Precision Studies of the Neutron Spin Structure using a Polarized Helium-3 Target at Jefferson Lab

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(University of Kentucky)

On behalf of the Jefferson Lab E12-06-110 and E12-06-121 Collaborations

The XVIth Quark Confinement and the Hadron Spectrum Conference

Cairns, Australia

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QCHSC-2024

Jefferson Lab

UK UNIVERSITY OF KENTUCKY

The Structure of the Nucleon

small Q2

non-perturbative QCD

Jefferson Lab

large Q2

perturbative QCD

Figure credit: BNL

Overview

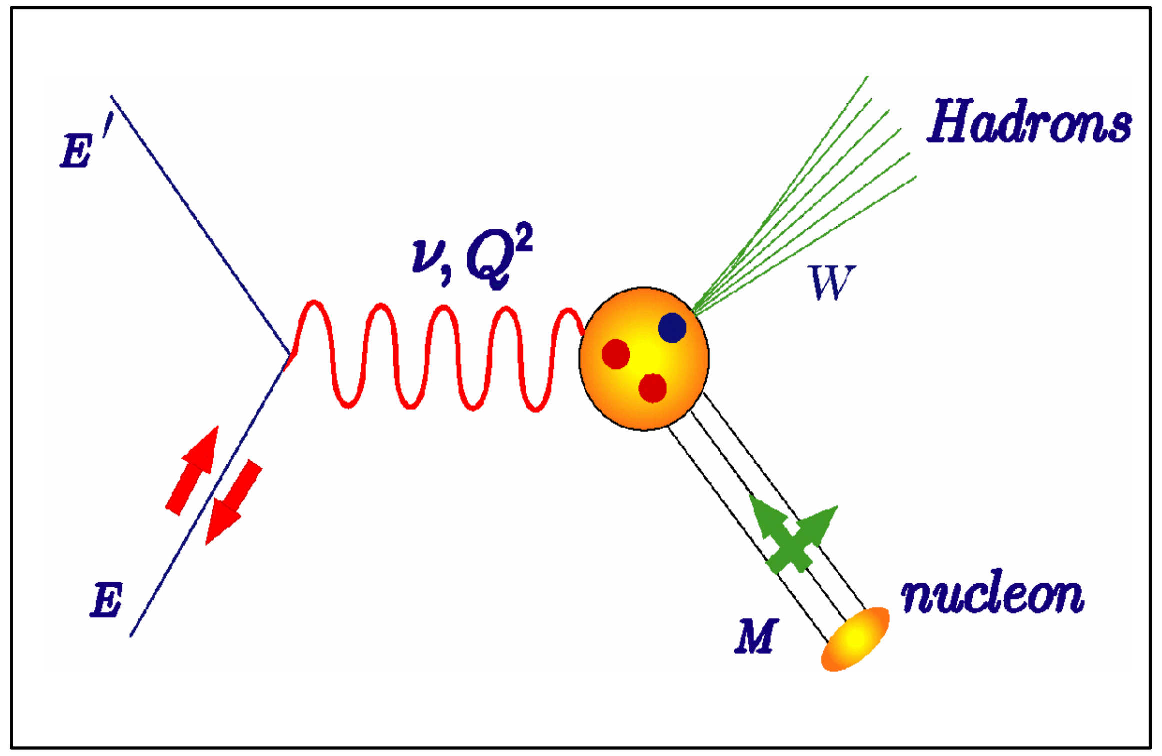
- Motivation for inclusive physics program using polarized ^3He
- Neutron spin-structure functions
  - Extraction of Q^2 dependence of twist-3 contribution to g_2^{3He} (g_2^n)
- Measurement of the virtual photon $A_1^{3He}(x)$ ($A_1^n(x)$)
- Summary and Outlook

Inclusive (DIS) Electron Scattering

Unpolarized structure functions: > 50 years of studies

$$\frac{d^2\sigma}{dE'd\Omega}(\uparrow\Uparrow + \downarrow\Uparrow) = \frac{8\alpha^2}{Q^4}\left[\frac{2}{M}F_1(x,Q^2)\cdot sin^2(\theta/2) + \frac{1}{\nu}F_2(x,Q^2)\cdot cos^2(\theta/2)\right]$$

$\longrightarrow$ *F_2: momentum distribution of quarks (IMF)*



Polarized structure functions: < 40 years of studies

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

$$\frac{d^2\sigma}{dE'd\Omega}(\uparrow\Rightarrow - \downarrow\Rightarrow) = \frac{4\alpha^2 E'2}{\nu E Q^2}sin(\theta)\left[g_1(x,Q^2) + \frac{2ME}{\nu}\cdot g_2(x,Q^2)\right]$$

$\longrightarrow$ *g_1: polarized momentum distribution of quarks (IMF)*

g_2: quark-gluon correlations

Extraction of Spin Structure Functions

Electron scattering asymmetries:

$$A_{\parallel} = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\downarrow\Uparrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\downarrow\Uparrow}} \qquad A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}}$$

$\uparrow \downarrow$ = spin direction of beam particles (electrons)

$\Uparrow$, $\Downarrow$, $\Rightarrow$, $\Leftarrow$ = spin direction of target particles

$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\frac{d^2\sigma_0}{d\Omega dE'}\left[A_{\parallel} + tan(\frac{\theta}{2})A_{\perp}\right]$$

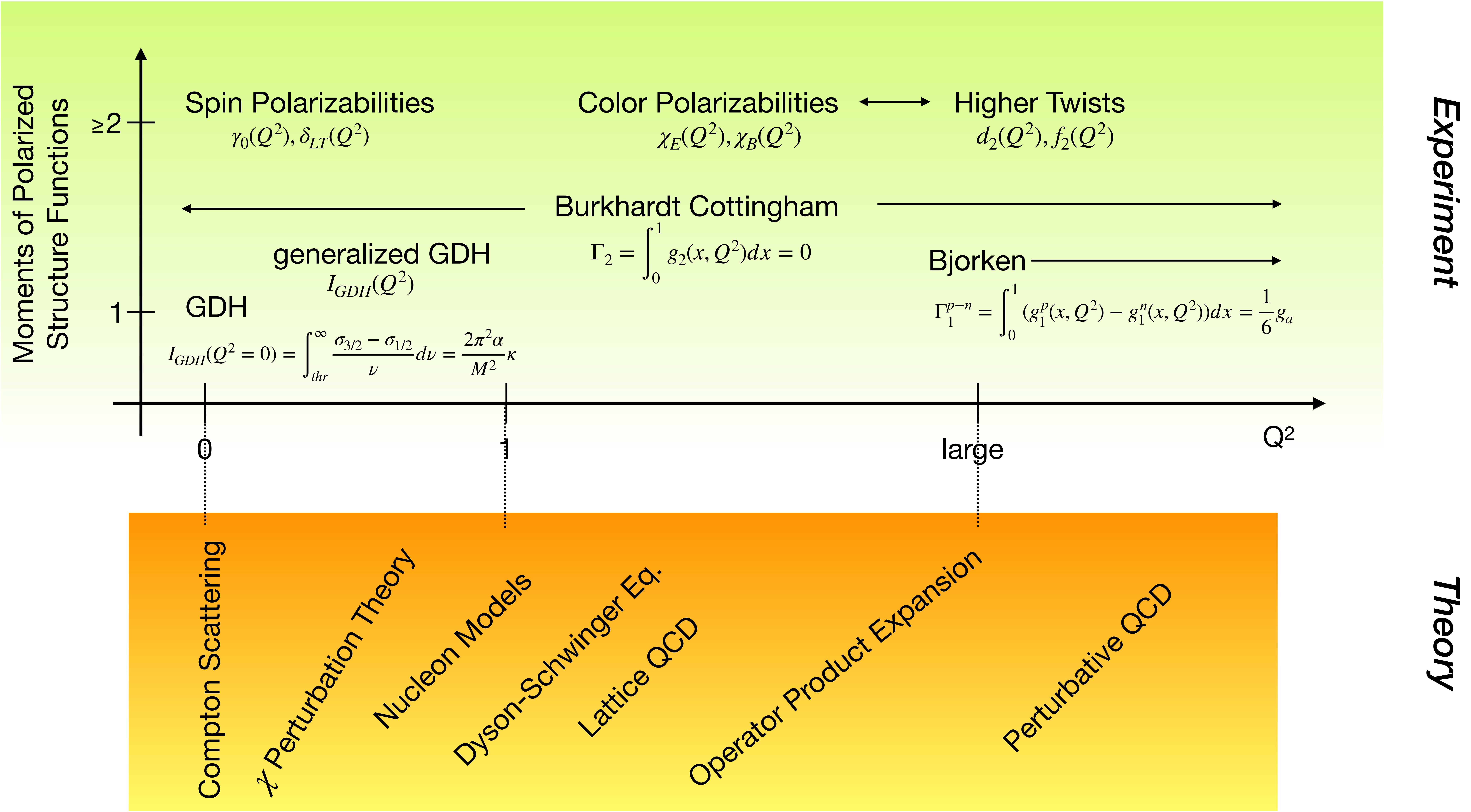
$$g_2 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\frac{d^2\sigma_0}{d\Omega dE'}\left[-A_{\parallel} + \frac{1+(1-y)cos(\theta)}{(1-y)sin(\theta}A_{\perp}\right]$$

Virtual photon asymmetries:

$$A_1 = \frac{A_{\parallel}}{D(1+\eta\xi)} - \frac{\eta A_{\perp}}{d(1+\eta\xi)} \qquad A_2 = \frac{\xi A_{\parallel}}{D(1+\eta\xi)} + \frac{A_{\perp}}{d(1+\eta\xi)}$$

η, ξ, d, D → kin. factors

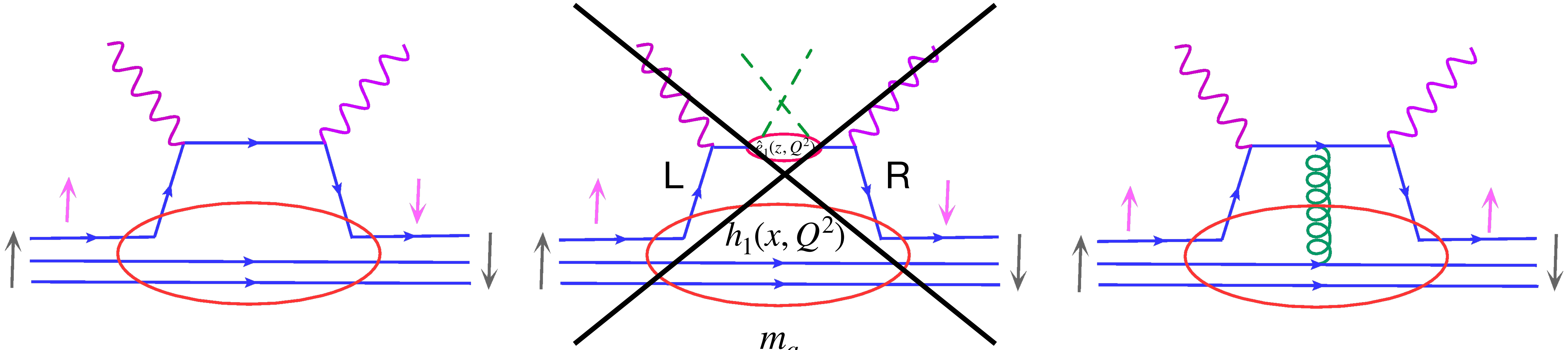
Transition from Non-perturbative to Perturbative QCD



The Inclusive Nucleon Spin-Structure Function g_2

- No simple interpretation in quark parton model
- Related to the transverse spin structure function $g_T(x, Q^2) = g_1(x, Q^2) + g_2(x, Q^2)$
- Can cleanly remove twist-2 contribution → probe quark-gluon correlations

The Inclusive Nucleon Spin-Structure Function g_2



twist-2 | twist-2 $\propto \frac{m_q}{M_n}$ (chiral-odd) | twist-3

$$\gamma^*(+1) + N\left(+\frac{1}{2}\right) \rightarrow \gamma^*(0) + N\left(-\frac{1}{2}\right)$$

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2) \quad \begin{cases} g_2^{WW}(x, Q^2) = -\,g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(y, Q^2) \\ \bar{g}_2(x, Q^2) = -\int_x^1 \frac{dy}{y} \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_1(y, Q^2) + \xi(y, Q^2)\right] \end{cases}$$

"transversity" "quark-gluon correlation"

g_2, d_2, and Color Forces

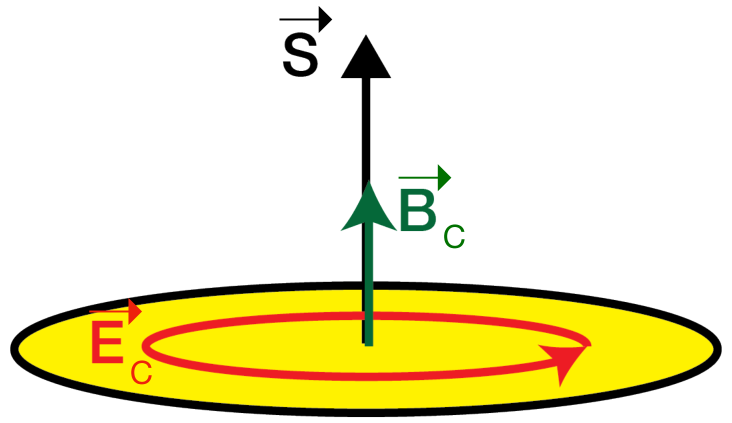
Operator product expansion: $\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \ldots = \mu_2 + \frac{M^2}{9Q^2}(a_2 + 4d_2 + 4f_2) + O\left(\frac{\mu_6}{Q^4}\right)$

μ_2 → determined by combination of singlet, triplet, and octet axial charges

$$a_2(Q^2) = \int_0^1 x^2 g_1(x,Q^2)dx$$ twist-2

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

$$f_2(Q^2) = \frac{9Q^2}{4M^2}\left(\int_0^1 g_1(x,Q^2)dx - \mu_2\right) - \frac{a_2(Q^2)}{4} - d_2(Q^2)$$ twist-4



$$\langle PS|\psi^\dagger g\mathbf{B_c}\psi|PS\rangle = \chi_B M^2 \mathbf{S}$$

$$\langle PS|\psi^\dagger \alpha \times g\mathbf{E_c}\psi|PS\rangle = \chi_E M^2 \mathbf{S}$$

Transverse forces exerted on struck quark due to remaining two quarks:

$$F_E = -\frac{M^2}{4}\chi_E = -\frac{M^2}{4}\frac{(4d_2 + 2f_2)}{3}$$

$$F_B = -\frac{M^2}{2}\chi_B = -\frac{M^2}{2}\frac{(4d_2 - f_2)}{3}$$

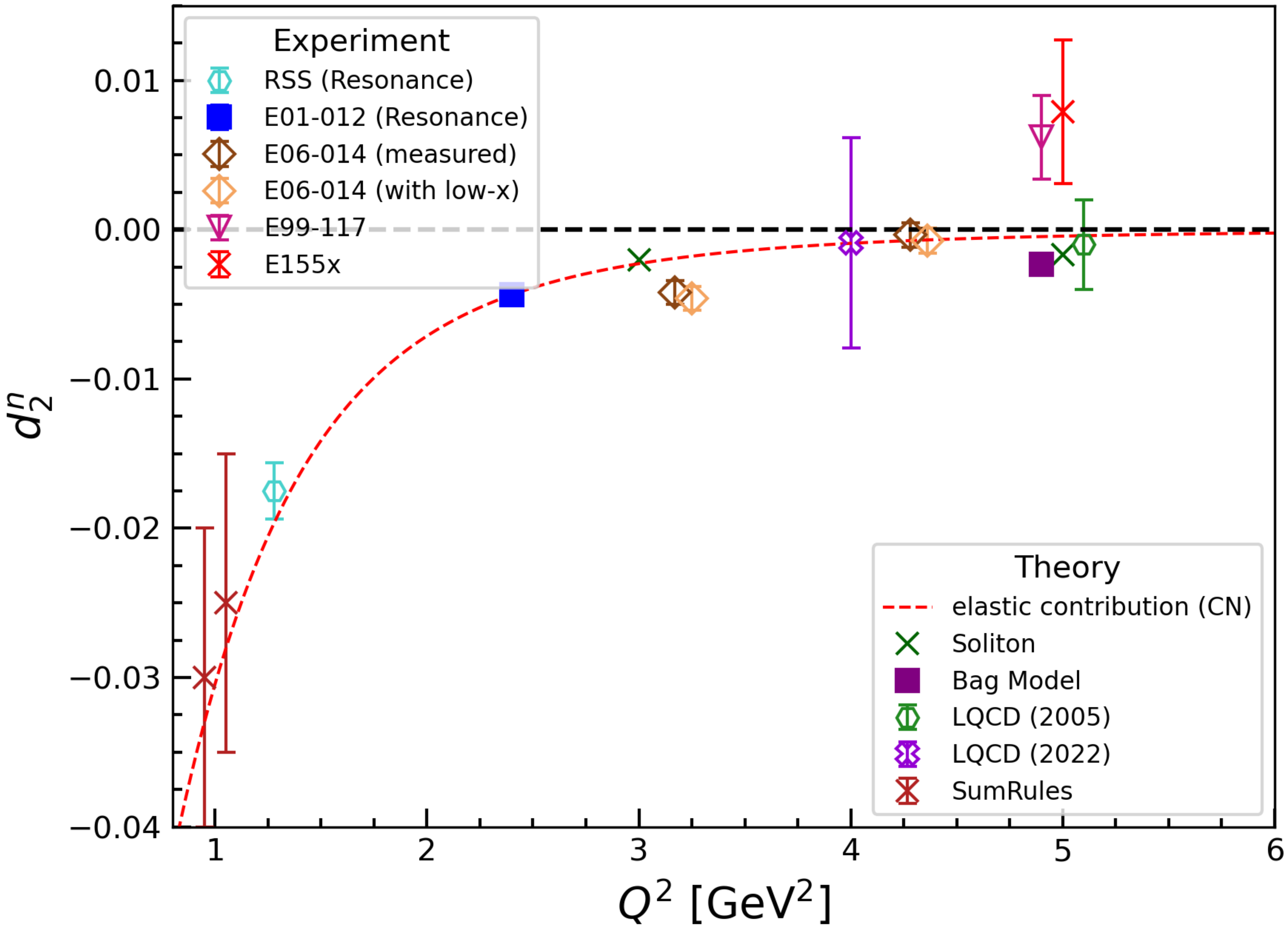
First results:

Q^2 (GeV^2)	F_E^n (MeV/fm)	F_B^n (MeV/fm)
3.21	$-26.17 \pm 1.32_{stat} \pm 29.35_{sys}$	$44.99 \pm 2.43_{stat} \pm 29.43_{sys}$
4.43	$-29.12 \pm 1.38_{stat} \pm 29.34_{sys}$	$30.69 \pm 2.55_{stat} \pm 29.40_{sys}$

M. Burkardt, Phys. Rev. D 88, 114502 (2013)
E. Stein et al., Phys. Lett. B 353, 107 (1995)
X. Ji, arXiv-ph/9510362 (1995)

M. Posik et al., Phys. Rev. Lett. 113, 022002 (2014)

World Data and Predictions: $d_2^n(Q^2)$



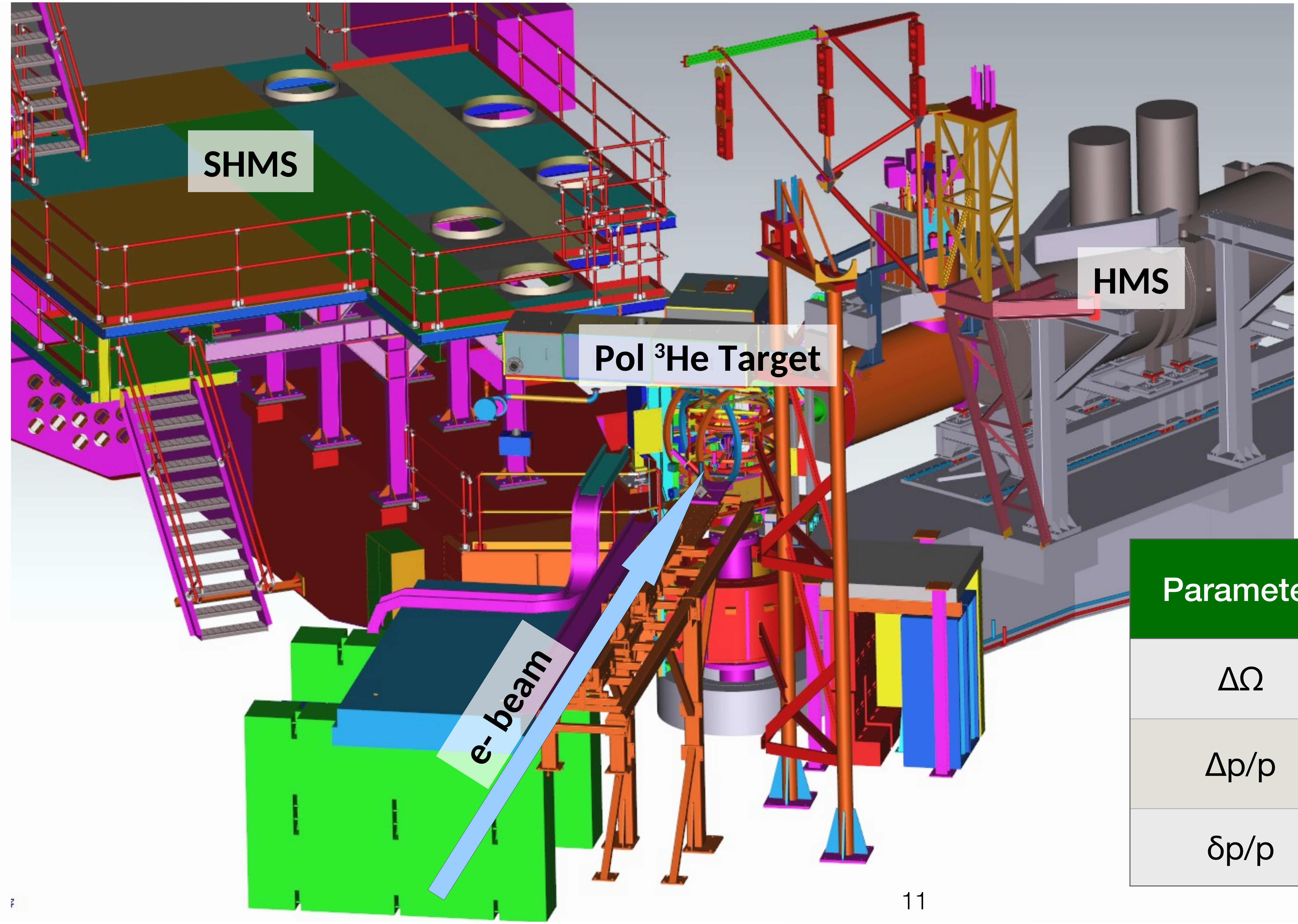
Note: Often data for

$g_1(x, Q^2)$ and $g_2(x, Q^2)$

have to be interpolated in Q^2!!

(systematic effect?)

Measure g_1^n, g_2^n over Large Range in x



Hall C at JLab

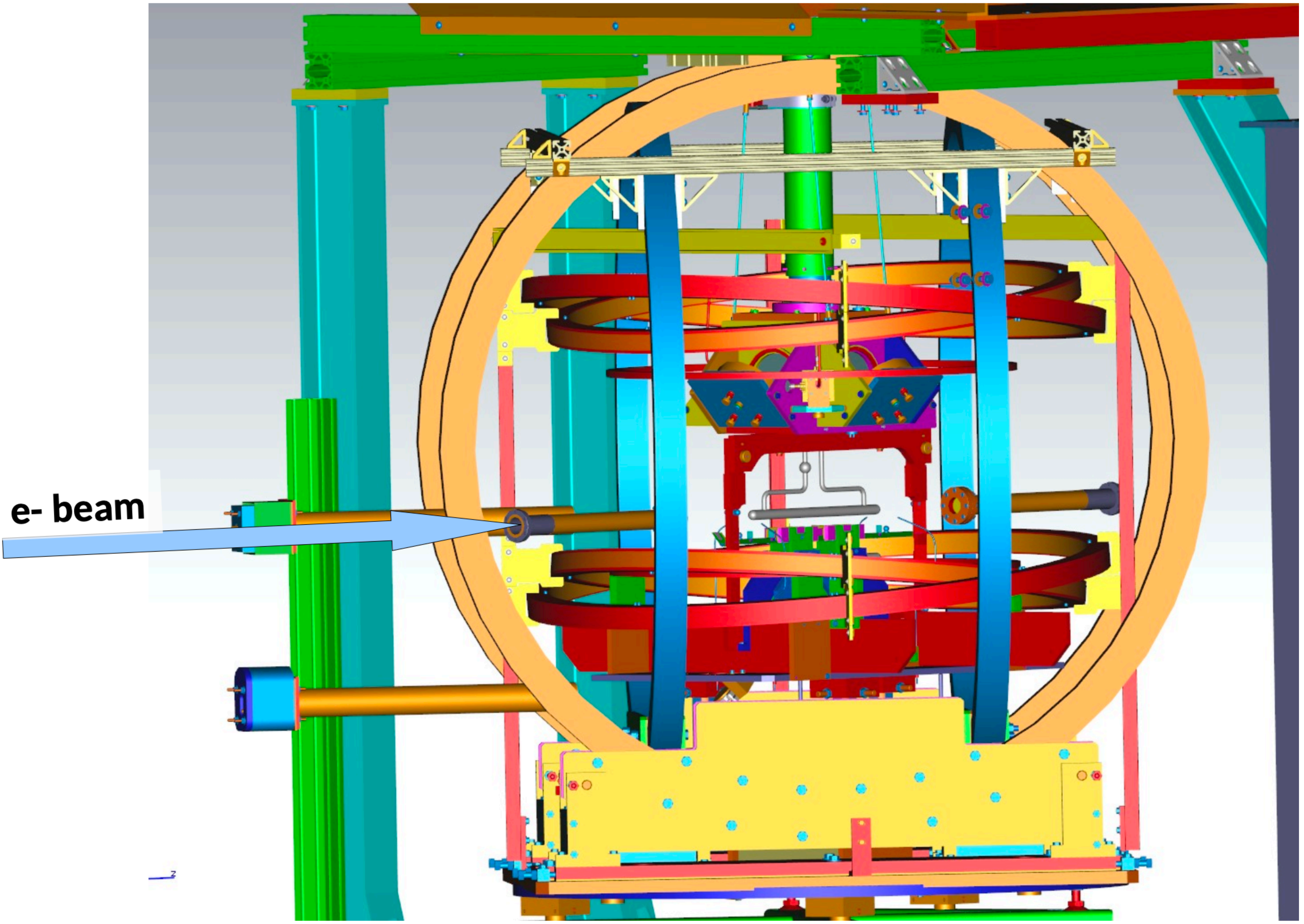
Experiments:

E12-06-110: A_1^n

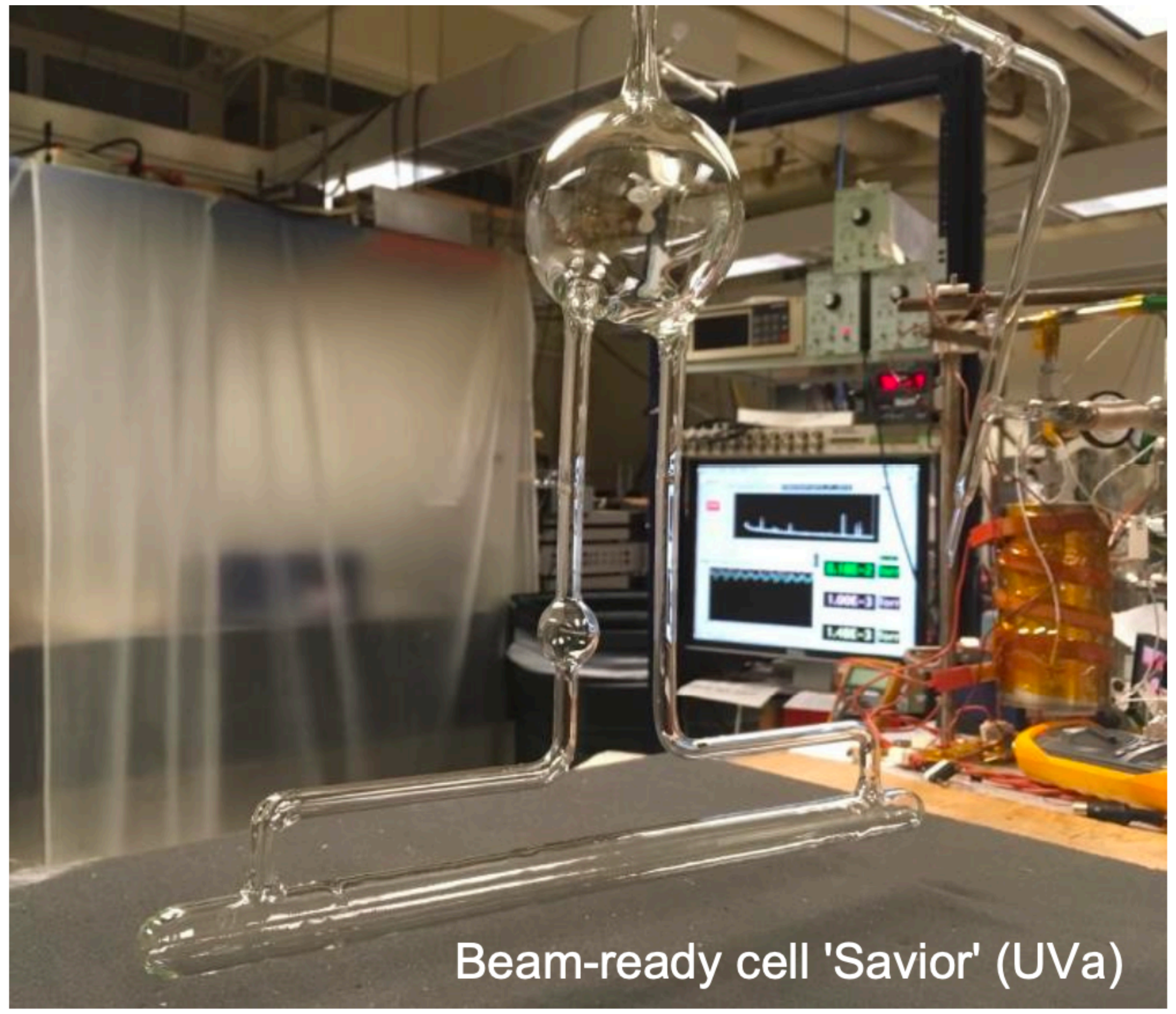
E12-06-121: d_2^n

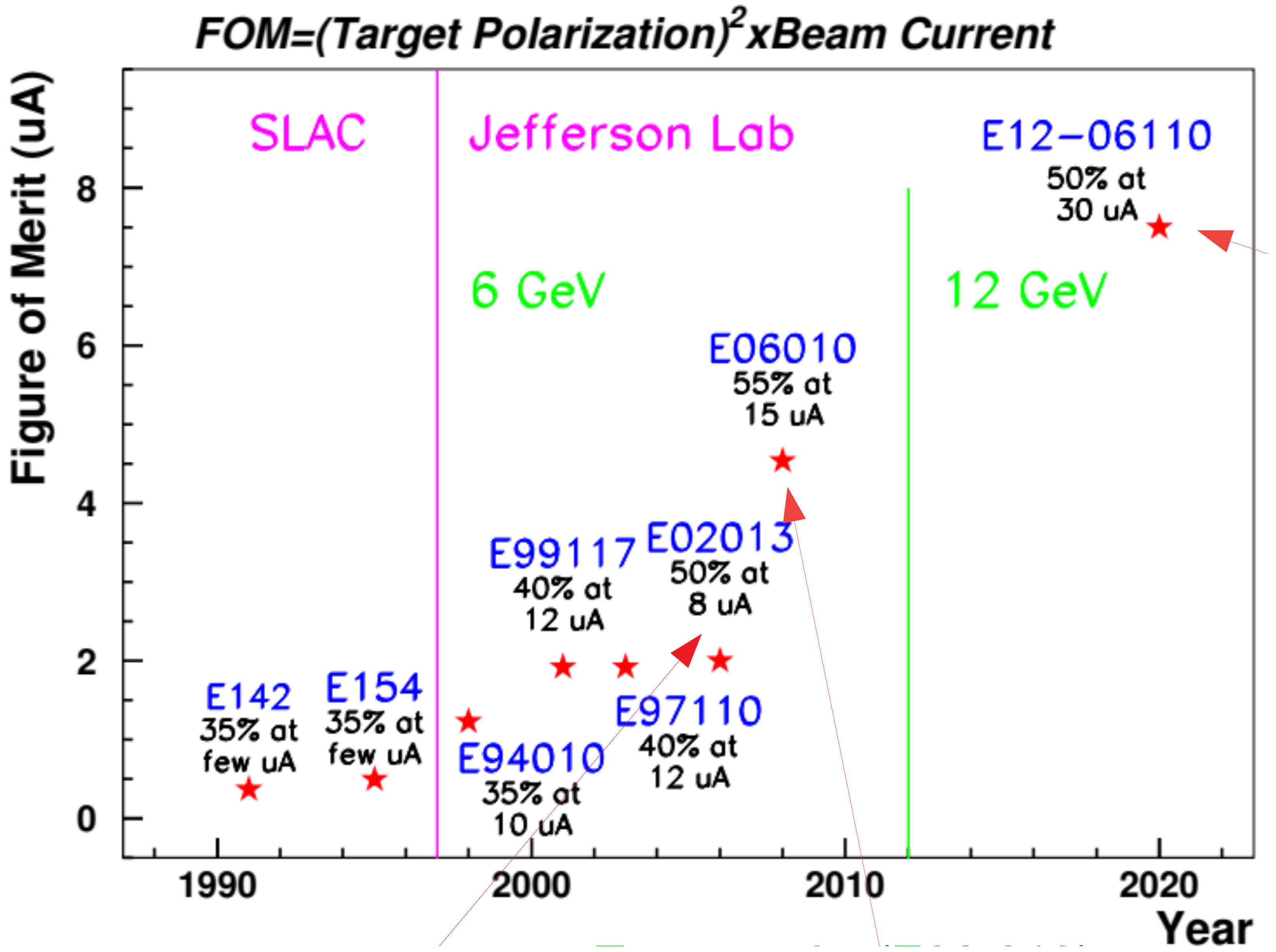
Parameter	SHMS	HMS
ΔΩ	2-4 msr	>6 msr
Δp/p	-15% →+25%	±10%
δp/p	0.1%-0.15%	<0.2%

Polarized Helium-3 Target

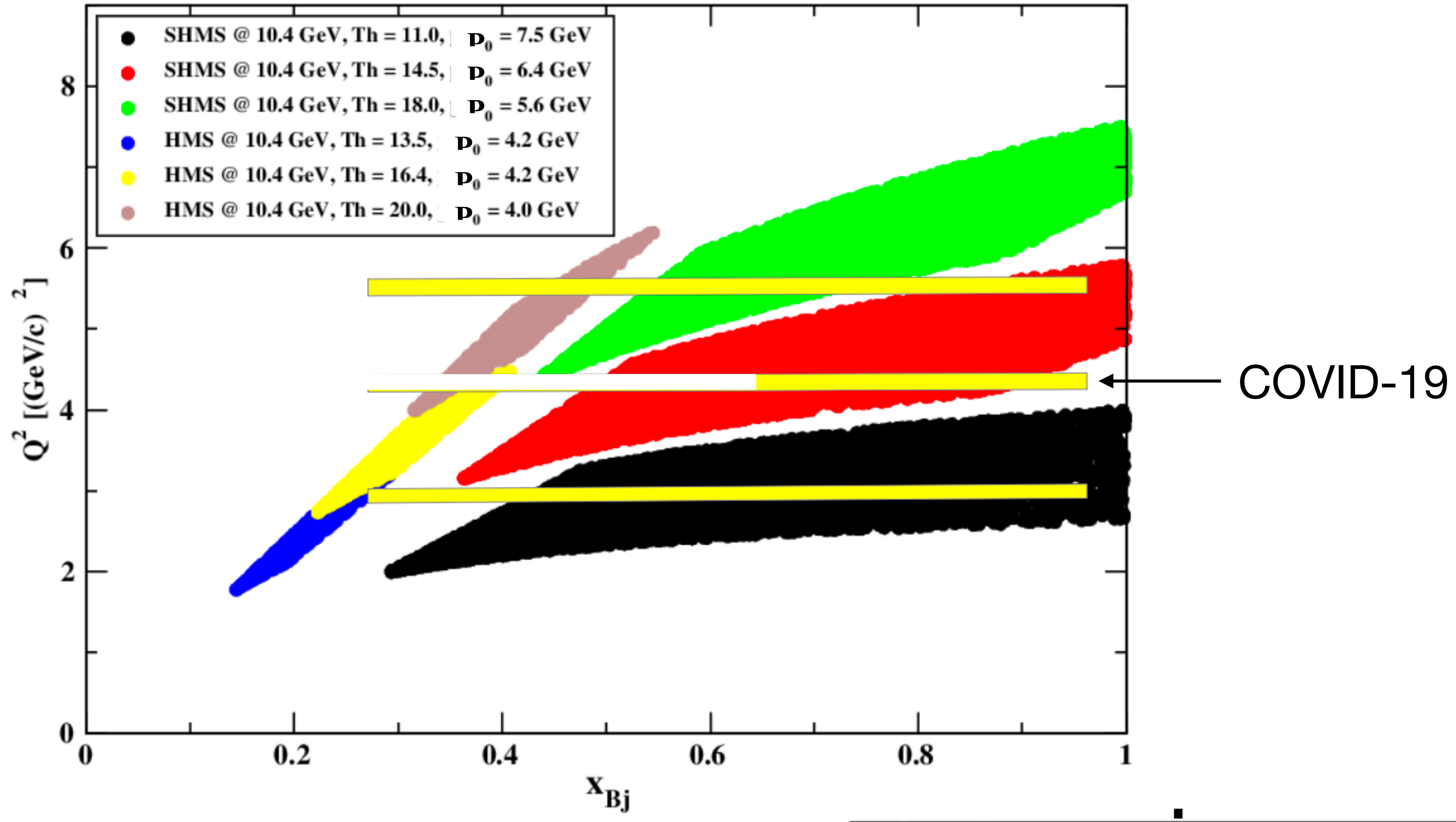


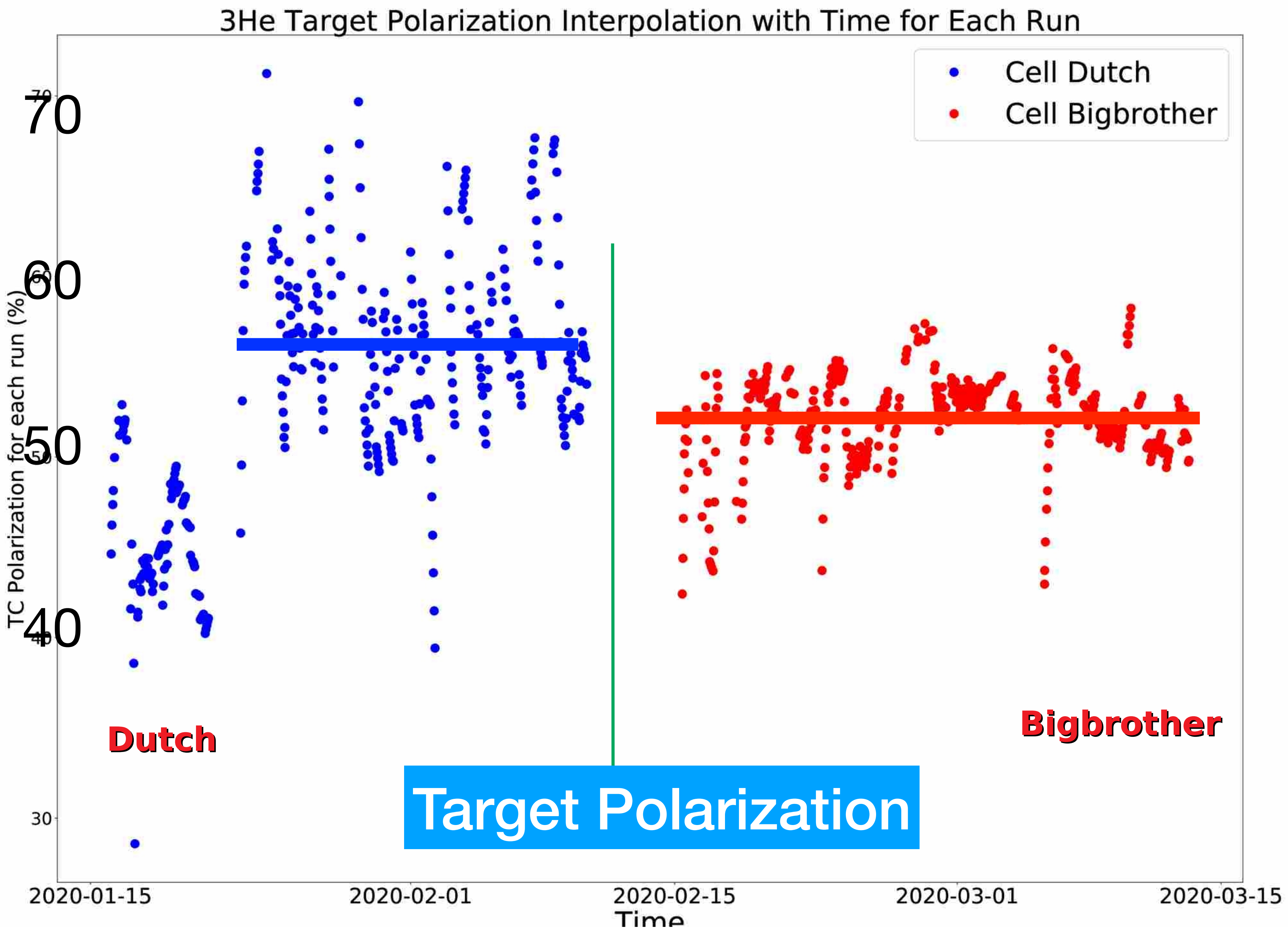
Method: Hybrid Spin Exchange Optical Pumping

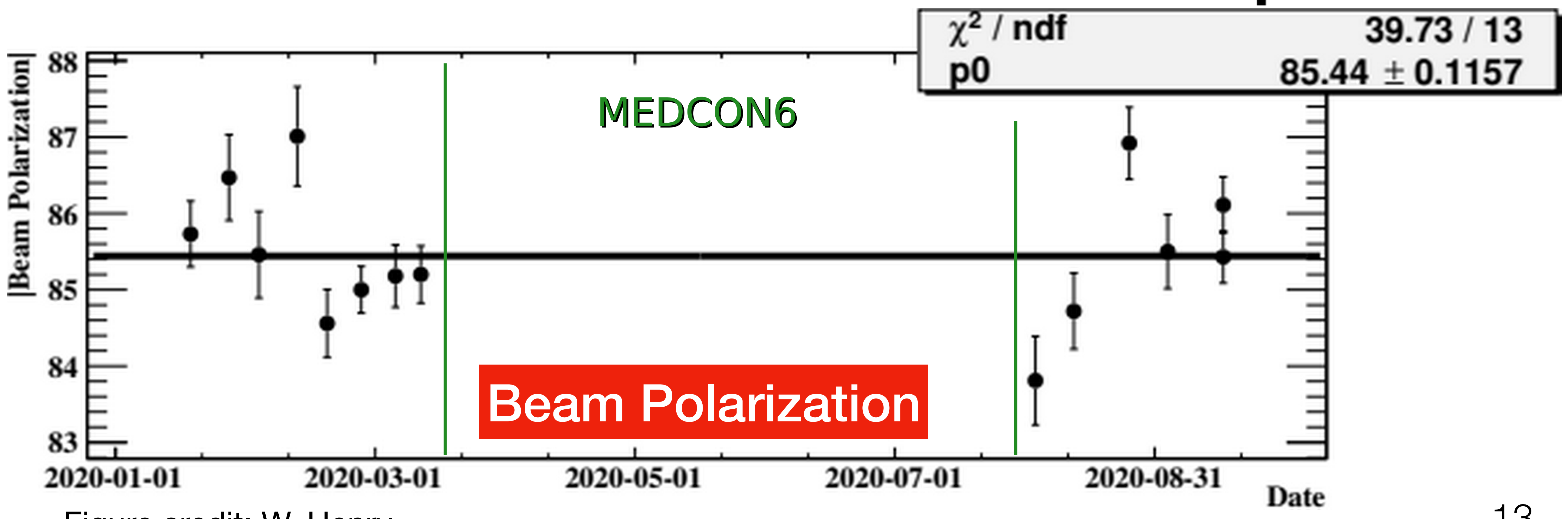




$d_2^n(Q^2)$: Experimental Conditions







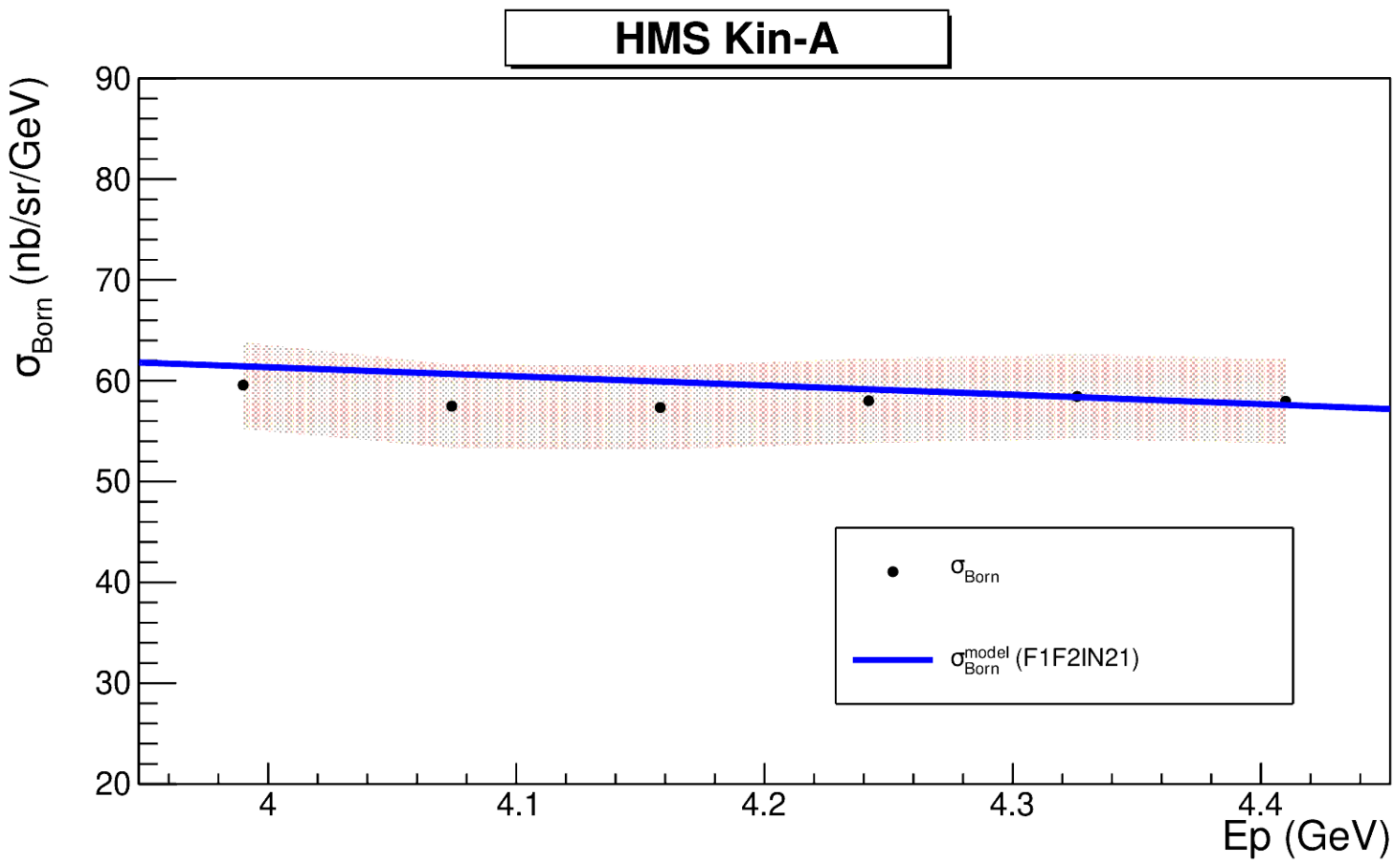
E_b = 10.38 GeV

I_b ~ 30 μA

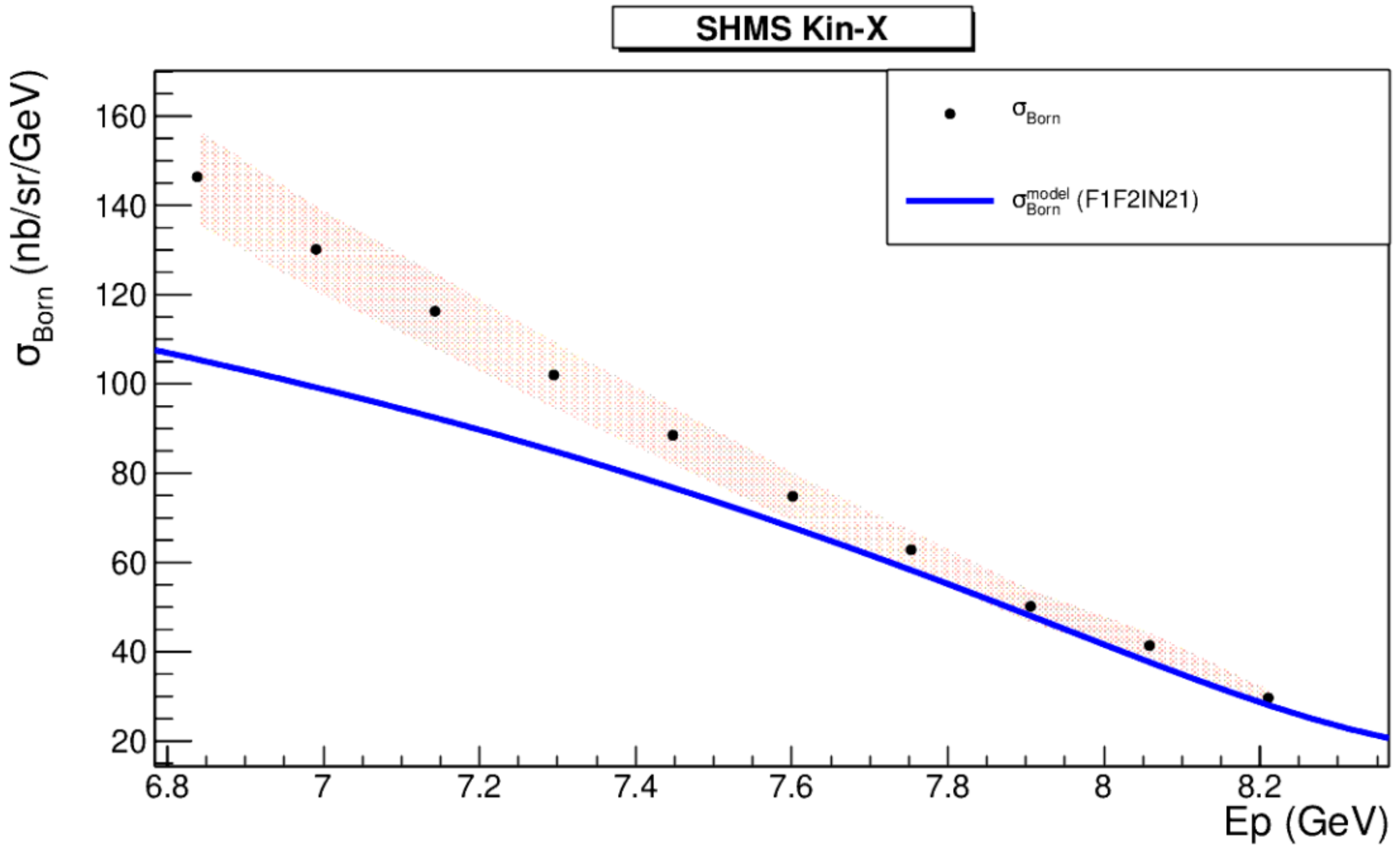
L ~ $2\times10^{36}/cm^2/s$

Figure credit: W. Henry

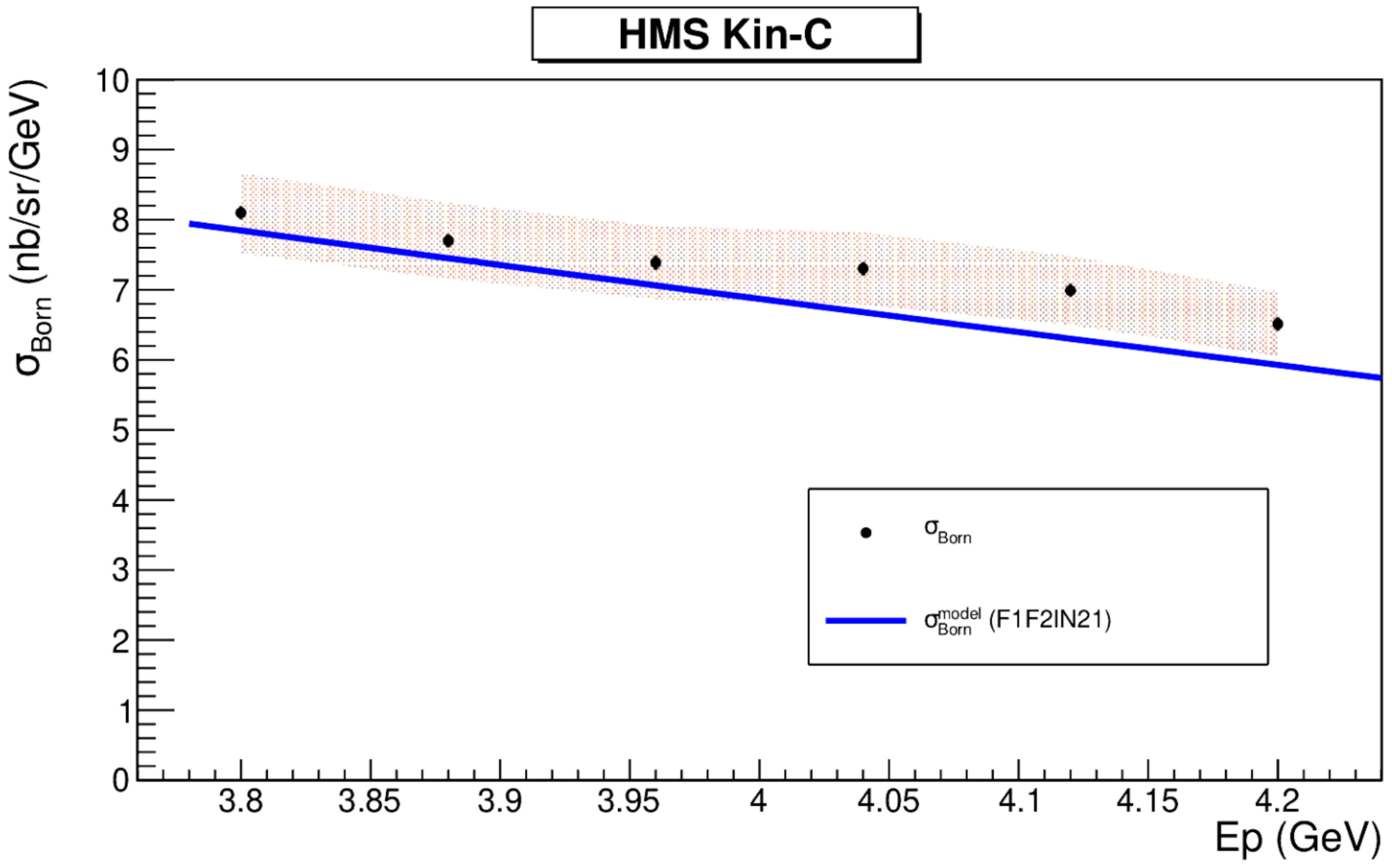
Extraction of Unpolarized Cross Sections



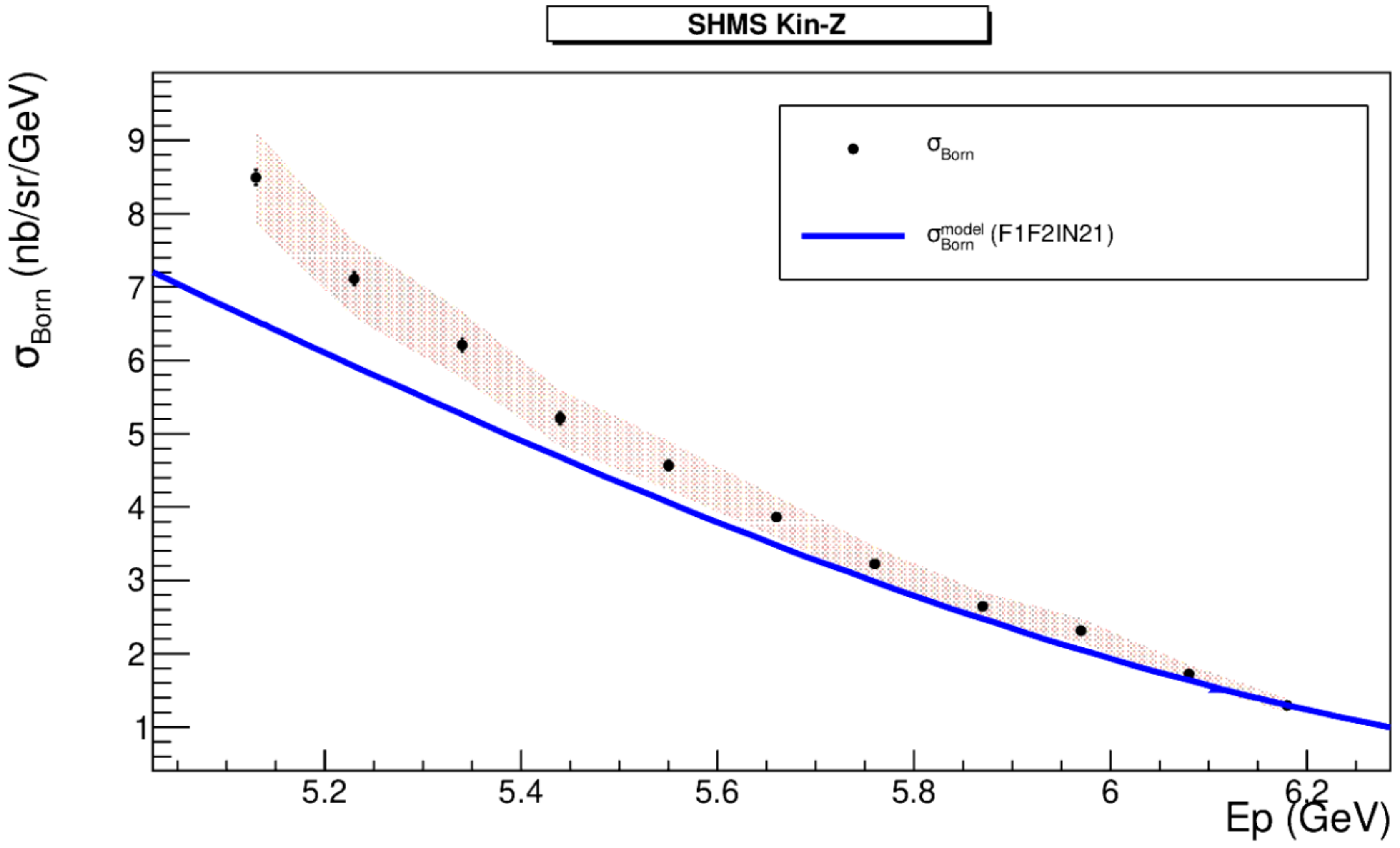
(a) HMS Kin-A: $\langle x \rangle$=0.207, $\langle Q^2 \rangle$=2.409 GeV^2/c^2



(a) SHMS Kin-X: $\langle x \rangle$=0.53, $\langle Q^2 \rangle$=2.86 GeV^2/c^2



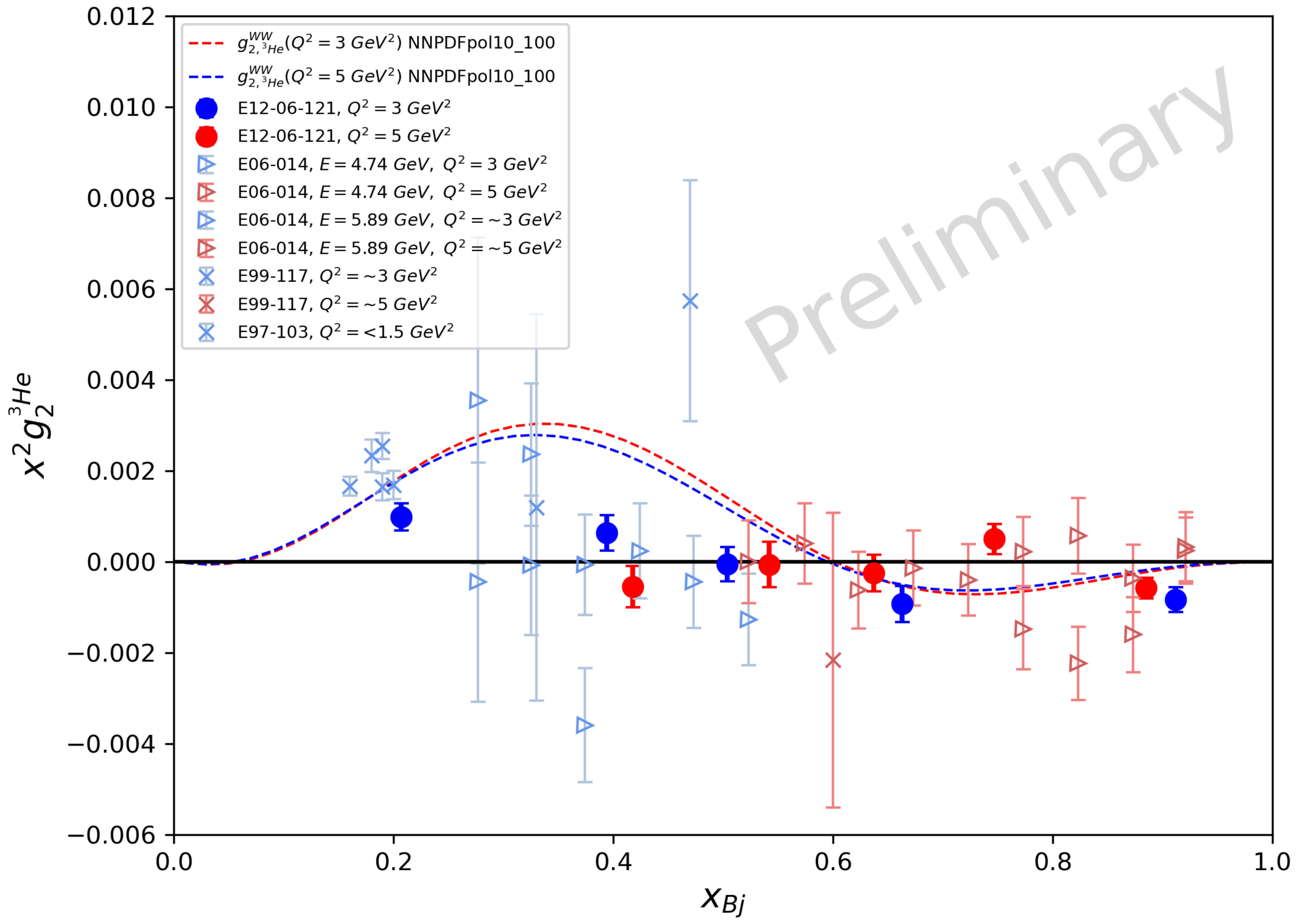
(b) HMS Kin-C: $\langle x \rangle$=0.418, $\langle Q^2 \rangle$=5.008 GeV^2/c^2



(b) SHMS Kin-Z: $\langle x \rangle$=0.63, $\langle Q^2 \rangle$=5.69 GeV^2/c^2

M. Roy, PhD thesis, University of Kentucky (2022)

x^2-Weighted g_2^{3He} Data



E12-06-121: Preliminary

- *No radiative corrections applied*
- *Statistical uncertainties only*

World data for $Q^2 \sim 3, 5\ GeV^2$ + E97-103 data

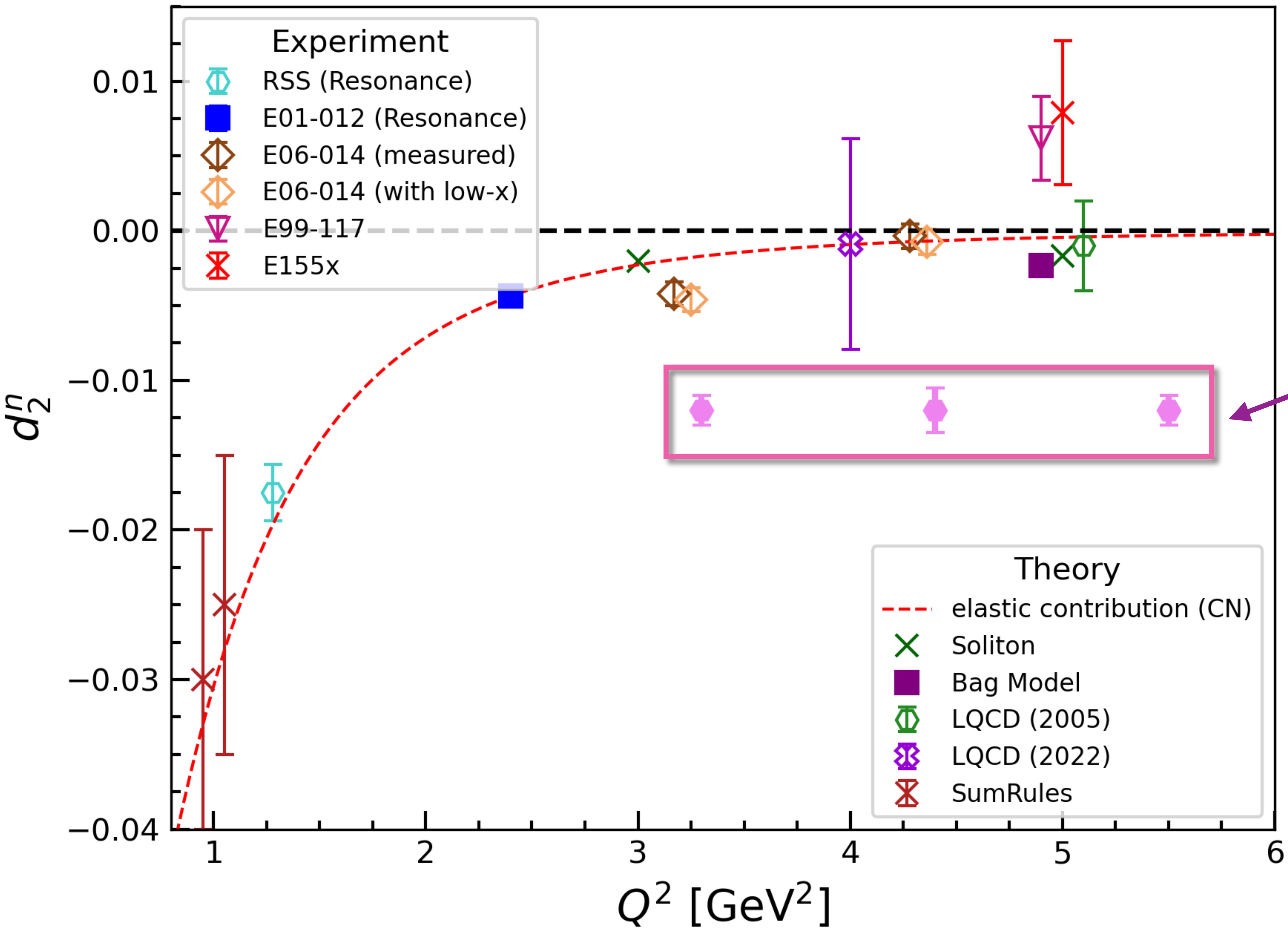
Dashed curves: (NNPDFpol)

$$g^{WW}_{2,^3He} = P_n g^{WW}_{2,n} + 2P_p g^{WW}_{2,p}$$

$$P_n = 0.86 \qquad P_p = -0.028$$

Analysis: J. Chen, William & Mary, (2024)

World Data and Predictions: $d_2^n(Q^2)$



Expected precision for E12-06-121

Virtual Photon Asymmetry A_1 at Large x_{Bj}

$$A_1(x,Q^2) = \frac{1}{F_1(x,Q^2)}\left[g_1(x,Q^2) - \cancel{\frac{4M^2x^2}{Q^2}g_2(x,W^2)}\right]$$

large Q^2

$$A_1^n(x) \approx \frac{4[\Delta d(x) + \Delta\bar{d}(x)] + \Delta u(x) + \Delta\bar{u}(x) + \Delta s(x) + \Delta\bar{s}(x)}{4[d(x) + \bar{d}(x)] + u(x) + \bar{u}(x) + s(x) + \bar{s}(x)}$$

$$\rightarrow A_1^n(x,Q^2) \approx \frac{g_1^n(x,Q^2)}{F_1^n(x,Q^2)} \approx \frac{4\Delta d + \Delta u}{4d + u}$$

(sea quark contributions ignored)

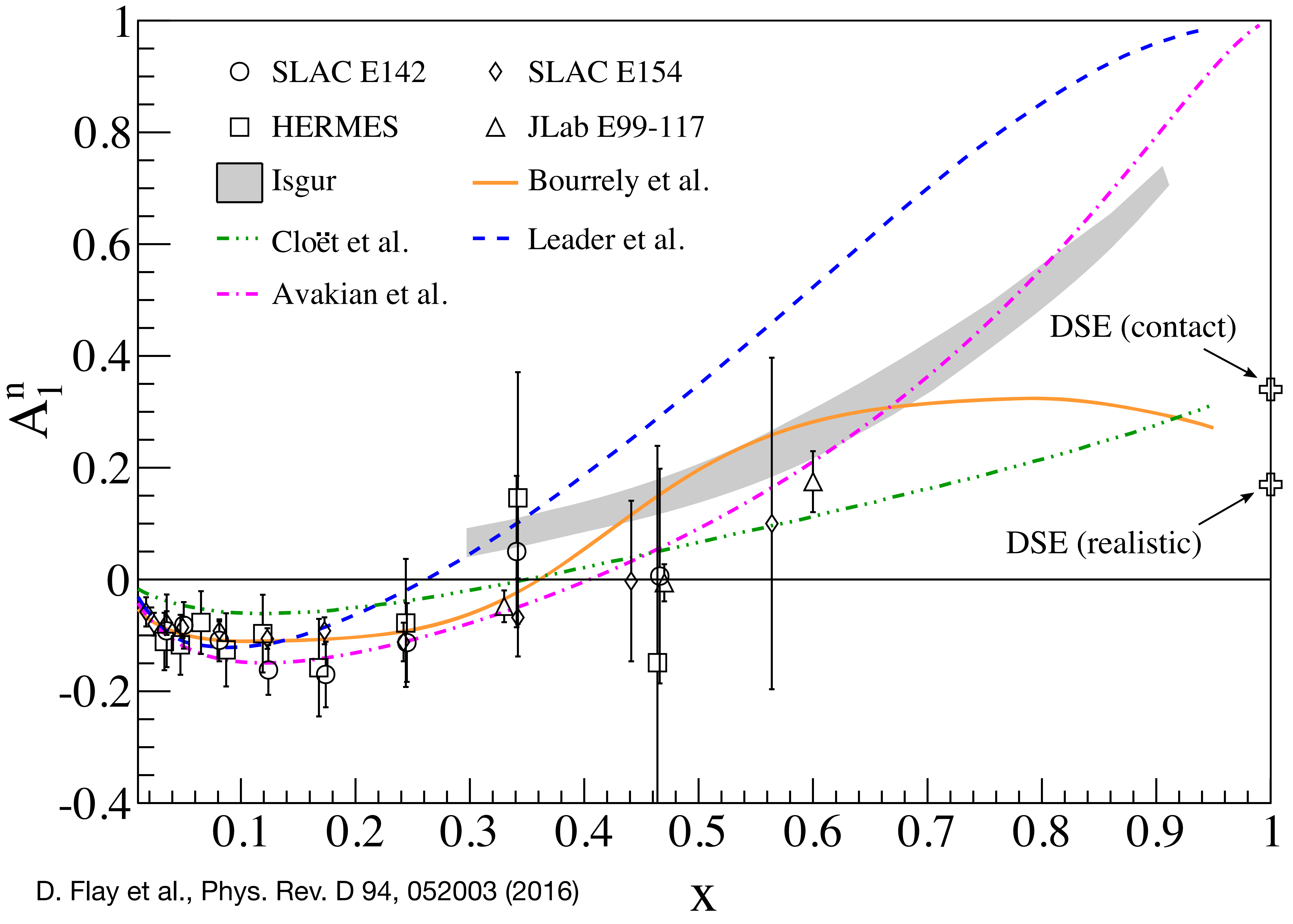
pQCD (using HHC)

$$\lim_{x\to 1} A_1^n = \frac{\Delta u}{u} = \frac{\Delta d}{d} = 1$$

Virtual Photon Asymmetry A_1^n at Large x_{Bj}

$$A_1^n = \frac{1}{P_n(1+\frac{0.056}{P_n})}\frac{F_2^{^3He}}{F_2^n}\left(A_1^{^3He} - 2\frac{F_2^p}{F_2^{^3He}}P_pA_1^p((1-\frac{0.014}{2P_p}))\right)$$

$$P_n = 0.86^{+0.036}_{-0.020} \qquad P_p = -0.028^{+0.094}_{-0.004}$$



D. Flay et al., Phys. Rev. D 94, 052003 (2016)

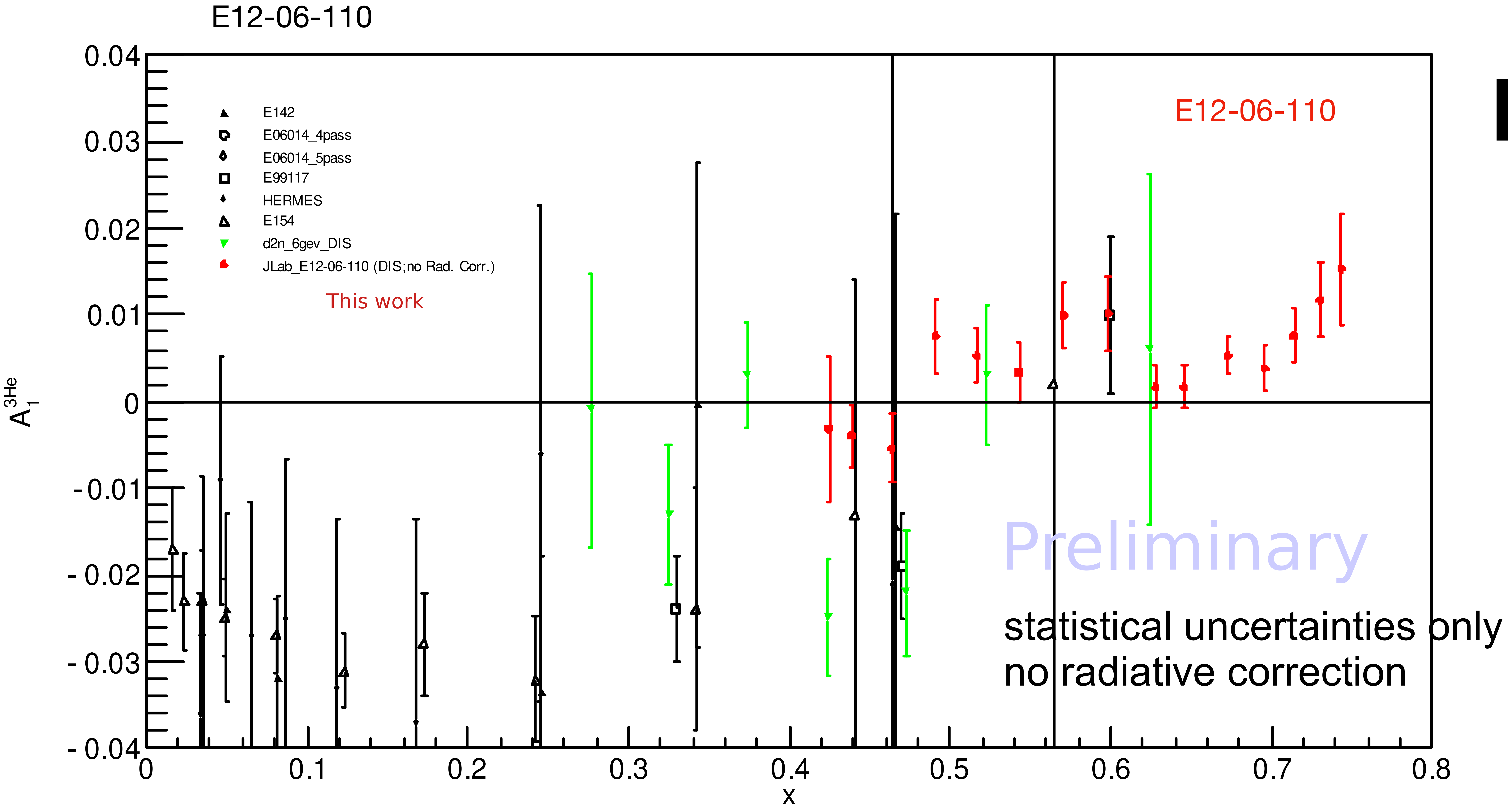
Extraction of *nucleon asymmetries*:

- nuclear effects
- proton: use previously measured data

F. Bissey et al., Phys. Rev. C 65, 064317 (2002)

J.J. Ethier, W. Melnitchouk, Phys. Rev. C 88, 054001 (2013)

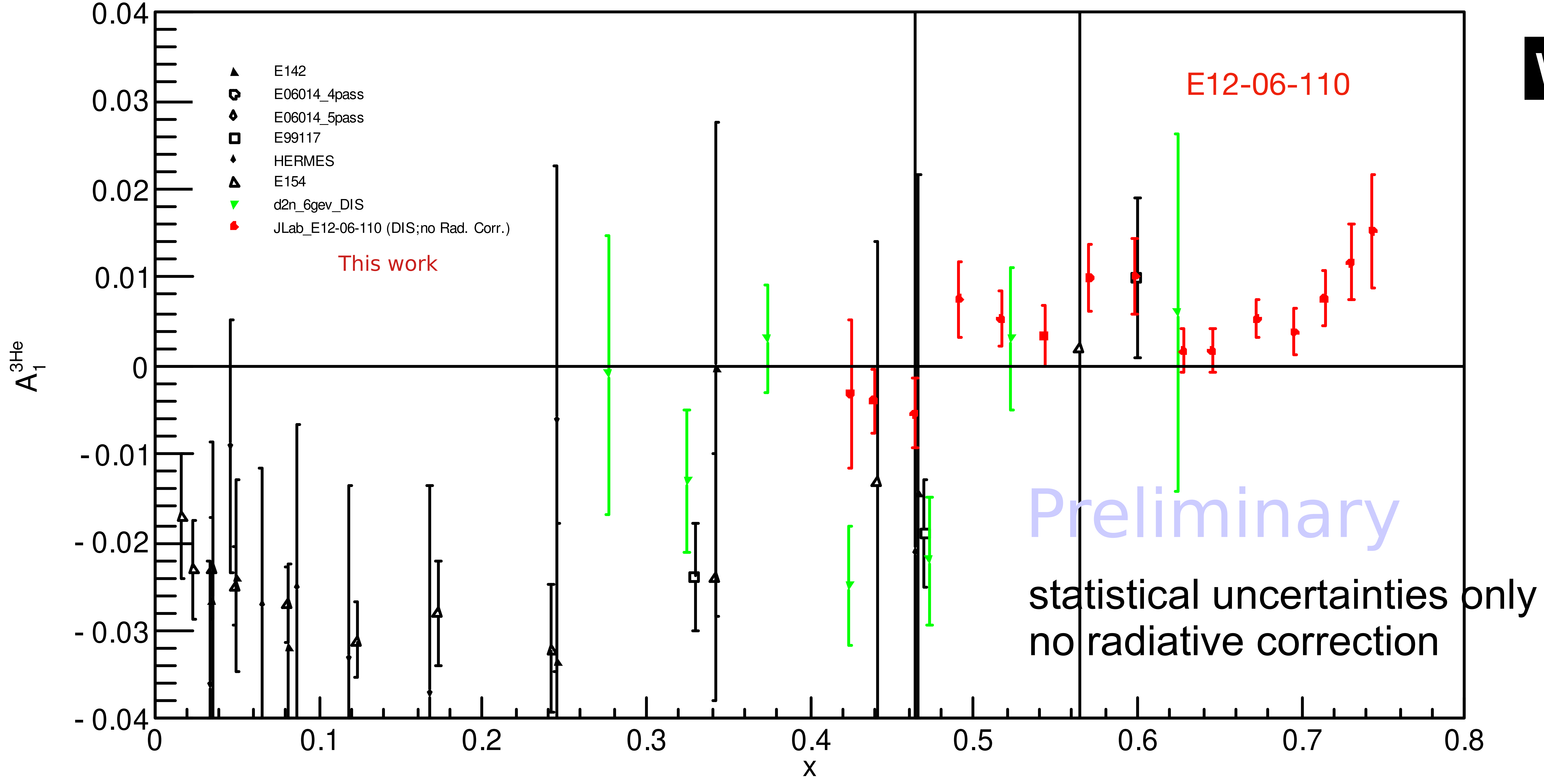
Preliminary A_1^{3He} Data (with DIS Cut)



W > 2 GeV

M. Chen, PhD thesis, University of Virginia (2023)

Preliminary A_1^{3He} Data (with DIS Cut)



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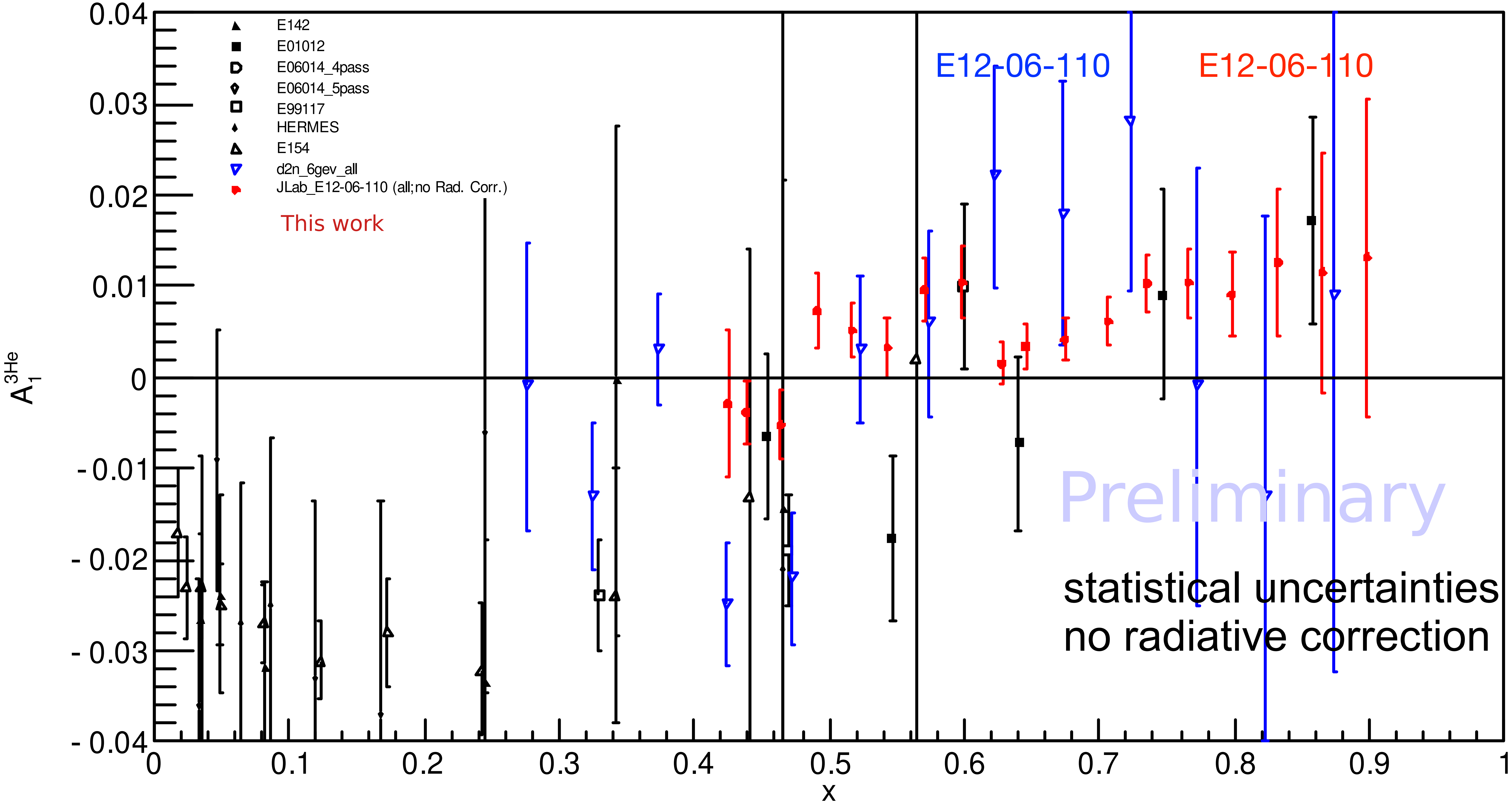
Preliminary A_1^{3He} Data without DIS Cut



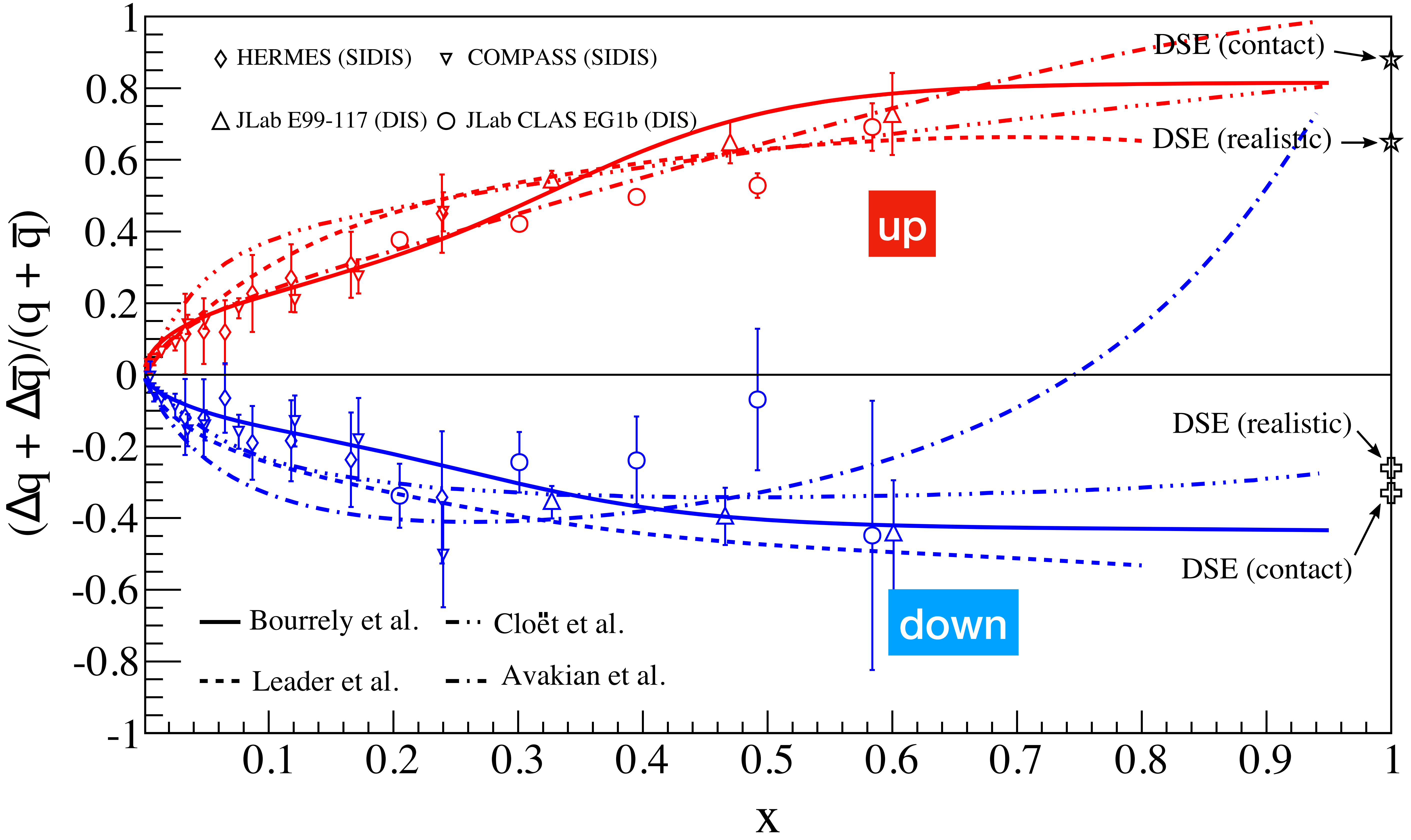
statistical uncertainties only
no radiative correction

all data

M. Chen, PhD thesis, University of Virginia (2023)

Flavor Decomposition

Existing data before E12-06-110



$$\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + R^{du}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4R^{du}\right)$$

$$R^{du} = \frac{d + \bar{d}}{u + \bar{u}}$$

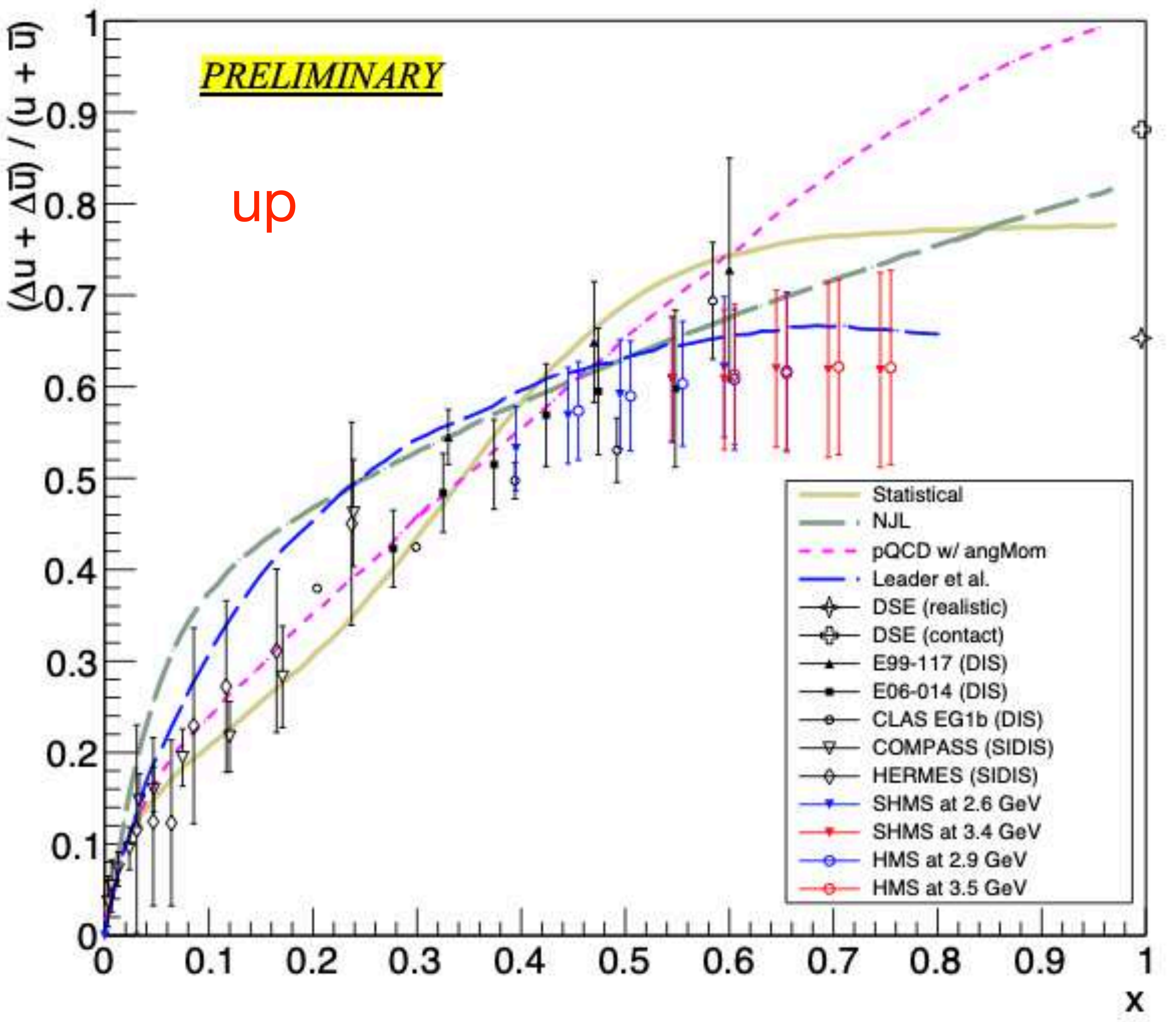
(without s, $\overline{\text{s}}$)

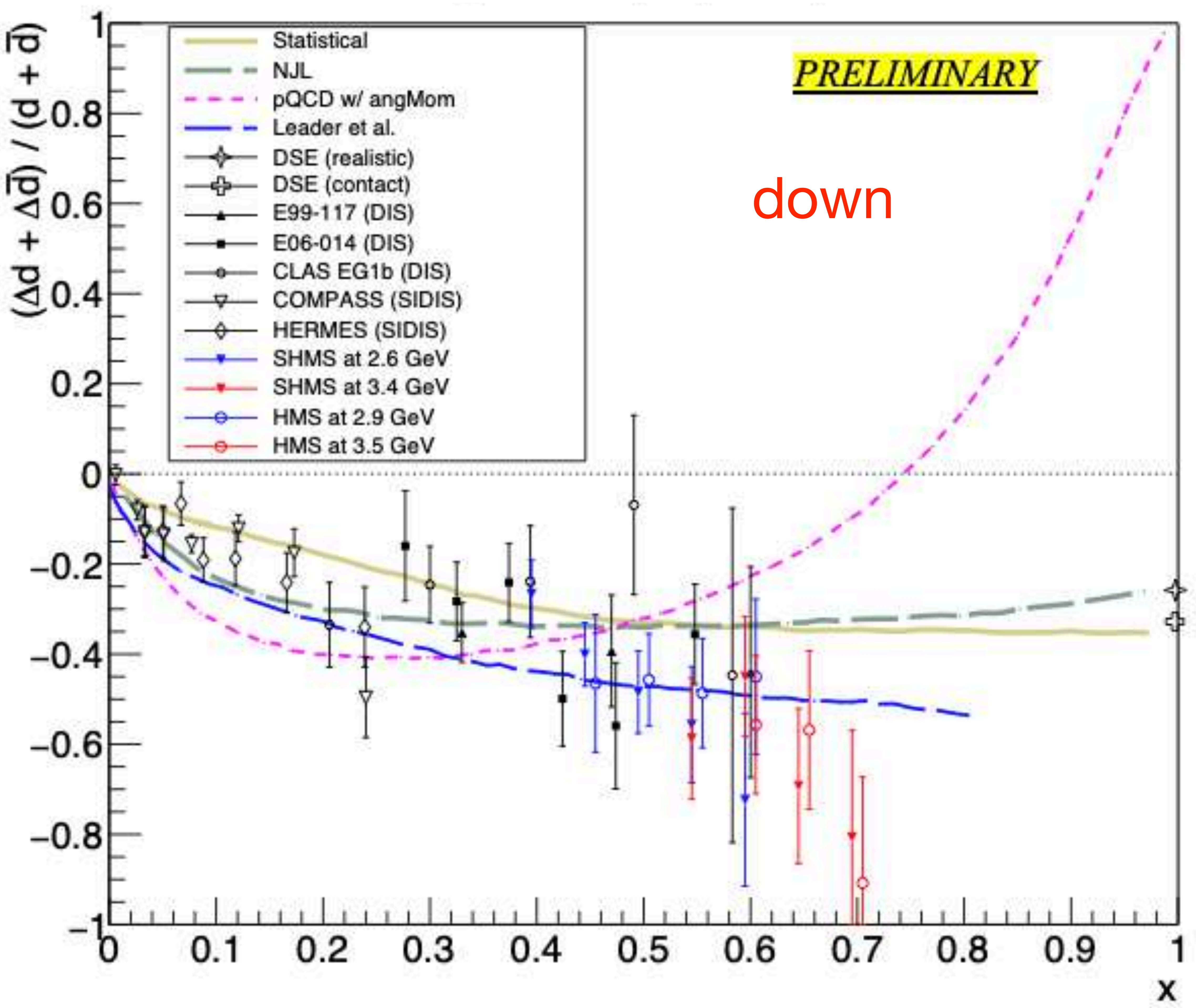
$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4\frac{1}{R^{du}}\right)$$

D. Flay et al., Phys. Rev. D 94, 052003 (2016)

Flavor Decomposition Including E12-06-110

E12-06-110 data included





M. Cardona, PhD Thesis, Temple University (2023)

Summary and Outlook

- Measured successfully $d_2^{3He}(x)$ ($d_2^n(x)$) at three different Q2, keeping Q2 constant over a large range in x (~0.4 < x < ~0.9).
- Extended measurements of virtual photon asymmetry $A_1^{3He}(x)$ ($A_1^n(x)$) from x ~ 0.6 to x~0.9
- d_2^n and A_1^n experiments in final stages of analyses
  - radiative corrections
  - extraction of neutron properties from ^3He (nuclear corrections)
  - systematic uncertainties
- Final results are expected soon

Thank you for your attention!

D. Androic, W. Armstrong, T. Averett, X. Bai, J. Bane, S. Barcus, J. Benesch, H. Bhatt, D. Bhetuwal, D. Biswas, A. Camsonne, G. Cates, J-P. Chen, J. Chen, M. Chen, C. Cotton, M-M. Dalton, A. Deur, B. Dhital, B. Duran, S.C. Dusa, I. Fernando, E. Fuchey, B. Gamage, H. Gao, D. Gaskell, T.N. Gautam, N. Gauthier, C.A. Gayoso, O. Hansen, F. Hauenstein, W. Henry, G. Huber, C. Jantzi, S. Jia, K. Jin, M. Jones, S. Joosten, A. Karki, B. Karki, S. Katugampola, S. Kay, C. Keppel, E. King, P. King, W. Korsch, V. Kumar, R. Li, S. Li, W. Li, D. Mack, S. Malace, P. Markowitz, J. Matter, M. McCaughan, Z-E. Meziani, R. Michaels, A. Mkrtchyan, H. Mkrtchyan, C. Morean, V. Nelyubin, G. Niculescu, M. Niculescu, M. Nycz, C. Peng, S. Premathilake, A. Puckett, A. Rathnayake, M. Rehfuss, P. Reimer, G. Riley, Y. Roblin, J. Roche, M. Roy, M. Satnik, B. Sawatzky, S. Seeds, S. Sirca, G. Smith, N. Sparveris, H. Szumila-Vance, A. Tadepalli, V. Tadevosyan, Y. Tian, A. Usman, H. Voskanyan, S. Wood, B. Yale, C. Yero, A. Yoon, J. Zhang, Z. Zhao, X. Zheng, J. Zhou

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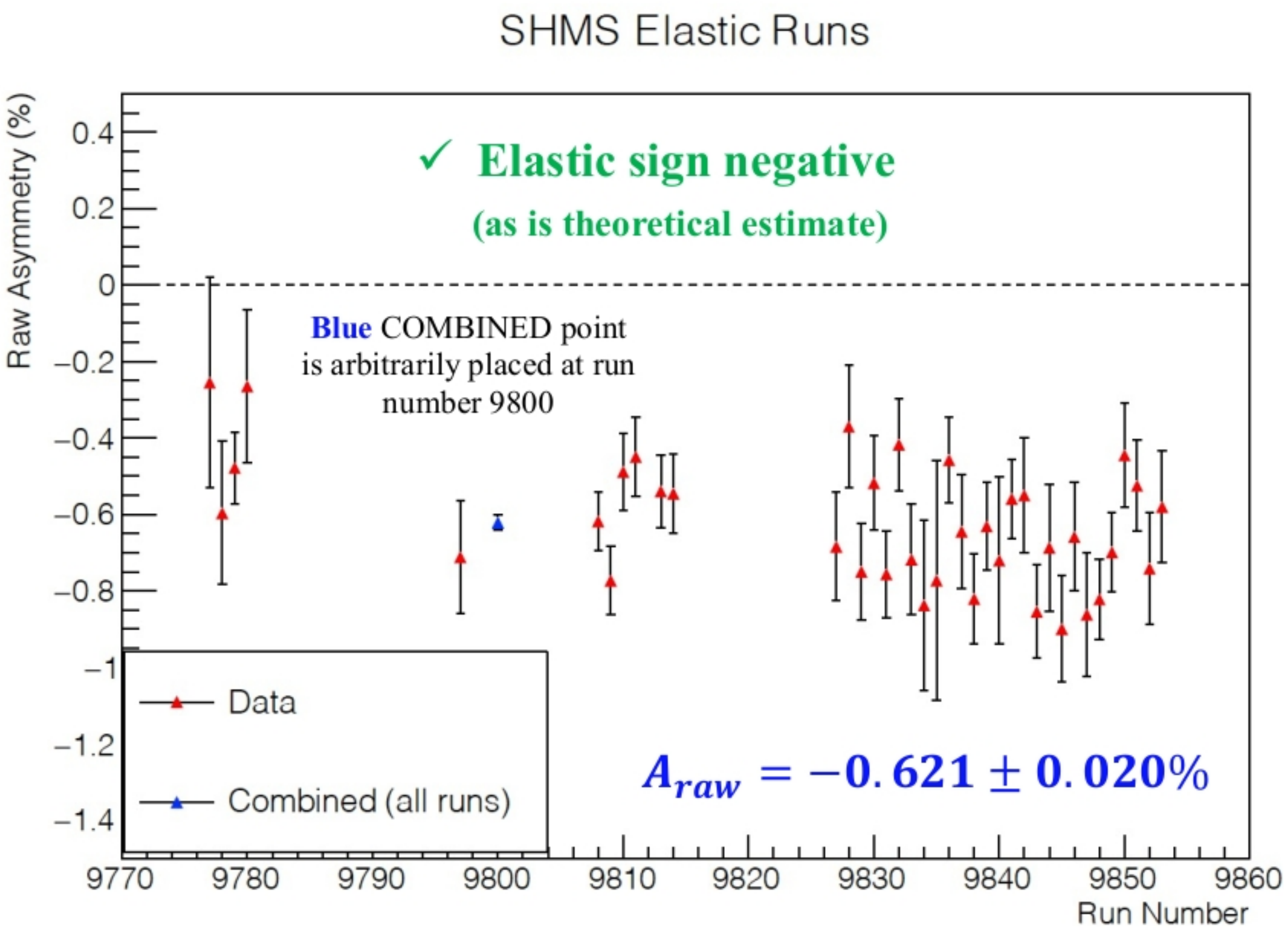
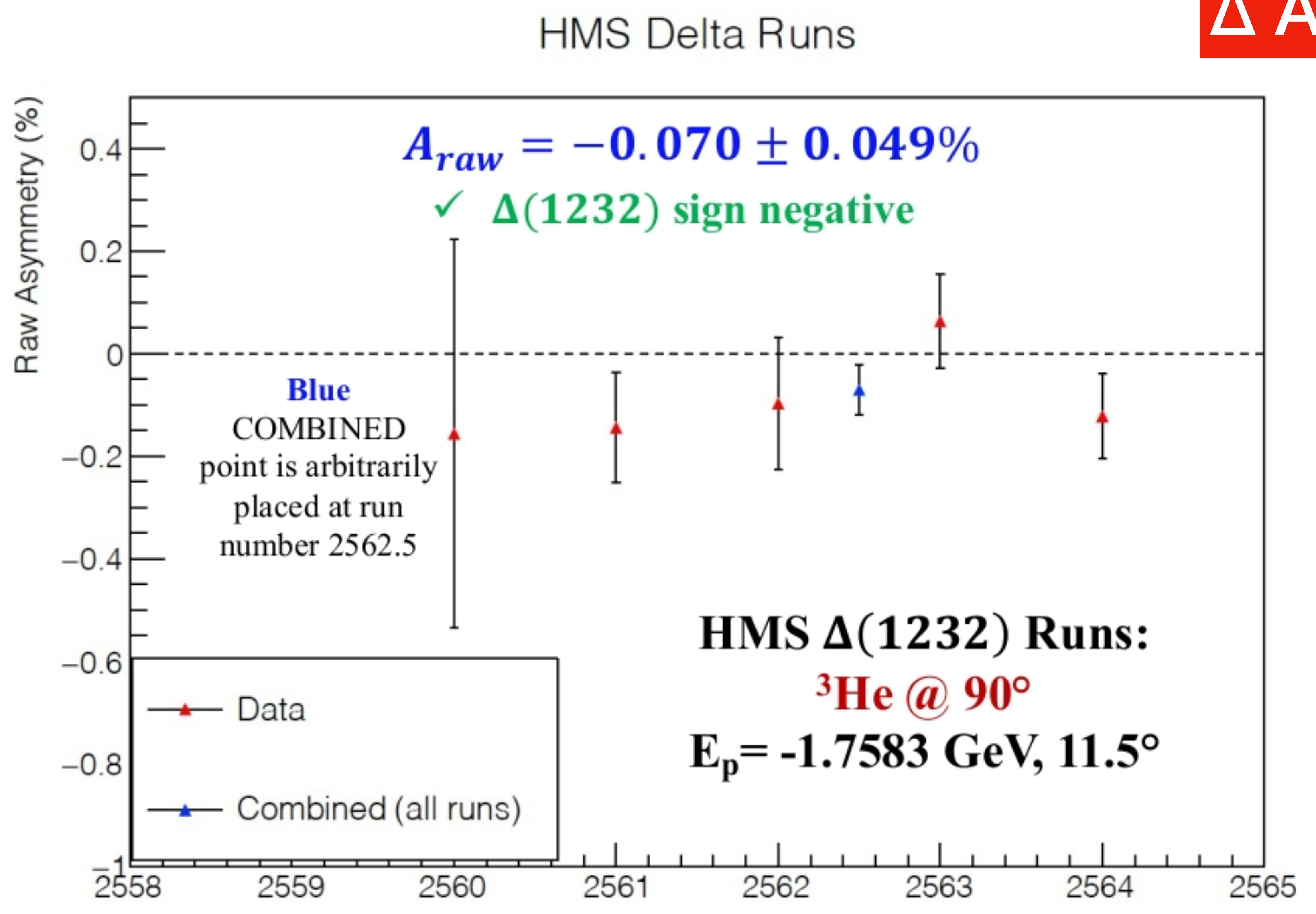
Backup Slides

Sign of the Asymmetries

Elastic Asymmetries



Δ Asymmetries



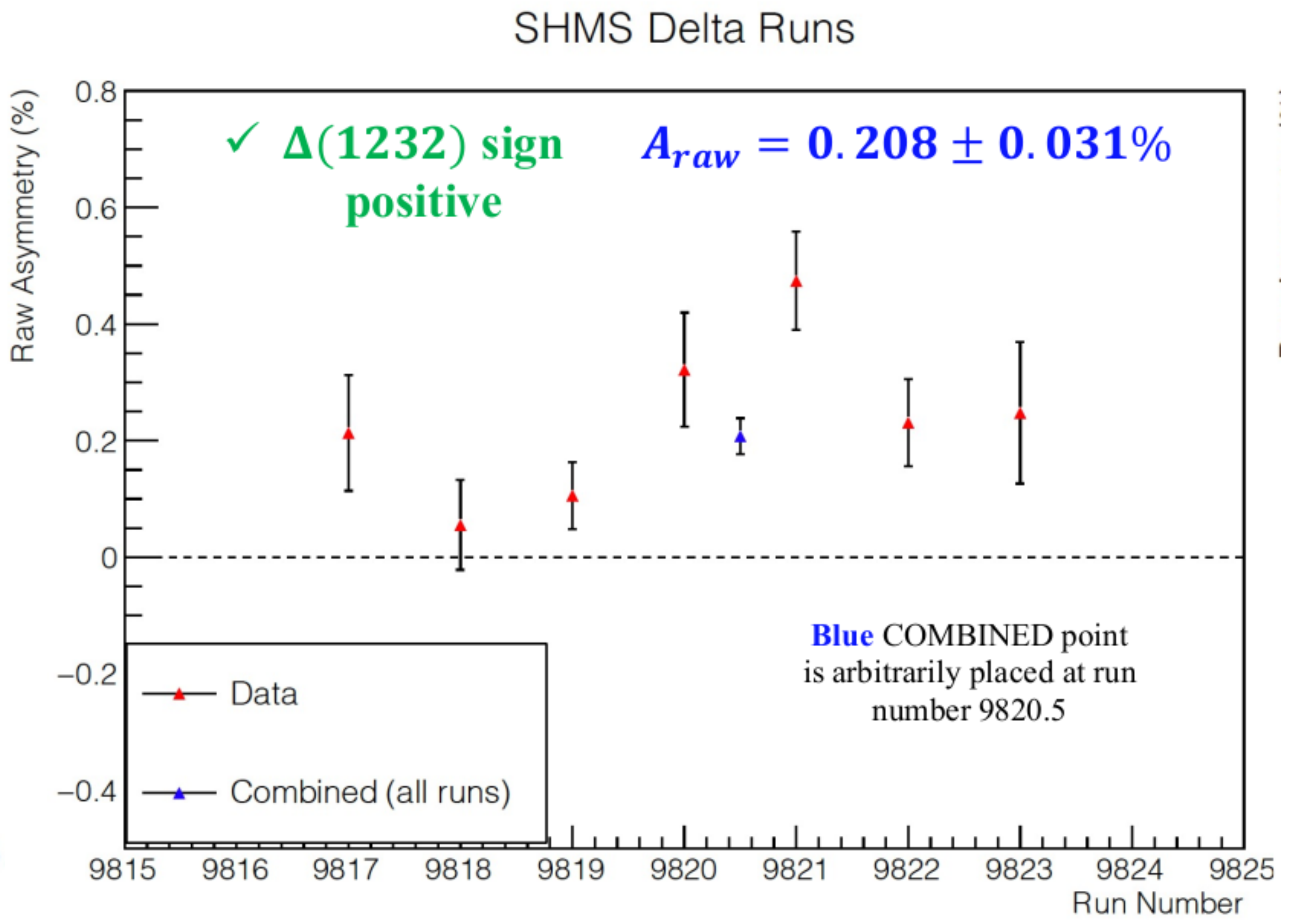


Figure credit: A. Tadepalli