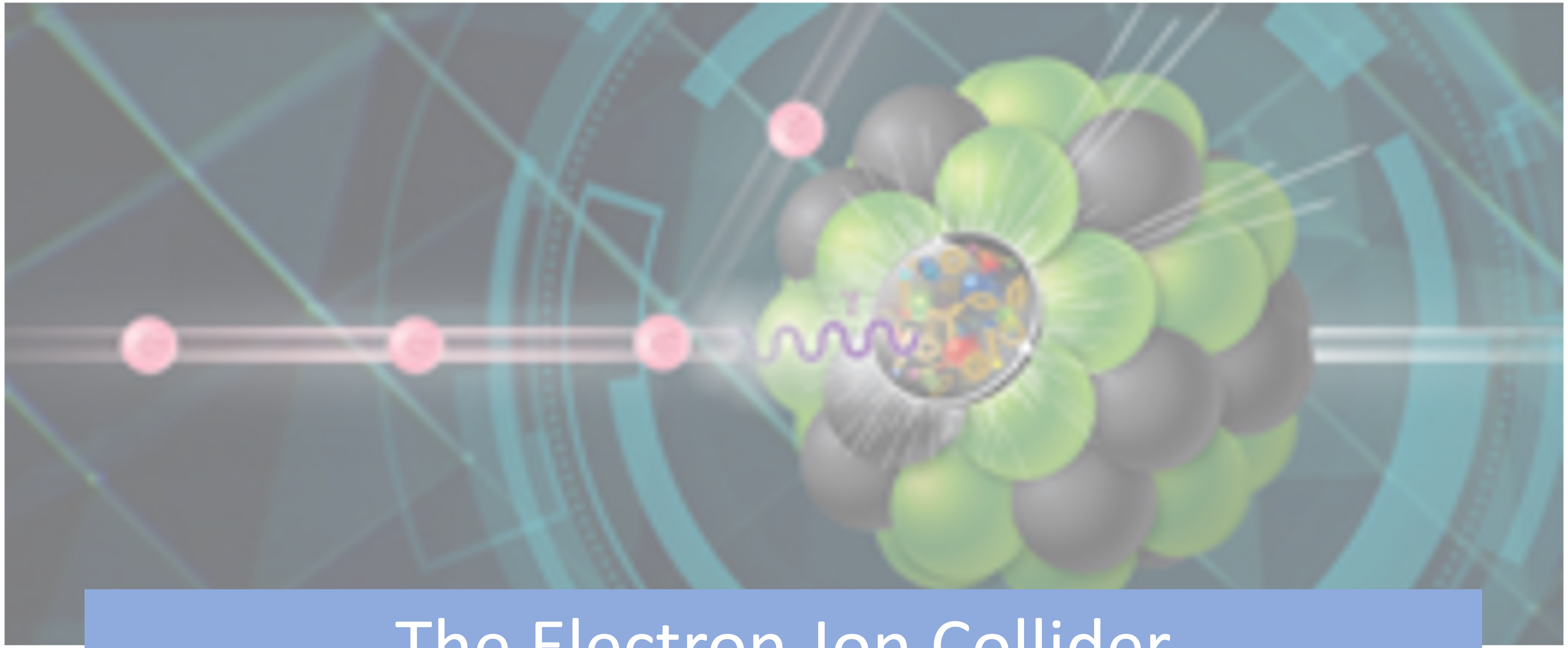


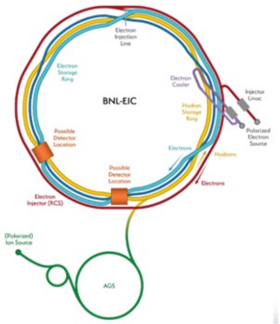
The Electron-Ion Collider
A new electron microscope for the nucleon

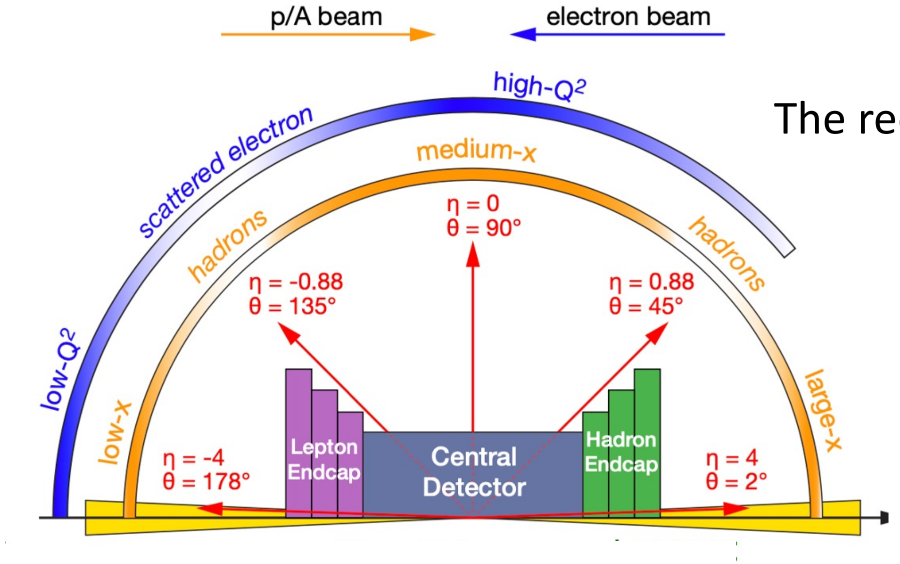
INFN-DOE Fermilab Summer Student program
Fermilab 24 July 2024

P. Antonioli
(INFN-Bologna)

How I tried to organize this talk...

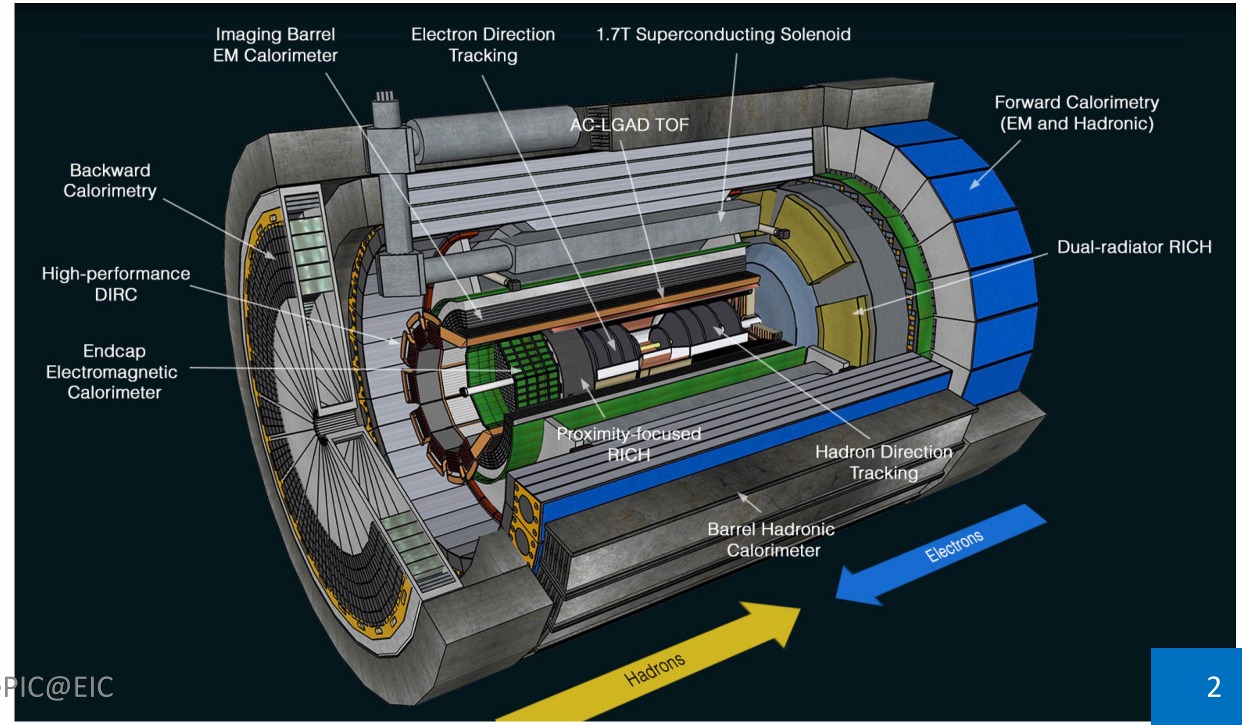
EIC fundamentals: the machine and the science program (*and timeline*)





The requirements for an EIC detector (*and some physics highlights)*

The ePIC detector (*and some R&D highlights, emphasis on PID*)



A new pair of glasses to look inside the nucleon

If Deep Inelastic Scattering is a pair of glasses to look inside the nucleon,
EIC is definetely a **new pair of glasses**!

Almost 60 years later **do we understand the hadrons?**

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

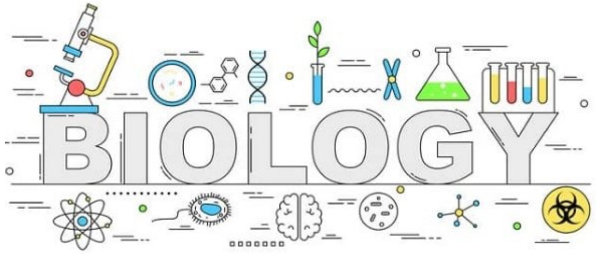
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the

If we ... ons and ... the brok ... look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-

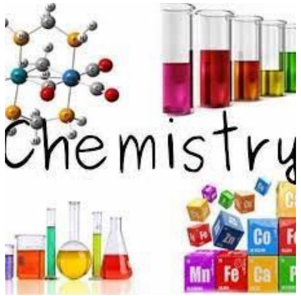
... yons and ... such a ... and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be

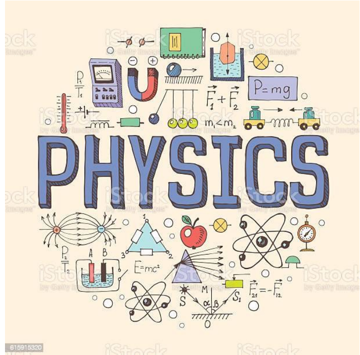
Hadrons are not elementary, but they are fundamental



cells are the fundamental building blocks in Biology



atoms are the fundamental building blocks in Chemistry

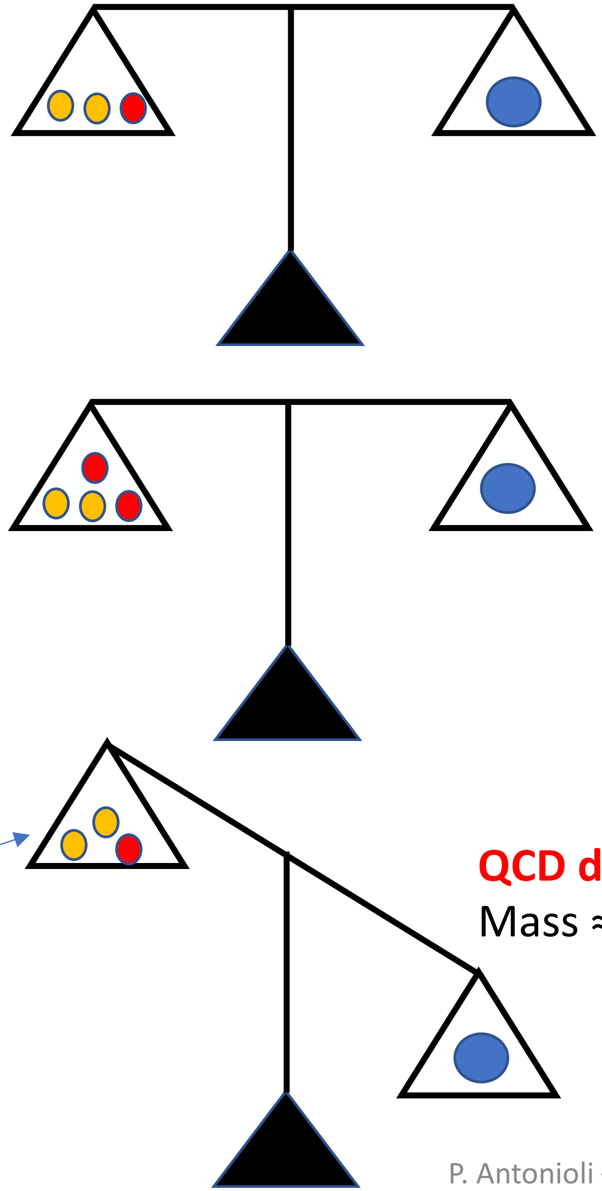


protons and neutrons can be rightly counted among the fundamental constituents of matter

A. Bacchetta, "Where do we stand with a 3-D picture of the proton", EPJ A 52 (2016) 163

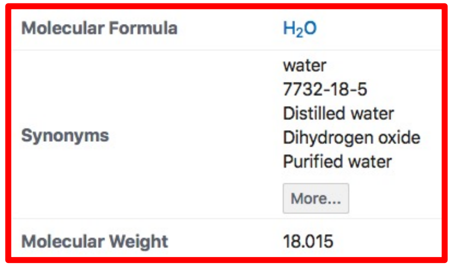
Why new glasses?

The way matter sums up in the nucleon is still quite a mistery!



- Hydrogen
- Oxygen

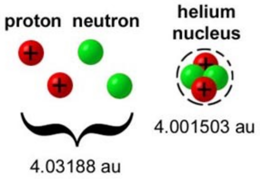
Water

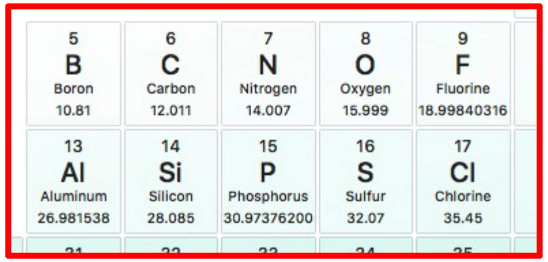


Molecular Formula	H_2O
Synonyms	water 7732-18-5 Distilled water Dihydrogen oxide Purified water More...
Molecular Weight	18.015

- Proton
- Neutron

Helium



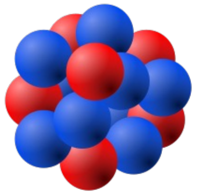


5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.99840316
13 Al Aluminum 26.981538	14 Si Silicon 28.085	15 P Phosphorus 30.97376200	16 S Sulfur 32.07	17 Cl Chlorine 35.45

- d quark
- u quark

Higgs mechanism:
Mass ≈ 1.78×10^{-26} g

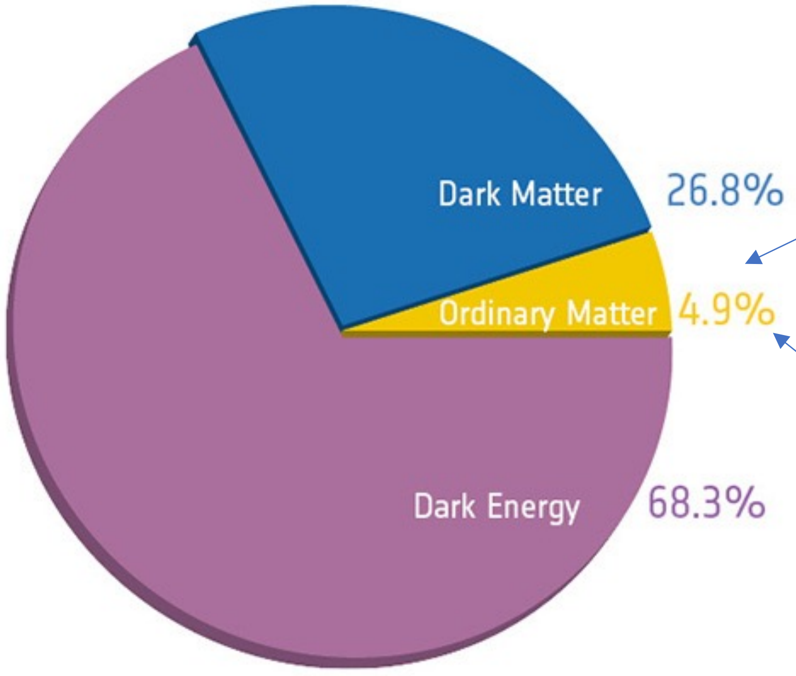
QCD dynamics makes 96% of proton mass!
Mass ≈ 168×10^{-26} g



proton

(and baryonic matter... is just 5% of the Universe....)

Why do we study the structure of the nucleon?

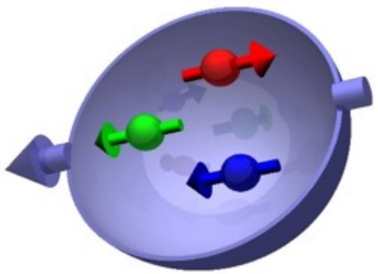


we are focusing on a few non elementary constituents of a small fraction of matter

but we can also say that

we are focusing on the most relevant fundamental constituents of our world's matter!

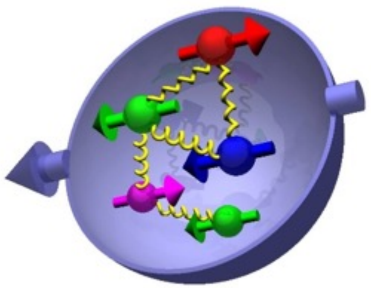
The spin of the proton: still a puzzle



Naive parton model:
all spin made by constituent quarks

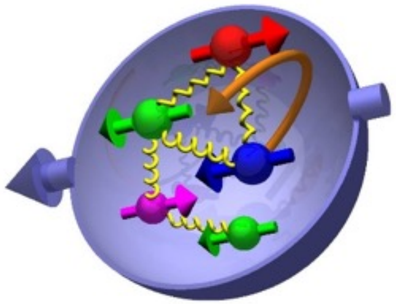
EMC, PLB 206 (1988) 364
→ spin of the proton is only partially made by valence quarks!

$\Delta\Sigma \approx 25\%$



From unpolarized PDFs we know Δg and Δq_s are sizeable!

Three decades efforts (DESY, BNL, JLAB, CERN, ...) estimates $\Delta g \approx 35\%$



And we can't neglegt orbital angular momentum

EIC as the machine to unveil the decomposition of the proton spin!

Solving the proton spin puzzle

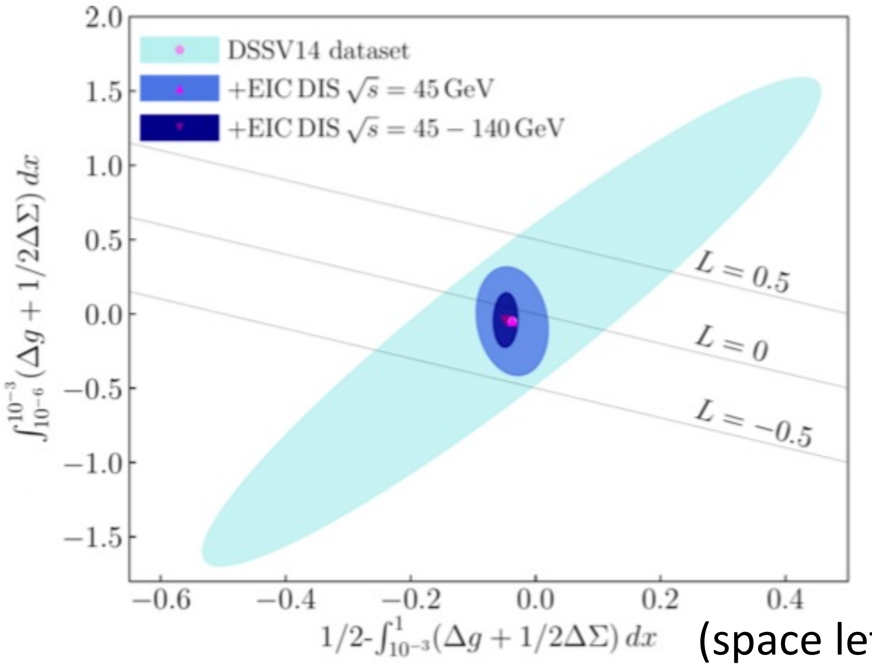
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_q(\mu) + L_g(\mu)$$

quark and gluon spin | orbital angular momentum

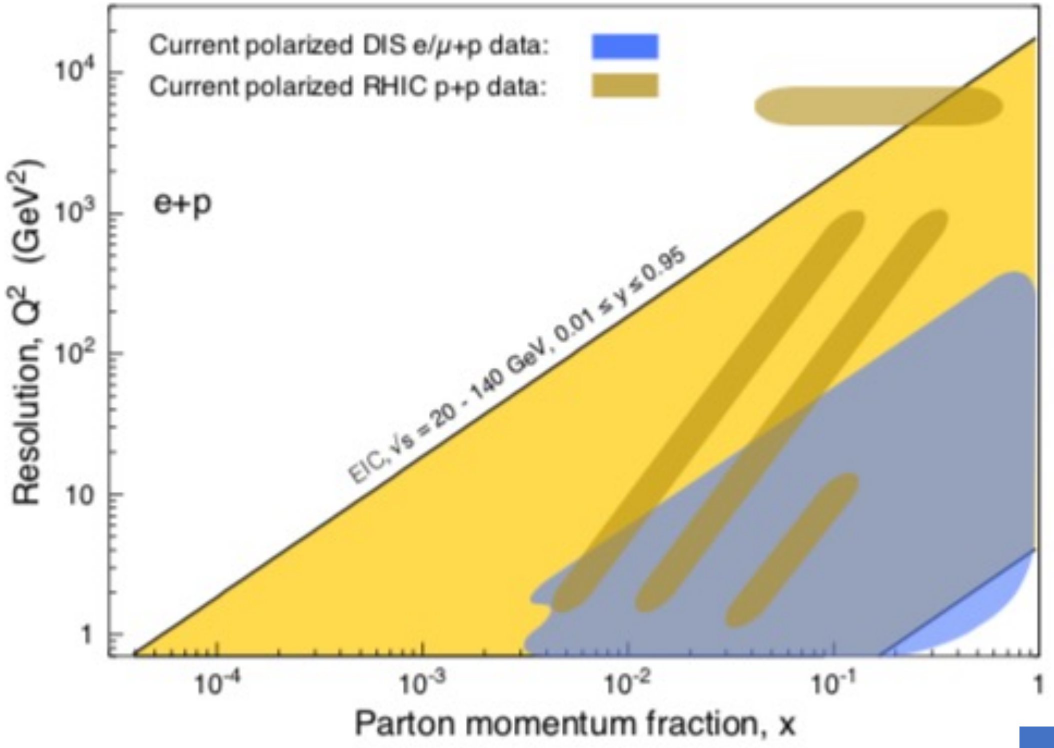
- the spin is the interplay between parton intrinsic properties & their interactions
- it is a dynamic not a static property!

- since late '80s we know $\Delta\Sigma$ is not the dominant term
- only 25% comes from quarks/anti-quarks – gluon contr. at 35%
- big uncertainties! → no data on $\Delta\Sigma$ and ΔG for $x < 5 \times 10^{-3}$

EIC will offer **polarized** beams in a largely unexplored x-Q^2 region!

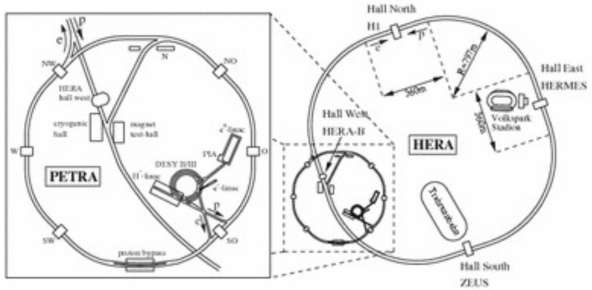


(space left for OAM!)

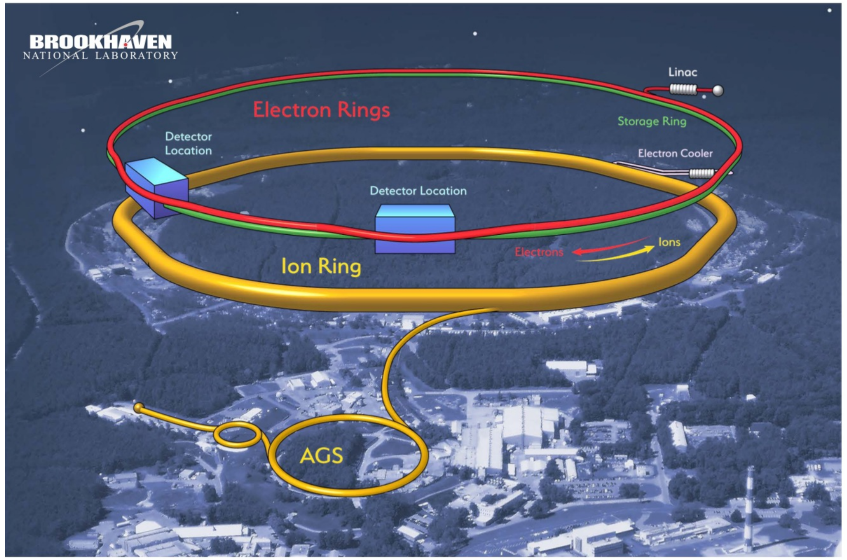


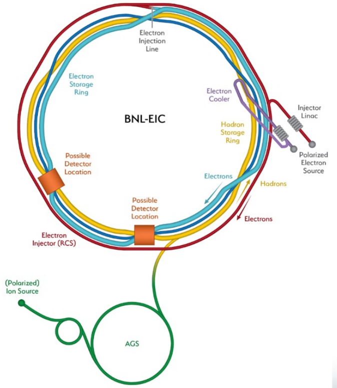
EIC can really resolve the spin components of the nucleon

A new microscope for nucleons is coming!



SLAC-MIT, HERA, ...



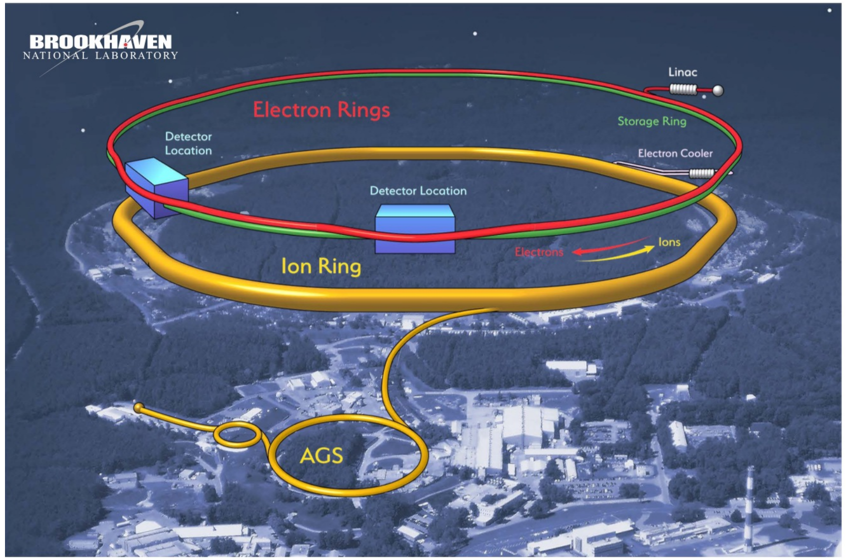


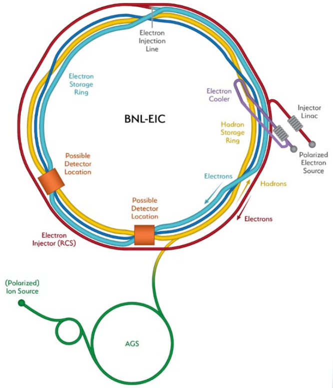
EIC 2031+

Three-ring design
- Hadron storage ring (HSR) 41-275 GeV
- Electron storage ring (ESR) up to 18 GeV (requires SC RF-cavities)
- Electron rapid cycling synchroton (RCS) (400 MeV to 18 GeV)
  [One existing hadron RHIC ring not used]

A new microscope for nucleons is coming!

“When HERA started in 1992, we only had vague notions of the structure of the proton,” says Rolf-Dieter Heuer, director for particle-physics research at DESY. “The measurements from HERA showed that the interior of the proton is like a thick, bubbling soup in which gluons and quark–antiquark pairs are continuously emitted and annihilated.”





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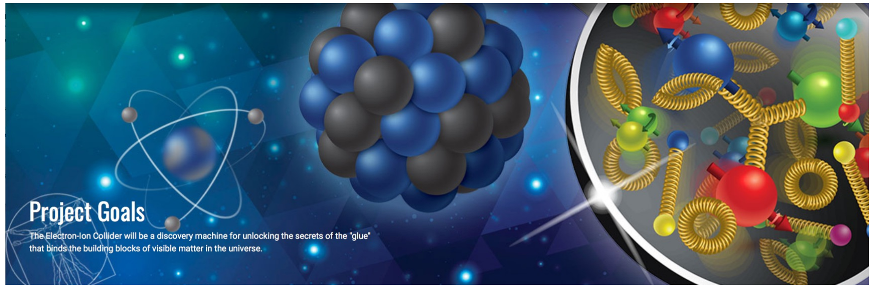
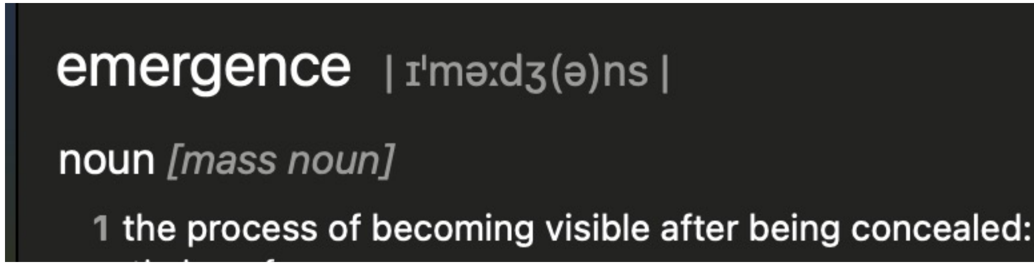
NORTH DAKOTA
MINNESOTA
Minneapo
SOUTH DAKOTA
IGAN
Toronto
Montreal
Ottawa
NEW BRUNSWICK
MAINE
VERMONT
NEW
NEW YO
NO
IOWA
NEBRASKA
Omaha
United States
PENNSYLVANIA
Philadelphia
New York
NJ
ILLINOIS
INDIANA
OHIO
Kansas City
St. Louis
Indianapolis
Cincinnati
MARYLAND
DE
KANSAS
MISSOURI
WEST VIRGINIA
KENTUCKY
VIRGINIA
Nashville
OKLAHOMA
Memphis
TENNESSEE
NORTH CAROLINA
ARKANSAS
Charlotte
Atlanta
SOUTH CAROLINA
MISSISSIPPI
ALABAMA
GEORGIA
Dallas

EIC physics: a machine to study the nucleon "glue"



A long list of key measurements to unveil the **emergence** of global properties of the nucleon from its constituentes

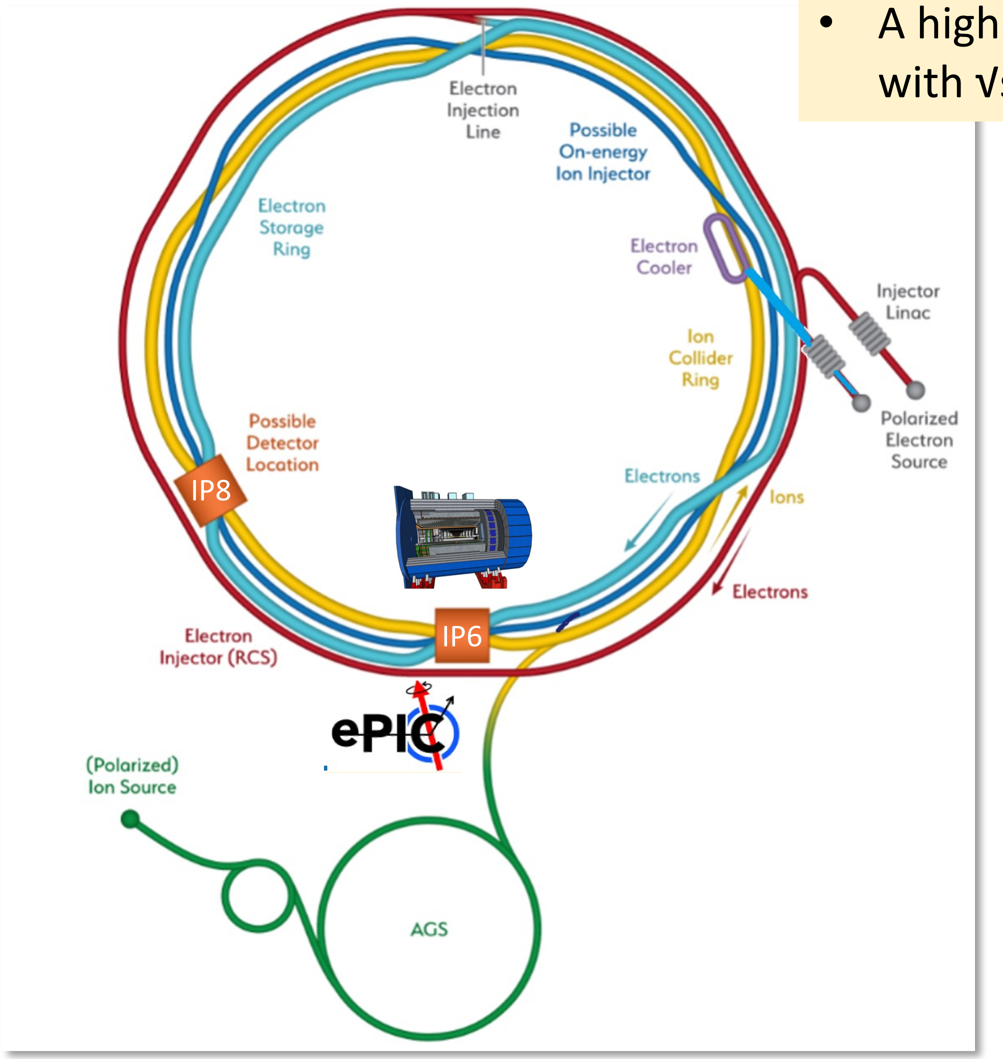


- How do the **nucleonic properties such as mass and spin emerge from partons** and their underlying interactions?
- **How are partons inside the nucleon distributed** in both momentum and position space?
- How do **color-charged quarks and gluons**, and jets, interact with a nuclear medium?
- How do the **confined hadronic states emerge** from these quarks and gluons?
- How do the **nuclear binding emerge** from quark-gluon interactions?
- How does a dense nuclear environment affect the dynamics of quarks and gluons, their correlations, and their interactions? **What happens to the gluon density in nuclei?** Does it saturate at high energy, giving rise to gluonic matter or a gluonic phase with universal properties in all nuclei and even in nucleons?

For a comprehensive EIC science program overview see for example:
M. Zurek, "Shedding light on visibile matter: an Overview of the EIC Science", April 3, 2023
E. Aschenauer, "The electron-ion collider: A collider to unravel the mysteries of visible matter", December 14, 2024

The collider

- Evolution of RHIC (pp/pA/AA) facility at BNL → electron ring (E_e = 5-18 GeV)
- A high luminosity ($10^{33} – 10^{34}$ $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 29 – 140 GeV

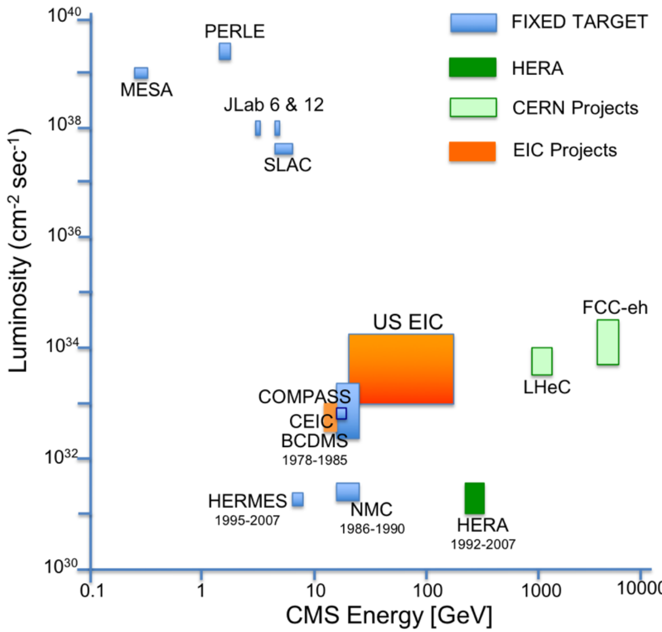


2.25 B$ project

EIC key points

<u>with respect to HERA</u>:

- luminosity x 100 to 1000 higher
- both (p, d, ^{3}He) and e polarized
- nuclear beams (d to U)



<u>with respect to fixed target facilities:</u>

- more than 2 decades increase in kinematic coverage in x and Q^2

Currently DoE supports EIC project for one detector, but the facility might support two detectors/IRs (IP6/IP8)

The collider

- Evolution of RHIC (pp/pA/AA) facility at BNL → electron ring (E_e = 5-18 GeV)
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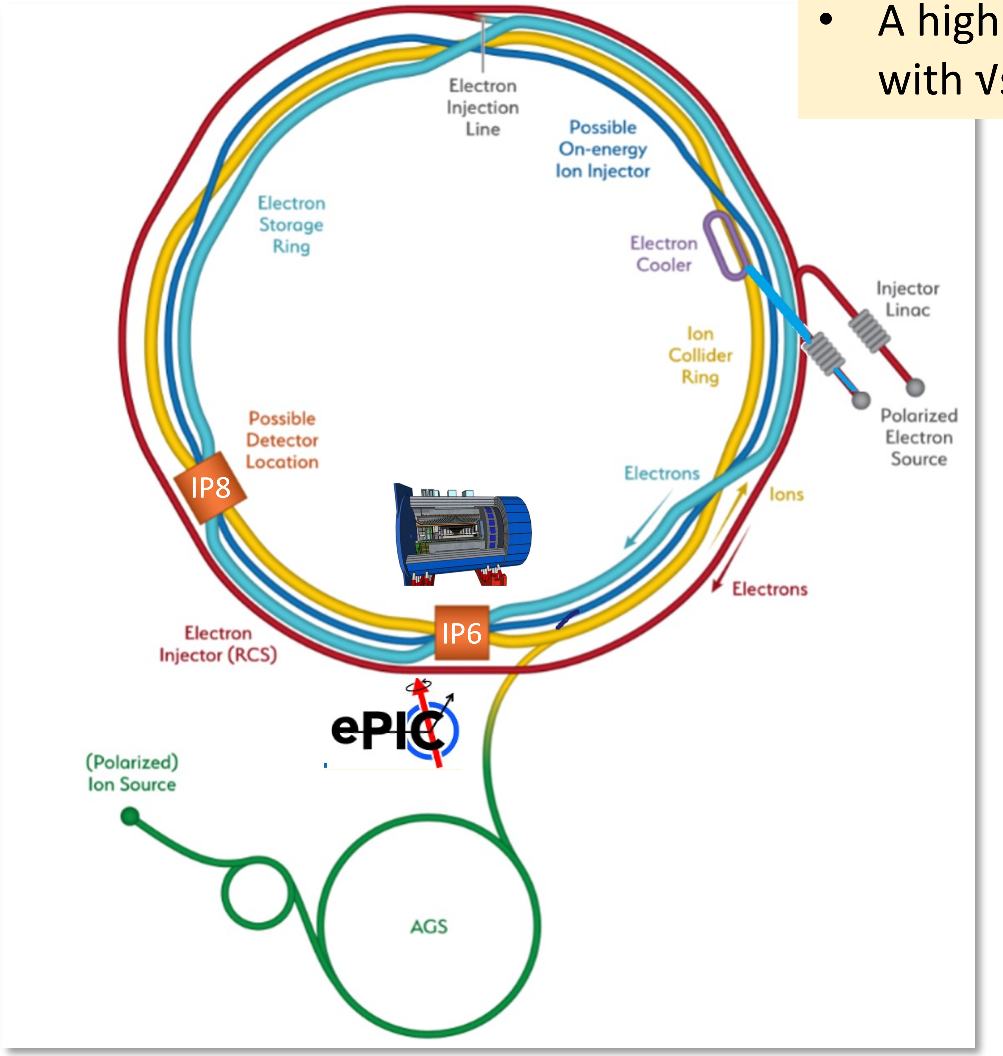
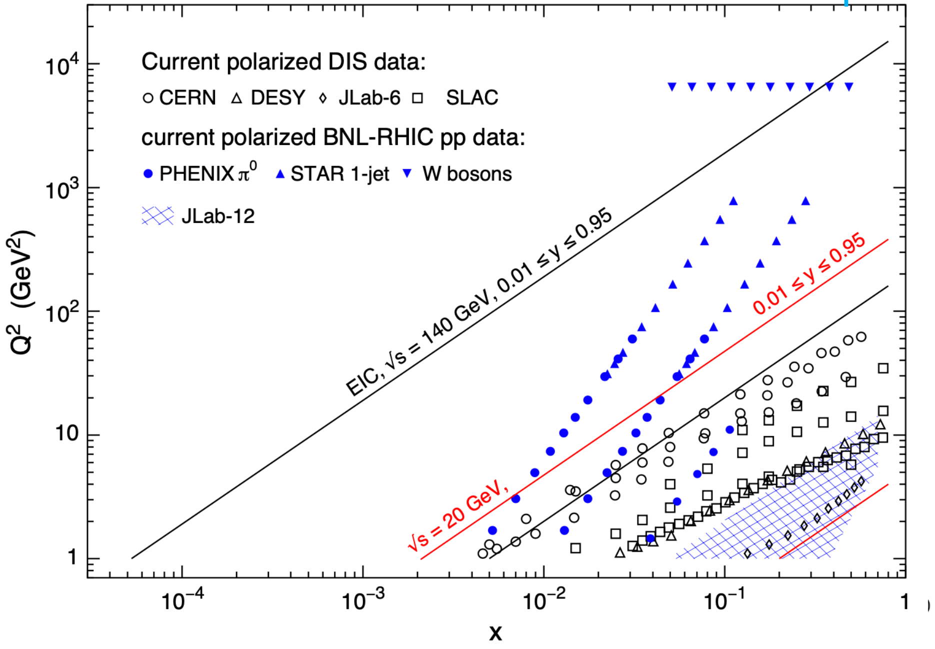


2.25 B$ project

EIC Yellow Report



EIC key points

<u>with respect to HERA</u>:

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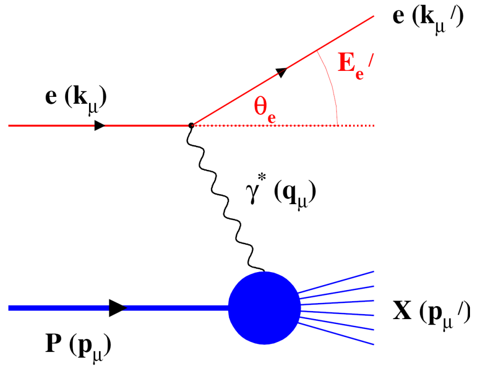
Currently DoE supports EIC project for one detector, but the facility might support two detectors/IRs (IP6/IP8)

DIS processes → physics

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities - Saturation



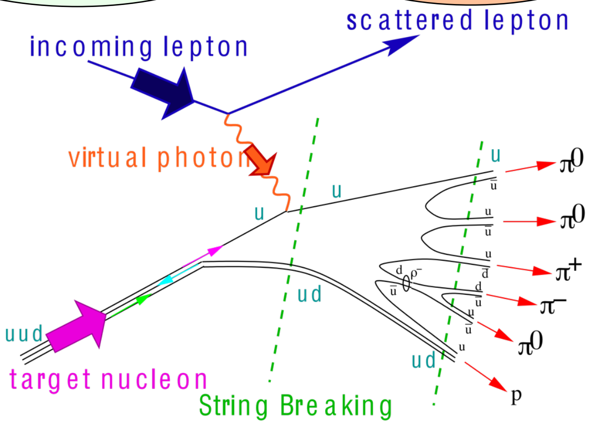
inclusive DIS

measure scattered electron
→ e/h PID
→ eCAL calorimetry

∫Ldt: 1 fb^{-1}

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.



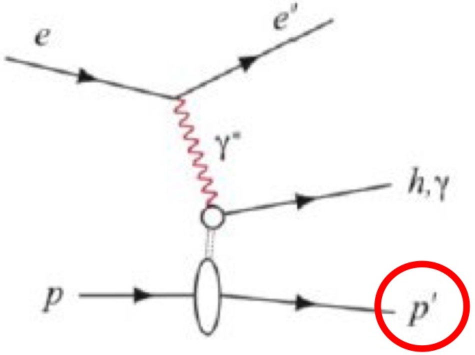
semi-inclusive DIS

measure electron and hadrons
→ hadron PID

10 fb^{-1}

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging



exclusive processes

measure all particles
→ hermeticity
→ design IR

10 - 100 fb^{-1}

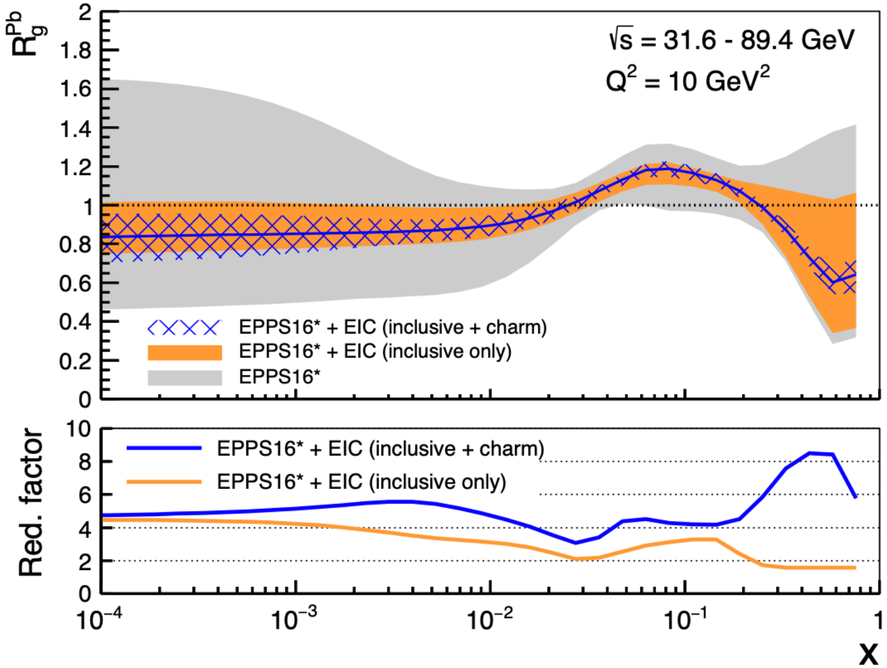
EIC extra-bonus: DIS in nuclei
- nPDF modifications
- gluon saturation (and its scale dependency from A) [jets]
- hadronisation in cold nuclear matter

Highlight 1 (nuclei): gluon saturation & nPDF

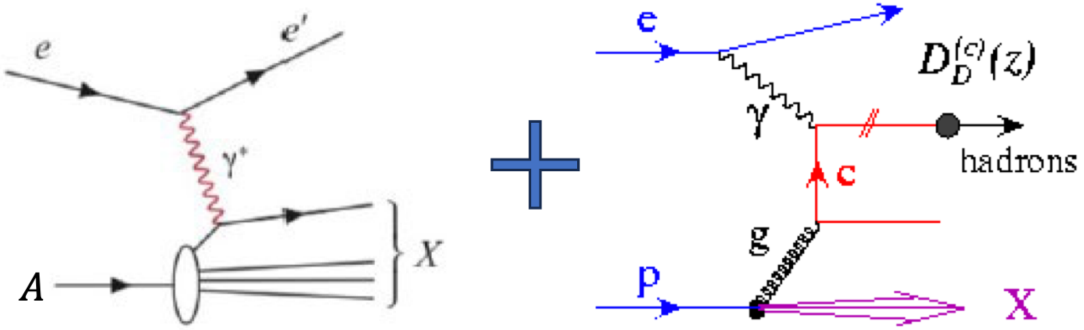
DGLAP and saturation models offer different prediction (Q^2 , A, x dependence)
channels → di-hadron angular correlations, diffractive particle production in eA
strategy→ large Q^2 span at fixed x performing A scan!

$$(Q_s^A)^2 \sim cQ_o^2\left(\frac{A}{x}\right)^{1/3}$$

Detector requirements:
- good tracking + forward calorimeters
- + very forward instrumentation



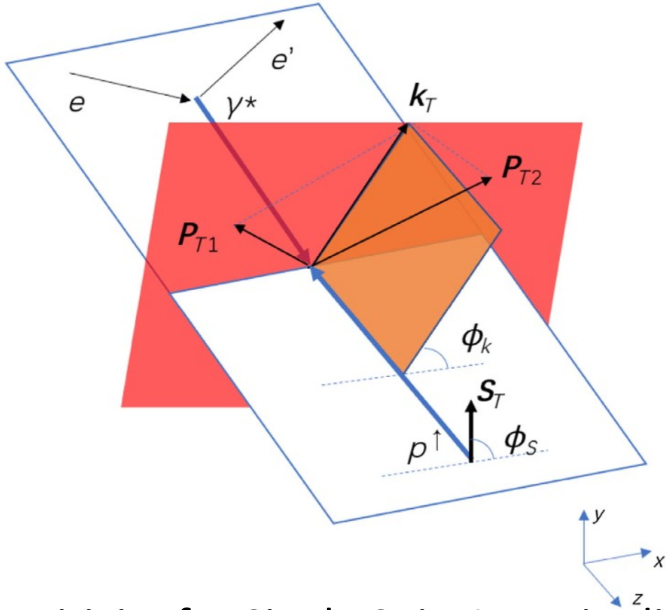
E. C. Aschenauer et al., Phys. Rev. D **96** (2007) 114005



- tag of scattered electron as a prerequisite
- **charm** → tag photon-gluon fusion → direct access to gluon

Detector requirements:
- vertexing (charm tagging)
- electron identification
- y resolution over large space!

Highlight 2: access to gluon Sivers function: TMD

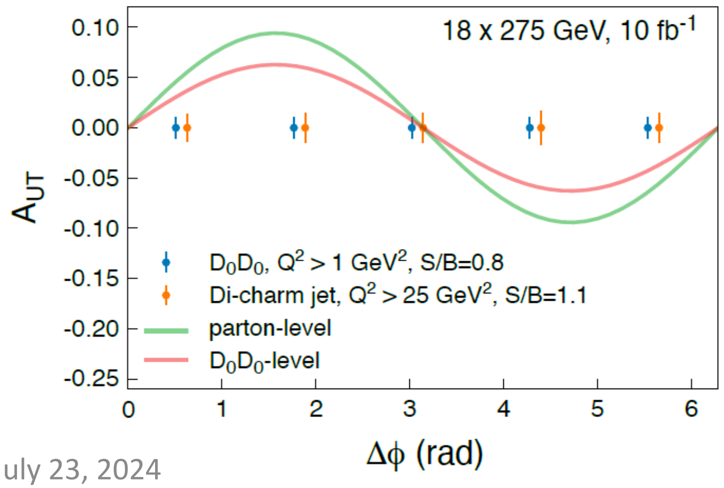


$$\frac{d\sigma}{dx\, dQ^2\, dz\, d\phi_S\, d\phi_h\, dp_T^h}$$

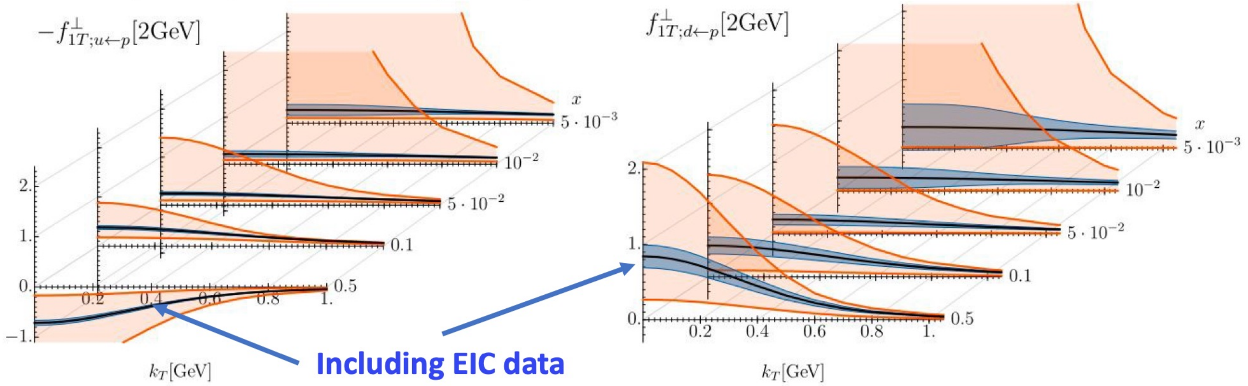
- **6-fold differential cross sections in SIDIS**
- **Azimuthal asymmetries and their modulations**

- access to Sivers TMD (D. W. Sivers, Phys. Rev. D 41, 83 (1990))
- access to gluon Sivers TMD via di-hadron and di-jet
- The Sivers function $f^{\perp}_{1T}$ encapsulates the correlations between a parton's transverse momentum inside the proton and the spin of the proton
- GSF (Gluon Sivers functions) poorly known (U. D'Alesio et al, JHEP 119 (2015))

Sensitivity for Single Spin Asym in di-charm
ATHENA simulation



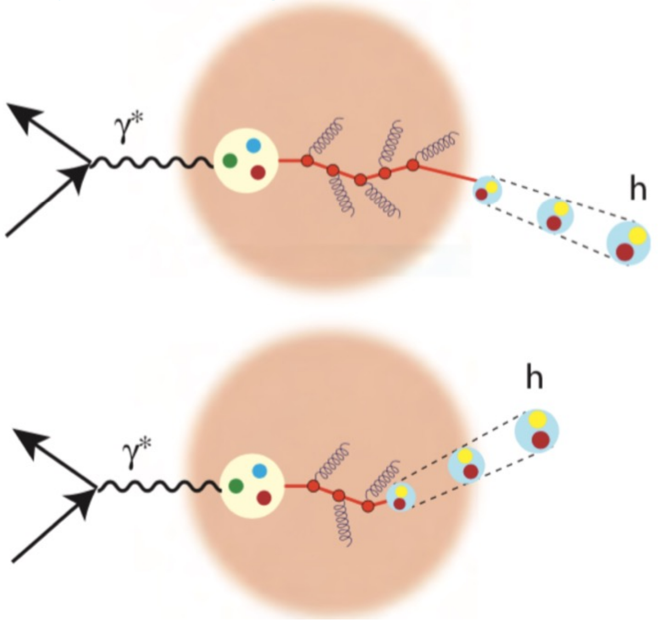
Expected impact on *u* and *d* quark Sivers distributions
R. Seidl, et al., NIMA 1049 (2023) 168017



Detector requirements:
azymuthal acceptance, PID, vertexing (HF), tracking, HCAL (for jets)

Highlight 3: hadronization in CNM

EIC White Paper
https://arxiv.org/abs/1212.1701



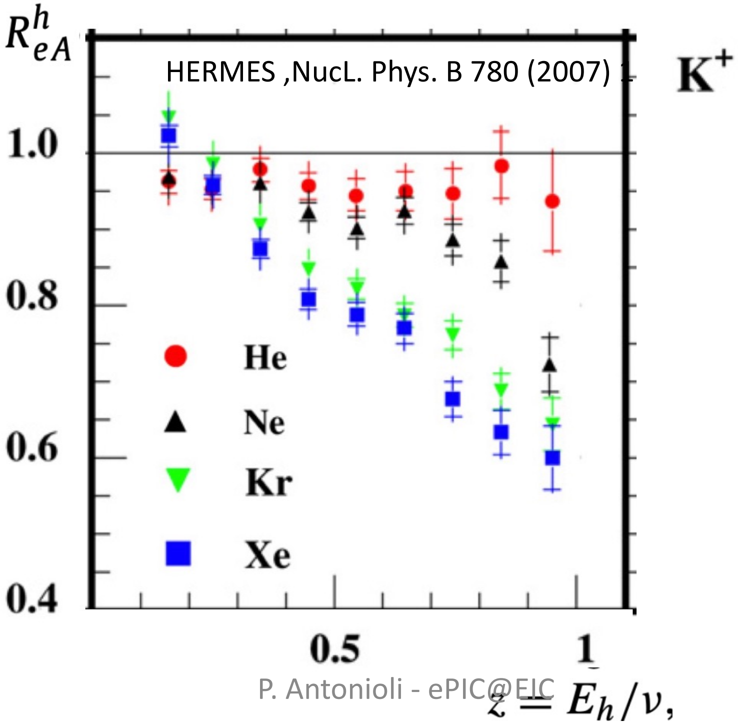
Basic idea: use Q^2 and $\nu = q \cdot p/M$ to control **where** hadronization happens

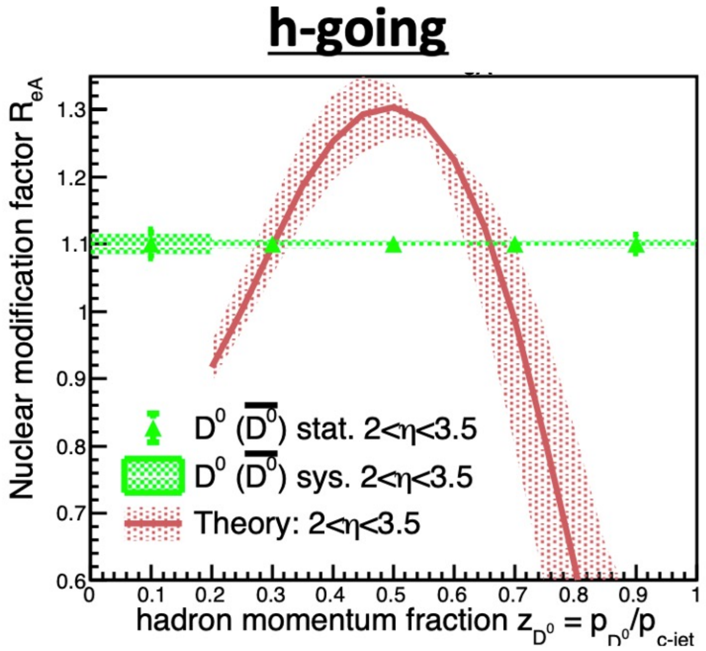
- effect foreseen for D^0/π (based on different FF) might be there also for HF baryons
- usually pre-hadron and absorption in CNM discussed for mesons (Kopeliovich et al., Nucl.Phys. A740 (2004) 211-245)
- role of **di-quark** for baryon hadronization (Adamov et al., Phys.Rev. D64 (2001) 014021)

Results for <u>light hadrons only</u> at <u>much lower energy</u> (fixed target e beam 27.6 GeV)

Detector requirements:
PID and HF-tagging

$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu, Q^2, z)}{N^{e}(\nu, Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu, Q^2, z)}{N^{e}(\nu, Q^2)}\right|_D}$$





1-year EIC operation

Projected: $\mathcal{L}^{int}_{ep} = 10.0\ \text{fb}^{-1}$, $\mathcal{L}^{int}_{eA} = 0.05\ \text{fb}^{-1}$

ECCE simulation: more details C. Wong @ DIS2022
Theory curves from: Li H, Liu Z and I. Vitev, PLB 816 (2021) 136261

Physics → detector requirements

- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements (w.r.t. for example LHC!)
- Electrons & jets in approx 8 η units
- Good momentum resolution
  - central: $\sigma(p)/p = 0.05\,\%\,p \oplus 0.5\,\%$
  - fwd/bkd: $\sigma(p)/p = 0.1\% \oplus 0.5\,\%$
- Good impact parameter resolution

- Excellent EM energy resolution
  - central: $\sigma(E)/E = 10\,\%/\sqrt{E}$
  - backward: $\sigma(E)/E < 2\,\%/\sqrt{E}$
- Good hadronic energy resolution
  - forward: $\sigma(E)/E \approx 50\,\%/\sqrt{E}$
- Excellent PID π/K/p
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c
- Low pile-up, low multiplicity., low int. rate (500 kHz at full lumi)

Hermeticity, low material budget tracker and PID make EIC detector design challenging

EIC Yellow Report: Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

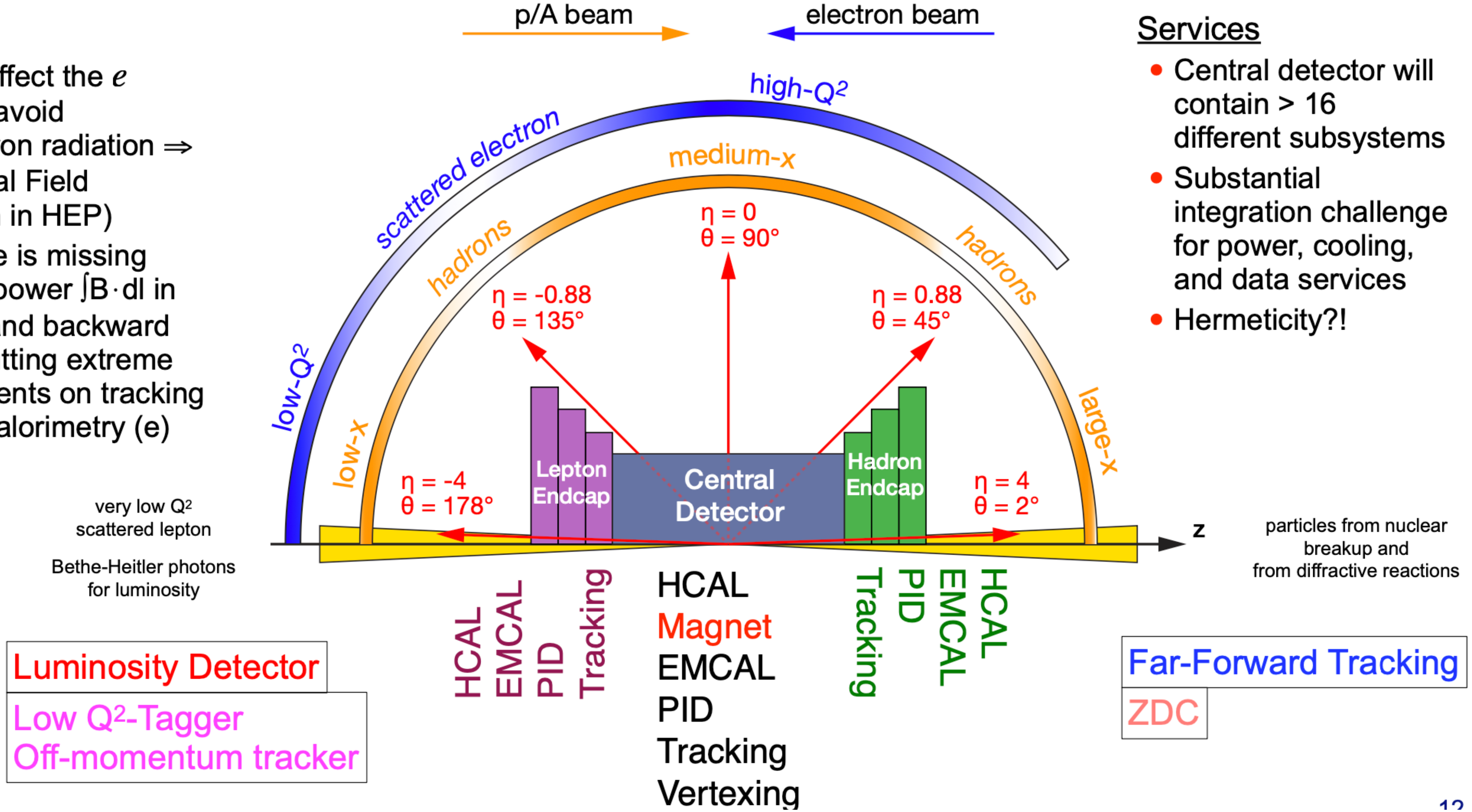
Physics → Detector requirements (II)

Magnet

- Cannot affect the e beam to avoid synchrotron radiation ⇒ Solenoidal Field (common in HEP)
- Downside is missing bending power $\int B \cdot dl$ in forward and backward region putting extreme requirements on tracking (h) and calorimetry (e)

Services

- Central detector will contain > 16 different subsystems
- Substantial integration challenge for power, cooling, and data services
- Hermeticity?!



credit: T. Ulrich

EIC Yellow Report: Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

ePIC design (barrel)

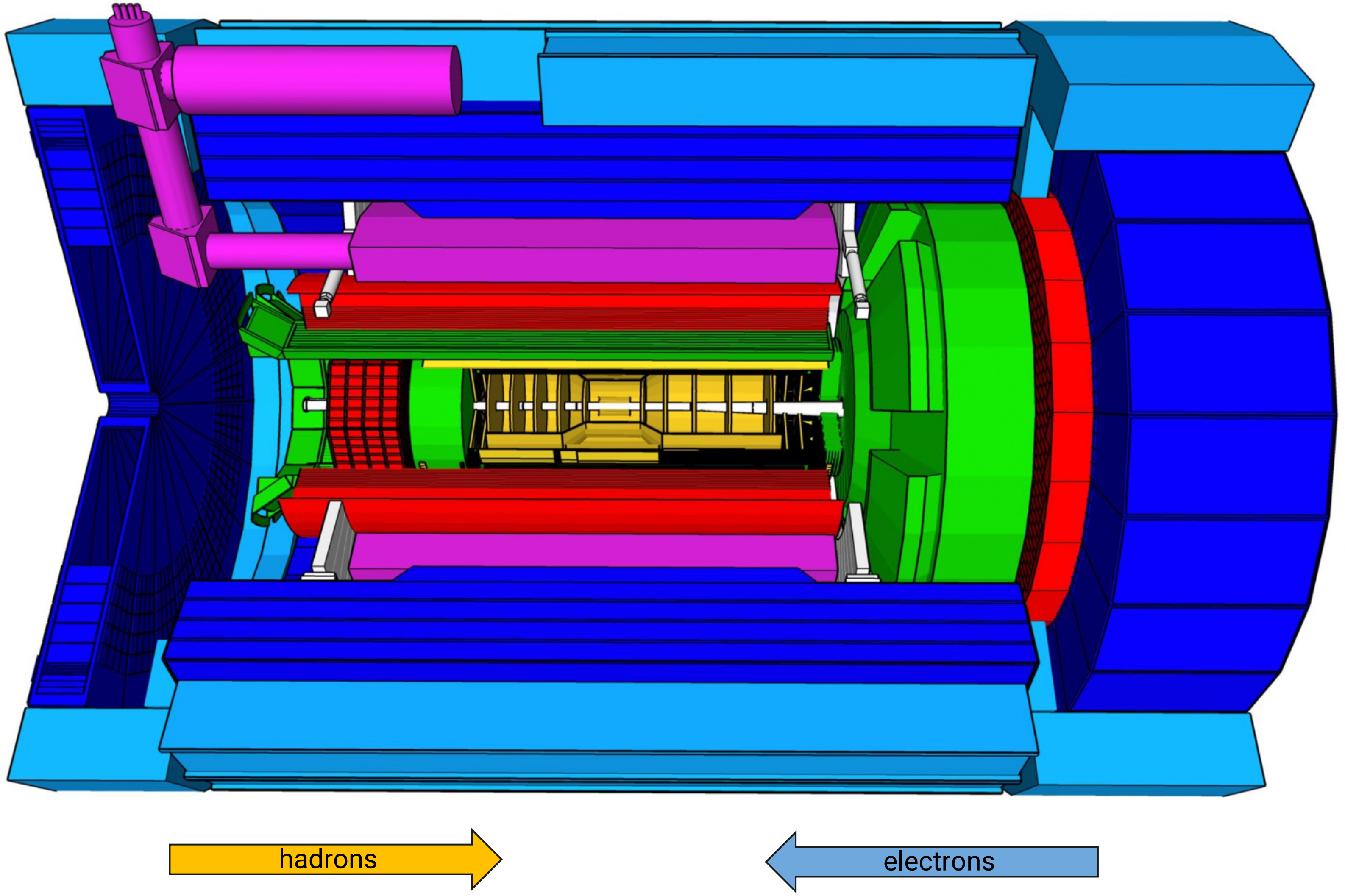
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



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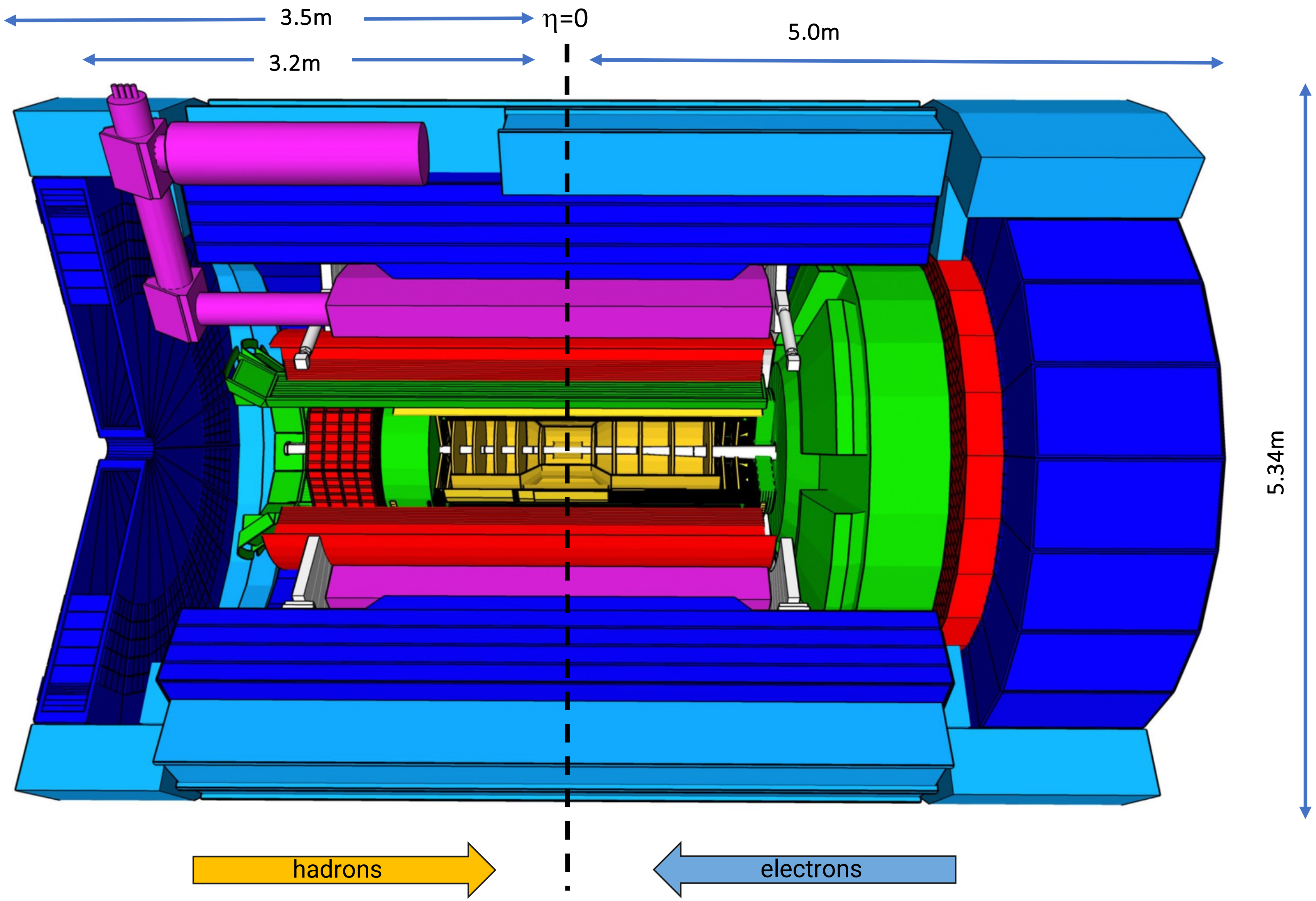
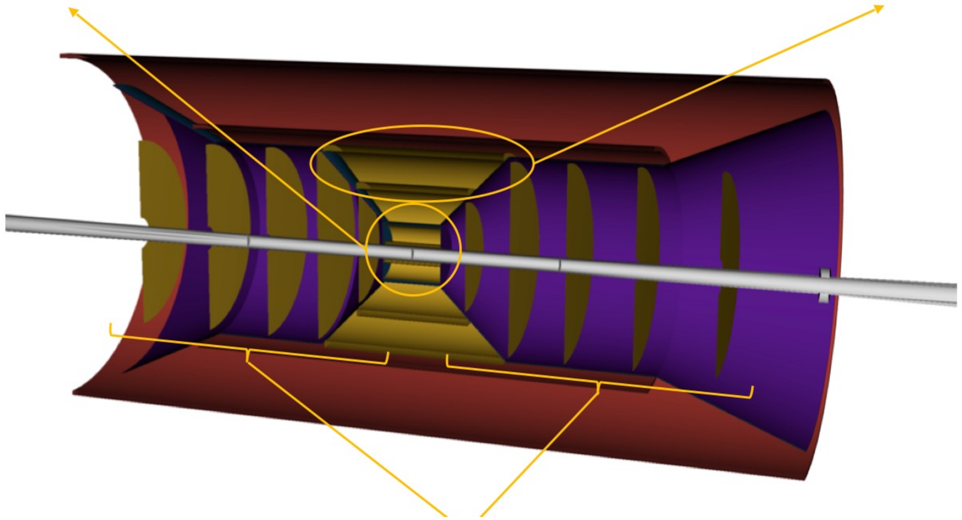
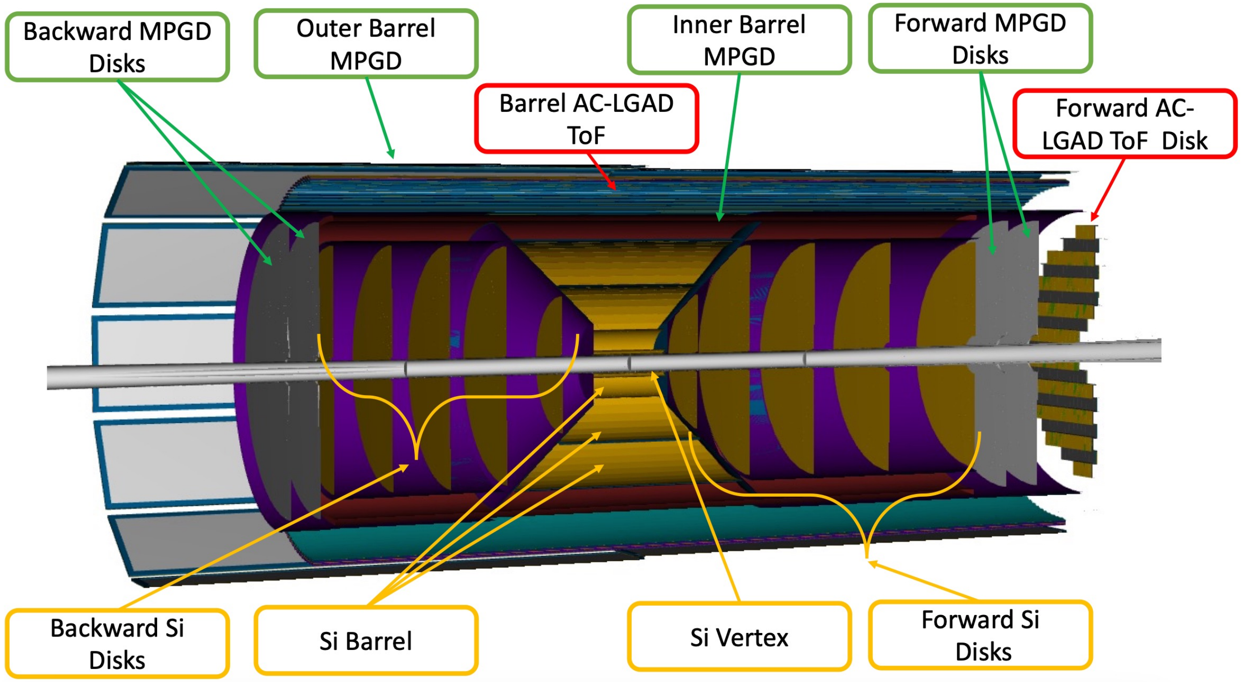


ePIC tracking: SVT and MPGD

Inner barrel (IB): 3 layers   Outer barrel (OB): 2 layers



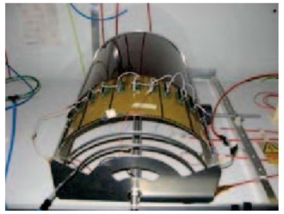
Electron/Hadron Endcaps (EE,HE)
5 disks on either side of IP



- one technology: MAPS @ 65 nm (ALICE ITS3)
- IB: First layer @ R ~ 3.6 cm - Material: 0.05% X/X_0 / layer
- OB: Material: 0.55% X/X_0 / layer
- EE/EH Material: 0.24% X/X_0 / layer
- pixel size O(20x20 μm^2)
- Total area 8.5 m^2

[arXiv:2302.01447](https://arxiv.org/abs/2302.01447)

- additional hit points for track reconstruction (~150 μm)
- fast timing hits for background rejection (~10-20 ns)
- MicroMega + uRWELL
- provide hit point over large angular range for PID
- new ASIC SALSA for readout (derived from ALICE SAMPA for TPC)

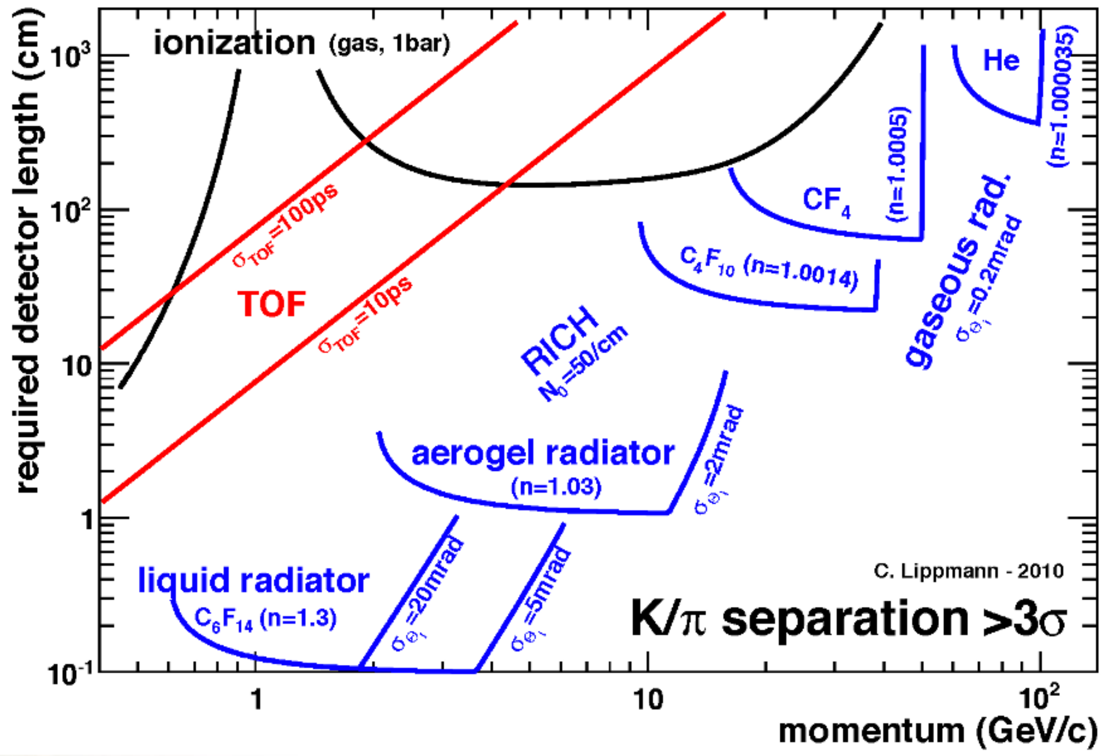


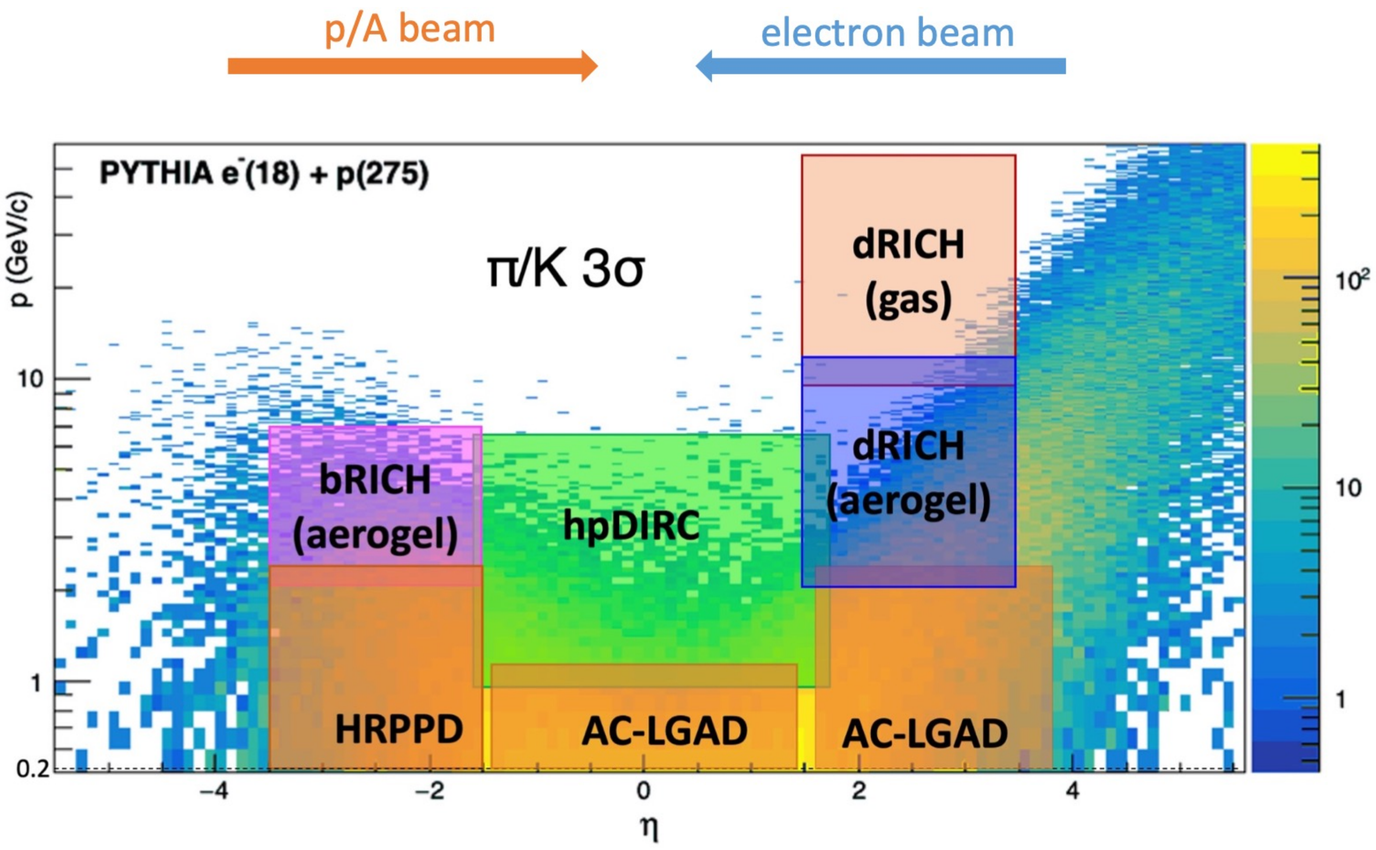
PID critical for EIC science

e-π separation
Cherenkov PID complements ECAL effort, especially at low momenta/backward region

hadron identification: SIDIS (→ TMD) , heavy flavour
ToF complements Cherenkov PID

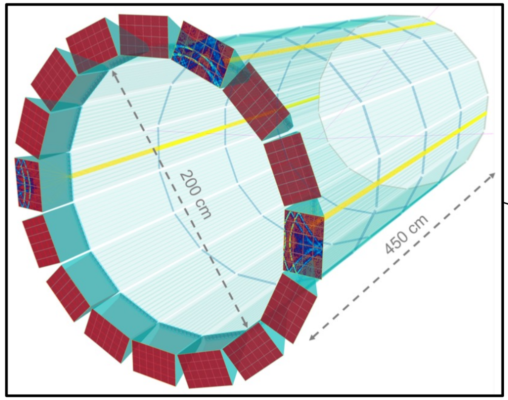
C. Lippmann, NIM A 666 (2012), 148





more than one technology needed to cover the entire momentum ranges at different rapidities

ePIC PID sub-systems



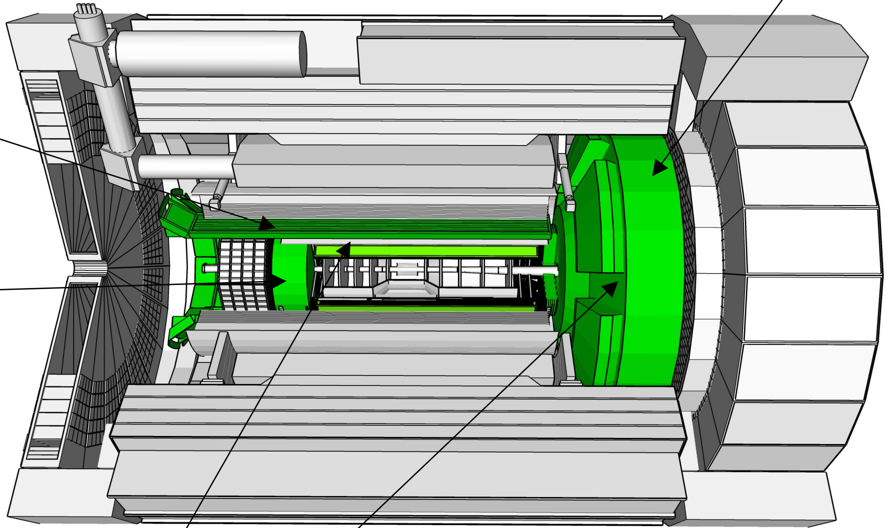
hpDIRC (High Performance DIRC)

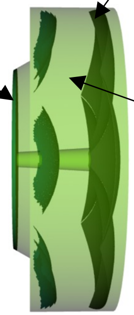
- Quartz bar radiator → Reuse of BaBAR DIRC bars
- photosensor: MCP-PMTs
- p/K 3s sep. at 6 GeV/c

dual radiator Forward RICH: dRICH

Aerogel z: 4cm
radius: 110 cm
0.3 mm acrylic filter

Spherical Mirrors
6 Azimuthal Sectors



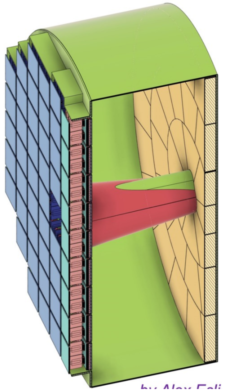


C_2F_6 Gas Volume
120 cm length
radius: 185 cm

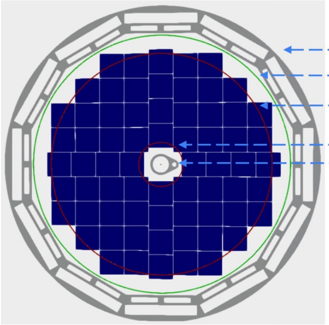
Photosensor: **SiPMs**

Backward RICH: pfRICH

- <u>Aerogel</u> Cherenkov Det.
- e, π, K, p separation → π/K 3σ sep. up to 7 GeV/c
- Photosensor:: **HRPPDs** to include TOF
- RICH with long proximity gap (~40 cm)

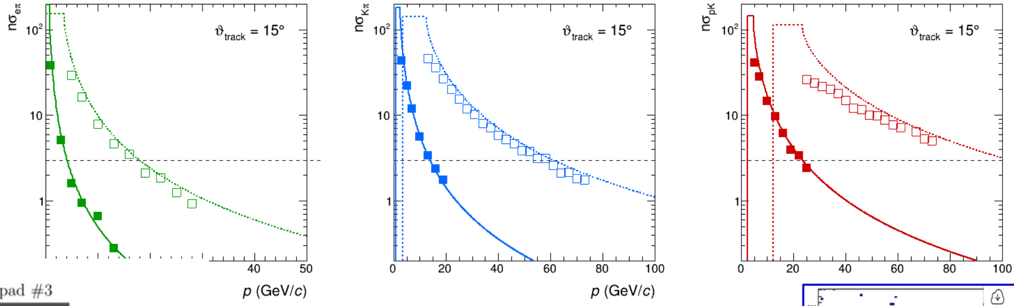


Sensor plane tiling scheme



dRICH sim.

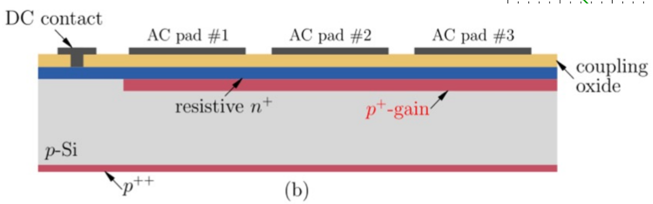
π/K 3σ sep. up to 50 GeV/c

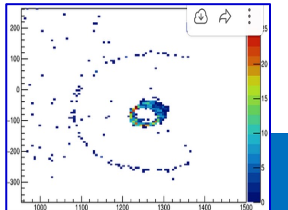


TOF

AC-LGAD (Low Gain Avalanche Detector)

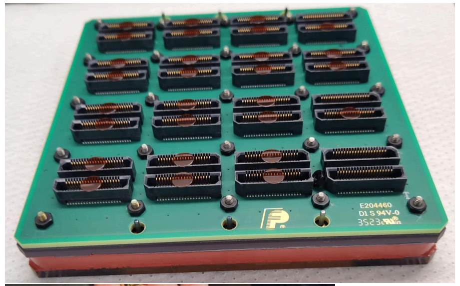
- 20-35 psec / σ=30 μm
- Accurate space point for tracking
- forward disk and central barrel

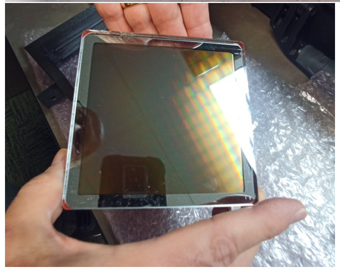


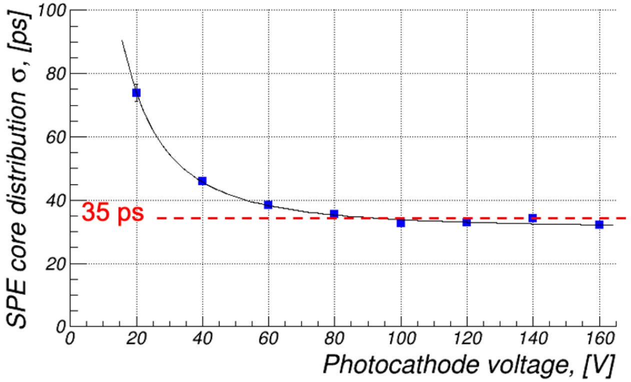


Photosensors R&D

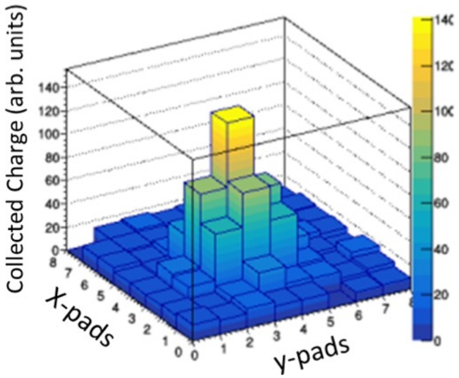
HRPPD: large area microchannel plates provided by INCOM with ePIC/EIC contributing to engineering

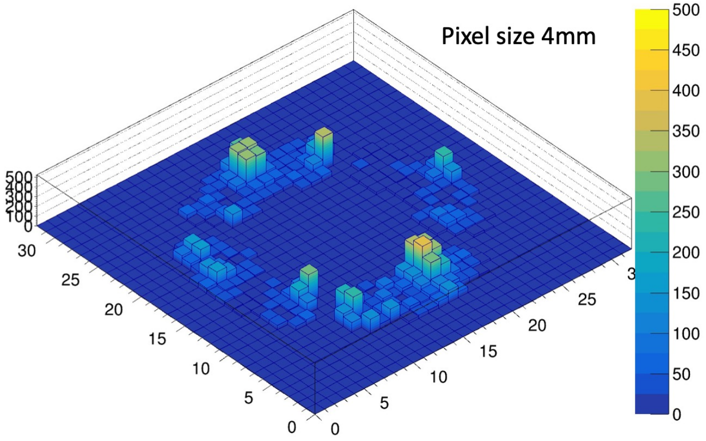






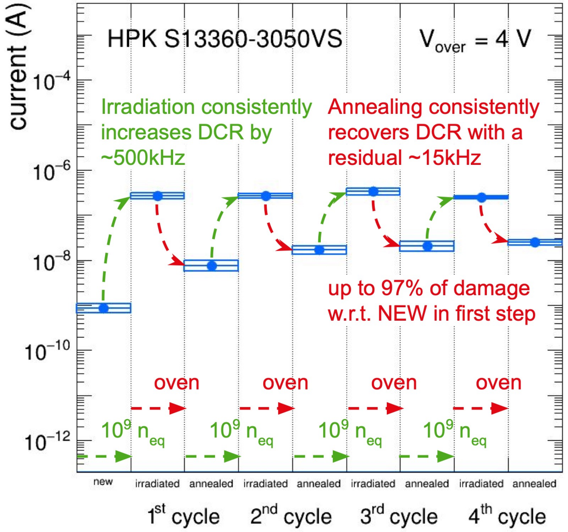
one photon → a multi-pixel cluster

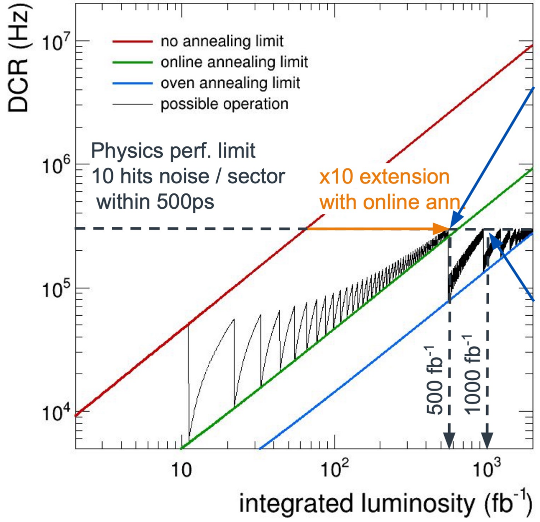


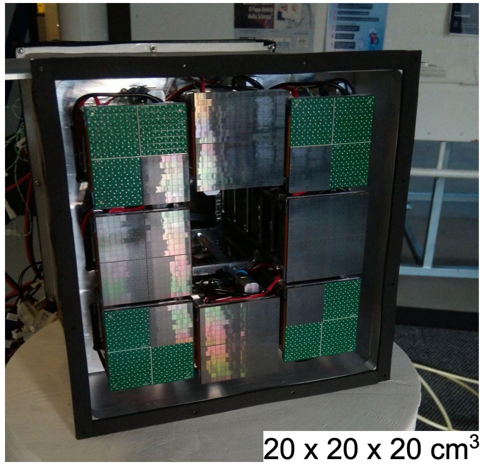


Single event with multiple photon clusters

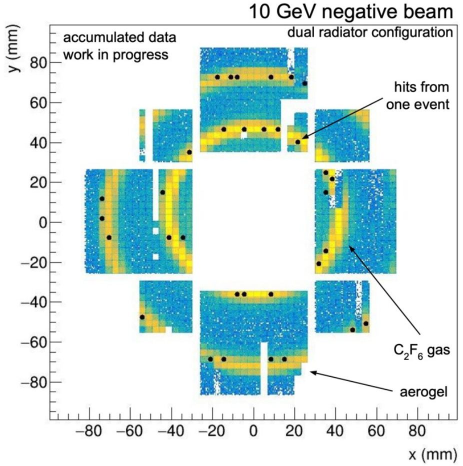
SiPM:
so far not used in RICH detectors, robust R&D to prove annealing cycles can manage DCR increase due to (moderate) radiation load





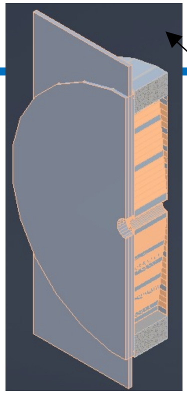


20 x 20 x 20 cm³

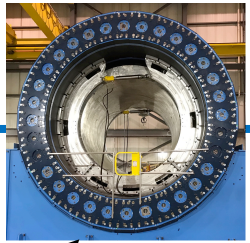


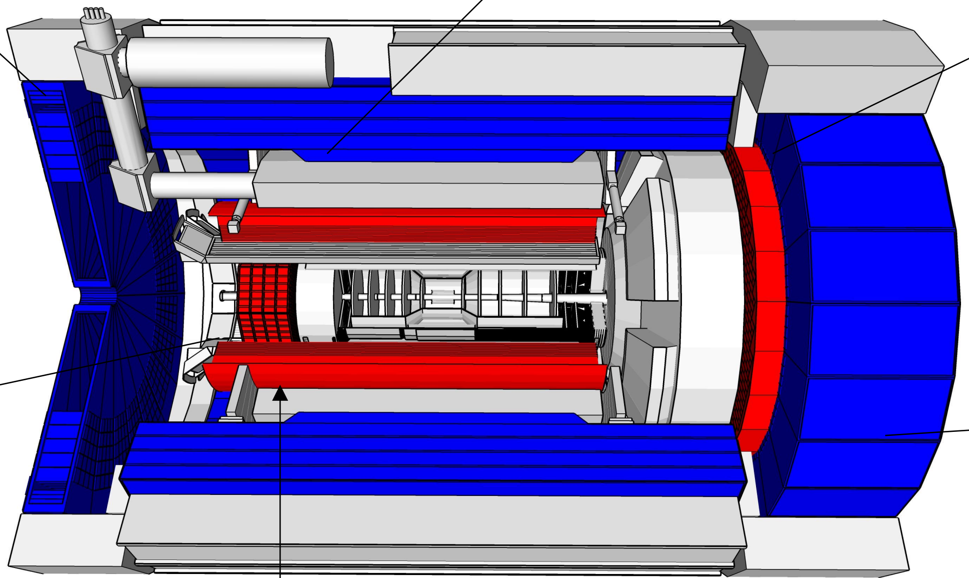
ePIC calorimetry

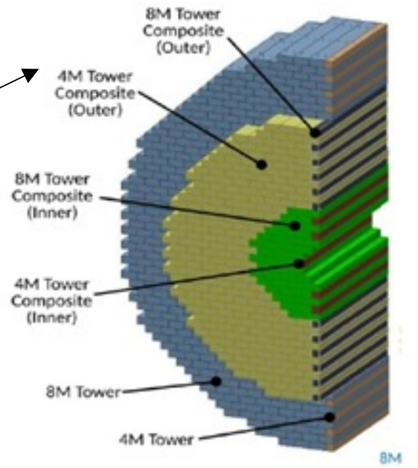
Backwards HCal
Steel/Scint Sandwich (10 layers)
(STAR re-use of scint. tiles)



Barrel HCAL
sPHENIX re-use
new SiPM

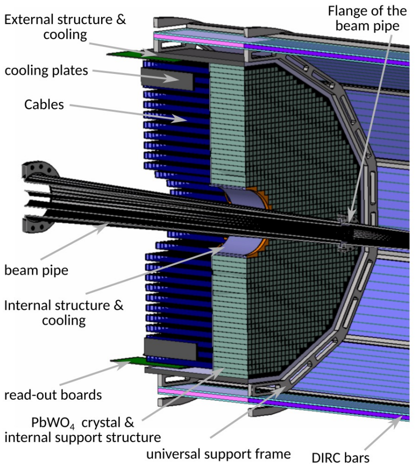




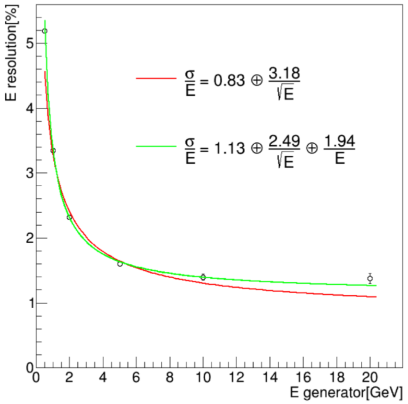


High granularity W-powder/SciFi EMCal:) keeps EM energy resolution at ~10%/√ E + 2%

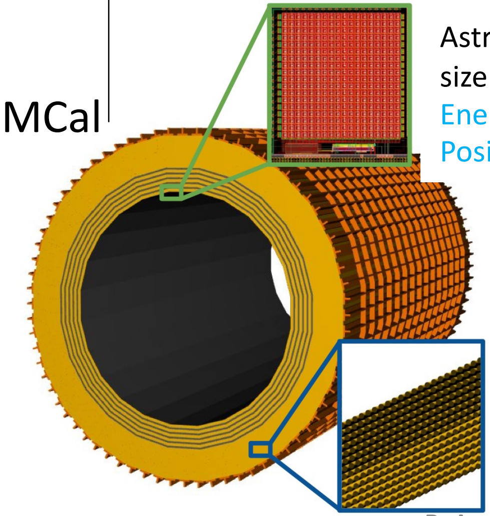
Longitudinally separated HCAL Steel/Sc & W/Sc sandwich with SiPMs embedded in Scintillator



Backwards EMCal. $PbW0_4$ crystals



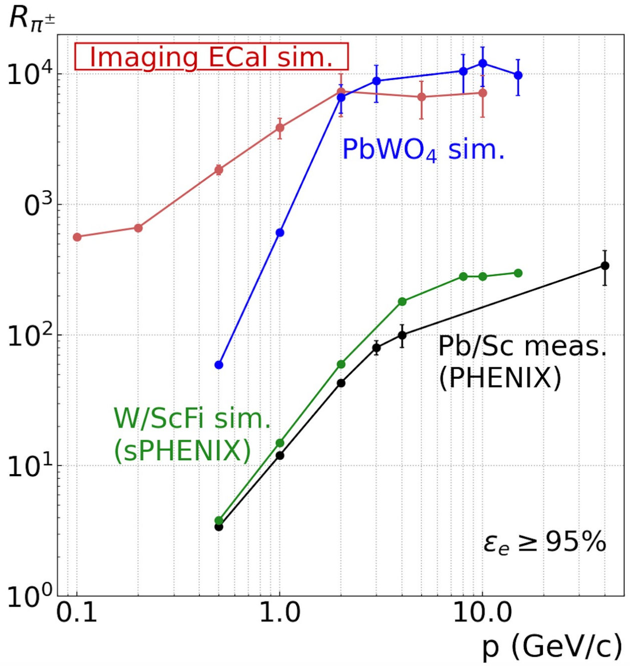
Barrel EMCal



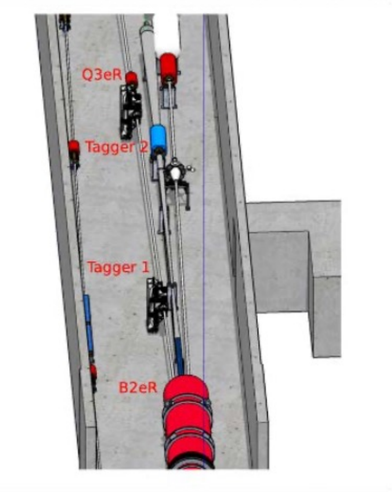
AstroPix: silicon sensor with 500x500 μm^2 size (NASA design). 4(+2) layers
Energy resolution - SciFi/Pb Layers: $5.3\% / \sqrt{E} \oplus 1.0\%$
Position resolution: O(pixel size)

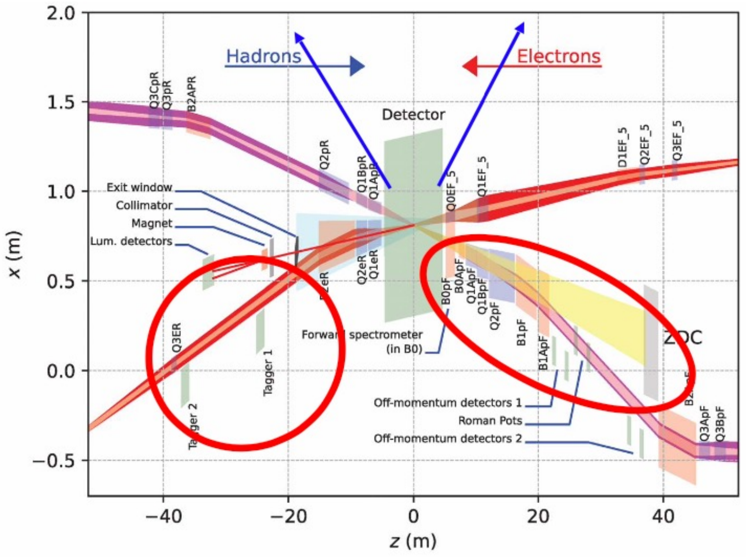
All calorimeters read with SiPM

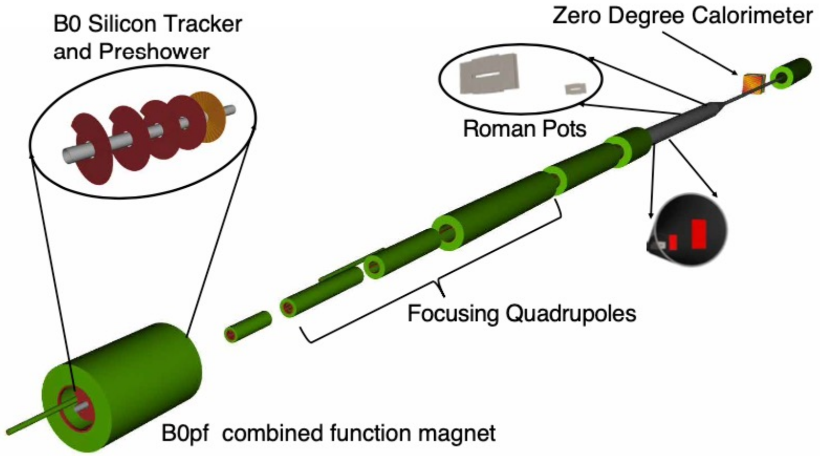
SciFi layers in Pb (GlueX design) with two-sided SIPM readout



ePIC, extended design (out of barrel)







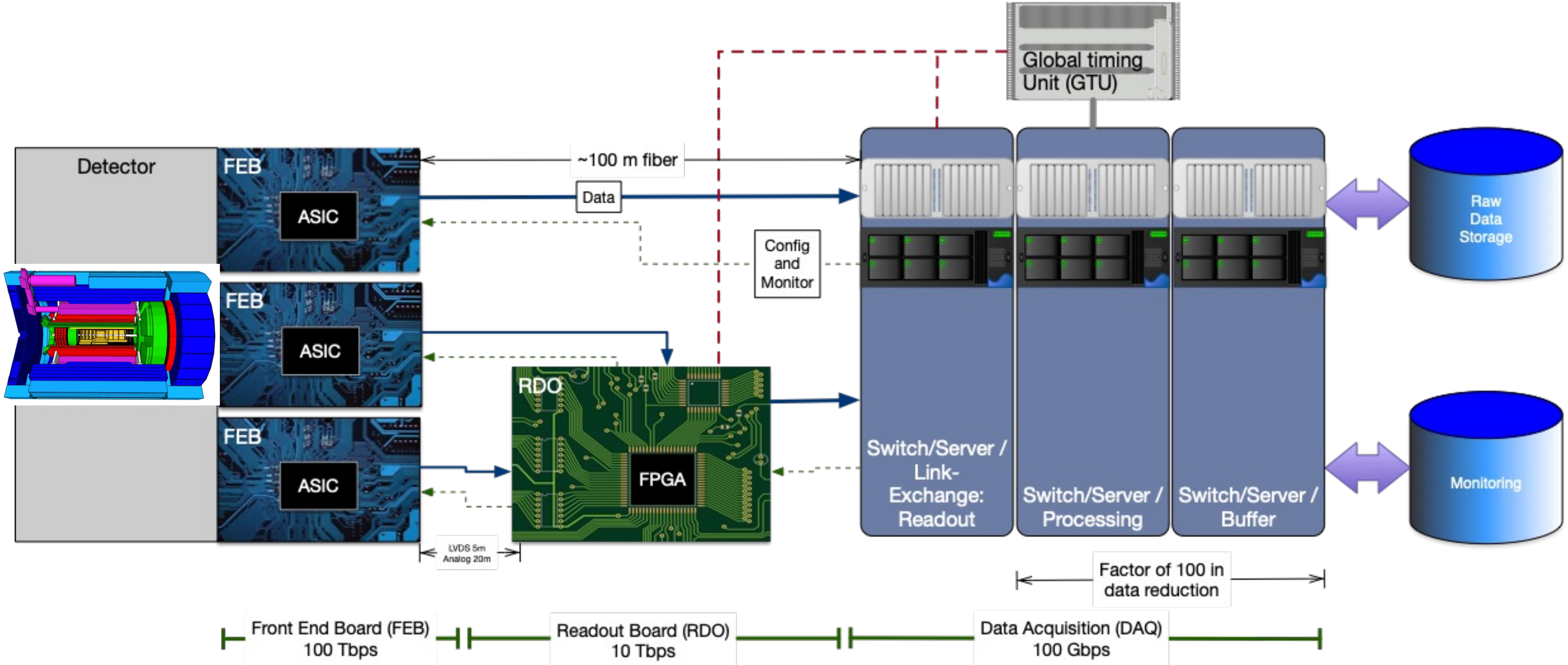
EIC physics includes final-states particles at $|\eta| > 4.5$.

- Need sub-systems integrated within and alongside the accelerator beam line
- **Far-Backward**
  - Luminosity monitor
  - Low-Q^2 tagging detectors $\Rightarrow$ scattered electron at small angles

- **Far-Forward**
  - B0 spectrometer $\Rightarrow$ silicon tracking system and photon EM calorimetry
  - Off-Momentum Detector (OMD) $\Rightarrow$ for particles from nuclear breakup
  - Roman Pots (RP) $\Rightarrow$ for tagging and reconstruction of protons
  - Zero-Degree Calorimeter (ZDC) $\Rightarrow$ for photons and neutrons

For exclusive physics instrumentation along the beamline is crucial

Streaming readout architecture and electronics



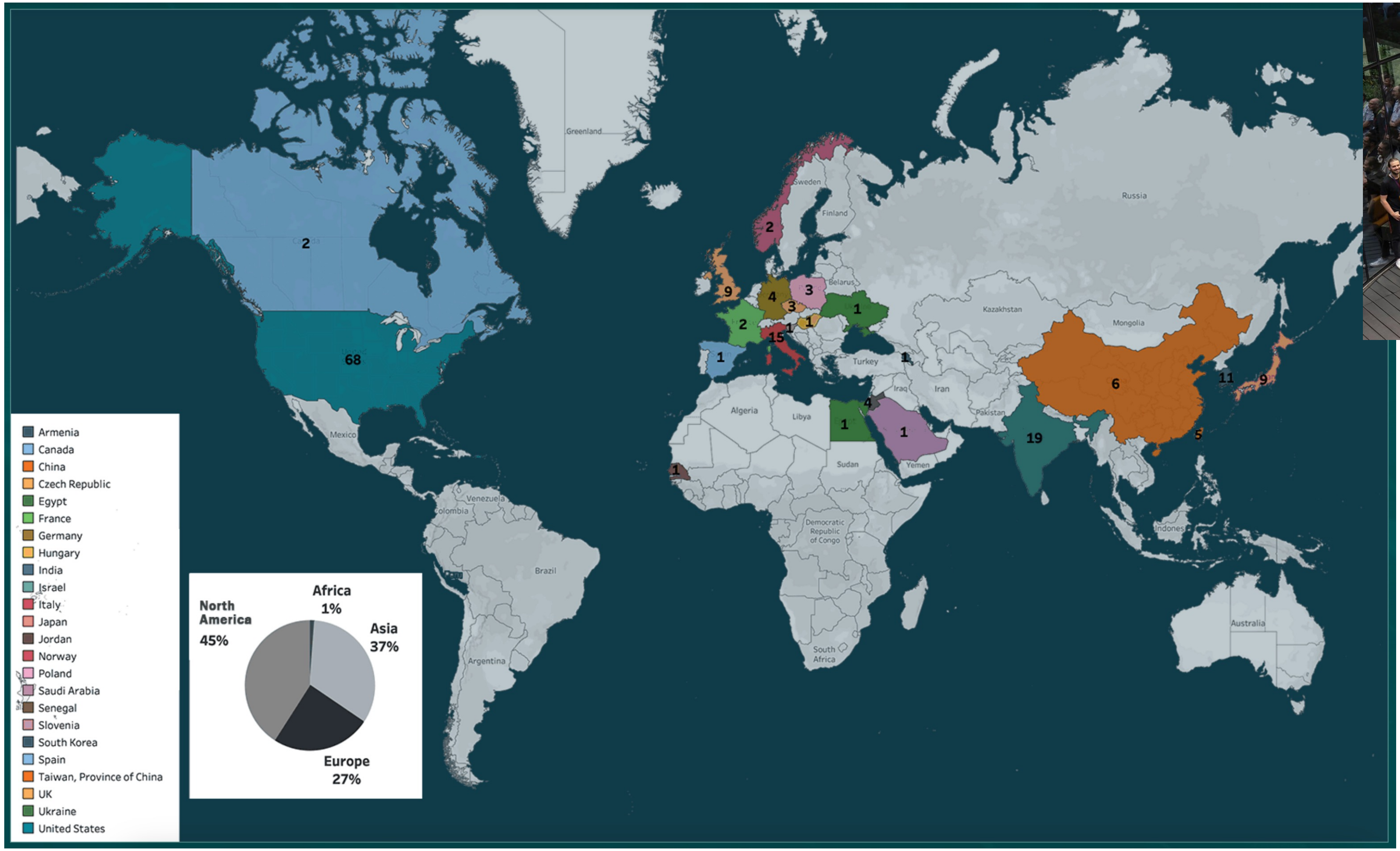
- **Triggerless** streaming architecture gives much more flexibility to do physics
- on-going **ASIC** developments for several detectors: SALSA (MPGD), ALCOR (dRICH), EICROC (AC-LGAD), CalSIPM (H2 HRPPD (HGCROC)
- Integrate **AI/ML** as close as possible to subdetectors → cognizant detector

New microscope for nucleons delivery time

- construction starts following RHIC shutdown (end of 2025)
- **8-9 years** from operations
- first year for machine commissioning
- 2033-2034 toward full luminosity

In a decade from now a new accelerator wil be available to scientists
A new electronic microscope for nucleons to play with

A new Collaboration in HEP/NP!



171 institutions from 24 countries
500+ members

John Lajoie
ePIC Spokesperson
Oak Ridge National Lab
lajoiejg@ornl.gov

Silvia Dalla Torre
ePIC Deputy Spokesperson
INFN
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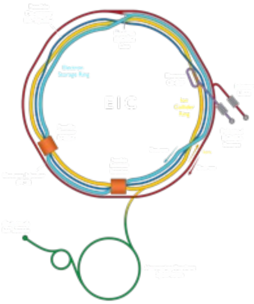
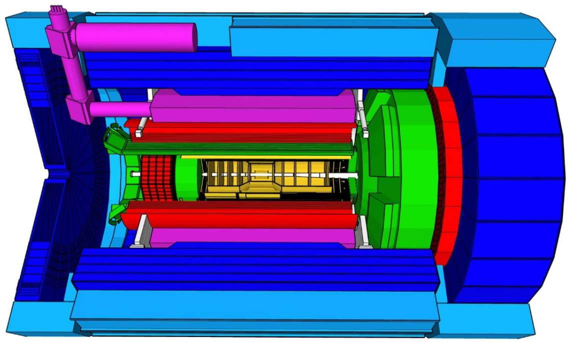
Summary and outlook



- **EIC project well on track**
  TDR (both for the accelerator and the detector) to be submitted by 2024
- **ePIC Collaboration** for "Detector 1" since 2022 and is maturing detector design toward TDR
- **ePIC detector** addresses the challenges of an EIC detector to deliver physics goals
- **ePIC** will be innovative: several novel technologies that will advance the state of the art
- BNL/EIC could as a new opportunity for INFN-DEO Summer Programs



credits for several slides and input: E. Aschenauer, S. Fazio, J. La Joie, S. Dalla Torre, T. Ulrich, M. Zurek


Backup

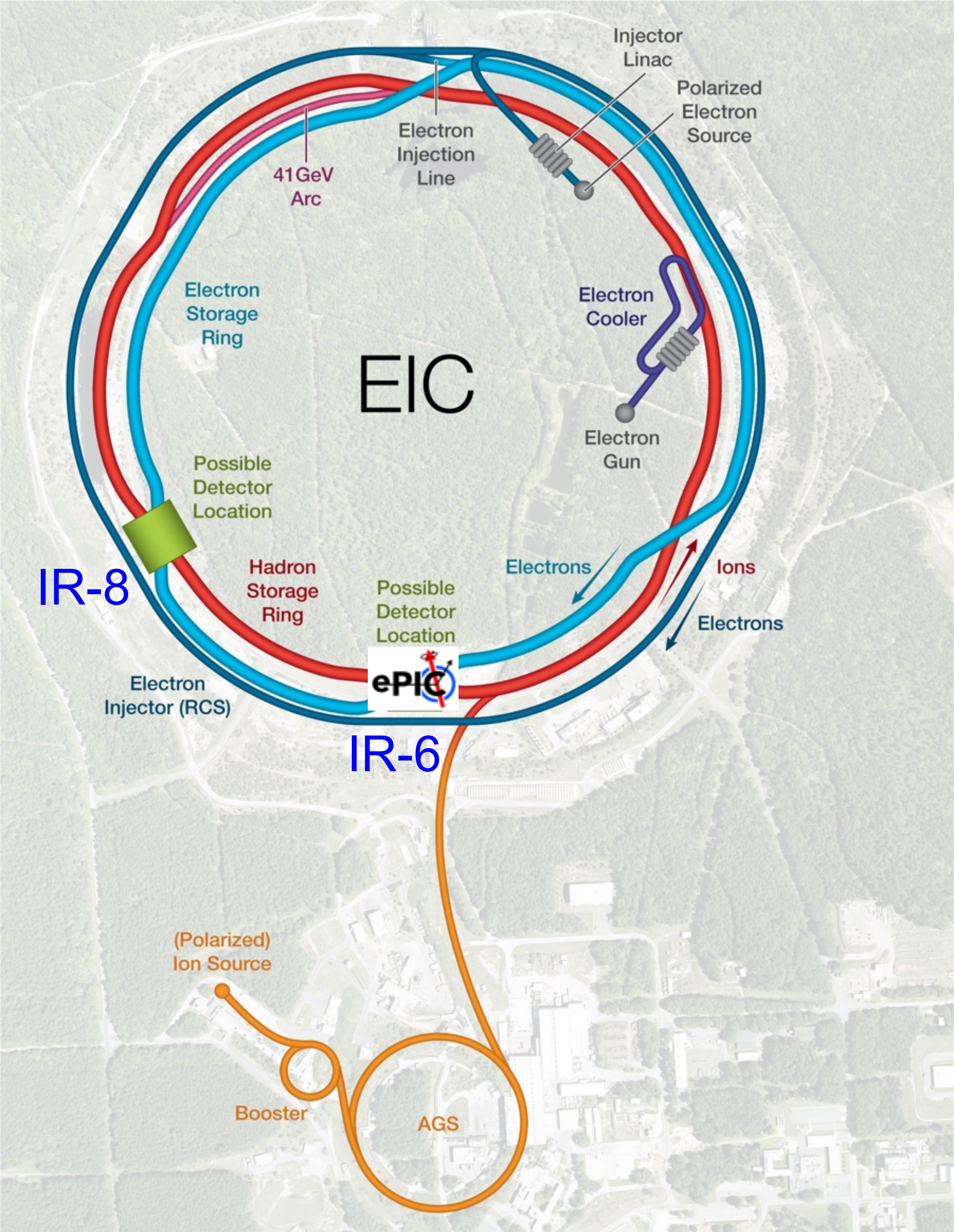
The collider (2)

- High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%

  → **requires high precision polarimetry**
- Large Center of Mass Energy Range:
  E_{cm} = 29 – 140 GeV

  → **Large Detector Acceptance**
- Large Ion Species Range: protons – Uranium

  → **unique opportunity to study Q_s evolution with x**

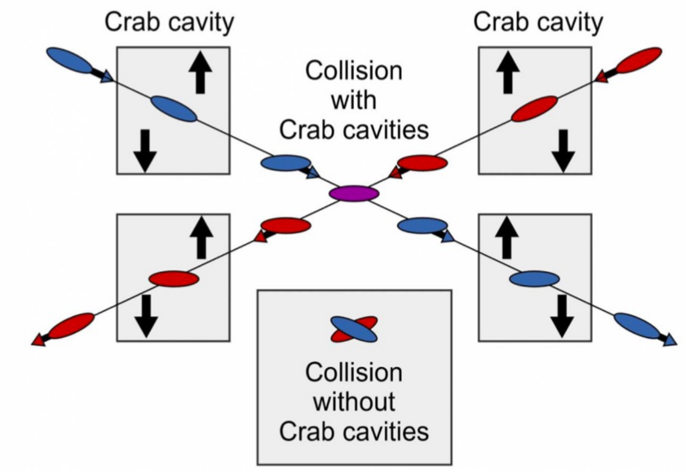


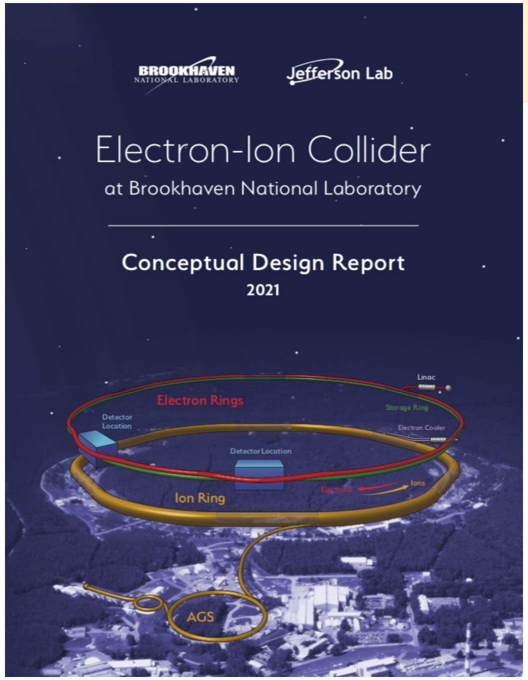
p: 41 GeV, 100 to 275 GeV p/A beam →  ← e beam **e: 5 GeV to 18 GeV**

Collider params

Hadron Storage Ring: 40 – 275 GeV
Electron Storage Ring: 5 – 18 GeV

→ 25 mrad Crossing Angle





Machine Conceptual Design Report:
https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

Params at maximum lumi

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β_x^* [cm]	80	45
Vertical β-function at IP β_y^* [cm]	7.2	5.6
Horizontal/Vertical fractional betatron tunes	0.228/0.210	0.08/0.06
Horizontal divergence at IP $\sigma_{x'}^*$ [mrad]	0.119	0.211
Vertical divergence at IP $\sigma_{y'}^*$ [mrad]	0.119	0.152
Horizontal beam-beam parameter ξ_x	0.012	0.072
Vertical beam-beam parameter ξ_y	0.012	0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	0.7
Hourglass and crab reduction factor [17]	0.94	
Luminosity [10^{34} cm^{-2}s^{-1}]	1.0	

→ Hadron beams cooling with innovative technique (Coherent Electron Cooling using FEL)
V.N. Litvinenko and Y. S. Derbenev, PRL 102 (2009) 114801

Yellow report requirements

η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2										
…															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						$2\%/\sqrt{E}+(1\text{-}3)\%$						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						~$50\%/\sqrt{E}+6\%$	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p+2.0\%$	~5% or less				π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~500 MeV	~$45\%/\sqrt{E}+6\%$	Useful for bkg, improve resolution
-3.0 — -2.5							σ_{xy}~30μm/p_T+ 40μm								
-2.5 — -2.0					$\sigma_p/p \sim 0.05\% \times p+1.0\%$		σ_{xy}~30μm/p_T+ 20μm								
-2.0 — -1.5									$7\%/\sqrt{E}+(1\text{-}3)\%$						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p+0.5\%$		σ_{xyz} ~ 20 μm, $d_0(z) \sim d_0(r\varphi)$ ~ 20/p_T GeV μm + 5 μm		$(10\text{-}12)\%/\sqrt{E}+(1\text{-}3)\%$		≤ 10 GeV/c			~$85\%/\sqrt{E}+7\%$	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p+1.0\%$		σ_{xy}~30μm/p_T+ 20μm			3σ e/π	≤ 30 GeV/c			~$35\%/\sqrt{E}$	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p+2.0\%$		σ_{xy}~30μm/p_T+ 40μm				≤ 30 GeV/c				
3.0 — 3.5							σ_{xy}~30μm/p_T+ 60μm				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
…															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\|t\|)/\|t\| < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c										