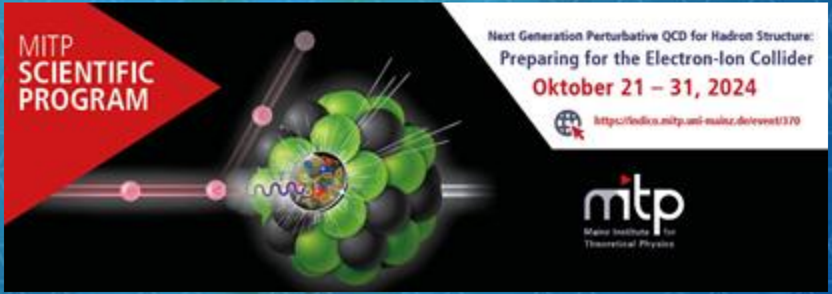
Oct 21 – 31, 2024
MITP - Mainz Institute for Theoretical Physics, Johannes Gutenberg University Mainz

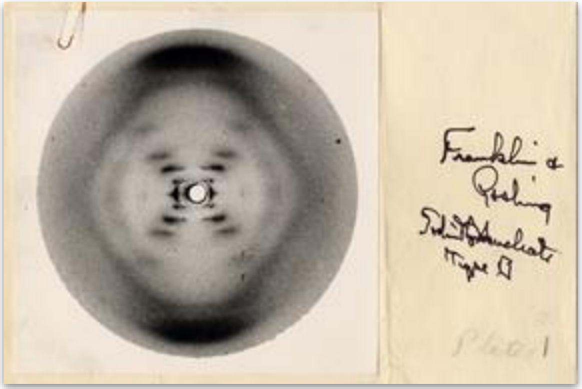


The EIC, the ePIC experiment, and the longitudinal proton spin

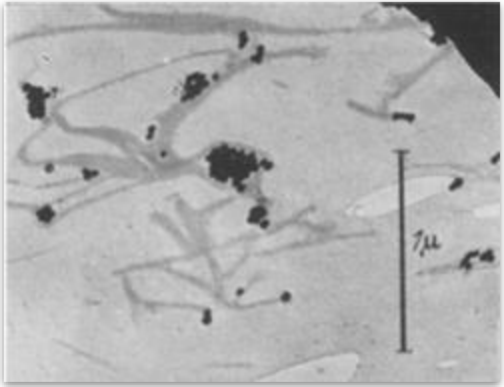
Maria ŻUREK, Argonne National Laboratory

ePIC

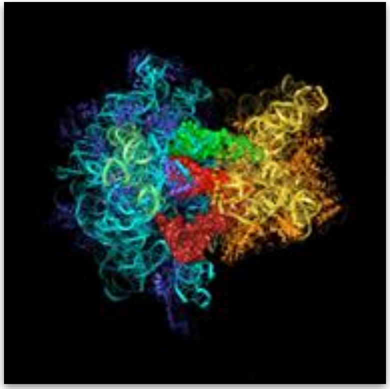
Argonne NATIONAL LABORATORY



Rosalind Franklin's "Photo 51" (1952) – DNA Double Helix

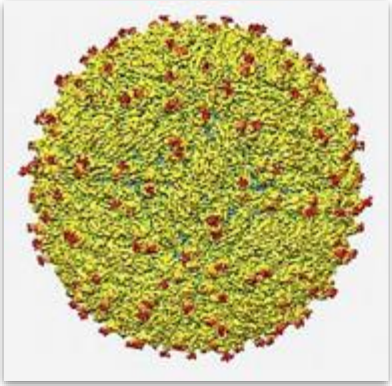


First Electron Microscope Image of a Virus (1939)



High-resolution Ribosome Structure (2000)

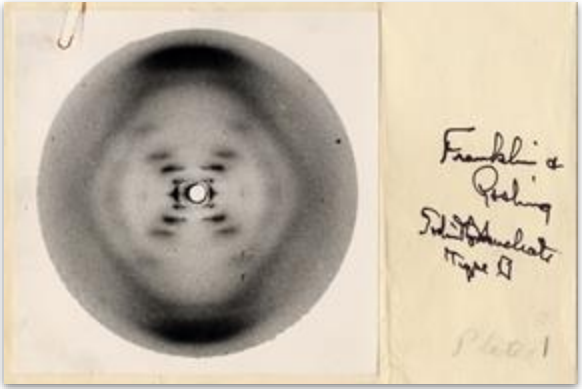
Hubble Deep Field Picture (1995)



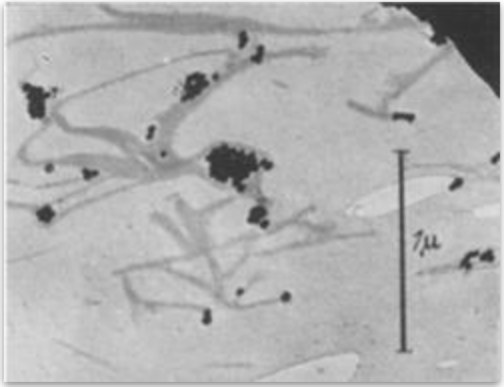
Cryo-EM Image of Zika Virus (2016)

First Image of a Black Hole (2019)

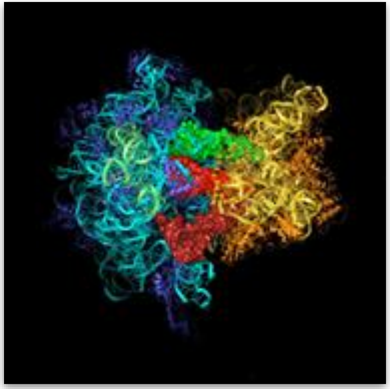
Pictures: See Bibliography on Slide 84



Rosalind Franklin's "Photo 51" (1952) – DNA Double Helix

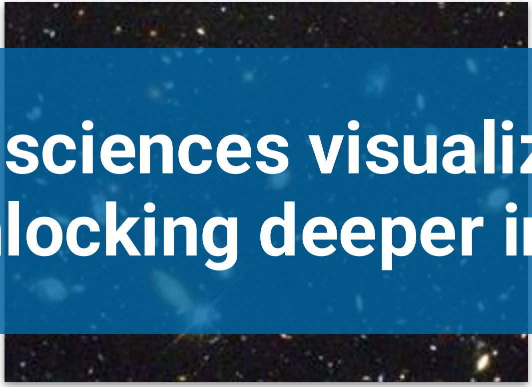


First Electron Microscope Image of a Virus (1939)



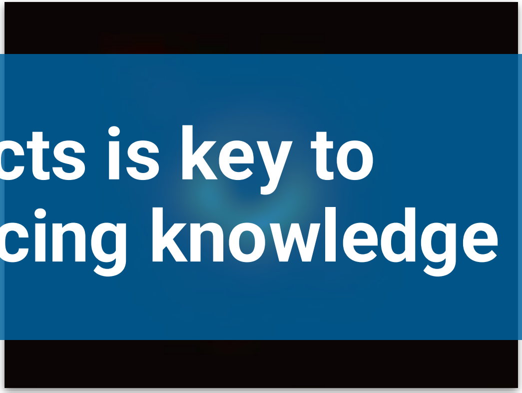
High-resolution Ribosome Structure (2000)

In sciences visualizing complex objects is key to unlocking deeper insights and advancing knowledge



Hubble Deep Field Picture (1995)

Cryo-EM Image of Zika Virus (2016)

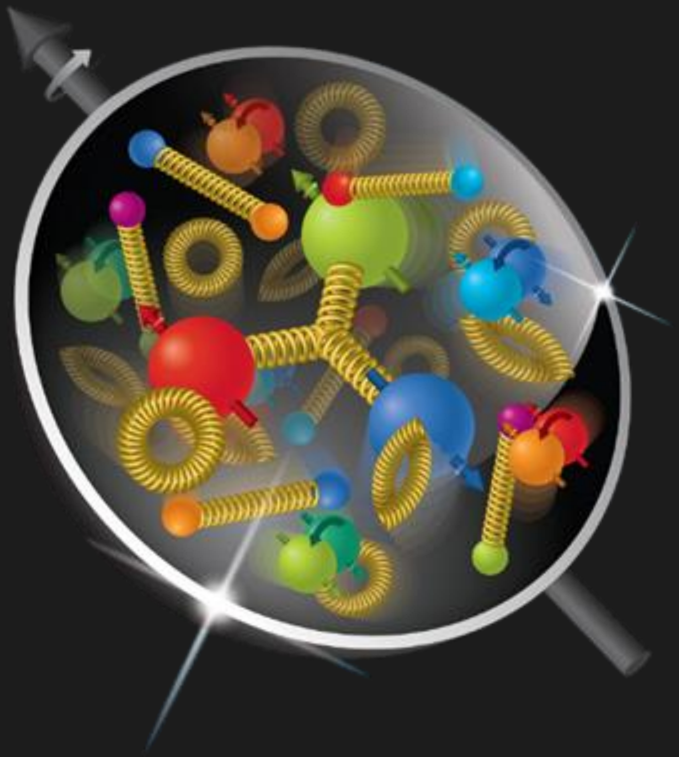


First Image of a Black Hole (2019)

Pictures: See Bibliography on Slide 84

The Electron-Ion Collider

The EIC Physics Quest

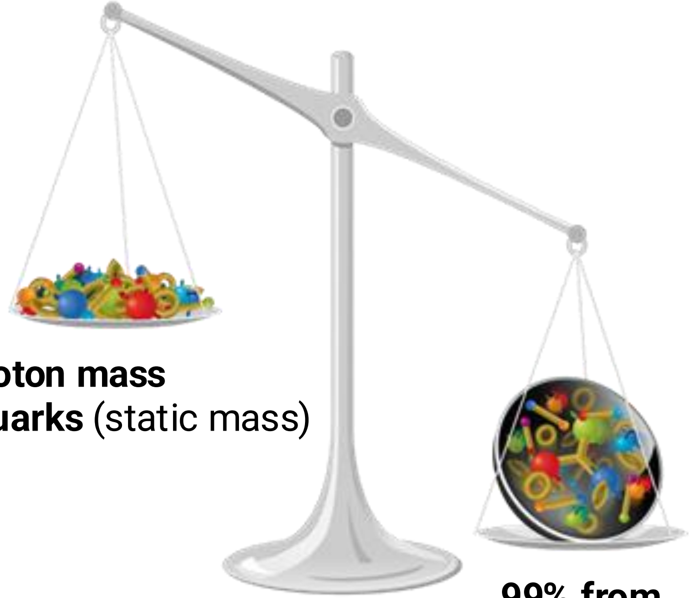


The EIC will uncover the hidden structure of protons and nuclei in 3D with precision offering new insights into the fundamental fabric of matter

Understanding the Glue that Binds Us All

The EIC Physics Quest

- How do the **nucleon properties like mass and spin emerge** from their partonic structure?
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



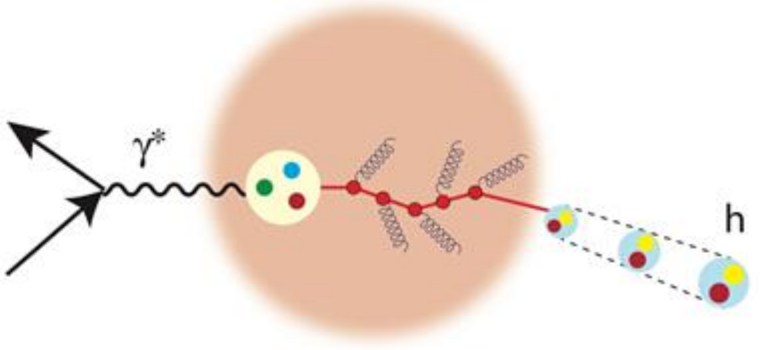
<1% proton mass from quarks (static mass)

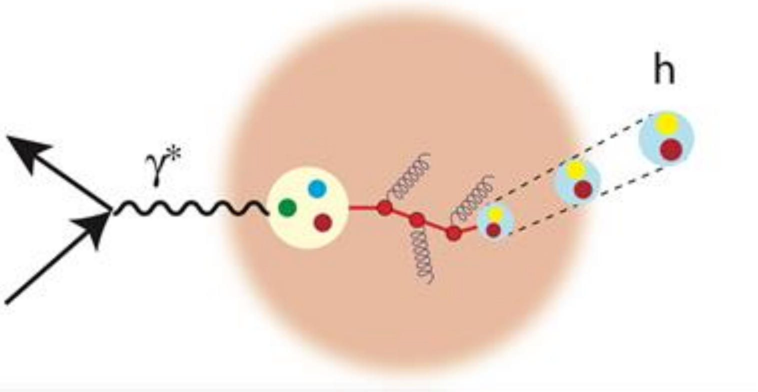
99% from interactions

Pictures: adapted from Brookhaven National Laboratory

The EIC Physics Quest

- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium?
- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?



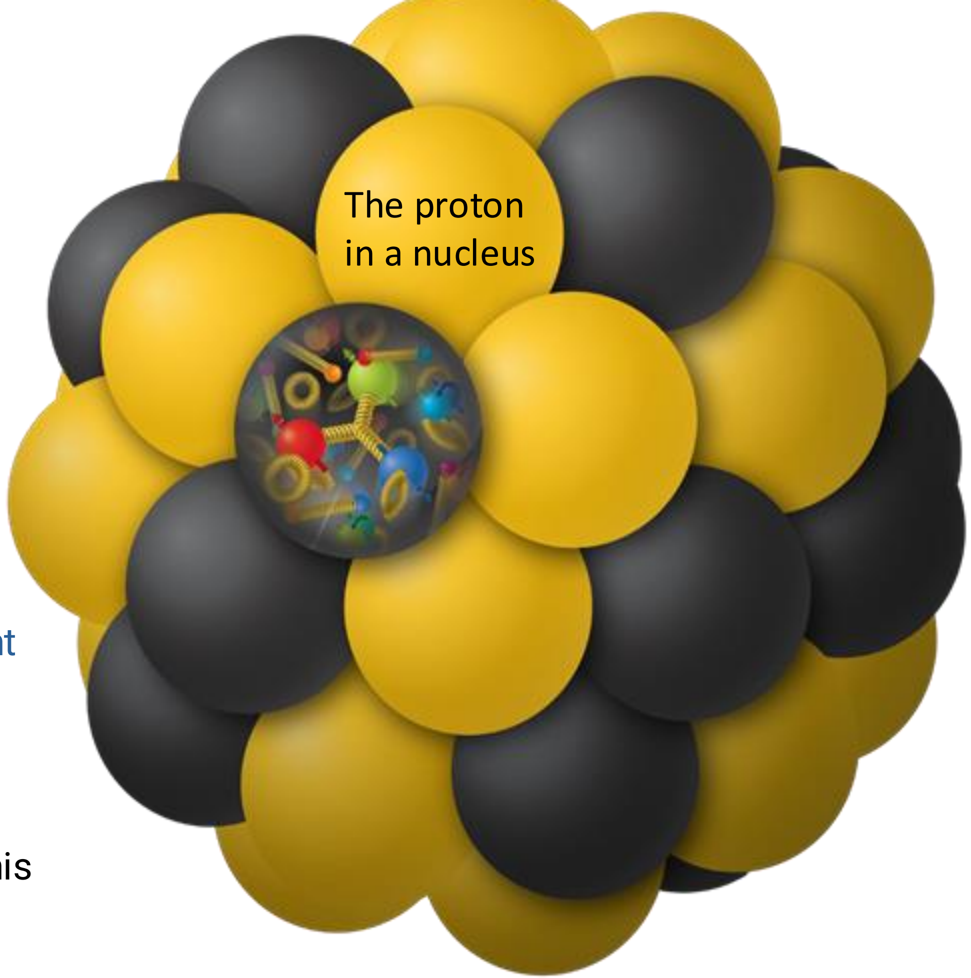


Pictures: adapted from EIC White Paper

The EIC Physics Quest

The proton (1980s)

The proton (2020s)

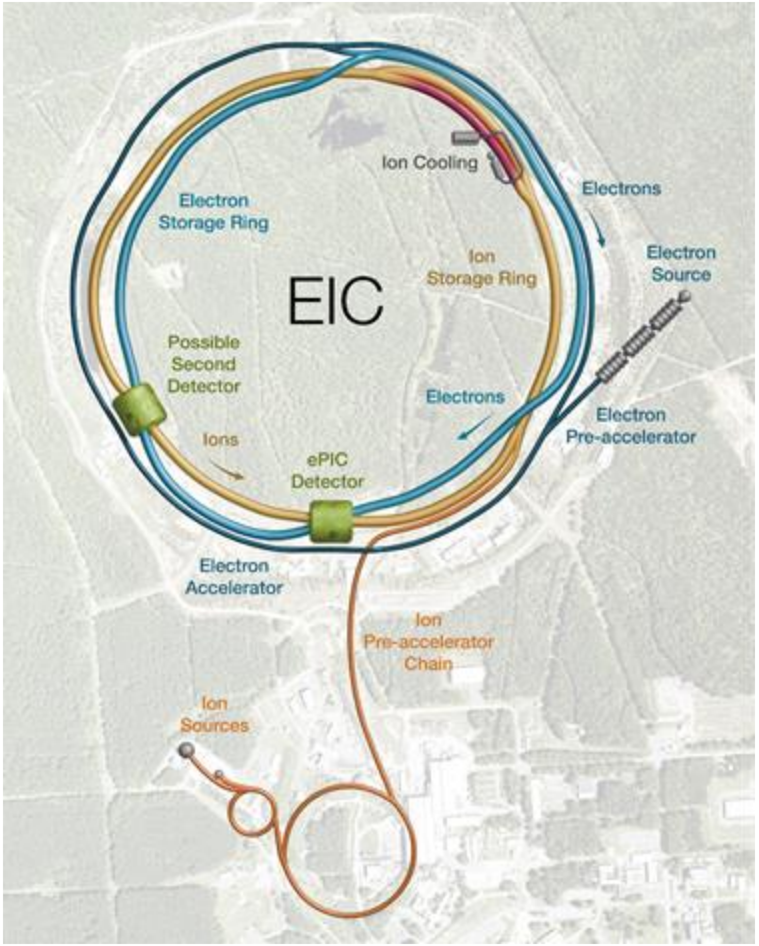


- How does a high-density nuclear environment affect the interactions, correlations, and behaviors of quarks and gluons?
- Is there a saturation point for the density of gluons in nuclei at high energies, and does this lead to the formation of gluonic matter with universal properties across all nuclei?

Pictures: adapted from Brookhaven National Laboratory

The EIC Facility

- The **only collider project anticipated in the near term**, ensuring cutting-edge exploration for years to come
- **Breakthrough precision**: Delivers luminosities 100 to 1000 times greater than HERA
- Explore QCD landscape over **large range of Q^2 and quark/gluon density (1/x)**



- **Spin-controlled collisions**: Both electrons and protons/light nuclei can be polarized, enabling unique spin-related studies
- Handles **nuclear beams** from light nuclei like deuterium up to heavy ions such as U
- Equipped with a **cutting-edge detector**, designed for high-precision data collection across a broad range of physics experiments

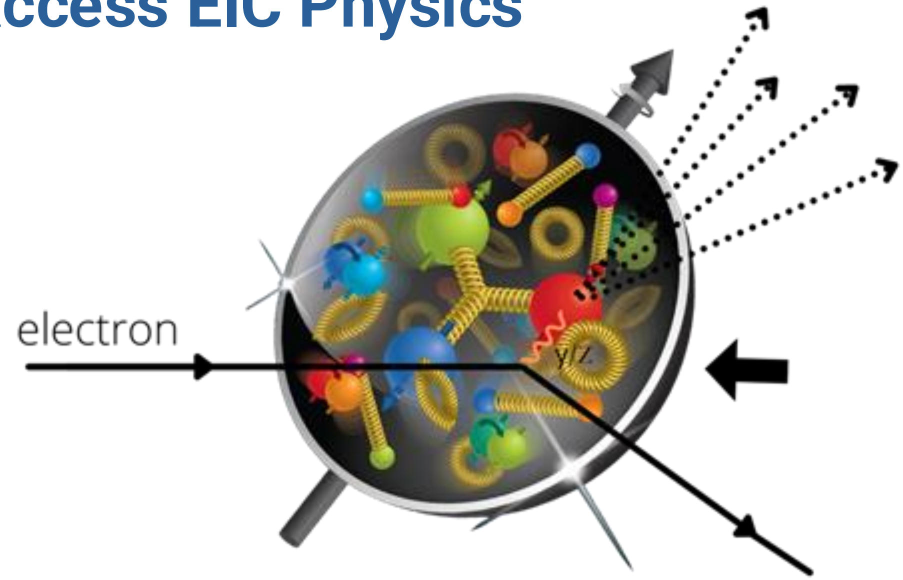
Picture: EIC Project Sharepoint

Experimental Processes to Access EIC Physics

$e + p \rightarrow e' + X$

Golden process to probe nucleons and nuclei with electrons, having no internal structure, providing the unmatched precision of electromagnetic interactions

- Access to **partonic kinematics** through scattered lepton on event level
- **Initial and final state** effects can be cleanly disentangled



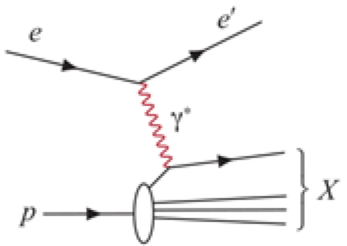
$$Q^2 = s \cdot x \cdot y$$

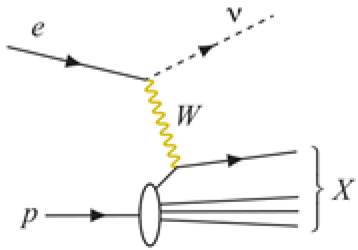
Q^2 - virtuality of the photon
s - center-of-mass energy squared
x - momentum fraction
y - inelasticity

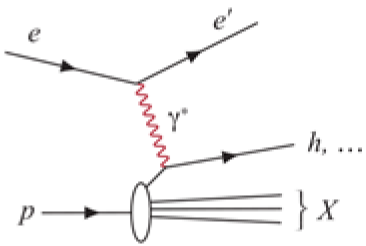
Pictures: adapted from Brookhaven National Laboratory

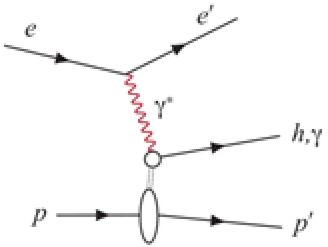
Experimental Processes to Access EIC Physics

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)









Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics

Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)

Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron

Deep Exclusive Processes

- Detection of all particles in event

Parton Distributions in nucleons and nuclei

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

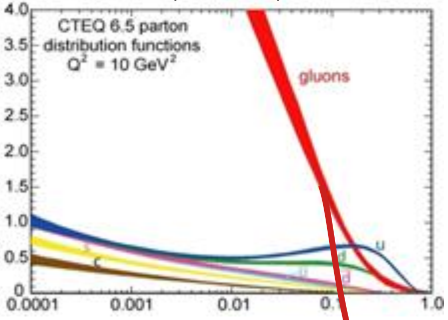
QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

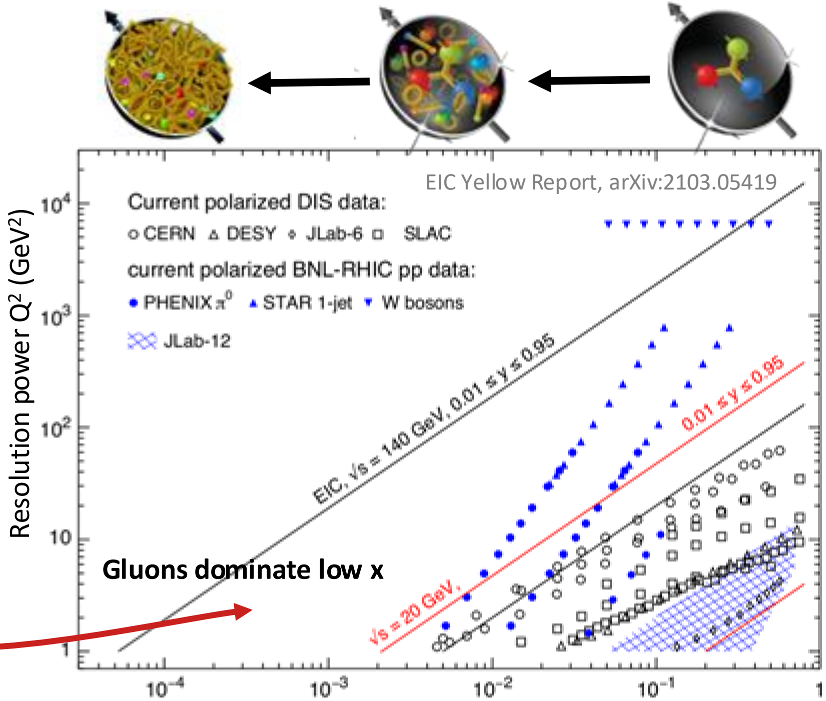
Probing Uncharted Territory

Unprecedented Access to Nucleon and Nucleus Structure

Quarks and gluons momentum fraction times their density inside the proton



Parton momentum fraction x



Parton momentum fraction x

Larger center of mass energy

Larger center of mass energy and luminosity

Pictures: adapted from Brookhaven National Laboratory

Experimental Realizations and Challenges

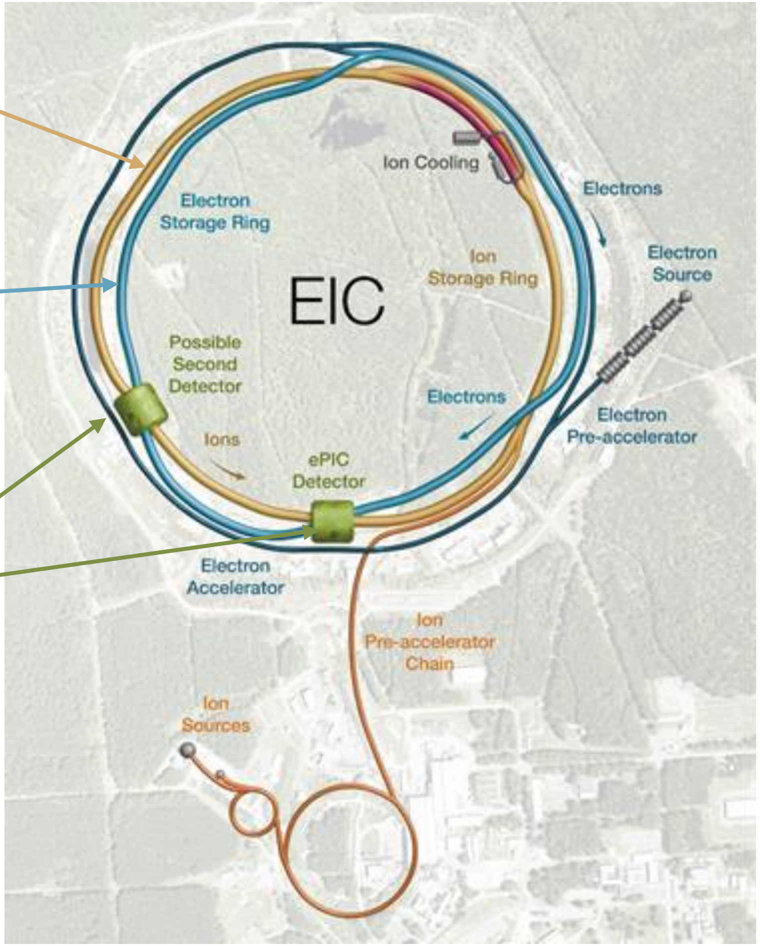
Hadron Storage Ring (RHIC Rings)
41, 100-275 GeV

Electron Storage Ring **5–18 GeV**

- Polarized electron source
- 400 MeV injector linac
- Rapid Cycling Synchrotron design to avoid depolarizing resonances

High luminosity Interaction Region(s)

- **Luminosity:**
  $L = 10^{33}–10^{34}\ cm^{-2}sec^{-1}$
  $10 – 100\ fb^{-1}/year$
- **Highly Polarized Beams:** 70%
- 25 mrad (IP1) crossing angle with crab cavities
- Bunch Crossing ~ 10.2 ns/98.5 MHz



Picture: EIC Project Sharepoint

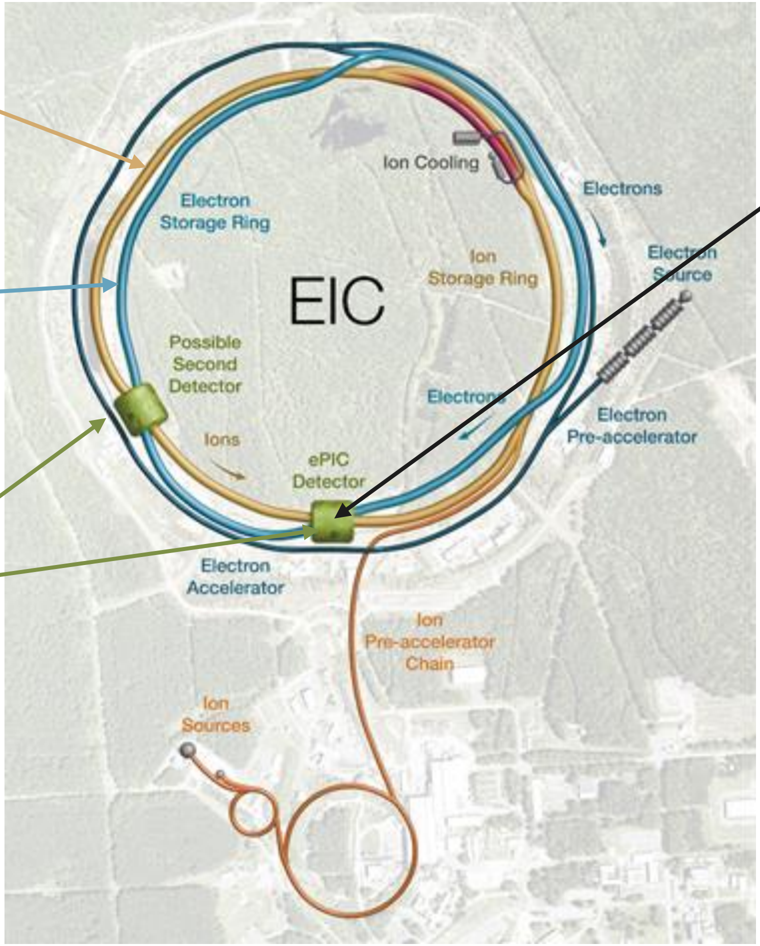
Hadron Storage Ring (RHIC Rings)
41, 100-275 GeV

Electron Storage Ring **5–18 GeV**

- Polarized electron source
- 400 MeV injector linac
- Rapid Cycling Synchrotron design to avoid depolarizing resonances

High luminosity Interaction Region(s)

- **Luminosity:**
  $L = 10^{33}–10^{34}\ cm^{-2}sec^{-1}$
  $10 – 100\ fb^{-1}/year$
- **Highly Polarized Beams:** 70%
- 25 mrad (IP1) crossing angle with crab cavities
- Bunch Crossing ~ 10.2 ns/98.5 MHz



Detector located at 6 o'clock of the EIC Ring

The **ePIC Collaboration** formed in July 2022 is dedicating to the realization of the project detector

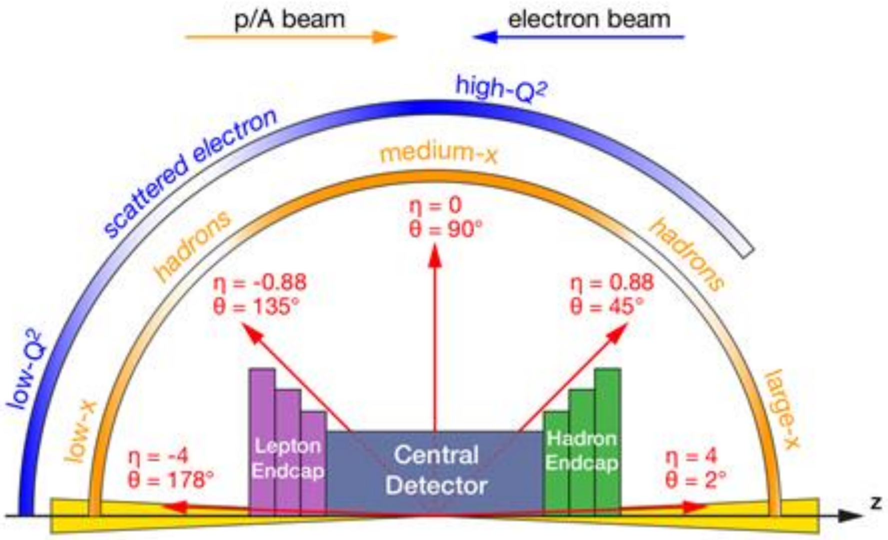
- 177 Institutions, 26 countries, 4 world's region
- Currently: > 850 collaborators (from 2024 survey)

Picture: EIC Project Sharepoint

EIC Detector Challenges and Requirements

p: 41, 100-275 GeV

e: 5-18 GeV



Large center-of-mass energy range: 29-140 GeV

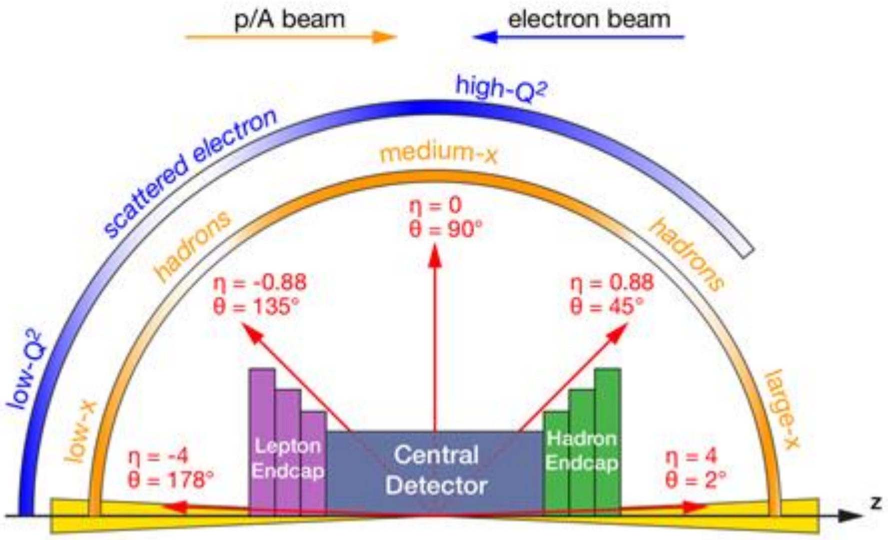
- Large detector acceptance

Picture: Yellow Report

EIC Detector Challenges and Requirements

p: 41, 100-275 GeV

e: 5-18 GeV



Large center-of-mass energy range: 29-140 GeV

- Large detector acceptance

Asymmetric beams

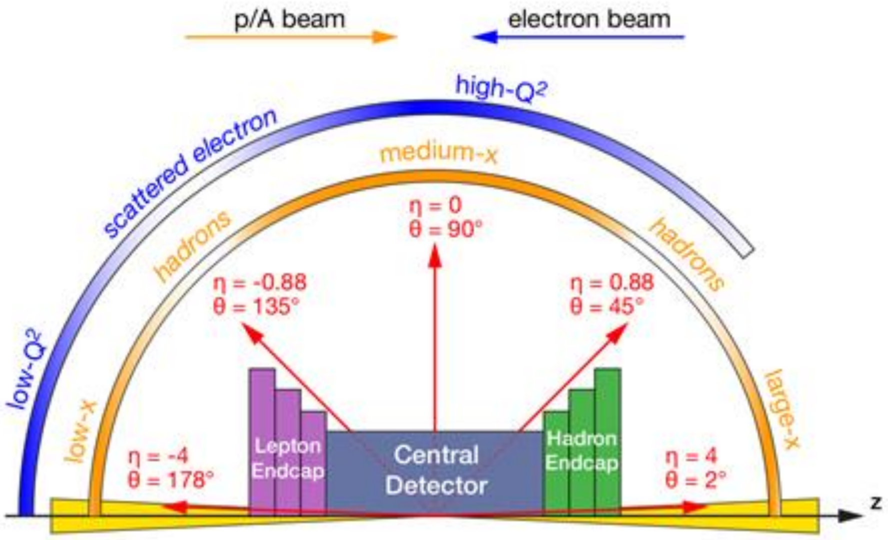
- **Asymmetric detector**: barrel with electron and hadron end caps

- Large central **coverage** (-4 < η < 4) **in tracking, particle identification**, em and hadronic **calorimetry**
  - High precision low mass tracking
  - DIS: Good e/h separation critical for scattered electron ID
  - SIDIS: + Separation of e, p, K, p on track level

EIC Detector Challenges and Requirements

p: 41, 100-275 GeV

e: 5-18 GeV



luminosity detectors
low Q2 tagger

Far-forward: particle from nuclear breakup and exclusive process

Large center-of-mass energy range: 29-140 GeV

- Large detector acceptance

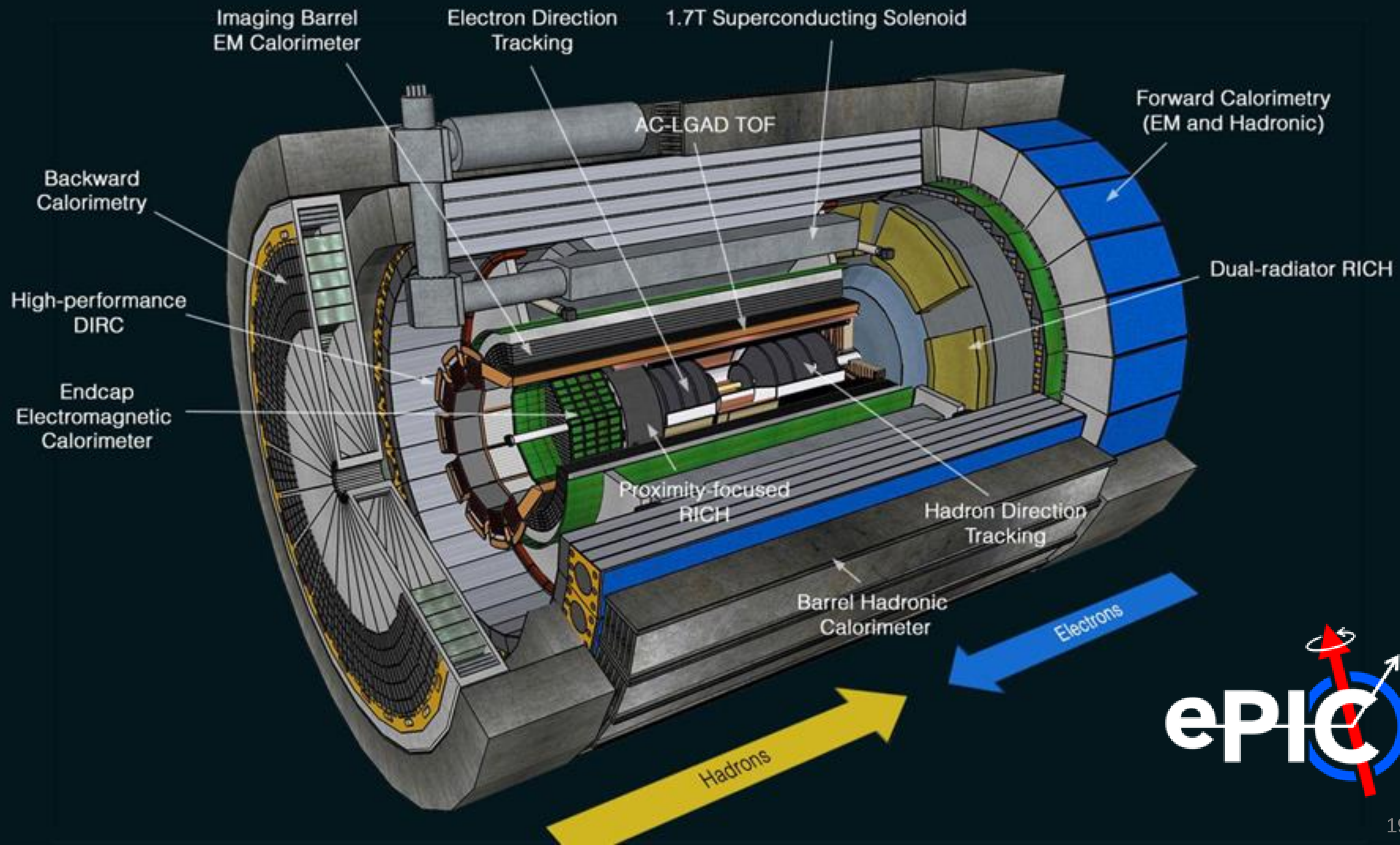
Asymmetric beams

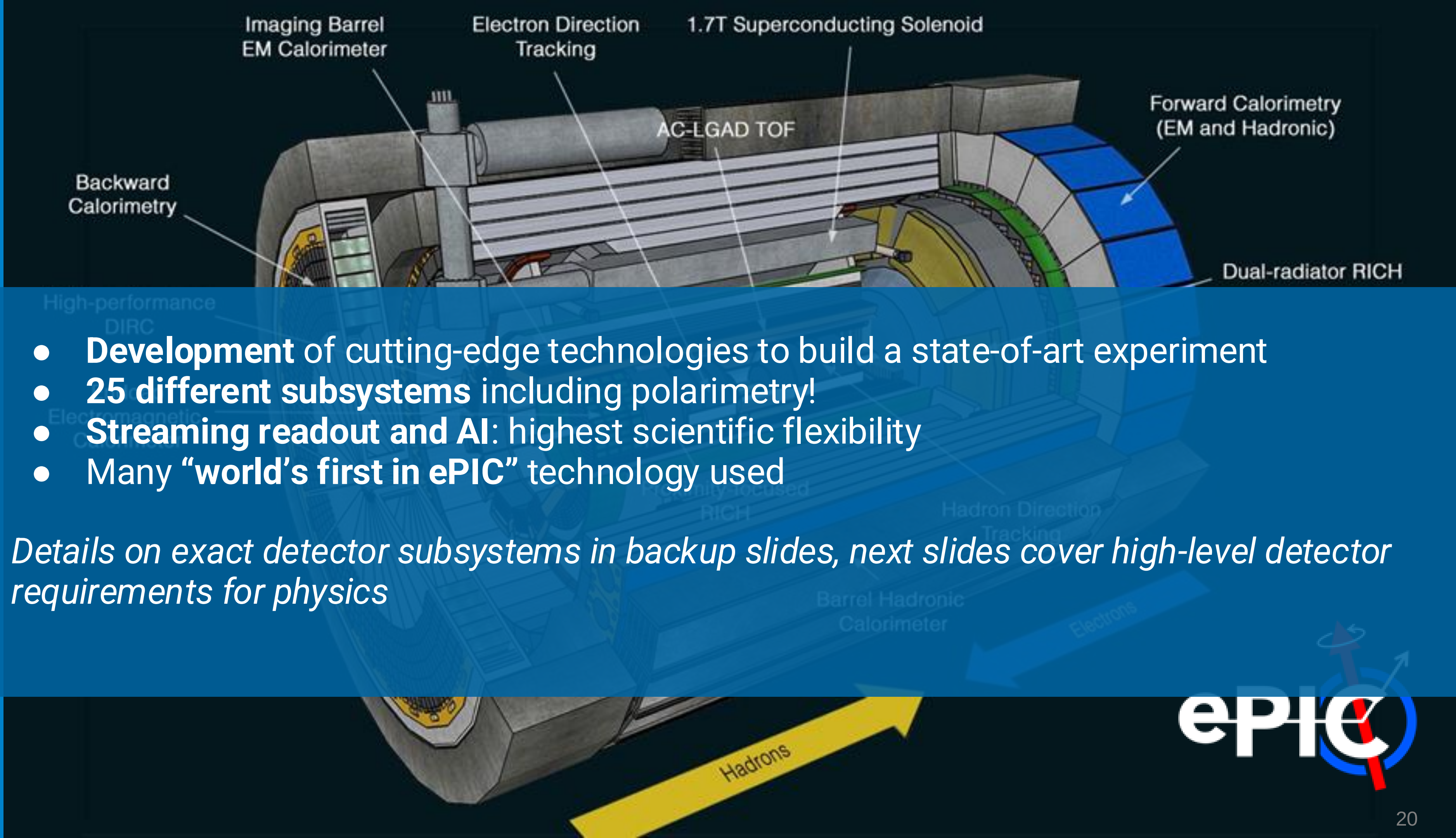
- **Asymmetric detector**: barrel with electron and hadron end caps
- Large central **coverage** ($-4 < \eta < 4$) **in tracking, particle identification**, em and hadronic **calorimetry**
  - High precision low mass tracking
  - DIS: Good e/h separation critical for scattered electron ID
  - SIDIS: + Separation of e, p, K, p on track level

Imaging science program with large ion species range: protons-U

- Exclusive processes: + Specialized detectors **integrated in the Interaction Region over 80m**

Picture: Yellow Report

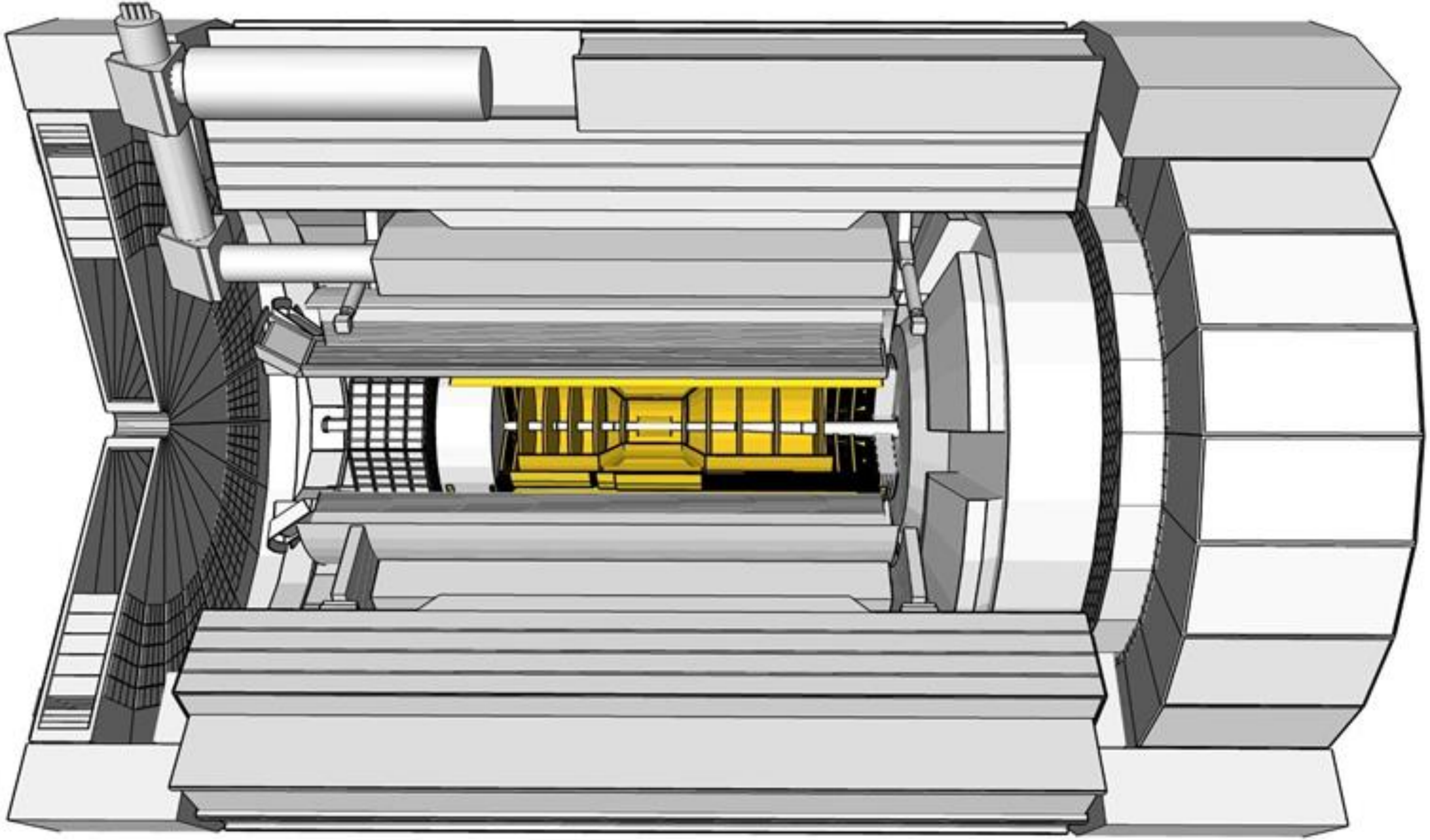

Imaging Barrel
EM Calorimeter
Electron Direction
Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry
(EM and Hadronic)
Backward
Calorimetry
High-performance
DIRC
Dual-radiator RICH
Endcap
Electromagnetic
Calorimeter
Proximity-focused
RICH
Hadron Direction
Tracking
Barrel Hadronic
Calorimeter
Electrons
Hadrons



- **Development** of cutting-edge technologies to build a state-of-art experiment
- **25 different subsystems** including polarimetry!
- **Streaming readout and AI**: highest scientific flexibility
- Many “**world’s first in ePIC**” technology used

Details on exact detector subsystems in backup slides, next slides cover high-level detector requirements for physics

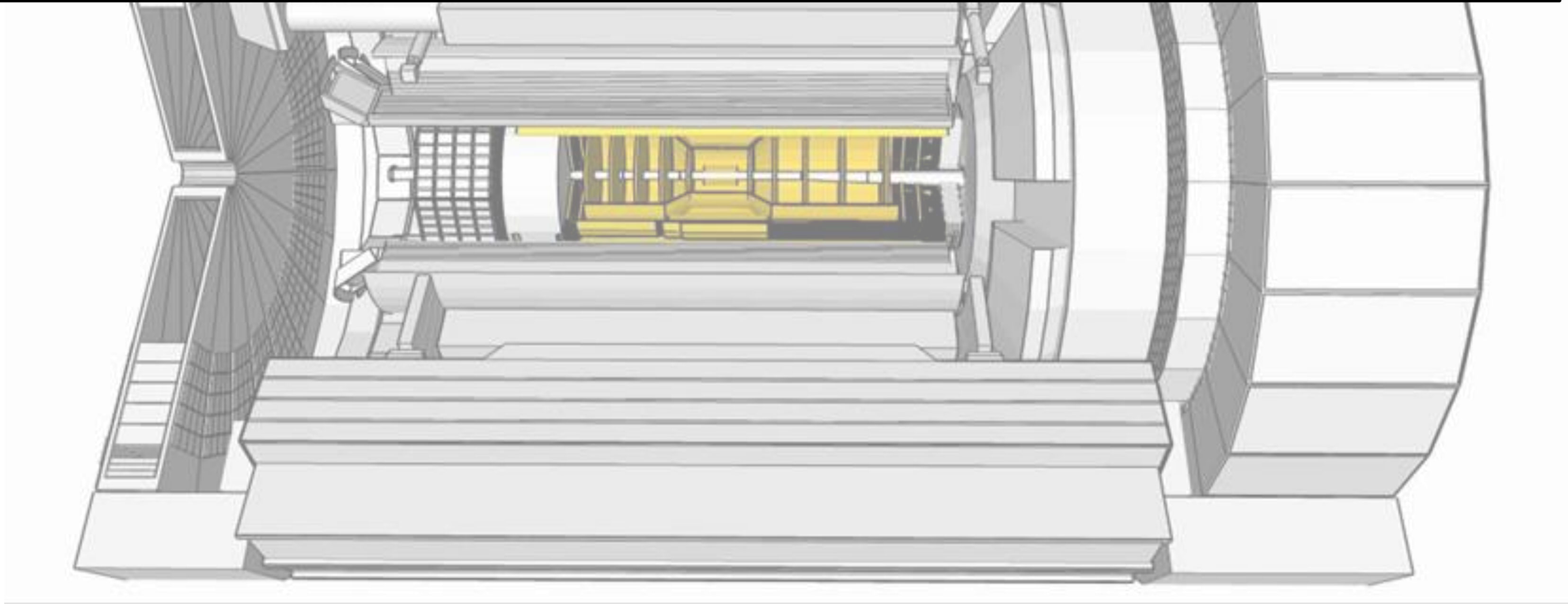
Tracking



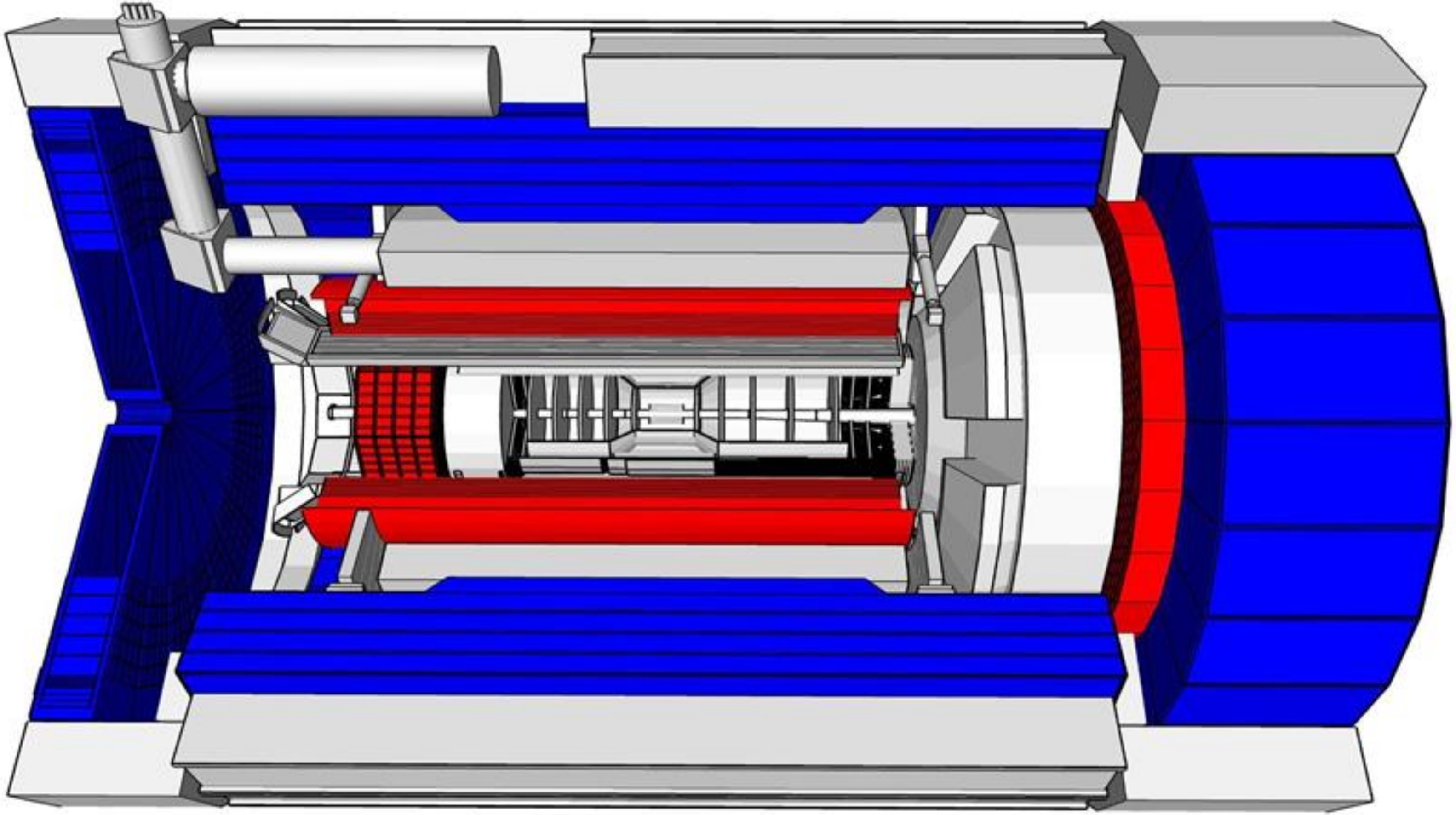
Tracking

Challenges: High precision low mass tracking, fine p_T and vertexing resolution (e.g., fundamental for DIS kinematics, exclusivity definition, SIDIS binning in p_T, …)

- High spatial-resolution and efficiency and large-area coverage (8 m^2 of Silicon Vertex Detector):
    - High pixel granularity
    - Very low material budget constraints also at large η (challenge for services)



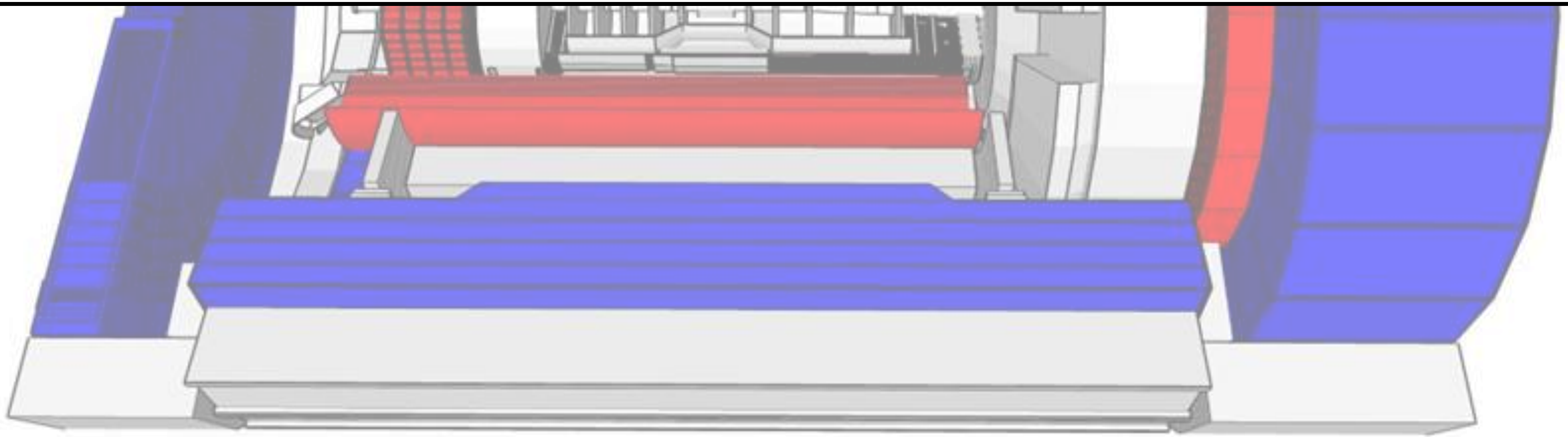
Calorimetry



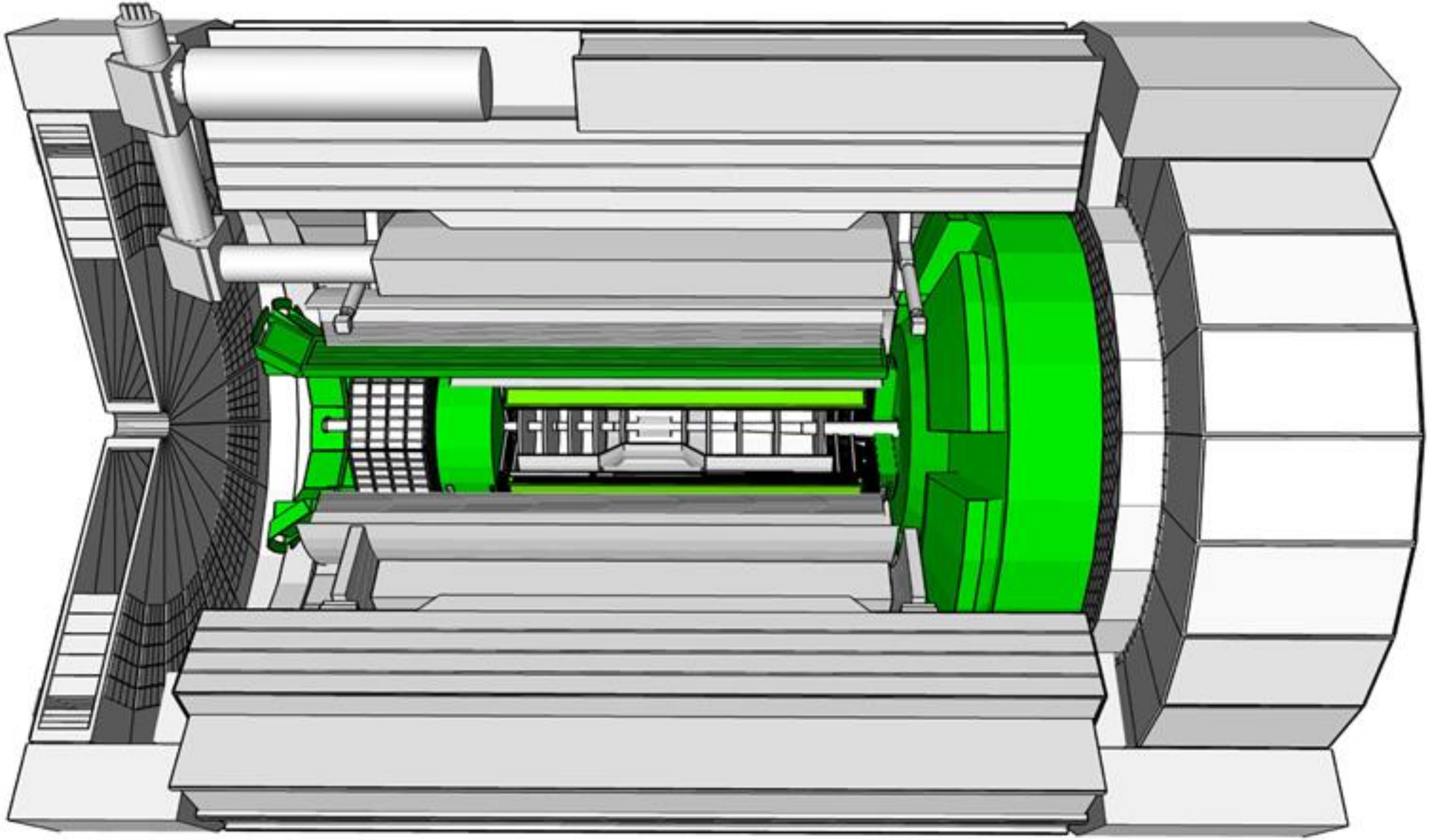
Calorimetry

Challenges:

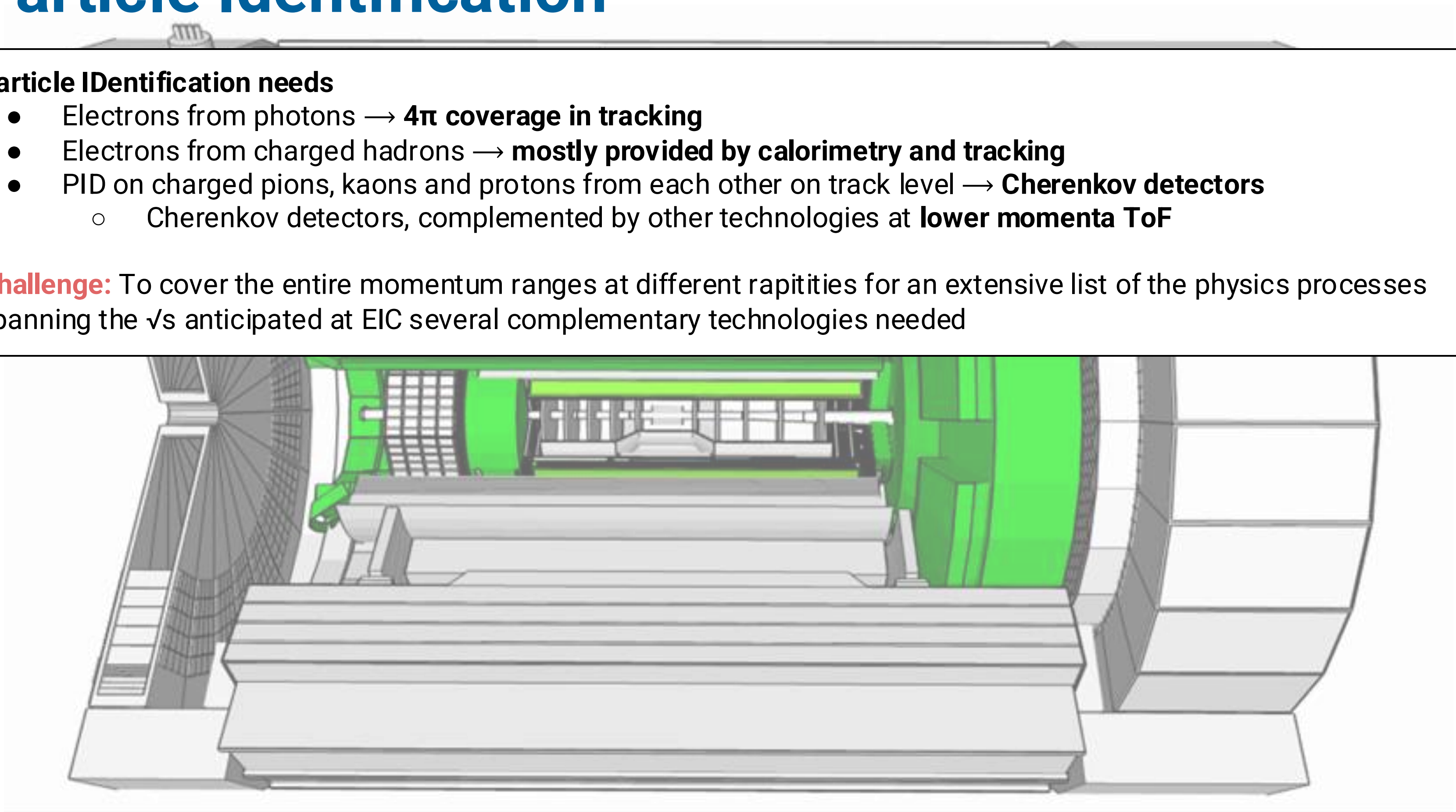
- Detect the **scattered electron** and **separate them from π** (up to 10^{-4} suppression factor in backward and barrel ECal)
- Improve the electron **momentum resolution at backward rapidities** (2-3% $/\sqrt{E} \oplus (1-2)\%$ for backward ECal)
  - e.g., DIS, SIDIS, …
- Provide **spatial resolution of two photons sufficient to identify decays $\pi^0 \to \gamma\gamma$** at high energies from ECals
  - e.g., Exclusive processes: DVCS, …
- Contain the **highly energetic hadronic final state and separate clusters** in a dense hadronic environment in Forward ECal and HCal
  - e.g., TMD studies with jets, kinematics definition for CC DIS, low y, …



Particle Identification



Particle Identification



Particle IDentification needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly provided by calorimetry and tracking**
- PID on charged pions, kaons and protons from each other on track level ⟶ **Cherenkov detectors**
    - Cherenkov detectors, complemented by other technologies at **lower momenta ToF**

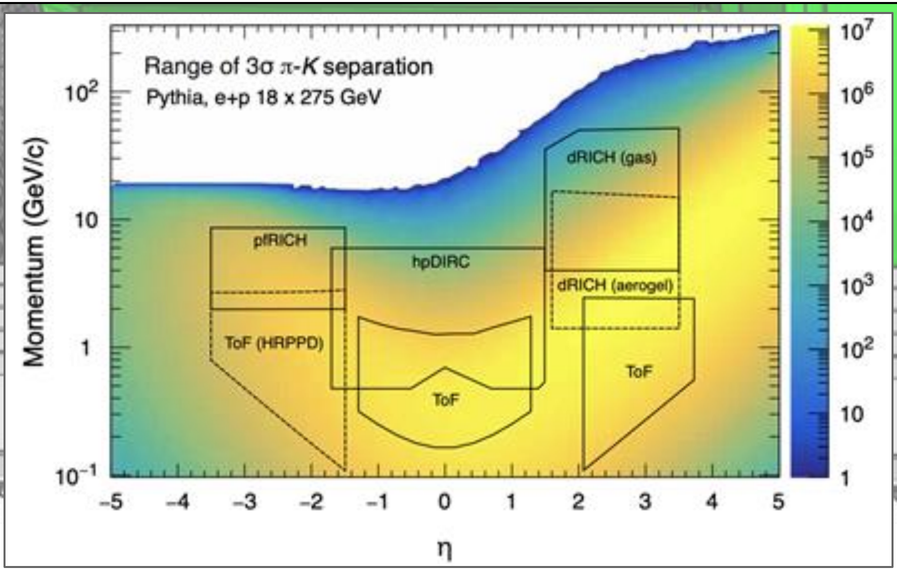
Challenge: To cover the entire momentum ranges at different rapitities for an extensive list of the physics processes spanning the √s anticipated at EIC several complementary technologies needed

Particle Identification

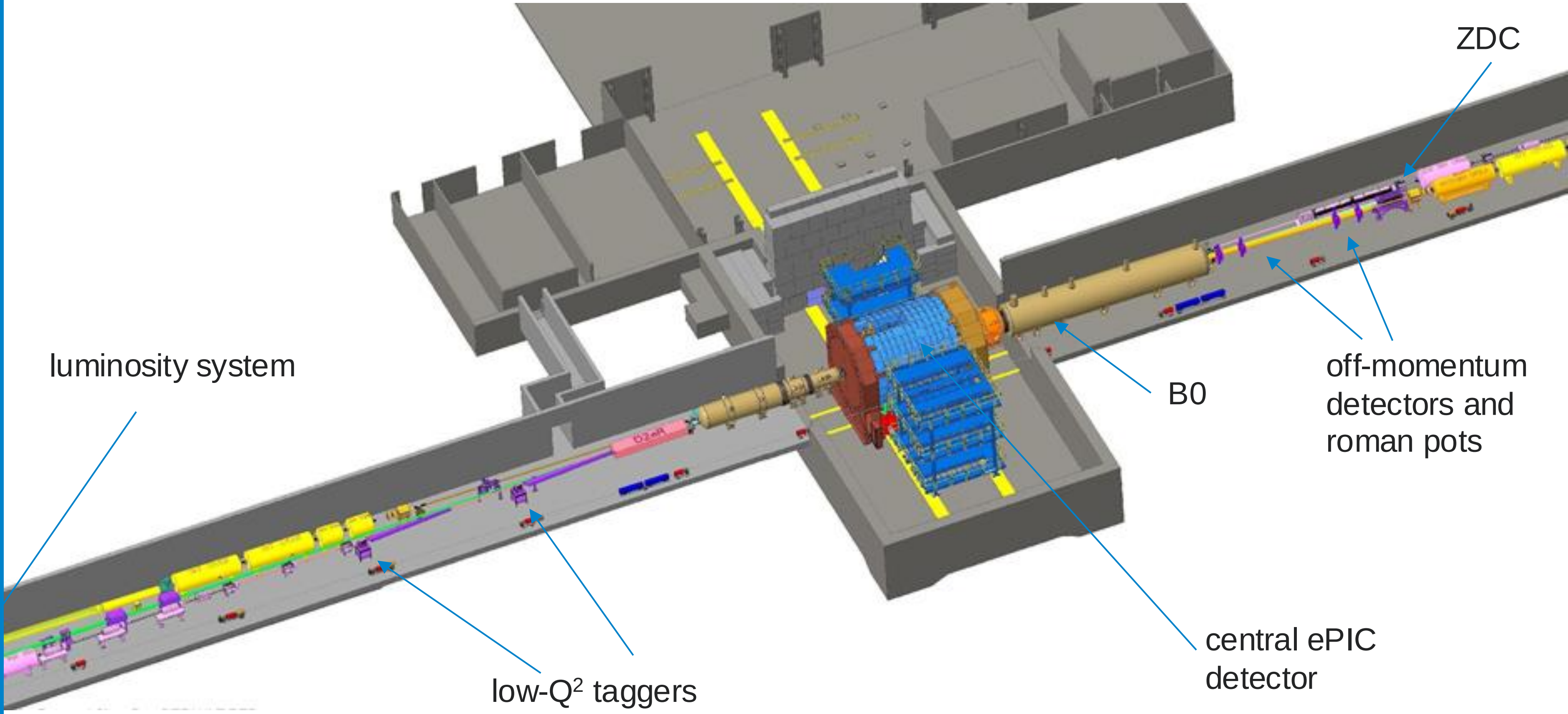
Particle IDentification needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly provided by calorimetry and tracking**
- PID on charged pions, kaons and protons from each other on track level ⟶ **Cherenkov detectors**
  - Cherenkov detectors, complemented by other technologies at **lower momenta ToF**

Challenge: To cover the entire momentum ranges at different rapitities for an extensive list of the physics processes spanning the √s anticipated at EIC several complementary technologies needed

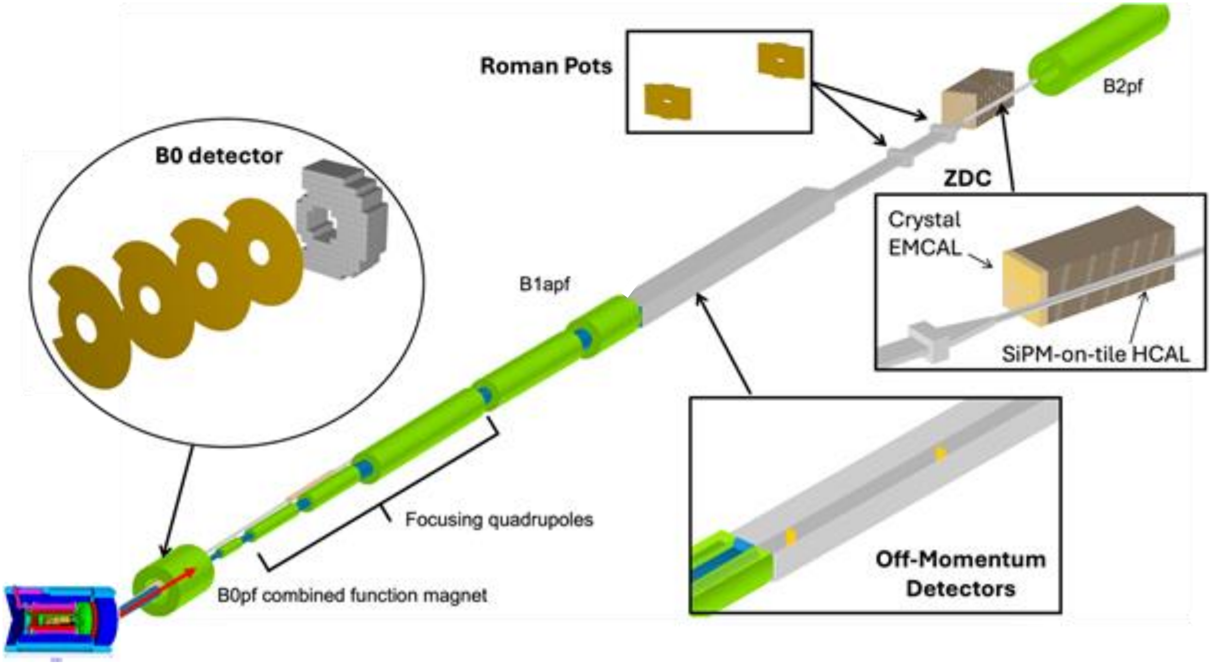


ePIC is more than 80 m long…



Pictures: EIC Project Sharepoint

Far-Forward Detectors



Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

Challenge:

The extended detector's array required to enable primary physics objectives: Detect particles from nuclear breakup and exclusive processes

Subsystems:

- **B0 detector:** Full reconstruction of charged particles and photons
- **Off-momentum detectors:** Reconstruction of charged spectators from breakup of light nuclei
- **Roman pot detectors:** Charged particles near the beam
- **Zero-degree calorimeter:** Neutral particles at small angles

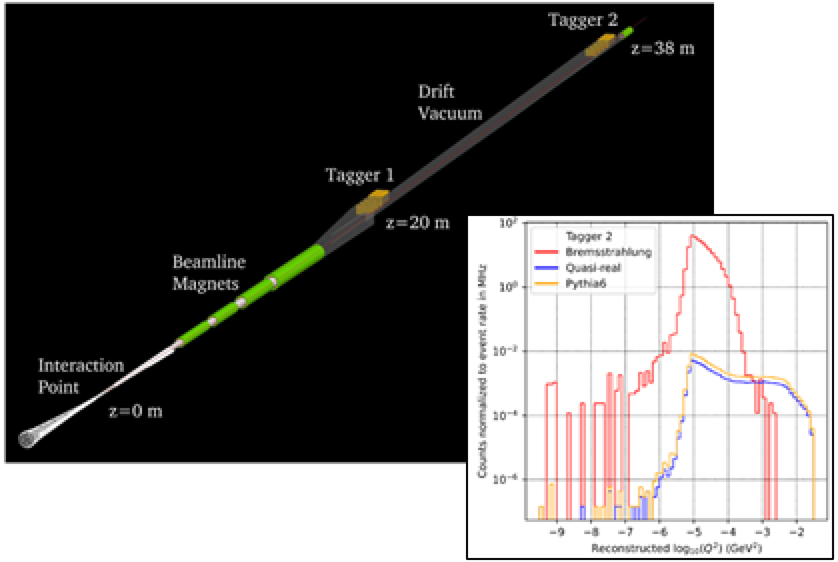
Far-Backward Detectors

Low-Q^2 tagger

Challenge: Allow quasi real (Q<<1) physics with electron detection in very forward rapidity

- high, non-uniform Bremsstrahlung background

Pixel-based trackers (Timepix4), with rate capability of > 10 tracks per bunch and calorimeters for calibration



Luminosity Spectrometer

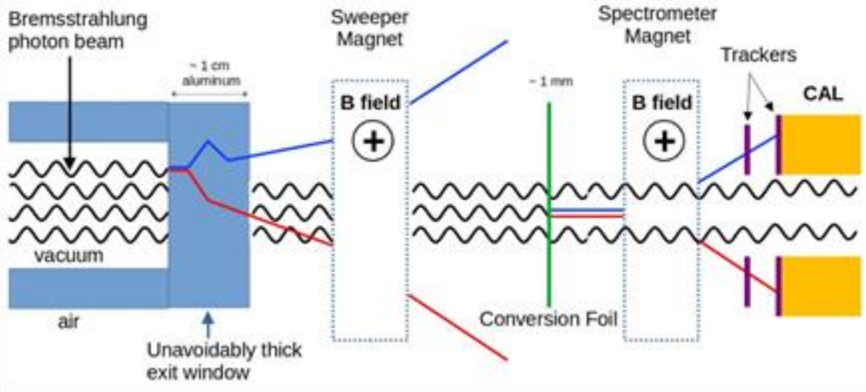
Challenge: Precise luminosity determination (<1%)

From Bremsstrahlung processes

e+p → e γ p

e+Au → e γ Au

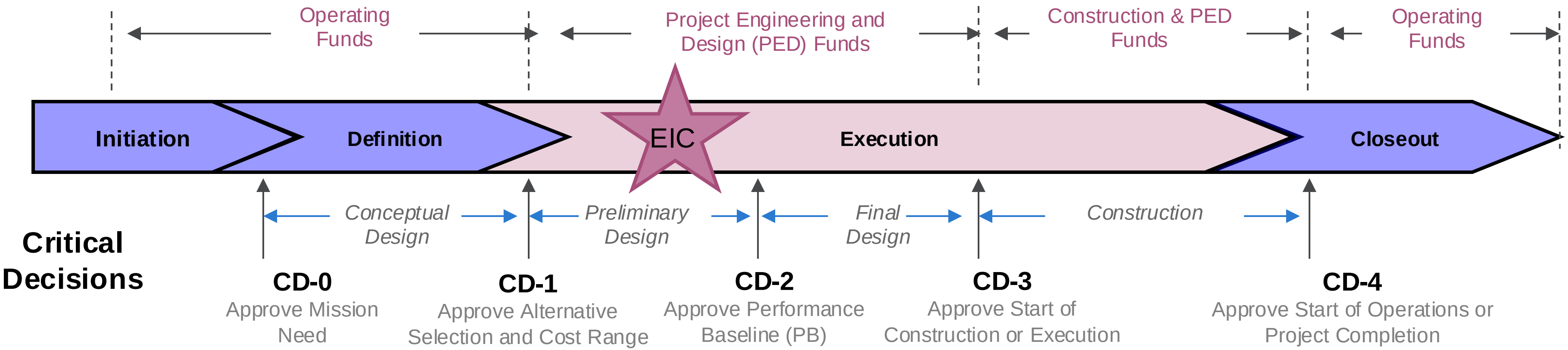
AC-LGAD and Scintillating Fiber $23X_0$ ECal



Schedule

Schedule

Critical Decisions and Where to Find Them

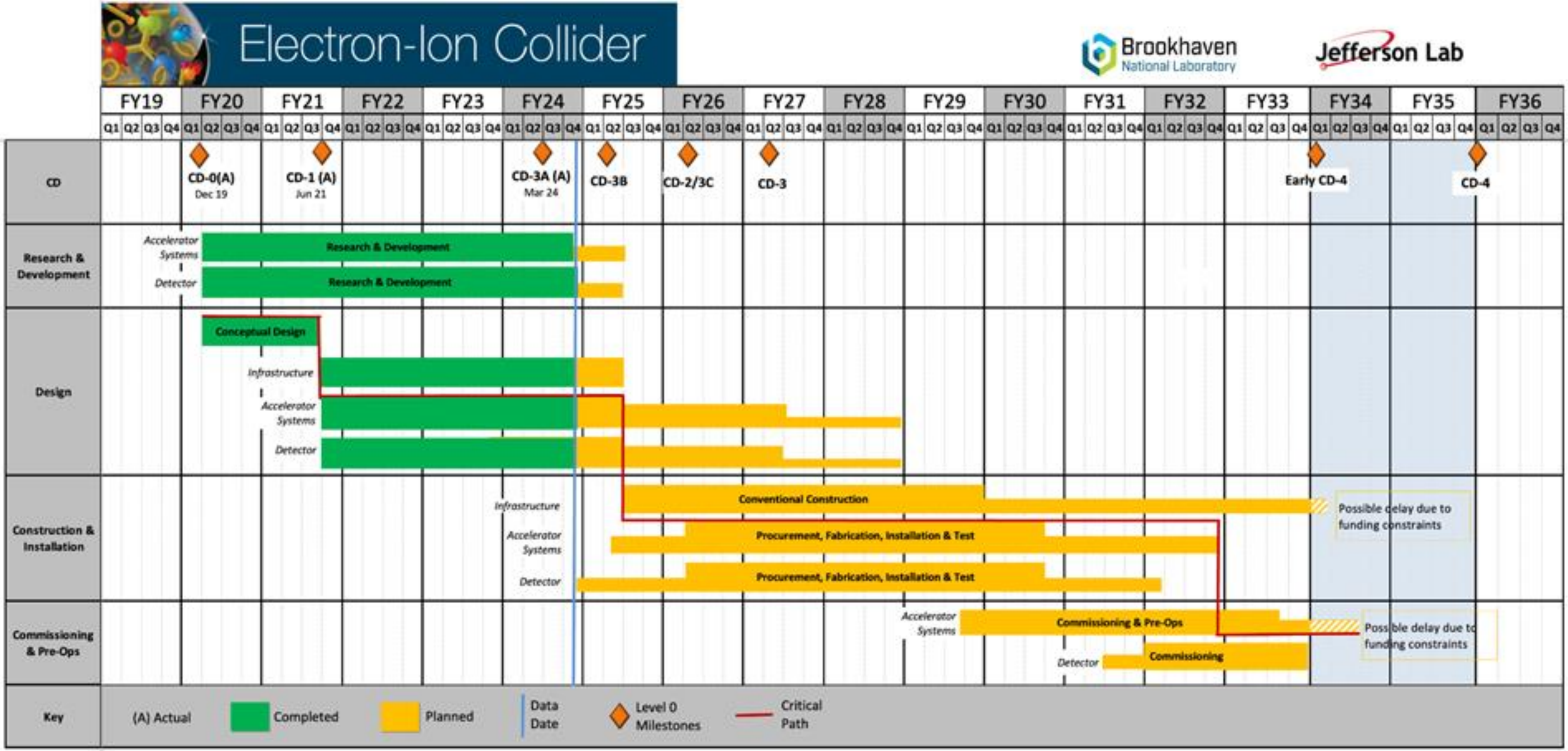


CD-0/Site Selection December 2019 ✓

June 2021 ✓

CD-3A ESAAB Mar 25, 2024 ✓

NEXT: CD-3B Q2 FY25

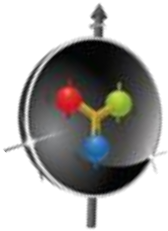


Picture: EIC Project Sharepoint

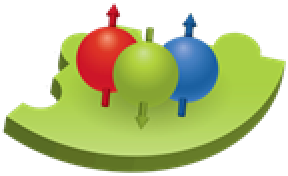
Longitudinal Spin Structure - Experimental Overview

Origin of the Proton Spin

What creates the proton's spin?



? =



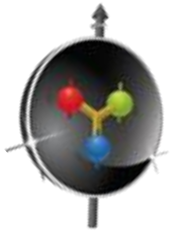
Proton Spin Puzzle →

After decades of experiments: **quark spins account for only about 30%** of the proton's spin

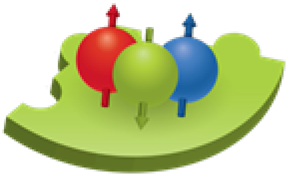
Pictures: adapted from Brookhaven National Laboratory

Origin of the Proton Spin

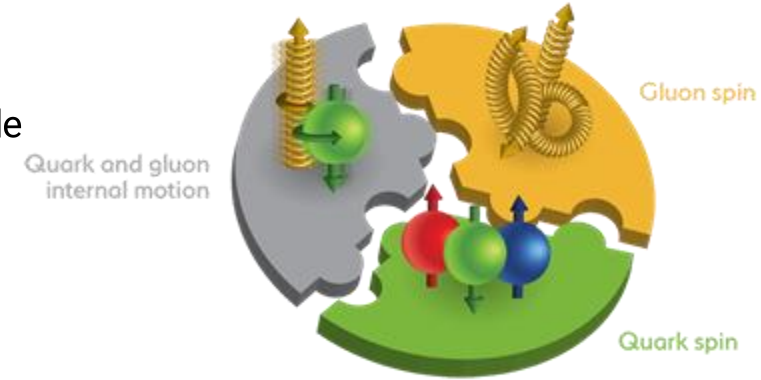
What creates the proton's spin?



? =



Proton Spin Puzzle



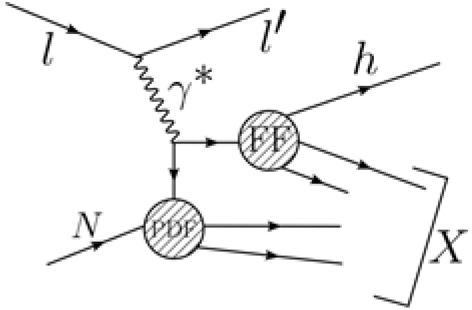
After decades of experiments: **quark spins account for only about 30%** of the proton's spin

We now know that **quarks, gluons**, and **their motion** all contribute, but the full picture remains elusive

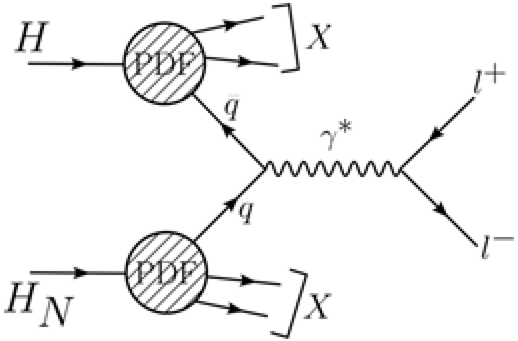
Pictures: adapted from Brookhaven National Laboratory

Complementary Experimental Probes

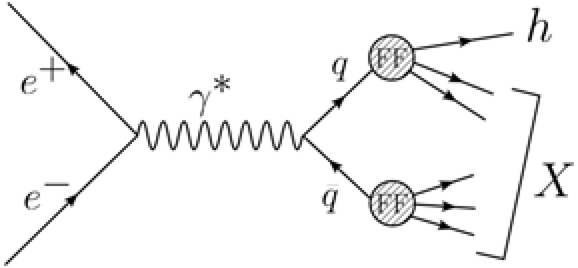
(Semi-Inclusive) Deep Inelastic Scattering

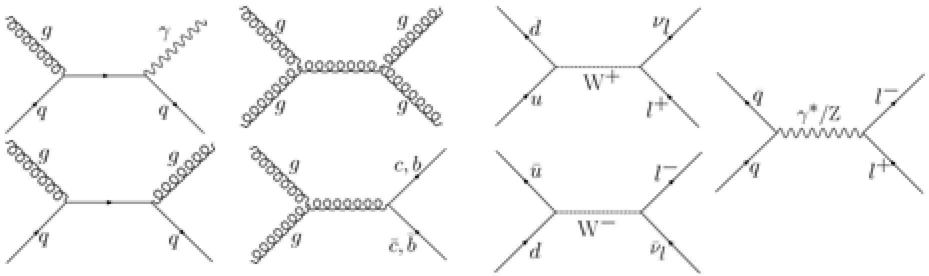


Hadron-hadron interactions



e+e- annihilation (access to FF)





Origin of the Proton Spin

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

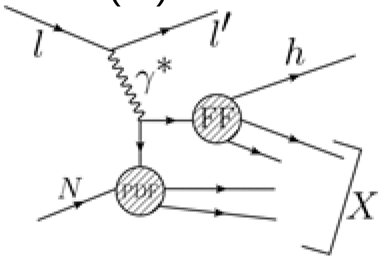
Composition of the proton spin:

Jaffe-Manohar sum rule:

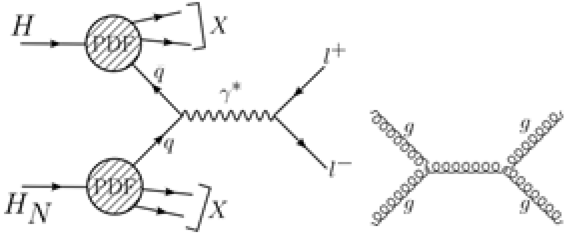
$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

Quark helicity | Gluon helicity | Quark canonical orbital angular momentum | Gluon canonical orbital angular momentum

(SI)DIS

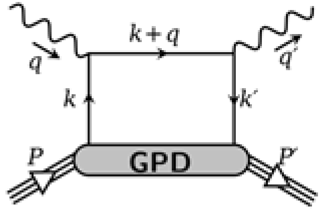


hadron-hadron processes



…

+ OAM (Ji's) from DVCS and DVMP



Longitudinal Spin Structure

- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- **Polarized DIS cross section** studied at **SLAC, CERN, DESY, JLab** encodes information about **helicity structure of quarks** inside the proton (double spin asymmetries)

$$\frac{d^2\sigma_{LL}(x,Q^2)}{dx\,dQ^2} = \frac{8\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{y^2}{4}\gamma^2\right)g_1(x,Q^2) - \frac{y}{2}\gamma^2 g_2(x,Q^2)\right]$$

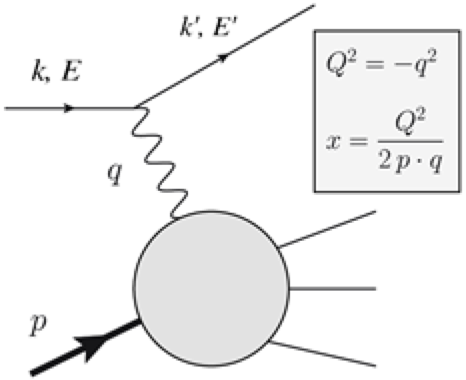
$\nu = E - E'$

$y = \nu/E,\ \gamma^2 = Q^2/\nu^2$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\, \Delta q(x)$$

In (LO QCD) Quark Parton Model

Quark helicity distribution



Experimental access through double spin asymmetries

$$A_{\|} = \frac{\sigma_{LL}}{\sigma_{UU}} = \frac{1}{P_B P_z}\cdot\frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}} = D(1+\eta\gamma)\,A_1$$

D - Depolarization factor

η - kinematic fator

A_1 - photon-nucleon asymmetry

$$A_1 = \frac{g_1}{F_1}$$

Longitudinal Spin Structure

- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions

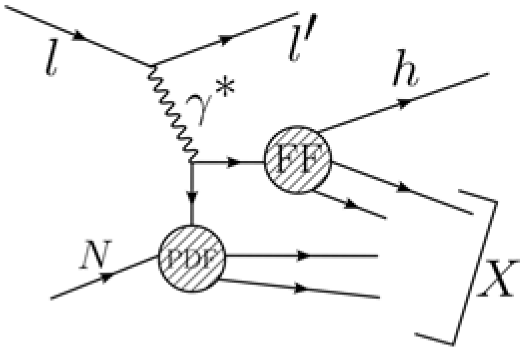
- Semi-Inclusive Deep Inelastic Scattering with charged pions and kaons adds **sensitivity to flavor-separated quark helicities** via the fragmentation functions $D_q^h(z,Q^2)$
    - valence parton content of h relates to the fragmenting parton flavor, particularly at high z
      z - fractional energy of the final-state hadron $z = E^h/v$

Photon-nucleon asymmetry for SIDIS

$$A_1^h = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \quad \xrightarrow{\text{LO}} \quad \frac{d^3\sigma_{1/2(3/2)}^h}{dx\, dQ^2\, dz} \propto \sum_q e_q^2\, q^{+(-)}(x,Q^2)\, D_q^h(z,Q^2)$$

$$A_1^h(x,Q^2,z) = \frac{\sum_q e_q^2\, \Delta q(x,Q^2)\, D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2\, q'(x,Q^2)\, D_{q'}^h(z,Q^2)}$$

Experimental access through double spin asymmetries (analogous to DIS)



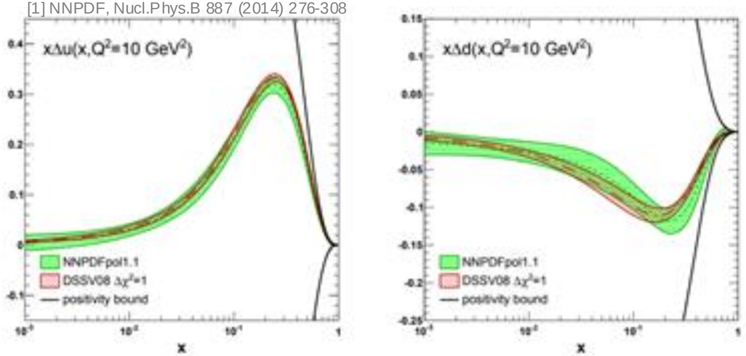
$\sigma^{SIDIS} = \hat{\sigma} \otimes PDF \otimes FF$

- Sensitivity to sea quarks at low x from $A_1^{\pi^-}$ ($\Delta\bar{u}$), $A_1^{\pi^+}$ ($\Delta\bar{d}$), A_1^K (Δs)

Longitudinal Spin Structure - Where Are We?

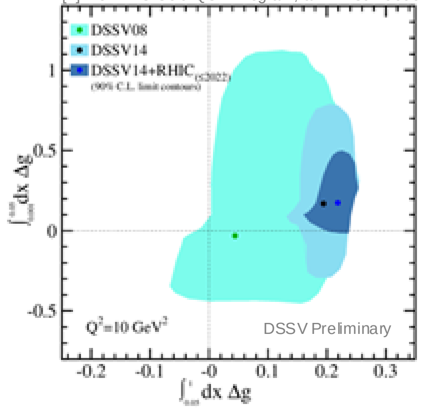
u and d quark helicities

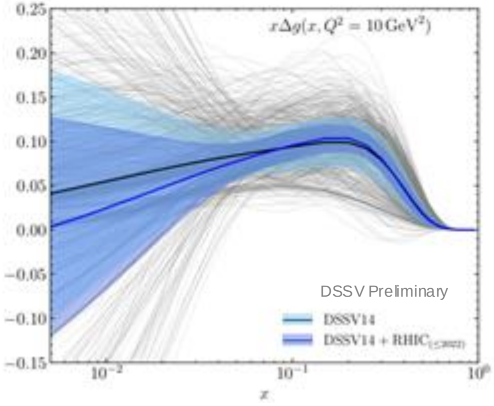
[1] NNPDF, Nucl.Phys.B 887 (2014) 276-308



Gluon Helicity

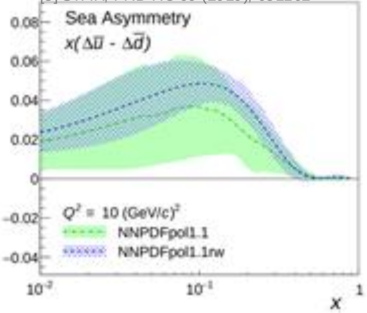
[2]The RHIC Cold QCD Program, arXiv:2302.00605



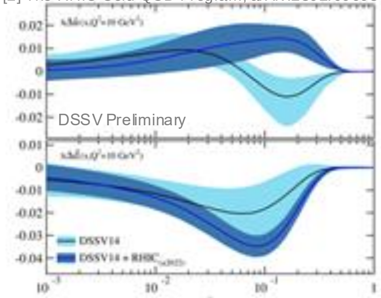


Sea-quark polarization asymmetry

[3] STAR, PRD RC 99 (2019), 051102



[2] The RHIC Cold QCD Program, arXiv:2302.00605



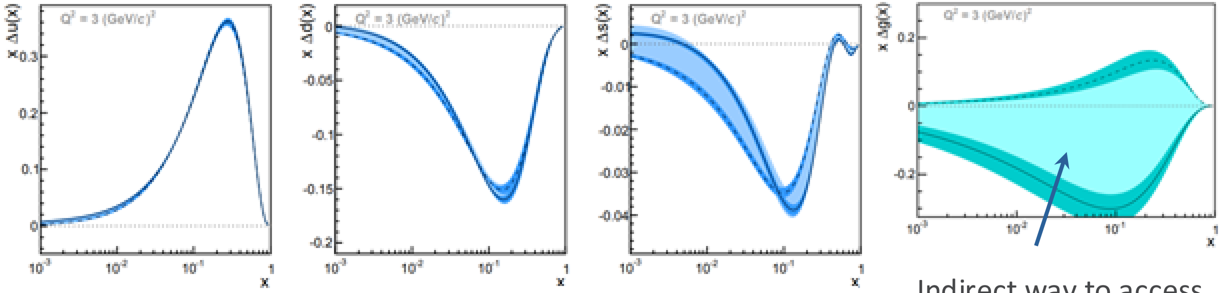
	NNPDF1.1[1]	DSSV08[1]
x	(0.001, 1)	
ΔΣ	$+0.25 \pm 0.10$	$+0.366^{+0.042}_{-0.062}$ $(+0.124)$

	DSSV14 + RHIC(2022)[2]	
x	(0.001, 0.05)	(0.05, 1)
ΔG	0.173 ± 0.156	0.218 ± 0.027

Insights from DIS

QCD fit to g_1 world data

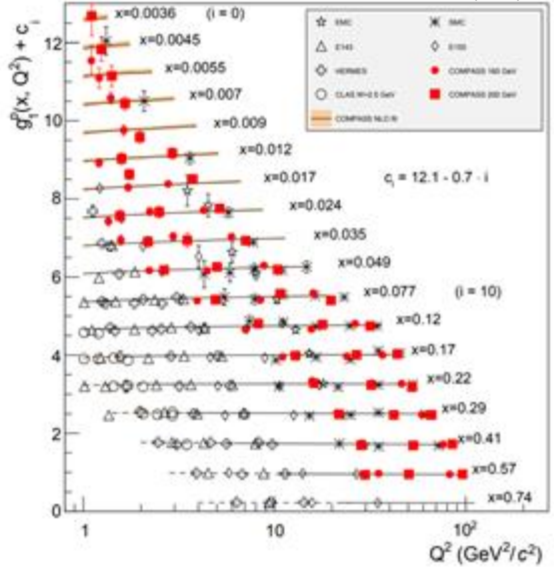
COMPASS, PLB 753 (2016) 18



First moment	Value range at $Q^2 = 3$ (GeV/c)^2
$\Delta\Sigma$	[0.26, 0.36]

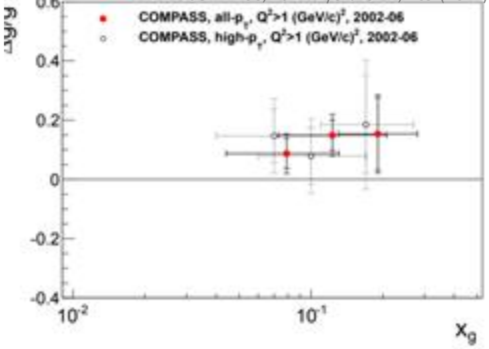
Indirect way to access gluon spin

COMPASS, PLB 753 (2016) 18

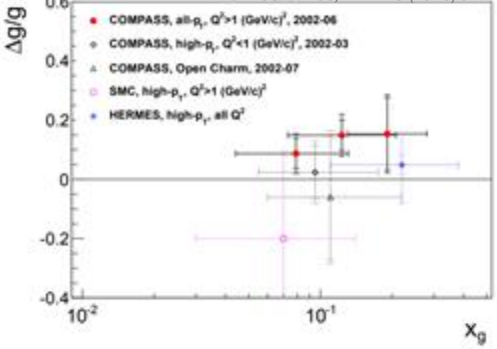


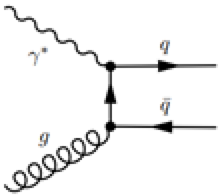
Direct access to Δg from SIDIS

COMPASS, Eur. Phys. J. C 77, 209 (2017)



COMPASS, PLB 718 (2013) 922





Photon-Gluon Fusion

Sensitive to Δg

SIDIS events with hadrons of large p_T

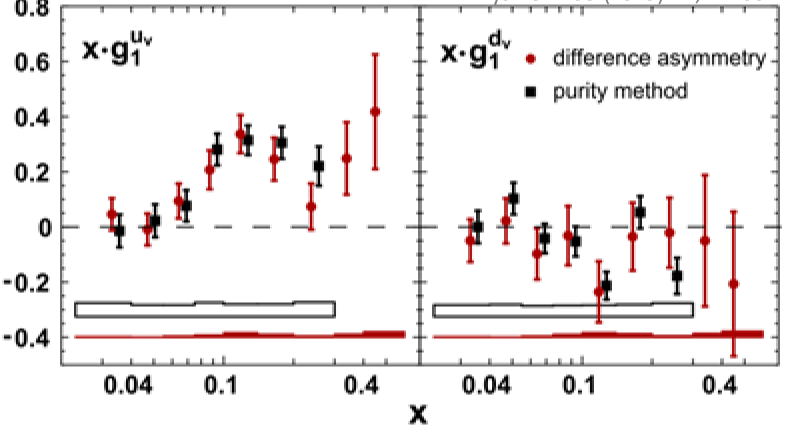
- Enhanced contribution of higher-order processes

Insights from DIS

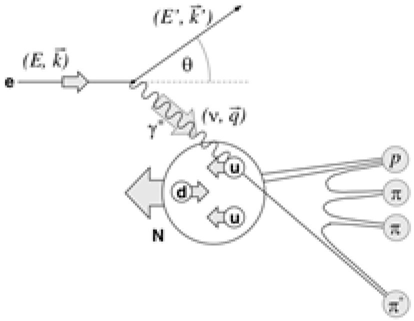
Flavor-separated valence-quark helicities from SIDIS (HERMES, COMPASS)

- Example for **final HERMES valence quark helicities** from electron and positron SIDIS with charged **pions and kaons** on **p and d targets**

Phys.Rev.D99 (2019) 11, 112001



virtual-photon-nucleon asymmetry



$$A_1^h \equiv \frac{\sigma^h_{1/2} - \sigma^h_{3/2}}{\sigma^h_{1/2} + \sigma^h_{3/2}}$$

Hadron charge-difference asymmetry: direct way to extract valence-quark helicities (depends on isospin-symmetry assumption of FF)

$$A_{1,d}^{h^+-h^-} \overset{\mathrm{LO\,LT}}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}} \qquad A_{1,p}^{h^+-h^-} \overset{\mathrm{LO\,LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

Here g_1 - helicity

Purity method: includes conditional probability that a hadron originated from a struck quark of flavor q (depends on a fragmentation model)

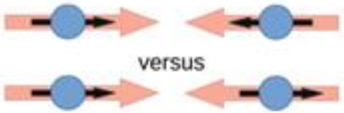
$$A_1^{\mathrm{h}}(x,Q^2,z) = \sum_q \mathcal{P}_q^{\mathrm{h}}(x,Q^2,z) \cdot \frac{\Delta q(x,Q^2)}{q(x,Q^2)}$$

Gluon spin from pp collisions

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

LO for illustration

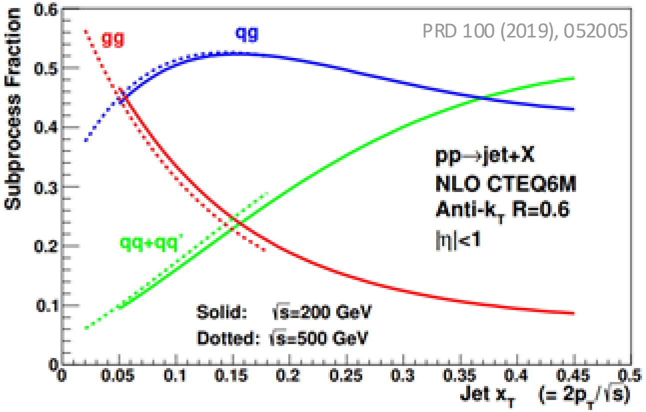
$$\vec{p} + \vec{p} \to \text{jet/dijet/hadrons} + X$$



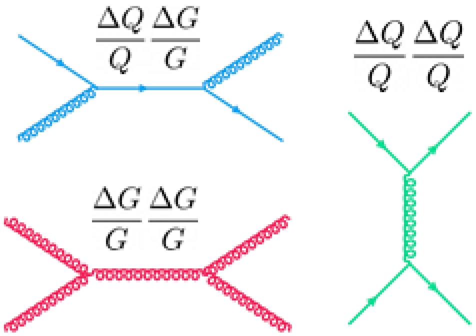
At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**

Cross-section measurement to support the NLO pQCD interpretation of asymmetries

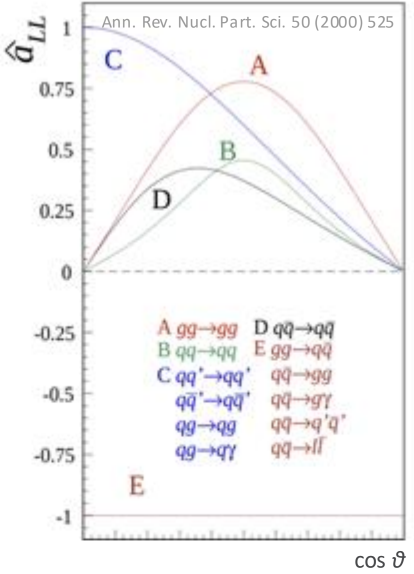
Which processes dominate at RHIC?



Subprocess fraction in central jet production

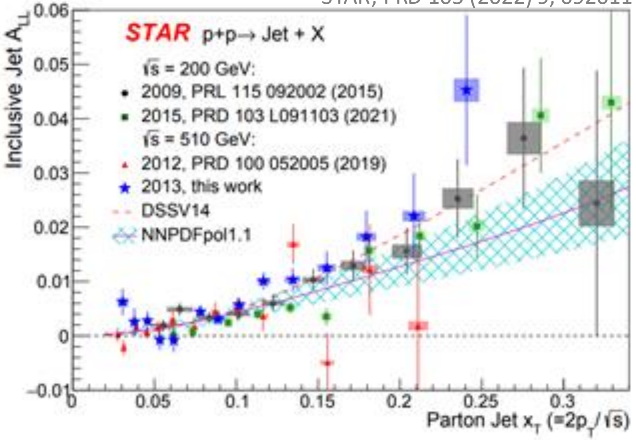


What are a_{LL} for these processes?

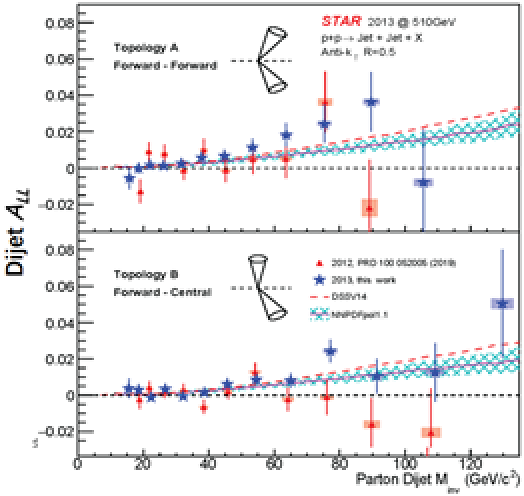


Gluon spin from pp collisions

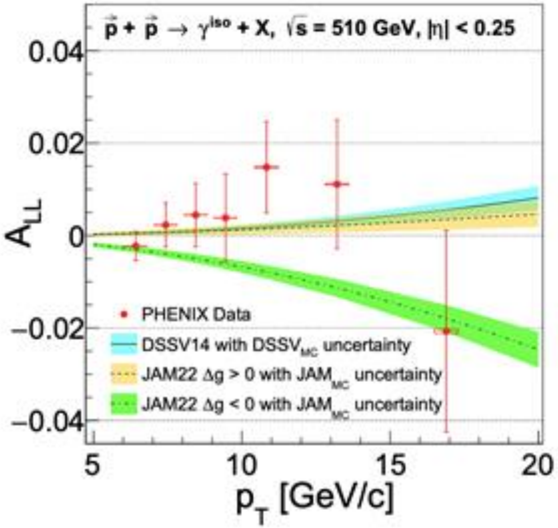
STAR, PRD 105 (2022) 9, 092011



STAR, PRD 105 (2022) 9, 092011



PHENIX, Phys.Rev.Lett. 130 (2023) 25, 251901



Higher √s and more forward rapidity push sensitivity to lower x

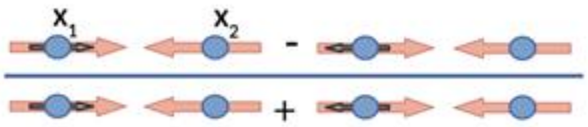
- Down to ~0.004 with STAR Endcap ($\eta < 1.8$) dijets at 510 GeV
- **Dijets** provide constraints to underlying partonic kinematics - **better constraints on functional form of ΔG(x)**
- **Direct photon** sensitive to gq → γq LO process; **clean access to Δg(x)** (no hadronization)
- **Consistent results from both energies and both experiments**

RHIC concluded data taking with longitudinally polarized protons in 2015

The data are anticipated to provide the most precise insights in Δg(x) well into the future

Sea-quark spin from pp collisions

Single spin asymmetry and cross sections for **W production**



$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

LO for illustration

Separation of quark flavor

- $W^+(W^-)$: predominantly u(d) and d(u)

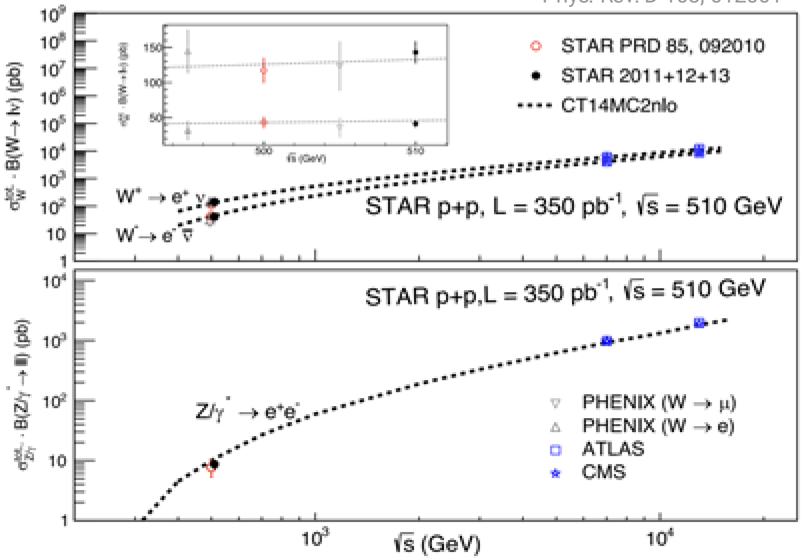
Maximal parity violation

- W couples to left-handed particles or right-handed antiparticles

The decay process is calculable

- Free from fragmentation function

Phys. Rev. D 103, 012001

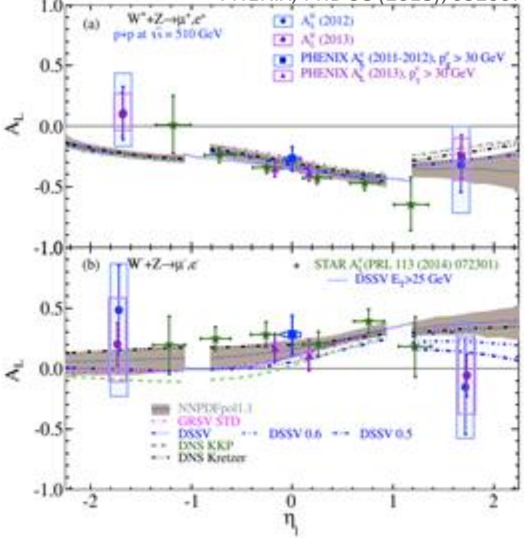


$W^{+/-}$ and Z cross section

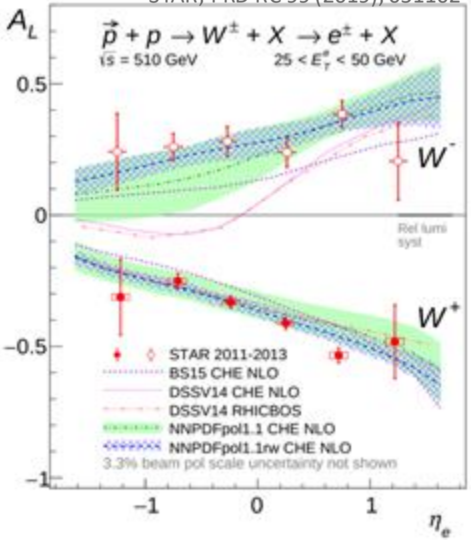
- Agreement between theory and experiment
- Support for the NLO pQCD interpretation of asymmetry measurements

Sea-quark spin from pp collisions

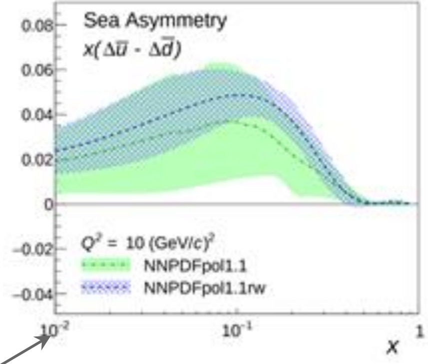
PHENIX, PRD 98 (2018), 032007



STAR, PRD RC 99 (2019), 051102



Flavor asymmetry for quark sea



Covered lepton η: $0.05 < x_1 < 0.25$

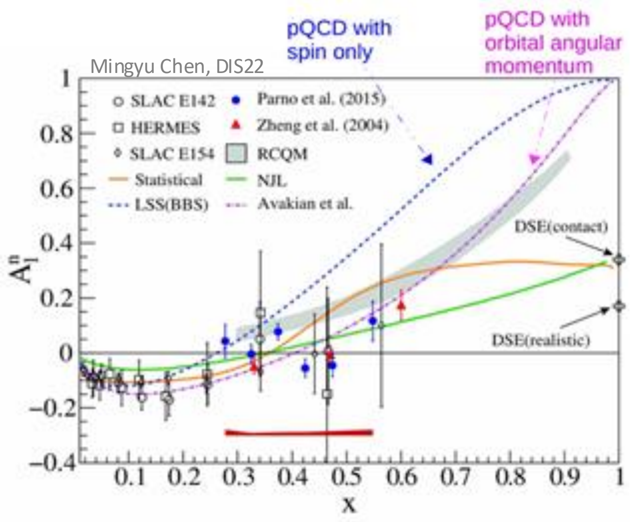
Full available data set analyzed from STAR (shown) and PHENIX (PHENIX, PRD 98 (2018), 032007)

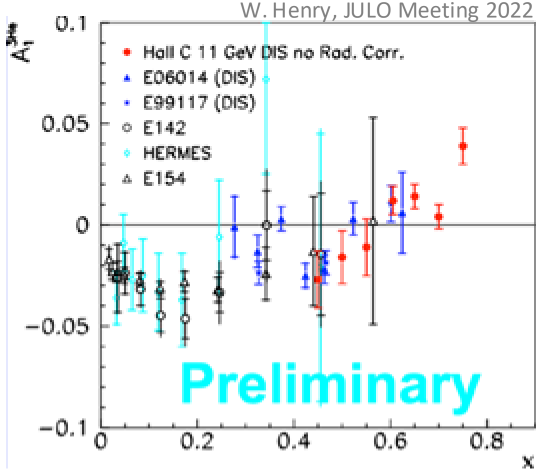
- **Significant preference for Δu over Δd** → Opposite to the spin-averaged quark-sea distributions
- Evaluations from DSSV and NNPDF agree with data in sea and valence quark region

Nucleon spin structure at high-x

Hall C A1n experiment with polarized ^{3}He target (E12-06-110)

- Measurement of the virtual-photon-nucleon asymmetry A_1 on polarized neutron (^{3}He) target
  $$\mathbf{A_1(x) \approx g_1(x)/F_1(x)} \text{ for large } Q^2$$
- Measurement of A_1 for proton (CLAS12) and neutron: extraction of **polarized to unpolarized parton distribution function** ratios **Δu/u** and **Δd/d** for large x region **0.61 < x < 0.77**
- Explore the **Q^2 dependence of A1n** at large x





Without radiative corrections

Statistical uncertainties only

Nuclear corrections to be applied

$$A_1^n = \frac{F_2^{^3He}\left[A_1^{^3He} - 2\frac{F_2^p}{F_2^{^3He}}P_pA_1^p\left(1 - \frac{0.014}{2P_p}\right)\right]}{P_nF_2^n\left(1 + \frac{0.056}{P_n}\right)}$$

Nucleon spin structure at high-x

Hall C A1n experiment with polarized ^{3}He target (E12-06-110)

- Measurement of the virtual-photon-nucleon asymmetry A_1 on polarized neutron (^{3}He) target
  $A_1(x) \approx g_1(x)/F_1(x)$ for large Q^2

- Measurement of A_1 for proton (CLAS12) and neutron: extraction of **polarized to unpolarized parton distribution function** ratios **$\Delta u/u$** and **$\Delta d/d$** for large x region **$0.61 < x < 0.77$**
- Explore the **Q^2 dependence of A1n** at large x

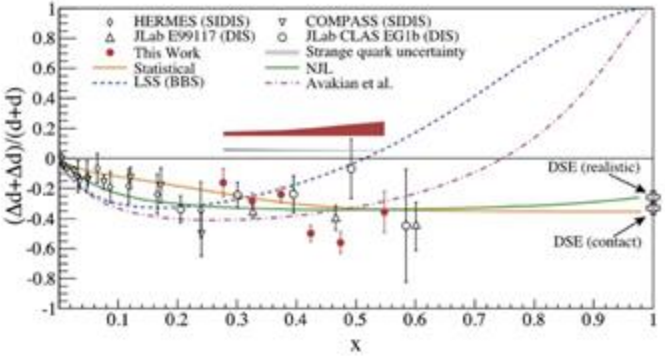
$$\frac{\Delta u + \Delta\bar{u}}{u+\bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + R^{du}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4R^{du}\right)$$

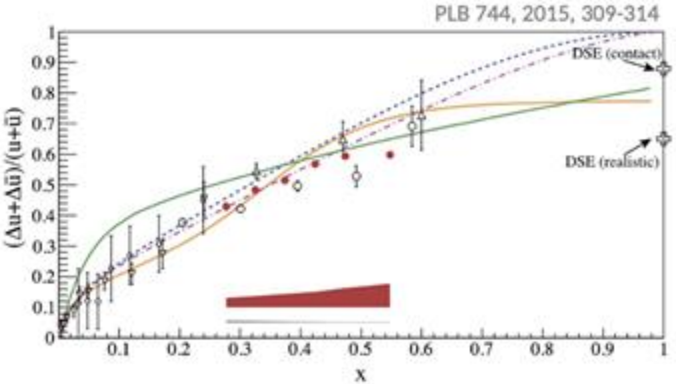
$$\frac{\Delta d + \Delta\bar{d}}{d+\bar{d}} = \frac{-1}{15}\frac{g_1^p}{F_1^p}\left(1 + \frac{4}{R^{du}}\right) + \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right)$$

where $R^{du} \equiv (d+\bar{d})/(u+\bar{u})$ and is taken from the CJ12

PLB 744, 2015, 309-314

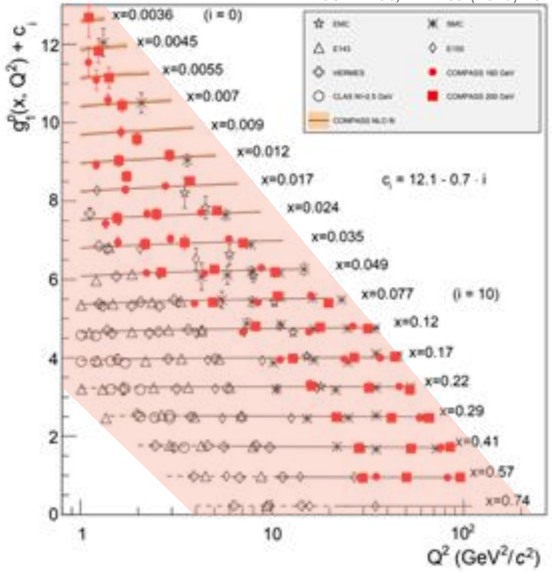
Example extraction of Δu/u and Δd/d from E06-014 Hall A Jlab predecessor measurement, red) with previous world DIS data and selected model predictions and parameterizations





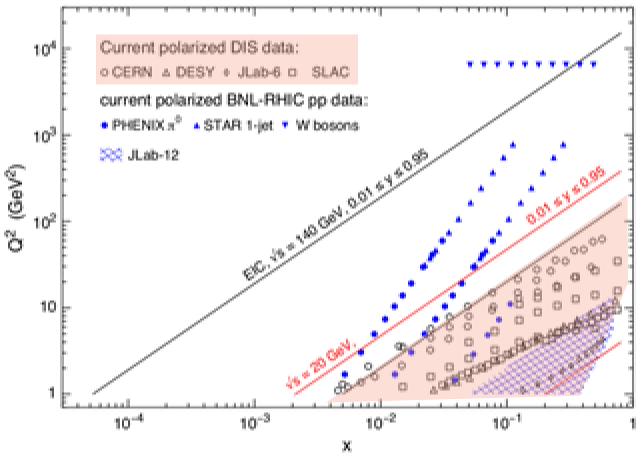
Longitudinal Spin Structure - Where Are We Going?

COMPASS, PLB 753 (2016) 18



Current DIS Data:
Down to $x \approx 0.005$
$Q^2 \approx$ 1-100 GeV^2

EIC, Yellow Report



EIC:
Down to $x \approx 10^{-4}$
$Q^2 \approx 1\text{-}10^3$ GeV^2 !

- Access to gluon spin through g_1 scaling violation
- different √s settings to maximize kinematic coverage

ΔΣ and ΔG Projections

Current world data

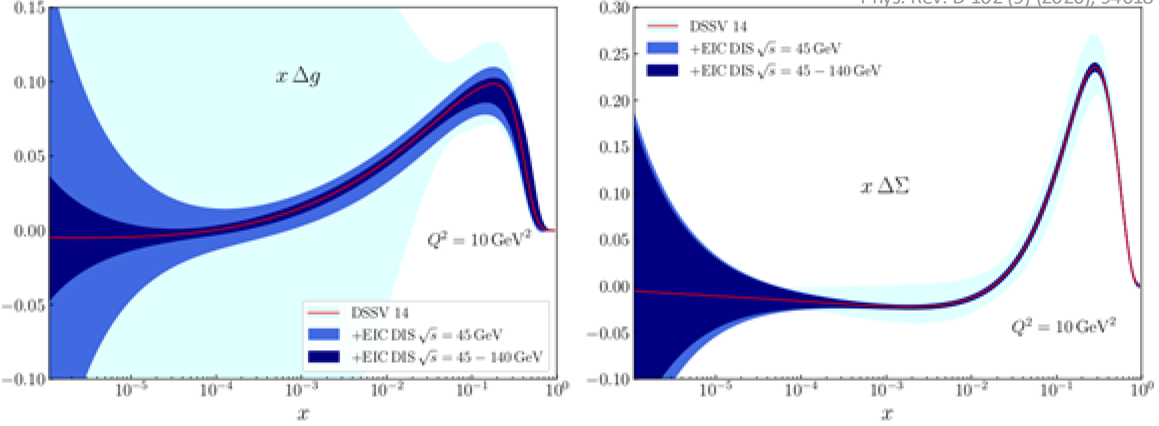
- Helicity distributions known for **$x >$ ~0.01** with good precision

Deep insight with EIC

- Precision down to **$x \sim 10^{-4}$**
- In addition to the sensitivity to the **quark sector**, **scaling violation in $g_1(x, Q^2)$ in inclusive DIS to access gluons**
- In addition to golden channel g_1, direct access to gluons in higher-order photon-gluon fusion: dijet, heavy-quark

Impact of the projected EIC DIS A_{LL} pseudodata ($L = 10$ fb^{-1}) on the gluon helicity and quark singlet helicity

Phys. Rev. D 102 (9) (2020), 94018

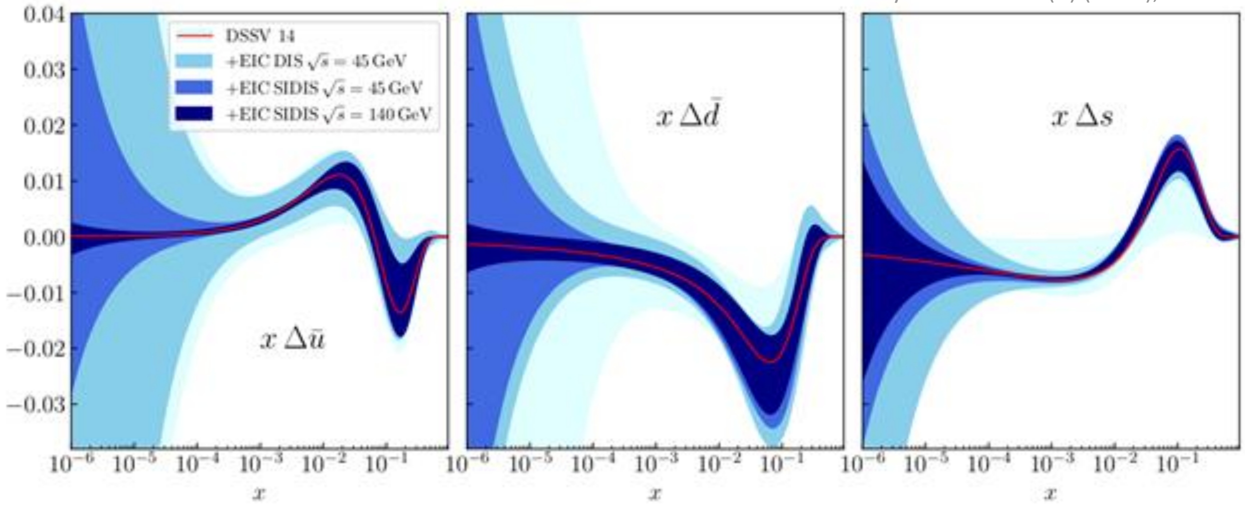


Sea Quark Helicities Projections

Sea quark helicities via SIDIS measurements with pions and kaons

- Tackle question of sea quark helicities contributions to the spin, in particular, the **strange sea polarization**
- **Highest impact at low x** from the data at the **highest collision energies**
- Sensitivity to sea quarks from $A_1^{\pi-}$ ($\Delta\bar{u}$), $A_1^{\pi+}$ ($\Delta\bar{d}$), A_1^{K} (Δs) with strongest correlations between A_1 and sea quark helicity distributions at low x
- Both pion asymmetries show a weaker but still significant correlation with strange quarks

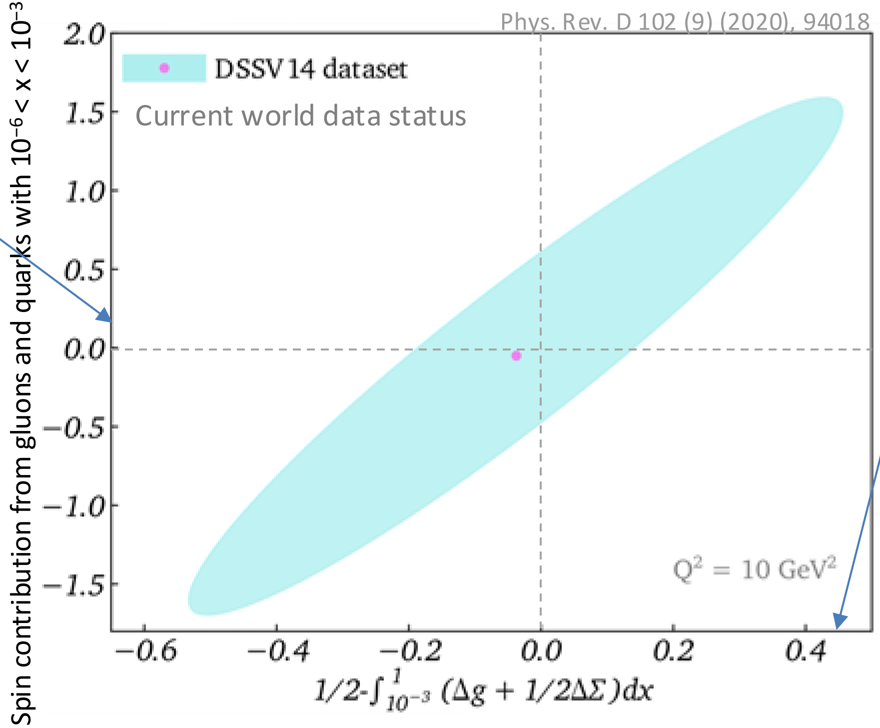
Phys. Rev. D 102 (9) (2020), 94018



Room Left for Angular Momentum

How much do the **spins of quarks and gluons very "deep" inside the proton** contribute to its spin?

Massive uncertainty range from -300% to +300% of the total proton spin!



Room left for potential contributions to the proton spin from angular momentum of gluons and quarks with x > 0.001

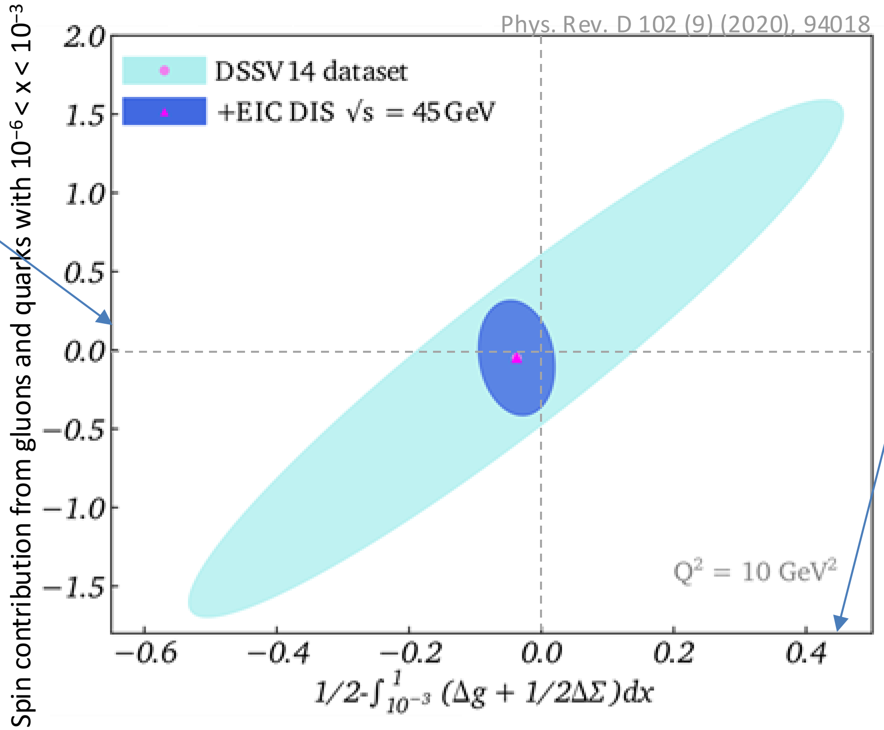
How much do **the motion of quarks and gluons** contribute to the proton's spin?

Close to zero—but with a huge uncertainty ranging from -100% to +80% of the total proton spin!

Pictures: adapted from arXiv:2007.08300

Room Left for Angular Momentum

How much do the **spins of quarks and gluons very "deep" inside the proton** contribute to its spin?



Room left for potential contributions to the proton spin from angular momentum of gluons and quarks with $x > 0.001$

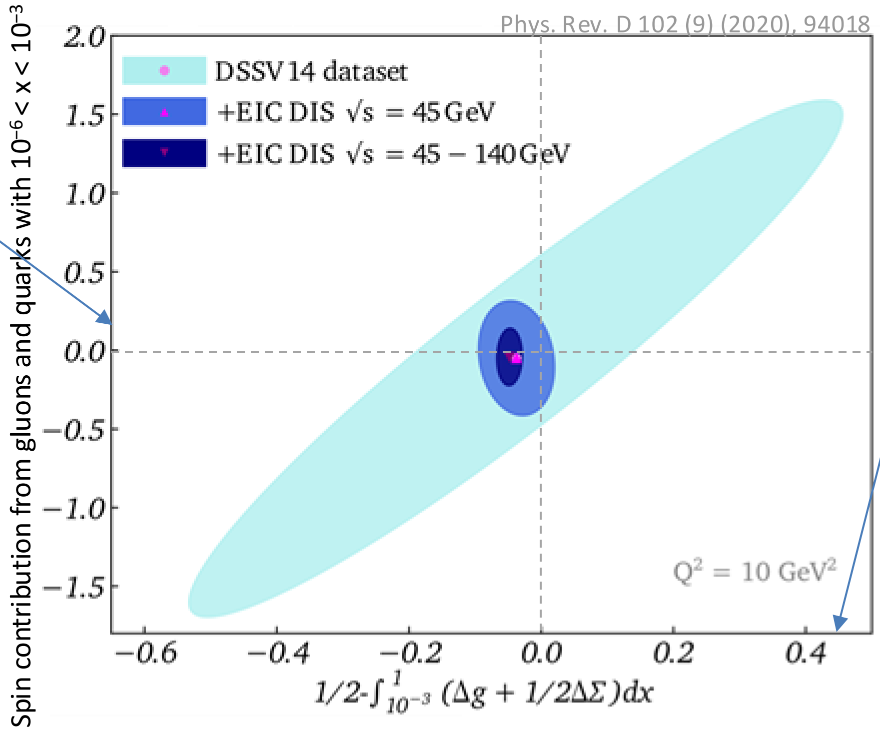
How much do **the motion of quarks and gluons** contribute to the proton's spin?

Pictures: adapted from arXiv:2007.08300

Room Left for Angular Momentum

How much do the **spins of quarks and gluons very "deep" inside the proton** contribute to its spin?

EIC aims to shrink this uncertainty about 10 times!



Room left for potential contributions to the proton spin from angular momentum of gluons and quarks with x > 0.001

How much do **the motion of quarks and gluons** contribute to the proton's spin?

EIC aims to shrink this uncertainty 22 times!

Pictures: adapted from arXiv:2007.08300

Summary

EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all

Access to EIC Physics through

- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

The EIC project is progressing towards construction, with the ePIC collaboration established and dedicated to its mission.

Experiments employing both lepton scattering processes and hadron-hadron interactions have unveiled the intricate nucleon spin structure.

- Decades of research encompassing Deep Inelastic Scattering, Semi-Inclusive Deep Inelastic Scattering, and proton-proton collisions have paved the way.

The Electron-Ion Collider promises precision in probing the longitudinal spin structure of nucleons across a wide range of x and Q^2

Backup

Proton Spin and ePIC Detector Requirements

Physics Question

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

Two established approaches to look at the compositions of the proton spin:

Ji sum rule:

$$\Delta\Sigma/2 + L_q + J_g = \hbar/2$$

- $\Delta\Sigma/2$: Quark helicity
- L_q: Quark orbital angular momentum
- J_g: Gluon helicity and orbital angular momentum

Jaffe-Manohar sum rule:

$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

- $\Delta\Sigma/2$: Quark helicity
- ΔG: Gluon helicity
- ℓ_q: Quark canonical orbital angular momentum
- ℓ_g: Gluon canonical orbital angular momentum

Ji sum rule:

- **Frame independent** spin sum rule
- **Quark and gluon Jq** (sum of ΔΣ/2 and Lq) **and Jg** can be obtained form Generalized Parton Distributions **(GPDs) moments**
- Phys. Rev. Lett. 78, 610–613 (1997)

Jaffe-Manohar sum rule:

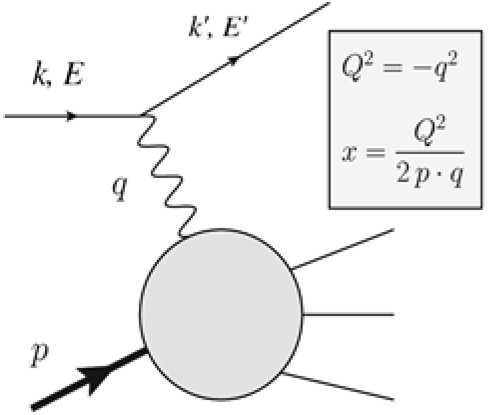
- All terms have **partonic interpretation**
- In infinite-momentum frame
- **ℓq and ℓg** (Twist-3 quantities) can be extracted **from GPDs**
- Nucl. Phys. B 337, 509–546 (1990)

DIS Kinematics

Reconstructed from **scattered electron** or **hadronic final state**

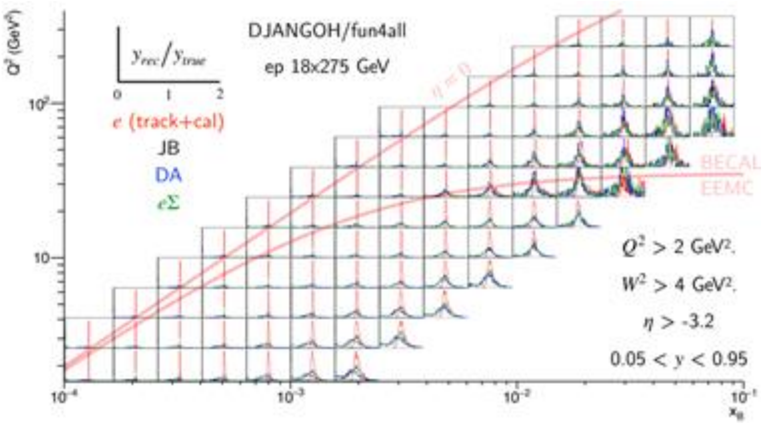
Inclusive NC: leveraging the overconstraint of kinematics to maximize the resolution

Resolution on conventional methods depends on events x-Q^2, acceptance and resolution effects, size of radiative processes



Advanced reconstruction methods in development for ePIC:

- Kinematic fitting (see, e.g., S. Maple, DIS23)
- Deep Learning Approaches (see, e.g., M. Diefenthaler et al., Eur.Phys.J.C 82 (2022) 11, 1064, C. Pecar, AI4EIC22)



Assessment of relative performance of reconstruction methods for measured phase space for ECCE and ATHENA

- Coverage driven by acceptance: $0.01 < y < 0.95$, $Q^2 > 1$ GeV^2
- y resolution: important role of data overlap at different √s

Proton Spin and ePIC Detector Requirements

Information on ΔΣ and ΔG

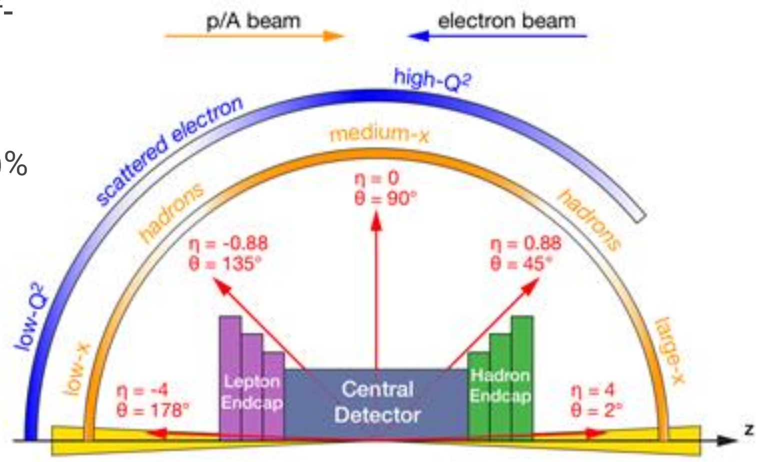
Longitudinally polarized e^- and p for over a wide range in center-of-mass energy (x-Q^2 coverage)

Low-x performance:

- Good EM calo in barrel region $\sigma_E/E = (7 - 10)\%/\sqrt{E} \oplus (1 - 3)\%$
- Superior in backward region $\sigma_E/E = 2\%/\sqrt{E} \oplus (1 - 3)\%$
- Electron-pion separation up to 10^4

Higher-x performance:

- Hadronic final state - good momentum resolution and calo measurement, in particular in the forward direction



Improved access to the sea quark helicities and TMD measurements - SIDIS with detected pions and kaons

- Particle ID over wide range of $|\eta| \leq 3.5$ with better than 3σ separation with different particle energy ranges: barrel (< 6 GeV/c), backward (< 10 GeV/c), forward (< 50 GeV/c)

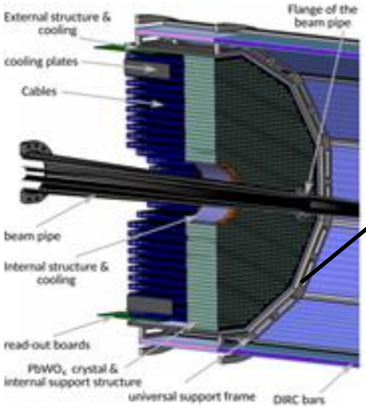
Access to Orbital Angular Momentum - GPD measurements

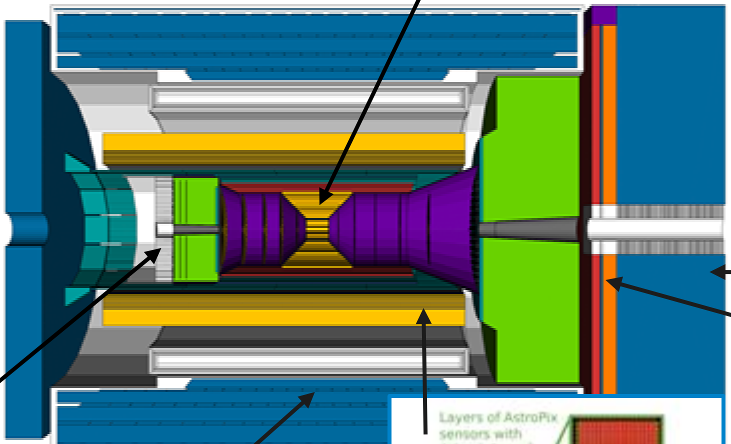
- Demanding program requiring high luminosity and detection of the forward-going protons scattered under small angles

Proton Spin and ePIC Detector Requirements

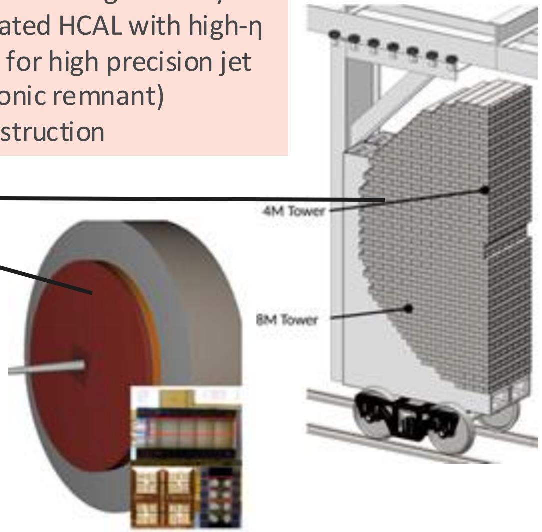
Electron momentum resolution - dominated by tracker in central region: Si MAPS Trackers + µMega (see backup for more details)

Superior EM energy resolution from Backwards EMCal - $PbWO_4$ crystals

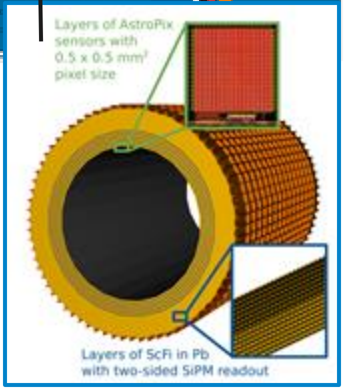




High granularity W/SciFi EMCal and longitudinally separated HCAL with high-η insert for high precision jet (hadronic remnant) reconstruction



Barrel HCAL (sPHENIX re-use)

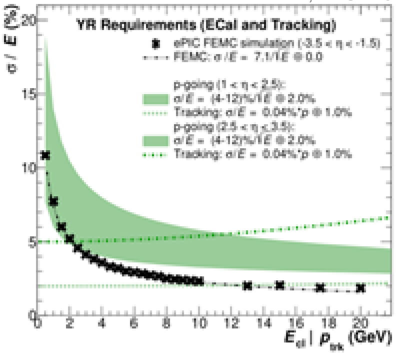


Barrel Imaging ECAL with good energy resolution from SciFi/Pb and high e/π separation supported by Si layers

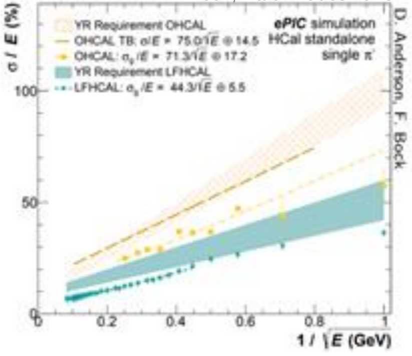
Proton Spin and ePIC Detector Requirements

p-going

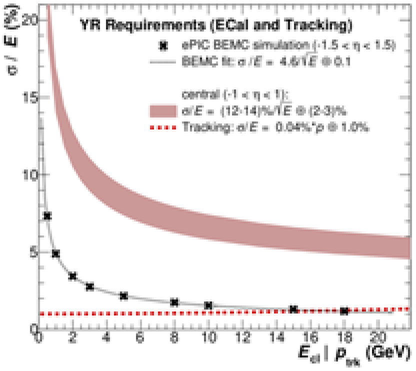
N. Schmidt, RAUM23



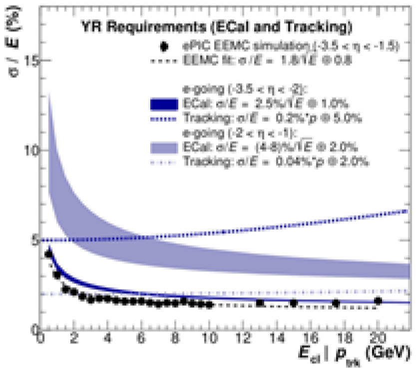
F. Bock, Hard Probes 2023



barrel



e-going



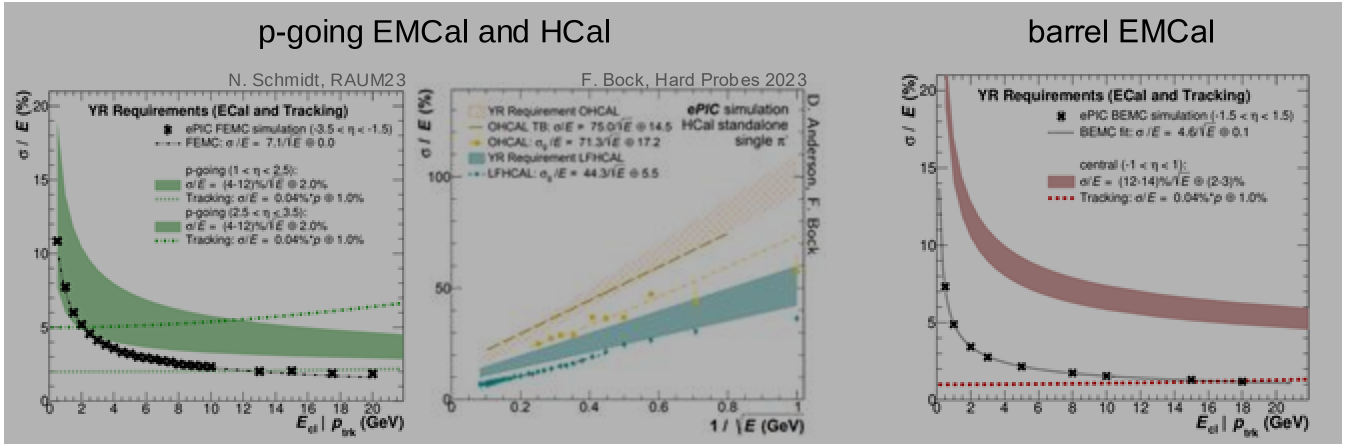
Performance of energy resolution

- Technologies fulfill YR requirements on energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry, tracking and reconstruction algorithms
- **Barrel:** electron momentum measurement predominantly from tracker, but e/π separation critical (EMCal for low energy pions, EMCal + HCal for higher energy pions)
- **e-going EMCal:** Energy resolution for e important for the backward rapidities + e/π separation
- **h-going EMCal + HCal:** energy resolution (EM and hadronic) for hadronic remnant reconstruction

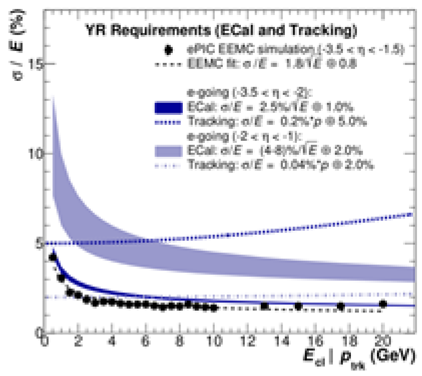
Example Backward e/π Performance for 10 x 100 GeV

p-going EMCal and HCal

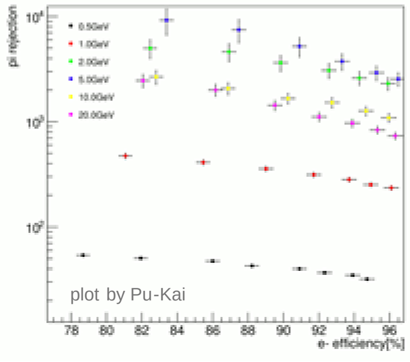
barrel EMCal



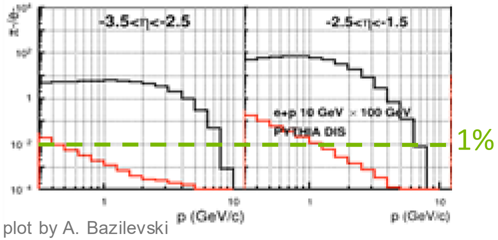
e-going EMCal



ePIC Simulation, E/p cut only



ePIC Simulation, E/p cut + E-p_z cut

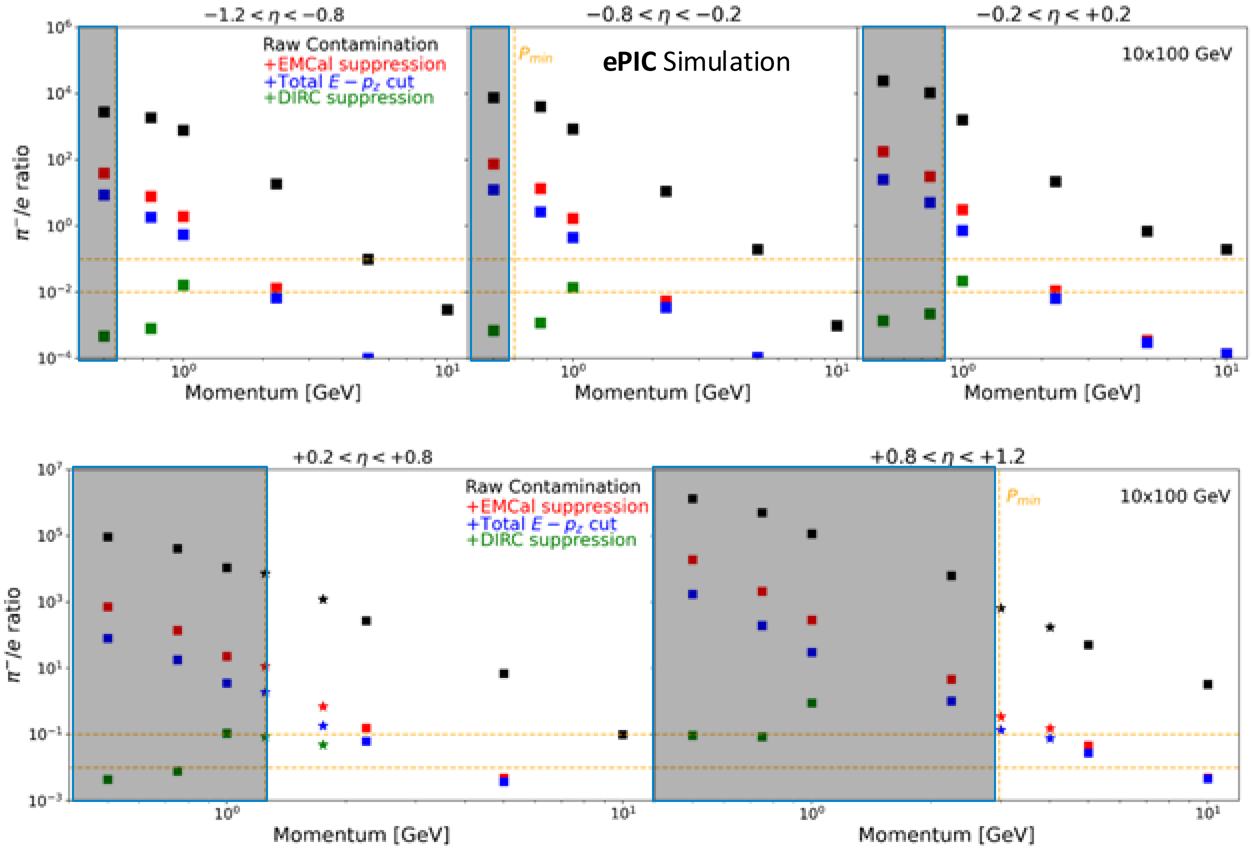


< 1% pion contamination expected for the DIS electron reconstruction

- Pythia DIS, no cut, initial π contamination
- E/p < 1-1.6E/p and E-p_z cut

Another strong suppression factor < 2.5 GeV from pfRHIC

Example Barrel e/π Performance for 10 x 100 GeV



Challenging goal: Achieve 90% electron purity from the combined detector performance (ECAL + DIRC)

- To keep pion contamination systematic uncertainty to required 1% level
- Impact of total E-pz cut, DIRC suppression and EMCal suppression studies

See also: B. Schmookler, ePIC Collaboration Meeting contribution (link)

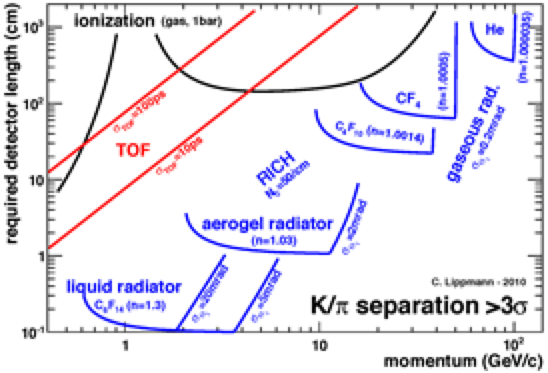
Requirement fulfilled in all η ranges

SIDIS and ePIC Detector Requirements

SIDS Measurements to probe fragmentation functions and flavor-separated quark helicities:

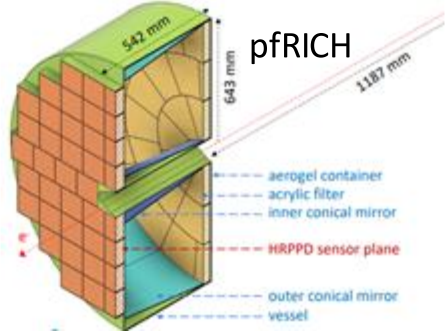
On top of the inclusive DIS requirements ⟶ Particle IDentification needs

- Charged pions, kaons and protons separation on track level ⟶ **Cherenkov detectors** complemented by **ToF** at lower momenta

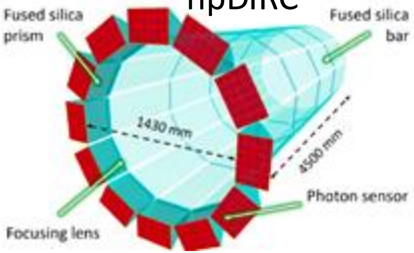


Region	Momentum	ePIC Technology
forward	< 50 GeV/c	dual-radiator RICH
central	< 6 GeV/c	high performance DIRC, AC-LGAD ToF
backward	< 10 GeV/c	proximity focusing RICH

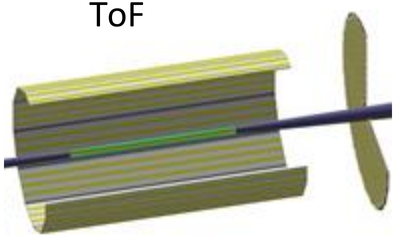
pfRICH



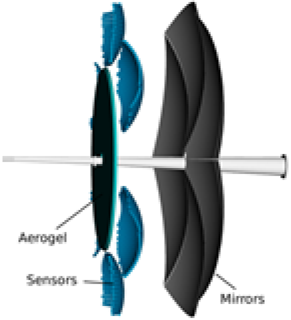
hpDIRC



ToF



dRICH



GPDs and Angular Orbital Momentum

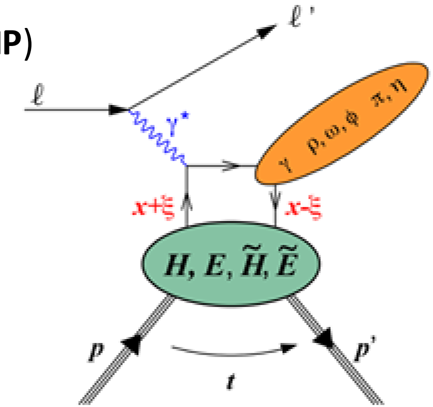
Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$ $\quad J_q = \frac{1}{2}\Delta\Sigma + L_q$

N / q	U	L	T
U	H		E_T
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T \quad \tilde{H}_T$

4 chiral-even and 4 chiral-odd quark **GPDs at leading twist** for a spin-½ hadron

Accessed via hard exclusive processes: cross section and asymmetries

- Deep virtual Compton scattering (**DVCS**) and hard exclusive meson production (**HEMP**)
- H, E accessed in vector meson production, all 4 chiral-even GPDs accessed in DVCS



DVCS and access to GPDs

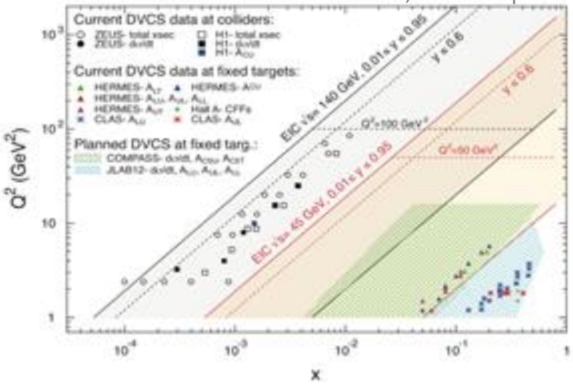
- Experimental access to GPDs via Compton Form Factors
- Different configurations: p and e polarization, beam charge → different CFFs
- proton + neutron DVCS → flavor separation of GPDs

$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx\, H^q(x,\xi,t)\left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon}\right)$$

GPDs at EIC: Snapshot

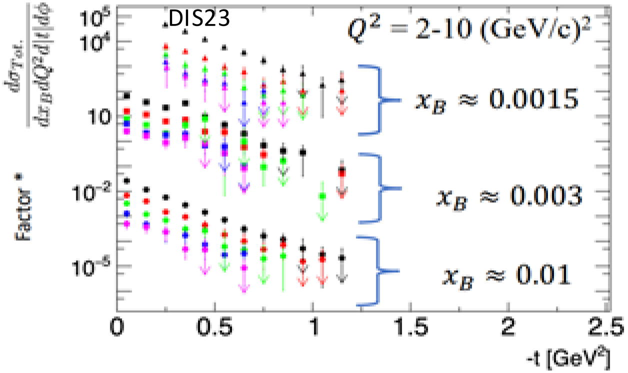
EIC kinematic reach: DVCS

EIC, Yellow Report



Projected DVCS cross-sections

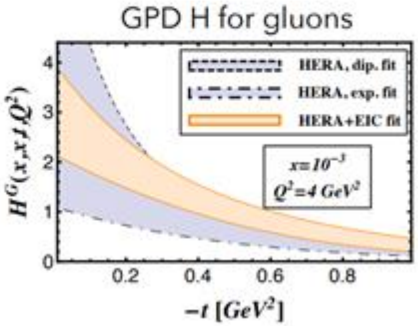
ECCE Simulation, 10 fb^{-1}, I. Korover, DIS23

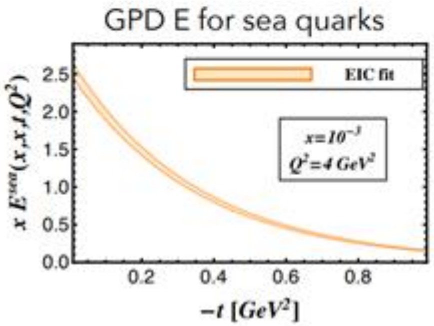


- ▲ e+p 18+275 GeV
- ■ e+p 10+100 GeV
- ● e+p 5+41 GeV

Strong constraints on extraction of Compton Form Factors from multidimentional binning

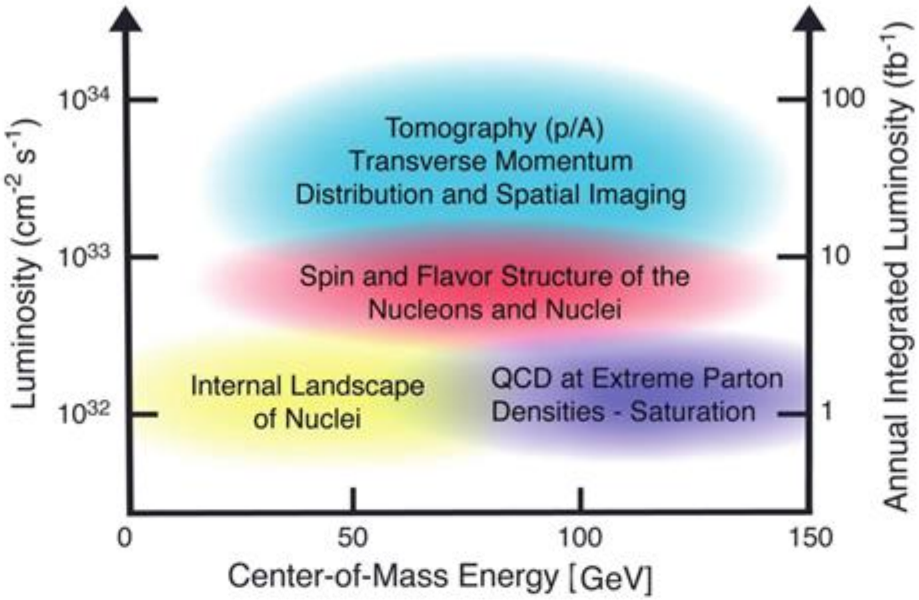
Anticipated constrain on GPDs H and E from EIC





- Different observables have different sensitivity to the GPDs, and measurements from multiple processes are needed for their flavour separation
- Measurements at EIC will provide significant constraints at low-x and enable extraction of as-yet unknown GPDs

Experimental Access to EIC Physics



Access to EIC Physics through

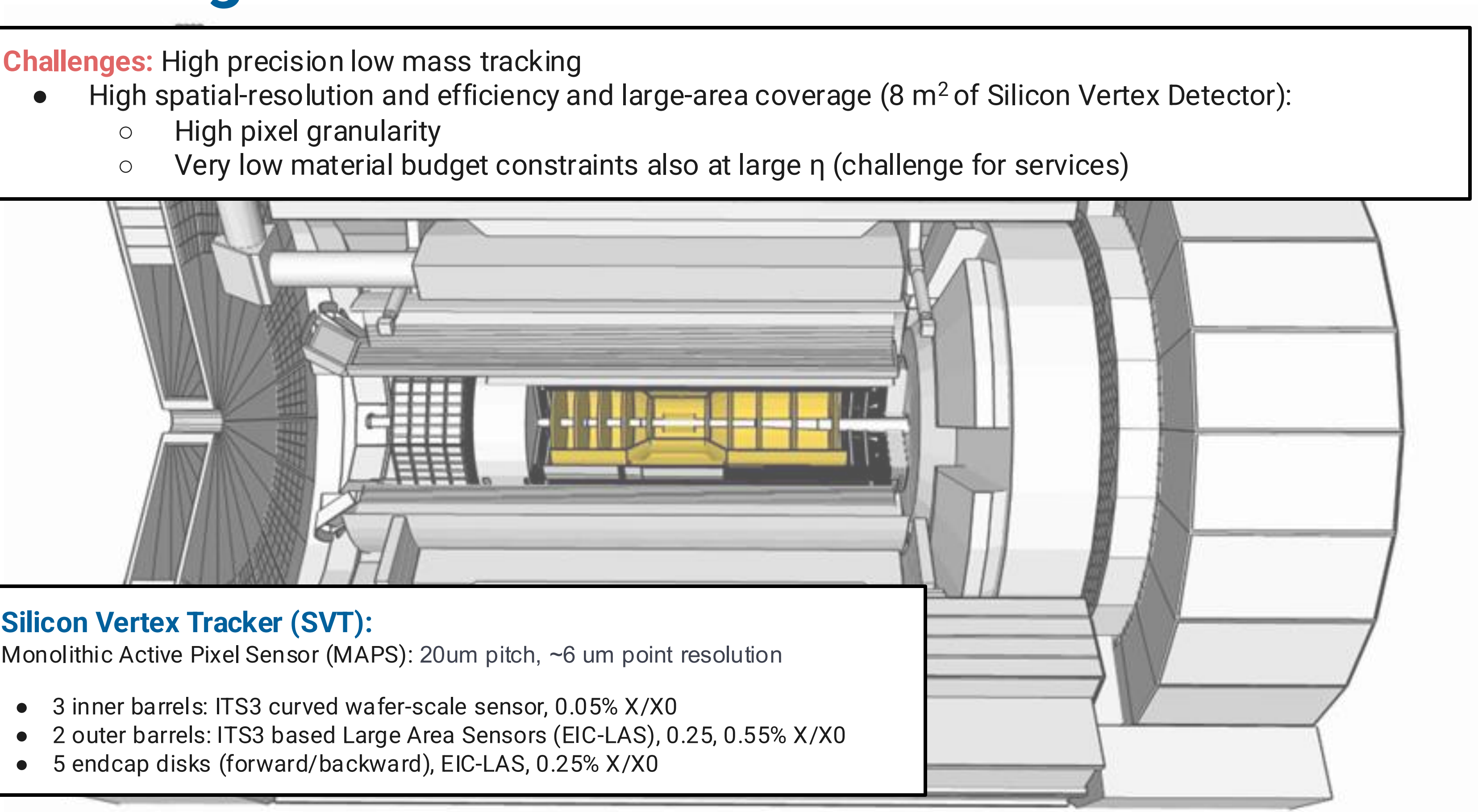
- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

ePIC Technology Choices

Tracking

Challenges: High precision low mass tracking

- High spatial-resolution and efficiency and large-area coverage (8 m^2 of Silicon Vertex Detector):
  - High pixel granularity
  - Very low material budget constraints also at large η (challenge for services)



Silicon Vertex Tracker (SVT):

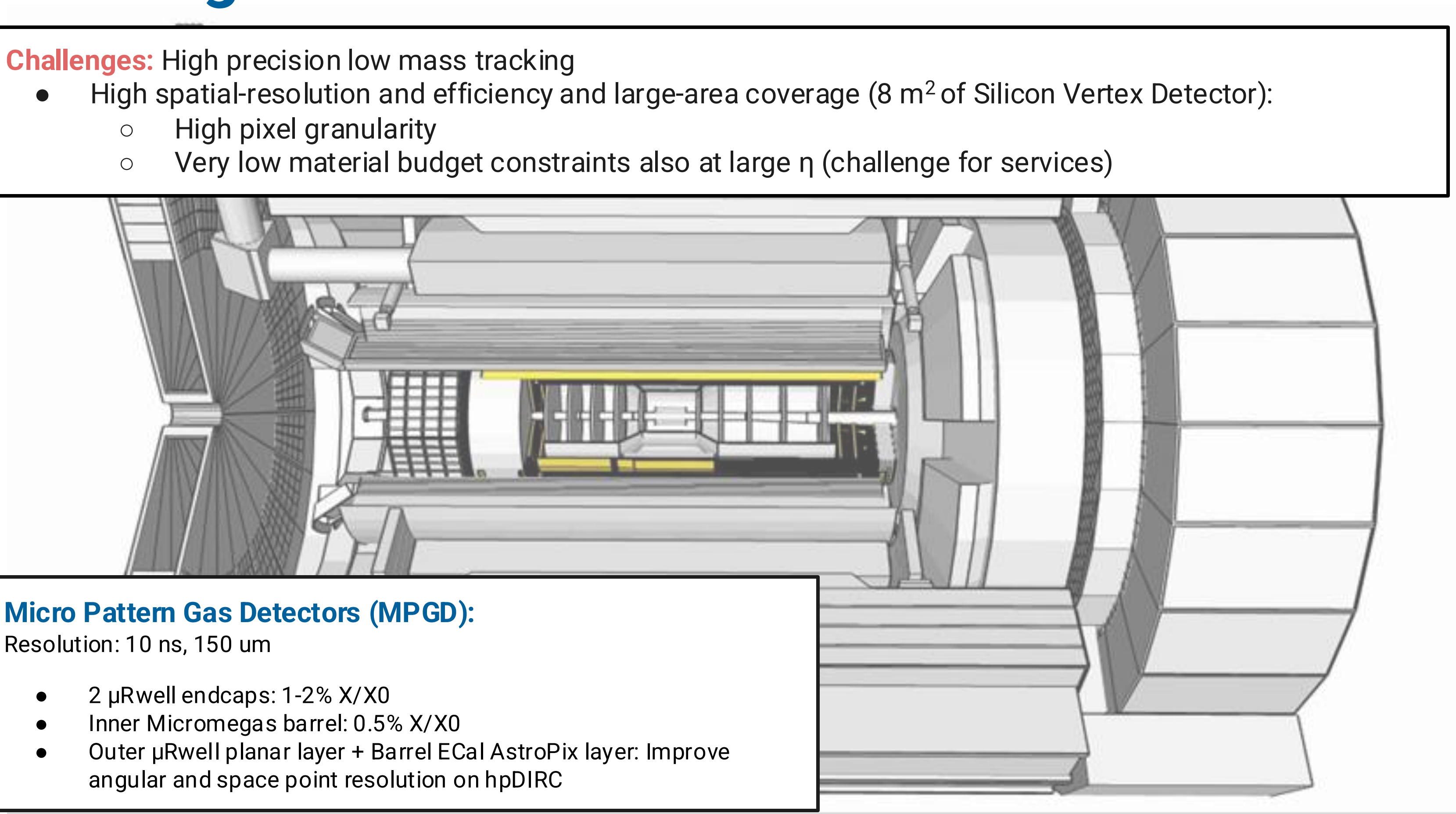
Monolithic Active Pixel Sensor (MAPS): 20um pitch, ~6 um point resolution

- 3 inner barrels: ITS3 curved wafer-scale sensor, 0.05% X/X0
- 2 outer barrels: ITS3 based Large Area Sensors (EIC-LAS), 0.25, 0.55% X/X0
- 5 endcap disks (forward/backward), EIC-LAS, 0.25% X/X0

Tracking

Challenges: High precision low mass tracking

- High spatial-resolution and efficiency and large-area coverage (8 m^2 of Silicon Vertex Detector):
  - High pixel granularity
  - Very low material budget constraints also at large η (challenge for services)

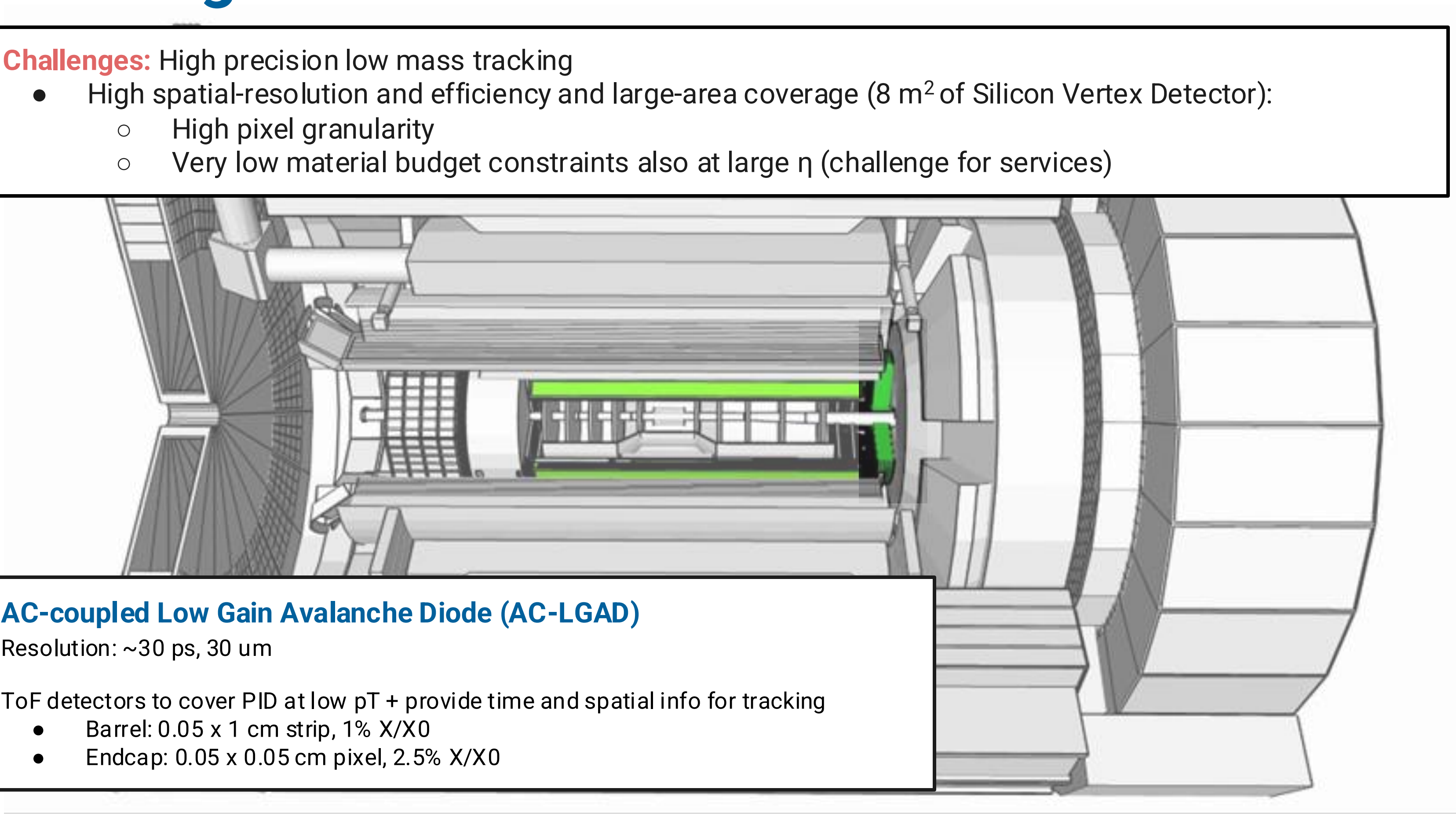


Micro Pattern Gas Detectors (MPGD):

Resolution: 10 ns, 150 um

- 2 μRwell endcaps: 1-2% X/X0
- Inner Micromegas barrel: 0.5% X/X0
- Outer μRwell planar layer + Barrel ECal AstroPix layer: Improve angular and space point resolution on hpDIRC

Tracking



Challenges: High precision low mass tracking

- High spatial-resolution and efficiency and large-area coverage (8 m^2 of Silicon Vertex Detector):
  - High pixel granularity
  - Very low material budget constraints also at large η (challenge for services)

AC-coupled Low Gain Avalanche Diode (AC-LGAD)

Resolution: ~30 ps, 30 um

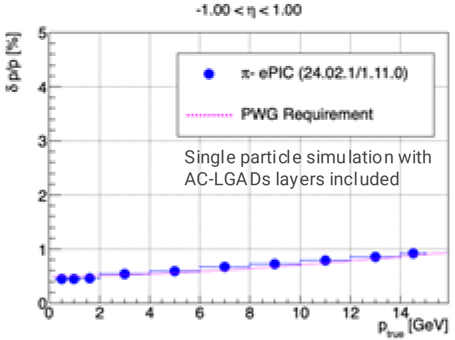
ToF detectors to cover PID at low pT + provide time and spatial info for tracking

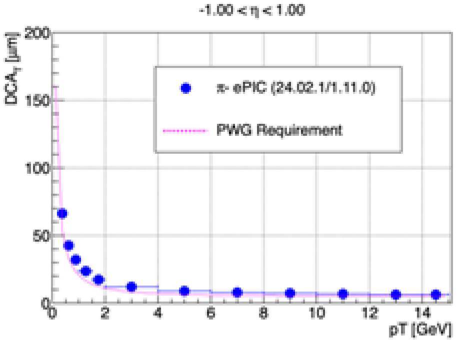
- Barrel: 0.05 x 1 cm strip, 1% X/X0
- Endcap: 0.05 x 0.05 cm pixel, 2.5% X/X0

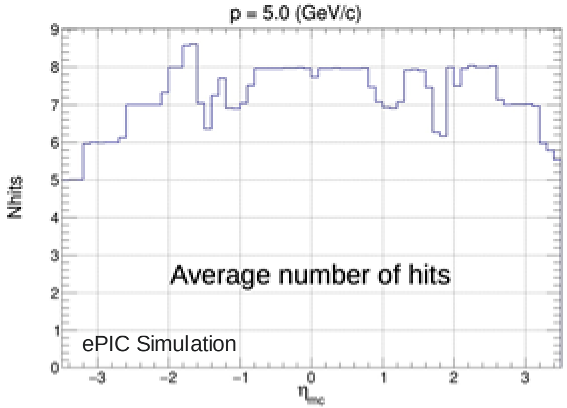
Tracking Performance

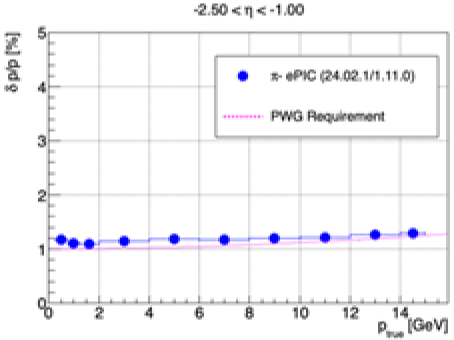
Momentum

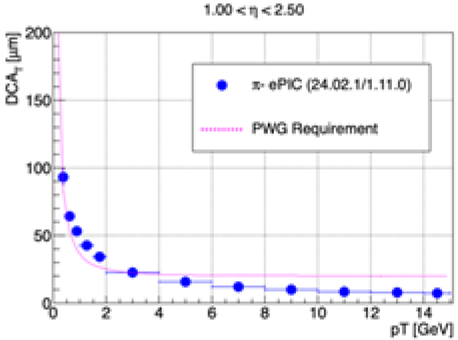
Distance of Closest Approach (DCA_T)







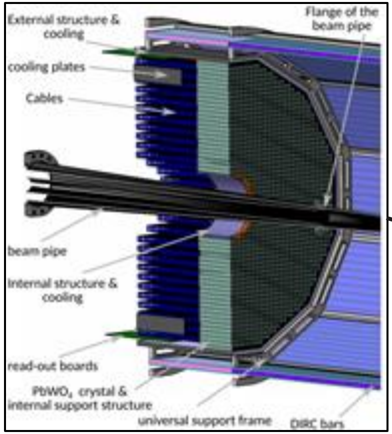


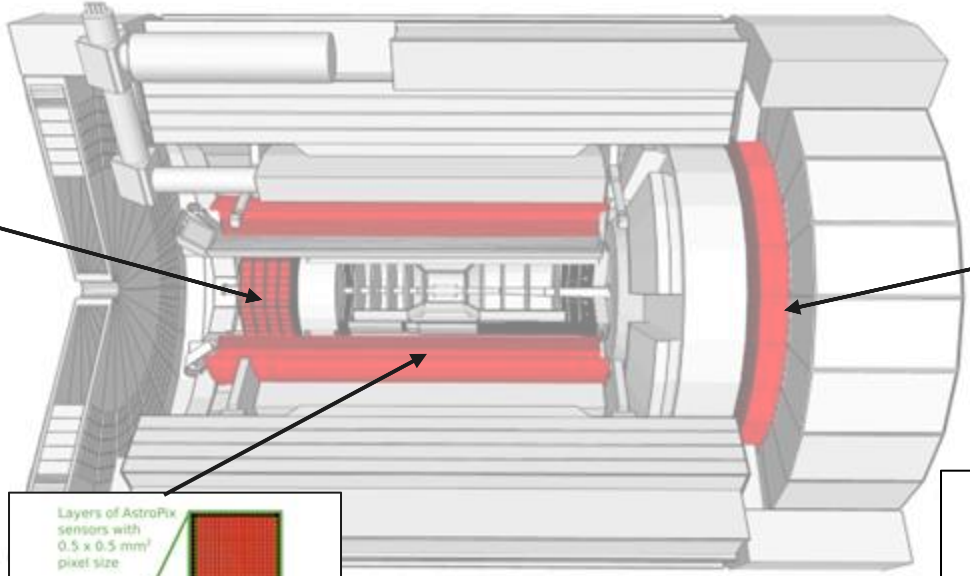


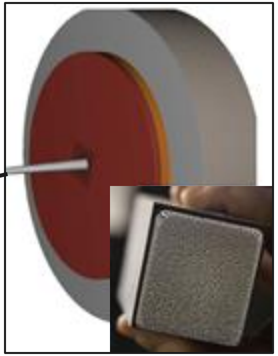
	Momentum Resolution	Spatial Resolution
Backward (-3.5 to -2.5)	~0.10%×p⊕2.0%	~ 30/pT μm ⊕ 40 μm
Backward (-2.5 to -1.0)	~ 0.05%×p⊕1.0%	~ 30/pT μm ⊕ 20 μm
Barrel (-1.0 to 1.0)	~0.05%×p⊕0.5%	~ 20/pT μm ⊕ 5 μm
Forward (1.0 to 2.5)	~0.05%×p⊕1.0%	~ 30/pT μm ⊕ 20 μm
Forward (2.5 to 3.5)	~0.10%×p⊕2.0%	~ 30/pT μm ⊕ 40 μm

- Backward/Forward momentum resolution in extreme η regions complemented by calorimetric resolution
- Meets PWG requirements elsewhere

Electromagnetic Calorimetry

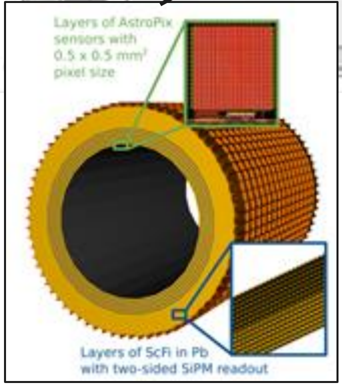






Backward EMCal $PbWO_4$ crystals

- 2 × 2 × 20 cm^3 crystals
- Readout: SiPMs 10μm pixel
- Depth: ~20 X0
- Cooling to keep temperature stable within ± 0.1 °C



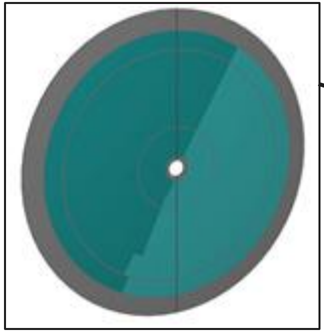
Imaging Barrel Calorimeter

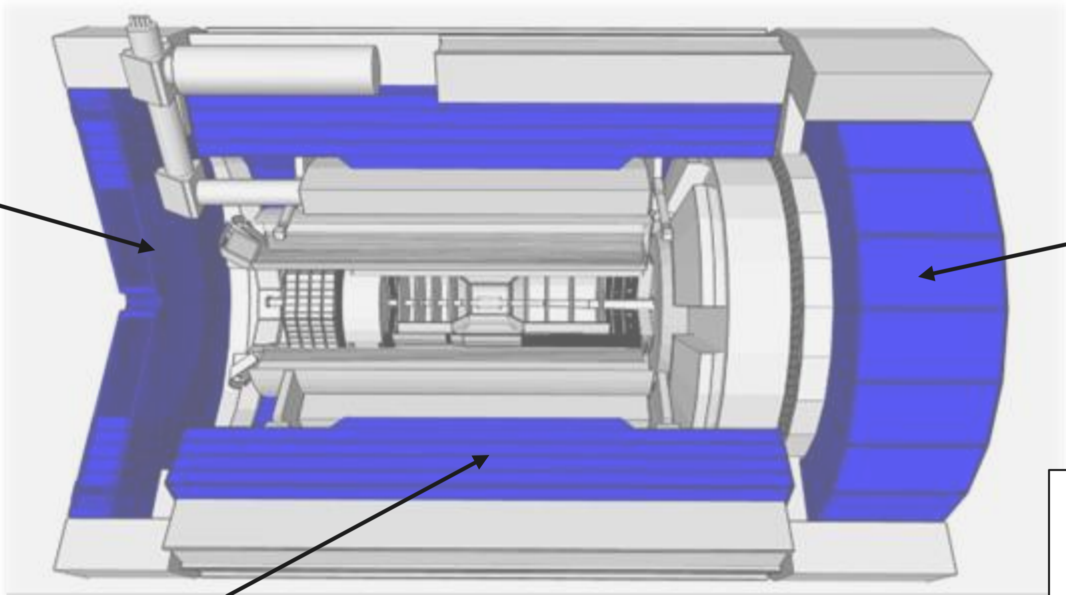
- 4(+2) layers of AstroPix MAPS sensor, 500x500 μm
- Interleaved with scintillating fiber/Pb layers
  - 2-side SiPM readout, 50 μm pixel
- Depth: ~17.1 X0

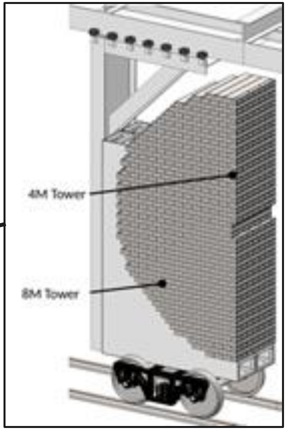
High granularity W/SciFi EMCal

- Tungsten powder mixed with epoxy + scintillating fibers
- 5 cm x 5 cm x 17 cm blocks
- 4 independent towers per block
- Readout: 4 SiPM per tower, 50 μm pixel
- Depth: ~23 X0

Hadronic Calorimetry







Backwards HCal

- Steel + large scintillator tiles sandwich
- SiPM readout
- Exact design still in progress

Barrel HCAL (sPHENIX re-use)

- Tilted Steel/Scintillator plates with SiPM readout

Refurbish for EIC

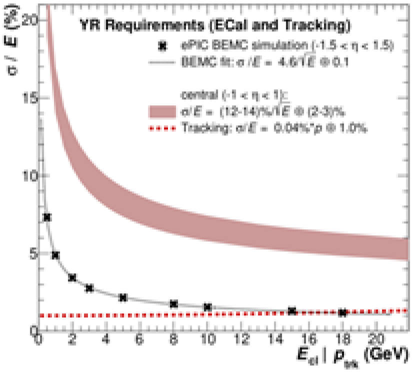
- Minor radiation damage replace SiPMs
- Upgrade electronics to HGCROC
- Reading out each tile individually

Longitudinally separated HCAL with high-η insert

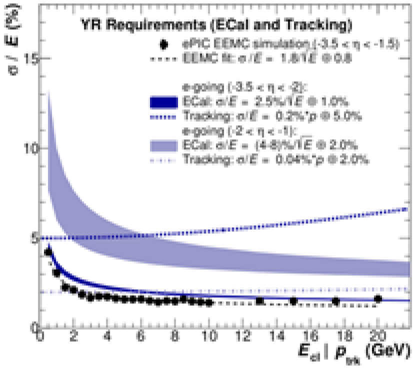
- Steel + Scintillator SiPM-on-tile
- Highly segmented longitudinally
- 65 layers per tower
  - 565,760 SiPMs
- Stackable for "easy" construction
- Highly segmented insert

Calorimetry Performance

Barrel

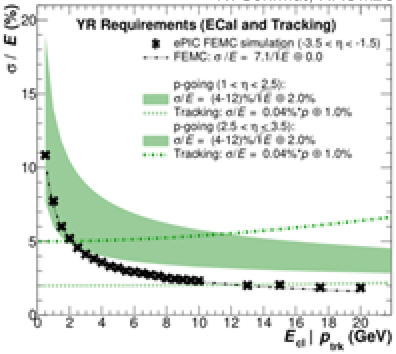


Endcap (e-going)

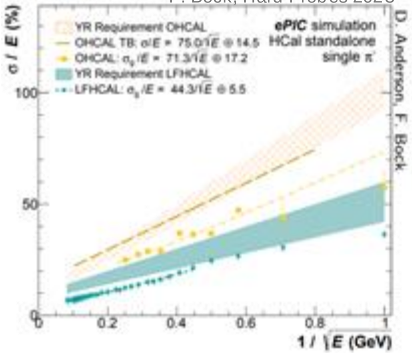


Endcap (p-going)

N. Schmidt, RAUM23



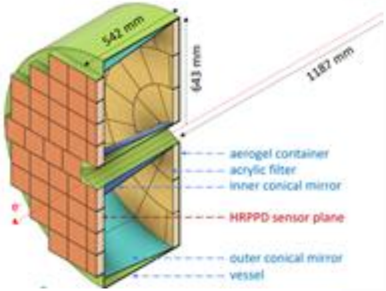
F. Bock, Hard Probes 2023



Particle Identification

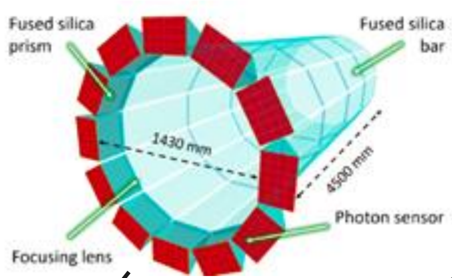
Proximity Focusing RICH

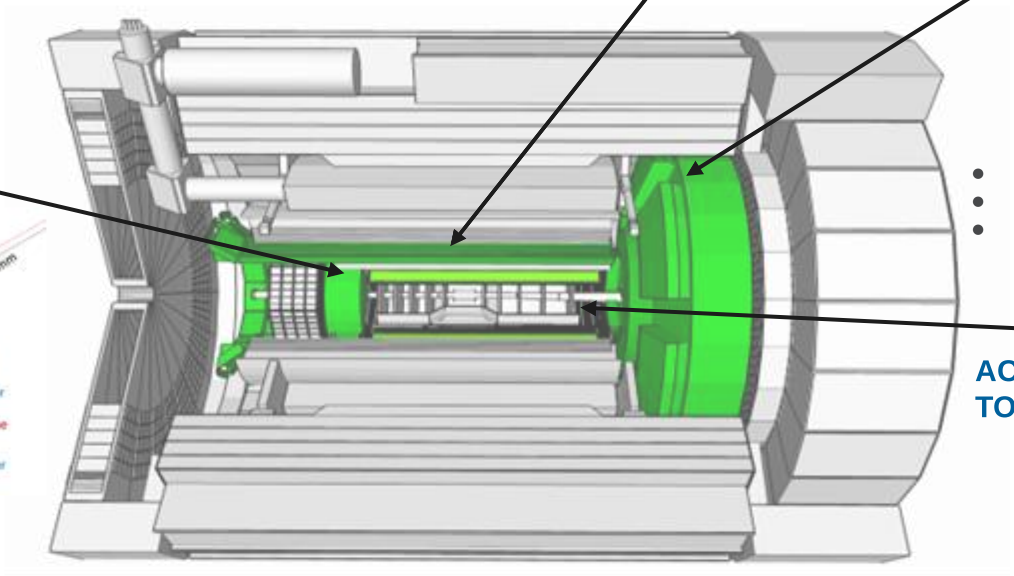
- Proximity gap >40 cm
- up to 7 GeV/c 3б π/K sep.
- High Rate Picosecond Photodetector (HRPPD) sensors
  - Provide also reference time (~20ps) for ToF



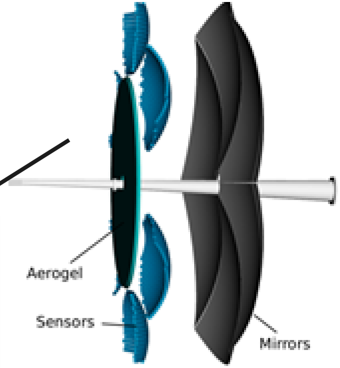
High-Performance DIRC

- Quartz bar radiator (BaBAR bars)
- light detection with MCP-PMTs
- Fully focused
- π/K 3б separation at 6 GeV/c

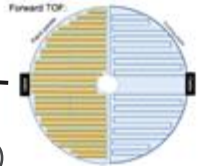




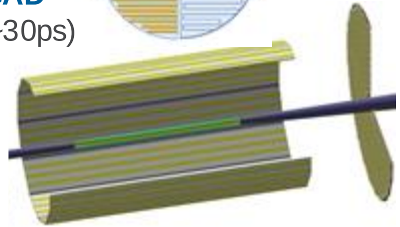
Dual-Radiator RICH (dRICH)



- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3б sep. at 50 GeV/c



AC-LGAD TOF (~30ps)



- Accurate space point for tracking ~30 um
- Forward disk and central barrel

Far-Forward and Far-Backward Detectors

	1st IR (IP-6)	2nd IR (IP-8)
Globally:	same accelerator highlights and challenges	
Geometry:	ring inside to outside	ring outside to inside
Crossing Angle:	25 mrad	35 mrad → more difficult to get acceptance at high h
	different blind spots different far-forward detector acceptances	
Luminosity:	same luminosity at both IRs same center-of-mass energy coverage	
IR-Design:	0.2 GeV < p_T < 1.3 GeV	2^{nd} Focus → improved low p_T acceptance at far-forward Roman Pots $x_L \sim 1 \rightarrow p_T \sim 0$
Experiment:	complementarity through different subdetector technologies	

Software and Computing

ePIC Software

Our software design is based on **lessons learned in the worldwide NP and HEP community** and a **decision-making process** involving the whole community. We will continue to work with the worldwide NP and HEP community.

Modular Simulation, Reconstruction, and Analysis Toolkit using tools from the NP-HEP community

MC Event Generators — Detector Simulations in Geant4 — Readout Simulation (Digitization) — Reconstruction in JANA2 — Physics Analyses

Edm4eic data model based on edm4hep and podio.
Geometry Description and Detector Interface using DD4hep.

Continuous Integration for Detector and Physics Benchmarks and Reproducibility

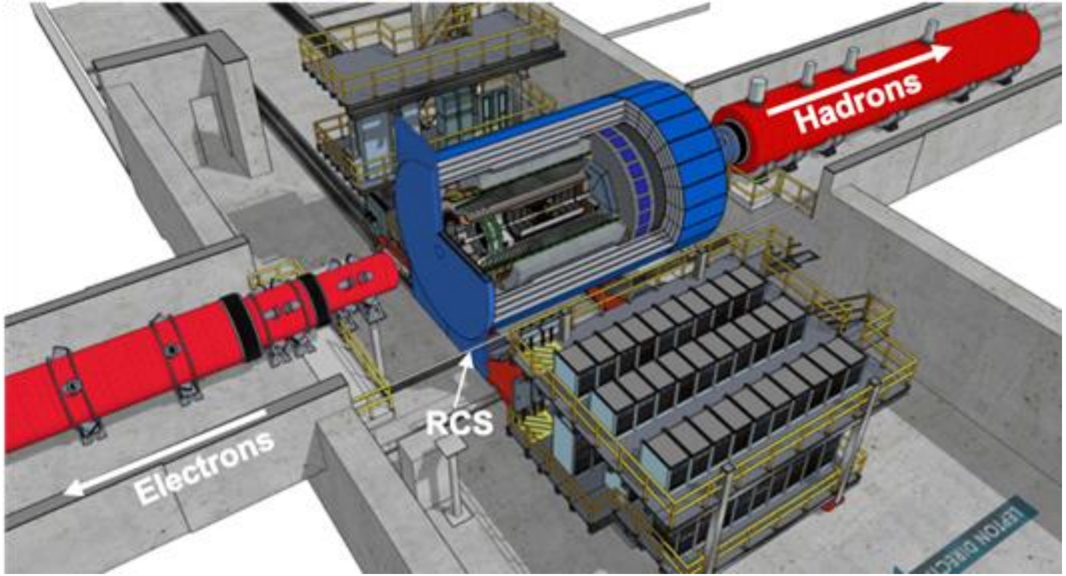
We are providing a production-ready software stack throughout the development:

- **Milestone**: Software enabled first large-scale simulation campaign for ePIC.

We have a good foundation to meet the near-term and long-term software needs for ePIC.

Optimize Physics Reach

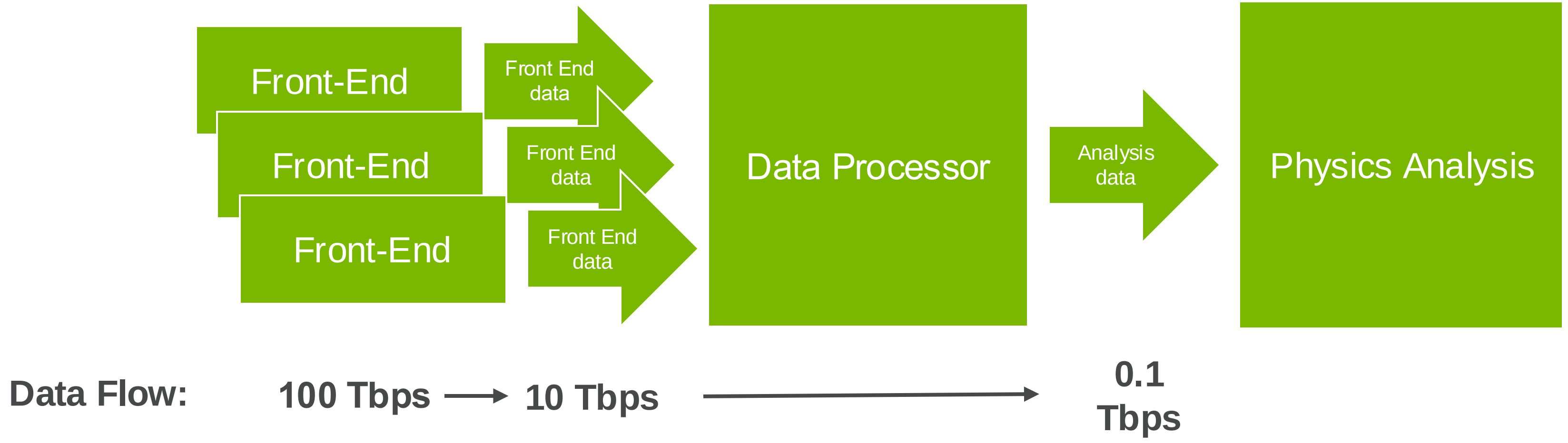
Integrated interaction and detector region (+/- 40 m)
Get ~100% acceptance for all final state particles, and measure them with good resolution. All particles count!



Compute-Detector Integration
Extend integrated interaction and detector region into detector readout (electronics), data acquisition, data processing and reconstruction, and physics analysis.

Compute-Detector Integration to Maximize Science

- **Problem** Data for physics analyses and the resulting publications available after O(1year) due to complexity of NP experiments (and their organization).
  - Alignment and calibration of detector as well as reconstruction and validation of events time-consuming.
- **Goal** Rapid turnaround of data for physics analyses.
- **Solution** Compute-detector integration using:
  - AI/ML for autonomous alignment and calibration as well as reconstruction in near real time,
  - Streaming readout for continuous data flow and heterogeneous computing for acceleration.



Bibliography

Pictures on Slide 2

1. **Rosalind Franklin's "Photo 51"**
    - **Citation**: IUCr Newsletter. Rosalind Franklin (1920–1958). Volume 28, Number 2. Available at: IUCr
2. **First Electron Microscope Image of a Virus**
    - **Citation**: Bawden, F. C., & Pirie, N. W. (1939). The visualisation of viruses using electron microscopy. Naturwissenschaften, 27, 292–299. DOI: 10.1007/BF01489805
3. **High-Resolution Ribosome Structure**
    - **Citation**: Ramakrishnan, V., Steitz, T. A., & Yonath, A. (2009). Nobel Prize in Chemistry for studies on the structure and function of the ribosome. Available at: LMB
4. **Hubble Deep Field**
    - **Citation**: NASA, Robert Williams, and the Hubble Deep Field Team (STScI). Hubble Deep Field. Available at: NASA
5. **Cryo-EM Image of Zika Virus**
    - **Citation**: Zhu, Y. et al. (2016). Cryo-EM analysis of the Zika virus. Science, 352(6284), 467–470. DOI: 10.1126/science.aaf5316
6. **First Image of a Black Hole**
    - **Citation**: The Event Horizon Telescope Collaboration et al. (2019). First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole. The Astrophysical Journal Letters, 875, L1. DOI: 10.3847/2041-8213/ab0ec7