Experimental Vistas in Precision Low-Energy Hadron and Nuclear Physics

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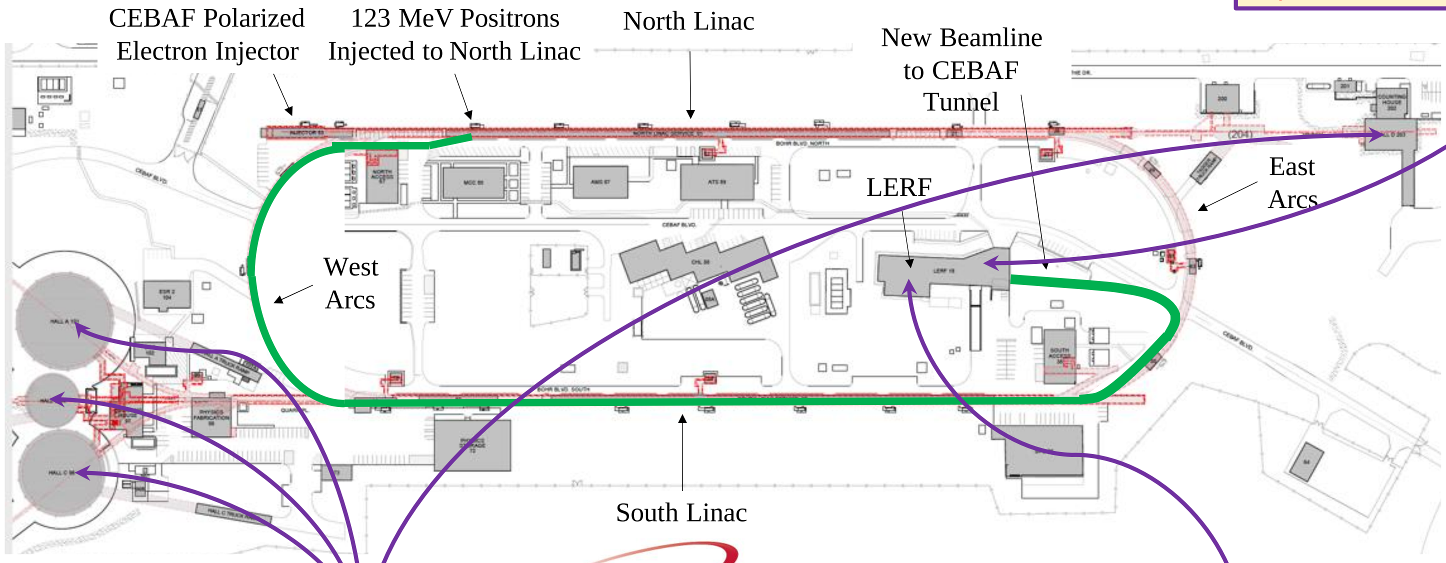
Synergies & Complementarities

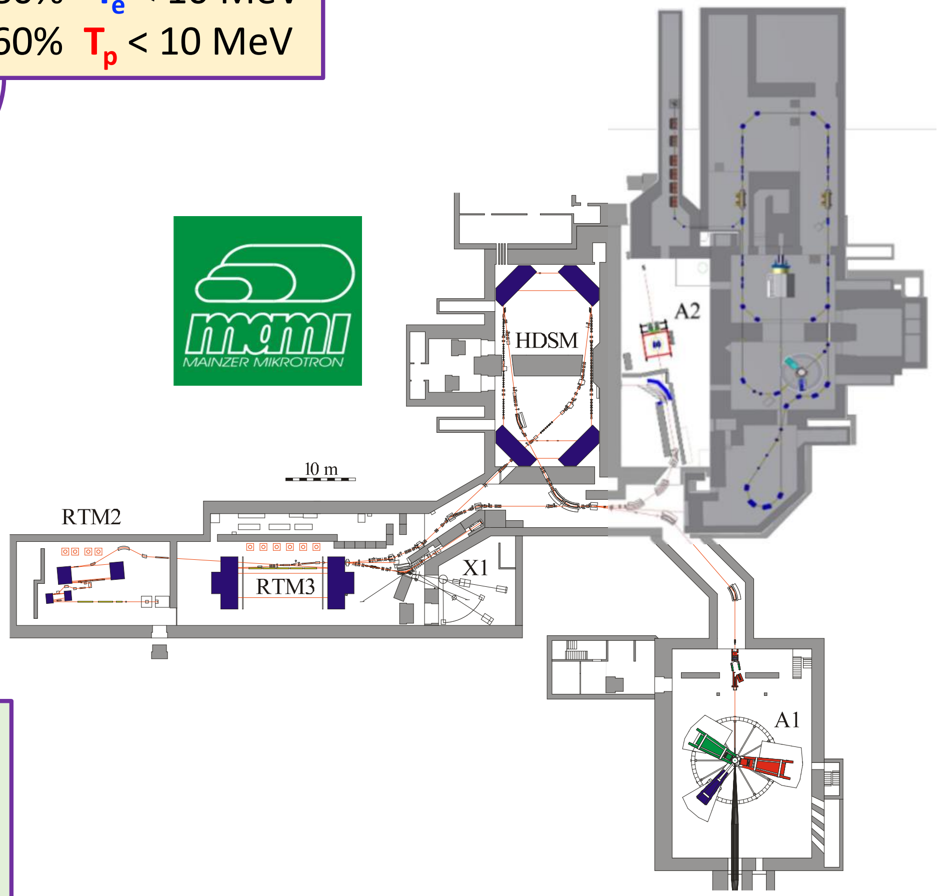
Physics @ **LERF**
at **very low beam energies**

I_e < 10 mA P_e > 80% T_e < 10 MeV
I_p < 10 nA P_p < 60% T_p < 10 MeV



Jefferson Lab

MESA



MAMI
MAINZER MIKROTRON

Physics @ **Ce$^+$BAF**
at high beam energies

I_p > 50 nA P_p > 60%. T_p < 12 GeV
I_p > 1 μA P_p < 10% T_p < 12 GeV

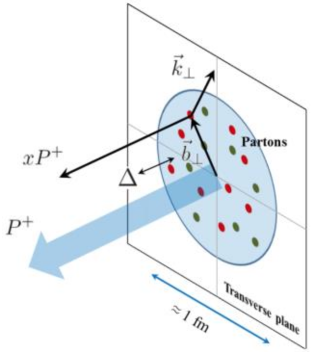
Physics @ **LERF**
at **low beam energies**

I_e < 1 mA P_e > 80% T_e < 150 MeV
I_p > 50 nA P_p > 60% T_p < 123 MeV
I_p > 1 μA P_p < 10% T_p < 123 MeV

The **HP2030** program ran at the *Institut Pascal* of the *Université Paris-Saclay* from October 21st up to November 8th 2024, associating the theoretically oriented **MDHS** initiative and the experimentally oriented **JPhys++** initiative.

https://indico.ijclab.in2p3.fr/event/10641/

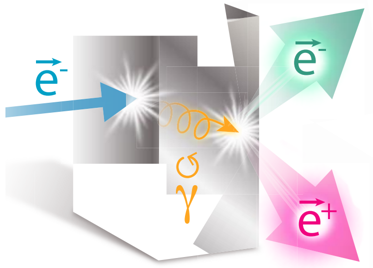
MDHS : Multidimensional Hadron Structure at the Dawn of the High-Precision Era



The scientific goal of **MDHS** was to initiate the reflexion about the **theoretical** and **phenomenological tools** needed to exploit the full potentiality of **high-precision data** (JLab, EIC) and to **connect experimental data with hadron structures**.

C. Mézrag and collaborators

JPhys++ : Physics Opportunities with Jefferson Lab Positron and Energy Upgrades



The scientific goal of **JPhys++** was to develop and obtain the scientific material necessary for **new experimental proposals** and **new directions of research** in support of the **JLab Upgrade Initiatives.**

E. Voutier and collaborators

Form factors

I. The proton charge radius r_E^p
II. The proton electric form factor $G_E^p(Q^2)$
III. The proton axial form factor $G_A^p(Q^2)$

Muti-photon exchange

I. Two-Photon Exchange (TPE) effects in elastic scattering
II. Coulomb corrections in DIS
III. Mott polarimetry

Compton form factors

I. Hadron dynamics
II. Deeply Virtual Compton Scattering (DVCS)
III. Double Deeply Virtual Compton Scattering (DDVCS)

Tests of the Standard Model

I. Dark matter search
II. Electroweak processes
III. Other phenomena

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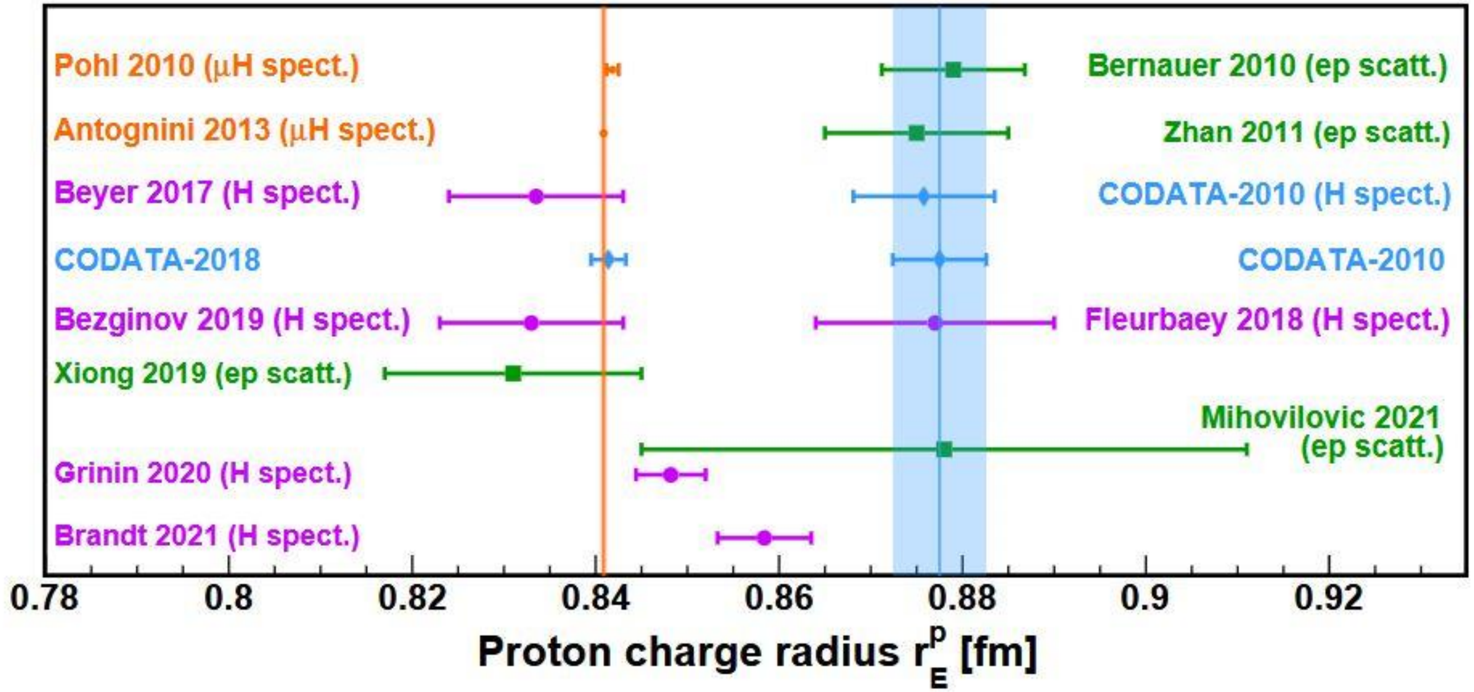
Proton Radius PuzzleS

- The proton radius puzzle originates from the disagreement between muonic hydrogen spectroscopy and electron scattering as well as ordinary hydrogen spectroscopy measurements of the proton electric charge radius.

W. Xiong, C. Peng, Universe 9 (2023) 182



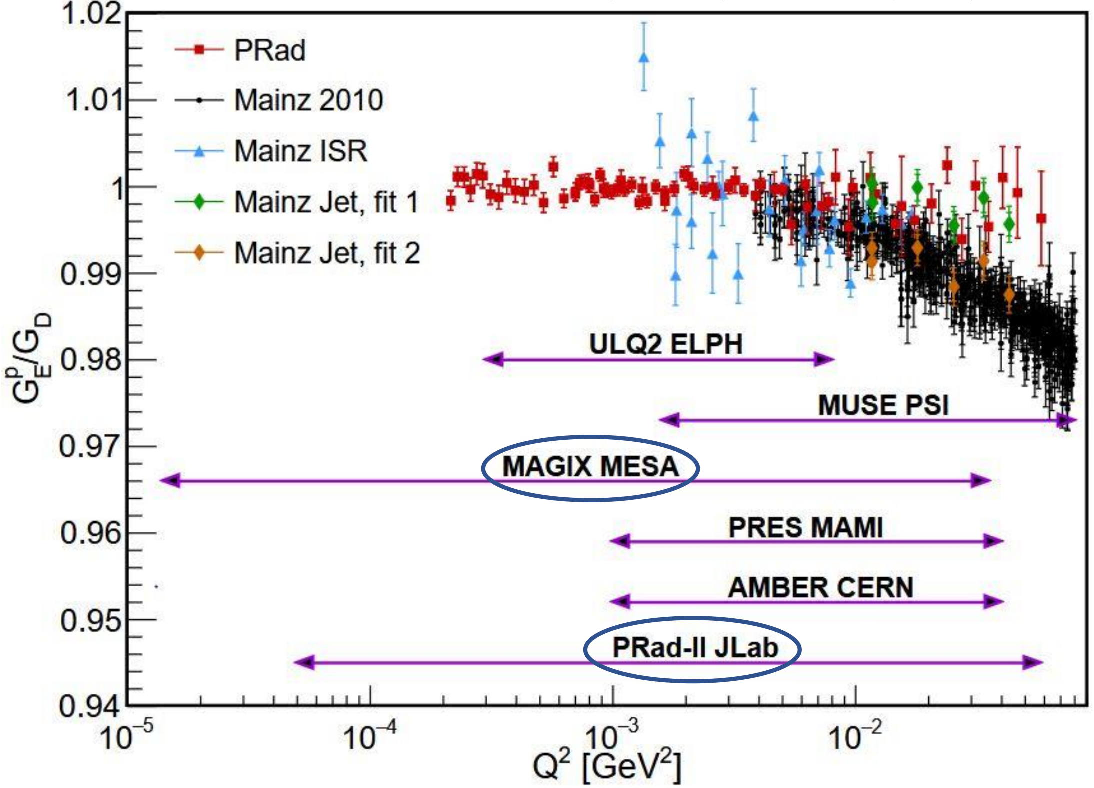
- Are the state-of-the art QED calculations incompletete?
- Are there additional corrections to the muonic Lamb shift due to the proton structure?
- Are higher moments of the charge distribution accounted for in the extraction of the charge radius?
- Is there an extrapolation problem in electron scattering data ?
- Has the violation of lepton universality been discovered?
- Is this an indication of new force carriers?

Electron Scattering Landscape

- After 14 years of investigations, the current status of electron scattering data points towards a tension between the latest PRad 2019 and Mainz 2010 data.

	r_E^p (fm)	$(\delta r_E^p)_{Sta}$ (fm)	$(\delta r_E^p)_{Sys.}$ (fm)	Reference
Mainz	0.879	0.005	0.005	PRL 105 (2010) 242001
PRad	0.831	0.007	0.012	Nature 575 (2019) 147
Mainz ISR	0.878	0.011	0.031	EPJ A 57 (2021) 107
Alarcon 2020	0.842	0.002	0.010	PRC 102 (2020) 035203
Lin 2022	0.840	0.003	0.002	PRL 128 (2022) 052002
Atac 2021	0.852	0.002	0.009	EPJ A 57 (2021) 65
Gramolin 2022	0.889	0.005	0.006	PRD 105 (2022) 054004
Atoui 2024	0.826	0.001	0.008	PRC 110 (2024) 015207

W. Xiong, C. Peng, Universe 9 (2023) 182

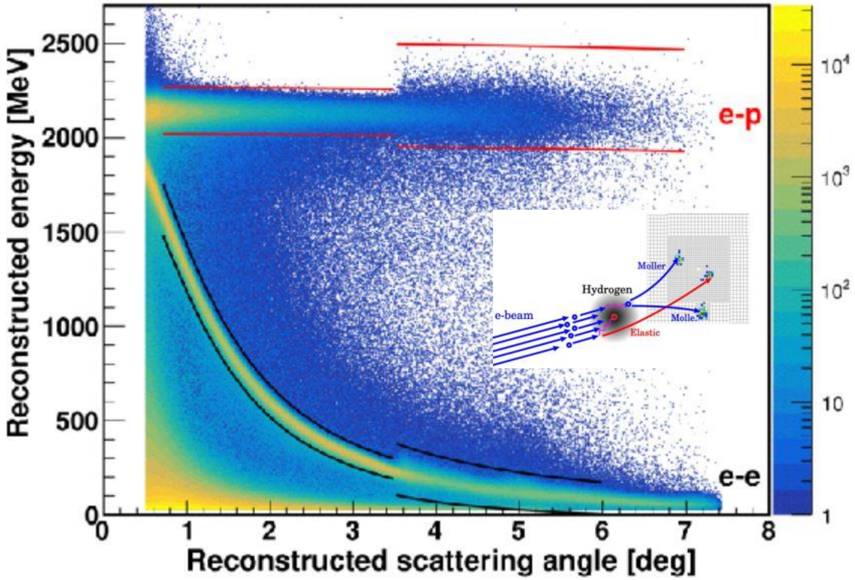


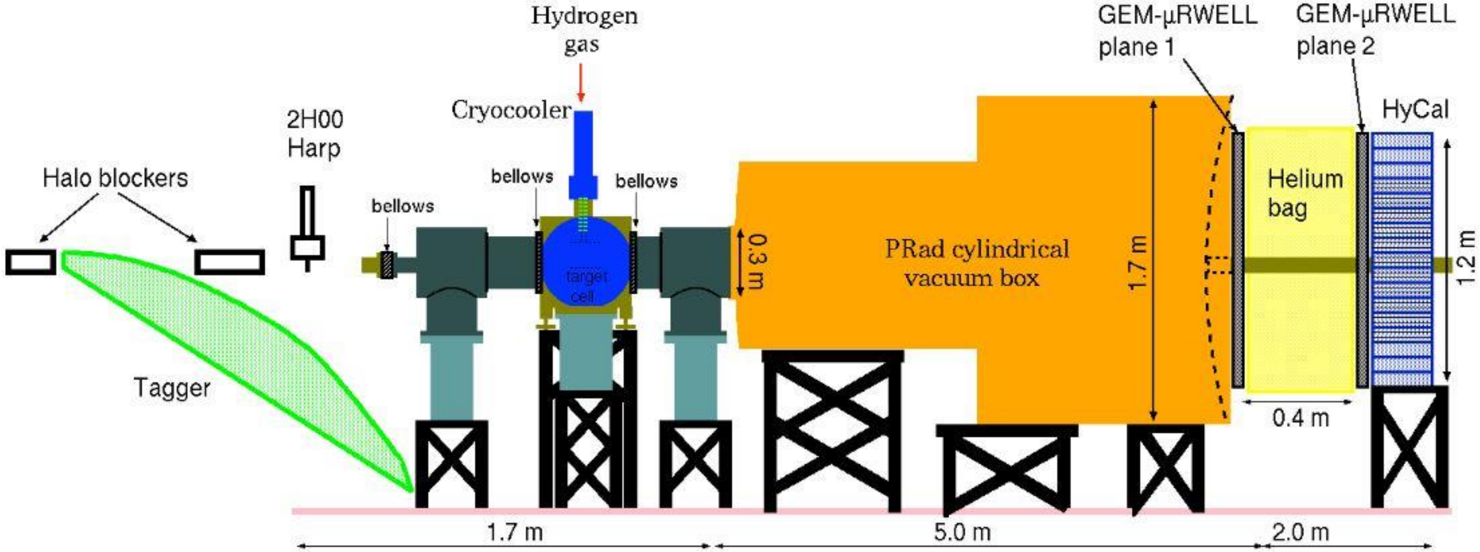
PRad-II A. Gasparian et al. PR12-20-004

- The second PRad experiment is designed to be **3.5 times more precise** than the first one, taking down the precision to **0.0043 fm**.
- This involves **improved statistics** (4 times less uncertainties) and hardware upgrade to **reduce systematics**.

- Full tracking capabilities with a second GEM/μRwell detection plane
- Small scintillators downstream of the target to veto Moller electrons and reach very low Q^2

- Upgrade DAQ electronics to fADCs
- Upgrade HyCal leadglass crystals to $PbWO_4$
- New beam halo blockers

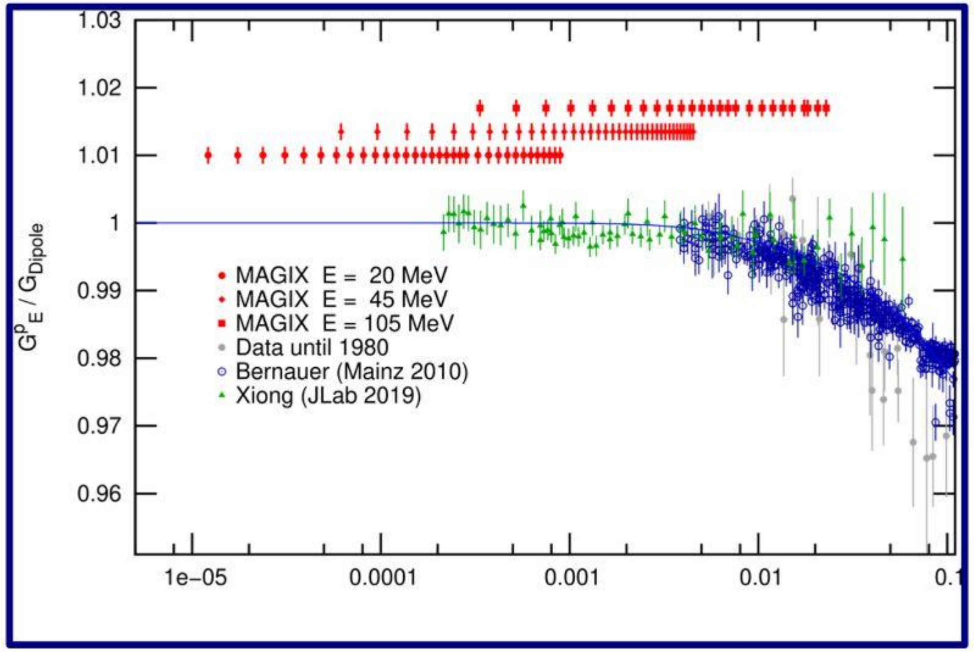


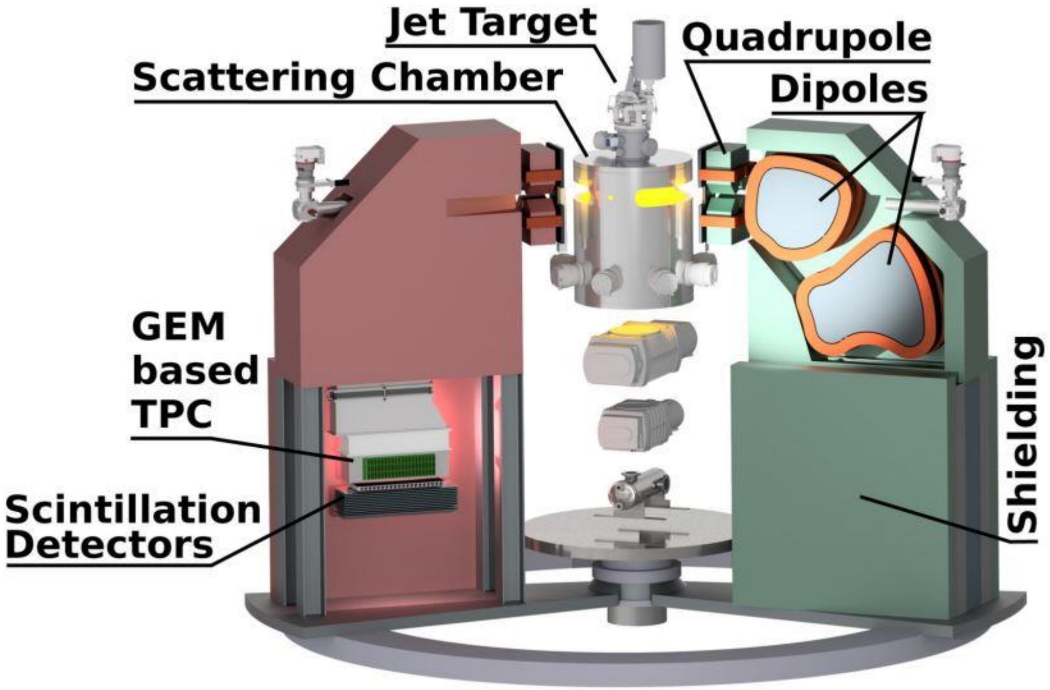


Data taking to start in November 2025

MAGIX

- The MAinz Gas Injection target eXperiment (MAGIX) is designed to operate at the Mainz Energy recovering Superconducting Accelerator (MESA) at a luminosity of $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Involving a windowless jet gas target, high resolution spectrometers ($\sim 10^{-4}$, 1 mrad), and a 1 mA electron beam current, the setup is expected to achieve electromagnetic form factor measurements with a precision better than 0.1%.





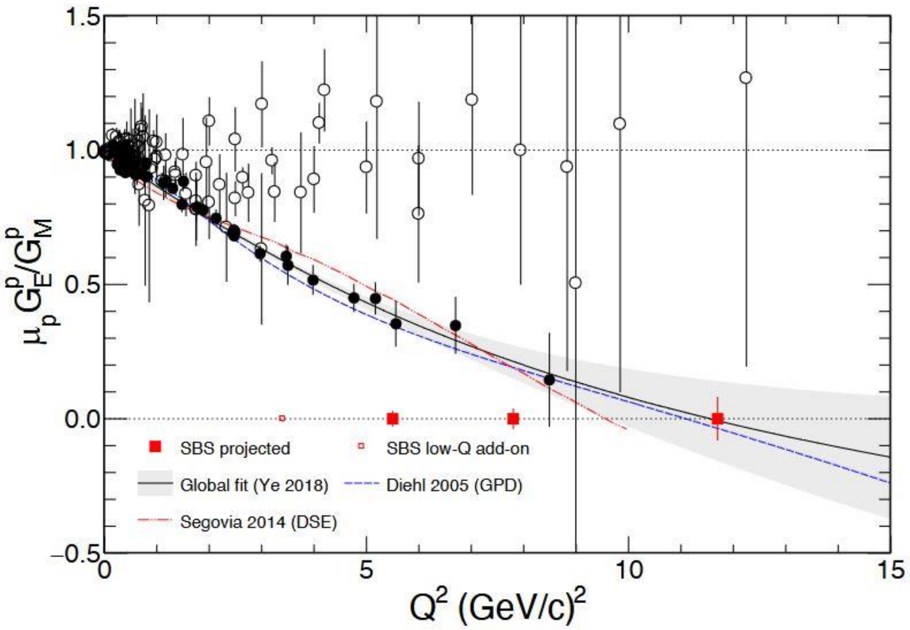
B.S. Schlimme et al. NIM A 1013 (2021) 165668

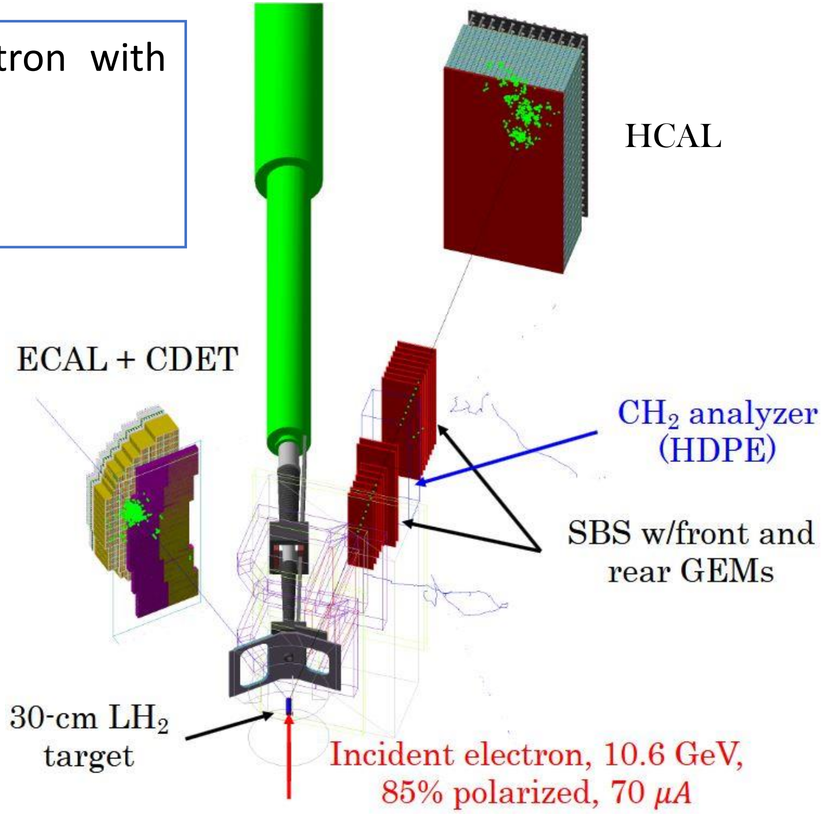
SBS-GEP @ Hall A

E. Cisbani, M.K. Jones,N. Lyanage, L. Pentchev, A. Puckett, B. Wojtsekhowski et al. E12-07-109

- The large Q^2 behaviour of the proton electromagnetic form factor ratio will be measured in the SBS-GEP polarization transfer experiment.

  - Novel high-temperature lead-glass calorimeter (ECAL) to detect scatterred electron with scintillator based coordinate detector (CDET)
  - GEM-based trackers with CH2 analyzer for proton polarimetry
  - HCAL for trigger and selection of high analyzing power scattering events





Data taking to start in February 2025

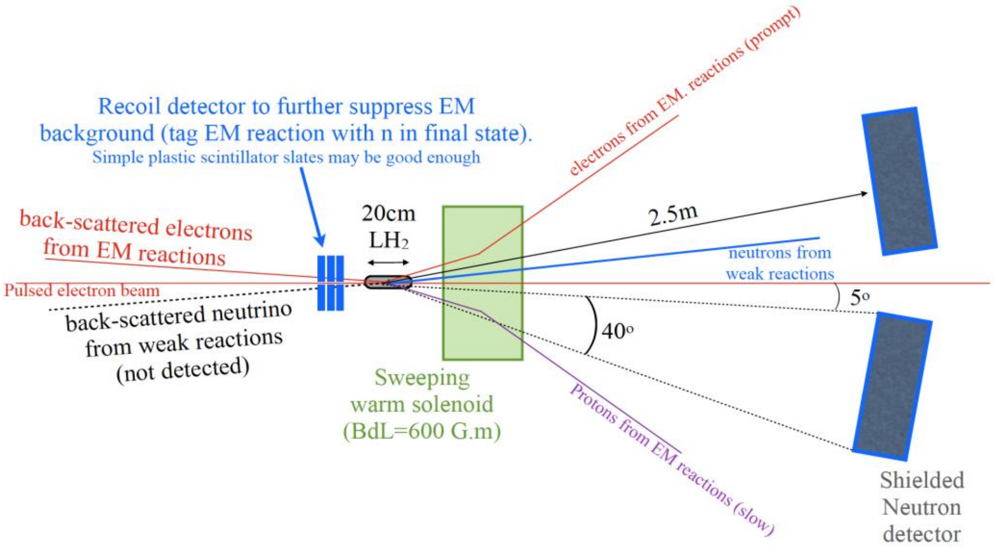
Axial Form Factor @ LERF

A. Deur @ HP2030

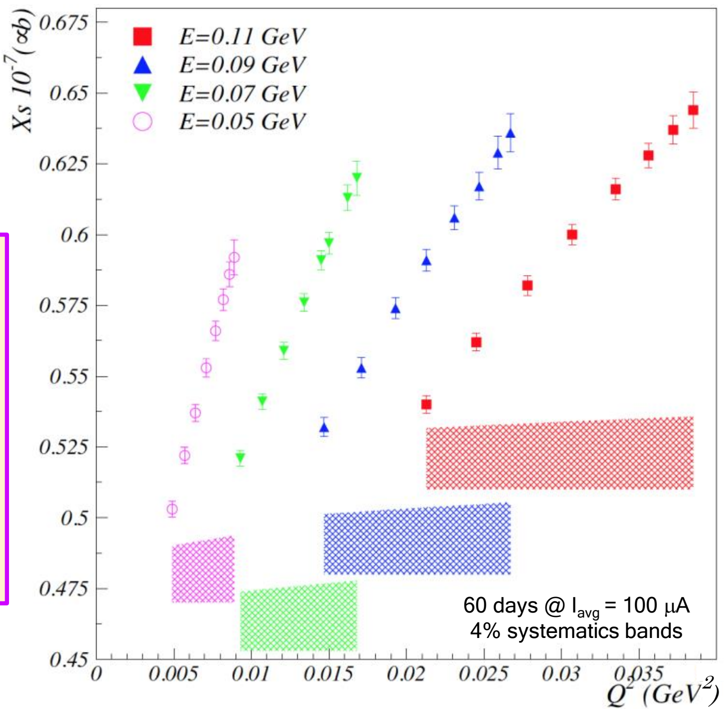
- Taking advantage of a high intensity (I_e < 1 mA), highly polarized (P_e > 80%) electron beam with low energy (T_e < 150 MeV), the axial form factor $G_A(Q^2)$ of the proton can be measured in **elastic scattering**, that is **inverse β-decay**.
- The experiment does not require new technology but demands a **well-designed detector** and very efficient **background suppression techniques**.

$$\vec{e}^- + p \longrightarrow n + \nu_e$$

***Inverse β-decay is** the cleanest access to $G_A(Q^2)$*



- **Pulsed** (50 MHz) electron beam
- High efficiency **neutron detector**
- **Sweeping** magnet
- Electron **recoil detector**
- **High purity LH_2** target with **Be windows**



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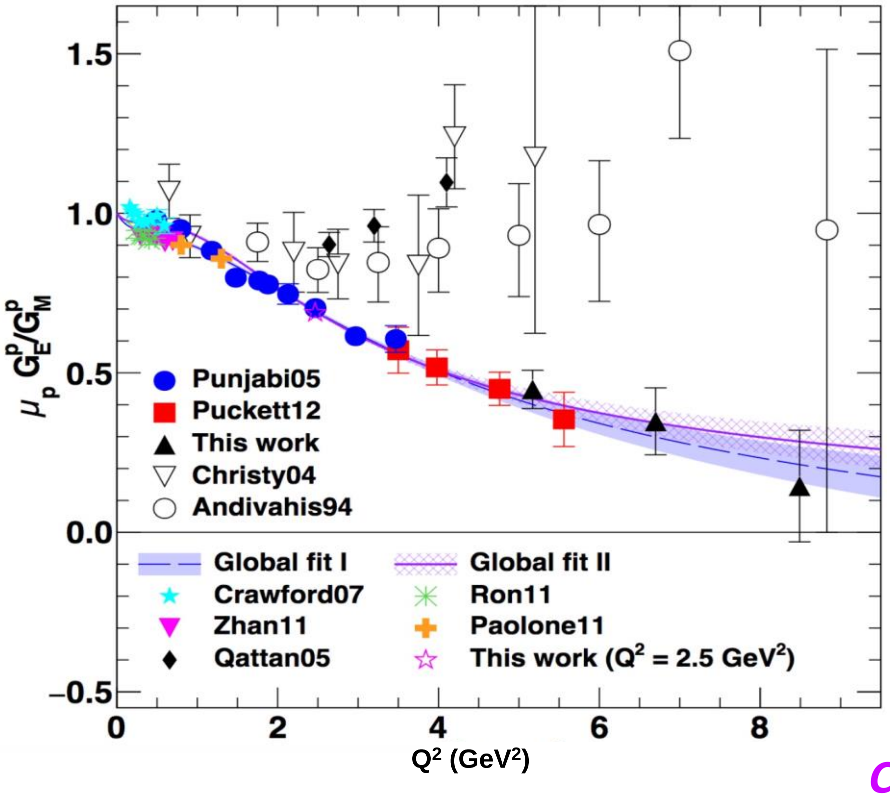
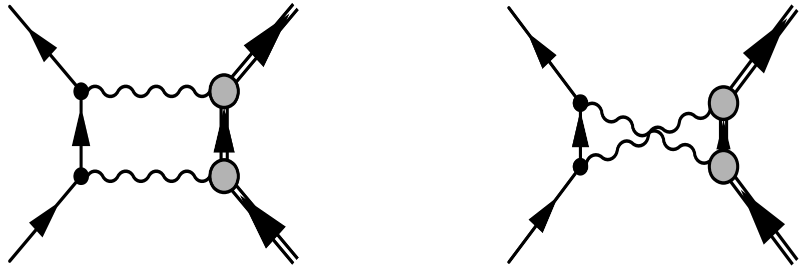
The Dilemma

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 within model-dependent approaches.

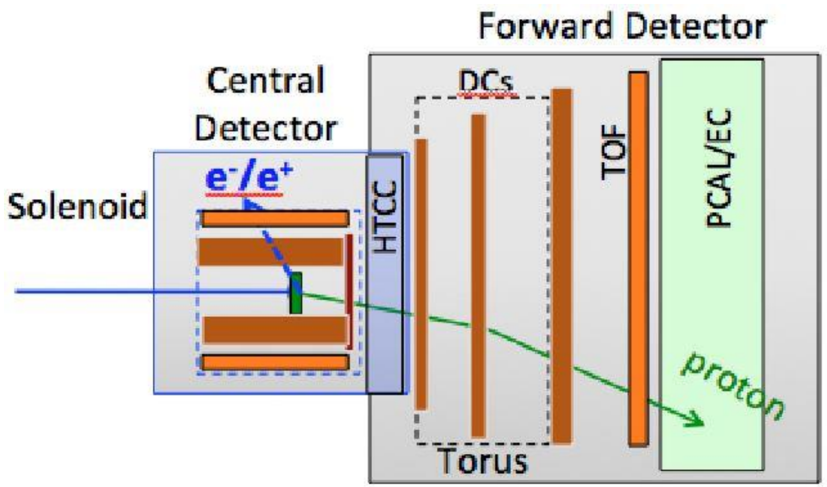
***Ce⁺BAF** has the unique opportunity to bring a **definitive answer** about TPE.*

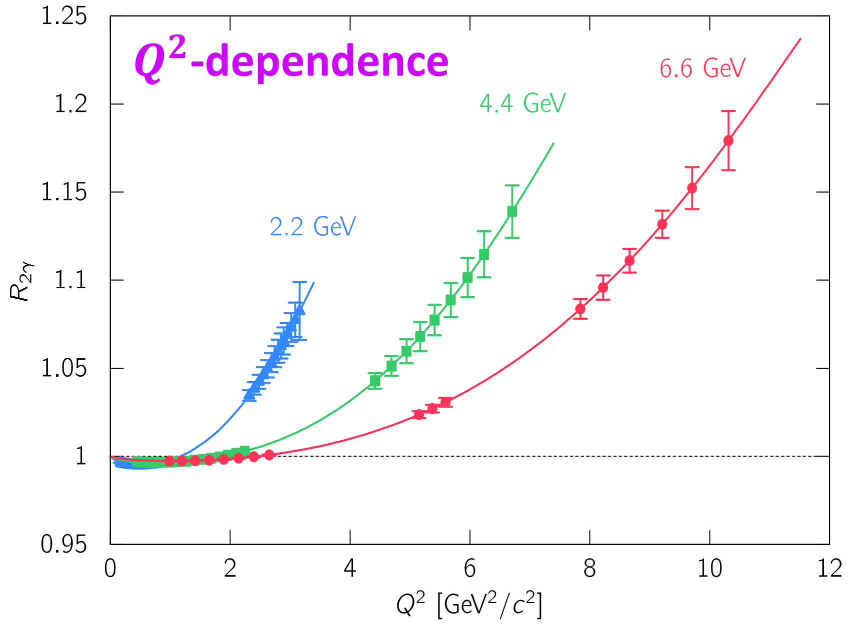
TPE Mapping

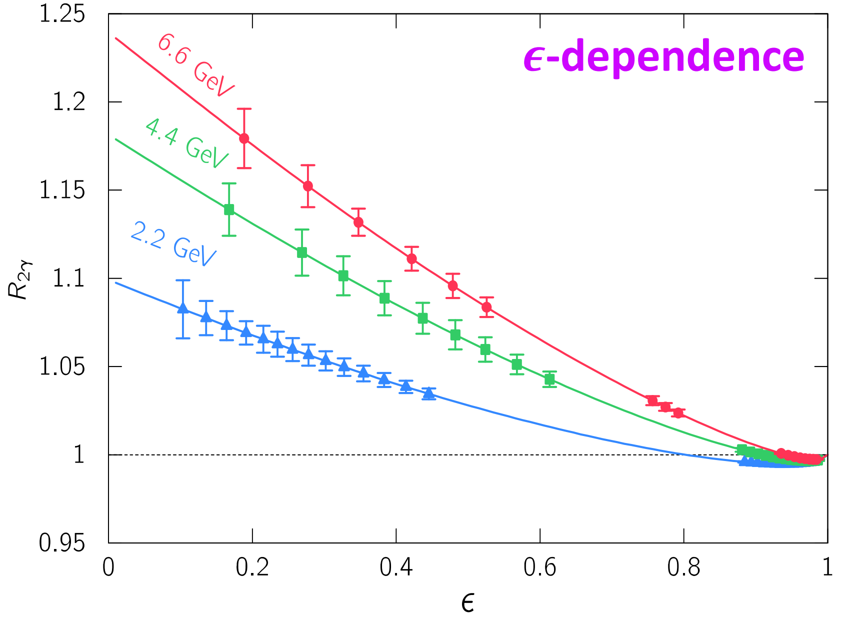
J.C. Bernauer et al. EPJ A 57 (2021) 144
A. Schmidt, J.C. Bernauer, V. Burkert, E. Cline, I. Korover, T. Kutz, S.N. Santiesteban et al. PR12+23-008

- 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, detecting leptons in the Central Detector and protons in the Forward Detector.
- The CLAS12 trigger will be modified to accept lepton detection in the Central Detector and elastic protons in the Forward Detector.

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





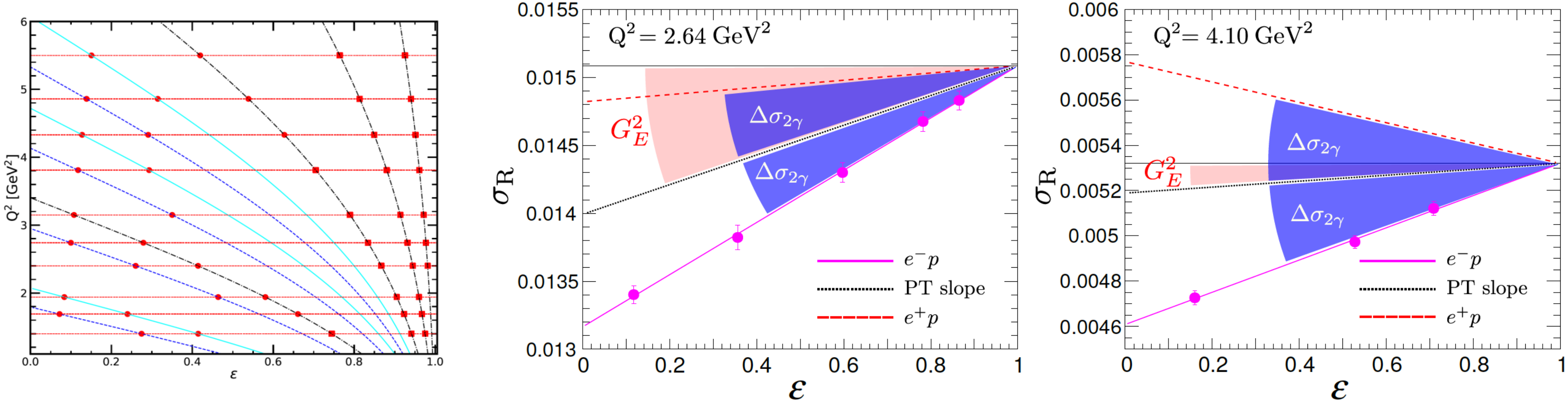


Super-Rosenbluth Slope

J.R. Arrington, M. Yurov EPJ A 57 (2021) 319
M. Nycz, J.R. Arrington, S.N. Santieseban, M. Yurov et al. PR12+23-012

- The direct comparison of the ε-slopes of the positron and electron elastic cross section doubles the sensitivity to a TPE signal.
- The positron and electron average data cancels TPE effects and allow to test the existence of additional effects from the comparison to polarization transfer data expectations.
- The Super-Rosenbluth technique will be used to measure the ε-dependence of the cross section.

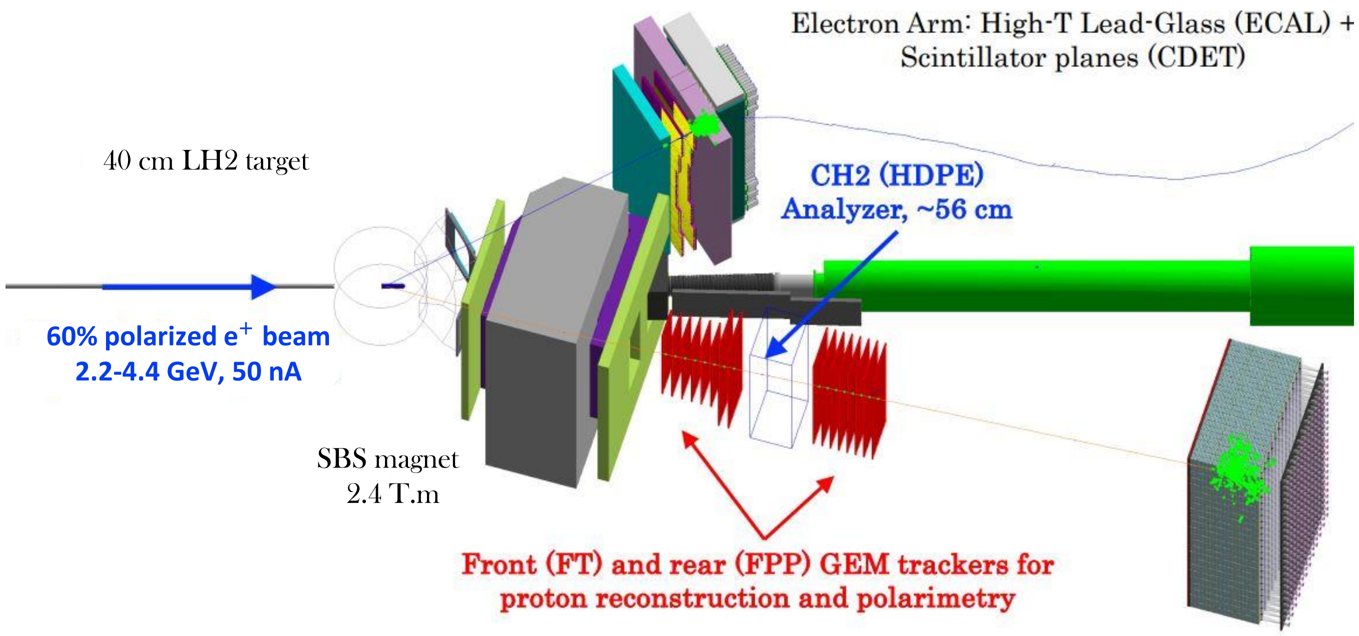
$$\sigma_R = G_M^2 \pm G_M \alpha_{\sigma_{2\gamma}} + \frac{\varepsilon}{\tau}\left(G_E^2 \pm \Delta_{\sigma_{2\gamma}}\right)$$



Polarization Transfer

A.J.R. Puckett, J.C. Bernauer, A. Schmidt EPJ A 57 (2021) 188 A.J.R. Puckett, J.C. Bernauer, A. Schmidt et al. LOI12+23-008

- The theoretical evaluation that **polarization transfer** experiments are much **less sensitive** to TPE effects than cross section measurements **must be confronted to experimental measurements**.
- Within the **same detector configuration** as the **SBS GEP** experiment and a **longer LH_2 target** (40 cm), the beam-to-proton polarization transfer in elastic scattering is proposed to be measured with a **2-4%** precision (statistics limited) in the **2.5-3.4 GeV^2** domain.



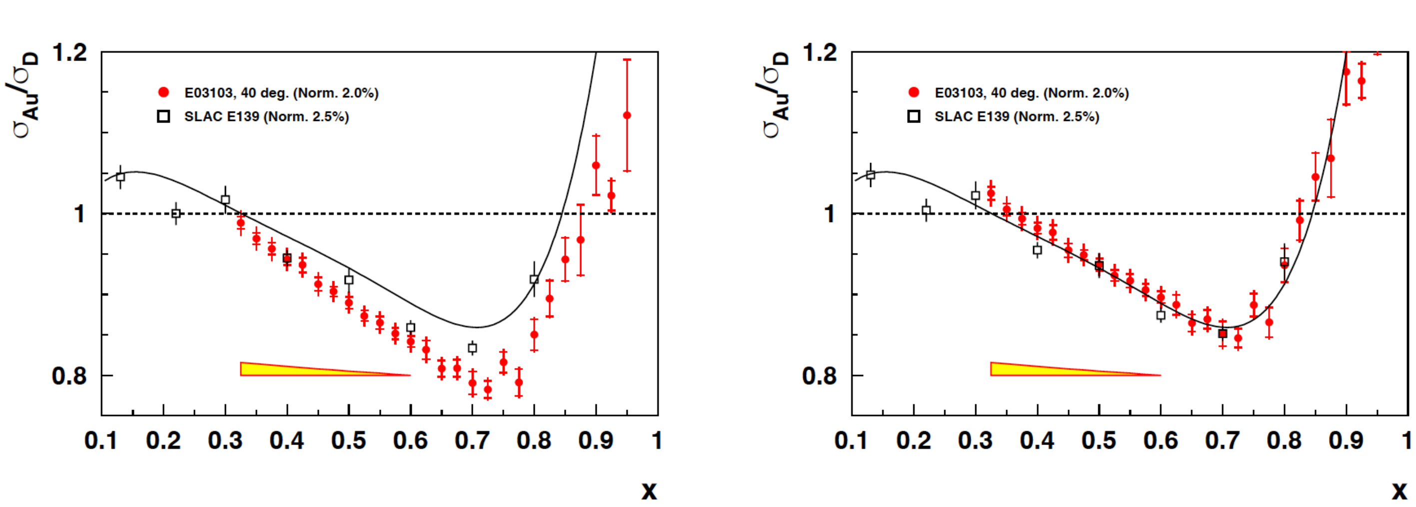
$$\frac{P_t}{P_l} \approx -\sqrt{\frac{2\epsilon}{(1+\epsilon)\tau}}\frac{G_E}{G_M}\left(1 \pm \left\{\begin{array}{c}\frac{\Re e[\delta\tilde{G}_M]}{G_M} \\ +\frac{\Re e[f_1(\delta\tilde{G}_E,\delta\tilde{F}_3)]}{G_E} \\ -2\frac{\Re e[f_2(\delta\tilde{G}_M,\delta\tilde{F}_3)]}{G_M}\end{array}\right\}\right)$$

Coulomb Effects

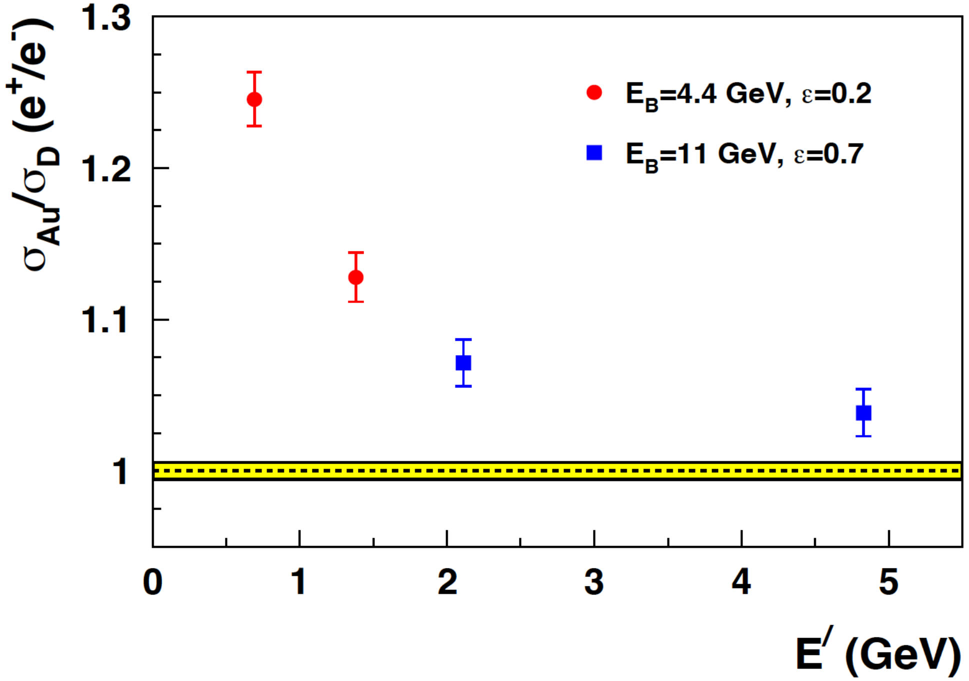
D. Gaskell, N. Fomin, W. Henry et al. PR12+23-003

- The comparison of **positron** and **electron cross sections** in the DIS regime provides unambiguous information about the size of **Coulomb corrections**.
- The double ratio of Au/D DIS cross sections **tests** the **prescriptions** of Coulomb corrections, of interest for the understanding of the **EMC effect**.

$$R_C = \left.\frac{\sigma_{\mathrm{Au}}}{\sigma_{\mathrm{D}}}\right|_{e^+} \Big/ \left.\frac{\sigma_{\mathrm{Au}}}{\sigma_{\mathrm{D}}}\right|_{e^-} = 1 + \Delta_C$$



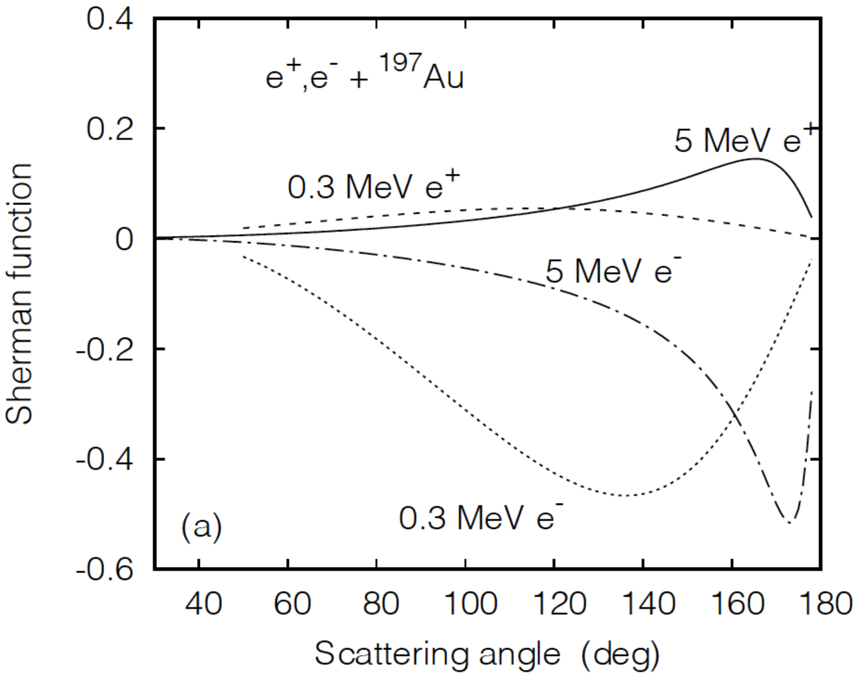
Impact of Coulomb corrections on JLab Hall C EMC data, determined from the Improved Effective Momentum Approximation.

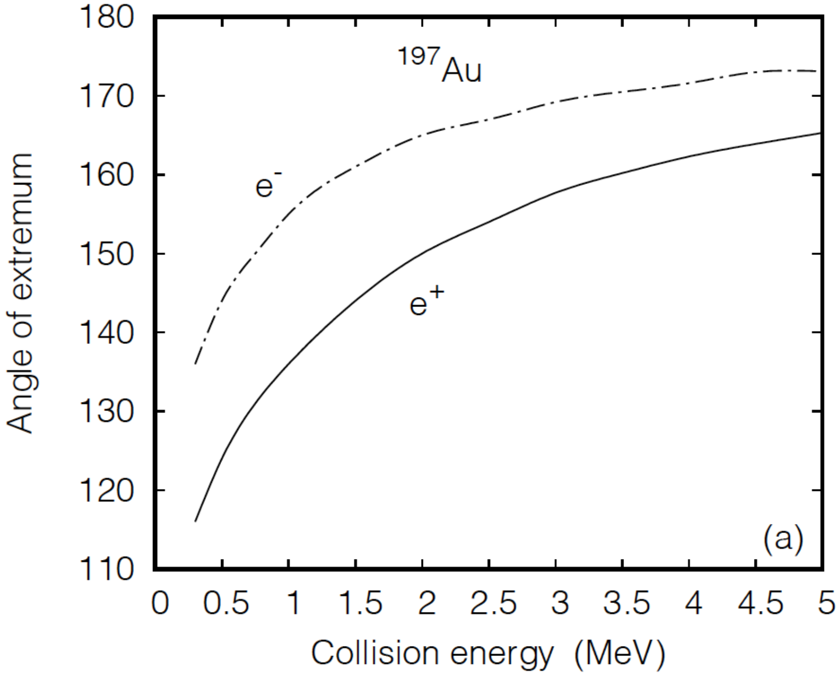


e^+ Commissionning @ LERF

D. Jakubaßa-Amundsen @ HP2030

- Multi-Photon Exchange is responsible of the sensivity of the elastic $e^{\pm}A$ interaction to the transverse polarization of the incoming lepton beam, which is expressed in terms of the Sherman function.
- It is the principle of operation of Mott polarimetry (Mott polarimeter at the CEBAF injector).





- The measurement of the angular distribution of the Sherman function with polarized e^- and e^+ in 1-10 MeV range is an opportunity for the commissionning of the Ce$^+$BAF e^-/e^+ source at LERF and is of interest to electron and positron polarimetry.

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Gravitational Form Factors

V.D. Burkert, L. Elouadrhiri, F.-X. Girod, C. Lorcé, P.E. Shanahan RMP 95 (2023) 041002

- **Experimental access** to the Gravitational Form Factors (GFFs) of hadrons is the novel quest for understanding **nucleon structure and dynamics**.
- GFFs may be **probed indirectly** in various exclusive processes: (Double) Deeply Virtual Compton Scattering, Time-Like Compton Scattering, Meson Production, J/Ψ production at threshold...

$$\langle p'|\hat{T}^{q}_{\mu\nu}|p\rangle = \bar{u}(p',\vec{s}')\left[\boldsymbol{M_2^q(t)}\,\frac{P_\mu P_\nu}{M} + \boldsymbol{J^q(t)}\,\frac{i(P_\mu\sigma_{\nu\alpha}+P_\nu\sigma_{\mu\alpha})\Delta^\alpha}{2M} + \boldsymbol{D^q(t)}\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4M}\right]u(p,\vec{s})$$

Mass/energy distribution — Angular momentum distribution — Forces & pressure distribution

Mechanical properties of hadrons can be obtained from the total $D(t) = \sum_q D^q(t) + D^g(t)$ GFF and its Fourier transform in terms of their **mechanical radius** and **shear force** and **pressure** distributions.

$$D(r) = \frac{1}{(2\pi)^3}\int d^3\Delta\, e^{-i\vec{\Delta}.\vec{r}}\, D(-\vec{\Delta}^2)$$

$$r^2_{\text{mech.}} = 6\,\frac{D(0)}{\int_{-\infty}^{0} dt\, D(t)}$$

$$s(r) = -\frac{1}{4M}\, r\, \frac{d}{dr}\left[\frac{1}{r}\frac{d}{dr}D(r)\right]$$

$$p(r) = \frac{1}{6M^2}\,\frac{1}{r^2}\frac{d}{dr}\left[r^2\frac{d}{dr}D(r)\right]$$

Experimental Access to D(t)

V.D. Burkert, L. Elouadrhiri, F.-X. Girod, Nature 557 (2018) 39

- The GFF D(t) can be accessed from the skewness dependence of the 2nd Mellin moment of the GPDs H and E which requires the GPDs knowledge over the whole physics phase space.

$$\int_{-1}^{1} x\, H^q(x,\xi,t)\, dx = M_2^q(t) + \xi^2\, \boldsymbol{D^q(t)} \qquad \int_{-1}^{1} x\, E^q(x,\xi,t)\, dx = 2\, J^q(t) - M_2^q(t) - \xi^2\, \boldsymbol{D^q(t)}$$

- GPDs are accessed in DVCS and DDVCS through Compton Form Factors (CFFs) which real and imaginary parts are related by a fixed-t dispersion relation

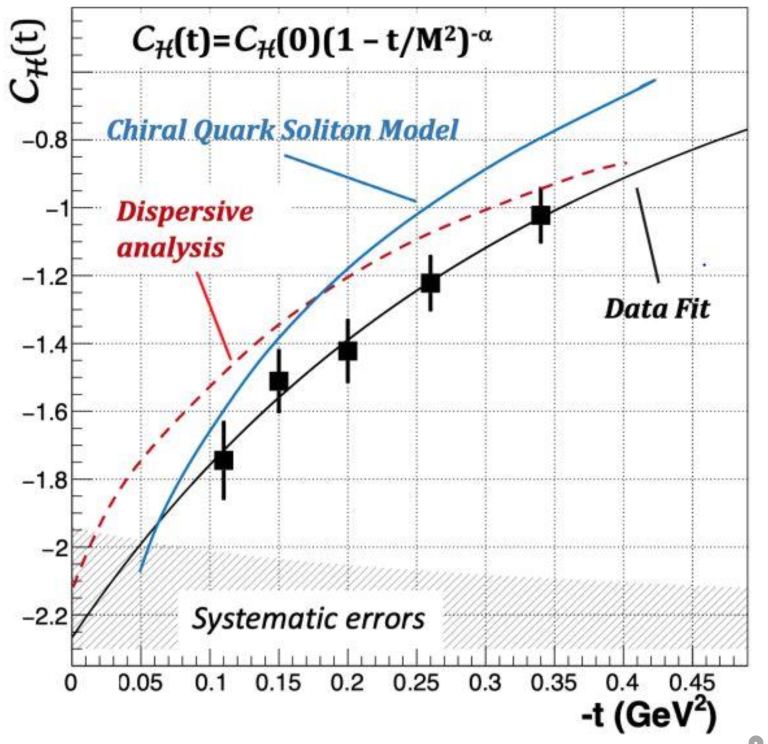
$$\mathfrak{Re}[\mathcal{H}(\xi,t)] + i\,\mathfrak{Im}[\mathcal{H}(\xi,t)] = \sum_q e_q^2 \int_{-1}^{1} \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] H^q(x,\xi,t)\, dx$$

$$\mathfrak{Re}[\mathcal{H}(\xi,t)] \overset{\text{LO}}{=} C_{\mathcal{H}}(t) + \mathcal{P}\left\{\int_{-1}^{1} \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] \mathfrak{Im}[\mathcal{H}(x,t)]\, dx\right\}$$

$$C_{\mathcal{H}}(t) = 2 \sum_q e_q^2 \int_{-1}^{1} \frac{D^q_{\text{term}}(z,t)}{1-z}\, dz \qquad D^q_{\text{term}}(z,t) = (1-z^2) \sum_{2n+1} d_n^q(t)\, C_n^{3/2}(z)$$

$$D^q(t) = \frac{4}{5} d_1^q(t)$$

V.D. Burkert et al. RMP 95 (2023) 041002

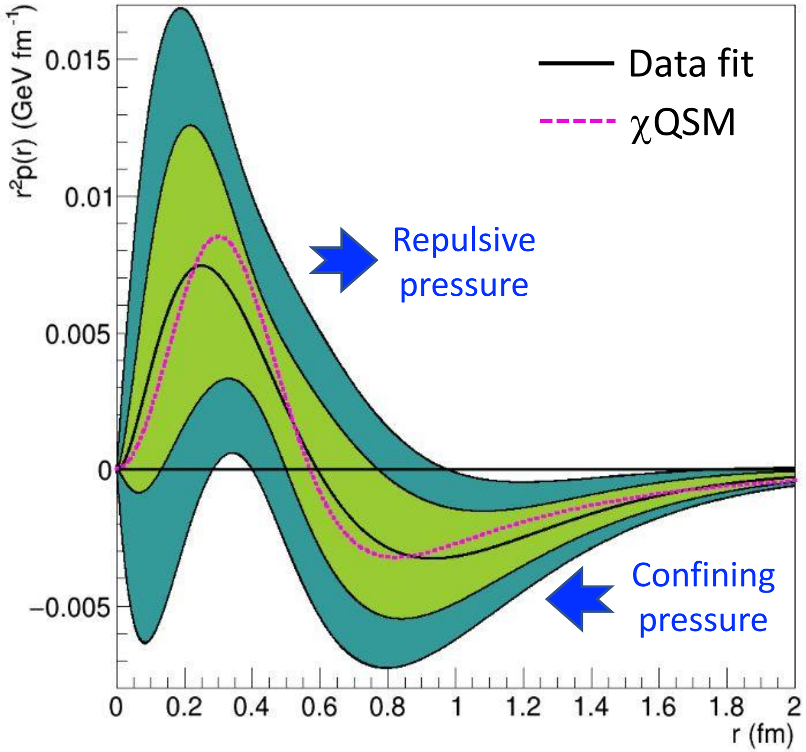


Dynamical Imaging

V.D. Burkert @ HP2030 Y. Hatta @ HP2030

- Measuring independently the **real and imaginary parts** of $\mathcal{H}$ provides access to **D(t)** and the mechanical properties of hadrons.

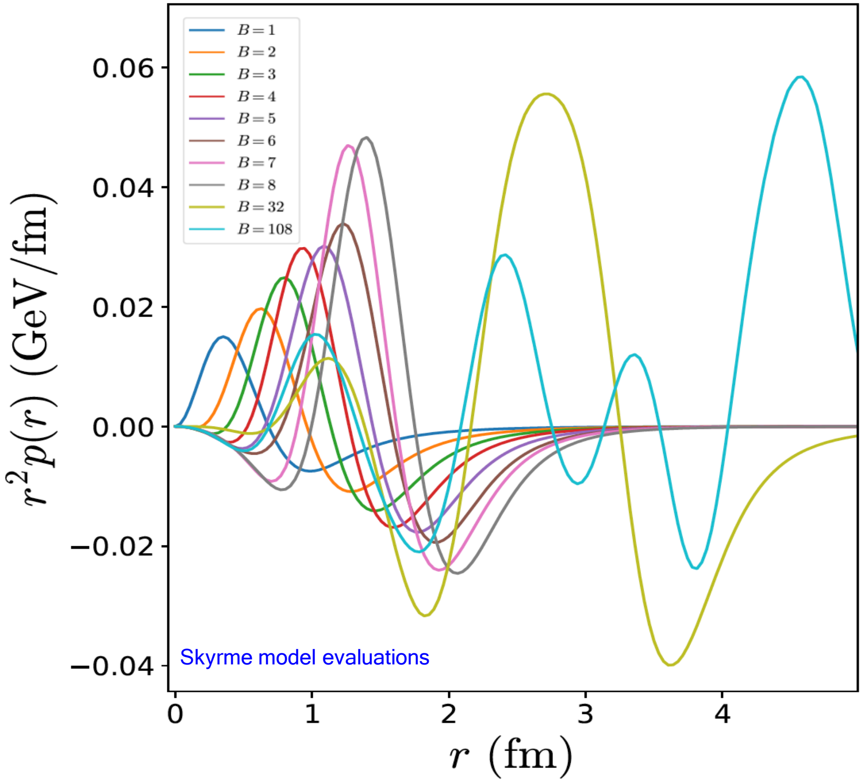
V.D. Burkert et al. RMP 95 (2023) 041002



$$r^{p}_{mech.} = 0.634 \pm 0.057 \text{ fm} < r^{p}_{E}$$

- Hadron stability suggests **D(0) < 0**, as found from DVCS data and theoretical models.
- A Skyrme modeling of nuclei predicts D(0) increases with the baryonic number as $D_B(0) \propto B^{1.7}$.
- Within the Skyrme model, the **pressure** is found **negative** at the center for all nucleus.

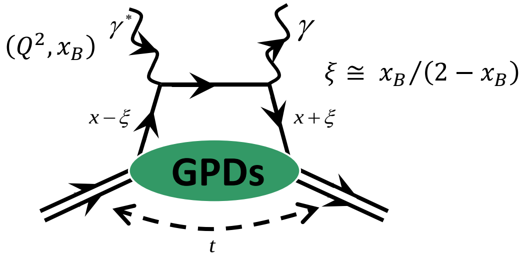
A.G. Martin-Caro et al. PRD 110 (2024) 034002



V.D. Burkert, L. Elouadrhiri, F.-X. Girod, Nature 557 (2018) 396 M.V. Polyakov, P. Schweitzer, IJMP A 33 (2018) 1830025 A.G. Martin-Caro, M. Huidobro, Y. Hatta PRD 108 (2023) 034014

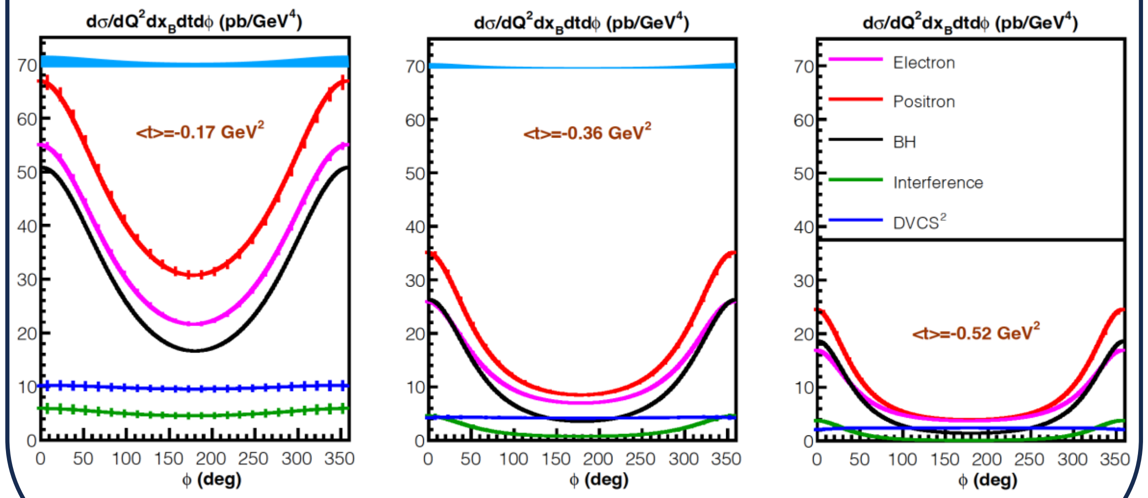
Interference Amplitude

A. Afanasev et al. EPJ A 57 (2021) 300 V.D. Burkert et al. EPJ A 57 (2021) 186



- The comparison between electron- and positron-induced photon production enables the separation of the 4 unknown amplitudes of the (e,epγ) process.
- Particularly it isolates the components of the DVCS⊗BH interference amplitude, providing a clean access to the real part of CFFs.

$$d^5\sigma_{00}^{\pm} = d^5\sigma_{BH} + d^5\sigma_{DVCS} \mp d^5\sigma_{INT}$$

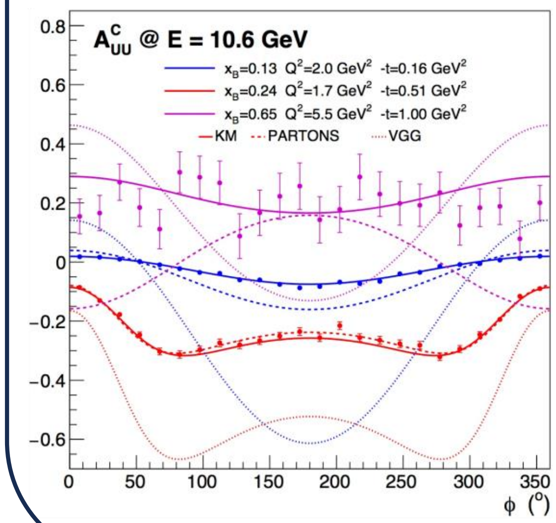


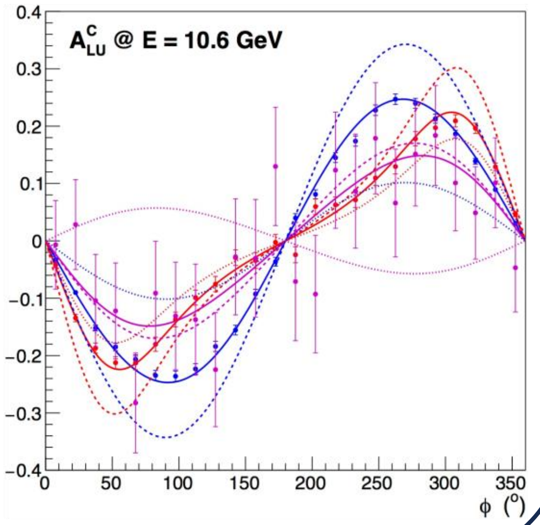
$x_B = 0.36$ $Q^2 = 4.0$ GeV^2

PR12+23-006 C. Muñoz Camacho et al.

$$A_{UU}^{C} = \frac{d^5\sigma_{INT}}{d^5\sigma_{BH} + d^5\sigma_{DVCS}}$$

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





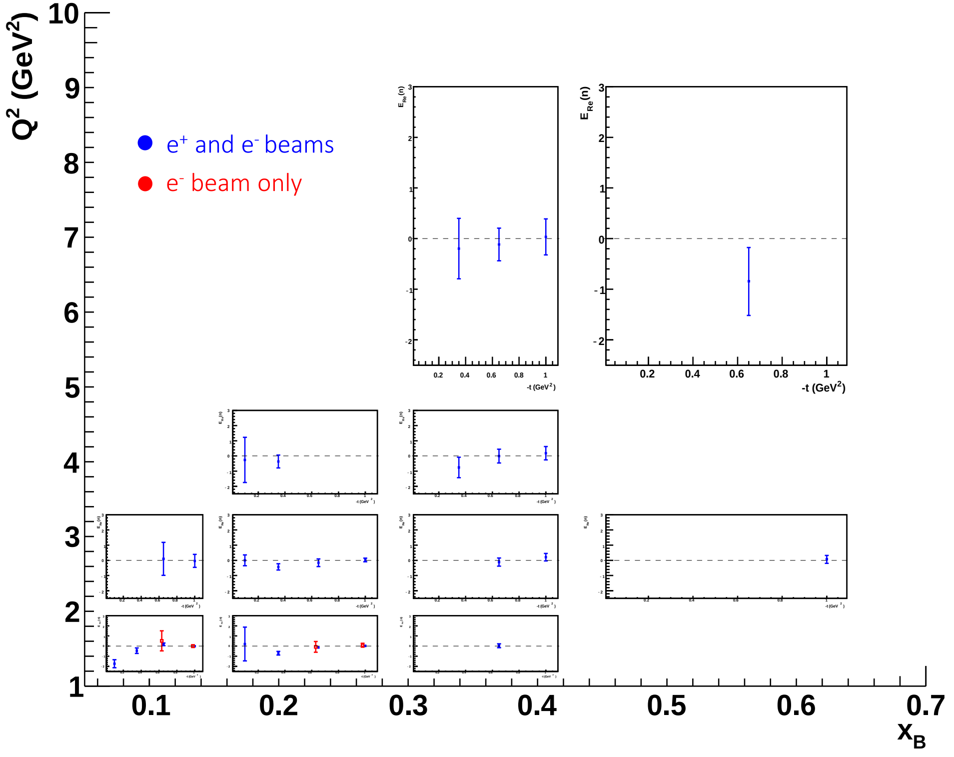
PR12+23-002 E. Voutier et al.

Irène Joliot-Curie

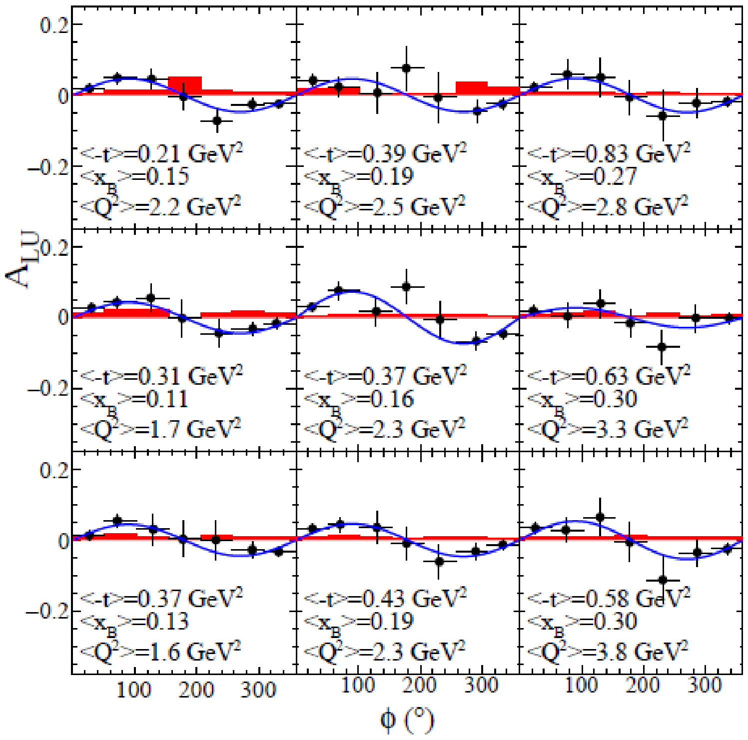
DVCS off neutrons

S. Niccolai et al. EPJ A 57 (2021) 226   H. Huang @ HP2030   S. Niccolai @ HP2030   L. Xu @ HP2030

- The **real part** of the CFF $\mathcal{E}_n$, of importance for the **Ji sum rule**, the **Gravitational Form Factors** of the neutron, and for **flavor separation** is hardly constrained experimentally without **Beam Charge Asymmetry** data.



A. Hobart et al. PRL 133 (2024) 211903



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

- CLAS12 BSAs recently published.
- BONUS12 ***analysis in progress***.
- ALERT experiment to run in 2025.

- NPS experiment recently completed.
- CLAS12 cross section ***analysis in progress***.

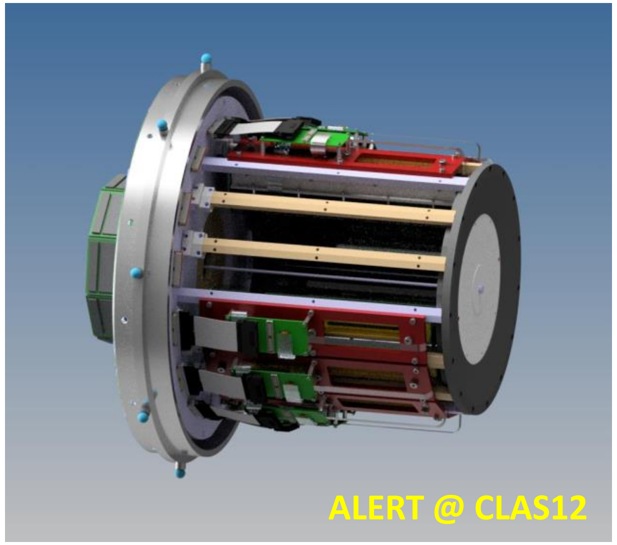
DVCS off Helium

S. Fucini et al. EPJ A 57 (2021) 273 W. Cosyn @ HP2030 R. Dupré @ HP2030 M. Rinaldi @ HP2030

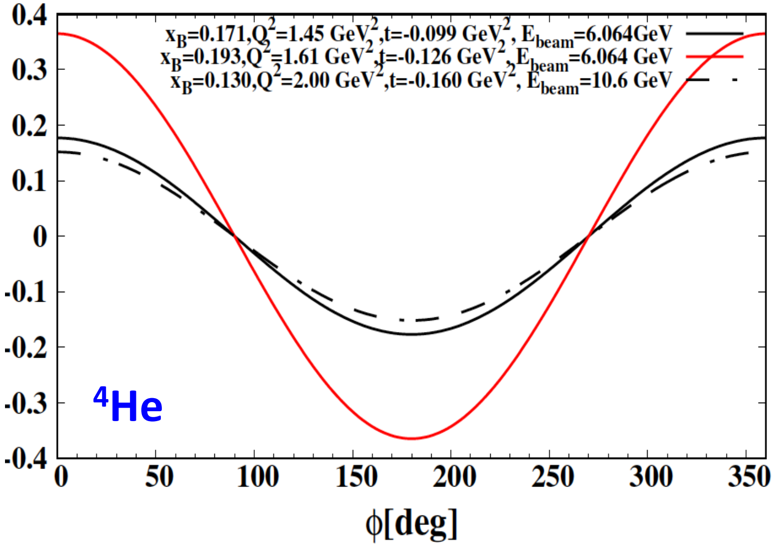
- The association of the **ALERT** recoil detector and the **CLAS12** spectrometer together with high-energy **electron** and **positron** beams offer a **new tool** to **investigate** the **nuclear force** and a **new path** to study the **EMC effect**.

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

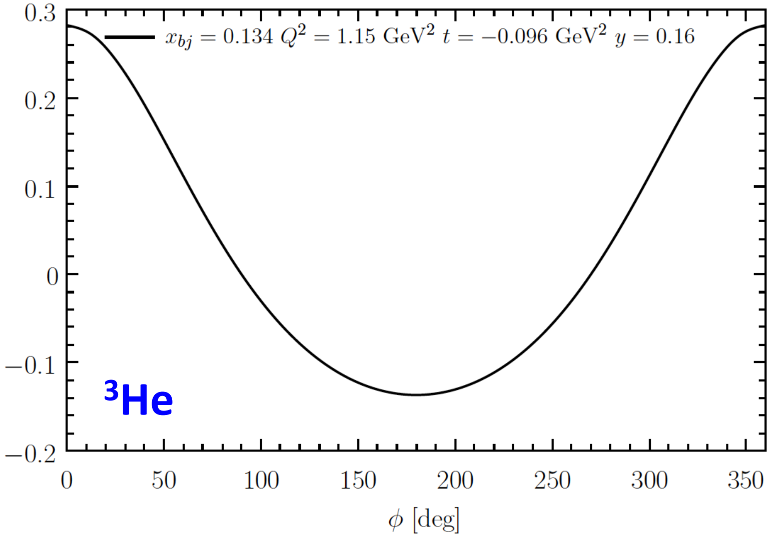
Connected to the nuclear GFF



Unpolarized Beam Charge Asymmetry



Nuclear tomography & dynamics



Sensitivity to neutron GPDs

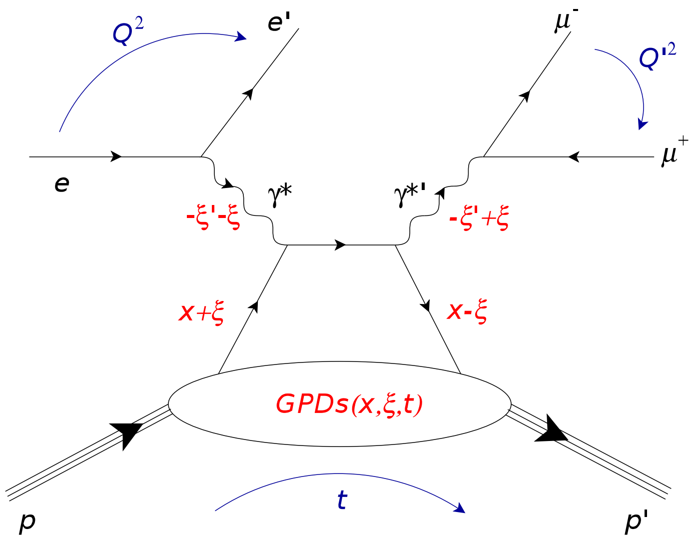
Double DVCS

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.

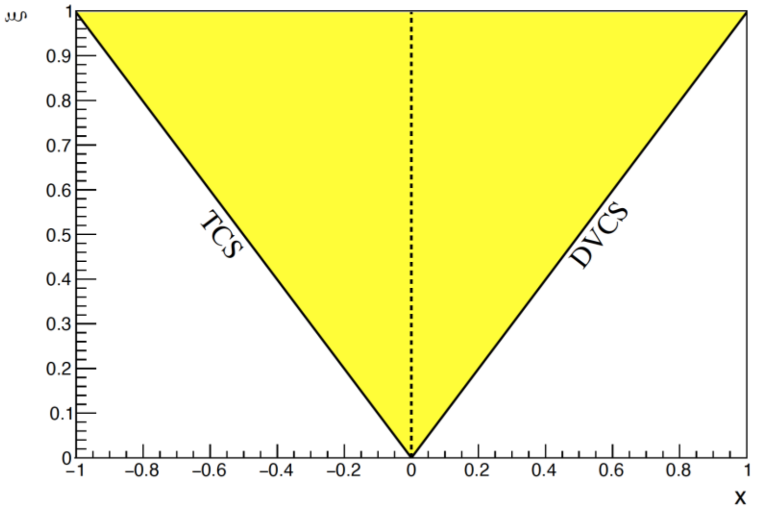
$$\mathcal{F}(\xi',\xi,t) = \mathcal{P}\int_{-1}^{1} dx\, F_+(x,\xi,t)\left[\frac{1}{x-\xi'} \pm \frac{1}{x+\xi'}\right] - i\pi F_+(\xi',\xi,t)$$

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



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

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

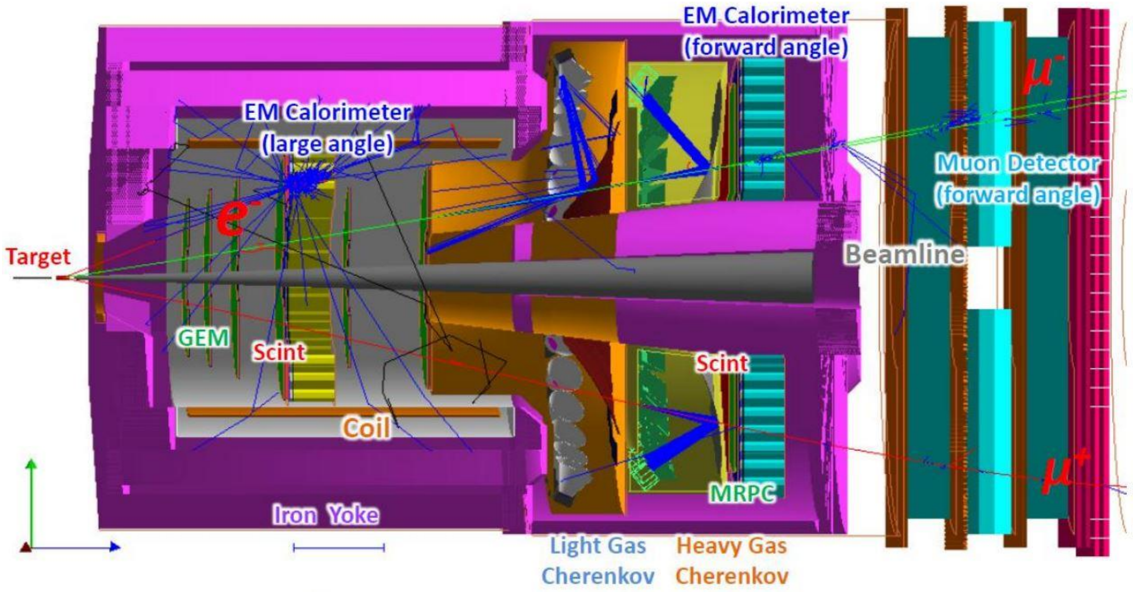


- Following the sign change of ξ' around $Q'^2=Q^2$, the CFF $\mathcal{H}$ and $\mathcal{E}$ **change sign**, providing a testing ground of **GPDs universality**.

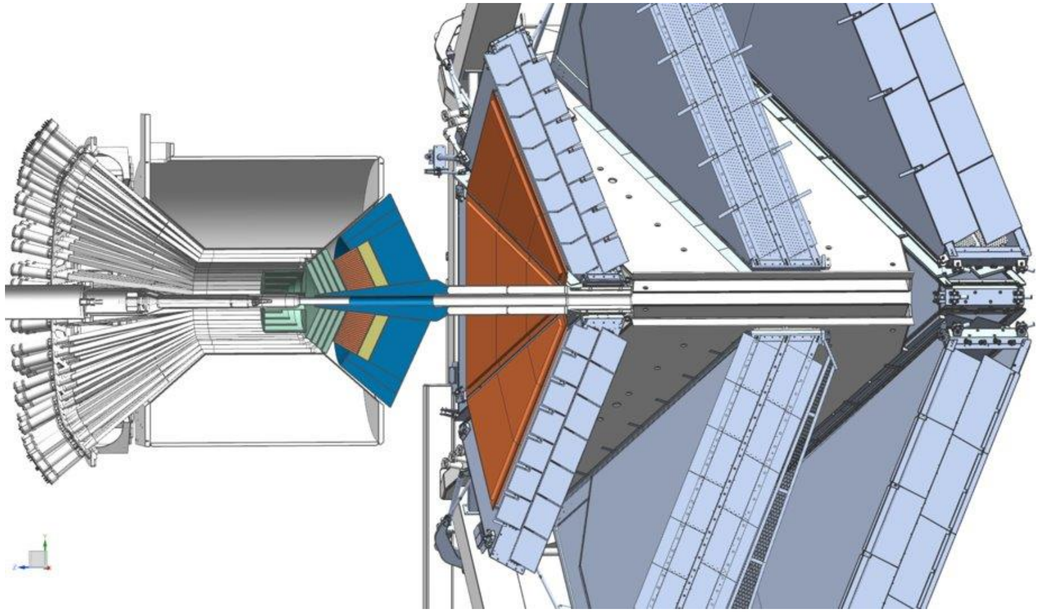
DDVCS Detectors

A. Camsonne, M. Boer, E. Voutier, Z. Zhao et al. LOI12-15-005/LOI12-23-012   S. Stepanyan et al. LOI12-16-004

- Two projects aim at measuring DDVCS on an unpolarized proton target either with a complemented SoLID or a transformed CLAS.
- The CLAS is designed to support a luminosity of $10^{37}\text{cm}^{-2}.\text{s}^{-1}$ while the SoLID may be capable of 10 times higher luminosity.



Adding forward muon detection capabilities to SoLID.



Transforming CLAS into a muon detector.

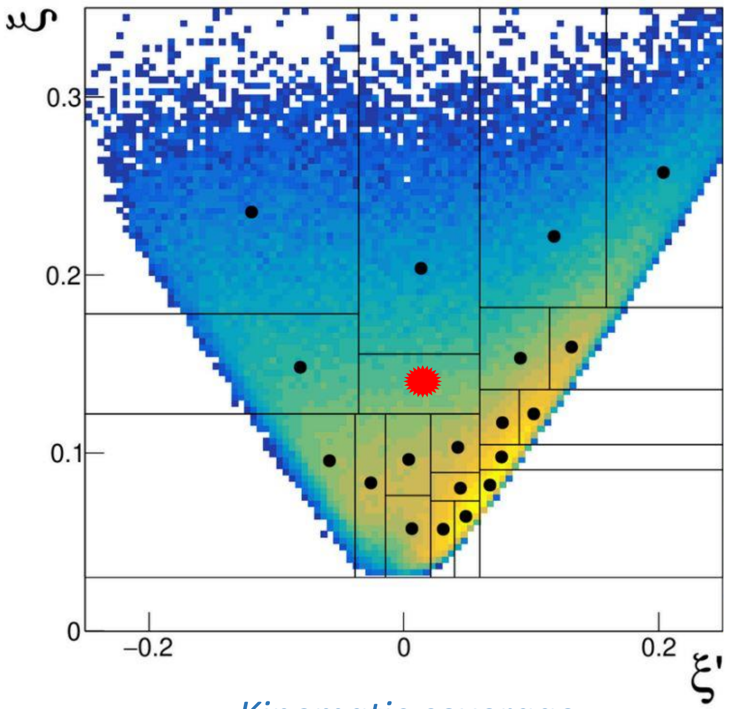
DDVCS Projections

S. Zhao et al. EPJ A 57 (2021) 240   K. Deja et al. PRD 107 (2023) 094035
J.S. Alvarado et al. @ HP2030   V. Martinez-Fernandez et al. @ HP2030   Z. Zhao @ HP2030

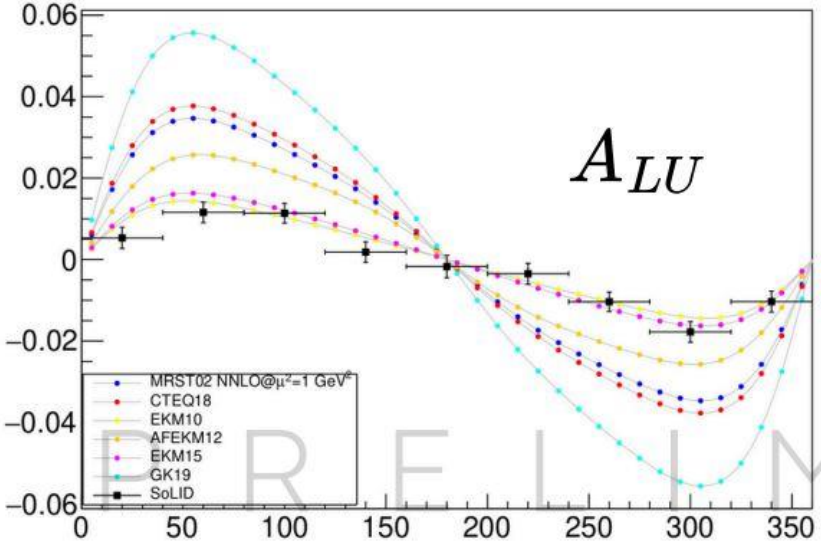
- Phase space and statistics projections have been worked out with the EpIC event generator assuming 100 days of beam at 10^{37}cm^{-2}.s^{-1} within the SoLID detector acceptance and considering some physics constraints.

$p_e > 1$ GeV/c $p_\mu > 1$ GeV/c
$W > 2$ GeV $Q'^2 + Q^2 > 1$ GeV^2

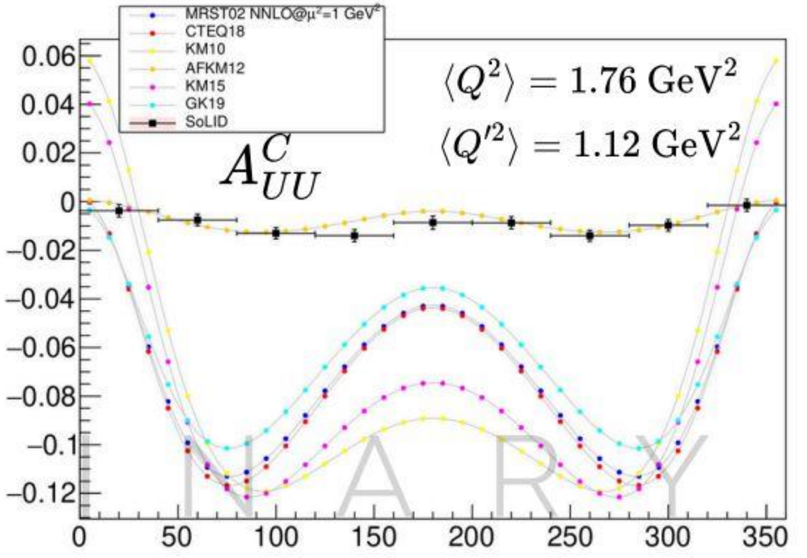
Sensitive BSA and BCA measurements can be achieved.



Kinematic coverage



Beam Spin Asymmetry



Beam Charge Asymmetry

Form factors

I. The proton charge radius r_E^p
II. The proton electric form factor $G_E^p(Q^2)$
III. The proton axial form factor $G_A^p(Q^2)$

Muti-photon exchange

I. Two-Photon Exchange (TPE) effects in elastic scattering
II. Coulomb corrections in DIS
III. Mott polarimetry

Compton form factors

I. Hadron dynamics
II. Deeply Virtual Compton Scattering (DVCS)
III. Double Deeply Virtual Compton Scattering (DDVCS)

Tests of the Standard Model

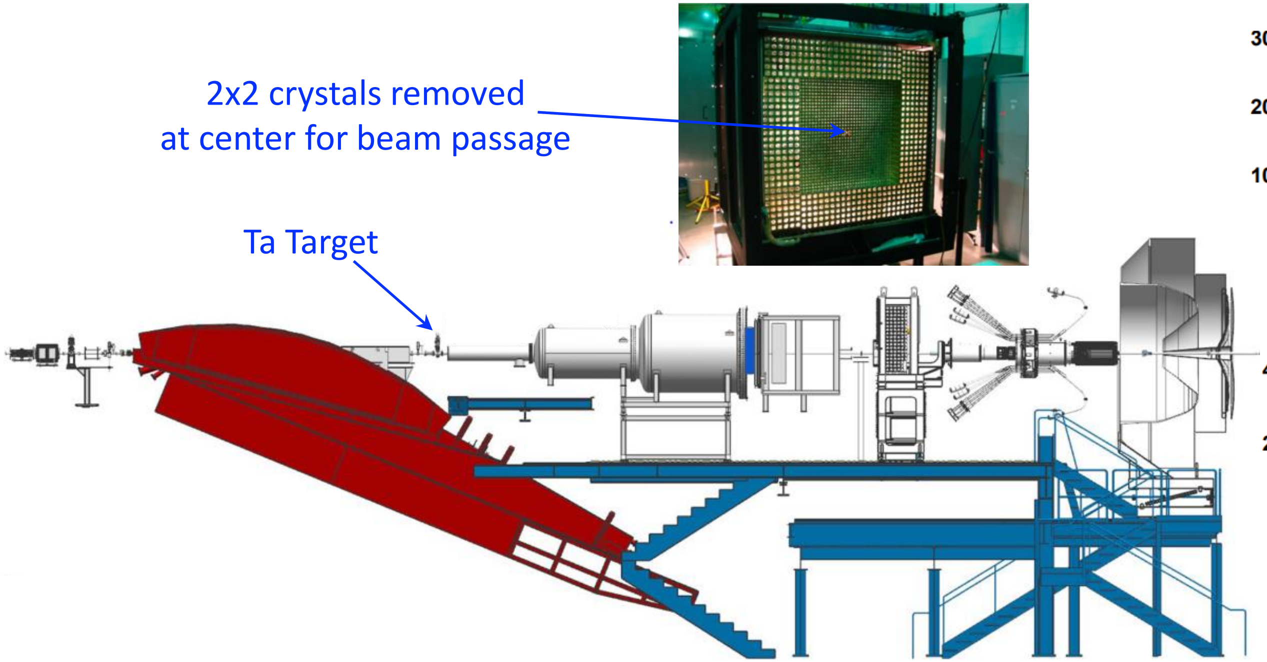
I. Dark matter search
II. Electroweak processes
III. Other phenomena

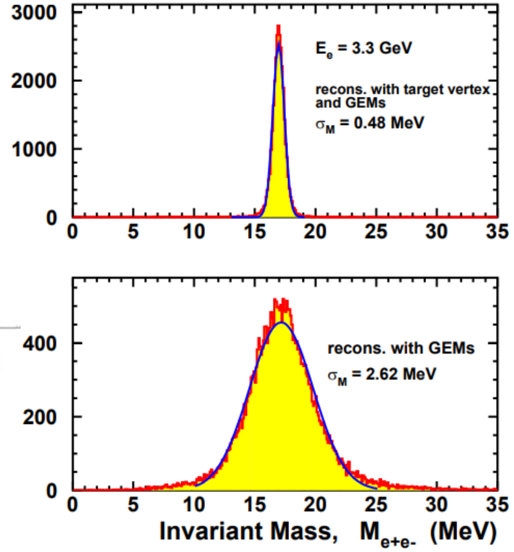
X17 Search @ PRad-II

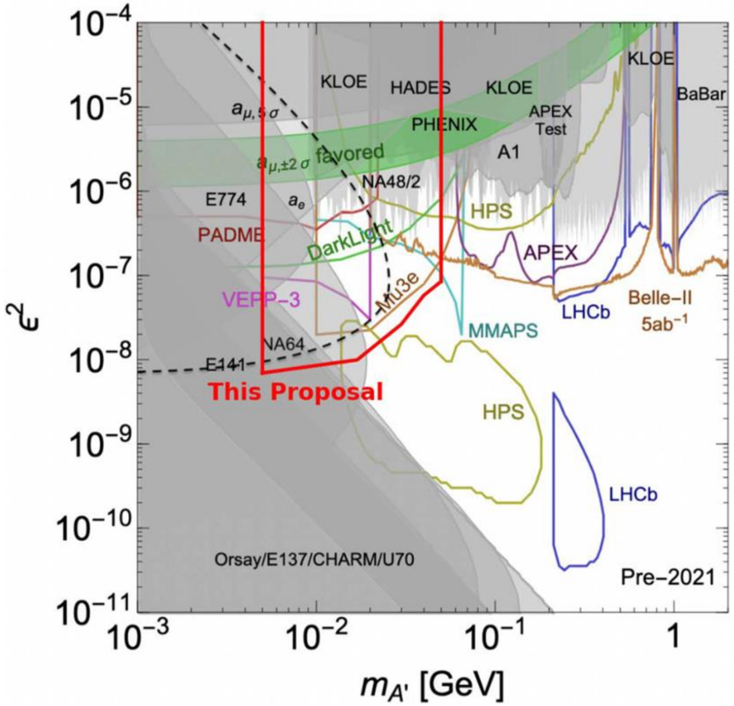
A. Gasparian, D. Dutta, H. Gao, T. Hague, N. Liyanage R. Paremuzyan, C. Peng, et al. E12-21-003

- Changing the interaction target for a 1 μm Tatalum foil, the **PRad-II detector** will perform a search for a dark photon in the **3-60 MeV** mass range in the e^+e^- and $\gamma\gamma$ **visible decay** channels.

> • Two GEM planes 40 cm apart tag charged particles, veto neutrals, and discriminate events not originating from the target

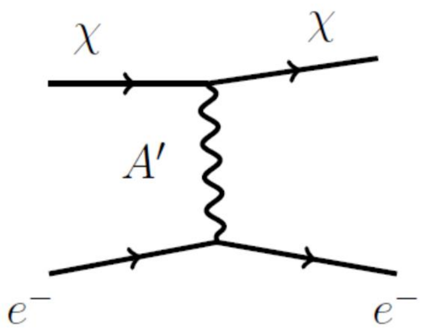




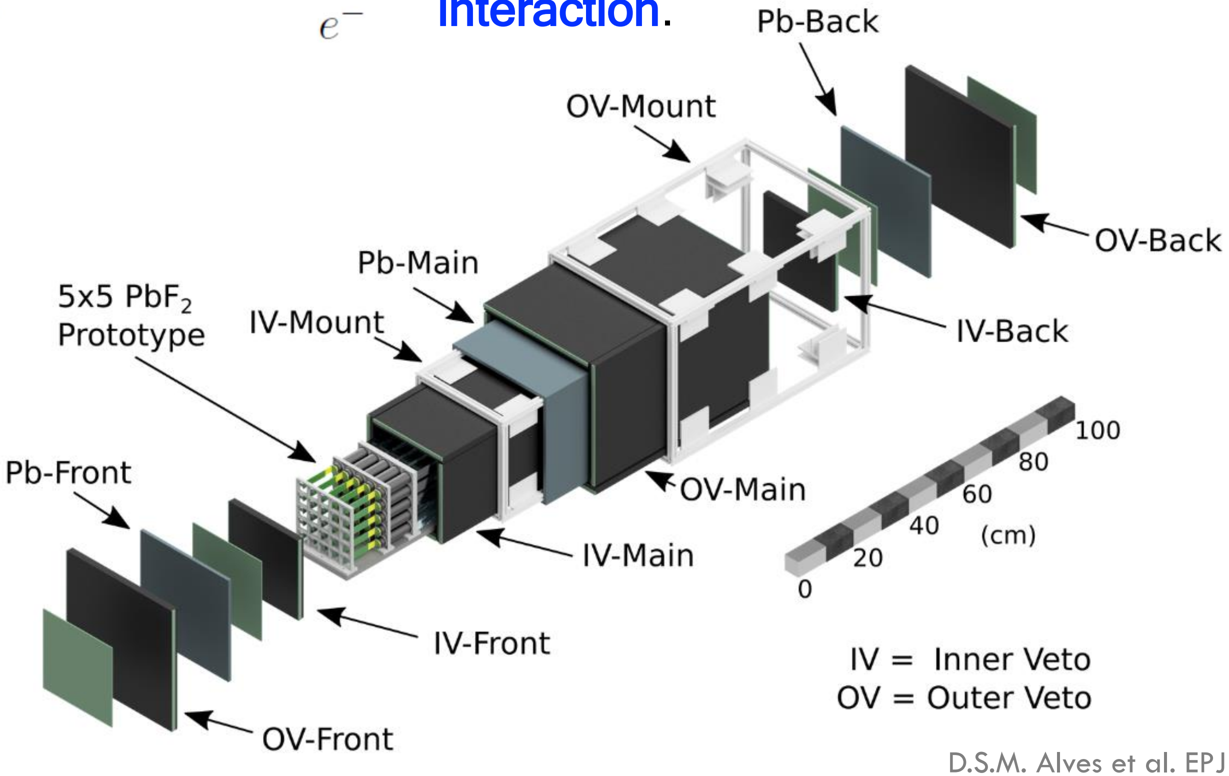


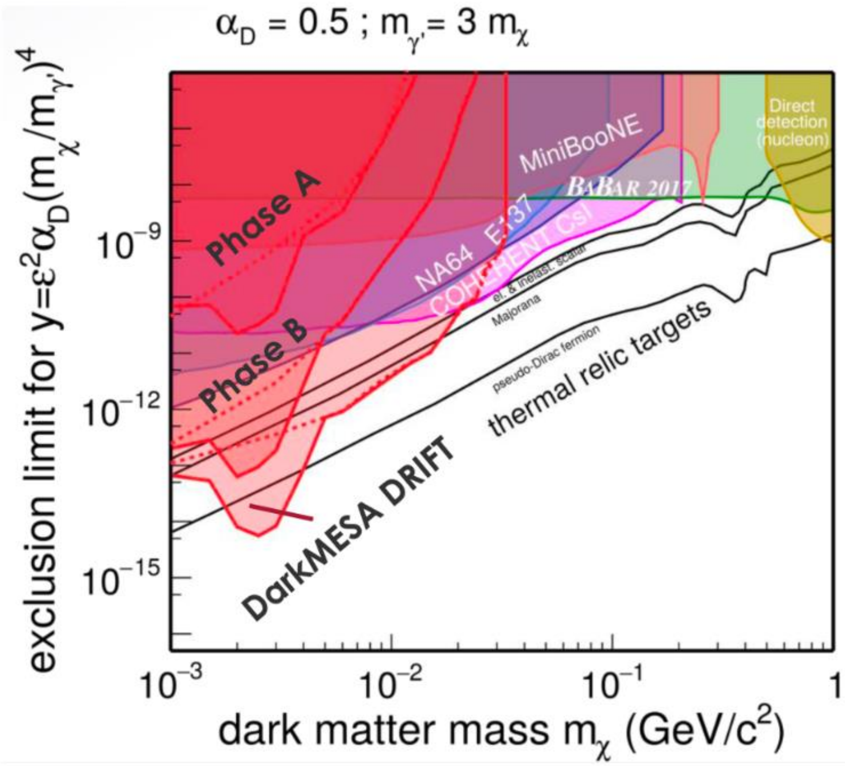
Data taking to start after PRad-II

Dark MESA



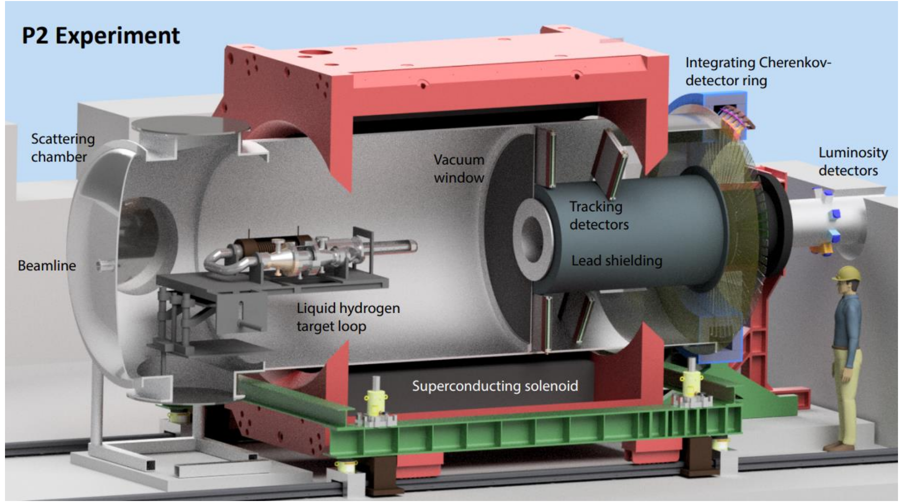
- The beam dump of the P2 experiment at MESA may serve as a source of dark matter particles via the $eZ \rightarrow eZ(\gamma' \rightarrow \chi\bar{\chi})$ reaction.
- The eventually produced dark matter particles are detected through the energy deposited into a large volume calorimeter (possibly complemented with a TPC) via scattering interaction.

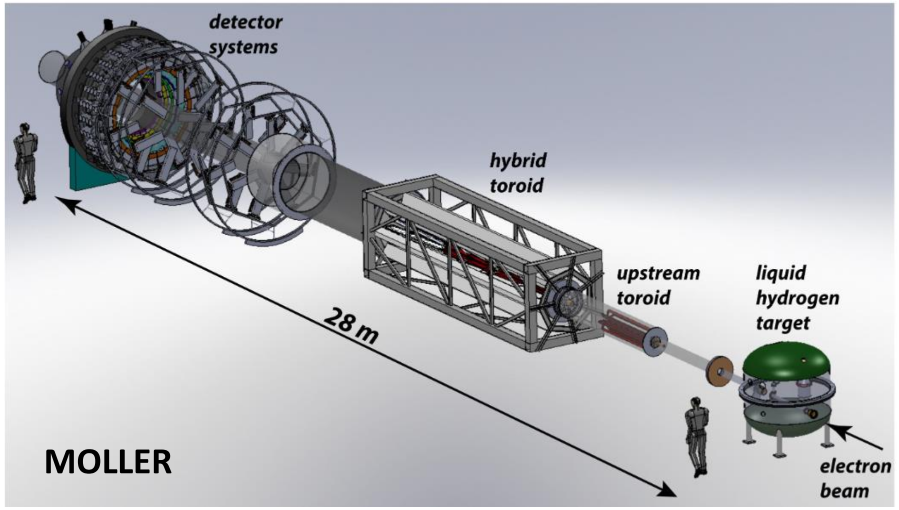




D.S.M. Alves et al. EPJ C (2023) 83

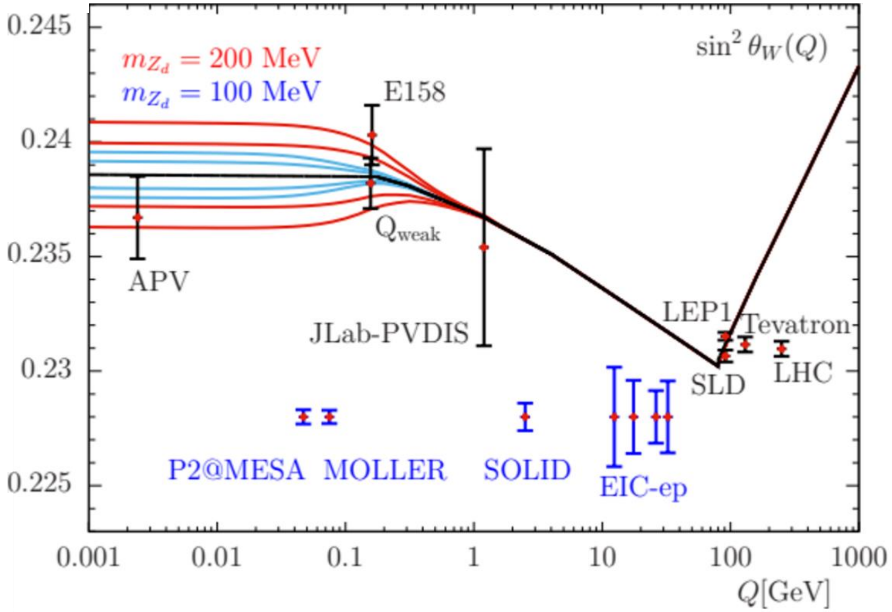
Weak Charge





- Measuring the weak mixing angle $\sin^2(\theta_W)$ at low Q^2 procures a stringent test of the Standard Model probing the existence of BSM physics at a ~50 TeV mass scale, and also can constrain the existence of dark matter particles.

Exp.	Part.	Precision (%)	Masse limit (TeV)
Qweak	p	4.5	33
P2	p	2.0	49
MOLLER	e	2.3	39
SoLID	q	0.6	22



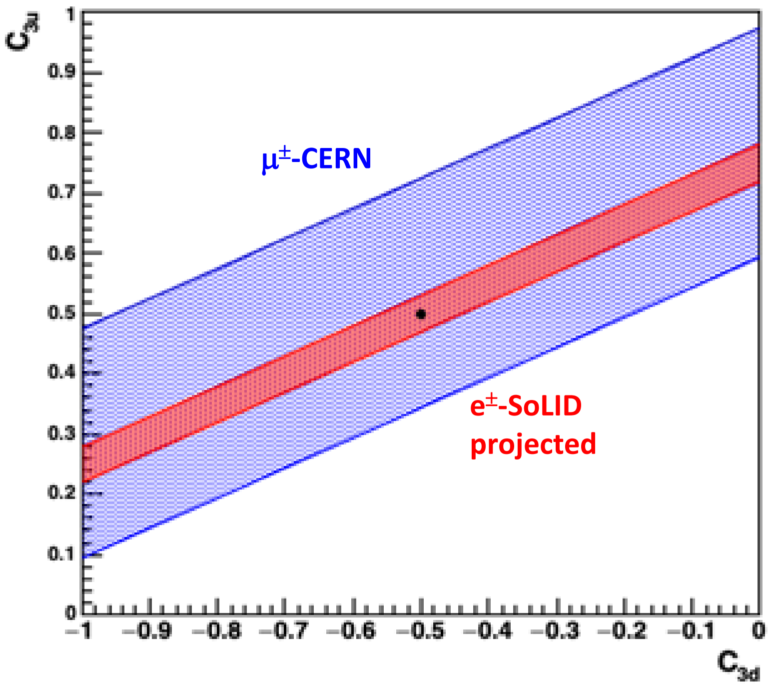
Electroweak Coupling @ Ce$^+$BAF

X. Zheng, J. Erler, Q. Liu, H. Spiesberger, EPJA 57 (2021) 5 X. Zheng et al. PR12-21-006
R. Trotta @ HP2030

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

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

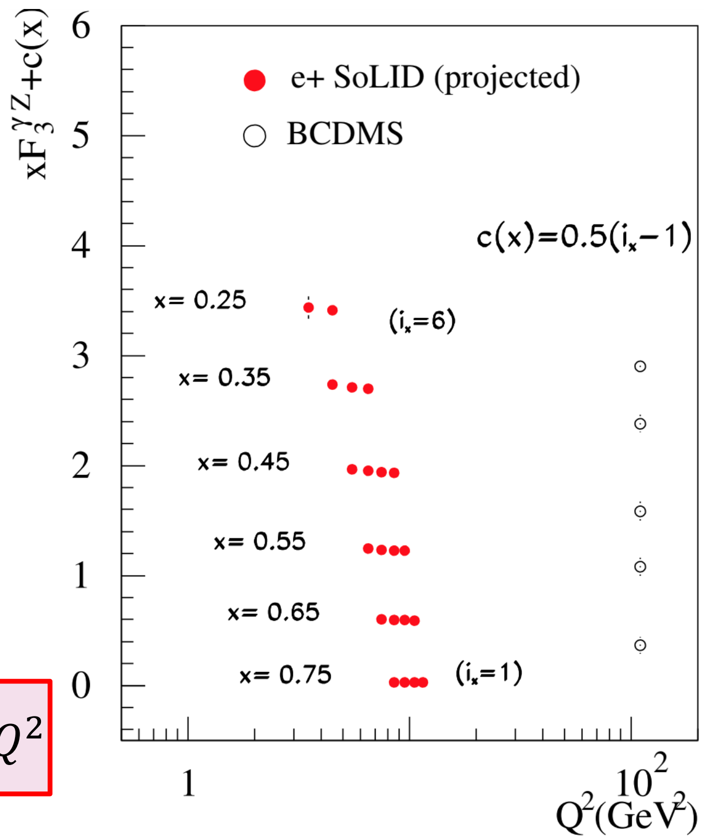
$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$



$$A_d^{e^+e^-} \approx -108\, Y(y)\, R_q(x) (2C_{3u} - C_{3d})\, Q^2$$
(in ppm/GeV²)

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

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



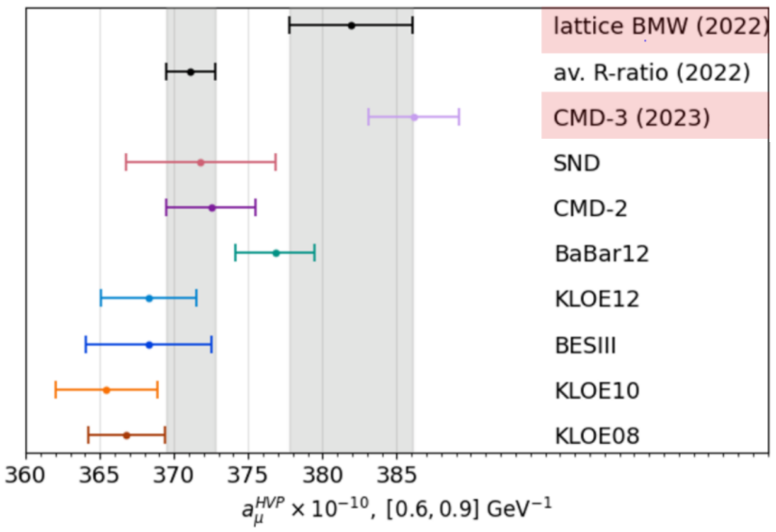
Atoms as Accelerators

F. Arias_Aragon, L. Darmé, G. Grilli di Cortona, E. Nardi, arXiv:2407.15941

- The Hadronic Vacuum Polarization (HVP) is the leading theoretical uncertainty in the determination of $(g-2)_\mu$.
- Serious disagreements on σ_{had} exist among different experiments as well as between data driven and lattice QCD results for HVP.

Taking advantage of the relativistic motion of inner atomic shells electrons of high Z materials, the $e^+e^- \to \pi^+\pi^-$ cross section can be measured at Ce$^+$BAF over a s-range of interest for the determination of $(g-2)_\mu$.

$$a_\mu^{HVP} = \int_{s_{th.}} ds\, \sigma_{had}(s)\; K(s)$$

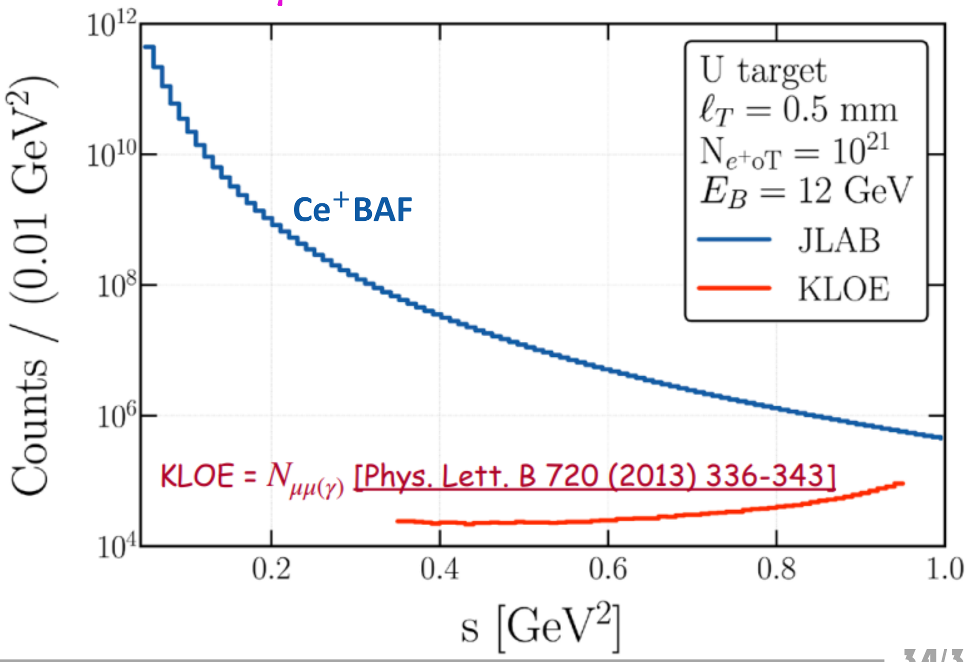


$$s_\pm = s_0 \pm 2\, E_{e^+}\langle p_{nl}^z\rangle - \langle \boldsymbol{p}_{nl}\rangle^2$$

$$s_0 \to 2m_e(E_{e^+} + m_e)$$

Atom acceleration effects have already been observed in Moller polarimetry.

L.G. Levchuk, NIM A 345 (1994) 496



- A rich and diverse experimental program is developing at MAMI and CEBAF in nuclear, hadronic and particle physics.
- Exciting hours to come with the advent of new accelerator capabilities, tomorrow MESA and $Ce^{+}BAF$ in a near future.

It is ideal time for
developing **collaborations**
and preparing future with
training a **new physicist generation**.

Summary & Outlook

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- Exciting hours to come with the advent of new accelerator capabilities, tomorrow MESA and $Ce^{+}BAF$ in a near future.

It is ideal time for developing **collaborations** and preparing future with training a **new physicist generation**.

What about producing positrons at MESA and accelerating them with MAMI?