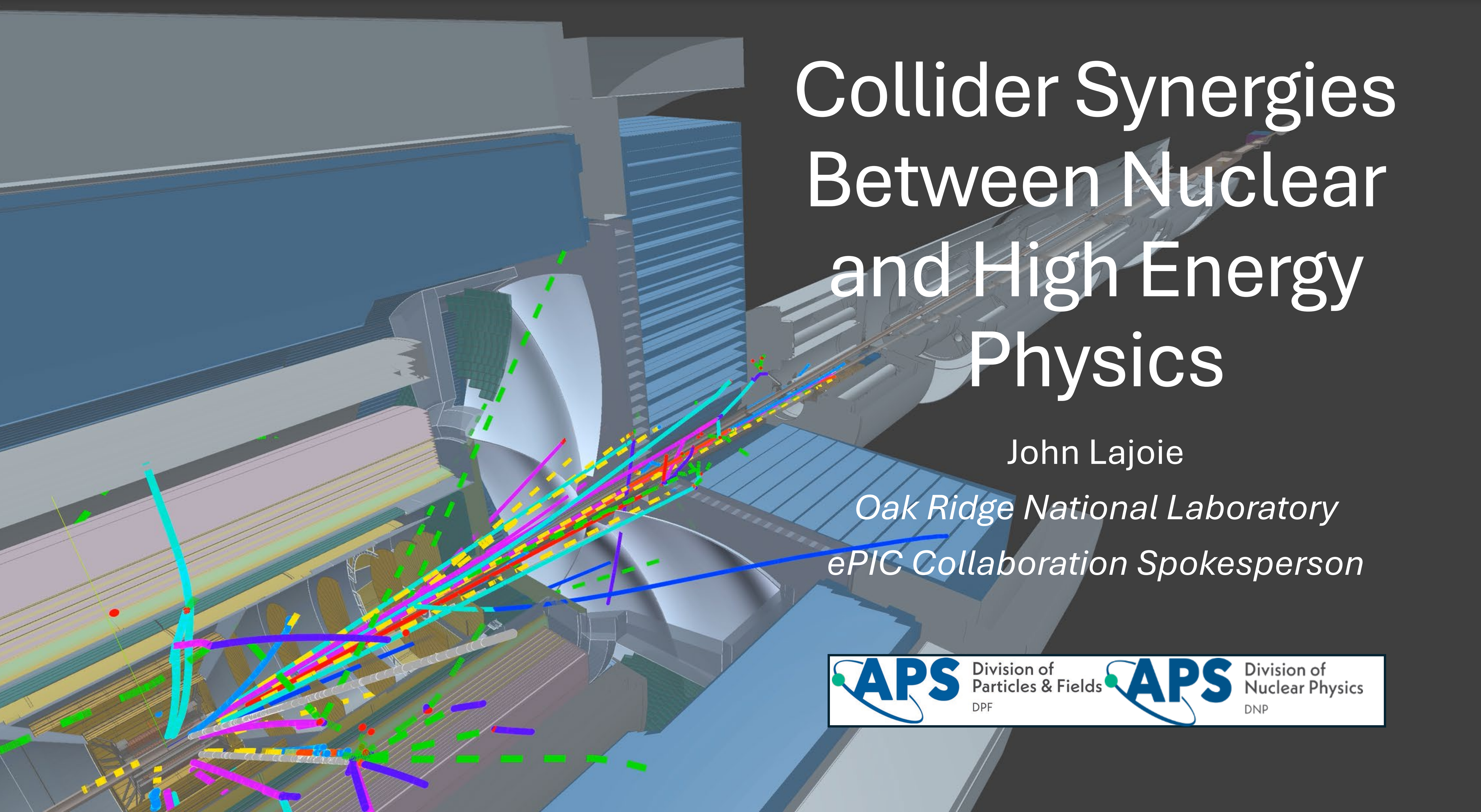


Collider Synergies Between Nuclear and High Energy Physics

John Lajoie

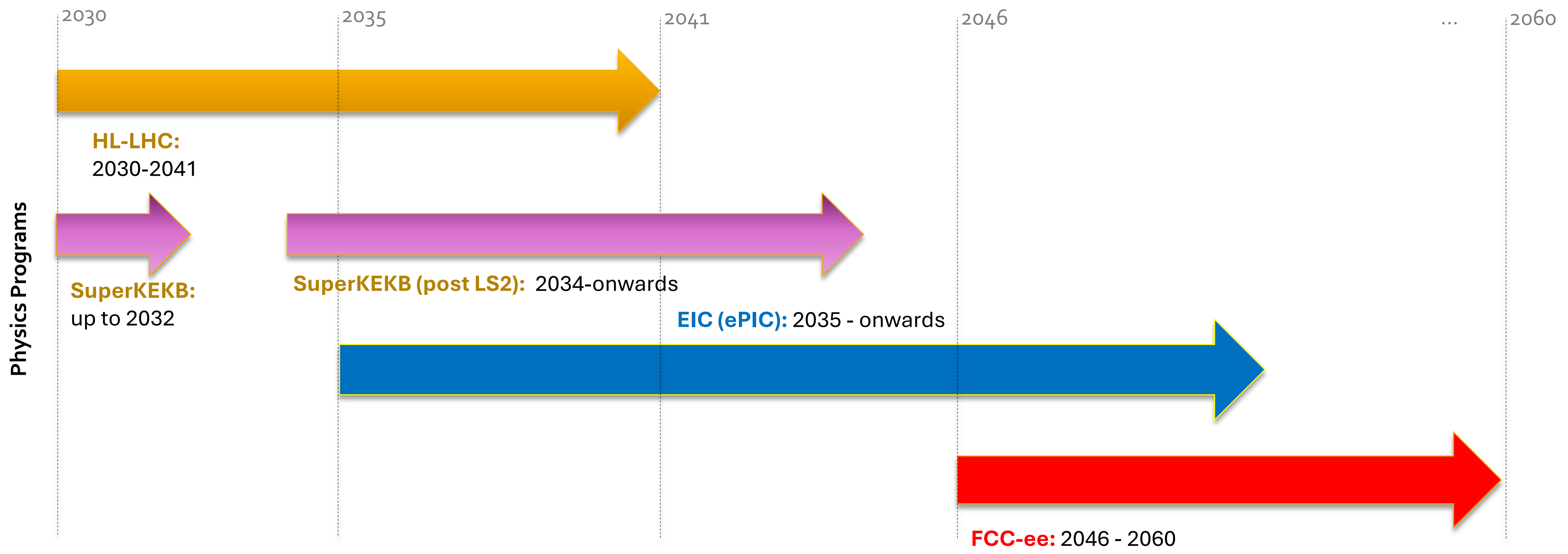
Oak Ridge National Laboratory

ePIC Collaboration Spokesperson

APS Division of Particles & Fields DPF

APS Division of Nuclear Physics DNP

Timelines for New Colliders

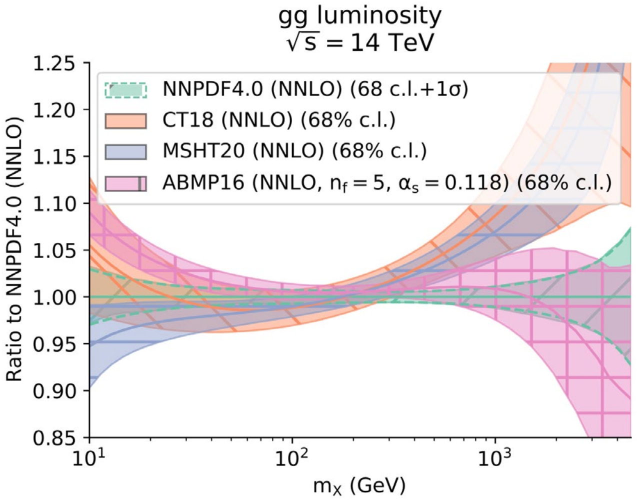


- **Phasing of different colliders allows for global R&D with current experiments/machines driving the deployment of technology**
    - HL-LHC, SuperKEKB (HEP) →EIC (NP) → FCC (HEP)
- **Partial overlapping and staggered start-up times allow for cross-fertilization of physics results**
- **Gap in time between in HEP/NP colliders allows for a balanced effort between communities**
    - For example, scientists can analyze LHC data while preparing for EIC
    - Scientists (especially early career) will be able to do research at EIC while preparing for FCC
    - Provides continuous opportunities for training the next generation HENP technical workforce

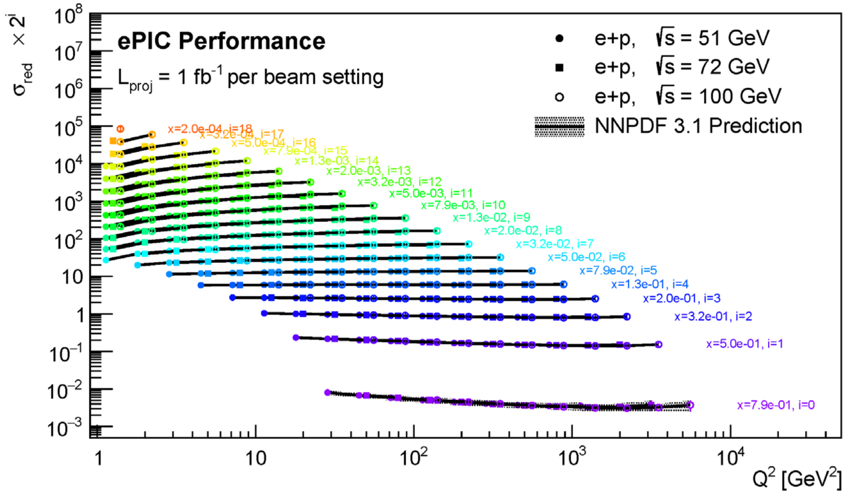
Synergies in Physics
Detector Technology Synergies
Accelerator Technology Synergies

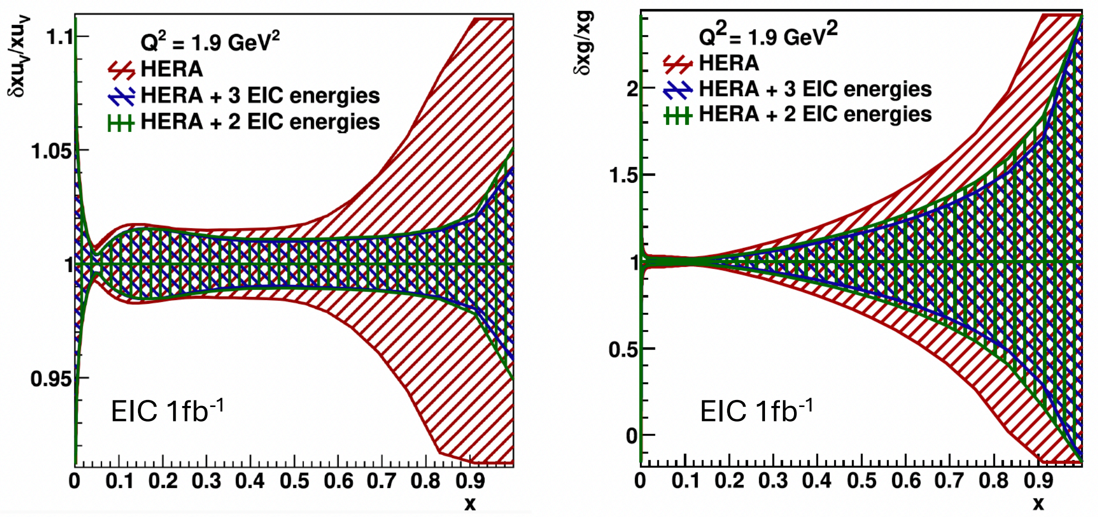
Physics Synergy Example - Proton PDFs

- $F_2(x, Q^2)$ **largely studied at HERA**
- Better precision often needed for precise calculations!
  - LHC impacts/needs PDF's mainly at large x (EIC coverage)
  - Not fully convergent between different global fitting groups
  - Large *x* BSM effects can hide



- Impact studies based on ePIC pseudodata and the conditions of the EIC early running (1 fb^{-1}) combined with HERA data:





arXiv:2602.00860

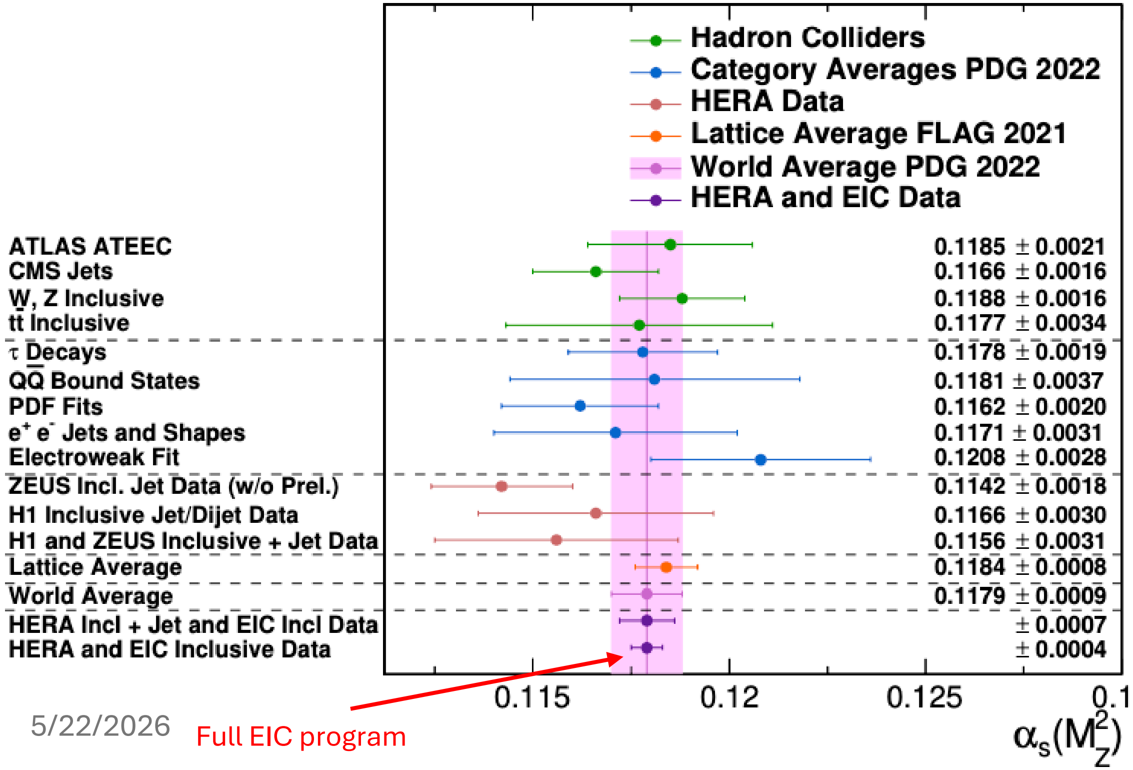
Physics Synergy Example - α_s

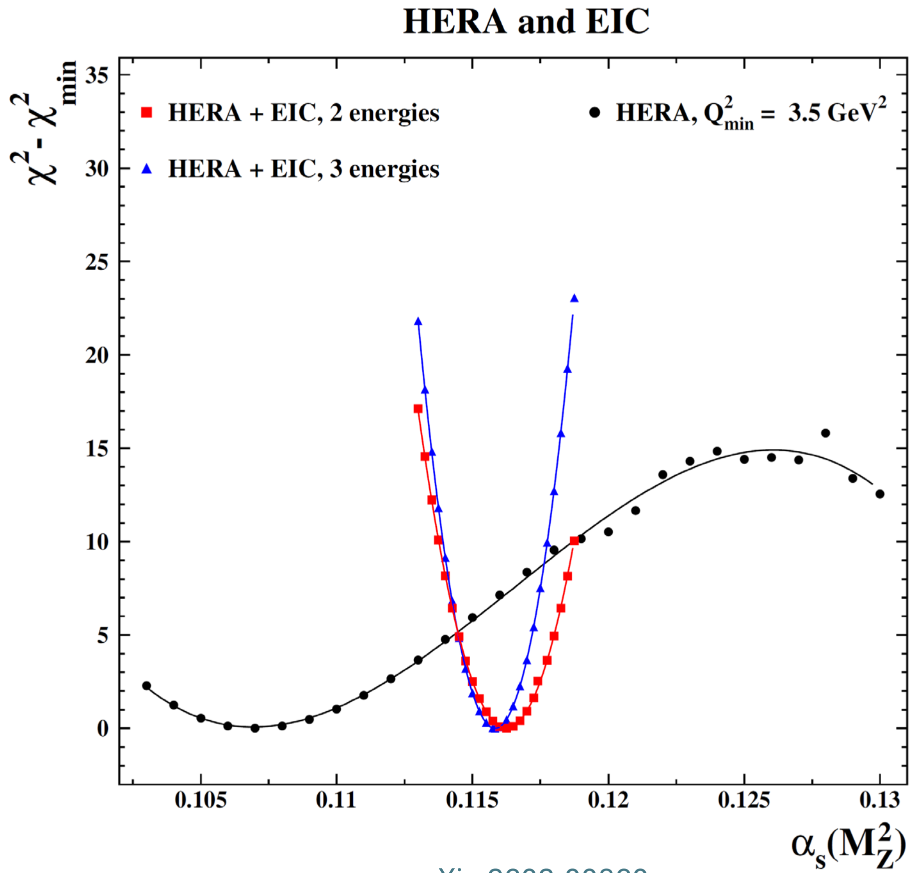
- HERA data alone (HERAPDF2.0) shows only limited sensitivity when fitting inclusive data only.
- Adding EIC (precision high x) data to HERA can lead to a precision a factor ~2 better than current world experimental average, and than lattice QCD average
    - Scale uncertainties remain to be understood (ongoing work)

2 EIC Energies (1fb^{-1} ea.): $\alpha_S(M_Z^2) = 0.1162 \pm 0.0008$

3 EIC Energies (1fb^{-1} ea.): $\alpha_S(M_Z^2) = 0.1158 \pm 0.0006$

EPJC (2023) 83: 1011





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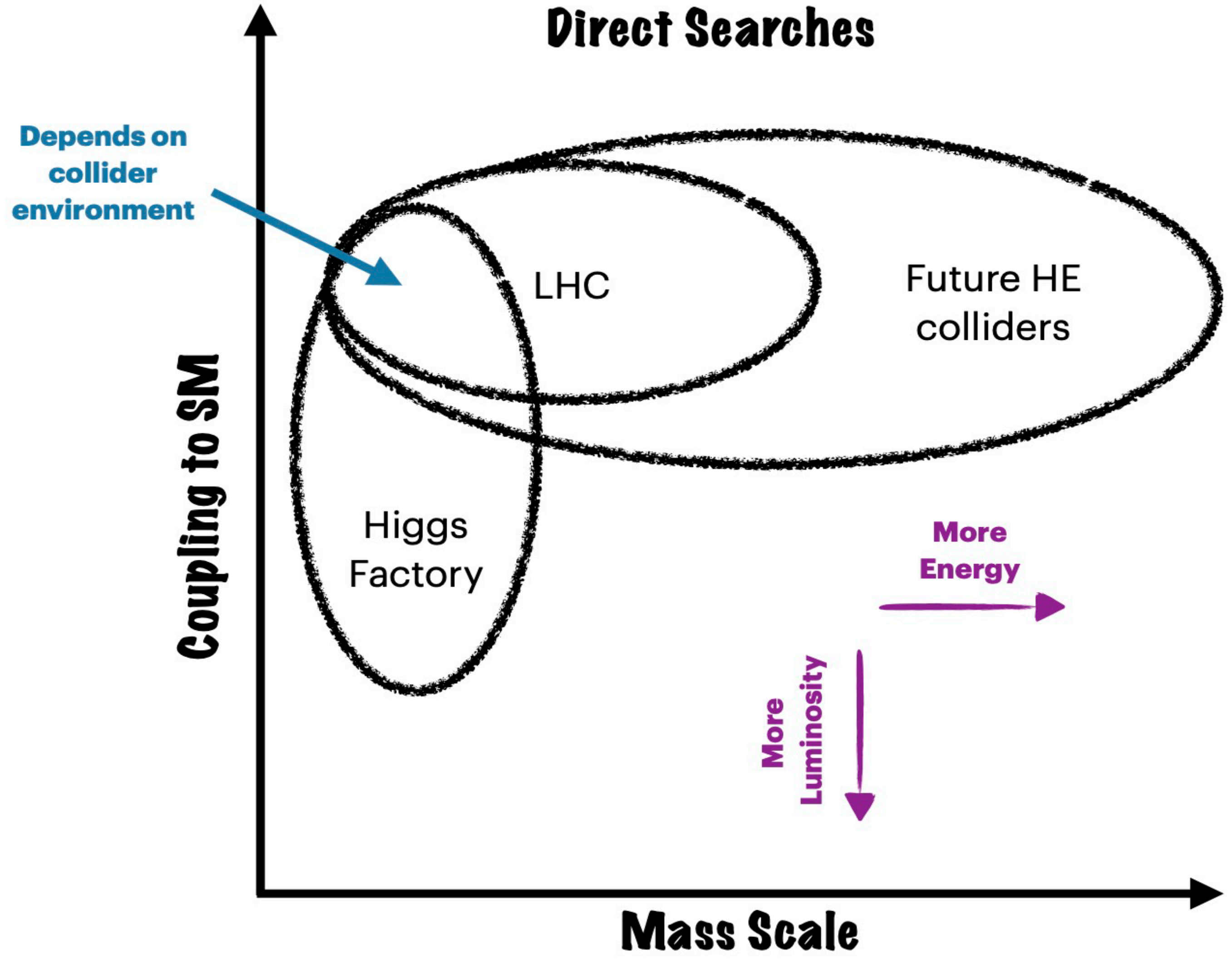
Search for New Physics



[The Snowmass 2021 Energy Frontier Report, arXiv:2211.11084]

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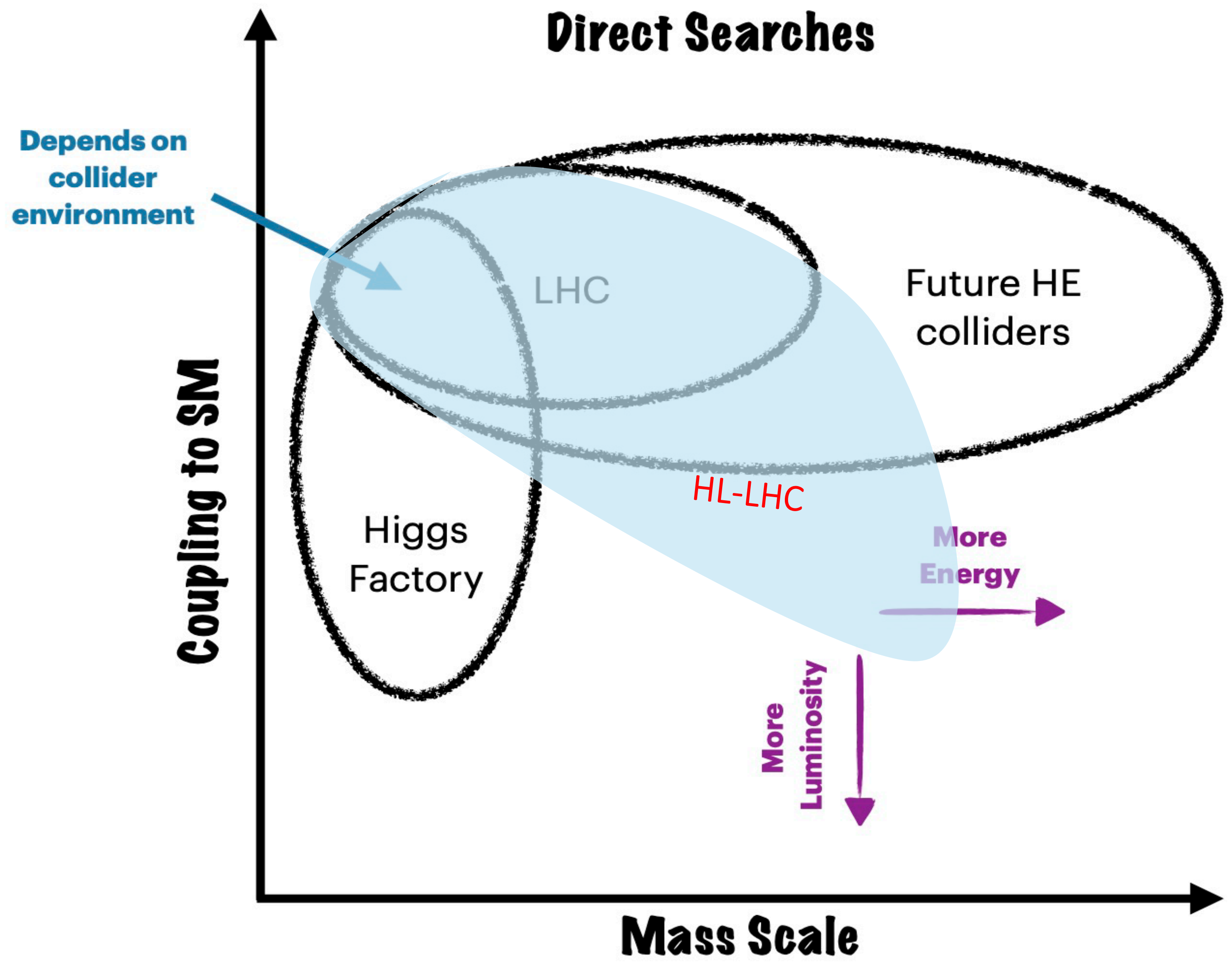

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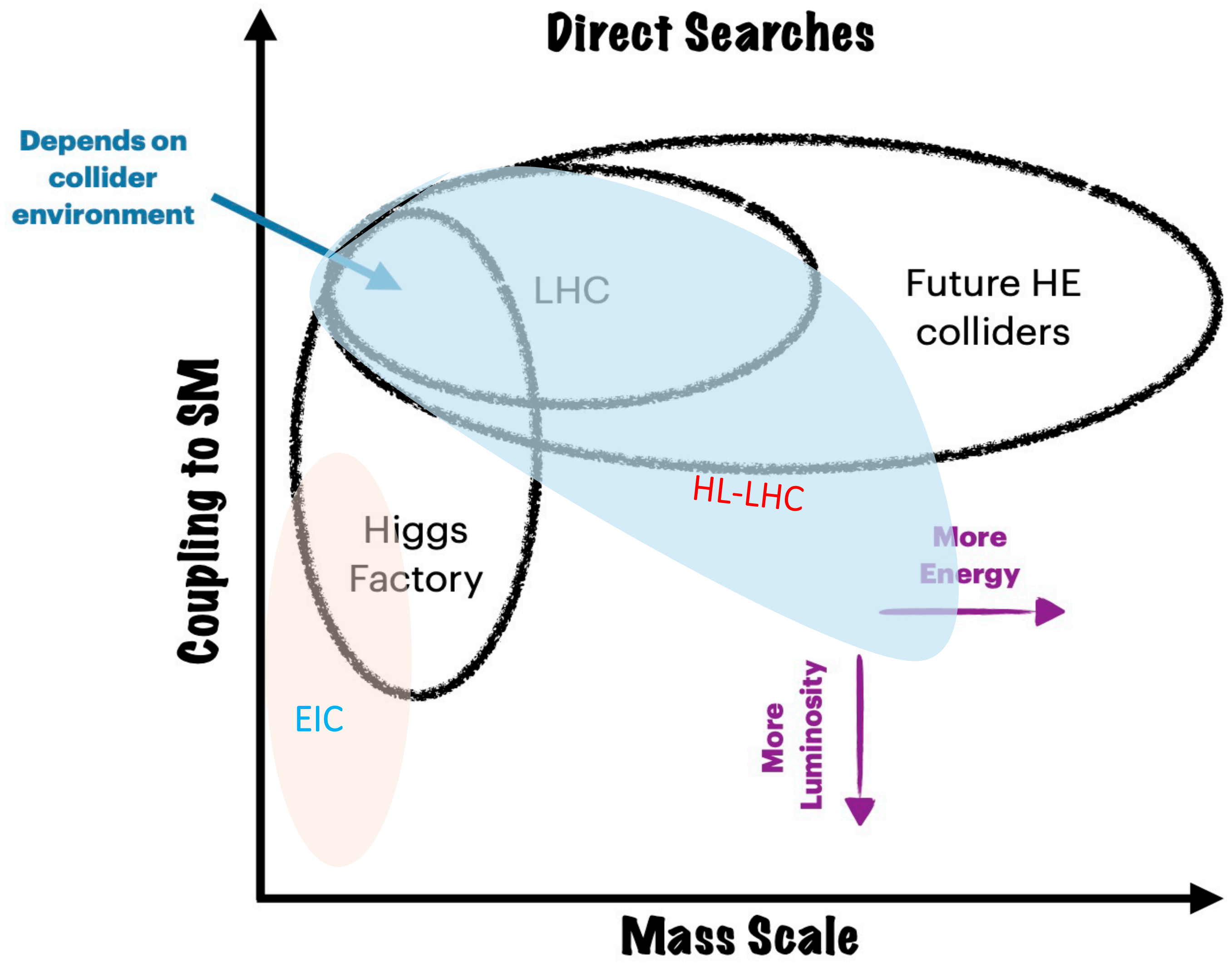
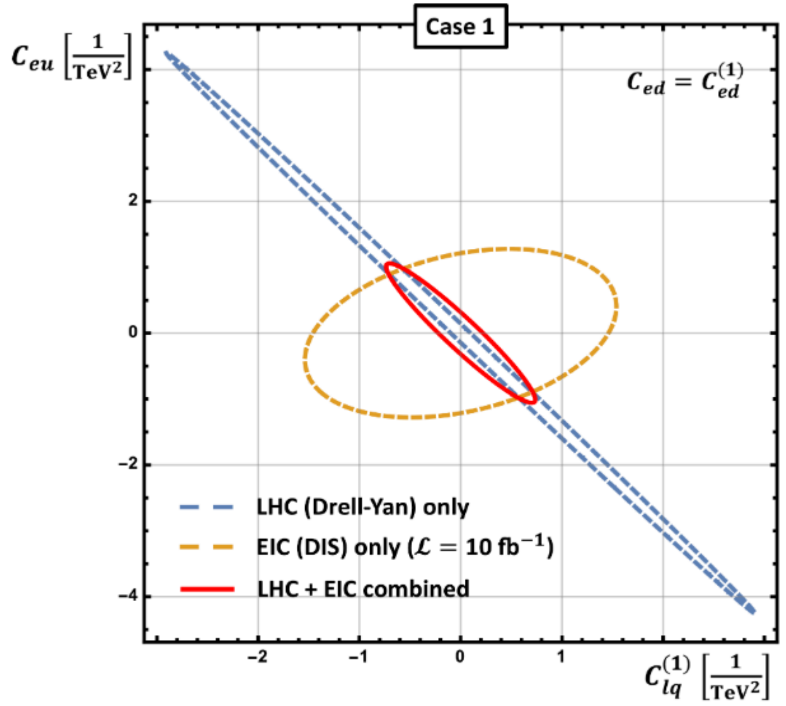


- Polarized DIS measurements at EIC can disentangle flat directions
- Complementary to LEP, LHC, and future high energy colliders
- **EXAMPLE:** Drell-Yan at the LHC provides strong constraints on EFT four-fermion operators, but can be **flat-directions**

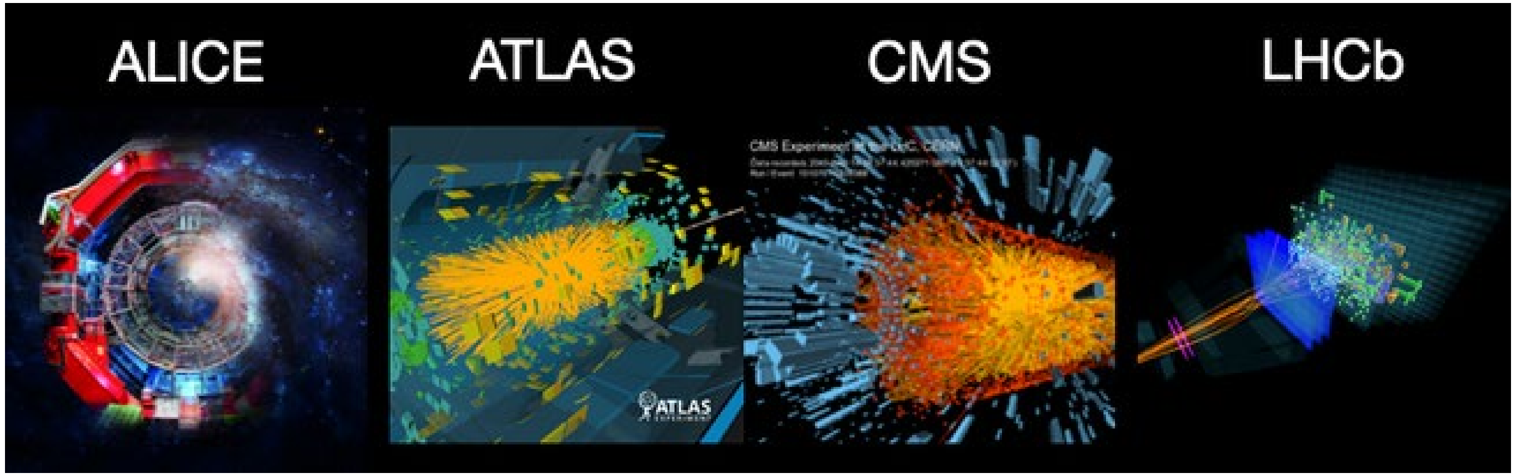
Boughezal, Petriello, Wiigand '20



MANY other examples: $sin^2\theta_w$, LFV, …

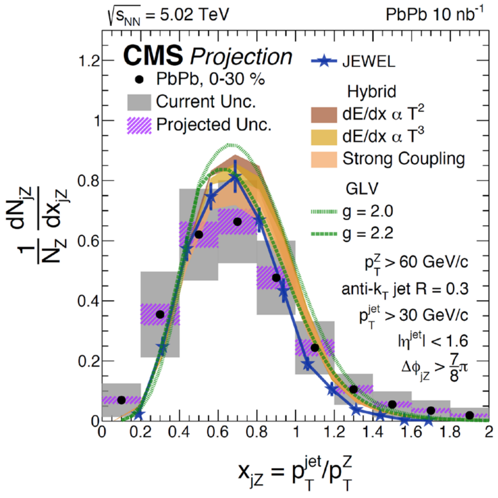
The Snowmass 2021 Energy Frontier Report, arXiv:2211.11084

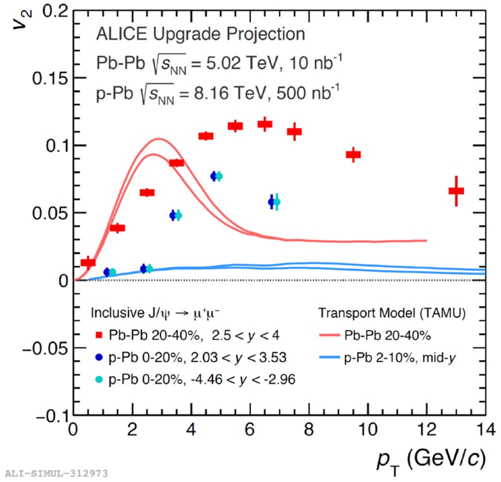
Heavy Ion Physics at the HL-LHC



Synergy Potential:

- Understanding hadronization (flavor dependent studies)
- Expanding QCD to high T and density (jets, heavy flavor)
- Novel quantum effects (entanglement, quantum fluctuations)





Datasets for ML/AI development and optimization

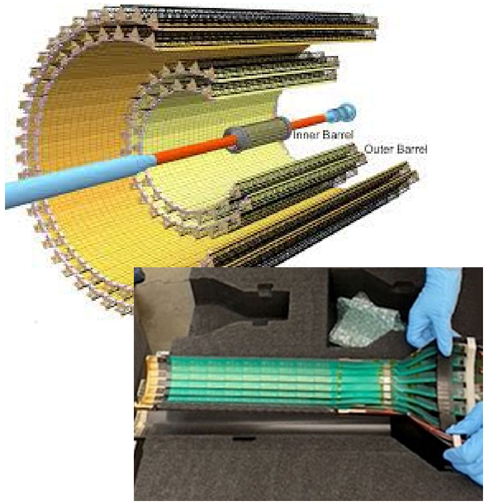
Workforce development for EIC and future colliders

Detector Synergy Example - MAPS

Monolithic Active Pixel Sensors (MAPS)

- **Low mass:** combine readout circuitry and sensing elements in a single and compact device
- **Commercial foundries** can be used
- **Cost savings**, i.e. in bump-bonding, cooling
- New MAPS process technology, e.g. 28 nm

First MAPS deployment was in the STAR exp. at RHIC



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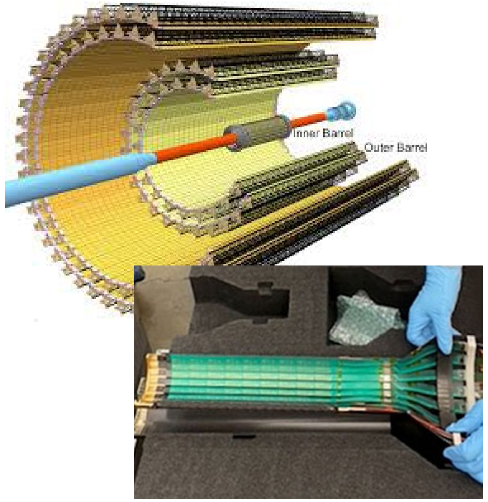

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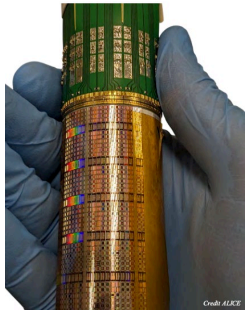
LHC's ALICE ITS3 for ultra-light Tracking



- Reduce **material thickness**
  Remove electrical substrate, mechanical support, and active cooling (air cooling) in detector acceptance
  - **MOSAIX device bent to the target radii** (Layer-0 as small as 19 mm)
  - Mechanically in place by carbon foam ribs

MOSAIX device

- Tower Jazz 65nm technology
- 50 μm thickness
- Stitching to create a wafer-scale chip of 26.6 x 1.95 cm^2
- Pixel size 22.8 × 20.8 μm pixel size
- In-pixel front end electronics
- Time resolution 0.1-2 μsec
- Power consumption <40 mW/cm^2

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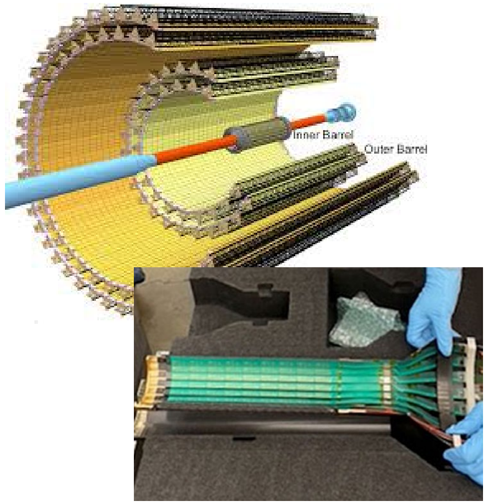

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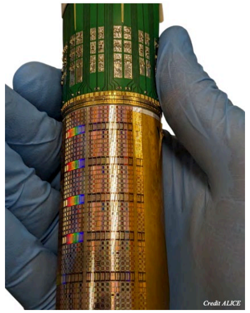

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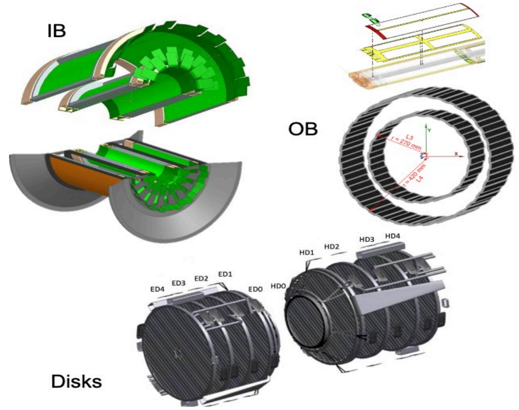
ePIC Silicon Vertex Tracker (SVT) is the innermost subsystem of the central detector and is **based on ALICE ITS3 design**



- **Barrel**
  - Inner Barrel: *curved, thinned* **MOSAIX device**
  - Outer Barrel: Large Area Sensor (LAS) derived from **MOSAIX** with a focus on large-area coverage in layers and disks
- **Endcap**
  - 5 Hadron Disk and 5 Lepton Disks (LAS Sensors)
- **Overall dimensions radius ~ 0.4 m, length ~ 2.2 m**

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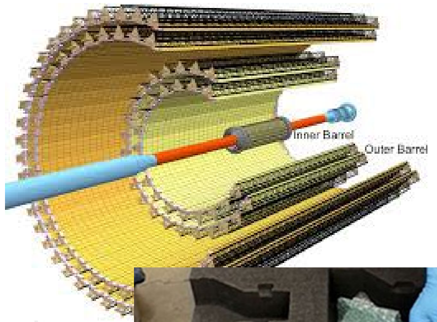

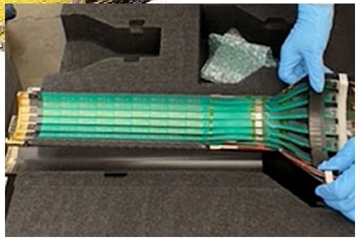

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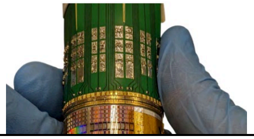

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Note also ITS3/LAS synergies with ALICE3.

All detector concepts for an FCC-ee detector have MAPS vertex detector (very similar requirements as at EIC).

Synergies not just in the sensors, but in carbon composite frame and support technologies, cooling, etc.

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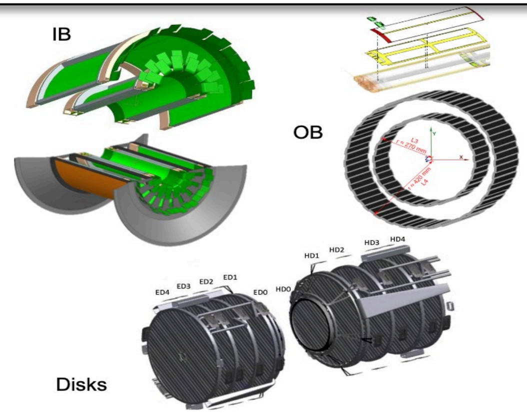
n



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Detector Synergy Example – ASICS

Evolution of readout ASICs from LHC to EIC, which in turn will benefit future experiments

ALTIROC
for ATLAS HGTD
(for LGAD sensor)

ETROC
for CMS ETL
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HGCROC
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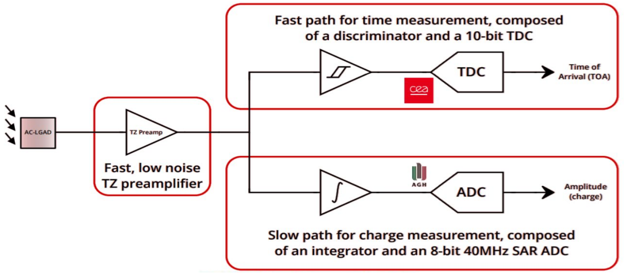
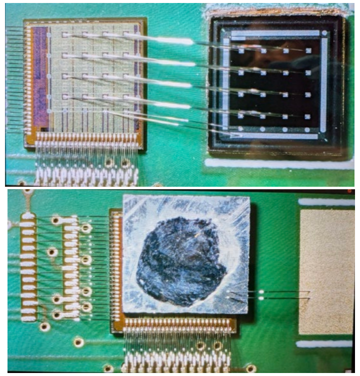


- 130 nm CMOS
- **500 x 500 μm² pixels**
- ~30 ps time resolution
- Low power ~ 1mW /ch
- Use signal signal sharing in AC-LGAD: **TDC data and 8 ADC values**



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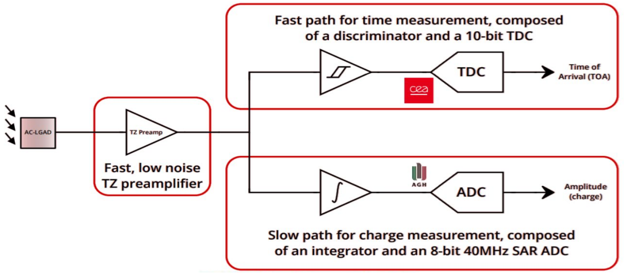

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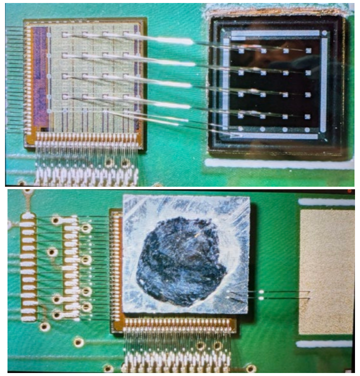

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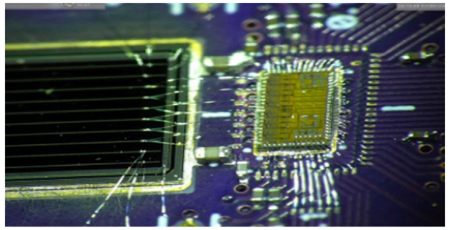

- 65 nm CMOS
- **0.5 mm x 1 cm strips**
- **Constant Fraction Discriminate (CFD) in chip**

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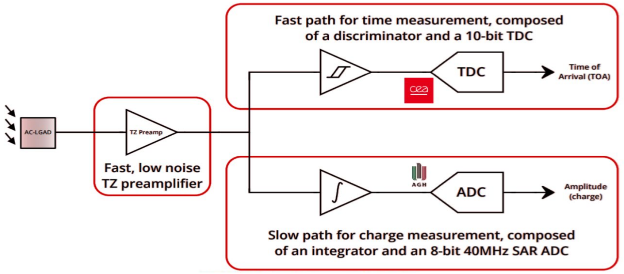

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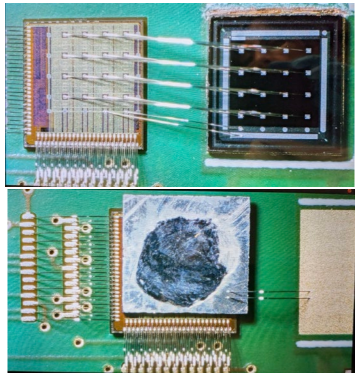

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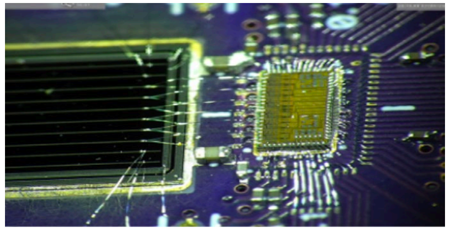

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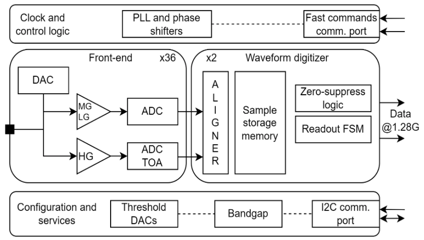
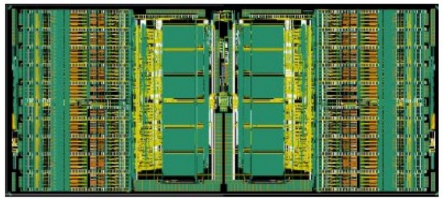
CALOROC
for ePIC *calorimeters*
(for SiPMs readout)



- **Charge and Time on a large Dynamic Range**
- 20 ps and < 500 ps for a MIP
- Low power
- Same ASIC structure (floorplan), ADC and TDC, readout, interfaces as HGCROC

HGCROC



Reference presentation

Other Detector Synergies

HEP-NP synergies have become stronger given the phasing of physics projects and the overlap in physics drivers

- Several technologies originated in HEP and were adopted and advanced at EIC with significant innovations
- Some technologies are driven by the EIC project given that HEP projects are farther in the future

Beam backgrounds

Solenoid Magnet

Micro-Pattern Gaseous Detectors (MPGDs)

Calorimetry

Low Gain Avalanche Diode (LGAD)

Photosensors

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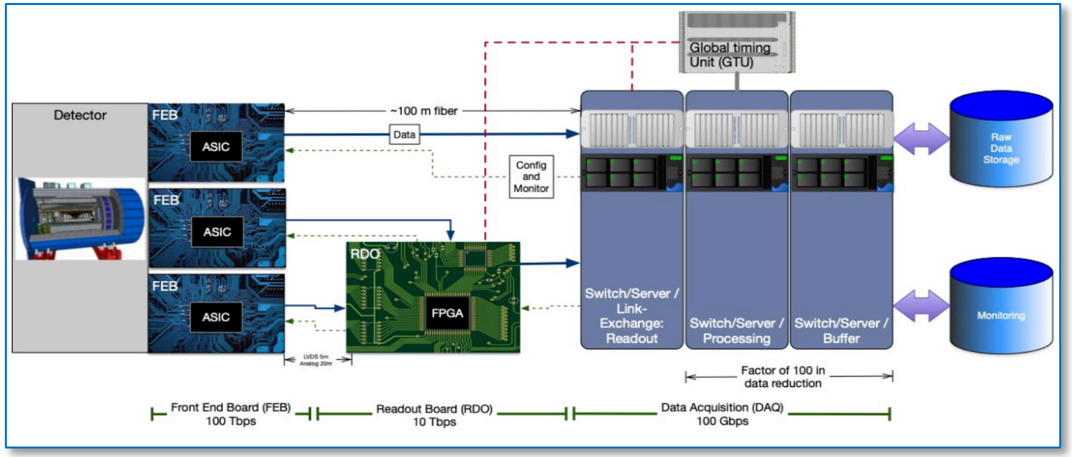
Photosensors → **Common R&D on photosensors in HEP and NP**

Computing and Data Analysis

Streaming Readout and DAQ

- High-speed data flow and zero dead time
- **sPHENIX** partial streaming, **LHCb** and **ALICE**
- Full streaming in **ePIC**



Streaming Computing Model

- Continuous calibration and alignment enables rapid delivery of scientific results.
- Resources organization across the computing hierarchy

AI/ML will be integrated into virtually every facet of the data processing pipelines of HEP/NP experiments

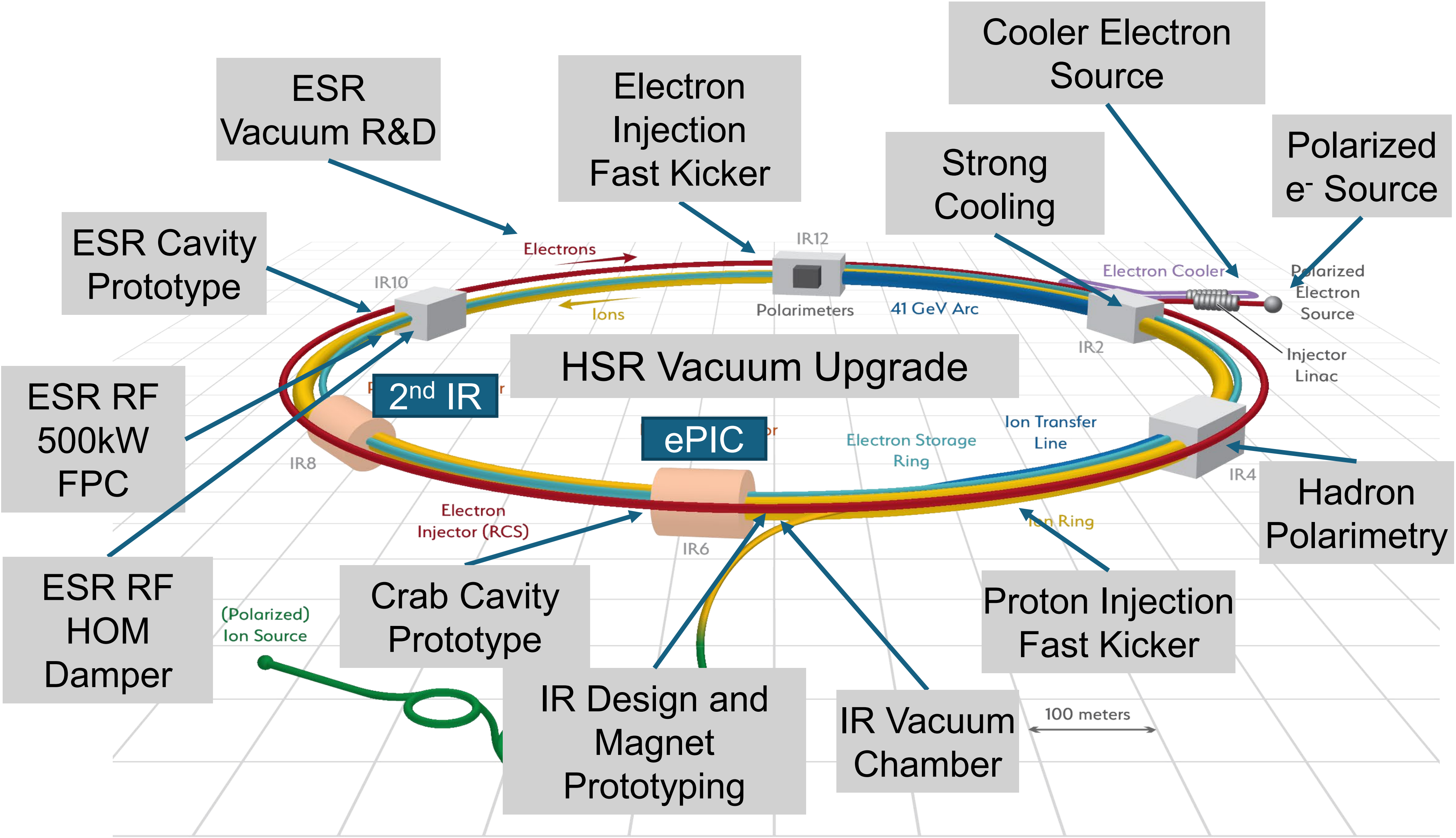
- EIC is being designed during the AI revolution and can take advantage of AI/ML since the design and R&D phase
- EIC may be the first large-scale detector optimized with machine learning.

AI4EIC workshop

AI/ML opportunities:

- **Adaptive Experimentation / AI-assisted Optimizations**
- **"Holistic" analysis:** full event information, and real-data
  - Simulations, Intelligent Data filtering, Particle Reconstruction and Identification (Calorimeters, Tracking, PID, Jets), Rapid Detector Diagnostics and Optimization, with systems capable of automatically Calibrating Detectors and Validating Data
- **Uncertainty Quantification** (event-level) and **Unfolding with Uncertainty**
- **Towards near Real-Time applications** (supported by Streaming Readout)

Accelerator Science and Technology Synergies



Accelerator Science and Technology Synergies

Synergies Between EIC and HL-LHC, FCC-ee:

Crab Cavities

- Operation with crossing angle
- Crab cavity design and operation
- Crab cavity low level RF control, beam loading, noise suppression …

Beam properties

- Beam-beam simulations and beam dynamics
- Electron cloud mitigation
- Ion sources
- Machine protection, collimation, beam-dump…
- Beam Instrumentation and Controls
- Vacuum liners and coatings etc.

Superconducting Magnets and Superconducting Radio Frequency Cavities

Machine Detector Interface

Synchrotron Radiation Simulations

Machine Learning and AI Integration

Conclusions

- Synergies between HEP and NP collider experiments in ***physics, detector technology and accelerator technology*** offer real opportunities that enhance both scientific missions.
  - This talk barely scratches the surface!

- Timescales in collider development allow for a ***virtuous cycle***:
  - R&D for current experiments/machines drive technology developments
- Cross-fertilization of physics results between HEP and NP drives intellectual development in both fields
- The staggered development of large facilities provides opportunities for scientists to analyze existing data while planning next-generation experiments.
  - A continuous development of the HENP technical workforce

Many thanks to Allesandro Tricoli, Elke Aschenauer, Anselm Vossen, Jin Huang, Megan Connors, and Rene Bellwied for material and discussions.

Additional Resources

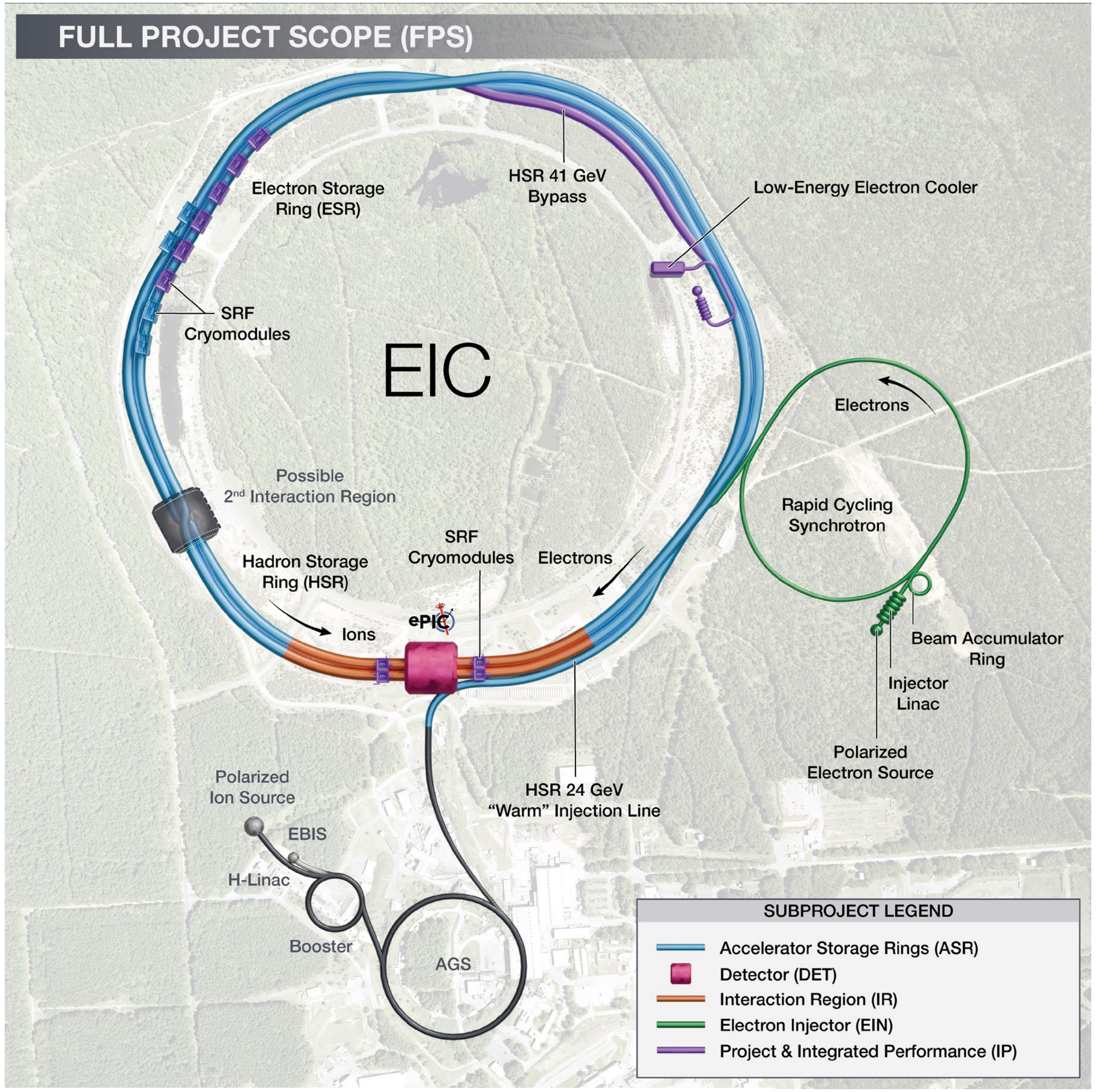
- Joint ECFA-NuPECC-APPEC Workshop "Synergies between the EIC and the LHC"
  - Jun. 19-21, 2022: https://indico.cern.ch/event/1170072/
  - Dec. 14-15, 2023: https://indico.desy.de/event/41404/
  - Sept. 22-24, 2025: https://indico.ifj.edu.pl/event/1417/
  - July 8-10, 2026: https://agenda.infn.it/event/49145/

- ePIC Input to European Particle Physics Strategy Update
  - https://indico.cern.ch/event/1439855/contributions/6461416/


BACK UP

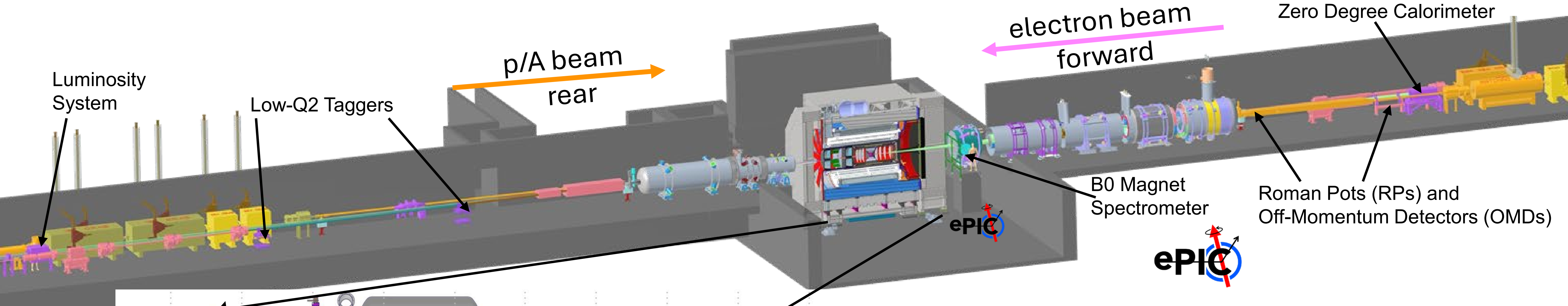
The Electron-Ion Collider

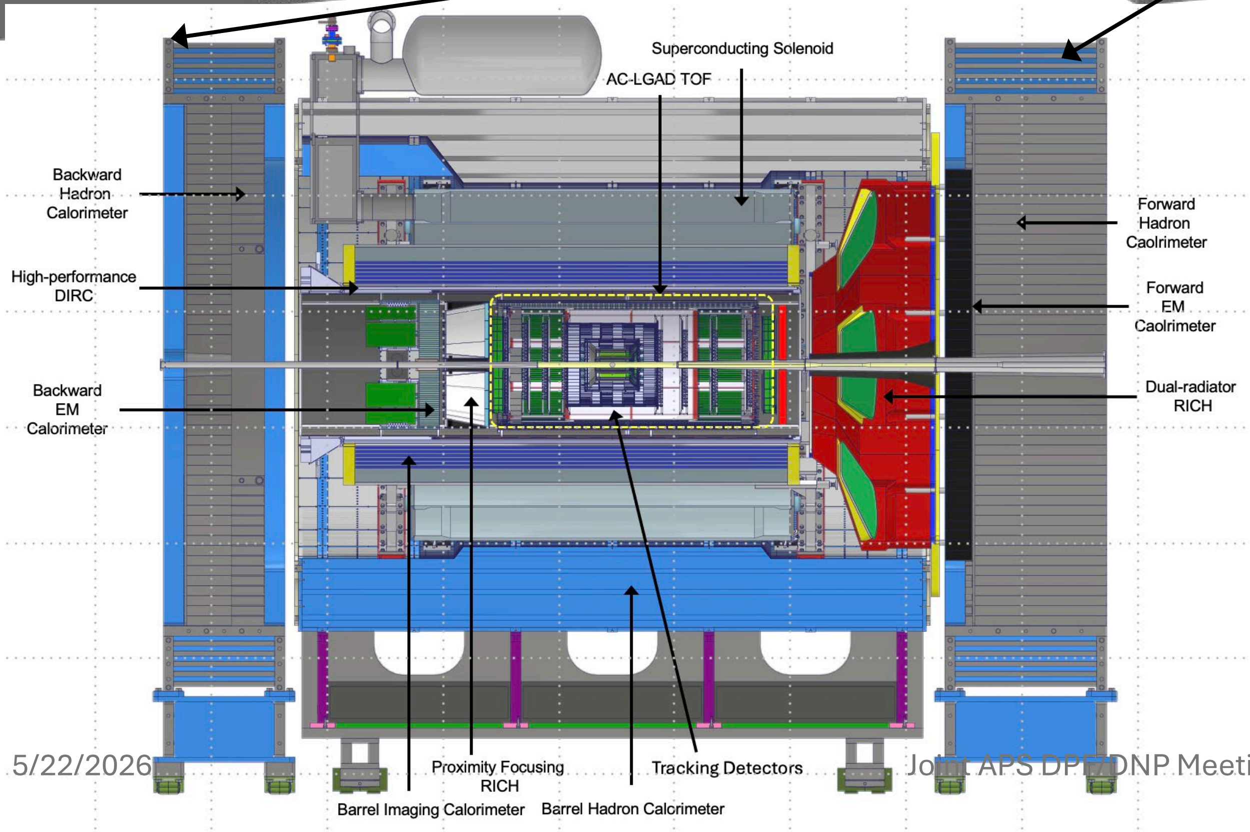
- A flexible facility that can deliver a variety of colliding species and energies with high polarization and luminosity.
- These are realized in the EIC as:
    - CMS energies from ~20-100 GeV (140 GeV upgradeable)
        - 41GeV, 100 to 275 GeV **hadrons**
        - Hadron species from p to U
        - **electrons** 5 GeV, 10 GeV
    - ~70% polarization for both electron and proton/light ions beams
    - Luminosities ~10^{33}-10^{34} /cm^2/sec
        - 10-100fb^{-1} integrated/year
    - Accommodate a future 2nd interaction region
- The EIC will be the only operating particle collider in the U.S. and the only large collider to be built in the next few decades.



The NAS physics requirements directly inform the EIC CD-0 Mission-Need Statement.

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





26 subsystems over ± 40 m

to measure particle momenta, energy and particle type

- 1.7T Solenoid (⌀ 2.84 m)
- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Micro-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxiliary detectors (Si + HCal + ECals)
- fully streaming readout electronics and data acquisition
  → integration AI/ML capabilities from the start
- electron and hadron polarimetry

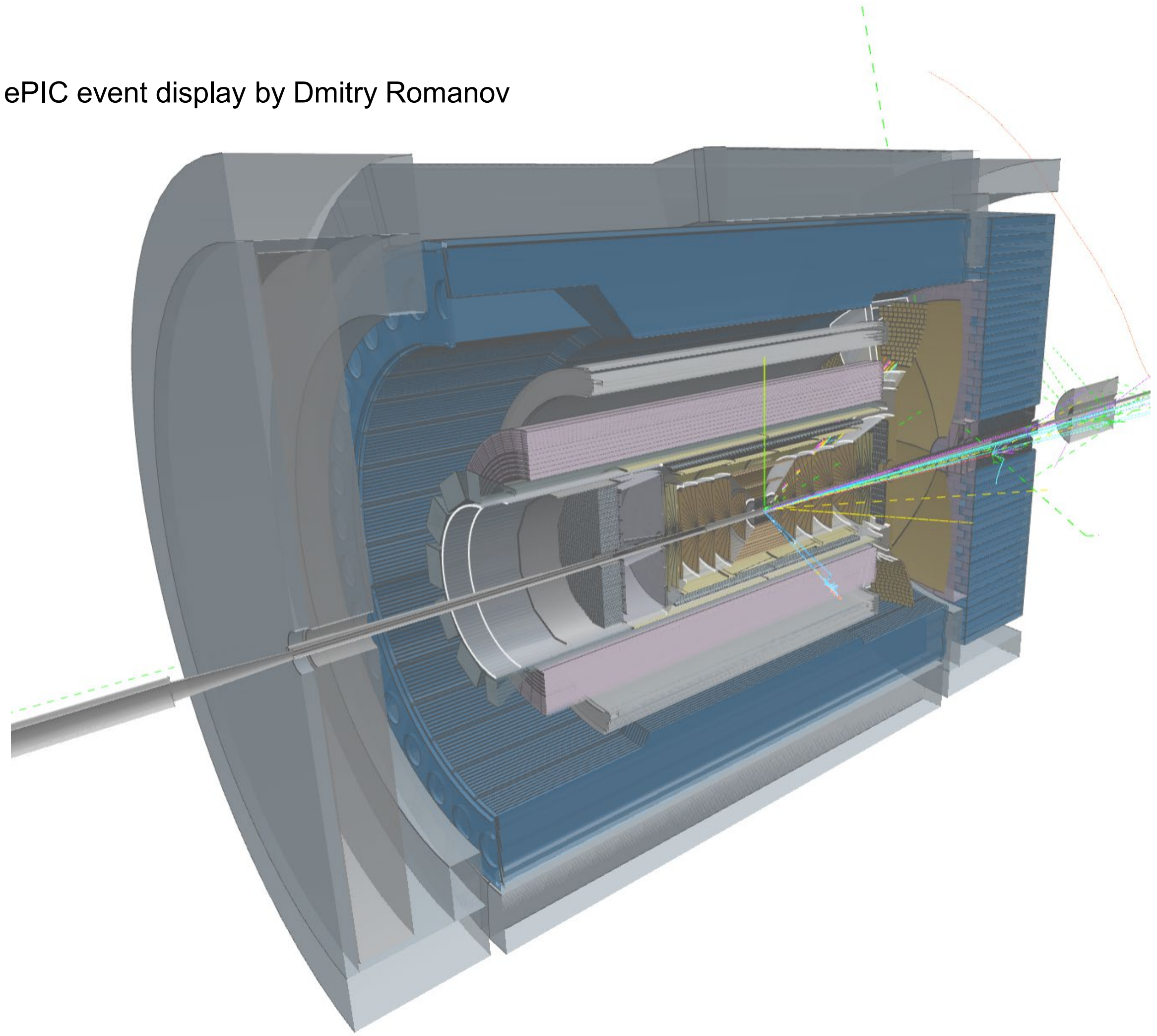
Integration, Installation and Infrastructure

Non-Beam Commissioning

See Tuesday WG6 talk by Alessandro Tricoli

Computing-Detector Integration

ePIC event display by Dmitry Romanov



Streaming Readout and DAQ:

- **High-speed data flow:** The front-end electronics are designed to support a total bandwidth of up to 50 Tbps, with over 3,000 fiber streams feeding data from the detector to the computing system.
- **Zero dead time:** By avoiding a traditional hardware trigger, the system eliminates dead time and allows for unbiased data collection.

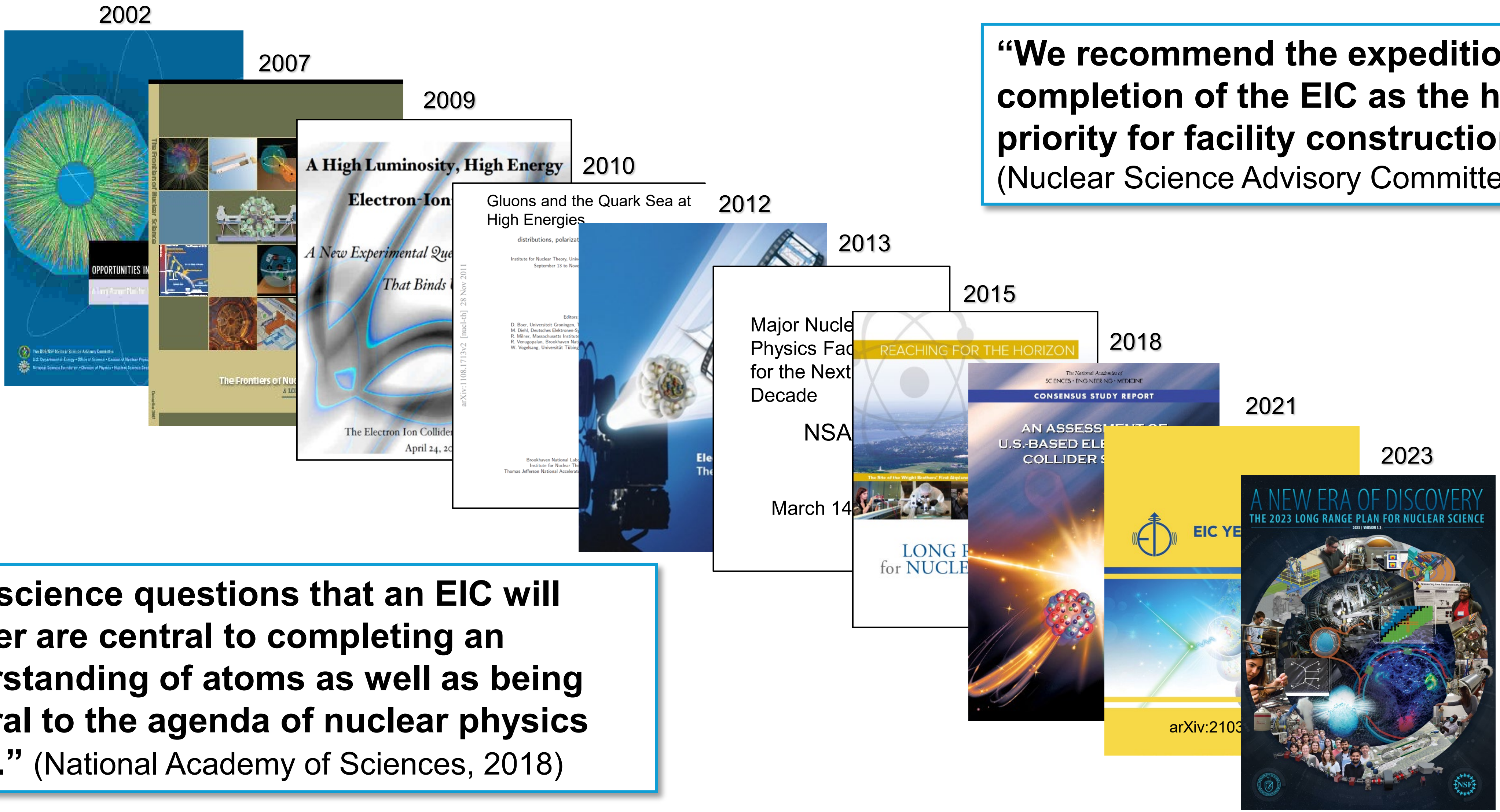
AI and ML in the Data Pipeline:

- **Intelligent data filtering:** AI/ML algorithms can select the most relevant collision events to study.
- **Real-time feedback:** AI can enable rapid detector diagnostics and optimization, with systems capable of automatically calibrating detectors and validating data.

Streaming Computing Model:

- **Continuous calibration and alignment:** Enables rapid delivery of scientific results.
- **Echelon Model:** Organizes resources across the computing hierarchy and enables international contributions.

EIC Scientific Case Built Over Decades



"We recommend the expeditious completion of the EIC as the highest priority for facility construction." (Nuclear Science Advisory Committee, 2023)

"The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today." (National Academy of Sciences, 2018)

EIC NAS Science Pillars

SPIN

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum

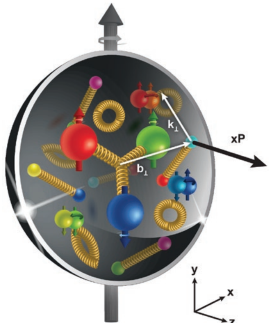
SPIN is one of the fundamental properties of matter.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

MASS

Does the mass of visible matter emerge from quark-gluon interactions?

Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called "QCD trace anomaly

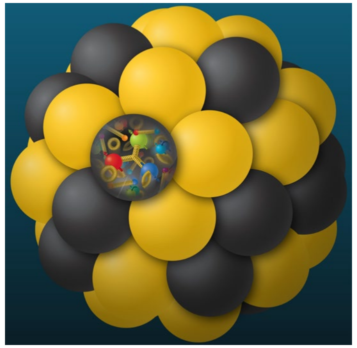


IMAGING

How can we understand their dynamical origin in QCD?
What is the relation to Confinement

How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

How do the nucleon properties emerge from them and their interactions?



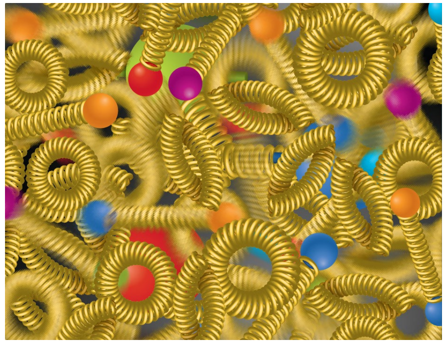
NUCLEI

How do the confined hadronic states emerge from quarks and gluons?

Is the structure of a free and bound nucleon the same?

How do quarks and gluons, interact with a nuclear medium?

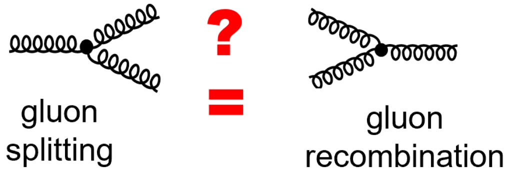
How do the quark-gluon interactions create nuclear binding?



GLUONS

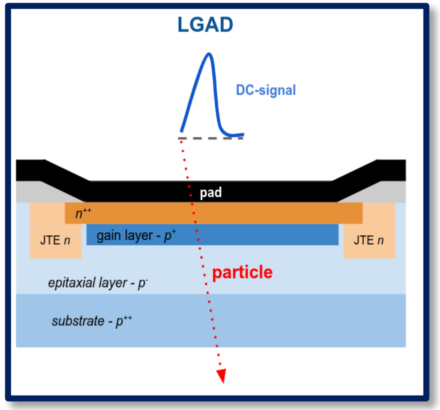
What happens to the gluon density in nuclei? Does it saturate at high energy?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?



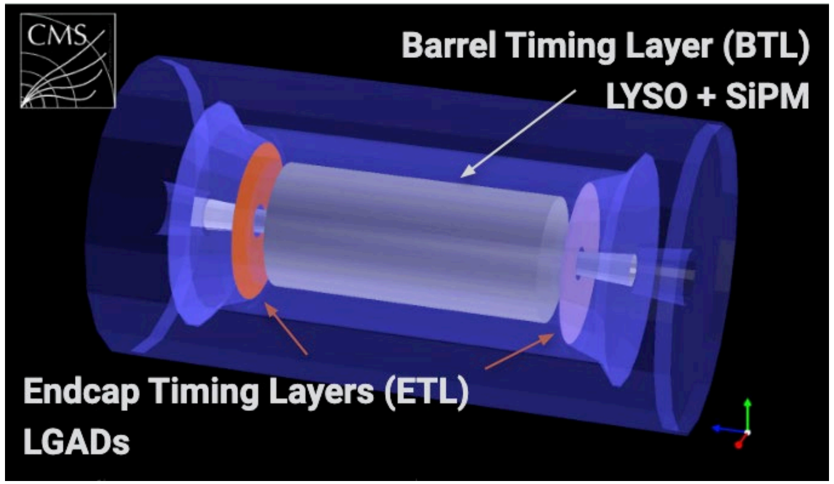
Synergy - LGADs

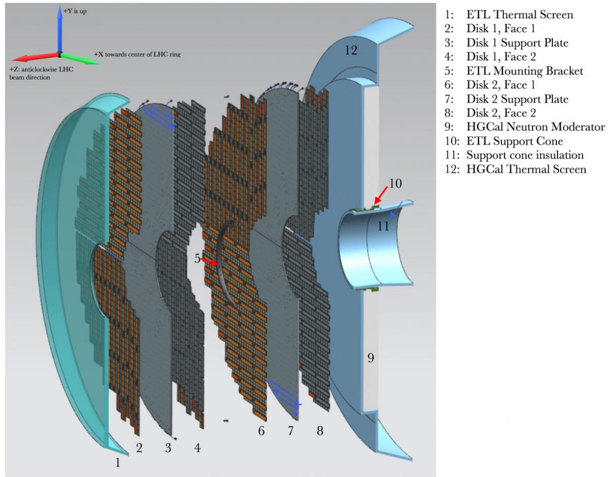
High electric field causes impact ionization by electrons in Silicon
➔ Gain (10x-100x)
➔ Fast-timing (~30 ps resolution)
➔ 1.3x1.3 mm^2 pads



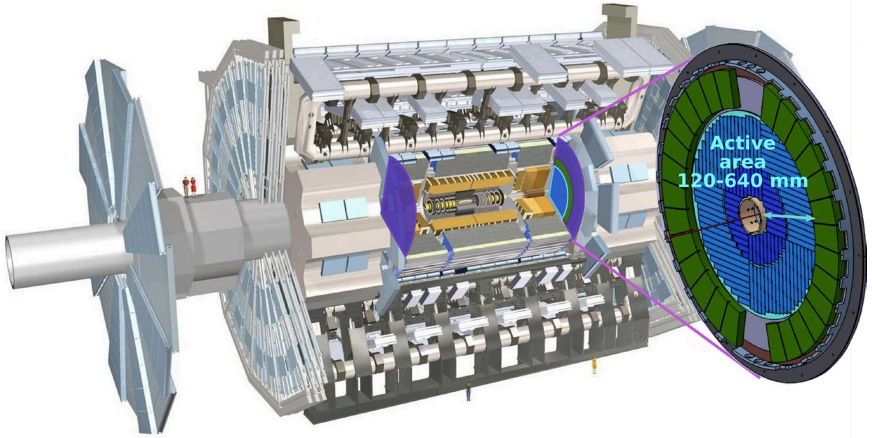
- **Low Gain Avalanche Diode (LGAD) R&D has had an explosion of interest in the last ~10 years since its first adoption by ATLAS and CMS for HL-LHC**
  - Pileup suppression
- **Many different LGAD technologies are being investigated**
  - Focusing on different challenges: radiation hardness, fill factor, timing, pixelation, photon detection
- **Several foundries in China, Europe, US and Japan**

CMS Endcap Timing Layer (ETL)

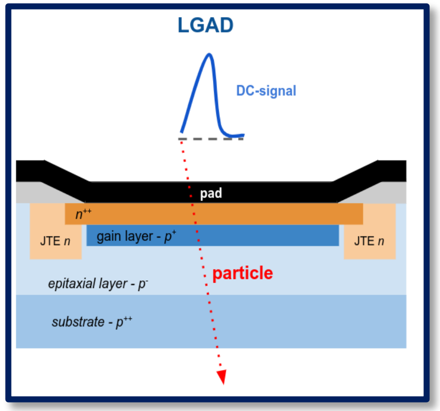




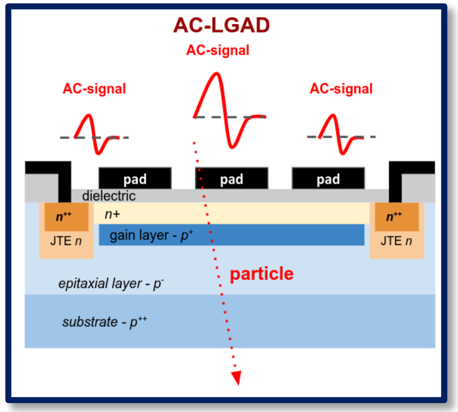
ATLAS High Granularity Timing Detector (HGTD)



Synergy - LGADs



Timing Only



Timing+Tracking

- **AC-LGAD:**
  - **Time-of-Flight** detectors to cover PID at low momentum
  - **Also provide spatial info for tracking**
  - **Resolution: ~30 ps, 30 µm** (with charge sharing)

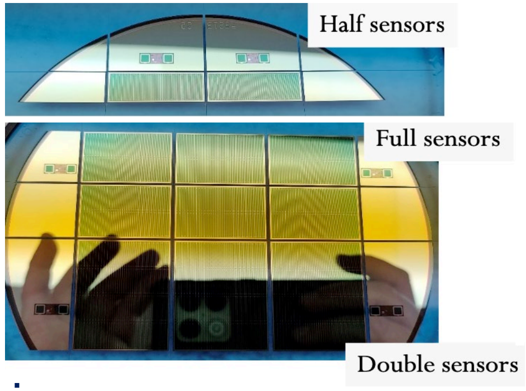
- **First deployment of AC-LGADs**
- **Largest AC-LGADs ever produced**

The ePIC detector at the EIC

- **4D tracking and Particle identification with Time-of-Flight (TOF)**
  - e/π/K/p at low/intermediate momentum
  - Good time resolution is needed
  - Barrel, end-cap and far-forward (luminosity Monitor, B-0, Roman Pots)

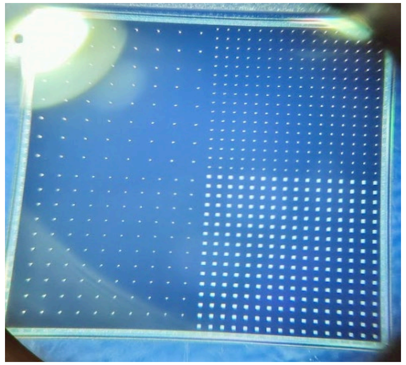
TOF layers based on AC-LGAD technology: Strips and Pixels

HPK wafer production



Strips:
- Sensor size: **3.2 x 2.2 cm²**
- Strips: **1 cm long**, width 40-50 µm, **pitch 500 µm**

HPK wafer production



Pixels:
- Sensor size: **1.6 x 1.6 cm²**
- Pixels: **pitch 500 µm**