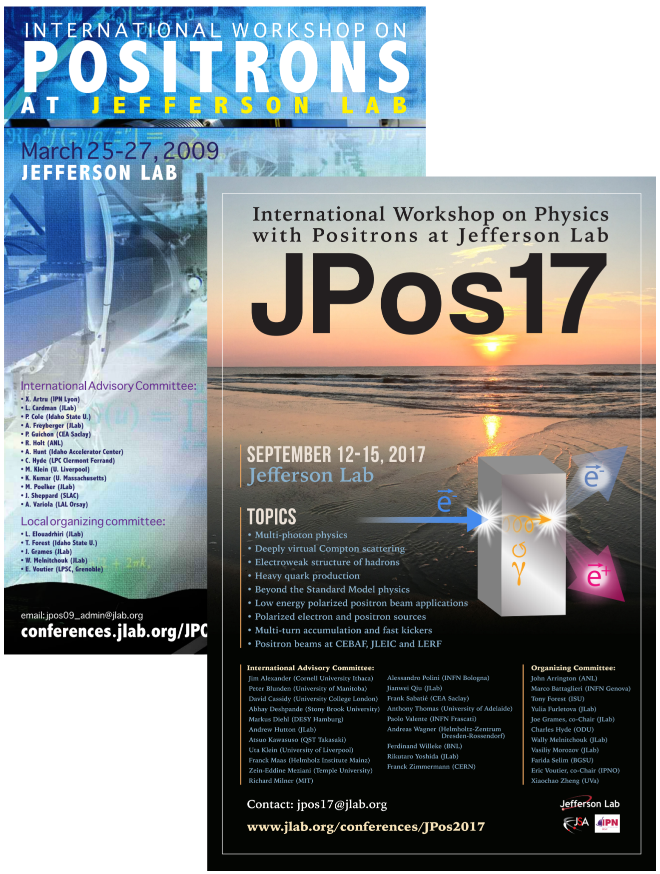
Electroweak Physics with SoLID and a future positron beam at JLab

Xiaochao Zheng, Univ. of Virginia

June 15th, 2022



Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

https://arxiv.org/abs/2007.15081

An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab

Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

https://arxiv.org/abs/2103.12555

Accessing weak neutral-current coupling g_{AA}^{eq} using positron and electron beams at Jefferson Lab

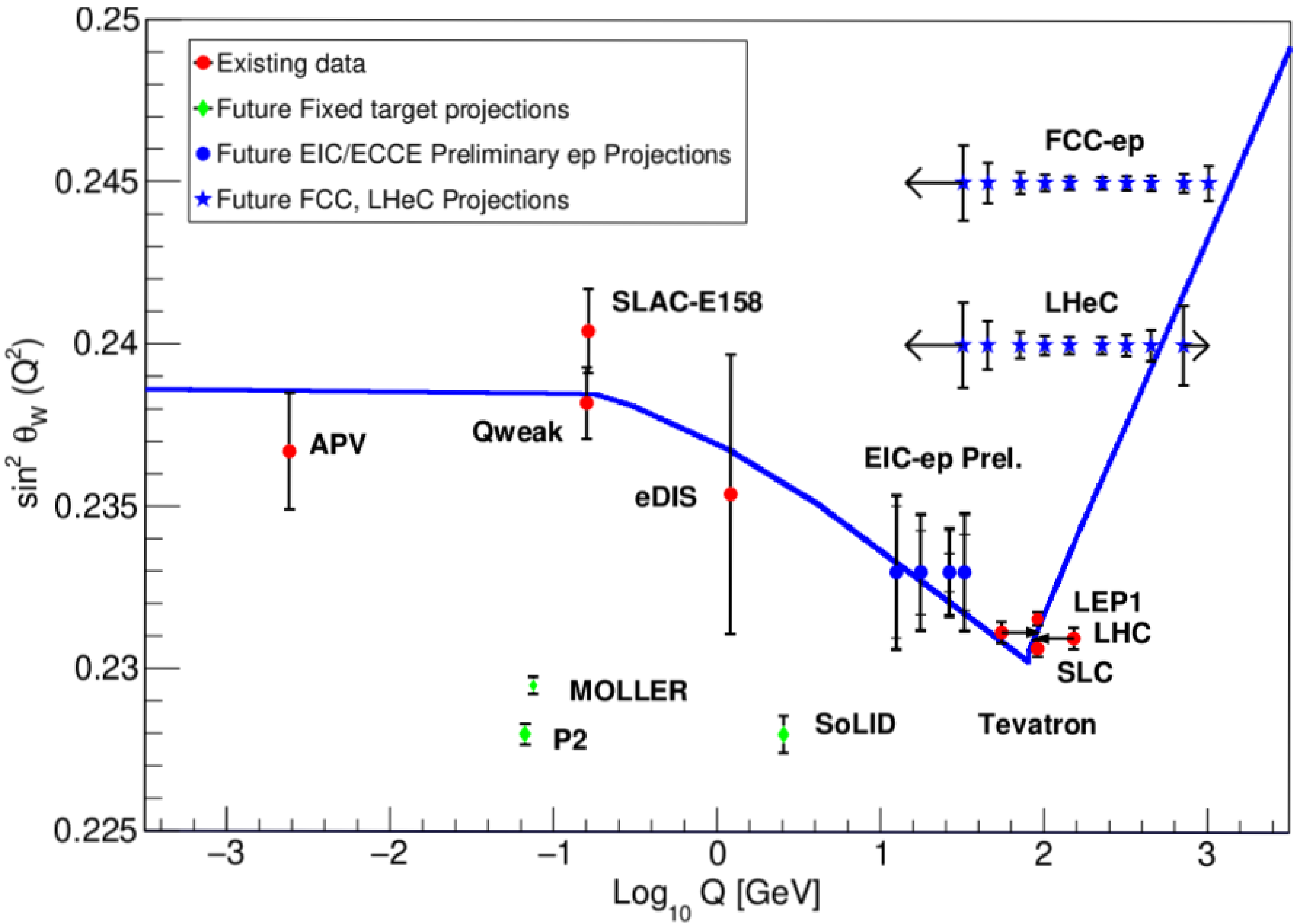
(A New Proposal to Jefferson Lab PAC-49)

Measurement of the Asymmetry $A_d^{e^+e^-}$ between $e^+ - ^2$H and $e^- - ^2$H Deep Inelastic Scattering Using SoLID and PEPPo at JLab

May 24, 2021

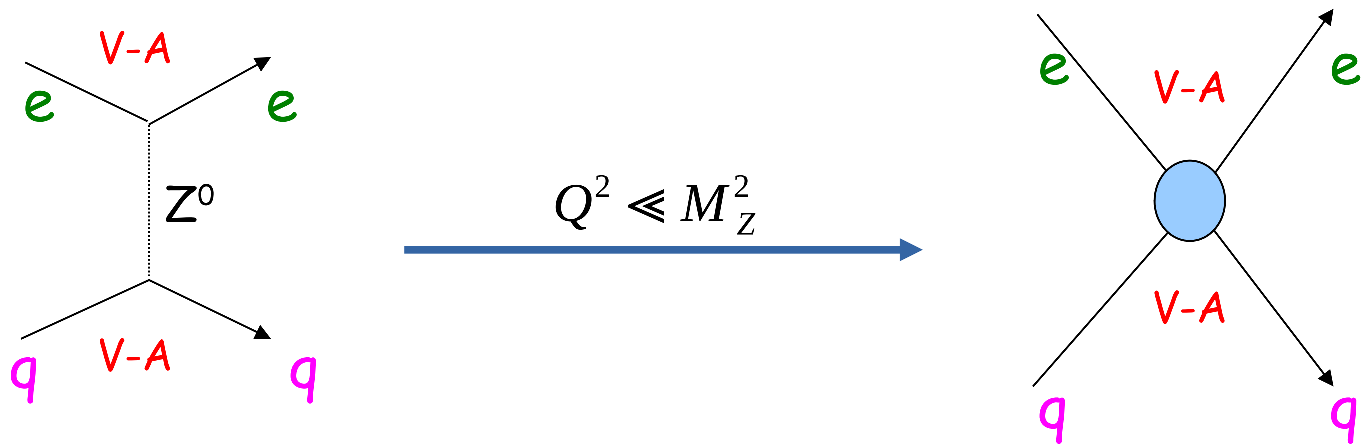
~~(pending approval from JLab Hall A and SoLID Collaborations)~~

The Landscape of Electroweak Physics Study



EIC projections from arxiv.org/2204.07557 [hep-ph]
LHeC projection (60GeV x 7 TeV, ~1000fb^{-1}) from EPJC 80 (2020) 9, 831 arxiv.org/2007.11799;
FCC-ep projections: priv. comm. D. Britzger
(points with uncertainties comparable to or smaller than Qweak are shown, full range shown as arrows)

Neutral-Current Effective Couplings in (Low Energy) Electron Scattering



$$L_{NC}^{lq} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{0q} \bar{l} \gamma^\mu l \bar{q} \gamma_\mu q + C_{1q} \bar{e} \gamma^\mu \gamma_5 l \bar{q} \gamma_\mu q + C_{2q} \bar{e} \gamma^\mu e \bar{q} \gamma_\mu \gamma_5 q + C_{3q} \bar{l} \gamma^\mu \gamma_5 l \bar{q} \gamma_\mu \gamma_5 q \right]$$

VV (identical to γ) AV, VA (parity-violating) AA

$$C_{1u} = 2 g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \qquad C_{2u} = 2 g_V^e g_A^u = -\frac{1}{2} + 2\sin^2(\theta_W) \qquad C_{3u} = -2 g_A^e g_A^u = \frac{1}{2}$$

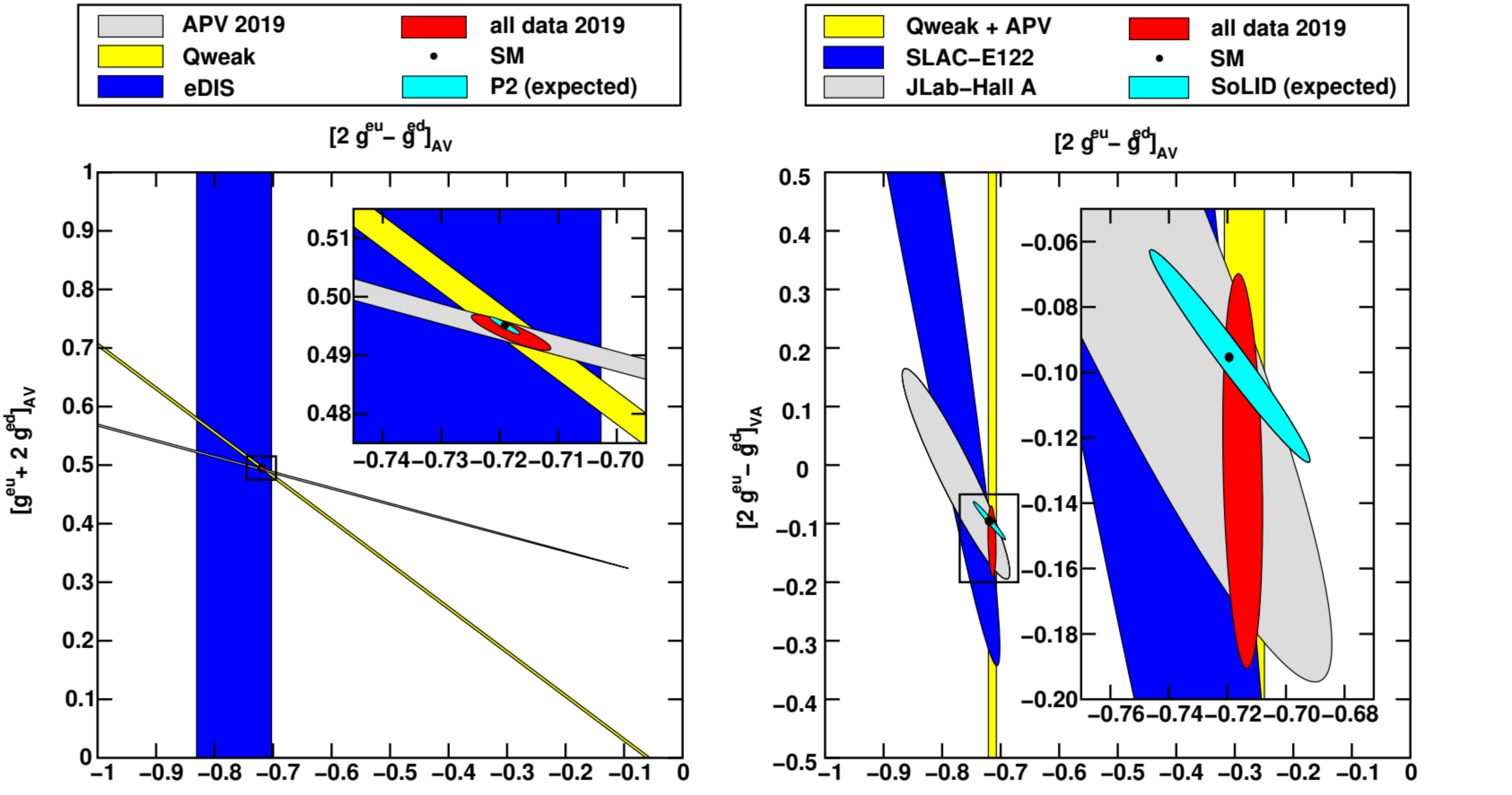
$$C_{1d} = 2 g_A^e g_V^d = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \qquad C_{2d} = 2 g_V^e g_A^d = \frac{1}{2} - 2\sin^2(\theta_W) \qquad C_{3d} = -2 g_A^e g_A^d = -\frac{1}{2}$$

- A new set of notation $g_{AV,VA,AA}^{eq}$ introduced in 2013 – Erler&Su, Prog. Part. Nucl. Phys. 71, 119 (2013)
- Example: In PVES, we can measure $C_{1,2}$

Current Knowledge on C_{1q}, C_{2q}

all are 68% C.L. limit

https://arxiv.org/abs/2103.12555



CERN for muon: $2C_{3u}^{\mu q} - C_{3d}^{\mu q} = 1.57 \pm 0.38$ Argento et al., PLB120B, 245 (1983)

In the Parton Model (low energy)

Parity-Violating

$$A_{RL}^{e^{\pm}} = \frac{\sigma_R^{e^{\pm}} - \sigma_L^{e^{\pm}}}{\sigma_R^{e^{\pm}} + \sigma_L^{e^{\pm}}}$$

$$\left(A_{RL}^{e^{\pm}} = -A_{LR}^{e^{\pm}}\right)$$

$$A_d = |\lambda| (108\, ppm)\, Q^2 \left[(2C_{1u} - C_{1d}) + Y(y)(2C_{2u} - C_{2d}) R_V(x) \right]$$

beam polarization

$$Y(y) = \frac{1 - (1-y)^2}{1 + (1-y)^2} \qquad R_V(x) = \frac{u_V(x) + d_V(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

(indicates spin flip of quarks)

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(indicates spin flip of quarks)

Lepton-Charge

$$A_{RL}^{e^+,e^-} = \frac{\sigma_R^{e^+} - \sigma_L^{e^-}}{\sigma_R^{e^+} + \sigma_L^{e^-}}$$

$$\left(A_{RL}^{e^+,e^-} \neq -A_{LR}^{e^+,e^-}\right)$$

$$A_{RL,d}^{e^+,e^-} = (108\,ppm) Q^2 Y(y) R_V(x) \left[|\lambda| (2C_{2u} - C_{2d}) - (2C_{3u} - C_{3d}) \right]$$

(flip |λ| for LR)

“B” in CERN measurement

$$A_{RR}^{e^+,e^-} = \frac{\sigma_R^{e^+} - \sigma_R^{e^-}}{\sigma_R^{e^+} + \sigma_R^{e^-}}$$

$$\left(A_{RR}^{e^+,e^-} \neq -A_{LL}^{e^+,e^-}\right)$$

$$A_{RR,d}^{e^+,e^-} = (108\,ppm) Q^2 \left[|\lambda| (2C_{1u} - C_{1d}) - Y(y) R_V(x) (2C_{3u} - C_{3d}) \right]$$

(flip |λ| for LL)

(no polarization needed!)

$$A_{unpol}^{e^+,e^-} = \frac{\sigma^{e^+} - \sigma^{e^-}}{\sigma^{e^+} + \sigma^{e^-}}$$

$$A_d^{e^+,e^-} = -(108\,ppm) Q^2 Y(y) R_V(x) (2C_{3u} - C_{3d})$$

“direct” access to $2C_{3u}$-C_{3d}

e^+e^- for Structure Function Study

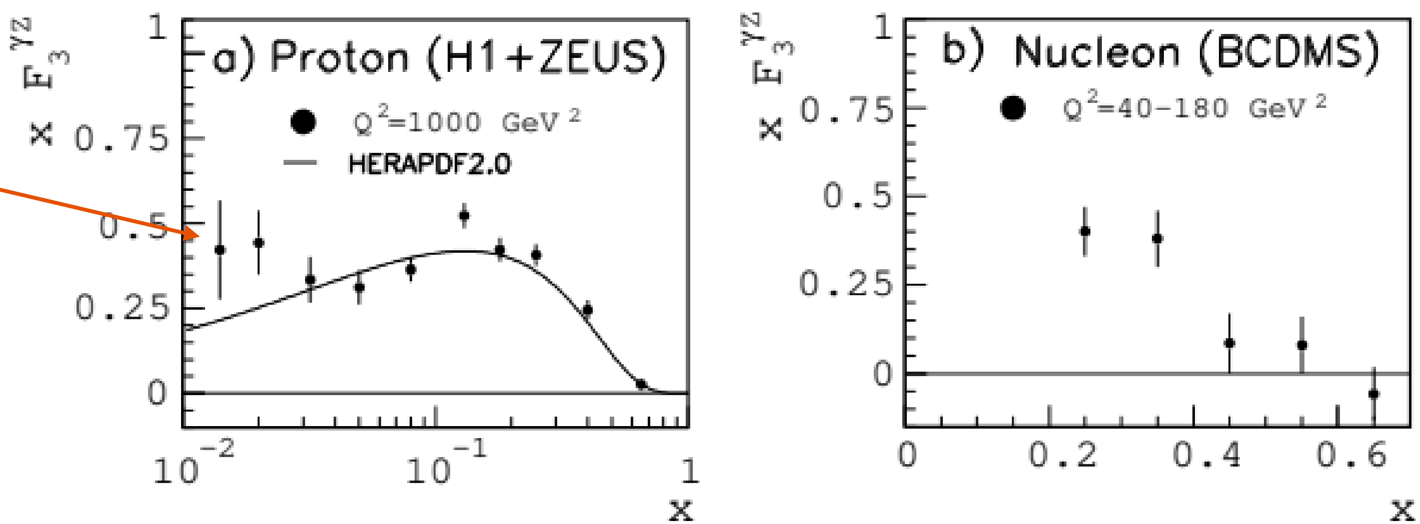
Approximately: $$A^{e^+e^-}_{\mathrm{unpol}} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{g_A^e}{2}Y(y)\frac{F_3^{\gamma Z}}{F_1^{\gamma}}$$

(in Apv, $F_3^{\gamma Z}$ is suppressed by g_V^e)

In the parton model: $$F_1^{\gamma}(x,Q^2) = 1/2\sum Q_q^2[q+\bar{q}]$$

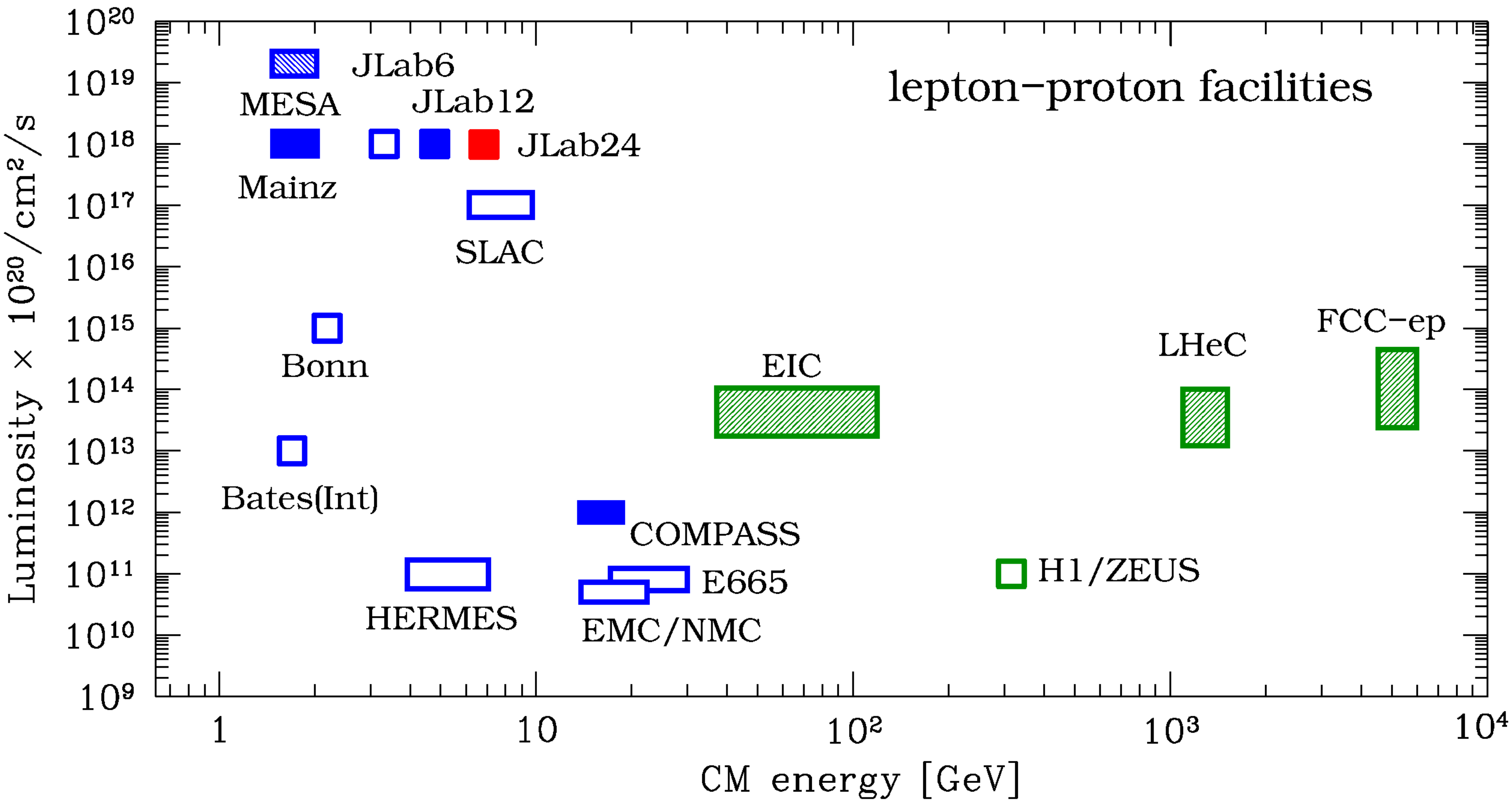
$$F_3^{\gamma Z}(x,Q^2) = 2\sum g_A^q[q-\bar{q}]$$

Low x HERA data pose question on $q_{\mathrm{sea}} = \bar{q}_{\mathrm{sea}}$

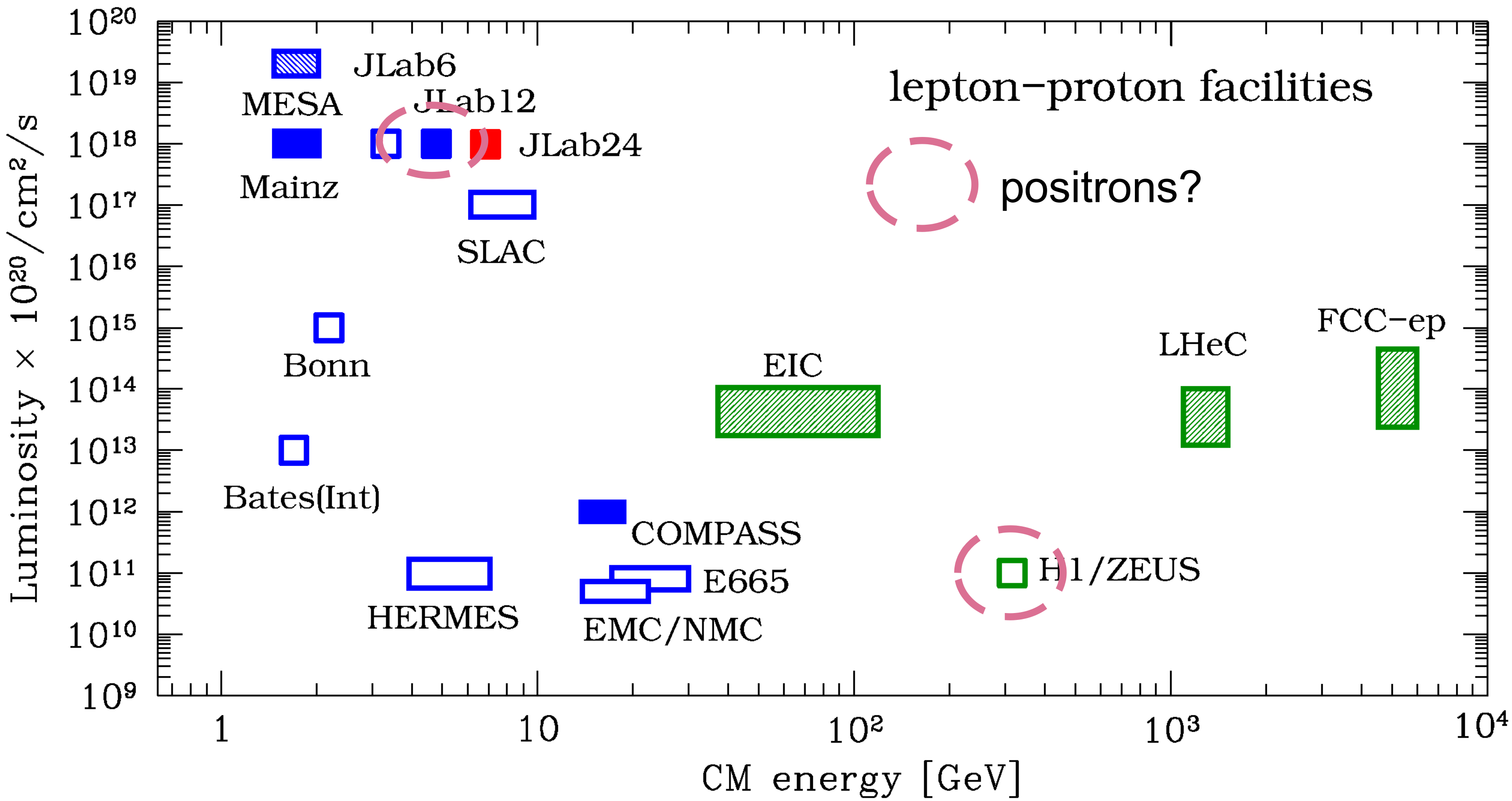


By measuring $A^{e+e-}_{p,d}$ we can access $F_3^{\gamma Z}(x,Q^2)$

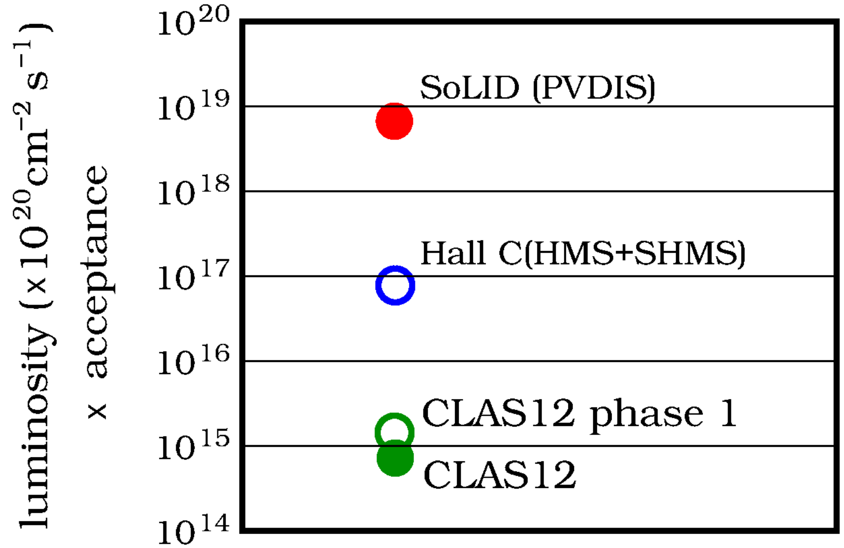
Designing the Experiment

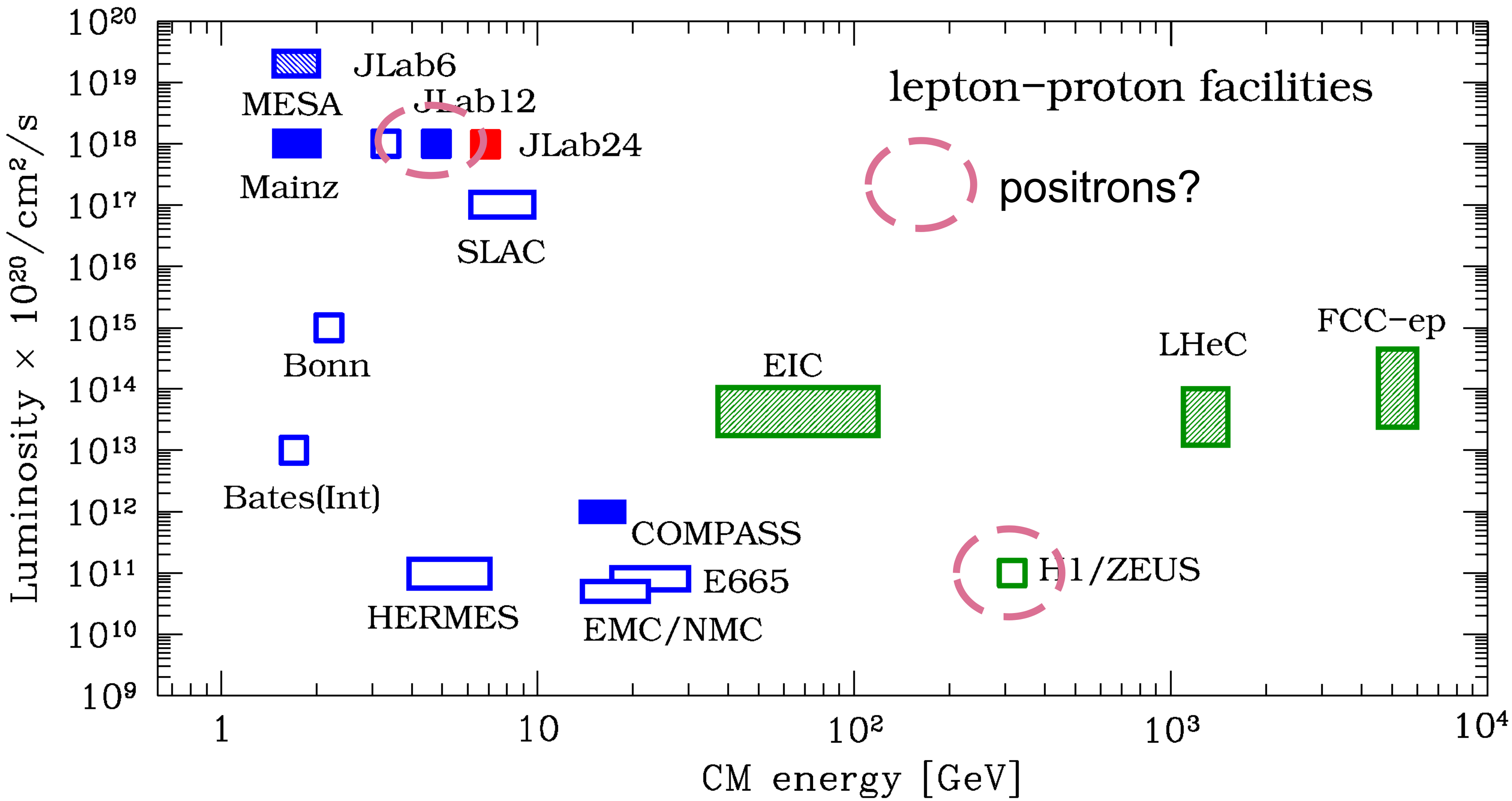


Designing the Experiment



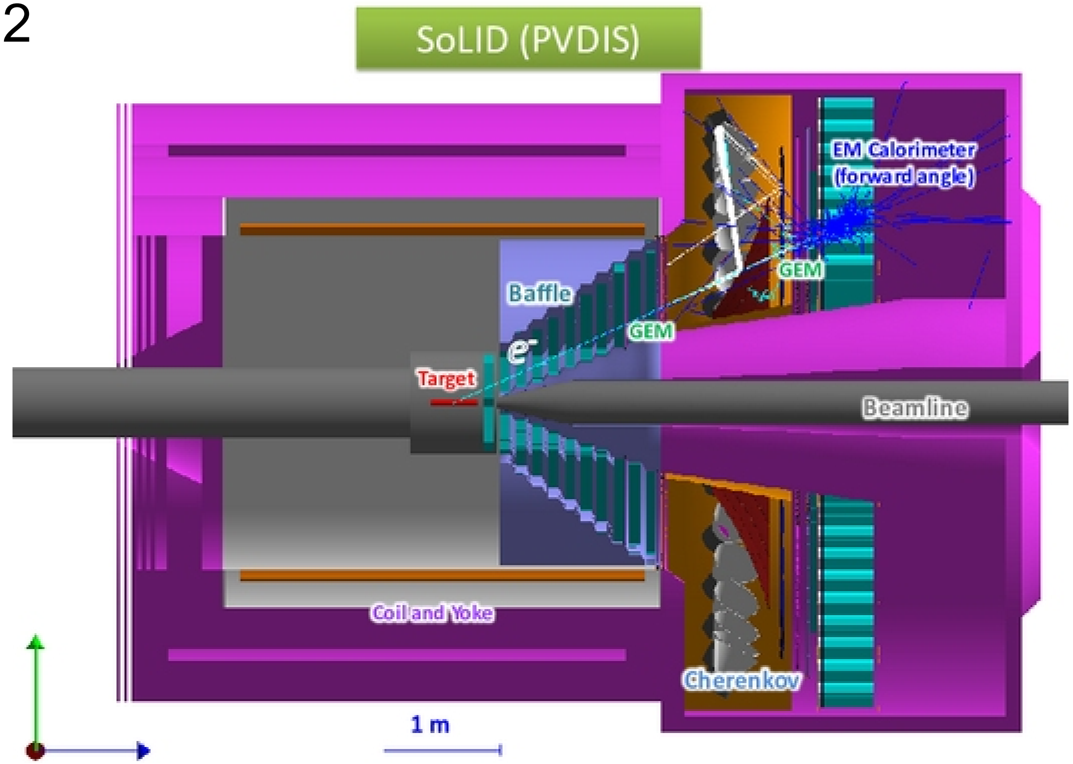
Designing the Experiment



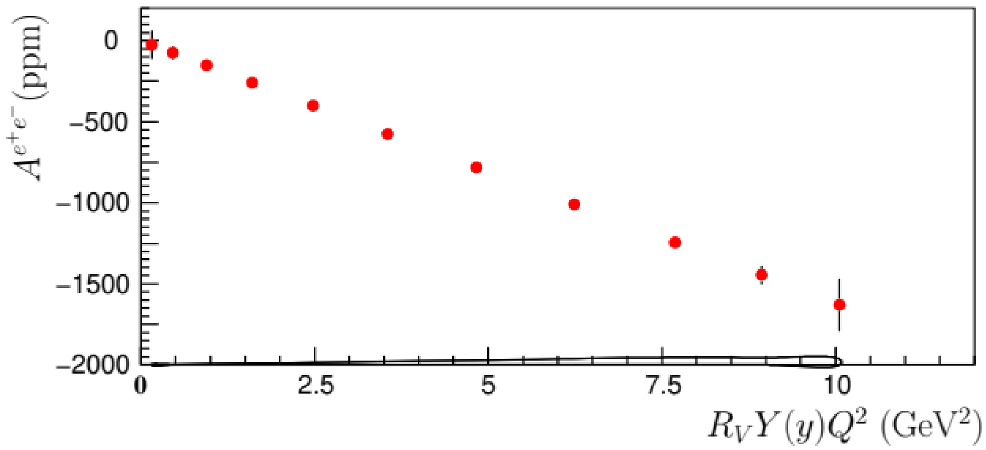


Designing the Experiment

- **SoLID PVDIS** configuration + 40cm LD2
- **PEPPo**: 3uA unpolarized beam
- **Reverse magnet** polarity of SoLID for positron detection



if we consider only statistics and assume A=0 at Q^2=0:



$$A_d^{e^+e^-} = -(108\ ppm) Q^2 Y R_V (2C_{3u} - C_{3d})$$

$$\rightarrow 1.5 \pm 0.007$$

Experimental challenges:

beam energy difference

beam luminosity difference

beam position difference

charged pion background

pair production background

magnet and detector stability

Theoretical challenges: – higher-order QED corrections

Experimental challenges:

beam energy difference

beam luminosity difference

beam position difference

charged pion background

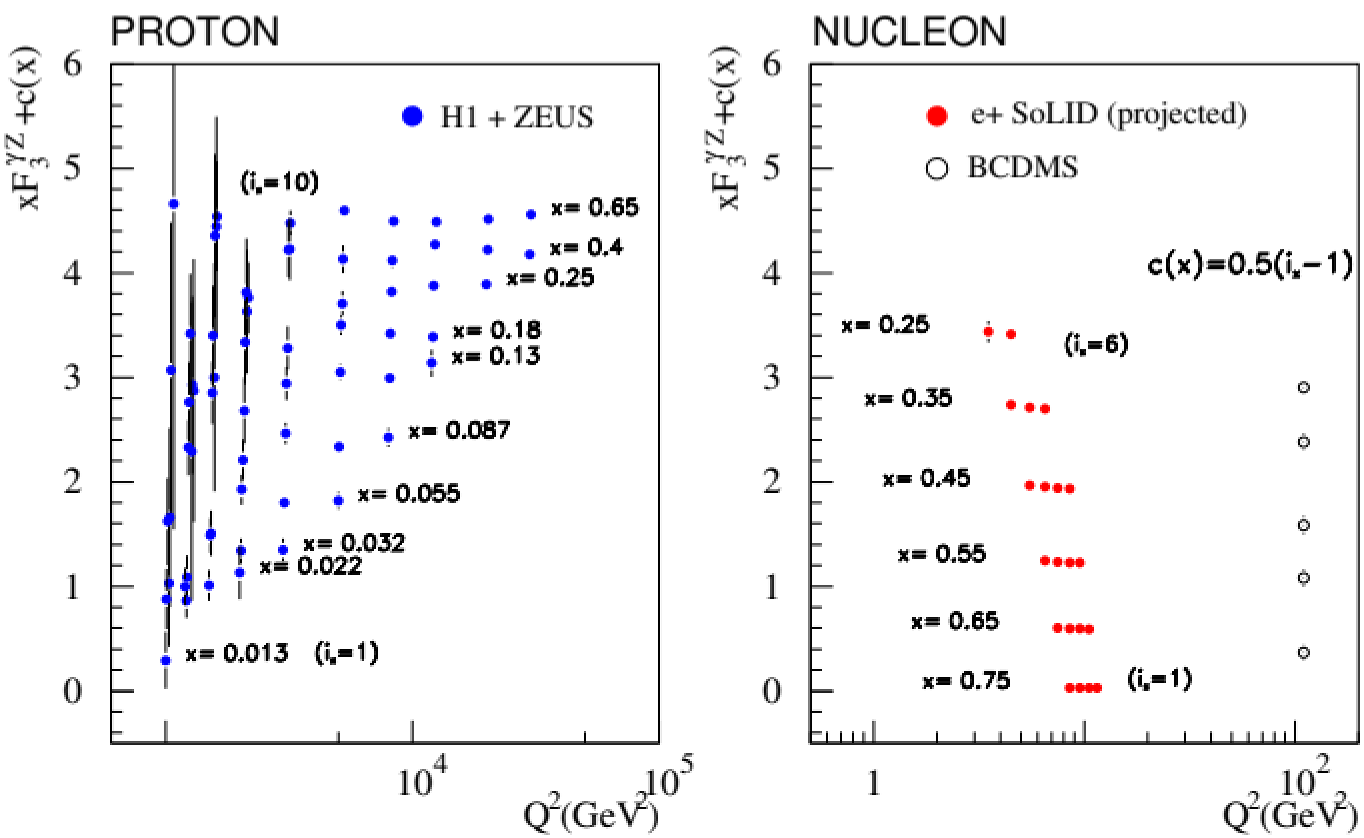
pair production background

magnet and detector stability

PR12-21-006 Lepton Charge Asymmetry

- 104 PAC days
- positron beam 3uA unpolarized
- beam control (1E-4 beam energy, ? beam position, “fast switch”)

$$\Delta\left(2C_{3u}-C_{3d}\right)_{\text{total}}=\pm0.053(\text{exp})\pm0.009(1\%\ \text{QED})$$
$$+0.000-0.035(\text{HT, CJ15})\approx\pm0.060$$



PAC49 report:

Issues: The PAC is pleased to see such an interesting and far-reaching proposal. … …At the same time, the requirements on the accelerator and theory are both daunting.

Summary: … … leads us to defer the proposal in its present form.

Summary

– By comparing e- vs. e+ DIS cross section, we can form lepton-charge asymmetry that is directly proportional to a new set of eq EW NC coupling: C_{3q} or g_{AA}.

– So far, challenges in both experimental and theoretical systematic effects are both daunting and require further work to make the measurement compelling.

– A phased-approach can also be considered: study TPE in DIS using 11 GeV and EW physics with a 22 GeV (e+) beam.

Backup

Summary of Challenges and Why They Exist?

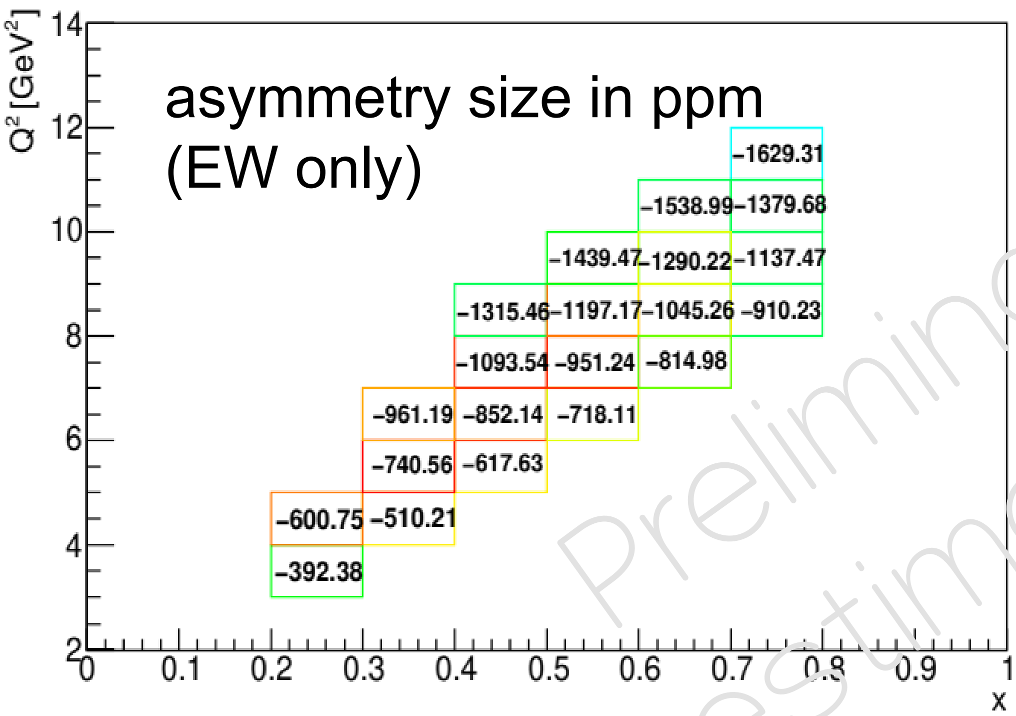
– With a positron beam, the best physics impact comes from comparison between e+ and e- scattering, rather than measuring the same observable (e.g. Apv) as electrons
– If positron vs. electron comparison is our goal, then all systematic effect related to the beam need to be controlled to high precision
– Frequent ("weekly") and fast switch between e+ and e- beams is required to control differences in beam and run conditions → impact on positron beam design.
– Measurements where signal is tiny (EW physics) will be extremely difficult

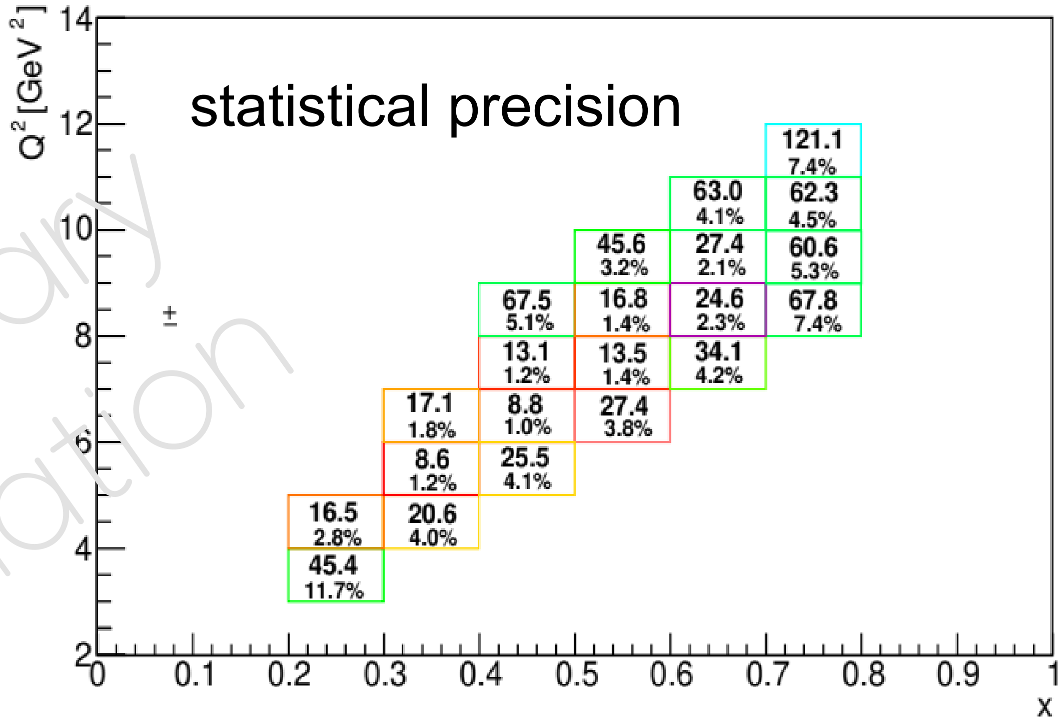
– Particle background effects on the detector, trigger, and DAQ system.

– There is no well established calculation for TPE (QED NLO) in DIS. All previous (SLAC) data indicated zero but with poor precision;
– HERA data provided only slight constraint on QED NLO in DIS

– We could consider a "phase" approach: study DIS TPE first, then EW physics

What can we do with 80 days of 3uA beam on a 40cm LD2 target? (in absence of all challenges):

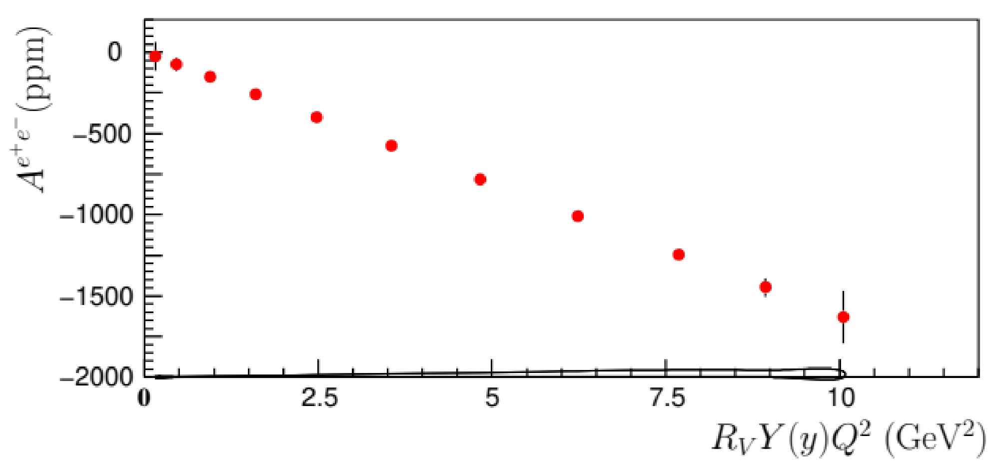




if we consider only statistics and assume A=0 at Q^2=0:

$$A_d^{e^+ e^-} = -(108\ ppm) Q^2 Y R_V (2C_{3u} - C_{3d})$$

$$\rightarrow 1.5 \pm 0.007$$



Past Experiment – BCDMS

1983 CERN, using polarized μ+ vs. μ- beams:

$$2\,C_{3u}^{\mu q} - C_{3d}^{\mu q} = 1.57 \pm 0.38$$

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

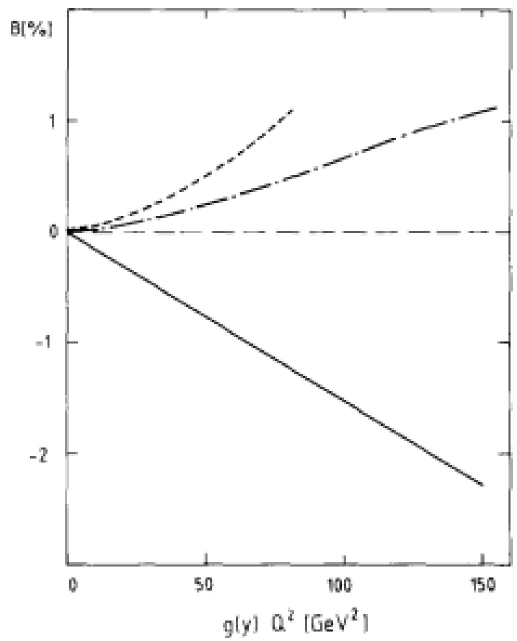


Fig. 2. The B asymmetry from $\gamma-Z^0$ interference to first order, calculated for a polarization $\lambda = 0.81$ and $\sin^2\theta_W = 0.23$ (solid line), and the asymmetry expected from higher order electromagnetic processes at beam energies of 120 GeV (dashed line) and 200 GeV (dashed–dotted line).

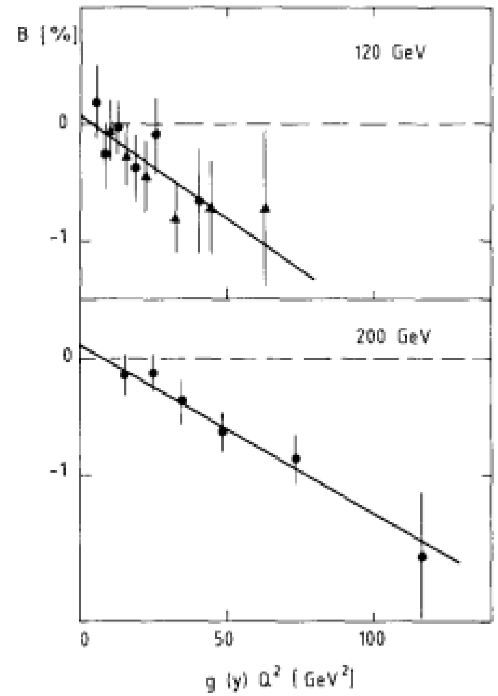


Fig. 3. The measured B asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy versus $g(y)Q^2 = Q^2 \times [1-(1-y)^2]/[1+(1-y)^2]$ [eq. (3)]. For the 120 GeV data, circles represent data with $Q^2 > 15$ GeV. Solid lines are straight line fits to the data.

netic and weak-electromagnetic effects according to ref. [6]: the magnitude of these corrections is shown

a measurement for the electron is highly desired

Experimental Challenges

QED higher order (scaled by 1/5) → ΔA_{QED}