Measurement of e^+/e^- – ^{2}H DIS Asymmetries Using SoLID and a Positron Beam at JLab

Xiaochao Zheng
Univ. of Virginia
April 17, 2021

– SM NC couplings
– all γZ interference asymmetries in lepton scattering
– measurement of $A^{e^+e^-}_{unpol}$ DIS asymmetry
– roadmap towards realization

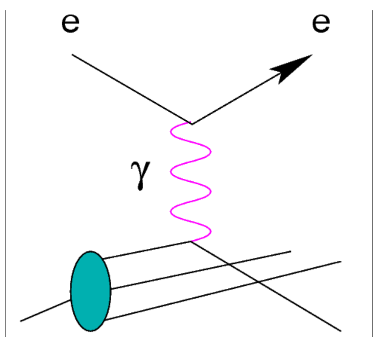
An idea being developed
https://arxiv.org/abs/2103.12555
https://arxiv.org/abs/2007.15081

Thanks to:
– David Flay, Joe Grames, Paul Reimer, Ye Tian, Eric Voutier, Jixie Zhang, Zhiwen Zhao
– Andrei Afanasev, Jens Erler, Qishan Liu, Hubert Spiesberger

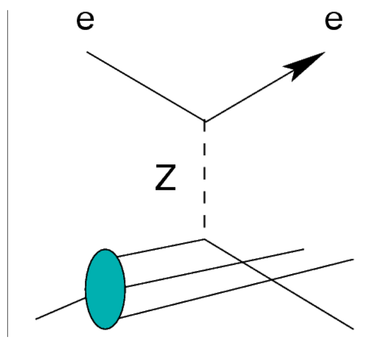
Neutral-Current Weak Interaction in Electron Scattering

In typical PVES: we measure parity violating asymmetries (A_{PV}) between left- and right-handed electron beam scattering off an unpolarized target

A_{NC} =



+



$$J_\mu^{NC}(lepton) = \left(\bar{u}_l \gamma_\mu \frac{1}{2}(c_V^l - c_A^l \gamma^5) u_l\right)$$

$$-i \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{M_Z^2}}{q^2 - M_Z^2}$$

$$J_\mu^{NC}(q) = \left(\bar{u}_q \gamma_\mu \frac{1}{2}(c_V^q - c_A^q \gamma^5) u_q\right)$$

at $Q^2 << M_Z^2$:

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

VV (identical to γ)

AV, VA (parity-violating)

AA

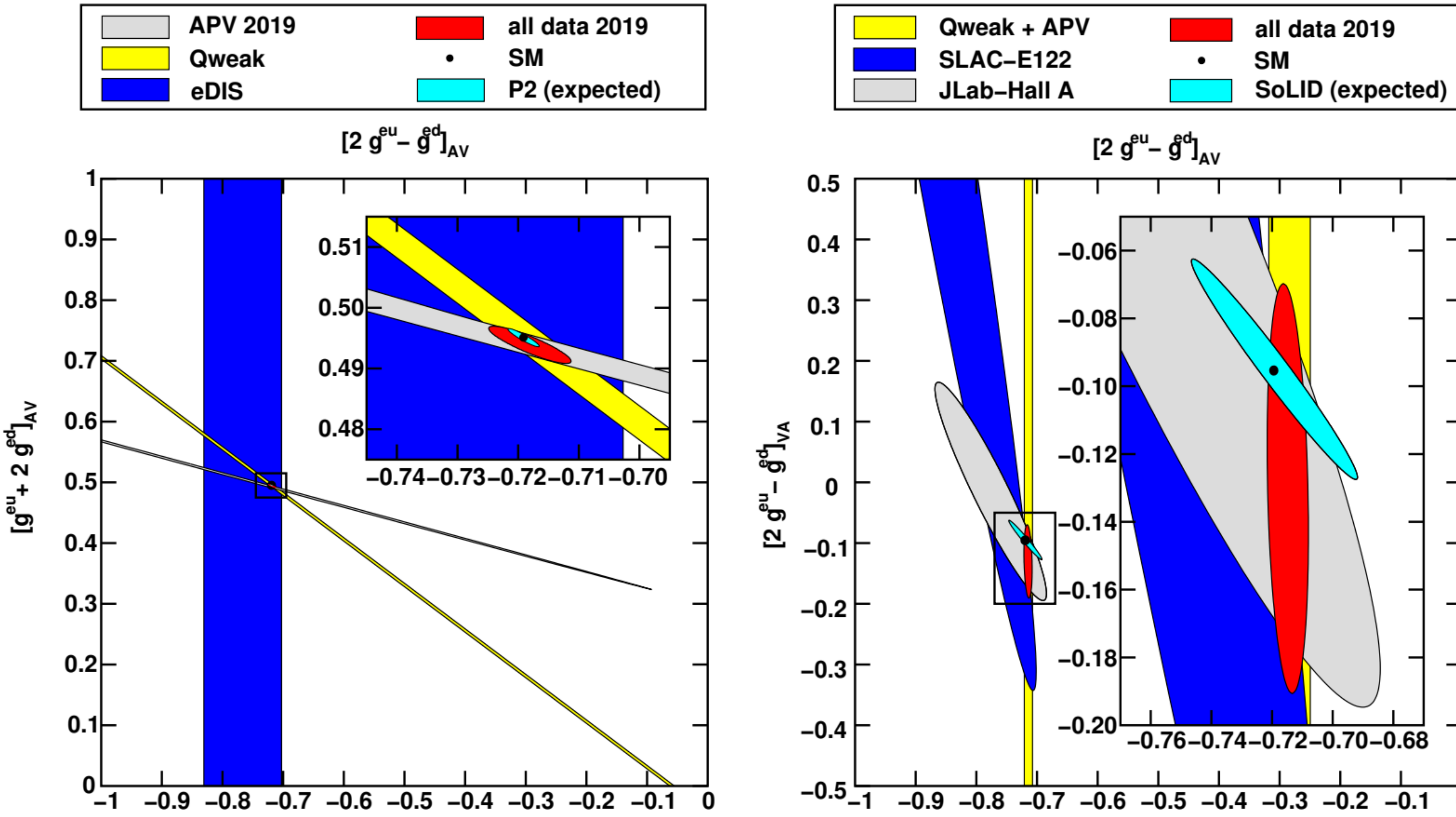
$$C_{1u} = 2 g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3} \sin^2(\theta_W) \qquad C_{2u} = 2 g_V^e g_A^u = -\frac{1}{2} + 2 \sin^2(\theta_W) \qquad C_{3u} = -2 g_A^e g_A^u = \frac{1}{2}$$

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

https://arxiv.org/abs/2103.12555

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

all are 68% C.L. limit



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

Asymmetries in Lepton – Nucleus DIS

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

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

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

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

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

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

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

In the Parton Model

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

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

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

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

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

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

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

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

beam polarization

$$Y(y)=\frac{1-(1-y)^2}{1+(1-y)^2}$$

(indicates spin flip of quarks)

$$R_V(x)=\frac{u_V(x)+d_V(x)}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$

$$y=\frac{E-E'}{E}$$

In the Parton Model

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

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

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

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)

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

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

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

(flip $|\lambda|$ for LR)

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

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

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

(flip $|\lambda|$ for LL)

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

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

In the Parton Model

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

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

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

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)

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

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

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

(flip |λ| for LR)

"B" in CERN measurement

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

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

(flip |λ| for LL)

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

not "charge conjugation" asymmetry

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

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

(no polarization needed!)

Designing the Experiment

Need high Q^2, high Y(y) → SoLID PVDIS configuration is ideal

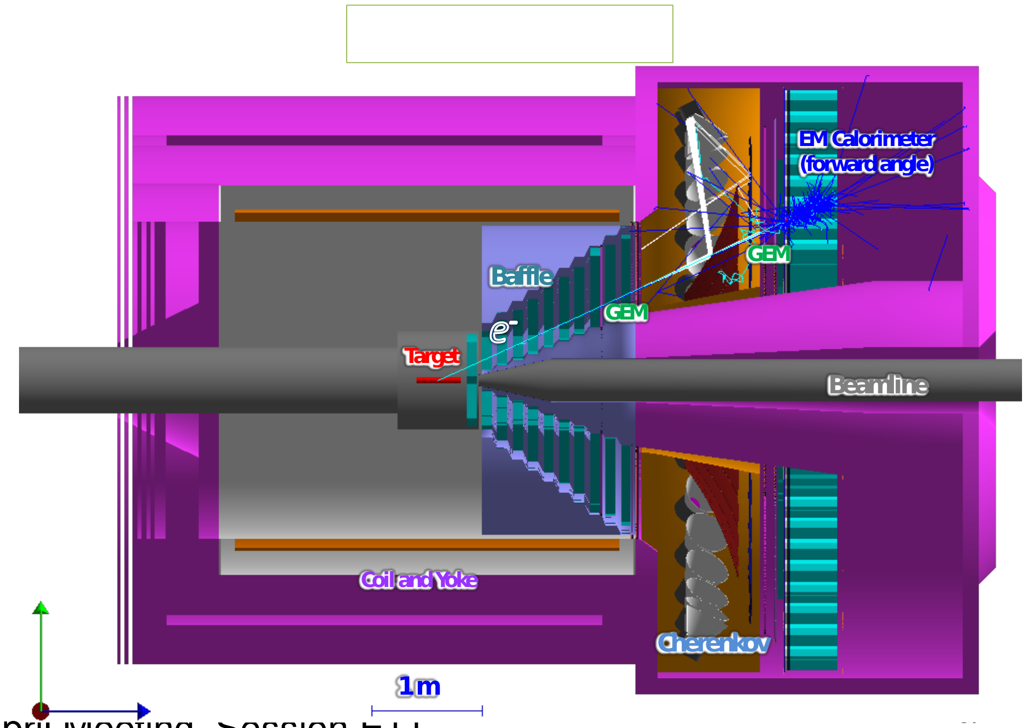
Need positron beam → PEPPo: up to 5uA for unpolarized, much lower for polarized. We will ask for 3uA, 88 days 11 GeV, some 6.6 GeV

Need positron detection → reverse magnet polarity of SoLID, run magnets always at full saturation (field difference < 1E-5)

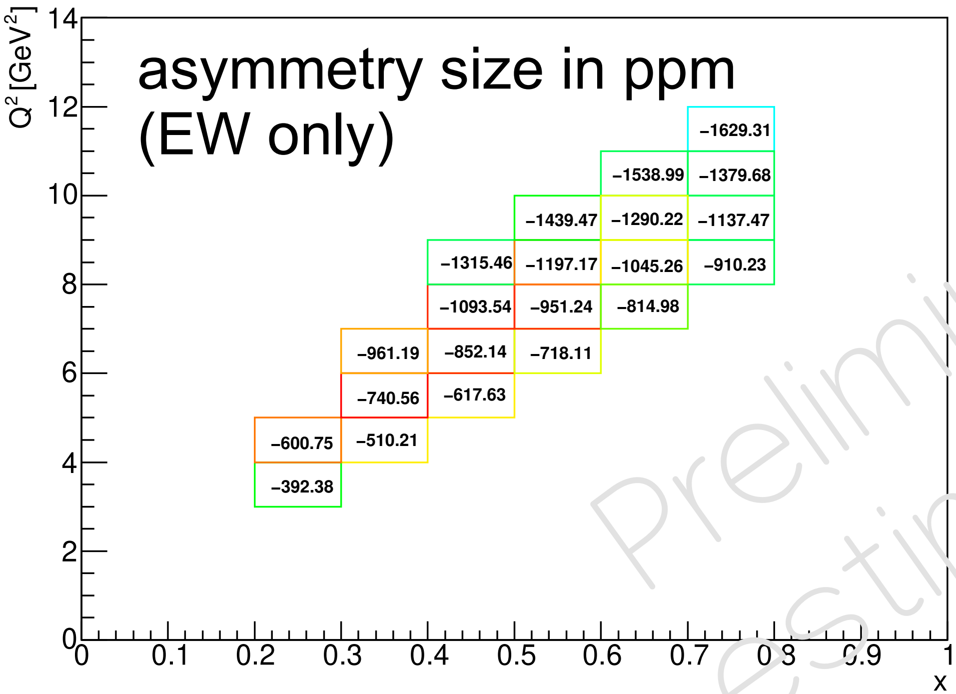
For each of e+ and e- run, also need reverse polarity runs to determine pair production background (8 of 88 days)

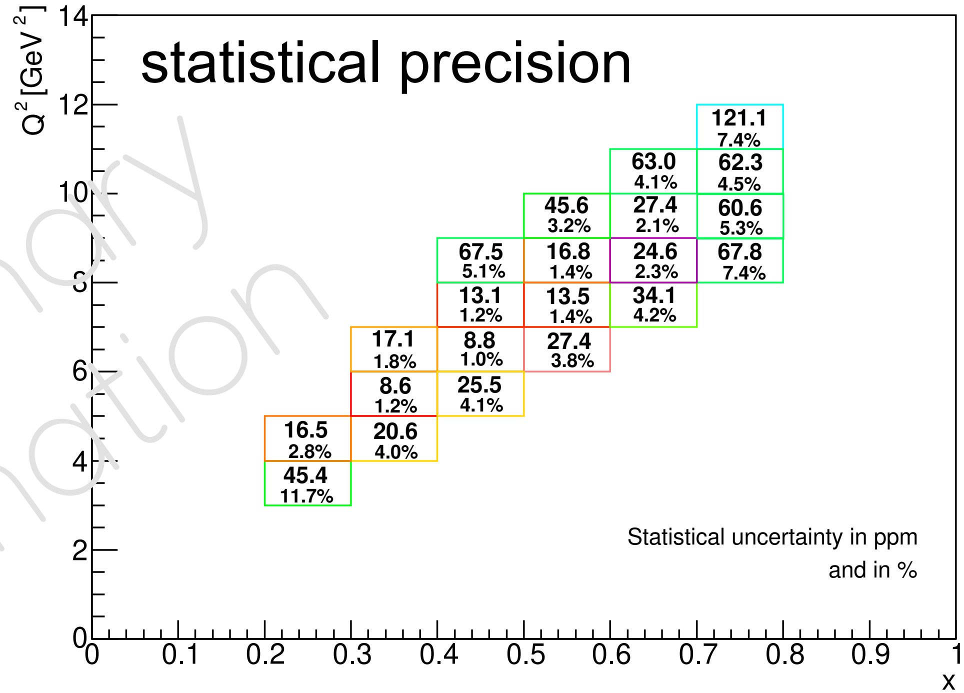
Experimental challenges:
- Ebeam, luminosity, charged pion and pair production background

Theoretical challenges:
- higher-order QED corrections
- higher-twist



What can we do with 80 days of 3uA beam? (in absence of all challenges):

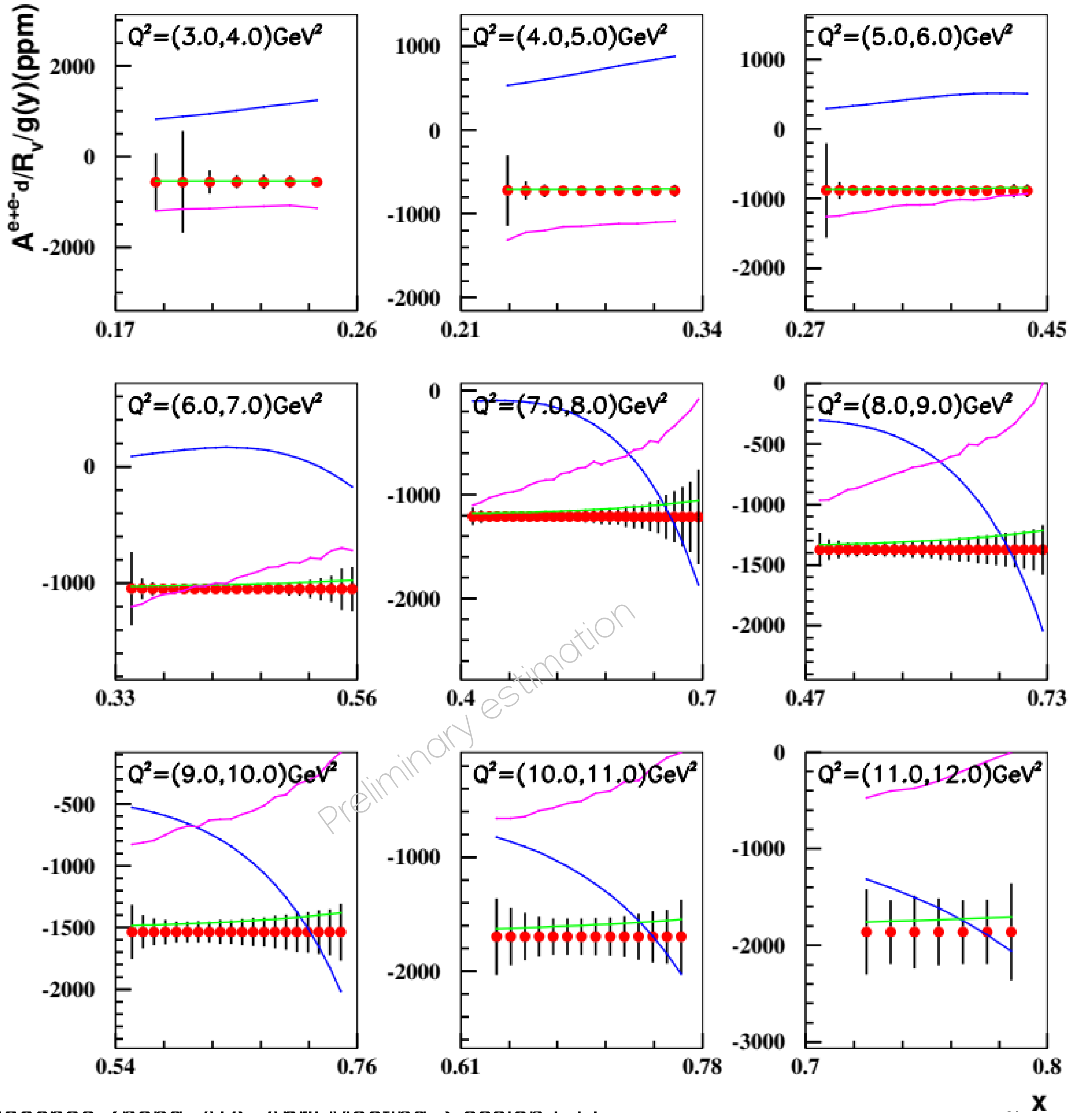




if we only consider statistics and assume A=0 at Q^2=0:

1.5 ± 0.007

Experimental Challenges

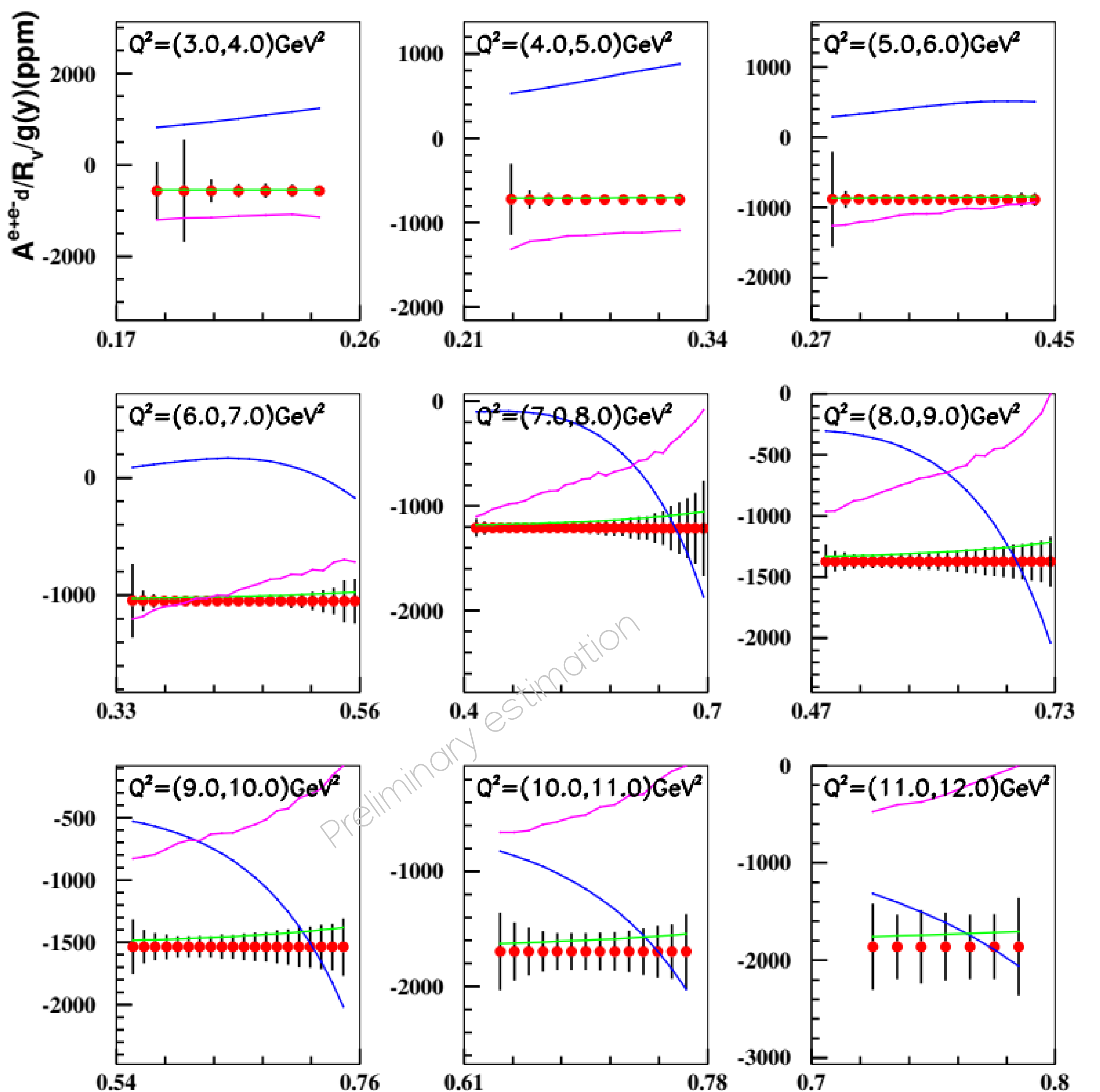


assuming:
Luminosity difference up to 1% (not shown)

Ebeam difference up to 5E-4 (the unknown part)

Eprime difference up to 1E-5

Experimental Challenges



assuming:
Luminosity difference up to 1% (not shown)

± 0.032

Ebeam difference up to 5E-4 (the unknown part)

Eprime difference up to 1E-5

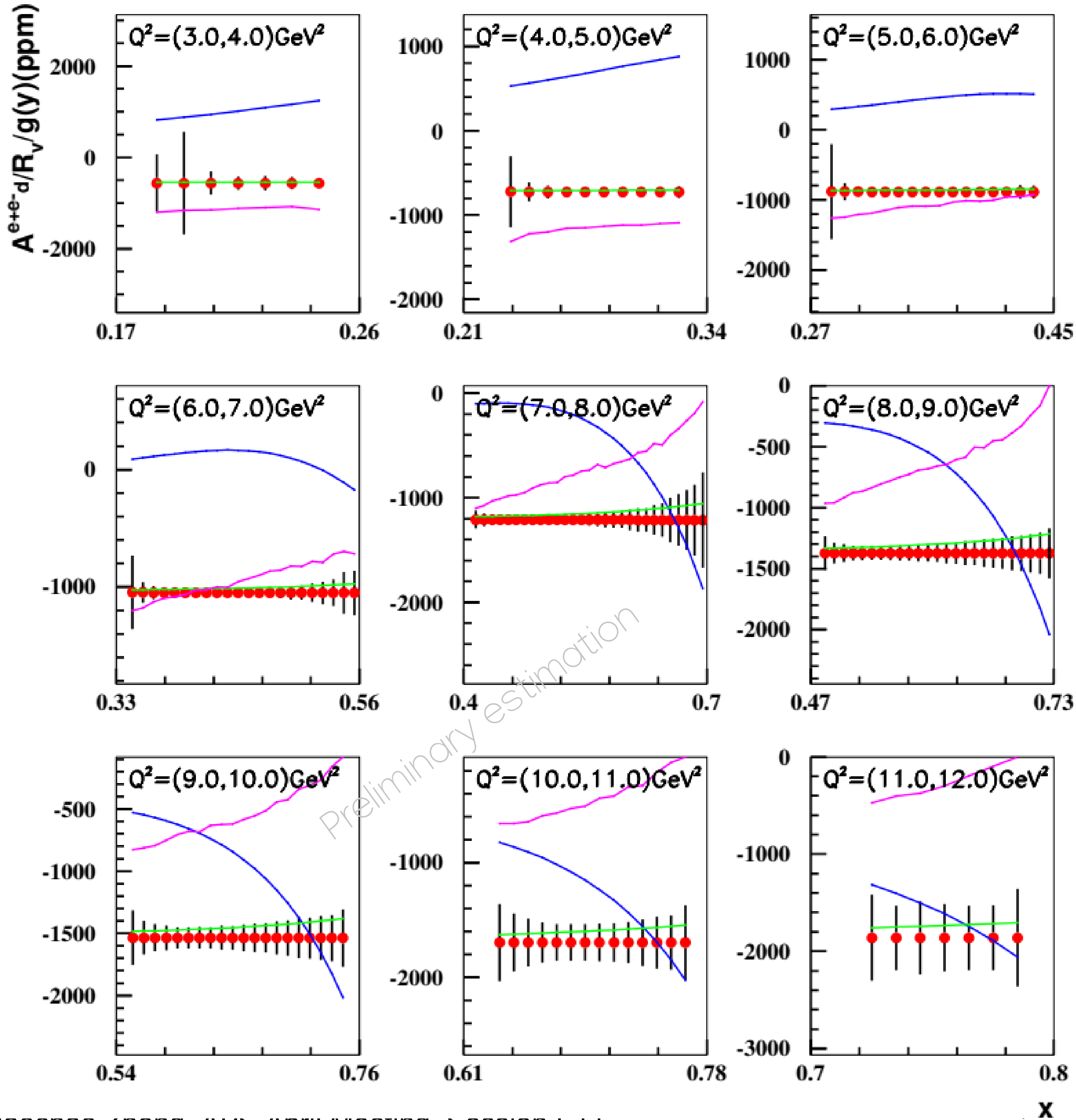
± 0.066

Theoretical Challenges

QED NLO term
(/5 !)

We used DJANGOH, a Monte Carlo program developed for HERA and modified for fixed-target experiments, just to have a sense how big the contribution is.

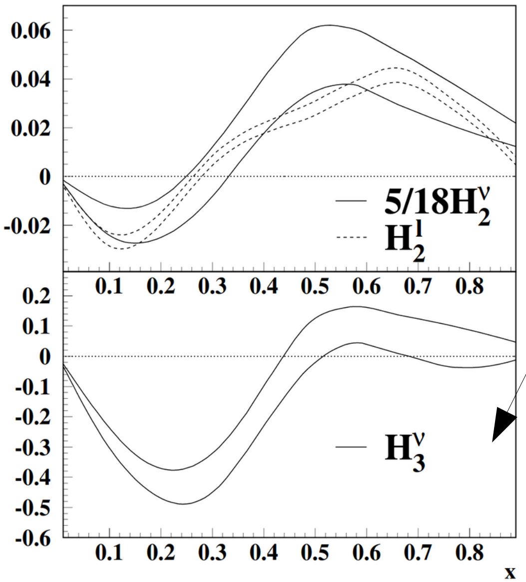
→ need to know to 1% for a meaningful extraction of C3q



More Theoretical Challenges

Higher twists! - most PVDIS studies focused on the c_1 term and found 10^{-3} effects.

For c_2 or $F_3^{\gamma Z}$, used neutrino results:



$$xF_3^\nu = xF_3^{\nu,\mathrm{LT}} + \frac{H_3}{Q^2}$$

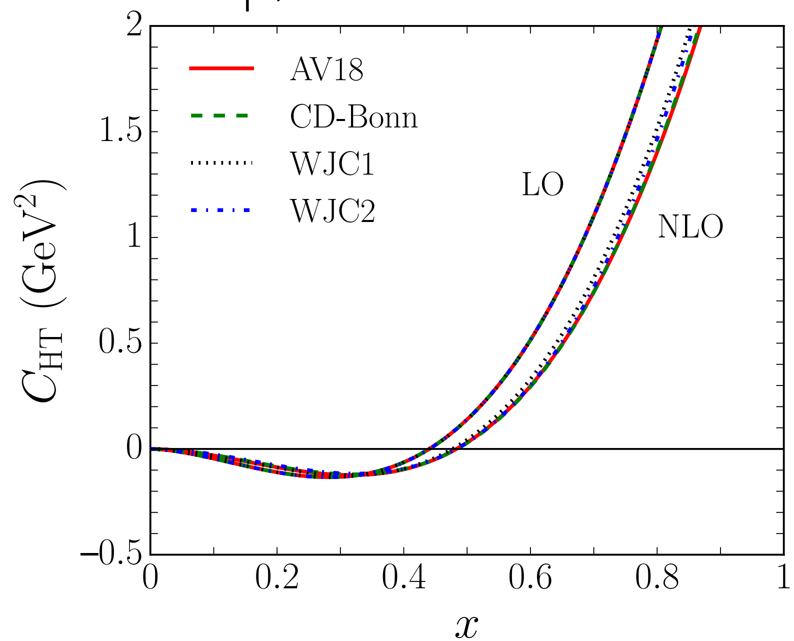
$$xF_{3,p}^\nu = 2x(u - \bar{d} + s - \bar{c})$$

$$xF_{3,d}^\nu = 2x(u_V + d_V + 2s - 2\bar{c})$$

AIP Conf.Proc.967:215-224,2007

https://arxiv.org/abs/0710.0124

For F_1^γ, used CJ's latest:



Phys.Rev.D 93 (2016) 11, 114017
e-Print: 1602.03154 [hep-ph]

– browsing through citations of this paper, I did not find any newer work on H3nu

– studied effect on asymmetries

– apply HT term and refit → ± 0.065 ?

Summary

– Exploratory measurement of e+ vs. e- DIS asymmetries using SoLID and a positron beam at JLab

– If all experimental systematic effects and QED higher order correction can be controlled or understood (1%), can provide the first direct measurement of the AA electron-quark effective couplings,

– total uncertainty can reach $2C_{3u}^{eq} - C_{3d}^{eq} = 1.5 \pm 0.104$? recall:

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

Preliminary estimation

– New physics mass limit:

$$\Lambda_{AA} = v\sqrt{\frac{\sqrt{5}\,8\pi}{\left|\left(2C_{3u} - C_{3d}\right)\right|}} \approx 5.7\,\mathrm{TeV}$$

– Take this to the EIC? (higher Q^2, less QED, maybe comparable to EW, but low y – big problem)

What about C_{3q}?

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

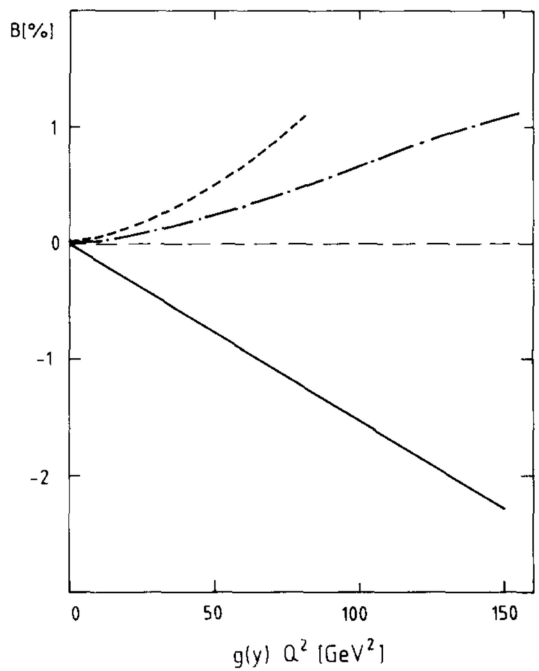


Fig. 2. The B asymmetry from γ–Z^0 interference to first order, calculated for a polarization $\lambda = 0.81$ and $\sin^2\theta_W = 0.23$ (solid line), and the asymmetry expected from higher order electromagnetic processes at beam energies of 120 GeV (dashed line) and 200 GeV (dashed–dotted line).

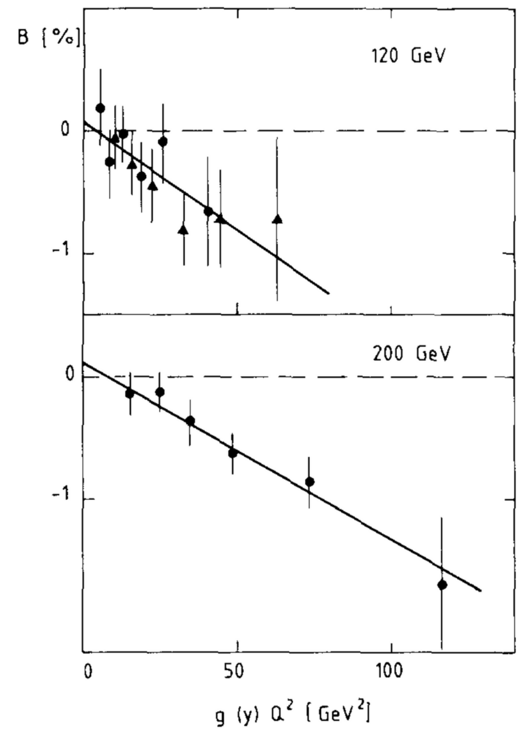


Fig. 3. The measured B asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy versus $g(y)Q^2 = Q^2 \times [1-(1-y)^2]/[1+(1-y)^2]$ [eq. (3)]. For the 120 GeV data, circles represent data with $Q^2 > 15$ GeV. Solid lines are

But a measurement for the electron is highly desired (and not just because of the muon g-2 release, the LHCb's beauty quark decay observation...)

Full expression in parton model

(done)

For the deuterium, adding s and c:

$$A_d = (540\ ppm) Q^2 \frac{2C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(y)[2C_{2u}(1+\epsilon_c) - C_{2d}(1+\epsilon_s)]R_V(x)}{5+R_S(x)+4R_C(x)}$$

$$A_d^{e^+e^-} = -(540\ ppm) Q^2 \frac{Y(y)[2C_{3u}(1+\epsilon_c) - C_{3d}(1+\epsilon_s)]R_V(x)}{5+R_S(x)+4R_C(x)}$$

$$R_S(x) = \frac{2[s(x)+\bar{s}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \qquad R_C(x) = \frac{2[c(x)+\bar{c}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \qquad \epsilon_{c(or\,s)} = \frac{2[c(x)-\bar{c}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$

(done) The general case

based on
Anselmino et al. [arXiv:hep-ph/9401264]
also in
Hobb et al. arXiv:0801.4791;
Brady et al.[arXiv:1108.4734 [hep-ph]].

For PVDIS:

$$A_{RL}^{e^-}=\frac{|\lambda|\,\eta_{\gamma Z}\left[g_A^e\,2\,y\,F_1^{\gamma Z}+g_A^e\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}+g_V^e(2-y)F_3^{\gamma Z}\right]}{2\,y\,F_1^{\gamma}+\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma}-\eta_{\gamma Z}\left[g_V^e\,2\,y\,F_1^{\gamma Z}+g_V^e\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}+g_A^e(2-y)F_3^{\gamma Z}\right]}$$

For A^{e+e-}:

$$\eta_{\gamma Z}=\frac{G_F Q^2}{2\sqrt{2}\,\pi\alpha}\frac{M_Z^2}{M_Z^2+Q^2}$$

$$A_{RL}^{e^+e^-}=\frac{\eta_{\gamma Z}\left(|\lambda|g_V^e+g_A^e\right)(2-y)F_3^{\gamma Z}}{2\,y\,F_1^{\gamma}+\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma}-\eta_{\gamma Z}\left(g_V^e+g_A^e\right)\left[2\,y\,F_1^{\gamma Z}+\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}\right]}$$

$$A_{RR}^{e^-}=\frac{\eta_{\gamma Z}\,g_A^e\left[-|\lambda|2\,y\,F_1^{\gamma Z}-|\lambda|\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}+(2-y)F_3^{\gamma Z}\right]}{2\,y\,F_1^{\gamma}+\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma}-\eta_{\gamma Z}\,g_V^e\left[2\,y\,F_1^{\gamma Z}+\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}+(2-y)F_3^{\gamma Z}\right]}$$