Measurement of e^+/e^- – ^2H DIS Asymmetries with SoLID and PEPPo at JLab

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(a new proposal for PAC49)

https://arxiv.org/abs/2103.12555

https://arxiv.org/abs/2007.15081

– Neutral-Current electron-quark effective couplings

– all γZ interference asymmetries in lepton scattering

– measurement of $A^{e^+ e^-}_{unpol}$ DIS asymmetry → roadmap towards realization

– projected results and summary

Thanks to:

– Alexandre Camsonne, David Flay, Joe Grames, Hanjie Liu, Dave Mack, Paul Reimer, Yves Roblin, Ye Tian, Eric Voutier, Weizhi Xiong, Jixie Zhang, Zhiwen Zhao

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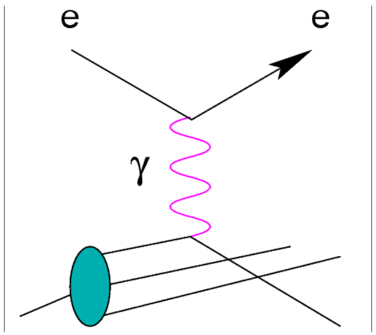
Neutral-Current Weak Interaction in Electron Scattering

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

$A_{NC} =$



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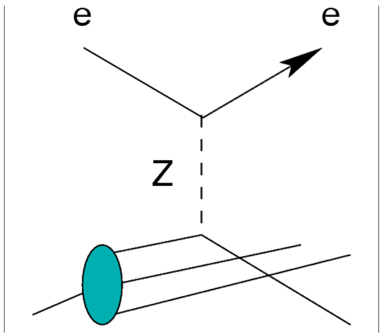


$$J_\mu^{NC}(lepton) = \left(\bar{u}_l \gamma_\mu \frac{1}{2}(c_V^l - c_A^l \gamma^5) u_l \right)$$

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

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

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

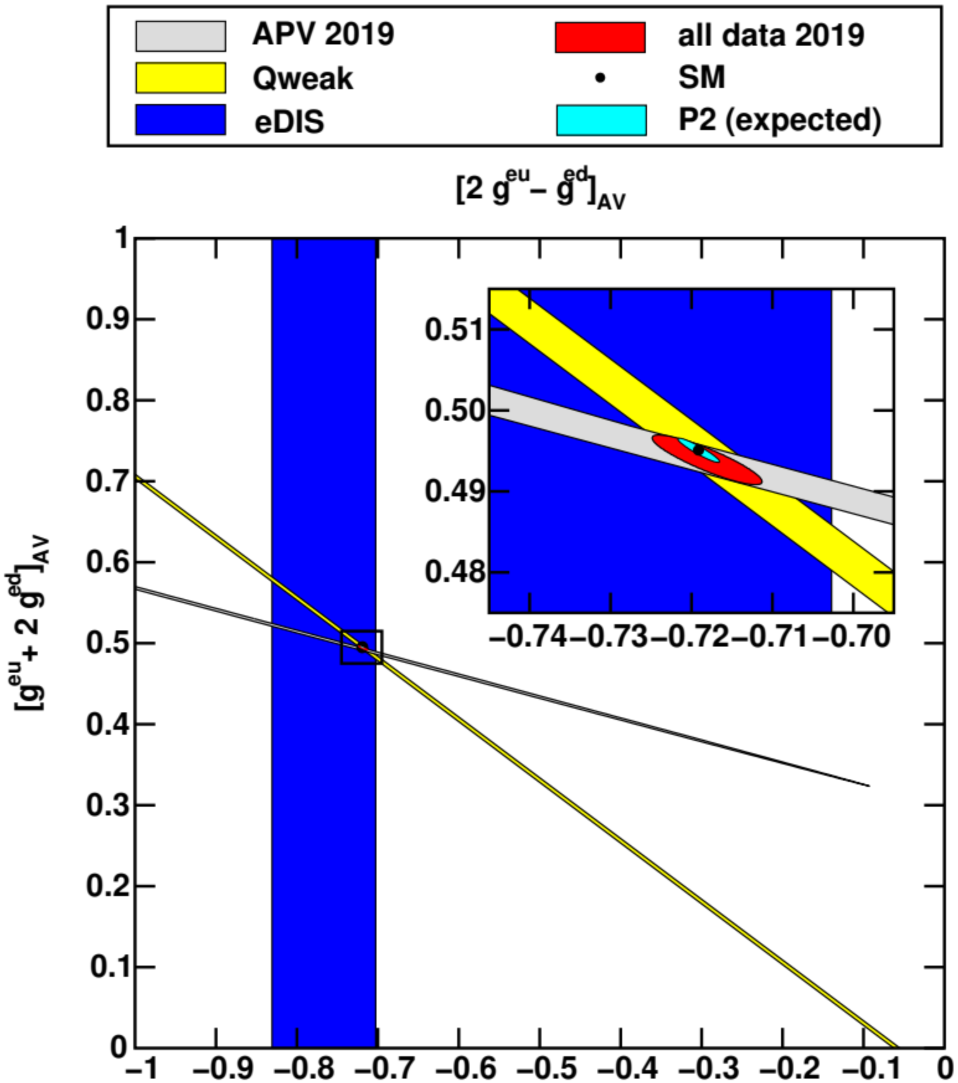
$$C_{1u} = 2 g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \quad C_{2u} = 2 g_V^e g_A^u = -\frac{1}{2} + 2\sin^2(\theta_W) \quad C_{3u} = -2 g_A^e g_A^u = \frac{1}{2}$$

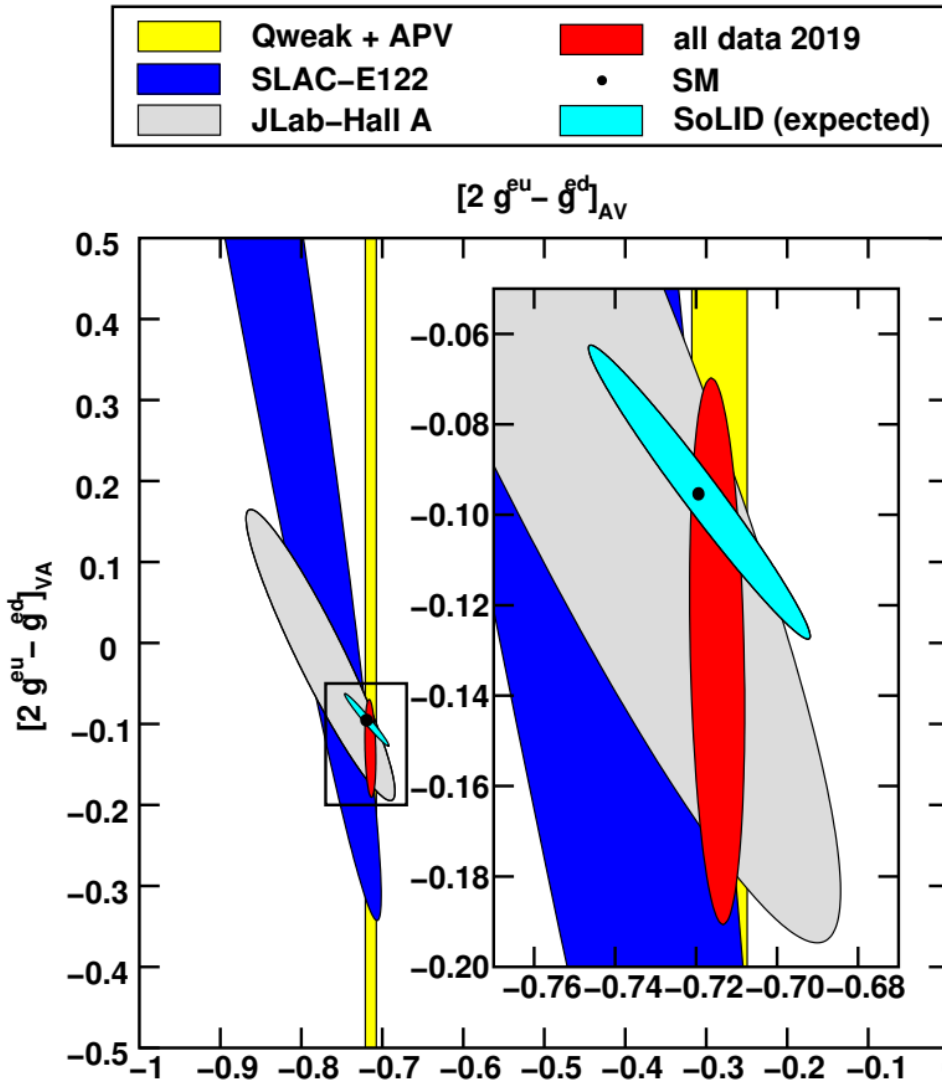
$$C_{1d} = 2 g_A^e g_V^d = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \quad C_{2d} = 2 g_V^e g_A^d = \frac{1}{2} - 2\sin^2(\theta_W) \quad C_{3d} = -2 g_A^e g_A^d = -\frac{1}{2}$$

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

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

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

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

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

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

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

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

In the Parton Model

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

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

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

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

beam polarization

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

(indicates spin flip of quarks)

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

In the Parton Model

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

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

(flip |λ| for LR)

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

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

(flip |λ| for LL)

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

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

In the Parton Model

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

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

beam polarization

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

(indicates spin flip of quarks)

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

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

(flip |λ| for LR)

"B" in CERN measurement

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

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

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

(flip |λ| for LL)

not "charge conjugation" asymmetry → "lepton charge" asymmetry is more appropriate

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

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

(no polarization needed!)

e^+e^- for Structure Function Study

Full expression
$$A_{RL}^{e^+e^-} = \frac{\eta_{\gamma Z}\left(|\lambda| g_V^e + g_A^e\right)(2-y) F_3^{\gamma Z}}{2yF_1^\gamma + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^\gamma - \eta_{\gamma Z}\left(g_V^e + g_A^e\right)\left[2yF_1^{\gamma Z} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}\right]}$$

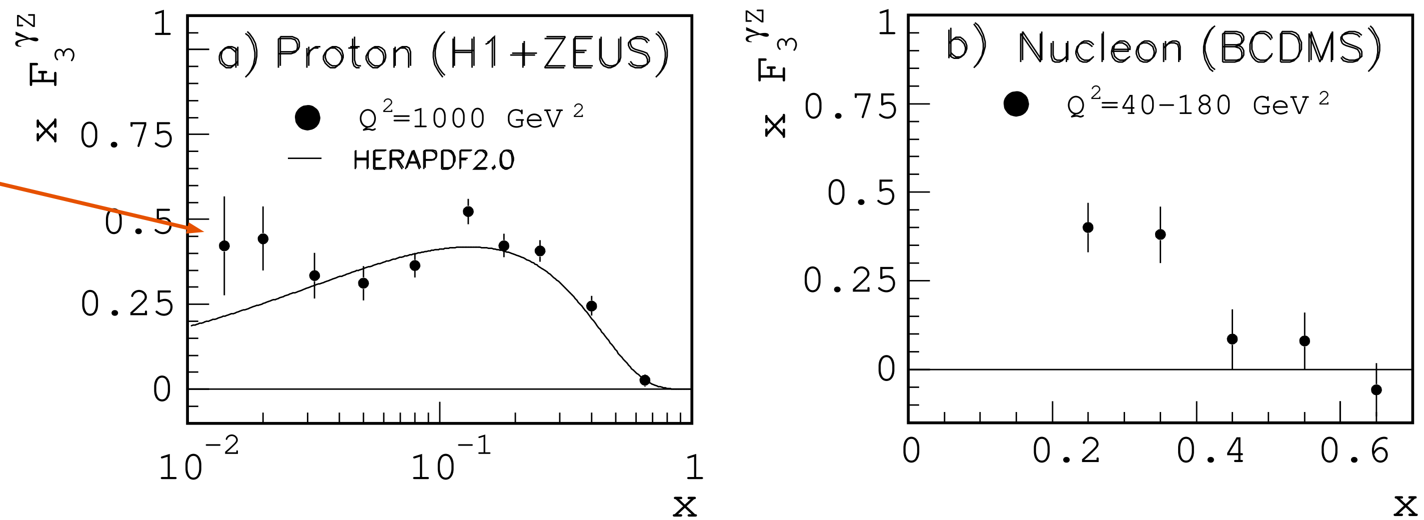
Approximation:
$$A_{RL}^{e^+e^-} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{g_A^e}{2}Y(y)\frac{F_3^{\gamma Z}}{F_1^\gamma}$$

In 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

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

($\rightarrow$ LHeC)



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

(remember in luminosity: 1 minute of JLab beam = HERA lifetime)

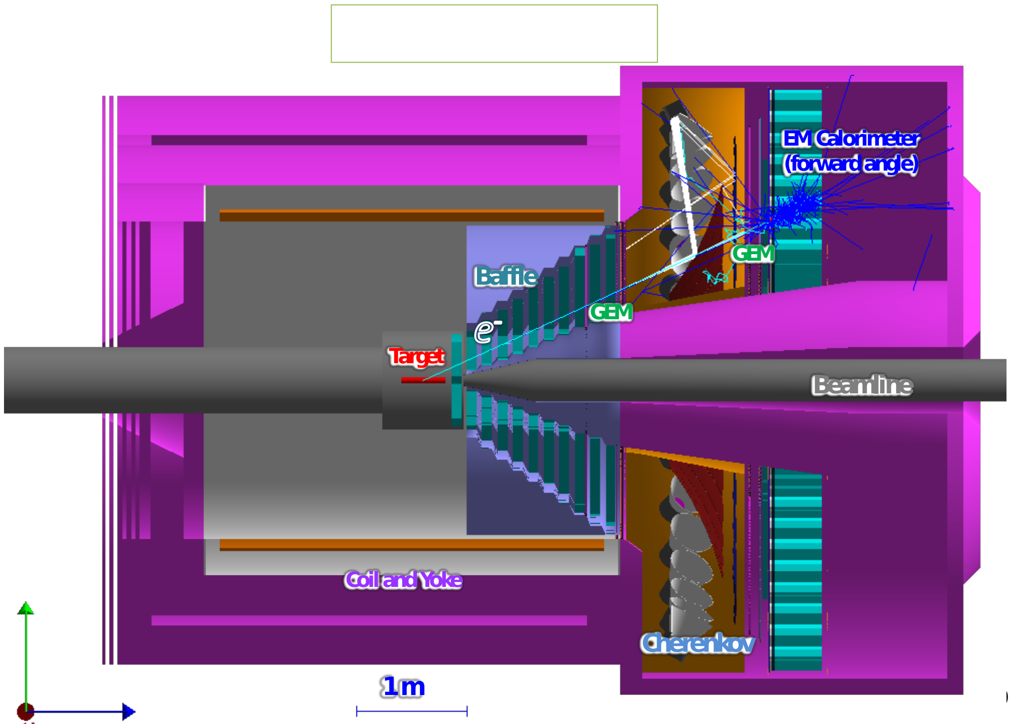
Designing the Experiment

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

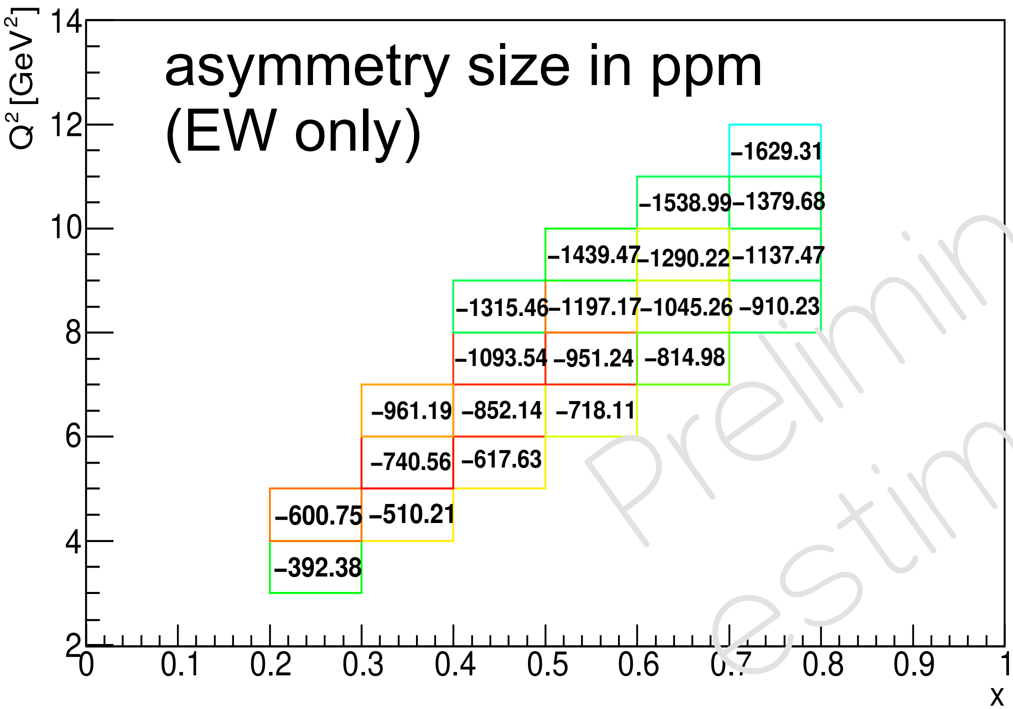
Need positron beam → PEPPo: up to 5uA for unpolarized, much lower for polarized. We ask for 3uA, 88 days 11 GeV, 8 days 6.6 GeV

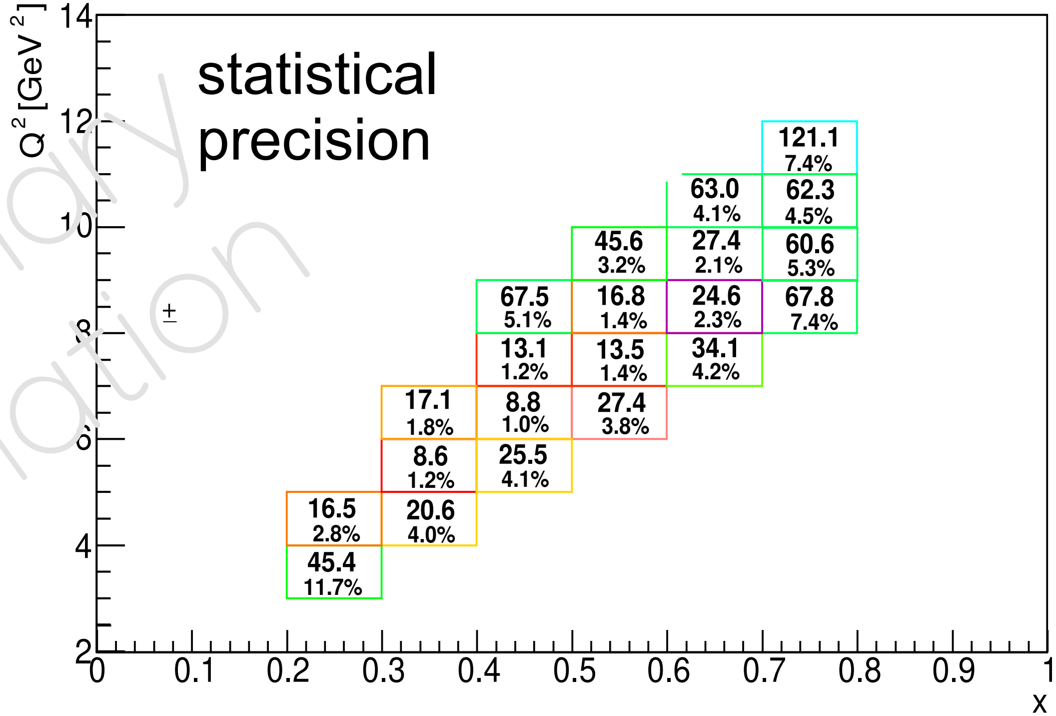
Need positron detection → reverse magnet polarity of SoLID, run magnets always at full saturation (field mapping tool → keep field difference < 10^{-5})

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



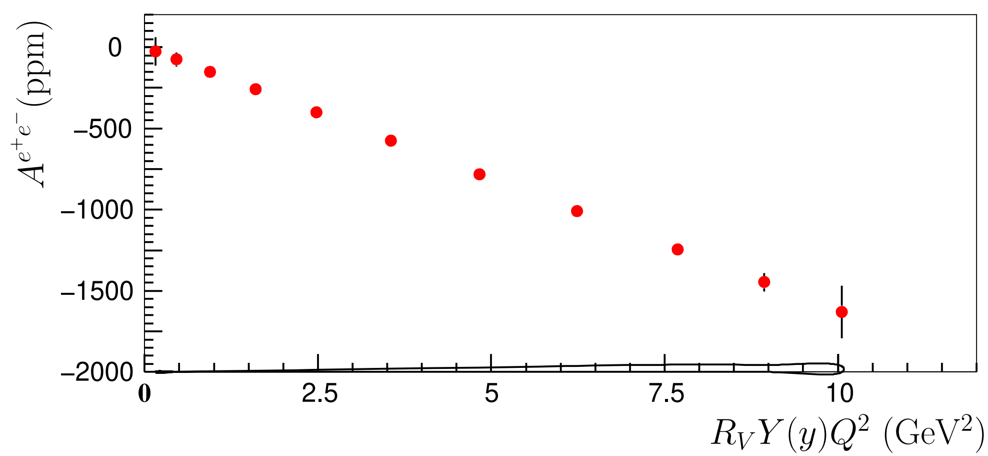
What can we do with 80 days of 3uA beam on a 40cm LD2 target? (in absence of all challenges):





if we consider only statistics and assume A=0 at Q^2=0: 1.5 ± 0.007

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



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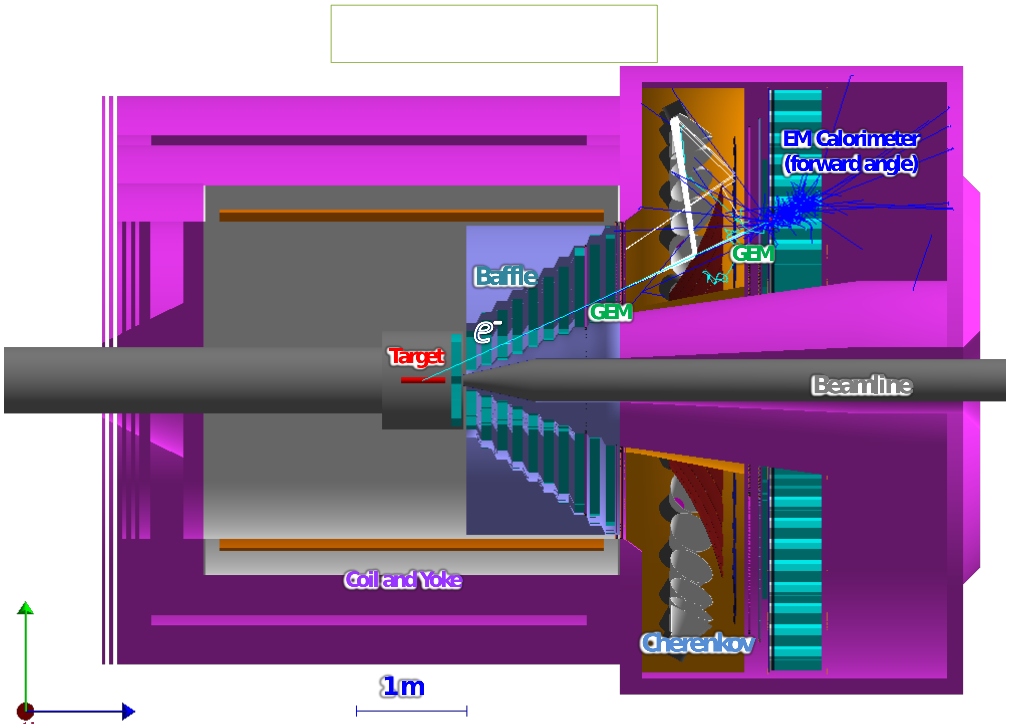
Experimental challenges:
- Ebeam, luminosity, charged pion and pair production background

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



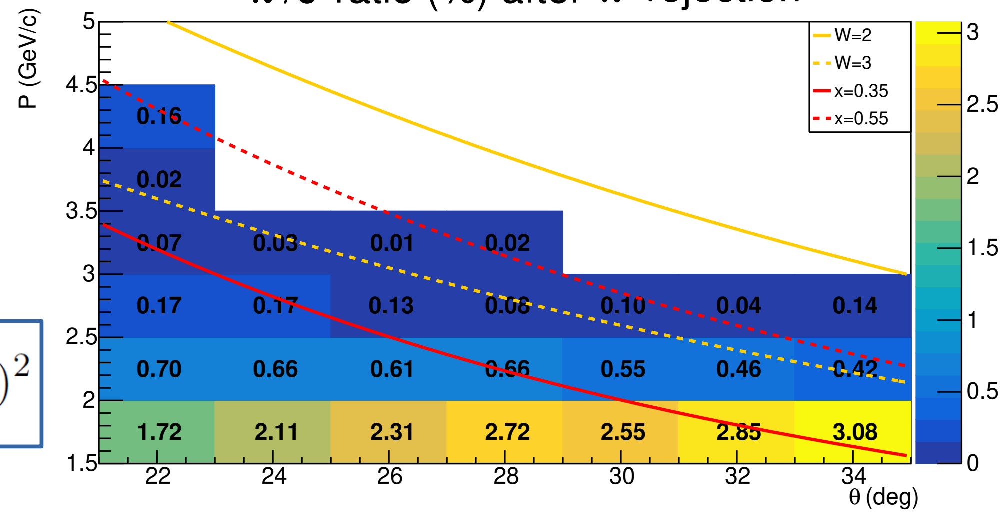
Background

For any background, measure bg asymmetry and apply correction: $A_{DIS} = (1+f)\, A_{total} - f\, A_{bg}$

pion or proton background: large asymmetry (30% for pion, 100% for proton)

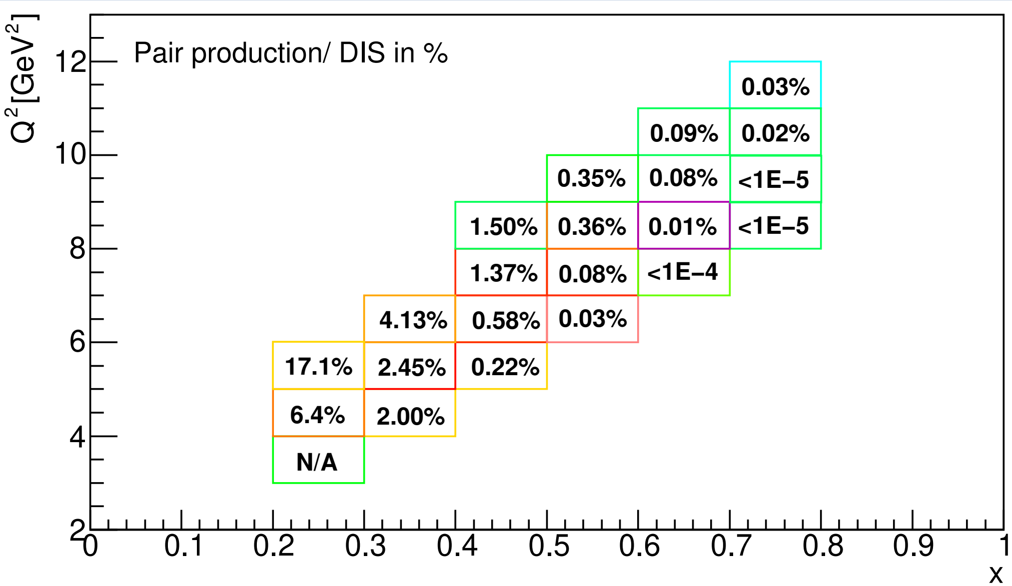
$$(\Delta A_{\rm DIS})^2_{\pi\ bg} = \frac{1}{N_{\rm DIS}} + \frac{f_{\pi/e}}{\eta_\pi N_{\rm DIS}/PS} + (A_{\rm total} - A_\pi)^2 (\Delta f_{\pi/e})^2$$

π^+/e^+ ratio (%) after π^+ rejection



Pair production: zero asymmetry in principle

$$(\Delta A^{\rm DIS})^2_{\rm pair} = \frac{1}{N_{\rm DIS}} + \frac{f_{\rm pair}}{\alpha N_{\rm DIS}} + (A_{\rm pair})^2 (\Delta f_{\rm pair})^2$$



→ spend (α =) 10% of beam time on reverse polarity runs, include effect in data projection

Target endcap: calculable → see proposal

List of Challenges

- slow drift in BCM → (unknown) luminosity difference $\Delta\,\mathrm{Lumi}$
- possible difference in Ebeam ("standard" Hall A → 5E-4) → can calculate effect $\Delta A_{E_b,max}$
- possible difference in magnet strength (E') → has a plan to control this to <1E-5 → can calculate effect $\Delta A_{E',max}$
- background difference (pi+/e+, proton/e+ vs. pi-/e-) → need high PID and know background contamination precisely; need high precision tracking study

- QED higher order contributions: (1) used Djangoh generator to calculate, proof-of-principle results exist (summer student working on improvement); ΔA_{QED} also talked to (2) A. Afanasev; (3) JLab theory group.
- Coulomb effect: follow Aste et al. https://arxiv.org/abs/nucl-th/0502074

Deuteron RMS radius: 2.1421 fm (https://www-nds.iaea.org/ardii) → $R_{eff}=\sqrt{\frac{5}{3}R_{rms}^2}$

→ $V_0=\frac{3}{2}\frac{\alpha\hbar Z}{R_{eff}}$ → $V_{eff}=(0.775\pm0.025)V_0$ and $\text{focusing factor (ff)}=\frac{E_b+V_{eff}}{E_b}$

→ $\sigma_{Coulomb}(E,E',\theta)=\sigma_{Born}(E+V_{eff},E'+V_{eff},\theta)*\mathrm{ff}^2$ – can calculate $\Delta A_{Coulomb}$

- Higher twist pretty much unknown for $F_3^{\gamma Z}(x,Q^2)$, calculated using CJ15's H_2 calculated for SoLID kinematics ΔA_{CJ15}

Experimental Challenges

luminosity difference up to 1% (scaled by 1/10 in the plot) →

Δ Lumi

Ebeam difference up to 5E-4 $\Delta A_{E_b,max}$

Eprime difference up to 1E-5

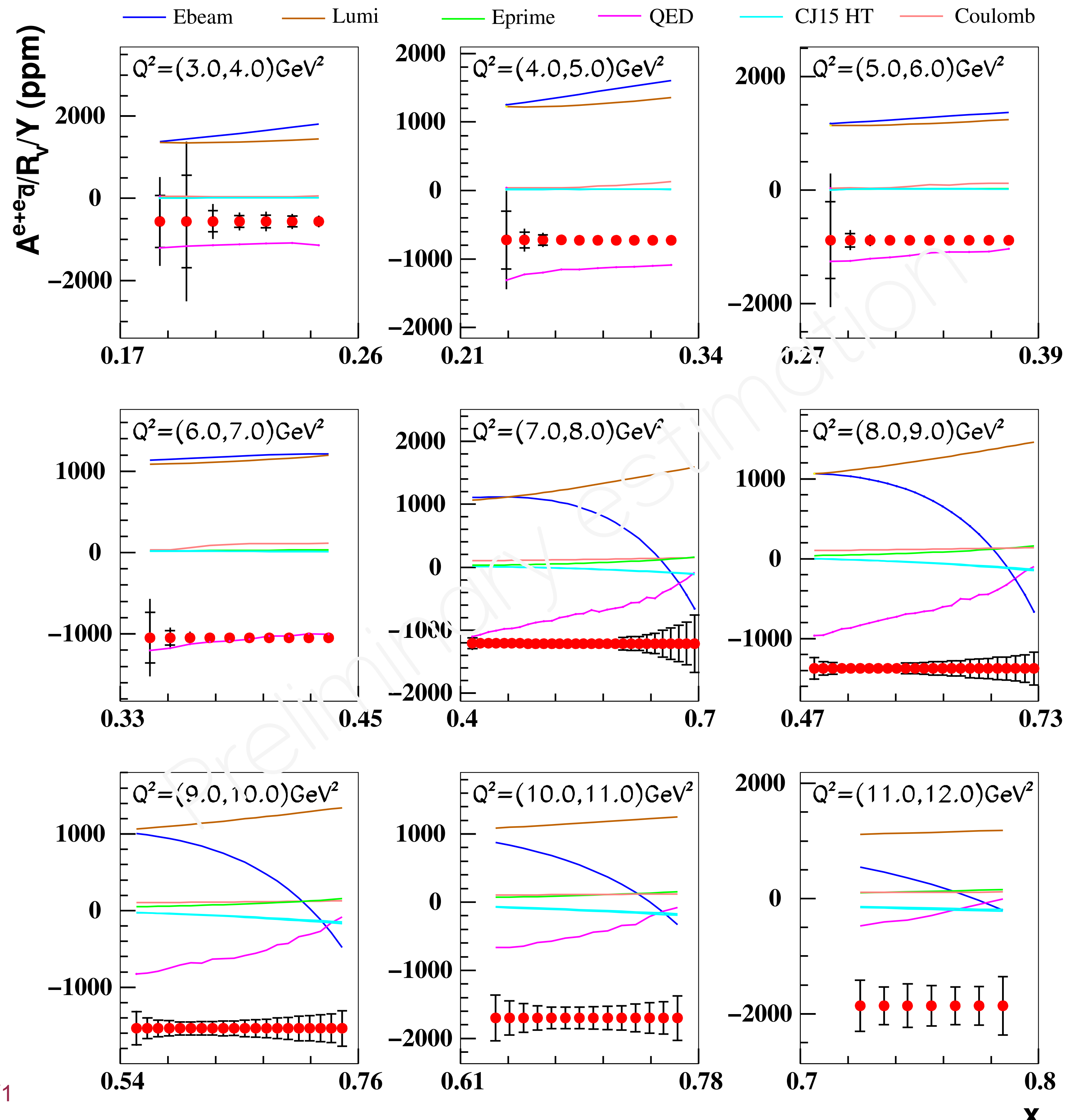
Coulomb correction

$\Delta A_{Coulomb}$

QED higher order

ΔA_{QED}

CJ15 HT: ΔA_{CJ15}



Generating Pseudo Data and Apply Multi-Parameter Fit

- For each set of pseudo data (each experiment), initialize random “pre” factors for lumi, Eb, and E’: $d_0(\text{lumi}) \in (-1\%, 1\%), d_1, d_2 \in (-1,1)$ that follow normal distribution;
- Calculate effect in each (x,Q2) bin the statistical uncertainty (using rates), and the expected maximum effect of lumi, Eb (using 5×10^{-4}), E’ (using 1×10^{-5}), and add background effect:

$$\Delta A_{stat}(x,Q^2), \quad d_0(\text{lumi}), \quad \Delta A_{Eb,\max}(x,Q^2), \quad \Delta A_{E',\max}(x,Q^2)$$

- Produce pseudo data in each fine (x,Q^2) bin, with statistical fluctuation, and add in effect of lumi, Eb, Ep:

$$A_{\text{data}}(x,Q^2) = A_{SM} + d_{stat}\,\Delta A_{stat+bg} + d_0 + d_1\,\Delta A_{Eb} + d_2\,\Delta A_{E'}$$

- Fit (analyze) all pseudo data points using

$$A_{\text{data}}(x,Q^2) = p_0 A_{SM}/1.5 + p_{\text{lumi}} + p_1\,\Delta A_{Eb} + p_2\,\Delta A_{E'} \qquad p_0 \rightarrow (2C_{3u} - C_{3d})$$

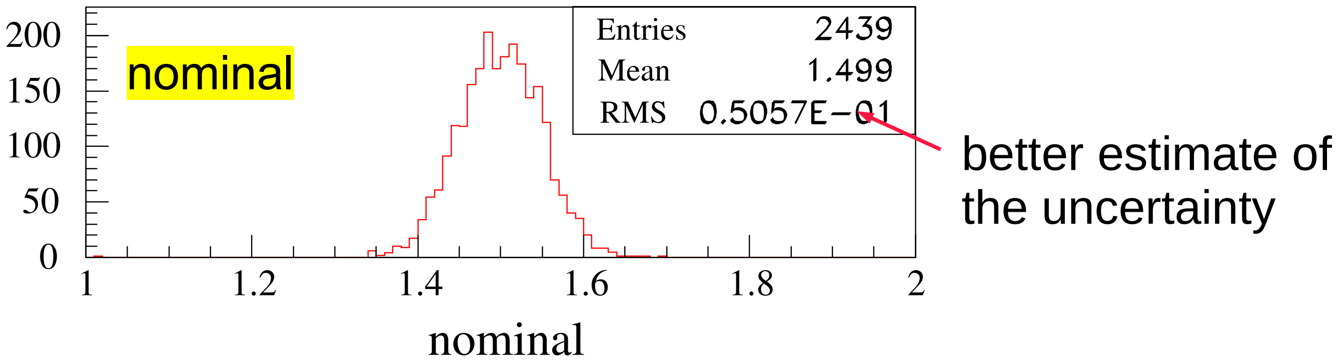
fitting pseudo data with lumi (“lumi fit”): $\Delta p_0 = \pm 0.032$

including also Eb factor (“2exp fit”): $\Delta p_0 = \pm 0.038$

including also E’ factor (“3exp fit”): $\Delta p_0 = \pm 0.065$ → Controlling E’ to <10^{-5} highly desired

Going Through the Process 1000 times

- Repeat for 1000 (or 3000) times and plot the fitted p_0:



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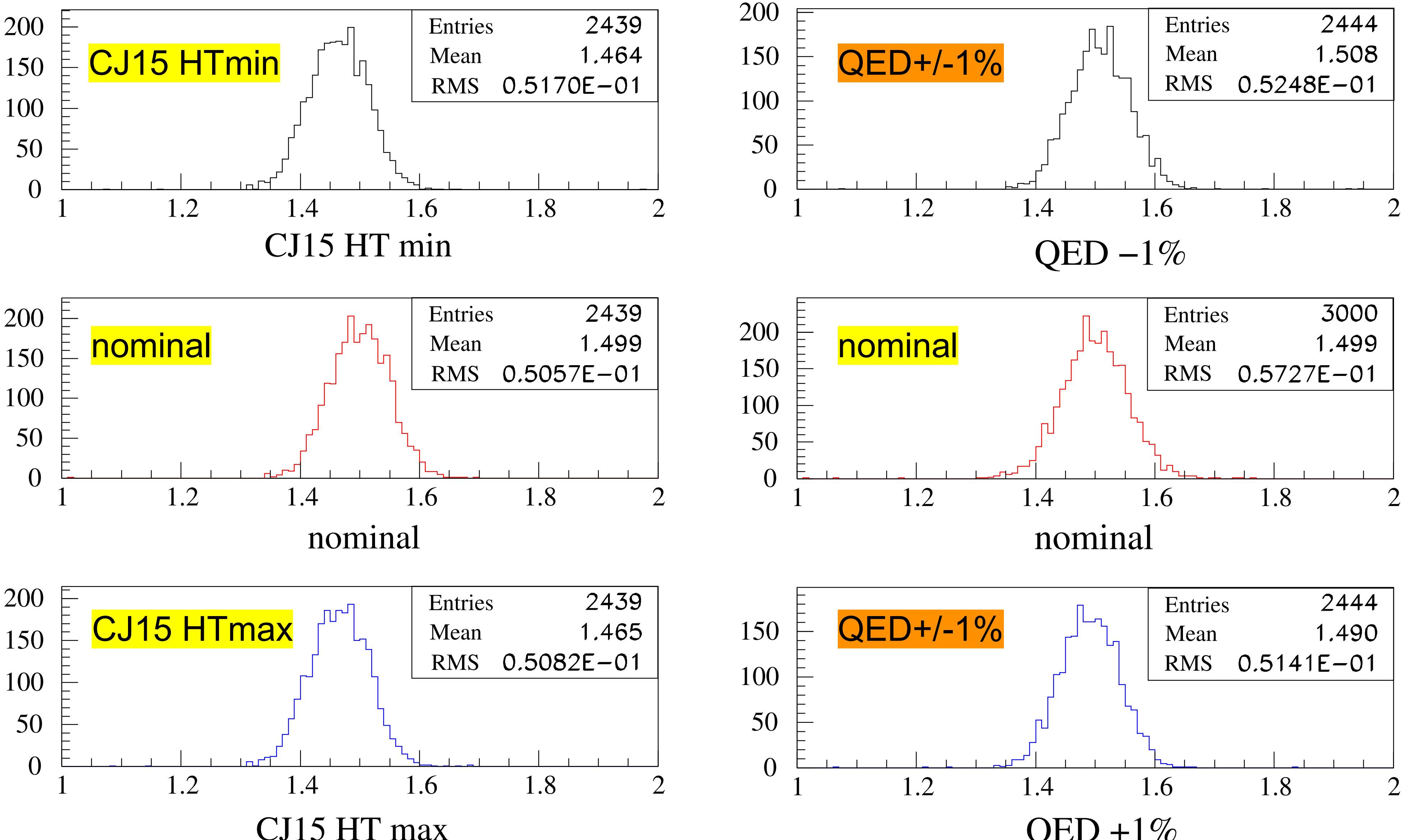
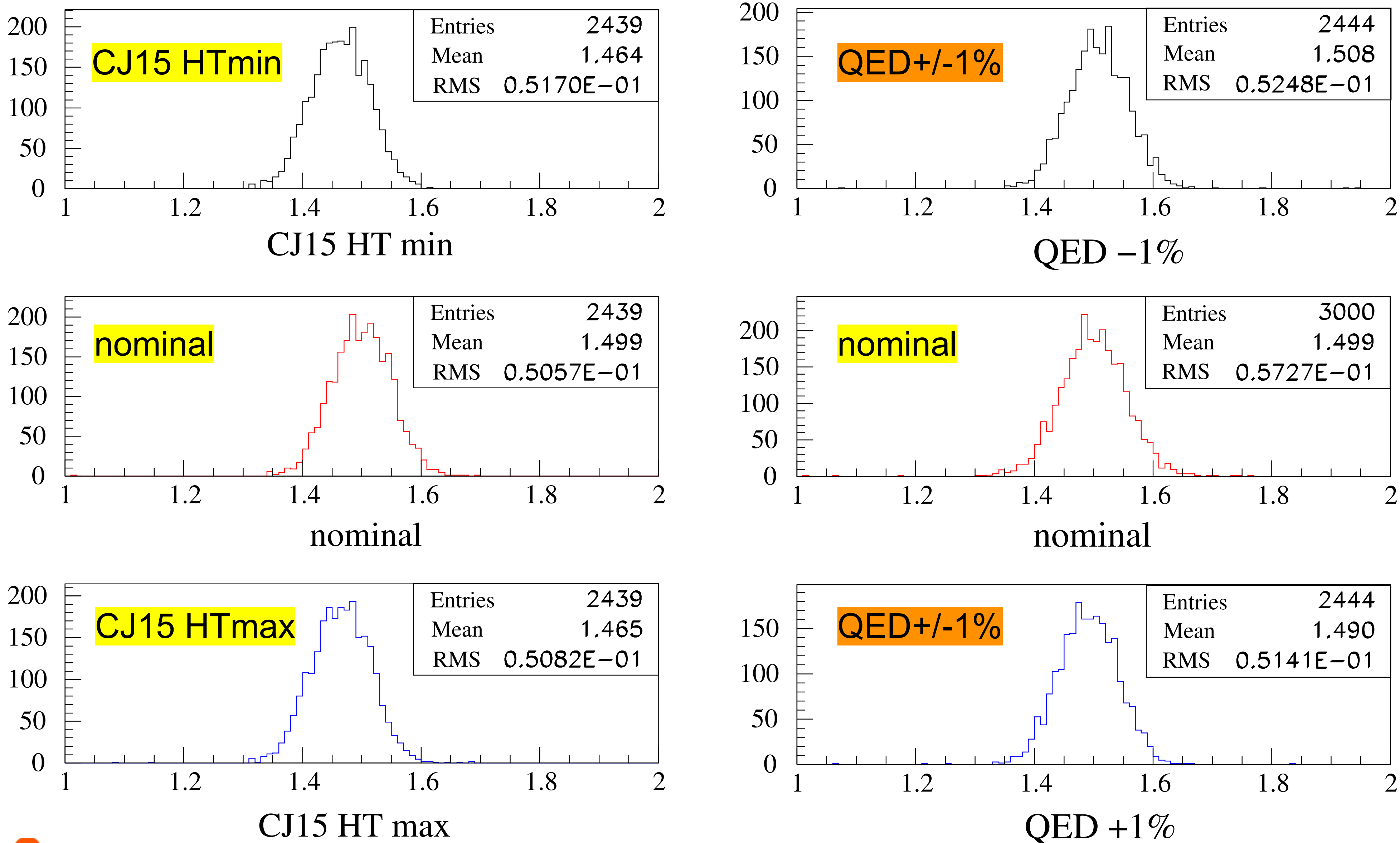


Going Through the Process 1000 times

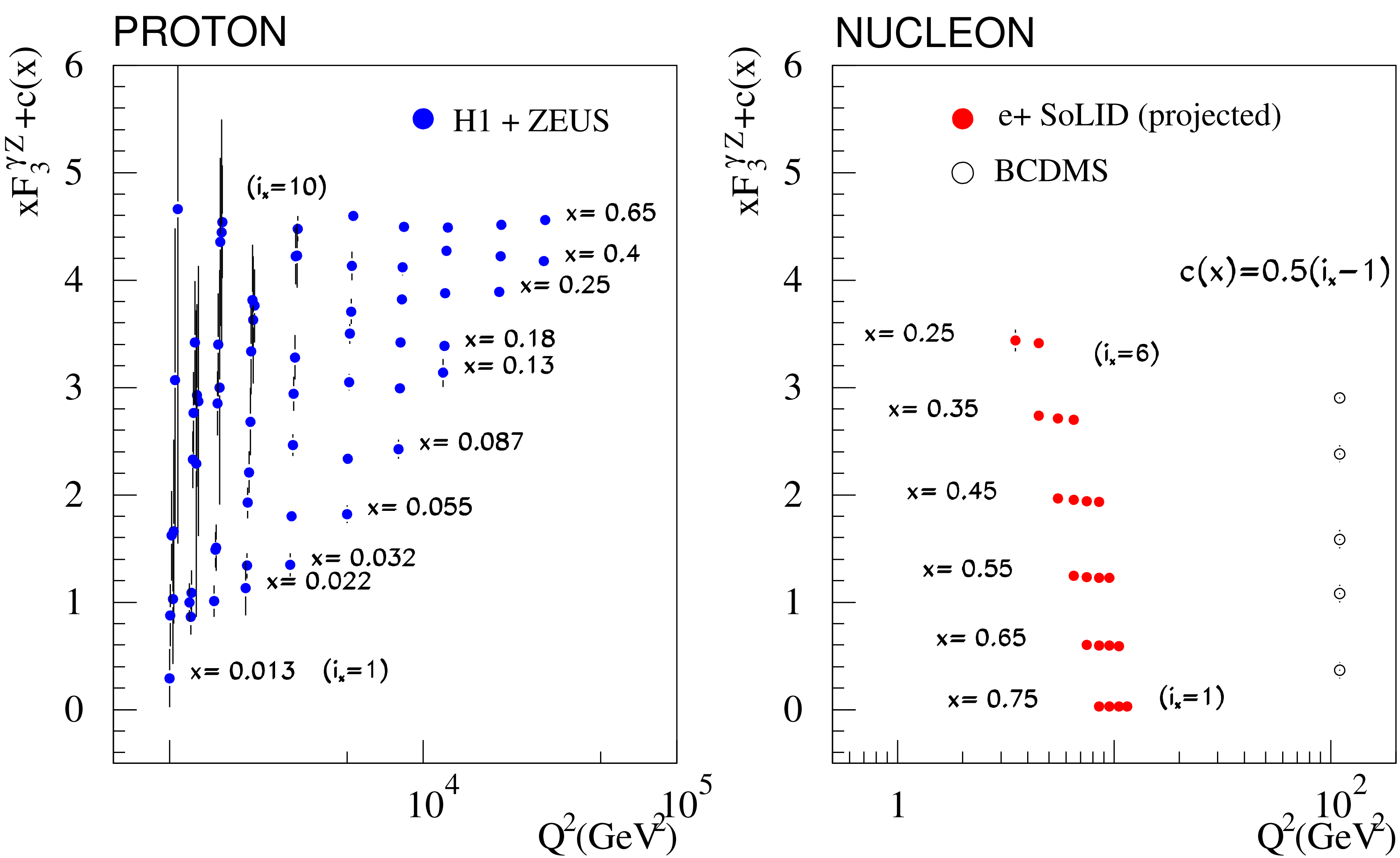
- Repeat for 1000 (or 3000) times and plot the fitted p_0:

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



Expected results on $F_3^{\gamma Z}$

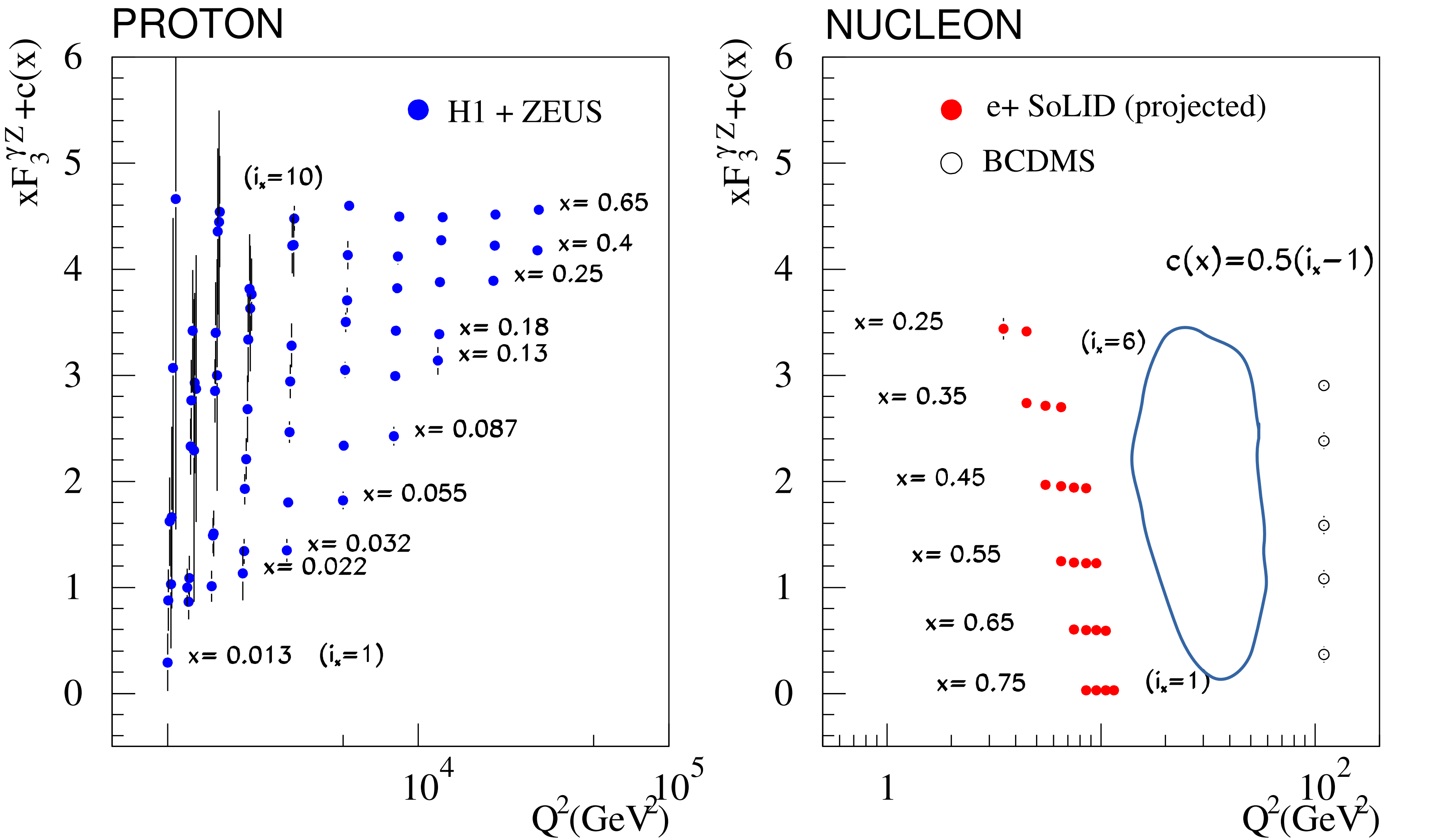
Take asymmetry results and multiply by F_1^{γ}, use fitted Eb and lumi values (and uncertainties)



Expanding this in the Future?

– Once we understand more of the e+ beam → repeat on the proton

– EIC filling the gap?



Summary and Outlook

– A positron beam greatly expand the horizon of physics topics we can study;

– Exploratory measurement of e+ vs. e- DIS asymmetries using SoLID and PEPPo at JLab, requesting 108 PAC days;

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

$$2C_{3u}^{eq} - C_{3d}^{eq} = 1.5 \pm 0.06$$

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

Preliminary estimation

$$\Lambda_{AA} = v\sqrt{\frac{8\sqrt{5}\pi}{|(2C_{3u} - C_{3d})|}} \approx 7.5\ \mathrm{TeV}$$

– Extraction of structure function $F_3^{\gamma Z}$ also possible;

Proposal PR12-21-06 for JLab PAC49 submitted

(updates will be sent to pwg@jlab.org and solid@jlab.org)

let's put this physics on the table!