PDM 2022,
La Biodola, 22-28 May 2022

ATHENA @ EIC

A Totally Hermetic Electron Nucleus Apparatus proposed for the **Electron-Ion Collider**

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on behalf of the ATHENA Collaboration

ATHENA

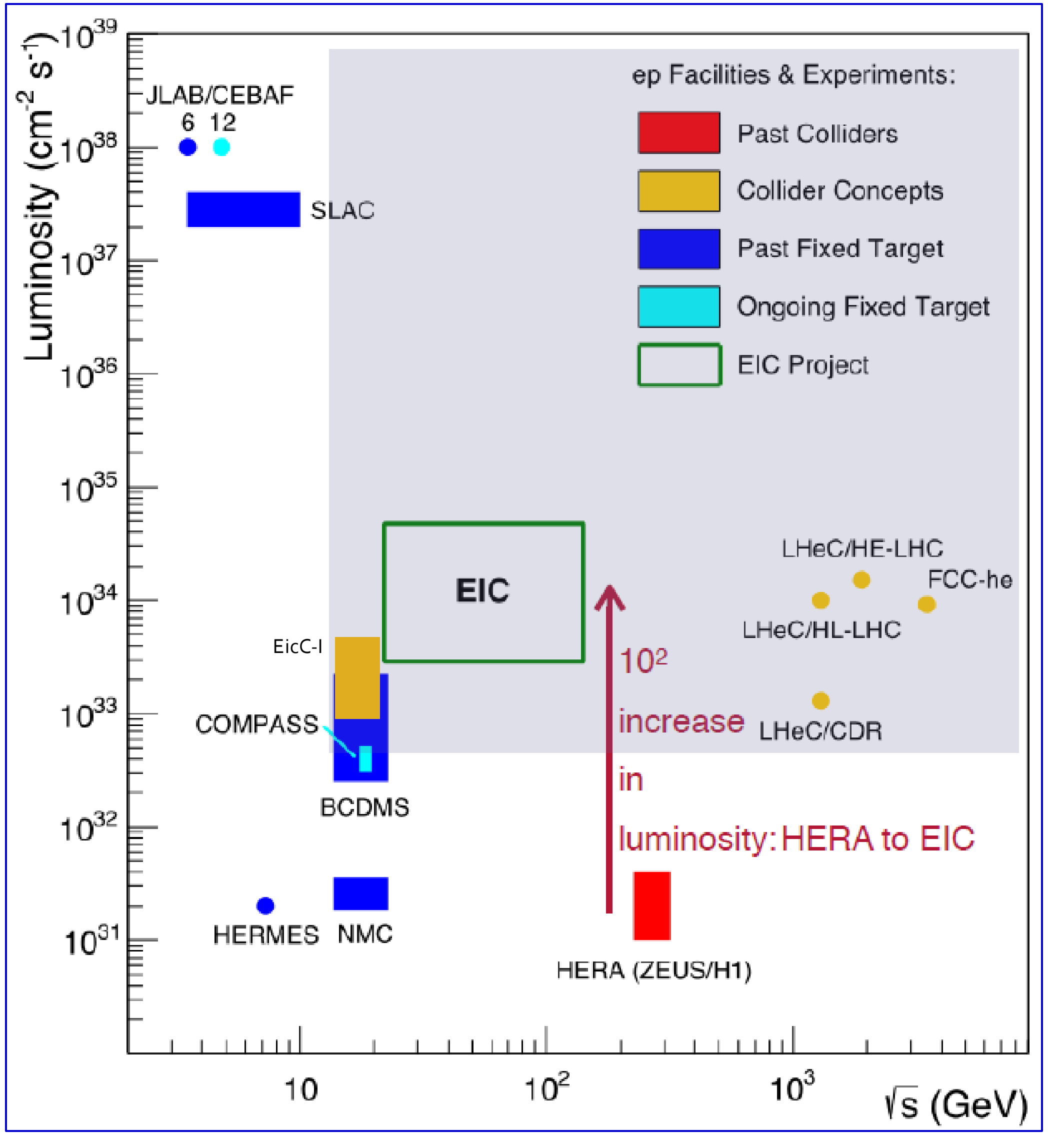
The Context

The EIC, WHY?

- Ultimate understanding of QCD

  - By answering to the open questions
    - ✓ N spin structure and overall N tomography
    - ✓ Origin of the N mass
    - ✓ Evolution of the gluons in high density nuclear matter and gluon saturation
    - ✓ …

  - By conjugating High Energy and High Luminosity enriched with Beam Polarization
    - ✓ Several e-h colliders proposed by the community
    - ✓ **The EIC is an approved project !**



The EIC, an approved project

https://www.energy.gov/articles/us-department-energy-selects-brookhaven-national-laboratory-host-major-new-nuclear-physics

Department of Energy

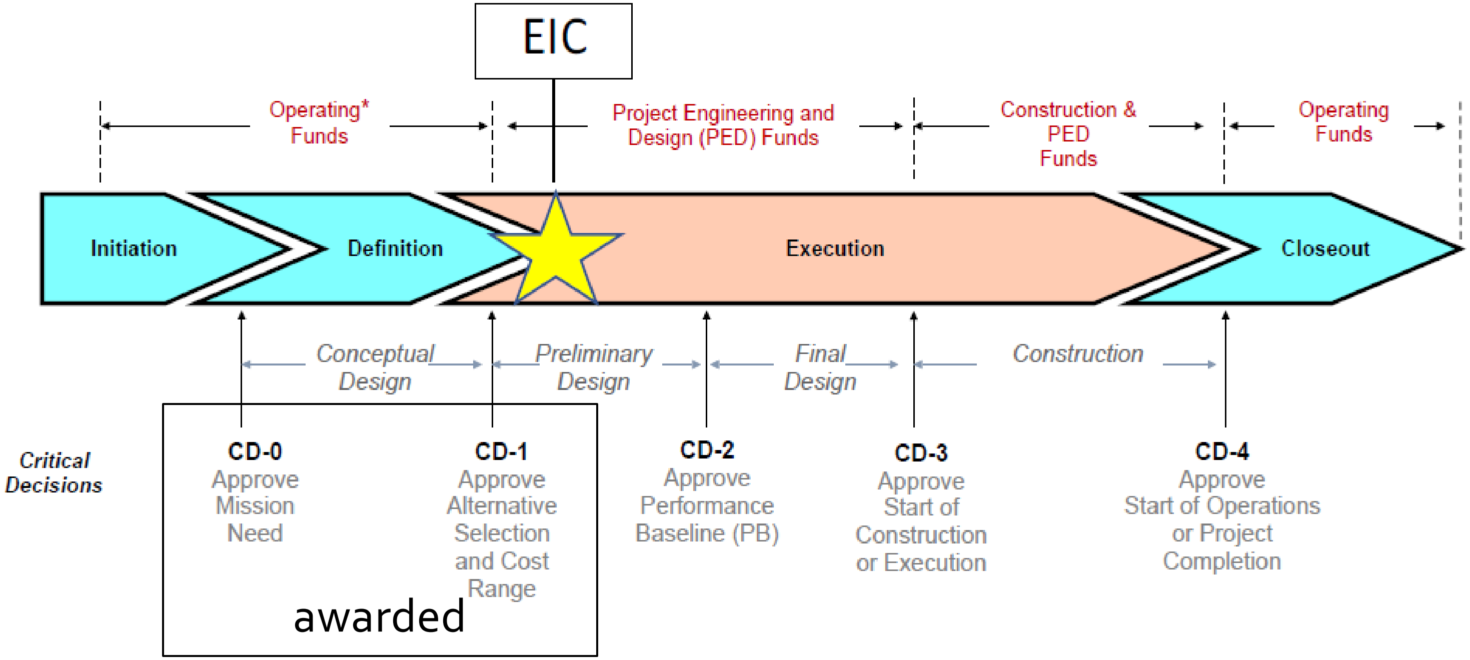
U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility. The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

Critical Decision-0 (CD-0), "Approve Mission Need", approved for the EIC on December 19, 2019.

Critical Decision-1 (CD-1), "Approve Alternative Selection and Cost Range", was awarded for the EIC on June 29, 2021.



The next milestones in front of the project
(present projection)

- CD2/3A~ Jan. 2024
(pre-TDR needed)
- CD-3 ~ Apr. 2025
(TDR)
- CD4A ~ 2031
(start of operation)
- CD4 ~ 2033
(project completion)

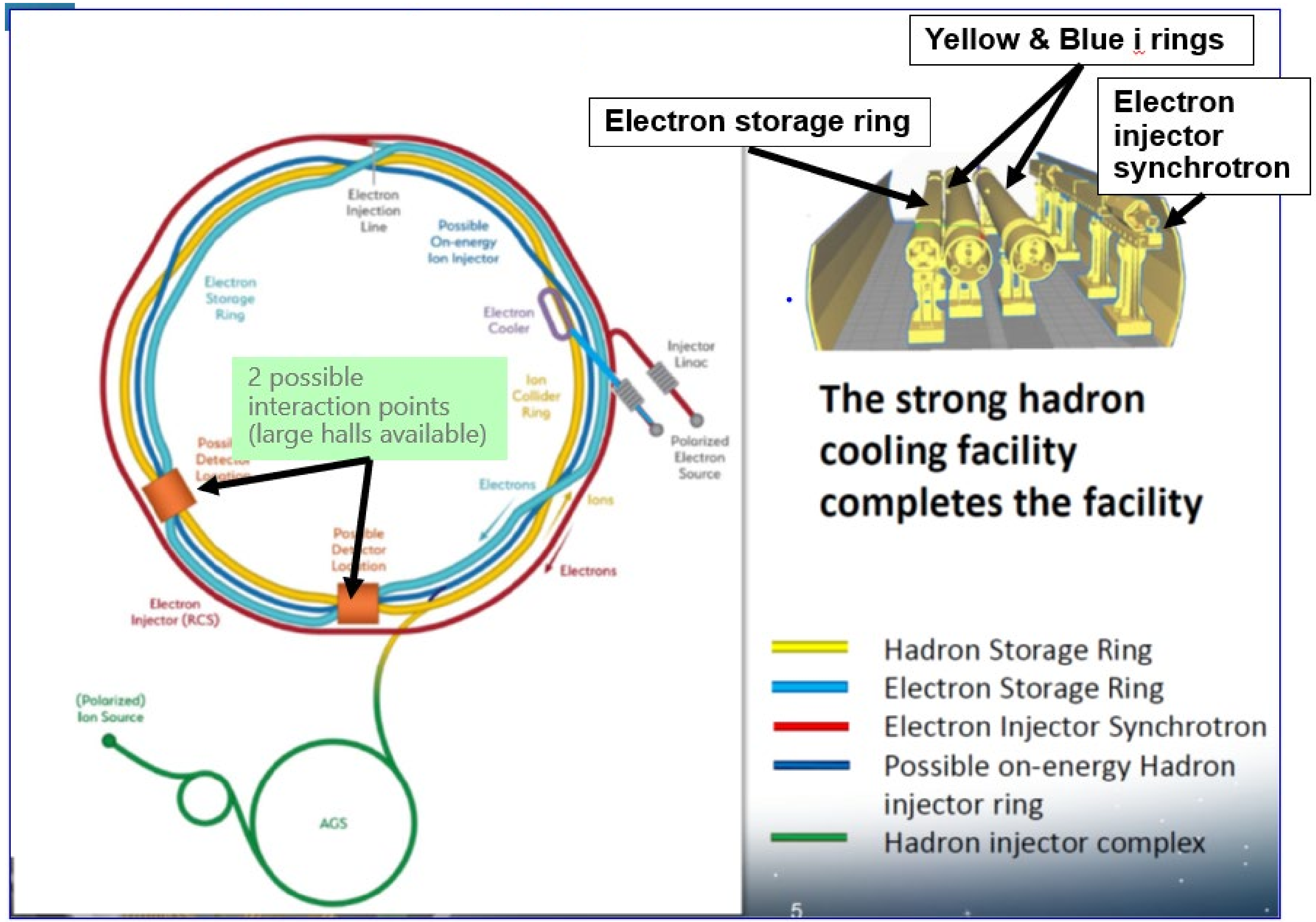
The EIC project in a nutshell

"SPECIFICATIONS":

- spanning a wide kinematical range
  - ECM: 20 – 141 GeV
- High luminosity
  - up to 10^{34} cm^{-2} s^{-1}
- highly polarized e (~ 70%) beams
- highly polarized light A (~70%) beams
- wide variety of ions: from H to U
- Number of interaction regions: up to 2
- True 4π-coverage
  - Fully integrated detector-IR
- **Detector**

collider design

detector design



h-sources, acceleration, polarization, storage ring

empowering the existing complex

e-sources, acceleration, polarization, storage ring

NEW

The EIC Detector

(general considerations)

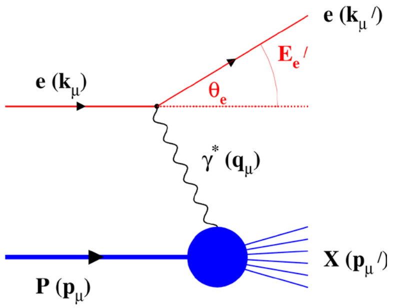
Detector requirements dictated by the Physics Scope

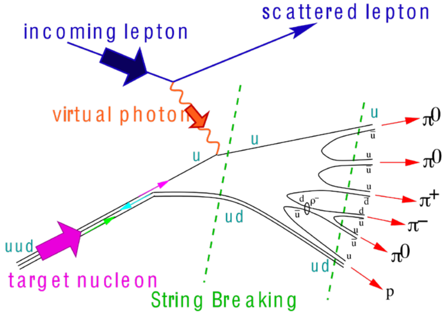
ATHENA

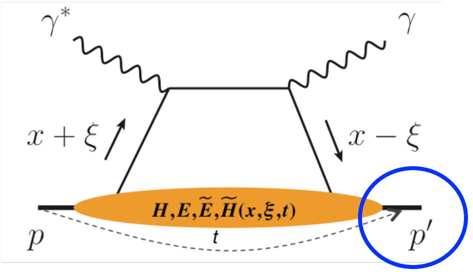
measurements by categories *(from WP & NAS Report)*

- Parton Distributions in nucleons and nuclei
- QCD at Extreme Parton Densities - Saturation
- Spin and Flavor structure of nucleons and nuclei
- Tomography Transverse Momentum Dist.
- QCD at Extreme Parton Densities - Saturation
- Tomography Spatial Imaging

process







Detector Requirements, *Including jet rec.onstruction*

inclusive DIS

- Detect ,measure and identify the scattered lepton
- hermeticity and h reconstruction
- jet reconstruction
- Acceptance & resolution for multi-dimensional binning: x, Q²

semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- Identify hadrons
- jet reconstruction
- Vertex resolution to reconstruct heavy hadron decays
- Acceptance & resolution for multi-dimensional binning: x, Q², z, p_T, Θ

exclusive processes (small cross-sections)

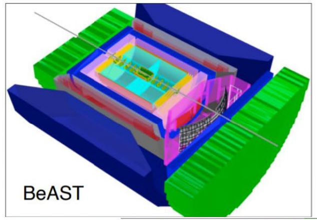
- measure all particles in event
- tagging nuclear fragments for background suppression
- e/π separation for background suppression
- identify hadron for background suppression
- Acceptance & resolution multi-dimensional binning: x, Q², t, Θ

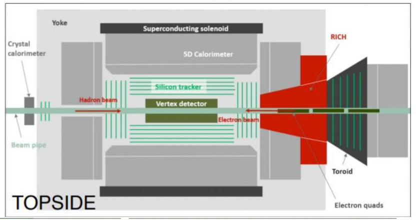
∫Ldt:

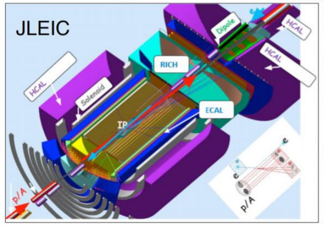
inclusive DIS	semi-inclusive DIS	exclusive processes
1 fb^{-1}	**10 fb^{-1}**	**10 - 100 fb^{-1}**

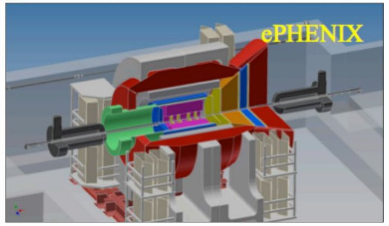
The evolution of the detector concept

- **White paper** (2012, 2014)
- followed by the initial concepts

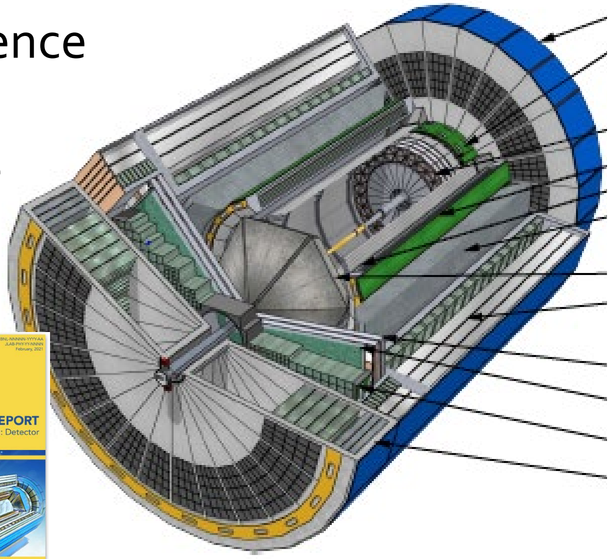




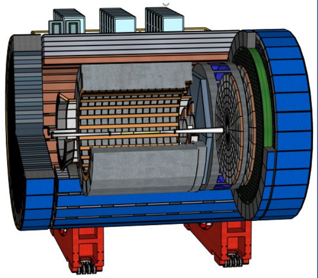




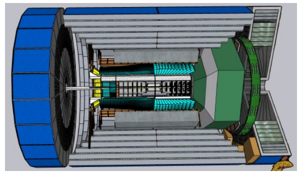
- The **Yellow Report** reference detector (**2020**)
  - A global effort of the EIC-User Group



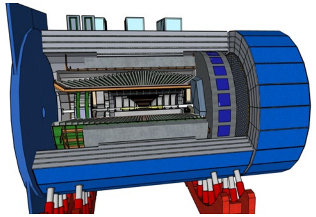
- The **Call for Detector proposals** (**2021**)
  - ATHENA
    - ✓ A Totally Hermetic Electron-Nucleus Apparatus
    - ✓ Concept: General purpose detector inspired by the YR studies based on a new central magnet of up to 3T



  - CORE
    - ✓ COmpact detectoR for the Eic
    - ✓ Concept: Nearly hermetic, general purpose compact detector, 2T baseline



  - ECCE
    - ✓ EIC Comprehensive Chromodynamics Experiment
    - ✓ Concept: General purpose detector based on 1.5T BaBar magnet



- **2022**: Merging of ECCE and ATHENA proposal strengths forming a new collaboration for **DETECTOR 1**
  - Ongoing process!

The evolution of the detector concept

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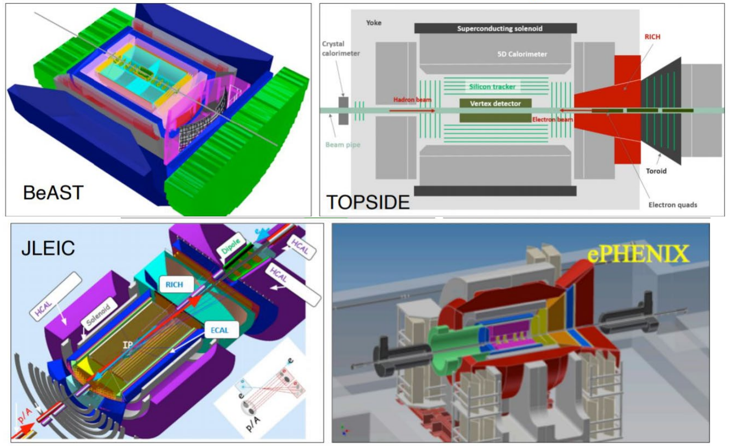

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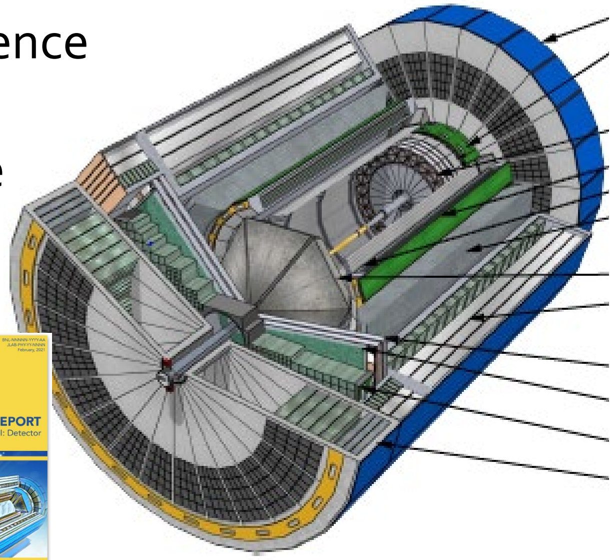

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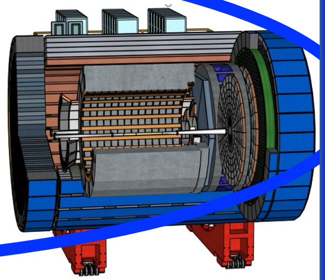

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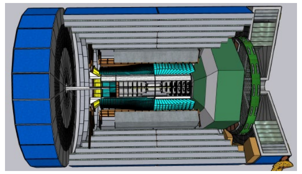

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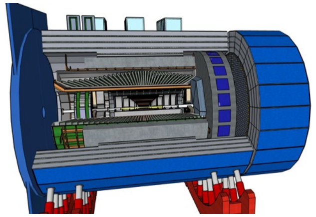

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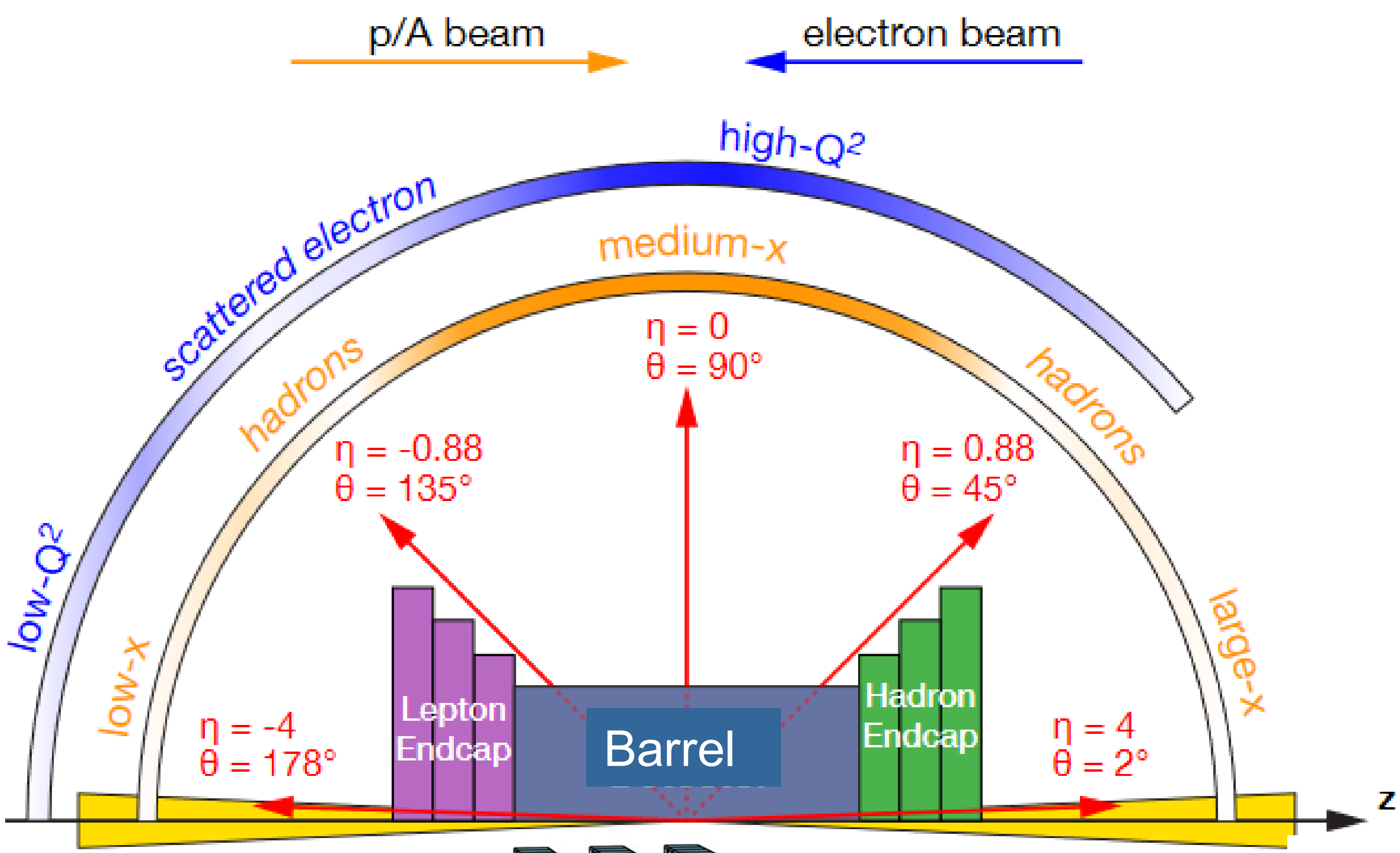
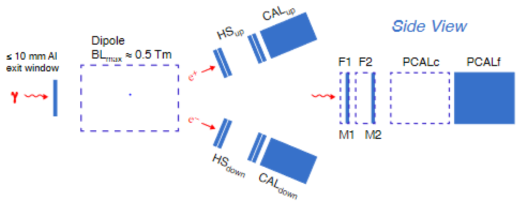
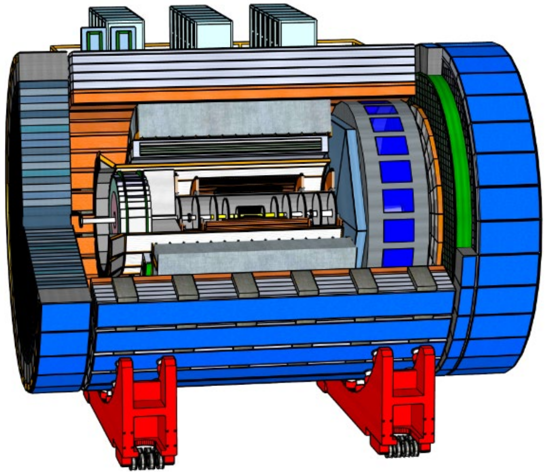
ATHENA DETECTOR



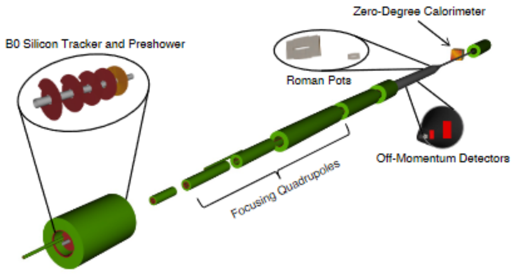
till ~ -40 m from IR

far - backward





Central detector
9.5 m long



far - forward

till ~ 40 m from IR

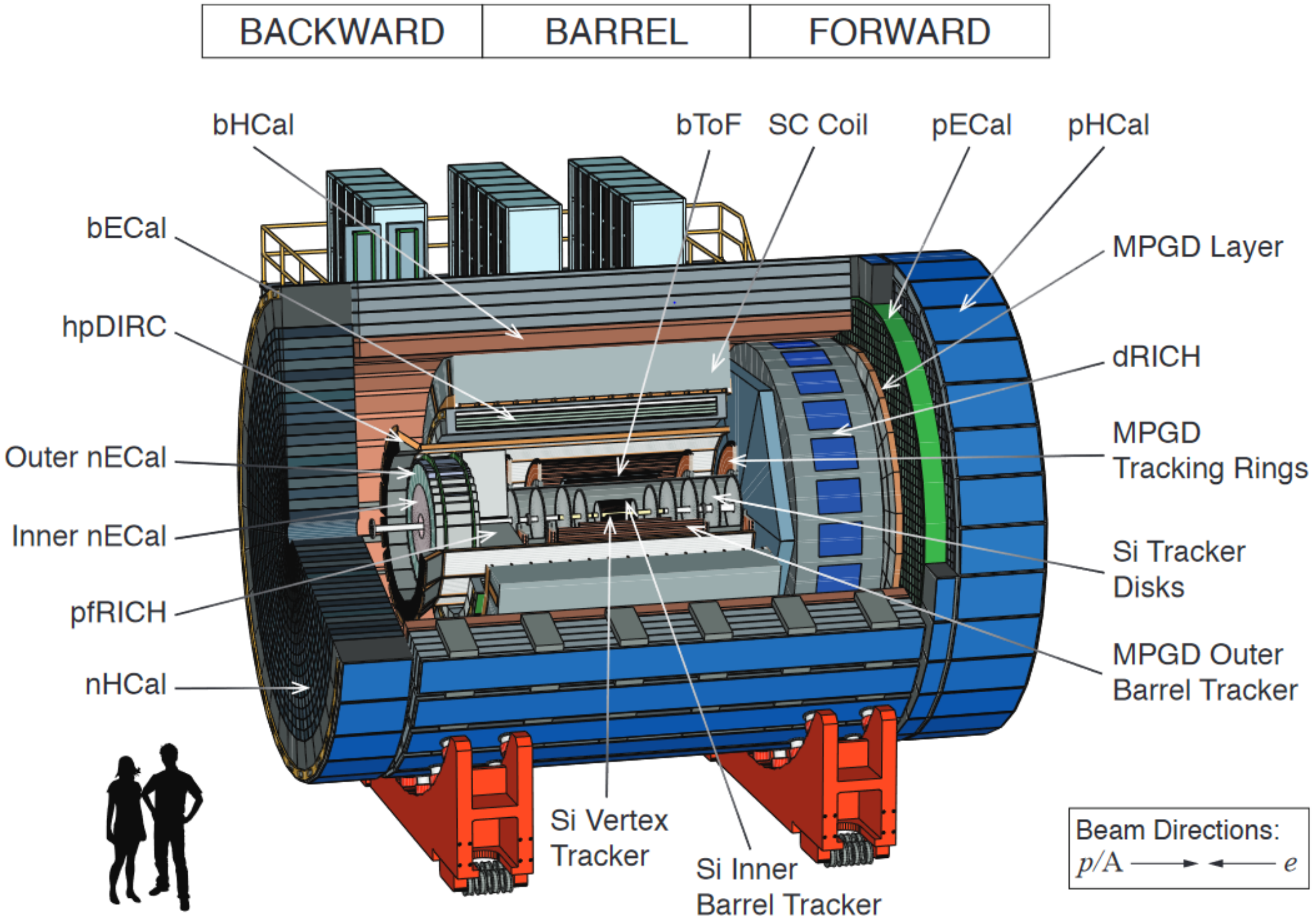
The ATHENA Detector

(by highlights)

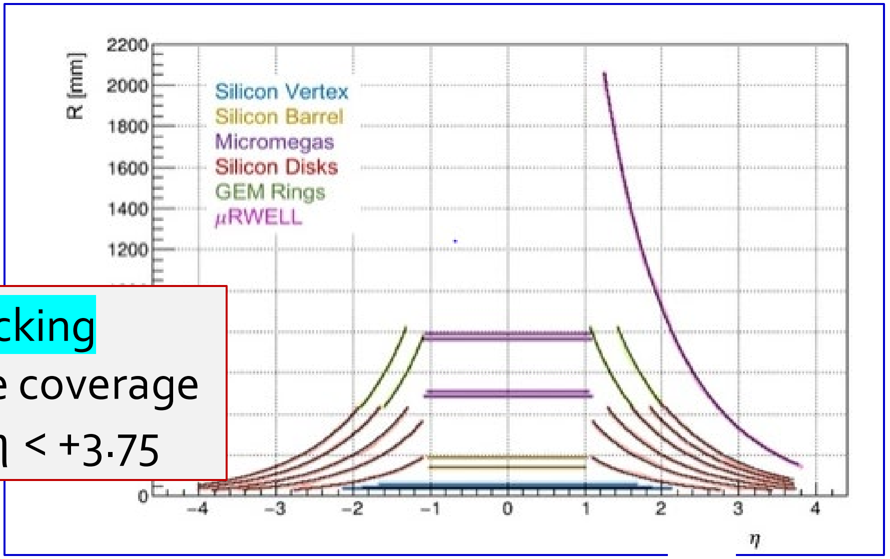
Central Detector Overview

- Highlights of the ATHENA design

  - Large-bore 3T solenoid, material budget in nuclear interaction length ~1.3 λ/λ_I
  - Hybrid tracking: Silicon pixel sensors by MAPS and state-of-the-art MPGDs
  - Calorimetry: Backward high-resolution crystal calorimeter / Barrel novel hybrid imaging/ sampling EM calorimeter / Forward high-energy jet reconstruction
  - PID: Large bore allows for layered, complementary, state-of-the-art PID technologies and innovative approach for single photon detection



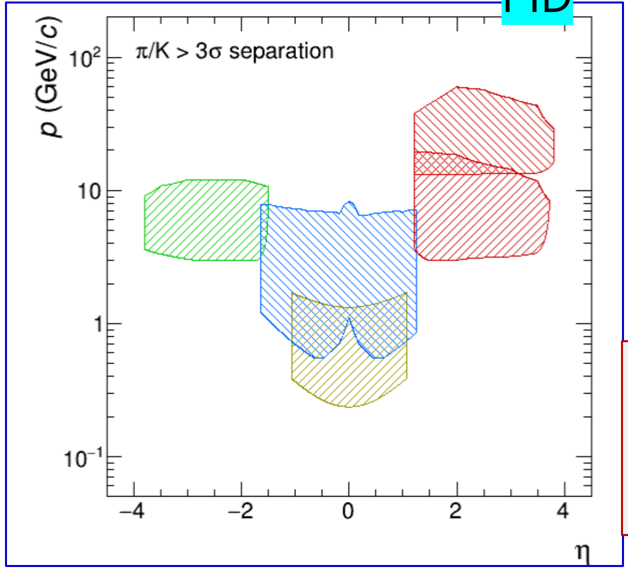
ATHENA – Central Detector acceptance



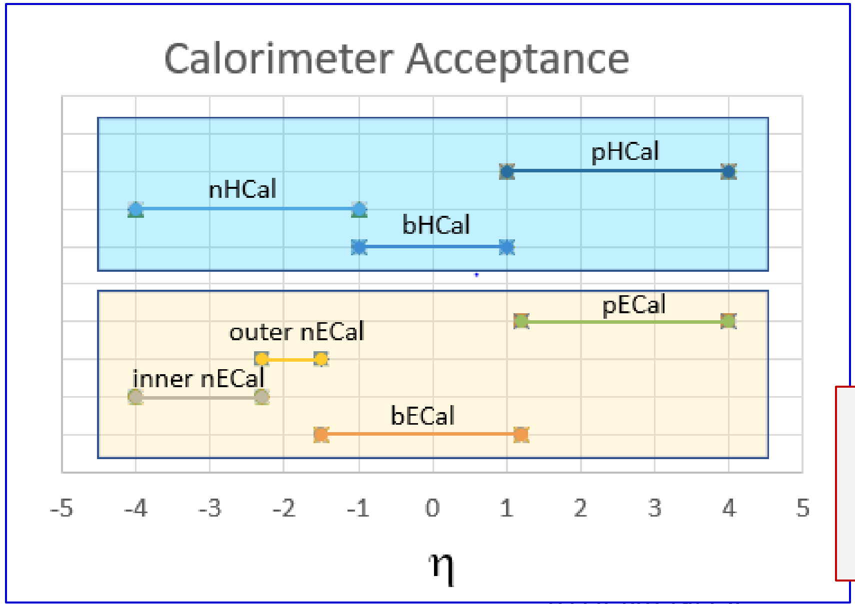
η

Tracking
Complete coverage
-3.8 < η < +3.75

PID



PID
Complete coverage
-3.8 < η < +3.7

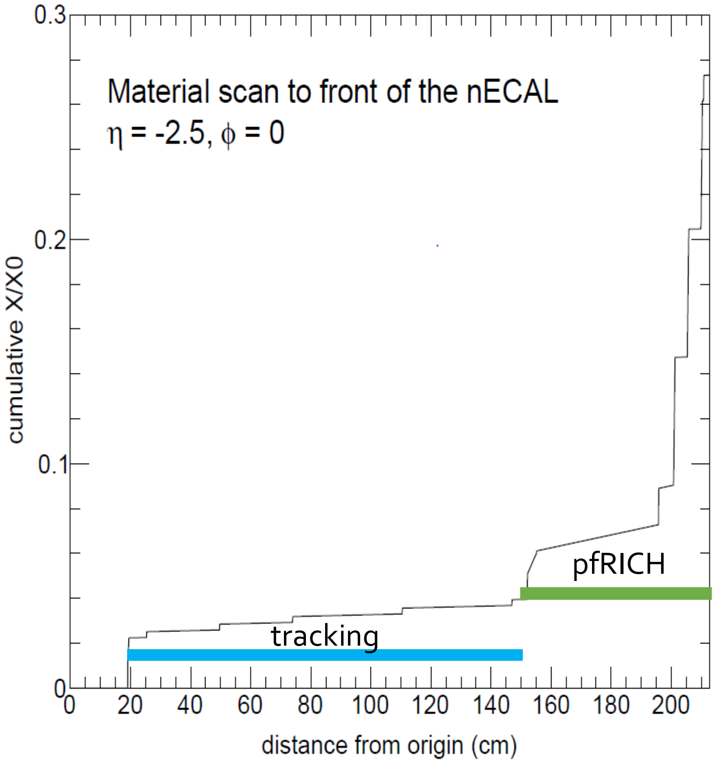


Calorimetry (E & H)
Complete coverage
-4 < η < +4

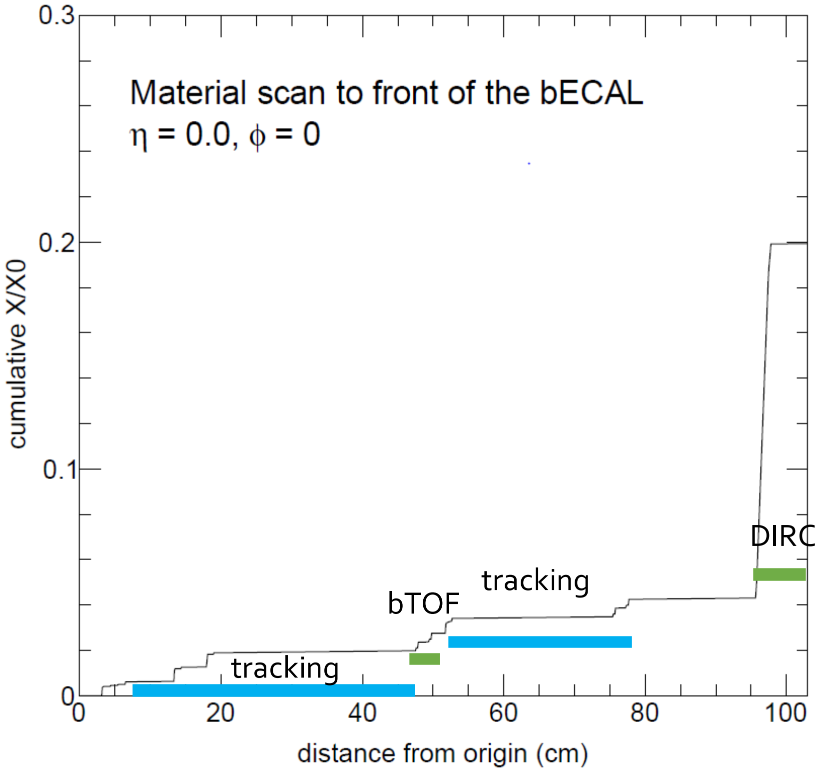
ATHENA – Material Budget in Central Detector

Material budget in front of ECals

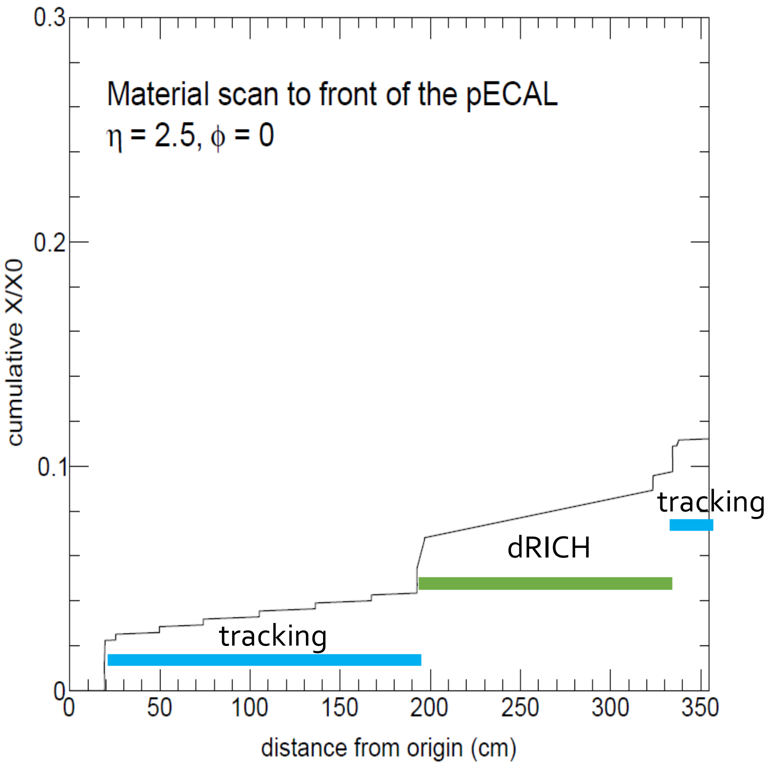
Backward endcap



Barrel



Forward endcap



ATHENA VERTEX & TRACKING, a description

Si Trackers *(from eRD16/eRD18/eRD25→eRD111)*

- **1 single technology**
- 65-nm technology MAPS (10 μm pitch, < 20 mW cm^{-2})
- Developed for ALICE ITS3
- EIC Si consortium (leadership within ATHENA)

- **Silicon Vertex**, 3 layers
  first layer @ R = 33 mm
  material: 0.05 X/X_0 / layer
- **Silicon barrel**, 2 layers
  material: 0.55 X/X_0 / layer
- **F & B Silicon disks**
  material: 0.24 X/X_0 / layer

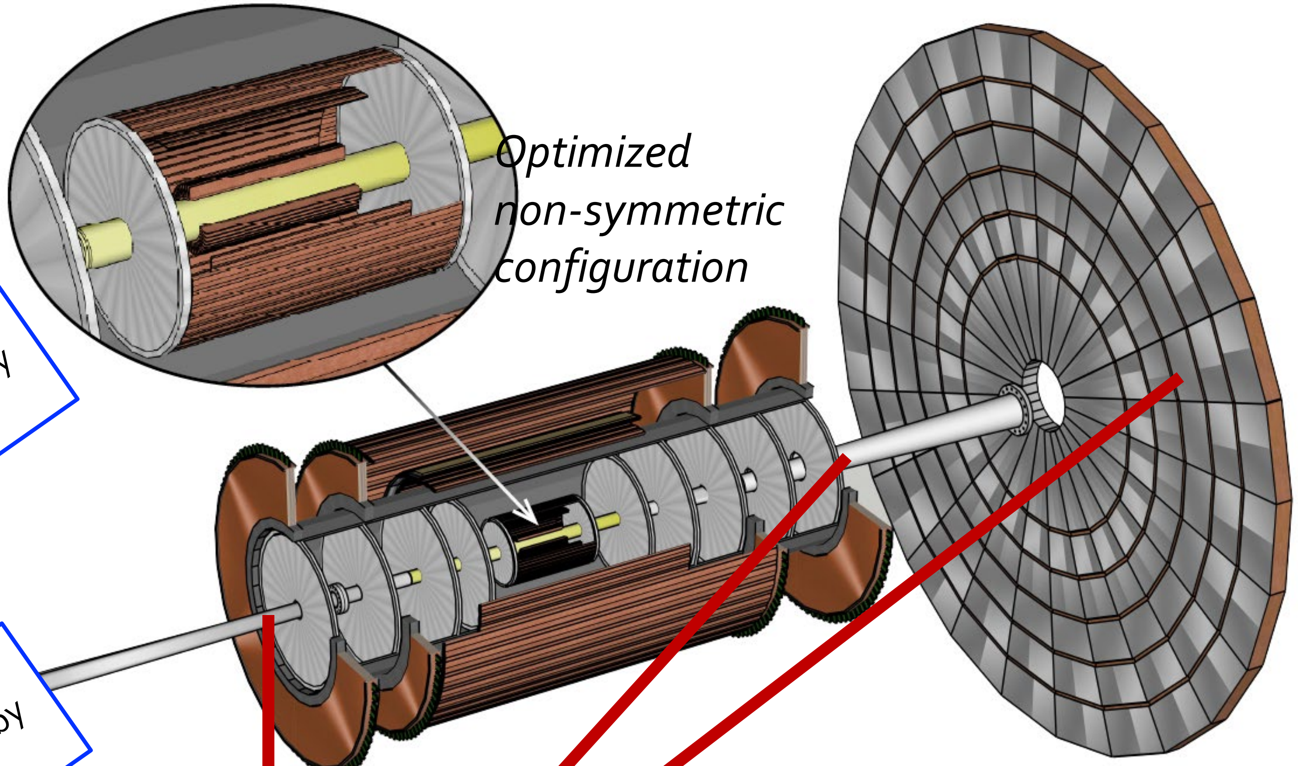
About MAPS in ATHENA
All details in the poster by
Giacomo Contin

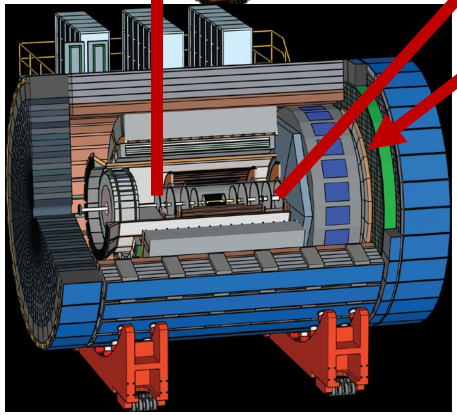
MPGDs *(from eRD3/eRD6→eRD108)*

- material < 1% X/X_0 / layer
- R&D needed for 2-D read-out

About MPGD in ATHENA
All details in the poster by
Matt Posik

- **barrel**, cylindrical, 2 x 2 layers, Micromegas
- **rings**, GEM
- **behind dRICH**, μRWELL





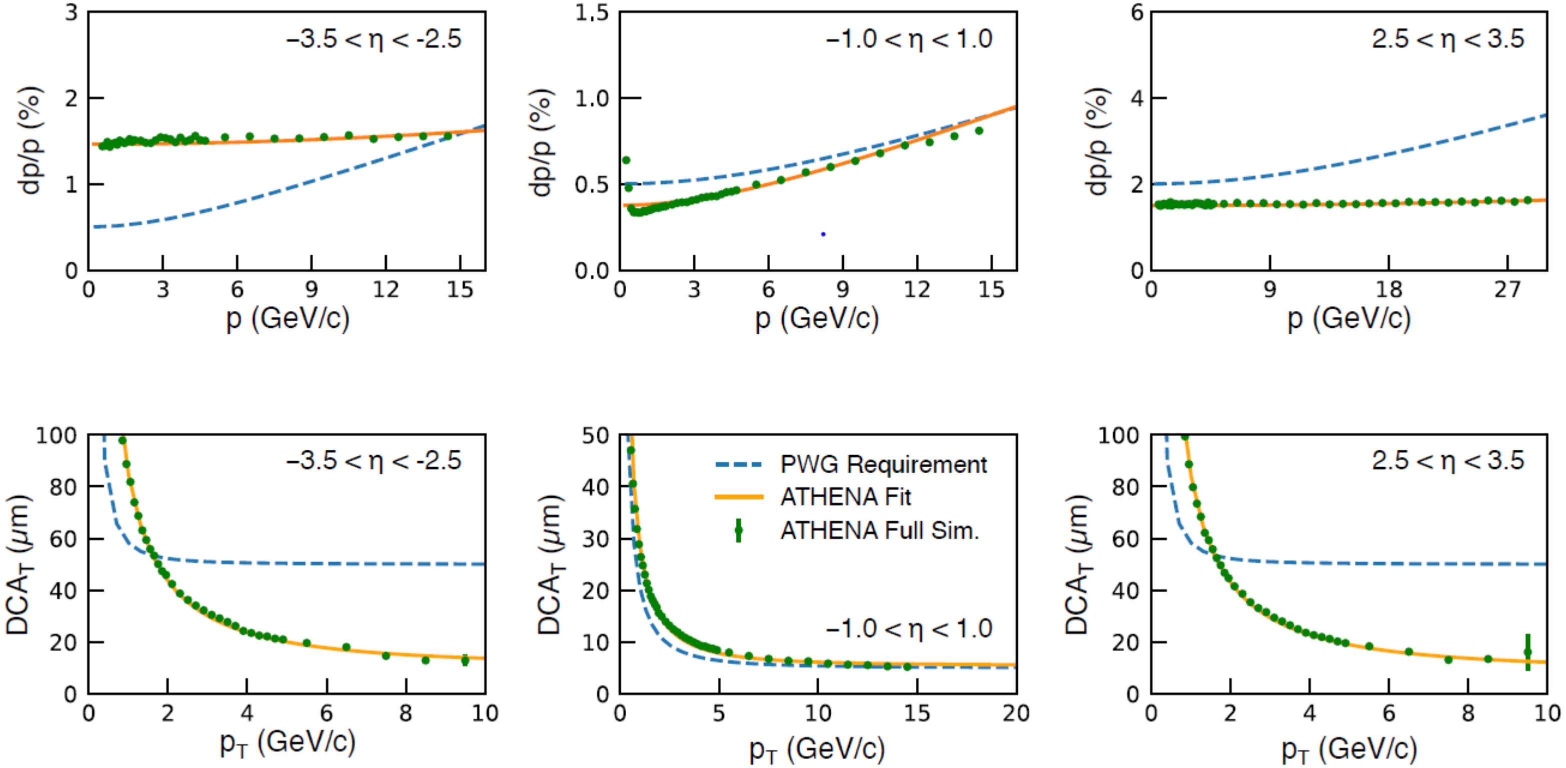
Additional space-point information (not included in present tracking studies)

- bTOF layer in front of Micromegas
- Imaging bECal, coordinate-measurement behind DIRC
- nECal high-granularity in the central region, behind pfRICH

ATHENA VERTEX &TRACKING, performances

Momentum resolution vs p in 3 η-bins

Transfer distance of closest approach to the primary vertex vs p in 3 η-bins



KEY INGREDIENTS for these PERFORMANCES

- High magnetic field / Maximized lever-arm/ Minimized material /Sensor pitch

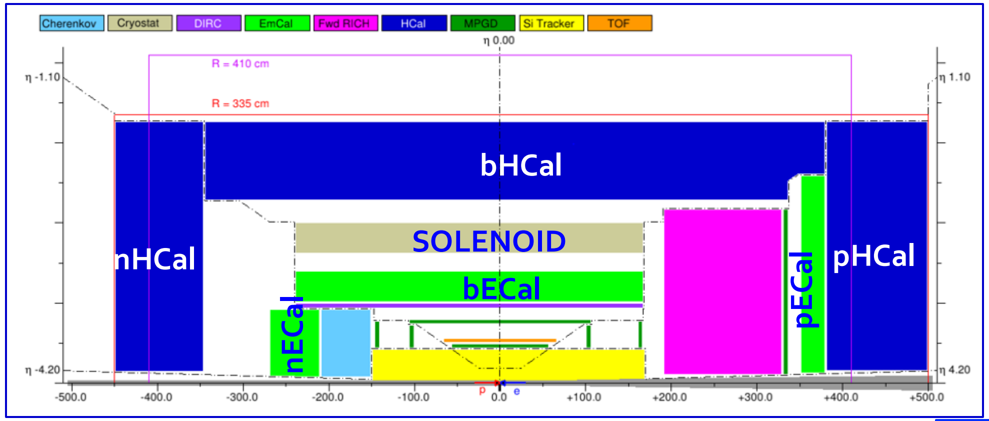
ATHENA Calorimetry, overview

- **Global characteristics of ATHENA Calorimetry:**
  - high granularity high resolution
  - Si PM sensors → fine time information

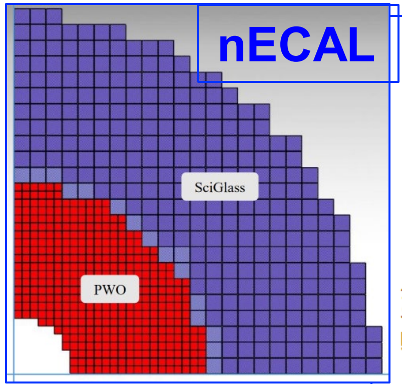
- **nECAL**
  - Finest resolution needed → PbWO4 crystals in the central part
  - eRD1→eRD105,eRD110 & EEEMCAL consortium

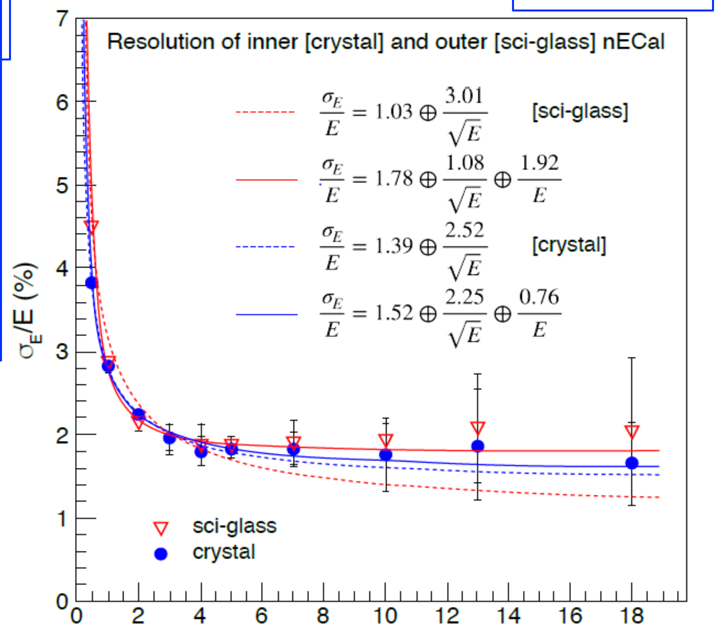
- **pECal & pHCAL,** compensated calorimeters
  - A global development, eRD1 → eRD107, eRD110
  - W/SciFi, Fe/Scint
  - Measurements of longitudinal shower development

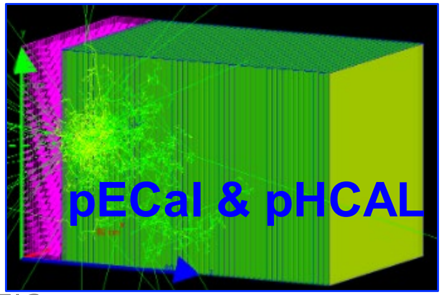
- **bHCal and nHCal**
  - Both Fe/Scint sandwich
  - Well established technology, no R&D needed
  - bHCal as tail catcher following bECal (~ 1 λ_I) and solenoid (~1.3 λ_I): 95 % of hadrons contained



nECAL





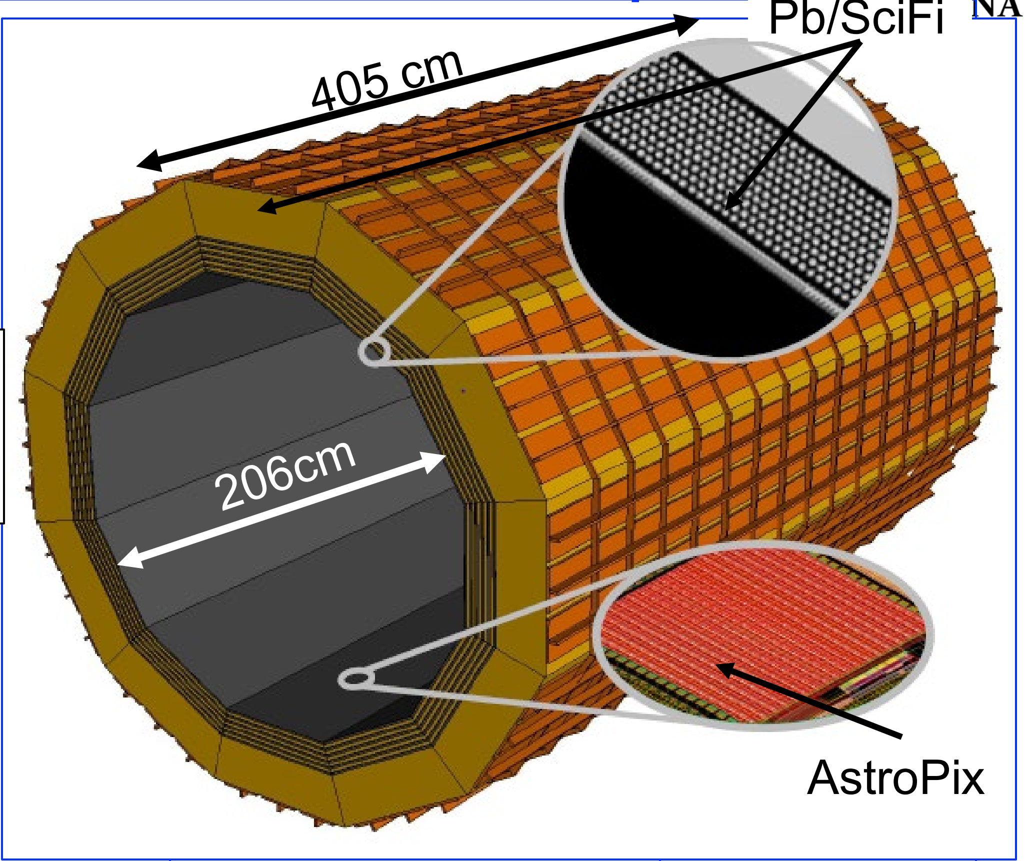


calorimeter stand alone

bECal (ECal in the barrel and part of backward endcap)

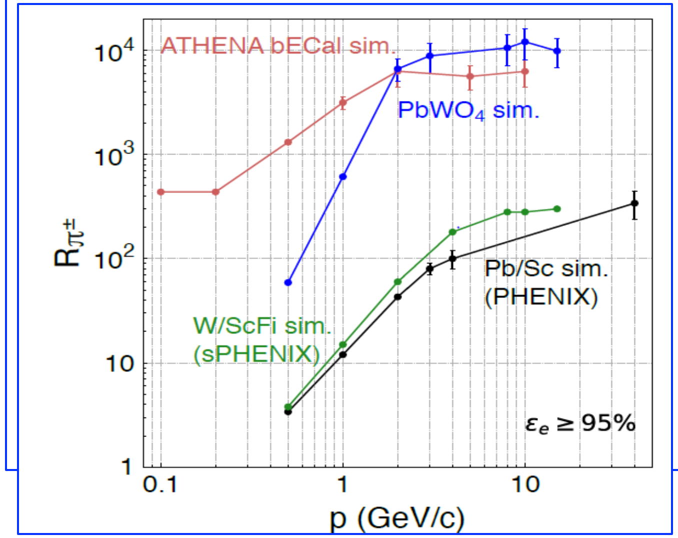
- Hybrid concept:
  - 6 imaging layer: AstroPix and Pb/SciFi
    - ✓ AstroPix, monolithic Si sensor, developed (from ATLASPix)
    - ✓ Pb/SciFi following KLOE, GlueX

also >1 λ_I contributing to bHCal

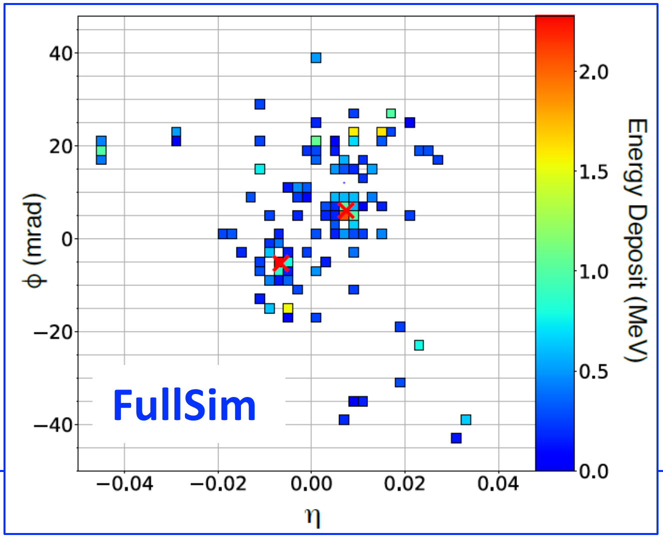


- Reconstruct scattered and secondary electrons
- Separate e/π
- Identify and reconstruct γ (also radiated from e)
- Identify π^0 also at high momenta

Separate e/π at low p



γ's from 15 GeV/c π^0 decay



expected performance

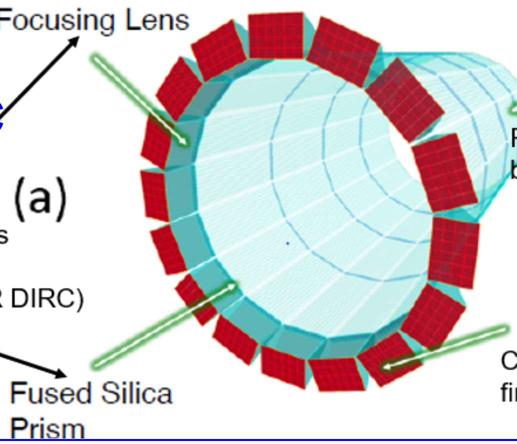
Energy Resolution	$5.5\%/\sqrt{E} \oplus 1\%^a$
e/π separation	$> 99.8\%$ pion rejection with 95% electron efficiency at $p \geq 0.1$ GeV/c^b.
E^γ_{min}	< 100 MeV^c
Spatial Resolution	Cluster position resolution for 5 GeV photons at normal incident angle is below $\sigma = 2$ mm (at the surface of the stave $r = 103$ cm) or 0.12°. For comparison, the minimal opening angle of photons from $\pi^0 \to \gamma\gamma$ at 15 GeV is $\sim 1.05°$ (about 19 mm – 37 pixels – of separation at $r = 103$ cm).

PID in ATHENA detector

barrel

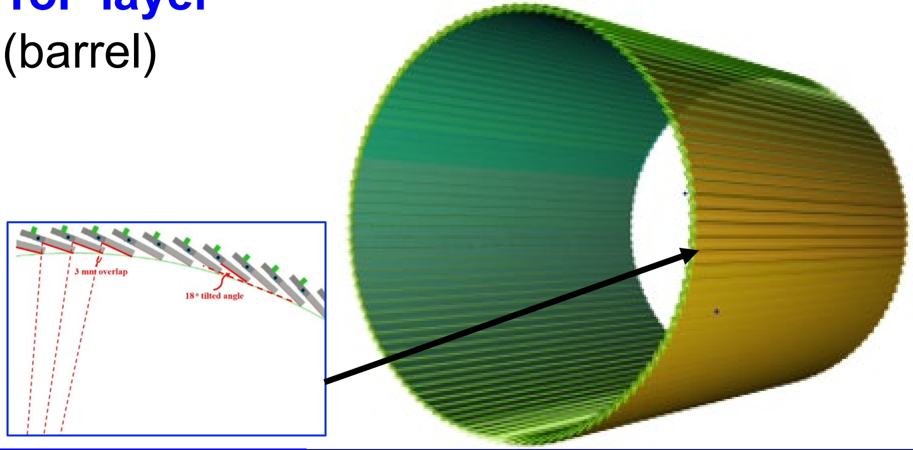
hpDIRC (barrel)

Prism & lenses allow focusing (not in BABAR DIRC)

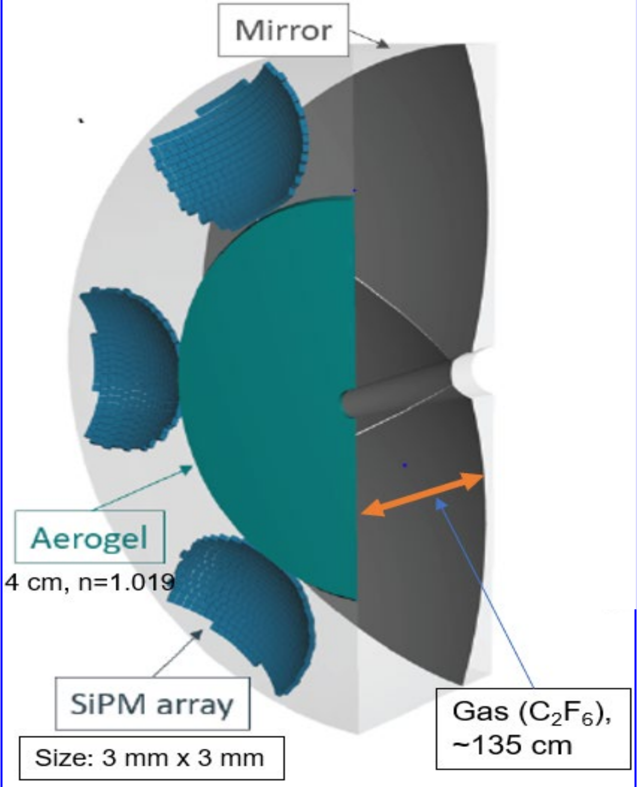


AC-LGAD ToF layer (barrel)

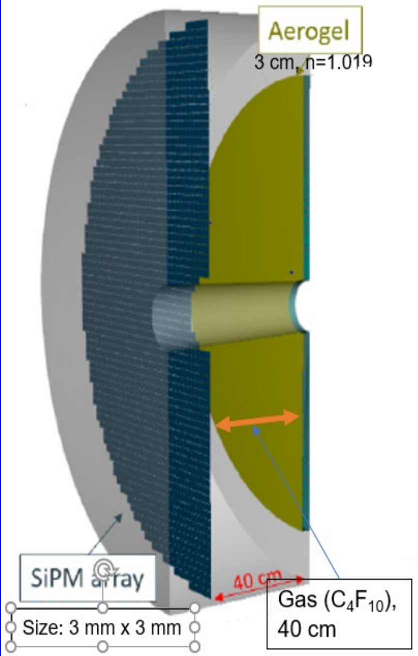
AC-LGAD: adding fine pixelization to LGAD (synergies with FF sensors)



dRICH (forward)



pfRICH (backward)



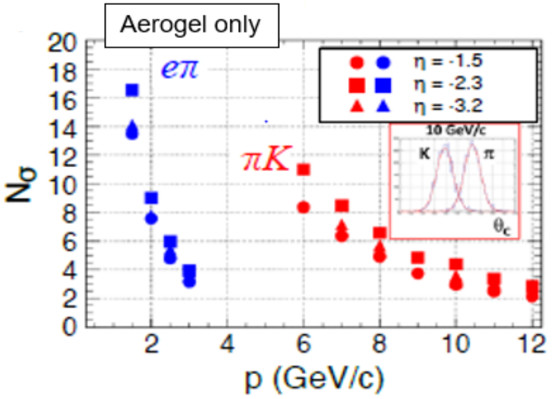
dRICH & pfRICH, large overlap of technologies

- SiPMs
- Aerogel
- Radiator gas

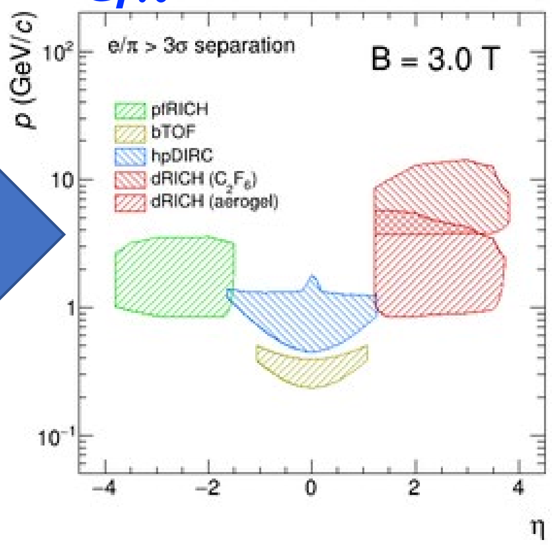
PID momentum acceptance

EXAMPLE:

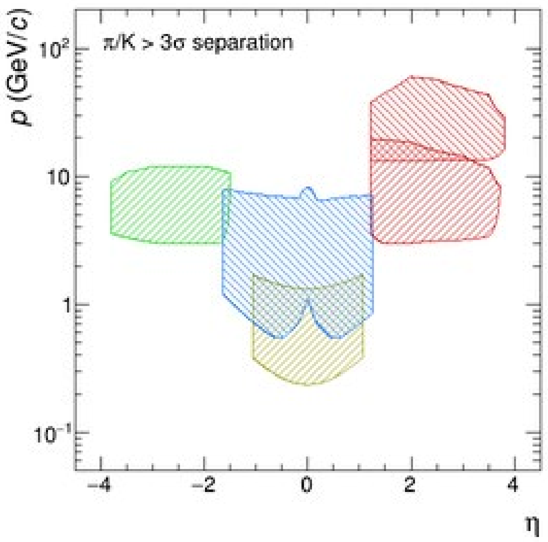
pfRICH, **FullSim**



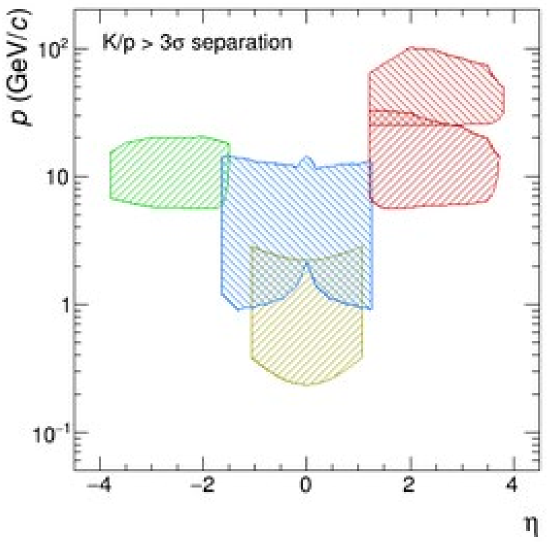
e/π



π/κ

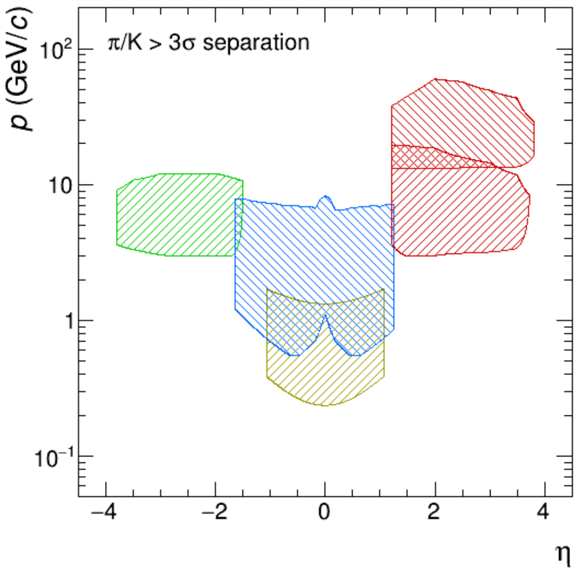


κ/p



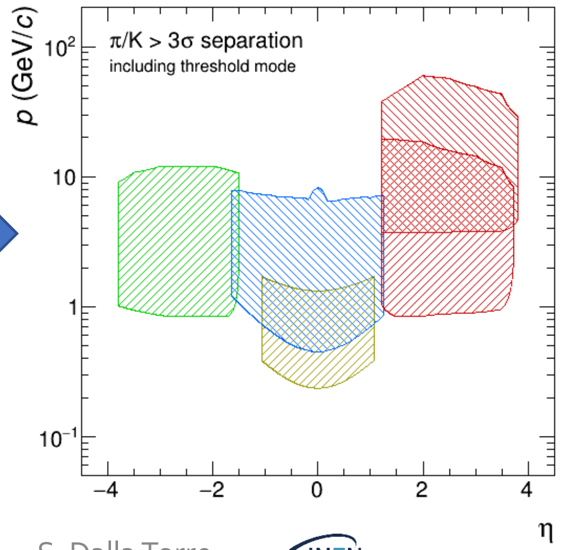
With positive identification of the higher mass particle in the couple

π/κ



Using also the Cherenkov threshold information

π/κ

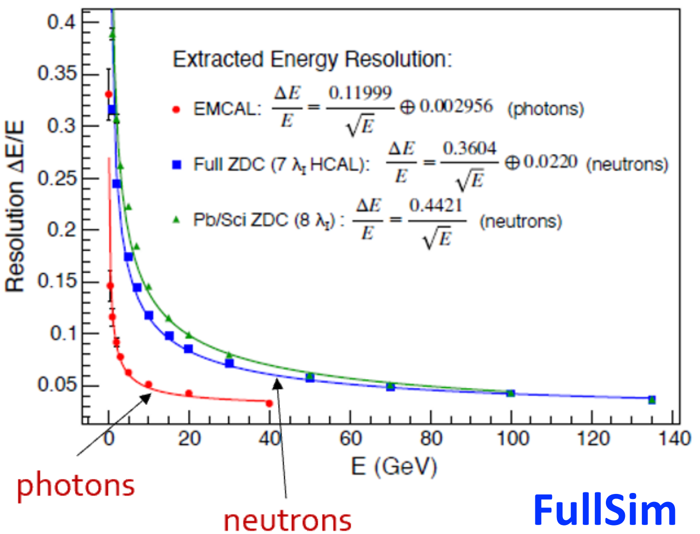


FAR FORWARD instrumentation

$\eta > 4.0$

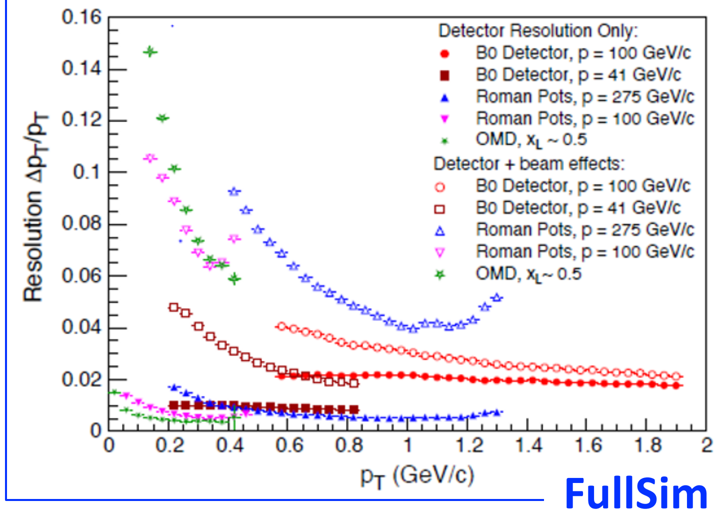
Detector	θ accep. [mrad]	Rigidity accep.	Particles	Technology
B0 tracker	5.5–20.0	N/A	Charged particles Tagged photons	MAPS AC-LGAD
Off-Momentum	0.0–5.0	45%–65%	Charged particles	AC-LGAD
Roman Pots	0.0–5.0	60%–95%*	Protons Light nuclei	AC-LGAD
Zero-Degree Calorimeter	0.0–4.0	N/A	Neutrons Photons	W/SciFi (ECal) Pb/Sci (HCal)

ZDC

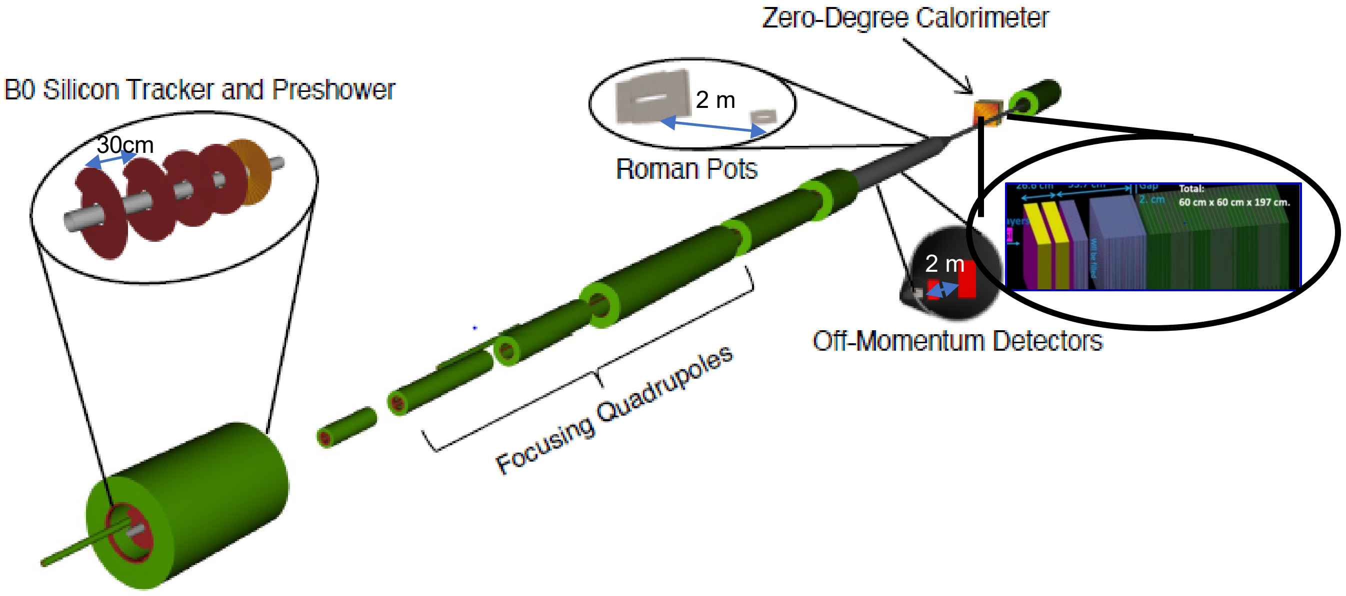


FullSim

FF trackers

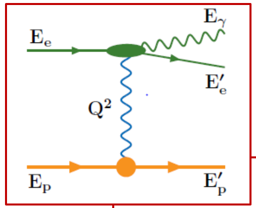


FullSim

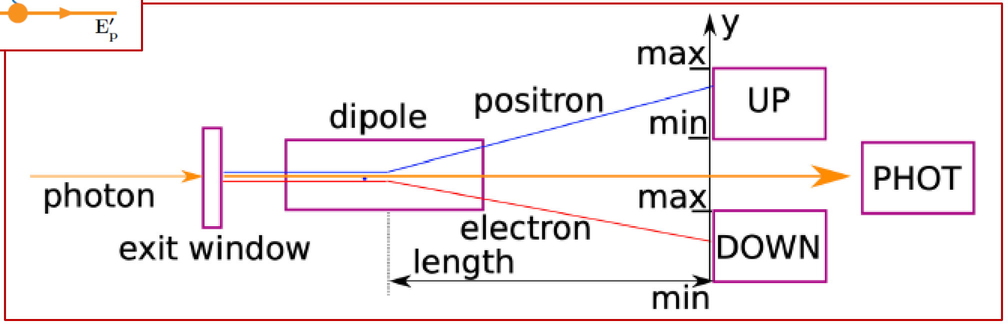


FAR BACKWARD

- measure IP6 luminosity with **an absolute precision better than 1% absolute and a relative precision better than 0.01%** using the electron-ion bremsstrahlung by three largely independent and complementary measurements
- electron detectors will also be used to tag low-Q^2 Events (photoproduction) in ATHENA



principle



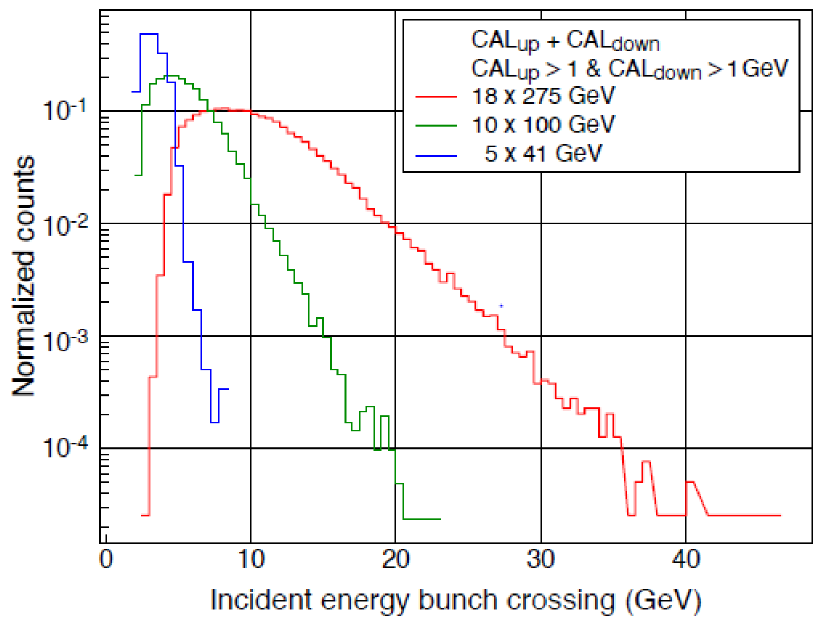
Technologies for the calorimetry:

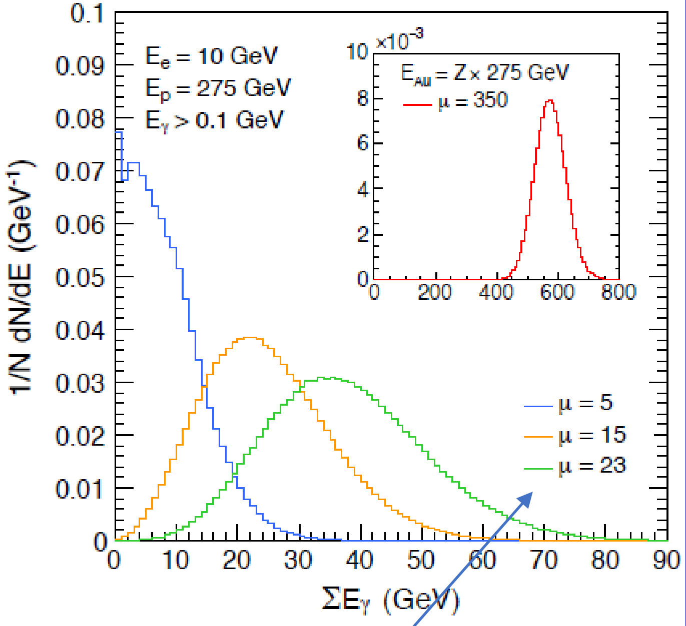
- Spaghetti W-calorimeter with radiation-hard scintillating fiber, read out with fast PMTs
- Cherenkov-radiating quartz fibers read out by SiPMs

different CM energy

PHOT

different Luminosity





FullSim

$L = 2.2$, 6.5 and 10×10^{33} cm^{-2}s^{-1}, corresponding to the average photon multiplicity μ

ATHENA **PERFORMACE** for **PHYSICS**

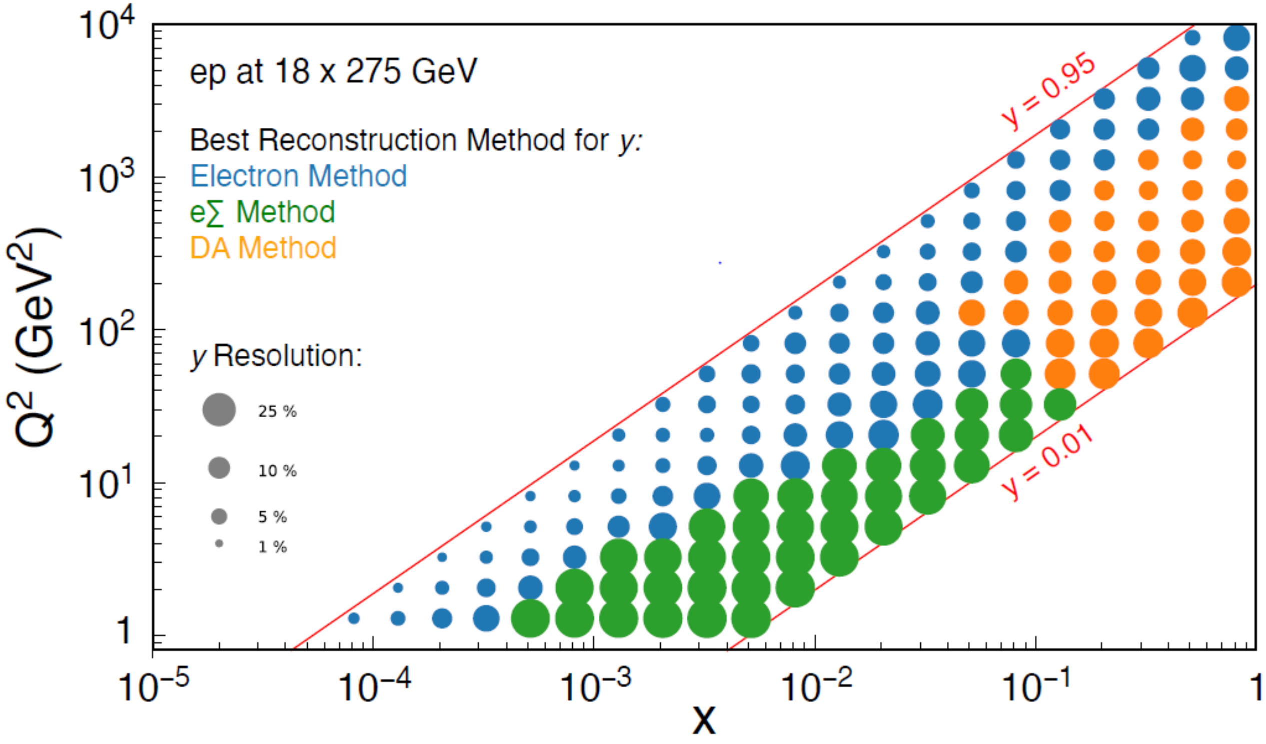
(selected items)

ACCEPTANCE AND PERFORMANCE for DIS

DIS resolution in the (x, Q^2) plane

- reconstruction via e only for NC, y not too small – **key:** ECal performance
- Reconstruction with support of hadrons (small y) - **key:** good reconstruction of the whole h final state
- For large QED radiation correction regions and CC, h detection only – **key:** good reconstruction of the whole h final state

Resolution in y
(reminder: $Q^2 \approx sxy$)

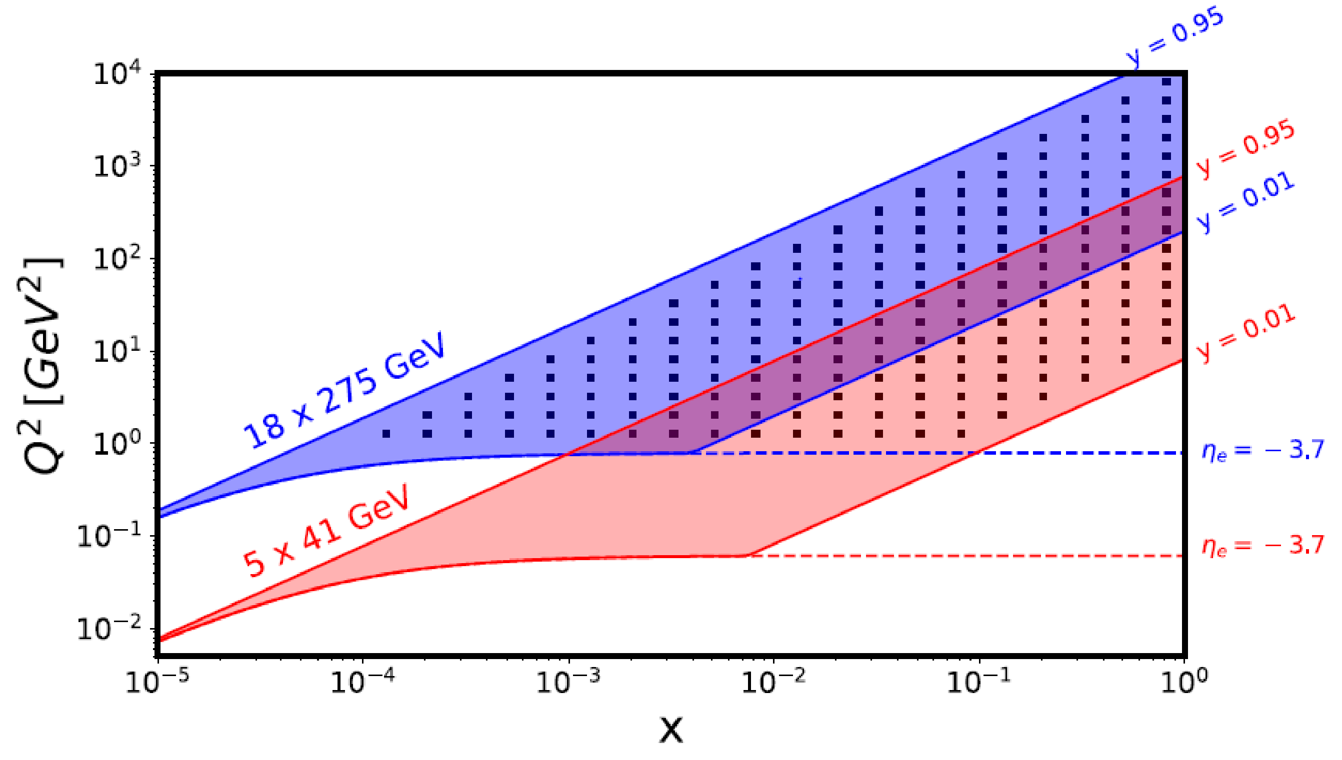


DIS reach in (x, Q^2) plane

ep SCATTERING, 100 fb^{-1} (=1 y of data taking)

[Q^2 > 1 , 0.01 < y < 0.95]

- grid of points: simulated unpolarized measurements
- negligible statistical error
- 1.5-2.5% systematic error point to point



inclusive NC cross section:

the fundamental ingredient for measurement of:

- collinear **parton densities**
- semi-inclusive, exclusive and hadronic final state **cross section**

Electron Identification

Sample purity respect to main background source, i.e. pions

Included in this study:

- NC DIS events from PYTHIA6
- ECal performance
- Kinematic cuts:

  Isolation of the scattered electron

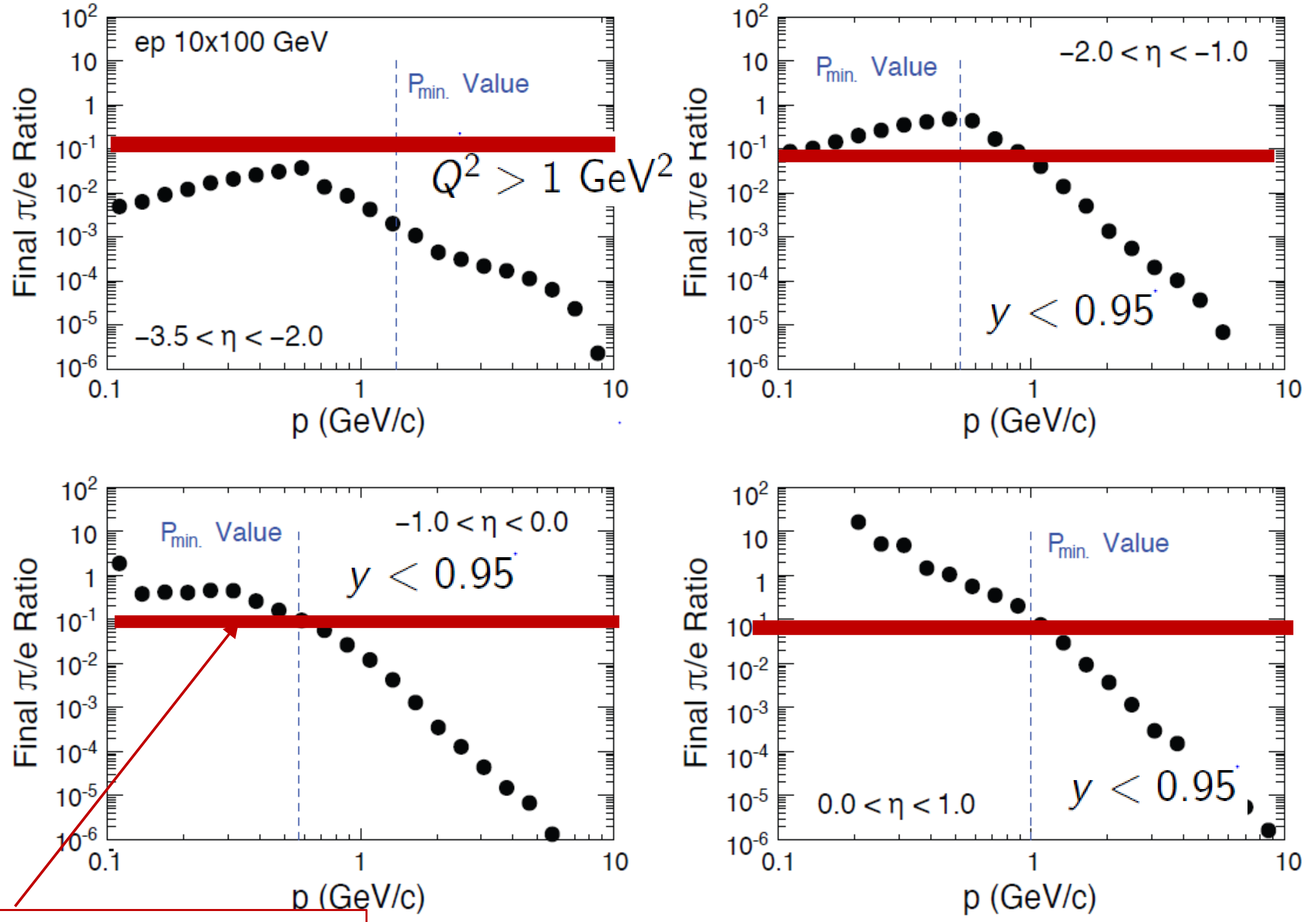
  e – Σ check

Not included:

- Contribution to e/π separation from PID devices

Final π- / e ratio

FastSim



10% contamination

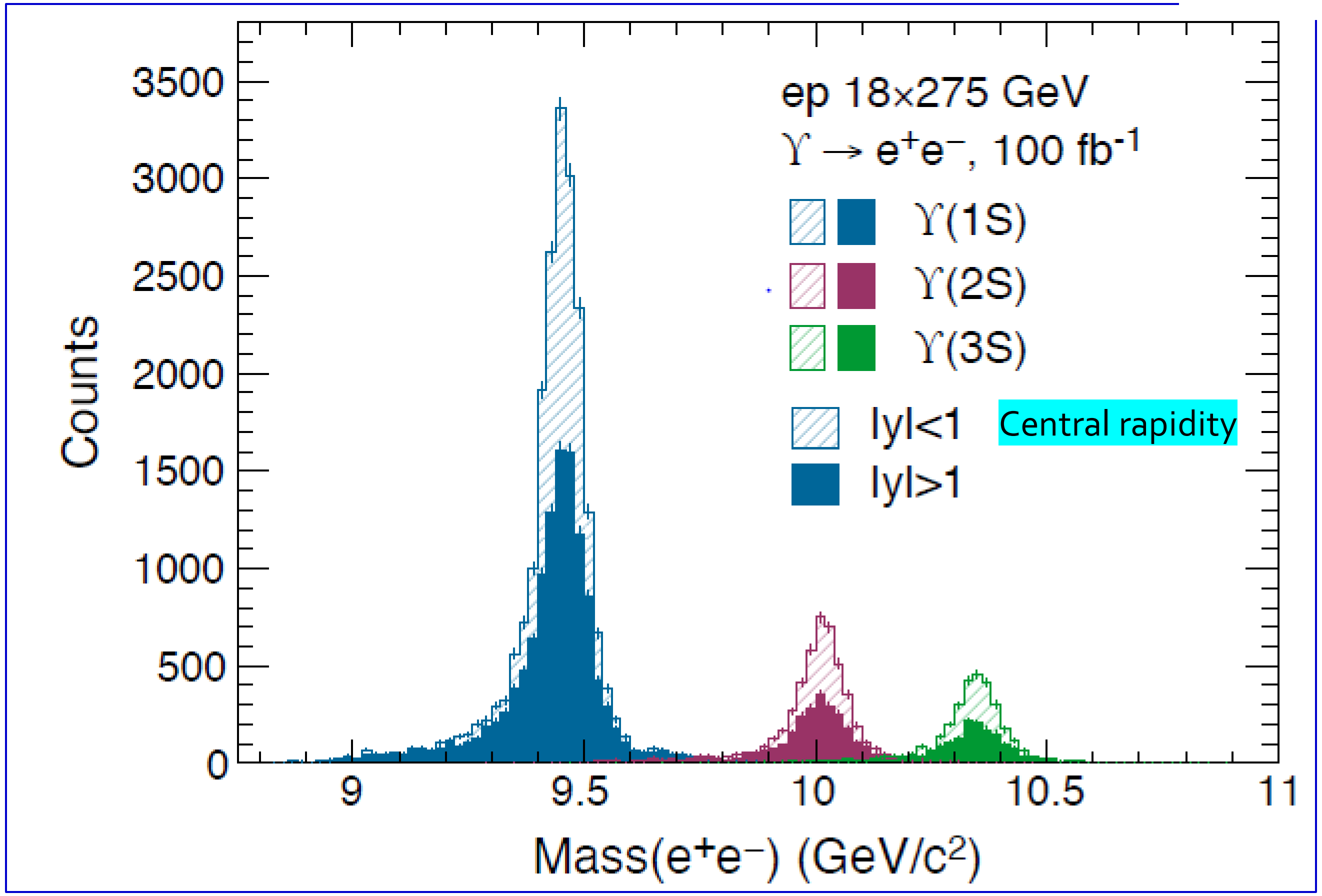
Lepton-pair invariant-mass resolution

Resolution demonstrated in the plot

- only a small low-mass shoulder from bremsstrahlung is observed
- possibility for correction with more advanced analysis (key is bECal)

Key for excellent resolution: low-mass tracking (including beam pipe)

FullSim



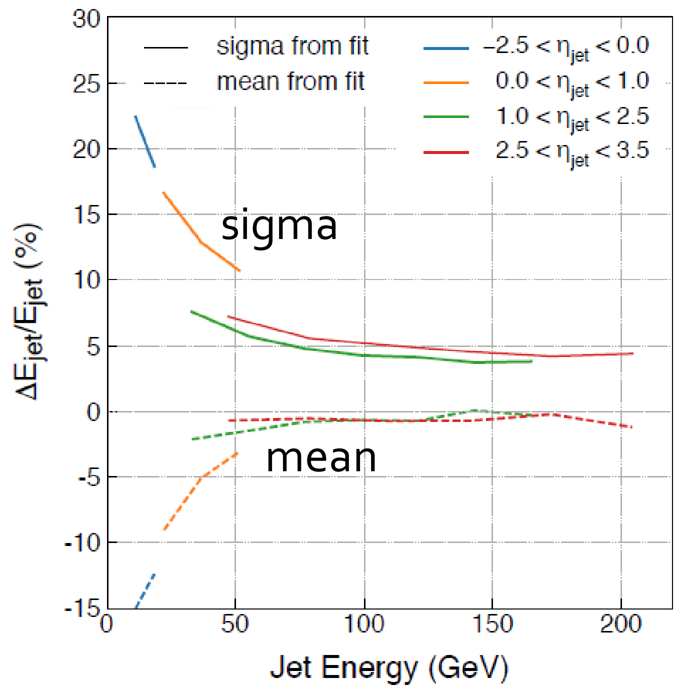
Jet reconstruction

Jets reconstructed with anti-k_T algorithm, R = 1.0, with energy-flow reconstruction

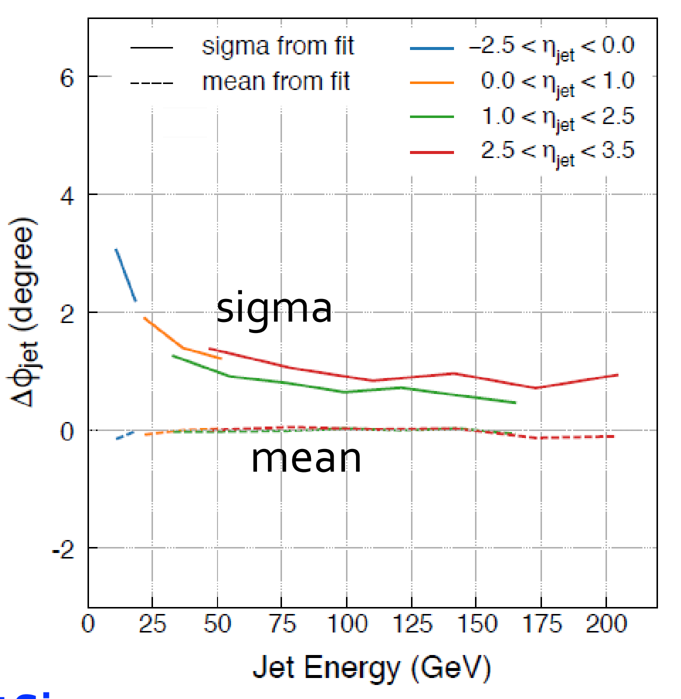
- Jet energy resolution better than 10% for E_{jet} > 40 GeV
- Jet azimuthal angle resolution better than 1 degree for E_{jet} > 25 GeV
- Low E_{jet} affected by threshold
- Very high E_{jet} affected by acceptance

KEY - tracking and calorimetry resolution

relative jet energy resolution



jet azimuthal angle absolute resolution



FastSim

Charm reconstruction, secondary vertices

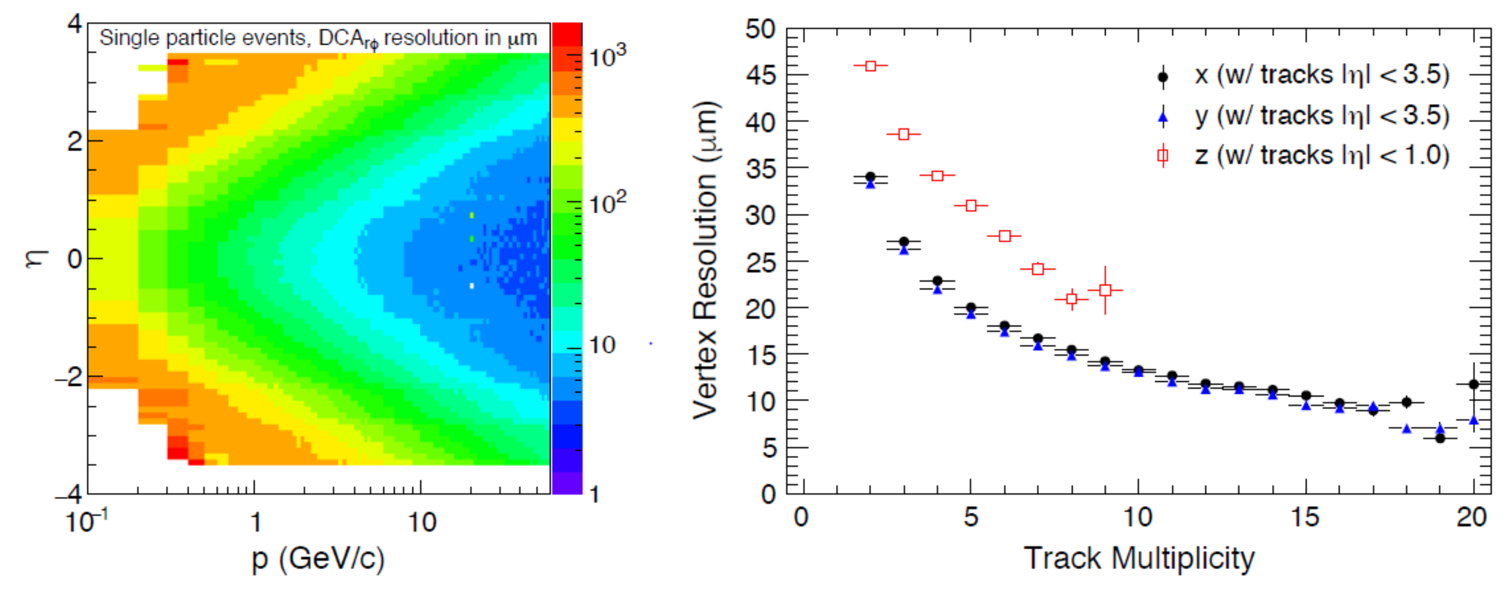
for secondary decays, for example, D^0 reconstruction

Key - resolution and low mass vertexing layers

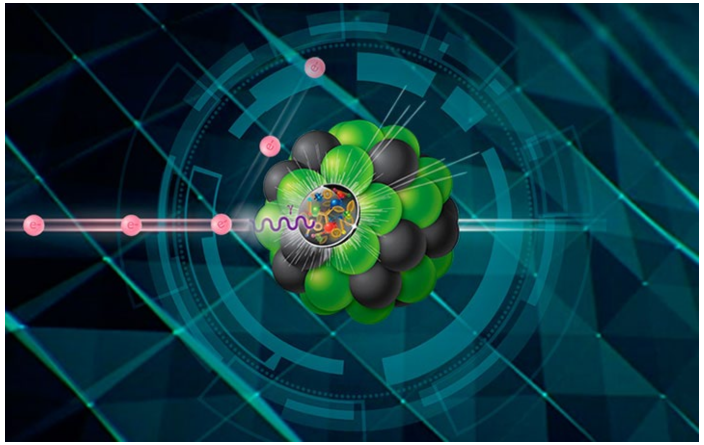
Single particle, resolution
Distance of Closest Approach (μm)

Longitudinal and transversal
Vertex resolution (μm)
vs track number

- displaced-track resolutions →
- Secondary decay reconstruction (D^0, …)
- good charm-jet tagging based on a displaced track counting
- charm efficiency 10% - 30% for 5-30 GeV/c, excellent purity (misidentification < 1%)



SUMMARY and PERSPECTIVES



- We have reported about the ATHENA effort
  - As underlined, more efforts in parallel
- Review of EIC detector proposals concluded in March 2022
- Merging of ATHENA and ECCE proposal strengths forming a new collaboration for DETECTOR 1
  - Ongoing process!
- 2nd experiment (DETECTOR 2) planned on a different timescale
  - CORE proposal a starting point
- Preparation of pre-TDR / TDR in front of us
  - A very exciting time is ahead of us to explore the structure and dynamics of matter at a new ep/eA collider facility, following years of preparation!
- Great opportunities for physics and frontier detectors → **Join us!**