g_2 Spin Structure Function at Jefferson Lab

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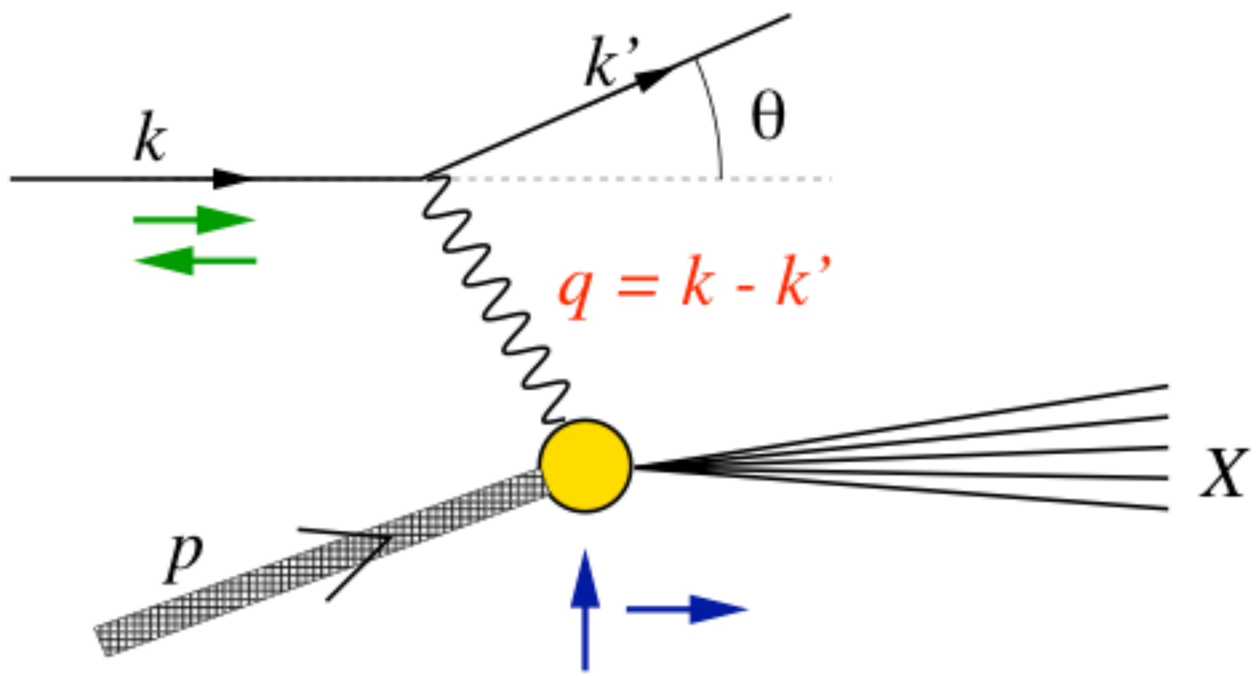
Outline

- Polarized DIS and spin structure functions
- Experiments at Jefferson Lab for g_2
- Spin Asymmetries of the Nucleon Experiment
- Other experiments for g_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

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

Polarized DIS

- Deep Inelastic Scattering
  - with polarized electron beams
  - and polarized targets
- Probes spin states of the quarks
- Spin structure functions, g_1 and g_2
  - 2 different target polarization directions

Cross Section & Spin Structure Functions

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

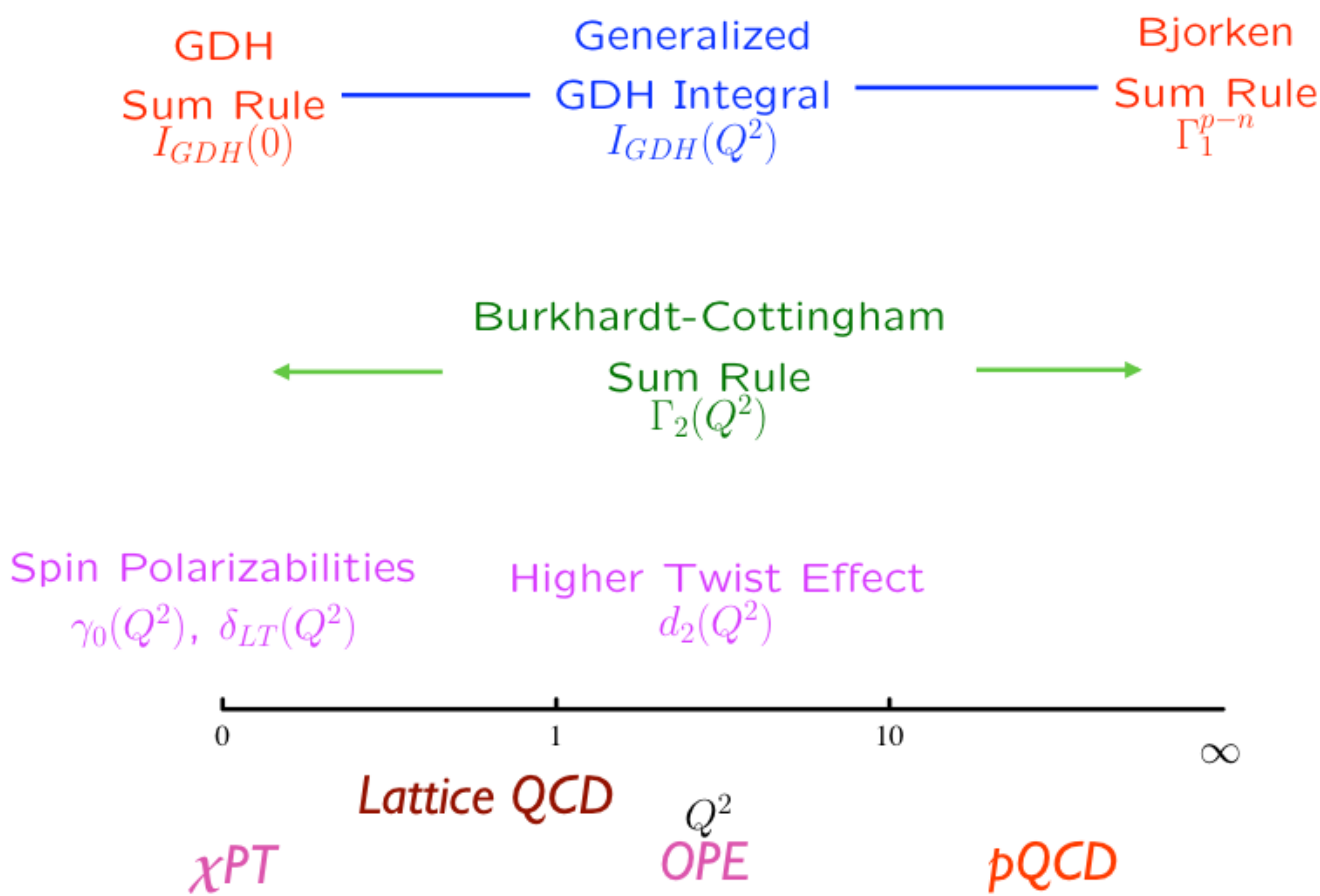
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1 - \frac{Q^2}{\nu}g_2\right]$$

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{E}\frac{1}{\nu^2}(\nu g_1 + 2Eg_2)$$

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

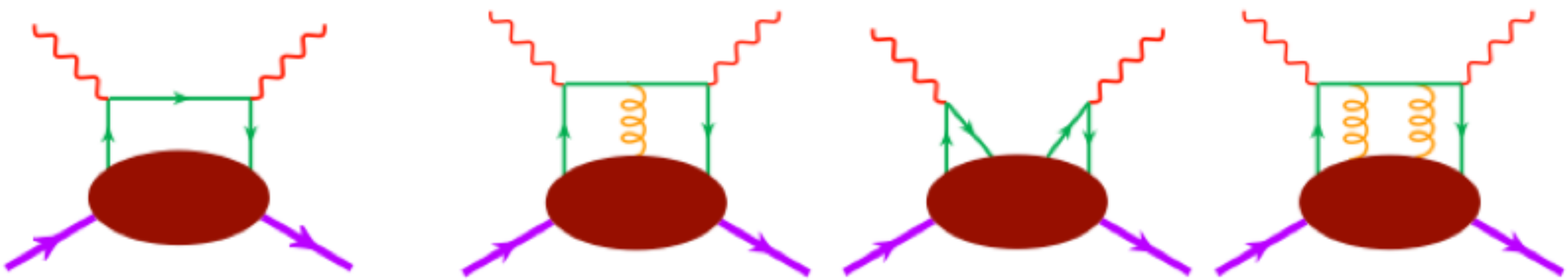
Probe Resolution & Theory Tools



g_2 and Higher Twists

- Decomposition of g_2

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



single quark scattering

$\tau = 2$

qq & qg correlations

$\tau > 2$

g_2 and quark-gluon correlations

g_2 and quark-gluon correlations

- a twist-2 term (Wandzura-Wilcek)

g_2 and quark-gluon correlations

- a twist-2 term (Wandzura-Wilcek)

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

g_2 and quark-gluon correlations

- a twist-2 term (Wandzura-Wilcek)

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

- a twist-3 term with a suppressed twist-2 piece

g_2 and quark-gluon correlations

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

- a twist-3 term with a suppressed twist-2 piece

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

g_2 and quark-gluon correlations

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Transversity

g_2 and quark-gluon correlations

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qg correlations

Interesting Features of g_2

- twist-3 effects: *quark-gluon* correlations
  - d_2 matrix element (3rd moment)
- Test of lattice QCD, QCD sum rules and quark models from moments
- Polarizabilities of color fields

$$\chi_B = \frac{1}{3}(4d_2 + f_2)$$
$$\chi_E = \frac{1}{3}(4d_2 - 2f_2)$$

Interesting Features of g_2

- Color Lorentz force on transverse polarized quark (3rd moment)
  - sign of d_2 related to the sign of the transverse deformation
- Contains chiral odd twist-2 = quark transverse spin (mass term)
  - test of quark masses (covariant parton models)

d_2 Matrix Element

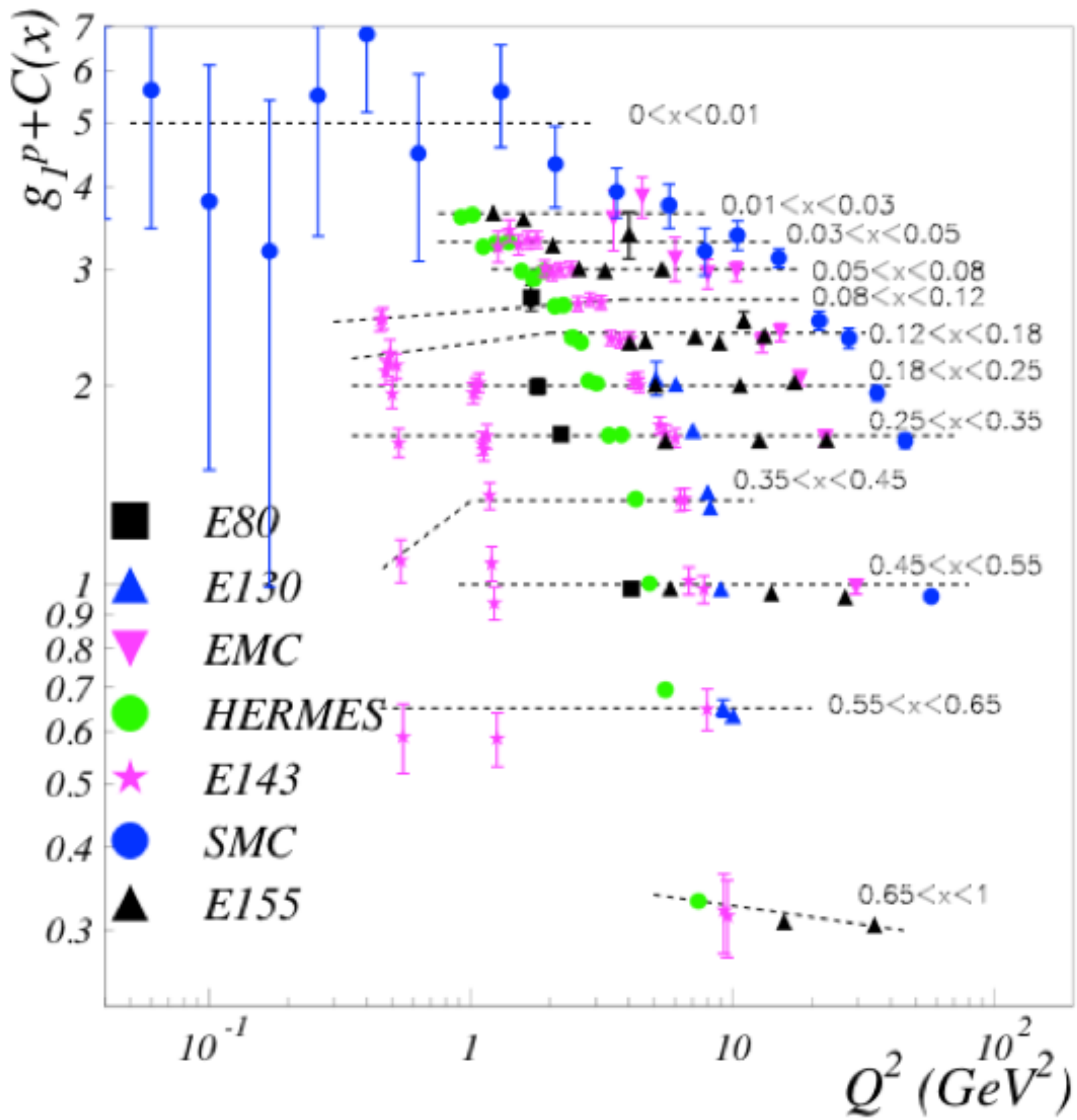
- Dynamical twist-3 matrix element

$$d_2(Q^2) = 3x^2 \int_0^1 \bar{g}_2(x, Q^2)\, dx$$

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

Proton g_1 Structure Function

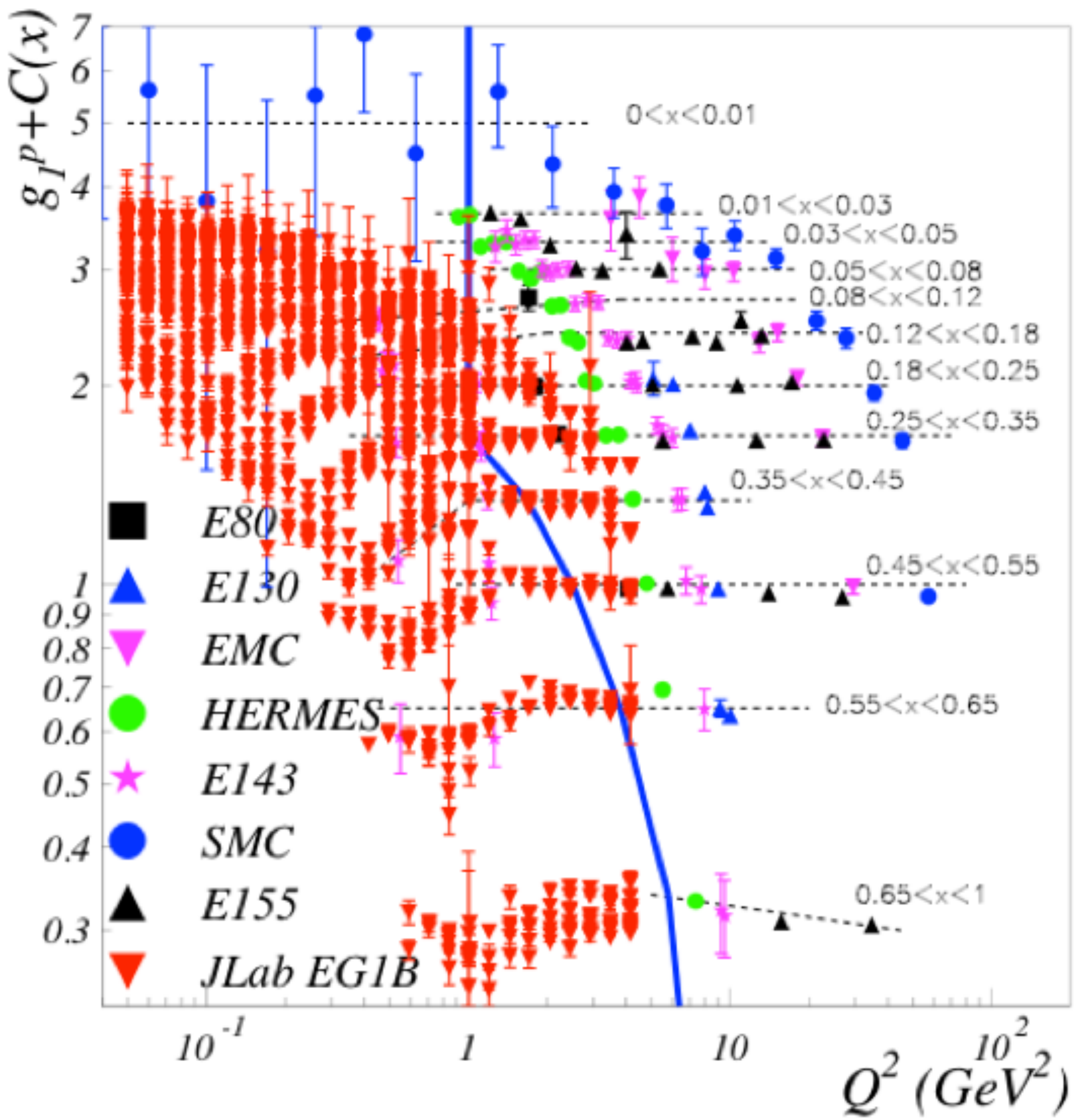
World data on the proton before JLab
(without COMPASS)



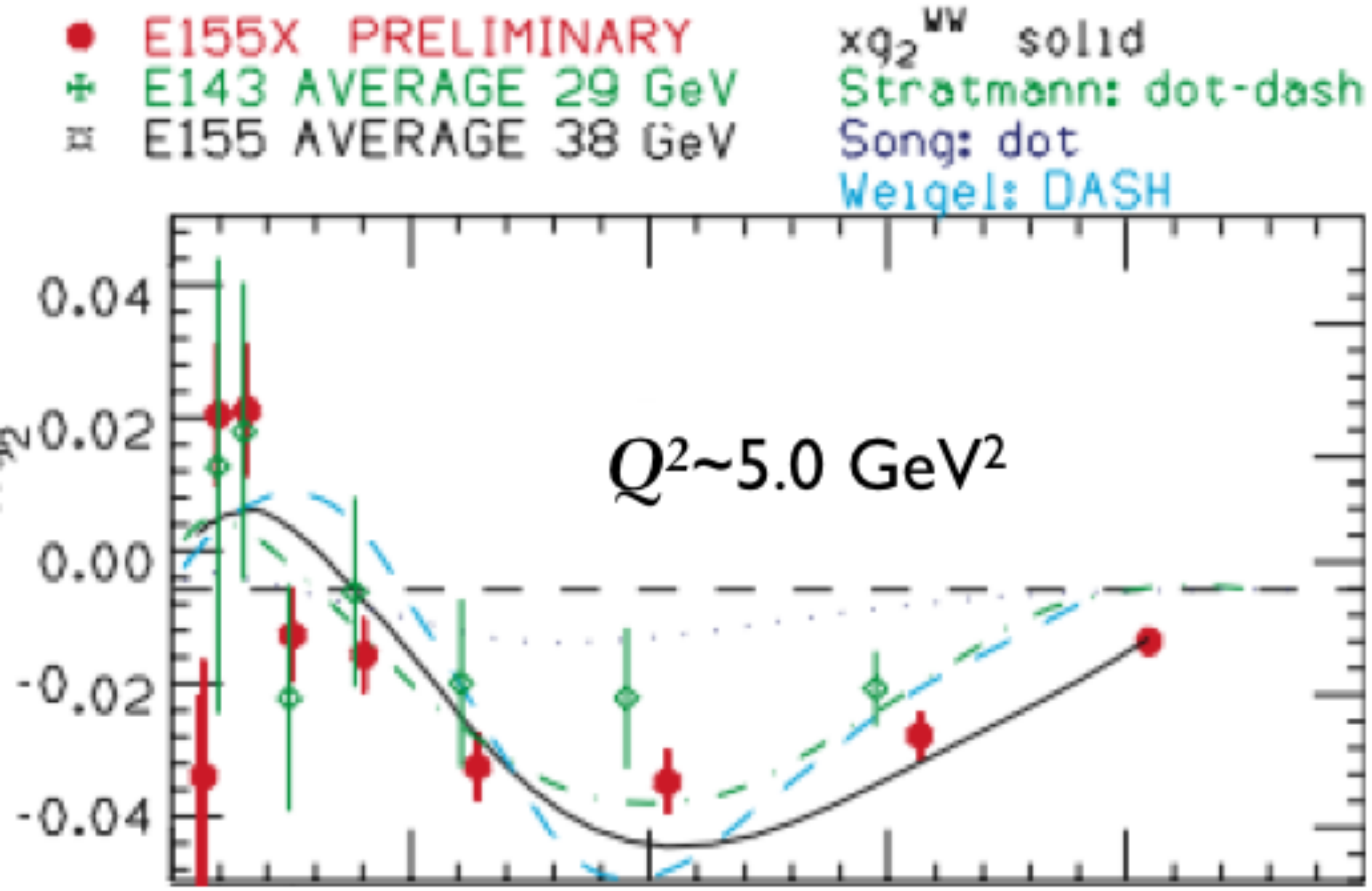
Proton g_1 Structure Function

World data on the proton before JLab
(without COMPASS)

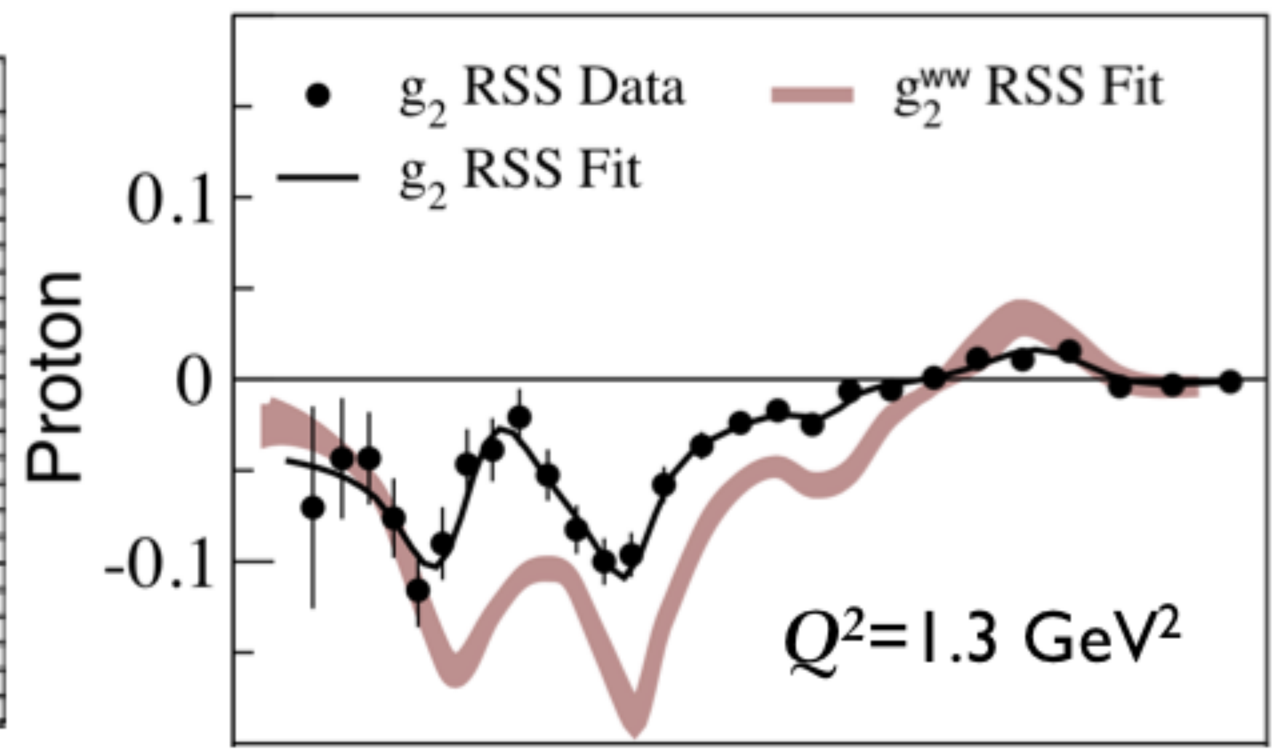
Jefferson Lab Hall-B data



World Data on Proton g_2



SLAC



JLab Hall-C (RSS)

World Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	SLAC JLab SANE	SLAC	SLAC JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	JLab E08-027		JLab E97-110
g_1 at high Q^2	SMC HERMES JLab EG1	SMC HERMES JLab EG1	HERMES
g_1 at low Q^2	SLAC HERMES JLab EG1	SLAC HERMES JLab EG1	HERMES
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

JLab Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	JLab SANE		JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	JLab E08-027		JLab E97-110
g_1 at high Q^2	JLab EG1	JLab EG1	
g_1 at low Q^2	JLab EG1	JLab EG1	
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

JLab Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	JLab SANE		JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	JLab E08-027		JLab E97-110
g_1 at high Q^2	JLab EG1	JLab EG1	
g_1 at low Q^2	JLab EG1	JLab EG1	
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

Hall-A

JLab Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	JLab SANE		JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	JLab E08-027		JLab E97-110
g_1 at high Q^2	JLab EG1	JLab EG1	
g_1 at low Q^2	JLab EG1	JLab EG1	
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

Hall-B

JLab Data on g_1 and g_2

Observable	H target	D target	^{3}He target
g_1, g_2 at high Q^2	JLab SANE		JLab E97-117 JLab E01-012 JLab E06-014
g_1, g_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
g_1, g_2 at $Q^2 \sim 0$	JLab E08-027		JLab E97-110
g_1 at high Q^2	JLab EG1	JLab EG1	
g_1 at low Q^2	JLab EG1	JLab EG1	
g_1 at $Q^2 \sim 0$	JLab EG4	JLab EG4	

Hall-C

JLab Experiments focusing on g_2

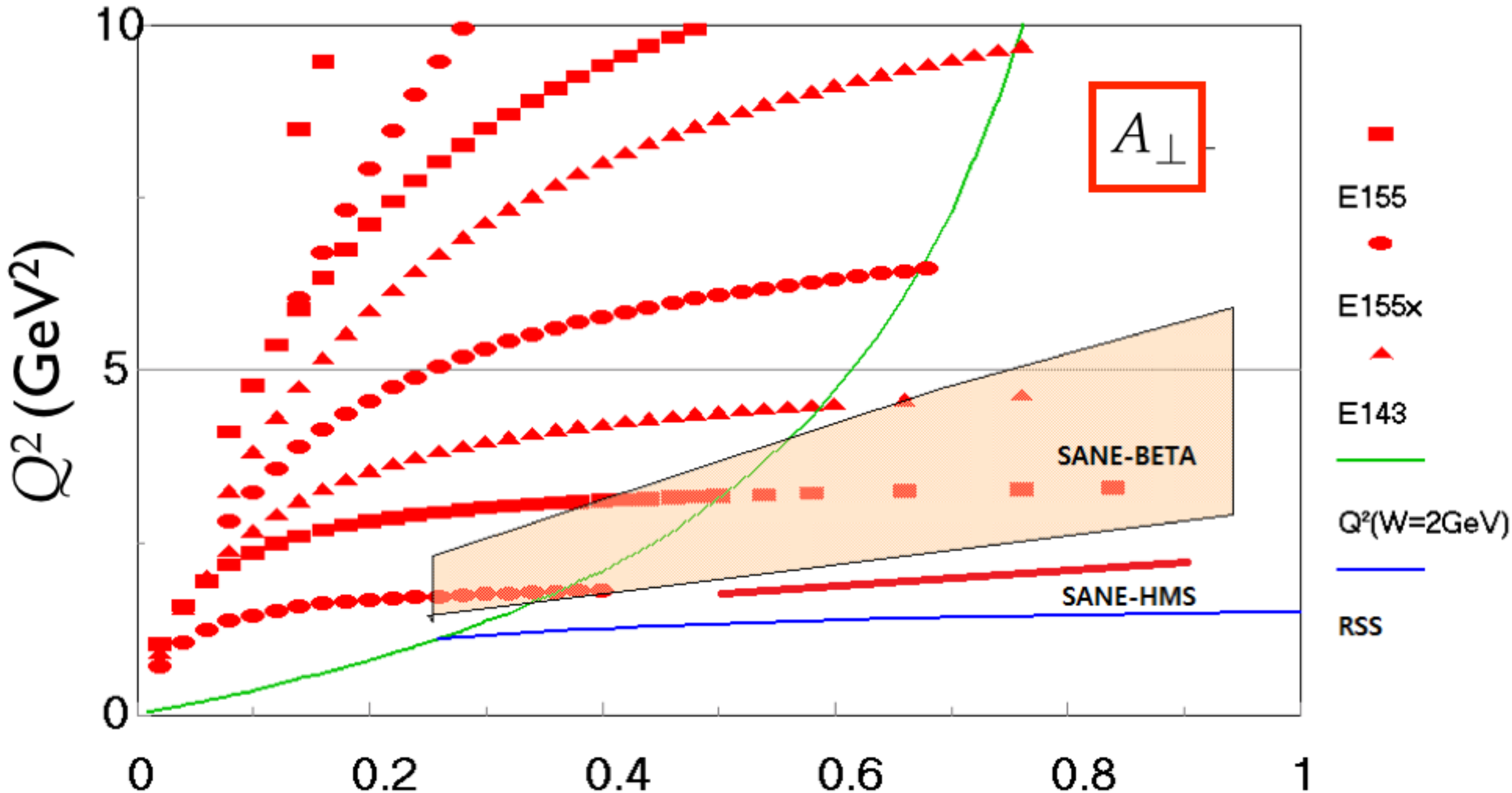
- SANE
    - proton, relatively high Q^2
- d_2^n
    - neutron, relatively high Q^2
- g_2^p
    - proton, very small Q^2
- d_2^n at 12 GeV

Spin Asymmetries of the Nucleon Experiment

Experiment Summary

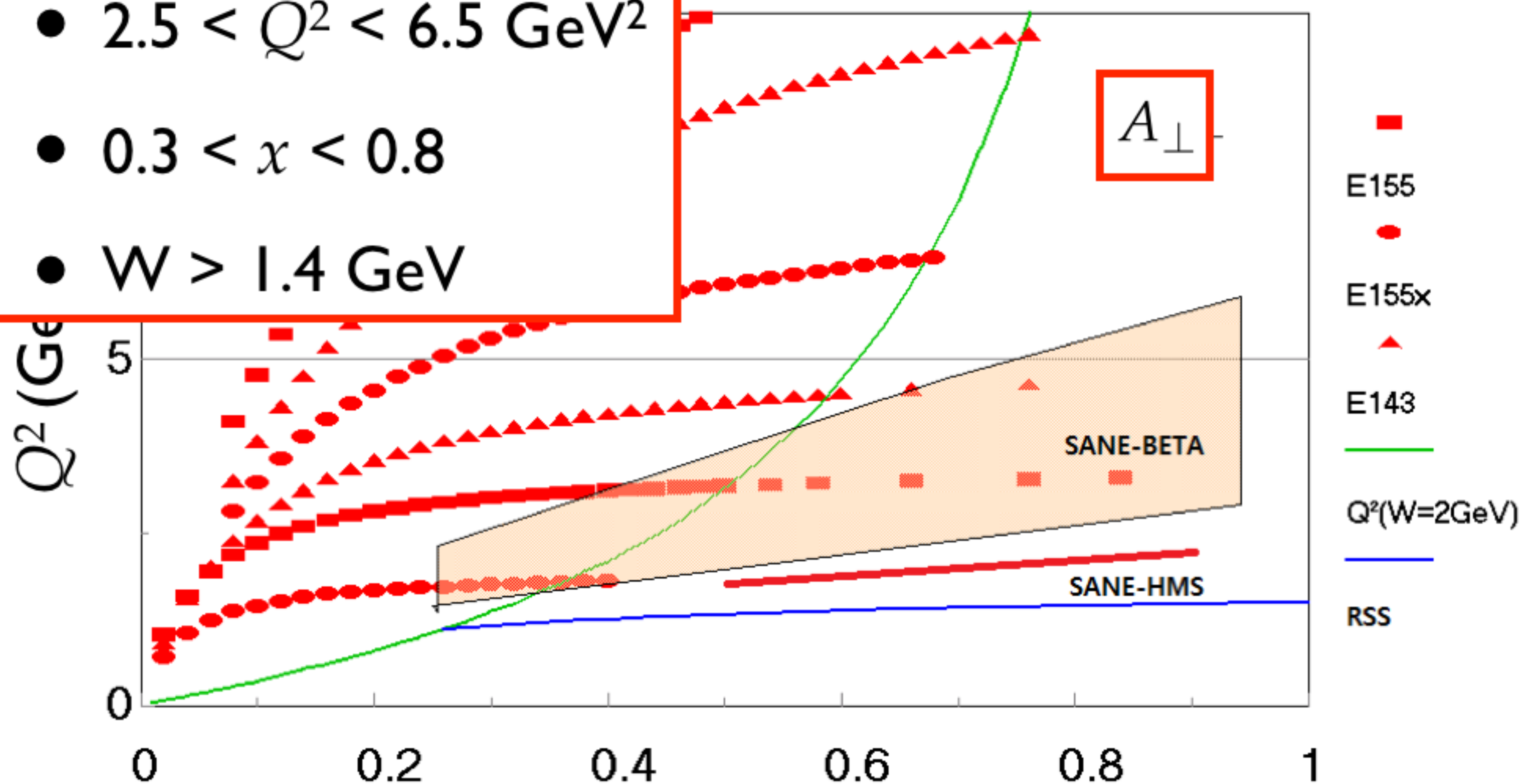
- **Beam**: polarized electron beam (Jefferson Lab) at **4.7** and **5.9** GeV
- **Target**: Polarized **Proton** (NH_3) target
  - Polarization: ~71%
  - Orientation: parallel (180°) or "**perpendicular**" (80°)
- **Detectors**: **BETA** and **HMS** of Hall-C
- Scattering angle: 40° for BETA, 15.5°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

Kinematic Coverage

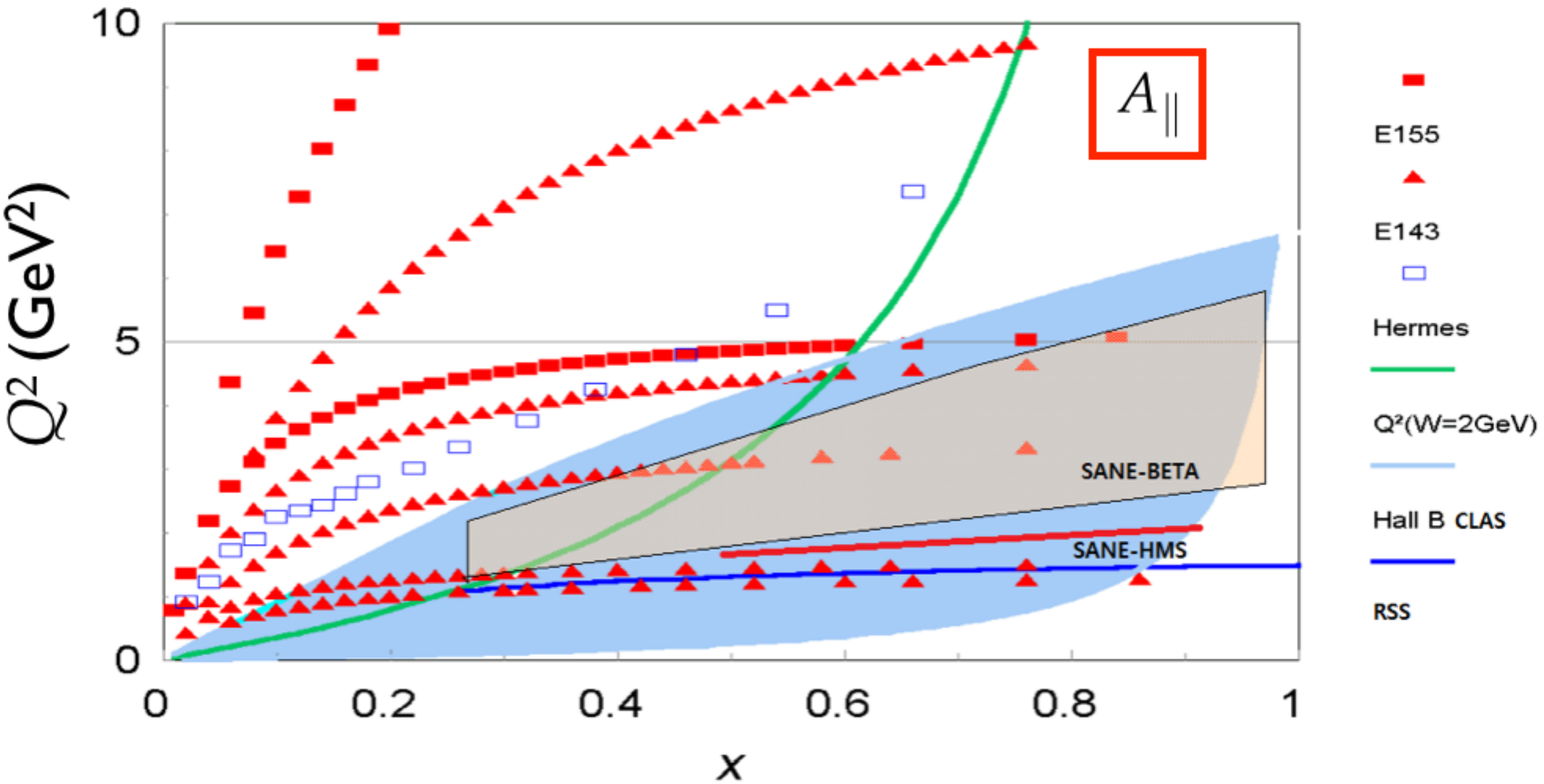


Kinematic Coverage

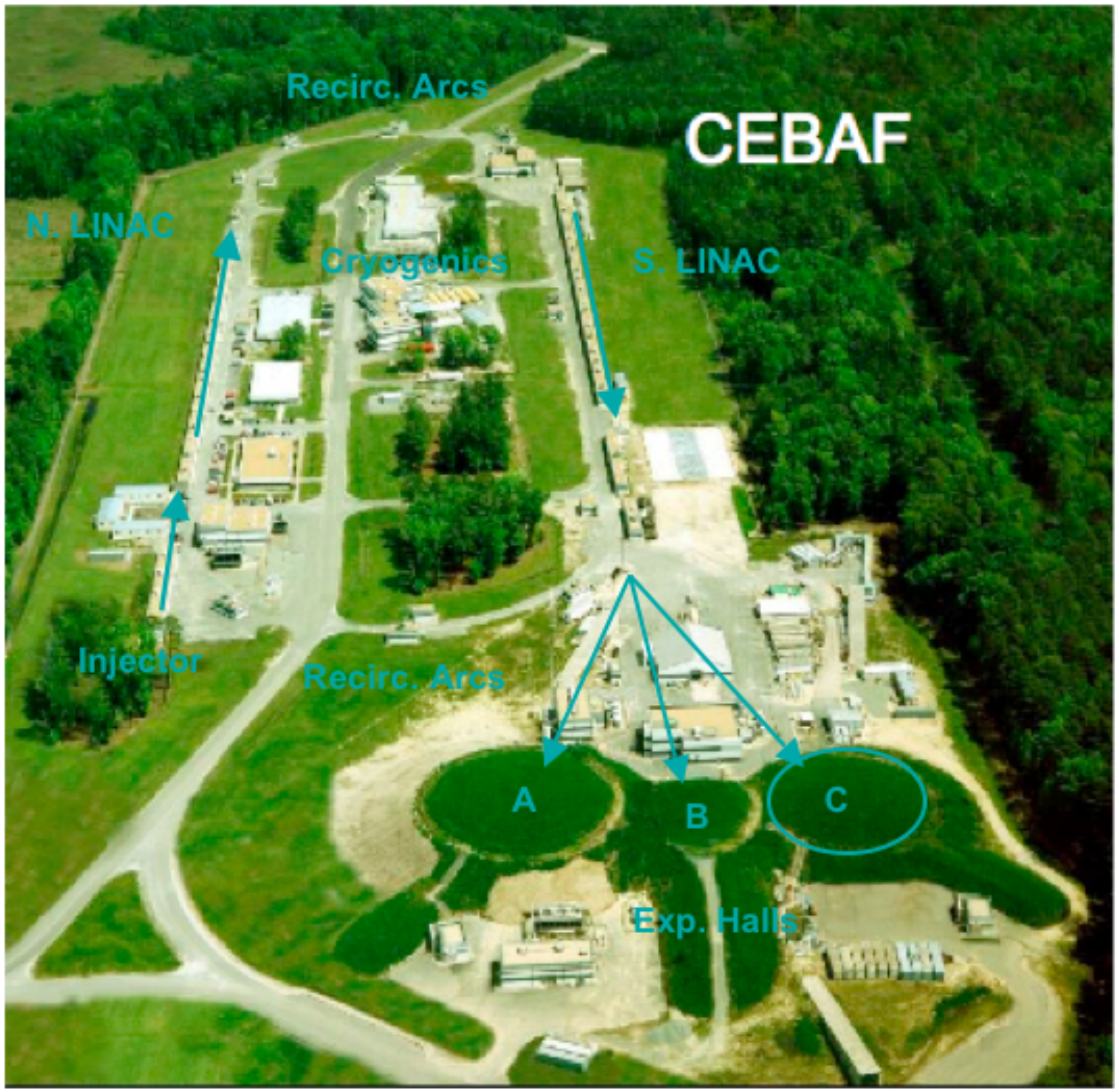
- $2.5 < Q^2 < 6.5$ GeV^2
- $0.3 < x < 0.8$
- W > 1.4 GeV



Kinematic Coverage

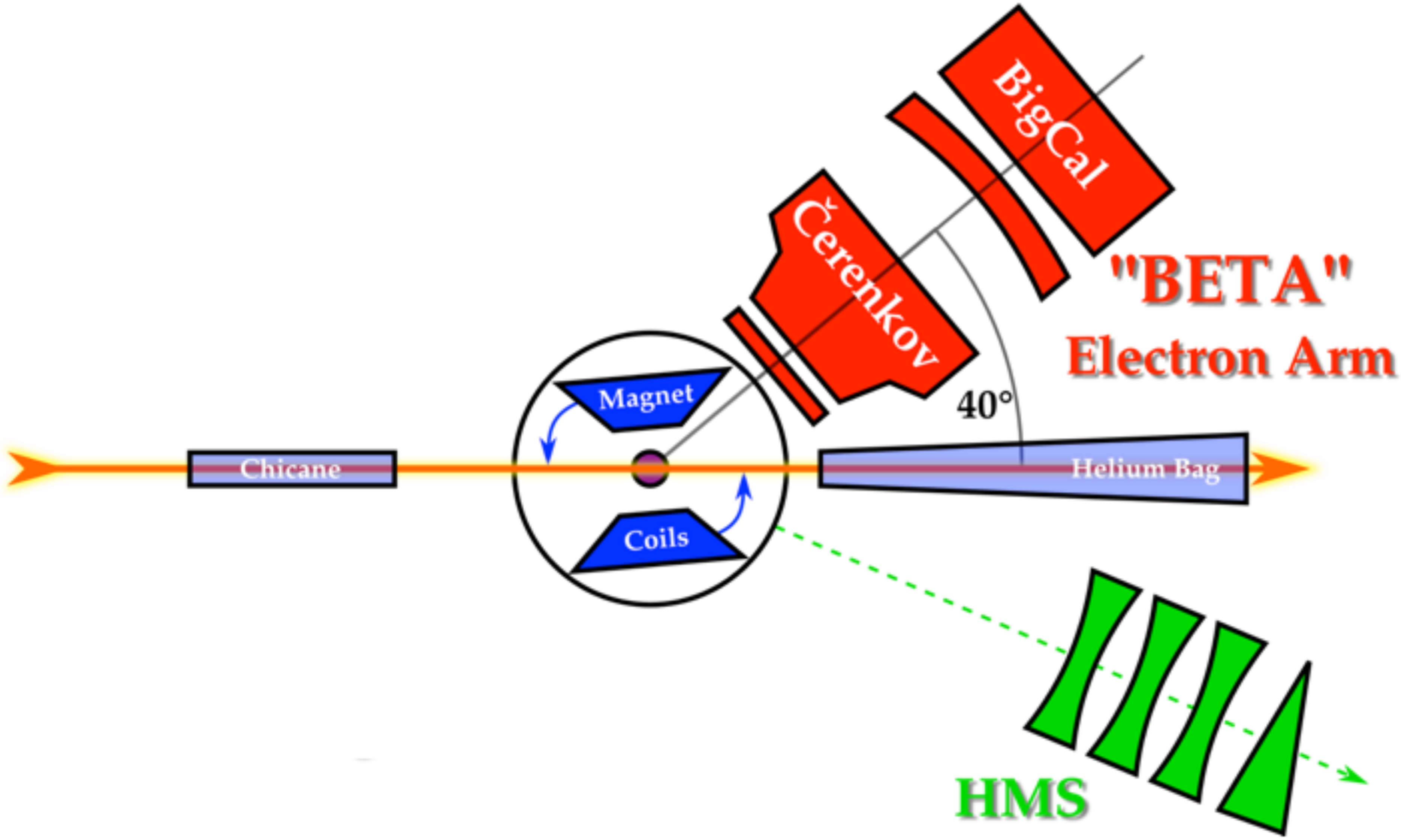


Jefferson Lab



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

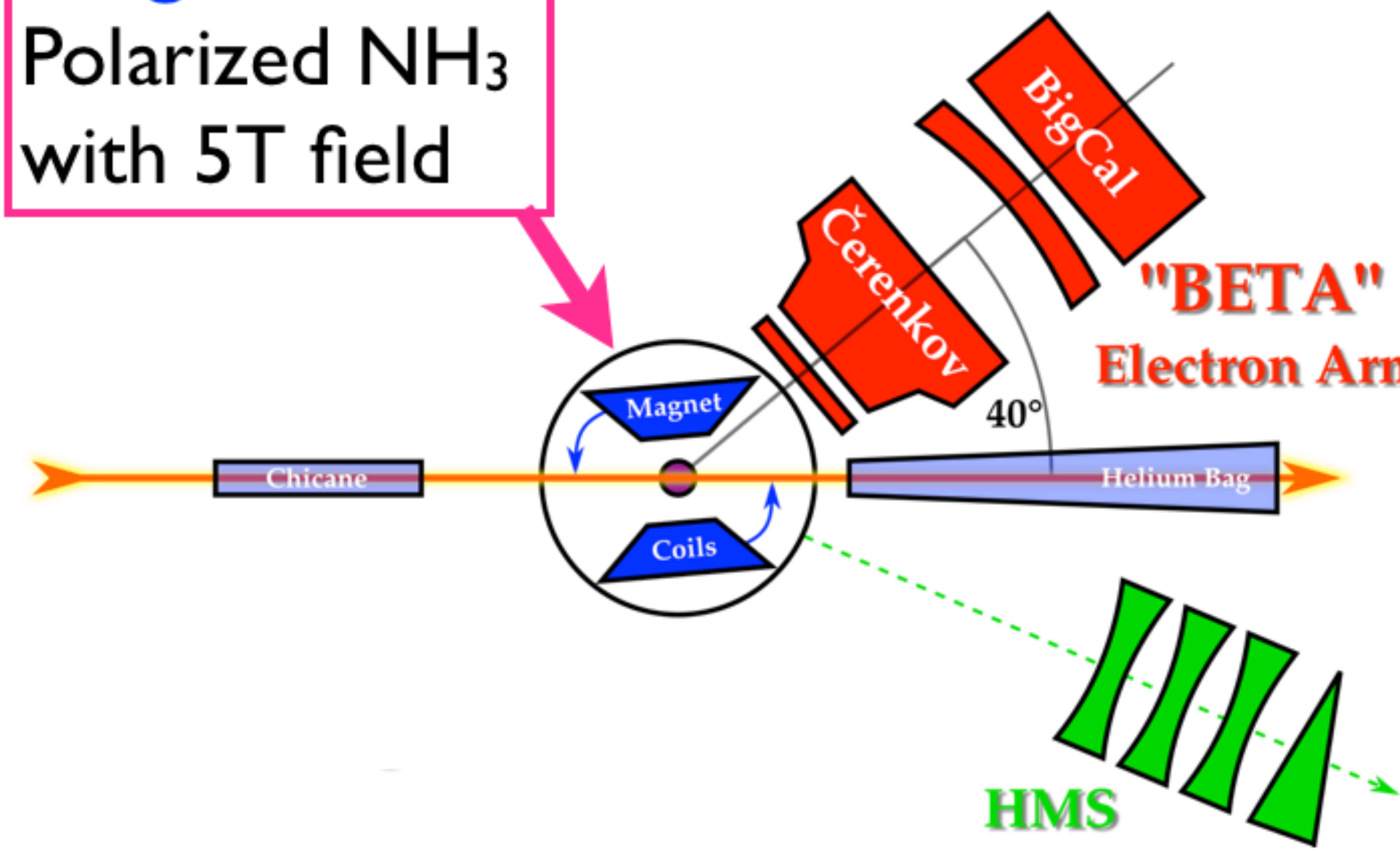
Setup



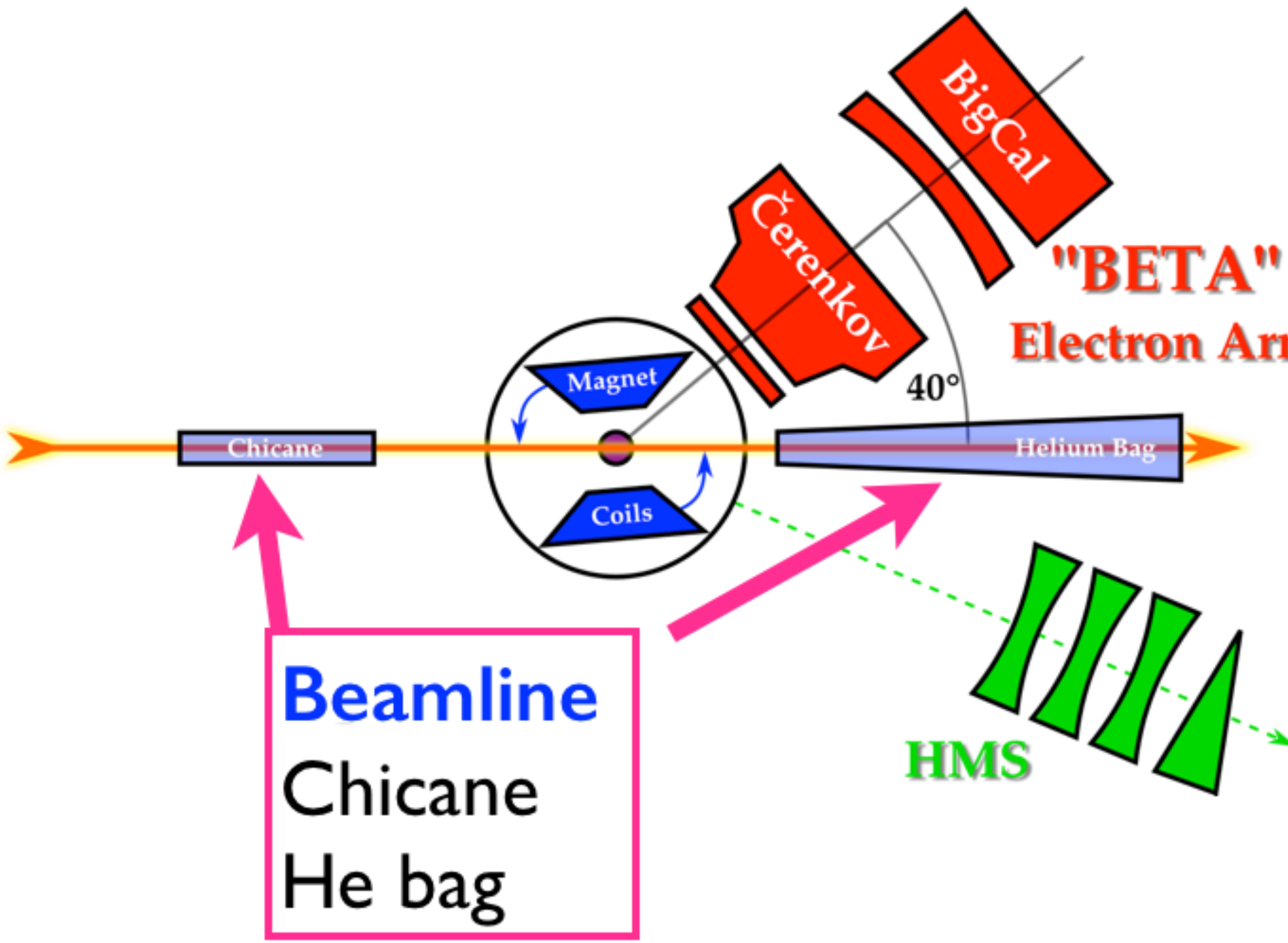
BigCal
Čerenkov
"BETA"
Electron Arm
40°
Magnet
Chicane
Helium Bag
Coils
HMS

Setup

Target
Polarized NH_3
with 5T field



Setup


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

Setup

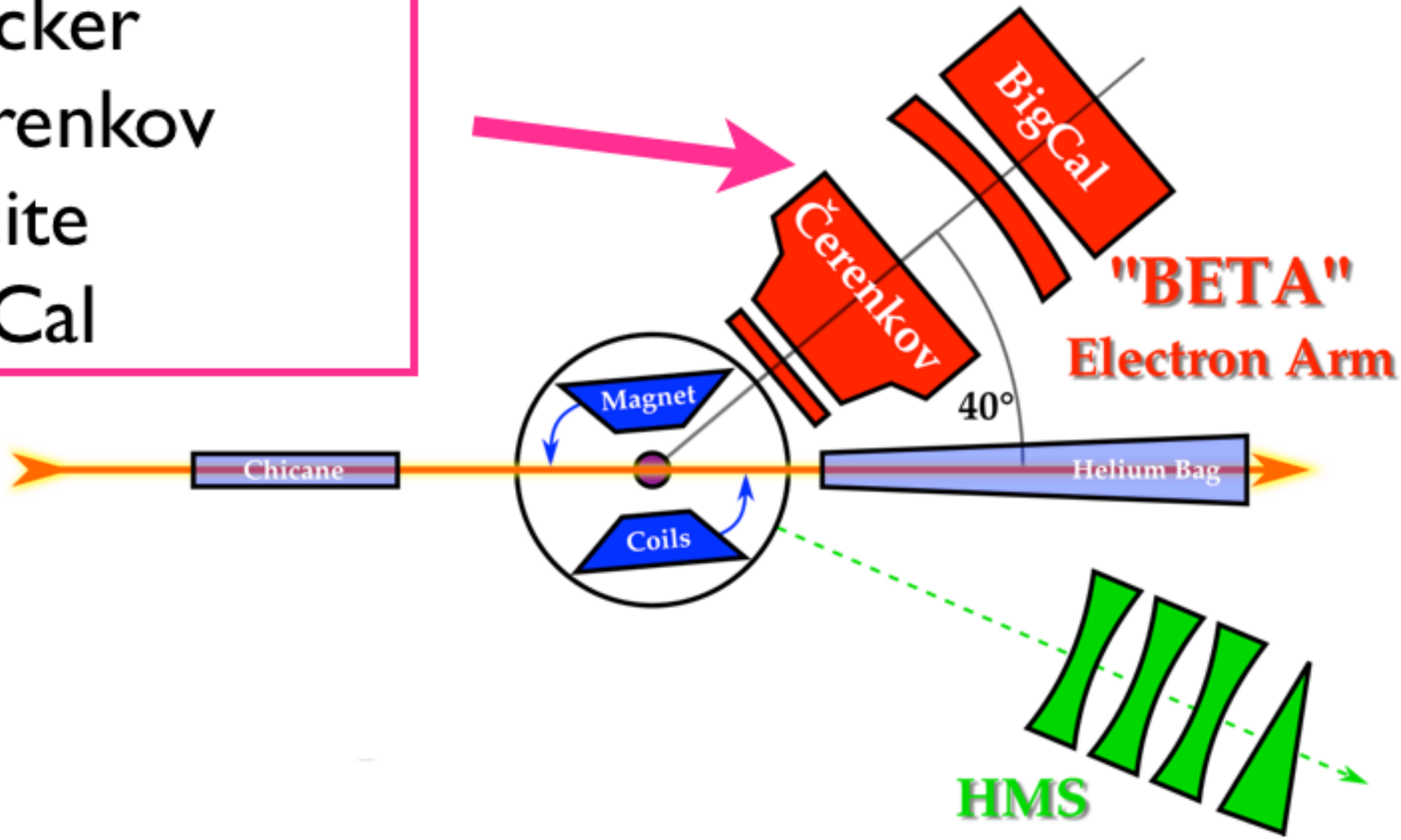
Electron Arm

Tracker

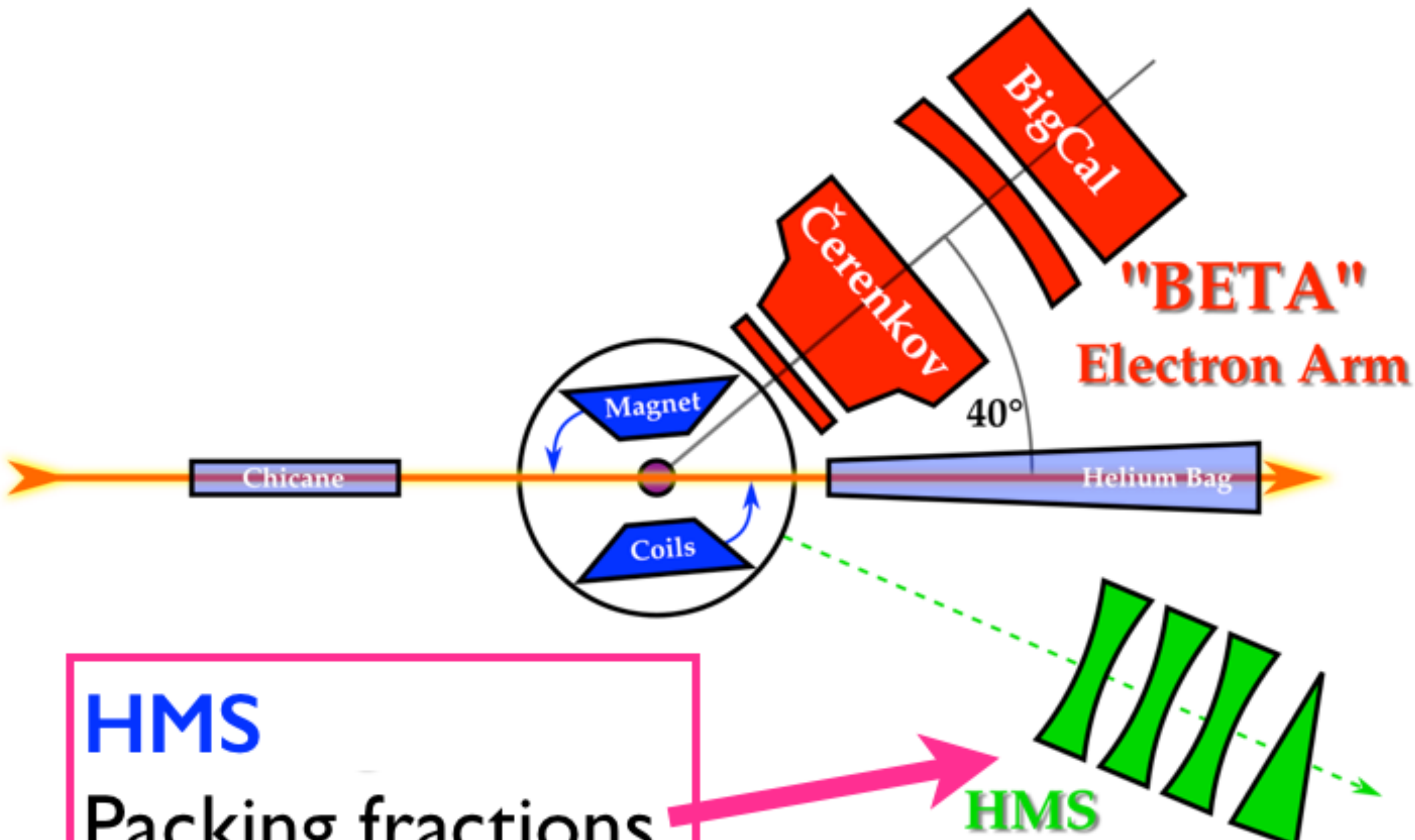
Cerenkov

Lucite

BigCal



Setup



HMS

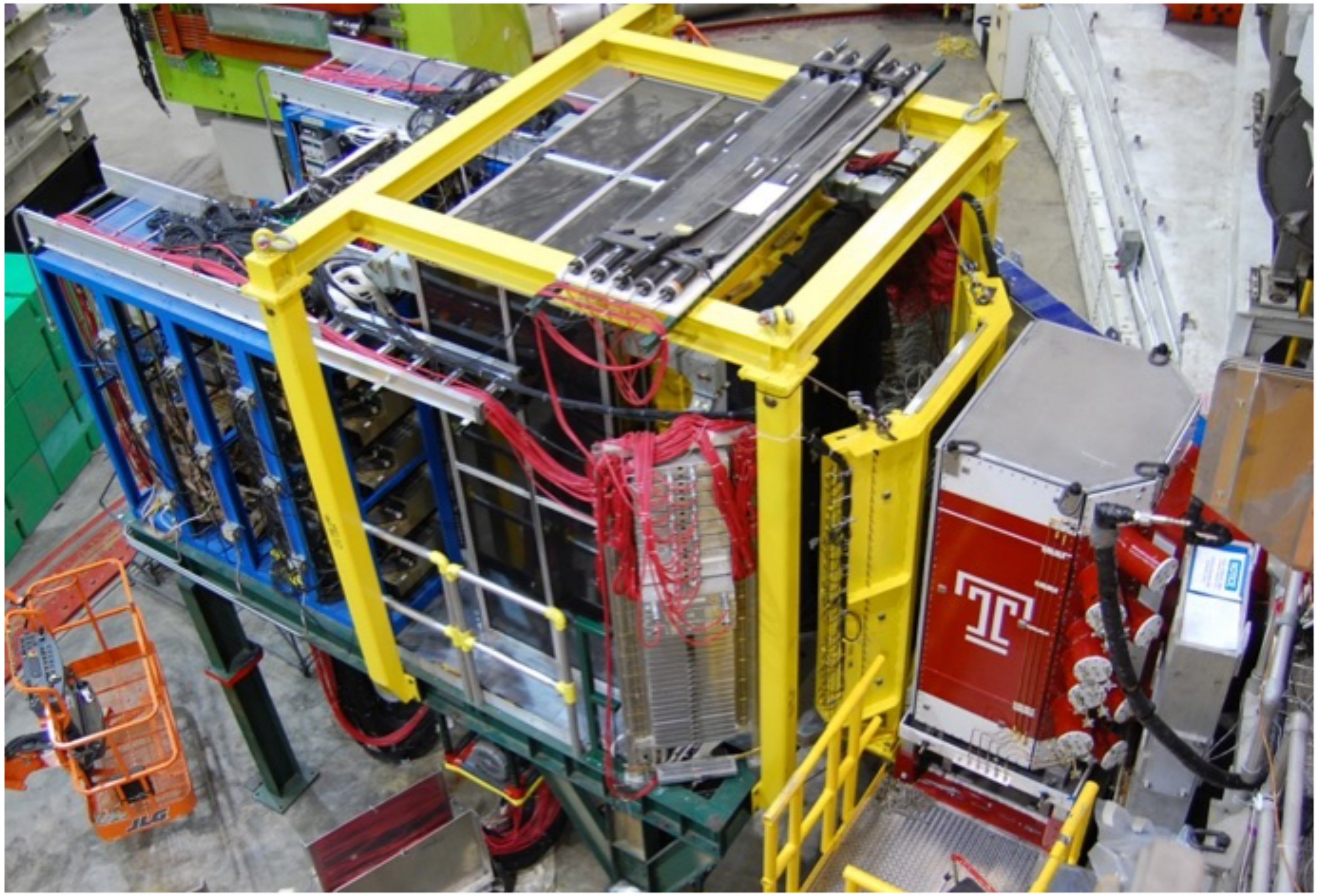
Packing fractions

Monitoring

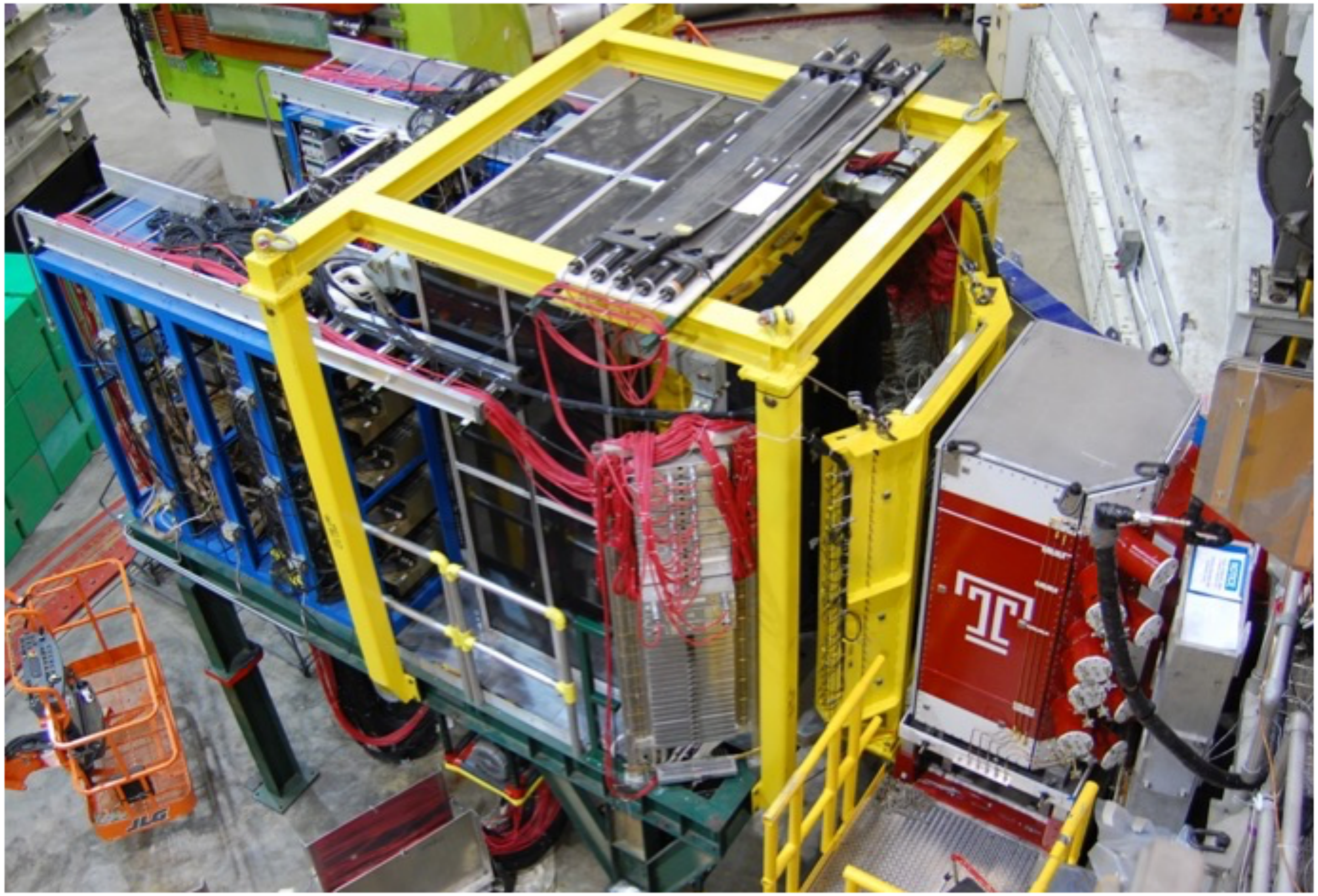
Big Electron Telescope Array

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

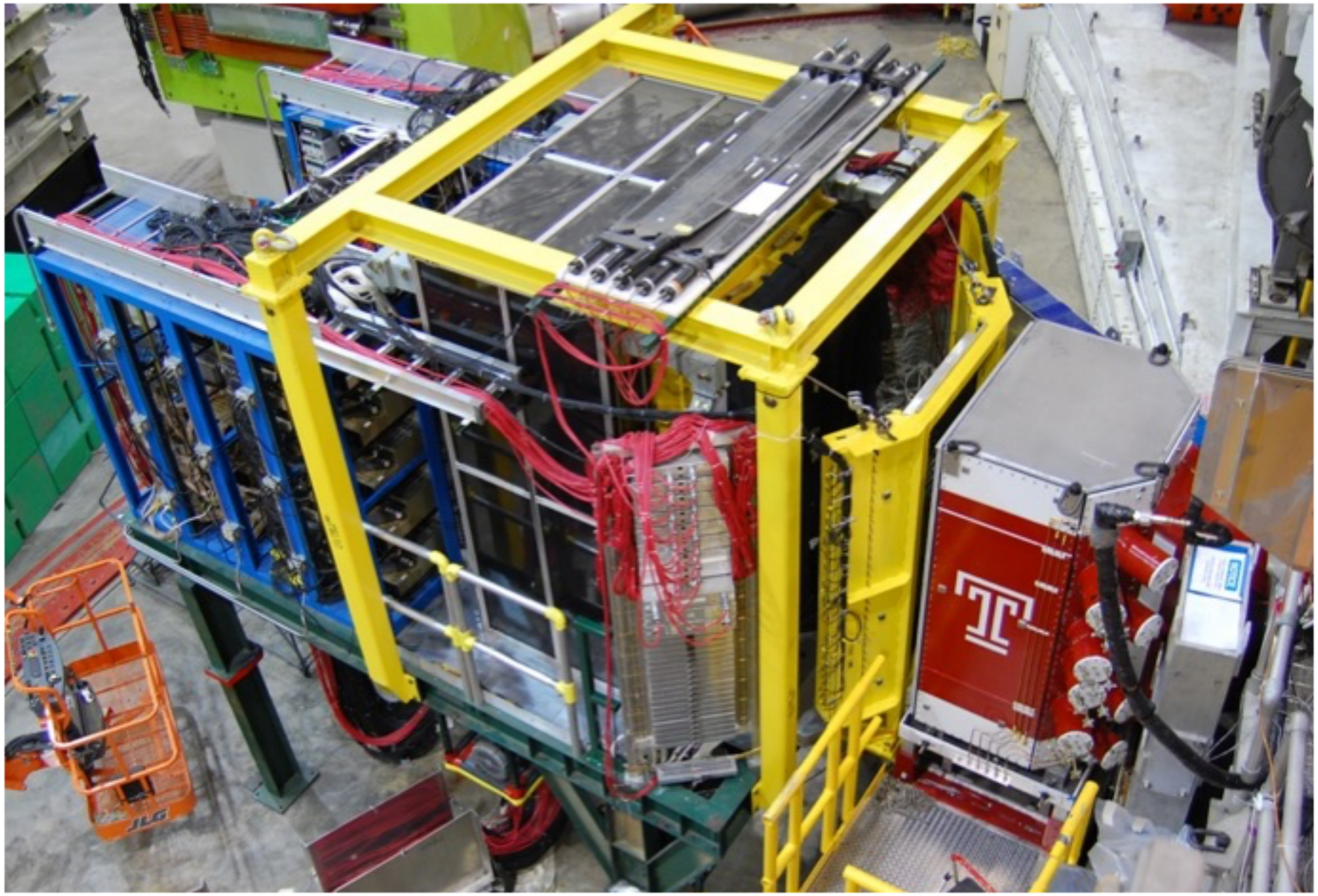
BETA



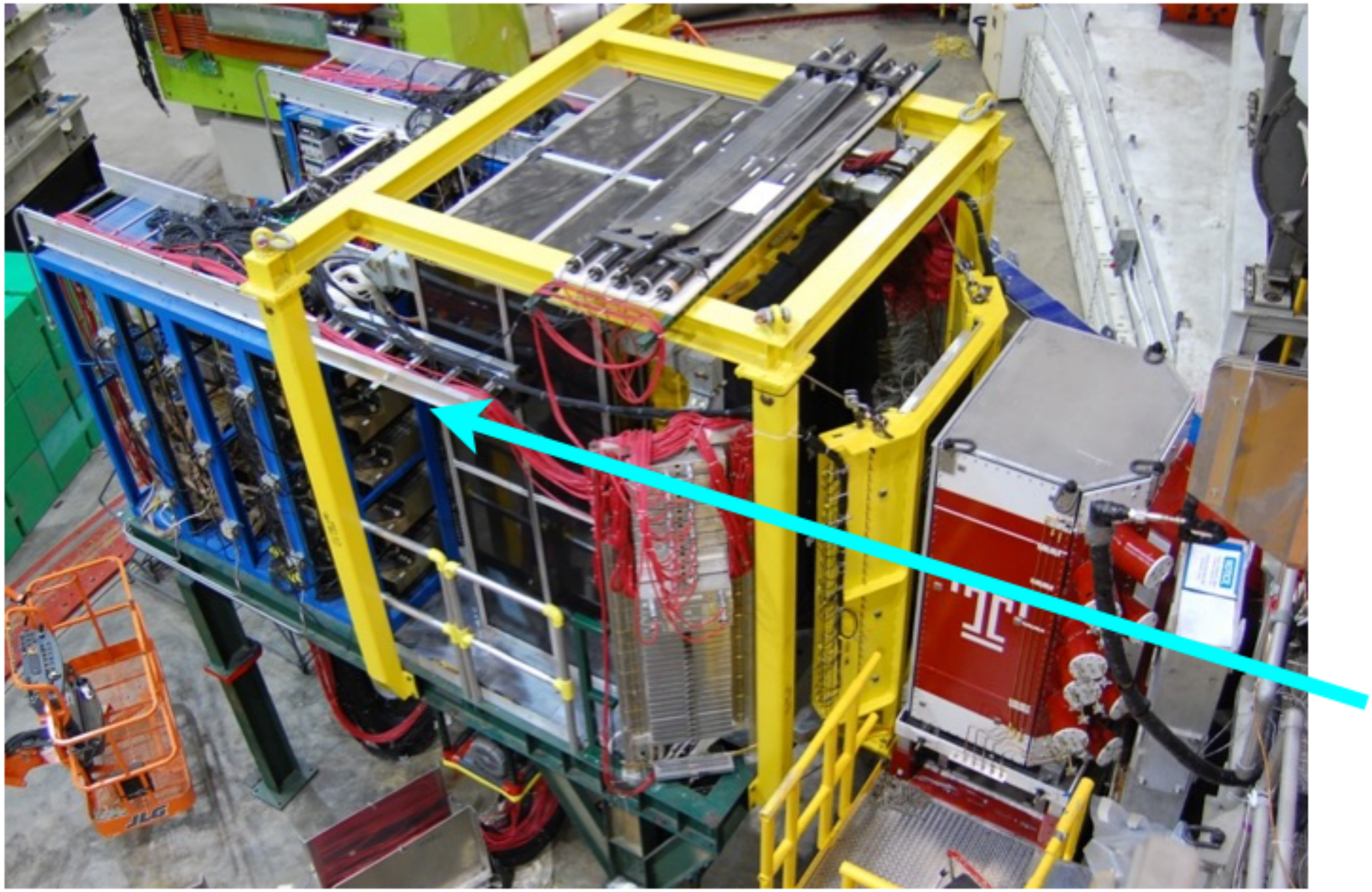
BETA



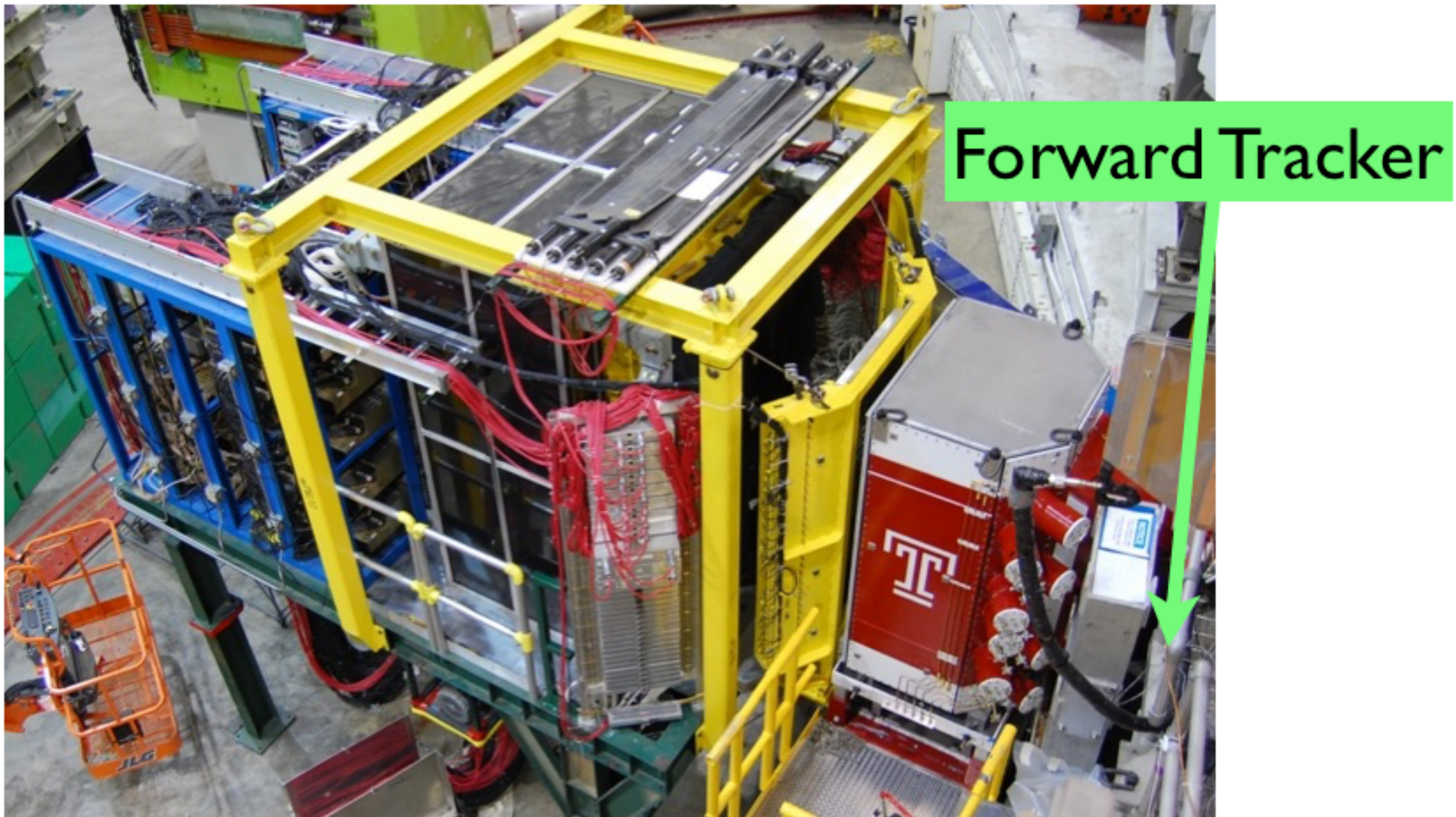
BETA



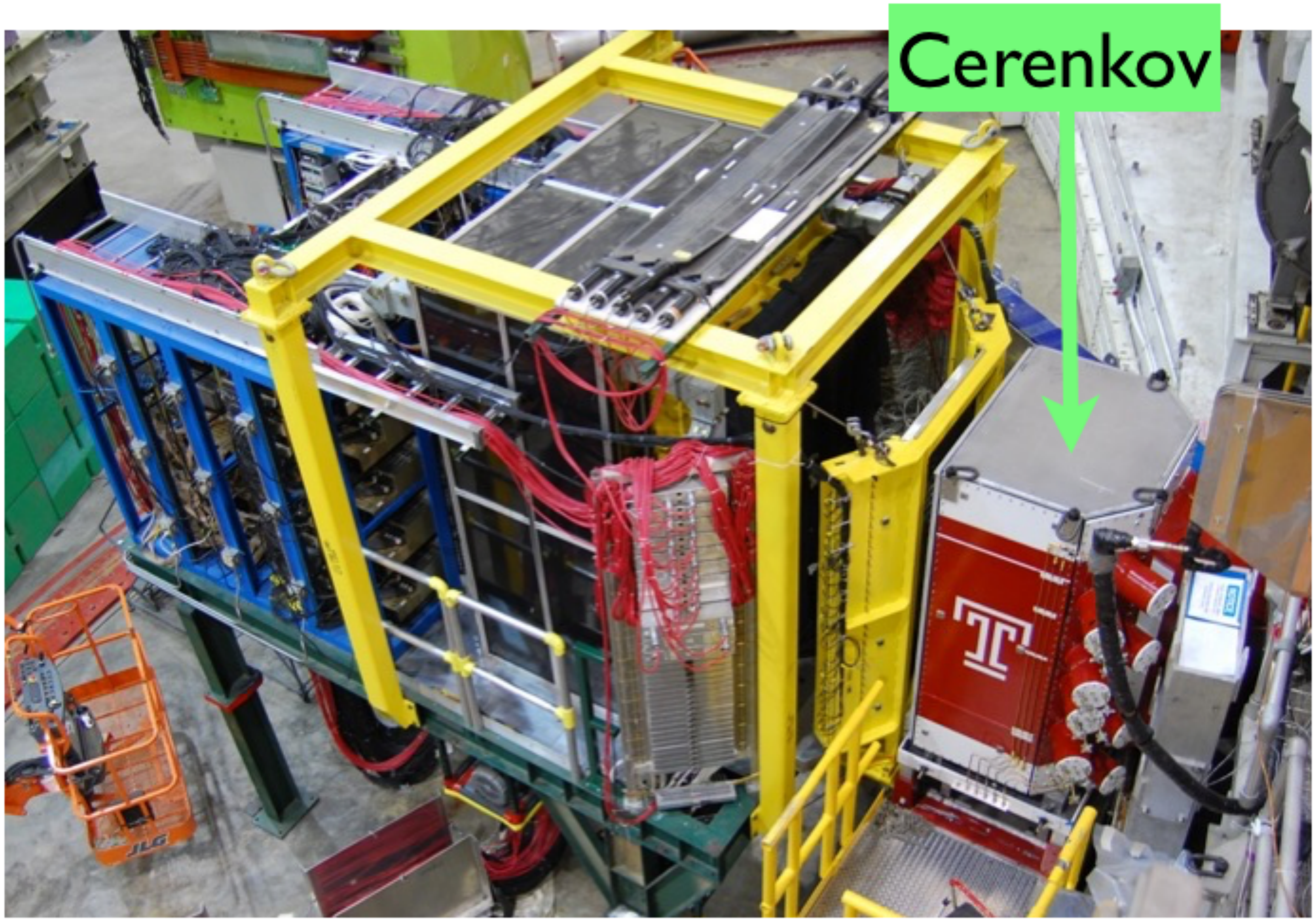
BETA



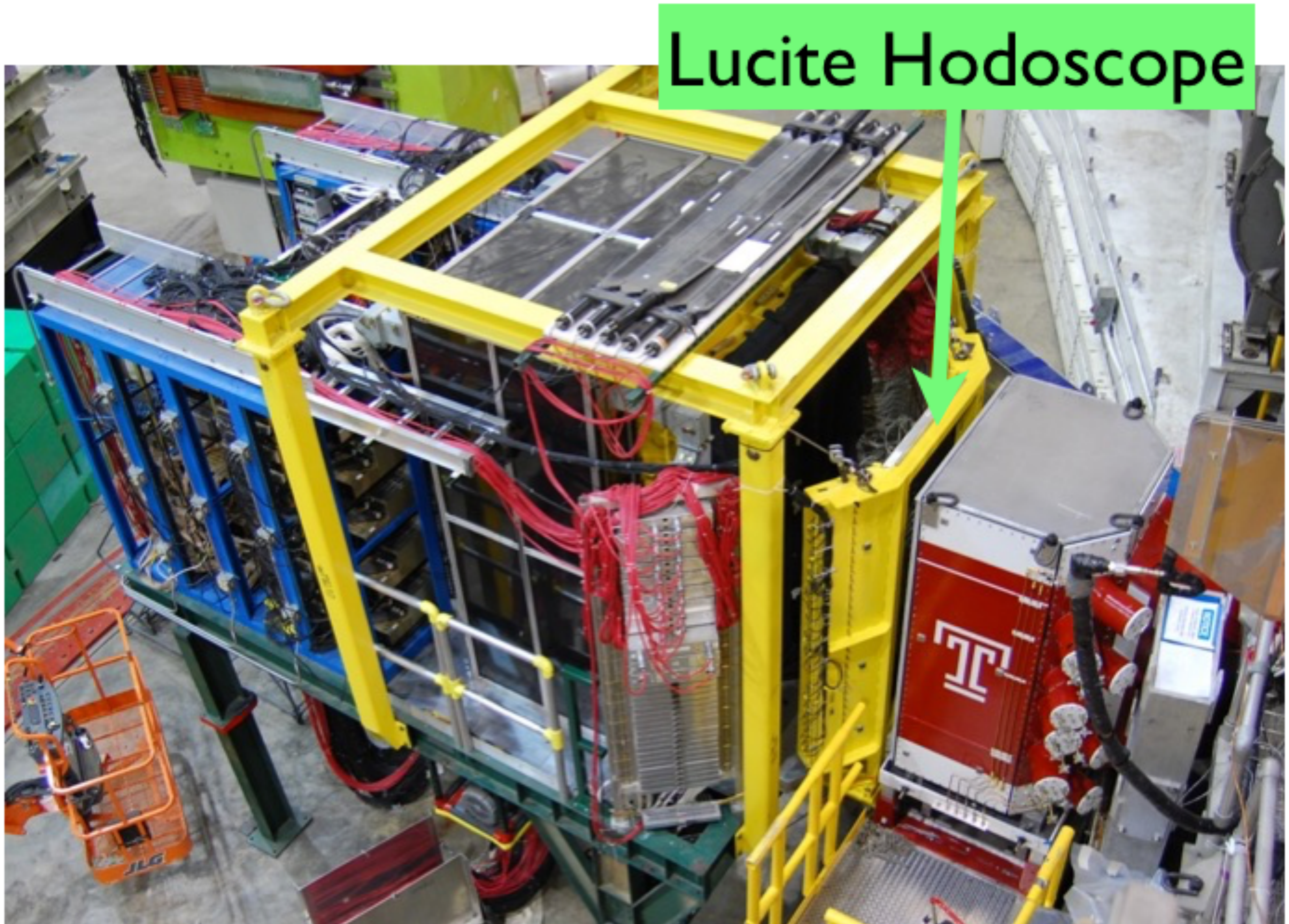
BETA



BETA



BETA



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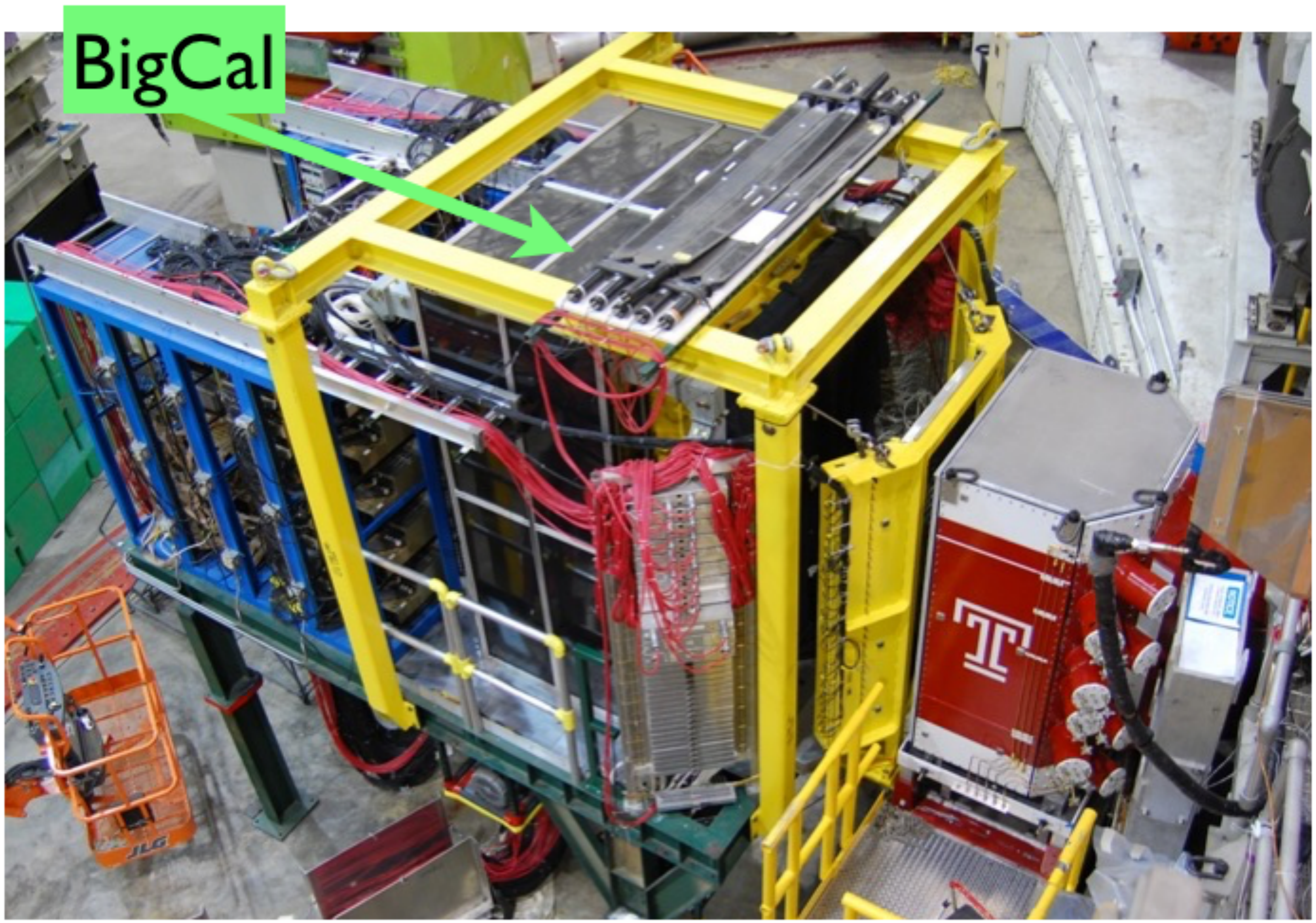
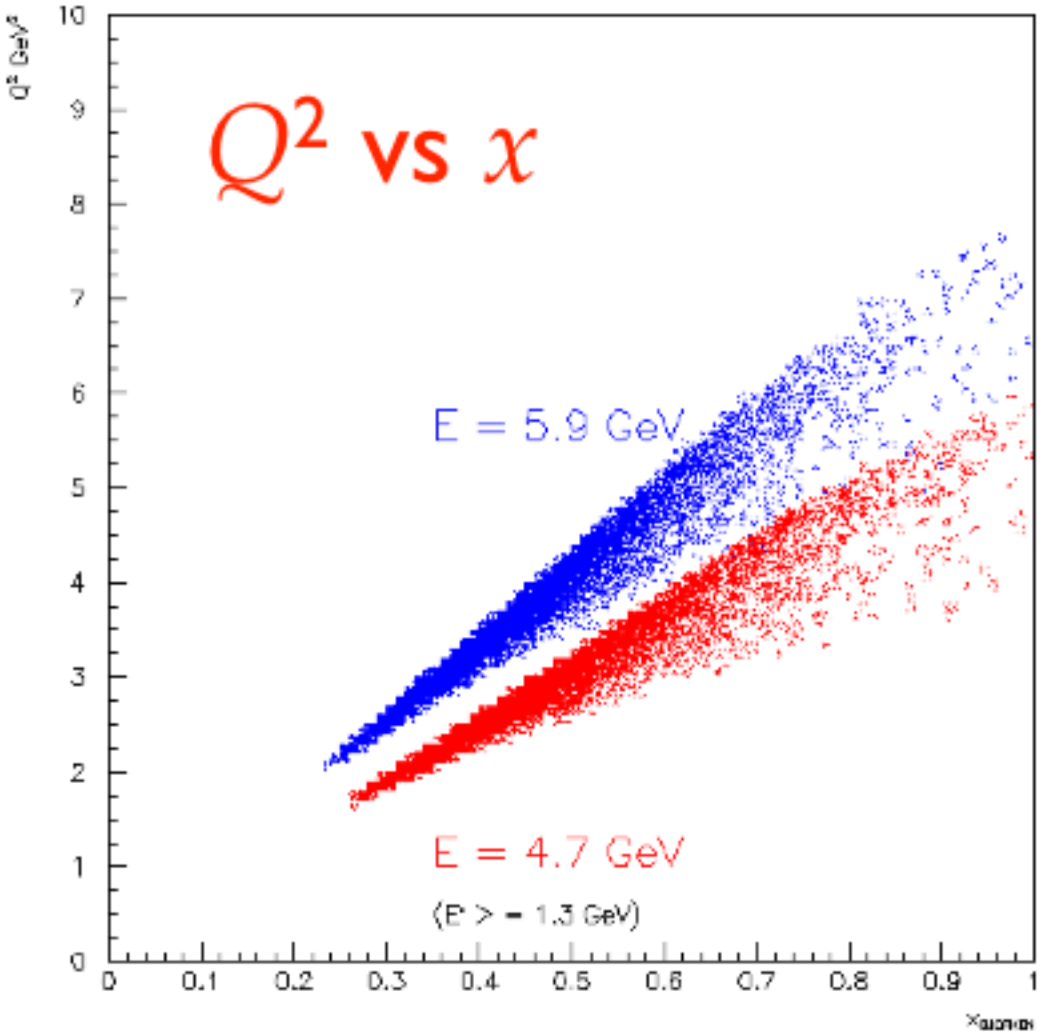
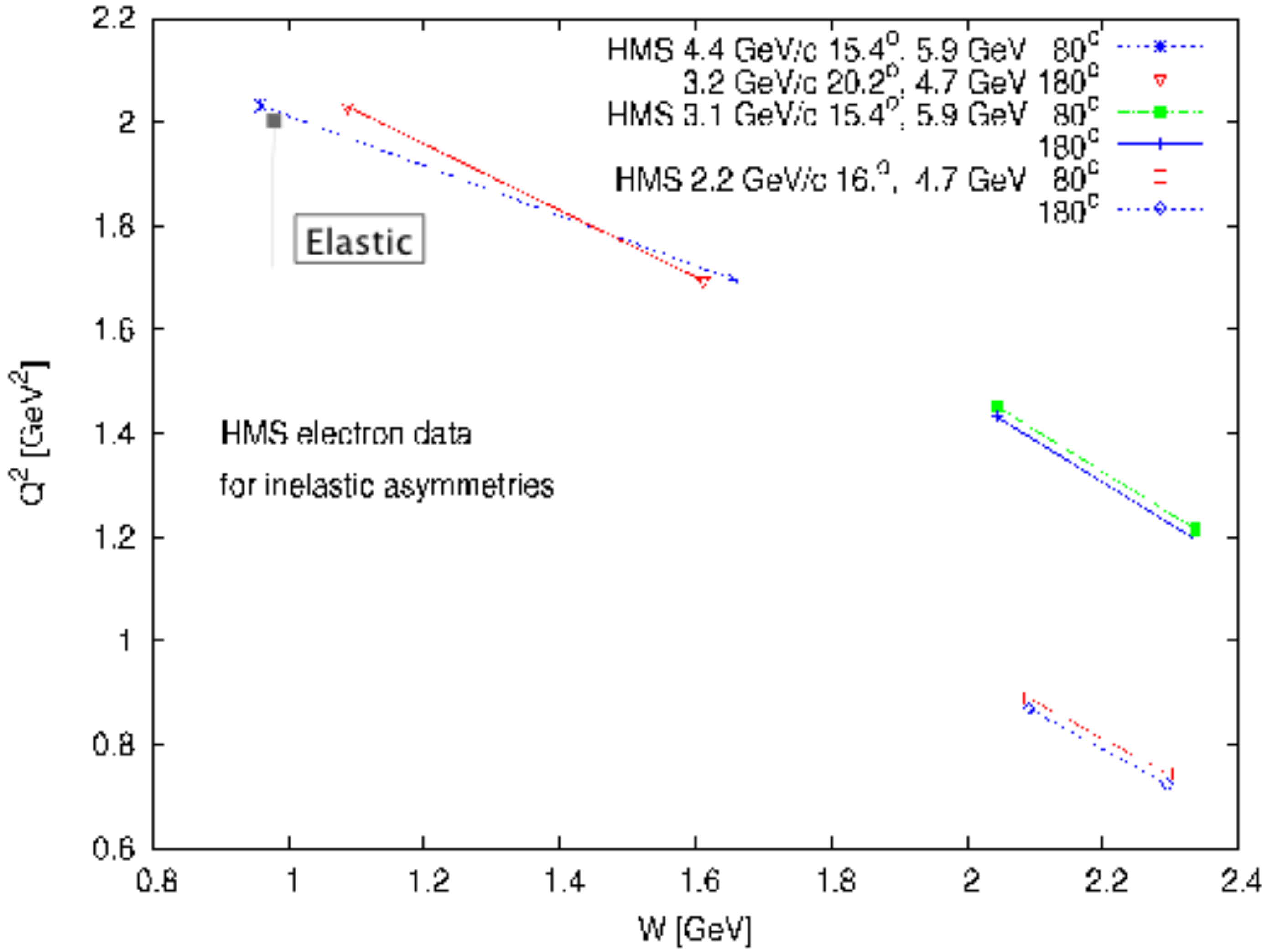


Kinematic Coverage

BETA

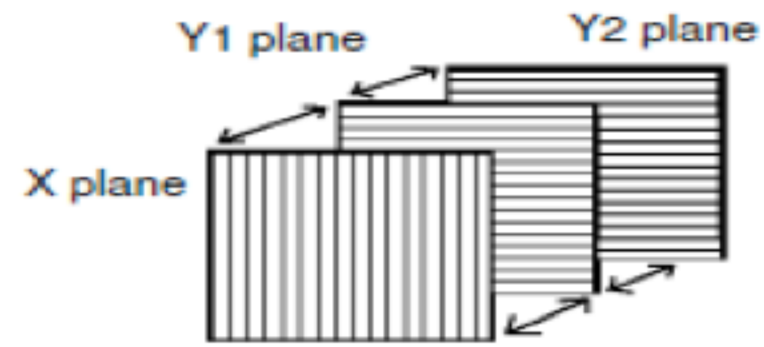


HMS



BETA

- Forward Tracker
  - 3 planes of Bicron Scintillators
  - Early particle tracking
- Cerenkov
  - N_2 gas
  - 8 sets of mirror + PMT
  - Particle ID



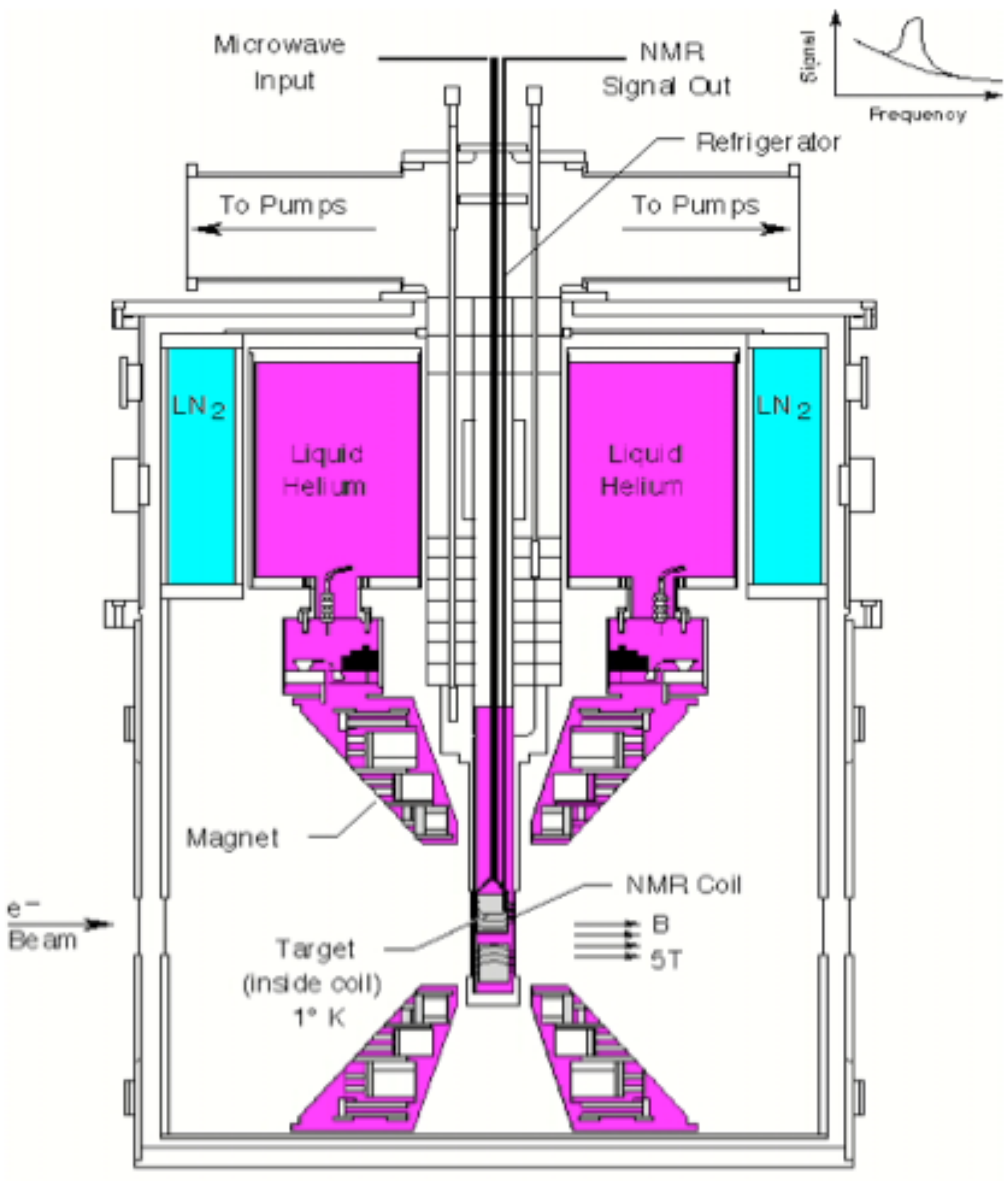
BETA

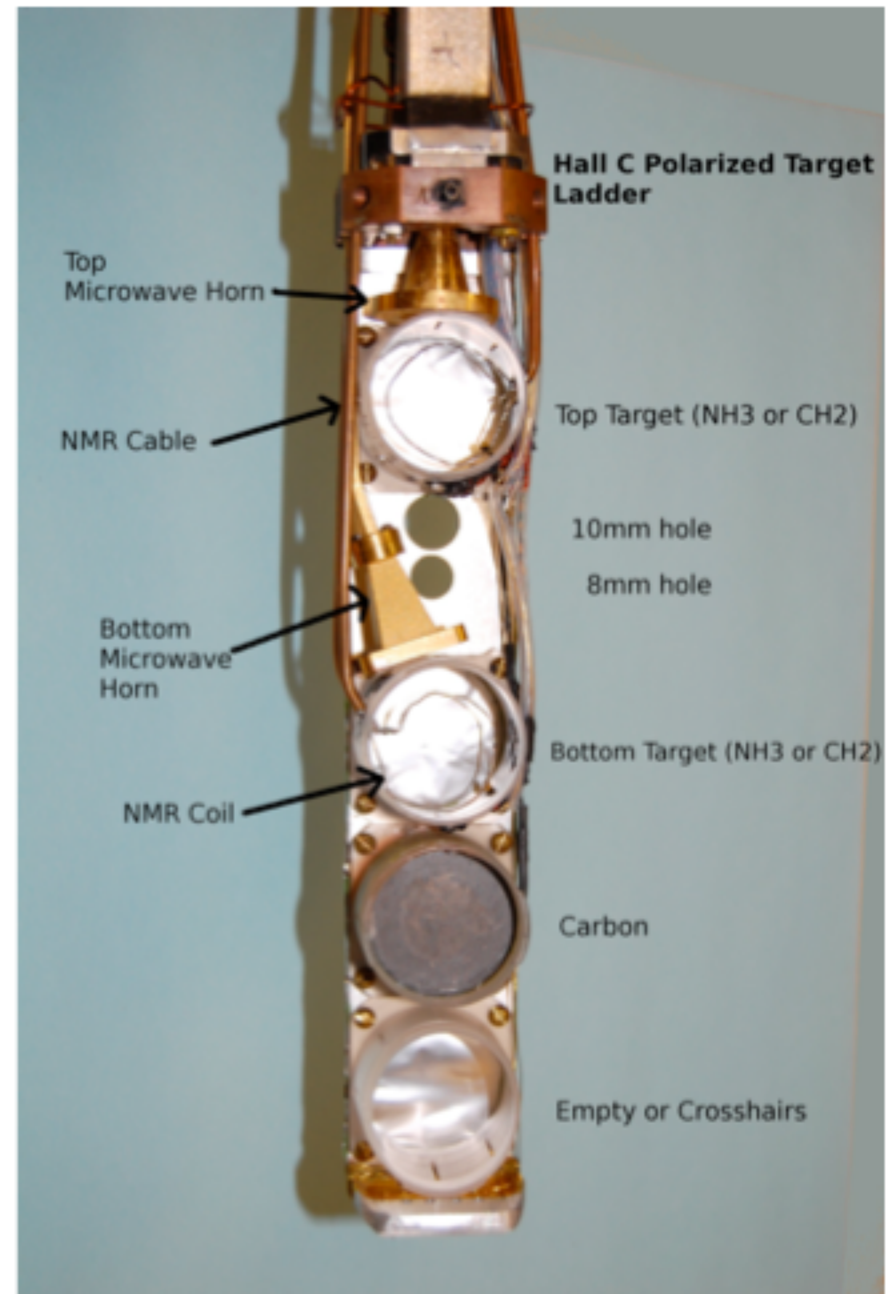
- Lucite Hodoscope
  - 28 bars of 6cm wide lucite
  - Vertically stacked bars for Y information
  - PMT's on both sides for X information
- BigCal
  - Lead glass calorimeter
  - 1744 blocks (about 4cm x 4cm each)
  - Position and energy measurement

BETA - Characteristics

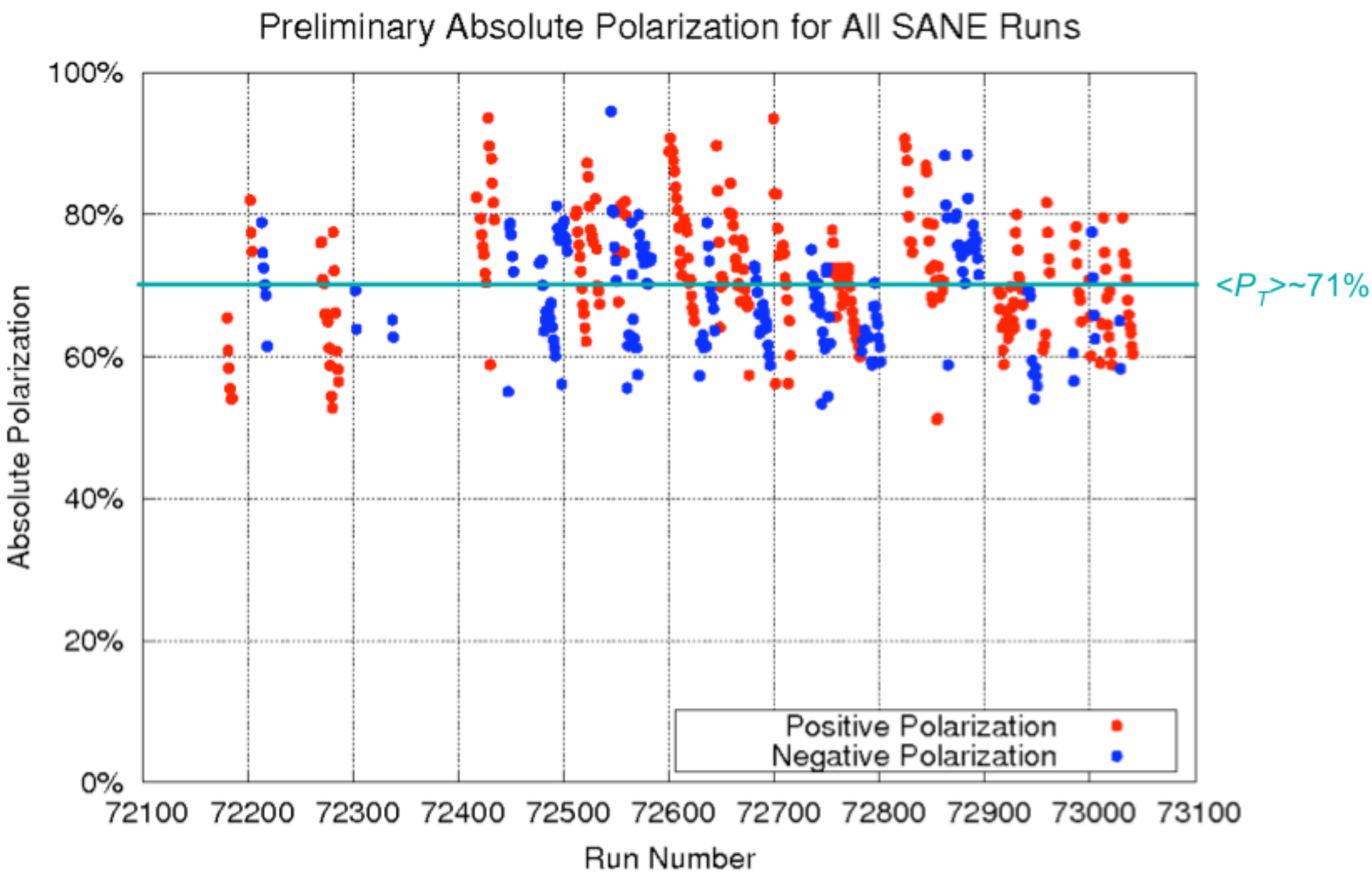
- Effective solid angle: 0.9 sr
- Energy resolution: 5%/$\sqrt{E(GeV)}$
- Angular resolution ~ 1mr
- Pion rejection of 1000:1
- Vertex resolution: ~ 5mm

Polarized NH_3 Target





Target Performance



Data Taking

Data Taking

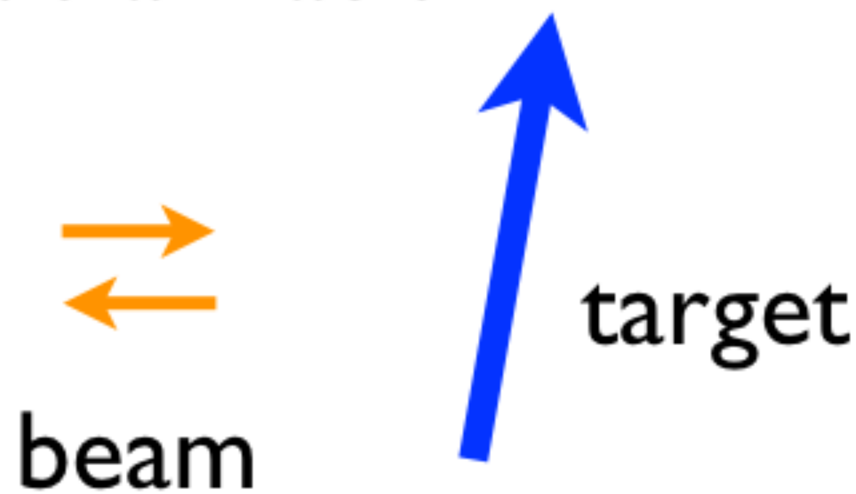
- For 2 beam energies: **4.7** and **5.9**

Data Taking

- For 2 beam energies: **4.7** and **5.9**
- 2 different orientations of polarizations

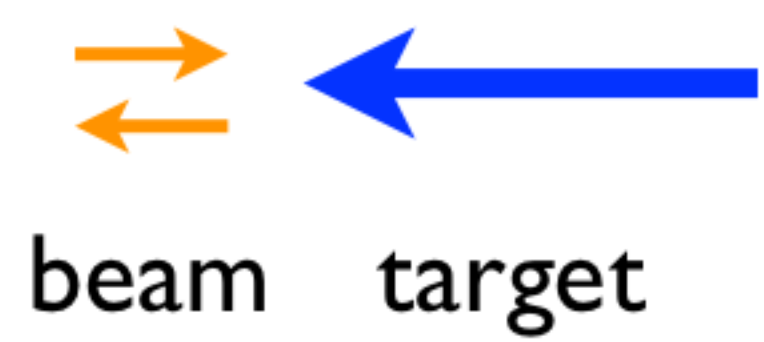
Data Taking

- 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



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

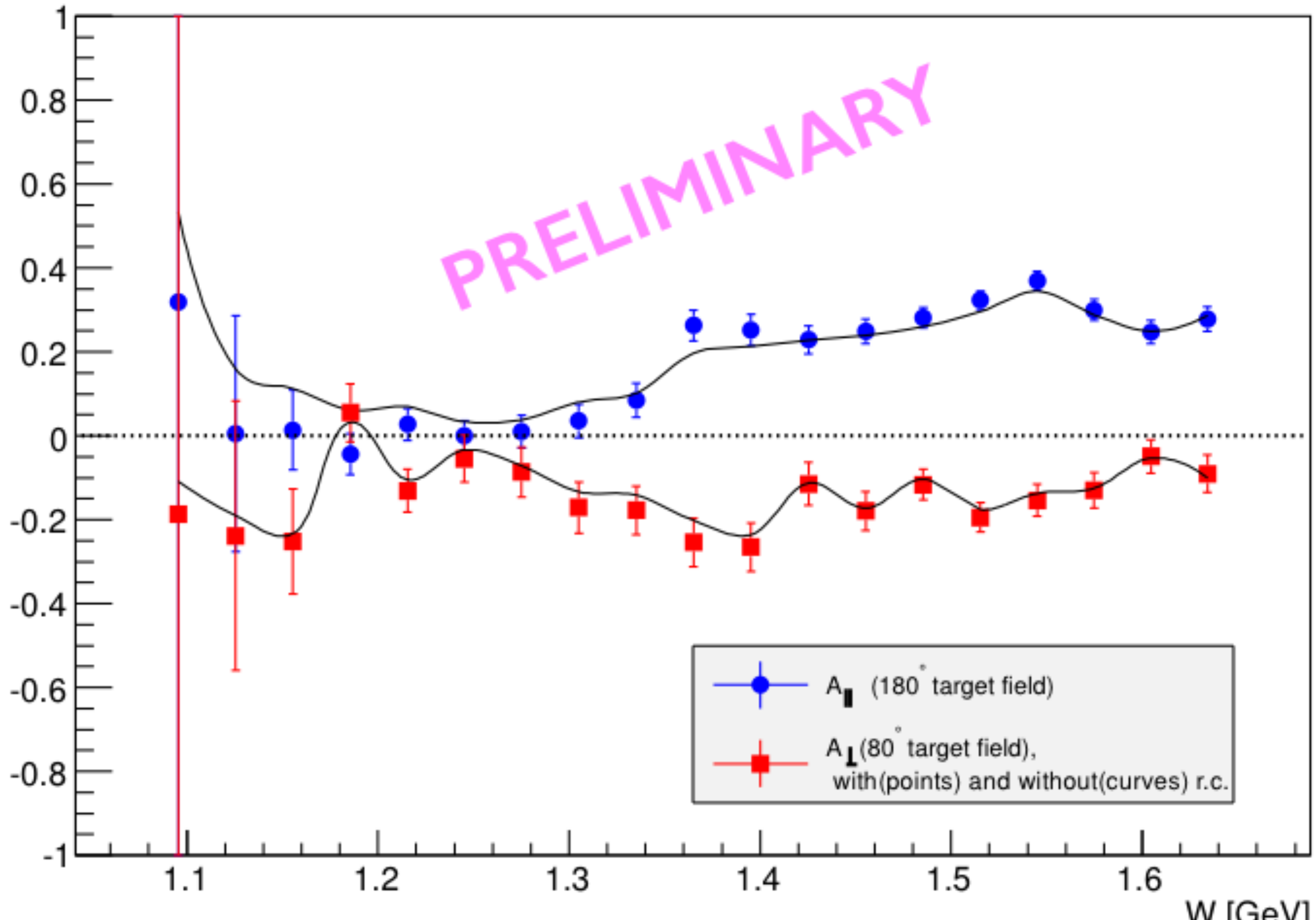
$$g_1 = \frac{F_1}{1+\gamma^2}\left(A_1 + \gamma A_2\right)$$

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

- d_2 matrix element

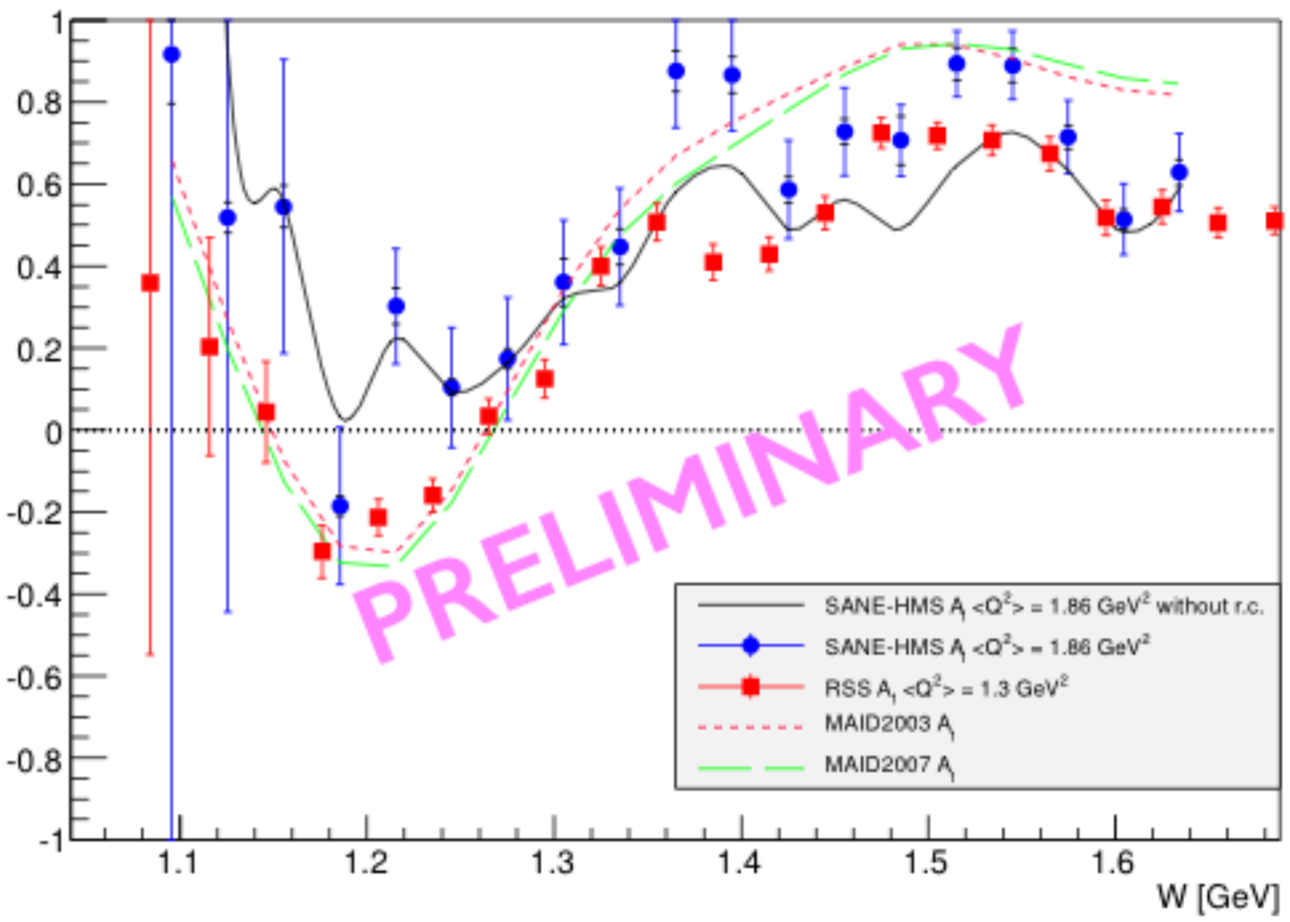
$$d_2(Q^2) = \int_0^1 \left[3g_2(x,Q^2) + 2g_1(x,Q^2)\right] dx$$

Parallel & Perpendicular Asymmetries

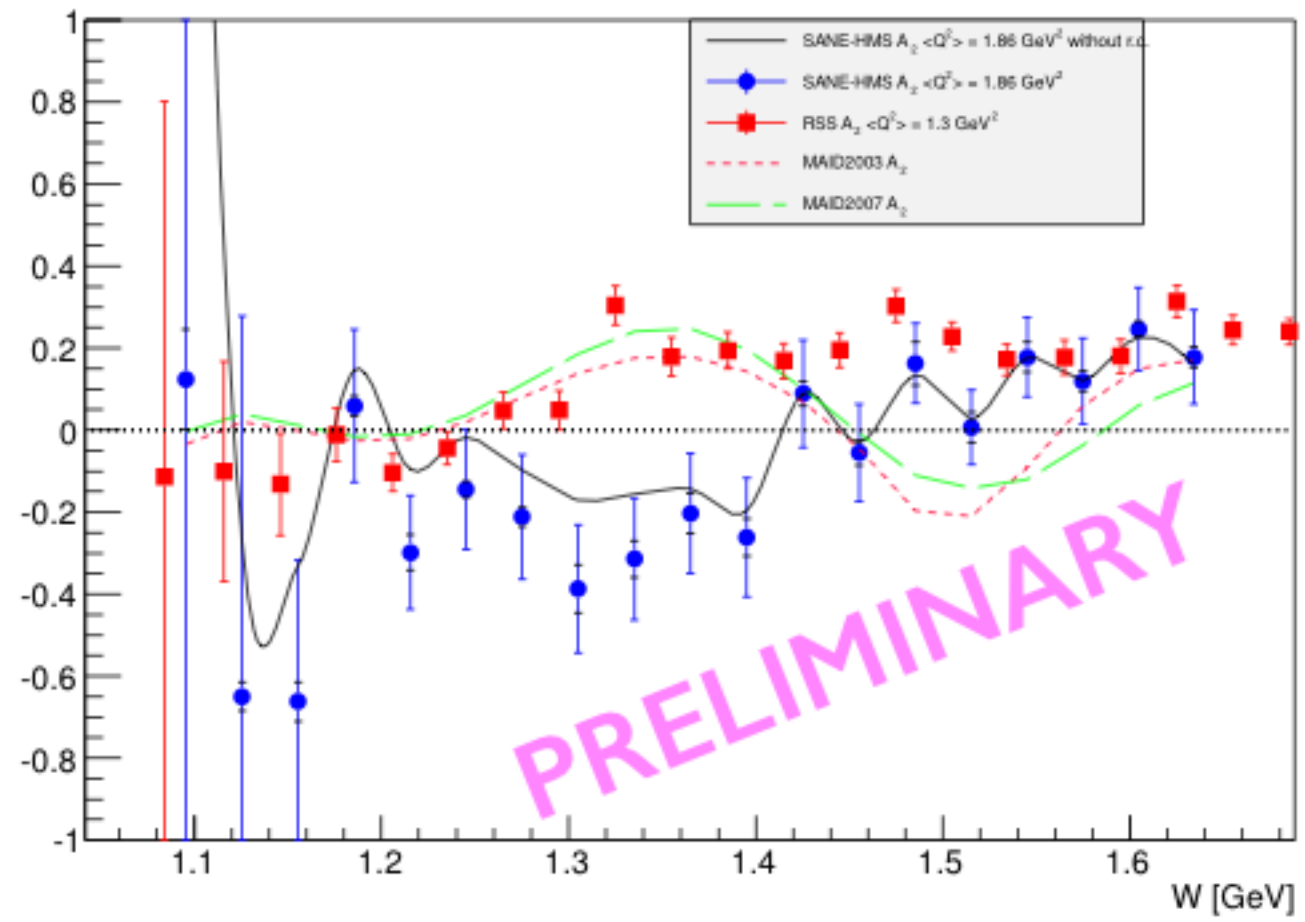


A_1 and A_2

A_1

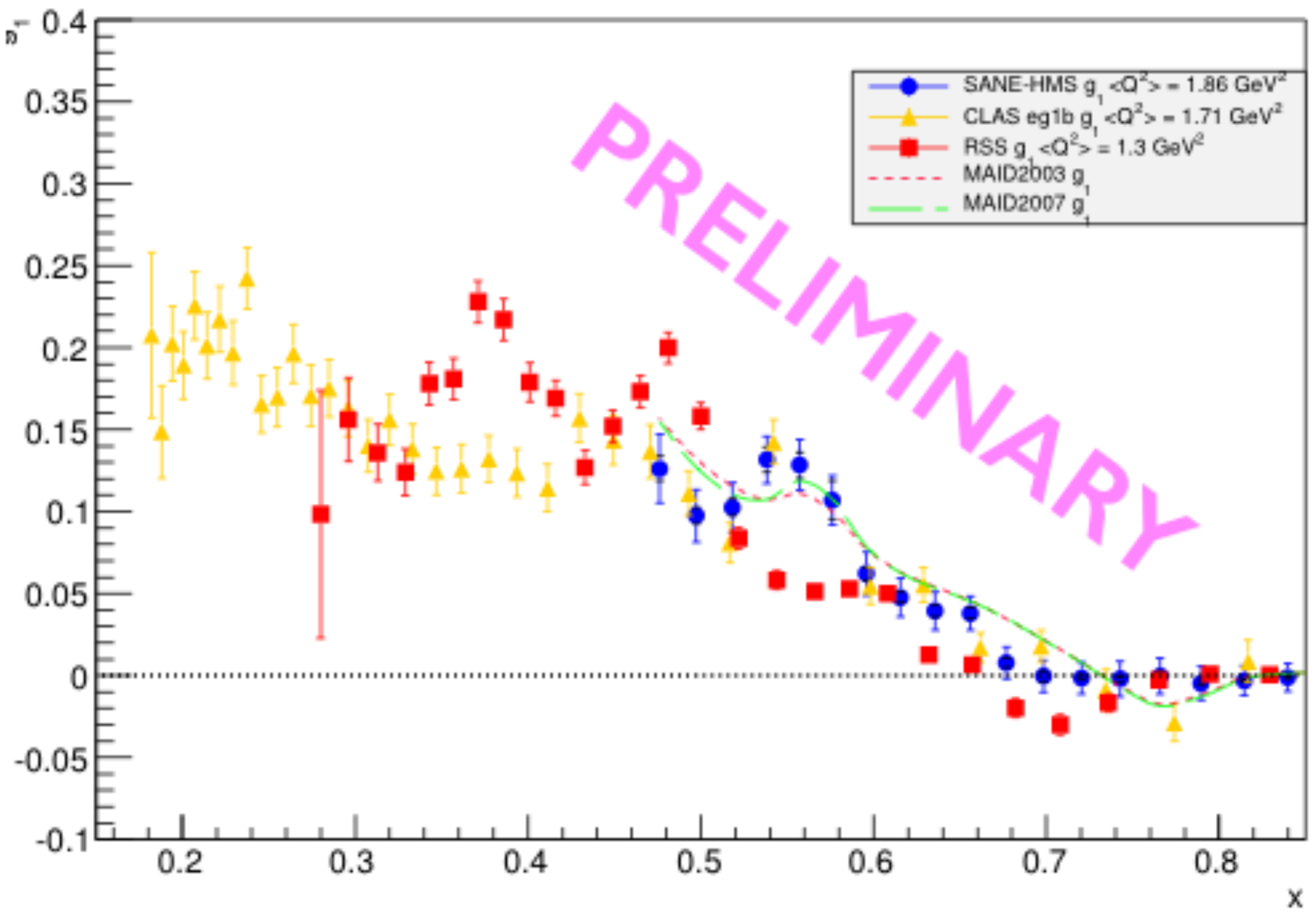


A_2

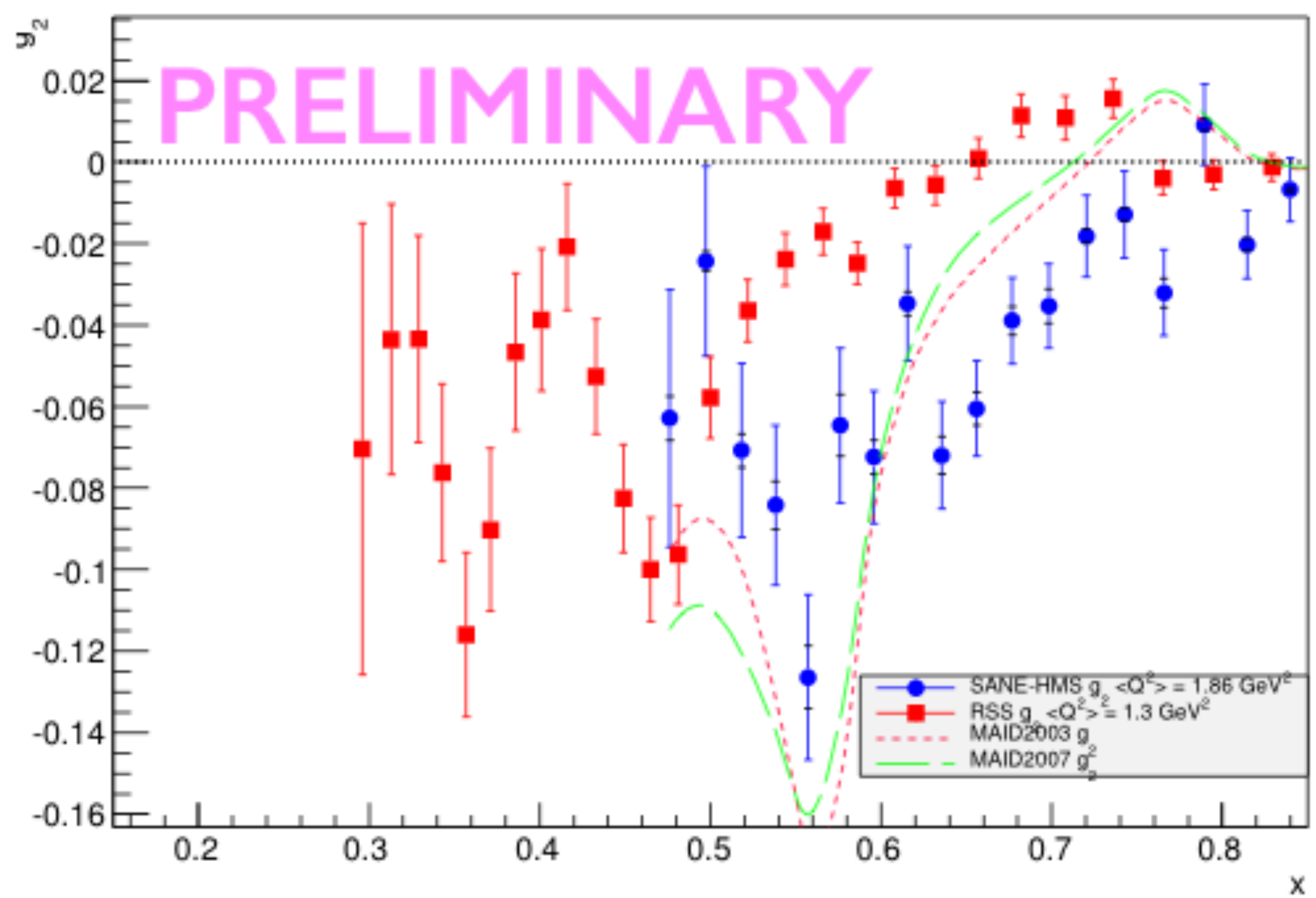


Proton g_1 and g_2

g_1

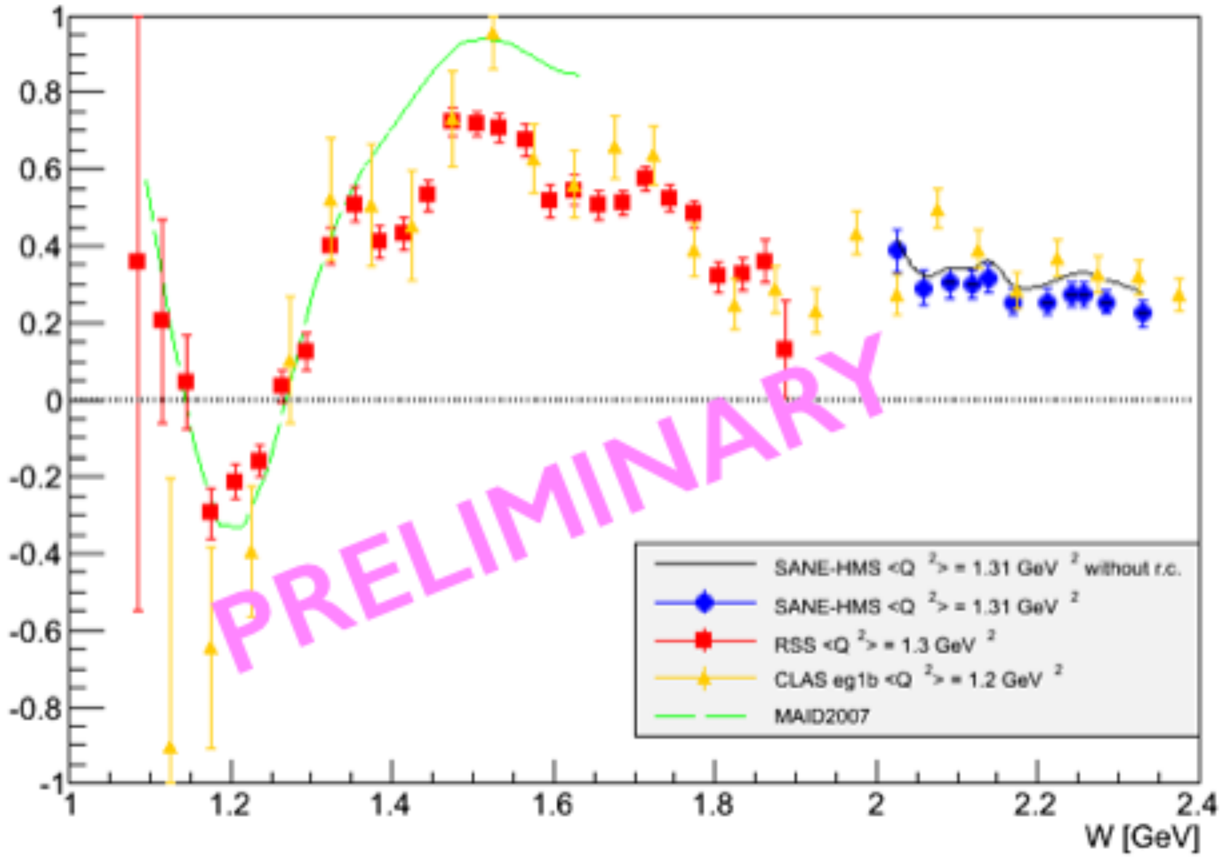


g_2

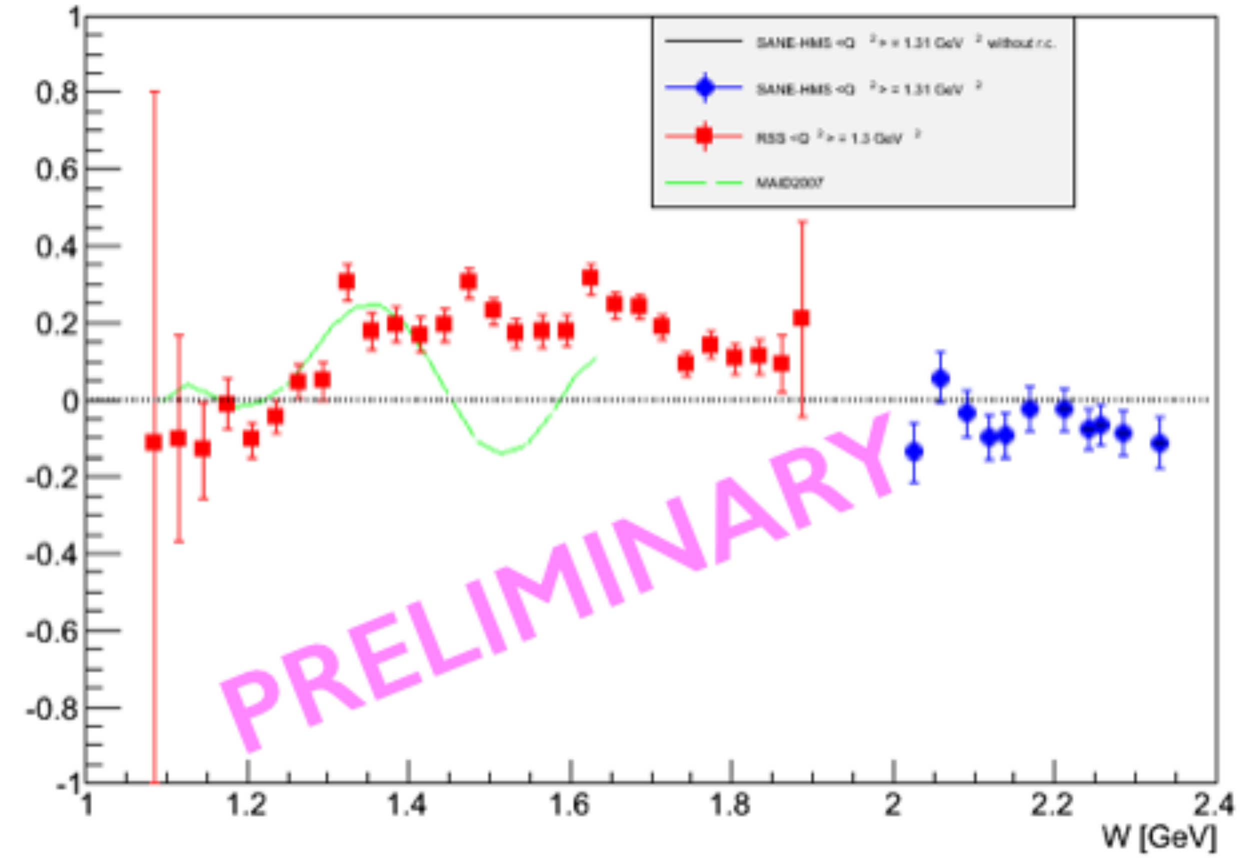


A_1 and A_2
(As an extension of RSS)

A_1

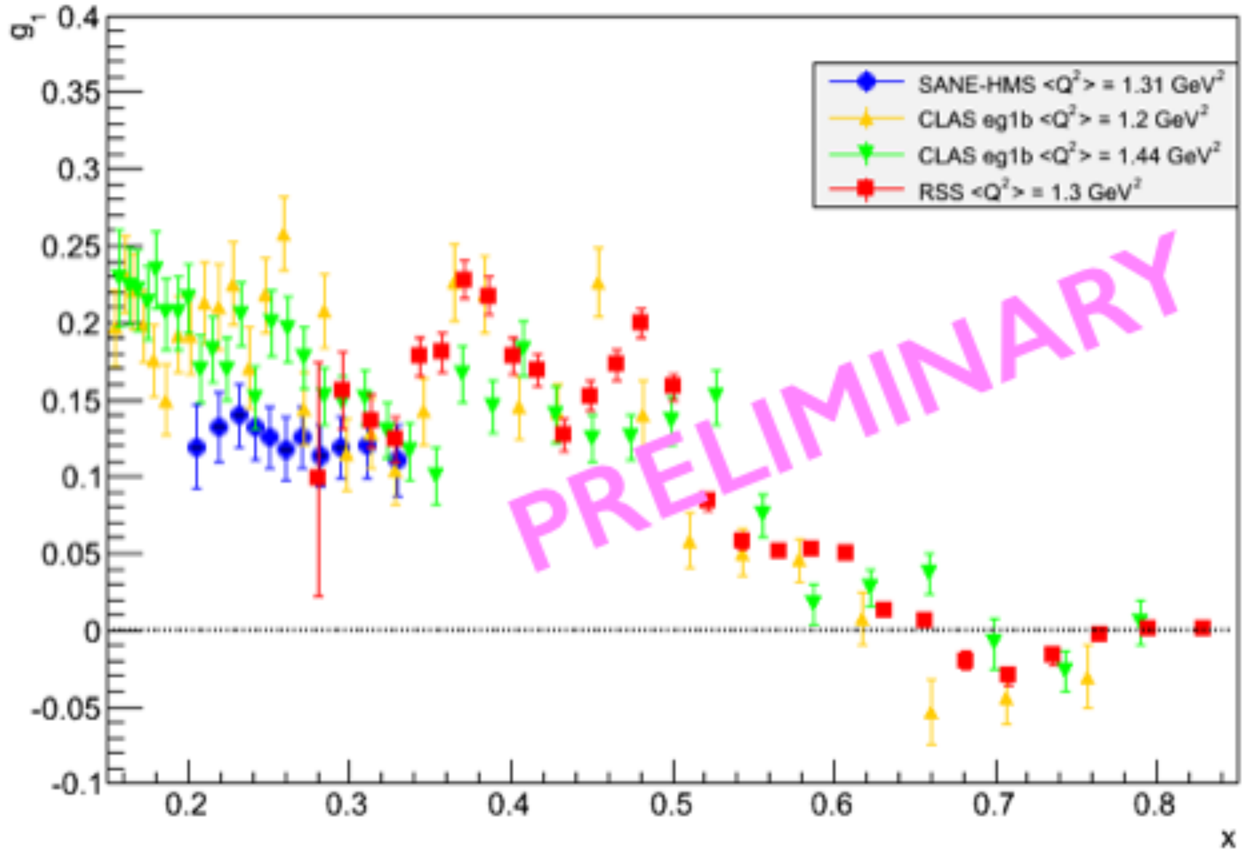


A_2

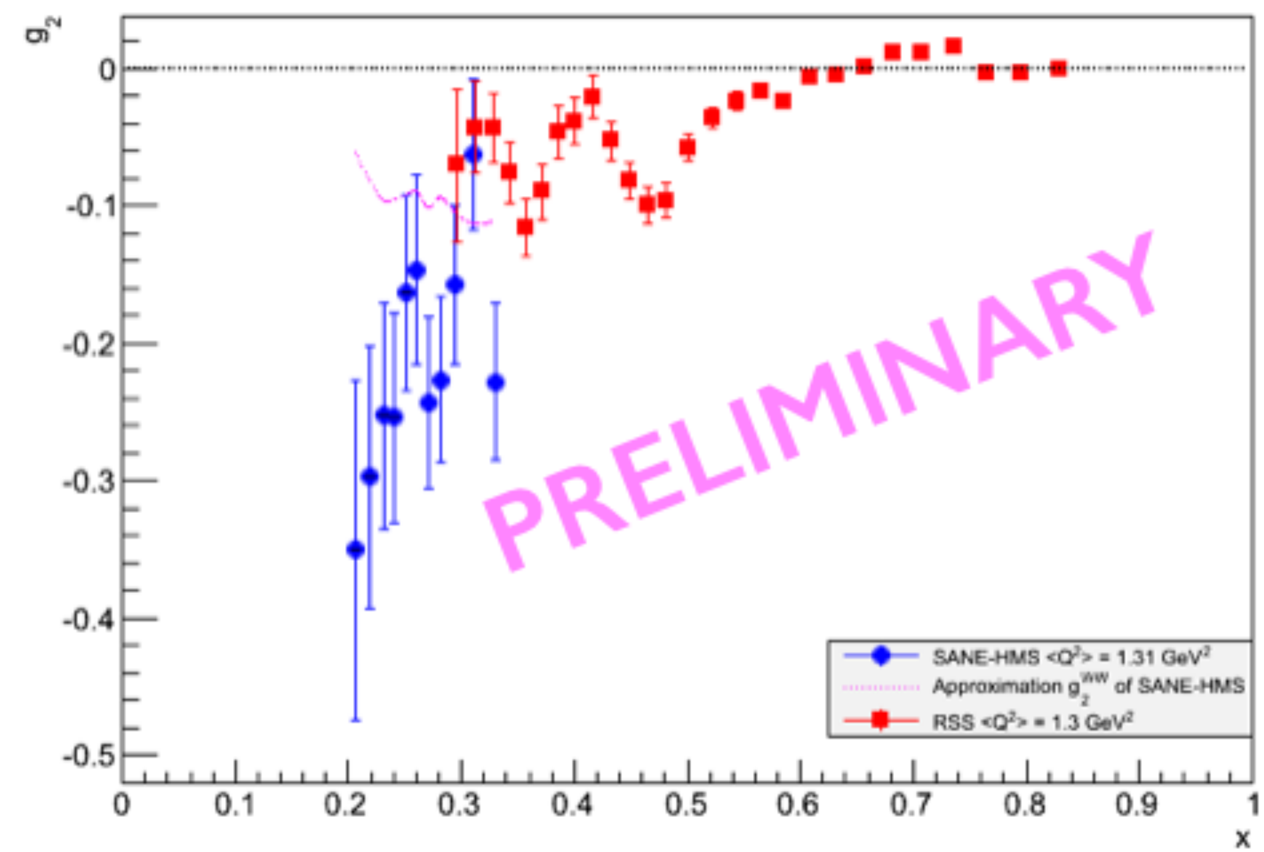


Proton g_1 and g_2 (As an extension of RSS)

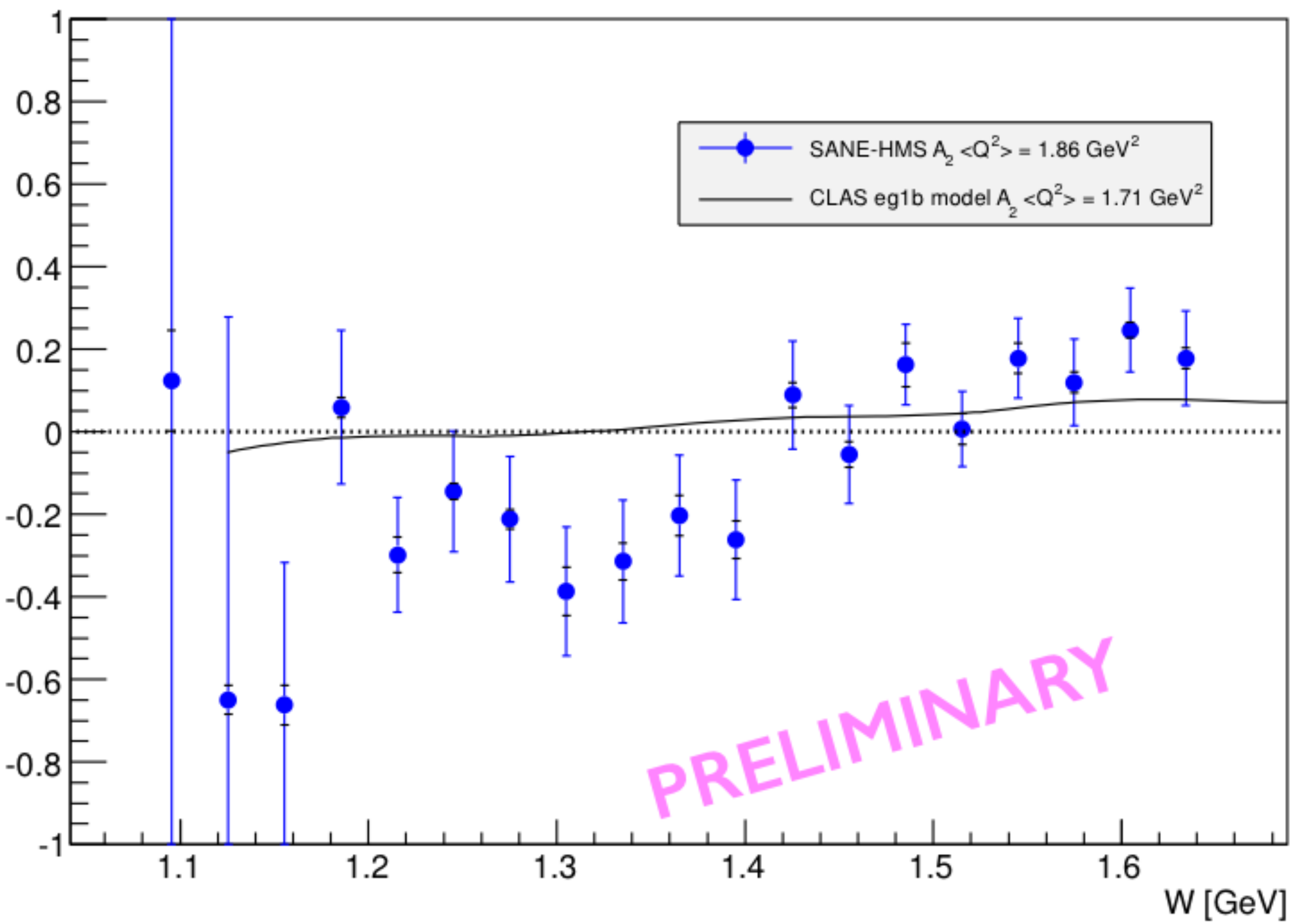
g_1



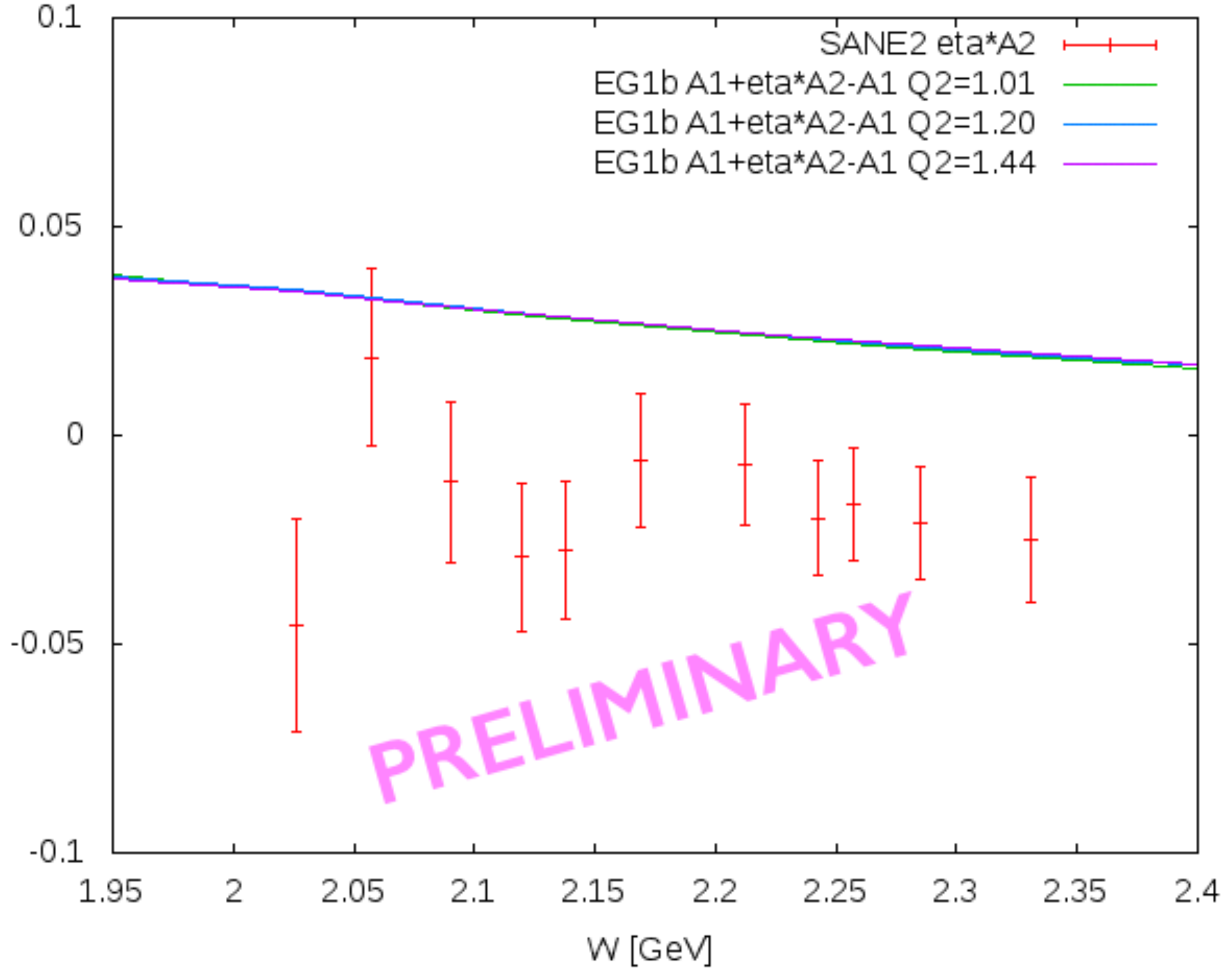
g_2



Proton A_2 and Model

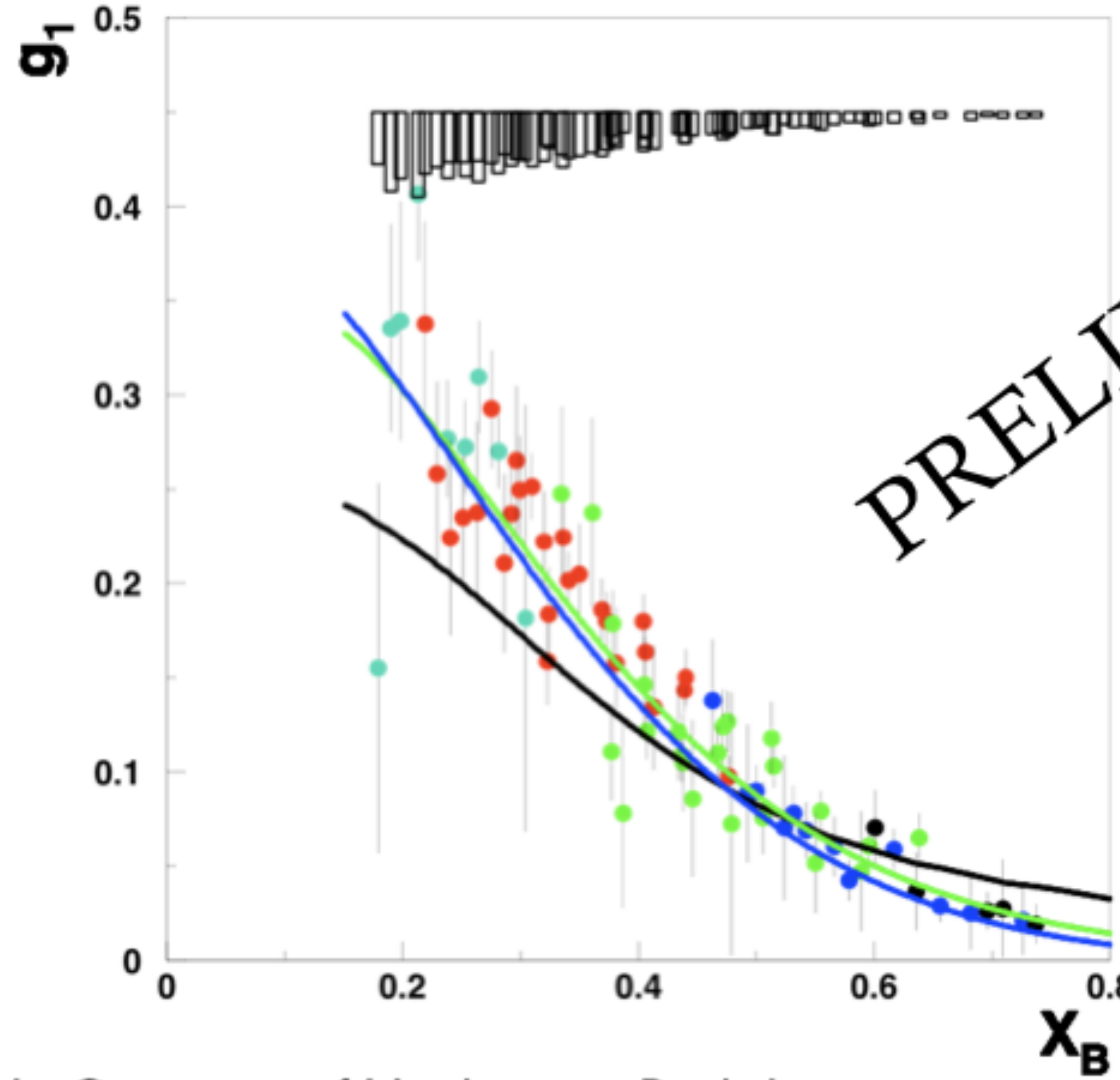


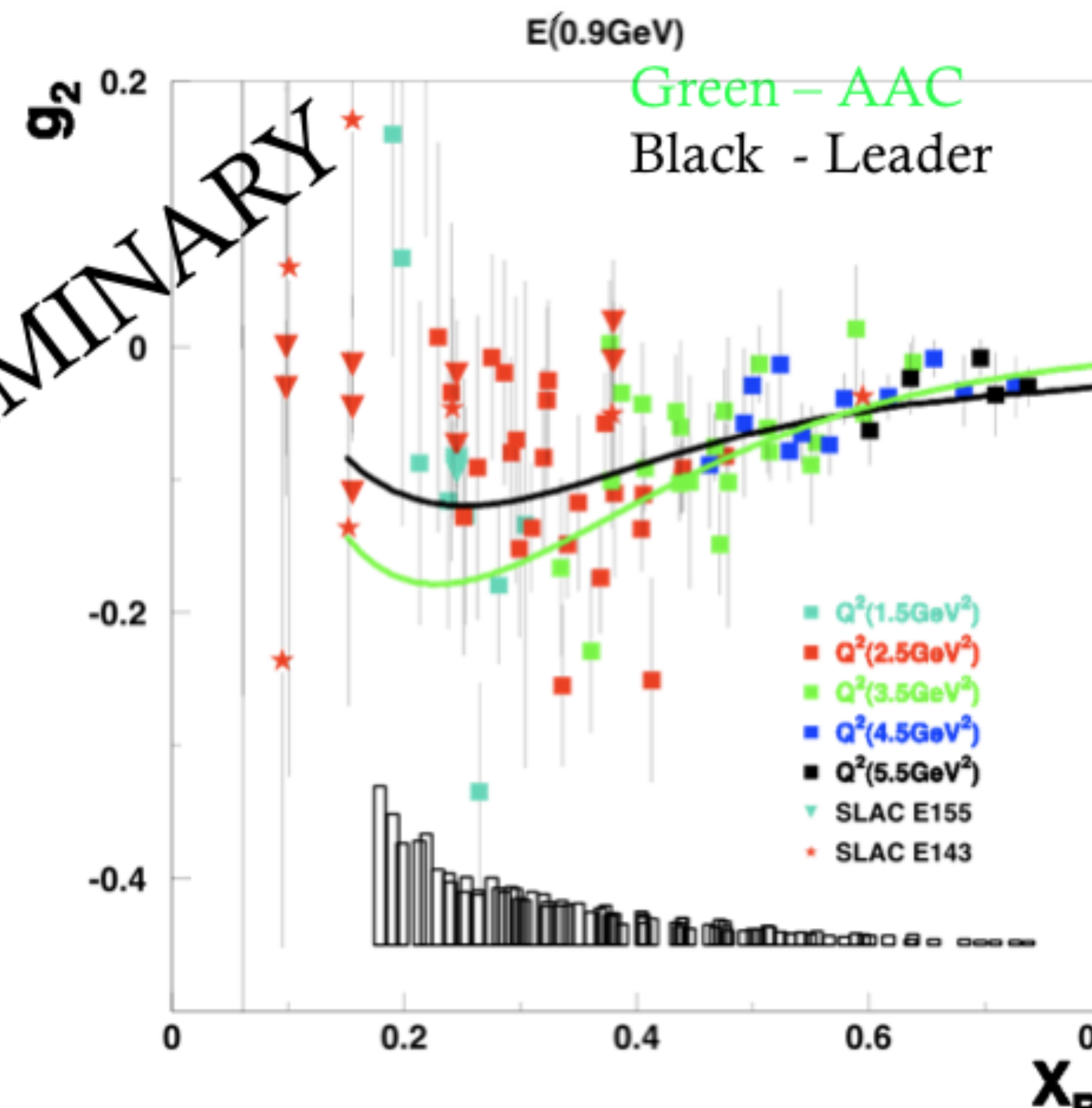
Proton A_2 and Model



Sneak Preview of Asymmetries from BETA

- g_1 agrees with AAC
- g_2 is much larger than g_2^{WW}

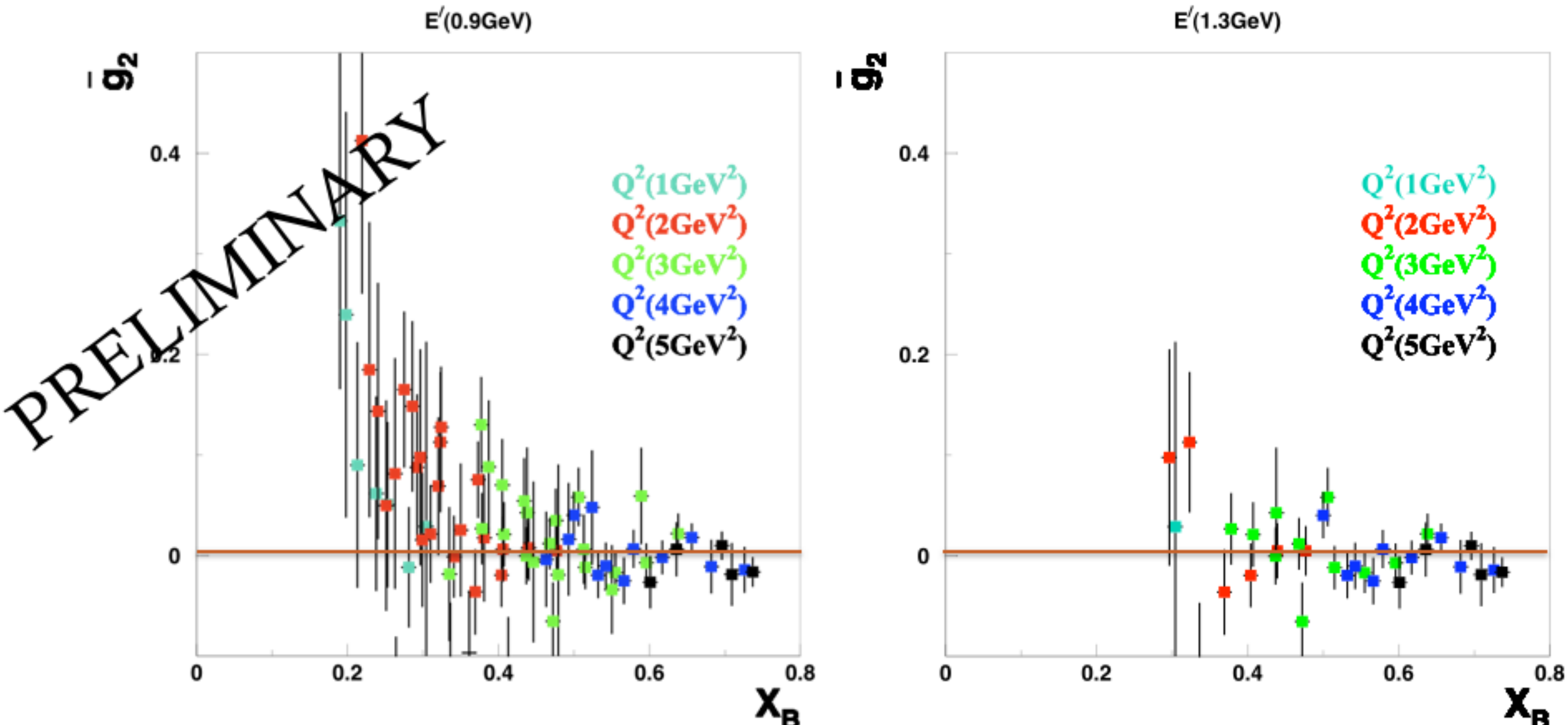




Slide Courtesy of Hovhannes Baghdasaryan

Spin Structure Functions $\overline{g}_2$ from BETA

- $\overline{g_2}$ rises at low x_B
- Contribution to d_2 can be sizable



Slide Courtesy of Hovhannes Baghdasaryan

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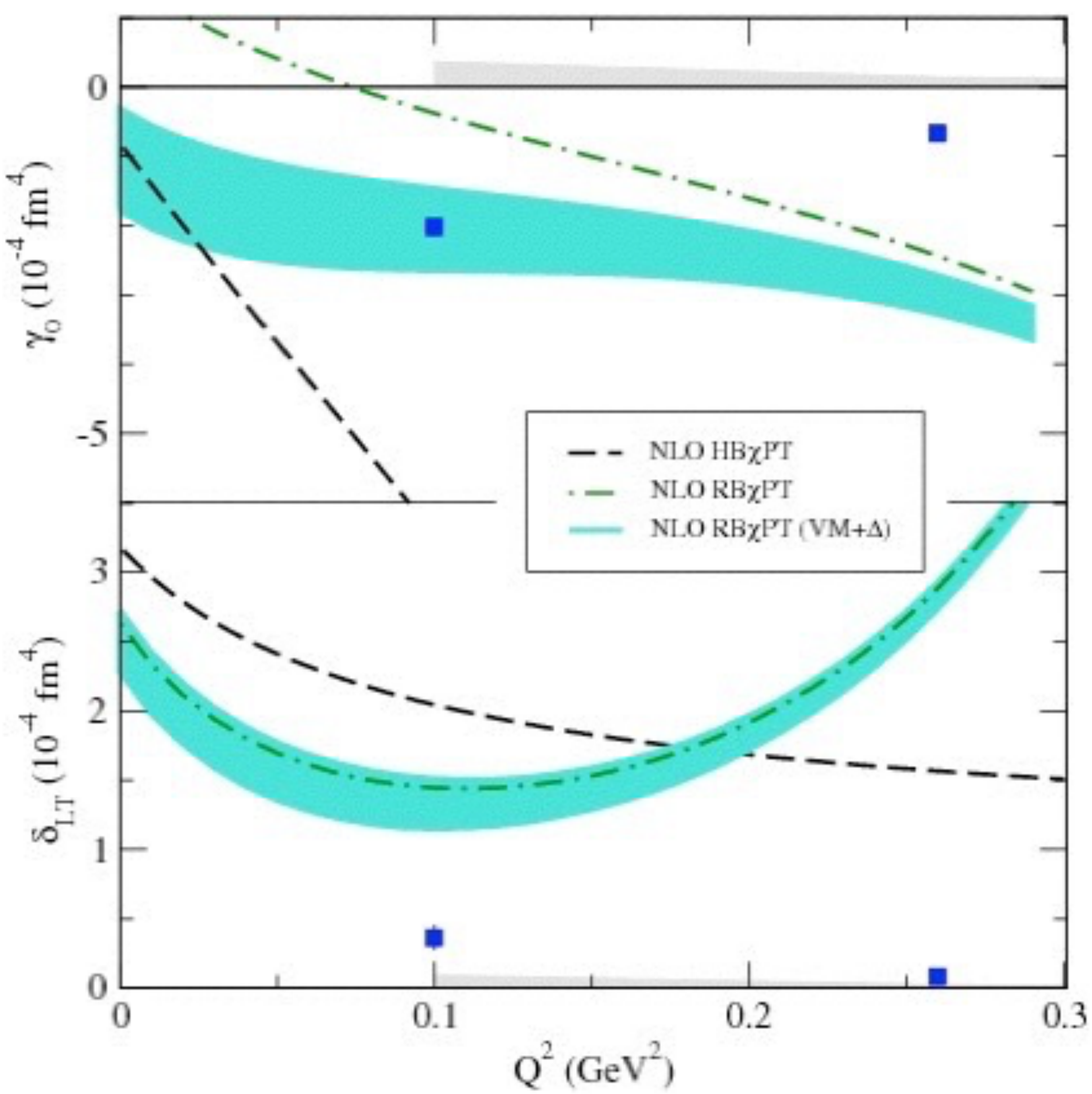
Spin Polarizabilities at Small Q^2

Neutron Spin Polarizabilities at Low Q^2

Neutron (E94010)



$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_x^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_x^{x_0} x^2\left[g_1 + g_2\right]$$

Possible clue from isospin combination with similar data on the proton

E08-027 : Proton g_2 Structure Function

Fundamental spin observable has never been measured at low or moderate Q^2

A- rating by PAC33

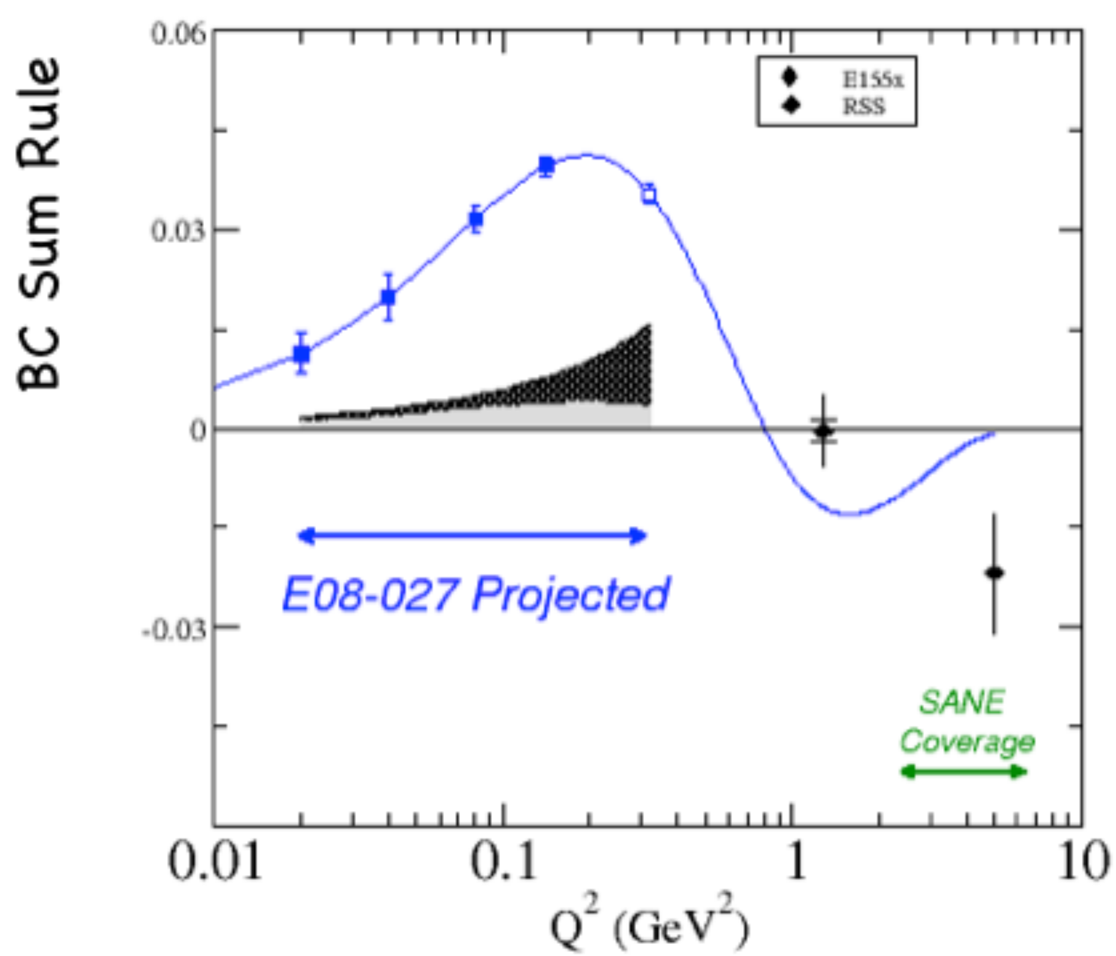
Spokesmen: Camsonne, Crabb, Chen, Slifer

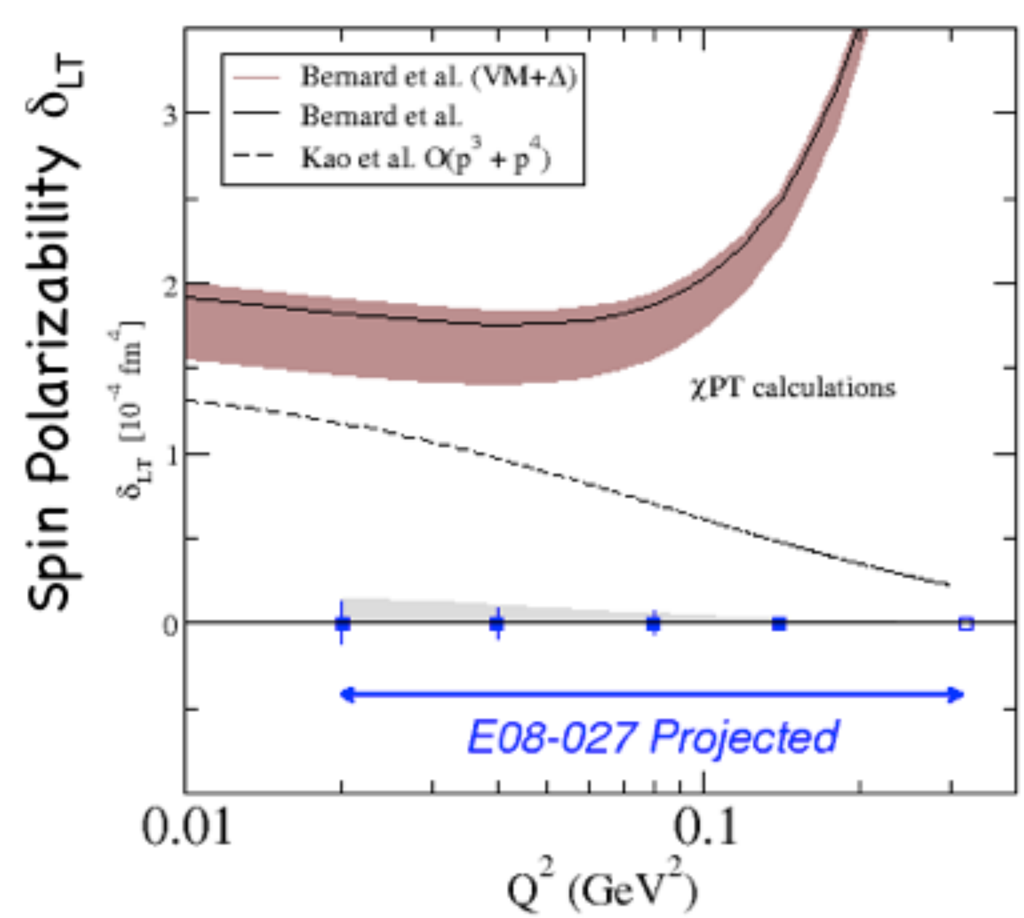
BC Sum Rule : violation suggested for proton at large Q^2, but found satisfied for the neutron & ^{3}He.

Spin Polarizability : Major failure (>8σ) of χPT for neutron δ_{LT}. Need g_2 isospin separation to solve.

Hydrogen HyperFine Splitting : Lack of knowledge of g_2 at low Q^2 is one of the leading uncertainties.

Proton Charge Radius : one of the leading uncertainties in extraction of <R_p> from μ–H Lamb shift.



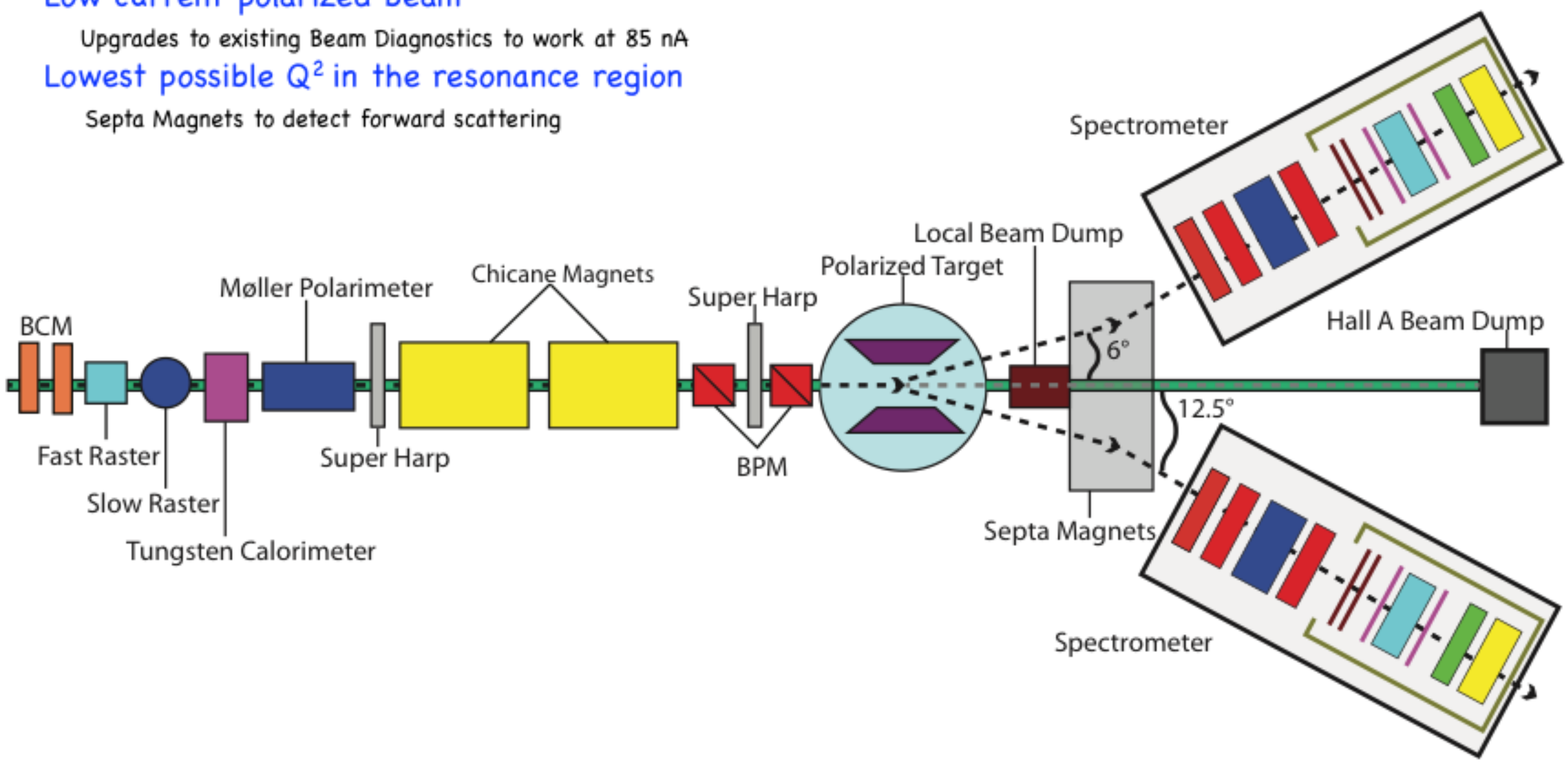


Experiment Overview

Polarized proton target
- upstream chicane
- downstream local dump

Low current polarized beam
- Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region
- Septa Magnets to detect forward scattering



Installation

Polarized proton target

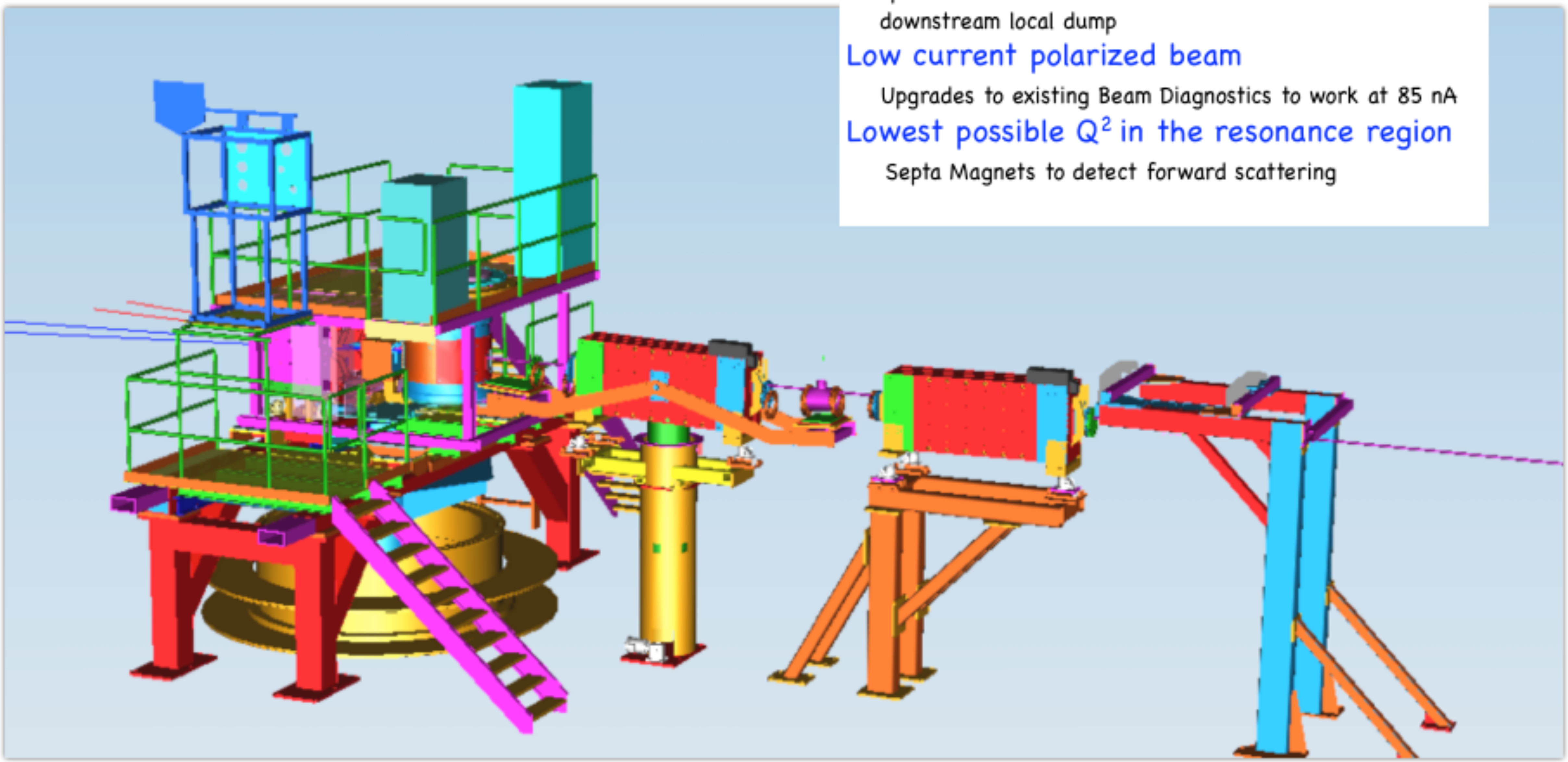
- upstream chicane
- downstream local dump

Low current polarized beam

- Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region

- Septa Magnets to detect forward scattering



Highlights and Preliminary Results

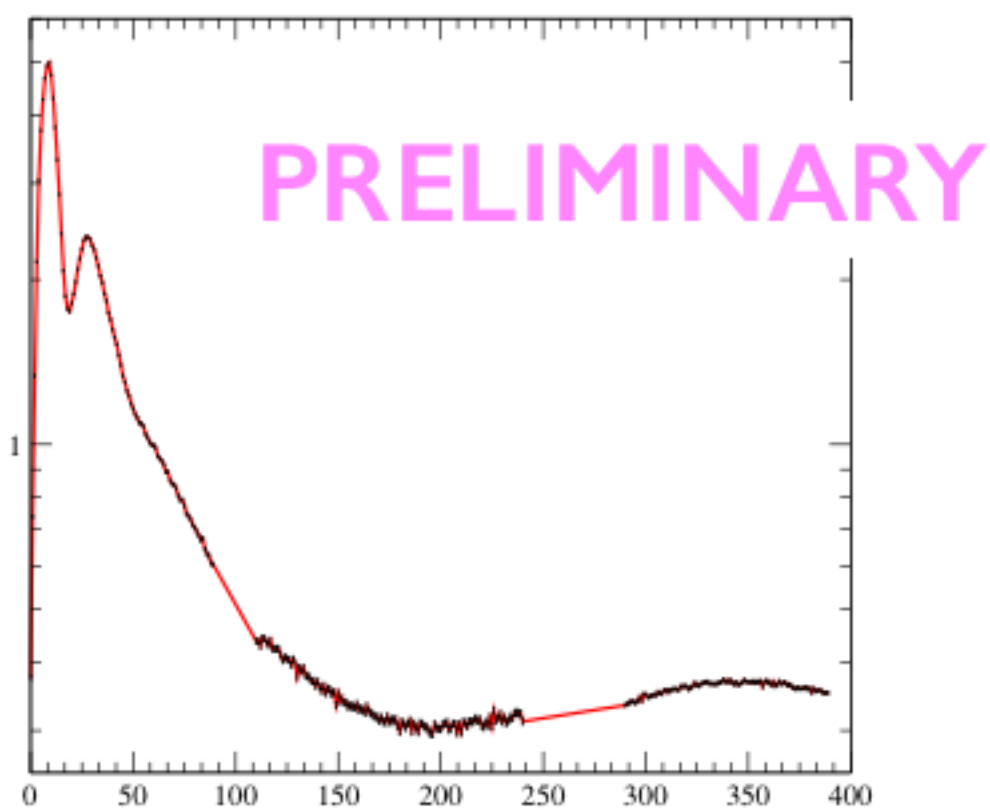
Will be the definitive measurement of g2p for $0.02 < Q^2 < 0.2$ GeV^2

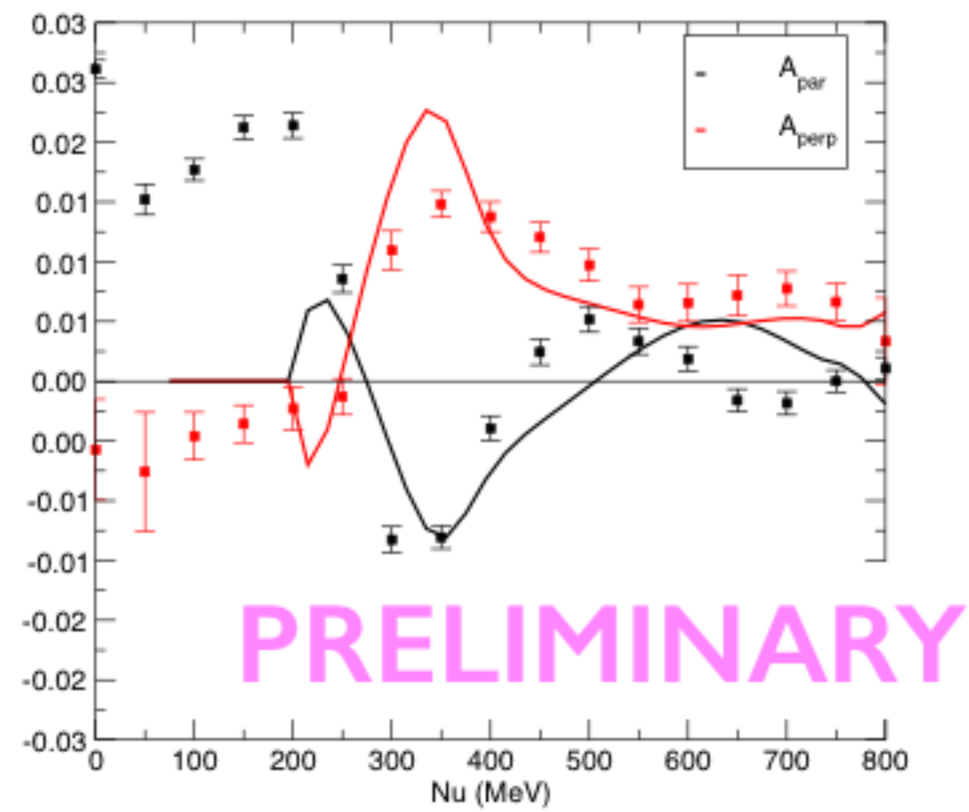
Largest Installation in Hall A History

Entire new suite of beamline diagnostics for operation at 50nA

DAQ rate was Hall A record : 6.5 kHz/HRS with <25% deadtime

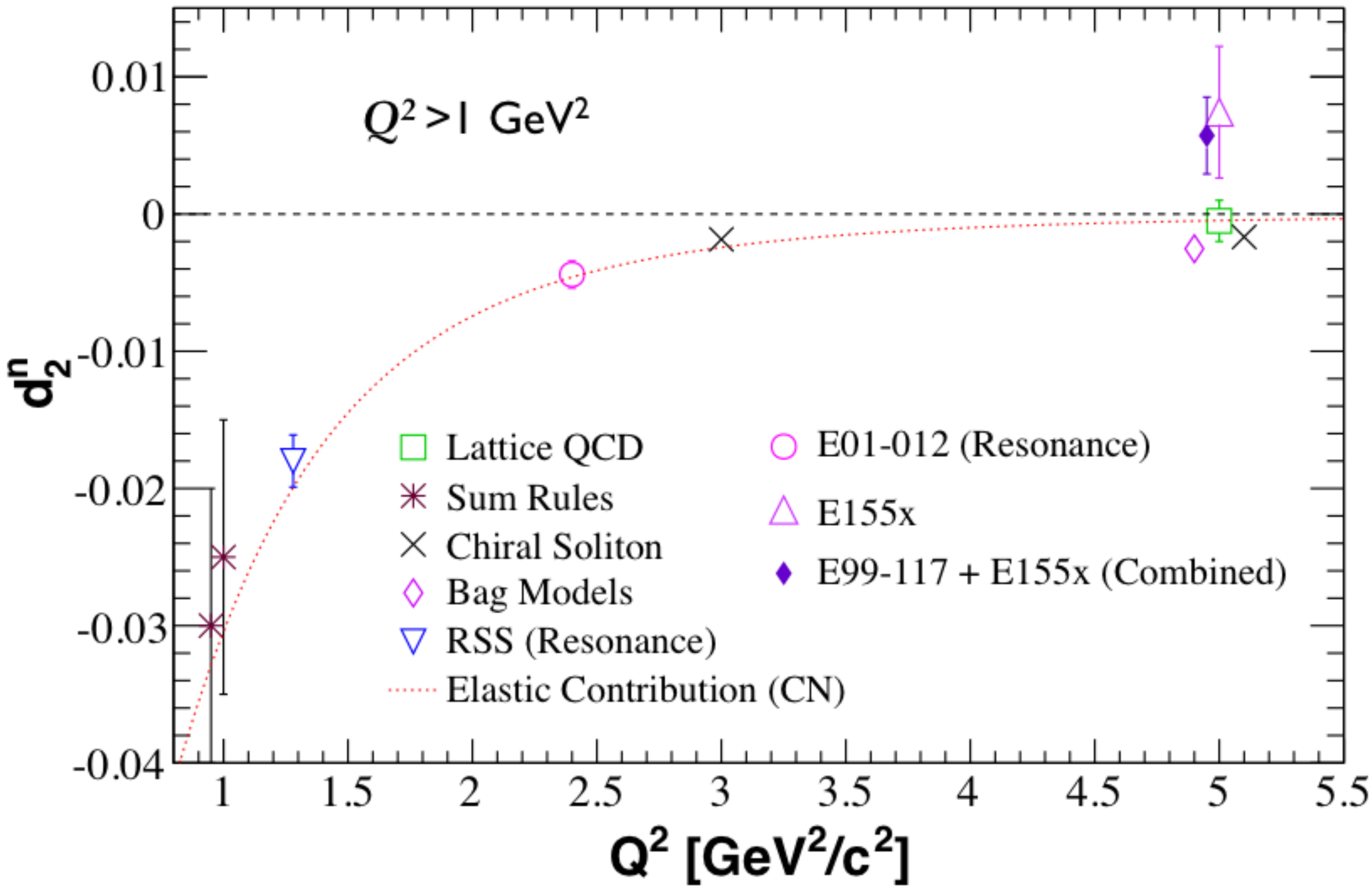
Polarized target performed very reliably





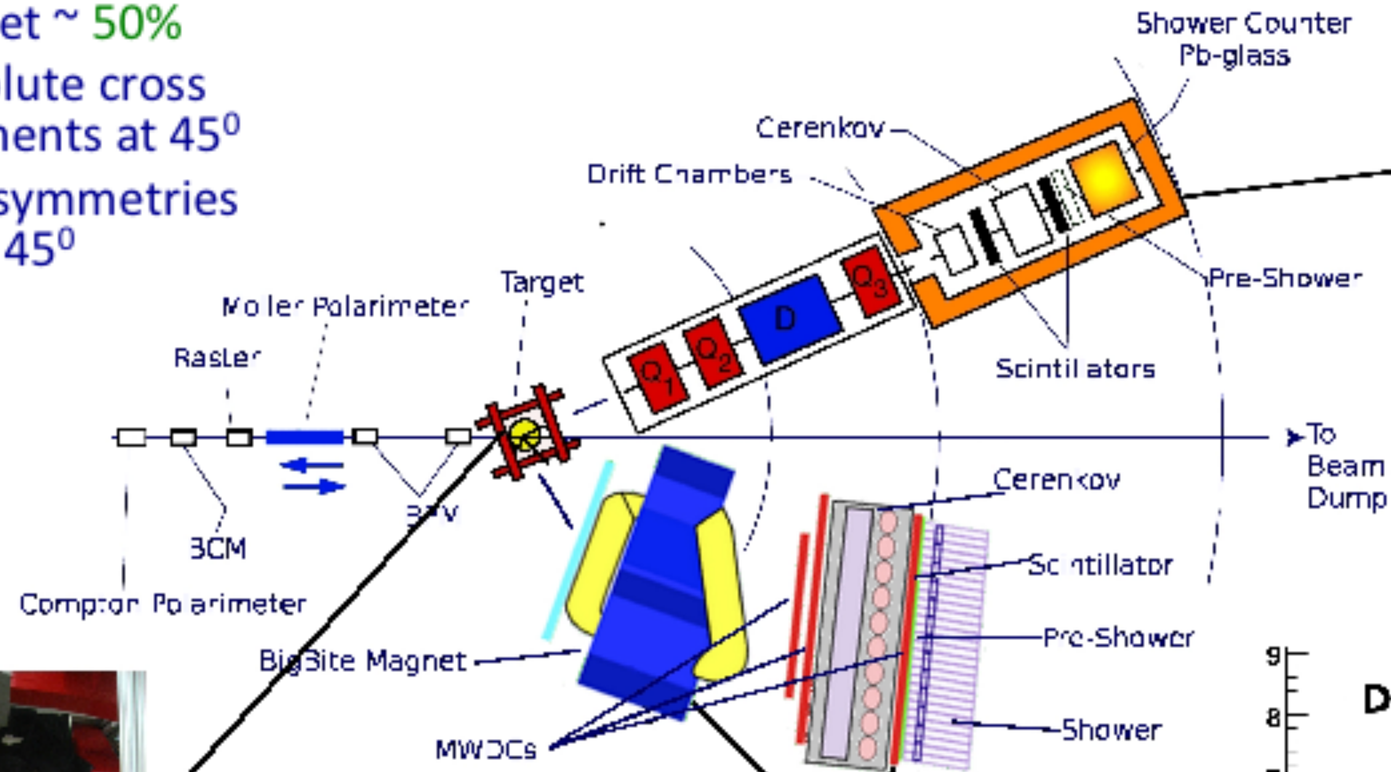
Precision Measurement of d_2^n

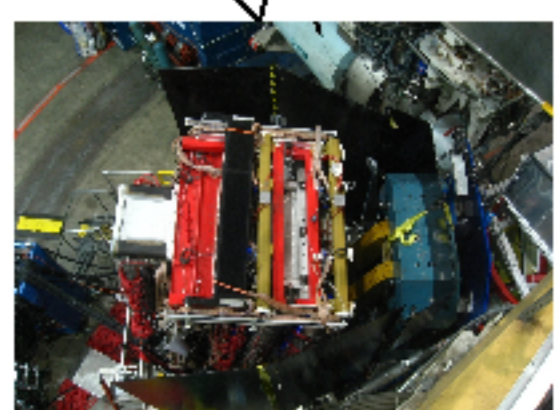
d_2^n World Summary

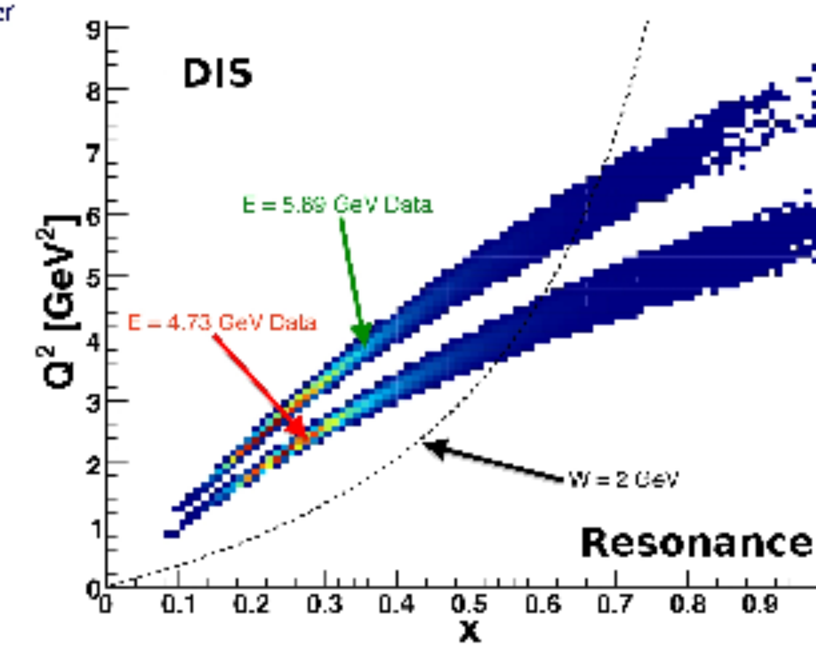


New Experiment at JLab

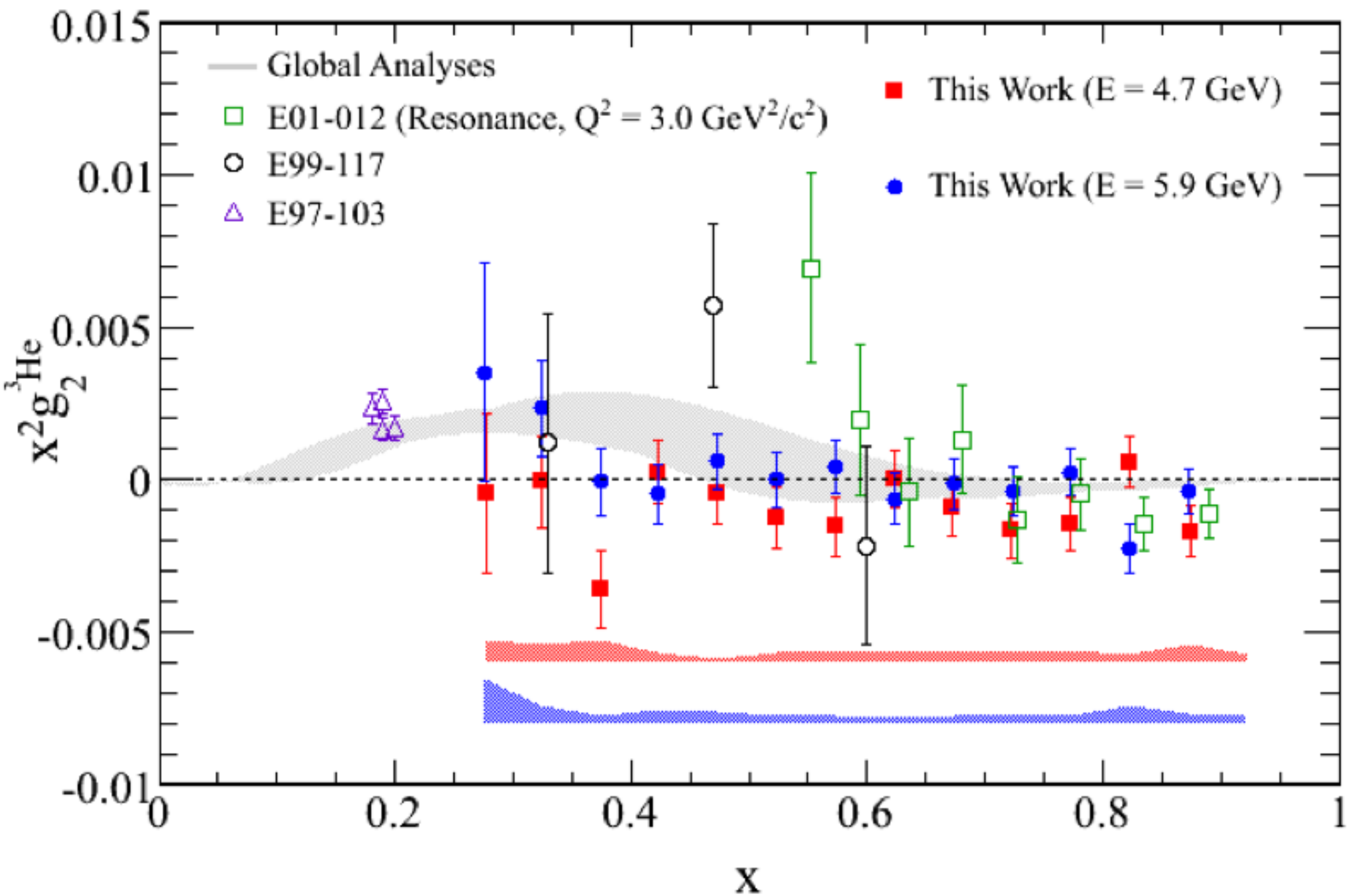
- Polarized electron beam: E=4.74, 5.89 GeV, polarization ~ 71%
- Polarized ^{3}He target ~ 50%
- HRS used for absolute cross section measurements at 45^0
- Bigbite used for asymmetries measurements at 45^0



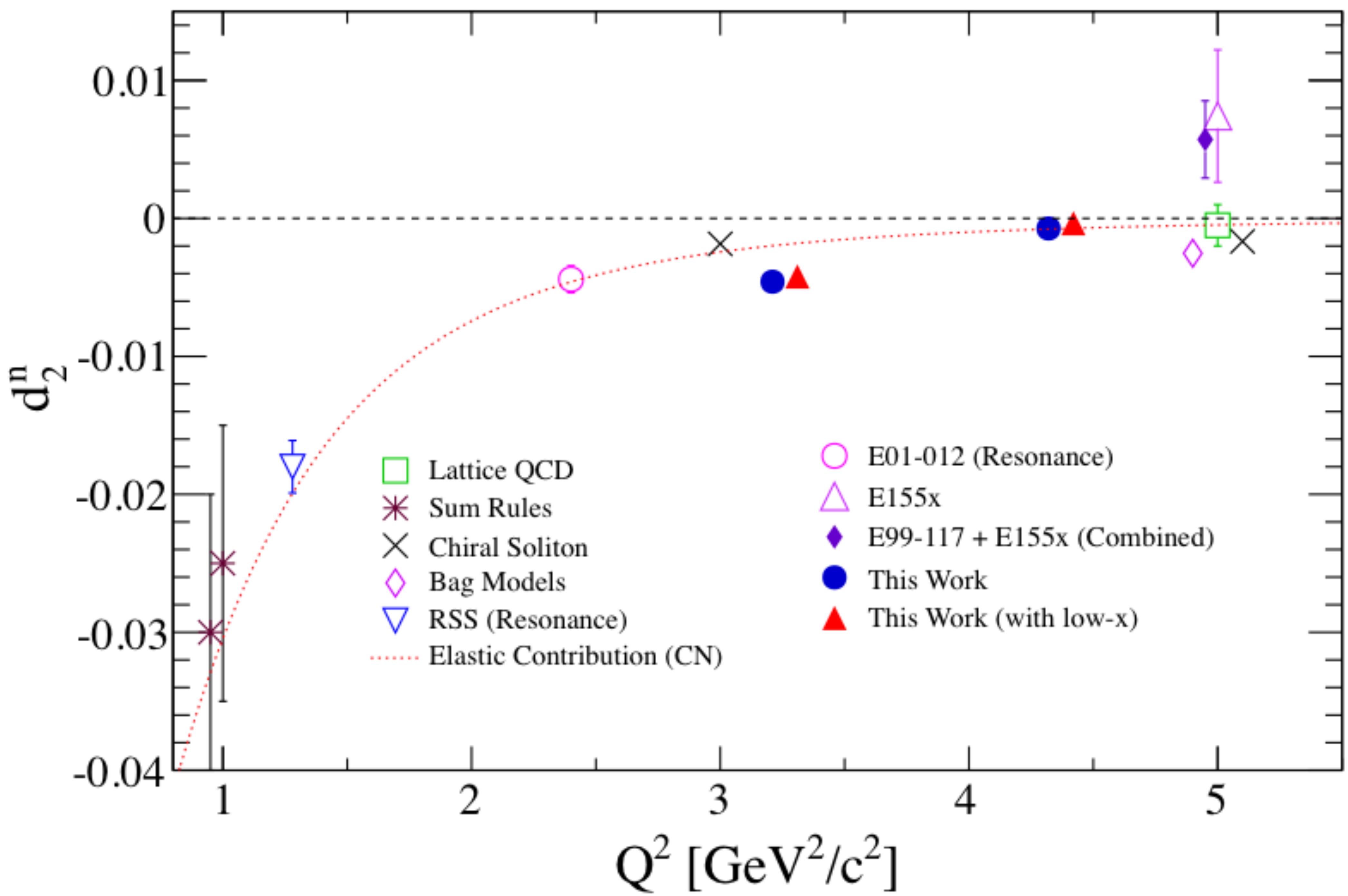




$g_2(^3He)$ Structure Function



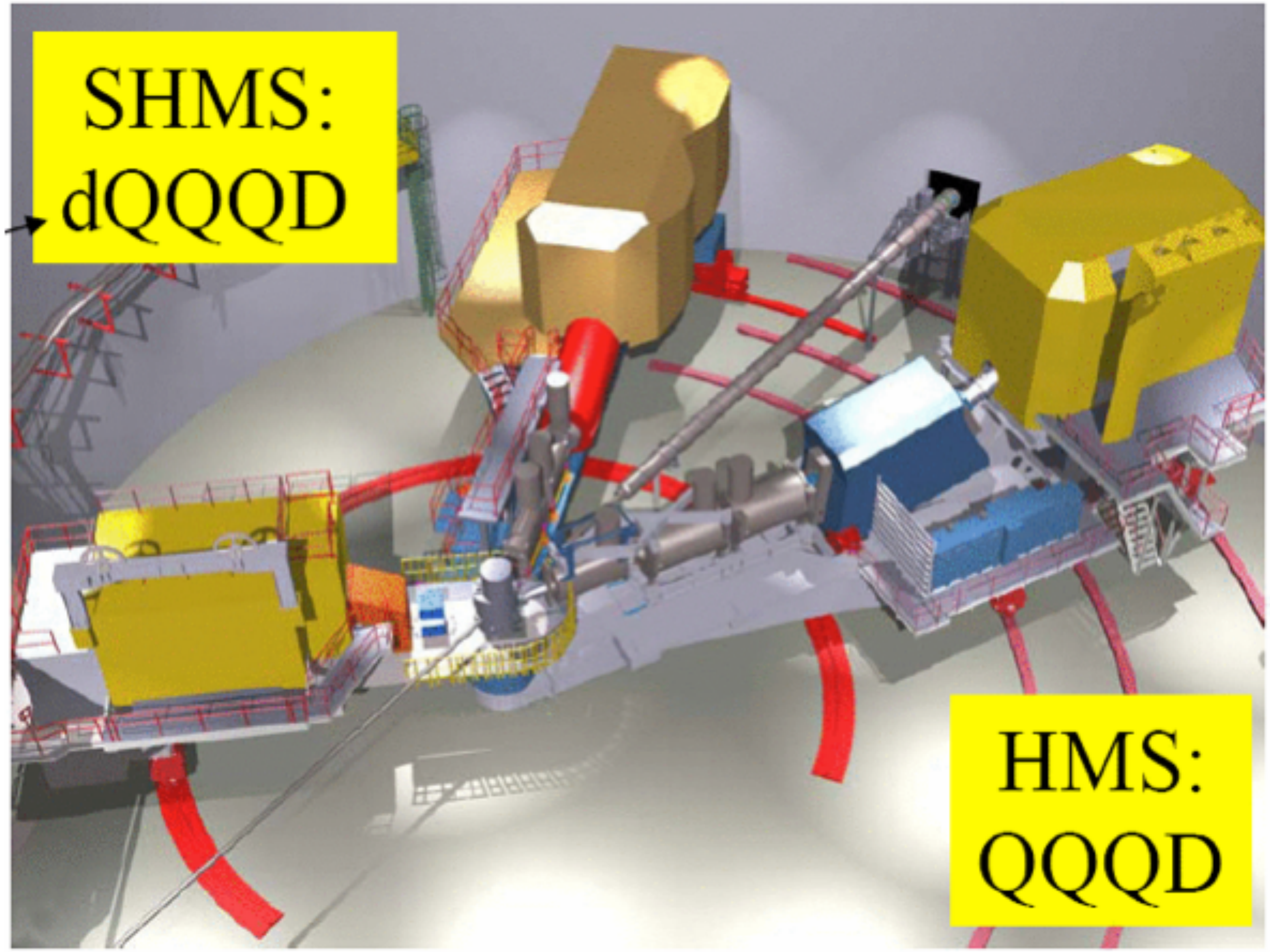
d_2^n Results



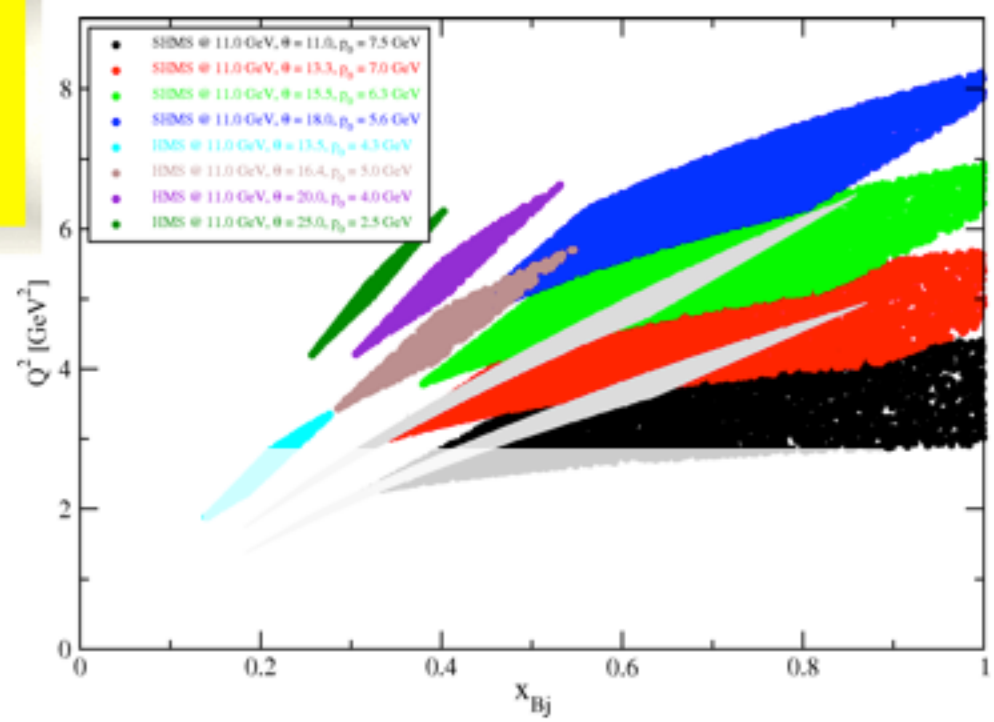
0.01
0
-0.01
-0.02
-0.03
-0.04
d_2^n
1
2
3
4
5
Q^2 [GeV^2/c^2]
Lattice QCD
Sum Rules
Chiral Soliton
Bag Models
RSS (Resonance)
Elastic Contribution (CN)
E01-012 (Resonance)
E155x
E99-117 + E155x (Combined)
This Work
This Work (with low-x)

Spin Structure Functions at 12 GeV

E12-06-121: d_2^n, g_2^n

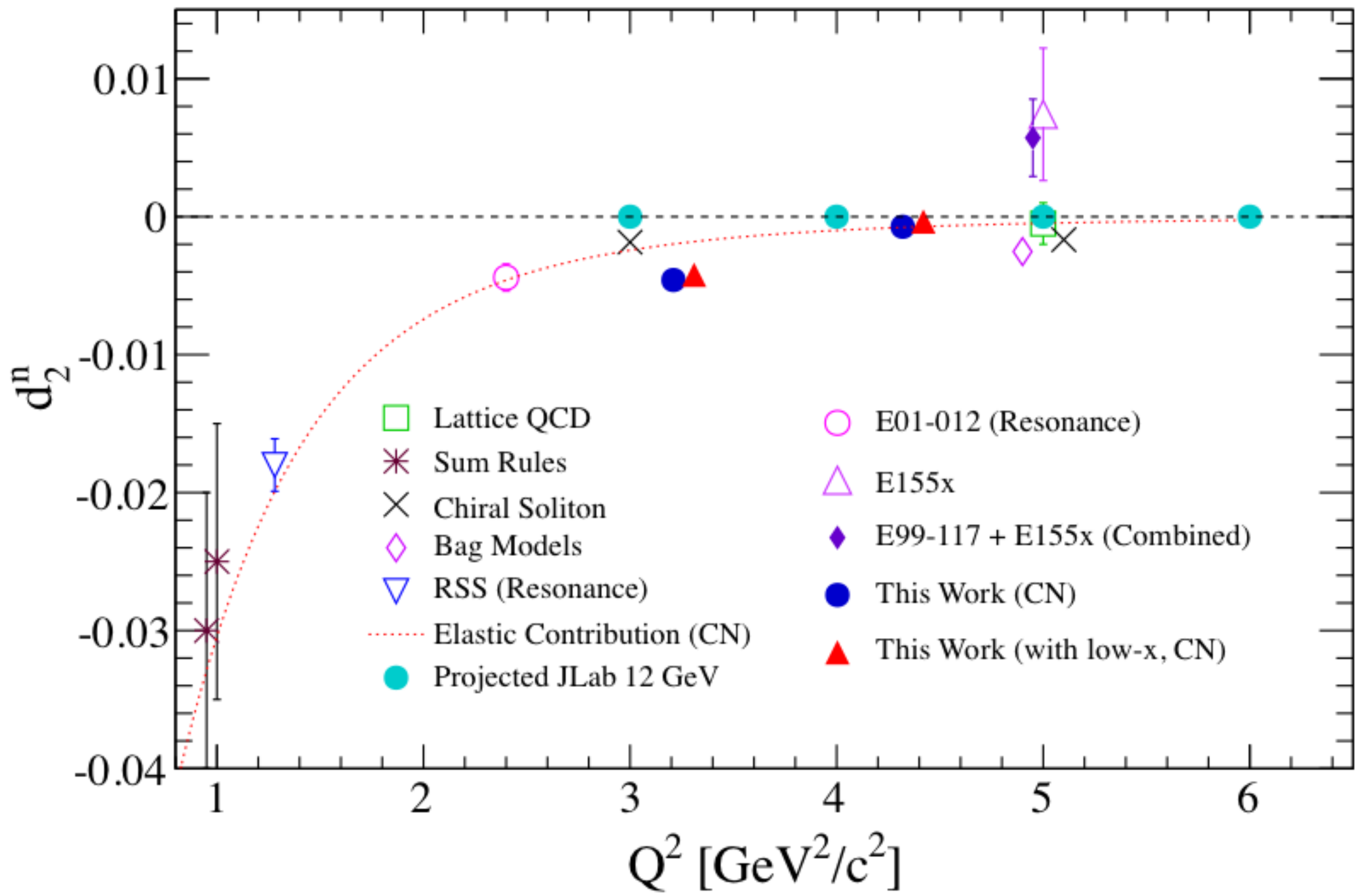


- <u>Hall C: SHMS + HMS</u>
- One beam energy
  - 11 GeV
- Each arm measures a total cross section independent of the other arm.
- Experiment split into four pairs of 125 hour runs with spectrometer motion in between.



- SHMS collects data at Θ = 11°, 13.3°, 15.5° and 18.0° for 125 hrs each
  - data from each setting divided into 4 bins
- HMS collects data at Θ = 13.5°, 16.4°, 20.0° and 25.0° for 125 hrs each

JLab 12 Projection of d_2^n



Summary (SANE)

- SANE measures double-spin asymmetries, $A_{\parallel}$ and $A_{\perp}$ of ep DIS
- Kinematic coverage of $2.5 < Q^2 < 6.5$, $0.3 < x < 0.8$,
- New non-magnetic detector BETA used for electron detection
- Expected to produce high precision data on d_2 and A_1
- Analysis finished for HMS data, publication is in preparation.

Summary

- Polarized DIS at various laboratories in the world
- Extensive measurements for g_1 over large Q^2 region
  - Both for the proton and the neutron
- Limited data for g_2, especially for the proton
  - Precision measurements of g_2/d_2: higher twists
  - Generalized spin polarizabilities
    - Test of χPT calculations: δ_{LT} puzzle
  - **New data will be available for the proton**