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U.S. DEPARTMENT OF ENERGY

Advancement of Noble Liquid Detectors R&D for High Priority HEP Experiments in 2023 P5 Report

PI: Hucheng Chen (PO)

Other investigators: Jack Fried (IO), Niccolo' Galice (IO), Shanshan Gao (PO), George Iakovidis (PO), Marc-Andre Pleier (PO), Veljko Radeka (IO), Sergio Rescia (IO), Scott Snyder (PO), Bo Yu (IO), Chao Zhang (PO), Manhong Zhao (PO)

02/20/2024

FY2025 NPP LDRD Type A Pre-Proposal

- **Proposal Title:**
  - *Advancement of Noble Liquid Detectors R&D for High Priority HEP Experiments in 2023 P5 Report*
- **Primary Investigator:**
  - *Hucheng Chen (PO)*
- **Other Investigators:**
  - *Jack Fried (IO), Niccolo' Galice (IO), Shanshan Gao (PO), George Iakovidis (PO), Marc-Andre Pleier (PO), Veljko Radeka (IO), Sergio Rescia (IO), Scott Snyder (PO), Bo Yu (IO), Chao Zhang (PO), Manhong Zhao (PO)*
- **Indicate if this is a cross directorate proposal: Yes**
- **If yes, identify other directorates/organizations: IO**
- **Program: HEP**
- **Proposal Term:**
  - *3 years, From: 10/2024 To: 09/2027*
- **Annual funding in FY25-FY27:**
  - *$600K/year*

Motivation: 2023 P5 Report

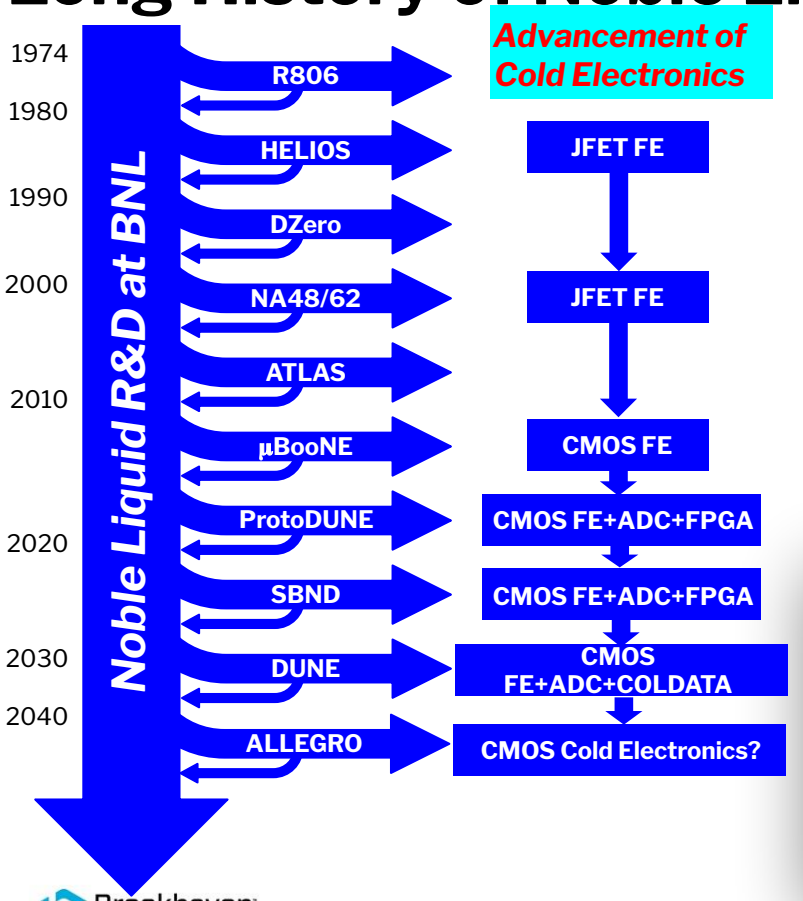
- **Recommendation 2**

Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

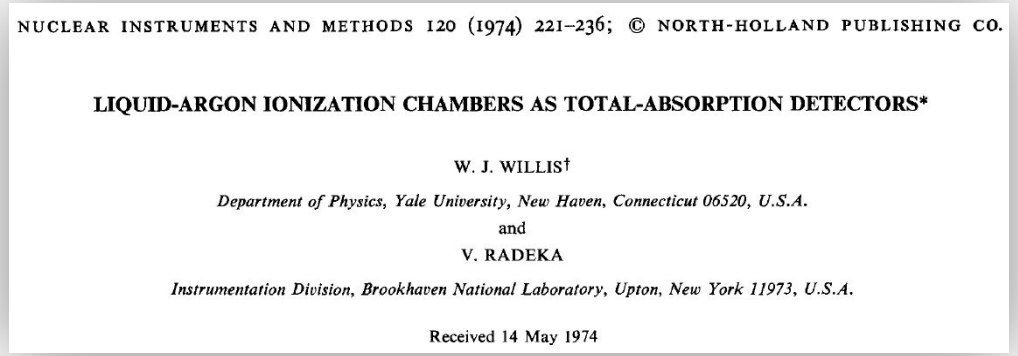
1. **CMB-S4**, which looks back at the earliest moments of the universe,
2. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam as the definitive long-baseline neutrino oscillation experiment,
3. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,
4. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,
5. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

- **BNL is well positioned to realize the high priority HEP experiments in 2023 P5 report**
  - ***LDRD 23-049: Capturing Leadership at the Future Higgs Factory for BNL***
  - ***LDRD 23-058: Dual Calorimetry and 6-D Tracking with LAr TPC for Physics Discovery***

Long History of Noble Liquid Detector R&D at BNL



- **BNL pioneered Liquid Argon based detector technology in 1974**
  - ***Unique experience in cryogenic electronics and low-noise microelectronics***
  - ***Strong collaboration between PO and IO for half a century***
- **R&D → Experiments → R&D**
  - ***Readout electronics*** has always been an ***integral*** part of detector R&D effort for ***precision measurement*** with noble liquid detector



NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

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Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.

and

V. RADEKA

Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

Received 14 May 1974

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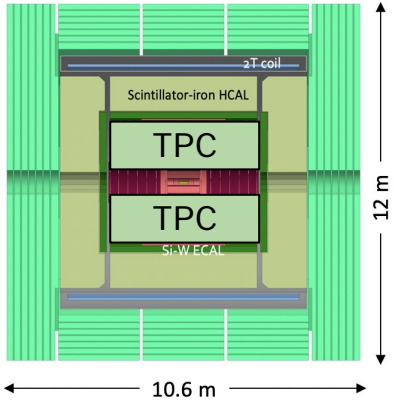
FCC-ee Detector Concepts

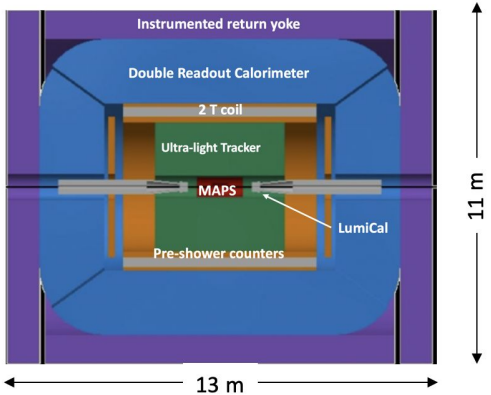
CLD/ILD'



- Well established design
  - ILC → CLIC detector → CLD
- Full Si vertex + tracker; study TPC option viability
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

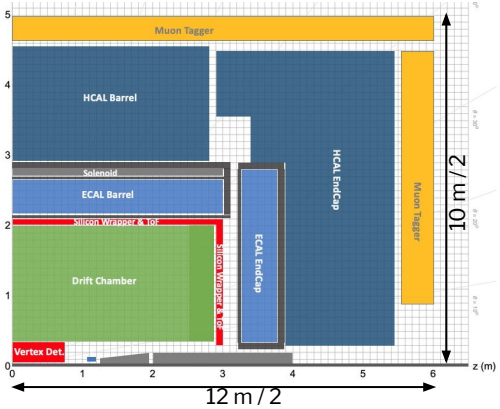
CDR

IDEA



- A bit less established design
  - But still ~15y history
- Si vertex detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO



- The "new kid on the block"
- Si vertex det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

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FCC-ee Calorimetry

baseline FCC-ee detector performance

track momentum	$\frac{\sigma_p}{p} = 0.02 \cdot 10^{-3} \cdot p_T(\text{GeV}) \oplus 1 \cdot 10^{-3}$
track impact parameter	$\sigma_{d_0} = \frac{15\,\mu\text{m}}{\sin^{3/2}\theta} \oplus 5\,\mu\text{m}$
electromagnetic energy	$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{15\%}{E_\gamma} \oplus 1\%$
electromagnetic energy xy position	$\sigma_{\gamma,xy} = \frac{6\,\text{mm}}{E(\text{GeV})} \oplus 2\,\text{mm}$

Table 135 Summary table of the expected energy resolution for the different electromagnetic calorimeter options considered in the studies of Ref. [435].

Technology	EM energy resolution (stochastic term)	(constant term)
Highly granular Si/W based	15–17%	1%
Dual readout Fibre (ECAL+HCAL)	11%	¡1%
Hybrid crystal (dual readout)	3%	¡1%
Highly granular noble liquid based ECAL	8–10%	¡1%

CLD

IDEA

ALLEGRO

- **FCC Midterm Report**
  - https://doi.org/10.17181/zh1gz-52t41
- **Status of the FCC Feasibility Study – Feb 13, 2024**
  - https://indico.cern.ch/event/1379648/
- **FCC Physics Case**
  - https://indico.cern.ch/event/1379648/contributions/5798881/attachments/2800097/4884826/Grojean_talk.pdf
- **Calorimetry at FCC-ee**
  - https://arxiv.org/abs/2109.00391

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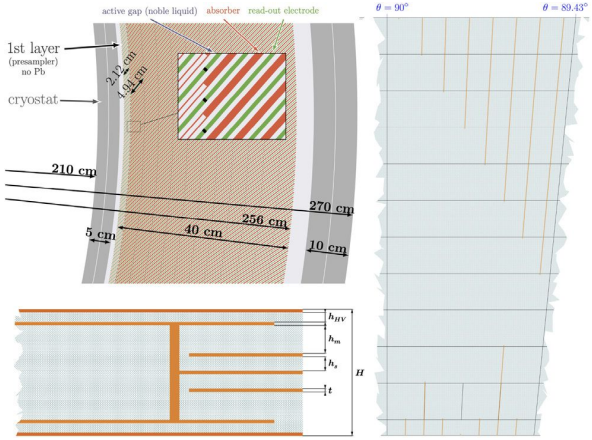
High Granularity Noble Liquid ECAL



- **Evolution of ATLAS calorimeter with much finer granularity for particle-flow reconstruction:**
  - $\Delta\phi$; $\Delta\theta$ = 10; 8 mrad
  - 12 longitudinal layers
  - ***Superior (~5x) SNR*** with cold electronics
  - Narrow strips in front for π_0 detection → ***BNL IP***
  - Slanted electrodes → ***sPHENIX like configuration***

- **ALLEGRO – general-purpose detector for FCC-ee**
  - ***A Lepton coLlider Experiment with Granular calorimetry Read-Out***
- **Highly-granular noble liquid ECAL a central and most studied feature**
  - ***LAr or LKr with Pb or W absorbers***
  - ***Multi-layer PCB as read-out electrode***
- **Vertex detector, drift chamber and ECAL inside 2 T solenoid, sharing cryostat**
- **HCAL and muon system outside solenoid**
- **Optimized for full FCC-ee physics program**
  - *Focus on particle-flow & particle ID performance*

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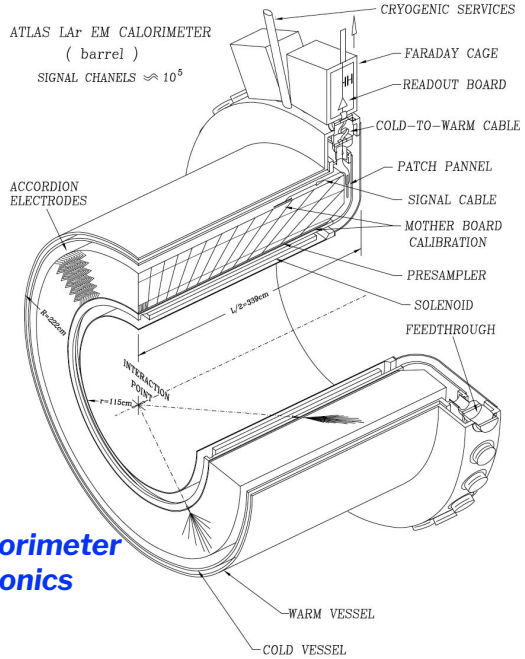
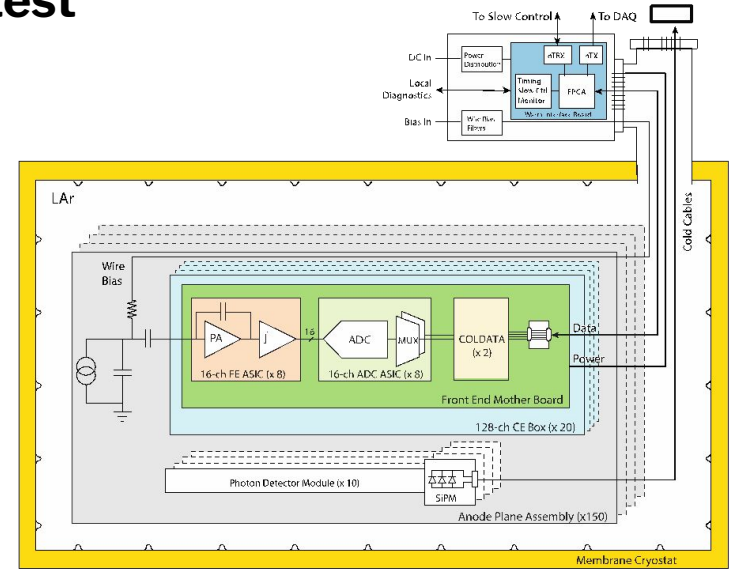
Integral System Design Approach

- **BNL has been leading the readout system design of large noble liquid detectors in the world**
- **An integral system design approach → from detector electrode to readout electronics, plus system integration test**



ATLAS LAr Calorimeter Readout Electronics System



DUNE FD1 TPC (and FD2 BDE) Readout Electronics System

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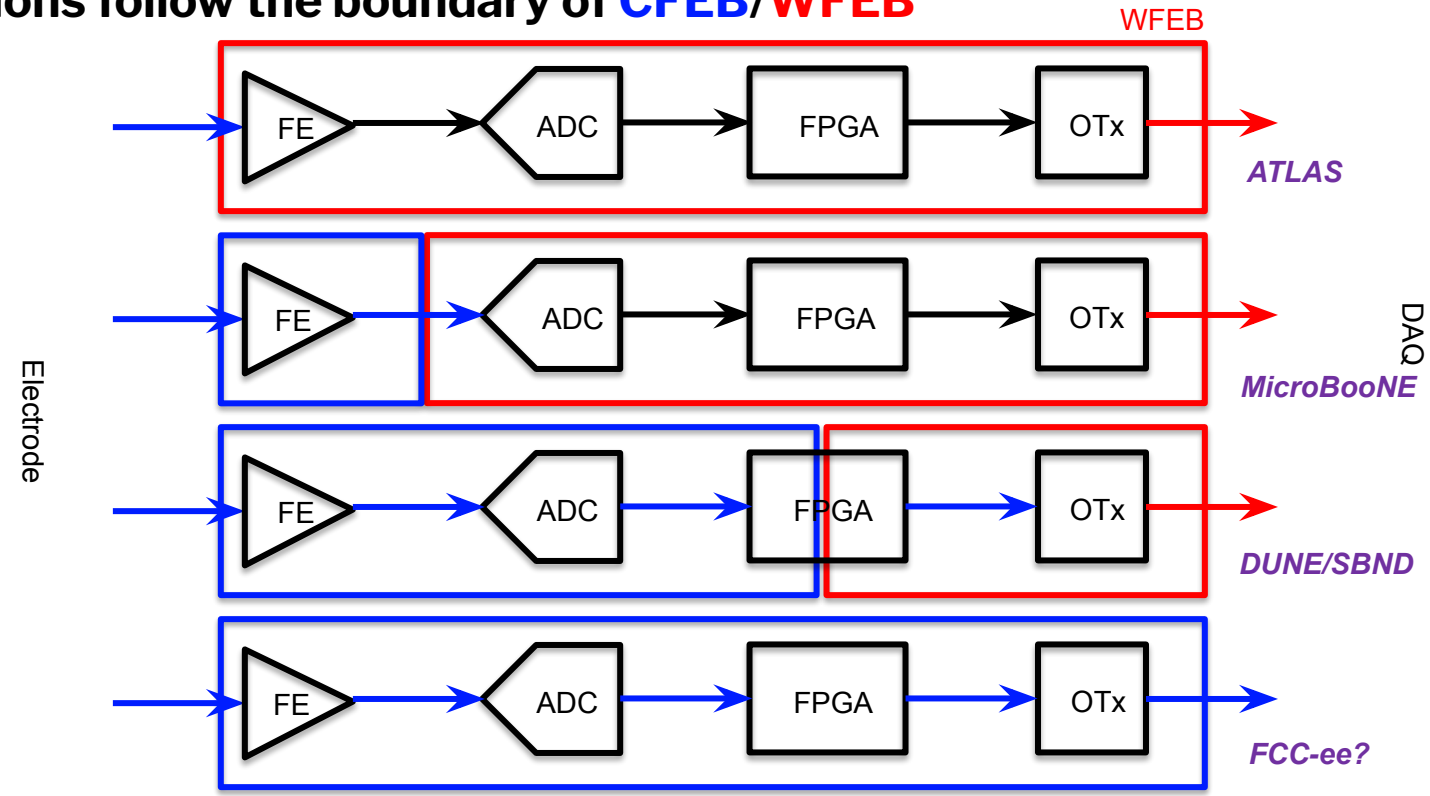
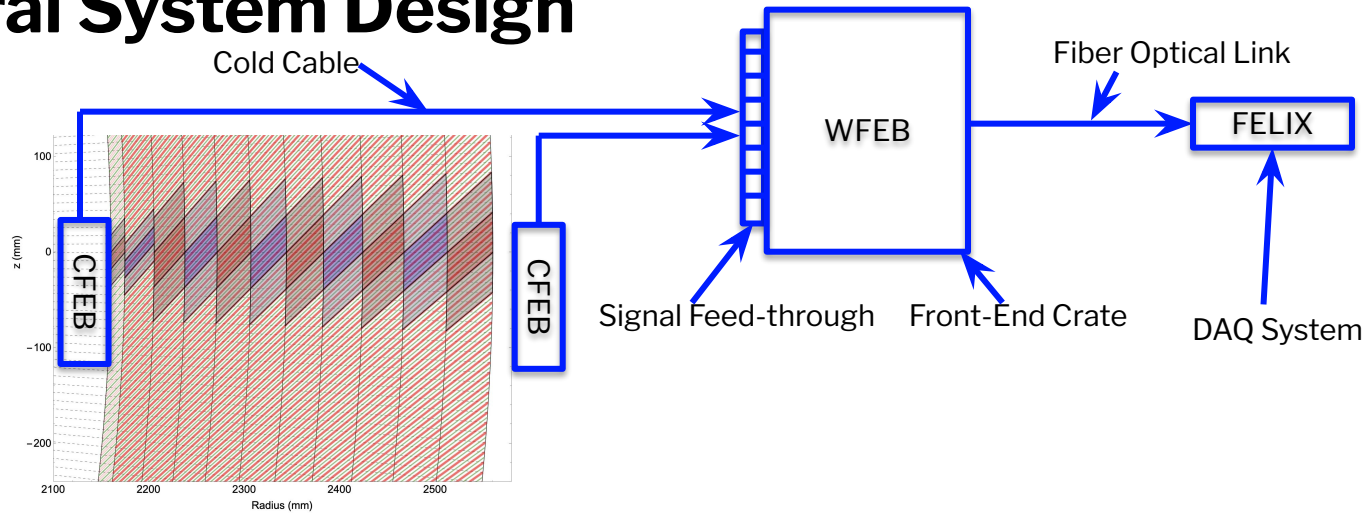
Front-End Readout Electronics

- **Options follow the boundary of CFEB/WFEB**



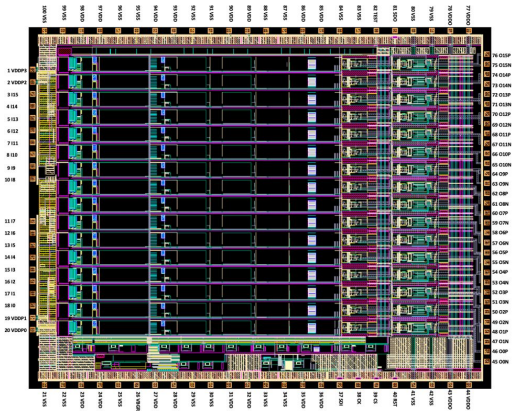
- **Potential Leverage of *Silicon Photonics* development in *LDRD 24-054***
  - ***Galvanically Isolated, High Spatial and Temporal Resolution Silicon Vertex and Tracking Detector with Large-Area Monolithic Active Pixel Sensors***

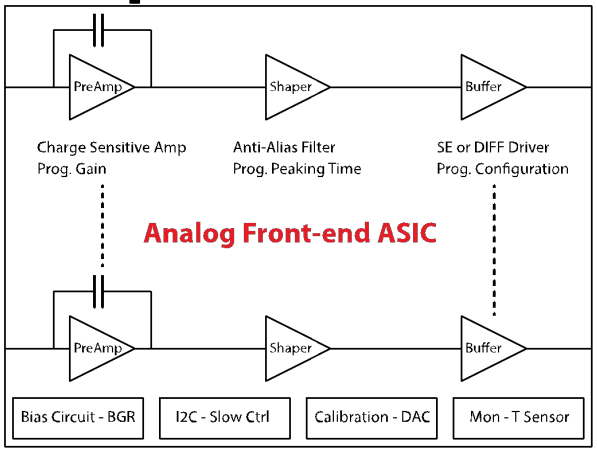
Integral System Design



- **Leverage of ATLAS and DUNE FD1/FD2**
  - Integration of cold front-end electronics with detector electrodes is crucial
  - The ***power management*** is critical for the integration, since FCC-ee has more stringent requirements due to ***continuous high-rate readout***
- **FCC-ee noble liquid calorimeter readout system**
  - CFEB (Cold Front-End Board) → FE ASIC (+ ADC + Serializer?)
  - Cold cables → Differential (coaxial, optical?) → Samtec, Axon, Gore
  - Signal feed-through → Vacuum insulation, vacuum cable? → ATLAS like, DUNE like, CERN design
  - Front-end crate → Faraday cage extension
  - WFEB (Warm Front-End Board) → (ADC +) FPGA + OTx
  - Fiber optical links to DAQ → FELIX based triggerless readout

Advanced AFE for Noble Liquid Detectors





- **Leverage of DUNE FD1/FD2 and *LDRD 23-058***
  - Further development of 65 nm cold FE ASIC with shorter peaking time (< 250 ns) is important to ***FCC-ee*** (Z pole operation with very high luminosity > 10^{36} $cm^{-2}s^{-1}$ and short bunch spacing < 25 ns)
  - Continuous development of FE ASIC from ***LDRD 23-058*** (250 ns to 2 us peaking time) will benefit ***DUNE FD3*** (photon detection with better time resolution)
- **Analog front-end ASIC with multiple (16+) channels and programmability**
  - Integrated auxiliary circuits for direct application in detector systems
  - High performance ***analog front-end block*** for easy expansion to targeted design of ***future experiments***
- **Key features and challenges**
  - ***65 nm*** CMOS with ***thick oxide*** → Max Vdd (1.8 V, 2.5 V) to support extended ***dynamic range***
  - ***Fast*** peaking time (in the order of 10 ns) → support signal processing with stringent ***time resolution***
  - ***Low*** power consumption → support detector electrodes with ***fine segmentations***
  - ***Cryogenic*** operation with ***long lifetime*** → achieve optimum ***SNR***
  - Long term goals: fast front-end architecture (~***GHz*** bandwidth), high ***radiation*** tolerance → ***FCC-hh***

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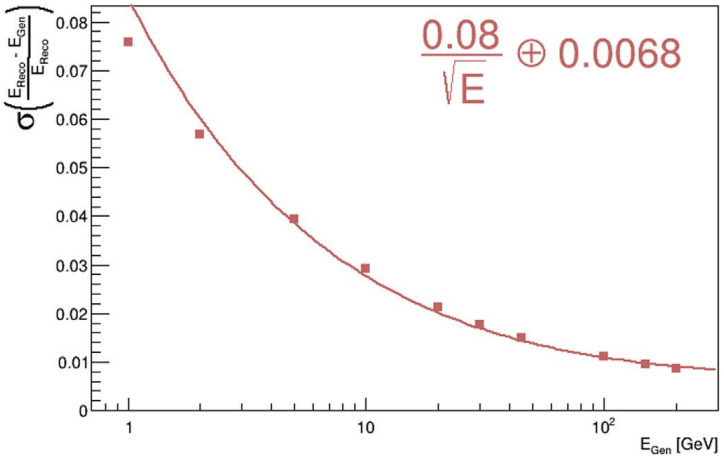
Detector Simulation

- **Leverage of ATLAS and *LDRD 23-049***
  - Detector simulation with different tracking options (silicon or low mass drift chamber, silicon wrapper as timing layer etc.) will guide the optimization of noble liquid ***calorimeter configuration*** and ***signal processing***
  - Close ***collaboration with the CERN*** team (cryogenics and magnet) is important



- **Preliminary simulations show excellent resolution**
  - Expect to use particle-flow and machine learning techniques for ultimate resolution
- **Use physics benchmark studies as inputs of detector requirements**
  - Further development of rudimentary simulation and reconstruction software
  - Many choices/optimizations to be exercised: optimal granularity, absorber geometry, absorber and ionization medium materials, warm or cold electronics, …

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Pre-Proposal

- **Take the integral system design approach to develop the full readout chain concept for the FCC-ee noble liquid calorimetry based on cold electronics**
  - ***Integral system design*** of detector electrode and front-end readout electronics
  - ***Cryogenic front-end ASIC*** development for the readout of PCB based electrode at FCC-ee rate
  - ***Simulation studies*** of detector performance for optimization of detector design

- **Project Team**
  - ***Integral system design*** → Veljko, Bo, Manhong, Sergio, Hucheng et al.
  - ***Cryogenic front-end ASIC*** → Prashansa (ASIC engineer), Chao (DUNE FD3), Jack, Niccolo' (DUNE FD3/nEXO), Shanshan et al.
  - ***Simulation studies*** → Postdoc (new hire), George (low mass drift chamber), Marc-Andre (BNL IB representative in DRD6), Scott et al.

Deliverables

- Take the integral system design approach to develop the *full readout chain concept* for the FCC-ee noble liquid calorimetry based on cold electronics, with inputs from both detector *simulation studies* and cryogenic front-end ASIC evaluation.

- *Prototype cryogenic front-end ASIC* with shorter peaking time (< 250 ns) produced in 65 nm CMOS technology.

- Evaluation of cryogenic front-end ASIC, detector simulation and optimization studies, full readout chain concept will be *reported in the FCC collaboration meetings*, e.g. FCC Physics Workshop, FCC Week and US FCC Workshop etc.

Milestones & Goals

- **Timeline and Milestones**

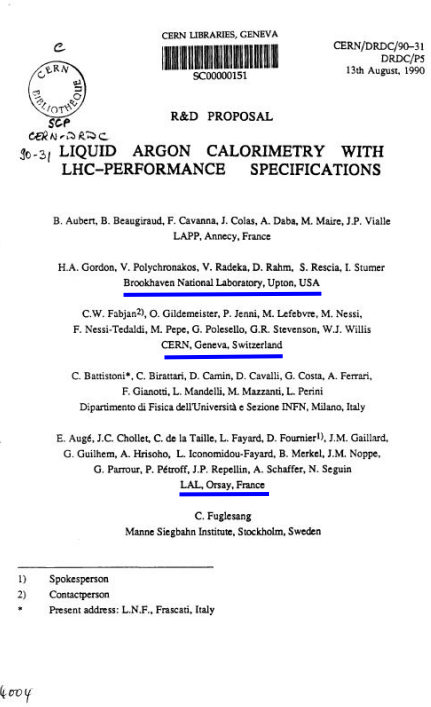
Activity and Milestone	FY2025	FY2026	FY2027
Readout system concept based on DUNE cold electronics	■		
Simulation studies of cryogenic front-end ASIC with short peaking time	■		
Implement effects such as crosstalk and noise in the detector simulation	■		
Publication, presentation of initial results	☆		
Power distribution and signal transmission schemes in the readout system design		■	
Prototype design of cryogenic front-end ASIC with short peaking time		■	
Study detector optimization related to electrode layout and tracking detector options		■	
Fabrication of cryogenic front-end ASIC with short peaking time		☆	
Prototype design and evaluation of cold readout electronics with PCB electrodes			■
Evaluation of cryogenic front-end ASIC with short peaking time			■
Reconstruction working sufficiently to study complex physics final states			■
Publication, presentation of readout chain concept and simulation software package			☆

- **Goals**
  - Take the integral ***system design approach*** to develop the ***full readout chain concept*** for the FCC-ee noble liquid calorimetry based on cold electronics
  - Getting ready to take significant ***leadership roles*** in the ALLEGRO CDR/TDR preparation and test beam module construction

Alignment with the Laboratory Mission and Vision

- **This proposal is well-aligned with the BNL vision to realize 10-year strategic plan for US particle physics in the context of a 20-year global strategy**
  - See recommendation 2 in 2023 P5 report
- **Return of Investment**
  - Noble Liquid Detectors R&D in the past decades have enabled BNL to take leadership roles in high priority HEP projects, such as ATLAS and DUNE
  - Advancement of Noble Liquid Detectors R&D will allow BNL to take new leadership roles in future HEP projects
    - US-FCC and ALLEGRO detector projects
    - DUNE FD3 and FD4 projects
  - Highly-granular noble liquid ECAL serves as the core of ALLEGRO detector, which opens great opportunity for significant contributions and leadership roles for BNL in other areas
    - Notably Outer Tracker and Trigger/DAQ systems
  - The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale
    - This LDRD will provide important investment for 3 years to enable BNL take leadership roles in FCC-ee detector construction project in strong collaboration with CERN

Long History of Collaboration with International Partners



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CERN/DRDC/90-31
DRDC/P5
13th August, 1990

R&D PROPOSAL

LIQUID ARGON CALORIMETRY WITH LHC–PERFORMANCE SPECIFICATIONS

B. Aubert, B. Beaugiraud, F. Cavanna, J. Colas, A. Daba, M. Maire, J.P. Vialle
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H.A. Gordon, V. Polychronakos, V. Radeka, D. Rahm, S. Rescia, I. Stumer
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C. Battistoni*, C. Birattari, D. Camin, D. Cavalli, G. Costa, A. Ferrari, F. Gianotti, L. Mandelli, M. Mazzanti, L. Perini
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Manne Siegbahn Institute, Stockholm, Sweden

1) Spokesperson
2) Contactperson
* Present address: L.N.F., Frascati, Italy

DRD 6: Calorimetry

Proposal Team for DRD-on-Calorimetry

January 15, 2024

Martin Aleksa[1], Etiennette Auffray[1], David Barney[1], James Brau[2], Sarah Eno[3], Roberto Ferrari[4], Gabriella Gaudio[4], Alberto Gola[5], Adrian Irles[6], Imad Laktineh[7], Marco Lucchini[8], Nicolas Morange[9], Wataru Ootani[10], Marc-André Pleier[11], Roman Pöschl[9], Philipp Roloff[1], Felix Sefkow[12], Frank Simon[13] Tommaso Tabarelli de Fatis[8], Christophe de la Taille[14], Hwidong Yoo[15] (Editors)

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[6]IFIC, CSIC-University of Valencia, Valencia, SPAIN
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[8]University and INFN Milano-Bicocca, Milano, ITALY
[9]IJCLab, Université Paris-Saclay, Orsay FRANCE
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[12]Deutsches Elektronen-Synchrotron DESY, GERMANY
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[14]OMEGA, Palaiseau, FRANCE
[15]Yonsei University, Seoul, SOUTH-KOREA

DRAFT

Contents

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- **1990 – RD3 proposal**
  - R&D proposal – Liquid Argon Calorimetry with LHC-performance specifications
  - LAr technology for collider
- **2024 – DRD6 proposal**
  - Work Package 2: Liquified Noble Gas Calorimeters
  - Proposal editors: Martin Aleksa (CERN), Nicolas Morange (IJCLab), Marc-Andre Pleier (BNL)
  - 7th FCC Physics Workshop
    - https://indico.cern.ch/event/1307378/contributions/5727834/attachments/2789875/4865189/ALLEGRO_Annecy_Juska_v1.pdf
- **CERN EP R&D has strong support of noble liquid calorimetry**
  - Led by Martin Aleksa (ATLAS LAr calorimeter PL, TC) with focus on PCB based electrode, magnet & cryostat
  - 2018 report: https://cds.cern.ch/record/2649646
  - 2023 proposal: https://cds.cern.ch/record/2850809?ln=de
  - 2024-2028 funding: 800 kCHF

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Financial

- **Proposed funding plan for 3 years**
  - 1 FTE ASIC EE
  - 0.8 FTE EE/ET
  - 0.8 FTE ME/MT
  - 1.5 FTE PD
  - 0.6 FTE RS
  - M&S ~ $120k including 1 MPW submission
- **Potential Future Funding**
  - The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale
    - US construction cost for offshore Higgs factory has a funding scale of $1-3B
  - Young investigators (Niccolo', Shanshan) are eligible to apply ECA in the coming years

Names of Suggested BNL Reviewers

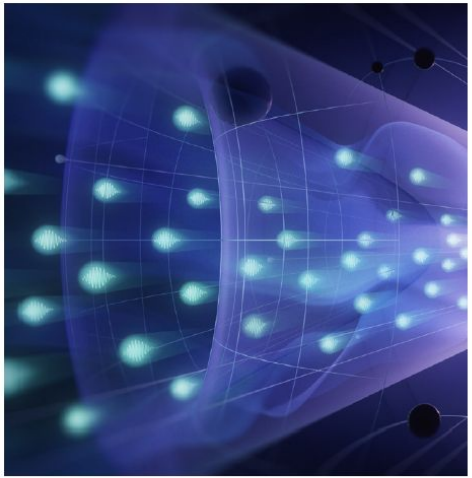
- Grzegorz Deptuch
- Steve Kettell
- Xin Qian
- Volodya Tishchenko
- Brett Viren

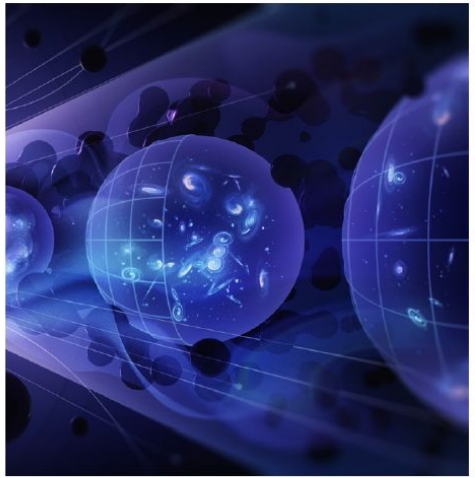
Summary

- **R&D of noble liquid detector in the past decades has successfully flourished BNL HEP program in both energy frontier and neutrino frontier**
  - BNL has been leading the ***readout system design*** of large noble liquid detectors in the world
- **2023 P5 report offers an excellent opportunity to advance the noble liquid detector R&D for future HEP experiments, which is well aligned with the with the BNL vision for future HEP program**
  - LDRD-A proposal is to take the integral ***system design approach*** to develop the ***full readout chain concept*** for the FCC-ee noble liquid calorimetry based on cold electronics
- **Broader impacts**
  - Will continue to maintain and advance BNL international leadership in noble liquid detector design, cold electronics development, detector performance studies and physics analysis in HEP experiments

Backup Slides

2023 P5 Report





Decipher the Quantum Realm

- Elucidate the Mysteries of Neutrinos
- Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

- Search for Direct Evidence of New Particles
- Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

- Determine the Nature of Dark Matter
- Understand What Drives Cosmic Evolution

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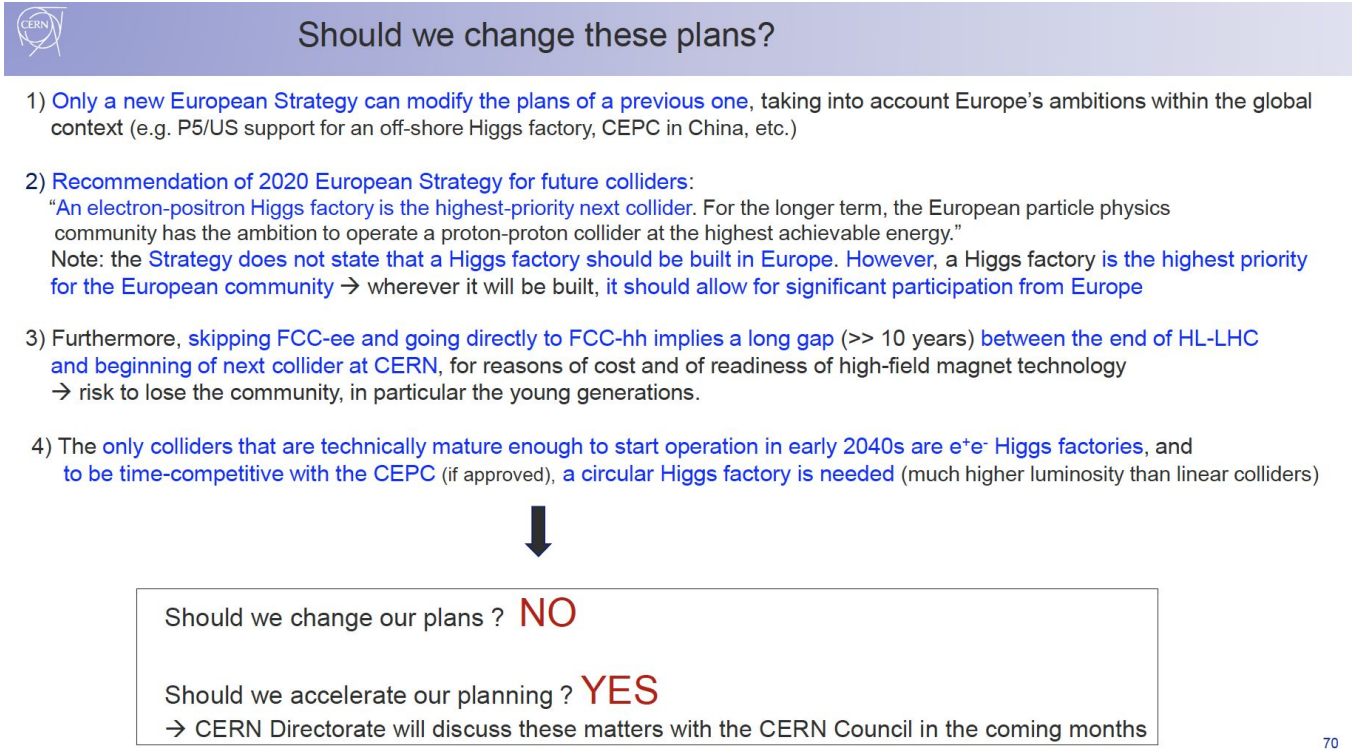
FCC Plan at CERN



- **2024 CERN DG New Year Presentation – Jan 25, 2024**
  - https://indico.cern.ch/event/1367641/

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FUTURE CIRCULAR COLLIDER

FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

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GEM Readout Electronics System with *Cold Electronics*

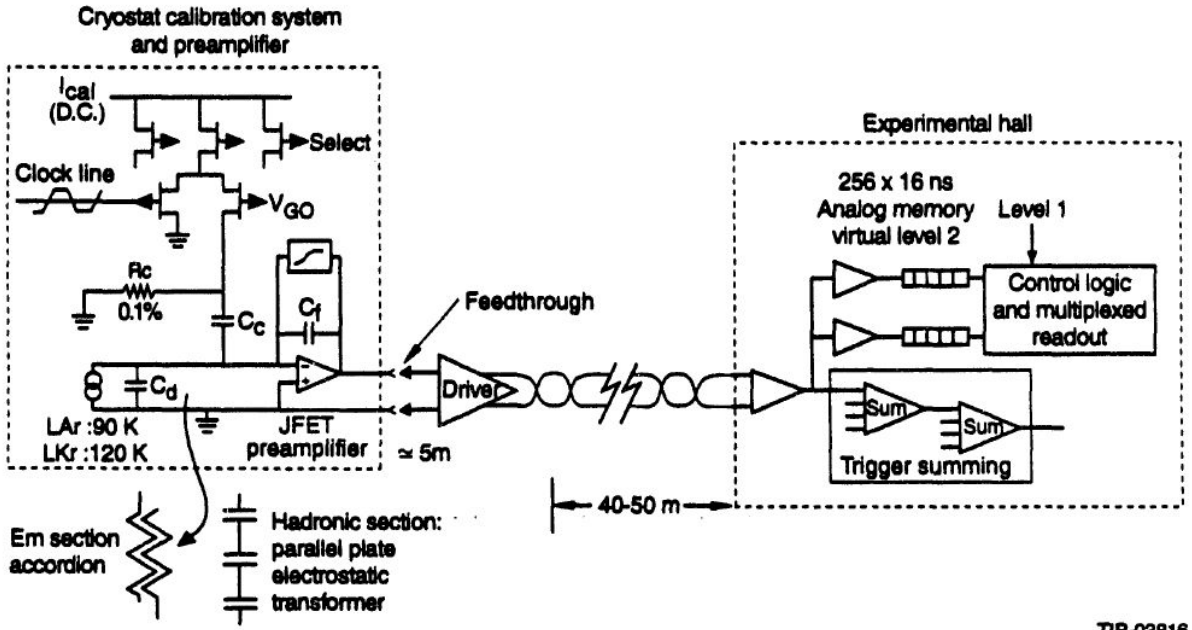
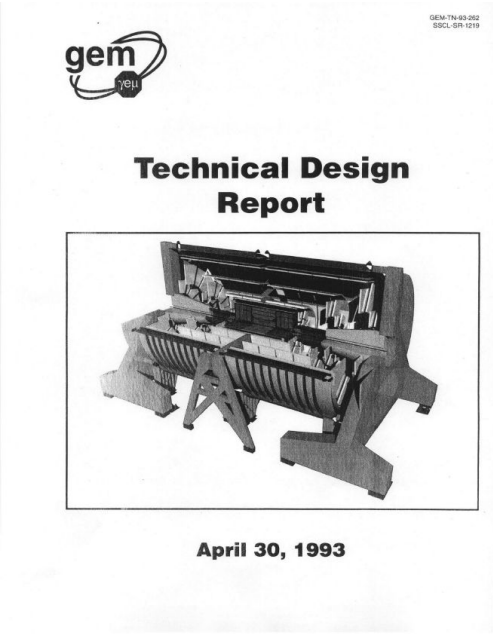


FIG. 5–32. Calorimeter readout chain.



- ***Liquid Krypton Calorimeter readout chain in 1993 GEM Technical Design Report***
  - GEM-TN-93-262
  - SSCL-SR-1219

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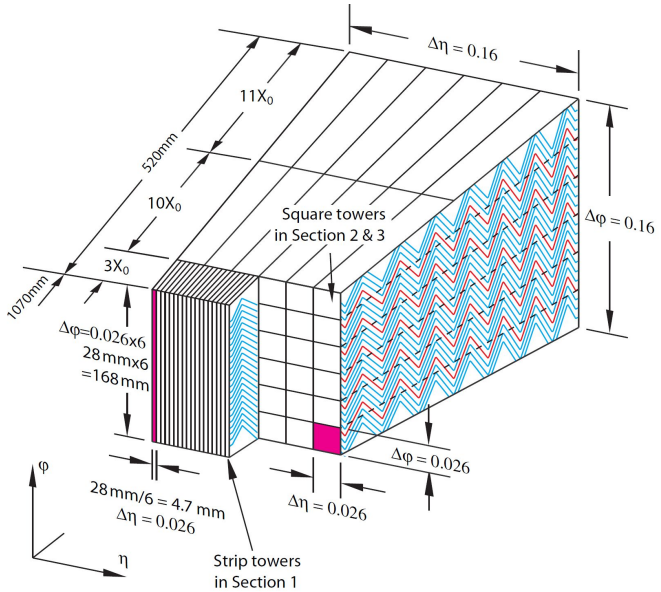
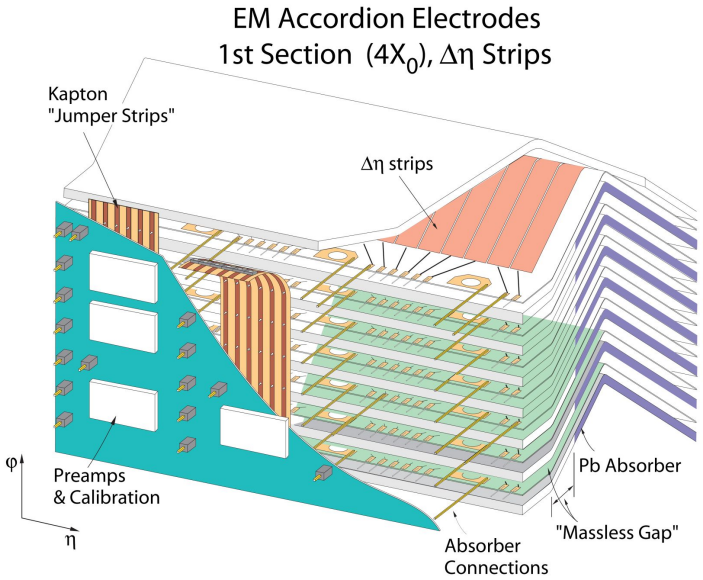
From GEM LKr to ATLAS LAr Calorimeter





- **In case one doesn't know where ATLAS LAr calorimeter drawings are coming from…Bo**
- **1994 NIM papers – Veljko, Hong and many BNL colleagues**
  - https://doi.org/10.1016/0168-9002(94)90085-X
  - https://doi.org/10.1016/0168-9002(94)91157-6

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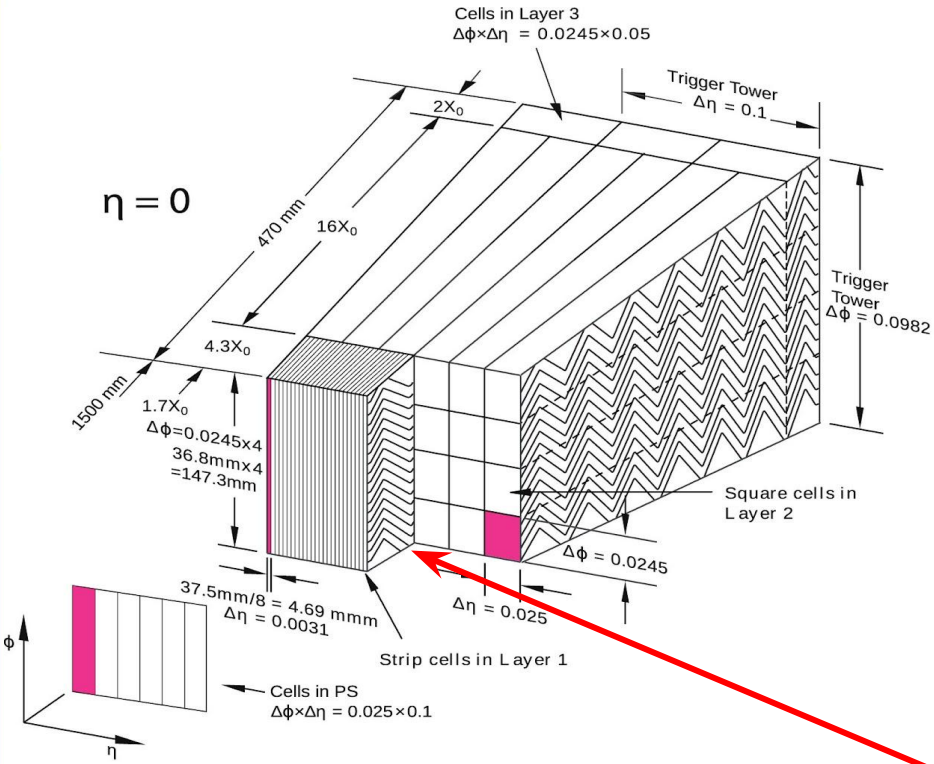
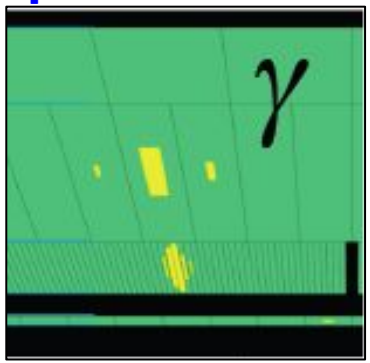
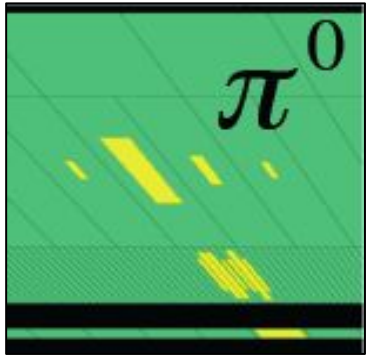
Design of LAr Calorimeter



- Accordion-shaped electrodes with pointing feature to ease segmentation
- Nearly hermetic coverage with 2π azimuthal angle
- Excellent energy resolution in *large dynamic range* (~50MeV to ~3TeV) and precision calibration (*< 0.25%*)





- Trigger Tower: ΔηxΔφ = 0.1x0.1, sum of 60 cells → stringent noise requirement
- Fine strip layer to allow efficient π^0 rejection or high γγ purity

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