ATHENA Proposal

A Totally Hermetic Electron Nucleus Apparatus proposed for IP6 at the Electron-Ion Collider

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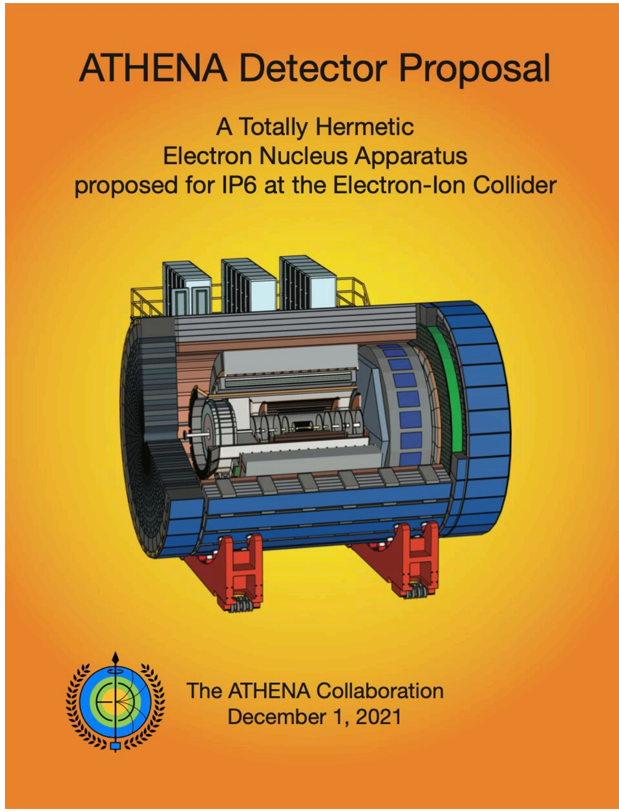
The ATHENA Proposal

- **Submitted on December 1st, 2021**
  - *within "Call for Proposal" dead-line*
  - *not (yet) a public document*
  - *available to all ATHENA collaborators*

- Presented at the DPAP (Detector Proposal Advisory Pannel) meeting
  - ✓ *December 13-15, 2021*
  - *Three ATHENA talks:*
    1. *Science, detector technology, performance by simulations (*Silvia Dalla Torre)
    2. *R&D and potential upgrade path (*Thomas Ullrich)
    3. *Collaboration & structure, cost & schedule(*Bernd Surrow)
  - *Slides available at:*

    https://indico.bnl.gov/event/13614/



The ATHENA Proposal, **STRUCTURE**

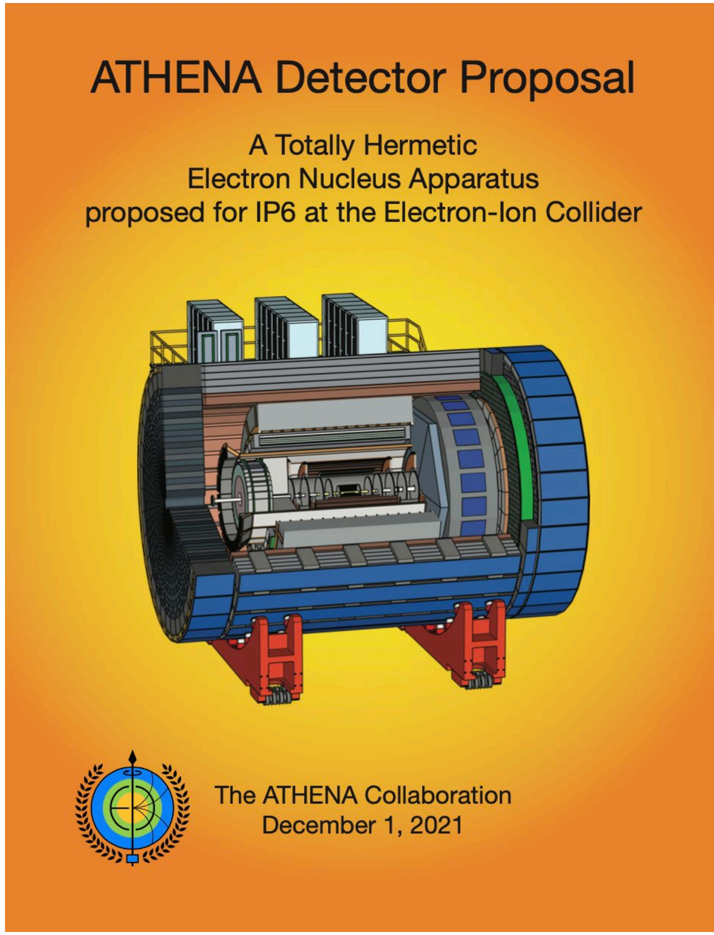
Reported in this talk in short form

- Introduction to ATHENA
- → The ATHENA Detector
- EIC Science with ATHENA
- → Collaboration
- → Cost and Schedule
- Acknowledgments

The Proposal

- Glossary
- Collaboration → *Authors (INFN: 71/ 438)*
- Detector Challenges
- Costing
- References

Appendices



SUPPLEMENTAL MATEREIAL: https://wiki.bnl.gov/athena/index.php/Supplemental_Material

The ATHENA Detector

What characterizes ATHENA, PHYSICS REACH

ATHENA

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

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities - Saturation

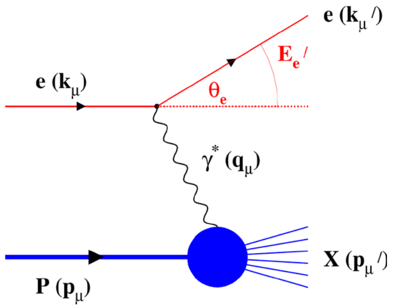
Spin and Flavor structure of nucleons and nuclei

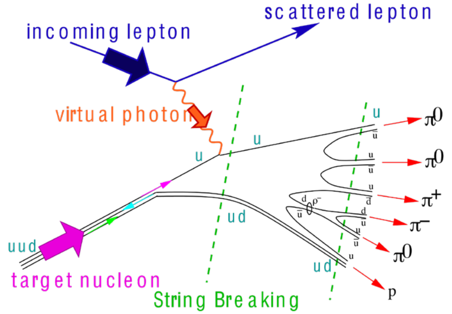
Tomography Transverse Momentum Dist.

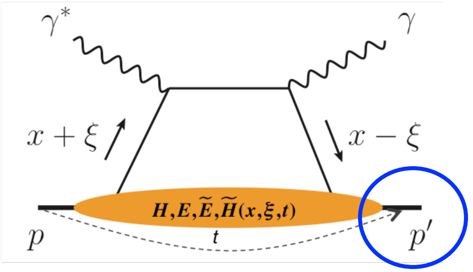
QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

process







inclusive DIS

- Detect and measure the scattered lepton
- hermeticity and h reconstruction
- jet reconstruction
- Acceptance & resolution for multi-dimensional binning: x, Q^2

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, Q^2, z, p_T, Θ

exclusive processes (small cross-sections)

- measure all particles in event
- tagging nuclear fragments for background suppression
- e/p separation for background suppression
- identify hadron for background suppression
- Acceptance & resolution multi-dimensional binning: x, Q^2, t, Θ

Detector Requirements, *Including jet rec.onstruction*

$\int$Ldt:

	inclusive DIS	semi-inclusive DIS	exclusive processes
$\int$Ldt:	**1 fb^{-1}**	**10 fb^{-1}**	**10 - 100 fb^{-1}**

What characterizes ATHENA, PHYSICS REACH

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

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities

Spin and Flav...

...ography ...patial ...aging

process

DETECTOR REQUIREMENTS FROM THIS ANALYSIS
→ALL MATCHED BY THE ATHENA DETECTOR

Detector Requirement *Including jet rec.onstruction*

...ertex resolution to reconstruct heavy hadron decays

• Acceptance & resolution for multi-dimensional binning: x, Q^2, z, p_T, Θ

...mall cross-sections)

...ent

...agments for background suppression

• e/p separation for background suppression

• identify hadron for background suppression

• Acceptance & resolution multi-dimensional binning: x, Q^2, t, Θ

$\int Ldt$:

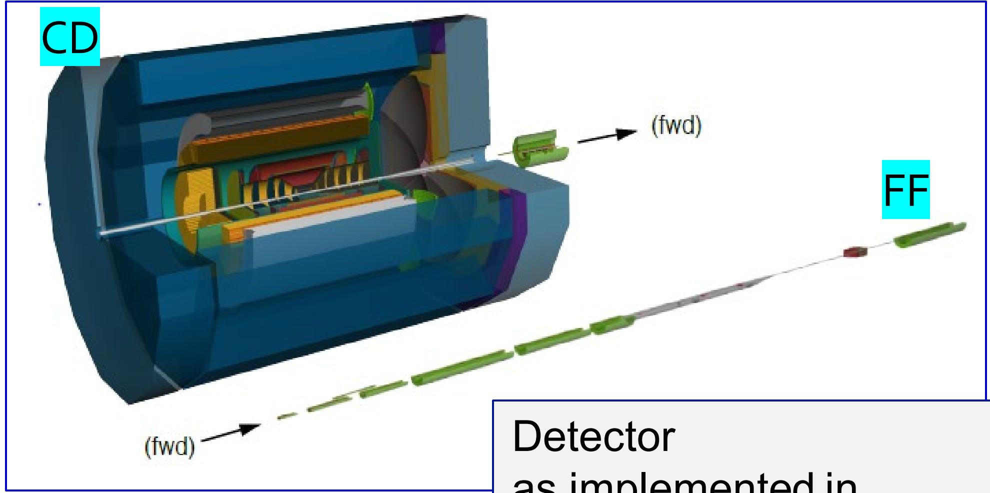
1 fb^{-1}

10 fb^{-1}

10 - 100 fb^{-1}

What characterizes ATHENA: **DETECTOR**

- INCLUDES
  - **CENTRAL DETECTOR** (CD)
  - **Far Forward** (FF) & **Far Backward** (FB) subdetectors



Detector
as implemented in
GEANT4 the FullSim

- **ATHENA DETECTOR matches ALL REQUIREMENTs** for EIC physics program by
  - Light, large-bore 3-T solenoid
  - Fully exploiting the IP6 potentialities (longitudinal and transversal space)
  - Careful choice of technologies, **several innovations since CDR/YR "reference"**
  - acceptance and hermeticity in CD:
    - ✓ careful integration of support structures and detector services to minimize gaps

- **Robust and realistic Detector**
  - careful balance between cutting-edge and mature technologies
  - Largely newly-built detectors that guarantee reliability over 10 y and more
  - Detector and support/services principle allowing for assembly/maintenance interventions

Getting familiar with the ATHENA detector

Solenoid

Barrel Tracking

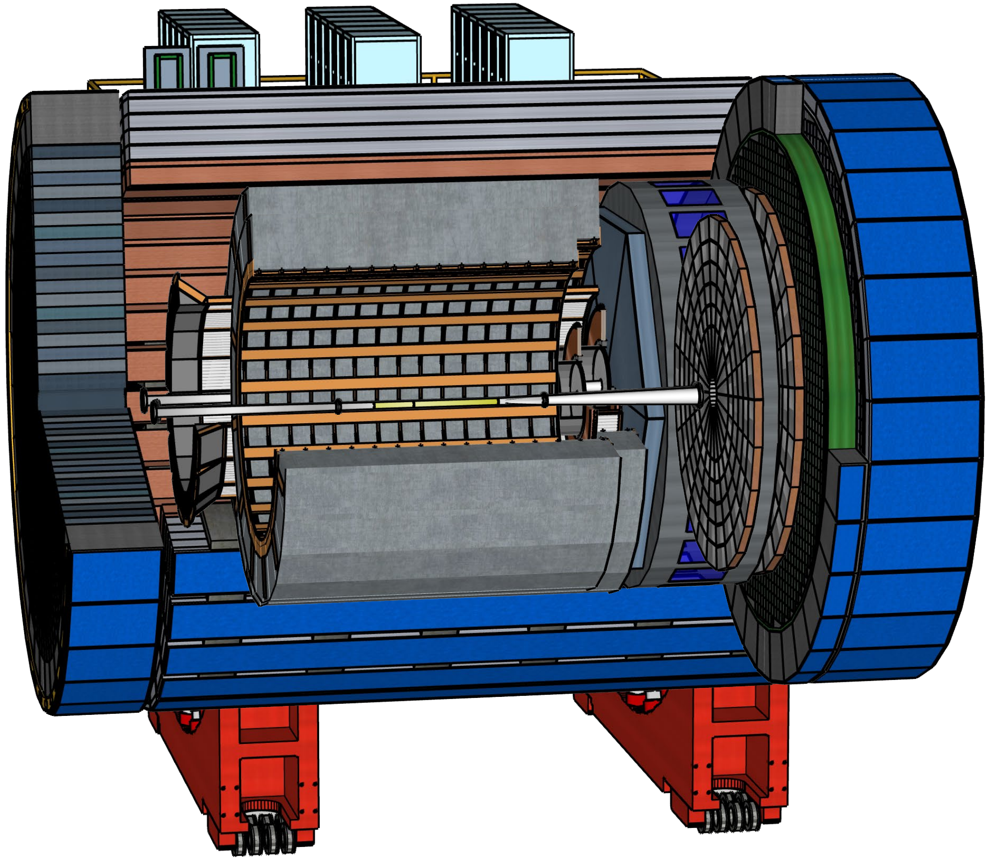
Endcap Tracking

PID

EM Calorimetry

H Calorimetry

Support Structure & Platforms



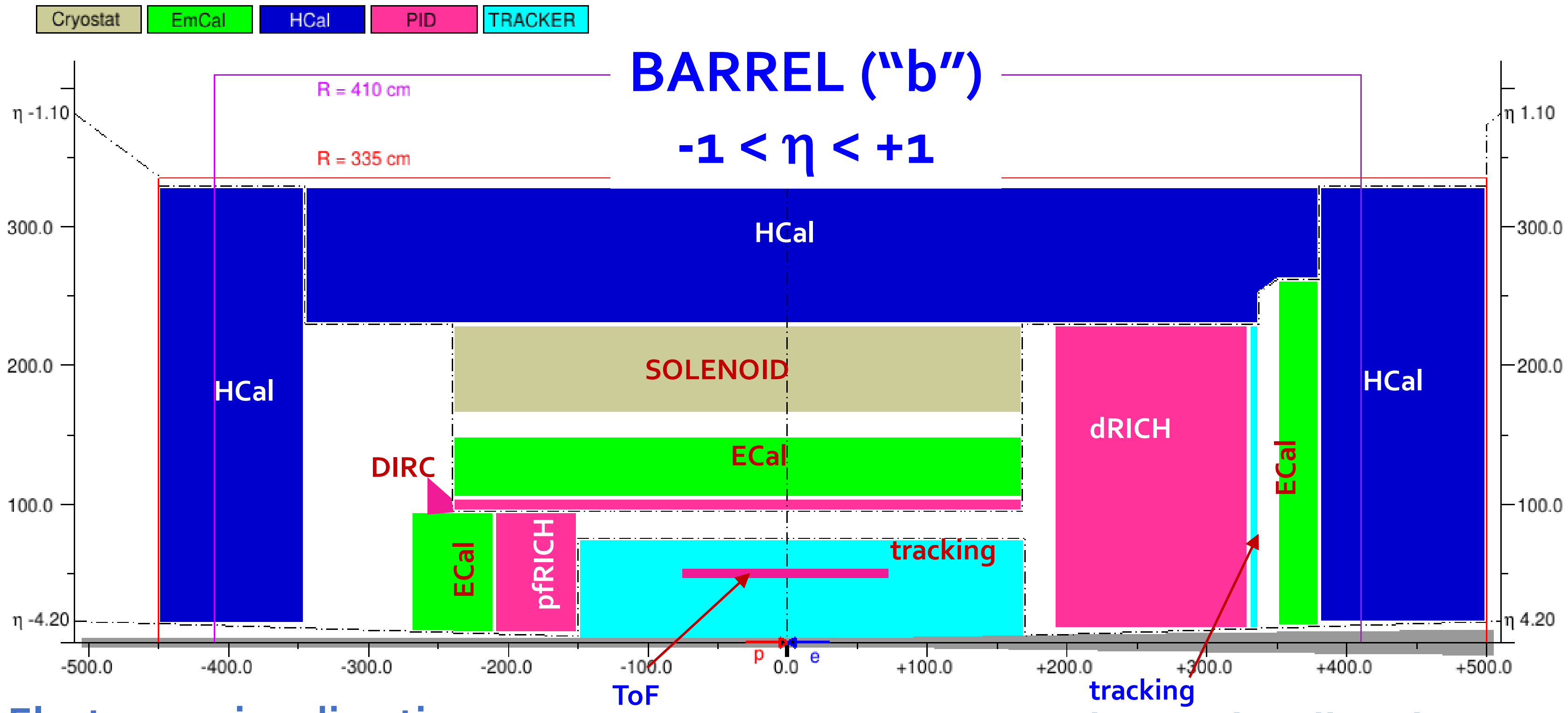
Getting familiar with the ATHENA detector

Hadron beam (41-275 GeV)

Electron beam (5-18 GeV)

Backward Endcap ("n")

$\eta < -1$



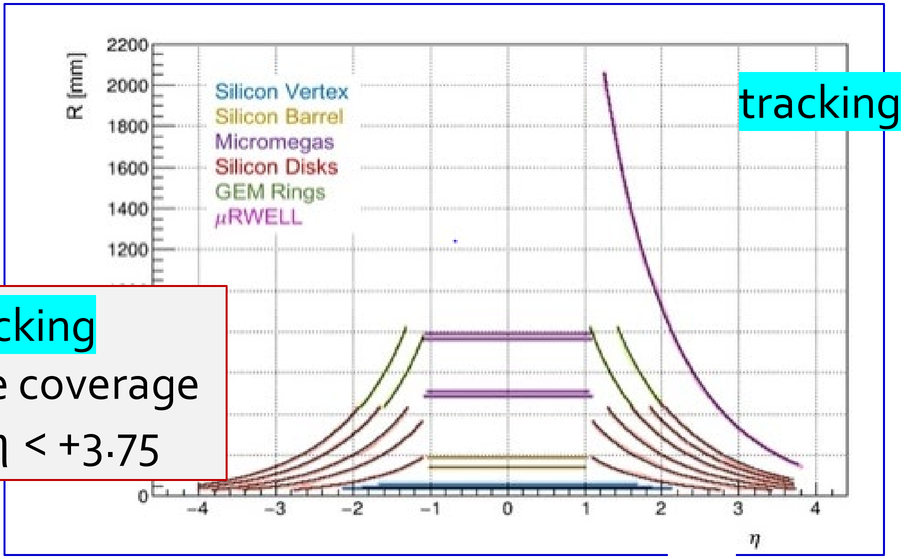
Forward Endcap ("p")

$\eta > +1$

Electron-going direction $-\eta$

Hadron-going direction $+\eta$

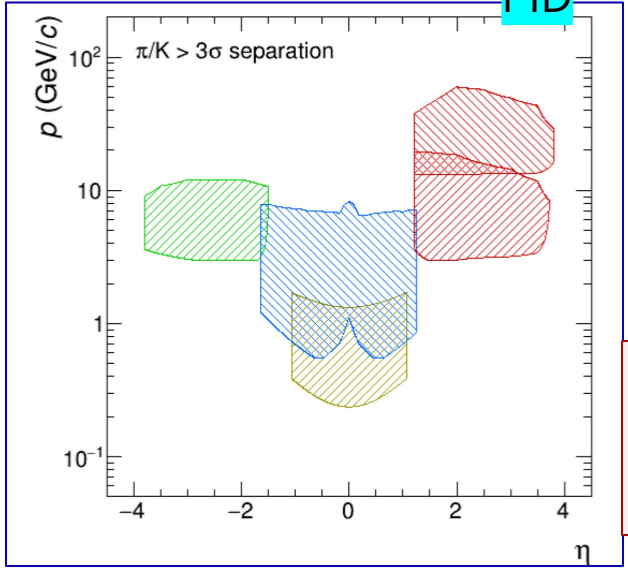
ATHENA – Central Detector acceptance



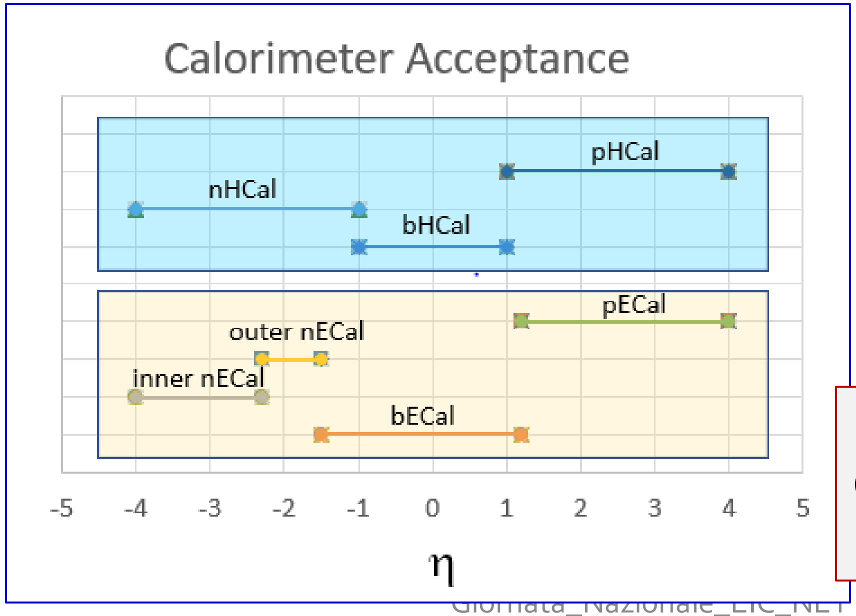
η

Tracking
Complete coverage
-3.8 < η < +3.75

PID



PID
Complete coverage
-3.8 < η < +3.7

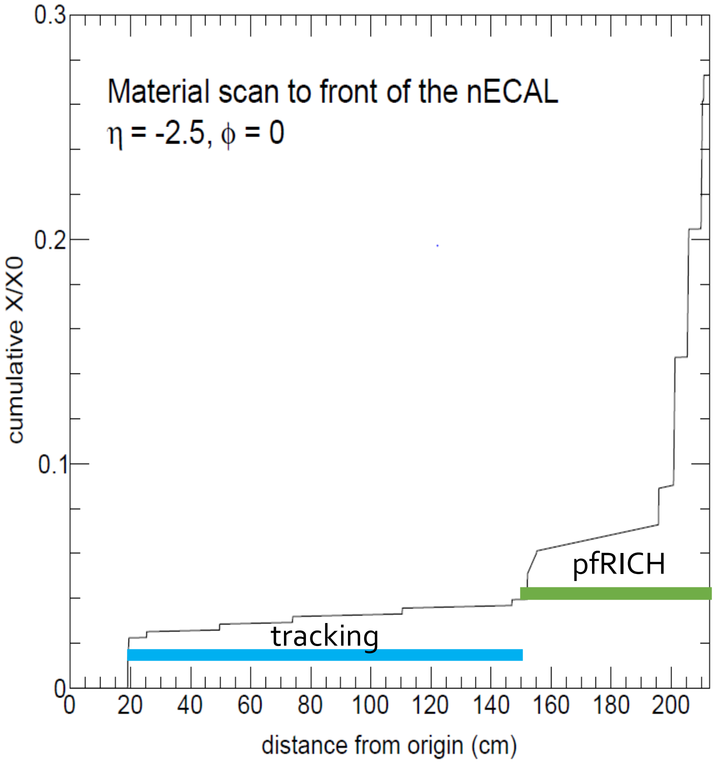


Calorimetry (E & H)
Complete coverage
-4 < η < +4

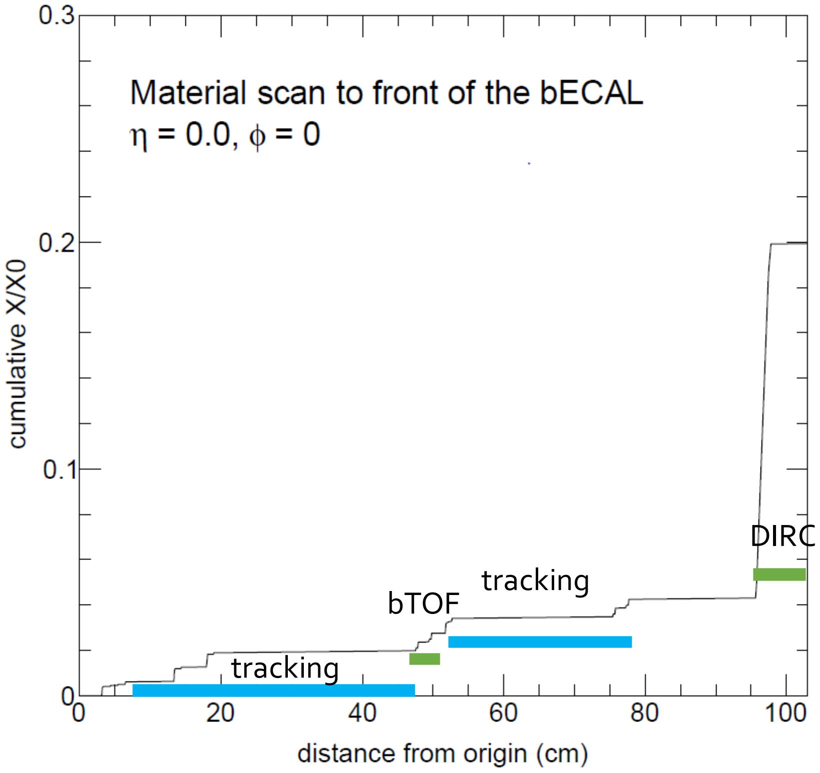
ATHENA – Material Budget in Central Detector

Material budget in front of ECals

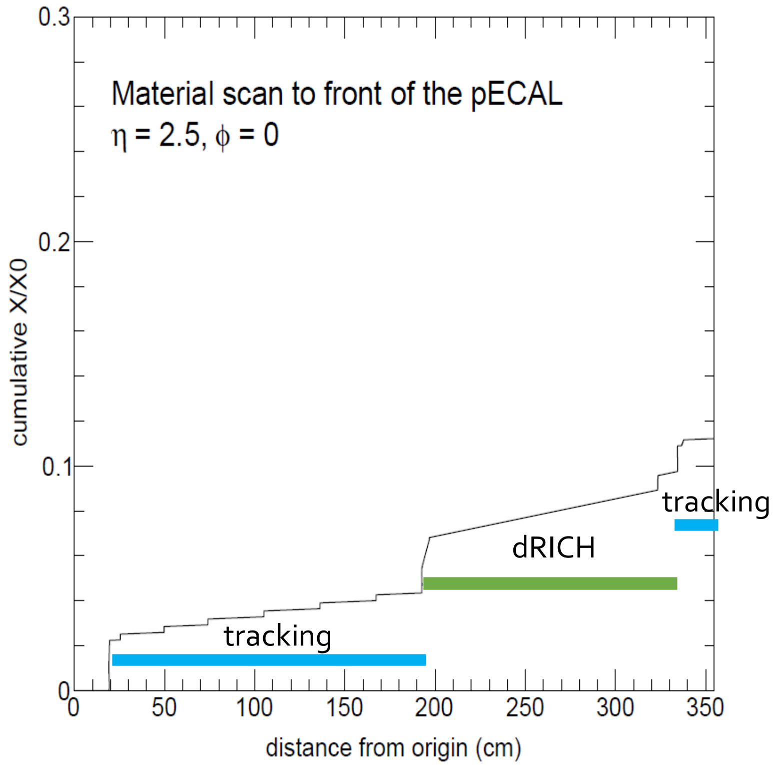
Backward endcap



Barrel



Forward endcap



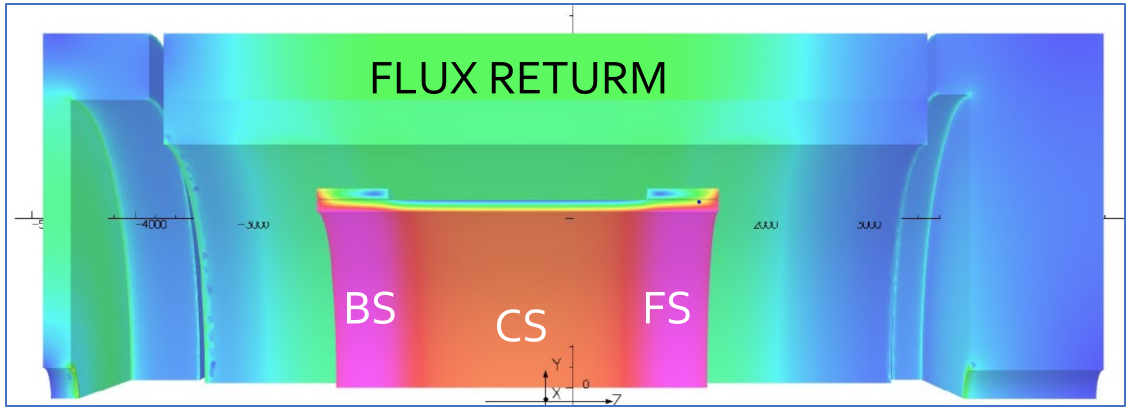
ATHENA SOLENOID, matching the requirements

REQUIREMENTS & ACHIEVEMENTS

Solenoid CDR available in Suppl. Mat. !

- Concerning **DETECTOR**
  - ✓ 3 T : 3.02 T in the center
  - ✓ Flat area in the volume around the beam axis (enough ∫B·dl): homogeneity at 27.5% level
  - ✓ Projective field in dRICH area (190<z<330 cm; 3.5<θ< 25 degree) : projective at 10.4% level
  - ✓ "Light" to preserve HCal in the barrel : material budget in nuclear interaction length ~1.3 λ/λ_I

- Concerning **accelerator complex**
  - ✓ Extremely small stray field in the regions z = {7:4; 8:0} m and z = {−5:3;−7:1} m : 10.5 mT and 7.2 mT, respectively



Studies with SIMULIA Opera package; simulated:
- Solenoid
- HCals, only relevant ferromagnetic sub-detectors

ATHENA VERTEX & TRACKING, a description

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

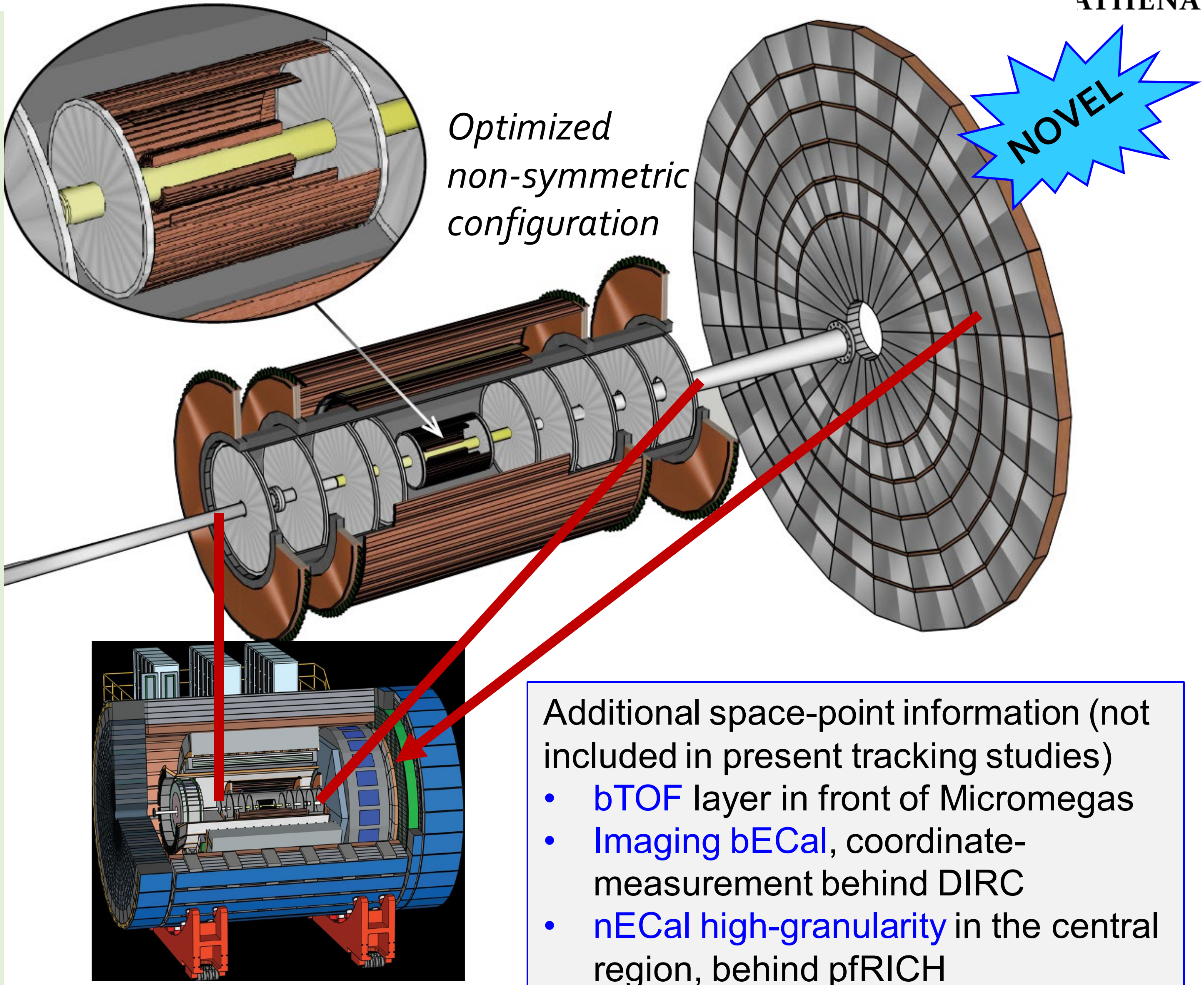
- **1 single technology**
- 65-nm technology MAPS (10 μm pitch, < 20 mW cm^{-2})
- Developed for ALICE ITS3
- EIC Si consortium (leadership within ATHENA)

- **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

MPGDs *(from eRD3/eRD6→eRD108)*

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

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

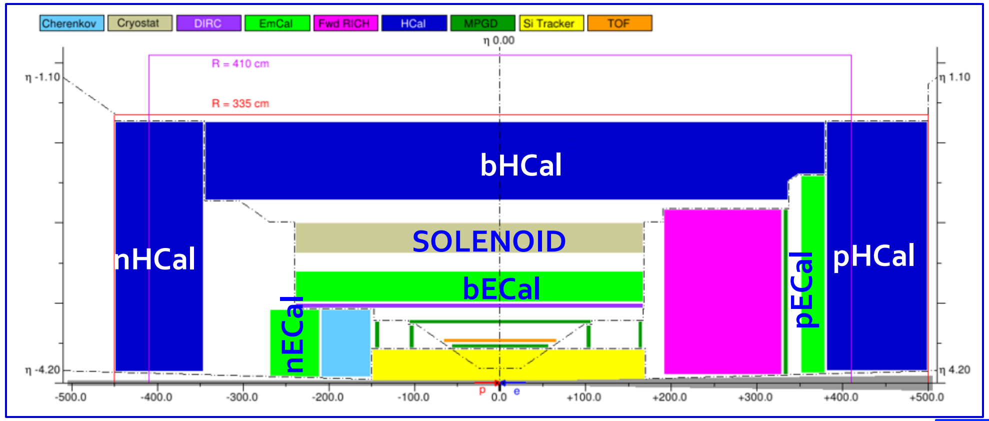


Additional space-point information (not included in present tracking studies)

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

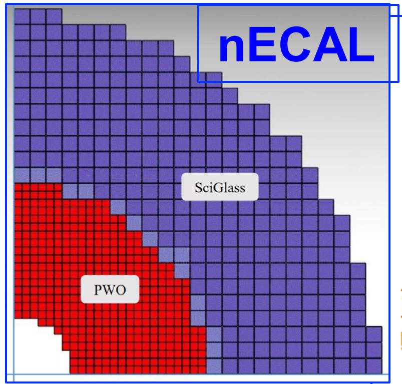
ATHENA Calorimetry, overview

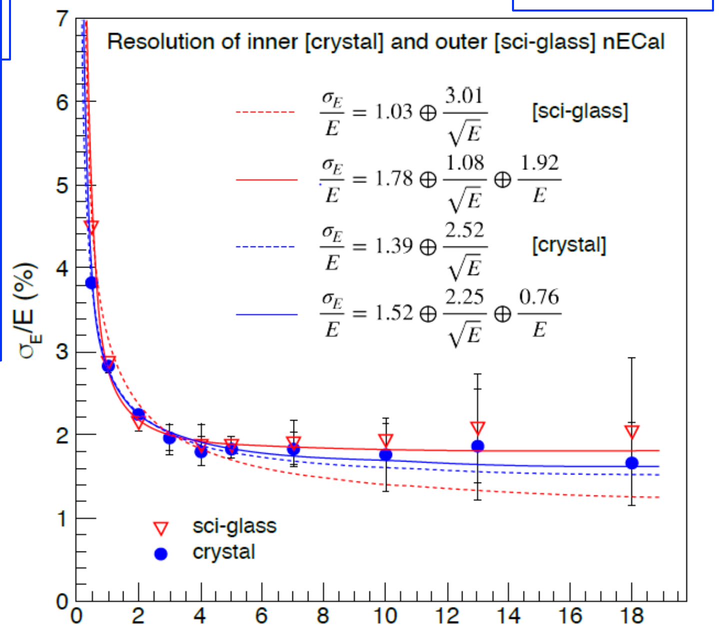
- **Global characteristics of ATHENA Calorimetry:**
  - ➢ high granularity high resolution
  - ➢ Si PM sensors → fine time information
  - ➢ ML algorithms for reconstruction already in use



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

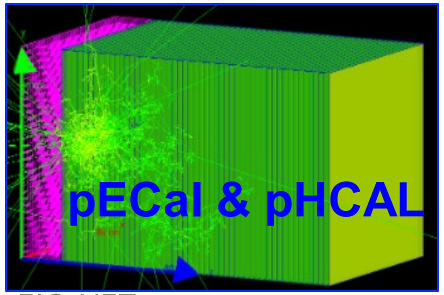
nECAL





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

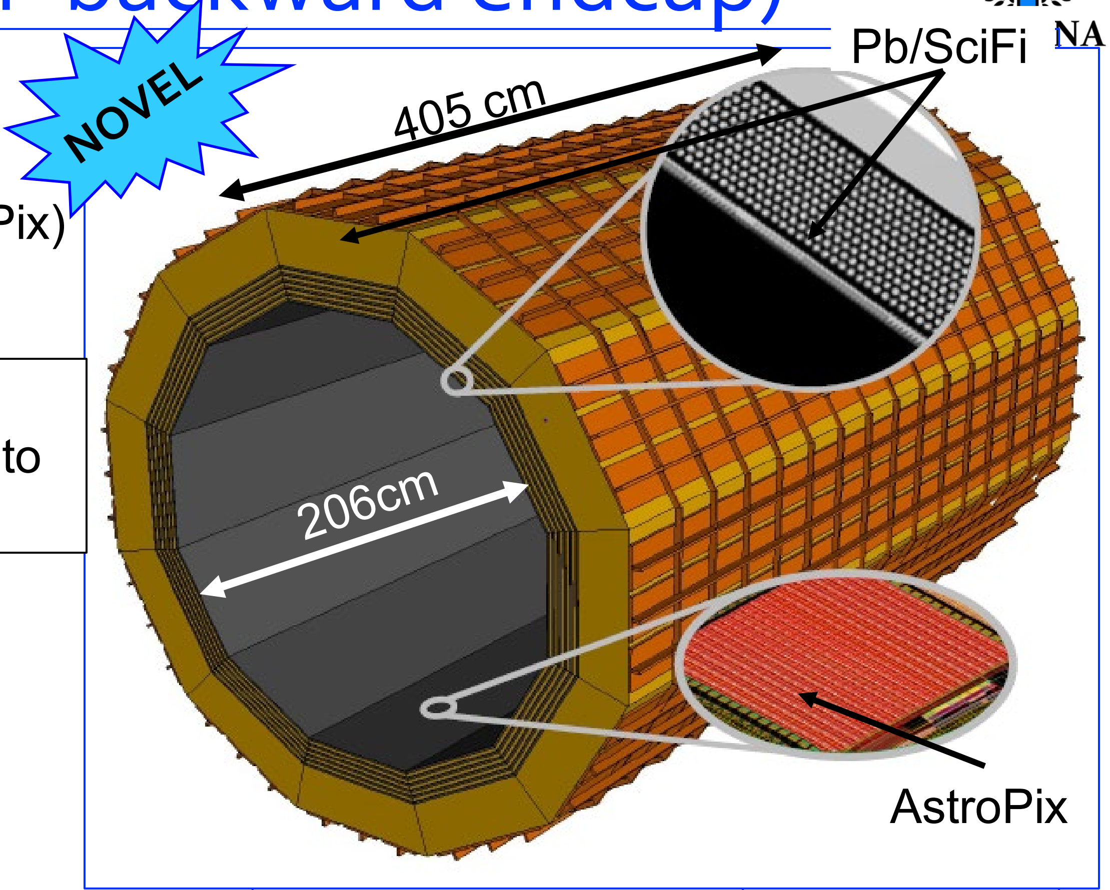
- **bHCal and nHCal**
  - ➢ Both Fe/Scint sandwich
  - ➢ Well established technology, no R&D needed
  - ➢ bHCal as tail catcher following bECal (~ 1 λ_I) and solenoid (~1.3 λ_I): 95 % of hadrons contained



FullSim,
calorimeter stand alone

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

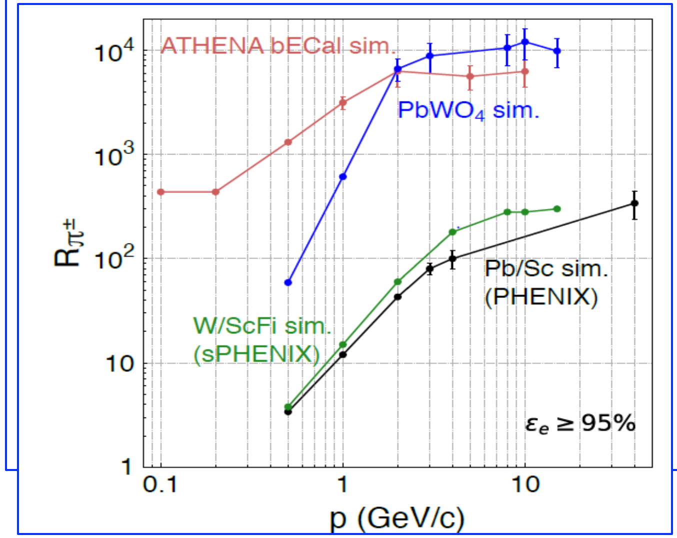
- Hybrid concept:
  - 6 imaging layer: AstroPix and Pb/SciFi
    - ✓ AstroPix, monolithic Si sensor, developed (from ATLASPix)
    - ✓ Pb/SciFi following KLOE, GlueX



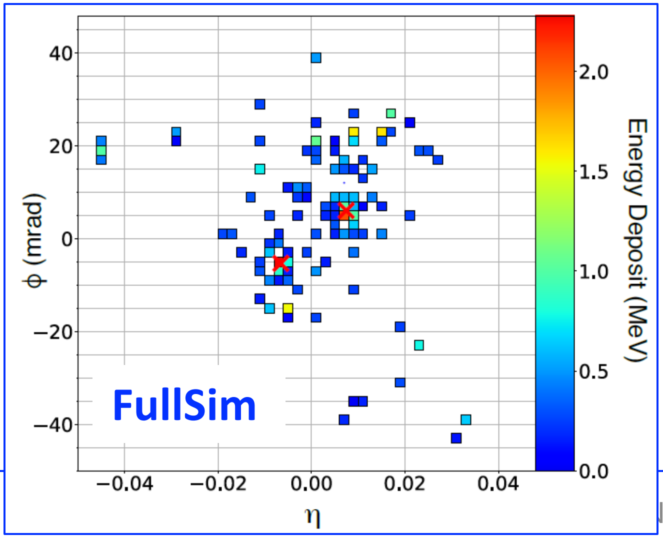
also >1 λ_I contributing to bHCal

- 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

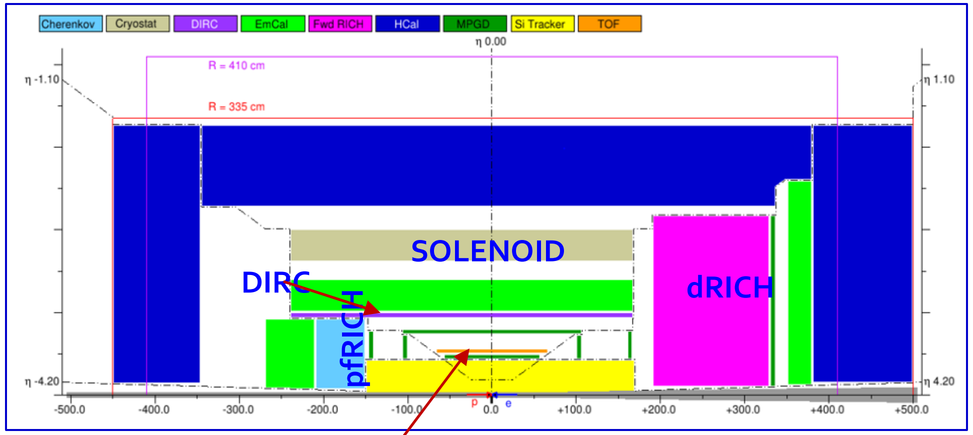


expected performance

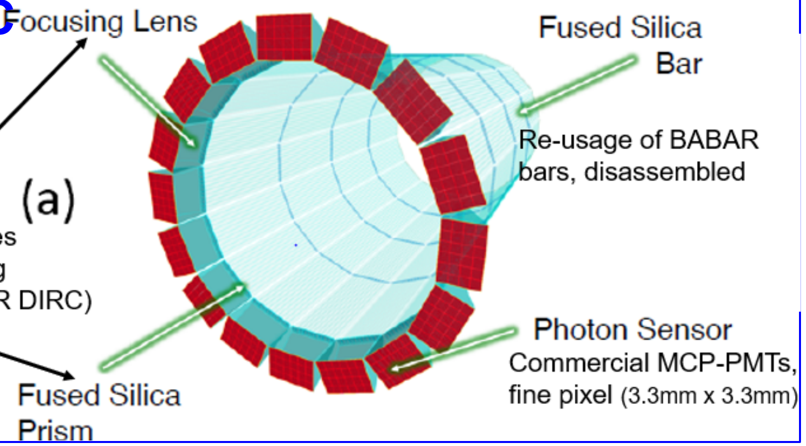
Energy Resolution	$5.5\%/\sqrt{E} \oplus 1\%^a$
e/π separation	> 99.8% pion rejection with 95% electron efficiency at $p \geq 0.1$ GeV/c^b.
$E^{\gamma}_{\min}$	< 100 MeV[c]
Spatial Resolution	Cluster position resolution for 5 GeV photons at normal incident angle is below $\sigma = 2$ mm (at the surface 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

- R&D - Cherenkov: eRD14, eRD6 → eRD102, eRD103, eRD110, eRD112
- R&D, AC-LGAD: eRD29 → eRD112

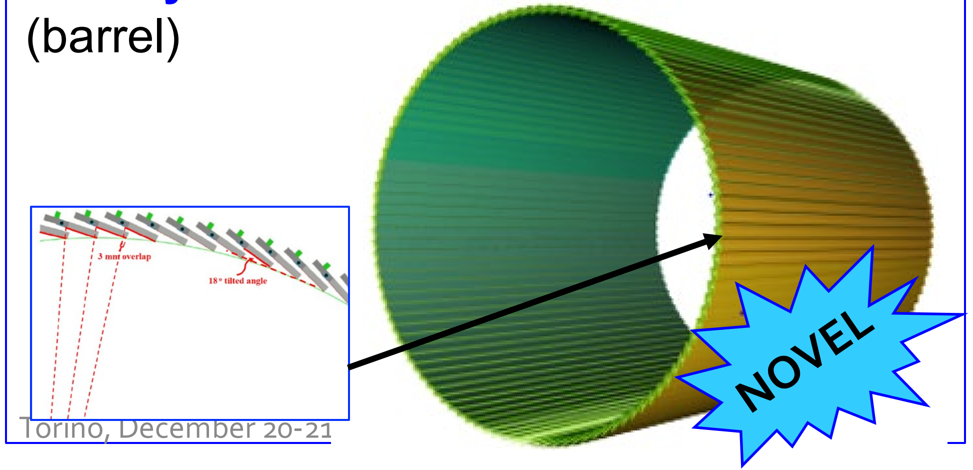


hpDIRC (barrel)

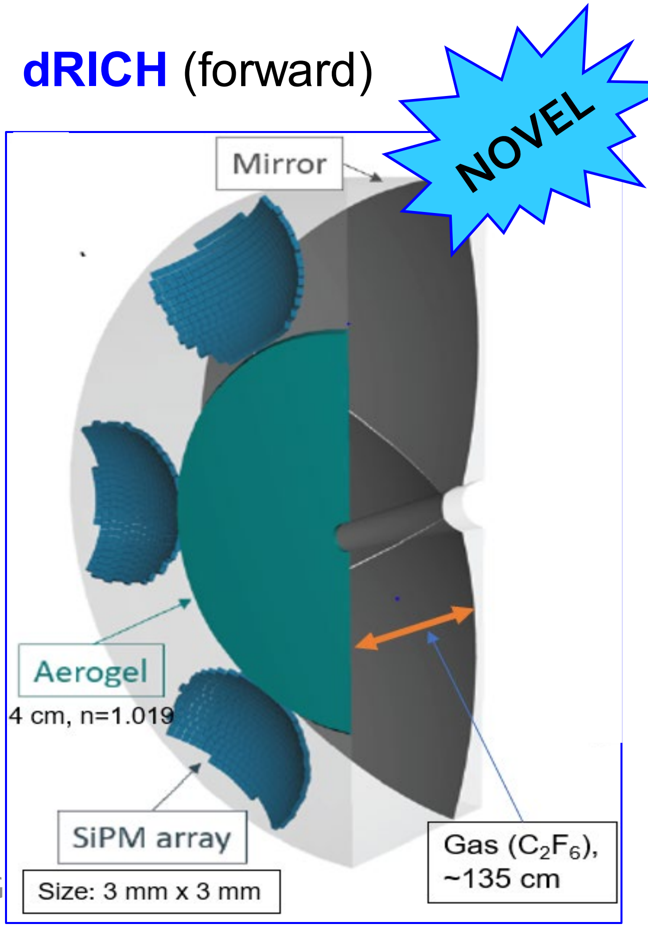


AC-LGAD ToF layer (barrel)

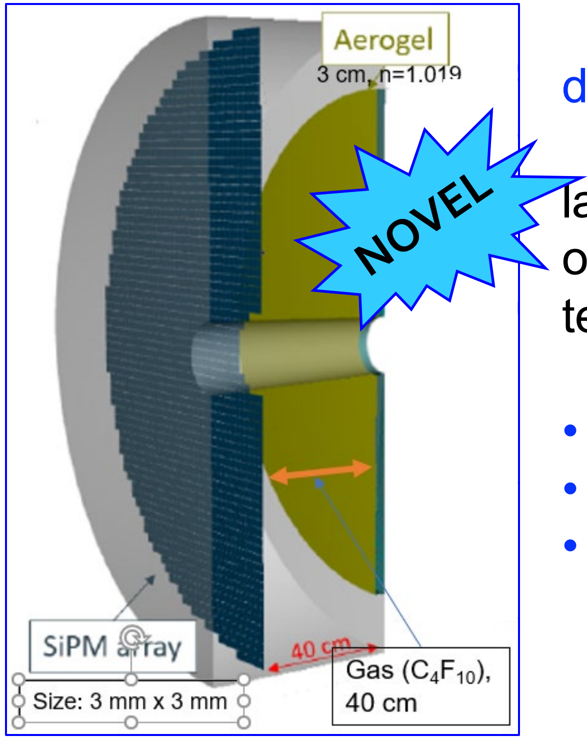
AC-LGAD: adding fine pixelization to LGAD (synergies with FF sensors)



dRICH (forward)



pfRICH (backward)



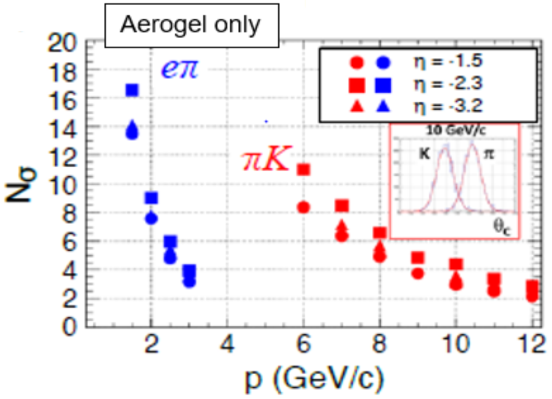
dRICH & pfRICH, large overlap of technologies

- SiPMs
- Aerogel
- Radiator gas

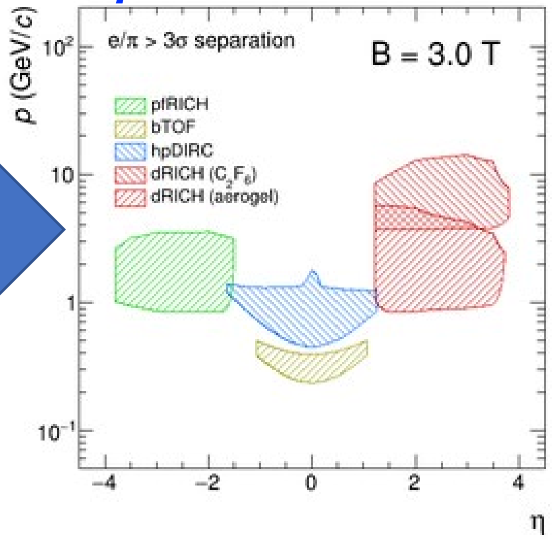
PID momentum acceptance

EXAMPLE:

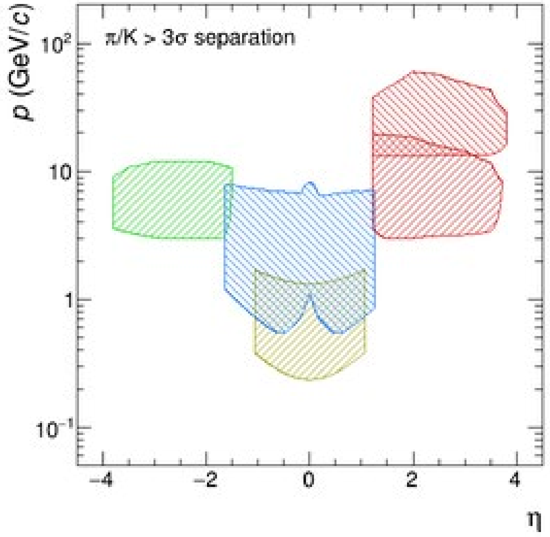
pfRICH, **FullSim**



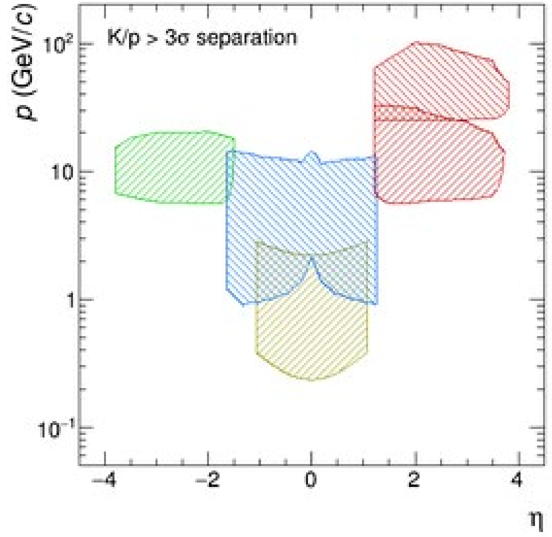
e/π



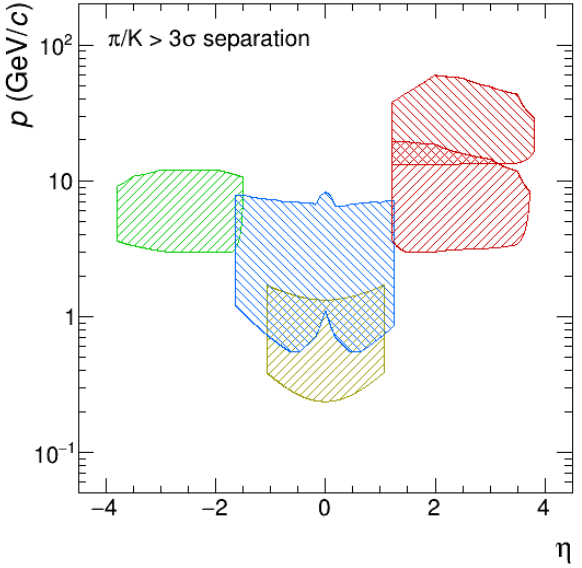
π/κ



κ/p

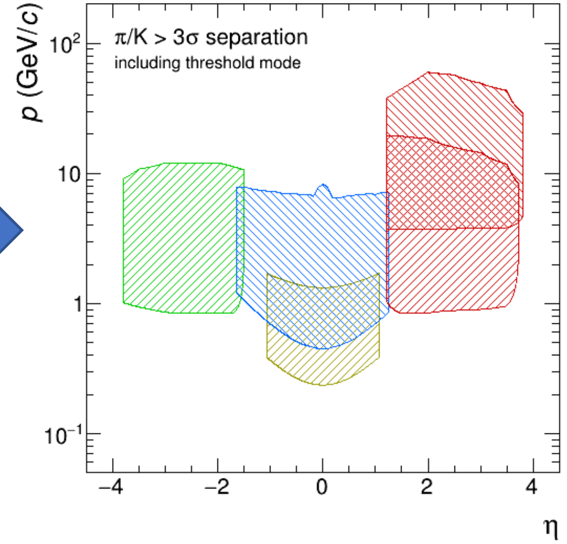


π/κ



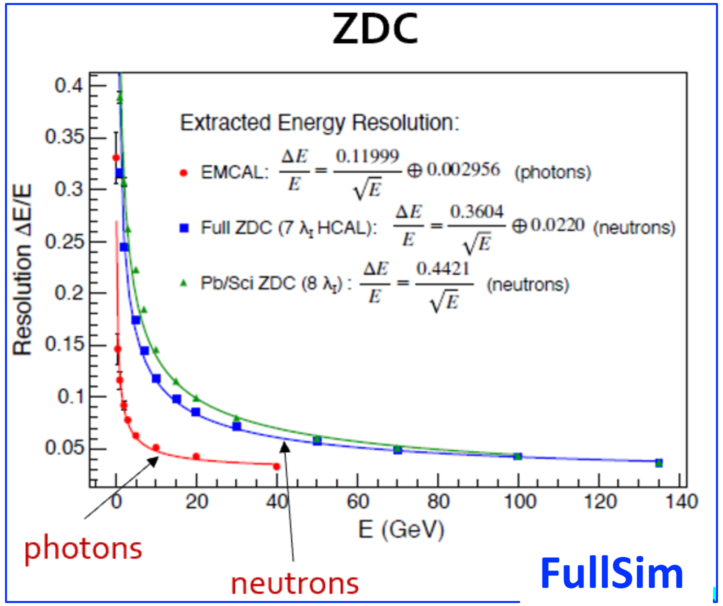
With positive identification of the higher mass particle in the couple

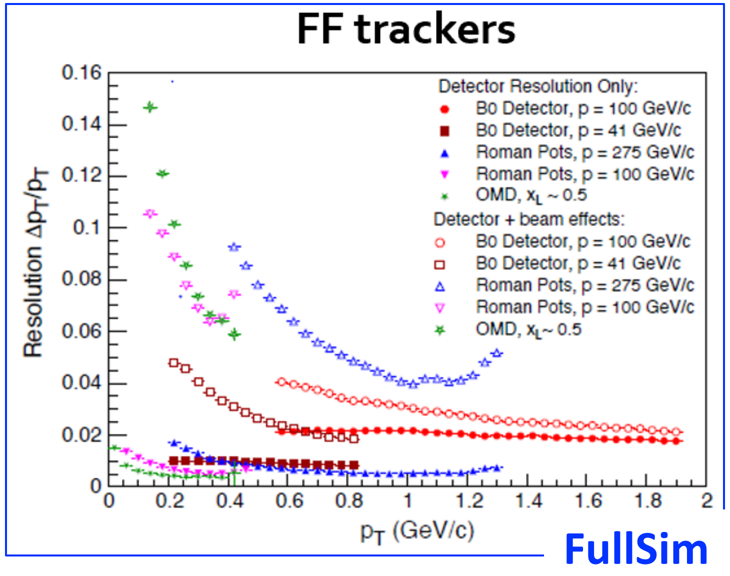
π/κ



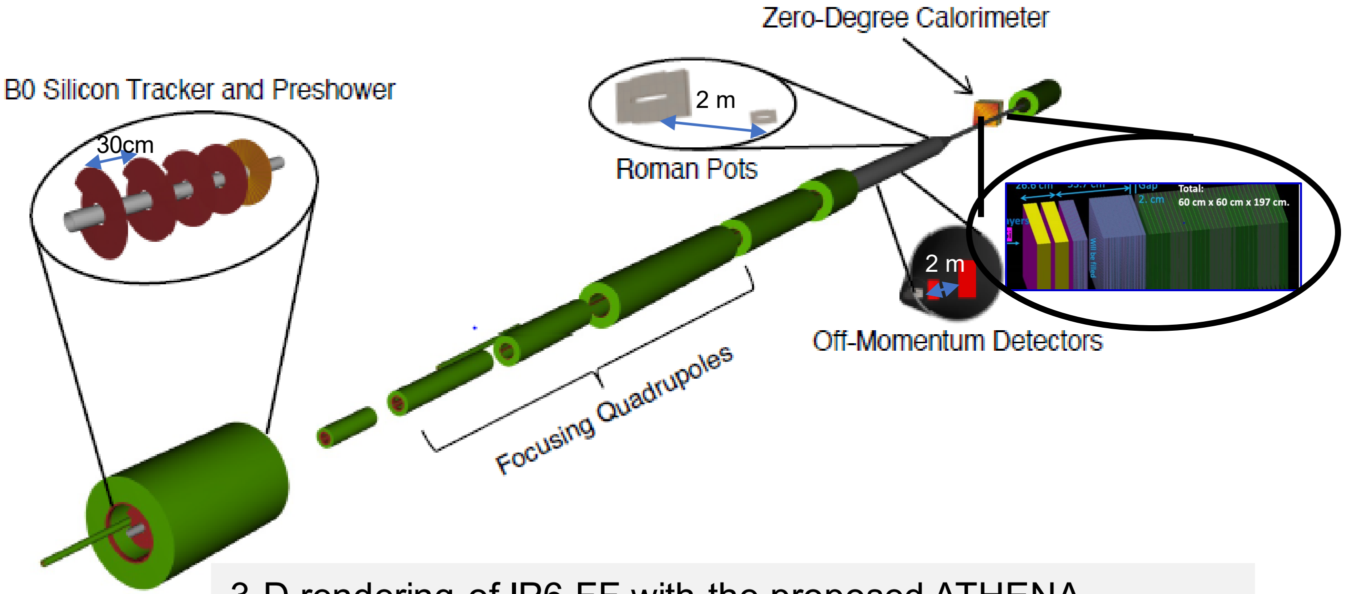
Using also the Cherenkov threshold information

FAR FORWARD instrumentation $\eta > 4.0$





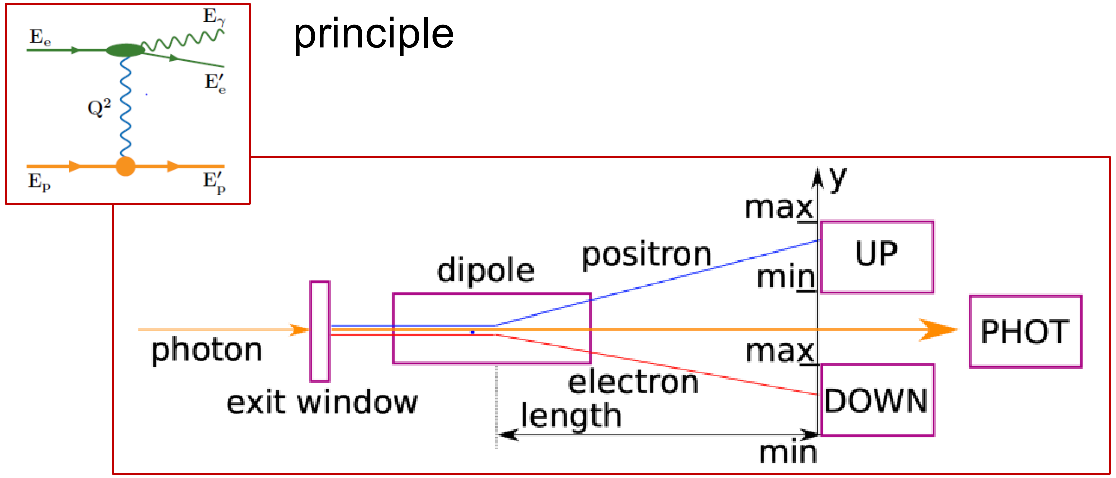
Detector	θ accep. [mrad]	Rigidity accep.	Particles	Technology
B0 tracker	5.5–20.0	N/A	Charged particles Tagged photons	MAPS AC-LGAD
Off-Momentum	0.0–5.0	45%–65%	Charged particles	AC-LGAD
Roman Pots	0.0–5.0	60%–95%*	Protons Light nuclei	AC-LGAD
Zero-Degree Calorimeter	0.0–4.0	N/A	Neutrons Photons	W/SciFi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



3-D rendering of IP6 FF with the proposed ATHENA instrumentation from the DD4HEP geometry implementation.

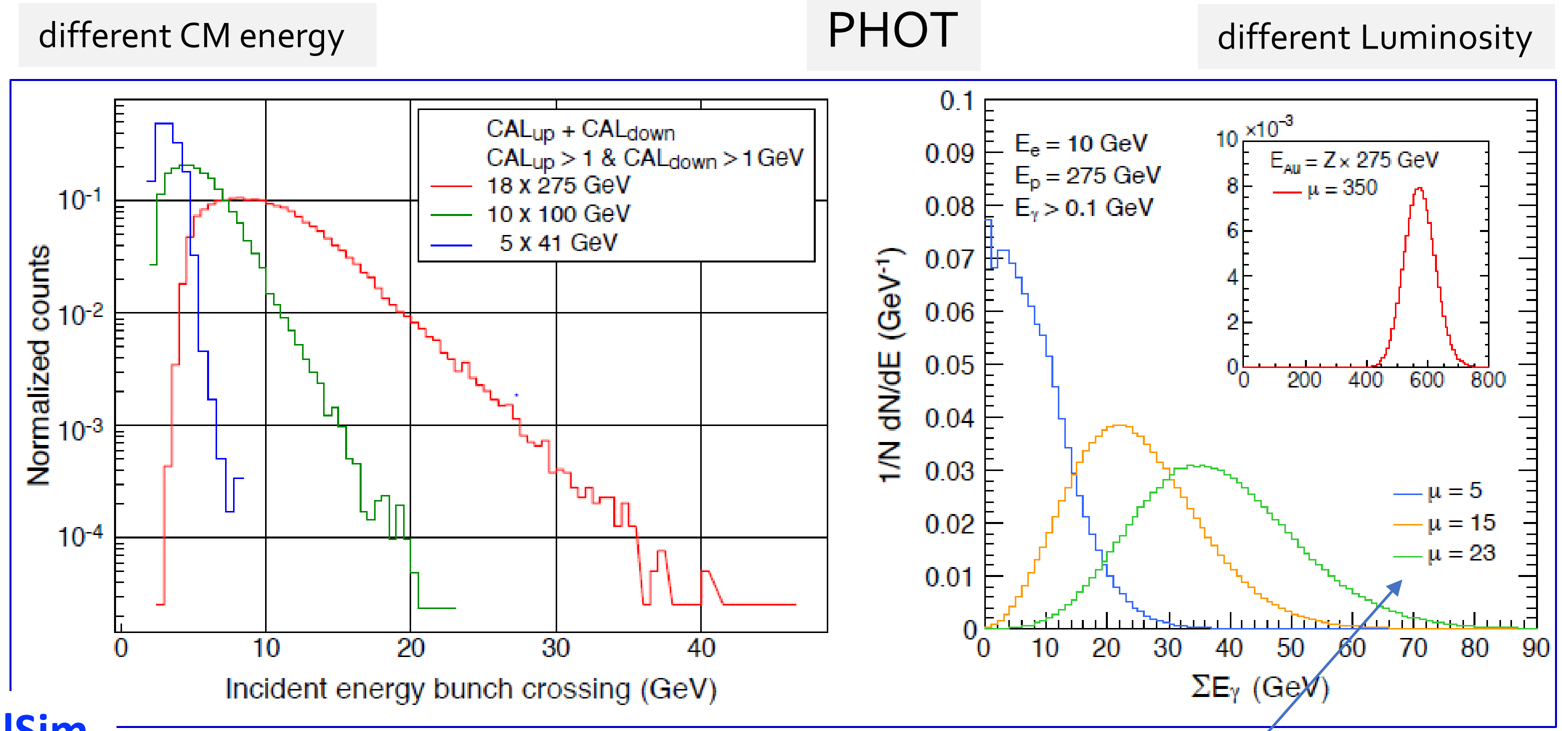
FAR BACKWARD

- 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



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



FullSim

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

ATHENA
SOFTWARE and **SIMULATION**
TOOLS

SOFTWARE & COMPUTING @ATHENA

- focused on modern scientific computing practices for state of the art approach
  - ➢ a toolkit of modular, orthogonal components
  - ➢ performance in heterogeneous computing environments (HTC, HPC)
  - ➢ mature, well-supported, and actively developed software components from cutting-edge CERN-supported software developed for the (HL-)LHC
  - ➢ detailed detector geometries in DD4hep: geometry services for GEANT4 simulation and our reconstruction algorithms

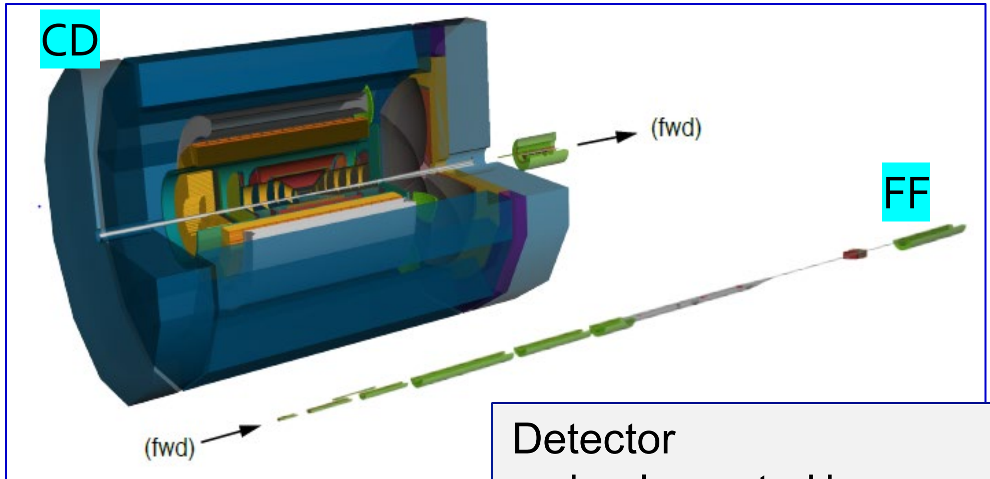
NOVEL

- For reconstruction:
  - ✓ Gaudi (suited for heterogeneous computing environments)
  - ✓ Juggler, our library of digitization, reconstruction, and analysis routines
  - ✓ ACTS for highly performant tracking
  - ✓ Tensorflow for Artificial Intelligence (AI)

- Included in the description:
  - ➢ **Central detector, solenoid, far-forward and far-backward, accelerator**

- Simulation performed on an extensive range of systems, including
  - ➢ OSG, JLab, BNL (including S3 storage), Compute Canada, ALCF, LCRC, NERSC, INFN-CNAF
  - ➢ A dedicated continuous-integration cluster at ANL

- The maturity and robustness of the software components enabled us to build out a performant simulation and reconstruction software stack over ~ 5 months (motivated and focused team).
- This setup prepares ATHENA for the next steps (TDR and following).
- This innovative approach, introduced within ATHENA, represents a significant step forward for the EIC community.

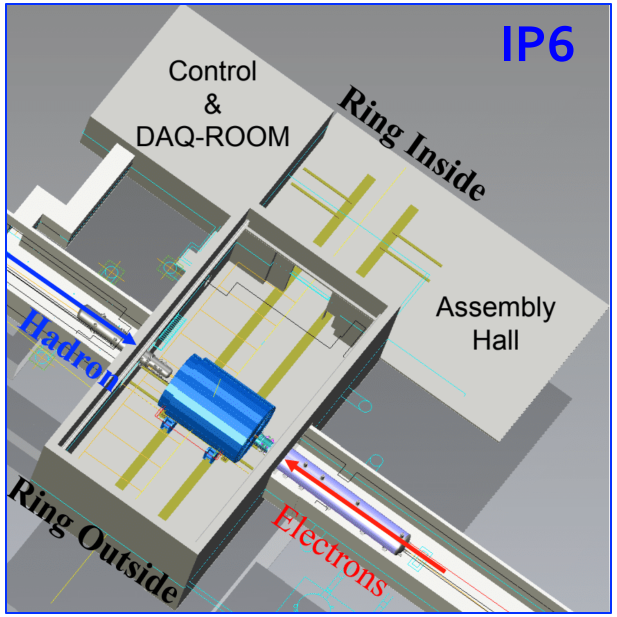


Detector as implemented in GEANT4 for FullSim

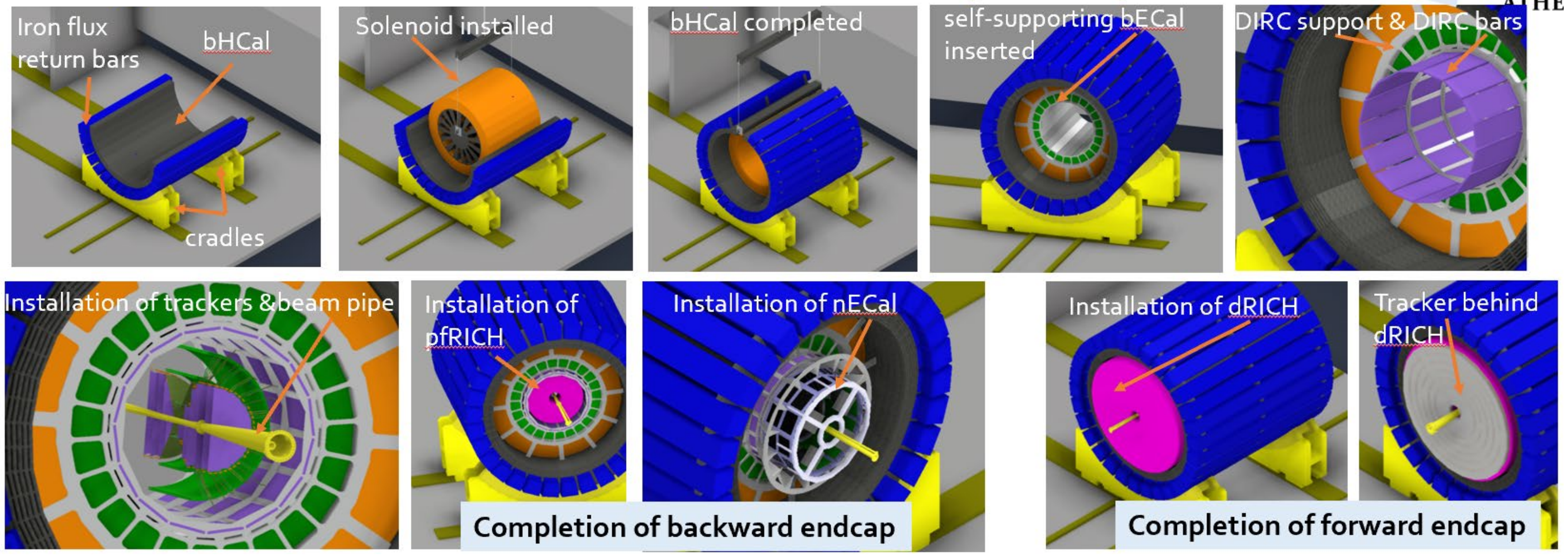
Integration and installation, in short

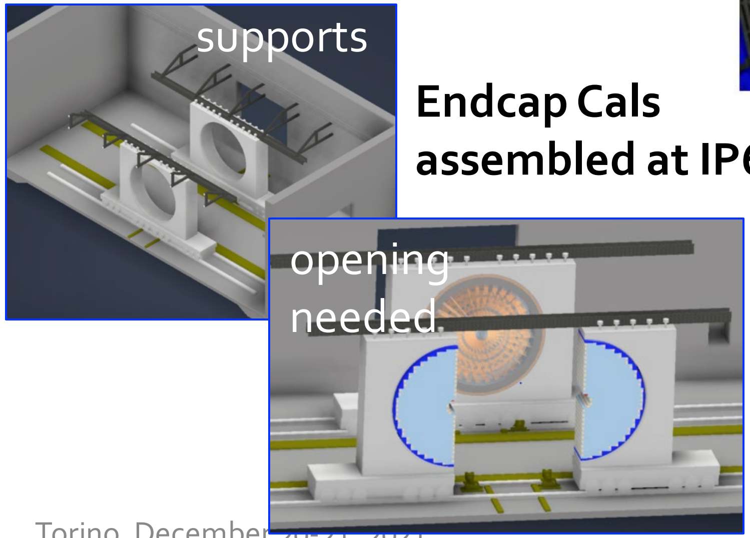
NOVEL

More in Suppl. Mat. !

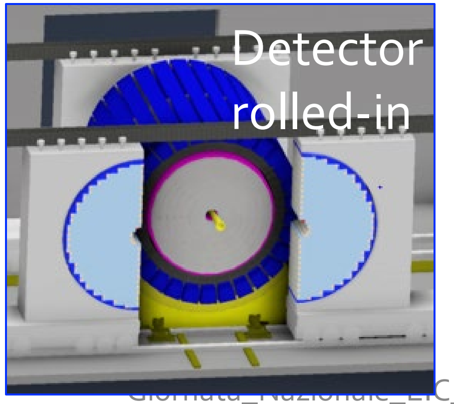


CD assembled in assembly hall and rolled-in





Endcap Cals assembled at IP6



- **Images from CAD studies**
- **All engineering aspects addressed at principle level, meets accelerator constraints**
- **Critical input for scheduling (discussed tomorrow)**

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

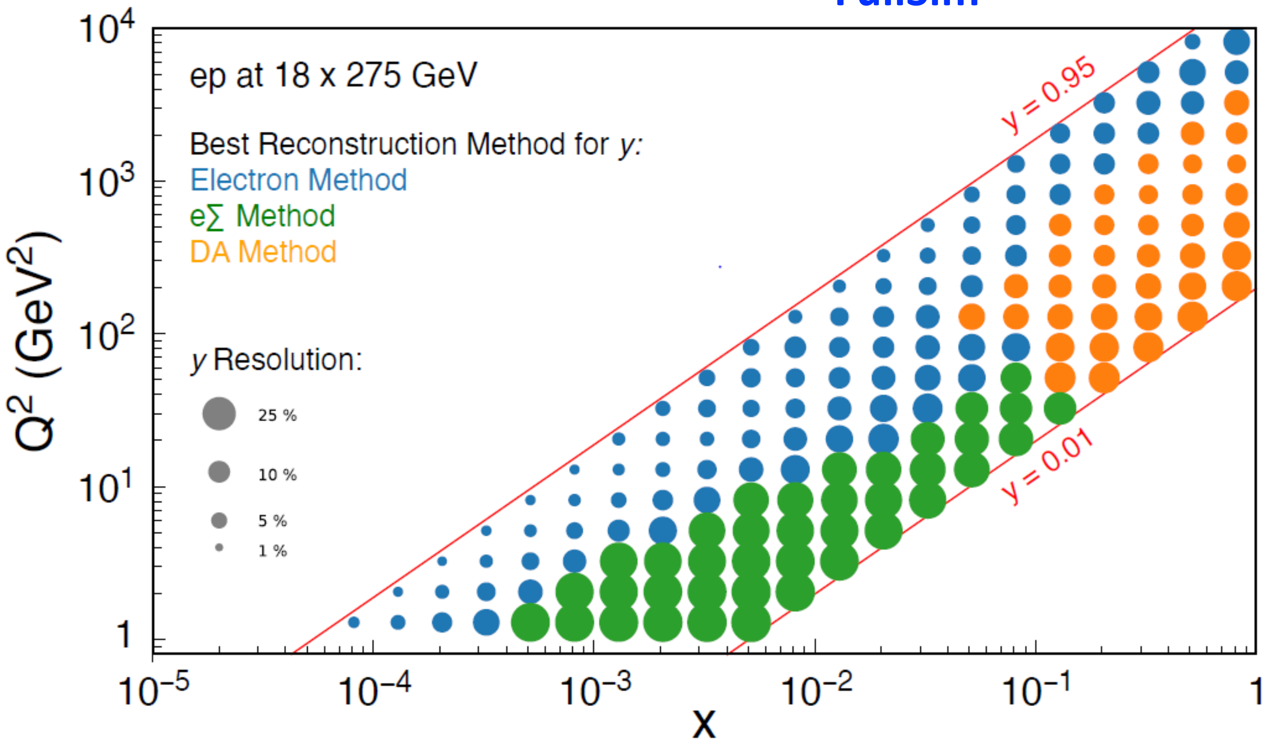
ACCEPTANCE AND PERFORMANCE for DIS

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: $Q^2 \approx sxy$)

FullSim



DIS reach in (x, Q^2) plane

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

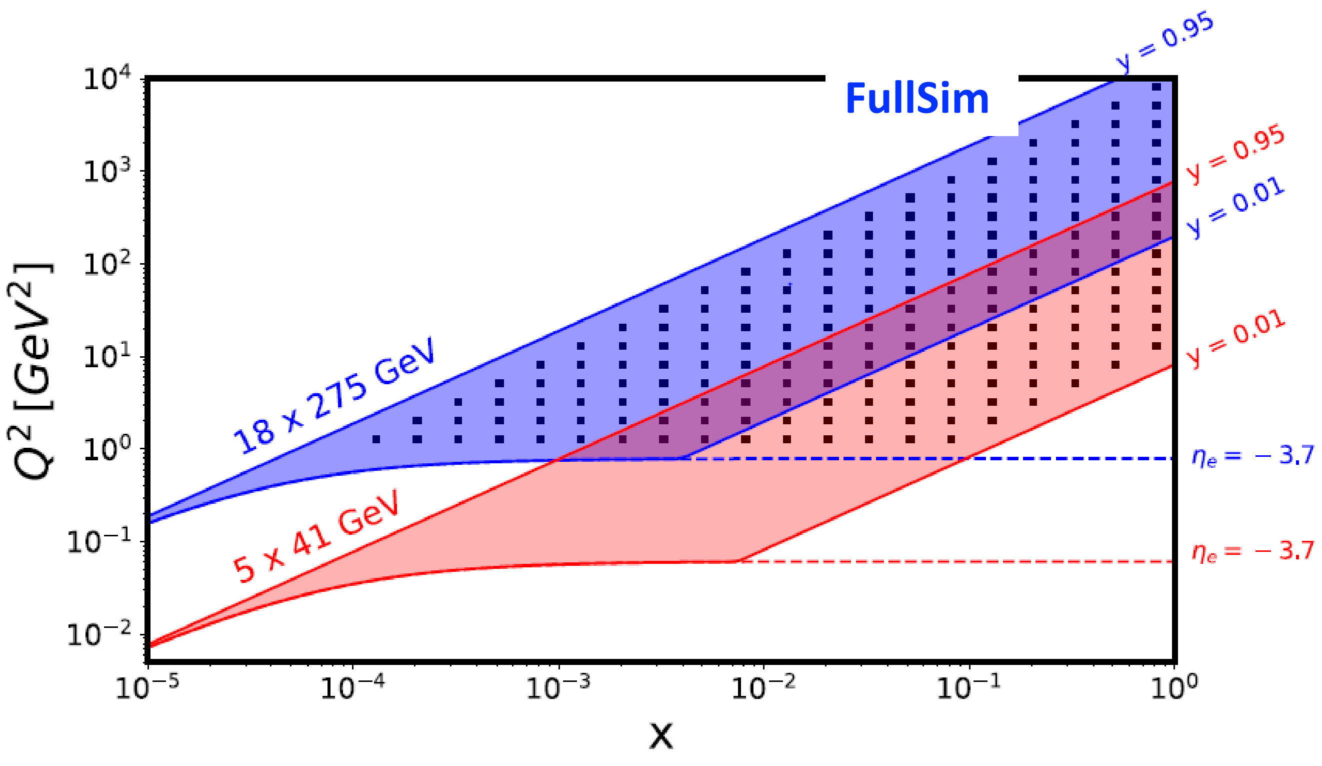
[Q^2 > 1 , 0.01 < y < 0.95]

- 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**

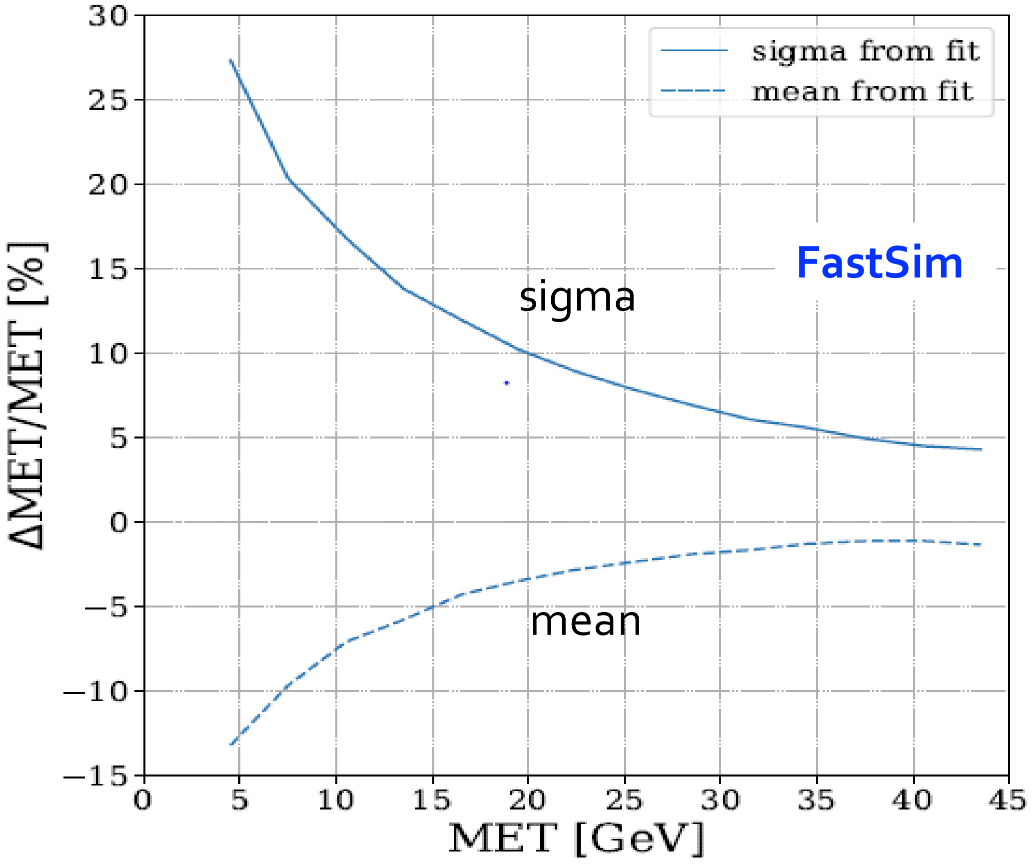


Missing Transverse Energy (MET)

<u>reconstructed MET</u> = vector p_T sum for all energy-flow objects

Needed for DIS kinematic reconstruction using hadron final state

***Key** for MET: hermeticity*



Adequate for CC studies for $Q^2 > 100$ GeV^2

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

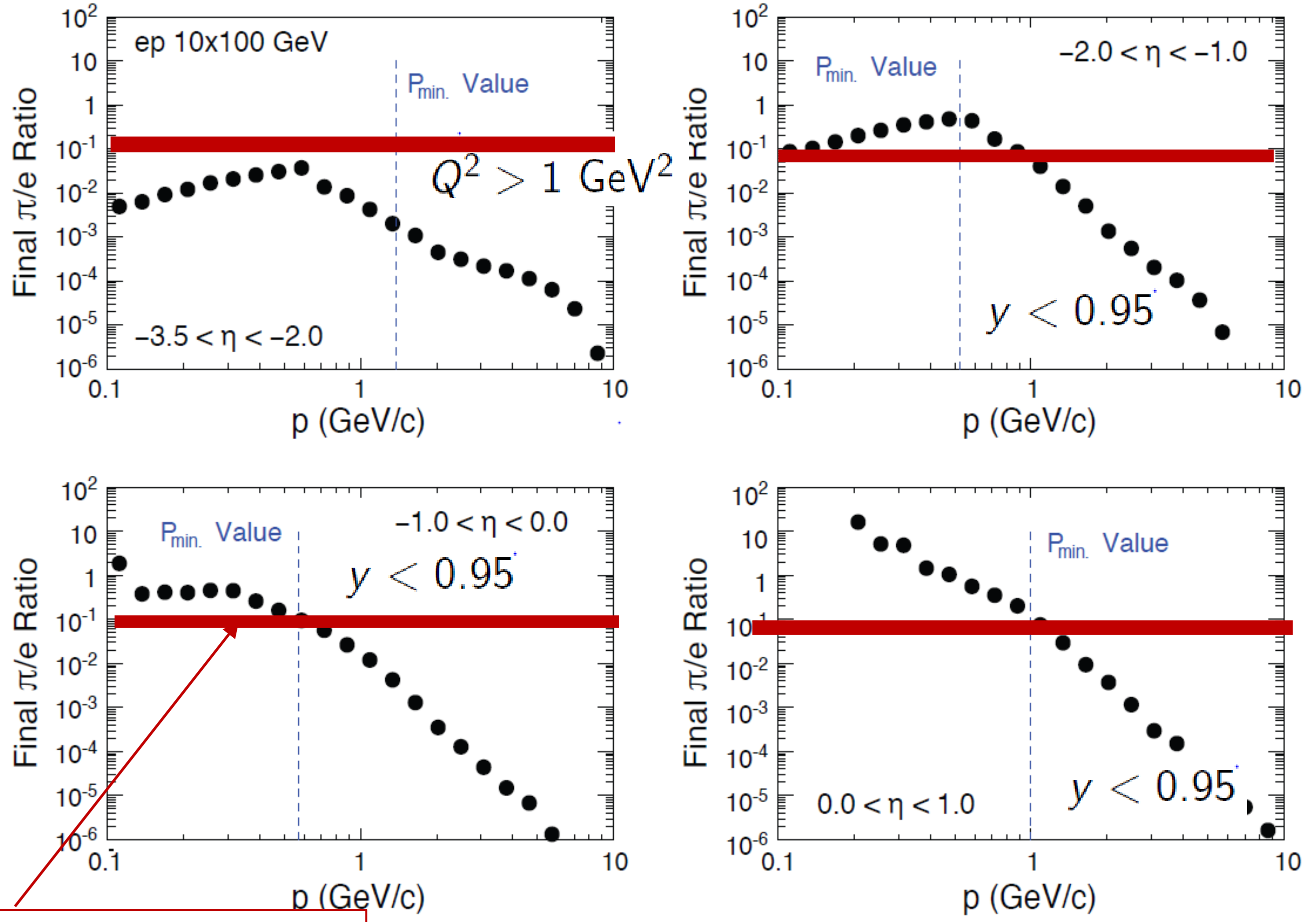
  e – Σ check

Not included:

- Contribution to e/π separation from PID devices

Final π- / e ratio

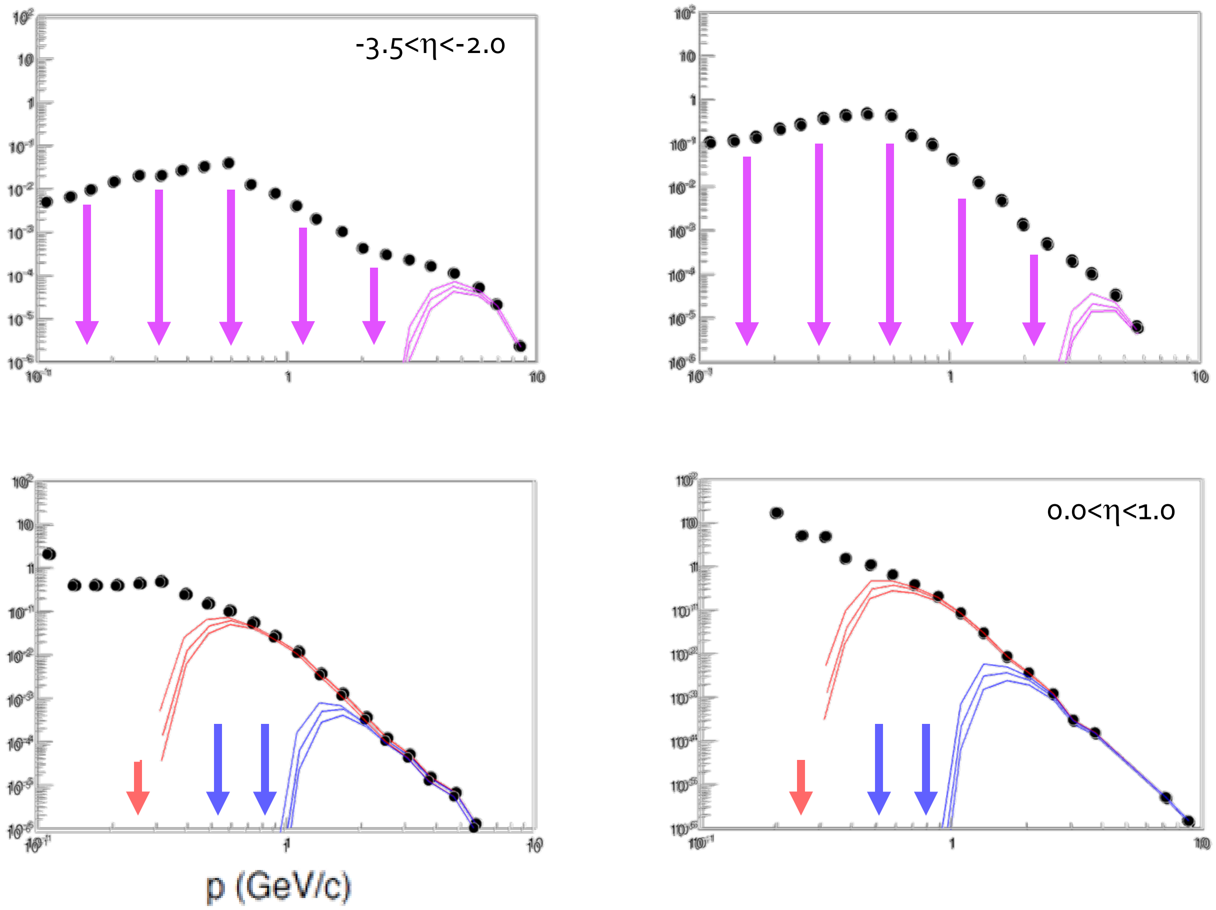
FastSim



10% contamination

Electron Identification **adding PID** *(post proposal)*

Final π- / e ratio



FastSim results below 10^{-6} indicated by downward arrows

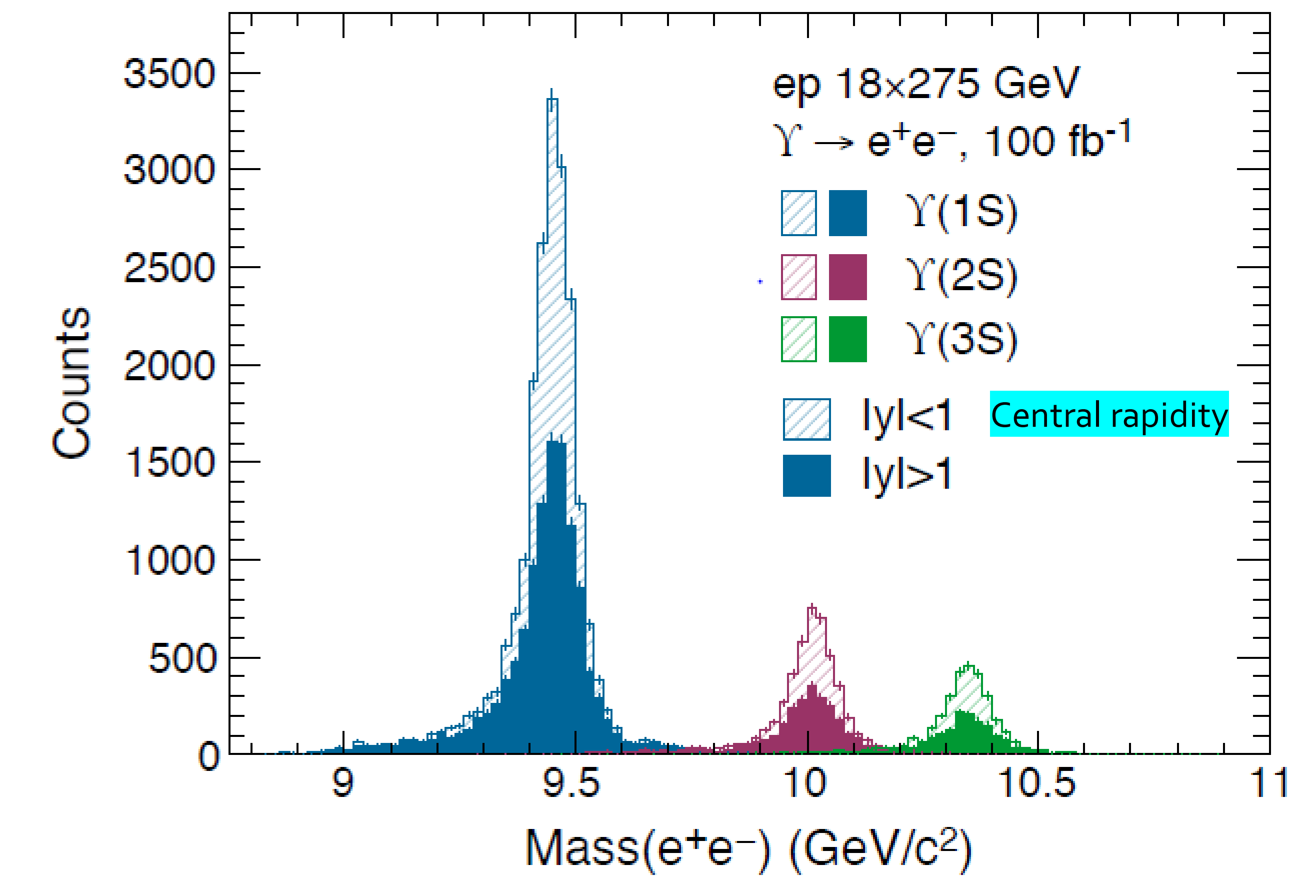
Lepton-pair invariant-mass resolution

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

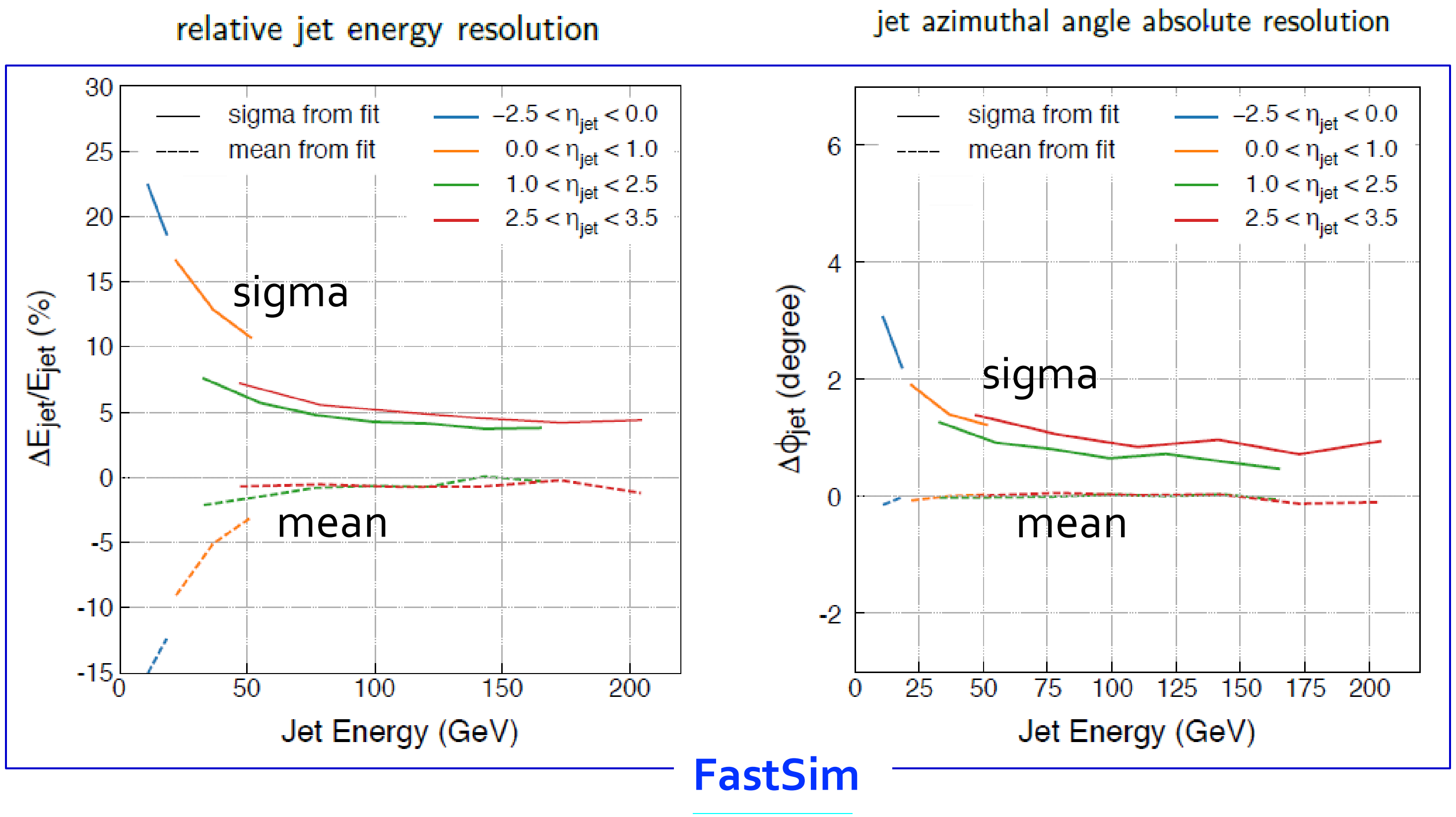


Jet reconstruction

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



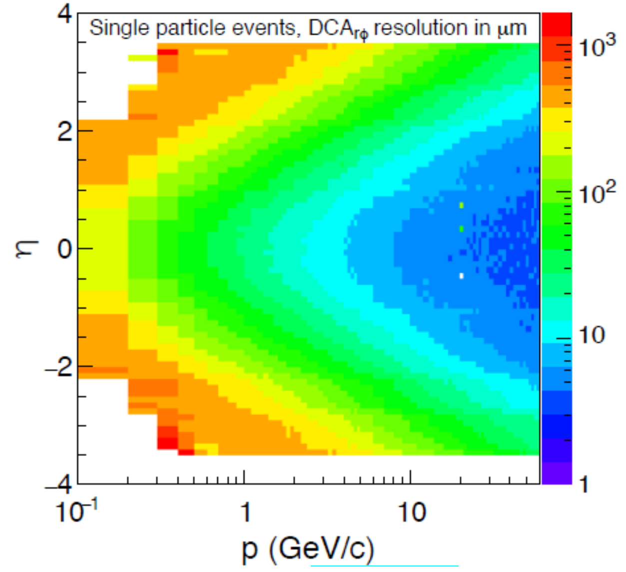
Charm reconstruction, secondary vertices

for secondary decays, for example, D^0 reconstruction

Key - resolution and low mass vertexing layers

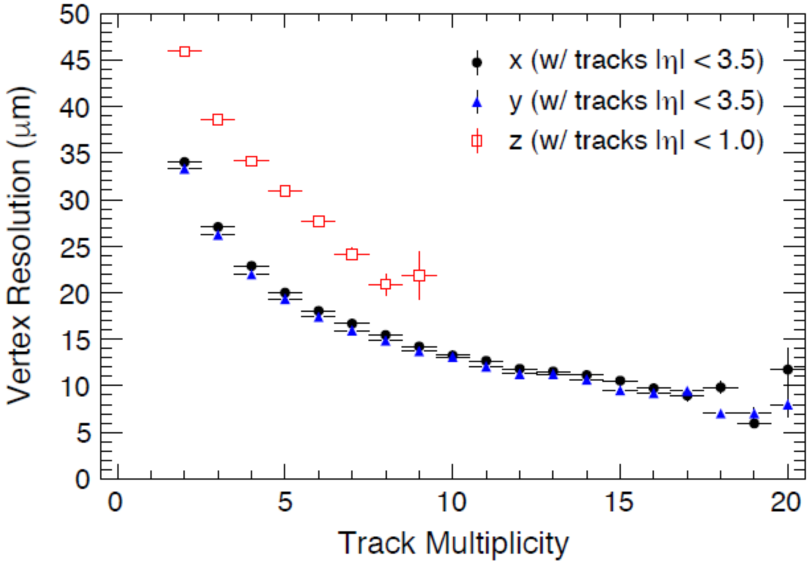
- displaced-track resolutions →
- good charm-jet tagging based on a displaced track counting
- charm efficiency 10% - 30% for 5-30 GeV/c, excellent purity (misidentification < 1%)

Single particle, resolution
Distance of Closest Approach (μm)



FullSim

Longitudinal and transversal
Vertex resolution (μm)
vs track number



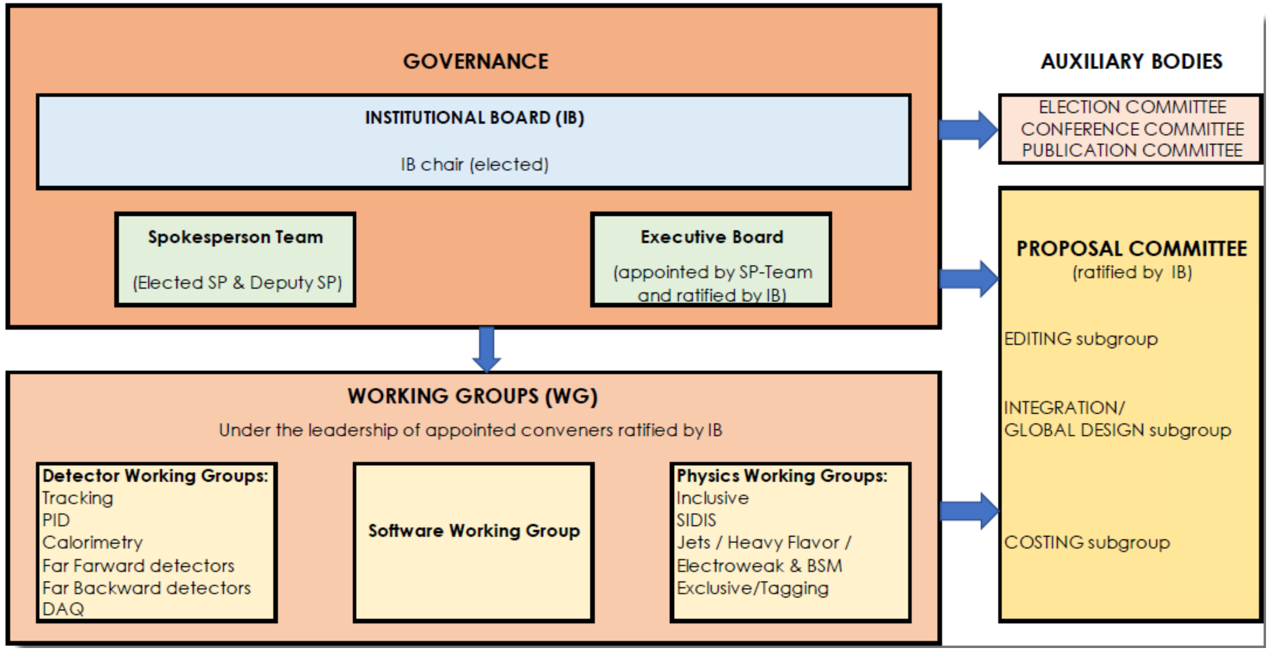
FastSim

COLLABORATION,

COSTING and SCHEDULE

ATHENA, HISTORY AND ORGANIZATION

- ATHENA detector proposal effort:
  - ➢Launched in March 2021
    - ✓Kick-Off meeting, March 12-13
- INFN groups join ATHENA, March 29th
- Collaboration name selected, May 18th
- Charter approved, July 2nd
- ATHENA structure



GOVERNANCE, fixed structure

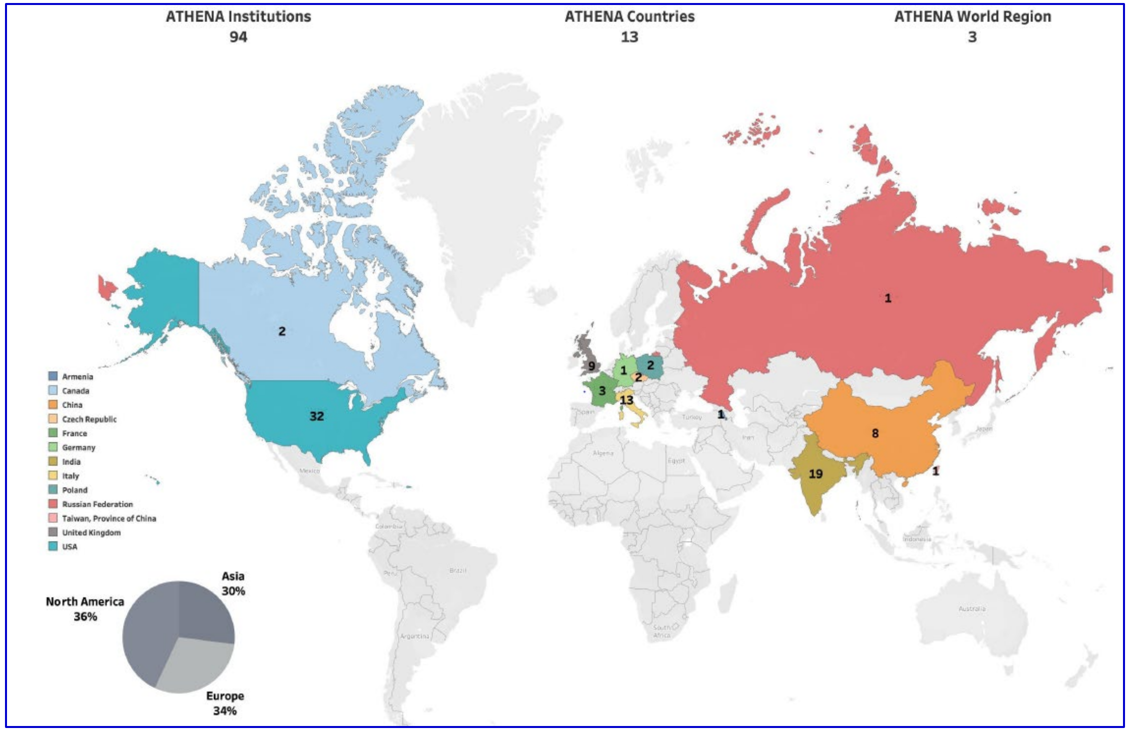
- ATHENA Charter documents organizational structure
- Institutional Board (IB): Governing body - Composed of all participating institutions
- Spokesperson (SP) Team: Representing collaboration and responsible for scientific and technical direction of experiment
- Executive Board (EB): Advising body to SP Team

Scientific coordination, it will evolve according to project phases

- Working Groups (WG): Central scientific bodies
  - Detector WGs (5)
  - Physics WGs (4)
  - Software Working Group
- Proposal Committee:
  - Editing subgroup
  - Integration/Global Design subgroup
  - Costing subgroup

What characterizes ATHENA:
the COLLABORATION

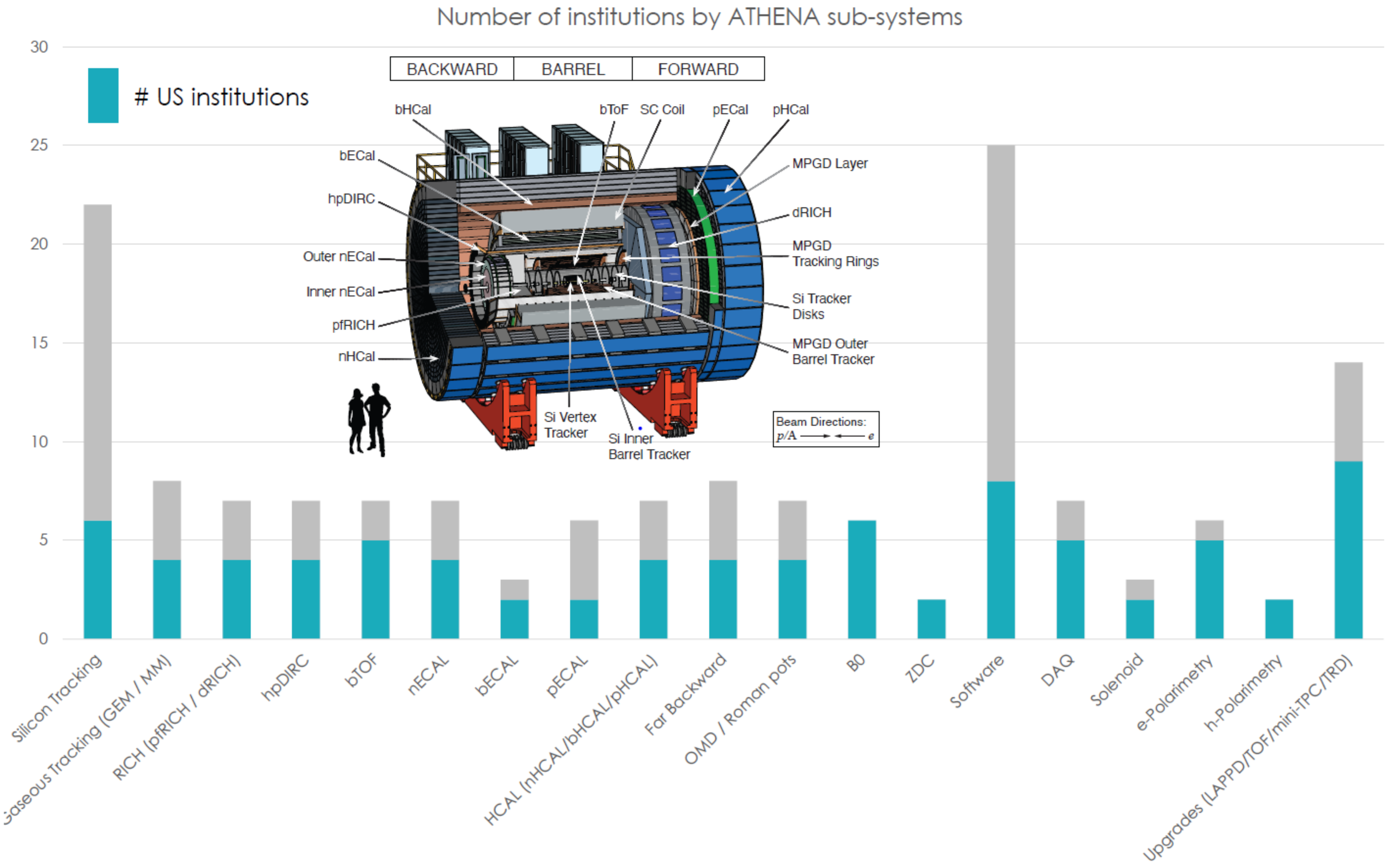
- Large, international, culturally diversified collaboration
  - 94 Institutes from 3 continents, 13 countries (2/3 non US)
  - Proposal: 438 authors
- ATHENA is a new collaboration, where the **formation process is ongoing**
  - Open to contributions from every new-comer
- A variety of cultural background
  - **DIS community** (HERA, COMPASS, JLab)
  - **Heavy ions** (RHIC, LHC)
  - **HEP** (LHC, Fermilab, Belle II)
- Many members with **long-term involvement in EIC development**
- Extensive detector expertise
  - From participation in previous experiments
  - long Involvement also with leadership roles in the 10 y-long R&D for EIC



- ATHENA chose to become a structured Collaboration
  - Adopting the ATHENA Charter
  - Elections for the main roles
- ATHENA is an engaged Collaboration
  - Already **TODAY 1/3 of the total sub-detector costs anticipated as in-kind**
  - Already **TODAY an impressive list of institutional interest for the ATHENA subsystems**

SUBDETECTORS and INSTITUTIONS

- ATHENA institutions cover a broad scientific background: Nucleon/ nuclear structure at RHIC/ JLab & HERA/COMPASS, Relativistic Heavy-Ion Physics at RHIC/LHC, HEP (LHC, FNAL, Belle II)
- Numerous ATHENA institutions: Dedicated detector EIC R&D programs
- ATHENA provides at its core significant experience in all detector areas

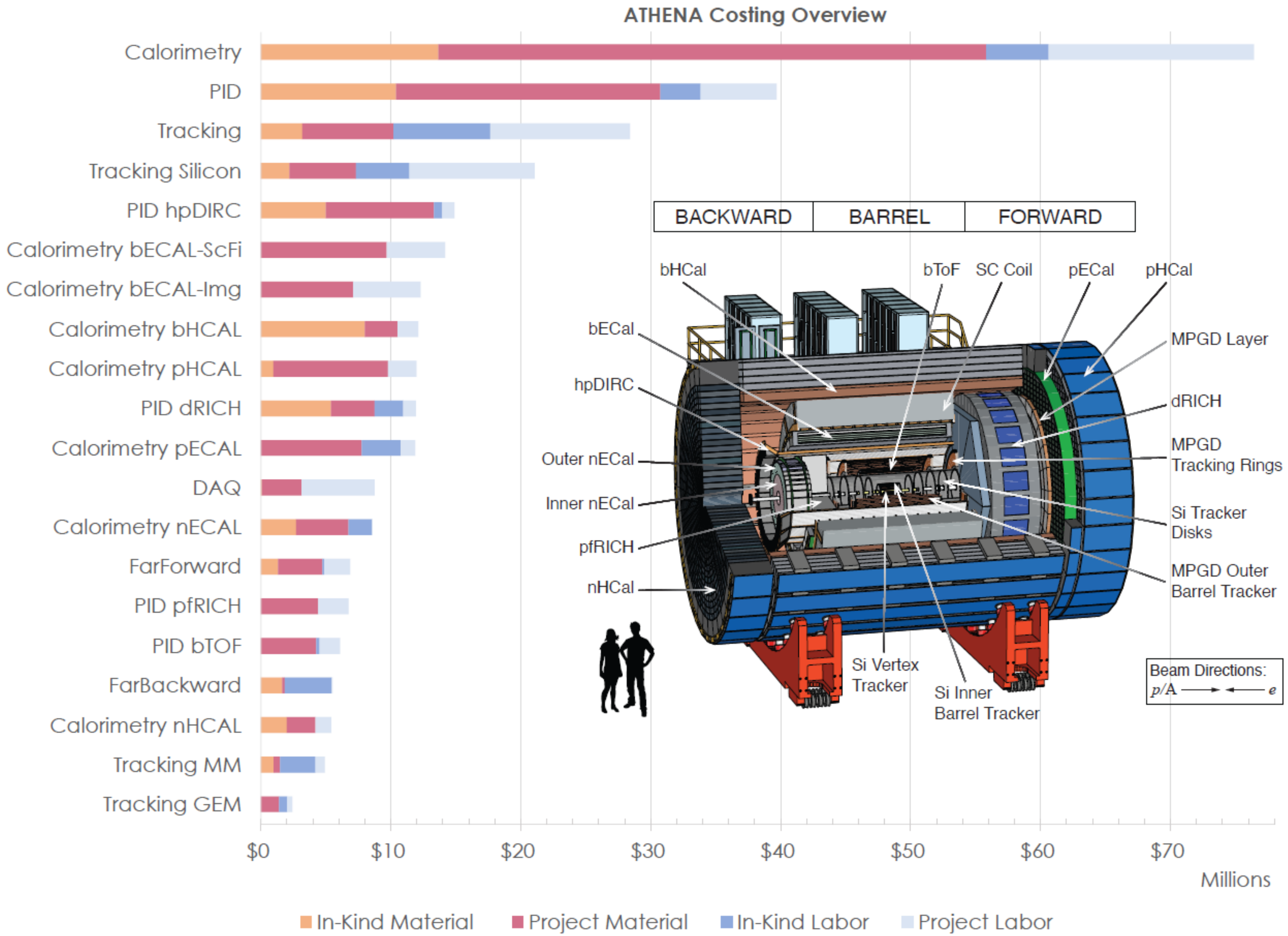


ATHENA, COSTING – the DETECTOR

Costing

- ATHENA costing for sub-system construction in 2021 USD:
- Largest cost drivers:
  - Calorimetry
  - PID
  - Tracking
- Total for sub-system construction in 2021 USD: $166M

	In-Kind	Project	Total	
Material	$30M	$76M	$106M	64%
Labor	$19M	$40M	$59M	36%
Total	$49M	$116M	$166M	
	30%	70%		



ATHENA, COSTING – the DETECTOR

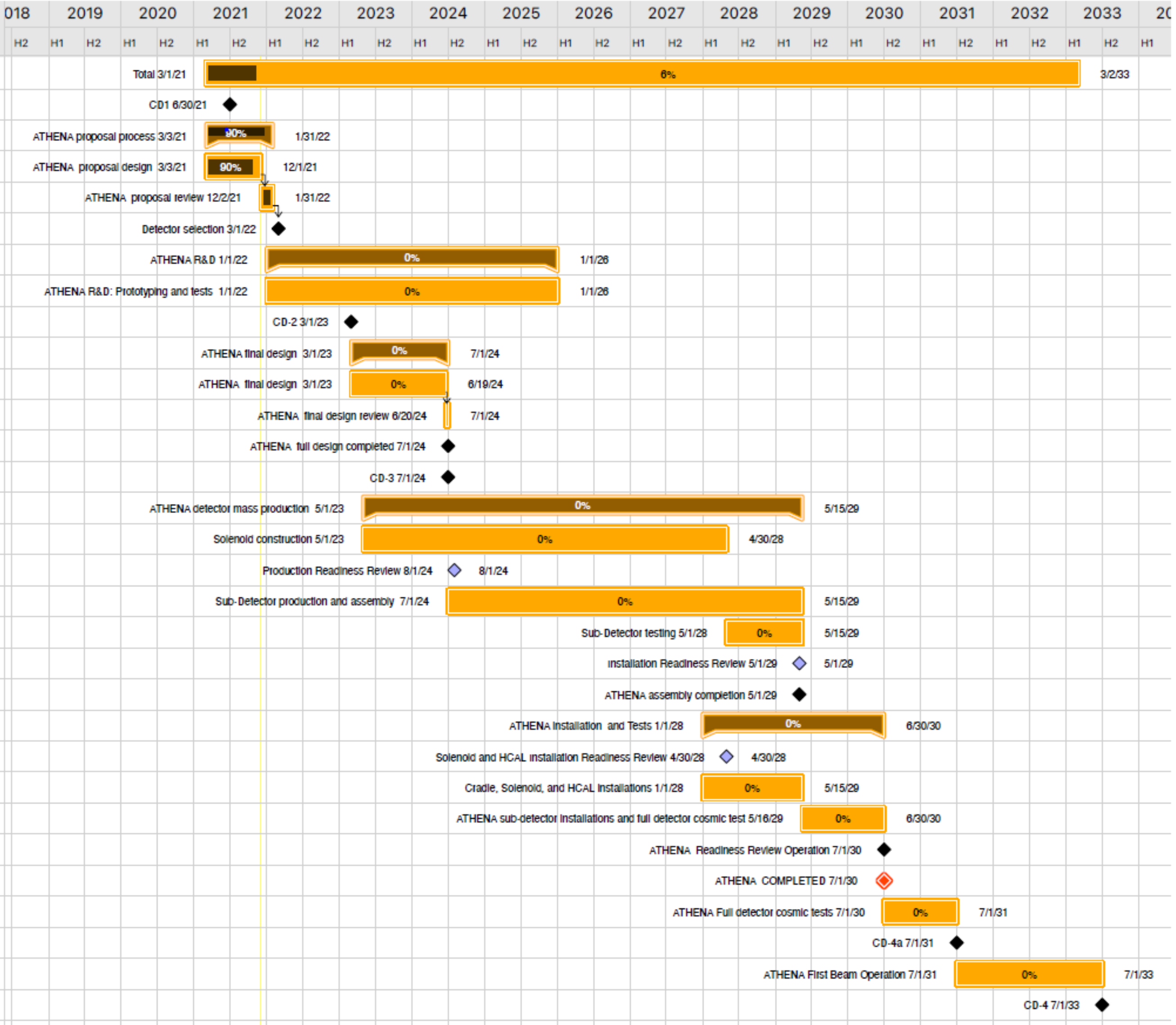
								2021 USD	*Escalated (rate 3.5 % / y)*
Grand Total	Total 2021	$30,290,473	$76,184,402	$106,474,875	$19,138,720	$39,998,289	$59,137,009	$165,611,884	$205,769,626
	(Fraction to Total 2021)	18.3%	46.0%	64.3%	11.6%	24.2%	35.7%	100.0%	
	Detector R&D							$25,339,863	$28,921,946
Global Systems	Detector Management								$7,400,000
	Magnet								$28,700,000
	Detector Infrastructure								$26,400,000
	Detector Pre Ops & Com.								$8,700,000
Grand Total	Total Escalated								$305,891,572

Estimated by the project

ATHENA SCHEDULE

- ATHENA schedule summarized in simplified Gantt chart with major activities and milestones:
  - CD-2
  - CD-3
  - Construction
  - Installation
  - Completion: 3rd Quarter of 2030 = CD-4Ae (early)

#	Name	Start
1	Total	3/1/21
2	CD1	6/30/21
3	**ATHENA proposal process**	3/3/21
4	ATHENA proposal design	3/3/21
5	ATHENA proposal review	12/2/21
6	Detector selection	3/1/22
7	**ATHENA R&D**	1/1/22
8	ATHENA R&D: Prototyping and tests	1/1/22
9	CD-2	3/1/23
10	**ATHENA final design**	3/1/23
11	ATHENA final design	3/1/23
12	ATHENA final design review	6/20/24
13	ATHENA full design completed	7/1/24
14	CD-3	7/1/24
15	**ATHENA detector mass production**	5/1/23
16	Solenoid construction	5/1/23
17	Production Readiness Review	8/1/24
18	Sub-Detector production and assembly	7/1/24
19	Sub-Detector testing	5/1/28
20	Installation Readiness Review	5/1/29
21	ATHENA assembly completion	5/1/29
22	**ATHENA Installation and Tests**	1/1/28
23	Solenoid and HCAL Installation Readiness F	4/30/28
24	Cradle, Solenoid, and HCAL installations	1/1/28
25	ATHENA sub-detector installations and full c	5/16/29
26	ATHENA Readiness Review Operation	7/1/30
27	ATHENA COMPLETED	7/1/30
28	ATHENA Full detector cosmic tests	7/1/30
29	CD-4a	7/1/31
30	ATHENA First Beam Operation	7/1/31
31	CD-4	7/1/33



BEST WISHES TO

YOU ALL !