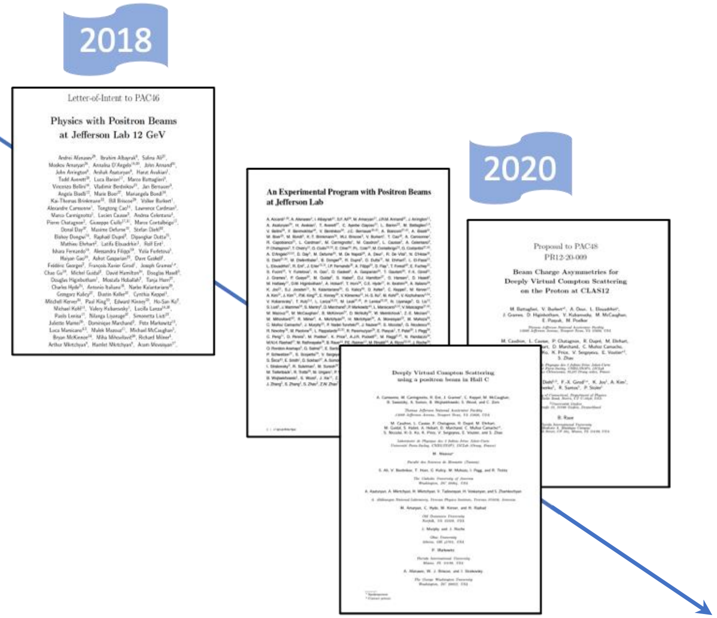
The Jefferson Lab Positron Experimental Program

e^+@JLab

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

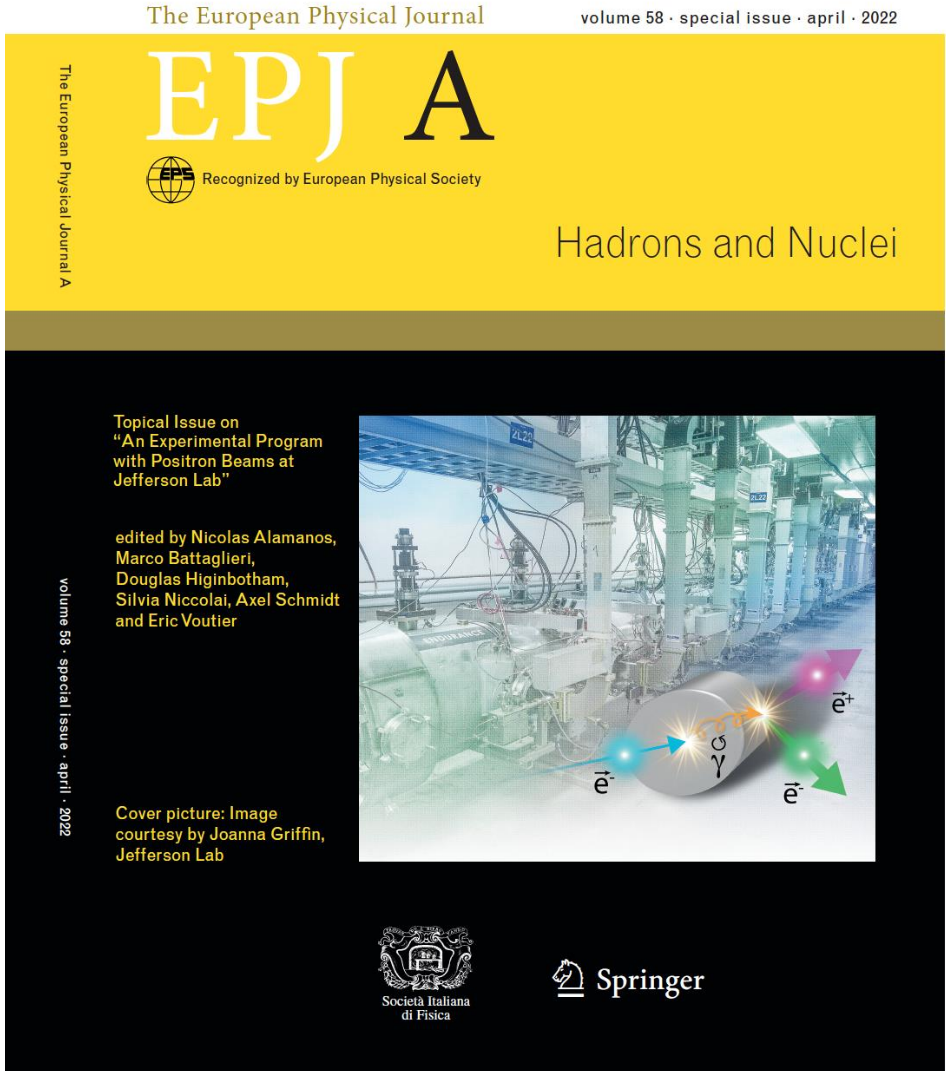
Université Paris-Saclay, CNRS/IN2P3/IJCLab, Orsay, France



- (i) Positron White Paper
- (ii) Two photon exchange
- (iii) Virtual Compton scattering
- (iv) Nucleon tomography
- (v) Towards e^+ beams @ CEBAF
- (vi) Positron injector concept

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

Positron White Paper



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

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

E. Voutier
IJCLab Irène Joliot-Curie

Positron Partial Program Summary

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	^4He	$+/-_s$	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	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
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(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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	Hall A	Hall B	Hall C	Hall D
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.

Operating Hall D with a positron beam is not an issue and may also take advantage of the additional photon source from e^+ annihilation.

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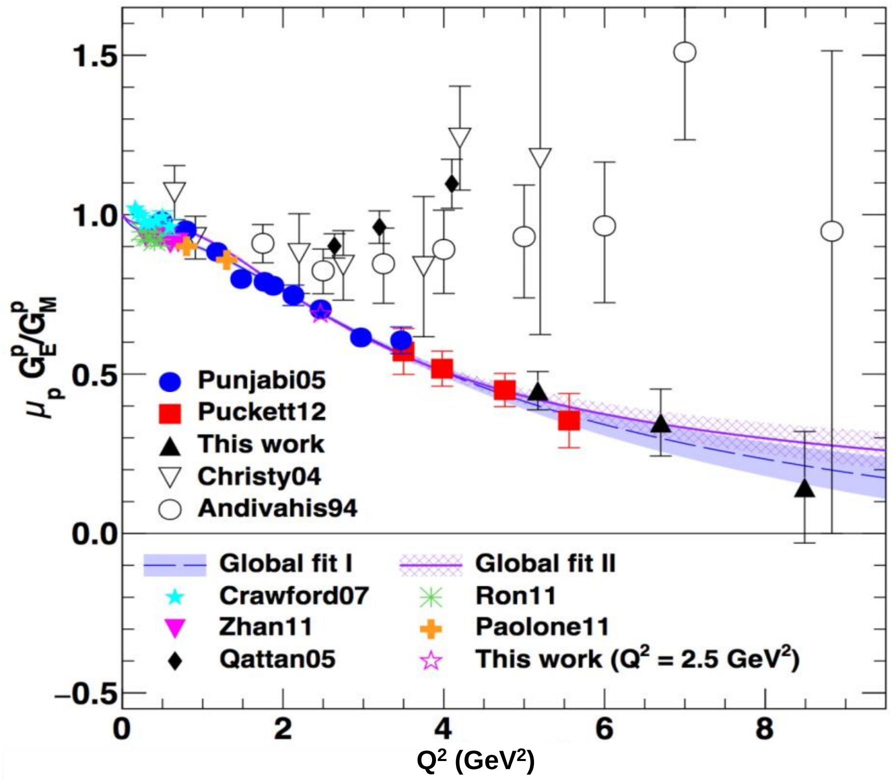
***6 Proposals** and **3 Letters-of-Intent** are expected for PAC51…*

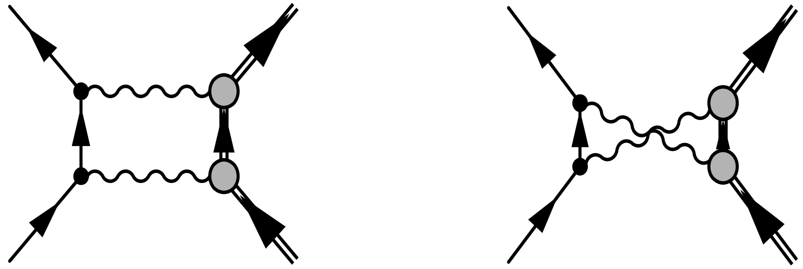
Two photon exchange

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.*

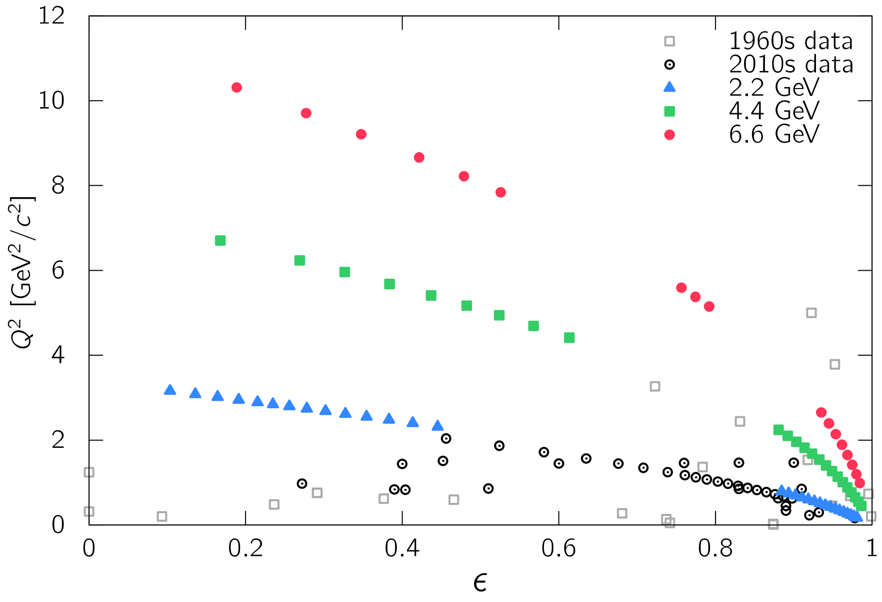
Two photon exchange

TPE @ CLAS12

J.C. Bernauer, V. Burkert, A. Schmidt et al.

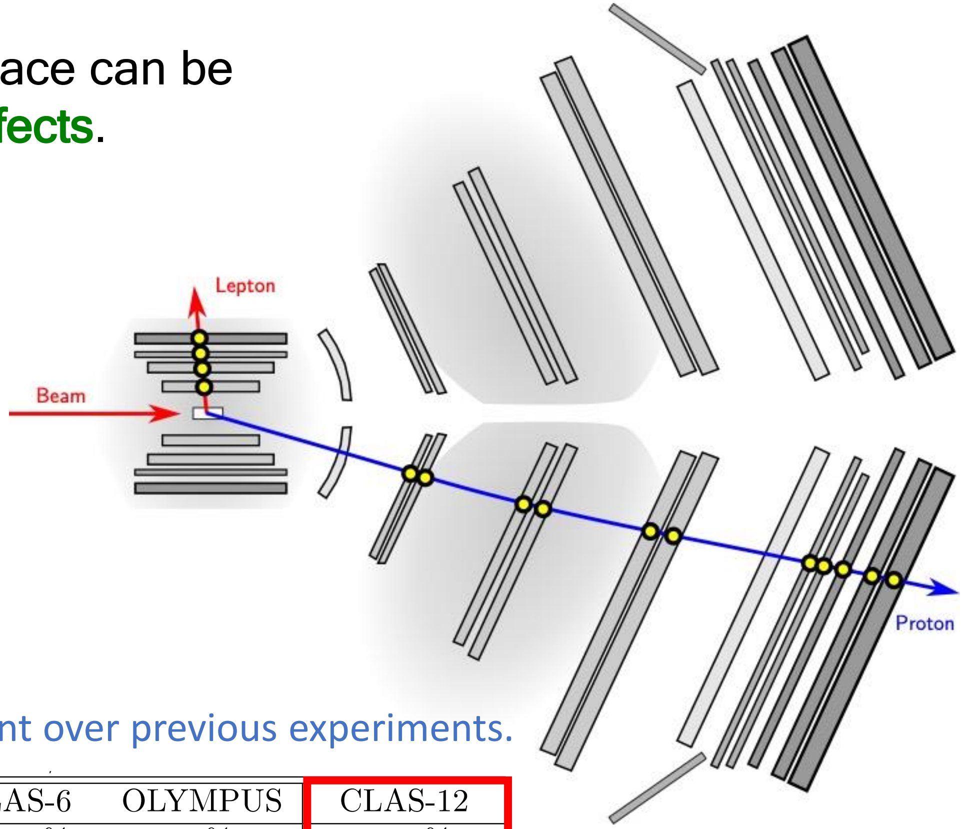
J.C. Bernauer, V. Burkert, E. Cline, A. Schmidt, Y. Sharabian, EPJ A 57 (2021) 144

- Using the CLAS12 spectrometer, an unprecedented (Q^2,ε) phase space can be covered, providing a **conclusive answer about** the relevance of **2γ-effects**.



Previous measurements lacked the kinematic reach to draw meaningful conclusions.

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



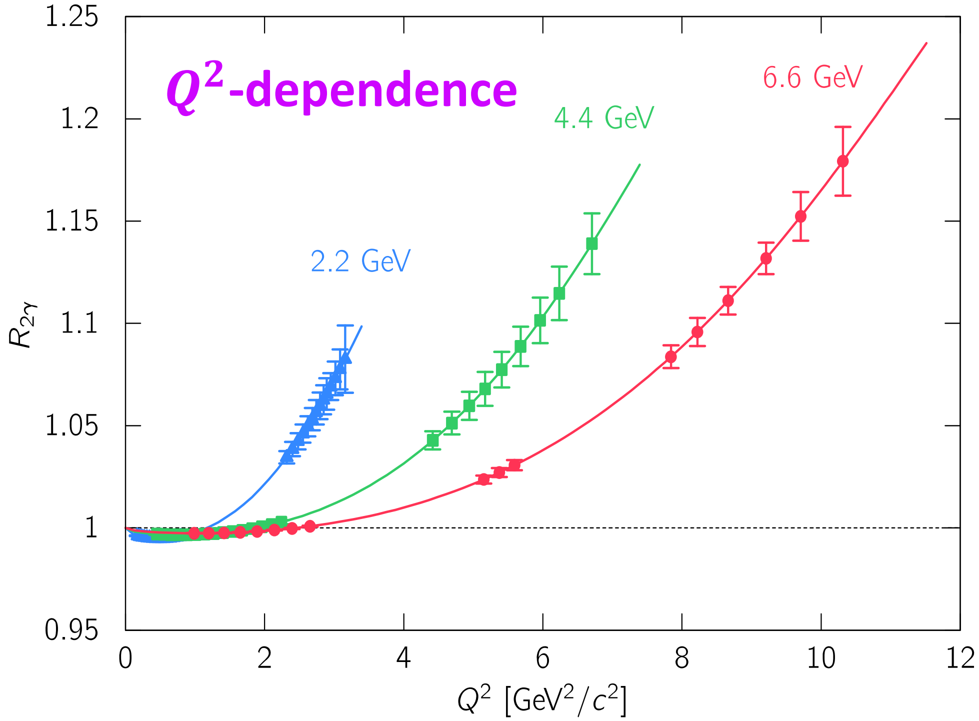
CLAS12 provides a big improvement over previous experiments.

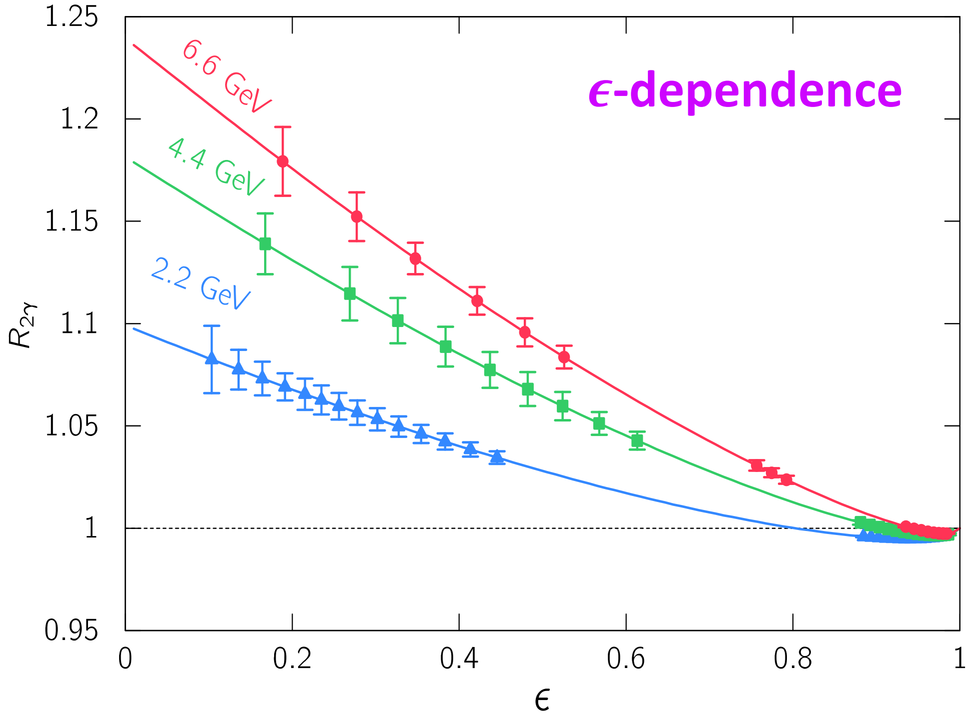
	VEPP-3	CLAS-6	OLYMPUS	CLAS-12
Azimuthal Acceptance	33%	50–85%	15%	> 90%
Luminosity [cm^{-2}s^{-1}]	10^{32}	$< 5 \cdot 10^{31}$	$2 \cdot 10^{33}$	10^{35}
Beam Energy [GeV]	1.0, 1.6	variable	2.0	2.2, 4.4, 6.6

Expected Sensitivity

- 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 will map-out two-photon exchange effects.
- The CLAS12 **trigger** will be **modified** to allow lepton detection in the Central Detector and proton detection in the Forward Detector.

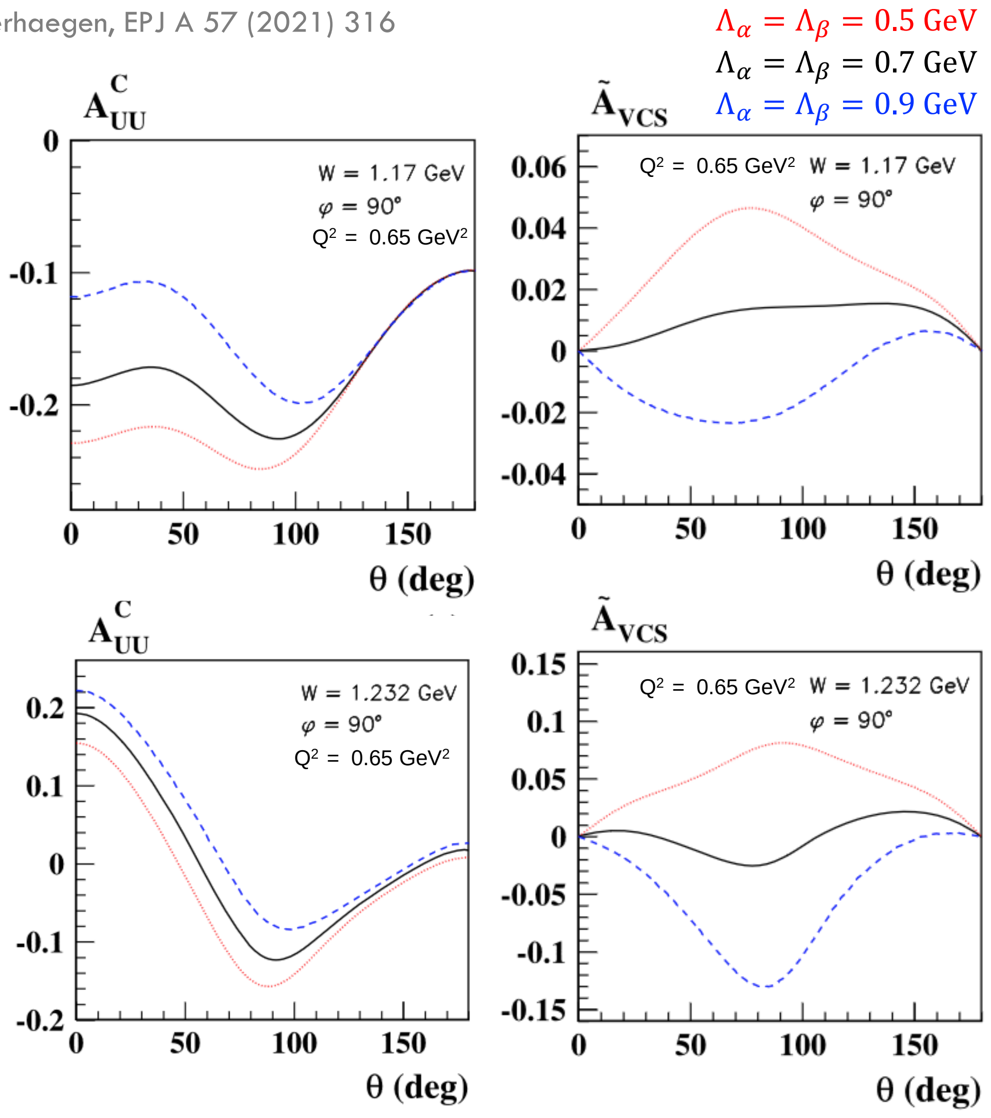
Courtesy of Axel Schmidt (GWU)





Experimental Observables

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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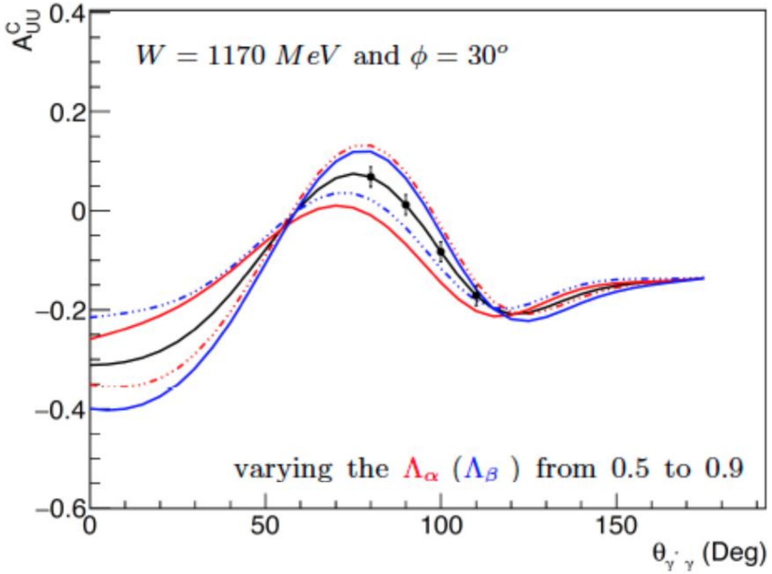
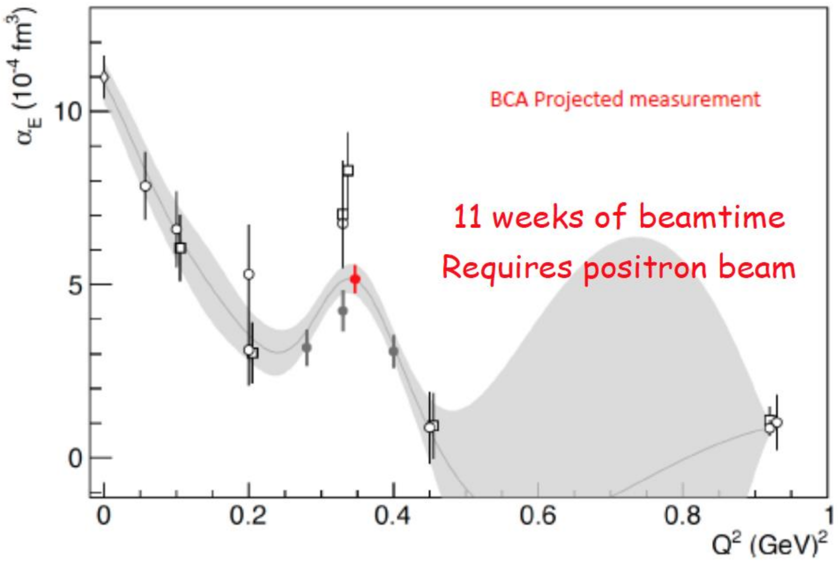
LoI12-23-###
N. Sparveris et al.

- A new experimental project to measure **unpolarized BCA** in the **VCS** channel has been evaluated.

Courtesy of Nikos Sparveris (TU)

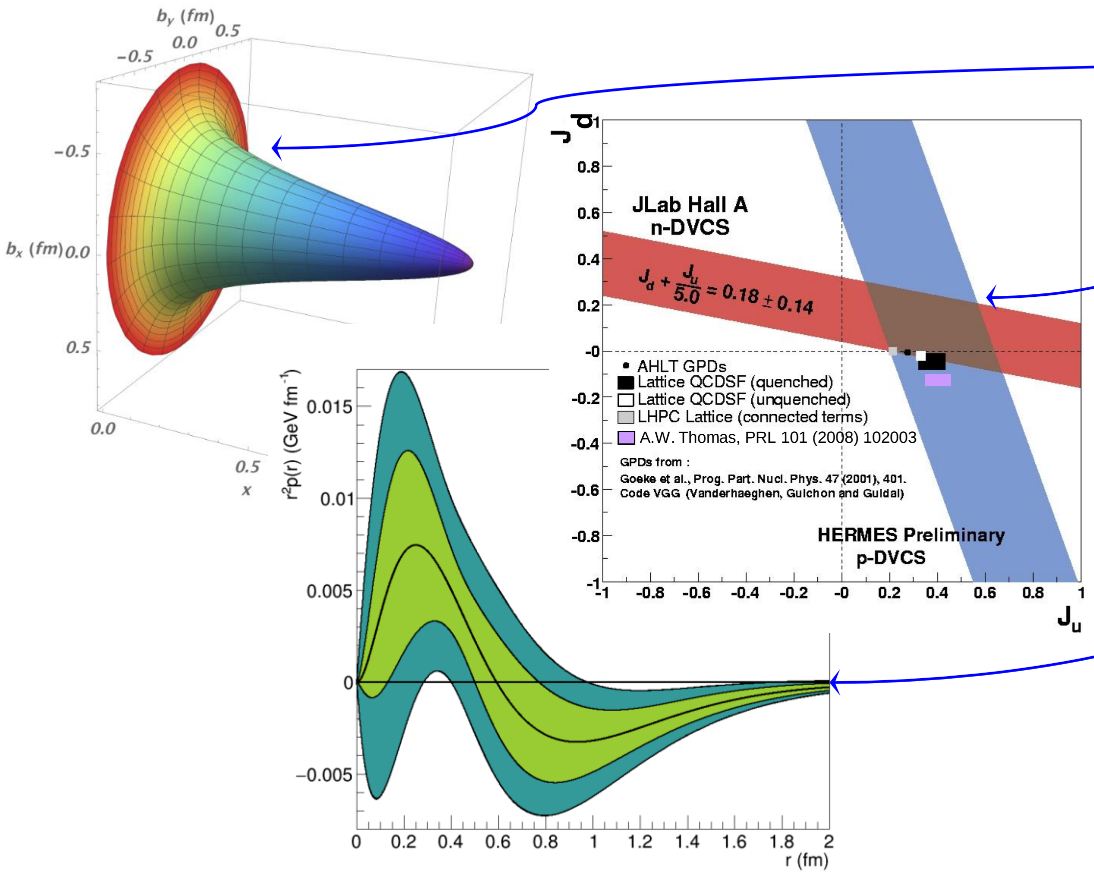




- 1 week of **electron beam** at 50 μA.
- 10 weeks of **positron beam** at 5 μA.

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.



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

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

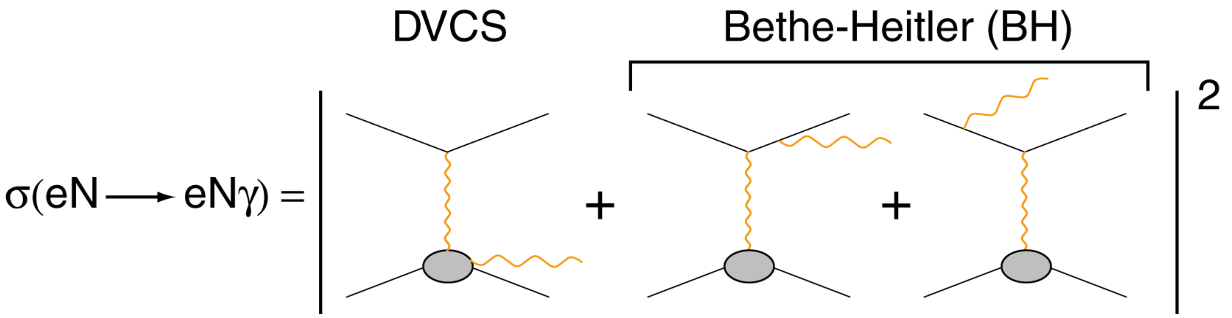
$$\int_{-1}^{1} x \sum_q H^q(x,\xi,t)\,dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

- **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 **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



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**

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

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

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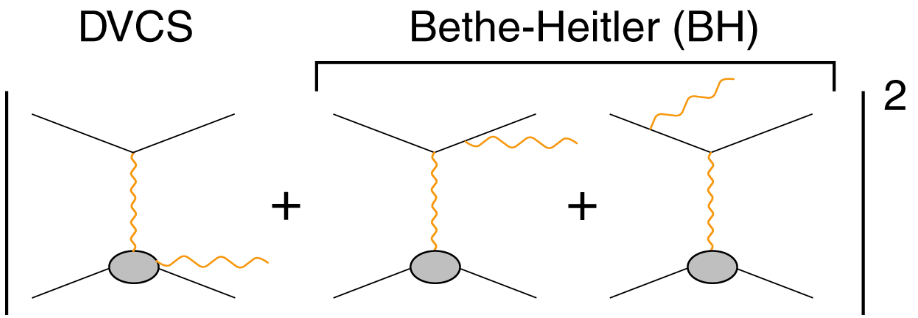
σ(eN ⟶ eNγ) =



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PR12-20-009

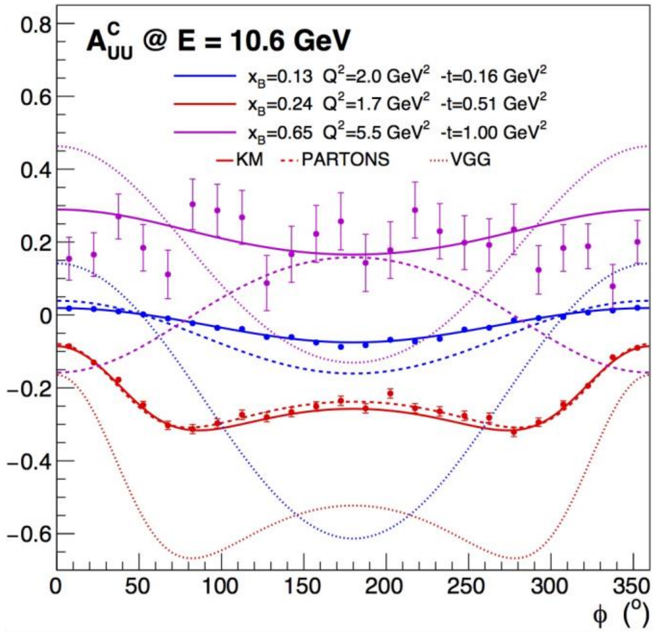
V. Burkert, L. Elouadrhiri, F.-X. Girod, S. Niccolai, E. Voutier et al.

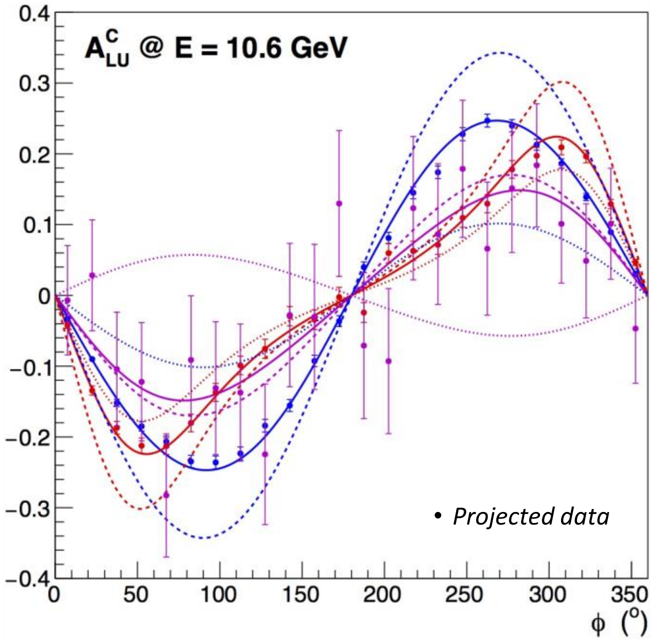
V. Burkert et al. EPJ A 57 (2021) 186

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

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



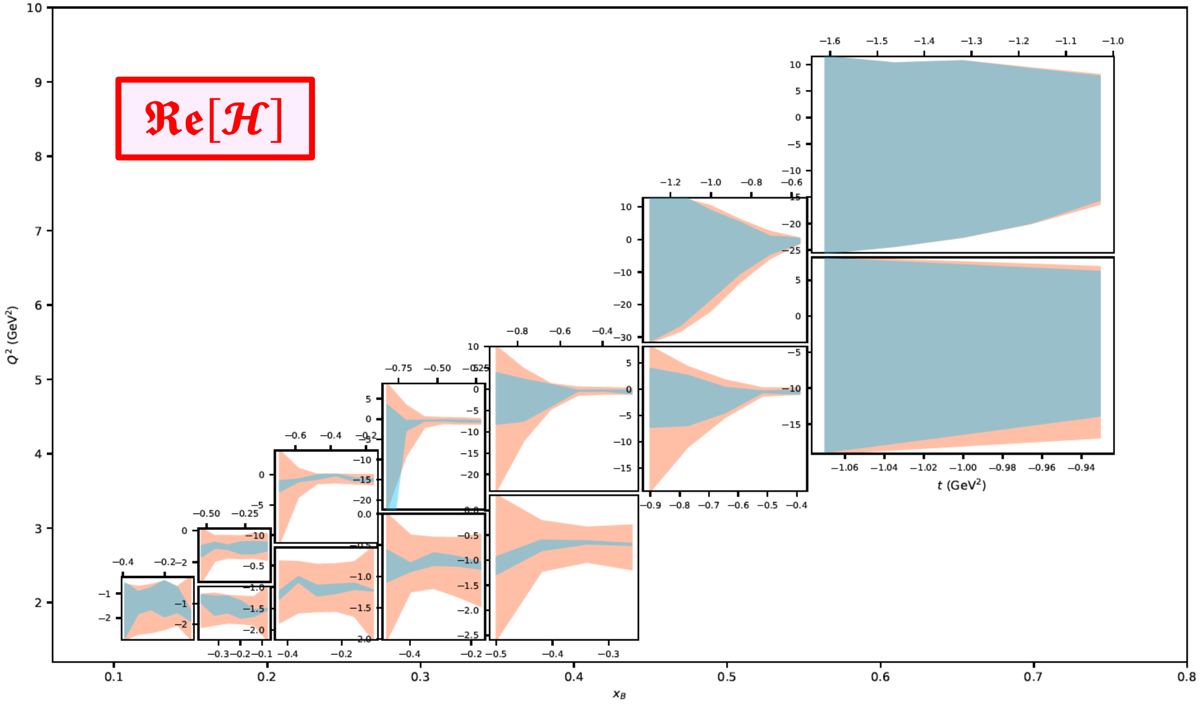


$$A^C_{LU} = \frac{d^5\tilde{\sigma}_{INT}}{d^5\sigma_{BH} + d^5\,\sigma_{DVCS}}$$

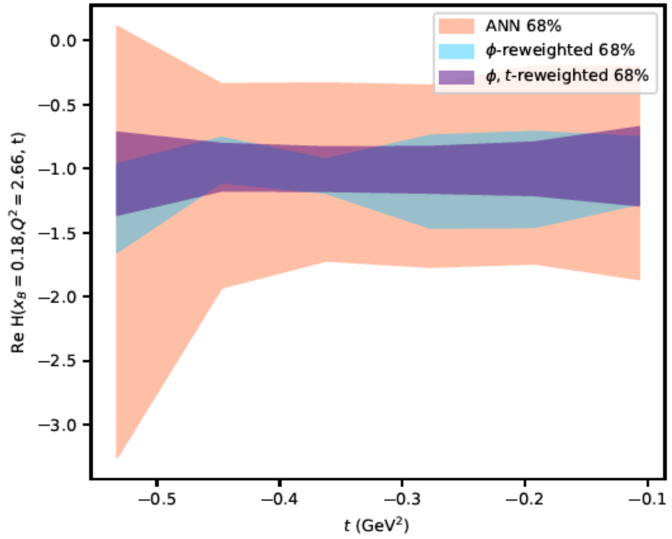
Impact of e^+ data

H. Dutrieux, V. Bertone, H. Moutarde, P. Sznajder, EPJ A 57 (2021) 300

- The **existing DVCS world data set** is analyzed within a **global fit** based on an Artificial Neural Network procedure within PARTONS to extract CFFs.
- The impact of **projected CLAS12 BCA** data on the proton is evaluated from a **Bayesian reweighting analysis** of CFFs.



- Improvement of the definition of the **68% confidence region** for $\Re e[\mathcal{H}]$.



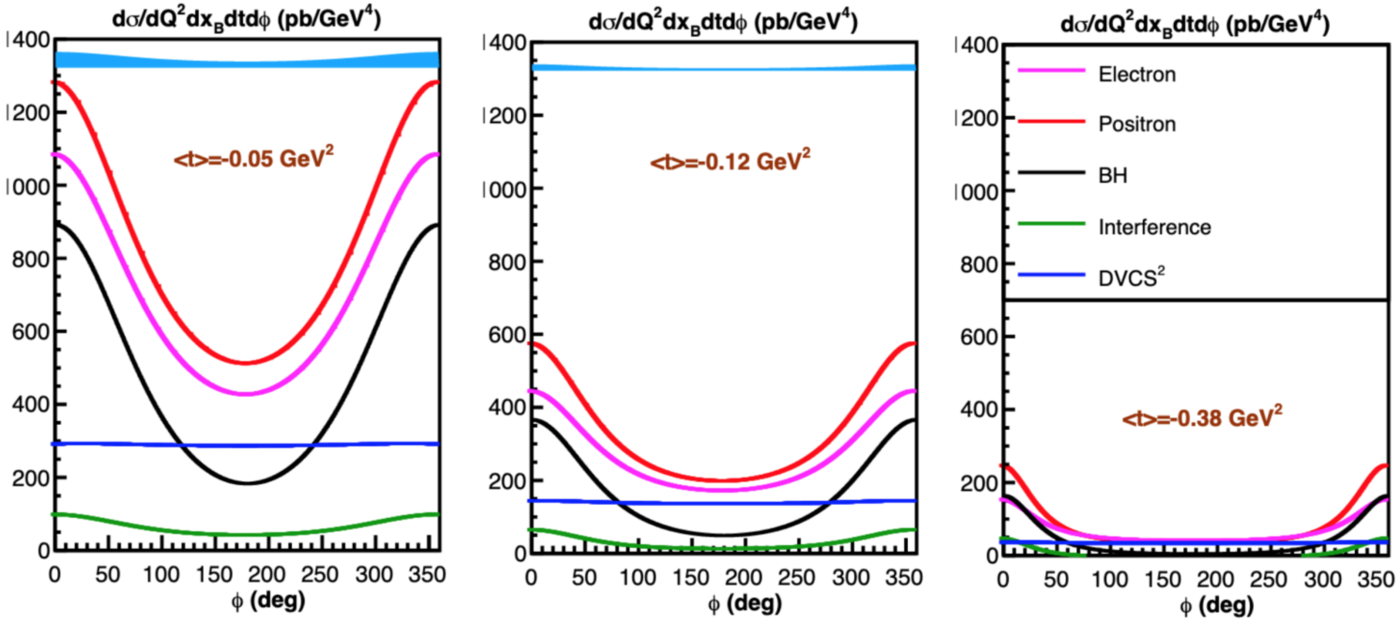
PR12-20-012

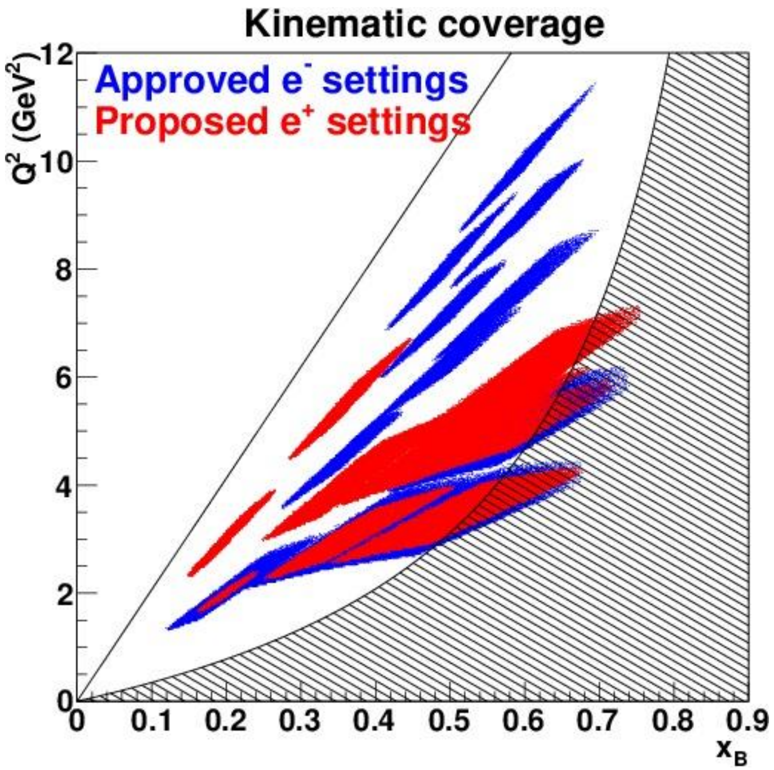
J. Grames, M. Mazouz, C. Muñoz Camacho et al.

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

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

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



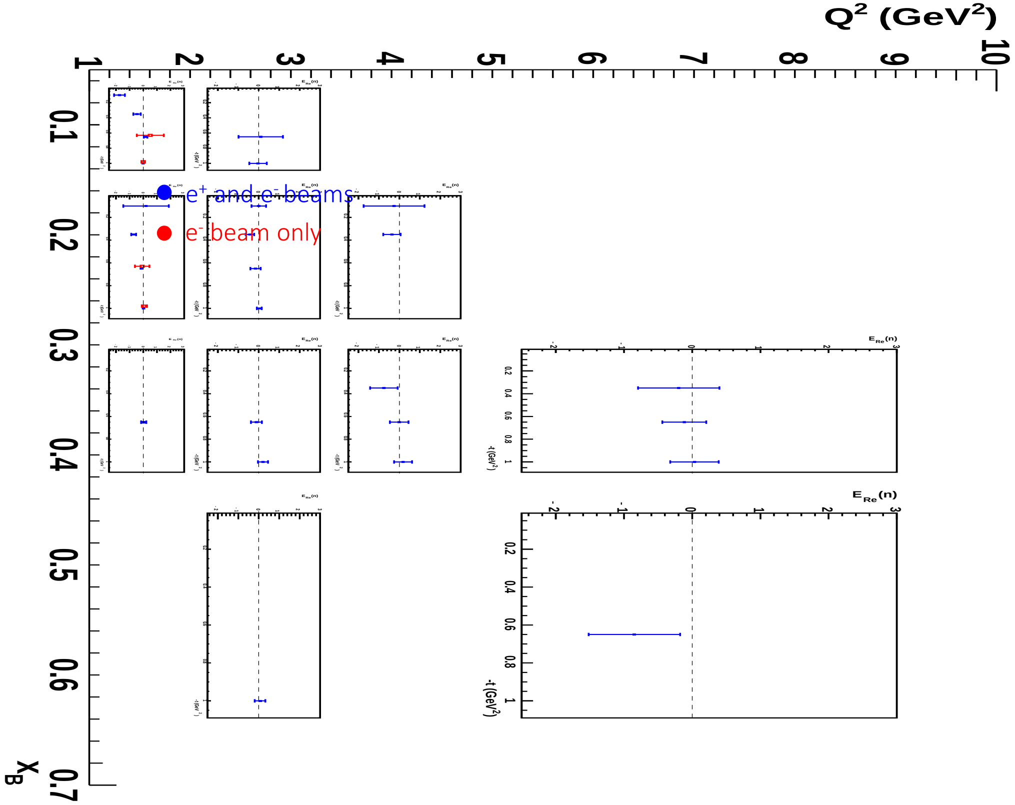


LoI12-18-004

Jefferson Lab Positron Working Group

S. Niccolai, P. Chatagnon, M. Hoballah, D. Marchand, C. Muñoz Camacho, E. Voutier, EPJ A 57 (2021) 226

- Contrary to H, the GPD **E flips the spin of the nucleon** and is consequently not constrained by Deep Inelastic Scattering data.



X. Ji, PRL 78 (1997) 610

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

$$A^{C}_{UU} \propto \frac{1}{F_2}\,\Re\mathrm{e}\left[\xi \widetilde{H}_n - \frac{t}{4M^2} E_n\right]$$

The **BCA** on the neutron accesses the **real part** of the CFF **E**, and is sensitive to $\widetilde{\mathrm{H}}$ at some kinematics.

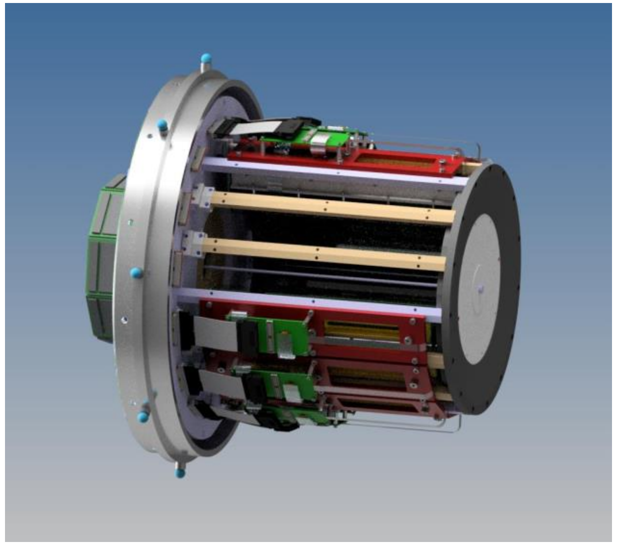
Coherent He-DVCS

M. Rinaldi, S. Scopetta, PRC 85 (2012) 062201; PRC 87 (2013) 035208
S. Fucini, M. Hattawy, M. Rinaldi, S. Scopetta, EPJ A 57 (2021) 273

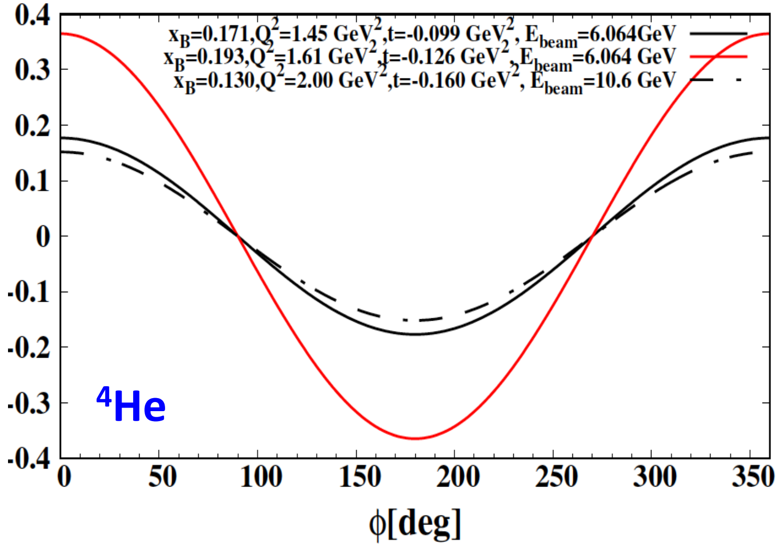
- The association of the **ALERT** recoil detector and the **CLAS12** spectrometer together with high-energy **electron** and **positron** beams offer a new tool for the **investigation** of the **nuclear force**.

$$\Re e[\mathcal{H}_A(\xi,t)] = \mathcal{P}\int_0^1 \left[\frac{1}{\xi+x}+\frac{1}{x-\xi}\right] H_A(x,\xi,t)\,dx = \frac{1}{\pi}\mathcal{P}\int_0^1 \left[\frac{1}{\xi+x}+\frac{1}{x-\xi}\right] \Im m[H_A(x,x,t)]\,dx - \delta(t)$$

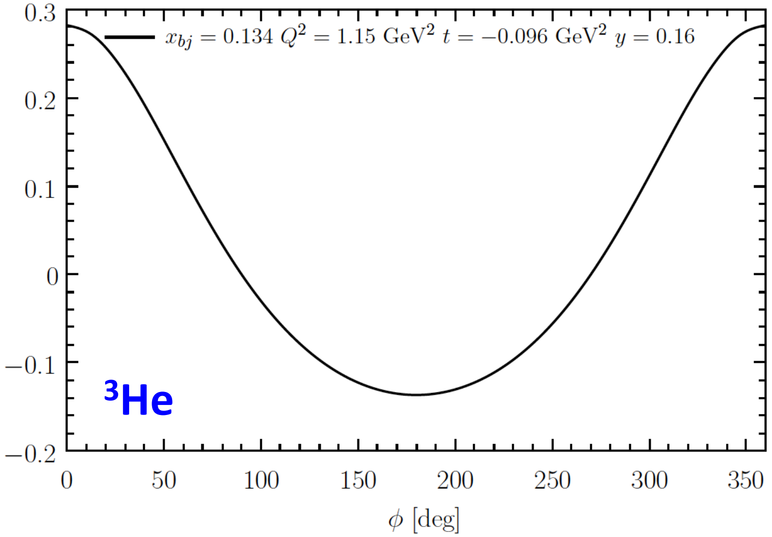
Courtesy of Raphaël Dupré (IJCLab)



Unpolarized Beam Charge Asymmetry



Nuclear imaging



Sensitivity to neutron GPDs

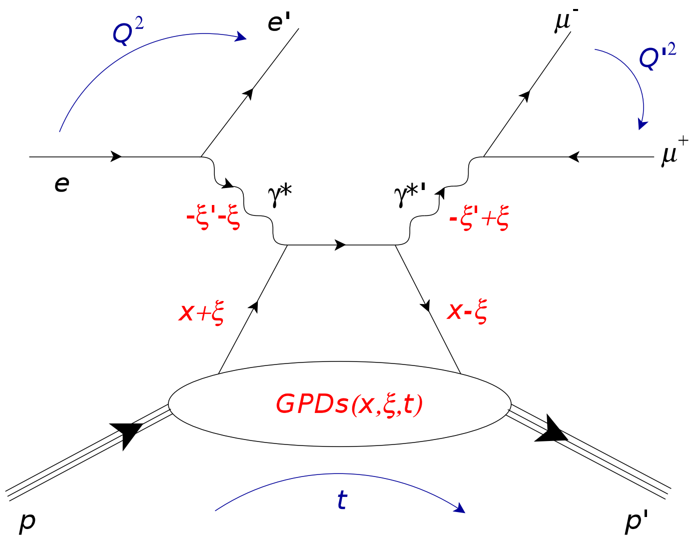
Double Deeply Virtual Compton Scattering

M. Guidal, M. Vanderhaeghen, PRL 90 (2003) 012001
A.V. Belitsky, D. Müller PRL 90 (2003) 022001; PRD 68 (2003) 116005

- Because of the virtuality of the final photon, **DDVCS** allows a direct access to GPDs at $x \neq \pm\xi$, which is of importance for their modeling and for the investigation of nuclear dynamics.

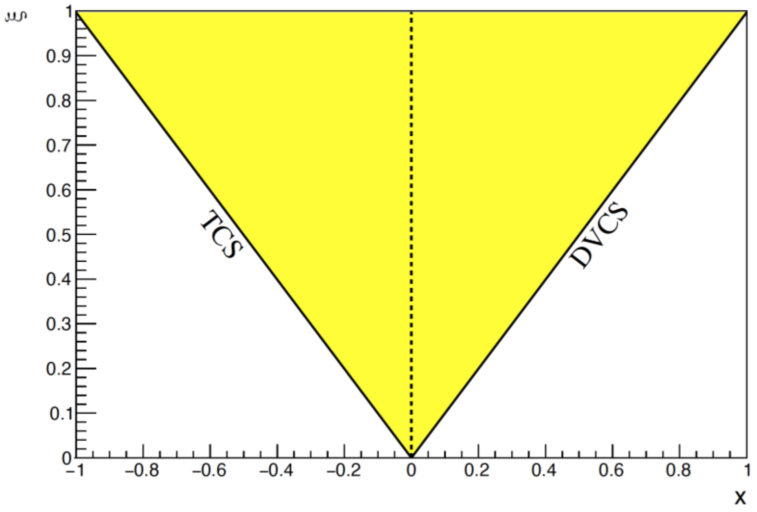
$$\mathcal{F}(\xi',\xi,t) = \mathcal{P}\int_{-1}^{1} dx\, F_+(x,\xi,t)\left[\frac{1}{x-\xi'} \pm \frac{1}{x+\xi'}\right] - i\pi F_+(\xi',\xi,t)$$

$$F_+(x,\xi,t) = \sum_q \left(\frac{e_q}{e}\right)^2 \left[F^q(x,\xi,t) \mp F^q(-x,\xi,t)\right]$$



$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$



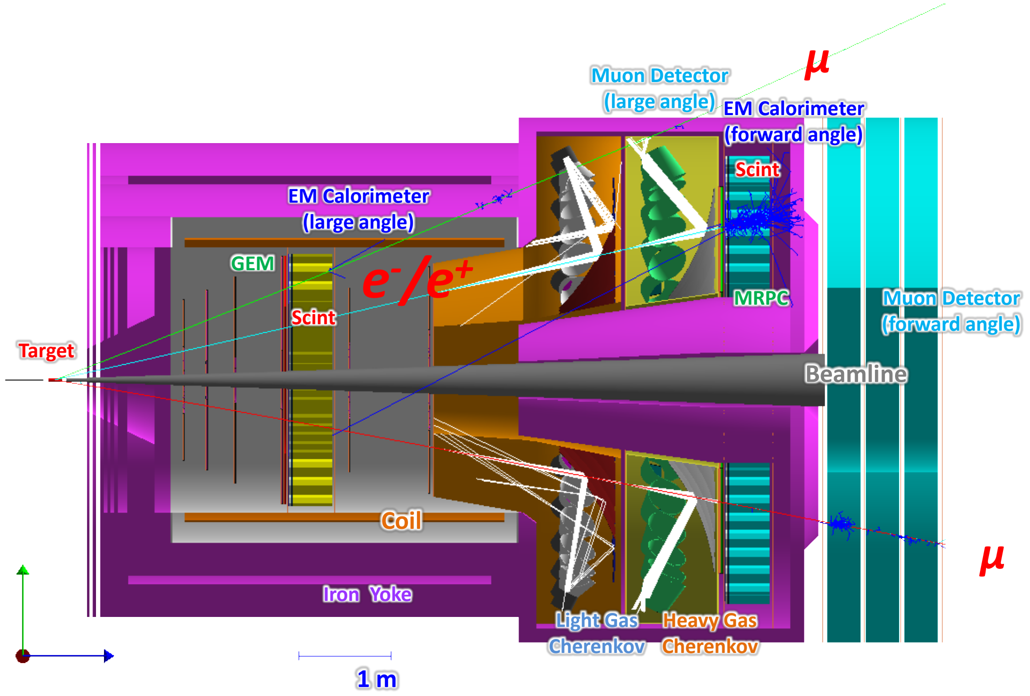
- Following the sign change of ξ' around $Q'^2=Q^2$, the CFFs $\mathcal{H}$ and $\mathcal{E}$ **change sign**, providing a testing ground of **GPDs universality**.

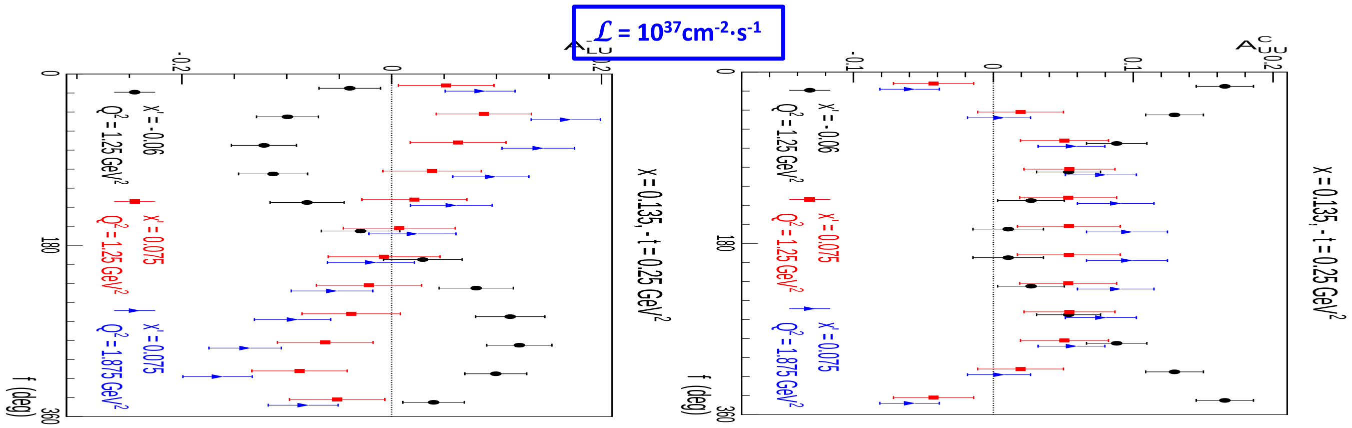
LoI12-15-005

M. Boer, A. Camsonne, K. Gnanvo, E. Voutier, Z. Zhao et al.

S. Zhao et al. EPJ A 57 (2021) 240

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

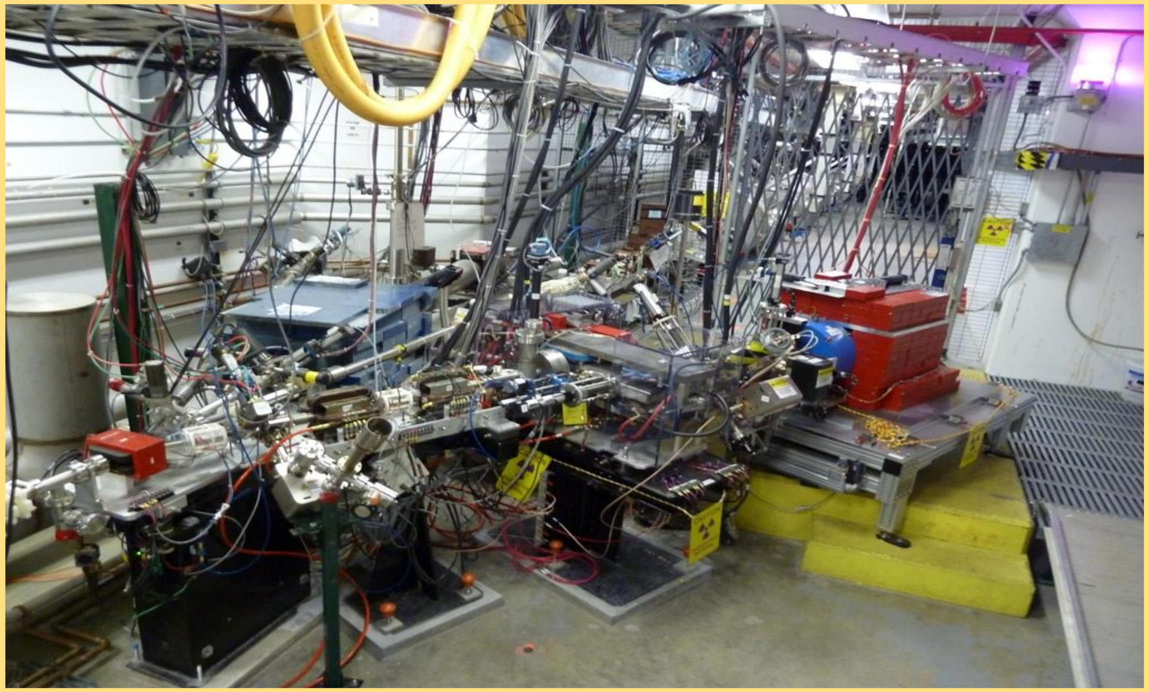




- The initial LoI discussed **electron BSA** measurements over a **50 days** run parasitic to the J/Ψ approved experiment.
- Completing this program with a **50 days positron beam** run would provide **unpolarized BCA** data.

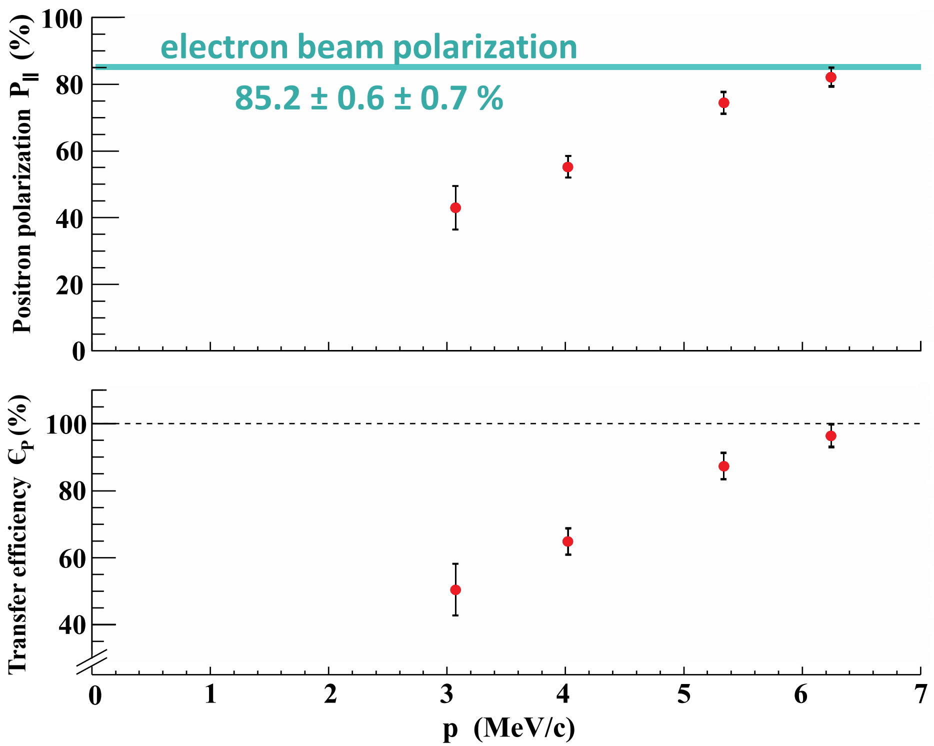
- The JLab positron source built on the PEPPo (Polarized Electrons for Polarized Positrons) experiment which demonstrated the feasibility of using bremsstrahlung radiation of **MeV Polarized Electrons** for producing **Polarized Positrons**.

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



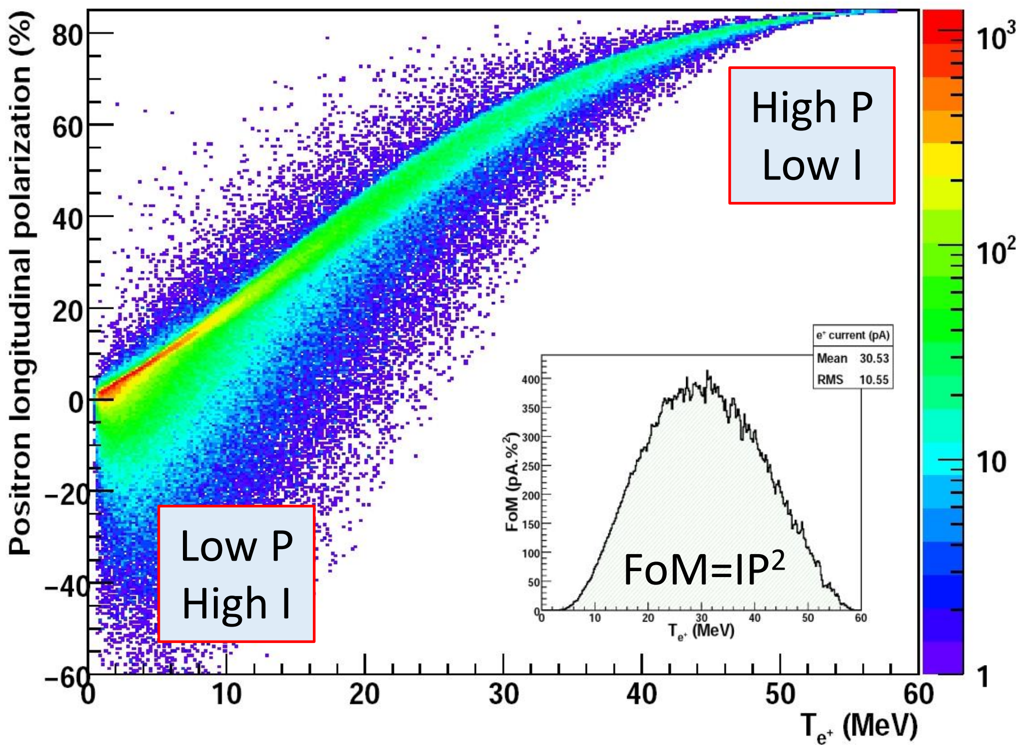
J. Grames, E. Voutier et al. JLab Experiment E12-11-105 (2011)

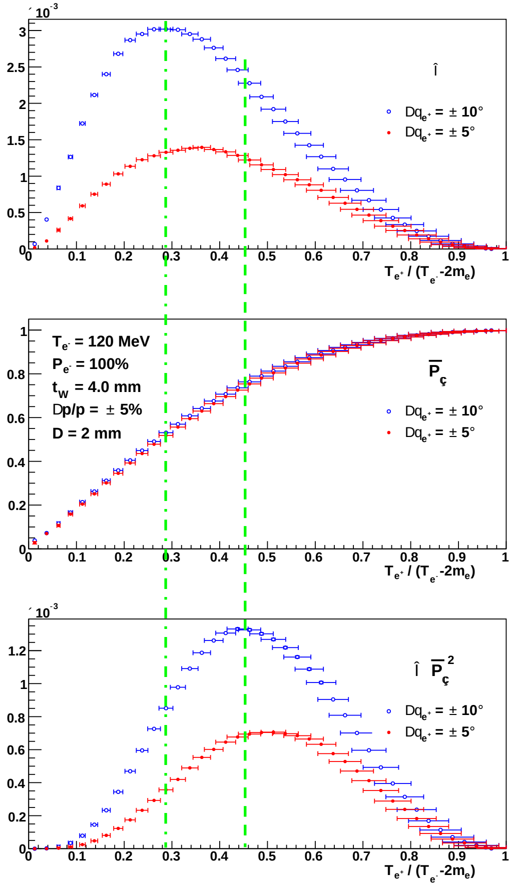
(PEPPo Collaboration) D. Abbott *et al.* PRL 116 (2016) 214801



E. Voutier
IJCLab Irène Joliot-Curie

- The positron **yield** (e^+/e^-) scales with the beam power (**Beam Energy × Beam Intensity**) and depends on the thickness of the production target.
- It is sensitive to the collection system characteristics which can be mimic by an **angular** and a **momentum acceptance**.

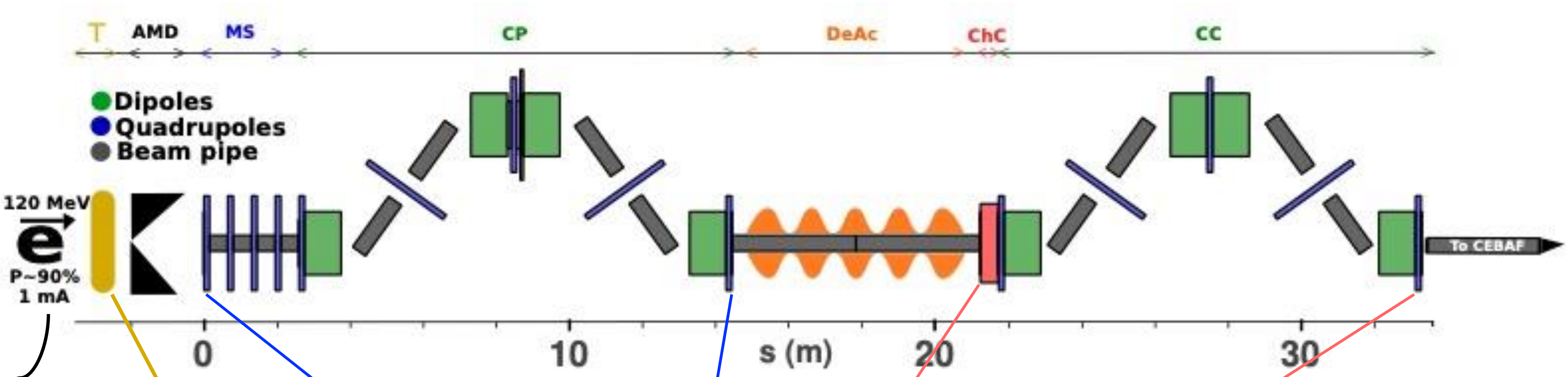




- Selection of e^+ momentum allows to operate the source from low to highly polarized modes.

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

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



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

Positron Production Target

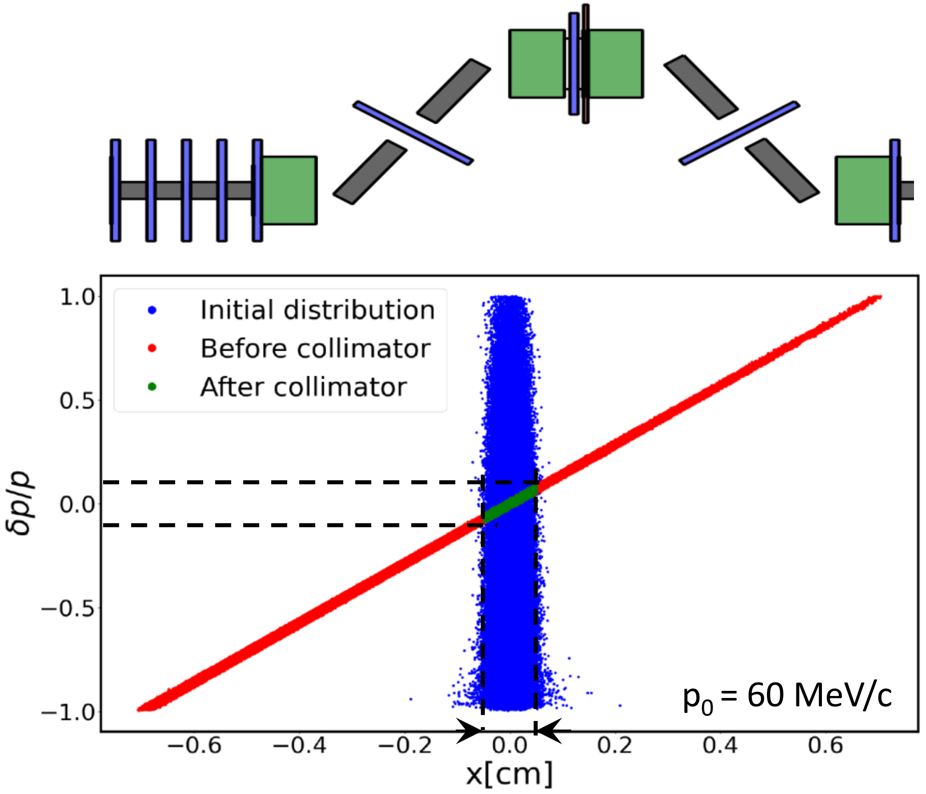
Momentum Selection Chicane

Beam Compression Chicane

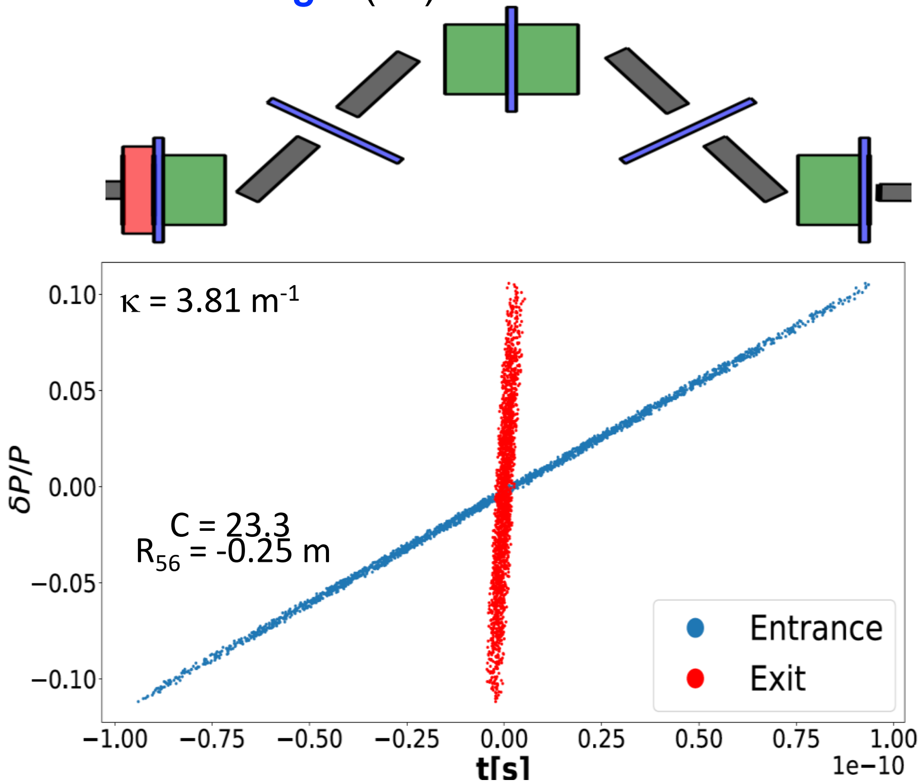
Nominal
I_{e+} > 50 nA @ P_{e+} = 60%
I_{e+} > 1 μA @ P_{e+} = 0%

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

- A FODO lattice combined with a matching section at the entrance ensure the **smallest beam size** and the **largest momentum dispersion** at the middle of the chicane where an efficient momentum collimation is achieved.

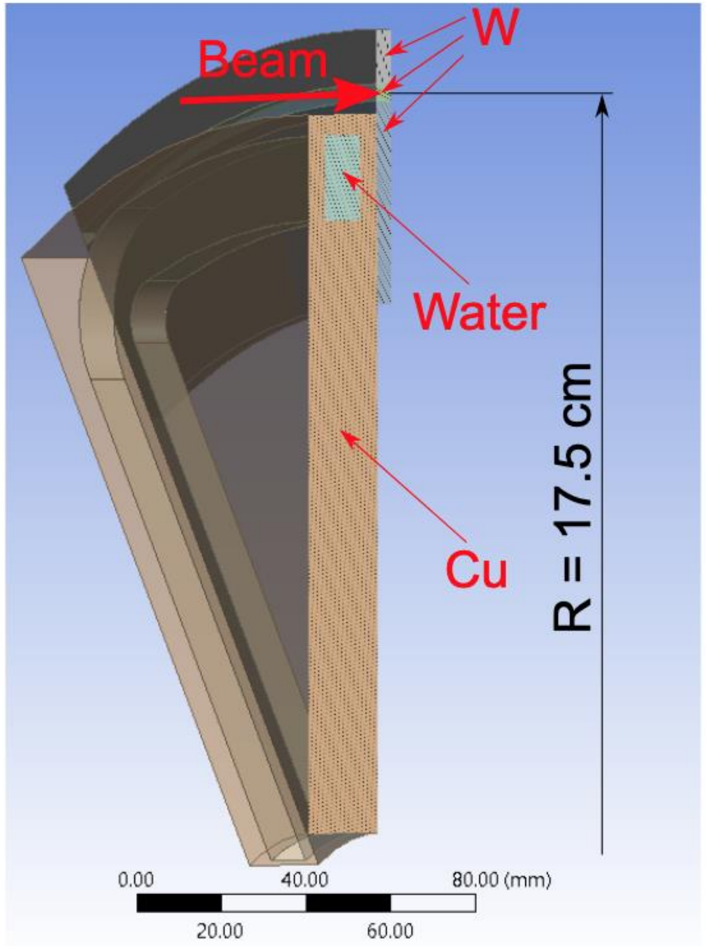


- A **cavity** at the entrance of a magnetic chicane creates a **correlation** between the **momentum dispersion** and the **bunch length**.
- The chicane is designed to feature the **appropriate R_{56}** to optimally **compress** the **bunch length** (Δz).



Work of Sami Habet (IJCLab/JLab) and of Yves Roblin (JLab)

1/6 segment of the e^+ target



- The electron beam deposits a power of **17 kW** in the **4mm** W target.
- The water channel with turbulent water flows at a speed of **2 m/s** and a **22°C** inlet temperature.
- The beam spot RMS size is **1.5 mm**.
- The rotation speed of the target is **2 m/s**.

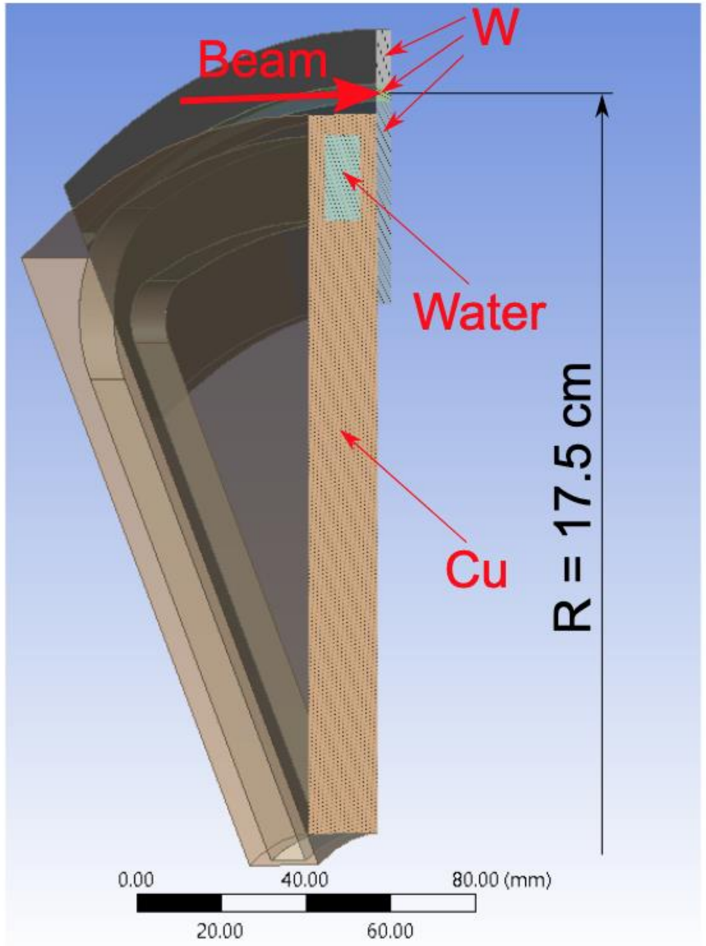
- The tungsten target will operate at an **average temperature** of **500°C** with a **peak temperature** at **680°C** at each rotation cycle.

What are the radiation hardness and the fatigue limits of the target material at operational conditions ?

Irradiation measurements at MAMI
Fatigue measurements at JLab

Work of Andriy Ushakov (IJCLab/JLab)

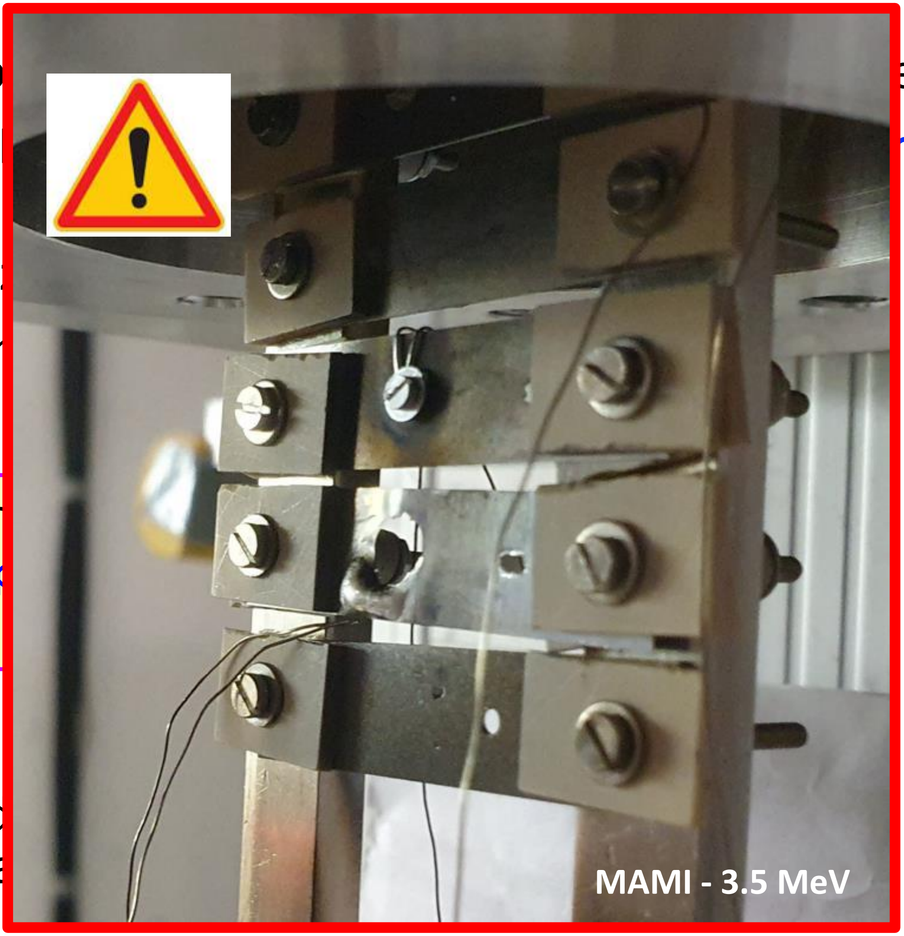
1/6 segment of the e⁺ target



- The electron beam dep … et.
- The water channel wit … n/s and a 22°C inlet tempe
- The beam spot RMS si
- The rotation speed of th

○ The tungsten tar of **500°C** with a cycle.

What are the rad the target materia



Irradiation measurements at MAMI
Fatigue measurements at JLab

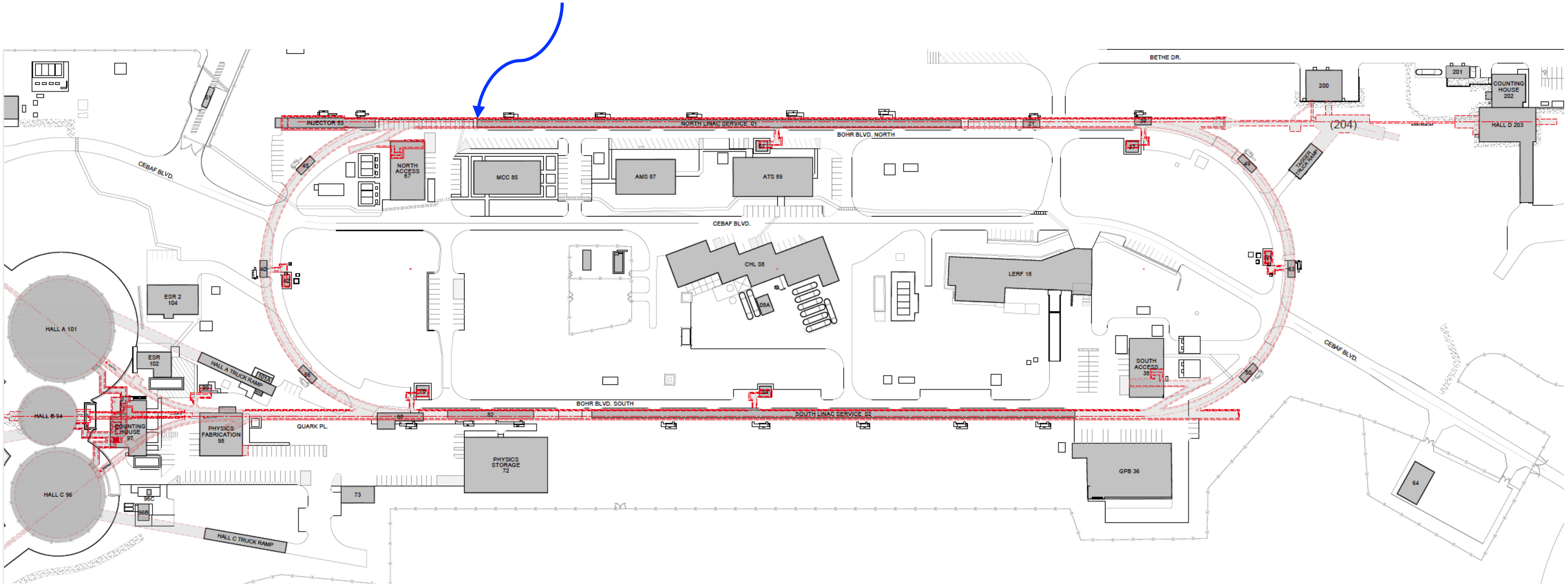
Work of Andriy Ushakov (IJCLab/JLab)

- Other challenges to address :
  - **Reduction** of **beam emittance** and **momentum dispersion** at the source;
  - Polarized electron gun capable of **1 mA** currents with a life time > **1 kC**;
  - High field (up to **2.5 T**) **DC solenoid** in high X-ray environment;
  - High energy **spin rotators**;
  - **Polarity reversal** of CEBAF magnets;
  - **Transport of e^+** beams **to** and **into** CEBAF;
  - e^+ beam **diagnostics** and **polarimetry**.

A **pre-CDR document** is due for the end of the calendar year 2023.

- Jefferson Lab as today: high CW beam **intensity**, high **polarization**, **multi-hall** delivery… a powerful and worldwide unique experimental facility!

e⁻ beam injection at 123 MeV



Positron injector concept

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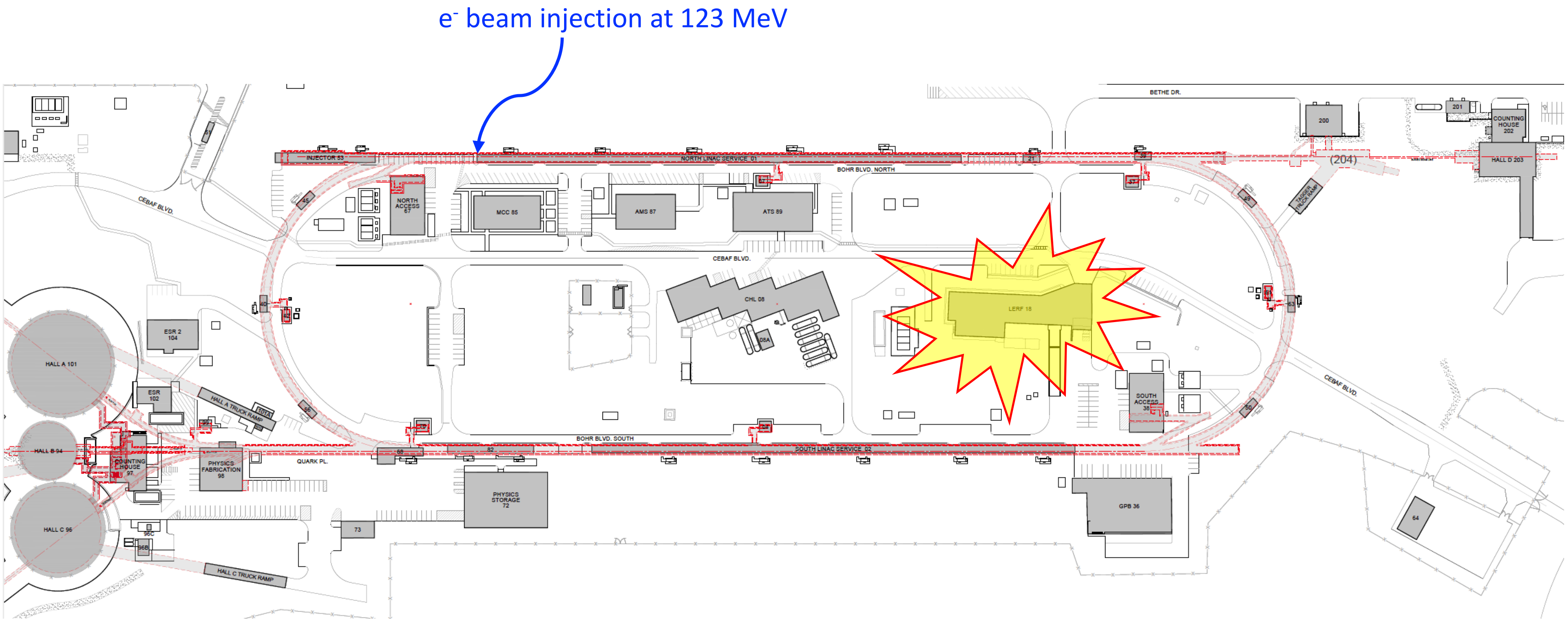
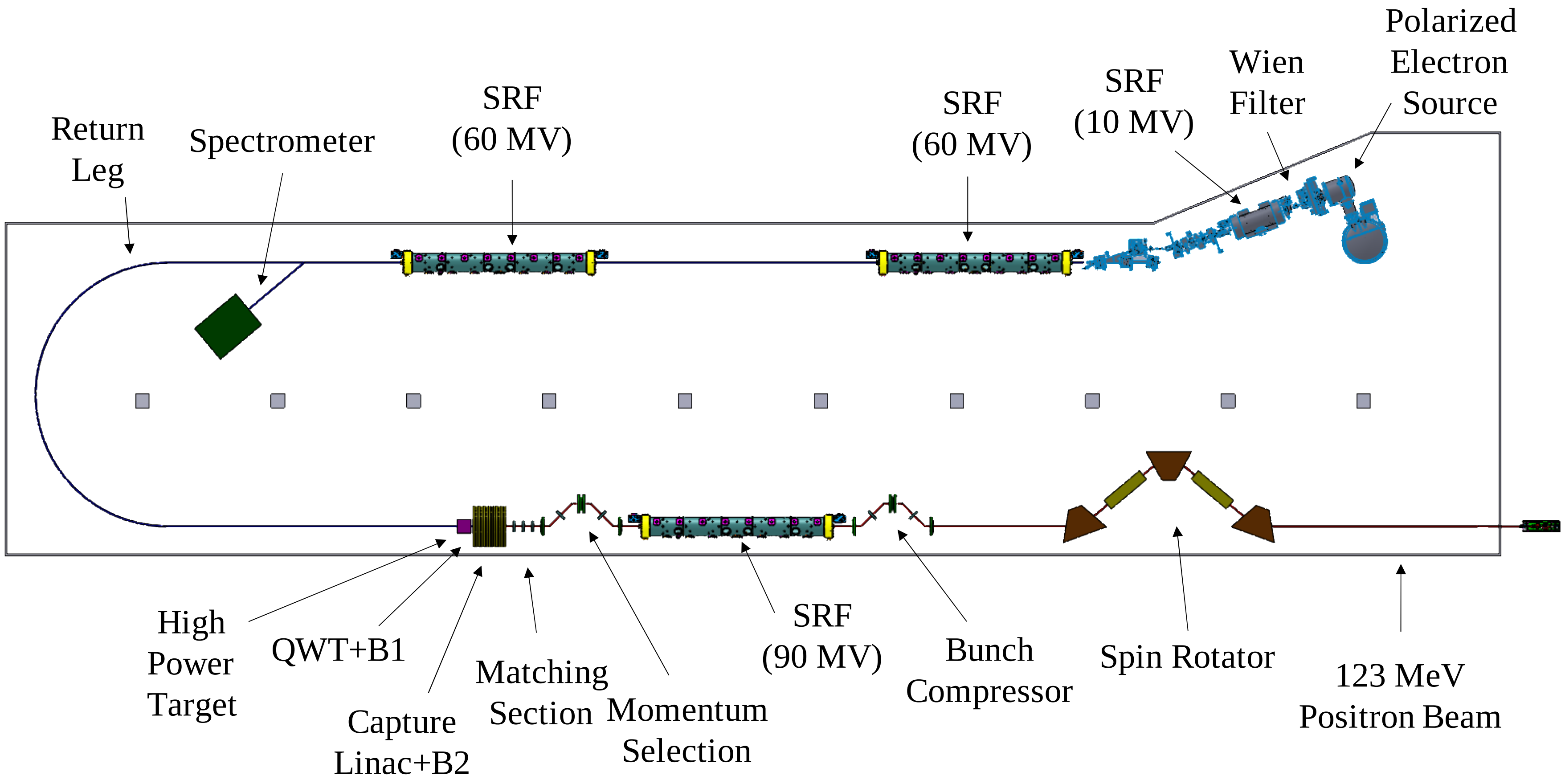
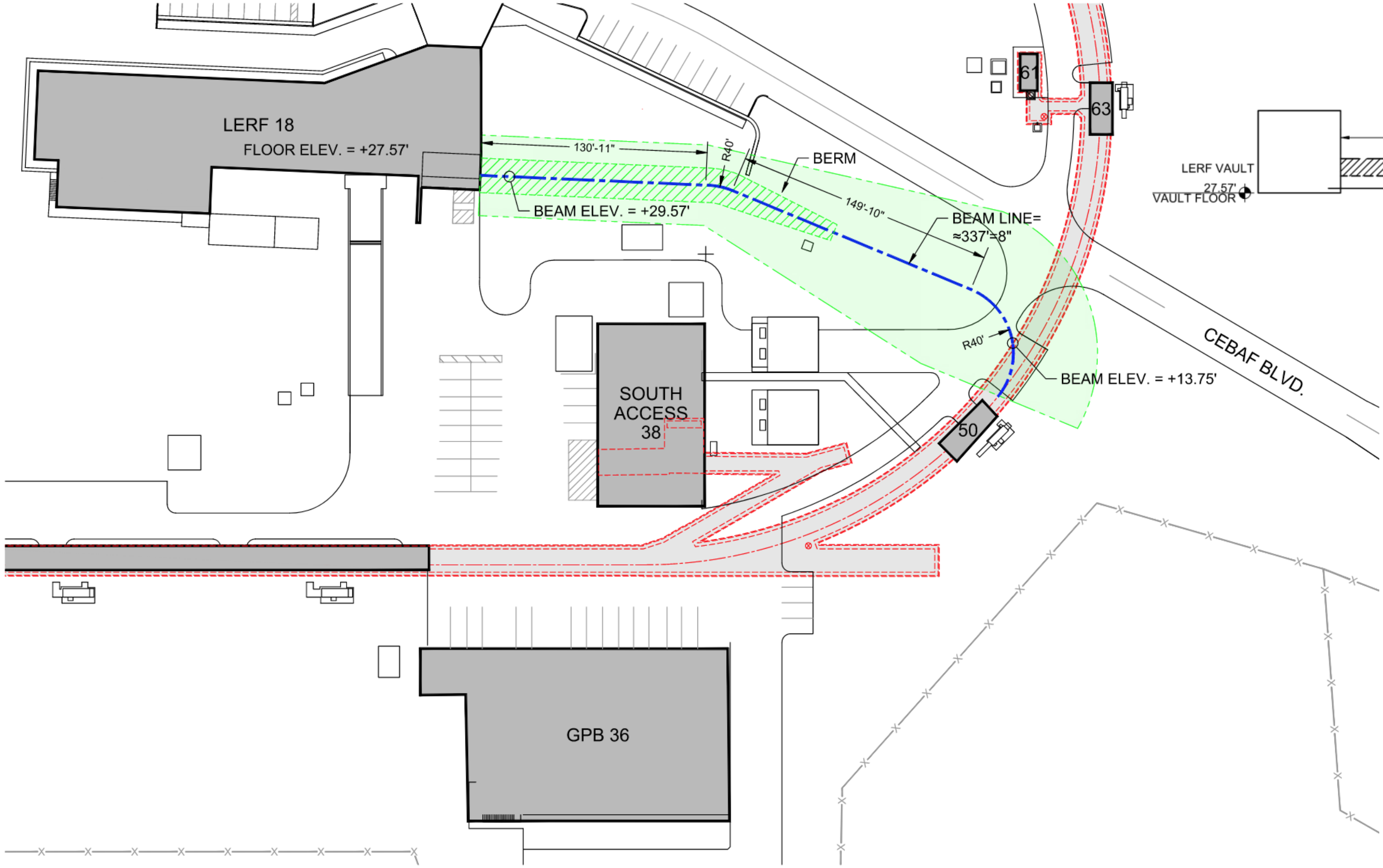


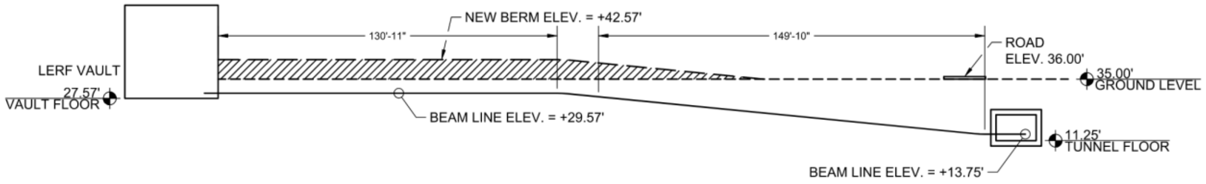
E. Voutier
IJCLab Irène Joliot-Curie

- Taking advantage of the existing infrastructure (electric and cryogenic power supplies, shielding…), the new positron injector would be installed at the LERF.



Positron injector concept



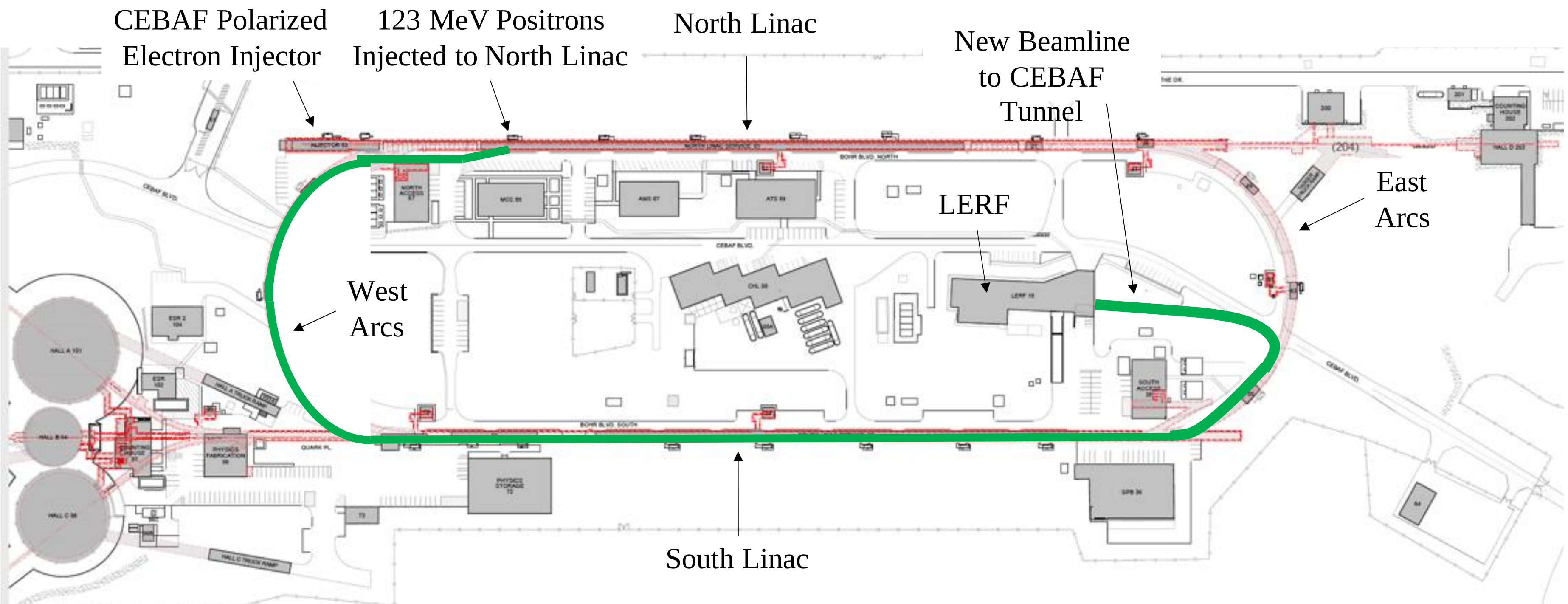


- A new tunnel would transport the positron beams from the LERF to CEBAF.
- The connection would occur in the arc region dealing, among others with different beam elevations at the LERF and CEBAF.

Work of Joel Dobeck (JLab)

Positron injector concept

- A new beam transport line attached to the ceiling of the existing tunnels will guide the 123 MeV positron beam till the injection point of the entrance of the North LinAc.



Work of Denis Turner and Yves Roblin (JLab)

Ce^{+}BAF Working Group

J. Benesch, A. Bogacz, L. Cardman, J. Conway, S. Covrig, J. Grames, J. Gubeli, C. Gulliford, S. Habet, C. Hernandez-Garcia, D. Higinbotham, A. Hofler, R. Kazimi, V. Kostroun, F. Lin, V. Lizarraga-Rubio, M. Poelker, Y. Roblin, A. Seryi, K. Smolenski, M. Spata, R. Suleiman, A. Sy, D. Turner, A. Ushakov, C. Valerio, E. Voutier, S. Zhang, Y. Zhang

Summary

- A rich and high impact experimental program asking for intense CW polarized and unpolarized positron beams at JLab has been elaborated, accounting for about 5 calendar years of CEBAF running.

Such beams would be a worldwide « première ».

- An R&D and construction plan is under progress, which goal is the production at the LERF of positron beams suitable for CEBAF acceleration within the 5 coming years.

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

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

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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 **CEBAF**, but also for **low beam energies** to be available at **LERF** an early stage of the project.

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>
> Consider submitting proposals not only for high energy experiments at CEBAF, but also for low beam energies to be available at LERF 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 @ $P_{e+} = 0\%$

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