# Scientific Opportunities at EIC with Both Lepton Signs

*A Personal Perspective*

- Introduction
- Electroweak
- DVCS
- Realization
- Summary

# Resources

**Workshop on Electroweak and BSM physics at EIC** **https://indico.bnl.gov/event/8110/**
6-7 May, 2020, Organizers: C. Gal, M. Gerike and W. Deconinck
*Center for Frontiers in Nuclear Science*, Stony Brook U.

- Experience of EW and BSM physics at HERA and lessons for EIC – E. Gallo (DESY)
- BSM and EW with positrons at EIC – W. Melnitchouk (JLab)
- Neutral-Current Weak Interactions at an EIC – Y. Zhao (IMP, CAS)

*Gluons and the quark sea at high energies: distributions, polarization, tomography*
INT, September 13 – November 19, 2010
**arXiv: 1108.1713**

*Physics with Positron Beams at Jefferson Lab 12 GeV*
LOI12-18-004 to PAC46
**arXiv: 1906.09419**


INTERNATIONAL WORKSHOP ON
POSITRONS
AT JEFFERSON LAB
March 25-27, 2009
JEFFERSON LAB
TOPICS:
• Positron-proton elastic scattering
• Deeply virtual Compton scattering
• New 12 GeV experiments with positrons
• Technology of positron sources
• Polarized positrons
• Electron/photon drivers
• Positron & electron polarimetry
• Applied physics with positrons
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• P. Cole (Idaho State U.)
• A. Freyberger (JLab)
• P. Guichon (CEA Saclay)
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• J. Sheppard (SLAC)
• A. Variola (LAL Orsay)
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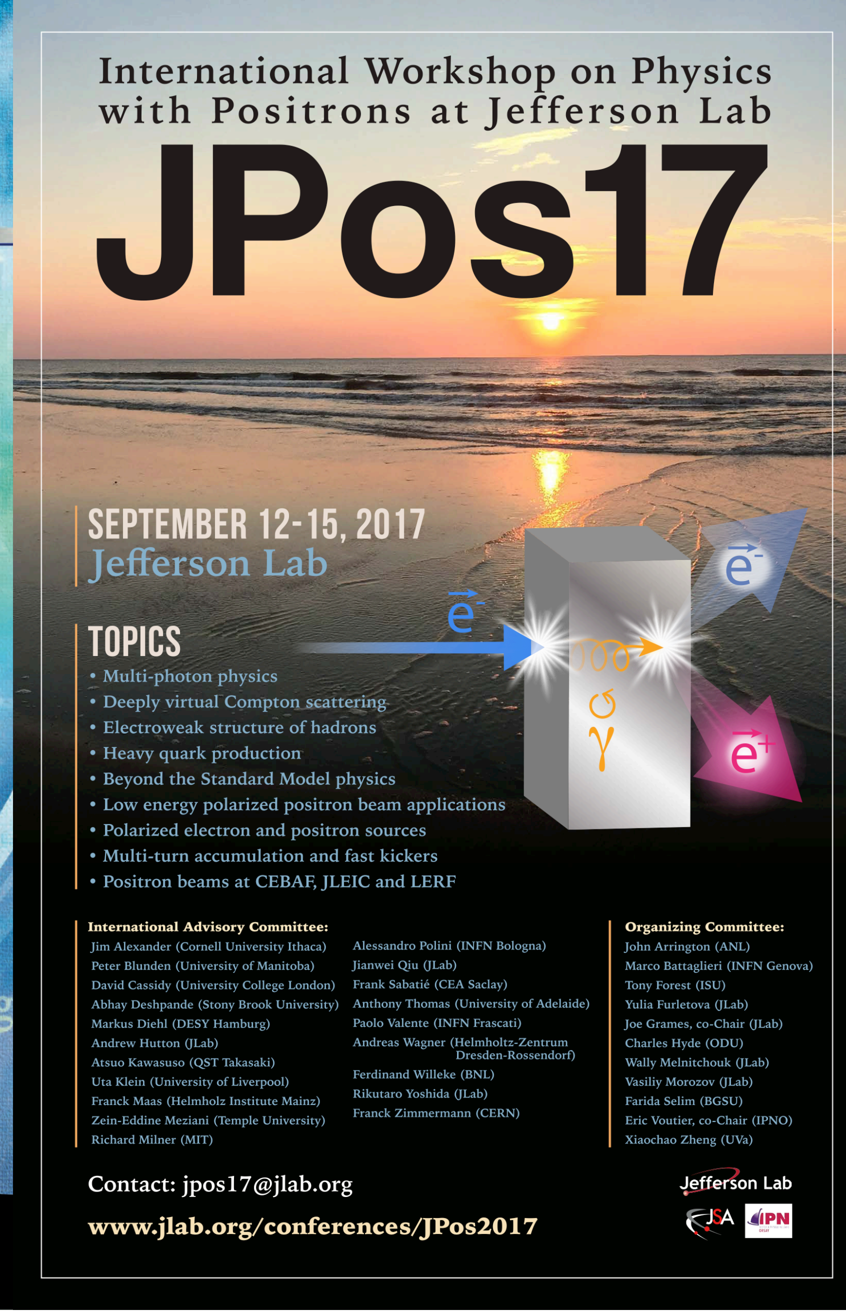
• J. Grames (JLab)
• W. Melnitchouk (JLab)
• E. Voutier (LPSC, Grenoble)
email: jpos09_admin@jlab.org
conferences.jlab.org/JPOS09
Jefferson Lab


International Workshop on Physics with Positrons at Jefferson Lab
JPos17
SEPTEMBER 12-15, 2017
Jefferson Lab
TOPICS
• Multi-photon physics
• Deeply virtual Compton scattering
• Electroweak structure of hadrons
• Heavy quark production
• Beyond the Standard Model physics
• Low energy polarized positron beam applications
• Polarized electron and positron sources
• Multi-turn accumulation and fast kickers
• Positron beams at CEBAF, JLEIC and LERF
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Contact: jpos17@jlab.org
www.jlab.org/conferences/JPos2017
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# Elastic Electron-Proton Scattering at Moderate $Q^2$

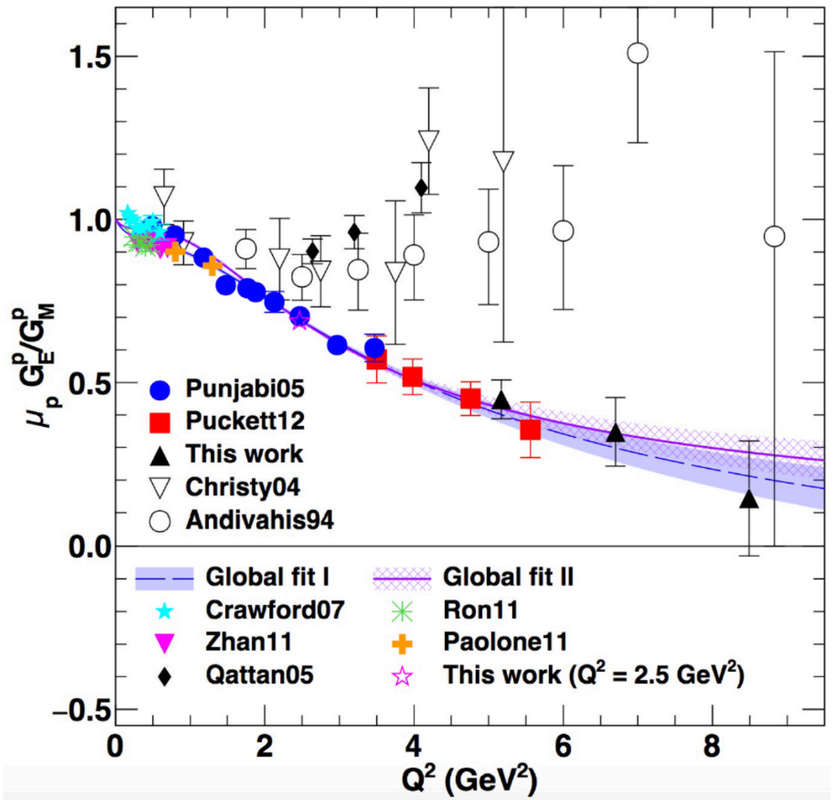
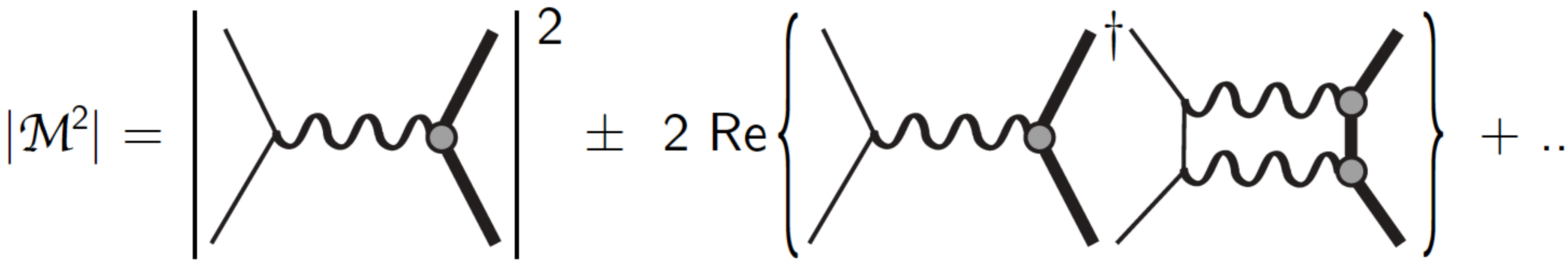


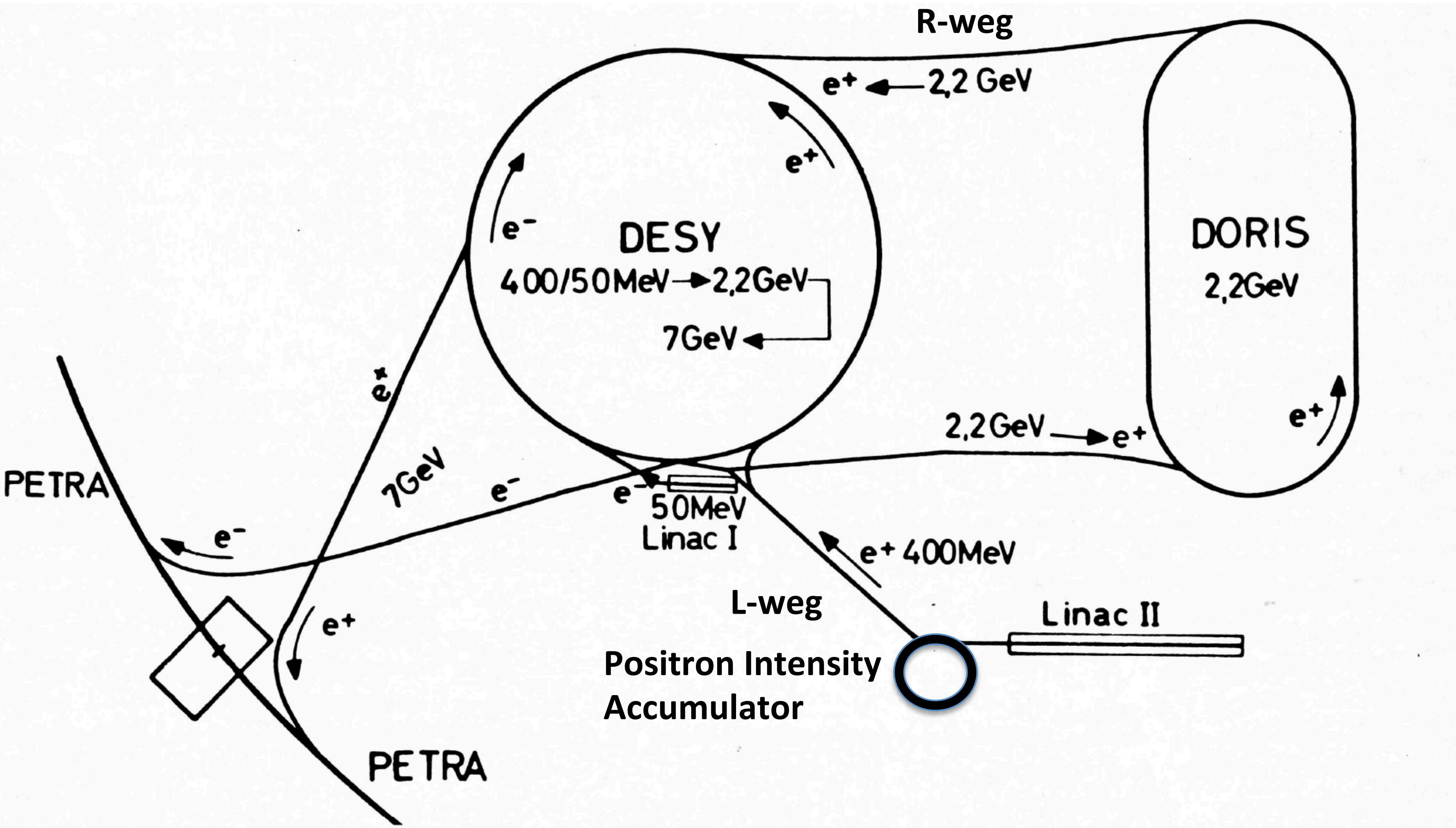

Figure 1. Rosenbluth (open and diamond symbols) and polarization transfer (all other symbols) experimental data for the ratio between the electric and magnetic form factor of the proton, together with global fits of polarization data [Puc17].

# Direct Access to Two-Photon Exchange

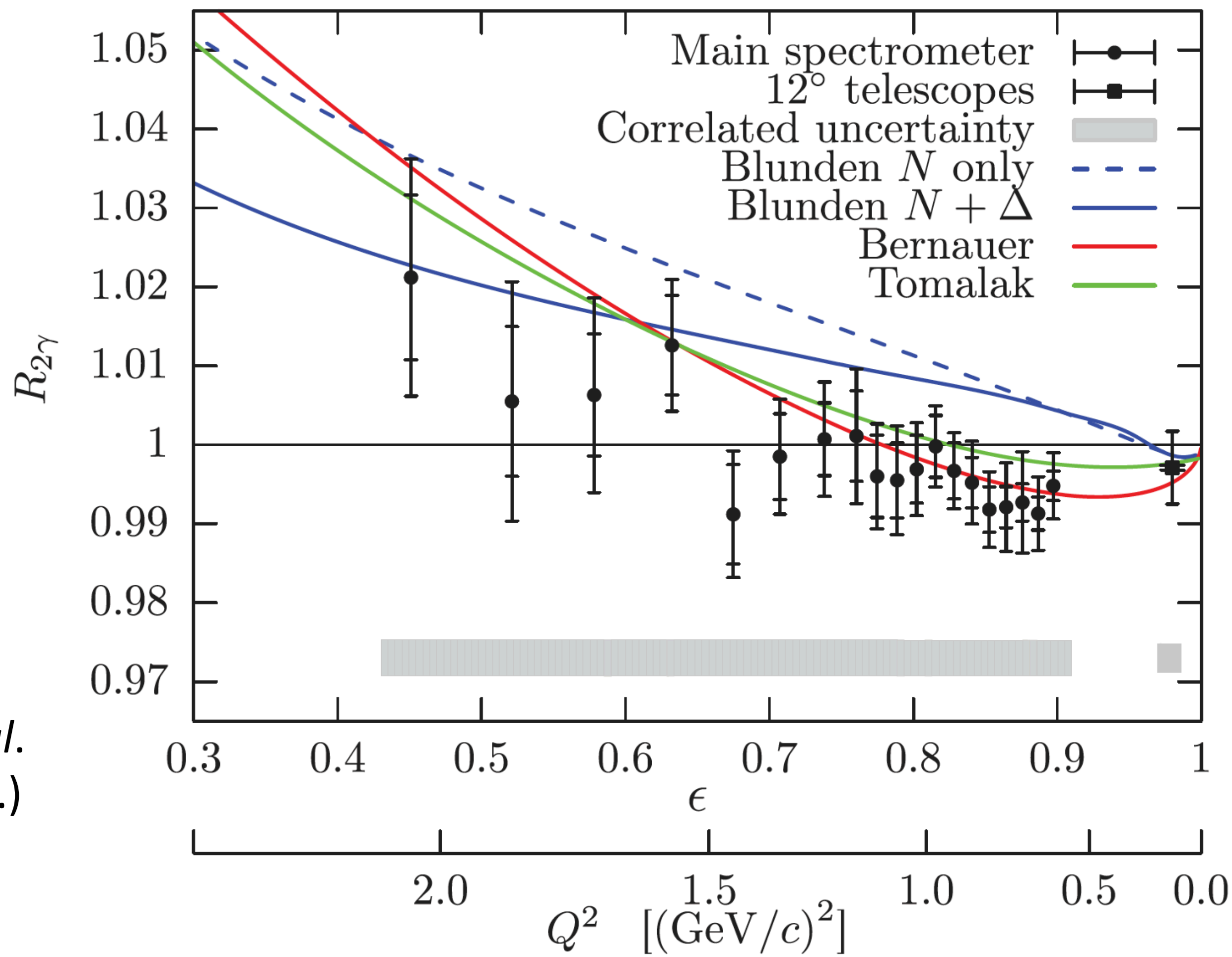


$$R_{2\gamma} \equiv \frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + \frac{4\mathrm{Re}\left\{\mathcal{M}_{2\gamma}\mathcal{M}_{1\gamma}\right\}}{|\mathcal{M}_{1\gamma}|^2}$$

# Positrons at DESY

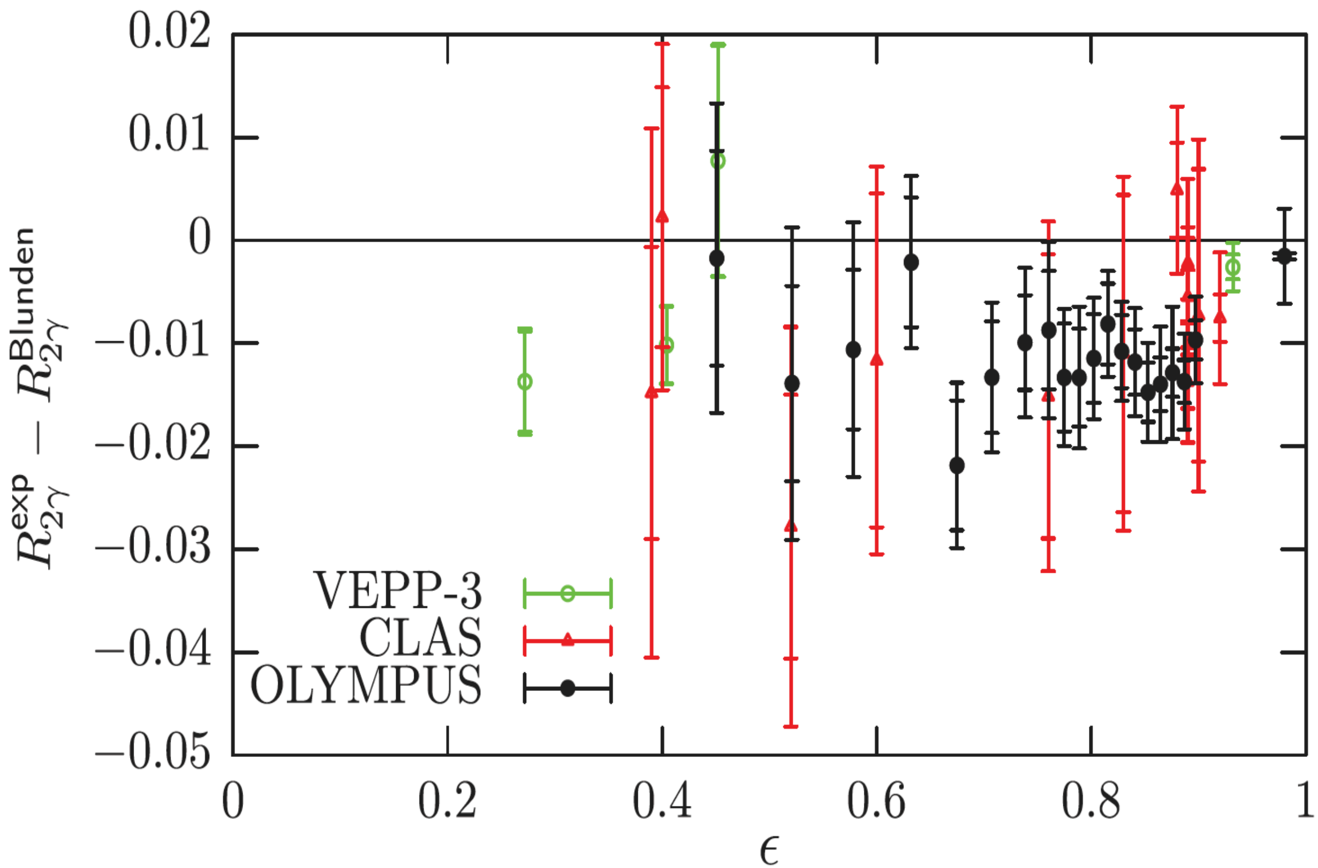


# OLYMPUS Data




B.S. Henderson *et al.* (The OLYMPUS Coll.) Phys. Rev. Lett. **118**, 092501 (2017)

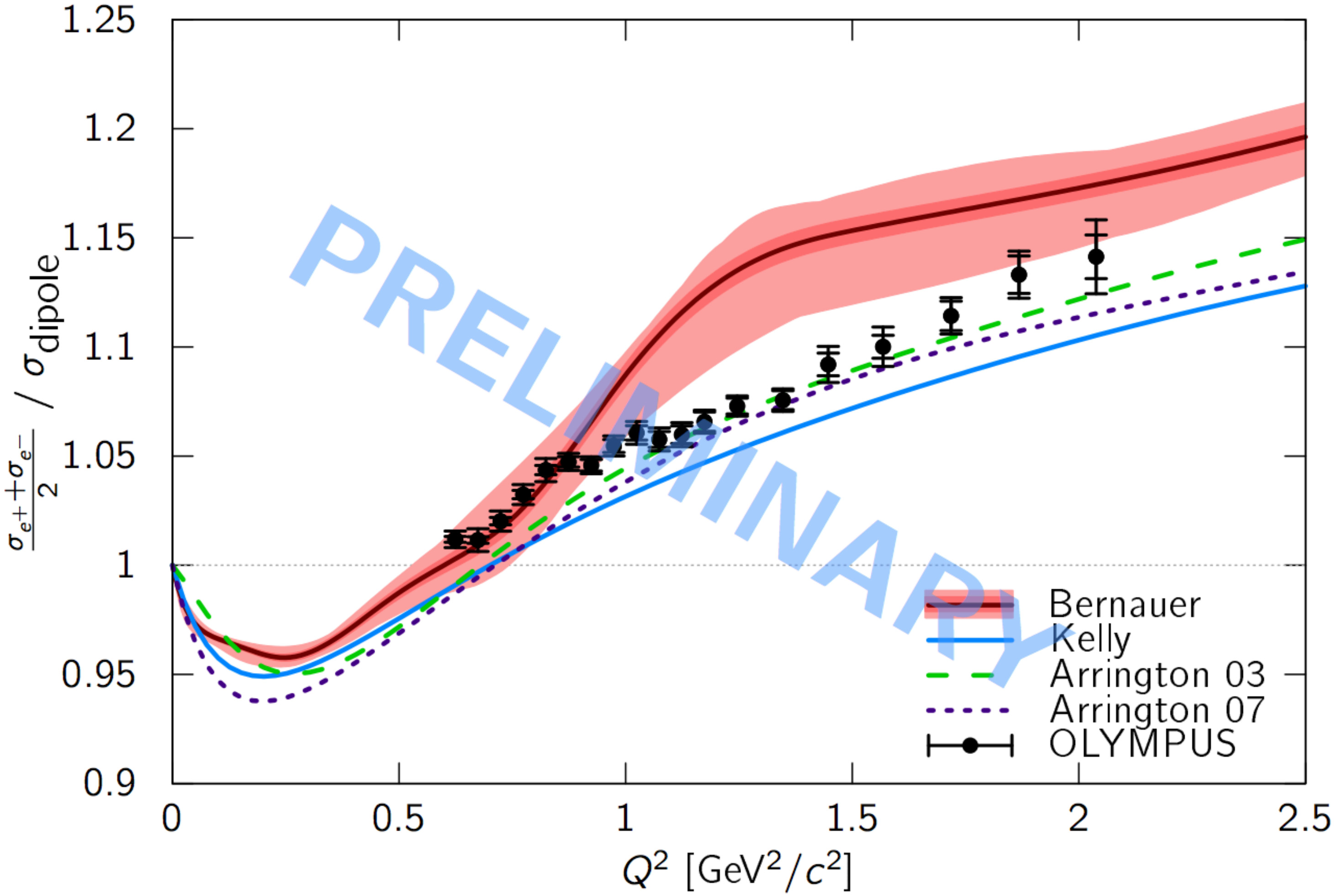
# World's Data




B.S. Henderson *et al.*
(The OLYMPUS Coll.)
Phys. Rev. Lett.
**118**, 092501 (2017)

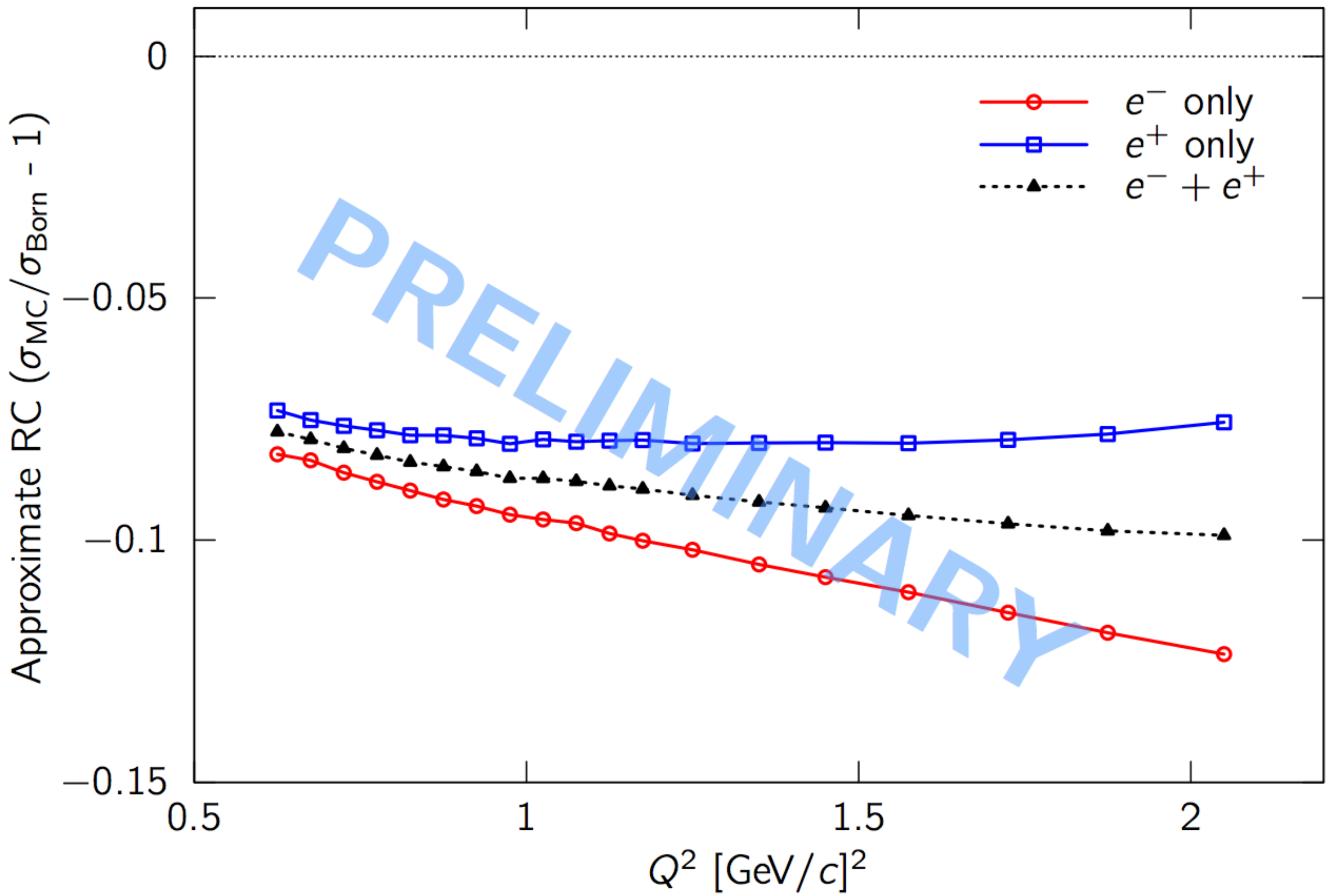
# Charge-averaged cross section

**A. Schmidt**
**Talk, yesterday**



# The charge-odd radiative correction is a significant fraction of the total.

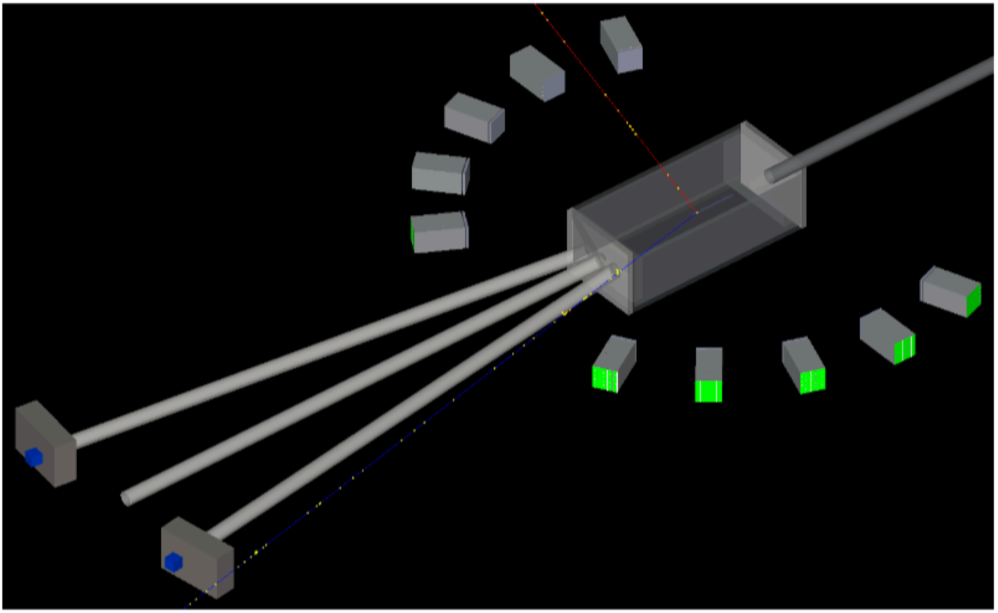
**A. Schmidt Talk, yesterday**



# Two Photon Exchange eXperiment (TPEX)

- Only facility in world that can deliver positron beams for foreseeable future for scattering experiments is at DESY:
  - 60 nA of electrons
  - 30 nA of positrons
  - 0.5 to 6.3 GeV energy
- Use DESY test beam facility.
- TPEX is a new experiment under development to scatter extracted e+/- beams from a liquid hydrogen target to measure $R_{2\gamma}$ up to $Q^2 = 4.6\ (\mathrm{GeV}/c)^2$.
- Led by Douglas Hasell (MIT).

# TPEX Layout



1. Arizona State University, Tempe, AZ, USA
2. Catholic University of America, Washington, DC, USA
3. Charles University, Prague, Czech Republic
4. George Washington University, Washington, DC, USA
5. Glasgow University, Glasgow, Scotland, UK
6. Hampton University, Newport News, VA, USA
7. Massachusetts Institute of Technology, Cambridge, MA, USA
8. Stony Brook University, Stony Brook, NY, USA
9. University of Michigan, Ann Arbor, MI, USA

- x 100 times luminosity of OLYMPUS.
- EM calorimeter using lead tungstate blocks.
- Test development at DESY under way.

# Collider Kinematics

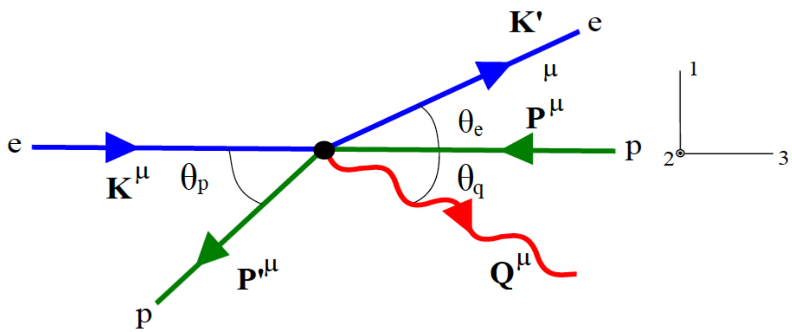



FIG. 1. (color online) Electron-proton elastic scattering in collider kinematics.

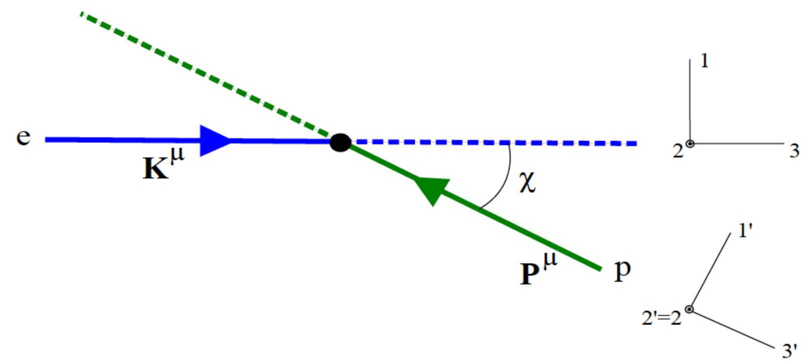


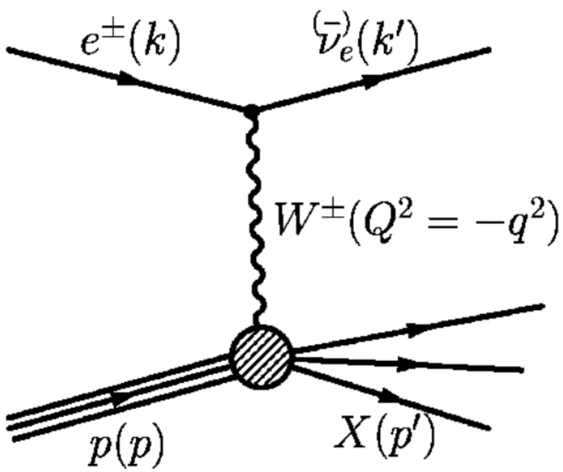

FIG. 2. (color online) Electron-proton elastic scattering in crossed-beams collider kinematics.

| | Kinematics I | Kinematics II |
|---|---|---|
| $k$ (GeV/c) | 10 | 2 |
| $p$ (GeV/c) | 250 | 50 |
| $k_{rest}$ (GeV/c) | 5329 | 213.2 |
| $\theta_e^{rest}$ (deg) at $\theta_e = 1^\circ$ | 0.00188 | 0.00938 |
| $\tan(\theta_e^{rest}/2)$ at $\theta_e = 1^\circ$ | $1.638{\times}10^{-5}$ | $8.187{\times}10^{-5}$ |
| $1 - \mathcal{E}$ at $\theta_e = 1^\circ$ | $5.410{\times}10^{-10}$ | $1.341{\times}10^{-8}$ |
| $\theta_e^{rest}$ (deg) at $\theta_e = 5^\circ$ | 0.00939 | 0.0469 |
| $\tan(\theta_e^{rest}/2)$ at $\theta_e = 5^\circ$ | $8.193{\times}10^{-5}$ | $4.096{\times}10^{-4}$ |
| $1 - \mathcal{E}$ at $\theta_e = 5^\circ$ | $1.633{\times}10^{-8}$ | $3.385{\times}10^{-7}$ |

TABLE I. Selected kinematics and rest-frame variables.

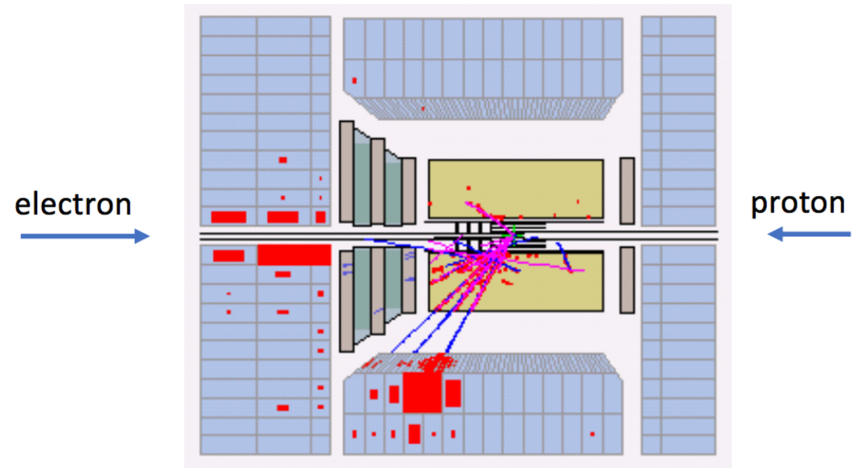
Sofiatti & Donnelly
Phys. Rev. C
**84,** 14606 (2011)

# Electroweak, HERA




- Kinematics of reconstructed from hadronic system
- Hadronic calorimeter resolution crucial

**E. Gallo**

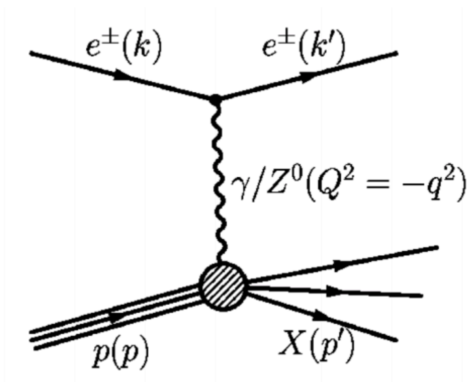


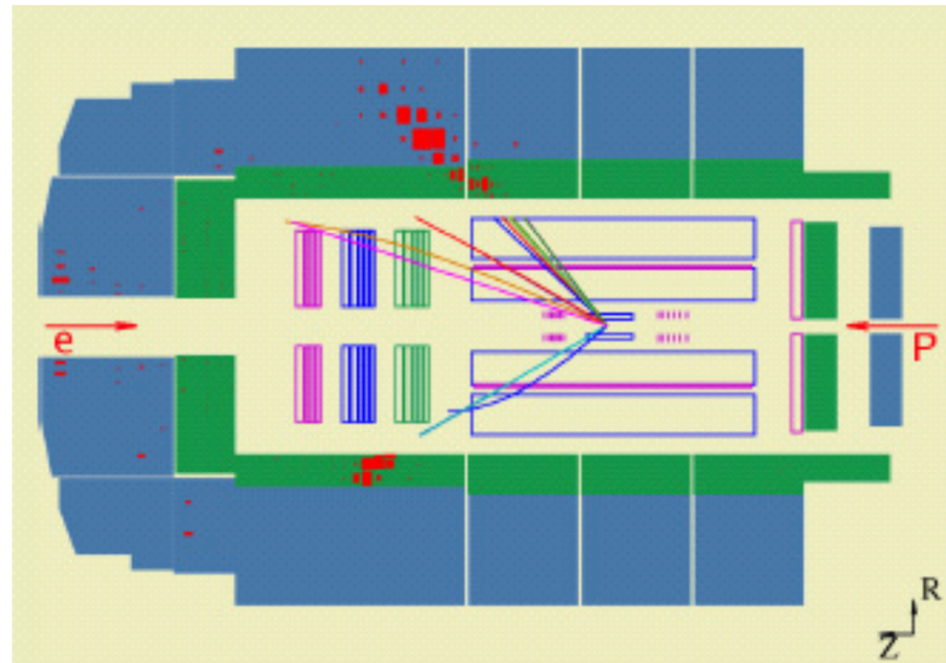

$$\frac{d\sigma^{e^+p}_{unpolCC}}{dQ^2dx} = \frac{G_F}{2\pi}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[\bar{u}_i(Q^2,x)+(1-y)^2 d_i(Q^2,x)\right]$$

$$\frac{d\sigma^{e^-p}_{unpolCC}}{dQ^2dx} = \frac{G_F}{2\pi}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[u_i(Q^2,x)+(1-y)^2 \bar{d}_i(Q^2,x)\right]$$

- Both electron and positron running crucial
- $e^+$ p suppressed by (1-y)
- Give information on u,d valence density separately

# Neutral current at high $Q^2$

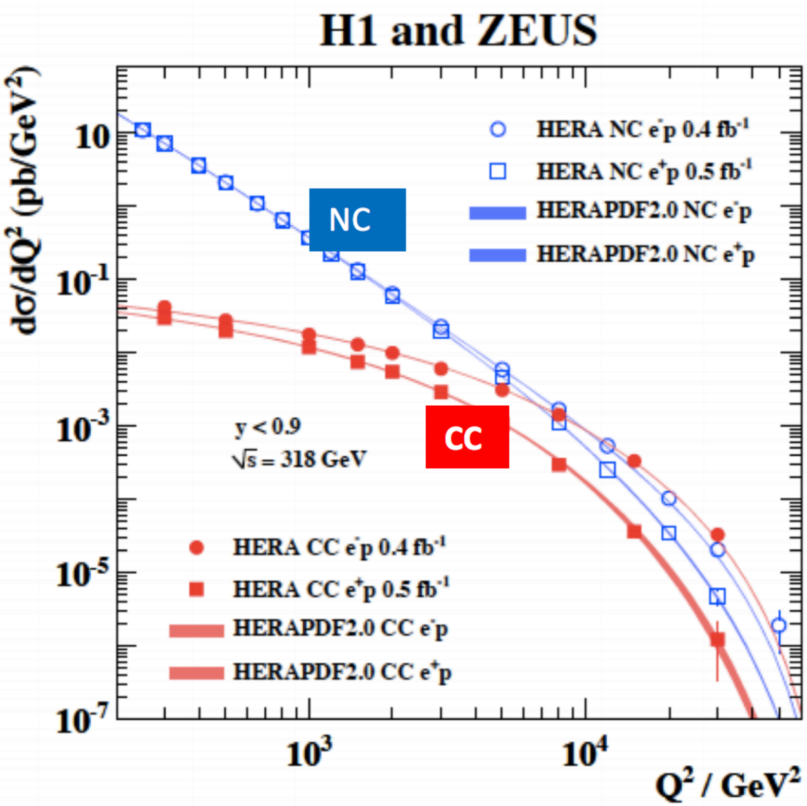


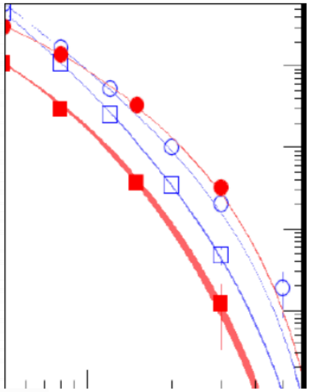

- Need electron identification at high angle, in the forward region, so optimized algorithm
- At high $Q^2$ the cross section (here expressed as reduced cross section) cannot neglect the $xF_3$ term

$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma^{\pm}}{dx dQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^{\pm} \mp \frac{Y_-}{Y_+} x\tilde{F}_3^{\pm} - \frac{y^2}{Y_+}\tilde{F}_L^{\pm}$$

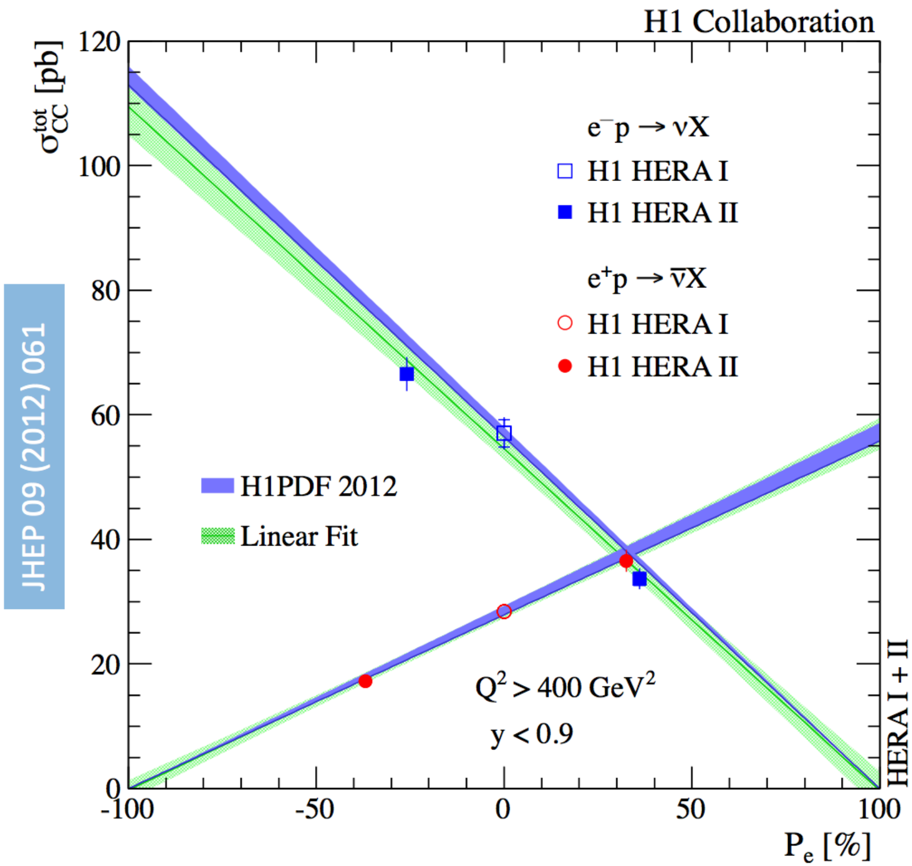
# NC+CC cross sections




- Textbook plot: at high $Q^2 \sim M_Z^2$, $M_W^2$. become of the same strength
- Here shown with the QCD prediction with the HERAPDF2.0 fit
- In NC gamma-Z interference and Z-exchange visible at very high $Q^2$

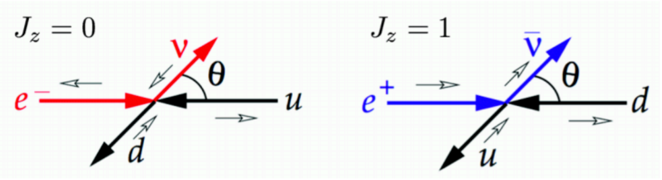


# CC polarized cross sections




$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}(P_e)}{\mathrm{d}x\mathrm{d}Q^2} = (1 \pm P_e)\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

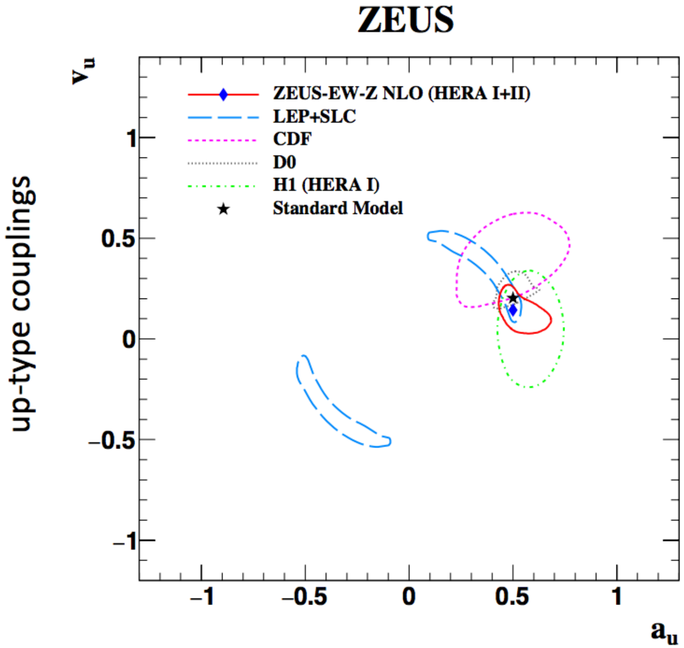
- Textbook plot: the charged current cross section goes to zero for right-handed electrons, as predicted by the SM

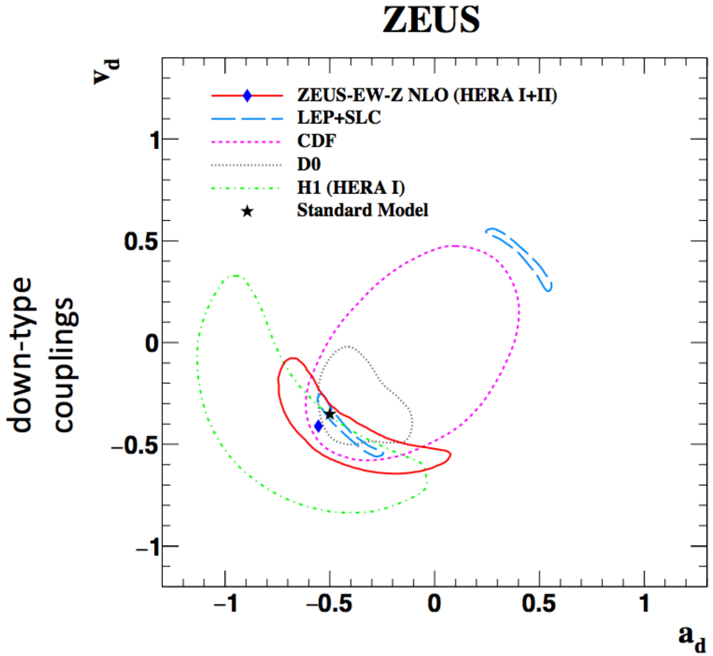


# Combined QCD+EW fit ZEUS-EW-Z

$v_u = 1/2 - 4/3\sin^2\theta_W,\ a_u = 1/2$

$v_d = -1/2 + 2/3\sin^2\theta_W,\ a_d = -1/2$




Phys. Rev. D 93 (2016) 092202

13+4 PDF fit ZEUS-EW-Z to constrain the Z to u,d couplings

Very competitive measurement - at least compared to Tevatron - and can constrain the sign

# Standard Model Test, HERA

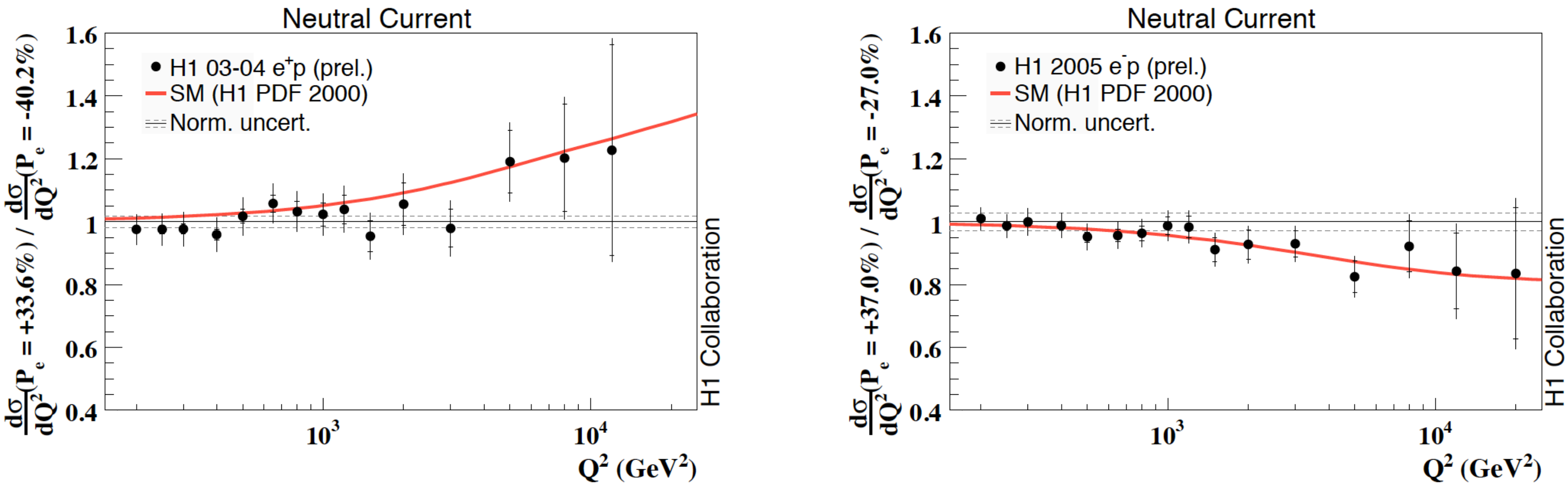
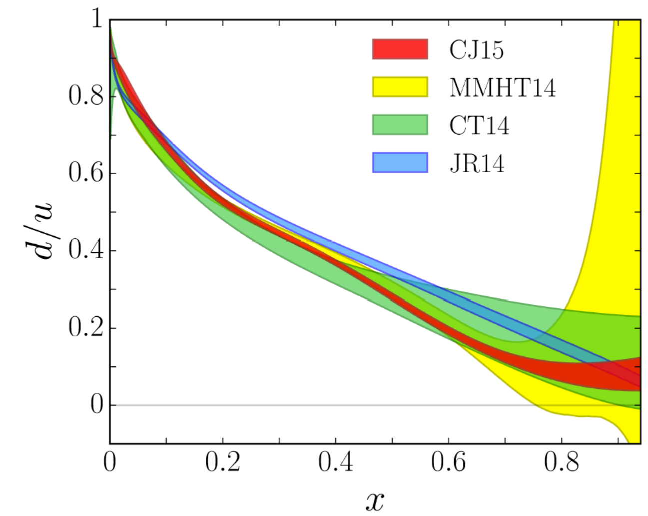


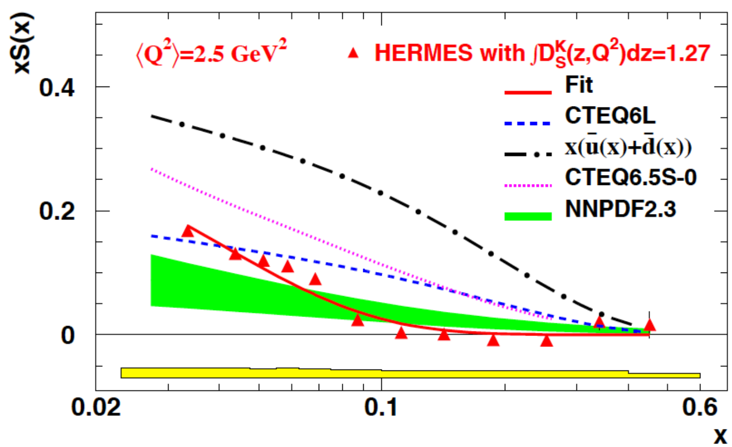

**Figure 5.** The ratio of the NC $d\sigma/dQ^2$ cross sections for the positive over negative lepton beam polarisation, for $e^+p$ (left) and $e^-p$ (right) scattering.

# Flavor separation with e⁻ and e⁺ DIS

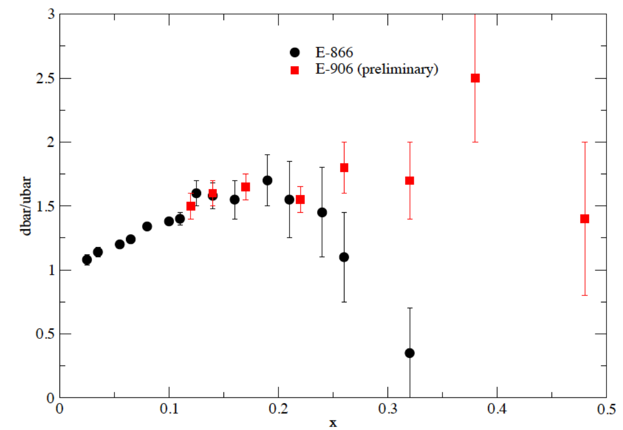
**W. Melnitchouk**

- *d/u* ratio at large *x*
- Light quark sea asymmetry
- Strange and anti-strange quark PDFs




*PRD 89 (2014) 097101*



# *d/u* ratio

Charged current structure functions in lowest order:

$$e^+p \to \bar{\nu} + X \quad \boxed{F_2^{e^+p,cc}(x,Q) \propto xd}$$

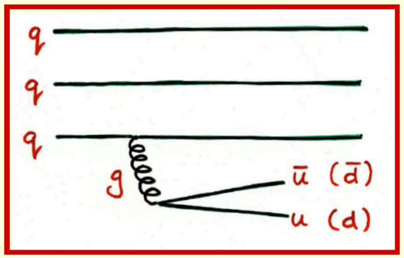
and

$$e^-p \to \nu + X \quad \boxed{F_2^{e^-p,cc}(x,Q) \propto xu}$$

- Allows direct extraction of *d/u* at large x
- Measured at HERA out x =0.4
- Need good statistical precision at larger *x*

# Light Quark Sea

- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)



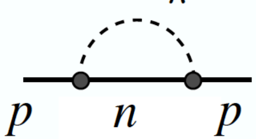

$\longrightarrow$ since $u$ and $d$ quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

- From chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

***A. Thomas (1984)***

$\pi^+ \longleftarrow (u\bar{d})$




$\longrightarrow$ $\boxed{\bar{d} > \bar{u}}$

# Flavor asymmetry of the light quark sea

Again, consider the charged current structure functions in lowest order

$$F_2^{e^+p,cc}(x,Q) = \boxed{2x(d+s+\bar{u}+\bar{c})}$$

and

$$F_2^{e^-p,cc}(x,Q) = \boxed{2x(u+c+\bar{d}+\bar{s})}$$

- If $xF_3^{e^-p,cc} = 2(\underline{u-\bar{d}-\bar{s}+c})$ and $xF_3^{e^+p,cc} = 2(\underline{d-\bar{u}-\bar{c}+s})$ can be extracted, one can separate the quark and antiquark PDFs
- If the charm PDF is perturbative, *i.e.* there is no intrinsic charm, then $c = \bar{c}$
- Can get information on $\bar{d}/\bar{u}$

# Strange Quarks

Measure charged current cross sections with a muon tag to select charm final states

$$e^+ s \to \bar{\nu} c \quad \text{followed by} \quad c \to s \mu^+ \nu_\mu$$

and

$$e^- \bar{s} \to \nu \bar{c} \quad \text{followed by} \quad \bar{c} \to \bar{s} \mu^- \bar{\nu}_\mu$$

- Note that the sign of the muon is the same as the sign of initial state lepton
- Potentially capable of separating $s$ from $\bar{s}$

# Flavor Decomposition in Polarized DIS

- With pure γ exchange in inclusive DIS:

$$g_1^P = \frac{1}{2}\left(\frac{4}{9}(\Delta u + \Delta\bar{u}) + \frac{1}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right)$$
$$g_1^n = \frac{1}{2}\left(\frac{1}{9}(\Delta u + \Delta\bar{u}) + \frac{4}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right)$$

- Assumption: SU(3) flavor symmetry
  - ✓ Additional inputs from β-decay of neutron and hyperons

    $\Delta u + \Delta d - 2\,\Delta s$ $\qquad\qquad$ $\Delta u + \Delta d$
  - ✓ SIDIS measurements also provide information with quark flavors, fragmentation functions provide different weights

**Electroweak interactions in DIS region at an EIC can have new inputs…**

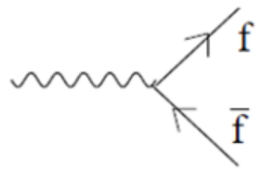
# Electroweak Interaction

Spin-1/2 particles carry two types of couplings: Axial and Vector

**Axial:** difference of strength for left/right handed states

**Vector:** Average of the two

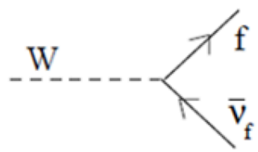
$\gamma$ $\quad -iQ\gamma^\mu$




No difference for left/right particle

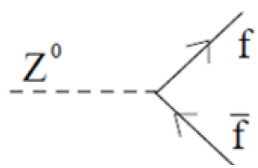
Vector coupling = Q

$W^\pm$ $\quad -i\frac{g}{\sqrt{2}}\gamma^\mu\frac{1}{2}\left(1-\gamma^5\right)$




Only interact with left-handed fermions

$Z^0$ $\quad -i\frac{g}{\cos\theta_W}\gamma^\mu\frac{1}{2}\left(g_V^e - g_A^e\gamma^5\right)$




Interact with both left and right handed fermions

$$g_A^e = -\frac{1}{2} \qquad g_V^e = -\frac{1}{2} + 2\sin^2\theta_W = -0.036$$

# W exchange in DIS region

$$A^{W^-} = \frac{2bg_1^{W^-} + ag_5^{W^-}}{aF_1^{W^-} + bF_3^{W^-}} ,$$

unpolarized CC structure functions

$$g_1^{W^-,p}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x),$$

$$g_5^{W^-,p}(x) = -\Delta u(x) + \Delta\bar{d}(x) - \Delta c(x) + \Delta\bar{s}(x)$$

$$g_1^{W^+,p}(x) = \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{c}(x) + \Delta s(x),$$

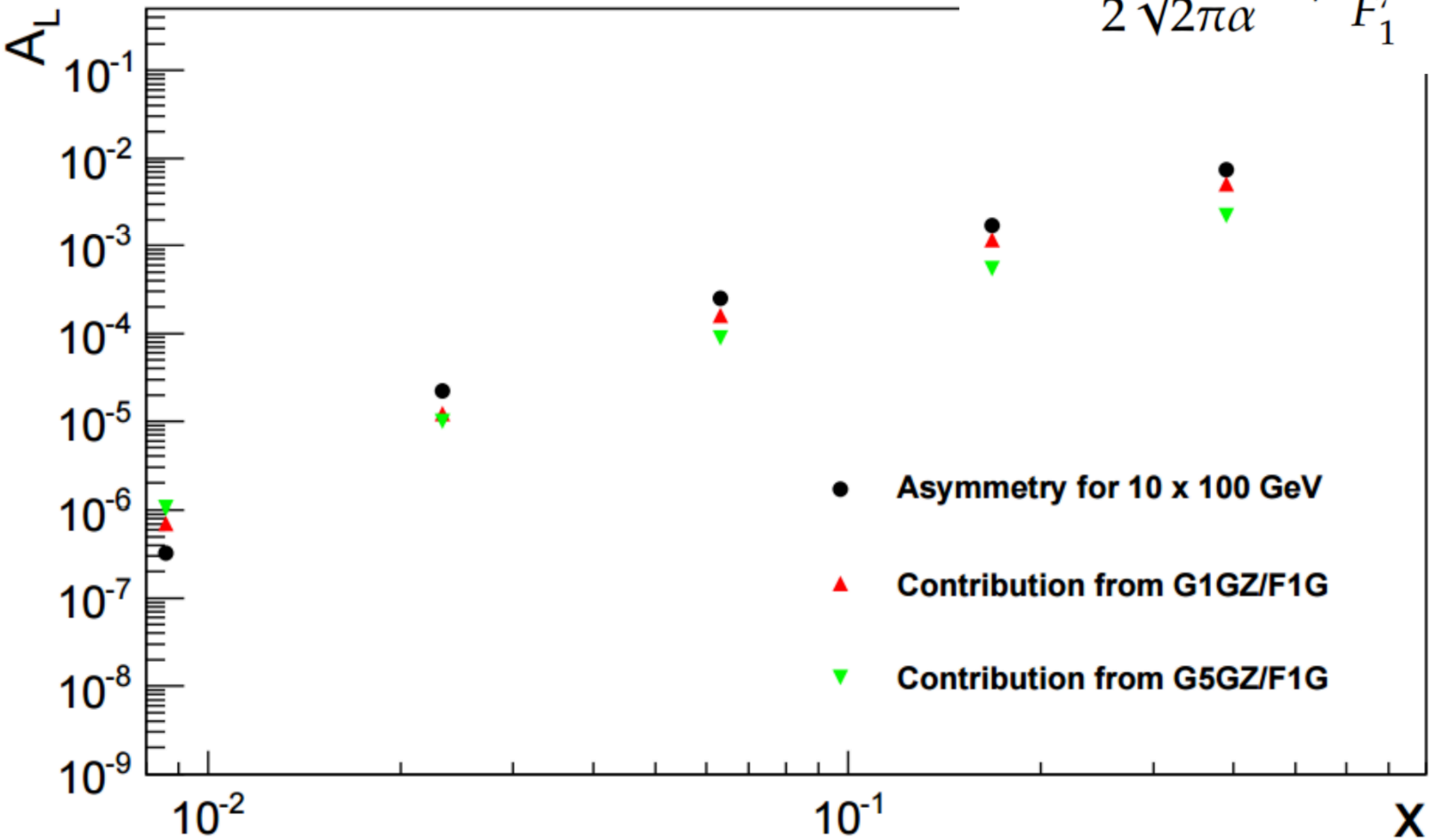
$$g_5^{W^+,p}(x) = \Delta\bar{u}(x) - \Delta d(x) + \Delta\bar{c}(x) - \Delta s(x)$$

Fundamental Sum Rule

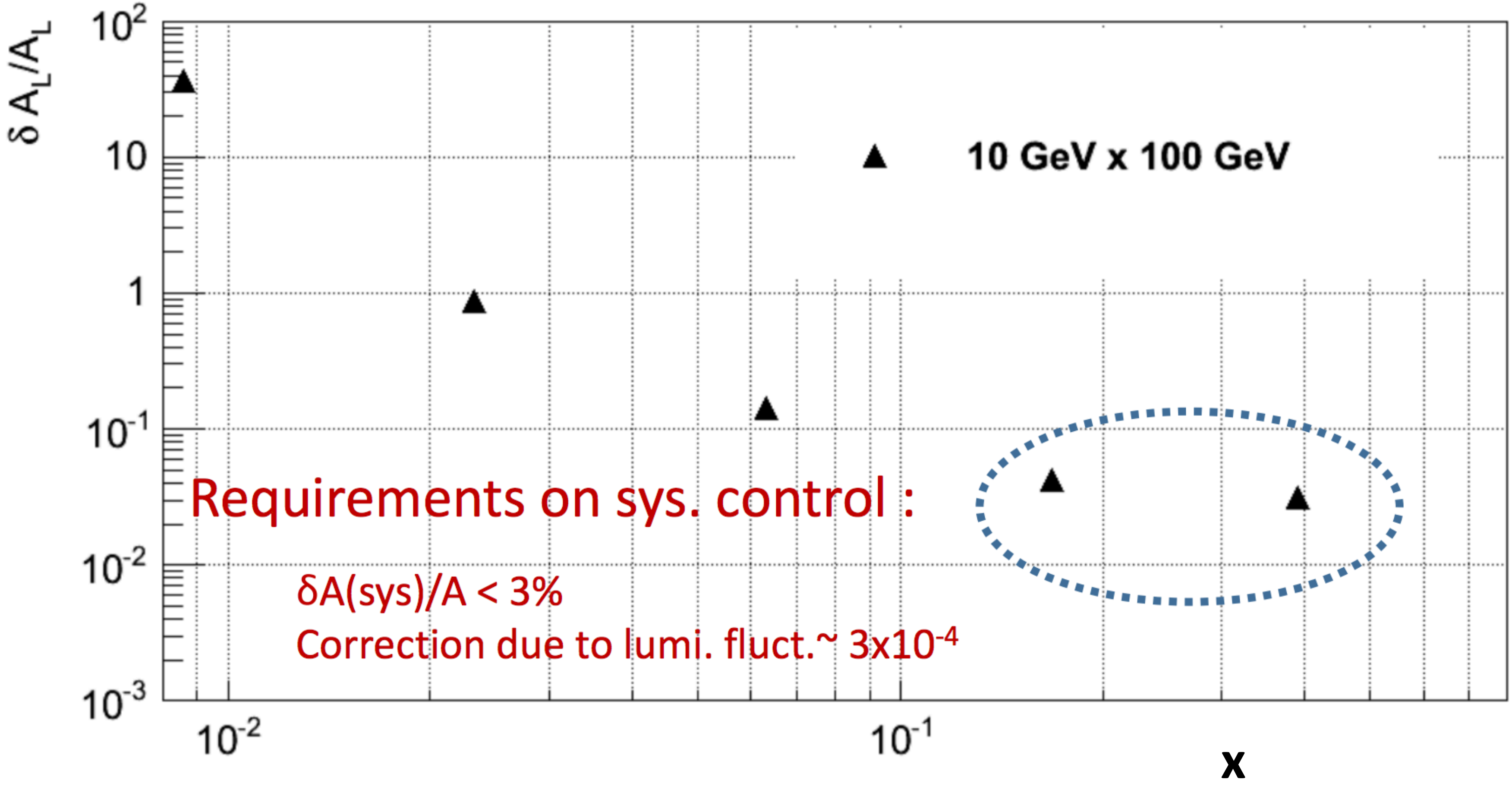
$$\int_0^1 dx \left[g_5^{W^+,p} - g_5^{W^+,n}\right] = \left(1 - \frac{2\alpha_s}{3\pi}\right) g_A ,$$

# Predicted asymmetries

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$



# δA/A as a function of x



## 1.12 Electroweak structure functions at the EIC

*Abhay Deshpande, Krishna Kumar, Felix Ringer, Seamus Riordan, Swadhin Taneja, Werner Vogelsang*

**arXiv: 1108.1713**

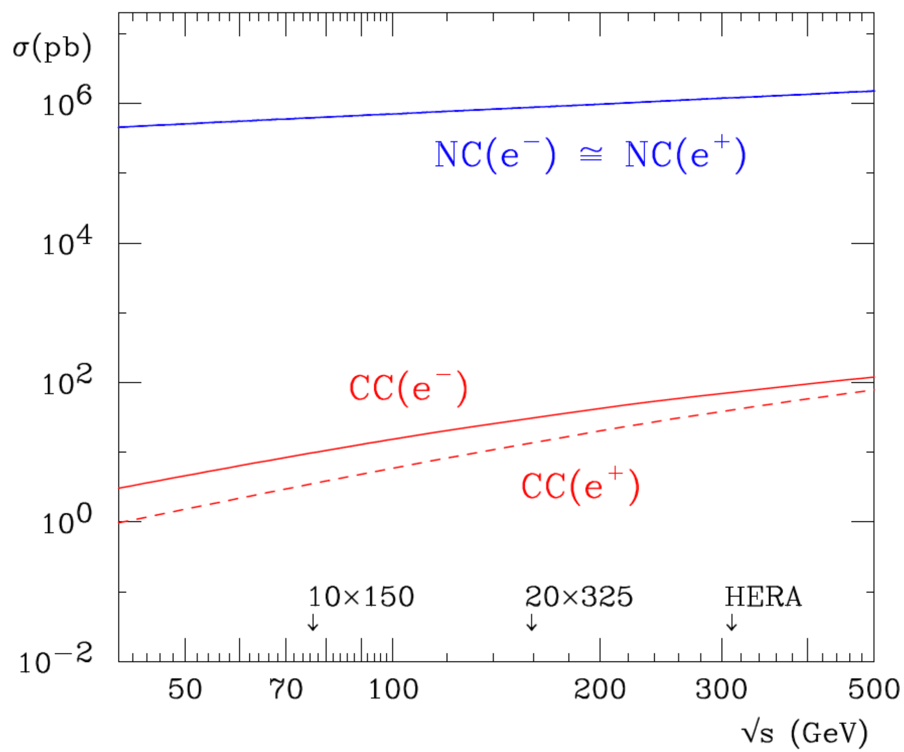



Figure 1.33. Total NC and CC cross sections for $Q^2 > 1$ GeV$^2$ as functions of the $ep$ $\sqrt{s}$.

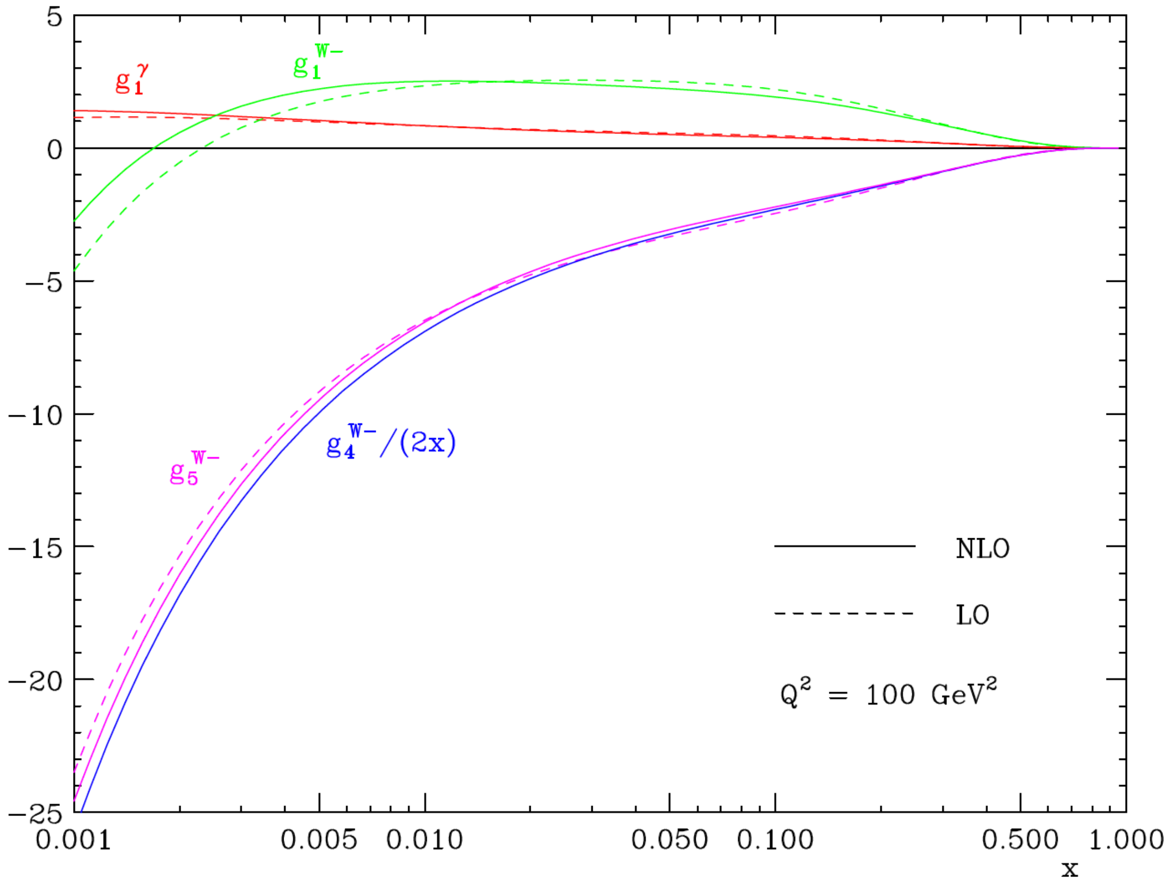



Figure 1.36. CC spin dependent structure functions $g_1^{W^-}$, $g_5^{W^-}$, and $g_4^{W^-}/2x$, at $Q^2 = 100$ GeV$^2$. The dashed lines show the LO results (the one for $g_4^{W^-}/2x$ is not shown in this case, since it coincides with that for $g_5^{W^-}$), while the solid curves are NLO. For comparison, we also show the electromagnetic $g_1^{\gamma}$.

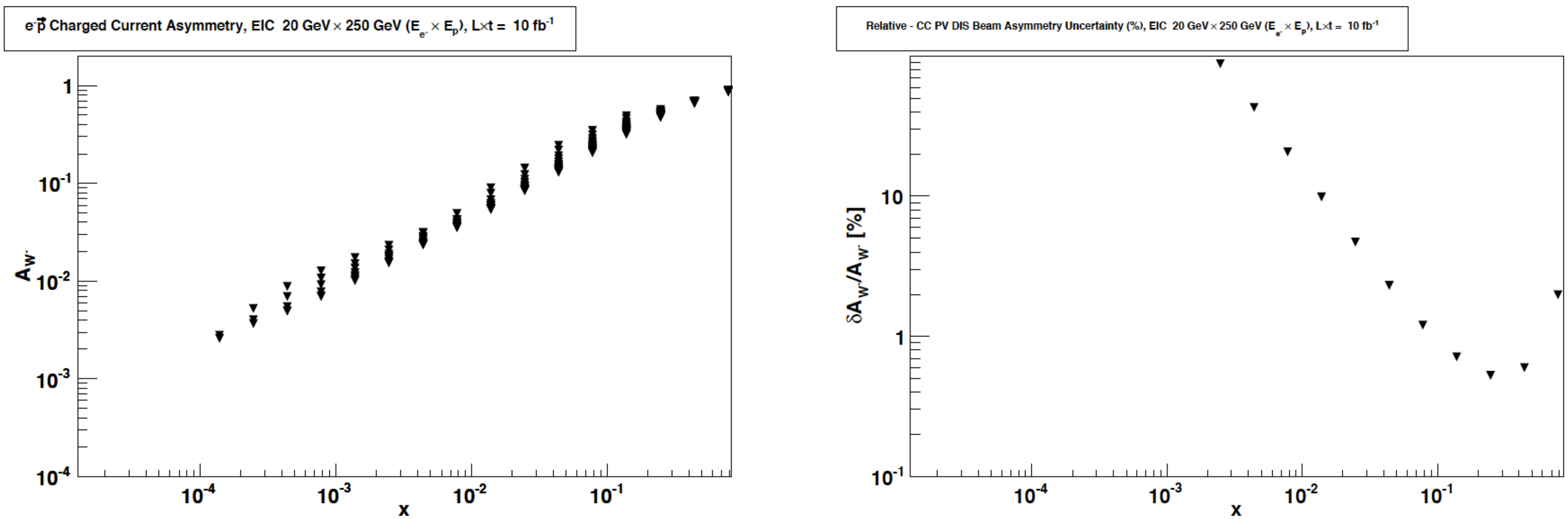
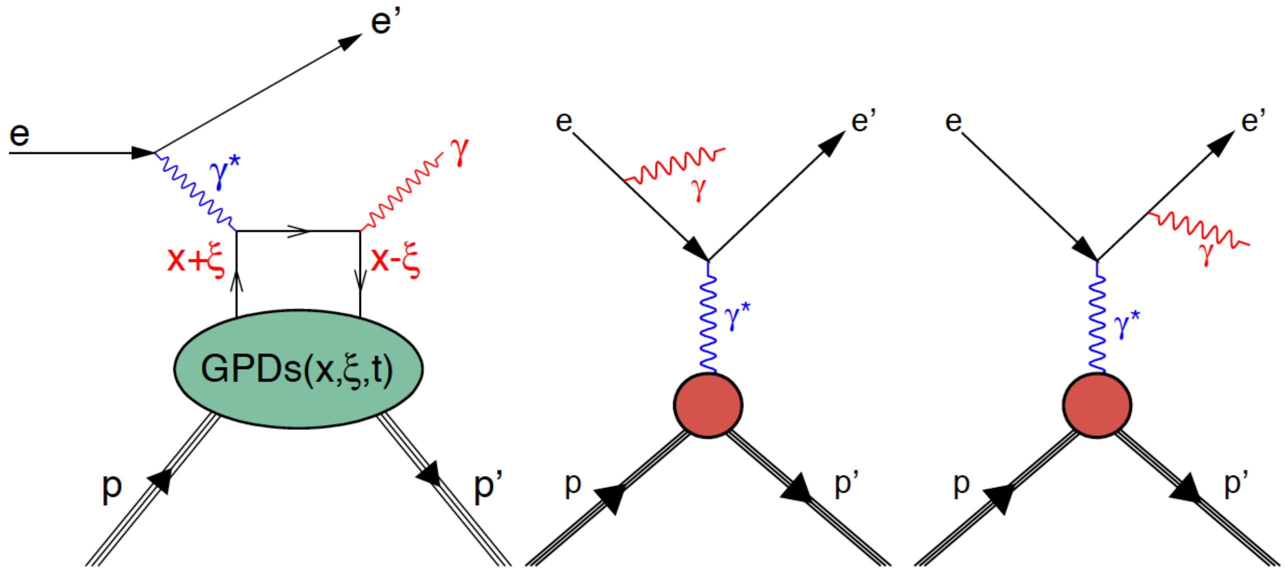
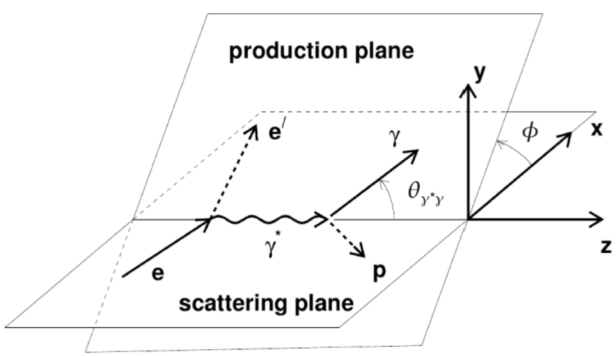



Figure 1.37. Left: spin asymmetry for CC $e^-\vec{p}$ scattering, as function of $x$ for various bins in $Q^2$. Right: resulting relative uncertainties of the asymmetry.

# Deeply Virtual Compton Scattering




(a) DVCS (b) Bethe Heitler




$$x_B \equiv \frac{Q^2}{2\mathbf{P}\cdot\mathbf{q}} \cong \frac{Q^2}{2M\nu},$$

$$\xi \equiv \frac{-q^2}{\mathbf{q}\cdot(\frac{\mathbf{P}+\mathbf{P'}}{2})} \approx \frac{x_B}{2-x_B}$$

**skewness variable**

$$y \equiv \frac{\mathbf{P}\cdot\mathbf{q}}{\mathbf{P}\cdot\mathbf{k}} \cong \frac{\nu}{E}.$$

$$t = (\mathbf{P}-\mathbf{P}')^2.$$

# Generalized Parton Distributions

| | Nucleon Helicity Conserving | Nucleon Helicity Inverting |
|---|---|---|
| Unpolarised GPDs | $H$ | $E$ |
| Polarised GPDs | $\widetilde{H}$ | $\widetilde{E}$ |

**Forward limit:**

$$H^q(x,0,0) = q(x),$$

$$\widetilde{H}^q(x,0,0) = \Delta q(x),$$

$$\int_{-1}^{1} H^q(x,\xi,t)dx = F_1^q(t),$$

$$\int_{-1}^{1} E^q(x,\xi,t)dx = F_2^q(t),$$

$$\int_{-1}^{1} \widetilde{H}^q(x,\xi,t)dx = G_A^q(t),$$

$$\int_{-1}^{1} \widetilde{E}^q(x,\xi,t)dx = G_P^q(t)$$

**Ji Sum Rule:**

$$J^q = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} x(H^q(x,\xi,t) + E^q(x,\xi,t))dx$$

# Using DVCS to Access GPDs

Cross section for ep -> ep γ:

$$\frac{d\sigma}{dx_B dy d|t| d\phi} = \frac{\alpha^3 x_B y}{8\pi Q^2 \sqrt{1+\epsilon^2}} \frac{\tau^{\ 2}}{e^3}$$

in which $\alpha$ is the fine structure constant, $e$ is the elementary charge, $\tau$ is the scattering amplitude and

$$\epsilon = 2x_B \frac{M_P}{Q}$$

where $M_P$ is the proton mass [40, 43]. The amplitude $\tau^2$ is given by

$$\tau^2 = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + I$$

where $\tau_{DVCS}$ is the DVCS amplitude, $\tau_{BH}$ is the Beth-Heitler amplitude and the interference term $I$ is expressed as

$$I = \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}.$$

# Interference Terms

$$\sigma^e_{\lambda 0} = \sigma_{BH} + \sigma_{DVCS} + \lambda\,\tilde{\sigma}_{DVCS} + e\,\sigma_{INT} + e\lambda\,\tilde{\sigma}_{INT}$$

e = charge of lepton

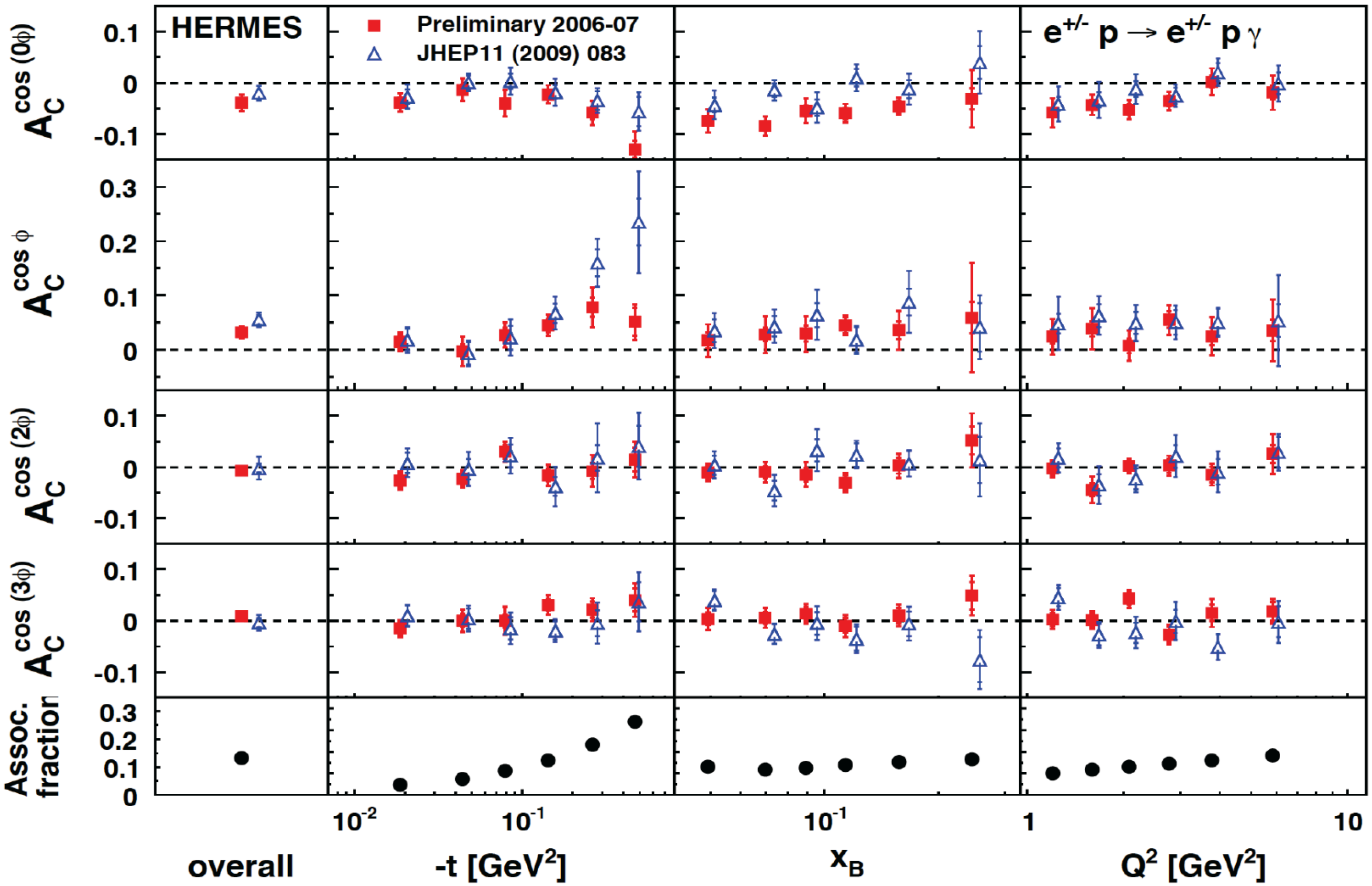
$$\sigma^e_{\lambda S} = \sigma^e_{\lambda 0} + S\left[\lambda\,\Delta\sigma_{BH} + \lambda\,\Delta\sigma_{DVCS} + \Delta\tilde{\sigma}_{DVCS} + e\lambda\,\Delta\sigma_{INT} + e\,\Delta\tilde{\sigma}_{INT}\right]$$

$$\begin{aligned}
\sigma_{INT} &\sim \mathcal{R}\mathrm{e}\left[A(\gamma^* N \to \gamma N)\right] \\
\tilde{\sigma}_{INT} &\sim \mathcal{I}\mathrm{m}\left[A(\gamma^* N \to \gamma N)\right] \\
\Delta\sigma_{INT} &\sim \mathcal{R}\mathrm{e}\left[A(\gamma^* \vec{N} \to \gamma N)\right] \\
\Delta\tilde{\sigma}_{INT} &\sim \mathcal{I}\mathrm{m}\left[A(\gamma^* \vec{N} \to \gamma N)\right]
\end{aligned}$$

Real and imaginary parts of the Compton amplitude.

The combination of polarized electron and polarized positron beams allows separation of the DVCS amplitudes over the full kinematic range.

# Beam Charge Asymmetry at HERMES



# DVCS Beam Charge Asymmetry at EIC

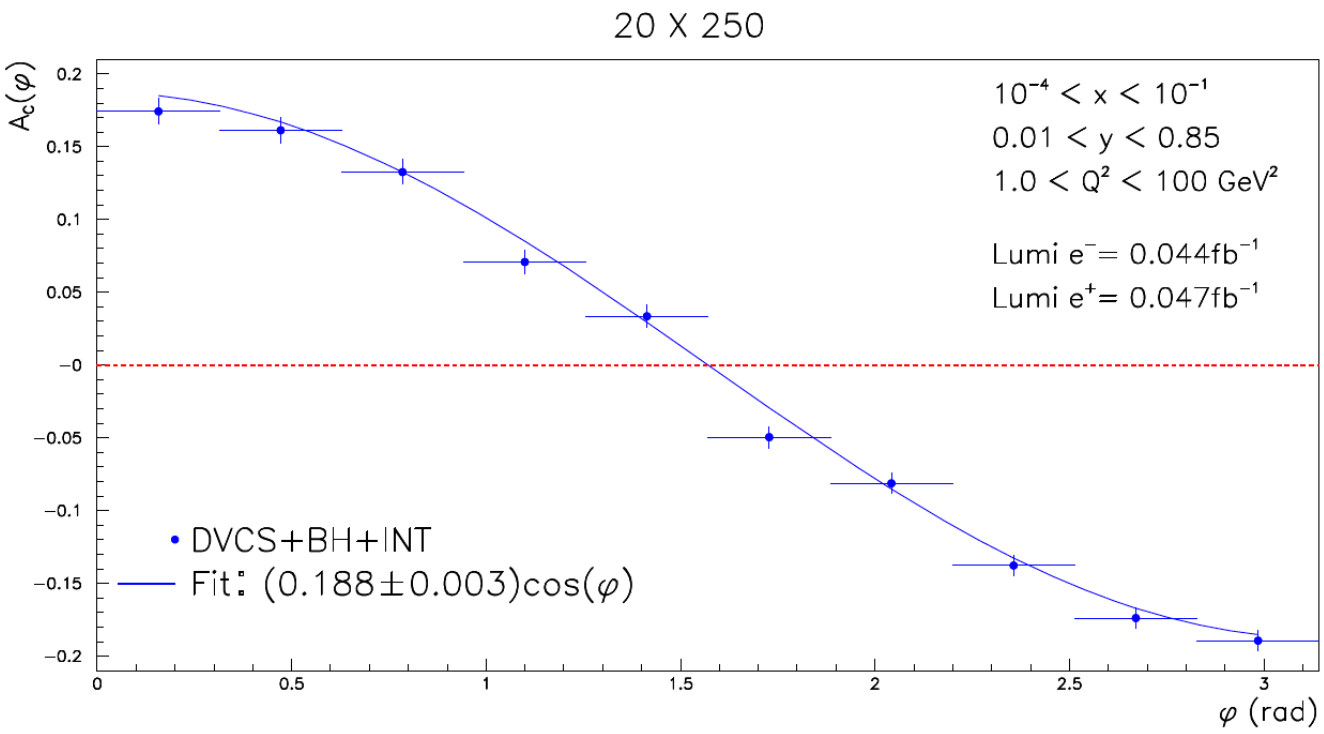



Figure 3.33. The beam-charge asymmetry $A_C$ as a function of the azimuthal angle $\phi$ between the production and scattering planes.

# DVCS Beam Spin Asymmetry

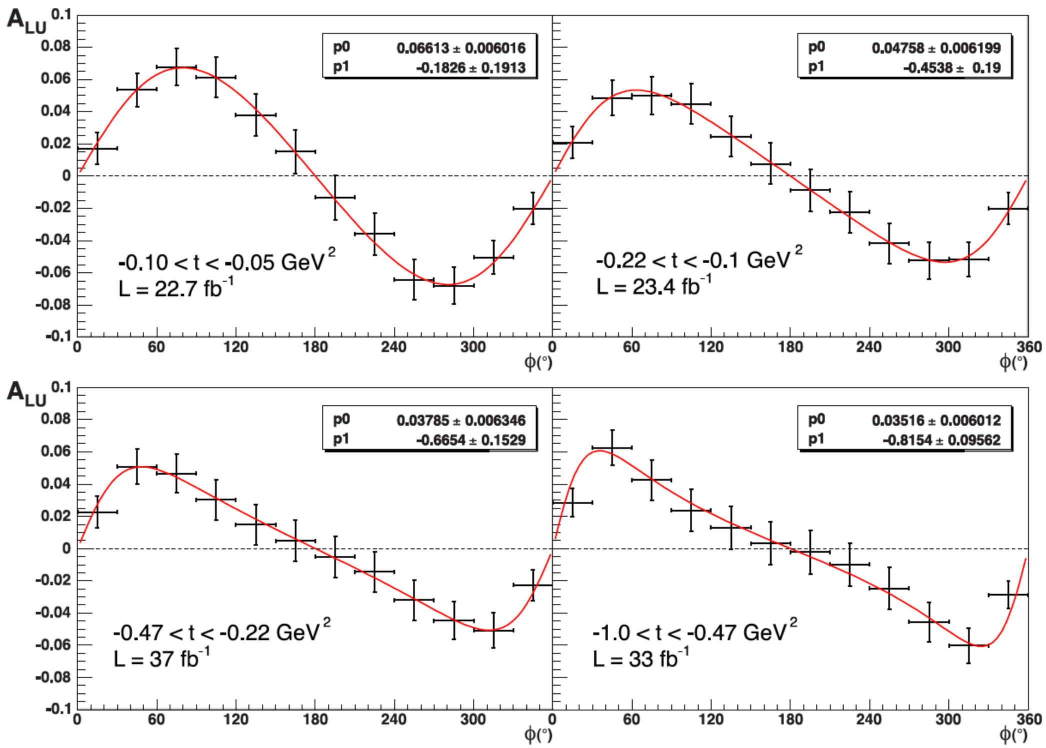



Figure 3.37. Photon electroproduction Beam Spin Asymmetries for the 20 × 250 EIC configuration, in the typical kinematic bin: $1.58 \cdot 10^{-3} < x_B < 2.51 \cdot 10^{-3}$, $3.16 < Q^2 < 5.61$ GeV$^2$ for four different $t$-bins as shown on each plot. The Monte Carlo was set up as to generate 90k events for each $t$-bin and the corresponding integrated luminosity is shown on each plot. Up to about 3 months of beam time with 50% efficiency is necessary to achieve 10 to 15% accuracy on the extracted $\sin\phi$ coefficient p0, sensitive to the imaginary part of CFF $\mathcal{H}$.

Letter-of-Intent to PAC46
LOI12-18-004

# Physics with Positron Beams at Jefferson Lab 12 GeV

- Two-photon exchange
- DVCS on neutron and proton
- Search for new physics in $e^+e^-$ final-states

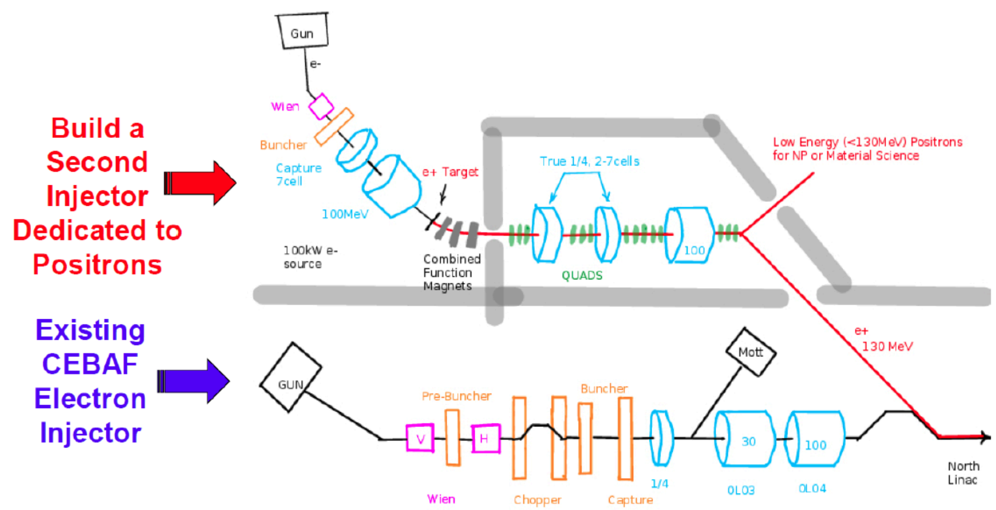
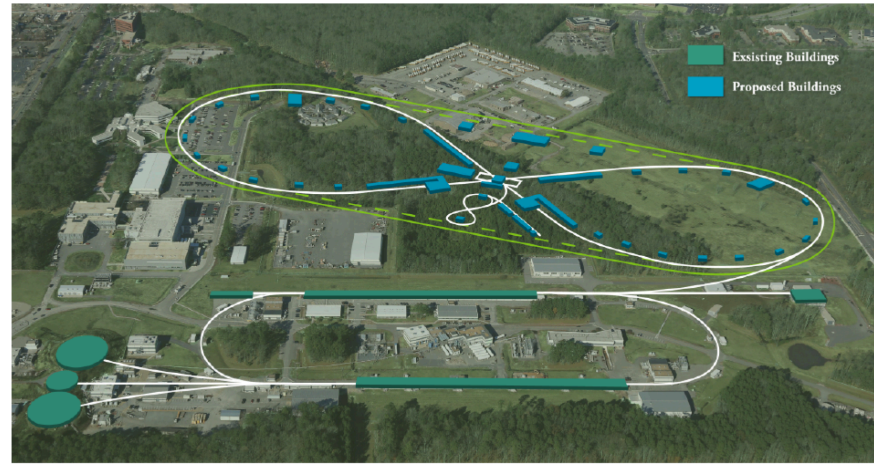


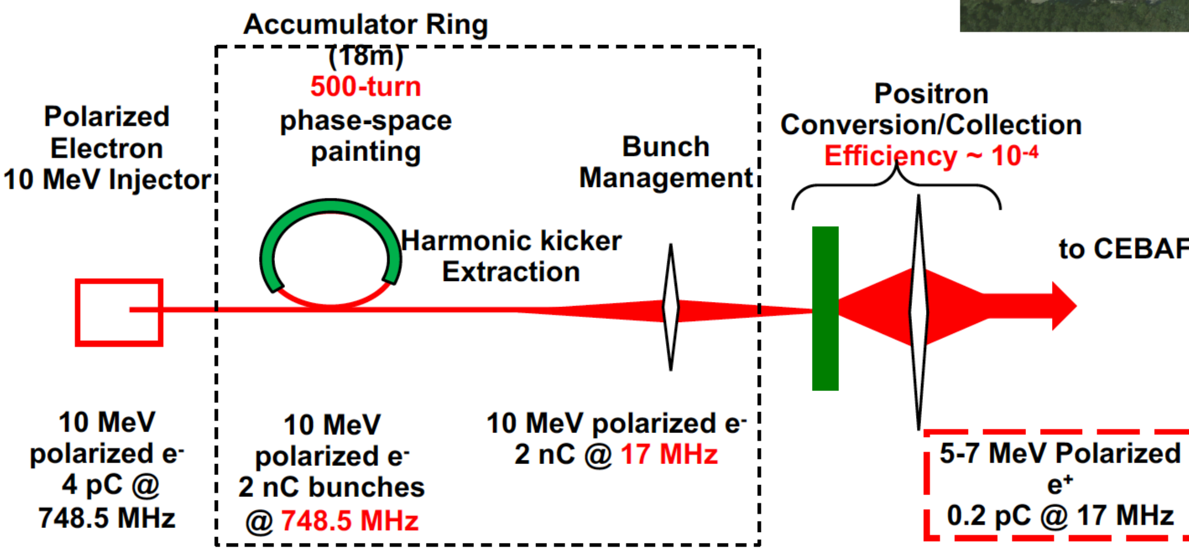

Figure 6. An approach to adding positron capability to CEBAF [Gol10].

# Polarized Positron beam at JLEIC. First polarized $e^+A$ collider.

A group (Joe Grames, Jiquan Guo, Fangley Lin, Vasiliy Morozov, Eric Voutier, Yuhong Zhang) is exploring a polarized positron injector suitable for Jefferson Lab Electron Ion Collider (JLEIC).

$\mathcal{L} \geq 10^{33} cm^{-2}s^{-1}$ $P_{e+} \geq 40\%$




- High voltage gun ~340kV peak
- Accumulator ring ~500 turns (CERN's LEIR has a design for 75-turn injection of $Pb^{54+}$)
- Harmonic kicker extraction (frequency should match 17MHz)
- Pulsed beam ~10nA current, as required for injection into JLEIC with a reasonably short injection time and reasonably high equilibrium polarization.

7

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Yulia Furletova (on behalf of PWG group)

# Summary

- Positron as well as electron beams are needed for a complete program of precision physics at EIC
  - QED expansion/radiative corrections
  - Electroweak
  - DVCS
- Technology in hand.
- Not in the initial scope of EIC project, but positron beams are highly desirable.