The Electron-Ion Collider
A world-wide unique collider to unravel the mysteries of visible matter

Elke-Caroline Aschenauer (BNL)

What is the EIC Facility

What is the EIC:

A high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

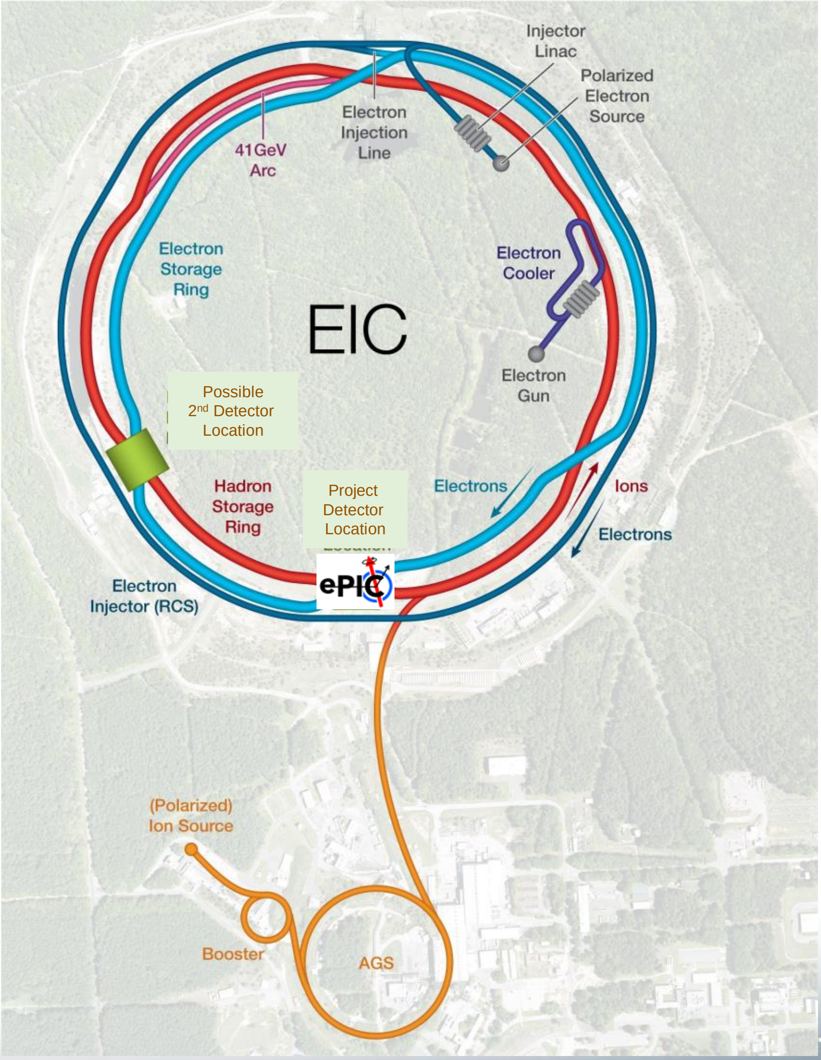
What is special:

EIC is the ONLY world-wide new collider in foreseeable future. Allows to remain at frontier of Accelerator S&T.

factor 100 to 1000 higher luminosity as HERA
both electrons and protons / light nuclei polarized,
nuclear beams: d to U
Fixed Target Facilities i.e.:
at minimum > 2 decades increase in kinematic coverage in x and Q^2

State of the art general purpose collider detector

Science Program: An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:



Why do we need different probes

Complementarity

QCD has two concepts which lay its foundation

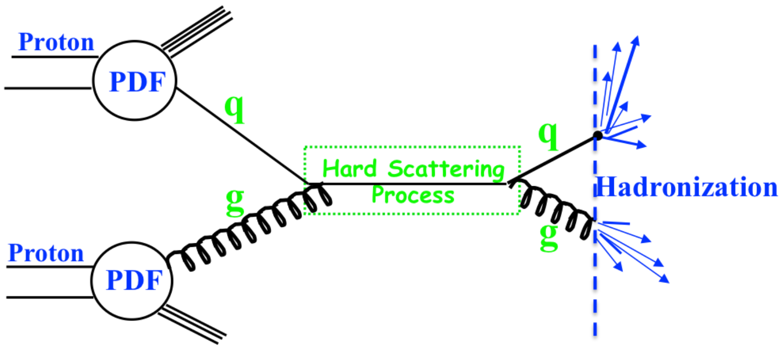
factorization and universality

To tests these concepts and separate interaction dependent phenomena from intrinsic nuclear properties

different complementary probes are critical

Probes: high precision data from ep, pp, e+e-

Factorization



(un)polarized cross section ~

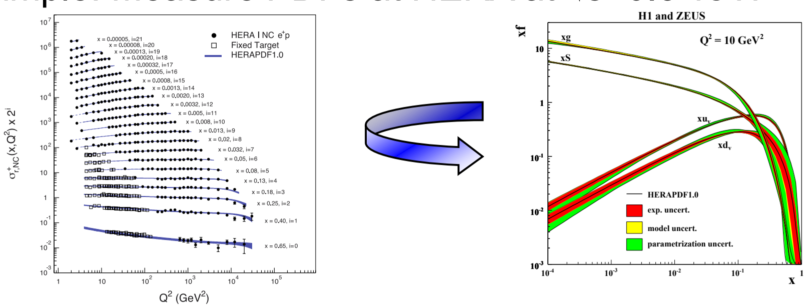
PDF ⊗ hard-scattering ⊗ Hadronization

hard-scattering : calculable in QCD

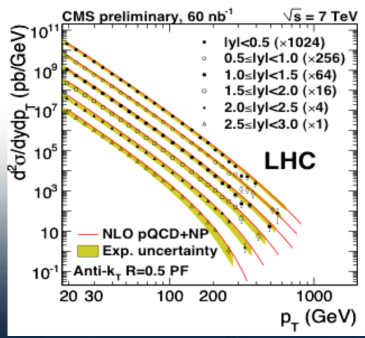
PDFs and Hadronization: need to be determined experimentaly

Universality

Example: Measure PDFs at HERA at √s=0.3 TeV:

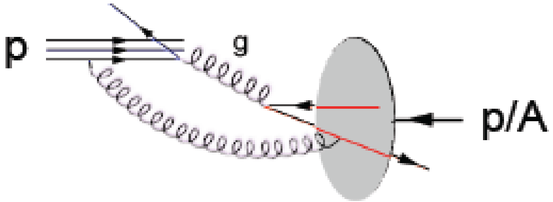


Predict pp and $p\bar{p}$ measurements at √s=0.2, 1.96 & 7 TeV



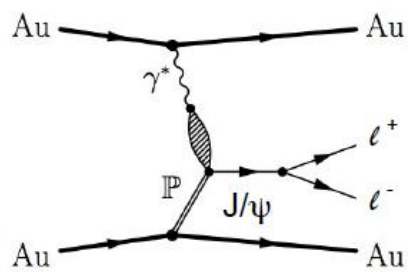
Different Processes

Hadron-Hadron:



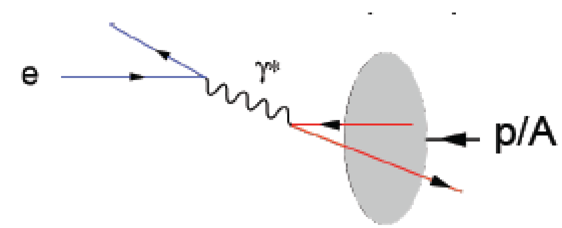
- probe has complex structure
- no simple access to parton kinematics:
  $\eta \rightarrow x$; $p_t^2 \rightarrow Q^2 \rightarrow x\text{-}Q^2$ strongly correlated
- Gluons can be accessed directly → qg & gg
  - gluon fragmentation

Ultra-Peripheral Collisions:



- Photon induced process
- no simple access to parton kinematics:
  $\eta \rightarrow x$; $M^2 \rightarrow Q^2$ can only be varied by VM
- access to initial state

Electron-Hadron:



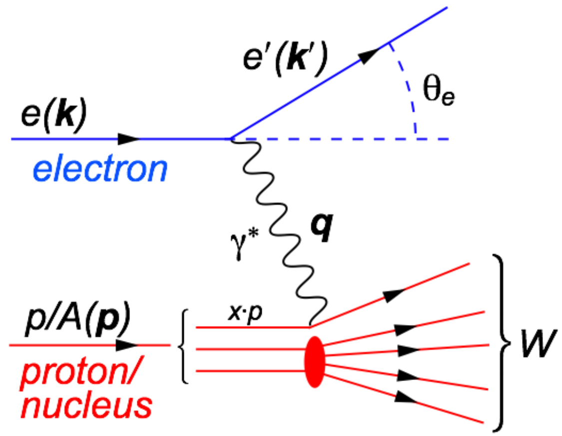
- Point-like probe → resolution
- High precision & access to partonic kinematics through scattered lepton
  → x_B, Q^2
- initial and final state effects can be cleanly disentangled
  - inclusive measurements of Structure functions only sensitive to initial state

What is needed to address the EIC Physics

The Golden Process:

Deep Inelastic Scattering (DIS):

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent determination of parton kinematics of physics processes



$$Q^2 = s \cdot x \cdot y$$

s: center-of-mass energy squared

Q^2: resolution power

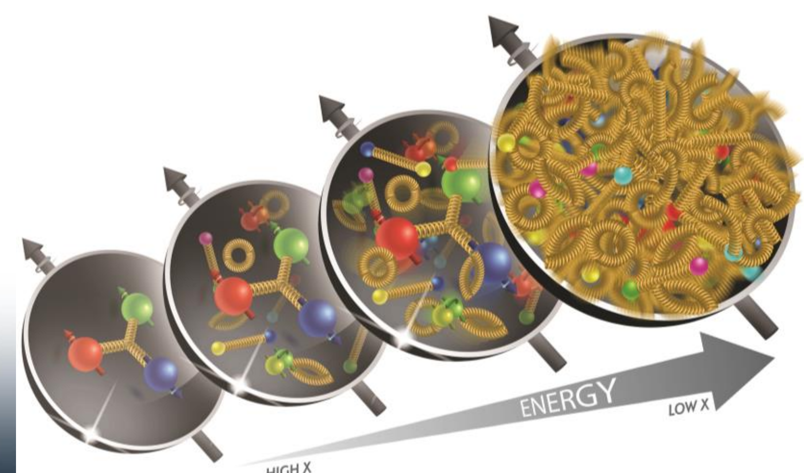
x: the fraction of the nucleon's momentum carried by the struck quark (0<x<1)

y: inelasticity

large kinematic coverage:

→ center-of-mass energy $\sqrt{s}$: 20 – 140 GeV

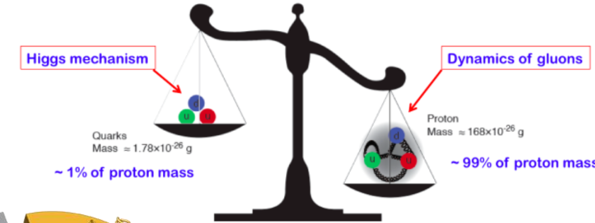
→ access to *x* and Q^2 over a wide range

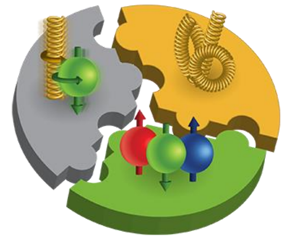


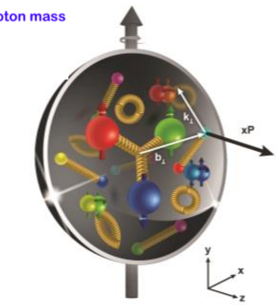
The EIC Physics

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

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







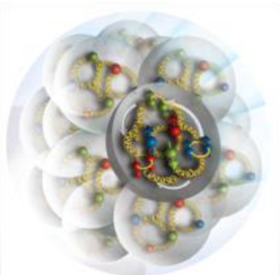
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

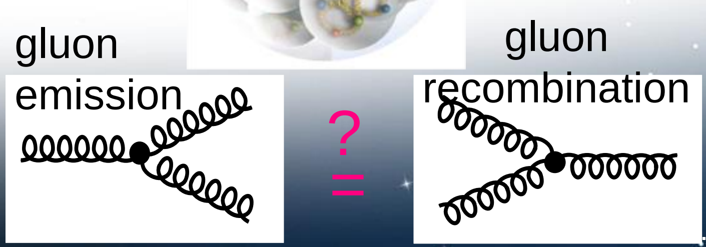
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How 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, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





EIC: The Path to Imaging Quarks and Gluons

4+1-D

Wigner function

$\mathbf{W(x, k_T, b_T)}$

$\int d^2 b_T$ $\int d^2 k_T$

2+1-D

$\mathbf{f(x, k_T)}$ — transv. mom. dep. PDF — semi-inclusive DIS

not related by Fourier transf.

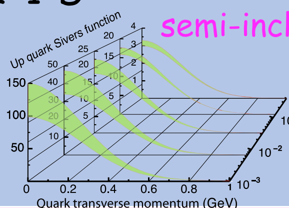
$\mathbf{f(x, b_T)}$ — impact par. dep. PDF

$\mathbf{b \leftrightarrow t}$

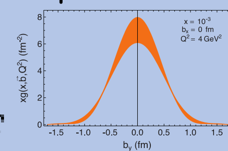
$\mathbf{H(x, 0, t)}$

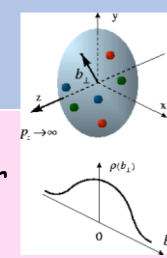
$\mathbf{\xi \rightarrow 0}$

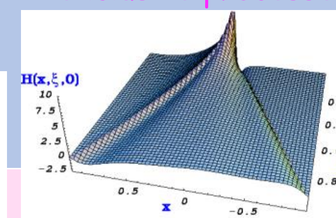
$\mathbf{H(x, \xi, t)}$ — generalized PDF — exclusive processes



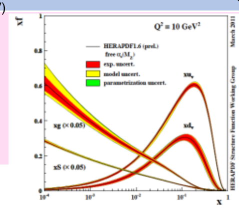
$\int d^2 k_T$ $\int d^2 b_T$ $\int dx$







1-D



$\mathbf{f(x)}$ — parton densities

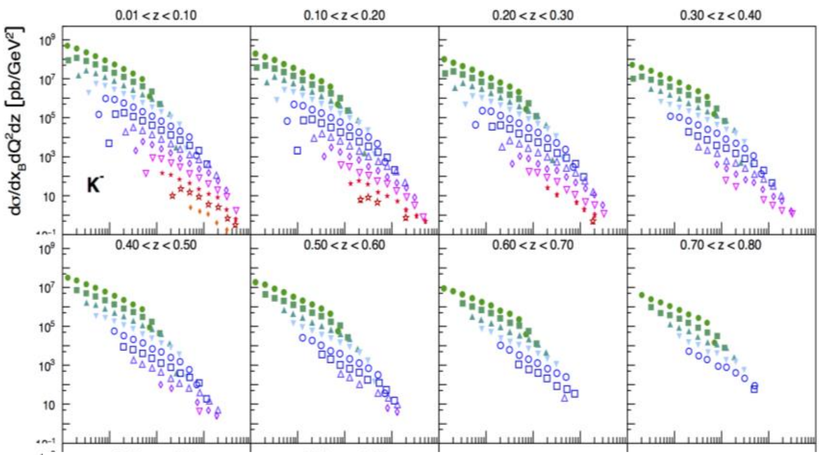
$\mathbf{F(t)}$ — form factor

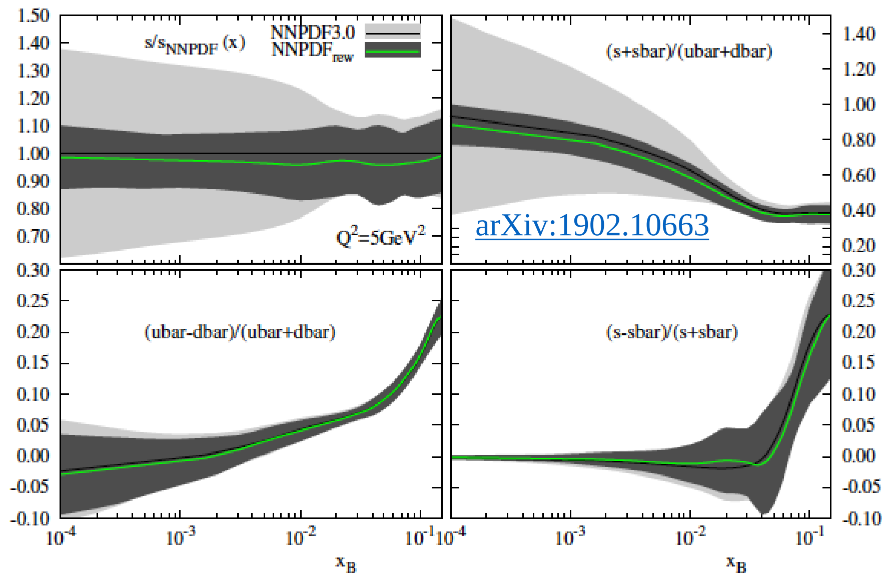
There are many reasons why one wants to have a 3d picture of nucleons and nuclei
collective effects are one of them.

Obtaining a full picture is definitely an other one

Unpolarized Flavor Structure

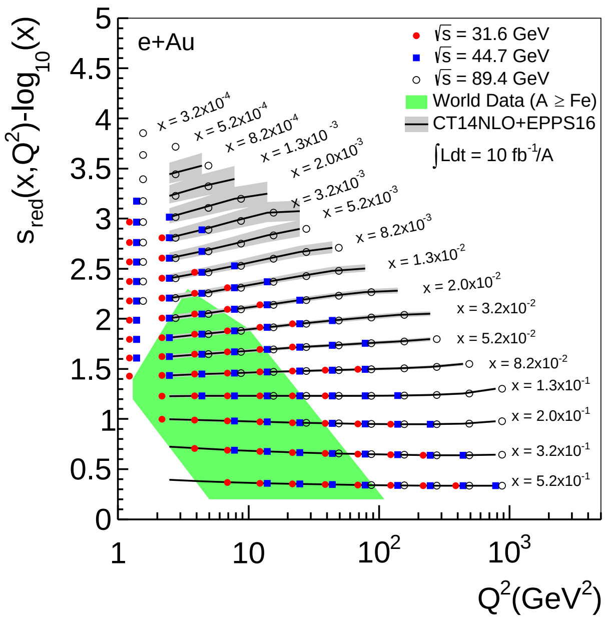
Proton



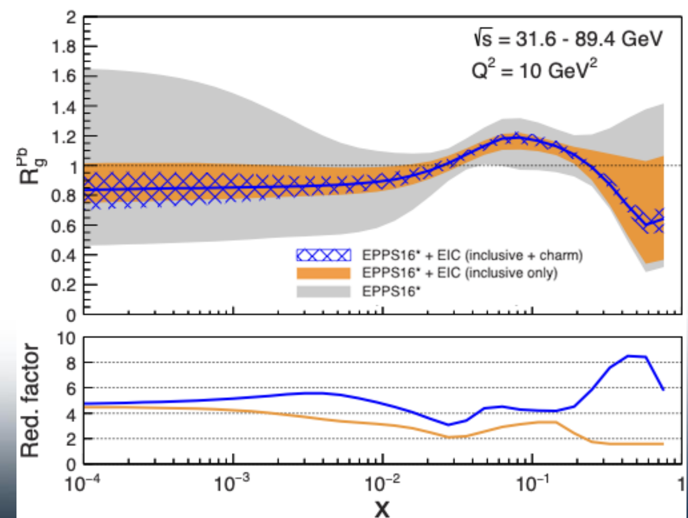


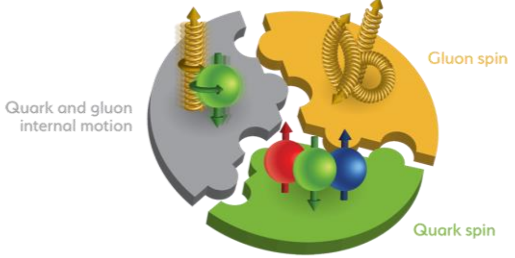
Simultaneous extraction of PDFs and FF required

Nucleus



same coverage in x, Q^2 for σ_{red}^{CC}



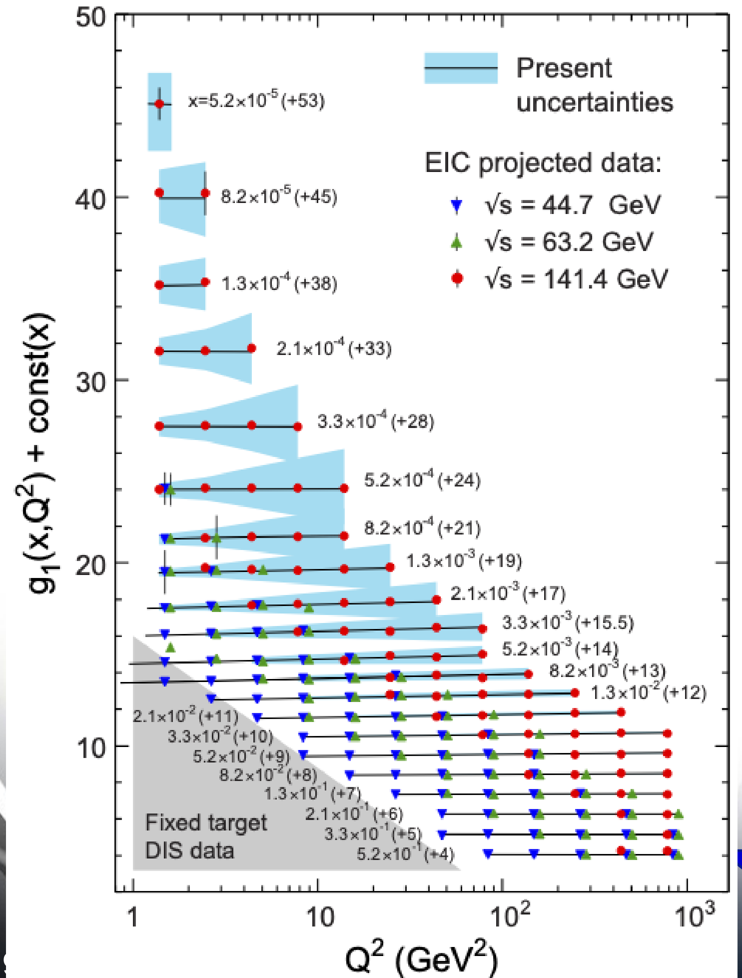


The Spin of the Proton

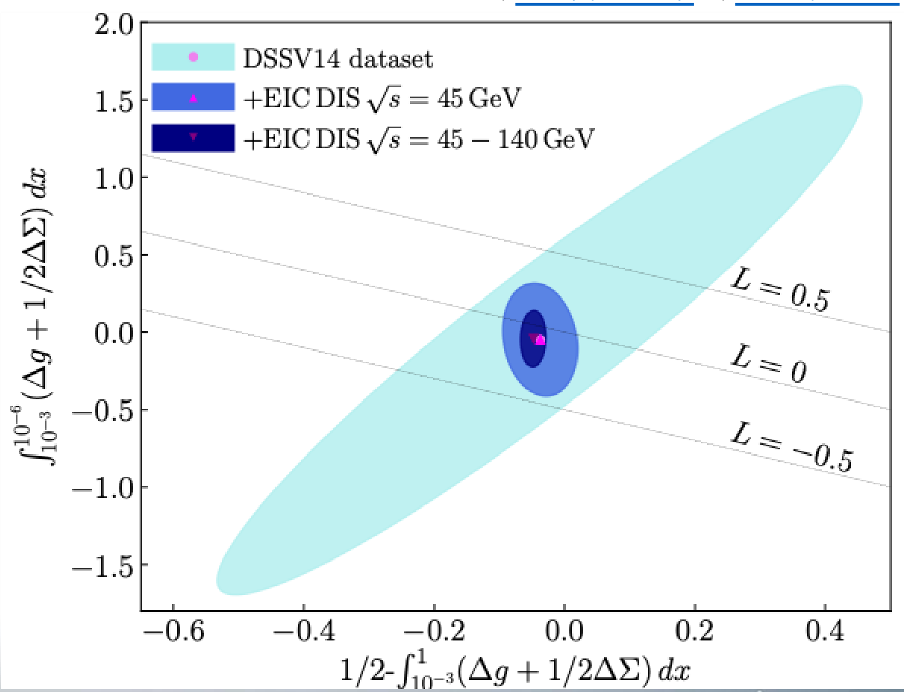
$$\frac{1}{2}\hbar=\left\langle P,\frac{1}{2}\left|J^z_{QCD}\right|P,\frac{1}{2}\right\rangle=\overbrace{\frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)}^{\text{total quark spin}}+\overbrace{\int_0^1 dx\Delta G(x,Q^2)}^{\text{gluon spin}}+\overbrace{\int_0^1 dx\left(\sum_q L_q^z+L_g^z\right)}^{\text{angular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

Key Observables: Structure function $g_1(x,Q^2)$ for proton and He^3/D → ΔΣ and ΔG

SIDIS double spin asymmetries for π, K → flavor separated Δq

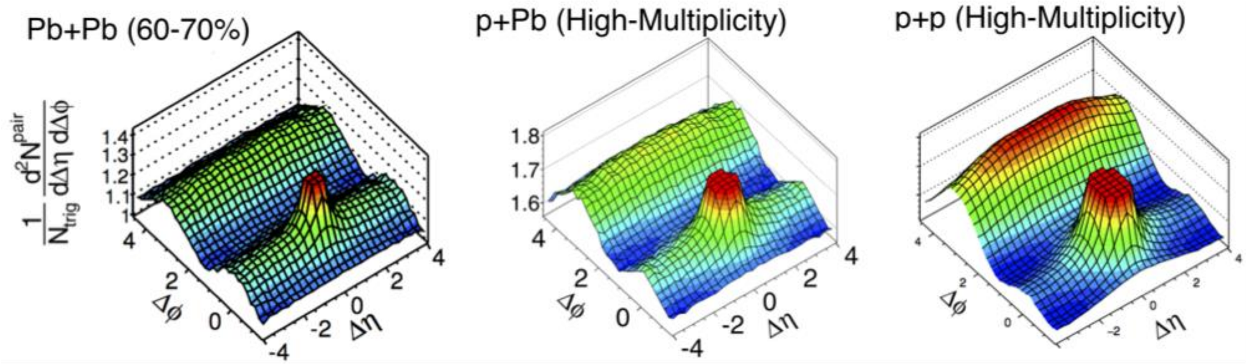


R. Sassot et al. arXiv:2007:083000
& 1509.06489 & 1206.6014



Proton structure important for QGP in small systems

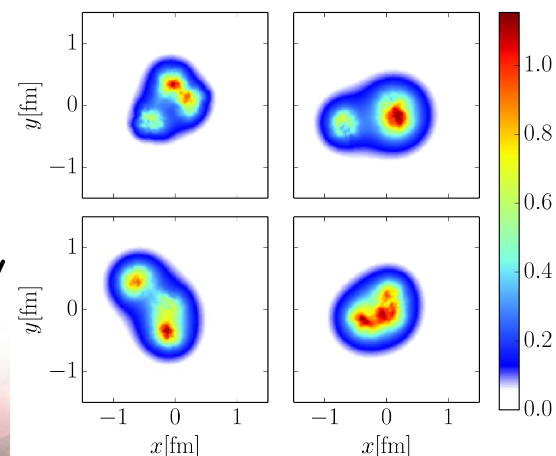
Collective phenomena seen in pA collisions, i.e. ATLAS & CMS



H. Mäntysaari & B. Schenke
arXiv:1607.01711

In a hydro-picture (used in AA) fluctuations in the proton are crucial to understand the seen pA@LHC behaviors

Examples of proton density profiles at $x \sim 10^{-3}$



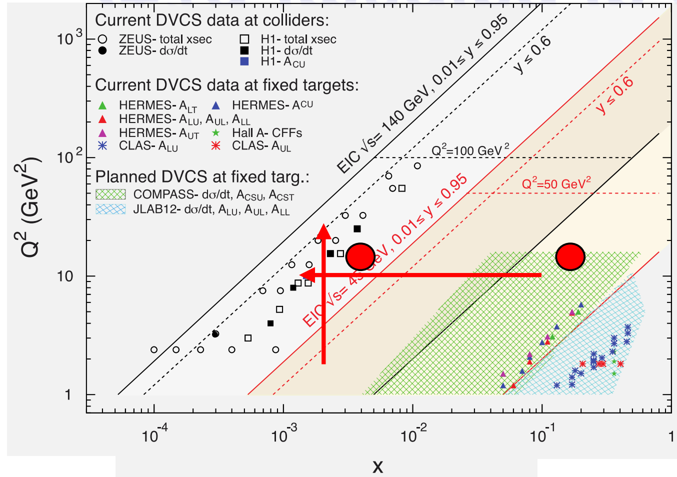
Study coherent and incoherent J/Ψ prod.

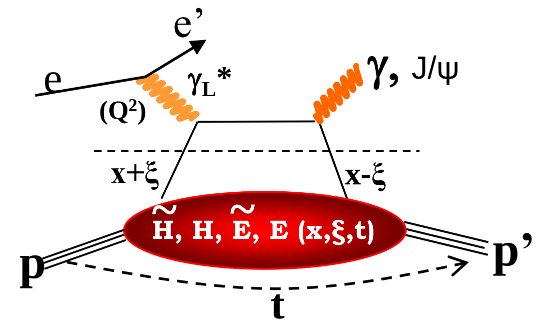
EIC can map out the spatial quark and gluon structure of the proton in x and Q^2

2+1d-Imaging in coordinate space

High precision imaging at EIC at low and high x

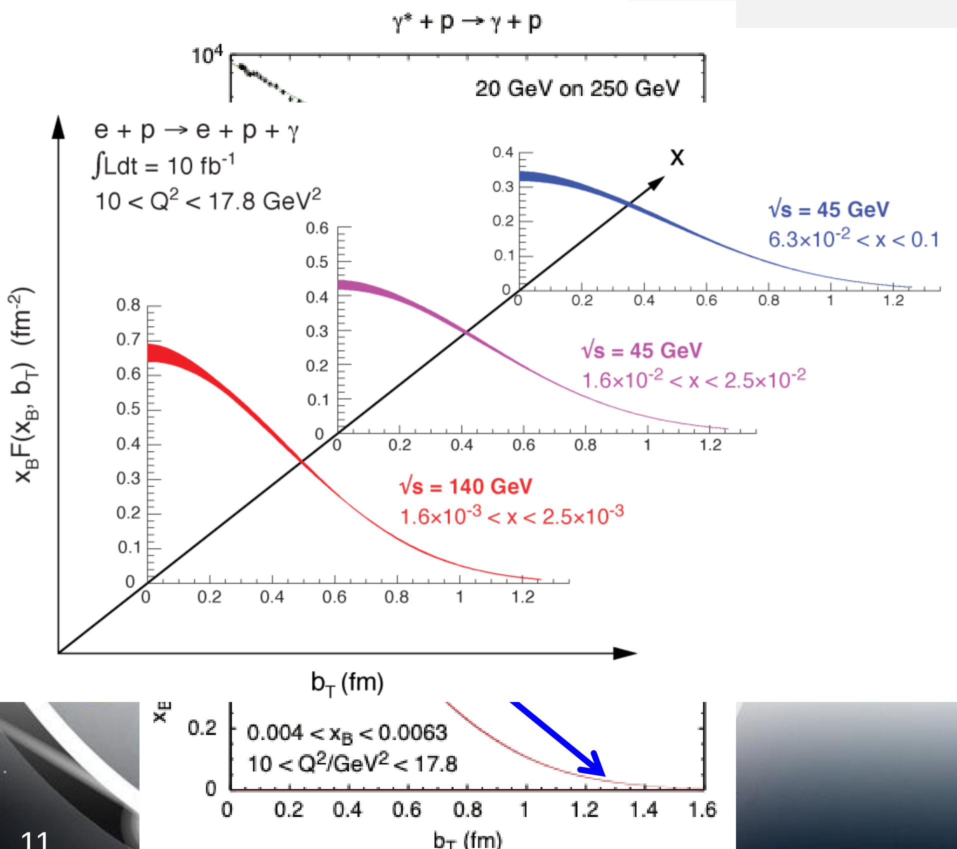
Golden channels:

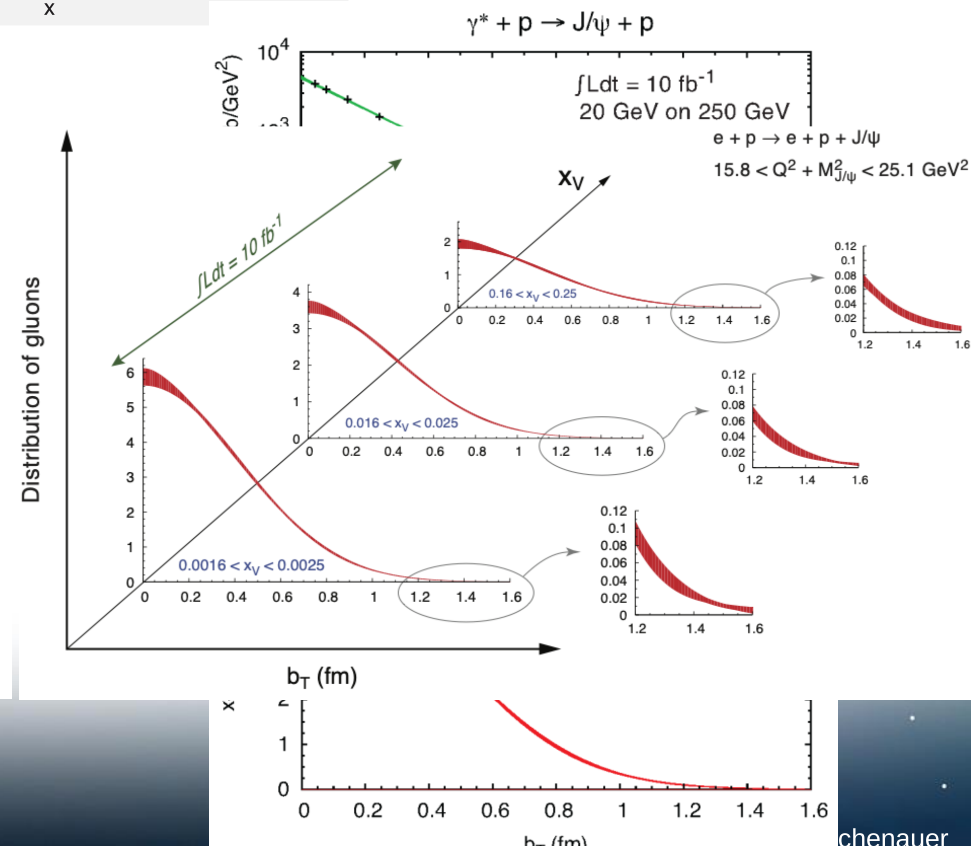




DVCS

J/ψ

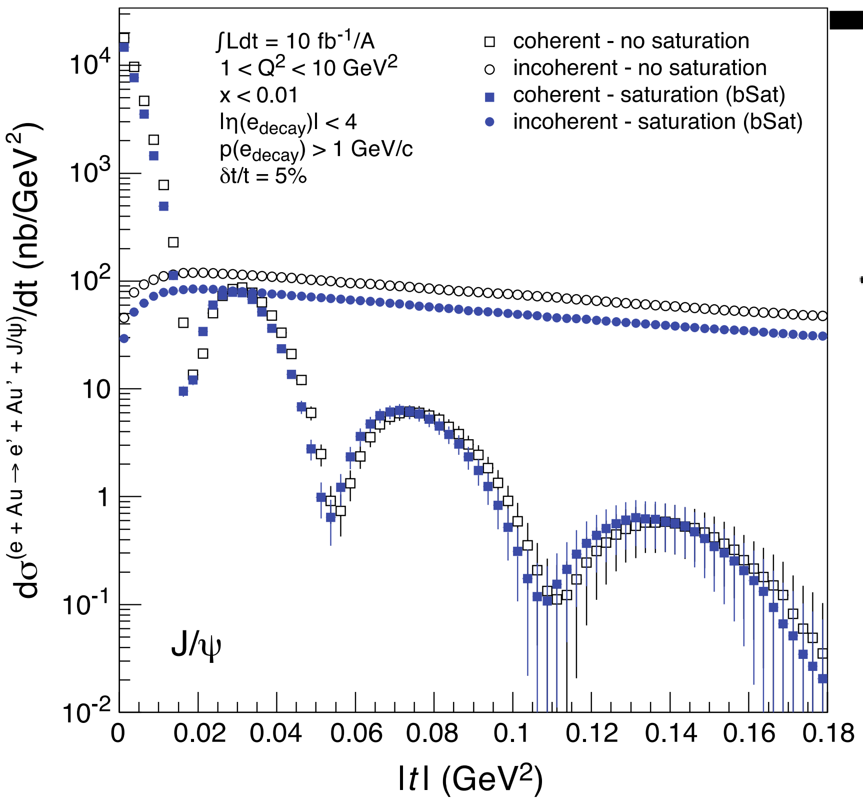




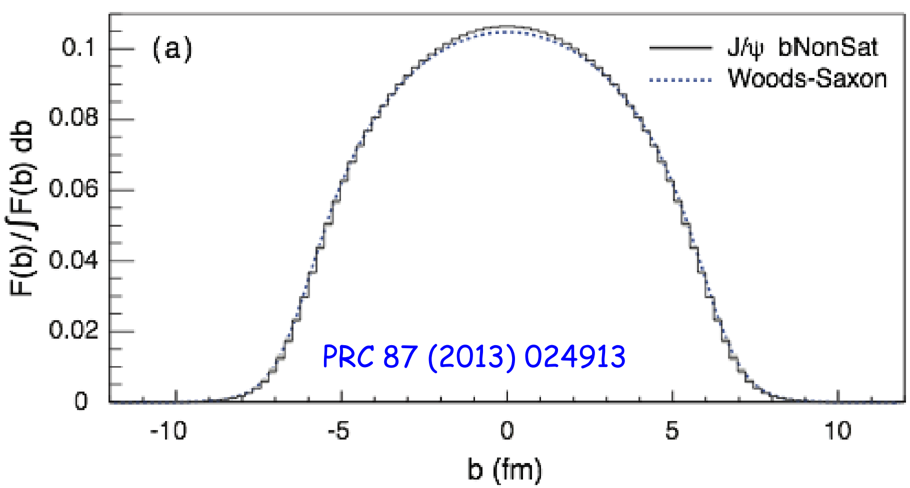
Spatial Gluon Distribution from dσ/dt

Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ, φ, ρ

Momentum transfer $t = |\mathbf{p}_{Au}-\mathbf{p}_{Au'}|^2$ conjugate to b_T



Fourier Transform



Coherent cross-section sensitive to average geometry

- Steepness and the position of first dip depends on density profile, non-linear effects and correlations

H.Mantysaari,B.Schenke PRC 101 (2020) 015203

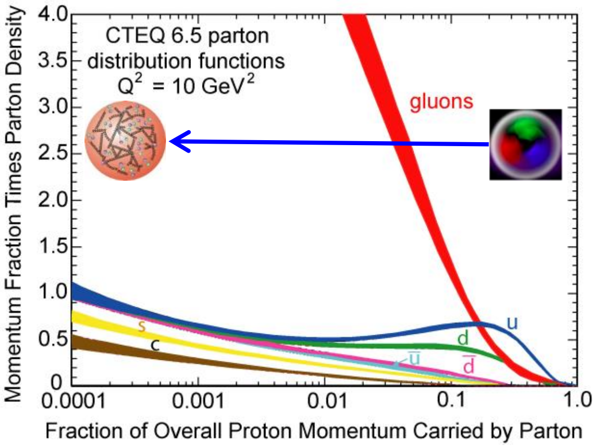
- Experimentally very challenging

Incoherent events are by themselves interesting

- Different |t| regions of the spectrum sensitive to different sizes
- Energy dependence of incoherent spectra with differential binning in |t| could tell us about growth of nuclei and evolution of fluctuations
- Recent results from Mantysaari, et al. (arXiv:2303.04866) show different regions of spectrum to be sensitive to different kinds of shape deformations e.g Uranium

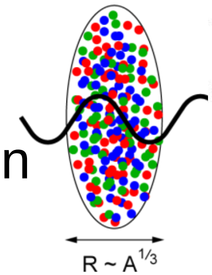
Studying non-linear QCD effects

- Does the rise of $g(x,Q^2)$ get tamed ?
- Important to understand the initial condition for heavy ion collisions



Scattering of electrons off nuclei:

- Probes interact over distances $L \sim (2m_N x)^{-1}$
- For $L > 2\ R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon
- Probe interacts *coherently* with all nucleons



$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

Nuclear "Oomph" Factor
Pocket Formula:

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A $\Rightarrow$ non-linear QCD regime reached at significantly lower $\sqrt{s}$ in nuclei than in proton

RHIC: Probing Non-linear Effects in QCD

Forward rapidities at STAR provide an absolutely unique opportunity to have very high gluon densities

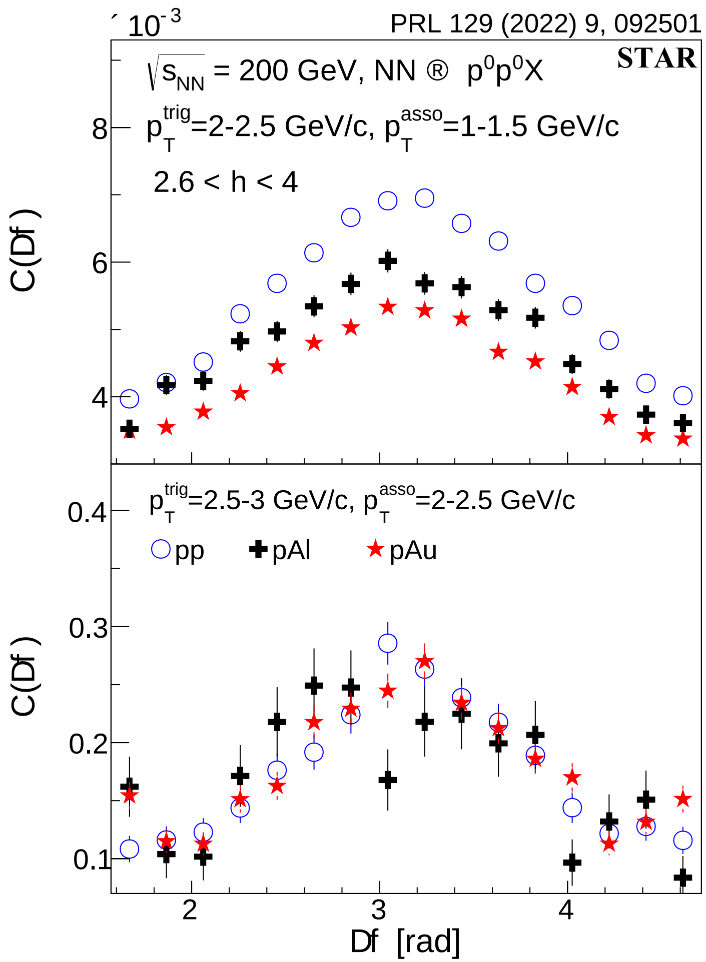
→ proton – Au collisions

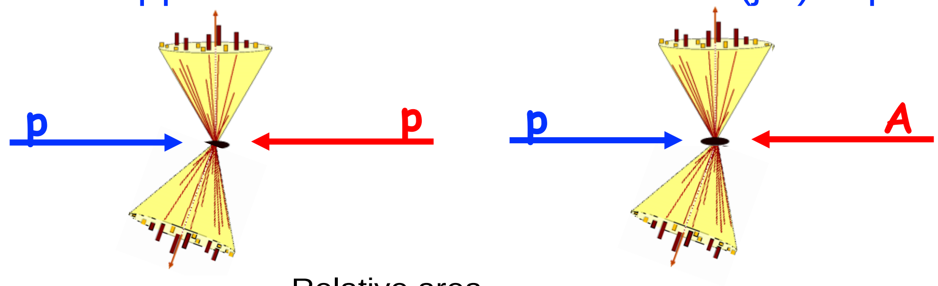
combined with an unambiguous observable

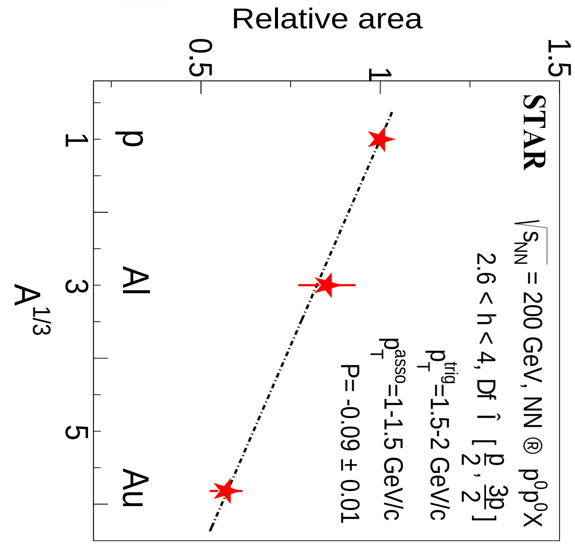
counting experiment of Di-hadrons (jets) in pp and pA

Non-linear QCD effects:

Disappearance of backward hadron (jet) in pA





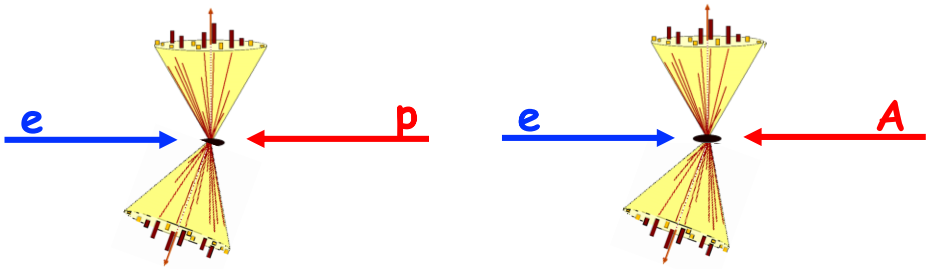


- **A dependence**: at low p_T more suppression in pAu than pAl in comparison to the pp
- **x dependence**: at high p_T (large x) no suppression in pA

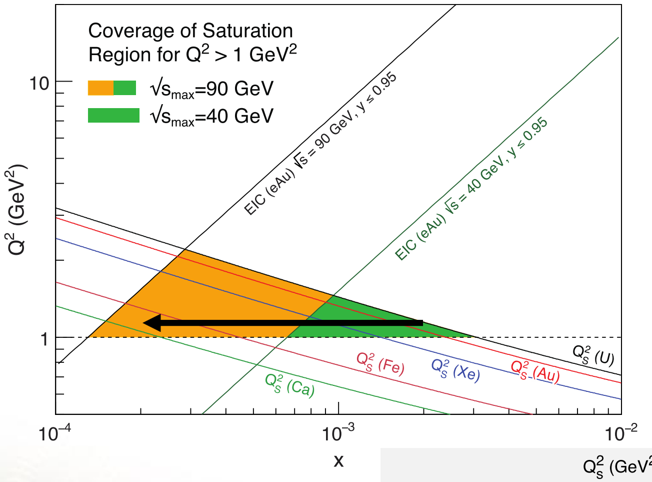
can EIC discover a new state of matter

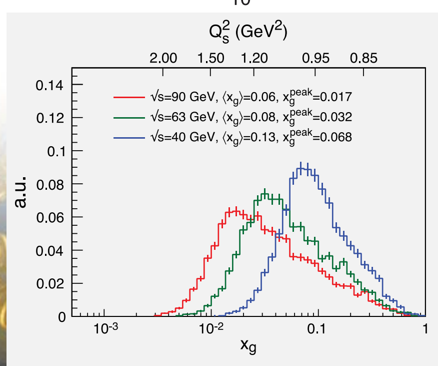
EIC has the unique opportunity
to have very high gluon densities
→ electron – lead collisions
combined with an observable

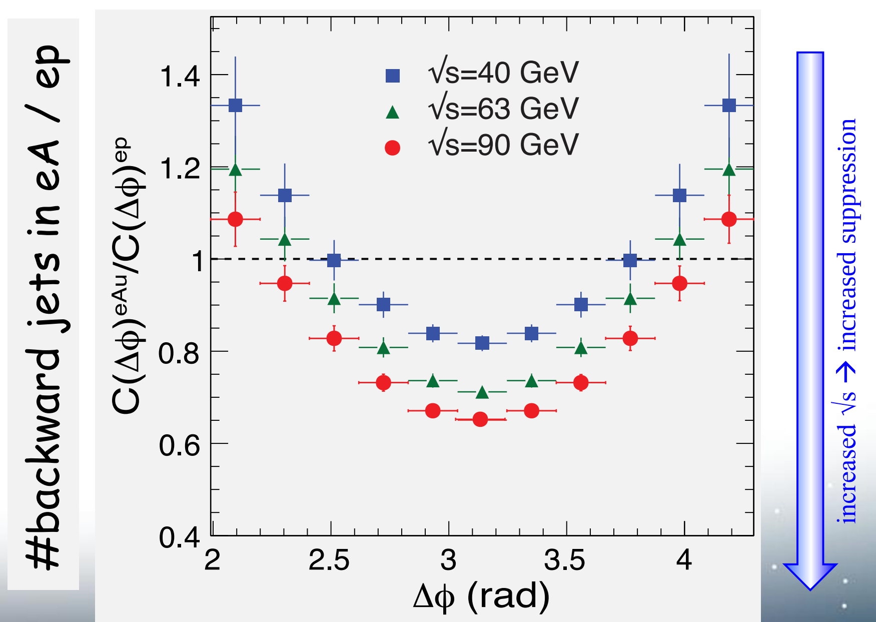
counting experiment of
Di-hadrons (jets) in ep and eA
Saturation:
Disappearance of backward hadron (jet) in eA



EIC can map the transition
from a linear to a non-linear QCD
regime→ evolution of Q_s with x







E.C. Aschenauer

Jet Physics at the EIC

The importance of jet probes was reflected in the EIC Yellow Report where they touched on nearly every major physics topic (Nucl. Phys. A, Vol 1026, 122447)

Jets have several properties which will make them important tools for realizing the EIC physics program

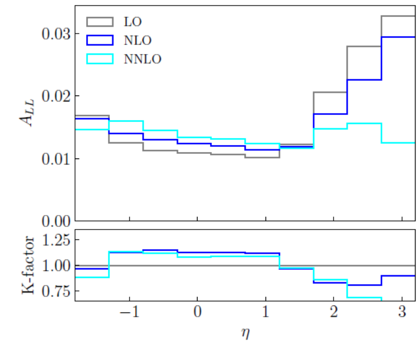
- Well understood theoretically and experimentally
- Excellent proxies for the underlying parton kinematics
- Showers probe QCD from hard interaction to hadronization scale within the same event – can explore dynamics at different time (angular) scales
- Precision tools exist to probe these shower properties - substructure

Global properties and parton structure of hadrons

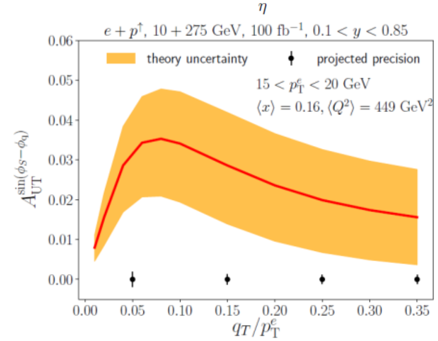
Multi-dimensional imaging of nucleons, nuclei and mesons

The nucleus: a laboratory for QCD

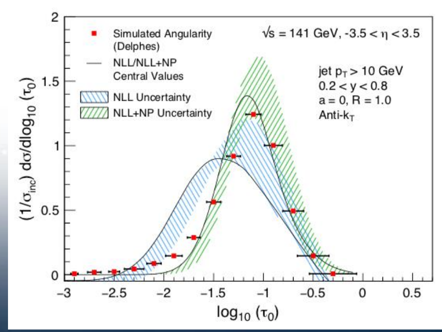
Understanding hadronization



Borsa, de Florian, Pedron `20

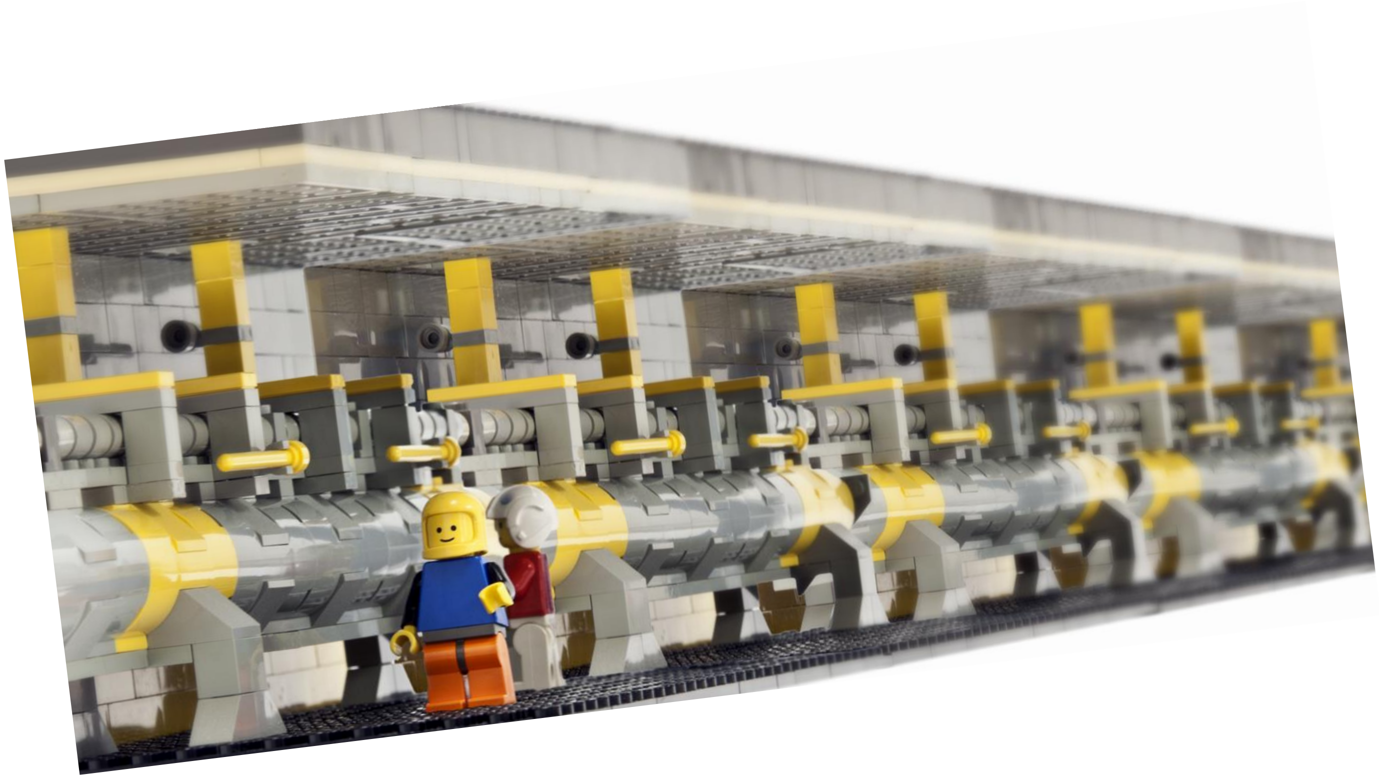


Arratia, Kang, Prokudin, Ringer `20

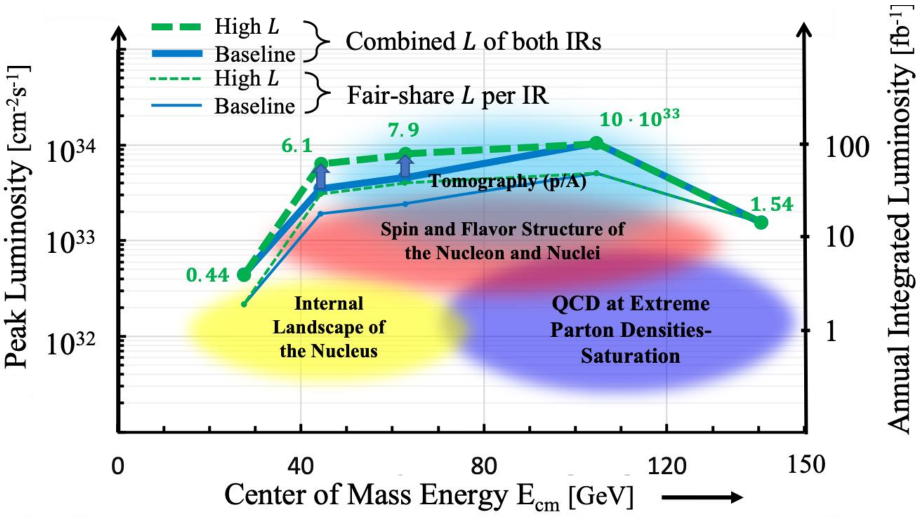


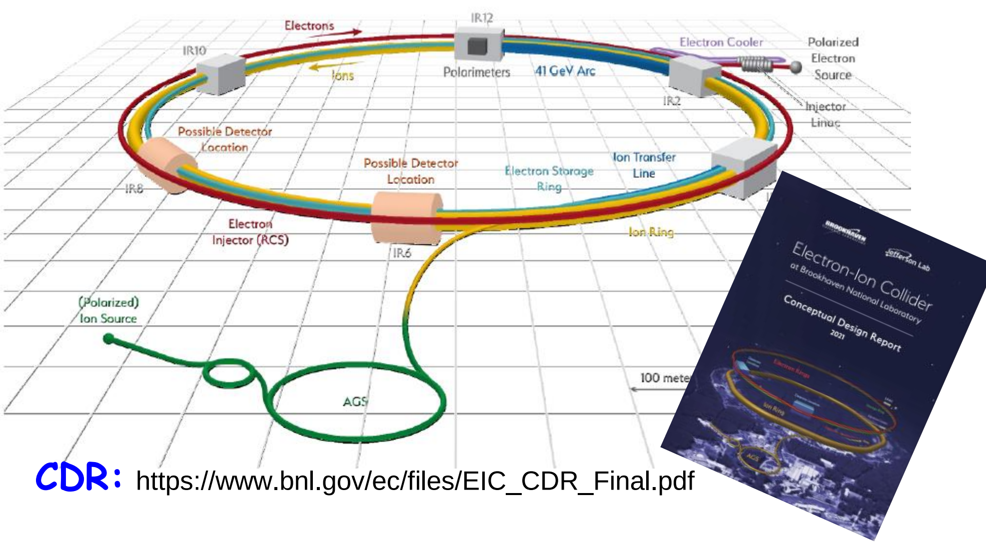
J. Adam et al 2022 JINST 17 P10019

The EIC Accelerator



EIC Machine Parameters

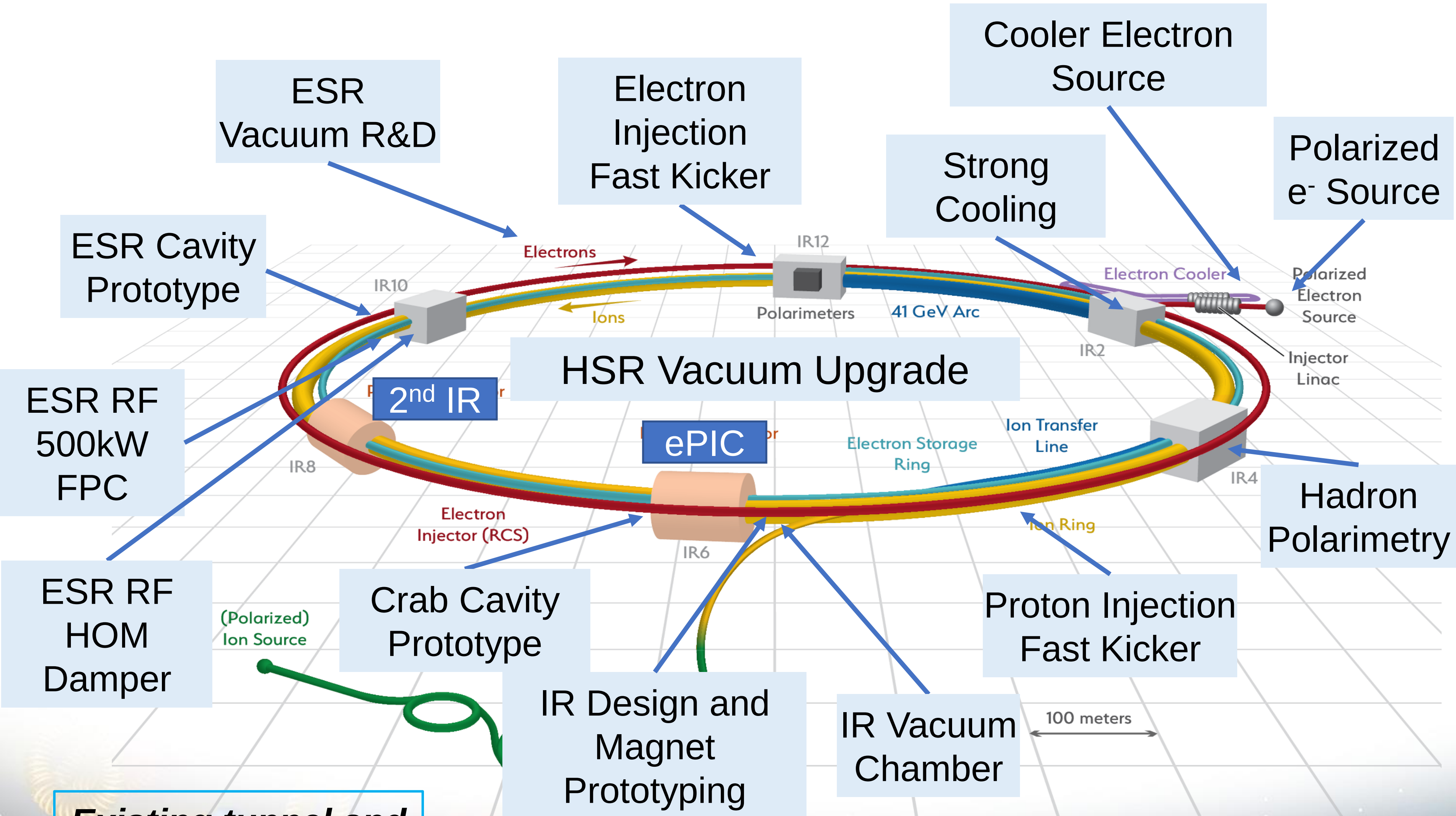




CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

Double Ring Design Based on Existing RHIC Facilities	
Hadron Storage Ring: 40, 100 - 275 GeV	**Electron Storage Ring: 5 - 18 GeV**
RHIC Ring and Injector Complex: p to Pb	9 MW Synchrotron Radiation
1A Beam Current	Large Beam Current - 2.5 A
10 ns bunch spacing and 1160 bunches	
Light ion beams (p, d, ^{3}He) polarized (L,T) > 70%	Polarized electron beam > 70%
Nuclear beams: d to U	**Electron Rapid Cycling Synchrotron**
Requires Strong Cooling: new concept →CEC	Spin Transparent Due to High Periodicity
One High Luminosity Interaction Region(s)	
25 mrad Crossing Angle with Crab Cavities	

Accelerator Science and Technology – Ongoing EIC R&D



Existing tunnel and experiment halls

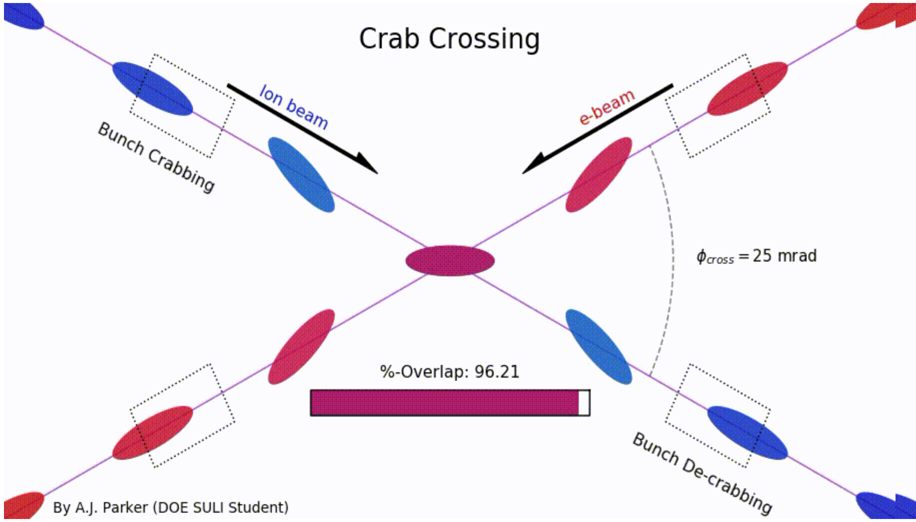
Why a Crossing Angle

- ❑ Brings focusing magnets close to IP
  → high luminosity
- ❑ Beam separation without separation dipoles
  → reduced synchrotron radiation background

But significant loss of luminosity

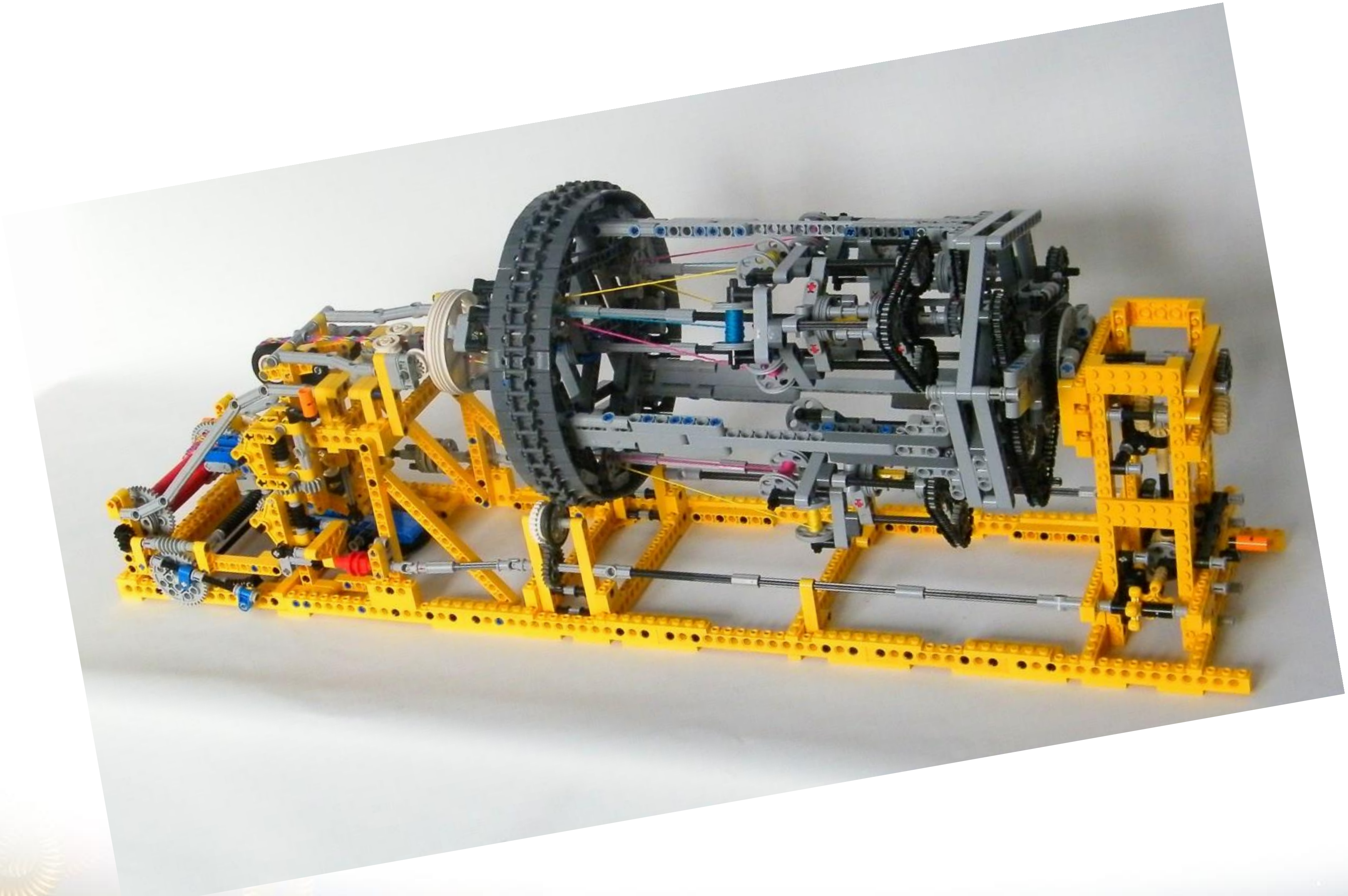
Solution: Crab crossing

- ❑ Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- ❑ Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- ❑ Actual collision point moves laterally during bunch interaction



Completely new concept for a collider

The EIC Detector



EIC Experimental program preparation

Year-long EIC User Group driven EIC Yellow Report activity (December 2019 – February 2021

- Science Requirements and Detector Concepts for the EIC
  arXiv:2103.05419 & Nucl. Phys. A 1026 (2022) 122447

BNL and TJNAF Jointly Leading Efforts Towards Experimental Program		
2020	Call for Expressions of Interest (EOI) https://www.bnl.gov/eic/EOI.php	May 2020
	EOI Responses Submitted	November 2020
	Assessment of EOI Responses	On-going[&]
2021	Call for Collaboration Proposals for Detectors https://www.bnl.gov/eic/CFC.php	March 2021
	BNL/TJNAF Proposal Evaluation Committee	Spring 2021
	Collaboration Proposals for Detectors Submitted	December 2021
2022	Decision on Project Detector – baseline "ECCE"	March 2022
	Process to consolidate ECCE & ATHENA to the EIC Project Detector	Spring 2022
	ePIC Collaboration* Formed – 160 institutions	July 2022
2023	ePIC Charter ratified & elected Leadership Team	February 2023
	Resources Review Board Meeting	April 2023
	ePIC Detector remaining technology choices made	April 2023

[&]Remains ongoing until formal agreements are in place – it originally led to confirmation that in-kind level assumed for the EIC detector was in range.

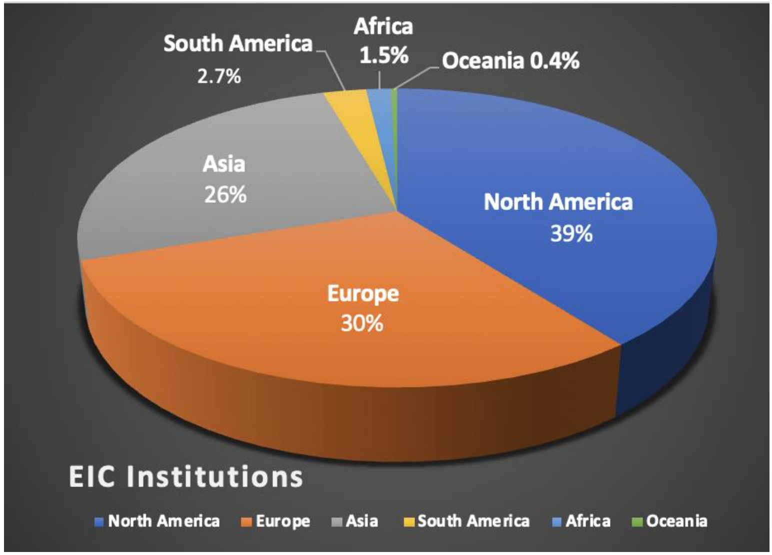
World-Wide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

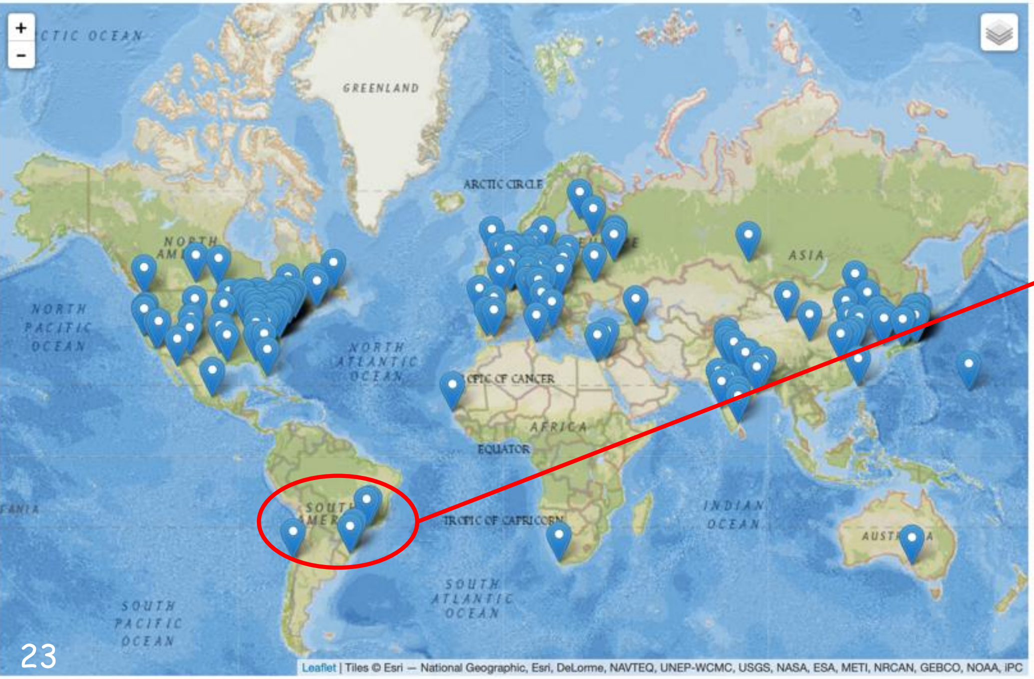
Formed 2016, Current Status

1387 collaborators, 36 countries, 271 institutions
(Experimentalists ~860, Theory ~360, Acc. Sci. 160)

- EICUG has continuously grown since its formation (400@01/2016), notably after CD-0 and site-selection
- Growth will continue as EIC project moves into construction



Location of Institutions



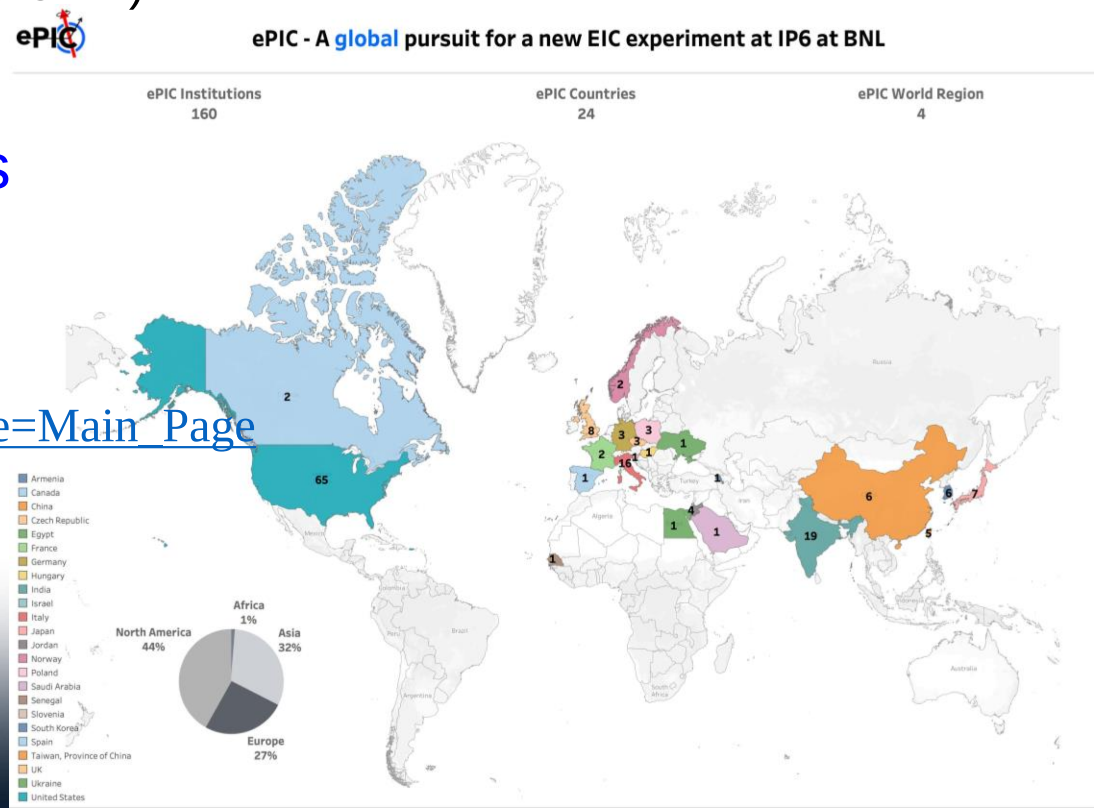
Next EIC-UG Meeting in person July 2023 in Warsaw Poland

Would love to welcome more collaborators from Brazil and Southamerica

The ePIC Collaboration

Collaboration fully formed

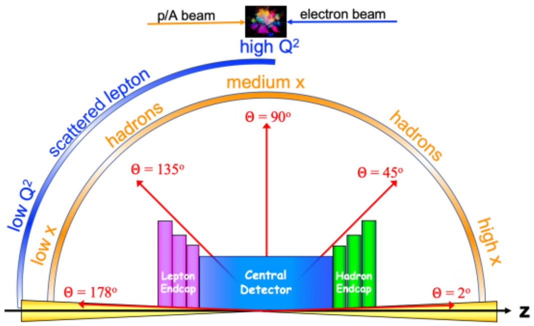
- December 2022: Collaboration Charter ratified
- February 14th 🫶 2023: Spokespeople elected
  Spokesperson: John Lajoie (Iowa)
  Deputy – Spokesperson: Silvia Dalla Torre (INFN Trieste)
- Collaboration Council fully formed
  Chair: Ernst Sichtermann (LBNL)
  Vice-Chair: Bernd Surrow (Temple Univ.)

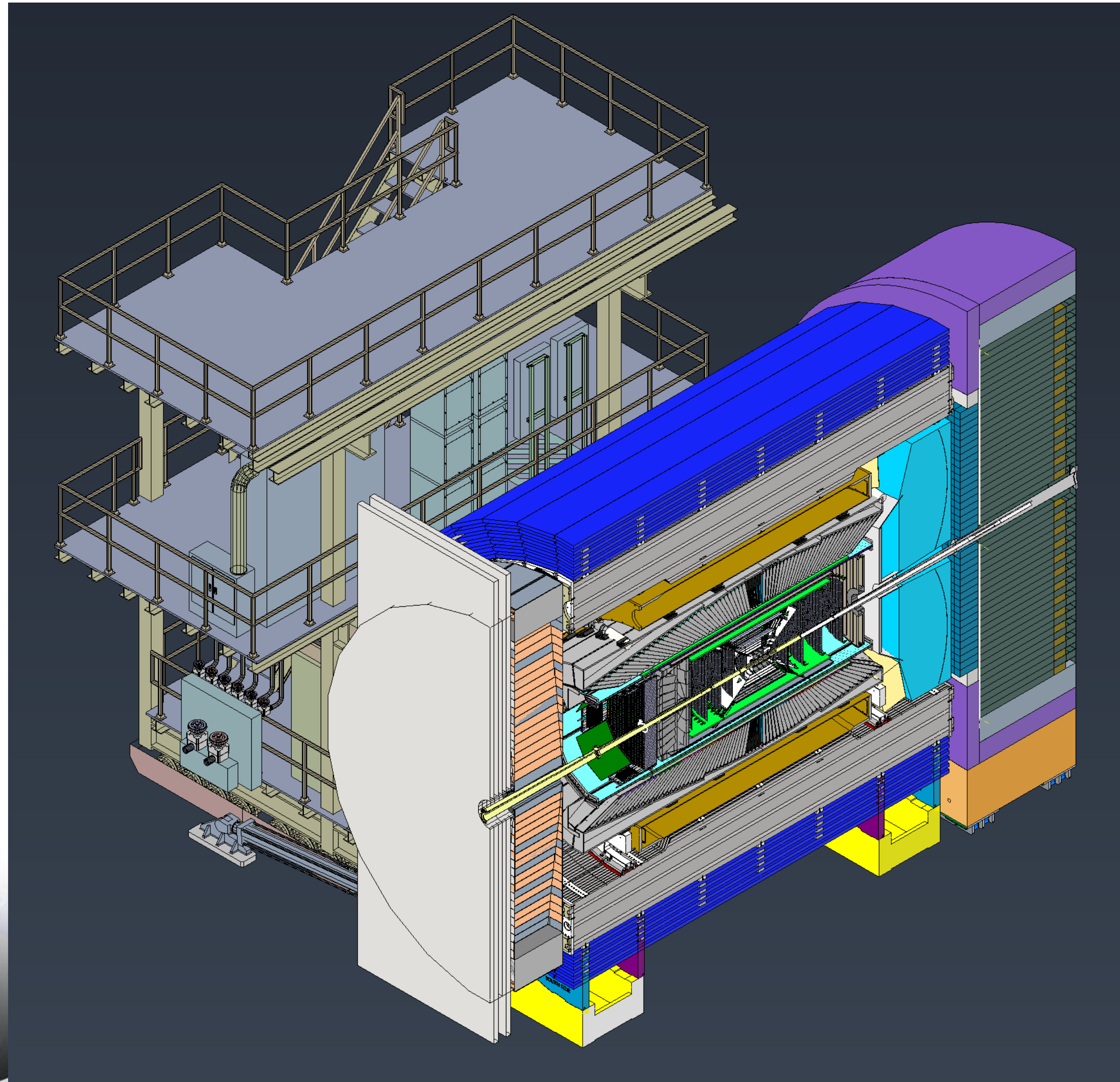


ePIC welcomes new groups and institutions

Details:
https://wiki.bnl.gov/EPIC/index.php?title=Main_Page

The ePIC Detector

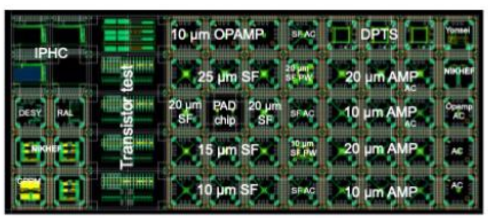


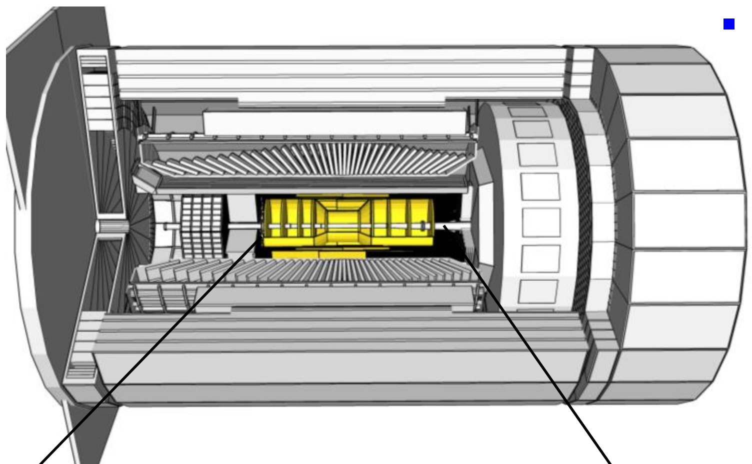


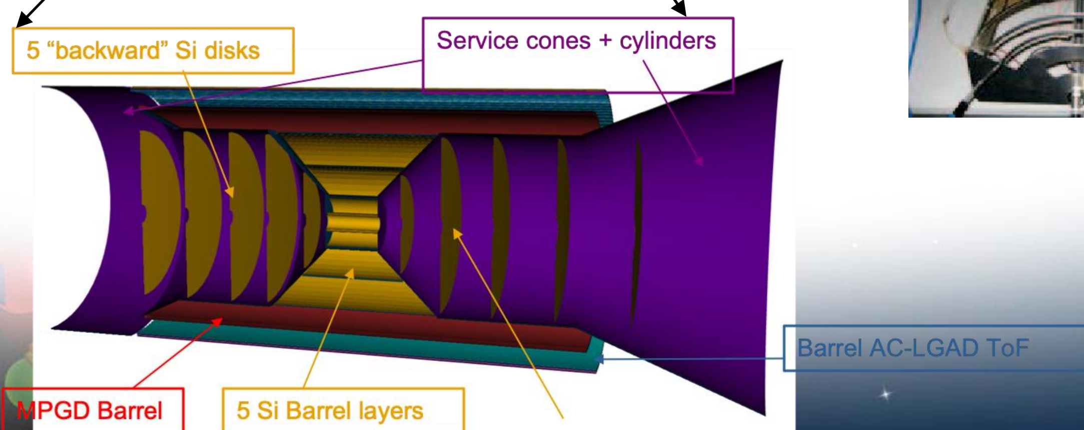
ePIC Tracking Detectors

Monolithic Active Pixel Silicon Tracker:

- 1 single technology: 65-nm MAPS
  - O(10 μm) pitch, <20 mW/cm^2
  - Developed for ALICE ITS3
- Silicon VERTEX (3 layers)
  - First layer @ R ~ 4 cm
  - Material: 0.05% X/X_0 / layer
- Silicon BARREL (2 layers)
  - Material: 0.55% X/X_0 / layer
- F & B Silicon DISKs (5 in Front and Back)
  - Material: 0.24% X/X_0 / layer



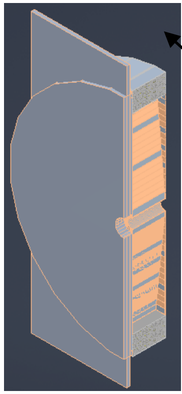




Multi Pattern Gas DetectorS:

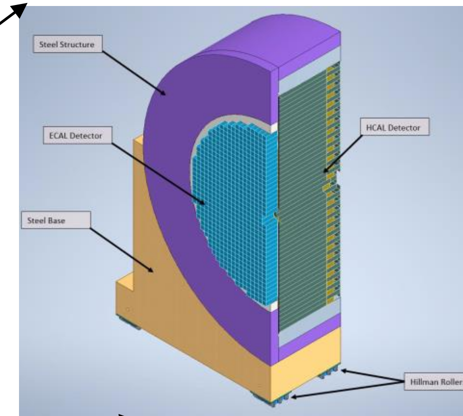
- Cylindrical microMEGAS
  - → Additional space point for pattern recognition / redundancy
  - → Ongoing geometry optimization
- µRWELL planar layer behind hpDIRC
  - → Impact point and direction for the ring seeding of hpDIRC
  - → Additional space point for pattern recognition / redundancy
  - → Not be required if imaging calorimeter is used

ePIC Calorimetry

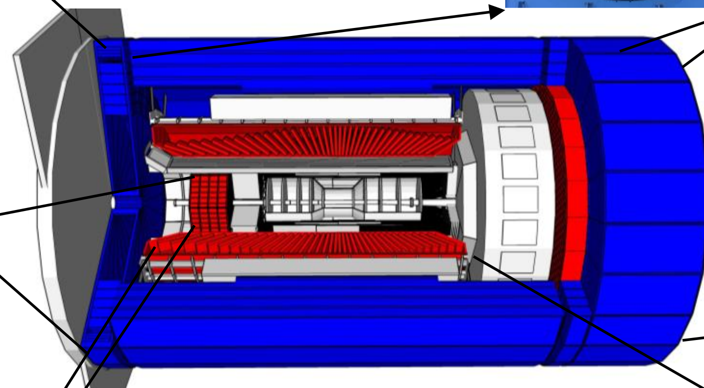


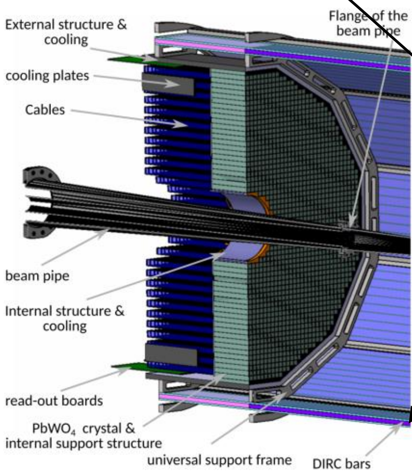
Backwards HCal
Steel/Sc Sandwich
tail catcher

Barrel HCAL
(re-used from
sPHENIX)



High granularity
W/SciFi EMCal





Backwards EMCal
PbW04 crystals
with SiPMs as
Photonsensors

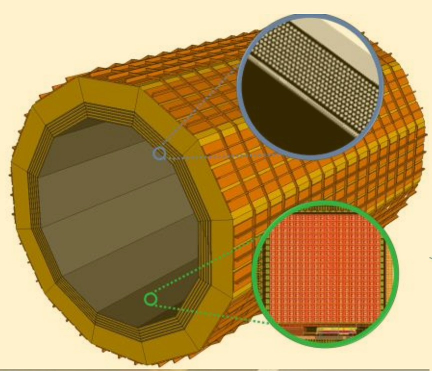
world's first
at ePIC

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

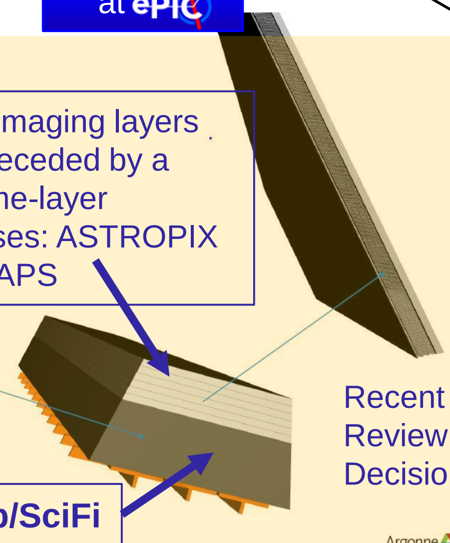
world's first
at ePIC

world's first
at ePIC

Barrel ECal: Pb/SciFi with
hybrid imaging part



5 imaging layers
preceded by a
time-layer
Uses: ASTROPIX
MAPS

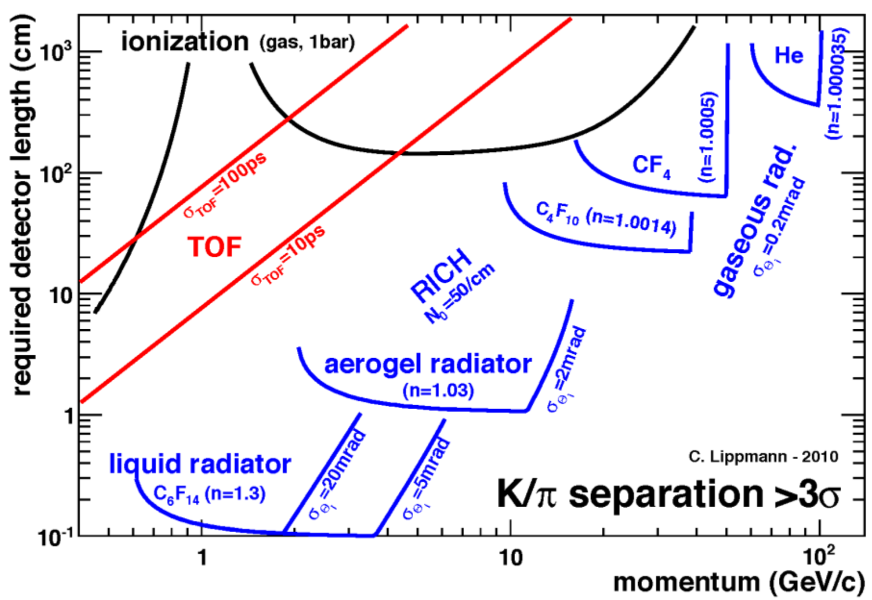


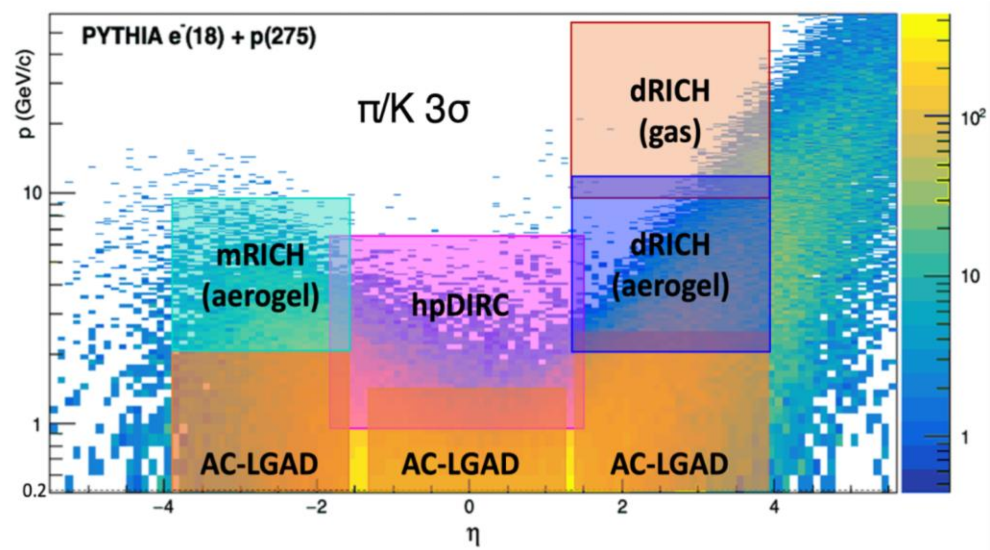
Pb/SciFi

Recent Technology Choice
Review completed 03/14/23
Decision by 04/21/23

Particle ID

- In general, need to separate:
  - Electrons from photons → 4π coverage in tracking
  - Electrons from charged hadrons → mostly provided by calorimetry & tracking
  - Charged pions, kaons and protons from each other on track level → Cherenkov detectors
    - Cherenkov detectors, complemented by other technologies at lower momenta
      Time-of-flight or dE/dx





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

Physics requirements:

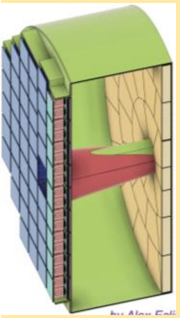
Rapidity	π/K/p and π0/γ	e/h	Min pT (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

ePIC Particle Identification Detectors

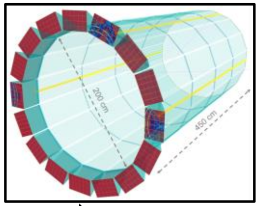
Backward RICH:
- Aerogel Cherenkov Det.
- e, π, K, p separation
- → π/K 3σ sep. at 10 GeV/c
- Photon-sensor:
  LAPPDs to include TOF

world's first at ePIC

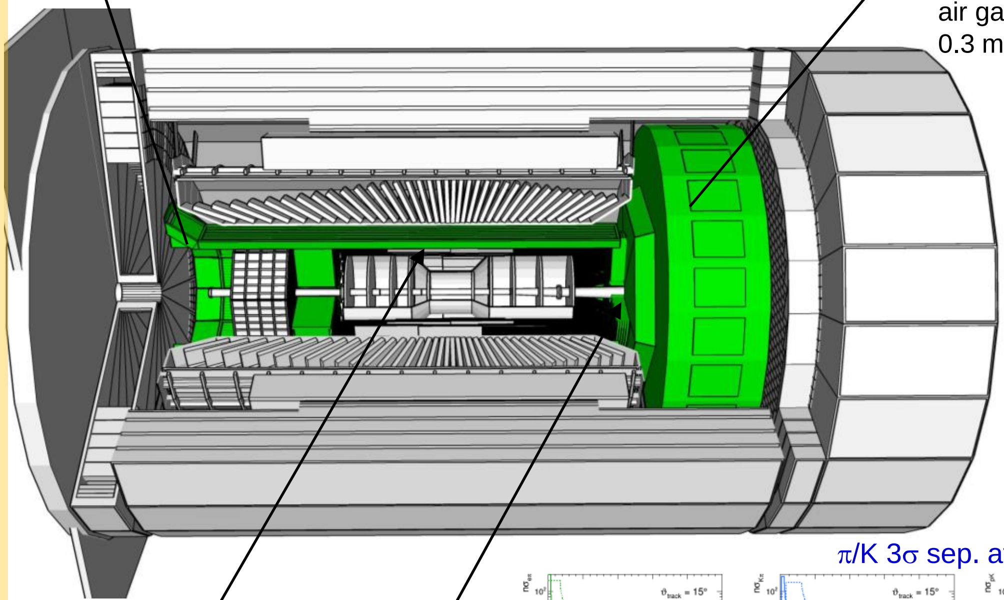
Single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)



Recent Technology Choice
Review completed 03/21/23
Decision by 04/21/23



hpDIRC (High Performance DIRC)
- Quartz bar radiator → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs
- Fully focused
- π/K 3σ sep. at 6 GeV/c



dual Radiator RICH

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

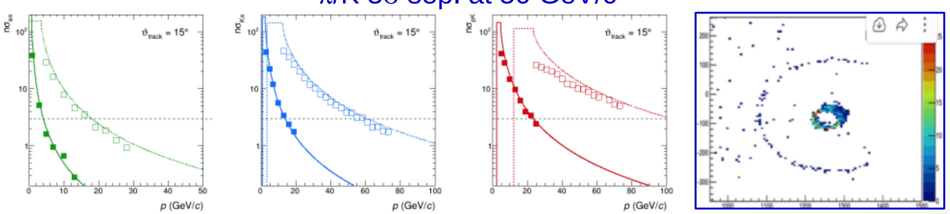
Spherical Mirrors
6 Azimuthal Sectors

C_2F_6 Gas Volume
120 cm length
radius: 185 cm
Tapered bore radius
Al vessel

Sensors tiled on spheres
→ SiPMs as Photonsensors

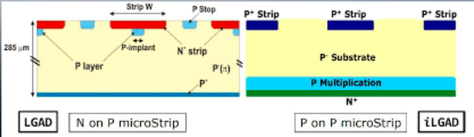
world's first at ePIC

π/K 3σ sep. at 50 GeV/c



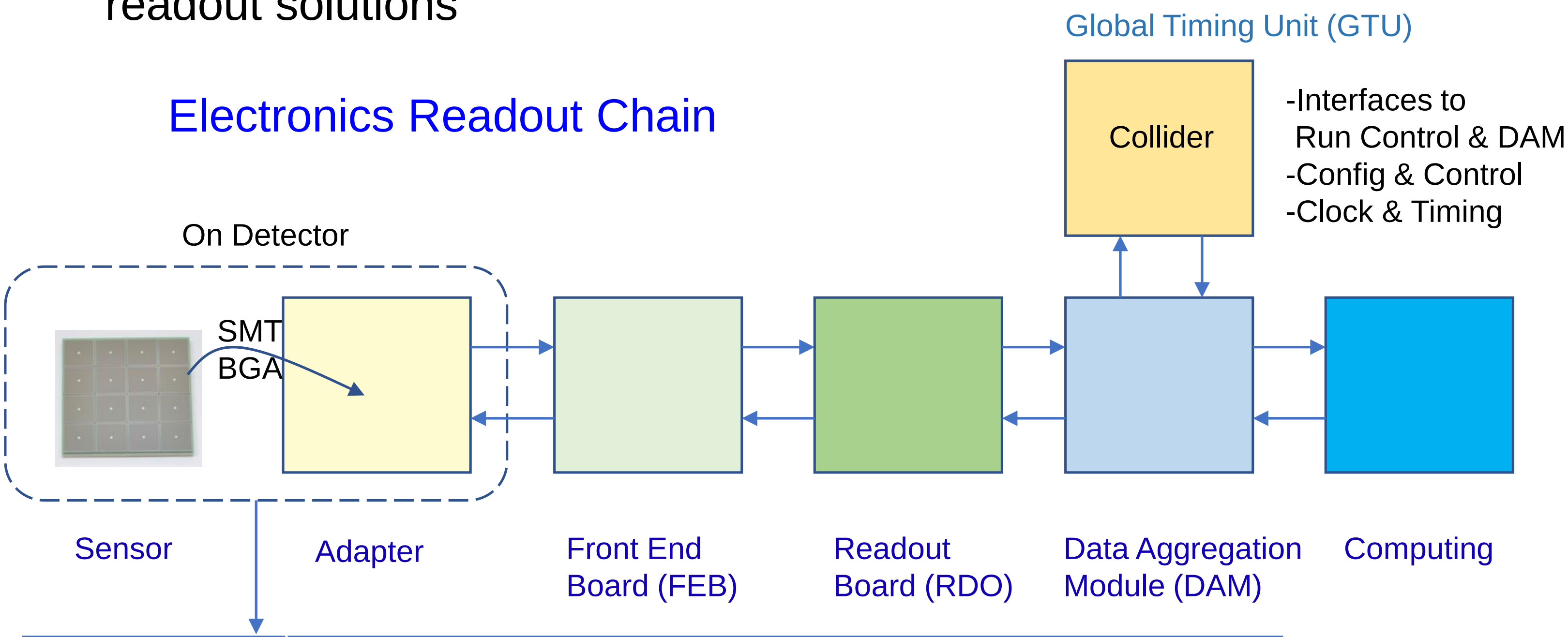
AC-LGAD (Low Gain Avalanche Detector)
- 20-35 psec
- Accurate space point for tracking
- forward disk and central barrel
- R&D and PED by International consortium HEP & NP

world's first at ePIC



- We have 23 different detector technologies in the ePIC detector
- It would be intractable if all have different readout electronics
  → the goal is to minimize the number of different ASICs and use common readout solutions

Electronics Readout Chain

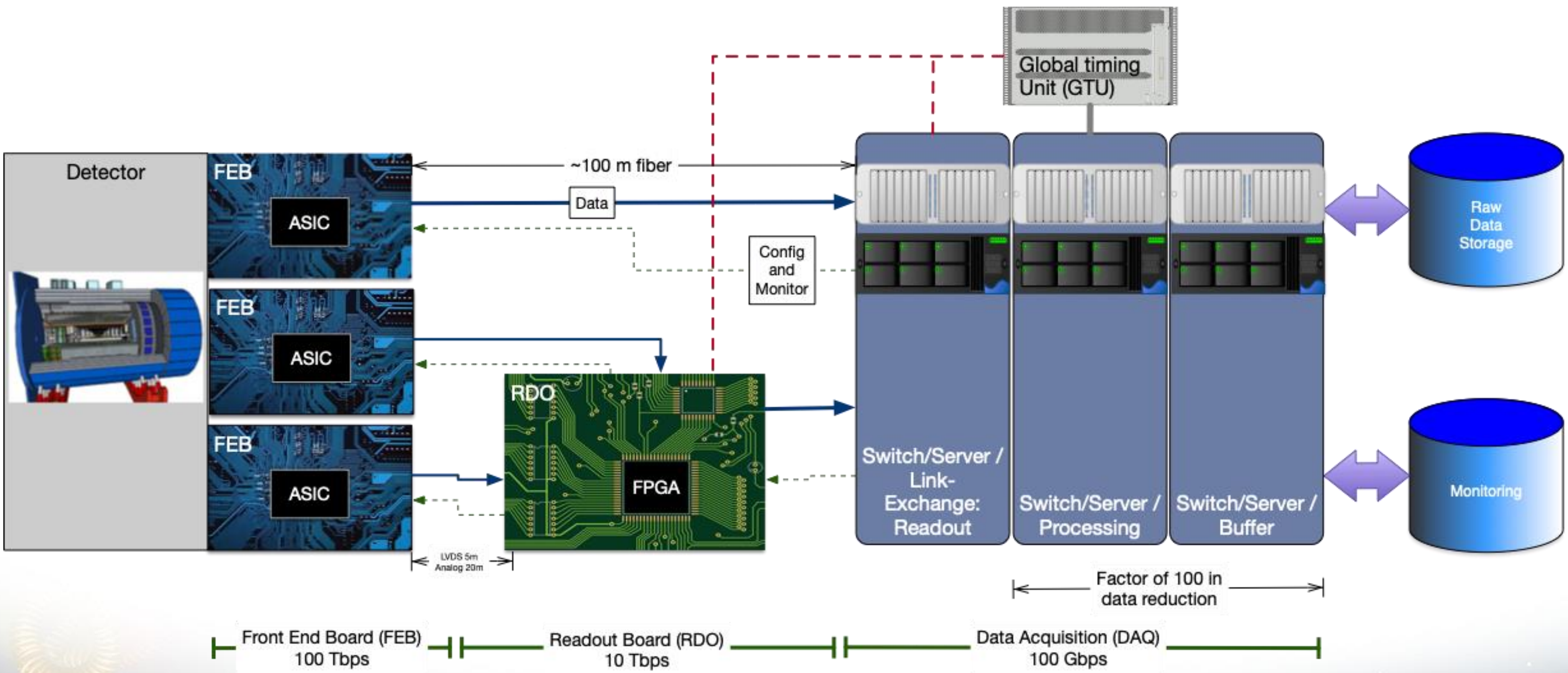


Detector Group	Channels			
	MAPS	AC/DC-LGAD	SiPM/PMT	MPGD
TOTAL	32 B	7.1M-54M	370k	100k
ASIC	ITS-3	EICROC FCFD HPsOC ASROC FAST	Discrete/COTS HGCROC3 ALCOR-EIC	SALSA

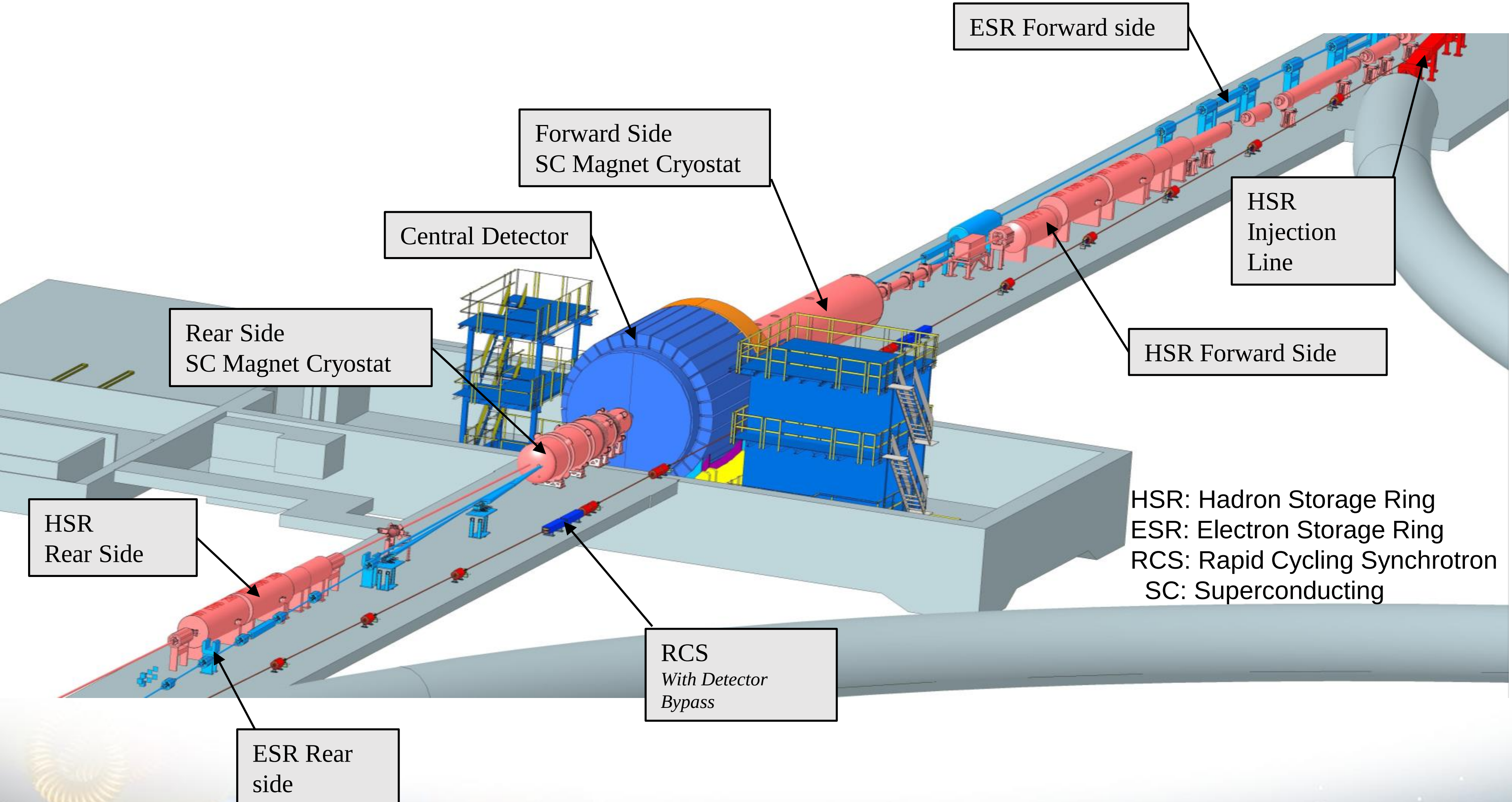
- We expect to need ITS-3 and 4-5 different ASICs
- Based on existing ASICs → reduce cost & time
- Much synergy with international efforts
  Salsa → Brazil

Streaming Readout Architecture

- Triggerless streaming architecture gives much more flexibility to do physics
- Rates quoted are at output of each stage
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector



Interaction Region Layout

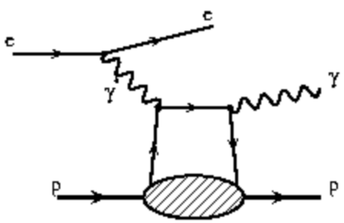


HSR: Hadron Storage Ring
ESR: Electron Storage Ring
RCS: Rapid Cycling Synchrotron
SC: Superconducting

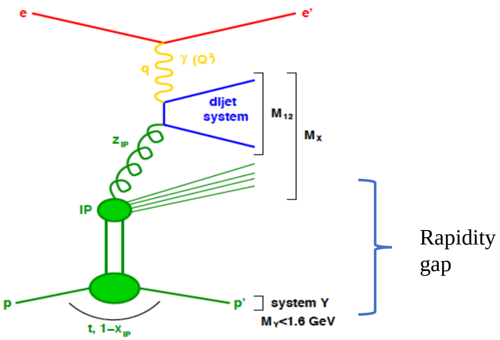
every cm counts → integration and communication with accelerator team is crucial

Far-forward physics at EIC

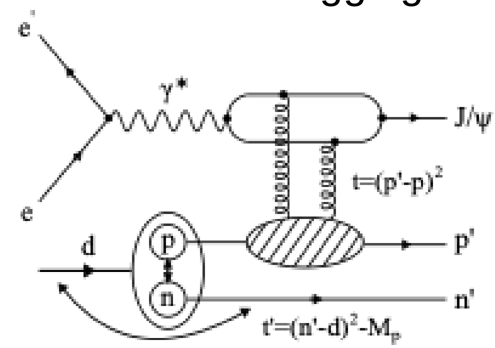
e+p DVCS events with proton tagging.



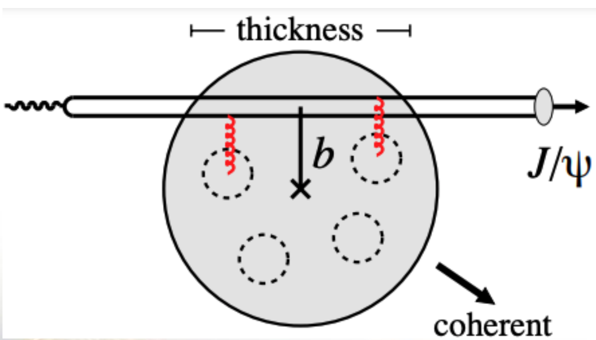
Diffraction



e+d incoherent J/Psi events with proton or neutron tagging

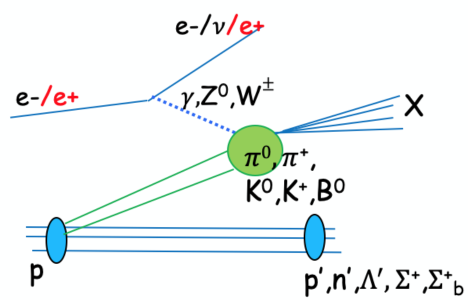


Saturation (coherent/incoherent J/ψ production)



Meson structure:

- with neutron tagging (ep→ (π) →e' n X)
- Lambda decays ($\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$)



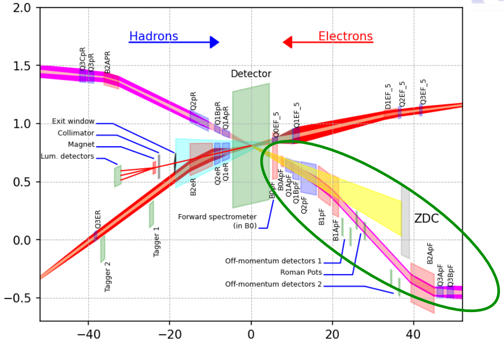
e+He3 with spectator proton tagging.

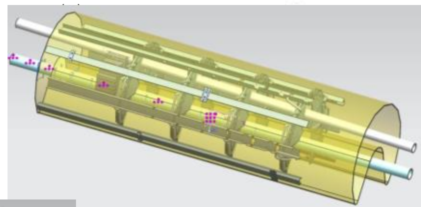
Tagging of coherent light ions (d, He3, He4) from coherent scattering.

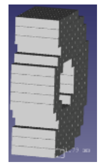
e+Au events with neutron tagging to veto breakup and photon acceptance.

….

Far-Forward Ancillary Detector Integration

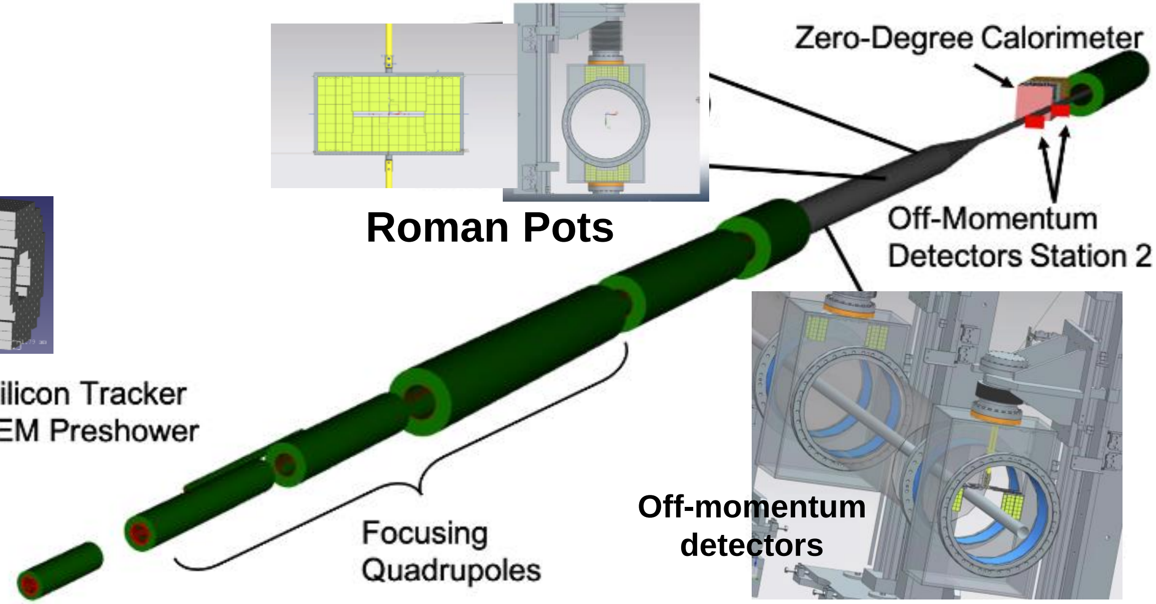




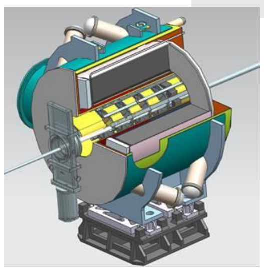


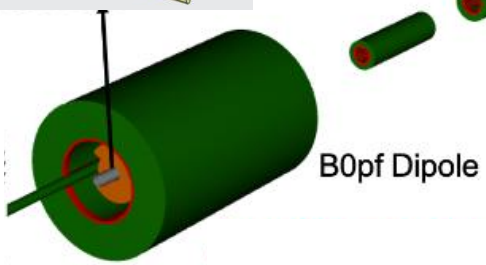
B0 Silicon Tracker and EM Preshower

Roman Pots



Off-momentum detectors



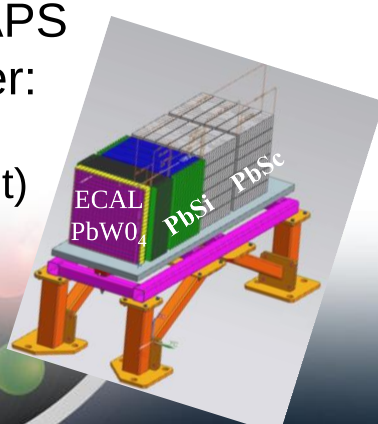


B0pf Dipole

IP magnets & ancillary detectors fully simulated in GEANT including all beam effects

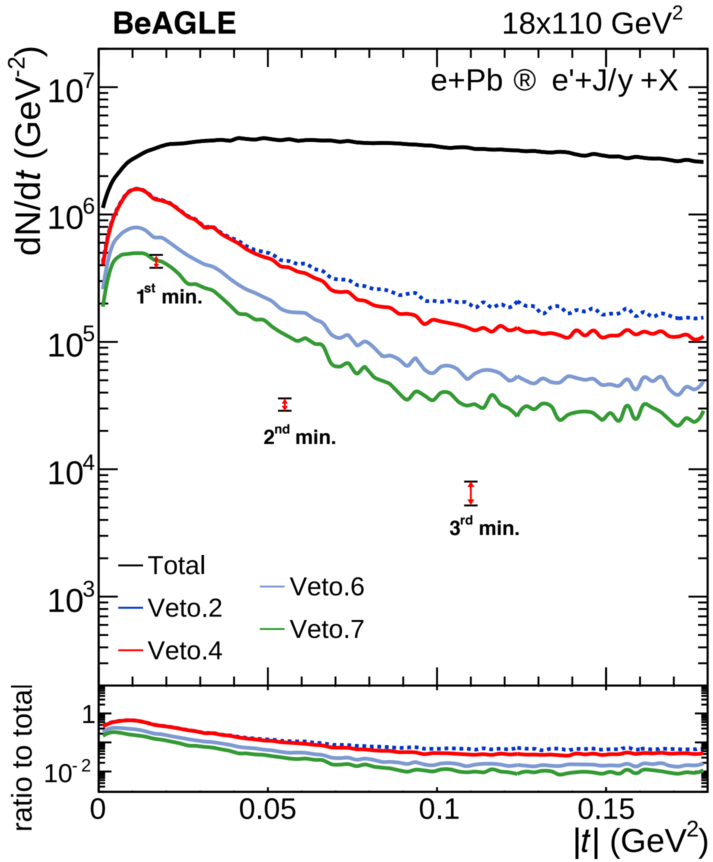
Technologies defined

- Silicon: AC-LGAD & MAPS
- Zero Degree Calorimeter:
  - ECAL (PbWO4)
  - HCAL (PbSi + PbScint)



Detector	Angular accept. [mrad]	p_T coverage
ZDC @ ~30m	θ<5.5 ($\eta > 6$)	p_T<1.3 GeV
Roman Pots	0*<θ<5.0 ($\eta > 6$)	*Low p_T(t) cutoff (beam optics)
Off-Momentum Detectors	0.< θ < 5.0 ($\eta > 6$)	Low-rigidity particles from nuclear breakups
B0 forward spectrometer	5.5 < θ < 20.0 (4.6< η < 5.9)	High p_T(t)

Vetoing Incoherent Events



Veto.1:
- no neutron in ZDC

Veto.2:
- Veto1 + no proton in Roman Pots

Veto.3:
- Veto2 + no proton in off-momentum detector

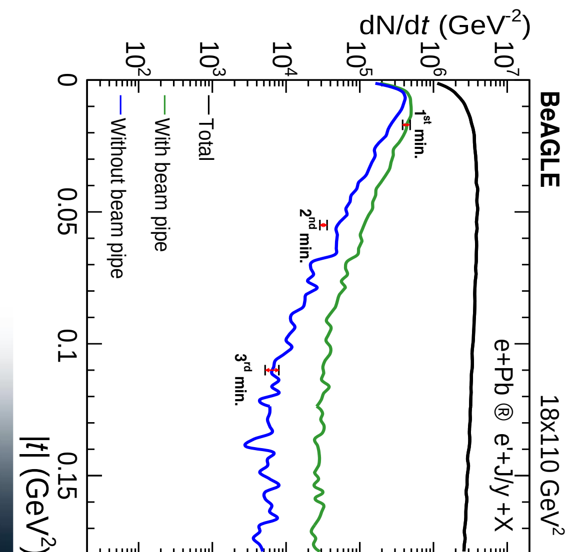
Veto.4:
- Veto3 + no proton in B0

Veto.5:
- Veto4 + no anything in preshower

Veto.6:
- Veto5 + no photon ***E>50MeV*** in ZDC

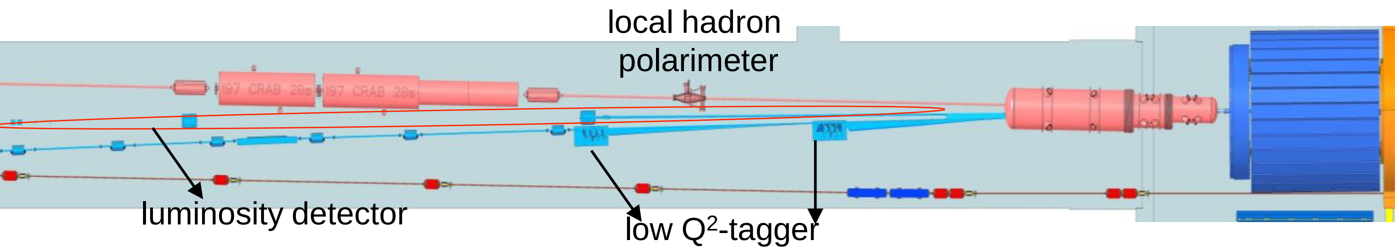
Veto.7:
- Veto6 + no activities $(|\eta| < 4.0\ \&\ p_T > 100\ \mathrm{MeV/c}\ \&\ E > 50\ \mathrm{MeV})$ other than e- and J/ψ in the main detector

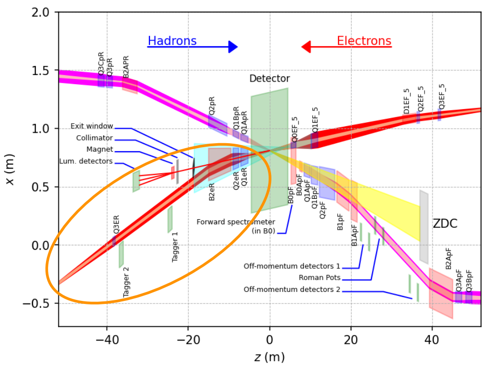
With these requirements, the rejection power is found to be not enough to reach the three minimum positions.



Beam pipe design and material critical to vetoing power

Luminosity Detector and Low Q^2 Tagger





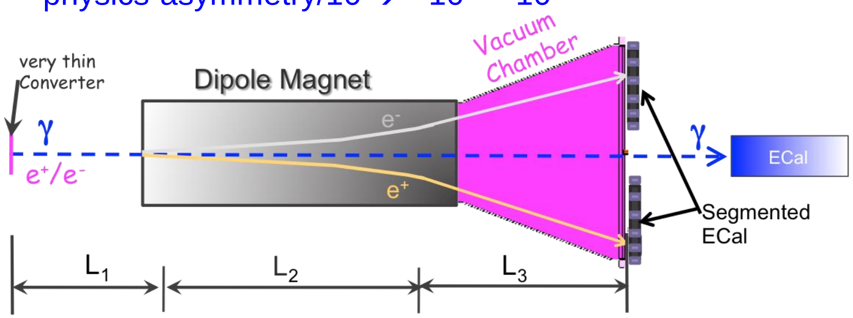
IP magnets, Lumi & low-Q^2 detectors fully simulated in GEANT including all beam effects and CAD layout

Luminosity Detector Concept:

Use Bremsstrahlung ep → epγ as reference cross section

Goals for Luminosity Measurement:

- Integrated luminosity with precision δL/L< 1%
- Measurement of relative luminosity:
  physics-asymmetry/10 → ~10^{-4} – 10^{-5}



Combine

pair spectrometer → high precision

with

zero degree photon calorimeter

→ fast feedback for collider

Technology:

Electromagnetic calorimetry with Si-tracking

Low Q^2-Tagger:

Purpose:

Detection of scatter electron for $Q^2 < 0.1$ GeV^2

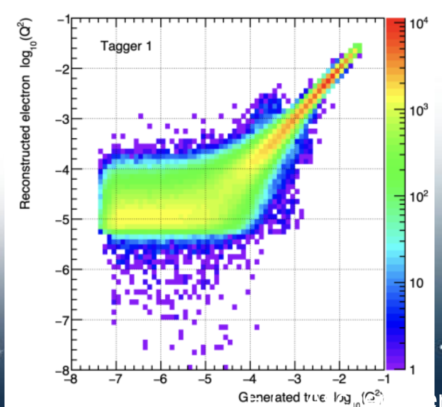
Critical for calibration of Lumi-detector

Beam divergence and energy spread impact performance

Technology:

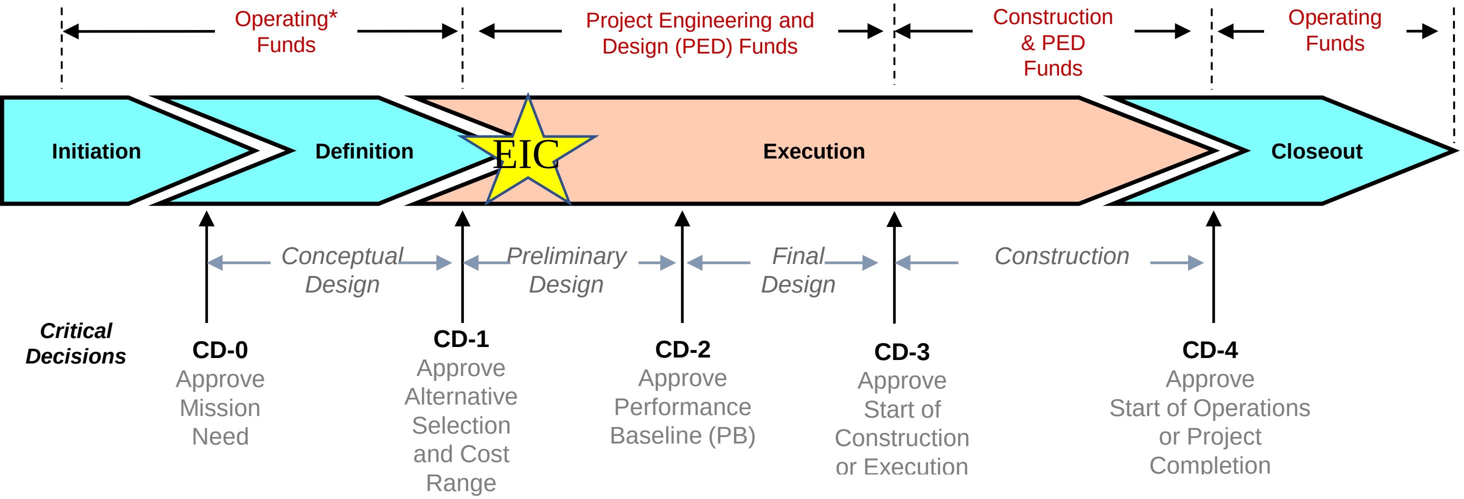
Electromagnetic calorimetry with Si-tracking

→ strong synergy with luminosity detector

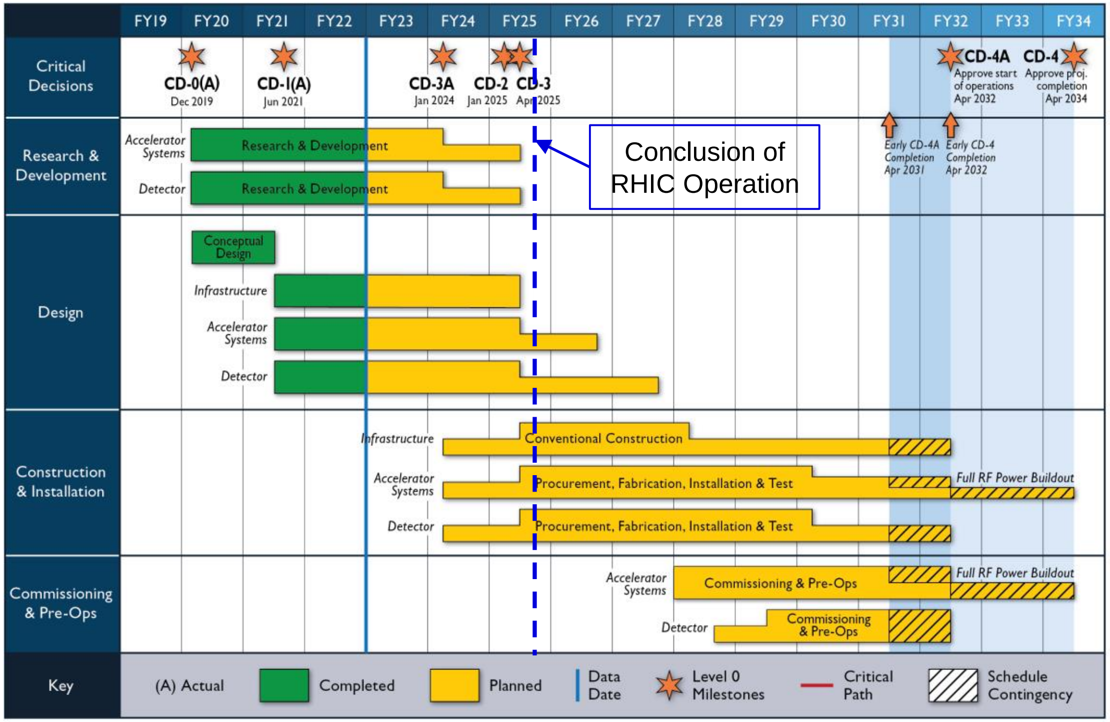


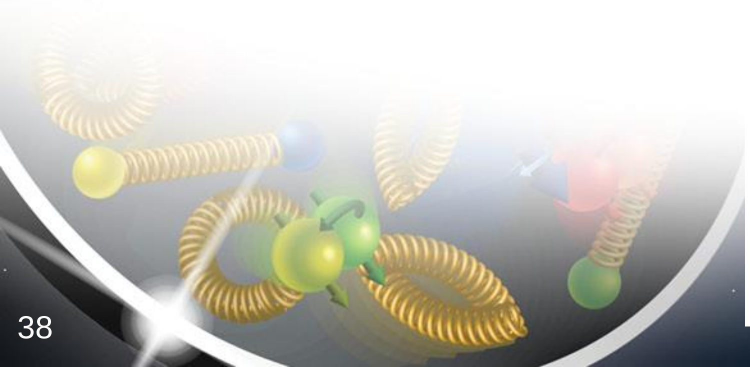
The EIC Project

Timeline: What is Coming

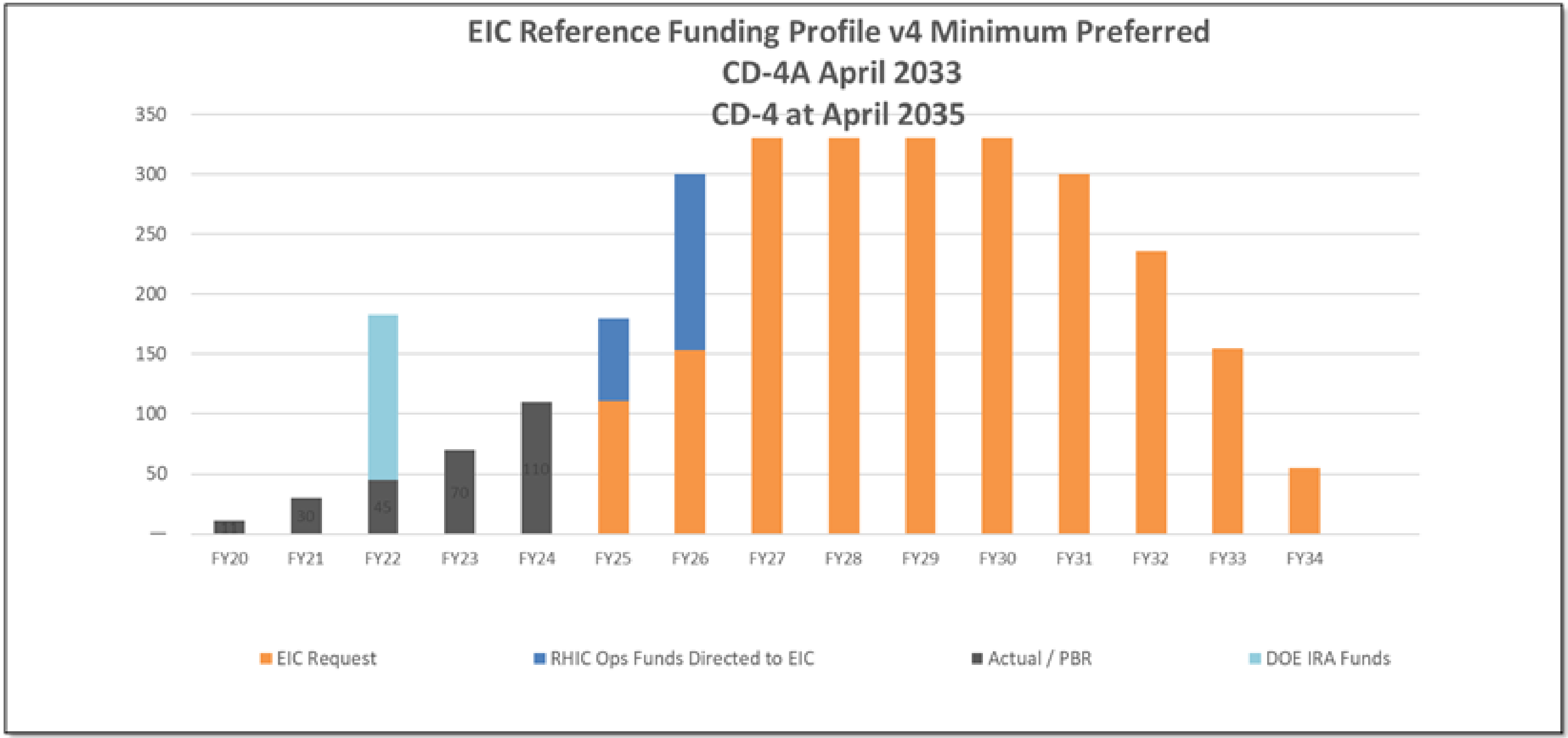


EIC Critical Decision Plan	
CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3a	**January 2024**
CD-2	January 2025
CD-3	**April 2025**
CD-4a early finish	April 2031
CD-4a	April 2032
CD-4 early finish	April 2032
CD-4	**April 2034**



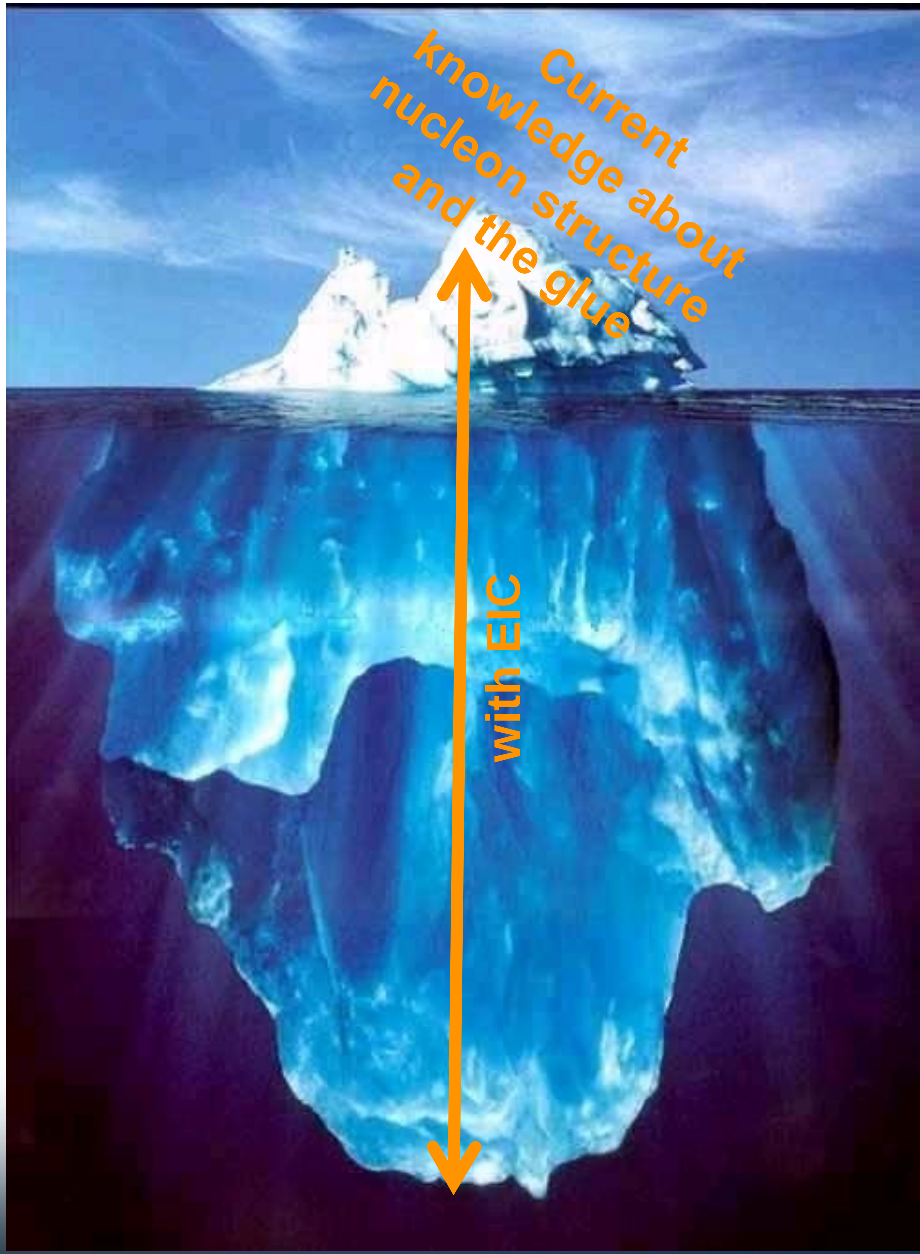


Project Funding Profile



- **Inflation Reduction Act funding of $138.24M** is a game changer and mitigates risk of slower than optimum ramp of new funding to the $150M/year needed.
- Possibility of significant package of long lead procurement items (CD-3A) helping to mitigate risks including procurement, supply chain, inflation and schedule.
- RHIC will shut down in June 2025 and significant RHIC Operations funding is redirected to EIC construction.

Take Away Message



Why is now the time to built EIC?

"all stars align":

- theory developments will allow to obtain the answers to the big questions discussed
- detector technologies allow for a collider detector with high resolution, wide acceptance and particle identification

BUT MOST IMPORTANTLY

- accelerator technologies allow to built a collider with
  - high luminosity
  - highly polarized electron and light hadron beams
  - a wide range in center of mass energies
  - hadron beams with highest A
  - demanding acceptance requirements can be realized in IR design

Let's get to work and built the EIC

Please join us

Engineers, Designers, Technicians, Administrators, Experimentalists, Theorists, Accelerator Physicists, ……

Jobs:
BNL: https://jobs.bnl.gov/search-jobs/eic?orgIds=3437&kt=1
JLab: https://www.jlab.org/recruiting
Science: https://www.bnl.gov/eic/


BACK UP

The EIC: A Unique Collider

EIC

collide different beam species: ep & eA
→ consequences for beam backgrounds
→ hadron beam backgrounds, i.e. beam gas events
→ synchrotron radiation

asymmetric beam energies
→ boosted kinematics
→ high activity at high $|\eta|$

Small bunch spacing: ~10 ns

crossing angle: 25mrad

wide range in center of mass energies
→ factor 6

both beams are polarized ~70%
→ stat uncertainty: $\sim 1/(P_1 P_2 (\int L\, dt)^{1/2})$

LHC /RHIC

collide the same beam species: pp, pA, AA
→ beam backgrounds
→ hadron beam backgrounds, i.e. beam gas events, high pile up

symmetric beam energies
→ kinematics is not boosted
→ most activity at midrapidity

moderate bunch spacing: 25 ns

no significant crossing angle yet (150 mrad now)

LHC limited range in center of mass energies
→ factor 2
RHIC wide range in center of mass energies :
→ factor 26 in AA and 8 in pp

no beam polarization
→ stat uncertainty: $\sim 1/(\int L\, dt)^{1/2}$

Differences impact detector acceptance and possible detector technologies

EIC Project Detector R&D Program & In-Kind

- in-kind contributions from Italy/INFN, France/IRFU, France/IN2P3, UK/STFC, etc.

						2023				https://wiki.bnl.gov/conferences/index.php/ProjectRandDFY23			
Project:	**eRD101**	**eRD102**	**eRD103**	**eRD104**	**eRD105**	**eRD106**	**eRD107**	**eRD108**	**eRD109**	**eRD110**	**eRD111**	**eRD112**	**eRD113**
Title:	mRICH	dRICH	hpDIRC	Silicon Service reduction	SciGlass	Forward ECal	Forward HCal	Cylindrical MPGD	ASIC/Electronics	Photosensors	Si-Vertex	AC-LGAD	Si-Sensor Development and Characterization
Contact:	X. He (GSU), M.Contalbrigo (U. Ferrara)	E. Cisbani (INFN-RM1), M.Contalbrigo (U. Ferrara), A. Vossen (Duke)	G. Kalicy (CUA), J. Schwiening (GSI)	L. Gonella (B'ham)	T. Horn and .L. Pegg (CUA)	H.Z. Huang (UCLA), O. Tsai (UCLA)	Friederike Bock (ORNL)	K. Gnanvo (UVA)	Fernando Barbosa (JLab)	Y. Ilieva (SC), C. Zorn (JLab), J. Xie (ANL), A. Kiselev (BNL), Pietro Antonioli (INFN)	Nicole Apadula (LBNL)	Zh. Ye (UIC)	Grzegorz Deptuch (BNL)
Proposal:	v1 (pdf)	v1 (pdf)	v1 (pdf), v2 (pdf)	v1 (PDF) v2 (pdf)	v1 (pdf)	v1 (pdf)	v1 (pdf), v2 (pdf)	v1 (pdf)	v1 (pdf), v2 (pdf), v3 (pdf)	v1 (pdf)	v1 (pdf) v2 (pdf)	v1 (pdf)	v1 (pdf) v2 (pdf)

INFN-Ferrara, Glasgow

INFN-Roma1, INFN-Ferrara

GSI

Birmingham, Brunel, RAL, INFN-Bari, INFN-Trieste, IMP, CCNU

IJCLab-Orsay, INFN-Genova, AANL/Armenia

Chinese EMCal Consortium

Valparaiso

CEA Saclay

IJCLab-Orsay, CEA Saclay, INFN-Torino

Nürnberg, GSI, INFN-Bologna, Cosenza, Ferrara, Genova, Trieste

IJCLAB/ Omega/ Saclay

Birmingham, Brunel, RAL, INFN-Bari, INFN-Trieste, IMP, CCNU

Strong synergies with CERN

CERN – EIC R&D Day November 2021 https://indico.cern.ch/event/1063927/

- MAPS: ALICE-3 – ITS-3 development
- PID: LHC-b and ALICE-3
- Photon-sensors: LAPPDs with LHC-b
- MPGD: long-term CERN R&D program RD51
- DAQ: strong developments on streaming DAQs for all LHC experiments
- AI/ML and high-performance distributed computing

EIC Project Detector R&D

MAPS-Tracker:
- Development of a full tracking detector solution composed of 65 nm MAPS sensors Modules from stitched sensors, barrel & discs, mechanics, integration & cooling
- reduce the services material load
  → Improved powering and readout system
- Development of the EIC sensor: design & characterization

MPGDs:
- Development of prototypes of cylindrical MPGDs & planar thin gap MPGDs

AC-LGAD:
- Develop system including sensors, ASIC & services for auxiliary detectors and ToF

PID-Detectors:
- DIRC: focus on Cosmic ray telescope (CRT), validation of BaBar bars reuse option, and completion of cost optimized hpDIRC design
- mRICH: optimize photonsensors + electronics; testbeam of improved prototype
- dRICH: Characterize mirror & aerogel; Assessment of dRICH prototype performance with the EIC detection plane

ECals:
- bECAL: Full characterization of full SciGlass block designed for EIC by beam test
- fECAL: construct 64 channel prototype to optimize light uniformity, light guides, verify performance by test beam

6.10 EIC Detector

6.10.01 Detector Management	6.10.08 Electronics
6.10.02 Detect. R&D & Physics Design	6.10.09 DAQ / Computing
6.10.03 Tracking	6.10.10 Detector Infrastructure
6.10.04 Particle Identification	6.10.11 IR Integration & Auxiliary Detectors
6.10.05 Electromagn. Calorimetry	6.10.12 Detector Pre-Ops & Commiss.
6.10.06 Hadronic Calorimetry	6.10.13 Detector #2 Development
6.10.07 Magnets	6.10.14 Polarimetry and Luminosity

Photon-Sensors:
WBS 6.10.04 & 05 & 06
- Assess current state of LAPPD performance. Improve design through iterations to fulfill EIC specifications
  - Spatial resolution for Cherenkov imaging applications
  - Timing resolution in a single photon mode
  - Timing resolution for Time-of-Flight purposes
  - Performance in a strong (inhomogeneous) magnetic field
  - QE & PDE spectrum optimization
  - Geometric form factor optimization

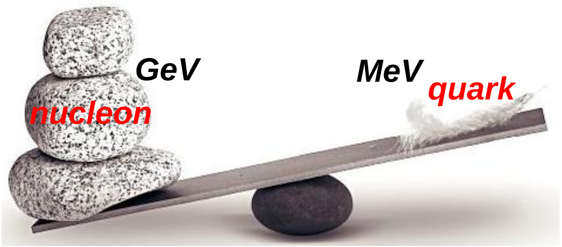
Electronics & DAQ/Computing
- Development of readout solutions for
  - calorimeters with SiPMs, ASIC based & ADC based
  - dRICH with SIPMs based on ALCOR
  - AC-LGAD readout chain with EICROC & FCFD
  - MPGD readout based on SALSA-ASIC

HCals:
- Prototype SC-tile production using machining & injection molding & detailed characterization
- Sensor board development
- first prototype of one full segment

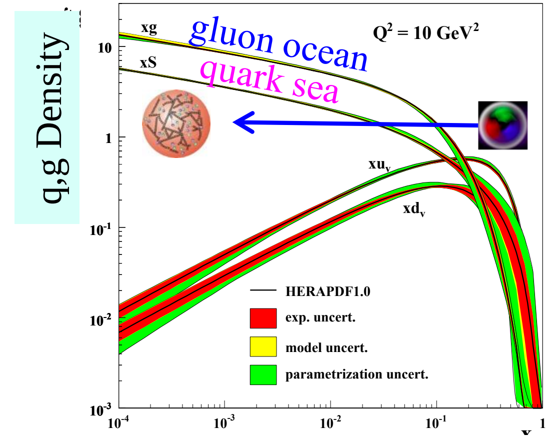
Hadron Polarimetry:
R&D through Accelerator
- validate concepts to veto breakup of He-3
- new targets for pC-polarimeters

What do we know: Mass of the Proton, Pion, Kaon

***Visible world:** mainly made of light quarks – its mass emerges from quark-gluon interactions.*



Density of quarks or gluons inside the proton



Fraction of overall proton momentum carried by q,g

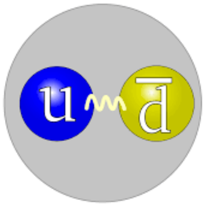
Proton

Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

Gluon rise discovered by HERA e-p

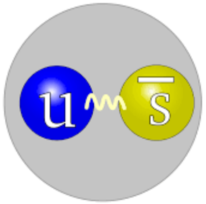
Pion

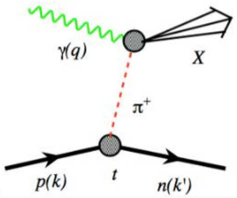
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

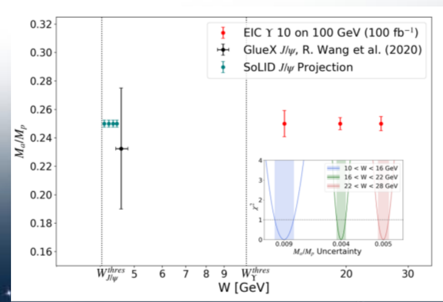
Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?





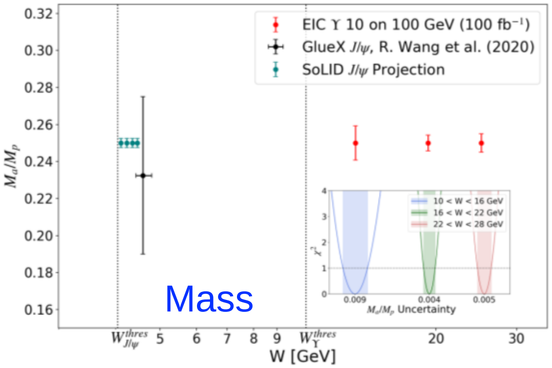
For the pion and the kaon the EIC will allow determination of the quark and gluon contributions to mass with the Sullivan process.

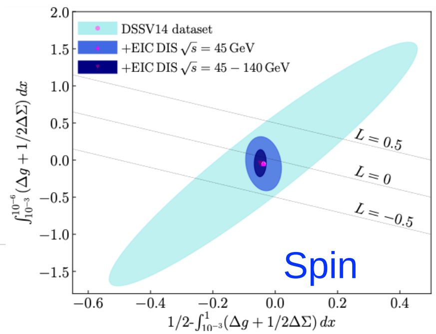
For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"



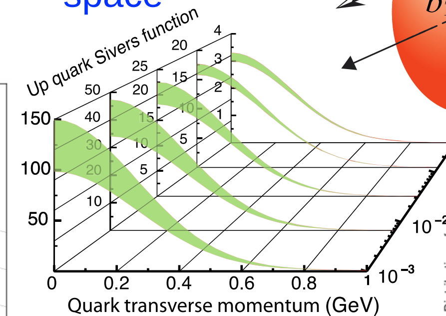
EIC Science Highlights

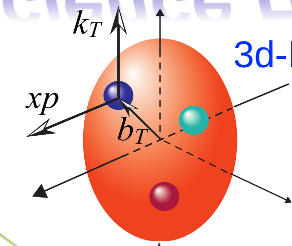
Proton:





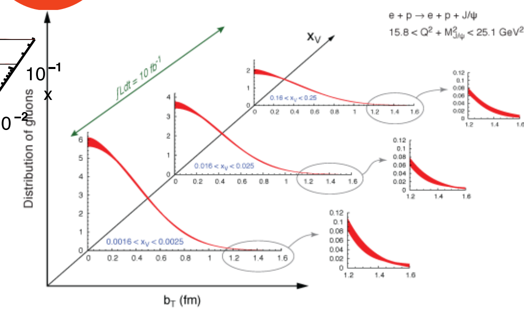
momentum space



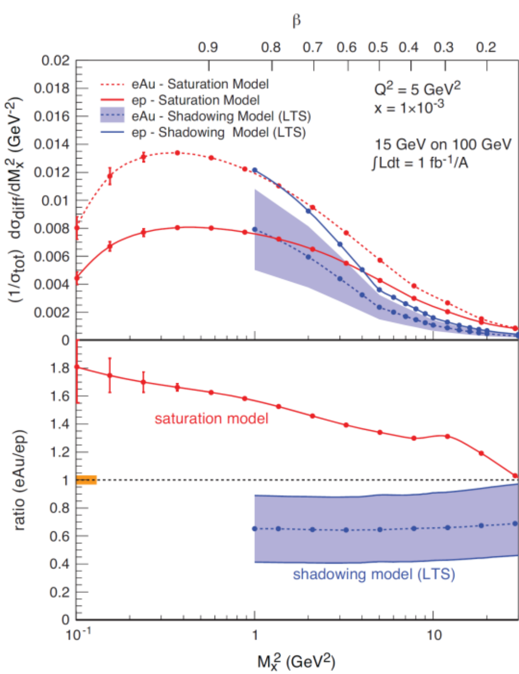


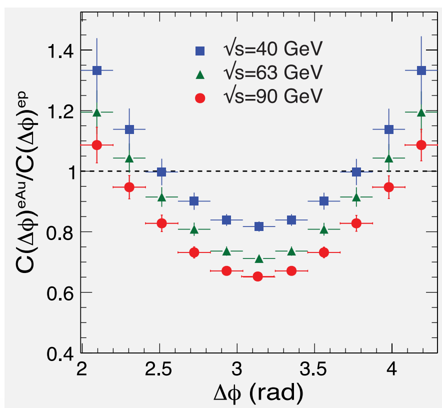
3d-Imaging

coordinate space



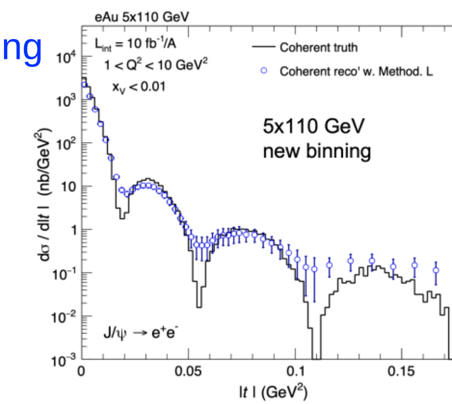
Nuclei:



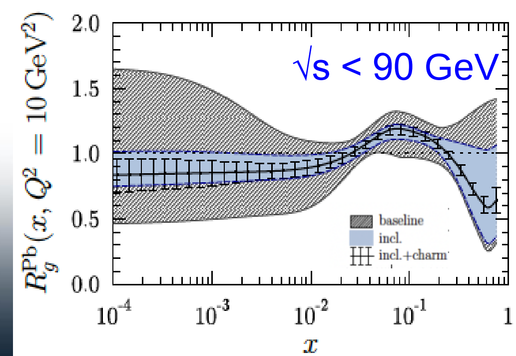


non-linear QCD effects
→ Saturation

3d-Imaging of nuclei



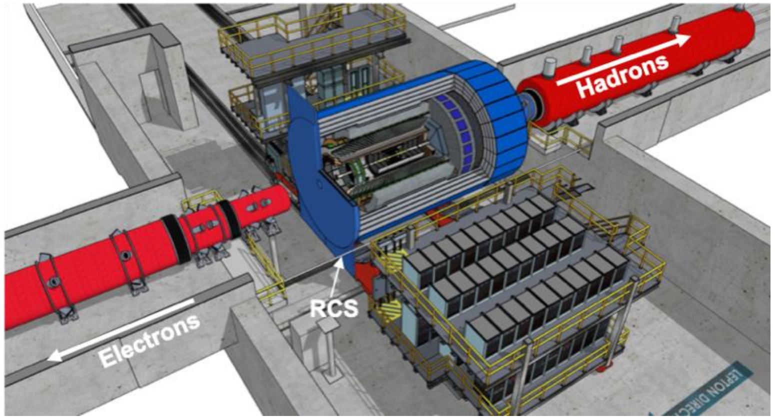
nPDF



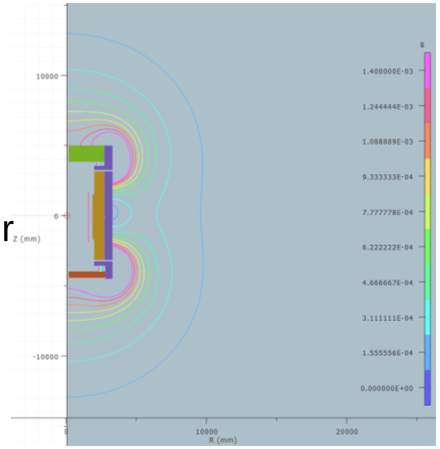
E.C. Aschenauer

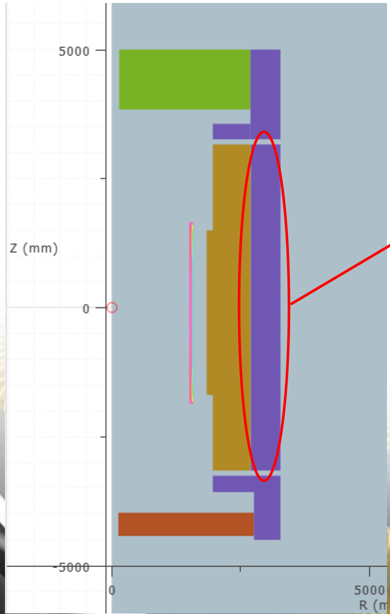
Flux Return layout

- Requirement for fringe field: <10 Gauss at forward and backward side and at RCS location

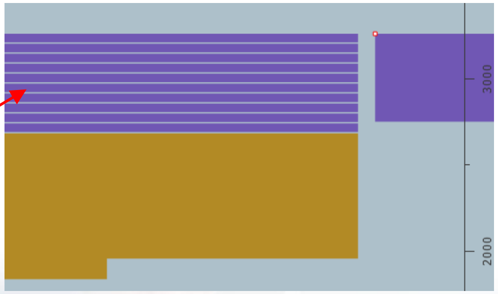


- Challenges detector design not symmetric
  - → critical that forces get balanced
- Consequences on design:
  - backward HCal moved as far back as possible add both sPHENIX flux return doors behind bHCal
  - forward HCal need to have first tungsten/Sc and then Steel/Sc
  - add additional steel around barrel HCal

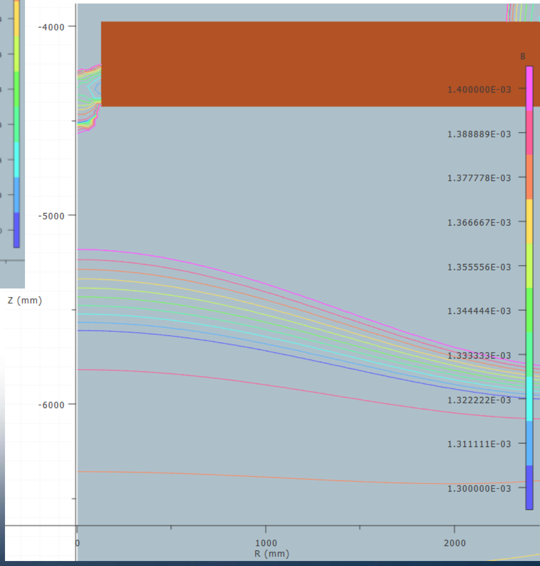




layered barrel extra flux return
6 layers 50 mm steel 40 mm air

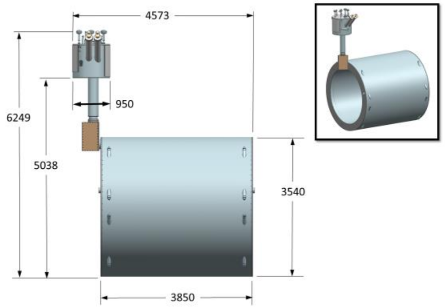


Reach 14 gauss and lower

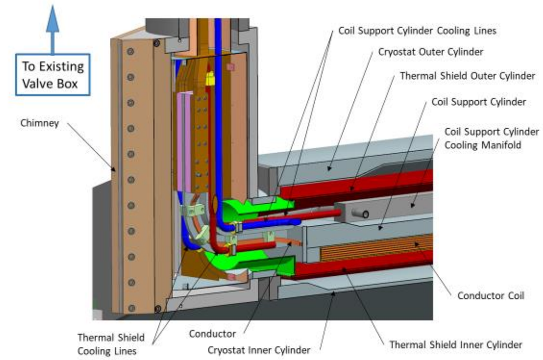


Solenoidal Magnet - MARCO

Large-scale superconducting detector magnets have a limited worldwide vendor supply and carry known technical, cost and schedule risk during the construction phase.
→ A "known" LLP candidate



EIC Magnet Assembly Envelope
Based on existing BABAR design and drawings



Section showing cooling lines and conductor exiting magnet through Heat Shield to Chimney Connection Box
Currently defining plumbing and conductor exit and interface with existing Chimney / Cryobox

❑ Magnet status:

- CD-1 Approval — June 2021
- 3T Detector solenoid preliminary design report — December 2021
- Incremental (30%) Design and Safety Review — February 2022
- DPAP closeout report – led to reduced field (< 3 T) — March 2022
- Contract for 60% Design Review — April 2022
- 60% design team formation and kick off meeting — May 3, 2022
- Mid-Project Progress meeting (@BNL, hybrid meeting) — June 28, 2022
- Point design adjusted to stretch goal of 2 T (operation at 1.7 T) — August 10, 2022
- 60% Design and safety Review — October 18, 2022
- 90% Design contract in place — December 2022
- Found qualified vendor willing to make conductor — January 2023

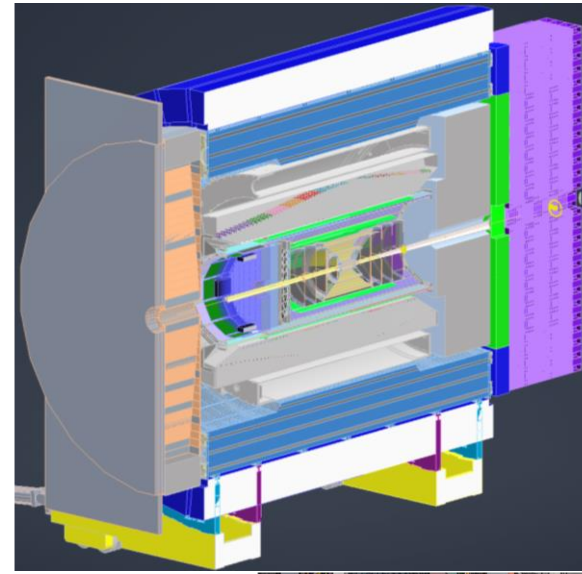
❑ Magnet planning:

- RFI on the street — February 2023
- 90% Design completion and review — September 2023
  (90% design completion is 100% - final design - for "Vendor Design-Build" procurement).
- P6: Milestone FDR date — 21 November 2023

→ Magnet is on track to be ready for procurement at CD-3A date

What is new/special for a EIC GPD

Radius/Distance from IP



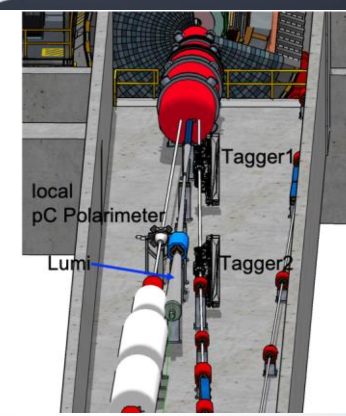
Vertex detector → Identify primary and secondary vertices,
Low material budget: 0.05% X/X_0 per layer;
High spatial resolution: 10 μm pitch CMOS Monolithic Active Pixel Sensor

Central tracker → Measure charged track momenta
MAPS – tracking layers in combination with micro pattern gas detectors
MPGD: μ-RWell or MicroMegas

electron and hadron endcap tracker → Measure charged track momenta
MAPS – disks in combination with micro pattern gas detectors

Particle Identification → pion, kaon, proton separation on track level
RICH detectors (modular and dual radiator RICH, DIRC) & Time-of-Flight
high resolution timing detectors (LAPPS, LGAD) 10 – 30 ps
novel photon sensors: MCP-PMT / LAPPD

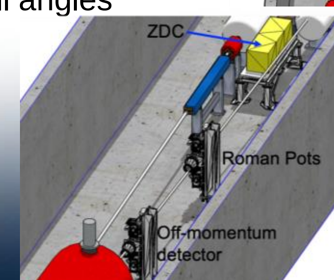
Electromagnetic calorimeter → Measure photons (E, angle), identify electrons
$PbWO_4$ Crystals (backward), W/SciFi Spacal (forward)
Barrel: Pb/SciFi+imaging part or new Scintillating glass → cost effective



Hadron calorimeter → Measure charged hadrons, neutrons and K_L^0
challenge achieve ~50%/√E + 10% for low E hadrons (<E> ~ 20 GeV)
Fe/Sc sandwich with longitudinal segmentation

DAQ & Readout Electronics: trigger-less / streaming DAQ
Integrate AI into DAQ → cognizant Detector

Very forward and backward detectors → scattered particles under very small angles
Silicon tracking layers in lepton and hadron beam vacuum
Zero – degree high resolution electromagnetic and hadronic calorimeter



Polarimetry
Lepton: integrated transverse and longitudinal Compton polarimeter
Hadron: absolute and relative hadron polarimetry in the CNI region

Background/Radiation

Important to note:

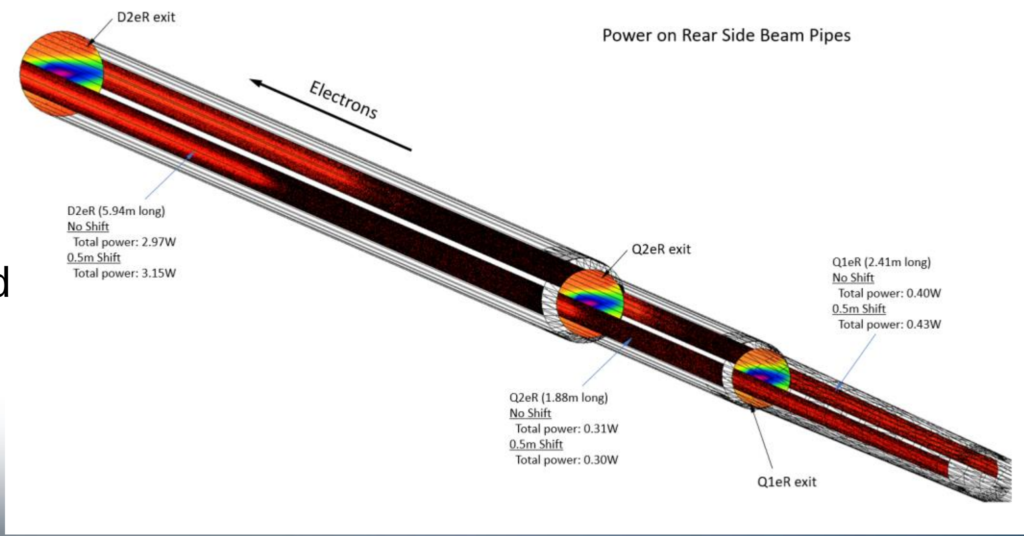
- low multiplicity per event: < 10 tracks
- $\eta > 2$: avg. hadron track momenta @ 141 GeV: ~20 GeV
- No pileup from collisions 500 kHz @10^{34} $cm^{-2}s^{-1}$ → coll. every 200 bunches
- radiation environment much less harsh than LHC → factor 100 less

The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance

- There are several background/radiation sources :
  - primary collisions
  - beam-gas induced
  - synchrotron radiation

Synchrotron Radiation:

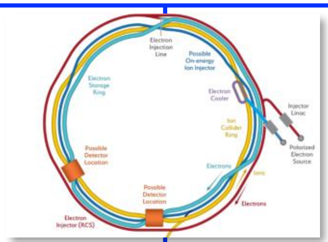
- Origin: quads and bending magnet upstream of IP
- Tails in electron bunches: can produce hard radiation
- Studied using Synrad3D



Complementarity for 1st-IR & 2nd-IR

Since CD-1 we made significant progress in the preliminary design for the 2nd IR with a focus on complementarity

	1st IR (IP-6)	2nd IR (IP-8)
Geometry:	ring inside to outside	ring outside to inside
	tunnel and assembly hall are larger Tunnel: ⃠ 7m +/- 140m	tunnel and assembly hall are smaller Tunnel: ⃠ 6.3m to 60m then 5.3m
Crossing Angle:	25 mrad	35 mrad secondary focus



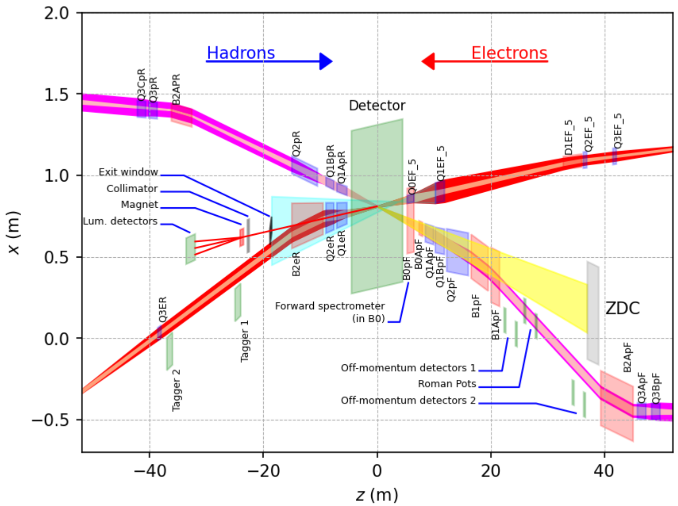
different blind spots
different forward detectors and acceptances
different acceptance of central detector

Luminosity:
more luminosity at lower E_{CM}
optimize Doublet focusing FDD vs. FDF
→ impact of far forward p_T acceptance

Experiment:
1.5 Tesla or 3 Tesla
different subdetector technologies

Progress – Interaction Region

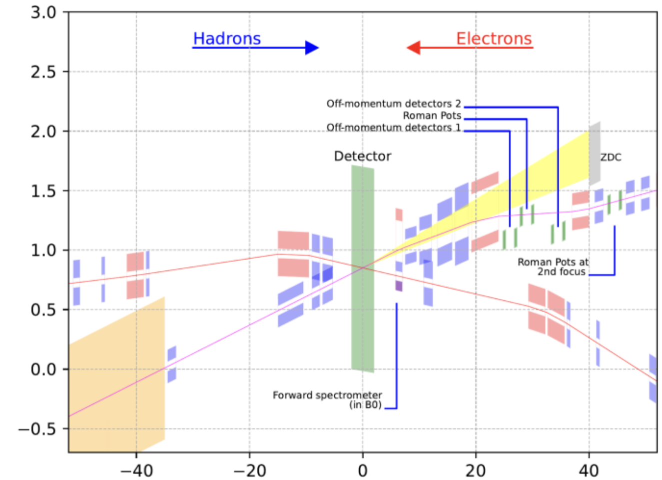
1^{st} IR (IP-6)



IR Highlights and Challenges

- High Luminosity → High current (~ 2.5 A)
- High number of bunches (1160, ~10 ns separation)
  - Avoid parasitic collisions at IR
    - Crossing angle
    - Both focusing elements close to IP
- Small β^* values (h: 80/7.2 cm, e:45/5.6 cm)
  - Strong final focus magnets close to IR
  - Aperture: challenging magnet designs
- Polarization
  - Lattice constraints to enable polarized beams
  - Polarized hadrons / electons
    - Polarimetry (local and global)
    - Spin rotators & Snakes
  - electrons: Frequent on-energy bunch replacements
- Experimental detector
  - Forward detectors
  - Experimental solenoid & compensation

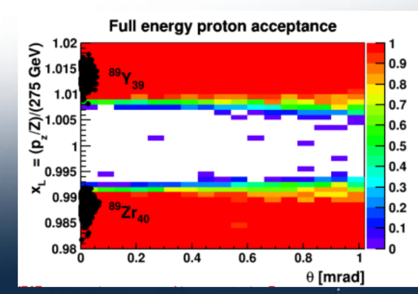
2^{nd} IR (IP-8)



- The same highlights and challenges as IP-6
- Different: **pre-conceptual** design with 35mr crossing angle and secondary focus for science complementary checks.
- Further study needed for the feasibility of the IR magnets → Nb3Sn magnets are being evaluated as an option.

2^{nd} focus enables:

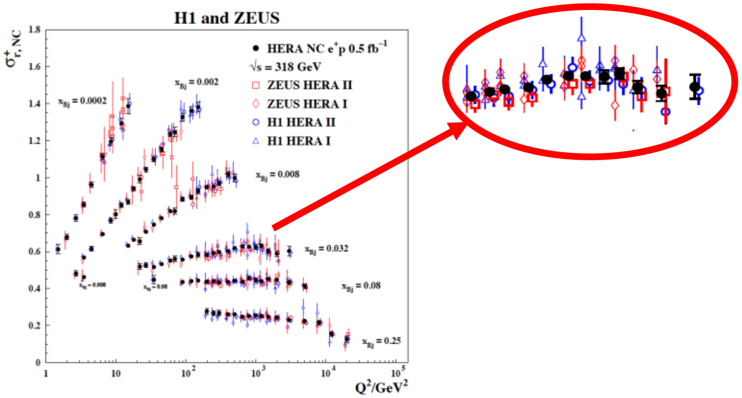
enhanced low P_T acceptance, DVCS on nuclei, Light ion tagging, Diffraction, improved Gluon imaging by detection of (A-1) nuclei



2^{nd} Detector: Complementary is Key

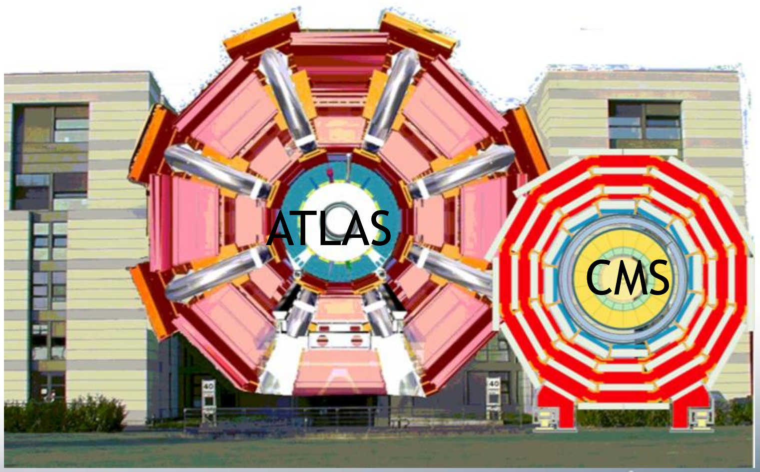
What do we want from "Complementary"

- **Cross-checking important results (obvious!)**
  - Many examples of wrong turns in history of nuclear and particle physics.
  - Independent cross checks (detector, community, analysis tools) are essential for timely verifications and corrections



- **Cross Calibration**
  - Combining data gave well beyond the √2 statistical improvement …
  - Different dominating H1, ZEUS systematics…
  - Effectively use H1 electrons with ZEUS hadrons
    … not all optimal solutions have to be in one detector…

- **Technology Redundancy**
  ... by applying different detector technologies and philosophies to similar physics aims
  - mitigates technology risk vs. unforeseen backgrounds
  - differently optimizes precision and systematics



- **Different primary physics focuses**
  ... EIC has unusually broad physics program
  (from exclusive single particle production to high multiplicity eA or γA with complex nuclear fragmentation)
  → Impossible to optimize for the full program in a single detector.
  → Impact on IR design