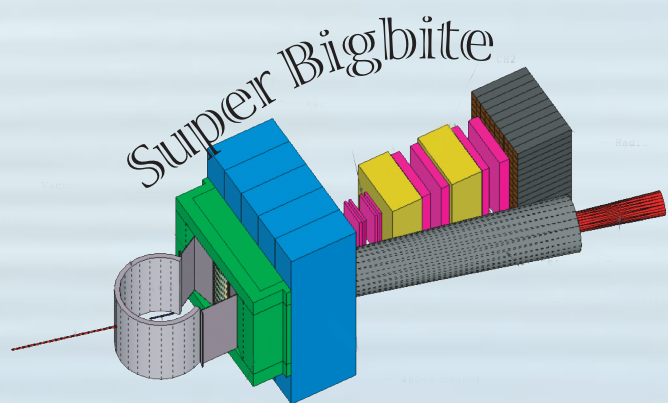


Experimental inputs to femtography from form factors and TMDs

- First - why we should care.
- JLab 6 GeV era elastic form factors
- JLab 12 GeV era elastic form factors
- SBS SIDIS Experiment looking at single-spin asymmetries on a transversely polarized ^3He target

Gordon D. Cates
July 24, 2026



It has been exactly 100 years since Schrodinger taught us how to visualize atoms

1926. № 6.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 79.

1. *Quantisierung als Eigenwertproblem;*
von *E. Schrödinger.*
(Zweite Mitteilung.)¹⁾

§ 1. Die Hamiltonsche Analogie zwischen Mechanik und Optik.
Bevor wir daran gehen, das Eigenwertproblem der Quantentheorie für weitere spezielle Systeme zu behandeln, wollen wir den *allgemeinen* Zusammenhang näher beleuchten, welcher zwischen der Hamiltonschen partiellen Differentialgleichung (H.P.) eines mechanischen Problems und der „zugehörigen“ *Wellengleichung*, d. i. im Falle des Keplerproblems der Gleichung (5) der ersten Mitteilung, besteht. Wir hatten diesen Zusammenhang vorläufig nur kurz seiner äußeren analytischen Struktur nach beschrieben durch die an sich unverständliche Transformation (2) und den ebenso unverständlichen Übergang von der *Nullsetzung* eines Ausdrucks zu der Forderung, daß das *Raumintegral* des nämlichen Ausdrucks *stationär* sein soll.²⁾

Der *innere* Zusammenhang der Hamiltonschen Theorie mit dem Vorgang der Wellenausbreitung ist nichts weniger als neu. Er war Hamilton selbst nicht nur wohlbekannt, sondern bildete für ihn den Ausgangspunkt seiner Theorie der Mechanik, die aus seiner *Optik inhomogener Medien* hervorgewachsen ist.³⁾ Das Hamiltonsche Variationsprinzip kann

1) Siehe diese Annalen 79. S. 361. 1926. Es ist zum Verständnis nicht unbedingt nötig, die erste Mitteilung vor der zweiten zu lesen.
2) Dieser Rechenvorgang wird in der vorliegenden Mitteilung nicht weiter verfolgt. Er sollte nur zur vorläufigen raschen Orientierung über den äußerlichen Zusammenhang zwischen der Wellengleichung und der H. P. dienen. ψ steht nicht wirklich zur Wirkungsfunktion einer bestimmten Bewegung in der von der Gleichung (2) der ersten Mitteilung behaupteten Beziehung. — Hingegen ist der Zusammenhang der Wellengleichung und der Variationsaufgabe selbstverständlich höchst real: der Integrand des stationären Integrals ist die Lagrange-Funktion für den Wellenvorgang.
3) Vgl. z. B. E. T. Whittaker, *Analytische Dynamik* (Deutsche Ausgabe bei Springer 1924). Kap. 11. S. 306 ff.

32

Annalen der Physik. IV. Folge. 79.

At left, the first of several papers by Schrodinger establishing both his famous equation as well as solutions for hydrogen.

At right, a paper from 1931 that used mechanical devices and photography to visualize the electron clouds for different states in hydrogen.

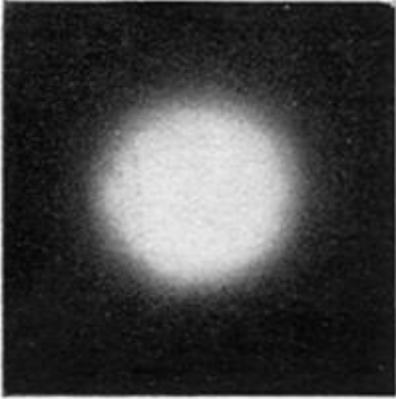
JUNE 1, 1931 PHYSICAL REVIEW VOLUME 37

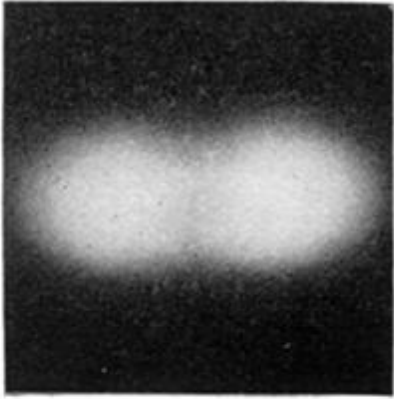
PICTORIAL REPRESENTATIONS OF THE ELECTRON CLOUD FOR HYDROGEN-LIKE ATOMS

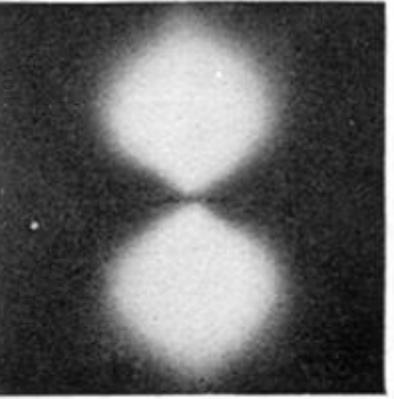
By H. E. WHITE
UNIVERSITY OF CALIFORNIA, BERKELEY
(Received April 21, 1931)

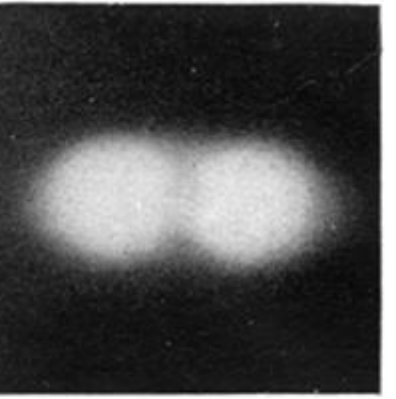
ABSTRACT

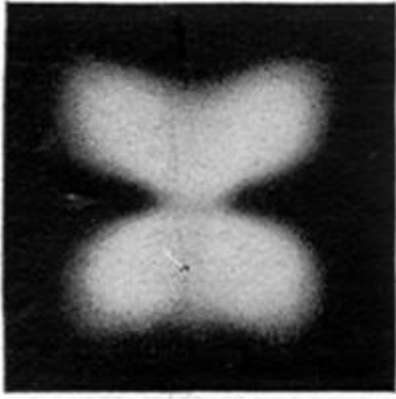
It is well known that the solutions of the wave-equation for hydrogen-like atoms may be represented graphically by interpreting $\Psi\Psi^*$ as a *probability density*. The

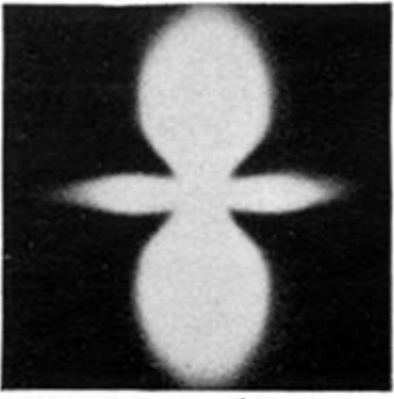

 $1s \quad m=0$

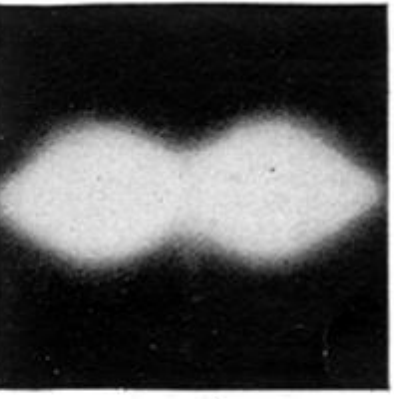

 $2p \quad m=1$

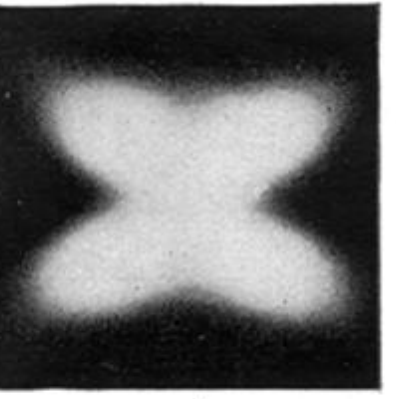

 $2p \quad m=0$


 $3d \quad m=2$


 $3d \quad m=1$

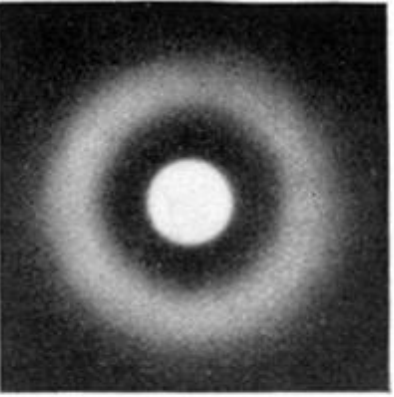

 $3d \quad m=0$

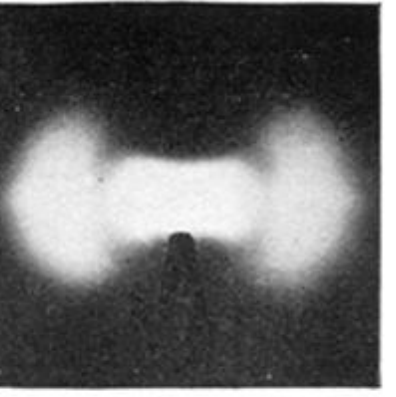

 $4f \quad m=3$


 $4f \quad m=2$


 $4f \quad m=1$


 $4f \quad m=0$


 $2s \quad m=0$


 $3p \quad m=1$

An exciting time for femtography

PHYSICAL REVIEW D **69**, 074014 (2004)

Quark imaging in the proton via quantum phase-space distributions

A.V. Belitsky,^{*} Xiangdong Ji,[†] and Feng Yuan[‡]

*Department of Physics, University of Maryland, College Park, Maryland 20742, USA
and Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA
(Received 8 September 2003; published 16 April 2004)*

PHYSICAL REVIEW LETTERS **135**, 261903 (2025)

First Global Extraction of Generalized Parton Distributions from Experiment and Lattice Data with Next-to-Leading-Order Accuracy

Yuxun Guo^{1,2,*}, Fatma P. Aslan,^{3,†} Xiangdong Ji^{4,‡} and M. Gabriel Santiago^{3,5,6,7,§}

¹Physics Department, *University of California*, Berkeley, California 94720, USA

²Nuclear Science Division, *Lawrence Berkeley National Laboratory*, Berkeley, California 94720, USA

³Center for Nuclear Femtography, *SURA*, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA

⁴Maryland Center for Fundamental Physics, Department of Physics, *University of Maryland*, 4296 Stadium Drive, College Park, Maryland 20742, USA

⁵Department of Physics, *Old Dominion University*, Norfolk, Virginia 23606, USA

⁶*Jefferson Lab*, Newport News, Virginia 23606, USA

⁷Department of Physics, *Temple University*, Philadelphia, Pennsylvania 19122, USA

QUARK IMAGING IN THE PROTON VIA QUANTUM . . .

PHYSICAL REVIEW D **69**, 074014 (2004)

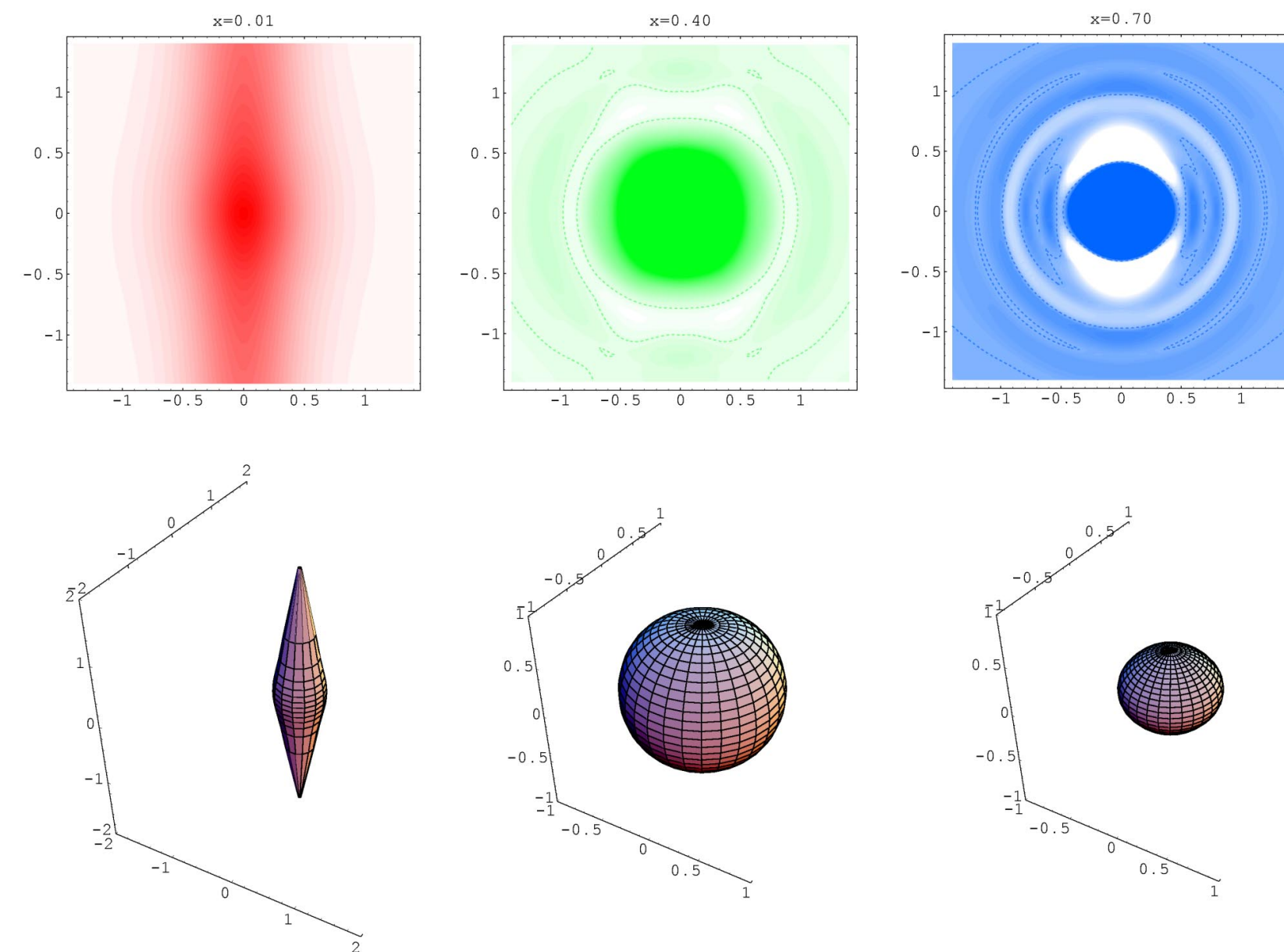


FIG. 1. The u -quark phase-space charge distribution at different values of the Feynman momentum for the nonfactorizable ansatz of generalized parton distributions (36). The vertical and horizontal axes correspond to z and $|\vec{r}_\perp|$, respectively, measured in femtometers. The (dashed) contours separate regions of positive (darker areas) and negative (lighter areas) densities. Below each contour plot we presented the shape of three-dimensional isodensity contours ($\rho = \text{const}$).

At left, images based on a nonfactorizable ansatz of GPDs.

At right, images based on data-constrained GPDs.

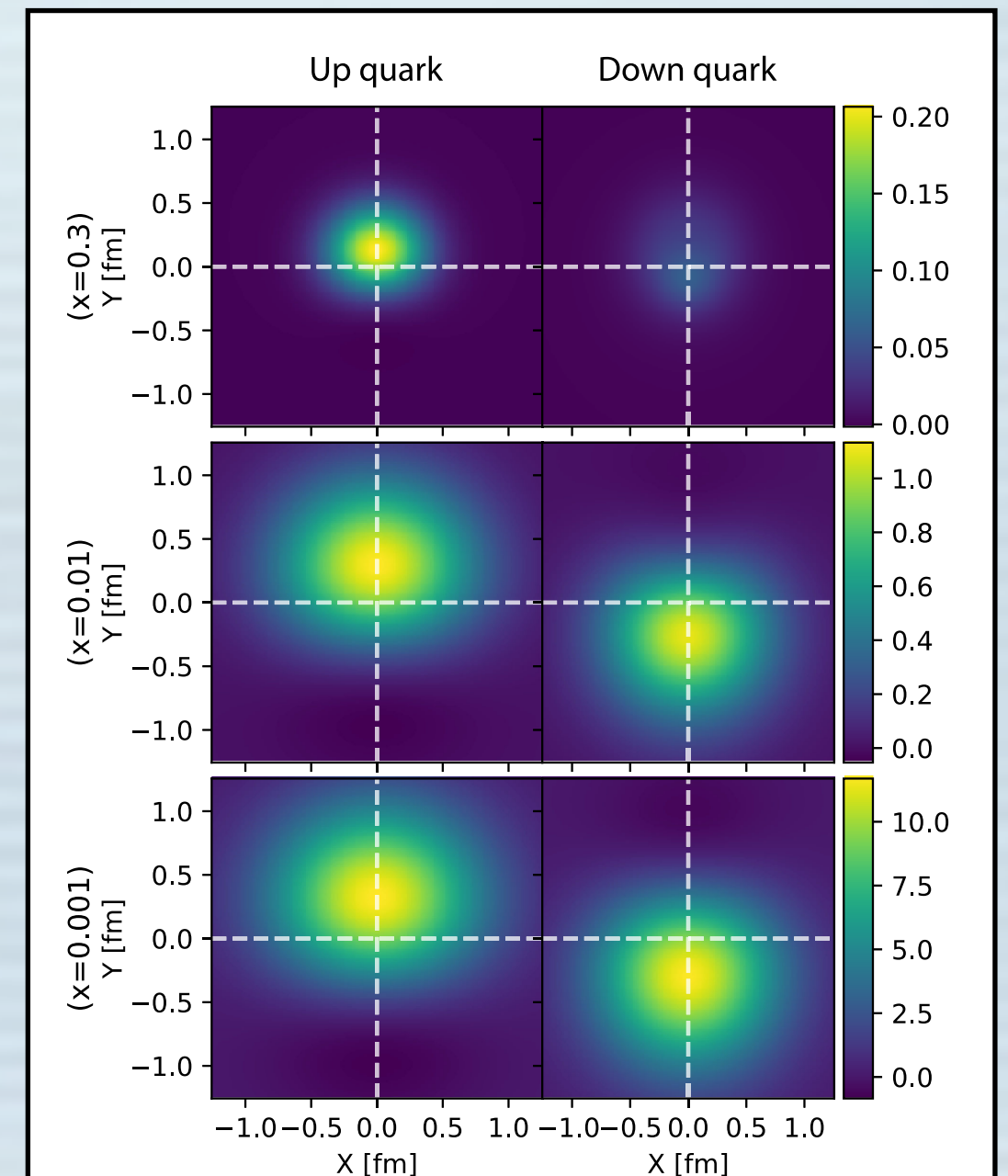


FIG. 5. The intrinsic transverse space distributions $\rho_{q,\text{In}}^X(x, \mathbf{b})$ of up and down quarks in a proton polarized in the X direction for $x = 0.3, 0.01$, and 0.001 with GUMP 1.0 GPDs at $\mu = 2$ GeV.

Visualizing quark orbital angular momentum

- Proton is polarized along the x-direction (horizontally).
- In the valence region, the up quark is above $y=0$, indicating motion about the x-axis and orbital angular momentum (OAM).
- In the valence region, the up quark dominates OAM.
- As x_{Bj} moves into the sea region, the OAM of the up and down quarks to some degree cancel one another.

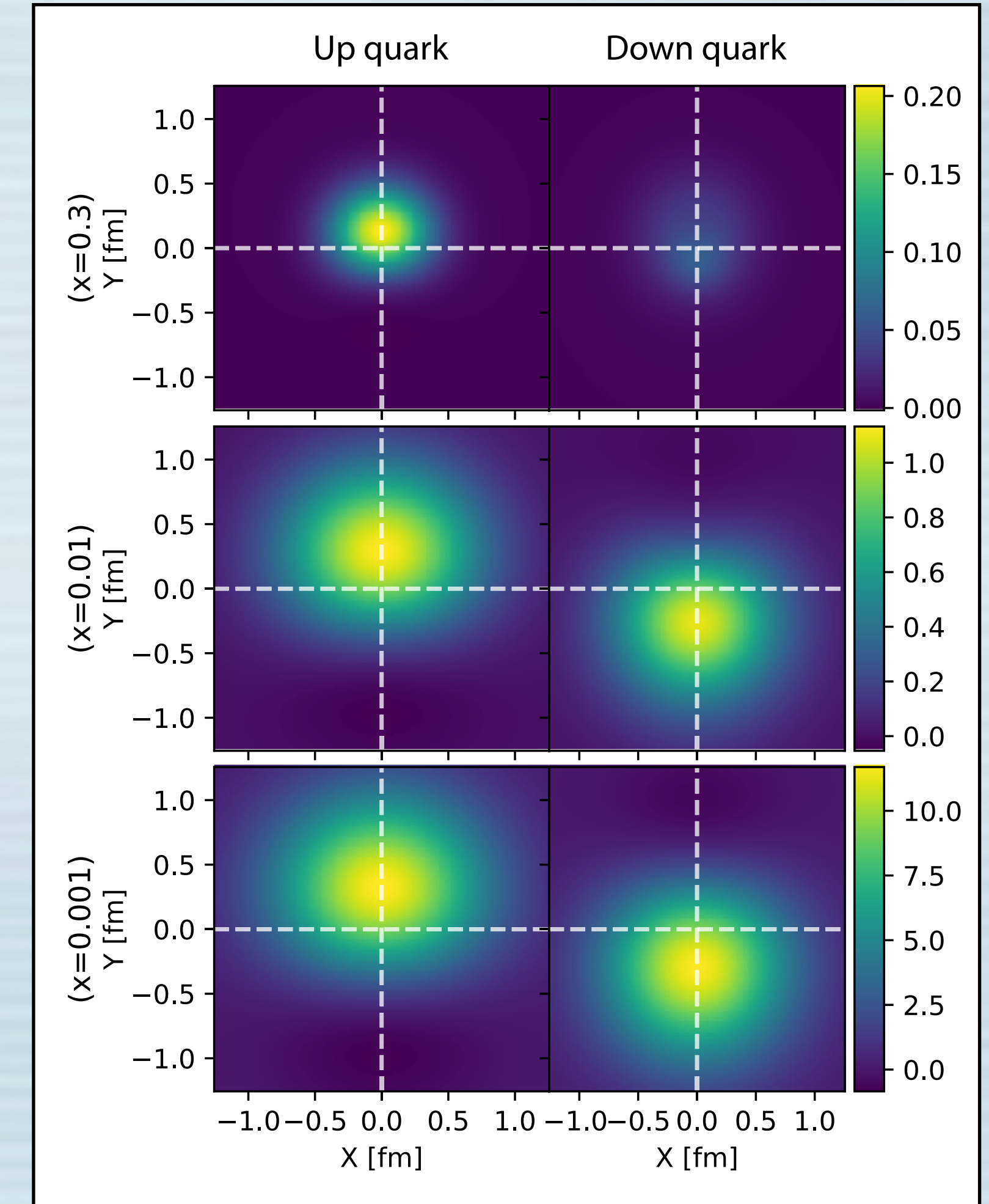
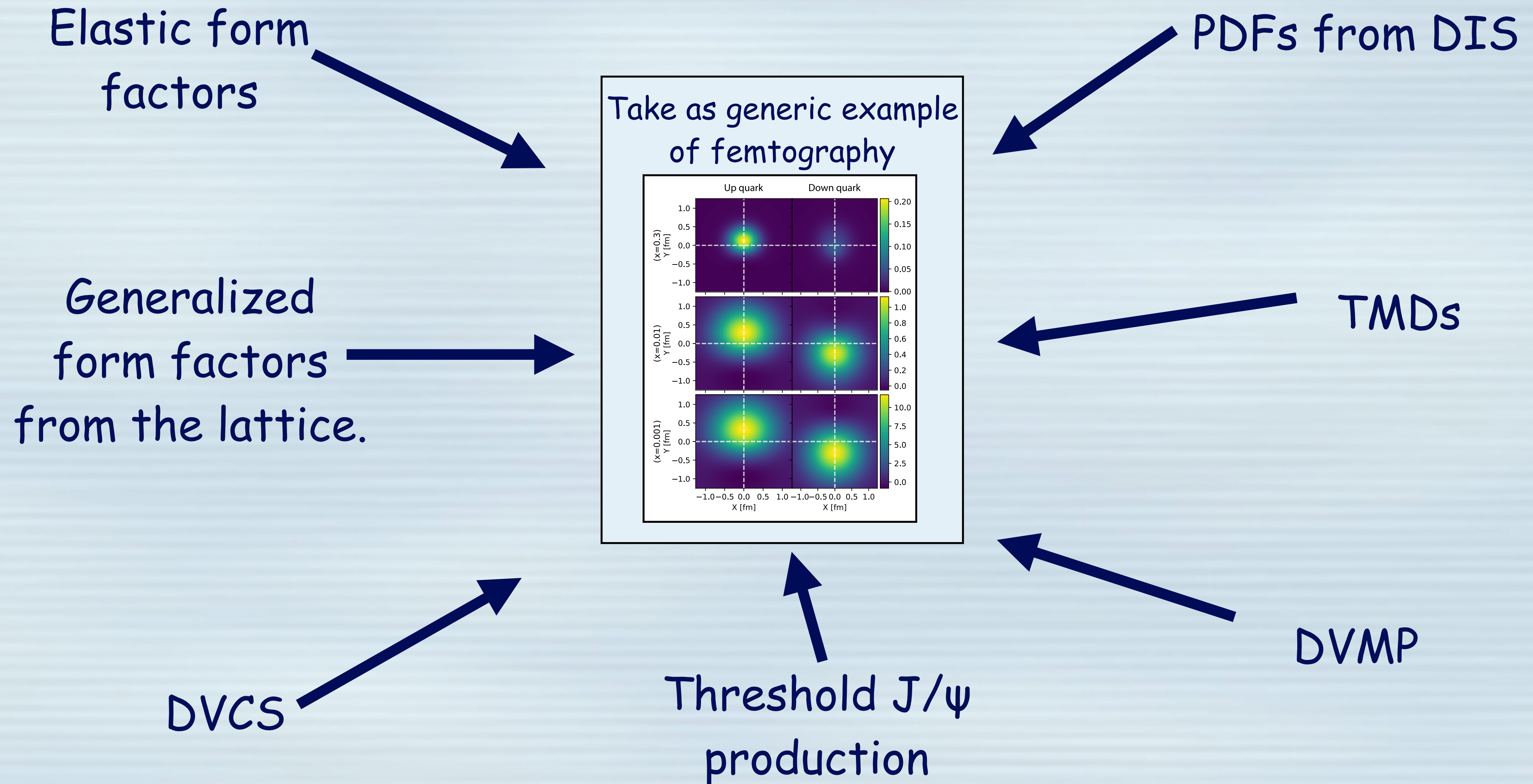


FIG. 5. The intrinsic transverse space distributions $\rho_{q,\text{In}}^X(x, \mathbf{b})$ of up and down quarks in a proton polarized in the X direction for $x = 0.3, 0.01$, and 0.001 with GUMP 1.0 GPDs at $\mu = 2$ GeV.

Inputs to femtography



Elastic nucleon form factors

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

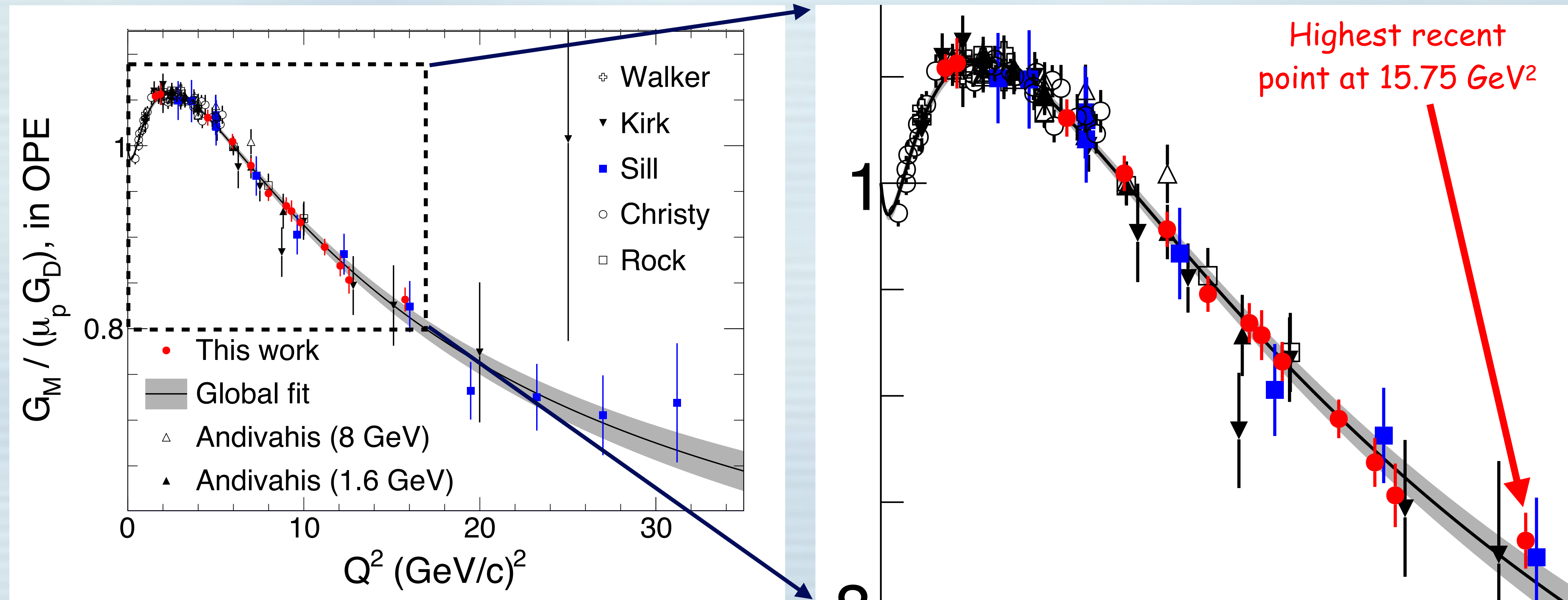
$$\int_{-1}^{+1} dx H^q(x, \xi, Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} dx E^q(x, \xi, Q^2) = F_2^q(Q^2)$$

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

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

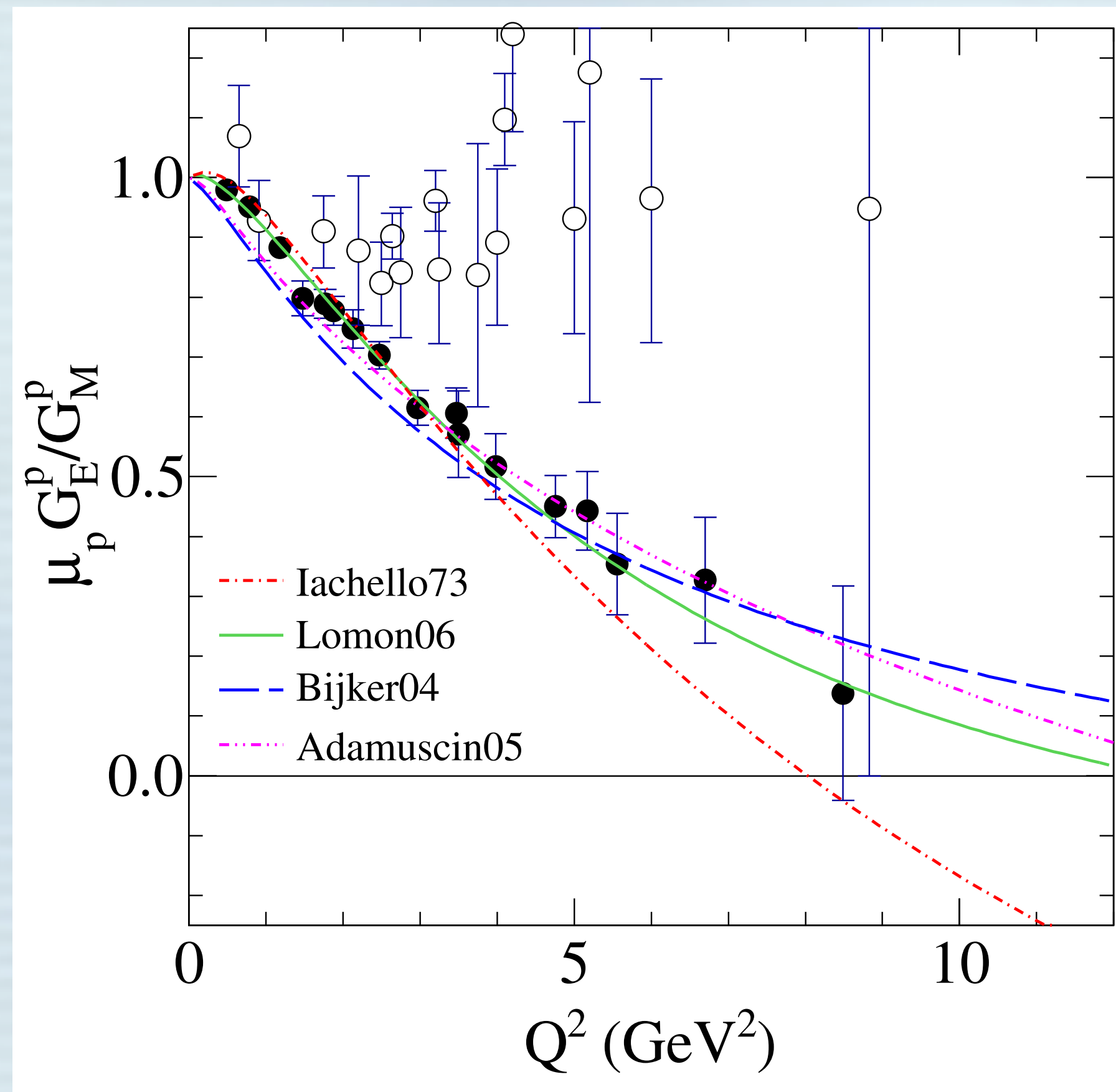
FFs thus play a an important role in the entire GPD program, one of the signature goals of the 12 GeV upgrade

The proton's magnetic form factor G_M^p is known quite accurately - including from recent data from JLab



Shown at left is the extraction of G_M^p resulting from JLab E12-07-108 (PRL v128, 102002 (2022)) providing new accurate data up to 15.75 GeV^2 . At right is a blown up version of the of the figure at left to better visualize the new points.

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.

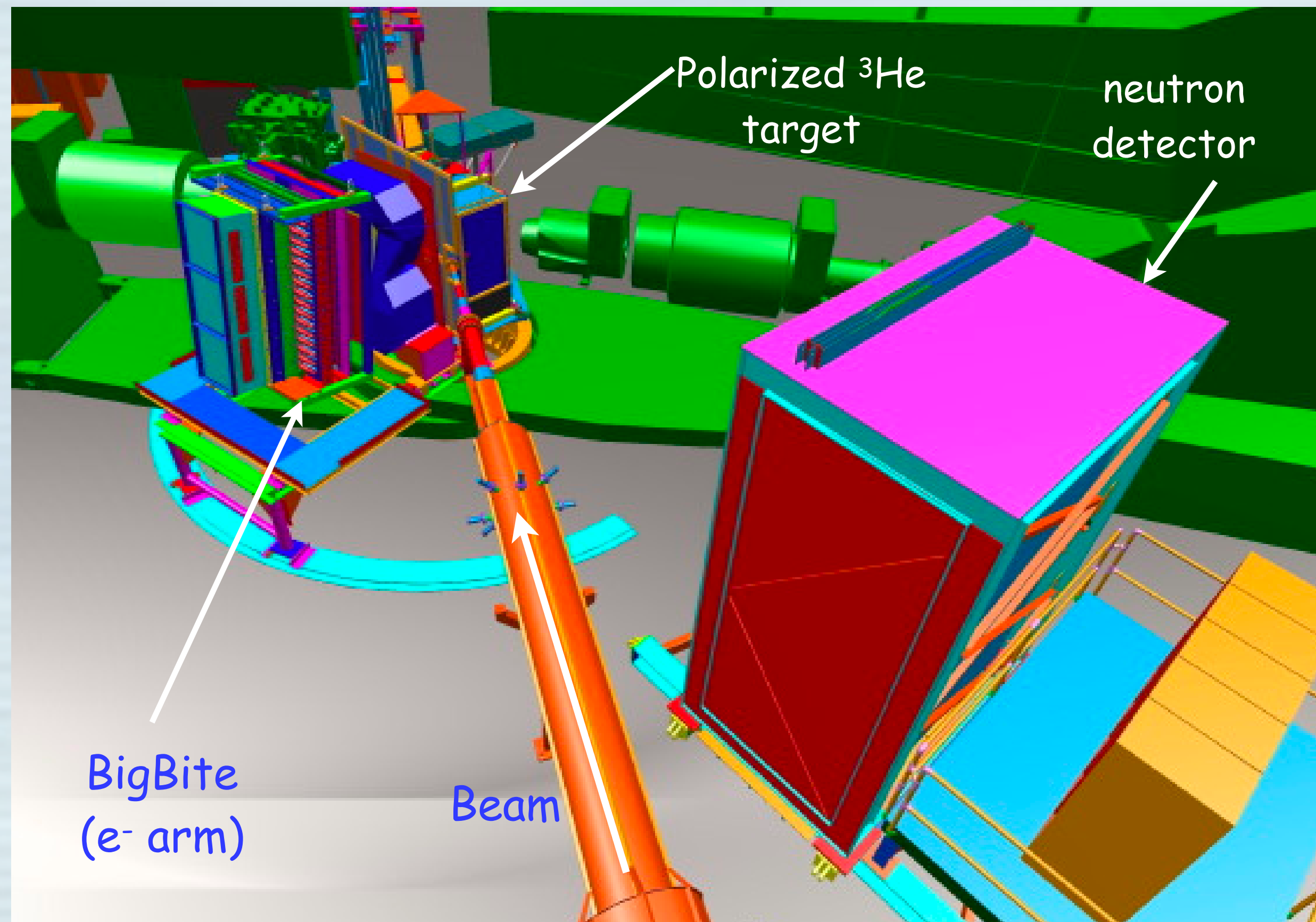
Resulted in the 2017
Bonner Prize in Nuclear
Physics being awarded to
Charles Perdrisat of
William and Mary



Explanations of the Q^2 behavior of G_E^p/G_M^p
emphasized the role of
quark orbital angular momentum.

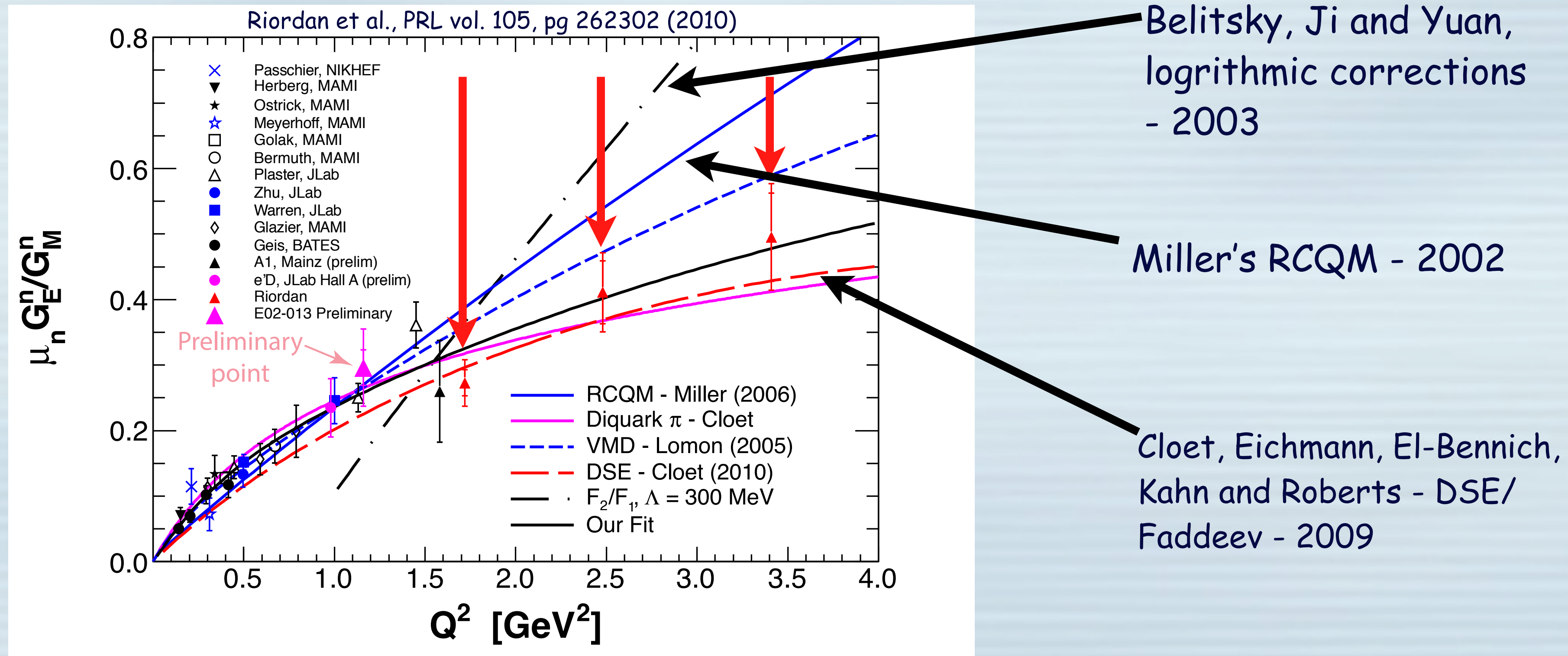
Indeed, that seems to be emerging from
the analysis of GPDs such as they are
known at present.

"GEn-I" - the first JLab experiment to measure G_E^n/G_M^n using polarized electrons and a polarized ^3He target



- The experiment measured double-polarization asymmetries in $^3\text{He}(\vec{e}, e'n)pp$
- The electron arm used Big Bite, an open geometry spectrometer using a single dipole, with a detector package that looked directly at the target.
- It also used a high luminosity polarized ^3He target, with a figure of merit more than 10x higher than E142 that measured the neutron spin structure.
- The neutron detector was, I believe the world's largest at that time.

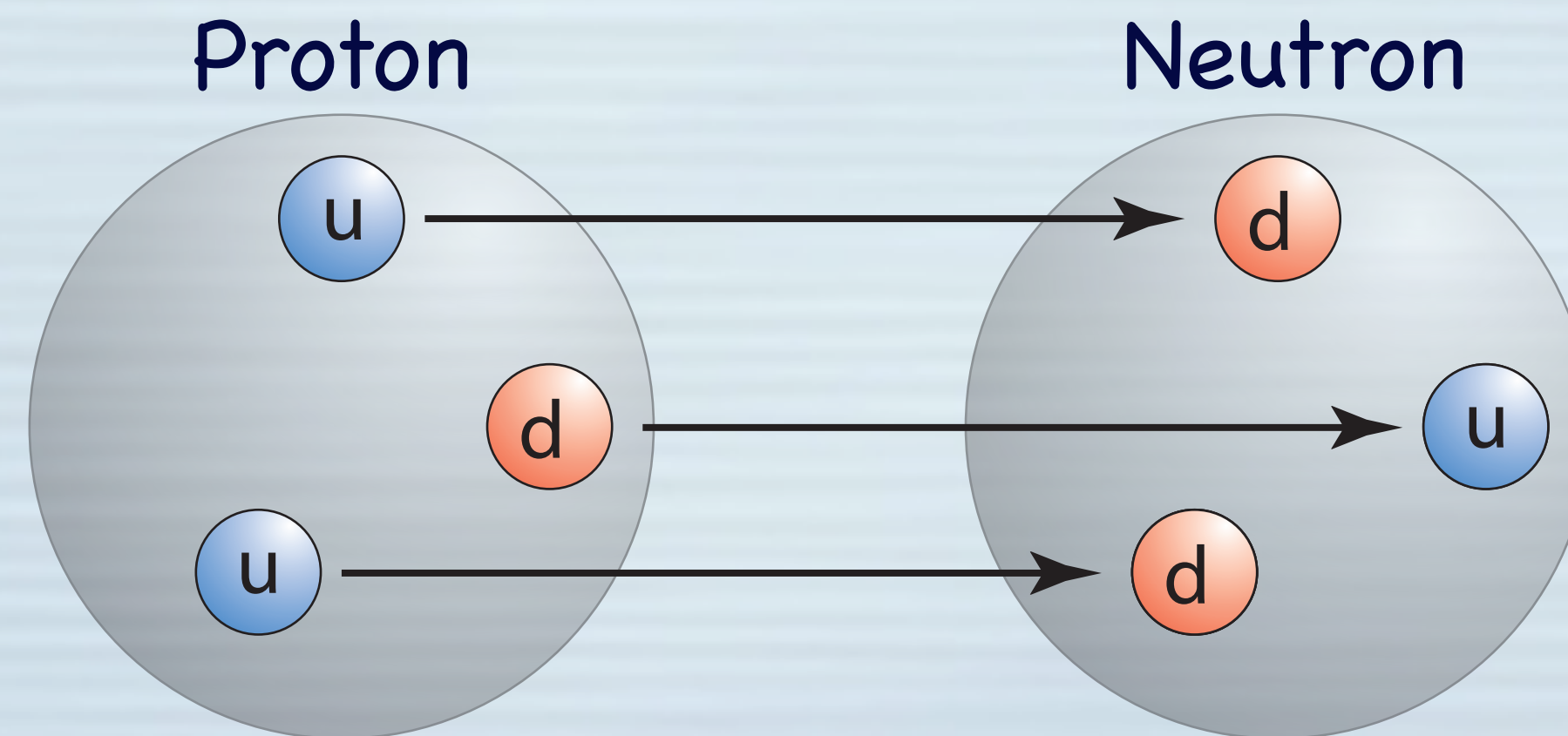
Data from the Hall A polarized ^3He experiment (E02-013) extended knowledge of G_E^n to high Q^2



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

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.



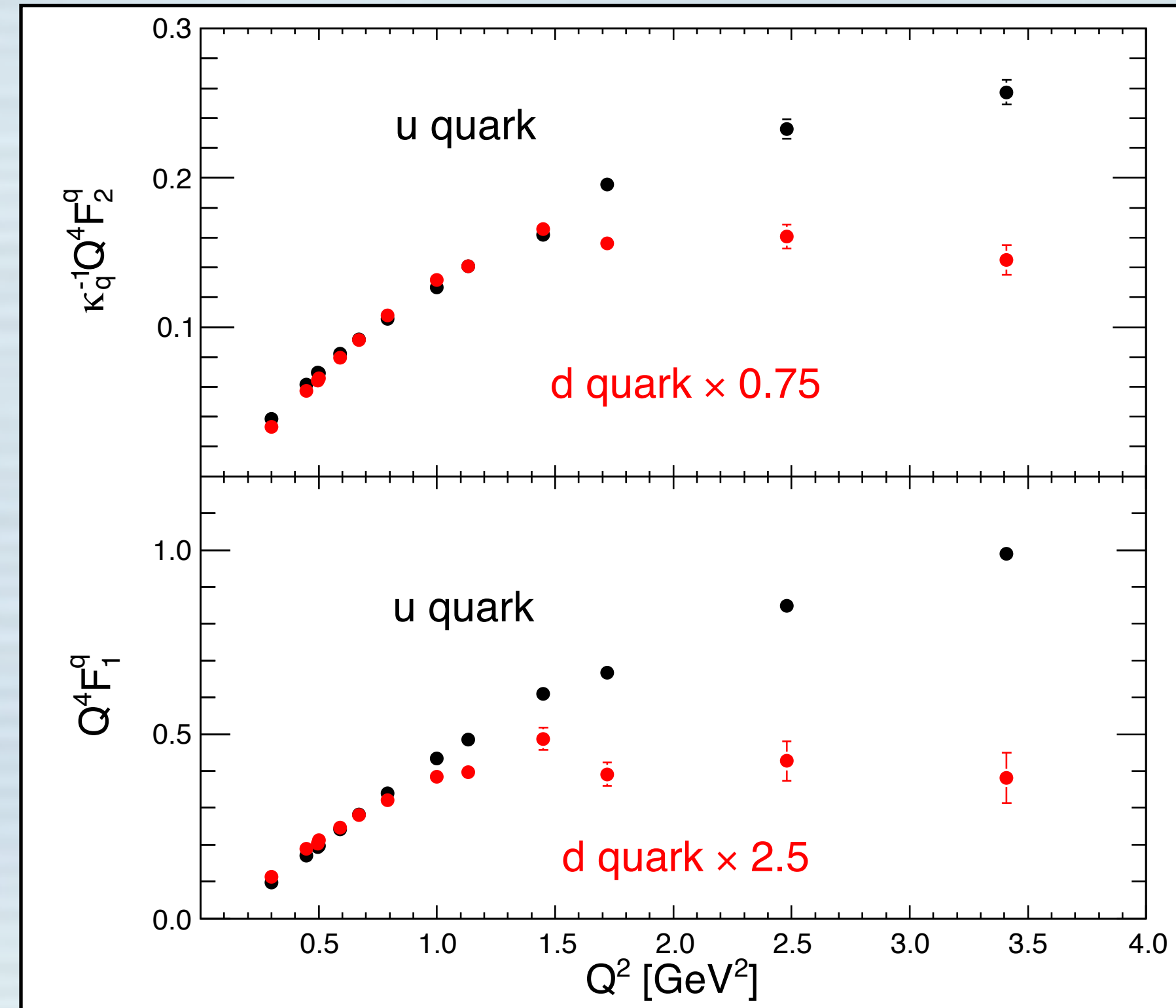
For the Dirac form factors (and similarly for the Pauli form factors):

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

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

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

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

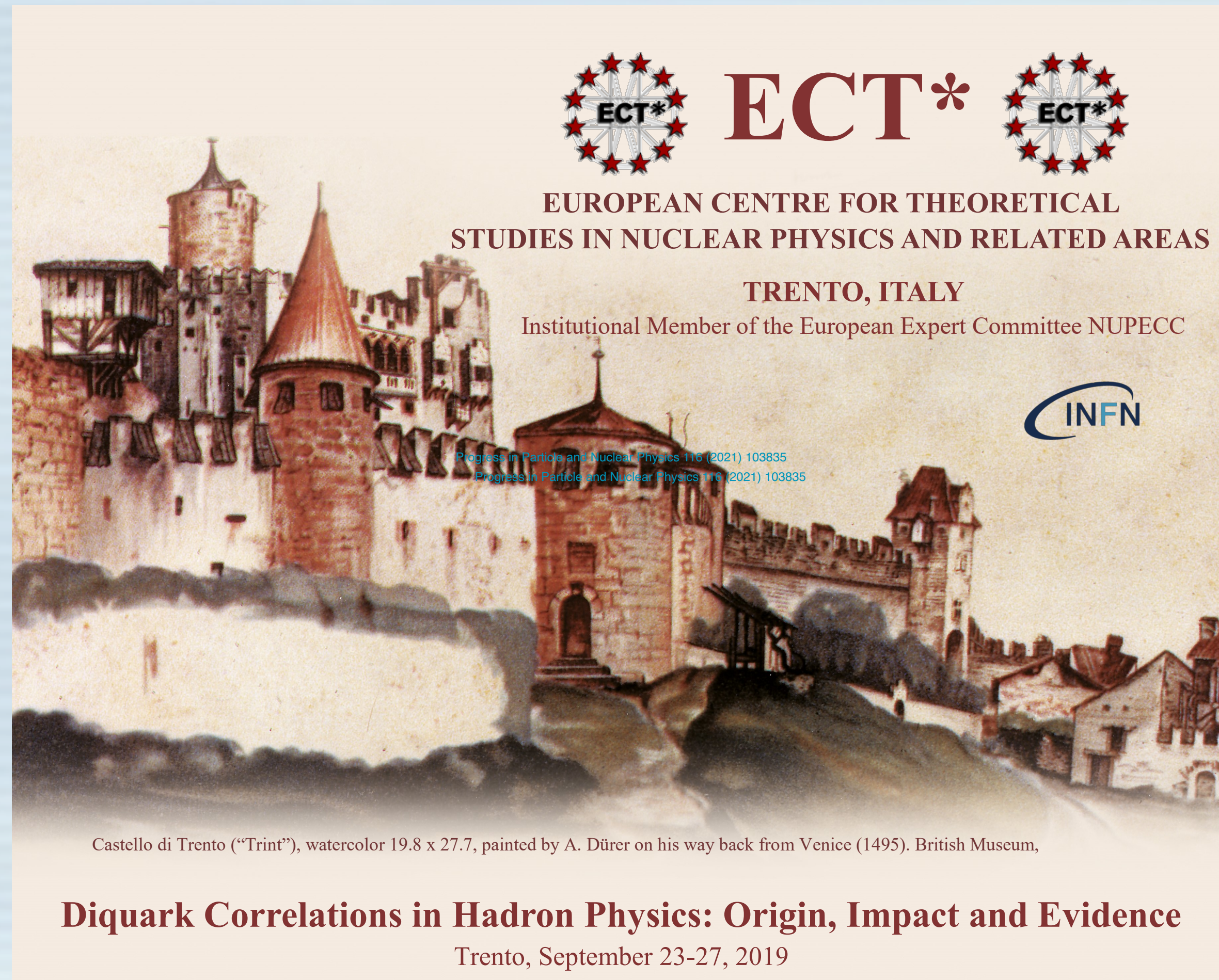


$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n \quad \text{and} \quad F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p$$

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)

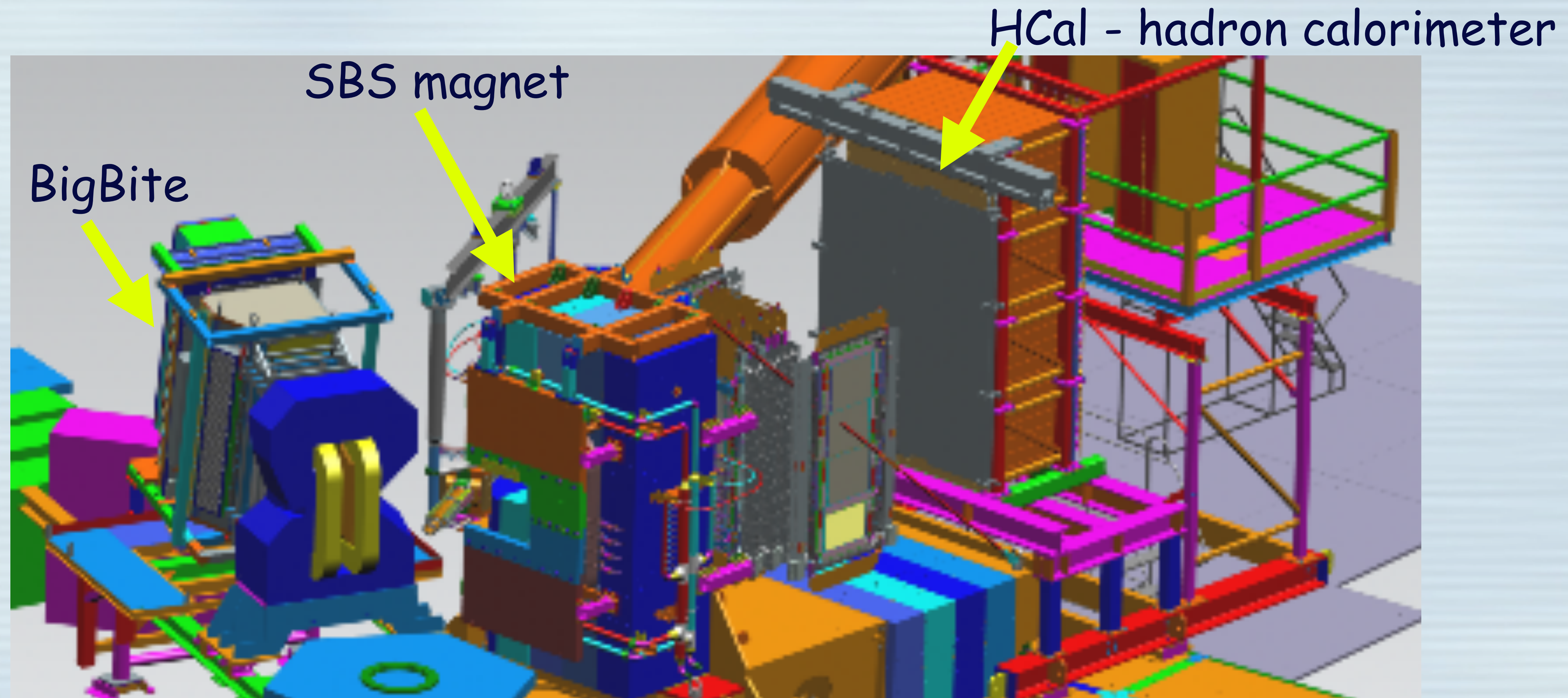


Review article grew out of the workshop: "Diquark Correlations in Hadron Physics: Origin, Impact and Evidence", Progress in Particle and Nuclear Physics 116 (2021) 103835".

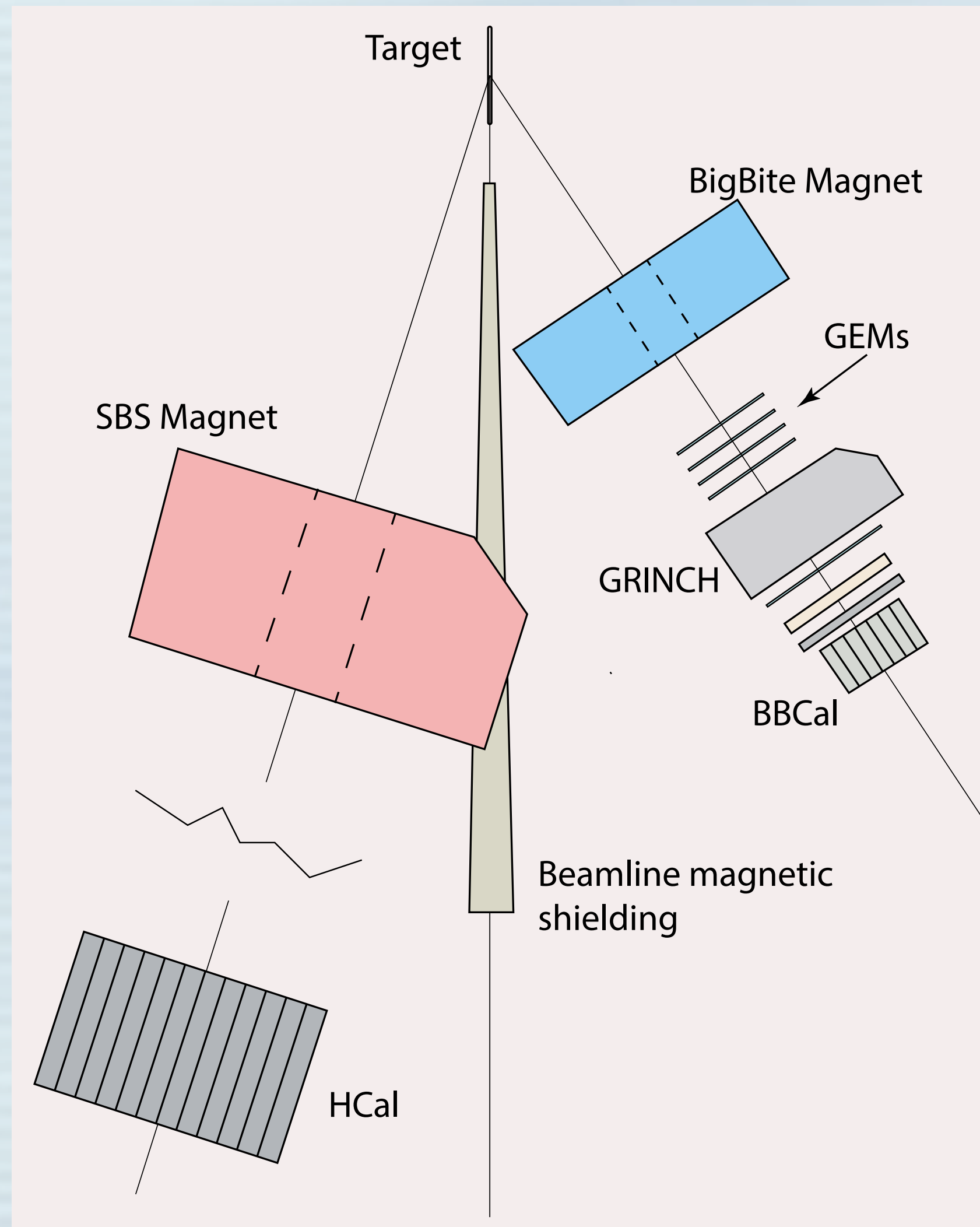
Nucleon form factors in the JLab 12 GeV era

The Super Bigbite Spectrometer (SBS) program

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

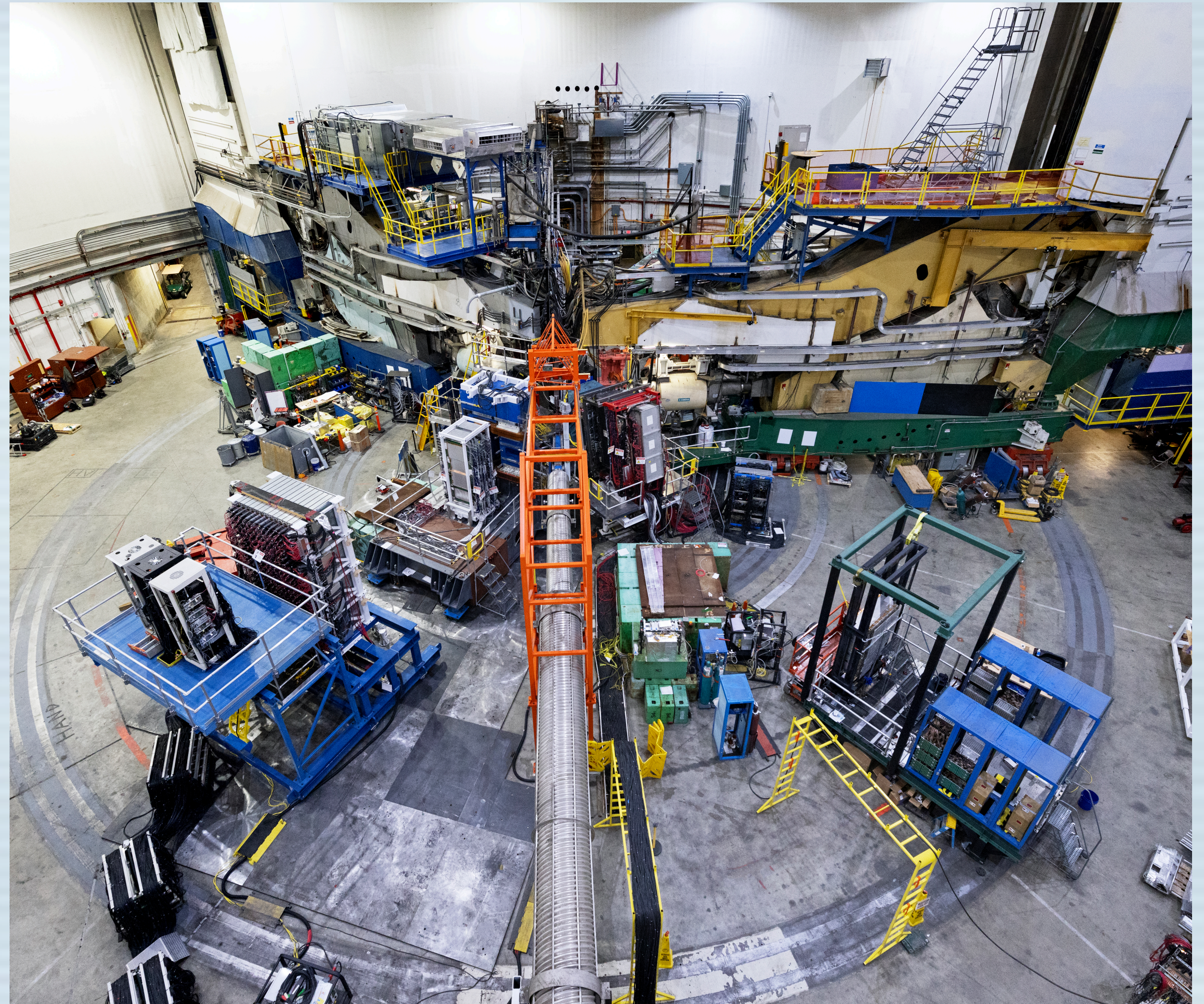
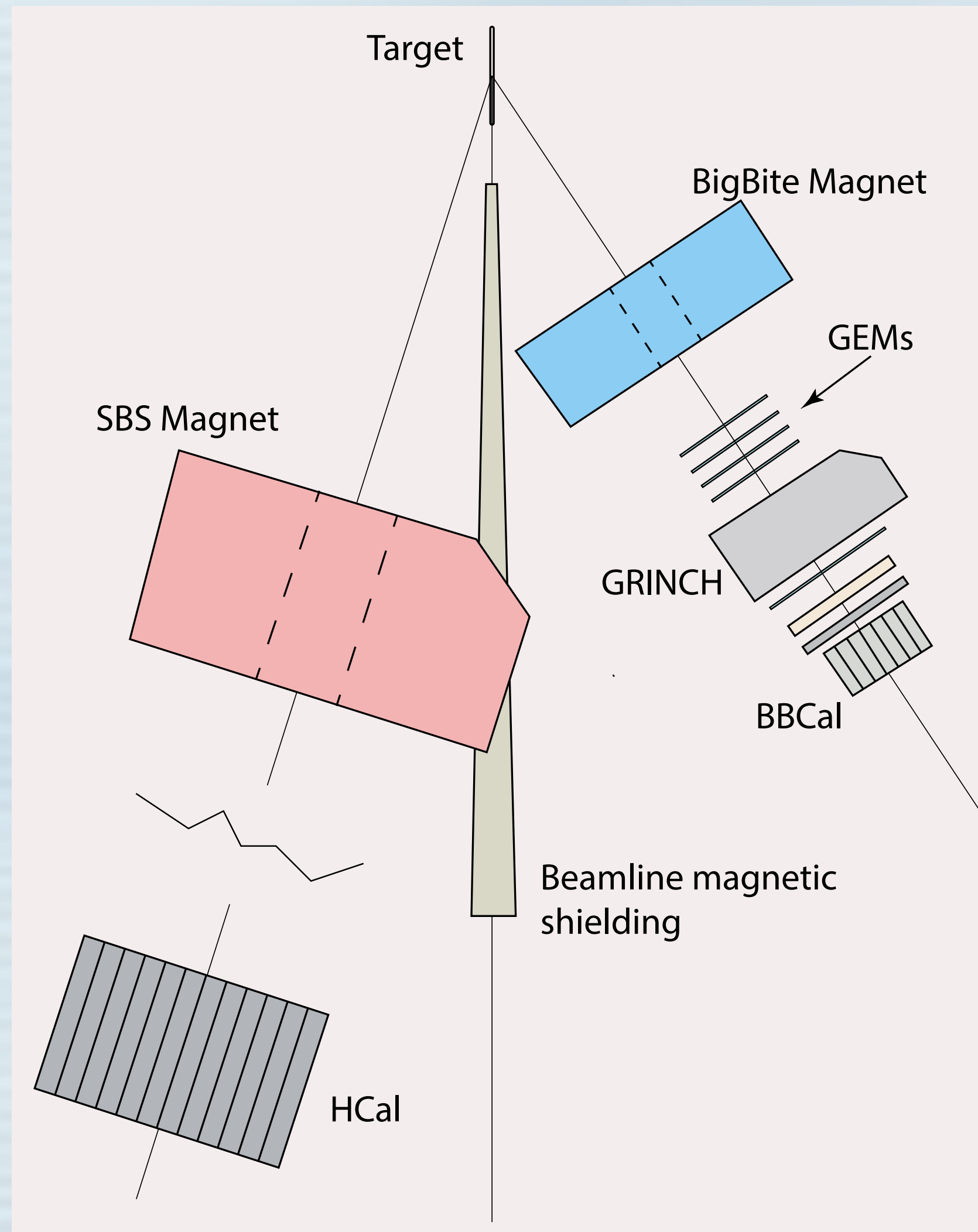


SBS for G_M^n , basically the same for G_E^n

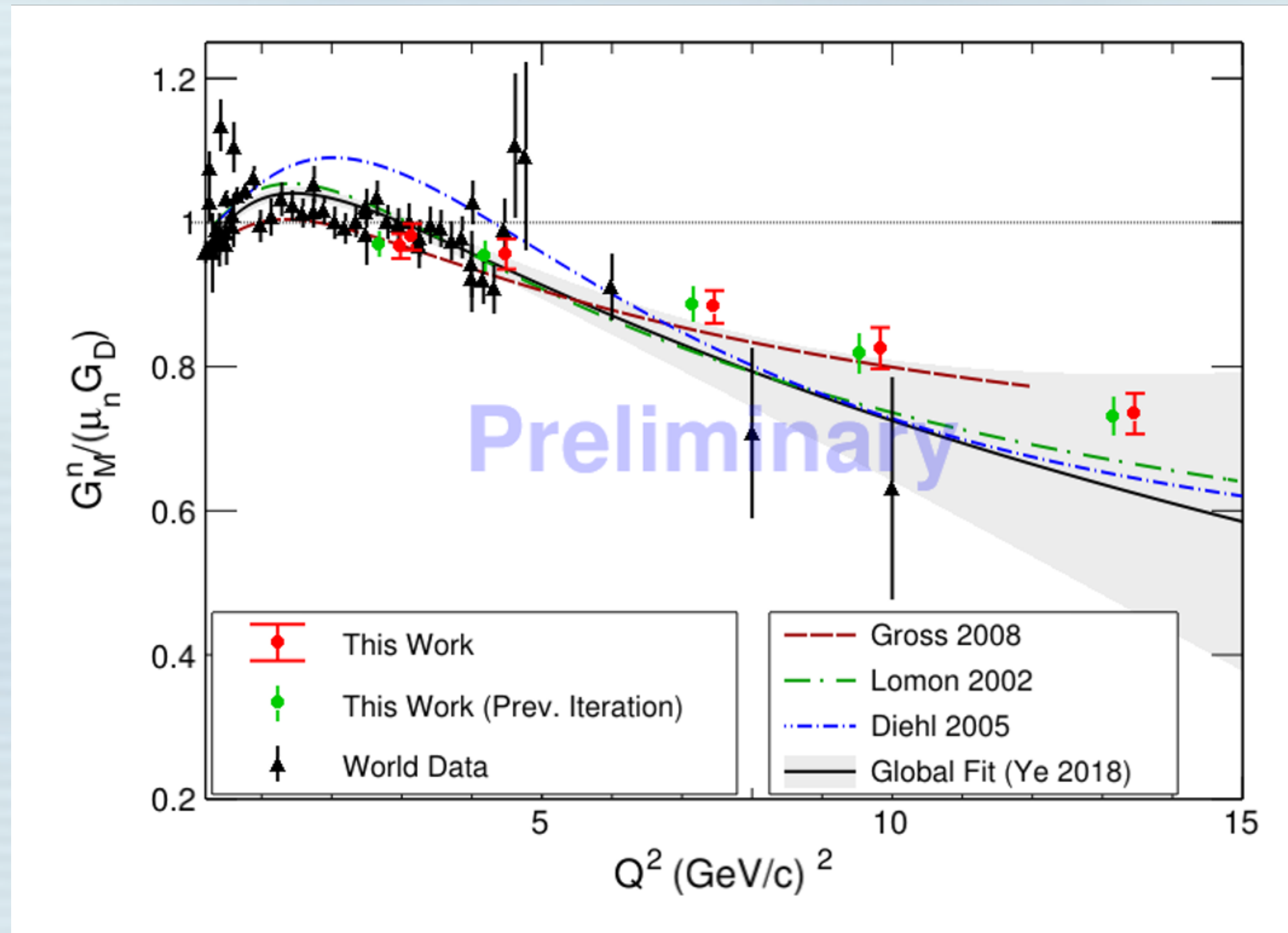


- Electrons detected by the BigBite spectrometer
- Gas Electron Multiplier (GEM) detectors allowed very high singles rates and $\sim 70\mu$ resolution.
- SBS magnet can operate at small angles and deflects protons but not neutrons enabling particle ID.
- Hadron Calorimeter (HCal) could operate at a relatively high threshold for detecting both protons and neutrons.
- Liquid deuterium target used for G_M^n
- Polarized ^3He target used for G_E^n

SBS for G_M^n , basically the same for G_E^n



Preliminary results from SBS for G_M^n

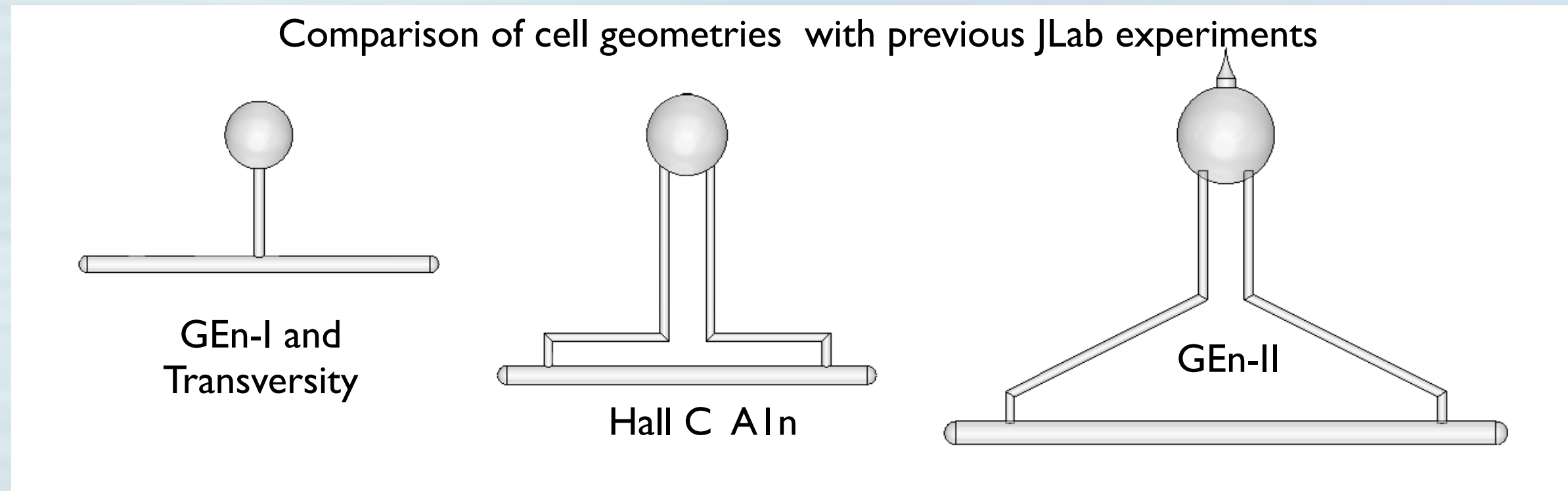


Used the "ratio method" based on directly comparing scattering cross sections for n and p using the same apparatus to measure G_M^n/G_M^p

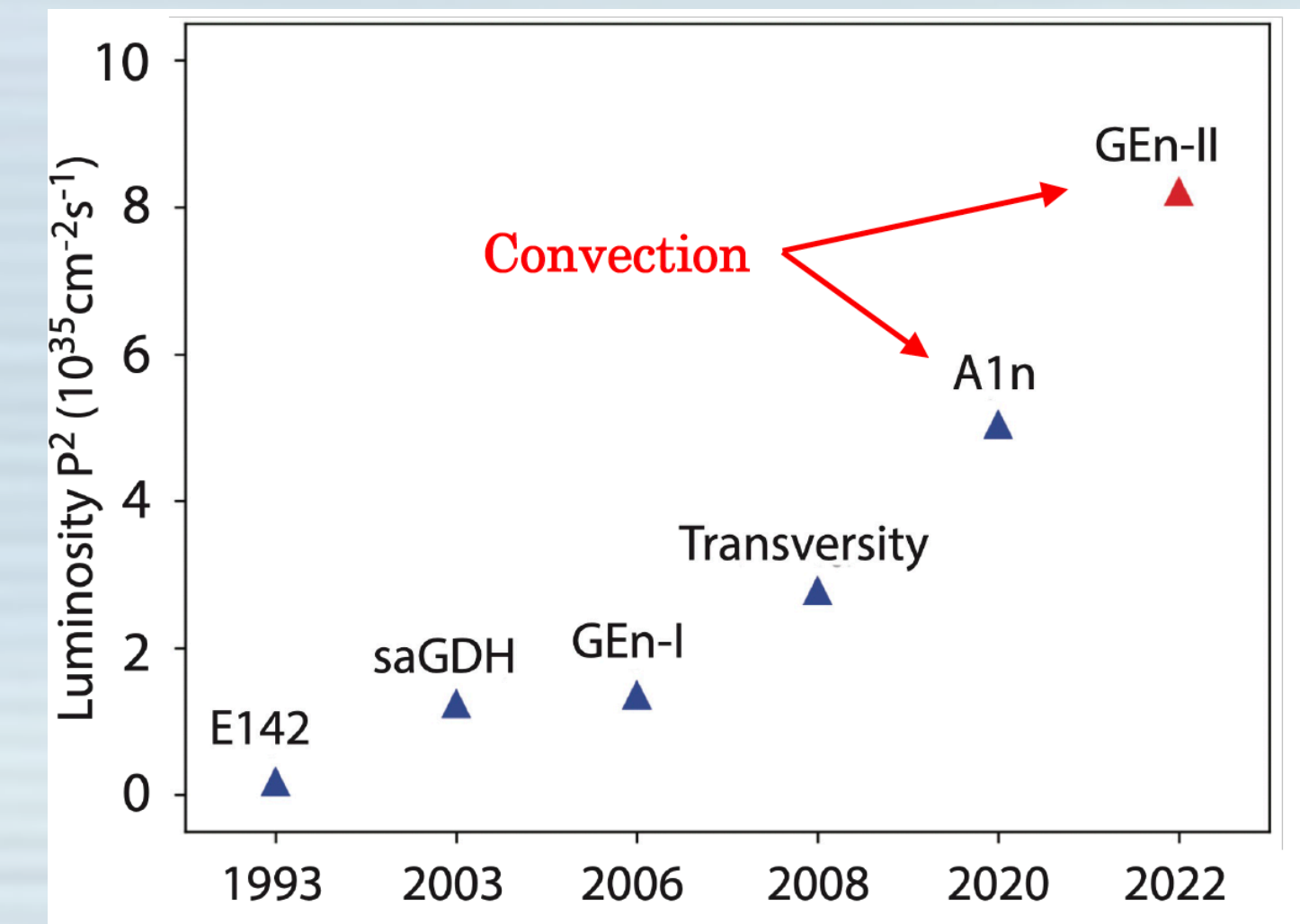
Slide at left from Andrew Puckett, analysis guru of the SBS program.

It really is a pretty stunning improvement of our knowledge of the magnetic form factor of the neutron.

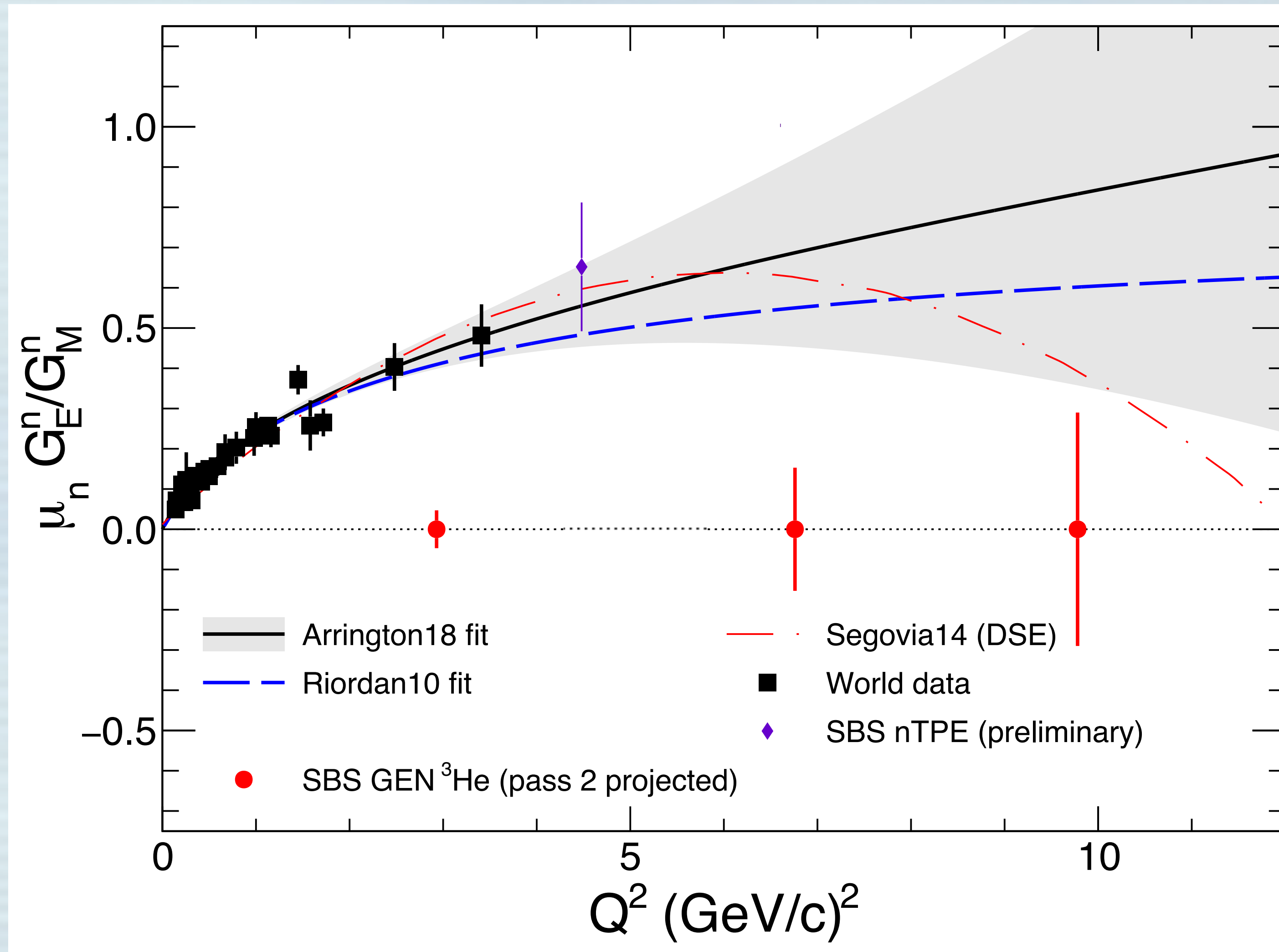
The polarized ^3He target for GEn-II



- Designed to handle luminosity more than two times higher than the polarized ^3He target used for the Hall C A1n exp.
- Target cells contain twice the volume of ^3He of previous target cells & target chamber is 60cm in length rather than 40cm previously.
- Cells are illuminated from two directions.
- Magnetic shielding protects the target from the fringe fields of the large SBS magnet.



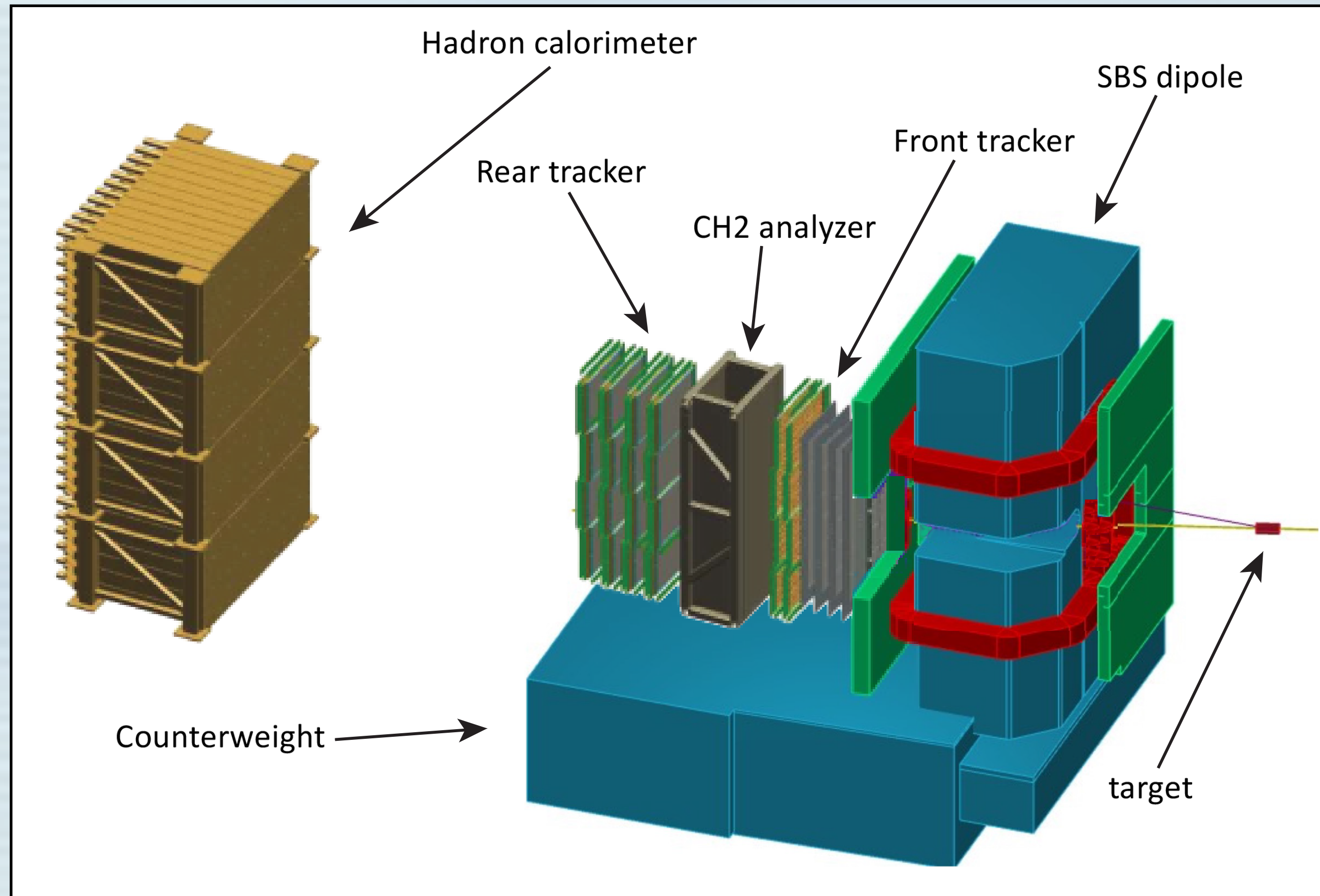
Current (2nd/3rd pass) errors for SBS for G_E^n



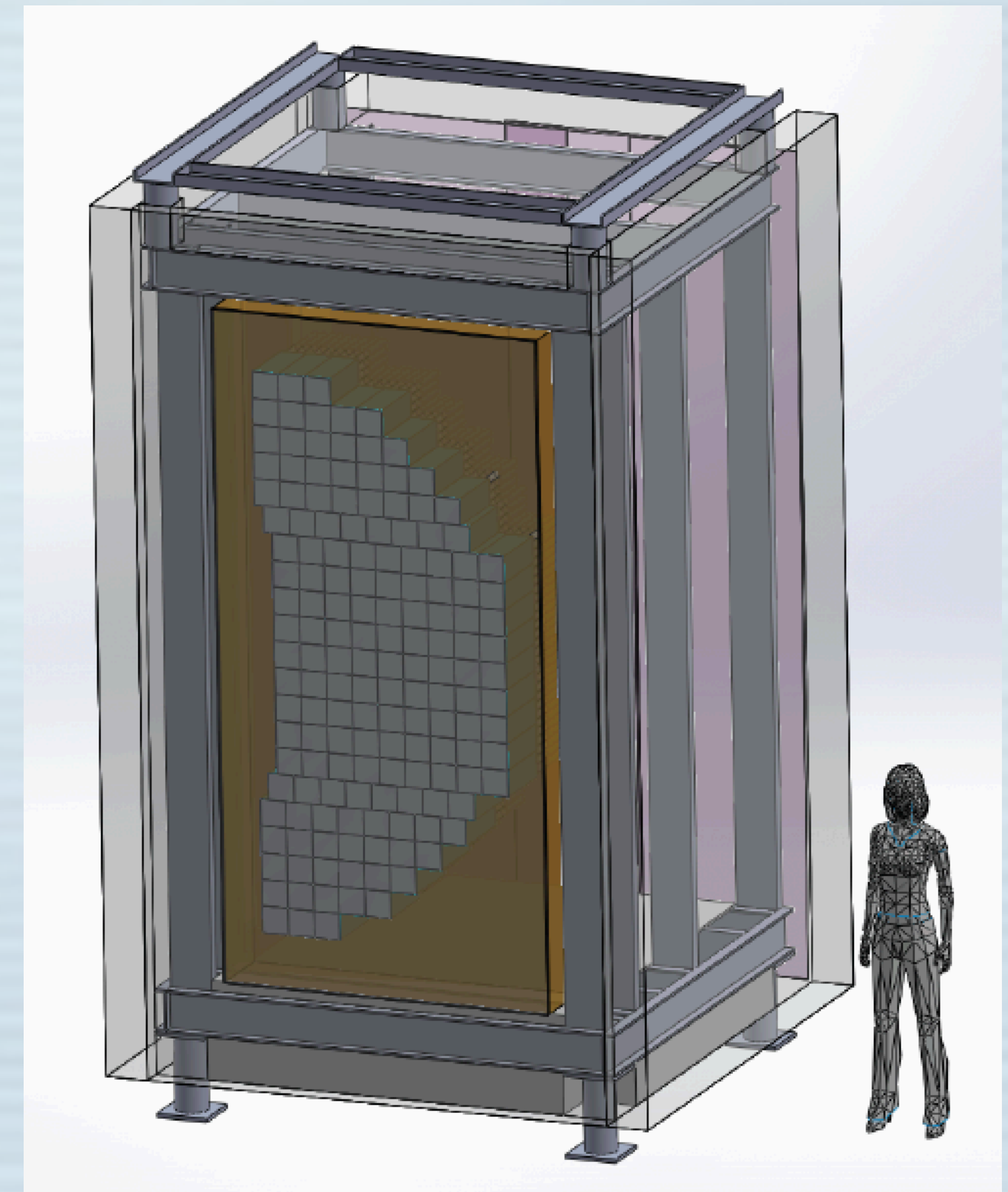
- Errors shown are based on analyzing a combination of the 2nd and 3rd replay of the data.
- Errors shown are those in Vimukthi Gamage's thesis, the 3rd thesis to give results.
- We have had significant improvement in our errors with each successive analysis.
- Our final errors could be up to a factor of $\sim 2^{1/2}$ smaller than the errors shown.



The SBS GEp experiment

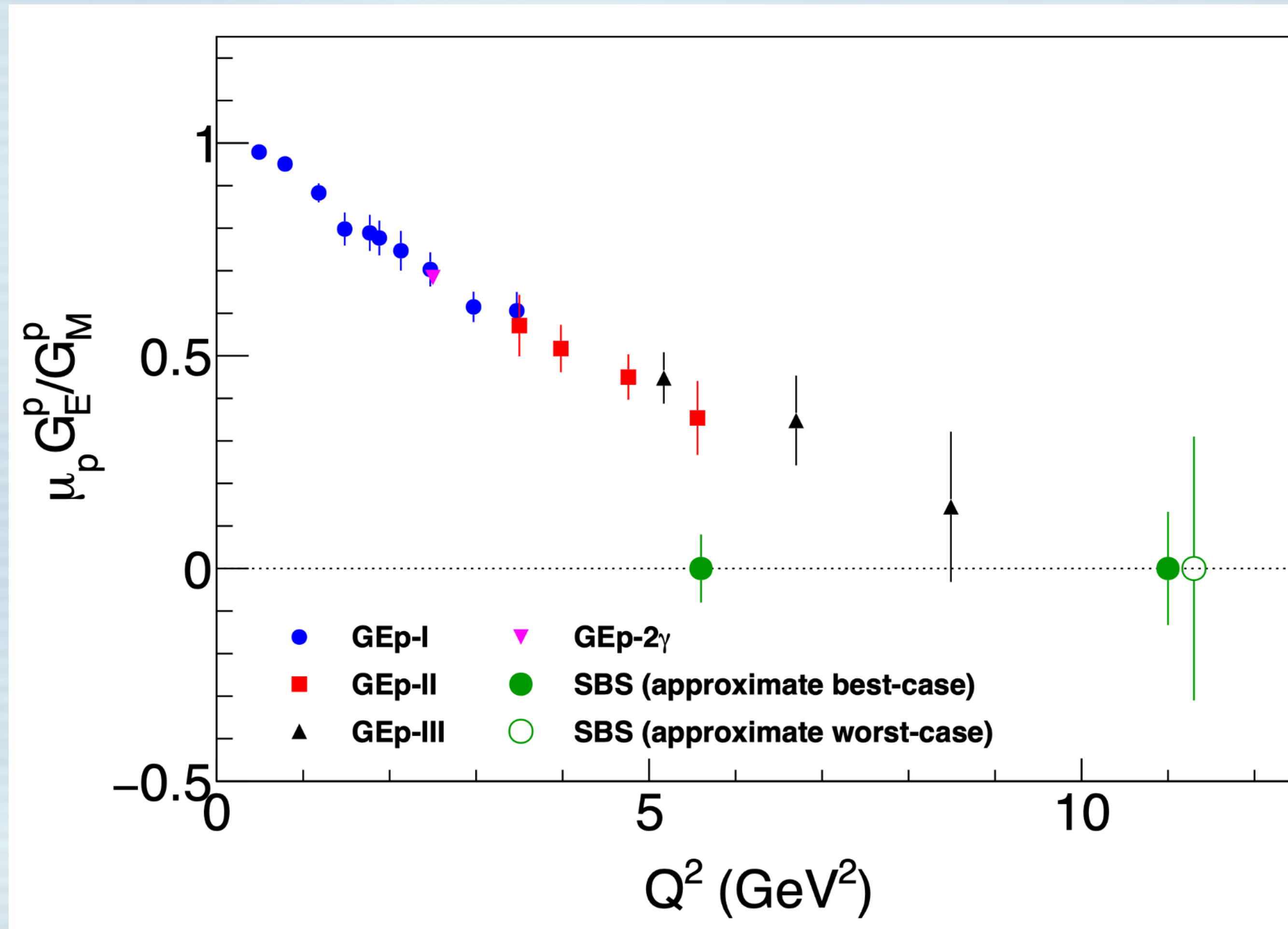


The hadron arm for the SBS GEp experiment



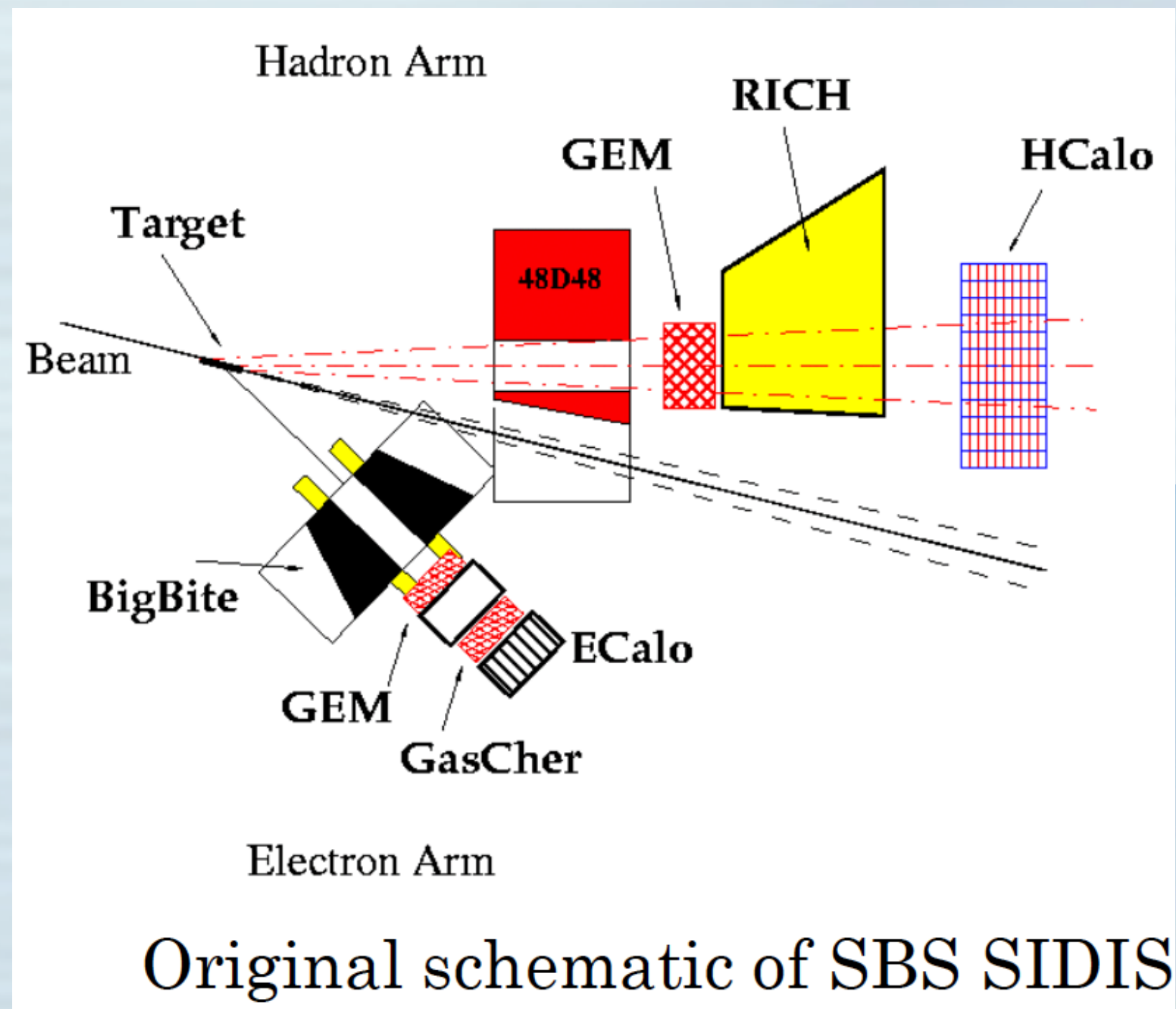
The electron arm of the SBS GEp experiment: ECal - electron calorimeter

Early error projections for the SBS GEp experiment



SBS SIDIS Experiment with a transversely polarized ^3He target

The SBS SIDIS experiment

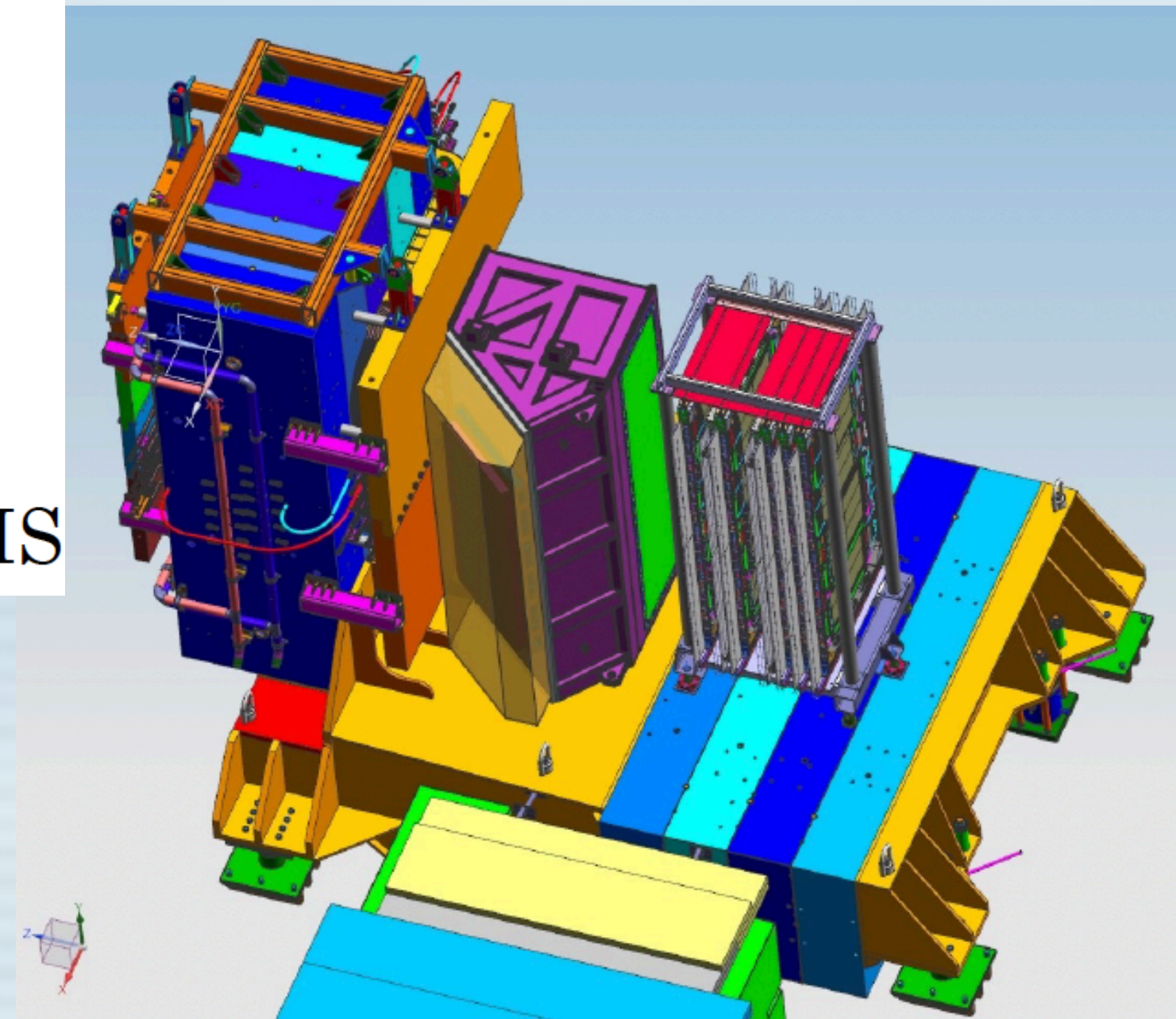


$$^3\vec{H}e(e, e', \pi^+)X$$

$$^3\vec{H}e(e, e', \pi^-)X$$

$$^3\vec{H}e(e, e', K^+)X$$

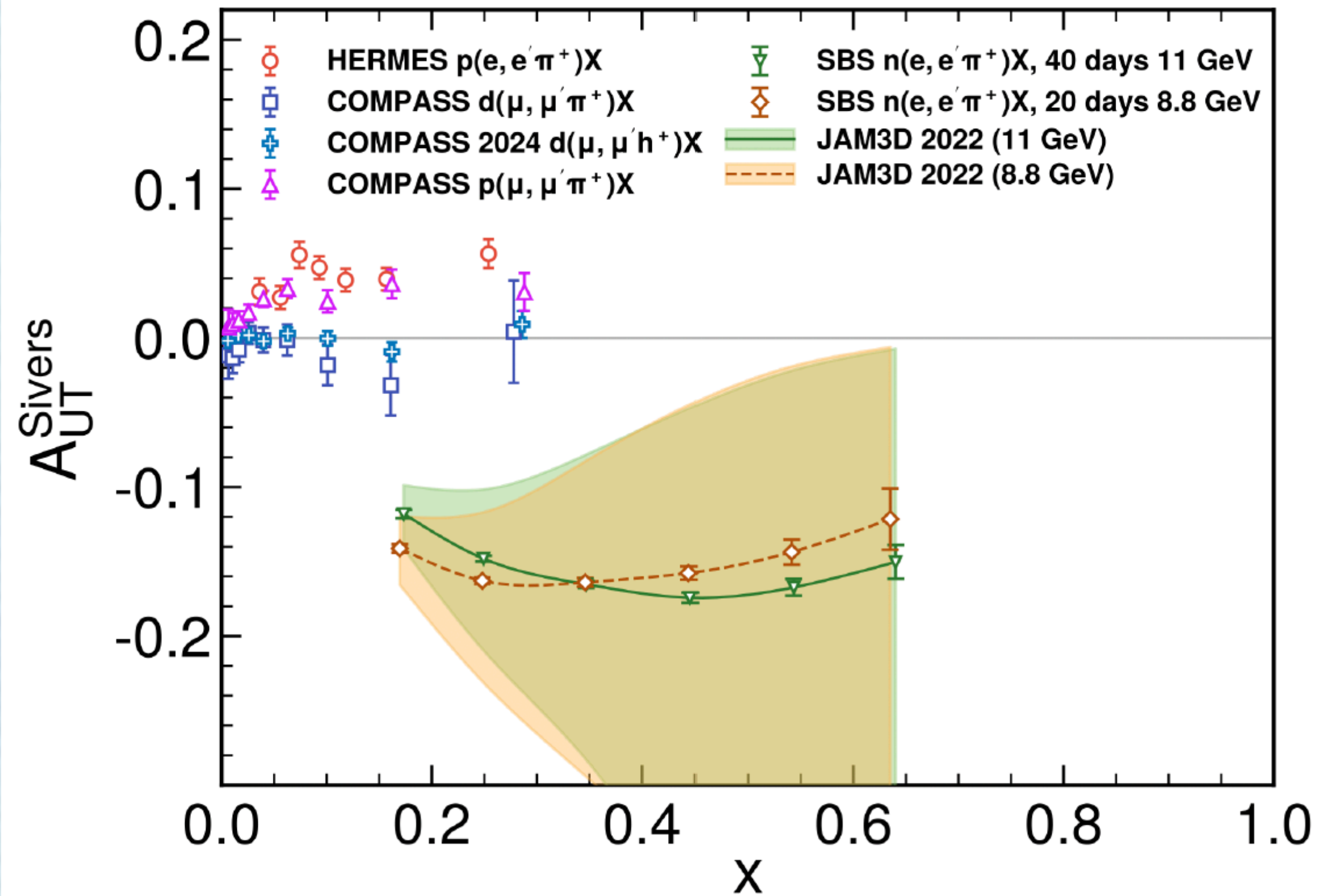
$$^3\vec{H}e(e, e', K^-)X$$



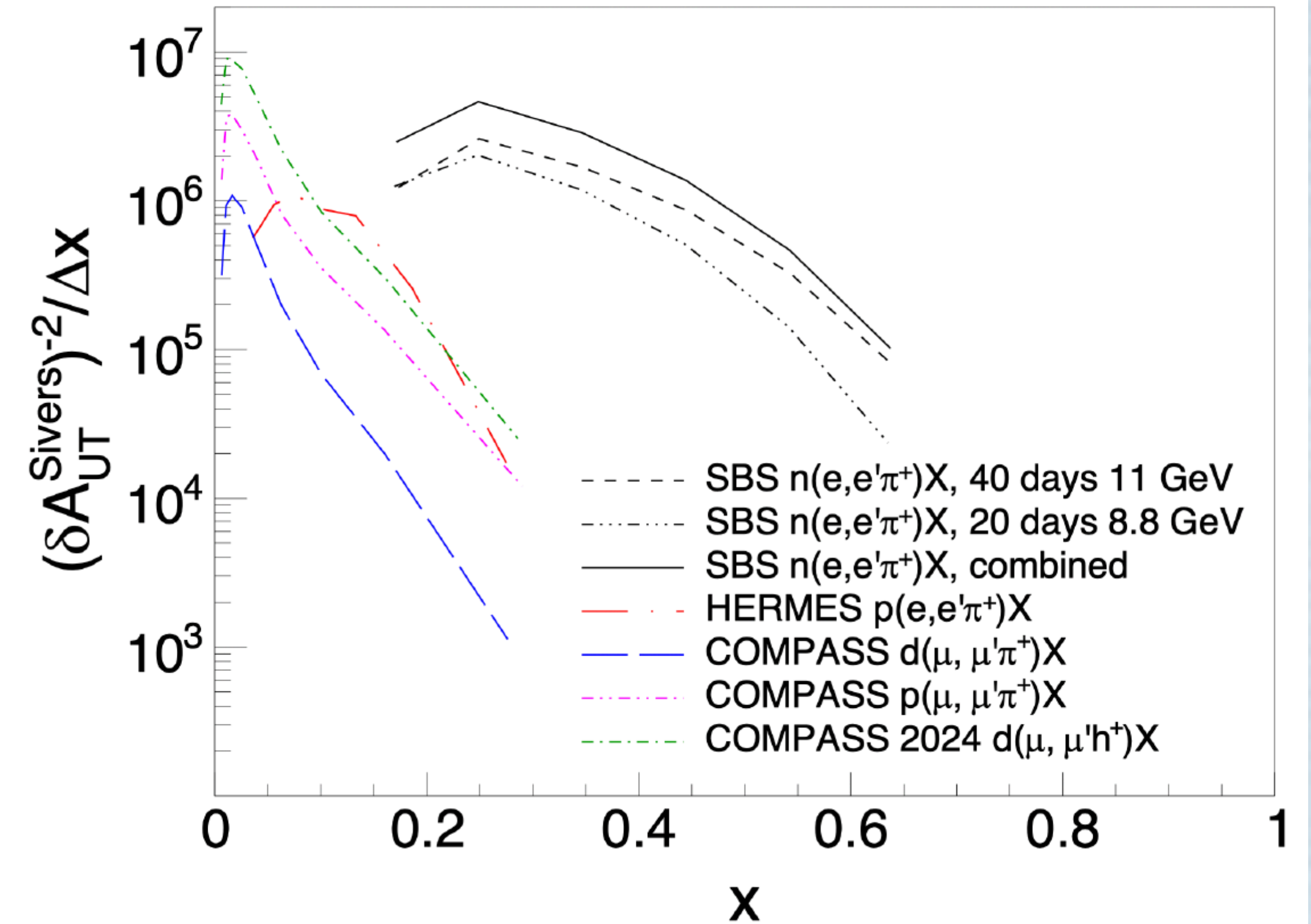
Detail of hadron arm

- Will measure single-spin asymmetries with a transversely polarized target
- Similar setup to the SBS GEn and GMn experiments.
- Will use the HERMES RICH for particle ID.
- Will acquire 10-100 times greater statistics than HERMES or COMPASS
- Kinematics focussed on high- x range.
- Scientific rating just upgraded to A

Example of projected results: A_{UT}^{Sivers} for $\vec{n}(e, e', \pi^+)X$

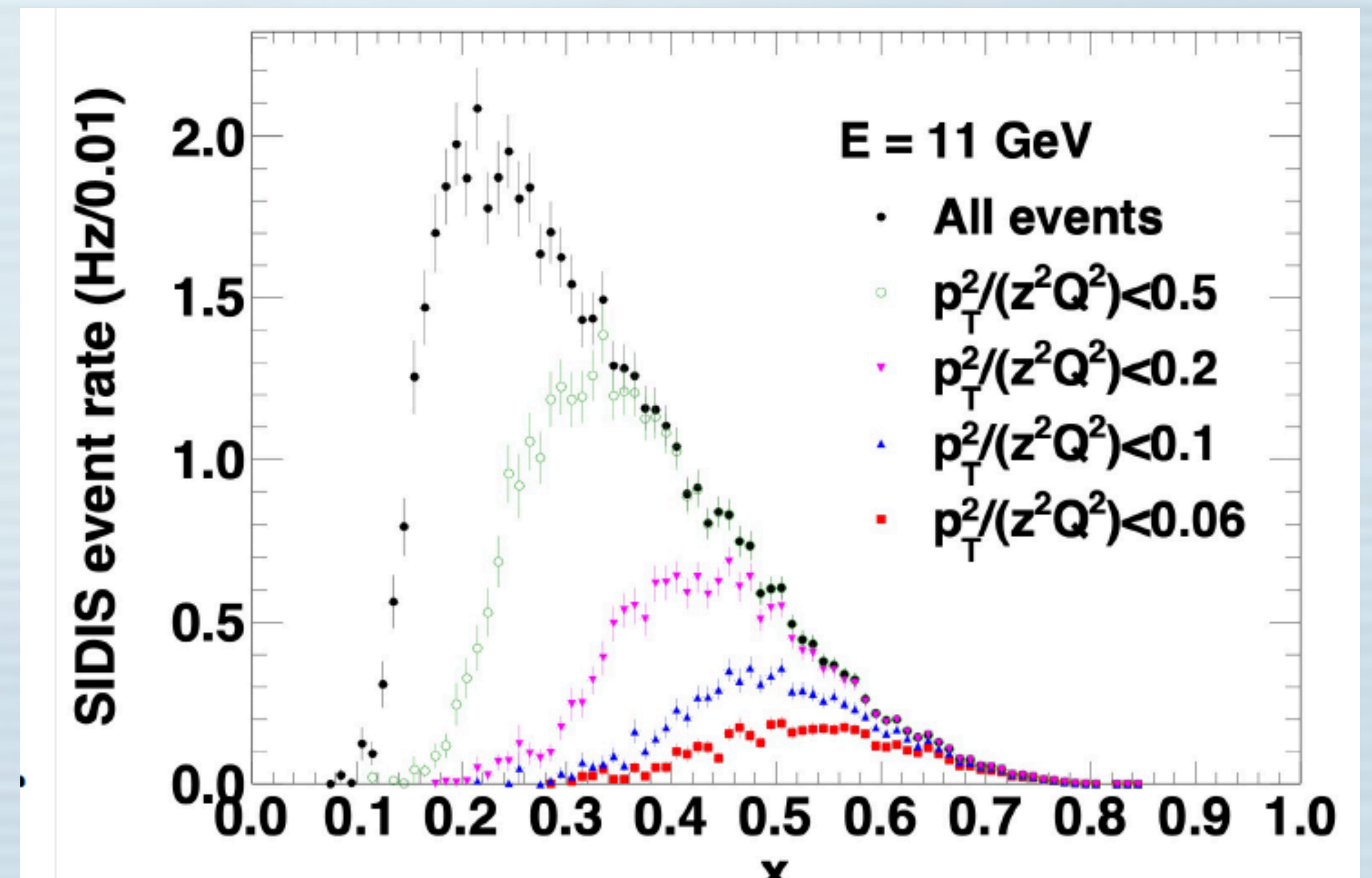
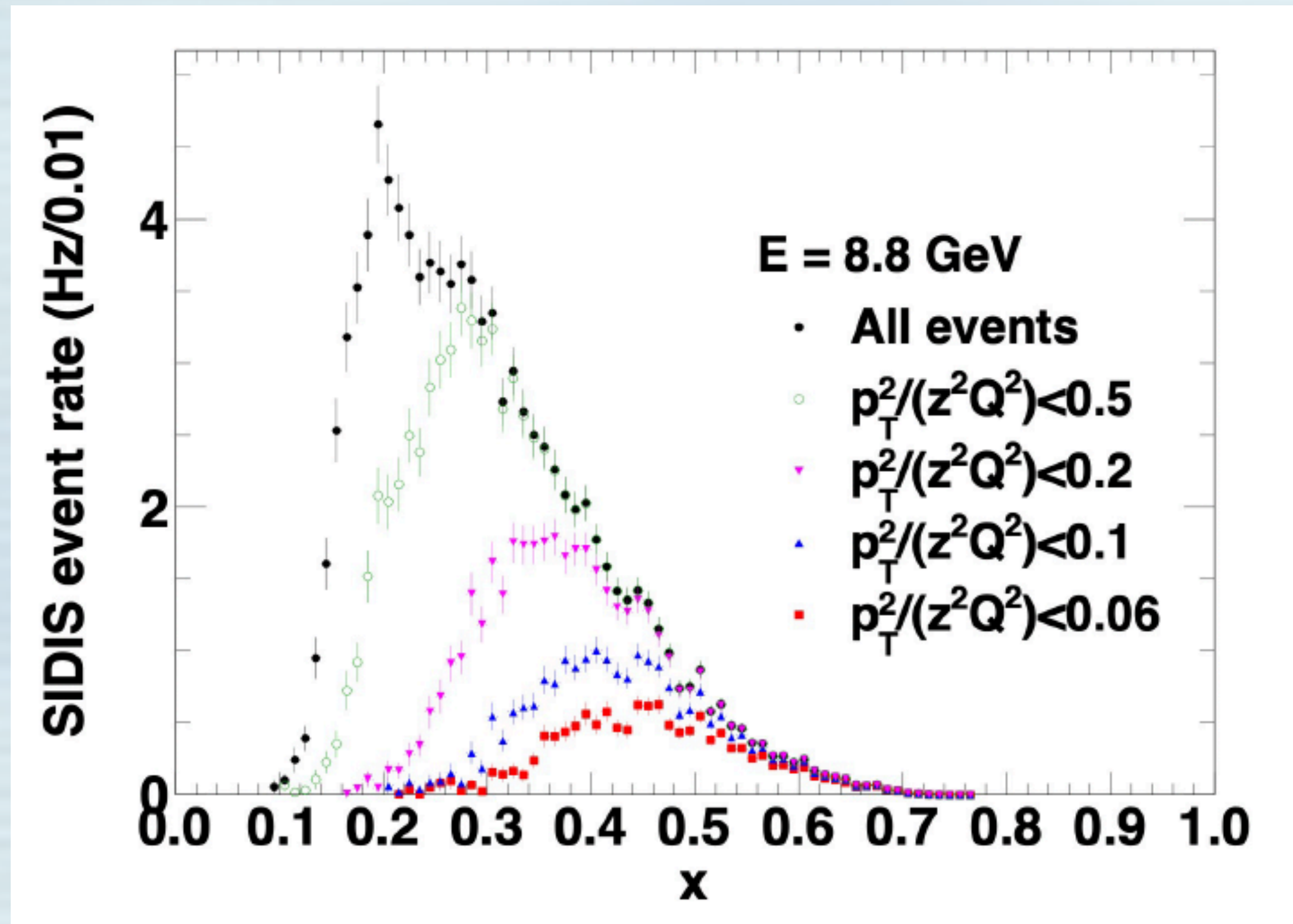


Example comparison of E12-09-018 projected neutron Sivers asymmetry to HERMES and COMPASS published data (including COMPASS 2022 deuteron data for unidentified charged hadrons)

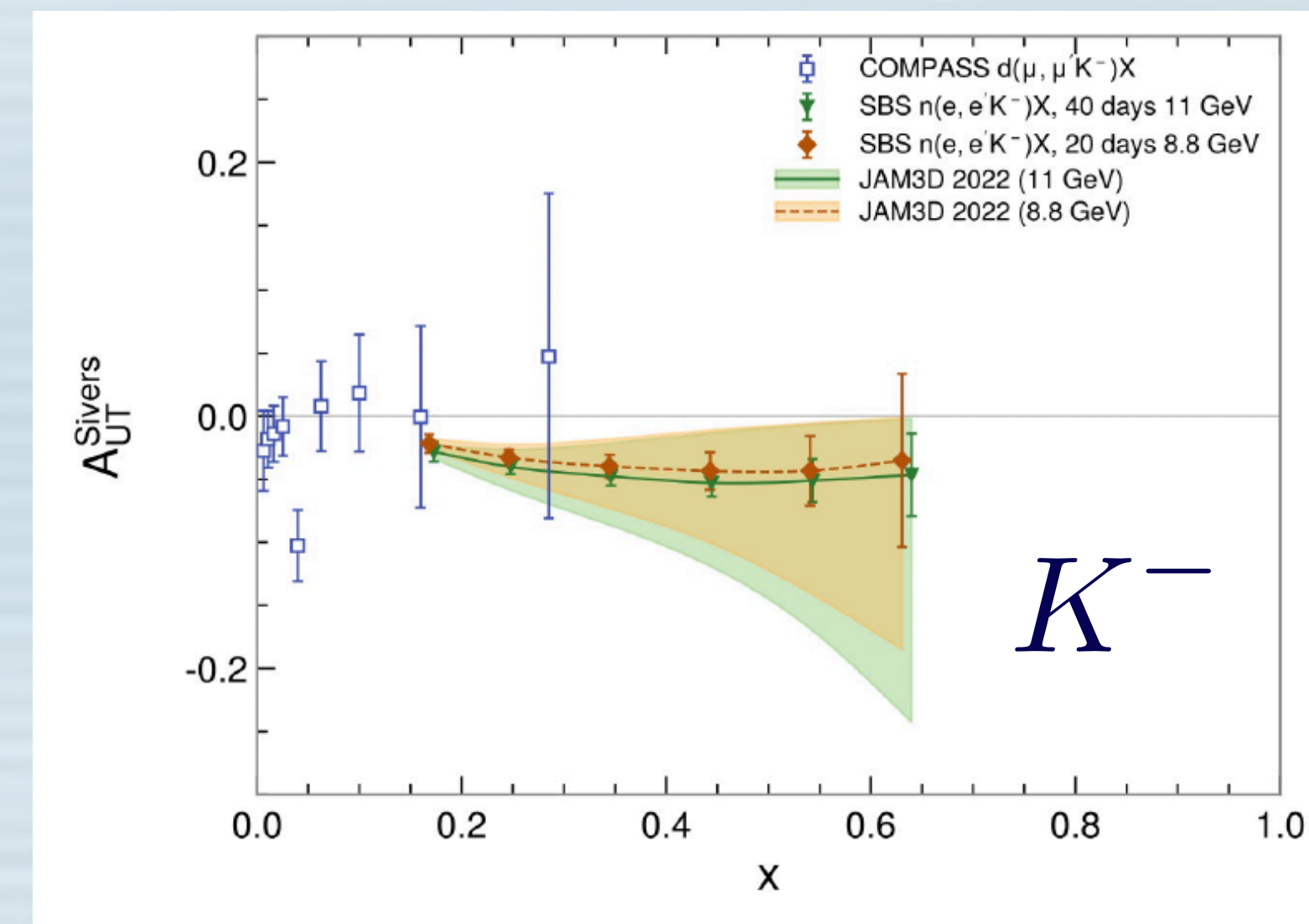
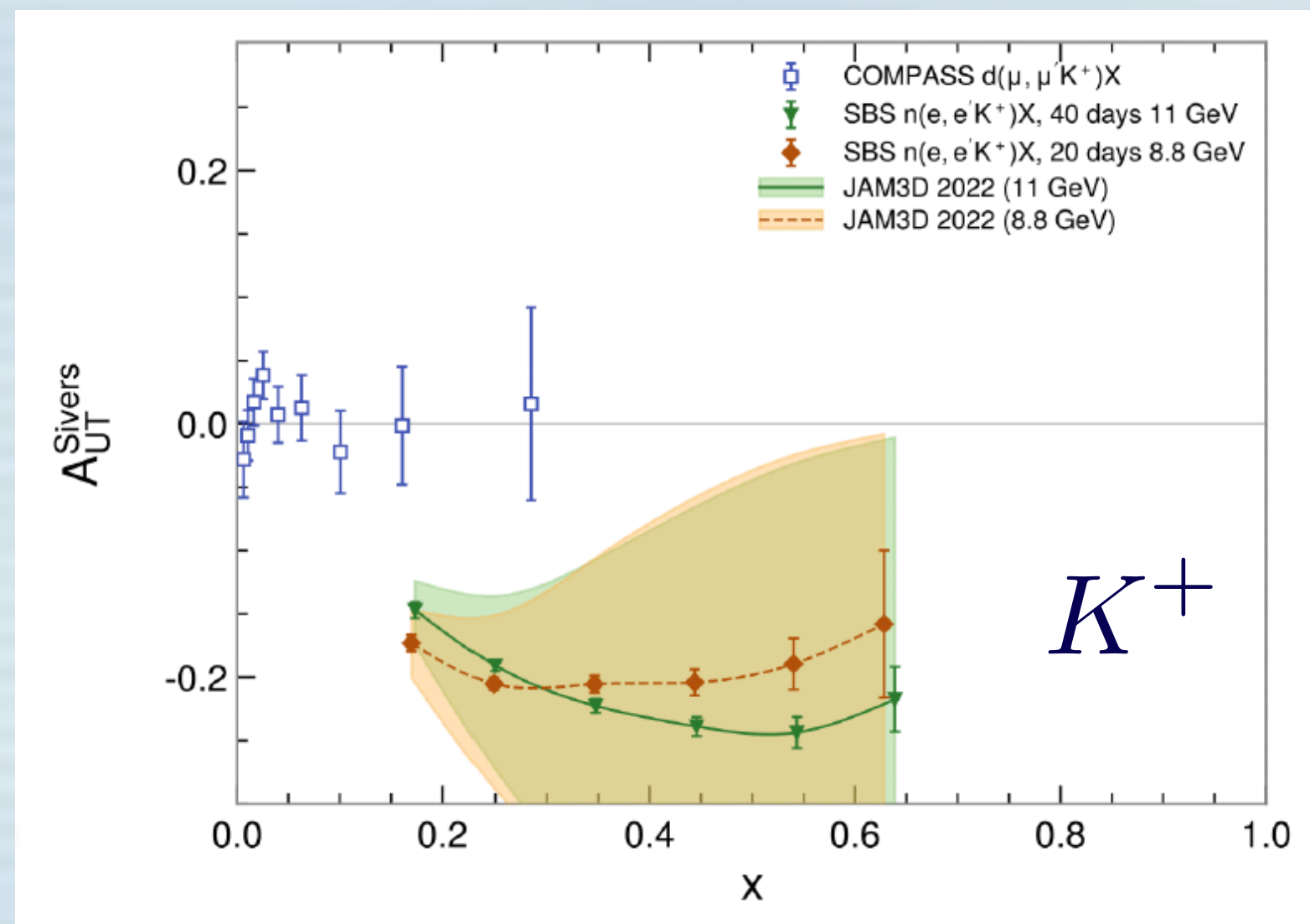
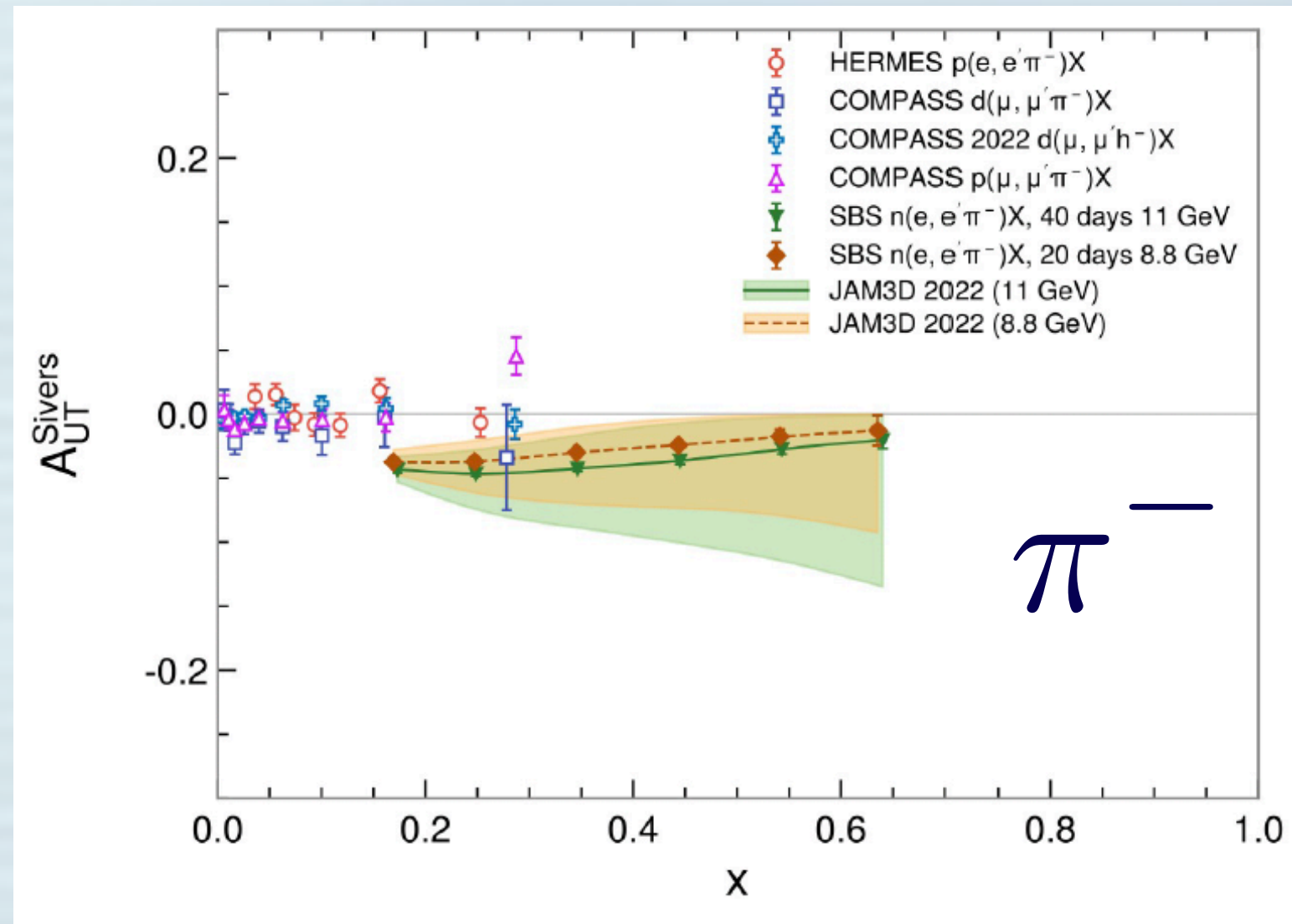


Same as left, plotted as statistical Figure-of-Merit (FOM) per x interval.

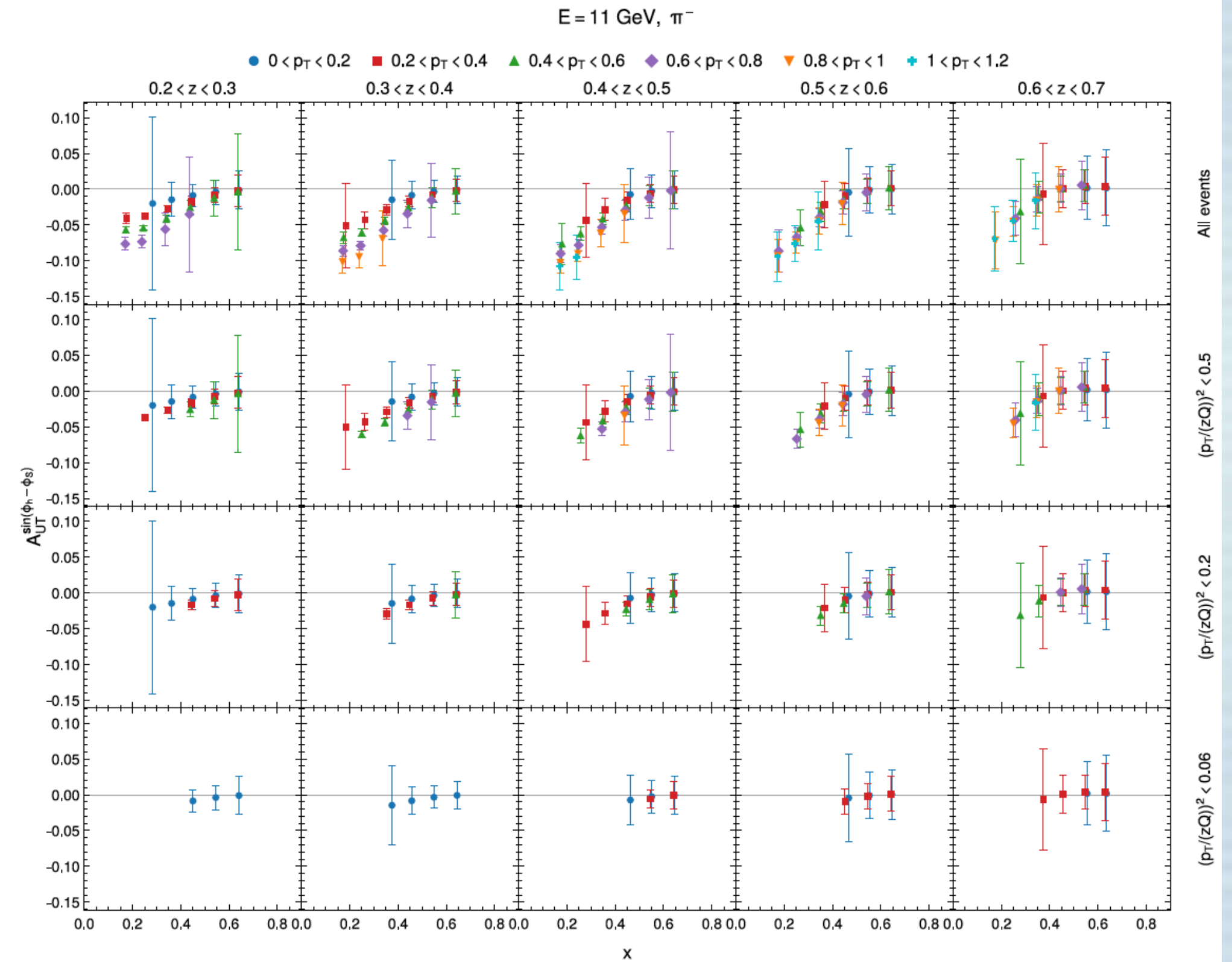
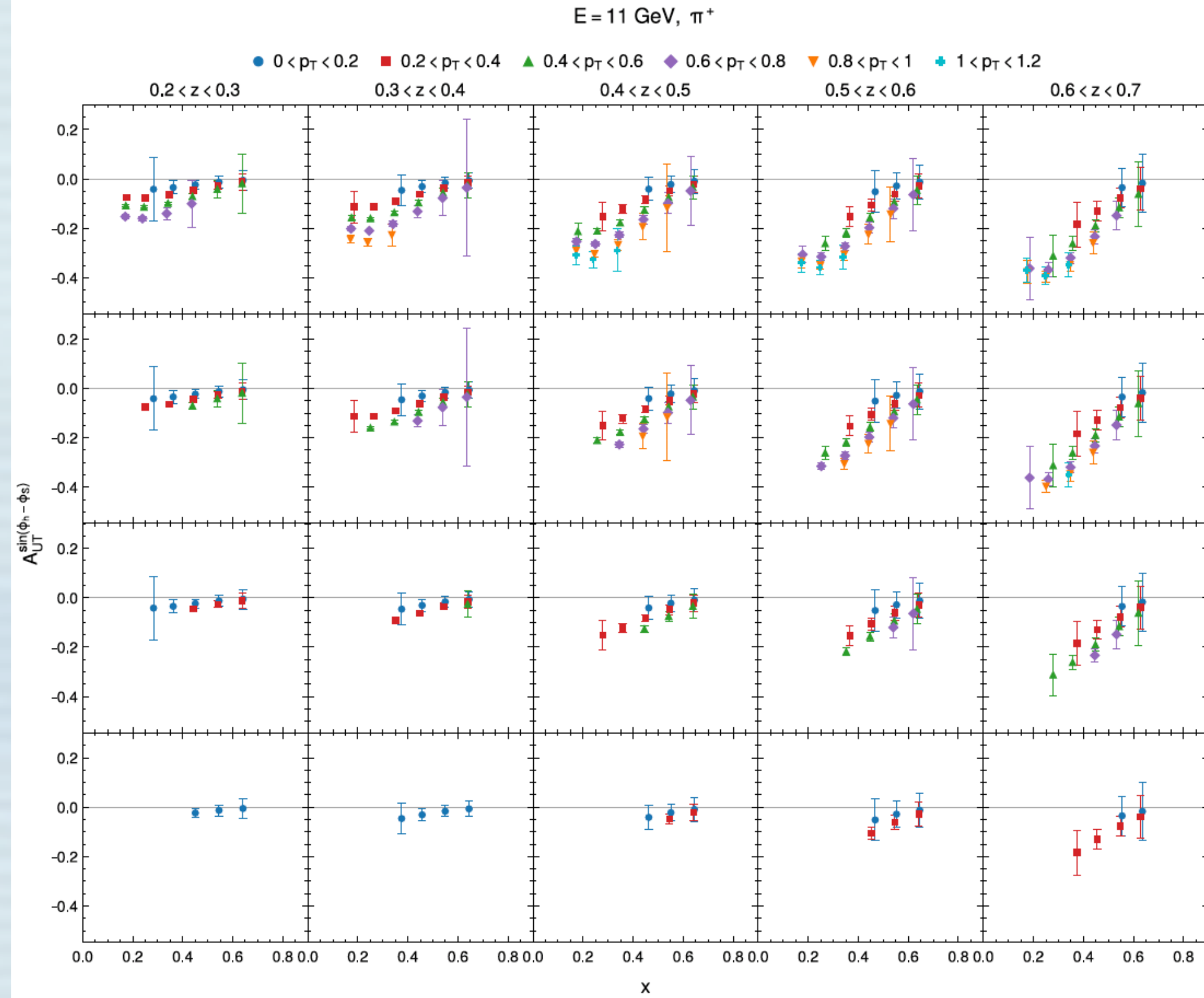
Coverage for $p_T^2/(z^2Q^2)$



Other hadrons



Fully Differential Analysis, Effects of $\frac{p_T}{zQ}$ Cuts



Summary

- Big improvements coming on elastic nucleon form factors
- Significant increase planned in Sivers, Collins, etc. on neutron
- It's an exciting time for femtography !

