INTRODUCTION TO THE DETECTOR TECHNOLOGIES FOR THE EIC

- Klaus Dehmelt

- The 2022 CFNS Summer School on the Physics of the Electron-Ion-Collider
- July 15, 2022

Stony Brook University | The State University of New York

Center for Frontiers in Nuclear Science

DETECTOR TECHNOLOGIES IN HEP

- High Energy Physics (HEP) → Particle Physics/Nuclear Physics
- Accelerator experiments
- Non-accelerator experiments

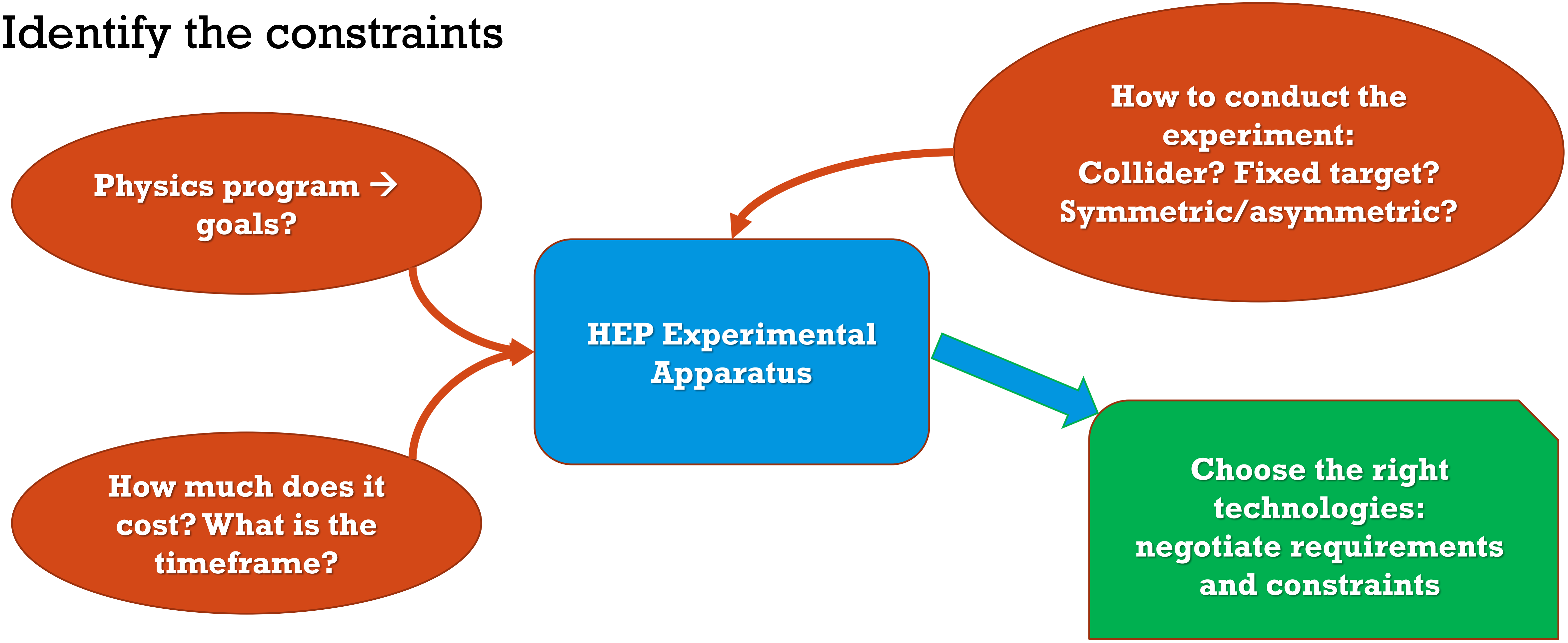
Focus on accelerator experiments

ACCELERATOR EXPERIMENTS

- Particles accelerated and "collided"
  - Collider experiments
    - Particle species accelerated and stored → storage ring, undergo several bunch collisions
    - Particle species accelerated and undergo single bunch collisions
    - Particle species are colliding in dedicated collision points
    - Experimental apparatus surrounding the collision point
    - Symmetric vs asymmetric collisions
  - Fixed target experiments
    - Particle species accelerated and extracted
    - Particle species interact – "collide" with particle species at rest
    - Experimental apparatus covering boosted region → very asymmetric collisions

DESIGN AN EXPERIMENTAL APPARATUS

- Identify the constraints

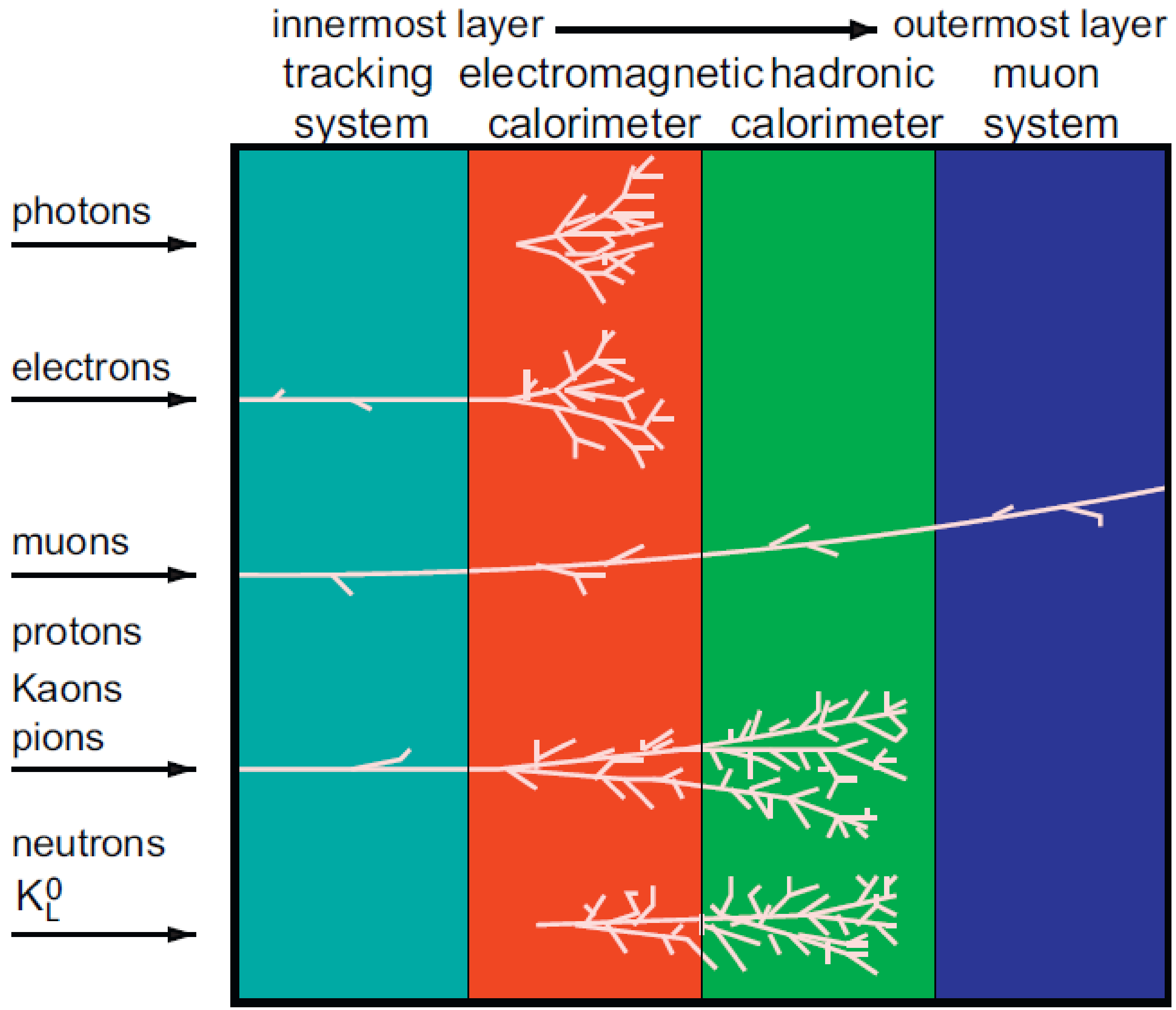


Detector Requirements

- Traditional Experiments

  Onion Structure

  - Trackers
    - Momentum measurement
    - Charge measurement
    - Non-destructive
  - Calorimeters
    - Detect neutral particles
    - Measure energy
    - Distinguish EM/Hadron interactions
    - Destructive
  - Others



DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Charged leptons
  - Photons
  - Hadrons/jets
  - "Missing" particles

DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Charged leptons
    - Electrons → charged particle and EM interaction with matter
    - Muons → charged particle and small interaction with matter

DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Photons
    - Neutral particle and EM interaction with matter

DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Hadrons/jets
    - Charged particles and EM and Hadronic interaction with matter
    - Neutral particles and Hadronic interaction with matter
    - Short lived hadrons → decay products

DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Hadrons/jets
    - Short lived hadrons → decay products

DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision

Particle	m [MeV]	Quarks	Main decay	Lifetime	$c\tau$ [cm]
$\pi^{\pm}$	140	$u\bar{d}$	$\mu\nu_{\mu}$	2.6×10^{-8} s	780
$K^{\pm}$	494	$u\bar{s}$	$\mu\nu_{\mu}$, $\pi\pi^{0}$	1.2×10^{-8} s	370
K_S^{0}	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^{0}	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_{e}$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

DETECTOR REQUIREMENTS

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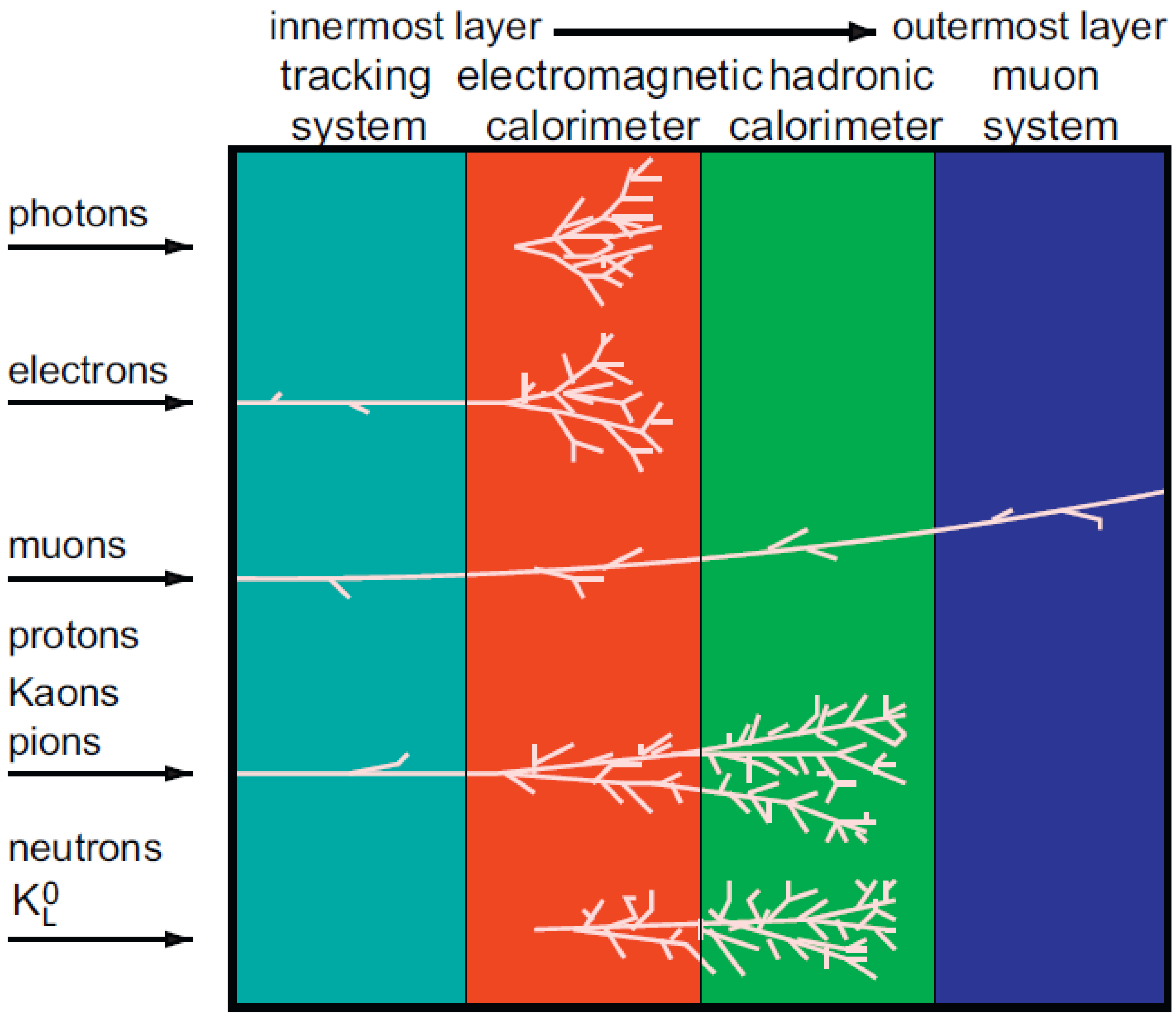
π^0 : τ ~ 85 attoseconds (10^{-18}s)

DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - "Missing" particles
    - Deduce from missing momentum/energy

DETECTOR REQUIREMENTS



DETECTOR REQUIREMENTS

- Almost all effects used in HEP detectors are of EM nature
  - Converting absorbed energy into electrical signal
- Detection sensitivity and performance are function of
  - Fluctuation in detector
  - Fluctuation of electronics
- Maximize detection sensitivity and resolution
  - Signal formation
  - Coupling to readout electronics
  - Fluctuation of electronics

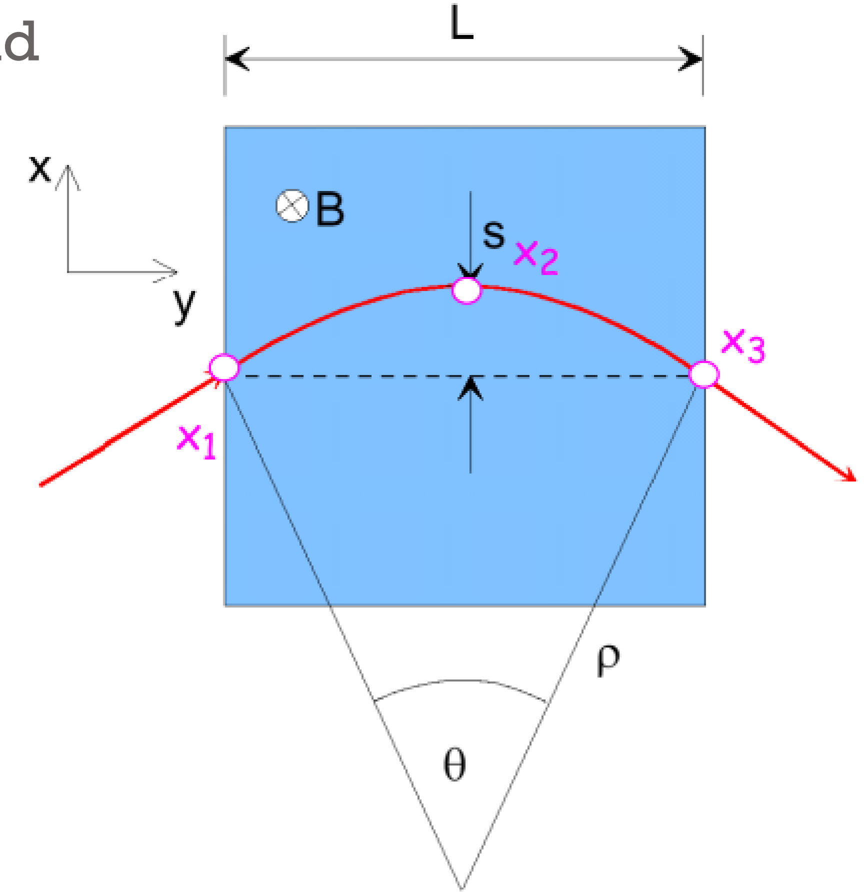
DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Charged particles → let them interact with magnetic field
    - Controlled deflection
    - Non-destructive measurement of charge and momentum

$$p_T = qB\rho$$

$$p_T[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

$$p = \frac{p_T}{\tan\theta}$$

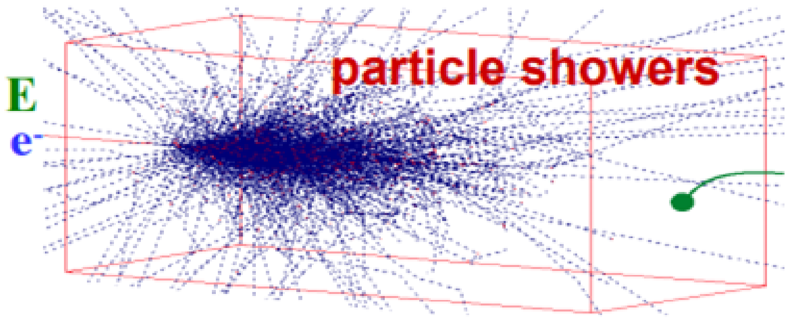


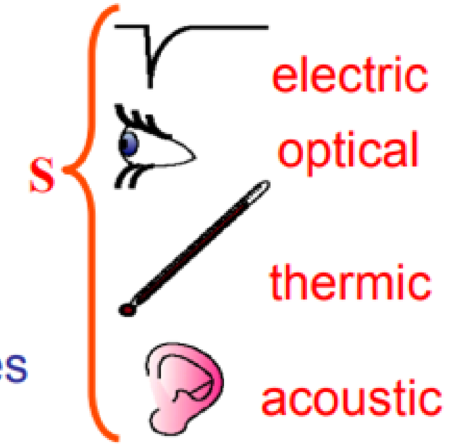
DETECTOR REQUIREMENTS

- Ideally → measure and identify all final products of collision
  - Measure energy
    - Stop particle in dense material
    - Measure signal proportional to energy deposit
    - Material different for EM and Hadronic interaction

Calorimetry makes use of various detection mechanisms:

- Scintillation
- Cherenkov radiation
- Ionization
- Cryogenic phenomena





Convert energy E of incident particles to detector response S:

$$S \propto E$$

PRIMER: EM CALORIMETRY

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length] [in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

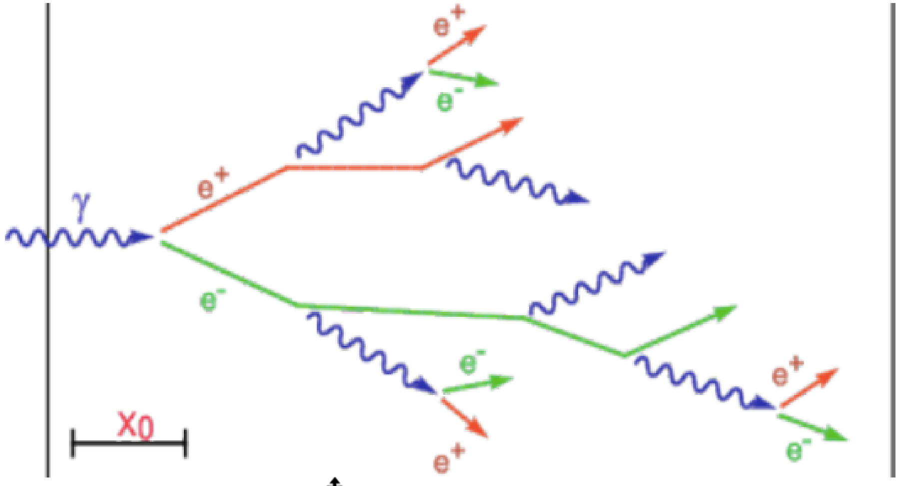
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only $(1/e)^{th}$ of its primary energy ... [i.e. 37%]

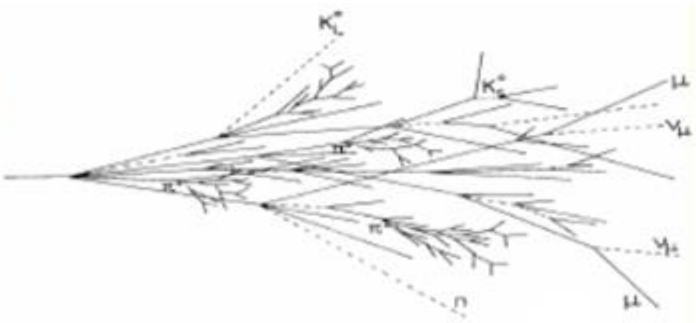


PRIMER: HADRONIC CALORIMETRY

- Importance of calorimetric measurement
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy

- In nuclear collisions numbers of secondary particles are produced
  - Partially undergo secondary, tertiary *nuclear reactions* ➔ formation of hadronic cascade
  - Electromagnetically decaying particles *(π,η)* initiate EM showers
  - Part of the energy is absorbed as nuclear binding energy or target recoil (*Invisible energy)*
- Similar to EM showers, but much more complex

  ➔ need simulation tools (MC)
- Different scale: hadronic interaction length

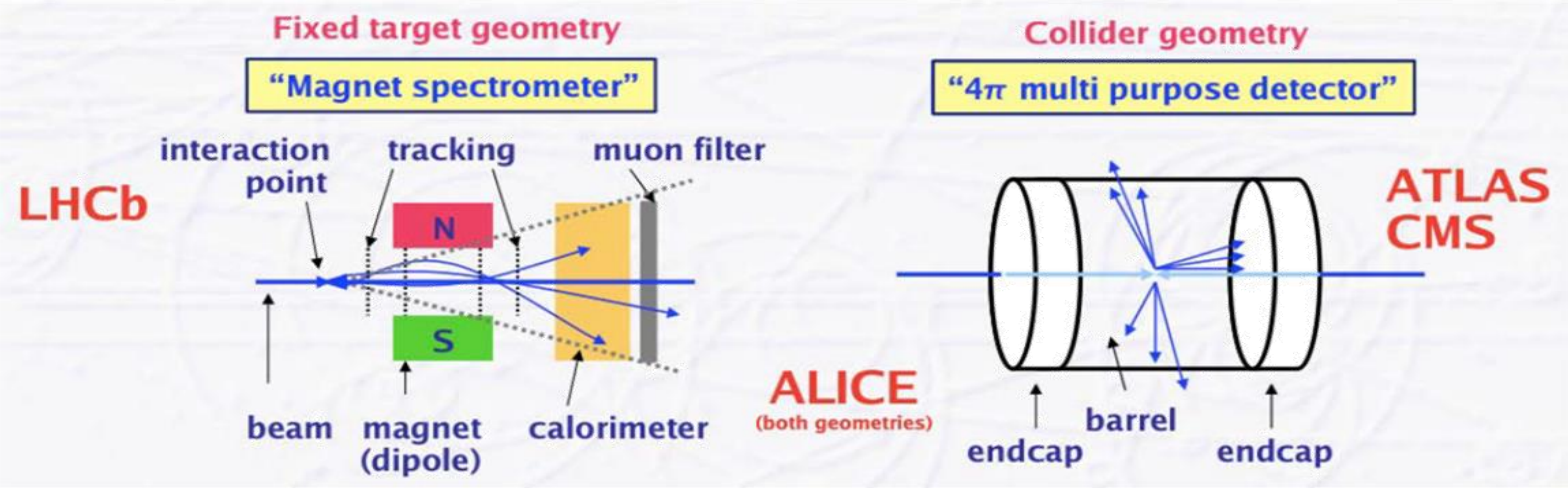


Detector Requirements

- Ideally → measure and identify all final products of collision
  - Identify particle
    - Basically, velocity measurement

      - Time of Flight
        - Fixed distance – fast readout
      - Transition radiation
        - Border crossing between media with different dielectric properties
      - Cherenkov radiation
        - Particle velocity greater than photon velocity in medium
      - Ionization loss – dE/dx
        - Specific energy loss per particle species

GEOMETRIES



Look at collision products in a small open angle along beam axis
Plane detectors perpendicular to beam

Particles to be detected over whole solid angle (4π)
Detectors arranged around beam axis with "onion structure"

(Incomplete) List of HEP Experiments

Bates Linear Accelerator (MIT)
BLAST , OOPS , SAMPLE

Beijing IHEP
ARGO-YBJ , BES , Tibet ASgamma

Brookhaven
BRAHMS , Crystal Ball (E913/914) , E787 , E821/muon g-2 , E850 , E852 , E863/ EMU01 , E864 , E865 , E869 , E877 , E881 , E885 , E890 , E891 , E895 , E905 , E906 , E907 , E909 , E910 , E913/914 (Crystal Ball) , E917 , E923 , E926 , E927 , E949, E953 , EIC , EMU01/E863 , High Gain Harmonic Generation FEL , ICAE , IFEL , IMB , LEGS , MECO , Microundulator FEL , NuMass/E952 , PHENIX , PHOBOS , pp2pp , Smith-Purcell , STAR , Zero Degree Calorimeter

CERN
ALEPH , ALICE , AMS , ANTARES , ASACUSA , ATHENA , Atlas (European) , ATRAP , CDHS neutrino experiment/WA1 , CERES/NA45 , CHORUS , CMS , CosmoLEP , CPLEAR/PS195 , Crystal Barrel/PS 197 , Crystal Clear/RD18 , DELPHI , EMU01 , FELIX , HARP , ICANOE , ISOLDE , L3 , LHC-B , MISTRAL , NTOF1, NTOF2, NTOF3 , NA45.2/IONS/EL.PAR , NA47/SMC , NA48, NA48.1, NA48.2 , NA49 , NA50 , NA51 , NA52/ Newmass , NA56/SPY , NA57 , NA58/COMPASS , NA59 , NA60 , NOMAD , OBELIX/PS201 , OPAL , OPERA , PAMELA , PS185 , PS205/HELIUMTRAP , PS210 , PS212/DIRAC , PS214/HARP , RD8 , RD11 , RD12/TTC , RD13 , RD27 , RD39/SMSD , RD41/ MOOSE , RD42 , RD44/Geant 4 , RD45 , RD46 , RD48/ ROSE , RD49/RADTOL , TOSCA , TOTEM , WA85 , WA92 (Beatrice) , WA94 , WA97 , WA98 , WA102

DESY
H1 , HERA-B , Hermes , TESLA , ZEUS

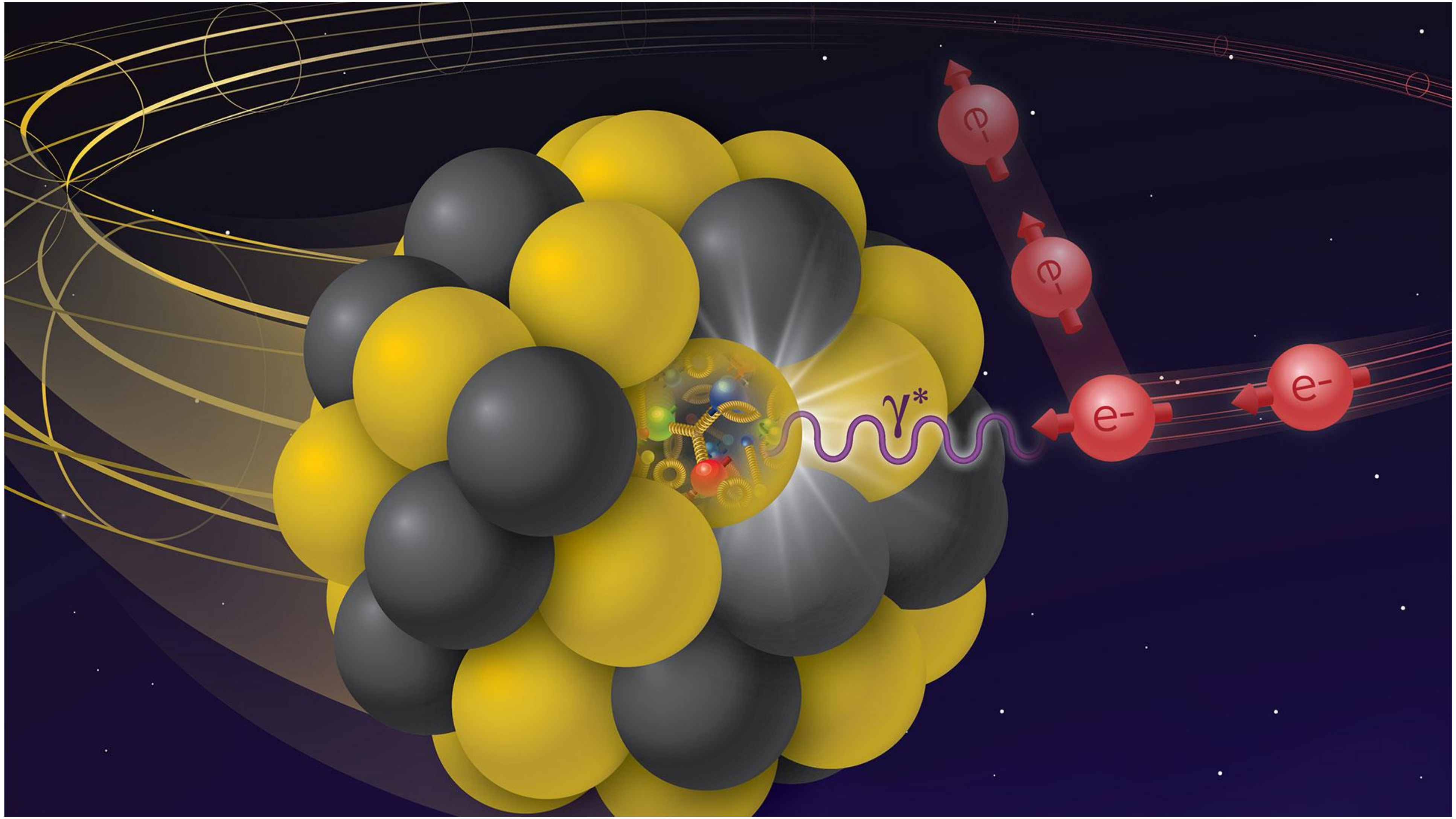
Fermilab
Antihydrogen/E862 , APEX/E868 , Auger Project , BooNE/E898 , BTEV/C0 , CDF/E830 , CDMS/E981 , CEX/E853 , Charmonium/E835 , CMS (US Server) , COSMOS/E803 , D0 (DZero)/E823 , Donut/E872 , E665 , E771 , E789 , Fermi III Project , FOCUS/E831 , HyperCP/E871 , KTEV/E799/E832 , MINOS/E875 , NuMI , NUSEA/E866 , NuTeV/E815 , SDSS , SELEX/ E781 , Zero Degrees/C0

Gran Sasso
BOREXino , CRESST , CUORICINO , DAMA , EASTOP, GALLEX(finished) , GENIUS , GNO , Heidelberg Dark Matter Search (HDMS) , Heidelberg-Moscow Experiment , ICARUS , LUNA , LVD , MACRO , MONOLITH , NOE , OPERA , USA

PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

Center for Frontiers in Nuclear Science

The Electron Ion Collider -EIC-



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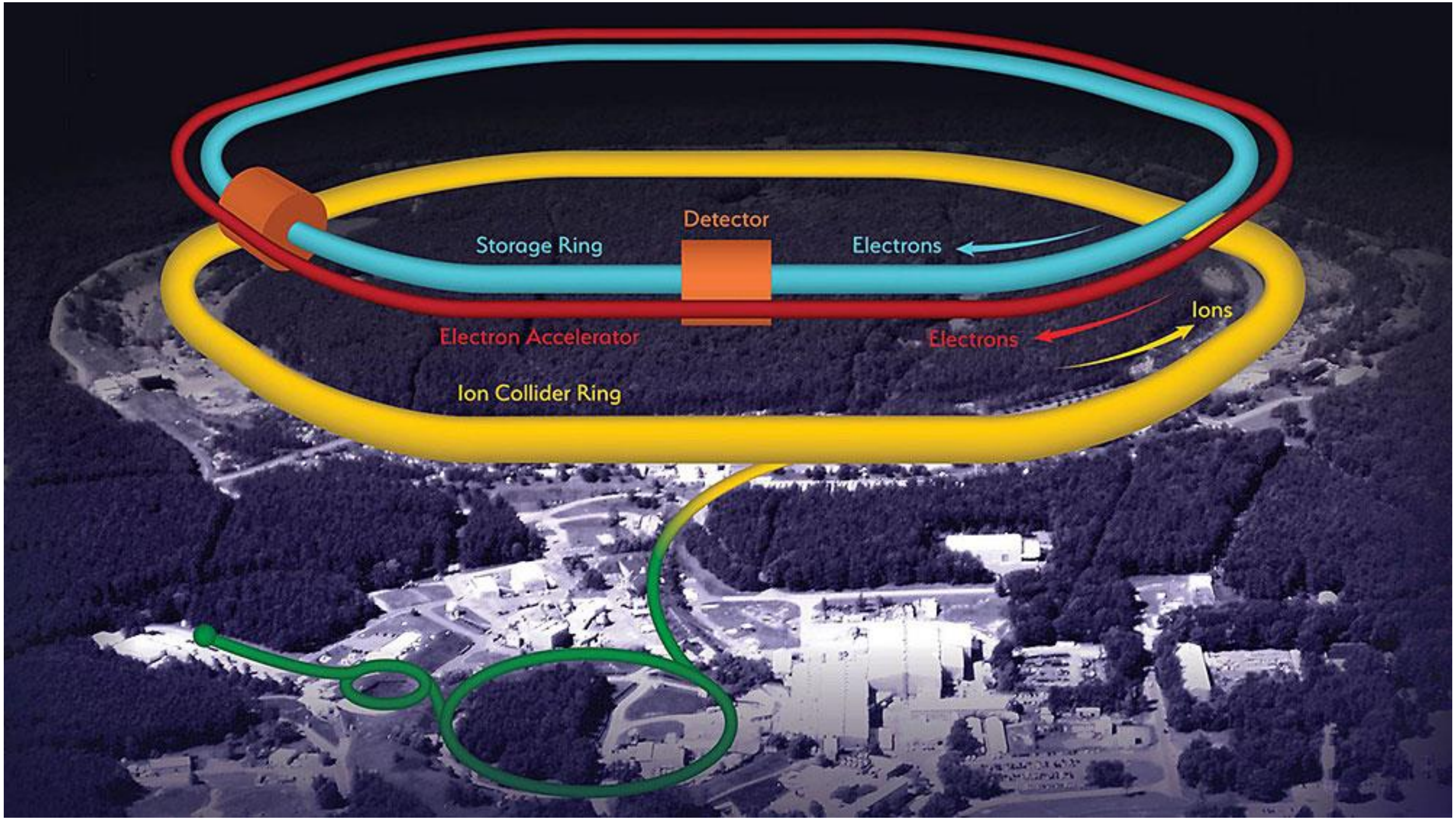

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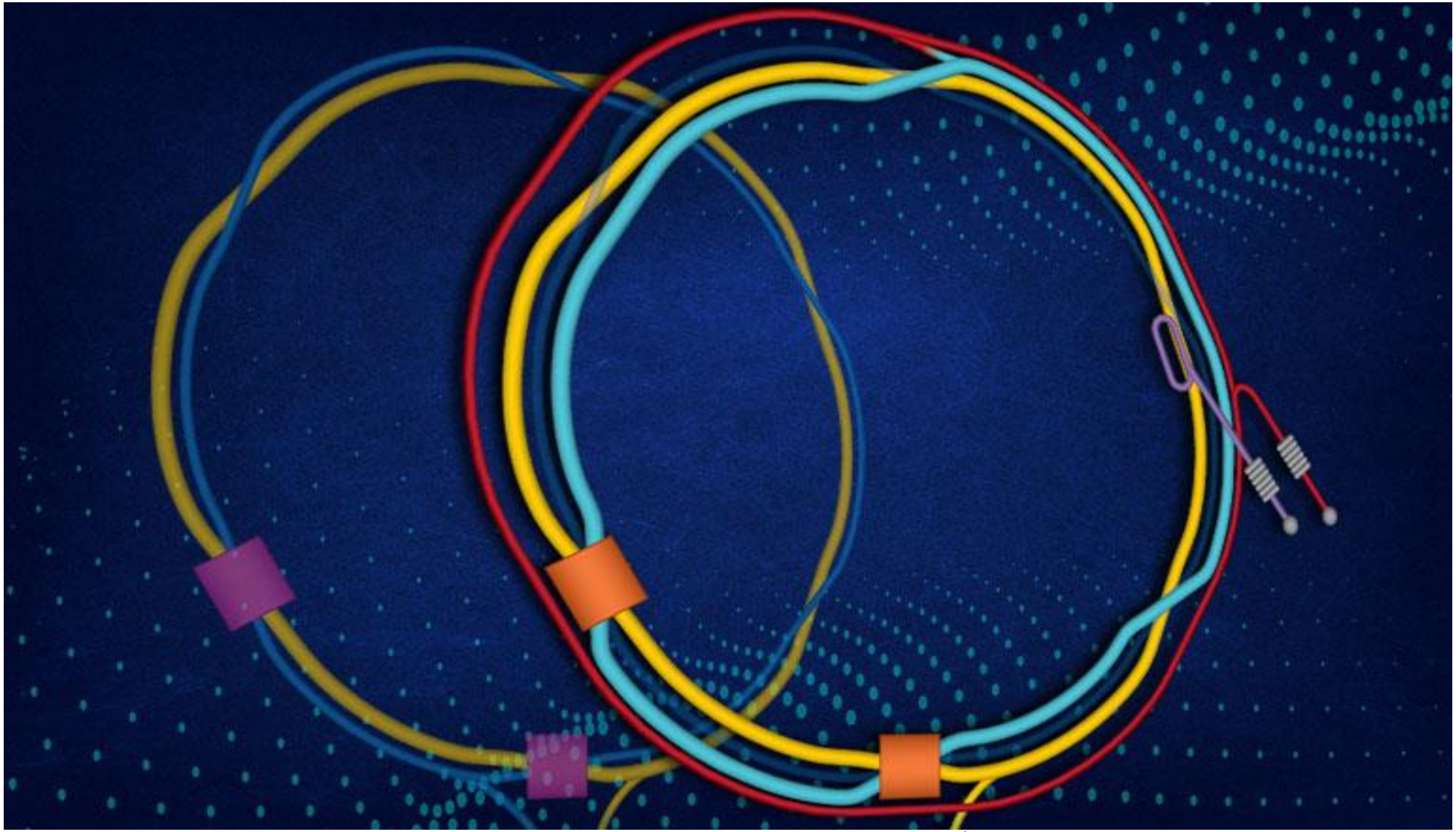
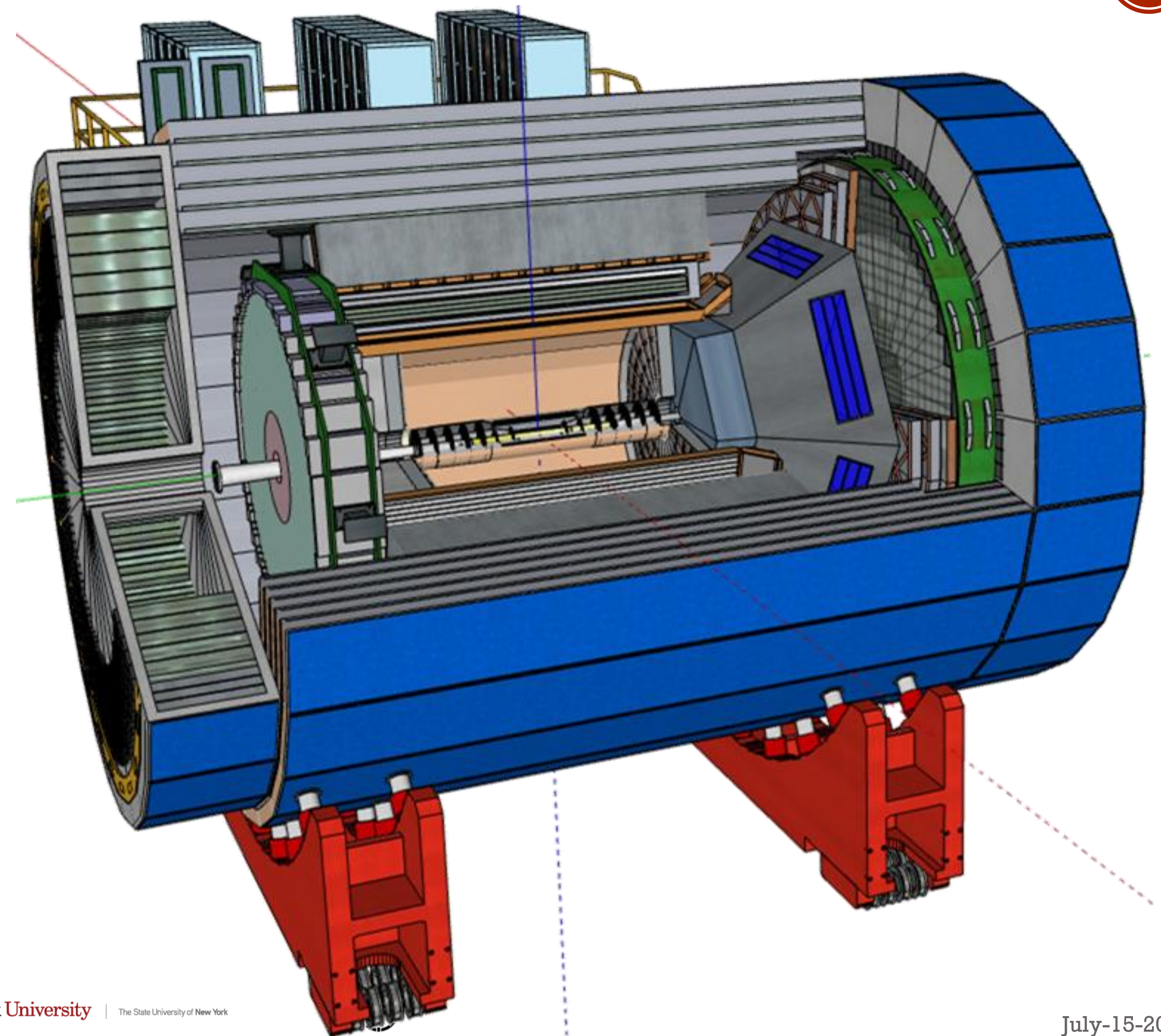


PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

The Electron Ion Collider -EIC-

- Needs Detector(s)
- Measure various observables
  - Momentum → tracking
  - Energy → calorimetry
  - Particle identity
  - Others



ELECTRON ION COLLIDER

- Three detector concepts introduced and discussed at the
  EIC Detector Proposal Advisory Panel Meeting (December 2021)

  - ATHENA
  - CORE
  - ECCE

ATHENA

Solenoid

Barrel Tracking

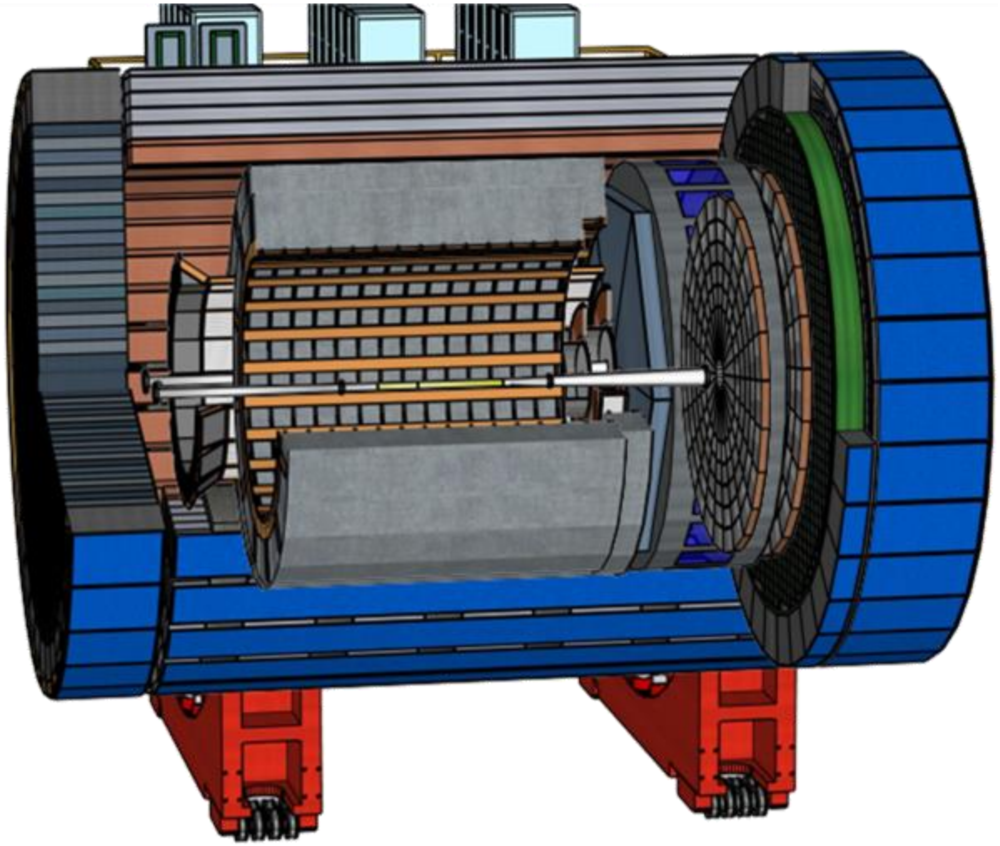
Endcap Tracking

PID

EM Calorimetry

H Calorimetry

Support Structure & Platforms

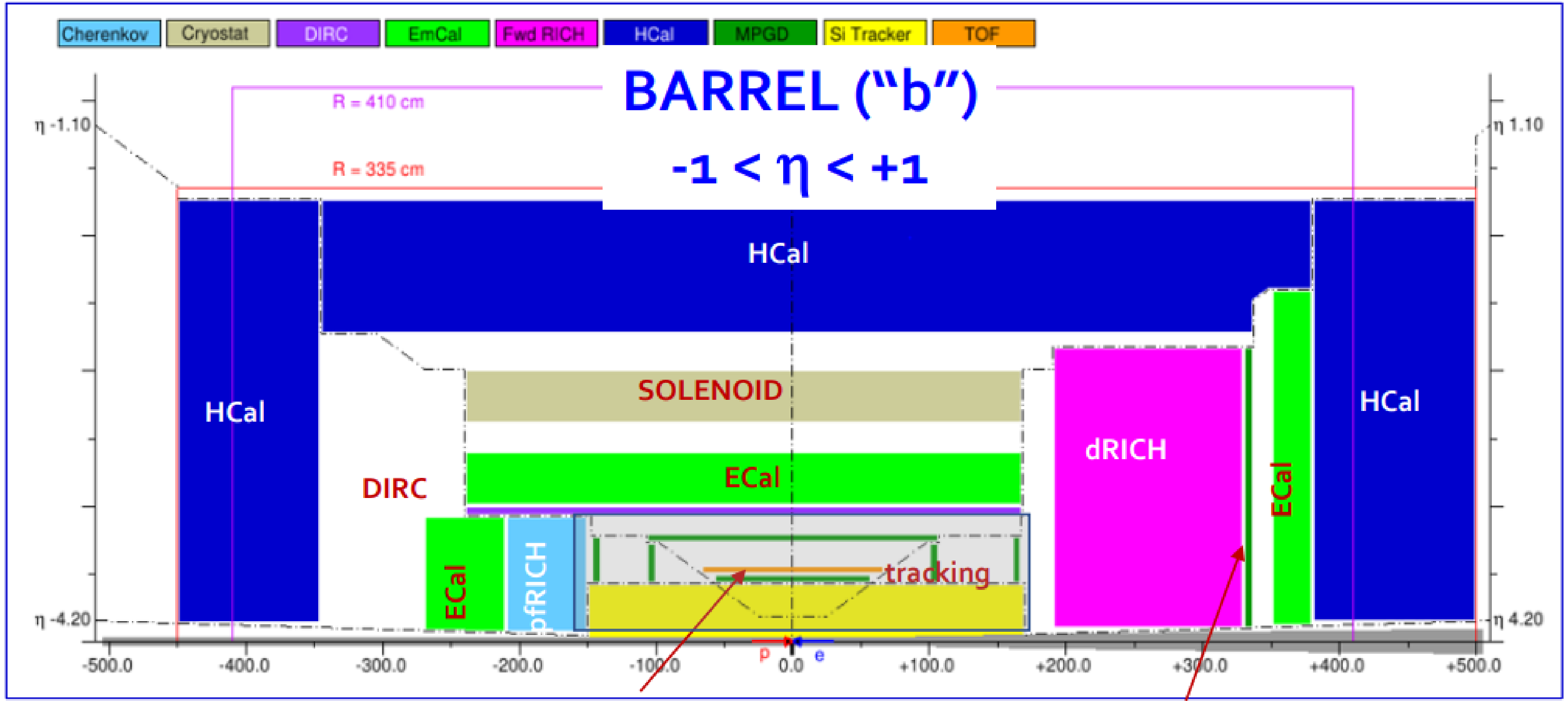


ATHENA

Hadron beam (41-275 GeV)

Electron beam (5-18 GeV)

Backward Endcap ("n")
η < -1

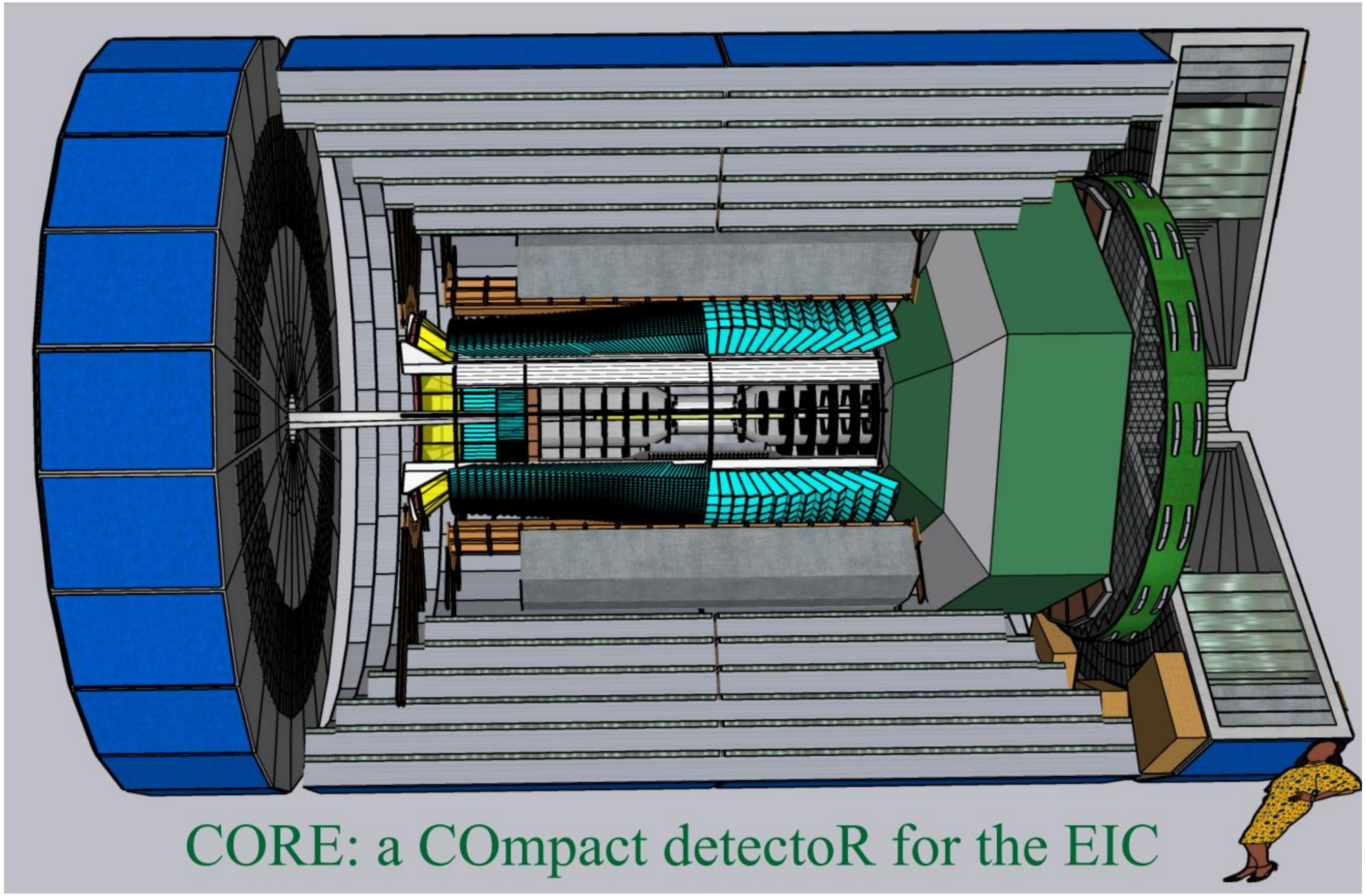


Forward Endcap ("p")
η > +1

Electron-going direction -η

Hadron-going direction +η

CORE

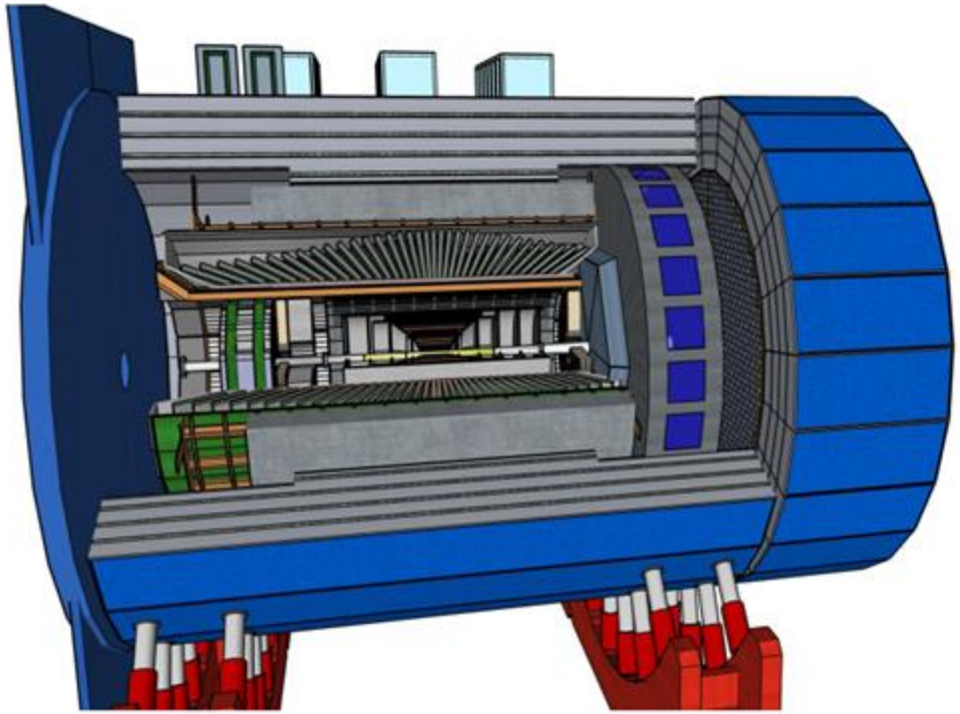


CORE

- Technologies and technology choices
  - EIC R&D
- Tracking
  - Silicon tracker, fwd MPGD tracker
- Particle Identification
  - Dual-radiator RICH, DIRC, LGAD TOF
- EM calorimetry
  - $PbWO_4$, W-shashlyk
- Hadronic calorimetry
  - fwd Hcal, KLM

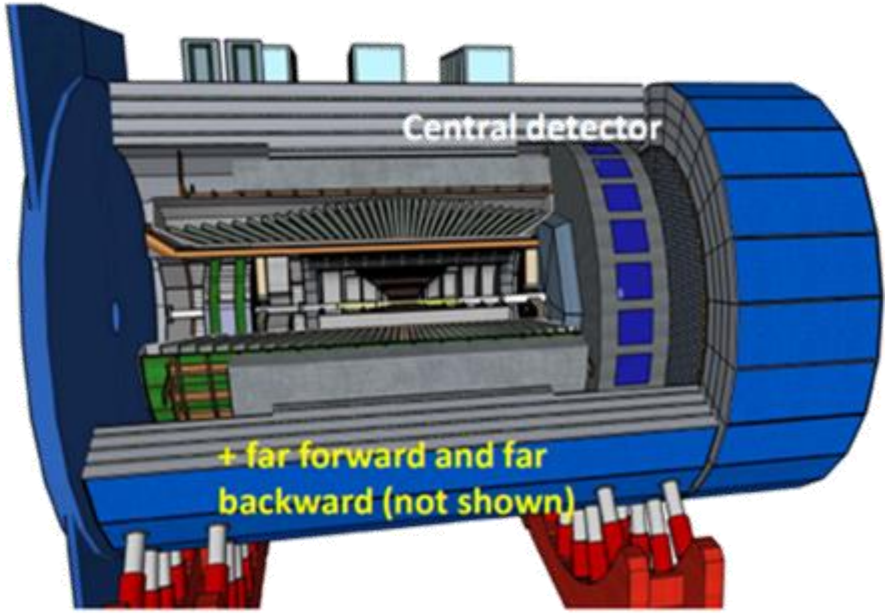
ECCE

EIC Comprehensive Chromodynamics Experiment



ECCE

EIC physics measurements require a detector with unique capabilities

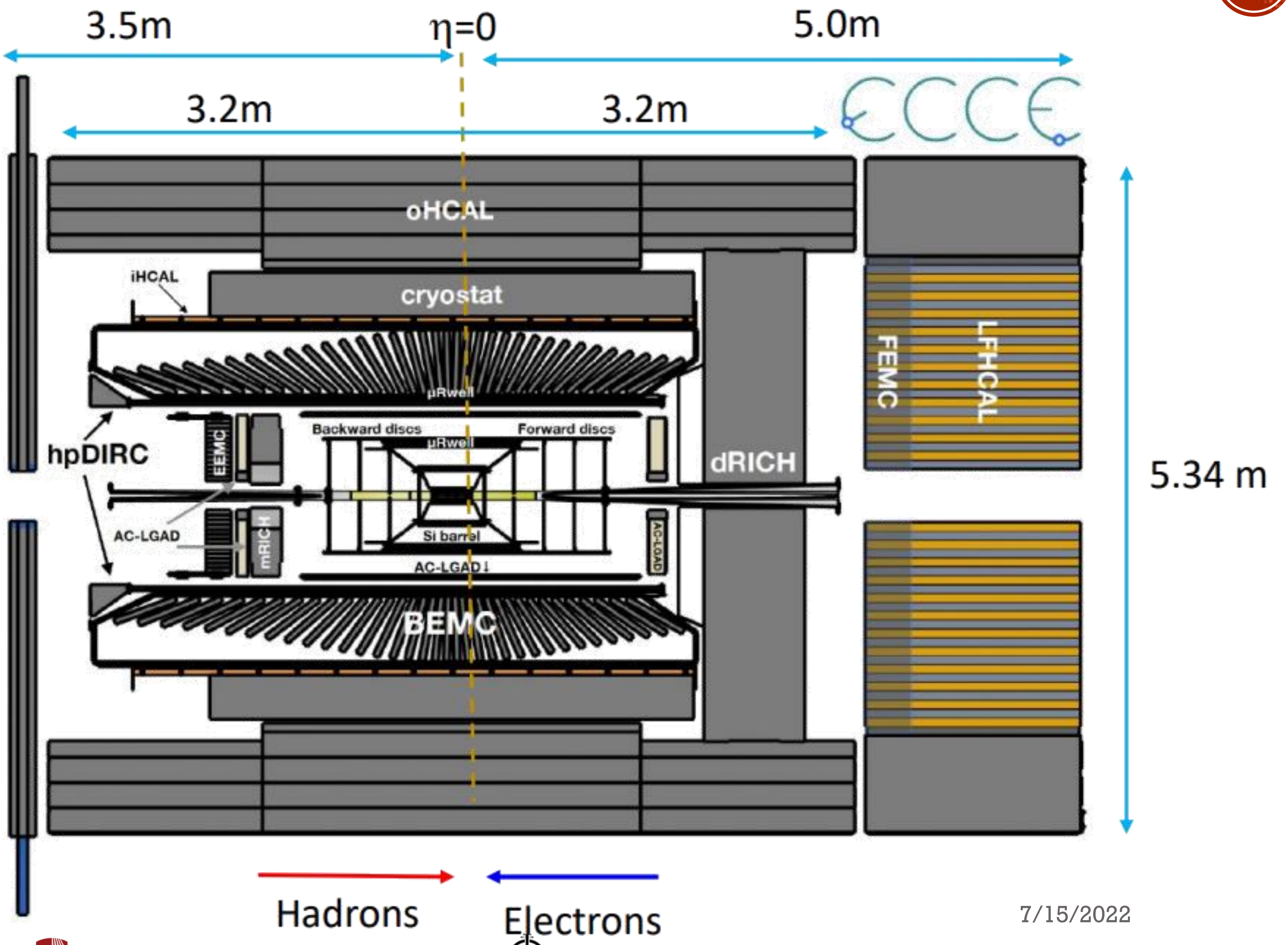


- Large rapidity at least $-3.5 < \eta < 3.5$ (YR) coverage; and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EMCal
- High performance PID to separate π, K, p at track level
  - also need good e/π separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, …
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

ECCE AS REFERENCE

The ECCE detector size is determined by the reuse of the BaBar magnet and sPHENIX HCAL, and further EIC detector needs:

- Needs +5 m on proton/ion side.
- Needs less space (-3.5 m) on electron side.
- The detector radius is 2.7 meter, with the RCS beam at 3.35 meter.



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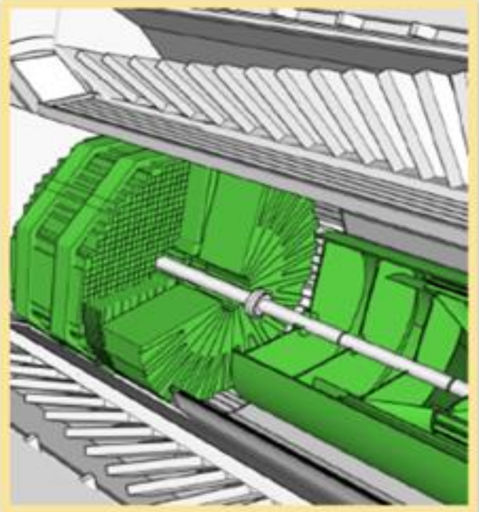
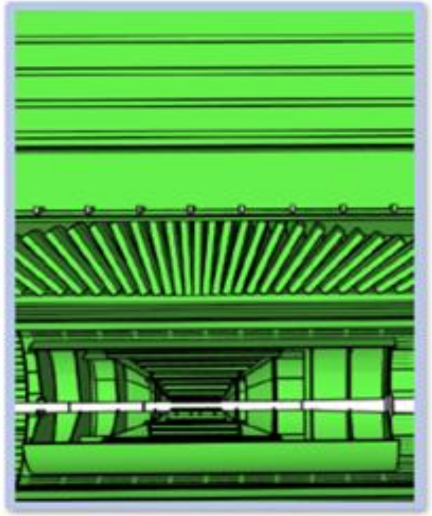
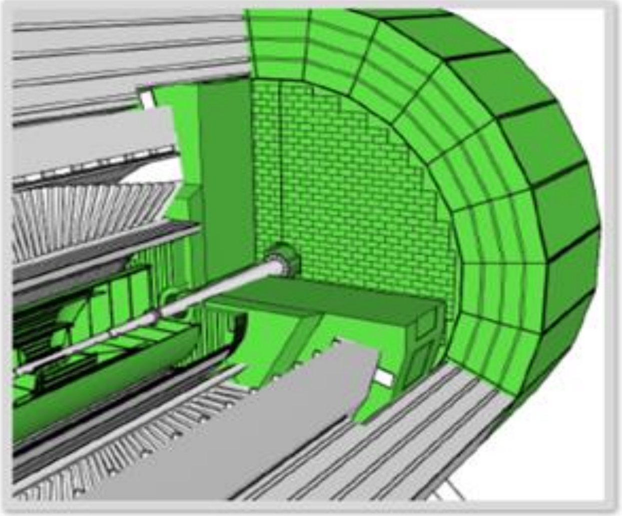






Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)

Forward Endcap

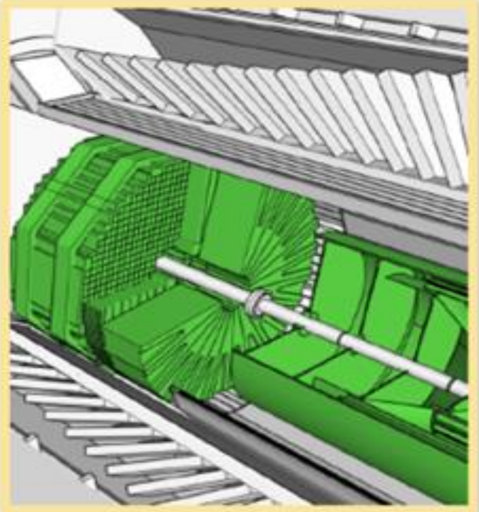
Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

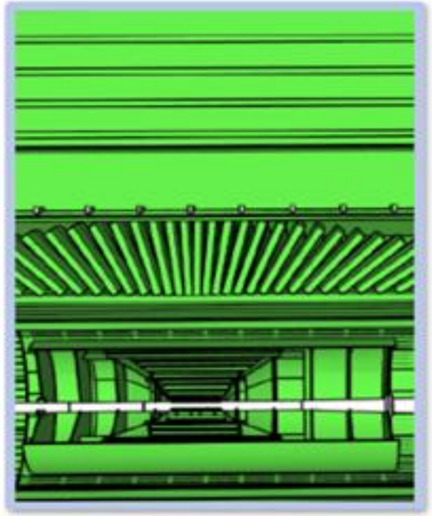
PID:
- dRICH
- AC-LGAD TOF

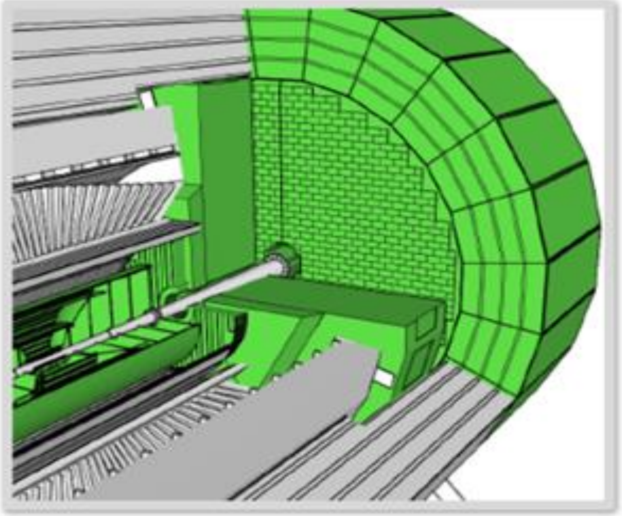
Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

ECCE

ECCE AS REFERENCE







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ECCE

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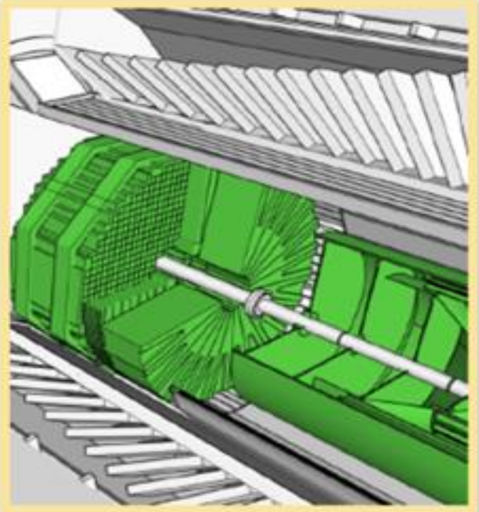

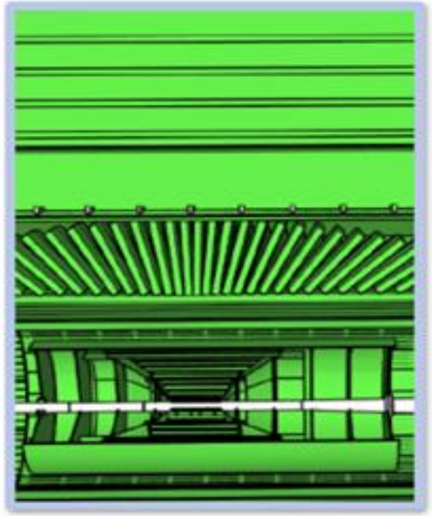

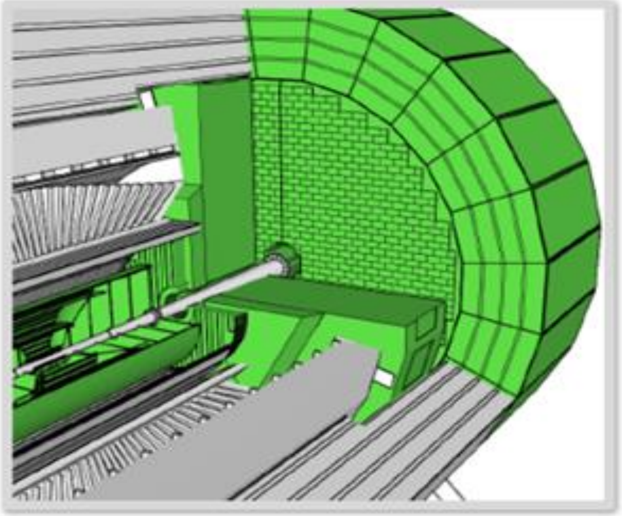

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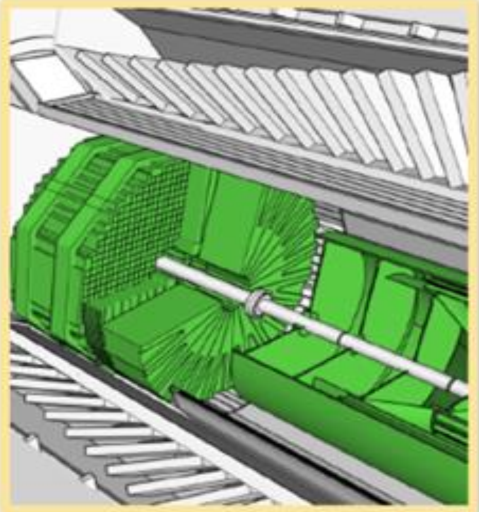

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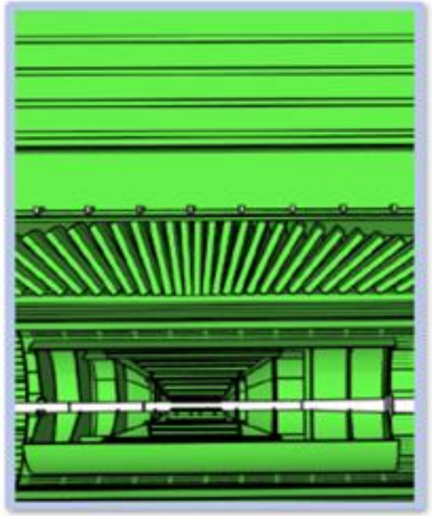

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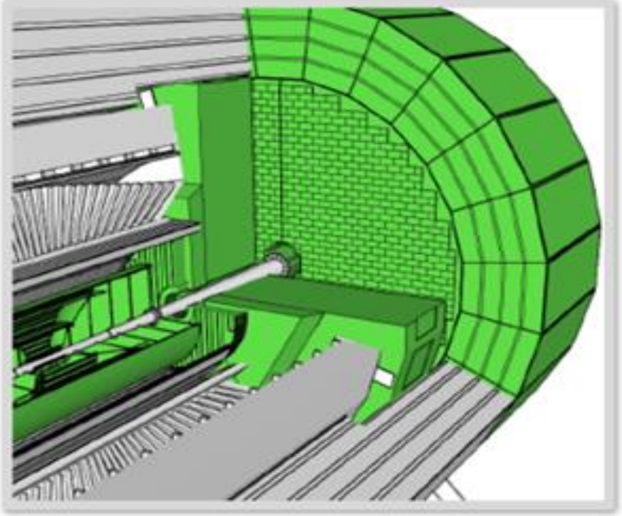
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

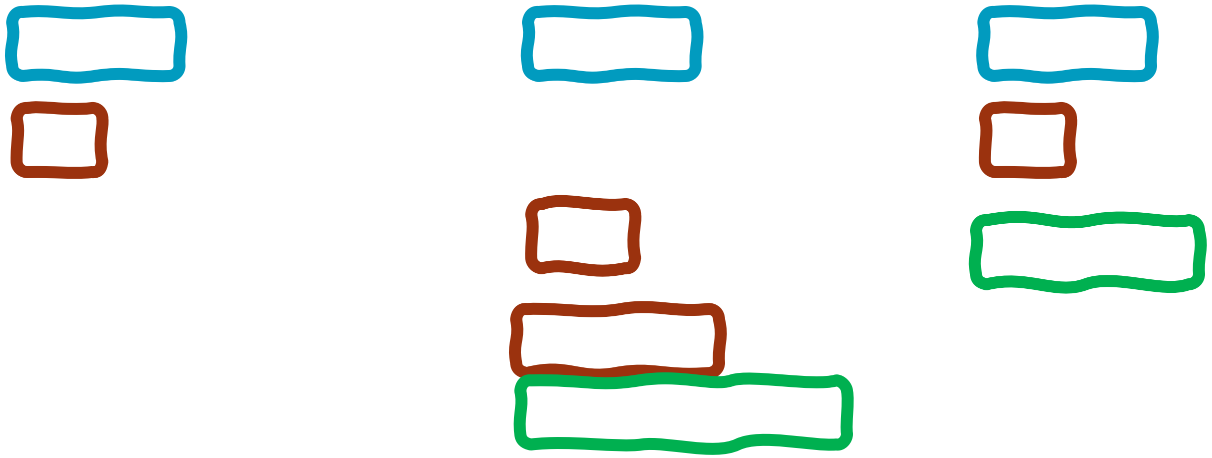
Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

ECCE AS REFERENCE

- PID → lecture
- Tracking → lecture
- Calorimetry → lecture



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- PID → lecture
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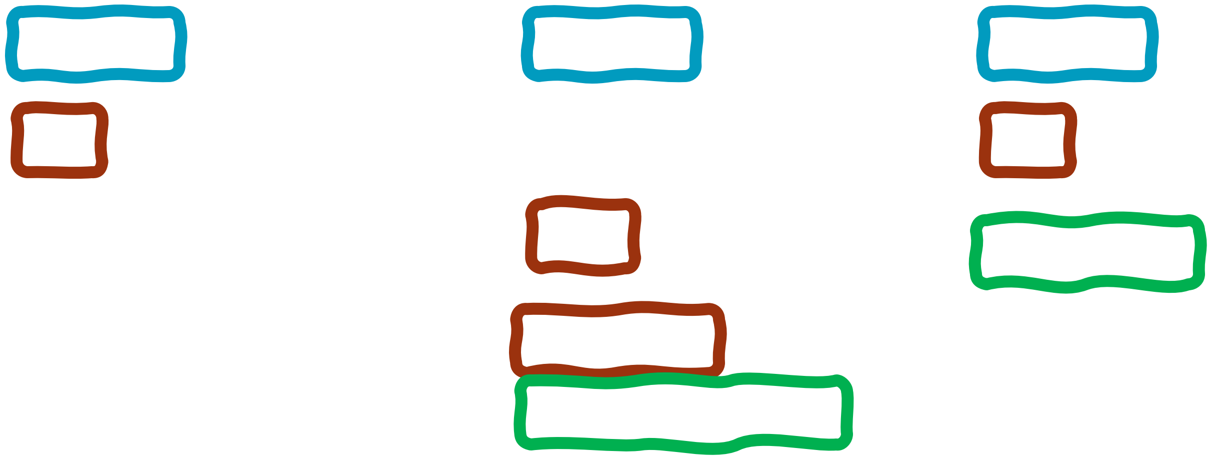

LAST SLIDE

- Particle detection mostly based on relatively "simple" physics principles
  - Well known and well simulated
- Particle detection techniques/technologies always evolving
  - Always in need for fresh/new/clever … ideas → detector R&D is a rich and rewarding field
- Implementation of detectors in large(r) scale experiment always challenging → needs many people and good organization
- Building the detector is not yet the end → need to understand the response and coordination of all components and the physics can come
  - BTW: Each detector produces signal that needs to be read out
    - Not covered here → Readout electronics is a field by itself