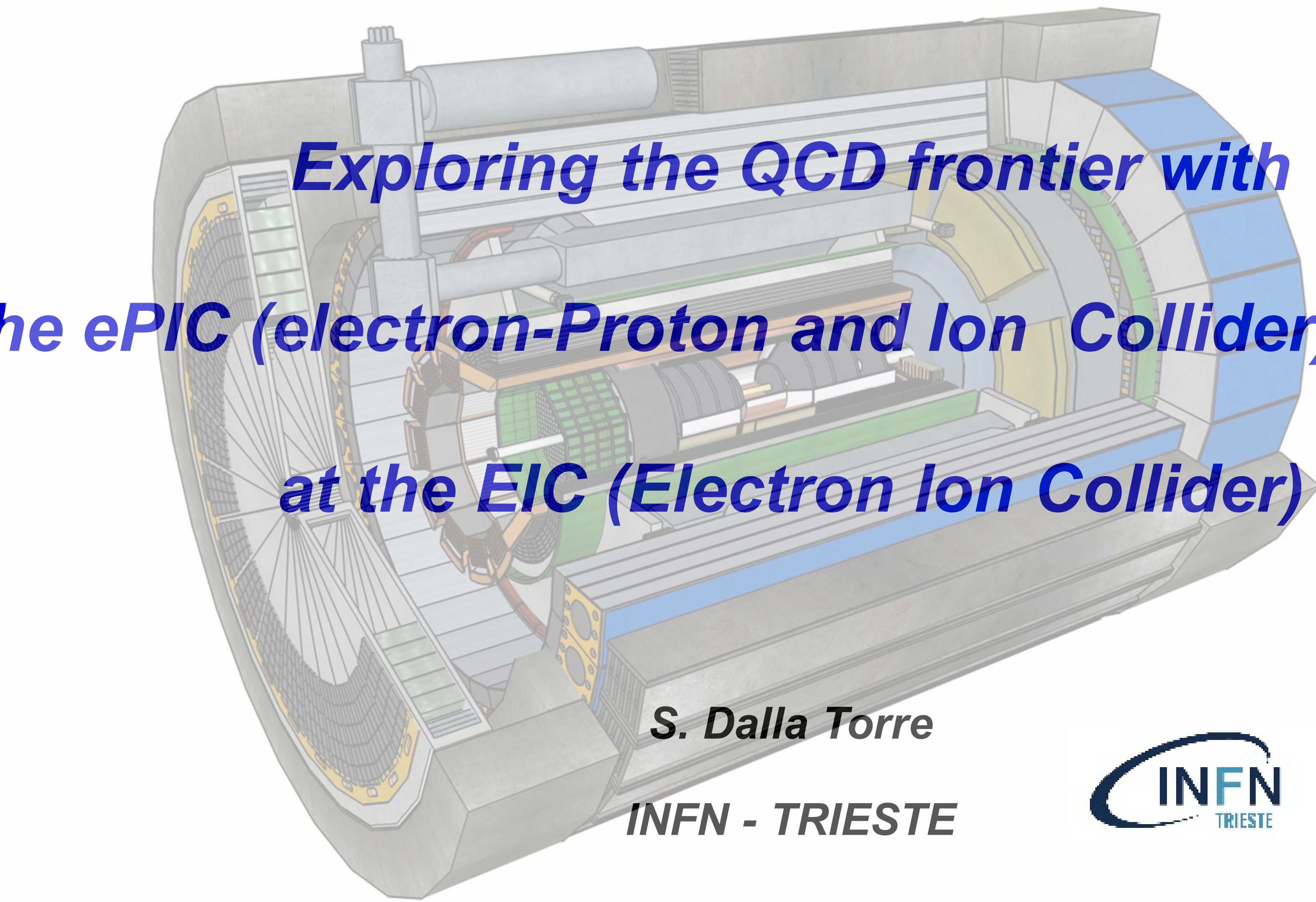


Exploring the QCD frontier with the ePIC (electron-Proton and Ion Collider) detector at the EIC (Electron Ion Collider)

S. Dalla Torre

INFN - TRIESTE

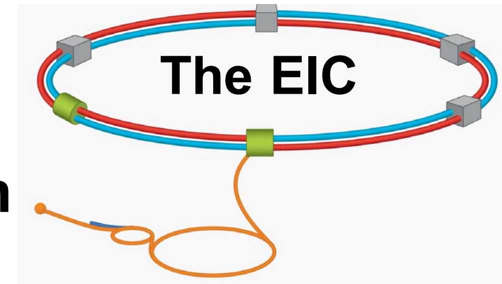
OUTLOOK

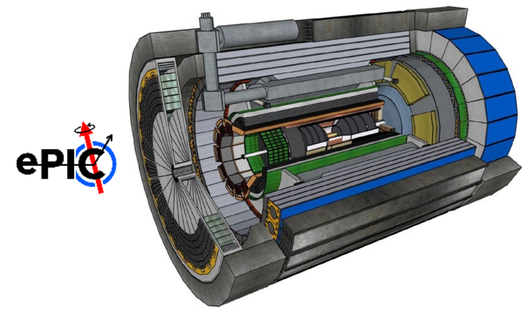
- **The ePIC context:**
  the EIC project and its physics scope

- **The ePIC detector**

The EIC Project in a nutshell

- **Enable the ultimate QCD exploration**
  - **By a high-luminosity polarized electron-ion collider: the EIC**
  - **By a detector highly integrated with the collider and capable to cope with the overall EIC physics scope, ePIC**

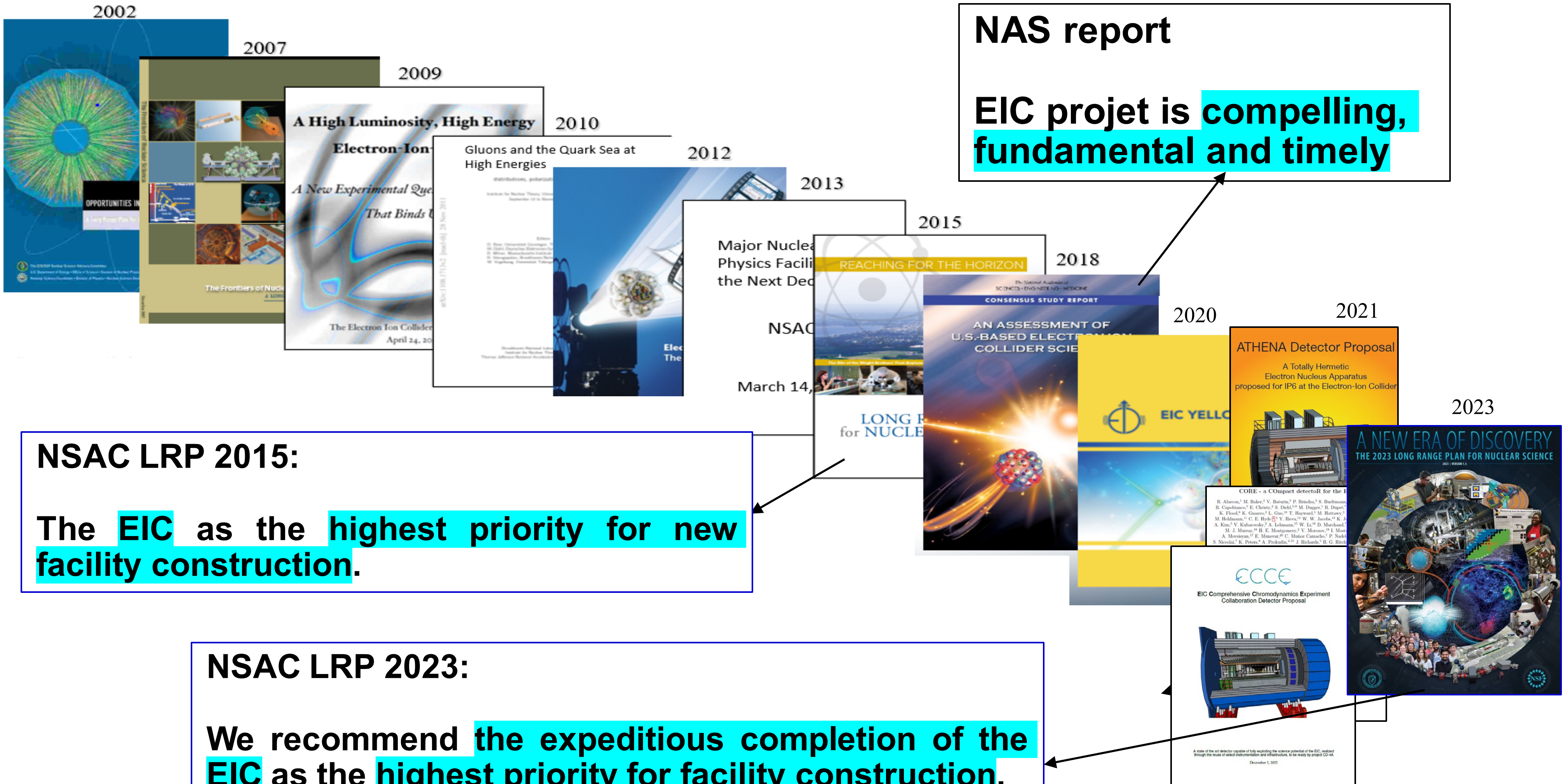




- **Status : approved project progressing towards its realization at BNL**

- **Key ingredients : the ample community supporting the EIC and the long dedicated effort path**

THE PATH TO THE EIC PROJECT



NAS report

EIC projet is compelling, fundamental and timely

NSAC LRP 2015:

The EIC as the highest priority for new facility construction.

NSAC LRP 2023:

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

Fresh news

Major Nuclear Physics Facilities for the Next Decade

Report of the NSAC Facilities Subcommittee accepted on April 26, 2024, by NSAC

"The EIC will be a new world-leading DOE facility at the forefront of scientific discovery. The Subcommittee ranks the EIC as **(a) absolutely central** in its potential to contribute to world-leading science in the next decade.''

"Concerning readiness of the facility for construction, we rank the EIC in category **(a) ready to initiate construction**."

DOE/NSF Nuclear Science Advisory Committee

The ePIC Collaboration

The community dedicated to the EIC science mission
by the realization of the ePIC detector

JLab, Jan. 2023

Warsaw, July 2023

ANL,
Jan. 2024

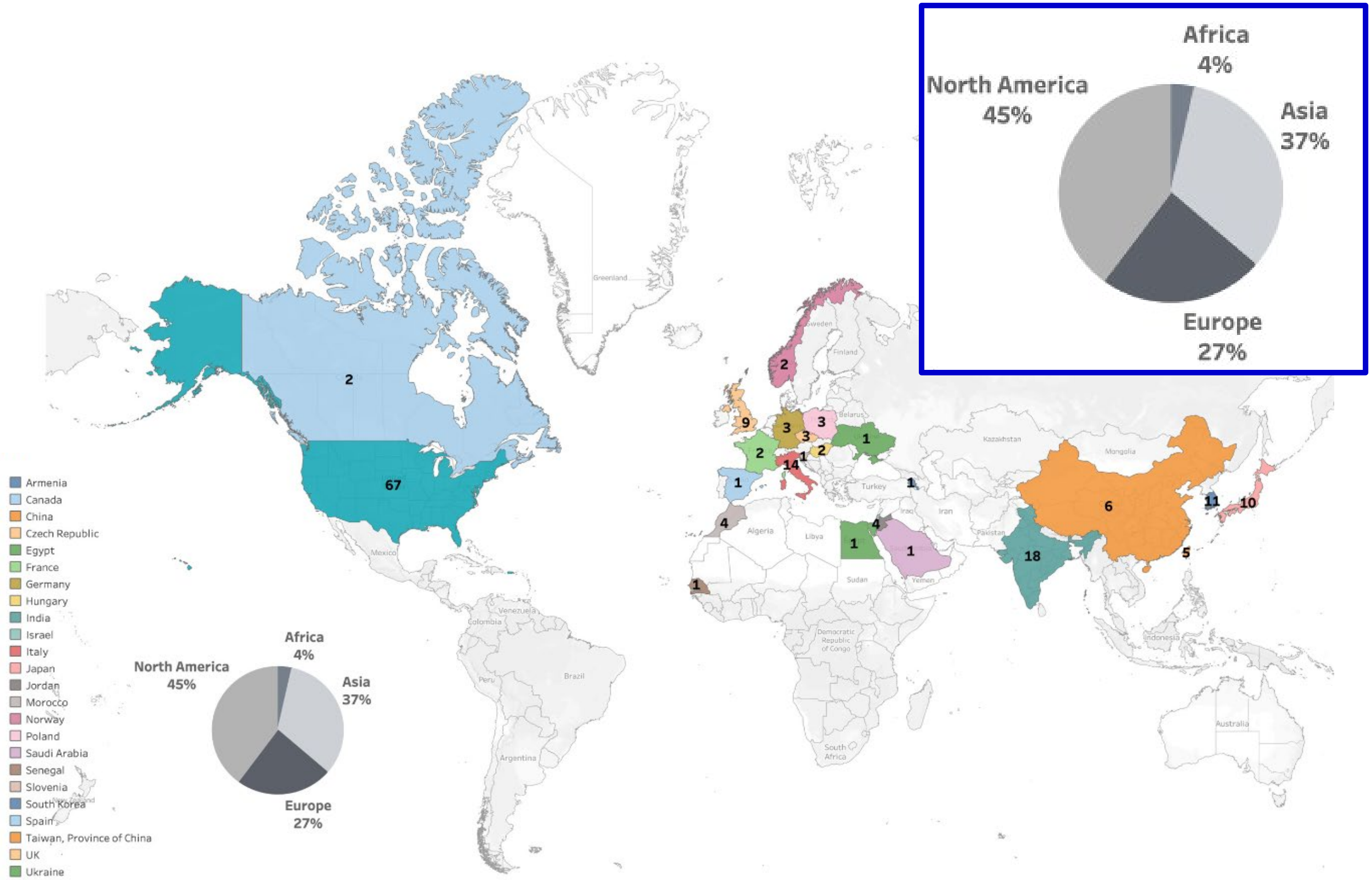
The ePIC Collaboration

ePIC Institutions	ePIC countries	ePIC World Regions
177	26	4

ePIC Initiated in July 2022

Currently:
>850 collaborators (from 2024 Institutional Survey)

>650 members active in ePIC activities



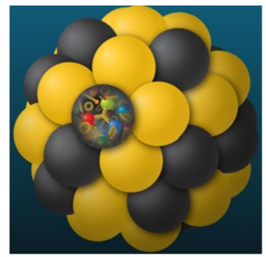
EIC PHYSICS: ultimate QCD exploration

In short words:

Investigate with precision the universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

In terms of major open questions:

How does the **spin** of the nucleon arise?

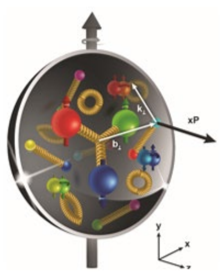


How do quarks and gluons **interact with a nuclear medium**?

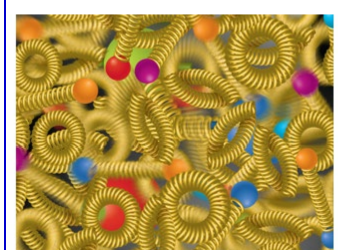
How do the **confined hadronic states** emerge?

How do the quark-gluon interactions create **nuclear binding**?

How does the **mass** of the nucleon arise?



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



What are the emergent properties of **dense system of gluons**?

Ultimate QCD exploration

REQUIREMENTS

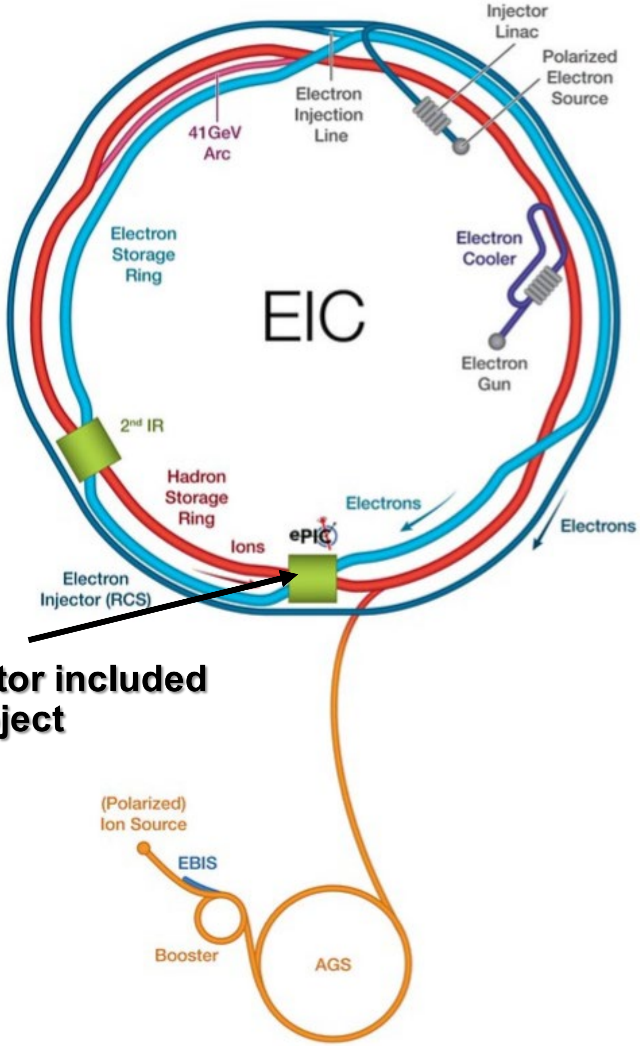
- **Access to gluon dominated region and wide kinematic range in x and Q^2**
- **Access to spin structure and 3D spatial and momentum structure**
- **Accessing the highest gluon densities ($(Q_s^A)^2 \sim c Q_o^2 \left(\frac{A}{x}\right)^{1/3}$)**
- **Studying observables as a function of x, Q^2, A, hadronic flavour, …**

THE EIC COLLIDER PROVIDES

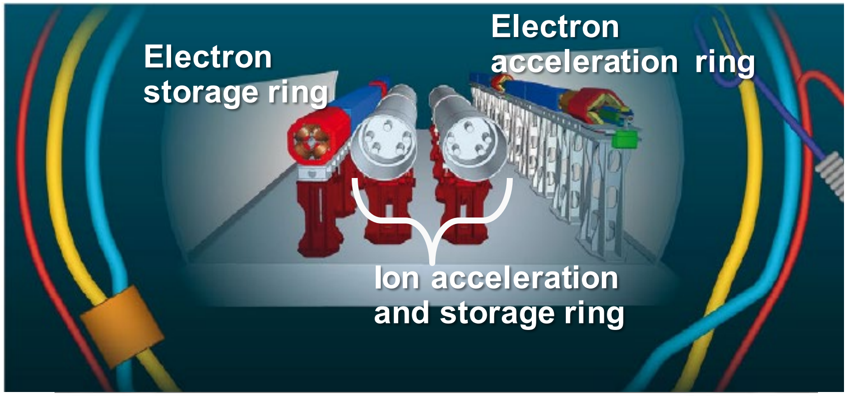
- ***Large center-of-mass energy range:***
  $\sqrt{s} = 21 - 140$ ***GeV***
- ***Polarized electron, proton and light nuclear beams ≥ 70%***
- ***Nuclear beams, the heavier the better (from H to U)***
- ***High luminosity (100 x HERA):*** $10^{33\text{-}34}$ ***cm***$^{-2}$ ***s***$^{-1}$

The EIC Collider

Usage of RHIC tunnel and RHIC p/ion complex



IP6 detector included in the project



- 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**

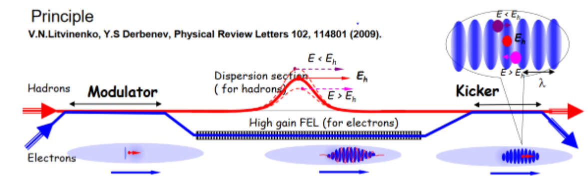
The EIC Collider

4 critical ingredients for HIGH LUMINOSITY

Coherent Cooling with FEL amplifier

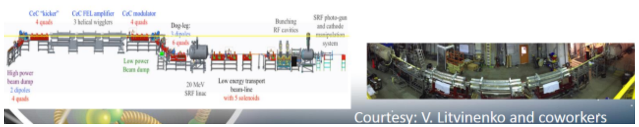
Principle

V.N.Litvinenko, Y.S Derbenev, Physical Review Letters 102, 114801 (2009).



→ cooling of high energy Hadron beams with high band-width; BW: **1THz**
short cooling times to balance strong **IBS**

Proof of Principle Experiment at BNL, ongoing



Strong Hadron Cooling

- Work continues on Strong Hadron Cooling, both the Coherent electron Cooling (CeC) approach and a backup solution based on a ring cooler
- Both approaches were reviewed in summer, no show stoppers found in either one

Bunches and beam crossing rates

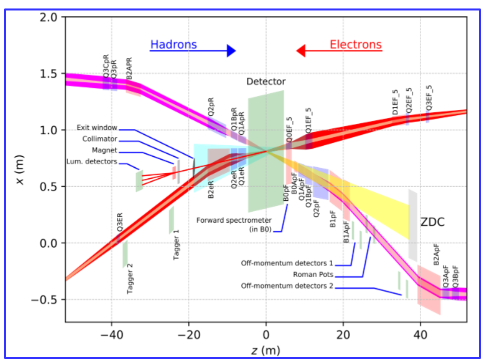
Species	p	e	p	e	p	e	p	e	p	e
Beam energy [GeV]	275	18	275	10	100	10	100	5	41	5
$\sqrt{s}$ [GeV]	140.7		104.9		63.2		44.7		28.6	
No. of bunches	290		1160		1160		1160		1160	

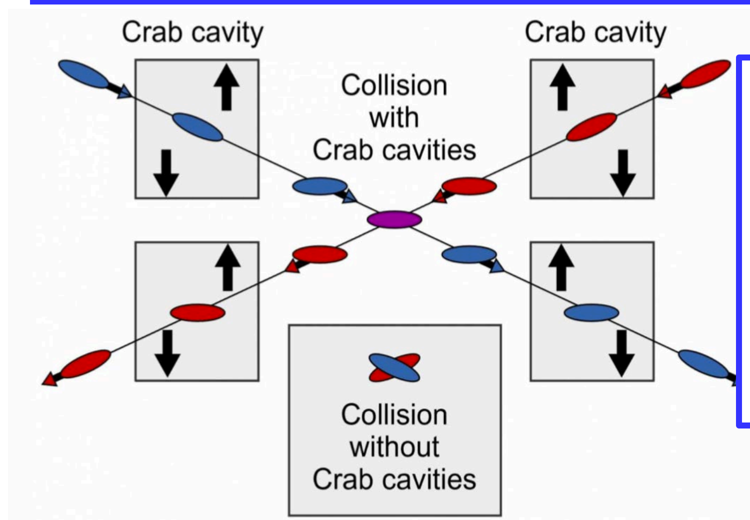
Species	Au	e	Au	e	Au	e	Au	e
Beam energy [GeV]	110	18	110	10	110	5	41	5
$\sqrt{s}$ [GeV]	89.0		66.3		46.9		28.6	
No. of bunches	290		1160		1160		1160	

Up to a beam crossing rate at the IR every 10ns

a challenge for the collider and the experiment !

Small β^*_y → quads close to IP leaving ~10 m for the detector





CRAB CROSSING ANGLE (25 mrad) to restore head-on collisions

The EIC Collider

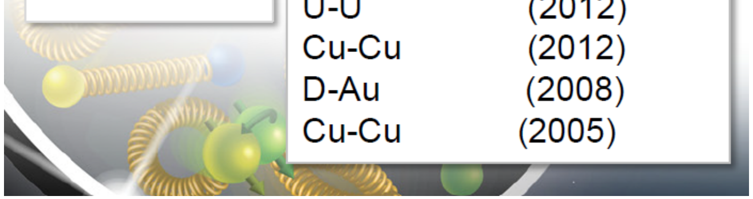
MORE unique aspects

ION SPECIES

The existing RHIC ion sources & ion acceleration chain provides already **today** all ions needed at EIC

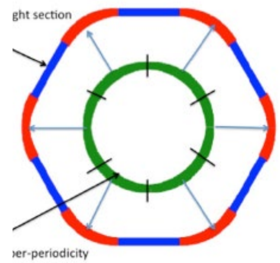
Ion Pairs in the RHIC Complex	
Zr-Zr, Ru-Ru	(2018)
Au-Au	(2016)
d-Au	(2016)
p-Al	(2015)
h-Au	(2015)
p-Au	(2015)
Cu-Au	(2012)
U-U	(2012)
Cu-Cu	(2012)
D-Au	(2008)
Cu-Cu	(2005)

Enormous versatility! is a unique capability!



BEAM POLARIZATION

ABOUT e POLARIZATION



➔ resonance free acceleration up >18 GeV

on average, every bunch refilled in 2.2 min

ABOUT p/ light ion POLARIZATION

presently

Measured RHIC Results:
- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

empowerment

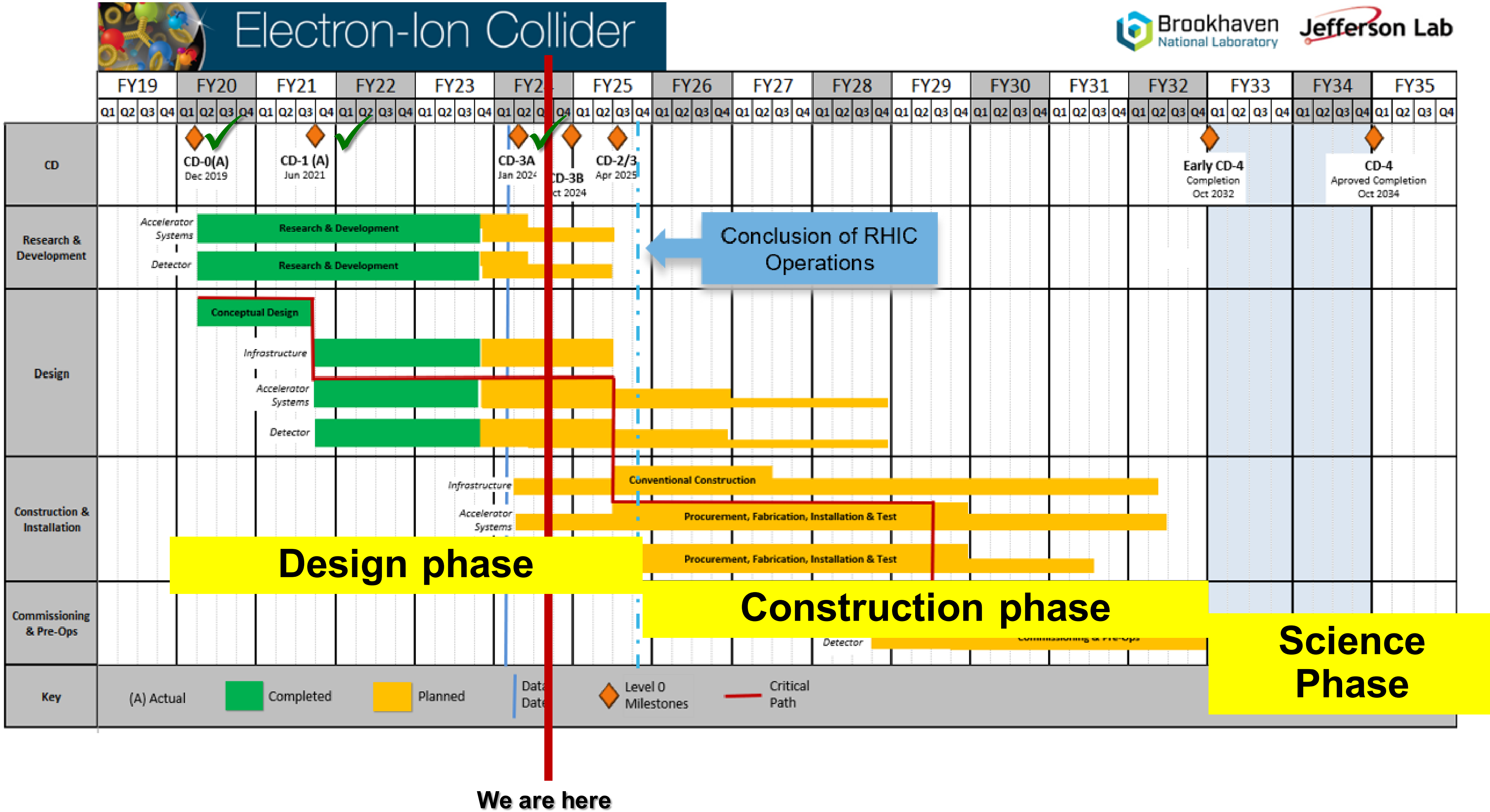
Planned near term improvements:

AGS: Stronger snake, skew quadrupoles, increased injection energy
➔expect 80% at extraction of AGS

RHIC: Add 2 snakes to 4 existing no polarization loss
➔ expect 80% in Polarization in RHIC and eRHIC

High polarization ^3He and D beams also possible

The EIC schedule



OUTLOOK

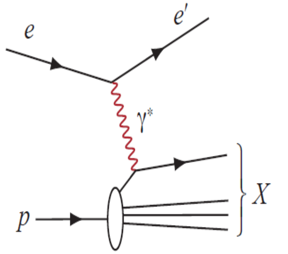
- **The ePIC context:**
  the physics scope and the EIC project

- **The ePIC detector**

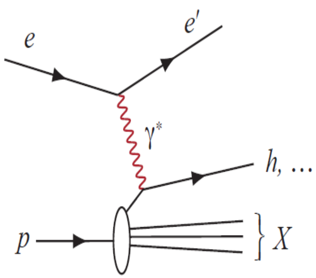
Ultimate QCD exploration

REQUIREMENTS → ePIC detector

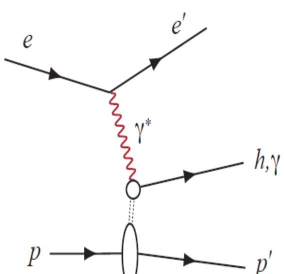
Measurement categories to address EIC physics:



- Inclusive DIS
  - fine multi-dimensional binning in x, Q^2



- Semi-inclusive DIS
  - 5-dimensional binning in x, Q^2, z, p_T, θ



- Exclusive processes
  - 4-dimensional binning in x, Q^2, t, θ to reach |t| > 1 GeV2

ePIC detector (Inclusive DIS):

- ***Large coverage (-3.5 < η < 3.5) for wide phase-space reach***
- ***Excellent EM-calorimetry with PID support for e/π separation***
- ***Fine resolution tracking by low mass detectors***

ePIC detector (Semi-inclusive DIS):

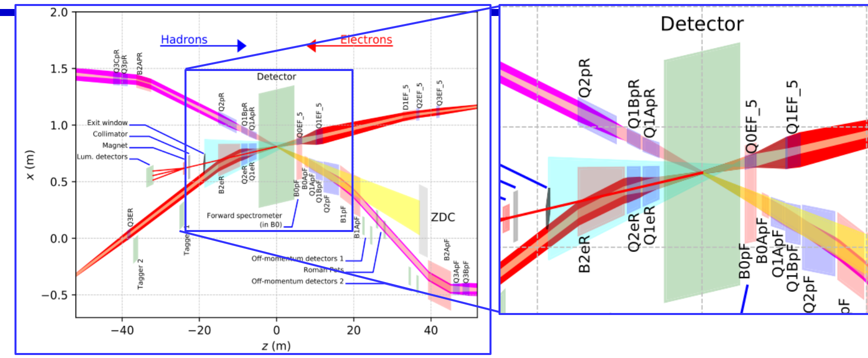
- ***Fine p_T resolution***
- ***Extended PID systems for hadron identification***
- ***H-calorimetry to attempt TMD assessment with jets (new world-wide), as tail chatter, for μ identification***

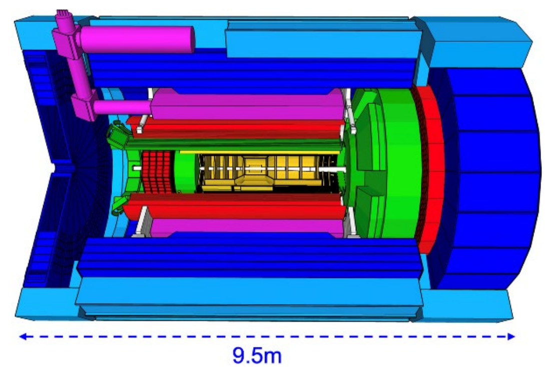
ePIC detector (Exclusive processes):

- ***Extend acceptance at extremely small scattering angles***
- ***Fine vertex resolution by tracking***

ePIC DETECTOR CHALLENGES

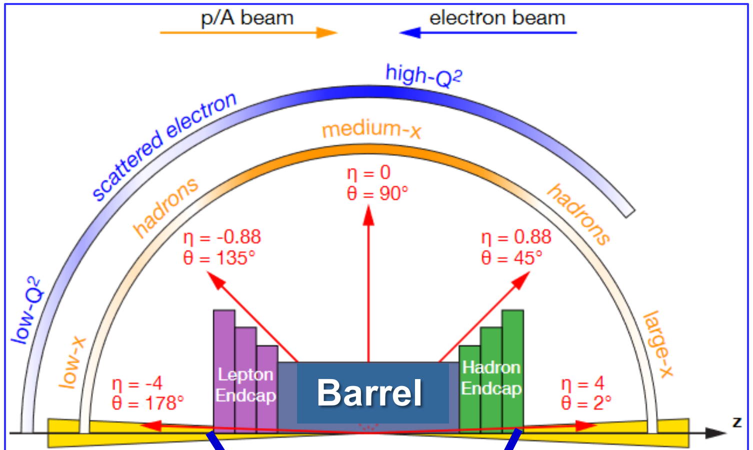
- *Small β^**
  - → *quads near to IP*
  - → *9.5 m to host the central detector*
- *Asymmetry beam energies*
  - → *Asymmetric detector design*
- *Far detectors highly integrated with the storage rings*
- *Synchrotron radiation background*
  - → *solenoid axis aligned with e beam*
  - → *p/ion beams follow a helical path in the CD solenoid*
- *Other physical backgrounds*
  - → *beam-gas scattering*
- *Crab crossing*
  - → *Vertex smearing to be removed with timing information fast timing in the range ~30 – 40 ps*
- *Bunch crossing rate and crossing time*
  - → *Up to a bunch crossing every 10 ns*
  - → *The whole bunch crossing takes ~ 3 ns*

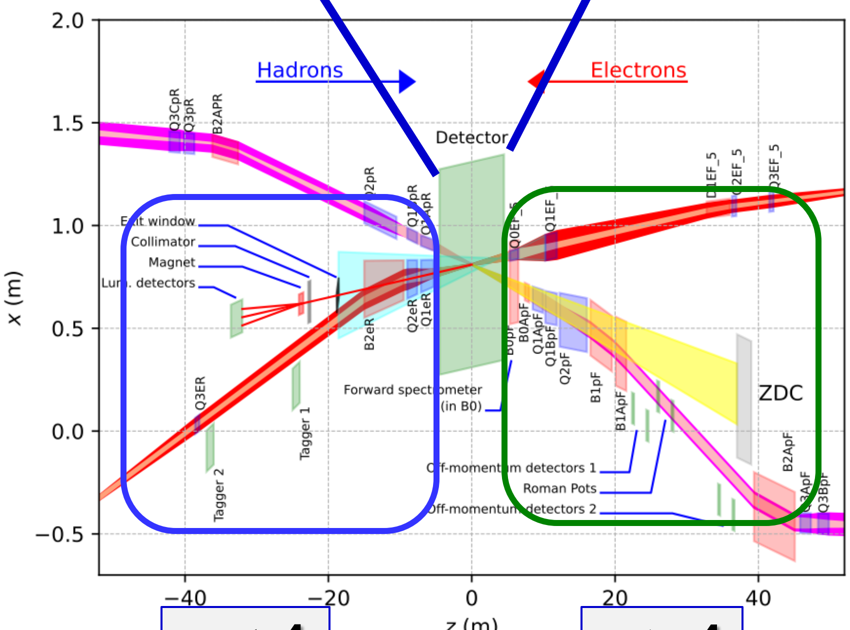




rates in kHz	5x41 GeV	5x100 GeV	10x100 GeV	10x275 GeV	18x275 GeV	Vacuum
Total ep	12.5 kHz	129 kHz	184 kHz	500 kHz	83 kHz	
hadron beam gas	12.2kHz	22.0kHz	31.9kHz	32.6kHz	22.5kHz	10000Ahr
	131.1kHz	236.4kHz	342.8kHz	350.3kHz	241.8kHz	100Ahr
electron beam gas	2181.97 kHz	2826.38 kHz	3177.25 kHz	3177.25 kHz	316.94 kHz	10000Ahr
DIS eA	kHz	kHz	kHz	/	/	
hadron beam (Au) gas	7.36kHz	10.3kHz	10.3kHz	/	/	10000Ahr
	79.1kHz	110.7kHz	110.7kHz	/	/	100Ahr

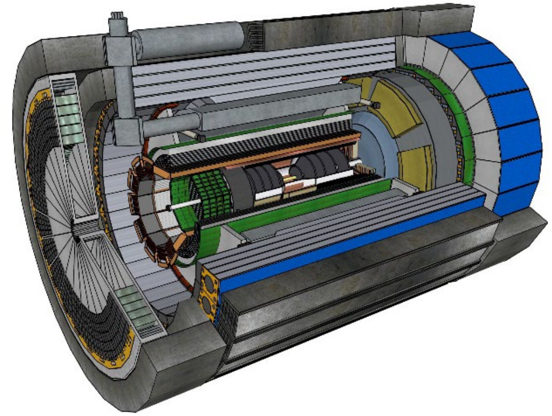
THE COMPLETE ePIC DETECTOR





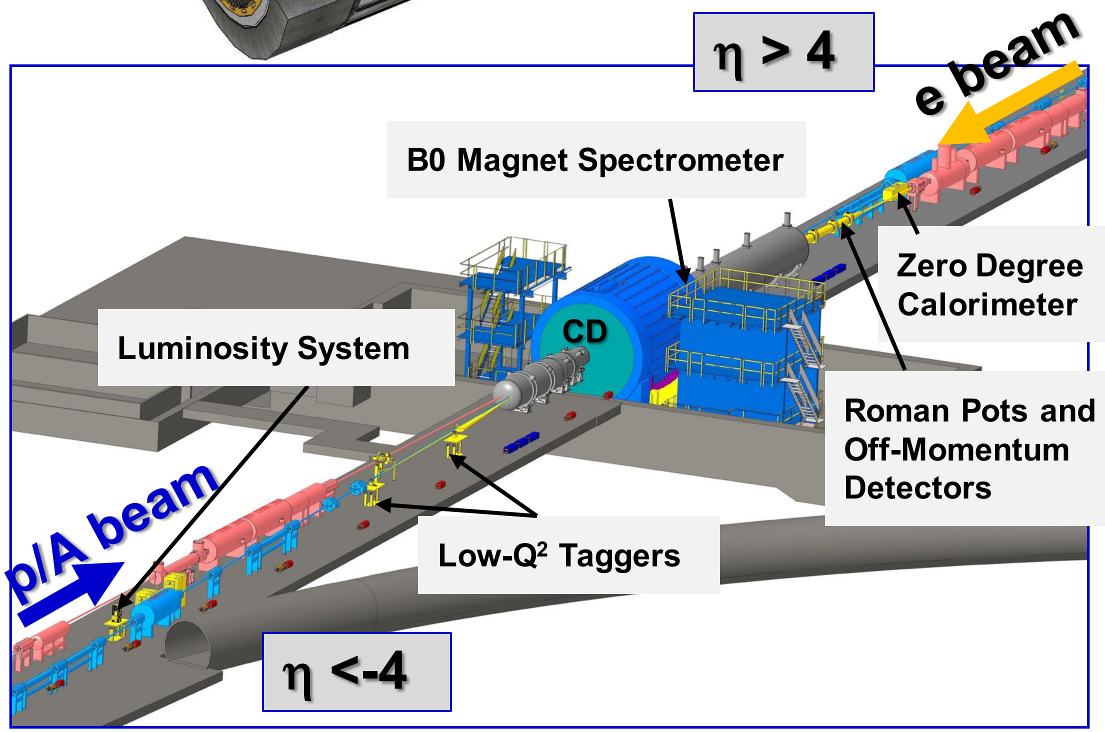
η <-4

η > 4

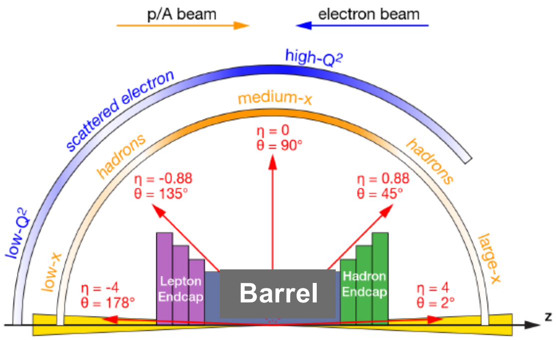


Central Detector (CD)

-4 < η < +4



ePIC Central Detector (CD)

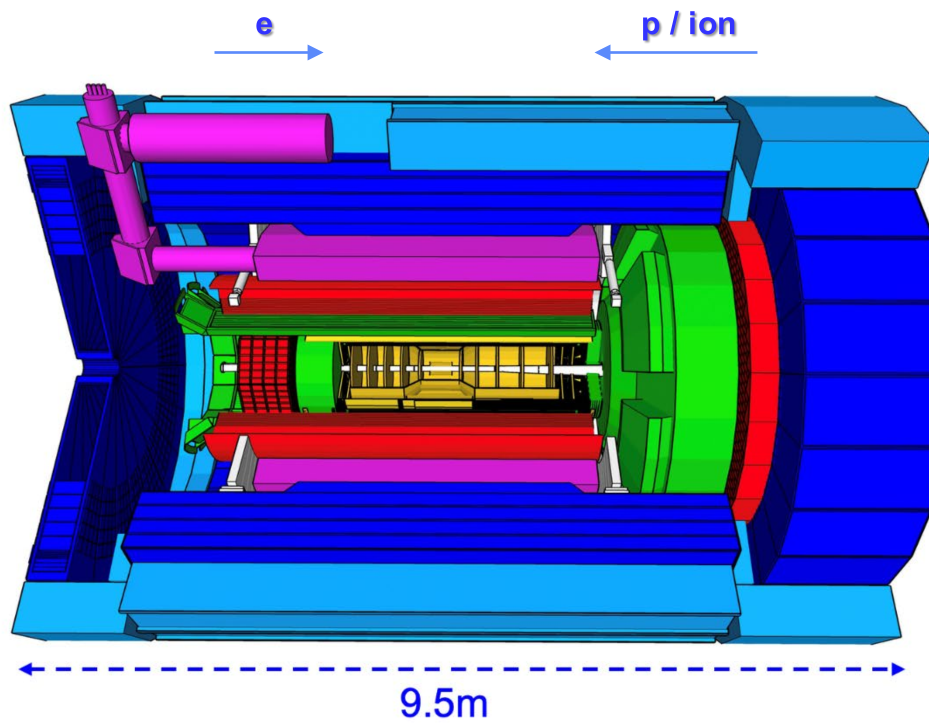


Very naturally organized in:

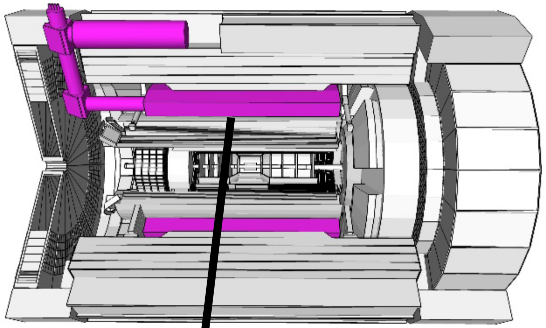
- **Backward endcap**
- **Barrel**
- **Forward endcap**

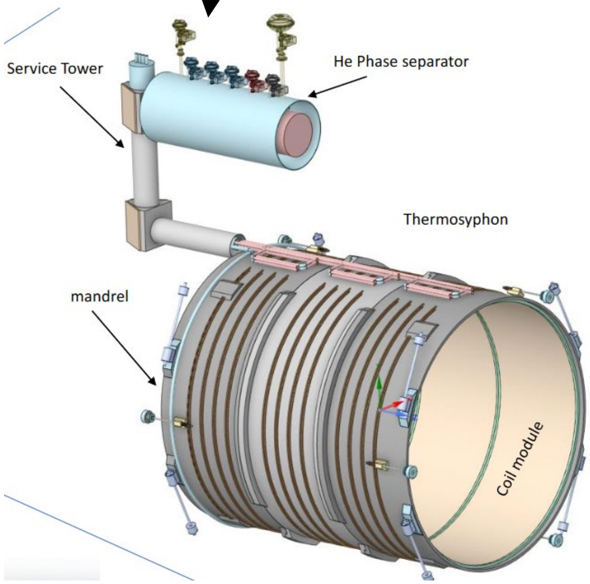
subsystems

- hadronic calorimeters
- Solenoidal Magnet
- e/m calorimeters (ECal)
- Time.of.Flight, DIRC, RICH detectors
- MPGD trackers
- MAPS tracker



The ePIC solenoid



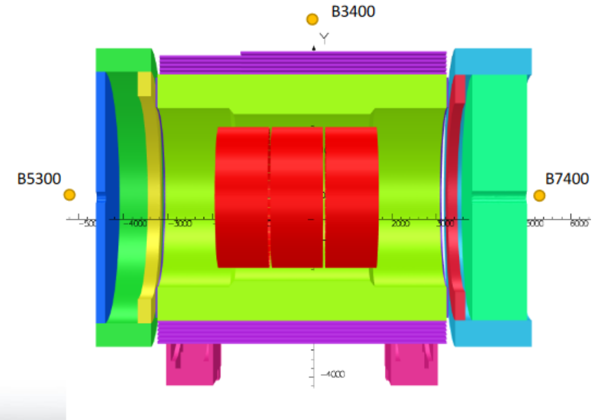


Parameter	Value
Coil length	3512 mm
Warm bore diameter	2840 mm
Cryostat length	< 3850 mm
Cryostat outer diameter	< 3540 mm

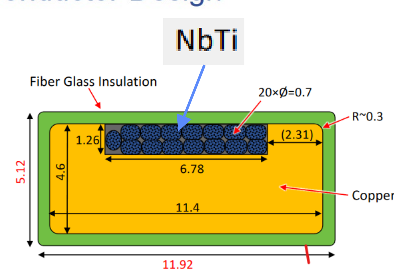
Parameter	Value	Comment
B5300 (B @ Z= -5300 mm)	< 10 G	**Stray field requirement is based on IR magnet location**
B7400 (B @ Z= 7400 mm)	< 10 G	
B3400 (B @ R= 3400 mm)	< 10 G	

Parameter	Value	Comment
Central Field B_0	2.0 T	**Magnetic Field Properties**
Lowest operating field	0.5 T	
Field Uniformity in FFA	12.5 % ± 100 cm around center 80 cm radius	
Projectivity in RICH Area	< 0.1 (mrad@30GeV/c) < 10 T/A/mm² From Z = 180 cm to 280 cm	

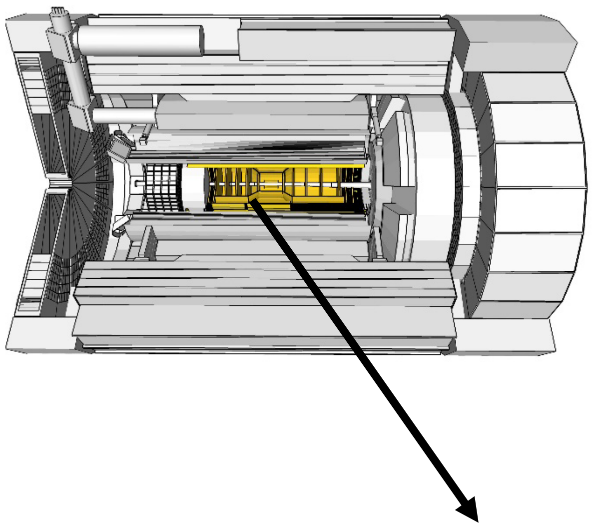
Reference field value: 1.7 T



Conductor Design



TRACKING IN ePIC CD

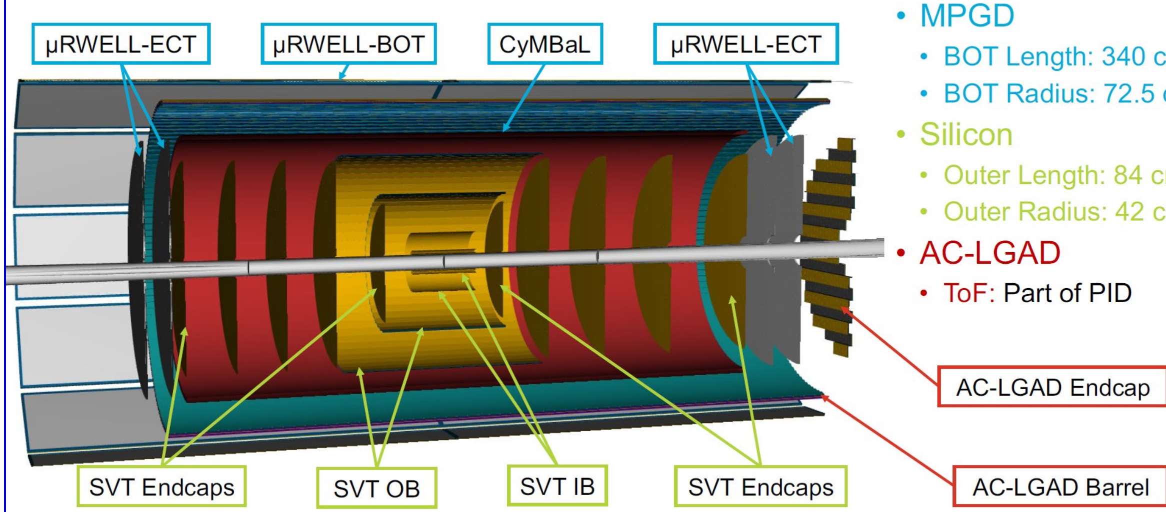


Complementary tracking technologies characterized by light materials

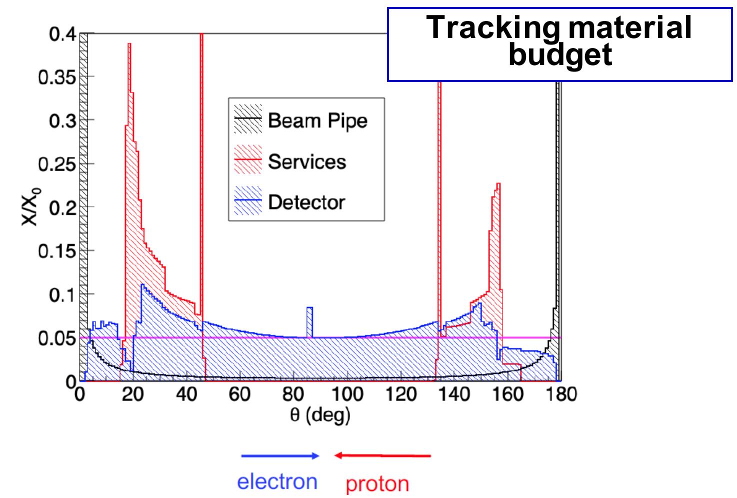
SVT: Si trackers based on ALICE ITS3 65 nm MAPS sensors
- **Fine space resolution ~ 6 μm**
- **Five cylindrical layers in the barrel and five disks in each endcap**

MPGD trackers
- **Good time resolution $\mathcal{O}$(10 ns)**
- **Cylindrical MICROMEGAS**
- **Planar μR-WELL with GEM pre-amplification**

Additional information
- AC-LGADs for ToF (PID) - very fine time resolution: 20/30 ps
- First layer of the barrel imaging EM calorimeter – fine space resolution (150 μm), good time resolution (~ 2 ns)



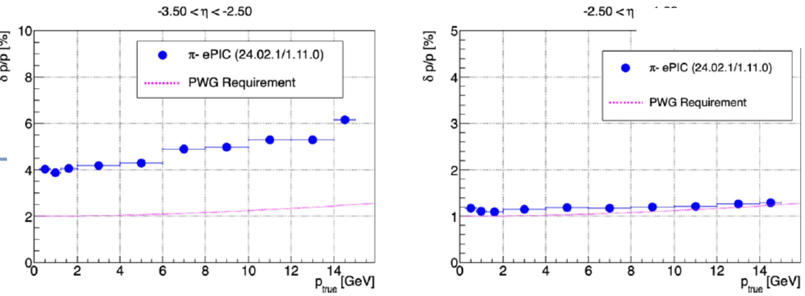
- MPGD
  - BOT Length: 340 cm
  - BOT Radius: 72.5 cm
- Silicon
  - Outer Length: 84 cm
  - Outer Radius: 42 cm
- AC-LGAD
  - ToF: Part of PID

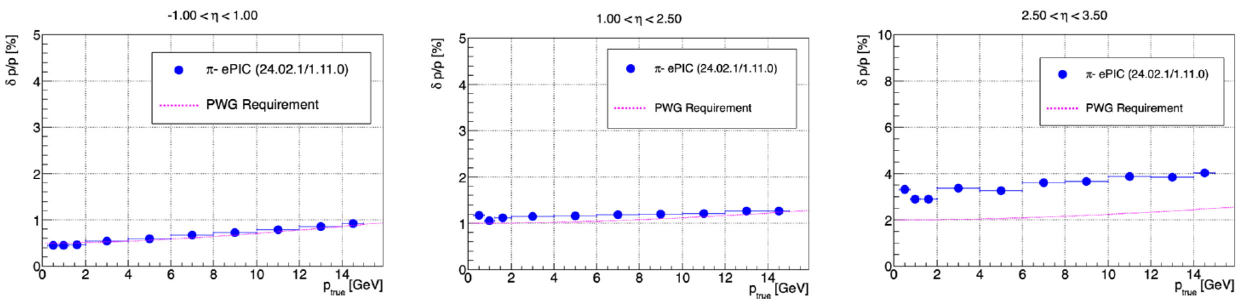


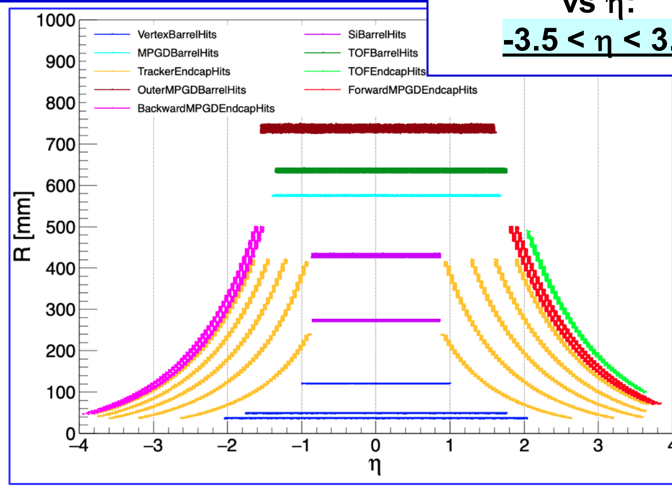
TRACKING IN ePIC CD

Tracking coverage vs η: -3.5 < η < 3.5

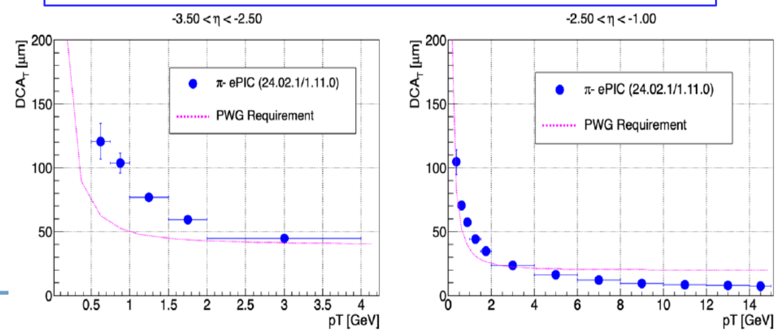
Momentum Resolution

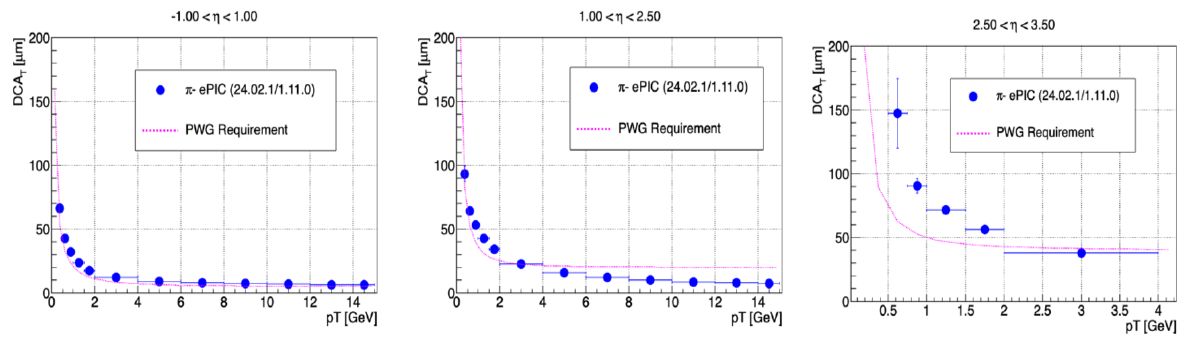






Pointing Resolution





- Single particle
  - Includes AC-LGAD layers
  - Extreme η regions will require use of other ePIC sub detector information
  - Follows requirements elsewhere

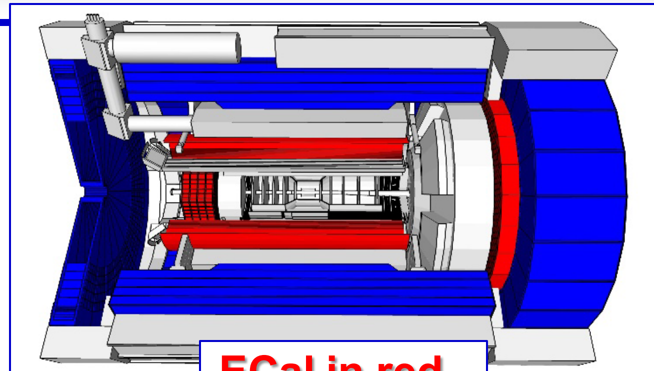
SENSORS FOR CALORIMETRY IN ePIC

SiPM sensors for all Calorimeters in ePIC

- **SiPMs recently introduced in calorimetry**
- direct experience is coming from the applications in GlueX, STAR and sPHENIX
- these colleagues now at work for ePIC calorimetry

Relevant SiPM features for ePIC calorimetry

- **Cost-effective** technology
- Operation in **magnetic field**
- Wide **dynamic range** with tuned parameters for the different calorimeters
- Low **noise** with appropriate thresholding
- Effect of the radiation
  - Not new, already addressed for STAR and sPHENIX
  - Further irradiation campaigns on-going

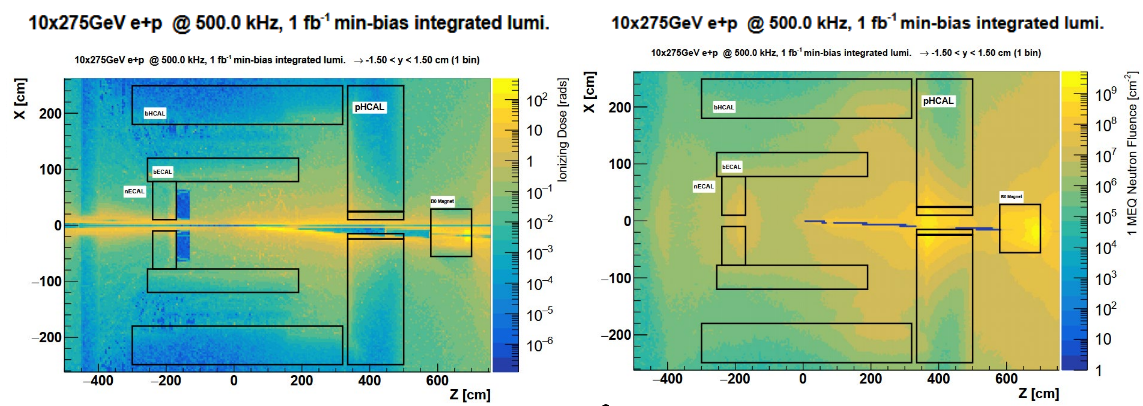


ECal in red
HCal in blue

SiPM requirements for HCals

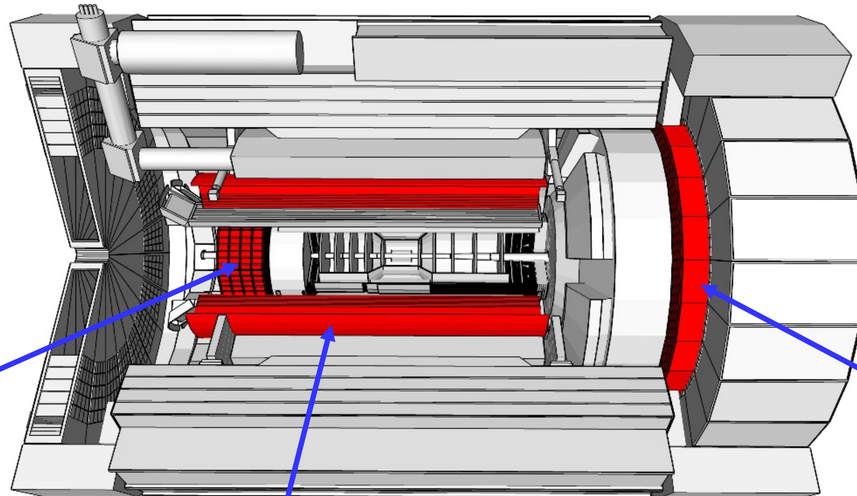
Parameter	Value
Size	1.3mm x 1.3mm
Pixel size	15 µm
Photon Detection Efficiency (PDE)	>25%
Dark Count Rate (DCR)	<400 kHz
Gain	> 5*10^5
Fill factor	>40%
Peak sensitivity	~450 nm

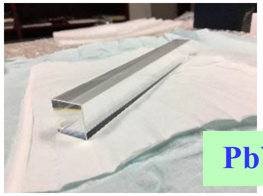
Rad Dose and Neutron Flux



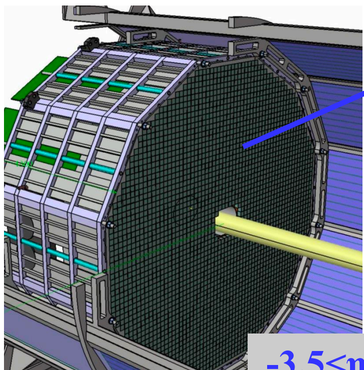
Doses and fluxes ~ 10^{-3} compared to HL-LHC

ELECTROMAGNETIC CALORIMETRY IN ePIC CD

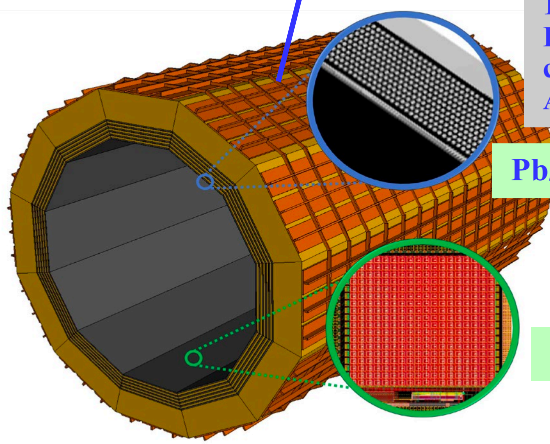




PbWO4



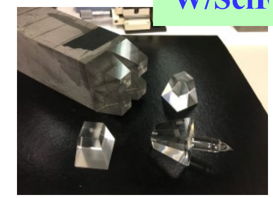
-3.5<η<-1.7
$22X_0$
~3k crystals
R_{outer}=64cm



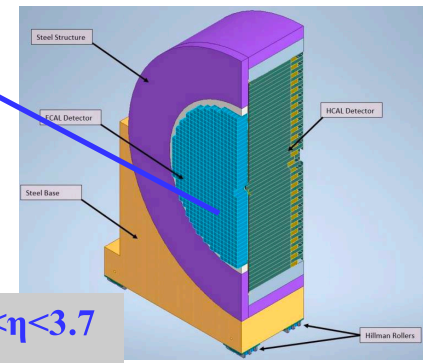
-1.7<η<1.4
$17X_0$
Pb/SciFi: 5760 readout ch.s
AstroPix: ~0.5B pixels

Pb/SciFi

AstroPix

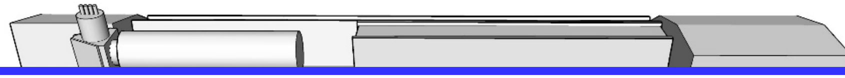


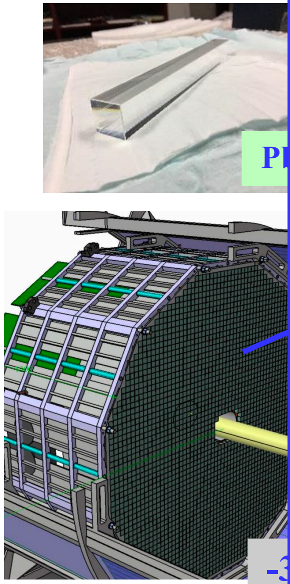
W/SciFi

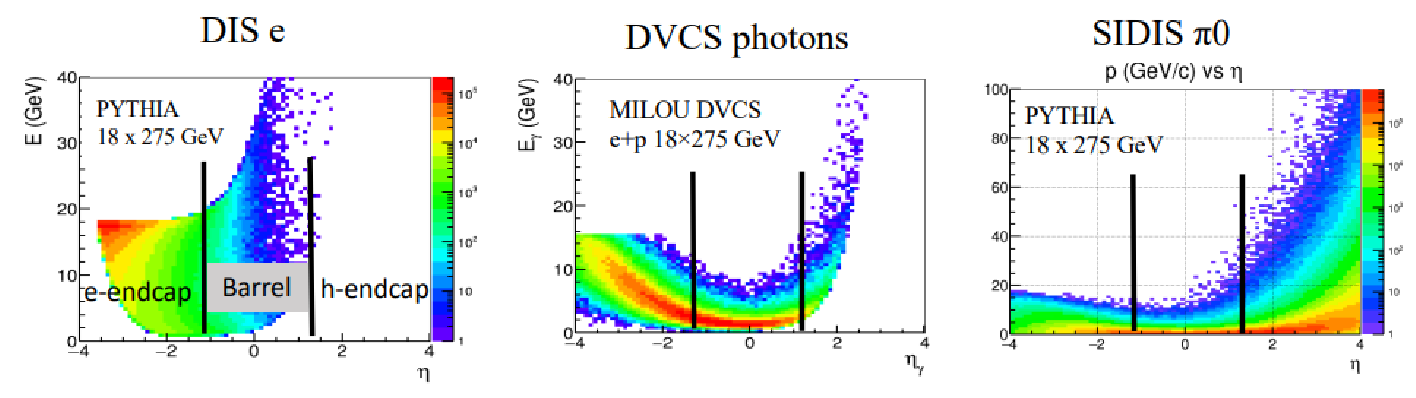


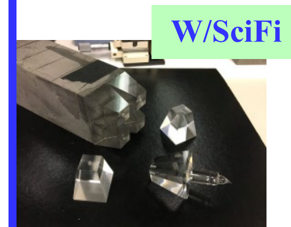
1.4<η<3.7
$23X_0$
~16k towers
R_{outer}=160cm

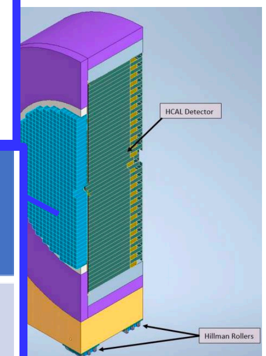
ELECTROMAGNETIC CALORIMETRY IN ePIC CD



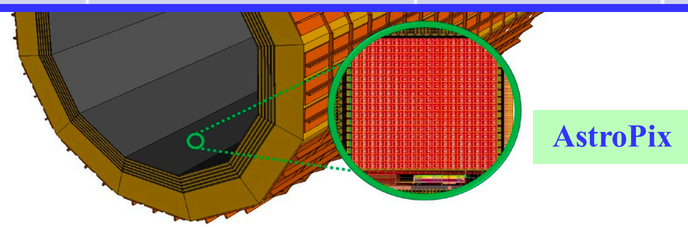








	σ_E/E	E range, GeV	$\pi^{\pm}$ suppression (In combination with other subsystems)	$\pi0/\gamma$ discr.
e-endcap	$\frac{(2-3)\%}{\sqrt{E}} \oplus (1-2)\%$	0.05–18 GeV	Up to 10^4	Up to 7 GeV/c
Barrel	$\frac{(7-10)\%}{\sqrt{E}} \oplus (1-3)\%$	0.05–50 GeV	Up to 10^4	Up to 10 GeV/c
h-endcap	$\frac{(10-12)\%}{\sqrt{E}} \oplus (1-3)\%$	0.1–100 GeV	Up to 10^4	Up to 50 GeV/c

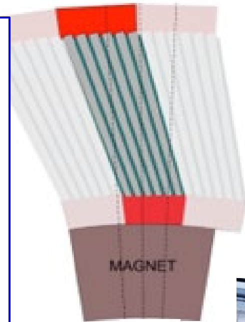


HADRON CALORIMETRY IN ePIC CD

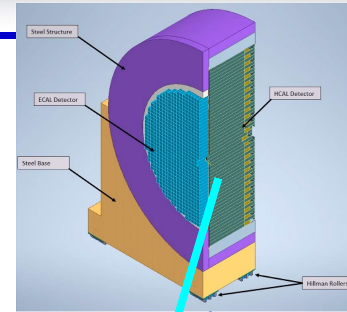
Backward and barrel:

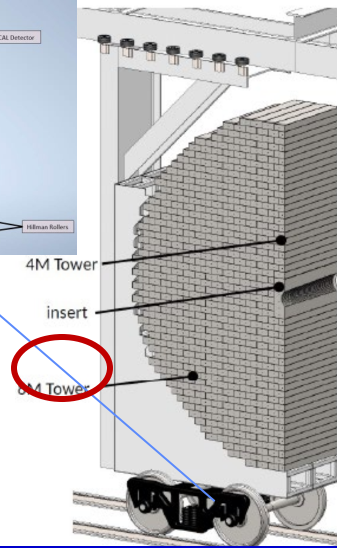
Steel/scintillator sampling calorimetry - CONSOLIDATED TECHNOLOGY

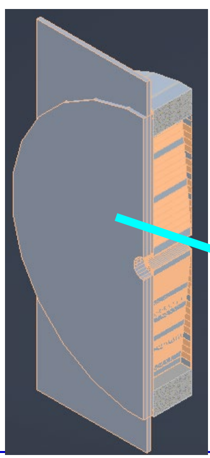
- Identification of neutral hadron jets, especially at low x
- Tail catcher for e/m calorimeter
- μ identification

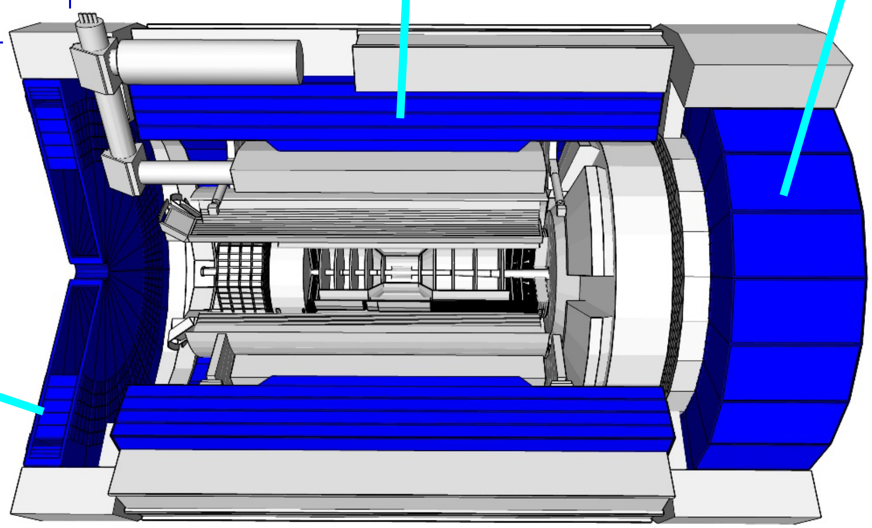


Barrel Hcal
(re-use from sPHENIX)









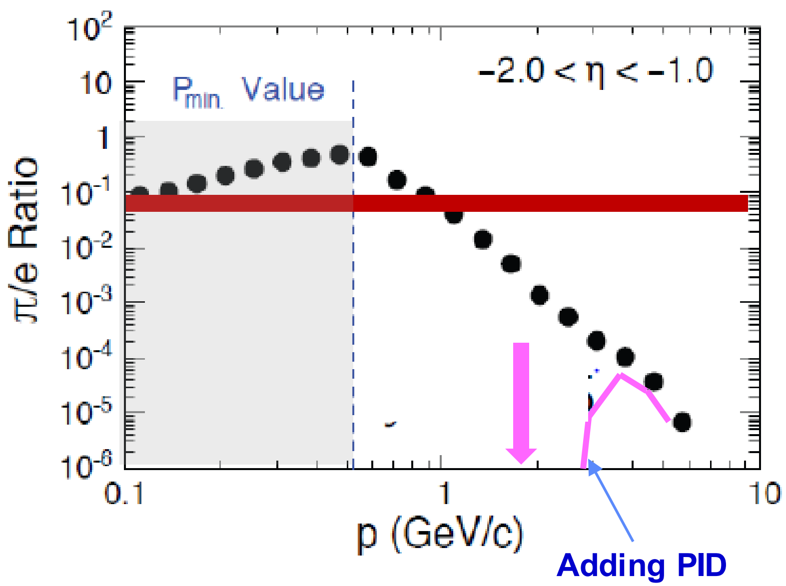
Forward endcap

- Original design inspired by CALICE development:
- "SiPM on TILE"
- High granularity insert at high η
- Jet energy measurement
- DIS kinematics reconstruction "Hadronic method"
- muon ID

The double role of PID in ePIC CD

Support electron identification, which cannot be provided by ECals only in DIS experiments with electron beams (see HERMES, JLab)

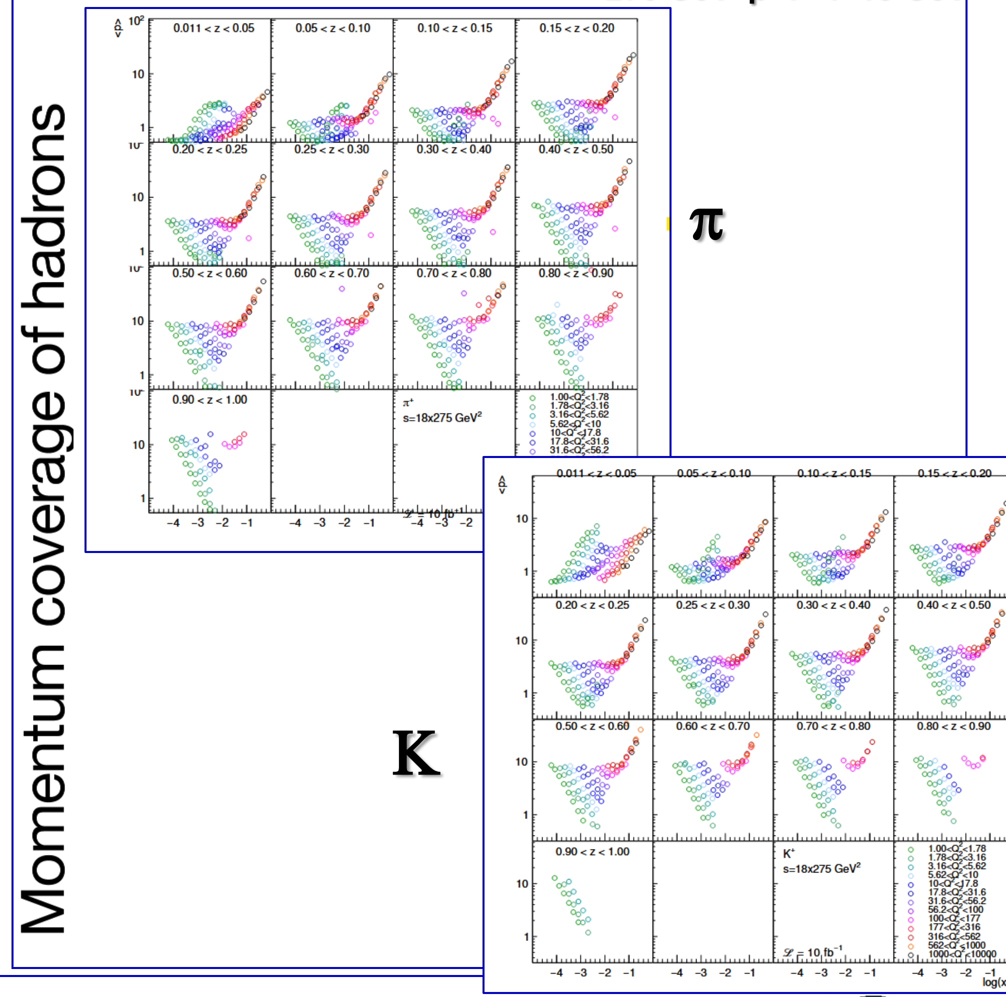
275 GeV p → ← 18 GeV



The different physics channels require π contamination in the electron sample down to 10^{-4}

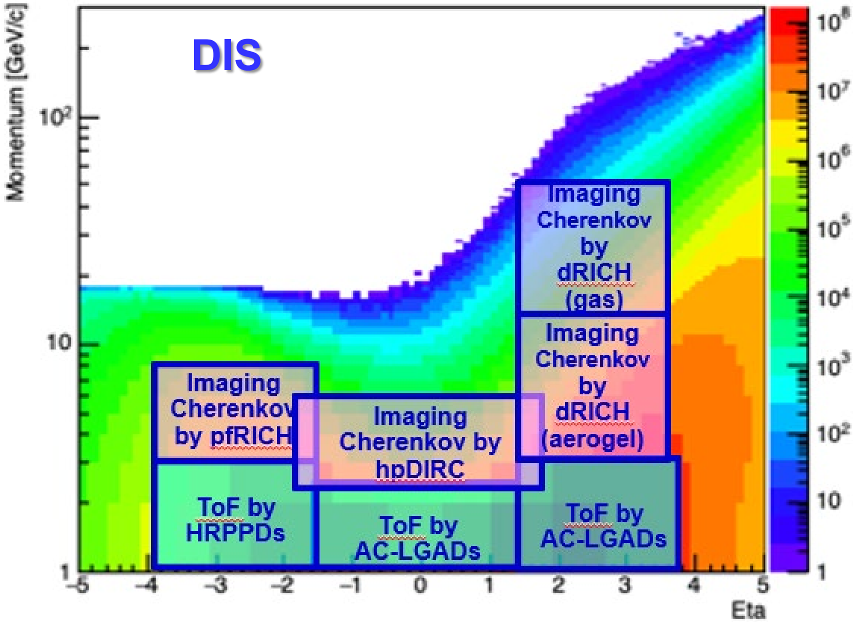
Hadron identification, a key ingredient for TMDs address by SIDIS and with the novel approach of jet reconstruction

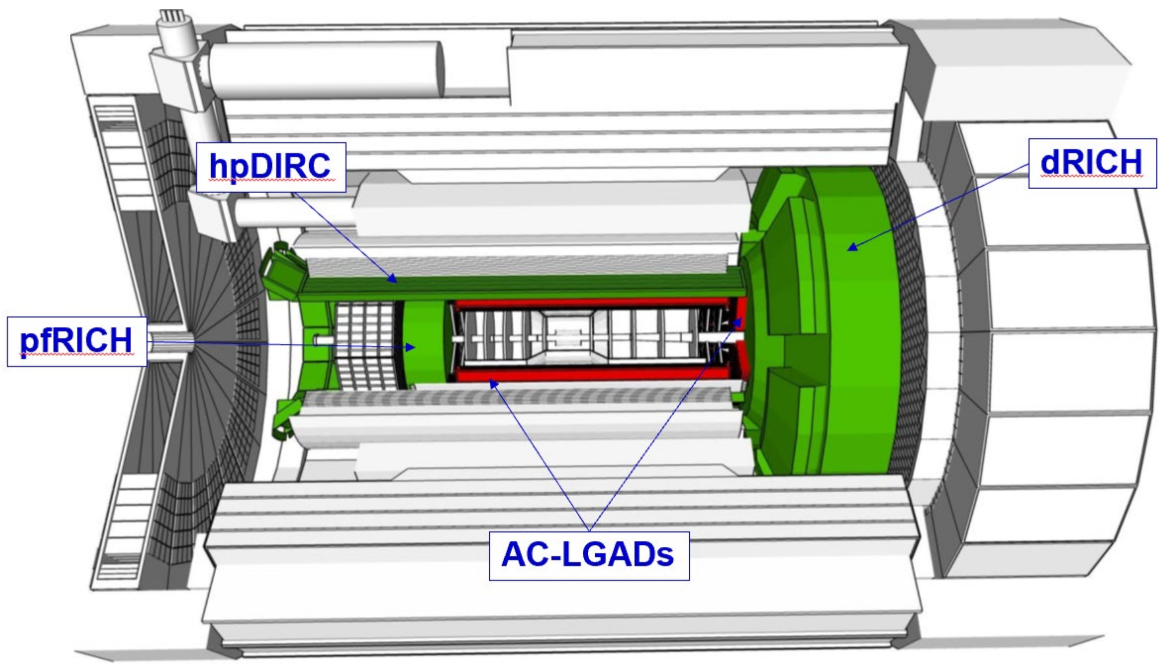
275 GeV p → ← 18 GeV



PID IN ePIC CD

Here performance areas are with reference to 3 σ π/K separation

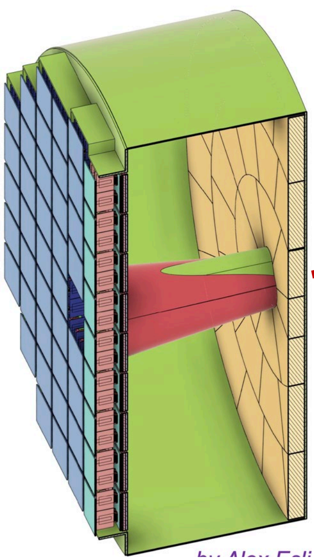


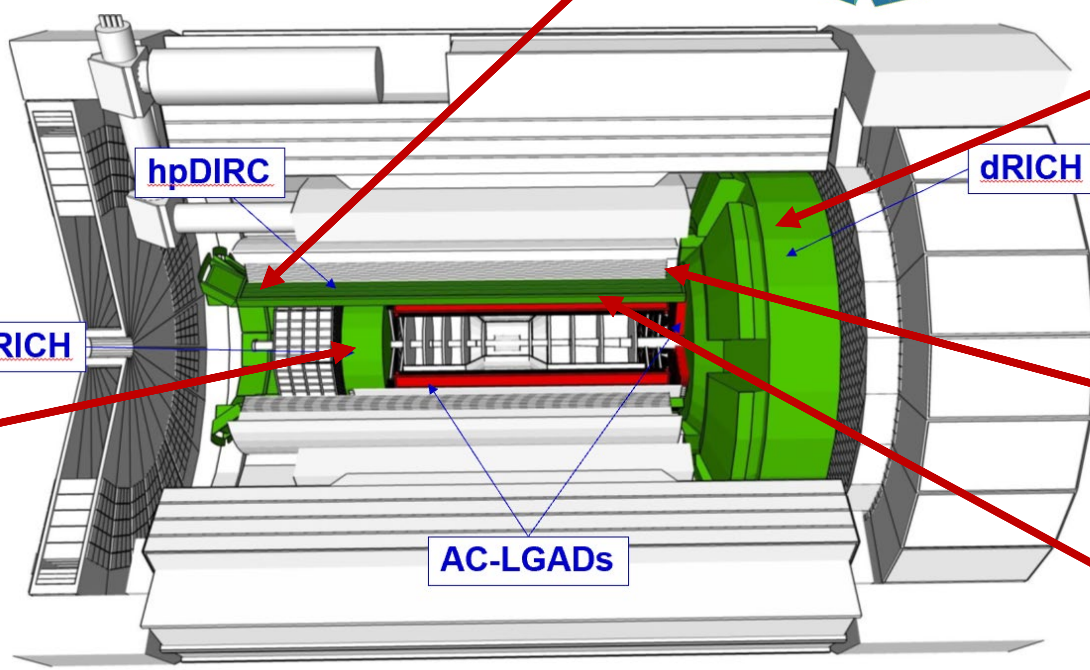


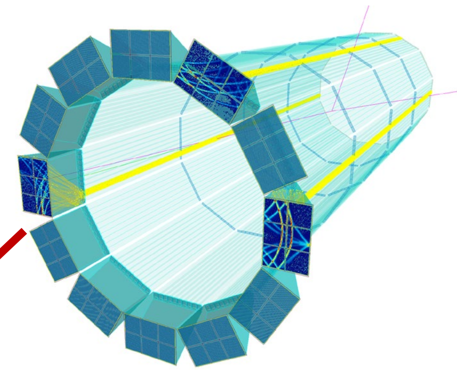
PID IN ePIC CD

Single volume proximity focusing aerogel RICH with long proximity gap (~30-40 cm)

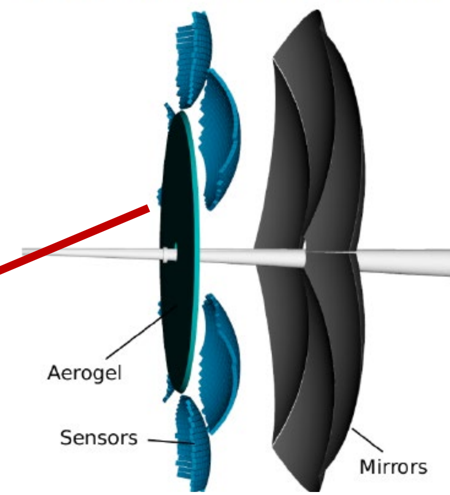
- Sensor: <u>HRPPDs →</u> includeTOF





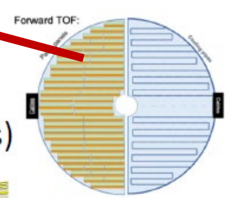


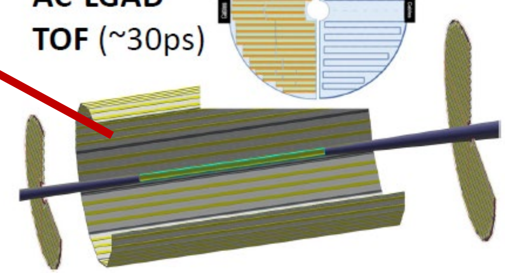
Dual-Radiator RICH (dRICH)



Single photon sensors: SiPMs

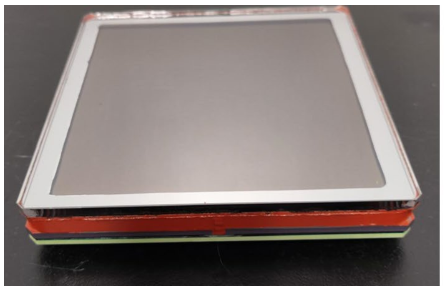
AC-LGAD TOF (~30ps)

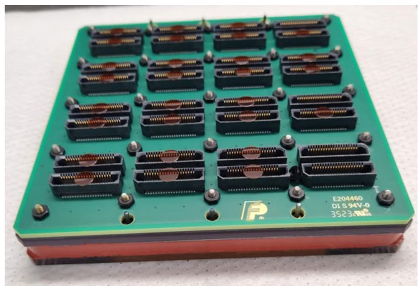


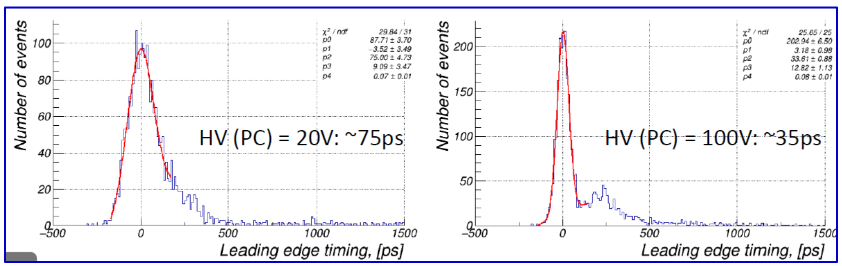


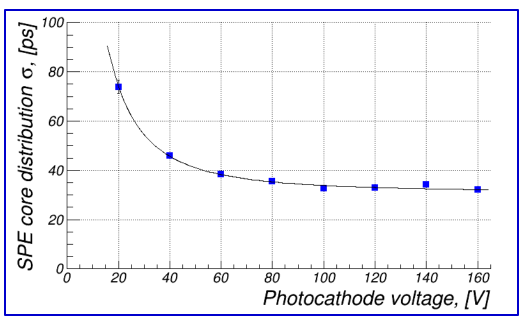
PHOTOSENSORS for CHERENKOV PID IN ePIC

For pfRICH (option for hpDIRC) :
HRPPDs by INCOM
→ large-size (12 x 12 cm^2) MCP-PMTs, pixelized





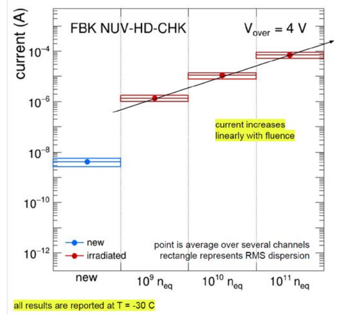




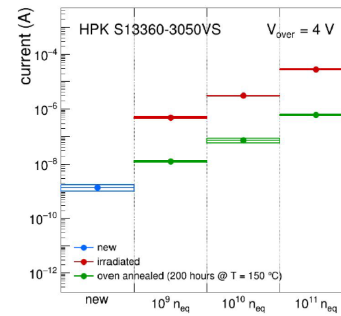
For dRICH : **SiPMs at -30°C**

→ Robust R&D for the validation

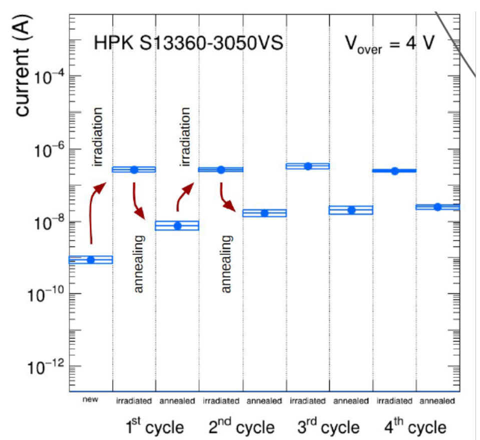
Studies of radiation damage on SiPM



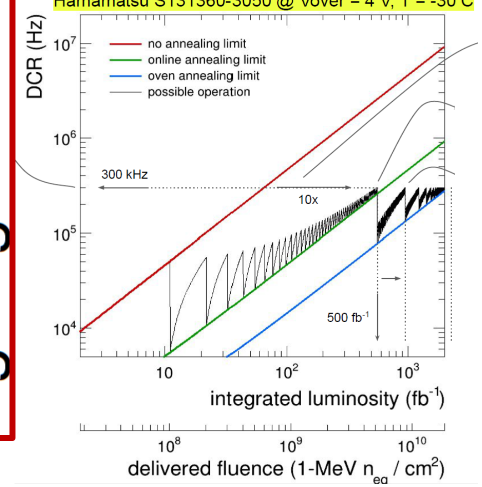
High-temperature annealing recovery
"Online" self-induced annealing



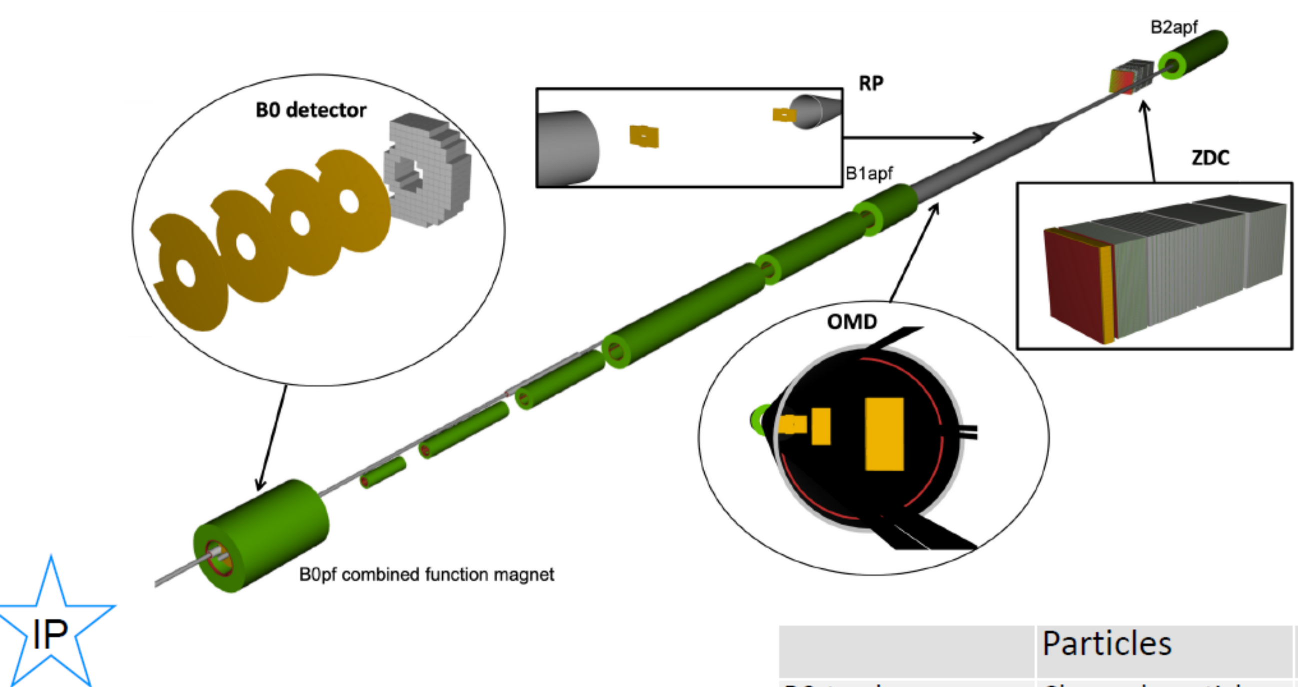
Repeated irradiation/ annealing cycles



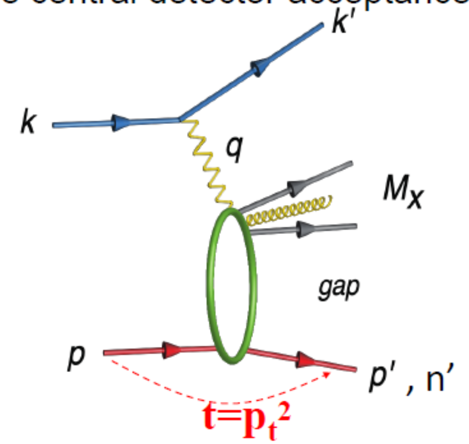
Ageing model



FAR FORWARD DETECTORS



Exclusive /diffractive reactions driving the design of FF area -> reconstruction of particles outside of the central detector acceptance

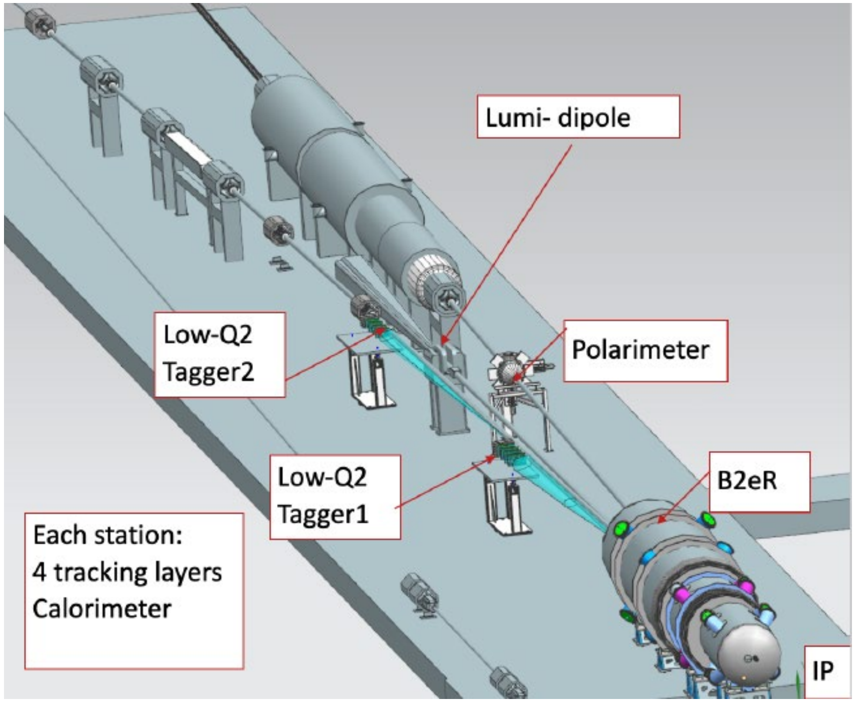


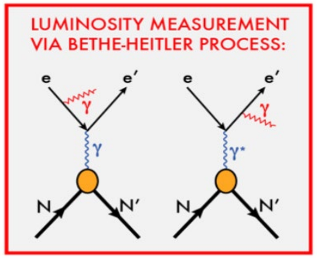
- ✓protons at wide range of p_T^2
- ✓protons with **different rigidity**
- ✓**neutrons and photons**

	Particles	Angle [mrad]		Distance from IP
B0-tracker	Charged particles Photons (tagged)	5.5 - 20		ca 6-7 m
Off-momentum	Charged particles	0-5.0	0.4< xL< 0.65	ca 23-25 m
Roman Pots	Protons Light nuclei	0*-5.0	0.6 < xL< 0.95	ca 27-30 m
ZDC	Neutrons Photons	0-4.0 (5.5)		ca 35 m

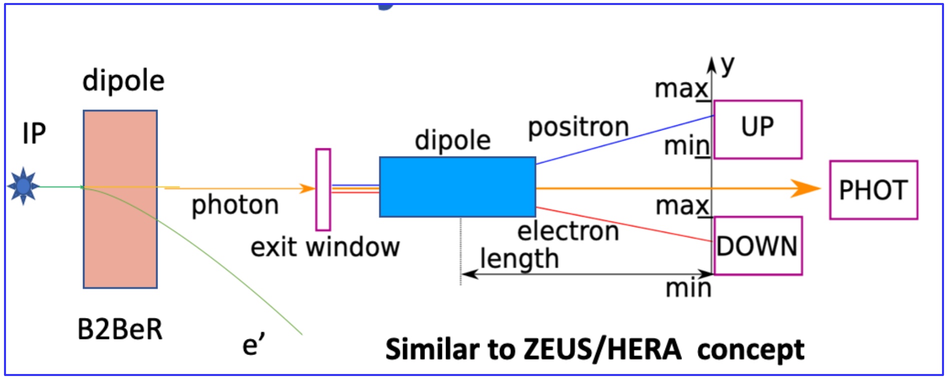
THE ePIC FAR BACKWARD DETECTORS

- This area is designed to provide coverage for the low-Q^2 events (photoproduction, $Q^2 < \sim 1 GeV^2$) . Need to measure a scattered electron position/angle and energy
- And luminosity detector (ep -> e'pγ bremsstrahlung photons)





Luminosity monitor



TAKEAWAY MESSAGES

The EIC is a unique project, the word only one approved for the ultimate understanding of QCD

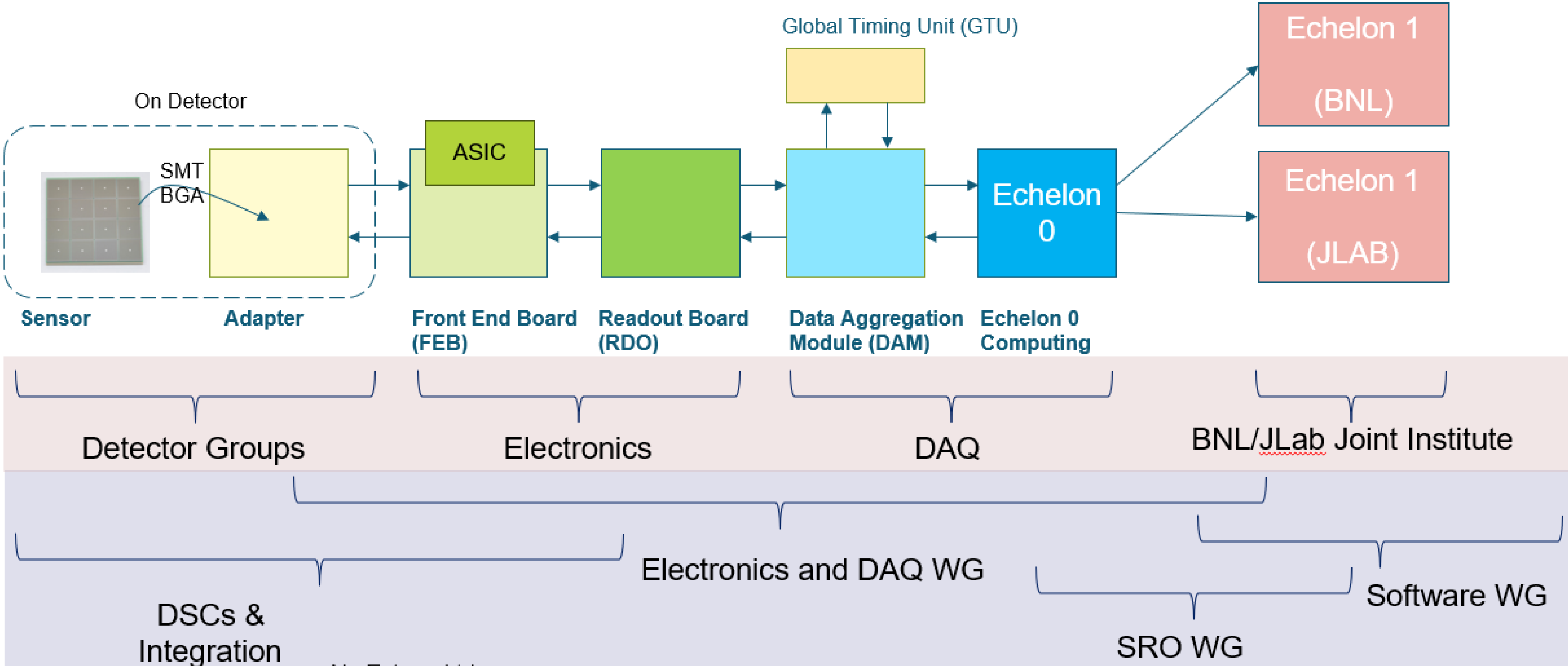
Most likely, the only novel high energy collider in the next 15-20 years

- **The EIC project is approved and progressing according to schedule**
- **The ePIC Collaboration for the project detector ePIC is working and highly committed**
  - **The ePIC detector design is dictated by the physics scope**
  - **A number of established and novel technologies needed to match this scope**
- ***Exciting perspectives in front of us designing, building, operating ePIC and progressing in physics with our detector***

THANK YOU

SPARE

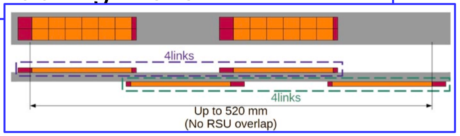
STREAMING - Detector, Electronics, DAQ, Computing



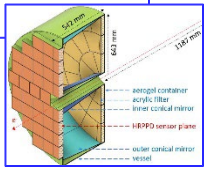
- No External trigger
- All collision data digitized but aggressively zero suppressed at FEB
- Low / zero deadtime
- Collision data flow is independent and unidirectional-> no global latency requirements
- Avoiding hardware trigger avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage ensuring that biases are controlled
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector

TECHNOLOGIES: WORLD FIRST AT ePIC

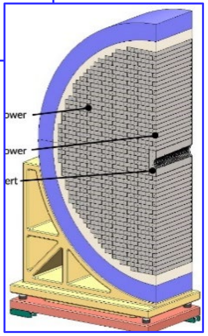
EIC Large Area Sensor (**LAS**), modification of ITS3 sensor with 5 or 6 RSU forming staves as the basic building elements *for the Outer Barrel and the Tracking Disks*

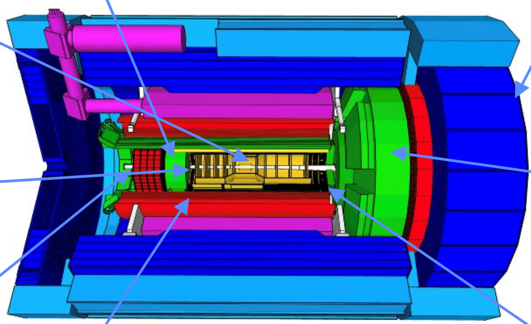


HRPPDs for Cherenkov imaging and Time-of-Flight *for pfRICH*

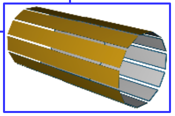


first-time **full-size CALICE-like calorimeter** in collider experiment *in the forward HCal*

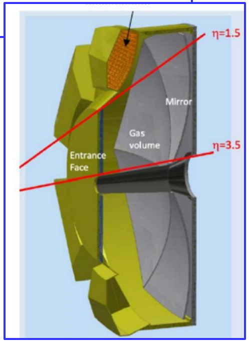




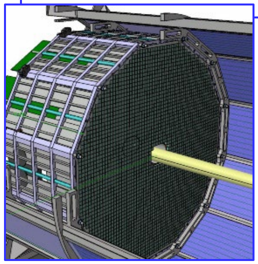
planar **double amplification (GEM & μRWELL)** modules & 2D-strip readout *for the MPGD outer trackers and disks*



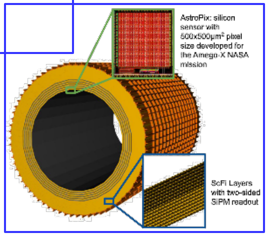
First use **of SiPMs as Photonsensors in a RICH** for the dRICH



SiPM as Photonsensors in crystal calorimetry *for backward endcap ECal*



Use of **ASTROPIX in Calorimetry** *for the imaging barrel ECal*



First time use of **AC-LGAD** in a collider detector *for barrel and forward endcap ToF*