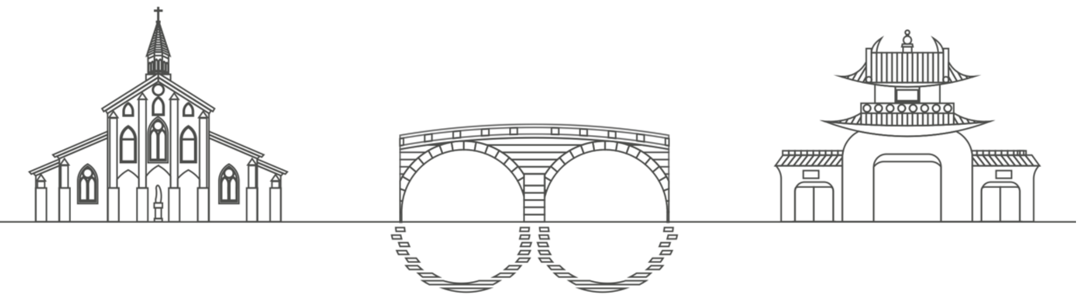
INFN
Istituto Nazionale di Fisica Nucleare

ePIC

HARD PROBES 2024

12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

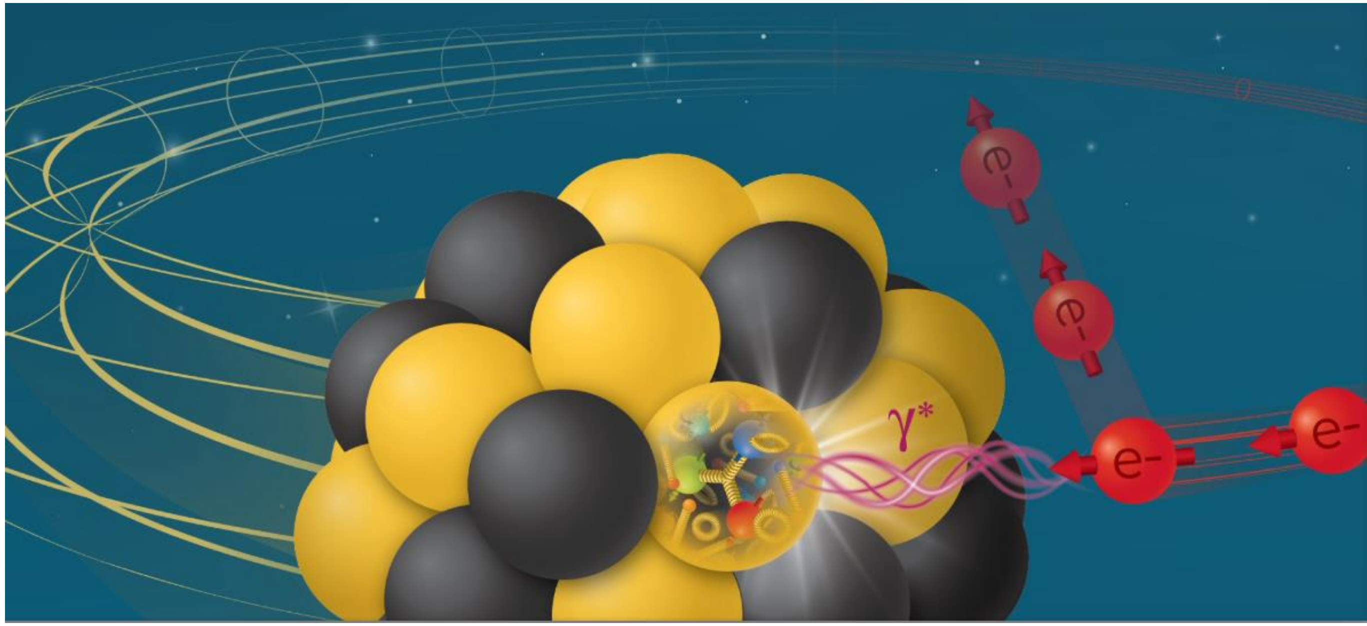
September 22-27, 2024, Nagasaki, Japan



Future facilities: Electron Ion Collider

P. Antonioli
INFN – Bologna
on behalf of the ePIC Collaboraton

Next  for QCD



Quarks as constituents of the hadrons at 60s this year...

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to 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-

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ 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

Quarks as constituents of the hadrons at 60s this year...

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Do we really understand **how** the quarks act as constituents of the hadrons?

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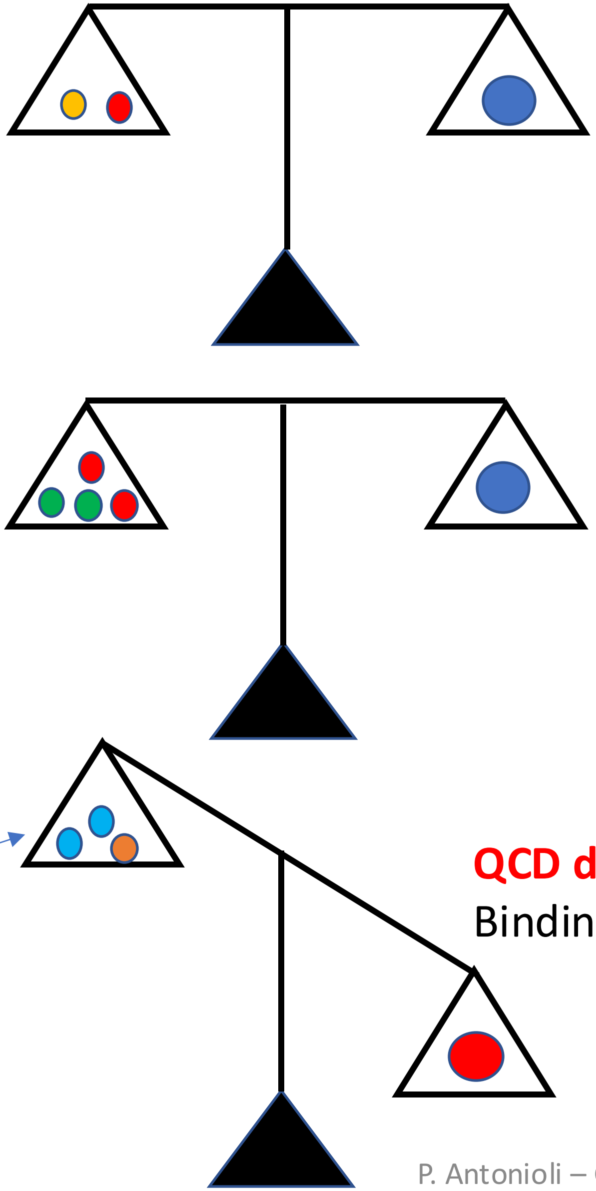
Why we still need microscopes for the nucleon?

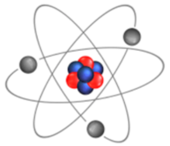
The way matter sums up in the nucleon is still quite a mistery!



Electron
Proton

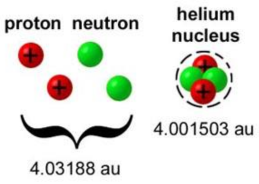
Hydrogen

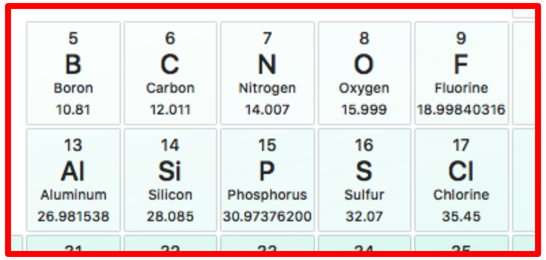
First ionization energy for the atoms iO(10 eV): is a tiny fraction of the atom mass



Proton
Neutron

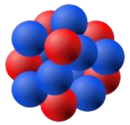
Helion





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

Binding mass is some percent of the nucleus mass



d quark
u quark

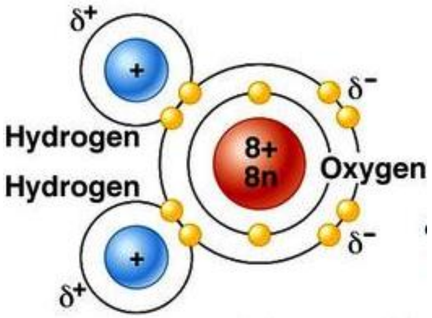
Higgs mechanism:
Mass ≈ 1.78×10^{-26} g

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

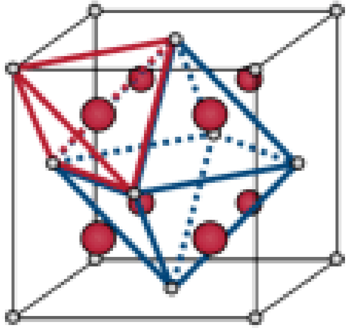
proton

Nuclear matter is indeed… different!

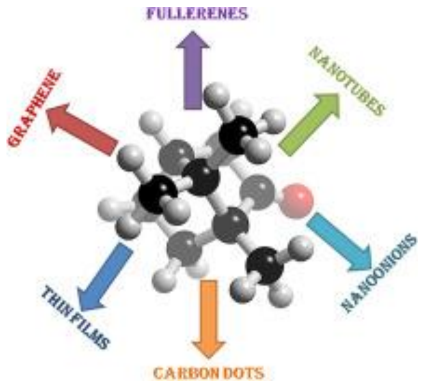
The usual matter has plenty of open space, localized mass and charge centers



Molecule



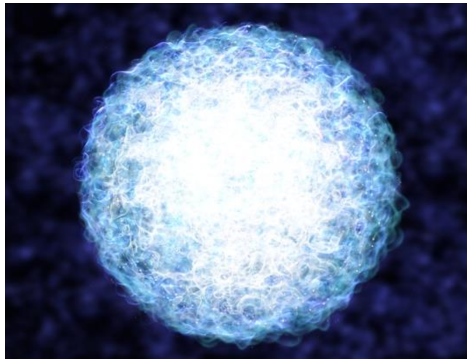
Crystal



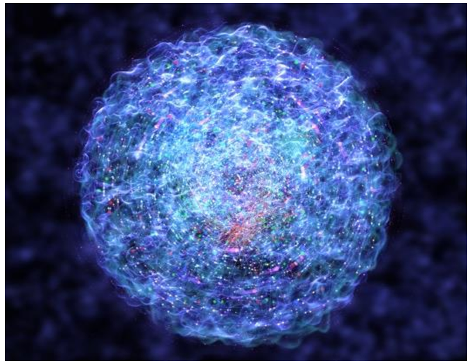
Nanomaterial carbon-based

The proton looks different at different x (the size of the probe!): the interactions and the structures are inextricably mixed

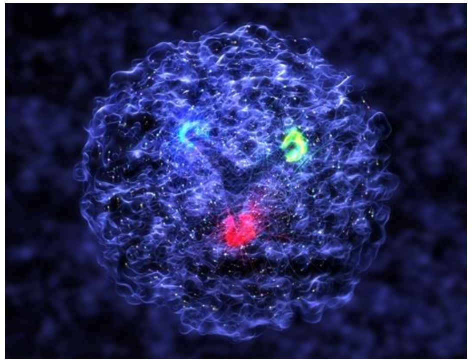
low-x



medium-x

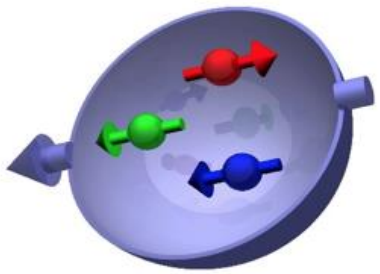


high-x



Fascinating video by R. Milner and R. Ent here: https://www.youtube.com/watch?v=G-9I0buDi4s
(Visualizing Proton Project by the MIT Center for Art, Science & Technology and Jefferson Lab)

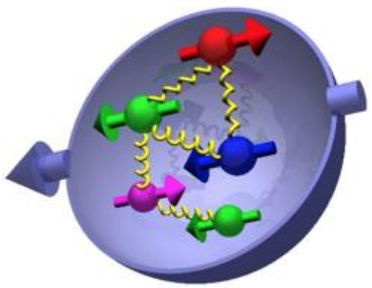
The spin of the proton: still a puzzle



Naive parton model:
all spin made by constituent quarks

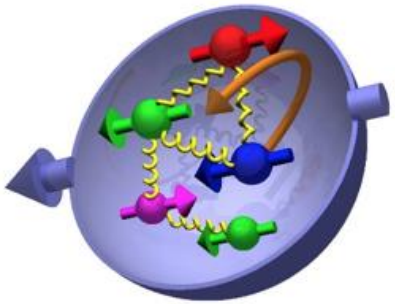
EMC, PLB 206 (1988) 364
→ spin of the proton is only partially made by valence quarks!

$\Delta\Sigma \approx 25\%$



From unpolarized PDFs we know Δg and Δq_s are sizeable!

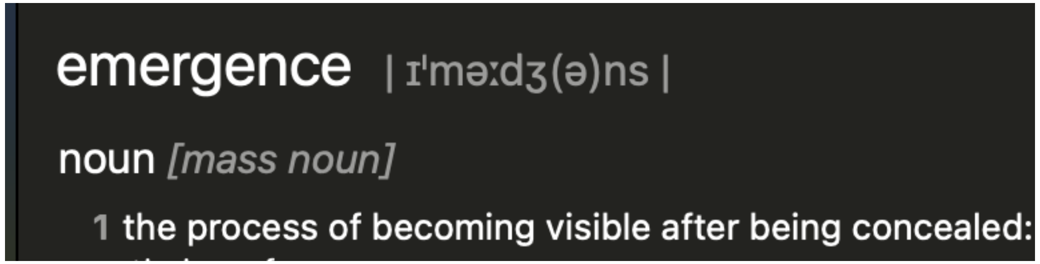
Three decades efforts (DESY, BNL, JLAB, CERN, ...) estimates $\Delta g \approx 35\%$
(and we complete ignore it for $x < 0.005$!)



And we can't neglegt orbital angular momentum

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

As for the **mass**, also the **spin** (and charge and magnetic moment) is a global property that **emerges** from the ineraction of its constituents


emergence | ɪˈməːdʒ(ə)ns |

noun *[mass noun]*

1 the process of becoming visible after being concealed:

EIC science program in five columns

Spin is one of the fundamental properties of matter.

All elementary particles, but the Higgs carry spin.

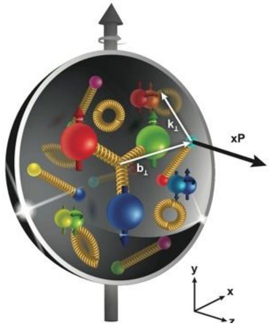
Spin cannot be explained by a static picture of the hadron. It is the interplay between the intrinsic properties and interactions of quarks and gluons

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum.

How the **mass** of visible matter emerge from quark-gluon interactions?

	Binding energy / Mass
`Atom	0.00000001
Nucleus	0.01
Nucleon	100

The EIC will determine an important term contributing to the proton mass → QCD trace anomaly



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

How do the nucleon properties emerge from them and their interactions?

How can we understand their dynamical origin in QCD?

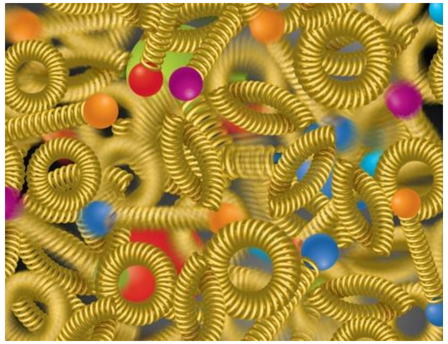
What is the relation to confinement?

Is the **structure of a free and bound nucleon** the same?

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

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



How many gluons can fit in a proton?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

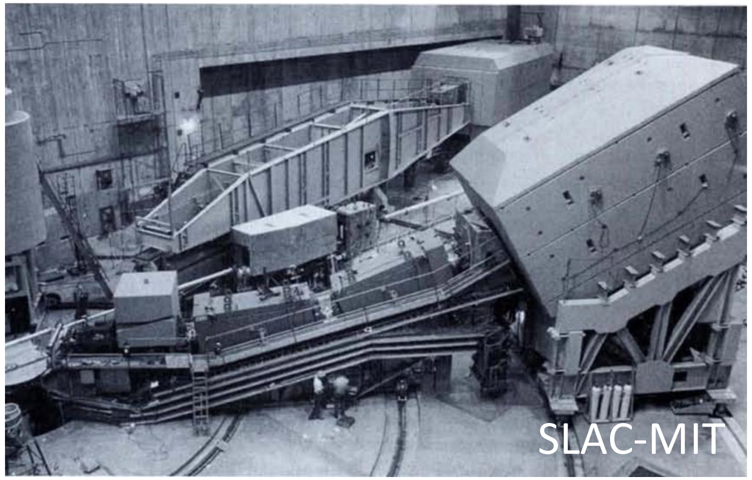
What happens to the gluon density in nuclei? Does it saturate at high energy?

gluon splitting

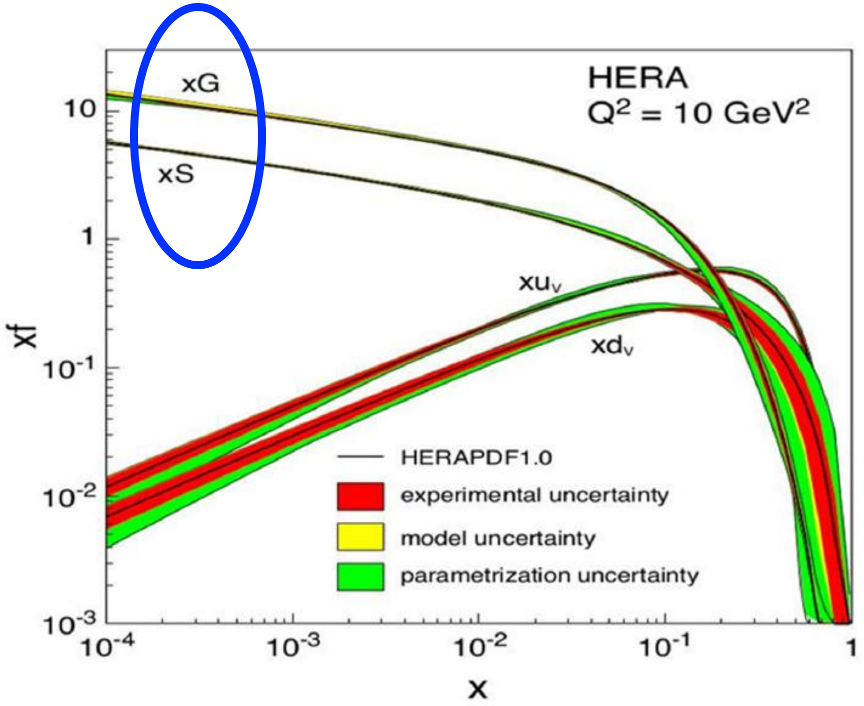
guon recombination

*EIC: 21st Century Laboratory of **Emergent** Dynamics in QCD*

DIS is the microscope to make that science!

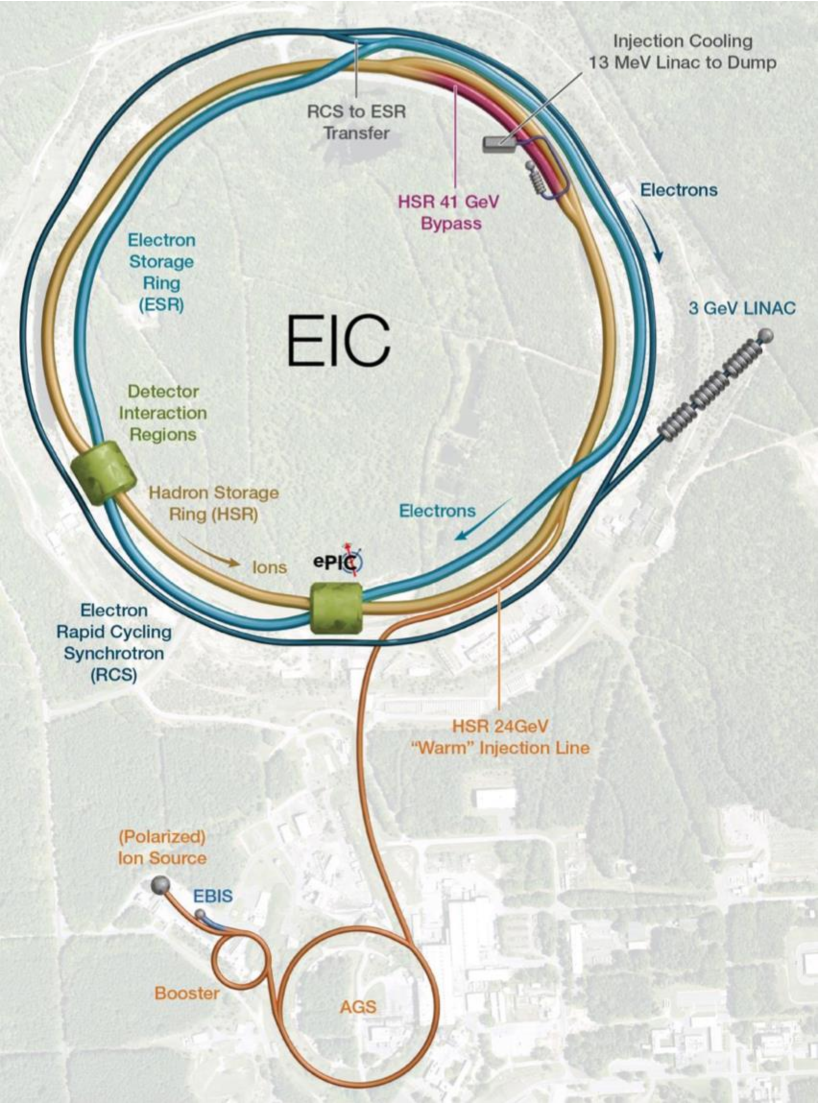


"When HERA started in 1992, we only had vague notions of the structure of the proton," says Rolf-Dieter Heuer, director for particle-physics research at DESY. "The measurements from HERA showed that the interior of the proton is like a thick, bubbling soup in which gluons and quark–antiquark pairs are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



EIC: Understanding the Glue that Binds Us All

The collider: a new electron microscope



Evolution of RHIC (pp/pA/AA) facility at BNL approved by DOE (CD-0) in January 2020

Project Design Goals

- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

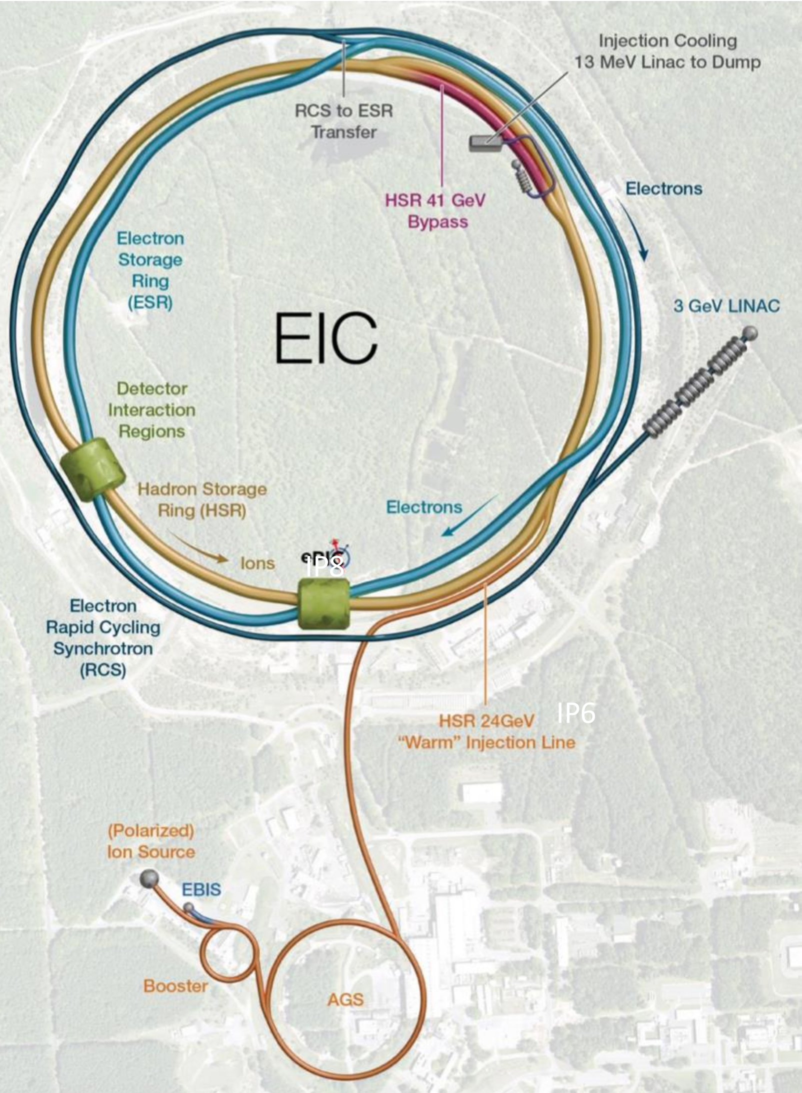
Strong support to EIC in 2023 NSAC long range plan

p/A beam → ← e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

The collider: energy and intensity frontiers



[EIC Conceptual Design Report](#)

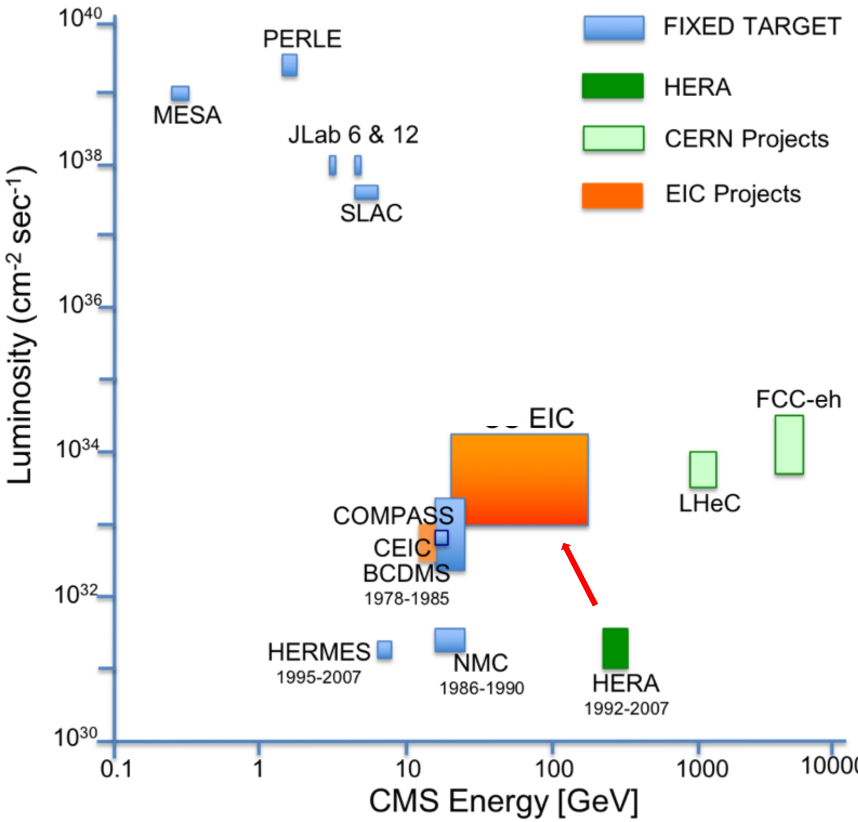
Strong hadron cooling, 25 mrad crab crossing angle, high frequency (BC/10 ns) key ingredients for high luminosity

with respect to HERA:

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

with respect to JLAB12:

- energy frontier vs intensity frontier



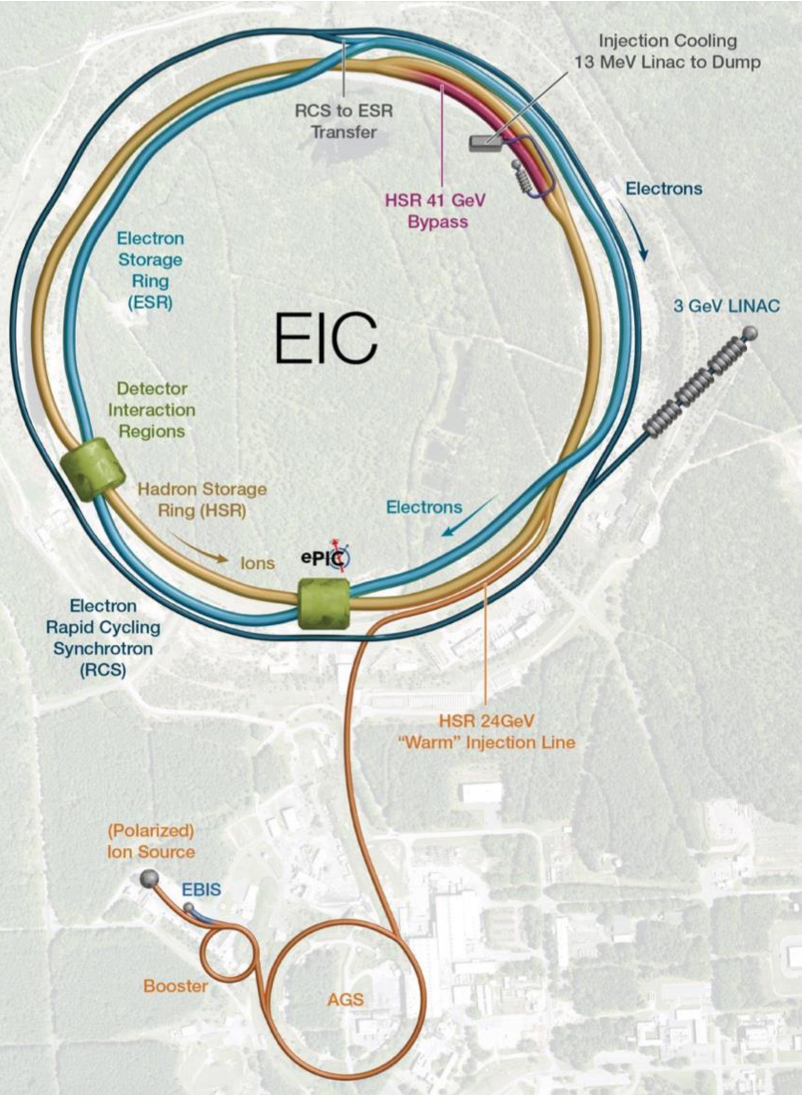
p: 41 GeV, 100 to 275 GeV

p/A beam

e beam

e: 5 GeV to 18 GeV

The collider: towards the land of gluons and quark sea



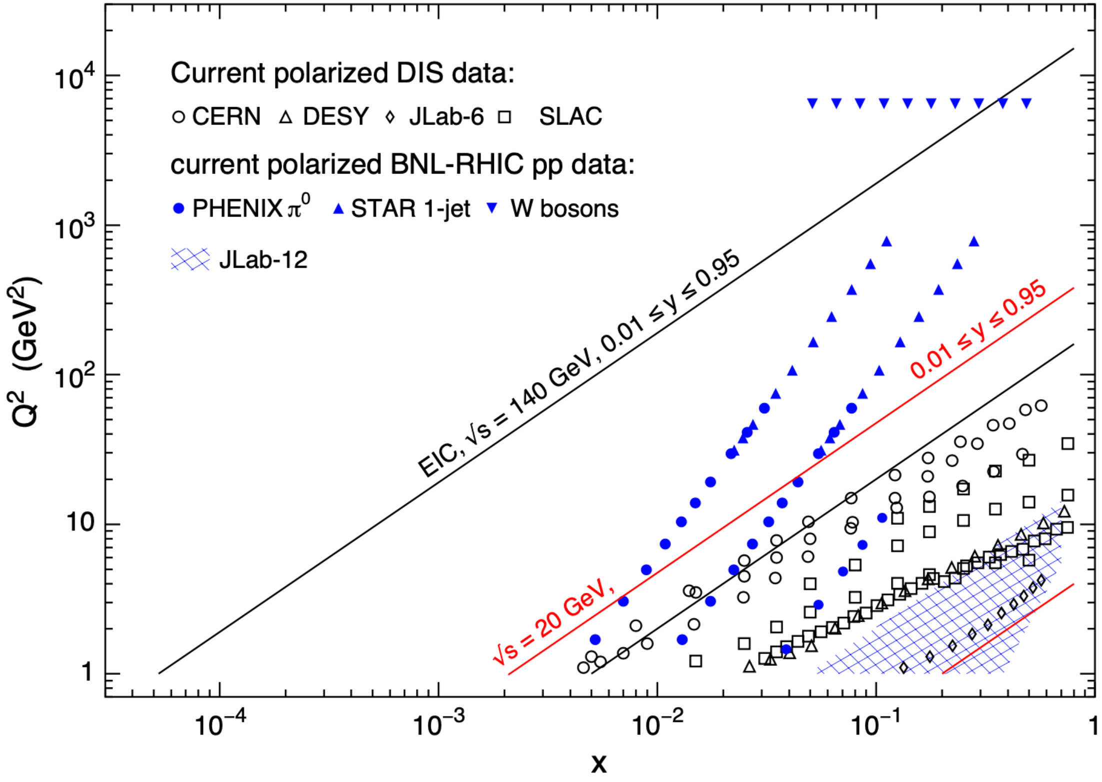
Flexible beam energies/c.m. maximizes nucleon exploration / tuning the microscope

with respect to fixed target facilities:

- more than 2 decades increase in kinematic coverage in x and Q^2
- JLAB12 covers well valence quarks

towards the land of gluons and quark sea

R. Abdlul Kalek at. al (EIC Yellow Report) Nucl. Phys A 1026 (2022) 122447



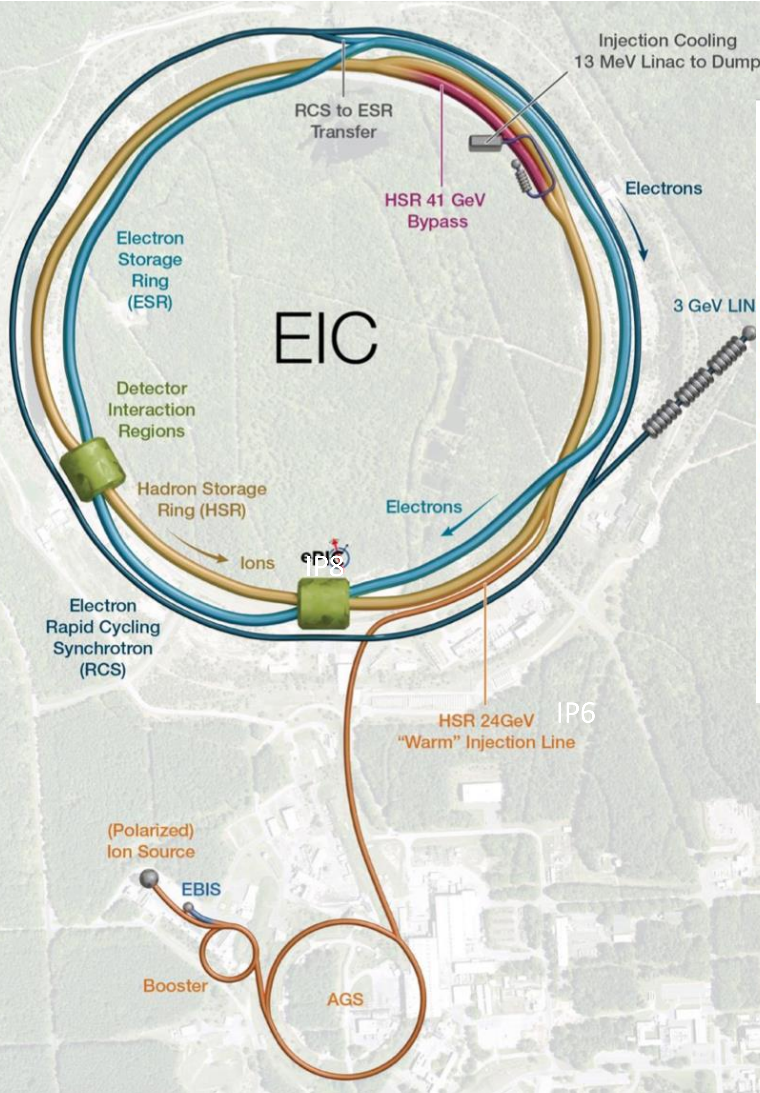
p/A beam

e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

The collider: the nuclei

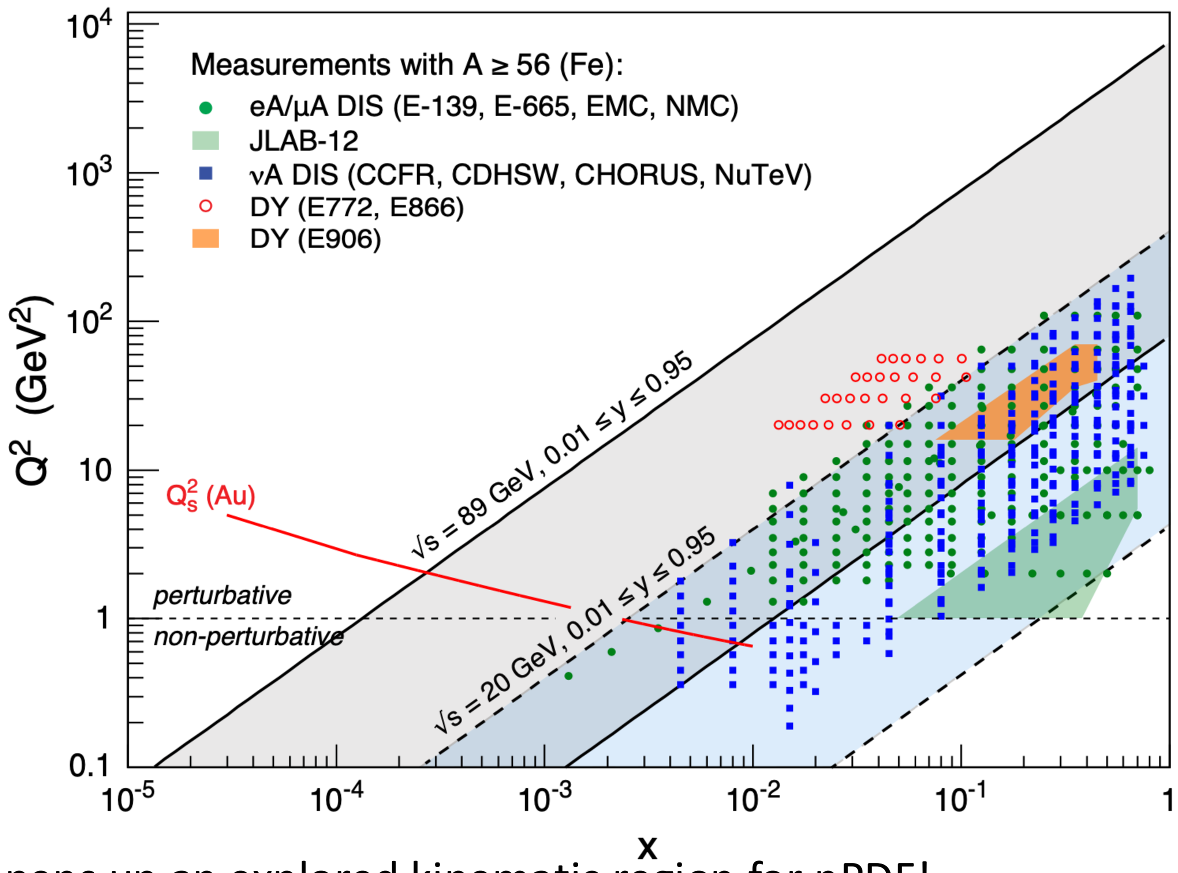


RHIC infrastructure has proven experience on accelerating all ions for the EIC

<u>Ion Pairs</u>
<u>in the RHIC Complex</u>

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)

[R. Abdlul Kalek at. al (EIC Yellow Report) Nucl. Phys A 1026 (2022) 122447]



The first e-A collider opens up an explored kinematic region for nPDF!
<u>Note</u>: don't forget UPC@LHC/RHIC (see this morning session!)

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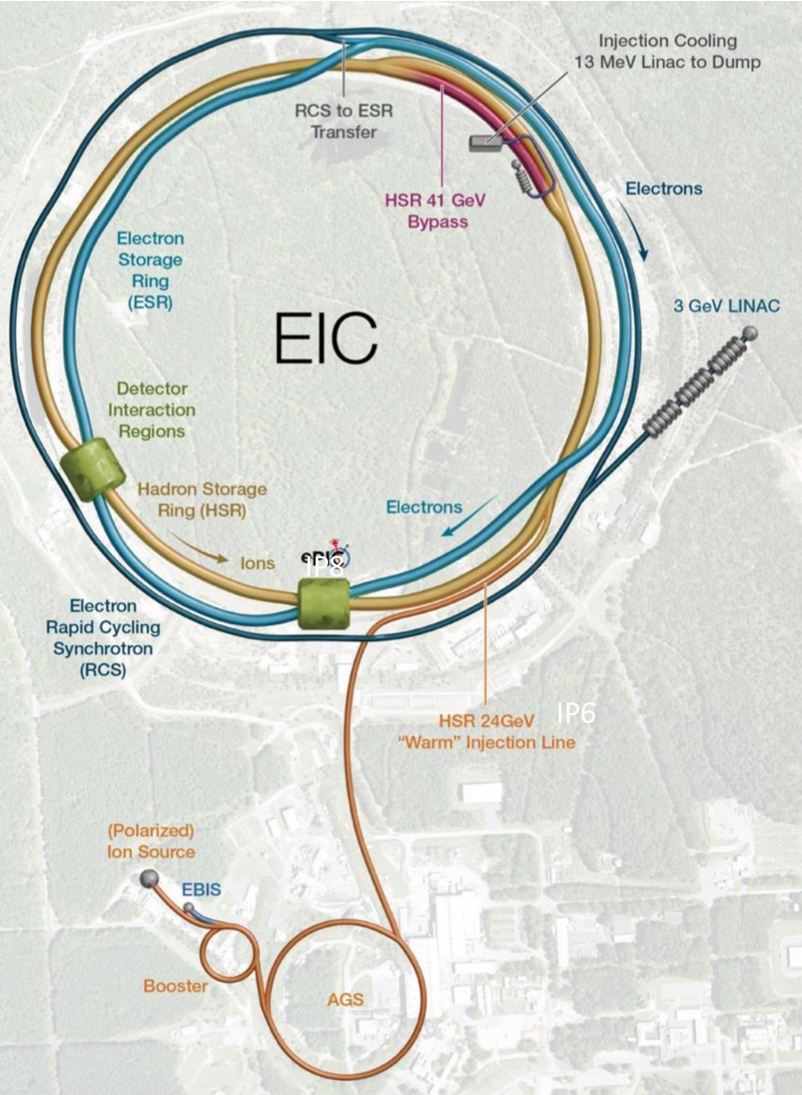
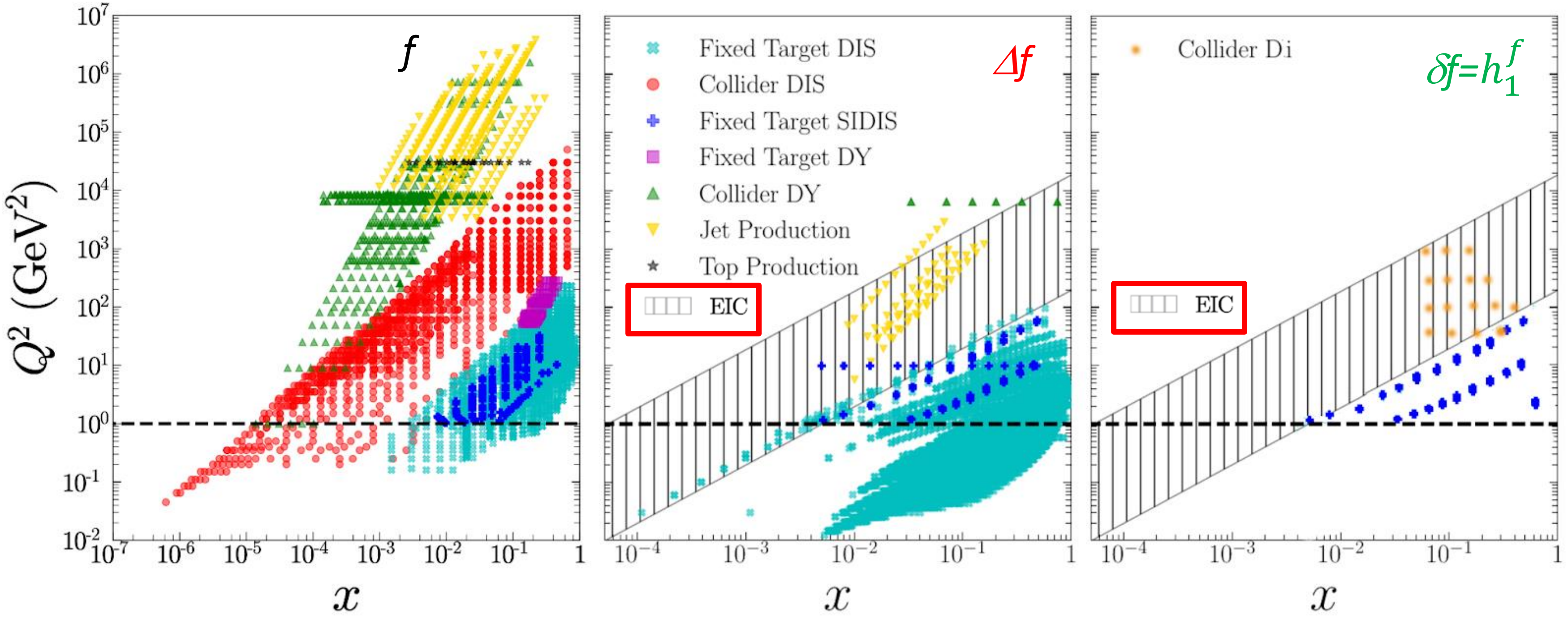
p/A beam	e beam
p: 41 GeV, 100 to 275 GeV →	← **e: 5 GeV to 18 GeV**

Worldwide data for collinear PDF and the EIC



Collinear PDF: unpolarized f, helicity $\Delta f = g_1$, transversity $\delta f = h_1^f$



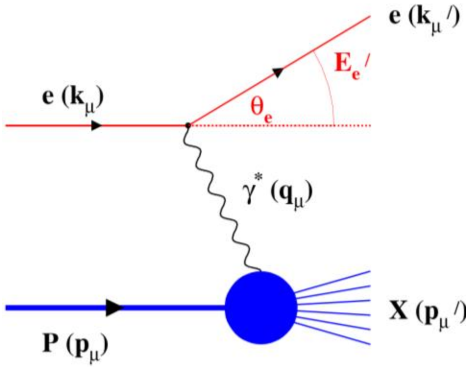
adapted from M. Constantinou et al., PPNP 121 (2021) 103908

Polarized beams unique asset!

DIS processes → physics/detector requirements

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities - Saturation



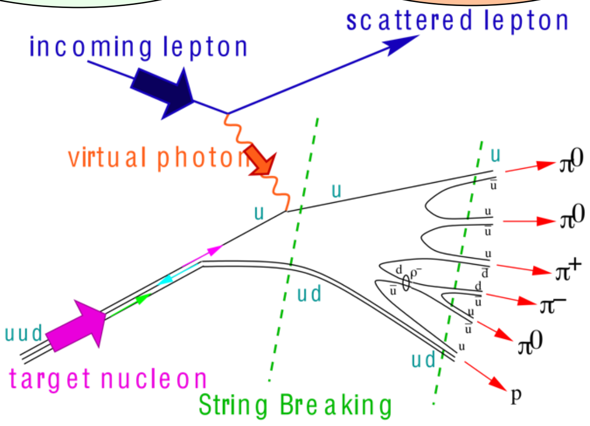
inclusive DIS

measure scattered electron
→ e/h PID
→ eCAL calorimetry

∫Ldt: 1 fb^{-1}

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.



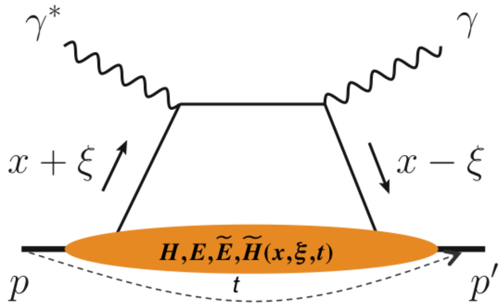
semi-inclusive DIS

measure electron and hadrons
→ hadron PID

10 fb^{-1}

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging



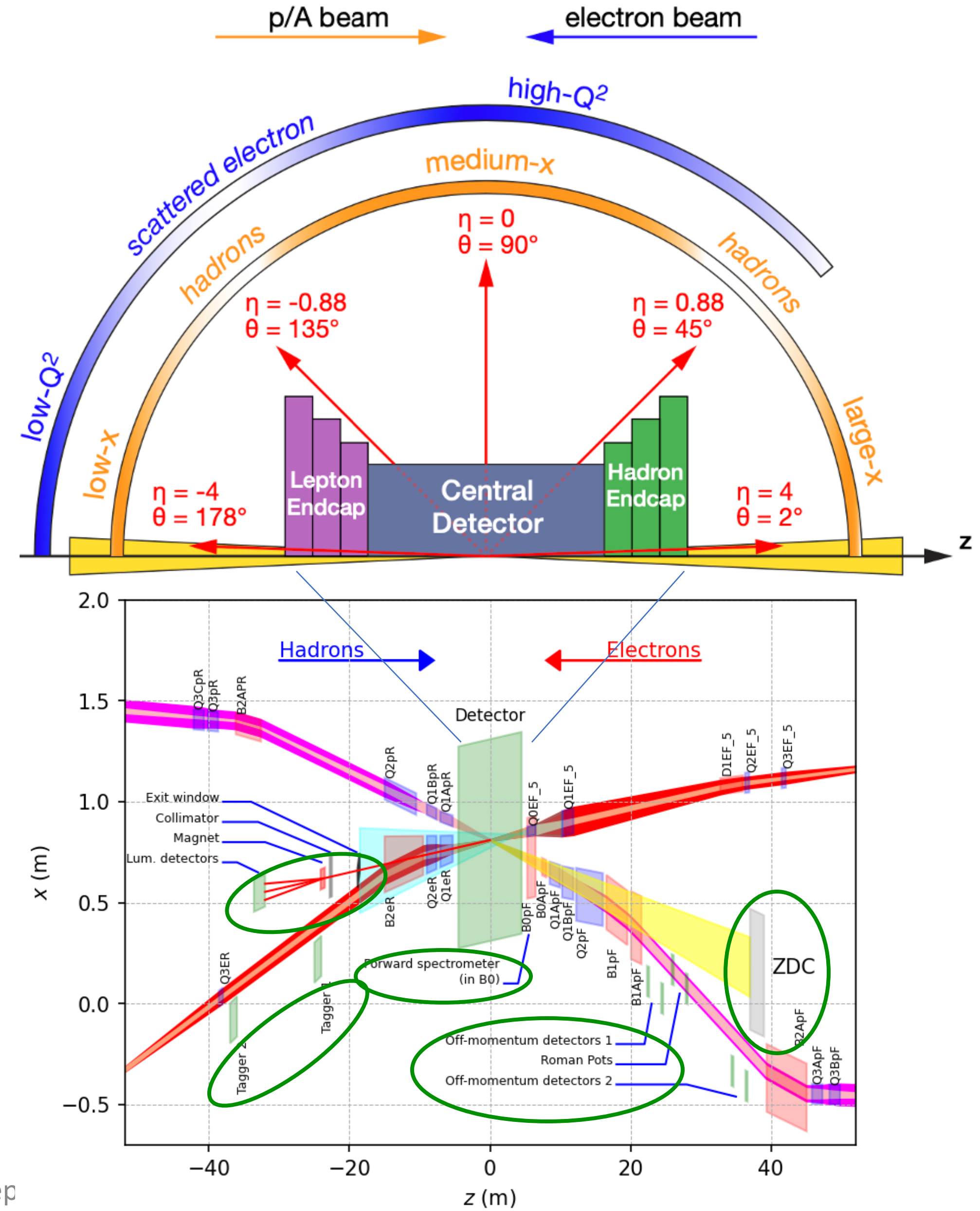
exclusive processes

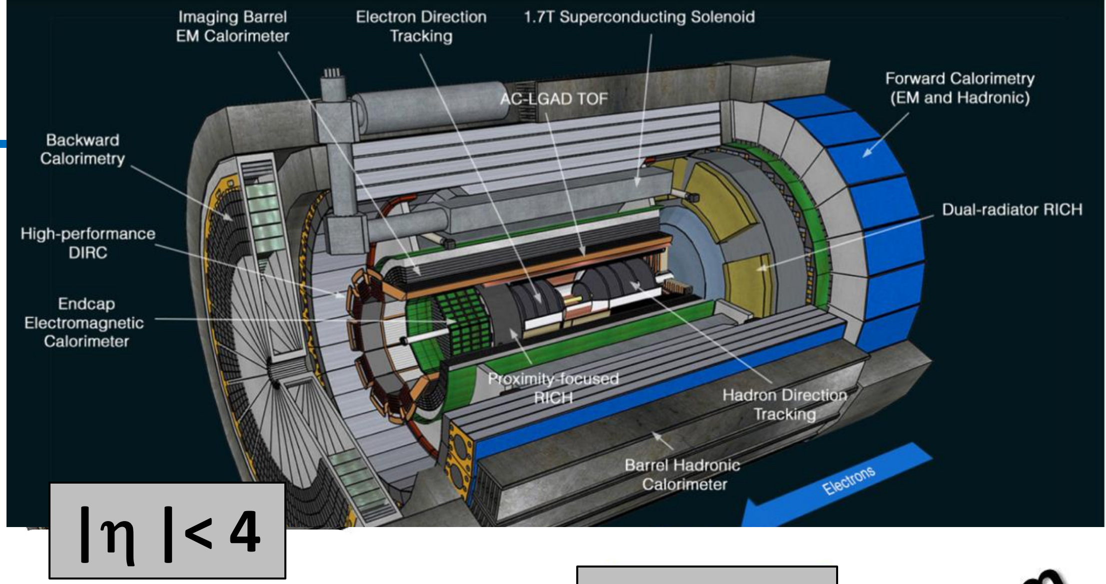
measure all particles
→ hermeticity
→ design IR

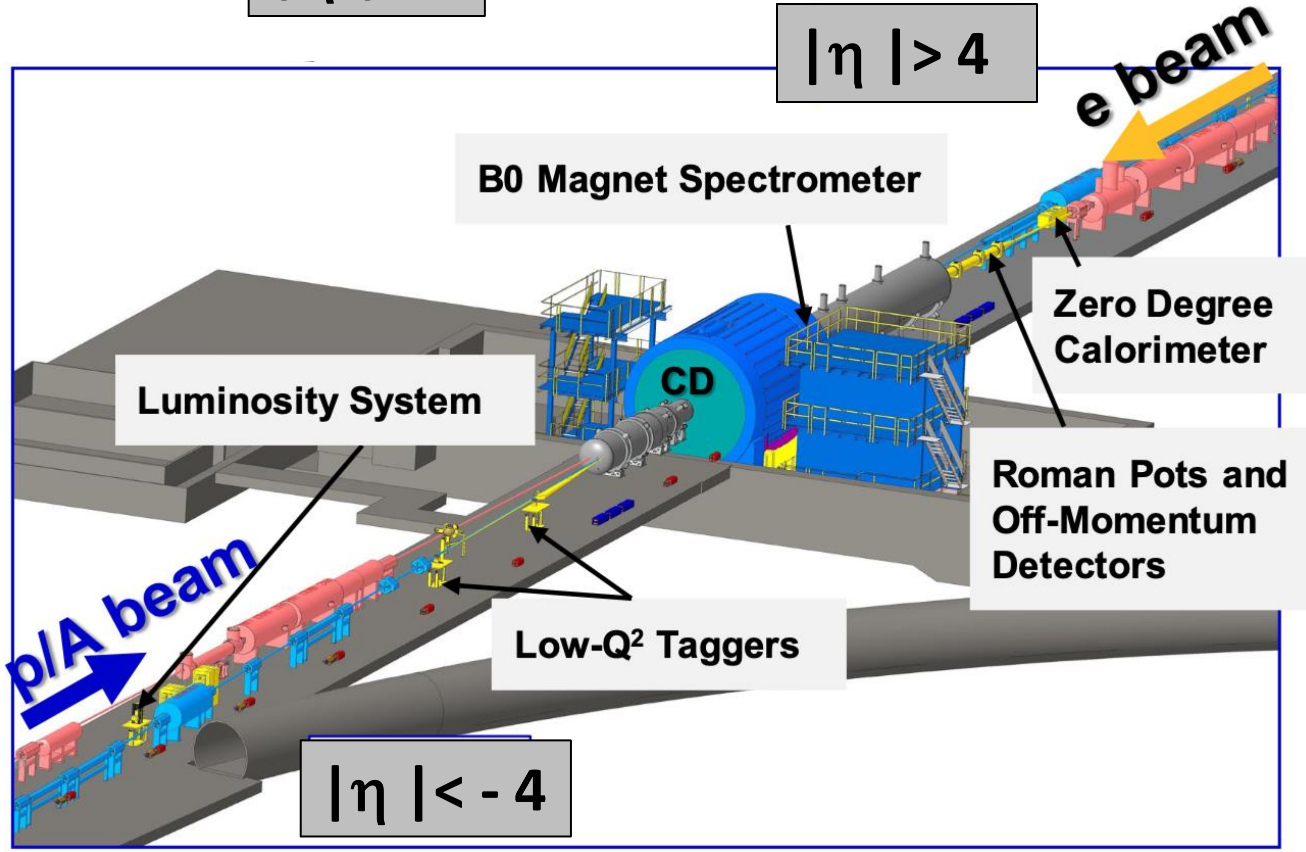
10 - 100 fb^{-1}

-→ ePIC Collaboration formed in 2022

so ePIC is… 90 m long







ePIC central detector design

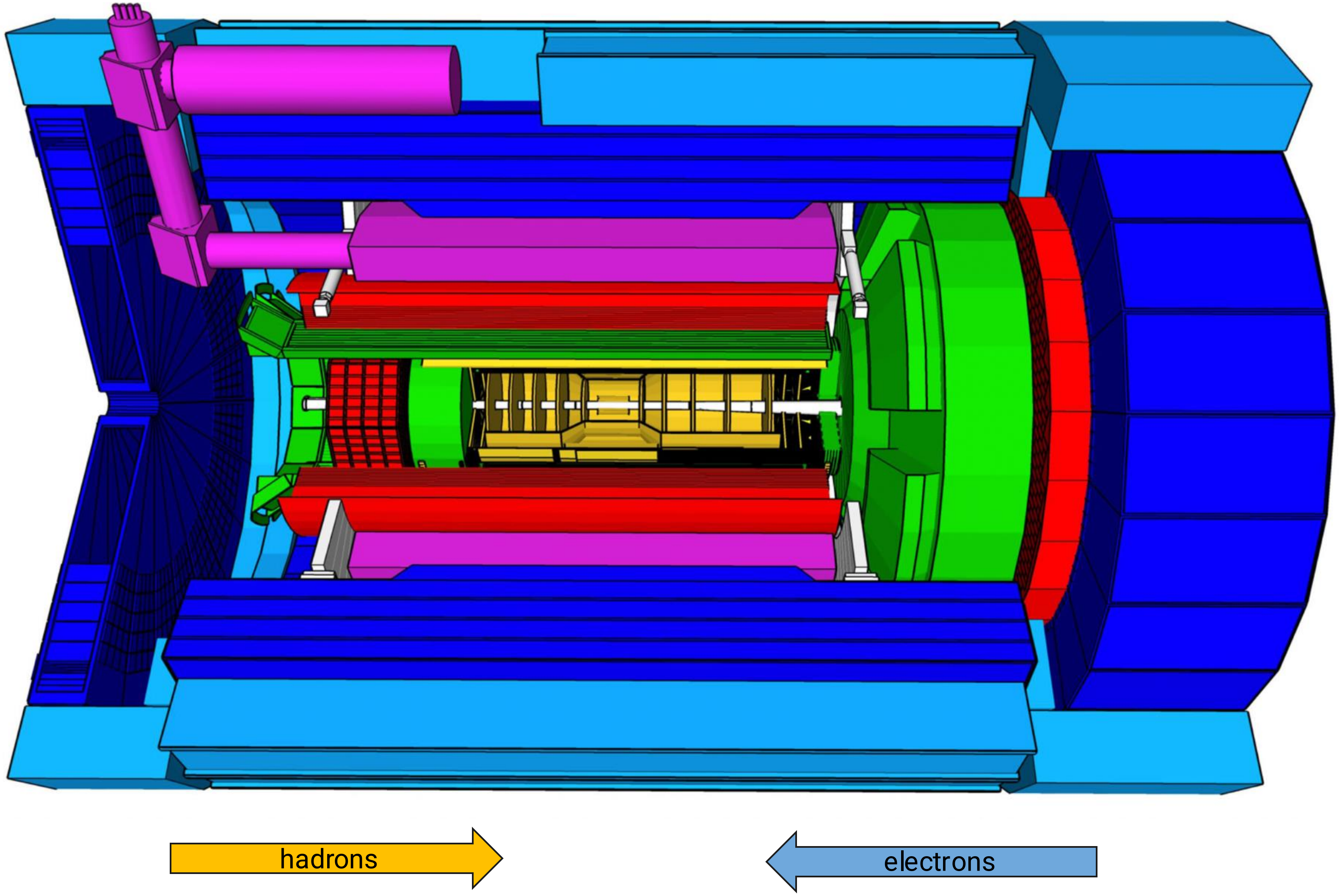
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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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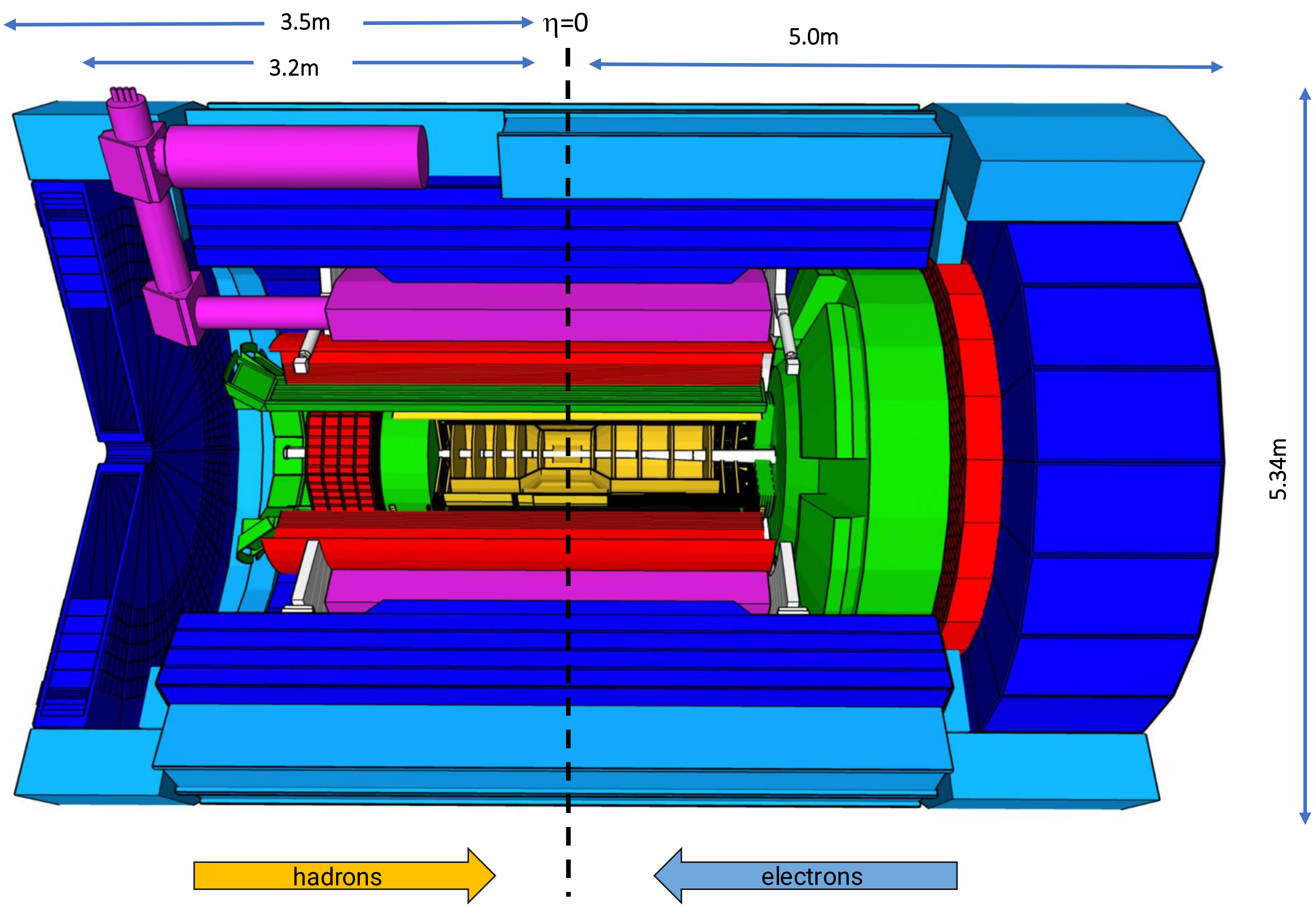
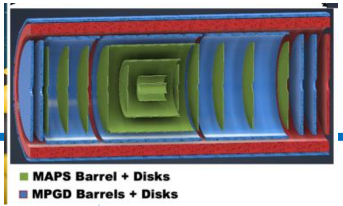
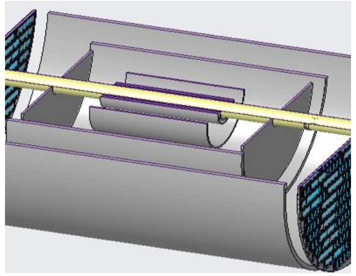
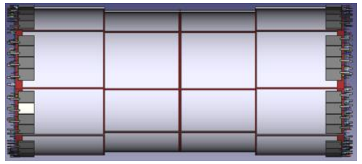


ePIC tracking detectors

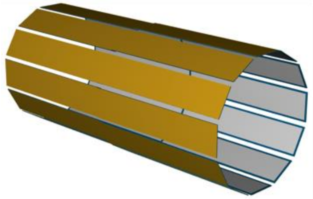


µVertex Tracker | Barrel Tracker | Outer Barrel MPGD Tracker | EndcapTracker

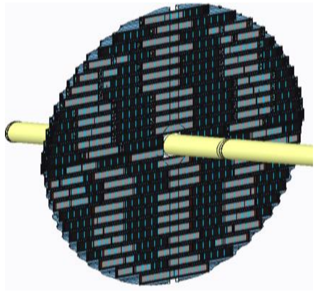




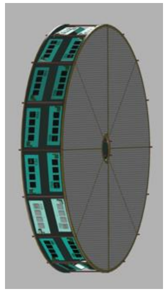
MicroMegas Tracker



µRWELL Tracker



MAPS Disks



GEM-µRWELL Disks

Main Function

µVertex / Barrel Tracker: Excellent momentum 0.05%pT⊕0.5% and spatial resolution 20µm/pT⊕ 5µm

µVertex Tracker: Displaced vertex reconstruction

MicroMegas Tracker: Provide redundancy and pattern recognition for tracking

µRWELL Tracker: Tracking close to hpDIRC detector to improve angular and space point resolution. Redundancy and pattern recognition for tracking

MAPS Disks: Excellent momentum 0.05 (0.10)% pT⊕1.0 (2.0)% and spatial resolution 30µm/pT⊕ (20 – 40) µm

GEM-µRWELL Disks: Provide redundancy and pattern recognition for tracking

Proven Technology

µVertex Tracker: Monolithic Active Pixel Sensor → ALICE ITS3 sensor (65 nm) small pixels (21x23 µm) and power consumption (<40 mW/cm^2)

MicroMegas Tracker: Cylindrical resistive Micromegas technology Used: ATLAS NSW, CLAS12, SPHENIX, MINOS& T2K TPC

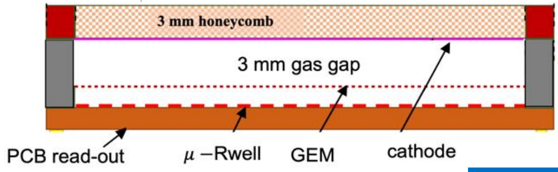
world's first at ePIC

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

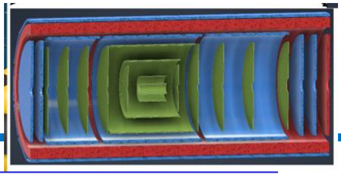
µRWELL Tracker: 24 planar Thin-gap & double amplification (GEM & µRWELL) modules & 2D-strip readout

MAPS Disks: EIC Large Area Sensor (LAS), staves as the basic building elements for the MAPS disks

GEM-µRWELL Disks: hybryd GEM-µRwell → increased gain

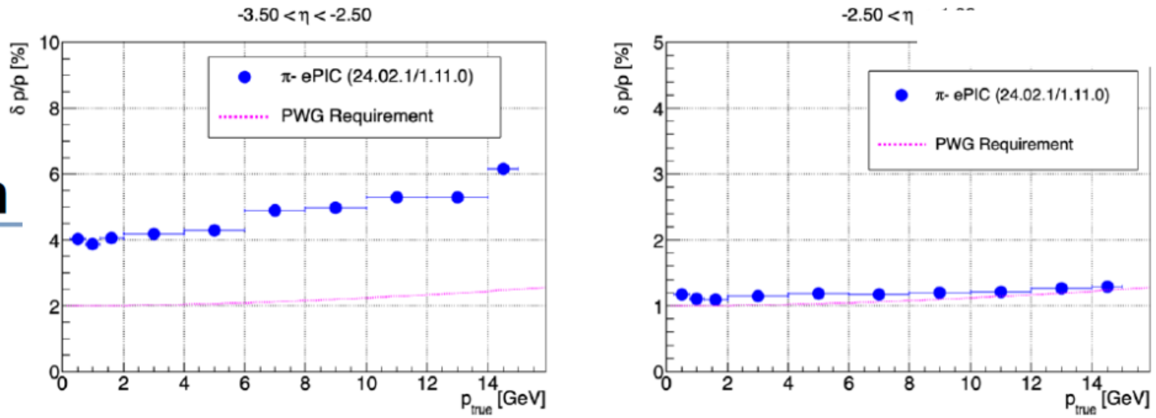


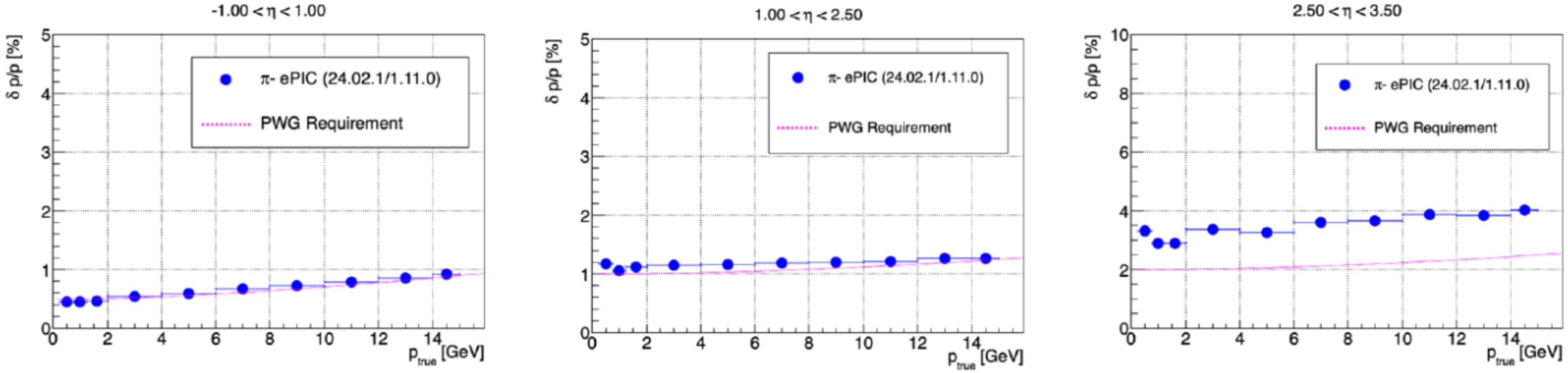
ePIC tracking detectors

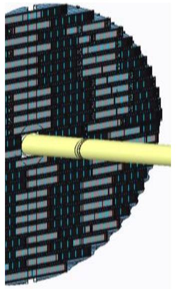


EndcapTracker

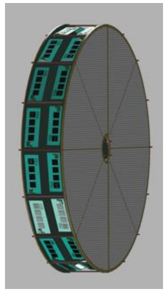
Momentum Resolution







MAPS Disks



GEM-μRWELL Disks

omentum 0.05
Ð1.0 (2.0)%
resolution
(20 – 40) μm

Provide redundancy and pattern recognition for tracking

mW/cm²)

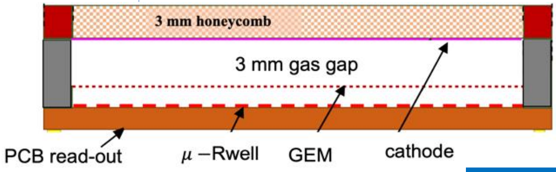
EIC Large Area Sensor (LAS), modification of ITS3 sensor with 5 or 6 RSU forming staves as the basic building elements for the Outer Barrel

world's first at ePIC

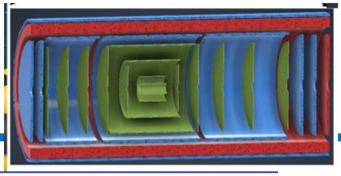
24 planar Thin-gap & double amplification (GEM & μRWELL) modules & 2D-strip readout

EIC Large Area Sensor (LAS), staves as the basic building elements for the MAPS disks

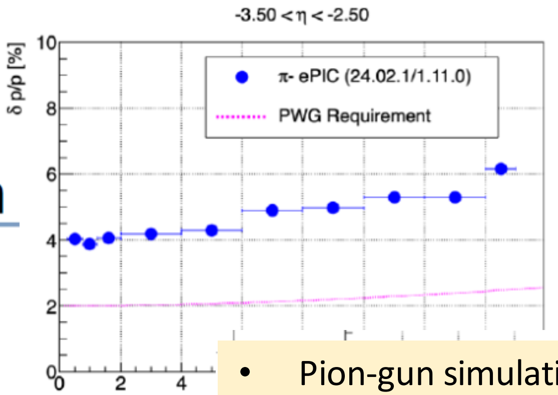
hybryd GEM-μRwell → increased gain

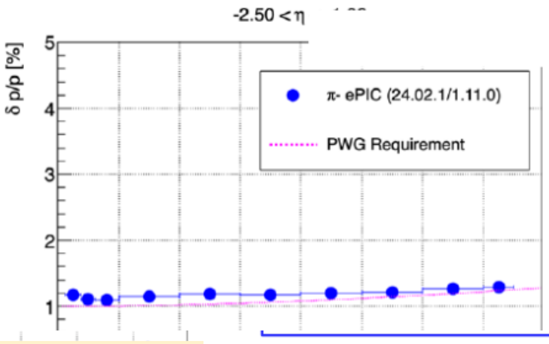


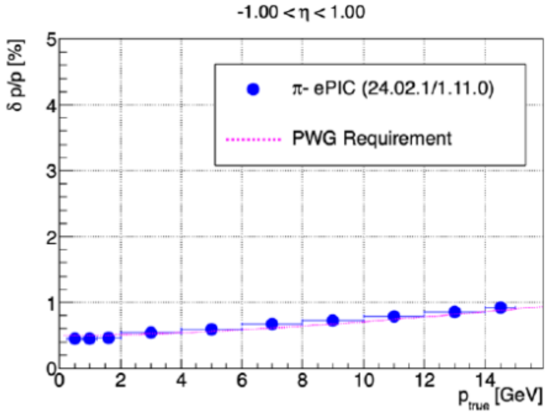
ePIC tracking detectors

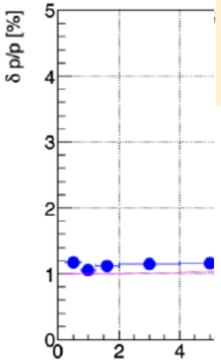


Momentum Resolution



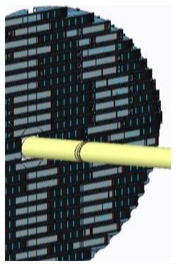




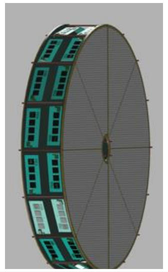


- Pion-gun simulation
- Reconstr. include AC-LGAD
- At extreme η need to use additional info from other det.
- Follows requiremens elsewhere

EndcapTracker

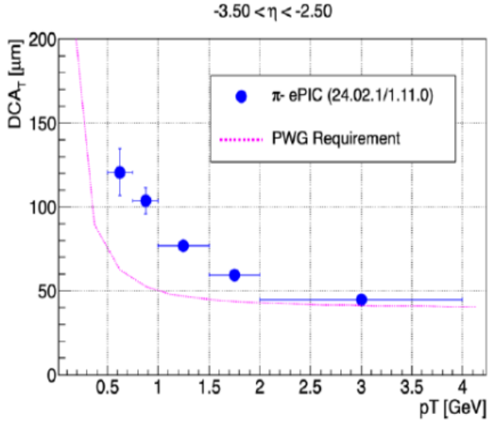


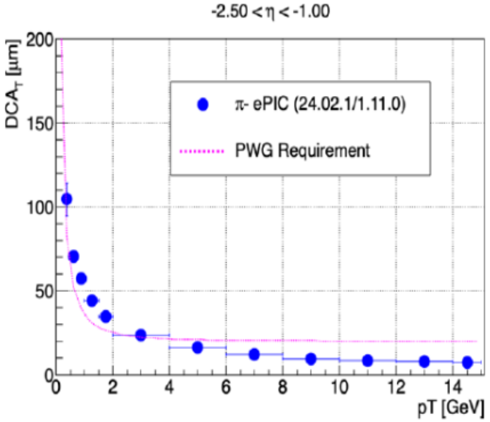
MAPS Disks

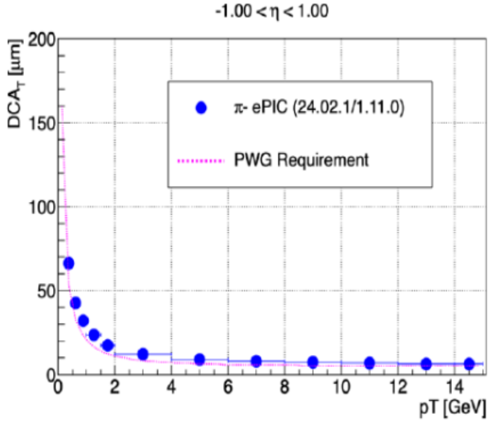


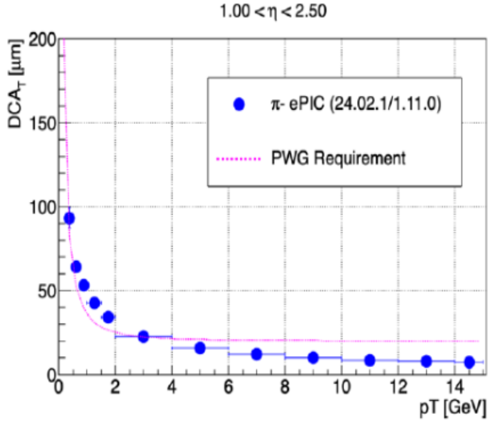
GEM-µRWELL Disks

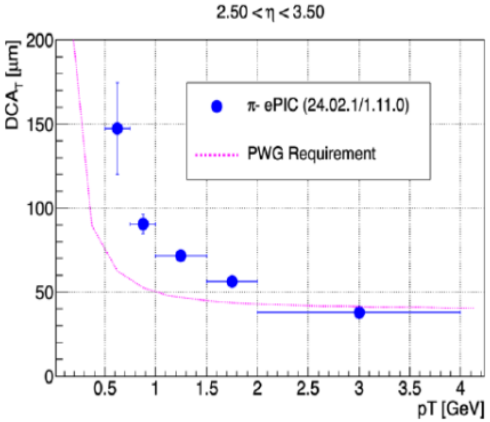
Pointing Resolution







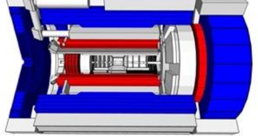


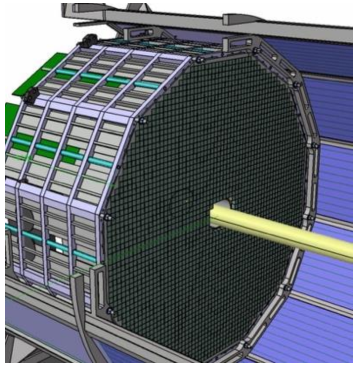


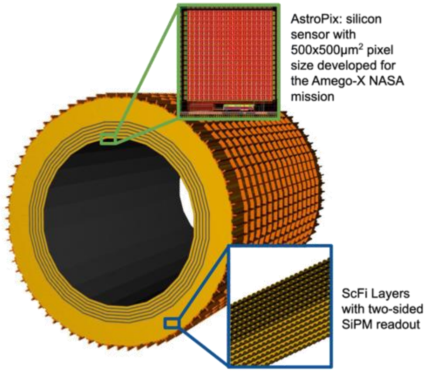
mW/cm²)

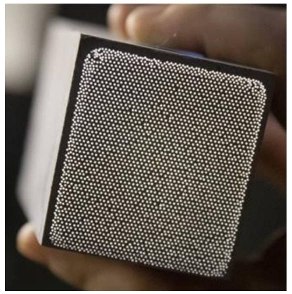
EIC Large Area Sensor (LAS), modification of ITS3 sensor with 5 or 6 RSU forming staves as the basic building elements for the Outer Barrel

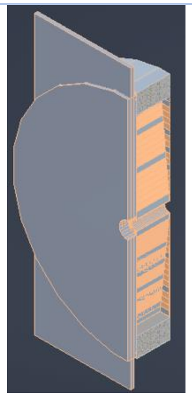
ePIC calorimetry

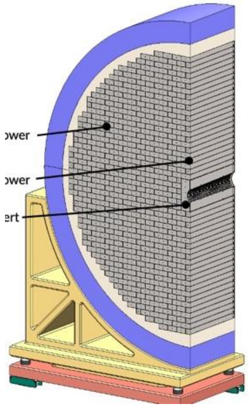






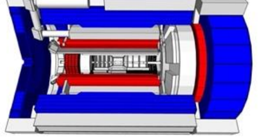


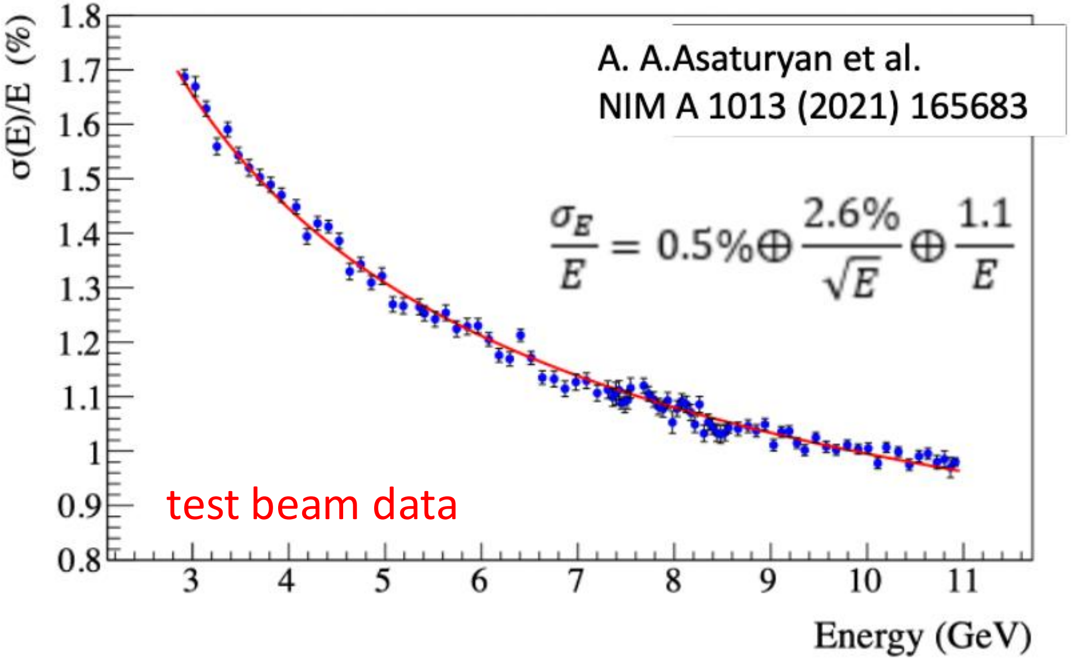


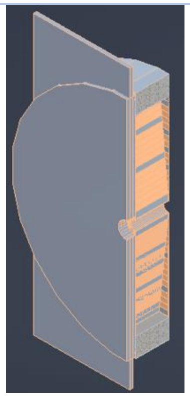


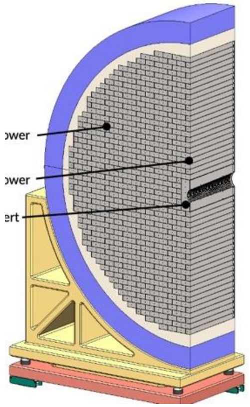
	Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
Main Function	scattered lepton detection → very high-precision	scattered lepton and γ detection, hadronic final state characterization	lepton and γ detection, hadronic final state characterization → π^0, γ separation	muon and neutral detection → improved jet Energy reconstruction	muon and neutral detection → improved jet Energy reconstruction	particle-flow measurements
Proven Technology	$PbWO_4$ – crystals	Pb/SciFi sampling part using SiPMs combined with imaging section (4 layers) interleaving Pb/SciFi with AstroPix sensor (500x500 μm^2) Res: $5.3\% /\sqrt{E} \oplus 1.0\%$	Tungsten-powder + SciFi SPACAL design Developed through EIC R&D and applied successfully in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
world's first at ePIC	SiPM as Photosensors	Use of ASTROPIX in Calorimetry				first-time full-size CALICE like calorimeter in collider experiment

ePIC calorimetry



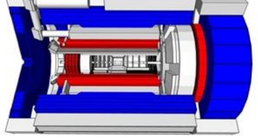


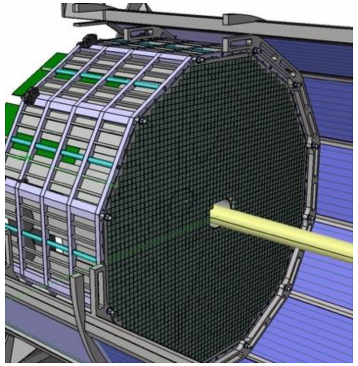
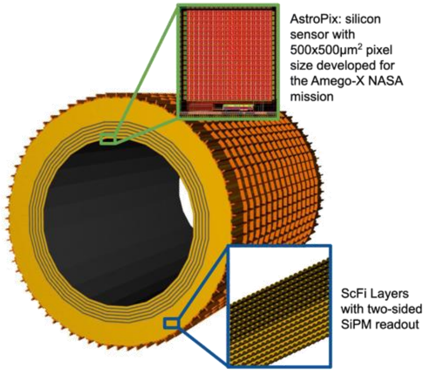
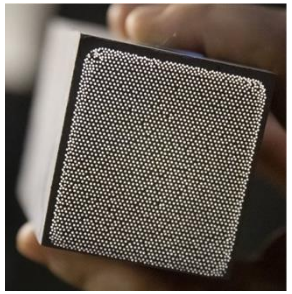
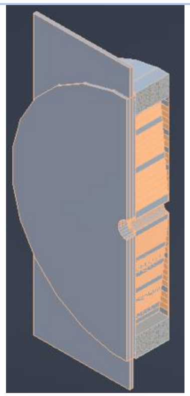
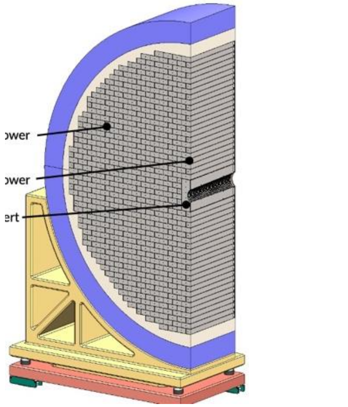


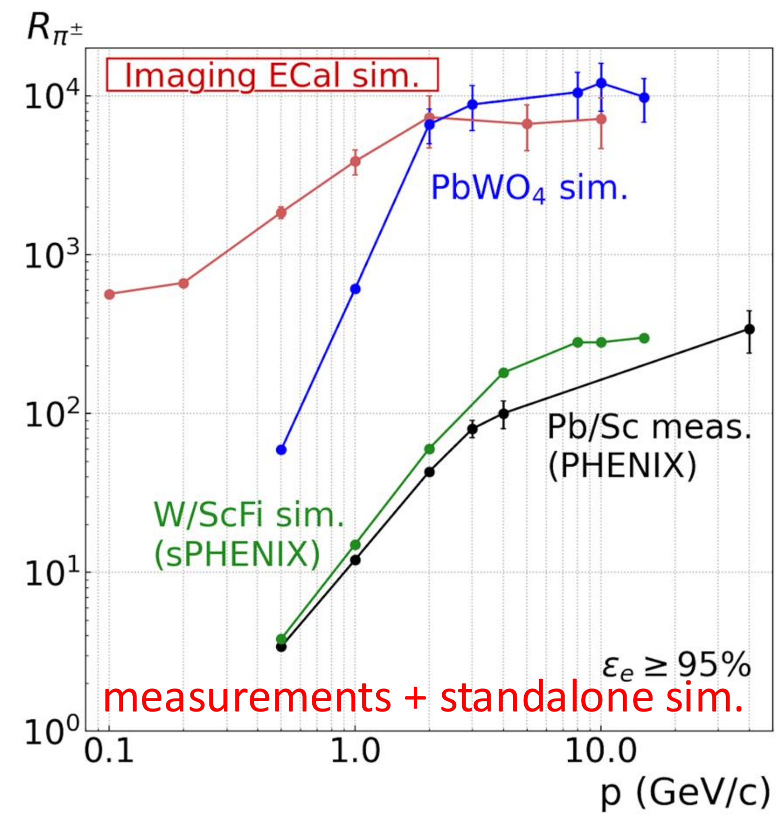


	Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
Main Function			l γ detection, final state ation → π^0, γ aration	muon and neutral detection → improved jet Energy reconstruction	muon and neutral detection → improved jet Energy reconstruction	particle-flow measurements
Proven Technology		with imaging section (4 layers) interleaving Pb/SciFi with ASTROPIX sensor (500x500 μm^2) Res: $5.3\% /\sqrt{E} \oplus 1.0\%$	wder + SciFi SPACAL design Developed through EIC R&D and applied successfully in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
world's first at ePIC	SiPM as Photosensors	Use of ASTROPIX in Calorimetry				first-time full-size CALICE like calorimeter in collider experiment

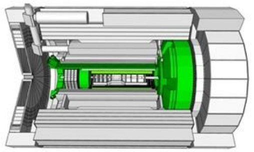
ePIC calorimetry

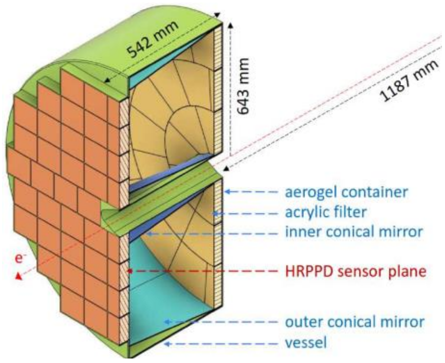
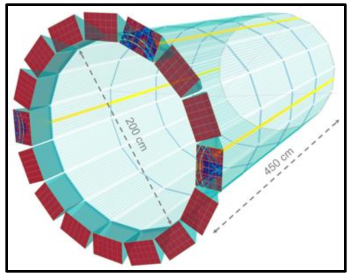
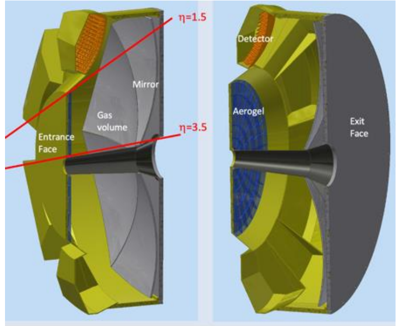
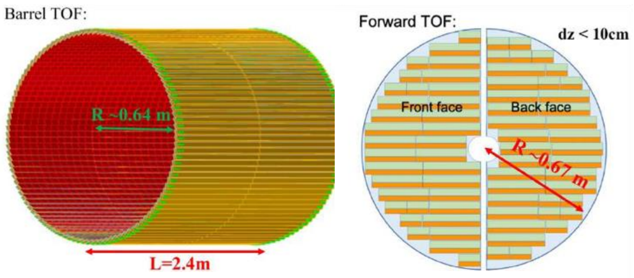


Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
					
Main Function					
scattered lepton → very high-p		ɟ γ detection, : final state zation → π^0, γ aration	muon and neutral detection → improved jet Energy reconstruction	muon and neutral detection → improved jet Energy reconstruction	particle-flow measurements
Proven Technology					
$PbWO_4$ – c		›wder + SciFi ign :hrough EIC plied in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
SiPM as Photo		world's first at ePIC			first-time full-size CALICE like calorimeter in collider experiment



ePIC Particle Identification



Backward RICH (pfRICH)	Barrel DIRC (hpDIRC)	Forward RICH (dRICH)	Time-of-Flight (Barrel, Forward)
			

Main Function

Backward RICH (pfRICH)

- e, π, K, p separation

→ π/K 3σ sep. up to 9 GeV/c and 10-20 ps timing → ToF

Barrel DIRC (hpDIRC)

e, π, K, p separation
→ π/K 3σ sep. at 6 GeV/c

Forward RICH (dRICH)

e, π, K, p separation
→ π/K 3σ sep. up to 50 GeV/c

Time-of-Flight (Barrel, Forward)

e, π, K, p separation through 20-35 ps ToF
Barrel: $0.15 < p_T < 1.5$ GeV/c
Forward: $0.15 < p_T < 2.5$ GeV/c

- Accurate space point for tracking

Proven Technology

Backward RICH (pfRICH)

Classical single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)

Barrel DIRC (hpDIRC)

High Performance DIRC

- Quartz bar radiator
  → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs

Forward RICH (dRICH)

Dual Radiator RICH

- Aerogel and C_2F_6 gas
- Spherical Mirrors (6 Az. Sectors)
- Photon-Sensors tiled on spheres

world's first at ePIC

Backward RICH (pfRICH)

First time use of large-area MCP as photosensors: HRPPDs
(→ Time-of-Flight)

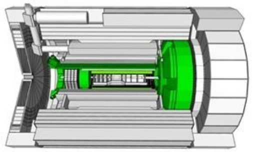
Forward RICH (dRICH)

First time use of SiPMs as Photosensors in a RICH

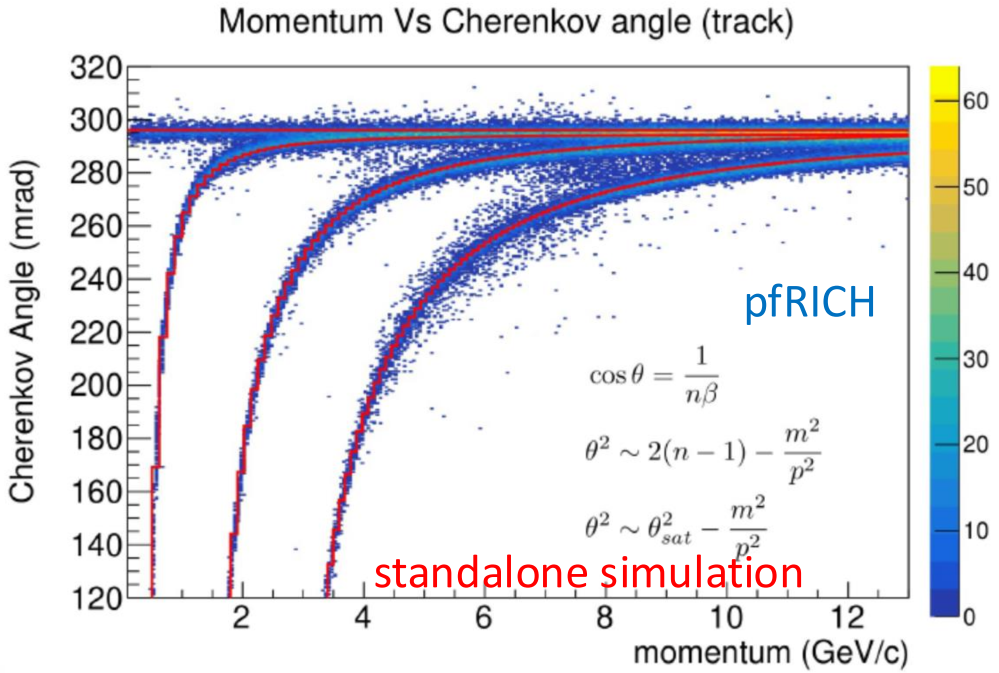
Time-of-Flight (Barrel, Forward)

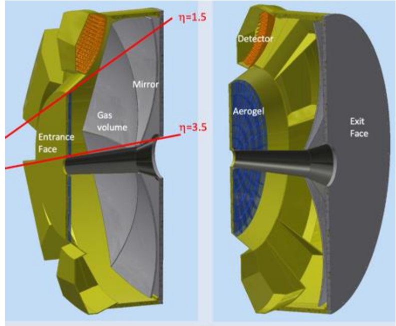
First time use of AC-LGAD (Low Gain Avalanche Detector) in collider detector

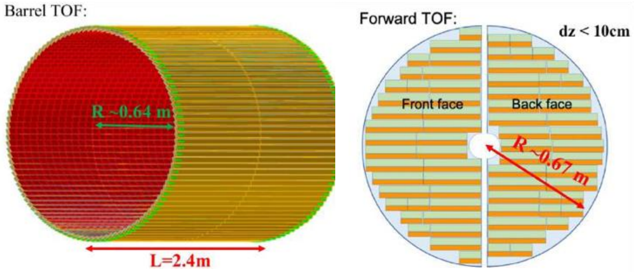
ePIC Particle Identification



Backward RICH (pfRICH)	Barrel DIRC (hpDIRC)	Forward RICH (dRICH)	Time-of-Flight (Barrel, Forward)







Main Function

eV/c

e, π, K, p separation
→ π/K 3σ sep. up to 50 GeV/c

e, π, K, p separation through 20-35 ps ToF
Barrel: $0.15 < p_T < 1.5$ GeV/c
Forward: $0.15 < p_T < 2.5$ GeV/c
- Accurate space point for tracking

Proven Technology

Classical single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)

- Quartz bar radiator
  → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs

Dual Radiator RICH
- Aerogel and C_2F_6 gas
- Spherical Mirrors (6 Az. Sectors)
- Photon-Sensors tiled on spheres

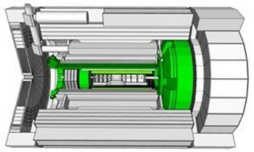
world's first at ePIC

First time use of large-area MCP as photosensors: HRPPDs
(→ Time-of-Flight)

First time use of SiPMs as Photosensors in a RICH

First time use of
AC-LGAD (Low Gain Avalanche Detector)
in collider detector

ePIC Particle Identification



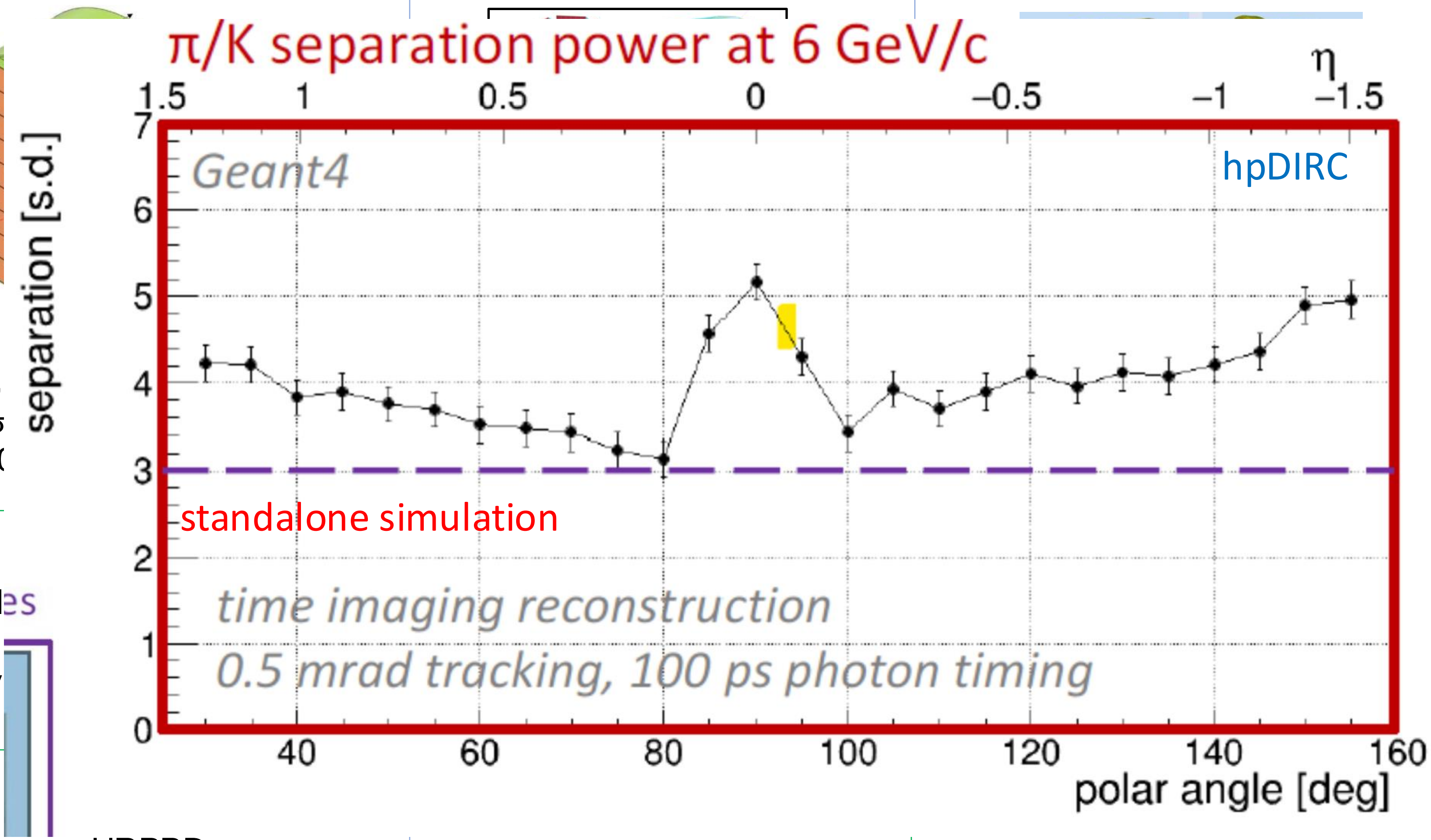
Backward RICH (pfRICH)

- e, π, K,
→ π/K 3σ
and 1(

Classical
focusing
proximity

First time
photosensors: HRPPDs
(→ Time-of-Flight)

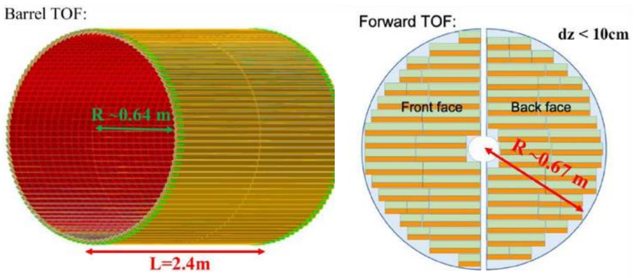
Barrel DIRC (hpDIRC)



Forward RICH (dRICH)

First time use of SiPMs as Photosensors in a RICH

Time-of-Flight (Barrel, Forward)

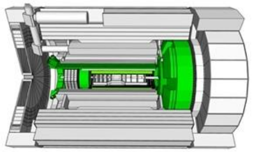


e, π, K, p separation through 20-35 ps ToF
Barrel: $0.15 < p_T < 1.5$ GeV/c
Forward: $0.15 < p_T < 2.5$ GeV/c

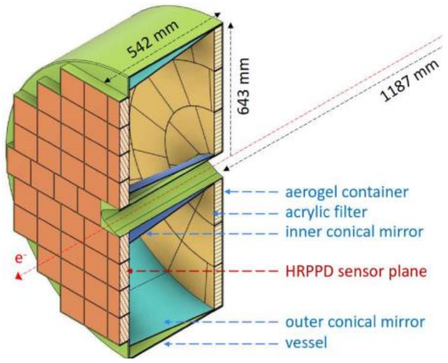
- Accurate space point for tracking

First time use of
AC-LGAD (Low Gain Avalanche Detector)
in collider detector

ePIC Particle Identification



Backward RICH (pfRICH)



- e, π, K, p separation

→ π/K 3σ sep. up to 9 GeV/c and 10-20 ps timing → ToF

Classical single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)

First time use of large-area MCP as photosensors: HRPPDs (→ Time-of-Flight)

Barrel DIRC (hpDIRC)

e

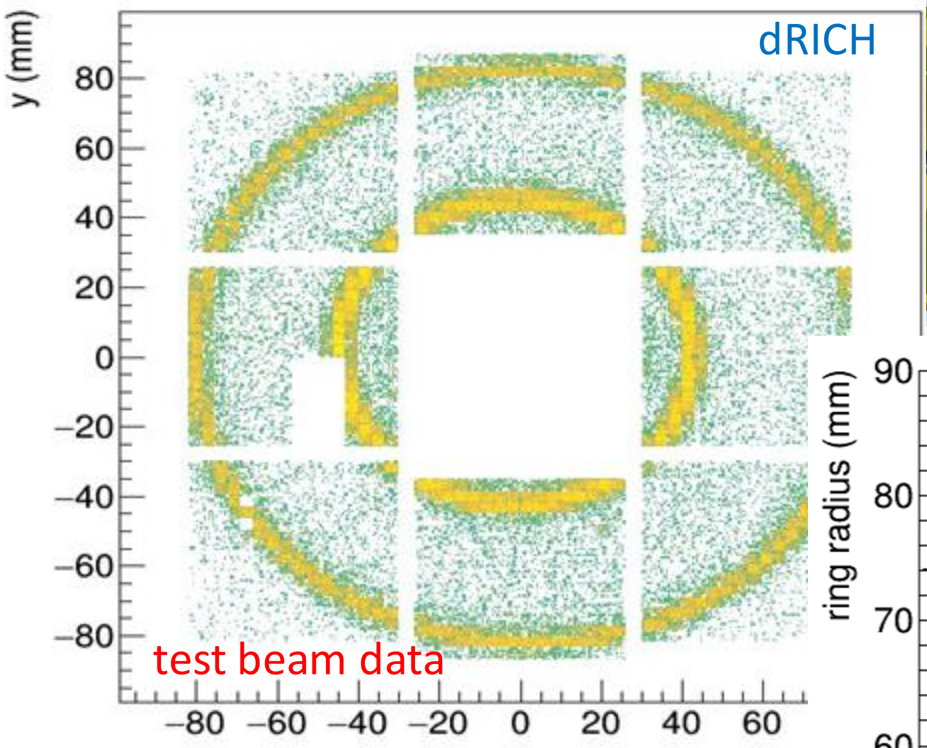
→

H

-

- light detection with MCP-PMTs

Forward RICH (dRICH)

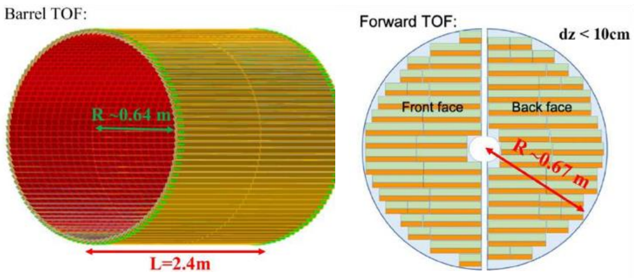


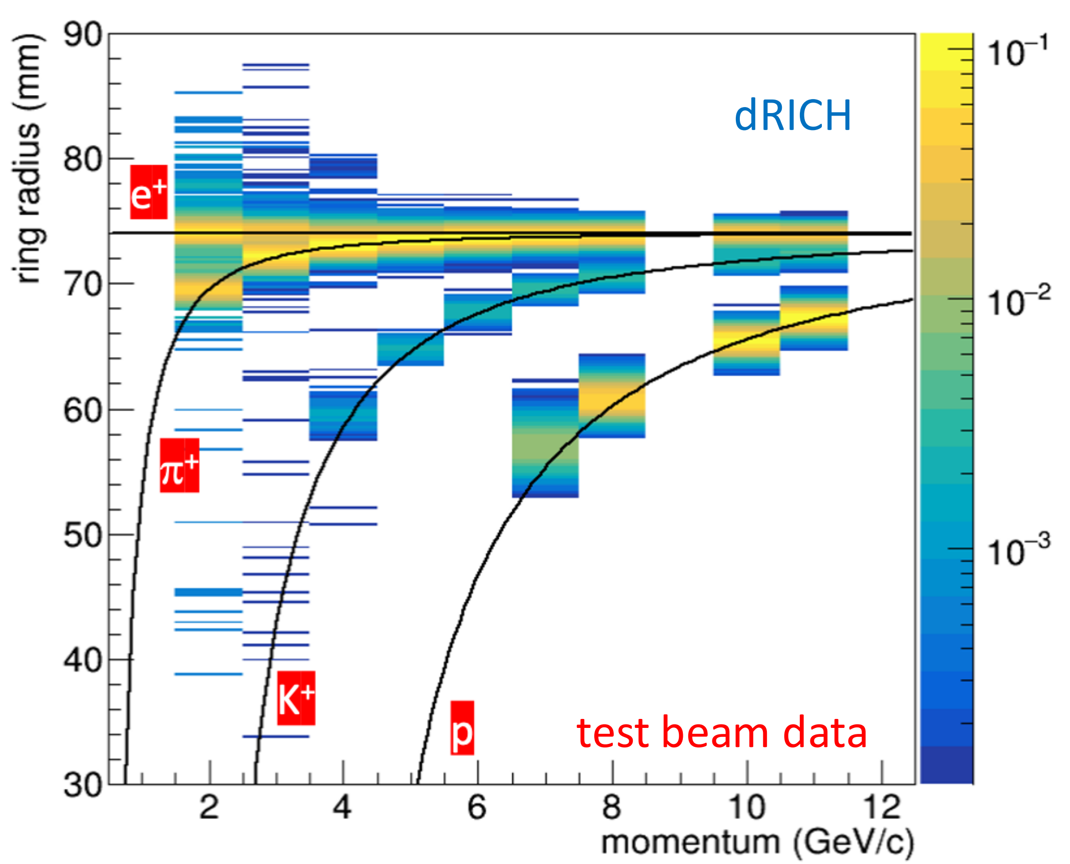
- Photon-Senso

world's first at ePIC

First time use of S
Photosensors in a

Time-of-Flight (Barrel, Forward)

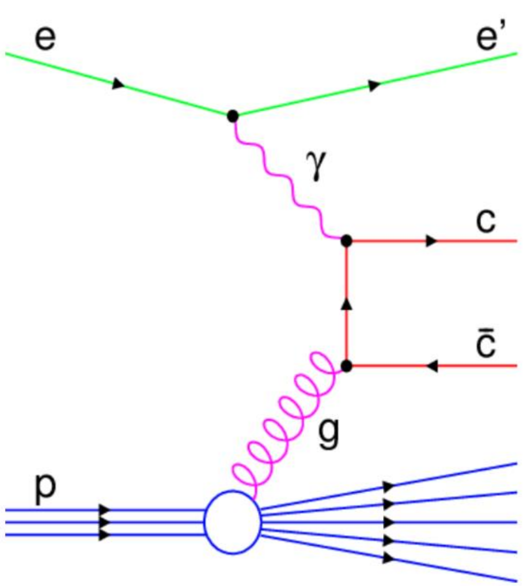




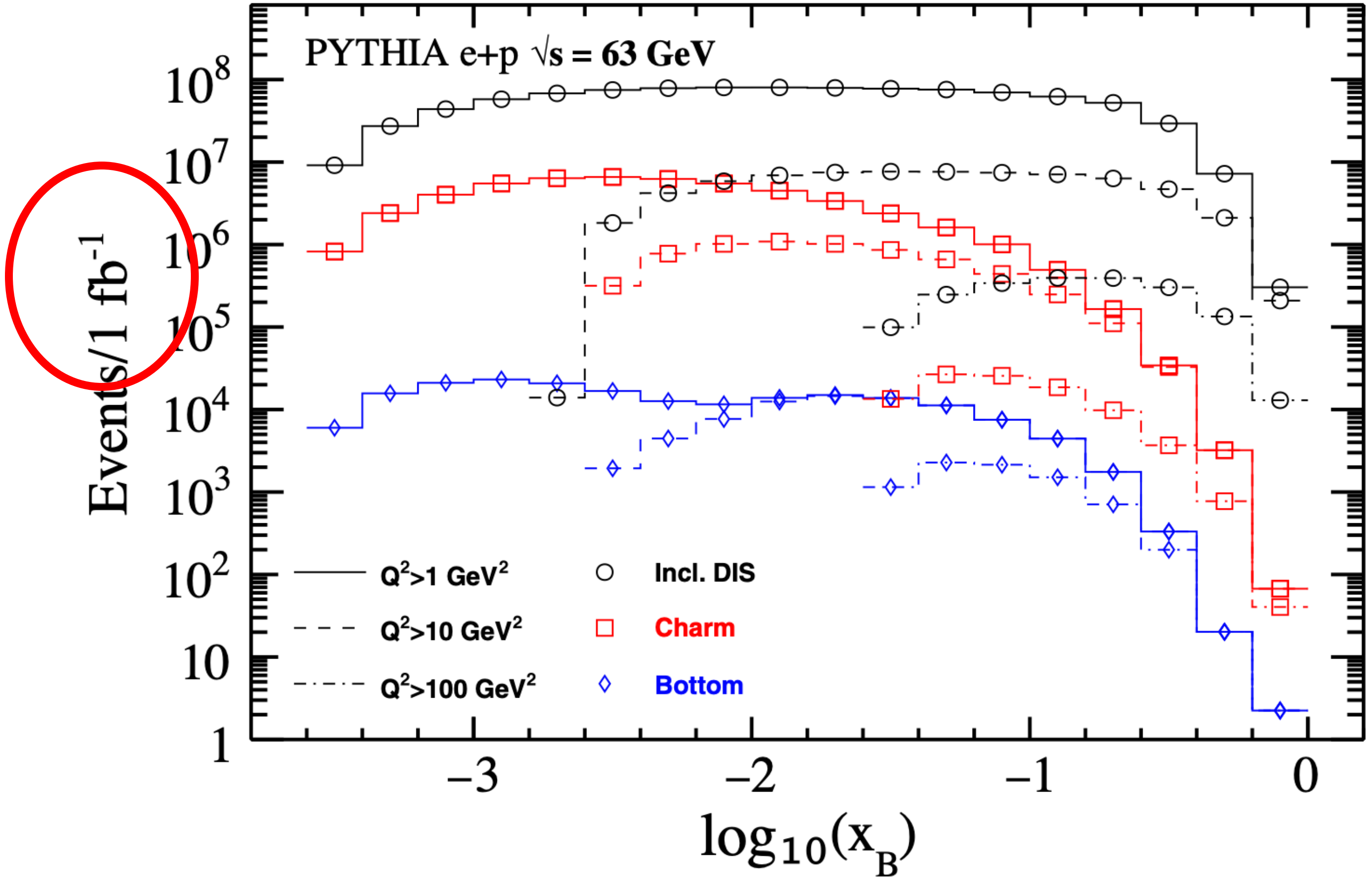
Some physics highlights

Disclaimer notice:
- Somehow "personal" selection
- ePIC Collaboration is moving towards TDR: many reference plots are on the making
- Tried "Hard Probes angle"

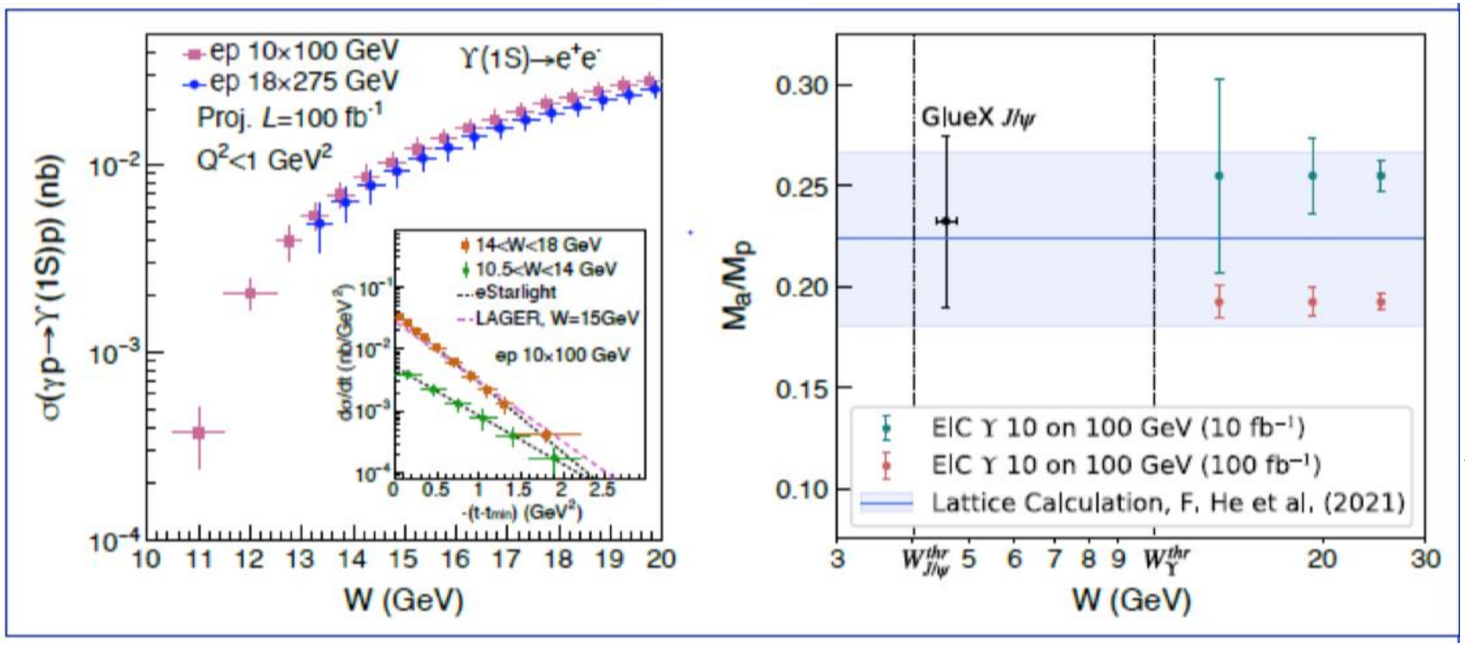
General remark: Heavy quark production in DIS: leading order contribution from photon gluon fusion process → a scanner for gluon distributions



M. Kelsey et al. Phys. Rev. D 104, 054002 (2021



Using vector mesons to unveil the proton mass composition



J/ψ and ϒ near threshold production gives access to trace anomaly Wang R. et al, Eur.Phys.J.C 80 (2020)

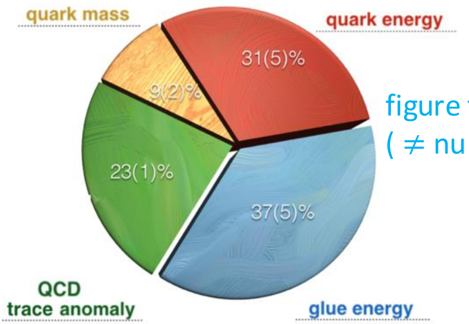
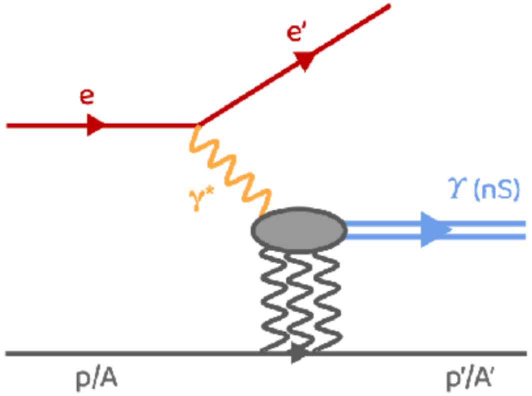
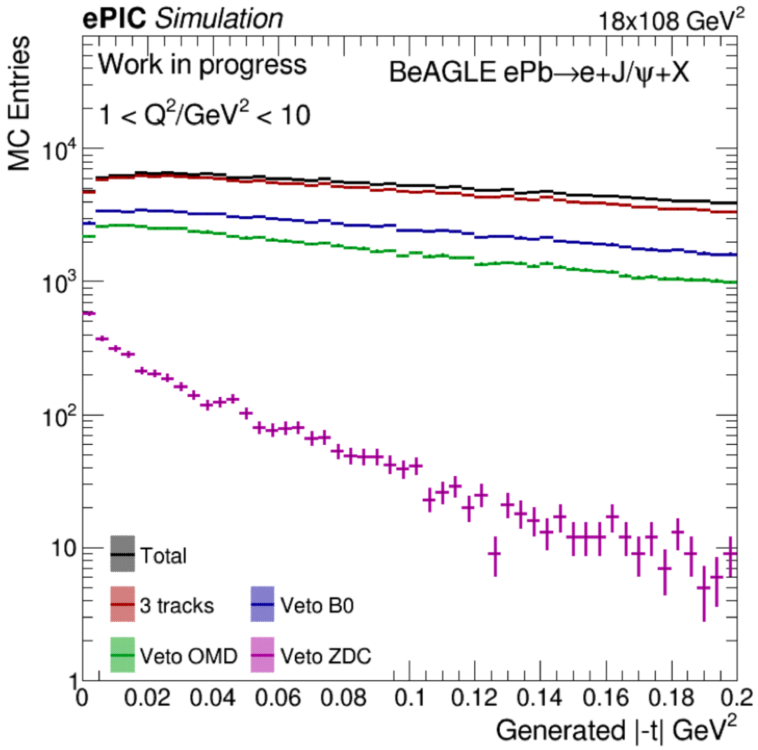


figure from Yi-Bo Yang et al, Lattice 2017
(≠ numbers in C. Lorce' et al., DIS2022)

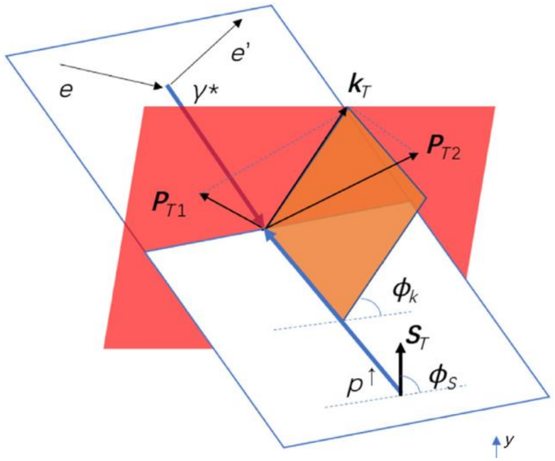
$$M_N = M_m + M_q + M_g + M_a$$



ϒ reconstructed in e^+e^- channel
ePIC is moving toward reconstructon (from standalone simulation)
→ here example of using far forward instrumentation to remove background from photon QC interaction in diffractive VM production in eA



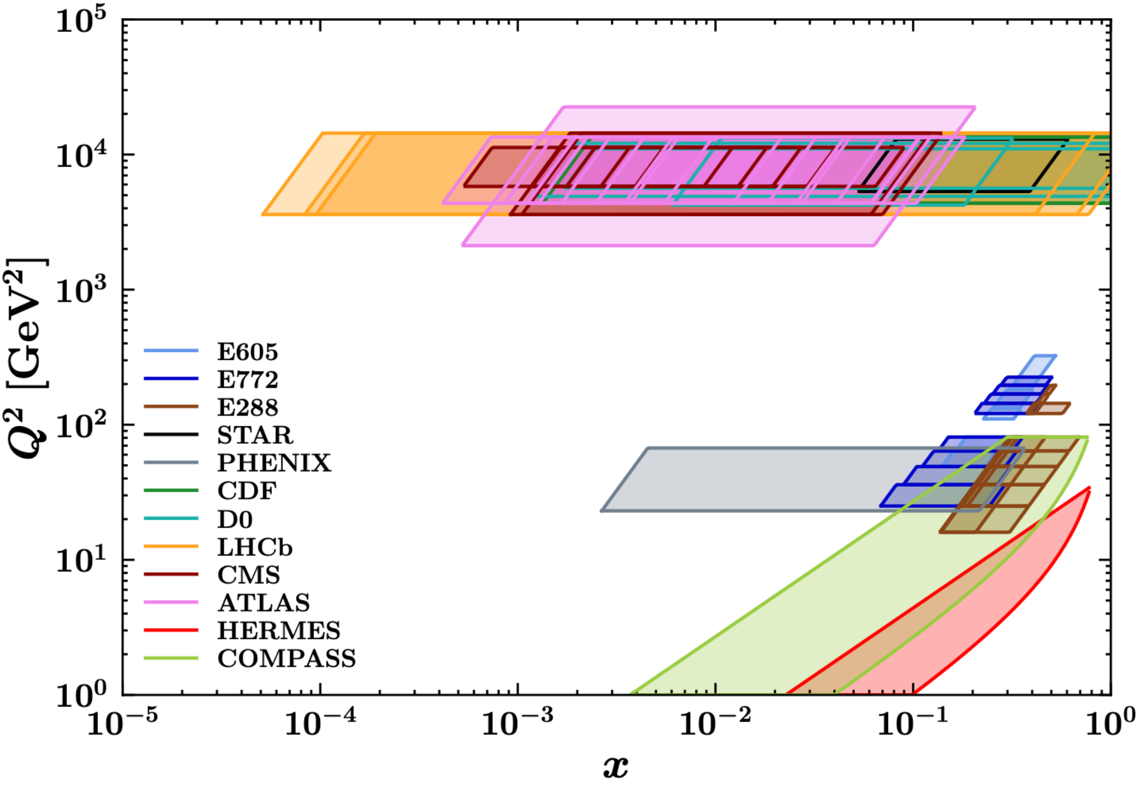
Semi-inclusive DIS and TMD



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

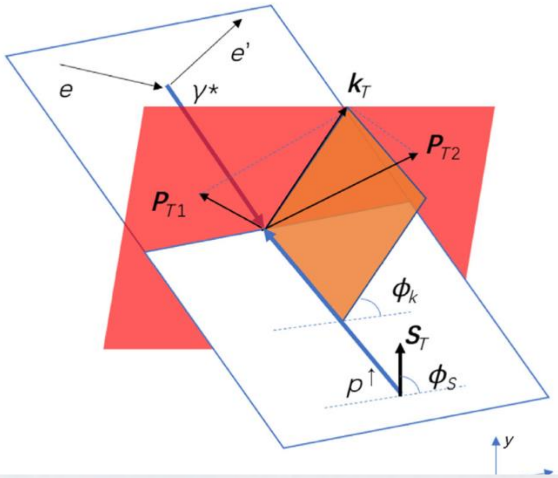
- **6-fold differential cross sections in SIDIS**
- **Azimuthal asymmetries and their modulations**

- 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))



MAPTMD24 extraction 2031 exp. points
A. Bacchetta et. al (MAP Coll.) JHEP **08** (24) 232, arXiv:2405.13833

Semi-inclusive DIS and TMD



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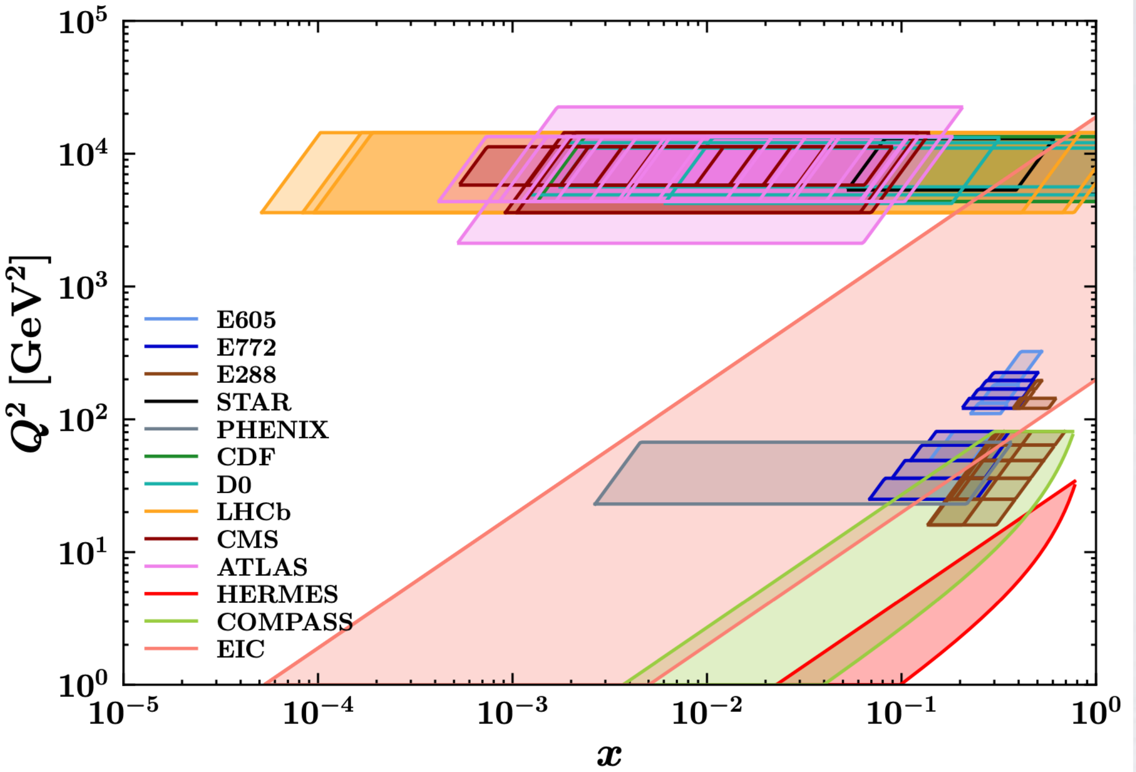
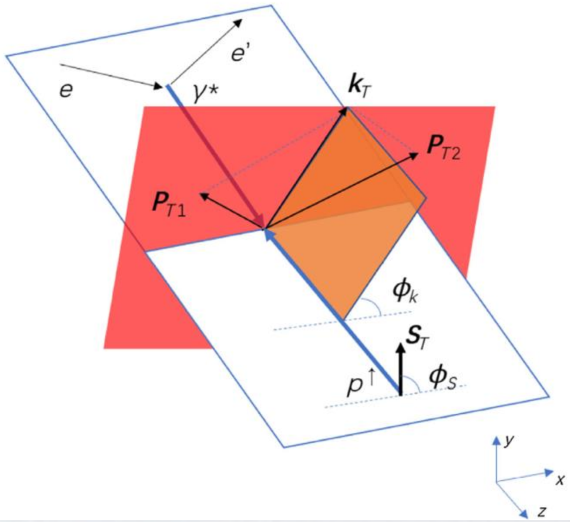


M. Cerutti, Ph.D. Thesis “[Precision phenomenology for nucleon femtography]”, Univ. Pavia (2024).

Semi-inclusive DIS and TMD



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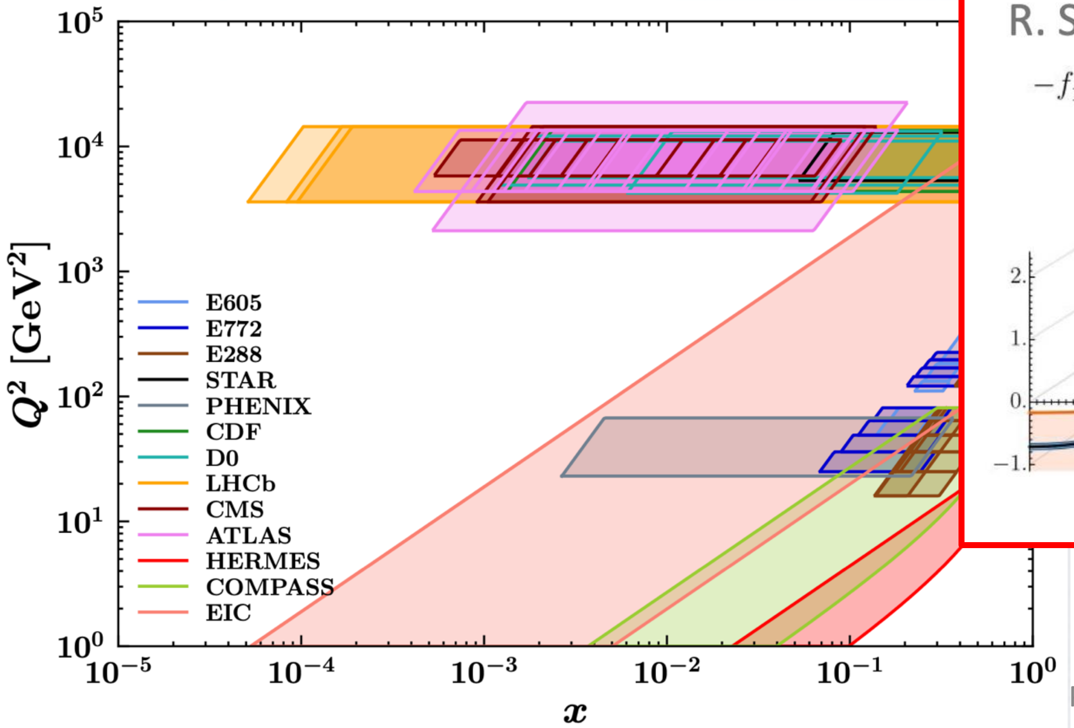
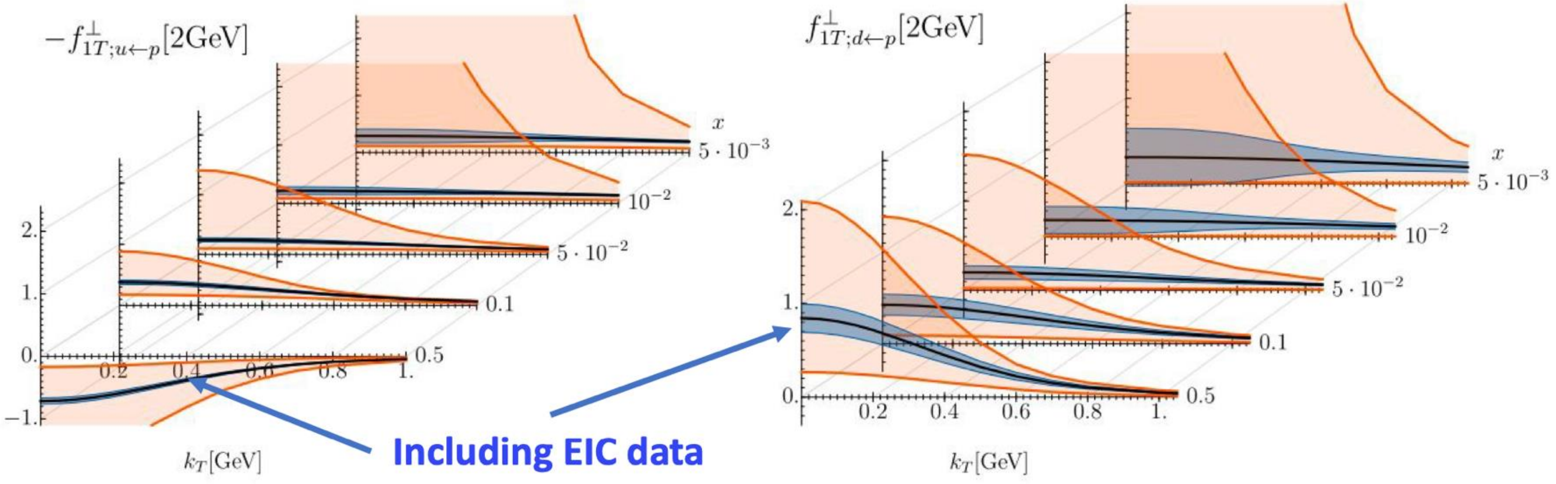


Expected impact on *u* and *d* quark Sivers distributions

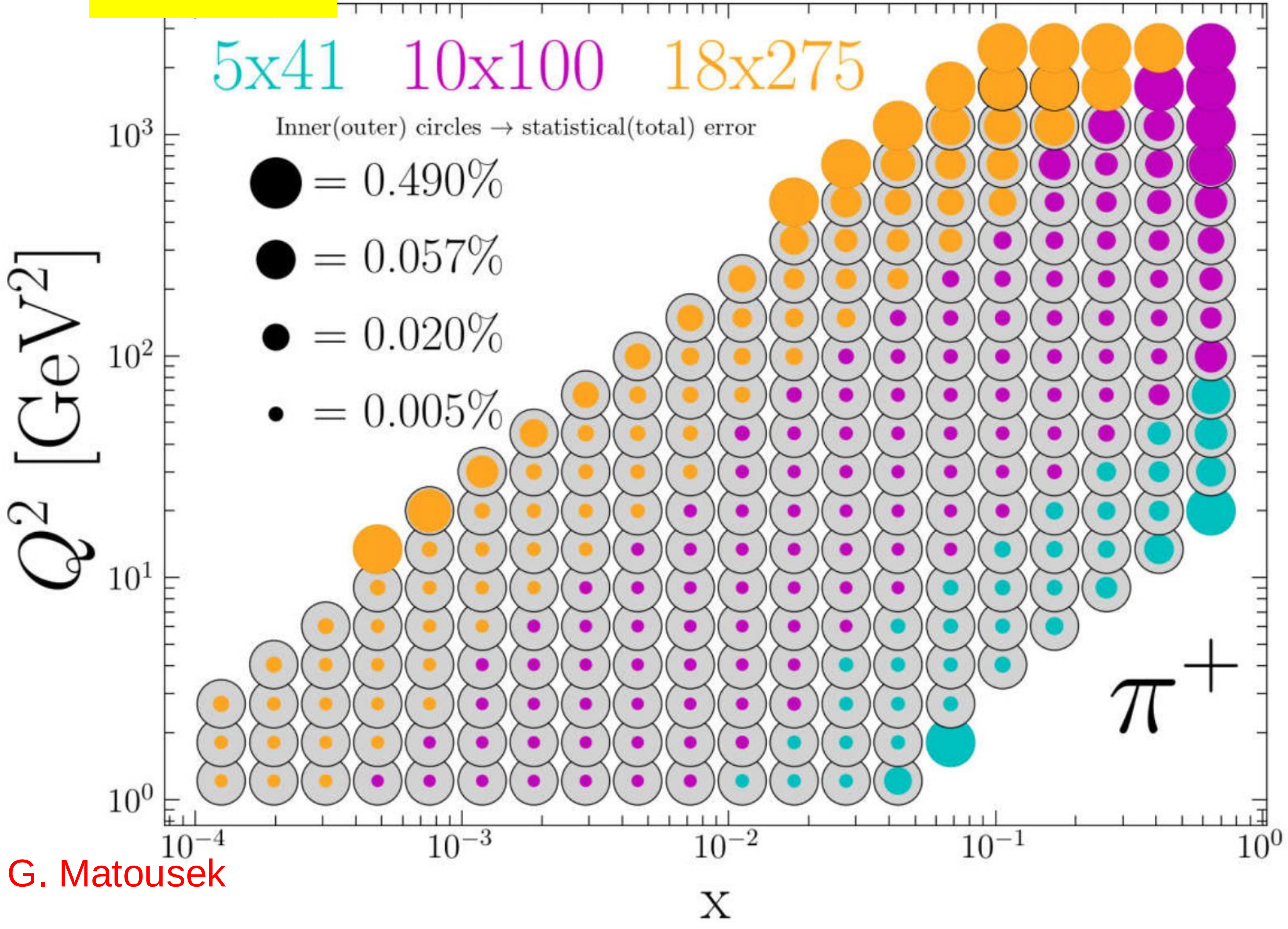
R. Seidl, et al., NIMA 1049 (2023) 168017



M. Cerutti, Ph.D. Thesis "Precision phenomenology for nucleon femtography", Univ. Pavia (2024).

SIDIS and TMD (unpolarized)

PRELIMINARY **ePIC** simulation

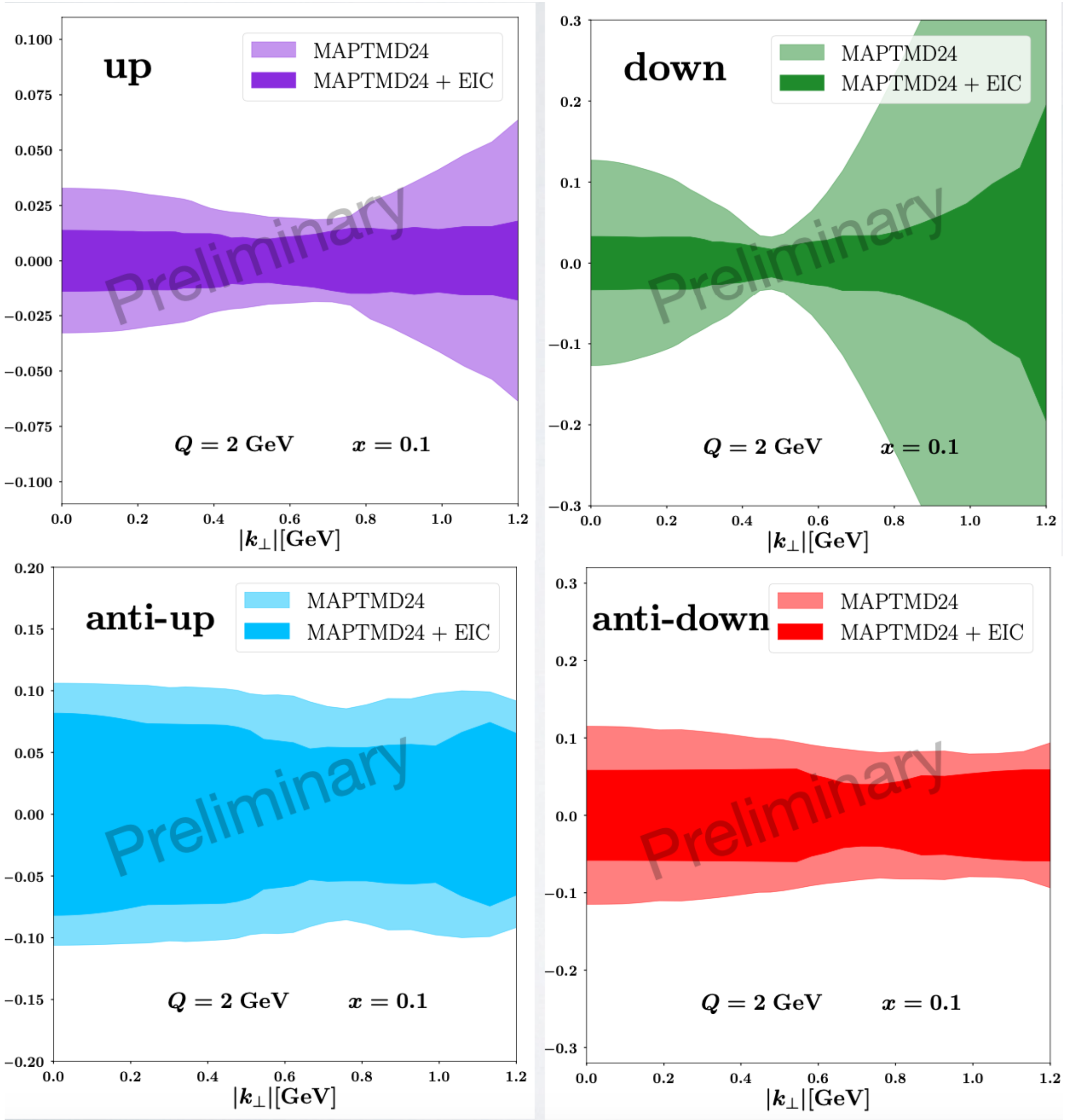


G. Matousek

$Q^2 > 1$ GeV^2
W>3 GeV
0.05 <y <0.95
at least 1 pion!
pT>0.1 GeV

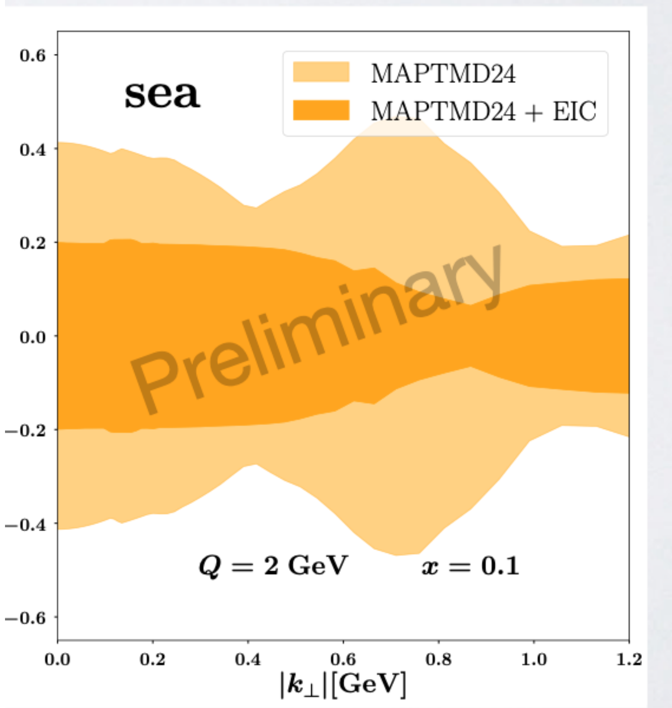
- collider flexibility is an asset!
- ePIC is moving from quick MC/standalone generators to full reconstructon flow!

Semi-inclusive DIS and TMD



MAPTMD24 extraction 2031 exp. points + 4532 EIC pseudodata points

EIC	# pts.	lumi [fb^{-1}]
5x41	1273	2.85
10x100	1611	51.3
18x275	1648	10

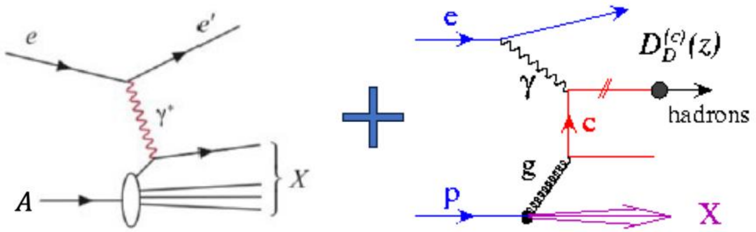


L. Rossi M. Radici A. Bacchetta (

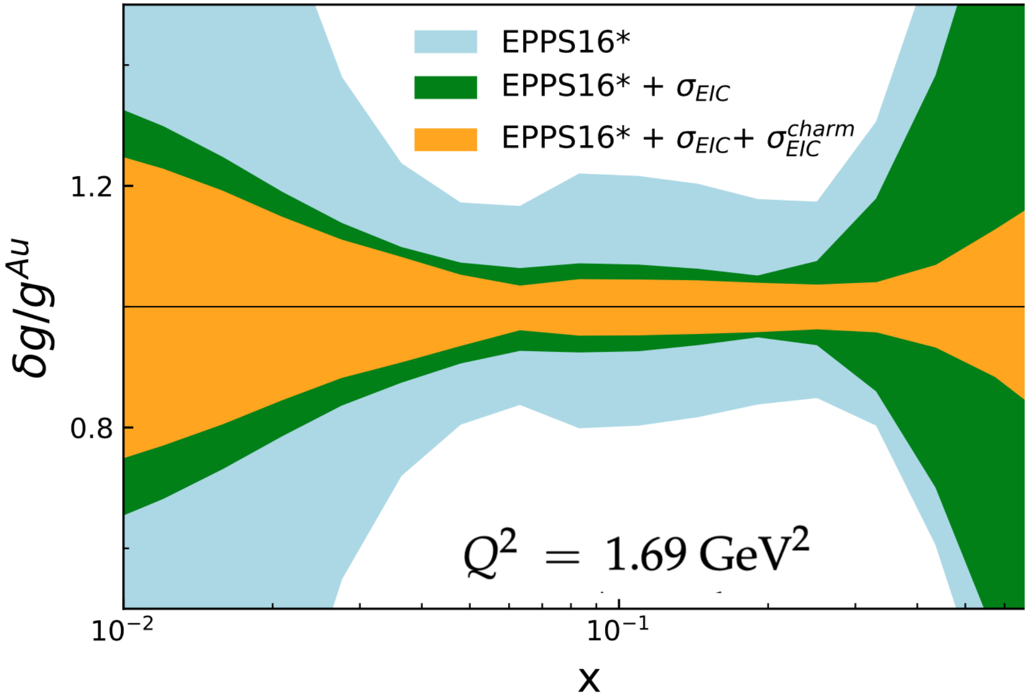
exploring gluons in the nucleon

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!

$$(Q_s^A)^2 \sim cQ_0^2 \left(\frac{A}{x}\right)^{1/3}$$

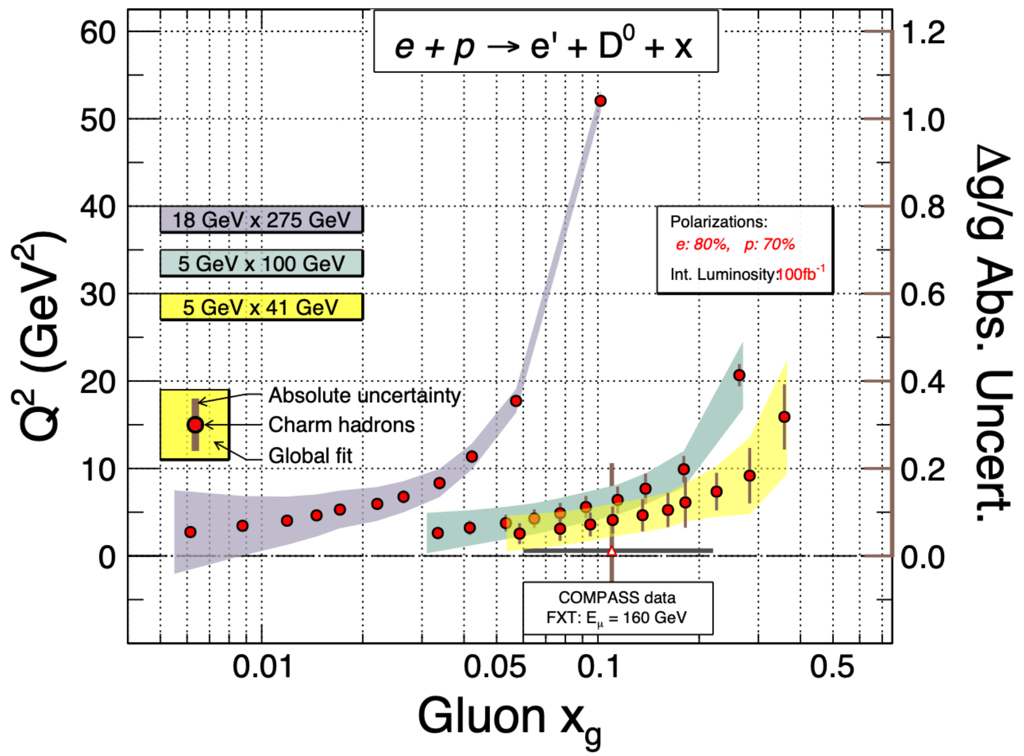


R. Abdlul Kalek at. al (EIC Yellow Report) Nucl. Phys A 1026 (2022) 122447



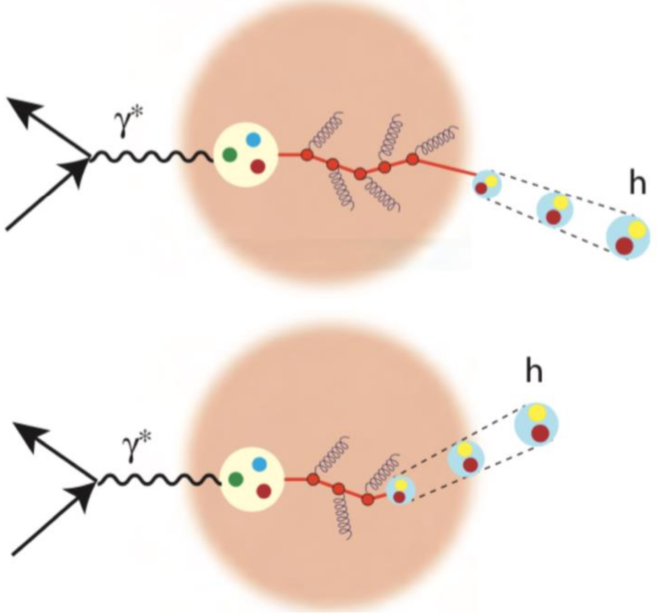
- **charm** → tag photon-gluon fusion → direct access to gluon

J. Arrington et al., arXiv:2102.08337



hadronization and CNM

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

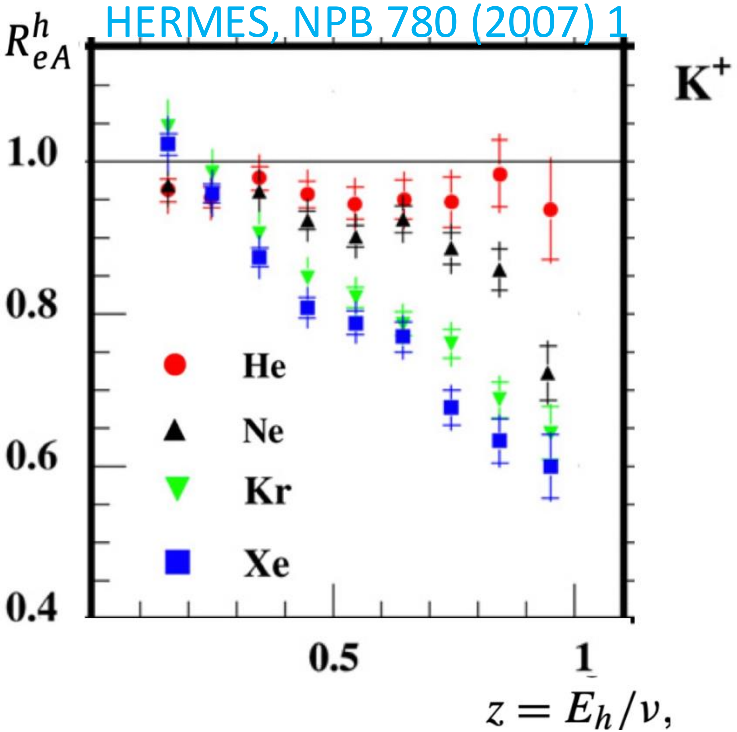


Basic idea: use Q^2 and $\nu = q{\cdot}p/M$ to control **where** hadronization happens

- 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)

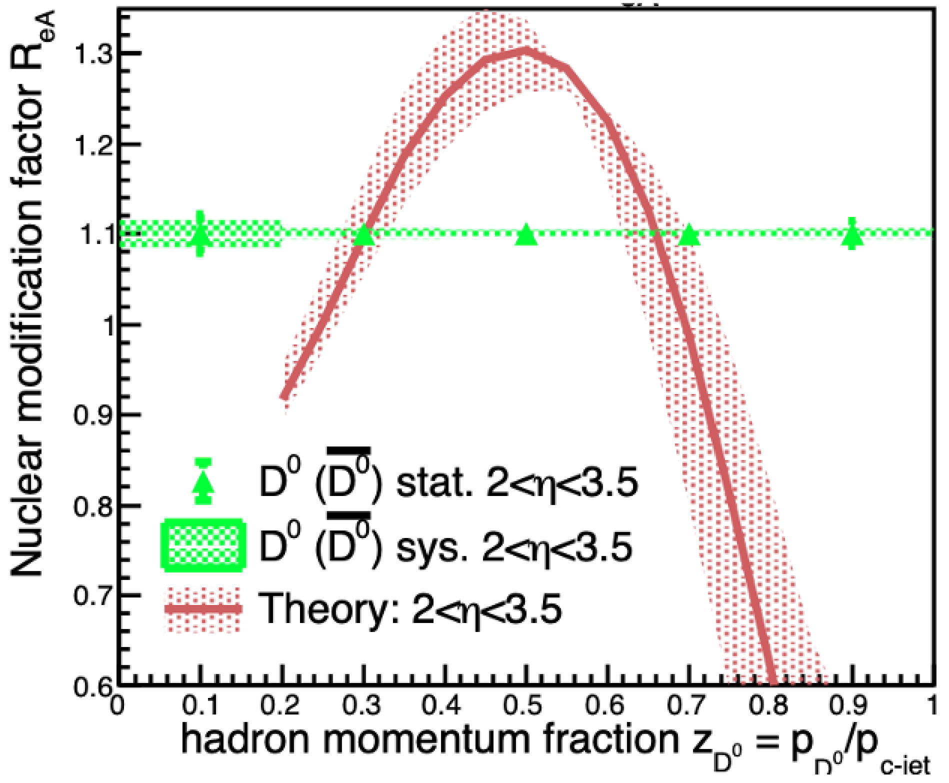
Results for light hadrons only at much lower energy (fixed target e beam 27.6 GeV)

HERMES, NPB 780 (2007) 1



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

C. Wong @ DIS2022

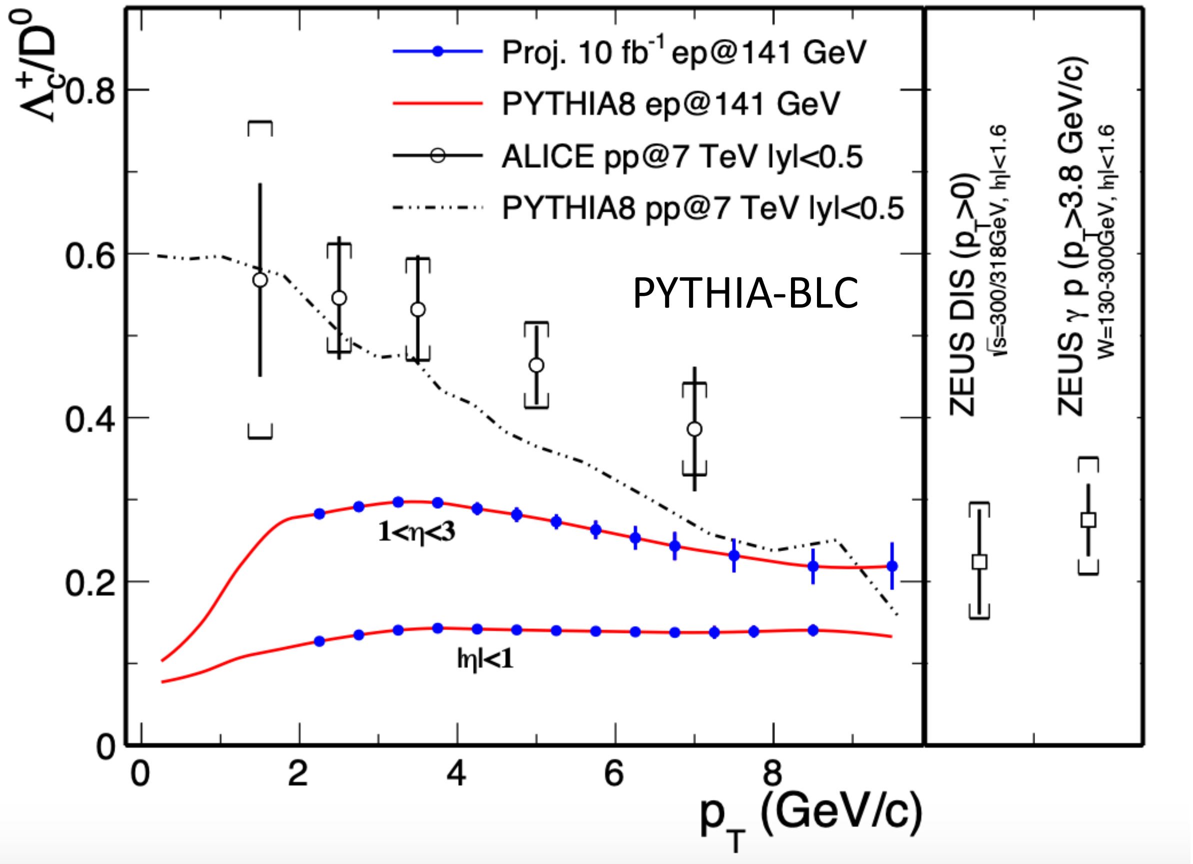


$\mathcal{L}^{int}_{ep} = 10.0\ \text{fb}^{-1},\ \mathcal{L}^{int}_{eA} = 0.05\ \text{fb}^{-1}$

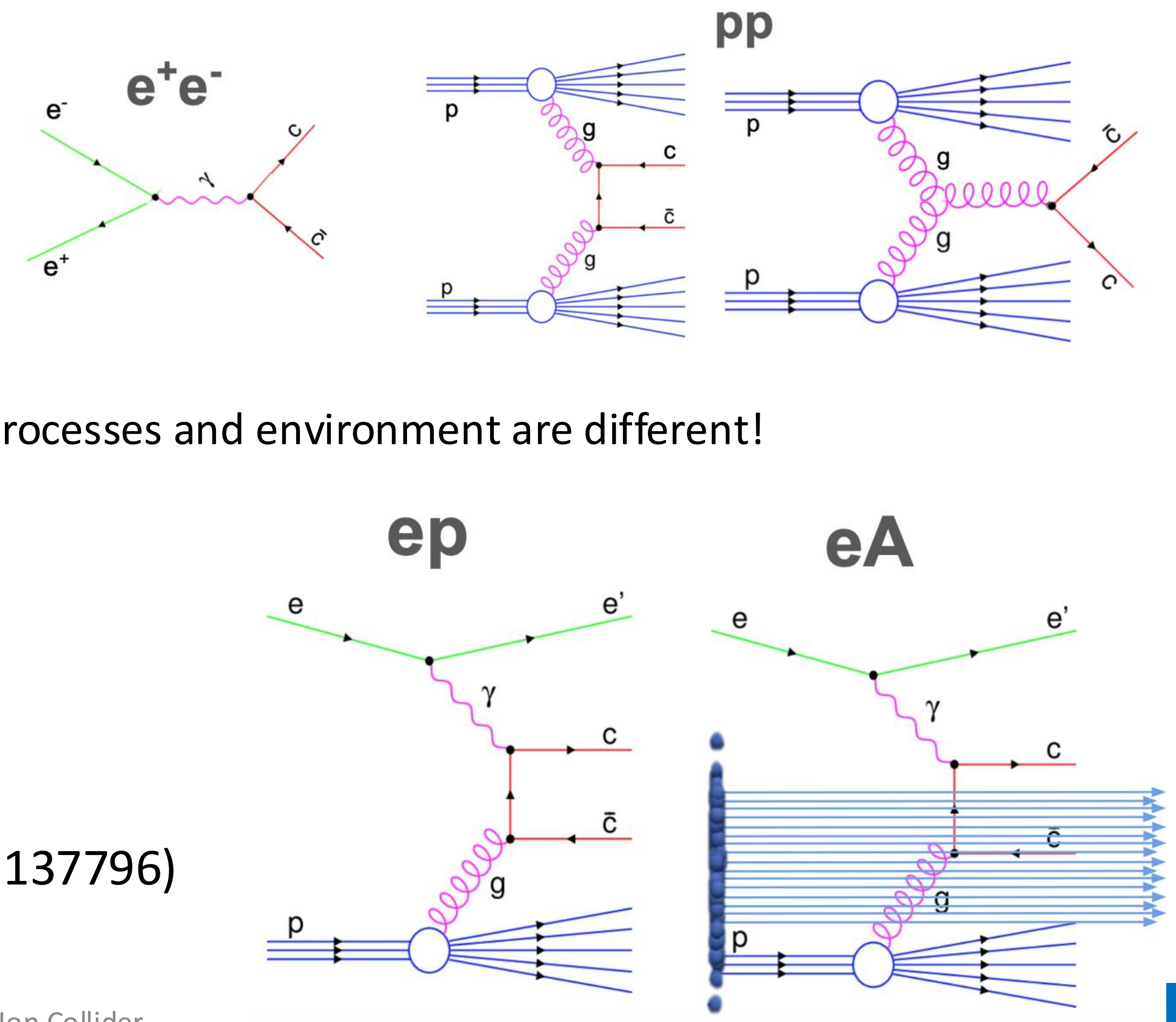
Theory curves from: Li H, Liu Z and I. Vitev, PLB 816 (2021) 136261

hadronization in ep: Λ_c/D_0

J. Arrington et al., arXiv:2102.08337



LHC surprise: universality of fragmentation functions violated seen ofr HF **baryons** already in **pp**



processes and environment are different!

- HERA2 Λ_c total lumi was just **120 pb^{-1}**
- ALICE studies vs event multiplicity (PLB 839 (2023) 137796) to be compared with ep mult. @ EIC!


WHEN?

EIC Schedule (official)

CD-3A:

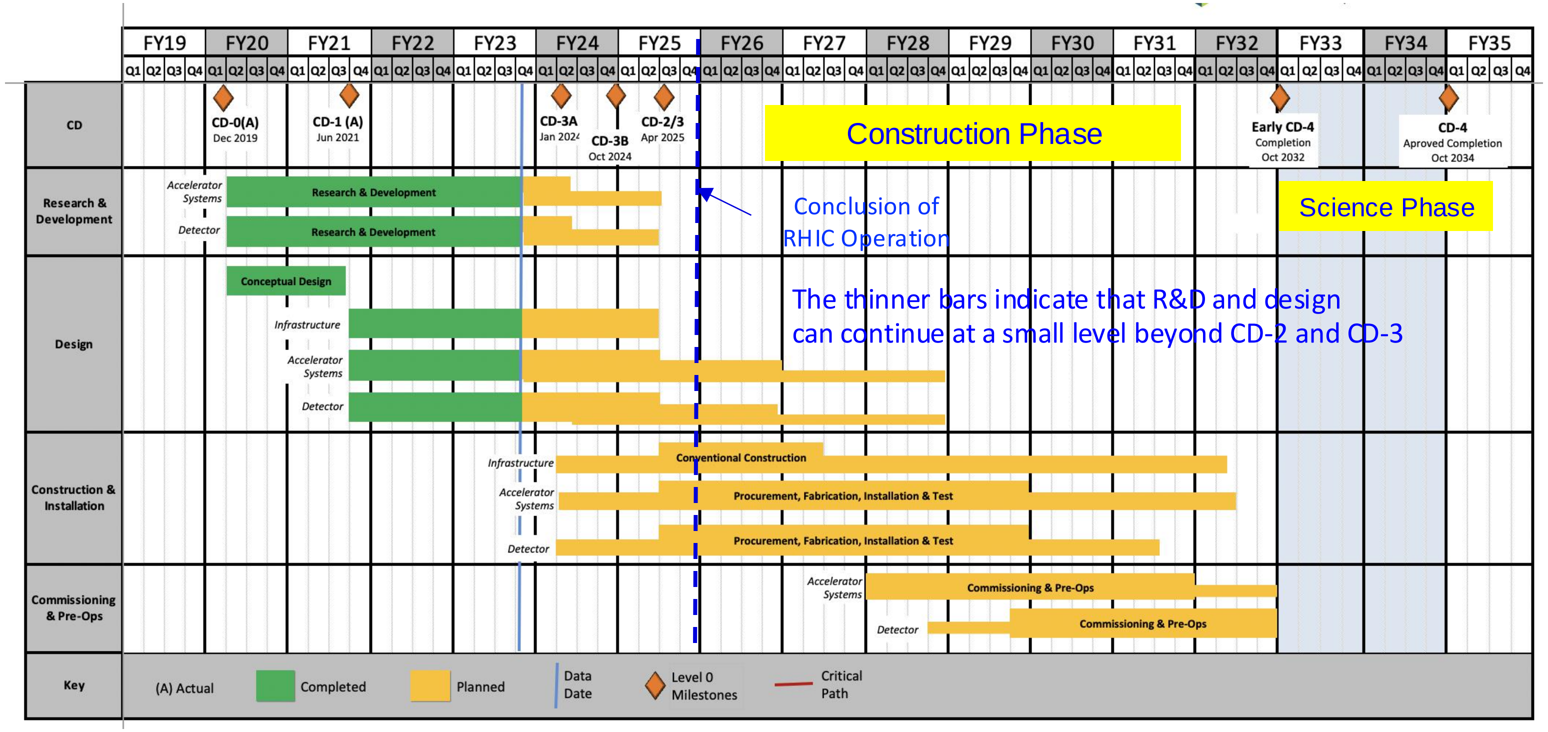
Approve start of long-lead procurements
CD-3A items passed final design review
All interfaces related to them are frozen
Waiting for ESAAB meeting for authorization

CD-2:

Approve prelim. design for all subdetectors
Design Maturity: >60%
Need "pre-"TDR (or draft TDR)
Baseline project in scope, cost, schedule

CD-3:

Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR



September 2022 EIC received $138M DOE Inflation Reduction Act funding → CD-3A

Current EIC Critical Decision Plan	
CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	March 2024 ✓
CD-3B	**October 2024**
CD-2/3	**April 2025**
early CD-4	October 2032
CD-4	**October 2034**

EIC Schedule (best guess from project management)

CD-3A:
Approve start of long-lead procurements
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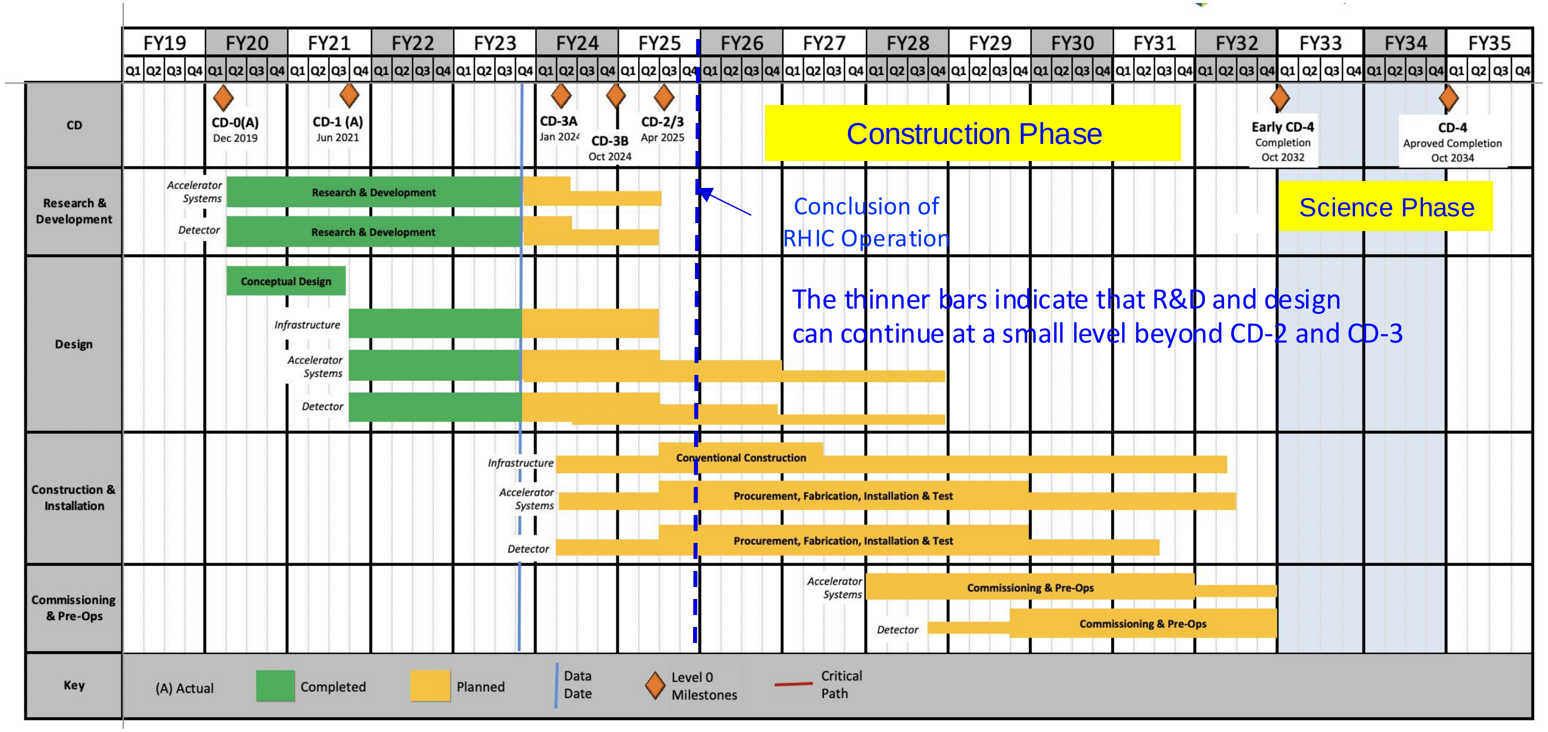

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CD-2/3	**April 2025**
early CD-4	October 2032
CD-4	**October 2034**

September 2022 EIC received $138M DOE Inflation Reduction Act funding → CD-3A

Updated Project Schedule: based on the actual appropriated FY24 funding ($98M), on uncertain FY25 budget scenarios (President's Budget is only ~$113M)

Updated EIC Critical Decision Plan	
CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	March 2024 ✓
CD-3B Review	**January 7-9 2025**
CD-2/3 Review	End of 2025
early CD-4	December 2034?
CD-4	December 2036?

(courtesy from R. Ent @ QNP2024)

Summary and outlook

- EIC is a unique, high-energy, high-luminosity, polarized beam collider for the ultimate **understanding of QCD**: the only new collider in the 15-20 years
- ePIC Collaboration formed in 2022 and ePIC detector on track towards **TDR** (CD-2 → CD→ 3)
- The ePIC detector was designed to fullfill the physics requirements: several **new technologies** will be also implemented → benefit for the larger community

new microscope delivery time:
8-9 years to first collisions for physics

a robust "early physics program" being discussed:
phased-approach for accelerator

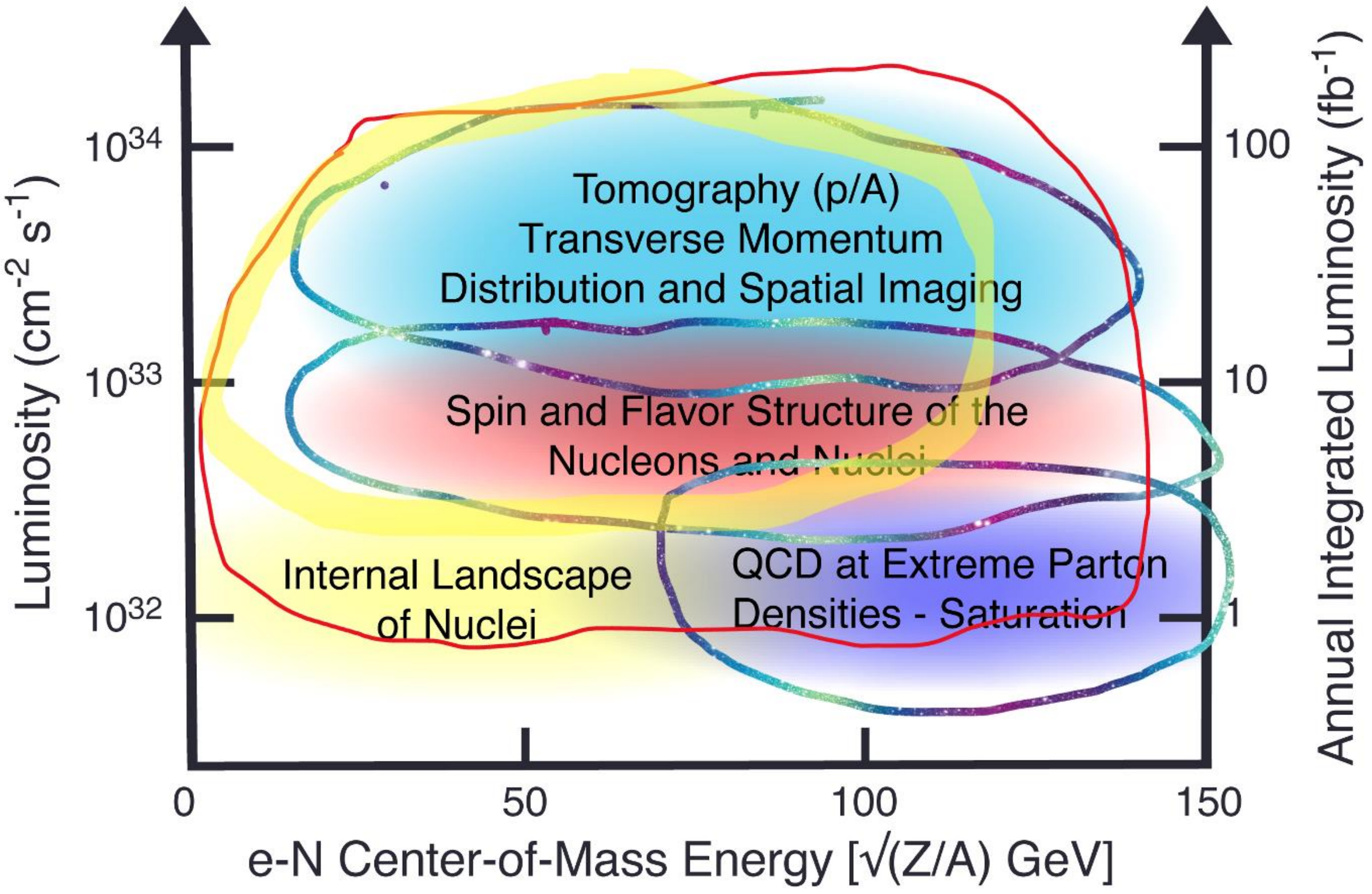
EIC physics will provide "unique baseline input" (PDF, nPDF, hadronization, ..) to "Hard Probes Conference" physics, stay tuned!

Some additional references (and many credits for some slides borrowed by these colleagues):

- EIC overview R. Ent @QNP 2024
- ePIC detector S. Dalla Torre @ CERN Deteector Seminar
- TMD/GPD: S. Fazio @ Mainz 2023
- exclusive procesess/diffraction + far forward/backward detectors A. Jentsch @ Diffraction 2024

Backup

EIC: luminosity vs physics reach



Spin

Mass

3D Imaging

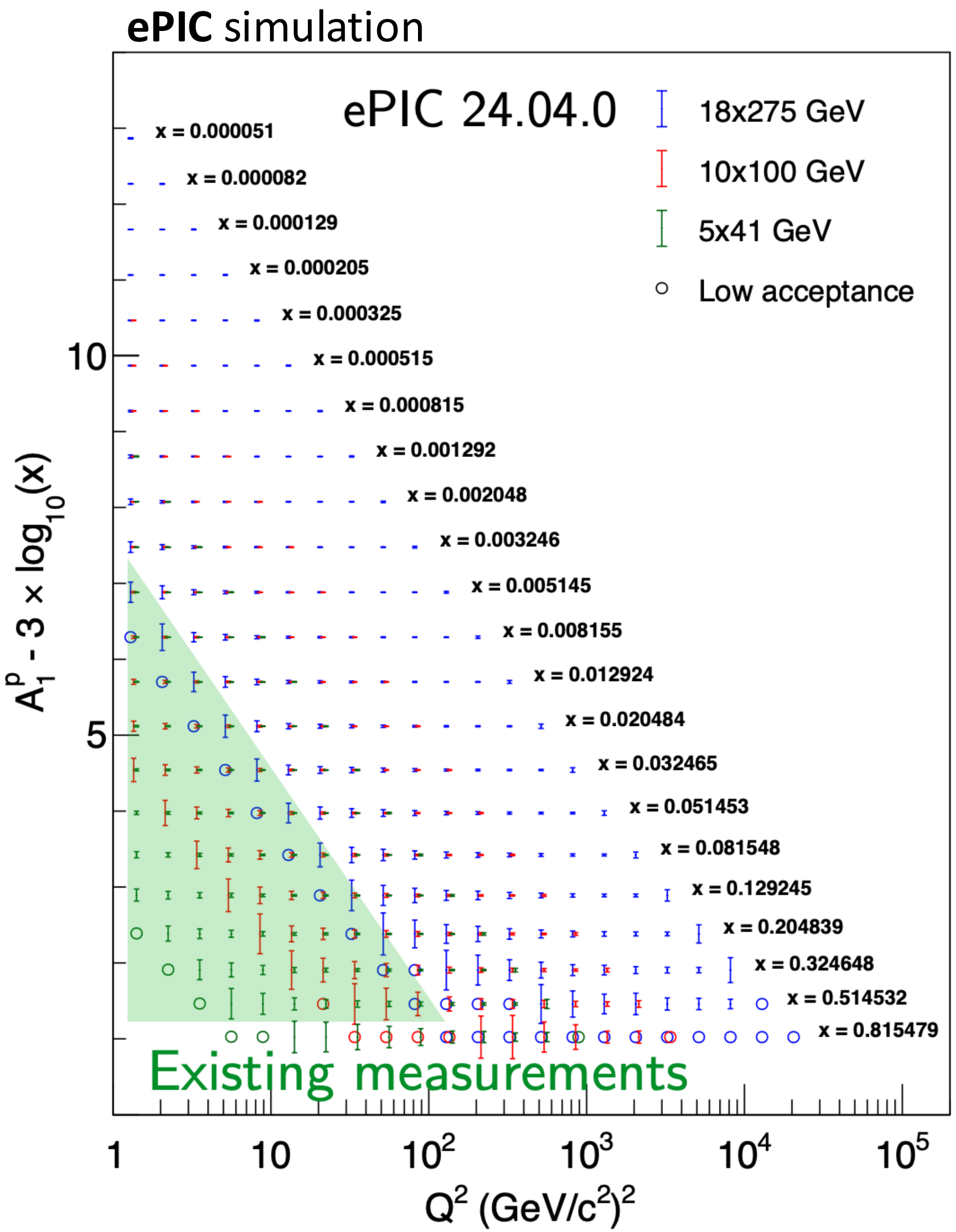
Quarks, Gluons & Nuclei

Dense gluon systems

Nucleon spin structure function

Double-spin asymmetries
Provide access to g_1 : spin-dependent structure function

Access to unexplored Q^2-x region, while allowing benchmark to existing data

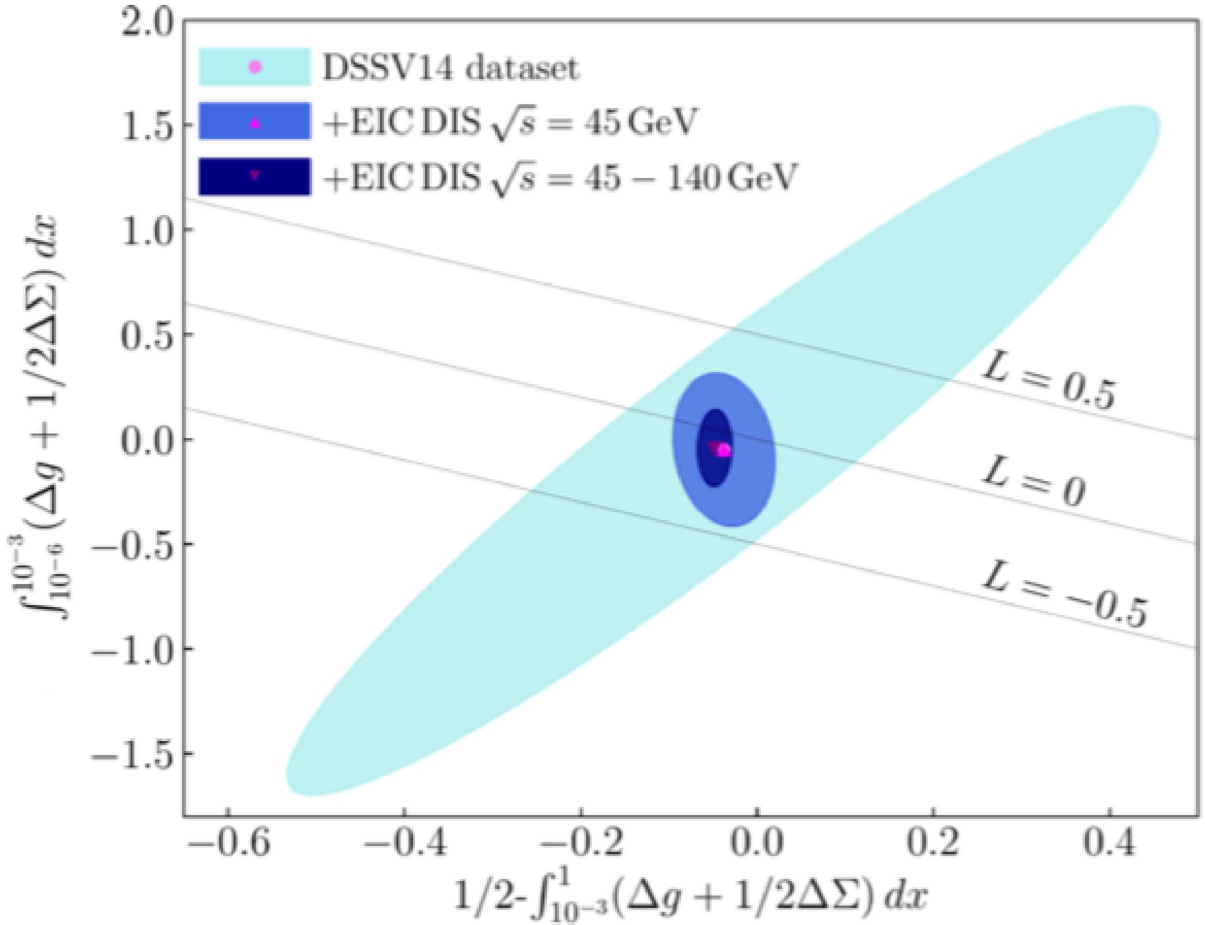


Solving the proton spin puzzle

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

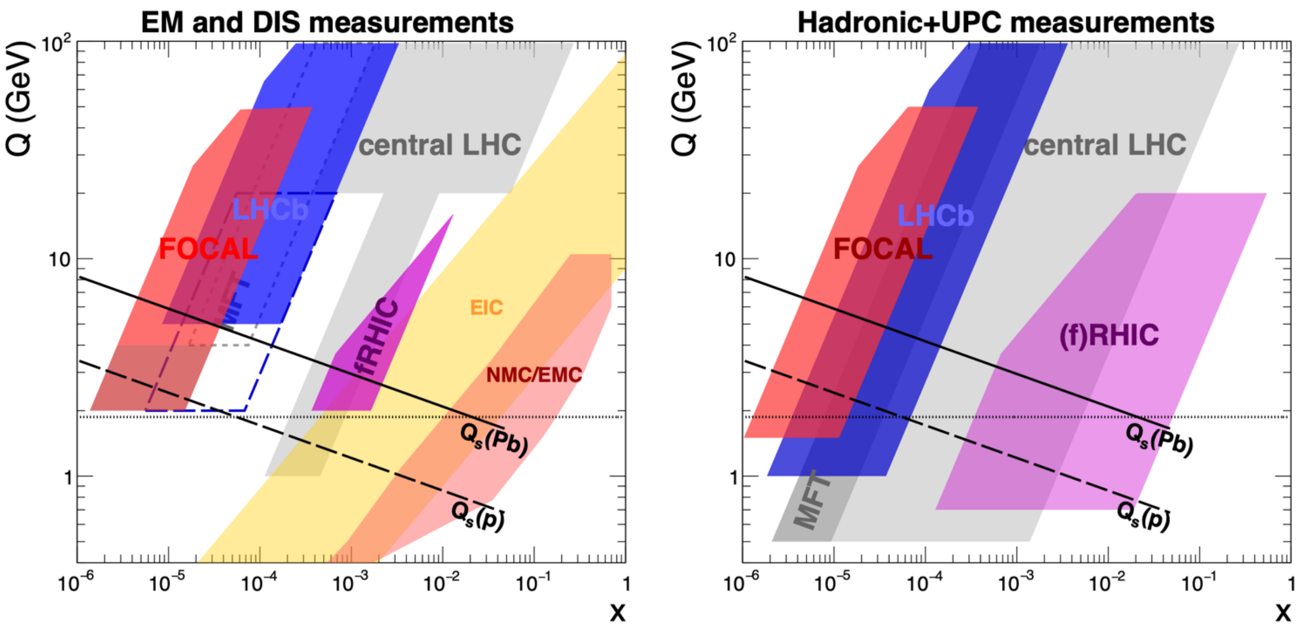
quark and gluon spin — orbital angular momentum

[R. Abdlul Kalek at. al (EIC Yellow Report) Nucl. Phys A 1026 (2022) 122447]



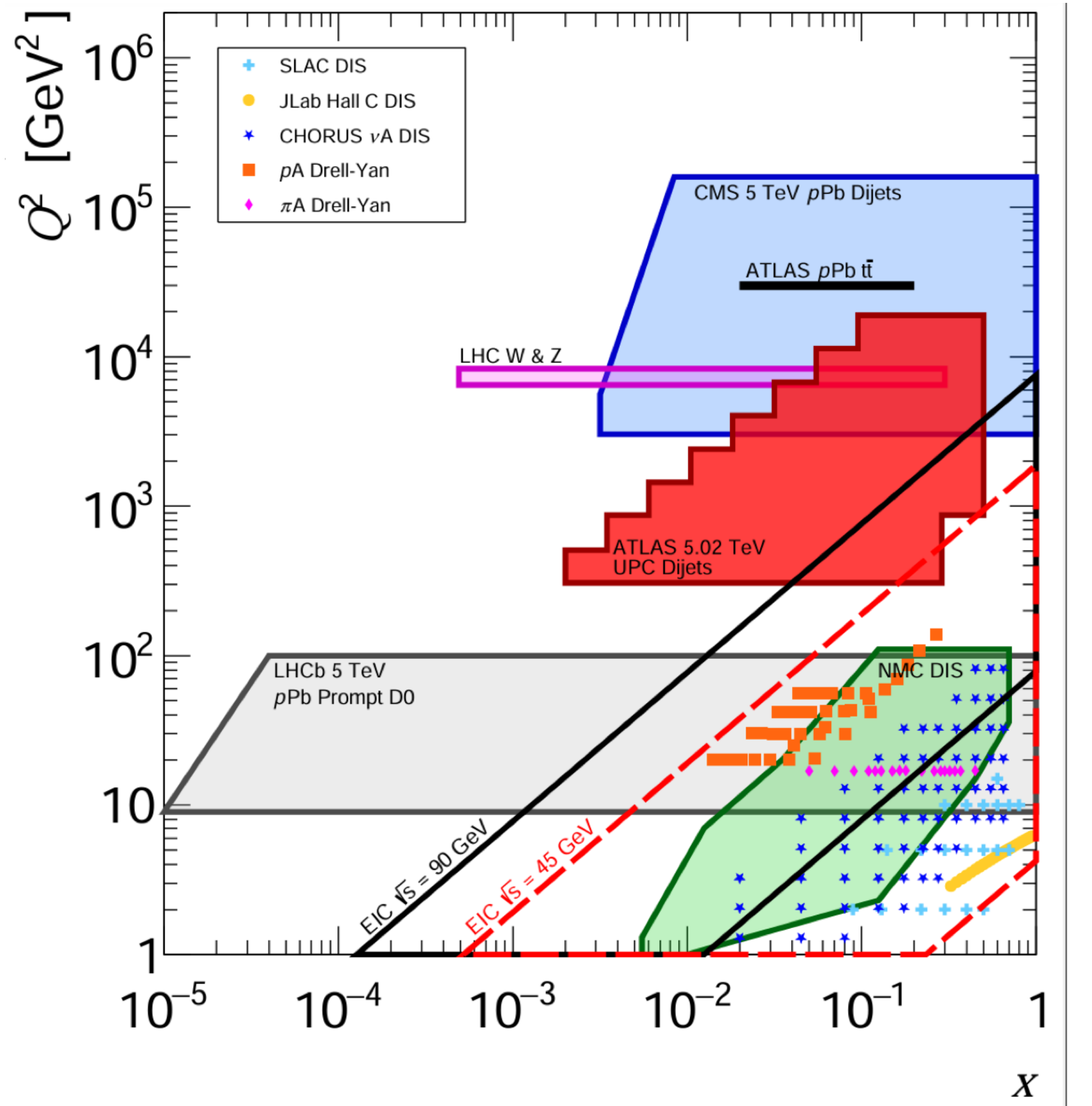
DIS, UPC and LHC/EIC/RHIC

from ALICE Collaboration, FOCAL LoI, CERN-LHCC-2020-009



Nice EIC & LHC & RHIC complementarity to kinematically map the nucleon....

B. Gilbert talk at this conference

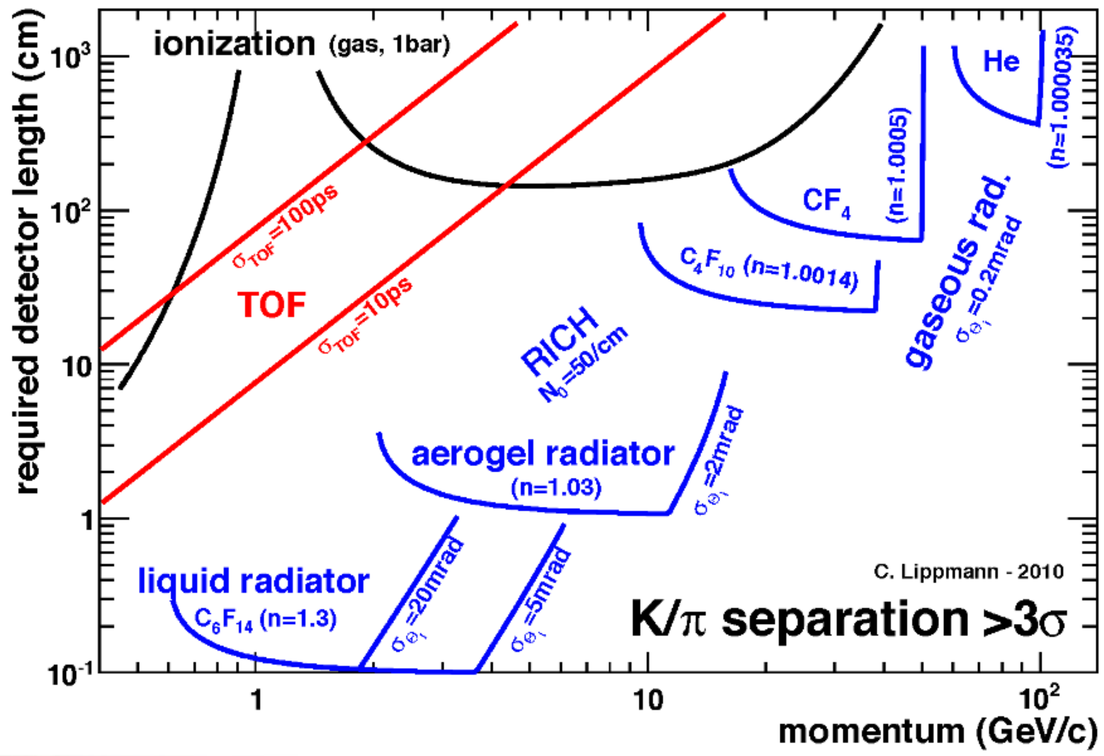


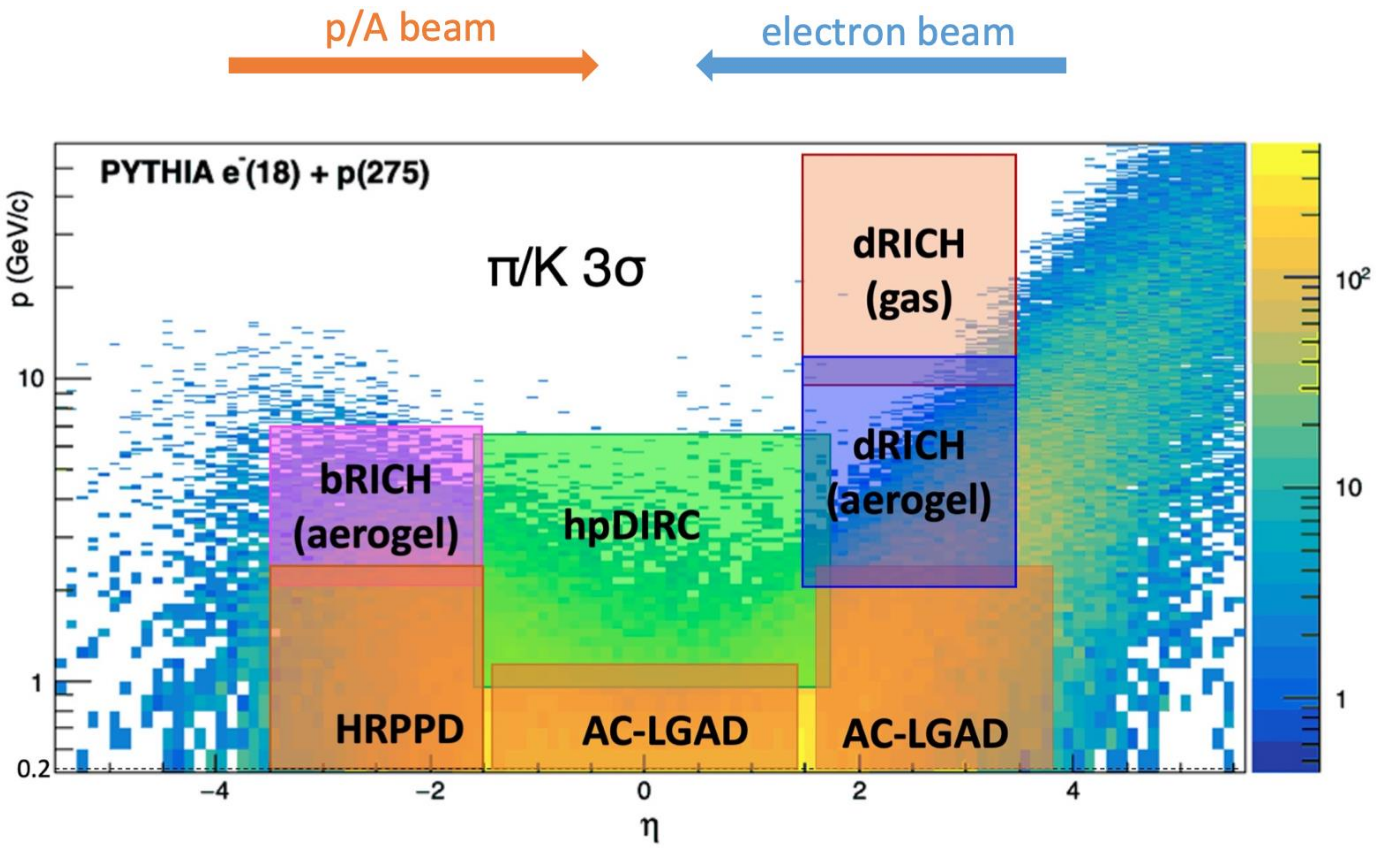
PID technlogies and momentum coverage

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 Collaboration

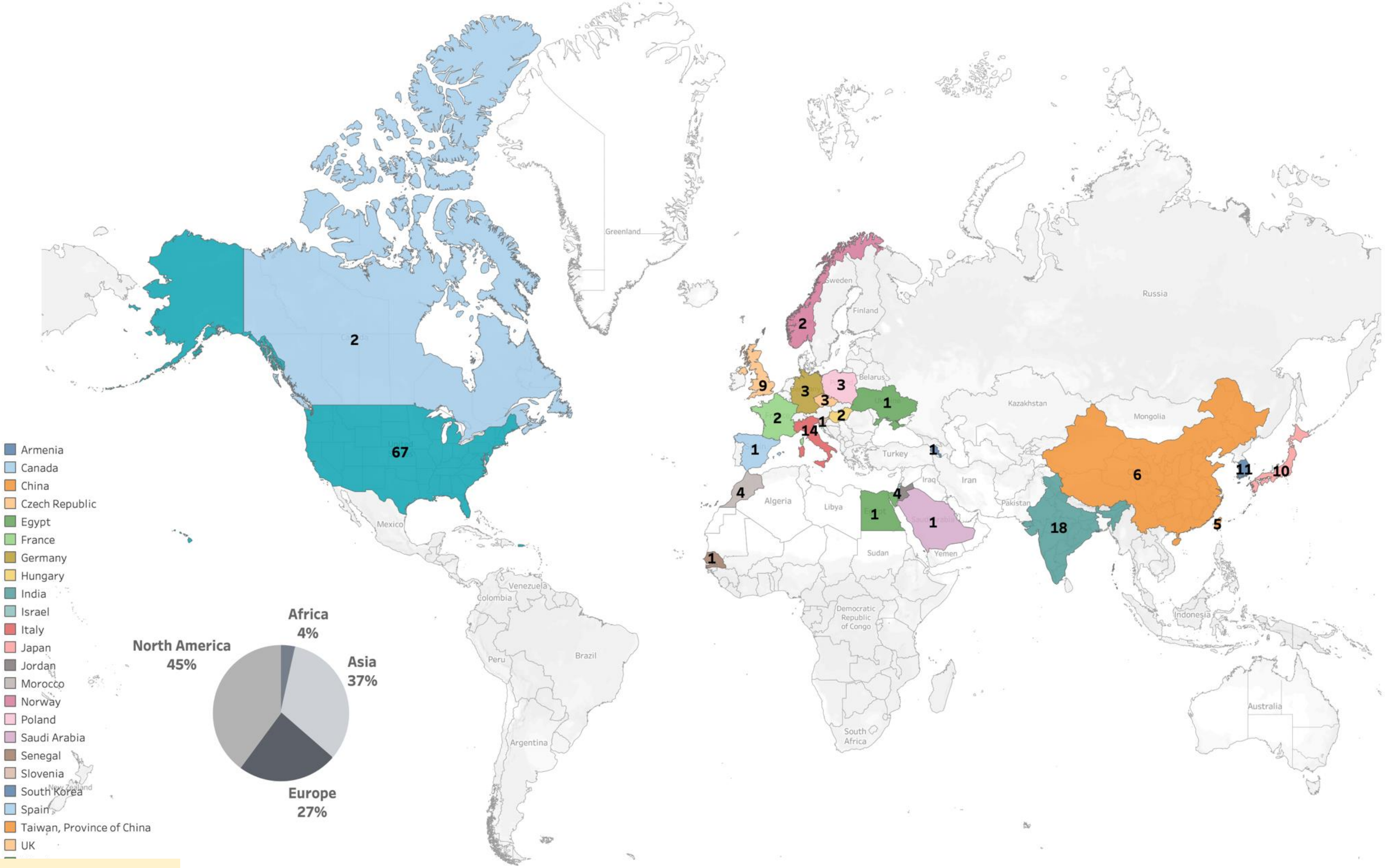
https://www.bnl.gov/eic/epic.php

ePIC Initiated in July 2022

> 850 collaborators

175 institutions
25 countries

67/175 – 35% US institutions



EIC User Group: 1537 members/40 countries

DOE national labs partnership (not incl. BNL/JLAB)

ePIC

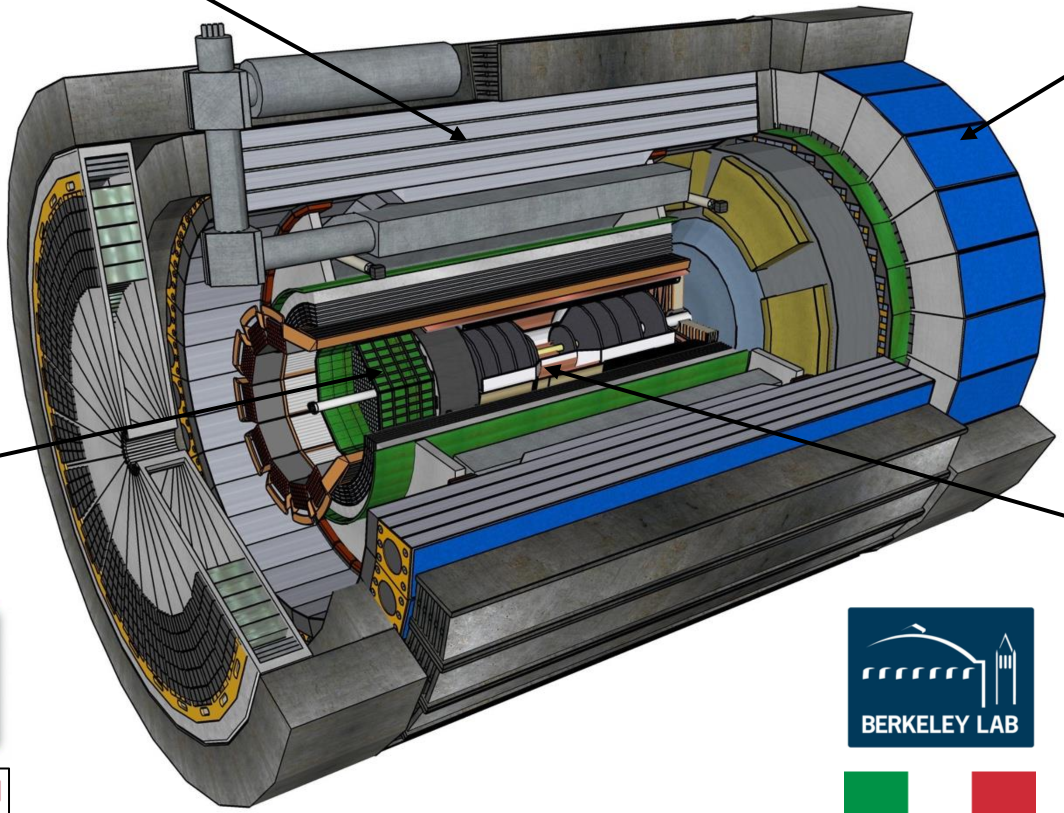
Barrel Electromagnetic Calorimeter

Argonne NATIONAL LABORATORY

Forward Hadron Calorimeter

OAK RIDGE National Laboratory

(ORNL also large involvement in DAQ/electronics)



Backward Electromagnetic Calorimeter

NSF

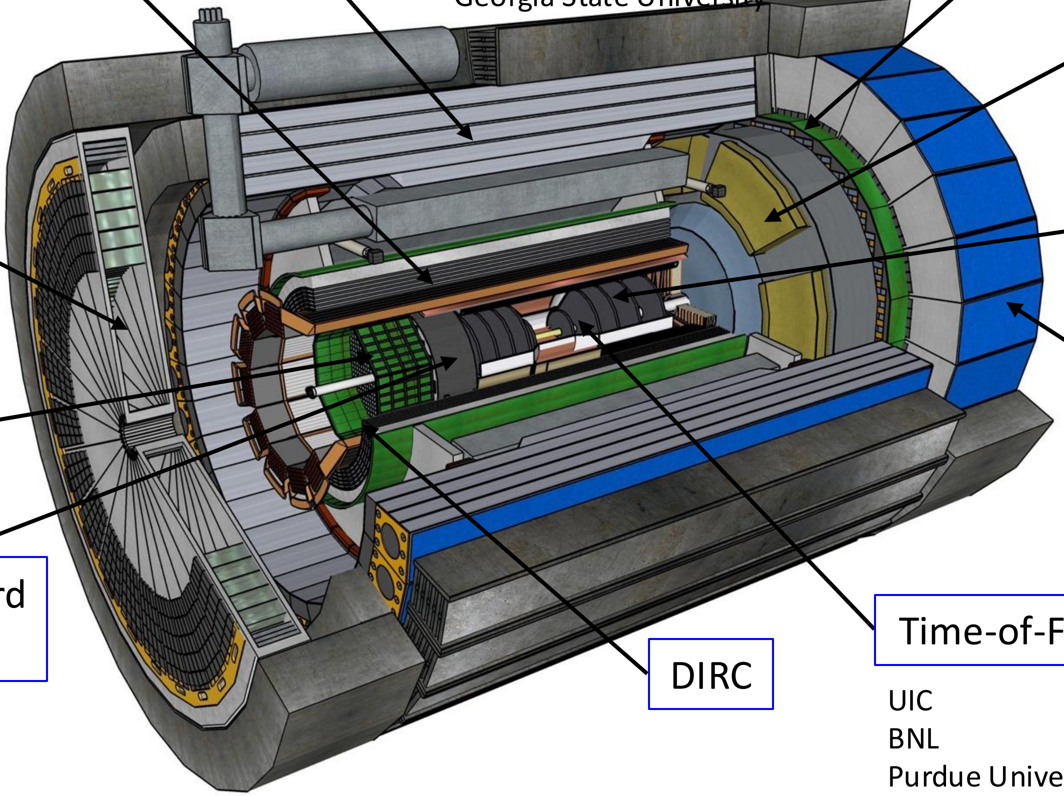
Silicon/MAPS Tracking Detectors

BERKELEY LAB

CERN

Los Alamos NATIONAL LABORATORY

ePIC US Universities partnerships



Barrel Electromagnetic Calorimeter
ANL
NASA Goddard Space Flight Center
Oklahoma State University
The Ohio State University
UC Santa Cruz
University of Connecticut

Barrel Hadron Calorimeter
Baruch College, NY
Columbia University
Iowa State University
BNL
Rutgers University
University of Connecticut
Georgia State University

Forward Electromagnetic Calorimeter
Indiana University
UCLA
UCR

Dual-radiator RICH
Duke University
Temple University

Tracking Detectors
LBNL
LANL
UC Berkeley
Purdue University
Florida Institute of Technology
JLab
Temple University
BNL

Forward Hadron Calorimeter
ORNL
Georgia State University
Yale University
ISU
Indiana University
UCR
University of Tennessee Knoxville
Valparaiso University
UT Austin

Backward Hadronic Calorimeter
BNL
Rutgers University
Georgia State University
UIUC
The Ohio State University

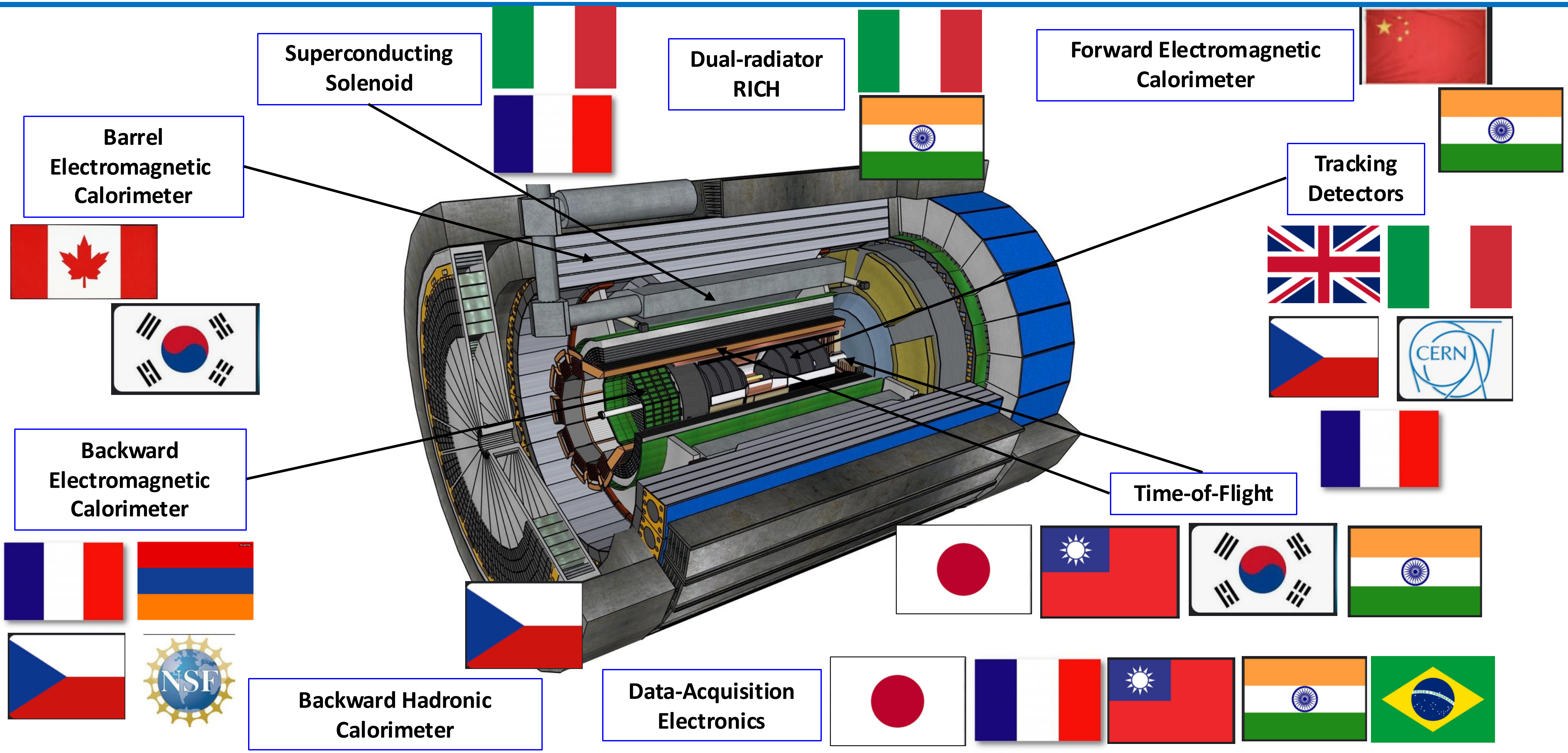
Backward Electromagnetic Calorimeter
Abilene Christian University
Catholic University of America
Florida International University
JLab
Lehigh University
MIT
University of Kentucky
William & Mary
Ohio University

Backward RICH

DIRC

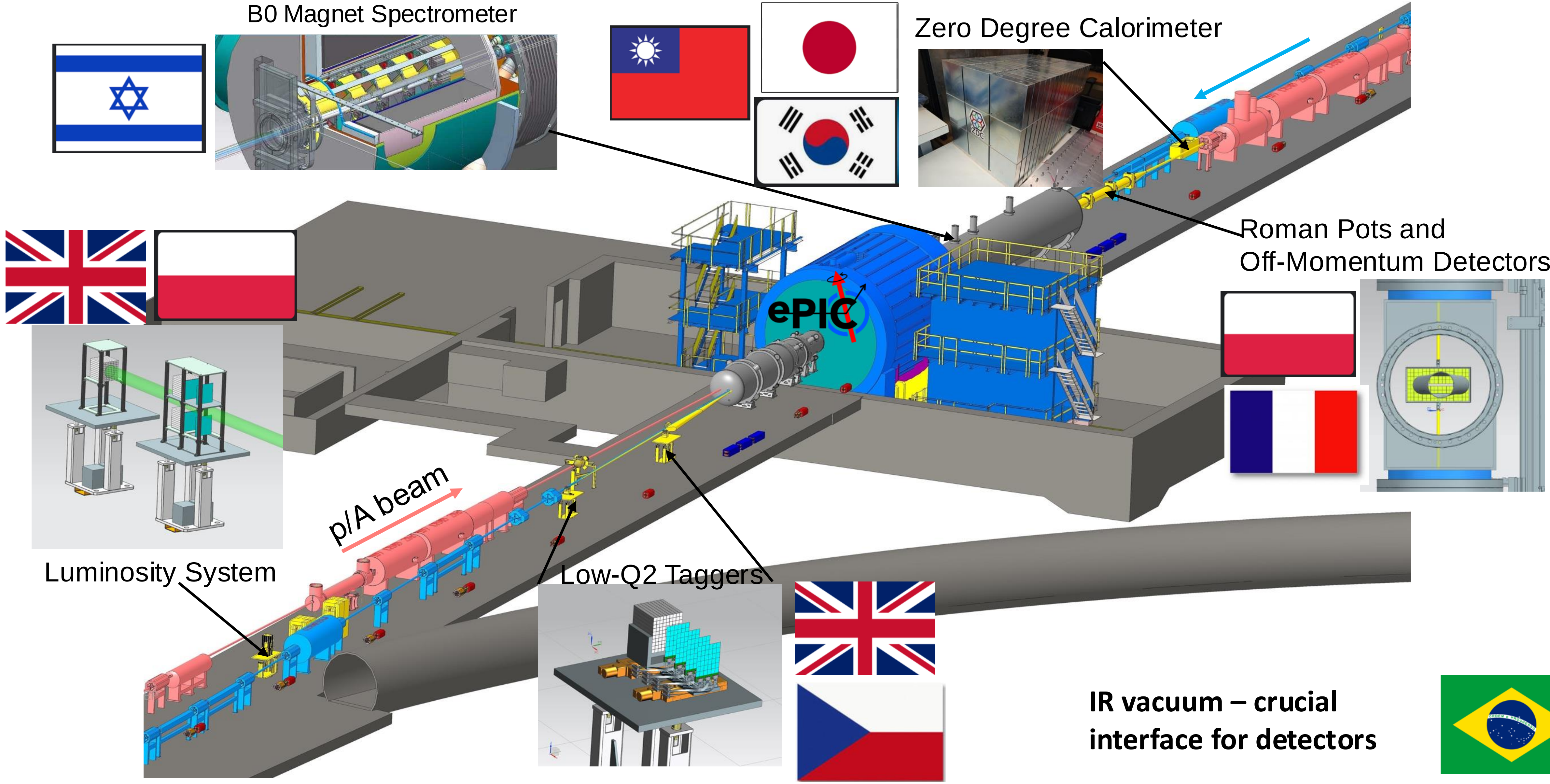
Time-of-Flight
UIC
BNL
Purdue University
RICE University
UC Santa Cruz
Kent State

ePIC international contributions/interests



EIC User Group: 1537 members/40 countries

ePIC international contributions/interests (II)



IR vacuum – crucial interface for detectors

Λ_c/D^0

Published ALICE plot Lc/D0 @ 13 TeV
with supersimposed (brutally PowerPointed) EIC prediction from
J. Arrington et al., arXiv:2102.08337