Overview of the JLab Positron Physics Program

<u>Andrei Afanasev</u>
The George Washington University
Washington, DC

Plan of talk

- Historical Introduction
- Jlab developments and Jlab Positron White Paper – an overview
- New ideas

Positron's discovery

August 1932: Discovery of the Positron

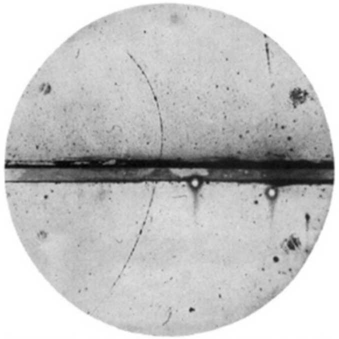


Photo Credit: Carl D. Anderson, *Physical Review* Vol.43, p491 (1933)

Anderson's cloud chamber picture of cosmic radiation from 1932 showing for the first time the existence of the anti-electron. The particle enters from the bottom, strikes the lead plate in the middle and loses energy as can be seen from the greater curvature of the upper part of the track.

Anderson spent most of his career at Caltech. His early research was on X-rays, but then Victor Hess discovered cosmic rays in 1930. At the advice of his mentor, Robert A. Millikan, Anderson turned his attention to studying those high energy particles. Most scientists were doing this by using cloud chambers: a short cylinder with glass end plates containing a gas saturated with water vapor. If an ionizing particle passes through the chamber, it leaves a trail of water droplets, which can be photographed. By measuring the density of the droplets, scientists can deduce how much ionization is produced—indicating the kind of particle that passed through.

Anderson built his own, improved version of a cloud chamber, incorporating a piston so that he could get the pressure to drop very rapidly. He also used a mixture of water and alcohol in the chamber. And he obtained much better photographs than his colleagues. He surrounded his chamber with a large electromagnet, which caused the paths of ionizing particles to bend into circular paths. By measuring the curvature of those tracks, he could calculate the particles' momentum and determine the sign of the charge.

His discovery snagged Anderson a Nobel Prize in Physics in 1936, at the age of 31

Early ideas for positron beams as probes of hadrons

PHYSICAL REVIEW D VOLUME 6, NUMBER 9 1 NOVEMI

Test for Fractionally Charged Partons from Deep-Inelastic Bremsstrahlung in the Scaling Region*

S. J. Brodsky, J. F. Gunion, and R. L. Jaffe
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 5 July 1972)

We show that measurements of deep-inelastic bremsstrahlung, $e^{\pm}+p\to e^{\pm}+\gamma+\text{anything}$, in the appropriate scaling region will provide a definitive test for fractionally charged constituents in the proton, provided the parton model is valid. More precisely, measurement of the difference between the scaling inclusive bremsstrahlung cross sections of the positron and electron will allow the determination of a proton structure function $V(x)$ which, unlike the deep-inelastic e-p structure functions, obeys an exact sum rule based on conserved quantum numbers. In particular, we show that $\int_0^1 dx\, V(x)=\frac{1}{3}Q+\frac{2}{9}B$ ($=\frac{5}{9}$ for a proton target) in the quark model, whereas $\int_0^1 dx\, V(x)=Q$ in the case of integrally charged constituents. Since the result is independent of the momentum distribution of the partons, the sum rule holds for nuclear targets as well. Since $V(x)$, which involves the cube of the parton charge, is related to odd-charge-conjugation exchange in the t channel, Pomeranchukon, and other C-even contributions are not present, so that $V(x)$ should have a readily integrable quasielastic peak. This, combined with the fact that there exists a simple kinematic region in which the difference is of the same order as the inclusive bremsstrahlung cross sections themselves, and the fact that there is no hadronic-decay background, should make this a feasible experiment on proton and nuclear targets.

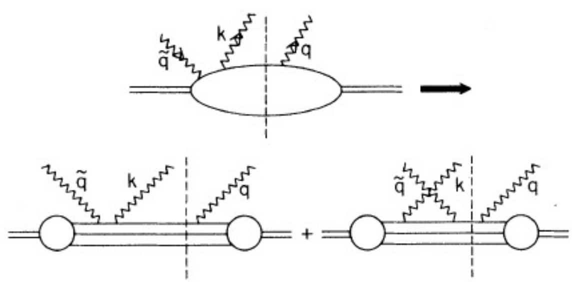


FIG. 3. The surviving single-parton contribution to the interference amplitude in the Bjorken scaling limit. The kinematical restrictions require that all three photons interact with the same parton. The result is proportional to the charge cubed of the parton.

PHYSICAL REVIEW D VOLUME 2, NUMBER 5 1 SEPTEMBER 1970

Up-Down Asymmetry in Inelastic Electron–Polarized-Proton Scattering*

Robert N. Cahn†
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
AND
Y. S. Tsai
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 2 April 1970)

We have investigated the up-down asymmetry in inelastic electron scattering from polarized protons. It is shown that the contributions from (possible) T violation and α^3 effects can be separated experimentally. We have demonstrated that the contribution of bremsstrahlung emission to the asymmetry is negligible. An expression for the two-photon-exchange contribution is obtained, assuming a proton intermediate state and $N^*(1238)$ final state. The expression has been evaluated numerically and found to be one order of magnitude smaller than the observed asymmetry. A general formalism for calculating the up-down asymmetry is presented and its physical significance discussed. The relation between T violation and the measurement of the asymmetry given by Christ and Lee is sharpened and the experimental results of the Berkeley-SLAC collaboration are discussed.

$$A(T\ \text{violation})=\frac{\sigma_{e^-\uparrow}-\sigma_{e^-\downarrow}+\sigma_{e^+\uparrow}-\sigma_{e^+\downarrow}}{\sigma_{e^-\uparrow}+\sigma_{e^-\downarrow}+\sigma_{e^+\uparrow}+\sigma_{e^+\downarrow}}$$

$$A(\alpha^3)=\frac{\sigma_{e^-\uparrow}-\sigma_{e^-\downarrow}-\sigma_{e^+\uparrow}+\sigma_{e^+\downarrow}}{\sigma_{e^-\uparrow}+\sigma_{e^-\downarrow}+\sigma_{e^+\uparrow}+\sigma_{e^+\downarrow}}$$

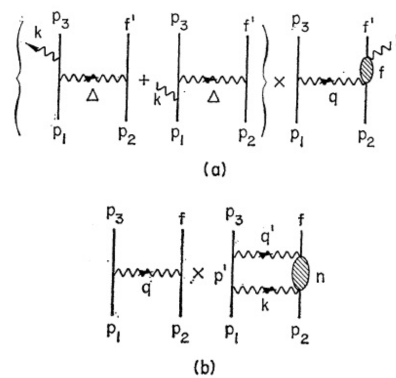


FIG. 2. Two classes of Feynman diagrams which contribute to the up-down asymmetry. f, f', and n are arbitrary states. p_2 represents the polarized target proton. p_1 and p_3 are incident and outgoing electrons, respectively.

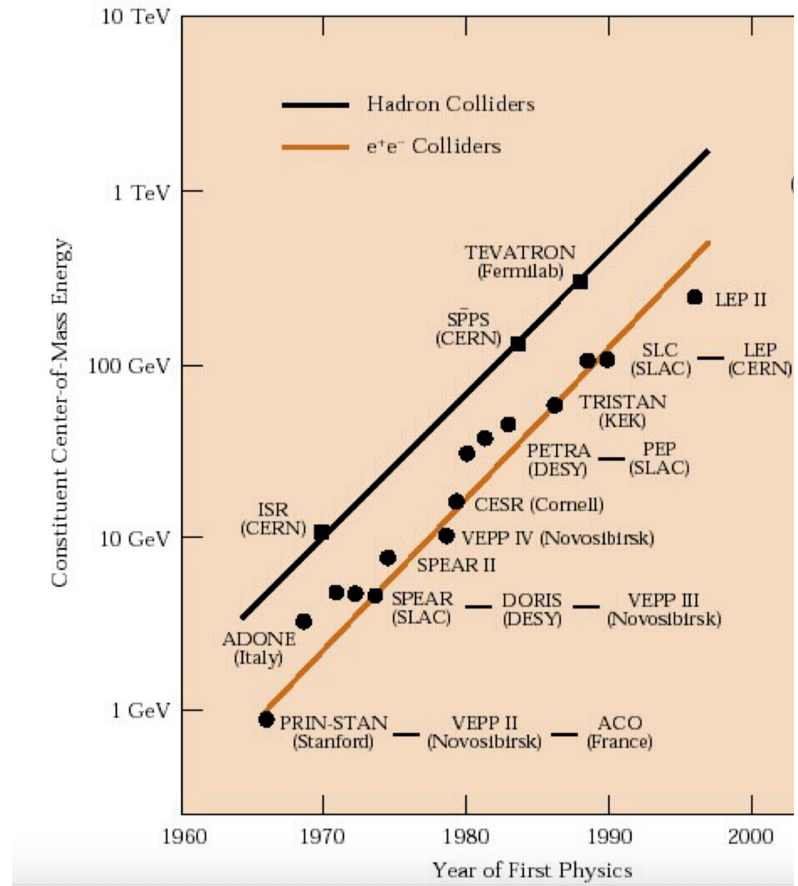
Positrons beams

- Electron-positron colliders
- Positrons for gamma-source
  from positron-in-flight annihilation
  LLNL (lots of data collected for
  photonuclear cross sections)
- Orsay: studied dispersive
  corrections on nuclei

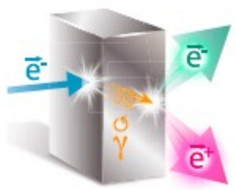
The linear accelerator that gave "LAL" at Orsay its name has delivered its last beam, but the laboratory's involvement with electron linacs remains as strong as ever.

On 19 December 2003 the Laboratoire de l'Accélérateur Linéaire at Orsay marked the final shutdown of its linear accelerator. The event, which was a highly nostalgic occasion, was commemorated by an official ceremony attended by many scientists, engineers and tech-

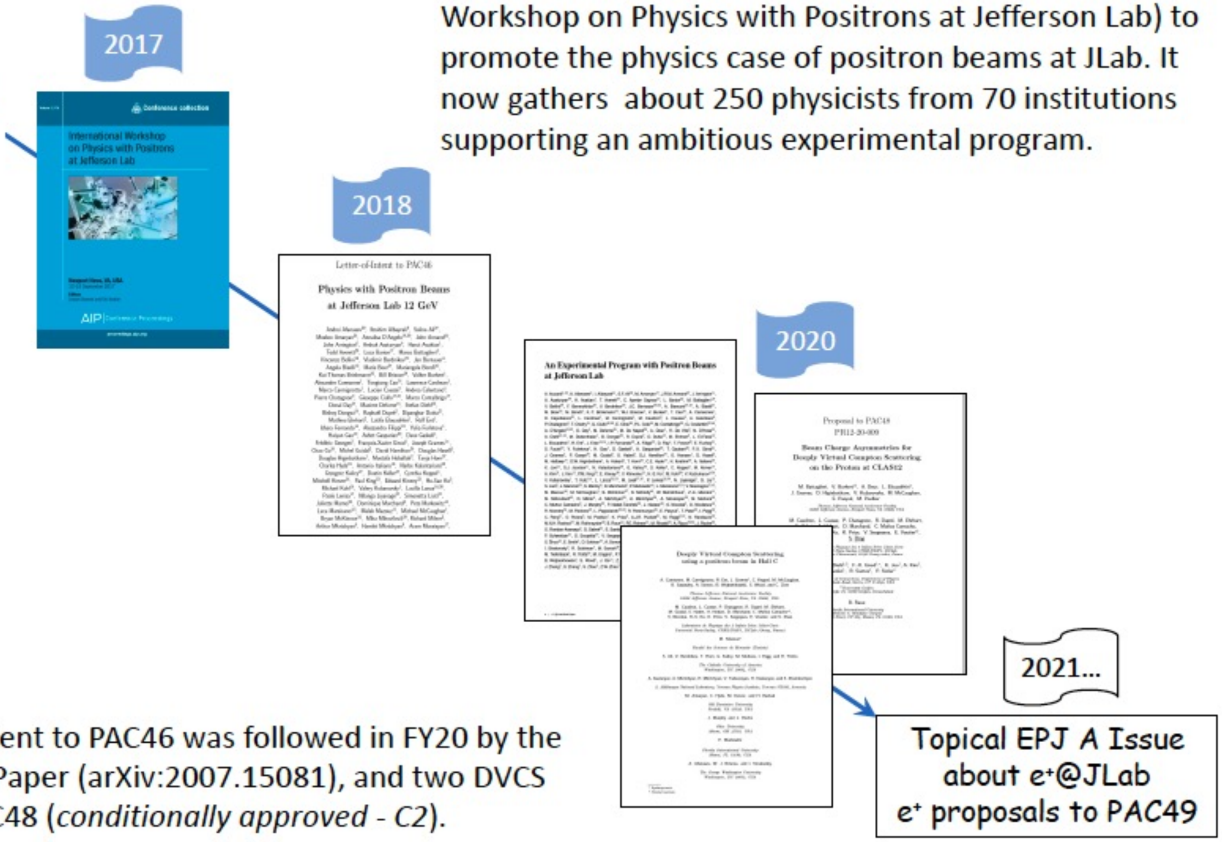
(CERN Courier June 2004)



Jlab Positron Working Group Timeline



The PWG was created in 2017 after JPos17 (International Workshop on Physics with Positrons at Jefferson Lab) to promote the physics case of positron beams at JLab. It now gathers about 250 physicists from 70 institutions supporting an ambitious experimental program.



The Letter-of-Intent to PAC46 was followed in FY20 by the e⁺@JLab White Paper (arXiv:2007.15081), and two DVCS proposals to PAC48 (*conditionally approved - C2*).

Milestone: Polarized Positrons at JLab

PRL **116,** 214801 (2016) PHYSICAL REVIEW LETTERS week ending 27 MAY 2016

Production of Highly Polarized Positrons Using Polarized Electrons at MeV Energies

D. Abbott,[1] P. Adderley,[1] A. Adeyemi,[3] P. Aguilera,[1] M. Ali,[1] H. Areti,[1] M. Baylac,[2] J. Benesch,[1] G. Bosson,[2] B. Cade,[1] A. Camsonne,[1] L. S. Cardman,[1] J. Clark,[1] P. Cole,[4] S. Covert,[1] C. Cuevas,[1] O. Dadoun,[5] D. Dale,[4] H. Dong,[1] J. Dumas,[1,2] E. Fanchini,[2] T. Forest,[4] E. Forman,[1] A. Freyberger,[1] E. Froidefond,[2] S. Golge,[7] J. Grames,[1] P. Guèye,[3] J. Hansknecht,[1] P. Harrell,[1] J. Hoskins,[10] C. Hyde,[8] B. Josey,[13] R. Kazimi,[1] Y. Kim,[1,4] D. Machie,[1] K. Mahoney,[1] R. Mammei,[1] M. Marton,[2] J. McCarter,[11] M. McCaughan,[1] M. McHugh,[14] D. McNulty,[4] K. E. Mesick,[9] T. Michaelides,[1] R. Michaels,[1] B. Moffit,[1] D. Moser,[1] C. Muñoz Camacho,[6] J.-F. Muraz,[2] A. Opper,[14] M. Poelker,[1] J.-S. Réal,[2] L. Richardson,[1] S. Setiniyaz,[4] M. Stutzman,[1] R. Suleiman,[1] C. Tennant,[1] C. Tsai,[12] D. Turner,[1] M. Ungaro,[1] A. Variola,[5] E. Voutier,[2,6,*] Y. Wang,[1] and Y. Zhang[9]

(PEPPo Collaboration)

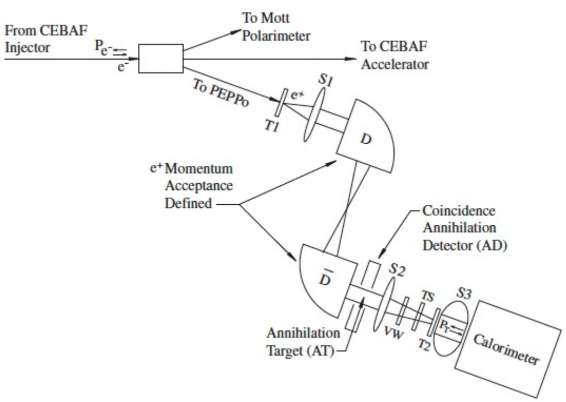


FIG. 1. Schematic of the PEPPo line and apparatus illustrating the principle of operation of the experiment based on the processes sequence $\vec{e^-} \xrightarrow{T1} \circlearrowleft{\gamma} \xrightarrow{T1} \vec{e^+} \xrightarrow{T2} \circlearrowleft{\gamma} \xrightarrow{S3} \gamma$ described in the text. The setup footprint is about 3×1.5 m^2.

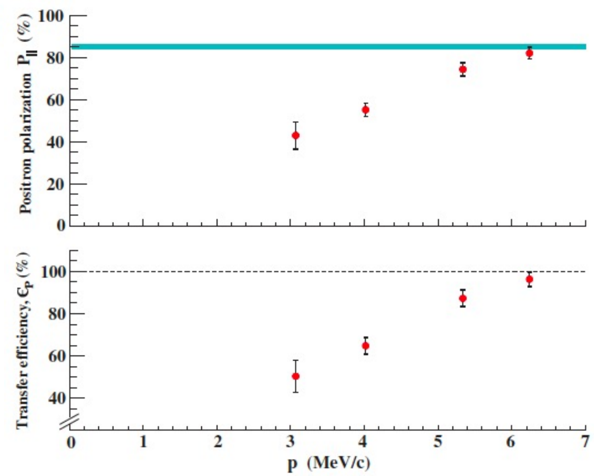


FIG. 4. PEPPo measurements of the positron polarization (top panel) and polarization transfer efficiency (bottom panel); statistics and systematics are reported for each point, and the shaded area indicates the electron beam polarization.

The e+@Jlab Topical Issue (EPJ A)

- https://epja.epj.org/component/toc/?task=topic&id=1430

The European Physical Journal A

An Experimental Program with Positron Beams at Jefferson Lab

Nicolas Alamanos, Marco Battaglieri, Douglas Higinbotham, Silvia Niccolai, Axel Schmidt and Eric Voutier (Guest Editors)

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Editorial

Topical issue on an experimental program with positron beams at Jefferson Lab
Nicolas Alamanos, Marco Battaglieri, Douglas Higinbotham, Silvia Niccolai, Axel Schmidt and Eric Voutier
Published online: 14 March 2022
DOI: 10.1140/epja/s10050-022-00699-6
Abstract | PDF (197.6 KB)

Open Access

Two photon exchange with nuclei from e^+/e^- elastic cross section ratios
T. Kutz and A. Schmidt
Published online: 28 February 2022
DOI: 10.1140/epja/s10050-022-00682-1
Abstract | PDF (287.9 KB)

A measurement of two-photon exchange in Super-Rosenbluth separations with positron beams
John R. Arrington and Mikhail Yurov
Published online: 29 November 2021
DOI: 10.1140/epja/s10050-021-00633-2
Abstract | PDF (752.7 KB)

Virtual Compton scattering at low energies with a positron beam
Barbara Pasquini and Marc Vanderhaeghen
Published online: 22 November 2021
DOI: 10.1140/epja/s10050-021-00630-5
Abstract | PDF (1.142 MB)

Probing charged lepton flavor violation with a positron beam at CEBAF (JLAB)
Y. Furletova and S. Mantry
Published online: 22 November 2021
DOI: 10.1140/epja/s10050-021-00624-3
Abstract | PDF (726.8 KB)

Deep-inelastic scattering with positron beams
W. Melnitchouk and J. F. Owens
Published online: 11 November 2021
DOI: 10.1140/epja/s10050-021-00622-5
Abstract | PDF (1.066 MB)

Deeply virtual Compton scattering using a positron beam in Hall-C at Jefferson Lab
A. Afanasev, I. Albayrak, S. Ali, M. Amaryan, J. R. M. Annand, A. Asaturyan, V. Bellini, V. V. Berdnikov, M. Boer, K. Brinkmann et al. (64 more)
Published online: 29 October 2021
DOI: 10.1140/epja/s10050-021-00581-x
Abstract | PDF (2.691 MB)

Direct TPE measurement via e^+p/e^-p scattering at low ε in Hall A
Ethan Cline, Jan C. Bernauer and Axel Schmidt
Published online: 18 October 2021
DOI: 10.1140/epja/s10050-021-00597-3
Abstract | PDF (1.071 MB)

Radiative corrections to the lepton current in unpolarized elastic *lp*-interaction for fixed Q^2 and scattering angle
A. Afanasev and A. Ilyichev
Published online: 30 September 2021
DOI: 10.1140/epja/s10050-021-00582-w
Abstract | PDF (529.9 KB)

The e+@Jlab Topical Issue (EPJ A), continued

Deeply virtual Compton scattering off Helium nuclei with positron beams
Sara Fucini, Mohammad Hattawy, Matteo Rinaldi and Sergio Scopetta
Published online: 15 September 2021
DOI: 10.1140/epja/s10050-021-00580-y
Abstract | PDF (547.3 KB)

An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab
A. Accardi, A. Afanasev, I. Albayrak, S. F. Ali, M. Amaryan, J. R. M. Annand, J. Arrington, A. Asaturyan, H. Atac, H. Avakian et al. (220 more)
Published online: 28 August 2021
DOI: 10.1140/epja/s10050-021-00564-y
Abstract | PDF (1.318 MB)

Light dark matter searches with positrons
M. Battaglieri, A. Bianconi, P. Bisio, M. Bondì, A. Celentano, G. Costantini, P. L. Cole, L. Darmé, R. De Vita, A. D'Angelo et al. (21 more)
Published online: 11 August 2021
DOI: 10.1140/epja/s10050-021-00524-6
Abstract | PDF (832.8 KB)

Impact of a positron beam at JLab on an unbiased determination of DVCS Compton form factors
H. Dutrieux, V. Bertone, H. Moutarde and P. Sznajder
Published online: 05 August 2021
DOI: 10.1140/epja/s10050-021-00560-2
Abstract | PDF (1.491 MB)

Double deeply virtual Compton scattering with positron beams at SoLID
S. Zhao, A. Camsonne, D. Marchand, M. Mazouz, N. Sparveris, S. Stepanyan, E. Voutier and Z. W. Zhao
Published online: 19 July 2021
DOI: 10.1140/epja/s10050-021-00551-3
Abstract | PDF (3.624 MB)

Deeply virtual Compton scattering on the neutron with positron beam
S. Niccolai, P. Chatagnon, M. Hoballah, D. Marchand, C. Munoz Camacho and E. Voutier
Published online: 08 July 2021
DOI: 10.1140/epja/s10050-021-00541-5

Target-normal single spin asymmetries measured with positrons
G. N. Grauvogel, T. Kutz and A. Schmidt
Published online: 29 June 2021
DOI: 10.1140/epja/s10050-021-00531-7
Abstract | PDF (444.2 KB)

Elastic positron–proton scattering at low Q^2
Tyler J. Hague, Dipangkar Dutta, Douglas W. Higinbotham, Xinzhan Bai, Haiyan Gao, Ashot Gasparian, Kondo Gnanvo, Vladimir Khachatryan, Mahbub Khandaker, Nilanga Liyanage et al. (4 more)
Published online: 19 June 2021
DOI: 10.1140/epja/s10050-021-00508-6
Abstract | PDF (1.674 MB)

Polarization transfer in $e^+p \to e^+p$ scattering using the Super BigBite Spectrometer
A. J. R. Puckett, J. C. Bernauer and A. Schmidt
Published online: 09 June 2021
DOI: 10.1140/epja/s10050-021-00509-5
Abstract | PDF (500.2 KB)

Beam charge asymmetries for deeply virtual Compton scattering off the proton
V. Burkert, L. Elouadrhiri, F.-X. Girod, S. Niccolai, E. Voutier, A. Afanasev, L. Barion, M. Battaglieri, J. C. Bernauer, A. Bianconi et al. (50 more)
Published online: 08 June 2021
DOI: 10.1140/epja/s10050-021-00474-z
Abstract | PDF (3.413 MB)

Accessing weak neutral-current coupling g^{eq}_{AA} using positron and electron beams at Jefferson Lab
Xiaochao Zheng, Jens Erler, Qishan Liu and Hubert Spiesberger
Published online: 27 May 2021
DOI: 10.1140/epja/s10050-021-00490-z
Abstract | PDF (647.0 KB)

Determination of two-photon exchange via e^+p/e^-p scattering with CLAS12
Jan C. Bernauer, Volker D. Burkert, Ethan Cline, Axel Schmidt and Youri Sharabian
Published online: 23 April 2021
DOI: 10.1140/epja/s10050-021-00462-3

Conditionally approved proposals by Jlab PAC48

PR12-20-009

Scientific Rating: N/A

Recommendation: C2

Title: Beam charge asymmetries for Deeply Virtual Compton Scattering on the proton at CLAS12

Spokespersons: V. Burkert, L. Elouadrhiri, F.-X. Girod, S. Niccolai, E. Voutier (contact)

Motivation: The goal is to measure the unpolarized and polarized Beam Charge Asymmetries (BCAs) of the $e^{+/-}\, p \to e^{+/-} p\, \gamma$ process on unpolarized hydrogen with CLAS12, using polarized positron and electron beams at 10.6 GeV. The DVCS cross section can be expressed in terms of Compton Form Factors (CFFs), which in turn may be written in terms of Generalized Parton Distributions (GPDs) using factorization. Accurate determination of both real and imaginary parts of the CFFs is essential for the analysis of hard exclusive processes and the determination of GPDs. To this end, it is proposed to measure

- the unpolarized beam charge asymmetry A^{C}_{UU}, which is sensitive to the real part of CFFs,
- the polarized beam charge asymmetry A^{C}_{LU}, which is sensitive to the imaginary part of CFFs,
- the beam-charge averaged beam spin asymmetry A^{0}_{LU}, which is in particular sensitive to higher twist effects.

The combination of measurements with oppositely charged incident beams is theoretically the cleanest way to access the CFFs described above. It hence provides a highly attractive way to constrain the GPDs. The kinematic range accessible with an 10.6 GeV beam on an proton target will allow one to investigate the Q^2 dependence at fixed x.

PR12-20-012

Scientific Rating: N/A

Recommendation: C2

Title: Deeply Virtual Compton Scattering using a positron beam in Hall C

Spokespersons: J. Grames, C. Munoz Camacho (contact), M. Mazouz

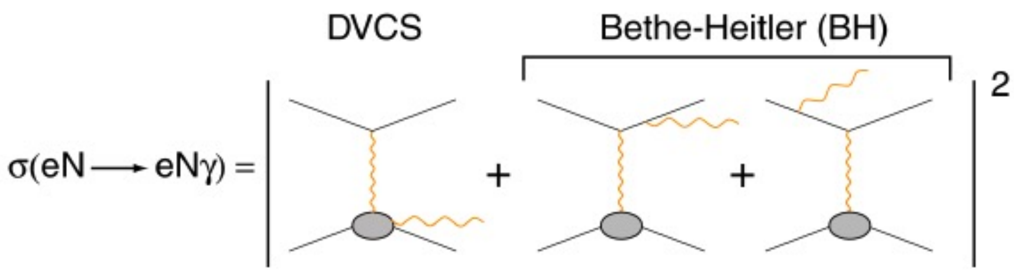
Motivation: The goal of the proposed experiment is to cleanly separate the squared Compton amplitude, $DVCS^2$, from the DVCS-BH (Bethe-Heitler) interference term in the process $e\, p \to e\, p\, \gamma$ at large Q^2. This separation allows one to disentangle the real and imaginary parts of the Compton Form Factors (CFFs), which can be expressed in terms of Generalized Parton Distributions (GPDs) using factorization. An accurate determination of both real and imaginary parts of the CFFs is essential for the analysis of hard exclusive processes and the determination of GPDs.

The combination of measurements with oppositely charged incident beams is the theoretically cleanest way to disentangle the contribution of the $DVCS^2$ term and its interference with the BH amplitude. It hence provides a highly attractive way to constrain the GPDs.

Motivation for DVCS with positrons

N(e,e'γN) Differential Cross Section

M. Diehl at the CLAS12 European Workshop, Genova, February 25-28, 2009



$$\sigma^{e}_{P0} = \sigma_{BH} + \sigma_{DVCS} + P_l\,\tilde{\sigma}_{DVCS} + e_l\left(\sigma_{INT} + P_l\,\tilde{\sigma}_{INT}\right)$$

Electron observables

$$\sigma^{-}_{00} = \sigma_{BH} + \sigma_{DVCS} - \sigma_{INT}$$

$$\sigma^{-}_{+0} - \sigma^{-}_{-0} = 2\tilde{\sigma}_{DVCS} - 2\tilde{\sigma}_{INT}$$

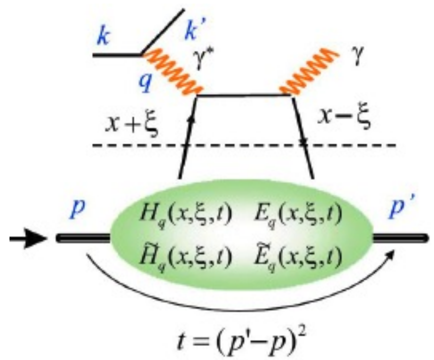
Electron & positron observables

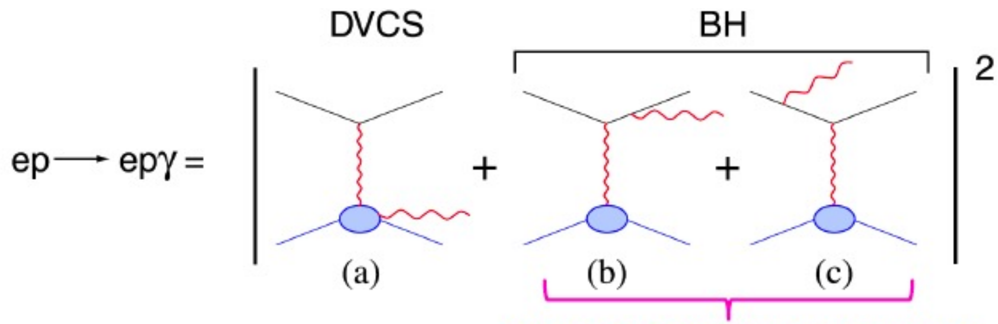
$$\sigma^{+}_{00} - \sigma^{-}_{00} = 2\sigma_{INT}$$

$$\left|\sigma^{+}_{+0} - \sigma^{+}_{-0}\right| - \left|\sigma^{-}_{+0} - \sigma^{-}_{-0}\right| = \left|\sigma^{+}_{+0} - \sigma^{-}_{+0}\right| - \left|\sigma^{+}_{-0} - \sigma^{-}_{-0}\right| = 4\tilde{\sigma}_{INT}$$

Polarized electrons and positrons allow to separate the unknown amplitudes of the cross section for electro-production of photons.

Motivation for DVCS with positrons





Calculable in QED with our ~1% knowledge of form factors at low momentum transfer

At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH}\cdot T^{DVCS})$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\,(T^{BH}\cdot T^{DVCS}) + |DVCS|^2$$

$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

Opposite sign for e- & e+

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} \quad - \quad \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} \quad + \ldots$$

2/19

Content of EPJ Topical issue

- Subtopics:
  - DVCS for GPDs (Afanasev, Albayrak et al; Burkert, Eloudhiri et al; Dutrieux et al.) and VCS for generalized polarizabilities (Pasquini, Vanderhaeghen), DVCS on nuclei (Fucini et al), double-DVCS (Zhao et al), DVCS on a neutron (Niccolai et al)
  - Elastic Scattering on Nucleons and Nuclei: ^{4}He (Kutz, Schmidt), ep-cross sections (Arrington, Yurov; Cline, Bernauer, Schmidt; Bernauer, Burkert et al), separation of rad corrections (Afanasev,Ilyichev), target-normal spin asymmetries (Grauvogel et al), proton's charge radius (Hague et al), polarization transfer (Puckett et al),
  - DIS: flavor separation of PDFs (Melnitchouk, Owens)
  - Fundamental symmetries: Lepton Flavor violation (Furletova, Mantry); neutral weak currents (Zheng et al)
  - Light Dark Matter search: Battaglieri et al.

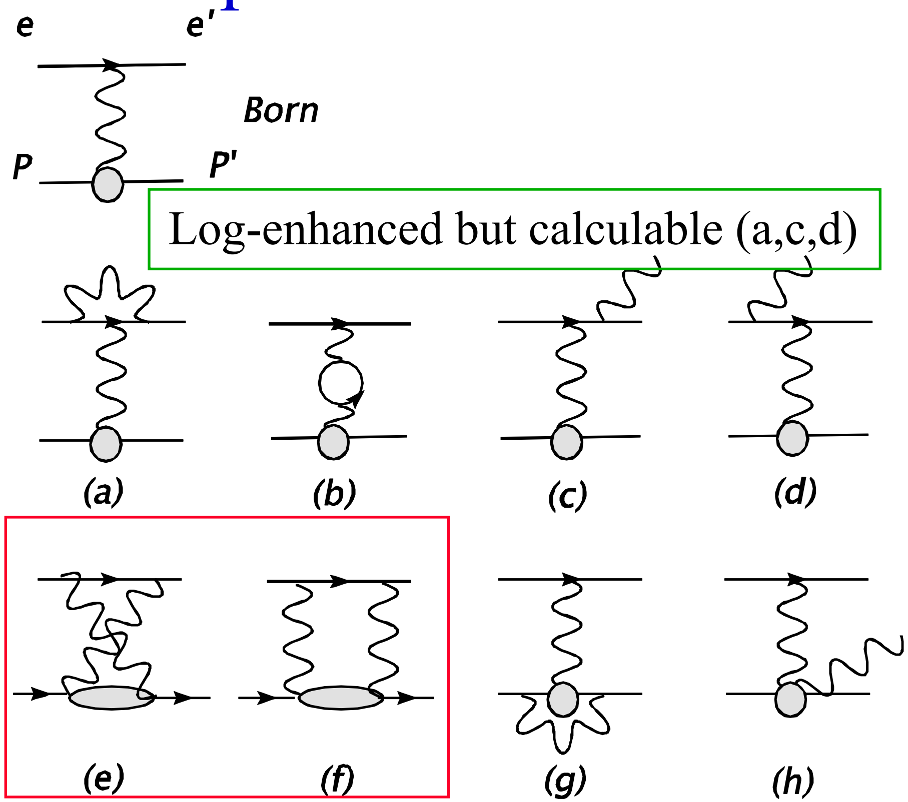
Remarks on Two-Photon Exchange

Two-photon exchange effects in elastic ep-scattering

Two-photon exchange effects in inclusive DIS

Two-photon exchange effects in exclusive and semi-inclusive electroproduction of pions

Complete radiative correction in NLO



Radiative Corrections:

- Electron vertex correction (a)
- Vacuum polarization (b)
- Electron bremsstrahlung (c,d)
- Two-photon exchange (e,f)
- Proton vertex and VCS (g,h)
- Corrections (e-h) depend on the nucleon structure

•Meister&Yennie; Mo&Tsai

•Further work by Bardin&Shumeiko; Maximon&Tjon; AA, Akushevich, Merenkov;

•Guichon&Vanderhaeghen'03:
Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% ...

Main issue: Corrections dependent on nucleon structure

Model calculations:

•Blunden, Melnitchouk,Tjon, Phys.Rev.Lett.**91**:142304,2003

•Chen, AA, Brodsky, Carlson, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004

•TPE physics reviews, e.g, Afanasev, Blunden, Hassel and Raue, PPNP **95** (2017) 245

•Positron experiments performed at Jlab (CLAS), DESY, VEPP.

Quark-Parton Calulations (cont)

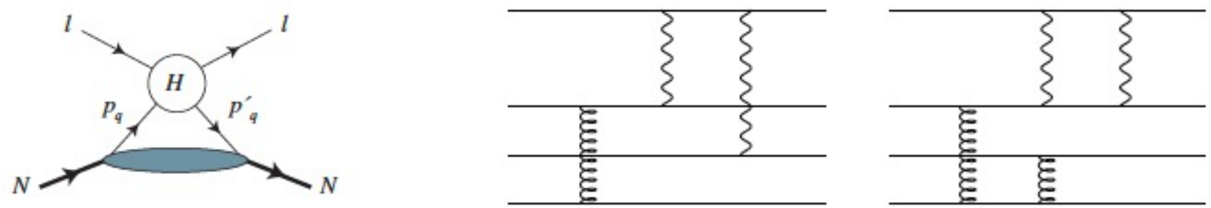


Figure 2.11: *Left:* TPE diagram in the GPD-based approach to eN scattering at high Q^2 [47, 48]. Both photons interact with the same quark, while the others are spectators. *Right:* Sample TPE diagrams in the QCD factorization approach. For the leading order term the photons interact with different quarks, with a single gluon exchange. The interaction of two photons with the same quark is of subleading order in this approach, as it involves two gluons. Figures taken from Ref. [49].

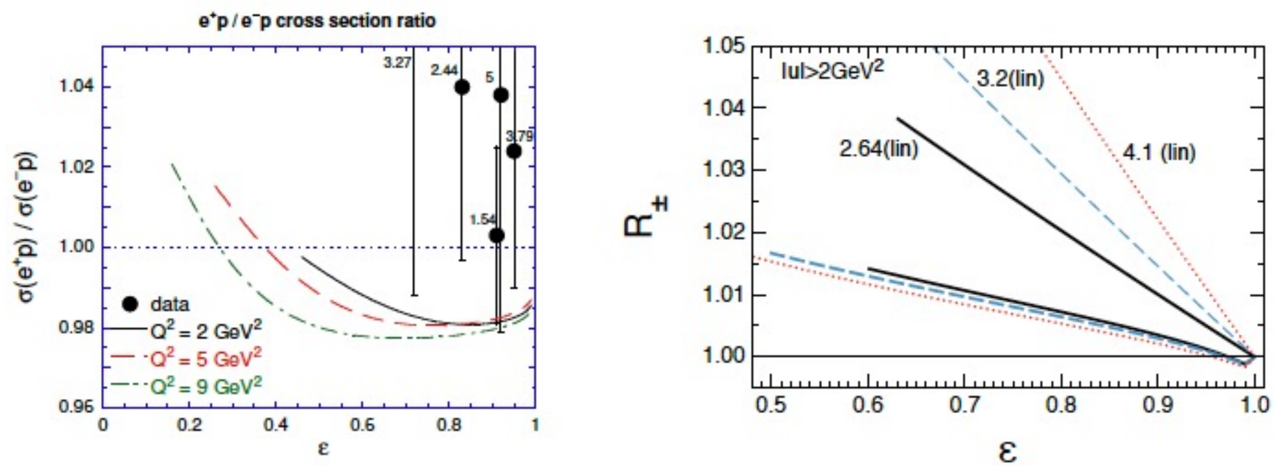


Figure 2.12: *Left:* Ratio of e^+p/e^-p elastic cross sections, taken from Ref. [48]. The GPD calculations for the TPE correction are for three fixed Q^2 values of 2, 5, and 9 GeV^2, for the kinematical range where $-u$ is above M^2. Also shown are early SLAC data [66], with Q^2 above 1.5 GeV^2. The numbers near the data give Q^2 for that point in GeV^2. *Right:* Ratio of e^+p/e^-p at high Q^2 calculated in the QCD factorization approach [65]. Also shown for comparison are the results (labelled *lin*) from the from the phenomenological fits of Ref. [67]. Figure taken from Ref. [65].

Positrons for Two-Photon Physics

LoI12-18-004
Jefferson Lab Positron Working Group

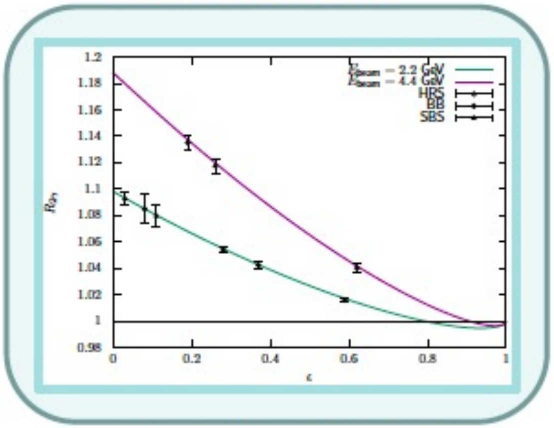
(Jefferson Lab Positron Working Group) A. Afanasev et al. arXiv:1906.09419 (2019)

- An unpolarized positron beam at CEBAF would rapidly and decisively test the TPE hypothesis, mapping out the 2γ-effects in the (Q^2,ε) space.

$$\boxed{R_{2\gamma} = \frac{\sigma_{e^+}}{\sigma_{e^-}} \approx 1 + \delta_{2\gamma}}$$

Hall A

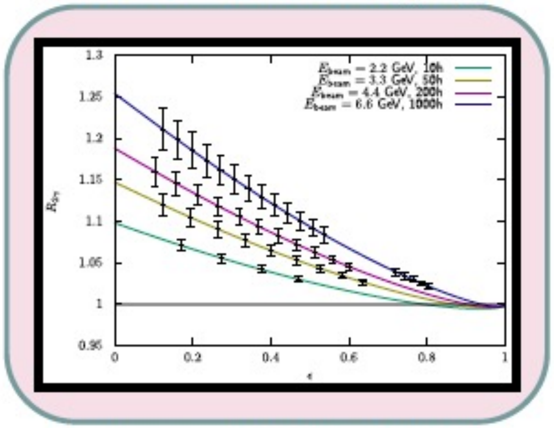
SBS can quickly test high-impact low-ϵ kinematics.



E. Cline et al. arXiv:2103.06301

Hall B

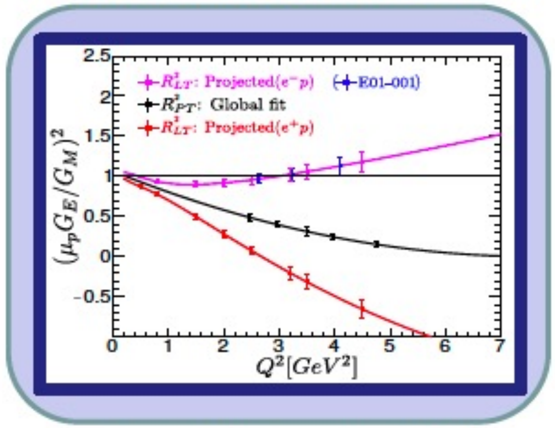
A modified CLAS12 detector will provide a kinematic mapping.



J. C. Bernauer et al., EPJA 57 144 (2021)

Hall C

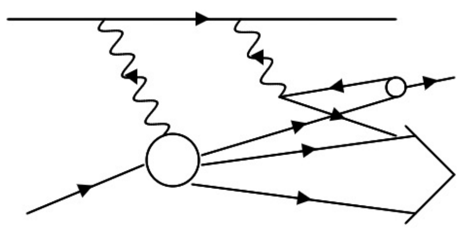
e^+ Super-Rosenbluth measurements to compare with previous e^- ones.

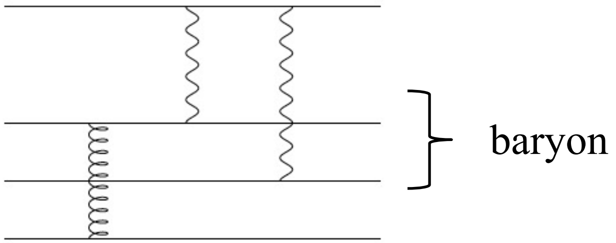


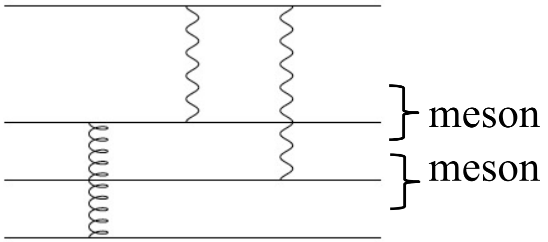
J. R. Arrington, M. Yurov., arXiv:2103.03752

Two-Photon Fragmentation for SIDIS

- Extending Kivel-Vanderhaeghen mechanism to SIDIS
  - Emission of an additional photon that converts into quark-antiquark pair leads do an additional mechanism for fragmentation
  - Produced hadron may be kinematically isolated (similar to higher-twist Berger's mechanism)

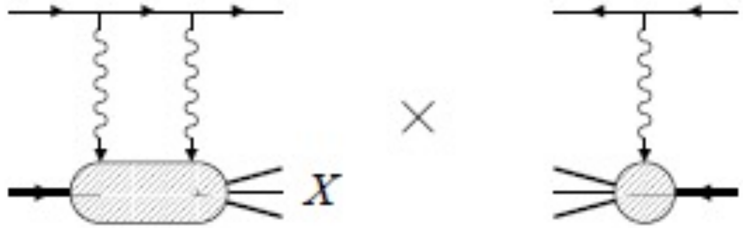


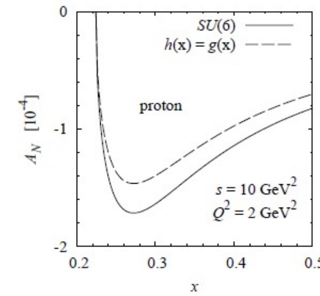


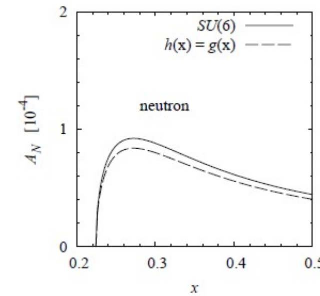


(a) one of the photons generates a q-qbar pair to form a final-state meson
(b) two-photon exchange facilitates baryon production from current fragmentation
(c) two-photon mechanism for production of fast meson pairs

Two-Photon Exchange in inclusive DIS







- Theory: Afanasev, Strikman, Weiss, **Phys.Rev.D77:014028,2008**
  - Asymmetry due to 2γ-exchange ~1/137 suppression
  - Addional suppression due to transversity parton density => predict asymmetry at ~10^{-4} level
  - EM gauge invariance is crucial for cancellation of collinear divergence in theory predictions
  - **Hadronic non-perturbative ~1% vs partonic 10^{-4}: Major disagreement**
- Prediction consistent with HERMES measurements who set upper limits ~(0.6-0.9)x10^{-3} : **Phys.Lett.B682:351-354,2010**
- **In contradiction to JLAB observation of per-cent asymmetry**
  J. Katich et al. Phys. Rev. Lett. **113,** 022502 (2014).

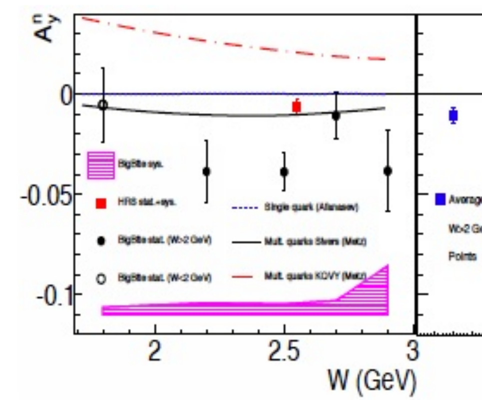
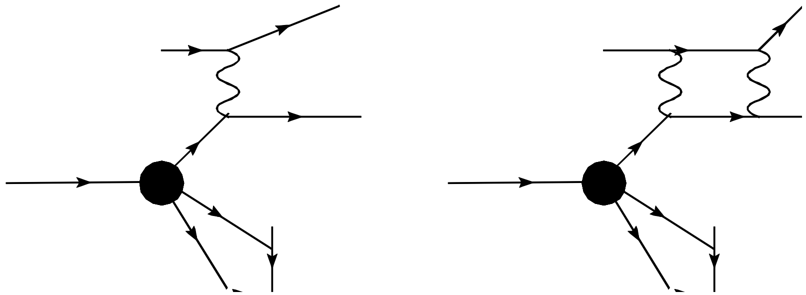


FIG. 3. Neutron asymmetry results (color online). **Left panel:** Solid black data points are DIS data ($W > 2$ GeV) from the BigBite spectrometer; open circle has $W = 1.72$ GeV. BigBite data points show statistical uncertainties with systematic uncertainties indicated by the lower solid band. The square point is the LHRS data with combined statistical and systematic uncertainties. The dotted curve near zero (positive) is the calculation by A. Afanasev *et al.* [11], The solid and dot-dashed curves are calculations by A. Metz *et al.* [12] (multiplied by −1). **Right panel:** The average measured asymmetry for the DIS data with combined systematic and statistical uncertainties.

Beam SSA: Partonic-Level Effect



• Interference of 1-photon and 2-photon exchange is responsible for the beam single-spin normal asymmetry (SSNA)

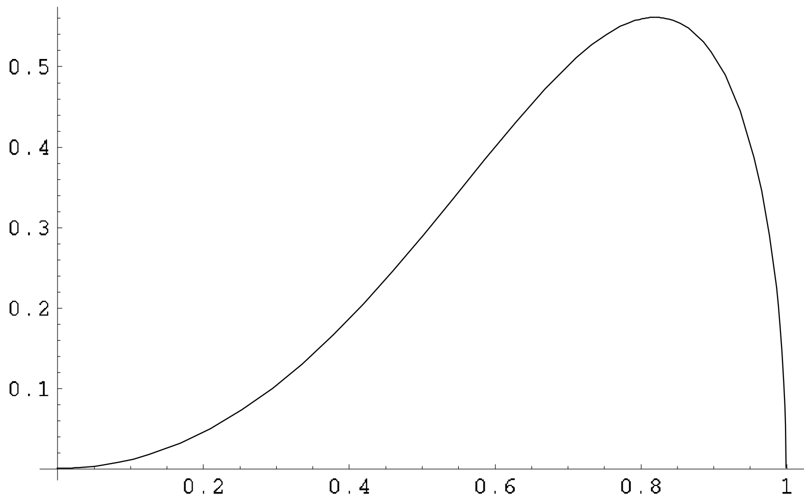
• Adapting Barut & Fronsdal, Phys.Rev. **120** (1960) 1891, we get at the leading twist:

$$A_n^{Beam} = \frac{\alpha\, y^2 \sqrt{1-y^2}}{1+(1-y)^2} \frac{m_e}{Q} \sum_q (e_q)^3$$

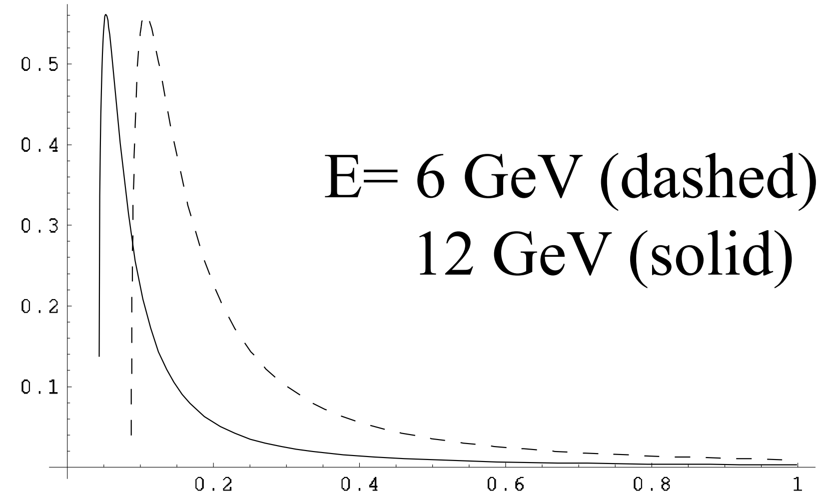
- Measured at JLAB PVDIS (upper limit in ~50ppm is set – limit of sensitivity)
- See also Marc Schlegel et al.

Magnitude of Beam SSA in Inclusive DIS
$Q^2 = 1\ \mathrm{GeV}^2$

Beam Asymmetry, ppm



y



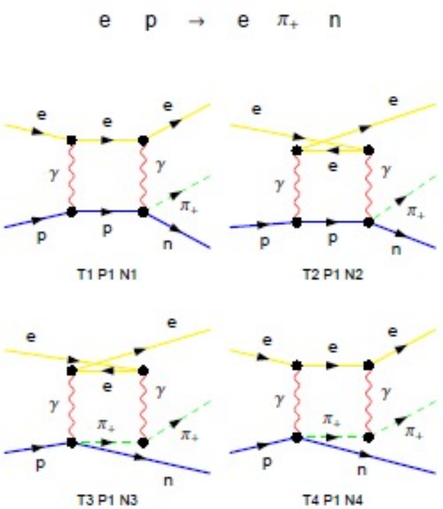
x

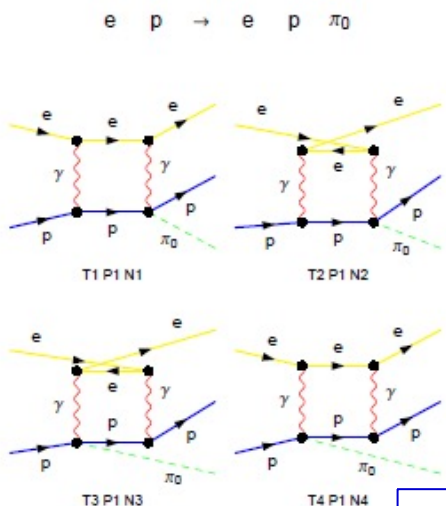
The leading-twist calculation predicts the effect around ½ ppm Regge-limit (optical theorem): 10-100ppm: AA PRB 599 (2004) 48 May be observed in dedicated experiments: **E12-22-004** Measurement of the Beam Normal Single Spin Asymmetry in Deep Inelastic Scattering using the SOLID Detector (Spokesperson: Michael Nycz)

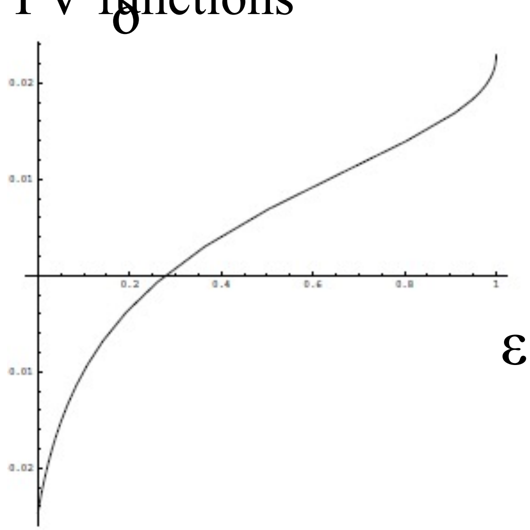
However, the spin asymmetry is due to an imaginary part of two-photon exchange Positrons and needed to access the real part.

Two-Photon Exchange in Exclusive Electroproduction of Pions

- Standard contributions considered, e.g., AA, Akushevich, Burkert, Joo, **Phys.Rev.D66:074004,2002** (Code EXCLURAD used for data analysis)
- *Additional contributions due to two-photon exchange*, calculated by AA, Aleksejevs, Barkanova, **Phys.Rev. D88: 053008, 2013**
  Calculated in soft-photon approximation, PV functions







Calculated ε-dependence of TPE correction.
Q^2=6 GeV^2, W=3.2 GeV, E_e=5.5 GeV .
Shows ±2% variation with ε.

Angular dependence of “soft” corrections
Phys.Rev. D88 (2013) 053008

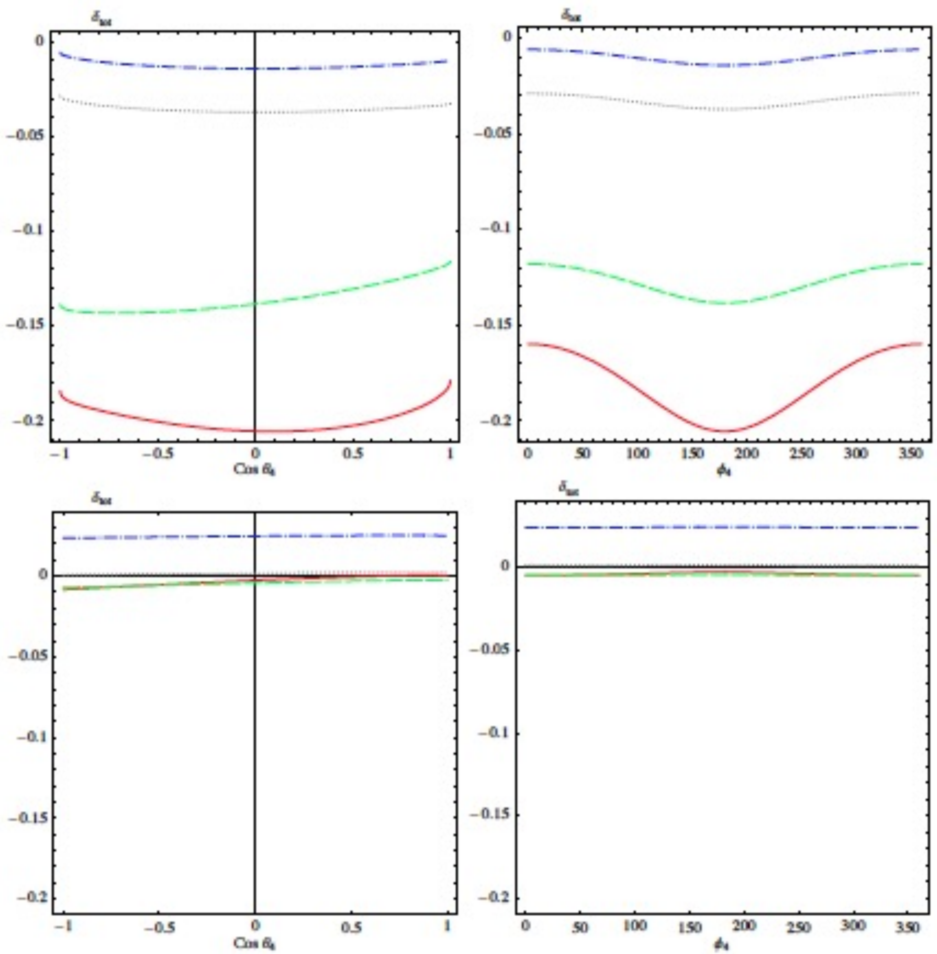


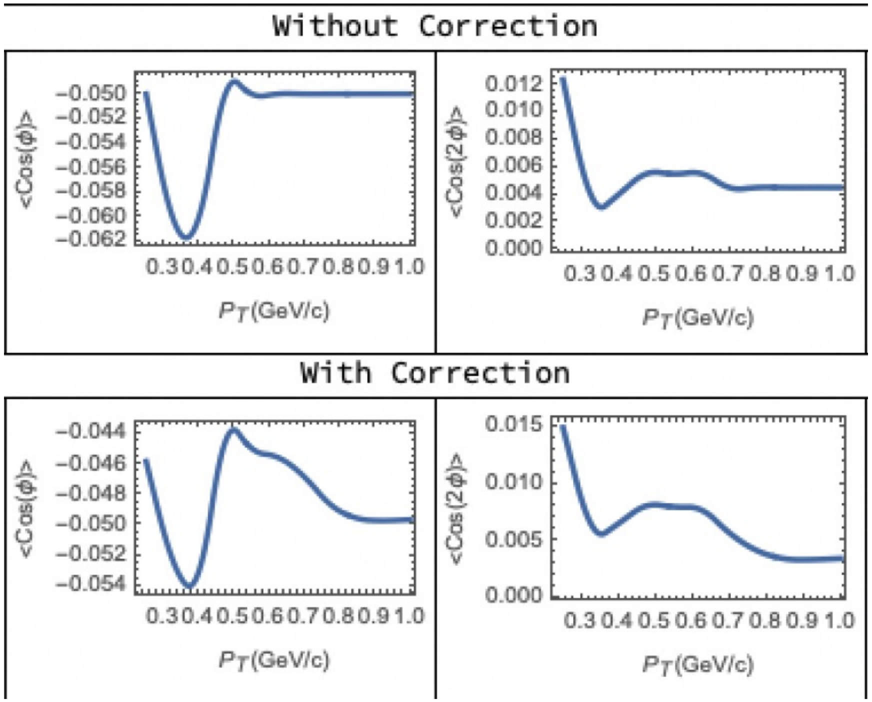
Figure 3: π^0 electroproduction two-photon box correction angular dependencies for the high $Q^2 = 6.36\,GeV^2$ (top row) and low $Q^2 = 0.4\,GeV^2$ (bottom row) momentum transfers, $W = 1.232\,GeV$ and $E_{lab} = 5.75\,GeV$. Left column: dependence on $\cos\theta_4$ with $\phi_4 = 180^\circ$. Right column: dependence on ϕ_4 with $\theta_4 = 90^\circ$. Dot-dashed curve - SPT, dotted curve - SPT with $\alpha\pi$ subtracted, dashed curve - SPMT, solid curve - FM approach.

“Soft” two-photon corrections significantly affect angular dependences

Magnitude of the two-photon effects is similar to electron and muon scattering

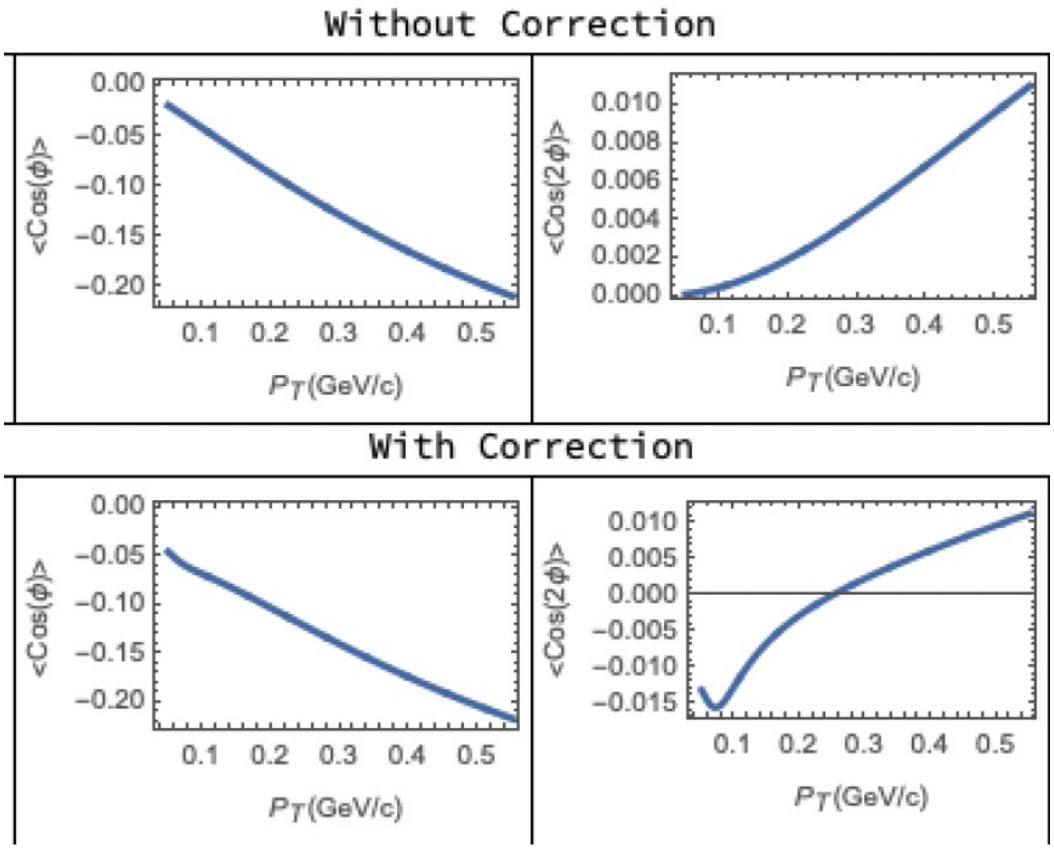
Calculations for SIDIS (S.Lee, AA, in preparation)

- COMPASS data with and without two-photon corrections (Adolph et al, Nucl Phys B, 886 (2014) 1046



Calculations for SIDIS (S. Lee, AA, in preparation)

- JLab data with and without two-photon correction (Yan at al, Phys Rev C95, 035209 (2017)).



Summary on QED loops

- Two-photon exchange
  - “Soft” photon corrections essential for cross section measurements, do not change spin asymmetries, but change charge asymmetries (eg, electron vs positron), model-independent
  - “Hard” photon corrections, alter spin structure of the amplitude, generate single-spin asymmetries, charge asymmetries, alter double-spin asymmetries
- <u>*JLAB experiments on SSA indicate QED loop effects of the same order as SSA from strong interactions*</u>
- Electron-Ion Collider program critically depends on one-photon-exchange assumptions for SIDIS; positrons at Jlab may verify prove these assumptions (or disprove?)
- Two-photon exchange effects an be analyzed by comparing cross sections with electron and positron beams: AA et al, Physics with Positron Beams at Jefferson Lab 12 GeV, arXiv:1906.09419

Lepton universality

- Universality: Electrons, muons and tau leptons have the same electroweak interaction strengths

nature physics
ARTICLES
https://doi.org/10.1038/s41567-021-01478-8
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Test of lepton universality in beauty-quark decays

LHCb collaboration*

The standard model of particle physics currently provides our best description of fundamental particles and their interactions. The theory predicts that the different charged leptons, the electron, muon and tau, have identical electroweak interaction strengths. Previous measurements have shown that a wide range of particle decays are consistent with this principle of lepton universality. This article presents evidence for the breaking of lepton universality in beauty-quark decays, with a significance of 3.1 standard deviations, based on proton-proton collision data collected with the LHCb detector at CERN's Large Hadron Collider. The measurements are of processes in which a beauty meson transforms into a strange meson with the emission of either an electron and a positron, or a muon and an antimuon. If confirmed by future measurements, this violation of lepton universality would imply physics beyond the standard model, such as a new fundamental interaction between quarks and leptons.

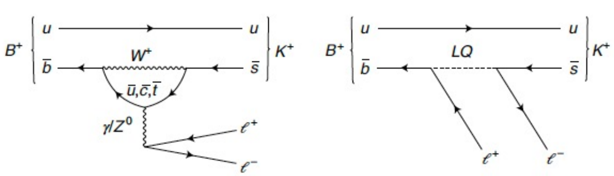

Fig. 1 | Contributions to $B^+ \to K^+\ell^+\ell^-$ decays in the SM and possible new physics models. A B^+ meson, consisting of $\bar{b}$ and u quarks, decays into a K^+, containing $\bar{s}$ and u quarks, and two charged leptons, $\ell^+\ell^-$. Left: the SM contribution involves the electroweak bosons γ, W^+ and Z^0, and the up-type quarks $\bar{u}$, $\bar{c}$ and $\bar{t}$. Right: a possible new physics contribution to the decay with a hypothetical leptoquark (LQ) which, unlike the electroweak bosons, could have different interaction strengths with the different types of leptons.

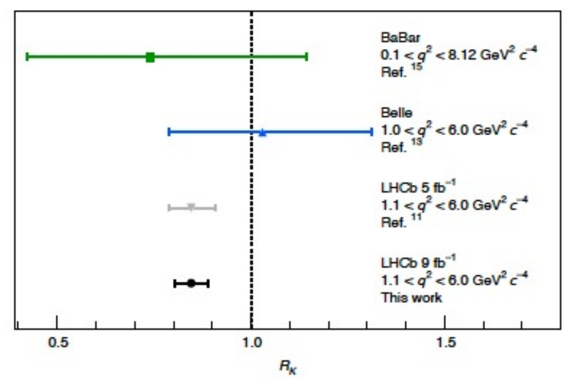

Fig. 4 | Comparison between R_K measurements. In addition to the LHCb result, the measurements by the BaBar[15] and Belle[13] collaborations, which combine $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^0_S\ell^+\ell^-$ decays, are also shown. The vertical dashed line indicates the SM prediction. Uncertainties on the data points are the combination of statistical and systematic and represent one standard deviation.

More Physics with Positron Beams

- Proposed: DVCS studies (motivated by an opportunity to access a real part of DVCS amplitude)
- Anticipated:
  - DDVCS
  - Radiative DIS and SIDIS (parton flavor separation, etc)
    - SJB et al: Deep-Inelastic Bremsstrahlung
  - Two-photon exchange in
    - Elastic $e^{\pm}p$ and $e^{\pm}A$ scattering
    - Electroproduction of mesons
    - DIS and Semi-inclusive DIS
    - Tests of CP- (or T-) violation
    - Tests of lepton universality
    - Tests of neutral currents
    - …….