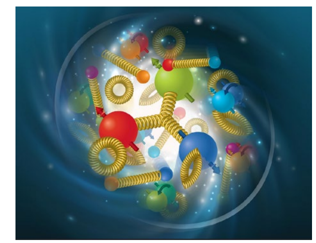
WILHELM UND ELSE HERAEUS-STIFTUNG

Forward Physics and QCD at the LHC and EIC

23 Oct - 27 Oct 2023



The Electron-Ion Collider (EIC)

and the ePIC experiment

S. Dalla Torre

INFN - TRIESTE

OUTLOOK

- The EIC project
- The EIC scientific scope
- The Collider
- ePIC – The project detector

BREAKING NEWS, January 2020

Department of Energy

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

JANUARY 9, 2020

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

Secretary Brouillette approved Critical Decision-0, "Approve Mission Need," for the EIC on December 19, 2019.

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

BREAKING NEWS, January 2020

Department of Energy

U.S. Depart...

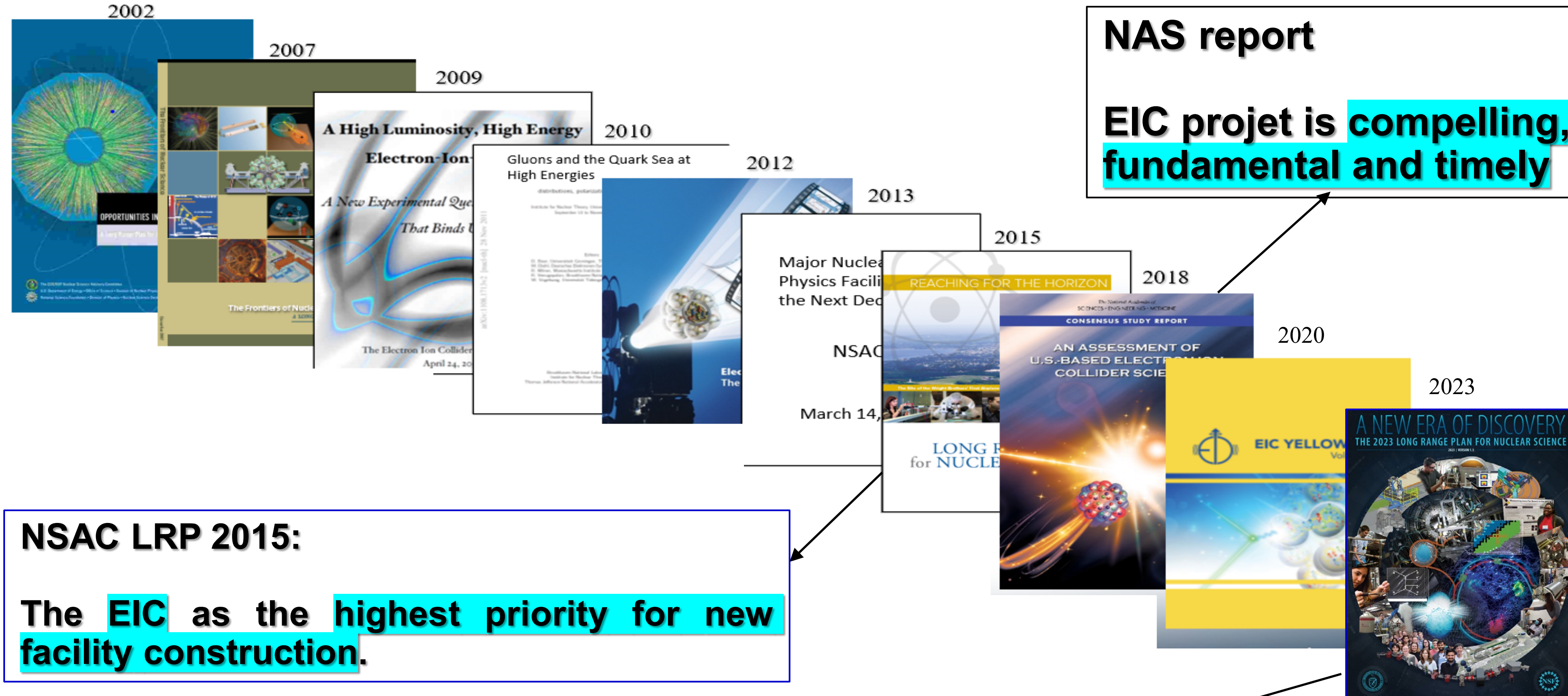
EIC is an approved project !

Most likely,
the only novel collider
in the next coming 20-30 years

...ion Need," for the EIC on December

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

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.

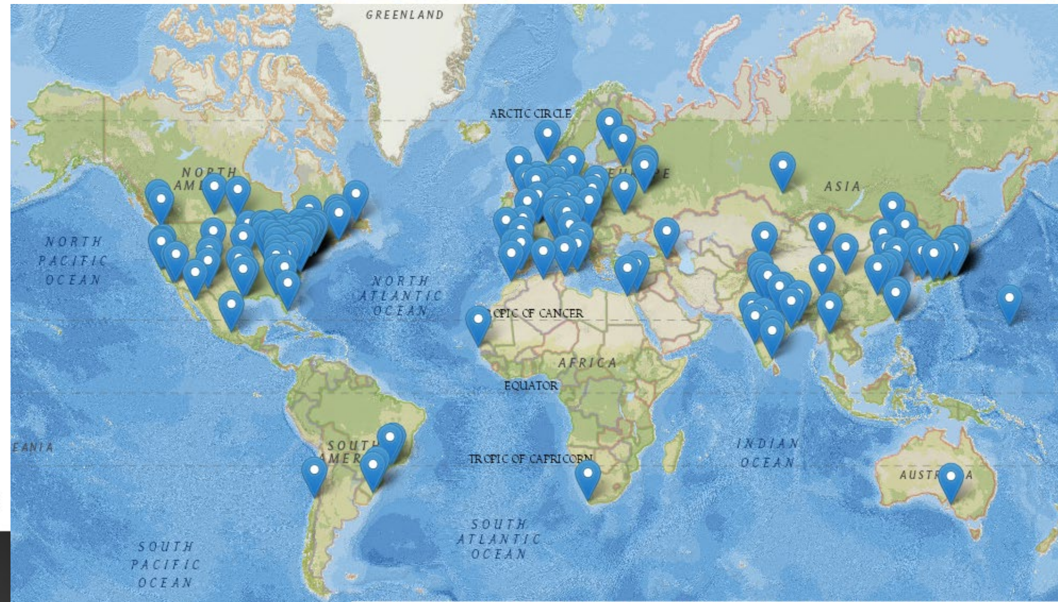
THE INTERNATIONAL COMMUNITY

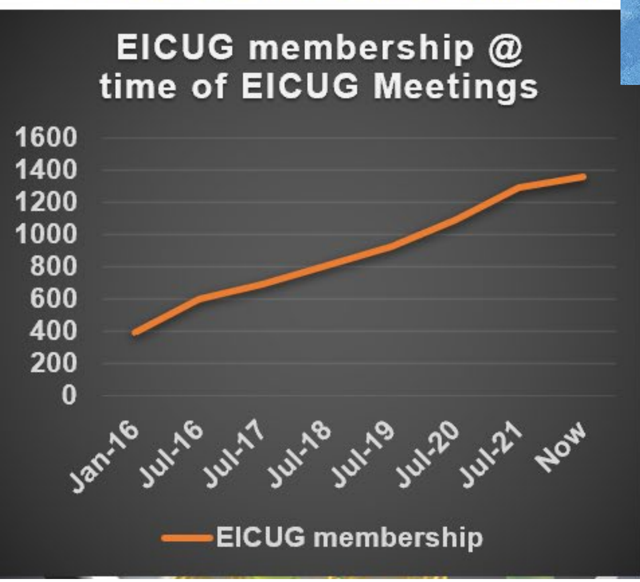
The EIC User Group:
https://eicug.github.io/

Formed 2016 –
- **1422 members**
- **38 countries**
- **291 institutions**

As of October 15, 2023

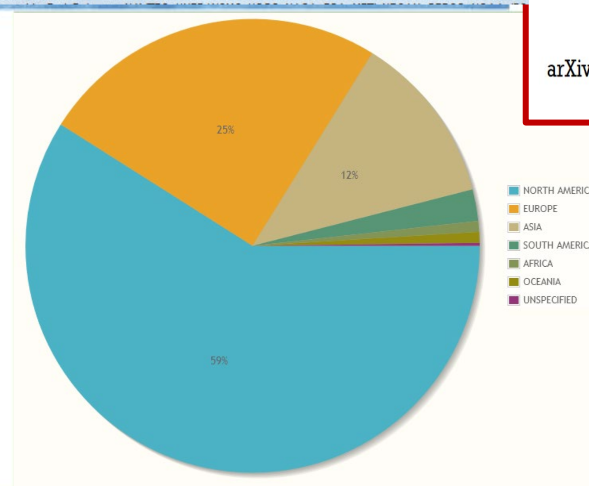
Strong and Growing International Participation.





Annual EICUG meeting

2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland

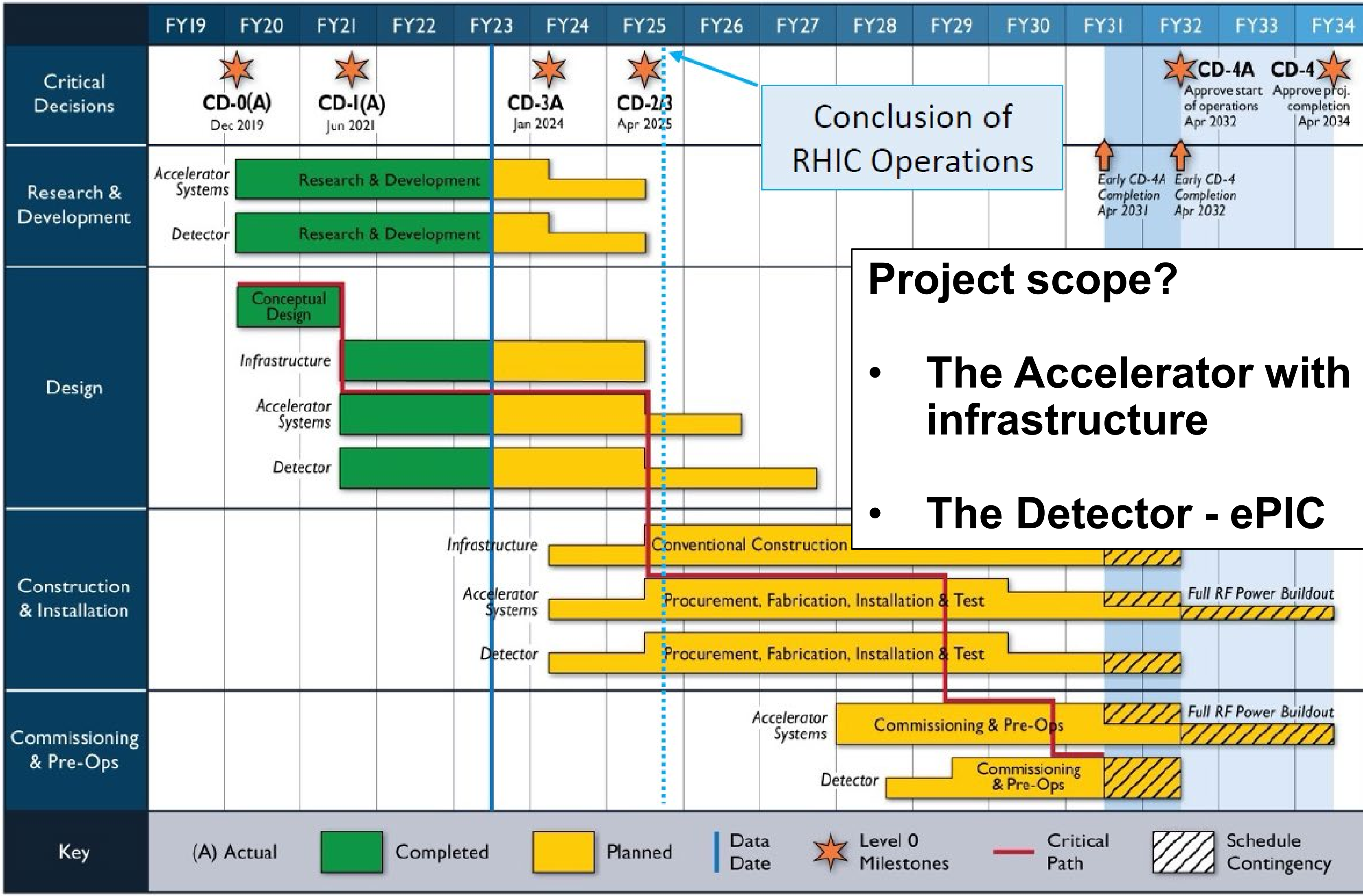


Among the main Achievements:
The Yellow Report

arXiv:2103.05419

Nucl. Phys. A 1026 (2022) 122447

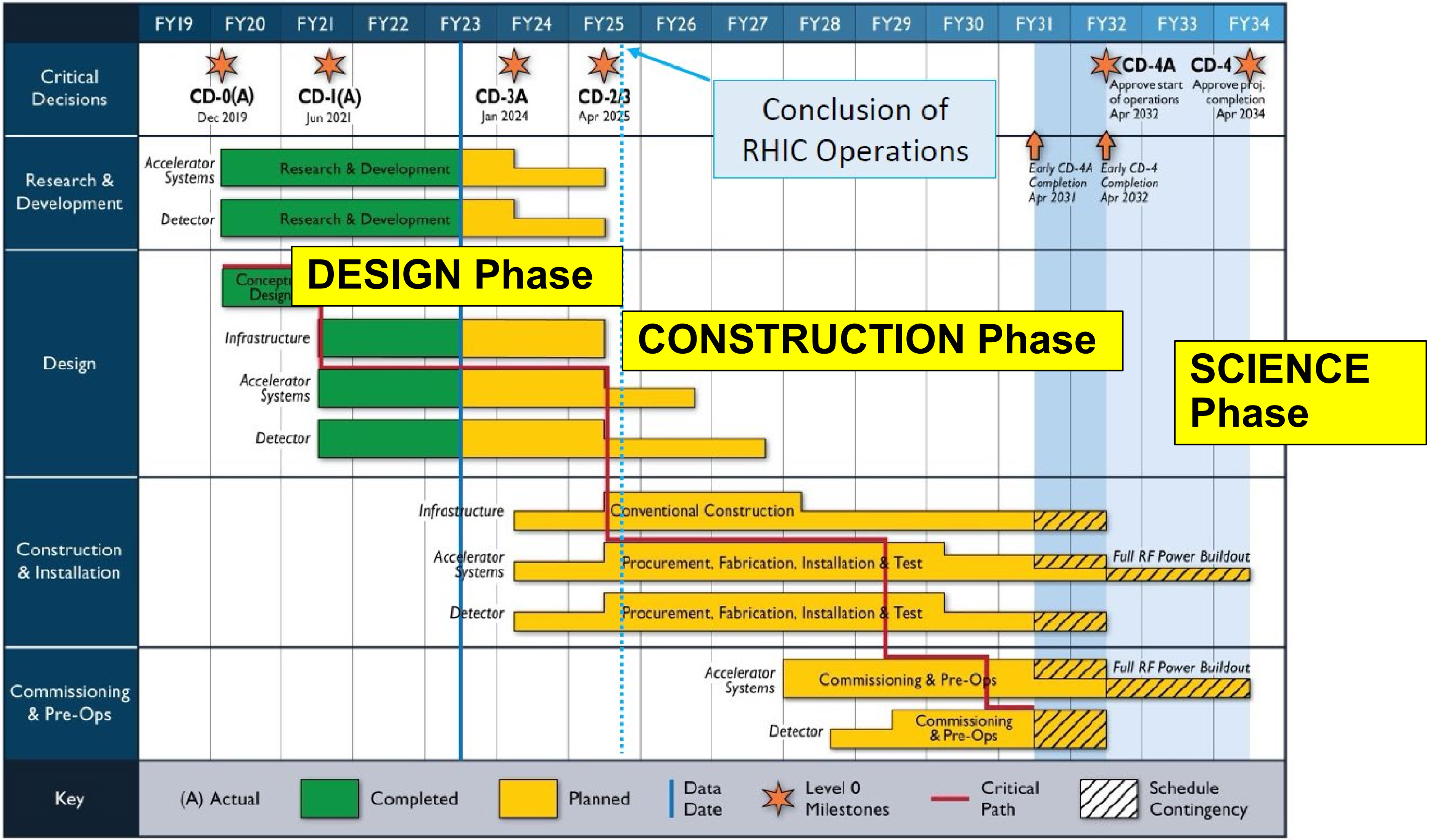
The EIC schedule



Project scope?

- **The Accelerator with its infrastructure**
- **The Detector - ePIC**

The EIC schedule



OUTLOOK

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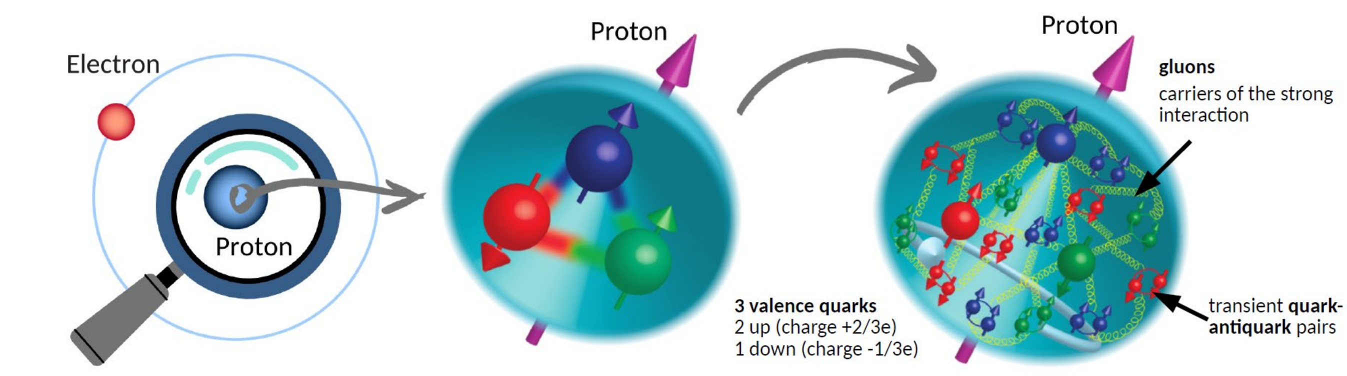
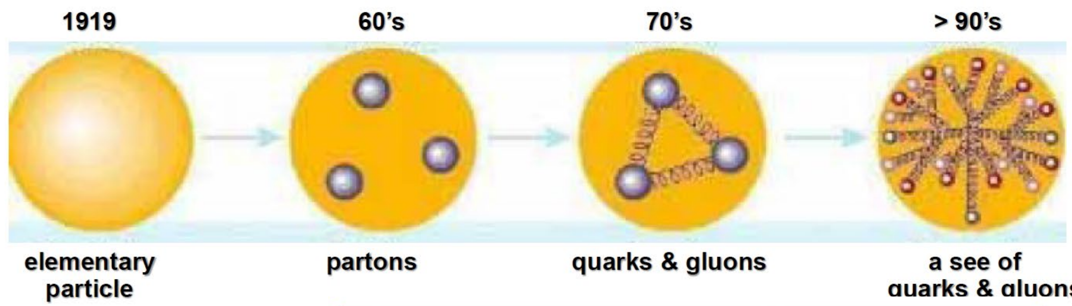
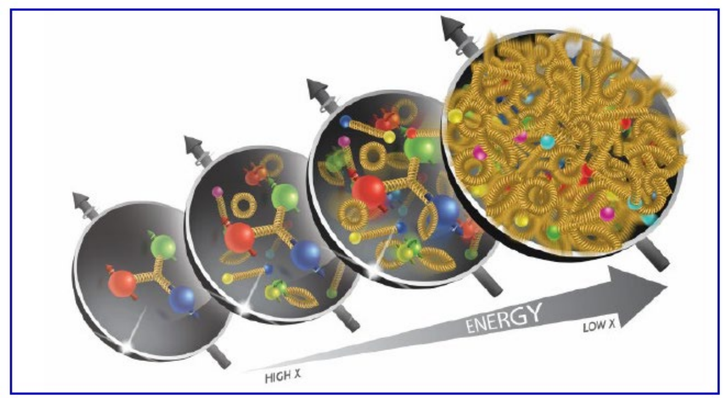
- **The EIC scientific scope**
- **The Collider**
- **ePIC – The project detector**

THE SCIENTIFIC SCOPE

The Evolving Understanding of the Structure of the Nucleon





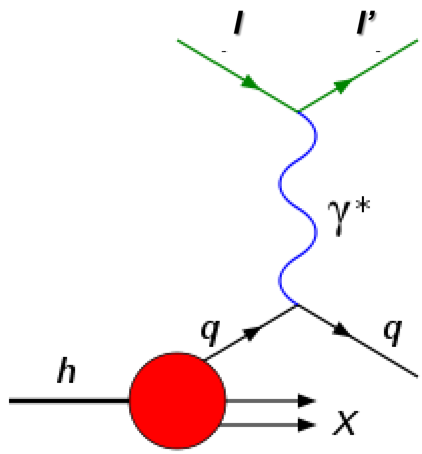


An evolution that has required time and improved "microscope" by increasing energy lepton probes and detectors of finer and finer precision

LEPTONS as HADRON PROBES @ HIGH ENERGY

Deep Inelastic Scattering – DIS

l – the lepton probe
l' – the scattered lepton
h – the hadron being studied: p, A
γ*- the virtual photon



The most used kinematic variables (Lorentz invariant):

$Q^2 = -q^2$, where q is the four-momentum of γ*

$q = p1 - p3$

$\nu = (p1 \cdot q)/M1$

$x = Q^2 / 2(p1 \cdot q)$ $\quad 0 < x < 1$

$y = 2(p1 \cdot q) / (p1+p2)^2$ $\quad 0 < y < 1$

} dimensionless, introduced by Bjorken

Important, about Bjorken x:

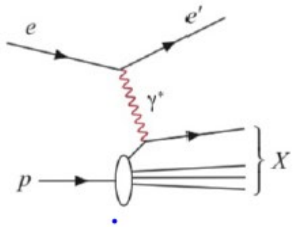
x is interpreted as the fraction of
the h momentum carried by the struck q;
this approximation is valid in the Lorentz frame,
where h and q masses can be neglected

LEPTONS as HADRON PROBES @ HIGH ENERGY

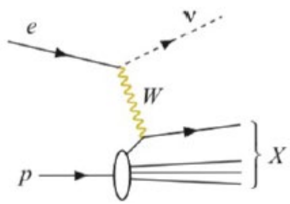
Deep Inelastic Scattering – DIS

Much more information can come when :

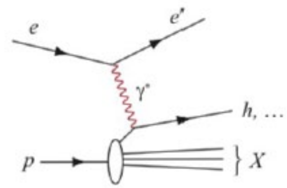
- Access to a wider phase space domain is made possible
- polarized particle scattering
- part of the final state is measured: SIDIS (Semi-Inclusive DIS)
- The whole final state is measured: exclusive reactions



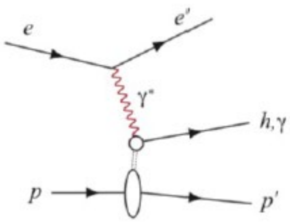
NC inclusive DIS
essential measurement: scattered electron



CC inclusive DIS
kinematics reconstructed via final state particles



Semi-Inclusive DIS
need to identify at least one hadron



Exclusive DIS
full reconstruction → hermeticity

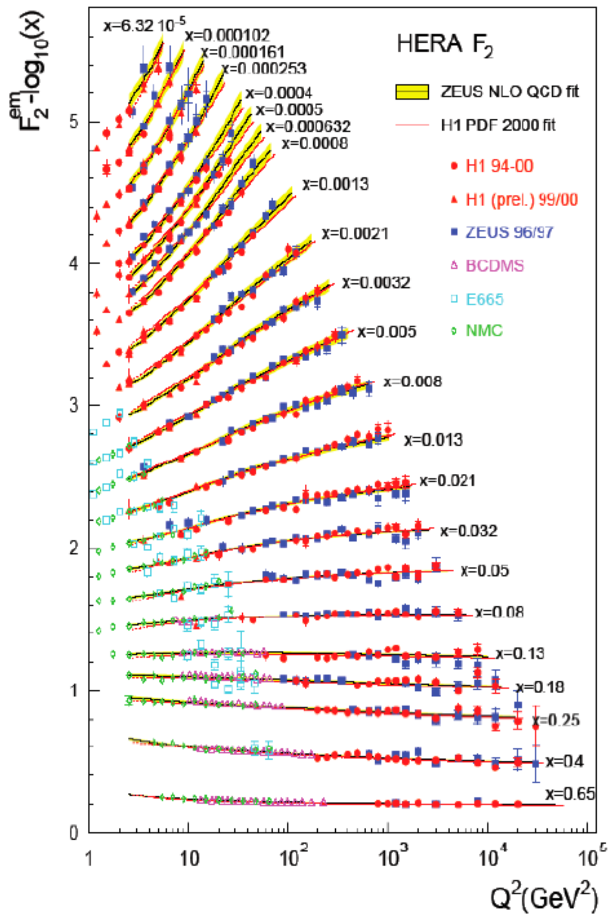
Open questions in QCD and nuclear matter

The study of Nuclear Physics is the quest to understand the origin, evolution, and structure of the matter of the universe

- How do the **properties of the proton** such as **mass** and **spin** emerge from the sea of quarks, gluons, and their underlying interactions?
- What is the **configuration and motion** of quarks and gluons located within the nucleon?
- What happens to the **gluon density** in nucleons and nuclei at small x?
- How do **quarks and gluons interact** with a nuclear medium?
- How do the **confined hadronic states** emerge from quarks and gluons?

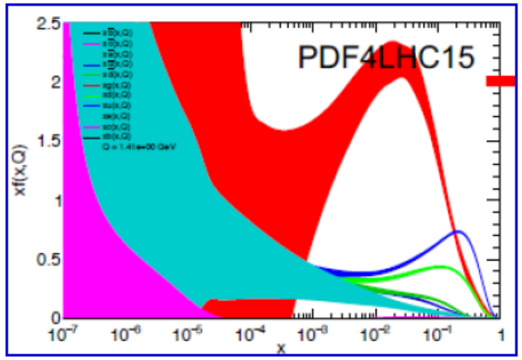
Exploring new territories

$F_2(x, Q^2)$ largely studied

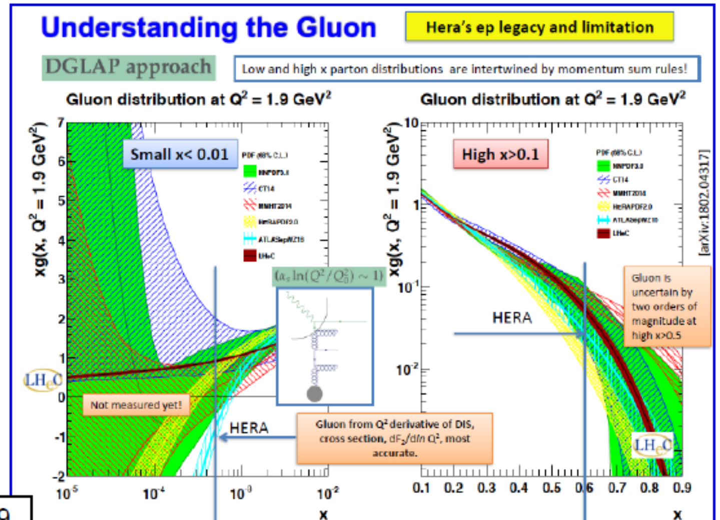


Nevertheless, specific kinematic regions not deeply explored

Quark distribution functions functions poorly known at very small x



Gluon distribution Functions need further exploration at small and large x



C. Gwenlan, DIS2019

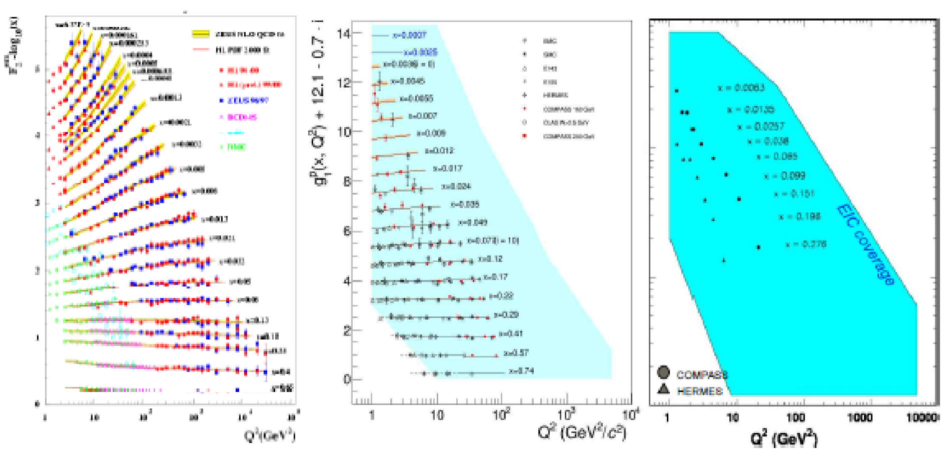
THE SCIENTIFIC SCOPE

TMDs and SPIN

The 8 leading-twist quark TMD PDF

TMD - Transverse-Momentum–Dependent

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \;\; h_{1T}^\perp$



momentum

spin

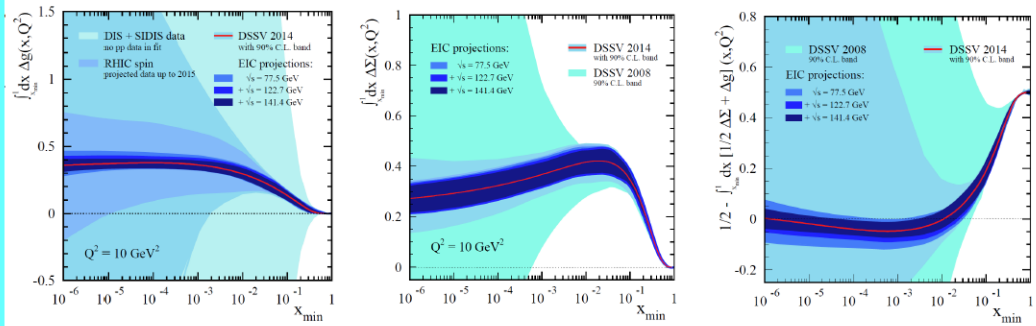
transverse spin ~ angular momentum

A. Bressan, "Prospettive per fisica adronica e collisionatori adronici"

A. Bressan, "Prospettive per fisica adronica e collisionatori adronici"

What do we know:

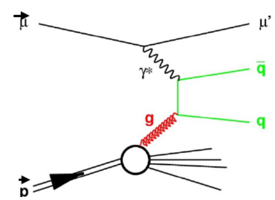
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle = \underbrace{\frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)}_{\text{total quark spin}} + \underbrace{\int_0^1 dx\Delta G(x,Q^2)}_{\text{gluon spin}} + \underbrace{\int_0^1 dx\left(\sum_q L_q^z + L_g^z\right)}_{\text{angular momentum}}$$



1/2 - Gluon 40% - Quarks 30% = orbital angular momentum

- **Gluon contribution needs a deeper exploration**

Photon Gluon Fusion: $\gamma g \to q\bar{q}$



High p_T hadron pair $q\bar{q} \to hh$

of course, by a SI-DIS measurement

- **Orbital momentum to be extracted from TMDs**

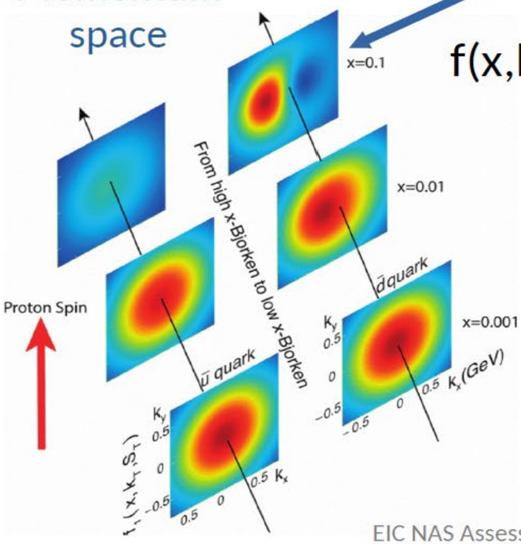
Spatial and Momentun structure of the N in 3D

Maria Żurek, EIC RRB, April 2023

Wigner functions
$W(x, b_T, k_T)$

$\int d^2 b_T$ → $f(x, k_T)$ $\int d^2 k_T$ → $f(x, b_T)$

Momentum space



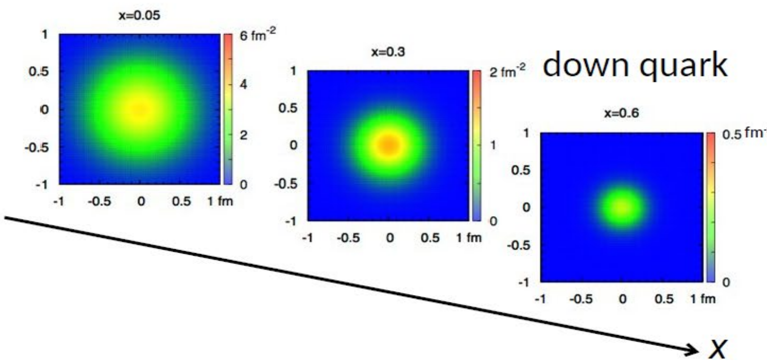
EIC NAS Assessment

MOMENTUM SPACE

Access to spin-orbit correlation (TMDs) via SIDIS

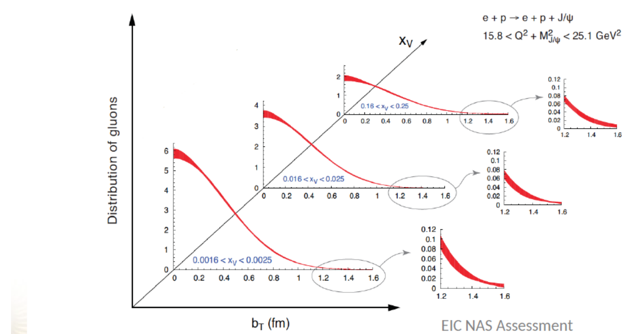
COORDINATE SPACE

Spin-dependent 2+1D coordinates space images from exclusive scattering



Nucleon tomography

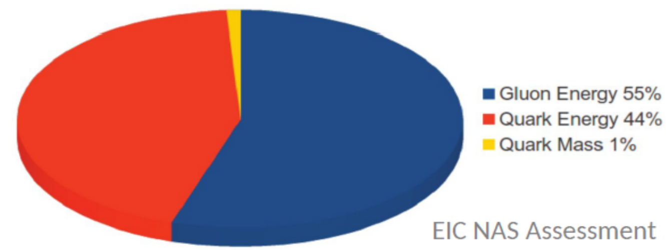
- Deeply Virtual Photon scattering – real photon is produced
- Deeply Virtual Meson production – quark-antiquark bound state is produced



THE SCIENTIFIC SCOPE

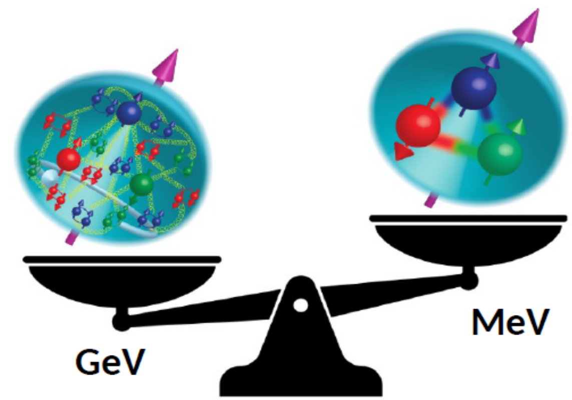
HOW DO NUCLEONS ACQUIRE MASS ?

Contributions to the total mass of the nucleon



- **Gluons have no mass** and **quarks are nearly massless**, but nucleons and nuclei are heavy, making up most of the visible mass of the universe
- Visible world mostly made out of light quarks: **masses emerge form quark-gluon interactions**

Proton (valence content *uud*) - mass ~940 MeV
- The mass is dominated by the energy of the highly relativistic gluonic fields
- EIC will allow determination of an important term contributing to the proton mass, the so-called “QCD trace anomaly” → accessible in exclusive reactions



What about the mass of light mesons?

Pions (valence content *ud*) mass ~140 MeV
- Cleanest expression of the emergent mechanism
- Empty or full of gluons?

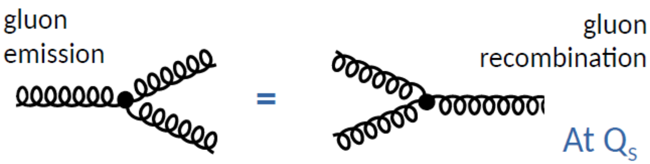
Kaons (valence content *us* – strange content!) mass ~ 490 MeV
- Probing boundary between emergent and Higgs-mass mechanisms
- More or less gluons than in pion?

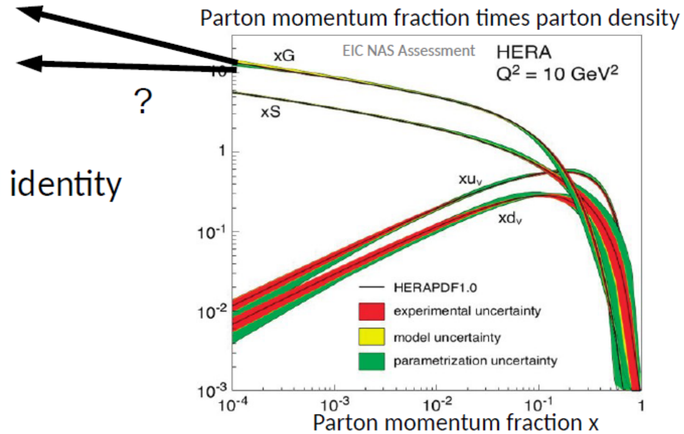
Maria Żurek, EIC RRB, April 2023

ACCESS TO A NEW STATE OF THE GLUONIC MATTER

What happens to the gluon density in nuclei?

- Number of gluon **grows in the low-x limit**
- At some point the **density becomes so large** that gluons lose their individual identity and are **strongly overlapping**



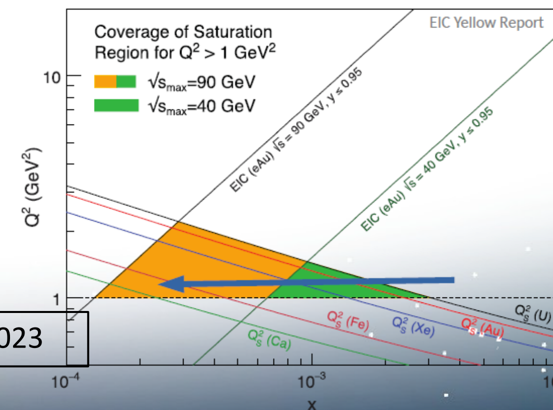


Q_s - resolution scale at which the number density so large that gluons are no longer independent → **saturated gluon matter**

EIC provides a unique opportunity to have very high gluon densities **electron – heavy nuclei (e.g., Pb) collisions**

Combined with an unambiguous observables, e.g., **di-jets in ep and eA, diffractive processes**

EIC will allow to unambiguously map the transition from a non-saturated to saturated regime



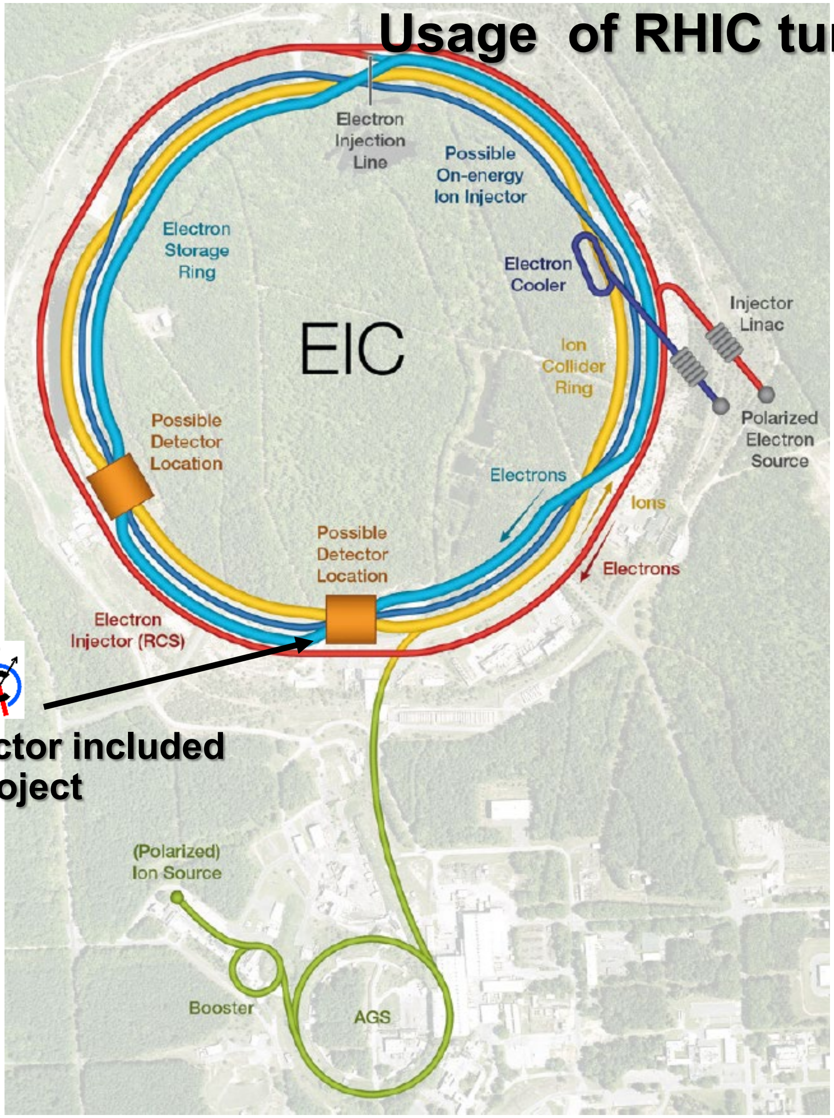
Maria Żurek, EIC RRB, April 2023

OUTLOOK

- **The EIC project**
- **The EIC scientific scope**
- **The Collider**
- **ePIC – The project detector**

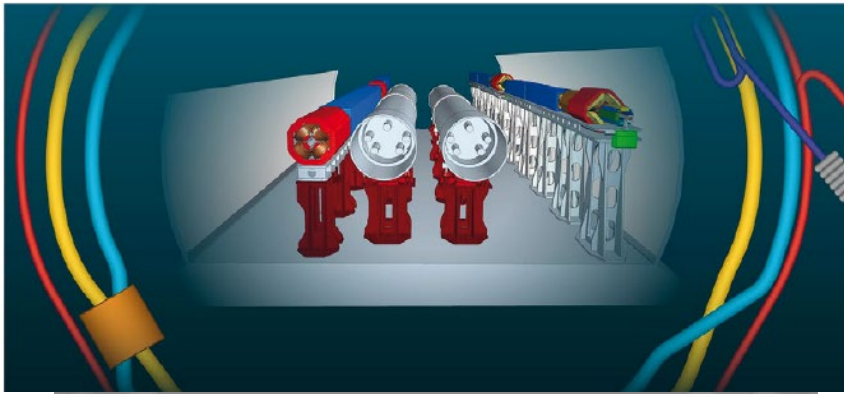
The EIC Collider

Usage of RHIC tunnel and RHIC p/ion complex



ePIC

IP6 detector included in the project



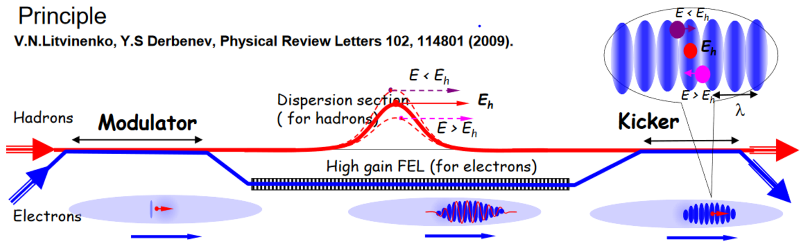
- spanning a wide kinematical range
  - **ECM: 20 – 141 GeV**
- High luminosity
  - up to 10^{34} cm^{-2} s^{-1}
- **highly polarized e (~ 70%) beams**
- **highly polarized light A (~70%) beams**
- wide variety of ions: **from H to U**
- **Number of interaction regions: up to 2**

The EIC Collider

3 critical ingredients for HIGH LUMINOSITY

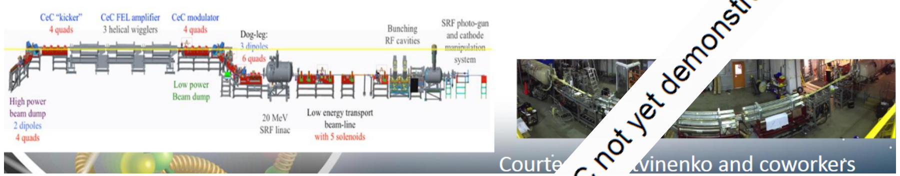
Coherent Cooling with FEL amplifier

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



CeC not yet demonstrated

Bunches and beam crossing rates

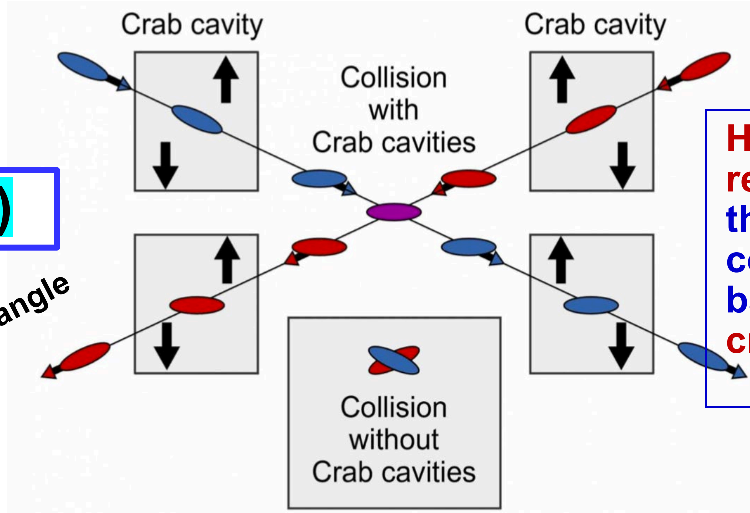
Species	p	e	p	e	p	e	p	e	p	e
Beam energy [GeV]	275	18	275	10	100	10	100	5	41	5
$\sqrt{s}$ [GeV]	140.7		104.9		63.2		44.7		28.6	
No. of bunches	290		1160		1160		1160		1160	

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 !

CRAB CROSSING ANGLE (25 mrad)



Head-on collision is restored by rotating the bunches before colliding and, then, back ("crab crossing")

For the first time a sizable crab crossing angle

The EIC Collider

MORE unique aspects

BEAM POLARIZATION

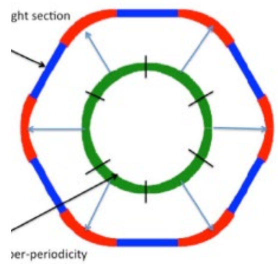
ION SPECIES

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!

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 ^{3}He and D beams also possible

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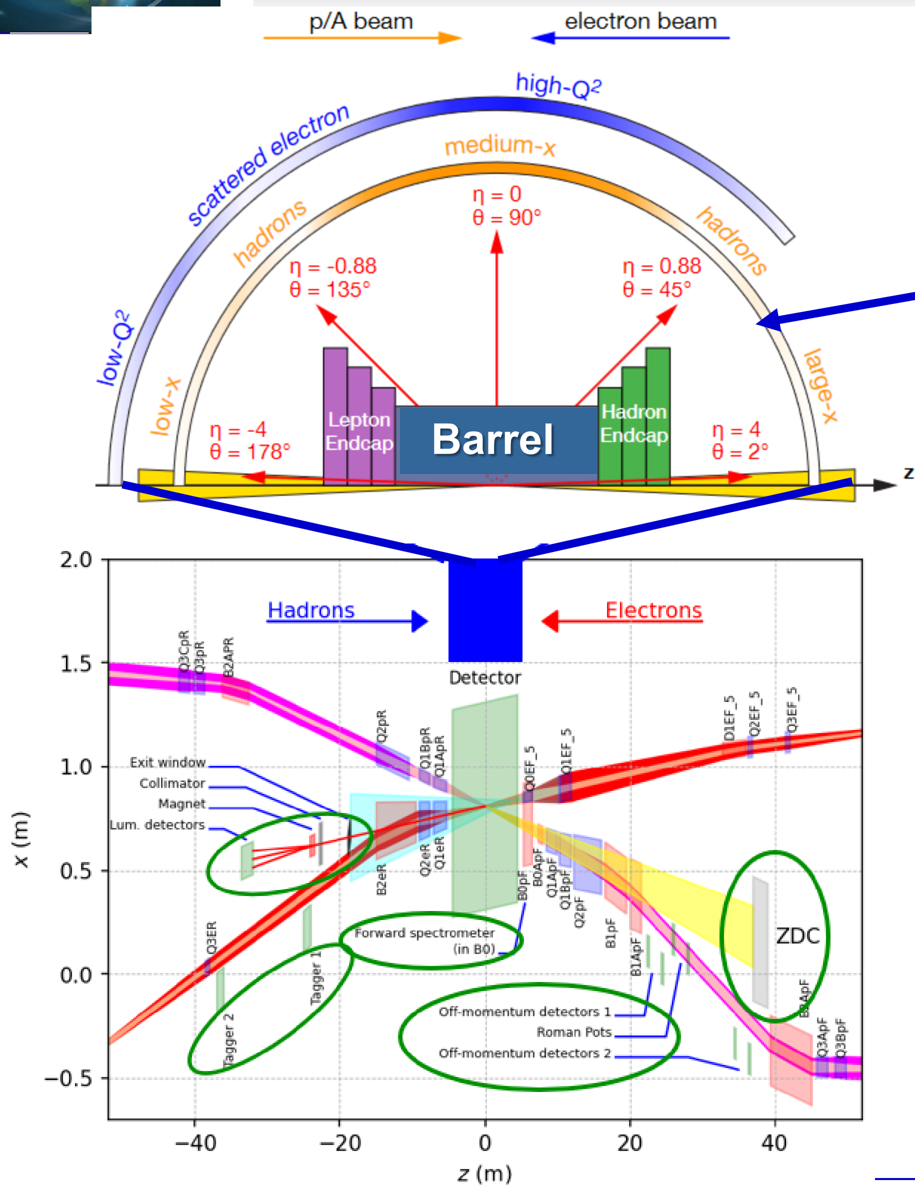
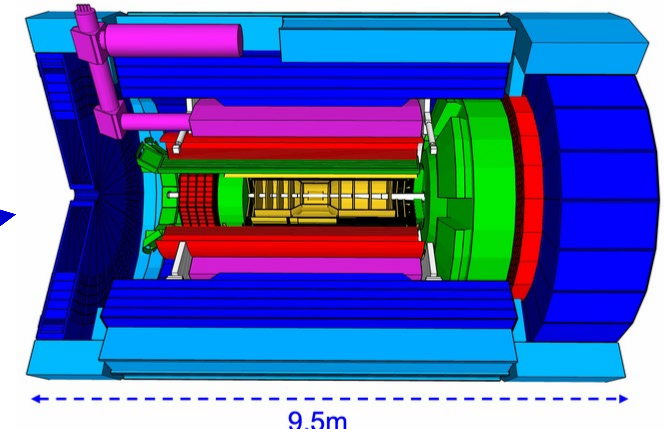
THE COMPLETE ePIC DETECTOR





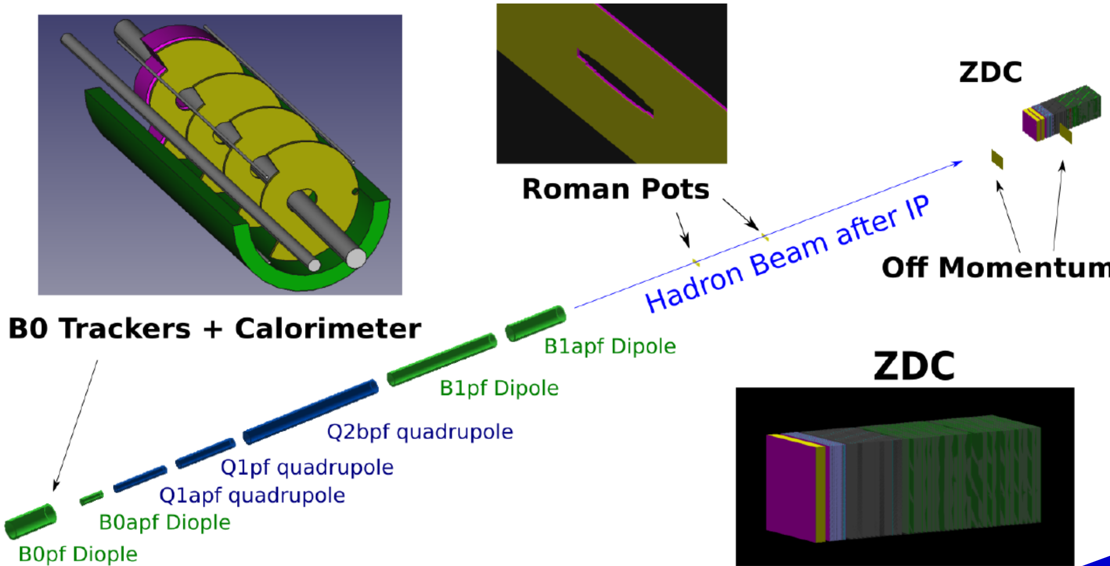
Central Detector (CD)

Total size detector: ~75m
Central detector: ~10m
Backward electron detection: ~35m
Forward hadron spectrometer: ~40m

Auxiliary detectors needed to tag particles with very small scattering angles both in the outgoing lepton and hadron beam direction (B0-Taggers, Off-momentum taggers, Roman Pots, Zero-degree Calorimeter and low Q2-tagger).

Far forward and backward

Far Forward



Far Backward

Figure: Low-Q^2 taggers

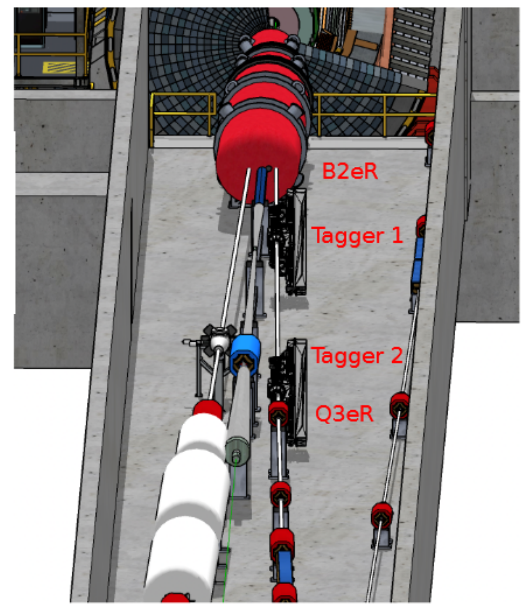
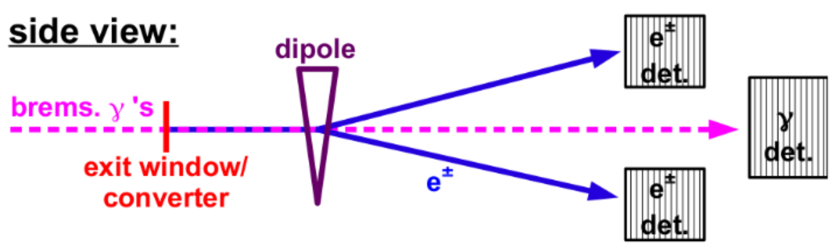
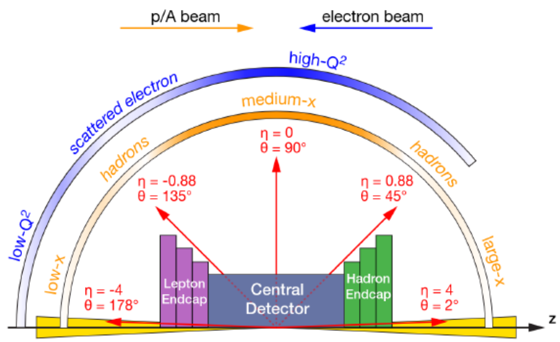


Figure: Luminosity detector



ePIC Central Detector



Formed by:

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

hadronic calorimeters

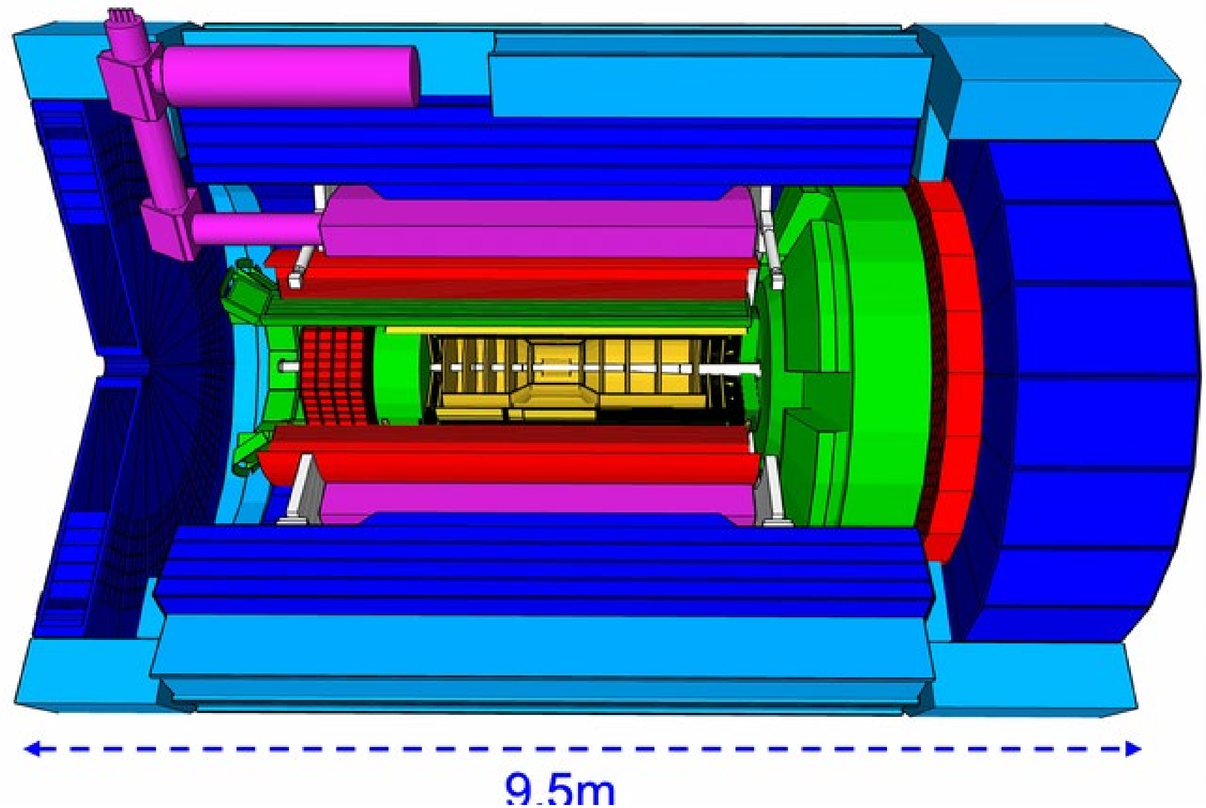
Solenoidal Magnet

e/m calorimeters (ECal)

Time.of.Flight, DIRC, RICH detectors

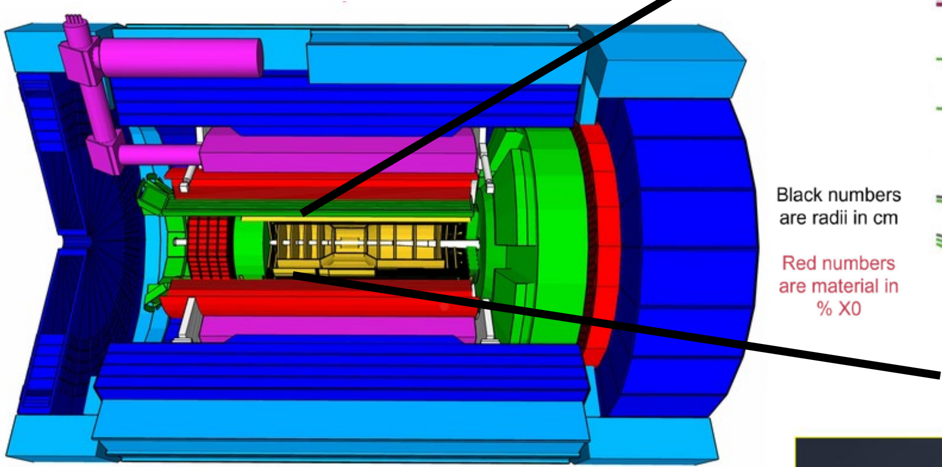
MPGD trackers

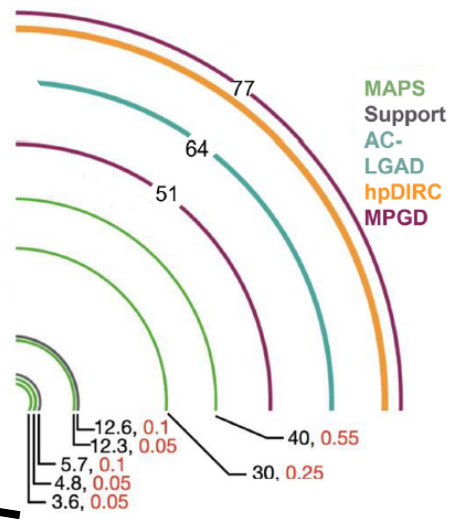
MAPS tracker



TRACKING IN ePIC CD

Tracking



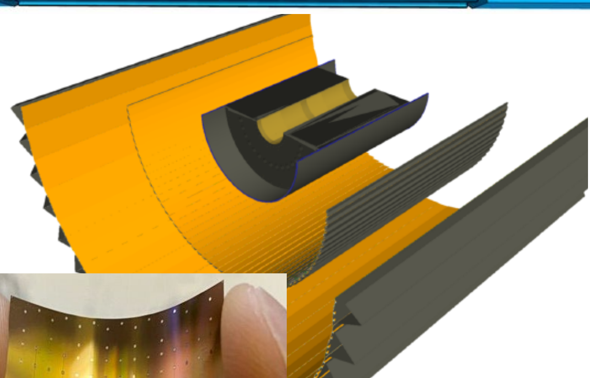


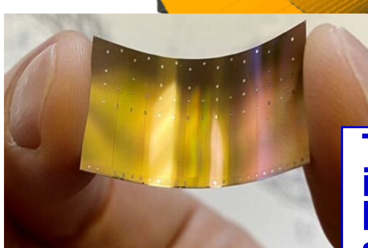
Si trackers based on ALICE ITS3 65 nm MAPS sensors

- **Five layers in the barrel and in the endcaps**

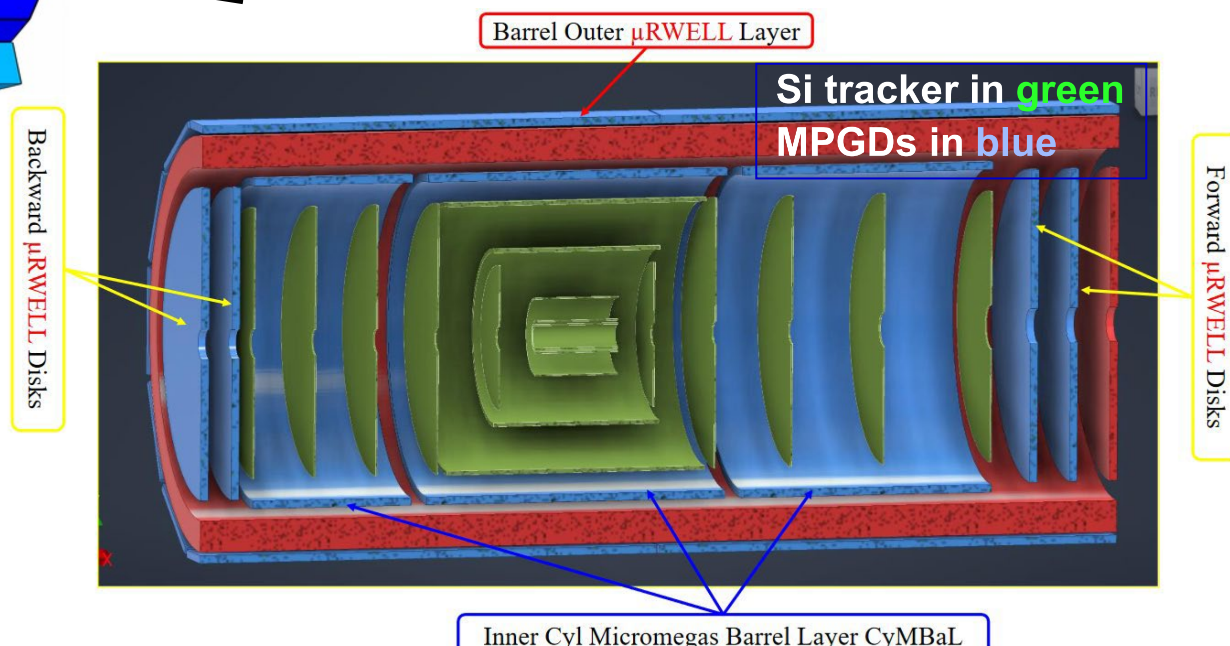
Supplemented by MPGD trackers

- **Cylindrical MICROMEGAS**
- **Planar μR-WELL**



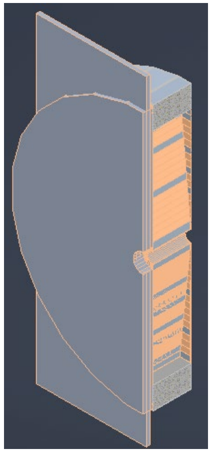


The 3 most internal layers are support-less !



CALORIMETRY IN ePIC CD

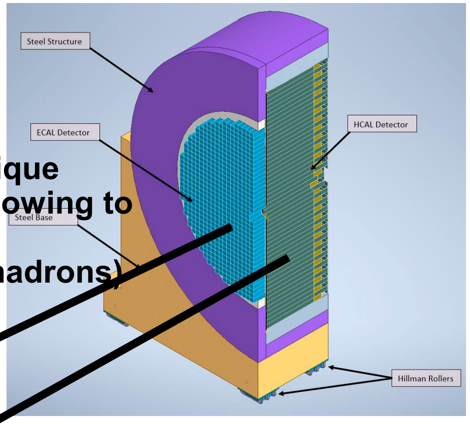
SiPMs of all Calorimeters

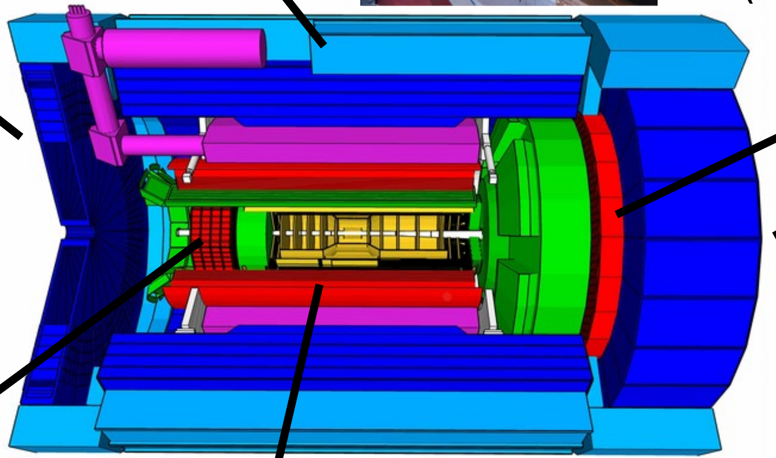


Backwards HCal
Steel/Sc Sandwich
tail catcher

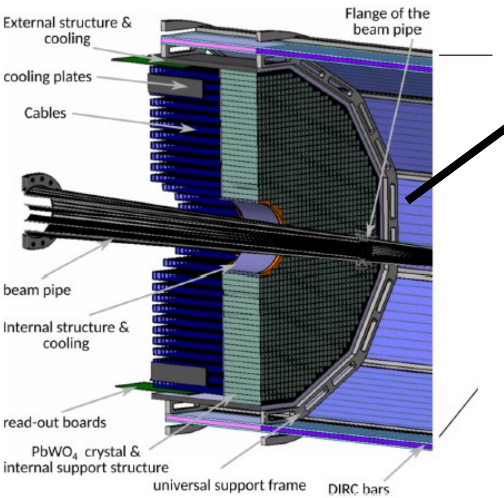
Barrel Hcal
(re-use from sPHENIX)

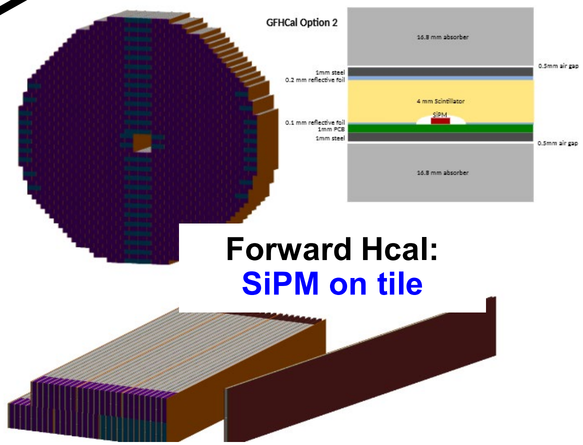
WScFi is a unique technology allowing to achieve e/h ~1 (response to hadrons)



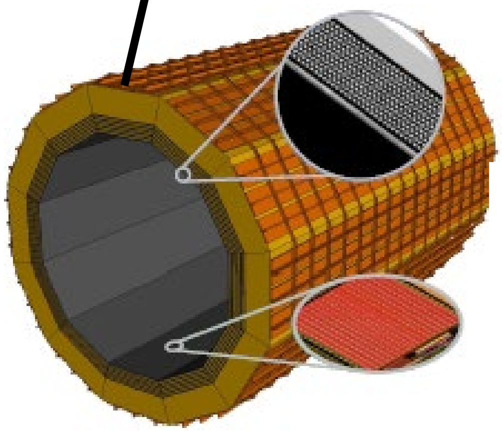


Backwards EMCal
PbW04 crystals





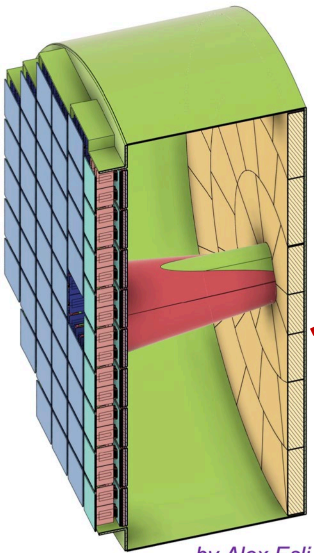
Forward Hcal:
SiPM on tile



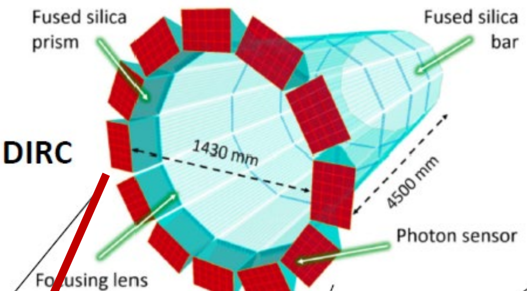
4 (6) layers of imaging calorimetry by Astropix MAPS, and sampling calorimetry by Pb/SciFi

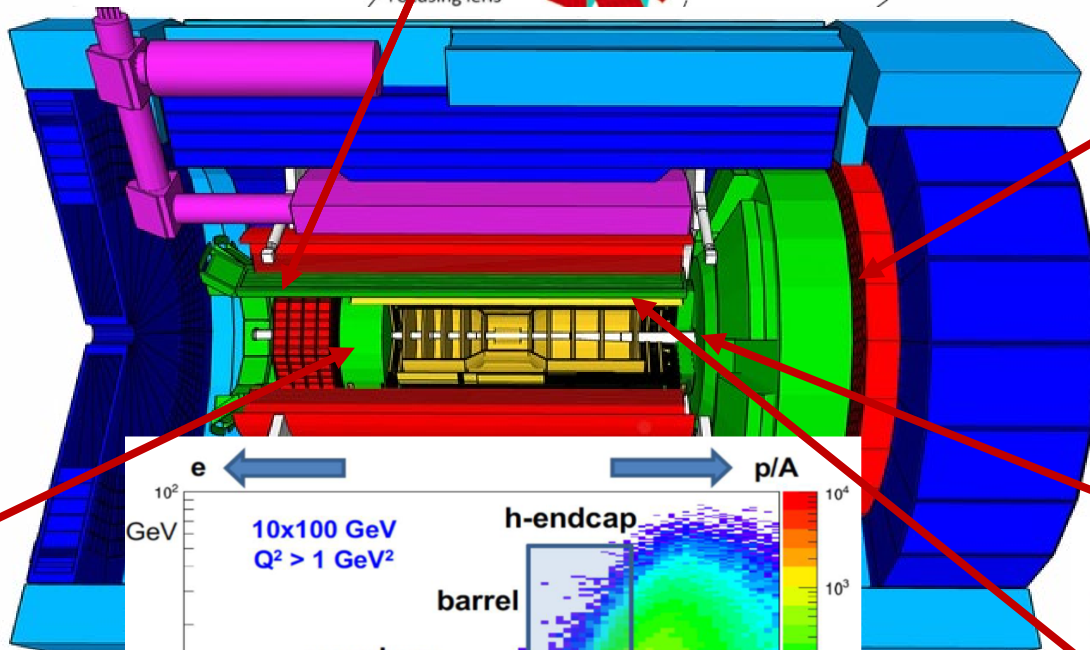
PID IN ePIC CD

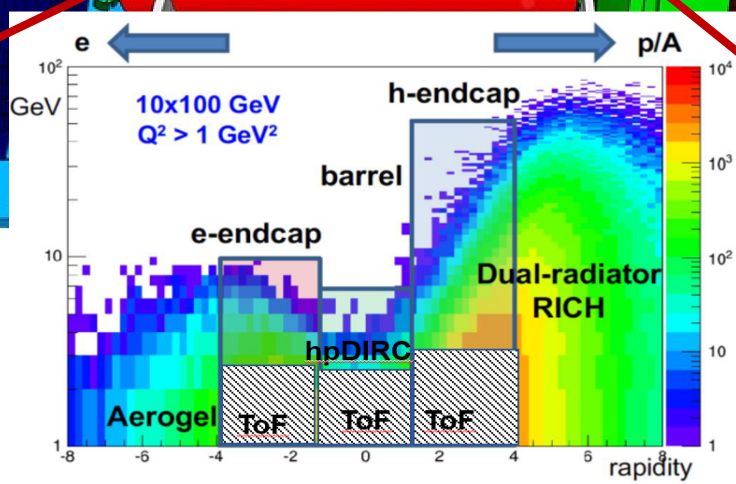
Single volume proximity focusing aerogel RICH with long proximity gap (~30-40 cm)
- **Sensor: HRPPDs → includeTOF**



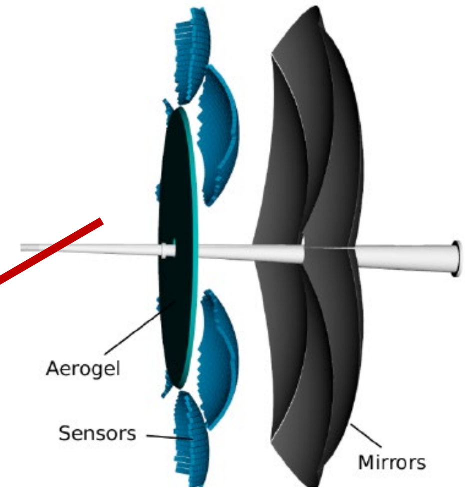
High-Performance DIRC





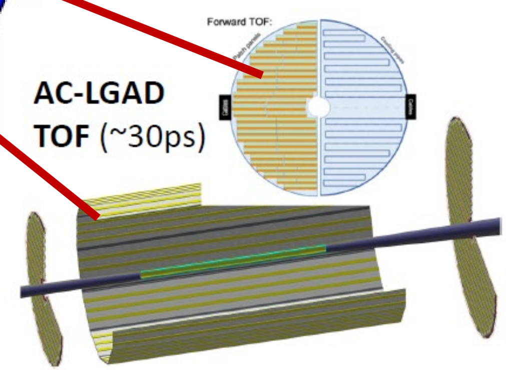


Dual-Radiator RICH (dRICH)

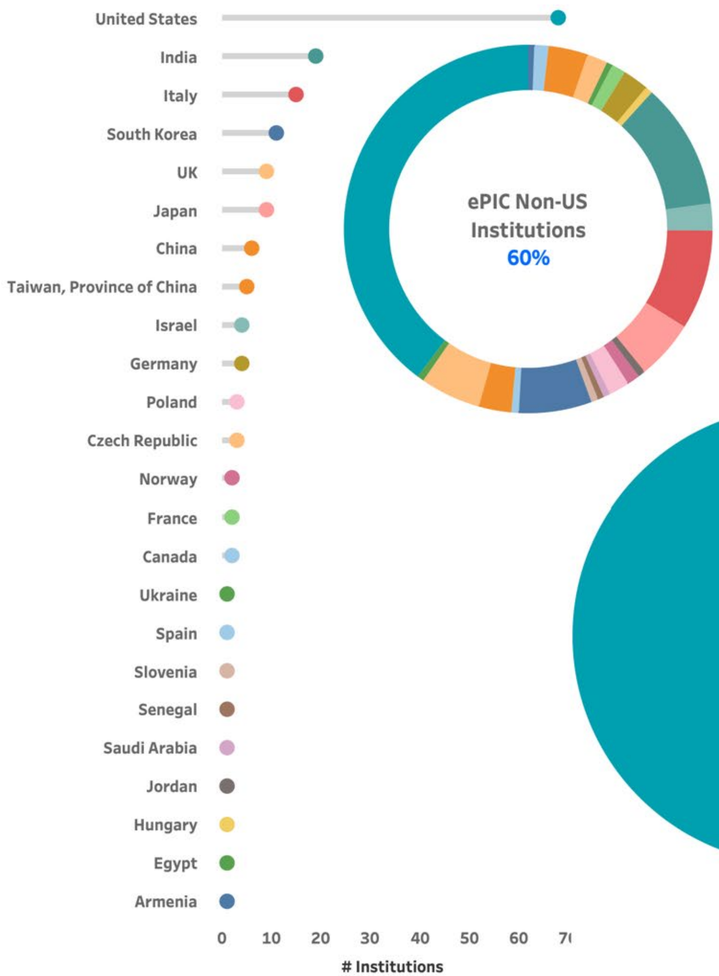


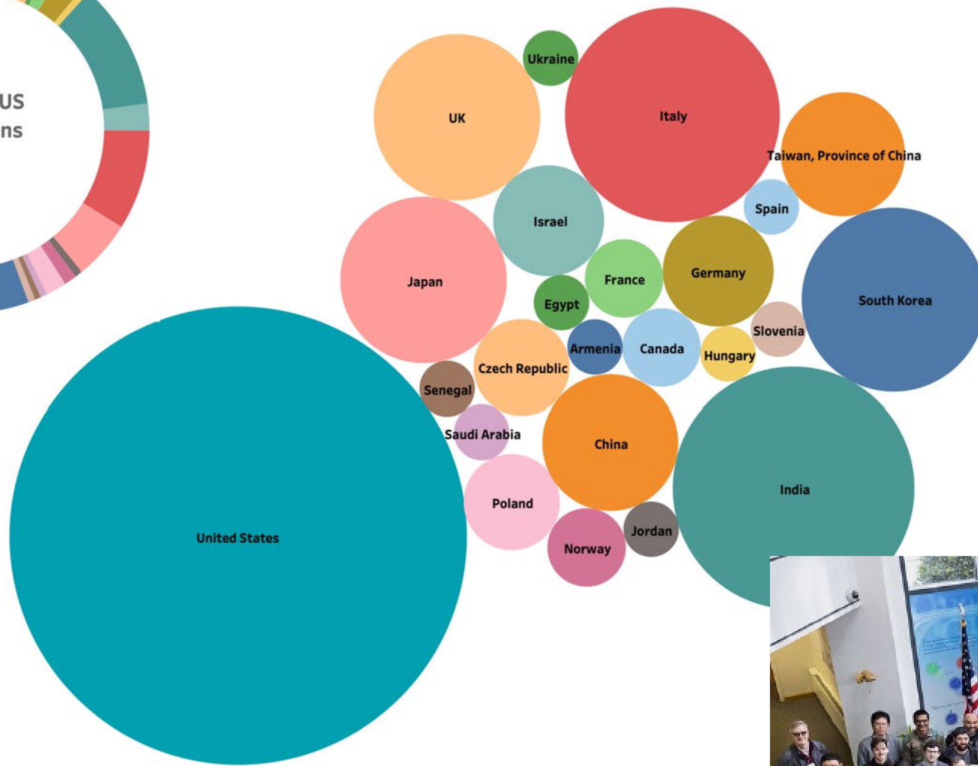
Single photon sensors: SiPMs

AC-LGAD TOF (~30ps)



The ePIC Collaboration





171 institutions and increasing
24 countries

500+ participants
A truly global pursuit for a new experiment at the EIC!

CONCLUDING REMARKS

The EIC is a unique project, the only concrete one around the world for the ultimate understanding of QCD

The only novel collider in the next 20-30 years

- **The EIC project is approved and progressing according to schedule**

- **The ePIC Collaboration for the project detector effort has kicked-off**

  ePIC is designing the detector for the TDR (CD2&3)

  EIC detector is an enormous undertaking that will require participation and expertise from both the US (Labs and academia) communities, as well as the international contributions (60% of Institutions from abroad world-wide) !

  - In parallel, the new Collaboration has been formed and structured

  - ***It is NOW the right time to join the effort and get involved !***
  - ***Have exciting perspectives with us designing, building, producing science within ePIC***