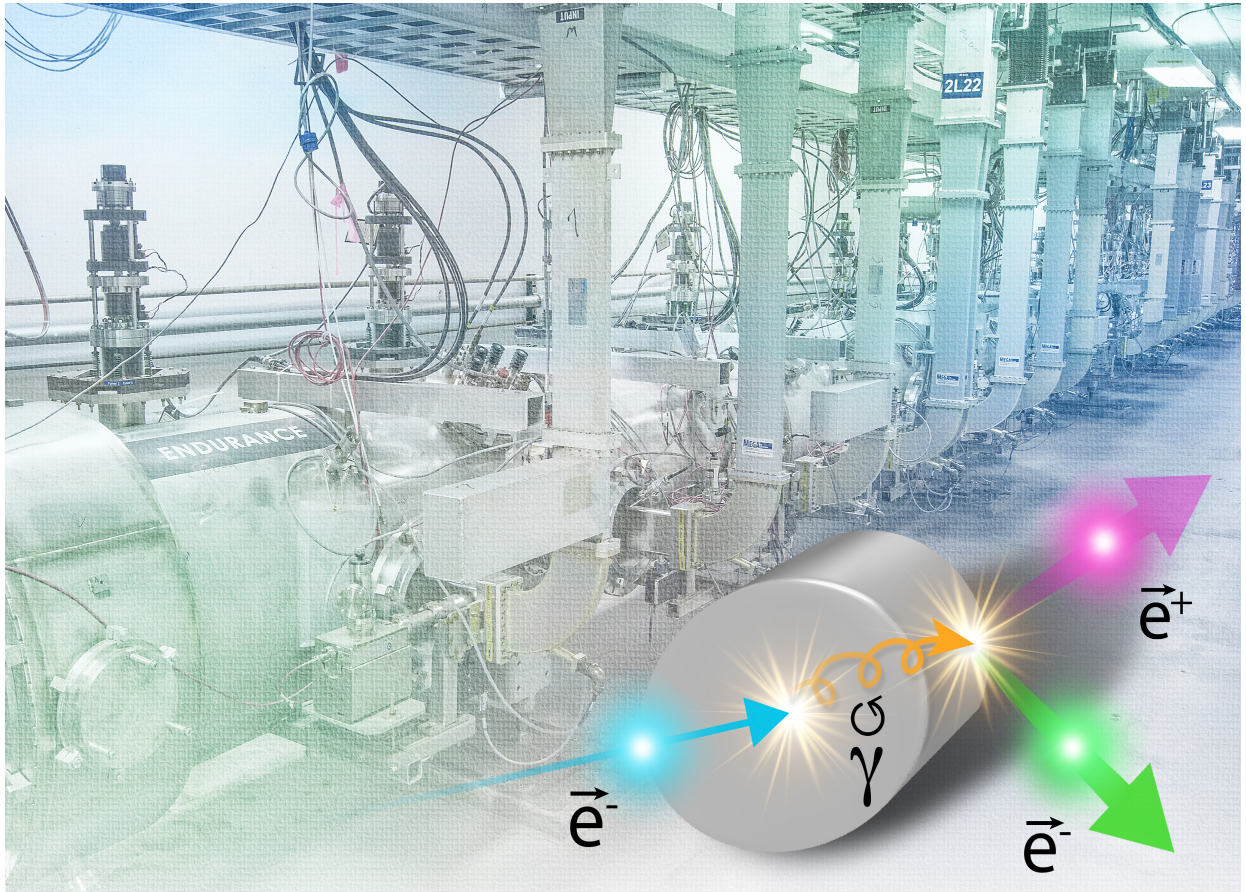
Science Case for Positrons at Jefferson Lab

12 GeV science experiments enabled by adding a positron source to the Jefferson Lab CEBAF accelerator.



Outline

(i) Short History of JLab Positron Program
(ii) Two-photon exchange
(iii) Nuclear structure
(iv) Beyond the standard model
(v) Conclusions

by

Holly Szumila-Vance, Douglas Higinbotham

Jefferson Lab

Polarized Electrons for Polarized Positrons (PEPPo)

https://doi.org/10.1103/PhysRevLett.116.214801

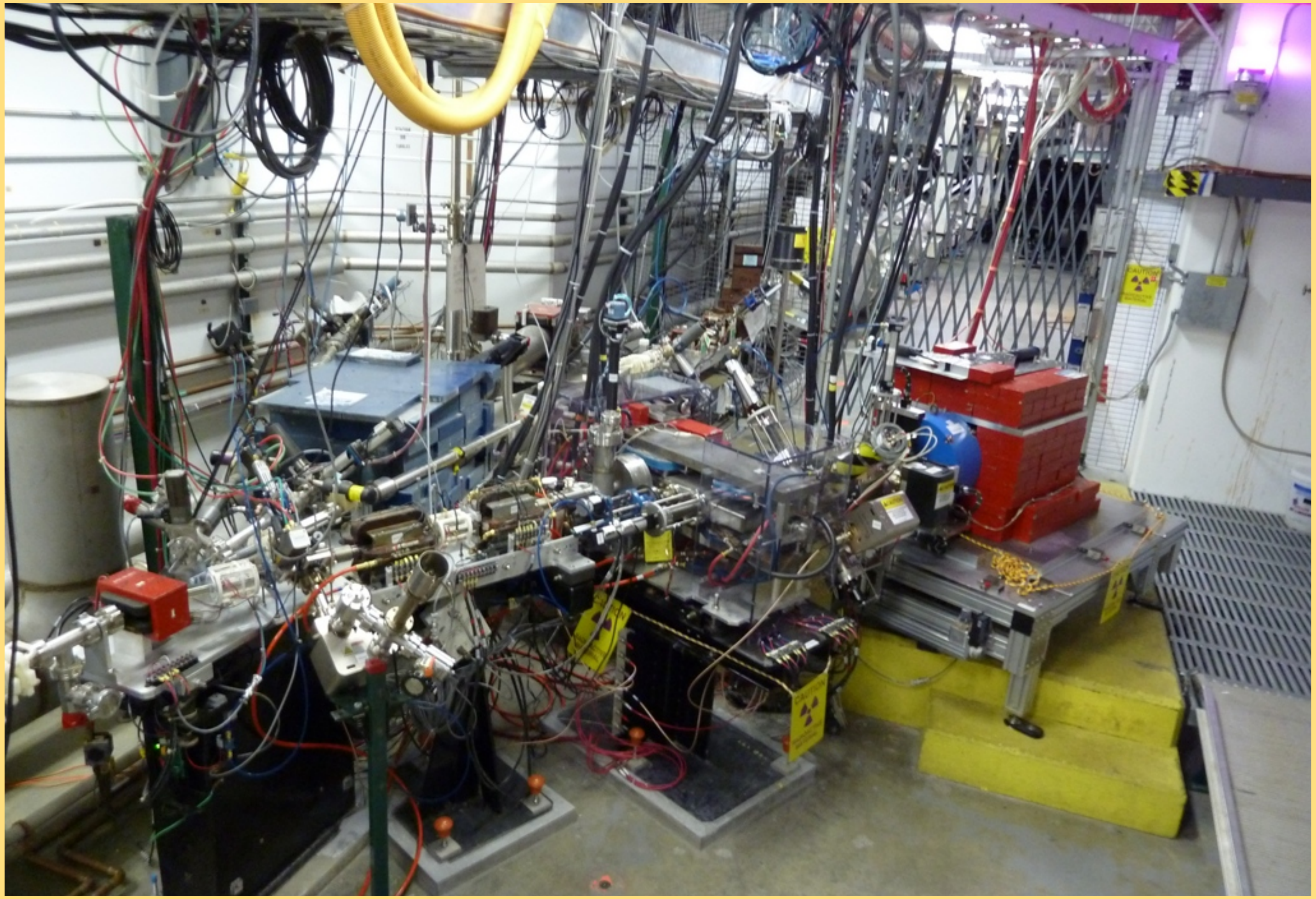
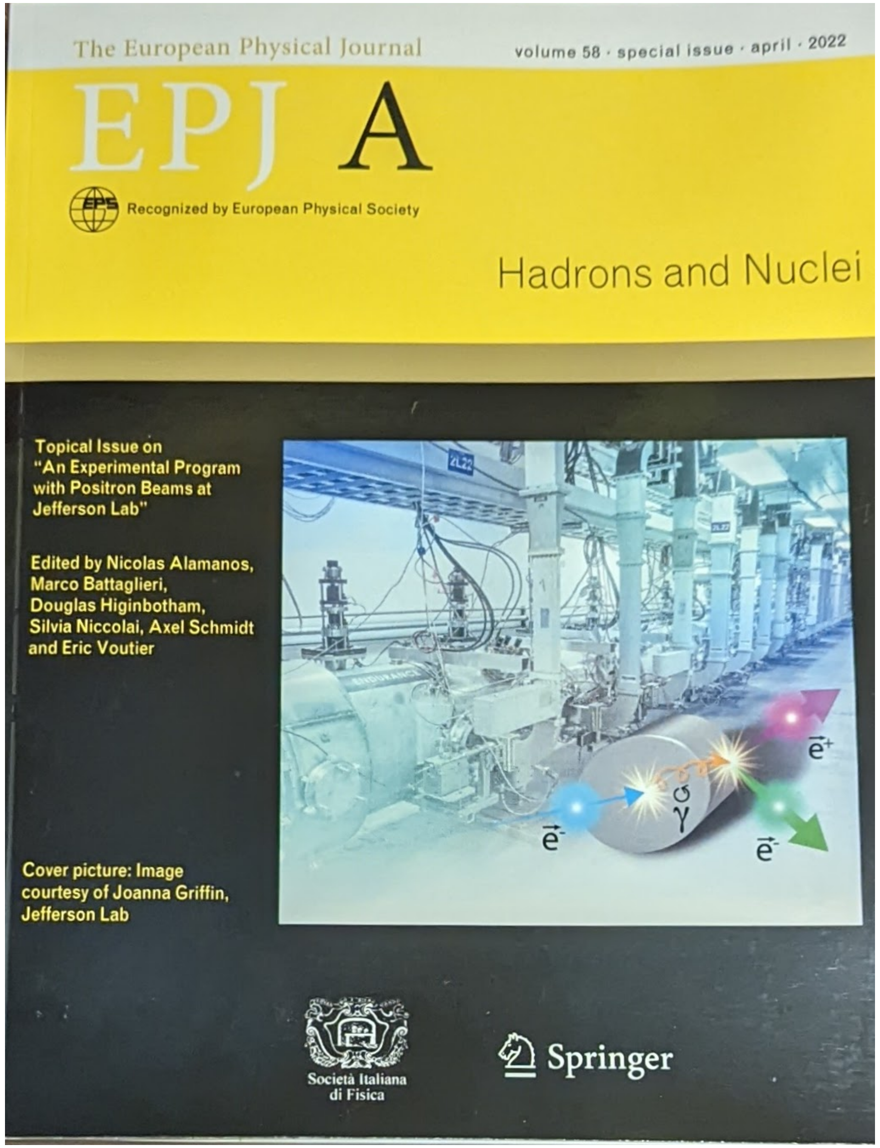


Photo of the PEPPo setup in the injector area of CEABF.

Positron Program White Paper Published 2022

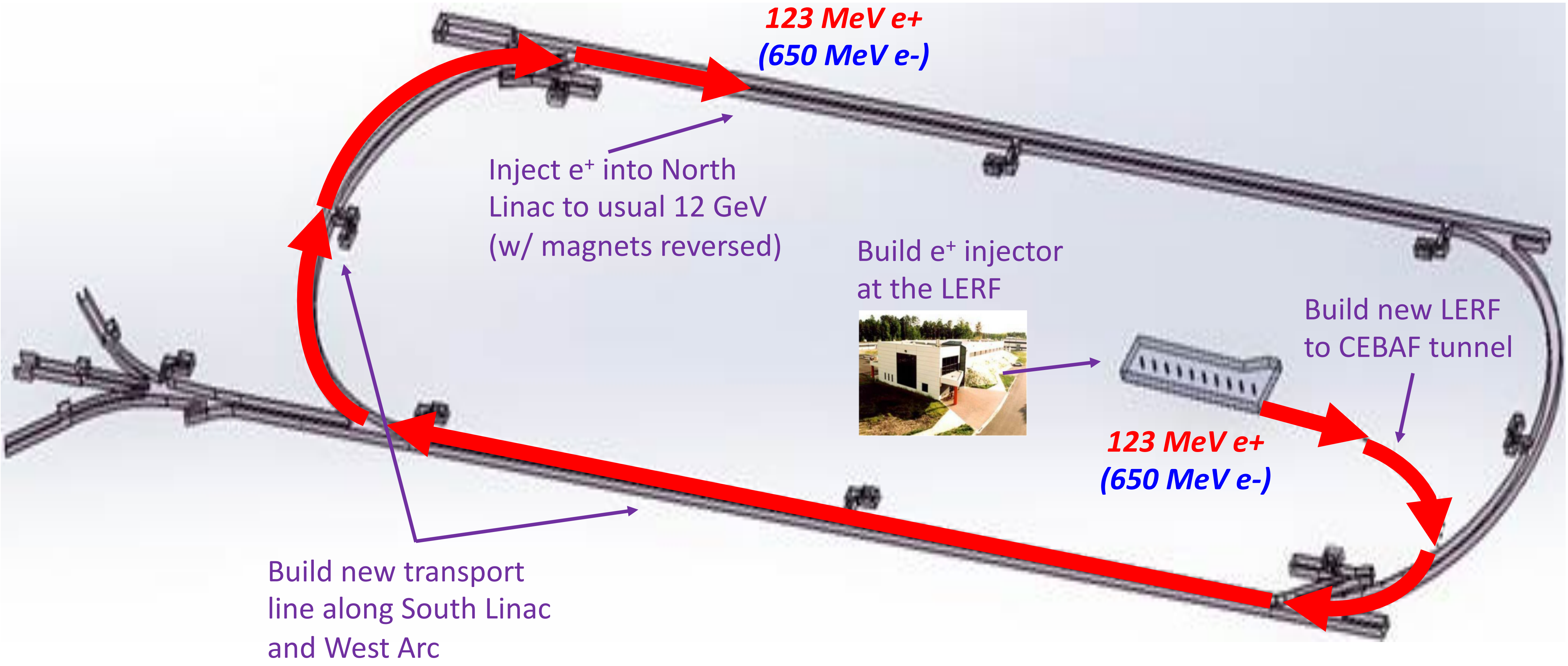
Experiment Label (EPJ A)	Short Name	Hall	Detector	Target	Polarity	p (GeV/c)	P (%)	I (μA)	Time (d)	PAC Grade
Two Photon Exchange Physics										
57:144	$H(e,e'p)$	B	CLAS12$^+$	H_2	$+/-_s$	2.2/3.3/4.4/6.6	0	0.060	53	
57:188	$H(\vec{e},e'\vec{p})$	A	ECAL/SBS	H_2	$+/-_p$	2.2/4.4	60	0.200	121	
57:199	r_p	B	PRad-II	H_2	$+$	0.7/1.4/2.1	0	0.070	40	
	r_d			D_2		1.1/2.2		0.010	39	
57:213	$\vec{H}(e,e'p)$	A	BB/SBS	$N\vec{H}_3$	$+/-_s$	2.2/4.4/6.6	0	0.100	20	
57:290	$H(e,e'p)$	A	HRS/BB/SBS	H_2	$+/-_s$	2.2/4.4	0	1.000	14	
57:319	SupRos	A	HRS	H_2	$+/-_p$	0.6−11.0	0	2.000	35	
58:36	$A(e,e')A$	A	HRS	He	$+/-_p$	2.2	0	1.000	38	
Nuclear Structure Physics										
57:186	p-DVCS	B	CLAS12	H_2	$+/-_s$	2.2/10.6	60	0.045	100	C2
57:226	n-DVCS	B	CLAS12	D_2	$+/-_s$	11.0	60	0.060	80	
57:240	p-DDVCS	A	SoLID$^\mu$	H_2	$+/-_s$	11.0	(30)	3.000	100	
57:273	He-DVCS	B	CLAS12/ALERT	^{4}He	$+/-_s$	11.0	60			
57:300	p-DVCS	C	SHMS/NPS	H_2	$+$	6.6/8.8/11.0	0	5.000	77	C2
57:311	DIS	A/C	HRS/HMS/SHMS		$+/-_s$	11.0				
57:316	VCS	C	HMS/SHMS	H_2	$+/-_s$		60			
Beyond the Standard Model Physics										
57:173	C_{3q}	A	SoLID	D_2	$+/-_s$	6.6/11.0	(30)	3.000	104	D
57:253	LDM	B	PADME	C	$+$	11.0	0	0.100	180	
			ECAL/HCAL	PbW04					120	
57:315	CLFV	A	SoLID$^\mu$	H_2	$+$	11.0				
								Total (d)	**1121**	

CLAS12$^+$ ≡ CLAS12 implemented with an Electromagnetic Calorimeter in the Central Detector
SoLID$^\mu$ ≡ SoLID complemented with a muon detector
$+$ Secondary positron beam
$-_s$ Secondary electron beam
$-_p$ Primary electron beam
(30) Do not require polarization but would take advantage if available at the required beam intensity



https://doi.org/10.1140/epja/s10050-022-00699-6

Low Energy Recirculator Facility (LERF) As The New Injector Facility for CEBAF



12 GeV Beam at CEBAF vs. $Ce^{+}BAF$

Machine Parameter	Electrons	Positrons
Hall Multiplicity	4	1 or more
Max. Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Repetition	249.5/499 MHz	249.5/499/1497 MHz
Duty Factor	100% cw	100% cw
Unpolarized Intensity	170 μA**	> 1 μA
Polarized Intensity	170 μA**	> 50 nA
Beam Polarization	> 85%	> 60%

** Total beam power at Jefferson Lab is limited to 1.1 MW with a max. of 0.9 MW to individual high power dumps.

Program Advisory Committee Positron Results (July 2023)

NUMBER	TITLE	CONTACT PERSON	HALL	DAYS REQUESTED	DAYS AWARDED	SCIENTIFIC RATING	PAC DECISION
PR12+23-002	Beam Charge Asymmetries for Deeply Virtual Compton Scattering on the Proton at CLAS12	Eric Voutier	B	100	100	**A-**	C1
PR12+23-003	Measurement of Deep Inelastic Scattering from Nuclei with Electron and Positron Beams to Constrain the Impact of Coulomb Corrections in DIS	Dave Gaskell	C	9.3	9.3	**A-**	C1
PR12+23-005	A Dark Photon Search with a JLab positron beam	Bogdan Wojtsekhowski	B	60			Deferred
PR12+23-006	Deeply Virtual Compton Scattering using a positron beam in Hall C	Carlos Munoz Camacho	C	137	137	**A-**	C1
PR12+23-008	A Direct Measurement of Hard Two-Photon Exchange with Electrons and Positrons at CLAS12	Axel Schmidt	B	55	55	**A**	**C1**
PR12+23-012	A measurement of two-photon exchange in unpolarized elastic positron–proton and electron–proton scattering	Michael Nycz	C	56	56	**A-**	C1

C1 = Conditionally Approved w/Technical Review by the Lab

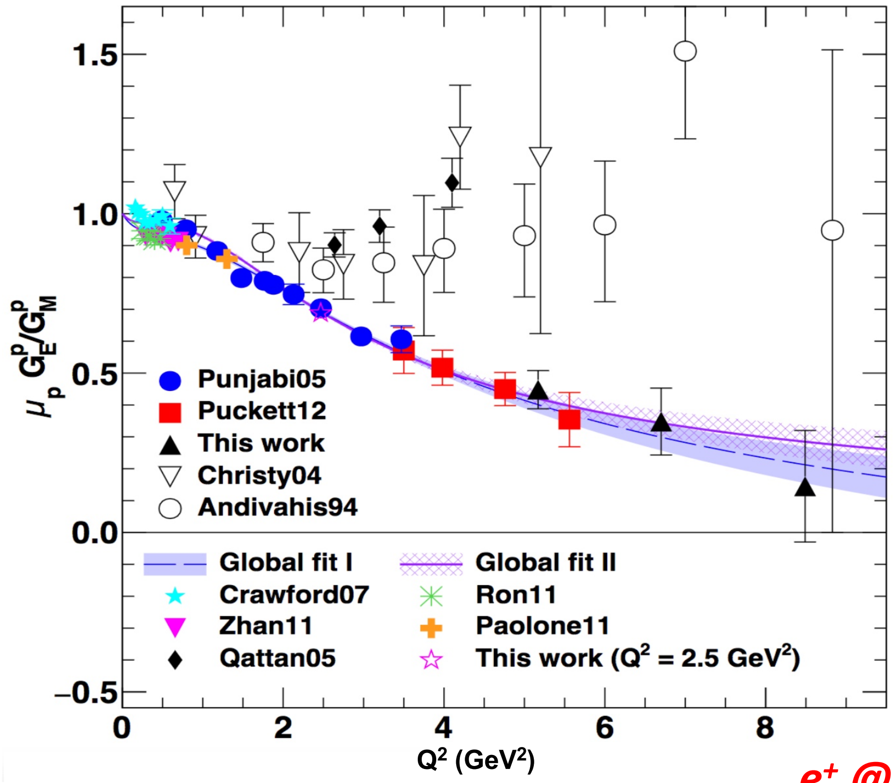
Approved 155 days Hall B & 202 days in Hall C for 357 total PAC days!
Three years of running at 34 weeks per year. (PAC day = two calendar day)

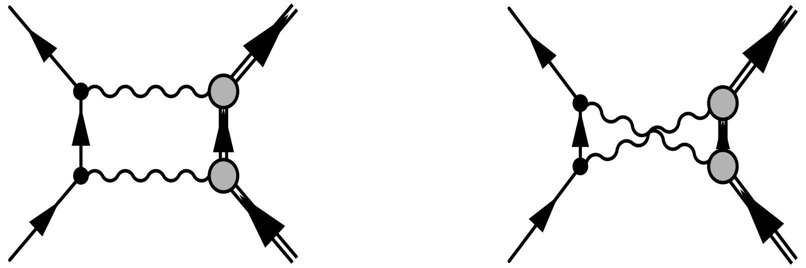
The Dilemma

P.A.M. Guichon, M. Vanderhaeghen, PRL 91 (2003) 142303 P.G. Blunden, W. Melnitchouk, J.A. Tjon, PRL 91 (2003) 142304

- Measurements of polarization transfer observables in electron elastic scattering off protons question the validity of the 1γ exchange approximation (OPE) of the electromagnetic interaction.

A.J.R. Puckett et al. PRC 96 (2017) 055203





Hard two-photon exchange (TPE) may be the cause of the form factor discrepancy at high Q^2.

- If TPE, the electromagnetic structure of the nucleon would be parameterized by 3 generalized form factors i.e. 8 unknow quantities.
- TPE can only be calculated with model-dependent approaches.

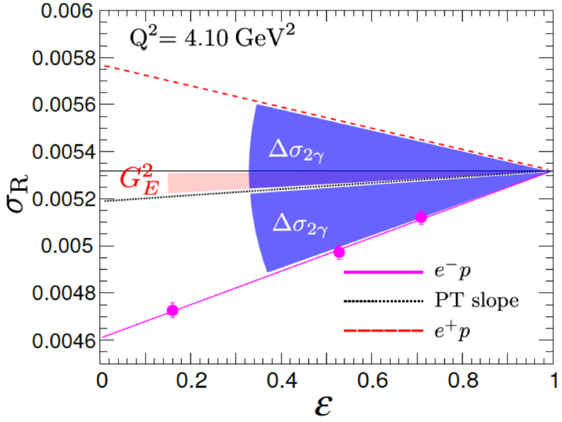
*e^+ @ JLab have the unique opportunity to bring a **definitive answer** about TPE.*

Experimental Observables

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

- The ratio of the positron and electron induced elastic cross sections measures TPE effects.

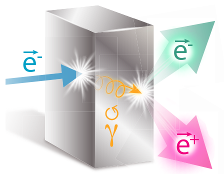
$$\sigma_R = G_M^2 + \frac{\varepsilon}{\tau} G_E^2 \pm 2\left\{ G_M \Re e\left[f_0\left(\delta\tilde{G}_M, \delta\tilde{F}_3\right)\right] + \frac{\varepsilon}{\tau} G_E \Re e\left[f_1\left(\delta\tilde{G}_E, \delta\tilde{F}_3\right)\right]\right\}$$



- The direct comparison of positron and electron Super-Rosenbluth separations doubles the sensitivity to a TPE signal, and test radiative correction hypotheses.

- The measurement of the polarization transfer of positrons to protons in the elastic scattering process is mandatory to establish its expected insensitivity to TPE.

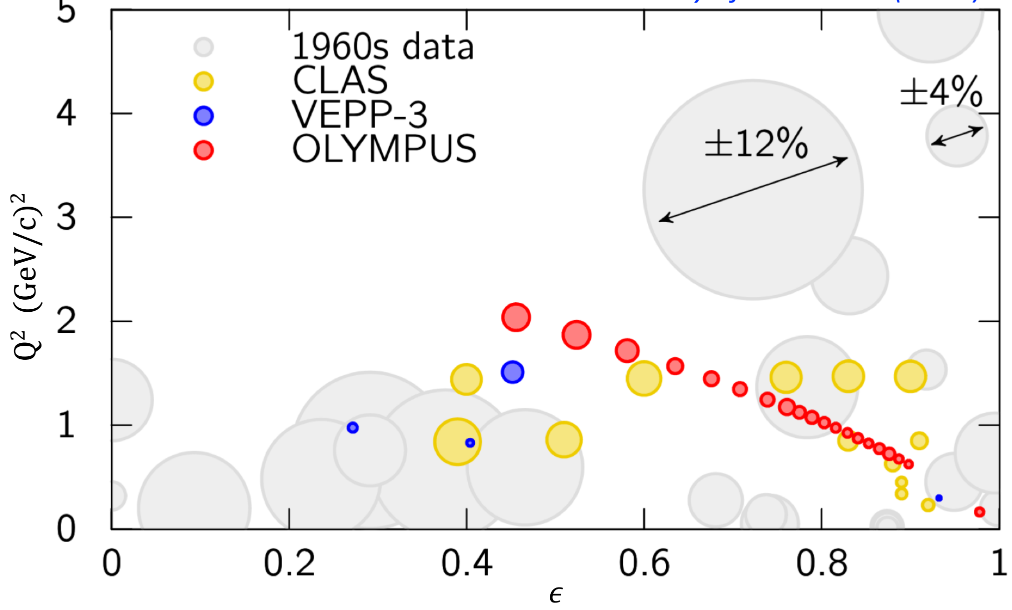
$$\frac{P_t}{P_l} \approx -\sqrt{\frac{2\epsilon}{(1+\epsilon)\tau}} \frac{G_E}{G_M}\left(1 \pm \left\{\frac{\Re e\left[\delta\tilde{G}_M\right]}{G_M} + \frac{\Re e\left[f_1\left(\delta\tilde{G}_E, \delta\tilde{F}_3\right)\right]}{G_E} - 2\frac{\Re e\left[f_2\left(\delta\tilde{G}_M, \delta\tilde{F}_3\right)\right]}{G_M}\right\}\right)$$

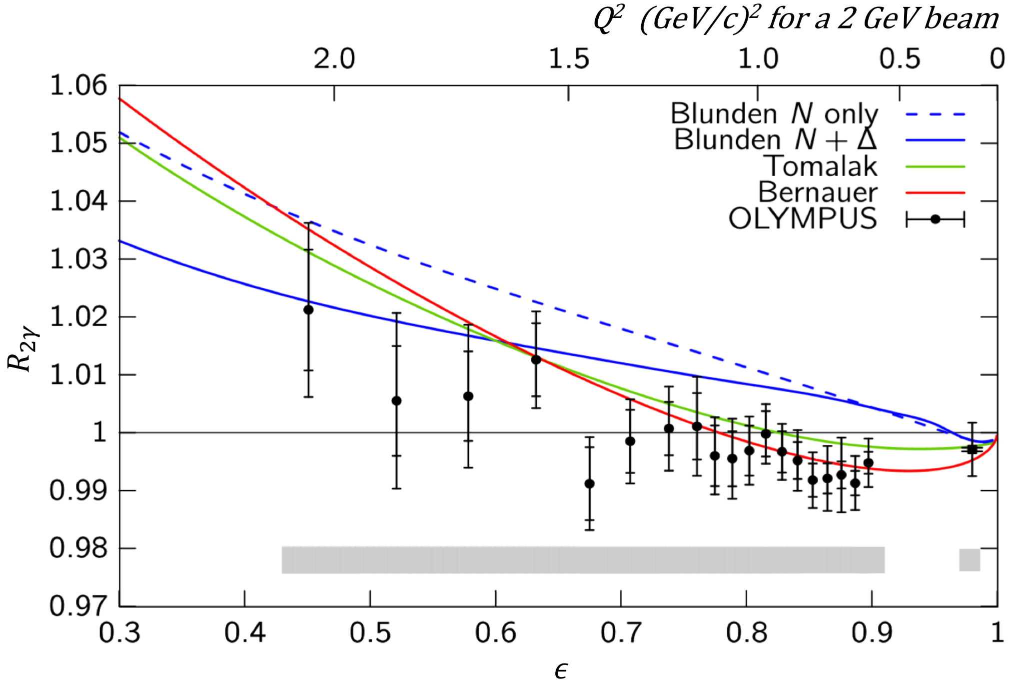


Current Knowledge

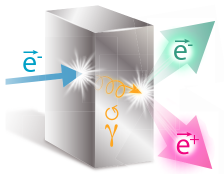
- Three experiments (CLAS,VEPP-3,OLYMPUS) recently attempted to measure TPE effects, but lacked the kinematical reach to draw meaningful conclusions.
- OLYMPUS seems to observe a small effect, barely consistent with expectations.

Courtesy of A. Schmidt (GWU)





(CLAS Collaboration) D. Adikaram et al. PRL 114 (2015) 062003 I.A. Rachek et al. PRL 114 (2015) 062005 (OLYMPUS Collaboration) B. Henderson et al. PRL 118 (2017) 092501

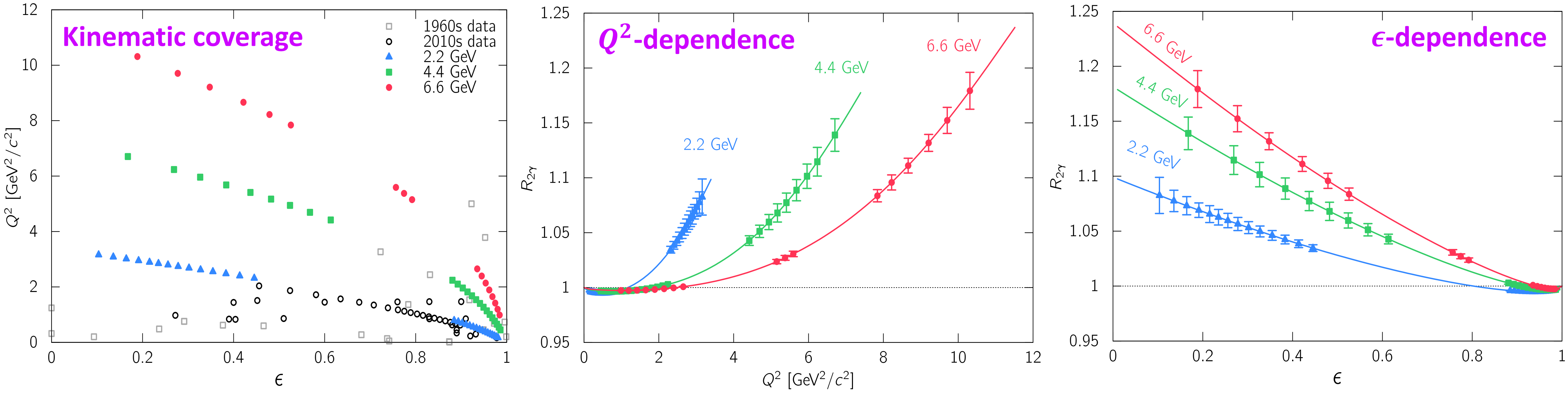


PR12+23-008

A. Schmidt, J.C. Bernauer, V. Burkert, E. Cline, I. Korover, T. Kutz, S.N. Santiesteban et al.

J.C. Bernauer et al. EPJ A 57 (2021) 144

- Over a run of **55 days**, alternating e^- and e^+ at 2.2-4.4-6.6 GeV and an intensity of 50 nA, the **TPE@CLAS12** experiment proposes to **map-out TPE effects**.
- The CLAS12 **trigger** will be **modified** to allow **lepton detection** in the **Central Detector** while protons will be detected in the Forward Detector.



And Beyond…

- The perspective of **positron beams** at JLab **nourishes further reflections** about the importance of **multi-photon effects** in other reaction mechanisms.

T. Kutz, A. Schmidt EPJ A 58 (2022) 36
A. Afanasev at the Positron Working Group Workshop, Charlottesville (2023)
D. Gaskell et al. JLab Proposal PR12+23-003
P. Gueye et al. JLab Letter-of-Intent LOI12+23-015

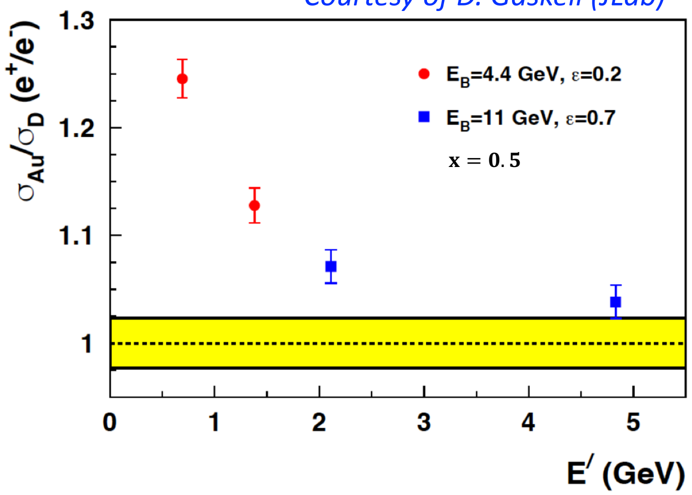
TPE and multi-photon effects in $e^{\pm}N$ interactions

- TPE in elastic scattering off nuclei
- Dispersive effects in A(e,e') inclusive scattering
- ...

TPE effects in Deep Inelastic Scattering (DIS)

- Magnitude of TPE effects in DIS experiments ?
- Magnitude of TPE and photon radiation by the hadrons in SIDIS ?
- Description of Coulomb corrections in the DIS regime
- ...

Courtesy of D. Gaskell (JLab)



*This **list** is not exhaustive but only **indicative** of the **current reflections**.*

Virtual Compton Scattering

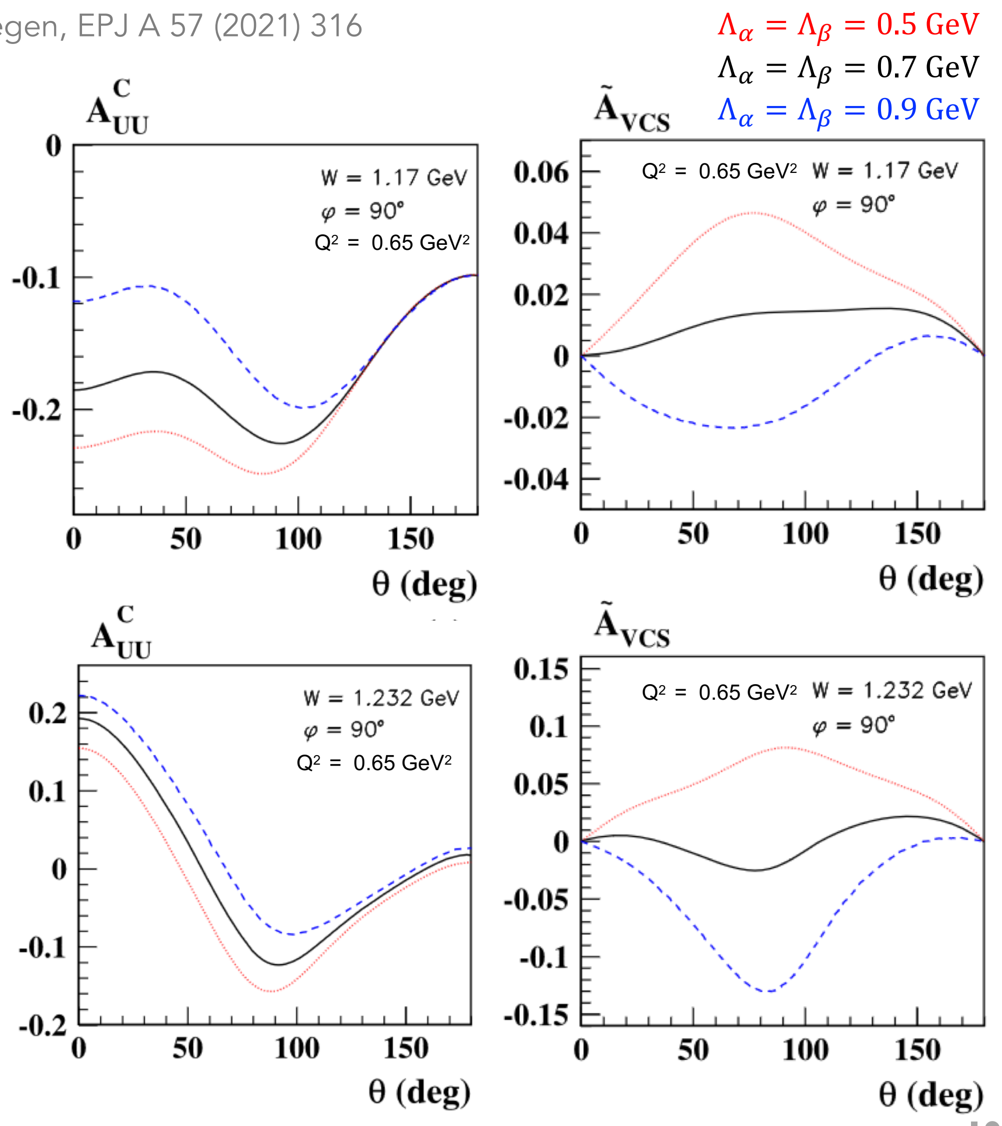
B. Pasquini, M. Vanderhaegen, EPJ A 57 (2021) 316

- The **comparison** of unpolarized/polarized electrons and positrons provides an independent path to access Generalized Polarizabilities (GPs).

$$d\sigma_P^e = d\sigma_{BH} + d\sigma_{VCS} + P d\tilde{\sigma}_{VCS} + e\,[d\sigma_{INT} + P d\tilde{\sigma}_{INT}]$$

$$A_{UU}^C = \frac{d\sigma_{INT}}{d\sigma_{BH} + d\sigma_{VCS}} \qquad \tilde{A}_{VCS} = \frac{2\,d\tilde{\sigma}_{VCS}}{d\sigma_{BH} + d\sigma_{VCS}}$$

- These new observables show **sizeable sensitivity** to GPs.
- $\tilde{A}_{VCS}$ is particularly sensitive to the **electric dipole** GP.



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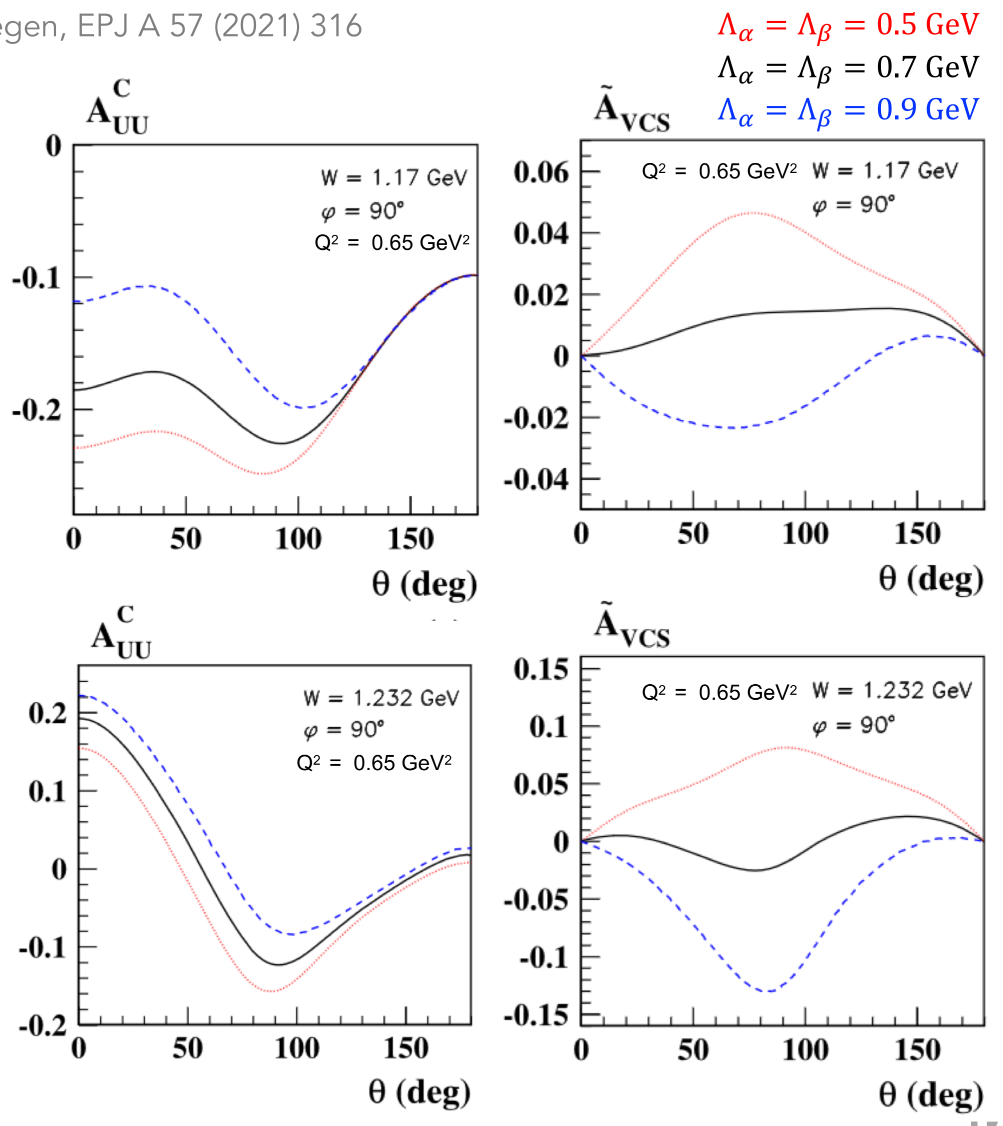


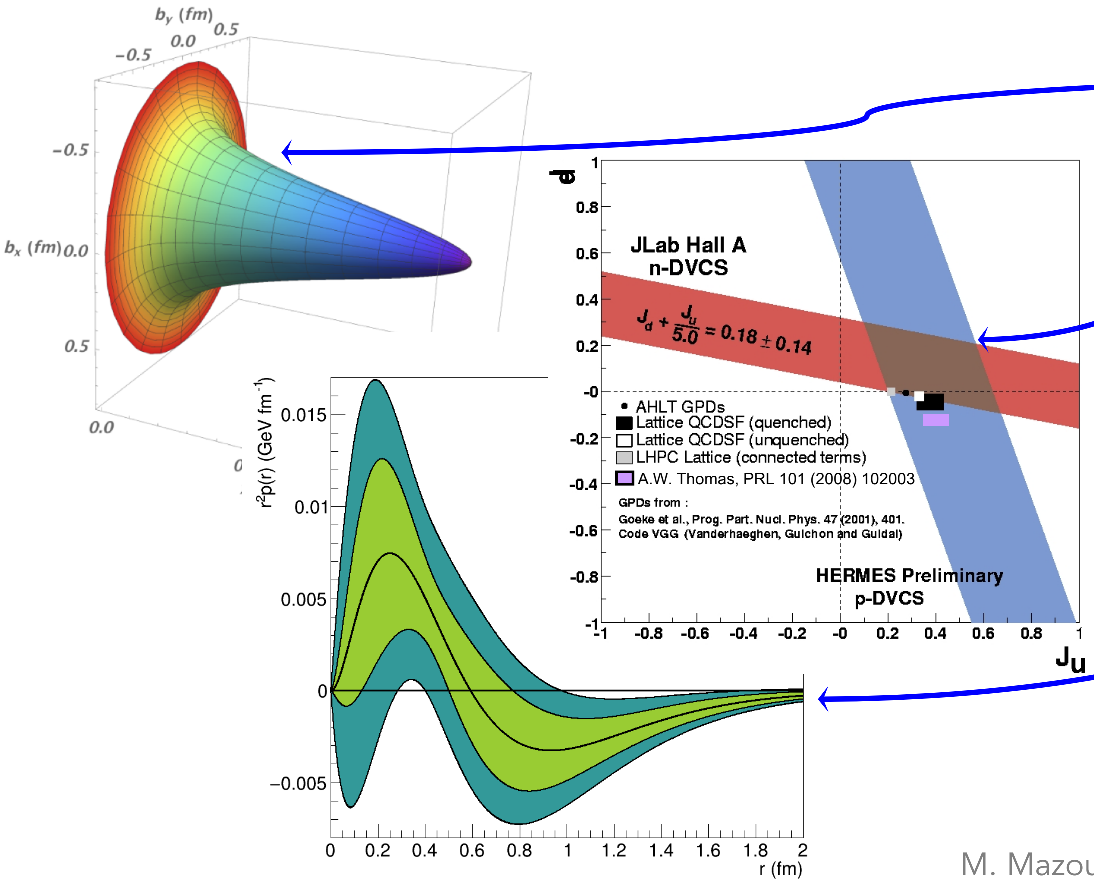
An experimental scenario is under study.

LOI12+23-001 N. Sparveris et al.

Generalized Parton Distributions

X. Ji, PRL 78 (1997) 610 M. Polyakov, PLB 555 (2003) 57
M.V. Polyakov, P. Schweitzer, IJMP A 33 (2018) 1830025

- **GPDs** encode the **correlations between partons** and contain information about the **internal dynamics of hadrons** like the **angular momentum** or the **distribution of the forces** experienced by quarks and gluons.



$$\rho_H^q(x,\boldsymbol{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2}\, e^{i\boldsymbol{b}_\perp\cdot\boldsymbol{\Delta}_\perp}\left[H^q(x,0,-\Delta_\perp^2) + H^q(-x,0,-\Delta_\perp^2)\right]$$

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

$$\int_{-1}^{1} x \sum_q H^q(x,\xi,t)\,dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

- **Unpolarized e^+ combined with unpolarized e^-** access the **real part** of the Compton Form Factors.
- **Polarized e^+ combined with polarized e^-** access the **imaginary part** of the Compton Form Factors (CFFs) and probe **higher twist effects**.

M. Mazouz et. al. PRL 9 (2007) 242501

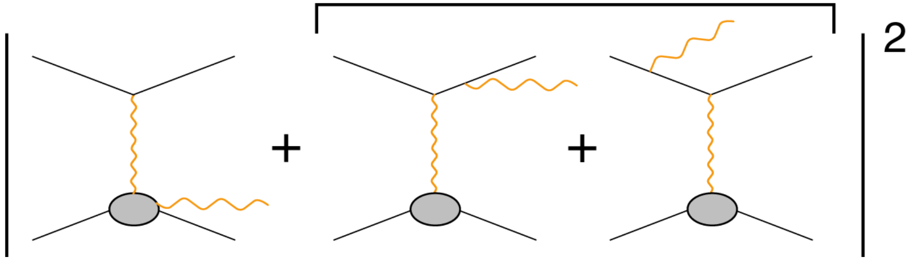
A. Airapetian et al. JHEP 06 (2008) 066 R. Dupré, M. Guidal, M. Vanderhaeghen, PRD 95 (2017) 011501 V. Burkert, L. Elouadrhiri, F.-X. Girod, Nat. 557 (2018) 396

Deeply Virtual Compton Scattering

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

DVCS   Bethe-Heitler (BH)

σ(eN ⟶ eNγ) =



CFF = Compton Form Factors

∝ to the **real part** of a **CFF linear combination**

∝ to the **imaginary part** of a **CFF linear combination**

$$d^5\sigma^{e}_{P0} = d^5\sigma_{BH} + d^5\sigma_{DVCS} + P\, d^5\tilde{\sigma}_{DVCS} - e\,[d^5\sigma_{INT} + P\, d^5\tilde{\sigma}_{INT}]$$

∝ to the **real part** of a **CFF bilinear combination**

∝ to the **imaginary part** of a **CFF bilinear combination**

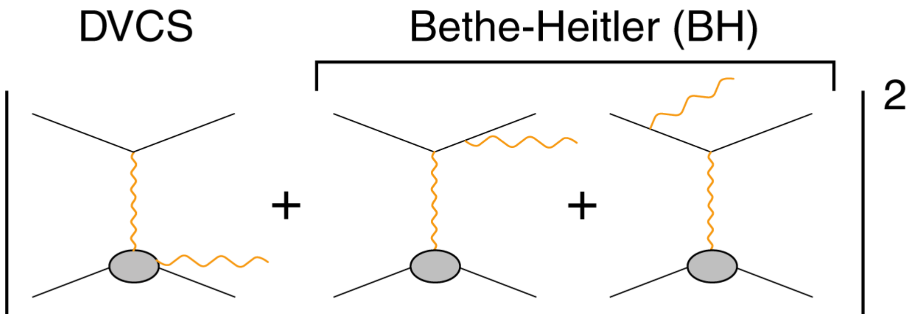
$$d^5\sigma^{e}_{PS} = d^5\sigma^{e}_{P0} + S\,[P\, d^5\Delta\sigma_{BH} + (P d^5\Delta\sigma_{DVCS} + d^5\Delta\tilde{\sigma}_{DVCS}) - e(P d^5\Delta\sigma_{INT} + d^5\Delta\tilde{\sigma}_{INT})\,]$$

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

Deeply Virtual Compton Scattering

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

$\sigma(eN \longrightarrow eN\gamma) =$



CFF = Compton Form Factors

$\propto$ to the **real part** of a **CFF linear combination**

$\propto$ to the **imaginary part** of a **CFF linear combination**

$$d^5\sigma^e_{P0} = d^5\sigma_{BH} + d^5\sigma_{DVCS} + P\, d^5\tilde{\sigma}_{DVCS} - e\,[d^5\sigma_{INT} + P\, d^5\tilde{\sigma}_{INT}]$$

$\propto$ to the **real part** of a **CFF bilinear combination**

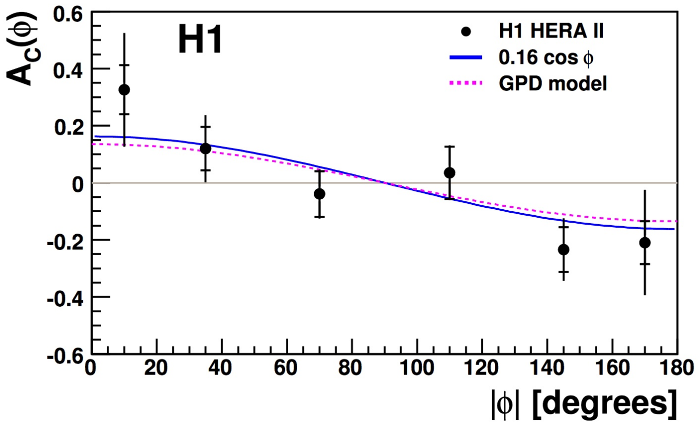
$\propto$ to the **imaginary part** of a **CFF bilinear combination**

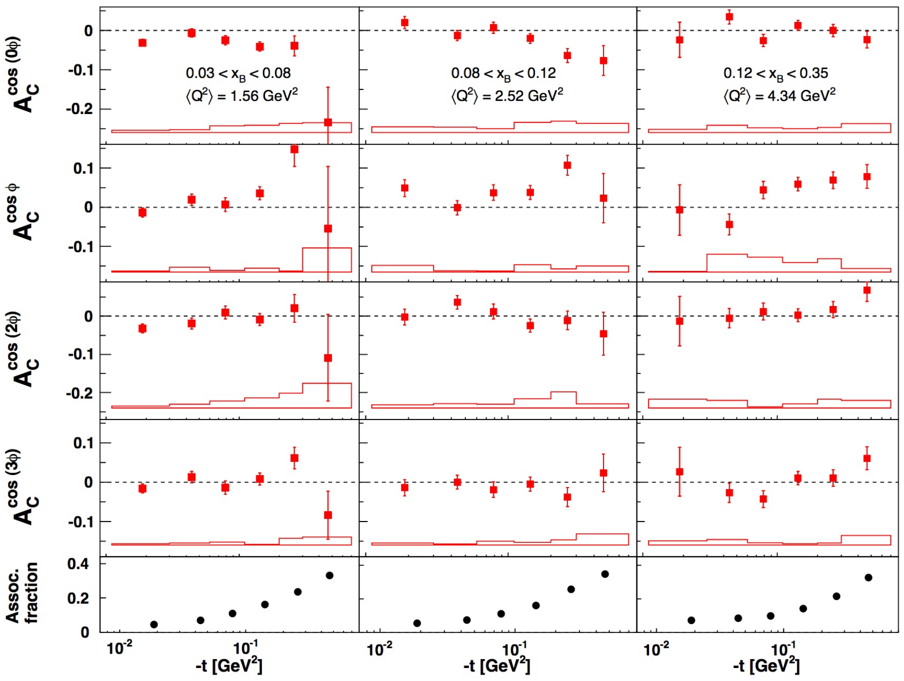
$$d^5\sigma^e_{PS} = d^5\sigma^e_{P0} + S\,[P\, d^5\Delta\sigma_{BH} + (P d^5\Delta\sigma_{DVCS} + d^5\Delta\tilde{\sigma}_{DVCS}) - e(P d^5\Delta\sigma_{INT} + d^5\Delta\tilde{\sigma}_{INT})\,]$$

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

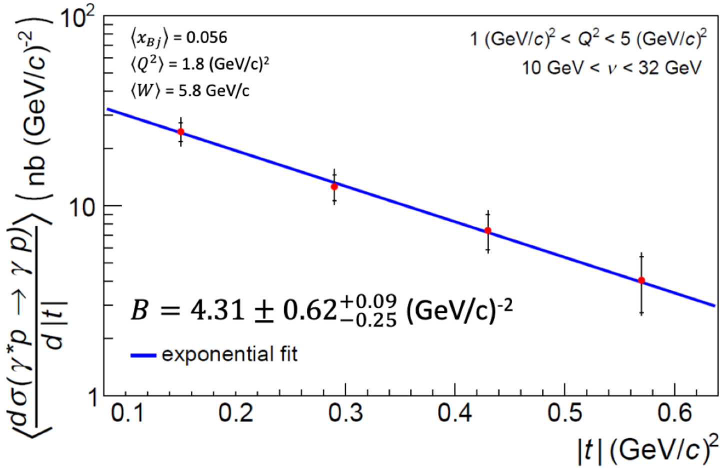
Current Knowledge

- Pioneering comparisons of DVCS with **electron** and **positron** beams at **HERA** and **HERMES demonstrated** the existence of a **BCA-signal**.
- Because of the $\overleftrightarrow{\mu}^{\pm}$ beam nature, the **COMPASS** experiment cannot combine beam charge and polarization independently.





$$\Sigma\sigma^{\pm}_{\mp P} = 2(d^5\sigma_{BH} + d^5\sigma_{DVCS} - P d^5\tilde{\sigma}_{INT})$$



(H1 Collaboration) F.D. Aaron et al. PLB 681 (2009) 391 (HERMES Collaboration) A. Airapetian et al. JHEP 06 (2008) 066 – 11 (2009) 083 – 07 (2012) 032
(COMPASS Collaboration) R. Akhunzyanov et al. PLB 793 (2019) 188

PR12+23-002

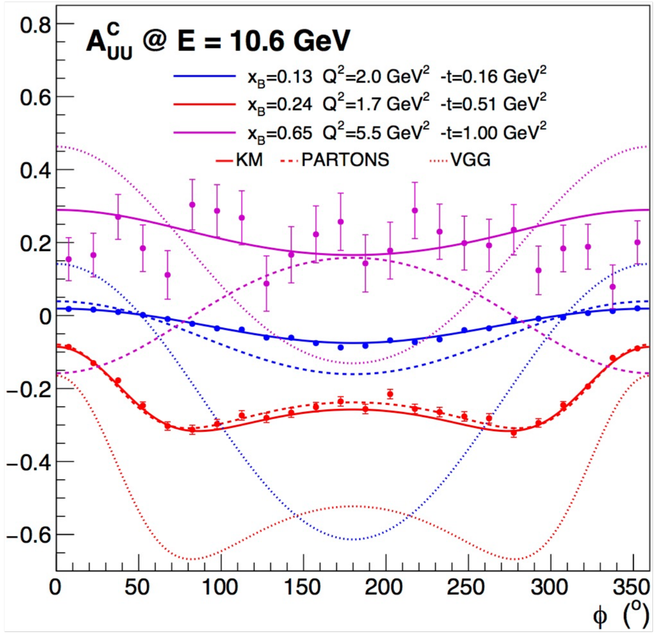
E. Voutier, V. Burkert, S. Niccolai, R. Paremuzyan et al.

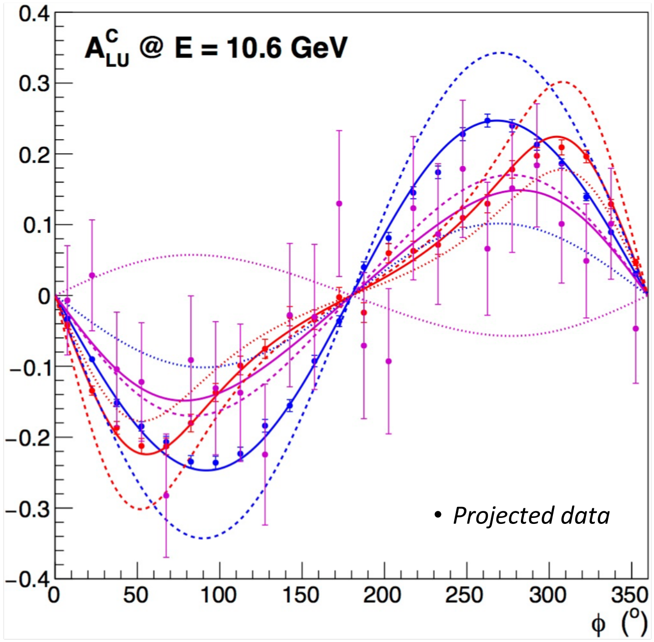
V. Burkert et al. EPJ A 57 (2021) 186

- Measurements of beam charge asymmetries with CLAS12 will provide a full set of new GPD observables:

  - the **unpolarized beam charge asymmetry** A^C_{UU}, sensitive to the **CFF real part**;
  - the **polarized beam charge asymmetry** A^C_{LU}, sensitive to the **CFF imaginary part**;
  - the **charge averaged beam spin asymmetry** A^0_{LU}, signature of **higher twist effects**.

$$A^C_{UU} = \frac{d^5\sigma_{INT}}{d^5\sigma_{BH} + d^5\sigma_{DVCS}}$$





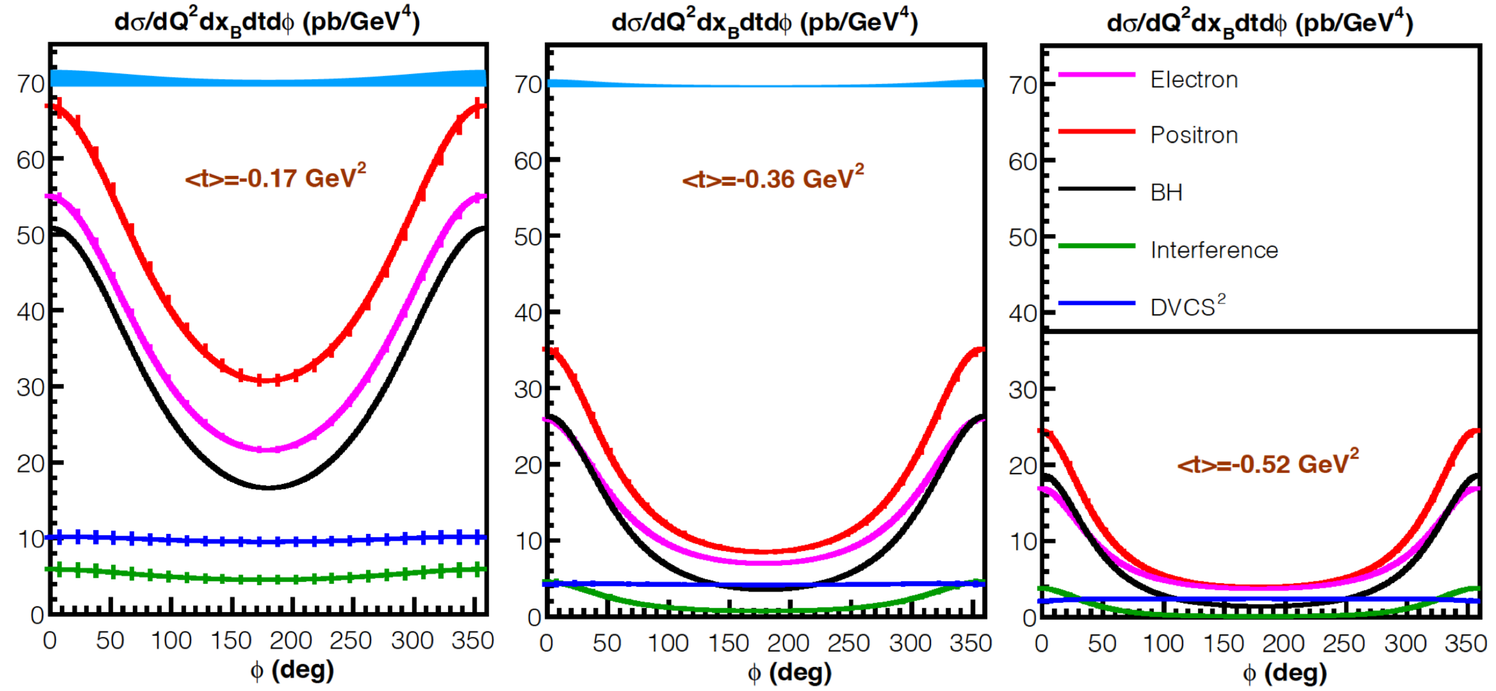
$$A^C_{LU} = \frac{d^5\tilde{\sigma}_{INT}}{d^5\sigma_{BH} + d^5\,\sigma_{DVCS}}$$

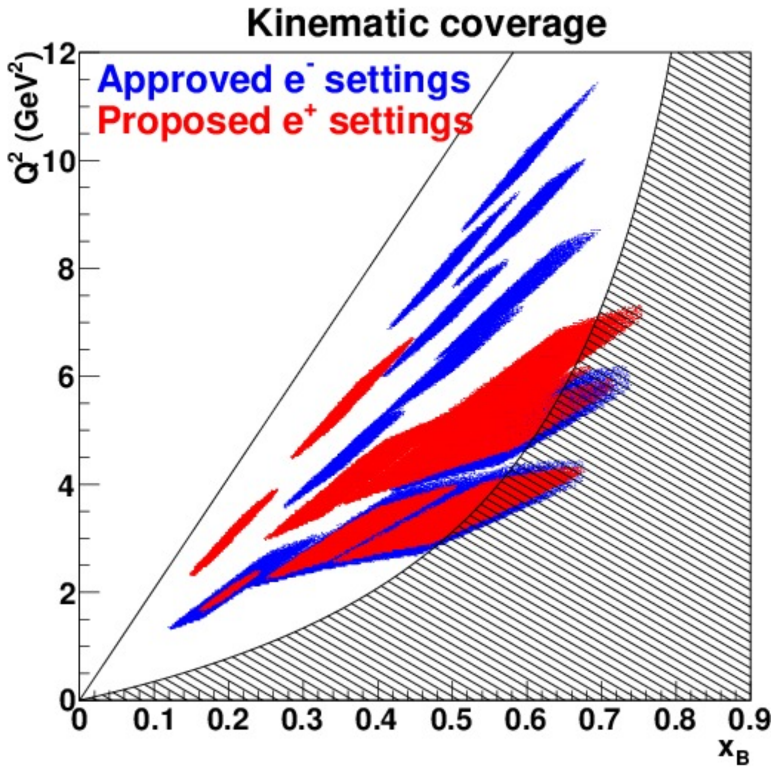
PR12+23-006
C. Muñoz Camacho, M. Mazouz et al.

A. Afanasev et al. EPJ A 57 (2021) 300

- Combining the HMS and the NPS spectrometers, precise cross section measurements with unpolarized positron beam are proposed at selected kinematics where electron beam data will soon be accumulated.

$x_B = 0.36 \quad Q^2 = 4.0\ GeV^2$



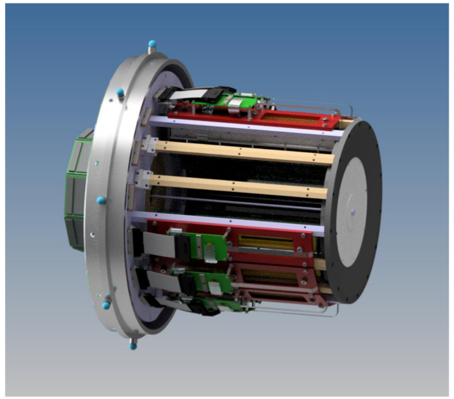


Nuclear structure

And Beyond...

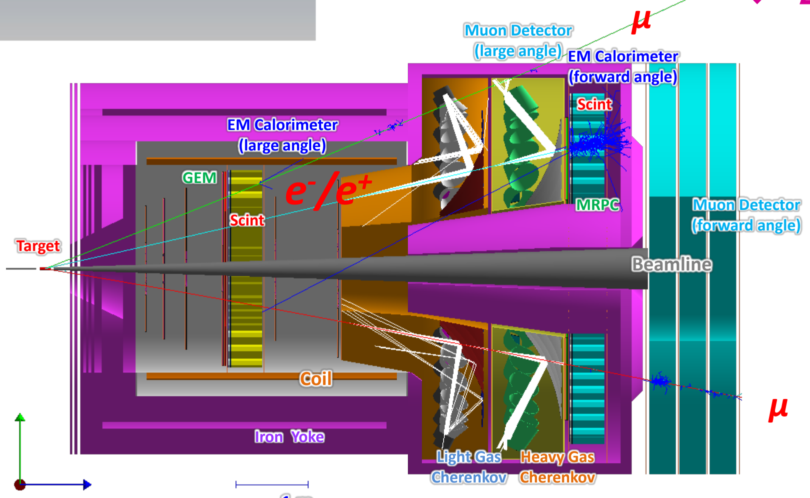
S. Niccolai, P. Chatagnon, M. Hoballah, D. Marchand, C. Muñoz Camacho, E. Voutier, EPJ A 57 (2021) 226
S. Fucini, M. Hattawy, M. Rinaldi, S. Scopetta, EPJ A 57 (2021) 273
S. Zhao et al. EPJ A 57 (2021) 240

ALERT



❖ *Generalized parton distributions*

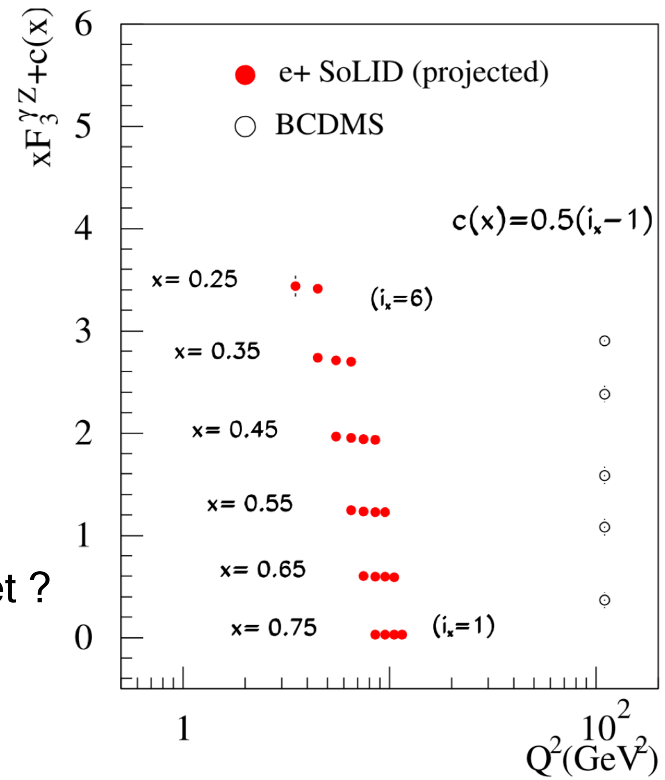
- DVCS off the neutron
- Coherent DVCS off the nucleus
- Incoherent DVCS off the nucleus
- Double DVCS off the proton
- DVCS off polarized targets ?
- ...



SoLID$^{\mu}$

❖ *Electroweak physics*

- Axial form factor of the proton
- DIS on a longitudinally polarized target ?
- Strangeness content of the nucleon ?
- Electroweak structure function $F_3^{\gamma Z}$
- ...



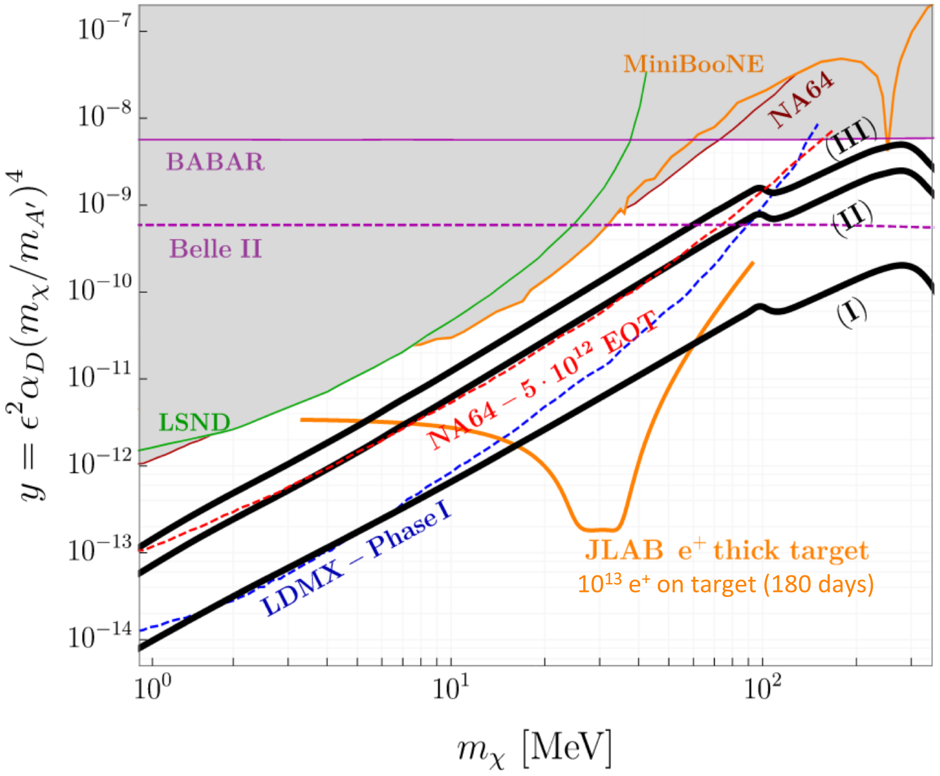
E. Aschenauer, T. Burton, T. Martin, H. Spiesberger, M. Stratman, PRD 88 (2013) 114025
W. Melnitchouk, J.F. Owens EPJ A 57 (2021) 311 X. Zheng et al. Jefferson Lab Proposal PR12-21-006 (2021)
D. Dutta et al. JLab Letter-of-Intent LOI12+23-002

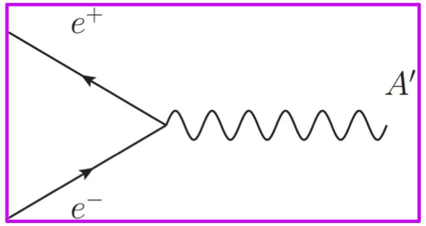
*This **list** is not exhaustive but only **indicative** of the **current reflections**.*

Direct Dark Matter Production

M. Battaglieri et al. EPJ A 57 (2021) 253

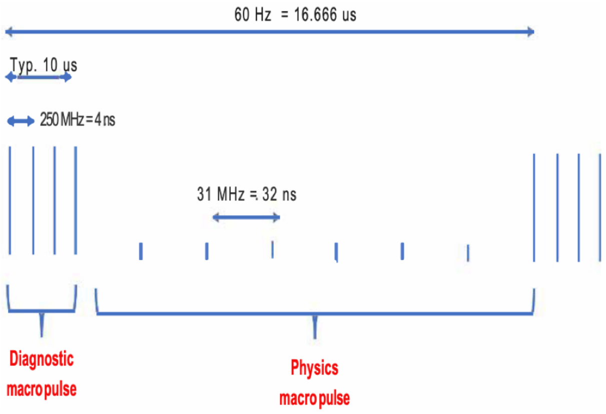
- A direct search of dark matter in the e^+e^- **annihilation** has been evaluted using a beam energy of **11 GeV** and a **180 days** data taking period.
- The measurement of an **energy deposit smaller** than the **e⁺ beam energy** signs the **production** of the *A'*.



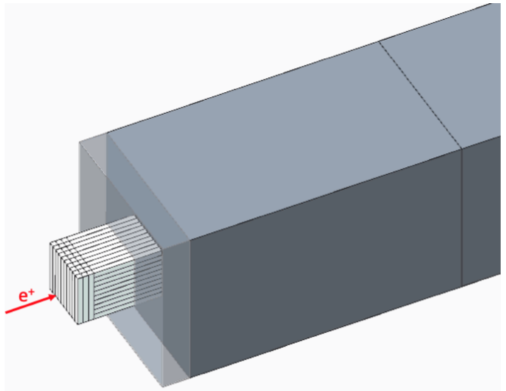


$$E_{miss} = E_{beam} - E_{CAL}$$

$$m_{A'} = \sqrt{2m_e E_{miss}}$$

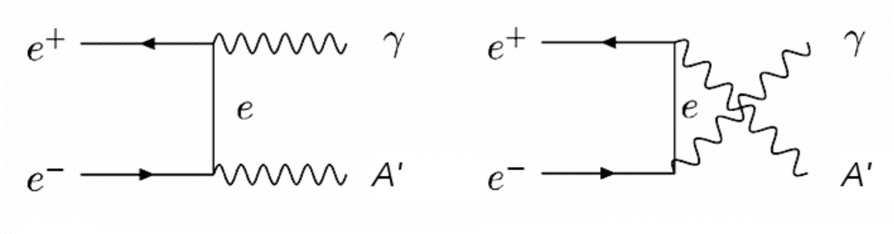


A specific time structure of the beam is required to avoid e⁺ beam pile-up in the detector.



*An **active thick target** completed with a **hadronic calorimeter** constitute the experimental set-up.*

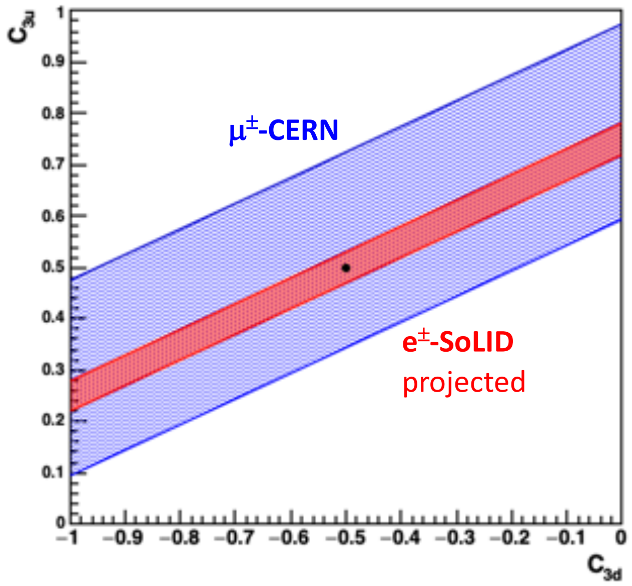
And Beyond...



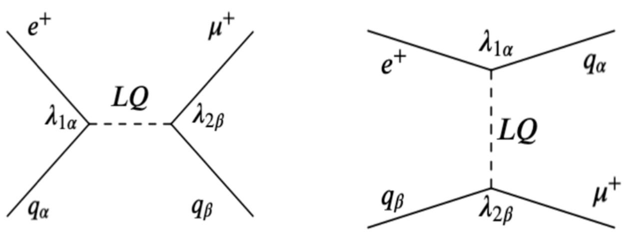
❖ *Testing standard model predictions*

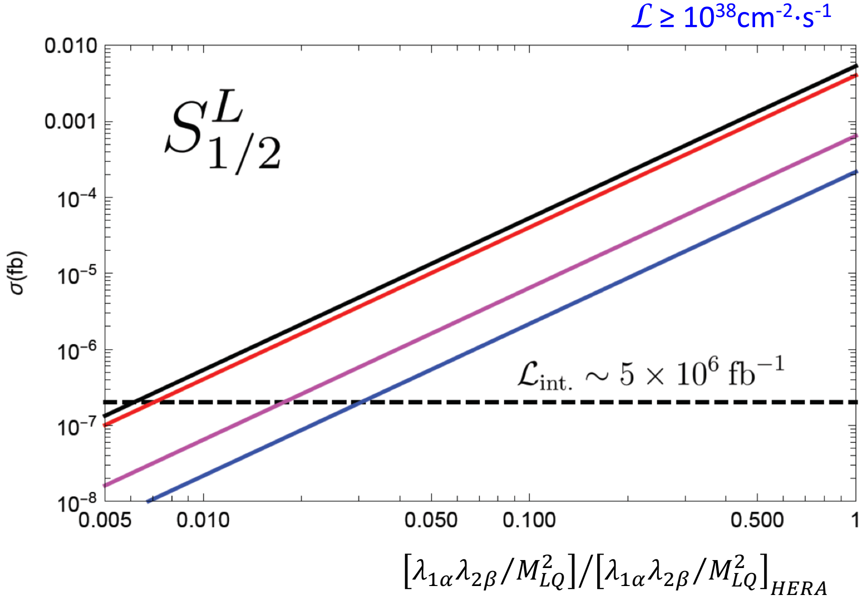
- Dark matter search
- Axial-axial neutral current coupling
- Charged lepton flavor violation ?
- ...

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$



$$e^\pm + N \longrightarrow \mu^\pm + X$$



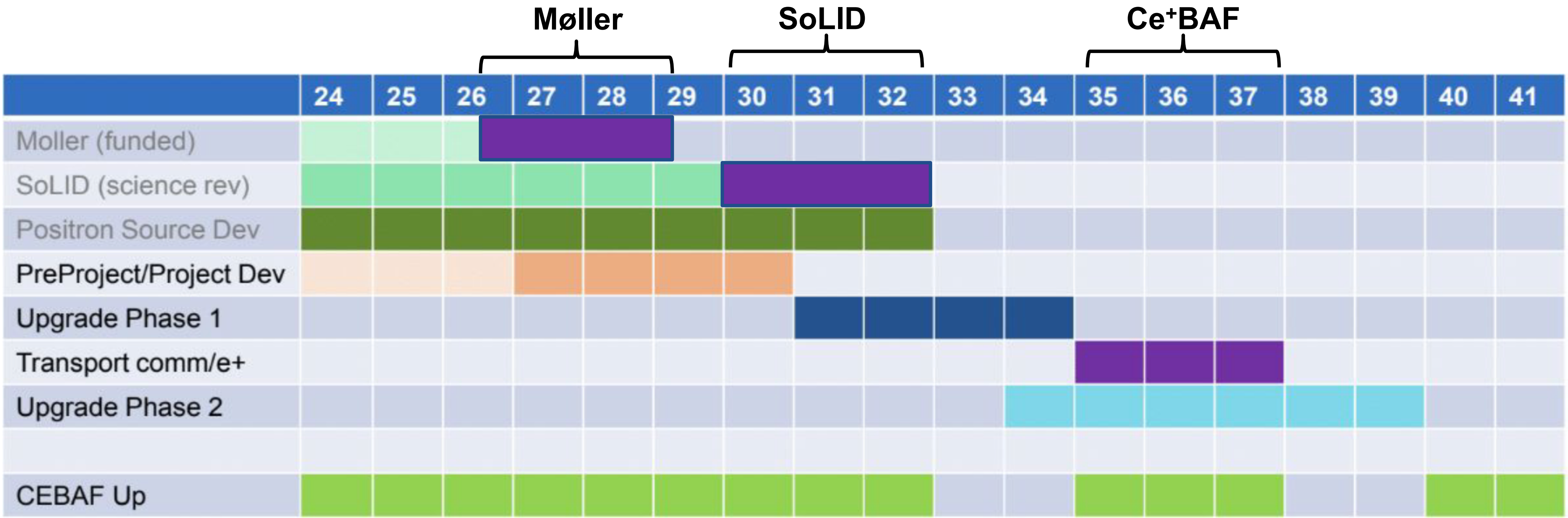


X. Zheng, J. Erler, Q. Liu, H. Spiesberger, EPJ A 57 (2021) 173 Y. Furletova, S. Mantry, EPJ A 57 (2021) 315
B. Wojtsekhowski et al. Jefferson Lab Proposal PR12+23-005 D. Mack Jefferson Letter-of-Intent PR12+23-005

*This **list** is not exhaustive but only **indicative** of the **current proposals**.*

Timeline

D. Dean at the International Workshop on CLAS12 Physics and Future Perspectives at JLab, Paris, March 21-24, 2023



- Phase 1 includes building a positron source and the tunnel & beamline connecting to CEBAF
- Phase 2 includes new permanent magnets to allow 22 GeV within current CEBAF footprint

Summary

- A rich and high impact experimental program asking for intense CW polarized and unpolarized positron beams at JLab has been elaborated, allowing us to measure new observables and to explore new reaction channels.

- A strong accelerator R&D effort is progressing towards the final design and implementation of polarized and unpolarized positron beams at Jefferson Lab.

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Experimental capabilities will concern
not only the **high energy Ce^{+}BAF** beam
but also **low energy** electron and positron beams to be available at **LERF**.

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LERF

$I_{e-} > 1$ mA @ $P_{e-} > 90\%$

$I_{e+} > 50$ nA @ $P_{e+} = 60\%$

$I_{e+} > 1$ μA @ $P_{e+} = 0\%$

$T_{e\pm} \lesssim 120$ MeV

Ce+BAF

$I_{e+} > 50$ nA @ $P_{e+} = 60\%$

$I_{e+} > 1$ μA @ $P_{e+} = 0\%$

$T_{e+} \lesssim 12$ GeV

Subscribe** to the JLab Positron Working Group mailing list **pwg@jlab.org