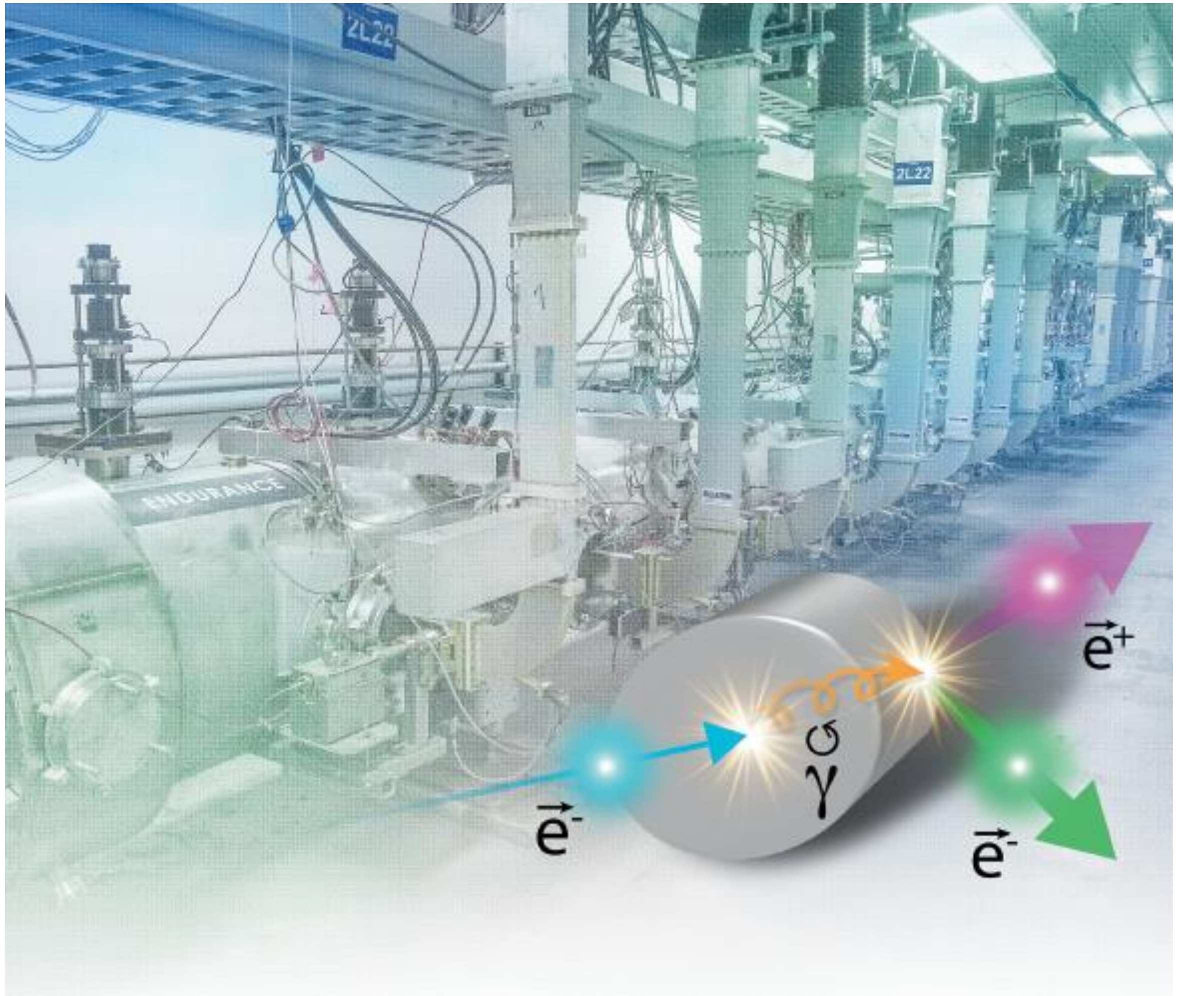
3D Structure of Hadrons probed with electrons and positrons



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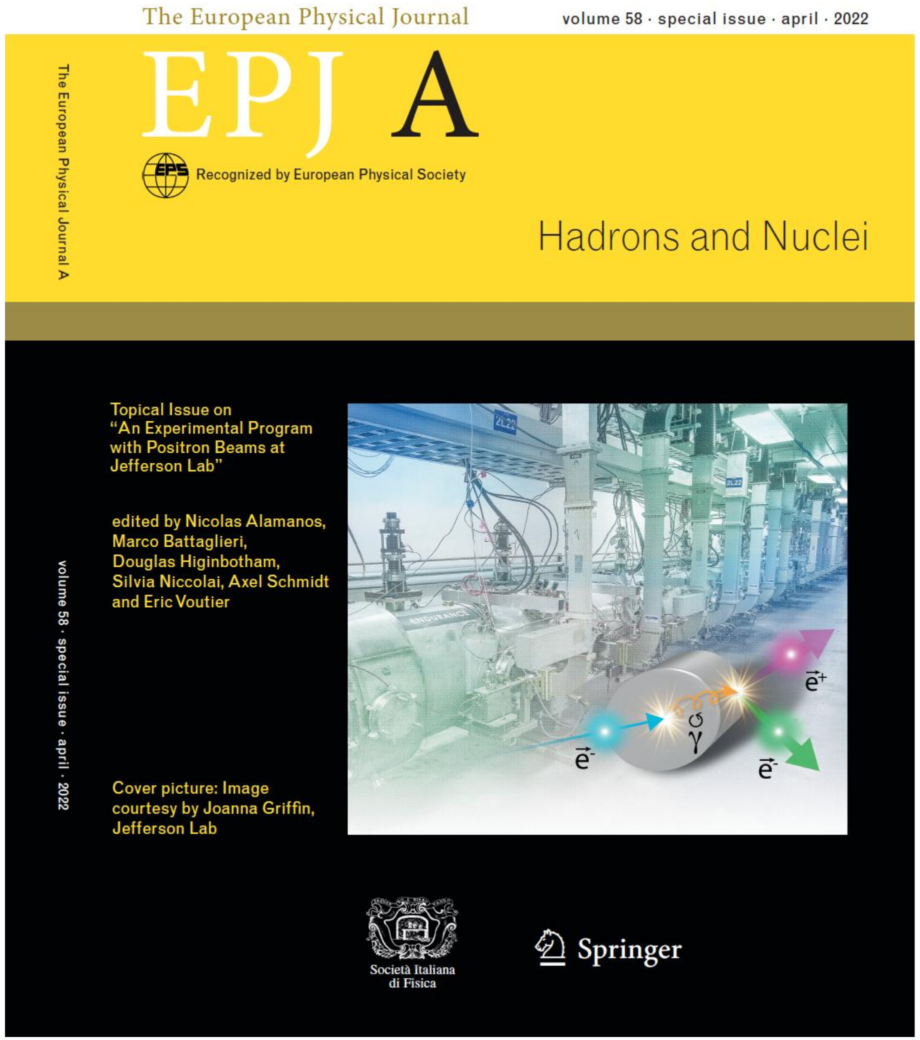
Outline

- ➢ Positron experimental program at Jefferson Lab
- ➢ Motivation of the 3D imaging of hadrons using a positron beam
- ➢ Developments towards the implementation of a positron beam at Jefferson Lab

Positron White Paper



- ❖ An EPJ A Topical Issue about an experimental positron program at CEBAF has been published.
- ❖ This document constitutes the final **JLab Positron White Paper**, gathering 19 single contributions and a summary article, all peer-reviewed.

Positron science program to date

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)	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 r_d	B	PRad-II	H_2 D_2	$+$	0.7/1.4/2.1 1.1/2.2	0	0.070 0.010	40 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 ECAL/HCAL	C $PbWO_4$	$+$	11.0	0	0.100	180 120	
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

- Experimental scenarios for DIS, VCS ($\gamma^* p \to \gamma p$), and CLFV ($e^+ N \to \mu^+ X$) need further evaluation.
- Opportunities for polarized target experiments would deserve more considerations.
- 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.

	Hall A	Hall B	Hall C
Unpolarized (d)	311	432	77
Polarized (d)	121	180	
Total (d)	**432**	**612**	**77**

Assuming 36 weeks/year of beam and 50% accelerator efficiency, this is 4.8 years of running.

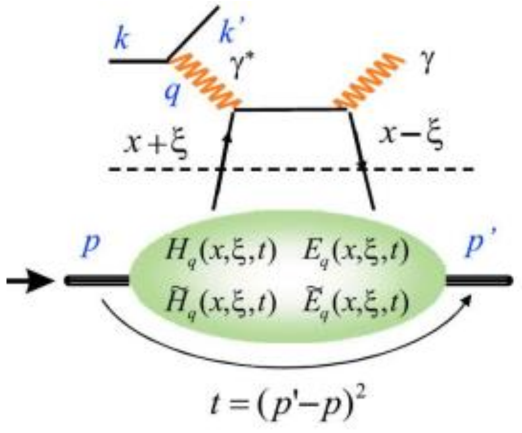
Proposals evaluated by JLab PAC (2020)

Two positron proposals on 3D imaging of hadrons were evaluated by the JLab Program Advisory Committee (PAC) in 2020

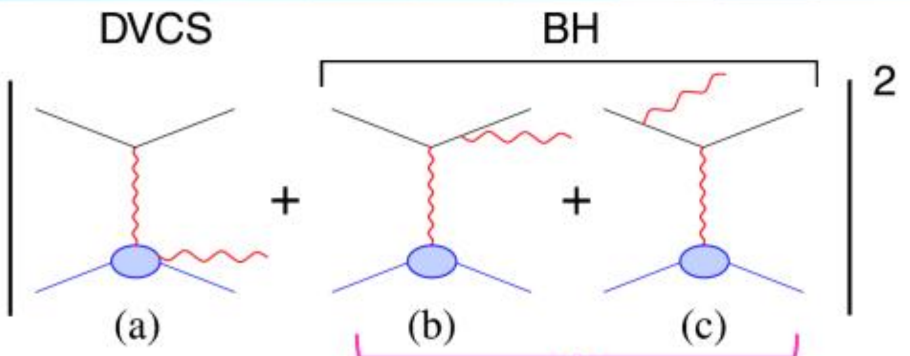
PAC48 report: "The Committee sees great physics potential in a positron program. We encourage a vigorous effort to explore the technical feasibility of providing positron beams, and we are looking forward to receiving further proposals in this area."

Additional talk by A. Schmidt tomorrow @ 11AM on Two-Photon-Exchange and BSM physics with positrons

Physics motivation



ep ⟶ epγ =



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

At leading twist:

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

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

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

Opposite sign for e- & e+

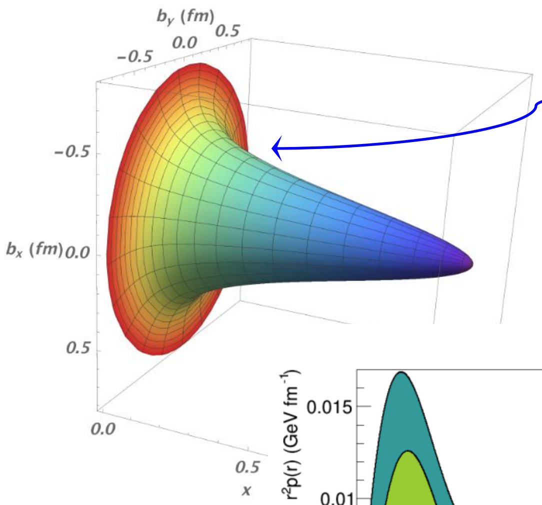
$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} \quad - \quad i\pi\, H(x=\xi,\xi,t) \quad + \ldots$$

Nucleon tomography with positrons

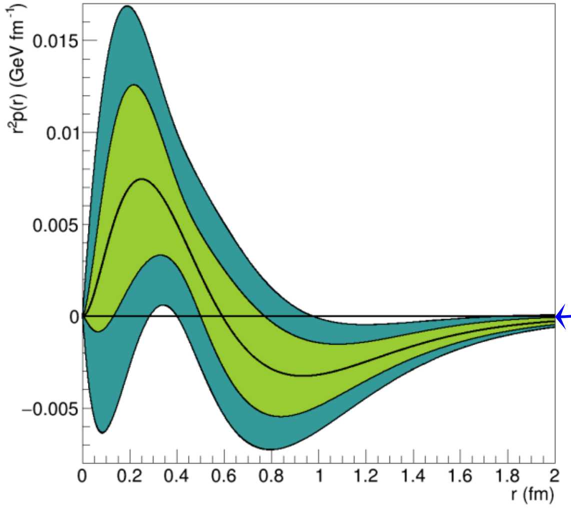
X. Ji, PRL 78 (1997) 610 M. Polyakov, PLB 555 (2003) 57 M.V. Polyakov, P. Schweitzer, IJMP A 33 (2018) 1830025

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.



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

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

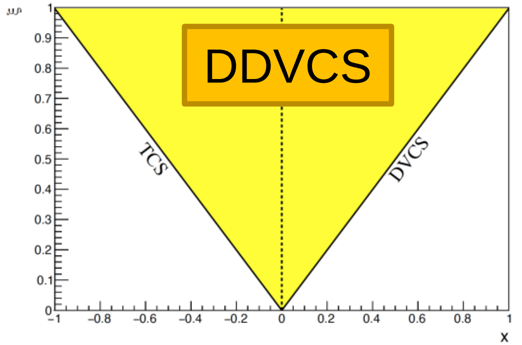


- **Unpolarized e$^+$ combined with unpolarized e$^-$** access the **real part** of the Compton Form Factors.
- **Polarized e$^+$ combined with polarized e$^-$** access the **imaginary part** of the Compton Form Factors (CFFs) and **higher twist effects**.

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

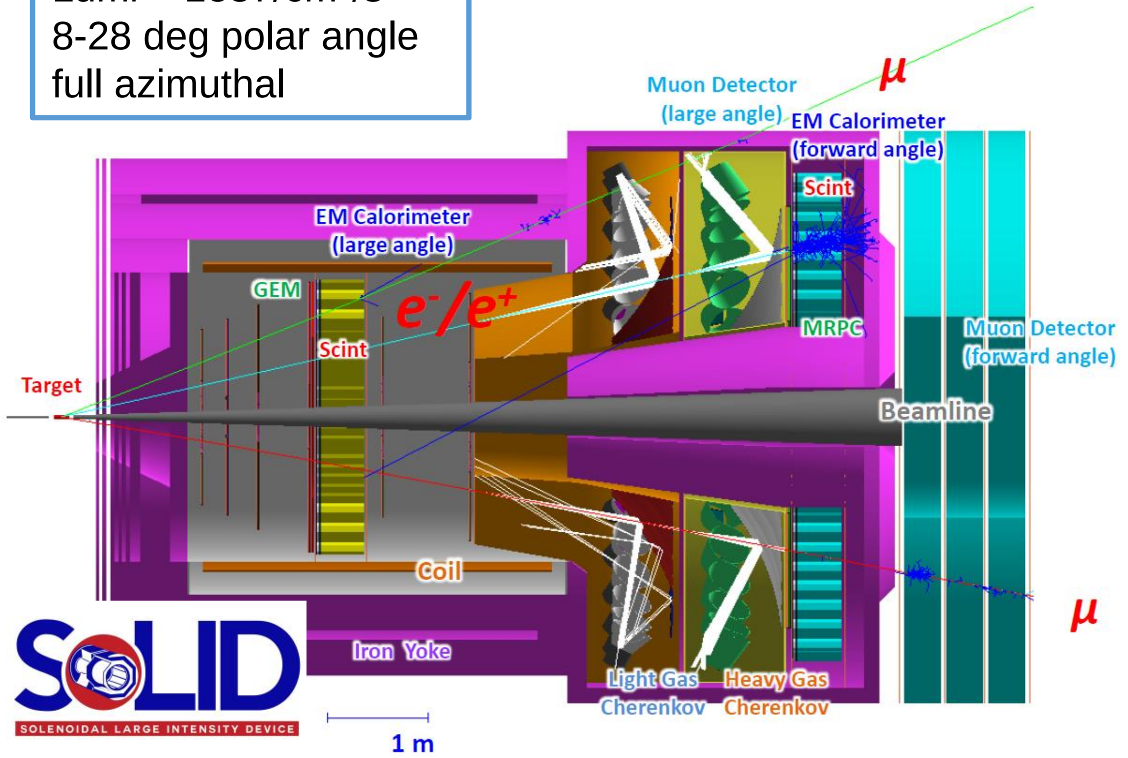
Double DVCS with e+ in Hall A & SOLID

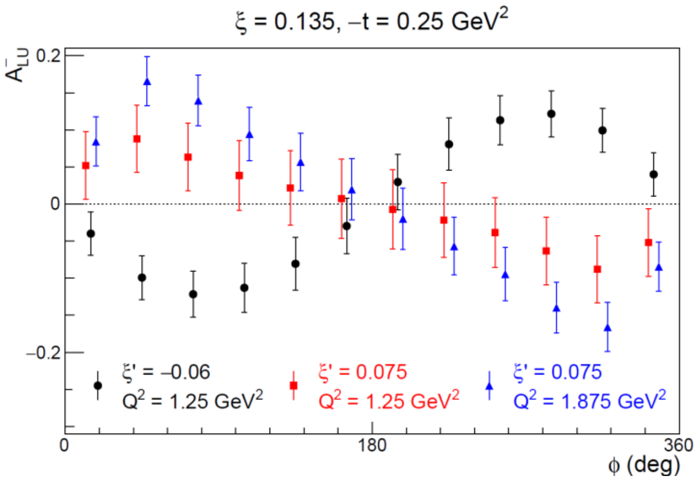
DDVCS explores wide off-axis kinematic region of GPDs, beyond **DVCS and TCS. The exclusive reaction has small crosssection and thus needs** **high luminosity and large acceptance.**



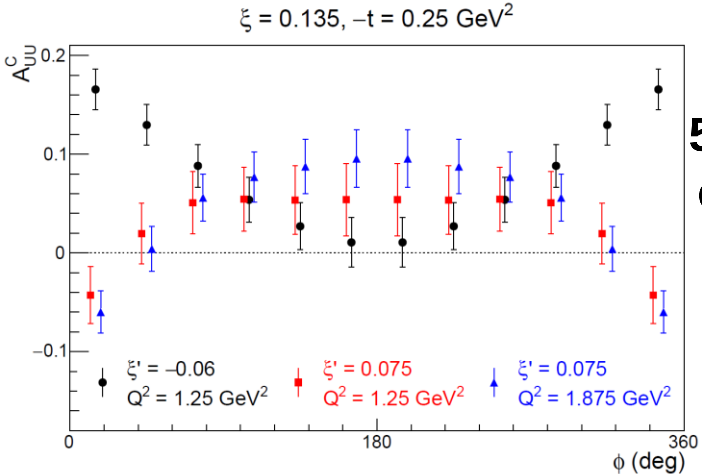
The SoLID apparatus completed with muon detectors at large and forward angles, enables DDVCS measurements with both polarized electron and positron beams at 11GeV.

Lumi = 1e37/cm^2/s
8-28 deg polar angle
full azimuthal

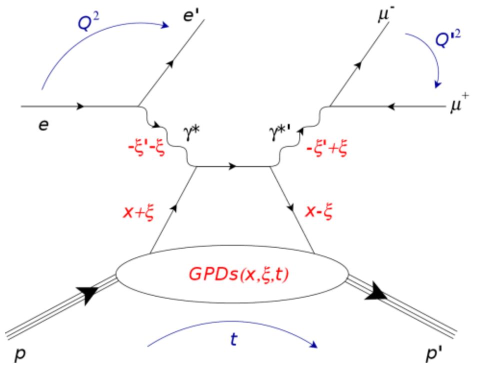


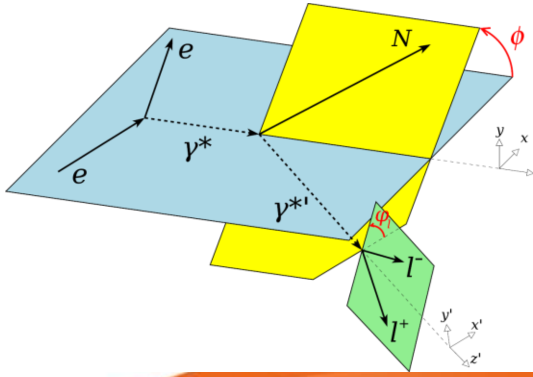


50 days e- BSA



50 days e+ BCA

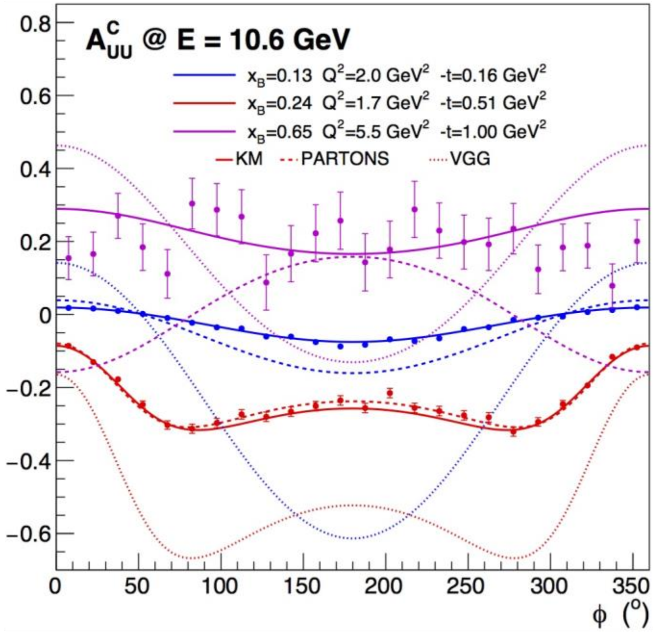




Measurements of beam charge asymmetries with CLAS12 will provide a full set of new GPD observables:

- 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 neutral beam spin asymmetry A^0_{LU}, signature of **higher twist effects**.

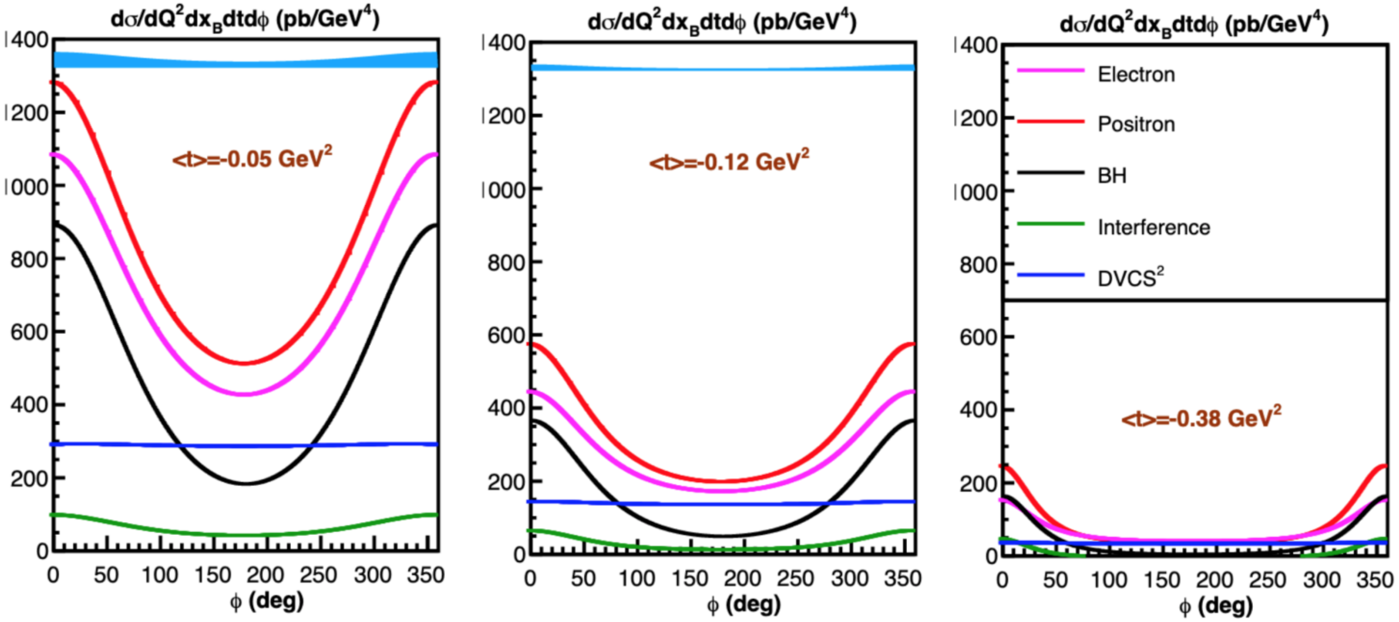
$$A^C_{UU} = \frac{d^5\sigma_{INT}}{d^5\sigma_{BH} + d^5\sigma_{DVCS}}$$

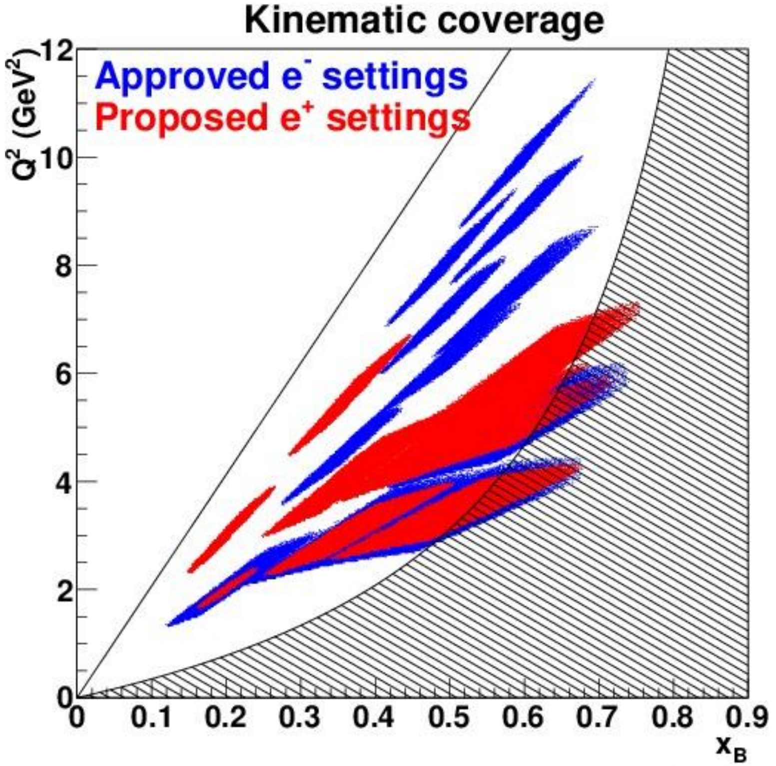


100 days of e+ beam

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

$x_B = 0.5 \quad Q^2 = 3.4\ GeV^2$





77 days of e+ beam

Proton Generalized Polarizabilities

Fundamental structure constants of the proton

They characterize the response of the proton to an external electric & magnetic field

Ongoing VCS program at JLab

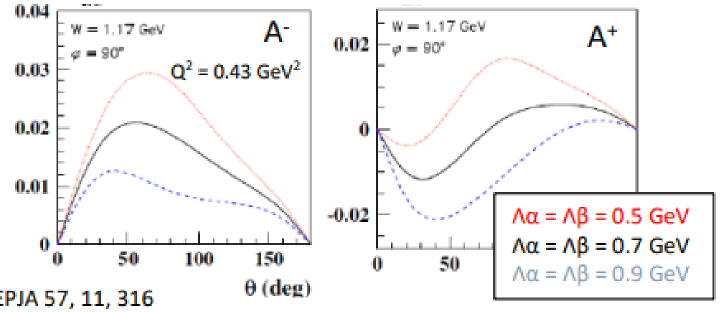
Extend the measurements of the electric & magnetic GPs at JLab utilizing the **existing experimental infrastructure** to improve the precision for the electric & magnetic GPs

Identify the shape of the structure in the electric GP, that is a valuable input for the theory in order to explain the underlying mechanism responsible for the effect.

Future: VCS with a positron beam

Future prospects with a positron beam at JLab:

Extend measurements & cross-check GPs via a different method

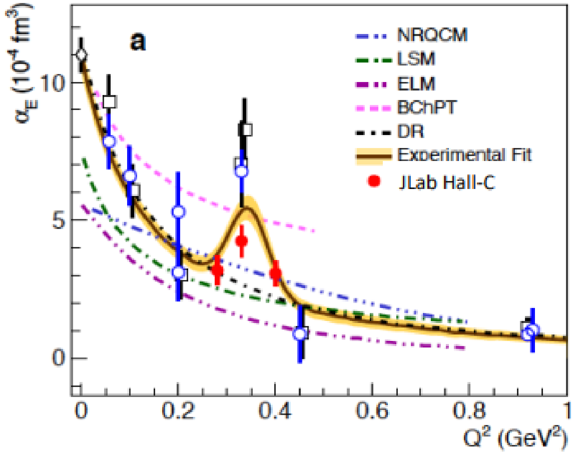


EPJA 57, 11, 316

The electron and positron beam-spin asymmetry as a function of the photon scattering angle

The proton electric generalized polarizability

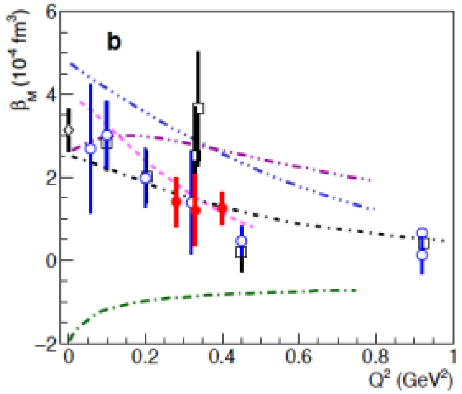
Electric "strechability" of the proton



Deviation from monotonic dependence – the theory can't explain it

Nature (in press)

The proton magnetic generalized polarizability



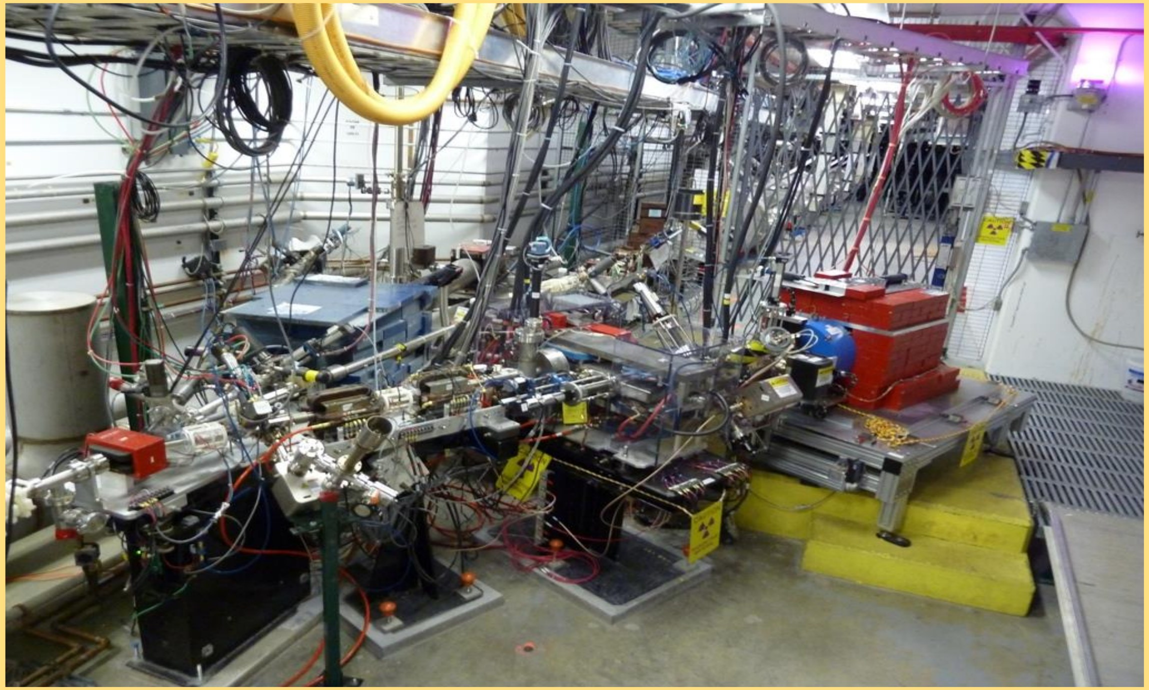
Decode the **competing paramagnetic and diamagnetic mechanisms** in the proton

Challenges for theory – Strong motivation for Lattice QCD calculations

Developments towards an e+ beam at JLab

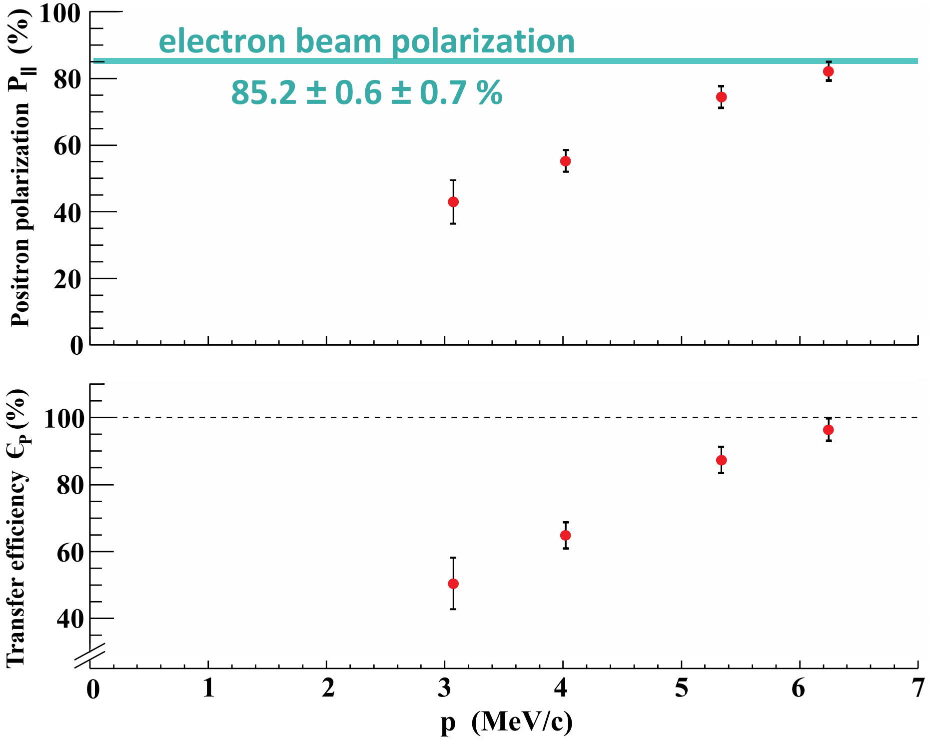
The JLab positron source built on the **PEPPo** (Polarized Electrons for Polarized Positrons) experiment which demonstrated the feasibility of using bremsstrahlung radiation of **MeV Polarized Electrons** for producing **Polarized Positrons**.

p_e = 8.2 MeV/c P_e = 85% I_e = 1 μA t_W = 1 mm $\mathcal{P}$ < 10 W



JLab Experiment E12-11-105 (2011)

(PEPPo Collaboration) D. Abbott *et al.* PRL 116 (2016) 214801

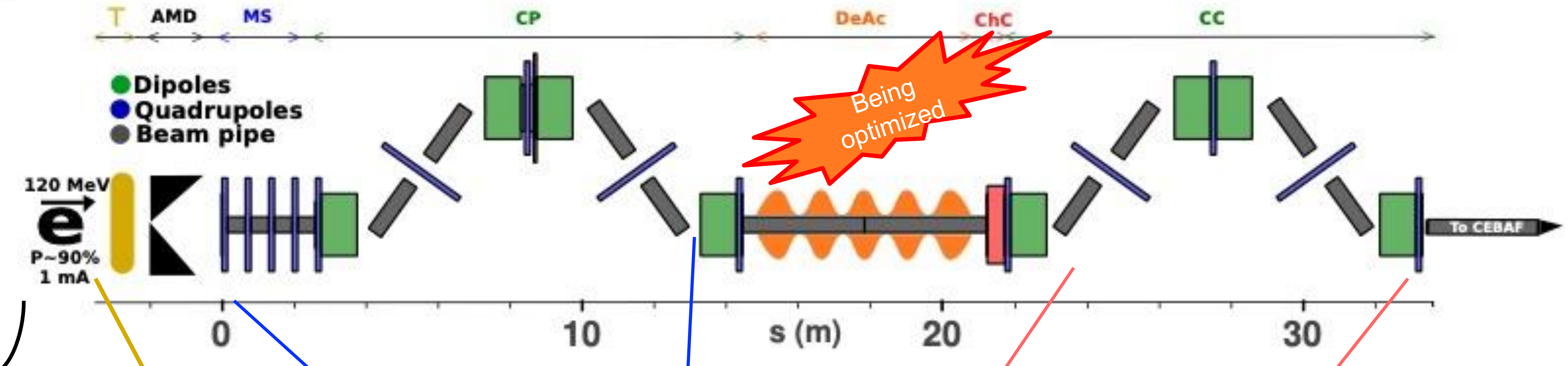


JLab LDRD FY21: Positron source development

JLab LDRD FY23: Transport of a degraded e- beam through CEBAF

Positron source

The design of the JLab positron source has evolved towards the today's latest concept :



$\mathcal{P}$ = 120 kW
beam power

Positron Production Target

Momentum Selection Chicane

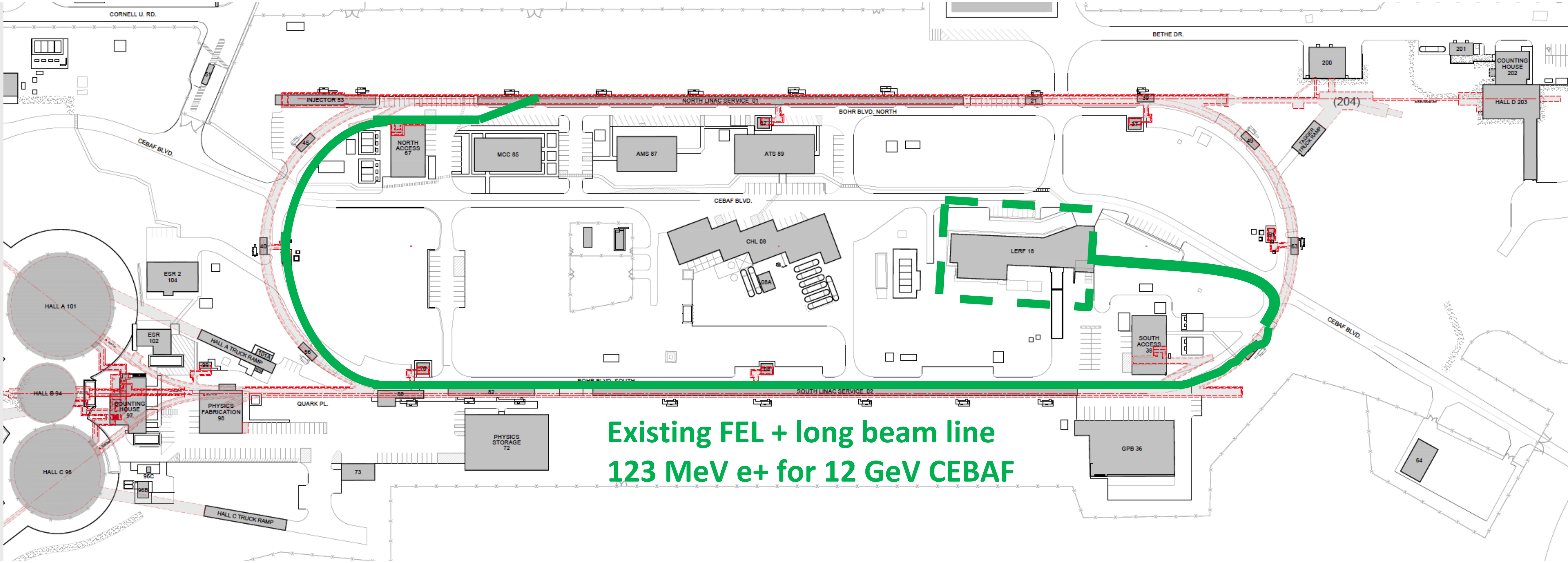
Beam Compression Chicane

Nominal
$I_{e+} > 100$ nA @ $P_{e+} = 60\%$
$I_{e+} > 3$ μA @ $P_{e+} = 0\%$

Very challenging
$I_{e+} = 1$ μA @ $P_{e+} = 60\%$
$I_{e+} = 10$ μA @ $P_{e+} = 0\%$

***High duty cycle**, **intensity**, and **polarization** distinguish JLab positron beam from any past or existing others.*

Possible e+ beam implementation at JLab



Summary

- Beam charge dependance critical to complete the 3D imaging of nucleon and nuclei (real part of Compton Form Factors: D-term, energy-momentum tensor…)
- Studies of two-photon exchange and BSM physics
- Unique capability in the world
- Stepping stone for a potential upgrade at EIC
- Multi-Hall, high intensity beam will enable a 5+ years program with JLab12

Initiative: We recommend the allocation of necessary resources to implement high duty-cycle polarized positron beams at CEBAF.

Using the 12 GeV CEBAF and capitalizing on positron source innovations at Jefferson Lab, high duty cycle polarized electron and positron beams, together with the outstanding capabilities of Jefferson Lab detectors, will enable a unique science program at the luminosity and precision frontier. It will comprise the mapping of two-photon exchange effects as well as essential measurements of the 3D structure of hadrons. It will also offer new opportunities to investigate electroweak physics and physics beyond the standard model.