Positron Physics at Jefferson Lab

e^+@JLab

Eric Voutier and the **Jefferson Lab Positron Working Group**

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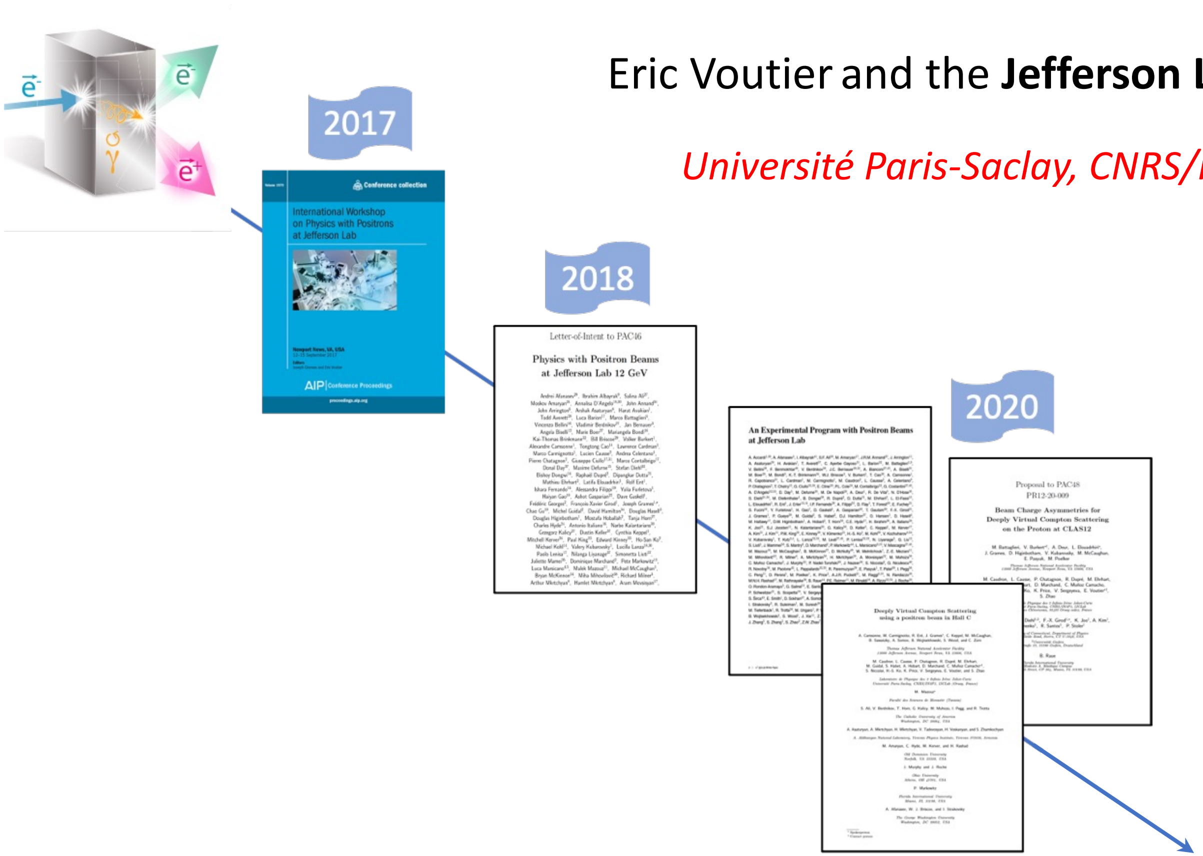
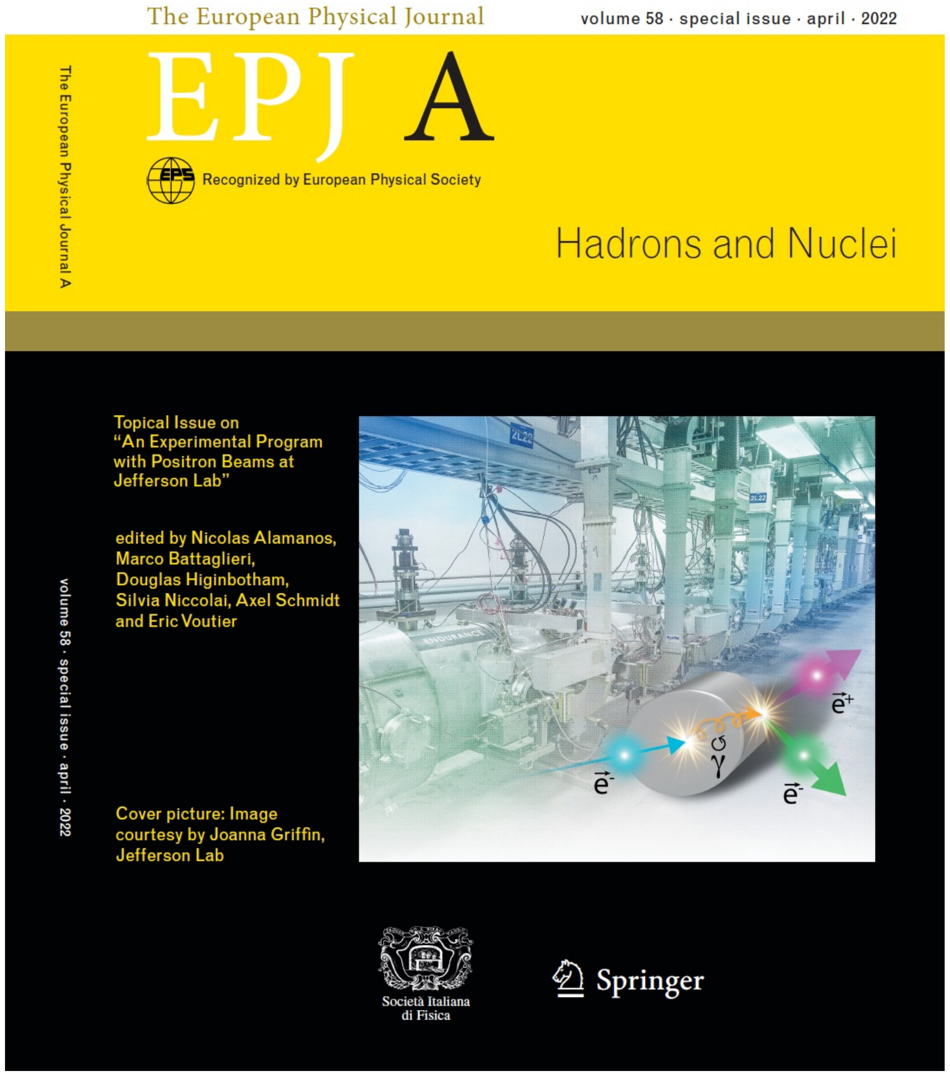


(i) Positron White Paper
(ii) Two photon exchange
(iii) Nuclear structure
(iv) Beyond the standard model

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement Nº 824093.



- The **JLab Positron Working Group** (PWG) developed the perspectives of an experimental program with **positron beams at CEBAF** in a topical EPJ A issue.

- This document constitutes the final **JLab Positron White Paper**, gathering 19 single contributions and a summary article, all peer-reviewed.

JLab PWG = ~**250** Physicists
from **75** Institutions and **16** countries

(Jefferson Lab Positron Working Group) A. Accardi *et al.* EPJ A 57 (2021) 261

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Positron Partial Program Summary

Experiment Label (EPJ A)	Short Name	Measurement Configuration: Hall	Detector	Target	Beam Parameters: Polarity	p (GeV/c)	P (%)	I (μA)	Time (d)
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
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
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
57:253	LDM	B	PADME	C	$+$	11.0	0	0.100	180
			ECAL/HCAL	$PbW0_4$					120
57:315	CLFV	A	SoLID$^\mu$	H_2	$+$	11.0			
								Total (d)	1121

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

- **TPE Physics** in elastic scattering globally asks for low beam energies.
- **Nucleon Structure Physics** and **Beyond the Standard Model Physics** ask for high beam energies.

➢ There exists strong opportunities for **polarized target experiments**, which have not been yet explored.

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➢ **6 Proposals** and **5 Letters-of-Intent** have been submitted to the 2023 JLab Program Advisory Committee

2023 Submissions @ JLab PAC51

Experiment			Measurement Configuration			Beam Parameters				
Short Name	Label	Contact	Hall	Detector	Target	Polarity	p (GeV/c)	P (%)	I (μA)	Time (d)
Two Photon Exchange Physics										
Coulomb Distorsion	PR12+23-003	D. Gaskell	C	HMS	LD_2,Au	+	4.4/11.	0	1.0	10
TPE@CLAS12	PR12+23-008	A. Schmidt	B	CLAS12	LH_2	$+/-_s$	2.2/4.4/6.6	0	0.075/0.075	55
Super-Rosenbuth	PR12+23-012	M. Nycz	C	HMS	LH_2	+/−	0.65−11.	0	1.0/20.	56
Polarization Transfert	LOI12+23-008	A. Puckett	A	SBS+BigCal	LH_2	+	2.2/4.4	60	0.200	120
Dispersive Effects	LOI12+23-015	P. Gueye	A,C	HRS or HMS	C,Al,Cu,Ca,Fe,Pb	+	0.6-4.4	0		
Nuclear Structure Physics										
DVCS BCAs	PR12+23-002	E. Voutier	B	CLAS12	LH_2	$+/-_s$	2.2/11.	60/60	0.050/0.050	100
DVCS XSection	PR12+23-006	C. Muñoz Camacho	C	SHMS+NPS	LH_2	+	6.6/8.8/11.	0	1.0	135
Polarizabilities	LOI12+23-001	N. Sparveris	C	SHMS+HMS	LH_2	+/−	2.2	0	5.0/50.	77
Axial Form Factor	LOI12+23-002	D. Dutta	A,C	mTPC+SBS	^{2}H	+	2.0-6.0	60	0.200	60
Beyond the Standard Model Physics										
Dark Photon Search	PR12+23-005	B. Wojtsekhowski	B	PRad	LH_2	+	2.2/4.4/11.	0	0.050	60
Dark Bhabha	LOI12+23-005	D. Mack	C	Pair Spec.	e^-	+	0.50-11.			

***More proposals** and **new ideas** to come…*

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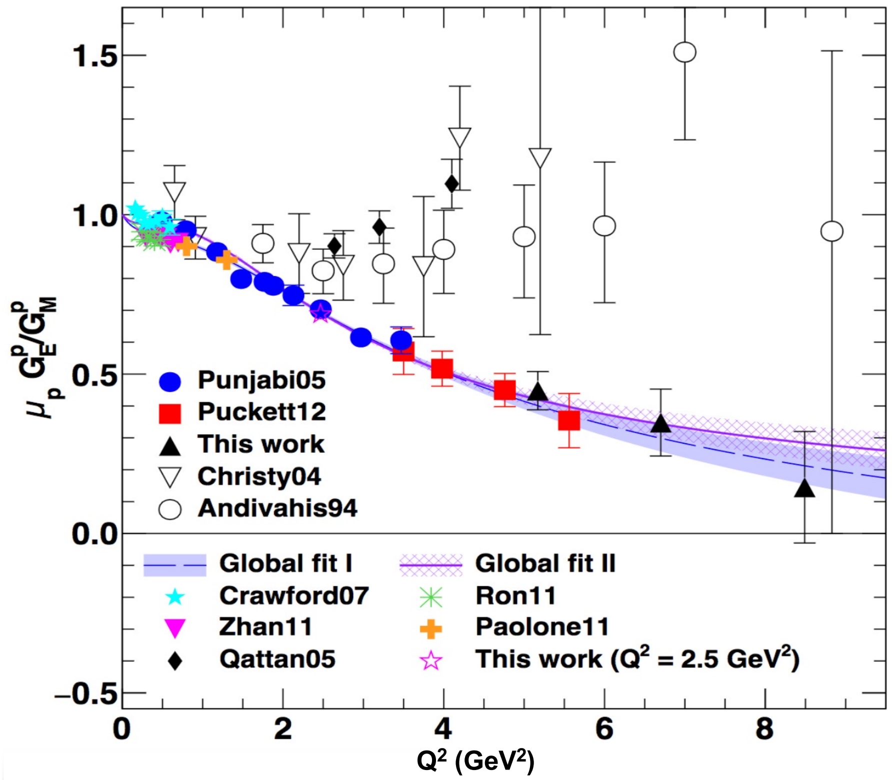
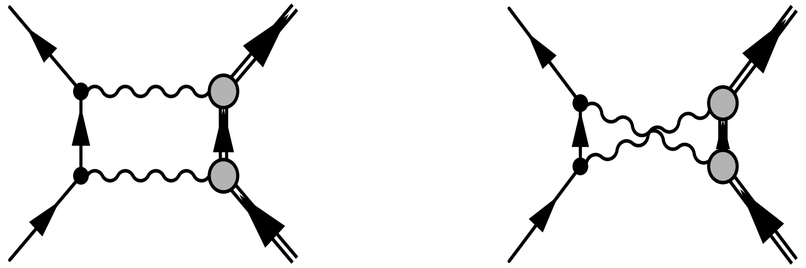
P.A.M. Guichon, M. Vanderhaeghen, PRL 91 (2003) 142303 P.G. Blunden, W. Melnitchouk, J.A. Tjon, PRL 91 (2003) 142304

➢ 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 within model-dependent approaches.

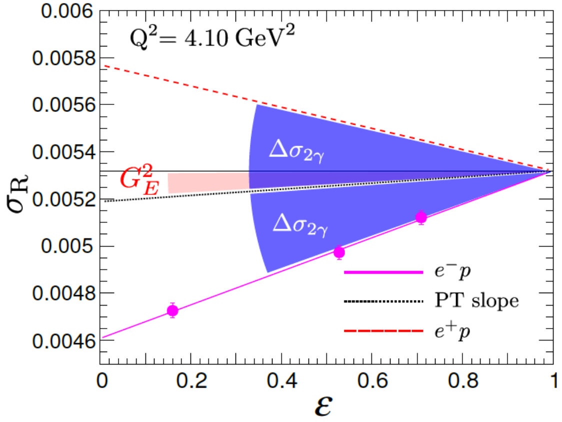
*e^+ @ JLab have the unique opportunity to bring a **definitive answer** about TPE.*

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.

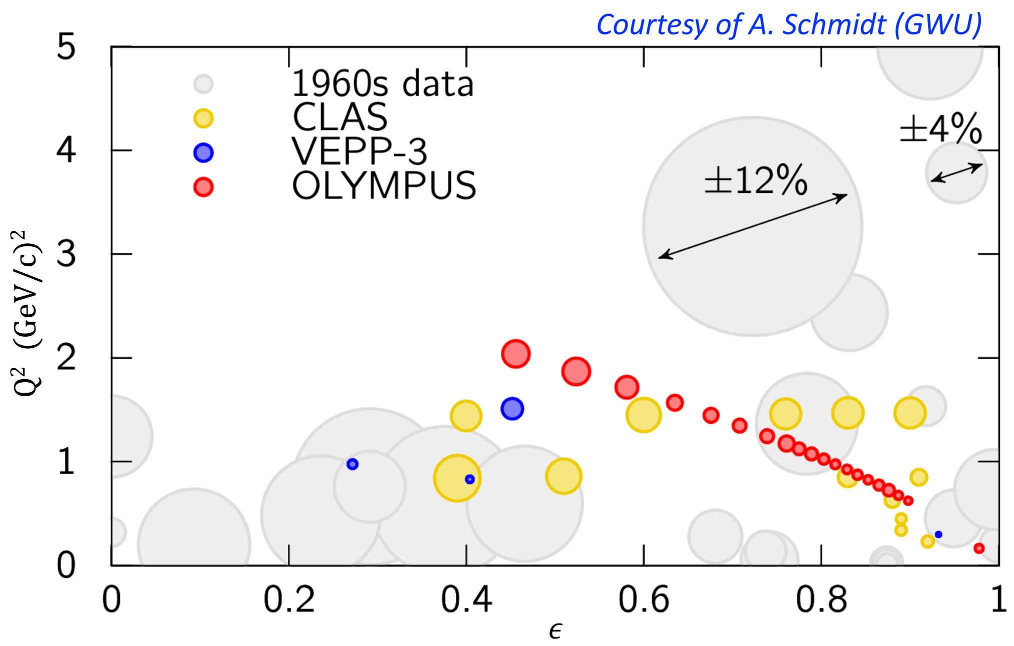
- The measurement of the **polarization transfer of positrons to protons** in the elastic scattering process is mandatory to **establish** its expected **insensitivity to TPE**.

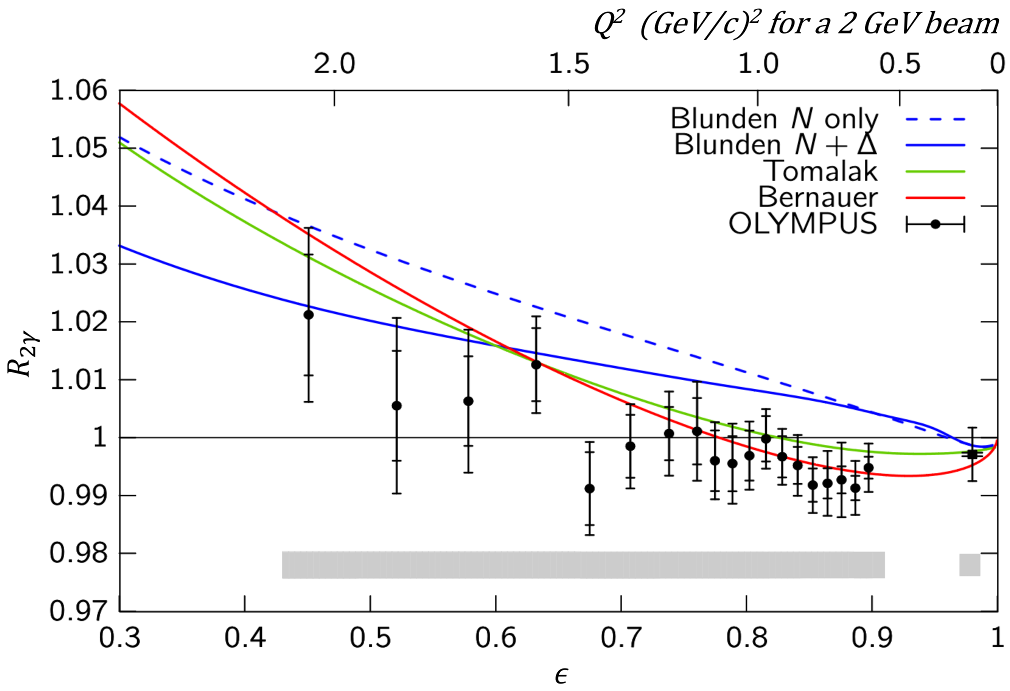
$$\frac{P_t}{P_l} \approx -\sqrt{\frac{2\epsilon}{(1+\epsilon)\tau}}\,\frac{G_E}{G_M}\left(1 \pm \left\{\frac{\Re e\left[\delta\tilde{G}_M\right]}{G_M} + \frac{\Re e\left[f_1\left(\delta\tilde{G}_E, \delta\tilde{F}_3\right)\right]}{G_E} - 2\,\frac{\Re e\left[f_2\left(\delta\tilde{G}_M, \delta\tilde{F}_3\right)\right]}{G_M}\right\}\right)$$

E. Voutier
IJCLab Irène Joliot-Curie

Current Knowledge

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





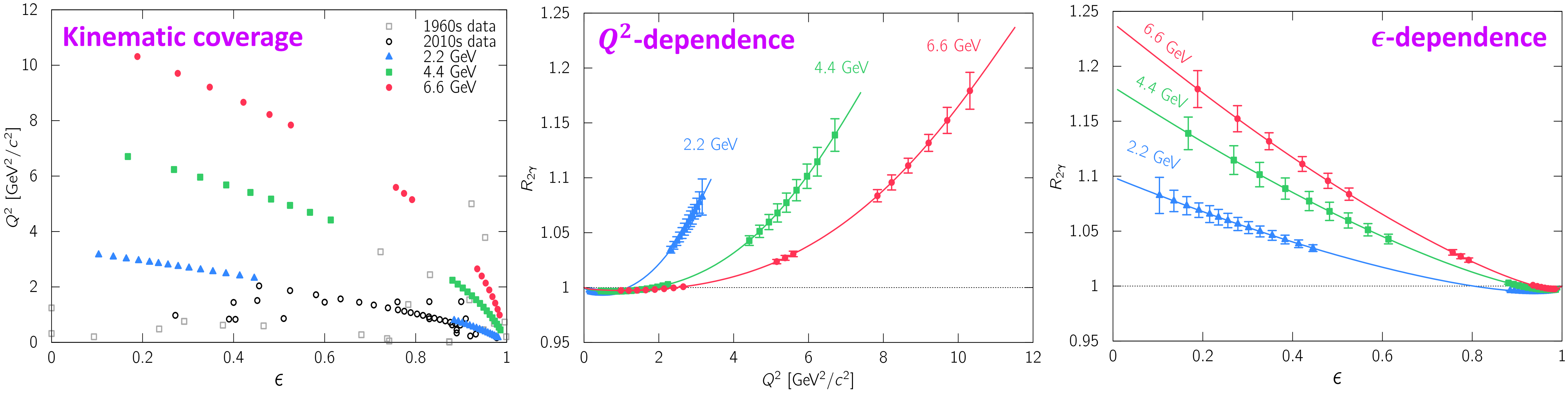
(CLAS Collaboration) D. Adikaram et al. PRL 114 (2015) 062003 I.A. Rachek et al. PRL 114 (2015) 062005 (OLYMPUS Collaboration) B. Henderson et al. PRL 118 (2017) 092501

$\mathcal{PR}$12+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 reflexions** 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

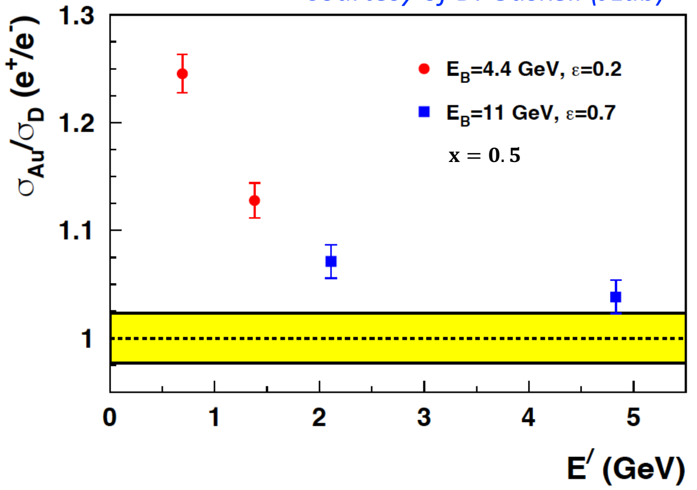
TPE and multi-photon effects in $e^{\pm}N$ interactions

- 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
- ...

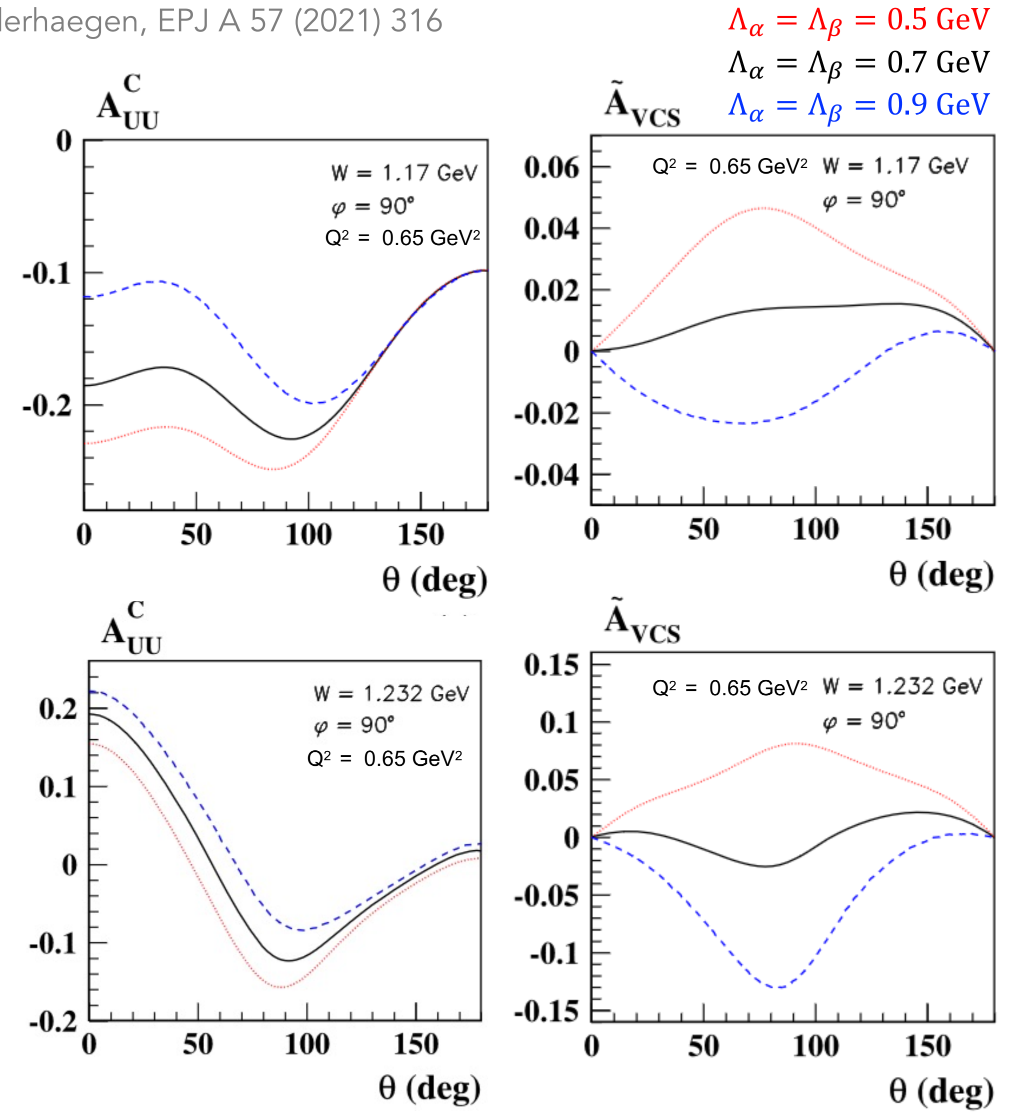
Courtesy of D. Gaskell (JLab)



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

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).

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

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

❖ These new observables show sizeable sensitivity to GPs.

❖ $\tilde{A}_{VCS}$ is particularly sensitive to the electric dipole GP.

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

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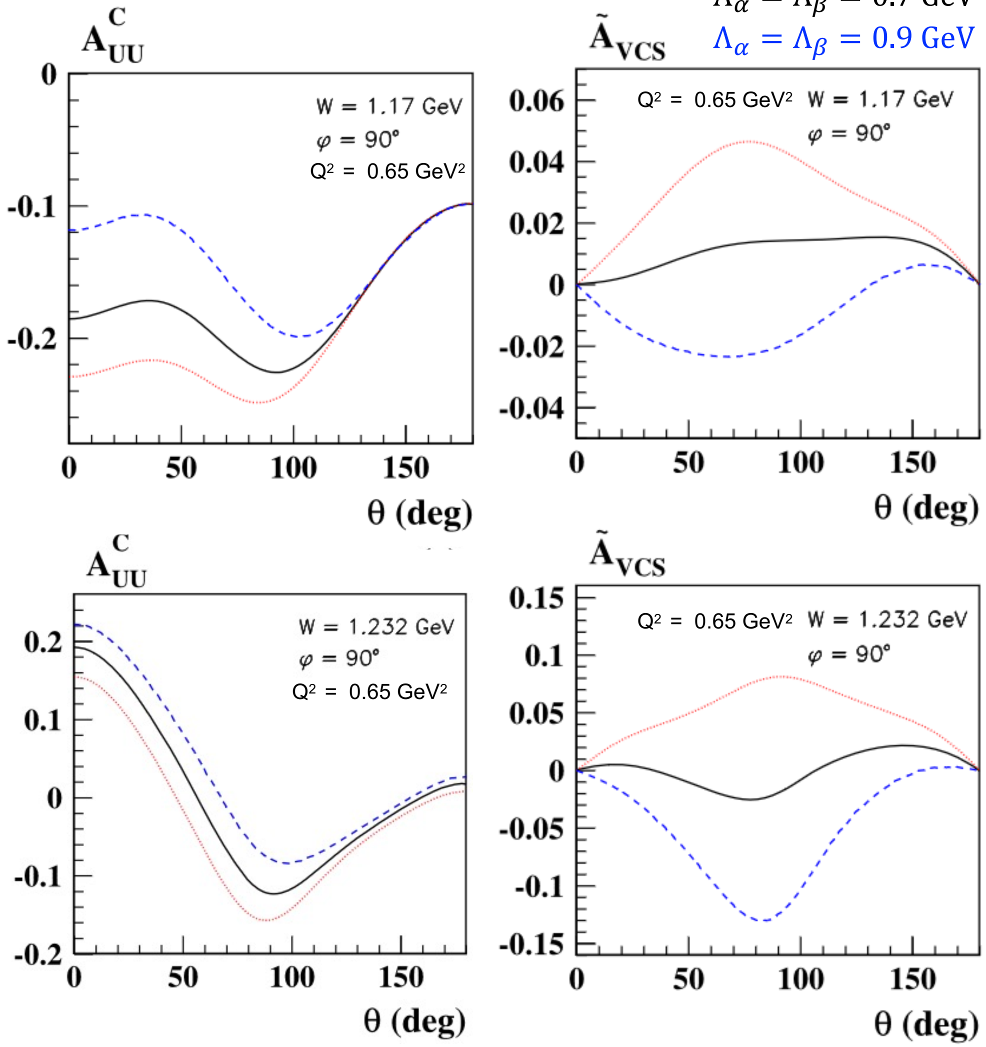


An experimental scenario is under study.

LOI12+23-001 N. Sparveris et al.

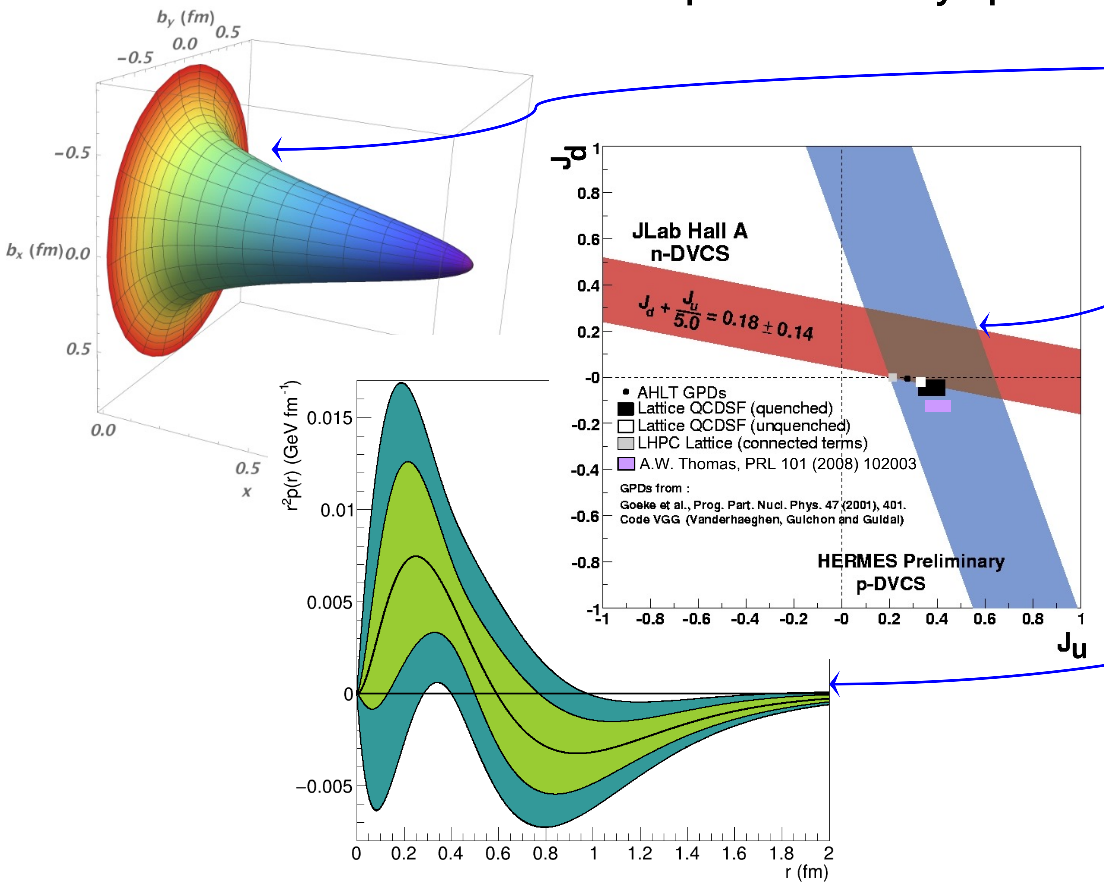
X. Ji, PRL 78 (1997) 610 M. Polyakov, PLB 555 (2003) 57 M.V. Polyakov, P. Schweitzer, IJMP A 33 (2018) 1830025

- Generalized Parton Distributions (**GPDs**) encode the **correlations between partons** and contain information about the **internal dynamics of hadrons** which express in properties like the **angular momentum** or the **distribution of the forces** experienced by quarks and gluons inside hadrons.

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

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

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



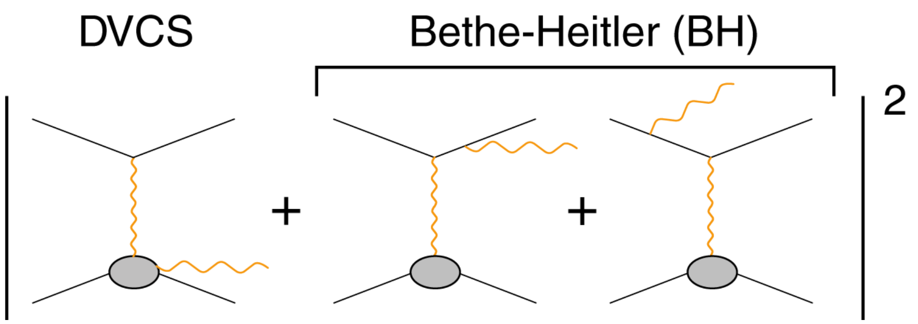
- **Unpolarized e$^+$ combined with unpolarized e$^-$** access the **real part** of the Compton Form Factors.
- **Polarized e$^+$ combined with polarized e$^-$** access the **imaginary part** of the Compton Form Factors (CFFs) and probe **higher twist effects**.

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

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



CFF = Compton Form Factors

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

$d^5\sigma_{DVCS}$: ∝ to the **real part** of a **CFF bilinear combination**

$d^5\tilde{\sigma}_{DVCS}$: ∝ to the **imaginary part** of a **CFF bilinear combination**

$d^5\sigma_{INT}$: ∝ to the **real part** of a **CFF linear combination**

$d^5\tilde{\sigma}_{INT}$: ∝ to the **imaginary part** of a **CFF linear 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.

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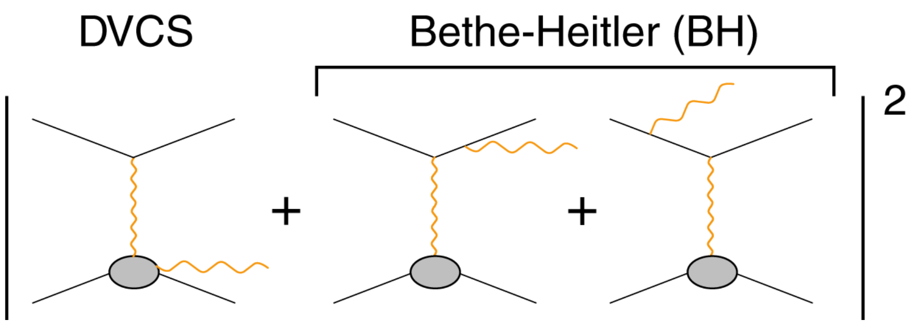

CFF = Compton Form Factors

$\propto$ 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**

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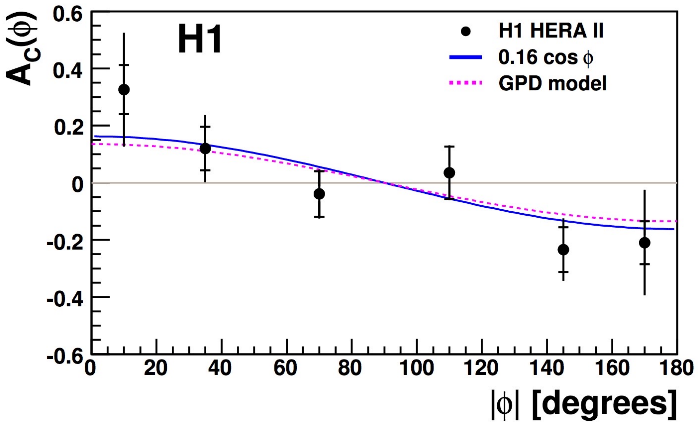
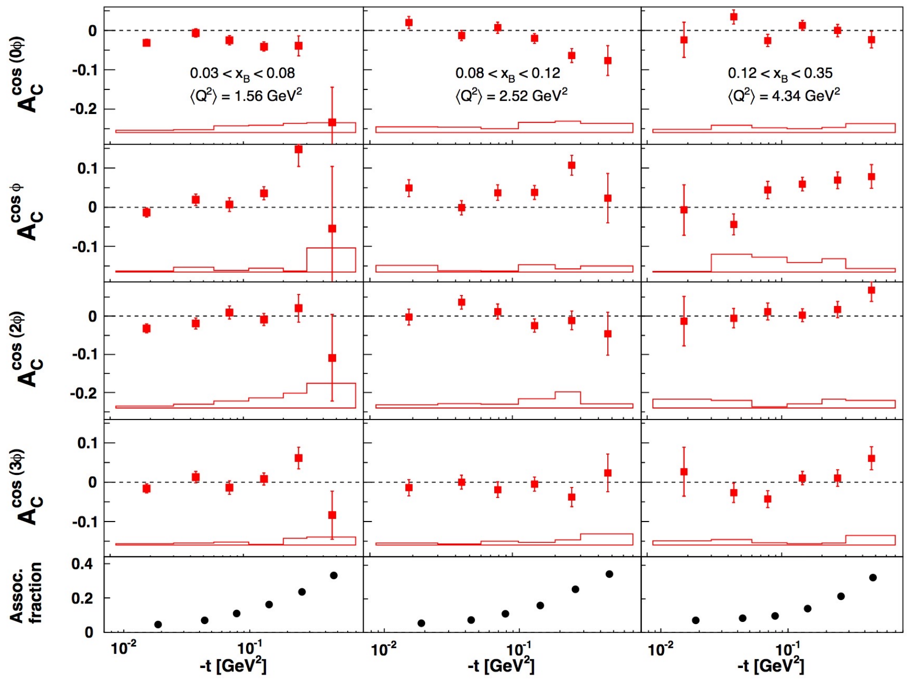
Polarized electrons and positrons allow to separate the unknown amplitudes of the cross section for electro-production of photons.

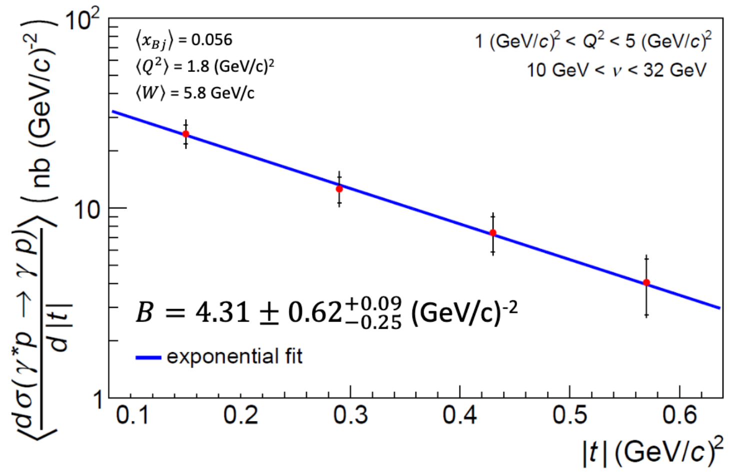
Current Knowledge

- 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

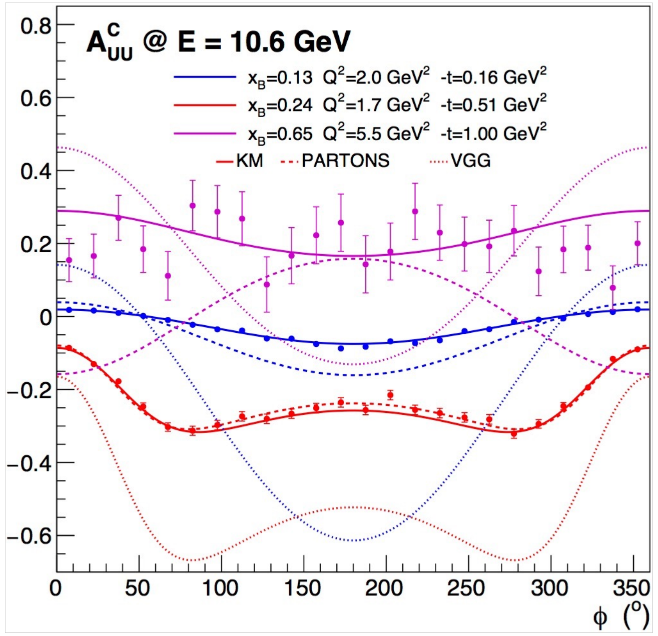
PR12+23-002

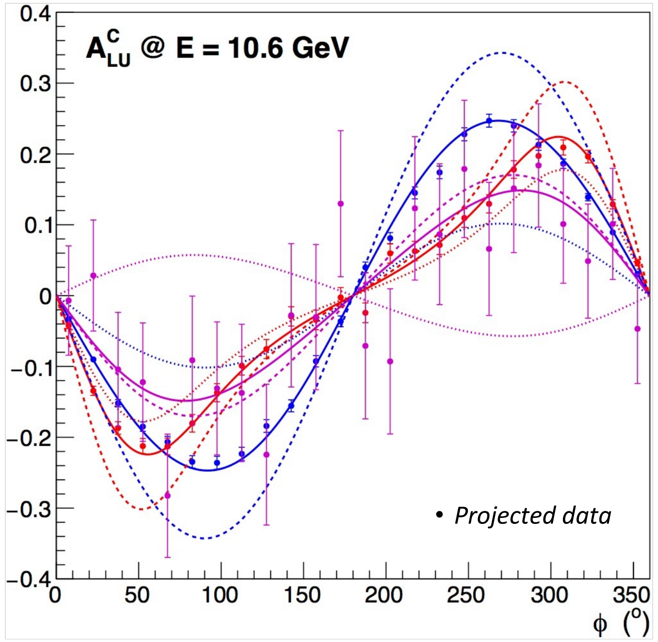
E. Voutier, V. Burkert, S. Niccolai, R. Paremuzyan et al.

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**.

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





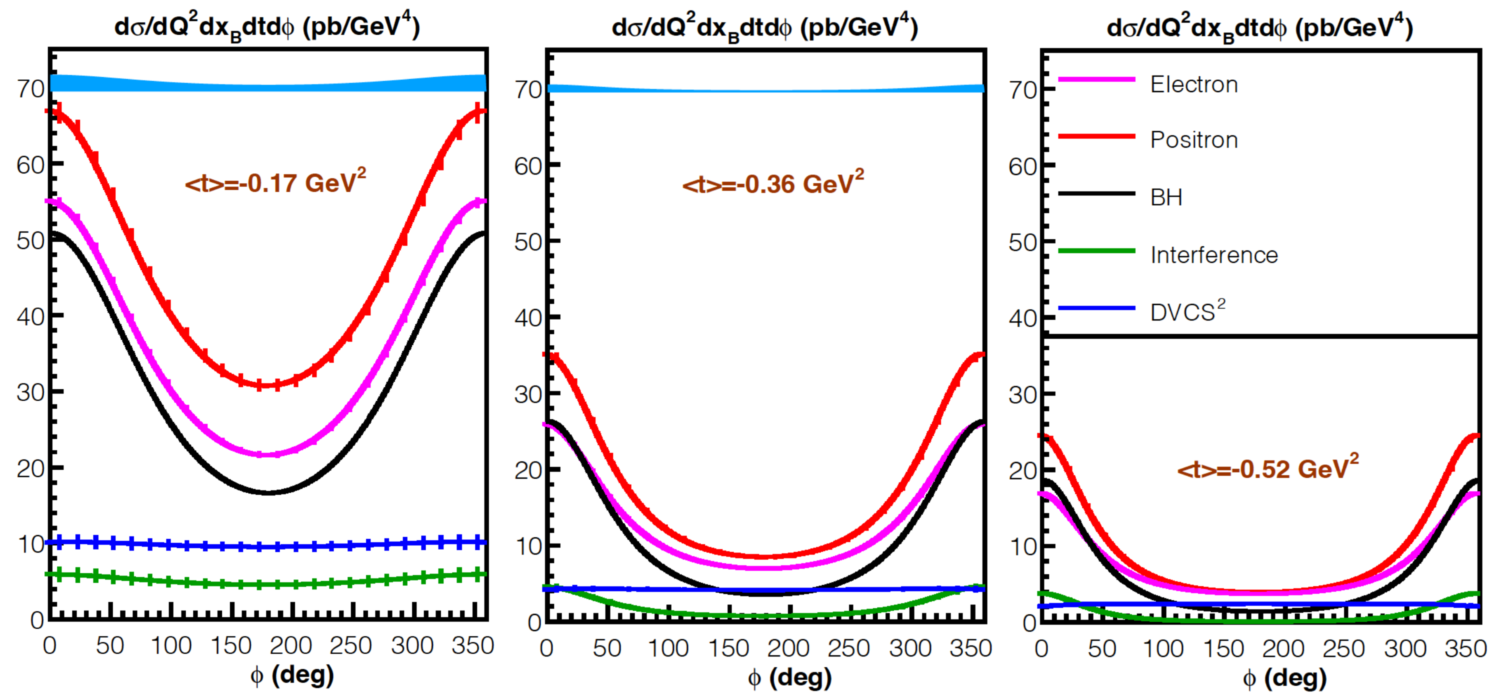
$$A^C_{LU} = \frac{d^5\tilde{\sigma}_{INT}}{d^5\sigma_{BH} + d^5\sigma_{DVCS}}$$

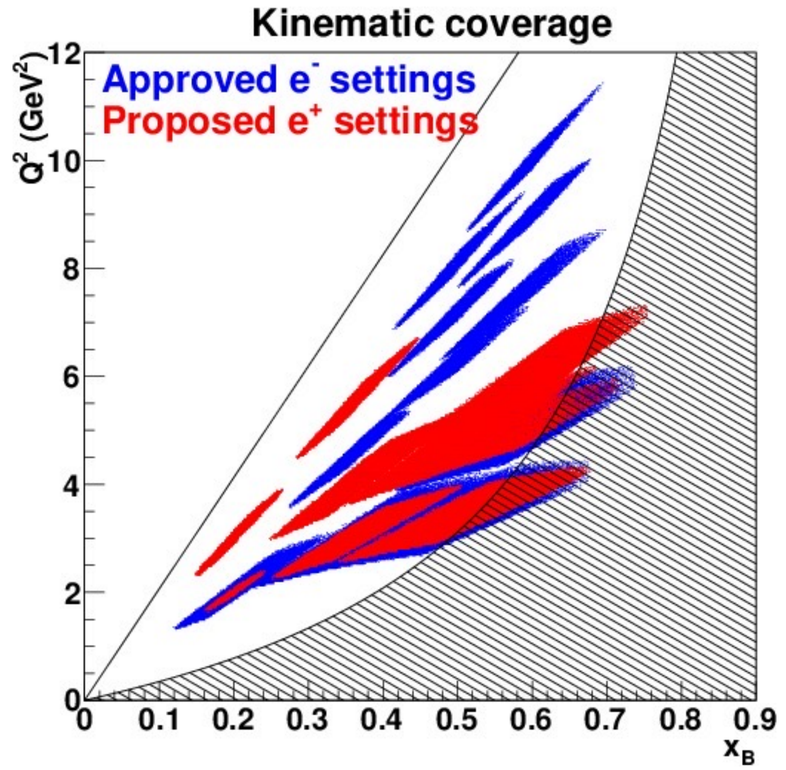
PR12+23-006
C. Muñoz Camacho, M. Mazouz et al.

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.

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

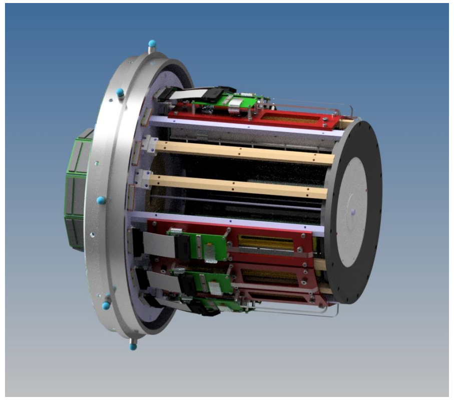




And Beyond...

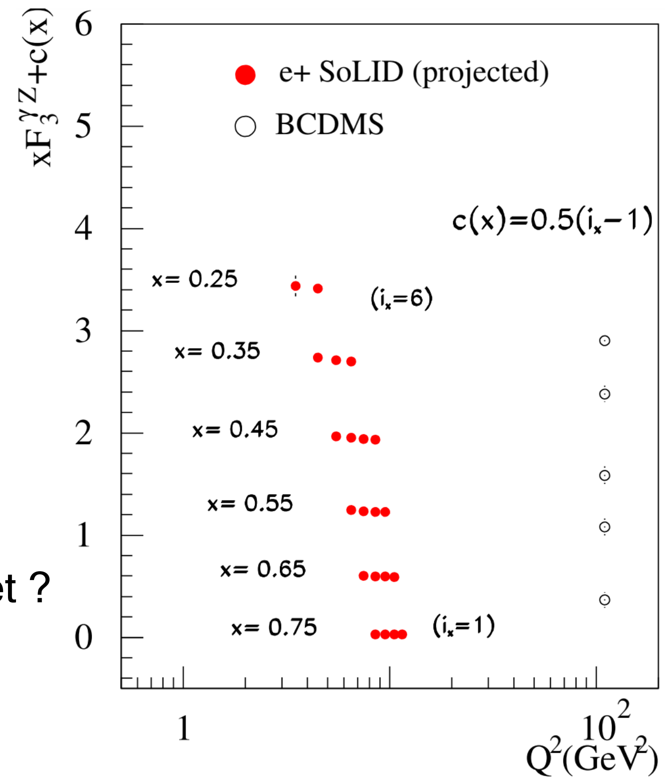
S. Niccolai, P. Chatagnon, M. Hoballah, D. Marchand, C. Muñoz Camacho, E. Voutier, EPJ A 57 (2021) 226
S. Fucini, M. Hattawy, M. Rinaldi, S. Scopetta, EPJ A 57 (2021) 273
S. Zhao et al. EPJ A 57 (2021) 240

ALERT



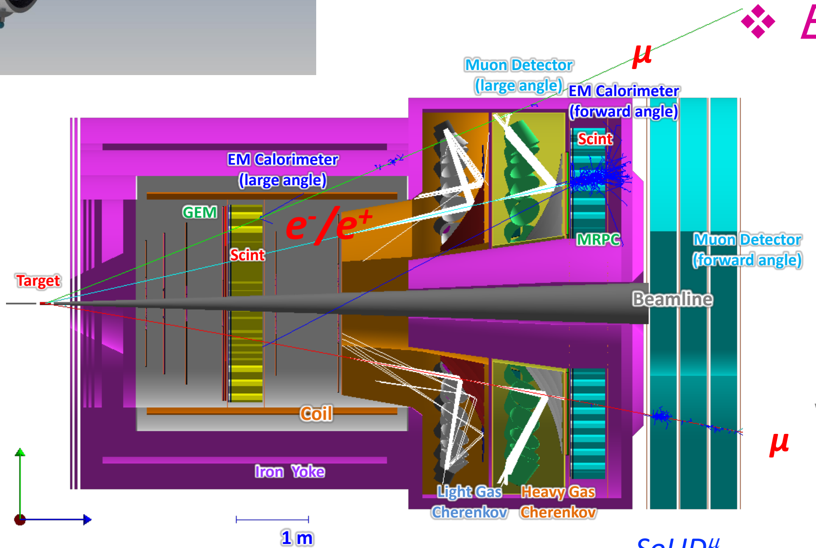
❖ *Generalized parton distributions*

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



❖ *Electroweak physics*

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



SoLID$^{\mu}$

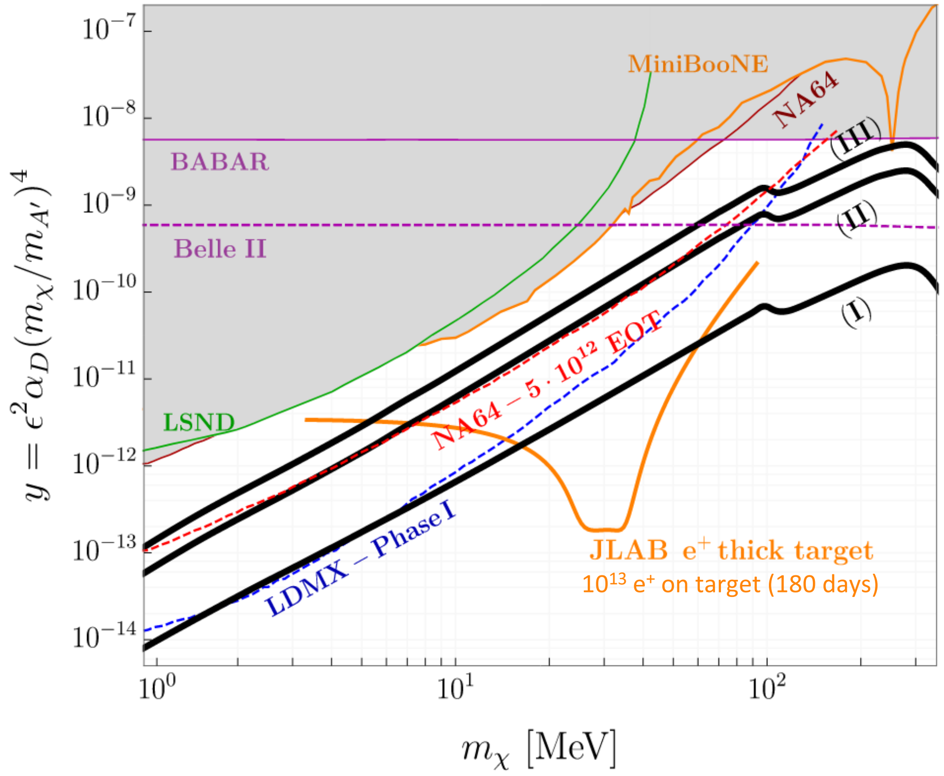
E. Aschenauer, T. Burton, T. Martin, H. Spiesberger, M. Stratman, PRD 88 (2013) 114025
W. Melnitchouk, J.F. Owens EPJ A 57 (2021) 311   X. Zheng et al. Jefferson Lab Proposal PR12-21-006 (2021)
D. Dutta et al. JLab Letter-of-Intent LOI12+23-002

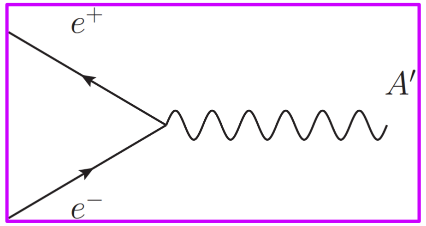
*This **list** is not exhaustive but only **indicative** of the **current reflexions**.*

Direct Dark Matter Production

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

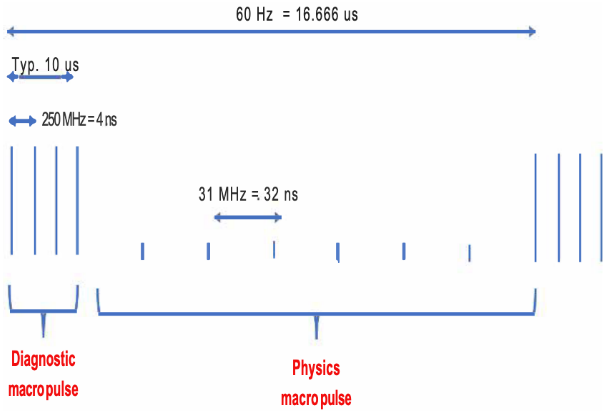
- A direct search of dark matter in the e^+e^- **annihilation** has been evaluted using a beam energy of **11 GeV** and a **180 days** data taking period.
- The measurement of an **energy deposit smaller** than the **e⁺ beam energy** signs the **production** of the *A'*.



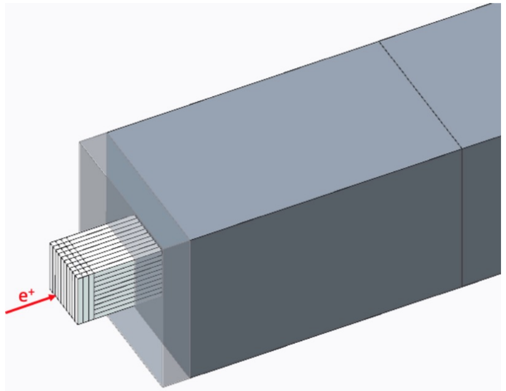


$$E_{miss} = E_{beam} - E_{CAL}$$

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



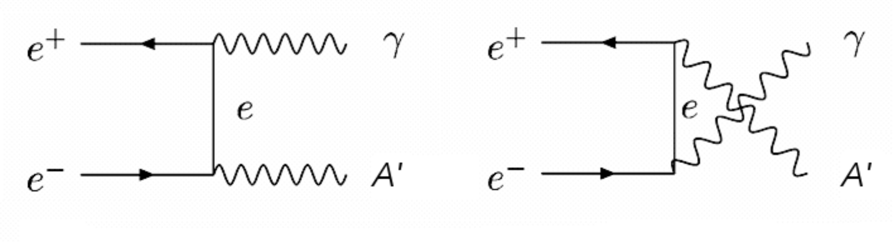
*A **specific time structure** of the beam is required to avoid e⁺ beam pile-up in the detector.*



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

E. Voutier
IJCLab Irène Joliot-Curie

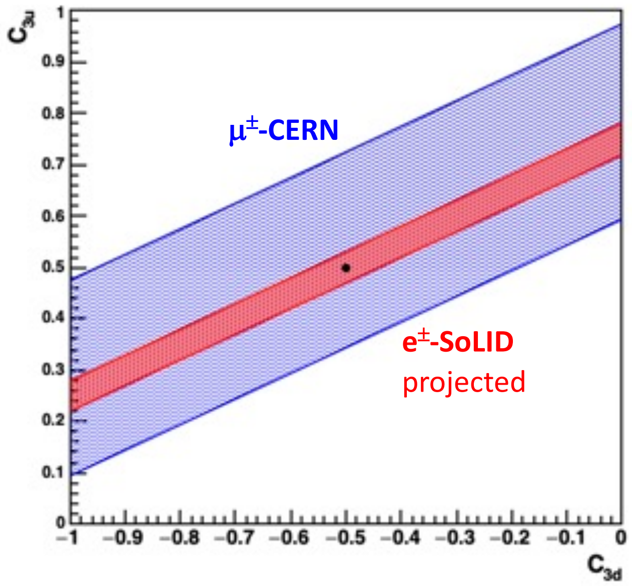
And Beyond...



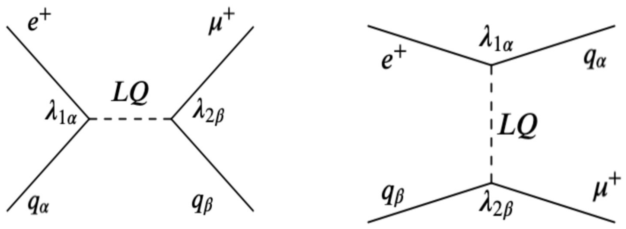
❖ *Testing standard model predictions*

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

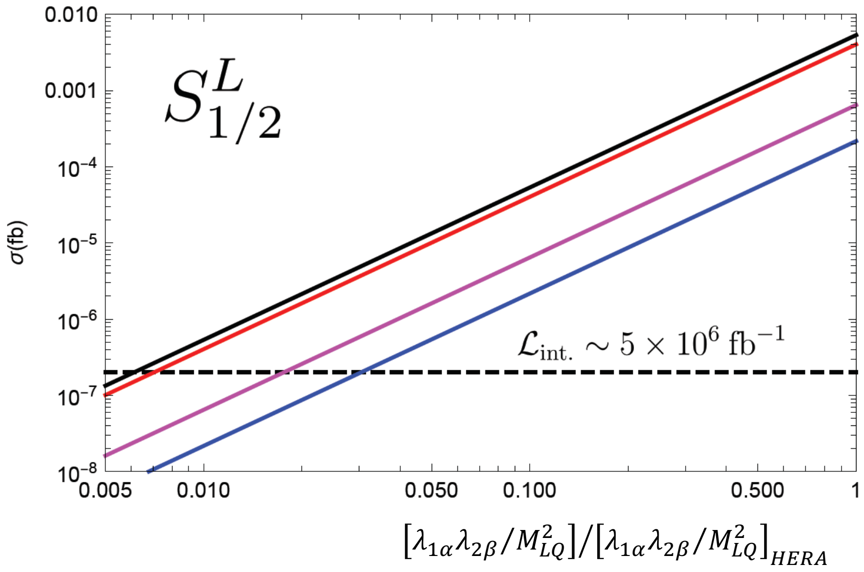
$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$



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



$\mathcal{L} \geq 10^{38}\text{cm}^{-2}\cdot\text{s}^{-1}$



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

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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.

These beams would be a world « première ».

- The efforts and interest of the JLab User Community for positron beams has resulted in the laboratory directing resources to begin R&D investigations. *(Y. Roblin presentation)*

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Ce⁺BAF

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

$I_{e+} > 1$ μA @ $P_{e+} = 0\%$

$T_{e^+} \lesssim 12$ GeV

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These beams would be a world « première ».

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- It is now time to submit the **experimental program** to the **evaluation** of the **JLab PAC**.

Consider submitting proposals not only for **high energy** experiments at **Ce$^+$BAF**, but also for **lower beam energies** to be available at **LERF** at an early stage of the project.

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

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