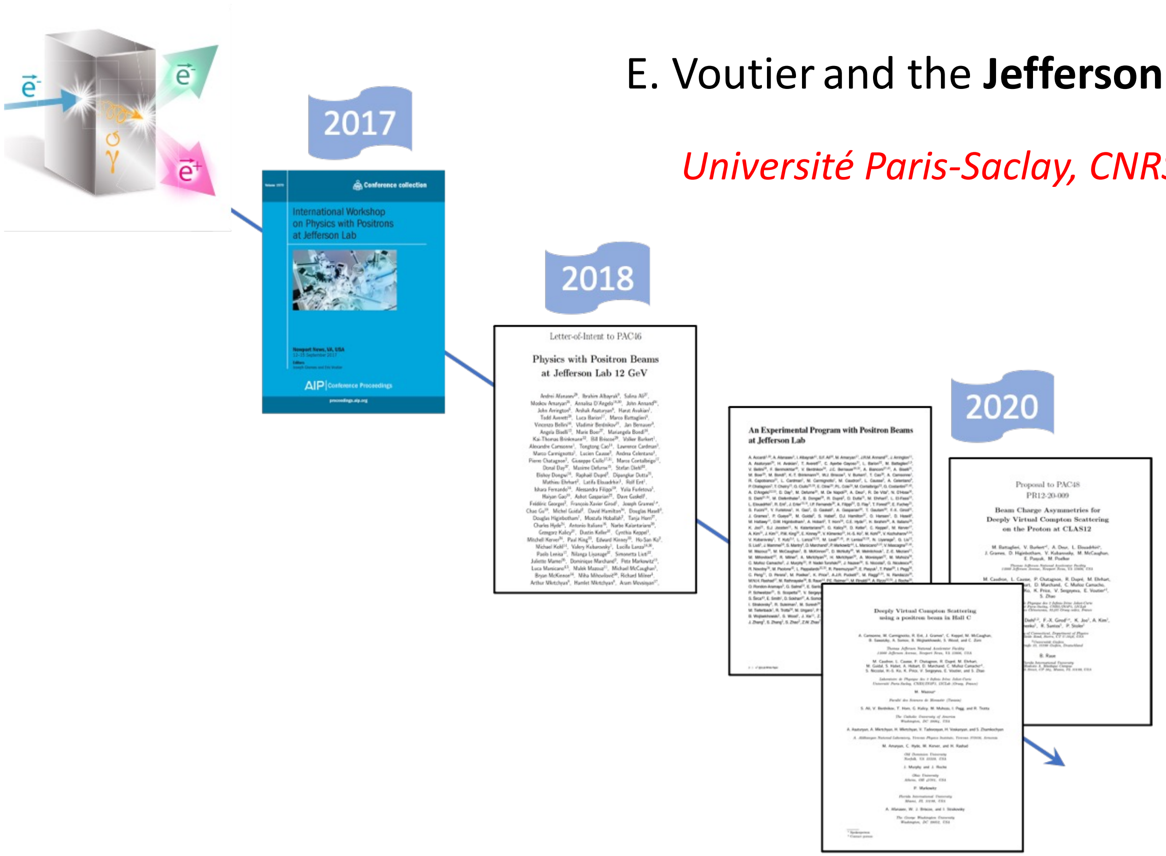
Positron Program at Jefferson Lab

e+@JLab

E. Voutier and the **Jefferson Lab Positron Working Group**

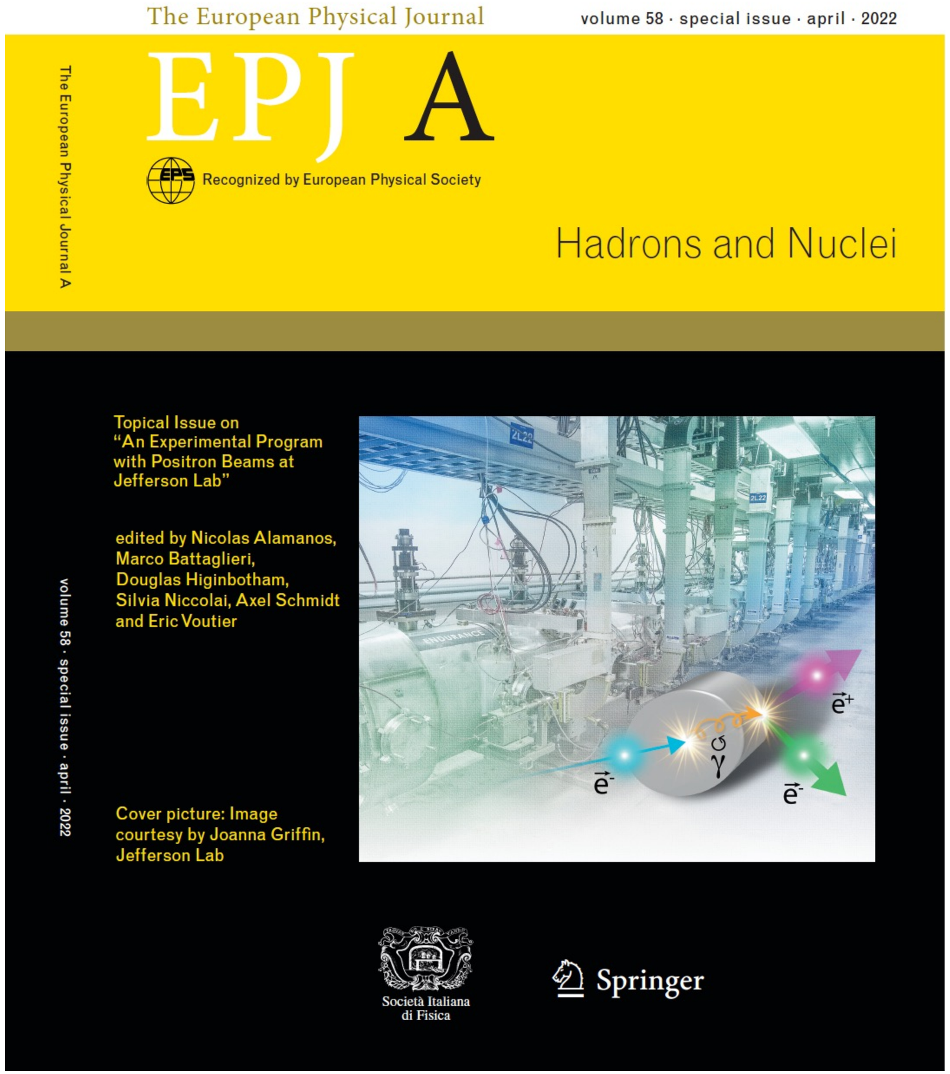
Université Paris-Saclay, CNRS/IN2P3/IJCLab, Orsay, France



(i) Positron White Paper
(ii) Two photon exchange
(iii) Nucleon tomography
(iv) Deep inelastic scattering
(v) Test of the Standard Model
(vi) Towards e^+ beams @ CEBAF

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 EPJ A Topical Issue about an experimental positron program at CEBAF has been released and will be distributed by Jefferson Lab.

  D. Higinbotham, contact person

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

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

Positron Partial Program Summary

Experiment Label (EPJ A)	Experiment 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	$PbW0_4$					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
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(30) Do not require polarization but would take advantage if available at the required beam intensity

- 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.

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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.

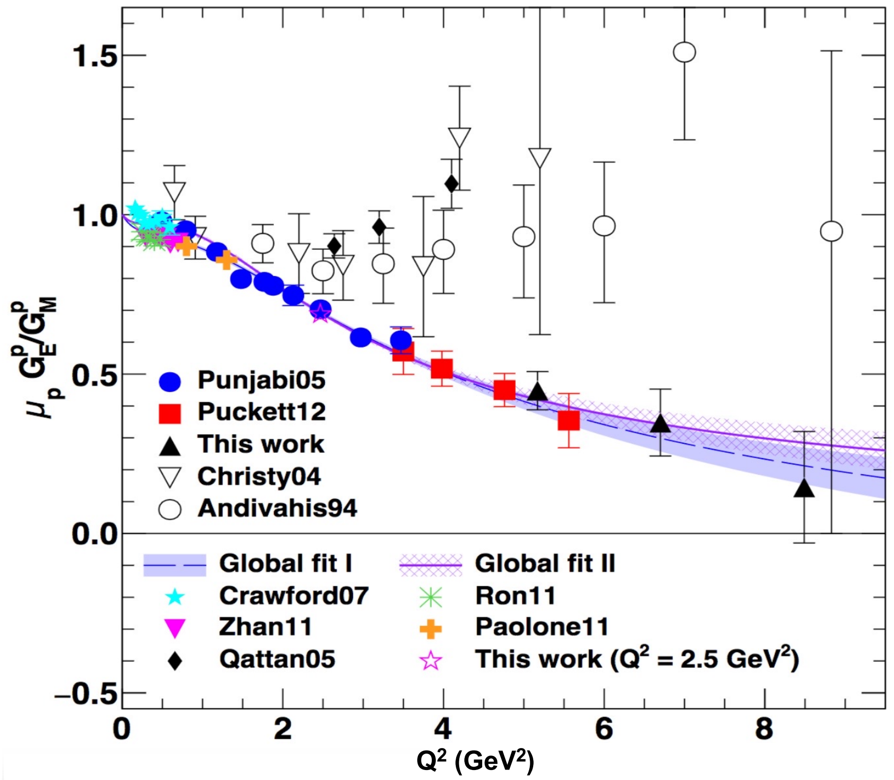
Operating Hall D with a positron beam is currently studied to understand, among others, the effect of e^+ annihilation on the photon energy profile and polarization.

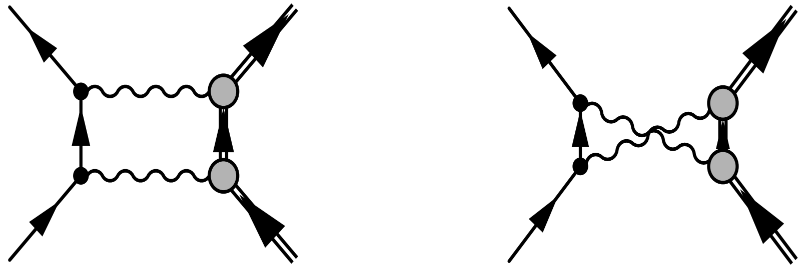
Two photon exchange

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.

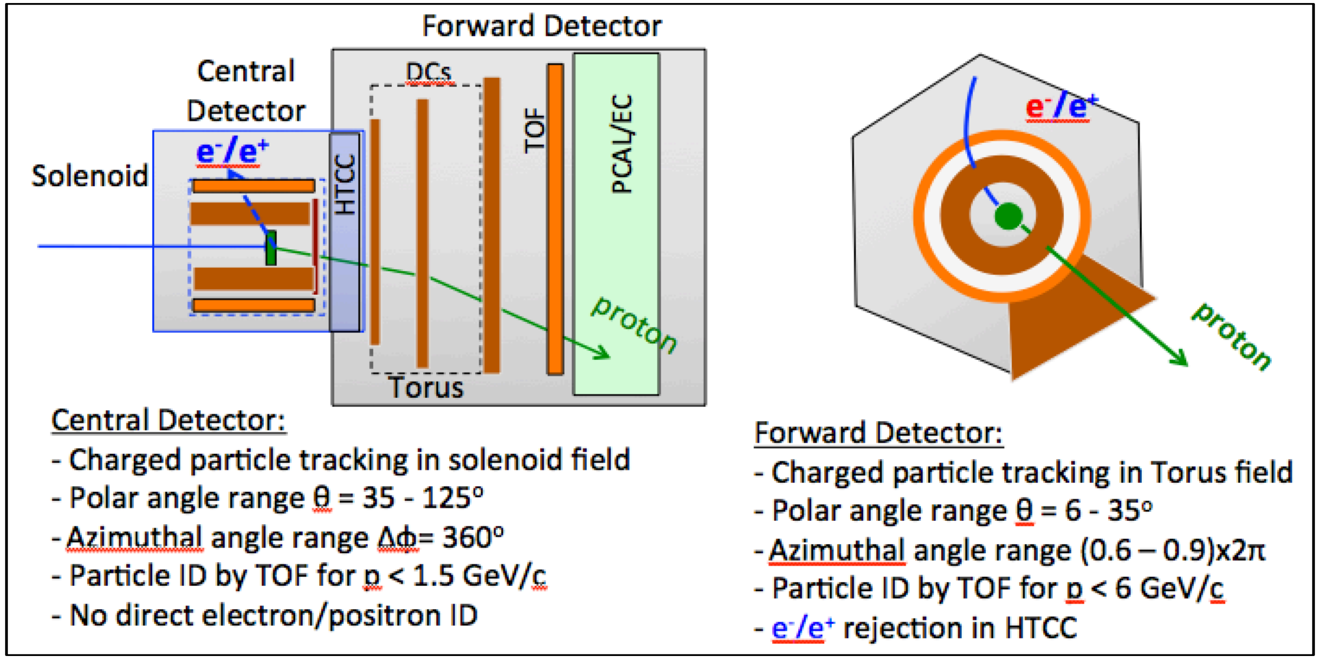
*e^+ @ JLab have the unique opportunity to bring a **definitive answer** about TPE.*

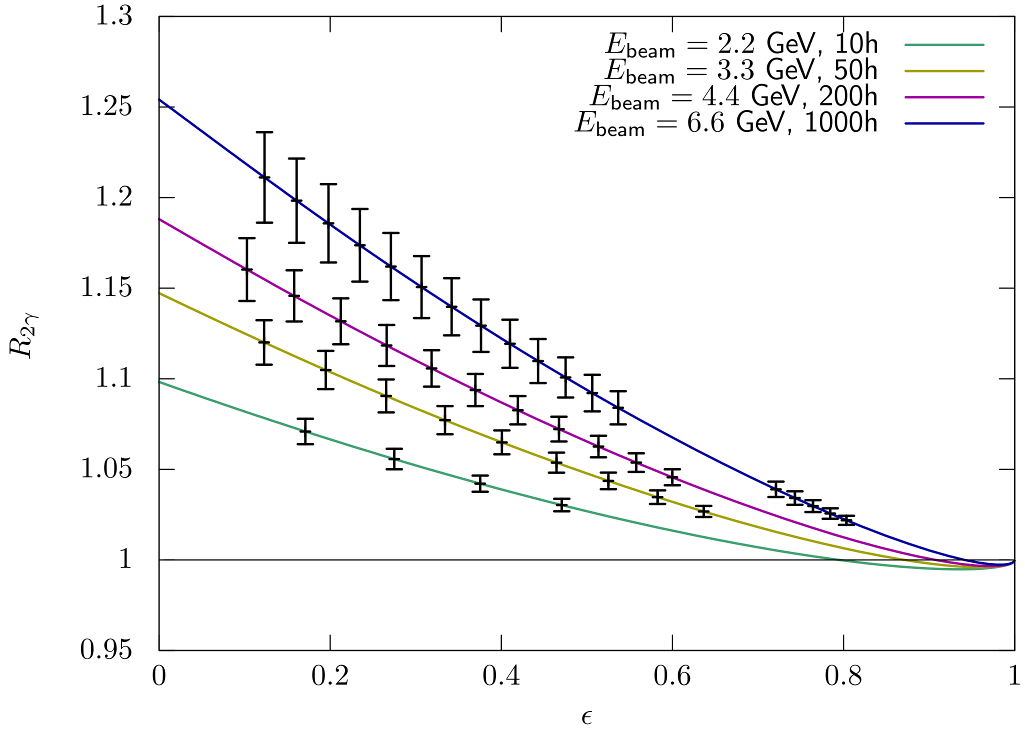
LoI12-18-004
Jefferson Lab Positron Working Group

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

- A **modified CLAS12** hosting an electromagnetic calorimeter in place of the Central Neutron Detector **maps out** the **2γ-effects** in the **(Q^2,ε)** space, providing a **conclusive answer about** the relevance of **2γ-effects**.

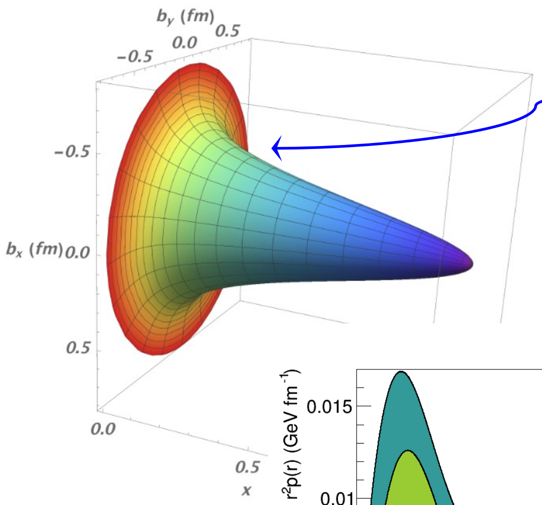
$$\boxed{R_{2\gamma} = \frac{\sigma_{e^+}}{\sigma_{e^-}} \approx 1 + \delta_{2\gamma}}$$

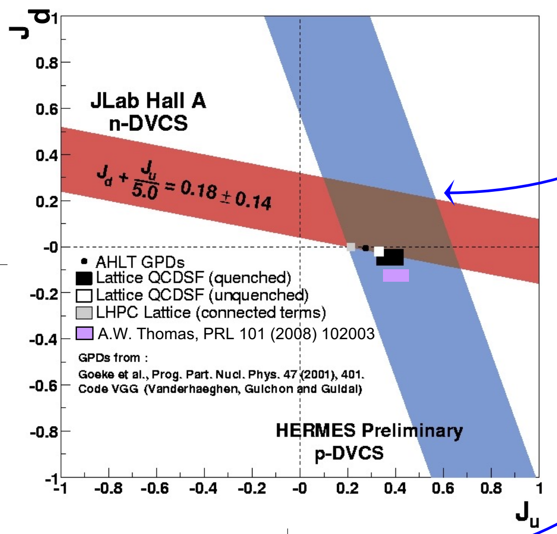


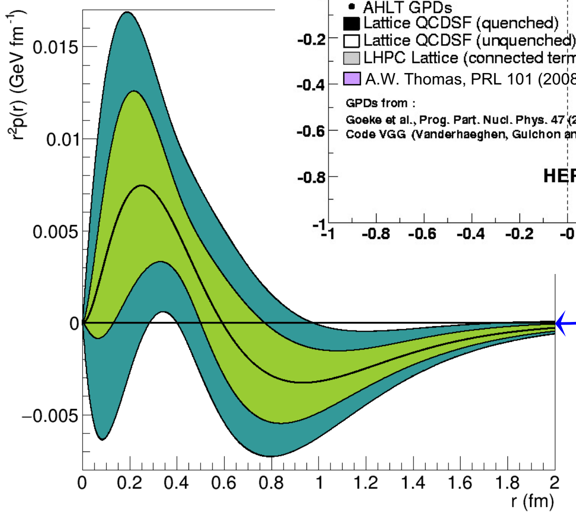


X. Ji, PRL 78 (1997) 610 M. Polyakov, PLB 555 (2003) 57 M.V. Polyakov, P. Schweitzer, IJMP A 33 (2018) 1830025

- 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

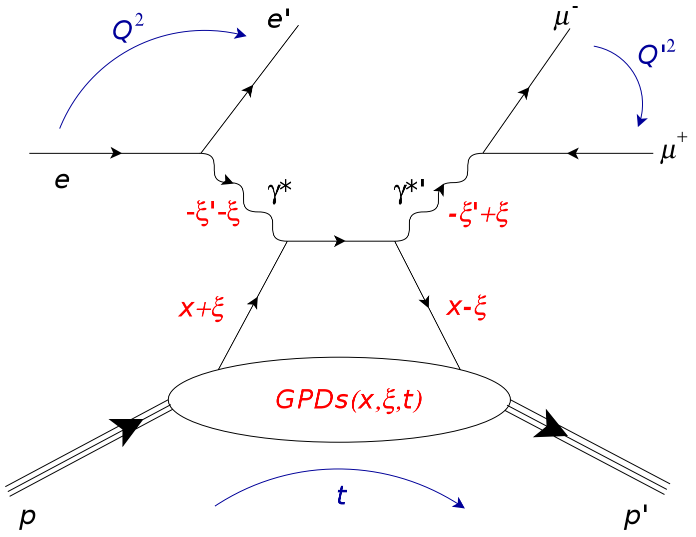
Double Deeply Virtual Compton Scattering

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 through sum rules.

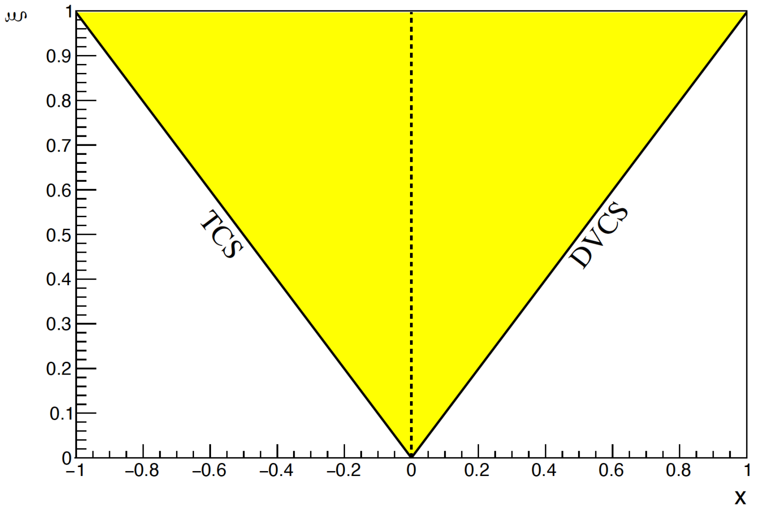
$$\mathcal{F}(\xi',\xi,t) = \mathcal{P}\int_{-1}^{1} dx\, F_+(x,\xi,t)\left[\frac{1}{x-\xi'} \pm \frac{1}{x+\xi'}\right] - i\pi F_+(\xi',\xi,t)$$

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

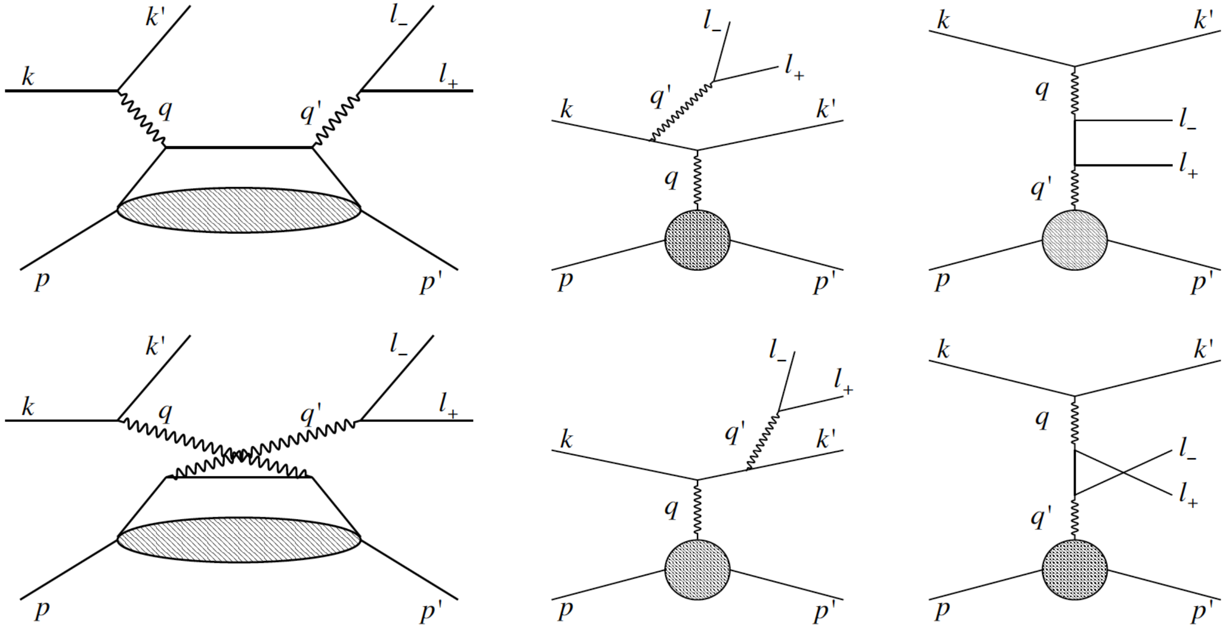


$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

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



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



DDVCS BH_1 BH_2

- The lepto-production of a lepton-pair off the nucleon involves two **Bethe-Heitler** like mechanisms.
- Integrating over the lepton-pair angles provides a beam charge and polarization dependence similar to DVCS.

$$d^7\sigma_P^e = d^7\sigma_{BH_1} + d^7\sigma_{BH_2} + d^7\sigma_{DDVCS} + \mathrm{P}\, d^7\tilde{\sigma}_{DDVCS} - e\left[d^7\sigma_{BH_{12}} + d^7\sigma_{INT_1} + \mathrm{P}\, d^7\tilde{\sigma}_{INT_1}\right] + d^7\sigma_{INT_2} + \mathrm{P}\, d^7\tilde{\sigma}_{INT_2}$$

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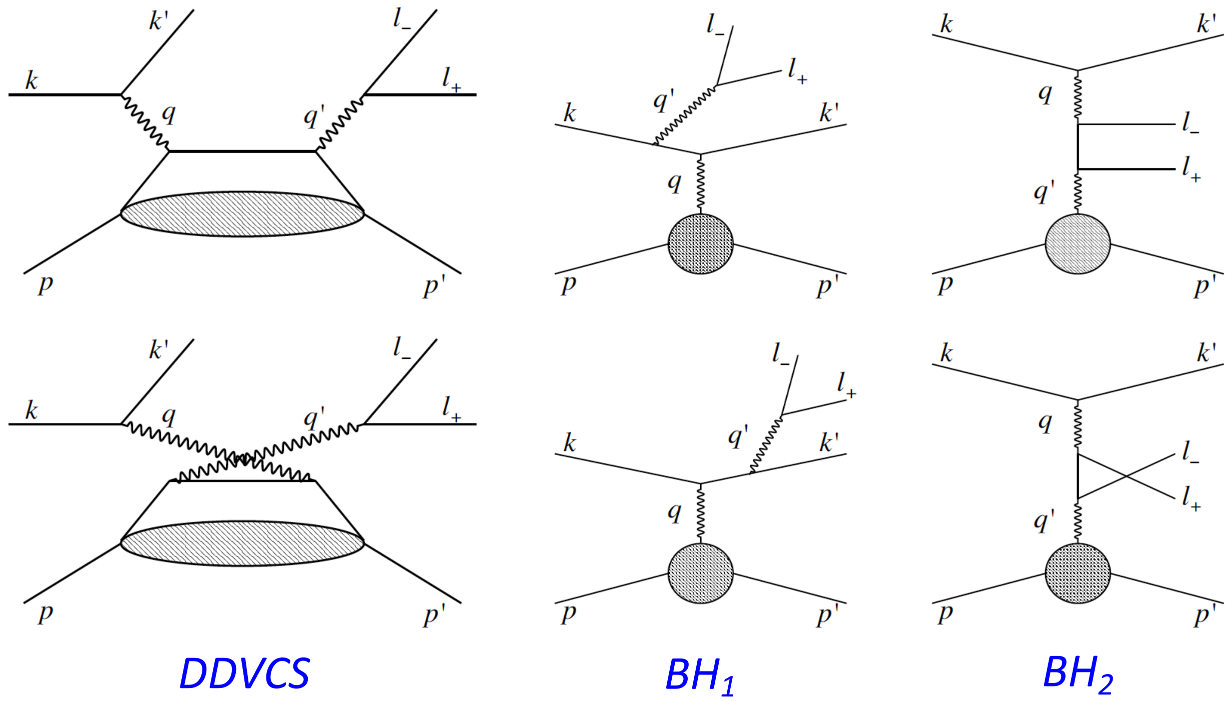

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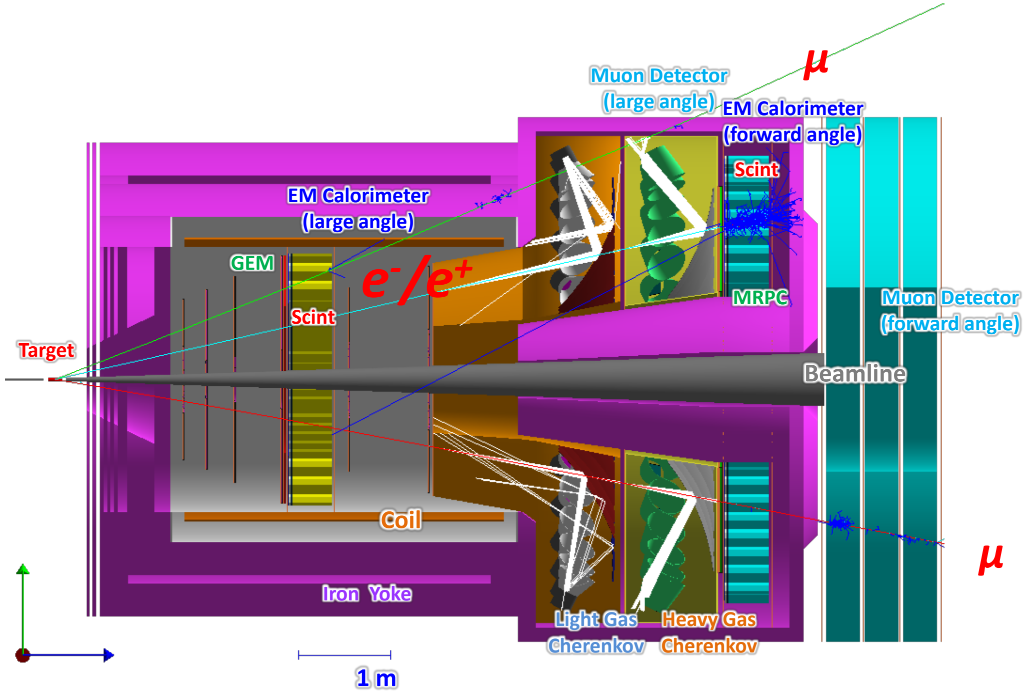
$$\boxed{d^5\sigma_P^e = d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} + P\, d^5\tilde{\sigma}_{DDVCS} - e\left[d^5\sigma_{INT_1} + P\, d^5\tilde{\sigma}_{INT_1}\right]}$$

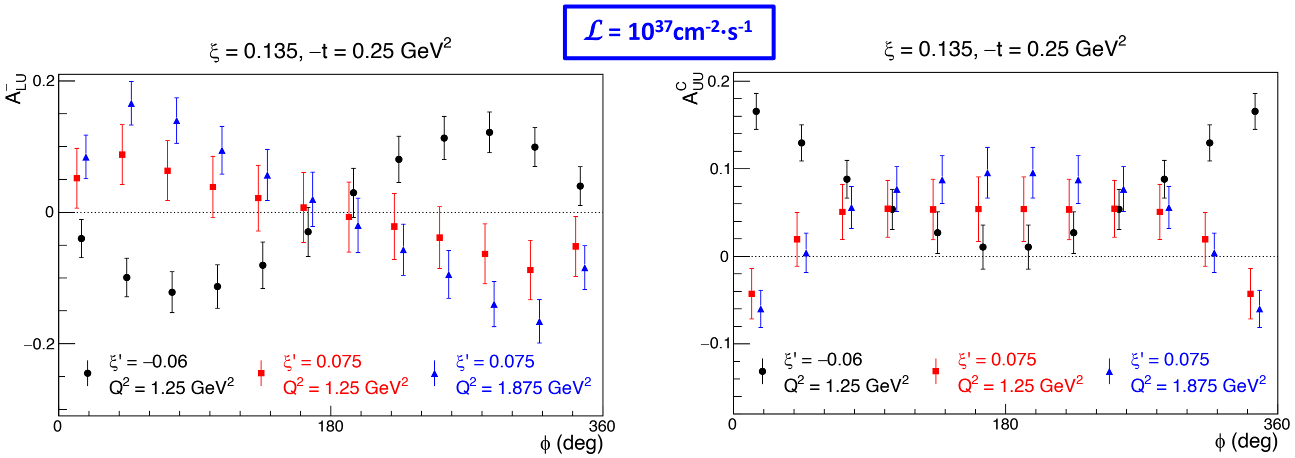
LoI12-15-005

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.

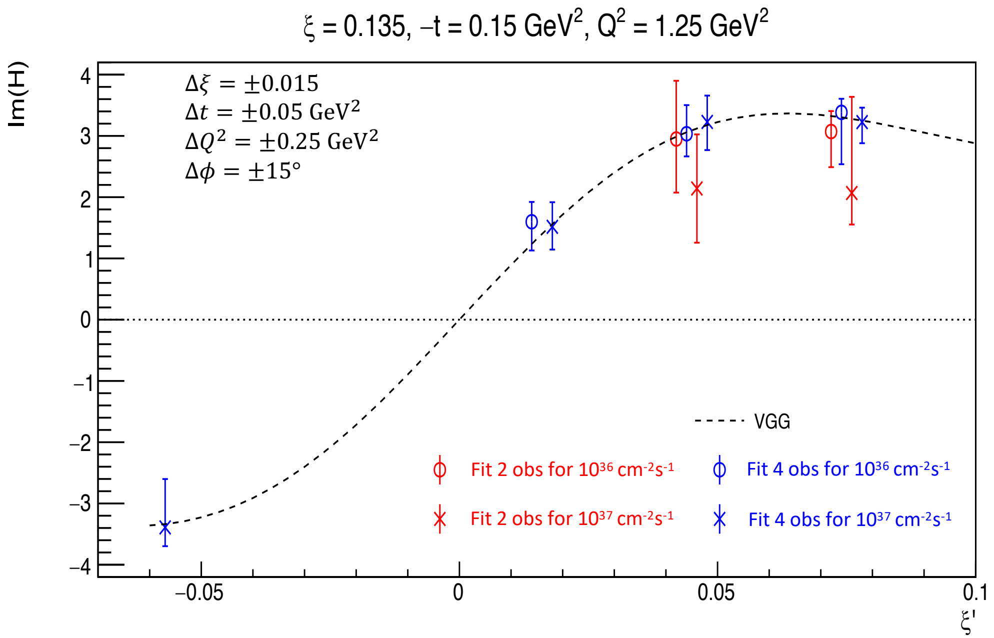


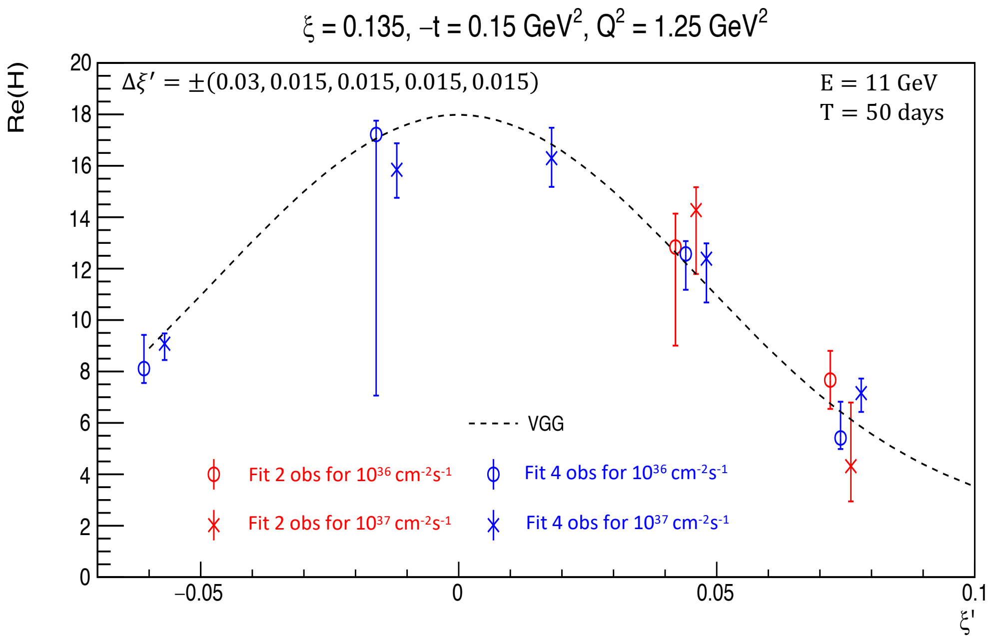


- The initial LoI discussed electron BSA measurements over a 50 days run parasitic to the J/Ψ approved experiment.
- Completing this program with a 50 days positron beam run would provide unpolarized BCA data.

Nucleon tomography

S. Zhao, PoS SPIN2018 068 (2019) S. Zhao, E. Voutier, JPCS 1643 (2020) 012198 S. Zhao, Doctorate Thesis, Université Paris Saclay (2020)
M. Guidal EPJ A 37 (2008) 319 S. Zhao et al. . EPJ A 57 (2021) 240





- Pseudo-data are generated from an **extented VGG** version including **all CFFs**.
- A local fit method at the leading twist and leading order is applied to experimental observables, considering 8 unknown CFFs and **electron only** or **electron and positron** scenarios.

***Positron beams improve CFF determination**, particularly $\mathfrak{Re}[\mathcal{H}]$.*
*A minimal luminosity of **10^{37} cm^{-2}s^{-1}** is needed to **cover efficiently the accessible phase space**.*

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Structure functions

E. Aschenauer, T. Burton, T. Martin, H. Spiesberger, M. Stratman, PRD 88 (2013) 114025

- **Charged** and **electromagnetic currents** access **different quark flavor combinations**.
- **High luminosity** and **polarization capabilities** may compensate the **small center-of-mass energy** at CEBAF, and enable access to **charged current physics**.

$$\frac{d^2\Delta\sigma^{e}_{PL}}{dx\,dy} = \frac{1}{2}\left[\frac{d^2\Delta\sigma^{e}_{P(-1)}}{dx\,dy} - \frac{d^2\Delta\sigma^{e}_{P(+1)}}{dx\,dy}\right] = -\frac{4\pi\alpha^2}{yQ^2}\,(1+eP)^2\left(\frac{G_F M_W^2}{4\pi\alpha}\,\frac{Q^2}{Q^2+M_W^2}\right)^2\left[Y_+ g_5^{W^e} + eY_- g_1^{W^e}\right]$$

Leading order

Polarized electron off protons

$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c \qquad g_5^{W^-} = -\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c$$

$$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c} \qquad g_5^{W^+} = \Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c}$$

Polarized positron off protons

Direct access to $\Delta\Sigma$

$$\boxed{g_1^{W^-} + g_1^{W^+} = \Delta\Sigma}$$

Access to the polarized strange PDF free of hadronization ambiguities

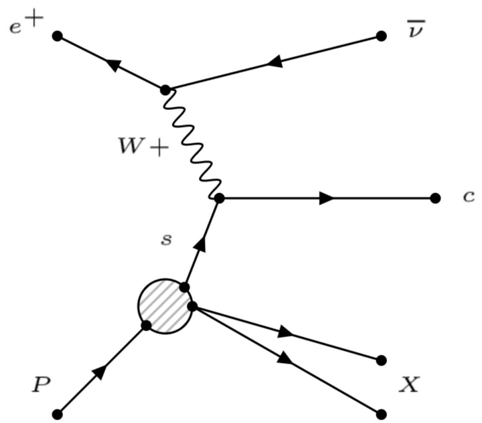
$$\boxed{g_5^{W^-}(p) - g_5^{W^+}(p) + g_5^{W^-}(n) - g_5^{W^+}(n) = 2\left[\Delta c + \Delta\bar{c}\right] - 2\left[\Delta s + \Delta\bar{s}\right]}$$

Strangeness Tagging

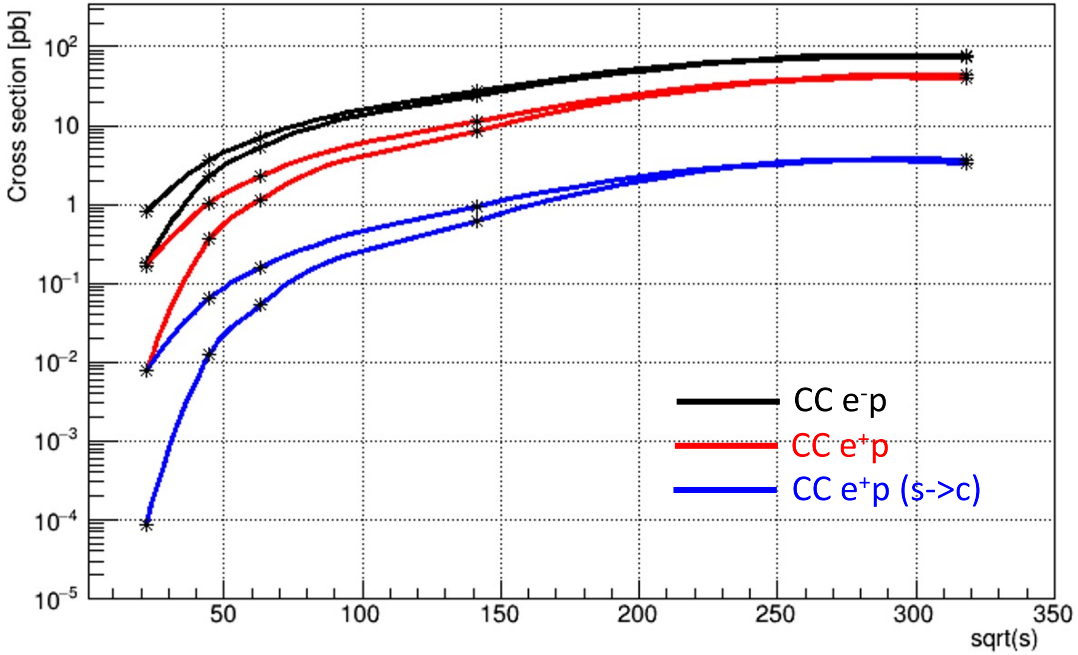
W. Melnitchouk, J.F. Owens, EPJ A 57 (2021) 311

- **Charm production** via **charged current** exchange preferentially couples to the **strange content** of the nucleon.

$$e^+ + \mathrm{p} \rightarrow \overline{\nu_e} + c + X \qquad e^- + \mathrm{p} \rightarrow \nu_e + \bar{c} + X$$



Yulia Furletova (JLab)



- While the **physics** interest of this channel has been **established**, a realistic **experimental scenario** is yet **to be elaborated** and **evaluated**.

PR12-21-006

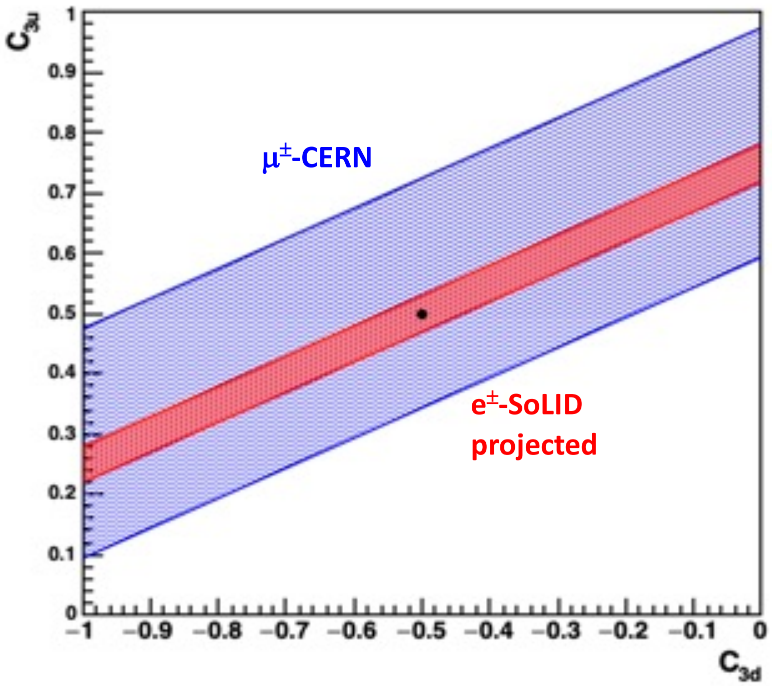
(SoLID and Hall A Collaborations) X. Zheng et al.

X. Zheng (JPos09) AIPCP 1160 (2009) 160   X. Zheng, J. Erler, Q. Liu, H. Spiesberger, EPJA 57 (2021) 5

- Comparing **unpolarized electron** and **positon** DIS scatterings accesses the C_{3q} axial-axial neutral current coupling, and the $F_3^{\gamma Z}$ structure function.

$$C_{3\frac{u}{d}} = -2\, g_A^e g_A^q = \pm\frac{1}{2}$$

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

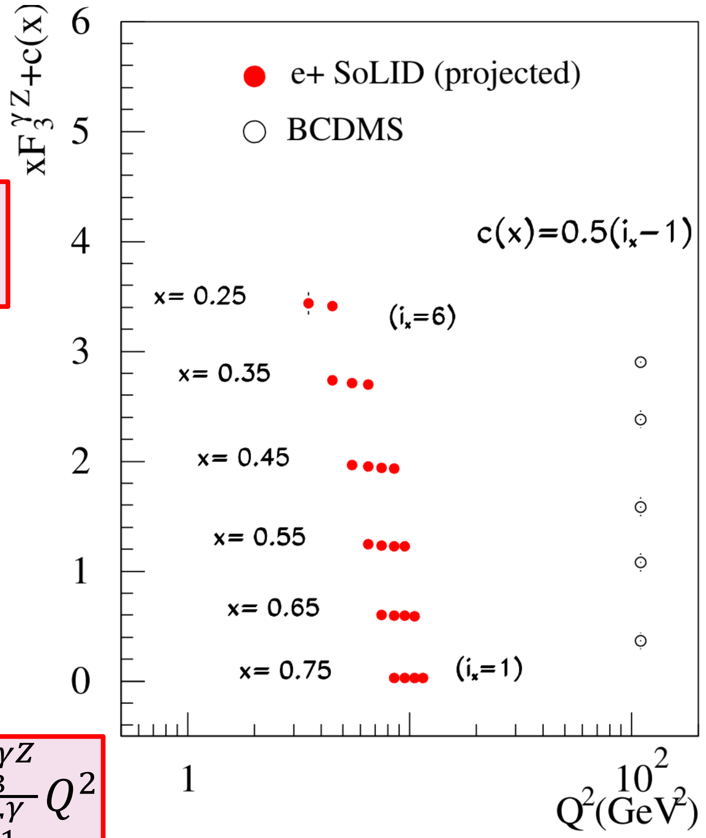


$$\boxed{A_d^{e^+e^-} \approx -108\, Y(y)\, R_q(x) (2C_{3u} - C_{3d})\, Q^2}$$

(in ppm/GeV^2)

$$\boxed{A_d^{e^+e^-} = \frac{d\sigma(e^+d) - d\sigma(e^-d)}{d\sigma(e^+d) + d\sigma(e^-d)}}$$

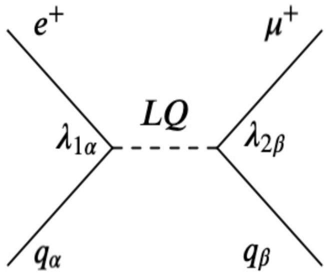
$$\boxed{A_d^{e^+e^-} = \frac{G_F}{2\sqrt{2}\,\pi\alpha} \frac{g_A^e}{2} Y_3 \frac{F_3^{\gamma Z}}{F_1^\gamma} Q^2}$$

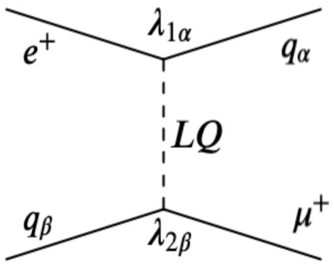


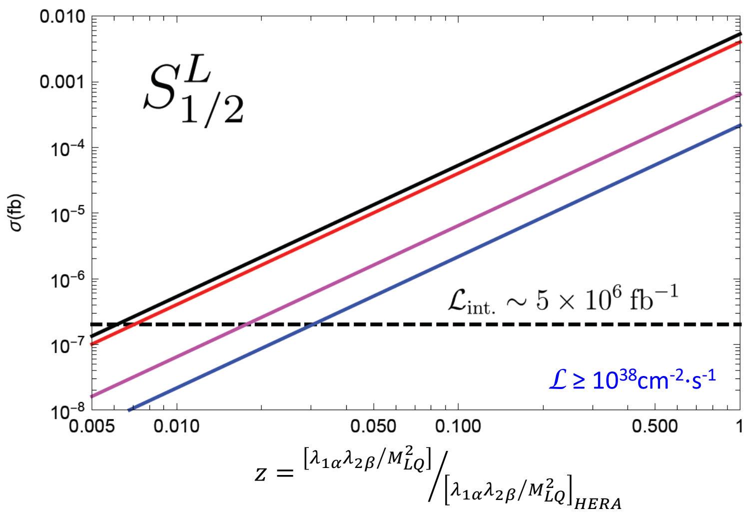
Lepto-Quark Scenario

W. Buchmuller, R. Ruckl, D. Wyler, PLB 191 (1987) 442
Y. Furletova, S. Mantry, (JPos17) AIPCP 1970 (2018) 030005; EPJ A 57 (2021) 315

- In spite of the small c.m. energy, the high luminosity at JLab enables **testing** Charged Lepton Flavor Violation (**CLFV**), and will allow for **substantial improvement over HERA** limits.







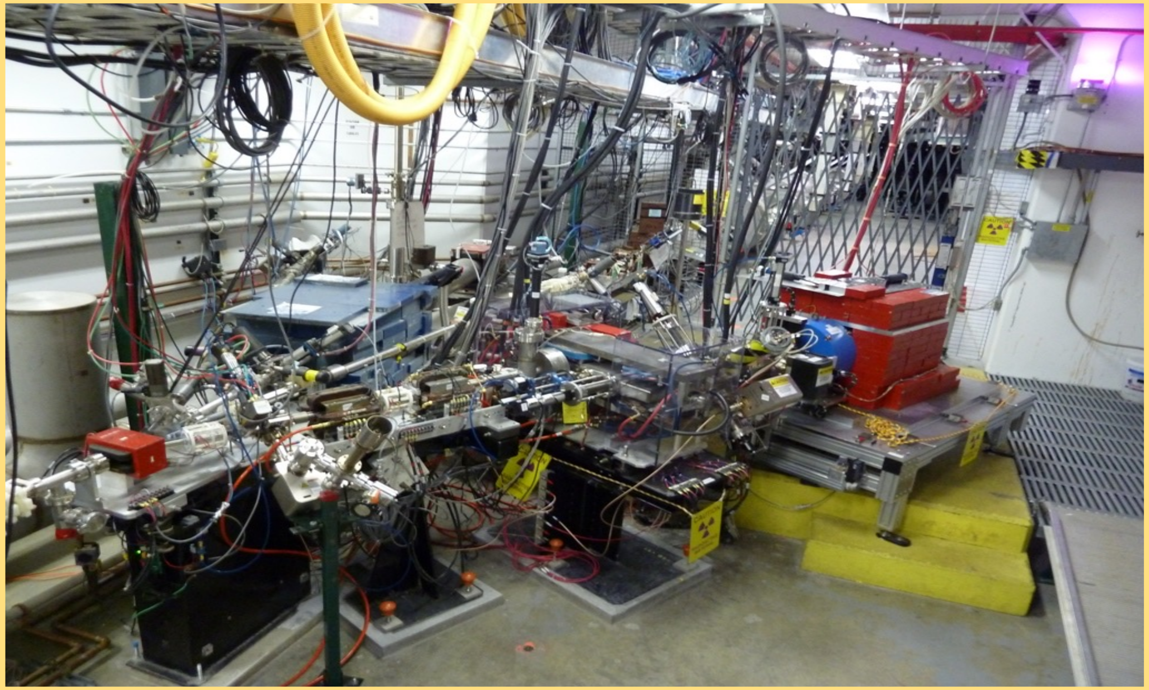
In the Lepto-Quark (LQ) scenario, up to **14 different LQs** may mediate transitions between quarks and leptons.

Type	J	F	Q	ep dominant process	Type	J	F	Q	ep dominant process
S_0^L	0	2	$-1/3$	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	V_0^L	1	0	$+2/3$	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$
S_0^R	0	2	$-1/3$	$e_R^- u_R \rightarrow \ell^- u$	V_0^R	1	0	$+2/3$	$e_L^+ d_R \rightarrow \ell^+ d$
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \rightarrow \ell^- d$	$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \rightarrow \ell^+ u$
S_1^L	0	2	$-1/3$	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	V_1^L	1	0	$+2/3$	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$
			$-4/3$	$e_L^- d_L \rightarrow \ell^- d$				$+5/3$	$e_R^+ u_L \rightarrow \ell^+ u$
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \rightarrow \ell^- d$	$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \rightarrow \ell^+ u$
$V_{1/2}^R$	1	2	$-1/3$	$e_R^- u_L \rightarrow \ell^- u$	$S_{1/2}^R$	0	0	$+2/3$	$e_L^+ d_L \rightarrow \ell^+ d$
			$-4/3$	$e_R^- d_L \rightarrow \ell^- d$				$+5/3$	$e_L^+ u_L \rightarrow \ell^+ u$
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \rightarrow \ell^- u$	$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \rightarrow \ell^+ d$

- Electron and **positron** beams have **different sensitivity** to LQs.
- Beam **polarization** would distinguish between **left-** and **right-handed** LQs.

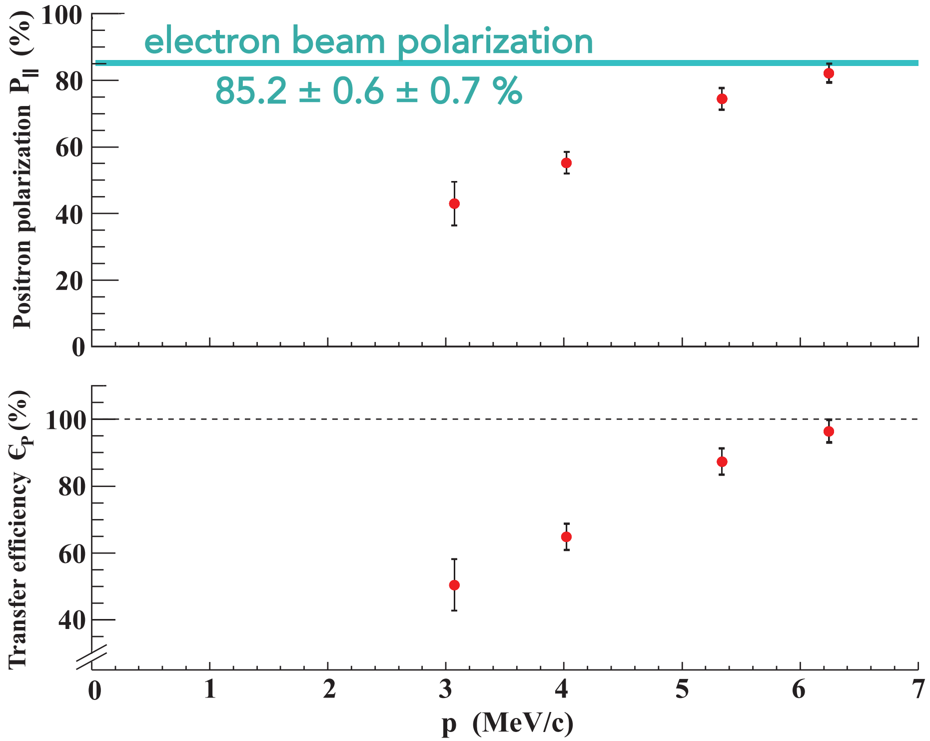
- The JLab positron source built on the **PEPPo** (Polarized Electrons for Polarized Positrons) experiment which demonstrated the feasibility of using bremsstrahlung radiation of **MeV Polarized Electrons** for producing **Polarized Positrons**.

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



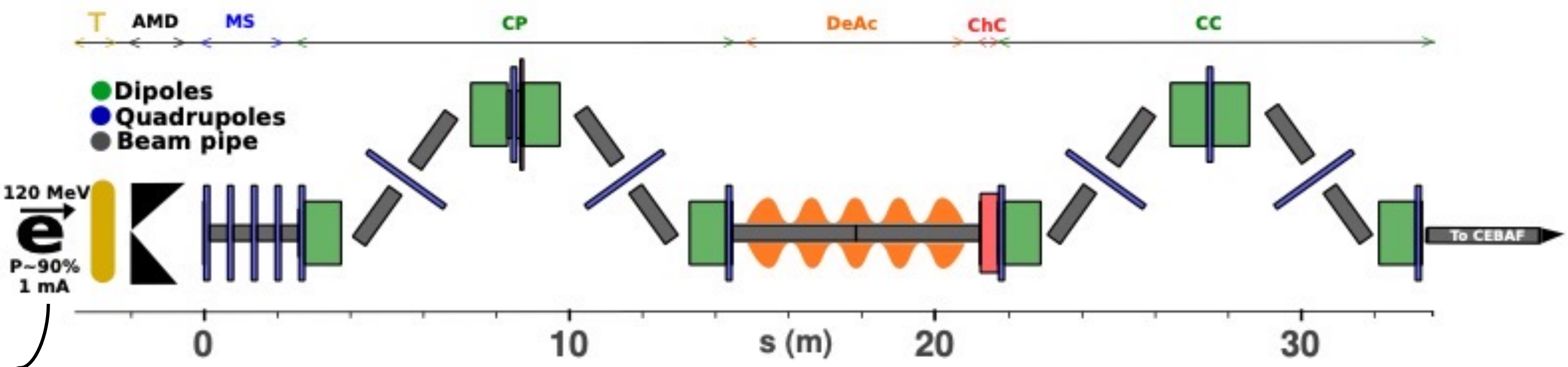
J. Grames, E. Voutier et al. JLab Experiment E12-11-105 (2011)

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



E. Voutier

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



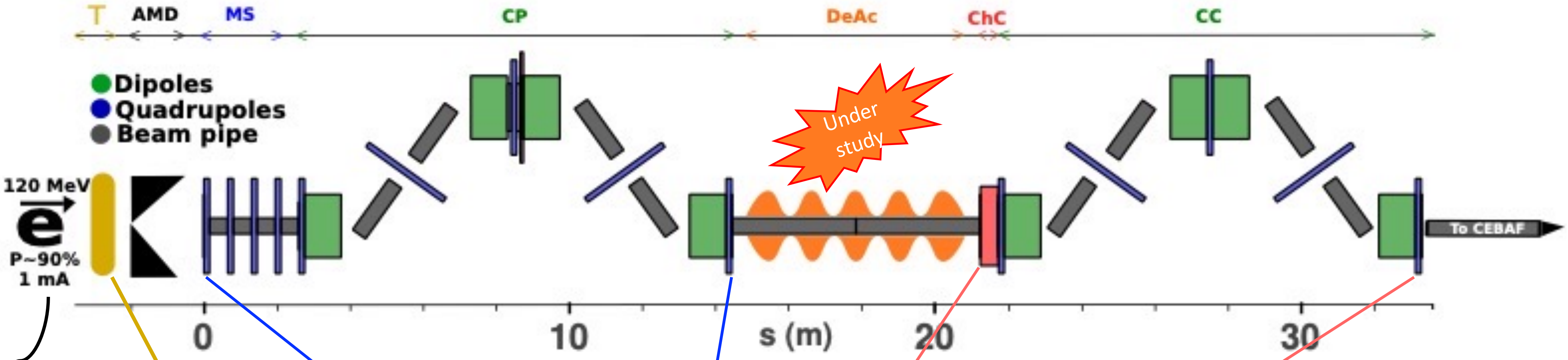
$\mathcal{P}$ = 120 kW
beam power

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.*

- The design of the JLab positron source 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 @ $P_{e+} = 60\%$

$I_{e+} > 3\ \mu$A @ $P_{e+} = 0\%$

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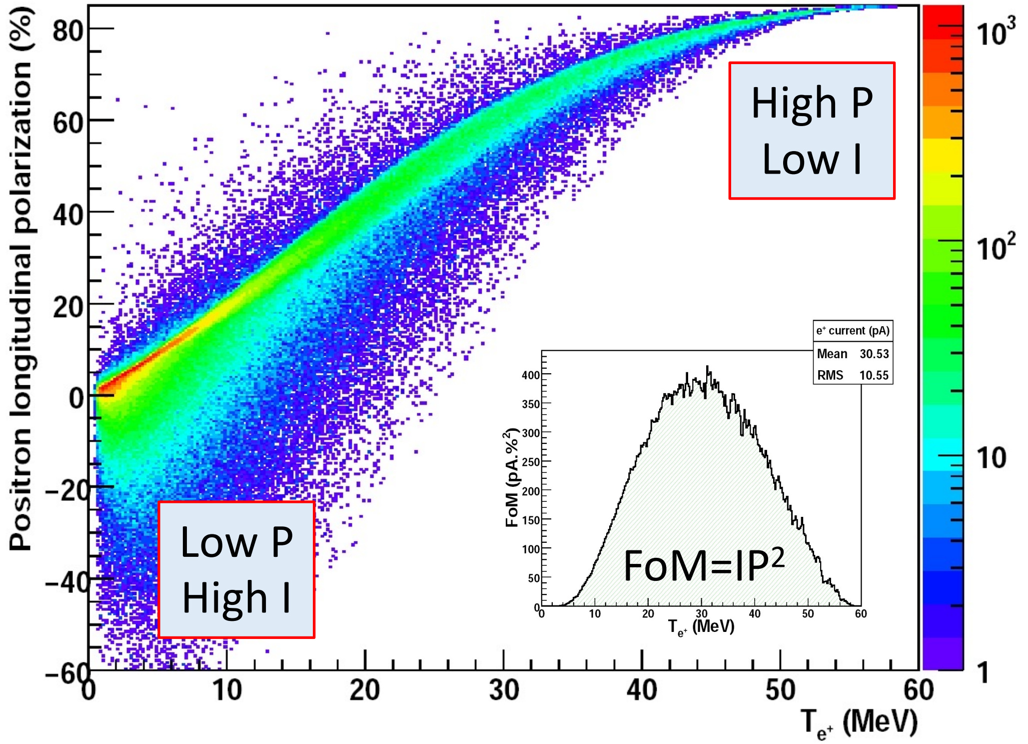
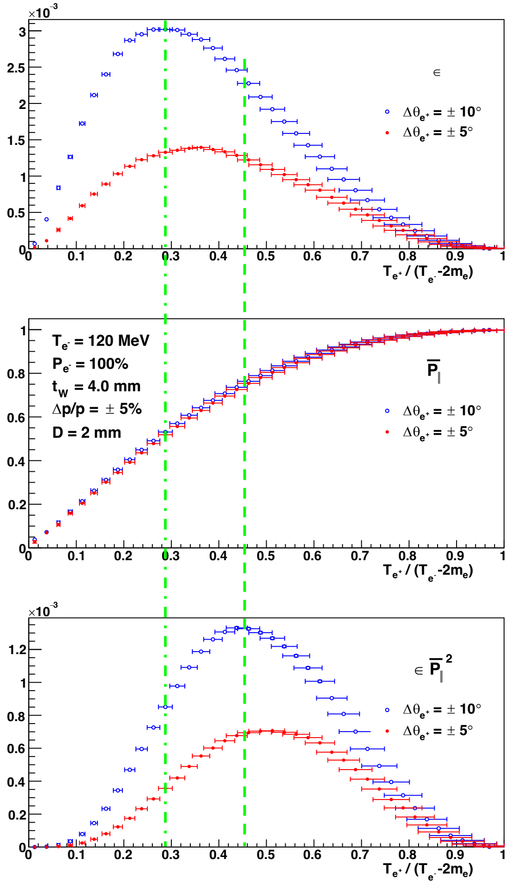
***High duty cycle, intensity**, and **polarization** distinguish JLab positron beam from any past or existing others.*

- 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**.

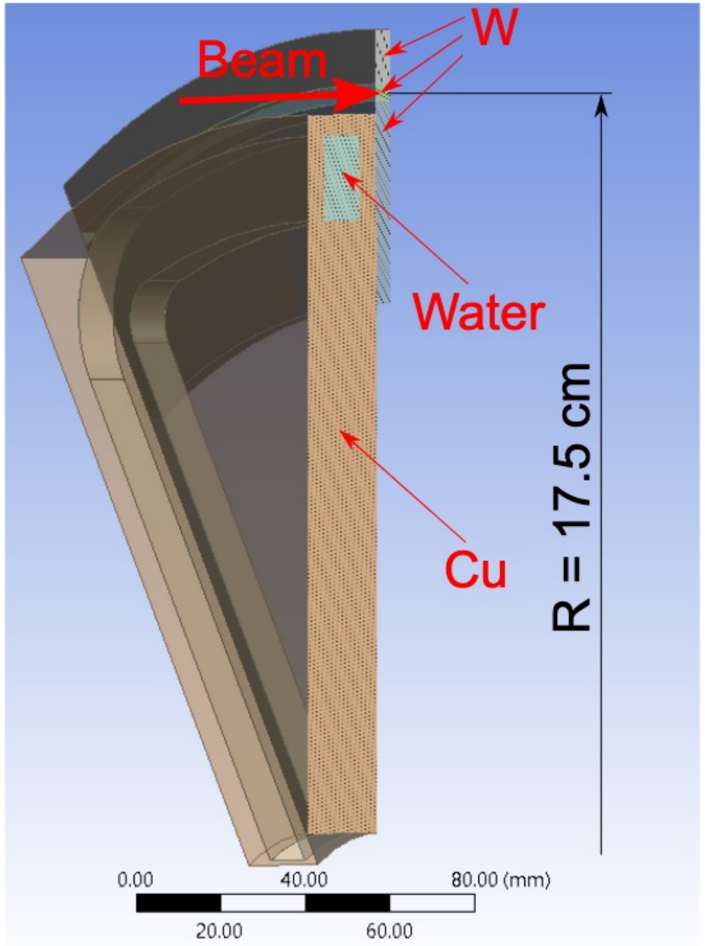




- Selection of e⁺ momentum allows to operate the source from low to highly polarized modes.

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

1/6 segment of the e⁺ target

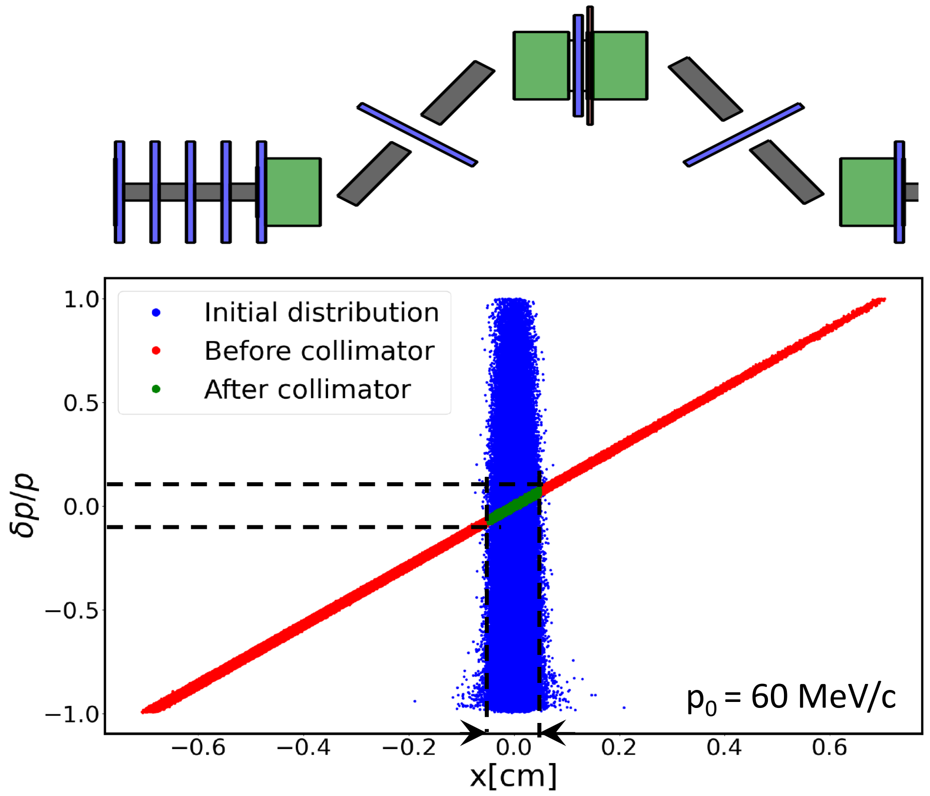


- The electron beam deposits a power of **17 kW** in the **4mm** W target.
- The water channel with turbulent water flows at a speed of **2 m/s** and a **22°C** inlet temperature.
- The beam spot RMS size is **1.5 mm**.
- The rotation speed of the target is **4 m/s**.

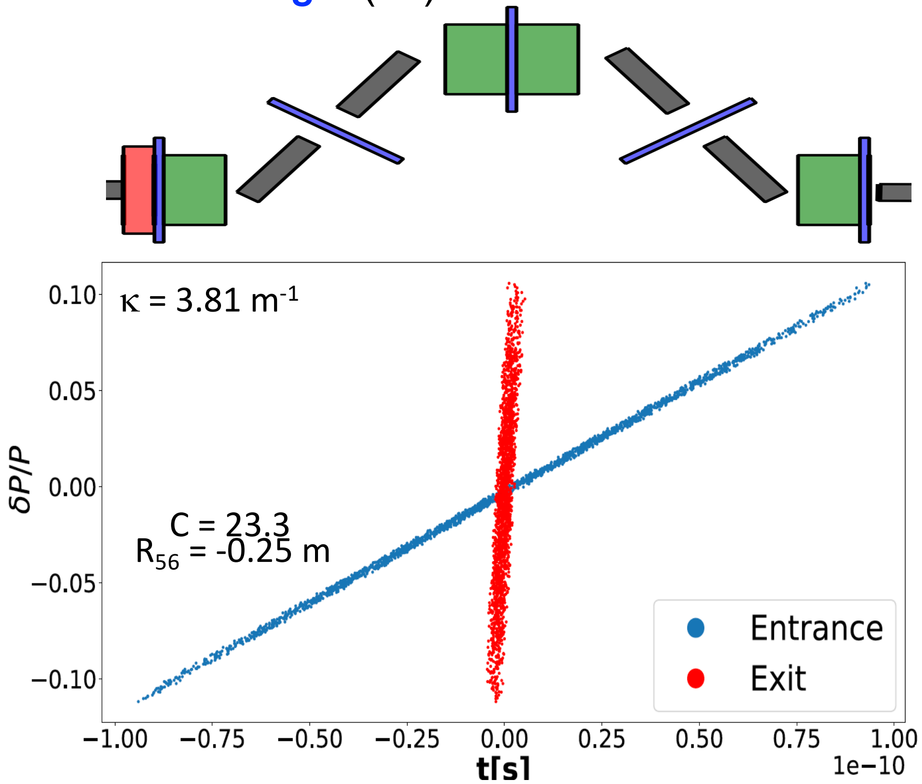
- The tungsten target will operate at an **average temperature** of **258°C** with a **peak temperature** at **376°C** at each rotation cycle.
- The cooling water reaches a temperature of **61°C**.
- The expected life time of the target is a bit more than **1 year** equivalent CEBAF operation.

Work of Andriy Ushakov (IJCLab)

- 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).

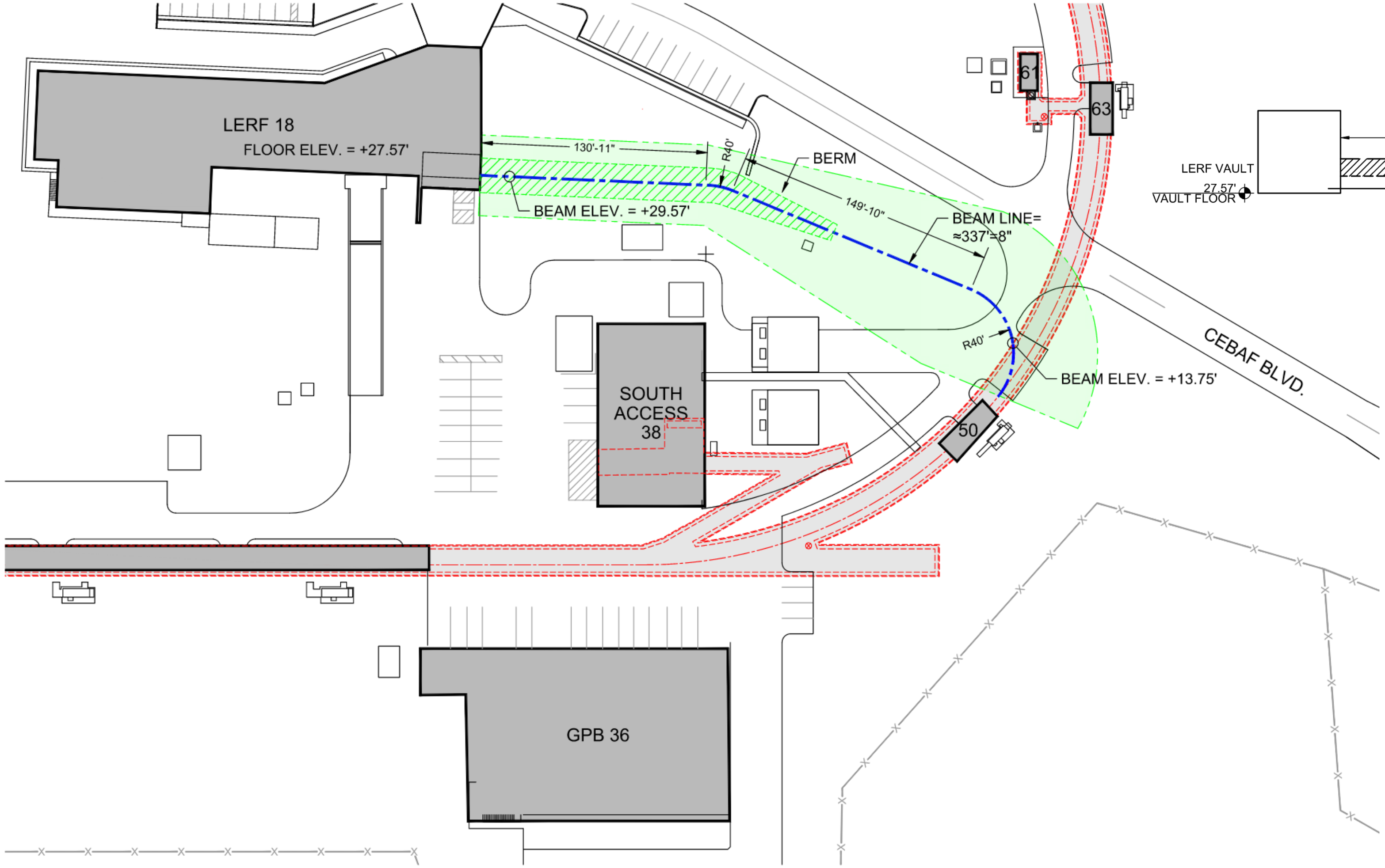


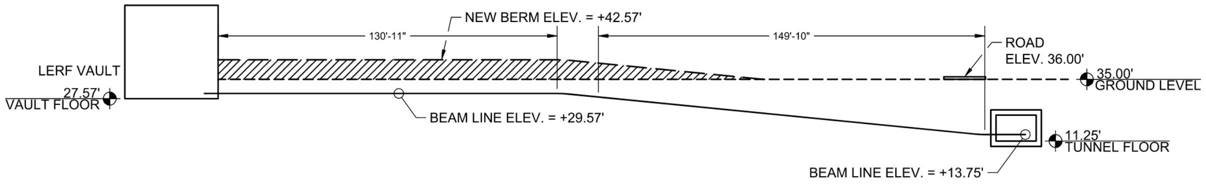
Work of Sami Habet (IJCLab/JLab) and of Yves Roblin (JLab)

- 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 path towards **e^+@CEBAF** is currently studied along the lines :

- Pursing **R&D** in all the areas required for e^+@CEBAF;
- Constructing at the **LERF** a prototype **e^+ injector** operating with **8 MeV** electron beams;
- Producing **e^+ beams suitable** for **CEBAF acceleration**;
- Upgrade to the final **120 MeV e^+ injector**.





- 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)

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.

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement N° 824093.

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**.

  - Several challenges to address from **beam production**, **instrumentation**, and **transport** to experimental halls.
  - The Positron White Paper is not exhaustive and there exists **opportunities** for **many other channels**.

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