Measurement of the Proton A_1 and A_2 Spin Asymmetries: Probing Color Forces

SANE Results

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The Strong Force

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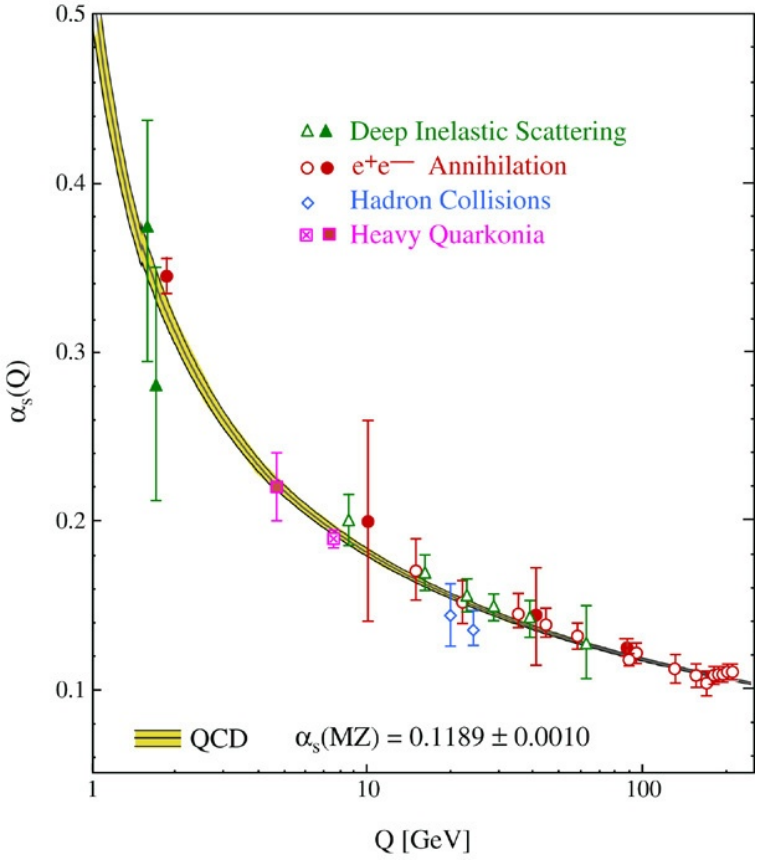
Quantum Chromodynamics

- $L_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$
- The degrees of freedom are the QCD quark and gluon fields, **not the constituent quarks!**
- The QCD coupling constant α_s is a function of Q^2.
- Asymptotic freedom $\rightarrow$ 2004 Nobel prize (Gross,Wilczek,Politzer)
- Many successful predictions from pQCD at high energies.



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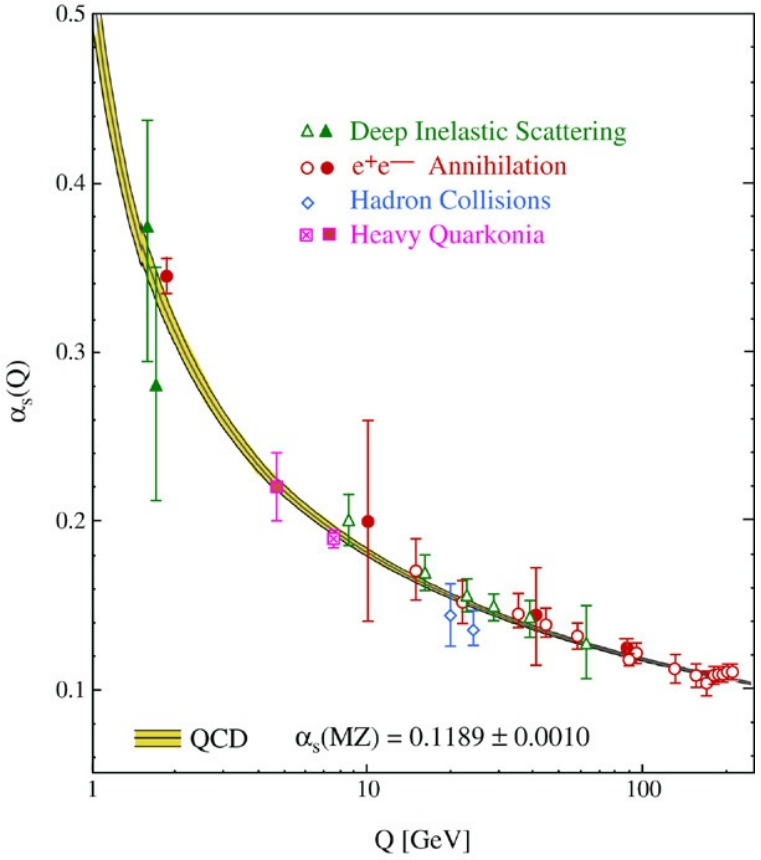

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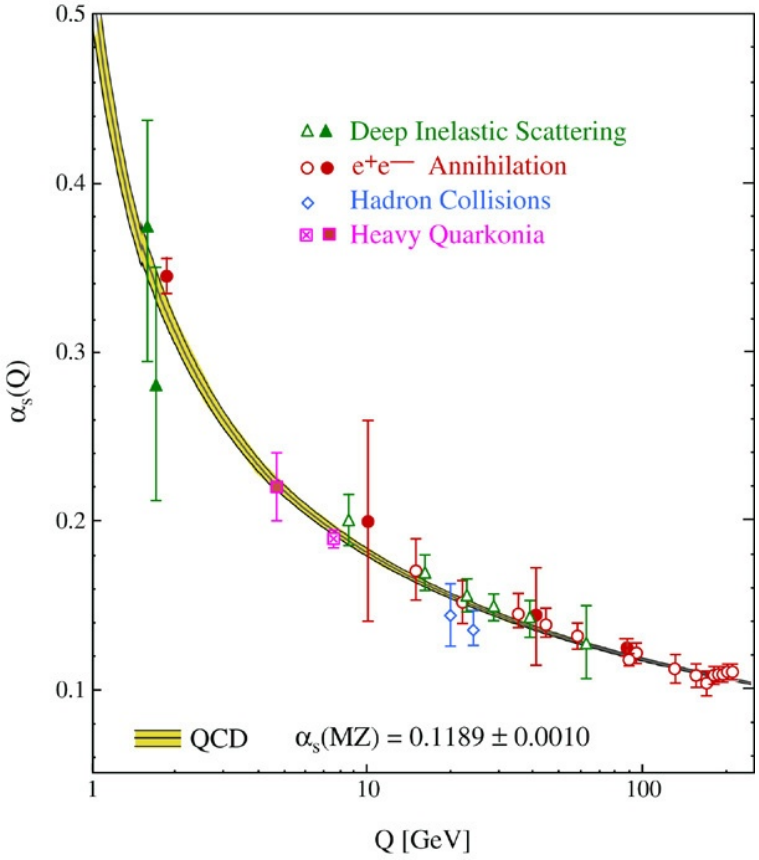

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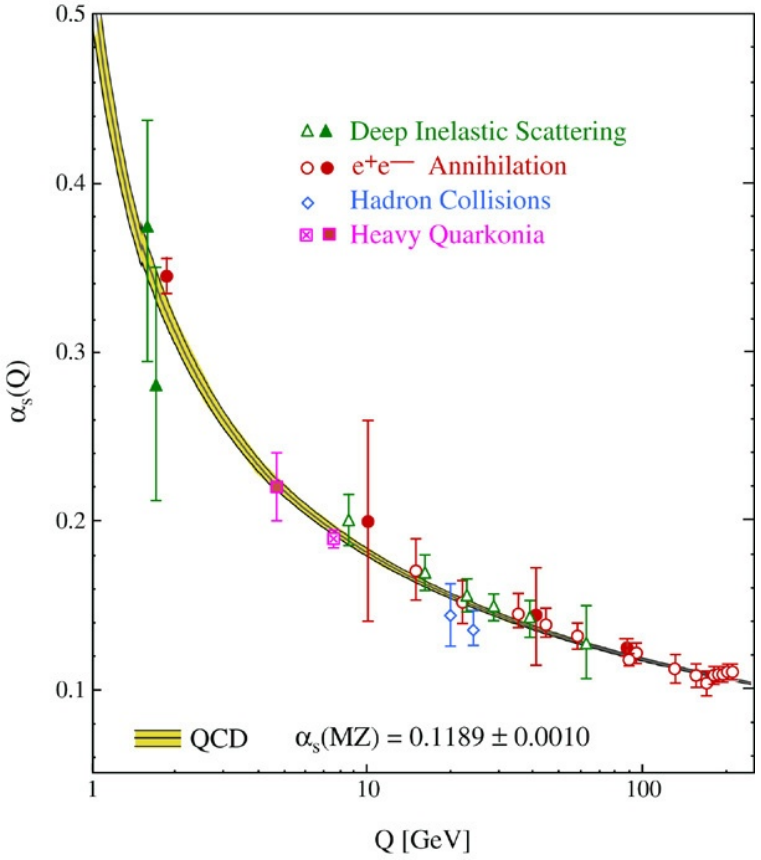


QCD is believed to be the correct theory of the strong force.
QCD should be able to describe the structure of the proton and neutron.
However, perturbative techniques cannot describe the complex bound state of quark and gluon fields composing the proton.

What does the nucleon look like?

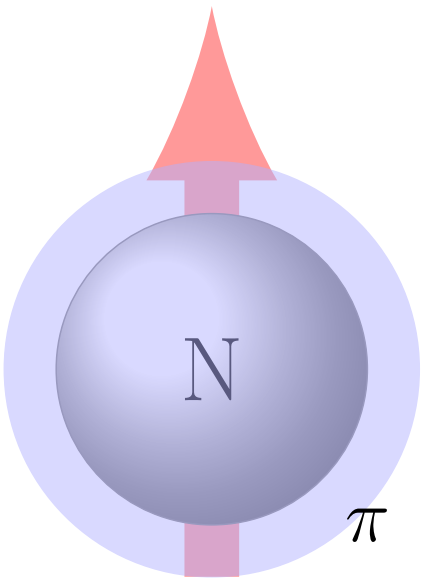
size $\longleftarrow$

Q^2 $\longrightarrow$

What does the nucleon look like?

size ← 1 fm

Q^2 → $1\mathrm{GeV}^2/c^2$



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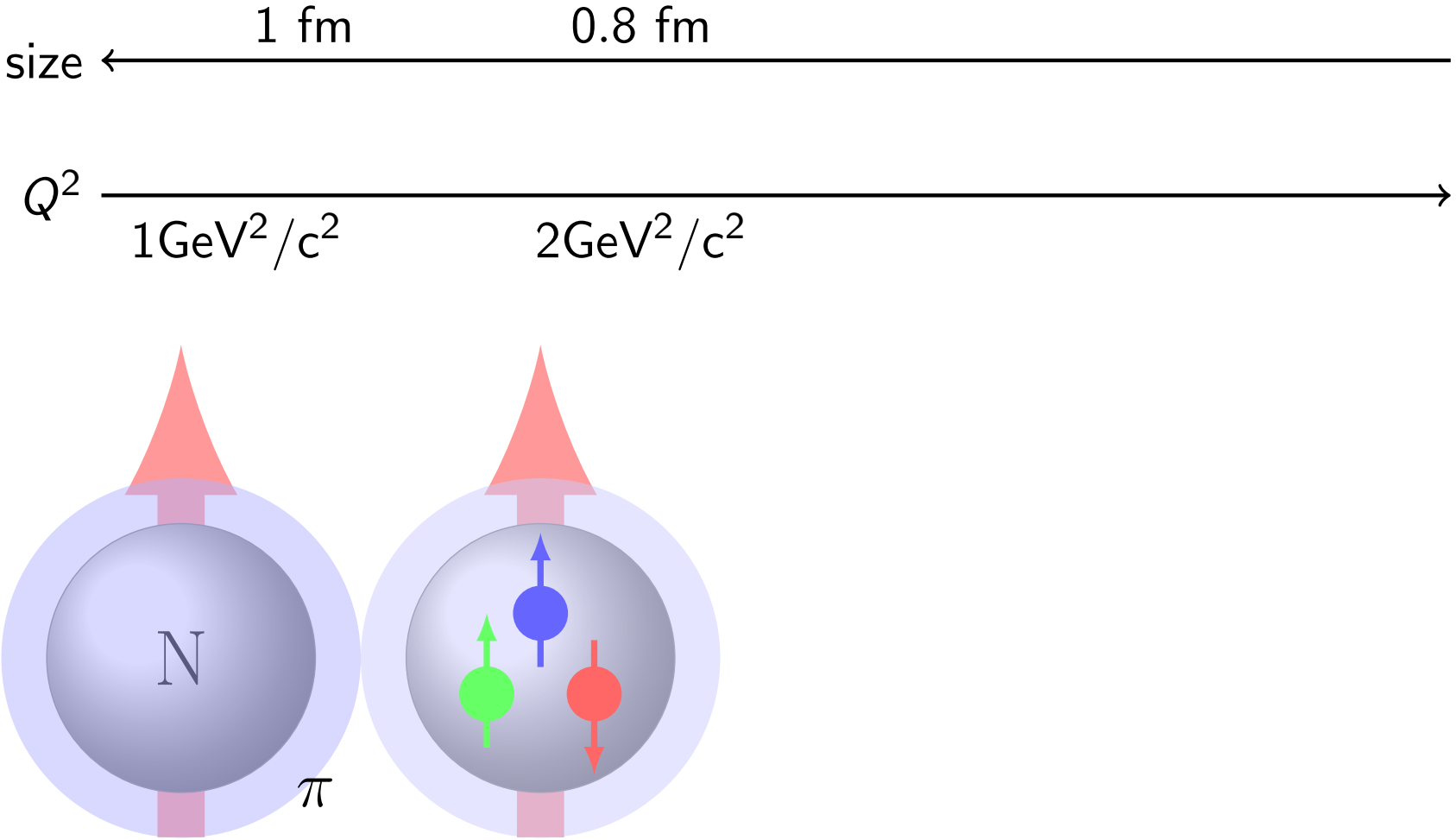
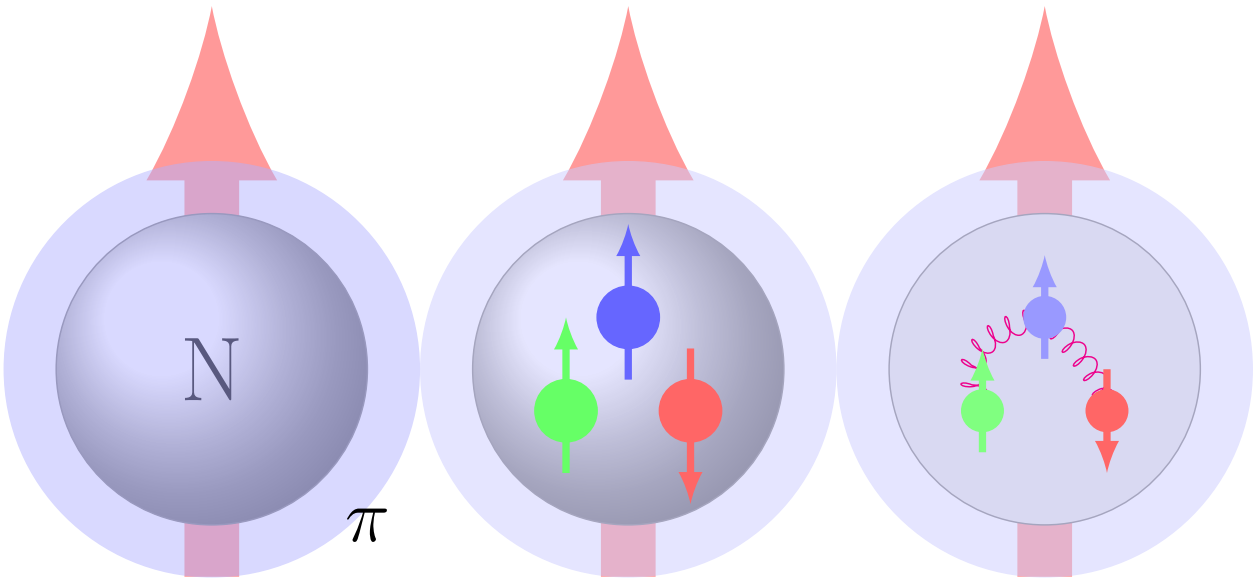


What does the nucleon look like?

size ← 1 fm — 0.8 fm — 0.4 fm

Q^2 → $1\mathrm{GeV}^2/c^2$ — $2\mathrm{GeV}^2/c^2$ — $10\mathrm{GeV}^2/c^2$



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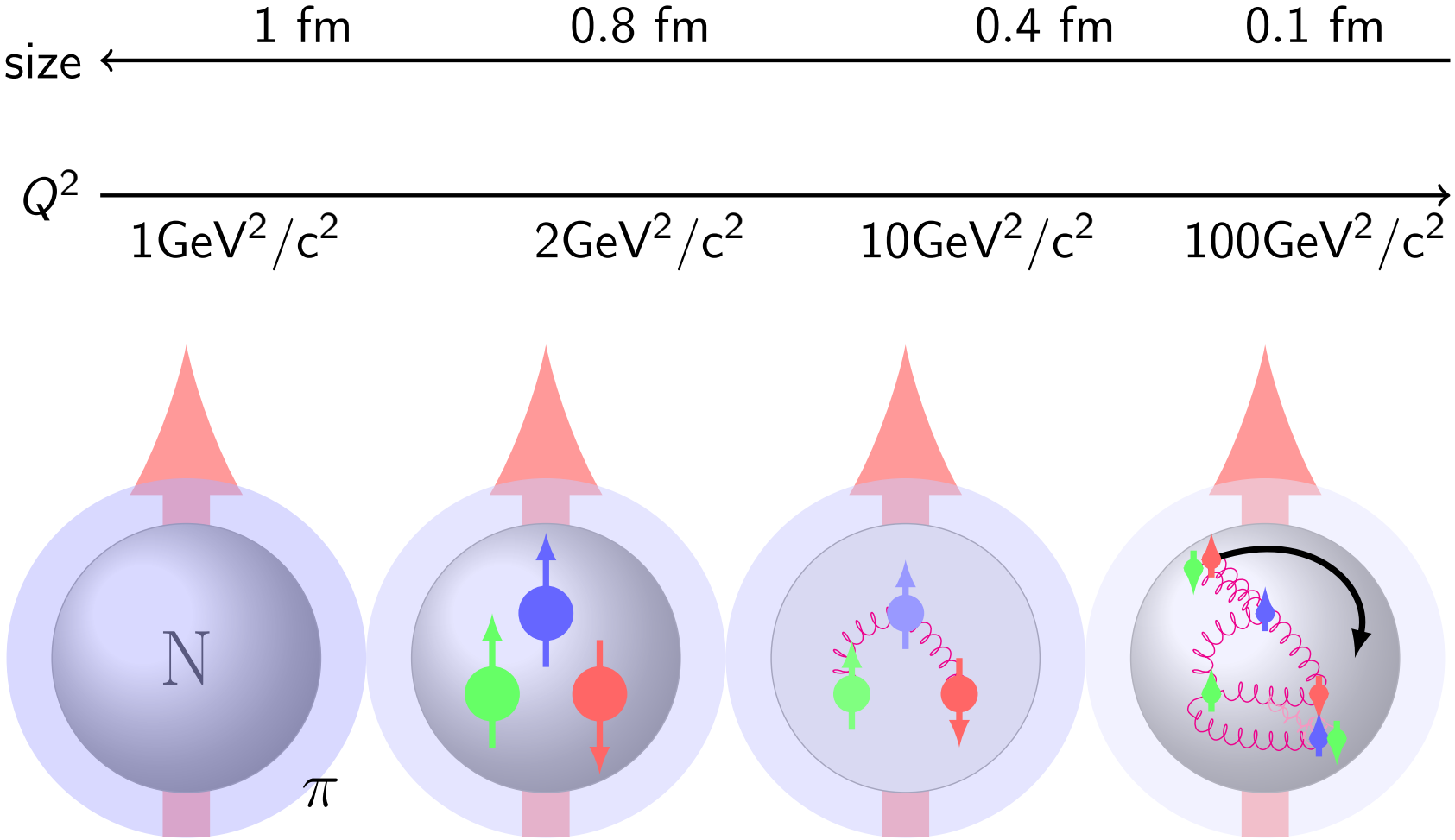

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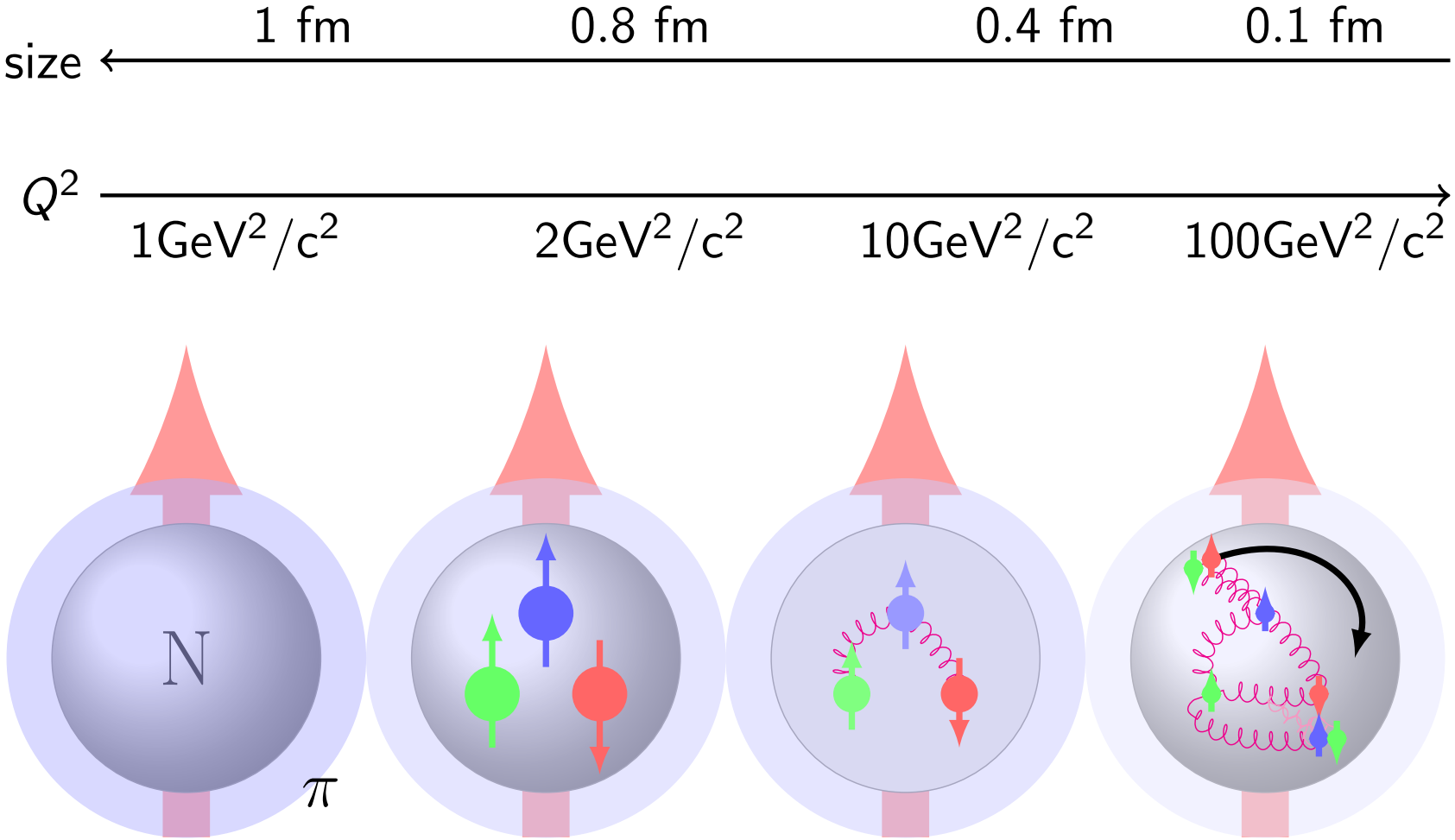
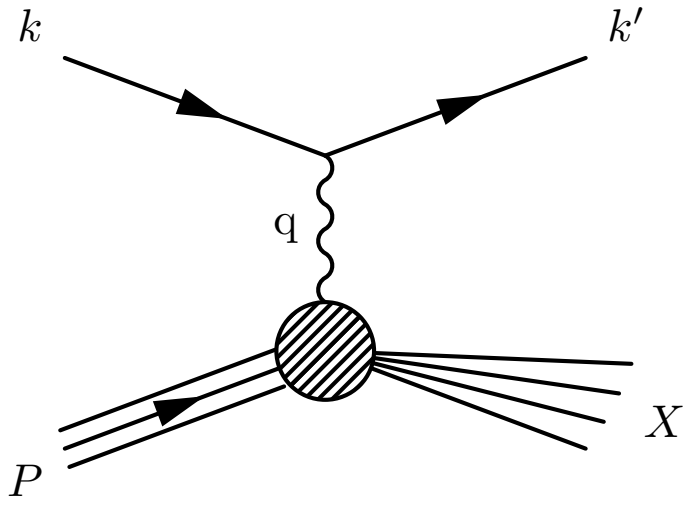


Use our understanding of pQCD at high Q^2 to begin to test our understanding at lower $Q^2 \rightarrow$ Operator Product Expansion

Deep Inelastic Scattering

Inclusive deep inelastic scattering experiments can probe the structure of the nucleon using both unpolarized and polarized targets and beams.



Unpolarized cross section

$$\sigma_0 = \frac{4\alpha^2 E'^2}{q^4}[2(F_1/M)sin^2(\theta/2) + (F_2/\nu)cos^2(\theta/2)]$$

The Bjorken variable

$$x = Q^2/(2p \cdot q) = Q^2/(2M\nu)$$

where $\nu = E - E'$ and

$$Q^2 = -q^2 = 4EE'sin^2(\theta/2)$$

x is the fraction of the total nucleon momentum carried by the struck quark.

$$F_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \; q_i(x, Q^2)$$

$$F_2(x, Q^2) = 2xF_1(x, Q^2)$$

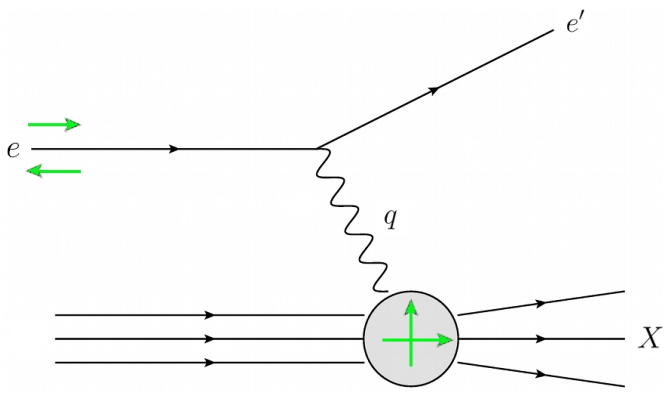
(Callan-Gross)

Polarized Deep Inelastic Scattering

Retaining the polarization of the initial states and taking the cross section differences for the two electron spin states yields the two measured double **spin** asymmetries

$$2\sigma_0 A_{\parallel} = -\frac{4\alpha^2}{Q^2}\frac{E'}{E}[(E+E'\cos\theta)g_1/M\nu - Q^2 g_2/M\nu^2]$$

$$2\sigma_0 A_{\perp} = -\frac{4\alpha^2}{MQ^2}\frac{E'^2}{E}\sin\theta\cos\phi[g_1/M\nu + 2E g_2/M\nu^2]$$



$$A_{\parallel} = \frac{d\sigma^{\Uparrow\downarrow} - d\sigma^{\Uparrow\uparrow}}{d\sigma^{\Uparrow\downarrow} + d\sigma^{\Uparrow\uparrow}}$$

$$A_{\perp} = \frac{d\sigma^{\Leftarrow\downarrow} - d\sigma^{\Leftarrow\uparrow}}{d\sigma^{\Leftarrow\downarrow} + d\sigma^{\Leftarrow\uparrow}}$$

Why a transverse target is needed

$$A_{\parallel} \propto g_1 - \frac{2Mx}{\nu} g_2$$

$\rightarrow$ g_2 suppressed by $1/\nu$.

$$A_{\perp} \propto g_1 + g_2$$

$\rightarrow$ In DIS region both contribute.

$\Rightarrow$ Directly sensitive to non-perturbative effects!

$$g_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2\ \Delta q_i(x, Q^2)$$

$$g_2(x, Q^2) = ?$$

A twist-3 sum rule

Using the Operator Product Expansion for the non-local operators showing up in the S matrix, one can arrive a the infinite set of sum rules below. For $n \geq 3$ and n odd, we have

$$\int_0^1 dx x^{n-1}\{g_1 + \frac{n}{n-1} g_2\} = \frac{1}{2}\sum_i \delta_i d^i_{n-1} E^n_{2,i}(Q^2, g) \tag{1}$$

For $n = 3$

$$\int_0^1 x^2\{2g_1 + 3g_2\}dx = d_2 \tag{2}$$

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Interpretations of d_2

- Color Polarizabilities (X.Ji)
- Average Color Lorentz force (M.Burkardt)

Quark-gluon Correlations

M. Burkardt

$$d_2 = \frac{1}{2MP^{+2}S^x}\langle P,S \mid \bar{q}(0)gG^{+y}(0)\gamma^+ q(0) \mid P,S\rangle$$

but with $\vec{v} = -c\hat{z}$

$$\sqrt{2}G^{+y} = -E^y + B^x = -(\vec{E} + \vec{v}\times\vec{B})^y$$

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$d_2 \Rightarrow$ average color Lorentz force acting on quark moving backwards (since we are in inf. mom. frame) the instant after being struck by the virtual photon. [a]

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

[a] M.Burkardt, Phys.Rev.D 88,114502 (2013)and Nucl.Phys.A735,185(2004).

Quark-gluon Correlations

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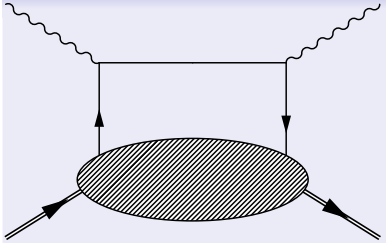

$$g_2^{WW}(x, Q^2) = -g_1^{LT}(x, Q^2) + \int_x^1 g_1^{LT}(y, Q^2)\mathrm{d}y/y$$
$$\equiv g_2^{tw2}(x, Q^2)$$

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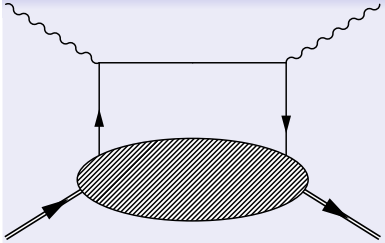

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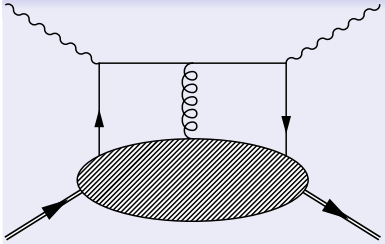
Twist-3 (Cortes, Pire, Ralston, 1992)



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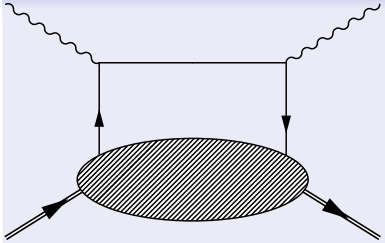

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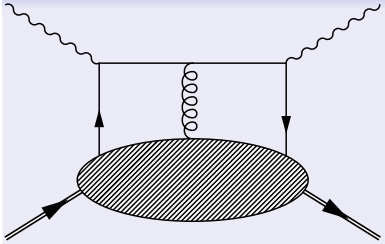

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$$d_2(Q^2) = 3\int_0^1 x^2 \bar{g}_2(x, Q^2)dx$$
$$= \int_0^1 x^2(2g_1(x, Q^2) + 3g_2(x, Q^2))dx$$

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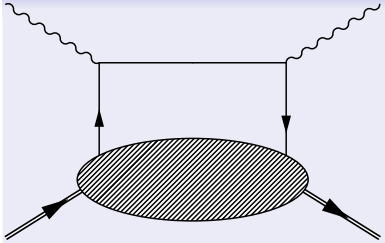

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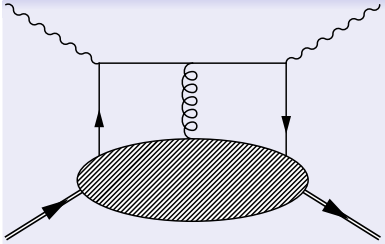

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As Q^2 decreases,
when do higher twists begin to matter?

Tangent: Quark OAM

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Ji (1997)

$$L_q = \int dx \frac{1}{2} \left(x(H+E)(x,\xi,\Delta) - \tilde{H}(x,\xi,\Delta) \right)$$

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From sum rules: Kiptily and Polyakov (2002)

$$\int dx\ x^2 G_2^{tw3}(x,0,0) = -\frac{2}{3}d_2 = -2\int x^2 \bar{g}_2(x)dx$$

Matching the integrands in the forward limit

$$G_2^{tw3}(x,0,0) = -2\bar{g}_2(x)$$

$$G_2^{WW}(x,0,0) = \frac{1}{3x}\tilde{H}(x,0,0) - \frac{2}{3}(H+E)(x,0,0)$$

Quark OAM

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Explicit spin-orbit anti-correlation
Lorcé (2014), Lorcé and Pasquini (2011)

Extracting $\bar{g}_2$

Inclusive DIS sensitive to $\bar{g}_2^q + \bar{g}_2^{\bar{q}}$
Need $\bar{g}_2^q - \bar{g}_2^{\bar{q}}$
At high-x is $\bar{g}_2^{\bar{q}} \simeq 0$?

Caveats

Neglects twist > 3
Need lower x (not x^2 weighted)

Quark OAM

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$
$$= \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

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New relation between Ji and J.M. Decompositions

$$\mathcal{L}_g + \mathcal{L}_q = 5 - 9J_g - \Delta G + 6x\bar{g}_2 \tag{3}$$

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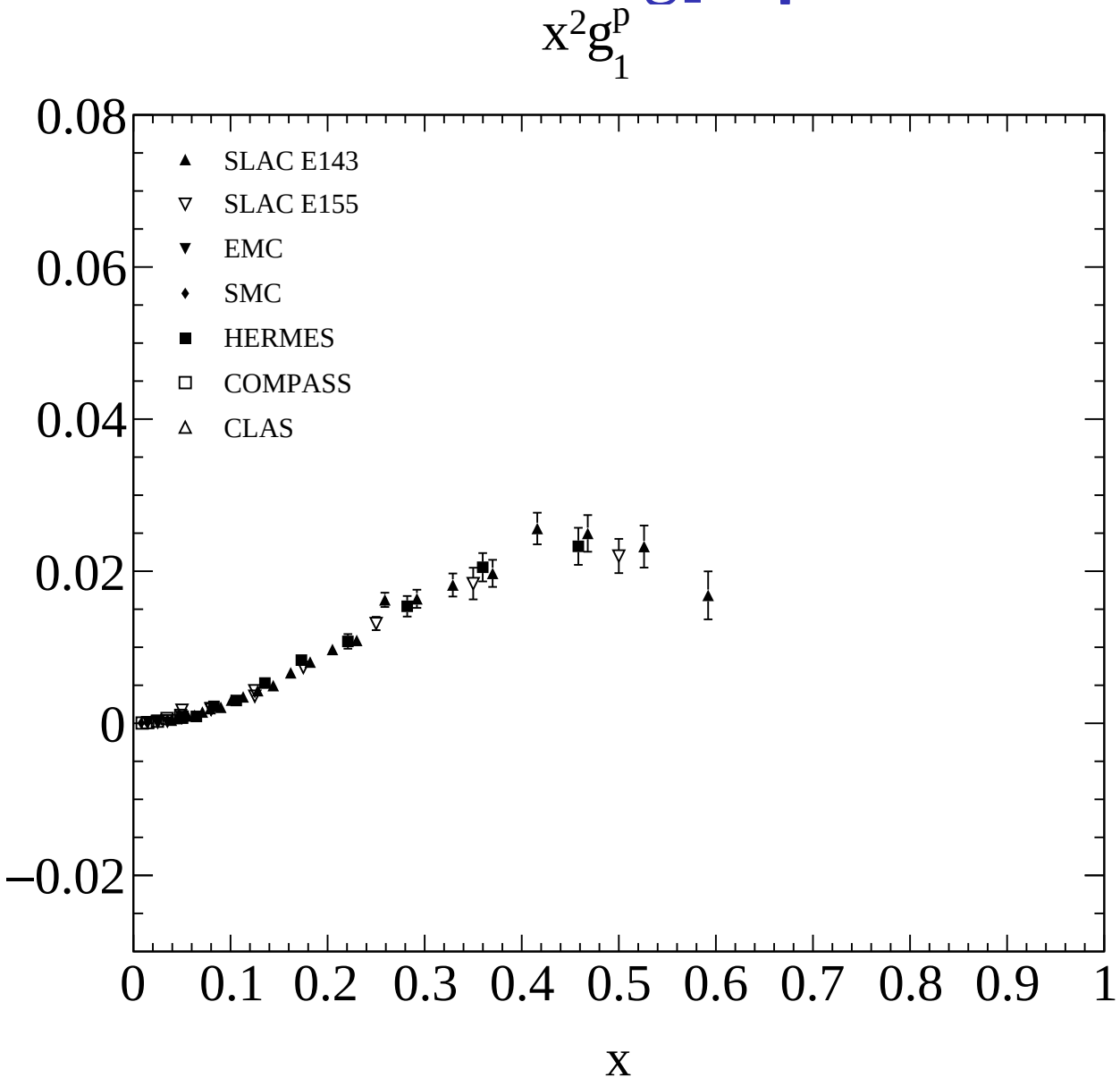
$\Delta L = \mathcal{L}_q - L_q$: Burkardt (2013)

Difference in angular momentum due to torque as the struck quark is ejected

$$\Delta L = \int_{x^-}^{\infty} dr^- \left[\vec{r} \times (\vec{E} - \hat{z} \times \vec{B})\right]^z \tag{4}$$

See Matthias Burkardt's talk later today!

Status of the Proton g_1 Spin Structure Function



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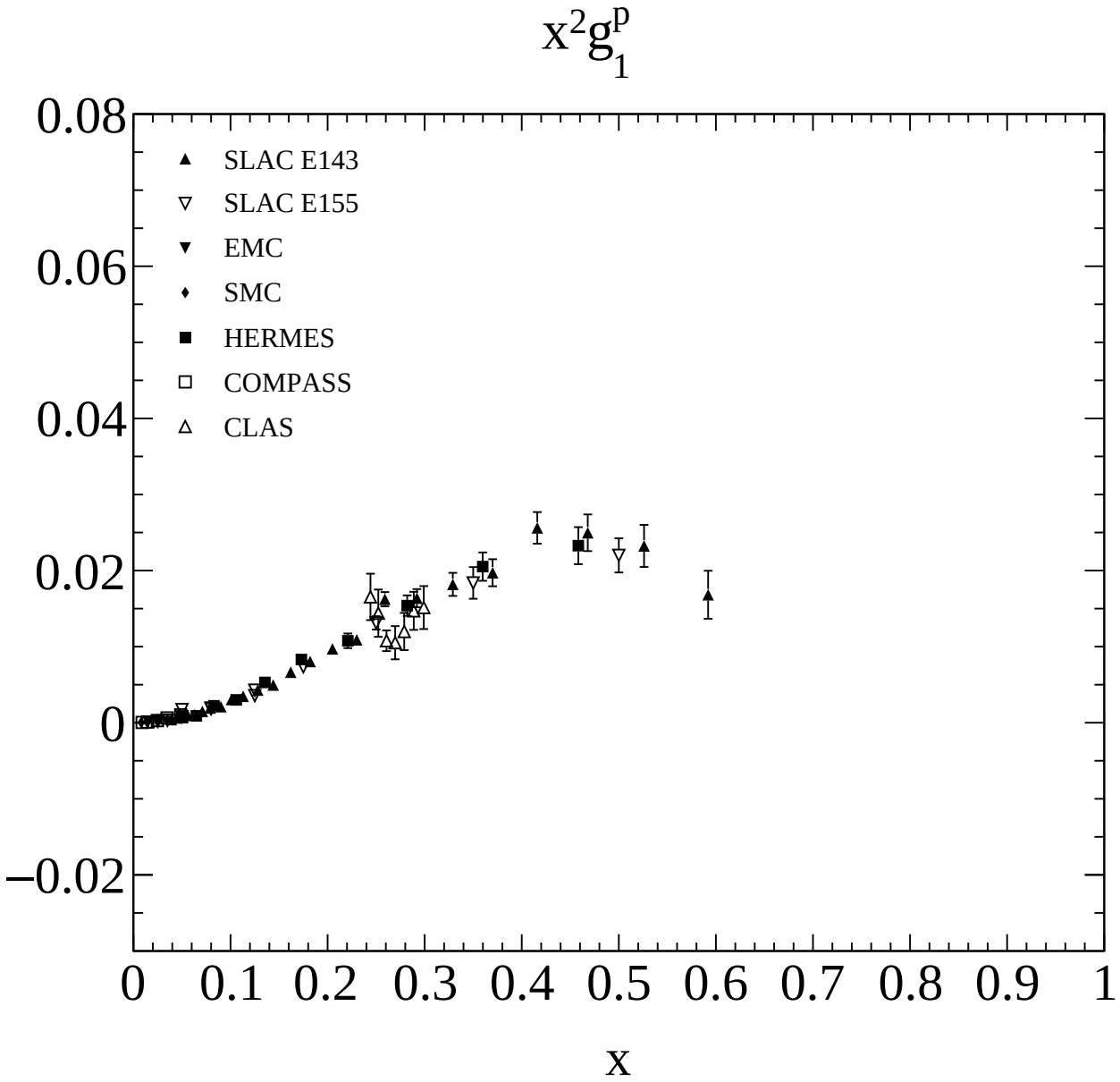

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- with CLAS data

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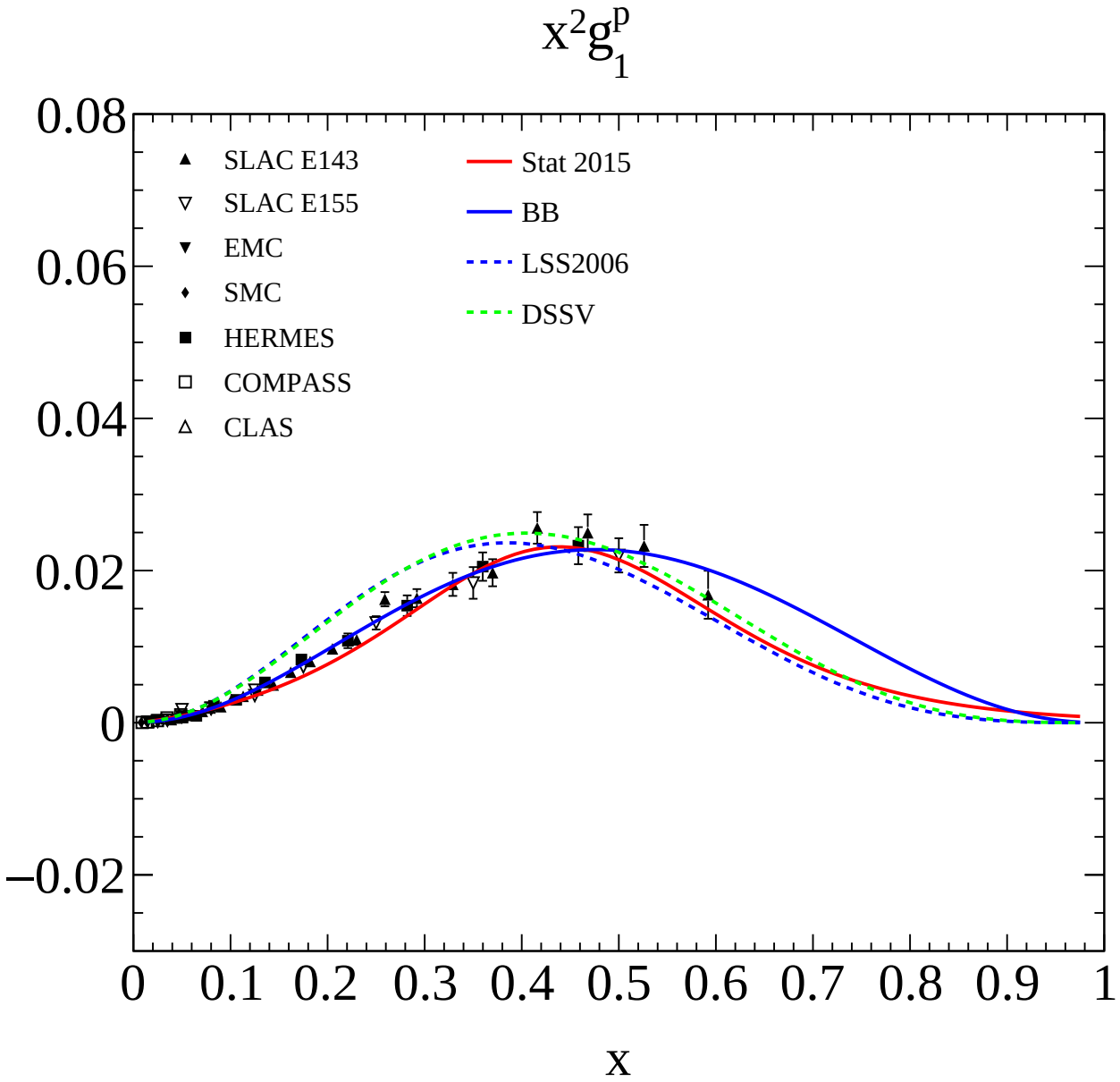
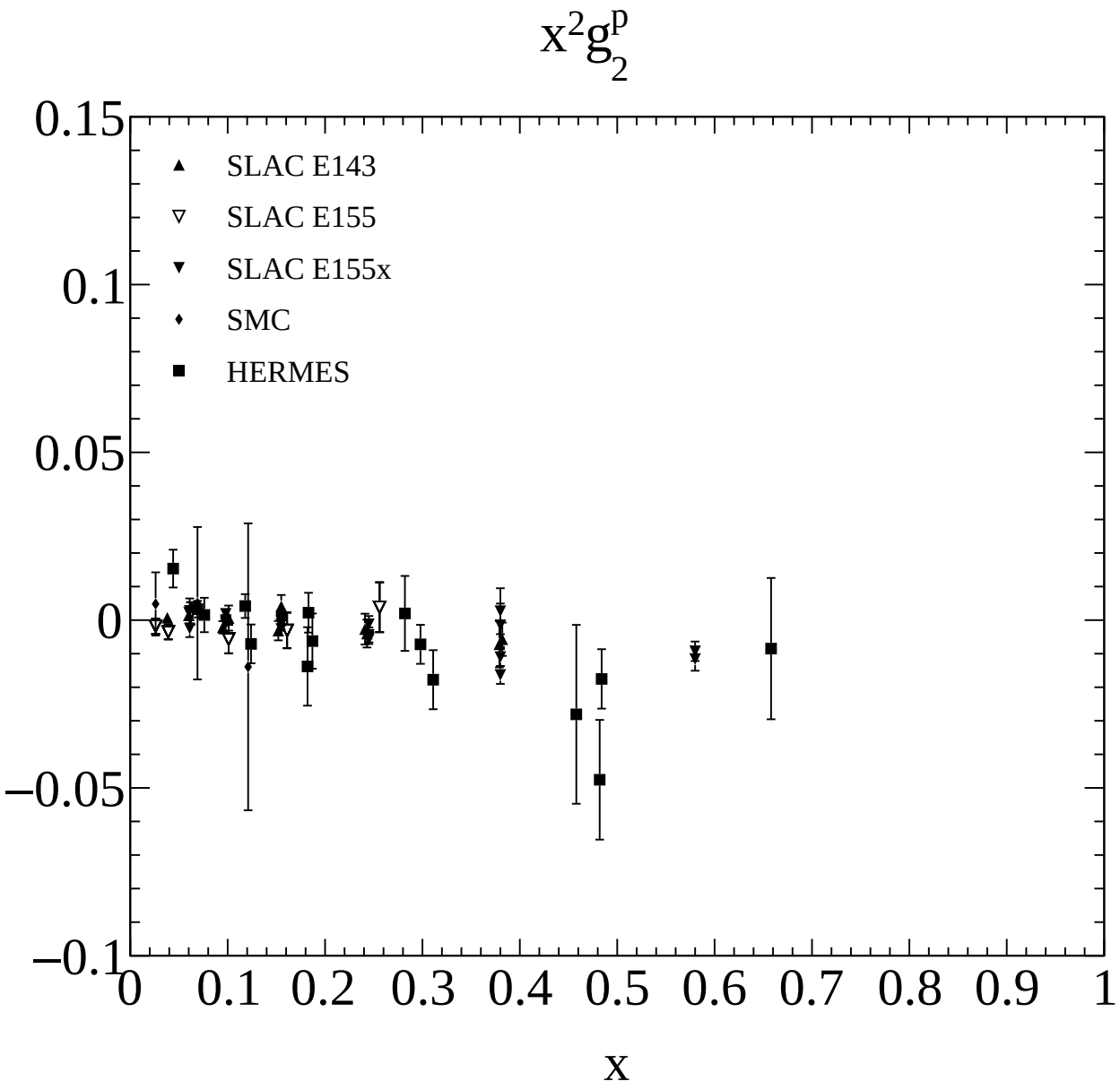


- g_1^p for $1.5 < Q^2 < 8.5$
- More high x data needed

Status of g_2 Spin Structure Function



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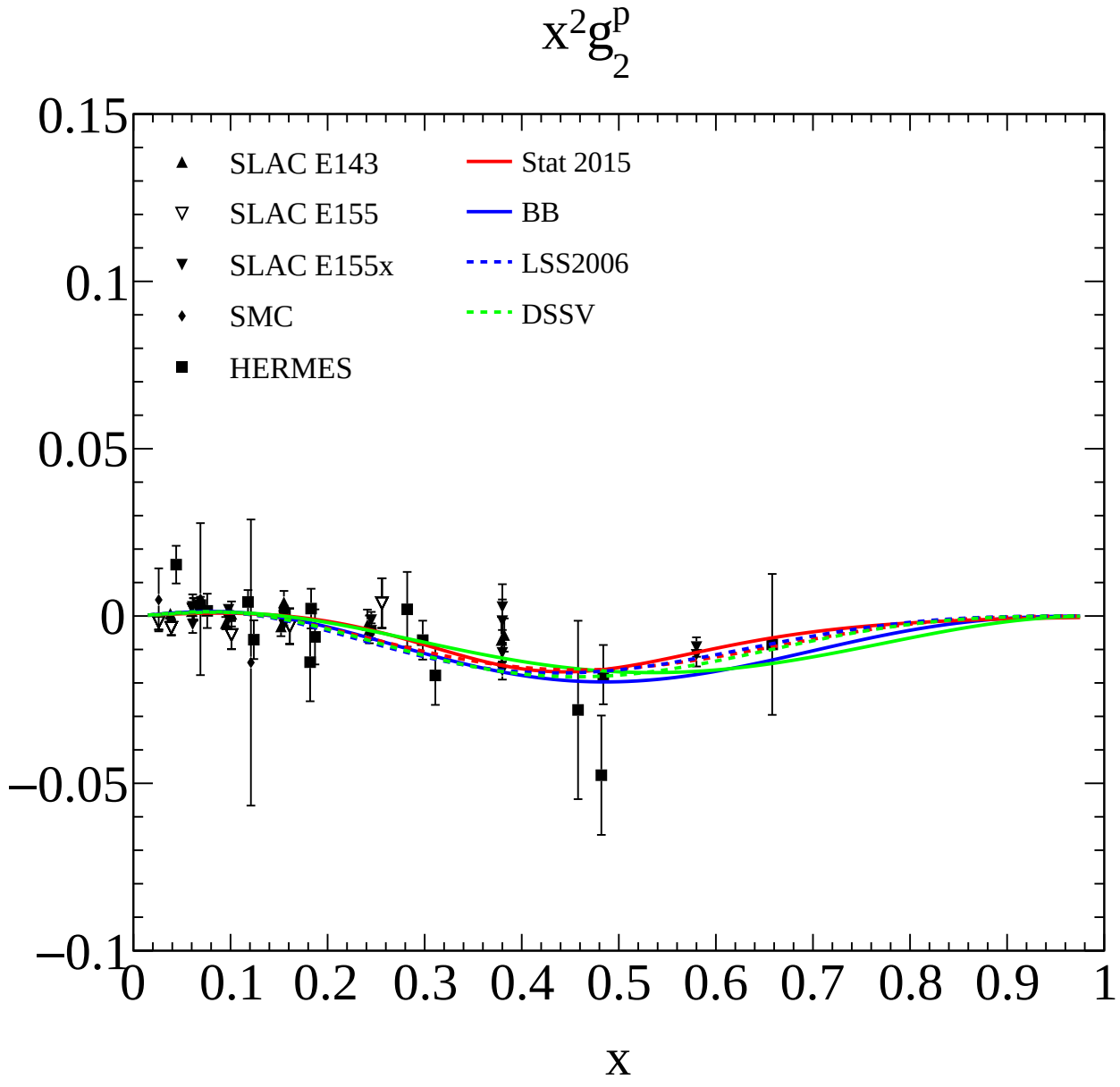

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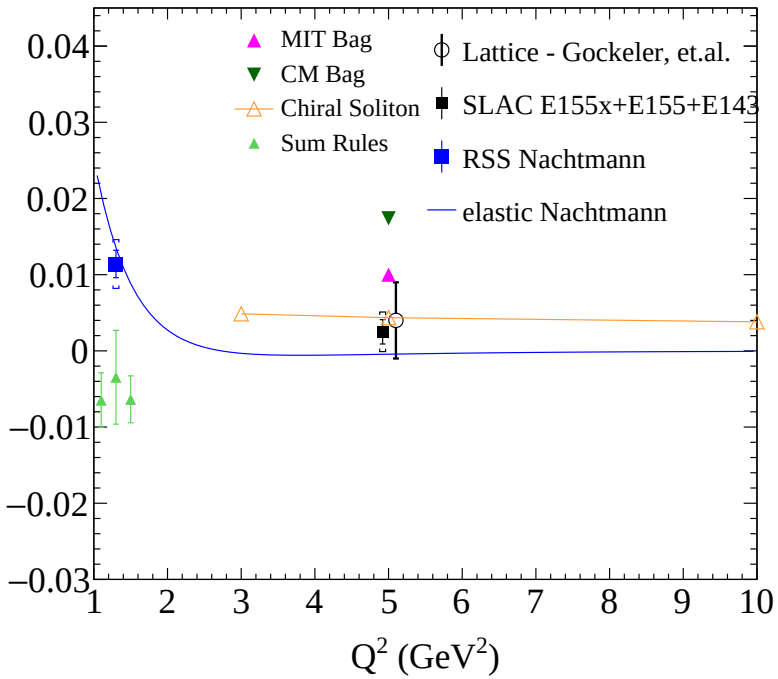

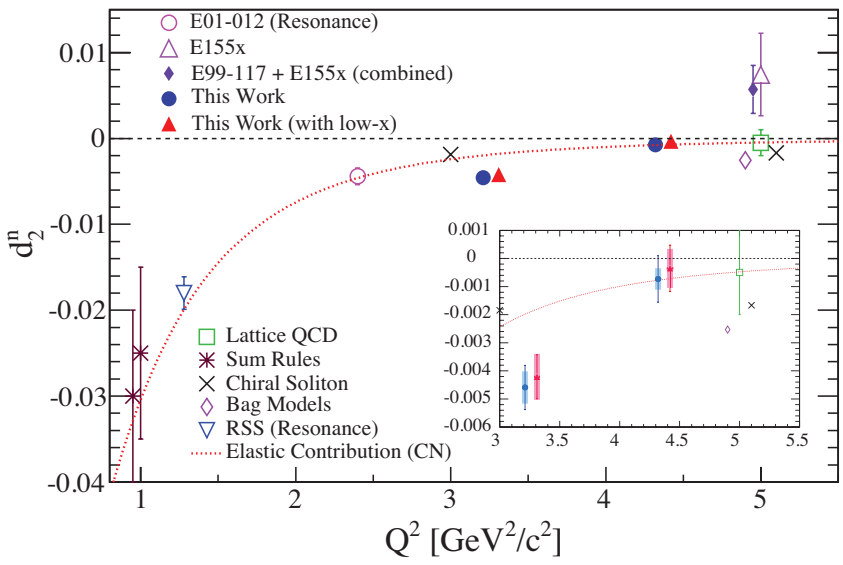

Recent results from d_2^n experiment

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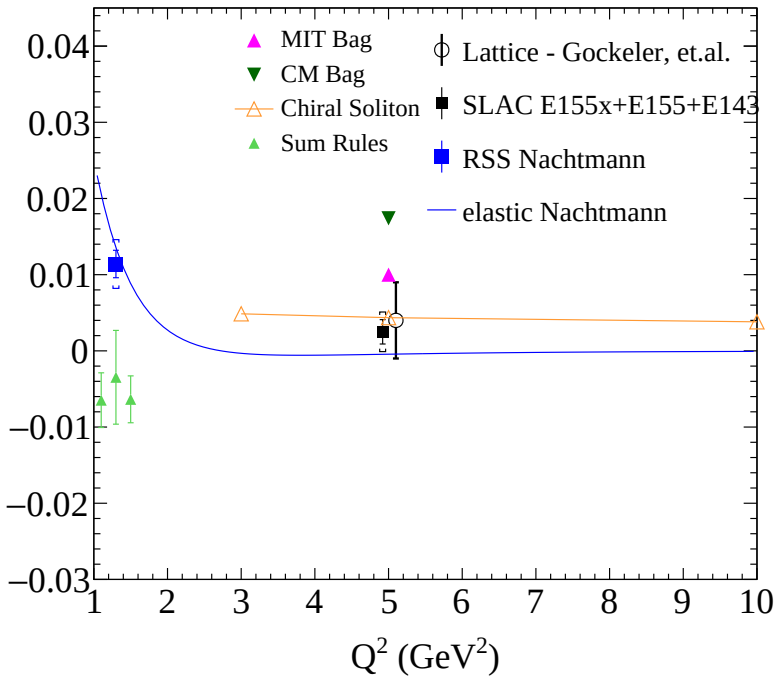

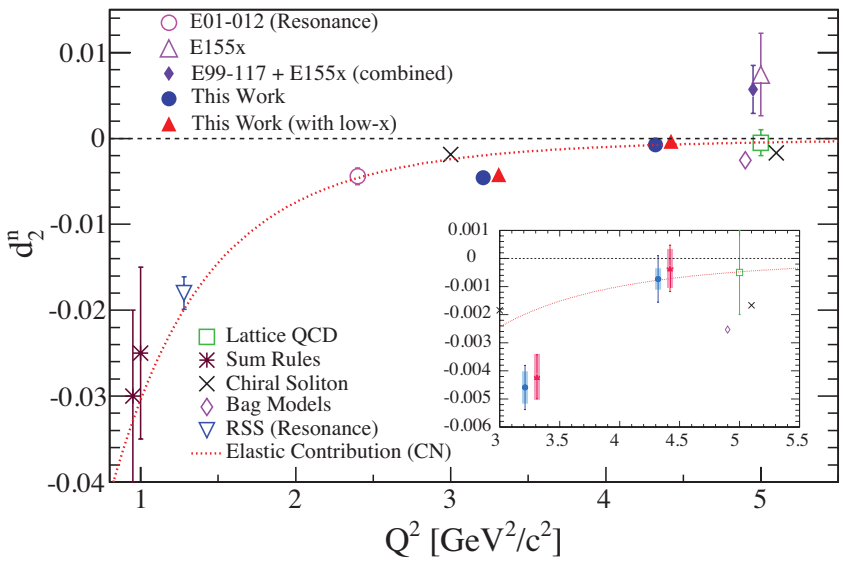

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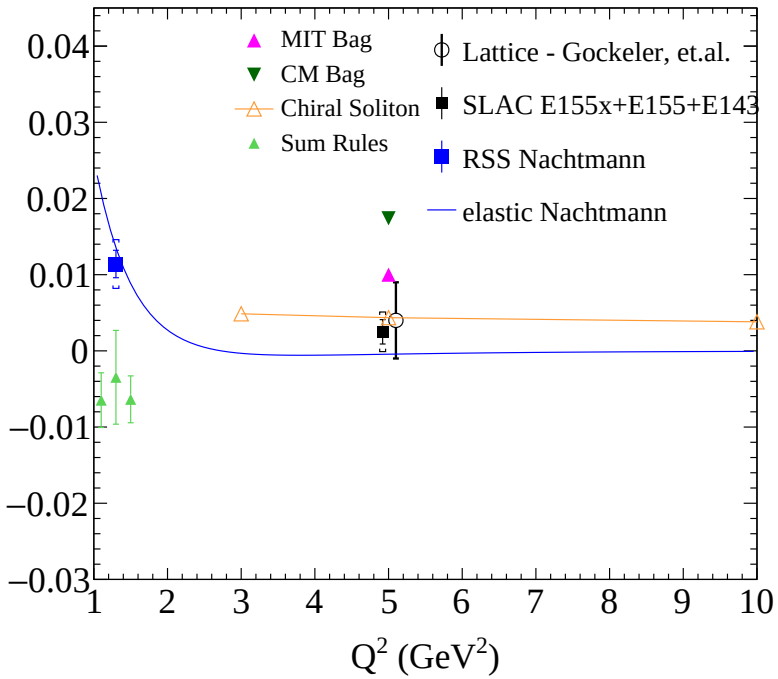

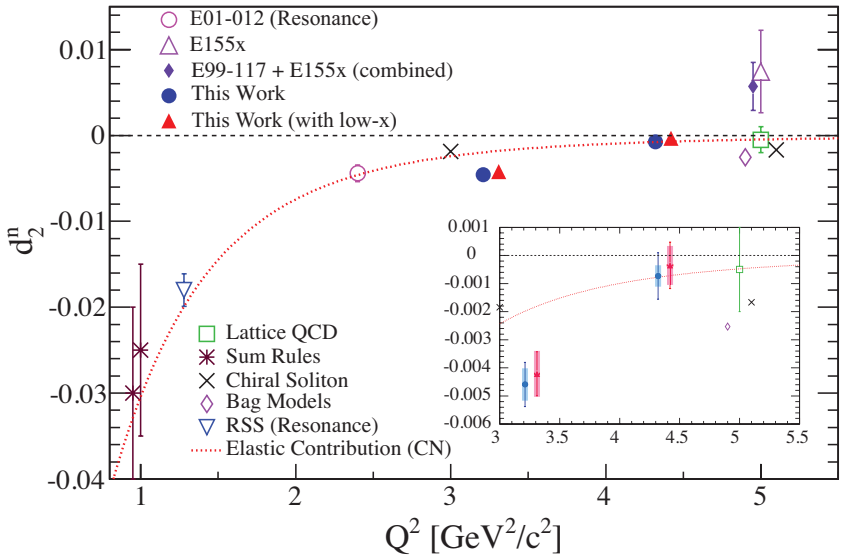

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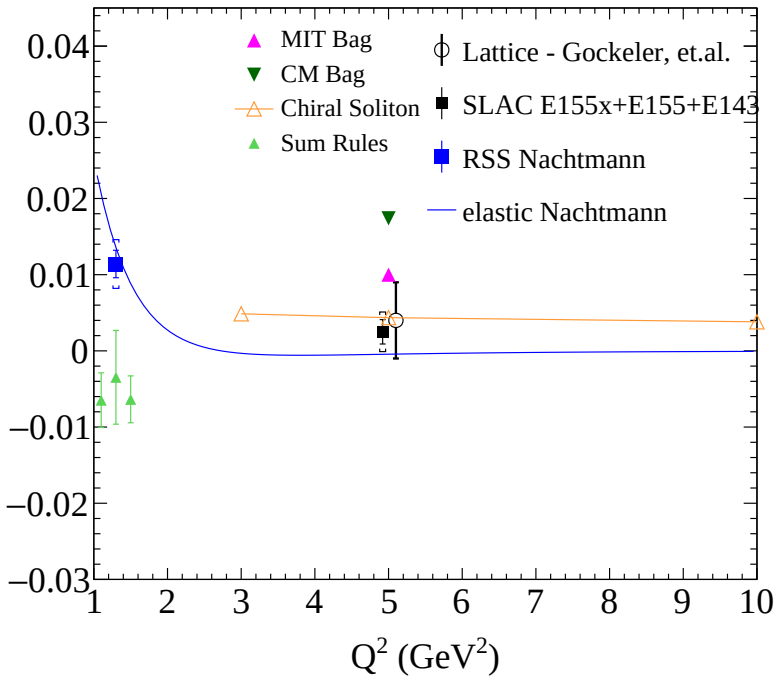

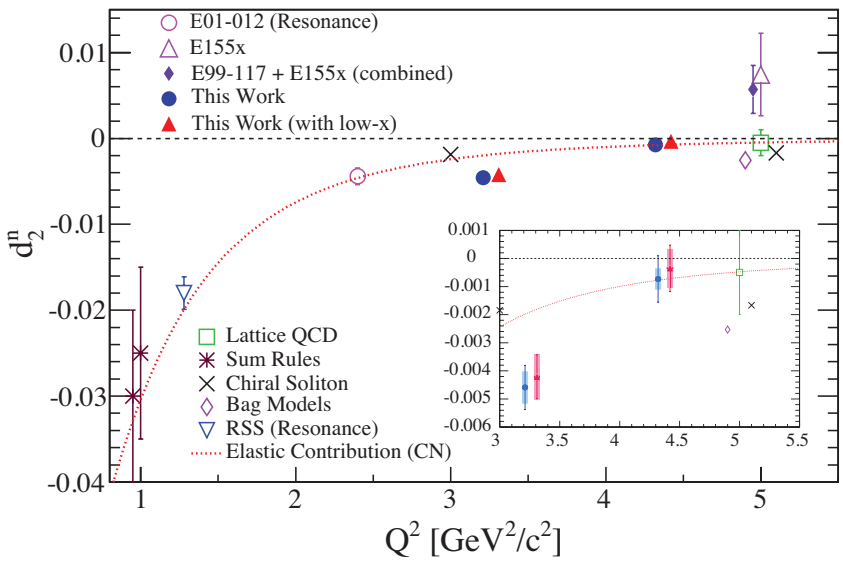

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- Agree with proton and (now) neutron results ...
- Updated and improved lattice results long overdue

Physics with g_2

- Polarized DIS is uniquely poised to provide insight into quark-gluon correlations.

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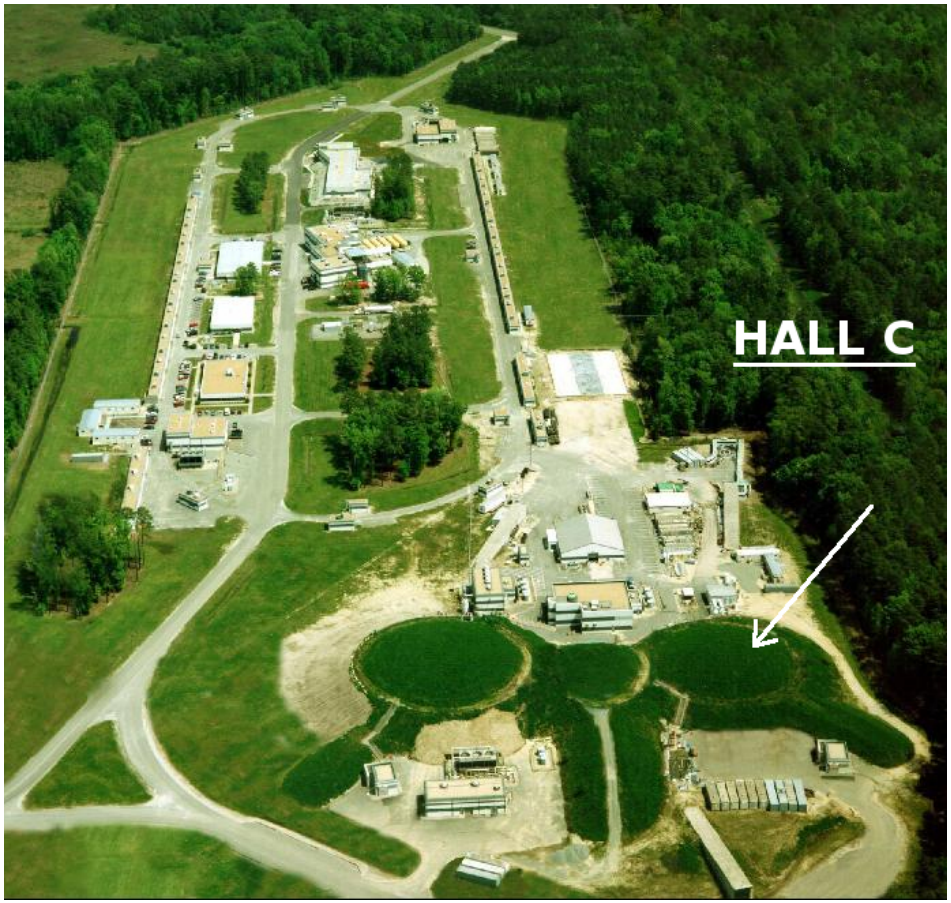
Precision measurments of g_1 and g_2 at JLab provide great insight into the non-perturbative structure of the nucleon and test our understanding of QCD

Spin Asymmetries of the Nucleon Experiment (E07-003)



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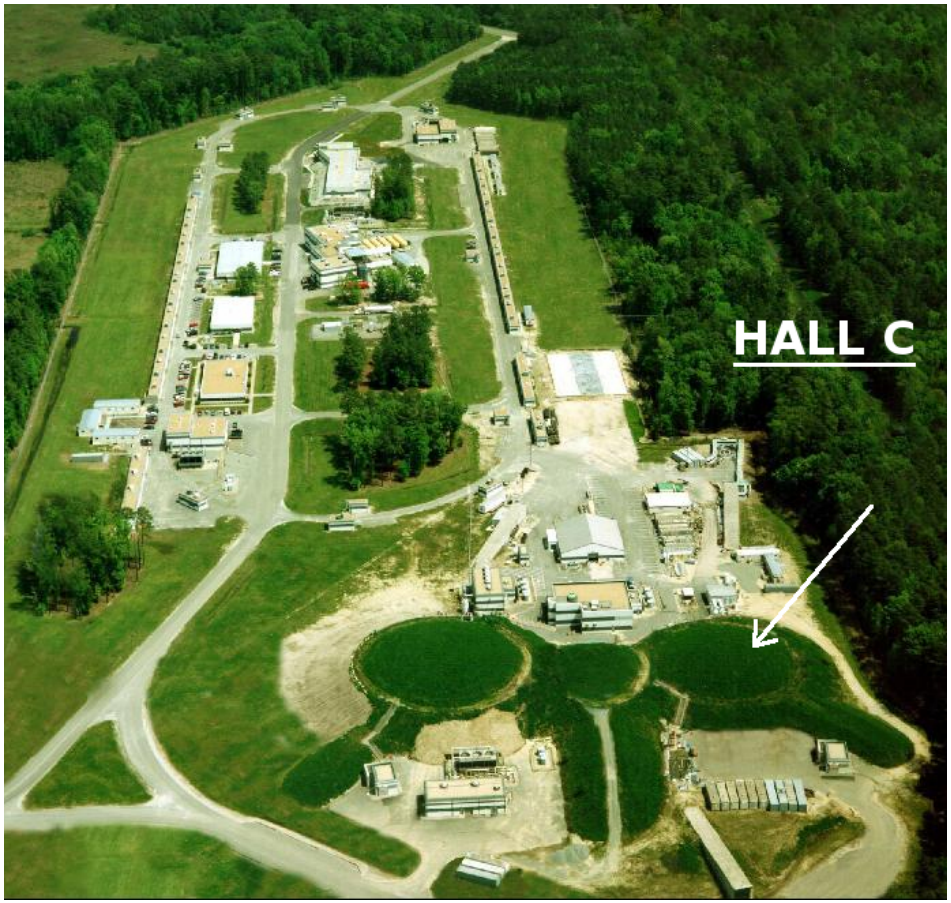

SANE Spokespersons

S. Choi (Seoul), M. Jones (JLab), Z-E. Meziani (Temple), O.A. Rondon (UVa)

Measured Asymmetries

Using Jefferson Lab's polarized electron beam with a polarized ammonia target, we measured the asymmetries A_{180} and A_{80},
where the 180 (80) indicates the target polarization is anti-parallel(near perpendicular) to the incoming beam direction.

The beam helicity is flipped rapidly (60Hz) allowing for the slowly varying experimental systematics to cancel.

Experimental Overview

SANE

- 4.7 GeV and 5.9 GeV beam energies

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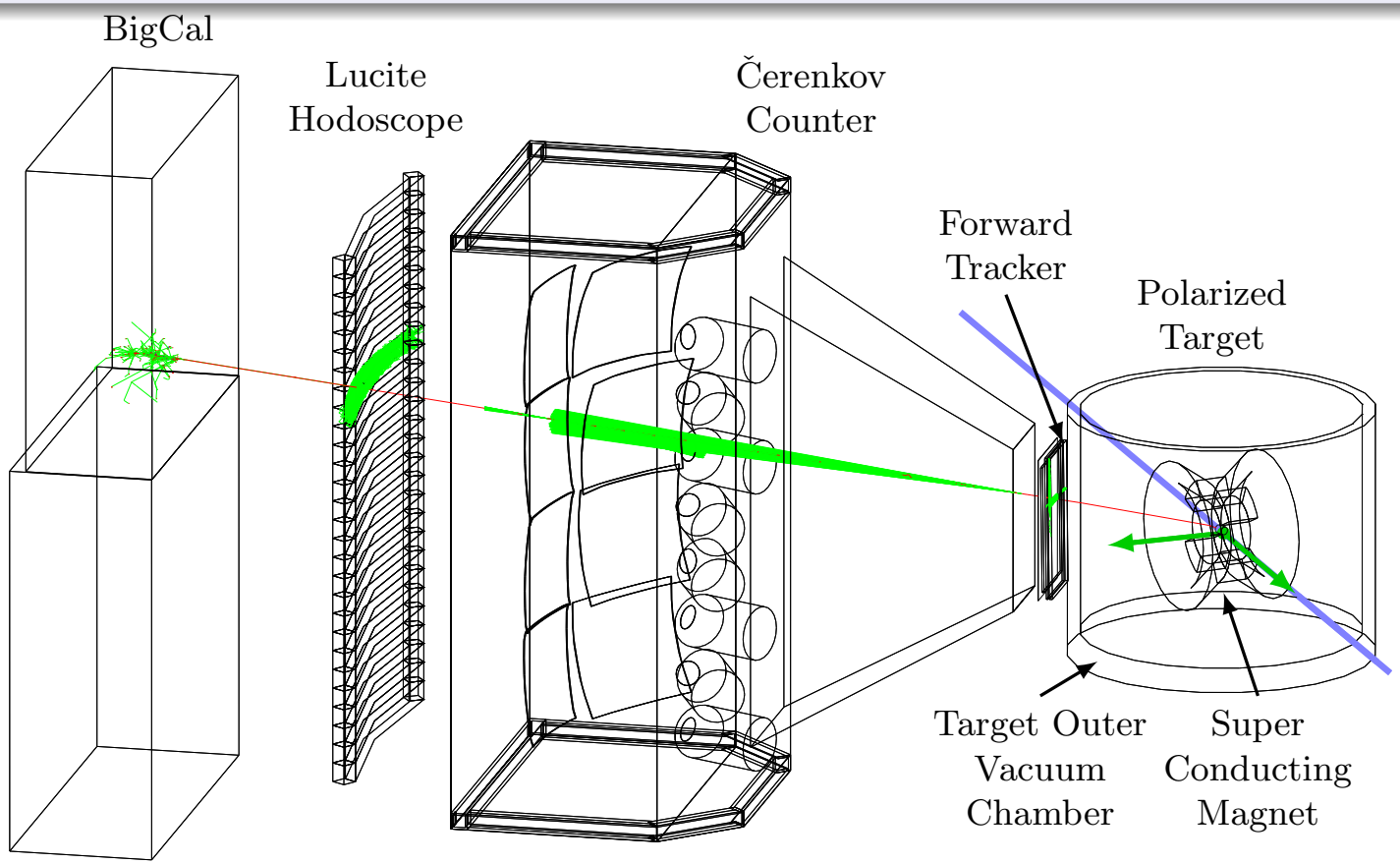
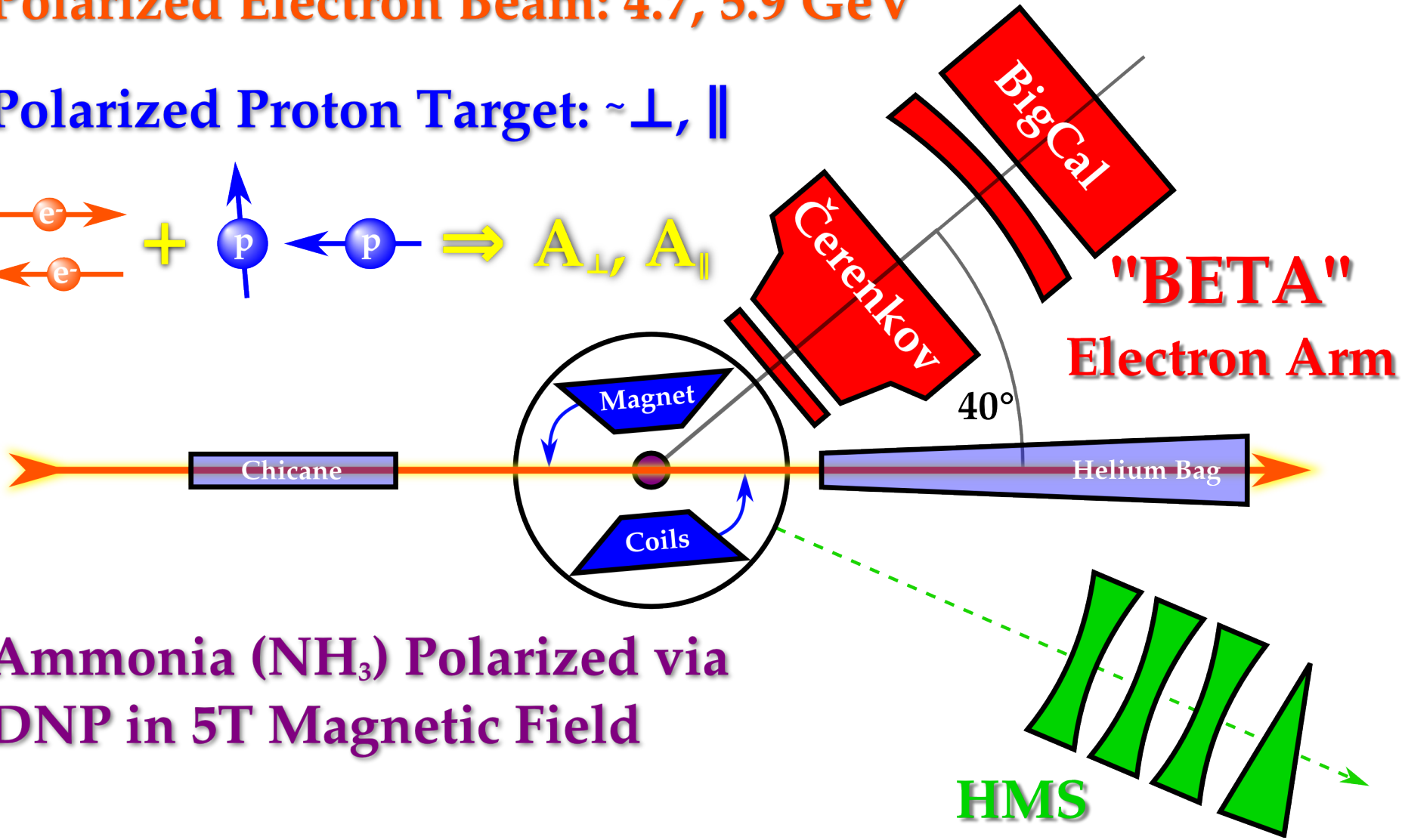
- **B**ig **E**lectron **T**elescope **A**rray



SANE

Polarized Electron Beam: 4.7, 5.9 GeV

Polarized Proton Target: ~⊥, ∥



Ammonia (NH_3) Polarized via DNP in 5T Magnetic Field

Detector Overview

BETA was a unique detector

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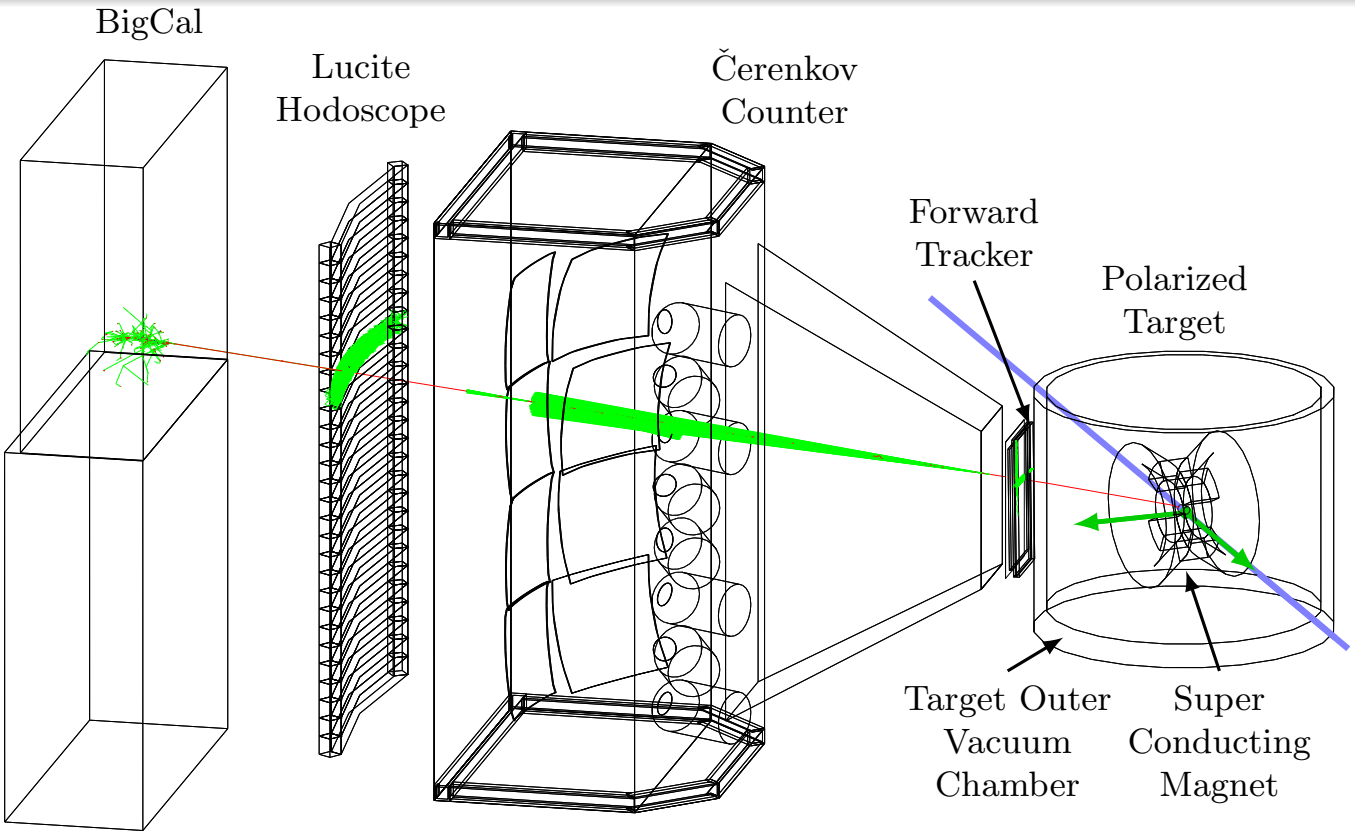
- Large solid angle, about 200 msr



Detector Overview

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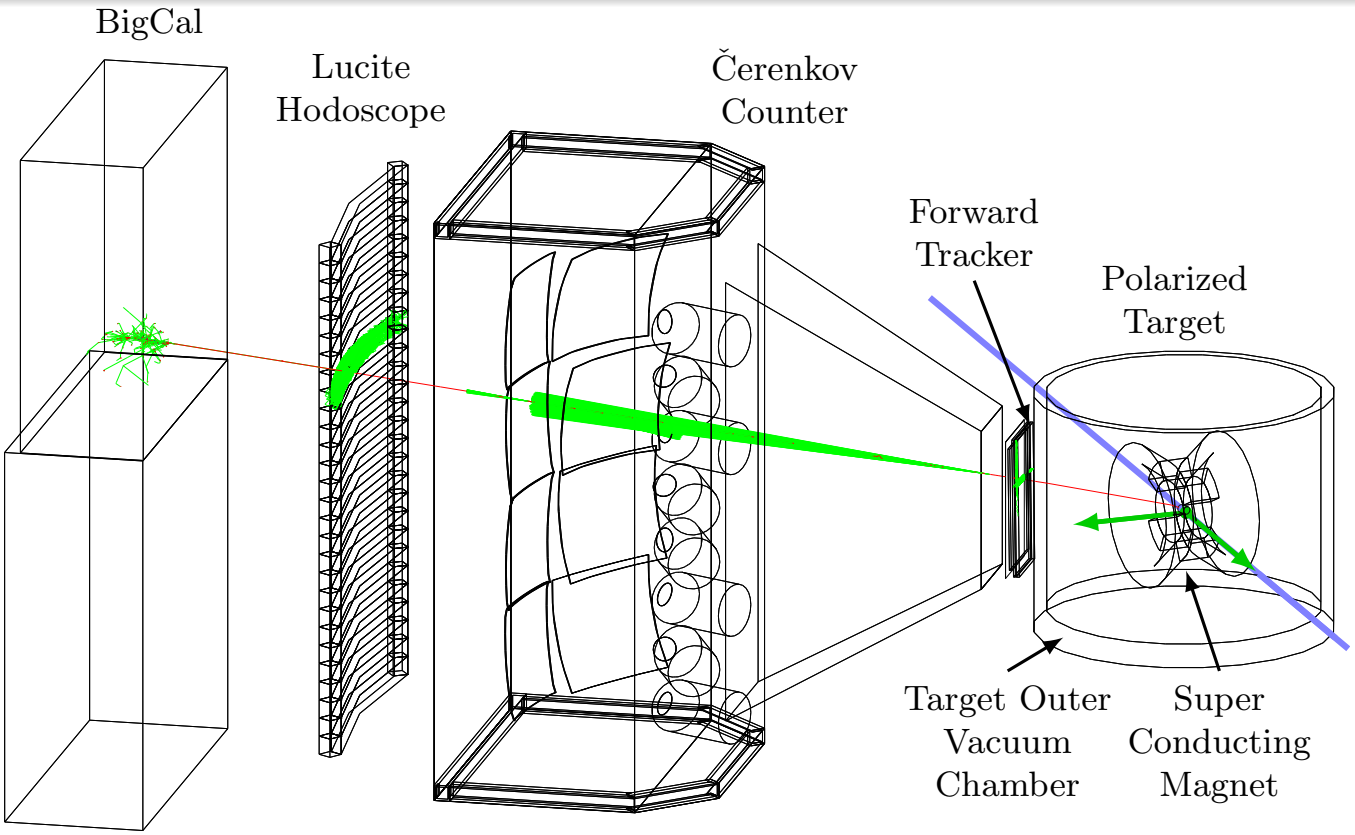
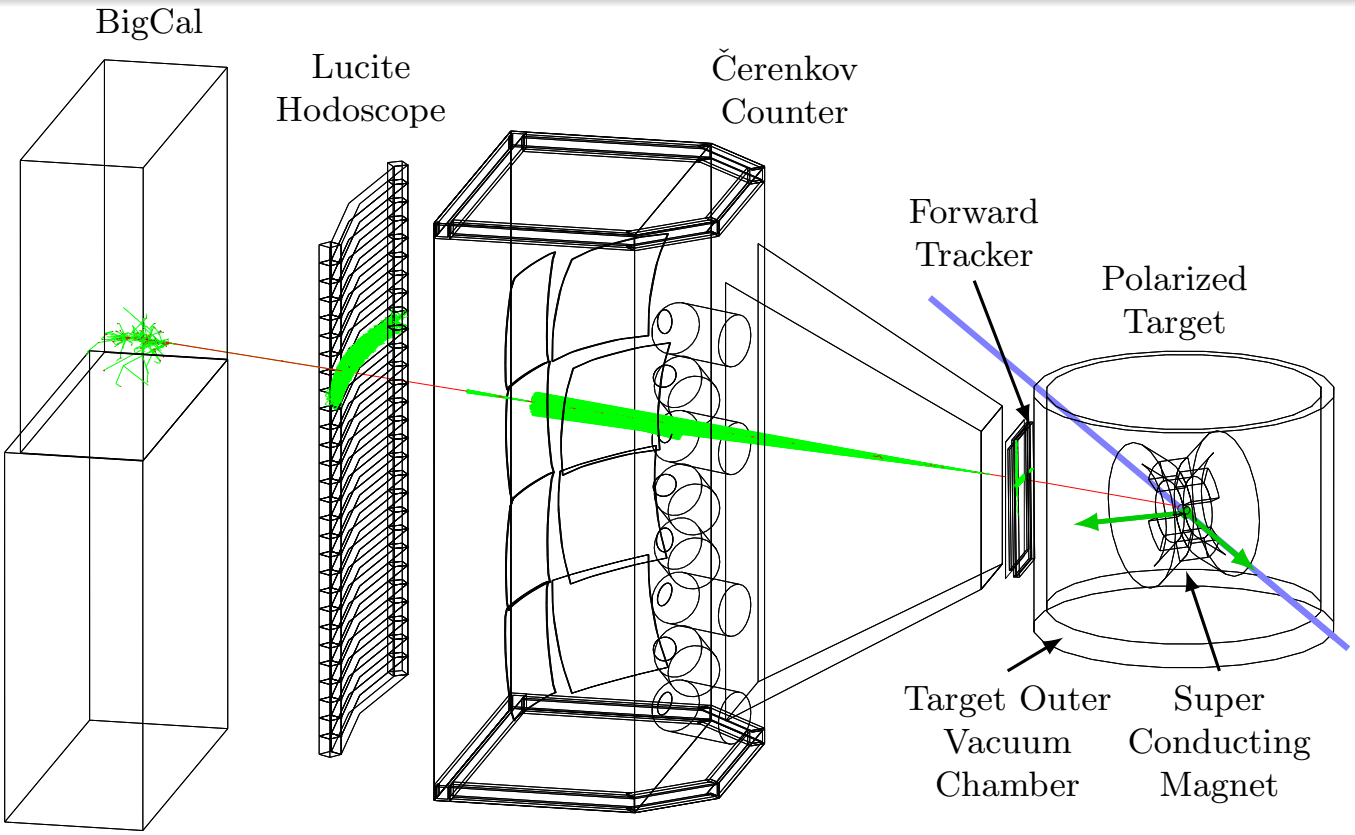
- Open configuration



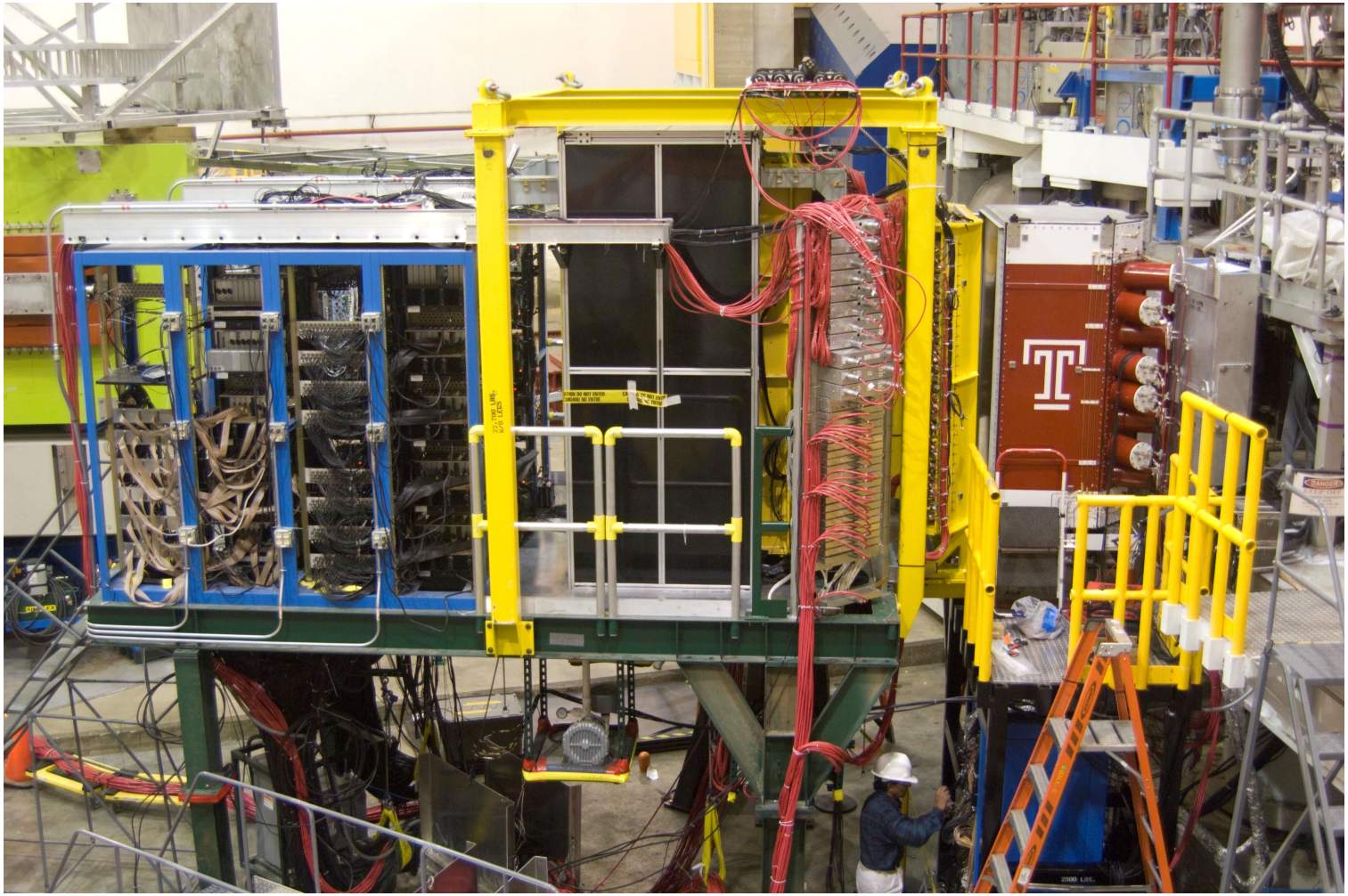
Detector Overview

BETA was a unique detector

- Large solid angle, about 200 msr
- Open configuration
- No momentum selecting magnet



Big Electron Telescope Array



SANE used BETA to detect inclusive electrons with a large acceptance at angles around 40°for energies above about 1 GeV.

BigCal

Two Sections

The upper section from Yerevan Physics Institute used during RCS experiment.

- It consists of $4 \times 4 \times 40 cm^3$ lead-glass blocks
- They are arranged in a 30×24 array

Lower section from IHEP in Protvino, Russia.

- It consists of $3.8 \times 3.8 \times 45 cm^3$ lead-glass blocks
- They are arranged in 32×32 array

1,744 lead glass blocks total.

Figure: Bigcal lead-glass blocks

Bigcal was previously used in the GEp series of experiments

SANE Gas Čerenkov

Gas Čerenkov is from Temple University.

Design

- Filled with nitrogen gas at atmosphere.
- Uses 4 spherical and 4 toroidal mirrors to focus light to photomultiplier tubes.
- Used 3 inch quartz window Photonis PMTs for UV transparency
- Mirror blanks were sent to CERN for special coating for high reflectivity far into the UV.

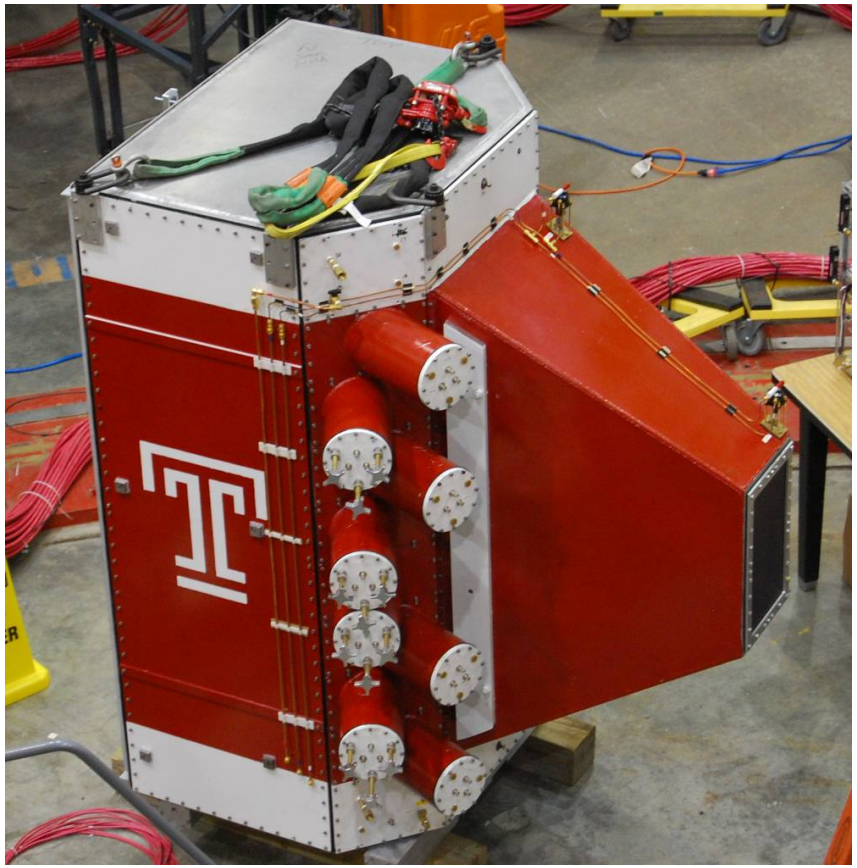
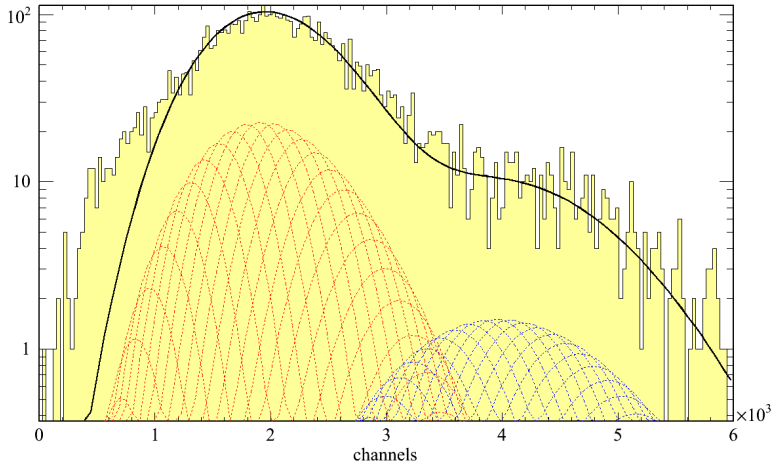
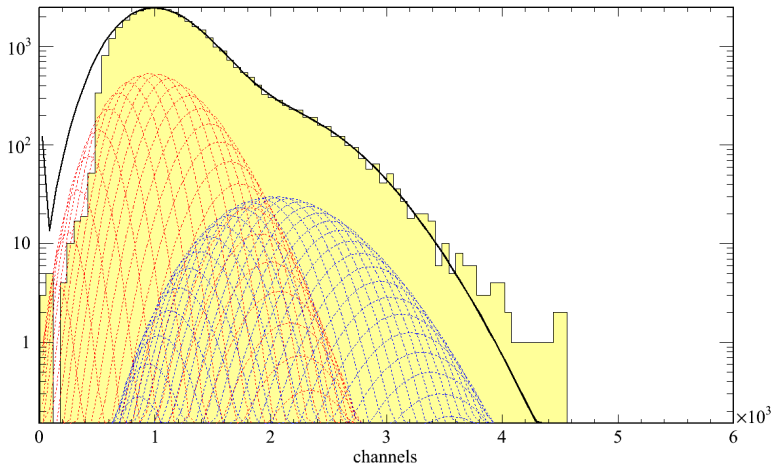


Figure: Gas Čerenkov on Hall C floor

Čerenkov ADCs



- PMT 5
- Spherical mirrors at large scattering angle.



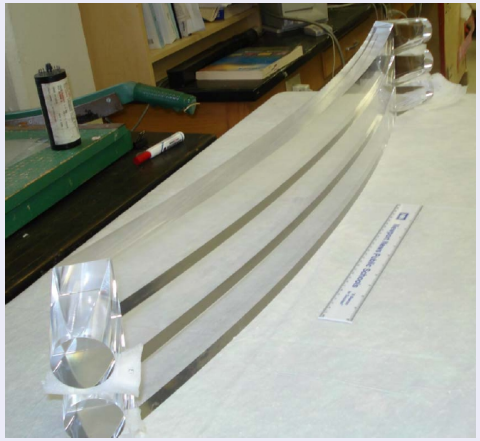
- PMT 4
- Toroidal mirror at small scattering angle.

Lucite Hodoscope

Lucite Hodoscope is from North Carolina A&T State University.

Design

- 28 curved Lucite bars with light guides mounted to edges cut at 45°
- PMT with light guide mounted at both ends of each bar.



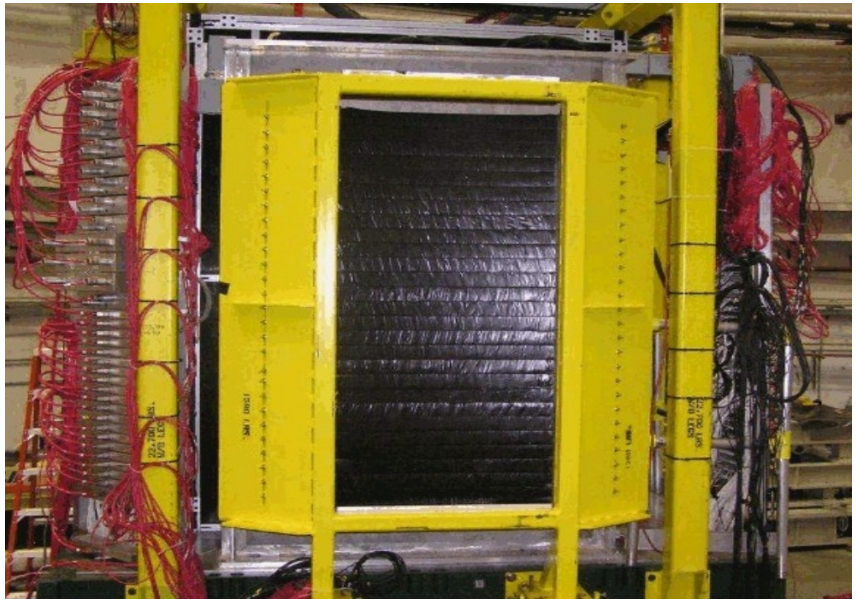


Figure: Lucite Hodoscope in Hall C

Forward Tracker

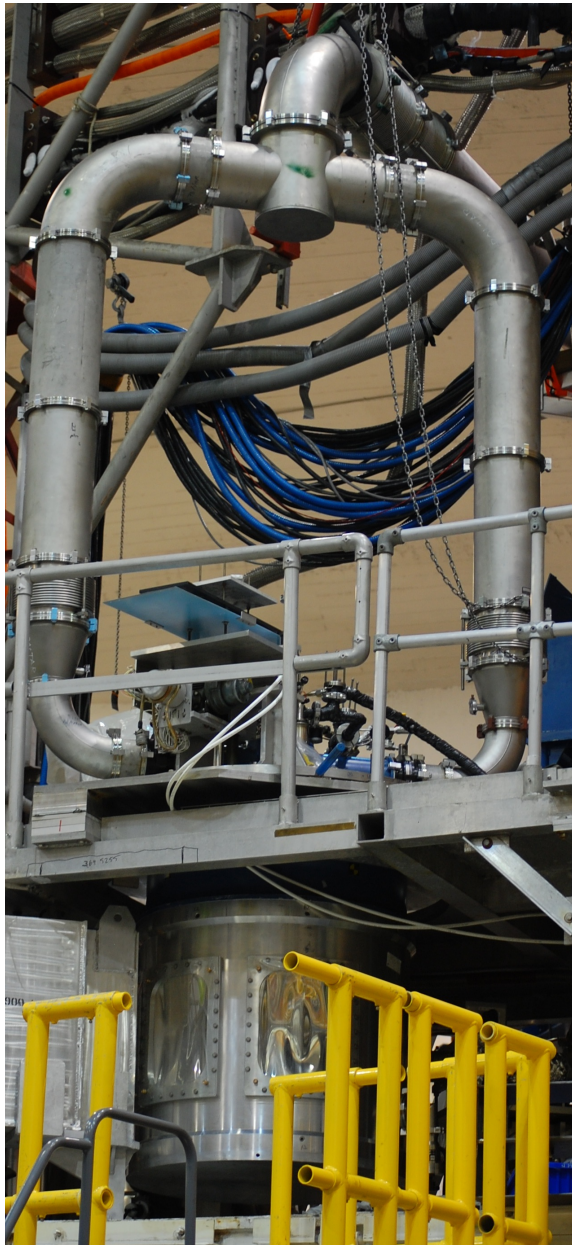
Forward tracker is from Norfolk State University and University of Regina

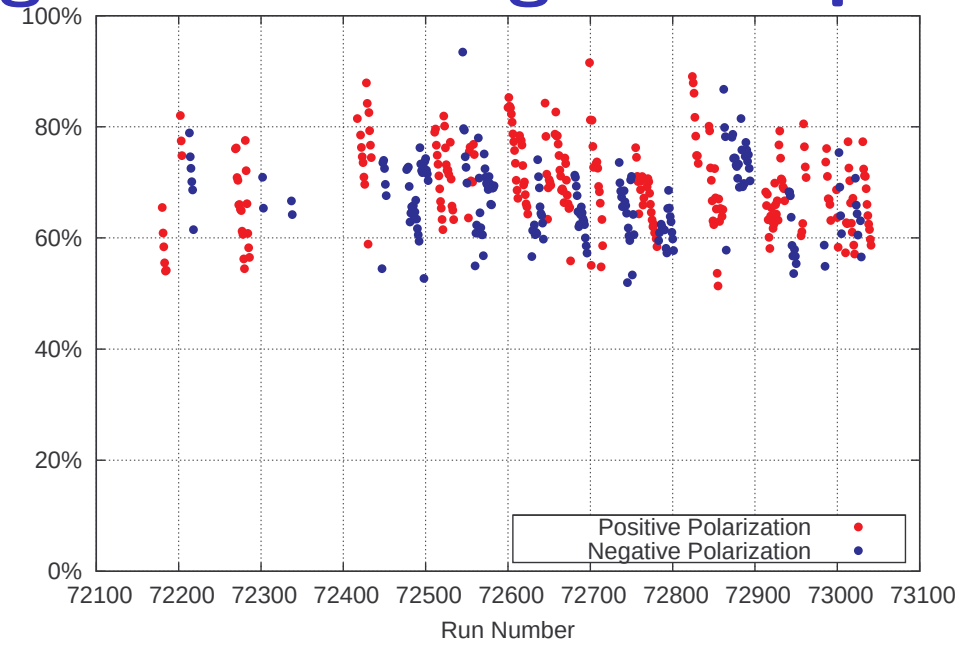
Design

- 3 layers of 3×3 mm^2 scintillators.
- 1 horizontally segmented layer closest to the target consisting of 72 segments
- 2 vertically segmented layers consisting of 128 segments each
- WLS fibers glued to each bar with fibers connected to Hamamatsu 64-Channel PMTs

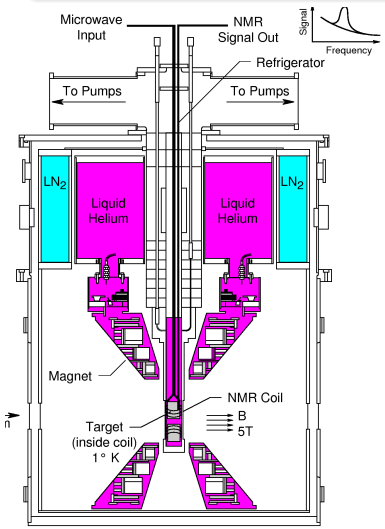
Figure: Forward tracker in position between Čerenkov snout and target OVC

Polarized NH_3 Target - UVa Target Group





Target polarization during the experiment by James Maxwell

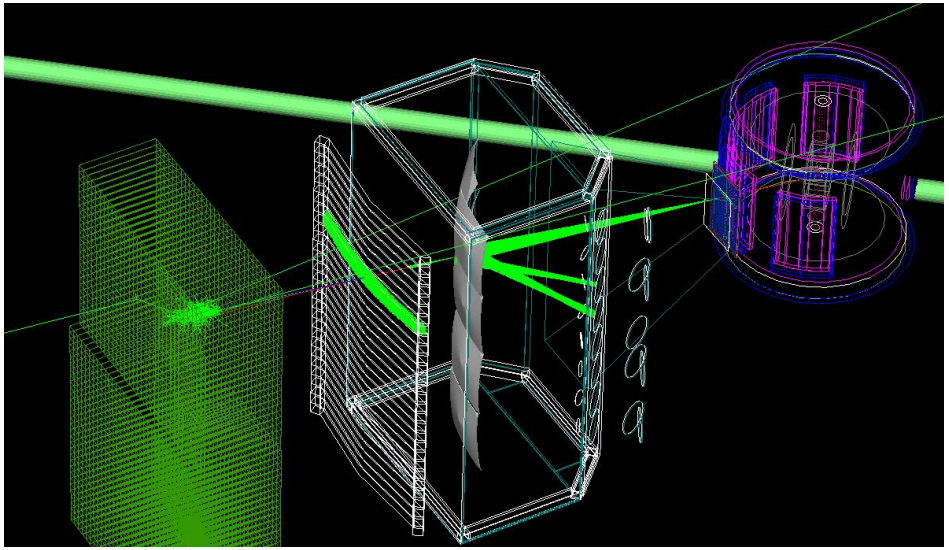


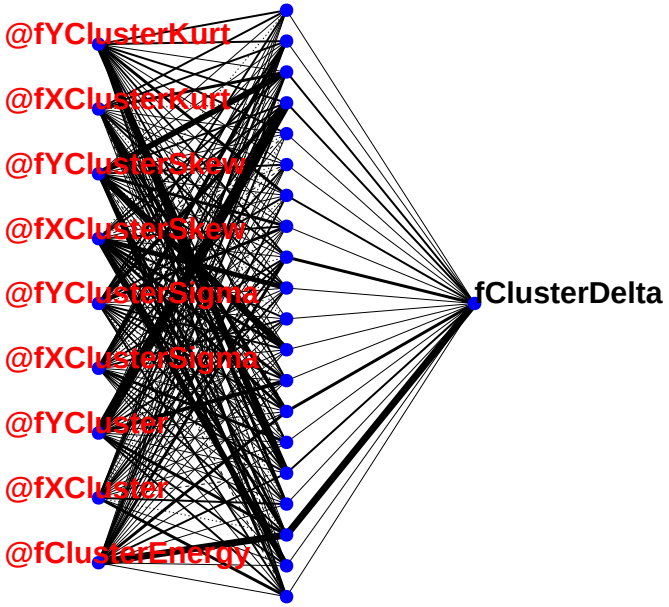
- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%

Neural Network Reconstruction

Three Neural Networks

1. Cluster position correction
   - Corrects cluster postion X-Y position





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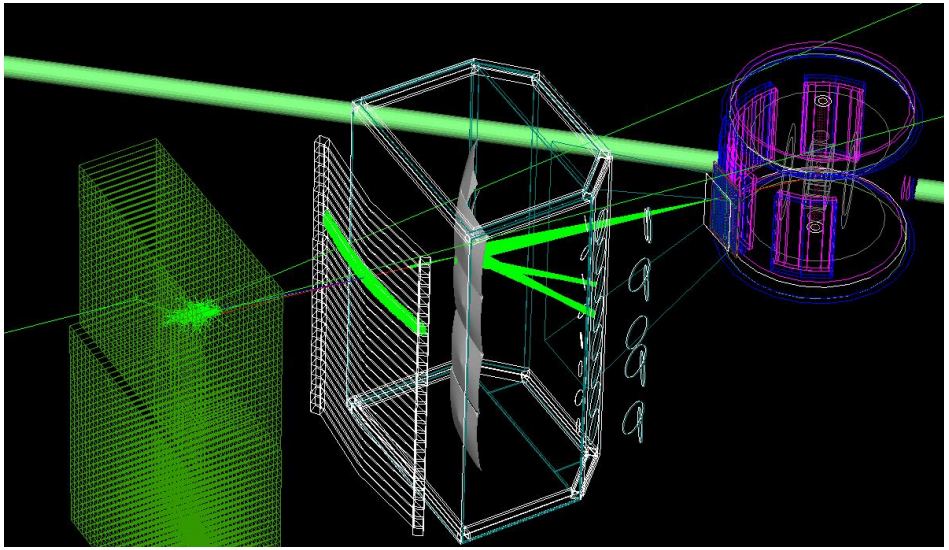

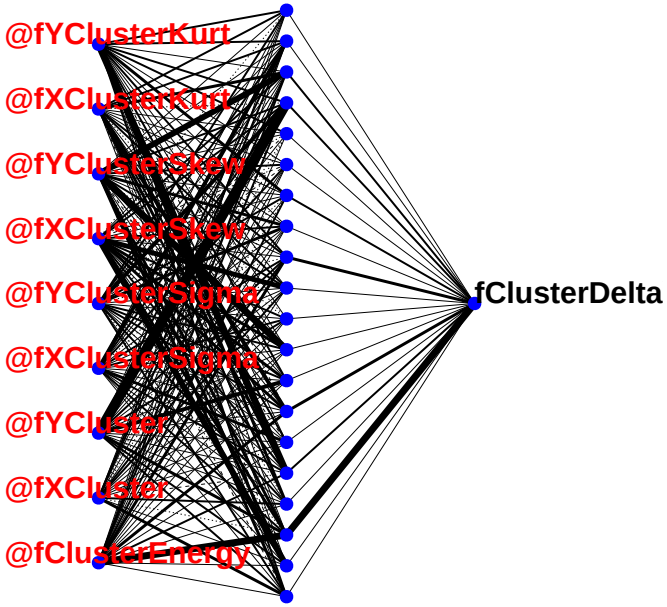

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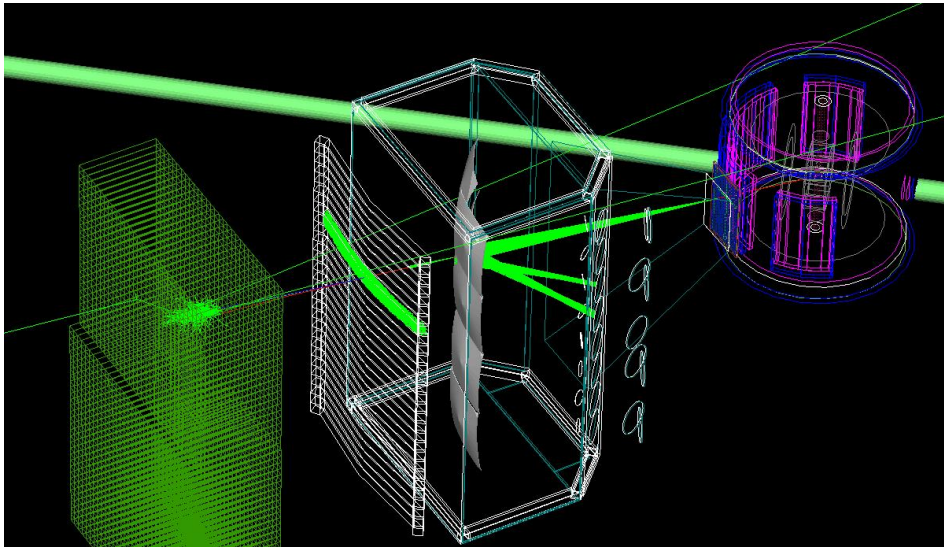
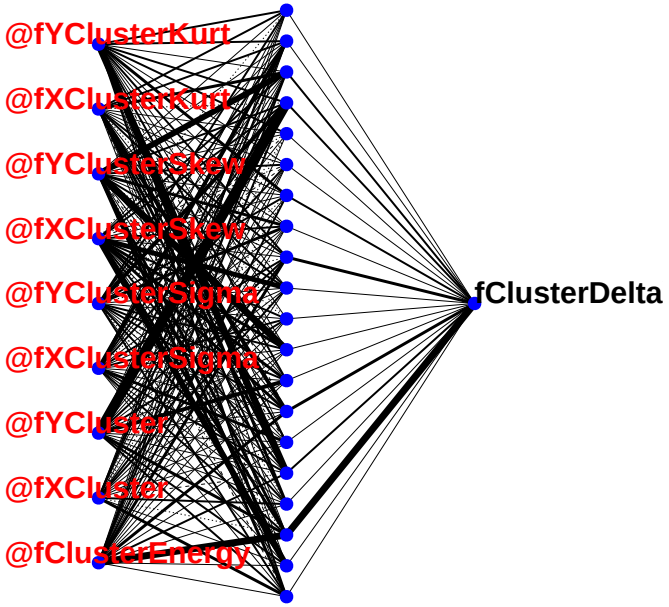
   - Returns scattering angles at the target
3. Track momentum vector correction
   - Corrections for the momentum vector at the face of BigCal





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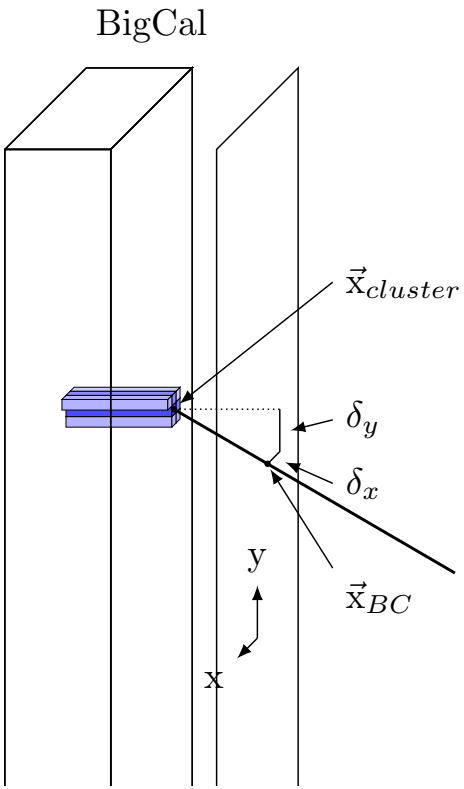
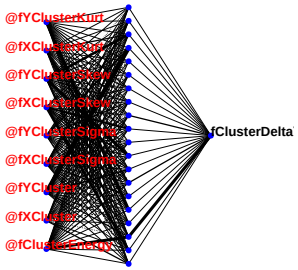
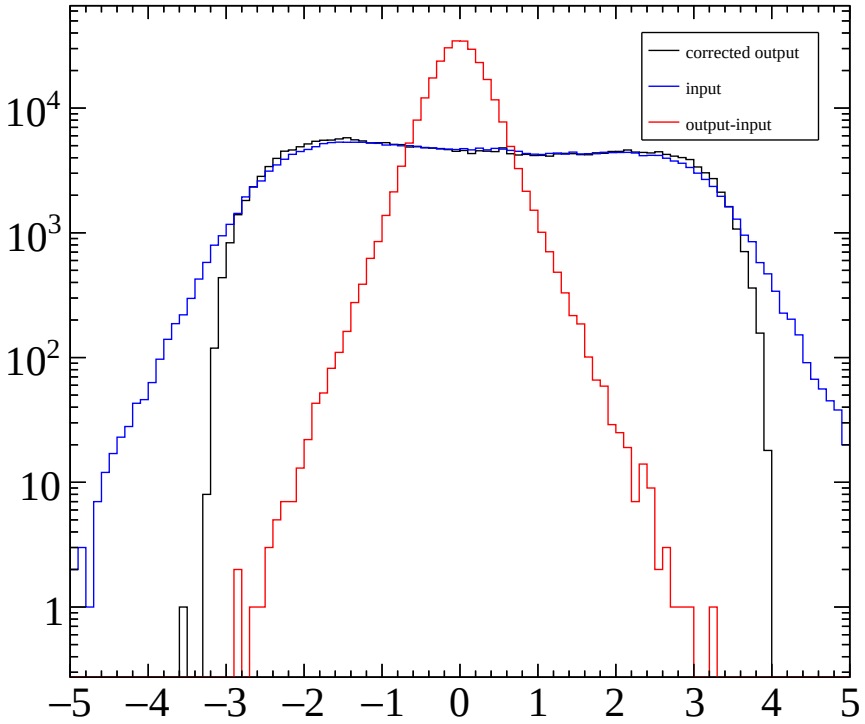


First moment → position
Second moment → standard deviation
Third moment → skewness
Fourth moment → peakedness





The Measured Asymmetry

$$A_{exp} = \frac{N_+ - N_-}{N_+ + N_-}$$

$$N_\pm = \frac{n_\pm}{Q_\pm L_\pm}$$

$n_\pm$ is the raw number of counts
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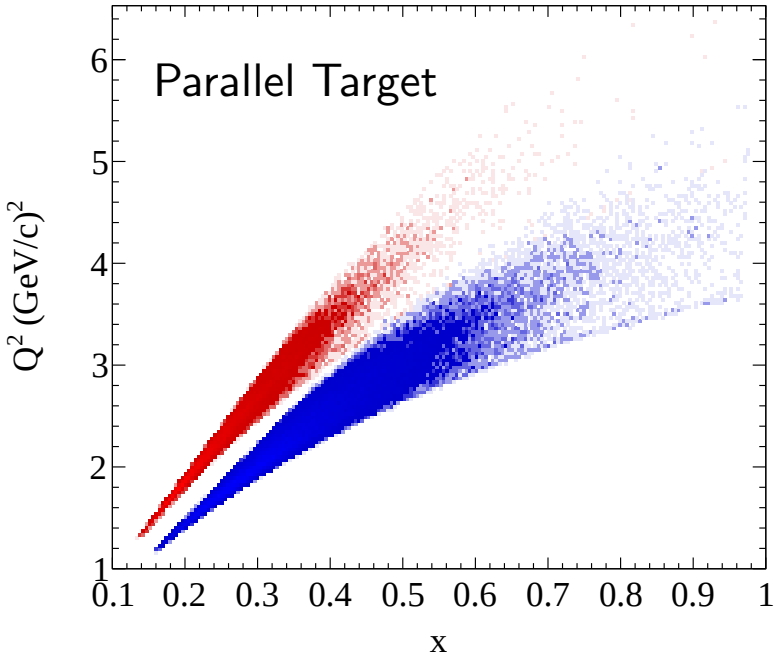
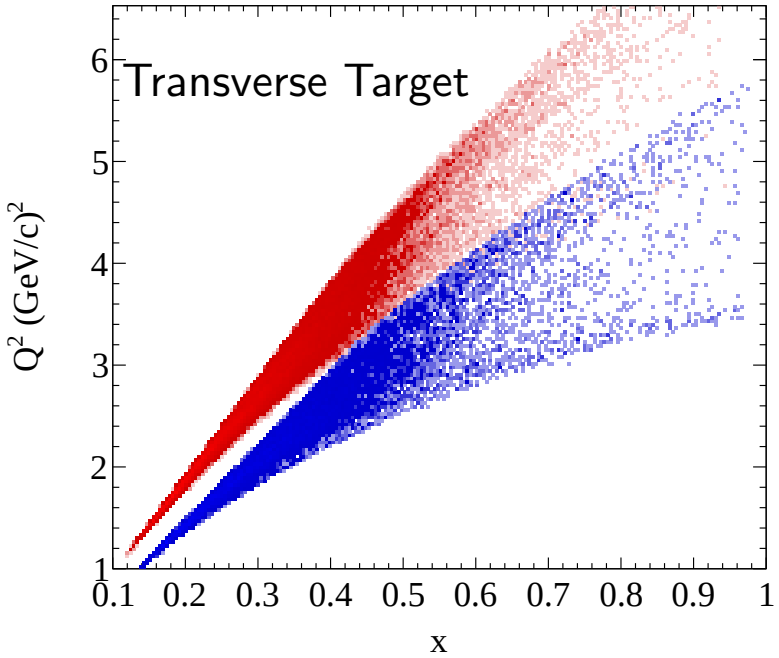
$L_\pm$ is the live time for each helicity.





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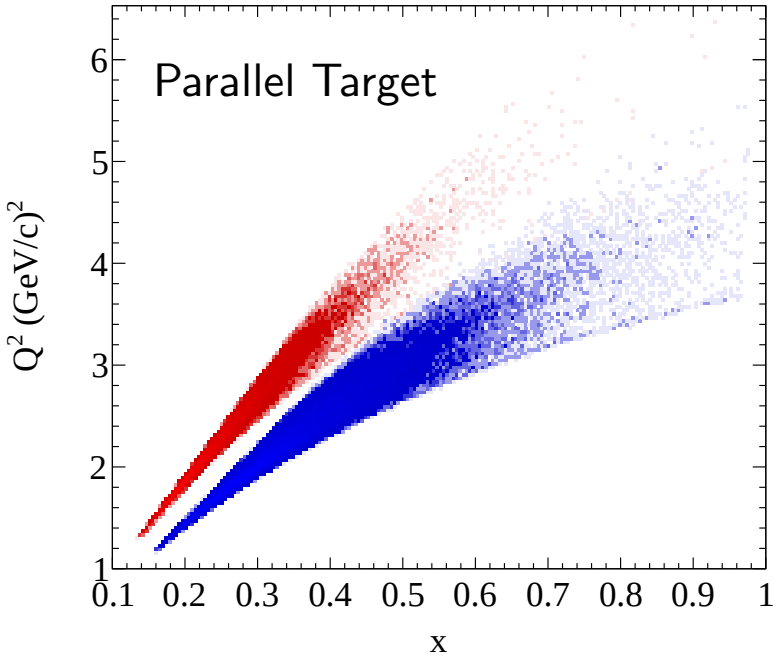
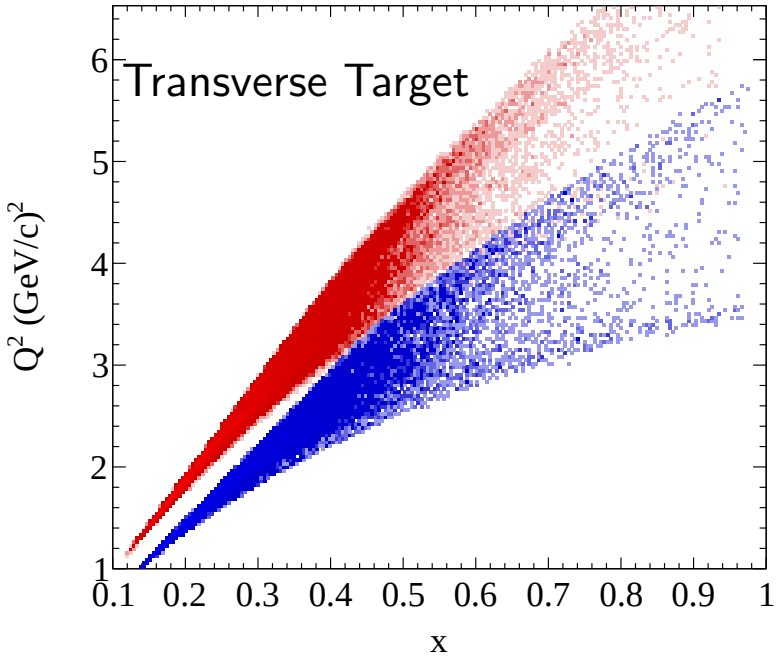
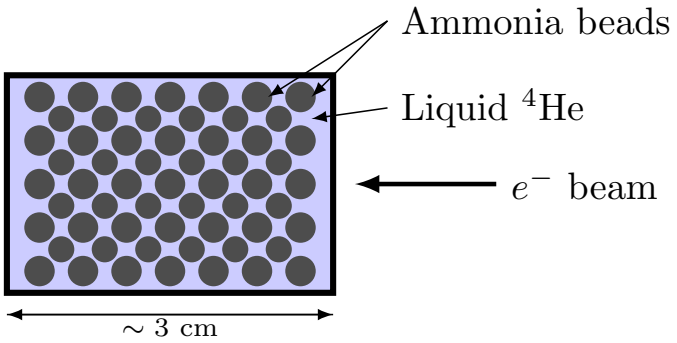




$$A = \frac{A_{exp}}{f P_{\mathrm{B}} P_{\mathrm{T}}}$$

where P_{B} and P_{T} are the beam and target polarizations.

Dilution factor



Packing Fraction

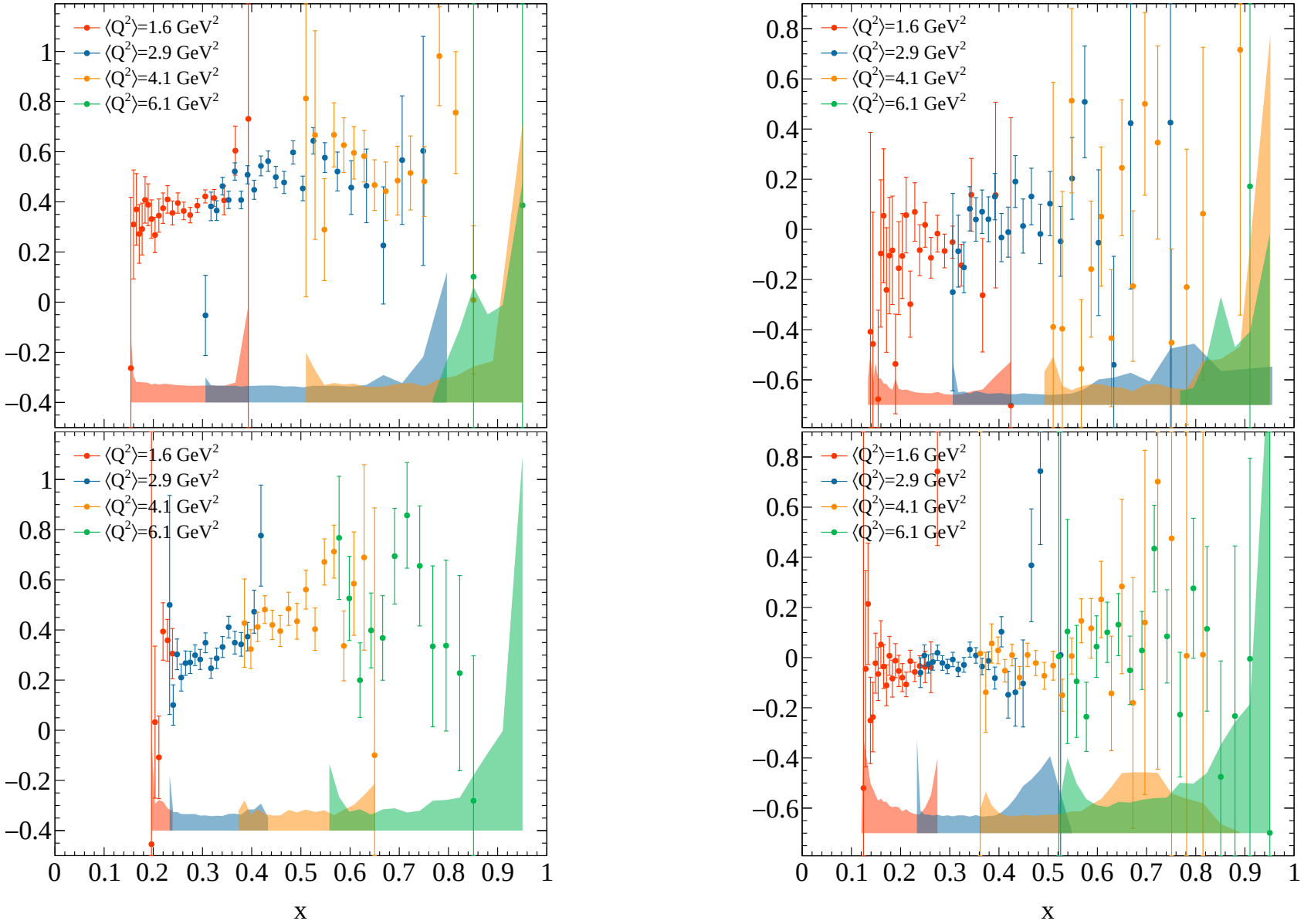
- PF obtained from HMS using F1F209 cross-section model.
- PF determines how much of target-cell volume is ammonia vs He.
- Roughly 60 percent

Hoyoung Kang, Narbe Kalantarians, and Anusha Liyanage

Dilution

- Takes into account scattering from unpolarized material in target.
- Need to know target geometry and material.
- Yields from montecarlo are normalized to data from C target of known thickness
- Function of W and Q^2

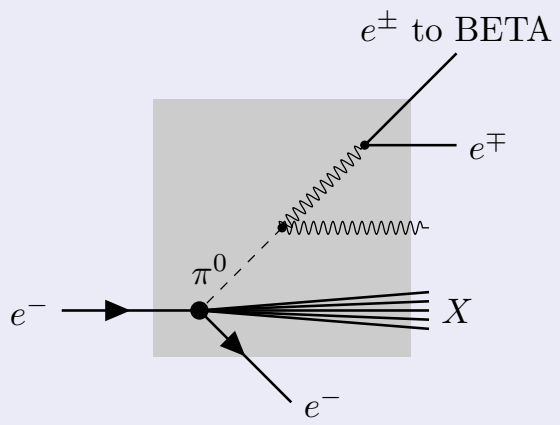
$$f(W, Q^2) = \frac{N_p \sigma_p(W, Q^2)}{N_p \sigma_p + \sum_i N_i \sigma_i(W, Q^2)}$$



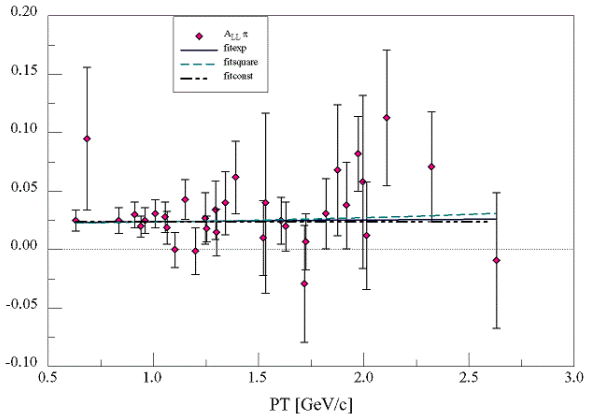
Only 50% of proposal due target magnet failure
Many thanks to JLab staff and others for fixing magnet.

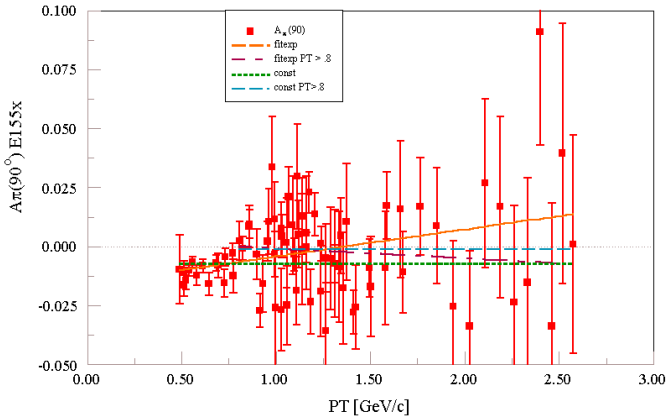
Pair Symmetric Background Corrections

Electroproduction

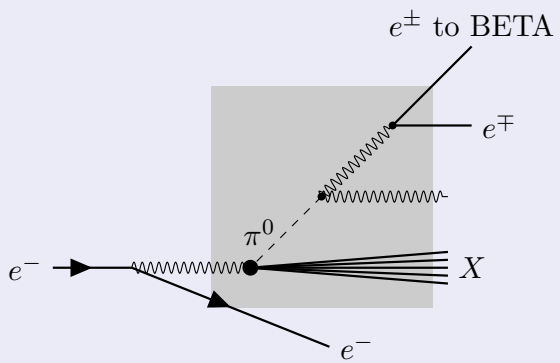


- Model production cross sections (using Wiser's fits)
- Run monte carlo to get $R = N^{e+}_{pair}/N^{e-}_{total}$
- Pion asymmetry from previous SLAC experiments (analysis by Oscar Rondon)





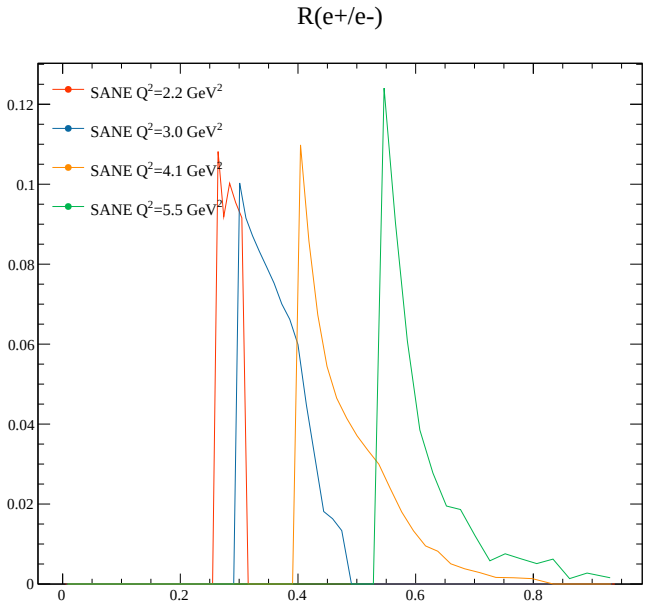
Photoproduction

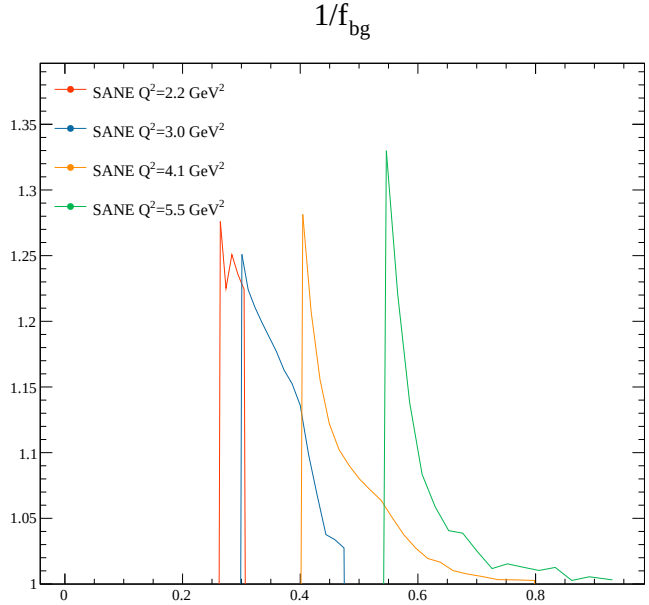


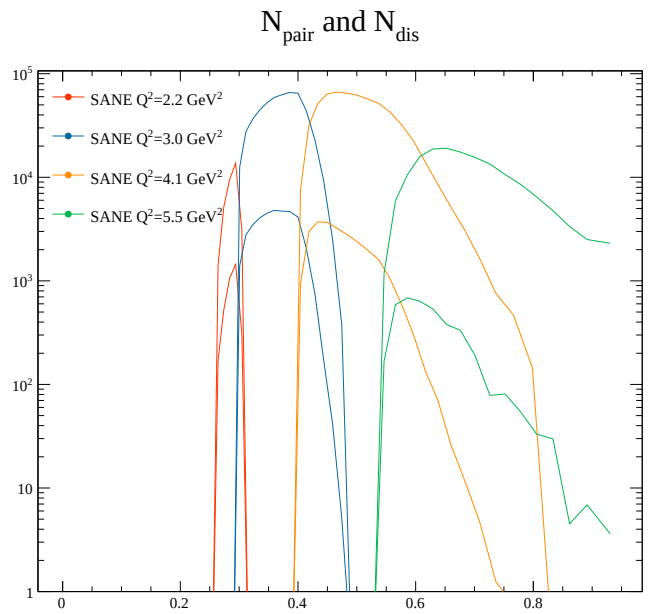
$$A^{bg}_{corr} = \left(\frac{1}{1-2R}\right) A_{raw} - \left(\frac{2RA_{pair}}{1-2R}\right)$$
$$= \frac{1}{f_{bg}} A_{raw} - C_{bg}$$

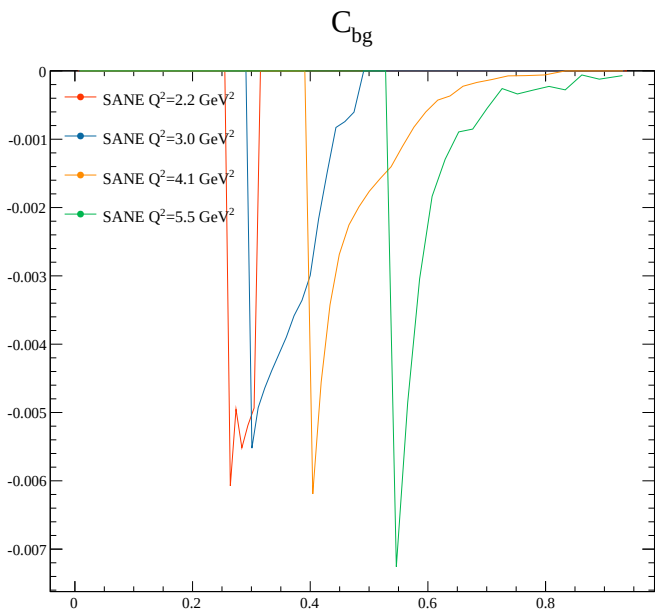
Currently working on finalizing background corrections.
Fitting inclusive pion electro- and photo- production.
(Wiser fit is almost 40 years old) $\rightarrow$ Fit will be very useful for future experiments.

Background Corrections

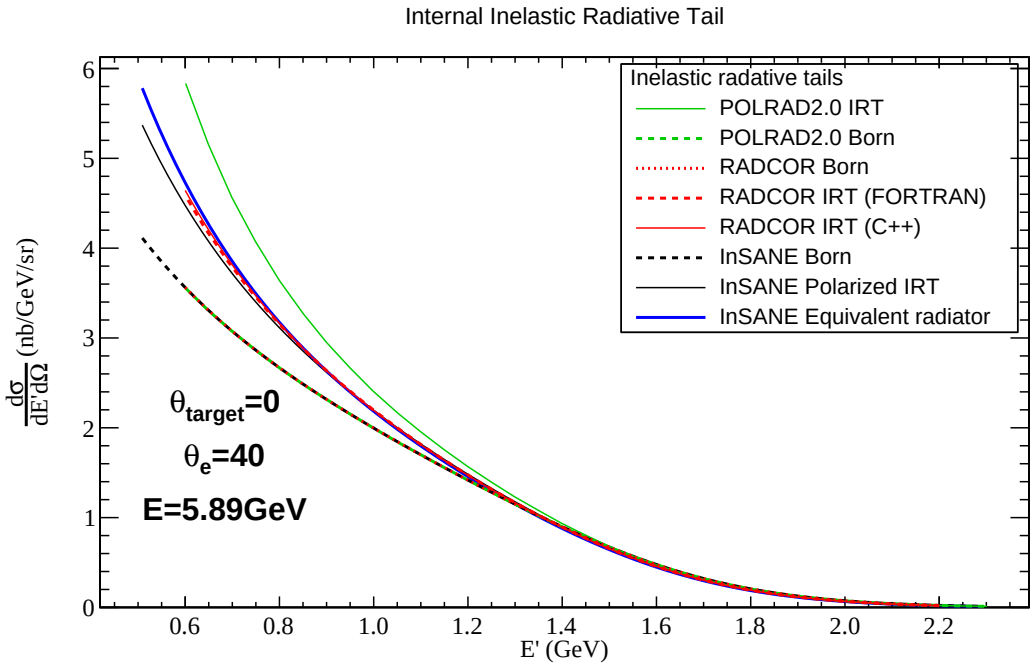








Radiative Corrections



New Radiative Correction Code

- Unpolarized formalism of Mo and Tsai[2]
  Includes internal *and* external radiative corrections.
- Polarized formalism of Akushevich, et.al.
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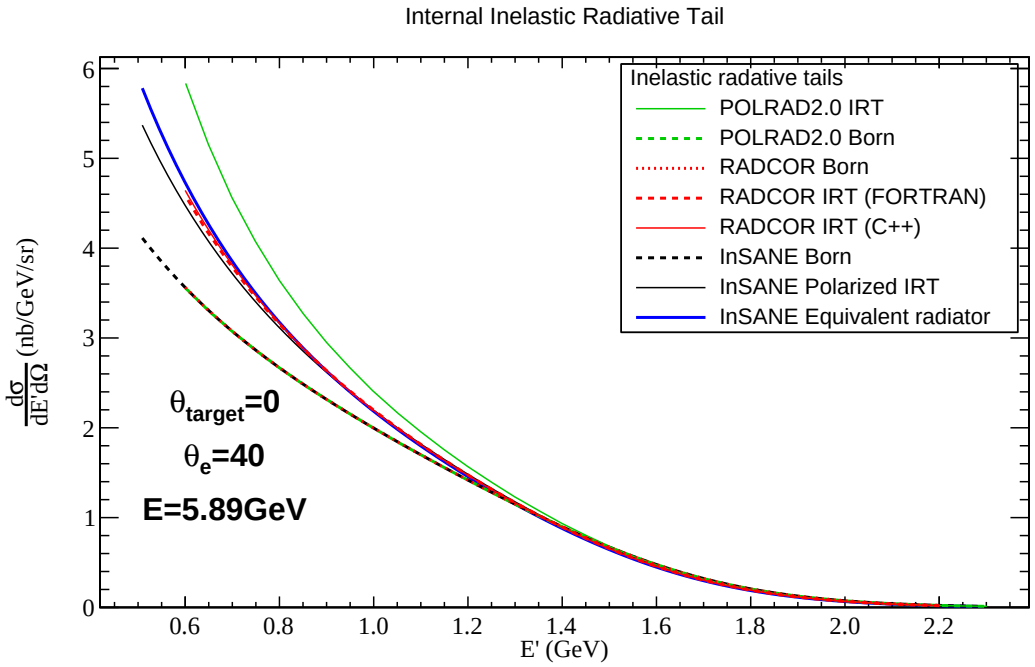

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Formalism Differences

- Polarized formalism treats only internal RCs
- External RCs calculated using beam depolarization term
- Unpolarized formalism does internal and external RCs

Elastic Radiative Tail Subtraction

Elastic

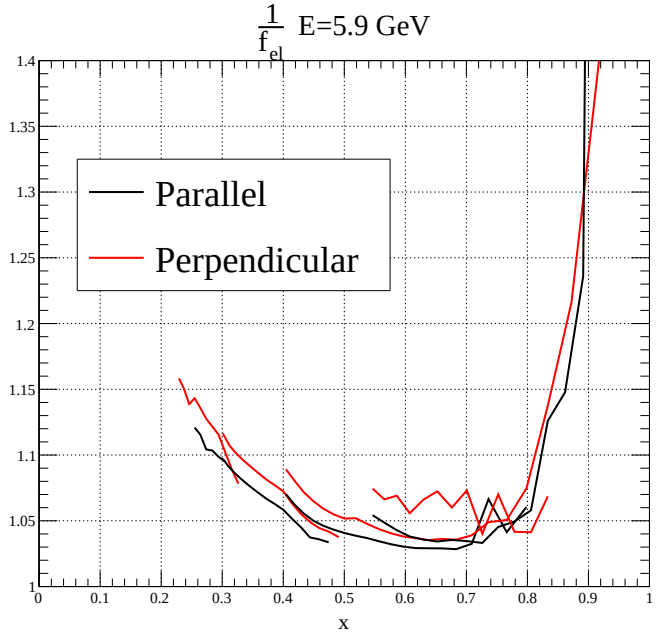
- Largest radiative correction
- Treated with polarization following Akushevich, et.al.
- Correction depends on accurate calculation of radiated inelastic cross section

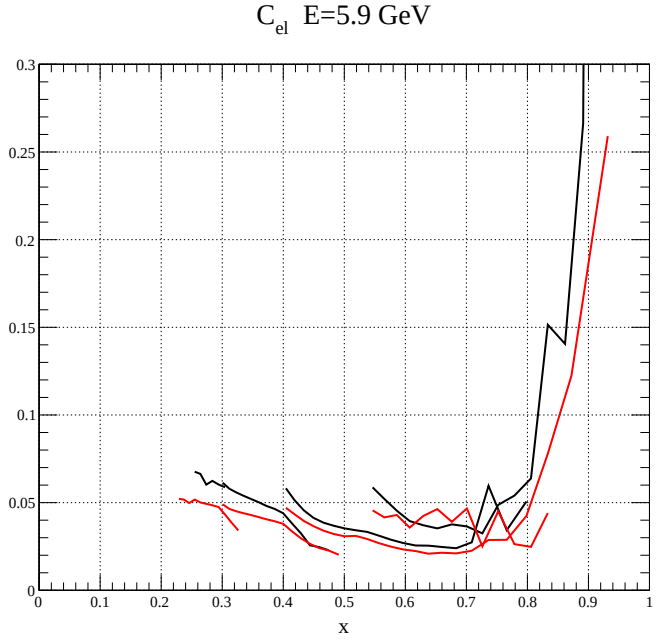
$$A_{corr}^{el} = \frac{A_{corr}^{bg}}{f_{el}} - C_{el}$$

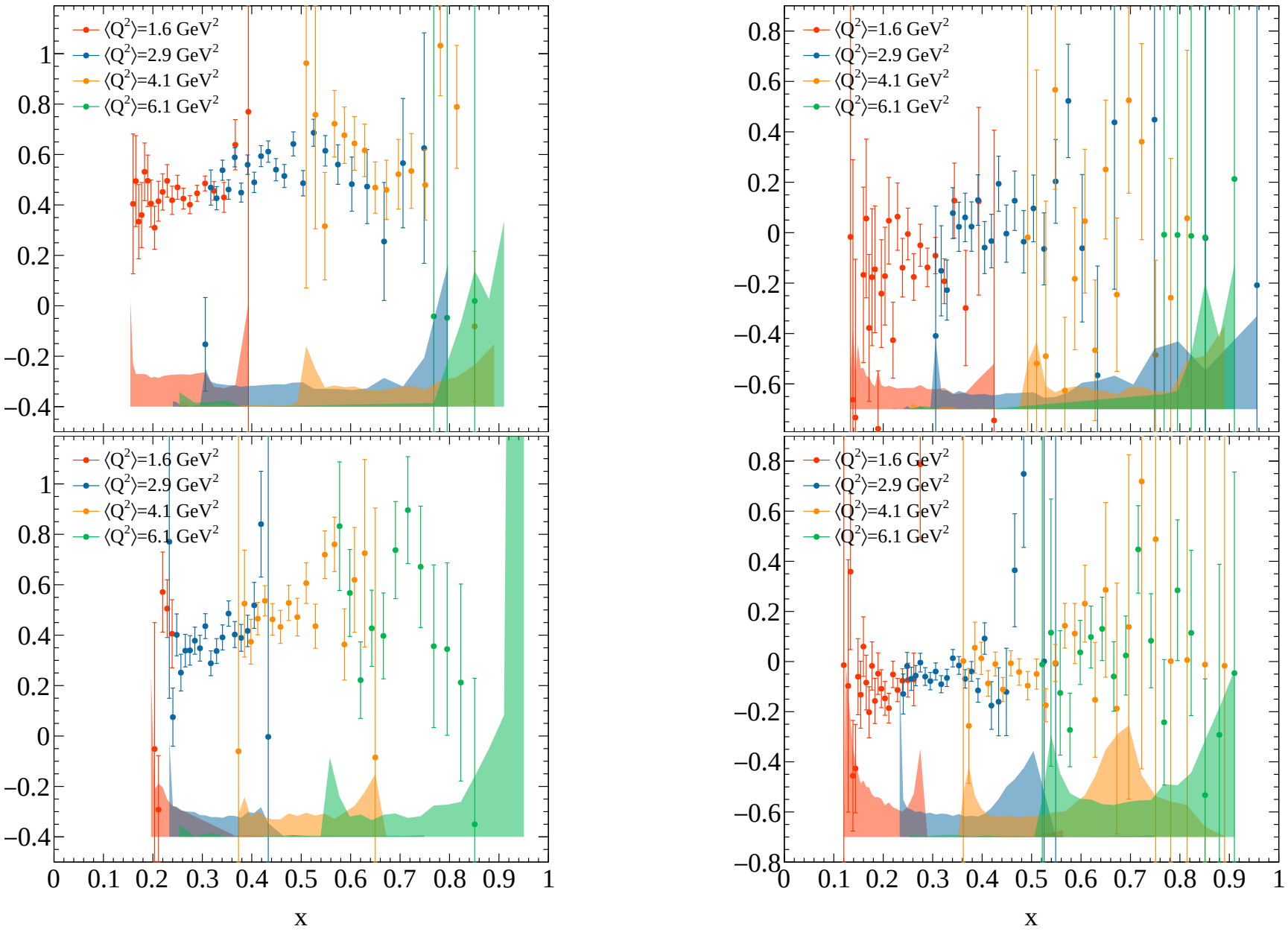
$$\frac{1}{f_{el}} = \frac{\Sigma_T}{\Sigma_{in}} \qquad C_{el} = \frac{\Delta_{el}}{\Sigma_{in}}$$

$$\Sigma_x = \sigma_x^+ + \sigma_x^-$$

$$\Delta_x = \sigma_x^+ - \sigma_x^-$$

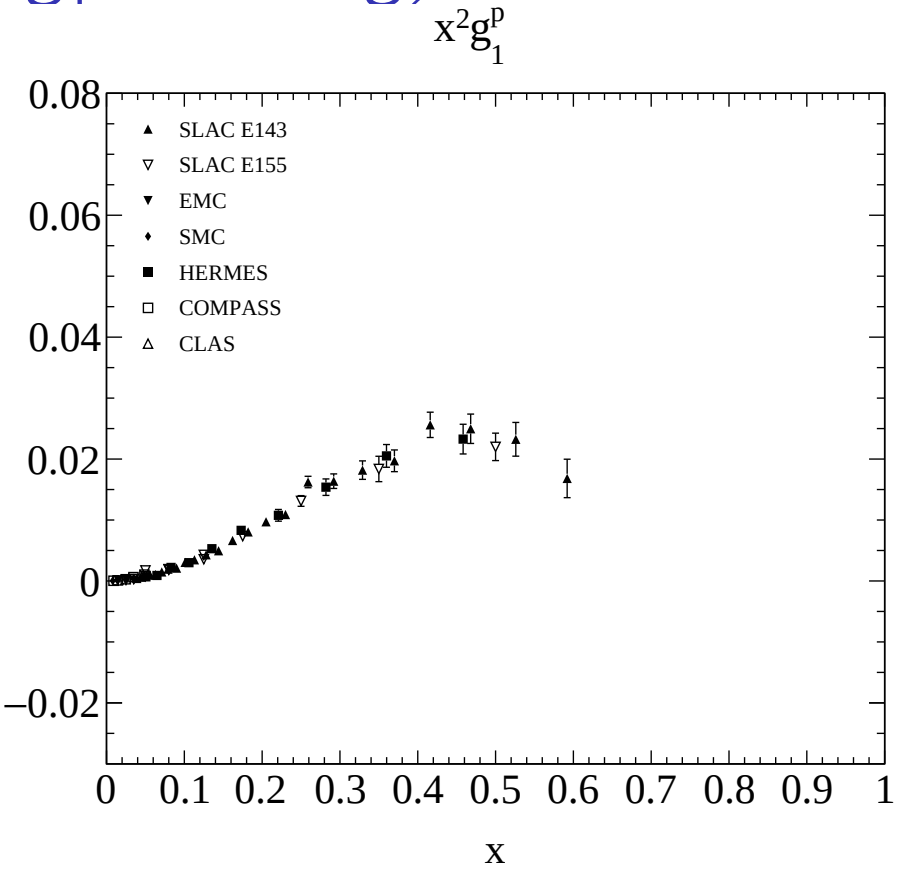


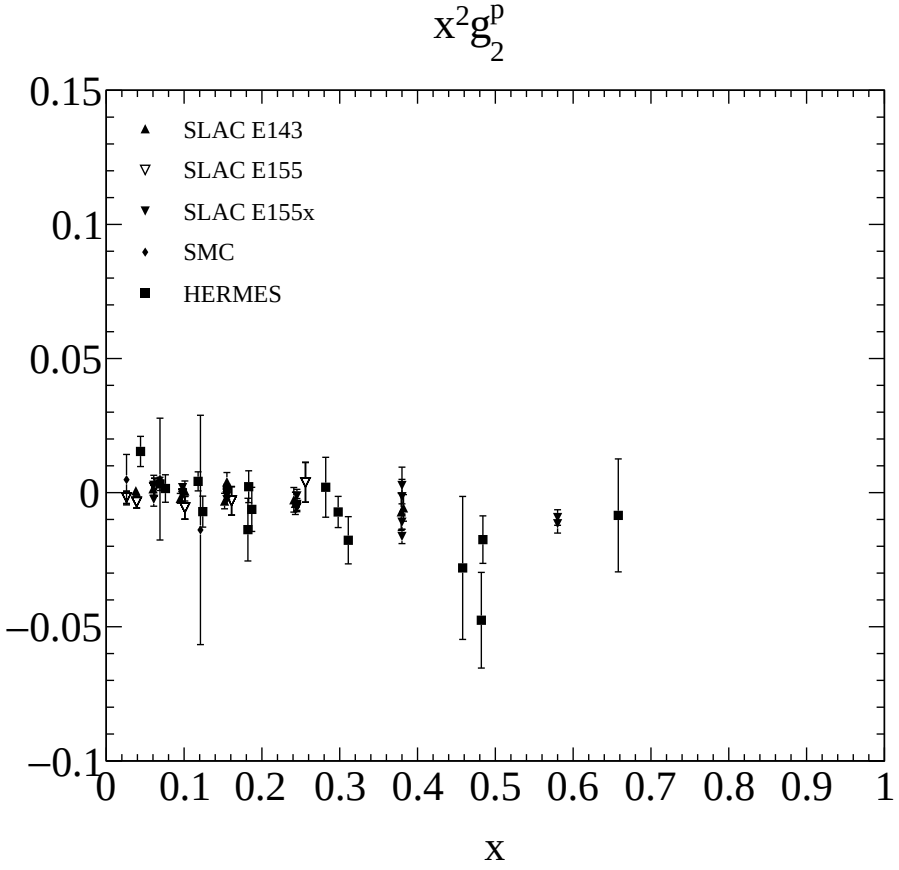




After all corrections

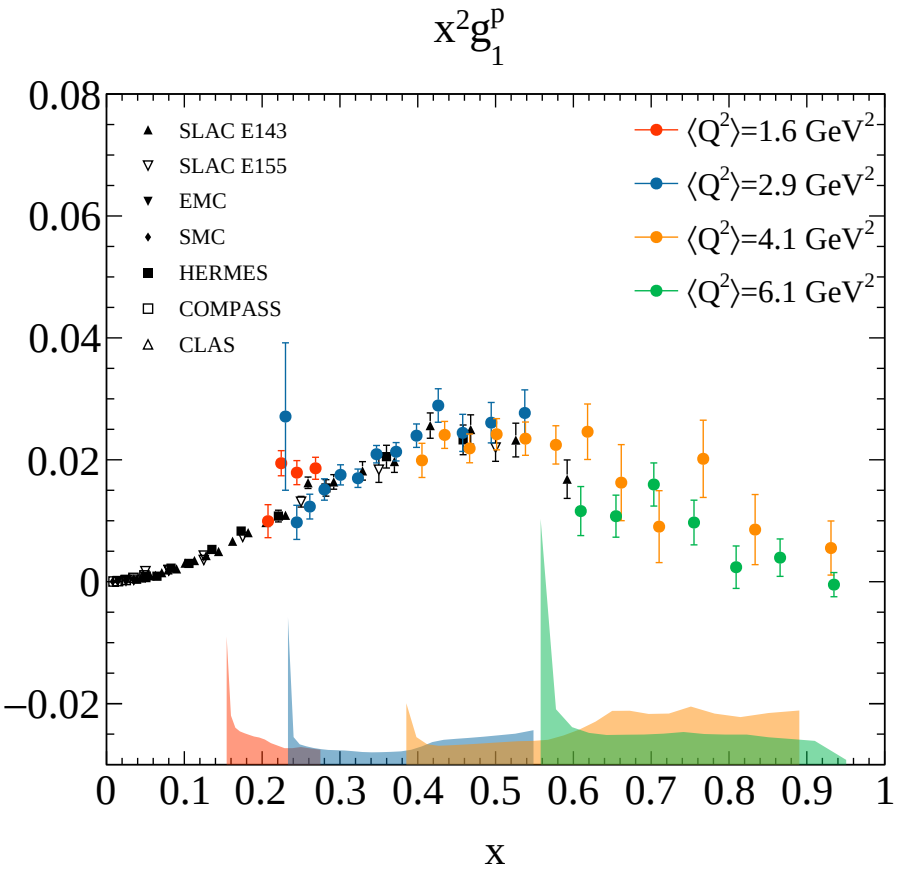
$x^2 g_1^p$ and $x^2 g_2^p$

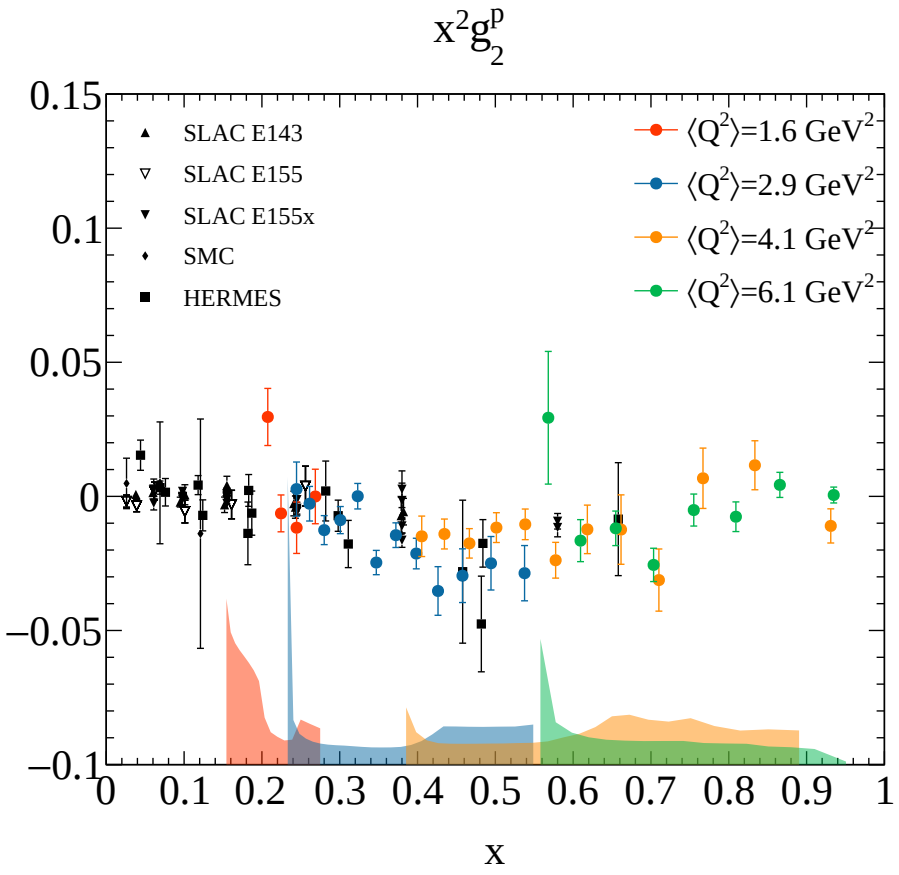




Models are showing g_2^{WW}.

$x^2 g_1^p$ and $x^2 g_2^p$





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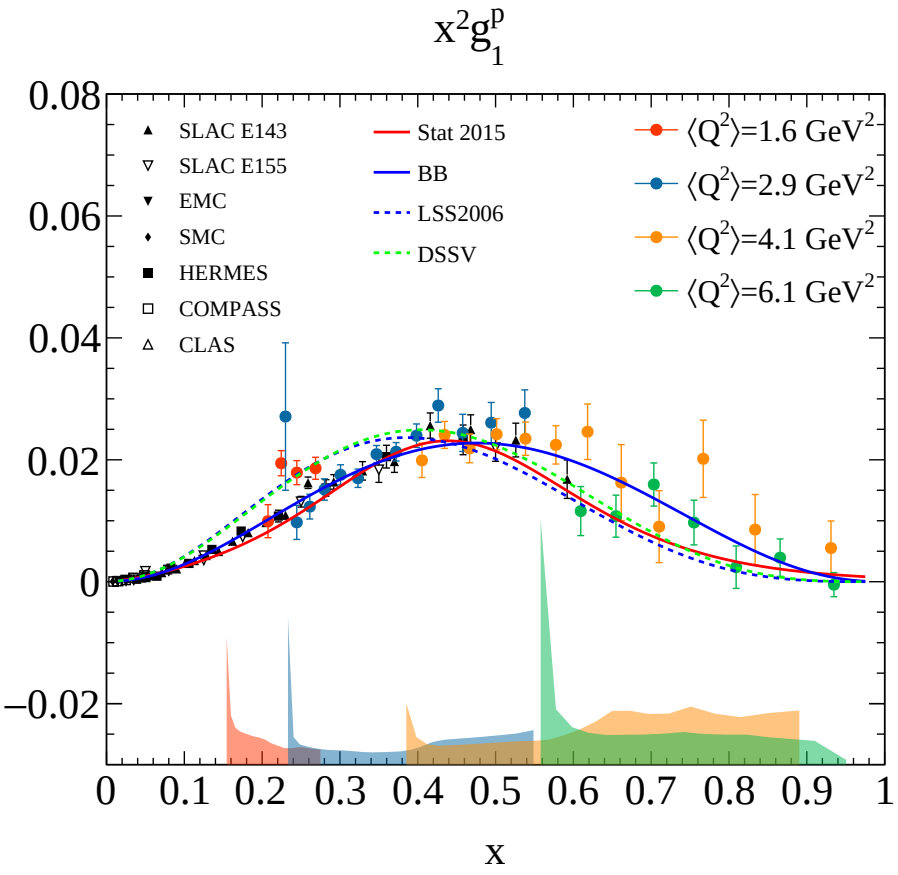

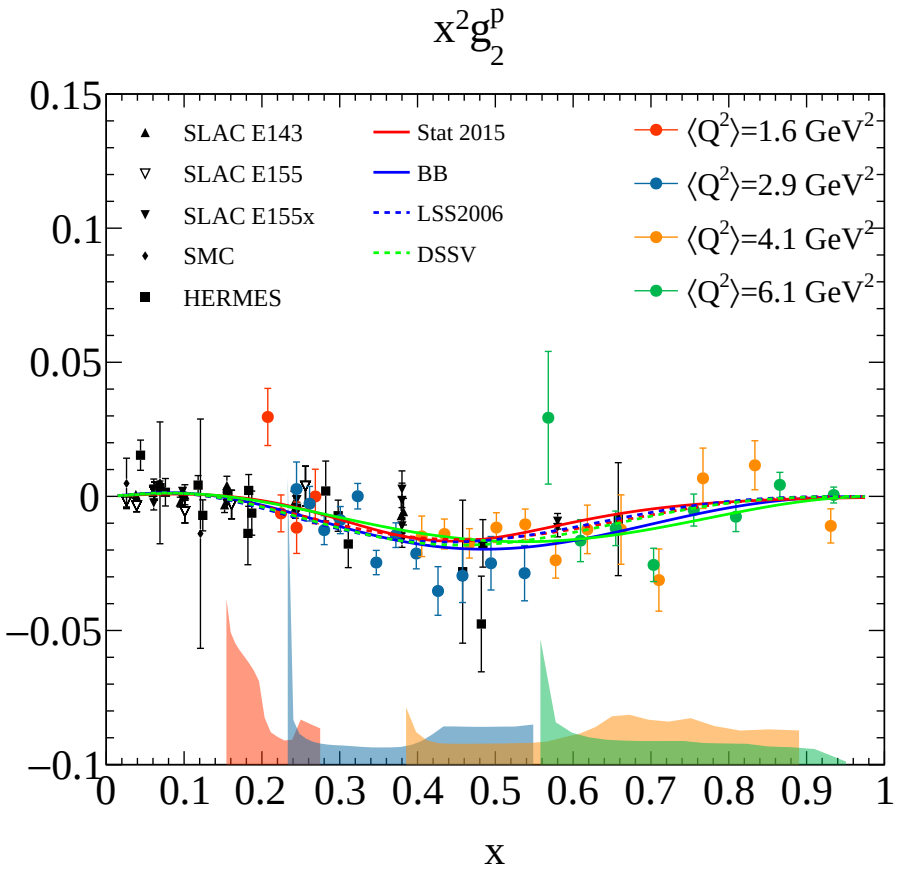

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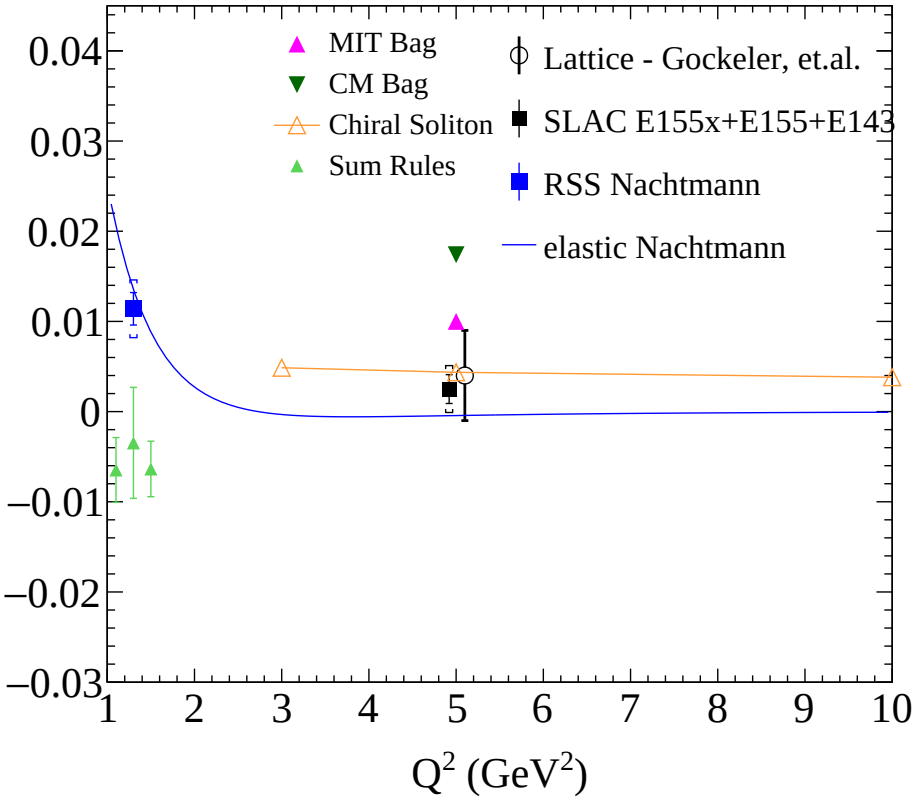
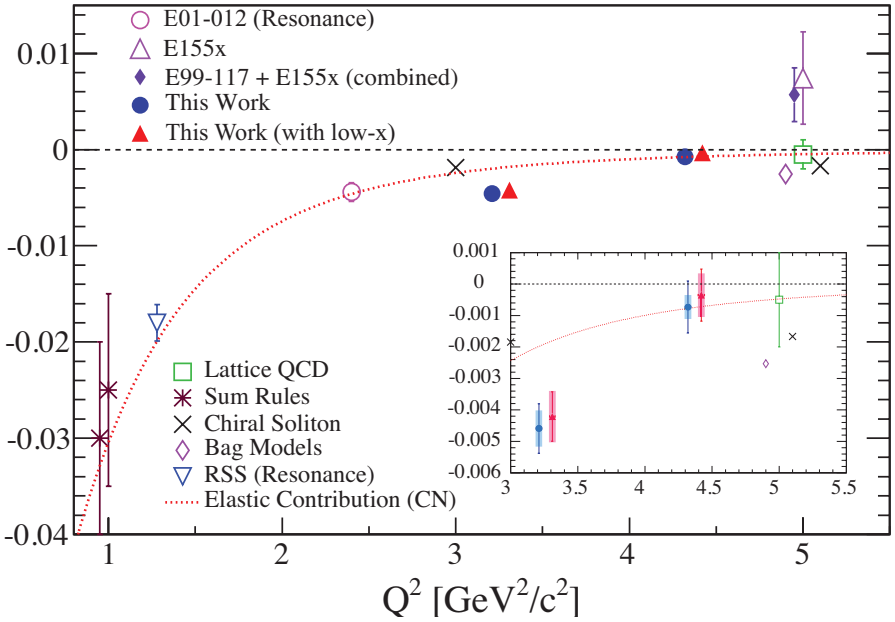
proton



neutron



Recent results from d_2^n experiment M.Posik, et.al. [3]

Existing data

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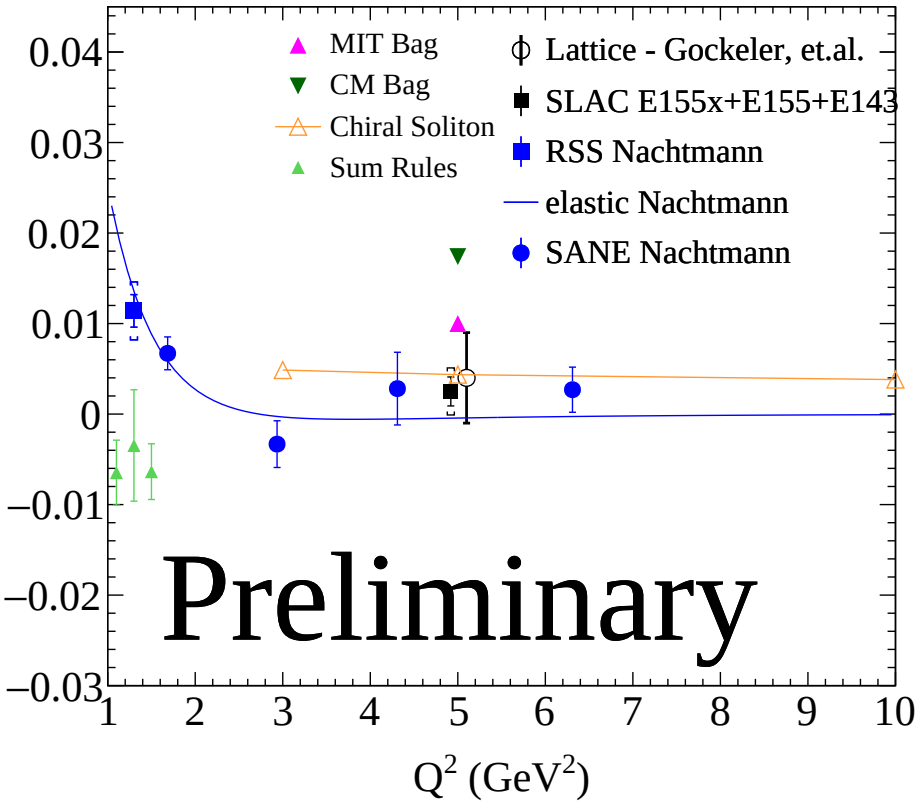

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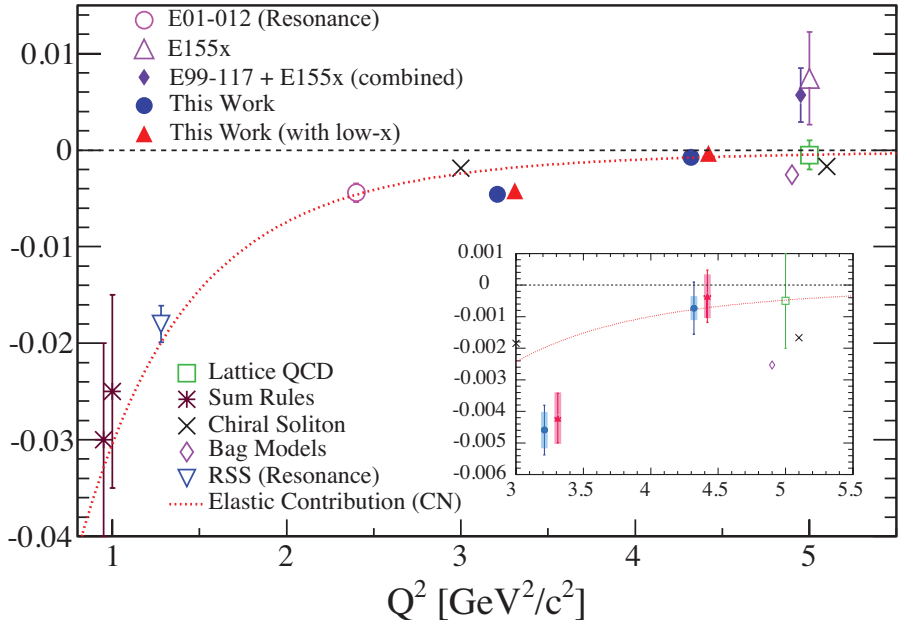

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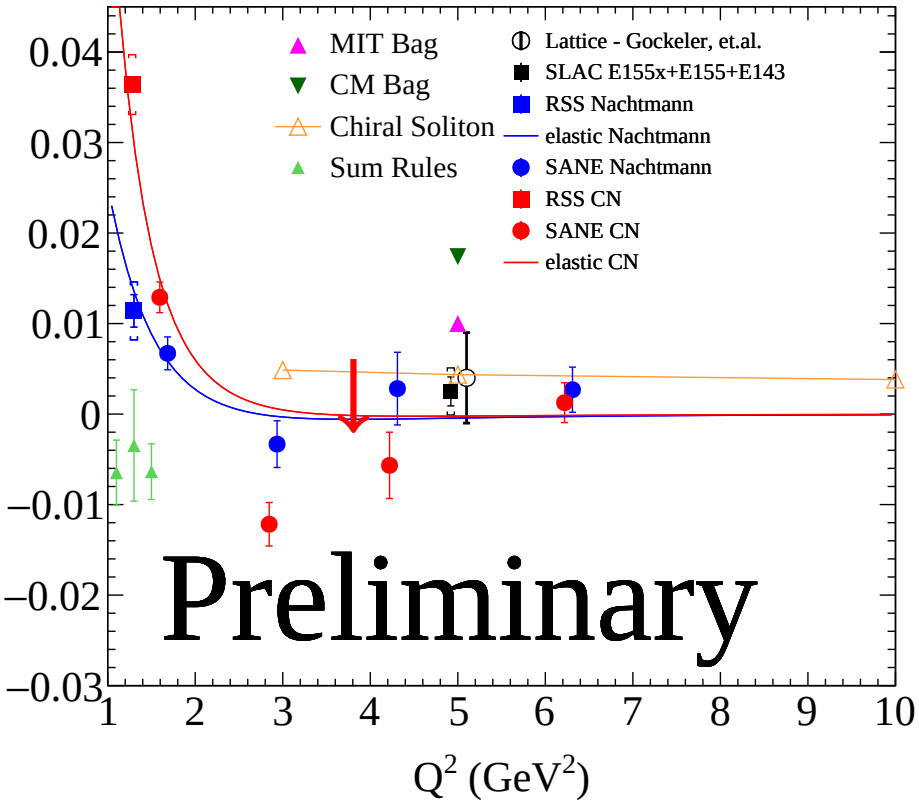

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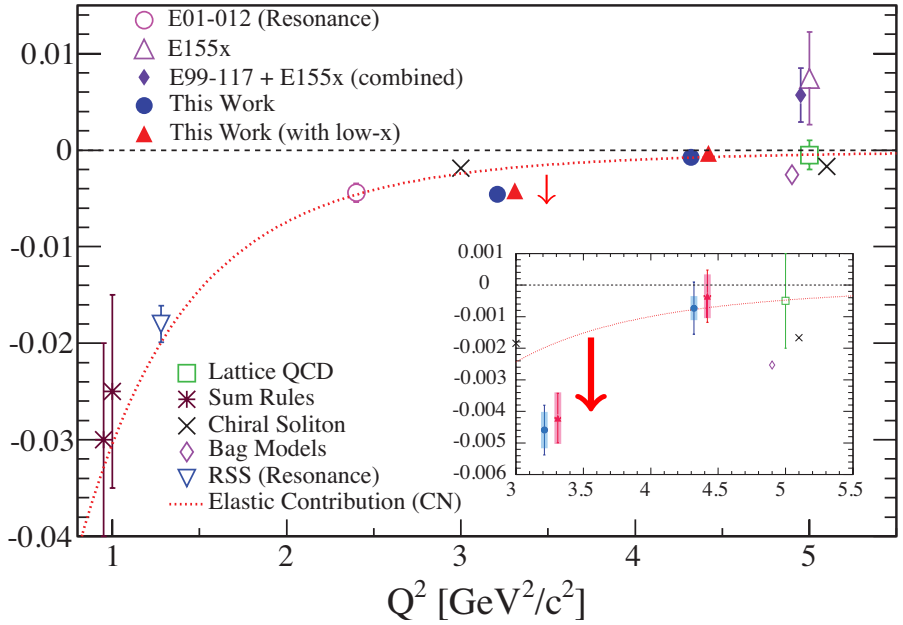

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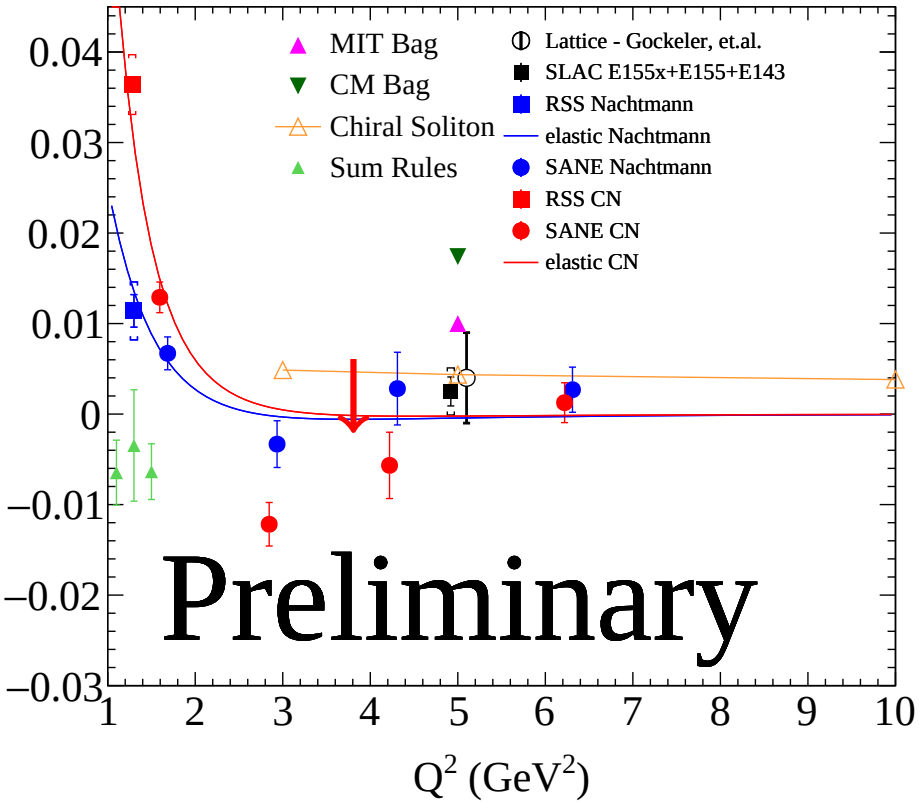

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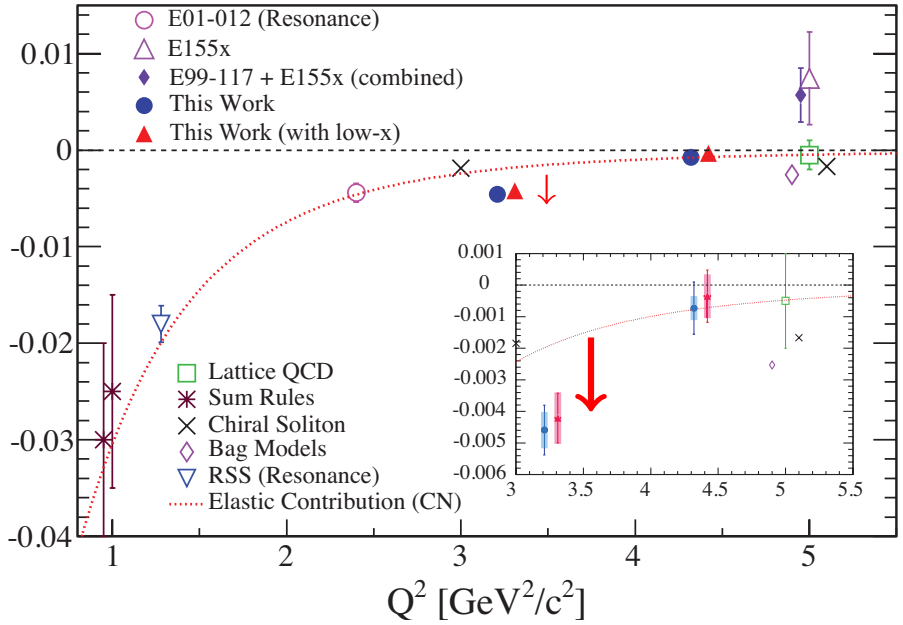

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- Updated Lattice calculations are long over due!

Conclusion (1/2)

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- $\bar{g}_2$ could provide information on quark OAM

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- SANE $\rightarrow$ SANE12 $\rightarrow$ InSANE?
- While a future EIC will focus on the **sea** quarks and gluons, JLab will continue to present a unique opportunity for studying QCD and the structure of the nucleon to high precision in the **valence region**.

Thank You!

SANE Collaboration (E-07-003)

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Yerevan Physics Institute, Yerevan, Armenia

SANE Ph.D. ~~student~~, M.S. Student, Student
(Affiliations as of end of run - March 2009)

References I

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[3] Posik, M., et al.
A Precision Measurement of the Neutron Twist-3 Matrix Element d_2^n: Probing Color Forces.
Phys.Rev.Lett. 113, 2 (2014), 022002.

Backup Slides

Radiated cross sections and asymmetries