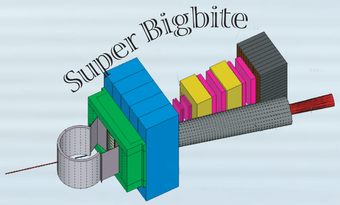
SBS: General Overview

- A quick description of the SBS program.
- Where the SBS program is right now.
- The physics of form factors at hight Q^2

Gordon D. Cates
January 26, 2023



University of Virginia

Jefferson Lab
EXPLORING THE NATURE OF MATTER

The ongoing SBS program

- G_M^n/G_M^p (E12-09-019) - Q^2 up to 13.5 GeV^2.

  COMPLETE!!! – October 2021 – February 2022

- G_E^n/G_M^n (E12-09-016) - Q^2 up to ~ 9.7 GeV^2.

  ONGOING!!! – October 2022 – present

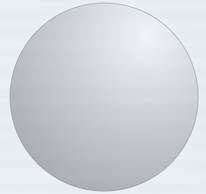
  - A_LL (E12-21-005) - Wide-angle pion photo production
  - GEn-RP (E12-17-004) - Q^2 ~ 4.5 GeV^2
  - K_LL (E12-20-008) - Wide-angle pion photo production

- G_E^p/G_M^p (E12-07-109) - Q^2 up to ~12 GeV^2.

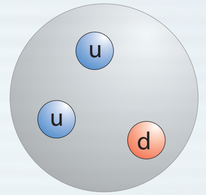
  Beginning roughly July 2024

Elastic form factors — a long history of discovery

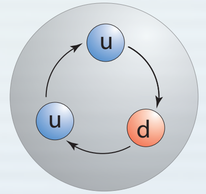
- Hofstadter's studies of the proton form factor (FF)
  - first direct measurement of the proton's size



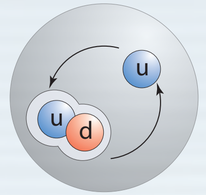
- Studies at SLAC of proton FFs at high Q^2
  - played a key role at SLAC leading to the discovery of quarks



- 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.



Two ways for measuring elastic form factors

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

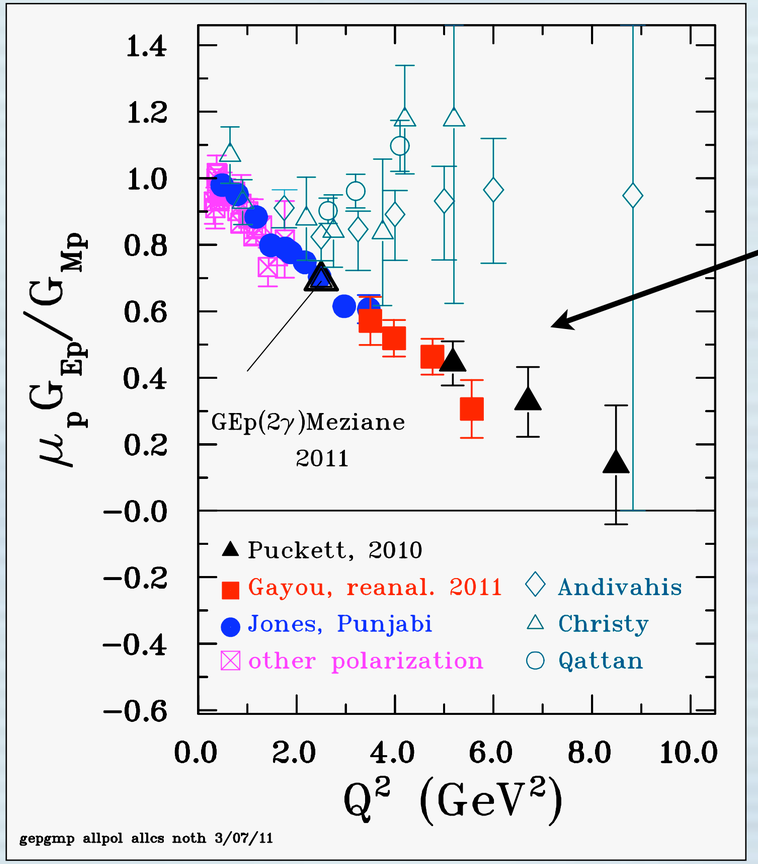
$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{\text{Mott}} \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)} \qquad \tau = Q^2/4M^2 \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

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 I 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

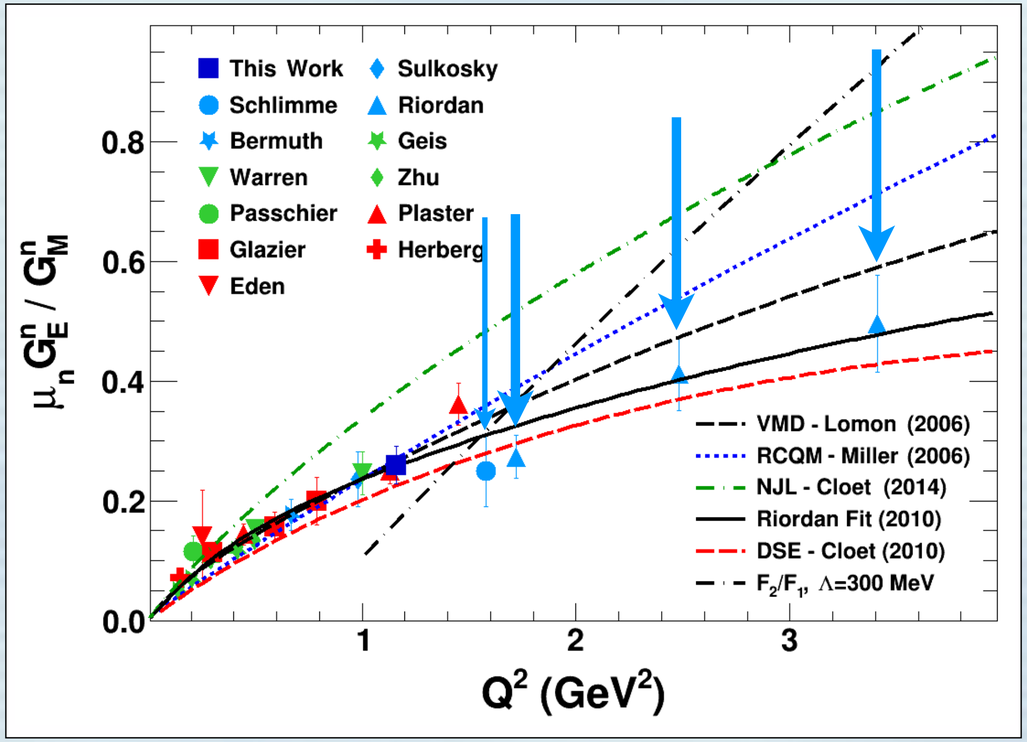
Explanations for the Q^2 behavior of G_E^p/G_M^p have emphasized the role of <u>quark orbital angular momentum</u>.

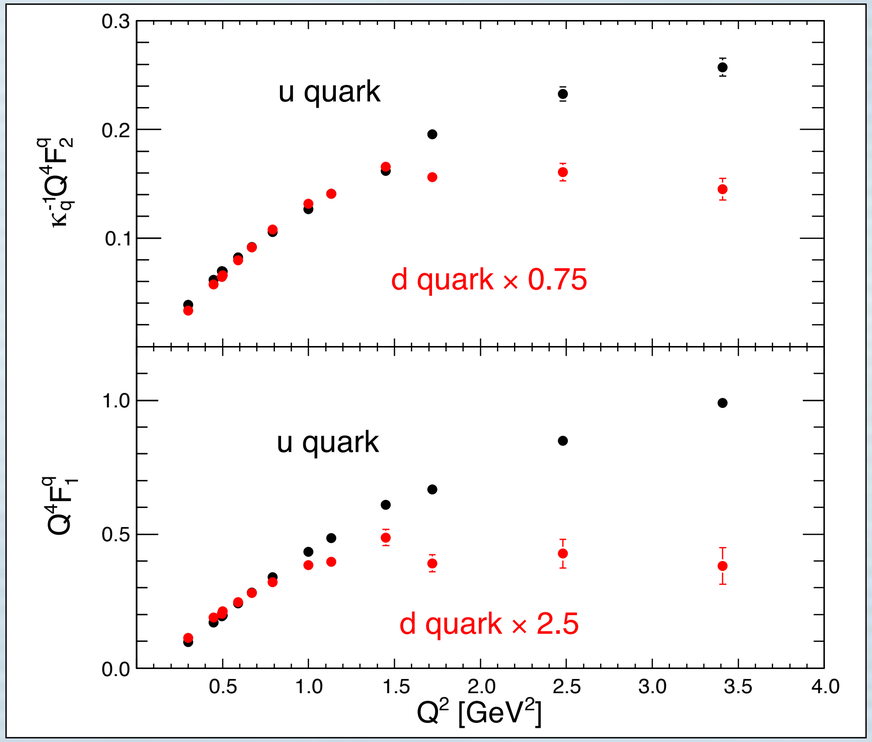
The Perdrisat experiment triggered greatly renewed interest in nucleon structure

- Perturbative QCD and scaling expectations
- Relativistic constituent quark model calculations
- Dyson-Schwinger Equation based calculations
- Light-front wave functions
- Even lattice QCD calculations (not easy at higher Q^2 !)

This list is nowhere near complete

GEn-I made it possible to extract the flavor separated contributions to the form factors





Distinctly different behavior was observed for the u- and d-quarks
Seen by many as strong evidence for di-quark correlations

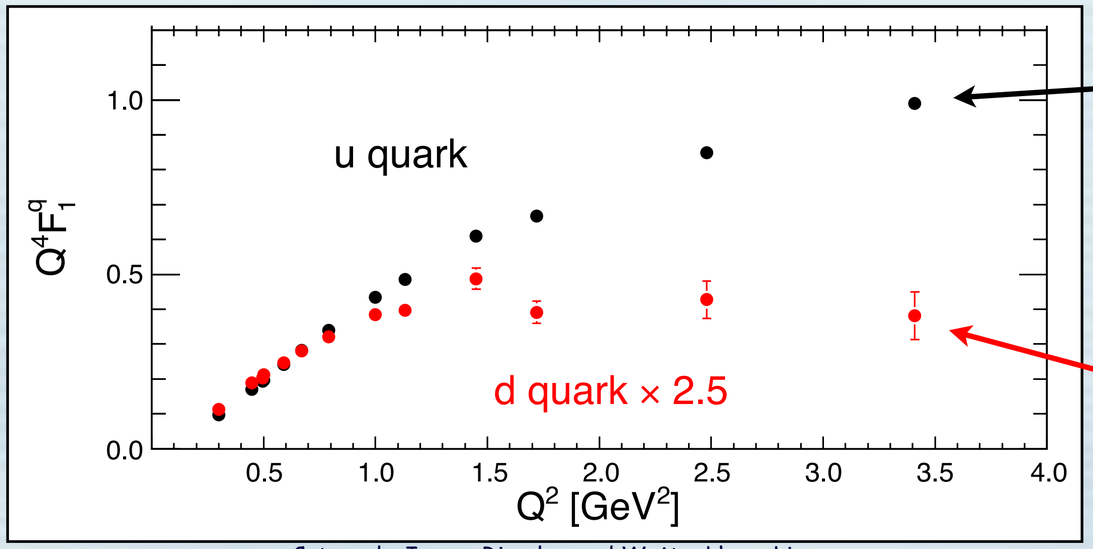
Workshop on diquarks at ECT* in Trento

(September 2019)

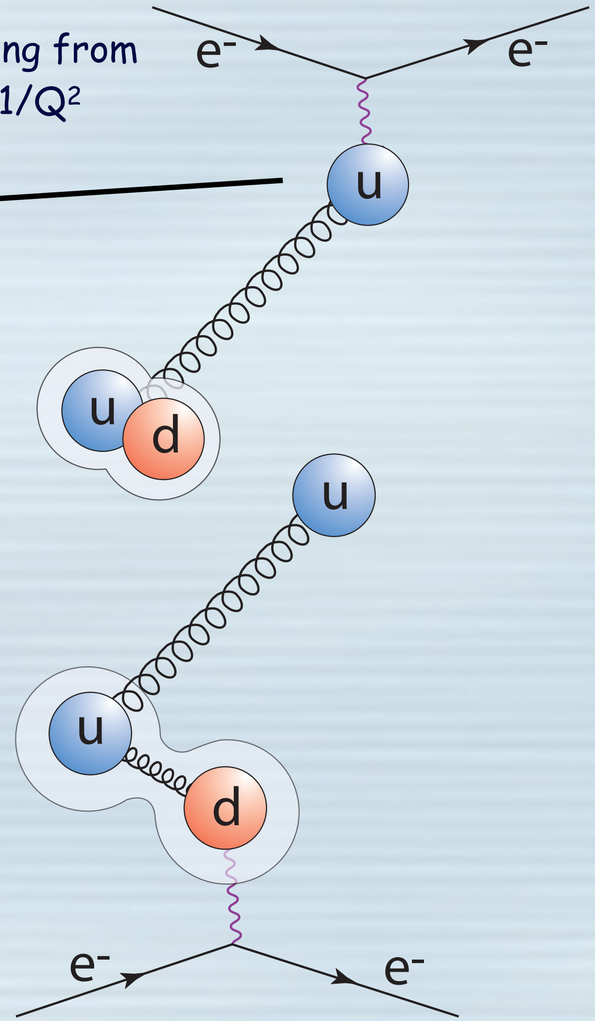
Review article grew out of the workshop: "Diquark Correlations in Hadron Physics: Origin, Impact and Evidence", Progress in Particle and Nuclear Physics 116 (2021) 103835".

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)

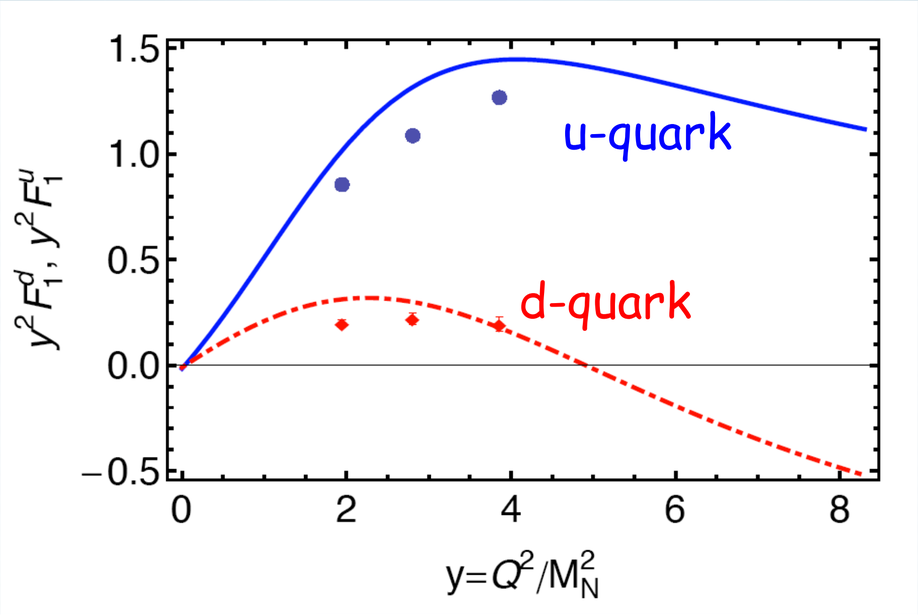


d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

DSE/Faddeev calculation of $Q^4F_1^u$ and $Q^4F_1^d$

Cloët, Roberts and Wilson, using the QCD DSE approach made …

" … a prediction for the Q^2-dependence of u- and d-quark Dirac and Pauli form factors in the proton, which exposes the critical role played by diquark correlations within the nucleon."



arXiv:1103.2432v1

With essentially no free parameters, this model preceded GEn-I and our extraction of the flavor separated form factors!

The FF data provide some of the most important constraints on certain GPDs

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

They can thus provide early insight into determining
the orbital 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

SBS is providing, by far, the most accurate data on the elastic nucleon form factors at high Q2

- SBS will nearly triple the range over which all the nucleon form factors are known.
- If history is any guide - we are sure to discover surprises
- For example - at what point will the "diquark-like behavior" break down?

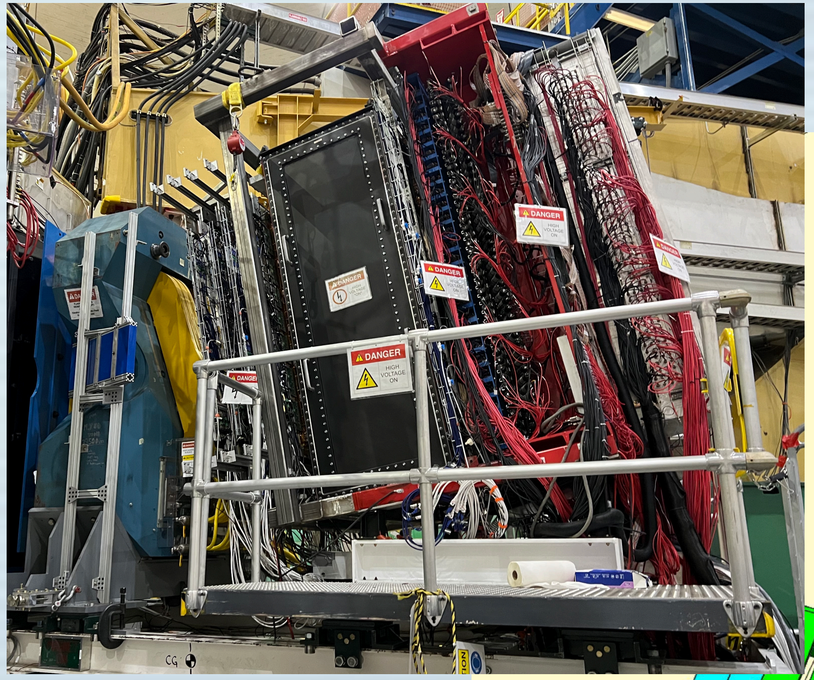
We are ~midway through SBS program

GMn is complete!

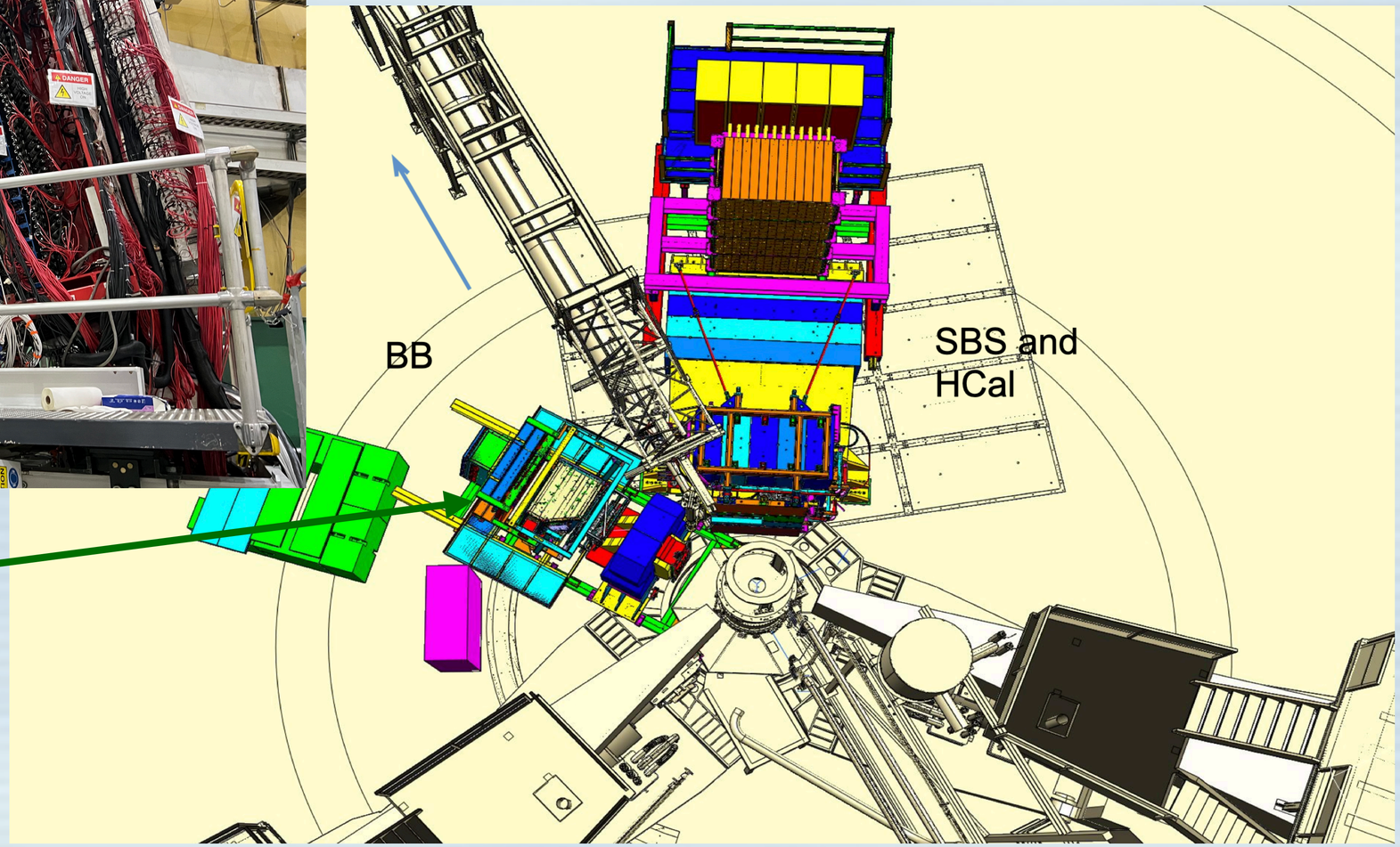
The final kinematic point for GEn is underway

GEp is next

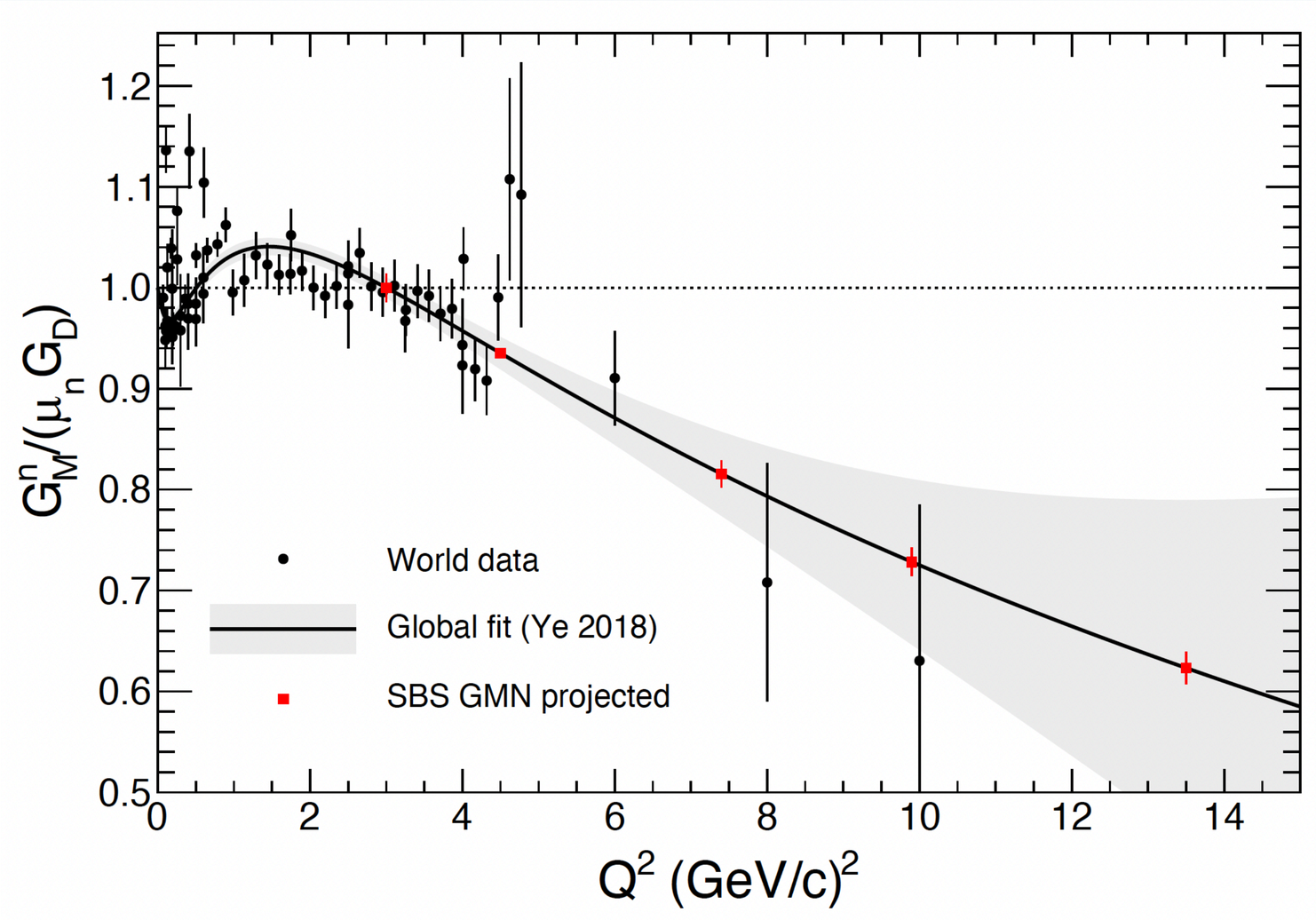
G_M^n/G_M^p (E12-09-019) — experimental layout



BigBite



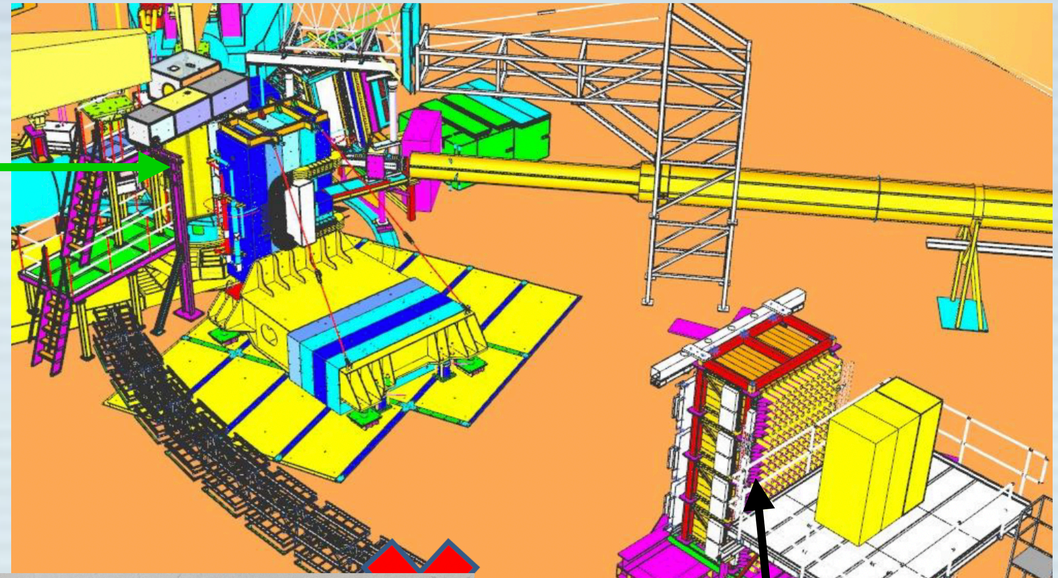
Projected errors for SBS GMn



Data acquired between
October 2021 - February 2022

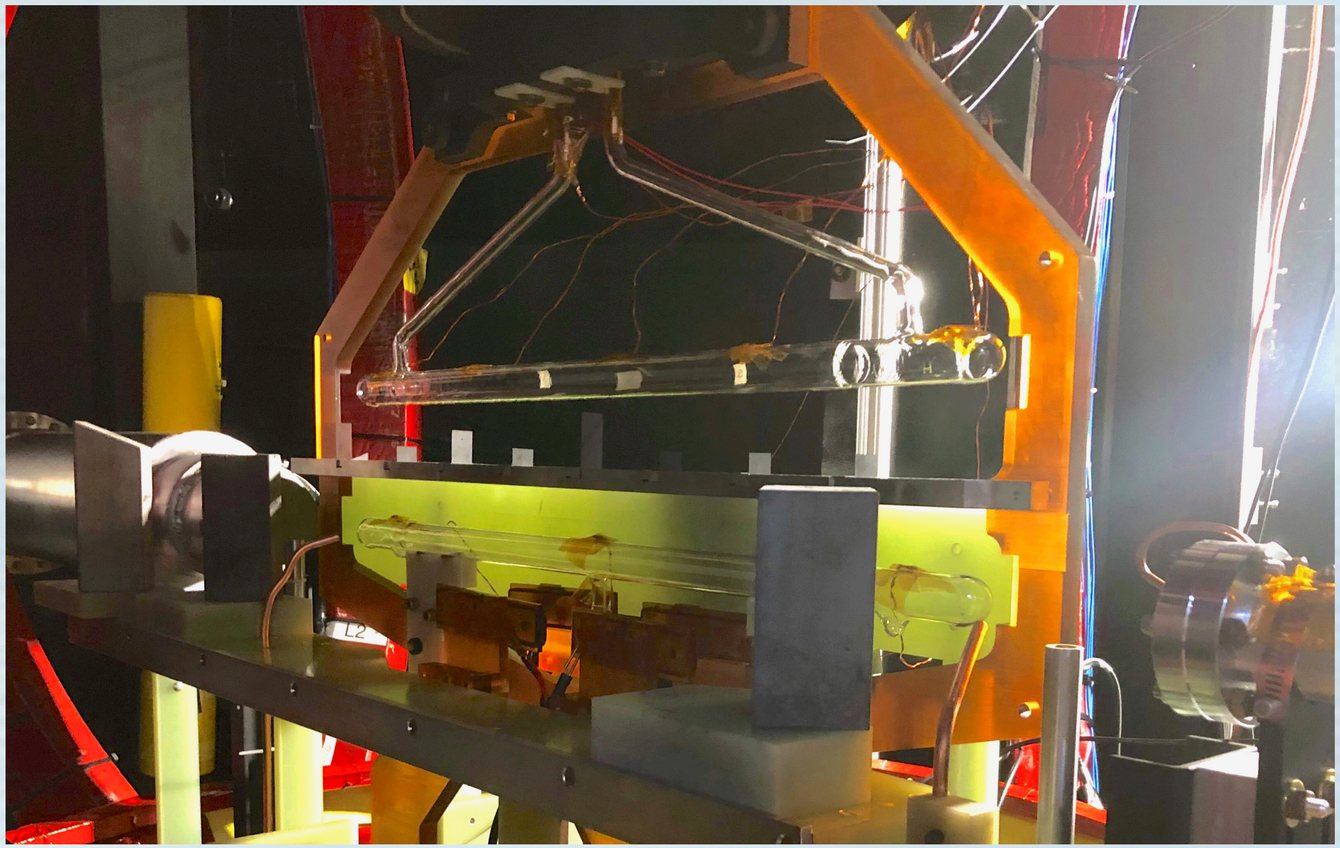
SBS GEn-II (E12-09-06) — experimental layout

^{3}He target



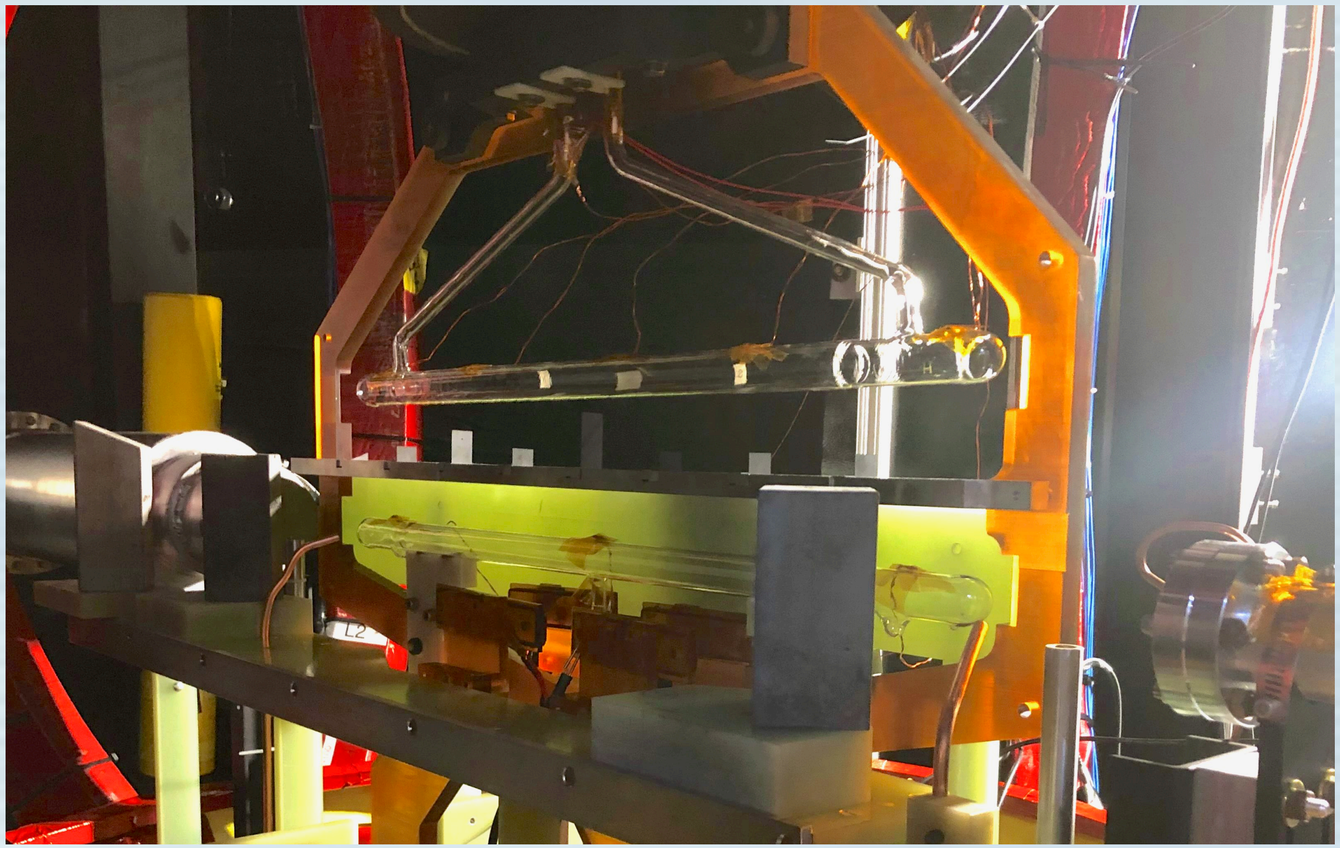
HCAL

Polarized ^{3}He target



- 6 STP liters 3He (versus 3 STP liters previously) in order to run at high current.
- Typically running at 45 μA (versus 30μA previously)
- 60cm target chamber (versus 40cm previously).
- Much of our running is at ~45%, yielding a FoM nearly twice that of previous targets.
- Note that A1n ran with a FoM nearly twice that of previous targets.

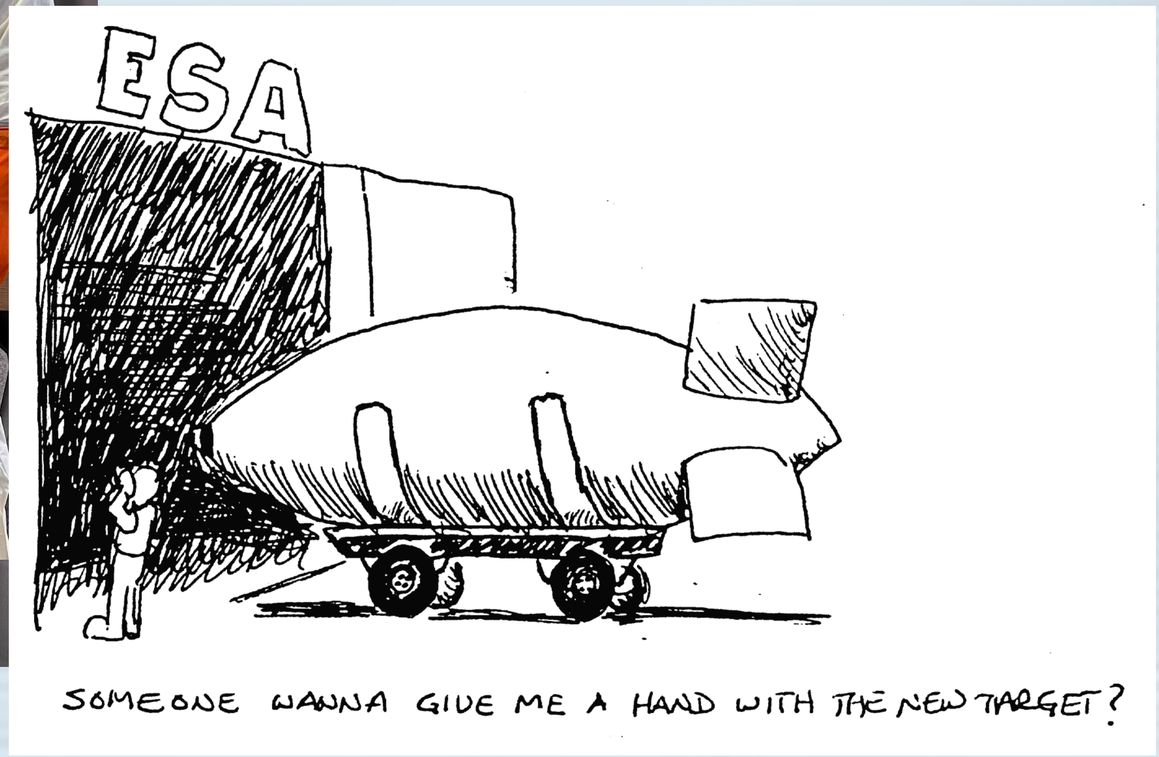
Polarized ^{3}He target



Our figure of merit is x200 what we achieved during SLAC E154, which to this day provides the most precise data on the neutron spin structure functions over the range in Bjorken x that we covered.

Polarized ^{3}He target

But some things never change ….



A big shout out to the polarized 3He target team!!!

ONSITE POLARIZED 3HE TARGET TEAM

Gordon Cates

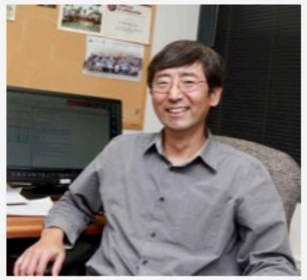
Todd Averett

Arun Tadepalli

David Flay*

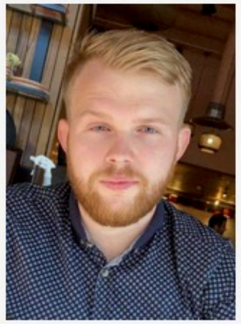
(*now at Johns Hopkins)

JP Chen

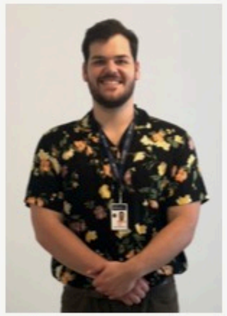


William Henry

Gary Penman



Hunter Presley

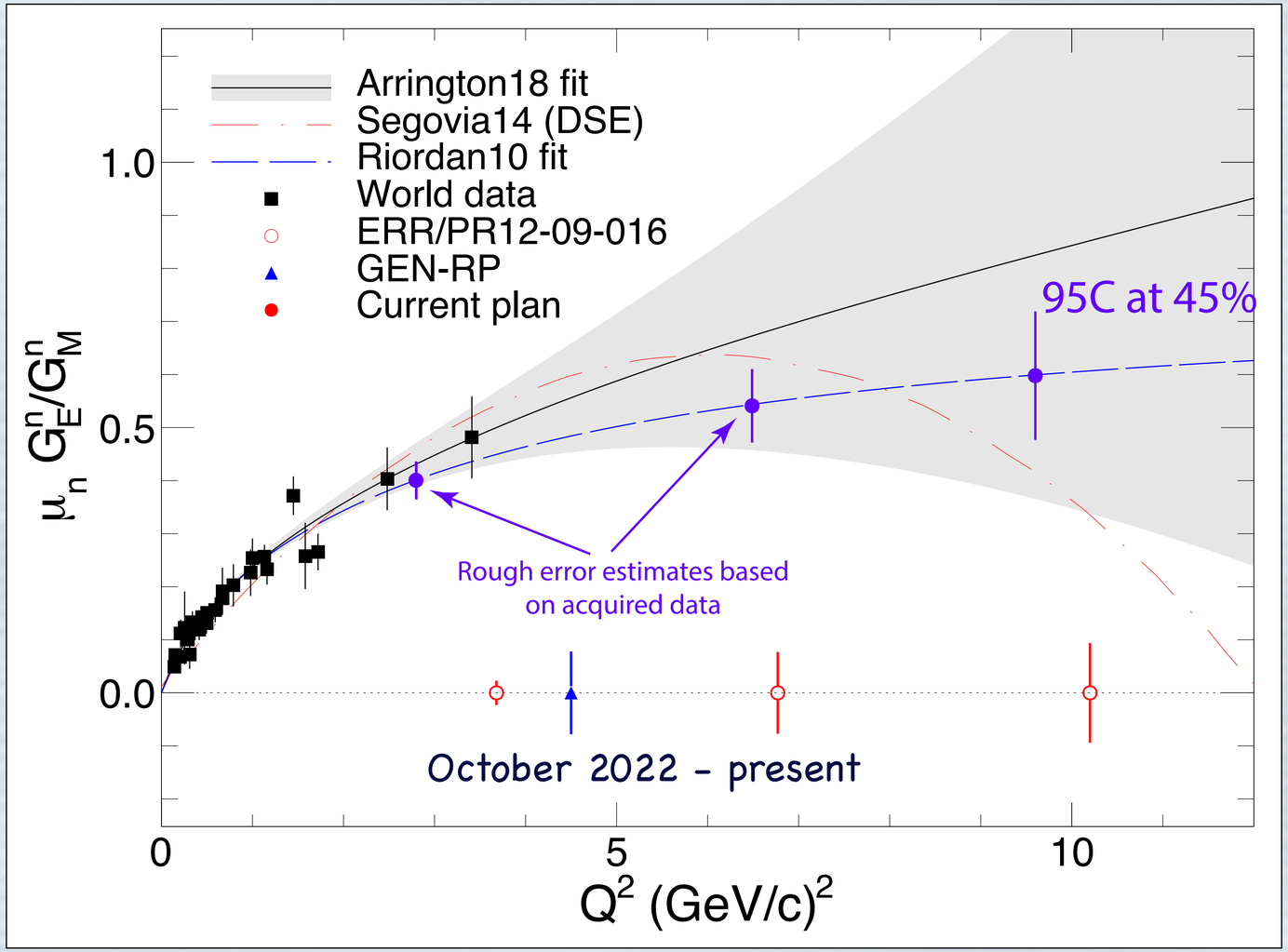


Kate Evans

Jack Jackson

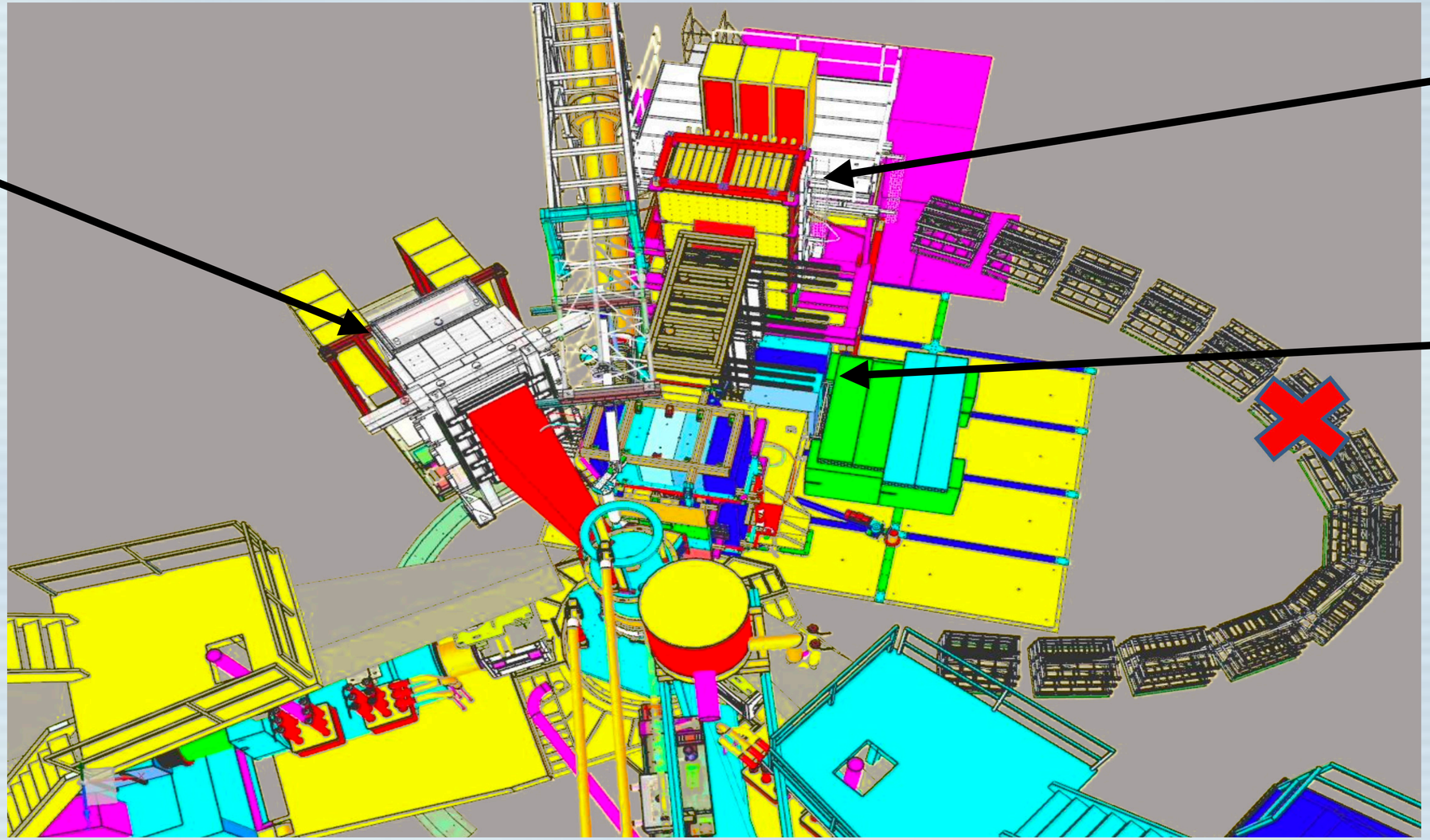
Check out Arun Tadepalli's talk (from whom I borrowed this image) tomorrow at 10:15

Projected errors for SBS GEn-II



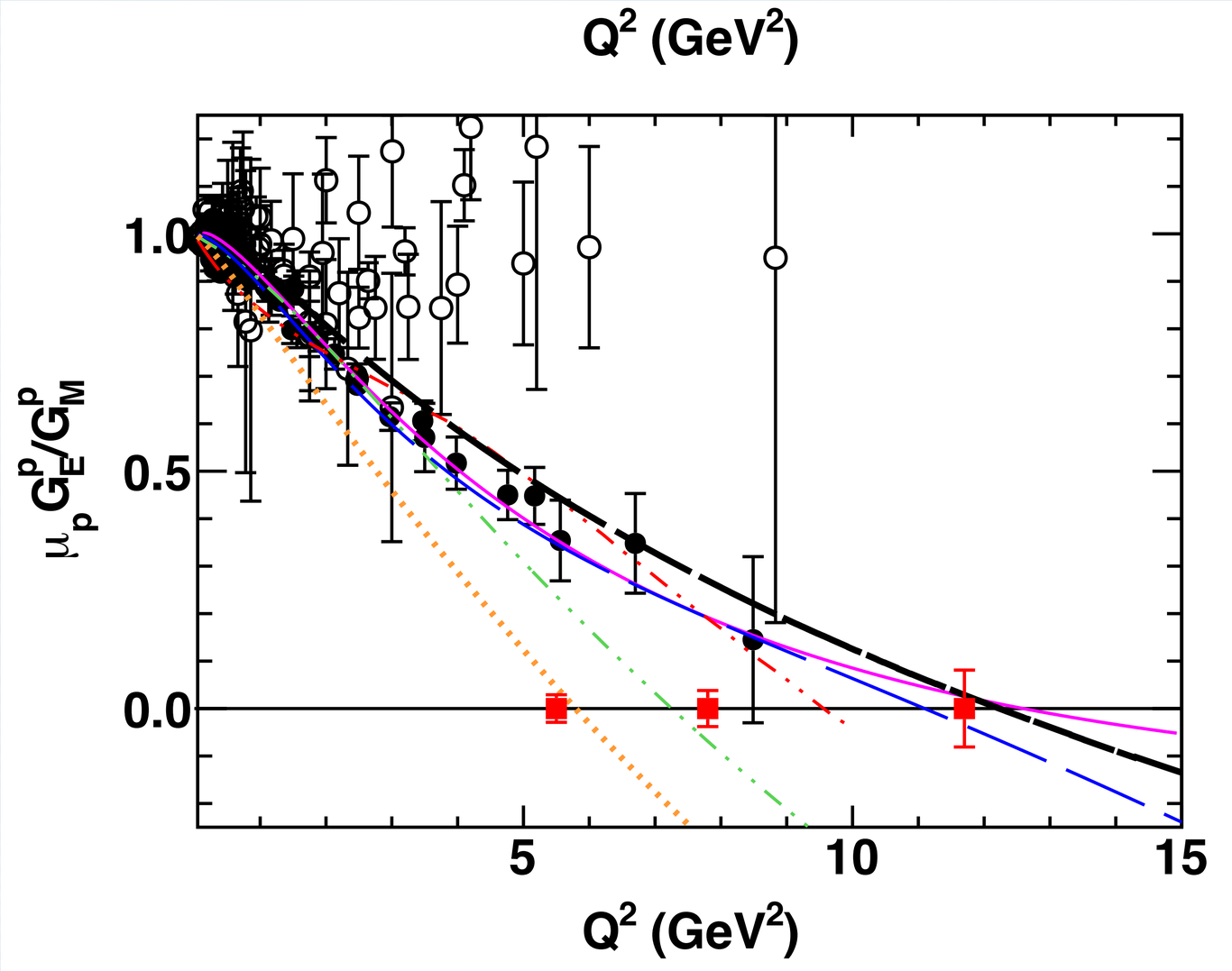
- Data have been acquired for two out of three kinematic settings.
- For those points, we have largely met the goals we presented to the ERR in October of 2020.
- We are on track for excellent data at our final kinematic setting.
- A bit more beam time would be wonderful !!!

G_E^p/G_M^p (E12-09-019) — experimental layout



In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks

Anticipated errors from G_E^p/G_M^p (E12-09-019)



Summary

- SBS is opening a new era for high Q^2 form factor studies and a broad new range of physics.
- Thus far, GMn and GEn-II appear to be a big success.
- It's a LONG experiment - we need help! Please sign up for shifts!!!