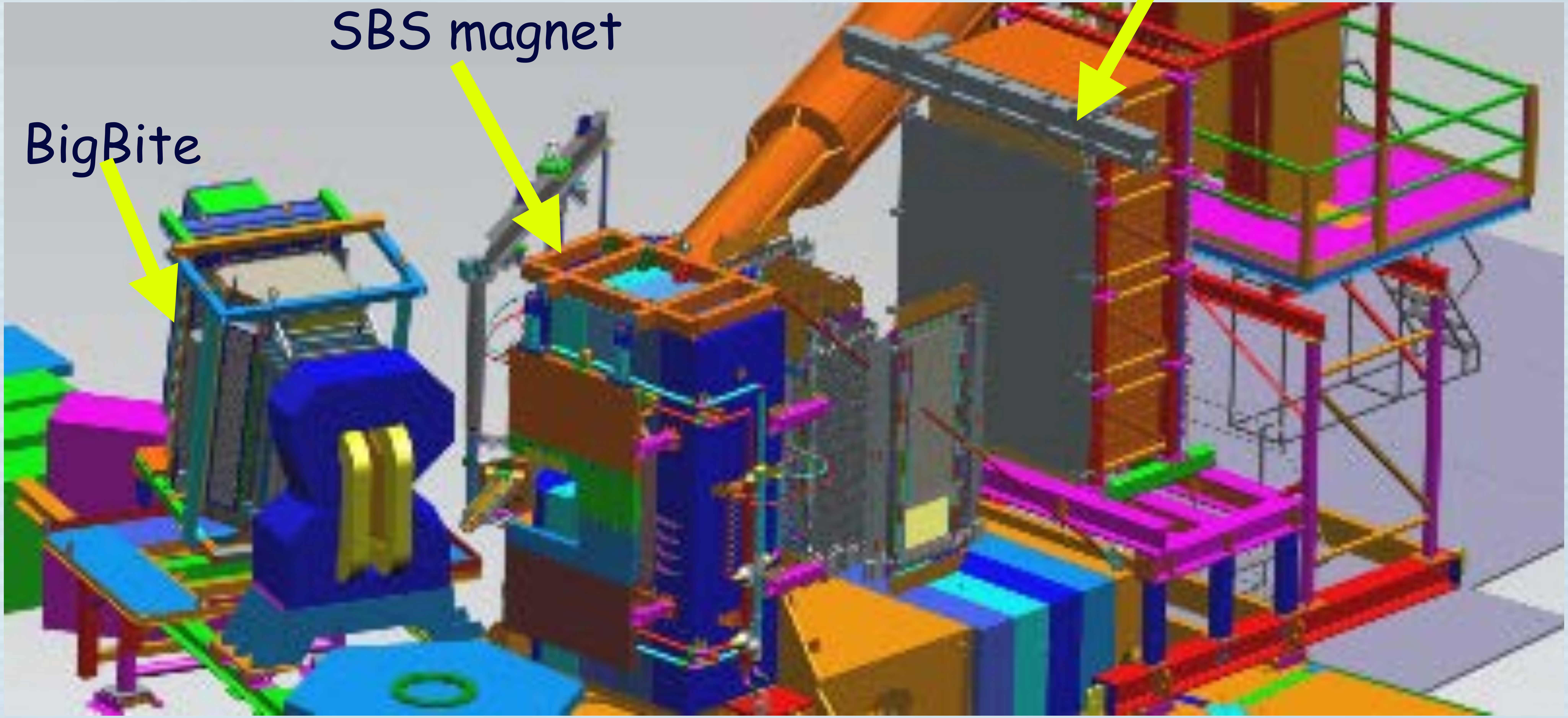
Shown at left is the extraction of G_M^p resulting from JLab E12-07-108 (PRL v128, 102002 (2022)).
At right is a blown up version of the of the figure at left to better visualize the new points.

The ongoing Super Bigbite Spectrometer (SBS) nucleon form factor program

- G_M^n/G_M^p (E12-09-019) - Q^2 up to 13.5 GeV^2. COMPLETE!!! – Oct. 2021 – Feb. 2022
- G_E^n/G_M^n (E12-09-016) - Q^2 up to ~ 9.7 GeV^2. COMPLETE!!! – Oct. 2022 – Oct. 2023
- G_En-RP (E12-17-004) - Q^2 ~ 4.5 GeV^2 Expected start – April 2024
- G_E^p/G_M^p (E12-07-109) - Q^2 up to ~12 GeV^2. Expected start – October of 2024

The Super Bigbite Spectrometer (SBS) program

(apparatus shown in roughly the configuration used for GMn and GEn measurements)

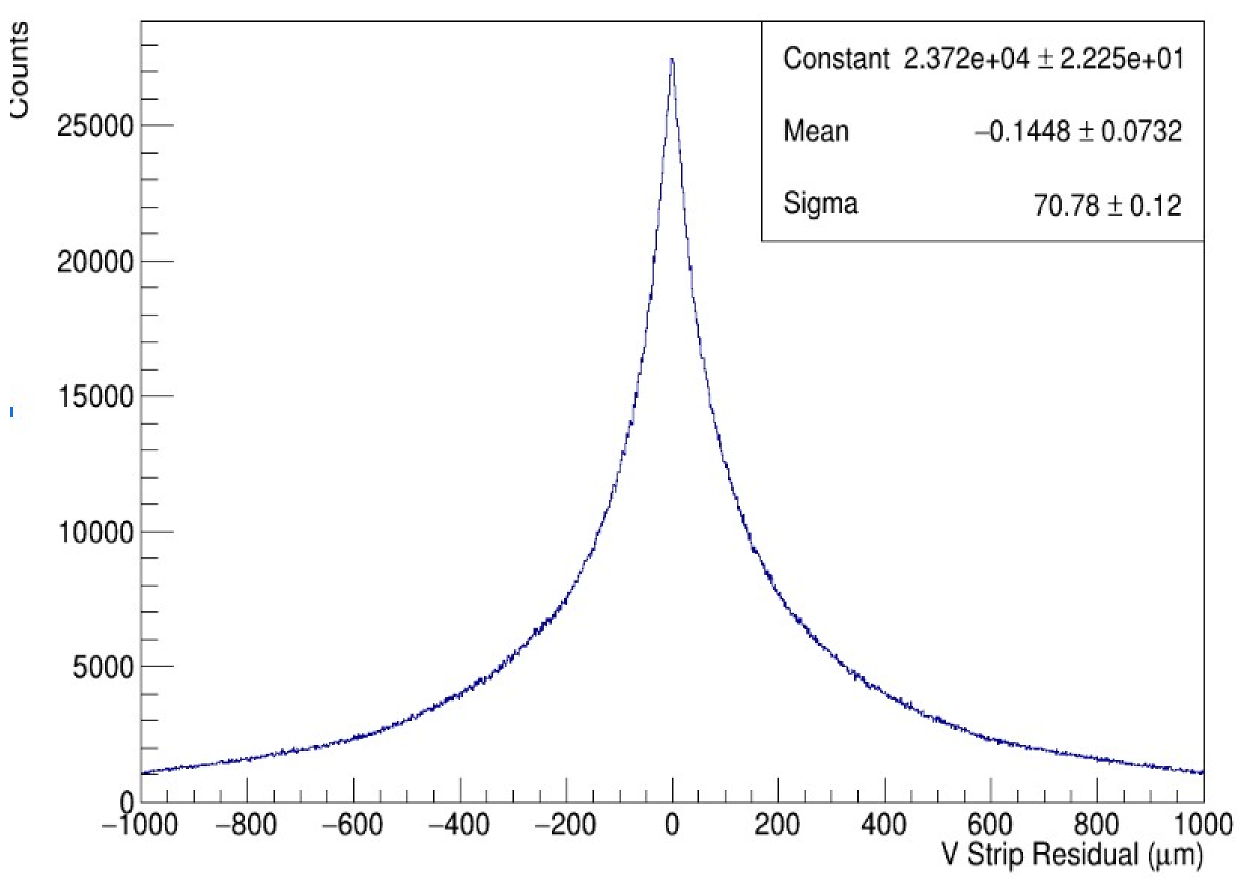


GEM performance in BigBite tracking

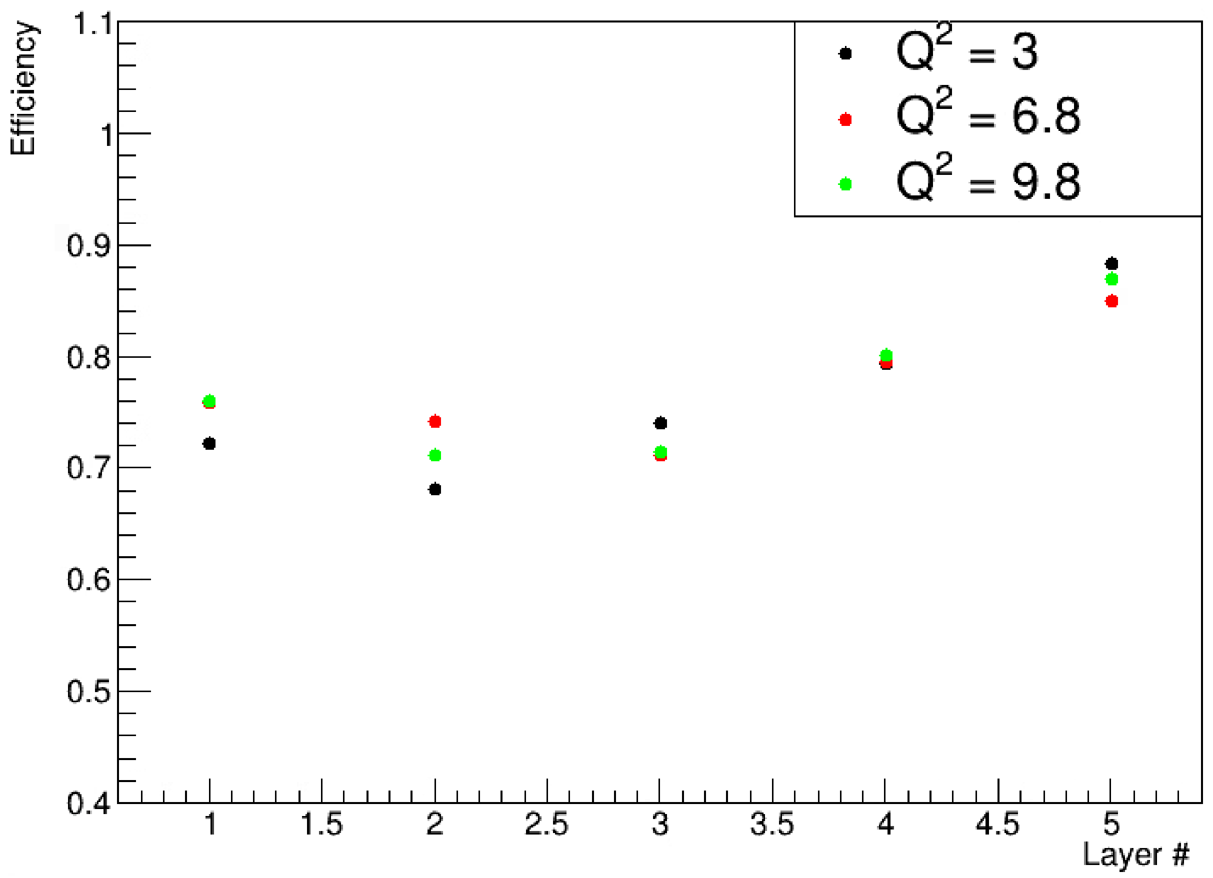
From Sean Jeffas

- Track resolution ~70 μm.
- Efficiency above 70% for highest beam currents at all kinematics.
  - Results likely 5-10% better after all calibrations and cuts applied.
- Occupancies reasonable for zero suppression and track finding.

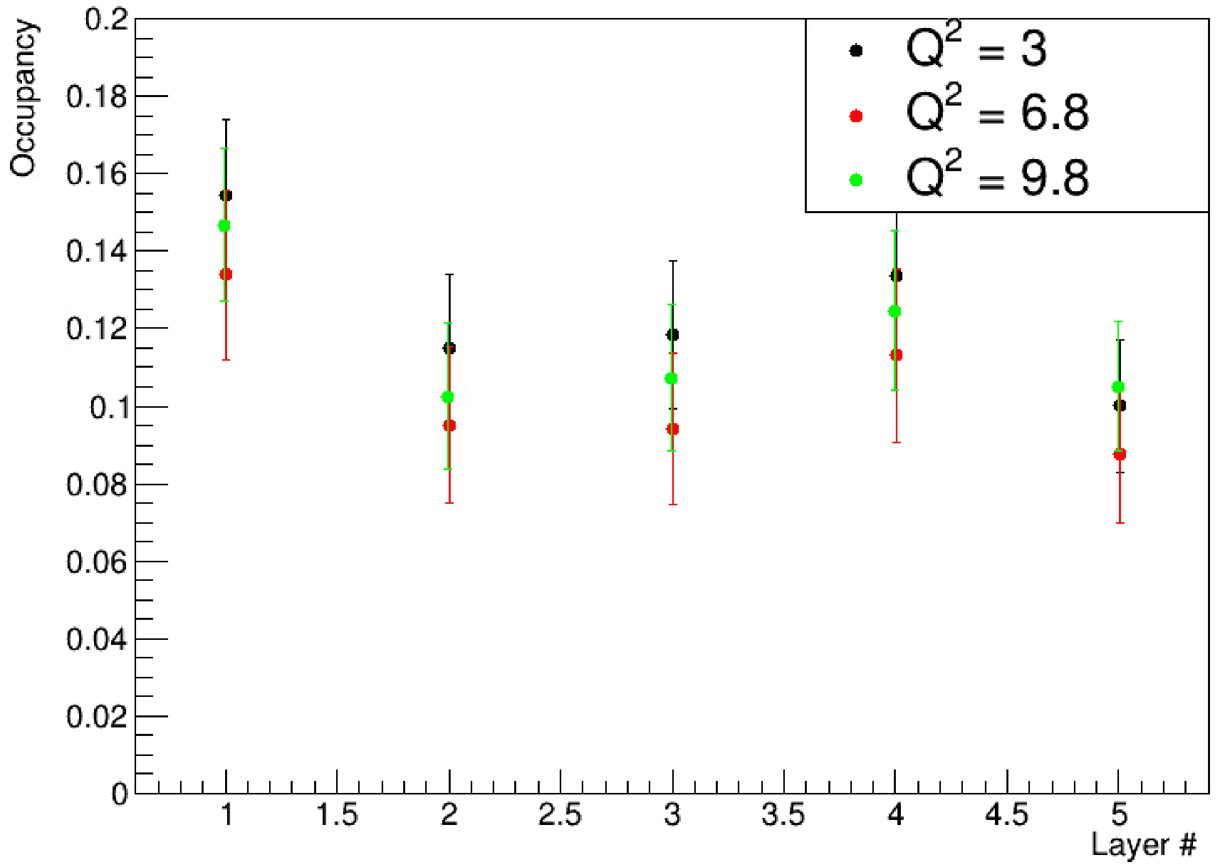
GEM V Strip Resolution

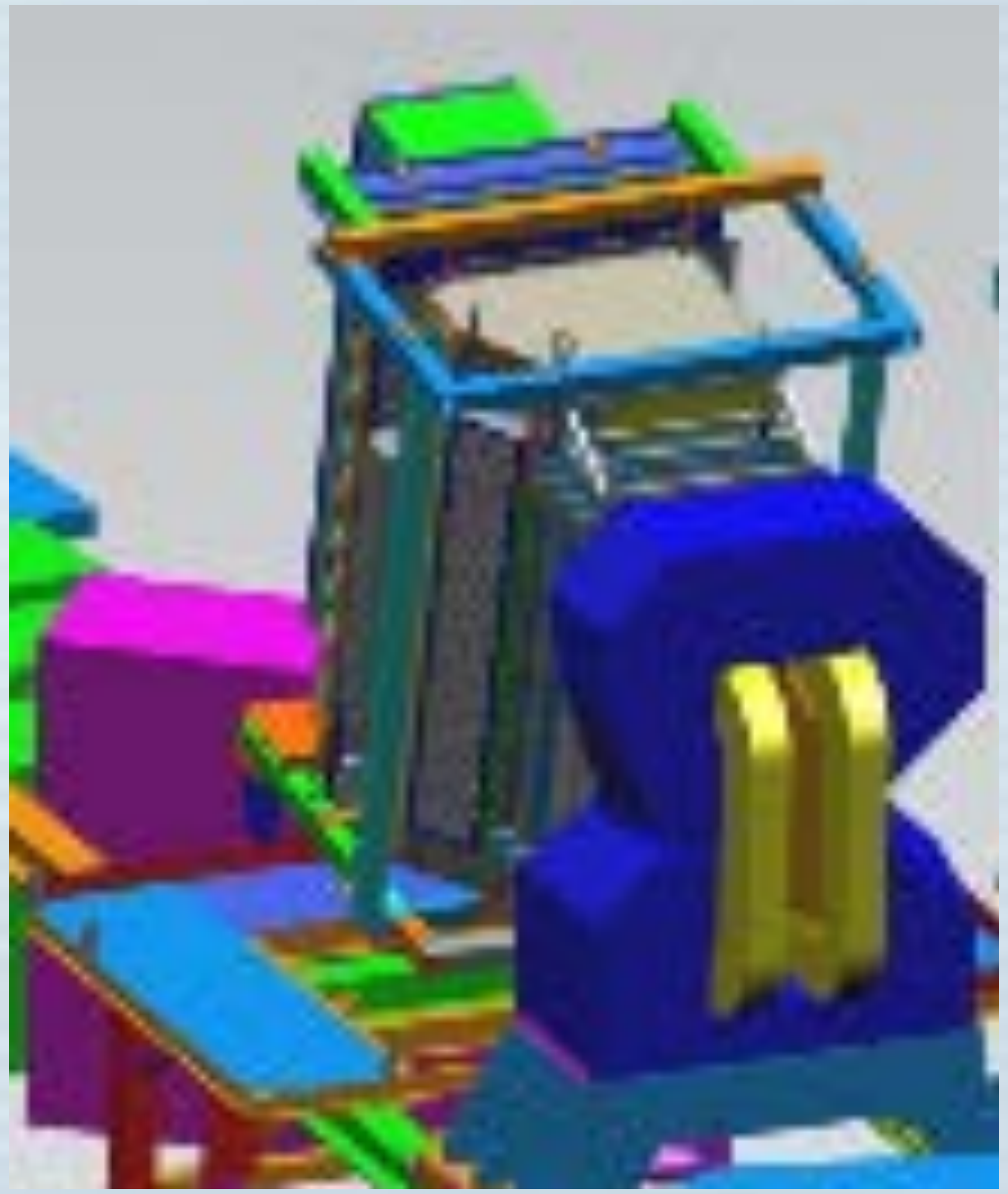


GEN GEM Layer Efficiency



GEN GEM Layer Occupancy

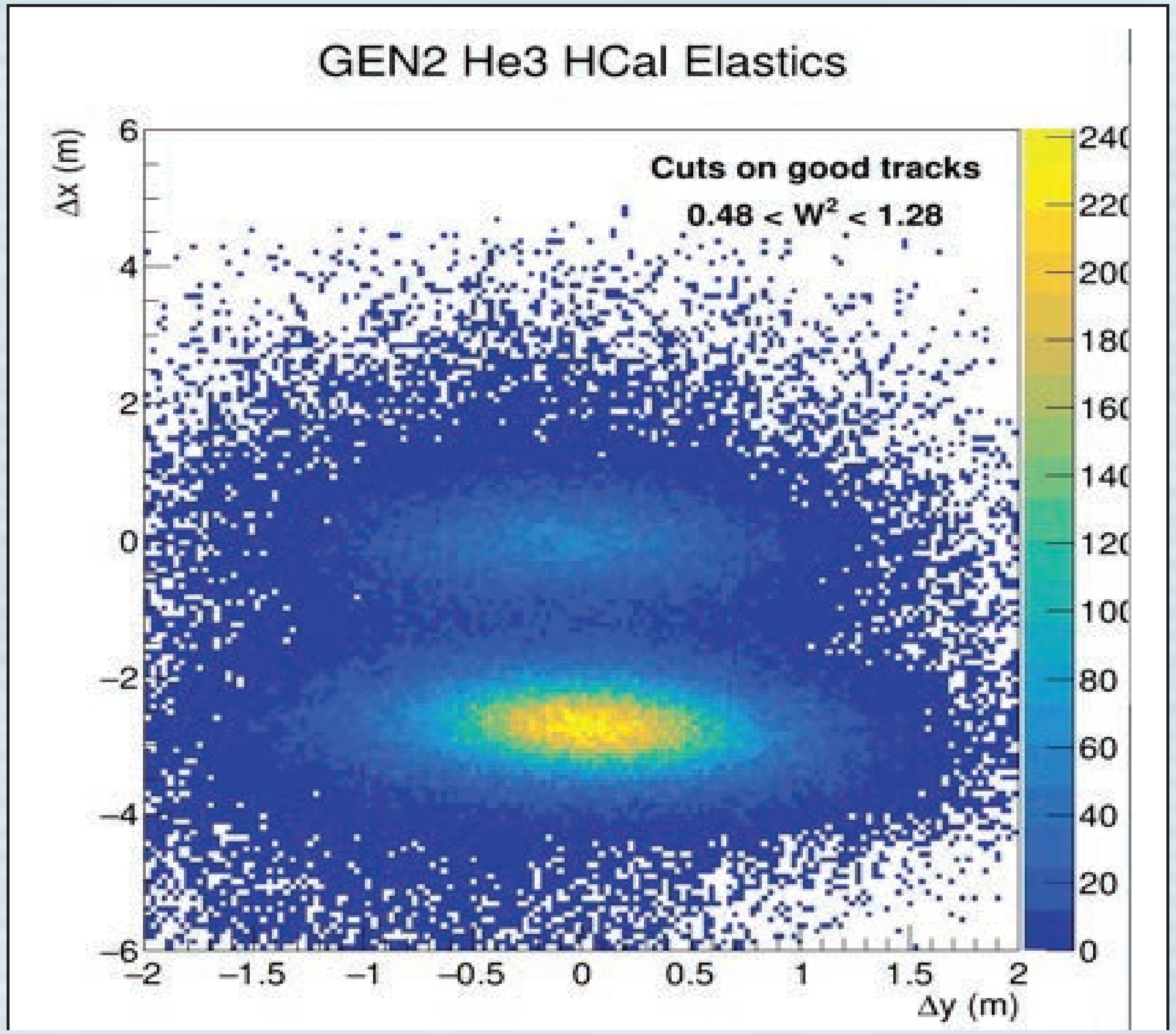




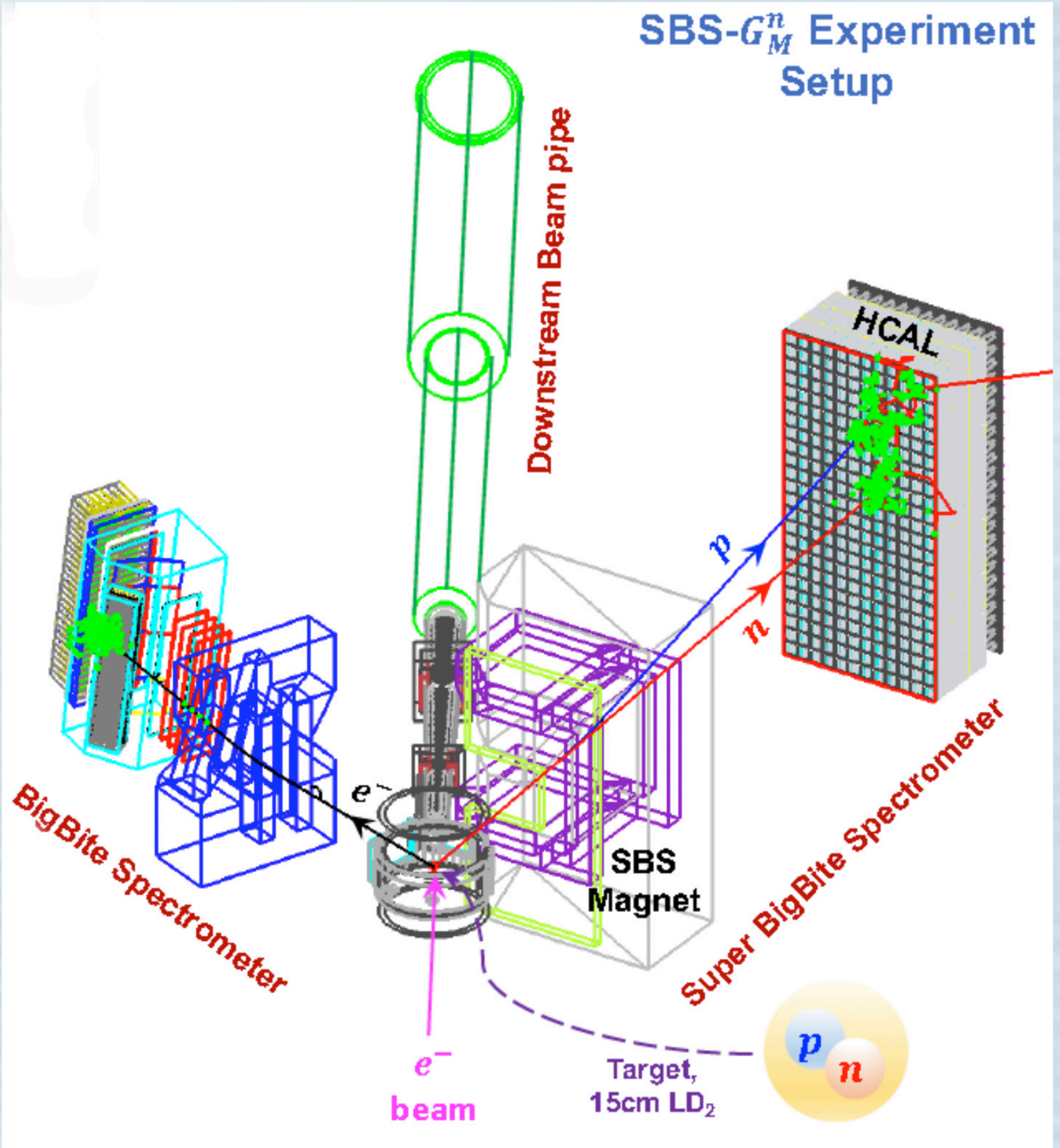
BigBite

- Singles rates were as high as 55 kHz/cm^2
- Tracking efficiencies were nonetheless in the range of 96-97%

SBS magnet and HCal - clean separation of neutrons and protons



Elastic events on HCal with good tracks on BigBite. The two axes represent displacement from straight-line projections based on the track in BigBite



Target performance during GEn-II vs. history

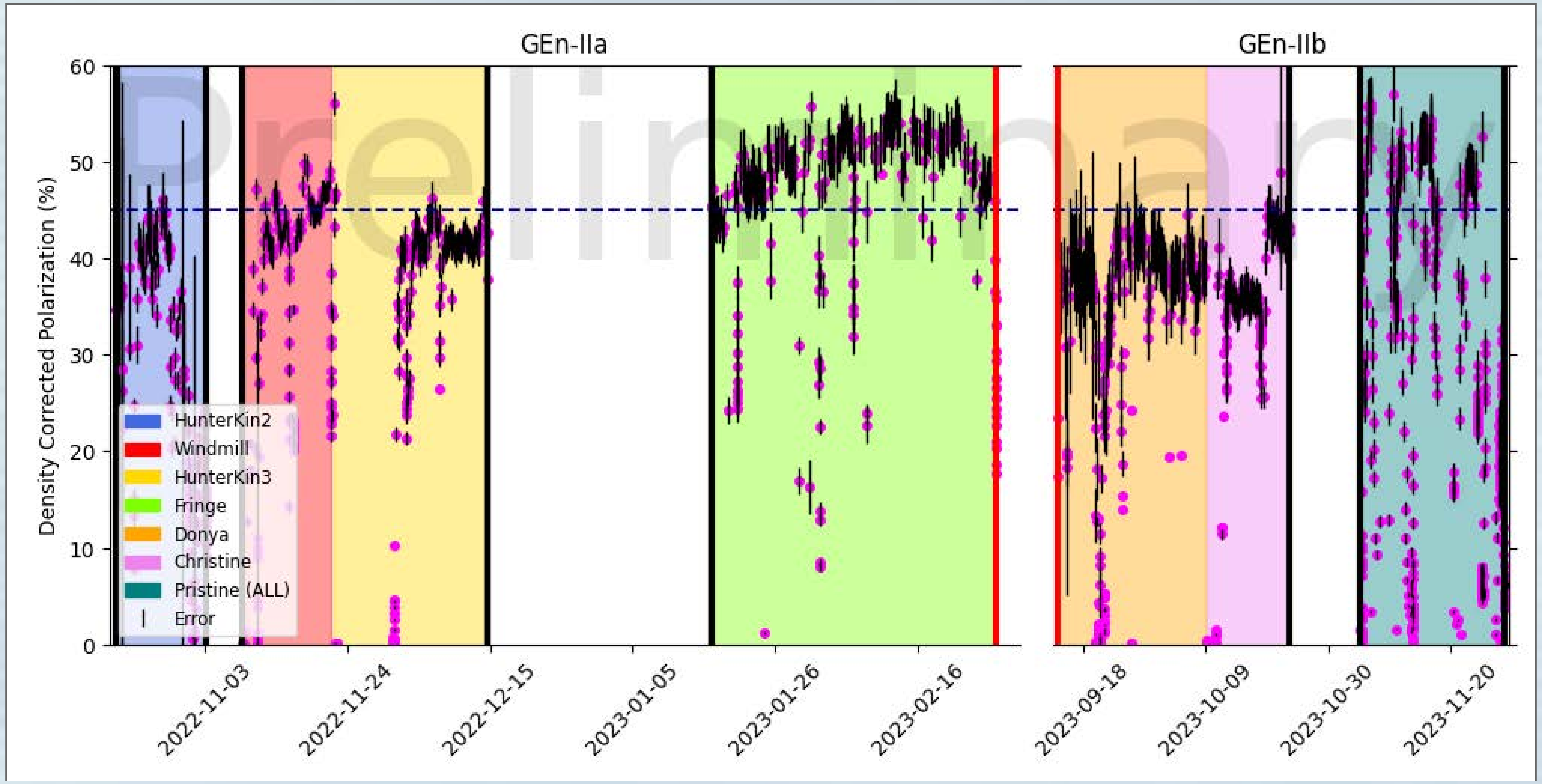
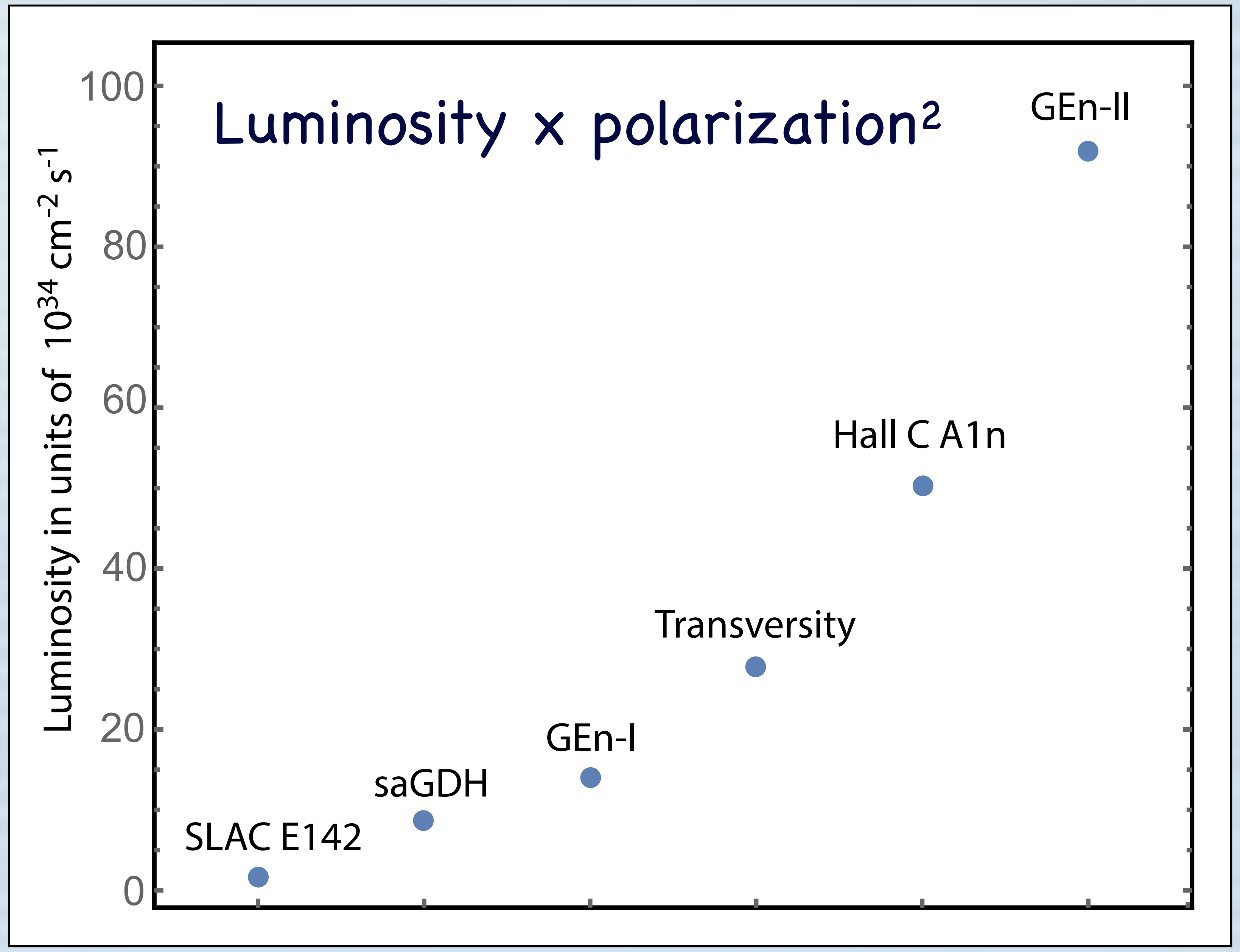
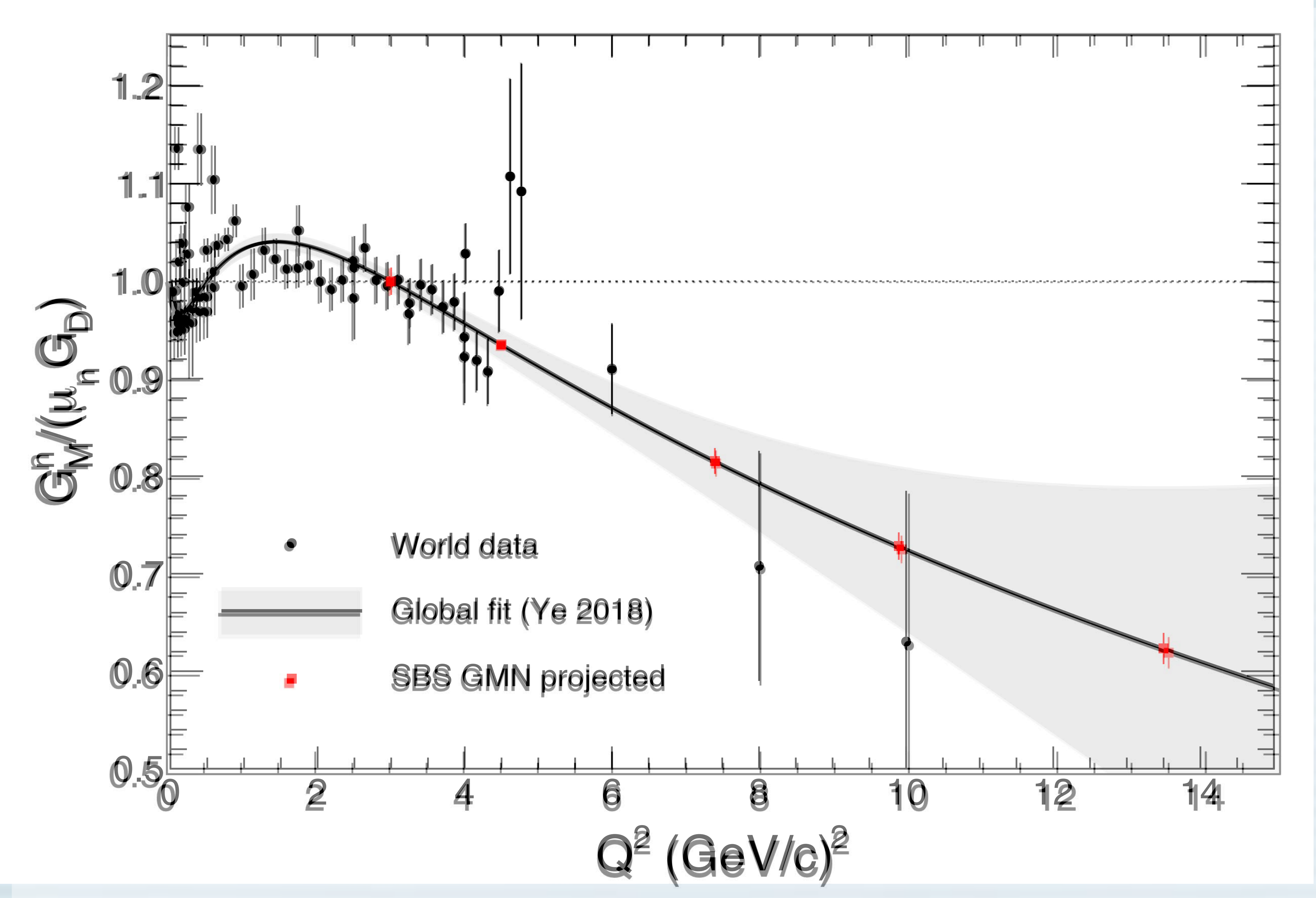


Figure-of-merit of polarized ^{3}He targets for various experiments over time



- Average polarization was around 45%

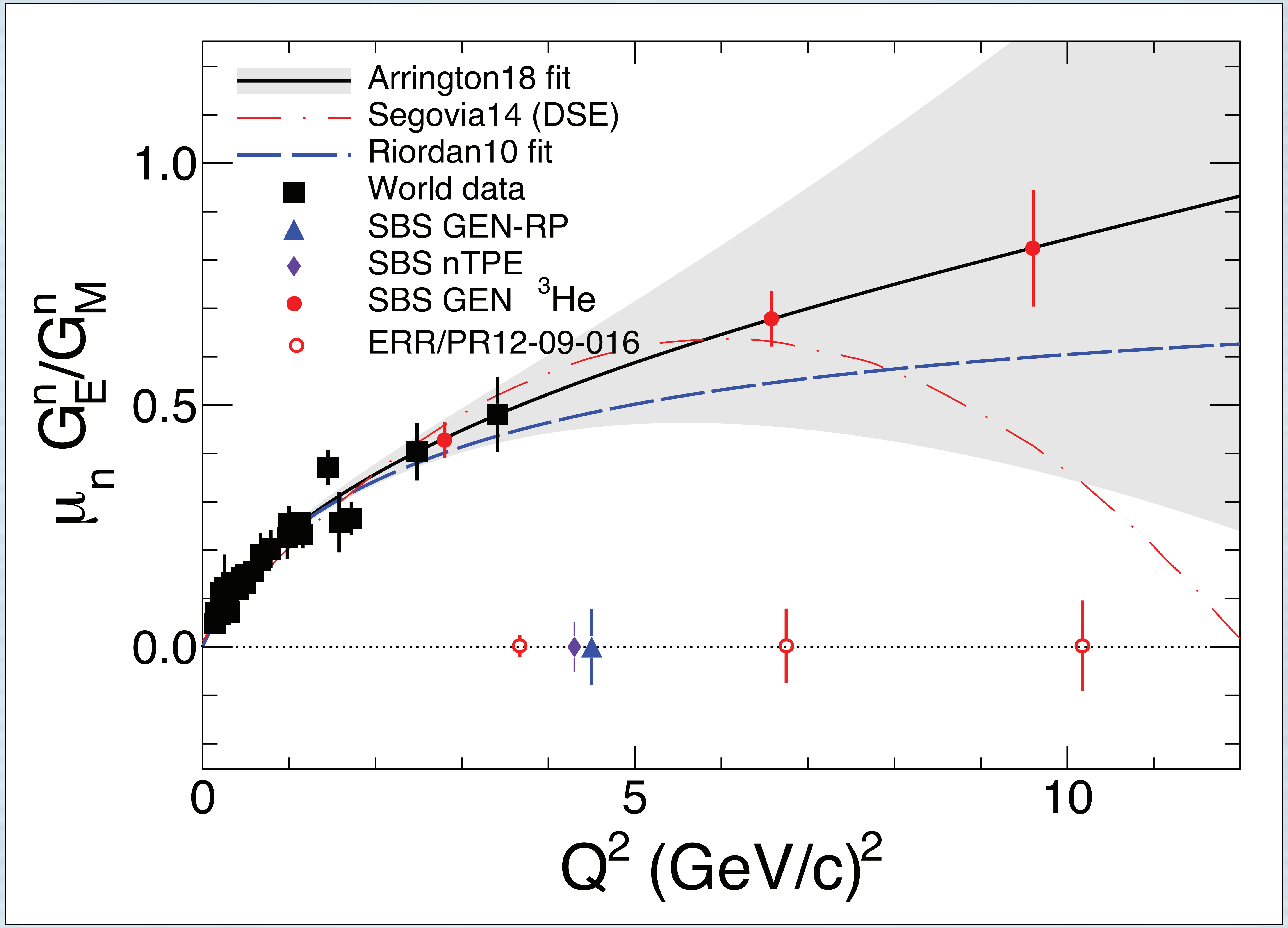
The Projected error bars from the SBS GMn experiment based on the actual acquired data



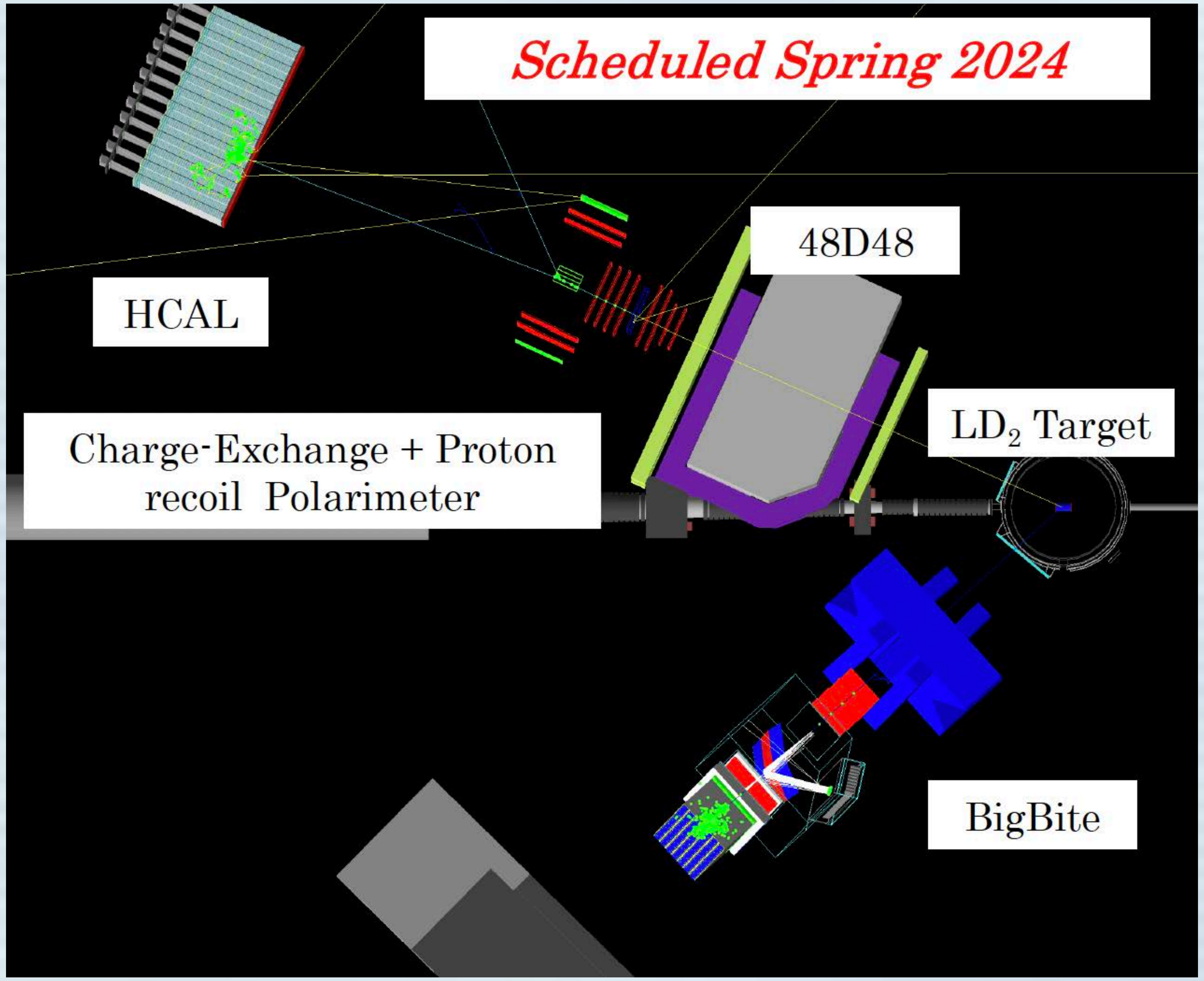
The SBS GMn experiment could establish a zero crossing in F1d/F1u, an observation that would be challenging to interpret within the GPD framework.

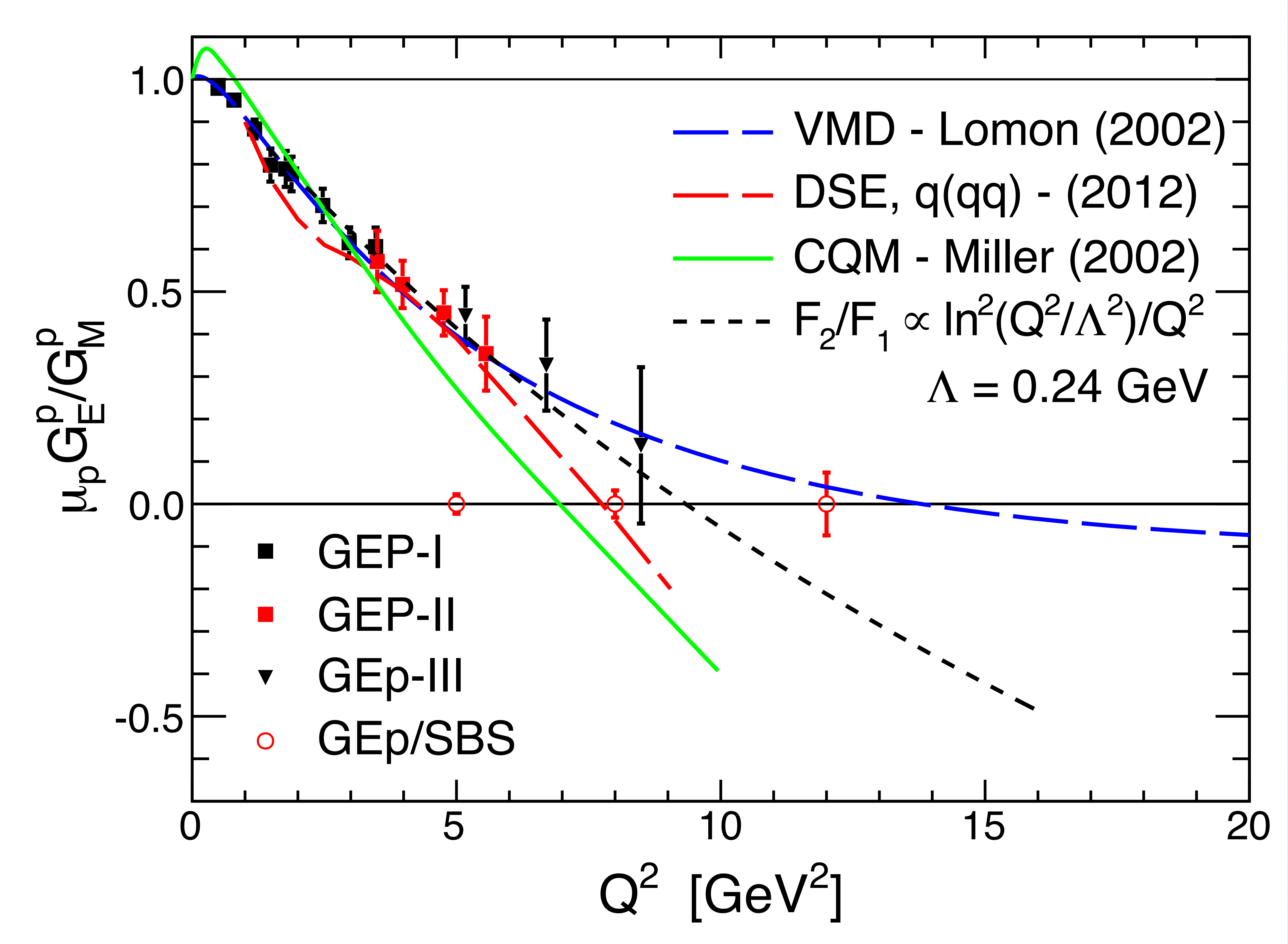
Projected errors for SBS GEn-II

- Data have been acquired for two out of three kinematic settings.
- Additional data taking is ongoing for our highest Q^2 point.
- The experiment will nearly triple the Q^2 range over which GEn is known.

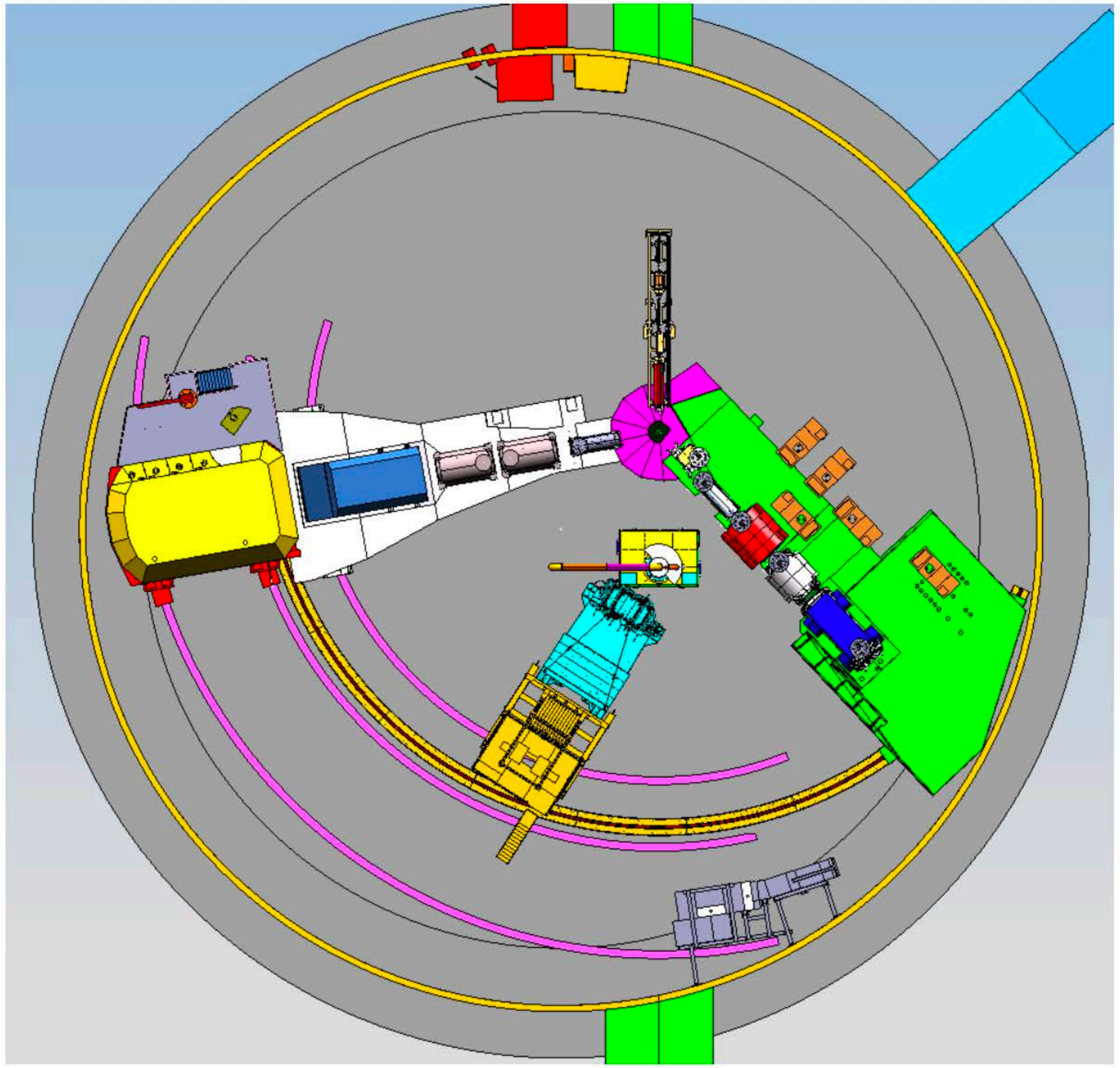


The Projected error bars from the SBS GEp experiment





SBS in Hall C looks feasible



SBS & Hcal 2.5m downstream of Polarized target and @32.5 degrees.

SBS shown with Hall A's cantilevered support structure (not needed for Hall C but why change a good thing).

From Steve Lassiter

Shown at left is layout for the TDIS experiment

Summary

- The elastic nucleon form factors seem to be the gift that just keeps on giving!
- The form-factor program at JLab will provide the definitive measurements of these important quantities for a very long time come.
- GSBS GEp comes next - please consider joining if you haven't already!