Future Directions in Experimental Hadronic Physics

A Personal High-level Perspective on About the Next Decade
No EIC nor JLab 22 GeV

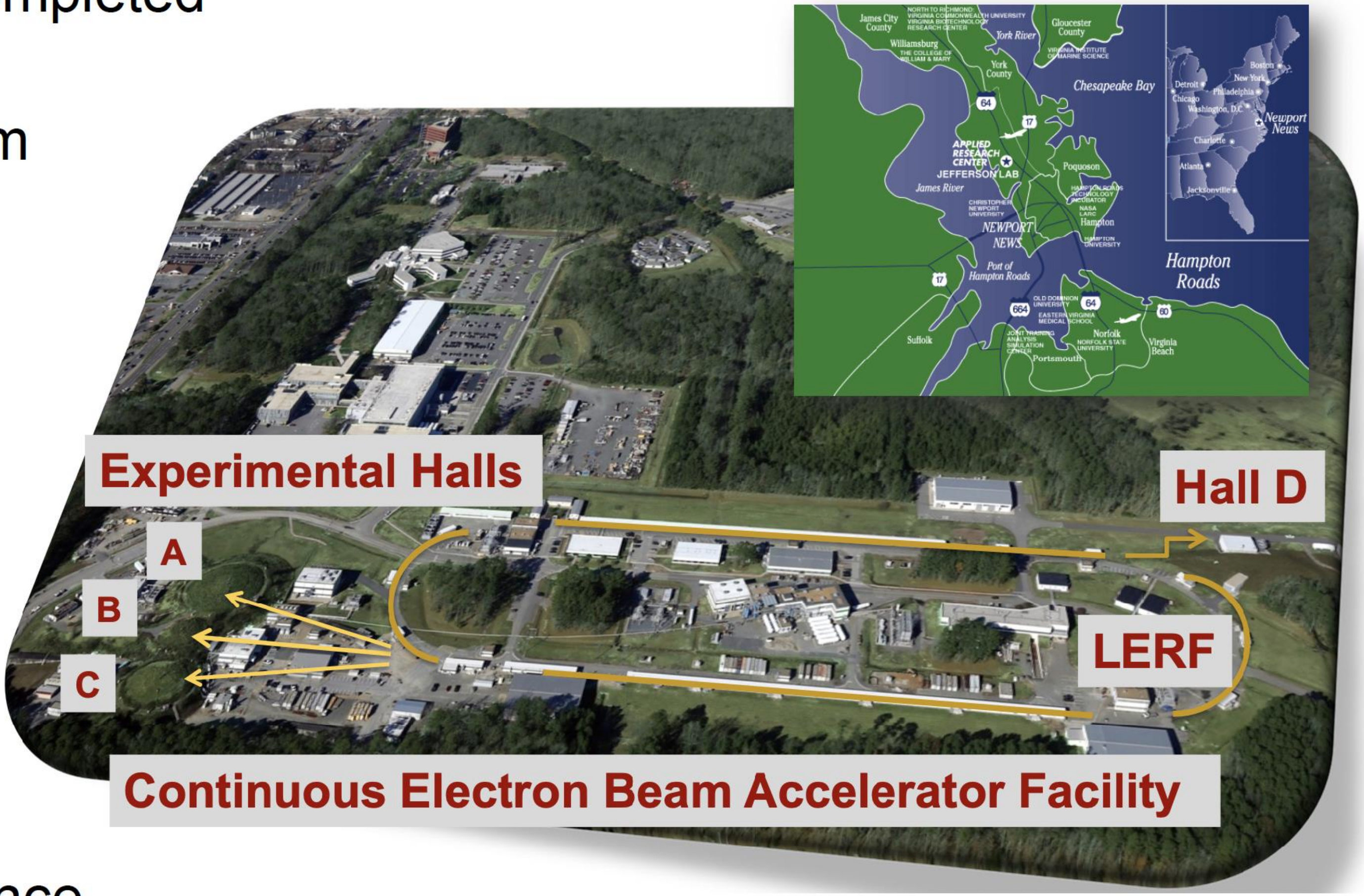
- USA
  - Jefferson Lab: CLAS12 upgrade, SoLID plans
  - Higs at Duke U.
  - Towards the EIC…..
- Europe
  - Bonn
  - Mainz
  - FAIR
  - AMBER at CERN
- Asia/Japan
  - KEK

With thanks for slides from:
R. Beck, N. Berger, M. Bondi, H. Gao, F. Hauenstein, B. Ketzer, J. Lajoie, N. Saito, C. Sfienti, S. Stengel, S. Stepanyan

Jefferson Lab - Experimental overview (1)

CEBAF upgrade completed in September 2017

- CW electron beam
- E_{max} = 12 GeV
- I_{max} = 90 μA
- Pol_{max} ~90%

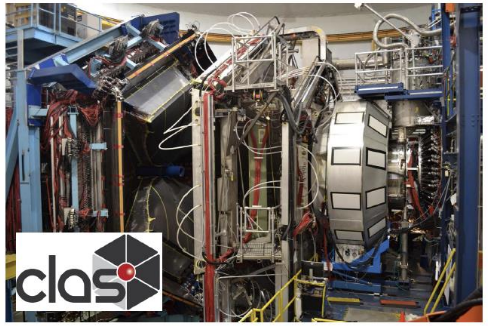


Physics operation

- 4 Halls running simultaneously since January 2018

Jefferson Lab - Experimental overview (2)

HALL C - precision determination of valence quark properties in nucleons and nuclei

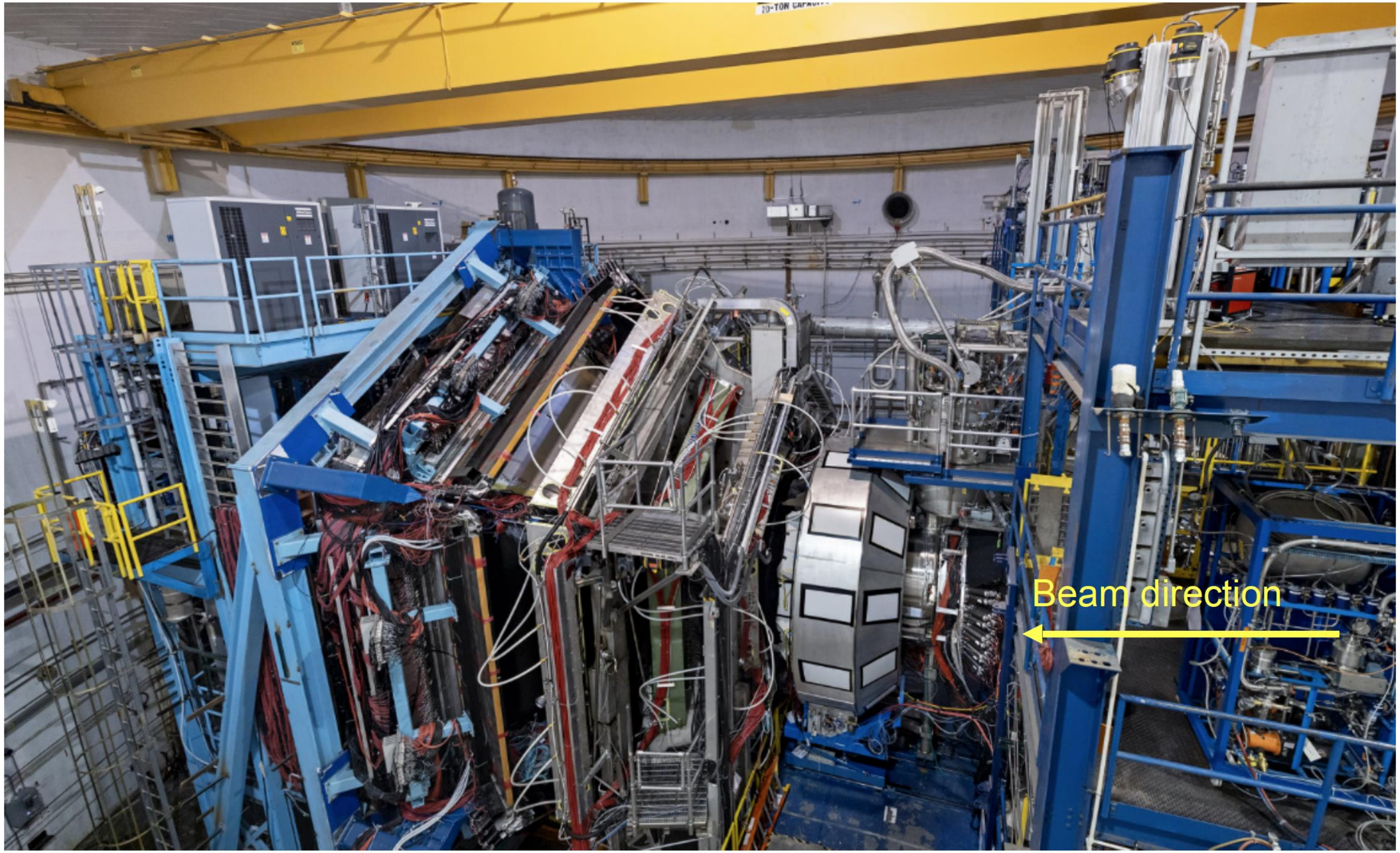


HALL B - understanding the 3D nucleon structure, hadron spectroscopy and nuclear effects

HALL D - exploring origin of confinement by studying exotic mesons

HALL A - form factors and PDFs, hyper nuclear physics, Physics BSM

CLAS12 in JLAB-HALL B

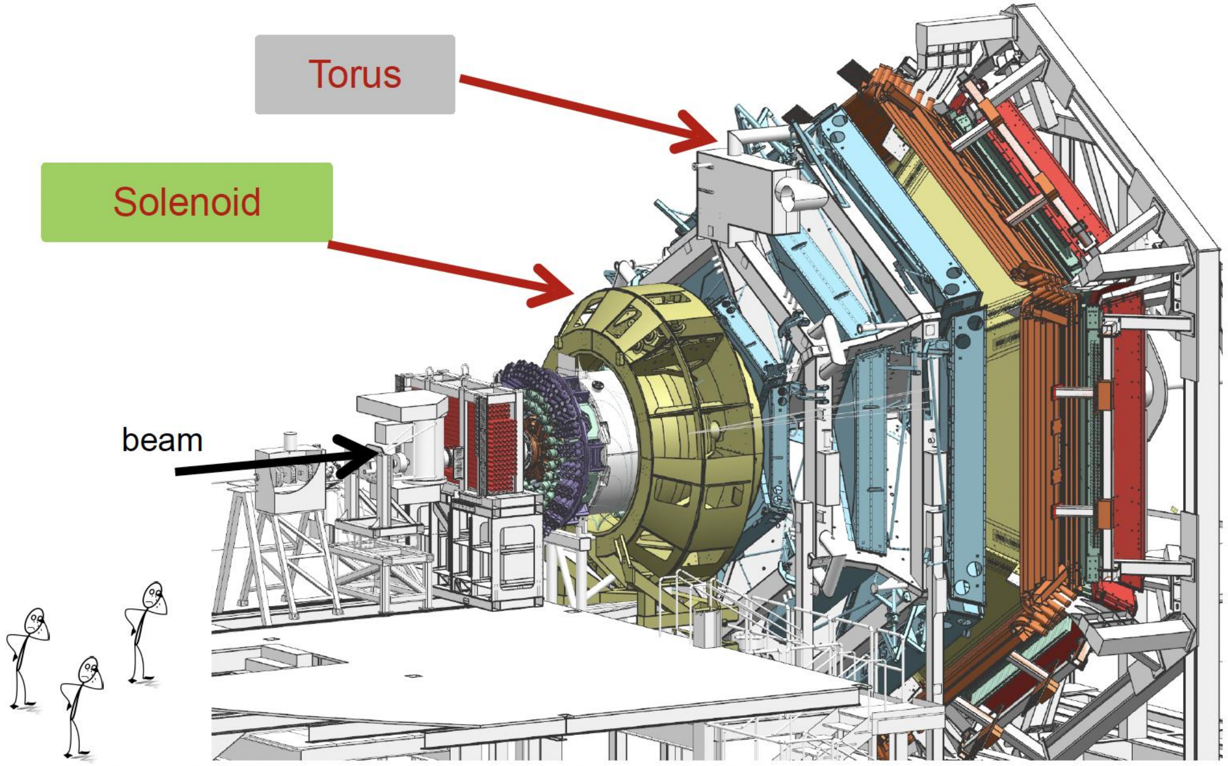


CLAS12 - Detector

CENTRAL
- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Detector
- Back-Angle Neutron Detector

	Forward	Central
Angular coverage	5° – 40°	35° – 135°
Momentum resolution	dp/p < 1%	dp/p < 5%
θ resolution	1 mrad	5 – 10 mrad
ϕ resolution	1 mrad/sinθ	5 mrad/sinθ

FORWARD
- High Threshold Cherenkov
- Forward Tagger
- Drift Chambers
- Low Threshold Cherenkov
- Ring Imaging Cherenkov
- Forward Time of Flight
- EM Calorimeter



Design Luminosity:

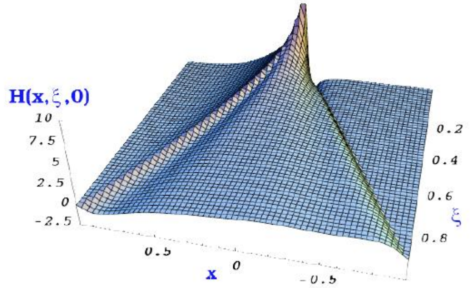
- **10^{35} cm^{-2}s^{-1}**

Physics targets:

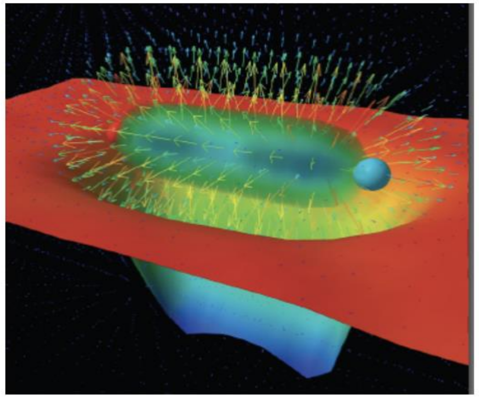
- LH_2, LD_2, LHe, LAr
- D, ^{4}He
- ^{12}C to ^{208}Pb
- Polarized NH_3, ND_3, ^{6}LiH, ^{7}LiD, ^{3}He-gas

CLAS12 physics program

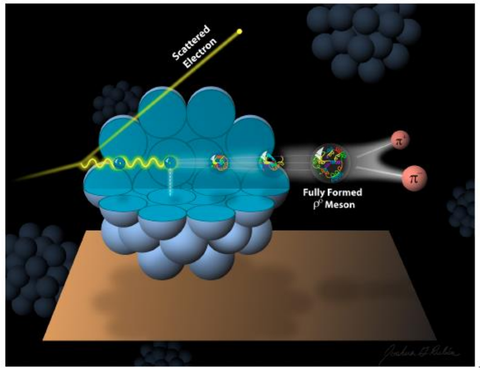
- The multidimensional structure of the nucleon – from form factors and PDFs to GPDs and TMDs



- Quark confinement and the role of the glue in meson and baryon spectroscopy



- The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons, short range correlation



Electro- and photo-production of muon pairs with μCLAS12: Double Deeply Virtual Compton Scattering, Timelike Compton Scattering, and J/ψ production

PR12-25-001

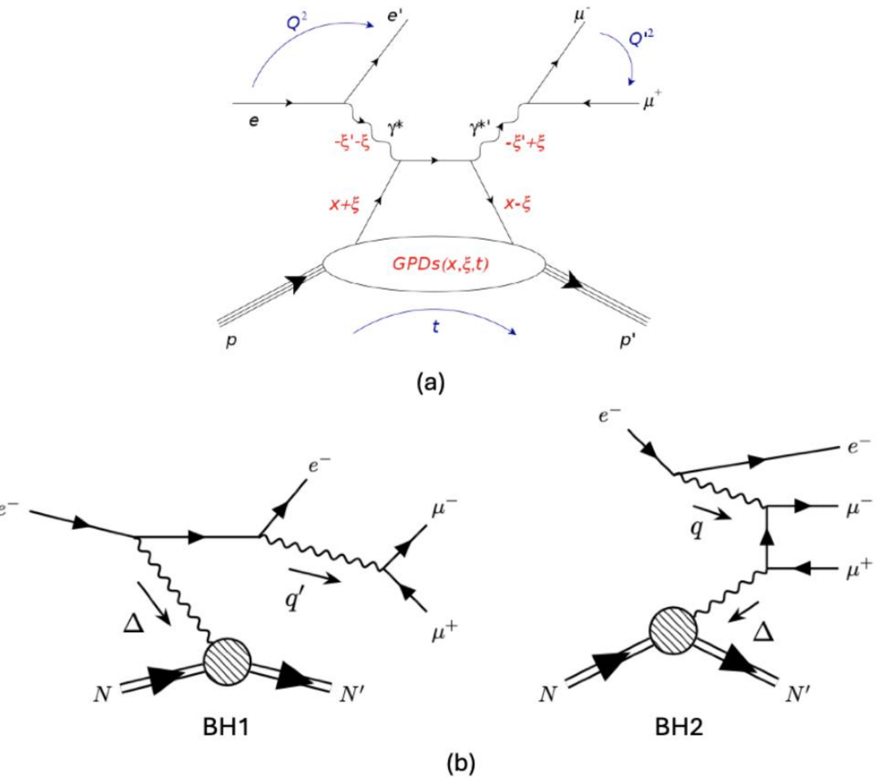


FIG. 9: Diagrams of the DDVCS process (a) and the BH process (b).

Motivation: The proposal presents an innovative experimental program to explore nucleon structure via Double Deeply Virtual Compton Scattering (DDVCS), Timelike Compton Scattering (TCS), and near-threshold J/ψ production, utilizing muon pairs in the final state:

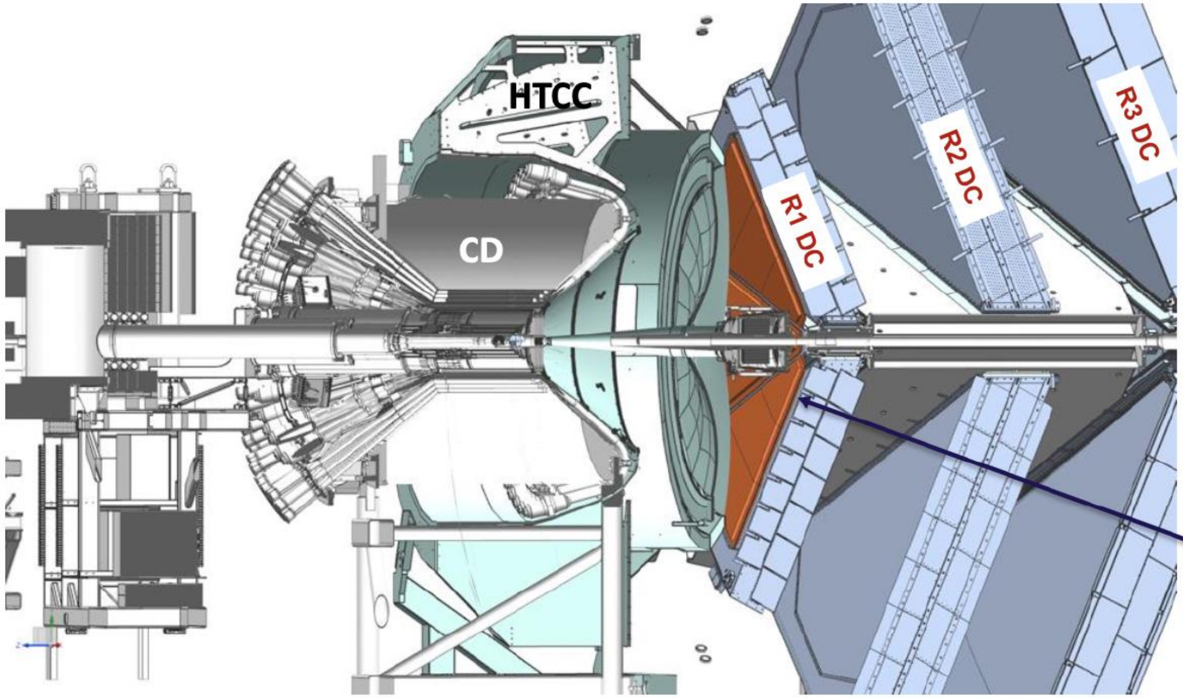
- **DDVCS** ($e\ p \rightarrow e'\ p'\ \mu^+\mu^-$) provides direct access to the full three-dimensional (x, ξ, t) mapping of Generalized Parton Distributions (GPDs) beyond the $x = \pm\xi$ constraint of DVCS/TCS, offering a unique opportunity to test the analytic structure of the Compton amplitude and its connection to QCD dispersion relations. Cross-section measurements and angular distributions will complement asymmetries to constrain both the real and imaginary parts of the Compton Form Factors (CFFs).
- **TCS** provides complementary sensitivity to the real and imaginary components of Compton Form Factors (CFFs), through observables such as photon beam polarization asymmetries and forward-backward angular asymmetries, providing a timelike counterpart to DVCS results and enabling stringent cross-checks of GPD universality.
- **Near-threshold J/ψ production** probes gluonic GPDs and the nucleon's gravitational form factors (GFFs), which encode information about the mass and pressure distributions inside the nucleon. Near-threshold J/ψ measurements will determine total and differential cross-sections, exploring gluonic contributions and gravitational form factors.
- **Search for exotic states**: The program also aims to investigate exotic states, such as hidden charm pentaquarks, by constraining or measuring their electroproduction cross sections. The anticipated J/ψ yield will be significantly higher (up to 25 times compared to current CLAS12 programs), allowing searches for pentaquark states and detailed studies of hidden charm dynamics.

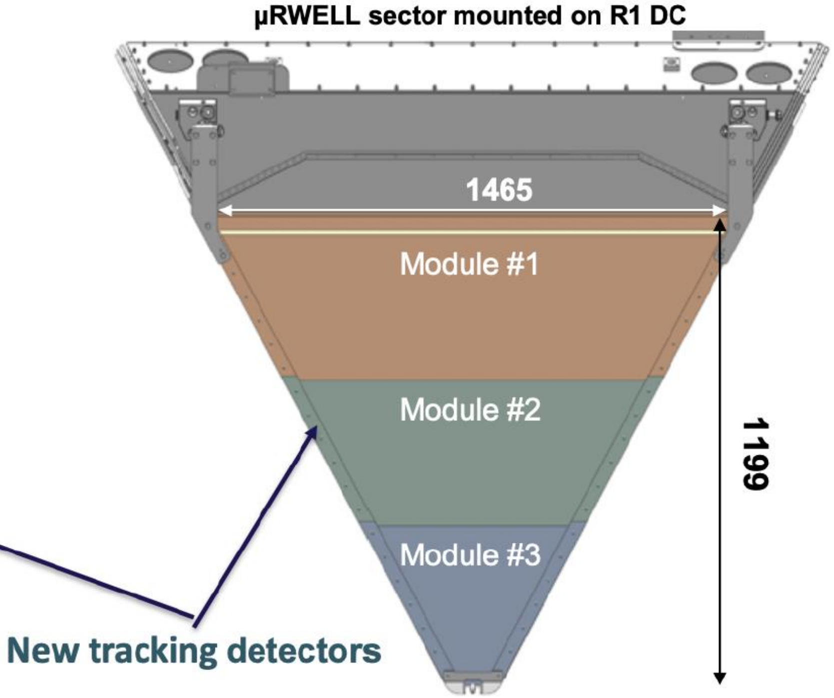
CLAS12 Luminosity upgrade, staged approach

- **Phase1**: achieve luminosity of $2x10^{35}$ $cm^{-2}s^{-1}$ for CLAS12 normal running conditions with charged particle reconstruction efficiency of >85%.
  - To support efficient and fast execution of the current program;
  - Support a growing demands of physics program with a low rate, exclusive reactions (TCS, J/Psi production,…);
  - Will need to upgrade forward tracking. The beam-line and the rest of the detector systems will perform at x2 higher luminosity;
- **Phase2**: achieve two orders of magnitude higher luminosities: μCLAS12 at > 10^{37} $cm^{-2}s^{-1}$
  - New physics opportunities for CLAS12 – DDVCS and e-J/ψ;
  - Requires a large acceptance forward calorimeter (FTCal-Large), a recoil detector and a forward vertex tracker

CLAS12 Luminosity upgrade - Phase 1 - Plans

To mitigate occupancy-related inefficiency of FD tracking, we plan to add faster tracking MPGD layers to the forward drift chambers.



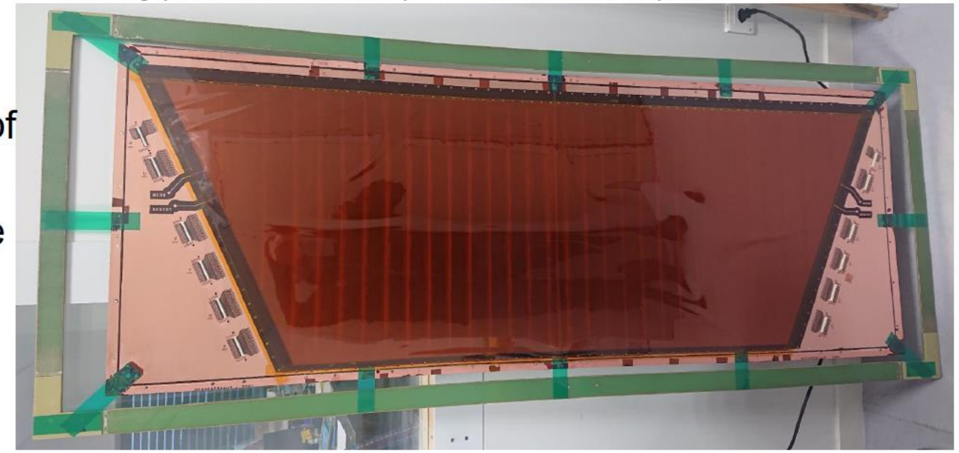


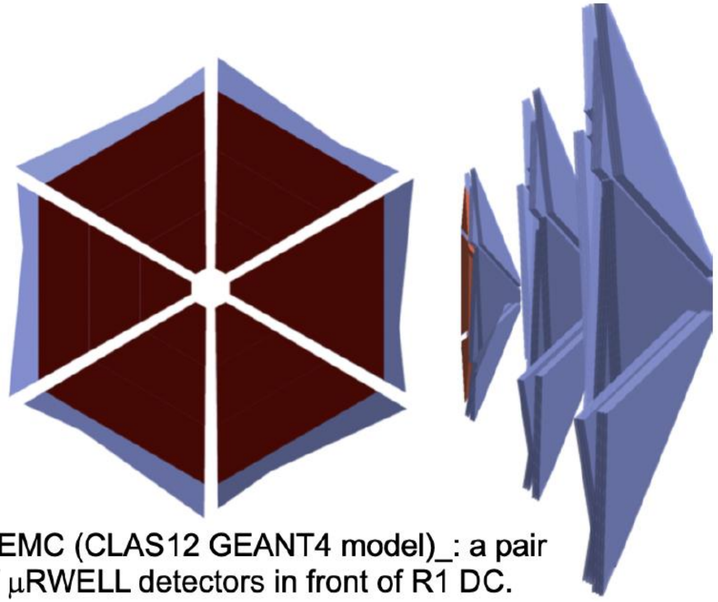
- Each layer will consist of 6 triangular large detectors
- Each detector will consist of three modules (there are no foils large enough to cover the whole R1).
- µRWell with 2-D, 10° stereo, strip readout with capacitive sharing, is the chosen technology

CLAS12 Luminosity upgrade - Phase 1 - Status

- Simulations fully developed and show:
  - no sizable degradation of momentum resolution with pair of such detectors in front of R1 DC
  - existing tracking software can already achieve the desired efficiency at higher luminosities
- Full-scale, single-sector, prototype assembled at CERN, in collaboration with University of Virginia
  - Trapezoid with an active area of [1460 mm – 1012 mm] × 50 mm
  - U & V strips at 10-degree stereo pitch = 1 mm
  - Capacitive-sharing R/O scheme
- Timeline:
  - 2024: testing of prototype
  - 2025: fabrication of full 6 sectors
  - 2026: installation

CLAS12 large μRWELL foil with U/V readout produced at Rui's MPT workshop at CERN



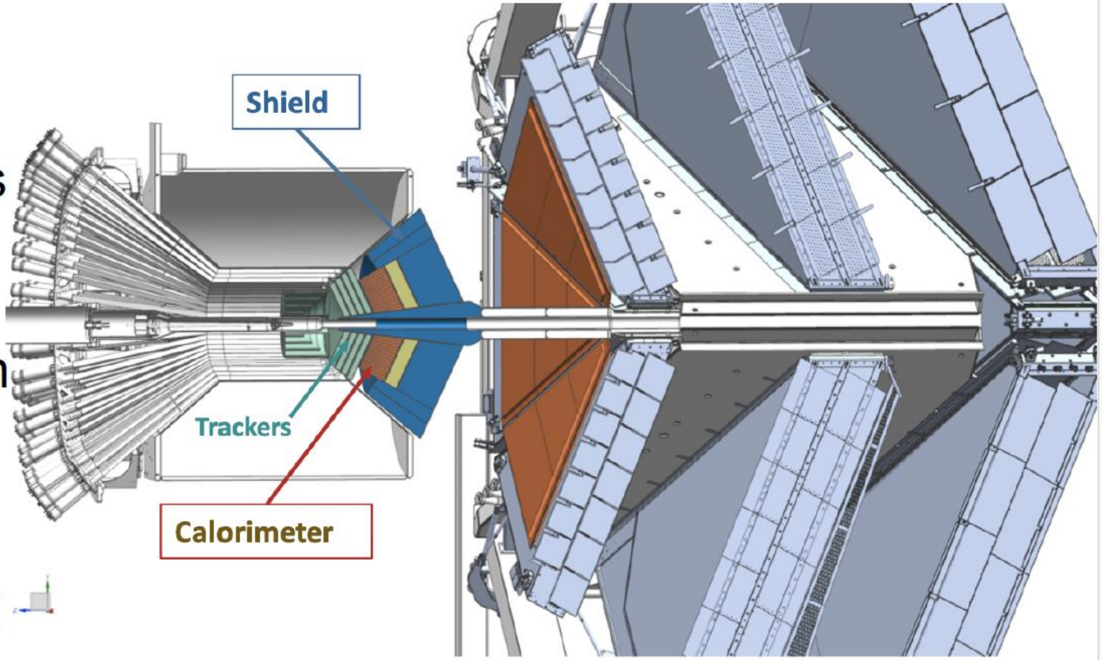


GEMC (CLAS12 GEANT4 model)_: a pair of μRWELL detectors in front of R1 DC.

CLAS12 Luminosity upgrade - Phase 2 - Plans

- Remove HTCC and block the CLAS12 forward with a W-shield and $PbWO_4$ calorimeter to prevent flooding of DC by EM background;
- Scattered electrons will be detected in the calorimeter, while shield will work as pion filter, as most of charged pions will shower and will not reach to the forward tracking system;
- Install fast, high rate MPGD trackers in front of the calorimeter for vertexing and inside the solenoid for recoil tagging.
- The existing downstream trackers and toroidal field become a muon spectrometer for luminosity of $10^{37} cm^{-1} s^{-1}$
- Time frame for Phase 2 is 6-8 years.

μCLAS12



Detector capable of measuring

$$ep \rightarrow e'p'\mu^+\mu^- \ \ @ \, L > 10^{37} cm^{-2} sec^{-1}$$

New Polarized ^{3}He Target for CLAS12

A concept for polarized ^{3}He targets for high luminosity scattering experiments in high magnetic field environments

J.D. Maxwell [a], R.G. Milner [b]

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.nima.2021.165590

Get rights and content

Combining two technologies: double-cell polarized ^{3}He target (Maxwell, Milner, NIM A, 2021.)

CLAS12's 5 T solenoid standard configuration

5.4 amg, comparable to SEOP

High Field MEOP

High magnetic field (5 T)

Polarization ~ 60%

Higher pressure (100 times) compared to typical low field MEOP (100 mbar vs 1 mbar)

Double-Cell Cryo Target

Polarize ^{3}He using MEOP at room temp (300 K)

Diffuse transfer to 5 K target cell

Density increase by 60 times

Proposal PR12-20-002 to PAC48

A program of spin-dependent electron scattering using a polarized ^{3}He target in CL

(Co-Spokespeople: H. Avakian, J. Maxwell, R. Milner, D. Nguyen)

P_T -dependence of n longitudinal spin structure

Nuclear corrections to SIDIS

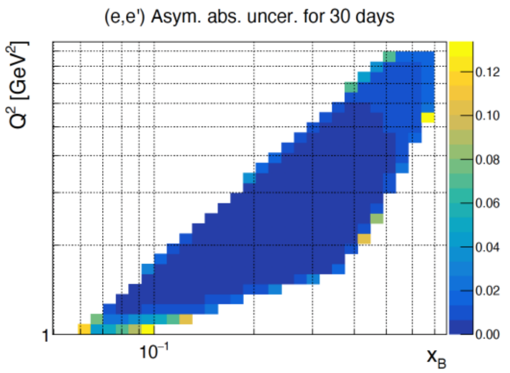
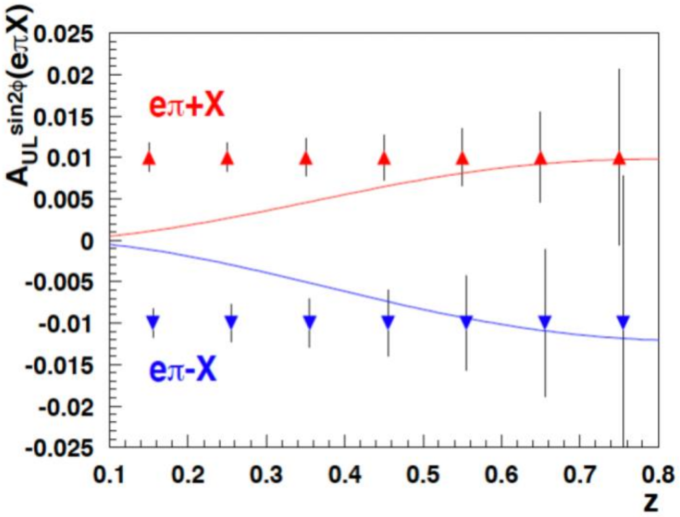


FIG. 13: Projected number of DIS events and absolute statistical uncertainty in the asymmetry for 30 days of running at 0.5 μA on the polarized ^{3}He target.

- Beam energy = 10.6 GeV
- Beam current = 500 nA
- Target thickness = 2.9 x 10^{21} ^{3}He cm^{-2}
- Target poln. = 50%
- Beam poln. = 80%
- Luminosity = 2.7 x 10^{34} nucleons/cm^{2}/s
- 30 days of running



$0.05 < x < 0.7$

$1 < Q^2 < 9$ (GeV/c)^2

$0.2 < z < 0.9$

$0 < p_T < 1.3$ (GeV/c)

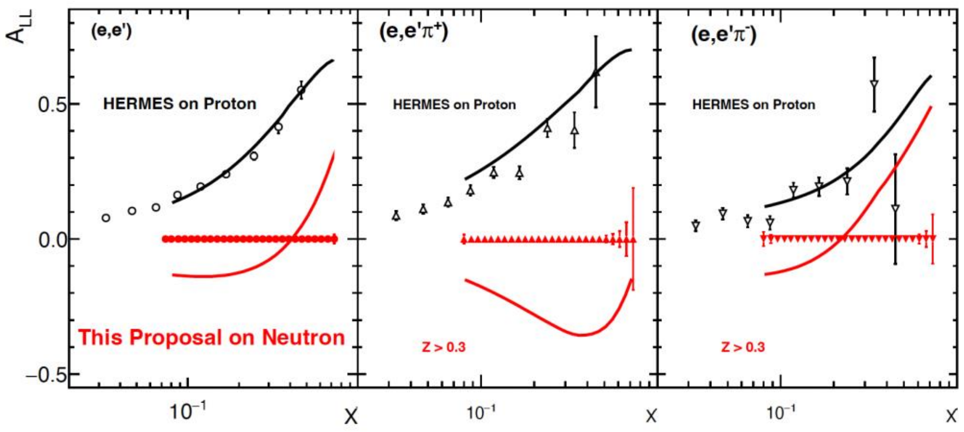


FIG. 15: $x-$dependence projection plot for charged pions, the black data points are HERMES data [83], the red data points are projection for this proposal for 30 days of running at 0.5 μA. The curves use GRV [84] PDFs, and $D_1(z)$ from DSS [85], with black curves calculated for proton, and red curves calculated for neutron.

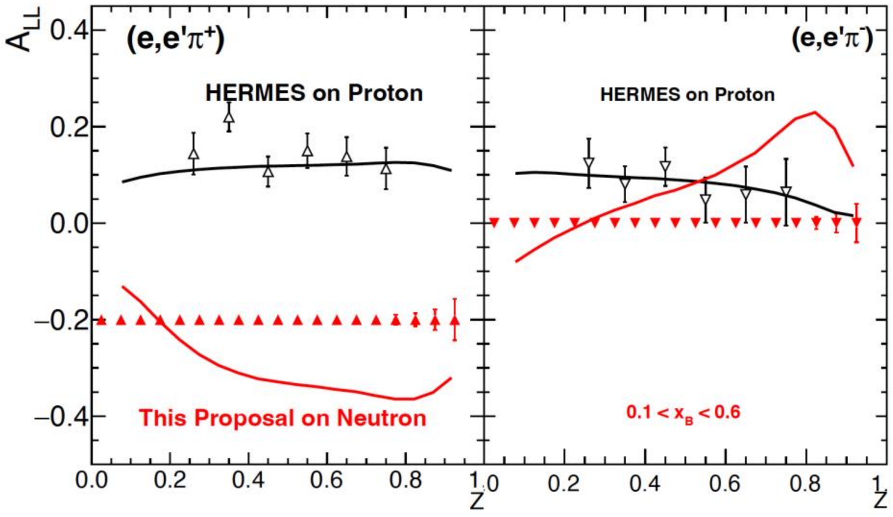


FIG. 16: $z-$dependence projection plot for charged pions in the valence region $0.1 < x < 0.6$, compared to the HERMES data on proton [86]. The curves use GRV [84] PDFs, and $D_1(z)$ from DSS [85].

Proposal PR12-20-002 to PAC48

A program of spin-dependent electron scattering using a polarized ^{3}He target in CL

(Co-Spokespeople: H. Avakian, J. Maxwell, R. Milner, D. Nguyen)

P_T -dependence of n longitudinal spin structure

Nuclear corrections to SIDIS

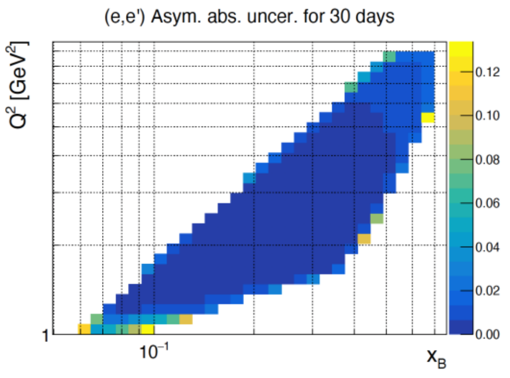
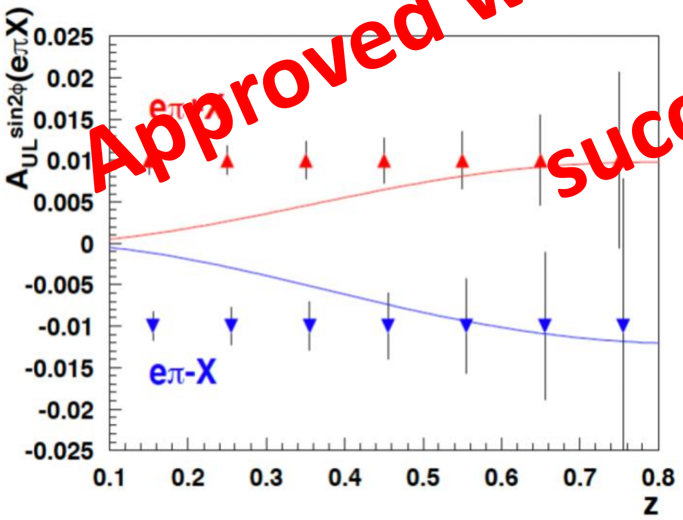


FIG. 13: Projected number of DIS events and absolute statistical uncertainty in the asymmetry for 30 days of running at 0.5 μA on the polarized ^{3}He target.

- Beam energy = 10.6 GeV
- Beam current = 500 nA
- Target thickness = 2.9 x 10^{21} ^{3}He cm^{-2}
- Target poln. = 50%
- Beam poln. = 80%
- Luminosity = 2.7 x 10^{34} nucleons/cm^2/s
- 30 days of running

Approved with high scientific priority conditional upon successful realization of the target



$0.05 < x < 0.7$

$1 < Q^2 < 9$ (GeV/c)^2

$0.2 < z < 0.9$

$0 < p_T < 1.3$ (GeV/c)

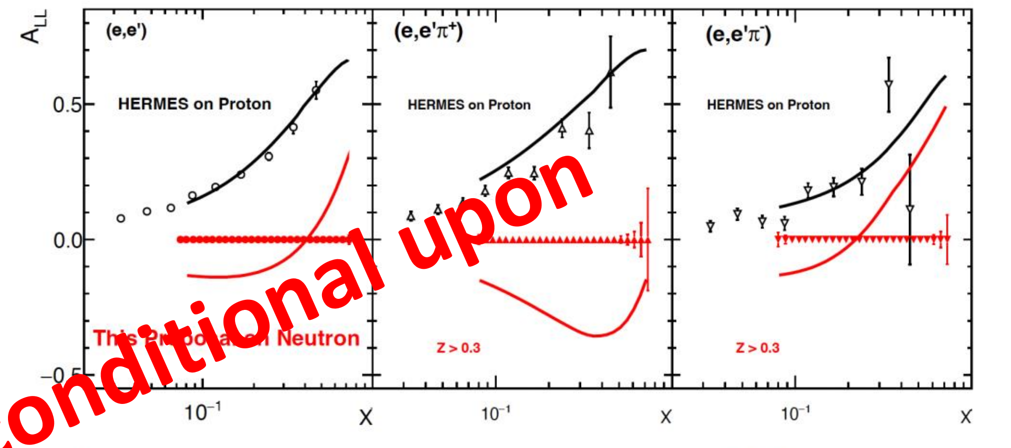


FIG. 15: $x-$dependence projection plot for charged pions, the black data points are HERMES data [83], the red data points are projection for this proposal for 30 days of running at 0.5 μA. The curves use GRV [84] PDFs, and $D_1(z)$ from DSS [85], with black curve calculated for proton, and red curves calculated for neutron.

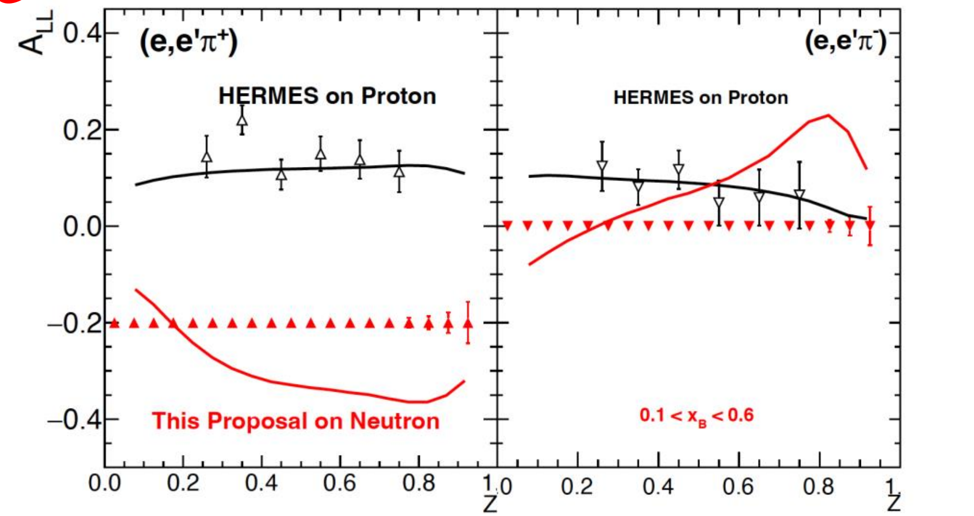


FIG. 16: $z-$dependence projection plot for charged pions in the valence region $0.1 < x < 0.6$, compared to the HERMES data on proton [86]. The curves use GRV [84] PDFs, and $D_1(z)$ from DSS [85].

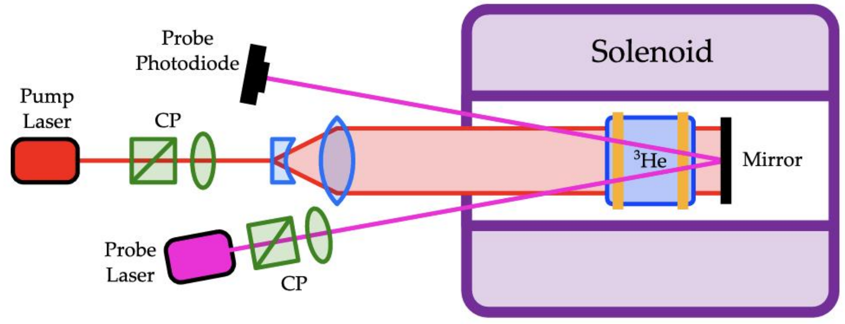


Figure 2: Diagram of high field polarizing apparatus and probe laser polarimeter.

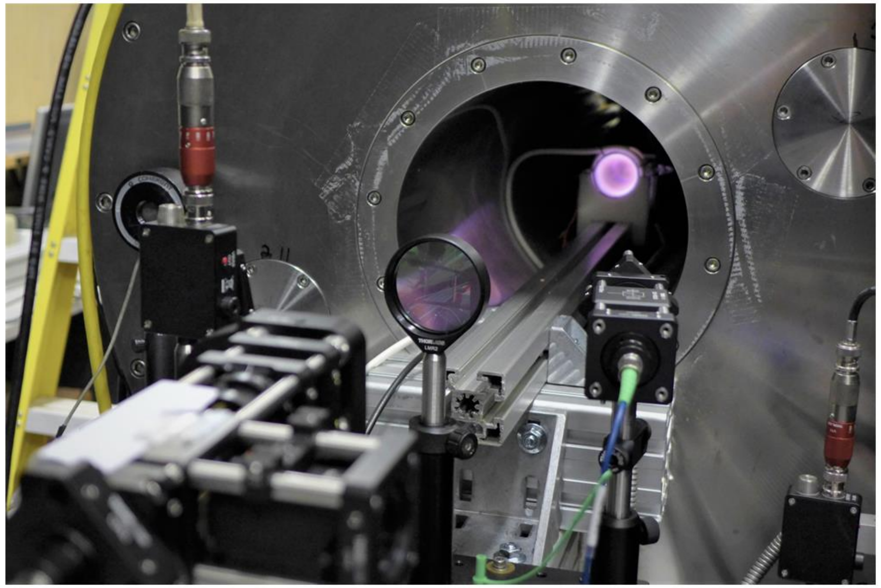


Figure 3: Photograph of the polarizing apparatus and EBIS spare solenoid warm bore. In the foreground are the pumping laser circular polarization optics. The probe laser fiber enters a circular polarizer on the right, and after passing through the cell the probe light is reflected by a mirror back to a photodiode on the left. The sealed cell is illuminated by the RF discharge plasma in pink; for this photograph it is much brighter than is effective for optical pumping.

Enhanced polarization of low pressure ^{3}He through metastability exchange optical pumping at high field

J.D. Maxwell [a], J. Alessi [b], G. Atoian [b], E. Beebe [b], C.S. Epstein [a], R.G. Milner [a],
M. Musgrave [a], A. Pikin [b], J. Ritter [b], A. Zelenski [b]

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.nima.2019.02.019

Get rights and content

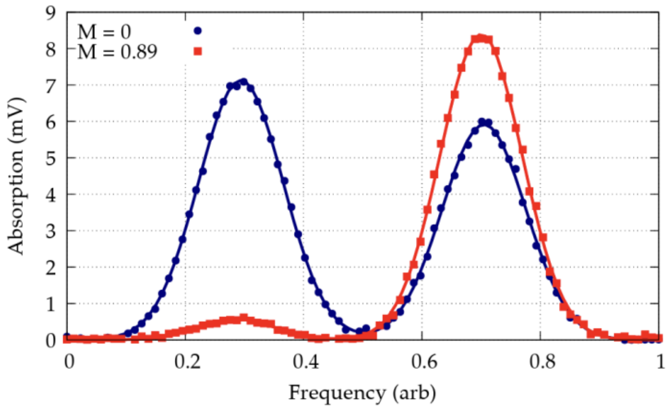


Figure 4: Example probe laser absorption signals with sample nuclear polarization at 0 and 89%, using a 1 torr sealed cell at 3 T. Both probe transition peaks are visible for each signal, as are the side-by-side Gaussian fits used to extract the peak amplitudes for analysis.

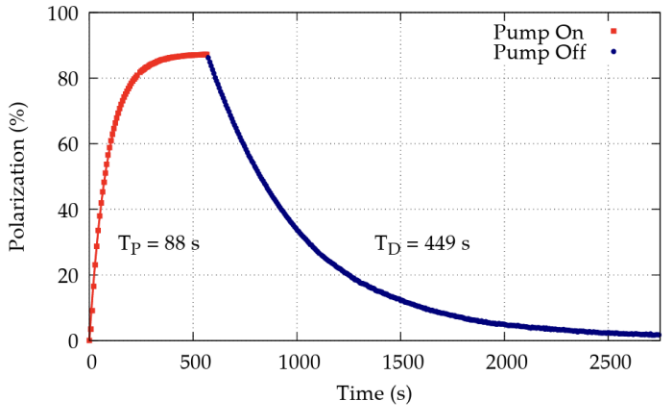


Figure 5: Typical pump and relaxation cycle at 2 T, showing exponential pumping build-up time T_P with the optical pumping active, and the relaxation time T_D after the pumping laser is blocked at 560 s.

Full Length Article

Metastability exchange optical pumping of ^{3}He at low pressure and high magnetic field

X. Li [a], J.D. Maxwell [b], D. Nguyen [b], J. Brock [b], C.D. Keith [b], R.G. Milner [a], X. Wei [b]

Show more

JLab, MIT, U. Tennessee, Shandong U.

Add to Mendeley Share Cite

https://doi.org/10.1016/j.nima.2023.168792 Get rights and content

Full Length Article

Polarizing ^{3}He via metastability exchange optical pumping using a 1.2 mbar sealed cell at magnetic fields up to 5 T

P. Pandey [a], H. Lu [b], J.D. Maxwell [c], J. Brock [c], C.D. Keith [c], X. Li [d], R.G. Milner [a], D. Nguyen [b]

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.nima.2025.170870 Get rights and content

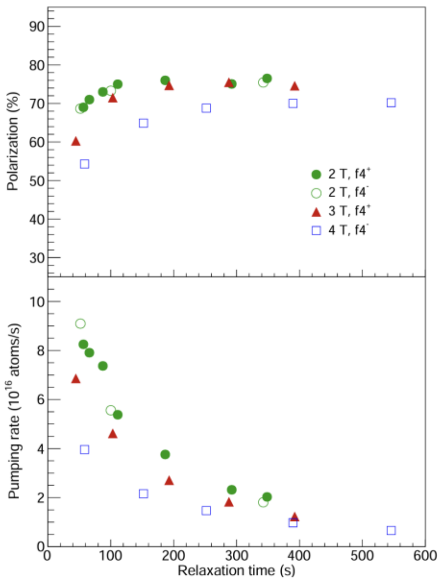


Figure 6: Maximum steady-state nuclear polarization and pumping rate measured with various discharge intensity levels (characterized by the relaxation time) at 2 T (circles), 3 T (triangles) and 4 T (squares) using the $f_4^{\pm}$ pumping schemes and a pump laser output power of 3 W. The closed and open symbols are for the σ^+ and σ^- schemes, respectively.

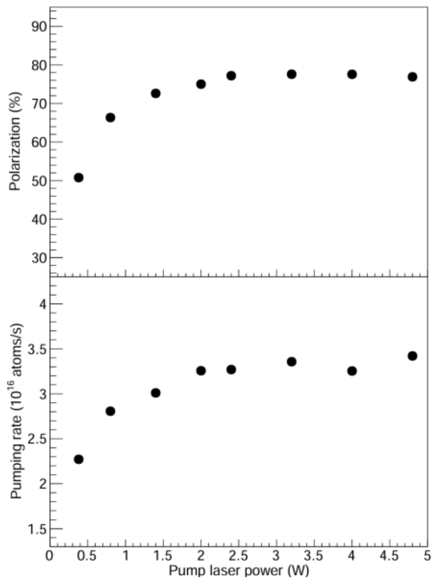


Figure 7: Maximum steady-state nuclear polarization and pumping rate measured with various on-cell pump laser power at 2 T using the f_4^- pumping transition. The discharge-on relaxation time corresponding to each data point is above 200 s.

Figure 2: Top: "Bone" style cell with 30 mm windows and a 25.4 mm diameter volume, showing the inductive electrode wound the length. Bottom: Discharge in the cell gets pushed to the edge while in the 5 T magnetic field.

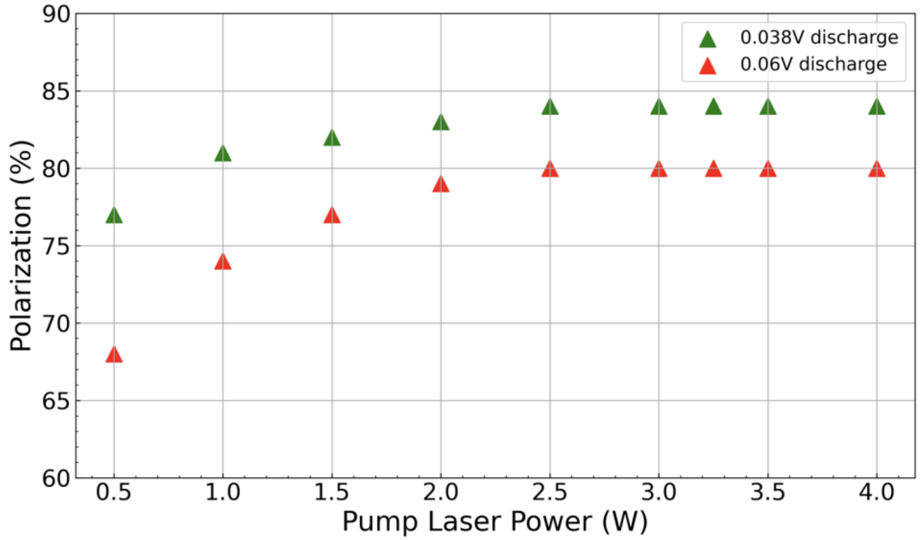
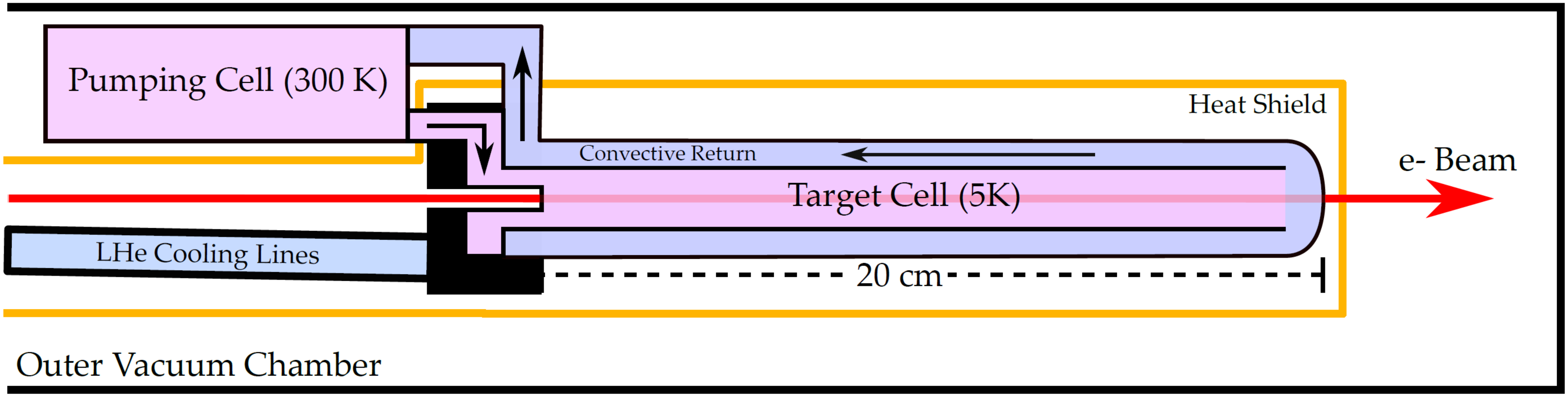


Figure 5: Maximum steady-state nuclear polarization measured at 5 T using the f_4^+ line for various pump laser power levels at two different discharge intensities.

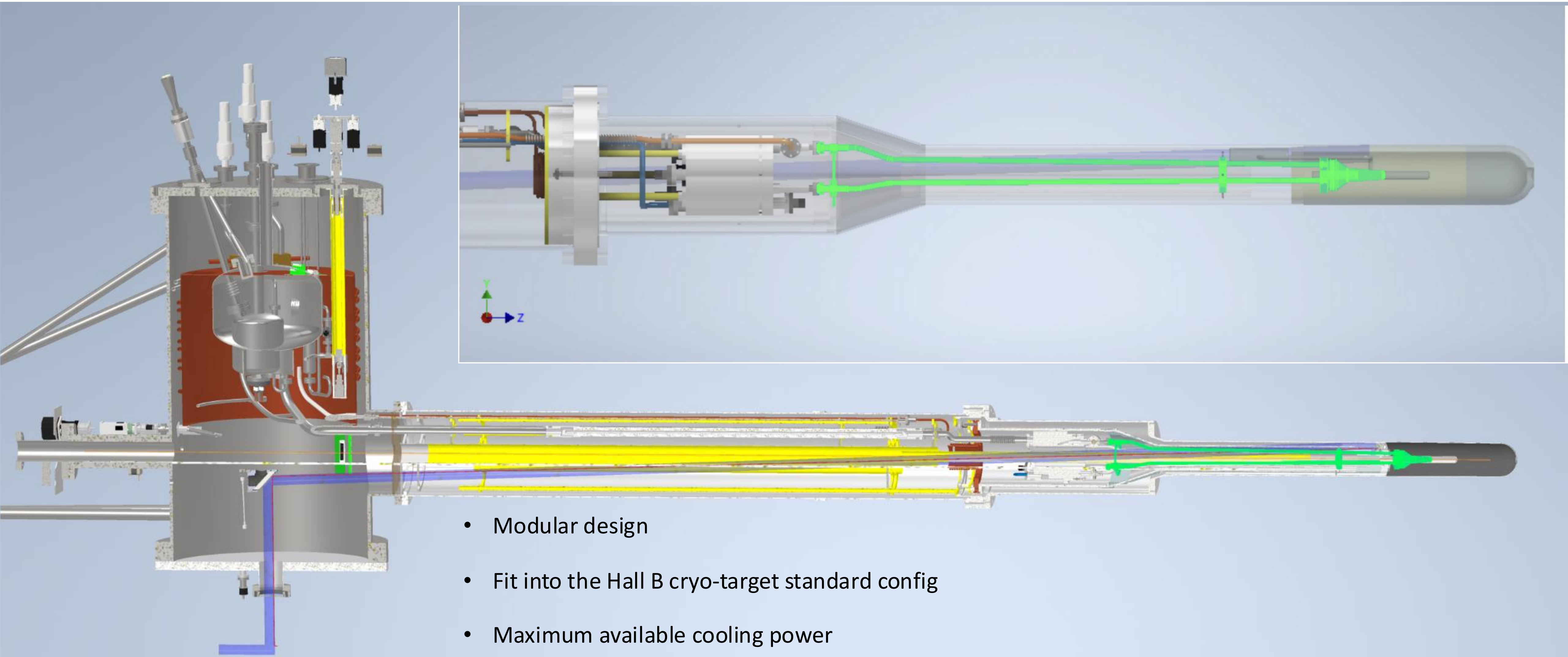
Richard Milner
EINN 2025

Double-cell Target Design

- Pumping Cell
  - 200 cm^3 borosilicate glass
  - Annular cylindrical volume
- Target Cell
  - 100 cm^3, 20 cm long aluminum cell
  - Cooled by LHe heat exchanger



Double-cell Target Design



- Modular design
- Fit into the Hall B cryo-target standard config
- Maximum available cooling power

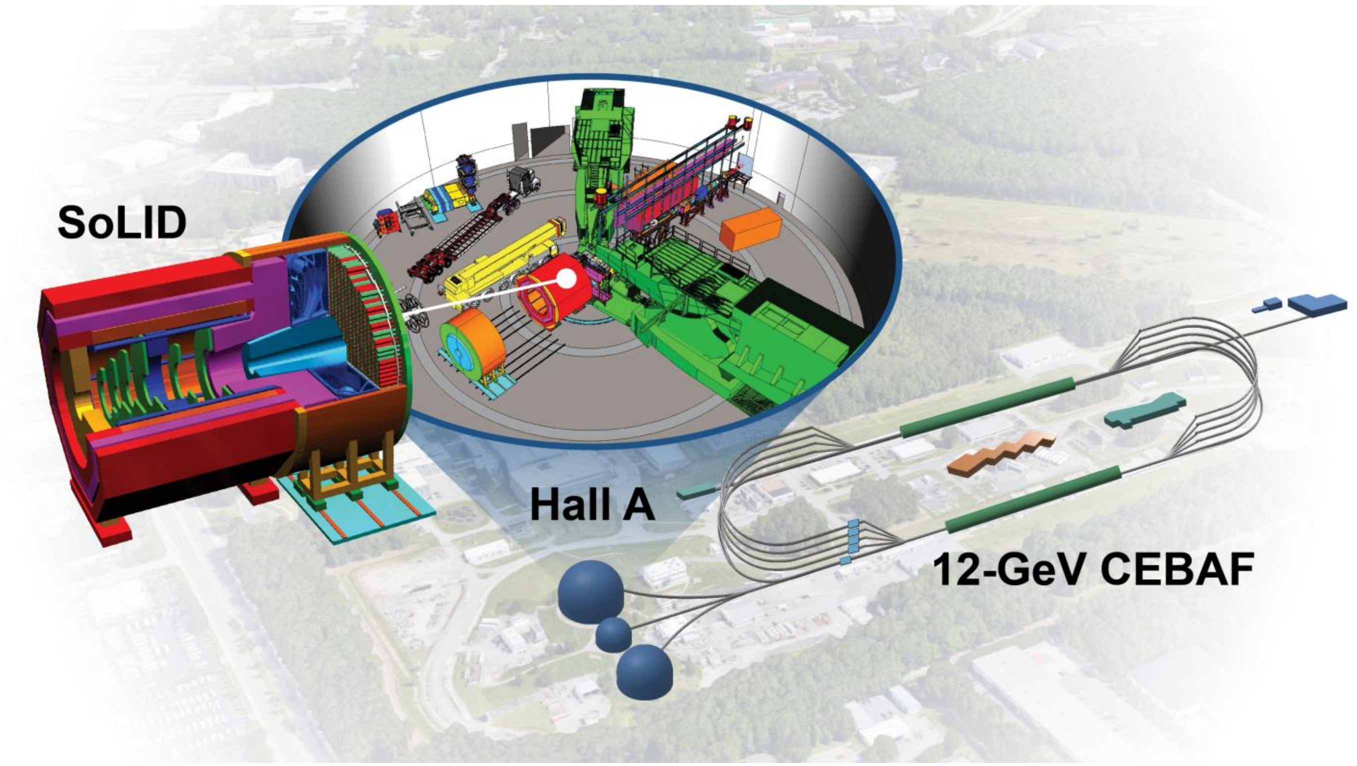
Interplay of Energy and Intensity

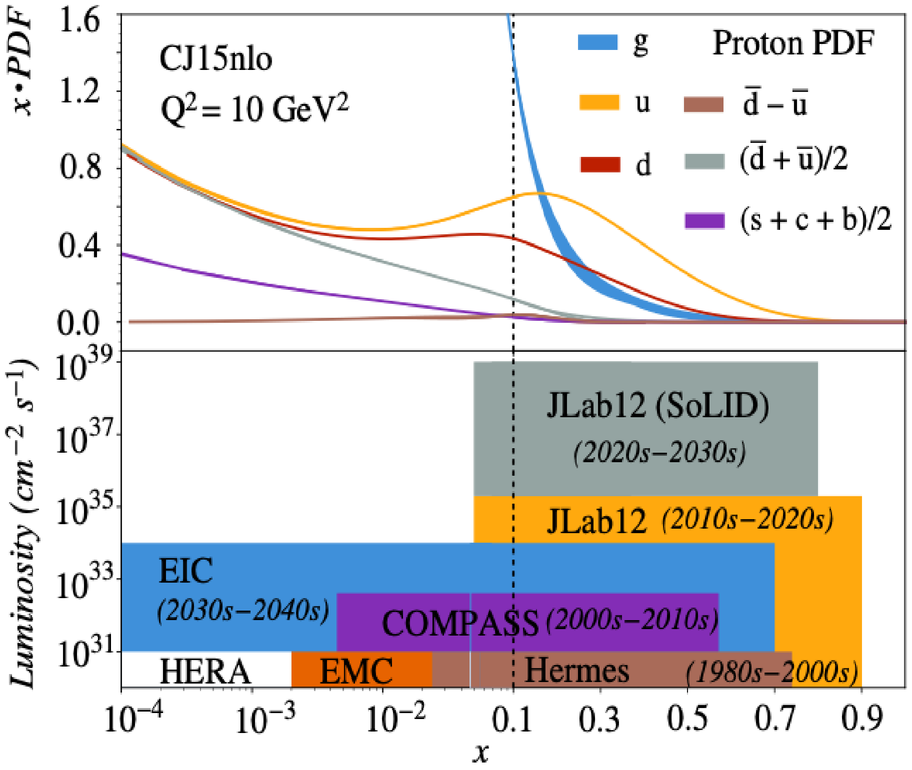
Structure of visible matter probed at JLab and the future EIC

Discoveries in Physics are often enabled by high-precision measurements and that is where

Solenoidal Large Intensity Device (SoLID) comes!

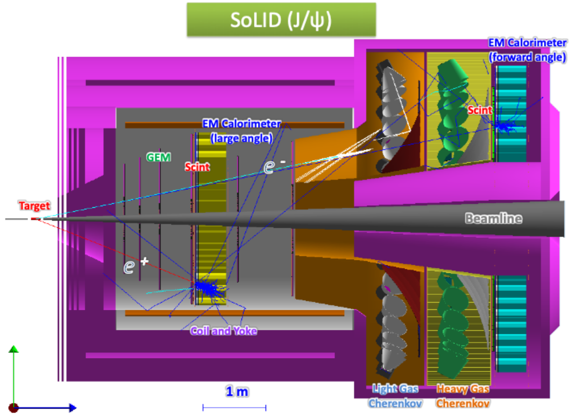
Up to 10^{39} $cm^{-2}s^{-1}$

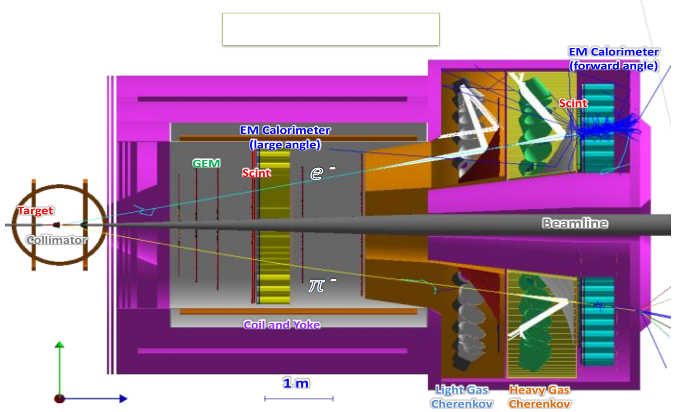


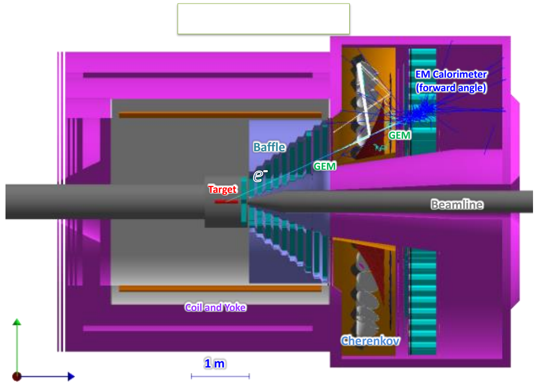


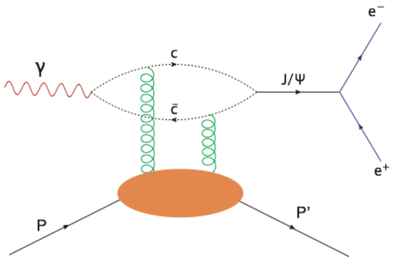
Haiyan Gao (Duke), Zein-Eddine Meziani (ANL)
https://www.innovationnewsnetwork.com/quantum-chromodynamics-at-the-intensity-frontier-with-a-precision-microscope/52920/

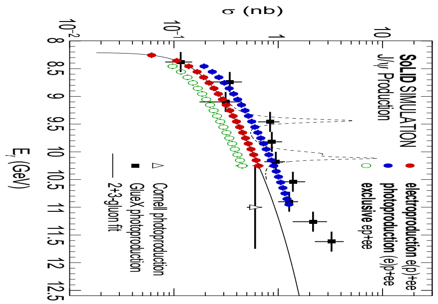
SoLID@JLab: QCD at the intensity frontier

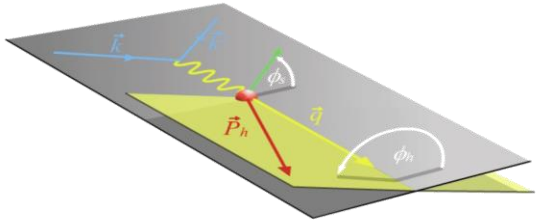


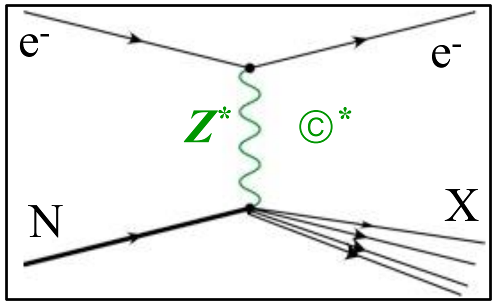


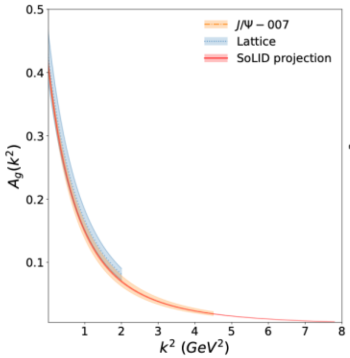


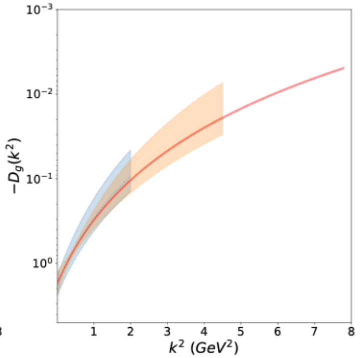


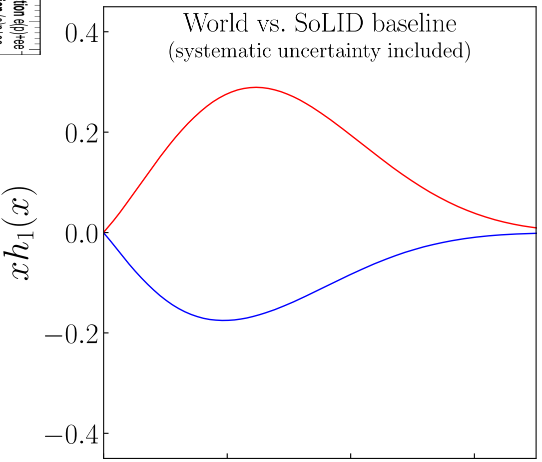


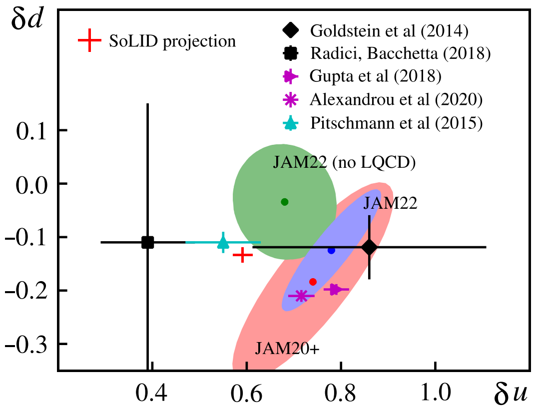


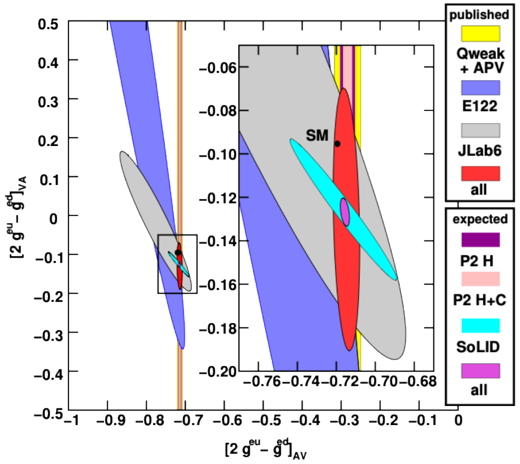










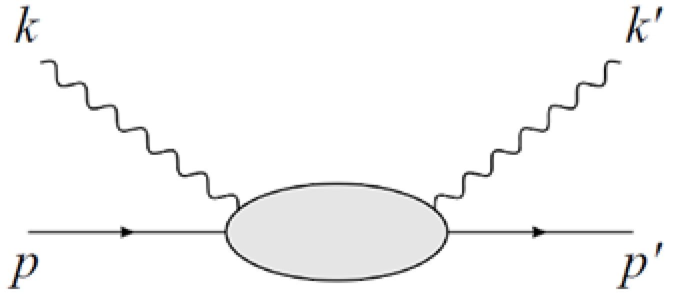


Nucleon Static Electromagnetic Polarizabilities

- Properties probing structure of the nucleon
- Characterizing responses to external EM fields
  - Structure responses -- induced dipole moments

$$\vec{\mathbf{d}}_{\mathbf{ind}} = \boldsymbol{\alpha}_{\mathbf{E1}}\, \vec{\mathbf{E}}\,,\ \vec{\mathbf{m}}_{\mathbf{ind}} = \boldsymbol{\beta}_{\mathbf{M1}}\, \vec{\mathbf{H}}$$

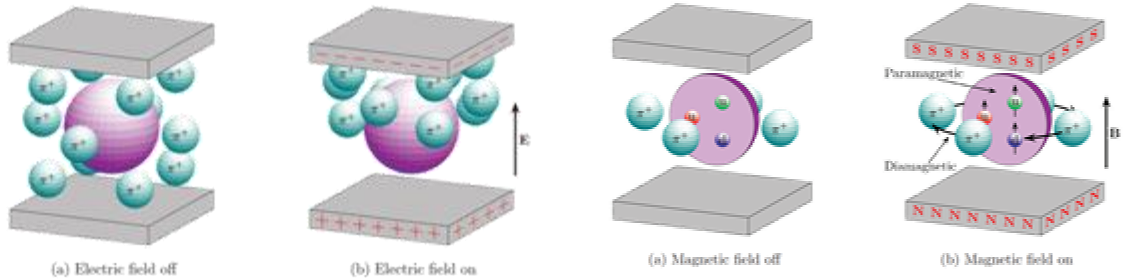
- Compton scattering is an effective probe of $\boldsymbol{\alpha}_{\mathbf{E1}}$ and $\boldsymbol{\beta}_{\mathbf{M1}}$
  → Photon provides external EM field



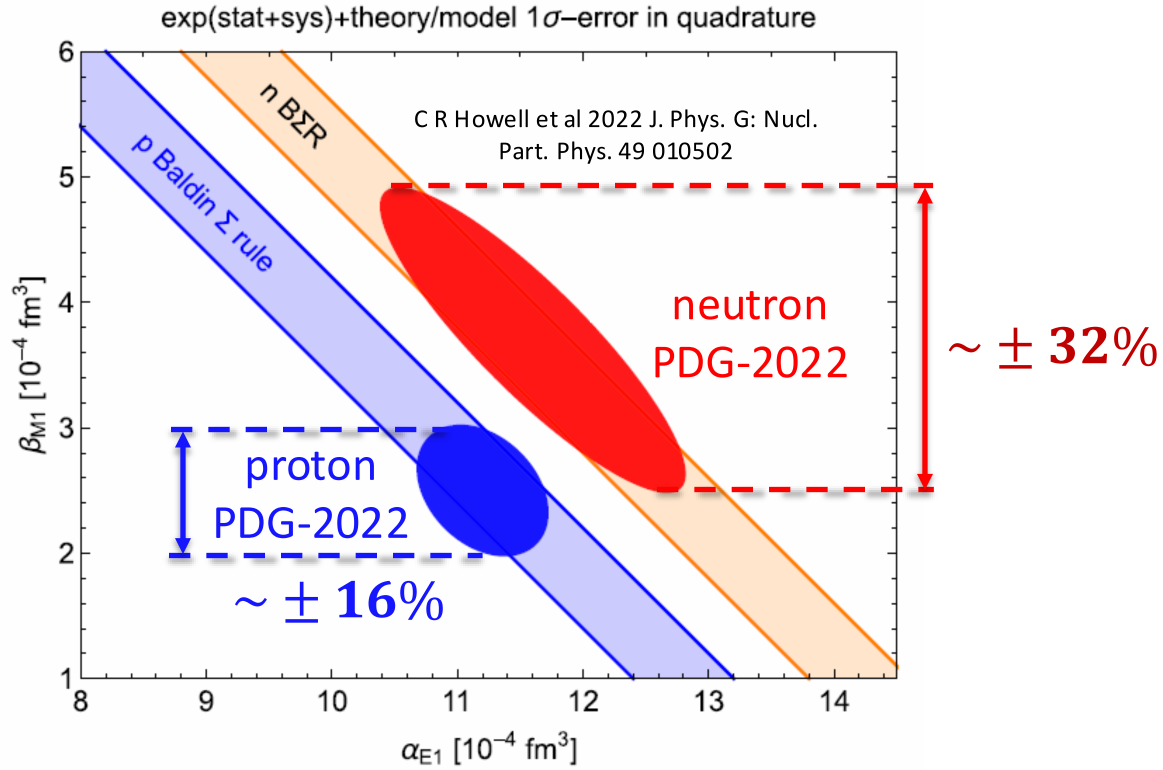
- Benchmark χEFT and lattice QCD calculations

Margaryan, Arman, et al. *The European Physical Journal A* 54.7 (2018): 125.
Grießhammer, Harald W., et al. *The European Physical Journal A* 60.6 (2024): 132.
Wang, Xuan-He, et al. *Physical Review Letters* 133.14 (2024): 141901.

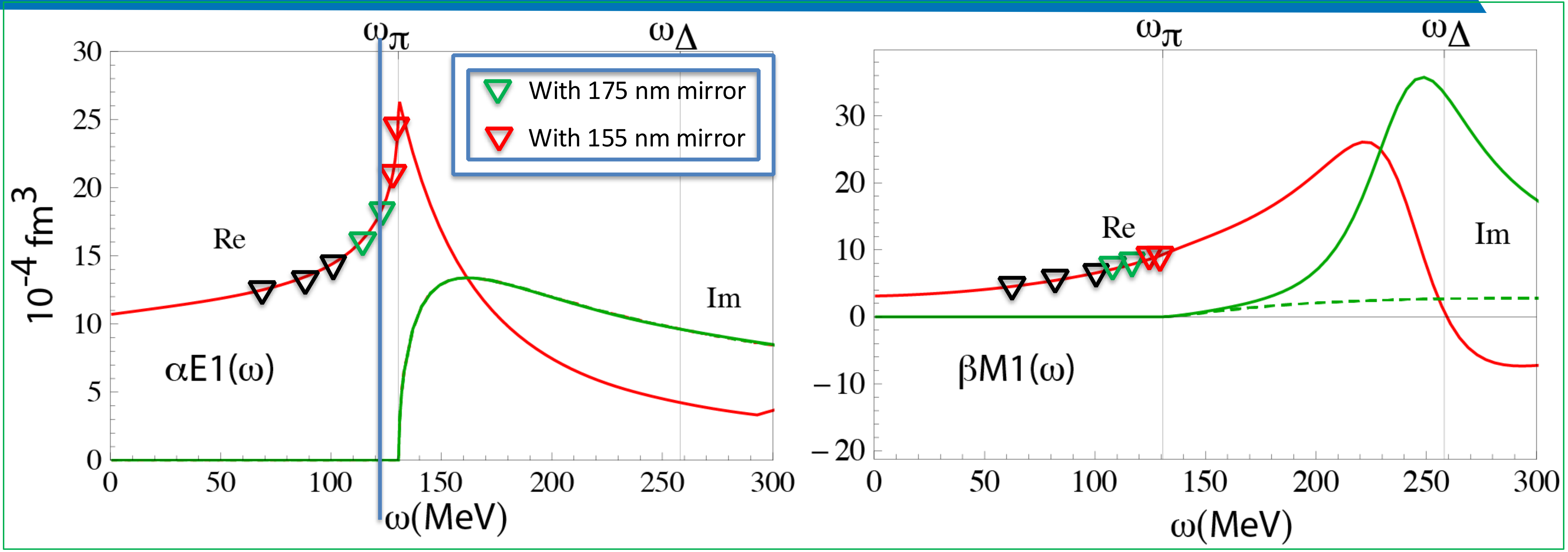
Electric polarizability (α_{E1}) **Magnetic polarizability (β_{M1})**



(Graphs credited to P. Martel)



HIGS: The Next Three Years



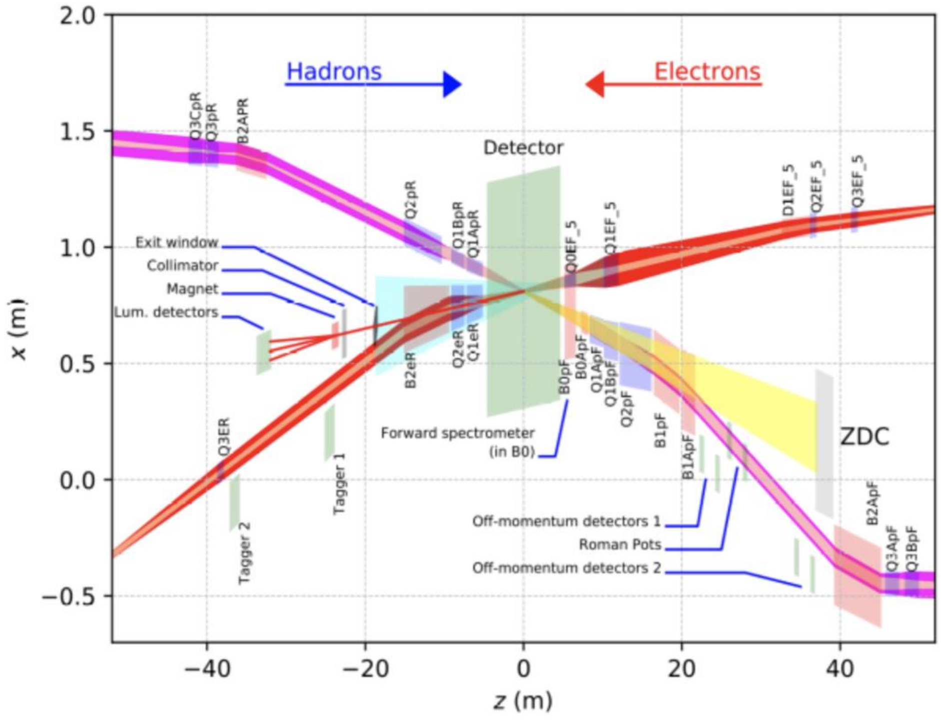
- **Reduce uncertainty in neutron α and β by a factor of 2**
  - Liquid ^{2}H target at E_γ = 61 MeV; done spring - summer 2022
  - Liquid ^{3}He target at E_γ = 60 and 100 MeV; done summer 2024
  - Liquid ^{4}He target at E_γ = 87 and100 MeV; done summer 2025
  - Liquid ^{3}He target at E_γ = 87 MeV
  - Liquid ^{2}H target at E_γ = 87 MeV
  - Liquid ^{3}He and ^{4}He targets at E_γ = 120 MeV (need 175-nm mirrors)
- **High precision measurement of proton α and β**
  - Liquid H target at E_γ = 87, 100 MeV, = 120 MeV (need 175-nm mirrors)

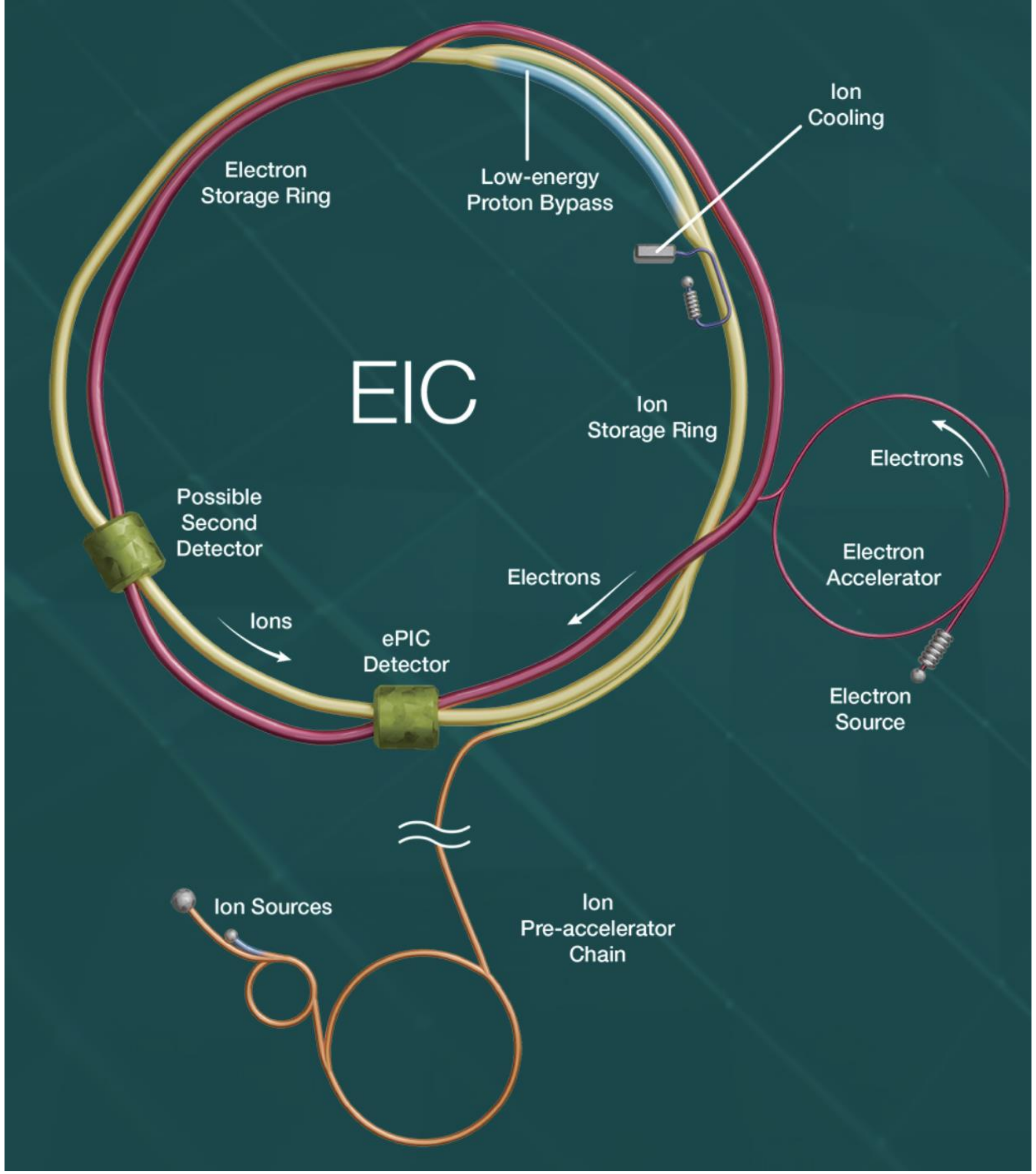
Towards the EIC.....

- Accelerator: RHIC operations expected to end in 2026 and construction of EIC in RHIC tunnel to get underway.
- ePIC detector design proceeding.
- EPIOS scientific consortium formed to realize polarized ion beams at EIC.

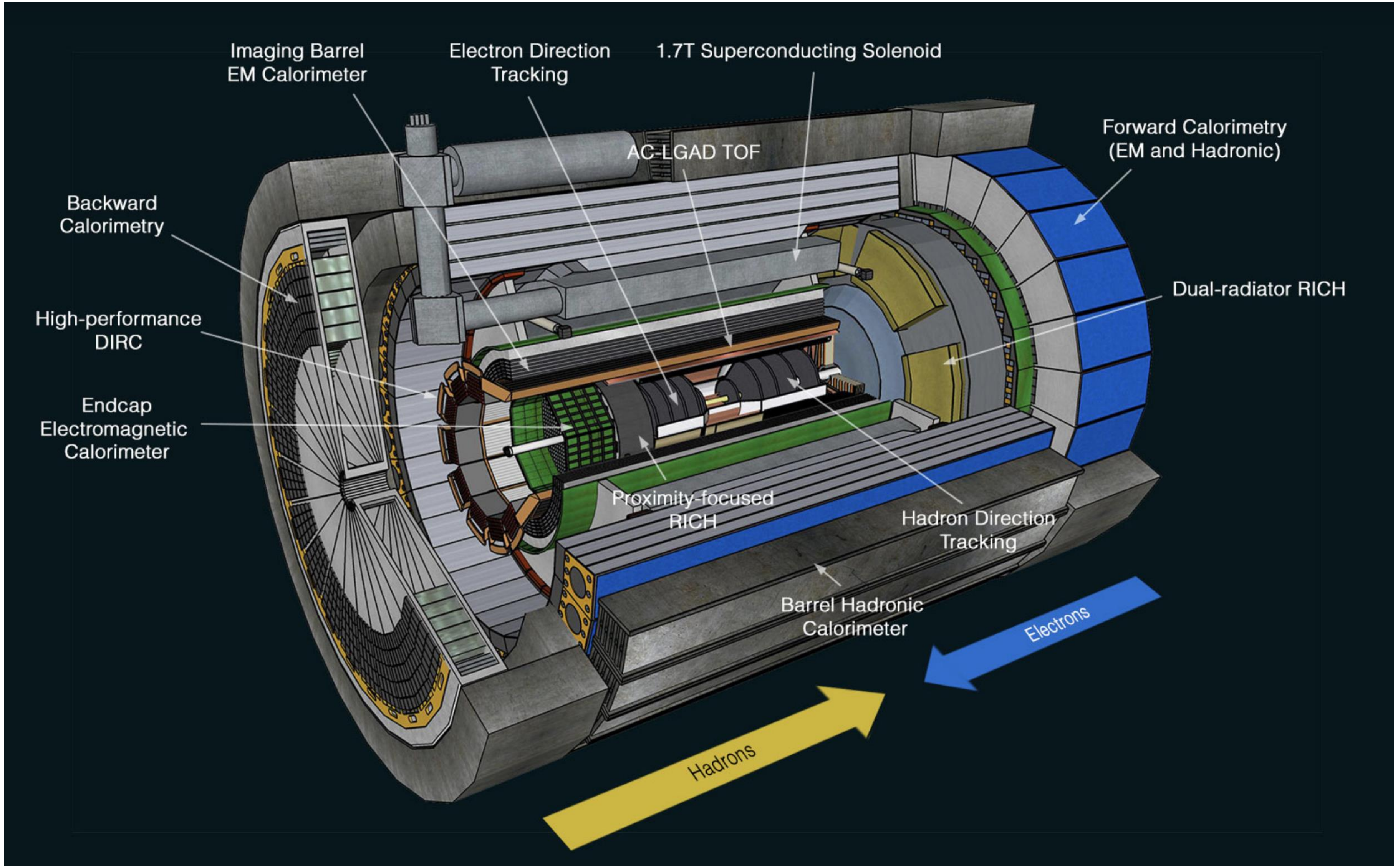
EIC Machine

New electron injector scheme

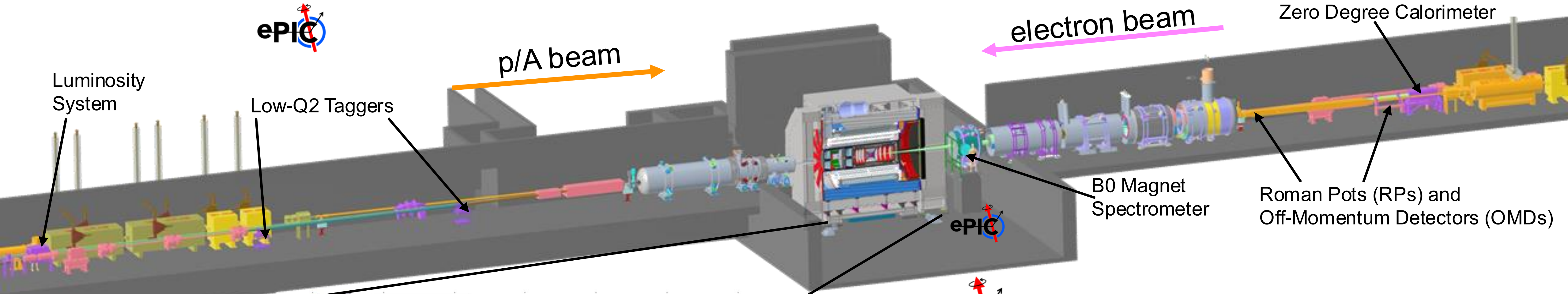


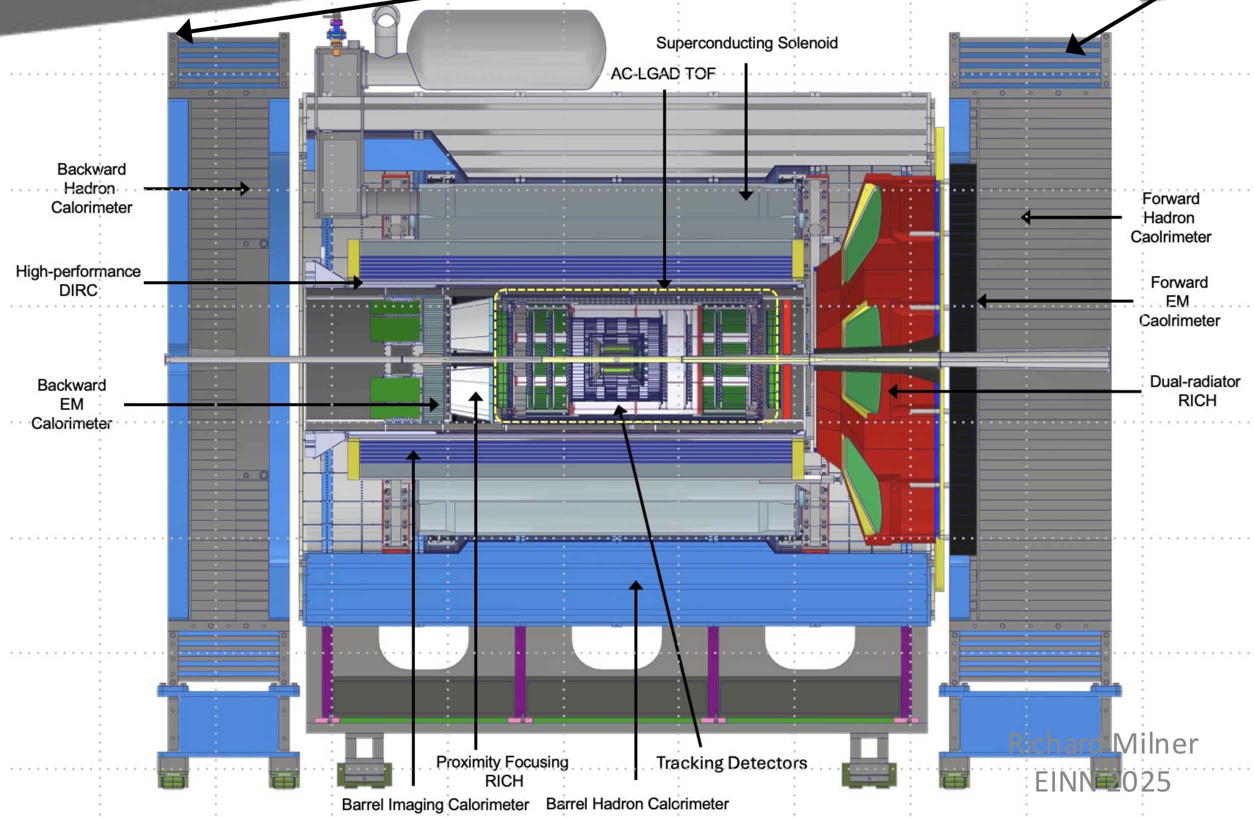


ePIC Detector



ePIC – The EIC State-of-the-Art General-Purpose Detector





ePIC

26 subsystems over ± 40 m
to measure particle momenta, energy and particle type

- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Multi-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxiliary detectors (Si + HCal + ECals)
- electron and hadron polarimetry

Integration, Installation and Infrastructure
Non-Beam Commissioning

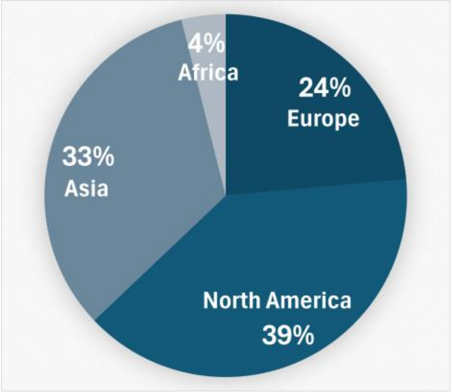
Highest scientific flexibility
→ fully streaming readout electronics and data acquisition
→ integration AI/ML capabilities from the start

The ePIC Collaboration

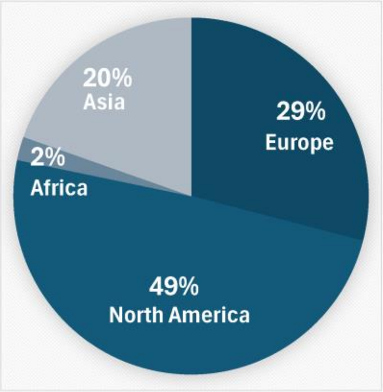
e
s
r
mission.

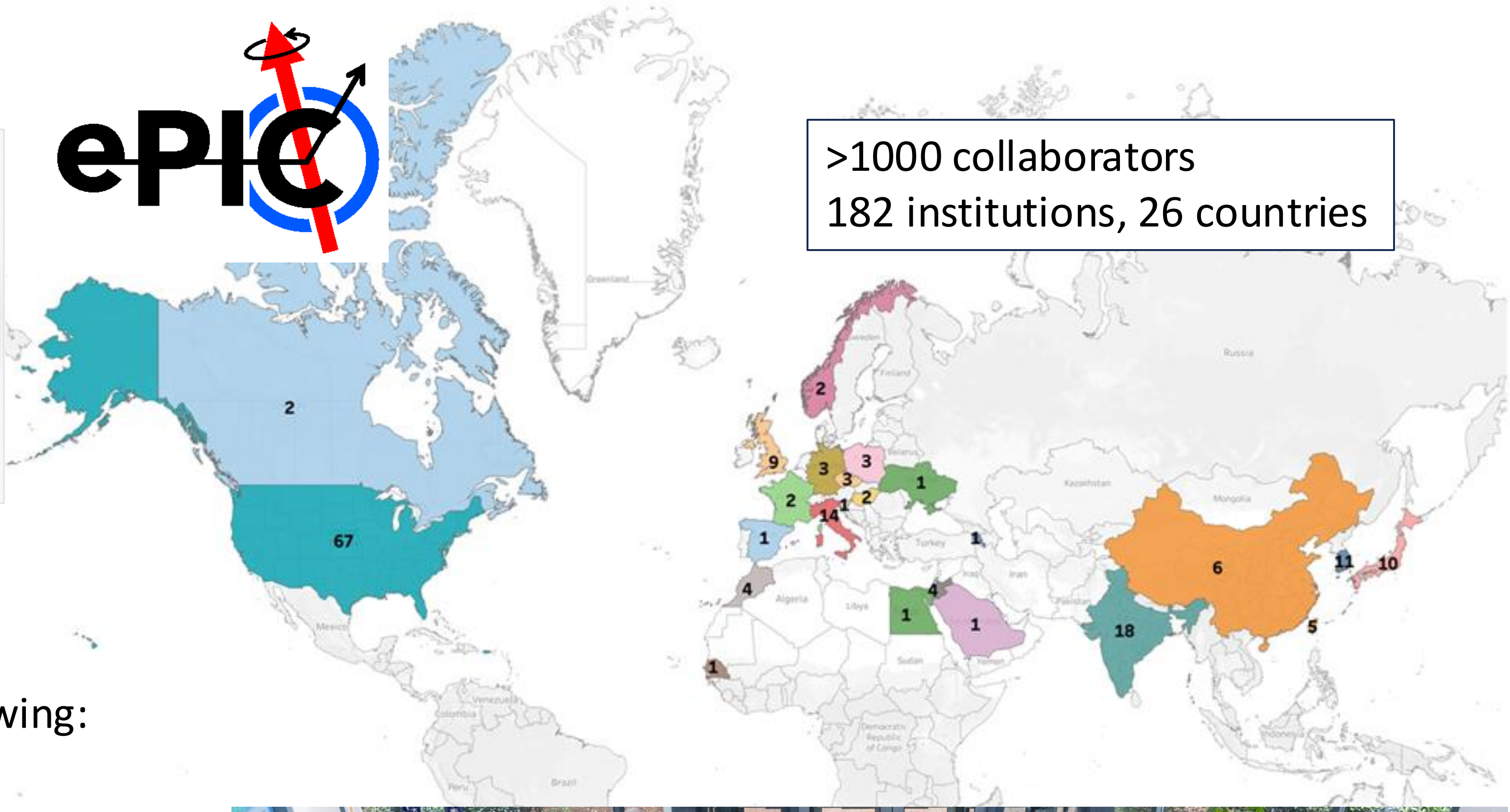
The ePIC Collabor
as unique as the e
detector.

Institutions:



Collaborators:





>1000 collaborators
182 institutions, 26 countries

The ePIC Collaboration is strong, active and growing:

- CERN Recognized Experiment
- Adding new collaborating institutions
- Ongoing subdetector design reviews

Current Collaboration Priorities:

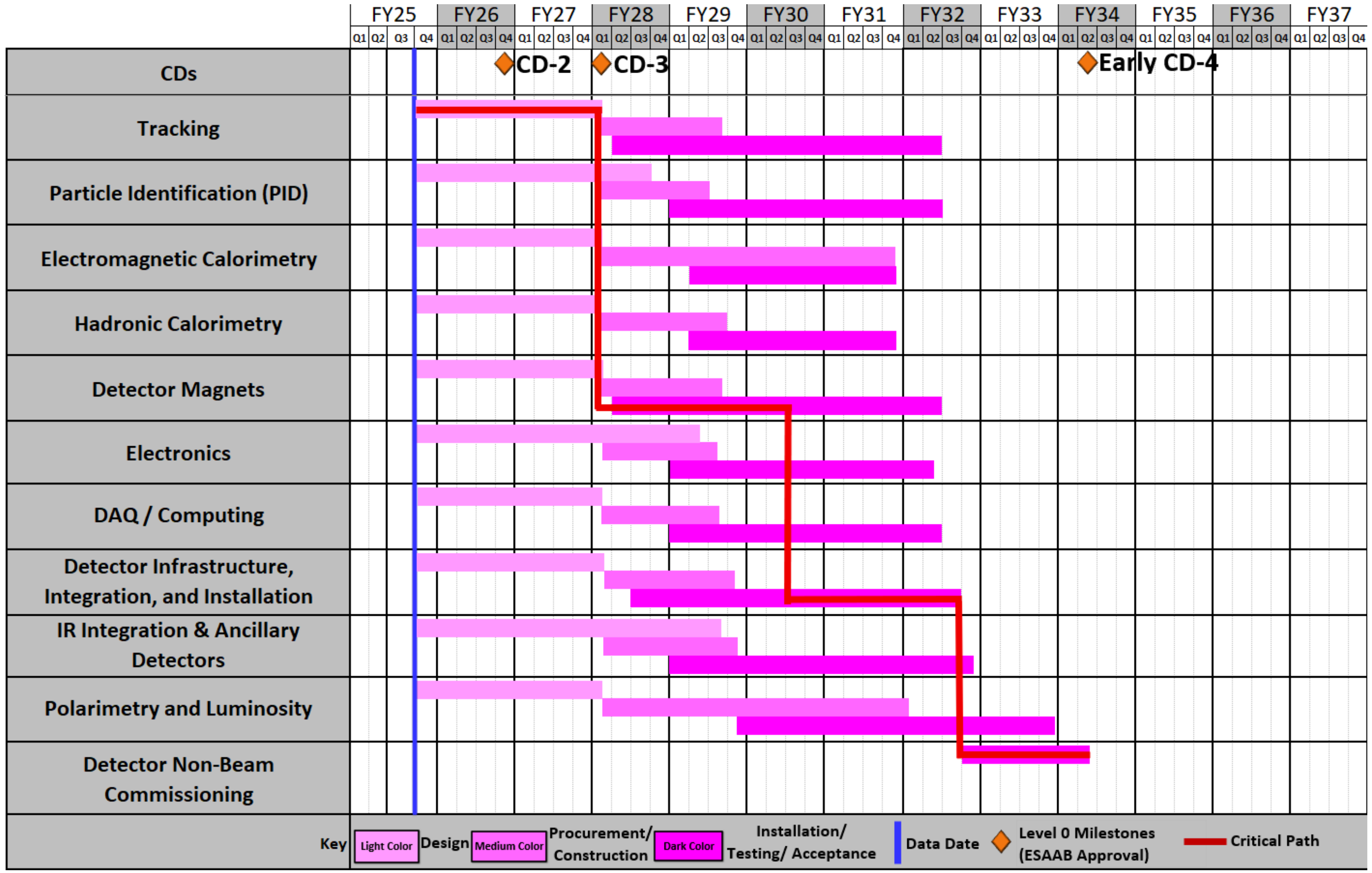
- Writing ePIC preTDR, v2.2 due Dec. 2025
- Developing the EIC Early Science plan:

Supporting baselining for the ePIC detector in 2026

ePIC Collaboration - July 2025

The Path to Realizing ePIC

- ePIC is working with the project to baseline the detector in 2026



Schedule Drivers:

- **To hold the date for a CD-2 Independent Project Review (IPR) expected not before June 2026**
- To keep the (inter)national user community engaged and limit the danger to lose groups
- all subdetectors need to be more or less ready at the same time to be assembled to ePIC
- Superconducting Solenoid → CD-3A item
- Silicon Sensors (MAPS, AC-LGAD & ASTROPIX)
- ASIC long time frames only one ASIC designed from scratch all others are modifications to existing ASICS
- Items with long production times, single vendor and complex assembly → CD-3A & CD-3B
- International agreements driving in-kind and MAPS design (agreement with CERN)

EIC Polarized IOn Source Scientific Consortium

https://arxiv.org/abs/2510.10794

Realizing the Scientific Program with Polarized Ion Beams at EIC

(The EPIOS Scientific Consortium)

Grigor Atoian,[1] Nigel Buttimore,[2] Giuseppe Ciullo,[3] Ian Cloet,[4] Marco Contalbrigo,[3] Jaydeep Datta,[5] Abhay Deshpande,[5] Shubham Dutta,[6] Oleg Eyser,[1] Muhammad Farooq,[7] Renee Fatemi,[8] Ishara Fernando,[9] Michael Finger,[10] Wolfram Fischer,[1] Dave Gaskell,[11] Prakash Gautam,[9,11] Ralf Gebel,[12,13] Boxing Gou,[14] Daoning Gu,[12,15] Yoshitaka Hatta,[1] Mohammad Hattawy,[16] Volker Hejny,[13] Kiel Hock,[1] Georg Hoffstaetter,[17,1] Haixin Huang,[1] Christopher Ianzano,[18] Jiangyong Jia,[5] Andro Kacharava,[13] Maggie Kerr,[18] Wolfgang Korsch,[8] Dario Lattuada,[19] Andreas Lehrach,[15,13] Minxiang Li,[14] Xiaqing Li,[20] Paolo Lenisa,[3] Win Lin,[5] James Maxwell,[11] Aleksei Melnikov,[21] Zein-Eddine Meziani,[4] Richard G. Milner,[18] William R. Milner,[22] Iurii Mitrankov,[5] Hamlet Mkrtchyan,[23] Prajwal MohanMurthy,[18] Christoph Montag,[1] Sergei Nagaitsev,[1] Charles-Joseph Naim,[5] Alexander Nass,[13] Dien Nguyen,[24] Nikolai Nikolaev,[25,26,27] Luciano Pappalardo,[3] Chao Peng,[4] Anna Piccoli,[3] Andrei Poblaguev,[1] Deepak Raparia,[1] Frank Rathmann,[1] Thomas Roser,[1] Premkumar Saganti,[28] Andrew Sandorfi,[9] Medani Sangroula,[1] Vincent Schoefer,[1] Yousif Shabaan,[29] Rahul Shankar,[3] Vera Shmakova,[1] Evgeny Shulga,[1] Jamal Slim,[30] Dannie Steski,[1] Bernd Surrow,[31] Noah Wuerfel,[18] and Yaojie Zhai[14]

[1] *Brookhaven National Laboratory, Upton, NY, USA*
[2] *School of Mathematics, Trinity College Dublin, Dublin, Ireland*
[3] *University of Ferrara and Istituto Nazionale di Fisica Nucleare, 44100 Ferrara, Italy*
[4] *Argonne National Laboratory, Lemont, IL, USA*
[5] *Stony Brook University, Stony Brook, NY, USA*
[6] *Saha Institute of Nuclear Physics, Kolkata, India*
[7] *University of New Hampshire, Durham, NH, USA*
[8] *University of Kentucky, Lexington, KY, USA*
[9] *University of Virginia, Charlottesville, VA, USA*
[10] *Charles University, Prague, Czech Republic*
[11] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*
[12] *GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany*
[13] *Forschungszentrum Jülich, Jülich, Germany*
[14] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China*
[15] *III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany*
[16] *Old Dominion University, Norfolk, VA, USA*
[17] *Cornell University, Ithaca, NY, USA*
[18] *Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA*
[19] *Università Kore di Enna & INFN-LNS, Enna & Catania, Italy*
[20] *Shandong University, Jinan, China*
[21] *Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia*
[22] *Research Laboratory for Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA*
[23] *A. I. Alikhanyan National Science Laboratory, Yerevan Physics Institute, Yerevan 0036, Armenia*
[24] *University of Tennessee, Knoxville, TN, USA*
[25] *L.D. Landau Institute for Theoretical Physics, Chernogolovka, Russia*
[26] *Moscow Institute of Physics and Technology, National Research University, Dolgoprudny, Moscow Region 141701, Russian Federation*
[27] *Bogoliubov Laboratory of Theoretical Physics, International Intergovernmental Scientific Research Organization, Joint Institute for Nuclear Research, Dubna, Moscow Region, 141980 Russia*
[28] *Prairie View A&M University, Prairie View, TX, USA*
[29] *American University in Cairo, New Cairo 11835, Egypt*
[30] *Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[31] *Temple University, Philadelphia, PA, USA*

(Dated: September 29, 2025)

- We identify the AGS as a very valuable platform to carry out beam studies of polarized sources, polarized beams and spin manipulators in the era when RHIC is dark. We recommend that EPIOS and the BNL-CAD together consider the possibilities and develop a plan that takes advantage of the AGS.

- Finally, we point out that the polarized atom sources required for the production of EIC polarized ion beams can also be utilized to feed windowless gas targets internal to a charged particle storage ring. If desired, this would make possible a program of fixed target physics at one of the storage rings in the EIC accelerator complex.

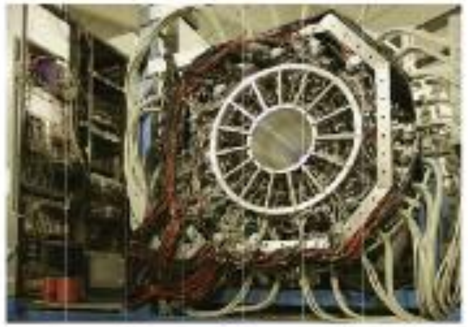
Bonn University

- Awarded this year with colleagues from HEP an Excellence Cluster Grant ***Color meets Flavor*** in a German-wide competition.
- This secures the future at Bonn inc. the electron stretcher facility ELSA (3.5 GeV) for the next seven years.
- It also provides funding for a big upgrade for the existing CBELSA/TAPS experiment.
- This new Excellenz Cluster includes also support for the hadron physics program at the AMBER and LHCb experiments at CERN.
- For some years, they have a new building (FDT) with high-quality lab space for developing and building new detectors.
- The future of hadron physics is bright at Bonn.

Photon-induced Baryon Physics at ELSA

Photon beam (linear & circular polarization):

- **CB-ELSA** 4π detector **+ TAPS + polarized target**
  - Double polarization experiments: $\vec{\gamma}\vec{p} \to \pi^0 p, \eta p, \pi^0\pi^0 p, \ldots$
  - Full kinem. coverage of asymmetries Σ, E, G, H, …
- **BGOOD** detector (charged final states)
  - BGO 4π calorimeter combined with forward spectrometer
  - Strangeness photoproduction at low momentum transfer and coherent photoproduction off the deuteron

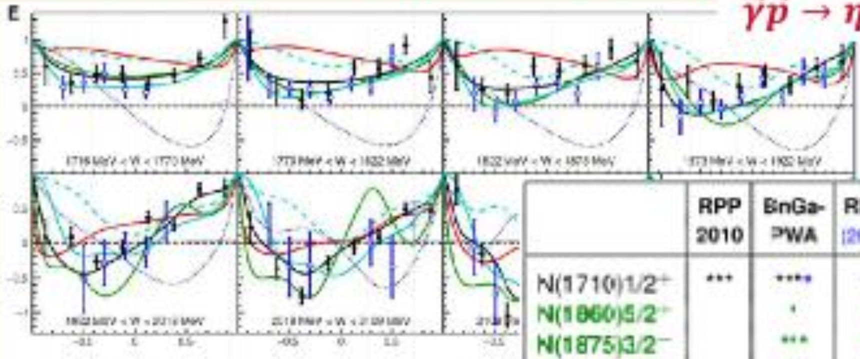


Crystal Barrel/TAPS

BGOOD

Polarization d.o.f.: key to resolve the baryon spectrum

$\vec{\gamma}\vec{p} \to \eta p$



$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

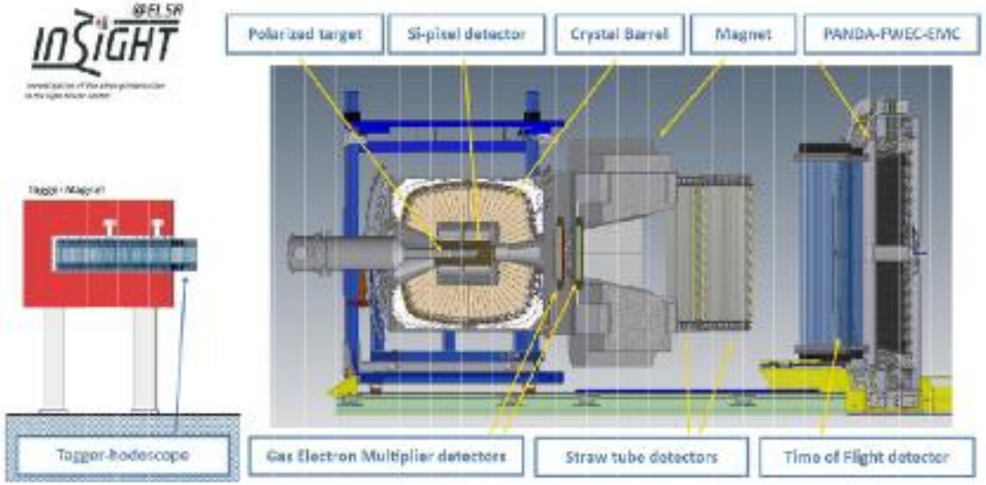
→ huge impact on knowledge of resonances in the second and third resonance region

	RPP 2010	BnGa-PWA	RPP'25 (2018-25)
$N(1710)1/2^+$	***	****	****
$N(1860)5/2^+$		*	**
$N(1875)3/2^-$		***	***
$N(1880)1/2^+$		***	***
$N(1895)1/2^-$		****	****
$N(1900)3/2^+$	**	****	****
$N(2060)5/2^-$		***	***
$N(2100)1/2^+$	*	***	***
$N(2120)3/2^-$		***	***
$\Delta(1600)3/2^+$	***	***	****
$\Delta(1900)1/2^-$	*	***	***
$\Delta(1940)3/2^-$	*	**	**
$\Delta(2200)7/2^-$	*	***	***

only examples shown

Future Directions ELSA @ Bonn

A new experiment as part of the new Cluster of Excellence „Color meets Flavor“:



Arrival of the PANDA-FWEC in Bonn:

at the FTD

➡ **Over almost the entire 4π-solid angle:**
- **High resolution photon measurements**
- **Precise charged particle detection**

Polarized beam and polarized target

➡ **unique possiblilities!**

Future Directions ELSA @ Bonn

After ELSA shutdown in 2026/27:

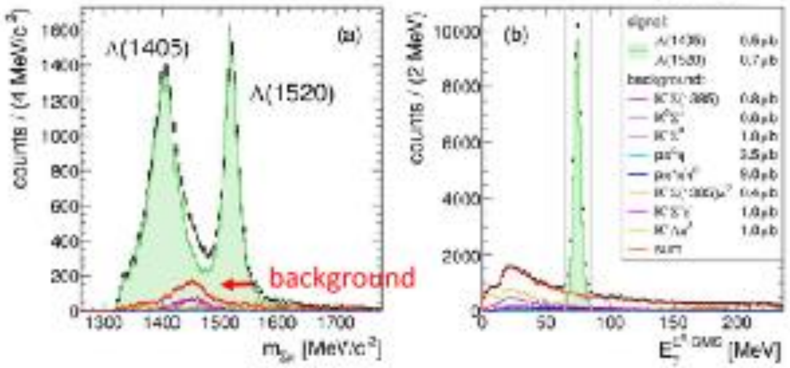
- **INSIGHT@ELSA: Non-strange and strange baryon spectroscopy:**

  Gain a complete picture of the N^*, Δ^*- baryon spectrum:

  ⇔ Polarized photoproduction off the polarized proton and neutron!
  (unambigious PWA not possible without polarization obs.)

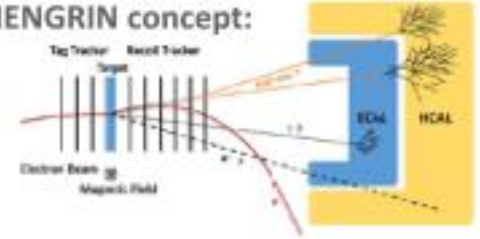
  Spectrum and properties of Λ^*, Σ^* ⇔ ".. field is starved for data"
  ⇔ multi-quark states? molecules? 2-pole structures?

$\gamma p \rightarrow K^+\Lambda^* \rightarrow K^+\Sigma^0\pi^0$ (isospin selective)



- **LOHENGRIN proposal: Search for Light Dark Matter** via dark bremsstrahlung
  – need 10^{15} Electrons on Target via ELSA slow extraction @ 500 MHz
  (EPJC 85 (2025) 5, 600)

LOHENGRIN concept:



- **ELSA also a key facility** (test beam)
  for the FTD (Forschungs- und Technologiezentrum Detektorphysik) at University of Bonn

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Mainz

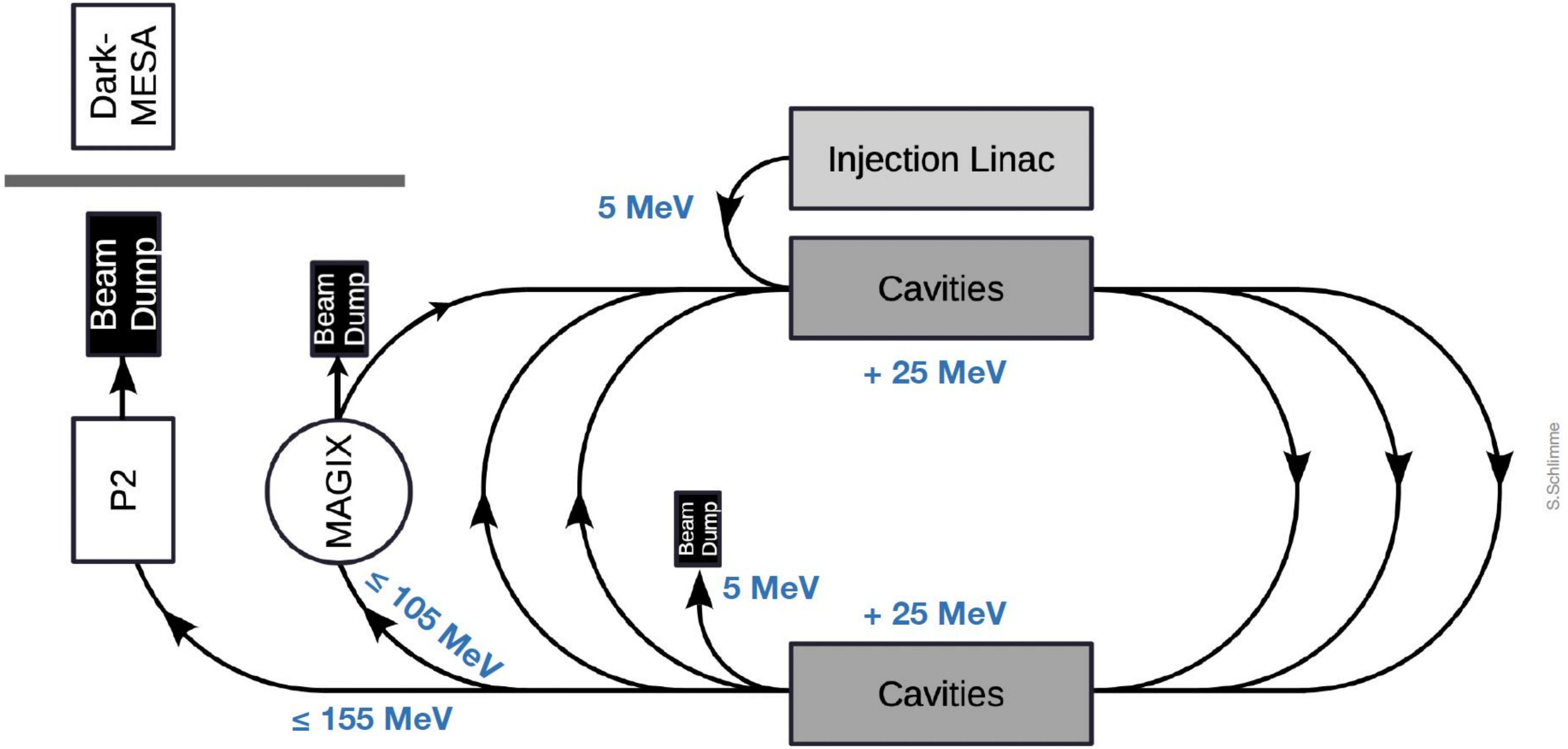
Unlocking physics with hadrons and nuclei

MESA - Mainz Energy-Recovering Superconducting Accelerator

155 MeV

- Energy-recovery mode for **high intensity** (MAGIX)
- Extracted-beam mode for **high polarisation** (P2)
- Beam dump experiment (**Dark**MESA)

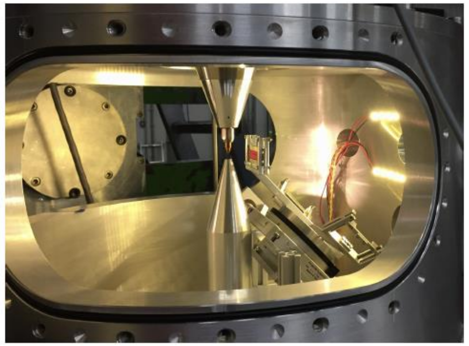
Let’s build MESA (7/7).

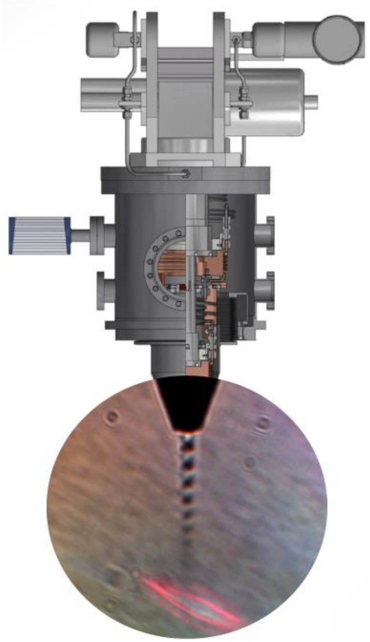


Mainz **E**nergy-recovering **S**uperconducting **A**ccelerator

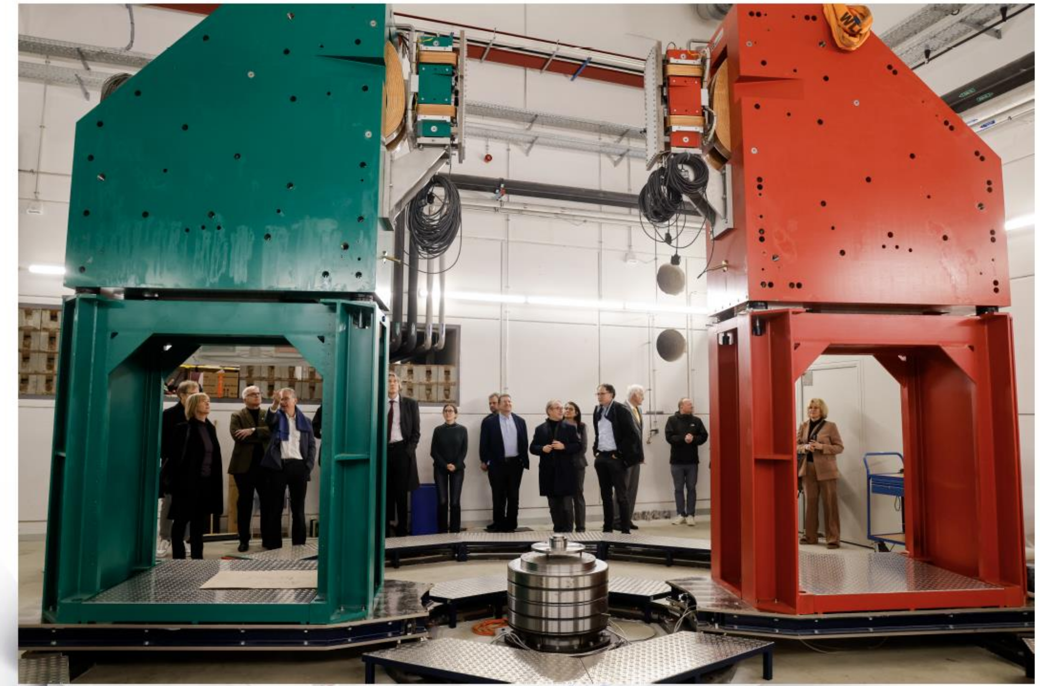
MAGIX

- **High-resolution spectrometers** ($\Delta p/p \leq 10^{-4}$)
- Cryogenic **windowless** gas-jet target



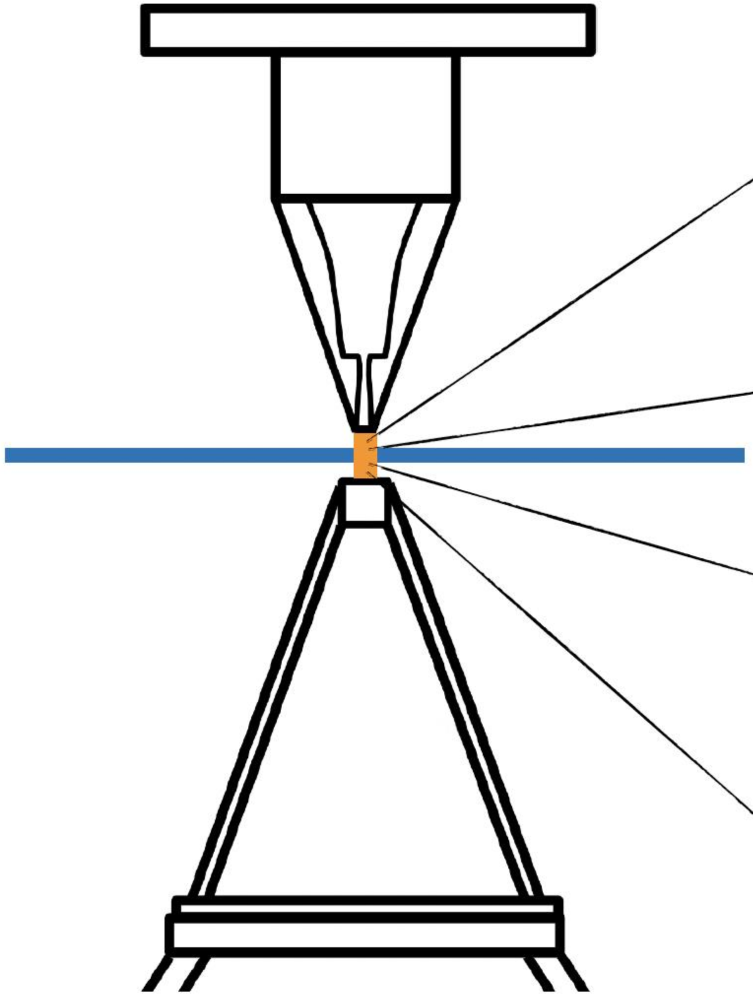


- Detection of **low-energy recoil particles**



A versatile physics program.

Does the logo look familiar?



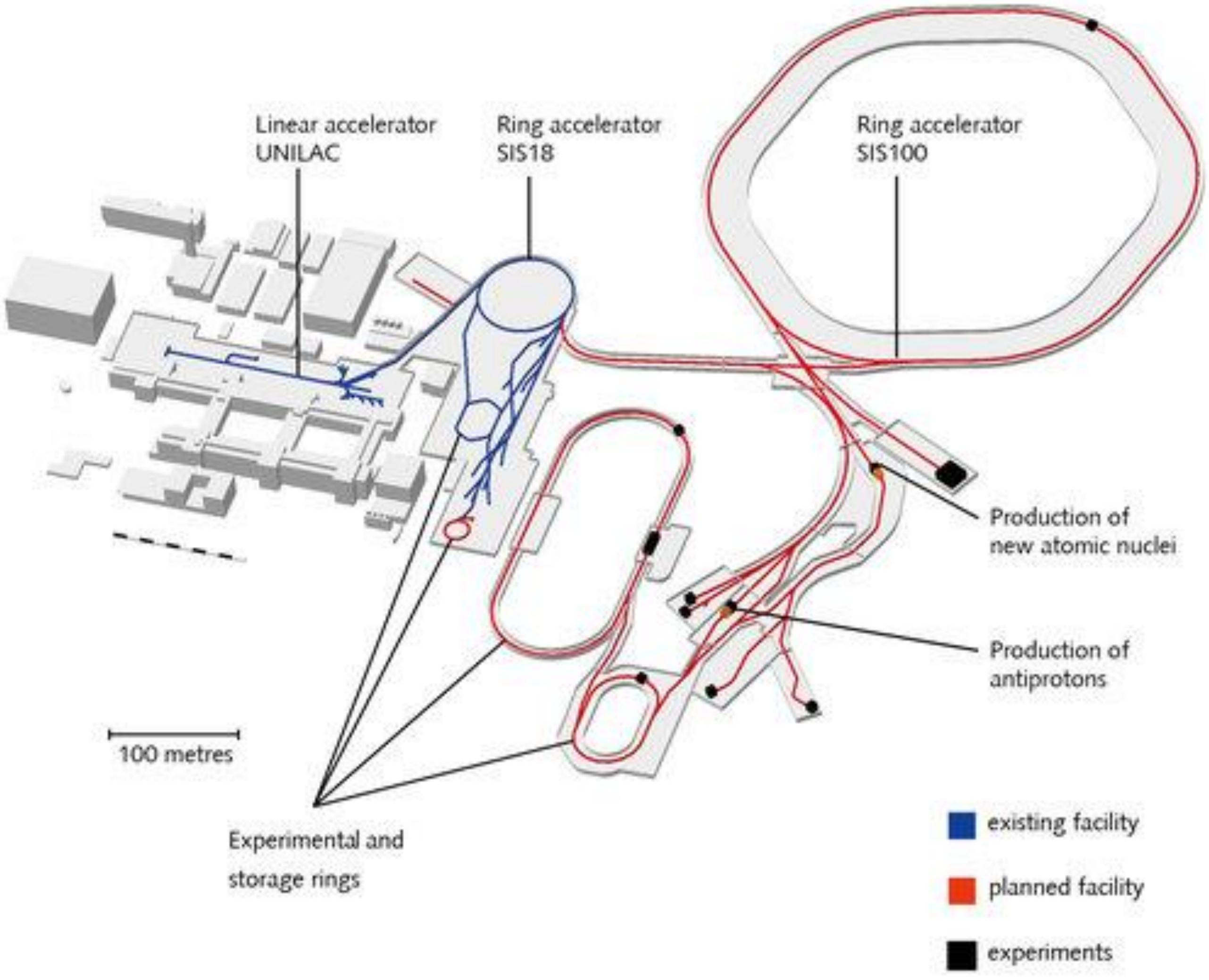
Hydrogen
- Electromagnetic form factors (G_E and G_M) of the proton
- …

Helium
- Transition form factor of ^{4}He
- …

Oxygen
- Astrophysical S-factor of the reaction $^{12}C(\alpha,\gamma)^{16}O$
- …

Argon
- Visible decay mode ($\gamma' \rightarrow e^- e^+$) of the hypothetical dark photon
- …

Planned FAIR Accelerator



Ring Accelerator SIS100

The SIS100 ring accelerator runs along an underground tunnel whose floor lies as deep as 17 meters under the earth's surface. The SIS100 has a circumference of 1,100 meters and can accelerate the ions of all the natural elements in the periodic table to speeds as high as 99% of the speed of light. The magnets that keep the ions in their paths are superconducting and are cooled to -269°C by means of liquid helium. The accelerated particles are either used directly for experiments or for the production of other particles, so-called secondary particles.

FAIR Construction Status October 2025

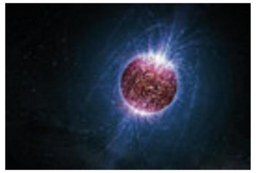
First beams in ~ 2028

FAIR's Four Experimental Pillars

NUSTAR — Stars and nuclei

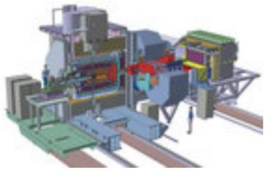
Nuclear Structure Astrophysics and Reactions. Experiments with atomic nuclei are the key to understanding stars.

CBM — Inside a neutron star



Compressed Baryonic Matter. The collision of atomic nuclei at high speeds can simulate the conditions inside supermassive objects for a split second.

PANDA — Antimatter research



Antiproton Annihilation at Darmstadt. How can antimatter help us understand the mass of matter and the strong force?

APPA — From atoms and planets to cancer therapy

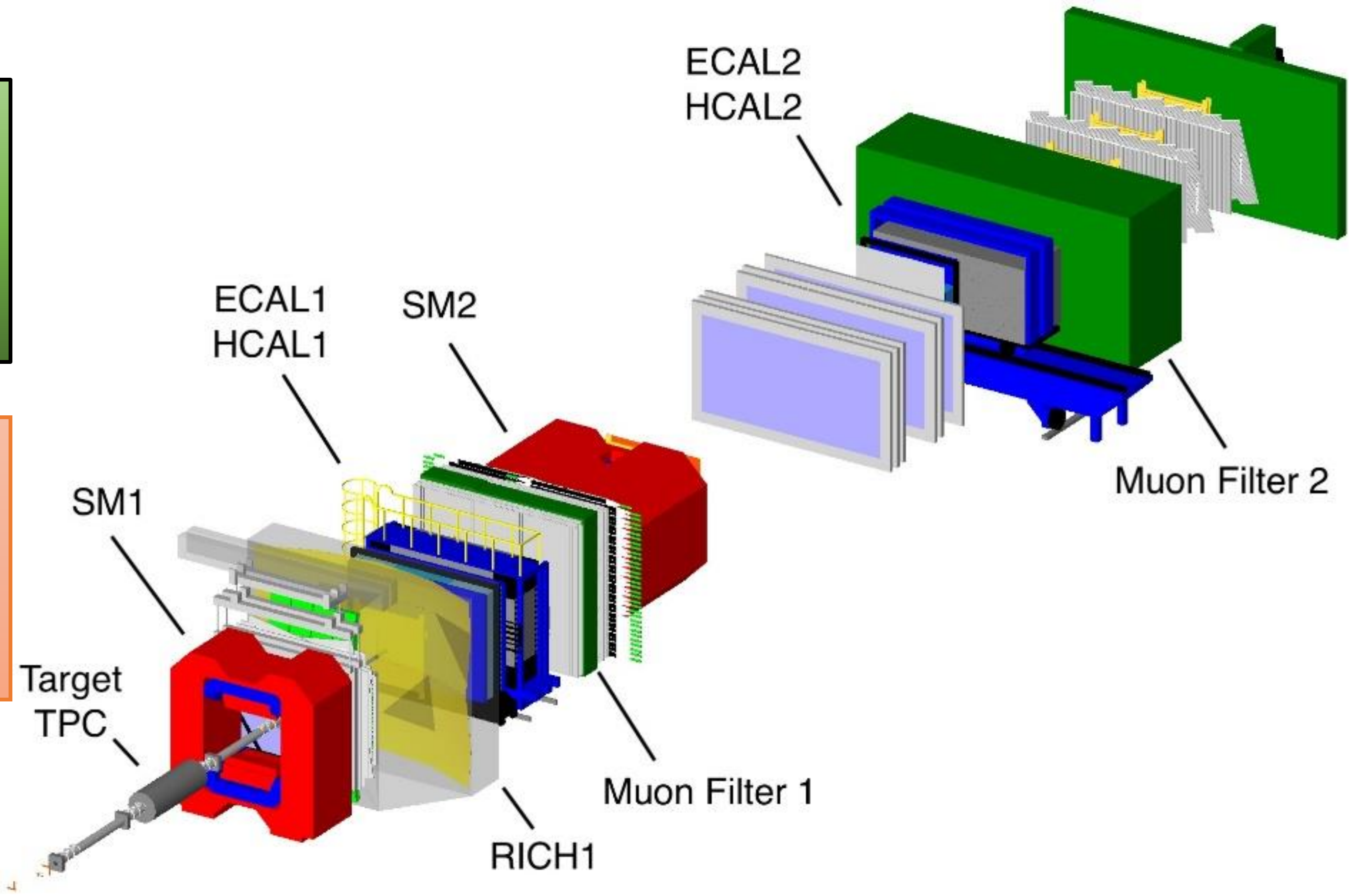
Atomic, Plasma Physics and Applications. From the investigation of atoms and macroscopic effects in materials or tissues all the way to engineering and medical applications.

AMBER – A QCD Facility at CERN's SPS M2 beam line

- Successor of COMPASS: LOI (2018) arXiv:1808.00848
- Upgraded spectrometer

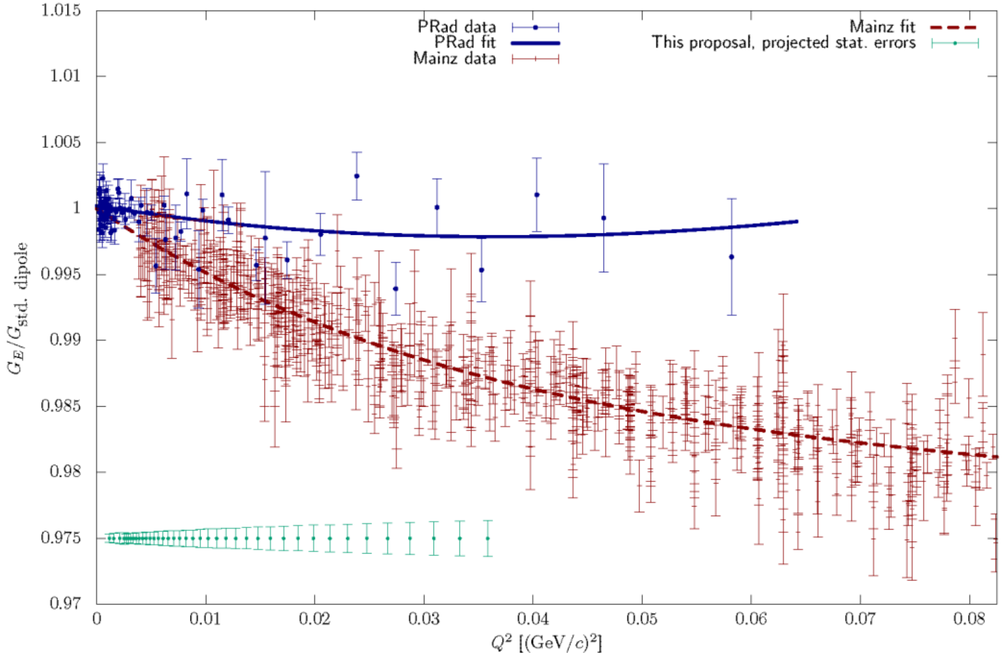
Phase-1: 2023 $\rightarrow$ 2031 (conventional beams)
- $\bar{p}$ production cross section for DM searches
- Proton radius: high-energy μ-p elastic scattering
- Pion/kaon quark PDFs: Drell-Yan process

Phase-2: 2031 $\rightarrow$ 2041 (high-intensity kaon beam)
- K gluon PDFs (DY, prompt photons)
- Strange meson spectroscopy
- Meson charge radii, Primakoff reactions



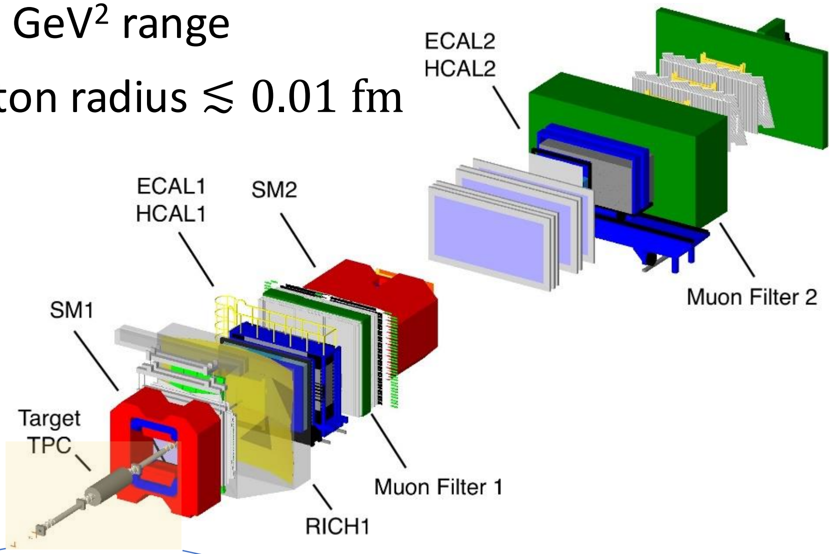
Proton Charge Radius

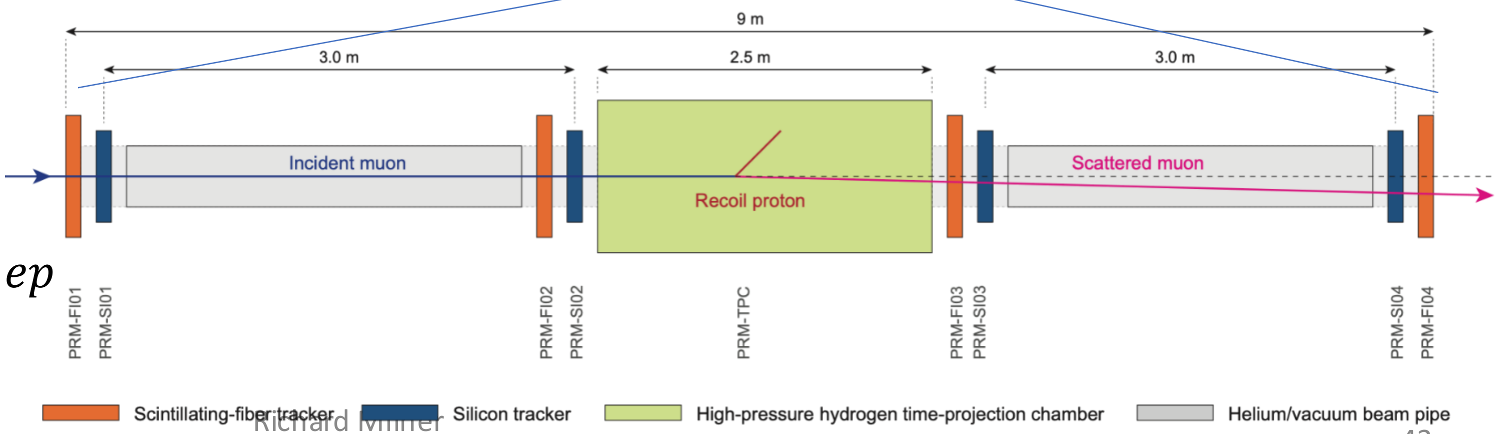
[AMBER Proposal, CERN-SPSC-2019-022]



Unique measurement: high-energy $\mu^{\pm}$ (100 GeV/c)

- ➢ goal: 70 million elastic scattering events in the $10^{-3} < Q^2 < 4 \cdot 10^{-2}$ GeV^2 range
- ➢ precision on the proton radius $\lesssim 0.01$ fm

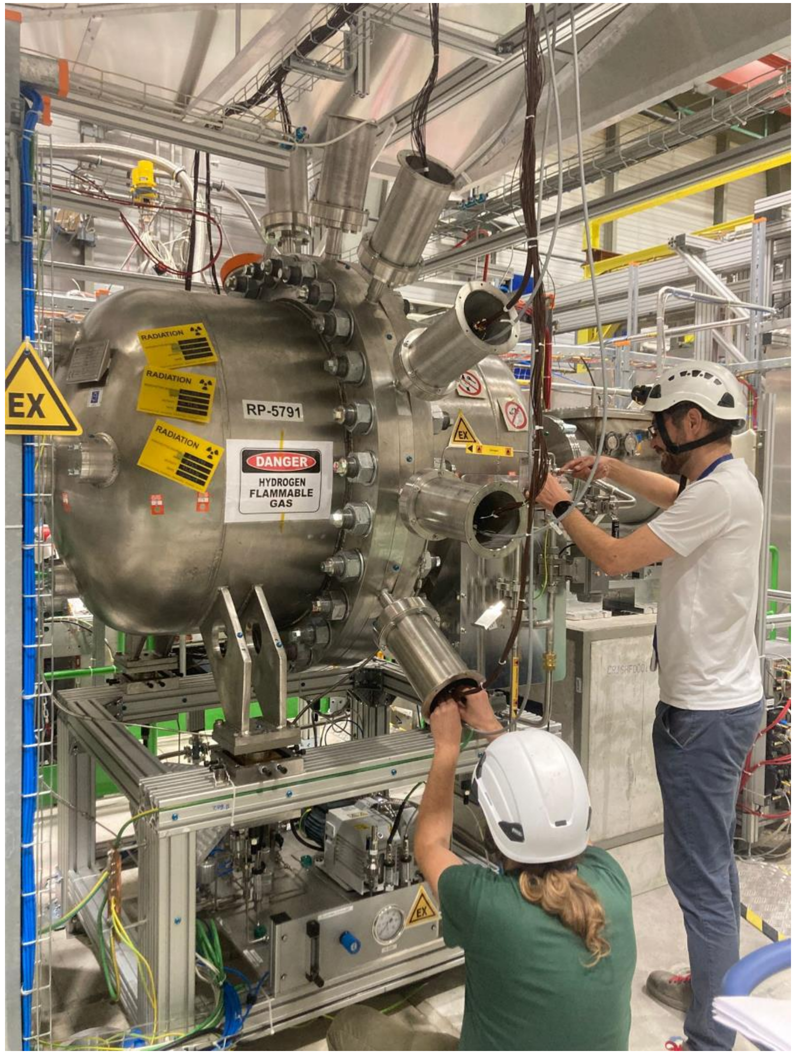


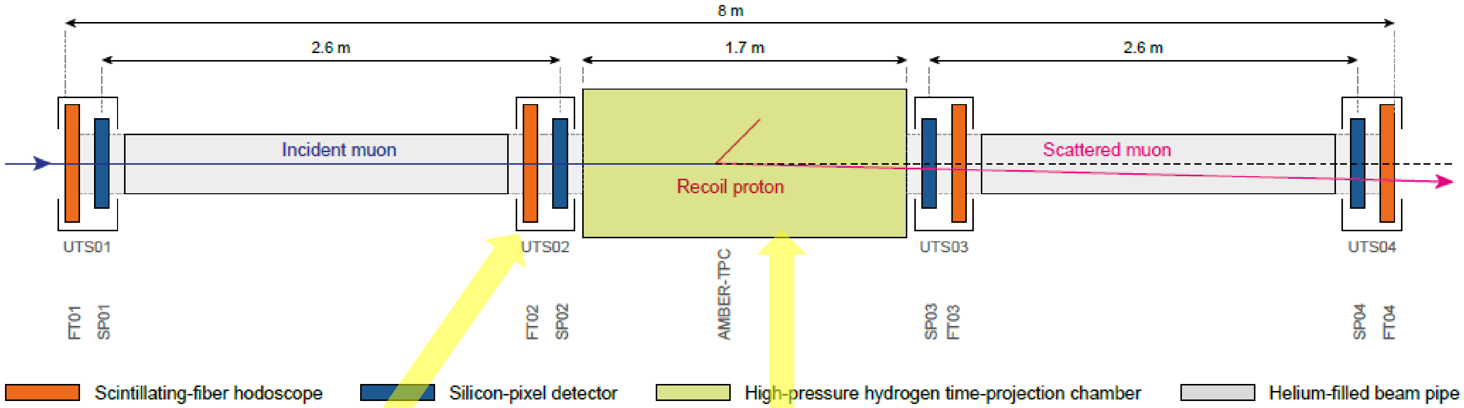


Why μp scattering?

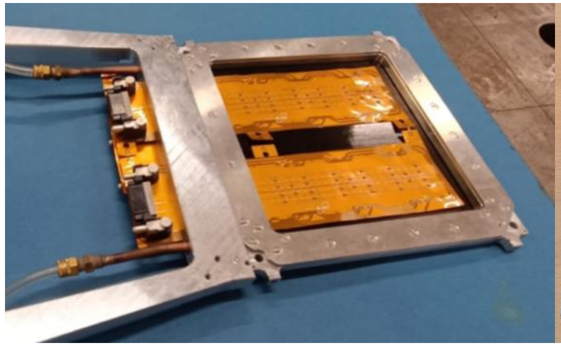
- different leptonic probe
- different systematic uncertainties
- >10 × smaller radiative corrections than ep
- provide precise data for global fit
- test lepton universality

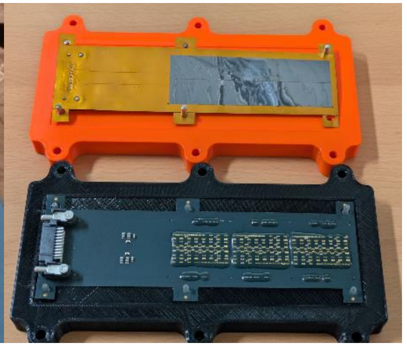
AMBER Gets ready for the Proton Radius

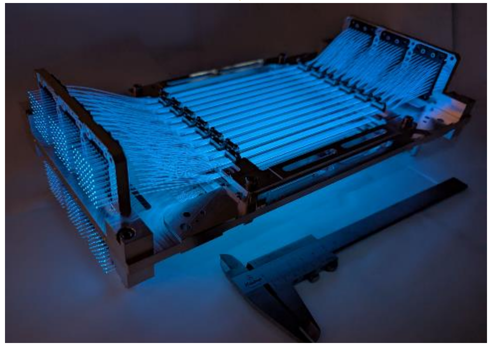




- High-pressure (20 barg H_2) active-target TPC installed in EHN2
- Precision vertexing using a combination of MAPS and scintillating fibers
- Muon PID using the AMBER spectrometer
- New free streaming DAQ







En route to provide the first measurement of the proton electric form factor with high-energy muons in 2026


KEK
IPNS
Institute of Particle and Nuclear Studies
IMSS
Institute of Materials Structure Science
QUP
International Center for Quantum Field Measurement Systems for Studies of Particle and Universe
ACCL
Accelerator Laboratory
ARL
Applied Research Laboratory
J-PARC
Japan Proton Accelerator Research Complex
大強度陽子加速器施設
J-PARC
Tsukuba Campus
Tokai Campus

Particle and Nuclear physics at J-PARC

Hadron Experimental Facility EXtension

Explore the origin of matter with nuclear, hadron, and flavor physics

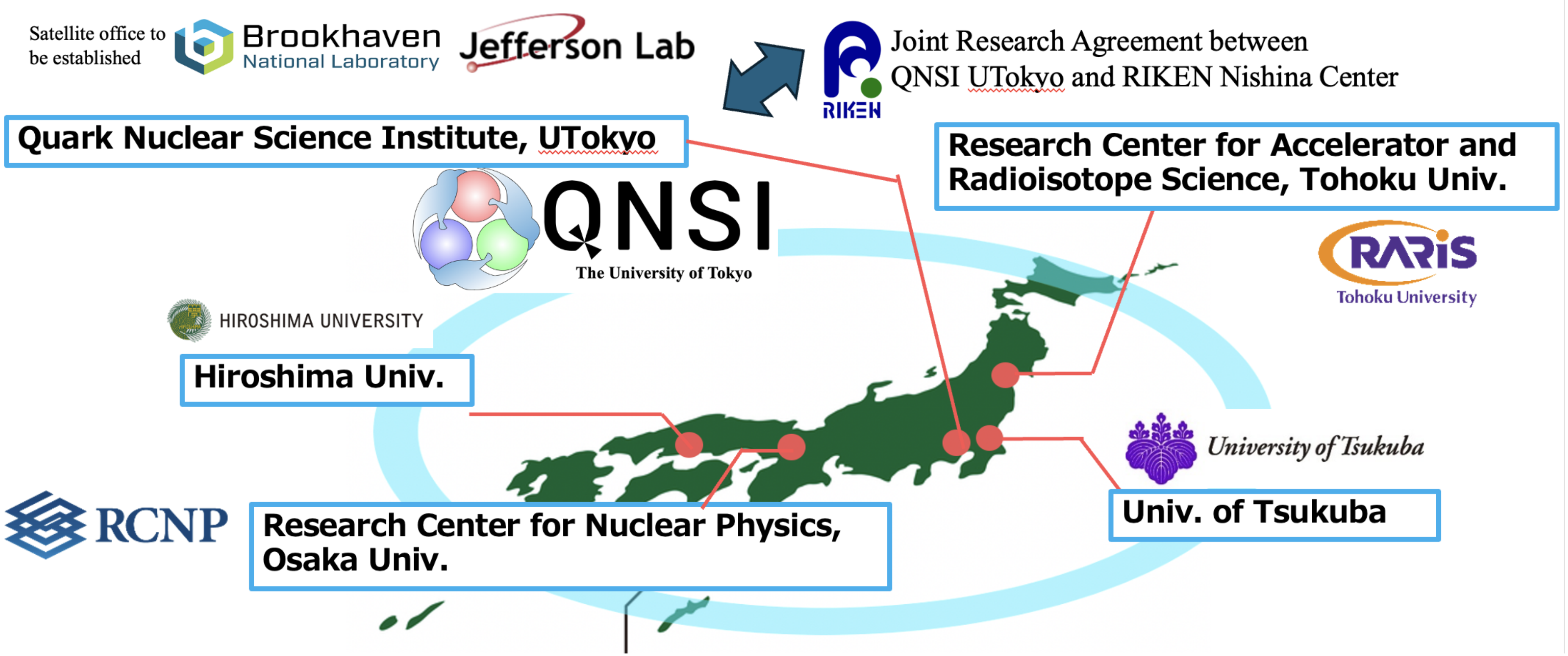
https://arxiv.org/abs/2110.04462

We started to receive funding for p20, and future planning is ongoing with domestic and international partners.

International Quantum Physics Network (IQPN)

Established in 2025 through inter-university collaboration in Japan

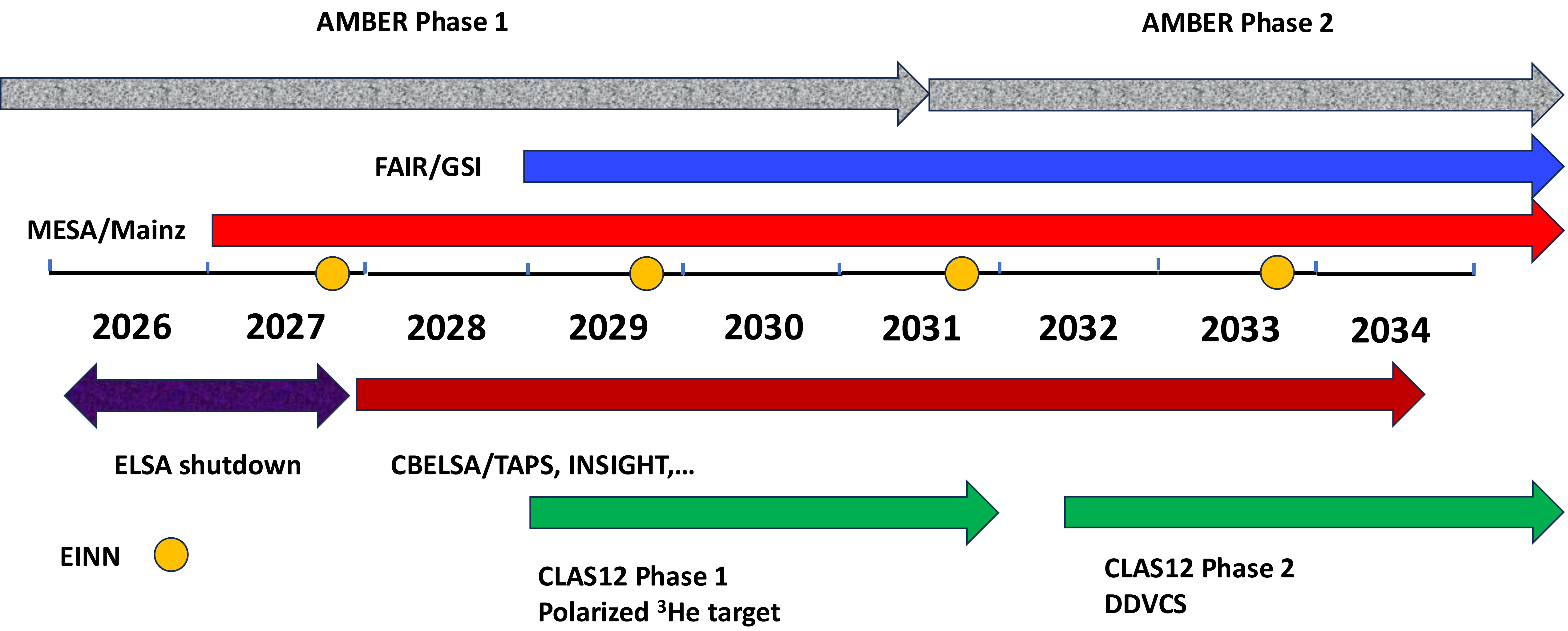
Through inter-university collaboration, we are building a cooperative framework with Japan's world-class accelerator facilities, J-PARC and RIBF, to continuously advance research related to the EIC project on an all-Japan basis



Summary

- Hadronic physics is a major international research effort with fundamental open questions being addressed:
  - imaging of quark and gluon structure of proton
  - precision measurement of hadron properties
  - search for new physics
- Currently, facilities are operating in Asia, Europe and N. America.
- There are significant upgrades of existing detectors and new detectors planned at these facilities.
- There are major new facilities (FAIR, EIC) expected to be realized over the next 5-10 years.
- Hadronic physics has a bright future well into the mid-twenty first century.

Possible Schedule



Possible Schedule

Also: AGS fixed target/BNL, SoLID/JLAB, HEFEX/J-PARC, ARIEL/TRIUMF…….