

# Electroweak Physics with SoLID and a future positron beam at JLab

Xiaochao Zheng, Univ. of Virginia  
May 4<sup>th</sup>, 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

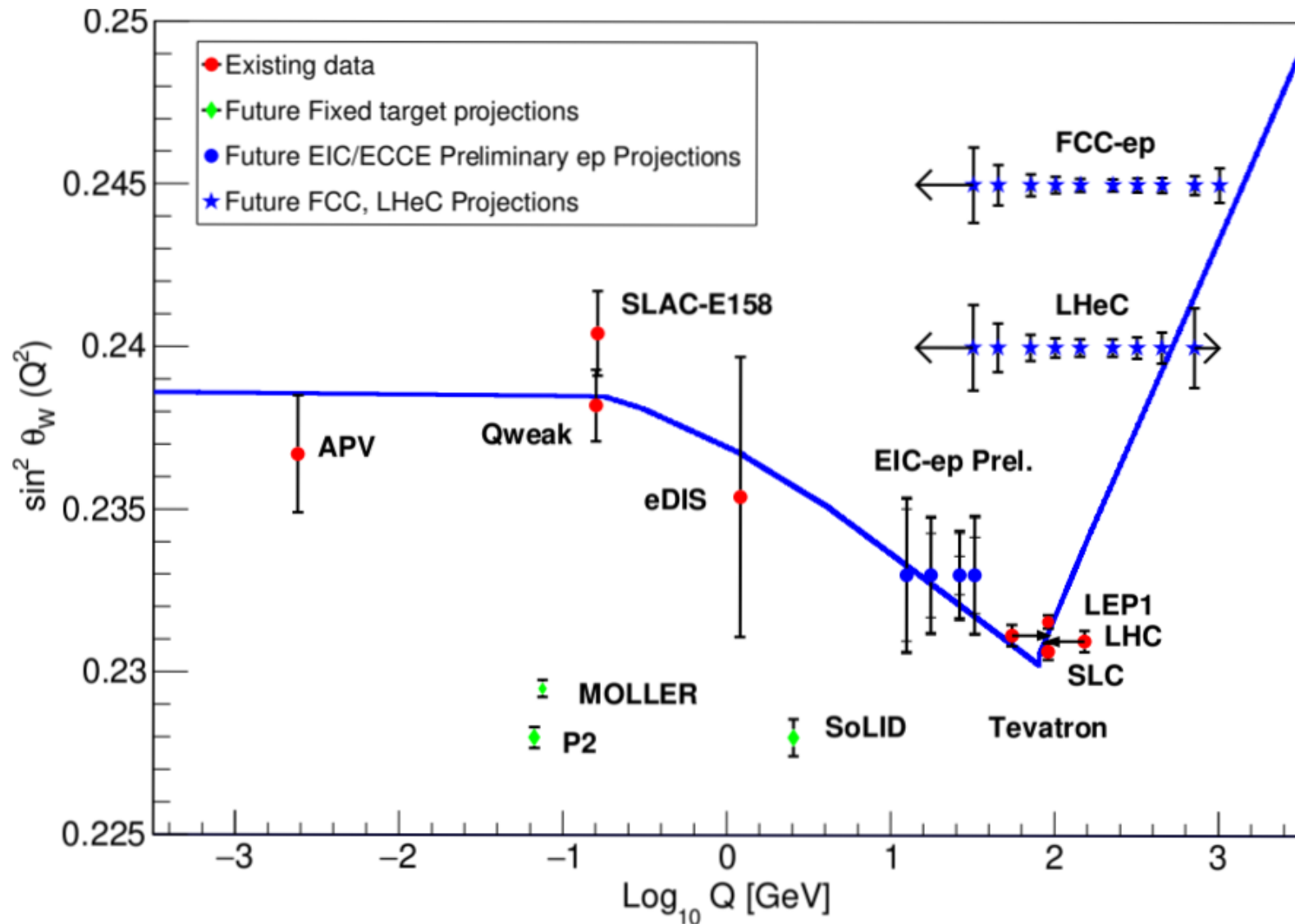
(A New Proposal to Jefferson Lab PAC-49)

Measurement of the Asymmetry  $A_d^{e^+e^-}$  between  $e^+ - {}^2\text{H}$  and  $e^- - {}^2\text{H}$   
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



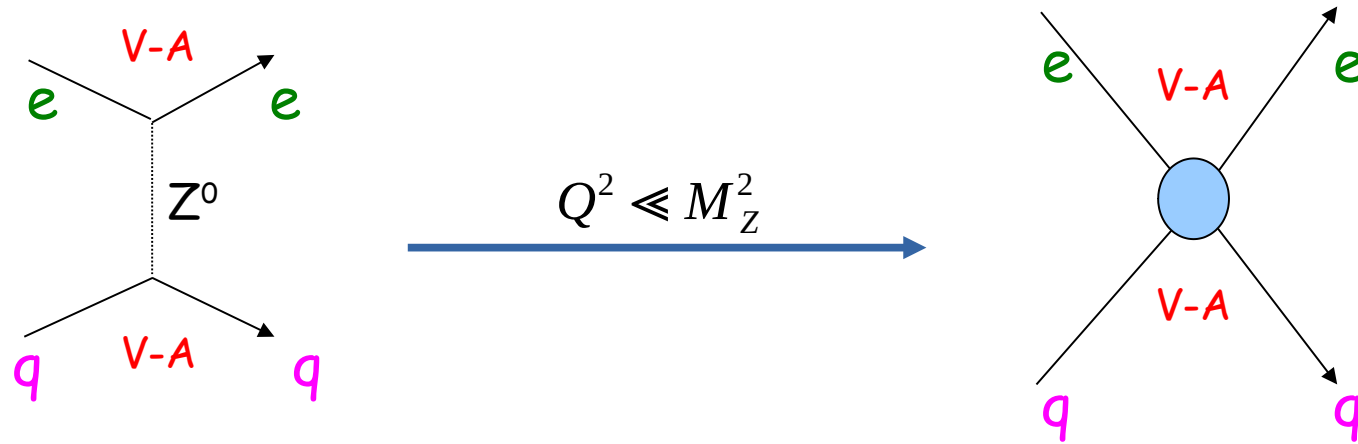
EIC projections from [arxiv.org/2204.07557](https://arxiv.org/abs/2204.07557) [hep-ph]

LHeC projection (60GeV x 7 TeV,  $\sim 1000\text{fb}^{-1}$ ) from EPJC 80 (2020) 9, 831 [arxiv.org/2007.11799](https://arxiv.org/abs/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  $\gamma$ )

AV, VA (parity-violating)

AA

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

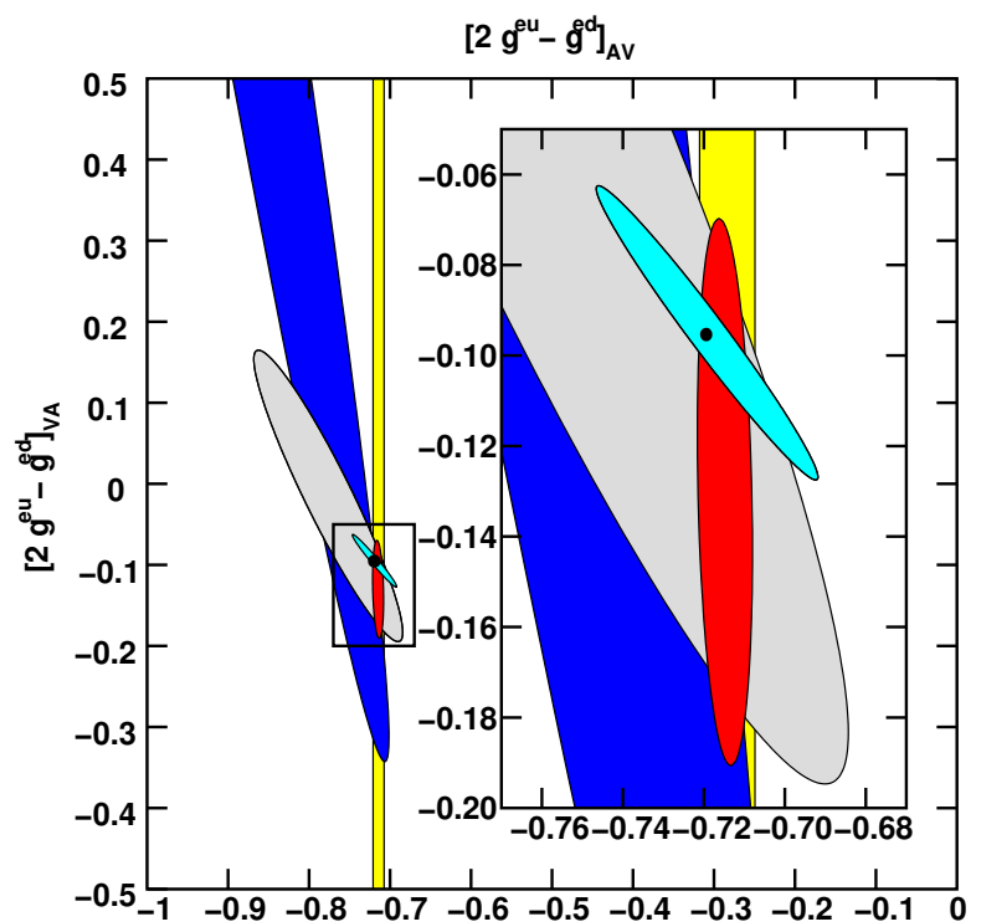
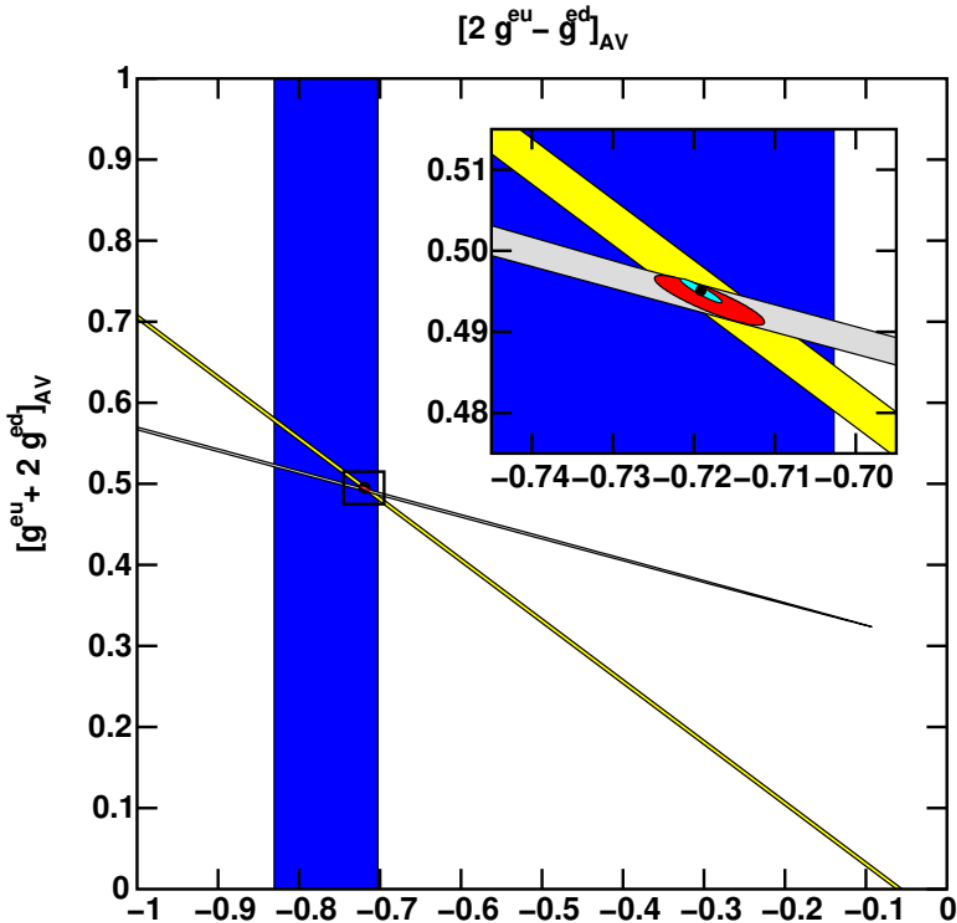
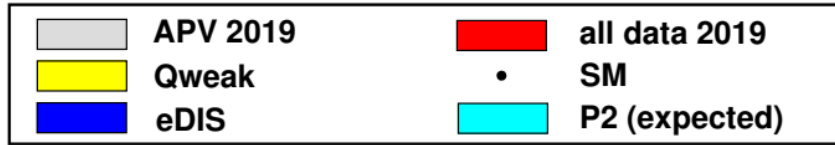
$$C_{1d} = 2 g_A^e g_V^d = \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W) \quad C_{2d} = 2 g_V^e g_A^d = \frac{1}{2} - 2 \sin^2(\theta_W) \quad C_{3d} = -2 g_A^e g_A^d = -\frac{1}{2}$$

- 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

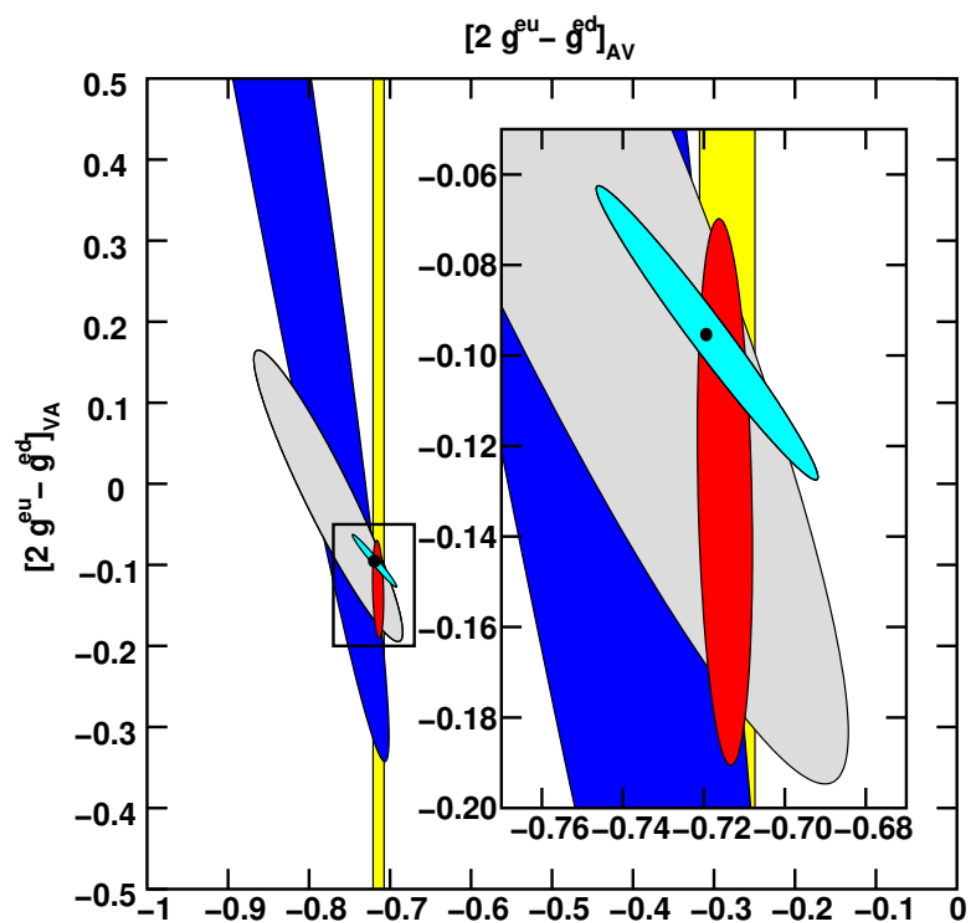
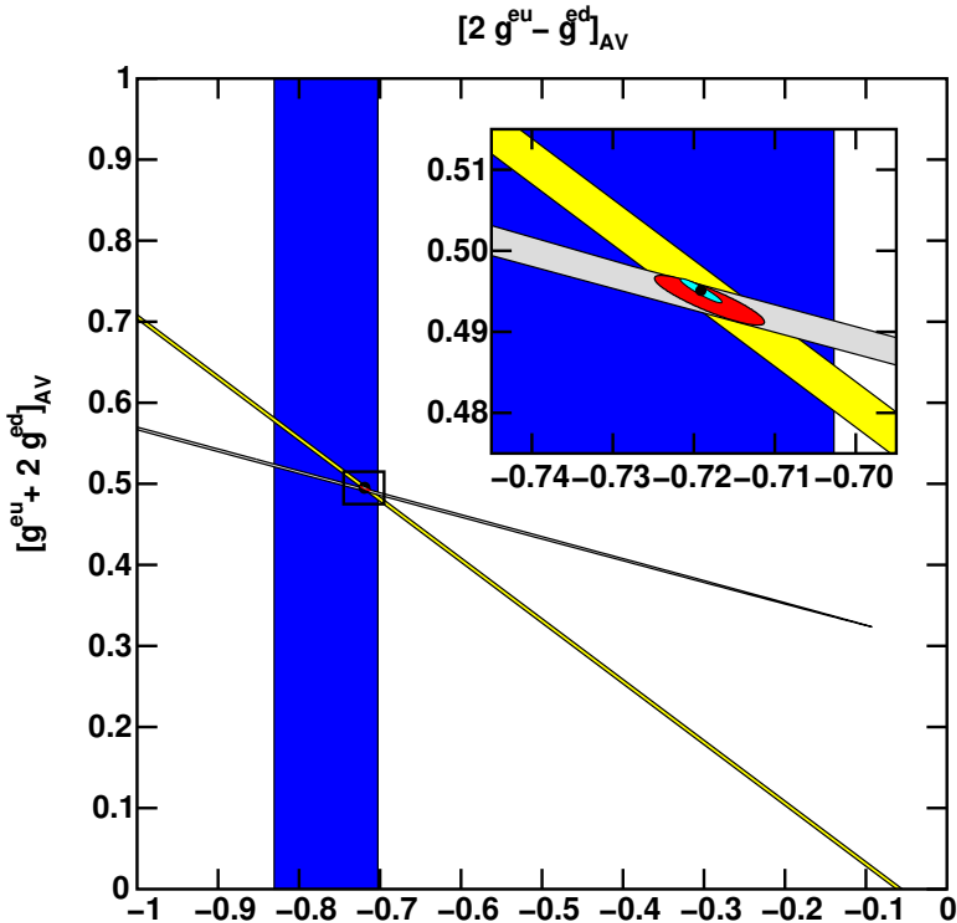
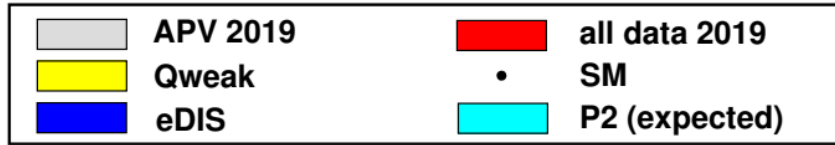
<https://arxiv.org/abs/2103.12555>



# 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)

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

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

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

beam polarization

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

(indicates spin flip of quarks)

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Parity-Violating

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

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

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

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Lepton-Charge

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

(flip  $|\lambda|$  for LR)

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

(flip  $|\lambda|$  for LL)

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

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

Lepton-Charge

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(flip  $|\lambda|$  for LR)

“B” in CERN measurement

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

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

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

(flip  $|\lambda|$  for LL)

(no polarization needed!)

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

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

“direct” access to  $2C_{3u} - C_{3d}$

# Past Experiment – BCDMS

1983 CERN, using polarized  $\mu^+$  vs.  $\mu^-$  beams:

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

Volume 120B, number 1,2,3

PHYSICS LETTERS

6 January 1983

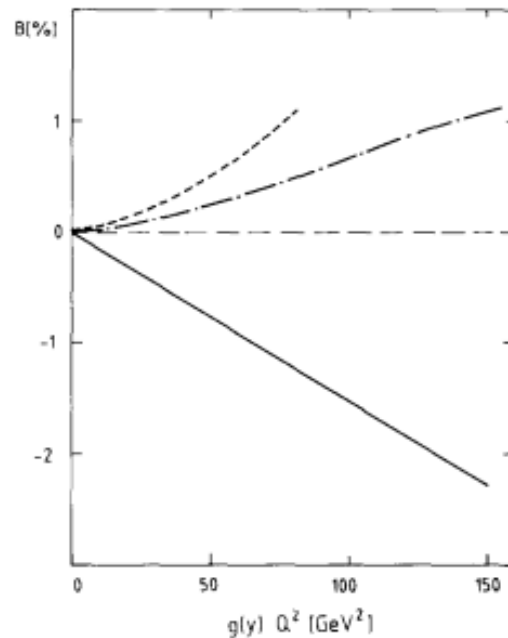


Fig. 2. The  $B$  asymmetry from  $\gamma$ - $Z^0$  interference to first order, calculated for a polarization  $\lambda = 0.81$  and  $\sin^2 \theta_w = 0.23$  (solid line), and the asymmetry expected from higher order electromagnetic processes at beam energies of 120 GeV (dashed line) and 200 GeV (dashed-dotted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

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

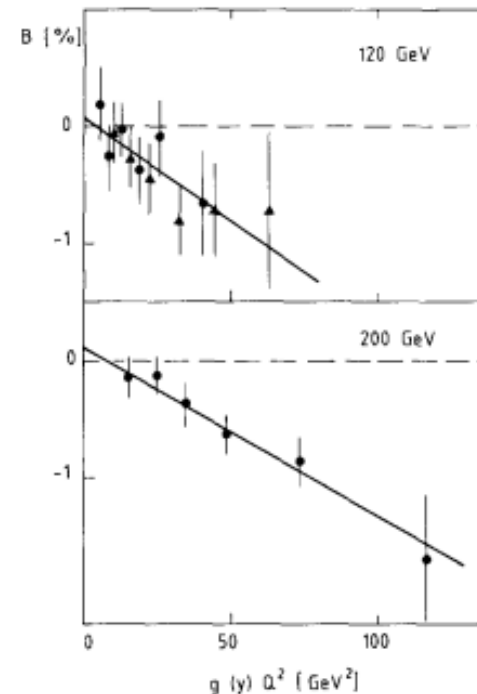


Fig. 3. The measured  $B$  asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy versus  $g(y)Q^2 = Q^2 \times [1 - (1 - y)^2] / [1 + (1 - y)^2]$  [eq. (3)]. For the 120 GeV data, circles represent data with  $Q^2 > 15$  GeV. Solid lines are straight line fits to the data.

a measurement for the electron is highly desired

# $e^+e^-$ for Structure Function Study

Approximately:

$$A_{\text{unpol}}^{e^+e^-} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{g_A^e}{2} Y(y) \frac{F_3^{\gamma Z}}{F_1^{\gamma}}$$

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

In the parton model:

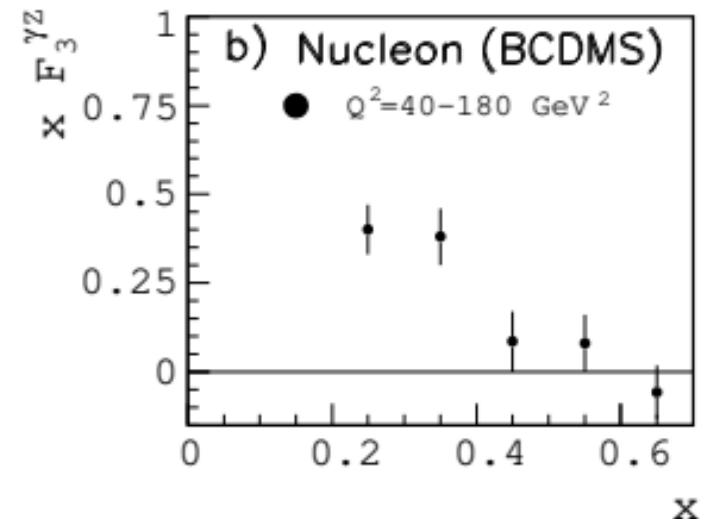
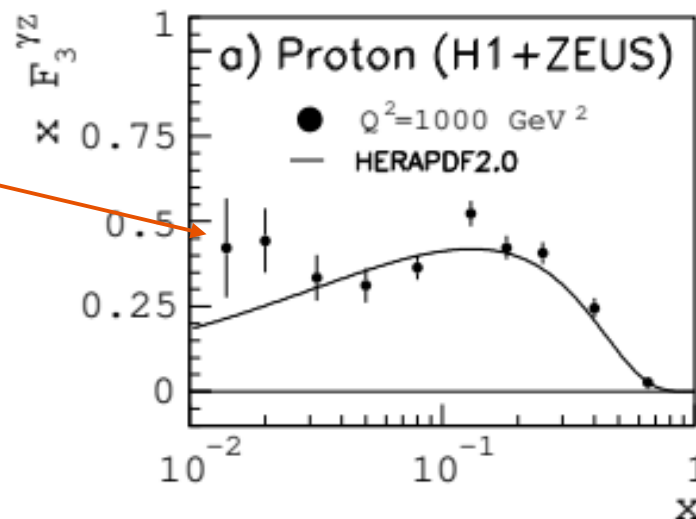
$$F_1^{\gamma}(x, Q^2) = 1/2 \sum Q_q^2 [q + \bar{q}]$$

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

Low x HERA data pose question on

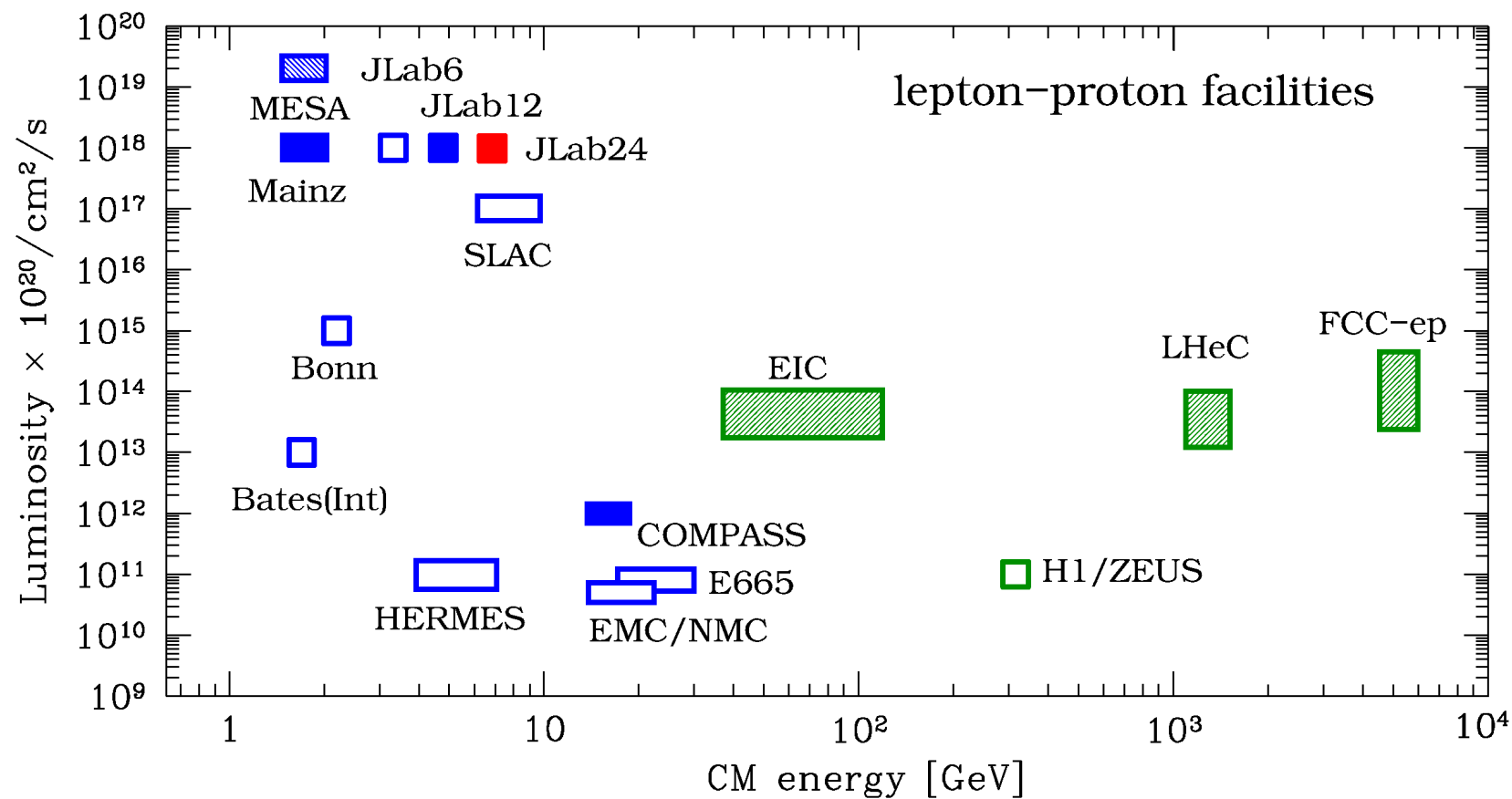
$$q_{\text{sea}} = \bar{q}_{\text{sea}}$$

(→ LHeC)

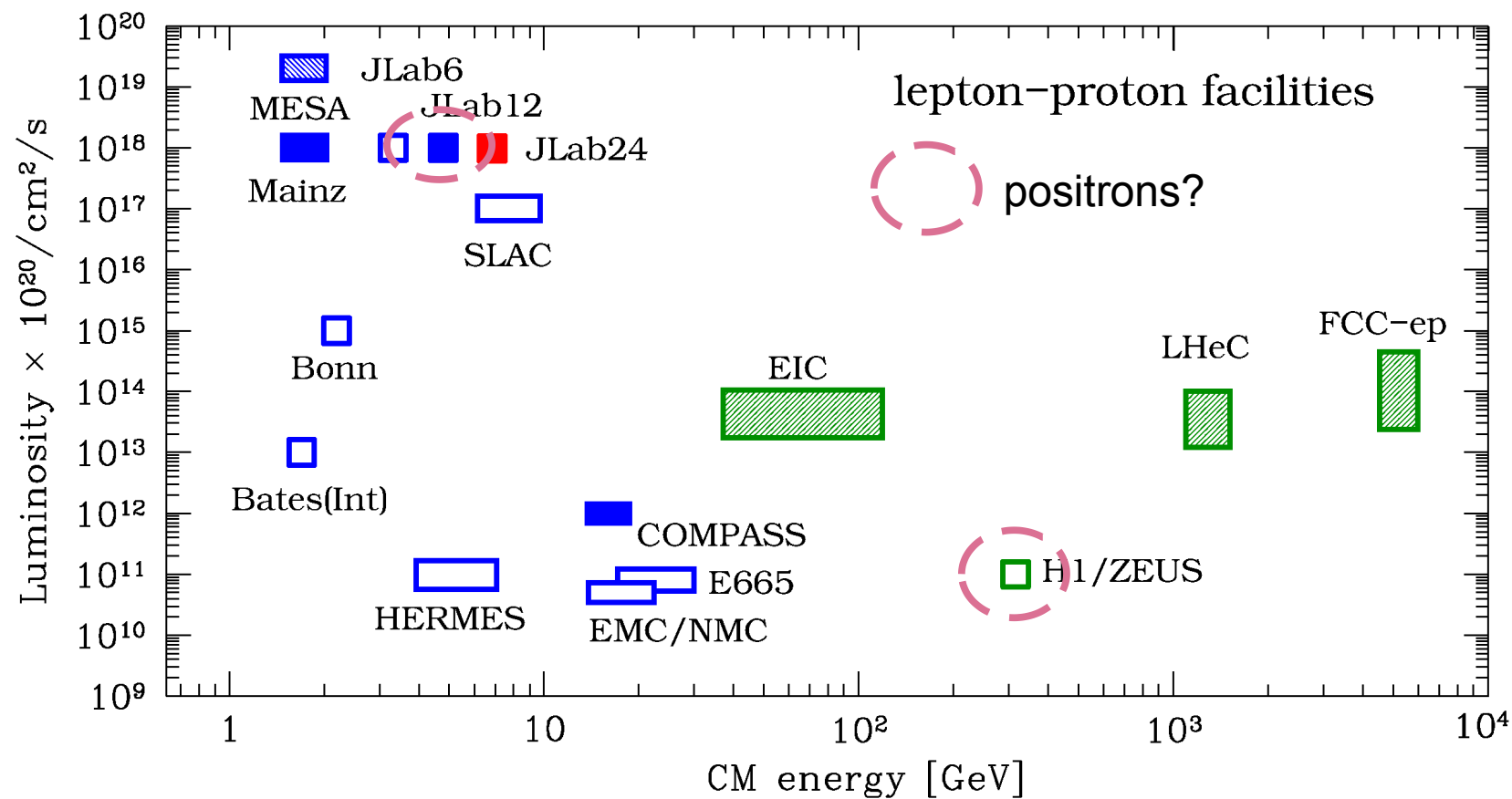


By measuring  $A_{p,d}^{e^+e^-}$  we can access  $F_3^{\gamma Z}(x, Q^2)$

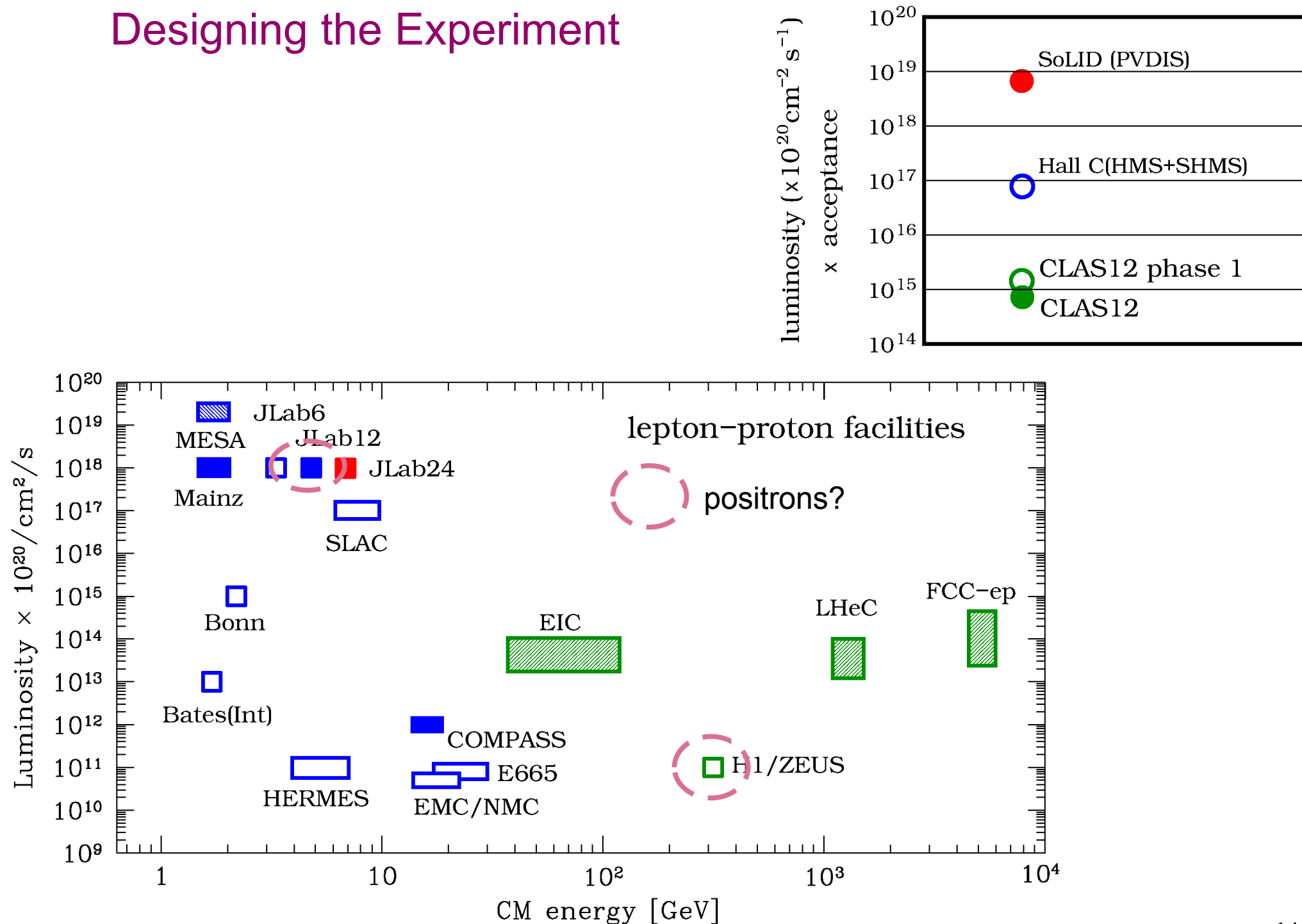
# Designing the Experiment



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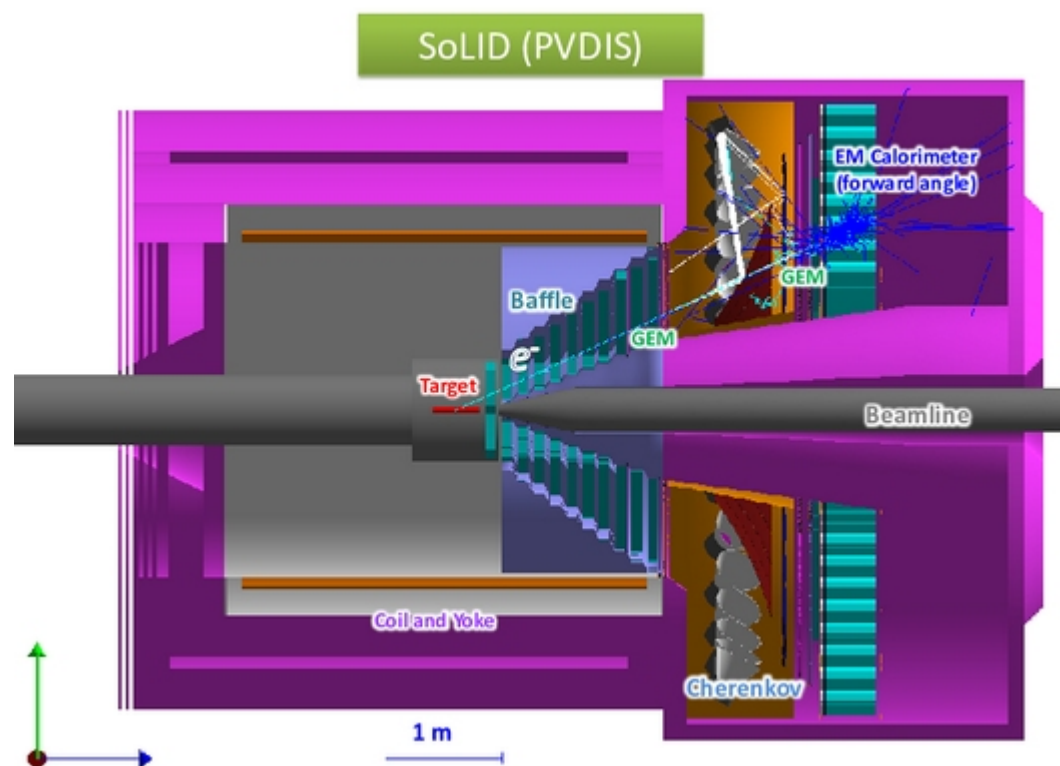


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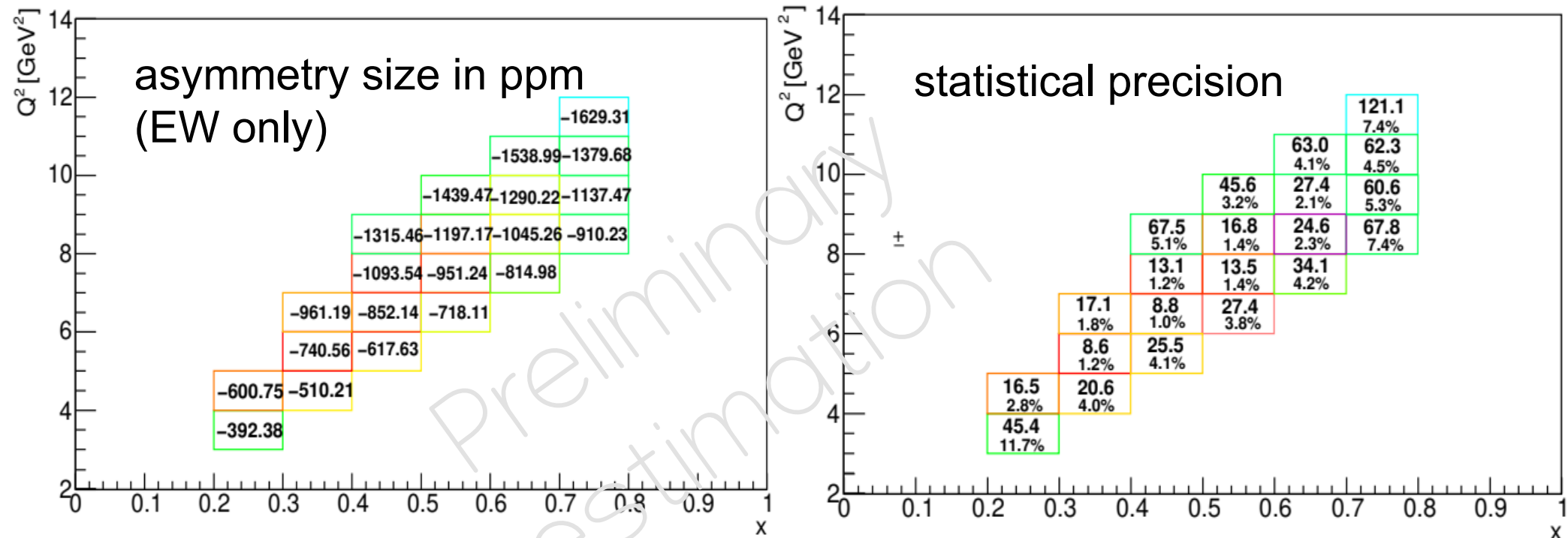


# Designing the Experiment

- ◆ Need high  $Q^2$ , high  $Y(y)$  → **SoLID PVDIS** configuration is ideal (40cm LD2)
- ◆ Need positron beam → **PEPPo**: up to 5uA for unpolarized. We can use 3uA, 88 days at 11 GeV, 8 days at 6.6 GeV, each split between  $e^+$  and  $e^-$  runs
- ◆ Need positron detection → **reverse magnet** polarity of SoLID, run magnets always at full saturation (field mapping needed to control field diff.  $< 10^{-5}$ )
- ◆ For each of  $e^+$  and  $e^-$  run, also need **reverse polarity runs** to determine pair production background (8 of 88 days)



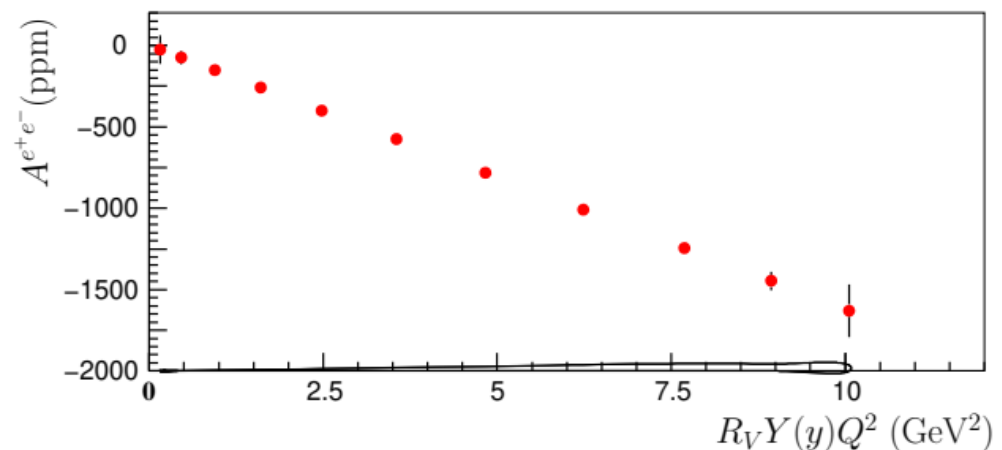
What can we do with 80 days of 3uA beam on a 40cm LD2 target? (in absence of all challenges):



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

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

$$\rightarrow 1.5 \pm 0.007$$



# Designing the Experiment

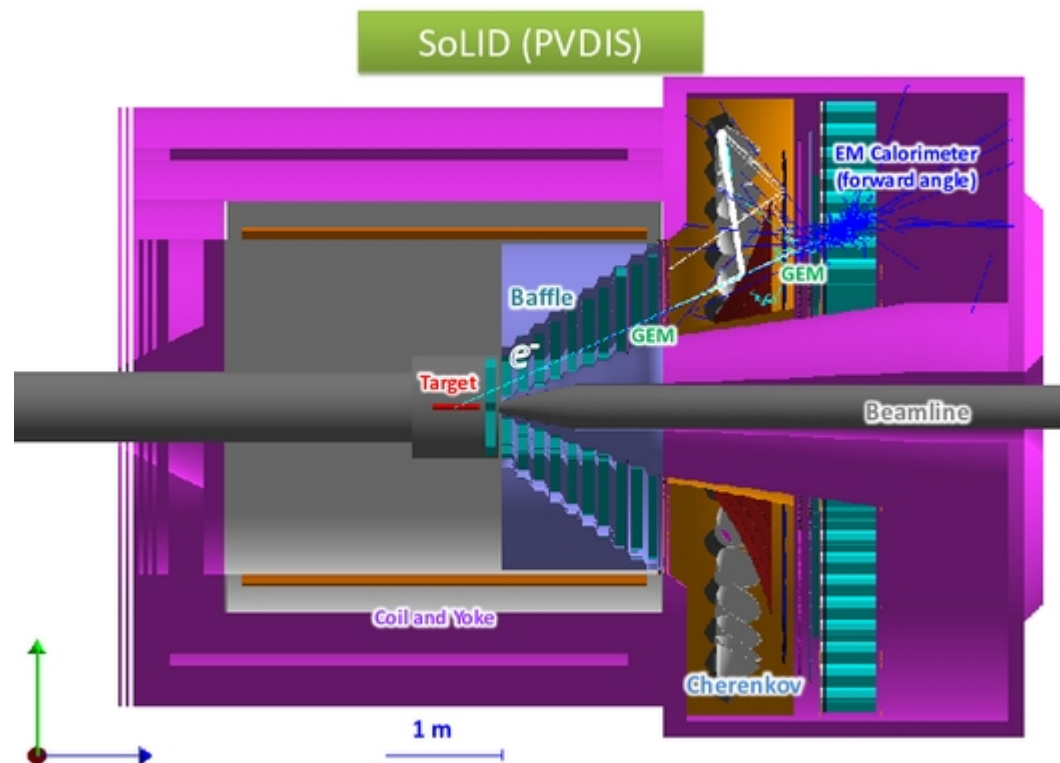
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## Experimental challenges:

- beam energy, luminosity;
- charged pion and pair production background
- magnet and detector stability

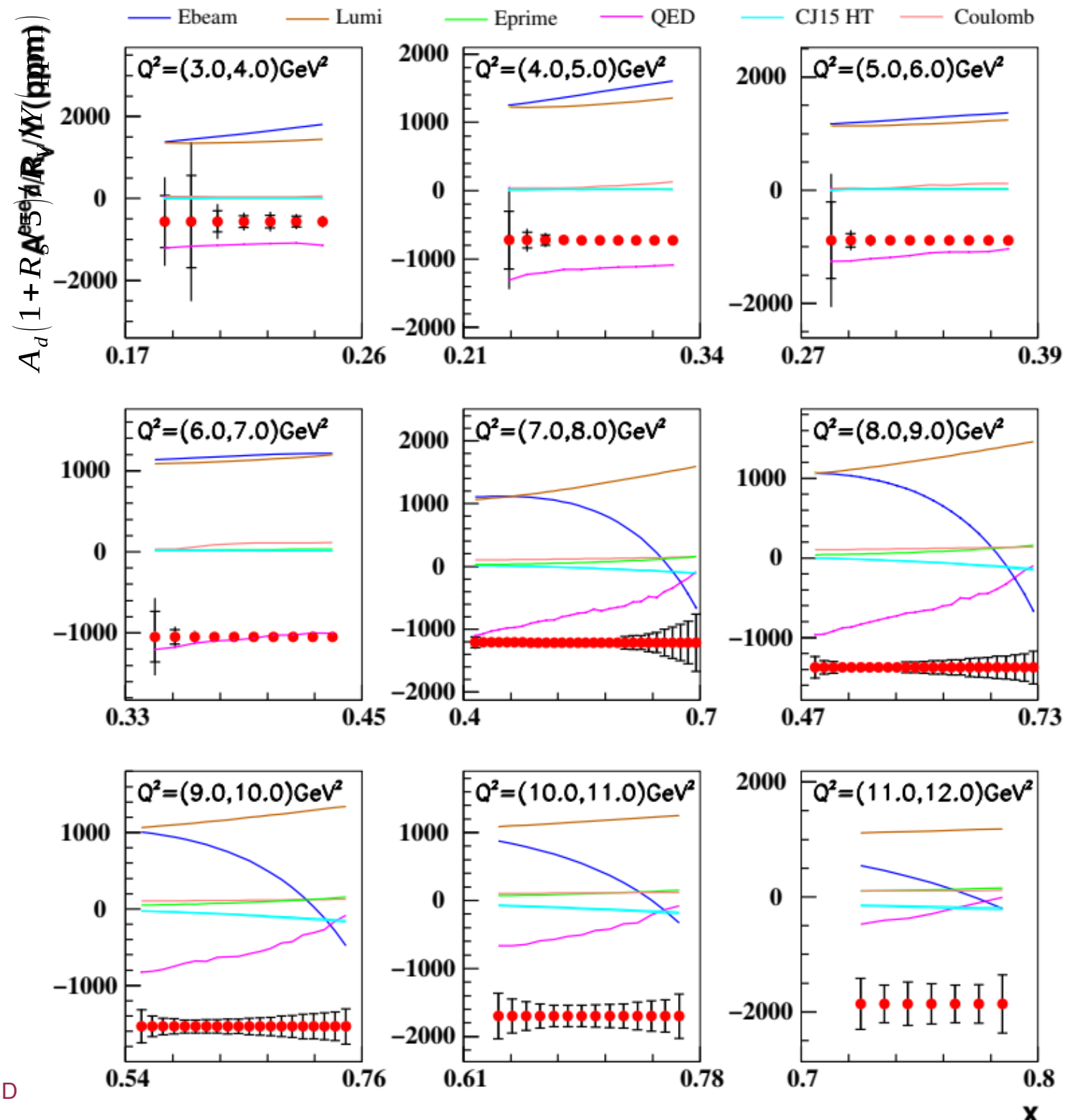
## Theoretical challenges:

- higher-order QED corrections



# Experimental Challenges

QED higher order (scaled by  $1/5$ )  $\rightarrow \Delta A_{QED}$



# PR12-21-006 Lepton Charge Asymmetry

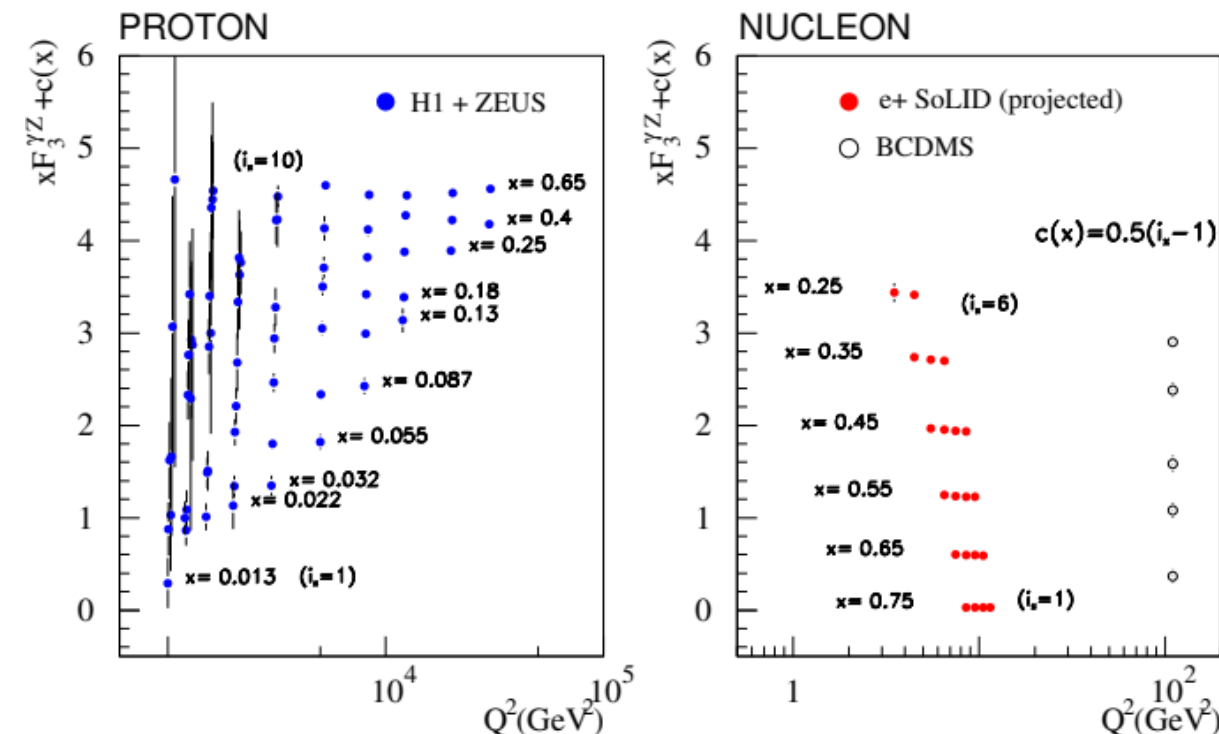
- 104 PAC days
- positron beam 3uA unpolarized
- beam control (1E-4 beam energy, ? beam position, “fast switch”)

$$\Delta(2C_{3u} - C_{3d})_{\text{total}} = \pm 0.053(\text{exp}) \pm 0.009(1\% \text{ QED}) \\ + 0.000 - 0.035(\text{HT, CJ15}) \approx \pm 0.060$$

## 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:** ... At this time, our concerns about the details of having the proper beam and the optimal theory extraction of the electron-quark couplings leads us to defer the proposal in its present form.



# 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.  $A_{PV}$ ) 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.
- If we can’t keep  $e^+$  and  $e^-$  beams to be (almost) exactly the same, the high luminosity would be sort-a useless (for EW study at least)
- Measurements where signal is tiny (EW physics) will be extremely difficult

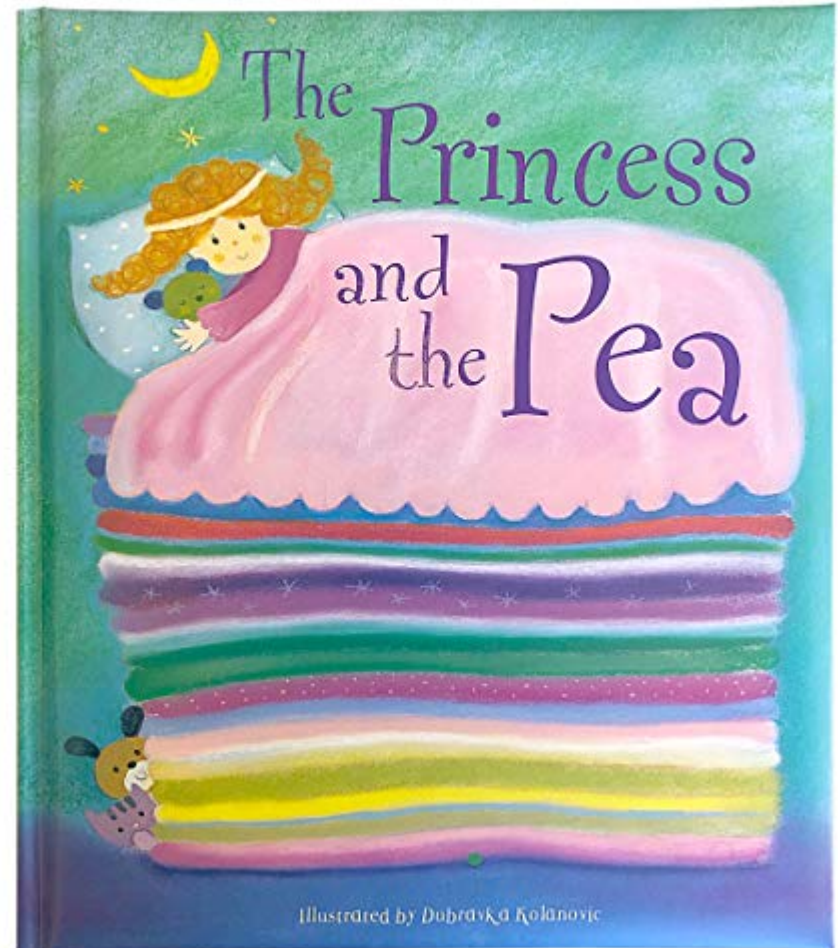
- Particle background effects on the detector, trigger, and DAQ system.

- 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 with 11 GeV and see if it’s realistic to study EW physics with 22 GeV (?)

# 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 prevent us from doing this measurement in a compelling way.
- Study will be continued, but the gain may be more in the process than in the outcome.

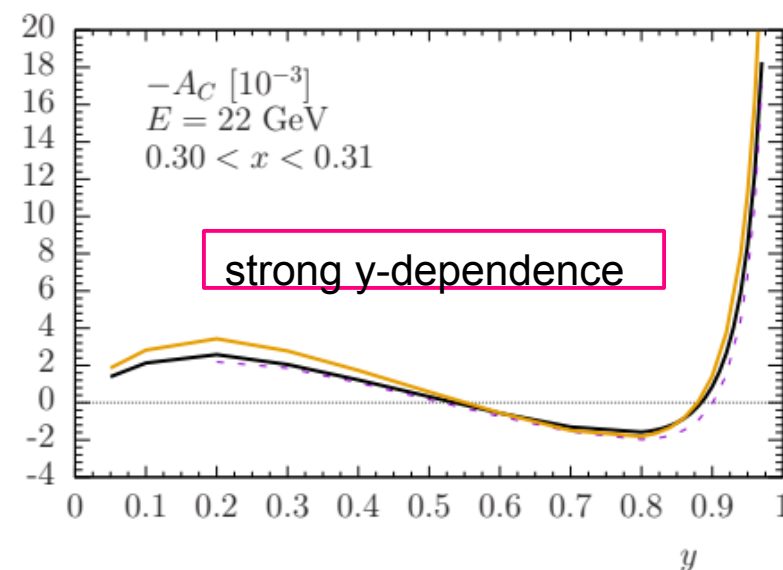
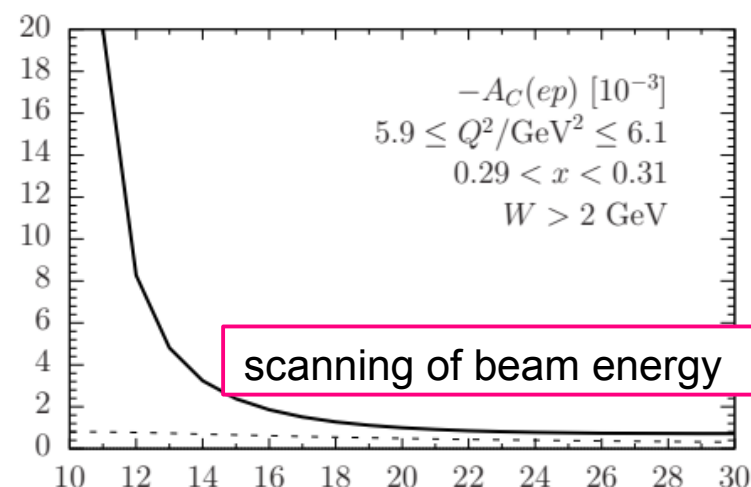
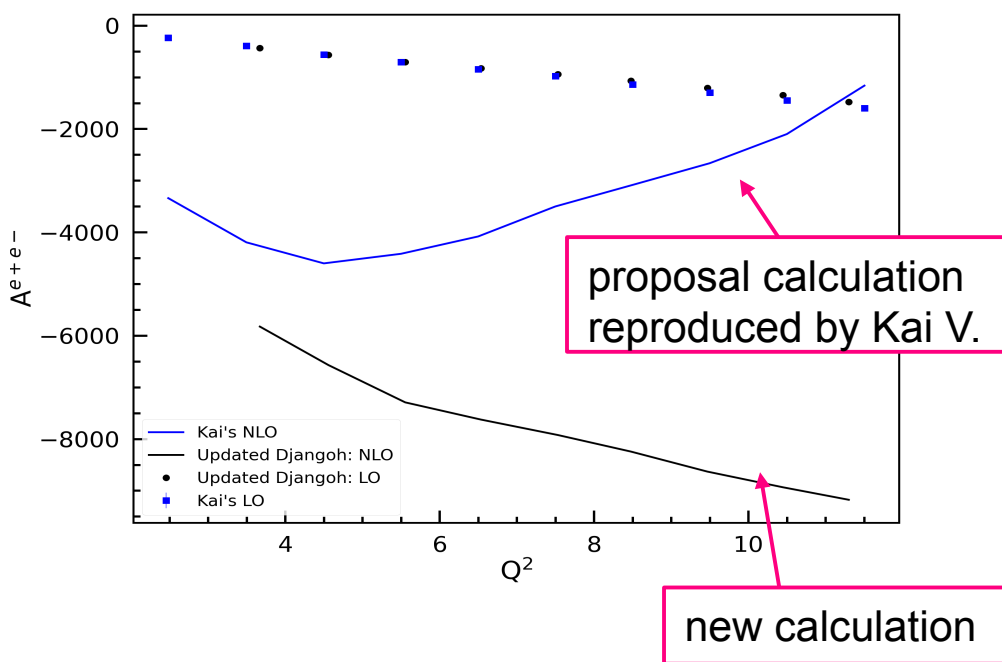


# Backup

# Idea: with positron beam, study TPE DIS (QED NLO) first

- **TPE in DIS using positrons:**
  - **New calculation** shows that NLO asymmetry is larger now for 11 GeV (than in the proposal), but at least 20 times much smaller at 22 GeV. Djangoh developer (Hubert S.) also suggested lower  $y$  settings; H. Spiesberger, DJANGO4.6.19

Djangoh 4.6.16 vs. 4.6.19 (lepton-charge for deuteron fixed target)



Idea: with positron beam, study TPE DIS (QED NLO) first

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  - We now have the tool for calculation, can do **FOM study** [target position/ scattering angle/  $(x, Q^2, y)$ ]:
    - develop the physics case (TPE in DIS?); multi-stage approach?
    - calculation of  $A^{e^+e^-}$  LO and NLO over a wide range of  $(x, Q^2)$ , optimize kinematics separately for:
      - TPE study (test NLO calculations, need  $NLO \gg LO$ )
      - electroweak study (need  $NLO \ll LO$ ), measure  $C_{3q}$  ;
      - possibly study NLO at 11 GeV and  $C_{3q}$  at 22 GeV?
  - Proposal focusing on testing TPE DIS calculation possible (2024?), and [e+@22 GeV](#) in the (far) future.

# Past Experiments – SLAC, HERMES, OLYMPUS (elastic), HERA

- D.L. Fancher et al, [Phys.Rev.Lett.37, 1323 \(1976\)](#)

13.5-GeV beams at **Stanford Linear Accelerator Center**, compared electron and positron inelastic scattering in  $1.2 < Q^2 < 3.3 \text{ (GeV/c)}^2$ ,  $2 < \nu < 9.5 \text{ GeV}$ . Found “e+/e- cross section ratio =  $1.0027 \pm 0.0035$  (including stat and syst effects), with no significant dependence on  $Q^2$  or  $\nu$ . This result has appreciably smaller errors to fine TPE effects in electron or muon scattering.”

Note:  $A_{e+e-} \sim 1E-4$ , Coulomb  $\sim 1E-5$  to  $1E-4$ , QED NLO  $\sim 1E-4$  for these kinematic settings.

- A. Airapetian et al., [JHEP 05 \(2011\) 126](#) – **HERMES** inclusive paper; G. Schnell p.v.: Overall normalization of DIS xsection was at **8% level**.

- B.S. Henderson et al., [Phys. Rev. Lett. 118 \(2017\) 092501](#) **OLYMPUS**

“The relative luminosity between the two beam species was monitored using tracking telescopes of interleaved gas electron multiplier and multiwire proportional chamber detectors at  $12^\circ$ , as well as symmetric Moller or Bhabha calorimeters at  $1.29^\circ$ . The uncertainty in the relative luminosity between beam species of **0.36%** was achieved.”

Note: 0.36% luminosity control is not going to help us

- V. Andreev et al. (**H1 Collaboration**), [Eur. Phys. J. C 78 \(2018\) 9, 777](#)  
luminosity  $\sim 2\%$  with partial cancellations, measured e- and e+ DIS cross sections.

Note: At HERA energy, QED NLO is relatively small