Measurement of e^+/e^- – ^2H DIS Asymmetries $A_{unpol}^{e^+e^-}$ with SoLID and PEPPo at JLab

(a new proposal for PAC49)

Xiaochao Zheng, Univ. of Virginia

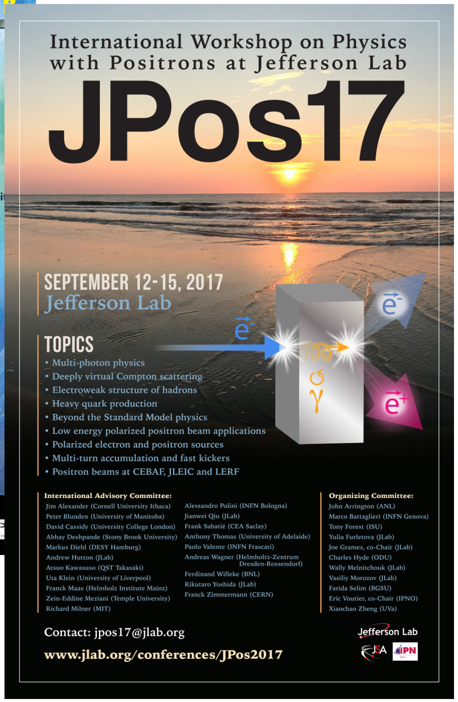
for the SoLID and Hall A Collaborations

https://arxiv.org/abs/2103.12555

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



Acknowledgment:

– Jay Benesch, Alexandre Camsonne, Jianping Chen, David Flay, Joe Grames, Paul Gueye, Shujie Li, Hanjie Liu, Dave Mack, Paul Reimer, Yves Roblin, Ye Tian, Eric Voutier, Weizhi Xiong, Jixie Zhang, Zhiwen Zhao

– Alberto Accardi, Andrei Afanasev, Jens Erler, Qishan Liu, Wally Melnitchouk, Jianwei Qiu, Nobuo Sato, Hubert Spiesberger

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The Landscape of Electroweak Physics Study

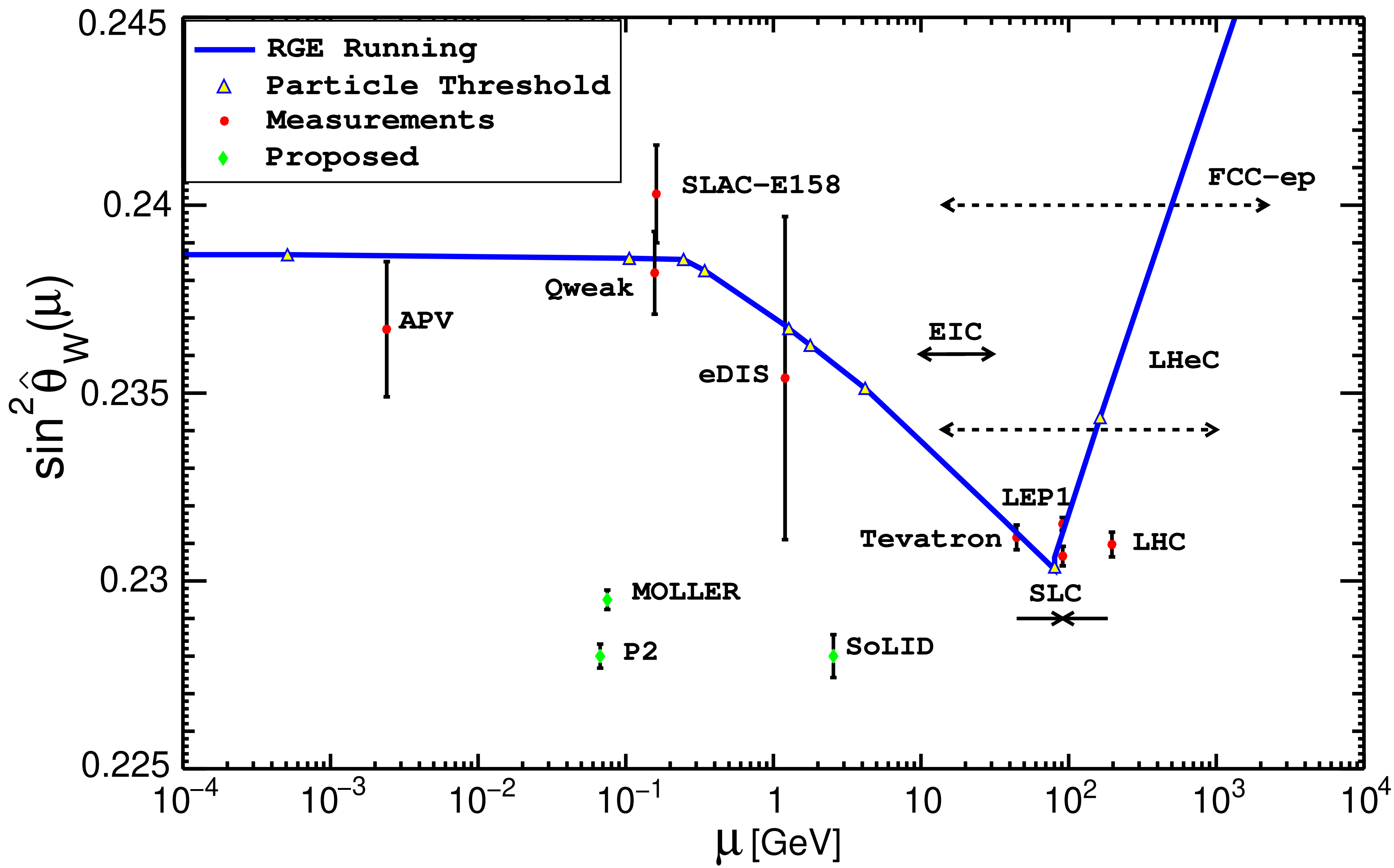
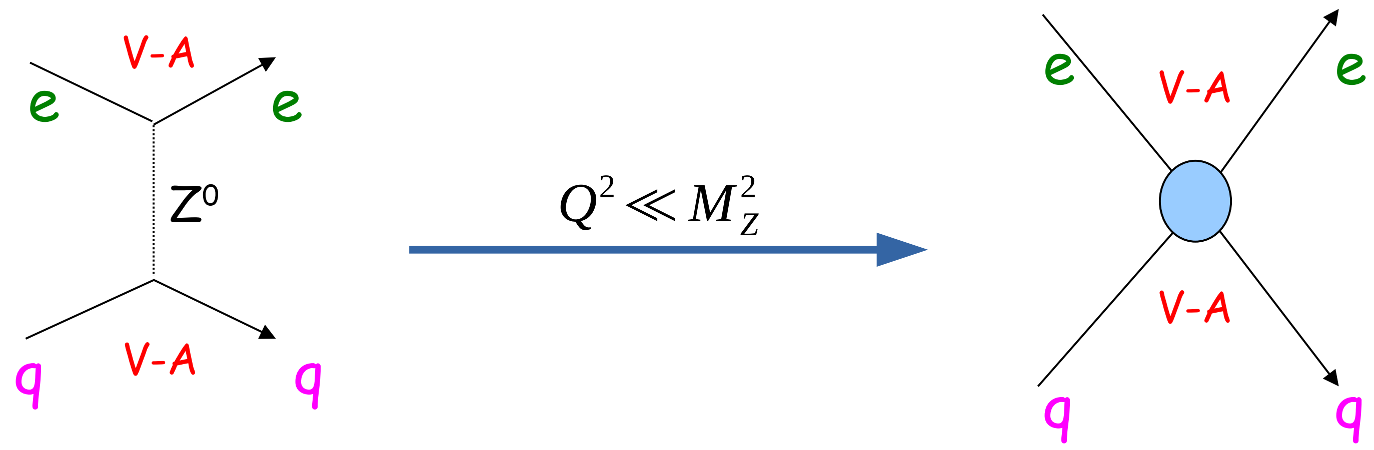


Figure updated from Erler, Ferro-Hernandez, JHEP03(2018) 196;
LHeC arrows showing Q^2 range from EPJC 80 (2020) 9, 831 arxiv.org/2007.11799;

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



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

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

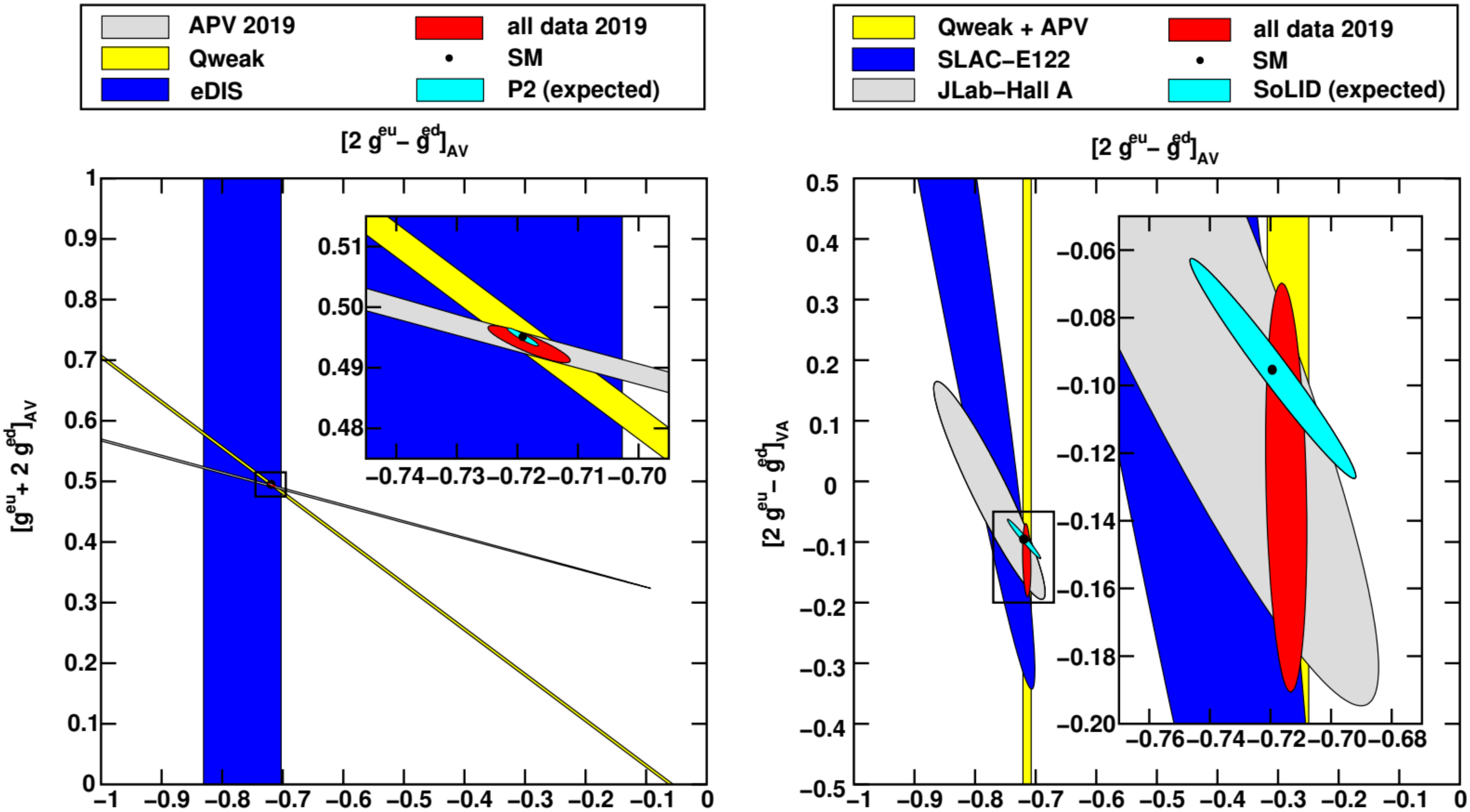
$$C_{1u} = 2 g^e_A g^u_V = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \qquad C_{2u} = 2 g^e_V g^u_A = -\frac{1}{2} + 2\sin^2(\theta_W) \qquad C_{3u} = -2 g^e_A g^u_A = \frac{1}{2}$$

$$C_{1d} = 2 g^e_A g^d_V = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \qquad C_{2d} = 2 g^e_V g^d_A = \frac{1}{2} - 2\sin^2(\theta_W) \qquad C_{3d} = -2 g^e_A g^d_A = -\frac{1}{2}$$

- A new set of notation $g^{eq}_{AV,VA,AA}$ 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



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

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

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

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

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

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

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

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

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

beam polarization

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

(indicates spin flip of quarks)

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

(flip |λ| for LR)

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

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

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

(flip |λ| for LL)

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

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

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

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(indicates spin flip of quarks)

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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)

(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: $$A^{e^+e^-}_{\text{unpol}} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{g^e_A}{2} Y(y) \frac{F^{\gamma Z}_3}{F^{\gamma}_1}$$

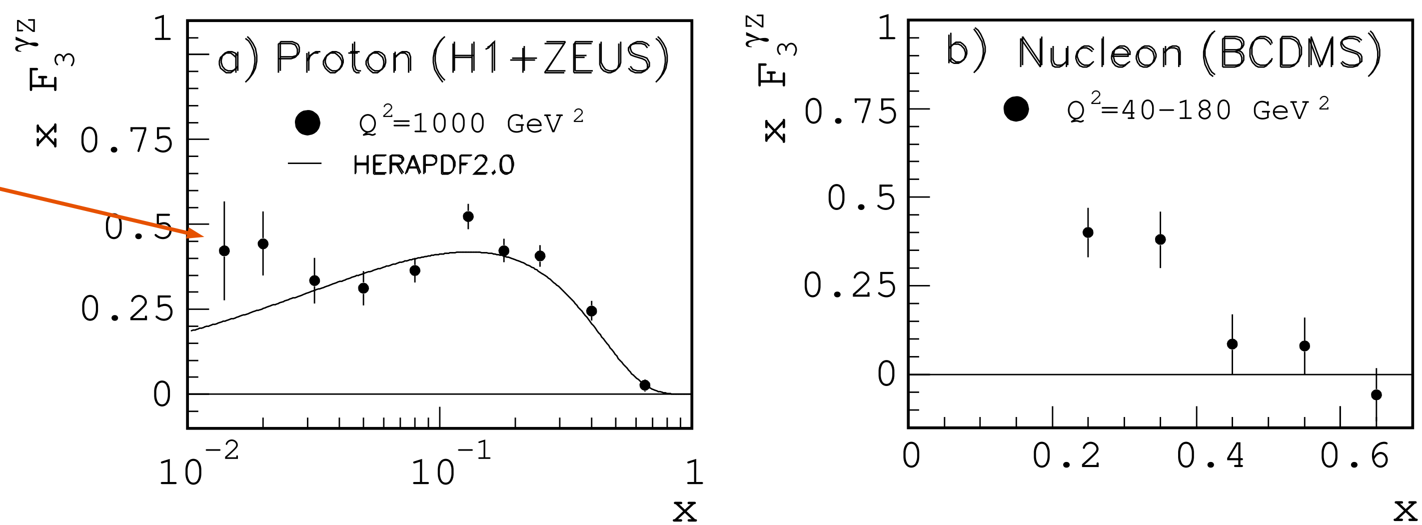
In the parton model: $$F^{\gamma}_1(x, Q^2) = 1/2 \sum Q^2_q [q + \bar{q}]$$

$$F^{\gamma Z}_3(x, Q^2) = 2 \sum g^q_A [q - \bar{q}]$$

Low x HERA data pose question on

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

(→ LHeC)



By measuring $A^{e+e-}_{p,d}$ we can access $F^{\gamma Z}_3(x, Q^2)$

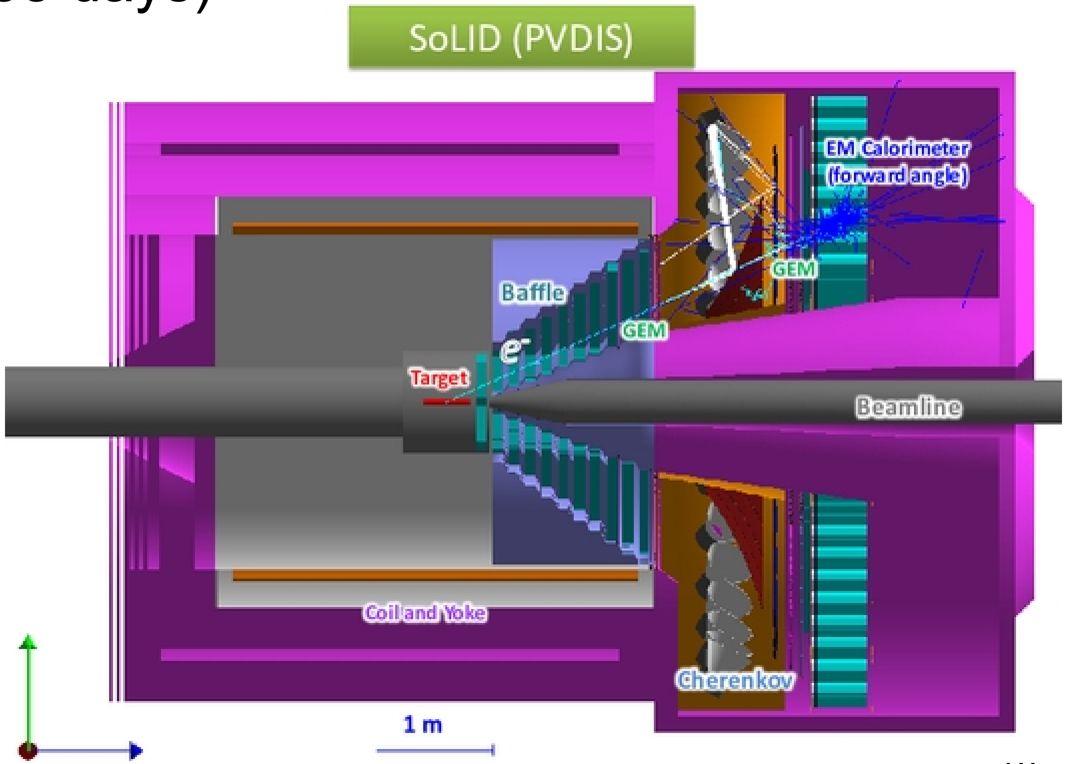
Designing the Experiment

Need high Q^2, high Y(y) → **SoLID PVDIS** configuration is ideal (40cm LD2)

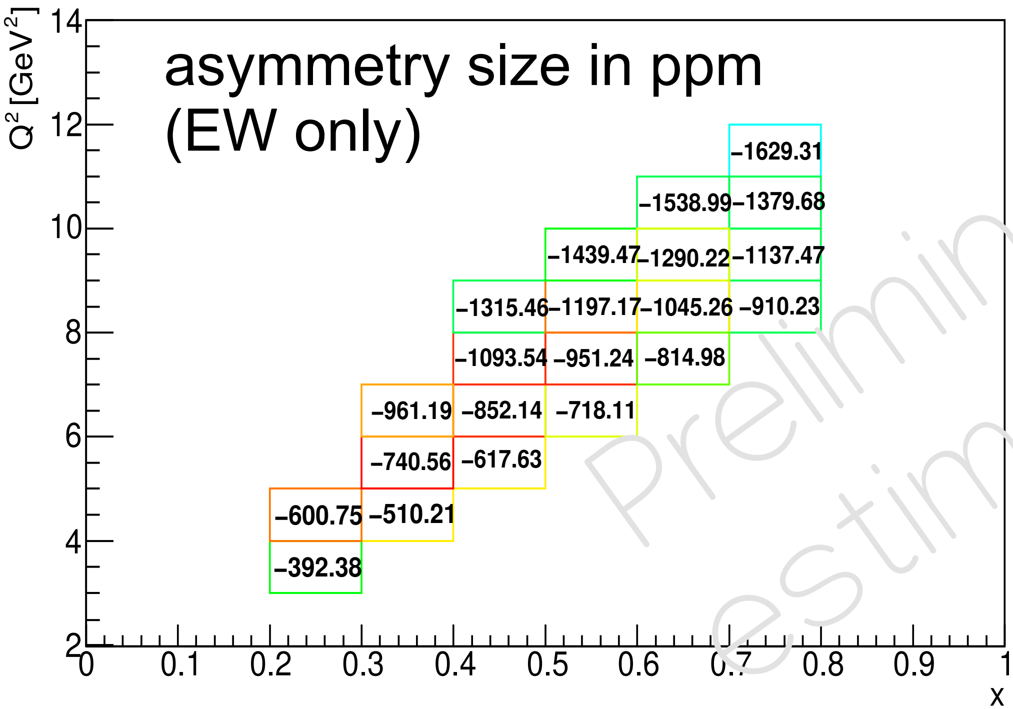
Need positron beam → **PEPPo**: up to 5uA for unpolarized. We ask for 3uA, 88 days at 11 GeV, 8 days at 6.6 GeV, each split between e+ and e- runs.

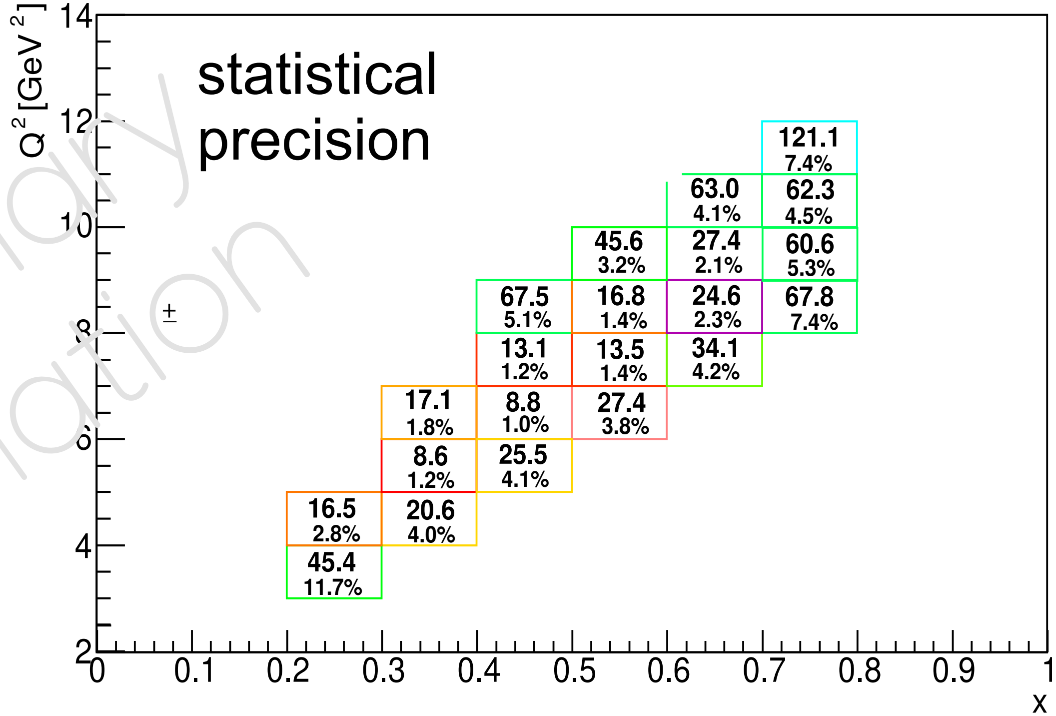
Need positron detection → **reverse magnet** polarity of SoLID, run magnets always at full saturation (field mapping tool by D. Flay→ field diff. < 10^{-5})

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



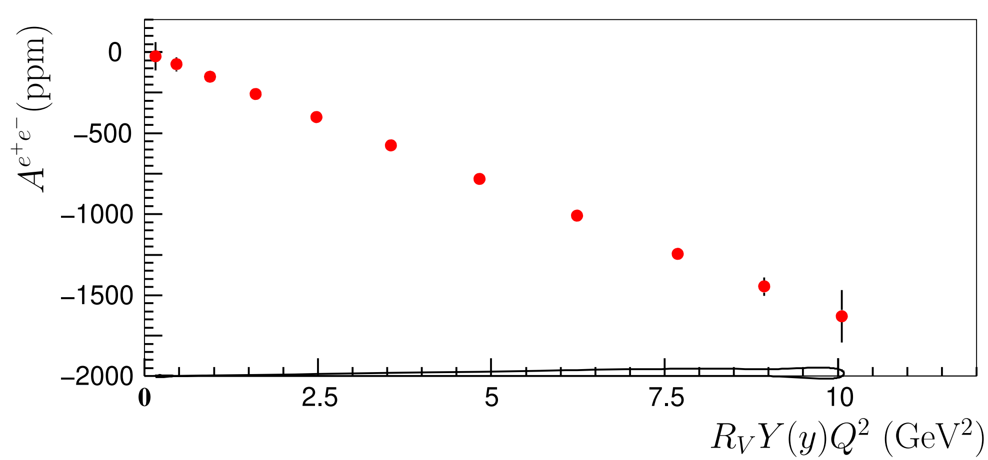
What can we do with 80 days of 3uA beam on a 40cm LD2 target? (in absence of all challenges):





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

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



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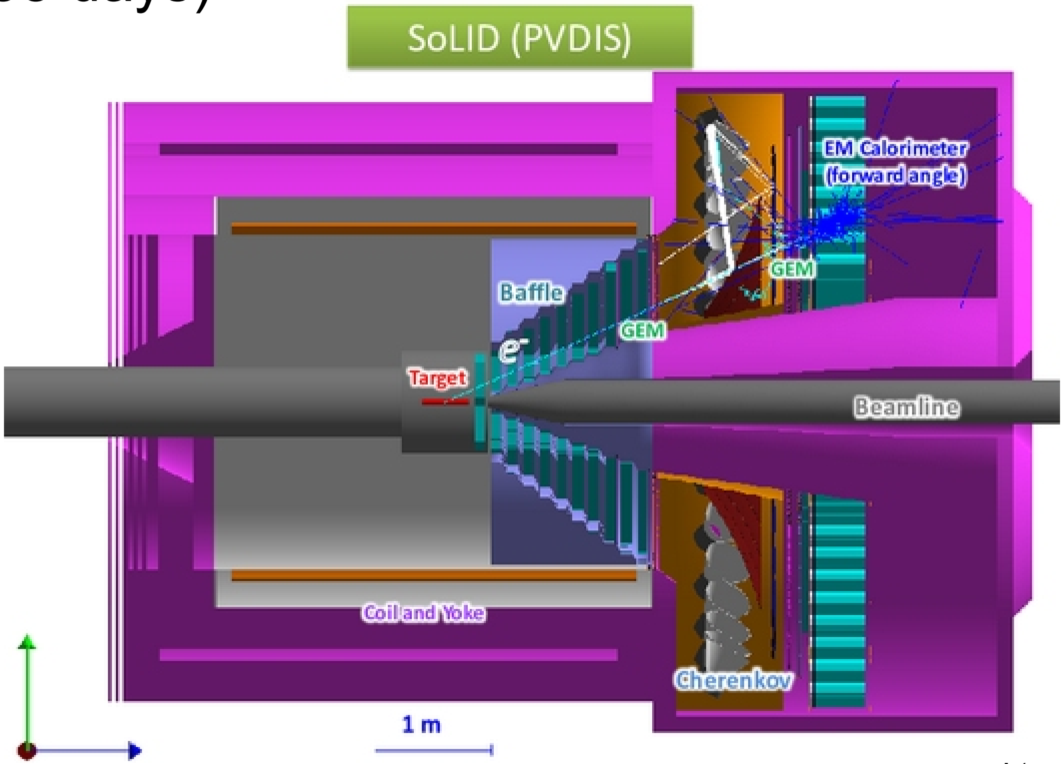


Experimental challenges:
- Ebeam, luminosity, charged pion and pair production background, magnet and detector stability

Theoretical challenges:
- higher-order QED corrections

All Possible Contributions to the Measured Asymmetry

- slow drift in BCM → (unknown) luminosity difference ΔLumi
- possible difference in Ebeam ("standard" Hall A → 5x10^{-4}) → can calculate effect $\Delta A_{E_b,max}$
- possible difference in magnet strength (E') → has a plan to control this to <1x10^{-5} → can calculate effect $\Delta A_{E',max}$
- background subtraction → bin by bin

- QED higher order contributions: used Djangoh generator to calculate, proof-of-principle results exist (summer student working on improvement): ΔA_{QED} ;
- Coulomb effect: follow Aste et al. https://arxiv.org/abs/nucl-th/0502074 (update from proposal):

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 $\text{focusing factor (ff)}=\frac{E_b+V_{eff}}{E_b}$

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

- Higher twist is 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

Eb difference up to 5×10^{-4}

$\Delta A_{E_b,max}$

E' difference up to 1×10^{-5}

$\Delta A_{E',max}$

Coulomb correction

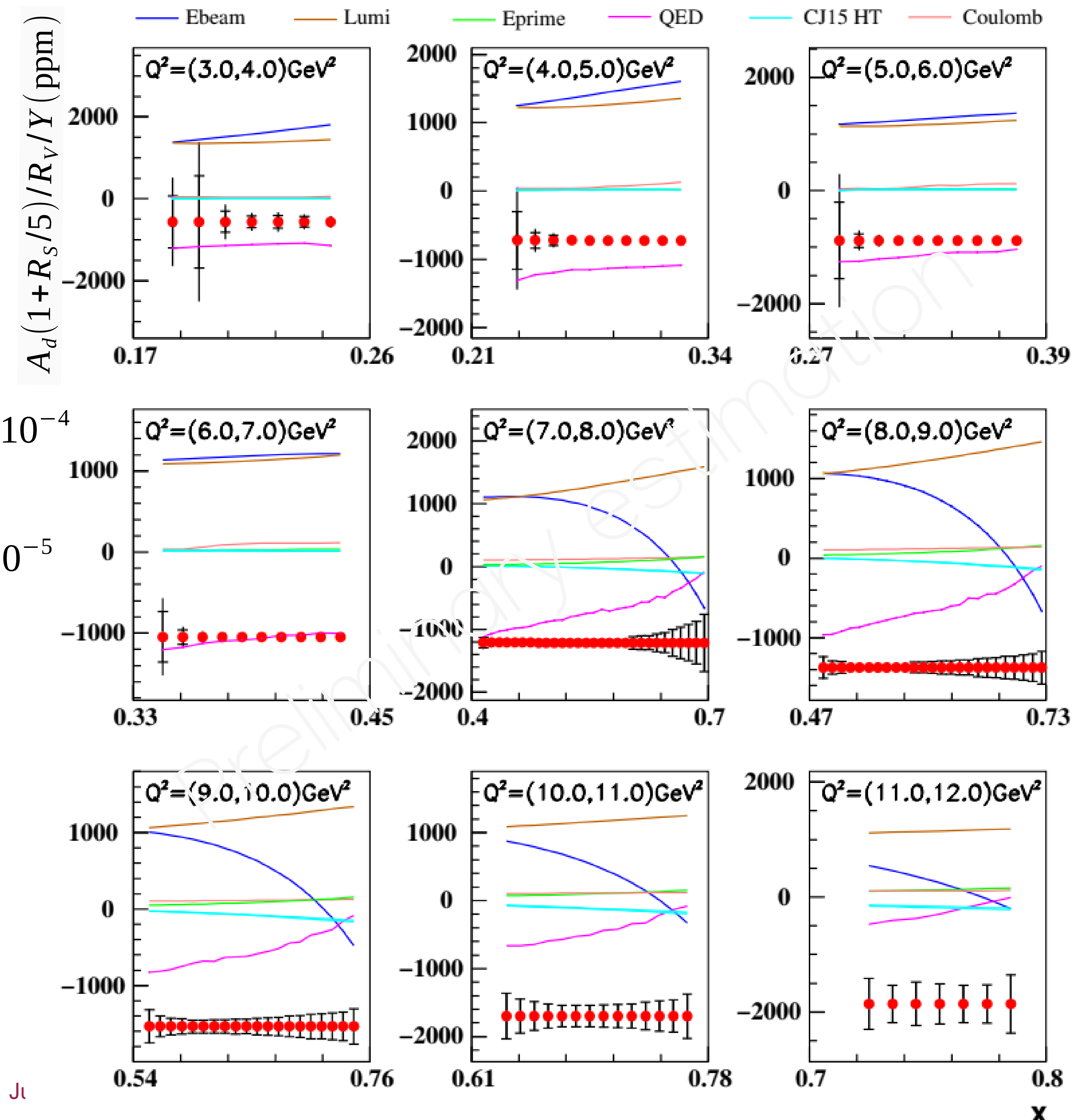
$\Delta A_{Coulomb}$

QED higher order (scaled by 1/5) →

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

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

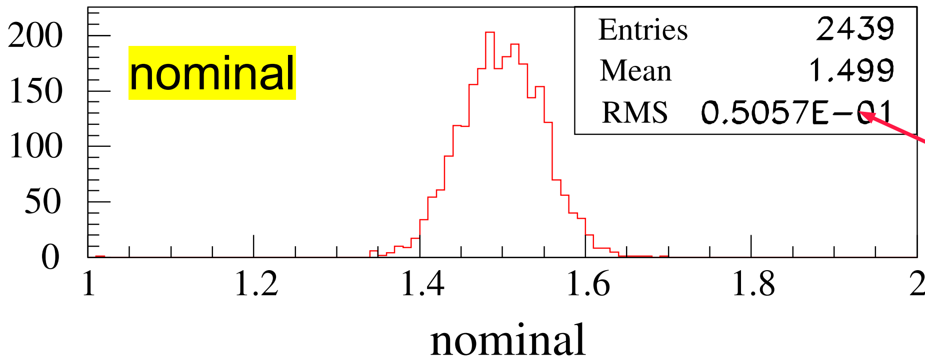
fitting pseudo data with lumi ("lumi fit"): $\Delta p_0 = \pm 0.032$

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

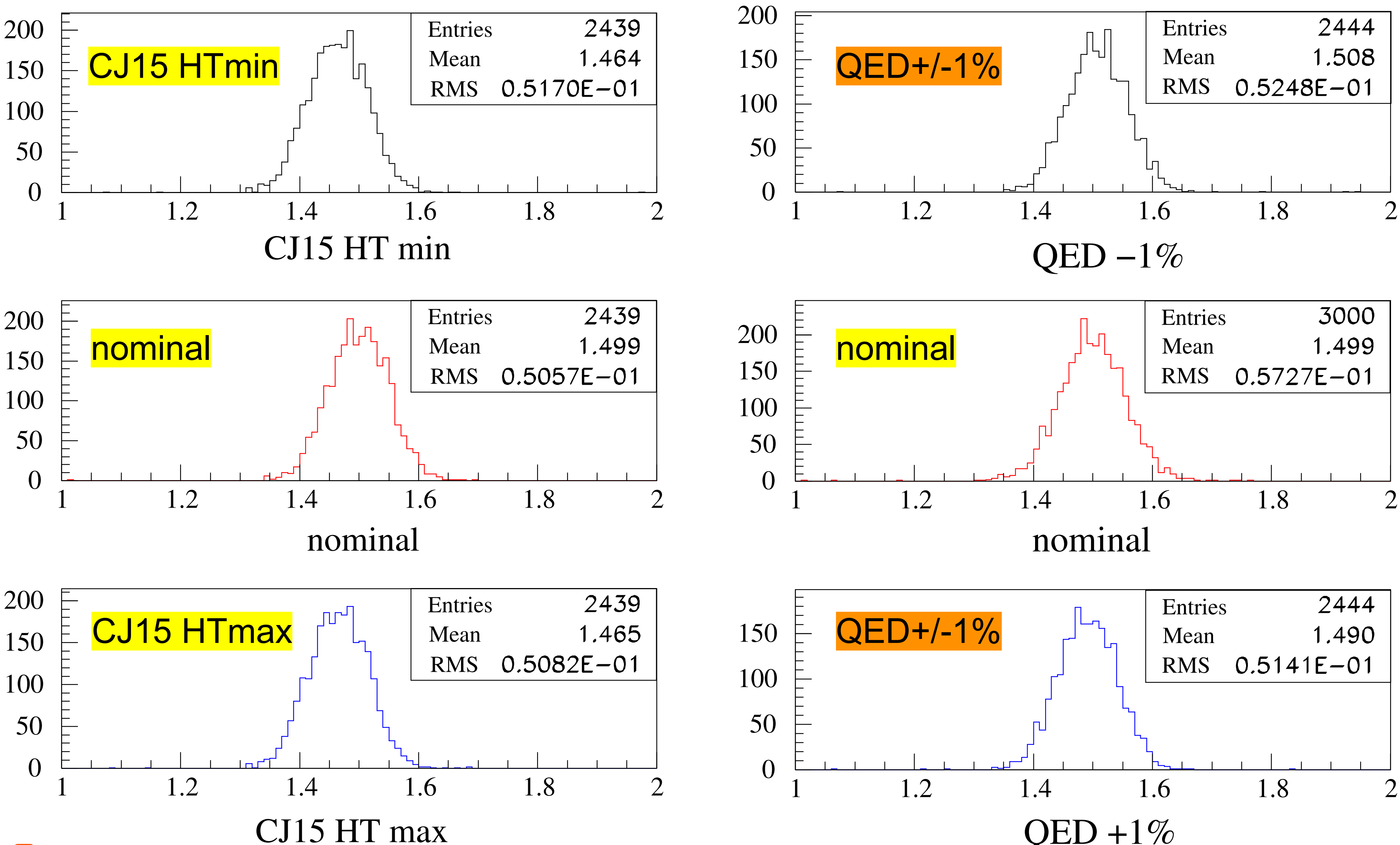
- Repeat for 1000 (or 3000) times and plot the fitted p_0:



better estimate of the uncertainty

Going Through the Process 1000 times

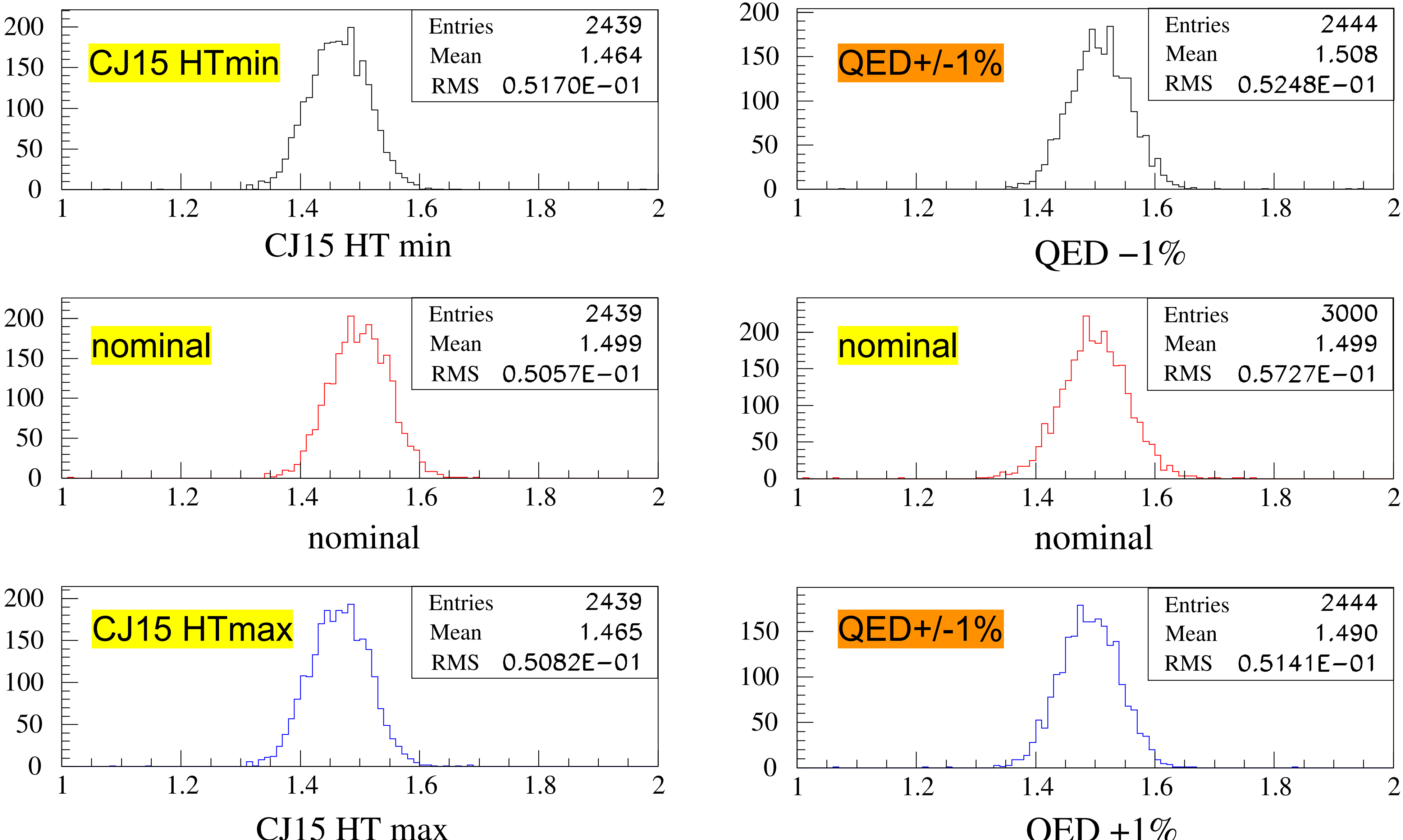
- Repeat for 1000 (or 3000) times and plot the fitted p_0:



Going Through the Process 1000 times

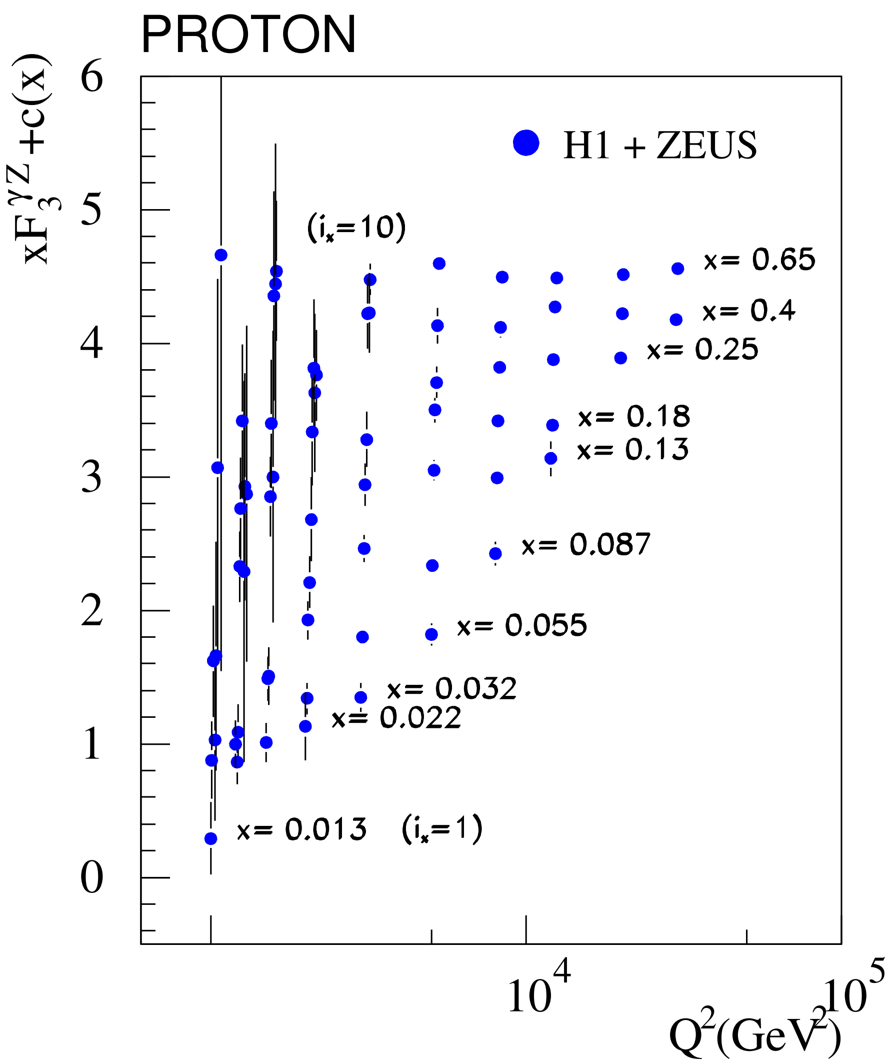
- Repeat for 1000 (or 3000) times and plot the fitted p_0:

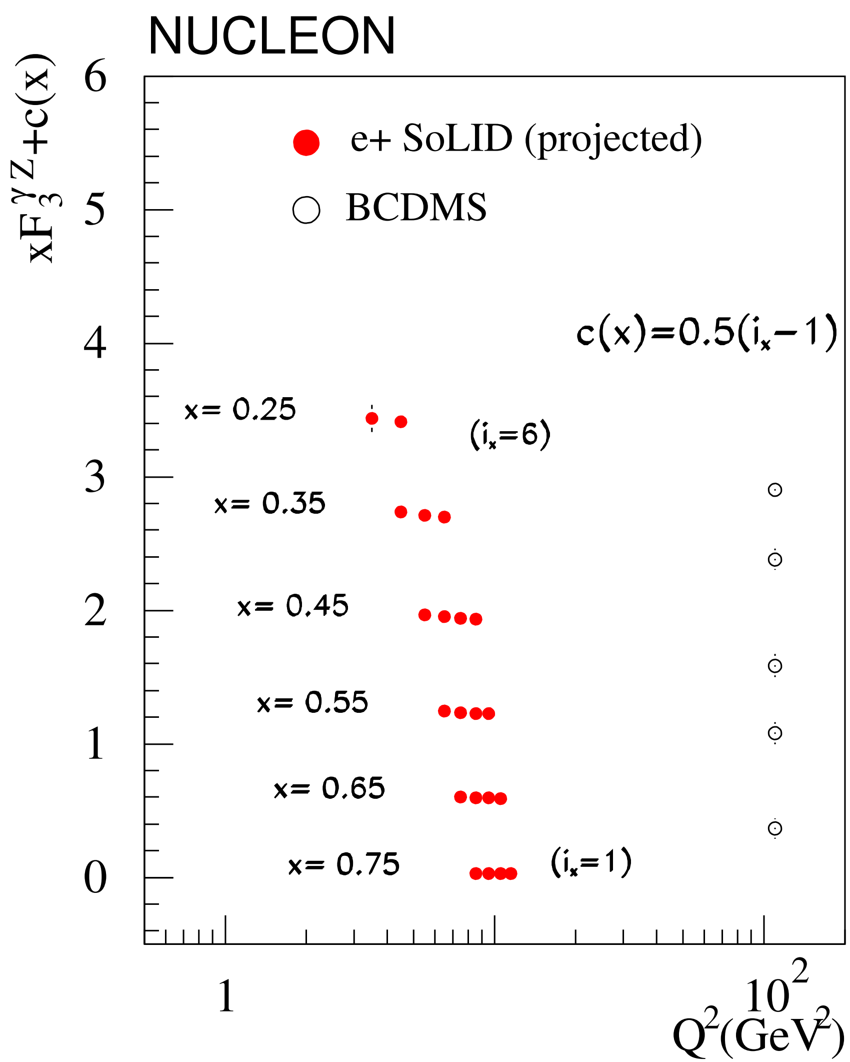
$$\Delta(2C_{3u}-C_{3d})_{\text{total}}=\pm0.053(\text{exp})\pm0.009(1\%\ \text{QED})+0.000-0.035(\text{HT, CJ15})\approx\pm0.060$$



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

Take asymmetry results and multiply by F_1^{γ}, use fitted Eb and lumi values (and uncertainties). 1% QED projection shown.





Updates after May 24th Submission/Responses

– Endorsed by SoLID Collaboration for “conditional approval”, endorsed by Hall A Collaboration

– Beam energy within 10^{-4} achievable, 10^{-5} possible → If both Eb and Ep are controlled to 10^{-5} level, can reach $\Delta p_0 = \pm 0.032$, any remaining Q^2 dependence must be from under-corrected QED or higher twist and non-zero intercept gives the luminosity difference.

– Beam position control at 20 microns level can be achieved with modified beamline (moving BPMs closer to Target and adding more beam monitors) after MOLLER.

– Target boiling monitoring is being considered (beam monitoring before+after target)

– Detector (tracking and PID) + DAQ and its Q^2 dependence → need end-to-end simulation of SoLID to fully understand the effect.

– Detector and other run condition slow drift → can study long term drift of precision experiments (PREX-2, MOLLER, PVDIS), may set limit on Lorentz invariance too.

– 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.

– A higher positron beam current will be beneficial.

– Techniques planned for e+/e- systematic control useful for other e+@JLab experiments or extension of this measurement (with future upgrades).

Theory Support and Roadmap

- Strong support from theory groups:
  - CTEQ-JLab Collaboration; https://arxiv.org/abs/1602.03154
  - A. Afanasev (GWU); https://arxiv.org/abs/hep-ph/0105032
  - T. Liu, W. Melnitchouk, J.W. Qiu, N. Sato (JLab); https://arxiv.org/abs/2008.02895 + long paper in prep.
  - J. Erler, H. Spiesberger (U. Mainz); Comput.Phys.Commun. 81 (1994) 381-402

- Calculation of A_QED, can we reach 1%? Uncertainty due to PDFs or structure functions? F_L? Uncertainty due to nucleon-resonance/QE/elastic?
- Modification due to nuclear Coulomb field – need DIS prescription for "Coulomb correction/distortion", QE method looks promising (effect is small).
- Higher twist: no data available on $F_3^{\gamma Z}$, calculations using H_3^{ν} and H_2 were only estimations, we hope to extract HT of $F_3^{\gamma Z}$ using our own data.
- Synergy with SoLID PVDIS program

Beam time request

Table 3: Beam time request for the proposed measurement. The target type "carbon" refers to carbon foils for optics and beam checkout, and "LD_2" refers to the 40-cm liquid deuterium target. Time needed to commission the PEPPo source, the positron beam and the secondary electron beam, and the time needed to switch between the two beams are not included.

Purpose	Beam energy and type, target	PAC days
General Commissioning	as needed, carbon	2
Compton tune	as needed, carbon	2
Production	11 GeV, 3 μA e^+ and e^- (PEPPo), LD_2	80
Reverse polarity runs	11 GeV 3 μA e^+ and e^- (PEPPo), LD_2	8
Reverse SoLID polarity	N/A	2
Radiative (bin migration) corrections	6.6 GeV 3 μA e^+ and e^- (PEPPo), LD_2	8
Pass changes	N/A	2
Total		104

Summary and Outlook

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

– **Exploratory measurement** of e+ vs. e- DIS asymmetries using SoLID and PEPPo at JLab, requesting 104 PAC days, novel method to "deal with" major experimental challenges regarding "**beam-charge quality control (analysis)**";

– If all experimental systematic effects and QED higher order corrections can be controlled or understood → **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

– Also results on **structure function** $F_3^{\gamma Z}$.

- first measurement of electron C_{3q}, and possibly the only facility that can do this → we will make an impact on the landscape of EW physics study!
- Exploratory, proof-of-principle, pave the way for future extensions (proton target, 24 GeV…) and other e+/e- experiments;
- Need SoLID and "fast switch" positron beam, may take 10+ years before this experiment runs, but also need to work out many technical, simulation, and theoretical details – We are asking for support from JLab + PAC so that we can devote our effort to this physics (program).

Backup Slides

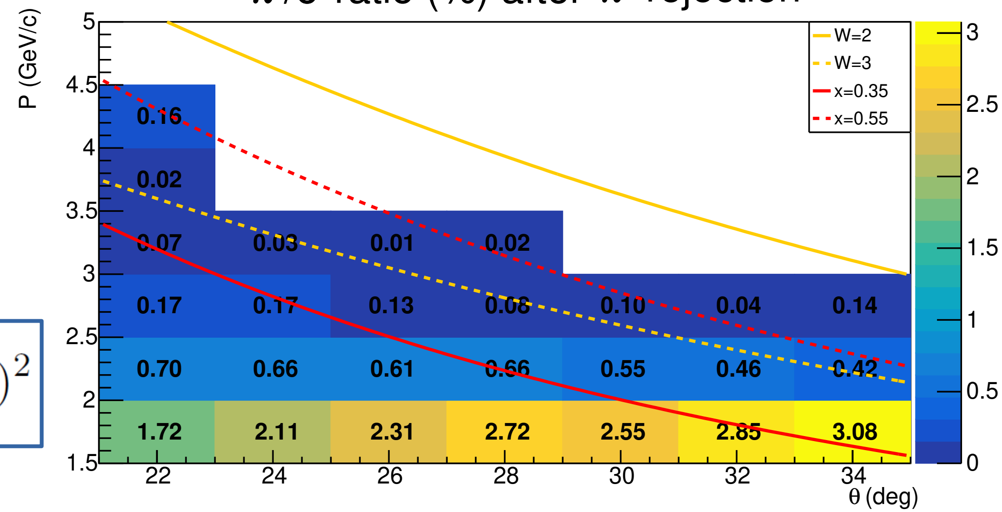
Background

For any background, measure its 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)

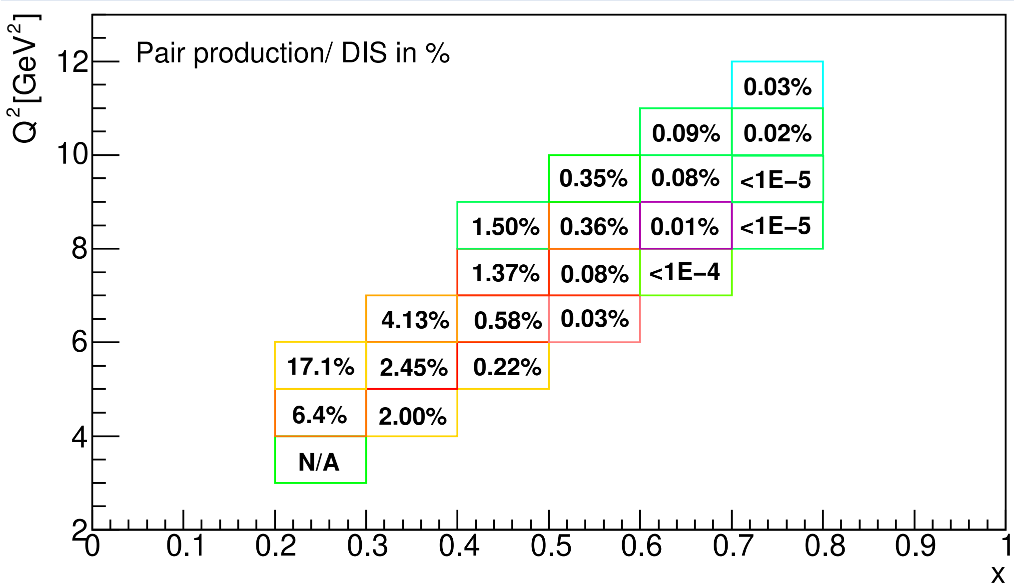
$$(\Delta A_{\rm DIS})^2_{\pi\ bg} = \frac{1}{N_{\rm DIS}} + \frac{f_{\pi/e}}{\eta_\pi N_{\rm DIS}/PS} + (A_{\rm total} - A_\pi)^2(\Delta f_{\pi/e})^2$$

π^+/e^+ ratio (%) after π^+ rejection



Pair production: zero asymmetry in principle

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



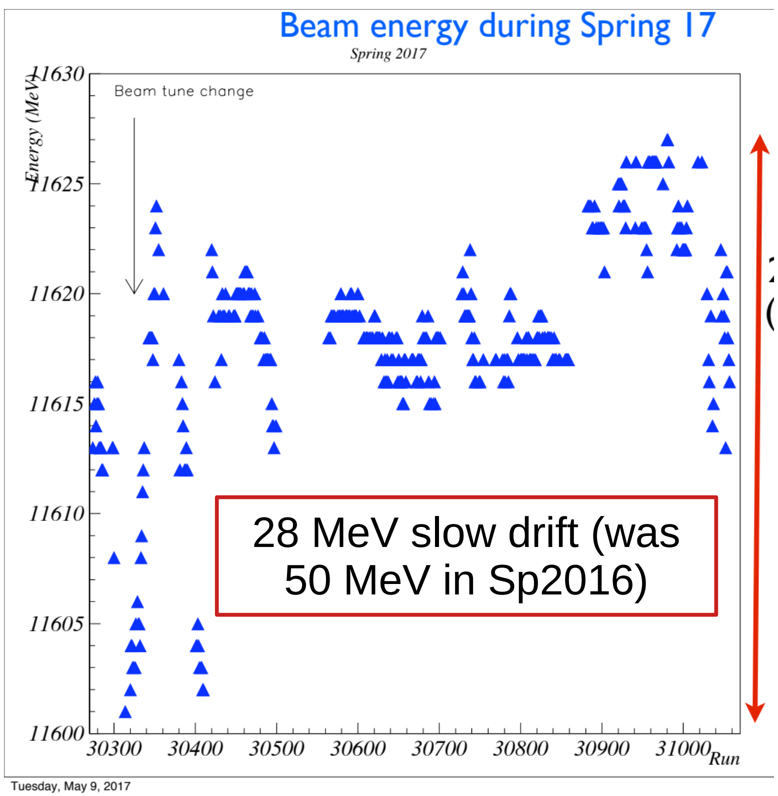
→ spend (α =) 10% of beam time on reverse polarity runs, include effect in data projection

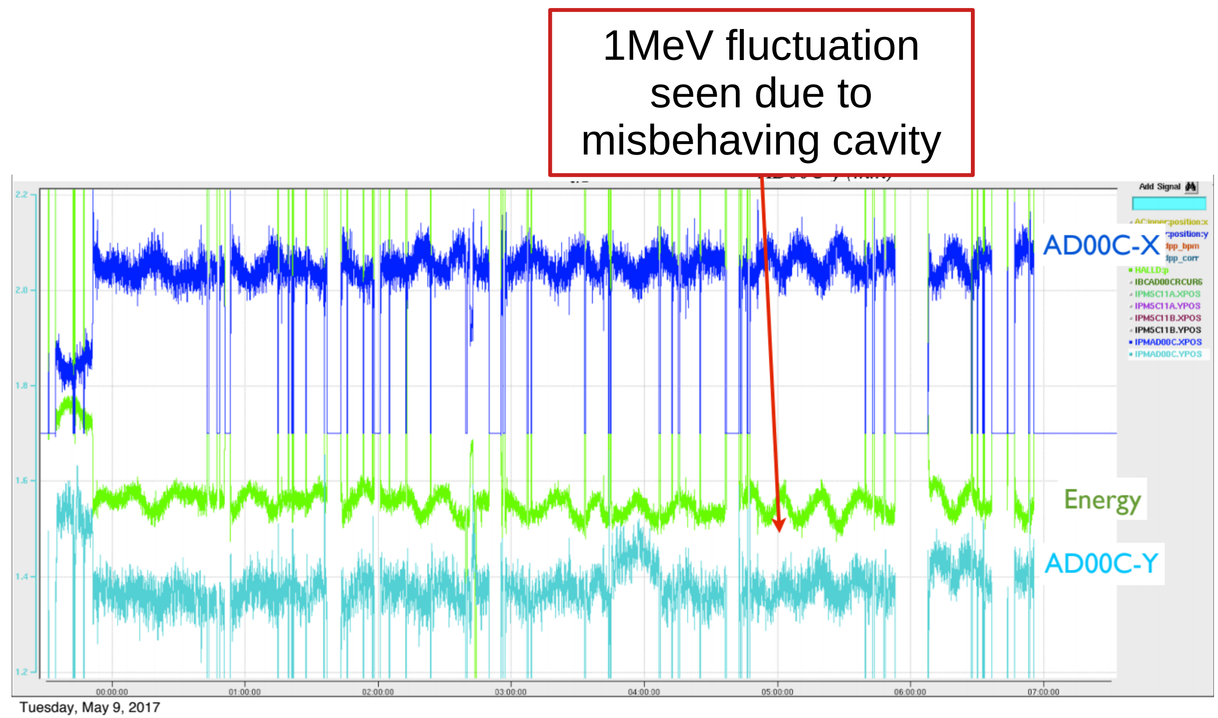
Target endcap: calculable → see proposal

Beam energy control

based on discussion with Y. Roblin, A. Deur

- Can be set at desired values by adjusting the arc dipoles and linacs;
- Can be monitored real-time to relative (1-2)x10^{-4} precision – achieved for GlueX Sp2017 run
- Slow drift (at the time scale of months) can be at the 10^{-3} level, possibly due to machine length change, but this slow drift can be corrected daily (or more frequently if needed). Correcting such drifts requires putting the beam into tune mode (invasive) for 10 minutes.
- Energy difference between e+ and e- run can reach 10^{-4} precision. (10^{-5} would be much nicer!)





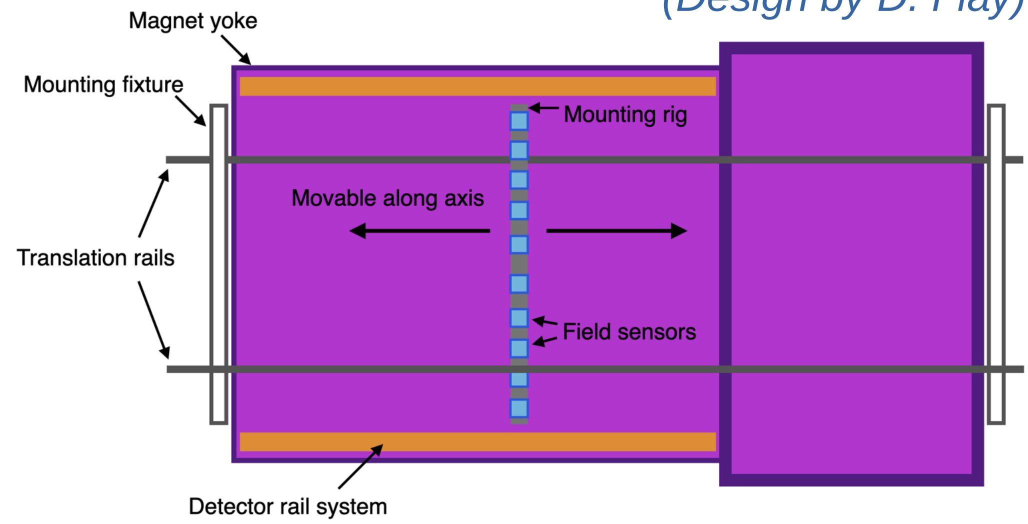
SoLID Magnetic Field: Mapping, Monitoring, Stabilization

Field Mapper

- Circular, rotatable array of magnetometers (3D Hall probes) to measure the magnetic field
- Mounting fixture & translation rails allow measurements along the magnet axis
- Positioning: Fiducialization & survey enables ≤ 1 mm alignment
- Magnetometer accuracy and resolution:
  - Accuracy: $\Delta B/B \sim 10^{-6}$, resolution: 10^{-4}
  - Can improve accuracy with NMR calibration ($< 10^{-6}$)

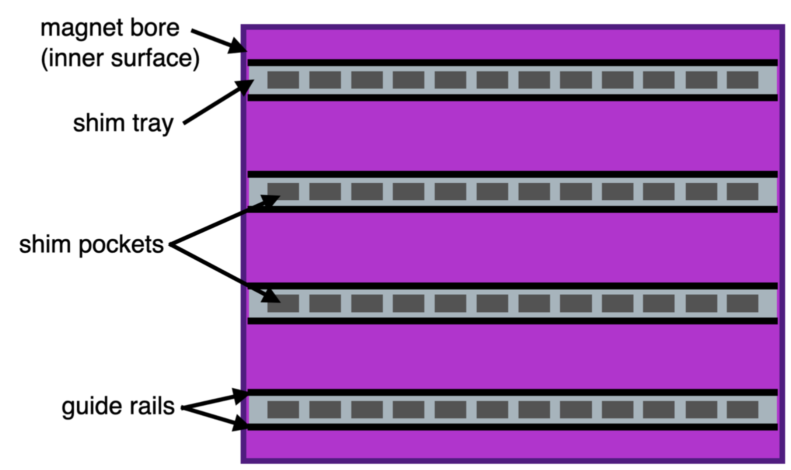
need to incorporate into SoLID design ASAP

(Design by D. Flay)

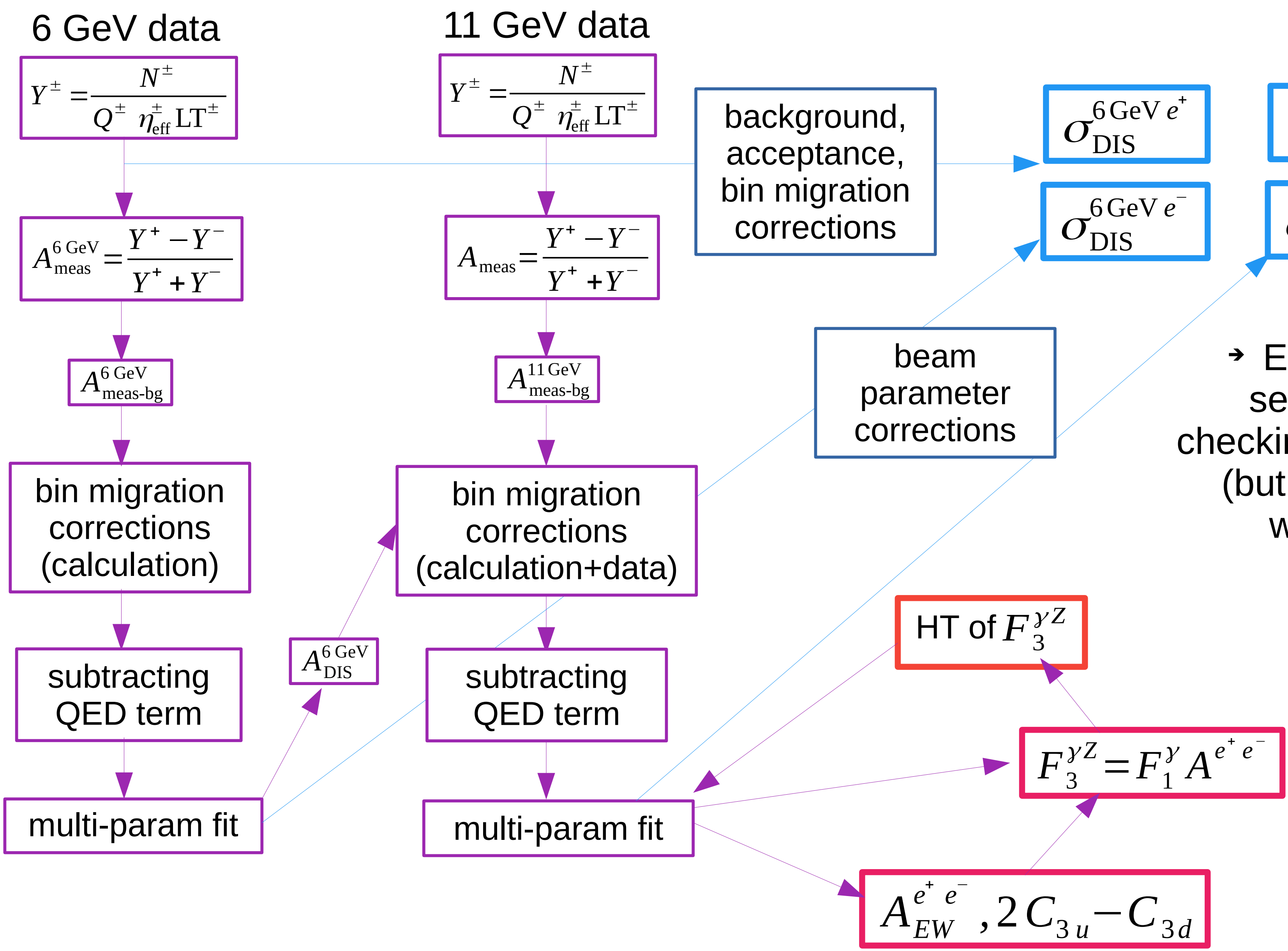


Uniformity, Monitoring, Stabilization

- Uniformity: Install tray of iron pieces along inner surface of magnet => shape the magnetic field
- Monitoring: Install magnetometers along the inner surface of magnet => real-time monitor of magnetic field stability
- Stabilization: Use fixed magnetometer data to feed back to main power supply to maintain constant magnetic field



Data Analysis Procedure (Cross Sections and Asymmetries)



- Extracting cross sections will help checking calculations (but must combine with asymmetry analysis)

Systematic Uncertainties

Source	Uncertainty on Asymmetry
Q^2	0.2%
bin migration	0.4%
event reconstruction	0.2%
DAQ deadtime	~0 if same for all events
particle background	varies by bin
PDF uncertainty	varies by bin, small
QED higher order	large, assuming 1% can be reached

- uncertainties due to run condition differences (luminosity, Eb, E', detector and PID efficiency) discussed separately.

- Extracting individual cross section will provide cross checks of the measurement (table is preliminary)

Source	Uncertainty on cross section
Beam charge	(0.5-1)%
Beam energy	$<5 \times 10^{-4}$
scattering angle	0.5mr
Target density	<0.1%
endcap subtraction	<1%
Q^2	0.2% on Q^2
bin migration	1-2%
event reconstruction	0.2%
DAQ deadtime	<0.5%
particle background	< 0.2%, varies
acceptance*	1-2%
tracking efficiency*	<0.1% (sim stat.)

* ***require end-to-end simulation***

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

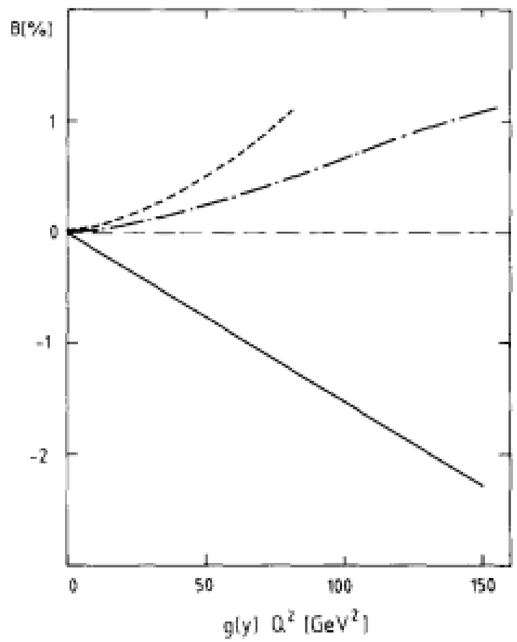


Fig. 2. The B asymmetry from $\gamma - Z^0$ interference to first order, calculated for a polarization $\lambda = 0.81$ and $\sin^2\theta_W = 0.23$ (solid line), and the asymmetry expected from higher order electromagnetic processes at beam energies of 120 GeV (dashed line) and 200 GeV (dashed–dotted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

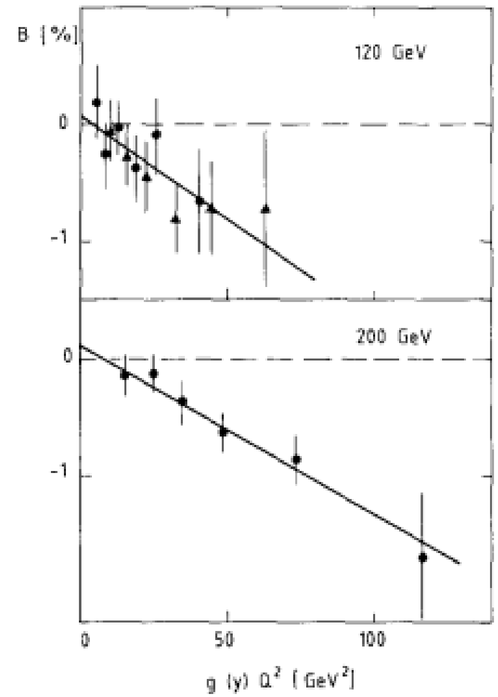


Fig. 3. The measured B asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy versus $g(y)Q^2 = Q^2 \times [1-(1-y)^2]/[1+(1-y)^2]$ [eq. (3)]. For the 120 GeV data, circles represent data with $Q^2 > 15$ GeV. Solid lines are straight line fits to the data.

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

a measurement for the electron is highly desired

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 $1.2 < Q^2 < 3.3$ $(GeV/c)^2$, $2 < \nu < 9.5$ GeV. Found “e+/e- cross section ratio = 1.0027 ± 0.0035 (including stat and syst effects), with no significant dependence on Q^2 or v. This result has appreciably smaller errors to fine TPE effects in electron or muon scattering.”

Note: Ae+e- ~ 1E-4, Coulomb ~ 1E-5 to 1E-4, QED NLO ~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^o, as well as symmetric Moller or Bhabha calorimeters at 1.29^o. The uncertainty in the relative luminosity between beam species of 0.36% was achieved.”

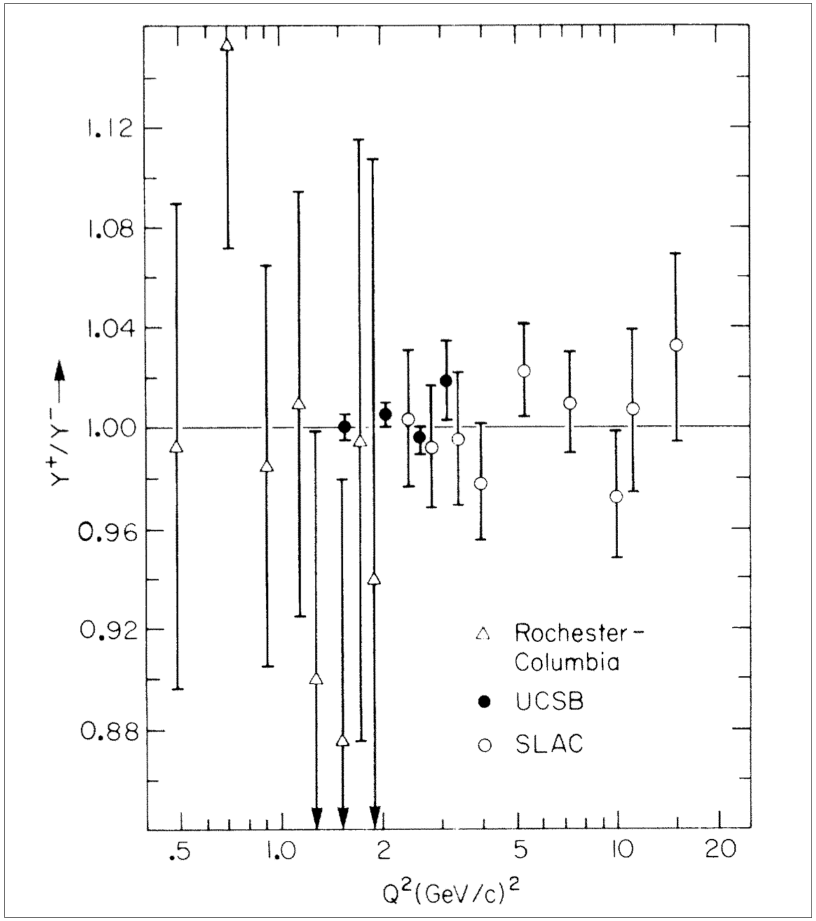
Note: 0.36% luminosity control is not going to help us

- V. Andreev et al. (**H1** Collaboration), Eur. Phys. J. C 78 (2018) 9, 777

luminosity ~ 2% with partial cancellations, measured e- and e+ DIS cross sections.

Note: At HERA energy, QED NLO is relatively small

SLAC 1976 Proton Inelastic Measurement



D.L. Fancher et al, Phys.Rev.Lett.37, 1323 (1976)

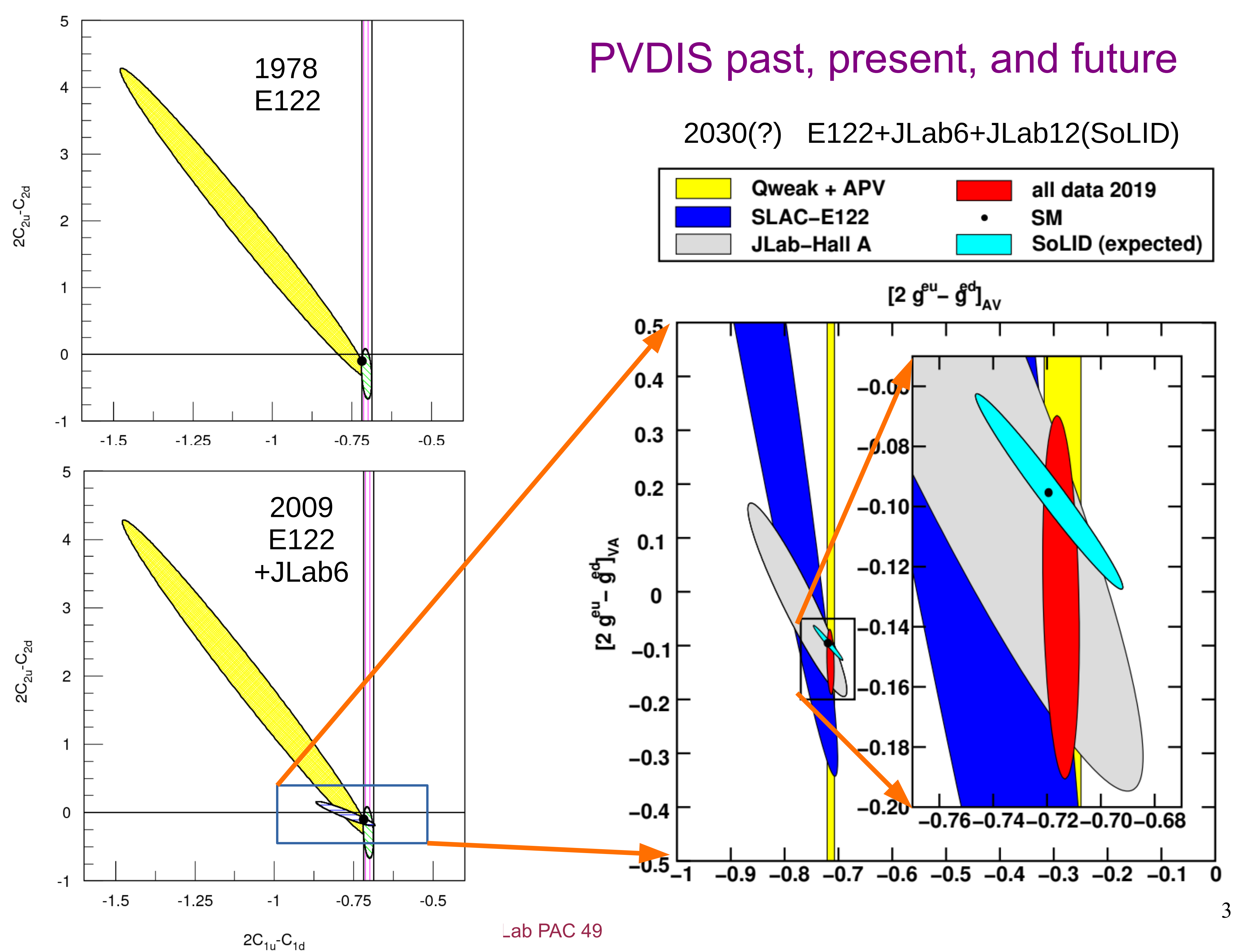
Q^2 $(GeV/c)^2$	Y_+	Y_-	Y_+/Y_-
1.3–1.8	227 054 ± 784	227 010 ± 729	1.0002 ± 0.0047
1.8–2.3	287 029 ± 804	285 228 ± 780	1.0063 ± 0.0039
2.3–2.8	167 359 ± 579	167 997 ± 583	0.9962 ± 0.0049
2.8–3.3	20 148 ± 210	19 766 ± 214	1.0191 ± 0.0150

E	Q^2	E'	ν	x
13.5	1.5	5.7	7.8	0.10
13.5	2.05	7.8	5.7	0.19
13.5	2.55	9.7	3.8	0.36
13.5	3.05	11.6	1.9	0.86

(Calculations done by M. Nycz, preliminary)

x_min	x_max	Q^2_min	Q^2_max	sig(e-)_LO	sig(e+)_LO	sig(e-)_NLO	sig(e+)_NLO	A_LO	A_NLO
0.08	0.14	1.3	1.8	7.679204	7.677651	7.948650	7.9462437	-0.000101	-0.0001514
0.14	0.26	1.8	2.3	5.269455	5.268194	5.205612	5.2043891	-0.000120	-0.0001174
0.26	0.52	2.3	2.8	2.853423	2.852809	2.526783	2.5263637	-0.000108	-0.0000830

PVDIS past, present, and future

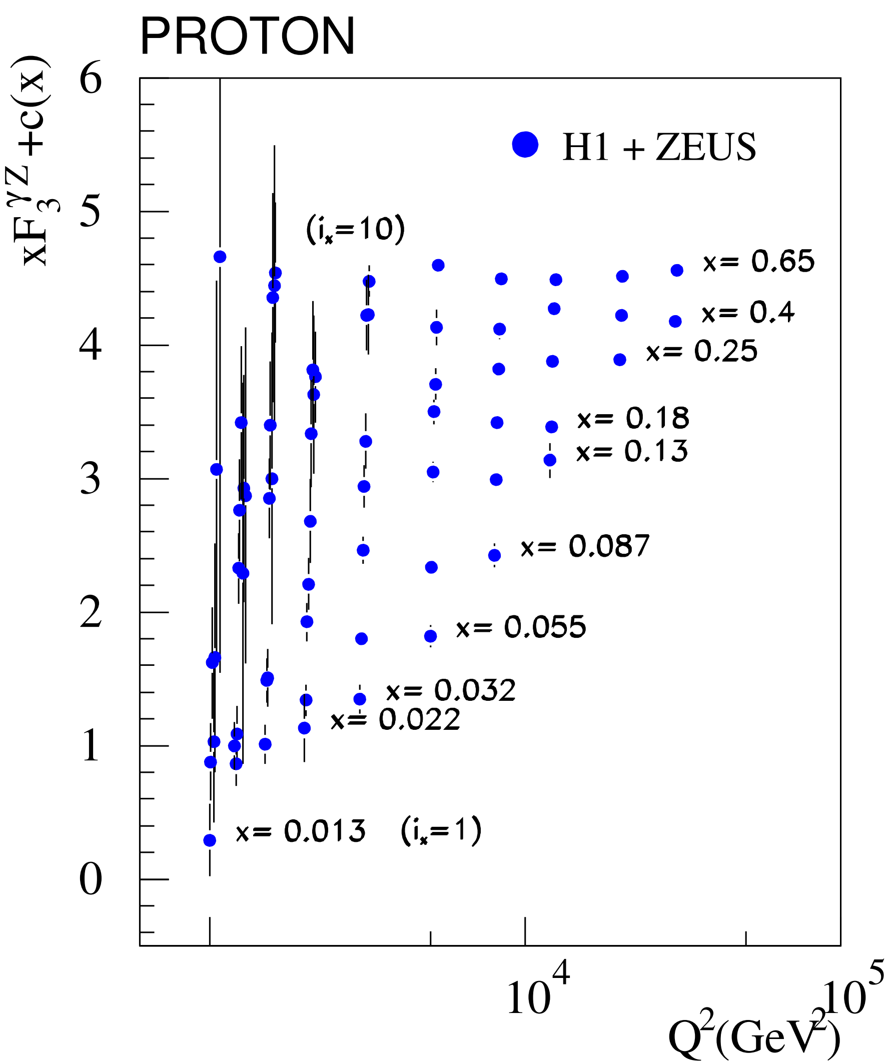


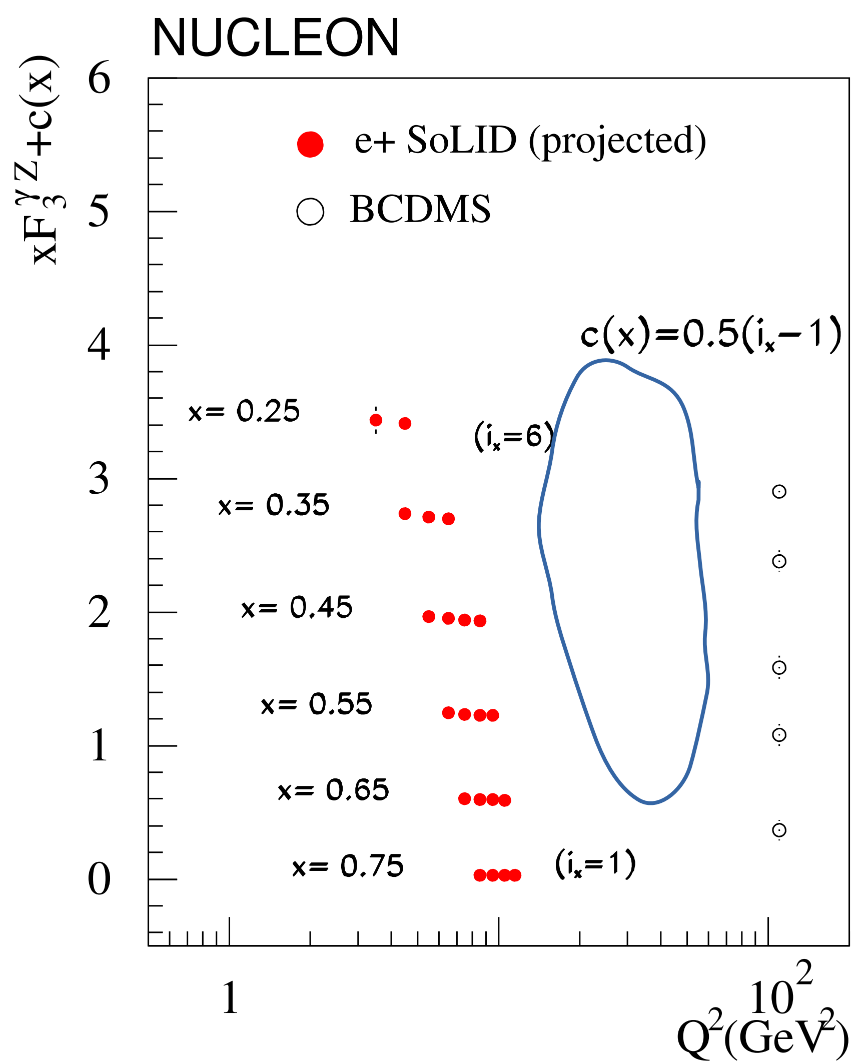
Future A^{e+e-} Measurements?

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

– JLab 24 GeV – calculation ongoing

– EIC – calculation ongoing





DJANGOH: Electron scattering at high Q^2 – DIS

Monte-Carlo approach in HERACLES and DJANGOH:
QCD-based event generation, valid at large Q^2: parton model

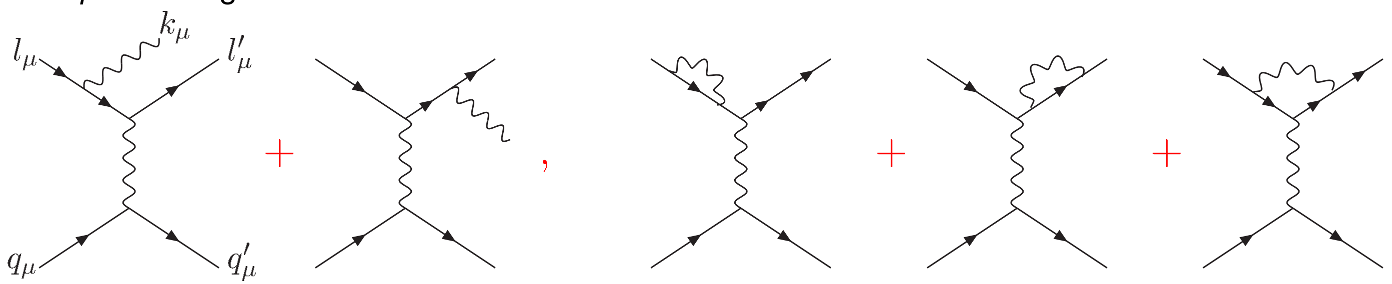
- Complete QED and electroweak corrections at $O(\alpha)$
- NC and CC scattering, polarized lepton, polarized nucleon
- Parton Distribution Functions from LHAPDF, models for low Q^2 structure functions
- Elastic tail
- Polarized nuclei
- Heavy nuclei: models for nuclear shadowing, nuclear parton distribution functions
- Interface to LEPTO, JETSET
- Jets, parton showers, hadronic final state
- SOPHIA for low-mass hadronic final states

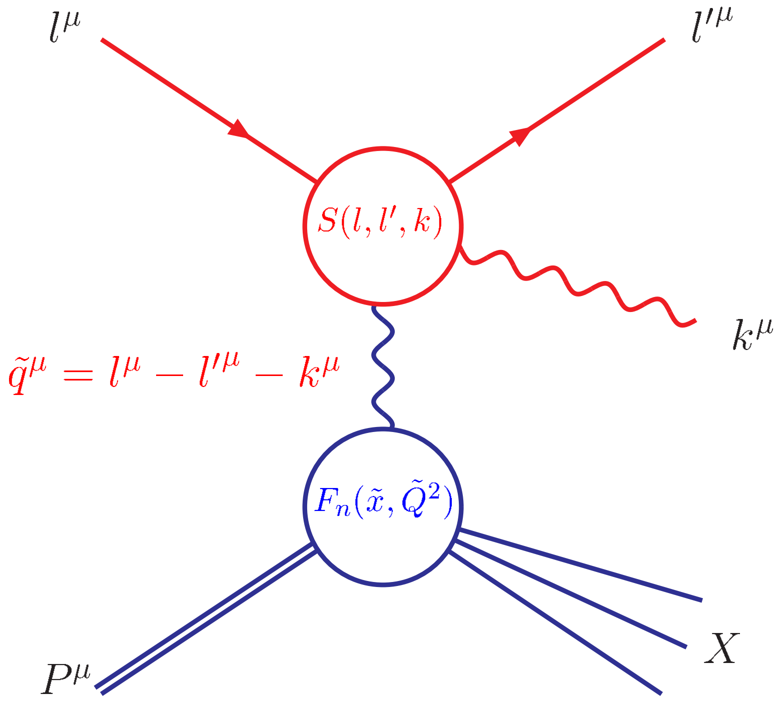
Used for HERA, EIC

Leptonic radiation

Feynman diagrams for leptonic radiation at $O(\alpha)$ (NC)

for *eq* scattering:



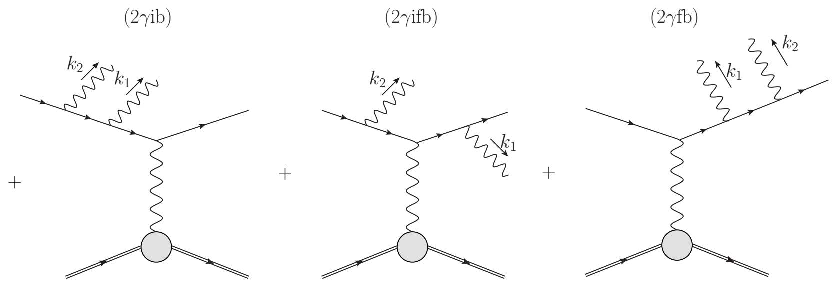


radiative leptonic tensor $S_{\mu\nu}(l, l', k)$ is

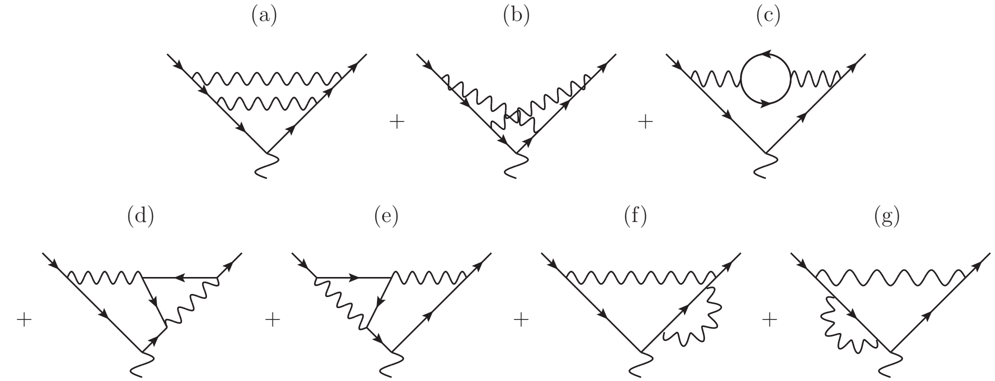
- gauge invariant
- infrared finite
- universal

(includes Born + loops: $\delta^{(4)}(k^\mu)$)

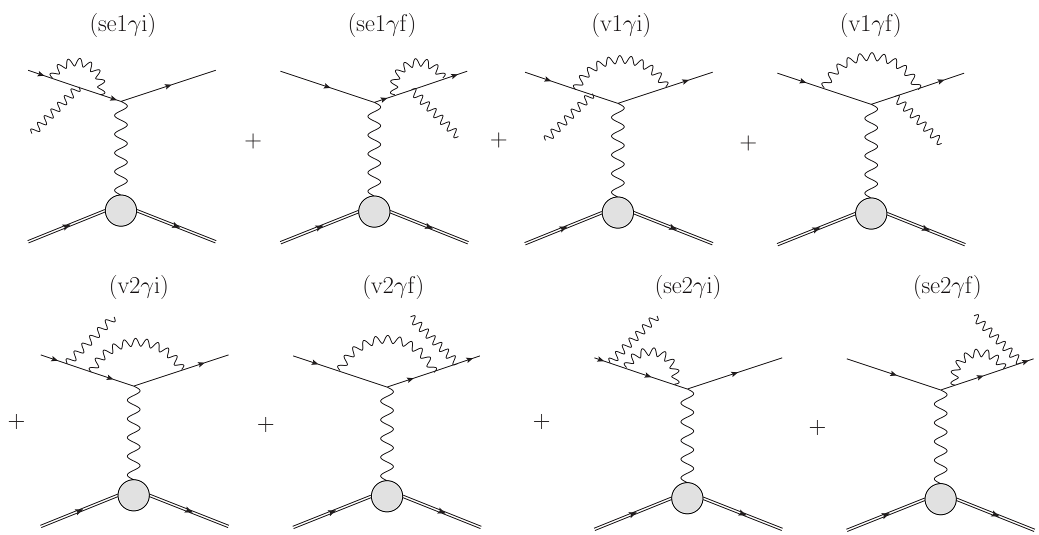
Second-order corrections



2-photon radiation



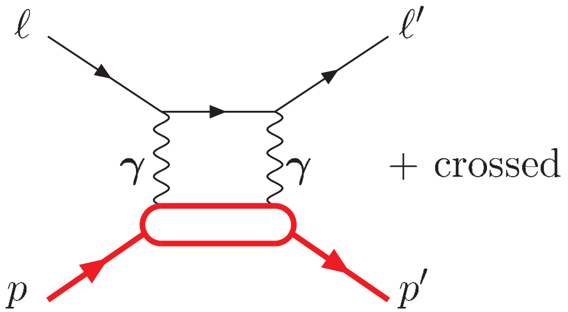
2-loop



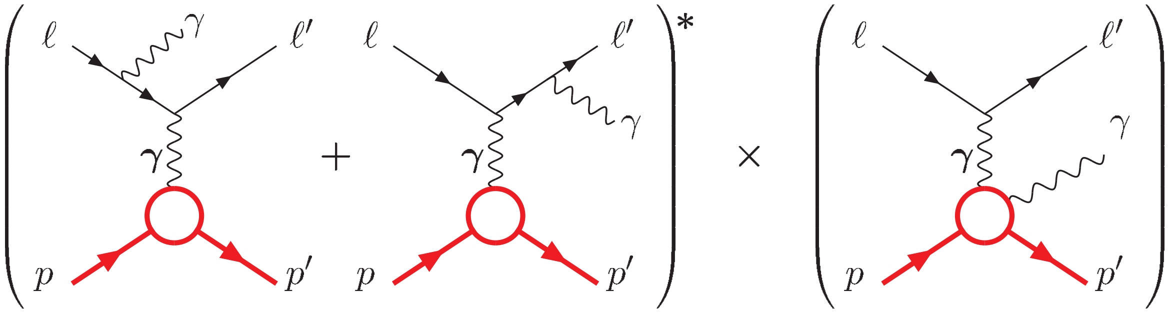
1-loop corrected 1-photon radiation

2-photon exchange

carries both
Q^2- and E-dependence



IR divergences cancel against real radiation:
Interference of leptonic and hadronic radiation

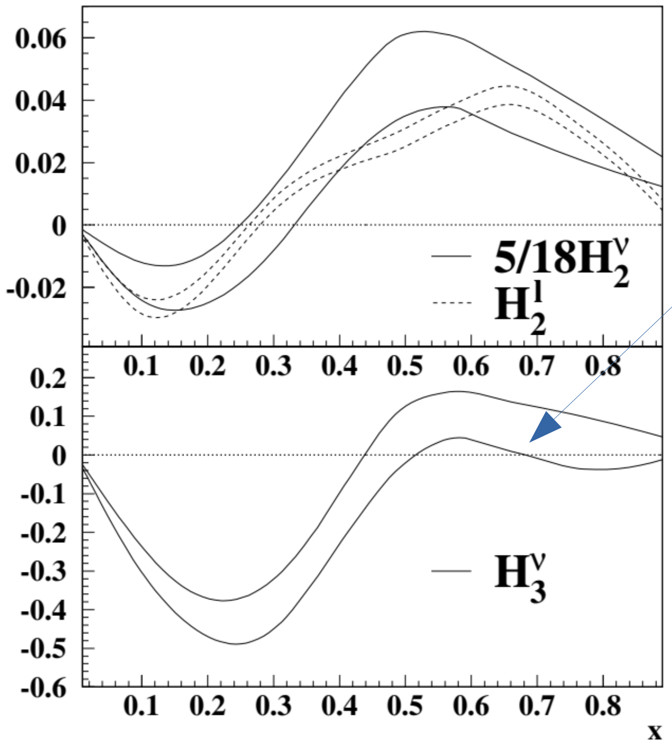


Mass singularites (large logs, $\ln(Q^2/m_e^2)$) cancel

Higher Twist Effects

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

neutrino results:



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

https://arxiv.org/abs/0710.0124

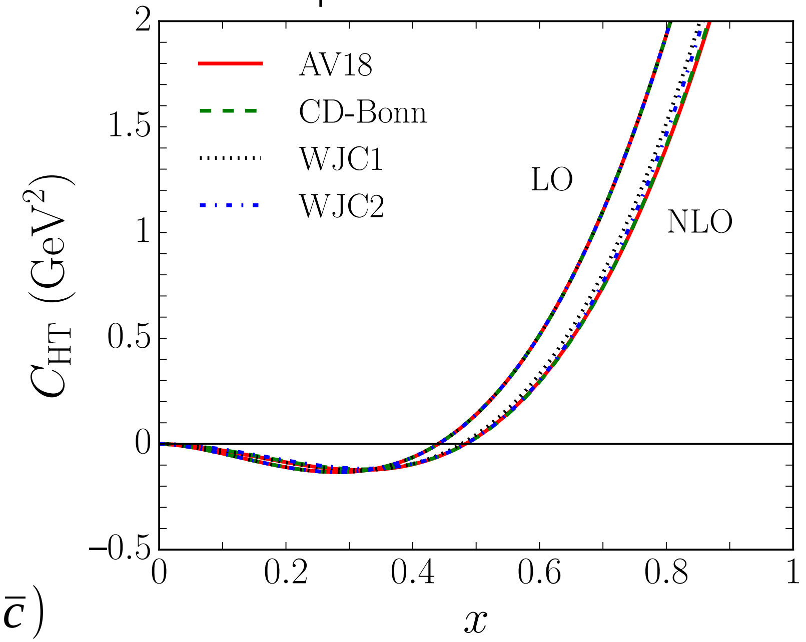
$$x F_3^\nu = x F_3^{\nu,\mathrm{LT}} + \frac{H_3}{Q^2}$$

(per nucleon definition)

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

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

HT of F_1^γ from CJ15:



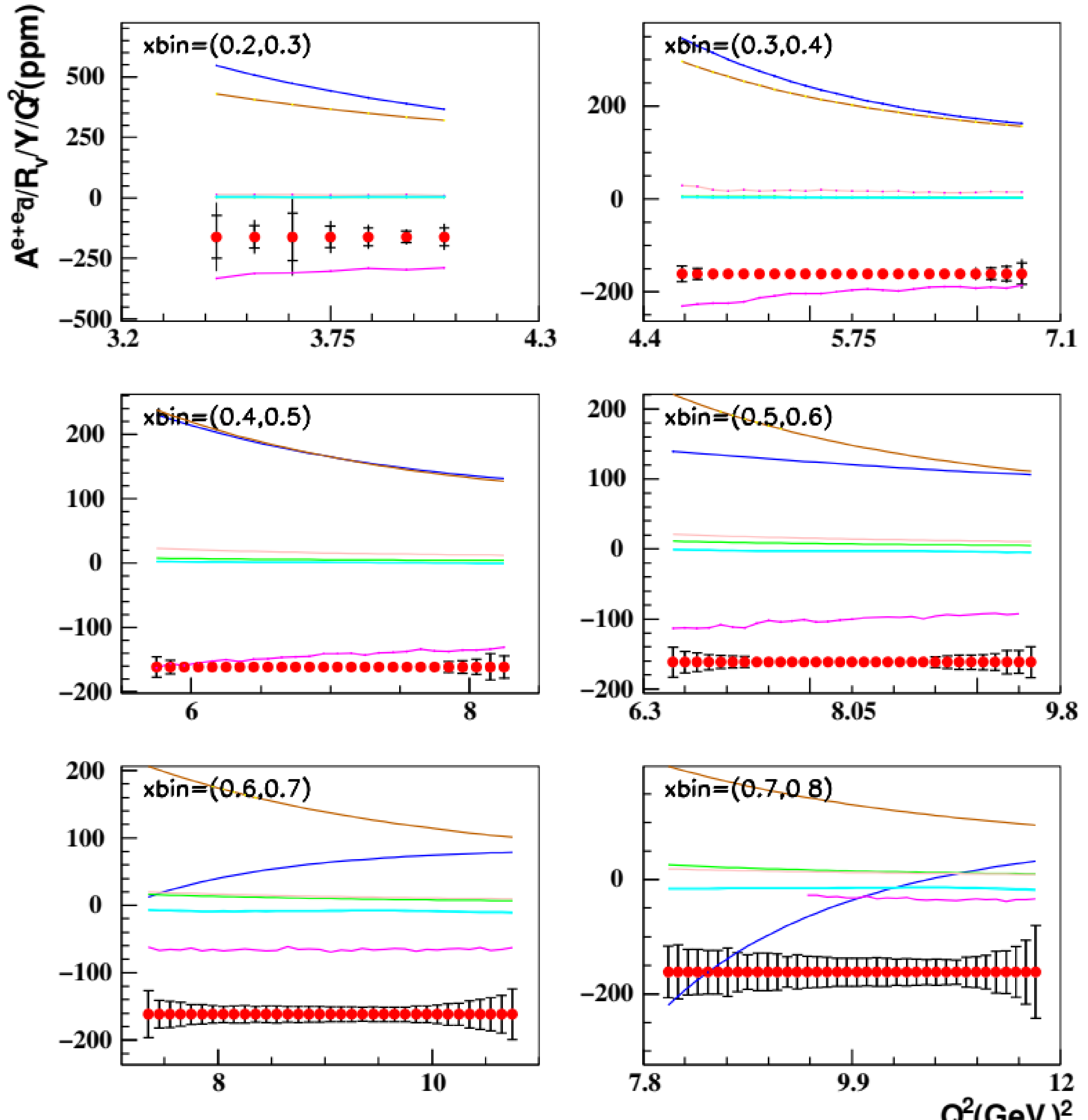
Phys.Rev.D 93 (2016) 11, 114017
e-Print: 1602.03154 [hep-ph]

– no newer work on H3nu, also confirmed with author

– low x HT >> CJ15’s HT on F2

Fitting with x-binned Q^2 dependence was not as good

but more kinematic dependence can be explored to improve the fitting sensitivity, e.g. vs. theta



Full expression in parton model

(done)

For the deuterium, adding s and c:

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

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

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

The general case

(done)

based on
Anselmino et al. [arXiv:hep-ph/9401264]

For PVDIS:

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

For $A^{e^+e^-}$:

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

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

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

$$\eta_Z=\eta_{\gamma Z}^2$$

Complete formula (also including *Z* terms):

– for numerator, replace $F_{1,2}^{\gamma Z}\rightarrow F_{1,2}^{\gamma Z}-2\,\eta_{\gamma Z}g_V^e F_{1,2}^{Z}$ and $g_V^e F_3^{\gamma Z}\rightarrow g_V^e F_3^{\gamma Z}-\eta_{\gamma Z}\left(g_V^e g_V^e+g_A^e g_A^e\right)F_3^{Z}$

– for denominator, replace $g_V^e F_{1,2}^{\gamma Z}\rightarrow g_V^e F_{1,2}^{\gamma Z}-\eta_{\gamma Z}\left(g_V^e g_V^e+g_A^e g_A^e\right)F_{1,2}^{Z}$

and $g_A^e F_3^{\gamma Z}\rightarrow g_A^e F_3^{\gamma Z}-2\,\eta_{\gamma Z}\left(g_V^e g_A^e\right)F_3^{Z}$

$$F_2^Z=1/2\sum\left(g_V^q g_V^q+g_A^q g_A^q\right)[q+\bar{q}]$$

$$F_3^Z=2\sum g_V^q g_A^q[q+\bar{q}]$$