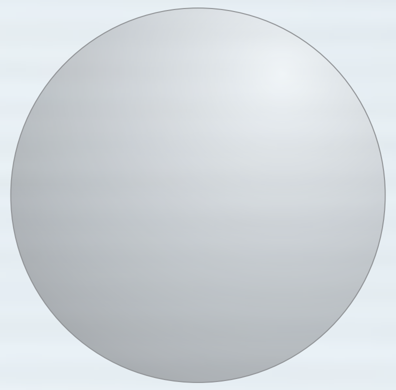
# Nucleon form factors

- Here I will focus mostly on the elastic nucleon form factors at high $Q^2$

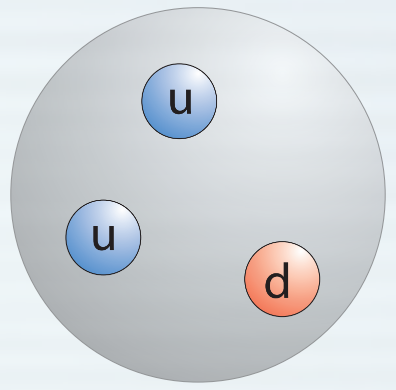
Gordon D. Cates
September 4, 2023

# Elastic form factors — a long history of discovery

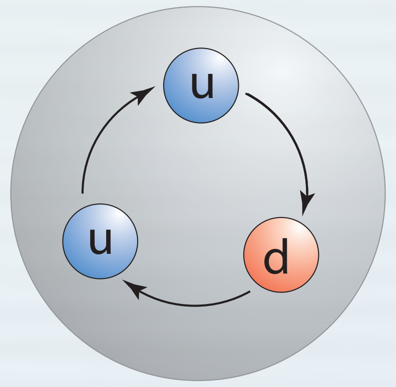
- Hofstadter's studies of the proton form factor (FF)
  - first direct measurement of the proton's size



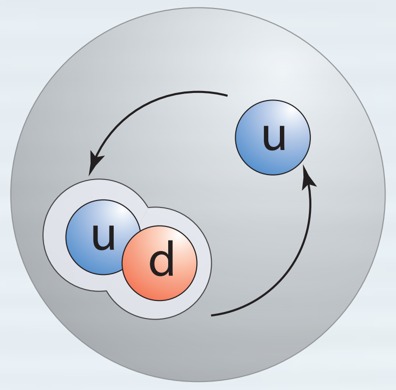
- Studies at SLAC of proton FFs at high $Q^2$
  - played a key role at SLAC leading to the discovery of quarks




- Discovery at JLab that $G_E^p/G_M^p$ decreases nearly linearly at high $Q^2$
  - Renewed focus on nucleon structure and the role of quark orbital angular momentum.




- Measurements at JLab of $G_E^n/G_M^n$ high $Q^2$
  - Provided, for the first time, the ability to separate the behavior of up and down quarks at high $Q^2$, and important evidence, beyond the missing states in the N* spectrum, for the existence of diquarks.



# The electromagnetic elastic nucleon form factors: a particularly clean probe of nucleon structure

The hadronic current:

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

The Sachs FFs:

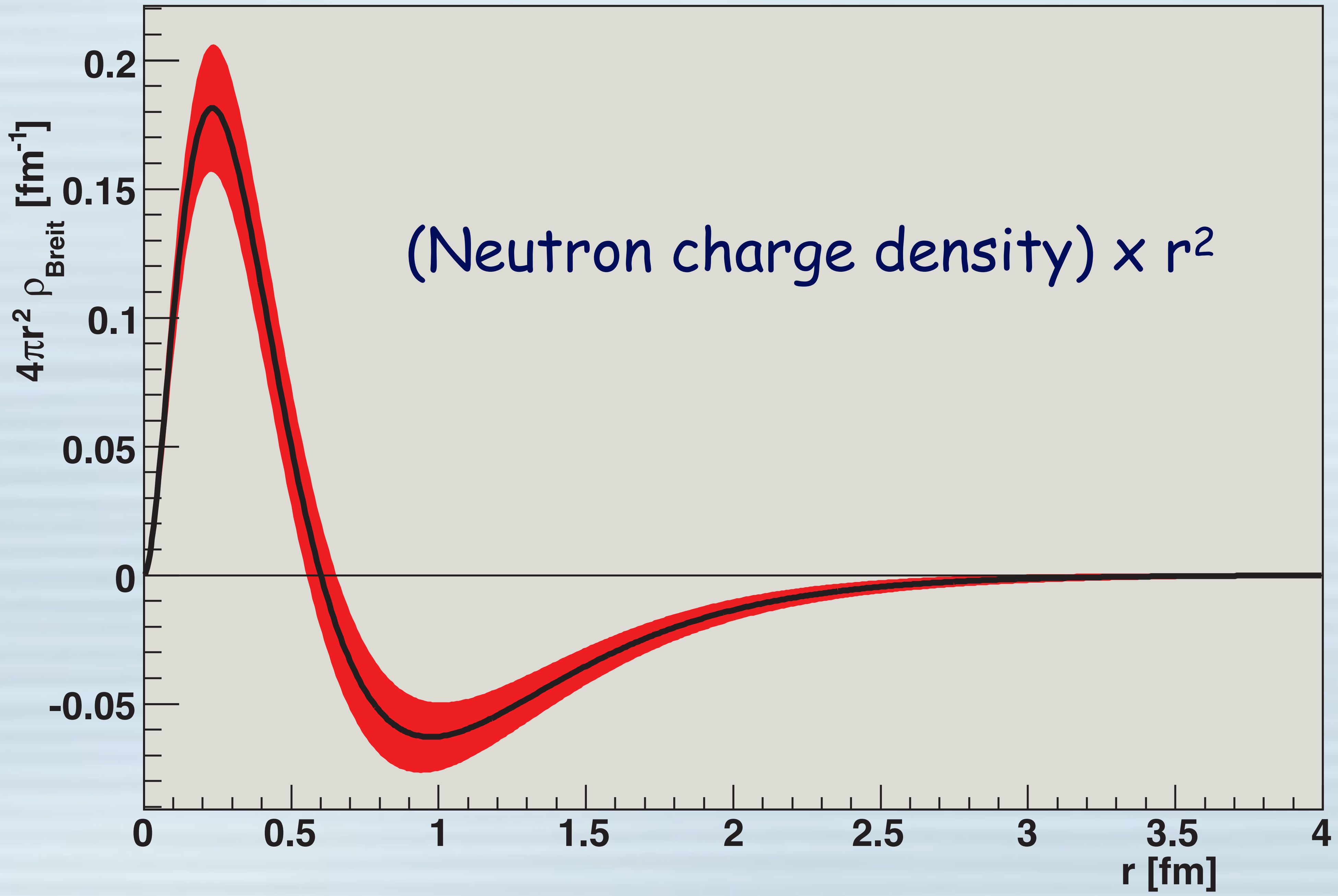
$$G_{_E} = F_1 - \tau F_2 \quad \text{and} \quad G_{_M} = F_1 + F_2$$

where

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

# A non-relativistic "snapshot" of the neutron

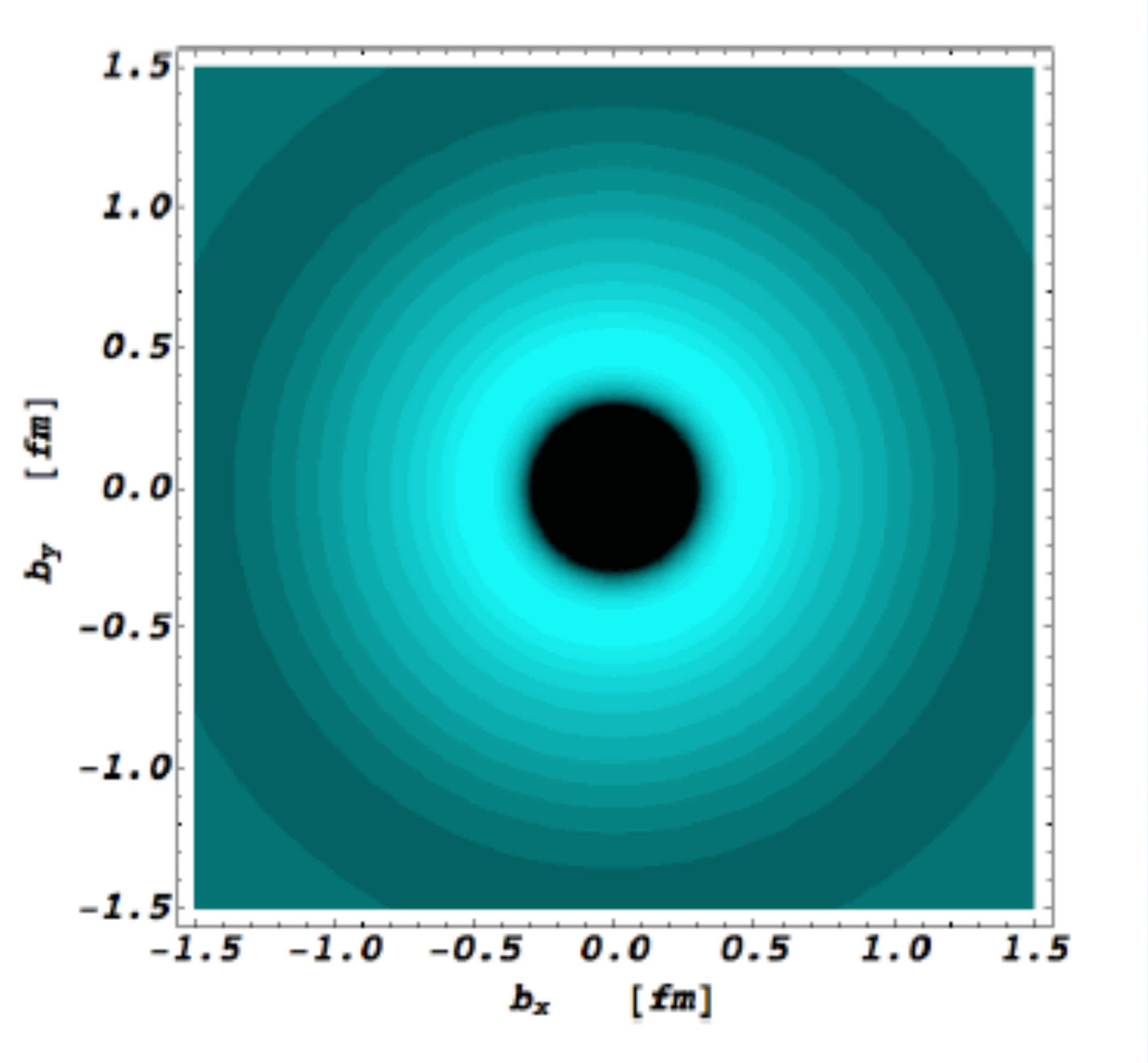
(in roughly the lab frame essentially taking the Fourier transform of $G_E^n$ )



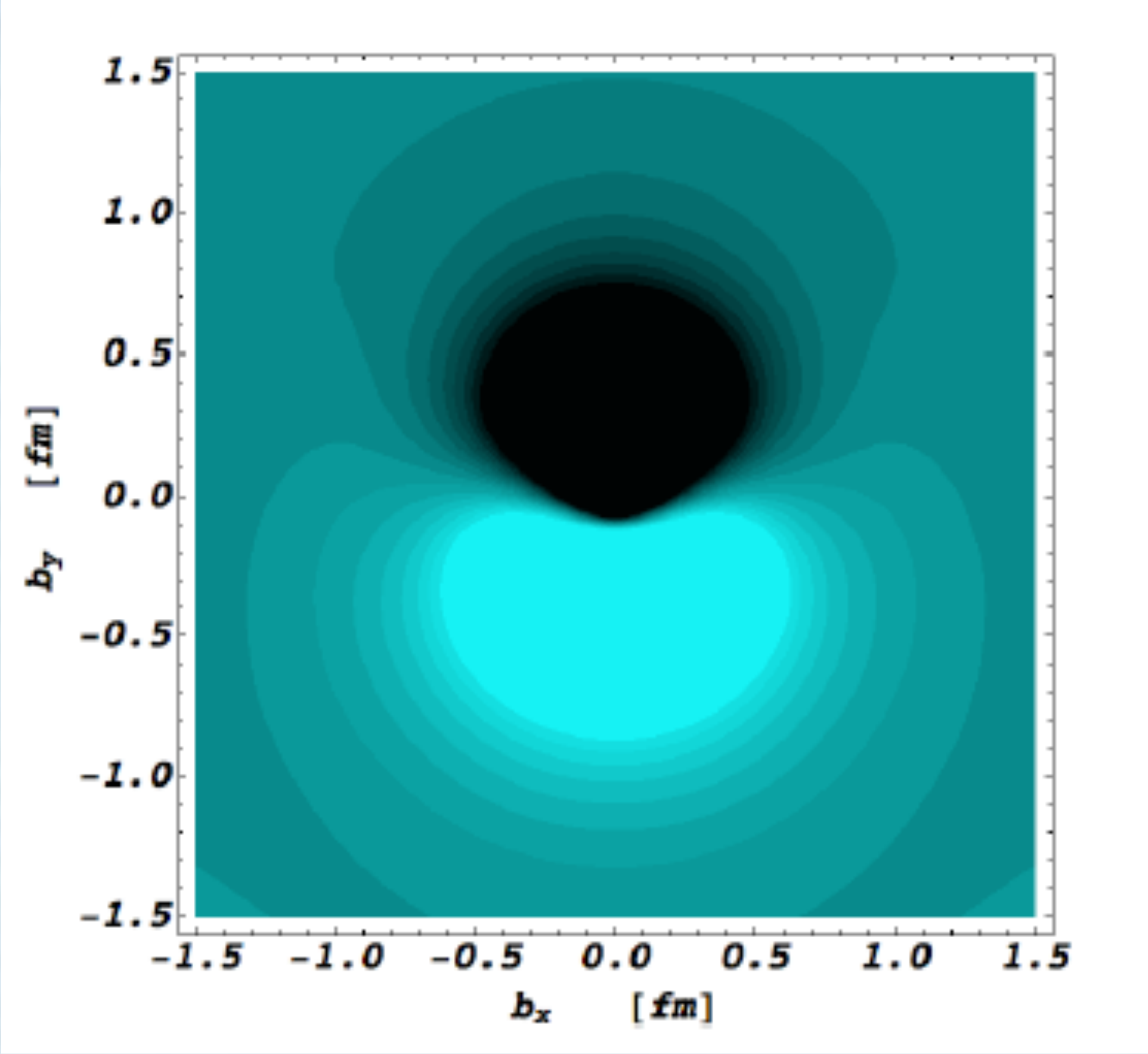

From the 2007 Long Range Plan

From the text of the Long Range Plan: "These results clearly identify the neutron's positively charged interior and negatively charged halo…" [from the pion cloud].

# A relativistic "snapshot" of the neutron
## (light-front density distribution)




Longitudinally
polarized neutron




Transversely
polarized neutron

Carlson and Vanderhaeghen, PRL v.100, pg.032004 (2008)

- Here we are seeing what we can think of as a charge density when viewed from a light front moving toward the neutron.
- Notice that the transversely polarized neutron appears to have an electric dipole moment - this is due to the magnetic dipole moment when viewed from a boosted reference frame

# 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

# Two ways for measuring elastic form factors

Rosenbluth separation: measure the cross section with various different kinematics (different $\epsilon$ but same $Q^2$) to extract $G_E$ and $G_M$ separately.

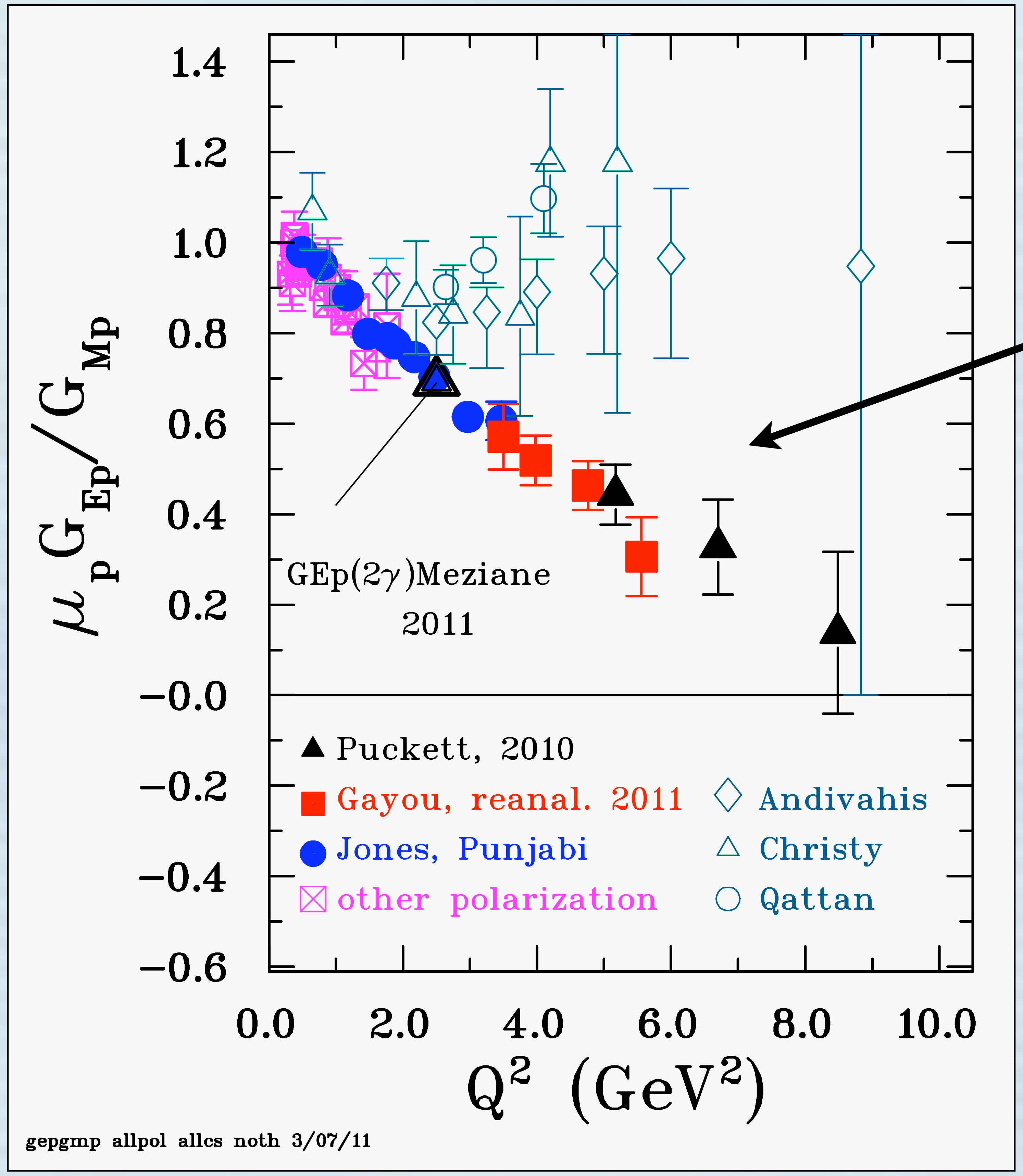
$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{\text{Mott}} \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon(1+\tau)} \qquad \tau = Q^2/4M^2 \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

The problem is that at high $Q^2$, the relative contribution from $G_E$ becomes quite small

Double-polarization techniques that allow you to measure the ratio $G_E/G_M$ and provides greatly improved accuracy at high $Q^2$. Below is the spin asymmetry when using polarized electrons and a polarized target (as in GEn-II).

$$A = \frac{-2\sqrt{\tau(\tau+1)}\tan(\theta_e/2)(G_E^n/G_M^n)}{(G_E^n/G_M^n)^2 + \tau[1 + 2(1+\tau)\tan^2(\theta_e/2)]}$$

# The measurements of $\mu_p G_E^p/G_M^p$ using the recoil polarization technique at JLab

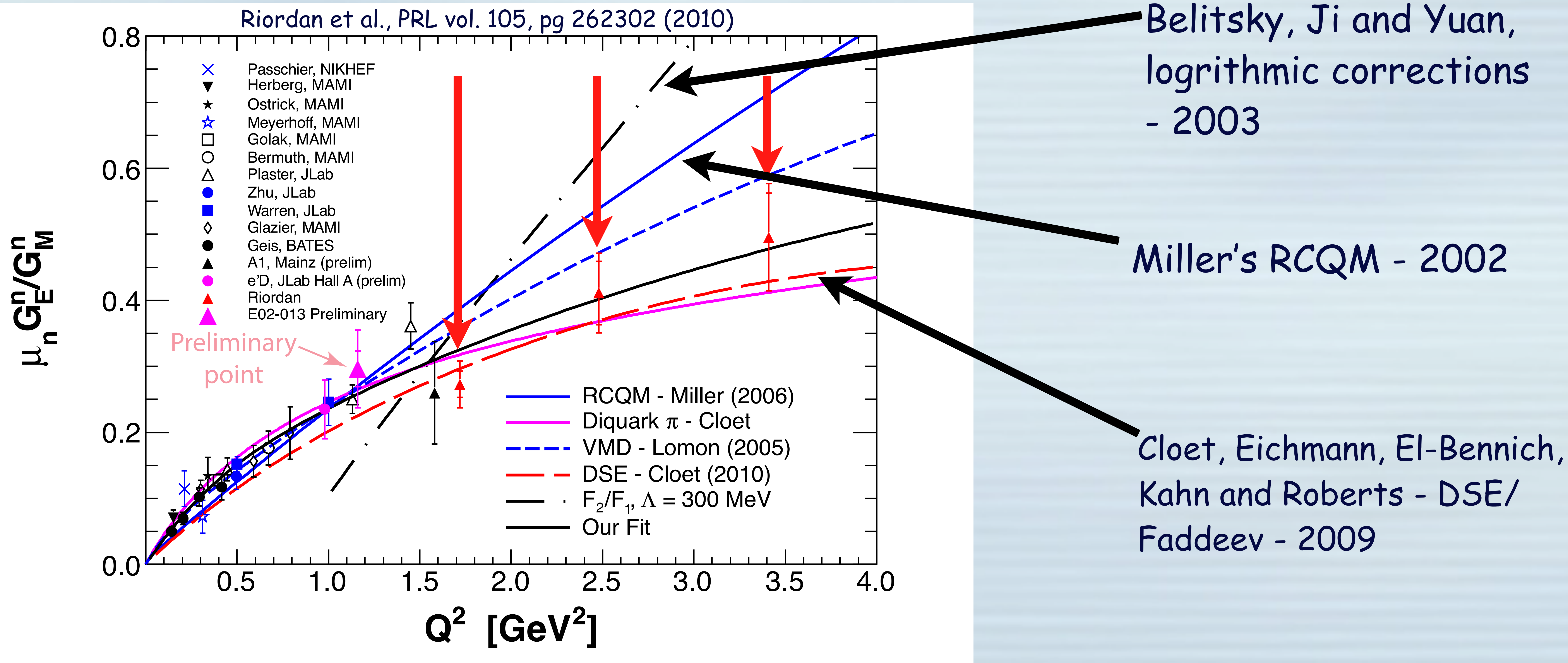



Data from both Rosenbluth separations and the double-polarization technique.

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 emphasized the role of <u>quark orbital angular momentum</u>.

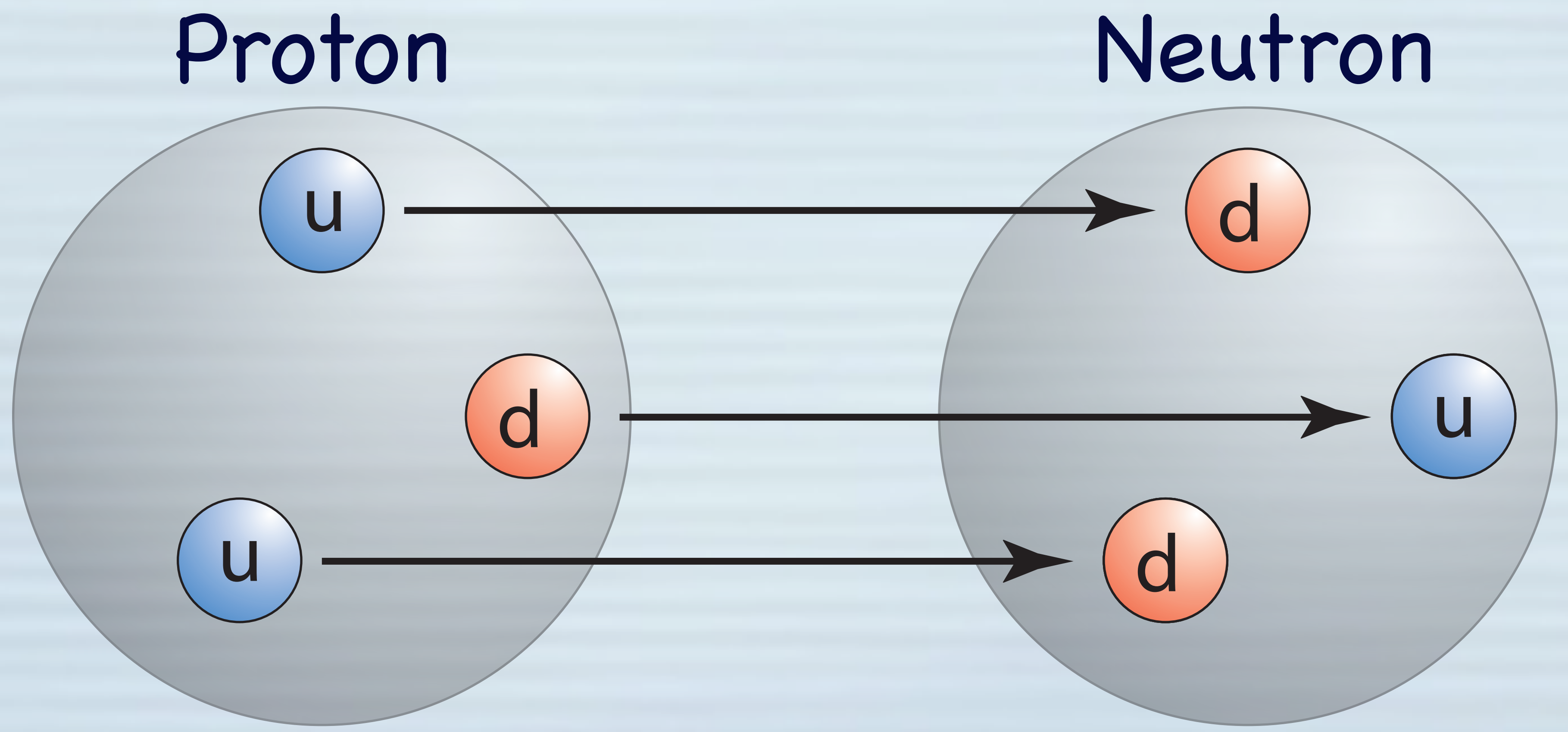
# Data from the Hall A polarized $^3$He experiment (E02-013) extended knowledge of $G_E^n$ to high $Q^2$




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

# Flavor-separated form factors

By assuming charge symmetry and combining data from both proton and the neutron, the individual contributions from the up- and down-quarks can be extracted.

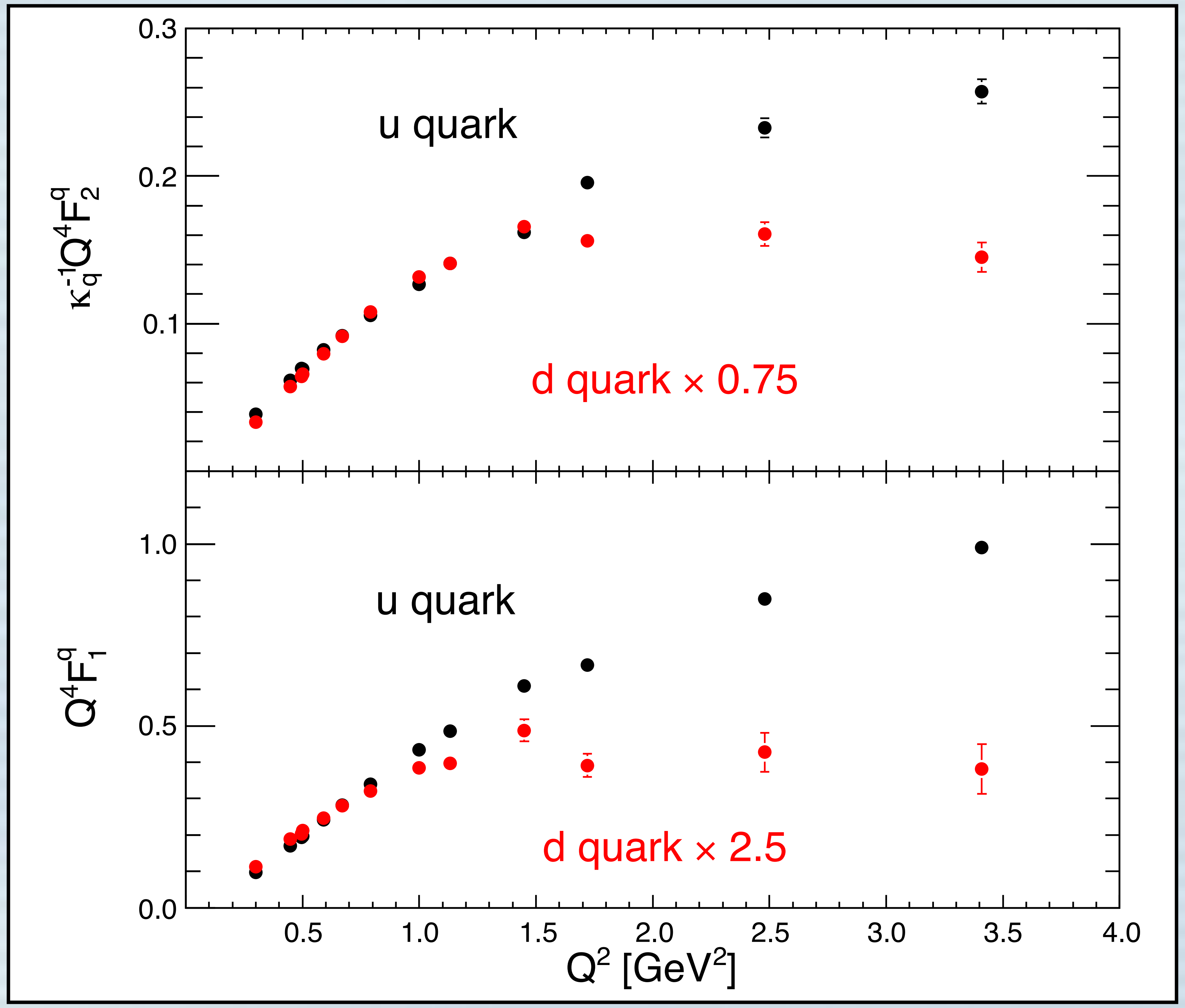



For the Dirac form factors (and similarly for the Pauli form factors):

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

# 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)

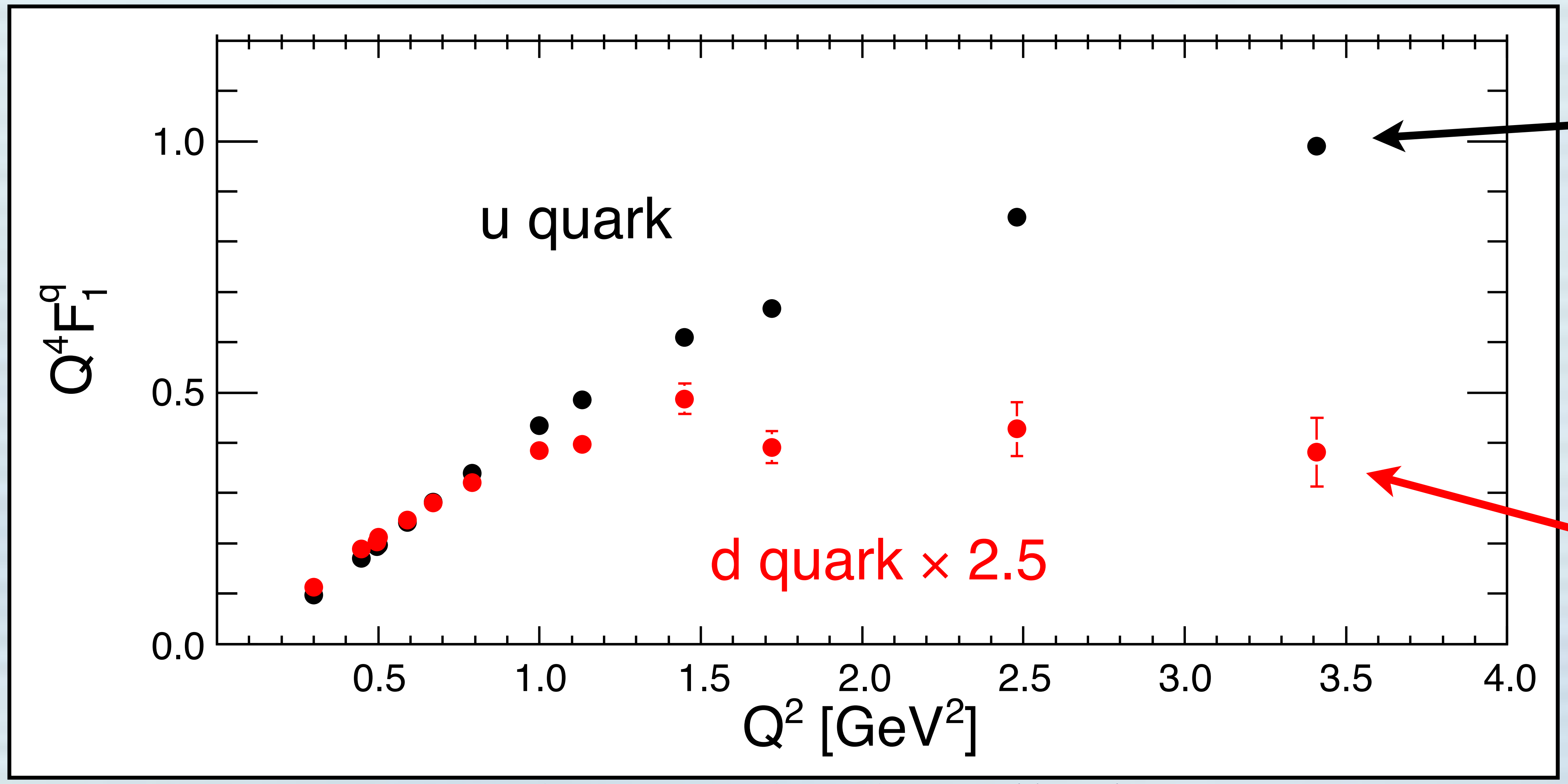



$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

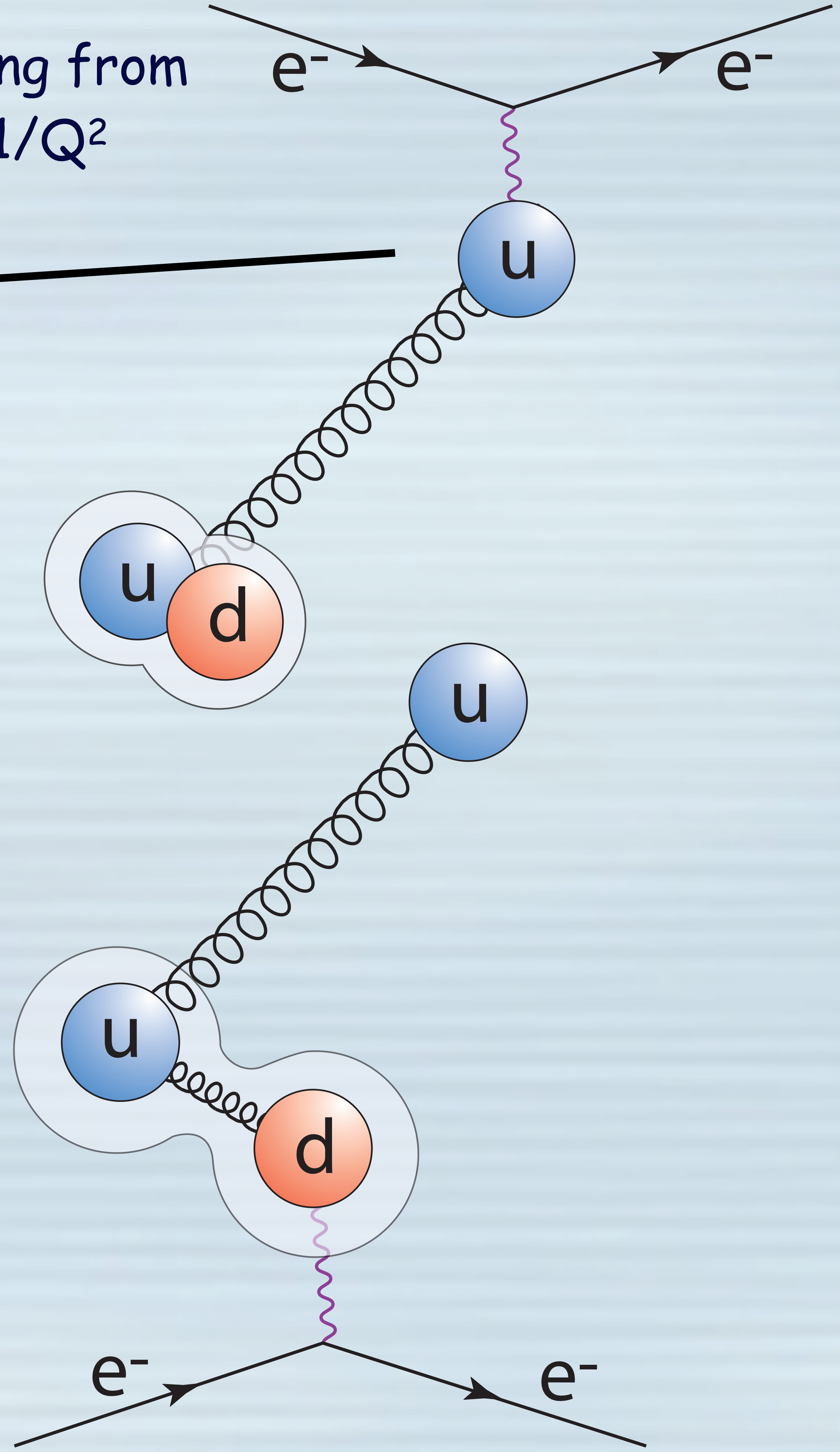
Many of the theoretical models that reproduce the above trends indicate the importance of <u>diquark correlations</u>.

# Simplified picture of how diquarks might influence the different $Q^2$ behavior of the u- and d-quark form factors

u-quark scattering amplitude is dominated by scattering from the lone "outside" quark. Two constituents implies $1/Q^2$

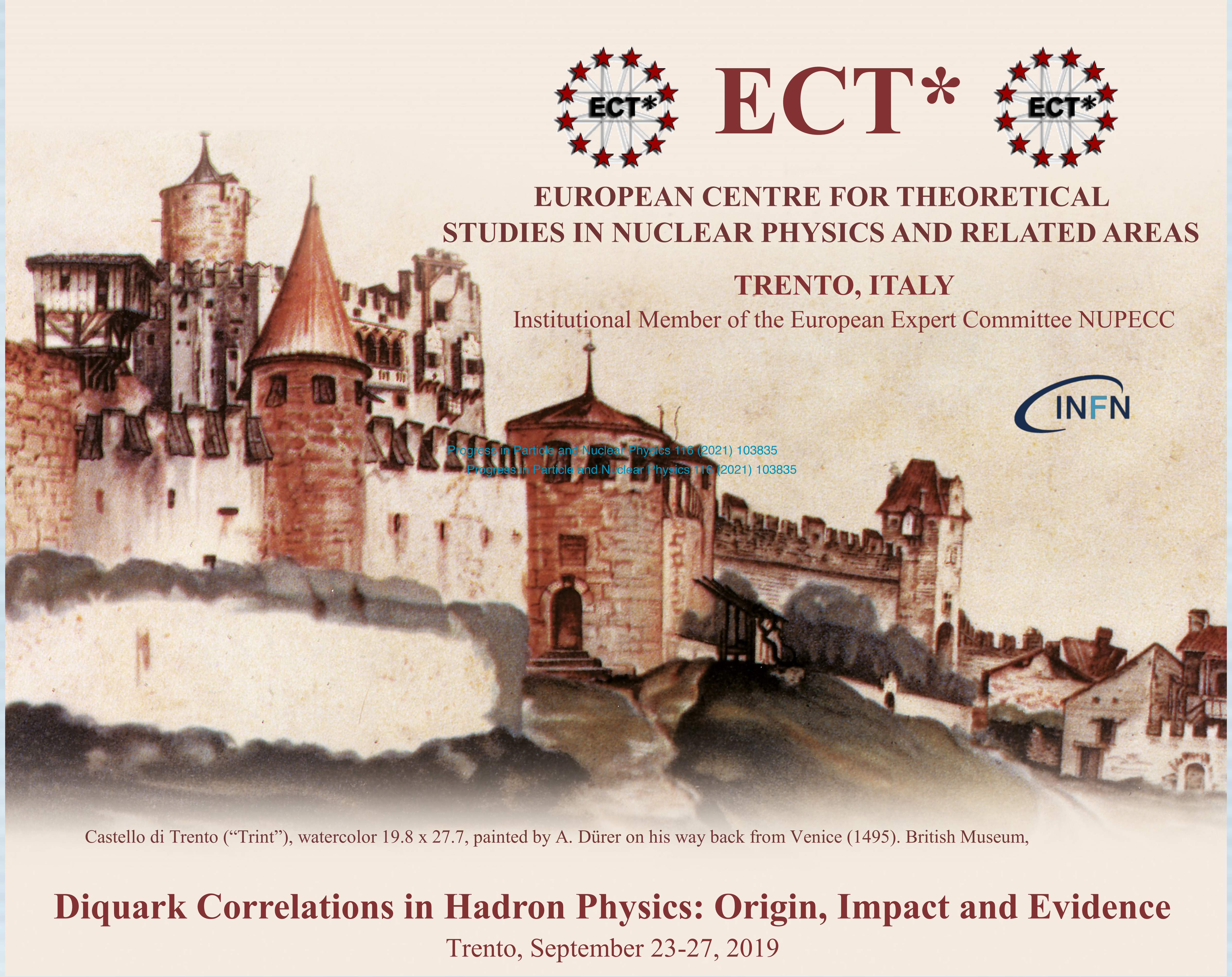



Cates, de Jager, Riordan and Wojtsekhowski,
PRL vol. 106, pg 252003 (2011)



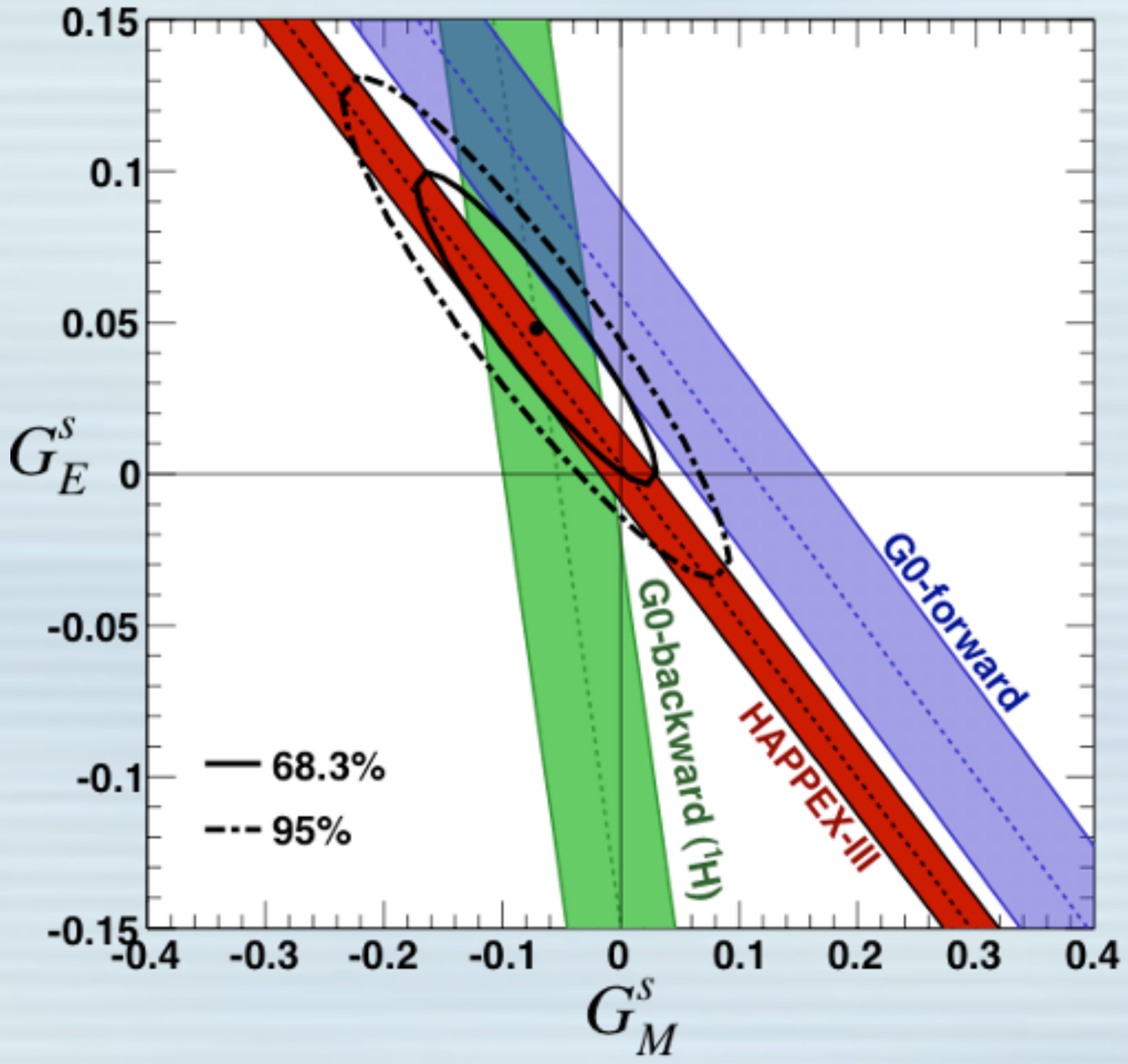

d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

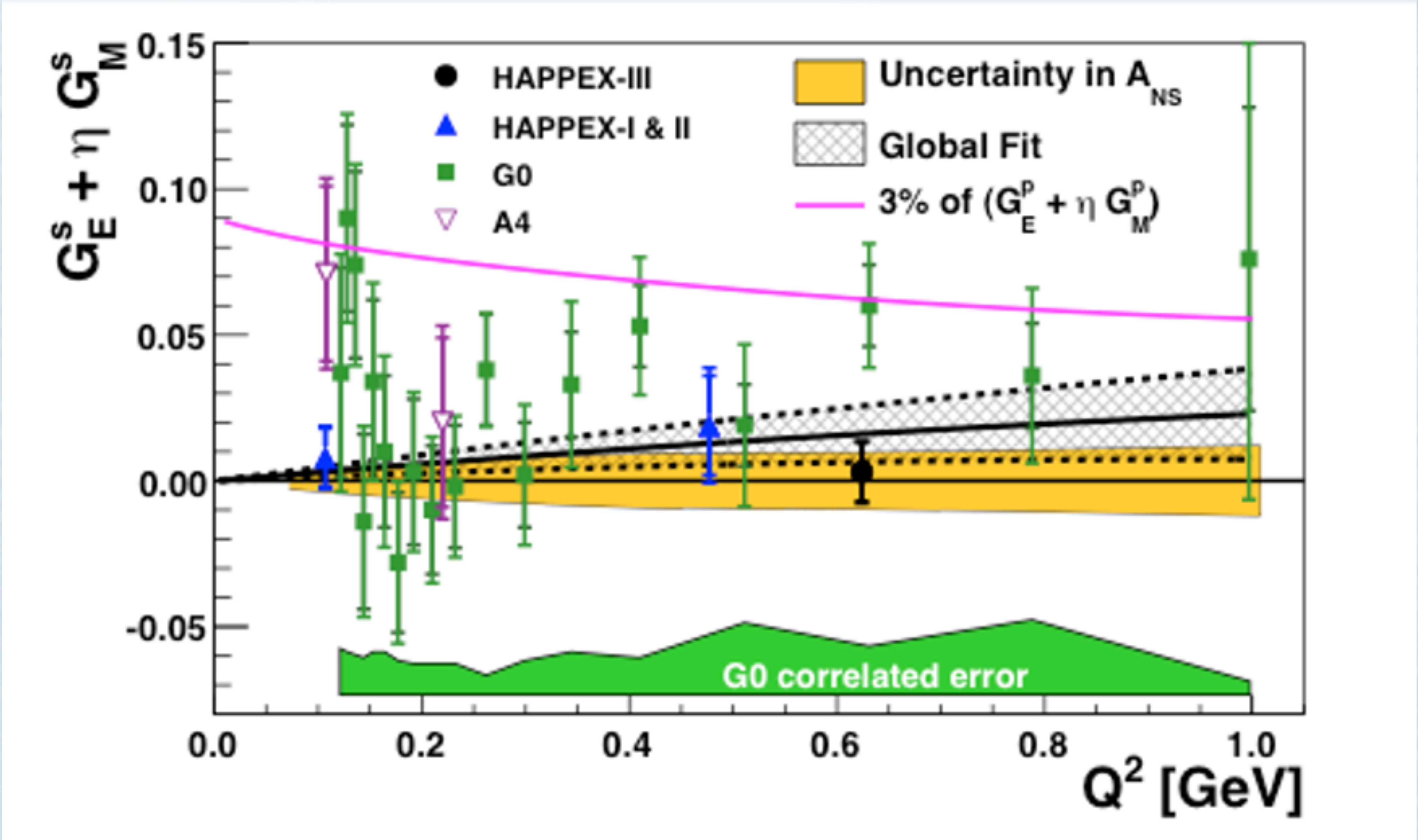
# Workshop on diquarks at ECT* in Trento
(September 2019)




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".

# Flavor separation depends on more than just charge symmetry



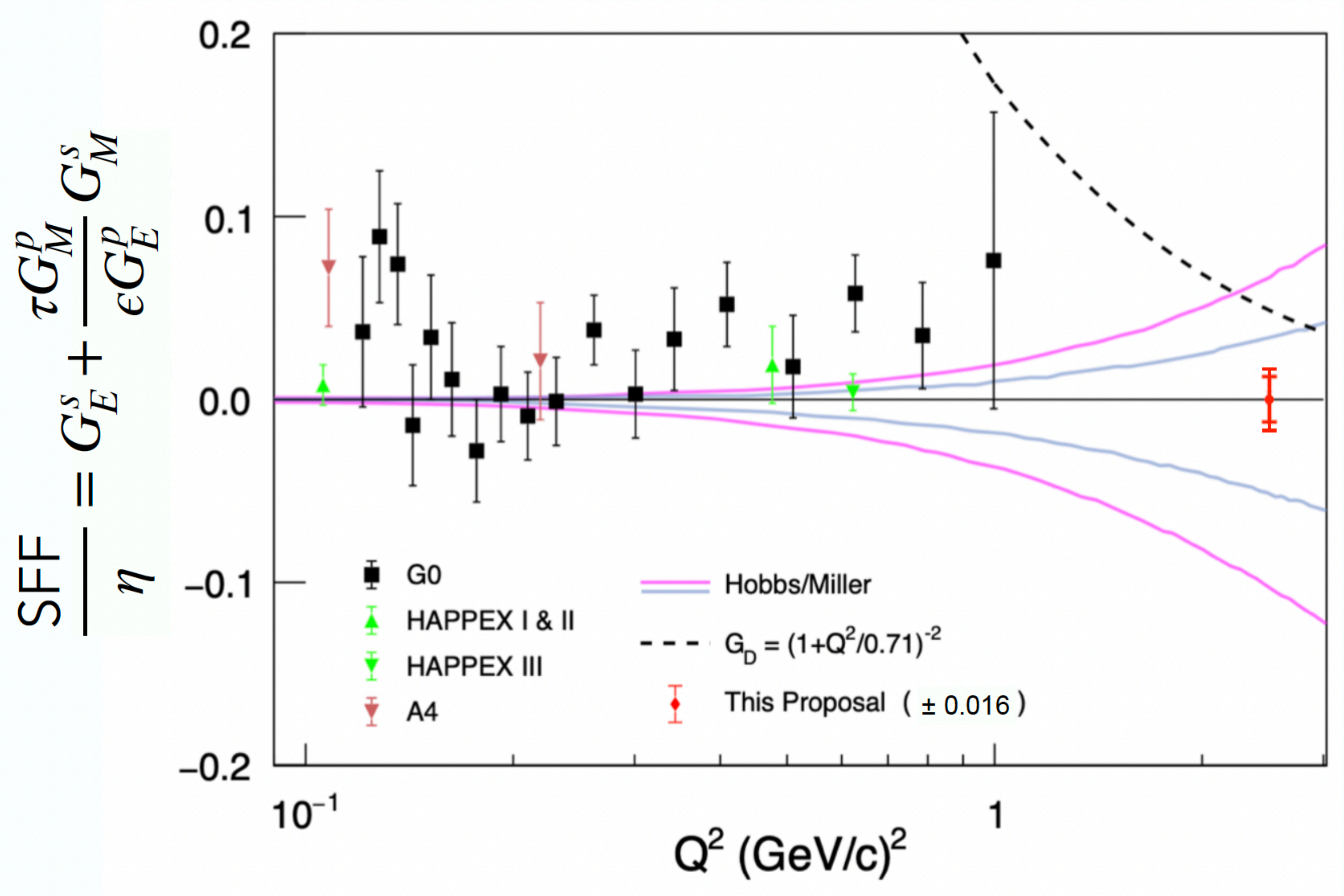

Shown above, determinations of the proton strange form factors using parity violation.

# Nucleon form factors in the JLab 12 GeV era

# Projected result

$\delta A_{PV} = \pm 6.2$ (stat) $\pm 3.3$ (syst)

$$\delta\left(G_E^s + 3.1 G_M^s\right) = \pm\, 0.013 \text{ (stat)} \pm\, 0.007 \text{ (syst)} = 0.015 \text{ (total)}$$




If $G_M^s = 0$, $\delta G_E^s \sim 0.015$, (about 34% of $G_D$)

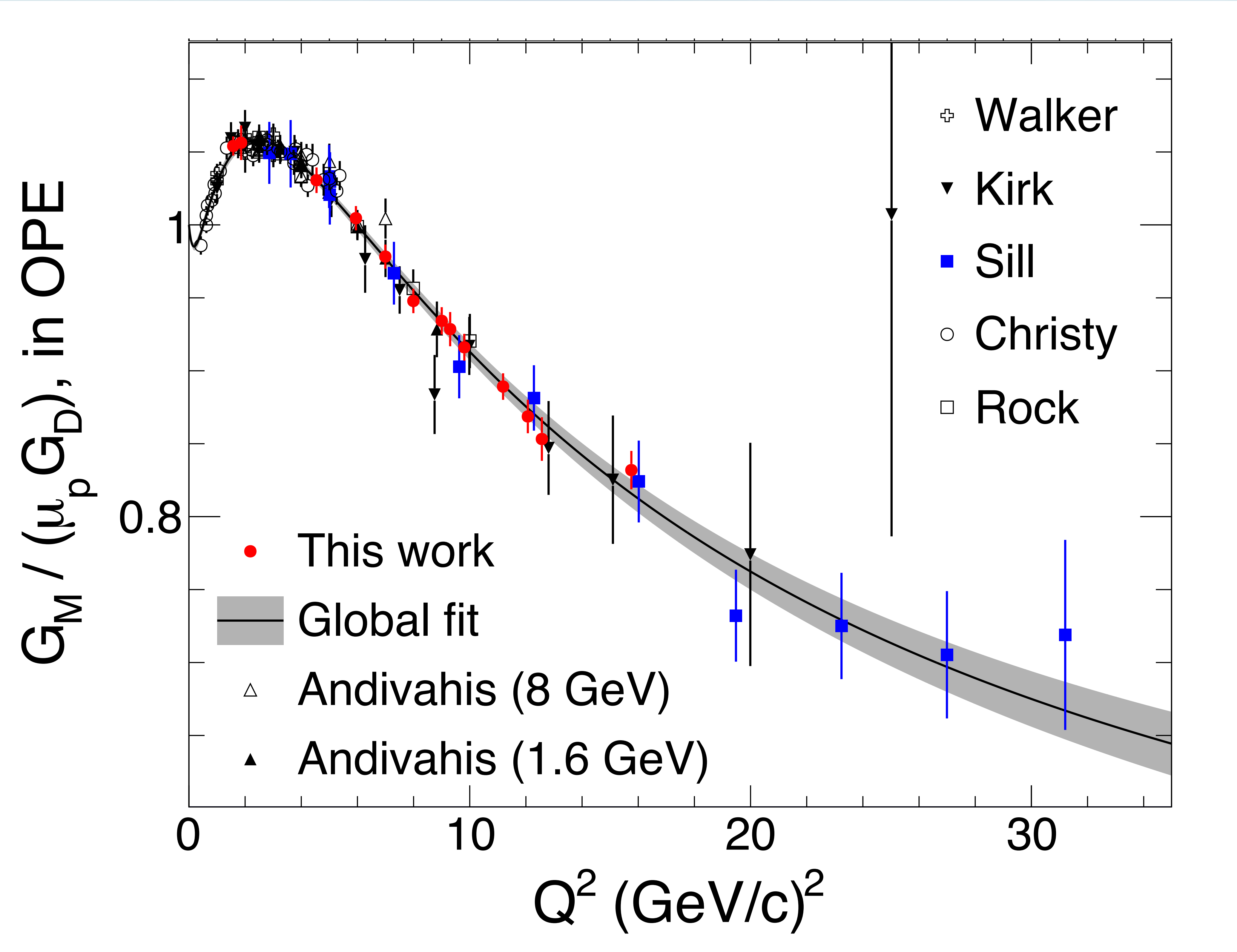
If $G_E^s = 0$, $\delta G_M^s \sim 0.005$, (about 11% of $G_D$)

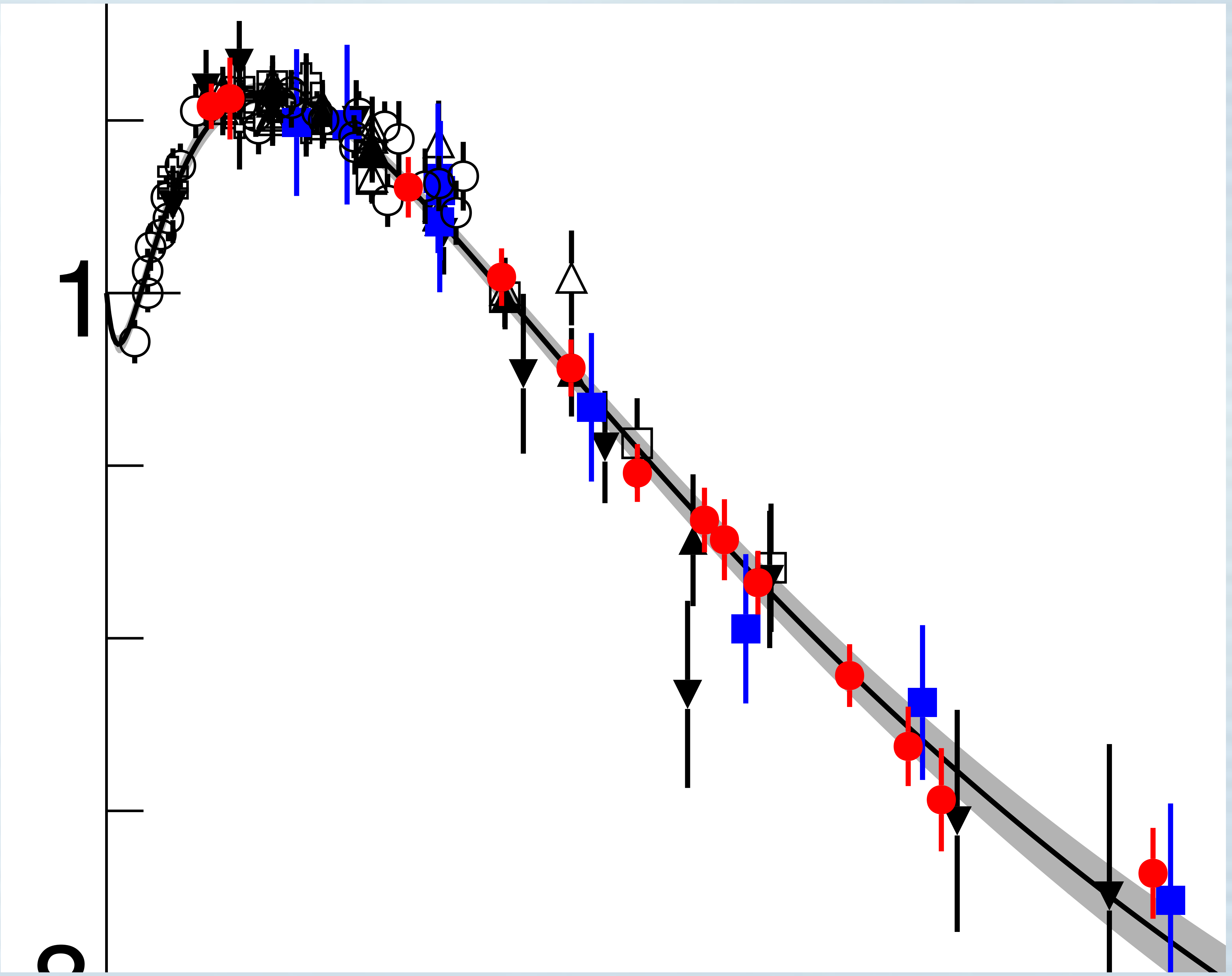
The proposed measurement is especially sensitive to $G_M^s$

The proposed error bar reaches the range of lattice predictions, and the empirically unknown range is much larger.

Courtesy of Kent Paschke

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



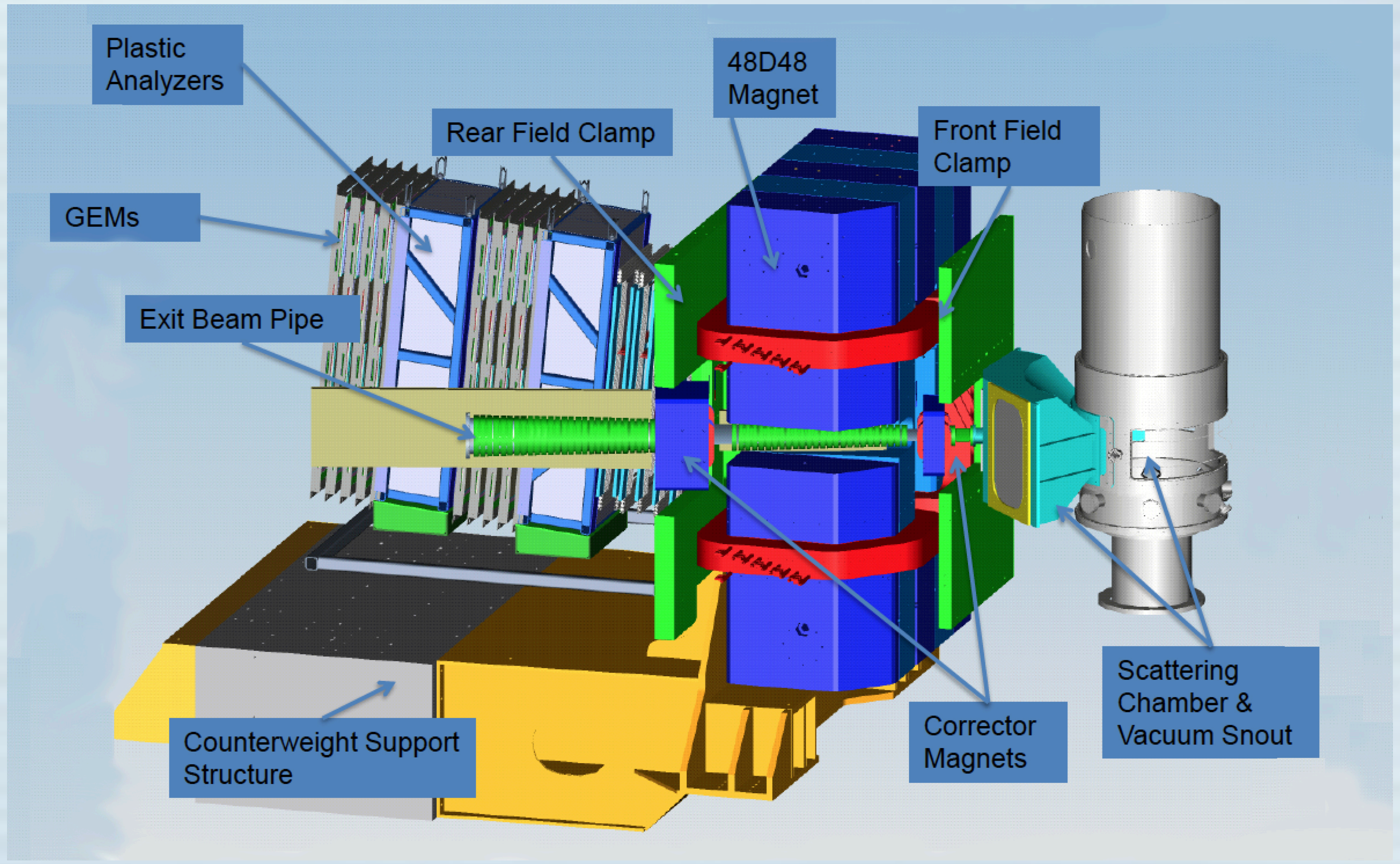



Shown at left is the extraction of $G_M^p$ resulting from JLab E12-07-108 (PRL v128, 102002 (2022)). At right is a blown up version of the of the figure at left to better visualize the new points.

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

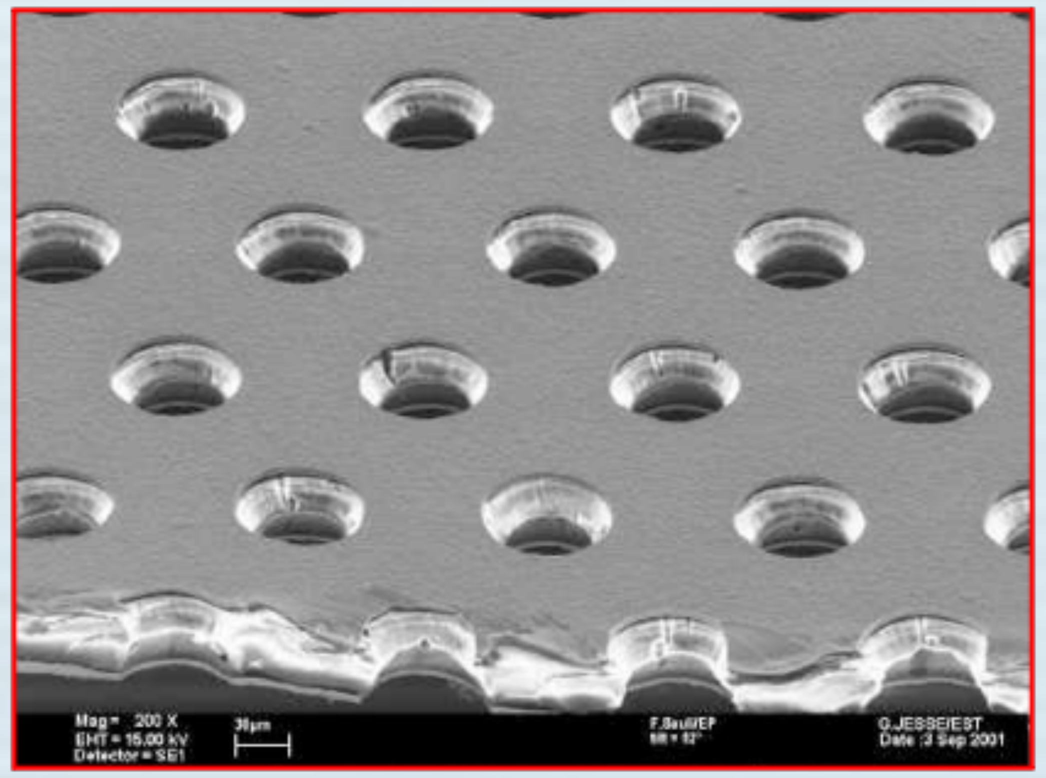
- $G_M^n/G_M^p$ (E12-09-019) - $Q^2$ up to 13.5 GeV$^2$. <u>COMPLETE!!! – Oct. 2021 – Feb. 2022</u>
- $G_E^n/G_M^n$ (E12-09-016) - $Q^2$ up to ~ 9.7 GeV$^2$. <u>ONGOING!!! – Oct. 2022 – present</u>
- $G_E$n-RP (E12-17-004) - $Q^2$ ~ 4.5 GeV$^2$ <u>Beginning roughly January of 2024</u>
- $G_E^p/G_M^p$ (E12-07-109) - $Q^2$ up to ~12 GeV$^2$. <u>Beginning roughly fall of 2024</u>

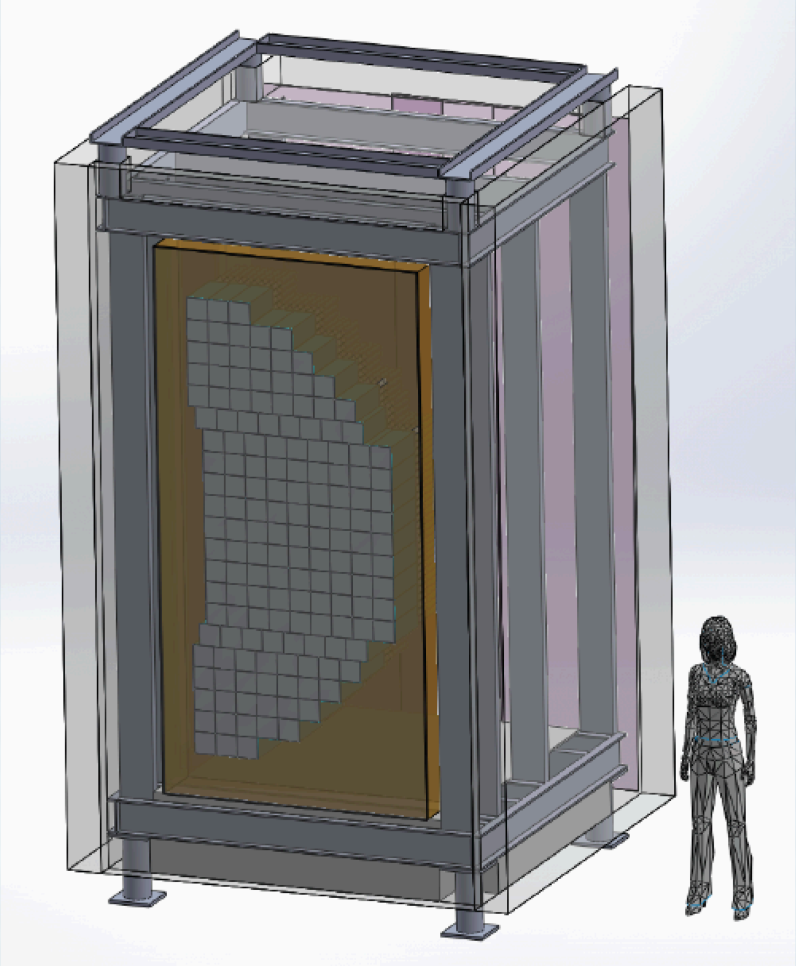
# What is SBS ?



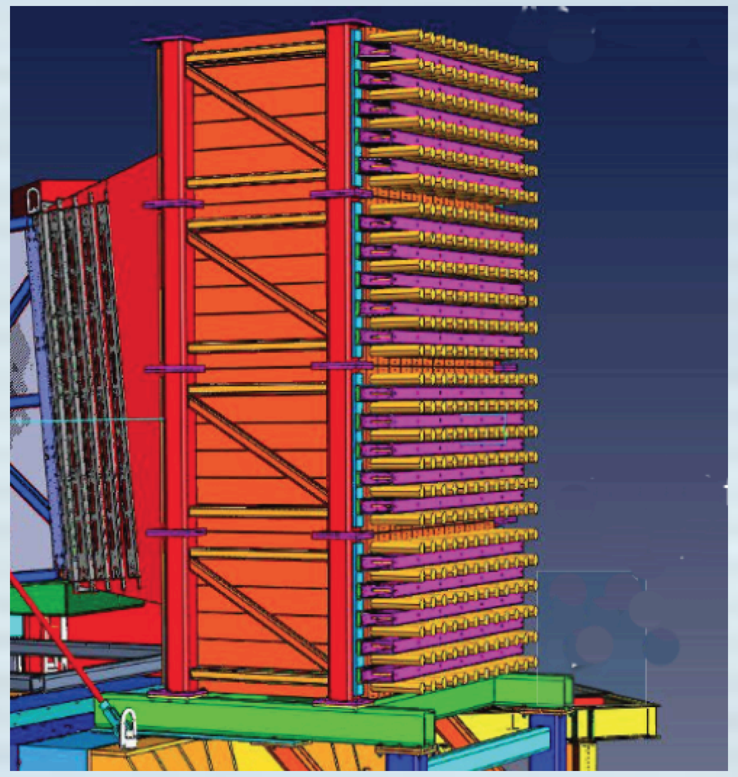

SBS configured for the $G_E^p$ experiment

GEM foil: 50 μm Kapton + few μm copper on both sides with 70 μm holes, 140 μm pitch

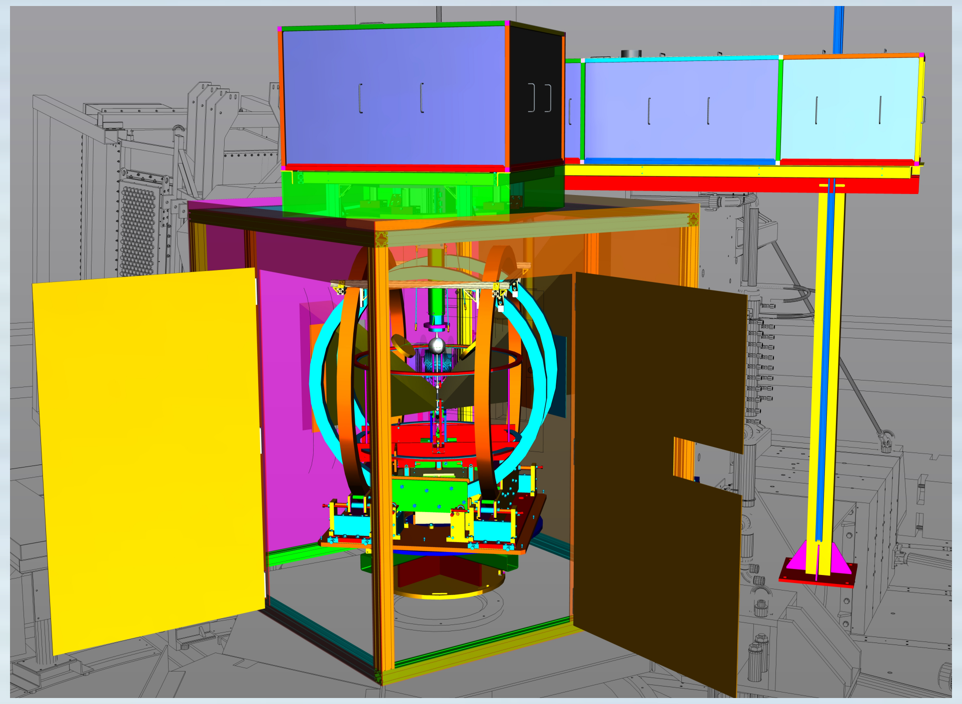




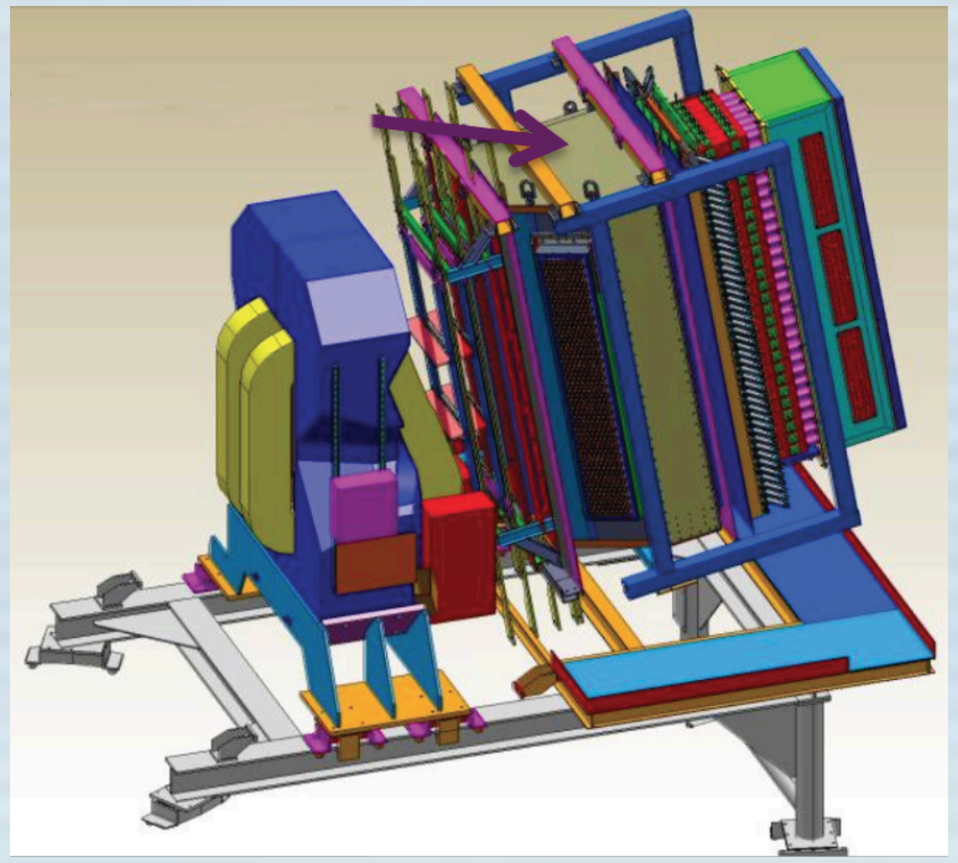
ECal - electron calorimeter



HCal - hadron calorimeter



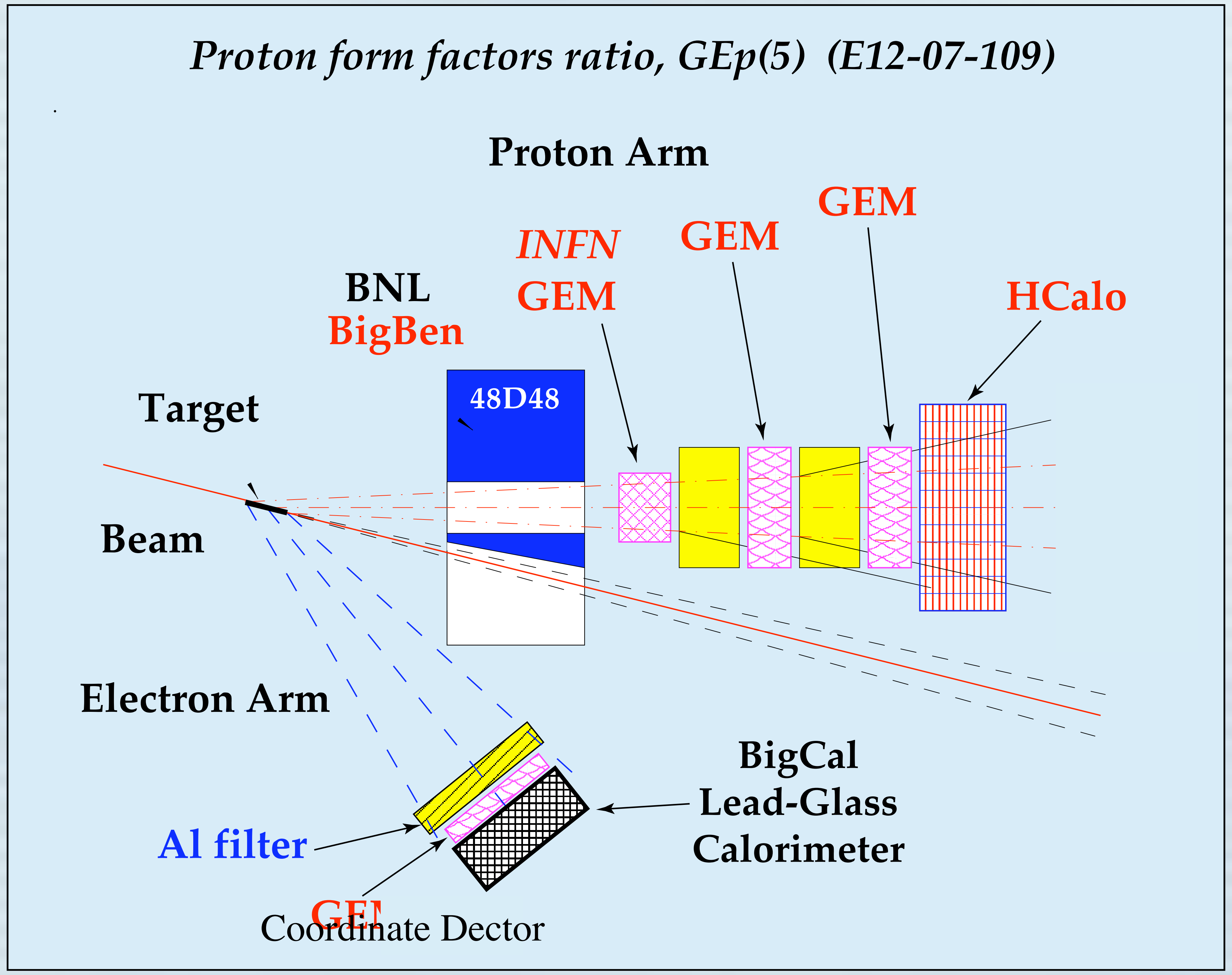
Polarized $^3$He target



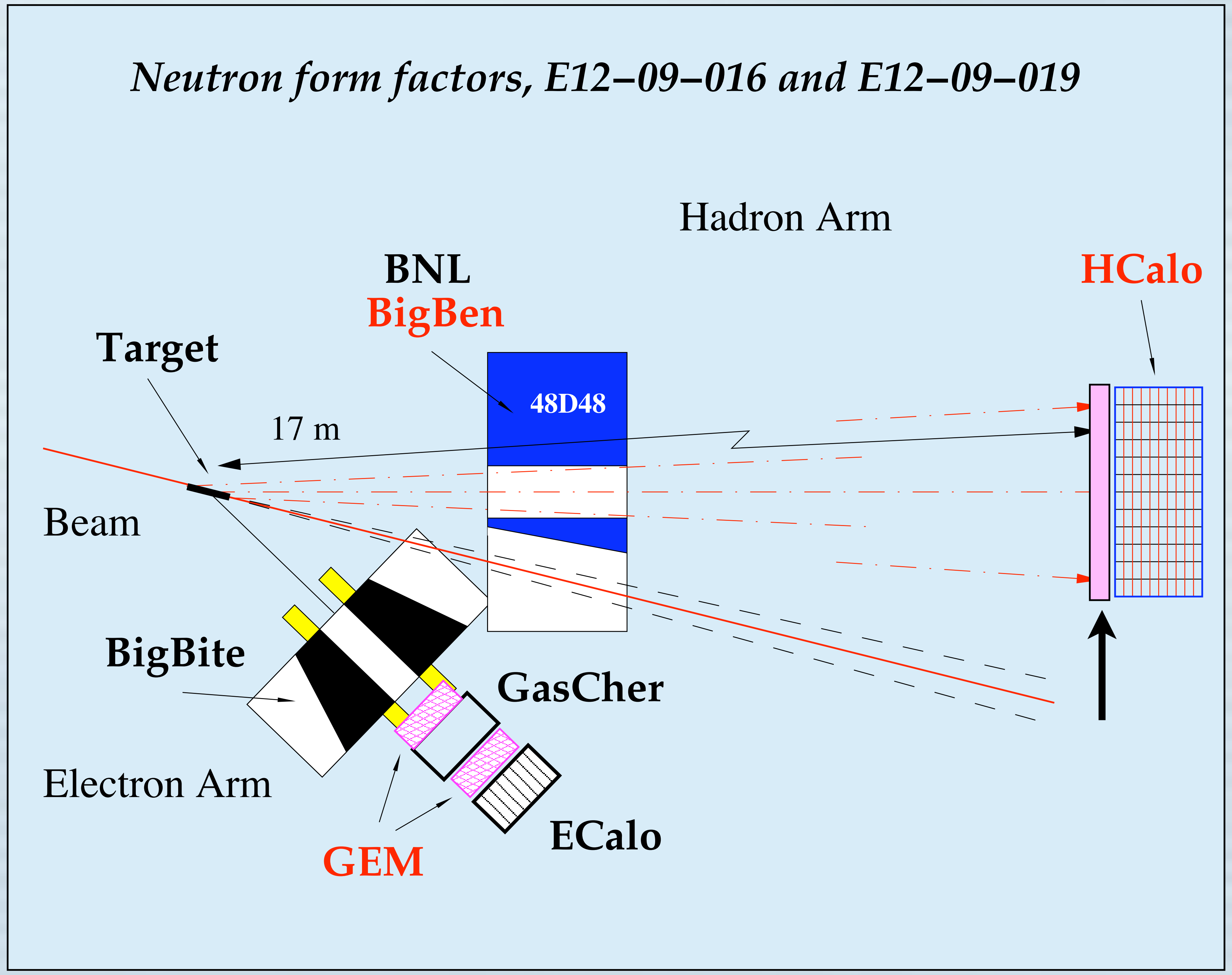
BigBite

Well …. with the primary construction and all its dependencies, it has lots of pieces.

# The SBS equipment will be configured differently depending on the experiment

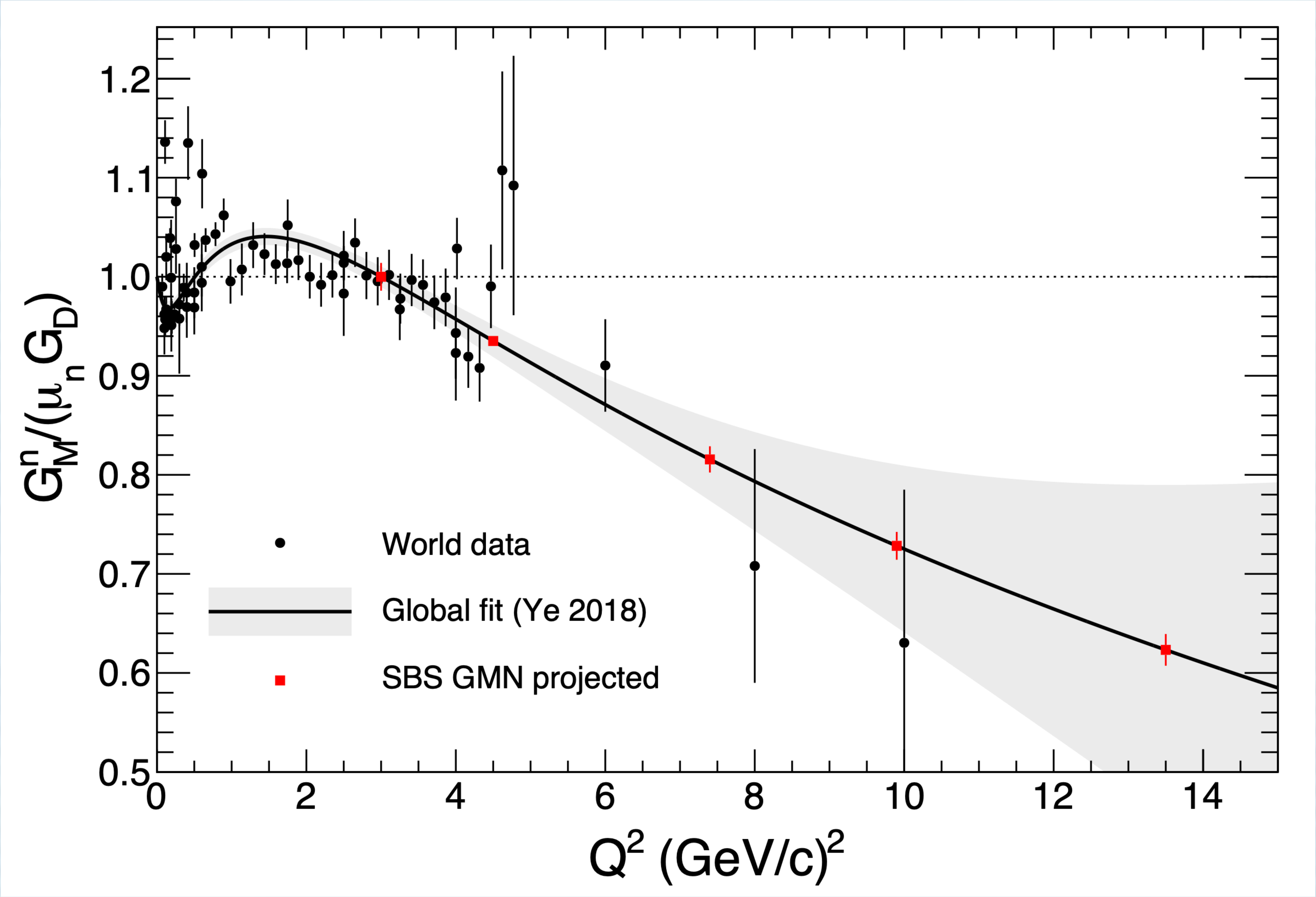



$G_E^p/G_M^p$




$G_E^n/G_M^n$ and $G_M^n/G_M^p$

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

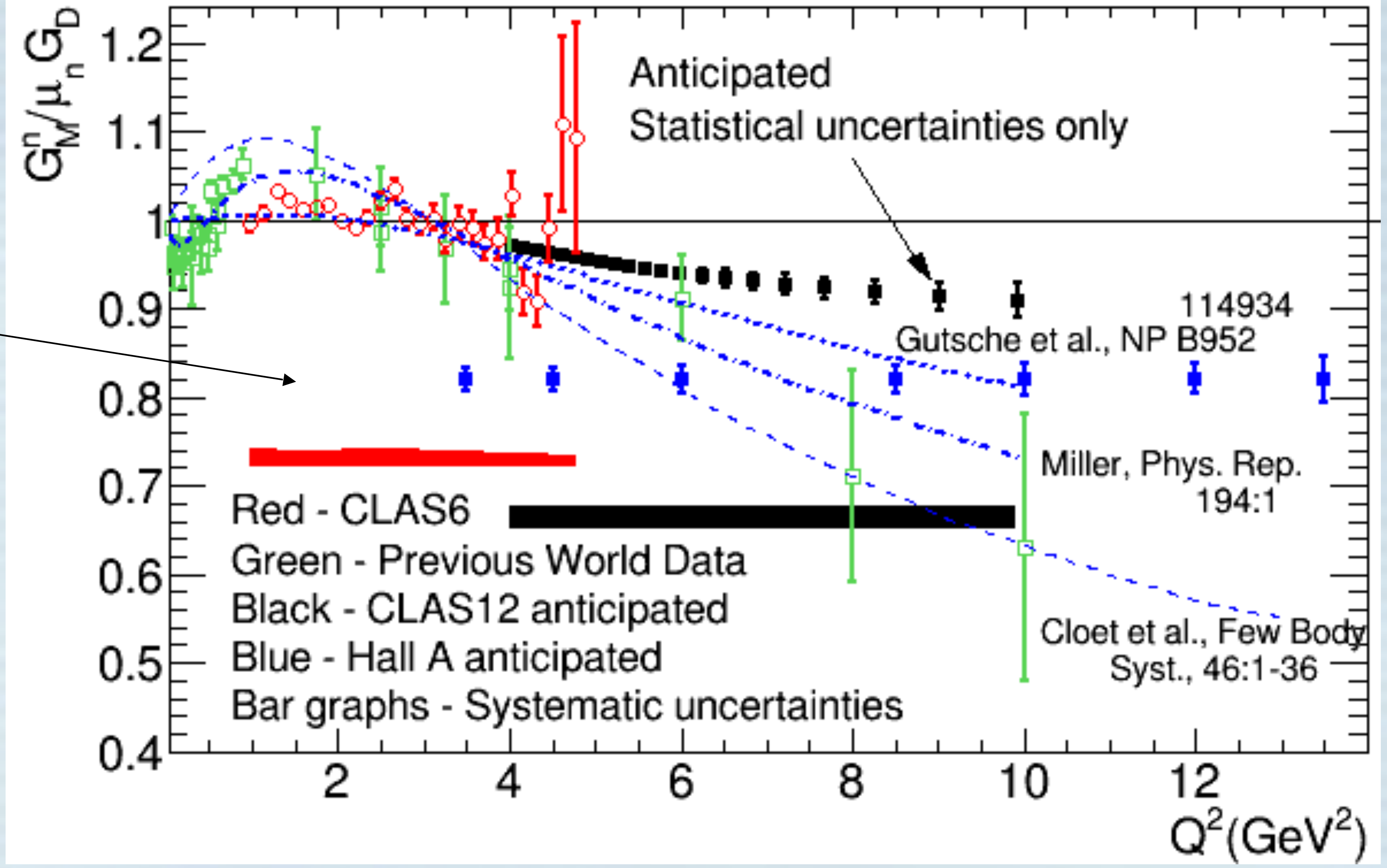



The SBS GMn experiment could establish a zero crossing in F1d/F1u, an observation that would be challenging to interpret within the GPD framework.

# Neutron Magnetic Form Factor in CLAS12

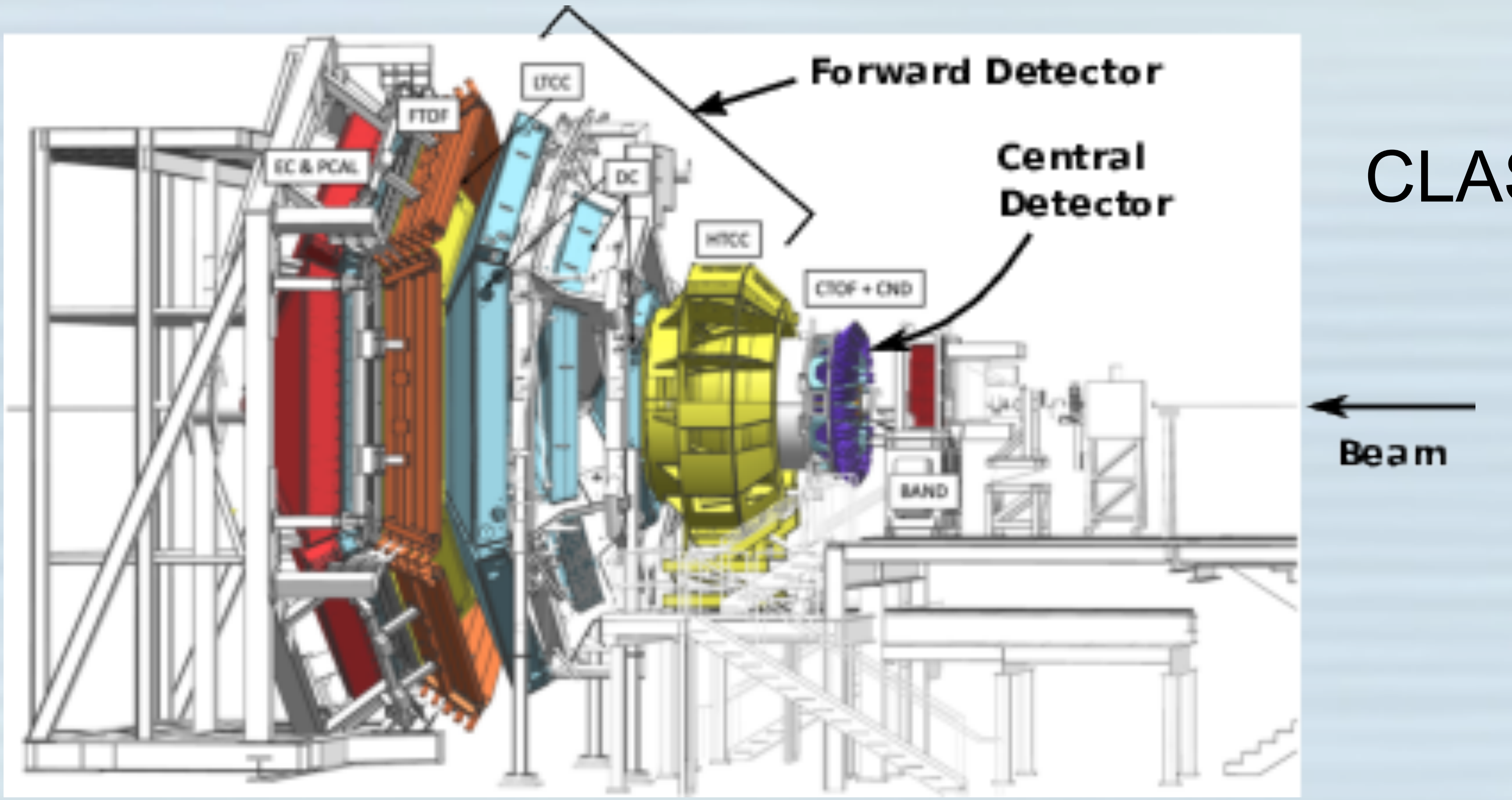
## $G_M^n$ Measurement with CLAS12 in Hall B

- Complementary to Hall A measurement – different systematic uncertainties.
- Uses the same *R=e-n/e-p* ratio method.
- Different $Q^2$ coverage than Hall A – higher angular density, smaller range.
- Run Group B, Lamya Baashen (FIU) thesis.




## The CLAS12 Detector

- Covers most of 4π.
- Forward Detector covers ϴ = 5 - 40 deg.
- Over 100,000 readouts in 40 layers.



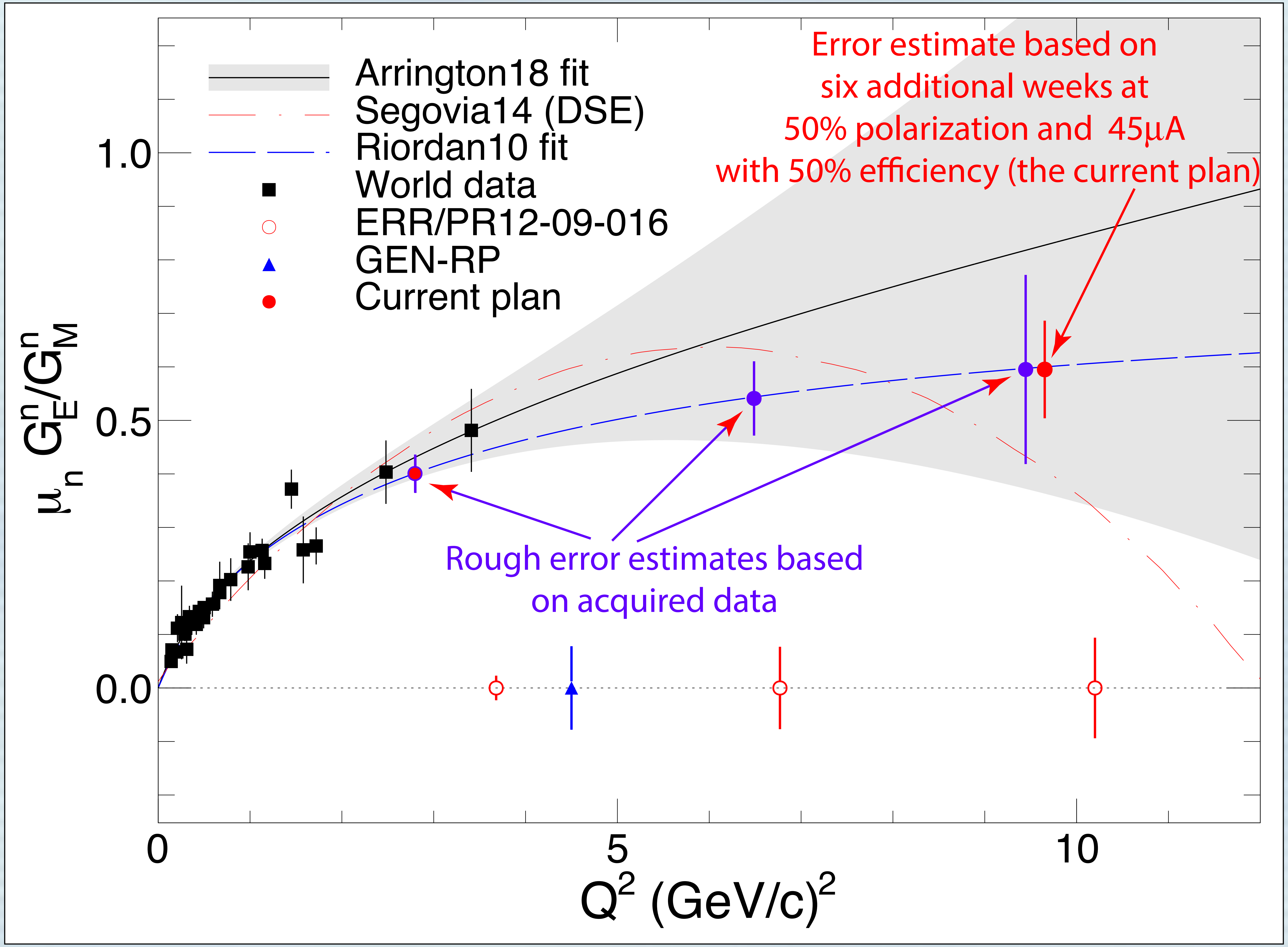

CLAS12

## The Data Set – CLAS12 Run Group B

- 43 Billion triggers at 10.2, 10.4, and 10.6 GeV.
- Average beam polarization ~86%.
- 43% of approved beamtime used.
- All runs have completed cooking/pass 1.

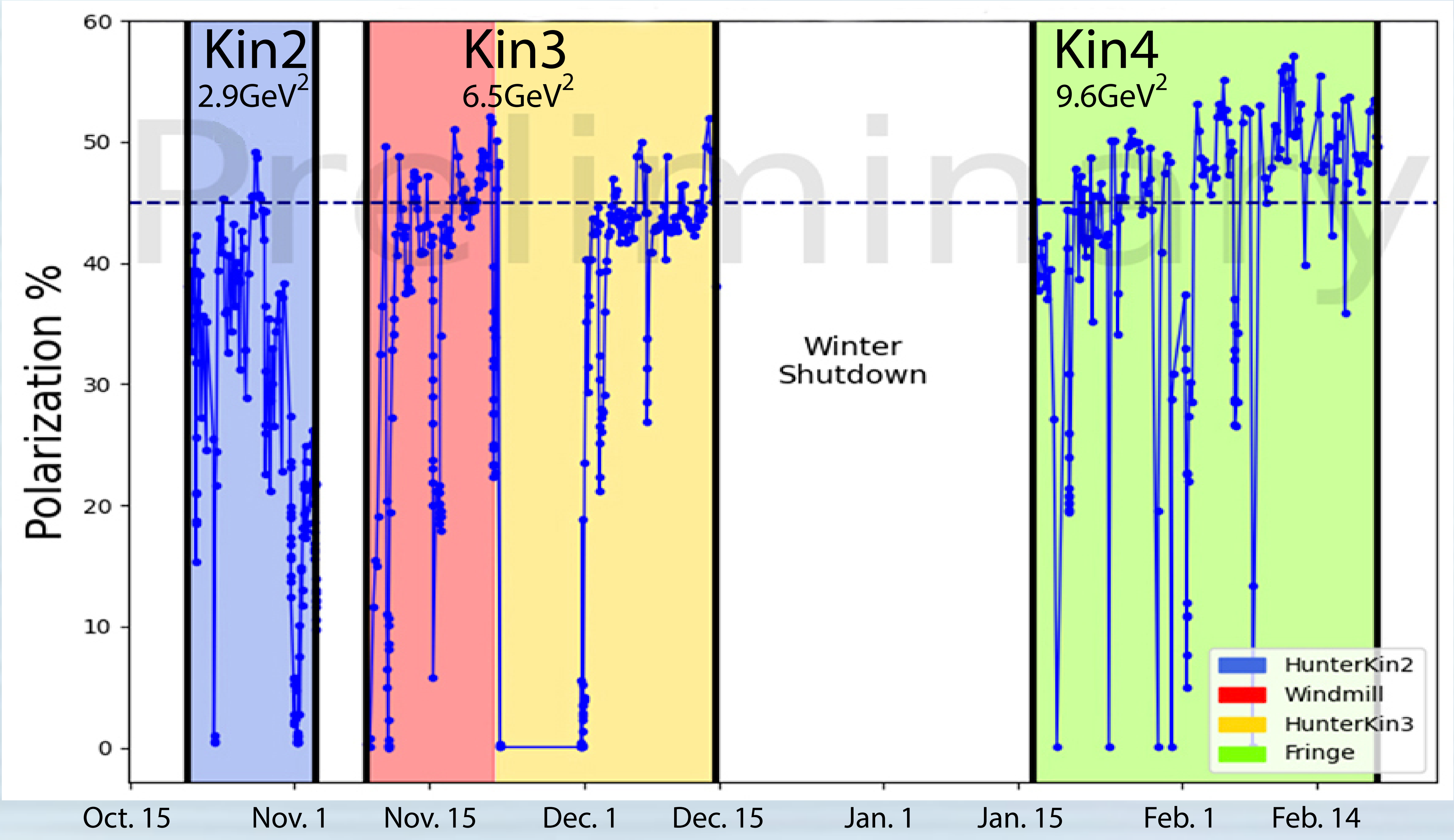
courtesy of J. Gilfoyle

# Projected errors for SBS GEn-II

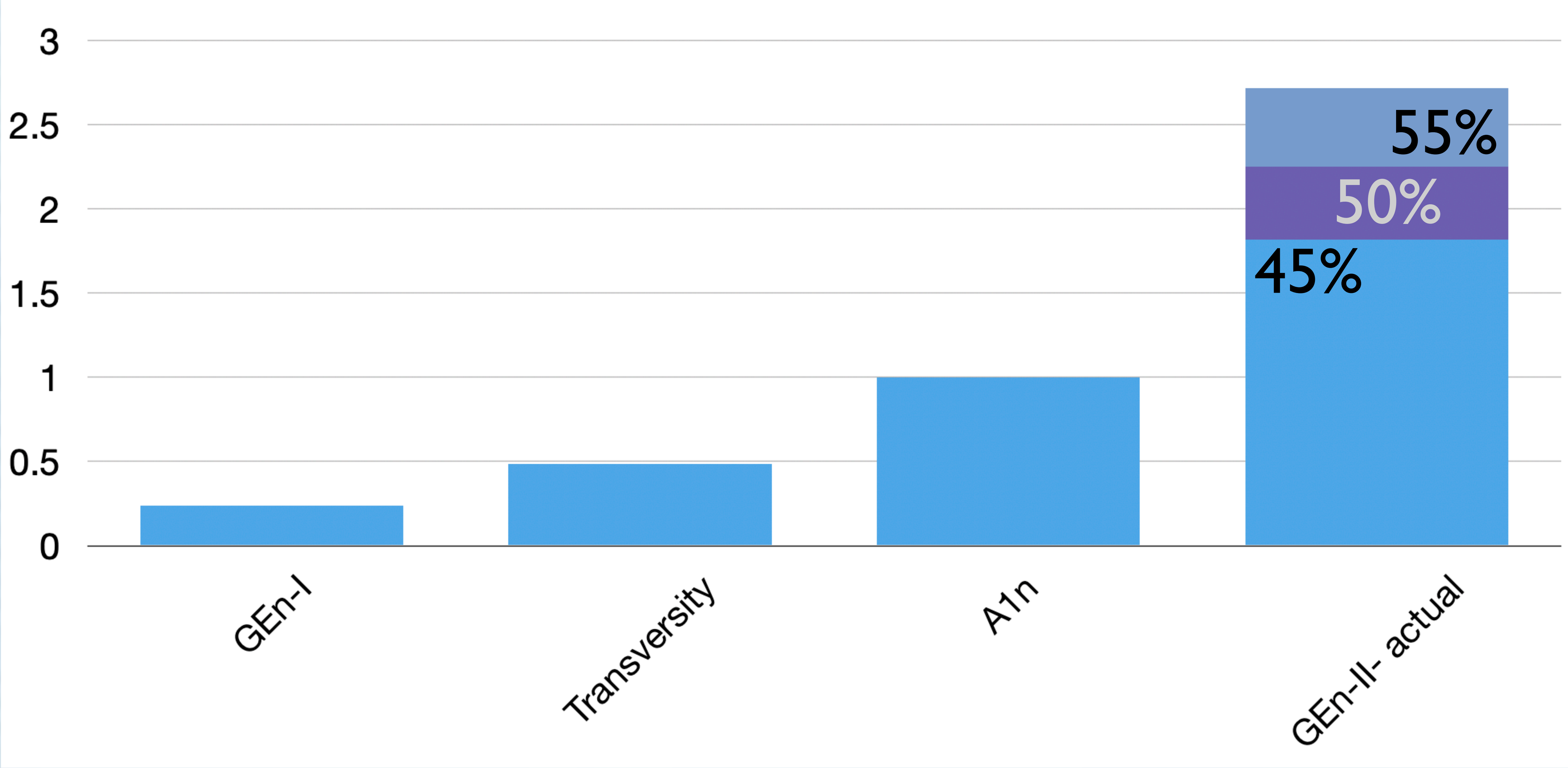



- Data have been acquired for two out of three kinematic settings.
- Additional data taking is scheduled for our highest $Q^2$ point.
- With these estimates, we will achieve something very close to our goal.

# Target performance during GEn-II vs. history

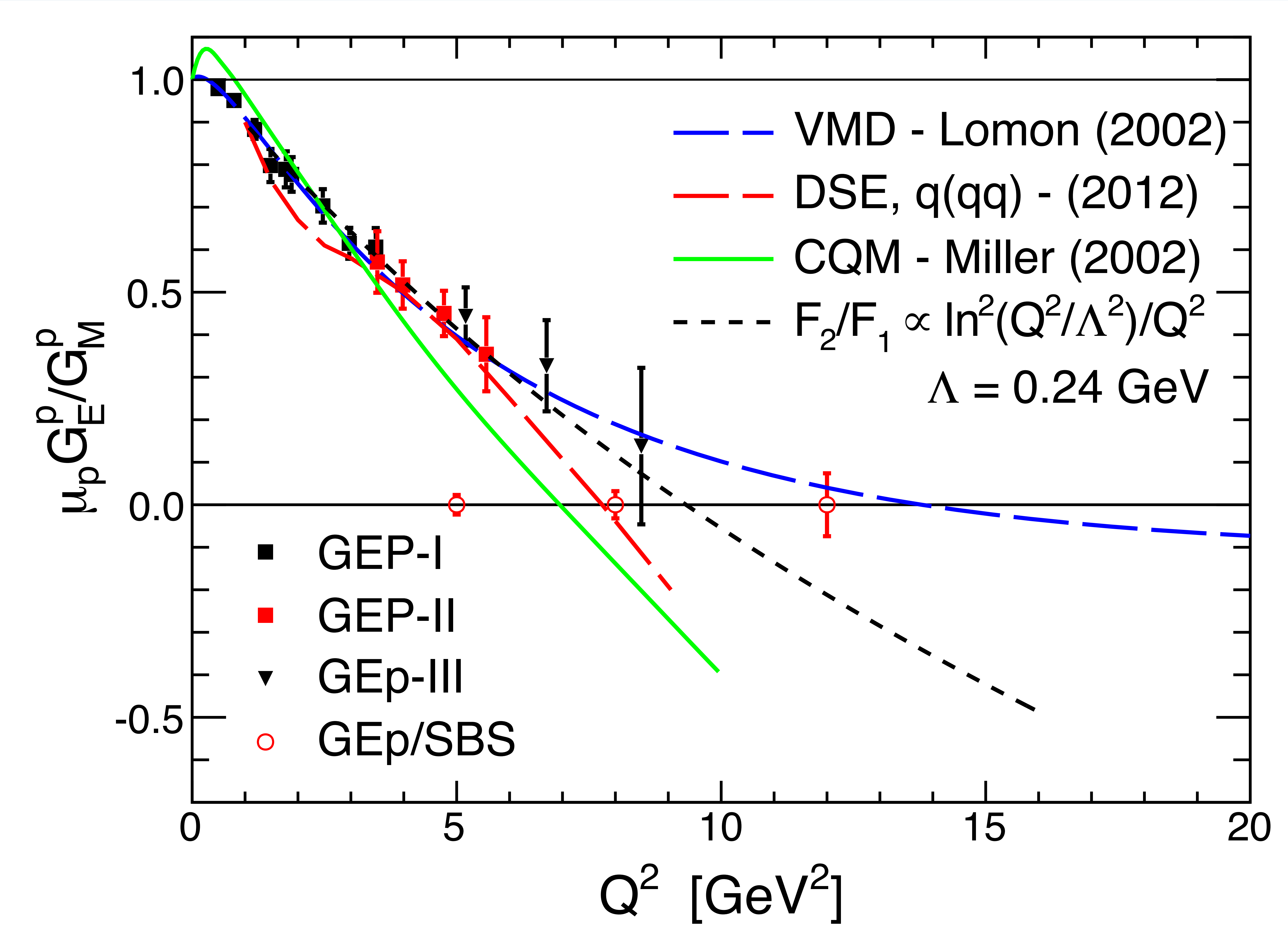



- Thus far, 45% polarization has been a typical polarization at 45μA.
- We have seen at high as 55% polarization at 45μA.
- We are aiming for 50% polarization for the balance of the run.




It is notable that during GEn-II, thus far, we have accumulated roughly the amount of charge of all previous $^3$He experiments at JLab.

# The Projected error bars from the SBS GEp 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.
- The precision and the Q2 reach of the JLab form factor program at JLab will provide valuable insights with real discovery potential.