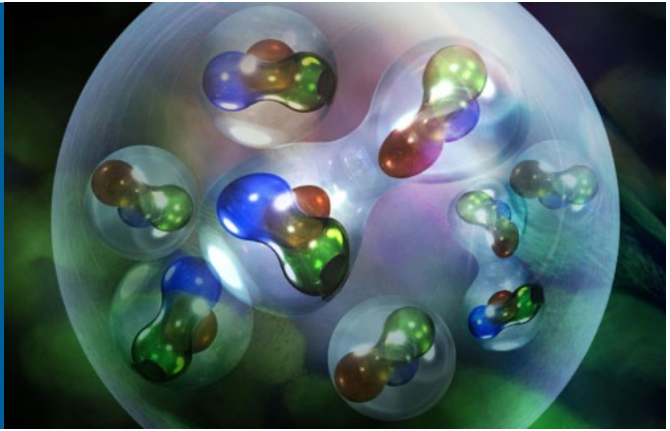
EXPERIMENTS AT AN EIC; ARGONNE PHY/MEP ACTIVITIES



ZEIN-EDDINE MEZIANI

Argonne National Laboratory

On behalf of

W. ARMSTRONG, S. JOOSTEN, V. NOVOSAD, J. KIM, C. PENG, POLAKOVIC, S. PRASAD, P. REIMER, M. SCOTT, J. XIE, M. ZUREK

U.S. DEPARTMENT OF ENERGY

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Seoul, Korea, 10/2022

Outline

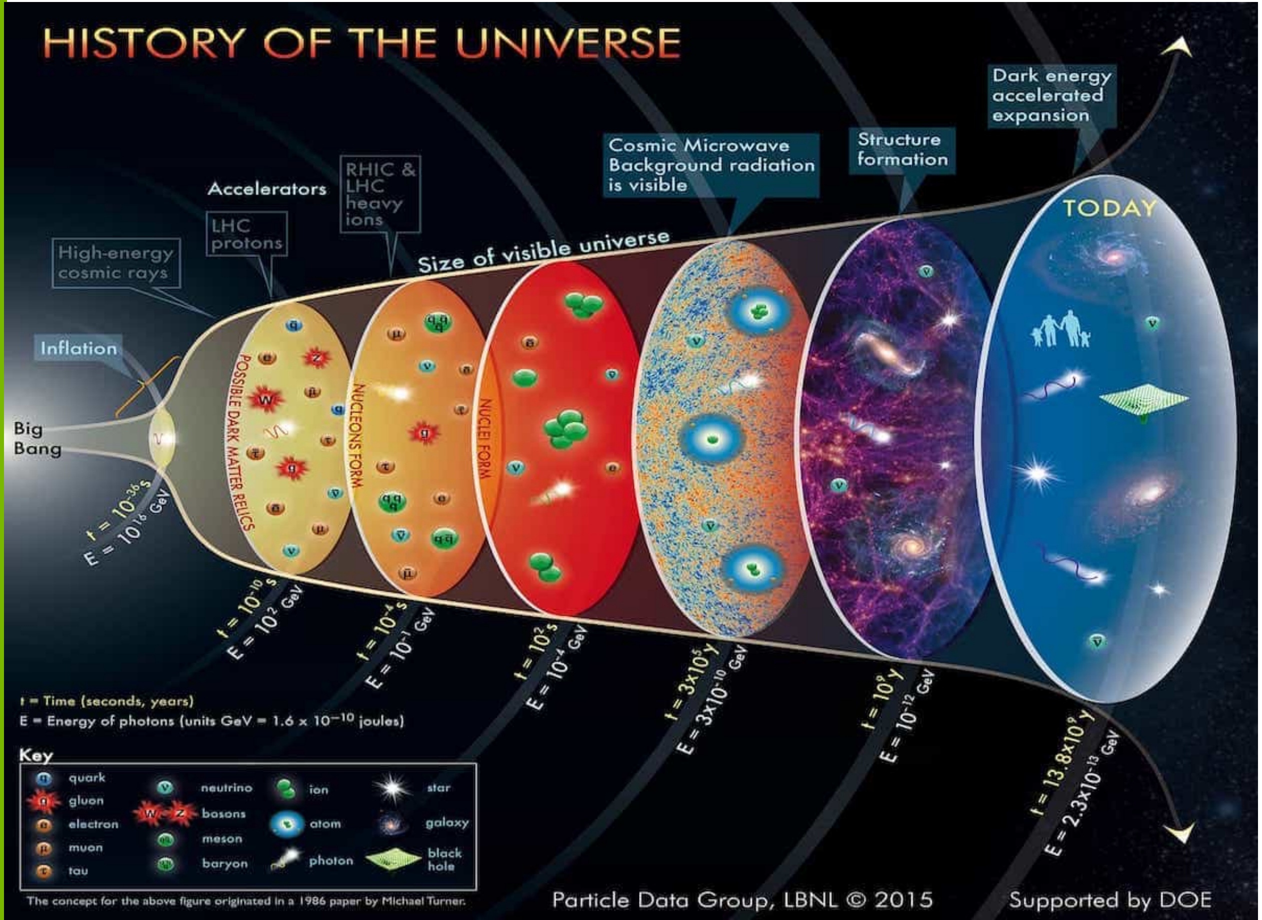
- The Gluonic Gravitational Form Factors of Nucleon and Nuclei
  - Exclusive Quarkonium (J/psi and Upsilon) Production at the EIC
- Argonne MEP group activities
  - Software for the EIC detector
  - Barrel imaging electromagnetic calorimeter
  - MCP-PMTs
  - Superconducting nanowire
- Summary

GLUONIC GRAVITATIONAL FORM FACTORS IN NUCLEONS AND NUCLEI

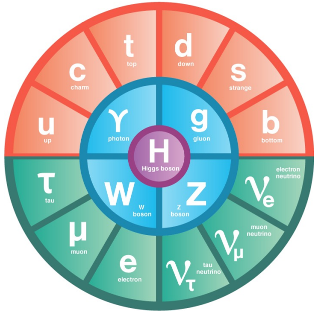
PROTON MASS

TO KNOW YOUR FUTURE YOU MUST KNOW YOUR PAST

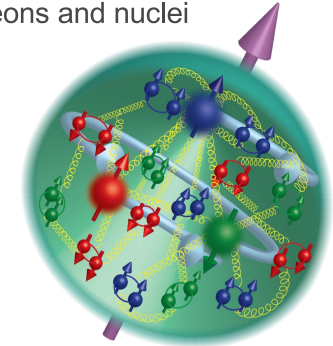
George Santanaya (American philosopher, poet and cultural critic: Born in Madrid, 1863-1952)



Standard Model of Particle Physics



Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass and spin to nucleons and nuclei



Nucleon: A fascinating strong interacting system of confined quarks and gluons

Argonne NATIONAL LABORATORY

Science Questions Enabled by Quarkonium Production at Threshold

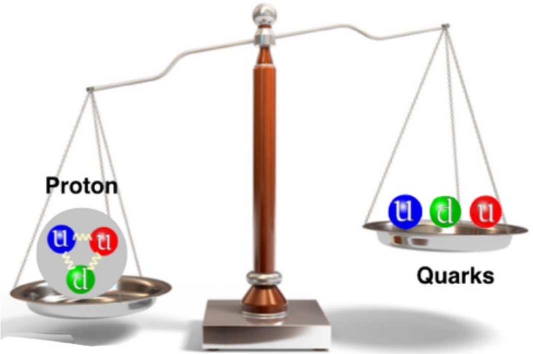
"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass

Frank Wilczek (1999, Physics Today)

- What is the origin of hadron masses?
  - A case study: the proton.

The 2015 Long Range Plan for Nuclear Science

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"



- Can we measure the gravitational form factors of the proton and nuclei?

Threshold electro- & photoproduction of quarkonia can probe the energy distribution of gluonic fields inside the proton and nuclei

How does QCD generates the nucleon mass?
Breaking of scale Invariance

See for example, **M. E. Peskin and D. V. Schroeder, An Introduction to quantum field theory, Addison-Wesley, Reading (1995), p. 682**

✧ **Trace of the QCD energy-momentum tensor:** D. Kharzeev Proc. Int. Sch. Phys. Fermi 130 (1996)

$$T^{\alpha}_{\alpha} = \underbrace{\frac{\beta(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta}}_{\text{QCD trace anomaly}} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{c,b,t} m_h (1+\gamma_{m_h}) \bar{Q}_l Q_l$$

with $\beta(g) = -b \frac{g^3}{16\pi^2} + \ldots,$ $\quad b = 9 - \frac{2}{3} n_h$

Gross, Wilczek & Politzer

At small momentum transfer, heavy quarks decouple:

M. Shifman et al., Phys. Lett. 78B (1978)

$$\sum_h \bar{Q}_h Q_h \to -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \ldots$$

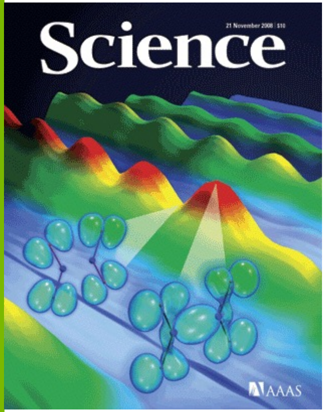
$$T^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l$$

✧ **Trace anomaly, chiral symmetry breaking, …**

$$M^2 \propto \langle P | T^{\alpha}_{\alpha} | P \rangle \xrightarrow{\text{Chiral limit}} \frac{\beta(g)}{2g} \langle P | G^2 | P \rangle$$

In the chiral limit we have a finite number for the nucleon and zero for the pion

Hadron Masses from Lattice QCD



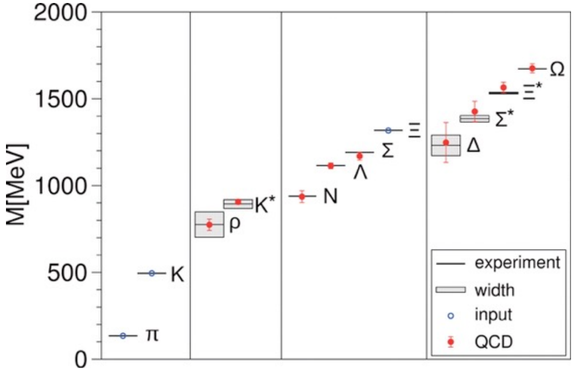
(2008)

Ab Initio Determination of Light Hadron Masses

S. Dürr, Z. Fodor, C. Hoelbling,
R. Hoffmann, S.D. Katz, S. Krieg, T. Kuth, L. Lellouch, T. Lippert, K.K. Szabo and G. Vulvert

Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233

589 citations



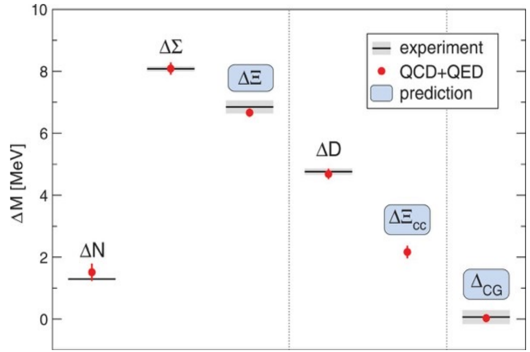
(2015)

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S.D. Katz,S. Krieg, L. Lellouch, T. Lippert, A. Portelli, K. K. Szabo, and B.C. Toth

Science **347** (6229), 1452-1455
DOI: 10.1126/science.1257050

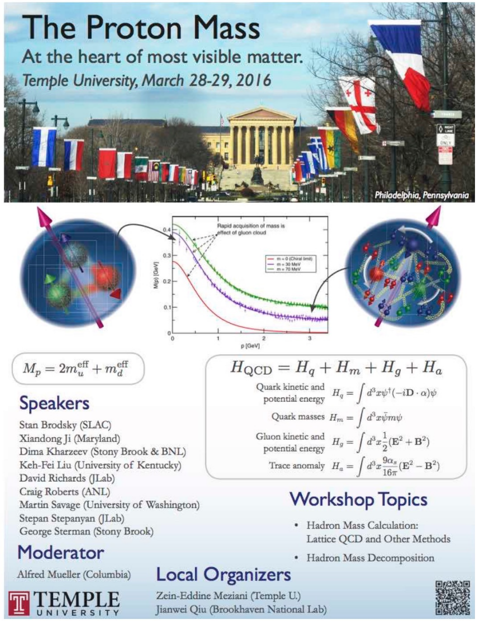
287 citations



How does QCD generate this? The role of quarks and of gluons?

THE PROTON MASS… A HOT TOPIC!

2016



2017

Jan. 2021

14-16 January 2021
Argonne National Laboratory
America/New_York timezone

https://indico.phy.anl.gov/event/2/

Access the trace anomaly through elastic J/psi and Upsilon production near threshold

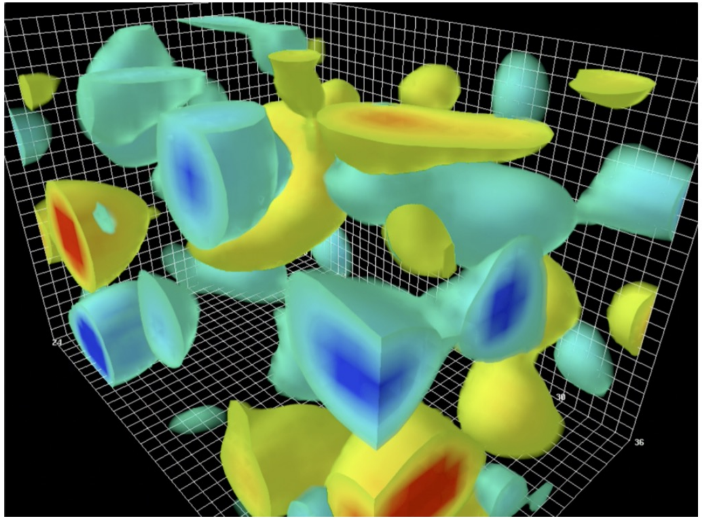
Due to COVID-19 a 2020 INT, proton mass workshop the 4th workshop in the series was held in June 2022

https://www.int.washington.edu/programs-and-workshops/20r-77

A HOLOGRAPHIC APPROACH

- Holography provides a string-based approach dual to Yang-Mills (YM)

Instantons (yellow) and anti-instantons (blue)



Leinweber et al. 2003
Cooled Yang Mills vacuum filled with topological gauge fields

Shuryak, Zahed

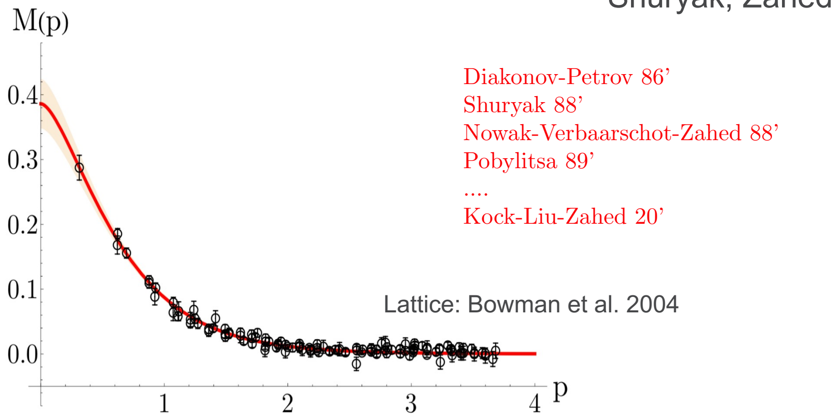


FIG. 2: Momentum dependence of the instanton induced effective quark mass in singular gauge (13) at LO (solid-curves), compared to the effective quark mass measured on the lattice in Coulomb gauge [21] (open-circles). The unit scale is GeV. We obtain a fitted parameter intervals $M(0) = 383 \pm 39$ MeV and $\rho = 0.313 \pm 0.016$ fm.

Vacuum; a liquid on Instantons
Gluon condensate in the nucleon is linked to the QCD vacuum compressibility which measures the diluteness of the QCD instanton vacuum as a topological liquid.

- Topological origin of mass
  - Vacuum conformal symmetry breaking by density of instantons and the rate of vacuum tunneling
  - Spontaneous chiral symmetry breaking follows simultaneously from the delocalization of the light quarks zero modes!

JI'S NUCLEON MASS DECOMPOSITION: A HAMILTONIAN APPROACH

Quarks, anti-Quarks , Gluons and Trace Anomaly in the nucleon rest frame

X. Ji PRL 74, 1071 (1995) & PRD 52, 271 (1995)

$$H_{QCD} = \int d^3x T^{00}(0, \vec{x})$$

$$M_N = \frac{\langle P|H_{QCD}|P\rangle}{\langle P|P\rangle}$$

$$H_q = \int d^3x\ \psi^\dagger\,(-iD\cdot\alpha)\,\psi$$

Quarks & anti-quarks kinetic and potential energy

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M_N$$

$$H_m = \int d^3x\ \psi^\dagger m\psi$$

Quarks masses

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b M_N$$

$$H_g = \int d^3x\ \frac{1}{2}\left(E^2 + B^2\right)$$

Gluons kinetic and potential energy

$$M_g = \frac{3}{4}\left(1-a\right) M_N$$

$$H_a = \int d^3x\ \frac{9\alpha_s}{16\pi}\left(E^2 - B^2\right)$$

Trace anomaly

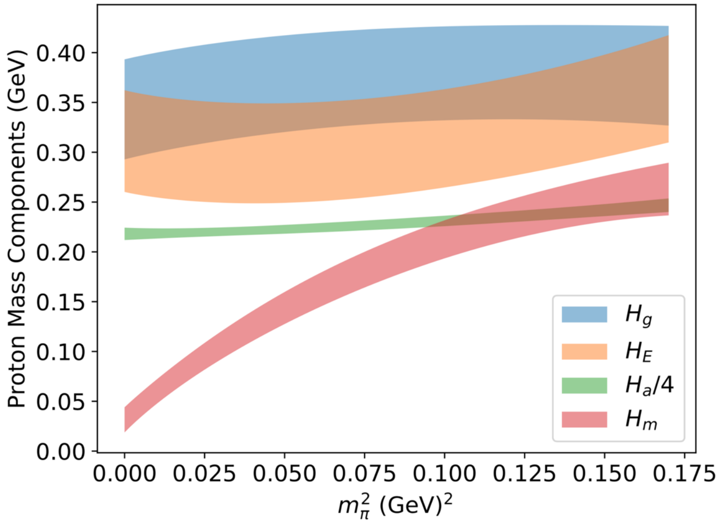
$$M_a = \frac{1}{4}\left(1-b\right) M_N$$

- $a(\mu)$ related to PDFs, well constrained
- **$b(\mu)$ related to quarkonium-proton scattering amplitude $T_{\psi p}$ near-threshold**

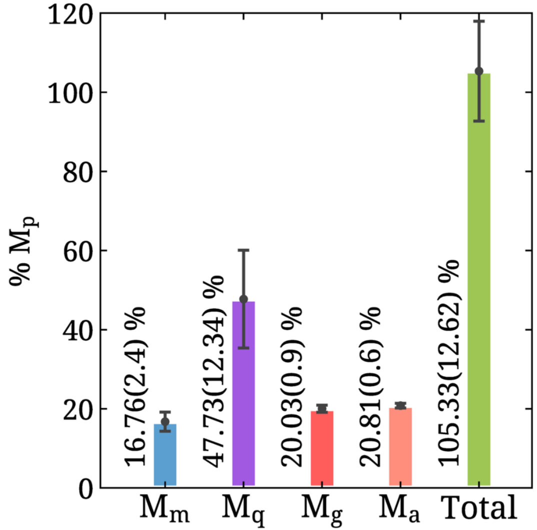
$$M_N = M_q + M_m + M_g + M_a$$

PROTON MASS ON THE LATTICE

Direct calculations of the trace anomaly were still missing until recently



Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

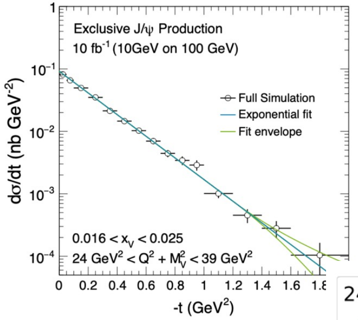


C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

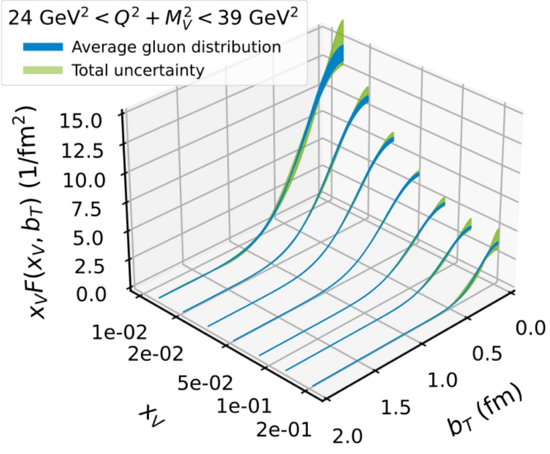
•He, Fangcheng and Sun, Peng and Yang, Yi-Bo, [χQCD Collaboration] "A Demonstration of Hadron Mass Origin from QCD Trace Anomaly *Phys.Rev.D* 104 (2021) 7, 074507

REALISTIC SIMULATIONS FOR THE ATHENA PROPOSAL

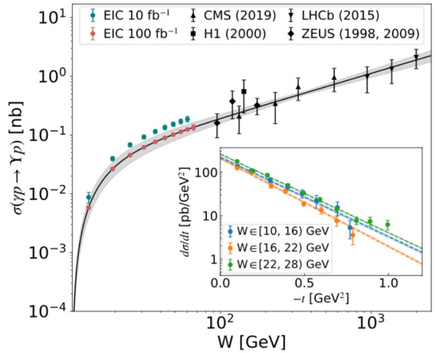
Imaging with exclusive quarkonium production

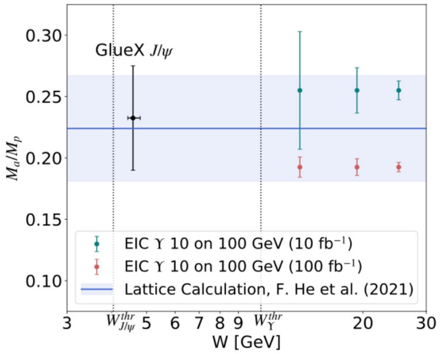


3D imaging with J/ψ DVMP from full simulations



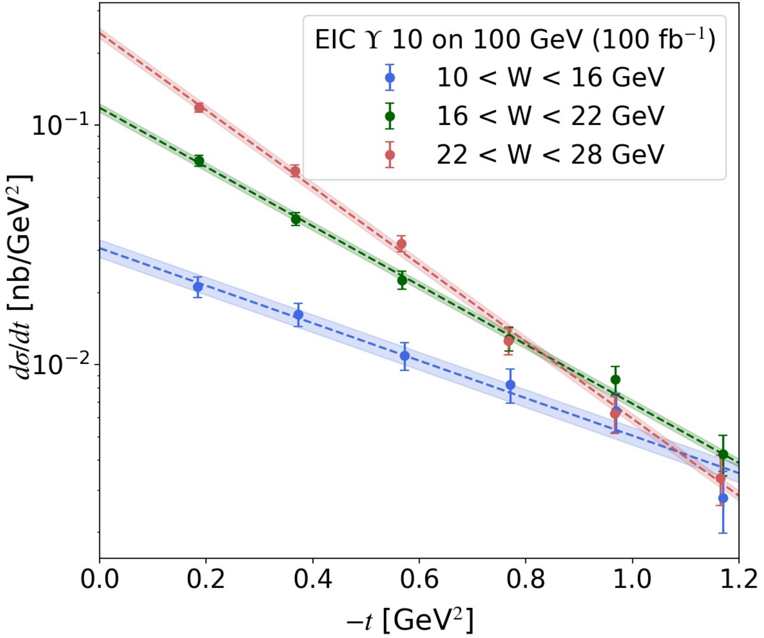
Studying the origin of the proton mass through near-threshold Υ production – even possible in year 1!

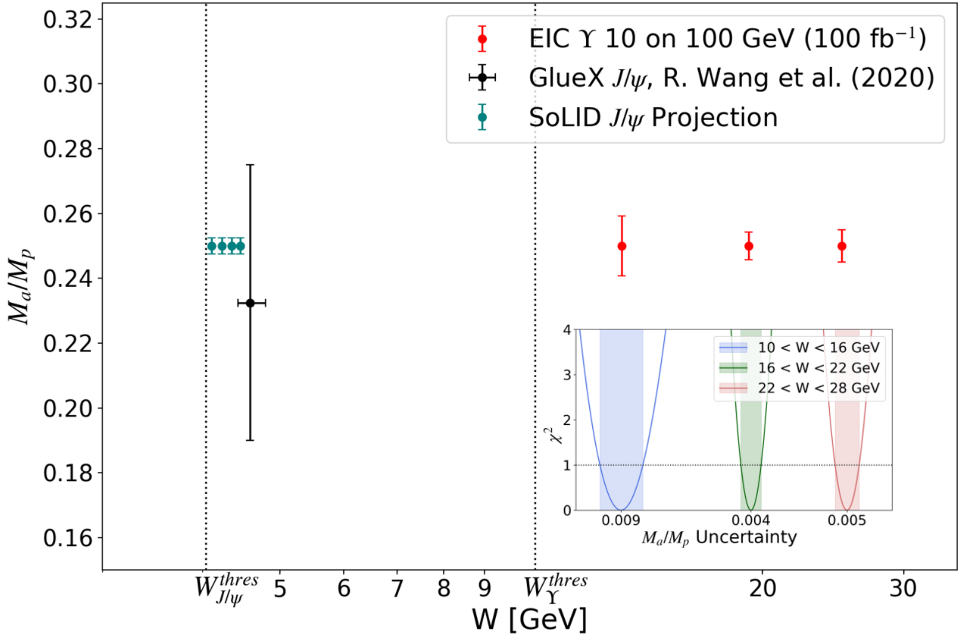




WHAT ABOUT THE EIC USING UPSILON PRODUCTION?

Using projected data of the t-distributions to be measured at EIC we show the impact on the uncertainty of the b parameter determination





ARGONNE MEP GROUP ACTIVITIES

This was was supported in part by DE-FG02-94ER40844 and DE-AC0206CH11357

IMAGING ELECTROMAGNETIC CALORIMETRY IN THE BARREL REGION

This was was supported in part by DE-FG02-94ER40844 and DE-AC0206CH11357

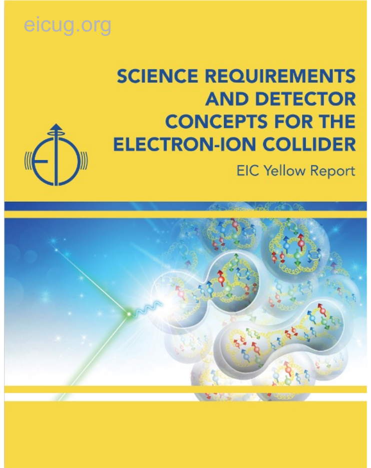
EIC CALORIMETRY REQUIREMENTS

Barrel ECAL in EIC Yellow Report

EIC Community outlined physics, detector requirements, and evolving detector concepts in the EIC Yellow Report.

EIC Yellow Report requirements for barrel ECal

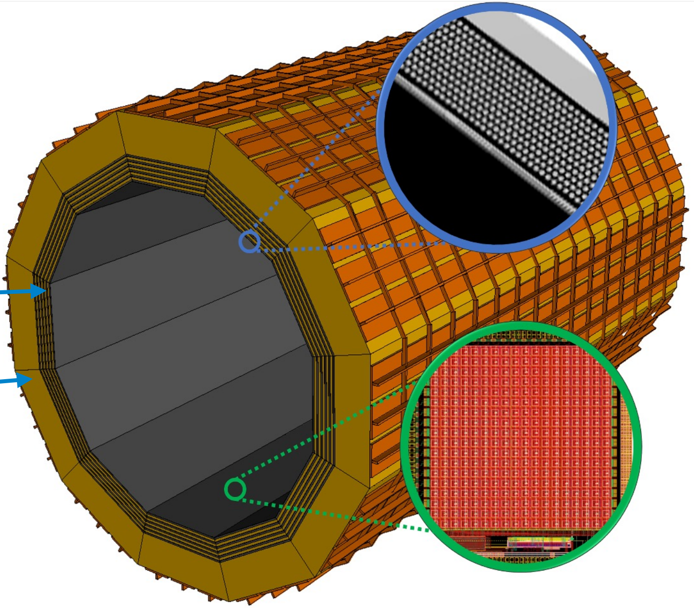
- Detection of electrons/photons to measure **energy and position**
- Require **moderate energy resolution** $(10-12)\,\%/\sqrt{E} \oplus (1-3)\%$
    - But! With high electron-pion separation at low momenta.
- Require **electron-pion separation up to 10^4** at low particle momenta
- Discriminate between **π^0 decays and single photons** from DVCS
- **Low energy photon** reconstruction ~100 MeV



Challenges: e/π PID, γ/π^0 discimination, dynamic range of sensors, available space

BARREL IMAGING BARREL EM CALORIMETRY

- **Hybrid concept**
  - Imaging calorimetry based on monolithic silicon sensors AstroPix (NASA's AMEGO-X mission) - 500 µm x 500 µm pixels NIM, A 1019 (2021) 165795
  - Scintillating fibers in Pb (Similar to GlueX Barrel ECal, 2-side readout w/ SiPMs) NIM, A 896 (2018) 24-42
- **6 layers of imaging Si sensors** interleaved with **5 Pb/ScFi layers**
- Followed by a **large chunk of Pb/ScFi section** (can be "extended" to inner HCAL)
- Total radiation thickness for EMCAL of ~21 X_0 (only ~38 cm! deep)



Energy resolution - SciFi/Pb Layers: $5.3\% / \sqrt{E} \oplus 1.0\%$

Position resolution - Imaging Layers (+ 2-side SciFi readout): with 1st layer hit information ~ pixel size

IMAGING LAYERS IN BARREL ECAL

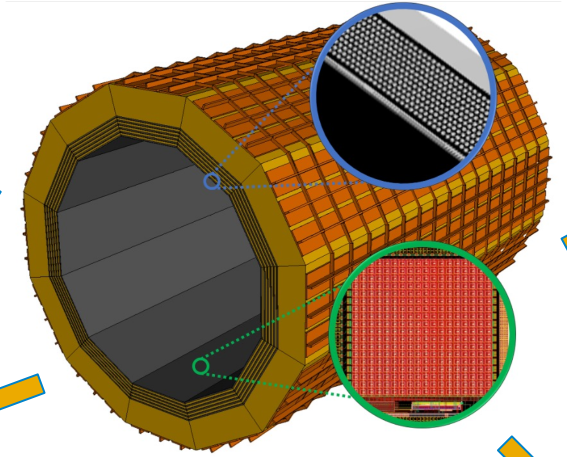
Excellent position resolution allowing precise 3D shower imaging

Significantly improved **electron/pion separation** with respect to E/p method

- Impact on DIS cross section and asymmetries

Separation of ɣs from π^0 decays at high momenta up to ~40 GeV/c.
Precise position reconstruction of **ɣs** (below 1 mm at 5 GeV).

- Impact on DVCS and photon physics



Precise measurement of **photon coordinates** and the **angle between electron and photon**

- Tagging **final state radiative photons** from nuclear/nucleon elastic scattering at low x to **benchmark QED internal corrections**

Allowing PID of **low energy muons** that curl inside the barrel ECal

- < ~1.5 GeV with 3T field
- < ~0.8 GeV/c for 1.5T field

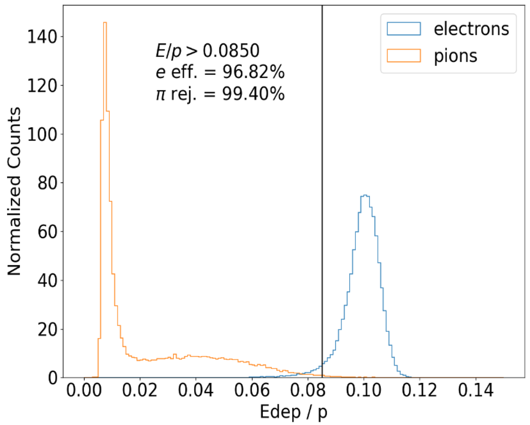
- Impact on J/psi reconstruction, TCS

Provides a **space coordinate for DIRC** reconstruction (no need for additional large-radius tracking detector)

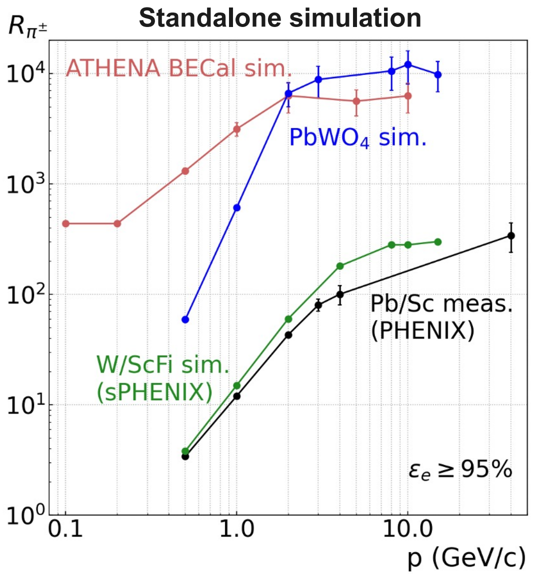
- Improving PID for SIDIS and beyond
- Improved tracking resolution for high-momentum particles

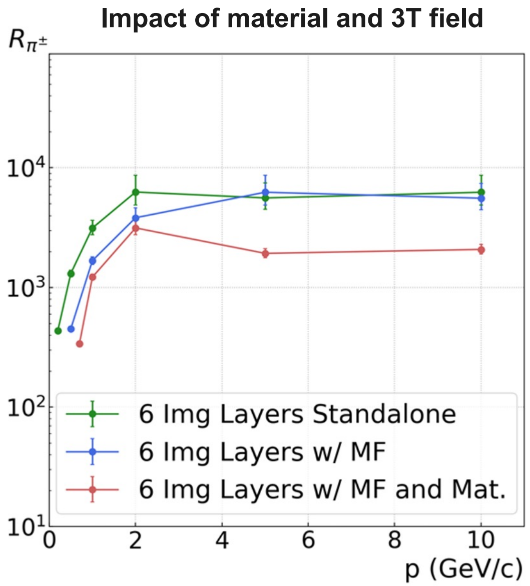
PERFORMANCE STUDY

Electron Identification



Initial cut on E/p from SciFi/Pb layers for e-π separation





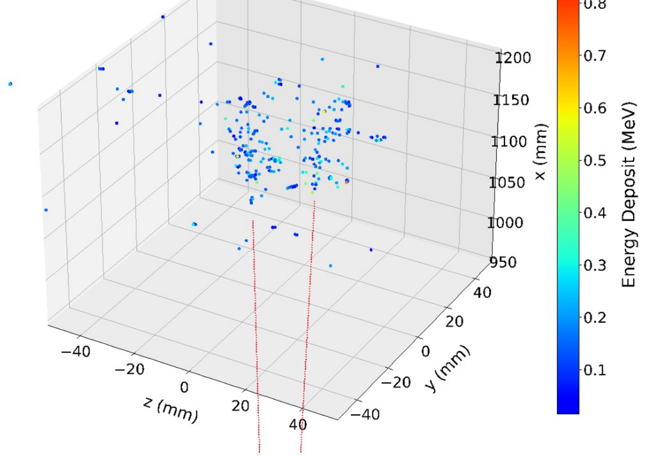
- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: E/p cut (SciFi) + Neural Network using 3D position and energy information from imaging layers

Electron-pion separation up to 10^4 in pion suppression at low particle-momenta

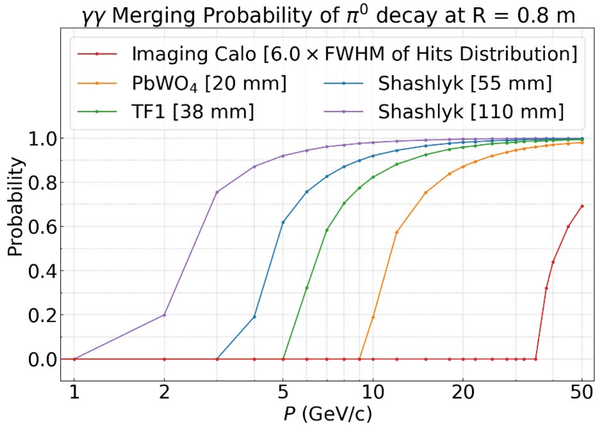
PERFORMANCE STUDY

Neutral pion identification

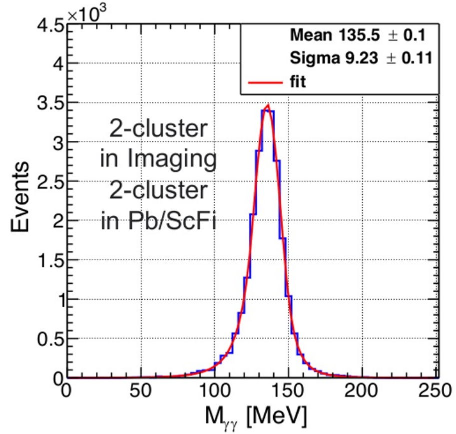
15 GeV $\pi^0 \rightarrow \gamma\gamma$



Separation of γ/π^0



M_{inv} reconstruction 2 GeV π^0



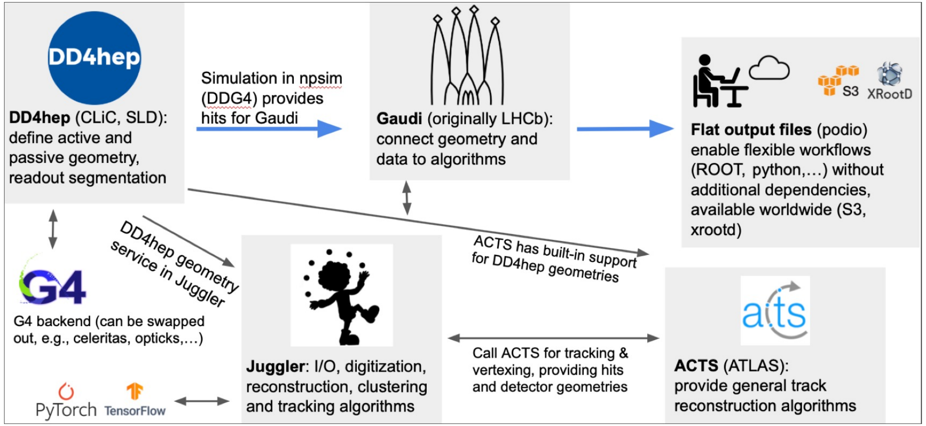
- **Goal:** Discriminate between decays and single from Deeply Virtual Compton Scattering (DVCS)
- Precise position resolution allow for excellent separation of γ/π^0 **based on the 3D shower profile**

Separation of two gammas from neutral pion well above 30 GeV

SOFTWARE AND COMPUTING FOR EIC

From EIC LDRD software to the software for the EPIC collaboration

- Philosophy: lets prepare for the future at EIC!
- Toolkit of modern software components, based on cutting-edge CERN-supported software where possible
- Ensure workflows enable heterogeneous environments using HTC and HPC
- **Based on simulation approach developed for the Argonne EIC LDRD**

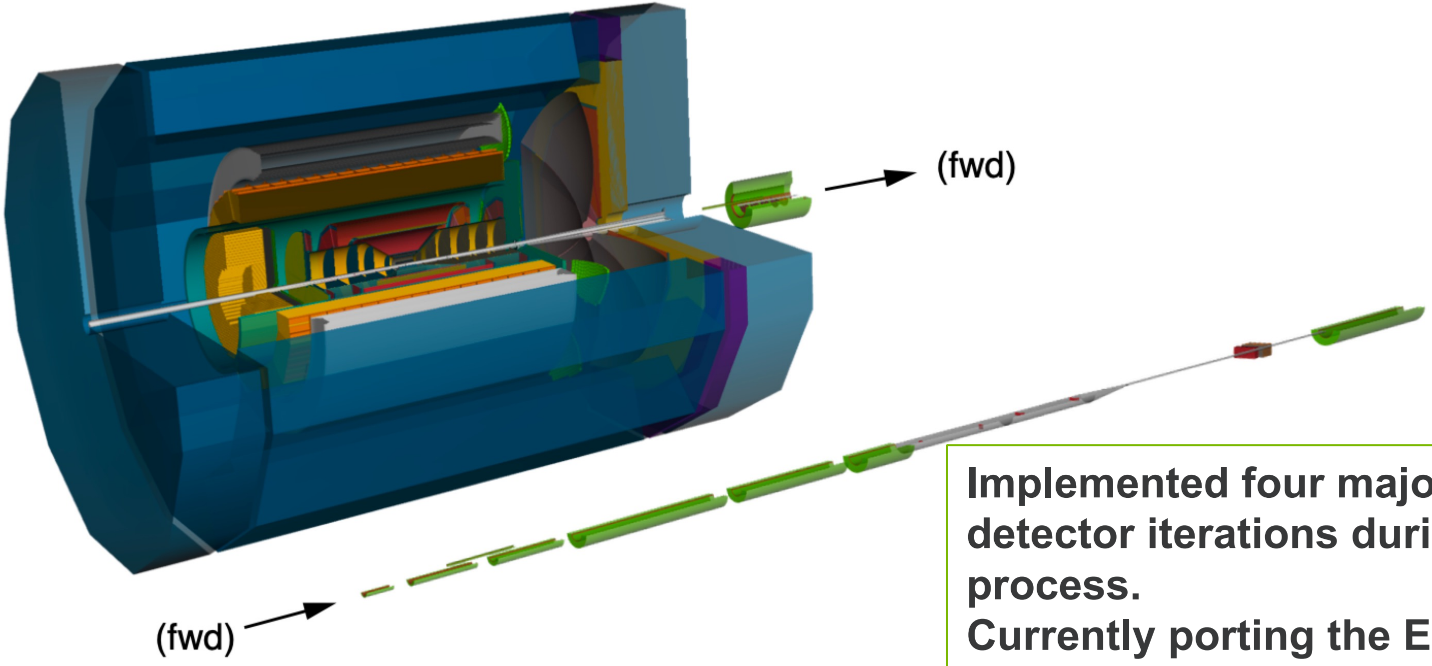


Highlights:

- Starting from our modern toolkit enabled effective detector optimization
- Performant full simulation/reconstruction for ATHENA in 4 months!
- **Toolkit will be the basis for computing at the EPIC itself**

EIC DETECTOR GEOMETRY IN DD4HEP

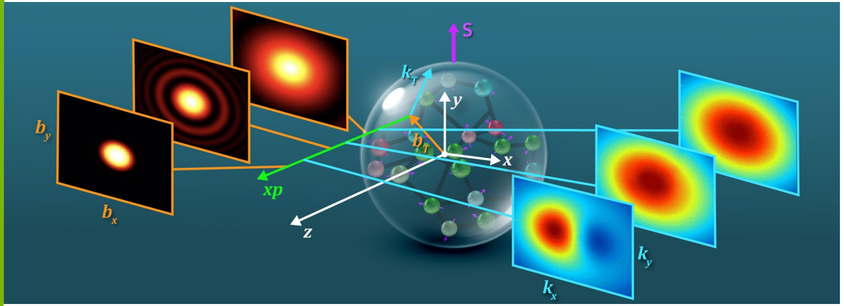
Online display: view.athena-eic.org

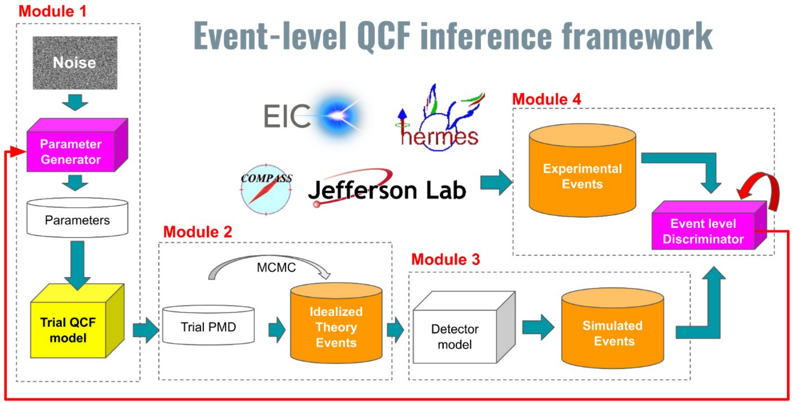


Implemented four major ATHENA detector iterations during optimization process.
Currently porting the EPIC Detector design into our toolkit for the first simulation campaign

FEMTOSCALE IMAGING OF NUCLEI USING EXASCALE PLATFORMS

The QuantOm Collaboration (https://www.anl.gov/phy/quantom)





The QUAntum chromodynamics Nuclear TOMography (QuantOm) Collaboration convenes domain scientists, applied mathematicians, and computational scientists to address the challenge of 3D imaging of quarks and gluons in nucleons and nuclei.

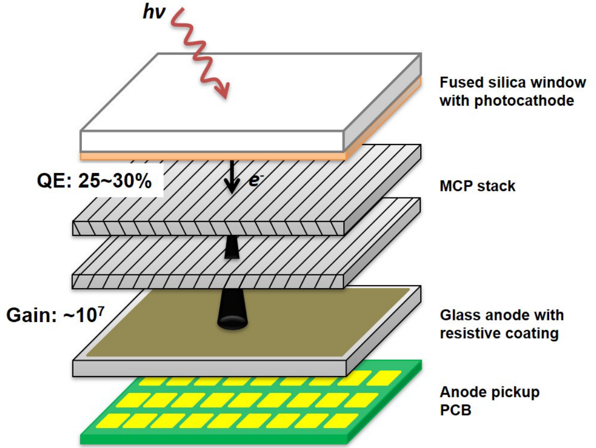
QuantOm is developing a unique event-level inference framework to obtain a quark and gluon tomography of nucleons and nuclei using high-energy scattering data.

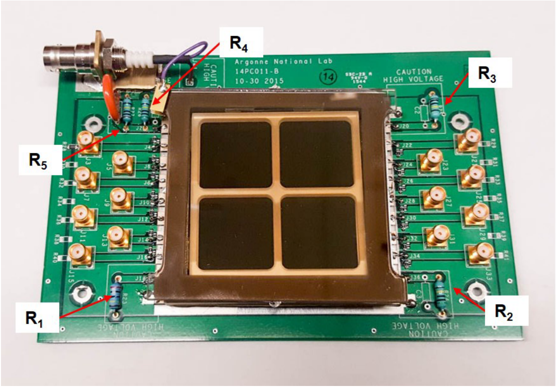
This event-level approach stands to have a transformational impact on the data analysis workflow that connects theory with experimentation.

Collaboration between Argonne, Jefferson Lab, and Virignia Tech

TARGETED MCP-PMT R&D FOR EIC

LOW-COST FULL GLASS/FUSED SILICA DESIGN





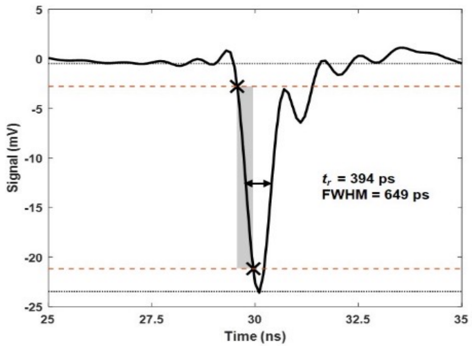
a) Full glass/fused silica design with mature fabrication process and low-cost;

b) Fused silica (or borosilicate glass with wavelength shifter) window extending sensitivity down to UV range for better Cherenkov light detection;

c) Newly developed small pore size MCPs for higher magnetic field tolerance and fast timing;

d) Reduced spacing internal geometry further improves the magnetic field tolerance and timing resolution;

e) Capacitively coupled electronic readout through fused silica for pixelated readout scheme.



TARGETED MCP-PMT R&D FOR EIC

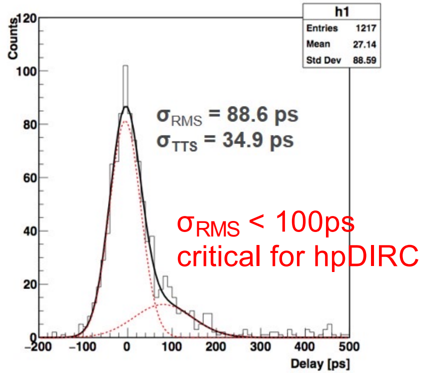
Detailed parameters and Performance of Argonne MCP-PMT

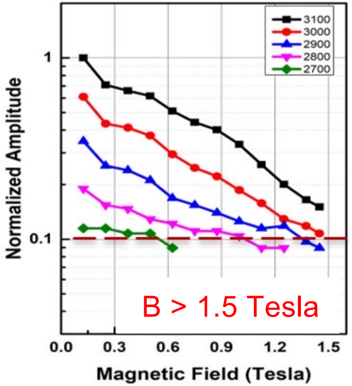
ANL **low-cost** MCP-PMT with 10 μm pore size MCPs and reduced spacing

MCP	Pore size	10 μm
	Length to diameter ratio (L/d)	60:1
	Thickness	0.6 mm
	Open area ratio	70 %
	Bias angle	13^{o}
Detector geometry	Window thickness	2.75 mm
	Spacing 1	2.25 mm
	Spacing 2	0.7 mm
	Spacing 3	1.1 mm
	Shims	0.3 mm
	Tile base thickness	2.75 mm
MCP-PMT stack	Internal stack height	**5.55 mm**
	Total stack height	11.05 mm

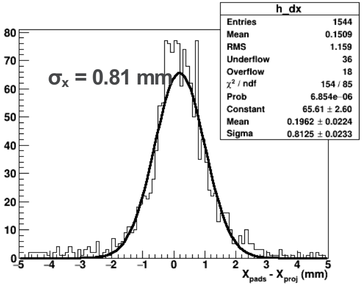
Gain Characteristic	Gain	2.0 × 10^{7}
Time Characteristic	Rise time	**394 ps**
	TTS RMS time resolution	88.6 ps
	TTS resolution	35 ps
Magnetic Field	Magnetic field tolerance	**Over 1.5 T**

J. Xie et al, 2020 JINST 15 C04038

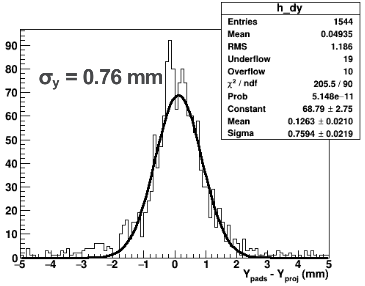




4 mm x 4 mm pixel



X direction



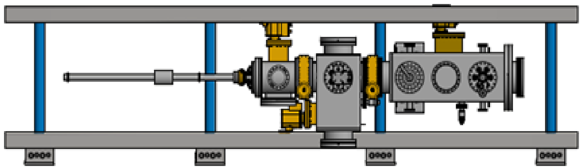
Y direction

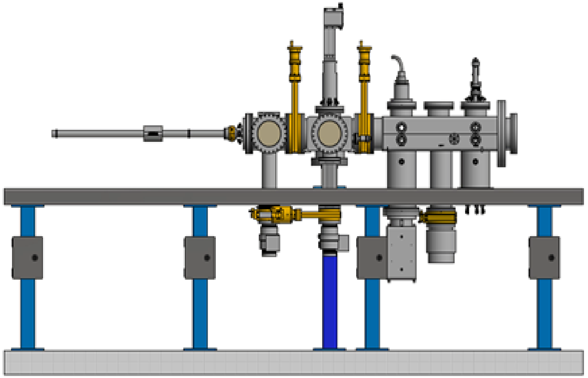
NEW ARGONNE 10X10 CM^2 MCP-PMT FABRICATION SYSTEM

- ✓ Practical device size: a size to replace 2x2 array of MaPMTs or 5” phototubes in many JLab detectors with the goal of an in par price with superior performance
- ✓ Adequate size to eliminate the cross support while maintaining successful sealing, full 10x10 cm^2 detection area. Tiled to create larger sensor areas.

Upgraded chamber size to accommodate 10x10 cm^2 MCP-PMT fabrication
Upgraded photocathode deposition chamber for high and uniform QE: uniform oven heating and substrate rotate mechanism

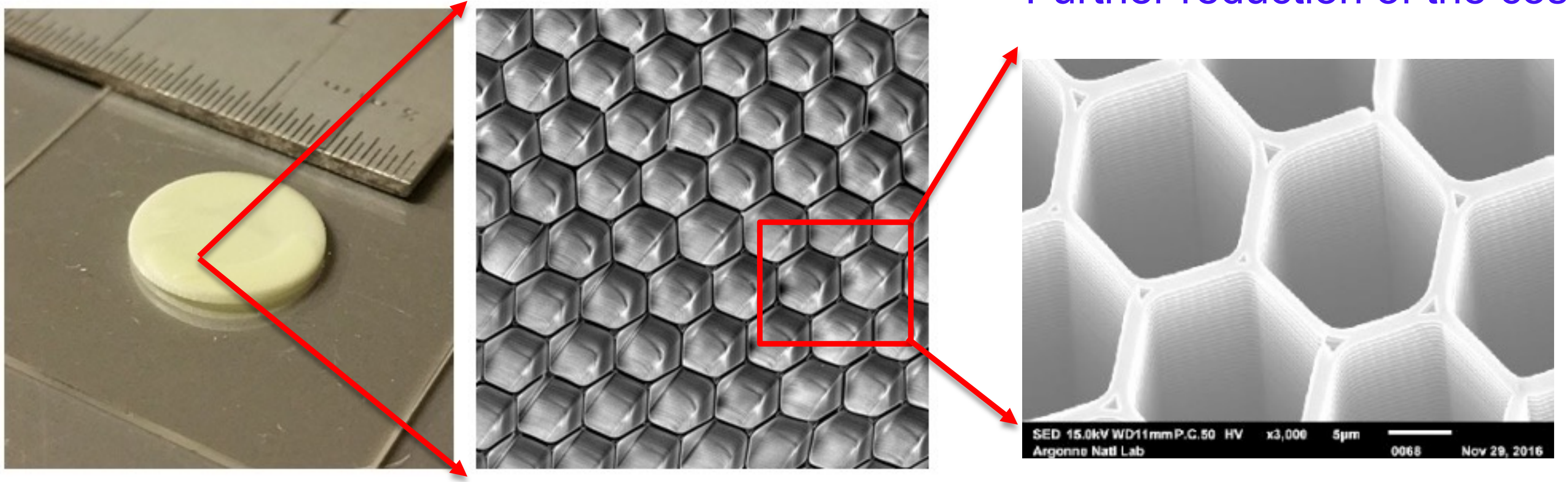
Recently delivered at Argonne, under final inspection before installation in cleanroom.





FUTURE 3-D PRINTED MCP

Further reduction of the cost



R. Wagner et al., 3D printed micro channel plate, method of making and using 3D printed micro channel plate
US patent: 10,403,464 Granted: 09/03/2019

Newly developed additive manufacturing technology for gain structure
Potential significant reduction of cost
Under support of SBIR and LDRD for 3D-printed MCP and integration of the MCP into photosensor.

Polarized Ion Beams Beyond Helium-3

Expanding science reach of EIC with polarized ion beams with A > 3

- Beyond the current scope of polarized H, D, ^{3}He beams
- Access to the **spin-dependent** structure of **nucleus**
- Benefit critical accelerator technologies
- Candidates: ^{6}Li (spin-1), ^{21}Ne (spin-3/2), and ^{129}Xe (spin-1/2)

Important physics programs enabled by polarized ^{6}Li at EIC

- Investigate a deuteron embedded in ^{6}Li (α core with two-nucleons)
  - b_1 structure function
  - gluon transversity distribution
- Polarized EMC effect
  - DIS on the valence p/n with tagging the recoiled $\alpha + n/p$
- Reference studies between nucleon and nucleus with polarized H, D beams
  - spin-1/2 nucleon or spin-1 deuteron embedded in ^{6}Li

Laser-driven Polarized Lithium-6 System

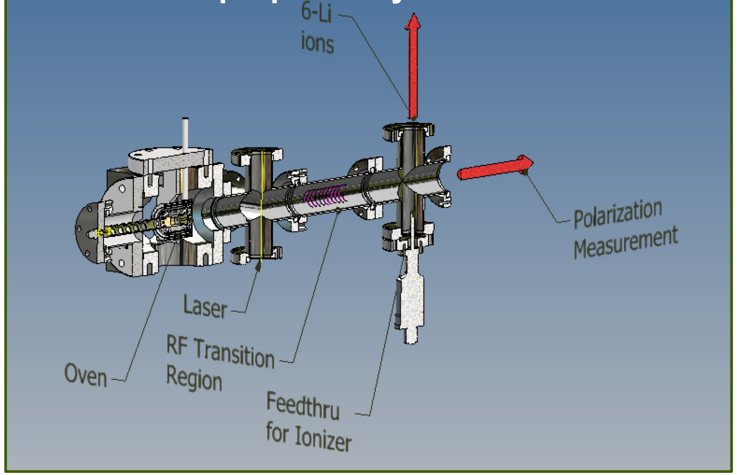
Laser-driven optical pumping system

- A proposed system to polarize ^{6}Li
- A well-developed technique

Phys. Rev. Lett., 42:1520–1523 (1979).
NIM-A, 329(1/2):37–45 (1993).

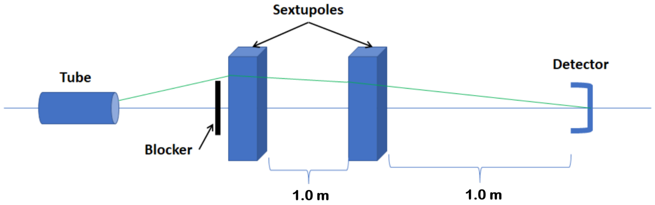
- Modification for spin-exchange optical pumping ^{21}Ne and ^{129}Xe

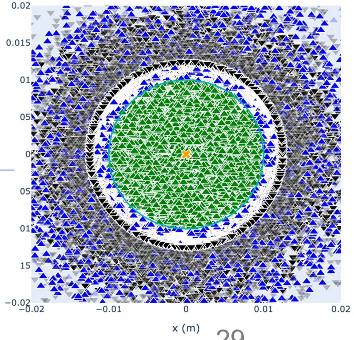
Schematic of proposed system

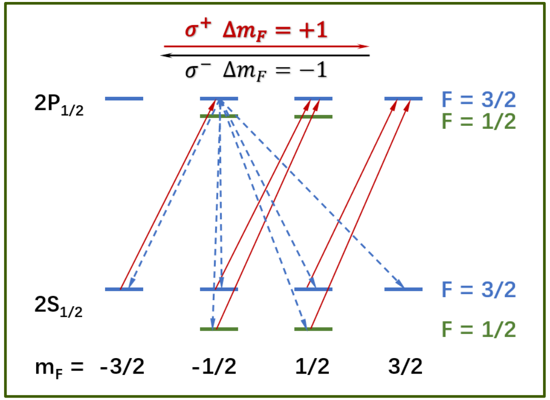


Breit-Rabbi polarimeter

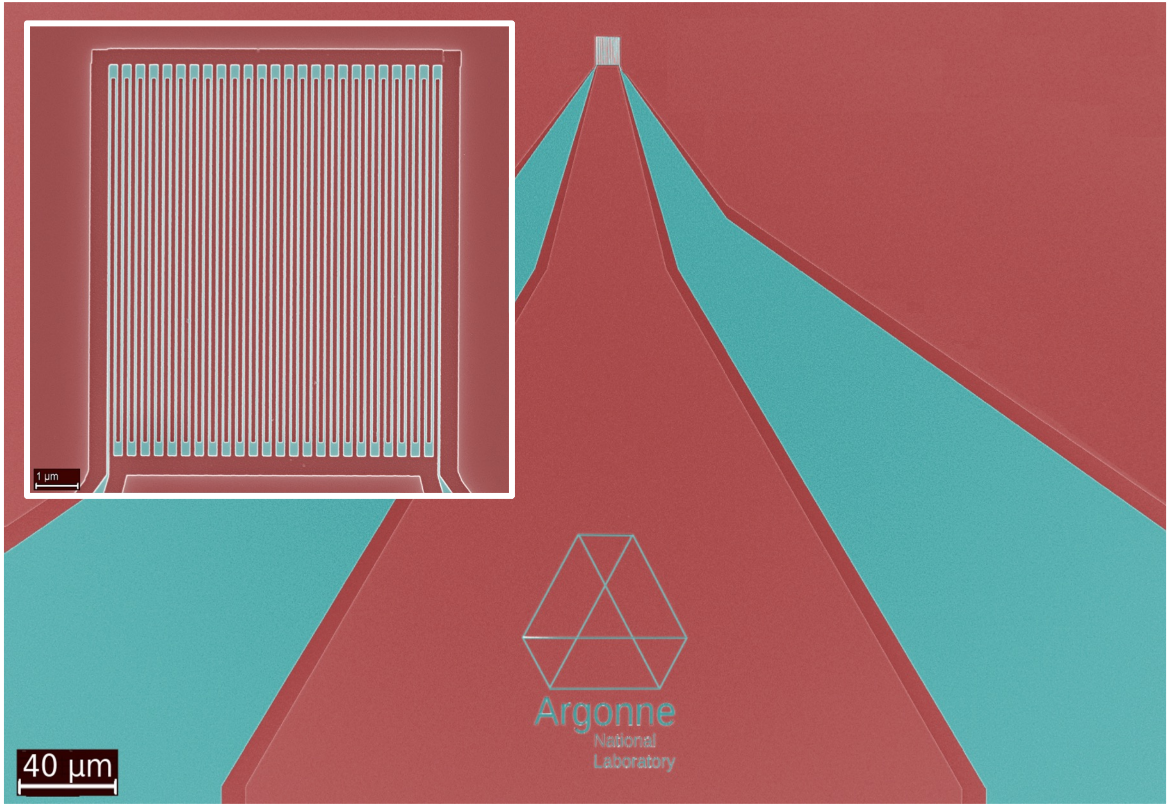
- Precision measurement to study depolarization
- Simulation package developed from ANL LDRD



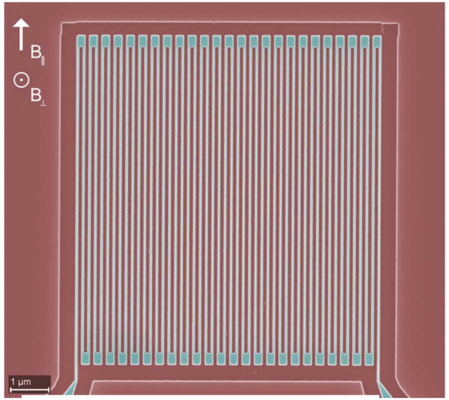


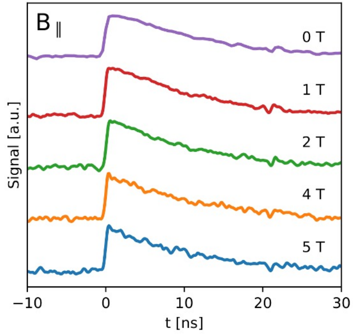


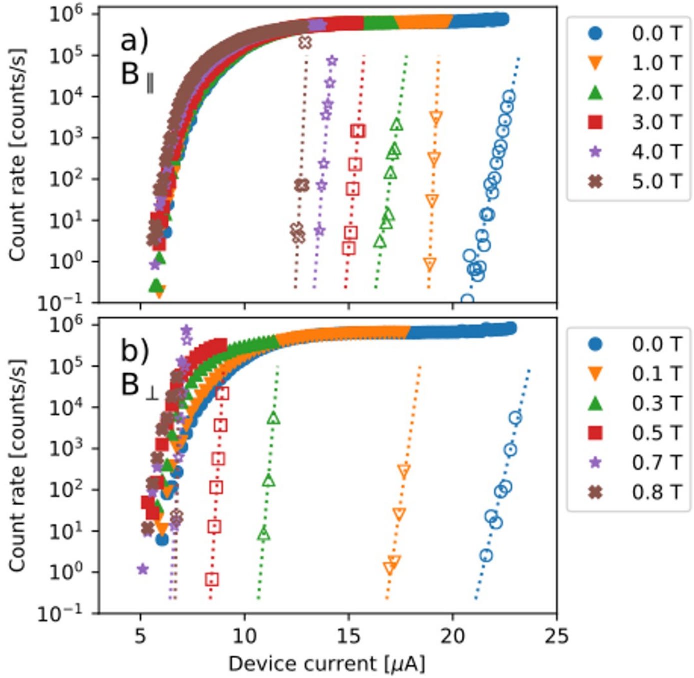
SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS

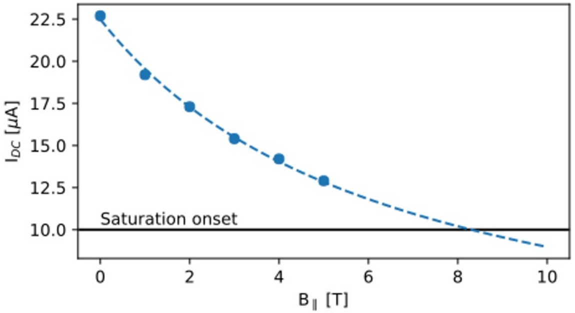


STRONG MAGNETIC FIELDS AND HIGH RATES

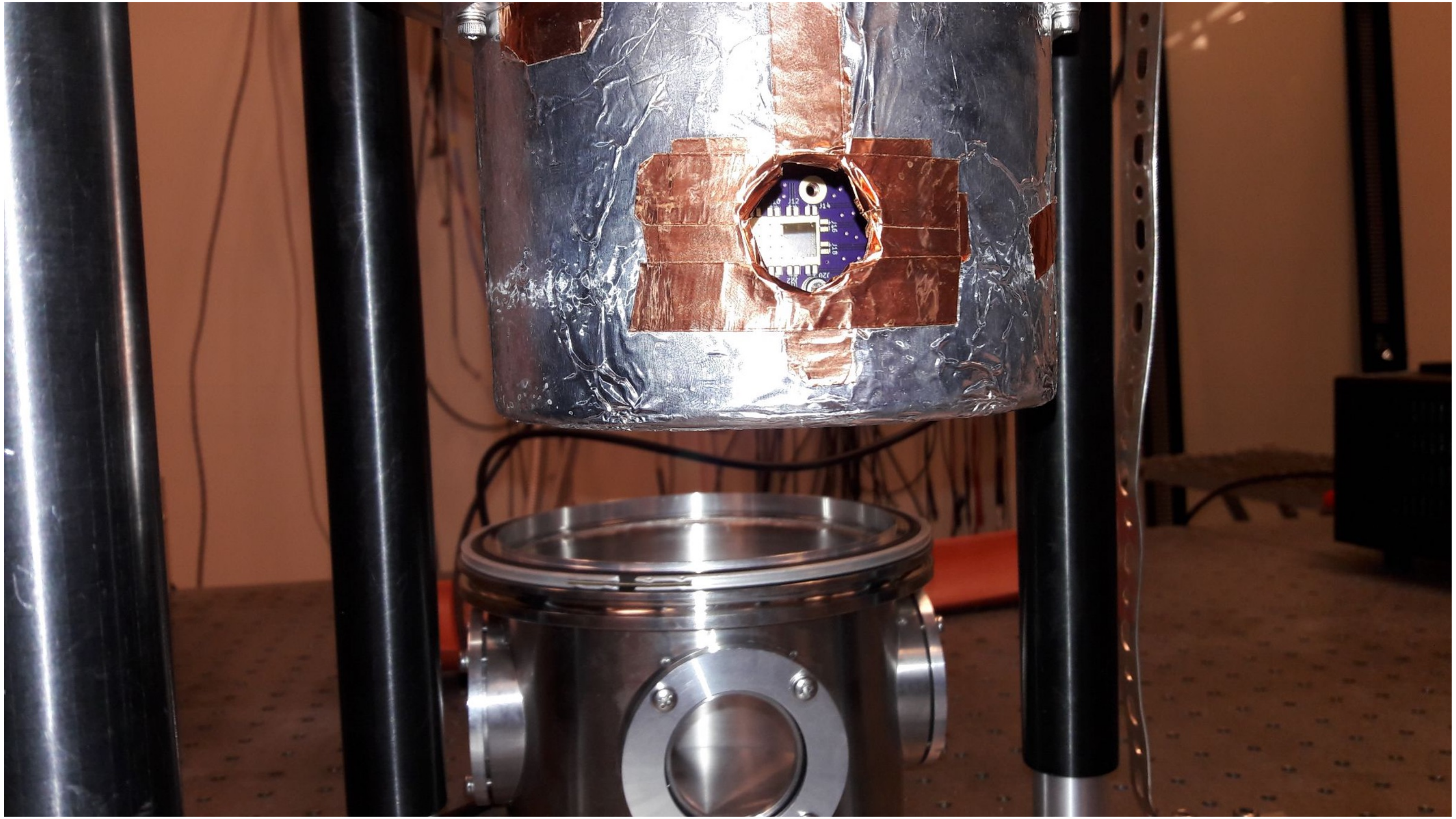




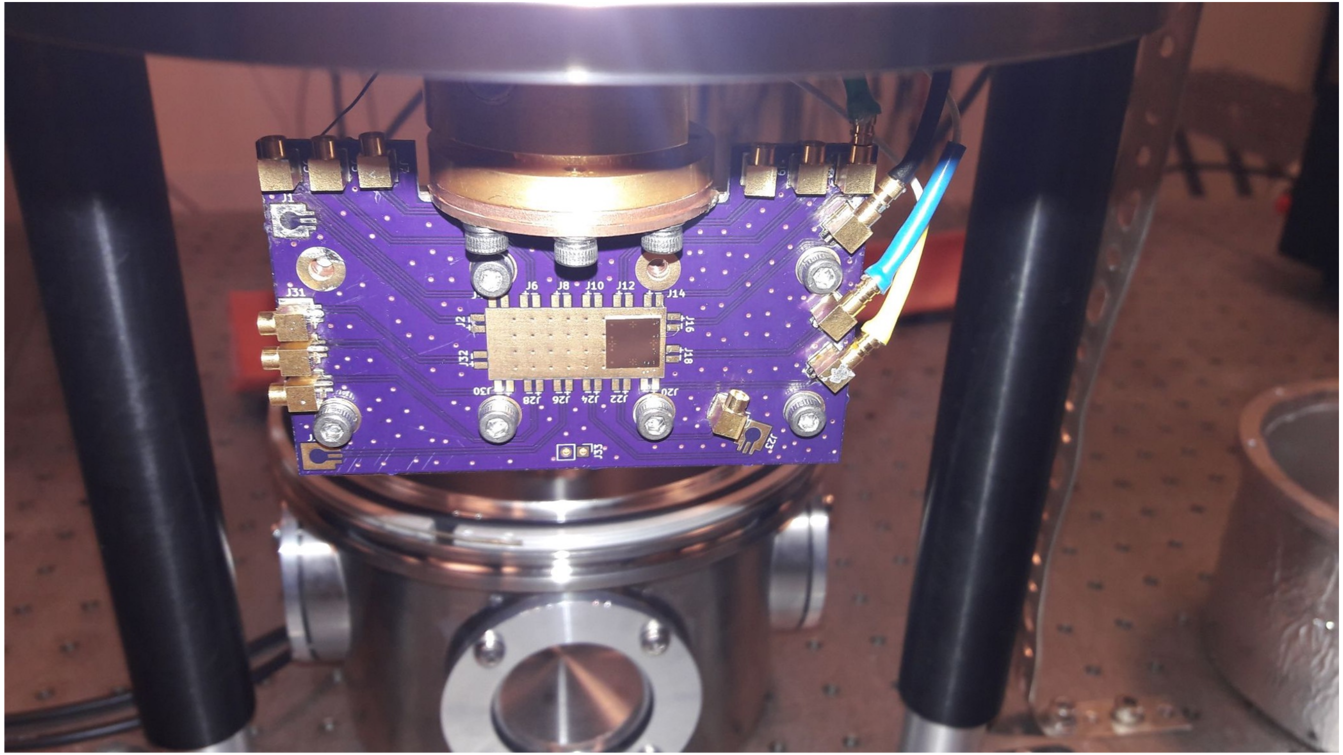




Can operate on strong magnetic fields with nearly zero dark count



DEVICE COLD FINGER MOUNTING PCB

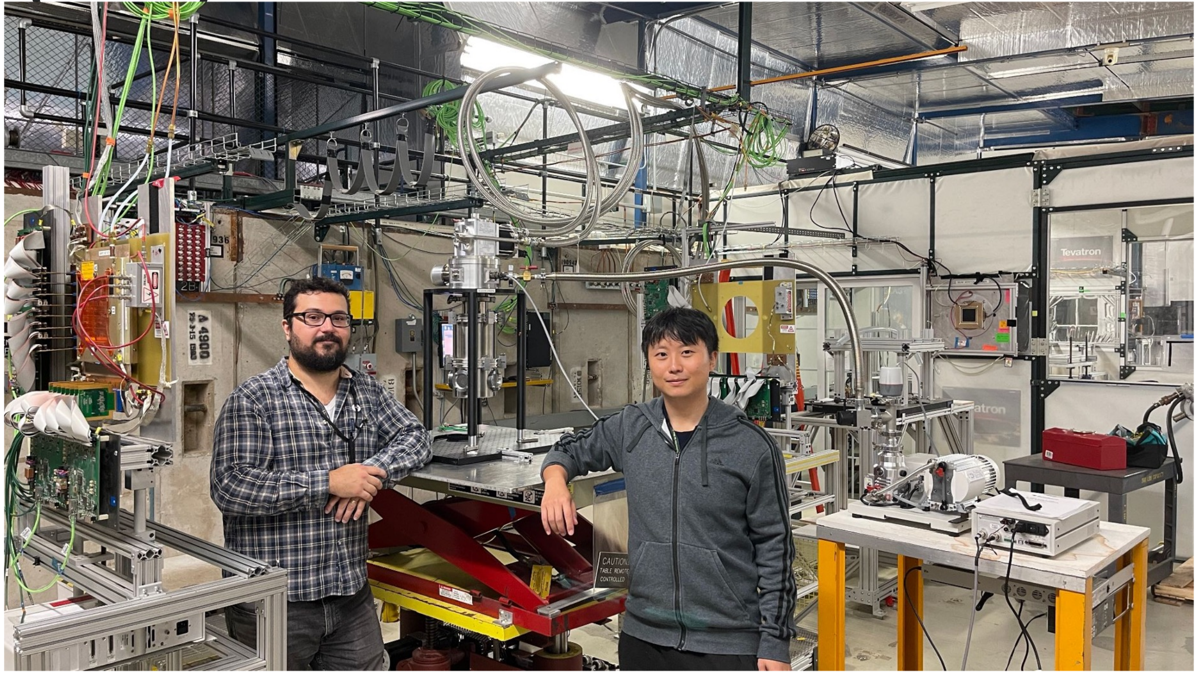


PARTICLE DETECTION UPDATE

Energy deposited

Particle	Energy	Approximate Energy loss in	
		100 um silicon	15 nm NbN
alpha	5 MeV	5 MeV	9.07 keV
electron	1 MeV	15 keV	15.8 eV
electron	100 MeV	~100 keV	~100 eV
proton	120 GeV	40 keV	24 eV

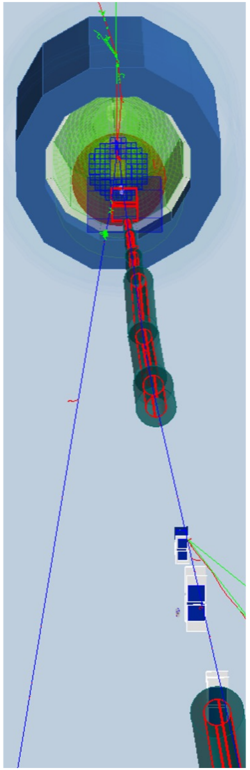
SETUP FOR OPERATIONAL READINESS CLEARANCE (ORC)

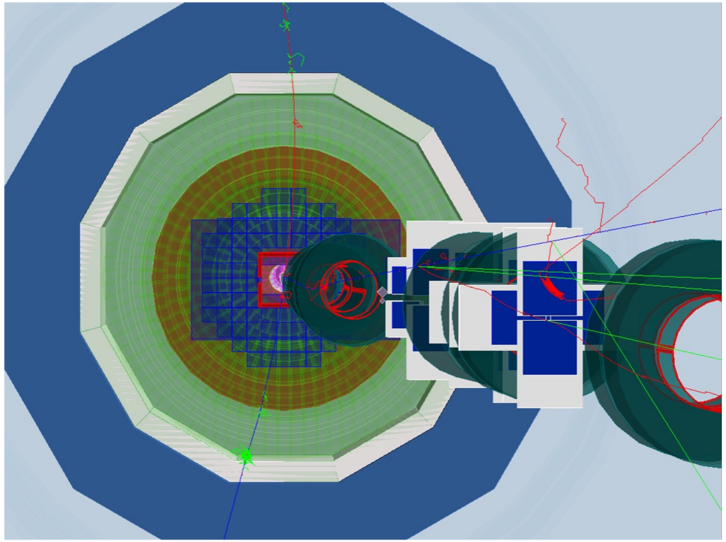


SUPERCONDUCTING NANOWIRE PARTICLE DETECTORS FOR THE EIC

Submitted in July 2020

Successful proposal for EIC Detector R&D at BNL: eRD28

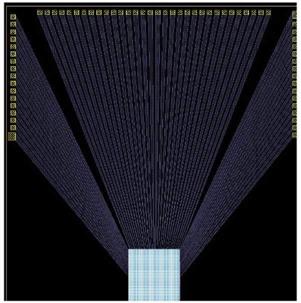


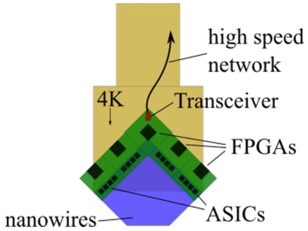


BNL EIC Detector R&D Committee:

Superconducting nanowires have never been deployed in a particle or nuclear physics experiment to our knowledge. As such, this proposal represents a true spirit of detector R&D. This project will have to solve many issues before it would have a working detector as indicated above. There are interesting synergistic activities with other projects under this program such as the polarimetry measurement. The idea to test a device in the Fermilab test beam and study the response to protons, electrons and pions is a very worthwhile exercise and would provide new information. We strongly recommend that at the least this aspect of the project is supported, funding permitting

- Will demonstrate the detection of low energy particles from radioactive sources at high rate and in high magnetic field.
- Fabricate a small pixel array for high energy particle detection





SUMMARY

- **The gluonic gravitational form factors will be measured at the EIC using Upsilon production and benchmarked against JLab measurement for Universality**
  - At large *s* using the GPDs formalism gluon densities will be extracted
  - Near threshold upsilon production will be used to measure directly the GFFs
  - The GFFs of light nuclei will be explored using coherent J/psi production with the tagging of light nuclei
- **Argonne Activities are commensurate with the EIC science interests of the ANL group**
  - Barrel imaging electromagnetic calorimetry (pending decision of the project)
  - Polarized light ion beams beyond ^{3}He
  - Far-forward tagging using a novel technology (superconducting nanowires)
  - Photosensors important for all RICH detectors (10x10 cm^2-MCP-PMTs)
  - Software kits and HPC consistent with the SciDAC proposals recently approved
- **Collaboration/Partnership from Korean groups with ANL on the Barrel Electromagnetic Calorimetry and else is most welcome!**

THANK YOU!

This was was supported in part by DE-FG02-94ER40844 and DE-AC0206CH11357