Spin Asymmetries of the Nucleon Experiment at Jefferson Lab

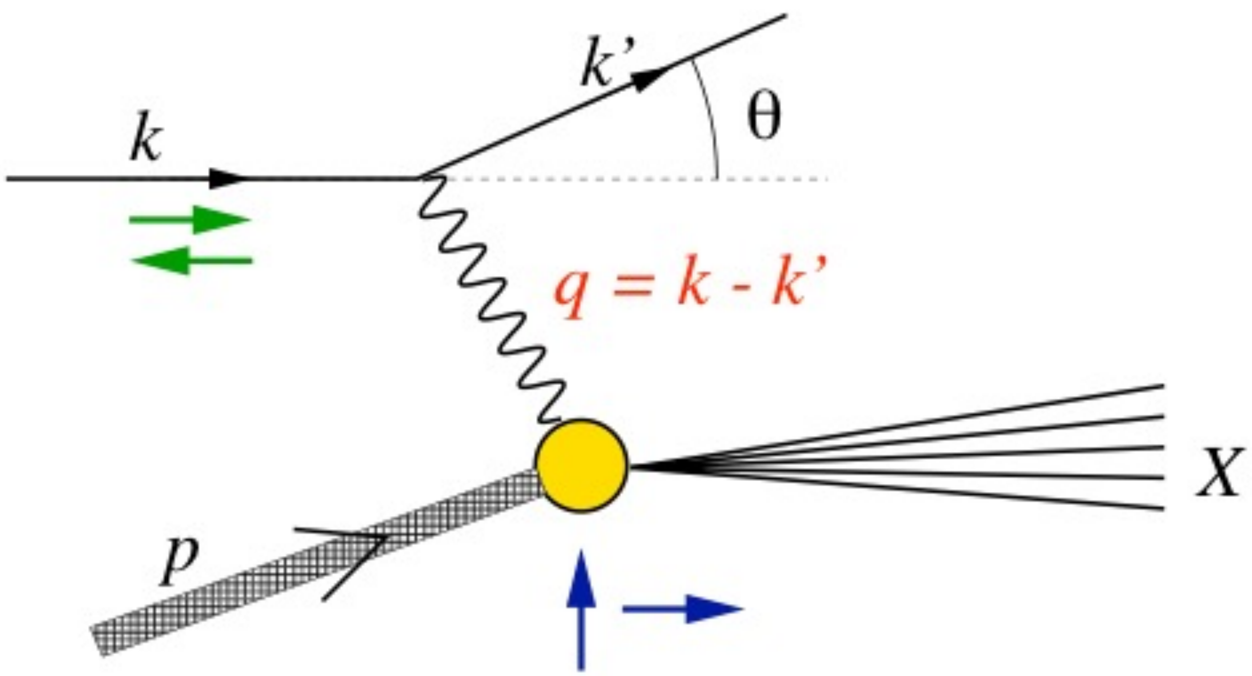
Seonho Choi
Seoul National University

APCTP Workshop
July 3, 2018
Pohang, Korea

Outline

- Polarized DIS and spin structure functions
- Moments of the spin structure functions
- Spin Asymmetries of the Nucleon Experiment
- Results on g_1, g_2 and d_2
- Summary

Inclusive e-N Scattering



- Four-momentum transfer

$$Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

- Energy transfer to the hadron

$$\nu = E - E'$$

- Mass of the hadronic residual (or invariant mass)

$$W = \sqrt{(p+q)^2}$$
$$= \sqrt{M_N^2 + 2M_N\nu - Q^2}$$

- Bjorken scaling variable

$$x_{\text{Bjorken}} = \frac{Q^2}{2M_N\nu}$$

Cross Section & Spin Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left[\frac{F_2}{\nu} + 2\frac{F_1}{M}\tan^2\frac{\theta}{2}\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1 - \frac{Q^2}{\nu}g_2\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin\theta}{MQ^2}\frac{E'^2}{E}\frac{1}{\nu^2}(\nu g_1 + 2E g_2)$$

Spin Structure Functions

- g_1: easy to understand, relatively easy to measure

$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2 \left[q_i^{\uparrow}(x,Q^2) - q_i^{\downarrow}(x,Q^2)\right]$$

- g_2: more complex
  - $g_2 = 0$ in naive quark model
  - sensitivity with target polarization perpendicular to beam polarization

Moments of Spin Structure Functions

First Moments

GDH Sum Rule ← **Generalized GDH Integral** → **Bjorken Sum Rule**

Chiral Perturbation Theory

Operator Product Expansion
Bjorken result for (p-n) at finite Q2

← Burkhardt-Cottingham Sum Rule →

Higher Moments

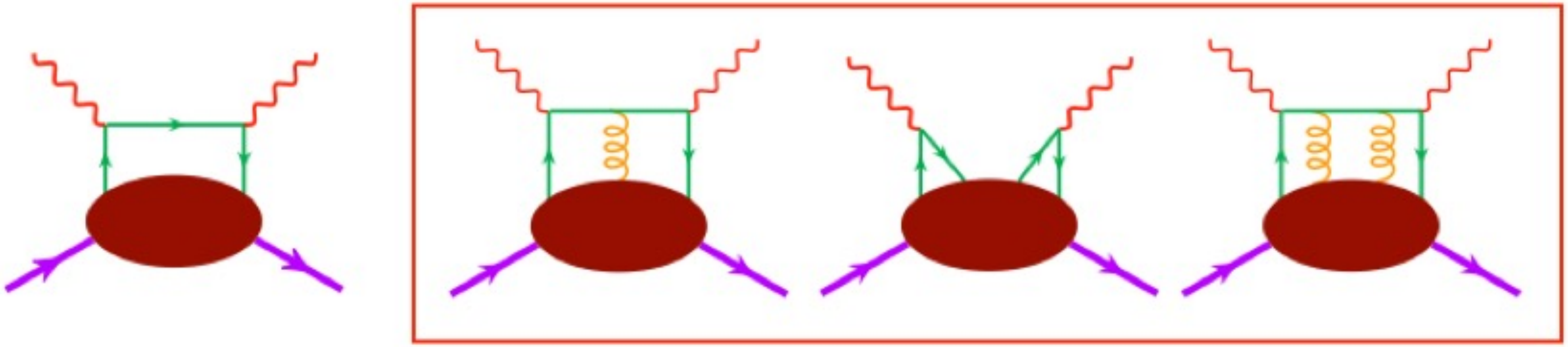
Spin Polarizabilities

Higher twists & color Polarizabilities

0 1 10

χPT *Lattice QCD* *OPE* *pQCD*

Higher Twist Effects



single quark scattering

$\tau = 2$

quark-quark &quark-gluon correlations

$\tau > 2$

$$\begin{aligned}\Gamma_1(Q^2) &\equiv \int_0^1 \mathrm{d}x\, g_1(x, Q^2) \\ &= \Gamma_1^{\mathrm{twist-2}}(Q^2) + \frac{M_N^2}{9\,Q^2}\left[a_2(Q^2) + 4\,d_2(Q^2) + 4\,f_2(Q^2)\right] + \mathcal{O}\left(\frac{M_N^4}{Q^4}\right)\end{aligned}$$

$\tau \equiv$ twist $\equiv$ operator dimension - spin

Moment of Spin Structure Function g_1

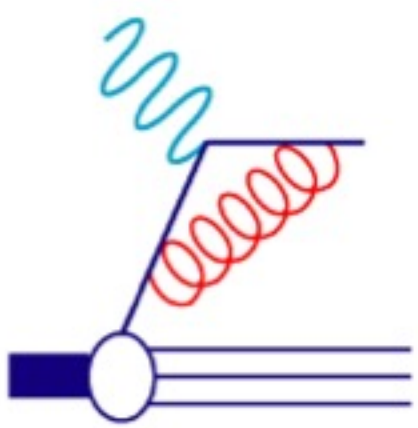
$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\, dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

leading twist   higher twists

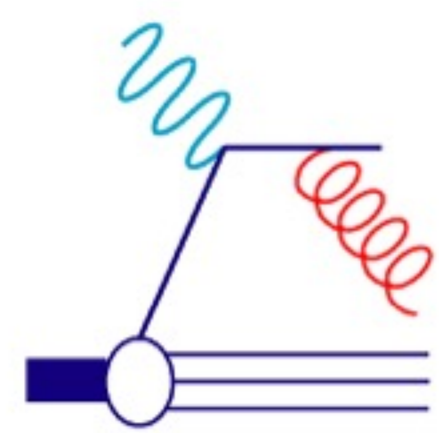
$$\mu_2^{p,n}(Q^2) = \left(\pm\frac{1}{12} g_A + \frac{1}{36} a_8\right) + \frac{1}{9}\Delta\Sigma + \text{pQCD corrections}$$

g_A=1.257, a_8 = 0.579 are the triplet and octet axial charges

$\Delta\Sigma$ = singlet axial charge



$$g_A = \Delta u - \Delta d$$
$$a_8 = \Delta u + \Delta d - 2\Delta s$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$



pQCD radiative corrections

Moments of Structure Functions

$$a_2(Q^2) \equiv 2\int_0^1 dx\, x^2\, g_1^{\text{twist-2}}(x, Q^2)$$ Target mass correction term

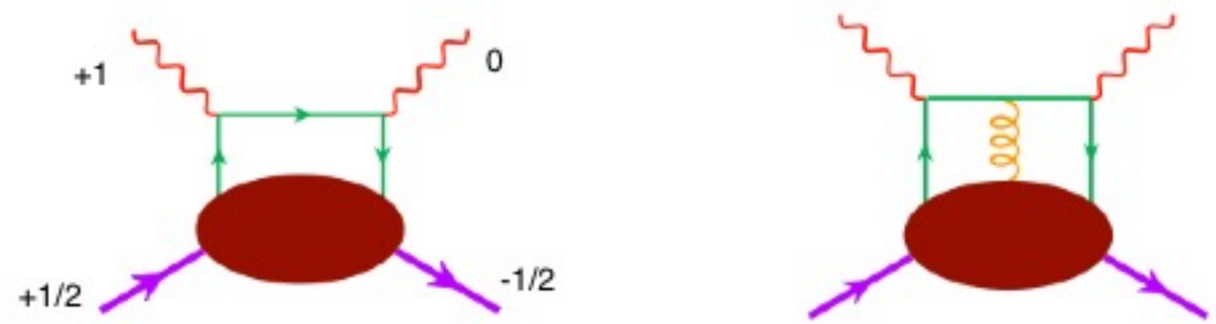
$d_2(Q^2)$ Dynamical twist-3 matrix element

$$d_2(Q^2) = \int_0^1 dx\, x^2 \left[2g_1(x, Q^2) + 3g_2(x, Q^2)\right] = \int_0^1 dx\, x^2\, \bar{g}_2(x, Q^2)$$

$f_2(Q^2)$ Dynamical twist-4 matrix element

$$f_2(Q^2) = \frac{1}{2}\int_0^1 dx\, x^2 \left[7g_1(x, Q^2) + 12g_2(x, Q^2) - 9g_3(x, Q^2)\right]$$

g_2 and quark-gluon correlations



$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

A twist-2 term (Wandzura & Wilczek, 1977)

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

A twist-3 term with a suppressed twist-2 piece (Cortex, Pire & Ralston, 1992)

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} \boxed{h_T(y,Q^2)} + \boxed{\xi(y,Q^2)}\right]\frac{dy}{y}$$

Transversity $\quad$ g-q correlations

$$\boxed{d_2 = 3\int_0^1 x^2 \bar{g}_2(x)\, dx = \int_0^1 x^2 \left[3g_2(x) + 2g_1(x)\right] dx}$$

Color Polarizabilities

Response of the gluon field under polarized nucleon (X. Ji, E Stein et al., 95)

Color magnetic and electric polarizabilities (in nucleon rest frame)

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS | \vec{O}_{B,E} | PS \rangle$$

where $\vec{O}_B = \psi^\dagger g \vec{B} \psi$

$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{E} \psi$$

$$d_2 = (\chi_E + 2\chi_B)/4$$
$$f_2 = \chi_E - \chi_B$$

d_2 and f_2 represent the response of the color B & E fields to the polarization of the nucleon

Lorentz Color Force

For a charge e moving at speed of light along -z direction, the EM Lorentz force can be written as

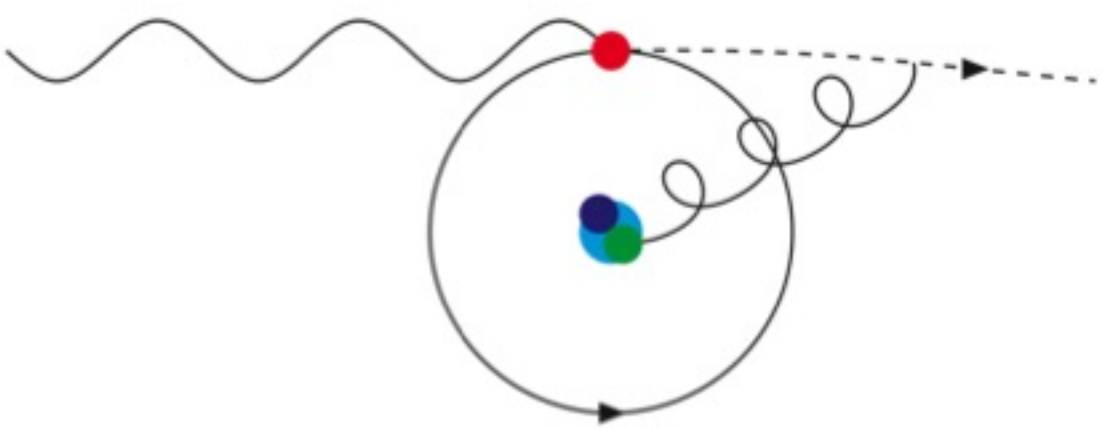
$$F^y = e\left[\vec{E} + \vec{v} \times \vec{B}\right]^y = e(E^y - B^x) = -e\sqrt{2}G^{+y}$$

Color Lorentz force reads:

$$\begin{aligned} F^y(0) &\equiv -\frac{\sqrt{2}}{2P^+}\langle P,S|\bar{q}(0)\gamma^+ G^{+y}(0)q(0)|P,S\rangle \\ &= -\frac{1}{2P^+}\langle P,S|\bar{q}\gamma^+(B^x - E^y)q|P,S\rangle \\ &= -\sqrt{2}MP^+S^x d_2 \quad (= -M^2 d_2) \end{aligned}$$

Average Color Lorentz Force

$$\int dx\, x^2\, \bar{g}_2(x) = \frac{1}{3} d_2 = \frac{1}{6MP^{+2}S^x} \langle P,S|\bar{q}(0)\gamma^+ G^{+y}(0) q(0)|P,S\rangle$$



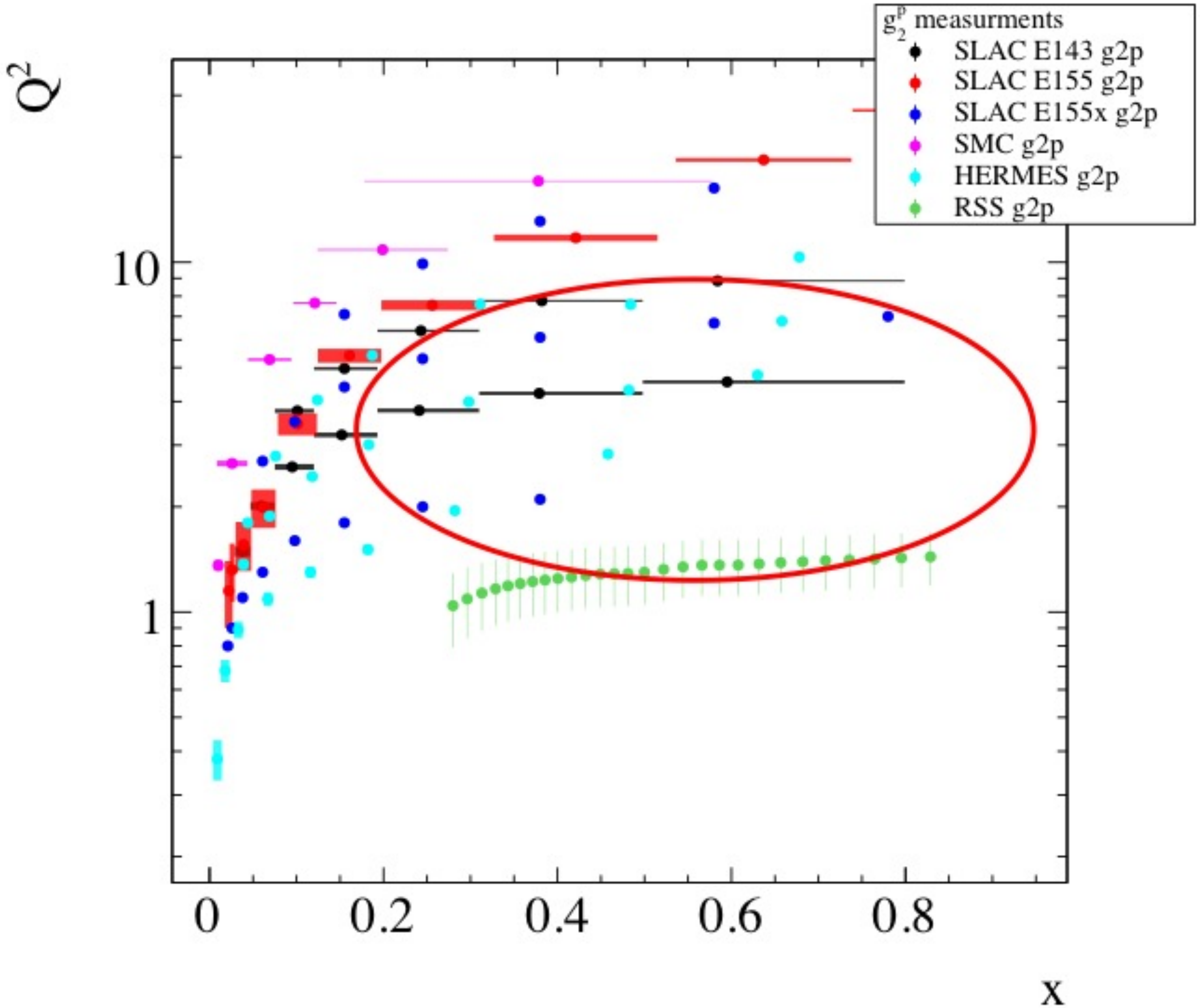
a measure for the **Color Lorentz force** acting on the struck quark in SIDIS at the instant **after being hit by the virtual photon**

$$\langle F^y(0)\rangle = -M^2 d_2$$

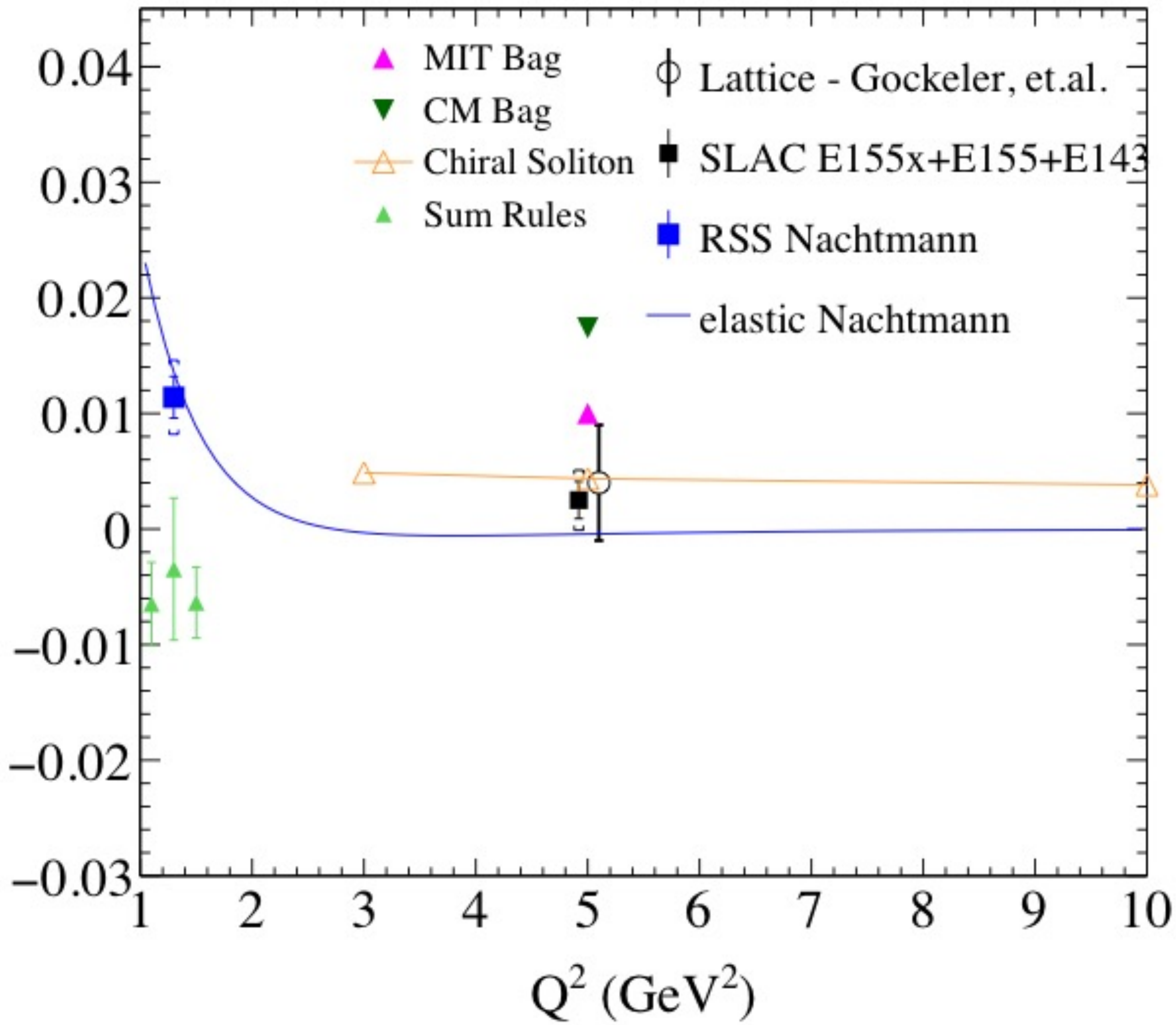
$$F_E^y(0) = -\frac{M^2}{4}\chi_E = -\frac{M^2}{4}\left[\frac{2}{3}\left(2d_2 + f_2\right)\right]$$

$$F_B^y(0) = -\frac{M^2}{2}\chi_B = -\frac{M^2}{4}\left[\frac{1}{3}\left(4d_2 - f_2\right)\right]$$

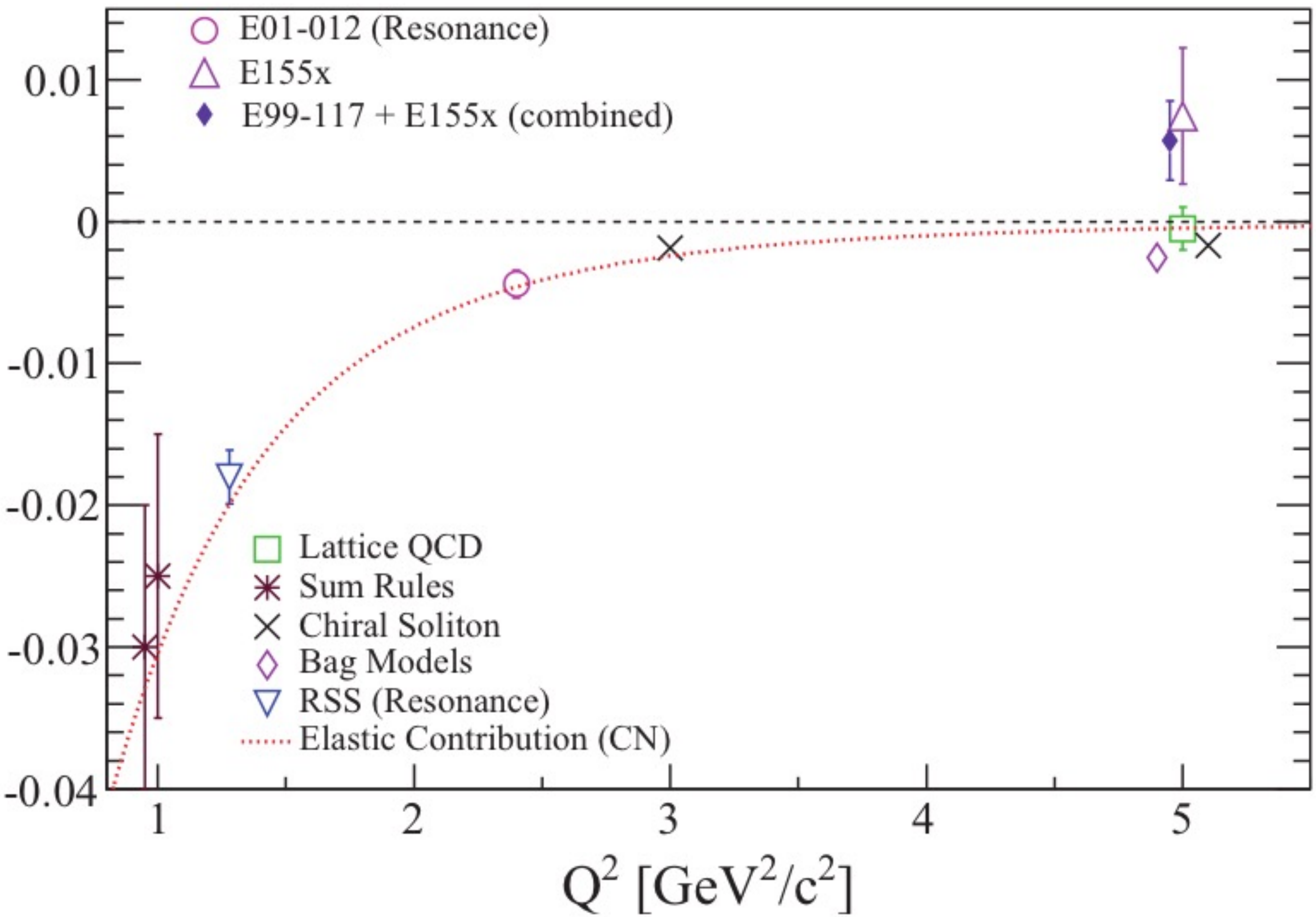
Previous Kinematic Coverage for Proton g_2



Previous Measurements & Predictions for Proton d_2



Previous Measurements & Predictions for Proton d_2



Spin Asymmetries of the Nucleon Experiment

Experiment Summary

- **Beam**: polarized electron beam (Jefferson Lab) at **4.7** and **5.9** GeV
- **Target**: Polarized **Proton** (NH_3) target
  - Polarization: ~71%
  - Orientation: parallel (180°) or "**perpendicular**" (80°)
- **Detectors**: **BETA** and **HMS** of Hall-C
- Scattering angle: 40° for BETA, 15.5° or 20° for HMS

SANE Collaboration

E. Brash, **P. Carter, M. Veilleux**
Christopher Newport University, Newport News, VA

W. Boeglin, P. Markowitz, J. Reinhold
Florida International University, Miami, FL

I. Albayrak, O. Ates, C. Chen, E. Christy, C. Keppel,
M. Kohl, **Y. Li**, **A. Liyanage**, P. Monaghan, **X. Qiu**,
L. Tang, **T. Walton**, **Z. Ye,** L. Zhu
Hampton University, Hampton, VA

P. Bosted, J.-P. Chen, S. Covrig, W. Deconink, A. Deur,
C. Ellis, R. Ent, D. Gaskell, J. Gomez, D. Higinbotham,
T. Horn, M. Jones, D. Mack, G. Smith, P. Solvignon, S. Wood
Thomas Jefferson National Accelerator Facility, Newport News, VA

A. Puckett
LANL, Los Alamos, NM

W. Luo
Lanzhou University, China

J. Dunne, D. Dutta, **A. Narayan,** **L.Ndukum**, **Nuruzzaman**
Mississippi State University, Jackson. MI

A. Ahmidouch, S. Danagoulian, **B. Davis,** **J. German**, **Martin Jones**
North Carolina A&M State University, Greensboro, NC

M. Khandaker
Norfolk State University, Norfolk, VA

A. Daniel, P.M. King, J. Roche
Ohio University, Athens, OH

A.M. Davidenko, Y.M. Goncharenko, V.I. Kravtsov,
Y.M. Melnik, V.V. Mochalov, L. Soloviev, A. Vasiliev
Institute for High Energy Physics, Protvino, Moscow Region, Russia

C. Butuceanu, G. Huber
University of Regina, Regina, SK

V. Kubarovsky
Rensselaer Polytechnic Institute, Troy, NY

L. El Fassi, R. Gilman
Rutgers University, New Brunswick, NJ

S. Choi, **H-K. Kang**, **H. Kang**, **Y. Kim**
Seoul National University, Seoul, Korea

M. Elaasar
State University at New Orleans, LA

W. Armstrong, **D. Flay,** Z.-E. Meziani, **M. Posik,**
B. Sawatzky, **H. Yao**
Temple University, Philadelphia, PA

O. Hashimoto, D. Kawama, **T. Maruta,**
S. Nue Nakamura, **G. Toshiyuki**
Tohoku U., Tohoku, Japan

K. Slifer
University of New Hampshire

H. Baghdasaryan, M. Bychkov, D. Crabb, D. Day, E. Frlez,
O. Geagla, N. Kalantarians, **K. Kovacs,** N. Liyanage,
V. Mamyan, **J. Maxwell, J. Mulholland**, D. Pocanic,
S. Riordan, O. Rondon, M. Shabestari
University of Virginia, Charlottesville, VA

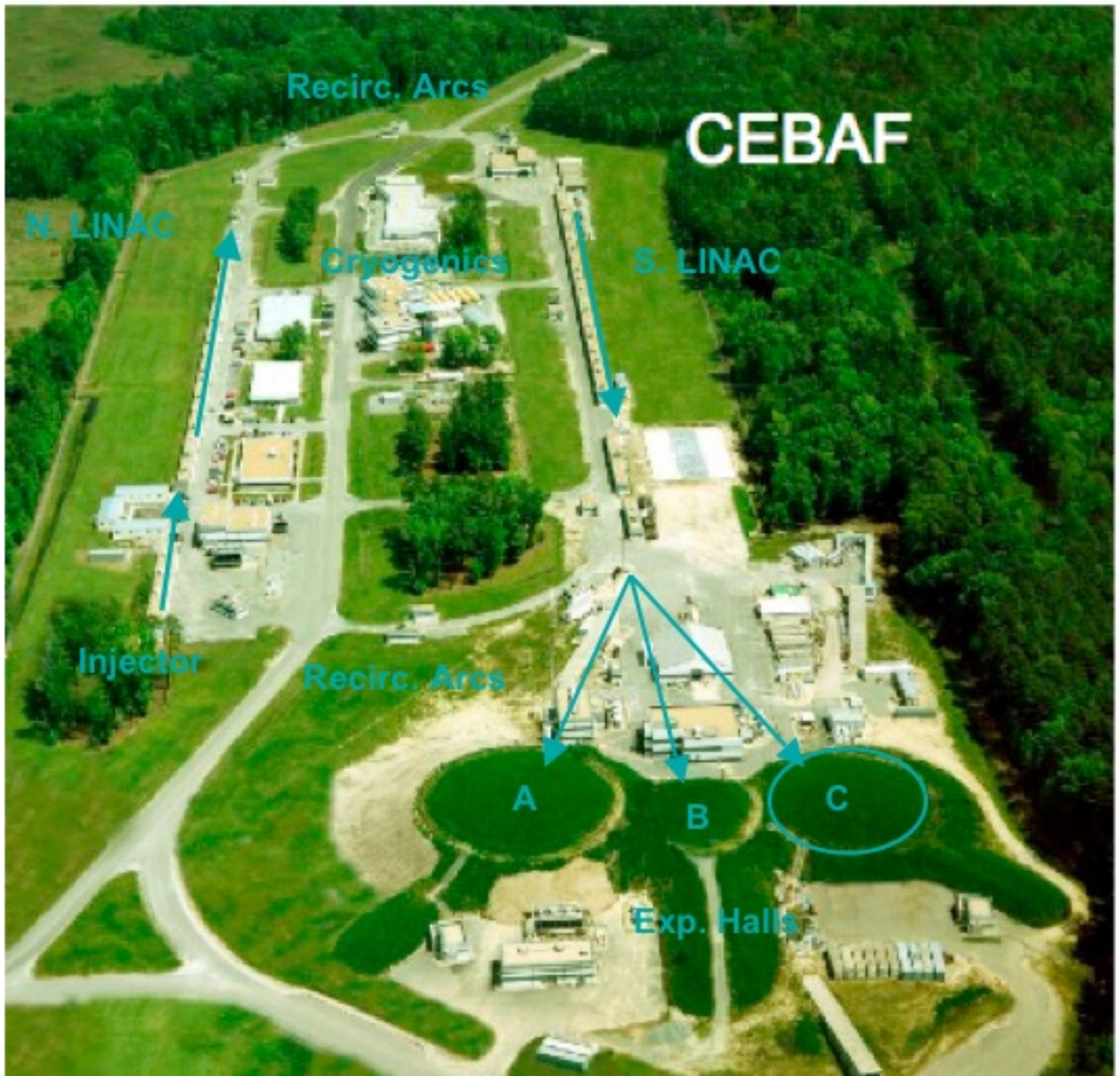
L. Pentchev
College of William and Mary, Williamsburg, VA

F. Wesselmann
Xavier Unniversity, New Orleans, LA

Asaturyan, H. Mkrtchyan, V. Tadevosyan
Yerevan Physics Institute, Yerevan, Armenia

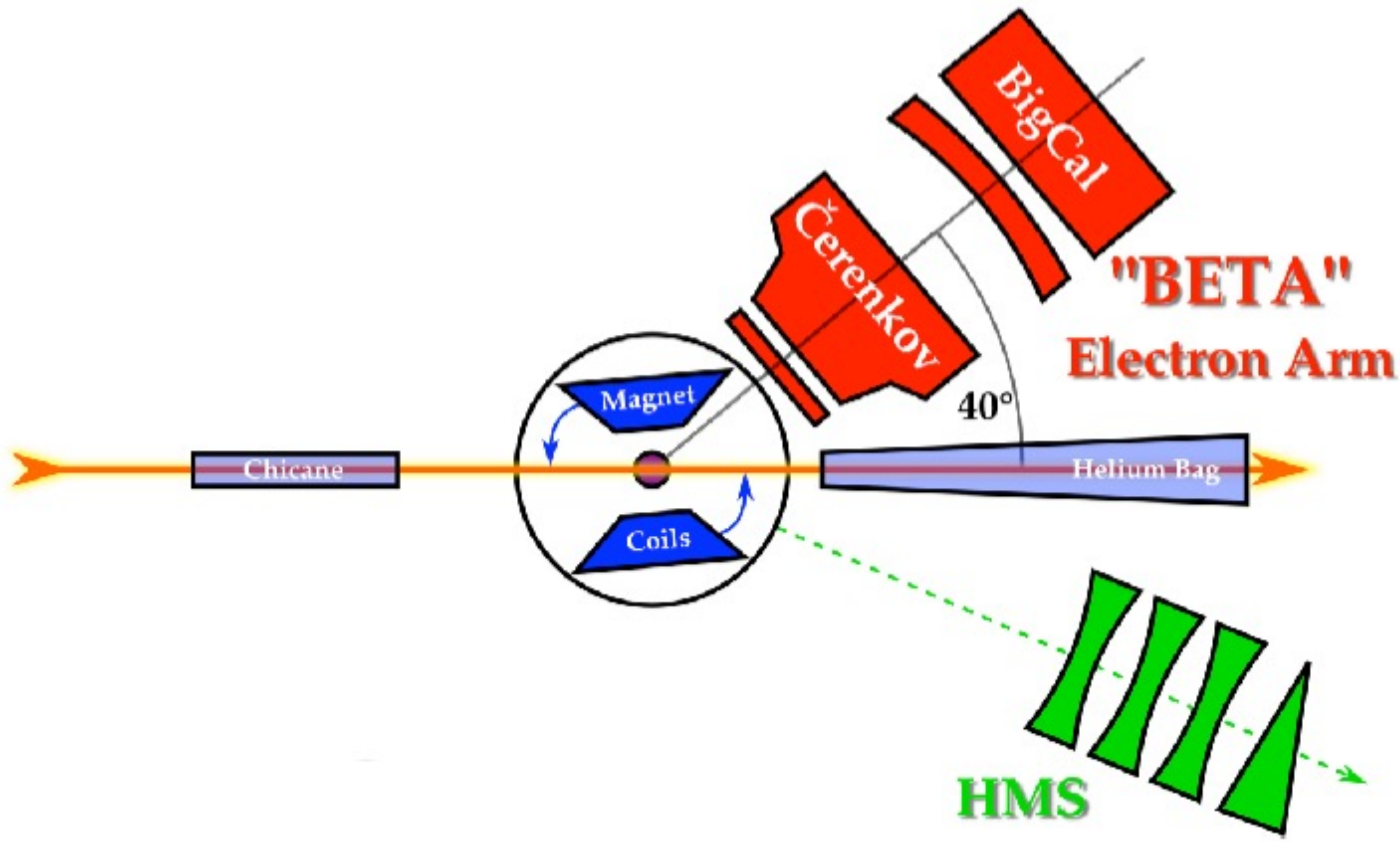
Ph.D. student, **M.S. Student**, **Student**

Jefferson Lab



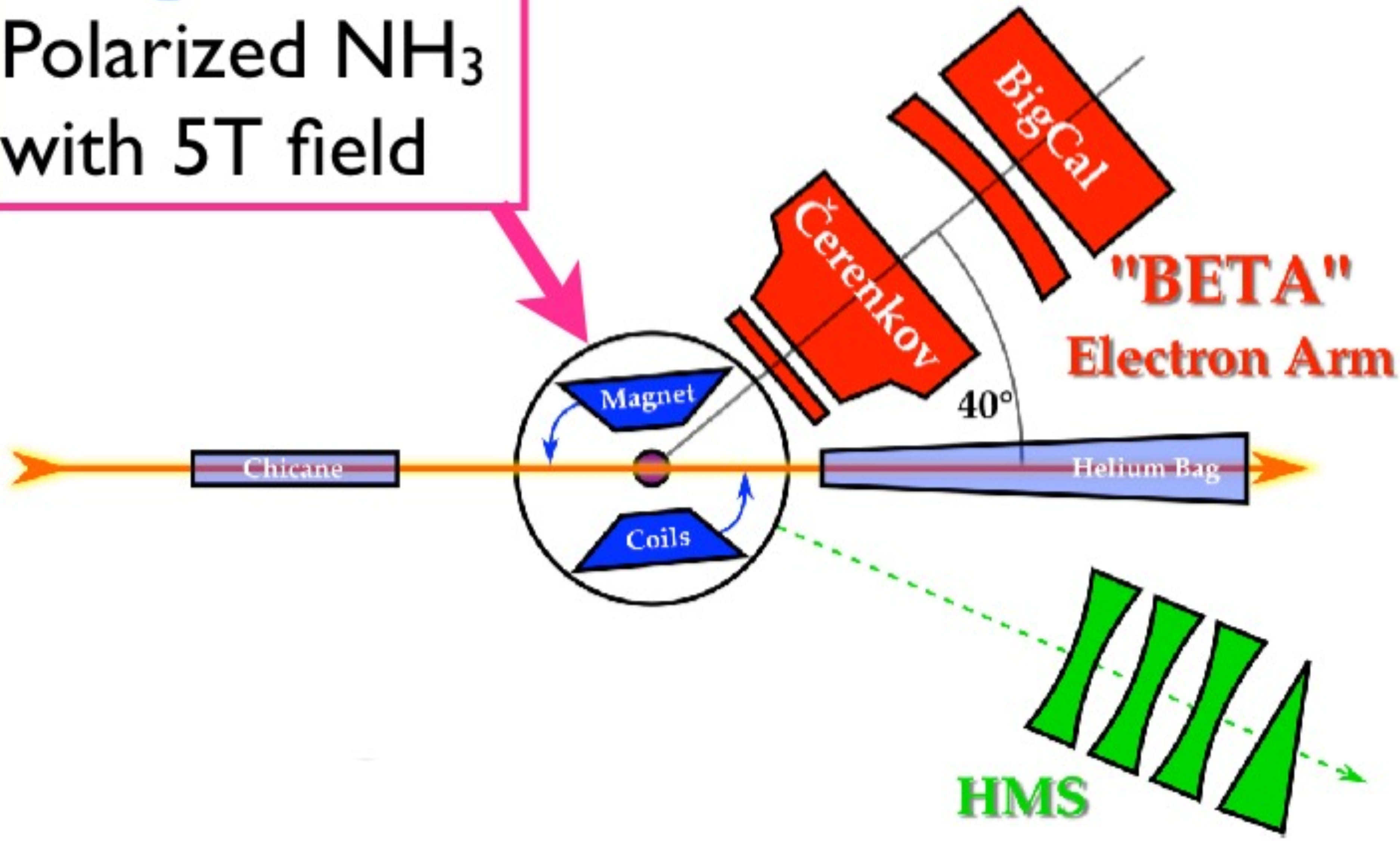
- 2 Linacs with recirculation
- Electron beam of energies up to 6 GeV
- 3 Experimental Halls in simultaneous operation

Setup

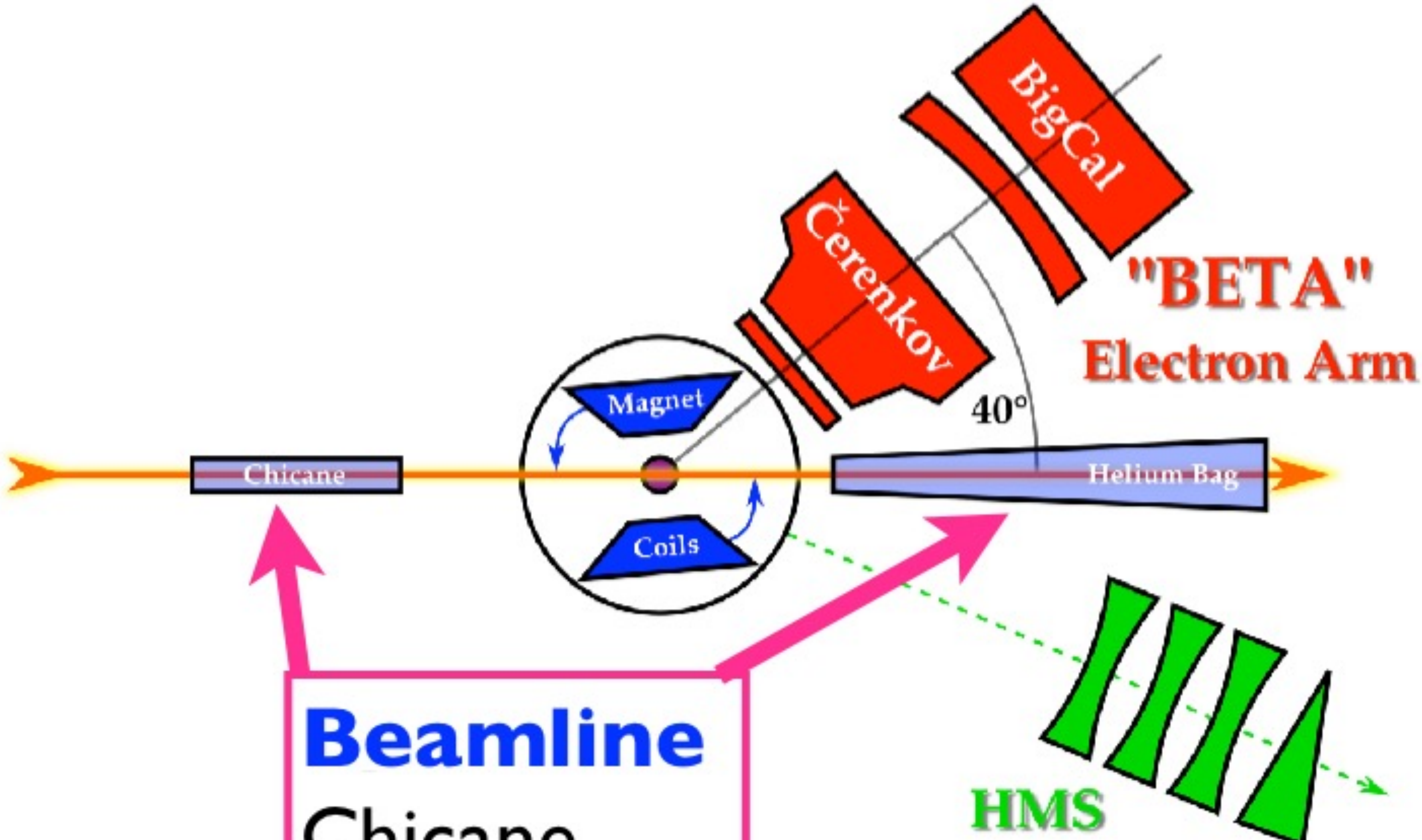

BigCal
Čerenkov
"BETA"
Electron Arm
40°
Magnet
Chicane
Helium Bag
Coils
HMS

Setup

Target
Polarized NH_3
with 5T field



Setup



Beamline

Chicane

He bag

Setup

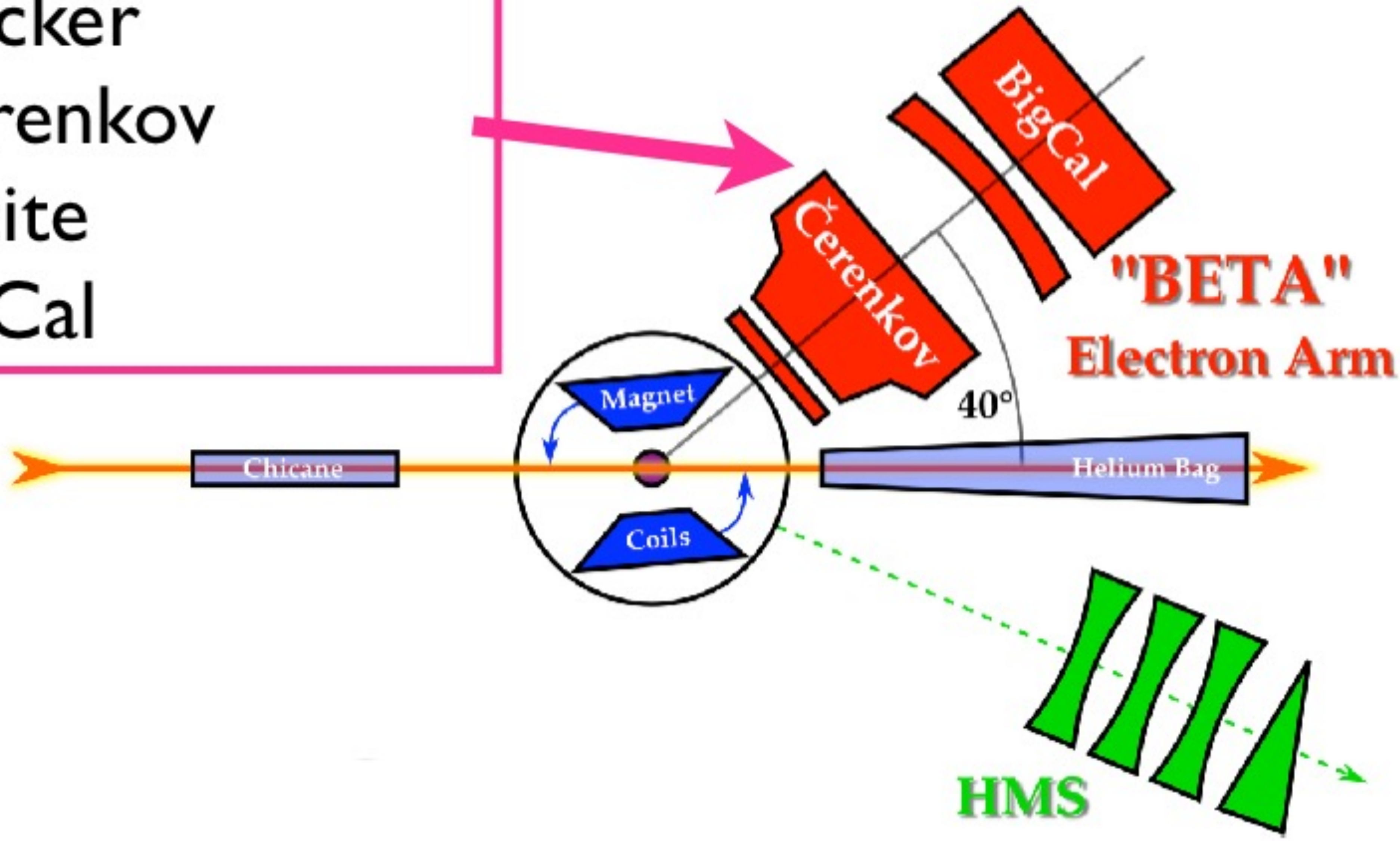
Electron Arm

Tracker

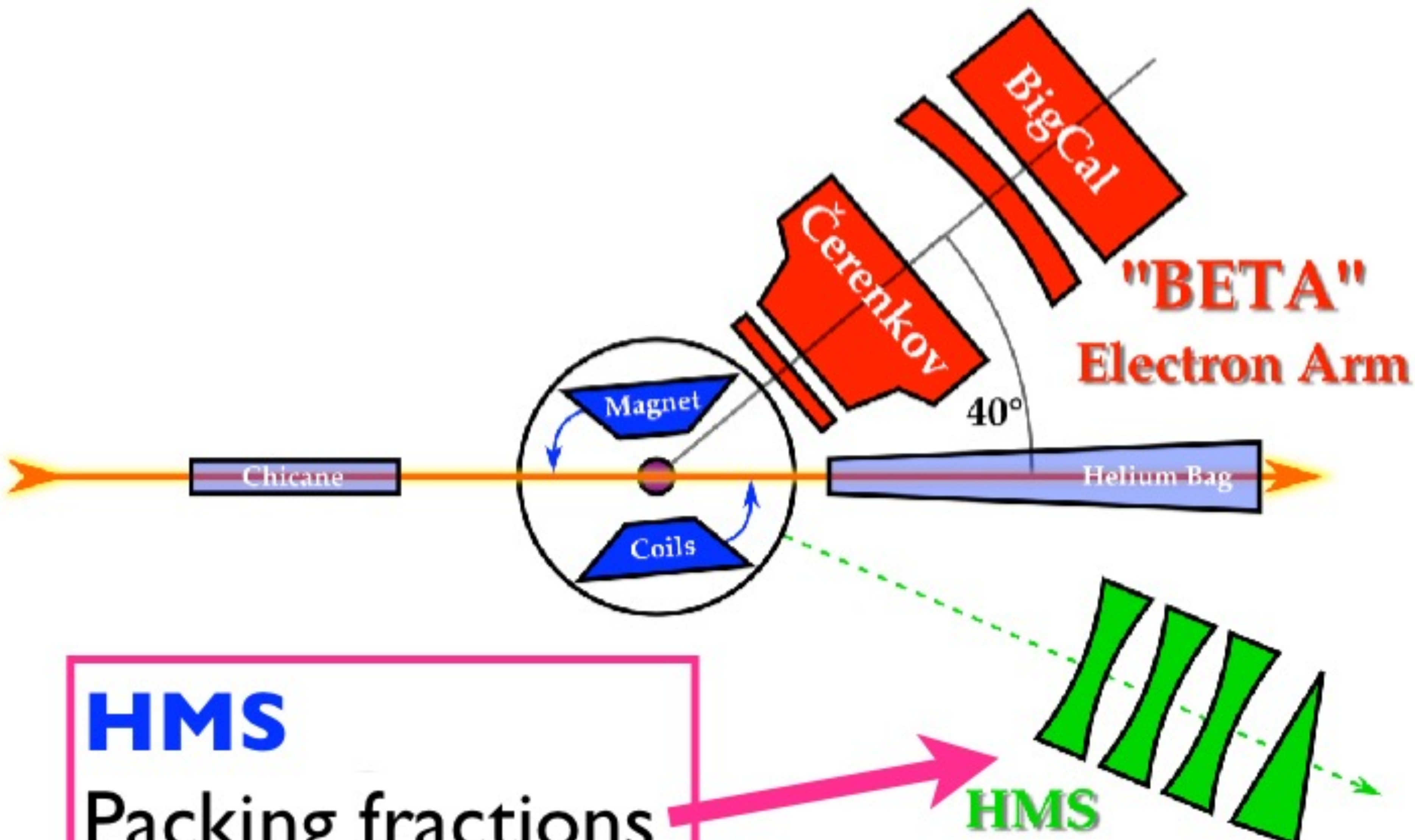
Cerenkov

Lucite

BigCal



Setup



HMS

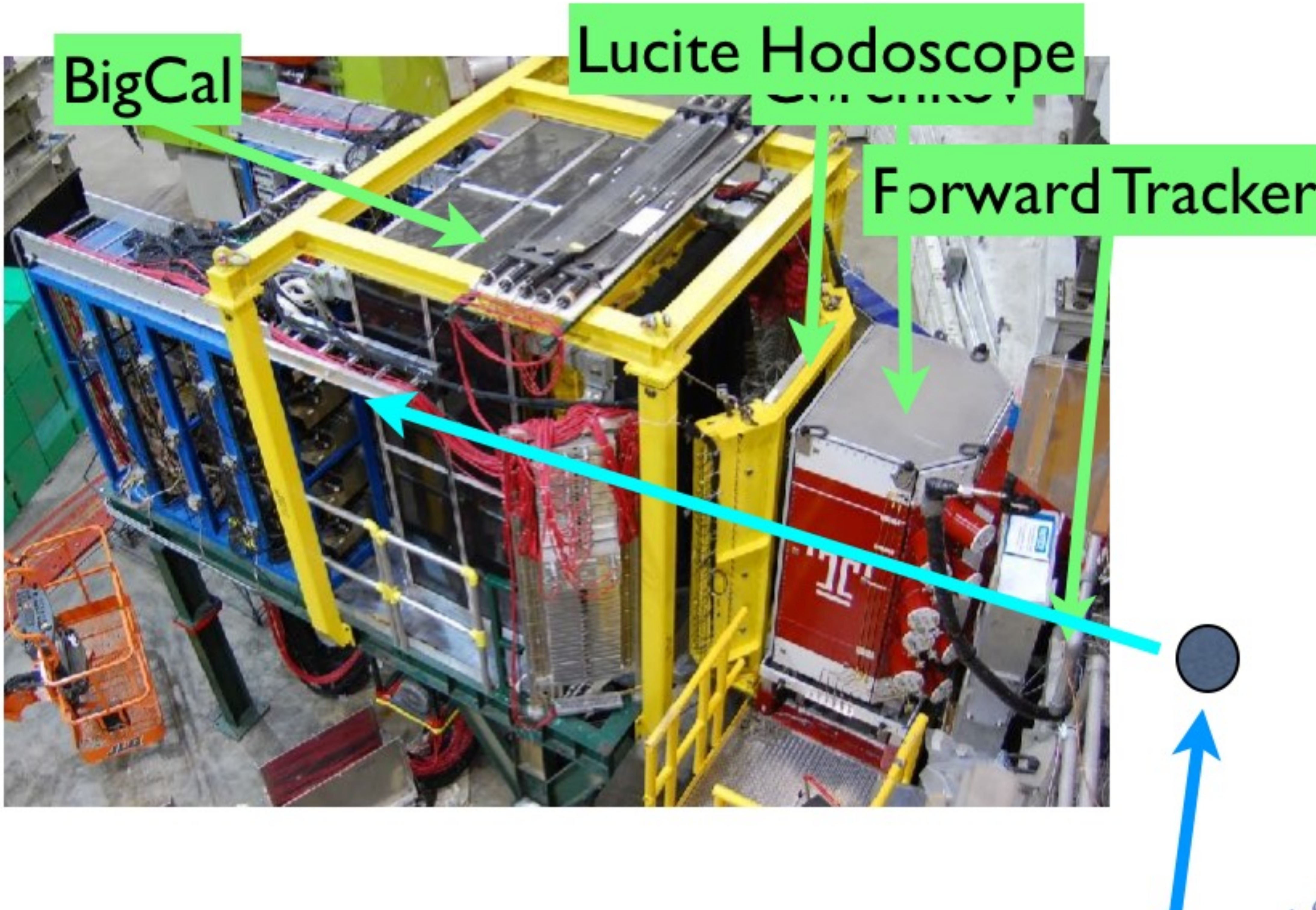
Packing fractions

Monitoring

Big Electron Telescope Array

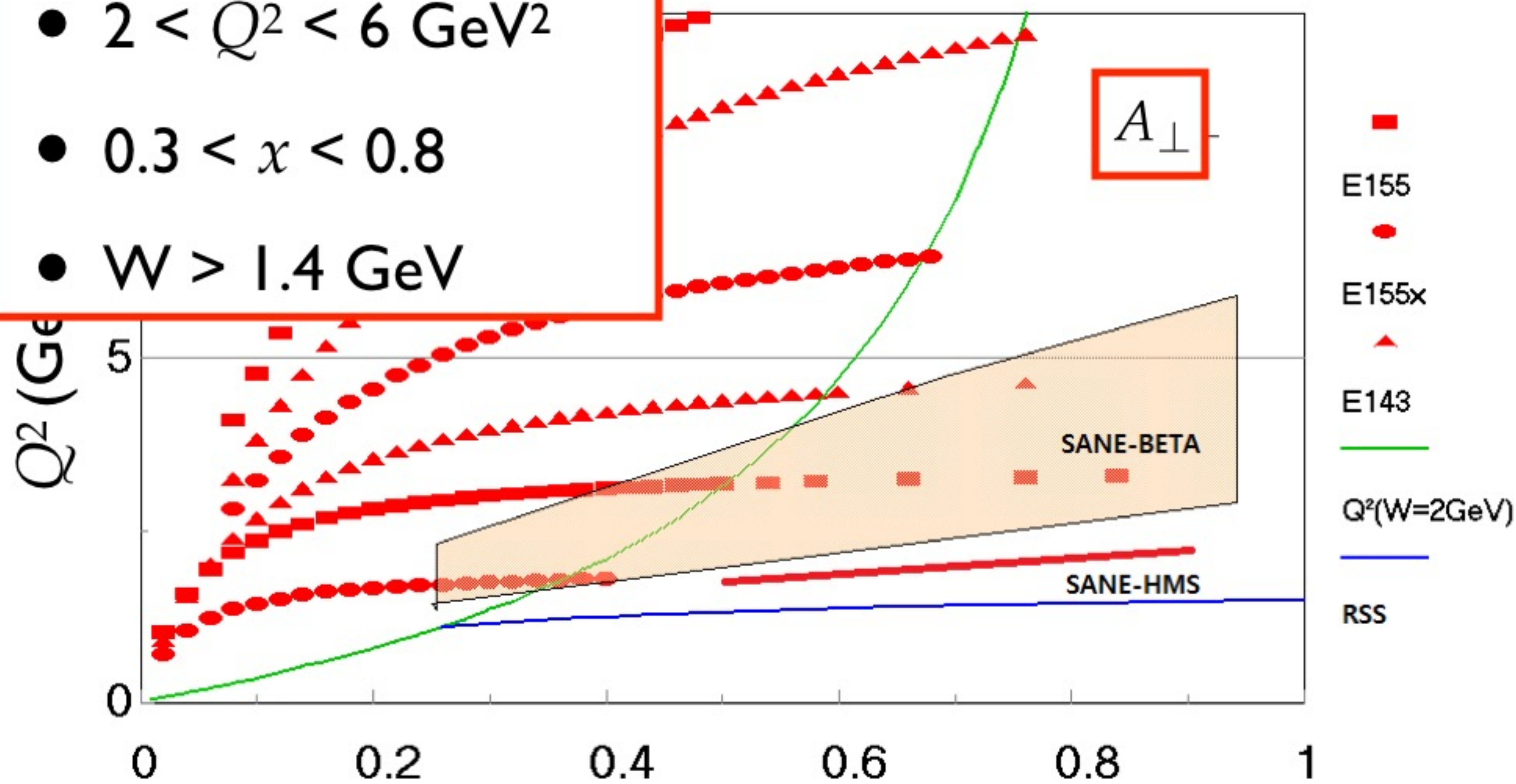
- Electron detector without magnet
- Should provide
  - **Tracking** information
    - Forward tracker, Lucite hodoscope, BigCal
  - **Particle id**entification
    - Cerenkov detector
  - **Energy** measurement
    - BigCal (Lead glass calorimeter)

BETA

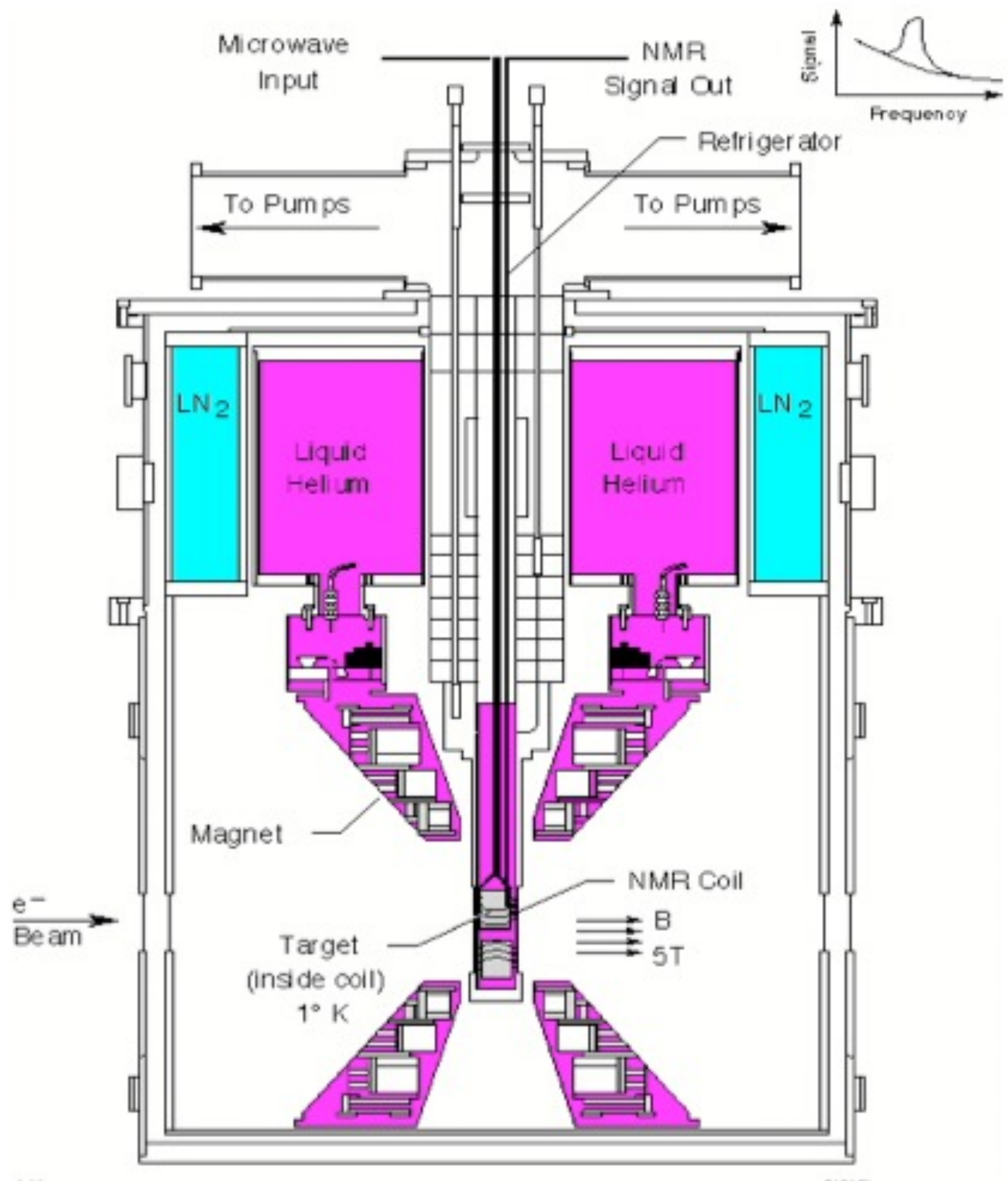


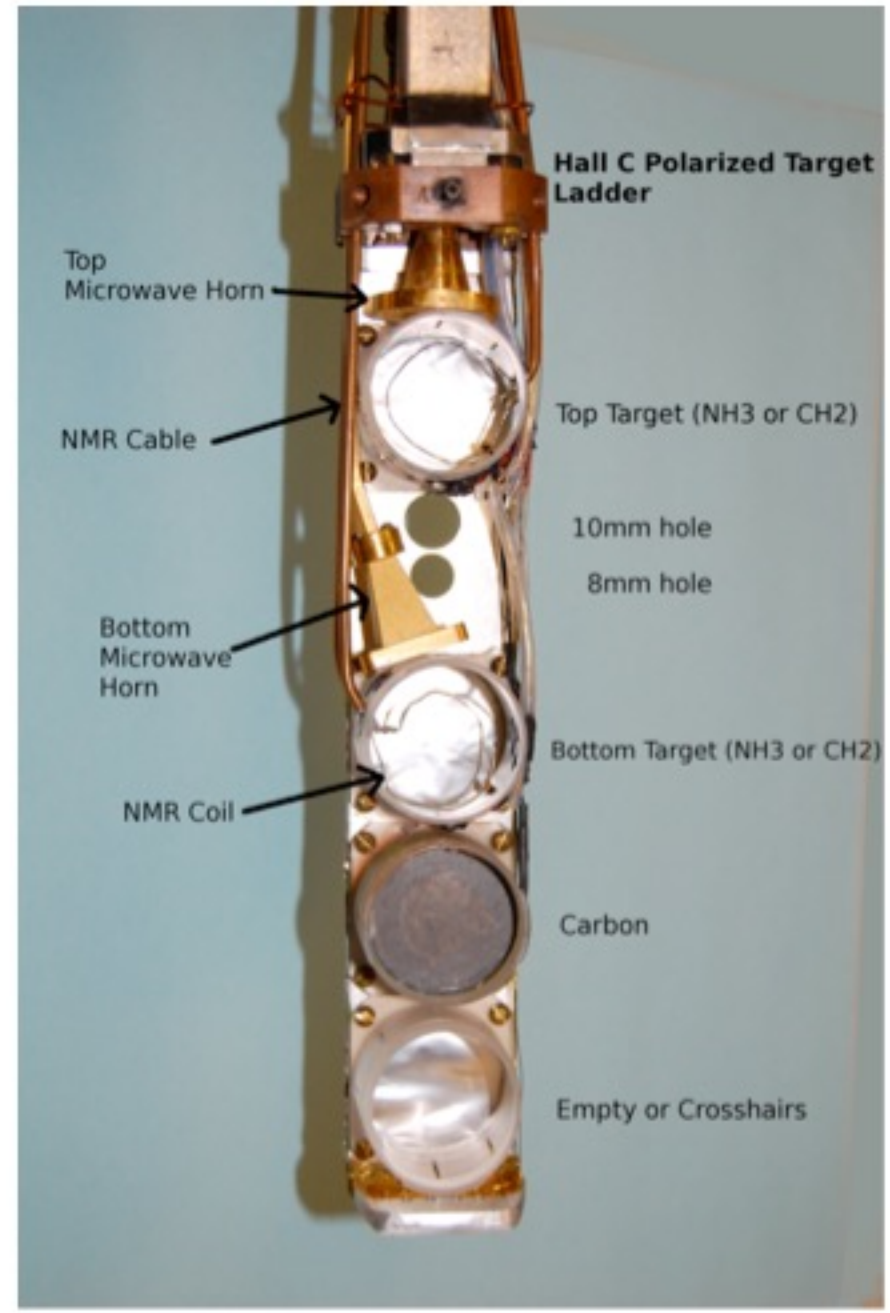
Kinematic Coverage

- $2 < Q^2 < 6$ GeV^2
- $0.3 < x < 0.8$
- W > 1.4 GeV



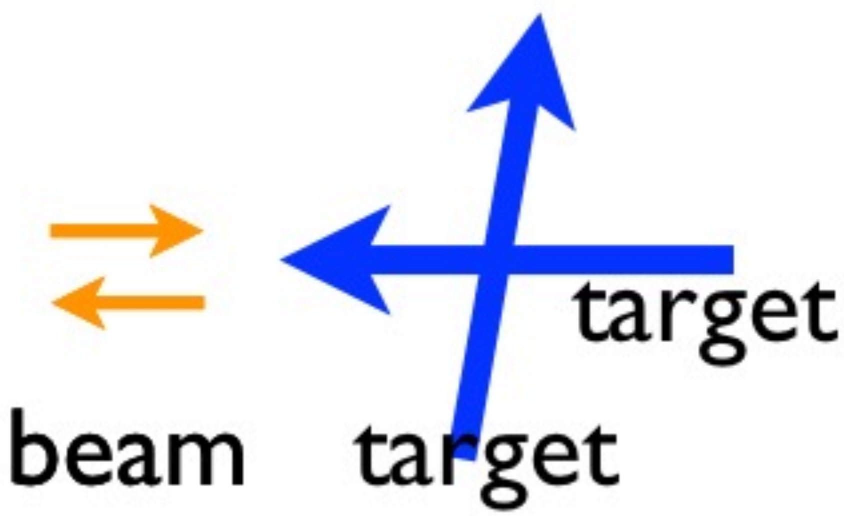
Polarized NH_3 Target





Data Taking

- For 2 beam energies: **4.7** and **5.9**
- 2 different orientations of polarizations
  - **perpendicular**: target polarization at 80° with respect to the beam polarization
  - **parallel**: 180°



Data Analysis

- Beam spin asymmetries

$$A_{\parallel}\, A_{\perp} = \frac{1}{f P_B P_T} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

- Physics asymmetries

$$A_1 = \frac{E - E' \cos\theta}{E - E'} A_{\parallel} - \frac{E' \sin\theta}{E - E'} A_{\perp}$$

Data Analysis

- Structure Functions

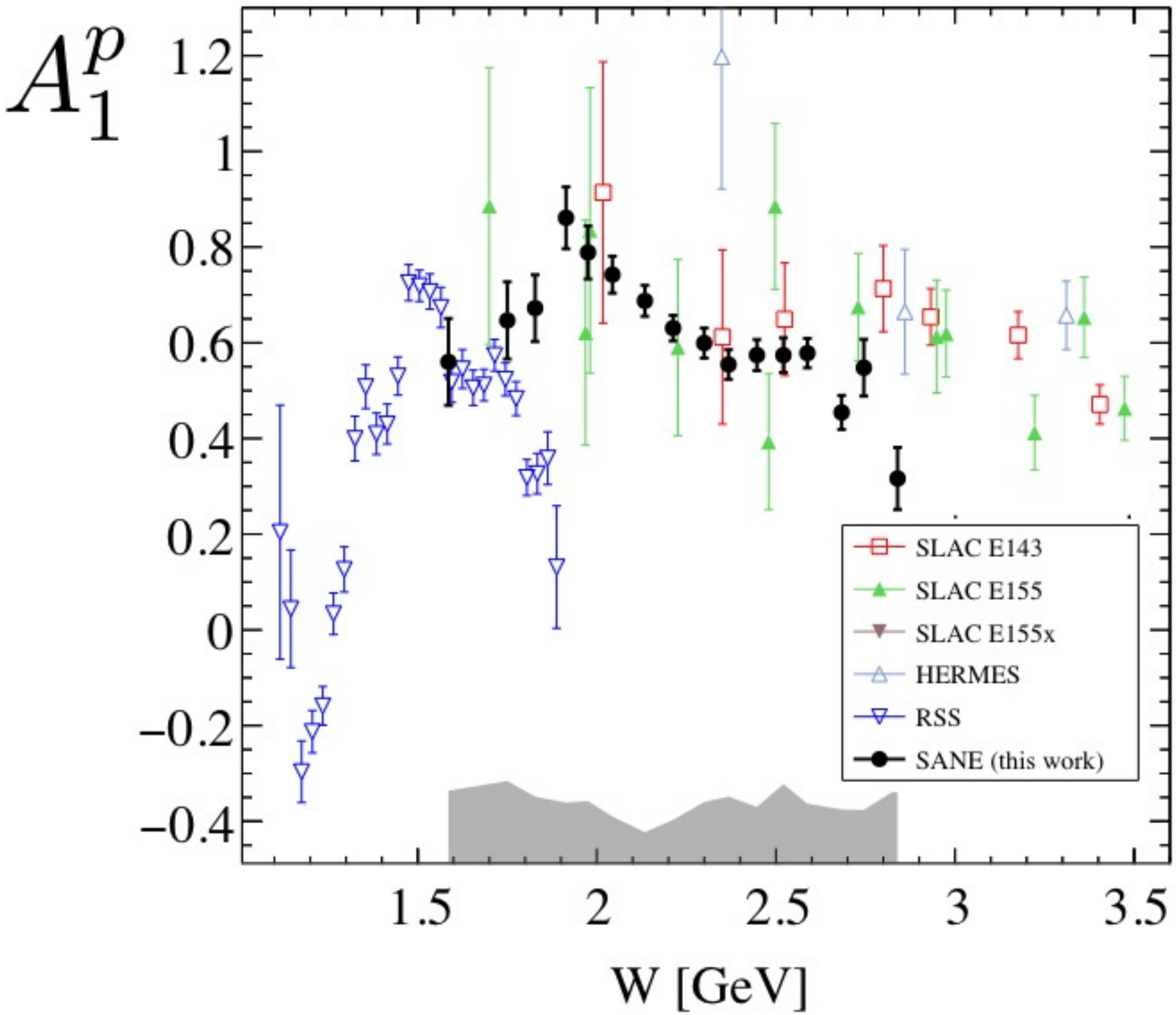
$$g_1 = \frac{F_1}{1+\gamma^2}\left(A_1 + \gamma A_2\right)$$

$$g_2 = \frac{F_1}{\gamma(1+\gamma^2)}\left(A_2 - \gamma A_1\right)$$

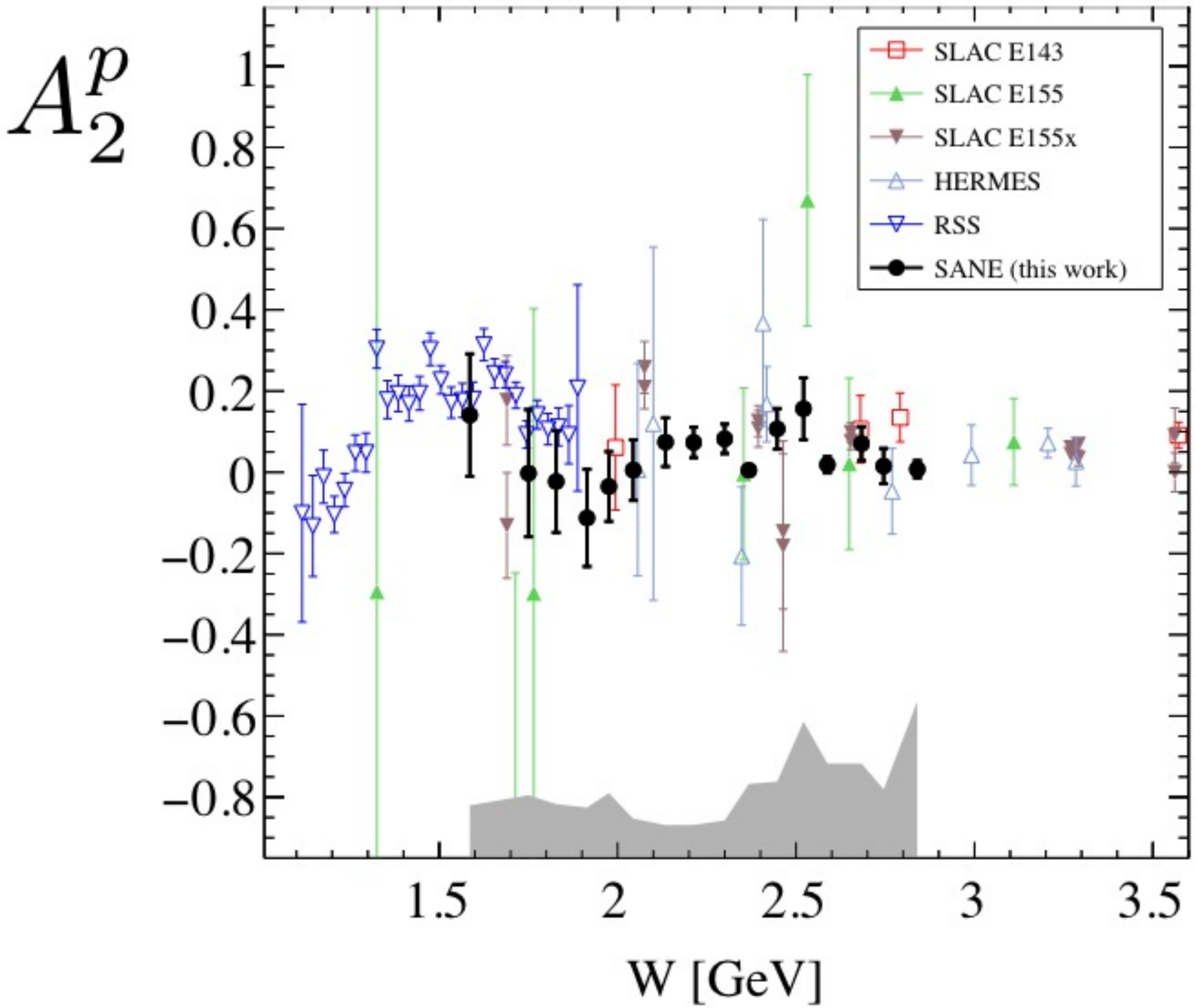
- d_2 matrix element

$$d_2(Q^2) = \int_0^1 dx\, x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]$$

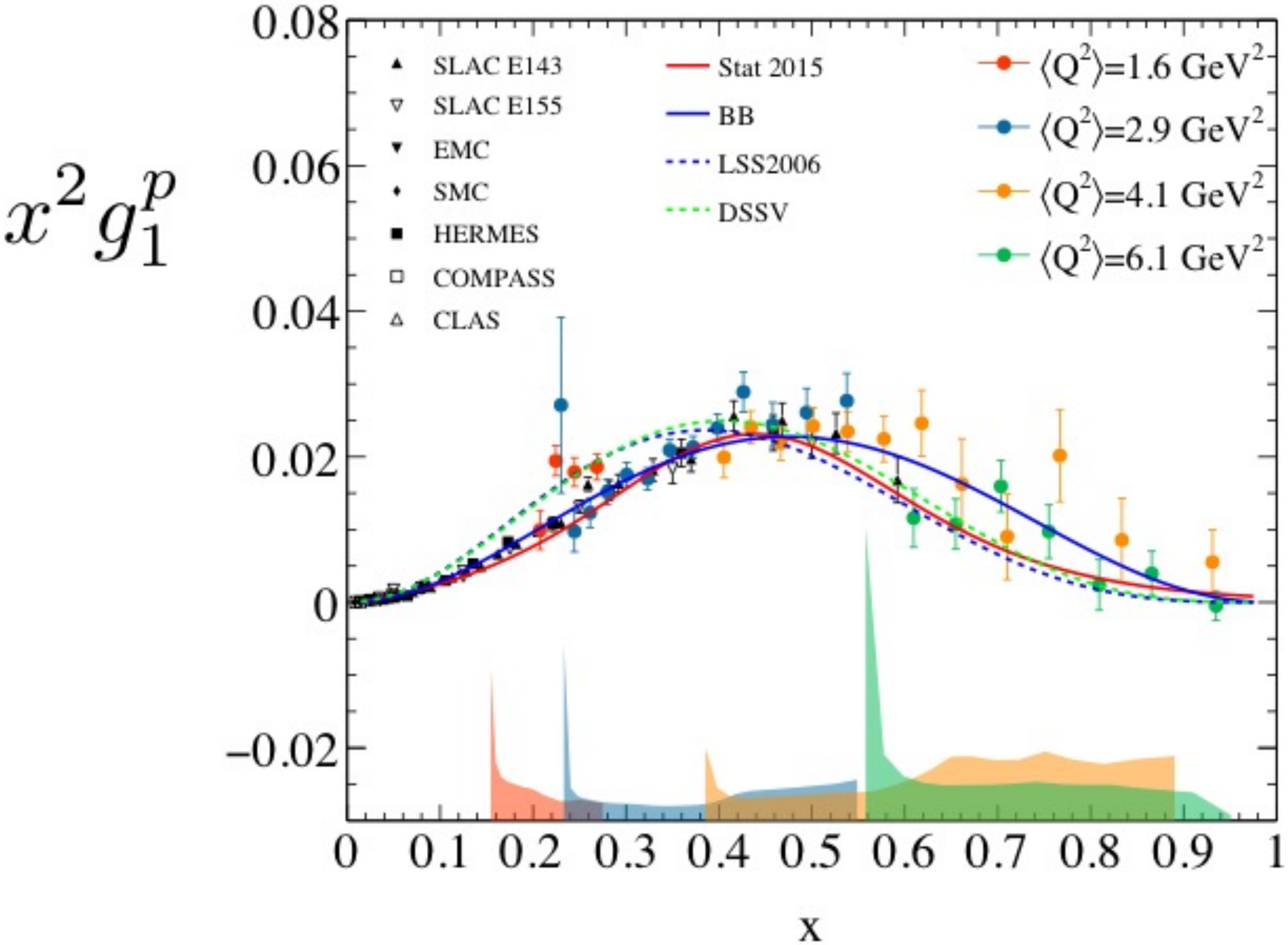
Asymmetries



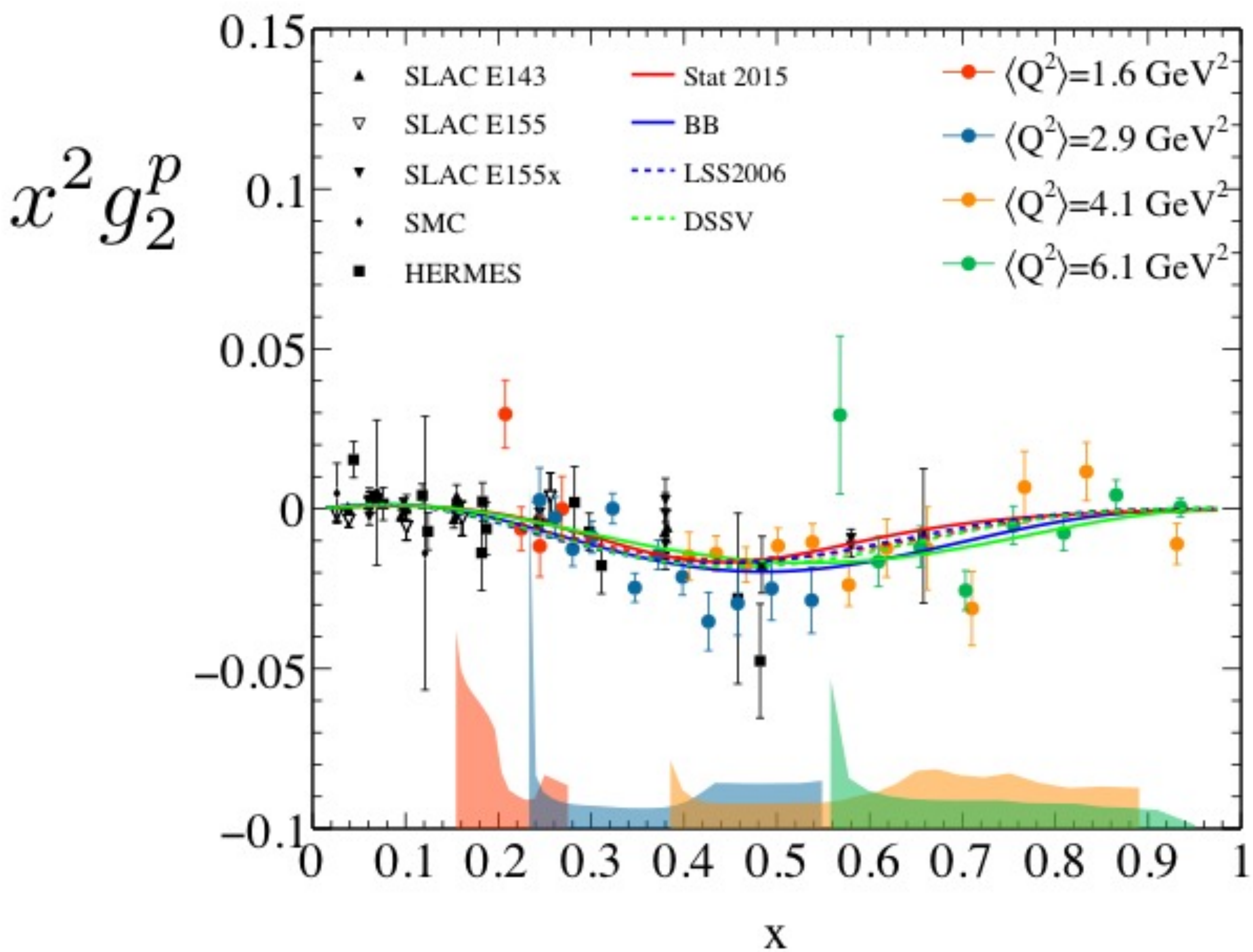
Asymmetries



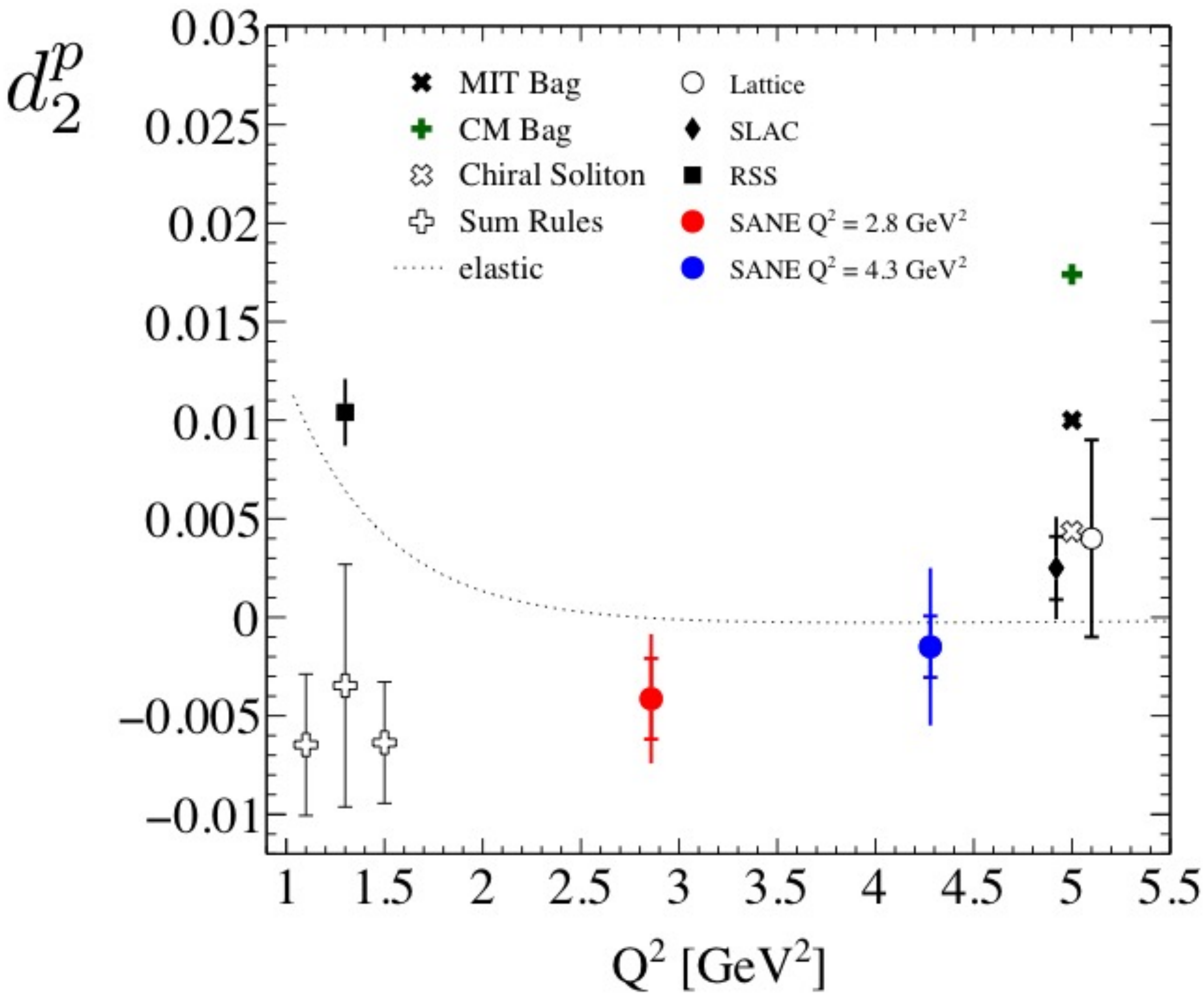
Results for Spin Structure Functions



Results for Spin Structure Functions



Results on Proton d_2



Submitted to PRL
Available as
arXiv:1805.08835

Summary

- SANE measures double-spin asymmetries, $A_{\parallel}$ and $A_{\perp}$ of ep DIS
- Kinematic coverage of $2 < Q^2 < 6$ GeV^2, $0.3 < x < 0.8$,
- New non-magnetic detector BETA used for electron detection
- Proton's spin structure functions g_1 and g_2 measured
- Two values of d_2 extracted at near constant Q^2
- Possible indication of a scale dependence of the color Lorentz force.