A measurement of the Neutron Spin Structure at High-x in the 12 GeV Era

William Henry
On behalf of the E12-06-110 Collaboration

June 13th, 2022

JSA

Jefferson Lab
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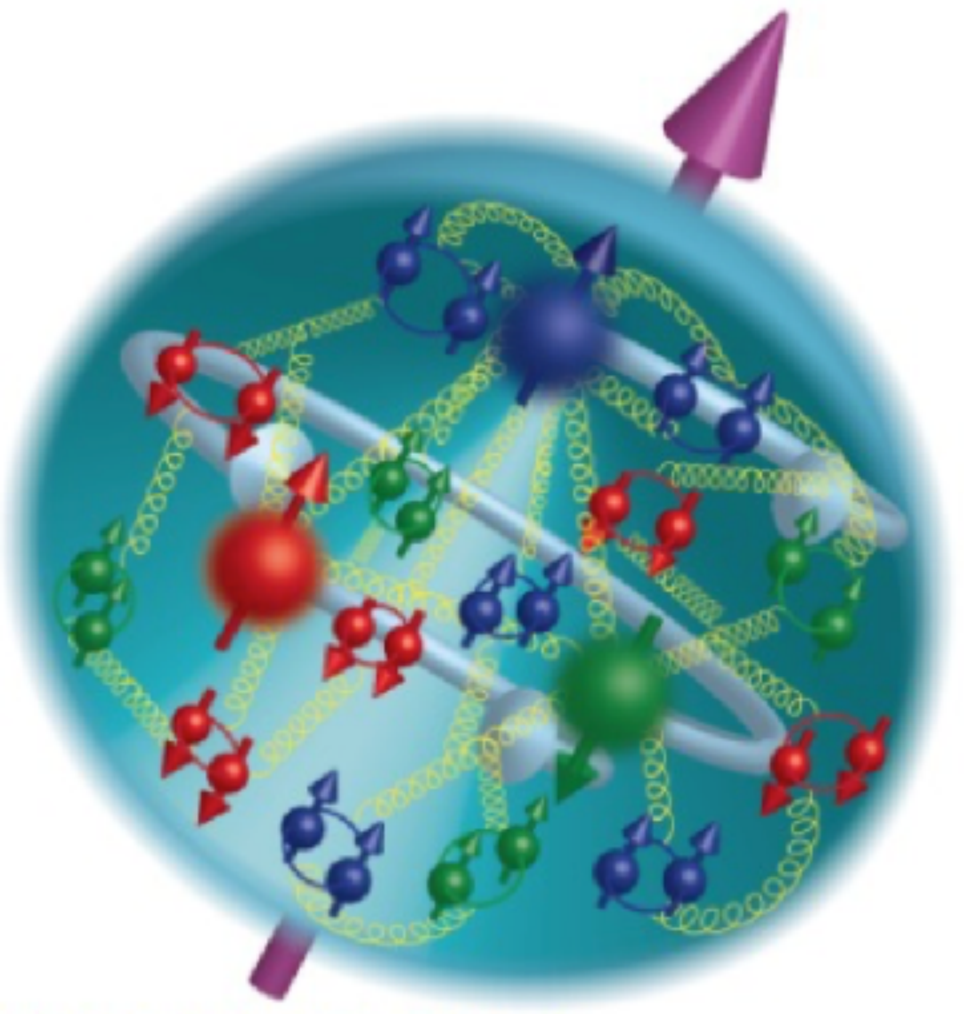
Nucleon Spin Crisis and Sum Rule



Nucleon spin sum rule:
(Jaffe & Manohar)

$$\frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark intrinsic spin}} + \underbrace{\Delta G}_{\text{gluon intrinsic spin}} + \underbrace{L_q}_{\text{quark OAM}} + \underbrace{L_g}_{\text{gluon OAM}}$$

- Ellis and Jaffe (1974) predicted a ~58% contribution from the valence quark intrinsic spin which early SLAC experimental data supported.
- The EMC collaboration (1988), and later SLAC E142, E143, and CERN's SMC found ΔΣ to be 12% ± 17%
- The disagreement between experiment and theory is know as the *Nucleon Spin Crisis*
- Current measurements show ΔΣ = 30% - 35% [22] and ΔG= ~20% [25]
-

Accessing Spin Structure: Polarized DIS cross sections

U: $$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\left(\frac{2}{M}F_1(x,Q^2)\sin^2\left(\frac{\theta}{2}\right) + \frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$

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

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

Quark Parton Model:

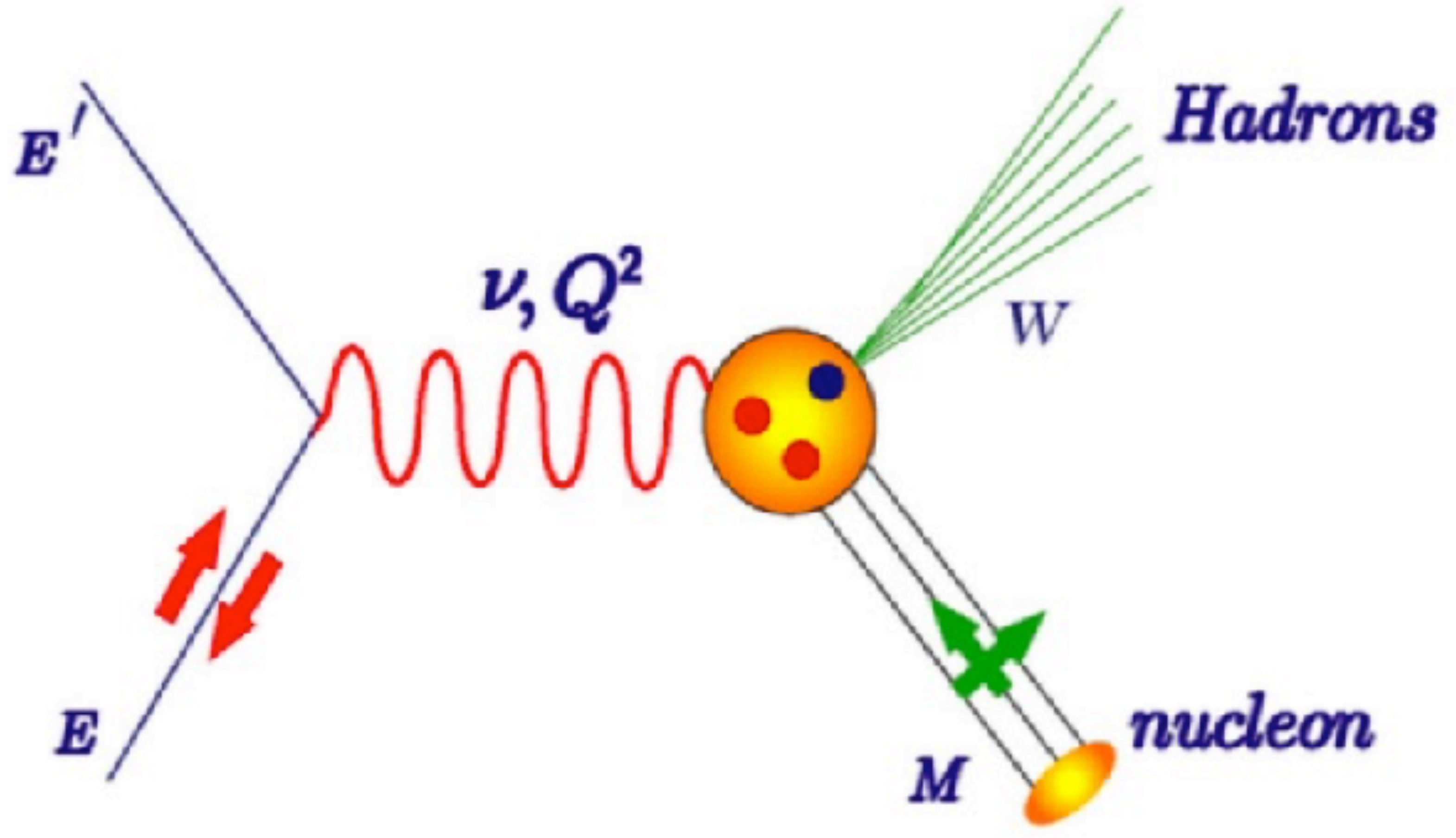
- $F_1(x) = \frac{1}{2}\Sigma e_i^2[q_i^{\uparrow}(x) + q_i^{\downarrow}(x)]$

where $q_i(x) = q_i^{\uparrow}(x) + q_i^{\downarrow}(x)$ is the probability of finding a quark q of flavor i with momentum fraction x

- $g_1(x) = \frac{1}{2}\Sigma e_i^2[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)]$

where $\Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$ is the sum over the helicity distribution for a quark q of flavor i with momentum fraction x

$Q^2 = 4EE'\sin^2(\theta/2)$	4-momentum transfer
$\nu = E - E'$	Energy transfer
$W = M^2 + 2M\nu - Q^2$	Final state hadronic mass
θ	Scattering angle
$x = Q^2/2M\nu$	Quark fractional momentum



- $g_2(x)$ describes the **transverse** spin structure of the nucleon, which vanishes in the QPM (quark-gluon correlations)

Credit Slide: Melanie Cardona (Rehfuss)

Accessing Spin Structure: polarized DIS cross sections

See my talk Thursday at The Hall A/C Collaboration meeting

U: $$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\left(\frac{2}{M}F_1(x,Q^2)\sin^2\left(\frac{\theta}{2}\right) + \frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$

This talk

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

Next talk by Junhao Chen

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

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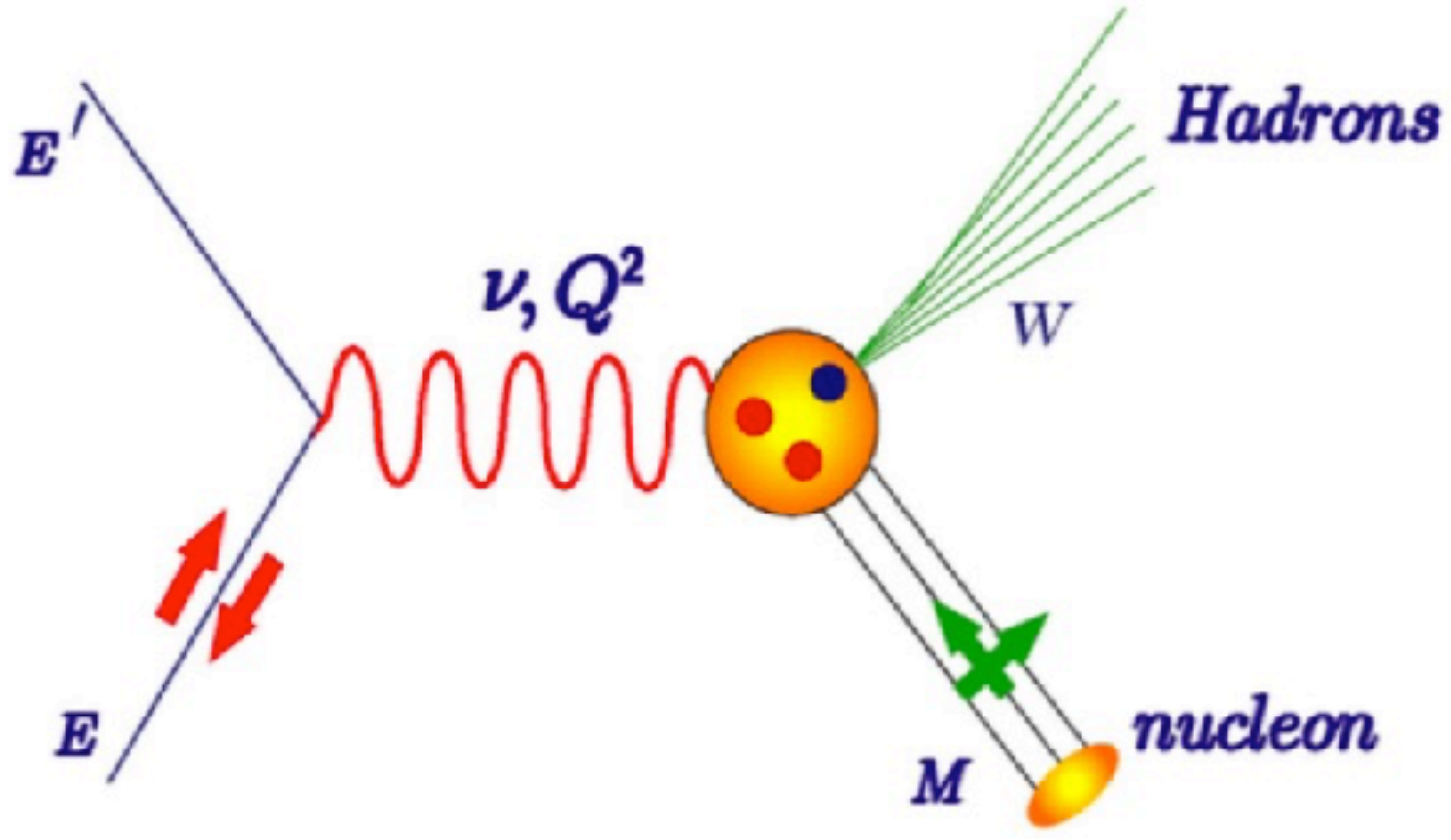
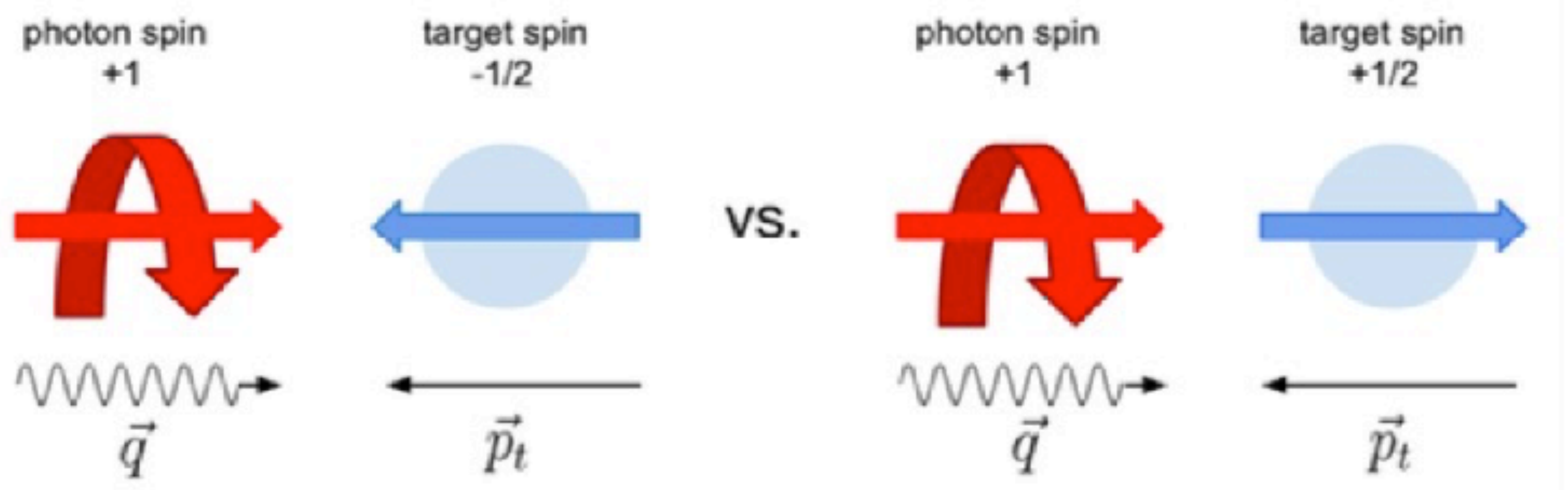


- $g_2(x)$ describes the **transverse** spin structure of the nucleon, which vanishes in the QPM (quark-gluon correlations)

Credit Slide: Melanie Cardona (Rehfuss)

The Observable A1: The Virtual Photon-nucleon Asymmetry



Anti-parallel spins
$h = 1 - \frac{1}{2} = \frac{1}{2}$

Parallel spins
$h = 1 + \frac{1}{2} = \frac{3}{2}$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

where $\gamma^2 = (2Mx)^2/Q^2$ and M = nucleon mass

For large Q^2, $\boxed{A_1 \approx g_1(x)/F_1(x)}$

- Our wide Q^2 range (over 10 GeV^2) will allow for further study of A_1's **Q^2 −dependence @ a given x value in the valence region**

- We need a transverse and longitudinal component to reconstruct the asymmetry along the virtual photon direction:

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

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

- $\sigma^{\downarrow\Uparrow}(\sigma^{\uparrow\Uparrow})$ is the cross section for a **longitudinally polarized target** with the electron spin aligned antiparallel (parallel) to the target spin

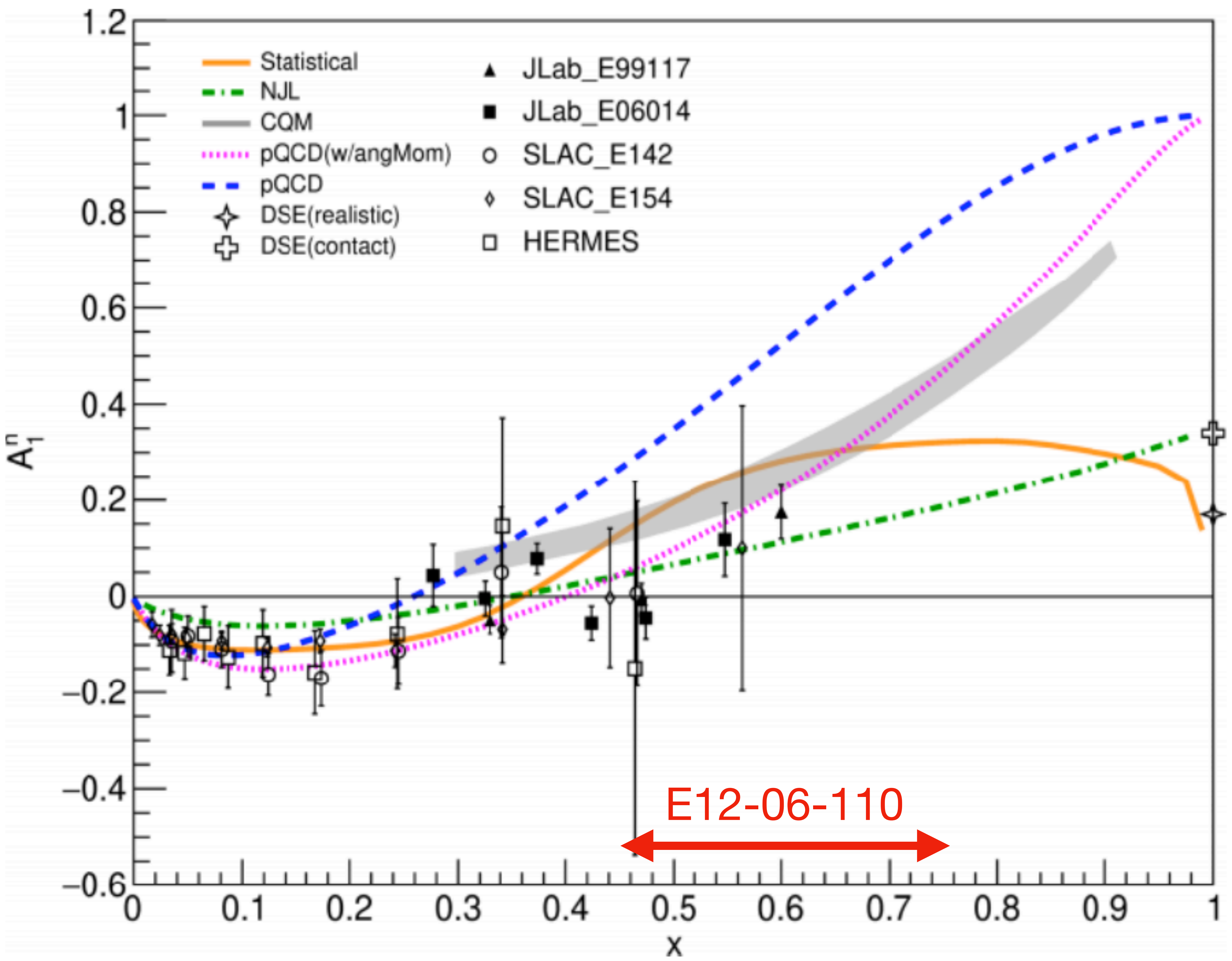
- $\sigma^{\downarrow\Rightarrow}(\sigma^{\uparrow\Rightarrow})$ is the cross section for a **transversely polarized target** with the electron spin aligned antiparallel (parallel) to the beam direction

- $\eta, \xi,$ and d are kinematic factors, and D depends on the ratio of the longitudinal and transverse virtual-photon absorption cross sections $R = \sigma_L/\sigma_T$

Slide Credit: Melanie Cardona (Rehfuss)

A1n at High-x: Predictions from various models

Existing World Data



The **valence domain** ($x > 0.5$):

- Free of sea effects ($q\bar{q}$ pairs and hard gluons)
- Spin is assumed to be carried by the valence quarks

→ A poorly-explored region due to low rates at high x (need high luminosity, Hall C's 12 GeV-era polarized ^{3}He target reached $2\text{x}10^{36}$ $\text{cm}^{-2}\text{s}^{-1}$!)

- **Which models will our data agree with**? How much of a role does L_q play in forming the nucleon spin?

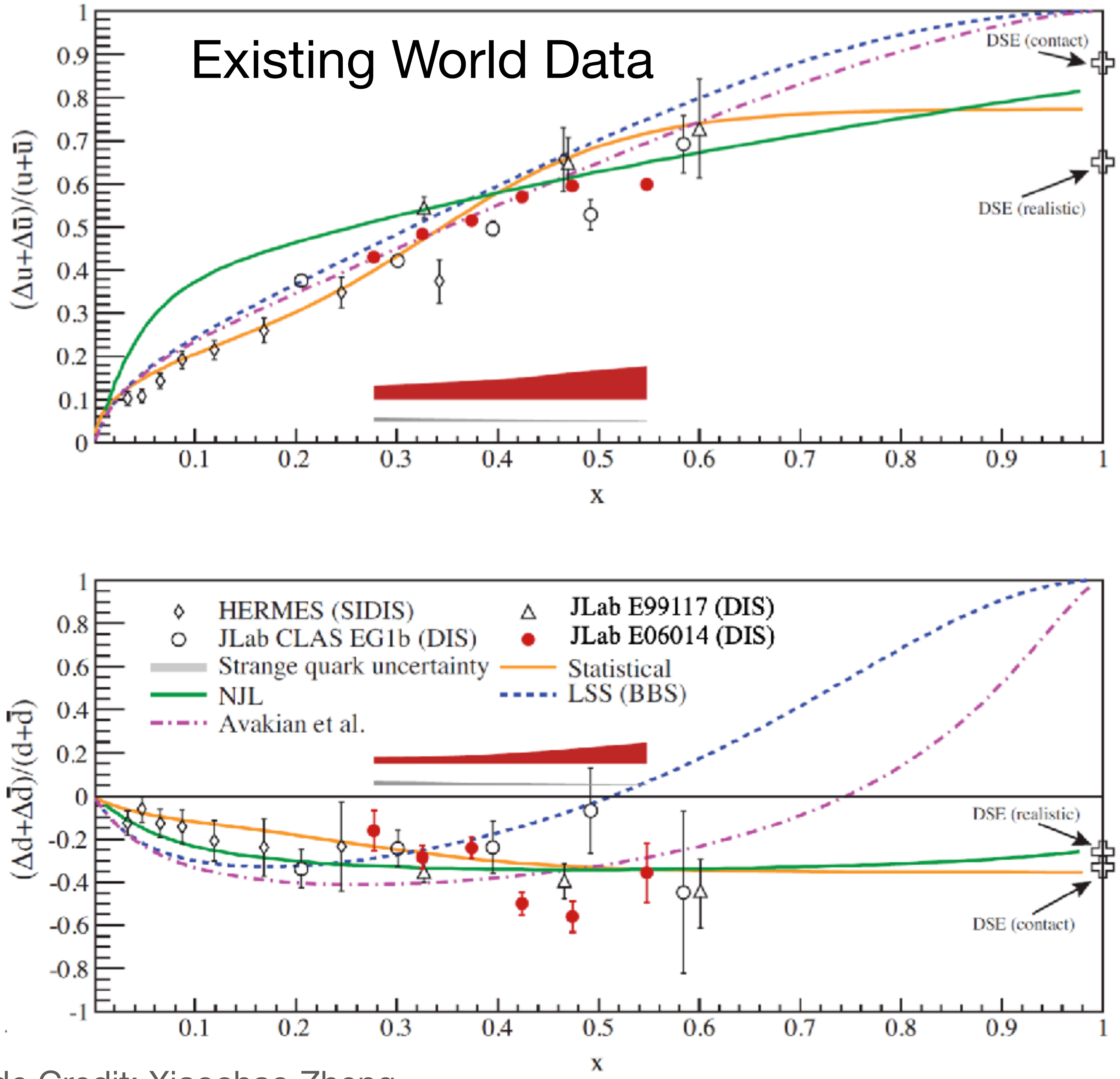
	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

Table 1: Selected predictions for the $x = 1$ value of the indicated quanti-

C. Roberts, R.Holt, S. Schmidt, Phys. Lett. B 727 (2013) 249. arxiv: 1308.1236

Credit Slide: Melanie Cardona (Rehfuss)

Polarized PDFs at High-x: Predictions from various models



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

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

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

D. Parno et al.

PRL 113 (2014) 2, 022002, 1404.4003

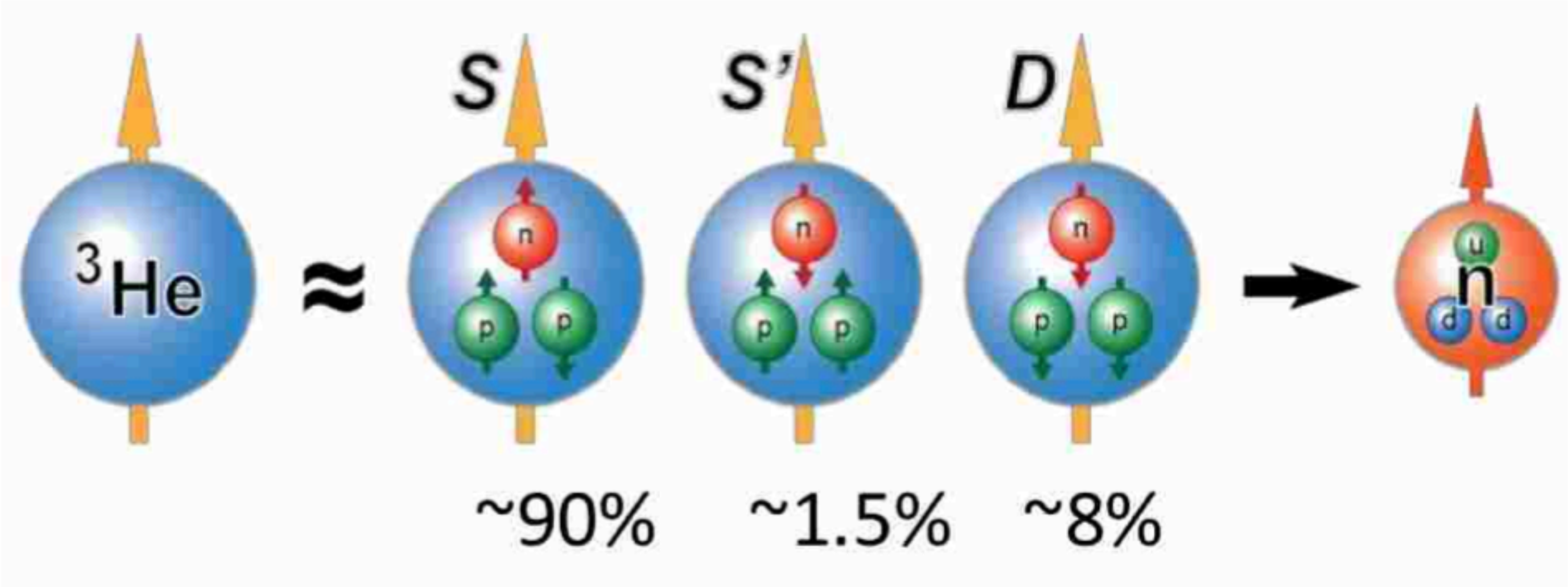
X. Zheng et al.

PRL 92 (2004) 012004, arXiv: nucl-ex/0308011;

PRC 70 (2004) 065207, arXiv: nucl-ex/0405006.

Slide Credit: Xiaochao Zheng

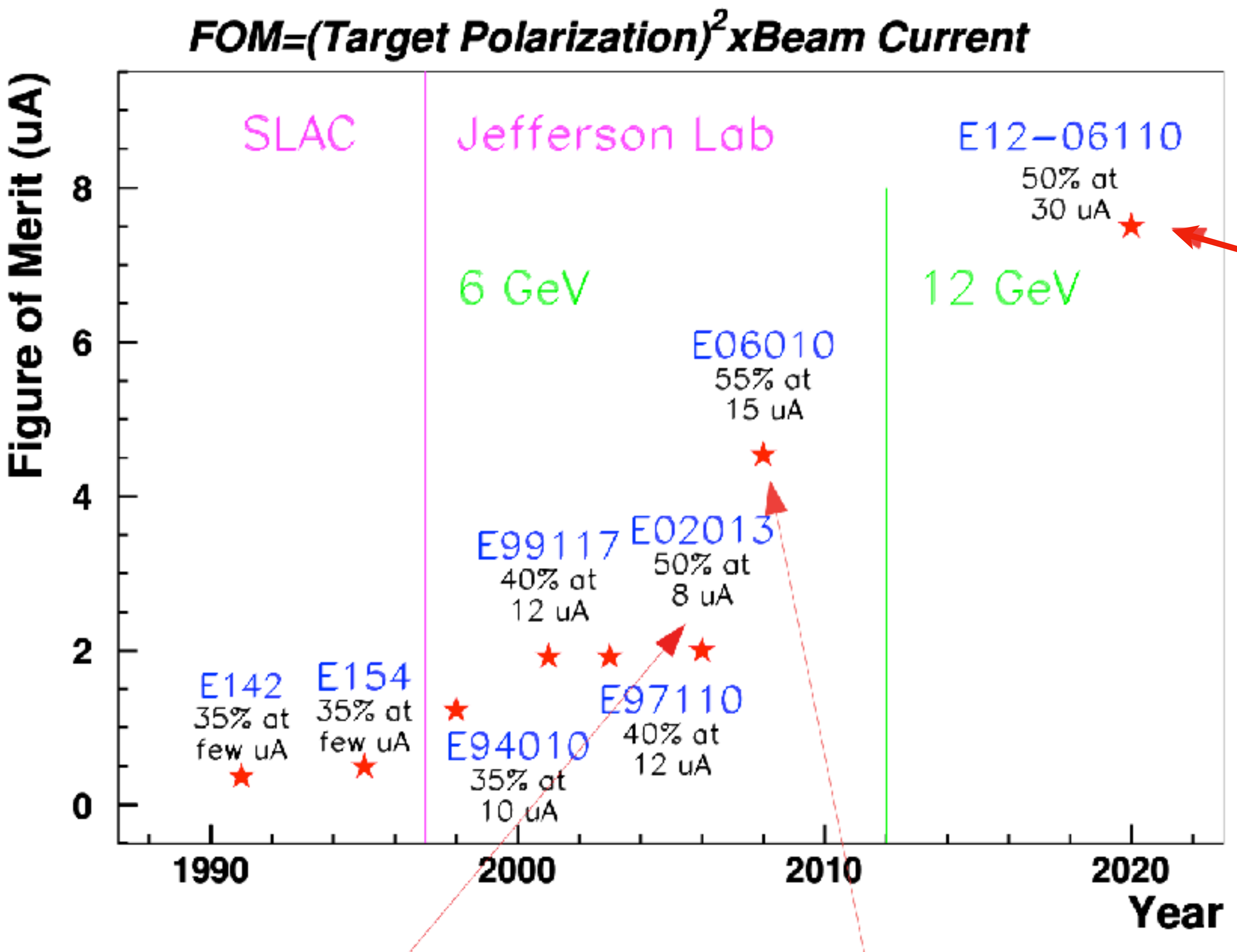
Polarized Helium 3 as an effective polarized neutron target



- Polarized target for study the spin structure of nucleon.
- Free neutron mean lifetime: 880.2 s.
- The unpaired neutron carries the majority of the ^{3}He nucleus polarization.
- Polarized ^{3}He is a good effective polarized neutron target.

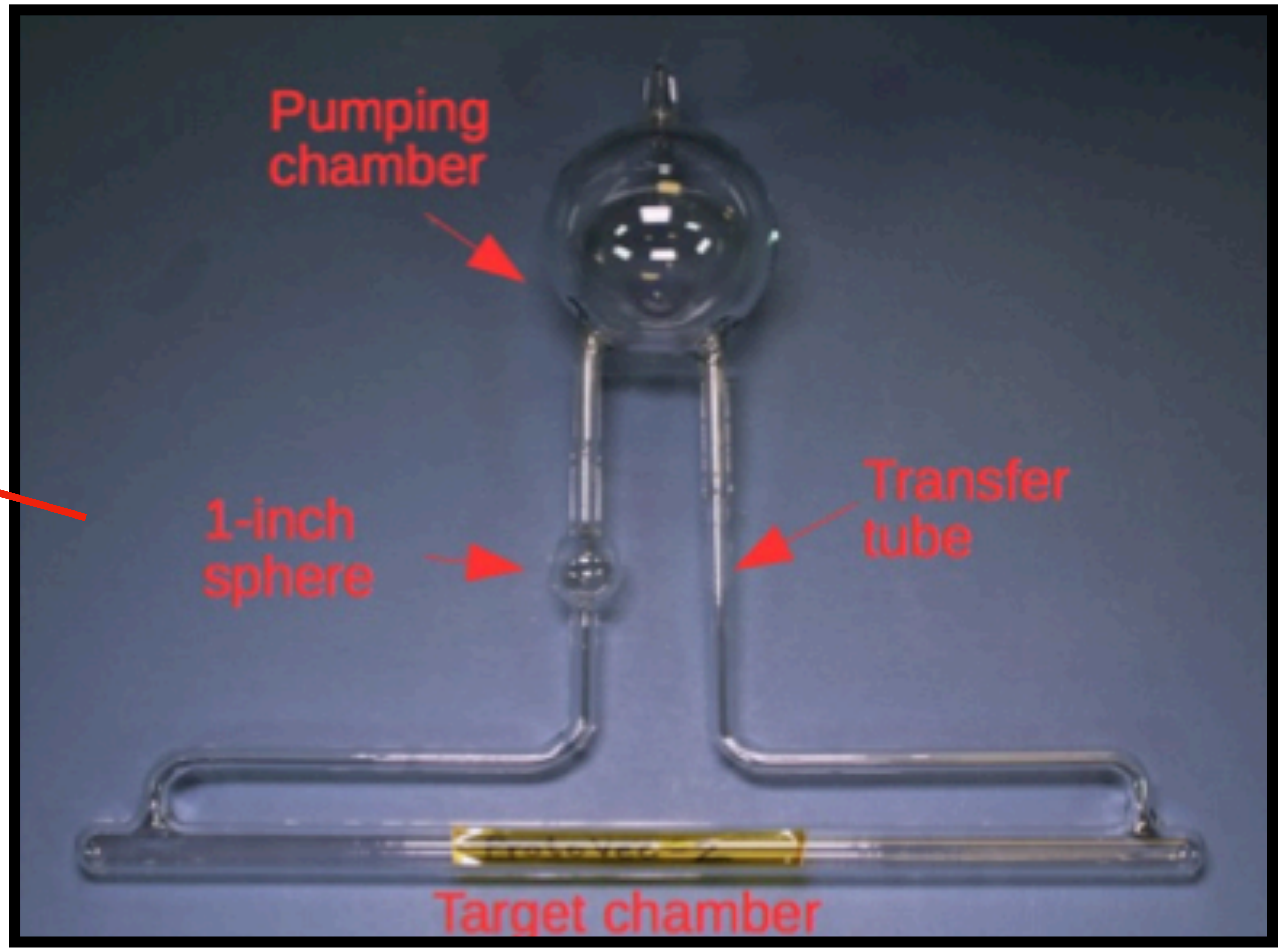
Slide Credit: Mingyu Chen

12 GeV Polarized Helium 3 Target



G_E^n (E02-013):
Started to use Rb/K hybrid alkali cell.

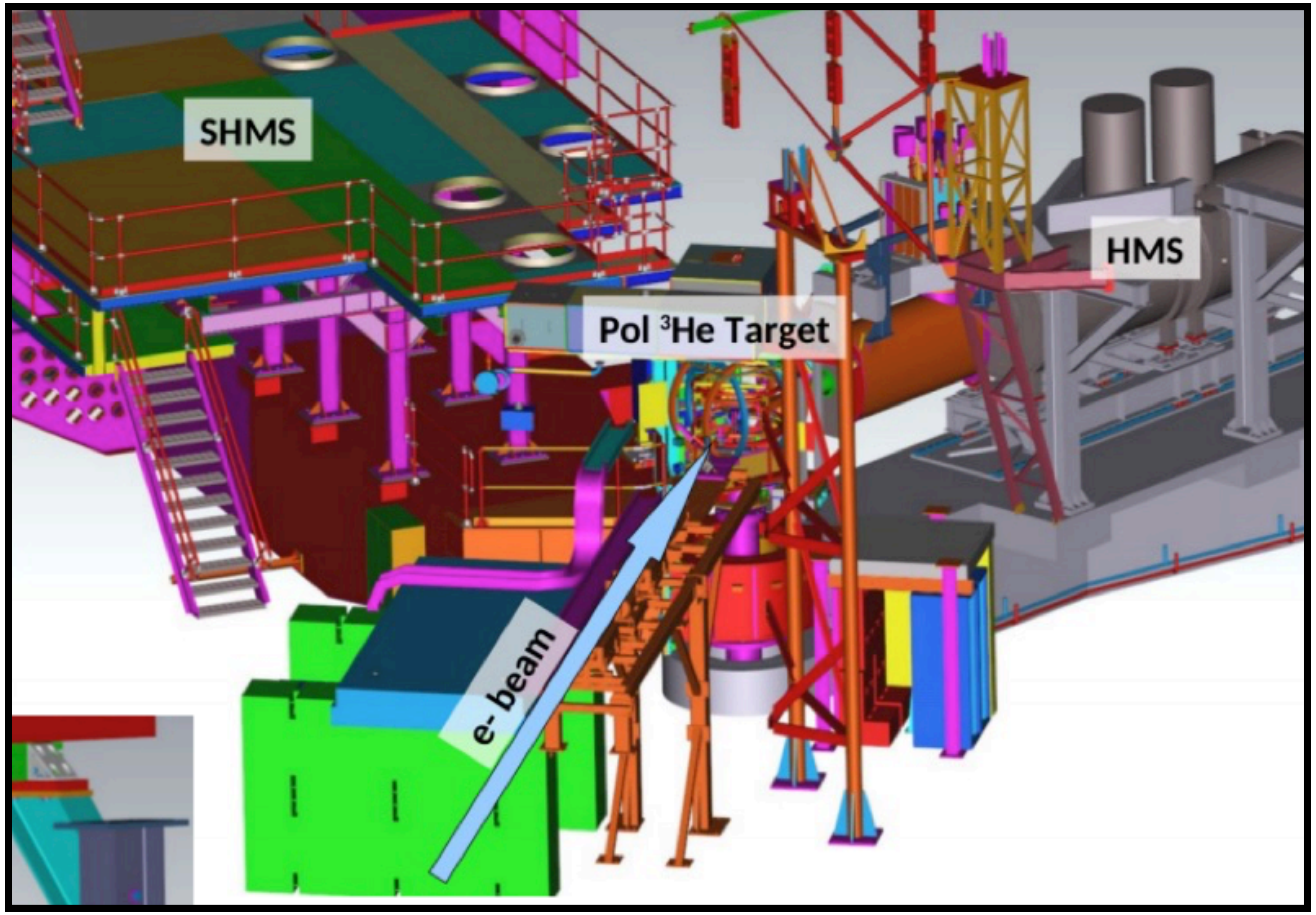
Transversity (E06-010):
Started to use narrow band laser.



- Target Chamber length: 40 cm
- Luminosity: ~ $2.2 \times 10^{36} cm^{-2}s^{-1}$
- Convection cell as opposed to 6 GeV diffusion cell
- GEn-II in Hall A will expects another factor of two increase in FOM

E12-06-110 in Hall C: Experimental Setup

- Experiment ran from January 12th to March 13th, 2020
- Polarized Helium-3 gas target
- 10.4 GeV Polarized e- beam
- Inclusive measurement, detected scattered e-
- SHMS: 30°; $P_{Central}$=2.6 & 3.4 GeV
- HMS: 30 °; $P_{Central}$=2.9 & 3.5 GeV
- Elastic and Δ(1232) asymmetry measured to check sign of $P_{Beam}P_{Target}$



Helium 3 Target Polarization

- Target polarization was routinely measured using NMR and pNMR measurments.
- EPR measurements provided absolute measurements and was used to calibrate NMR and pNMR measurements.
- More details in next talk by Junhao Chen

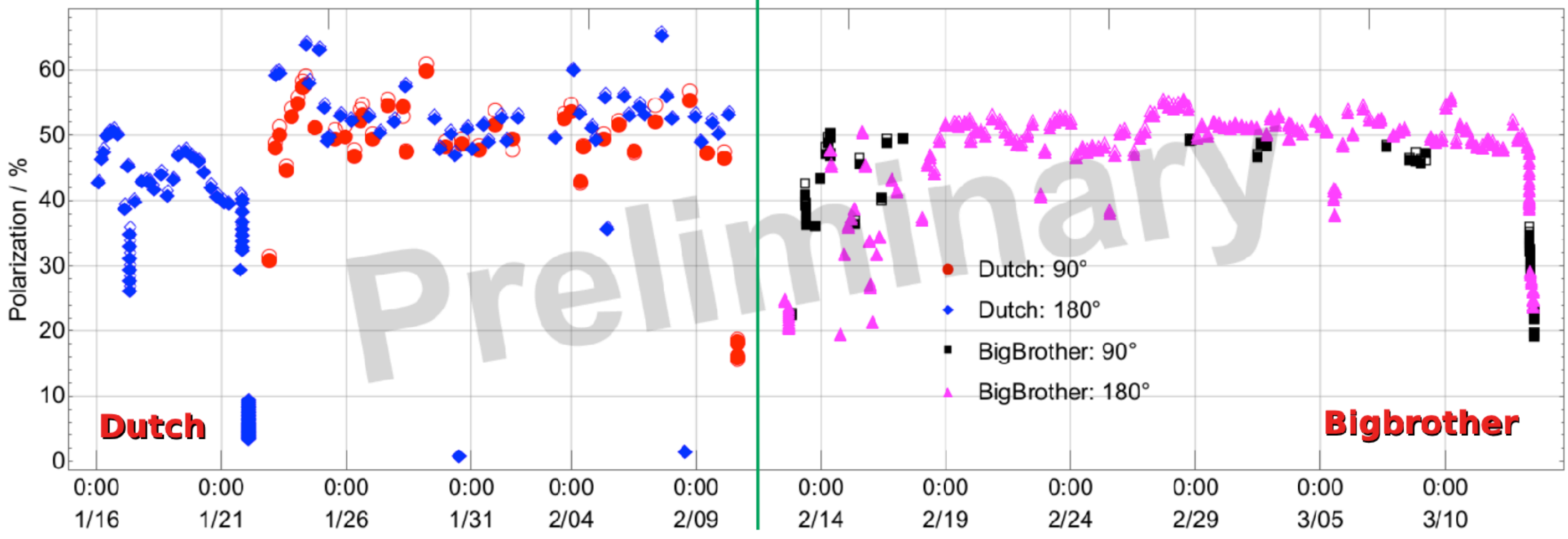
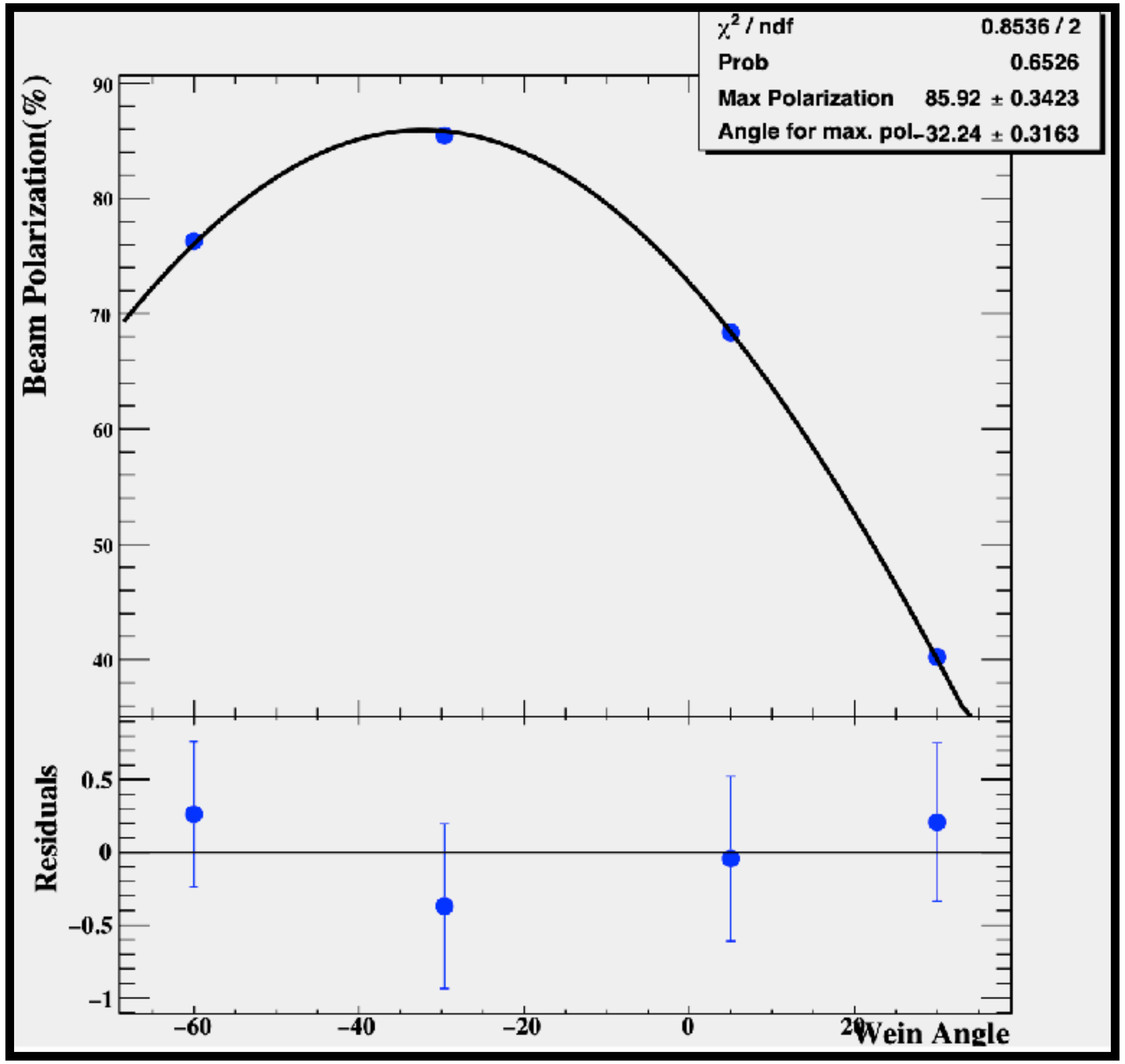


Figure Credit: Junhao Chen

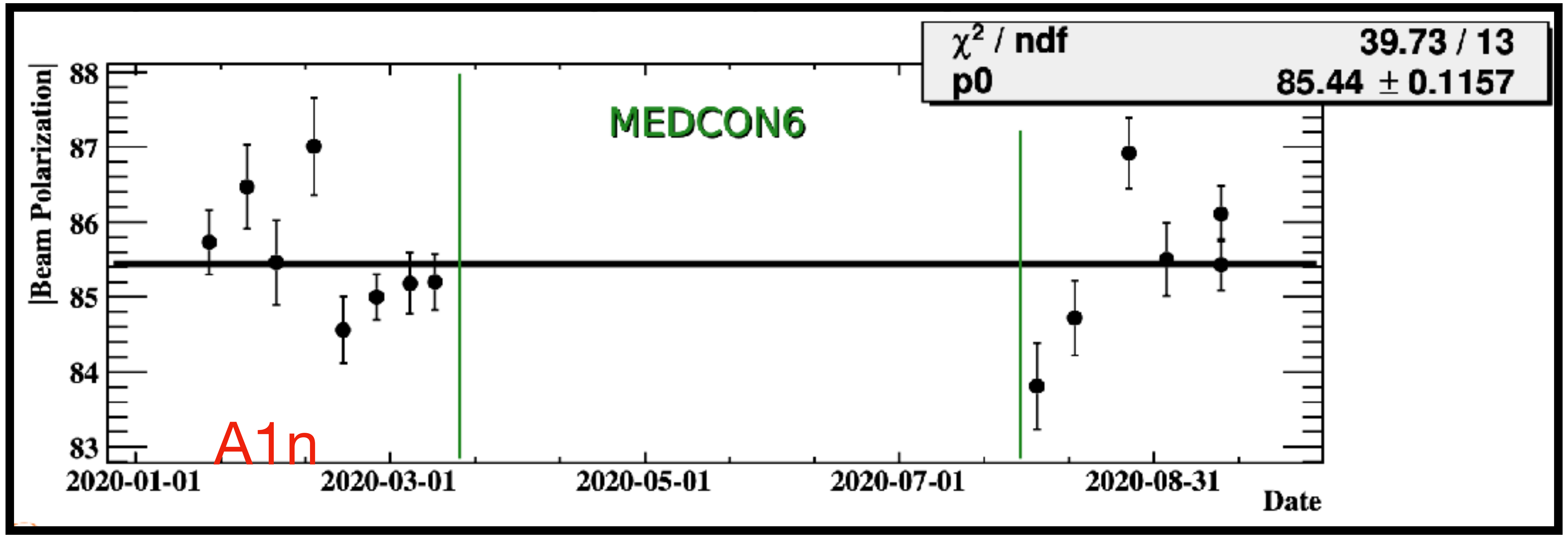
Beam Polarimetry

Hall C Spin Dance



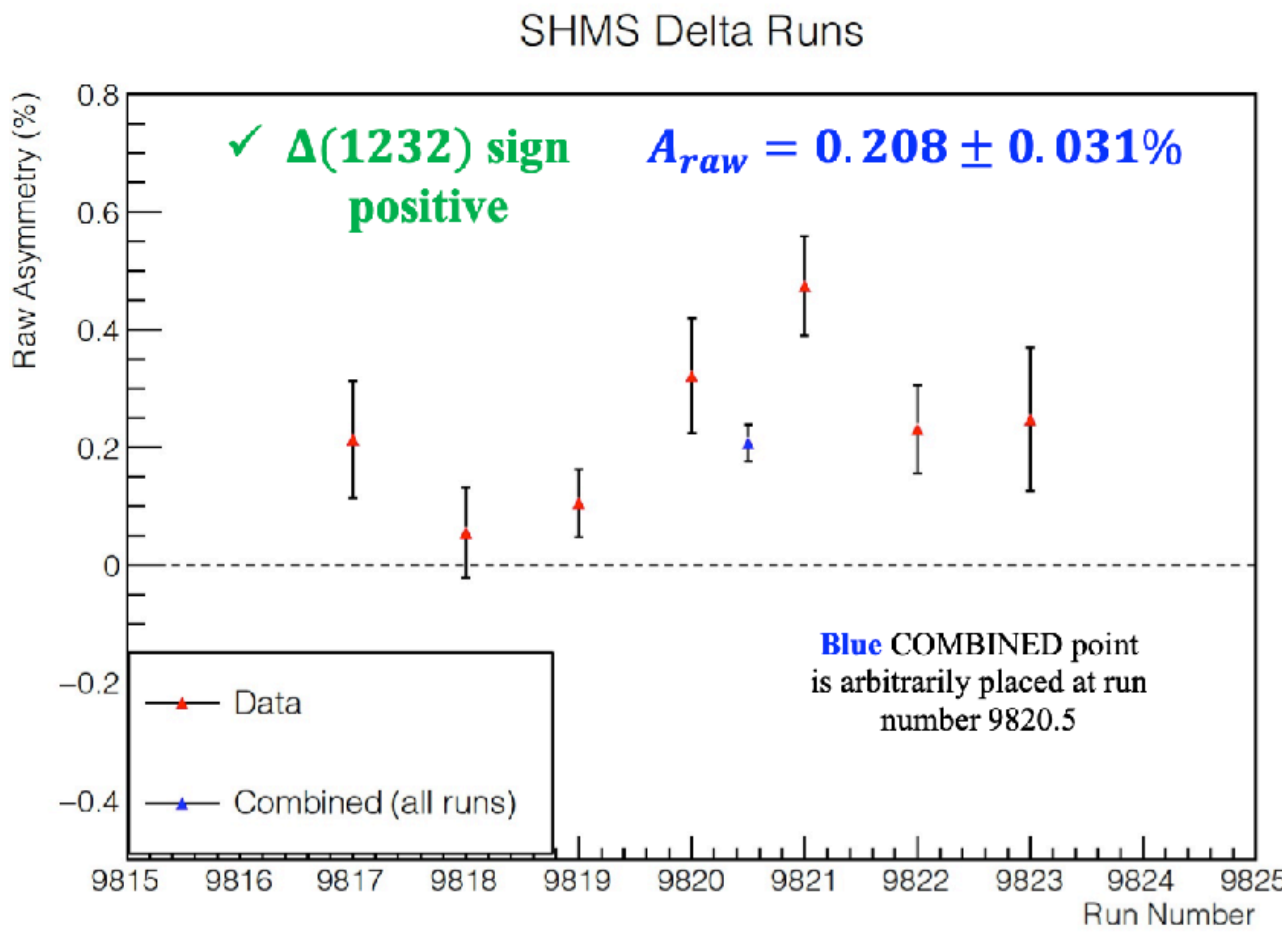
- Beam polarization measured using the Møller polarimeter
- Measurements were taken approximately once per week. One shift required per measurement.
- First time in 12 GeV era polarized beam was required in Hall C
- Møller analysis complete (3% total relative error)

Moller Measurements for A1n/d2n

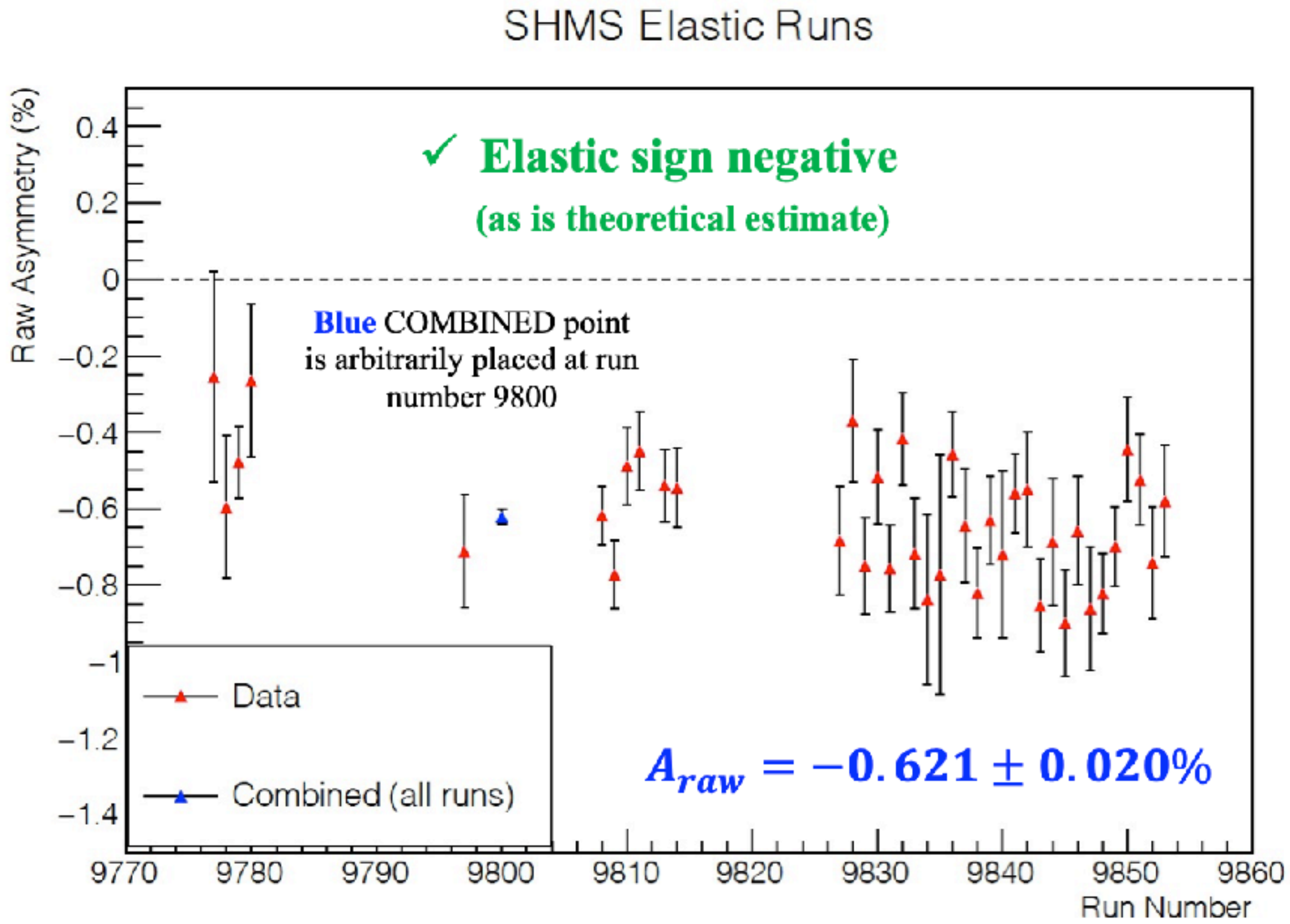


Beam and Target Polarization Sign Convention Checks

- Elastic and Δ(1232) asymmetry measured to check sign of $P_{Beam}{*}P_{Target}$
- Target spin direction set by holding field (90° or 180°)
- “Slow” reversal of electron polarization by IHWP and Wein-Flip



Transverse Target Polarization



Longitudinal Target Polarization

Figure Credit: Melanie Cardona (Rehfuss)

Preliminary A_1 (3He) Result

$$A_{raw} = \frac{\frac{N^+}{Q^+\eta^+} - \frac{N^-}{Q^-\eta^-}}{\frac{N^+}{Q^+\eta^+} + \frac{N^-}{Q^-\eta^-}},$$

$N^{\pm} \sim$ helicity-sorted counts
$Q^{\pm} \sim$ integrated beam charge
$\eta^{\pm} \sim$ DAQ live-time

$$A_{phys} = \frac{A_{raw}}{P_b P_t f_{N_2}}$$

$P_b \sim$ Beam polarization ~ 85%
$P_t \sim$ ^{3}He target polarization ~ 50%
$f_{N_2} \sim$ Nitrogen dilution factor ~ 0.92

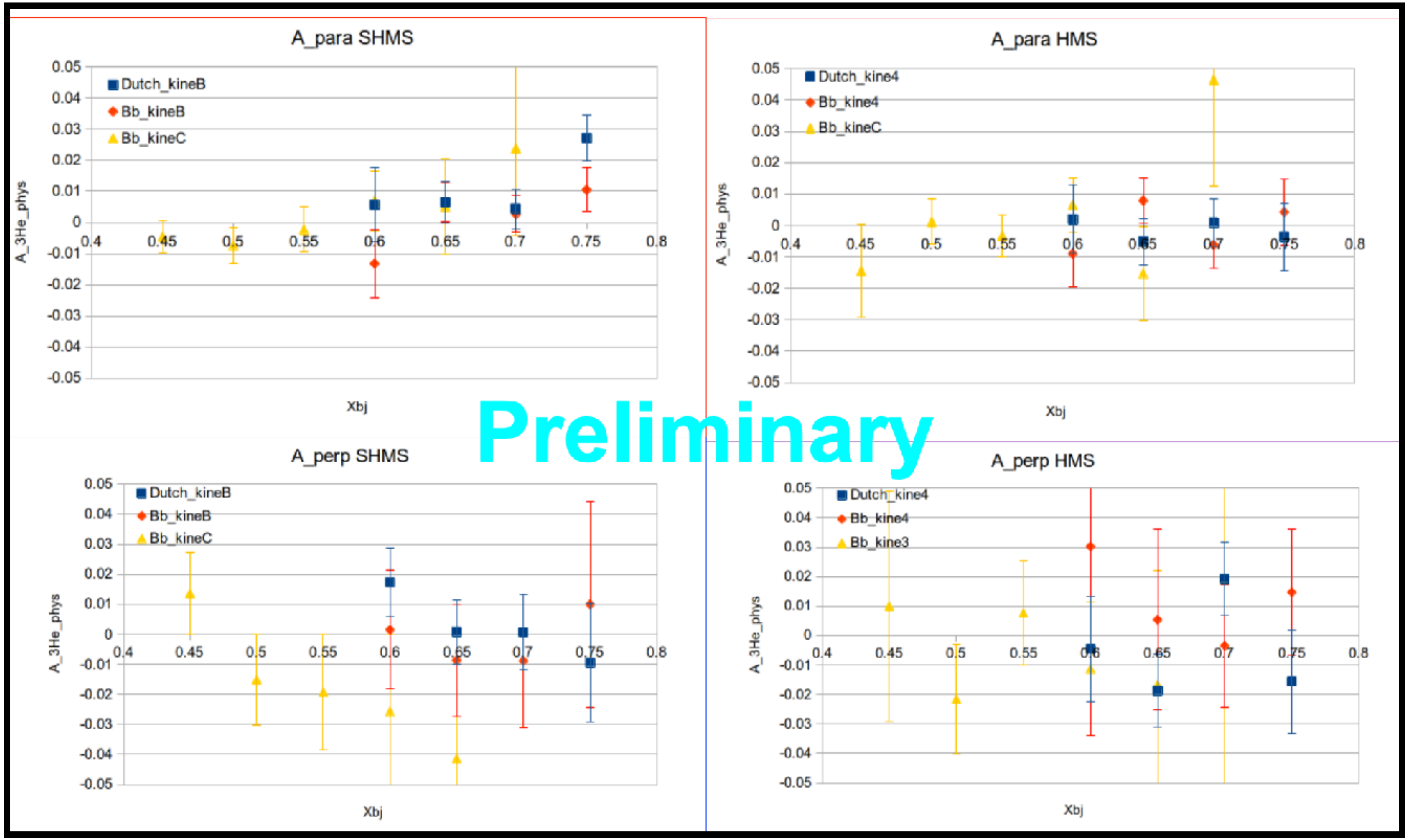


Figure Credit: Mingyu Chen

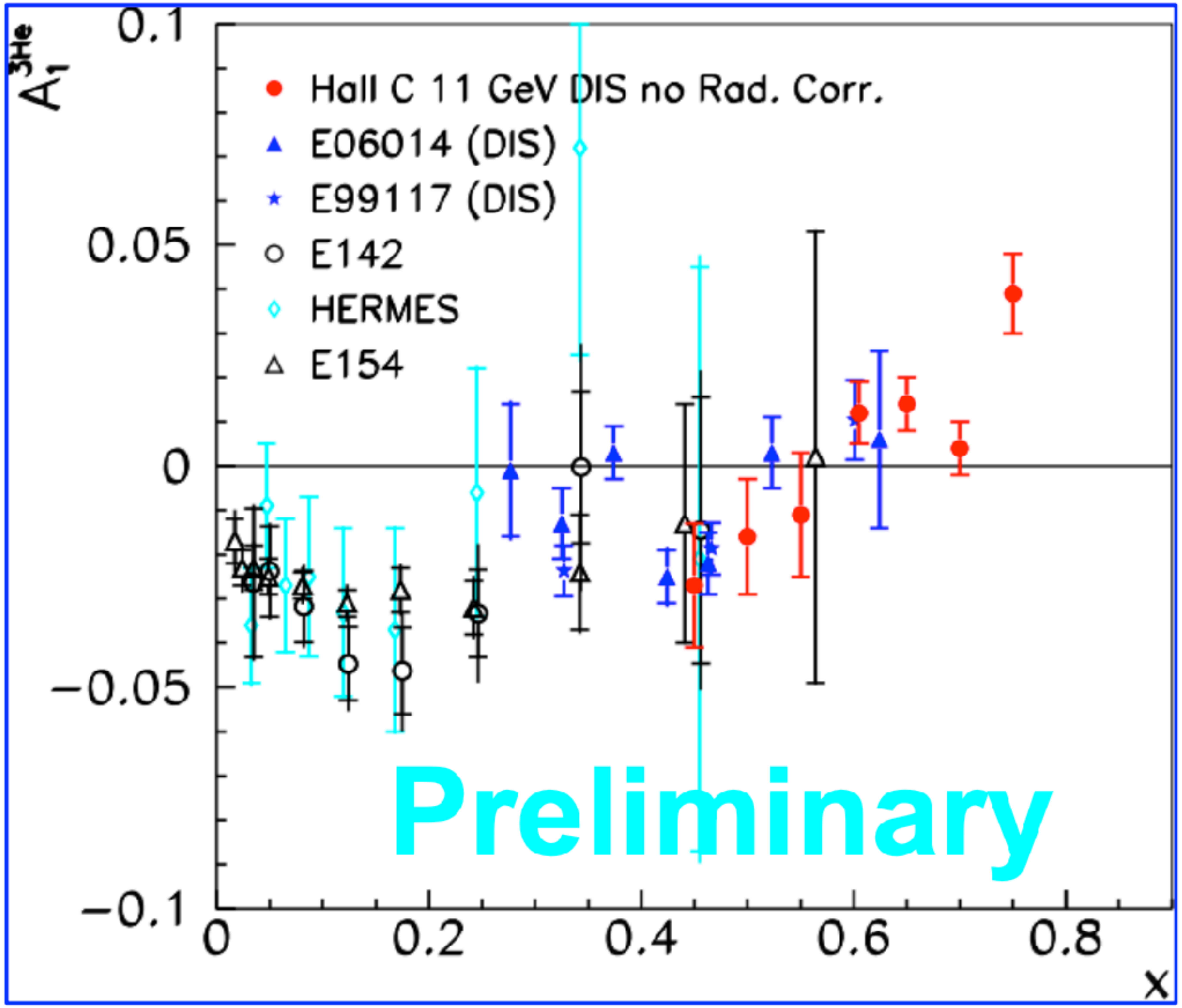
Preliminary A_1 (3He) Result

These are **without** radiative corrections

statistical uncertainties only

Next to do: Radiative corrections, then nuclear corrections:

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



Slide Credit: Xiaochao Zheng

Summary and Acknowledgments

E12-06-110 is a high-impact experiment on nucleon spin-structure

- The measurements of $\boldsymbol{A_1^n}$ **at high** $\boldsymbol{x}$ allow us to test fundamental predictions of the nucleon spin structure
- Combined with precision proton data, the high-precision neutron data will allow us to extract polarized-to-unpolarized quark PDF ratios distributions (Δq) and **spin-flavor distributions** ($\Delta u/u$) and ($\Delta d/d$)

The results will help answer questions like,
How much of a role does $\boldsymbol{L_q}$ play?
(to what degree are the quarks' spin aligned parallel to the nucleon spin?)

People

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

PhD Candidates Spokespeople

Institutions

A.I. Alikhanian National Science Laboratory; Argonne National Laboratory; Artem Alikhanian National Laboratory (AANL).; Christopher Newport University; Duke University; Florida International University; Hampton University ; James Madison University ; Jefferson Lab; Kent State University; Mississippi State University; Ohio University; Old Dominion University; Rutgers University; Syracuse University; Temple University; The College of William and Mary; Univ. of Ljubljana; University of Connecticut; University of Kentucky; University of Kentucky; University of New Hampshire; University of Regina; University of Tennessee; University of Virginia; University of Virginia; University of Zagreb

Slide Credit: Melanie Cardona (Rehfuss)