

# *The **E**lectron-**I**on **C**ollider (EIC)*

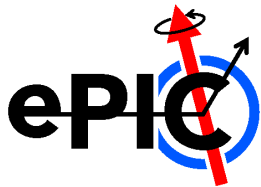
## *and the **ePIC** experiment*



**S. Dalla Torre**  
**INFN - TRIESTE**

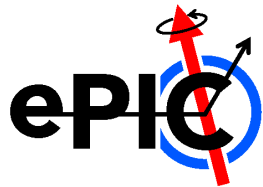
# EIC continuously present at MENU2023 !

- **Constantia Alexandrou, Nucleon Structure from Lattice QCD**
  - **Salvatore Fazio, Multidimensional partonic imaging at the future Electron-Ion Collider**
  - **Anselm Vossen, Perspectives of SIDIS measurements**
  - **Barbara Pasquini, Exploring the hadron structure with GPDs and TMDs**
  - **Jianwei Qiu, Electron-Ion Collider - A Giant CT Scanner for Nucleons and Nuclei**
- ... and also, indirectly, in many reports about experimental and theoretical studies providing the scientific frame for the physics at EIC and complementary approaches**



- **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

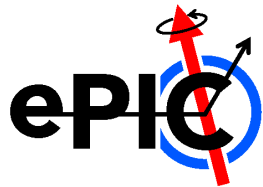
JANUARY 9, 2020

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

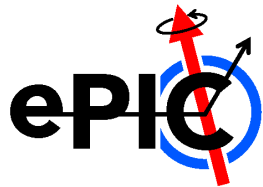
U.S. Department of Energy

**EIC is an approved project !**

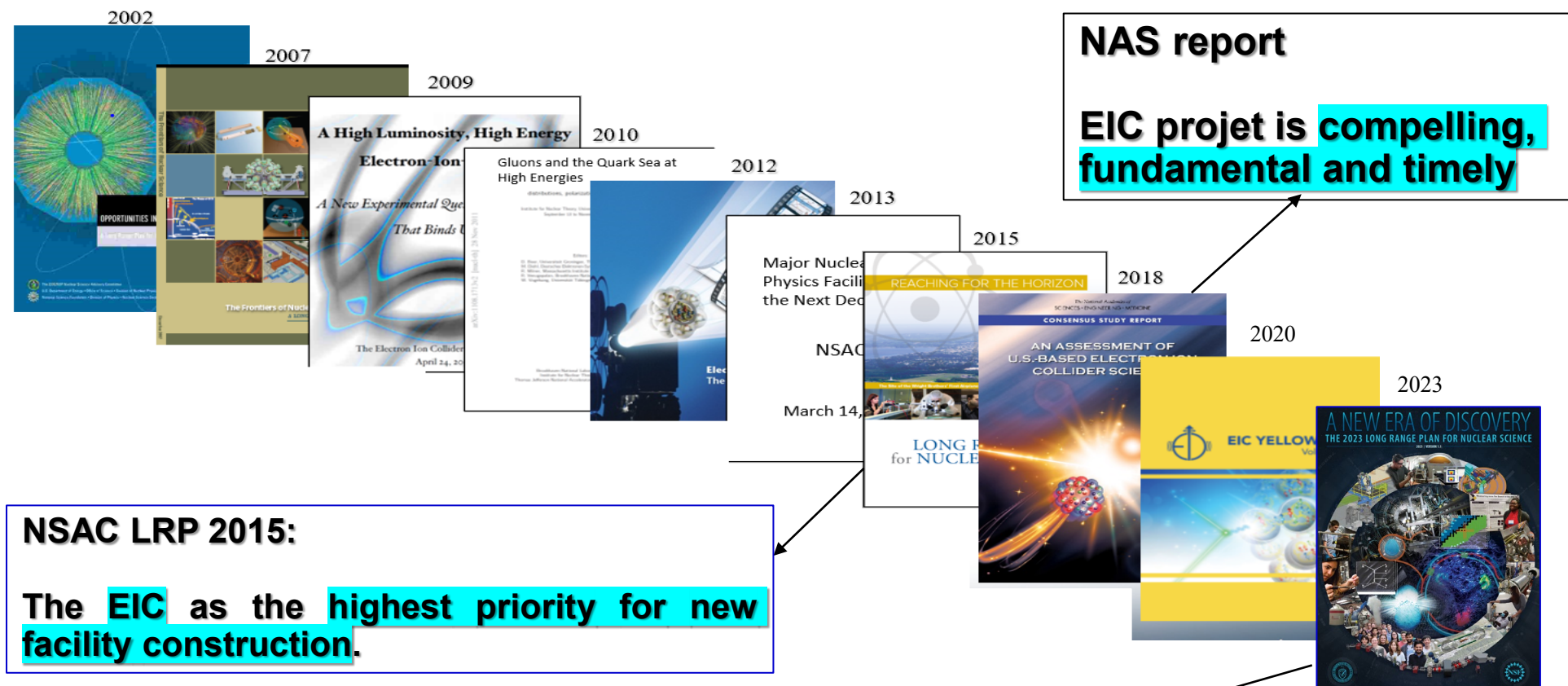
**Most likely,  
the only novel collider  
in the next coming 20-30 years**

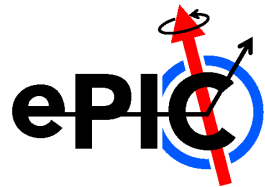
...on need," for the EIC on December

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



# THE PATH TO THE EIC PROJECT





# THE INTERNATIONAL COMMUNITY

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

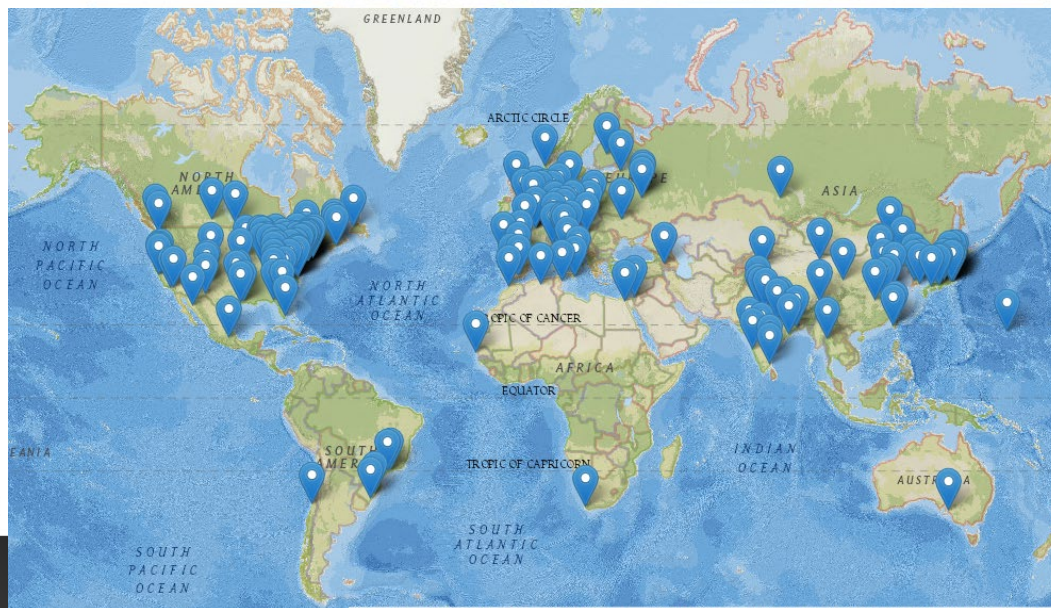
Formed 2016 –

- 1422 members
- 38 countries
- 291 institutions

As of October 15, 2023

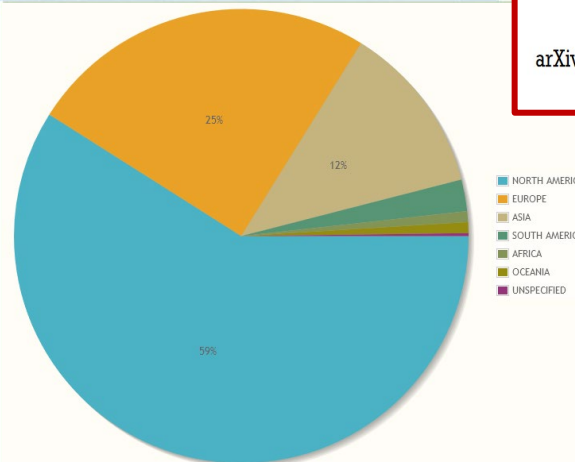
**Strong and Growing  
International Participation.**

EICUG membership @  
time of EICUG Meetings



## 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



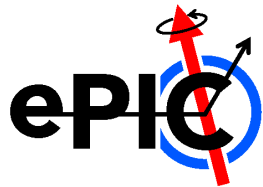
Among the main  
Achievements:  
**The Yellow Report**



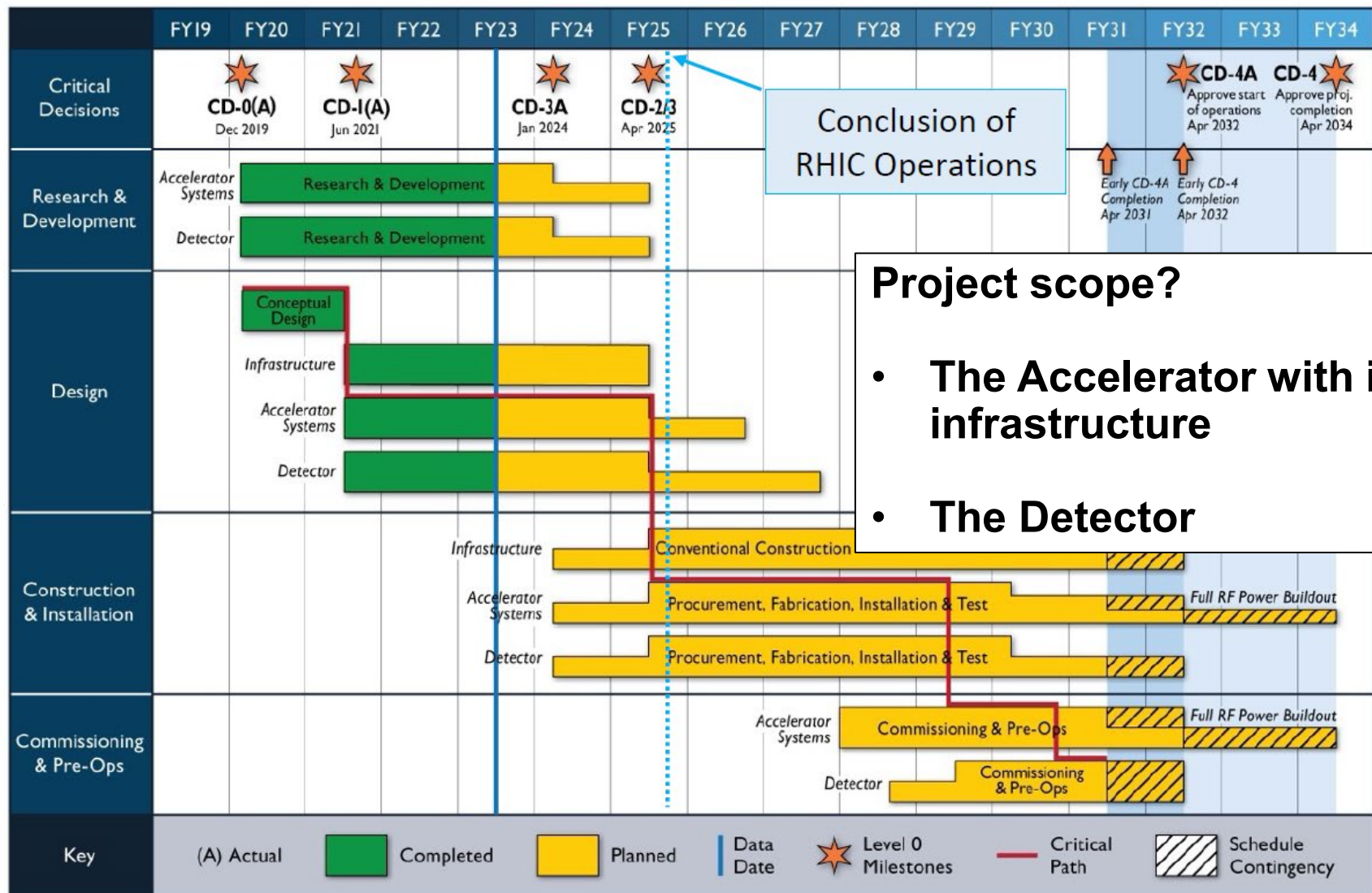
arXiv:2103.05419

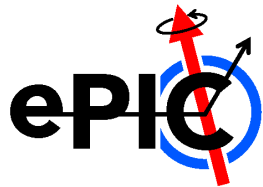
**Nucl. Phys. A 1026  
(2022) 122447**



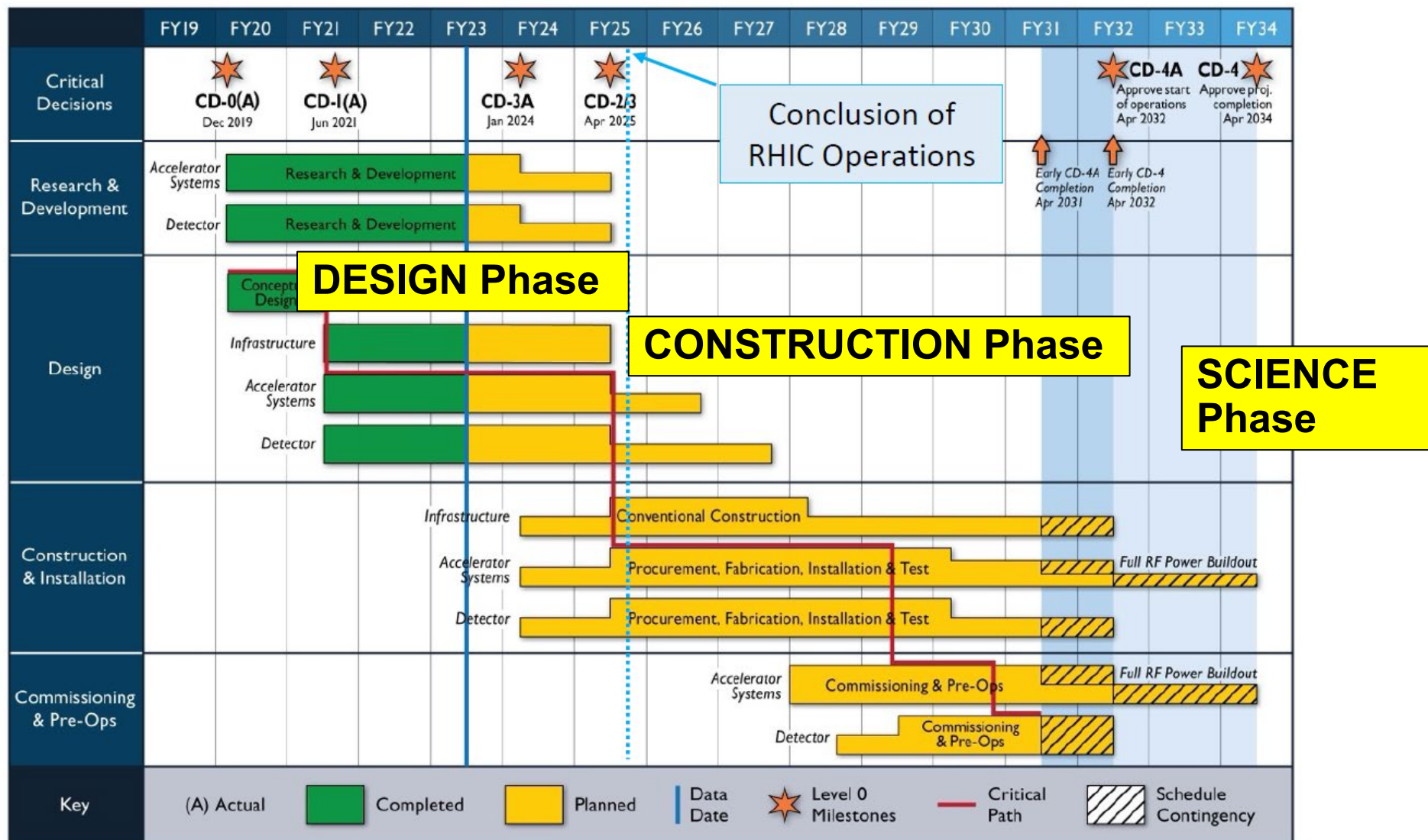


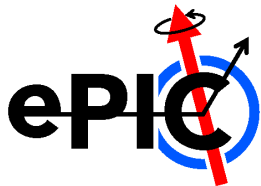
# The EIC schedule





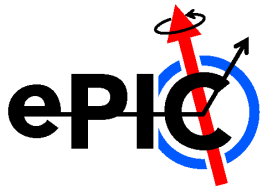
# The EIC schedule





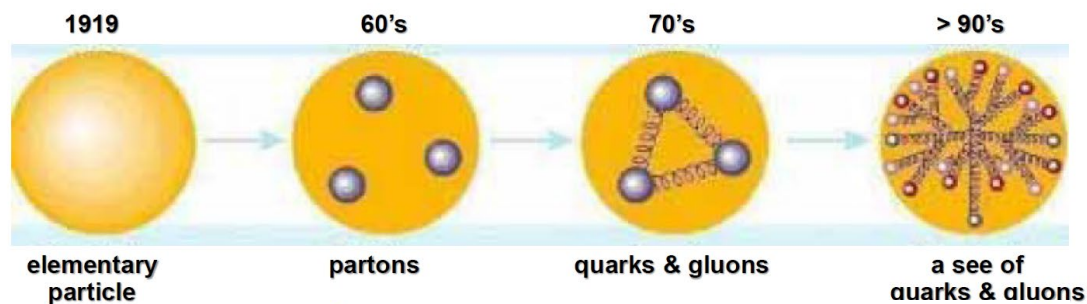
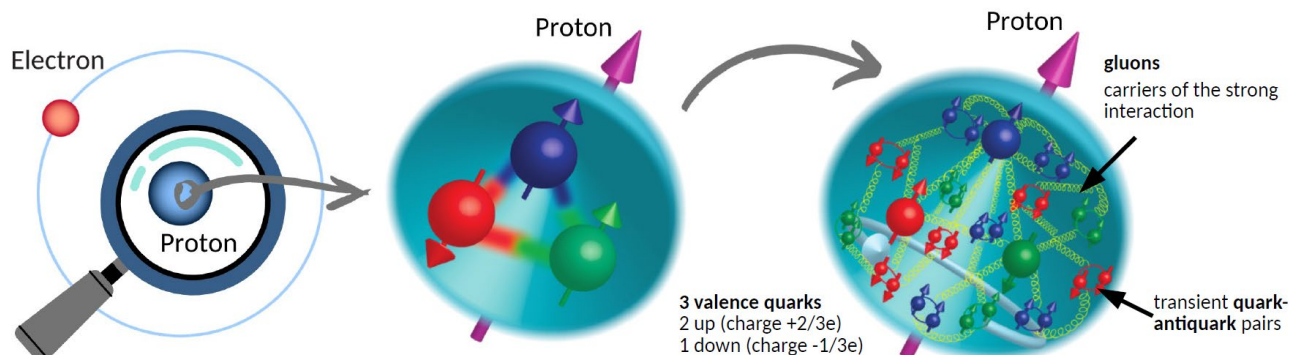
- **The EIC project**
- **The EIC scientific scope**
- **The Collider**
- **ePIC – The project detector**



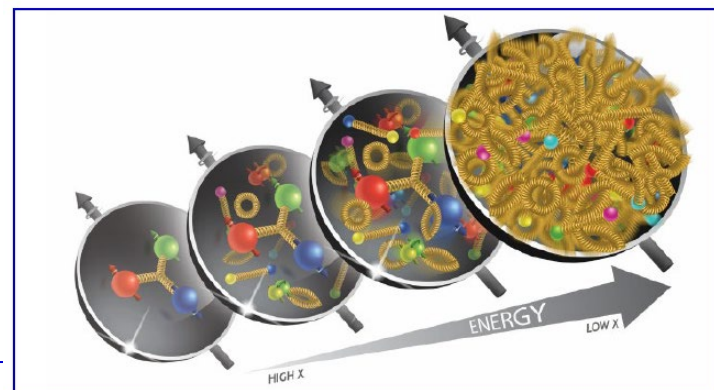


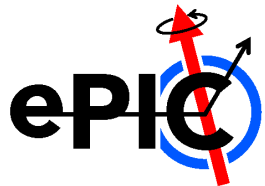
# THE SCIENTIFIC SCOPE

## 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



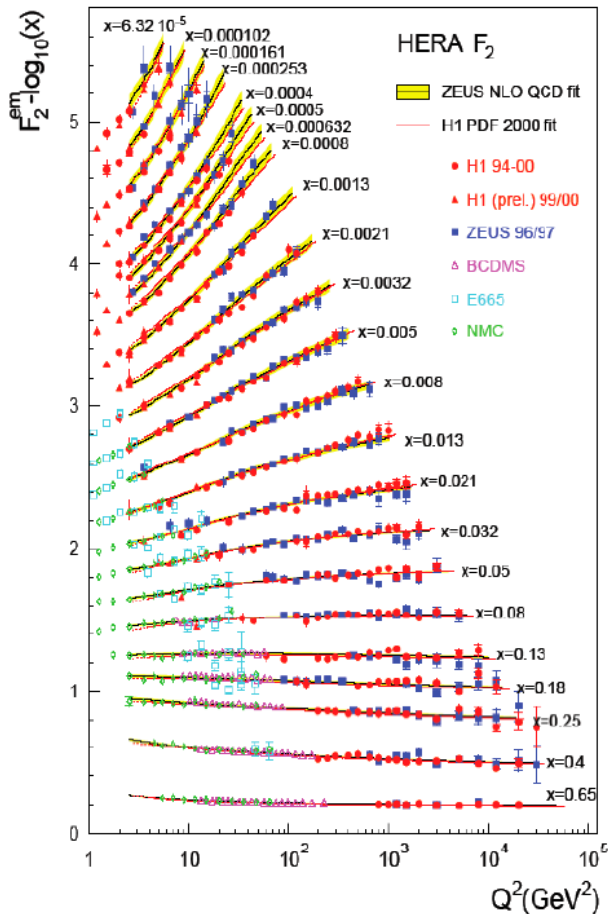


## Open questions in QCD and nuclear matter

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

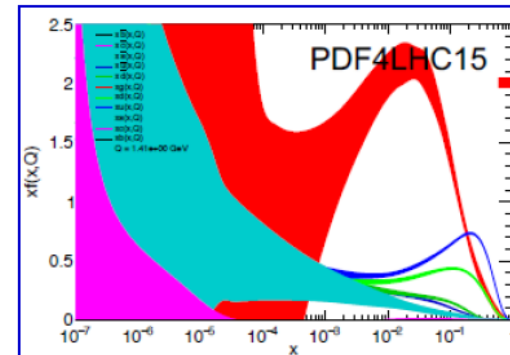
- How do the **properties of the proton** such as **mass** and **spin** emerge from the sea of quarks, gluons, and their underlying interactions?
- What is the **configuration and motion** of quarks and gluons located within the nucleon?
- What happens to the **gluon density** in nucleons and nuclei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

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



Nevertheless,  
specific kinematic regions not deeply explored

Quark distribution  
functions  
poorly  
known at  
very small  $x$



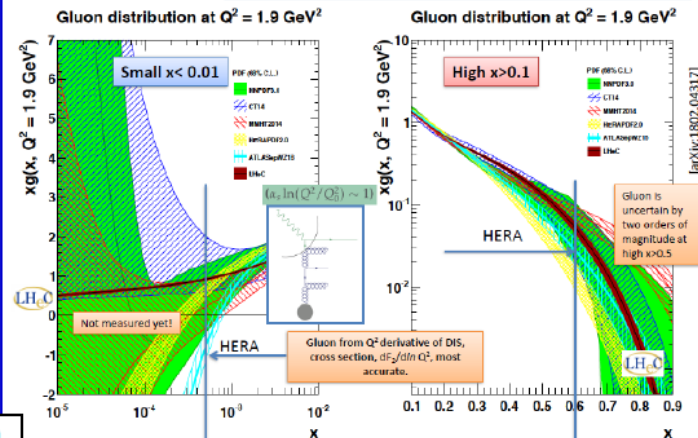
Gluon distribution  
Functions need  
further  
exploration at  
small and large  $x$

### Understanding the Gluon

Hera's ep legacy and limitation

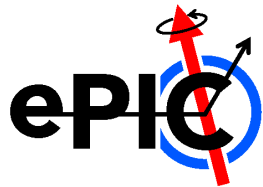
DGLAP approach

Low and high  $x$  parton distributions are intertwined by momentum sum rules!



C. Gwenlan, DIS2019





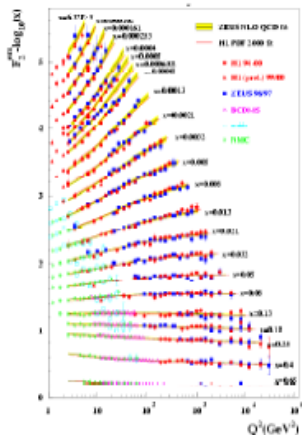
# THE SCIENTIFIC SCOPE

## TMDs and SPIN

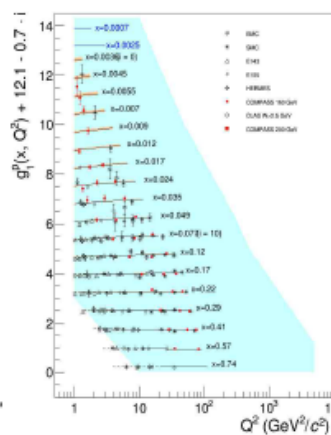
### The 8 leading-twist quark TMD PDF

#### TMD - Transverse-Momentum-Dependent

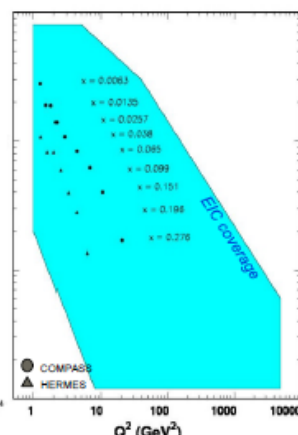
$N/q$	$U$	$L$	$T$
$U$	$f_1$		$h_1^\perp$
$L$		$g_1$	$h_{1L}^\perp$
$T$	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1$ $h_{1T}^\perp$



momentum



spin

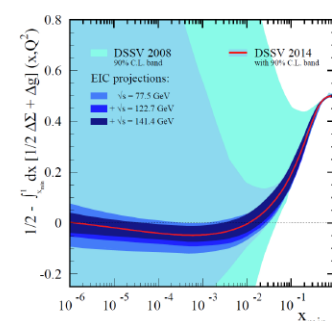
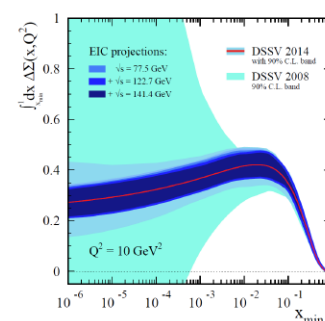
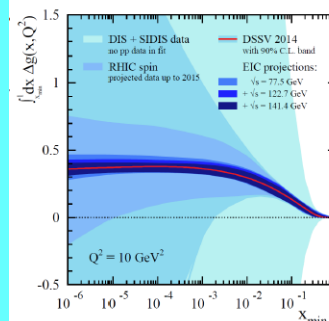


transverse  
spin ~ angular  
momentum

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

What do we know:

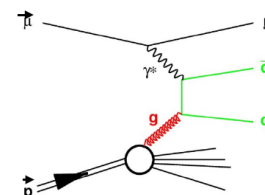
$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} \middle| J_{QCD}^z \middle| P, \frac{1}{2} \right\rangle = \frac{1}{2} \int_0^1 dx \Delta \Sigma(x, Q^2) + \frac{1}{2} \int_0^1 dx \Delta G(x, Q^2) + \frac{1}{2} \int_0^1 dx \left( \sum_q L_q^z + L_g^z \right)$$



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

- Gluon contribution needs a deeper exploration

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



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

of course, by a SI-DIS measurement

- Orbital momentum to be extracted from TMDs

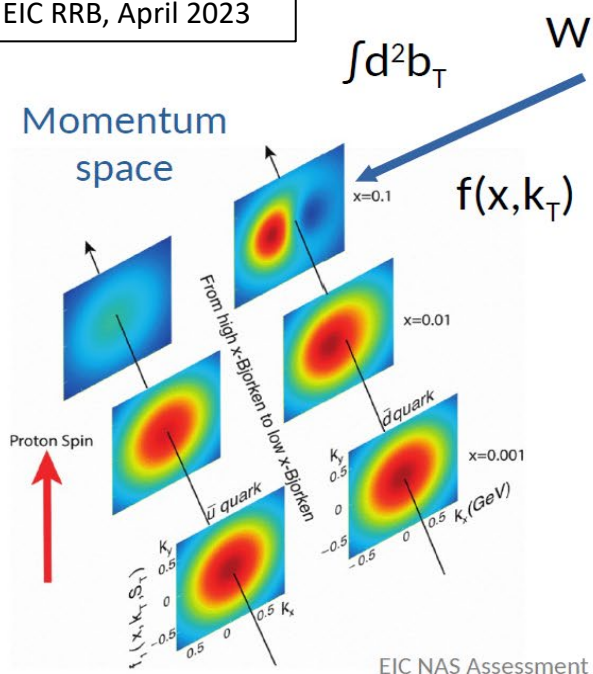
A. Bressan, "Prospettive per fisica adronica e collisionatori adronici"



# THE SCIENTIFIC SCOPE

## Spatial and Momentum structure of the N in 3D

Maria Żurek, EIC RRB, April 2023

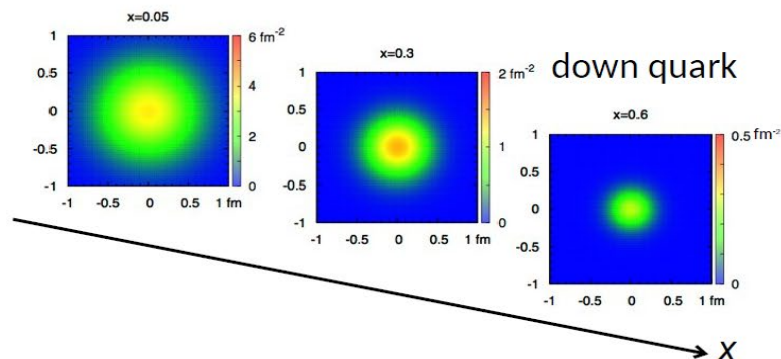


### MOMENTUM SPACE

Access to spin-orbit correlation (TMDs) via SIDIS

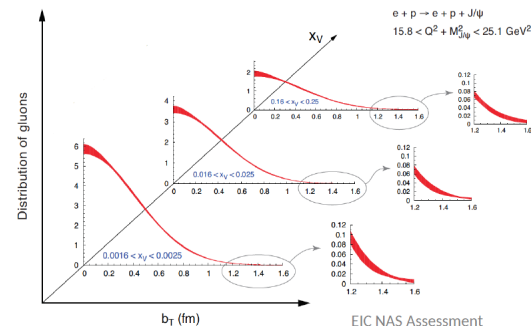
### COORDINATE SPACE

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



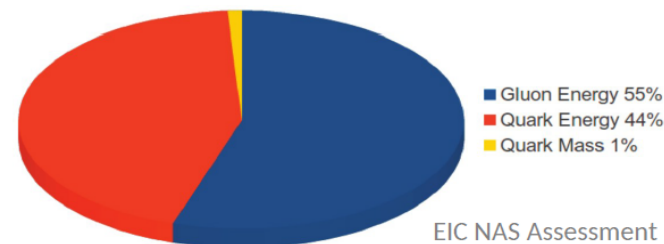


# THE SCIENTIFIC SCOPE

## HOW DO NUCLEONS ACQUIRE MASS ?

- **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 from quark-gluon interactions**

Contributions to the total mass of the nucleon



**Proton** (valence content  $uud$ ) - mass  $\sim 940$  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”  $\rightarrow$  accessible in exclusive reactions

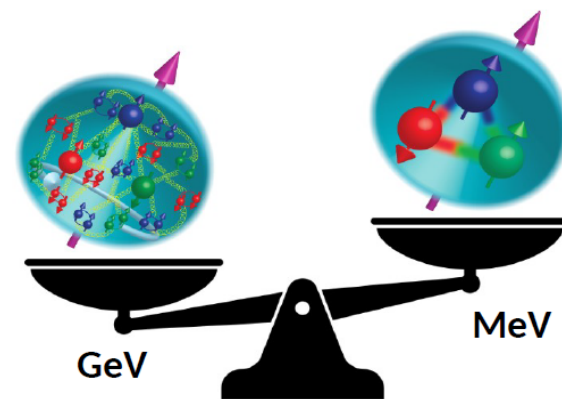
What about the mass of light mesons?

**Pions** (valence content  $ud$ ) mass  $\sim 140$  MeV

- Cleanest expression of the emergent mechanism
- Empty or full of gluons?

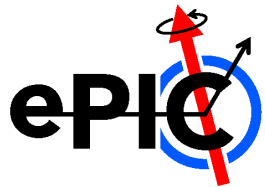
**Kaons** (valence content  $us$  – strange content!) mass  $\sim 490$  MeV

- Probing boundary between emergent and Higgs-mass mechanisms
- More or less gluons than in pion?



Maria Žurek, EIC RRB, April 2023



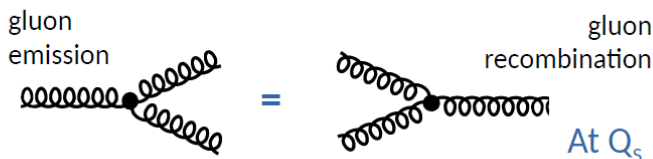


# THE SCIENTIFIC SCOPE

## 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**

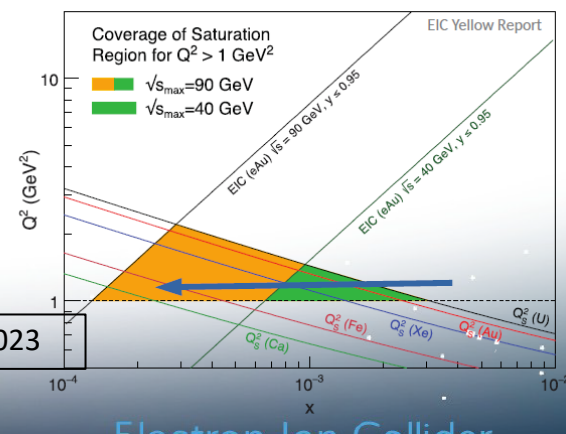
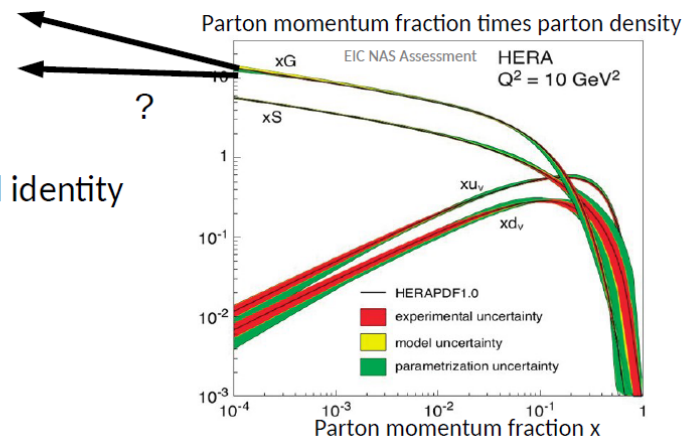
EIC provides a unique opportunity to have very high gluon densities

**electron - heavy nuclei (e.g., Pb) collisions**

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

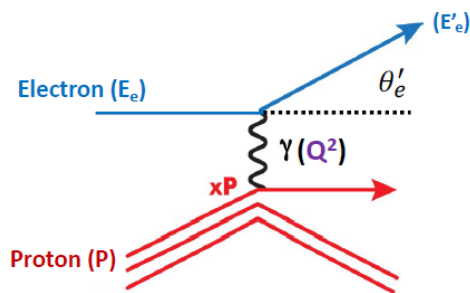
**EIC will allow to unambiguously map the transition from a non-saturated to saturated regime**

Maria Žurek, EIC RRB, April 2023



## How to address the many challenging open questions ?

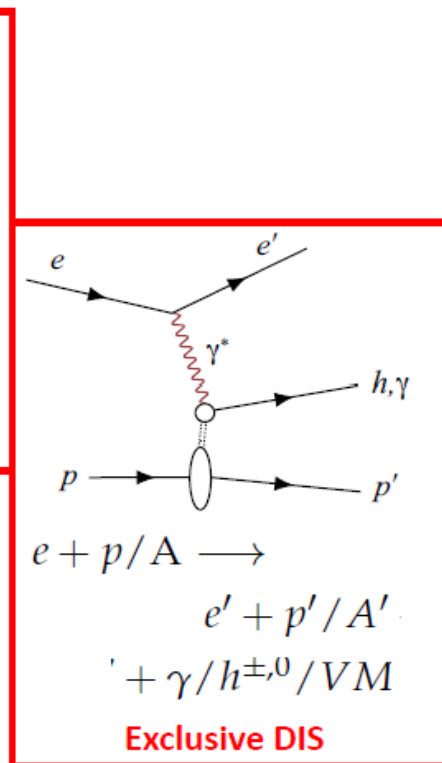
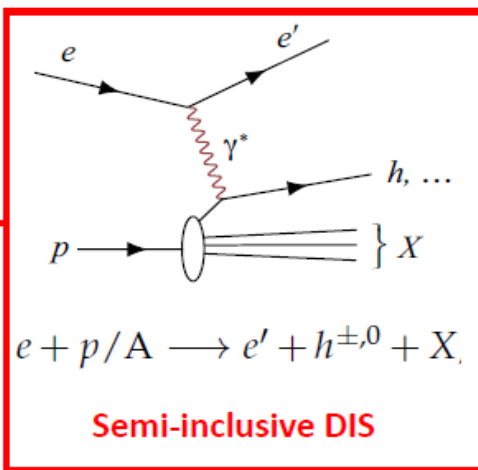
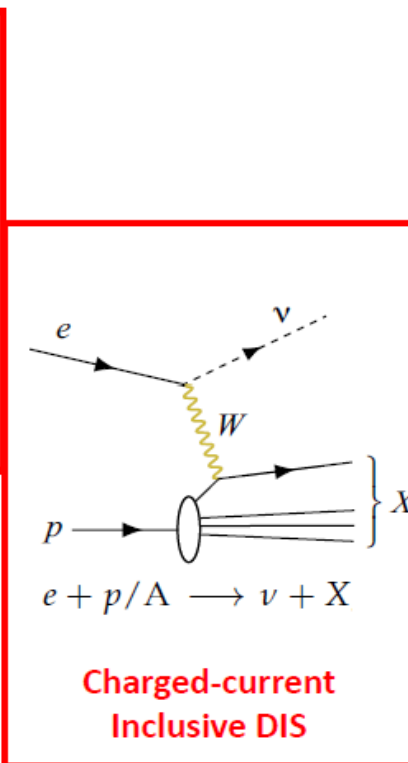
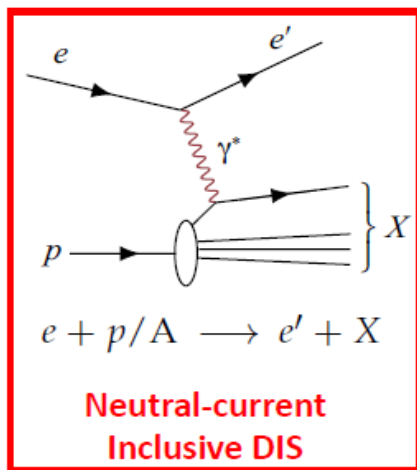
**DIS**

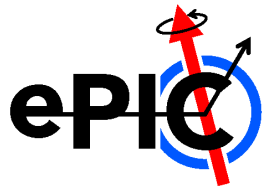


$$Q^2 = 2E_e E'_e (1 - \cos \theta'_e)$$

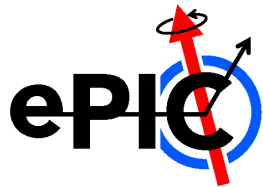
$$x = \frac{Q^2}{2pq}$$

Measure of momentum fraction of struck parton



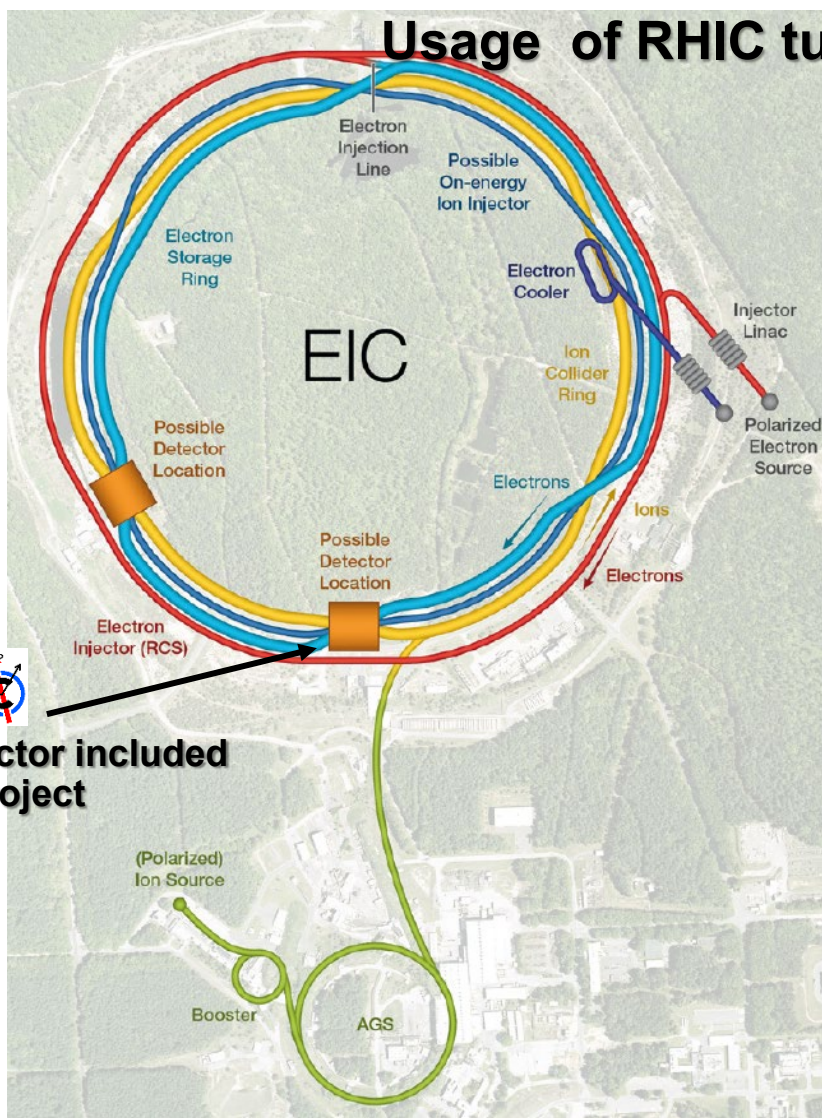


- **The EIC project**
- **The EIC scientific scope**
- **The Collider**
- **ePIC – The project detector**

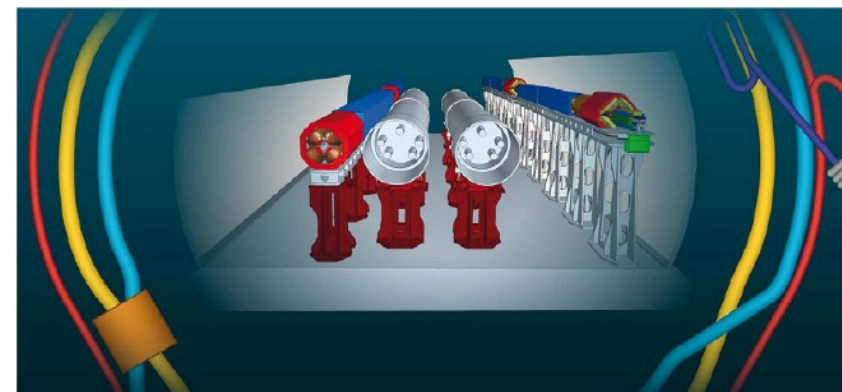


# The EIC Collider

## Usage of RHIC tunnel and RHIC p/ion complex

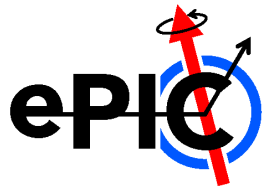


**IP6 detector included in the project**



- spanning a wide kinematical range
  - **ECM: 20 – 141 GeV**
- High luminosity
  - up to  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- **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**





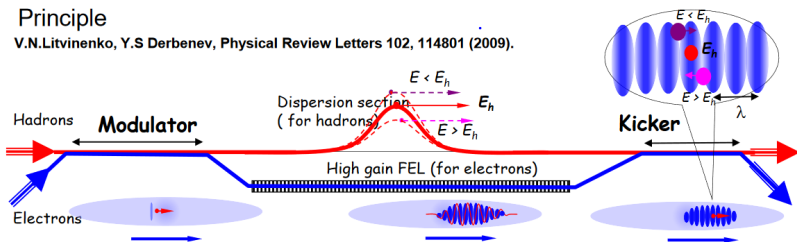
# The EIC Collider

## 3 critical ingredients for HIGH LUMINOSITY

### Coherent Cooling with FEL amplifier

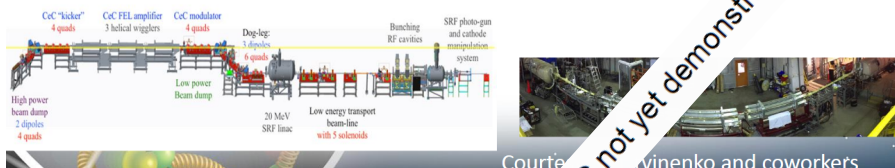
#### Principle

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

## CRAB CROSSING ANGLE (25 mrad)

For the first time a sizable crab crossing angle

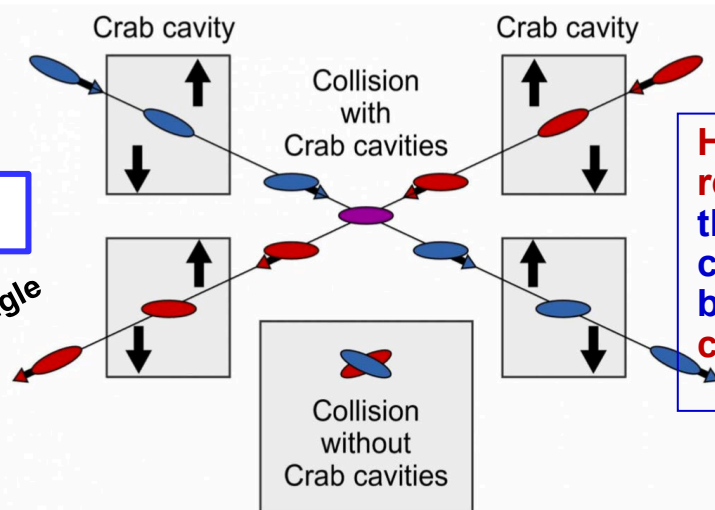
### Bunches and beam crossing rates

Species	<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>
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	<i>e</i>	Au	<i>e</i>	Au	<i>e</i>	Au	<i>e</i>
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 !





# The EIC Collider

**MORE unique aspects**

**BEAM POLARIZATION**

## ION SPECIES

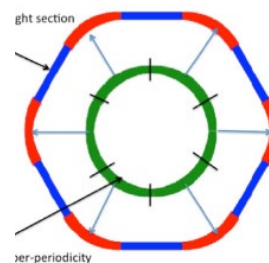
The existing RHIC ion sources & ion acceleration chain provides already **today** all ions needed at EIC

Enormous versatility!  
is a unique capability!

### 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)

## 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:

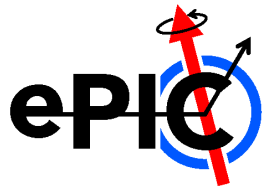
**AGS:** Stronger snake, skew quadrupoles, increased injection energy

→ expect 80% at extraction of AGS

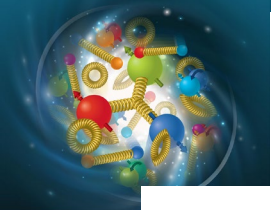
**RHIC:** Add 2 snakes to 4 existing no polarization loss

→ expect 80% in Polarization in RHIC and eRHIC

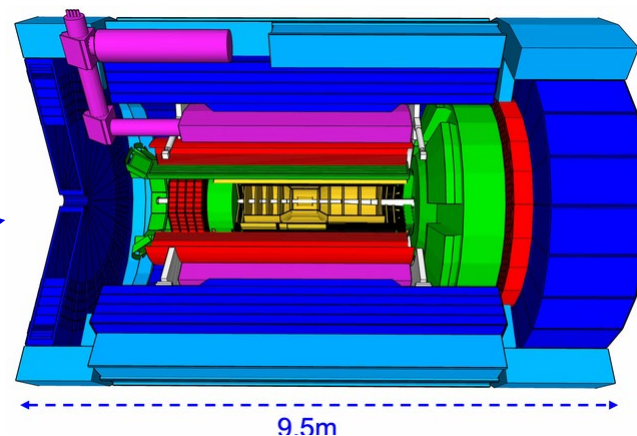
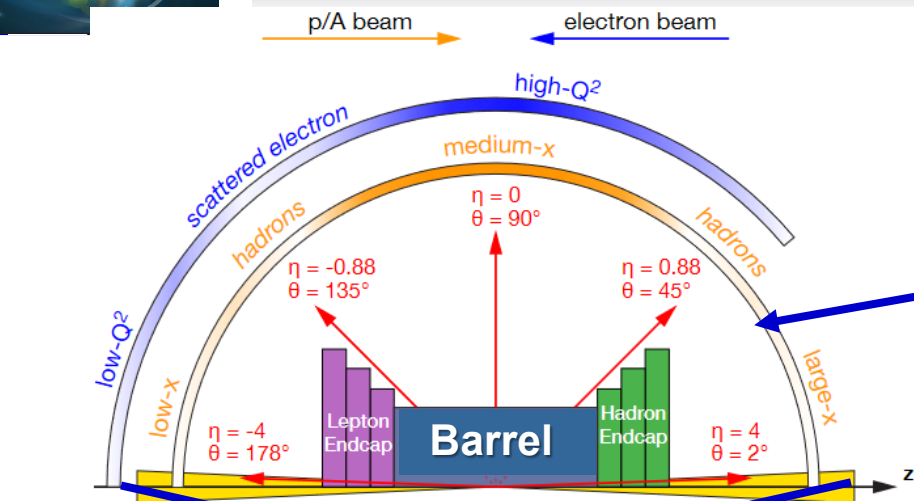
High polarization  $^3\text{He}$  and D beams also possible



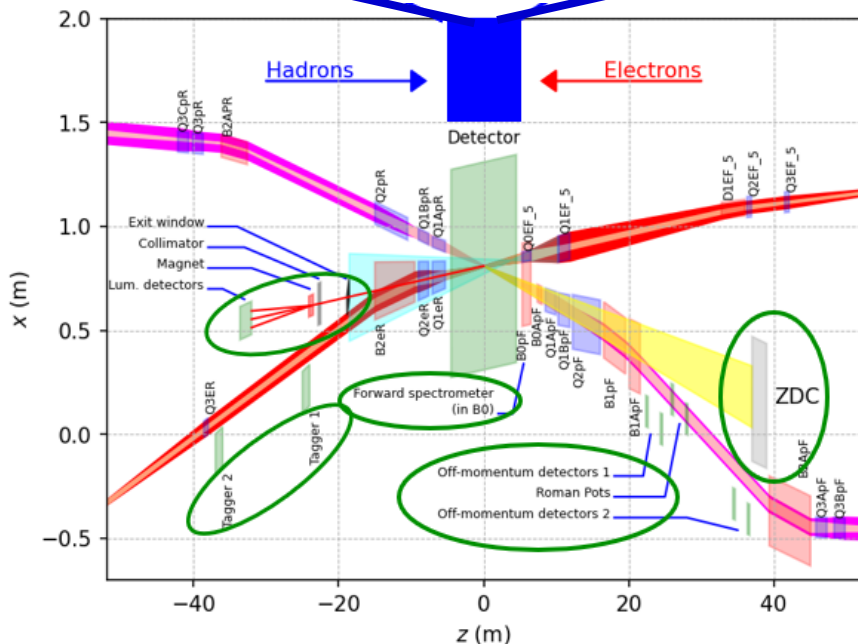
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# THE COMPLETE ePIC DETECTOR



**Central Detector (CD)**



Total size detector: ~75m

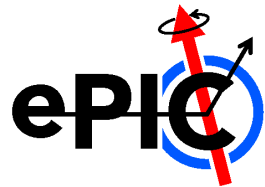
Central detector: ~10m

Backward electron detection: ~35m

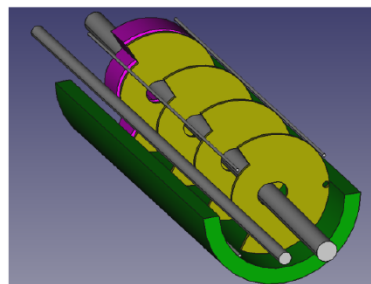
Forward hadron spectrometer: ~40m

**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



Roman Pots

ZDC

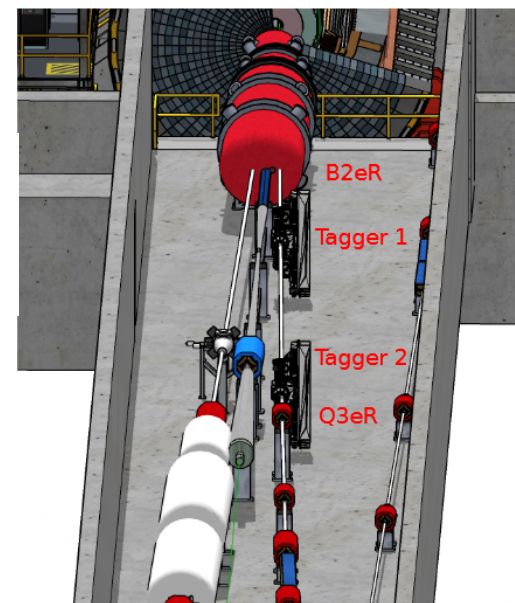


Off Momentum

Hadron Beam after IP

**Far Forward**

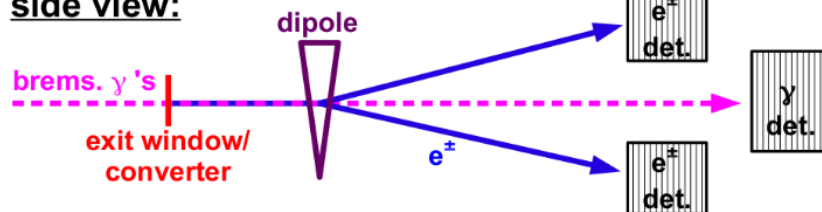
Figure: Low- $Q^2$  taggers

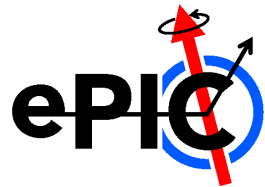


**Far Backward**

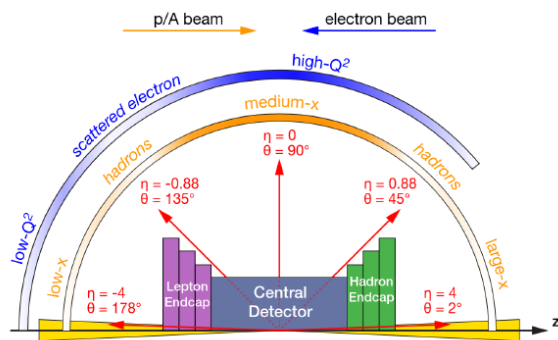
Figure: Luminosity detector

side view:





# ePIC Central Detector



Formed by:

- Backward endcap
- Barrel
- Forward endcap

hadronic calorimeters

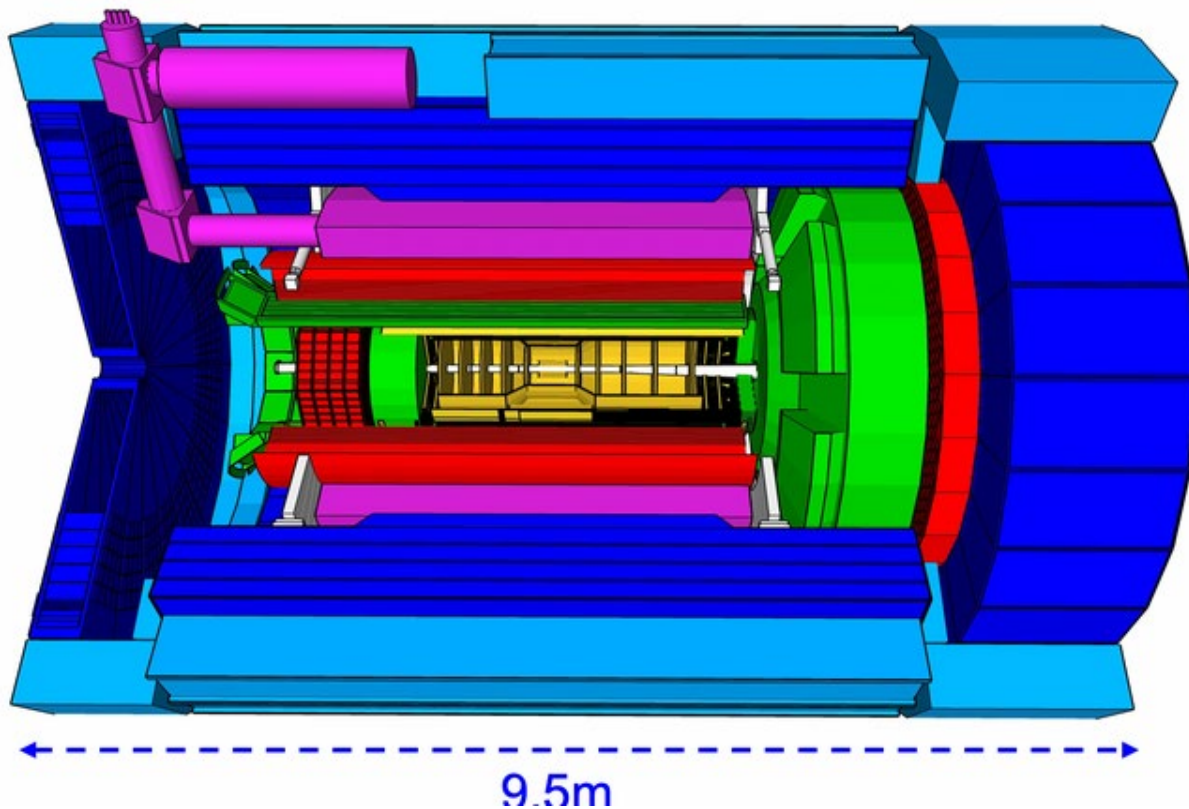
Solenoidal Magnet

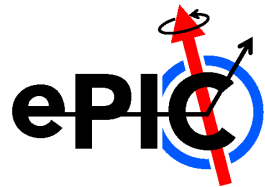
e/m calorimeters  
(ECal)

Time of Flight,  
DIRC,  
RICH detectors

MPGD trackers

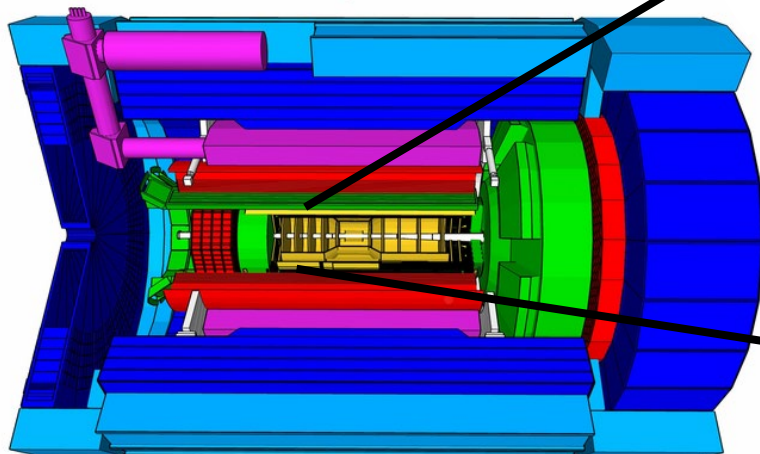
MAPS tracker





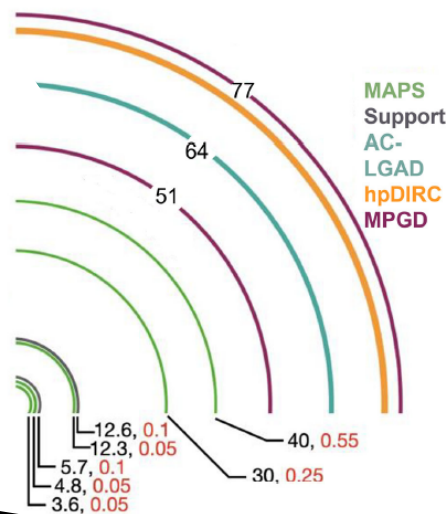
# TRACKING IN ePIC CD

## Tracking



Black numbers  
are radii in cm

Red numbers  
are material in  
% X<sub>0</sub>

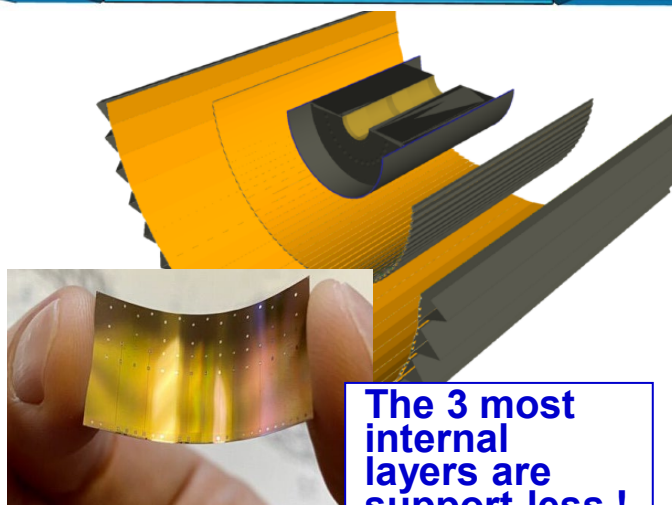


Si trackers based on ALICE ITS3 **65 nm MAPS sensors**

- Five layers in the barrel and in the endcaps

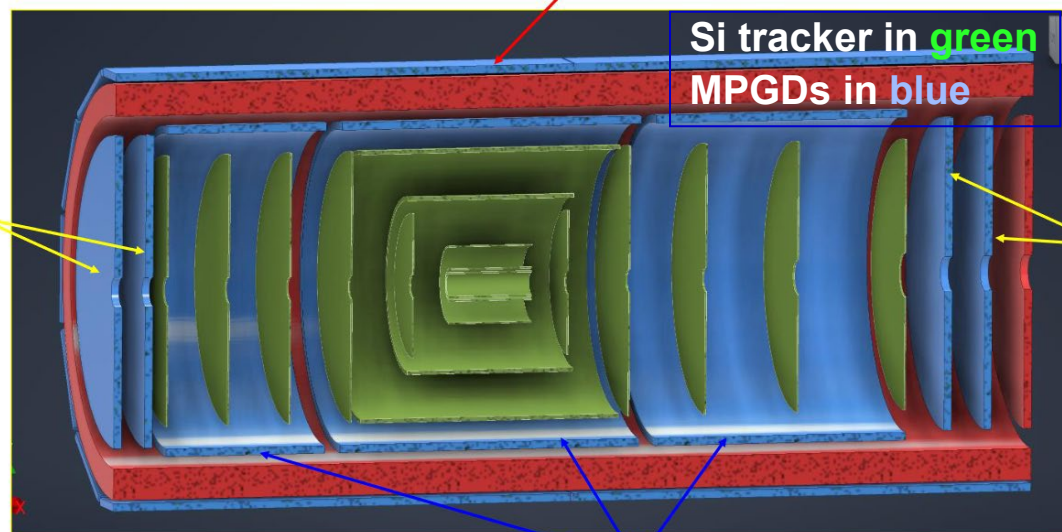
Supplemented by MPGD trackers

- Cylindrical MICROMEGAS
- Planar  $\mu$ R-WELL



The 3 most  
internal  
layers are  
support-less !

Backward  $\mu$ RWELL Disks



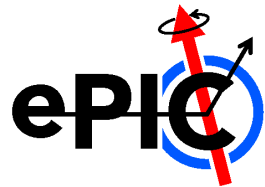
Barrel Outer  $\mu$ RWELL Layer

Si tracker in **green**  
MPGDs in **blue**

Forward  $\mu$ RWELL Disks

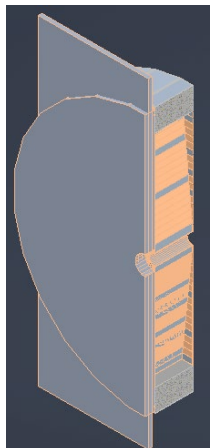
Inner Cyl Micromegas Barrel Layer CyMBaL



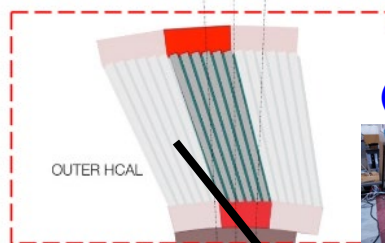


# CALORIMETRY IN ePIC CD

## SiPMs of all Calorimeters



**Backwards HCal  
Steel/Sc Sandwich  
tail catcher**

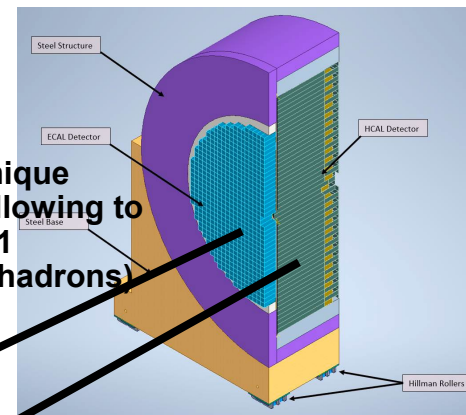


**Barrel Hcal  
(re-use from sPHENIX)**

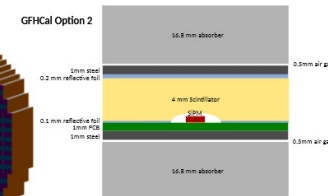
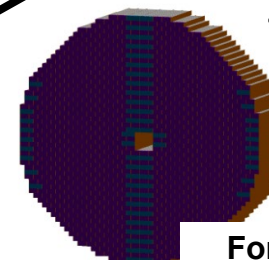
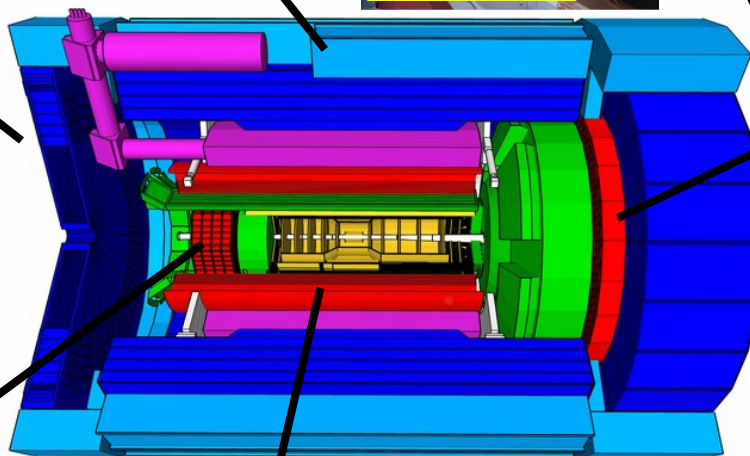
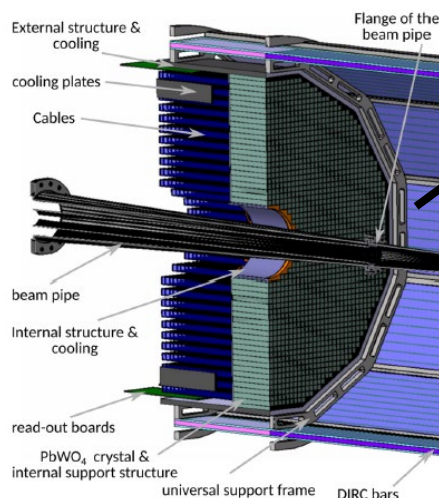


Fe/Sc sandwich,  $\sim 3.5 \lambda_0$

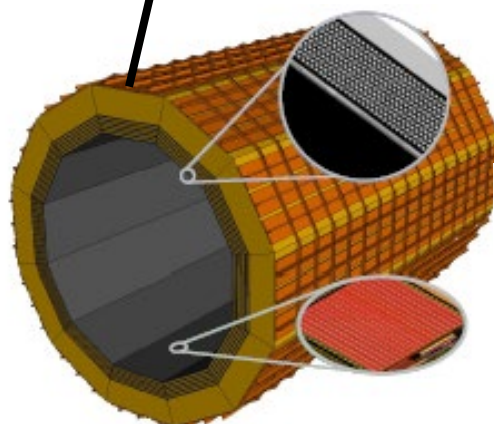
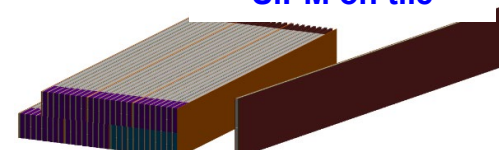
WScFi is a unique technology allowing to achieve  $e/h \sim 1$  (response to hadrons)



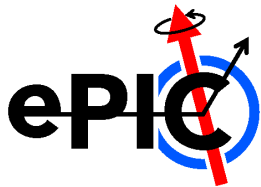
**Backwards EMCal  
PbWO<sub>4</sub> crystals**



**Forward Hcal:  
SiPM on tile**



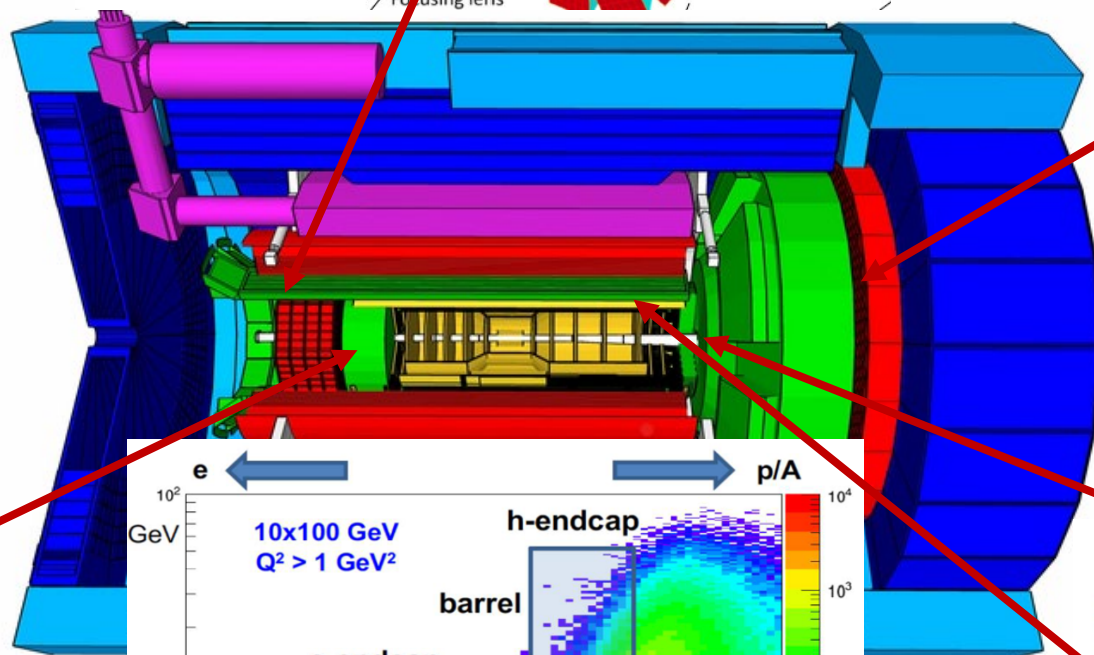
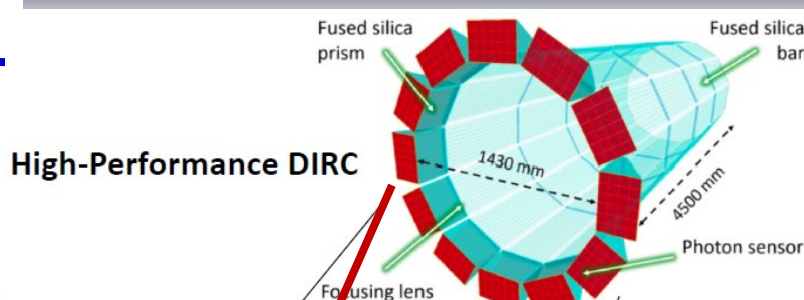
**4 (6) layers of imaging  
calorimetry by Astropix  
MAPS,  
and sampling  
calorimetry by Pb/SciFi**



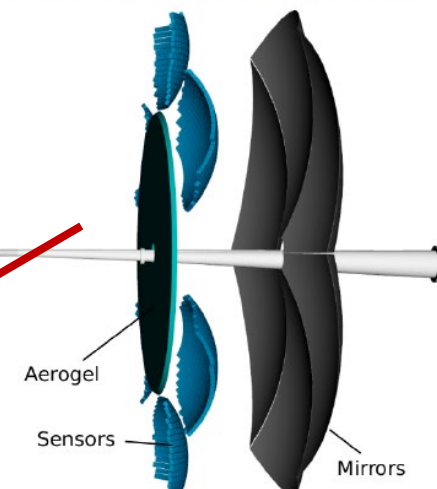
# PID IN ePIC CD

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

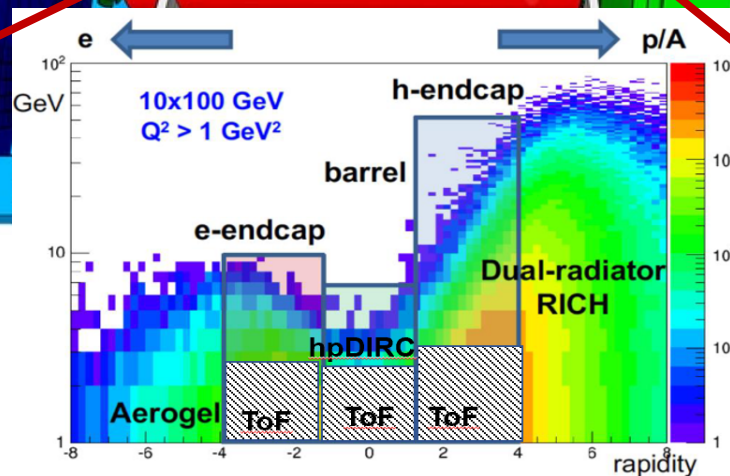
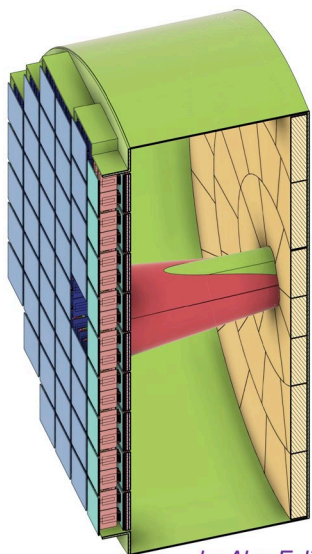
- Sensor:  
HRPPDs →  
include TOF



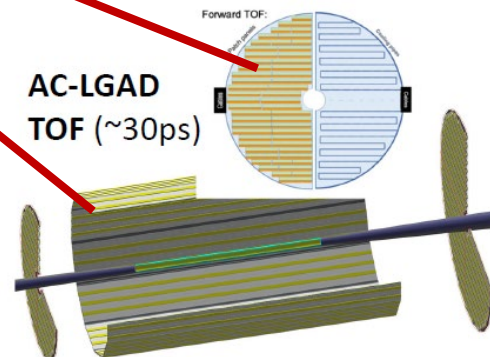
Dual-Radiator RICH (dRICH)



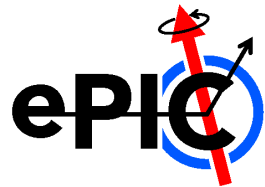
Single photon  
sensors: SiPMs



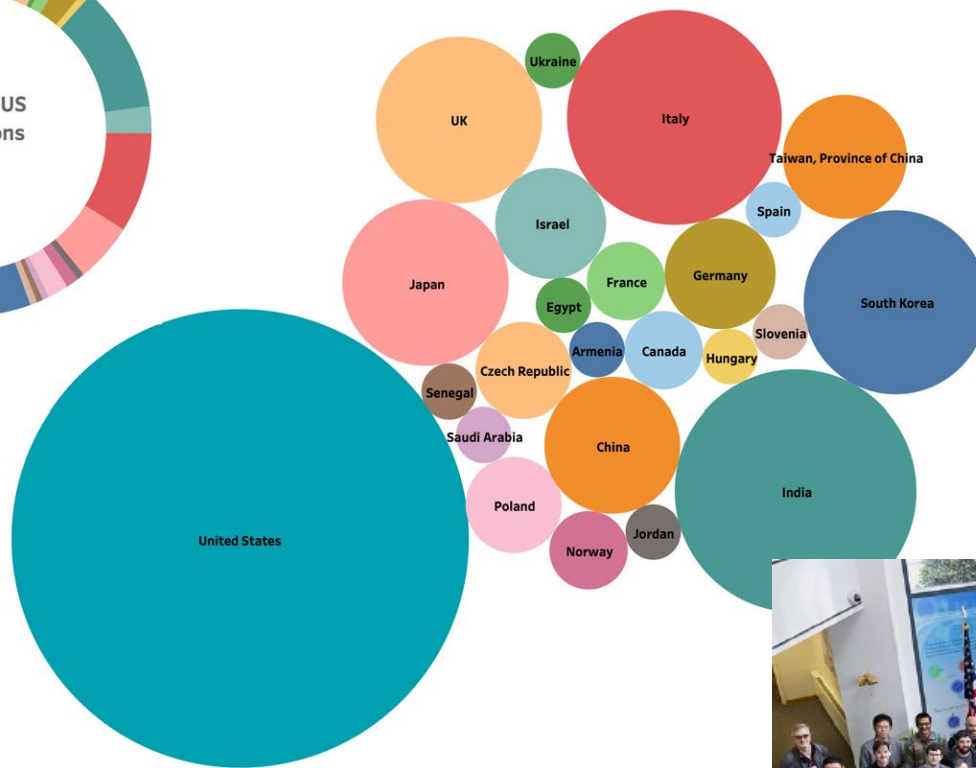
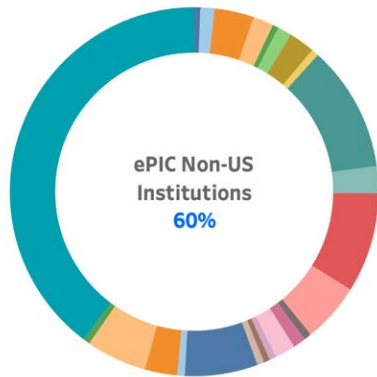
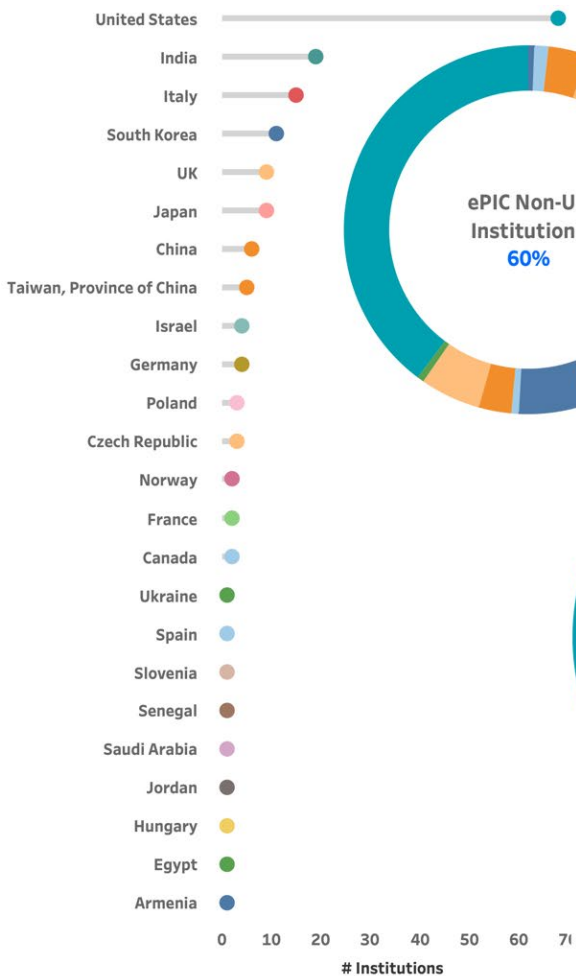
AC-LGAD  
TOF (~30ps)







# The ePIC Collaboration

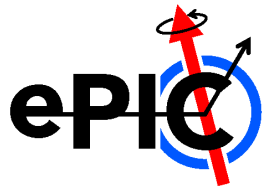


171 institutions and  
increasing  
24 countries

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 being 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*