Stony Brook University, USA, June 2-13, 2024
The 2025 CFNS-SURGE Summer Workshop on the Physics of the Electron-Ion Collider

Experimental Introduction to Electron-Ion Collider Physics

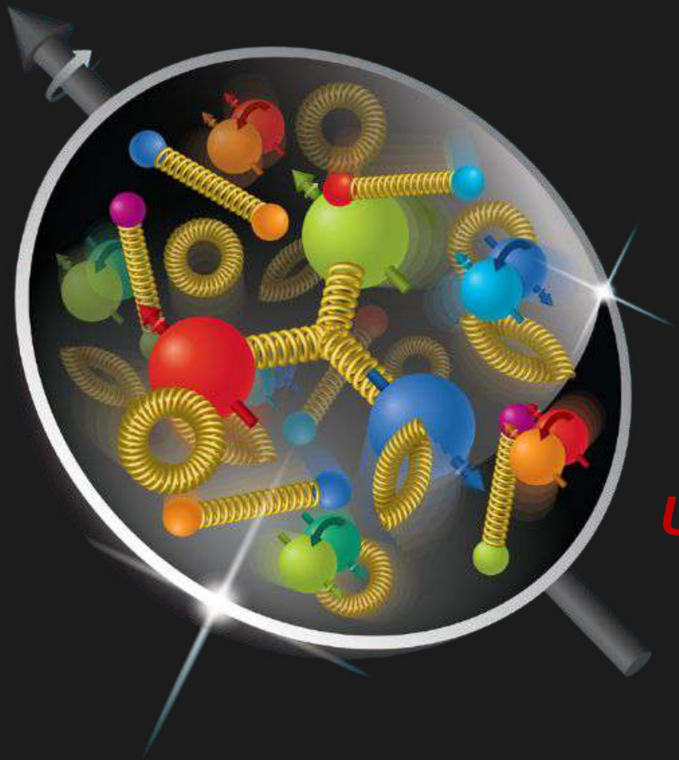
Lecture 2: Exploring Proton and Nuclear Structure at the EIC

Maria ŻUREK, Argonne National Laboratory

Argonne NATIONAL LABORATORY

(Selected) Open Questions that EIC will address

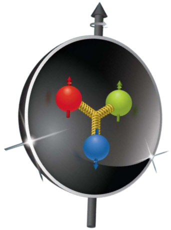
The EIC Physics Quest



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

Understanding the Glue that Binds Us All

Unraveling the Mystery of the Origin of the Proton Spin



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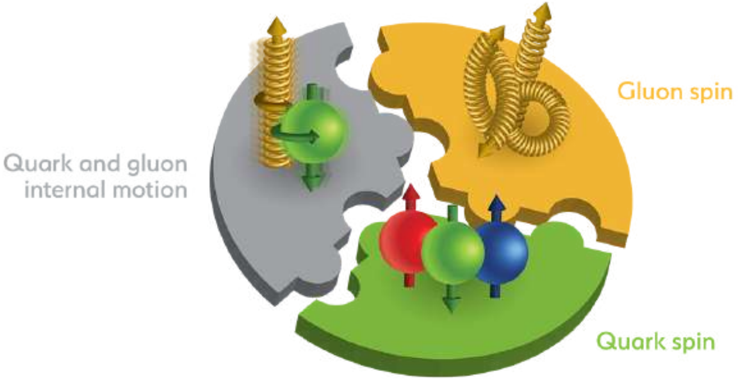
Proton Spin Puzzle



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

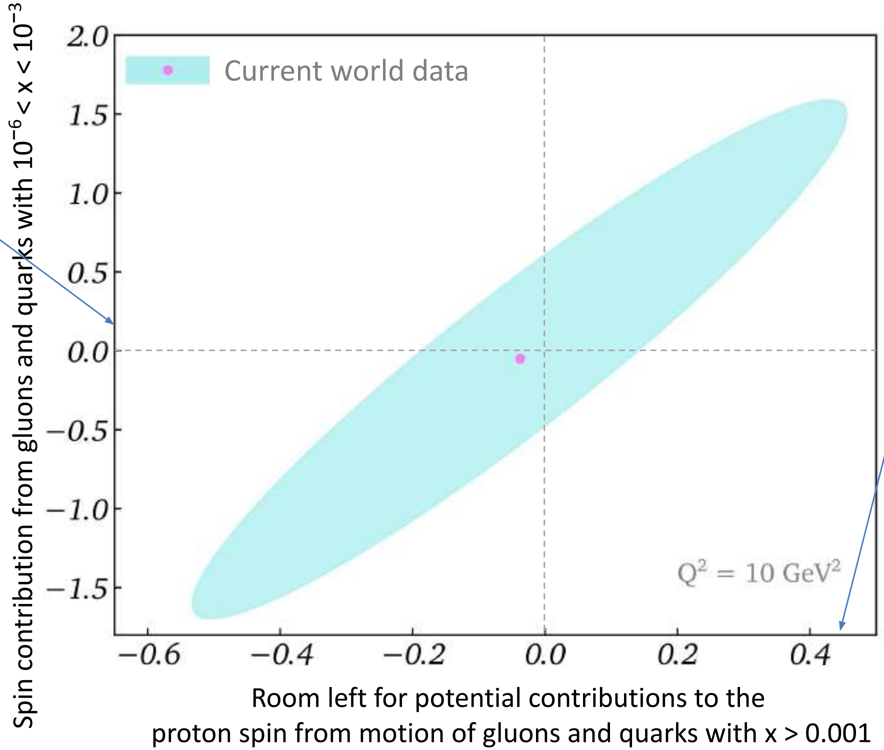
We now know that **quarks, gluons**, and **their motion** all contribute, but the full picture remains elusive

Pictures: adapted from Brookhaven National Laboratory

Origin of the Proton Spin - Unknown Components

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!



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

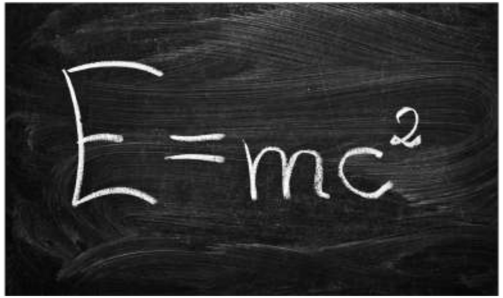
Close to zero—but with a huge uncertainty ranging from -100% to +80% of the total proton spin!

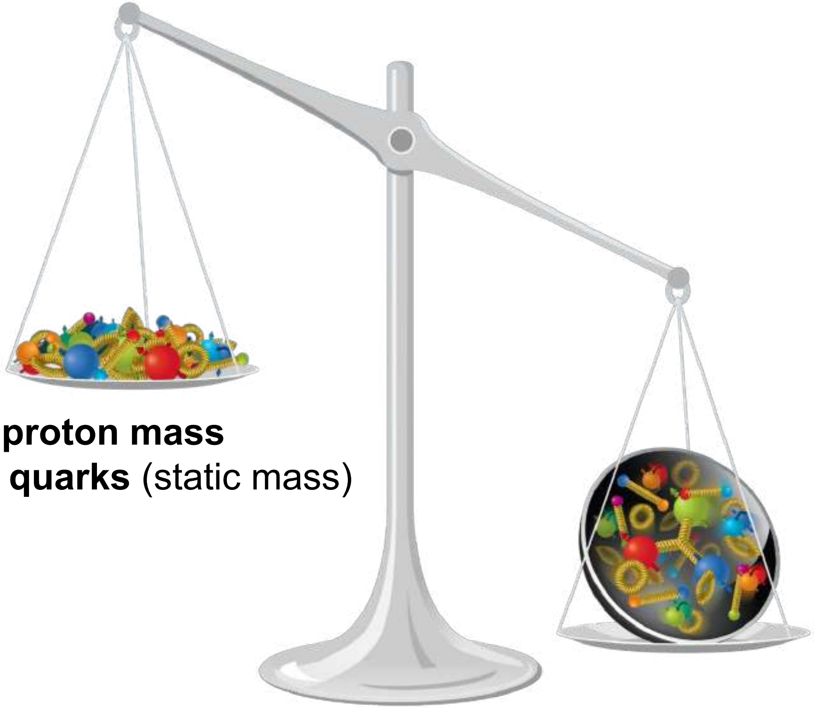
Pictures: adapted from arXiv:2007.08300

How do Protons and Neutrons Acquire Mass?

Gluons have no mass and **quarks are nearly massless**, but protons and nuclei are heavy, making up most of the visible mass of the Universe

Where does the mass of the visible world come from?





<1% proton mass from quarks (static mass)

99% from interactions

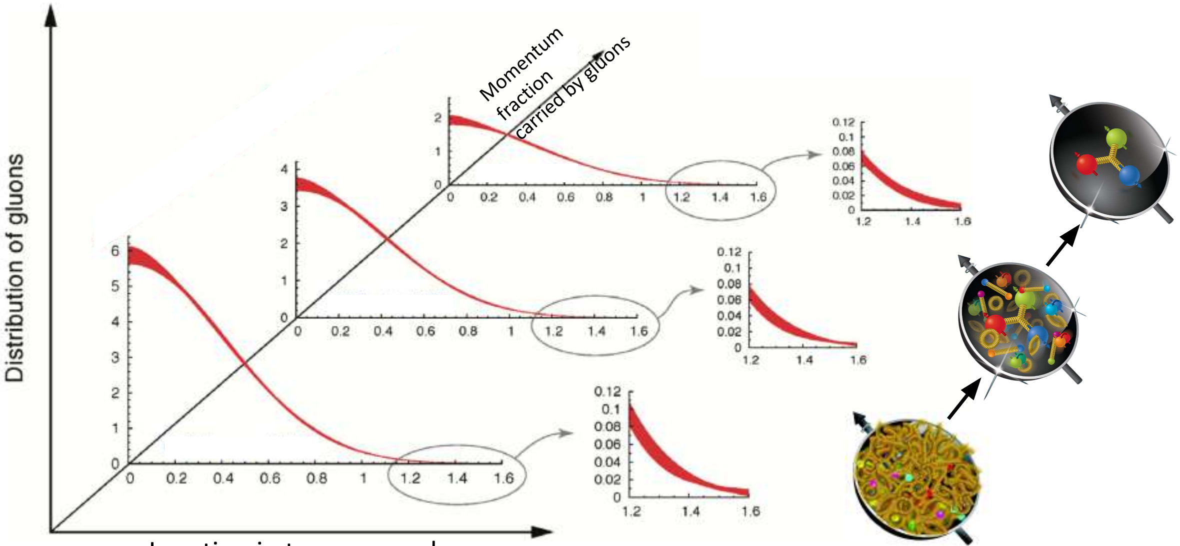
Our mass arises from the energy of the strong force between quarks and gluons!

3D Mapping of Gluons Inside Matter

EIC will provide the **first ever 3D images of gluons inside protons:**

- How do gluon interactions contribute to the **proton's mass**?
- How do they mediate the forces that **bind quarks together**?

- Analogous to how the discovery of DNA's double helix unveiled the structure and organization of genetic information

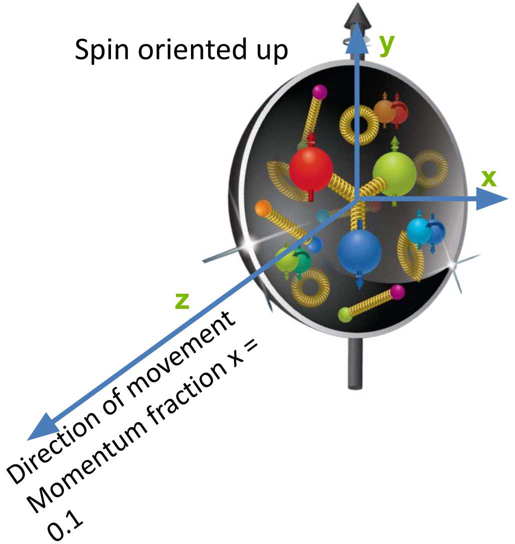


Location in transverse plane to the proton movement in fm (10^{-15} m)

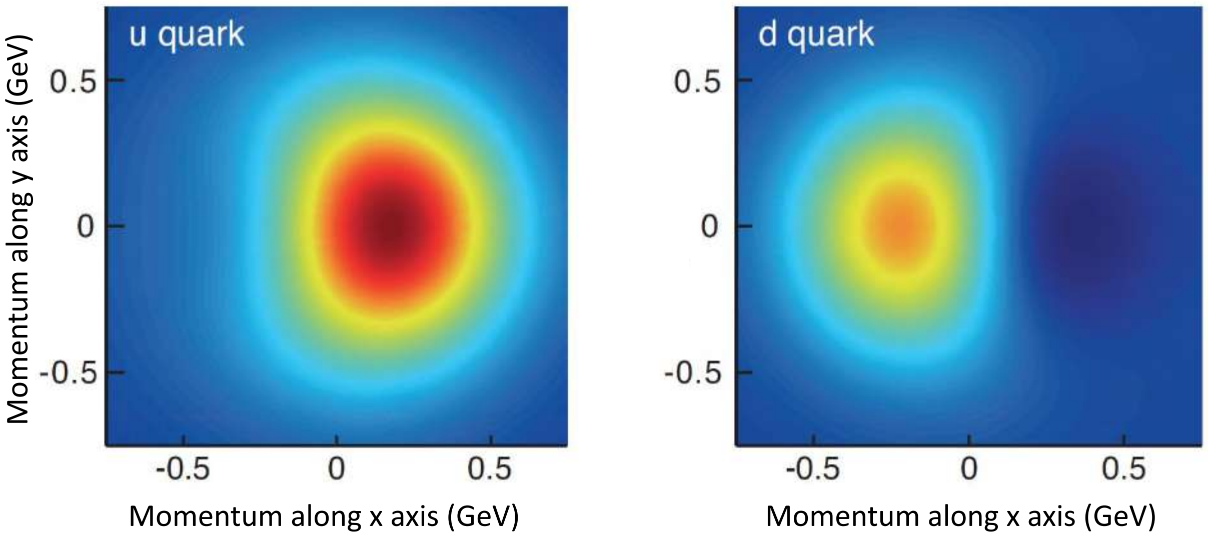
EIC will **3D map gluons inside protons** using special reactions that keep the proton intact and produce a quark-antiquark bound state

Motion of Gluons and Quarks Inside the Proton

The EIC will create the first 3D map of gluon and sea quark motion inside the proton, revealing their correlation with the proton's spin.



The color code indicates the probability of finding the up and down quarks



Current Understanding: Existing 3D maps only illustrate the motion of quarks, leaving the dynamics of gluons and sea quarks completely unexplored

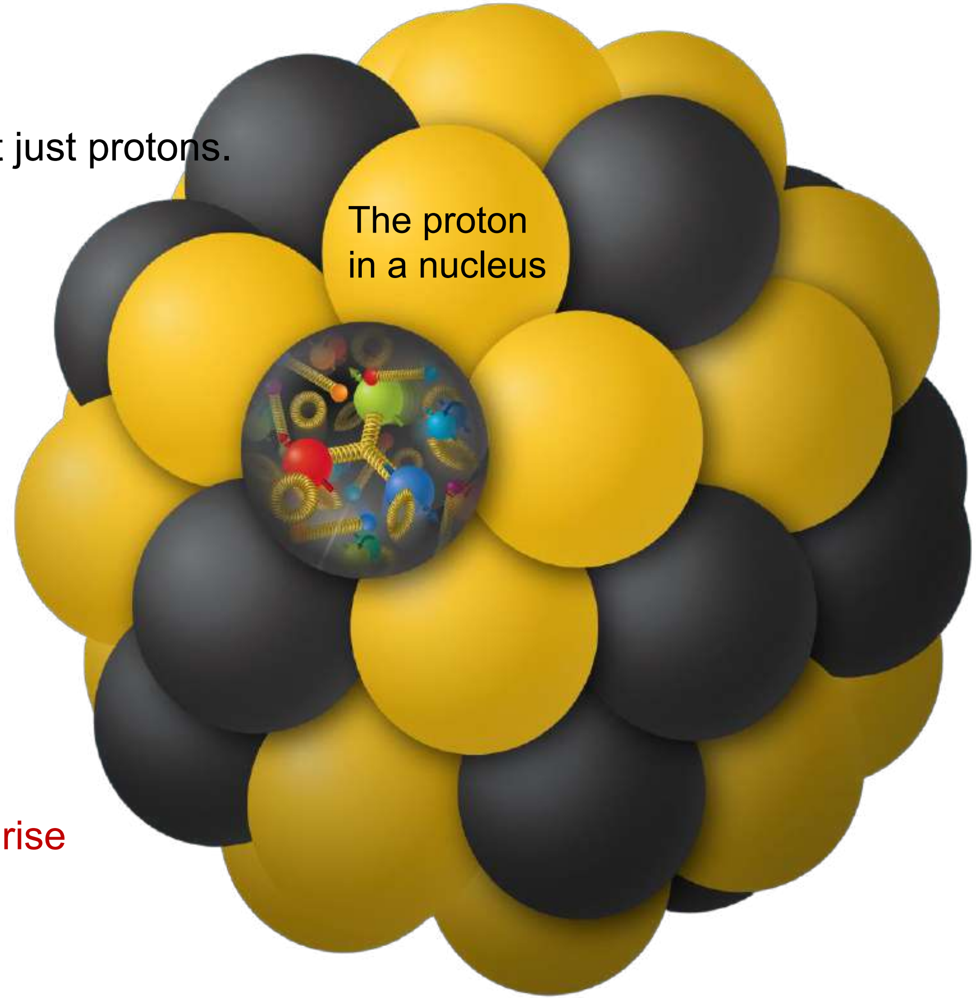
Pictures: adapted from Brookhaven National Laboratory and EIC White Paper

Heart of Nuclear Matter

We are made of atoms, with heavier nuclei, not just protons.

The proton (1980s)

The proton (2020s)



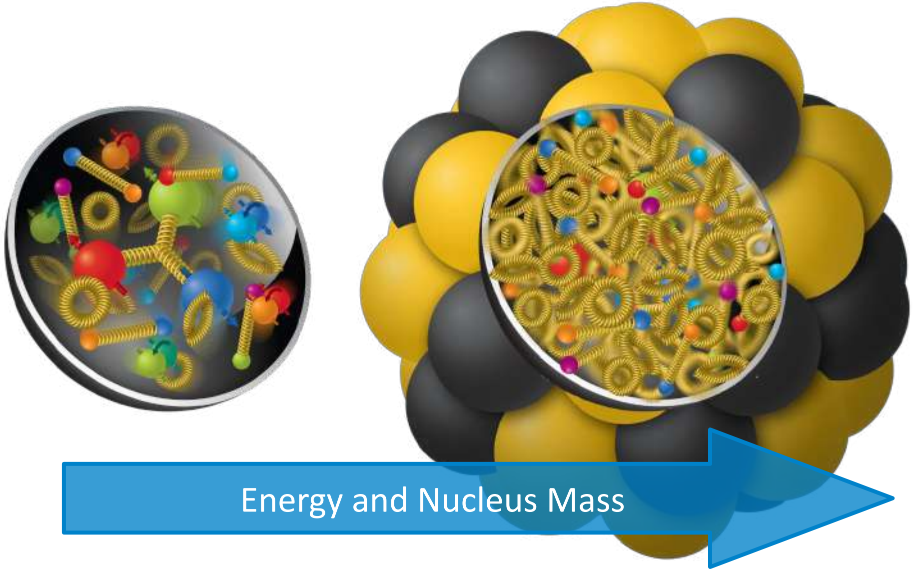
How does a high-density nuclear environment affect the behaviors of quarks and gluons?

The EIC will provide a complete view of the nucleus with insights into interactions that give rise to the forces binding protons and neutrons together in nuclei

Pictures: adapted from Brookhaven National Laboratory

New State of Gluonic Matter

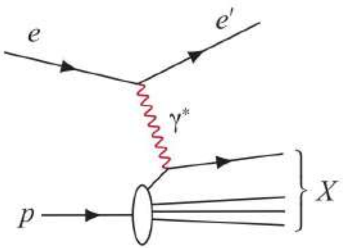
- High-energy protons are packed with **increasing numbers of gluons**
- At extreme densities, gluon multiplication halts, **giving rise to a new state of matter**—this is gluon saturation
- **Heavy ion beams** at the EIC are key to creating the extreme conditions needed to study and **magnify this effect**



The EIC will probe the unexplored dense gluon environments, potentially unveiling new states of matter and deepening our understanding of the fundamental forces that bind everything in the visible Universe

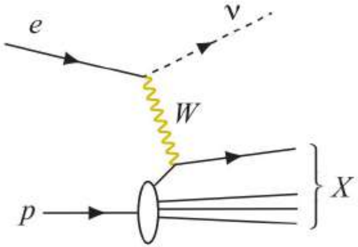
Pictures: adapted from Brookhaven National Laboratory

Experimental Access EIC Physics



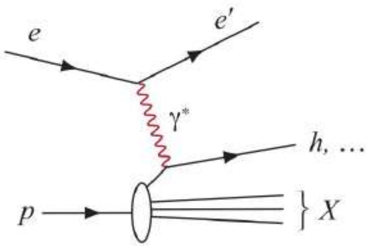
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



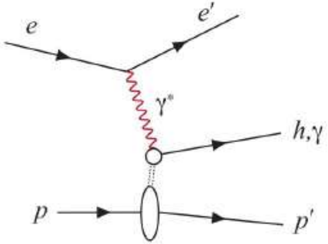
Charged Current DIS

- 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

Case Study: Proton Spin

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:

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

Quark helicity

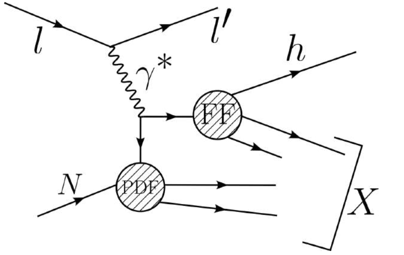
Gluon helicity

Quark canonical orbital angular momentum

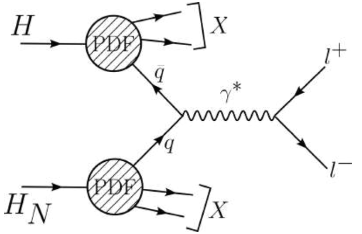
Gluon canonical orbital angular momentum

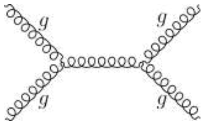
+ OAM (Ji's) from DVCS and DVMP

(SI)DIS



hadron-hadron processes





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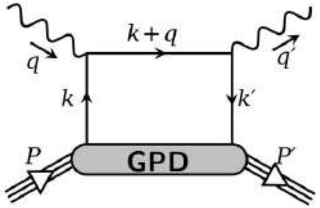
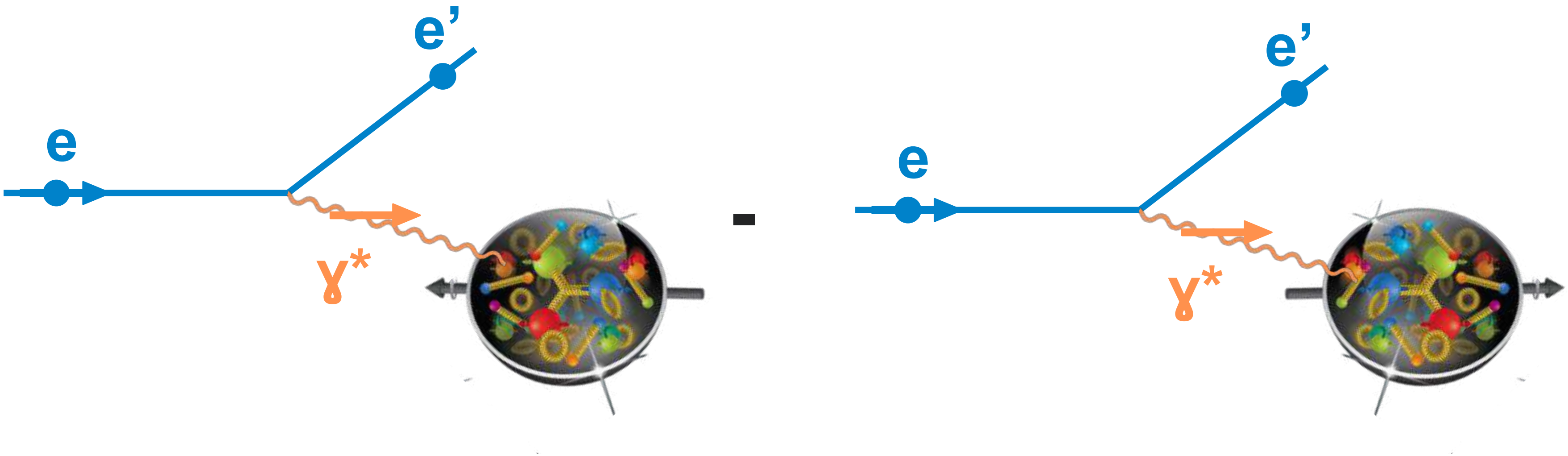


Case Study: Extracting $g_1(x, Q^2)$ via A_{LL}



Reaction: Polarized DIS
Access through: Difference of cross-sections with different longitudinal spin orientation of e and proton
Observable: Longitudinal double-spin asymmetry A_{LL}
Goal: Extract the spin-dependent structure function $g_1(x, Q^2)$
Key physics: Quark and gluon spin contributions to the proton's total spin

Access to helicity structure function?

Unpolarized DIS Cross Section

$$\frac{d^2\sigma_{\text{unpol}}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\cdot\left[y^2 F_1(x,Q^2) + \left(1 - y - \frac{M^2x^2y^2}{Q^2}\right)F_2(x,Q^2)\right]$$

Both lepton and nucleon are longitudinally polarized, additional spin-dependent part:

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

$\nu = E - E'$

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

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

In (LO QCD) Quark Parton Model

Quark helicity distribution

Why Measure Asymmetries?

Cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{1}{\mathcal{L}_{\text{int}}} \cdot \frac{N_{\text{obs}}}{\Delta x\,\Delta Q^2 \cdot \epsilon \cdot A} \cdot C_{\text{rad}} \cdot C_{\text{bin}}$$

- C_{rad}: Radiative QED effects
- C_{bin}: Bin smearing / unfolding
- ϵ: Detector + reconstruction efficiency
- A: Acceptance
- $\mathcal{L}_{\text{int}}$: Luminosity from QED process
- Background and trigger corrections as needed

Why Measure Asymmetries?

Instead of cross sections, we measure **asymmetries**:

- Cleaner (many systematics cancel)
- Don’t require absolute luminosity

electron and proton spins anti-aligned

electron and proton spins aligned

$$A_{LL} = \frac{\sigma^{\rightarrow\Rightarrow} - \sigma^{\rightarrow\Leftarrow}}{\sigma^{\rightarrow\Rightarrow} + \sigma^{\rightarrow\Leftarrow}}$$

$A_1(x, Q^2) \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$ with known kinematic factor D:

$$A_{LL} \approx D(y) \cdot A_1(x, Q^2)$$

$D(y) = \frac{y(2-y)}{1+(1-y)^2}$ *(depolarization factor)*

proton and γ* spins anti-aligned

proton and γ* spins aligned

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

What Do We Measure?

number of scattered electrons with particular electron-proton spin orientations

$$A_{\parallel} = \frac{1}{P_B P_z} \cdot \frac{\frac{N^{\overset{\rightarrow}{\Leftarrow}}}{\mathcal{L}^{\overset{\rightarrow}{\Leftarrow}}} - \frac{N^{\overset{\rightarrow}{\Rightarrow}}}{\mathcal{L}^{\overset{\rightarrow}{\Rightarrow}}}}{\frac{N^{\overset{\rightarrow}{\Leftarrow}}}{\mathcal{L}^{\overset{\rightarrow}{\Leftarrow}}} + \frac{N^{\overset{\rightarrow}{\Rightarrow}}}{\mathcal{L}^{\overset{\rightarrow}{\Rightarrow}}}}$$

spin dependent luminosity: reduced to spin dependent relative luminosity:

$$A_{\parallel} = \frac{1}{P_B P_z} \cdot \frac{N^{\Rightarrow\Rightarrow} - R \cdot N^{\Rightarrow\Leftarrow}}{N^{\Rightarrow\Rightarrow} + R \cdot N^{\Rightarrow\Leftarrow}}$$

$R = \mathcal{L}^{\Rightarrow\Rightarrow} / \mathcal{L}^{\Rightarrow\Leftarrow}$: spin-dependent relative luminosity

beam polarization

electron polarization

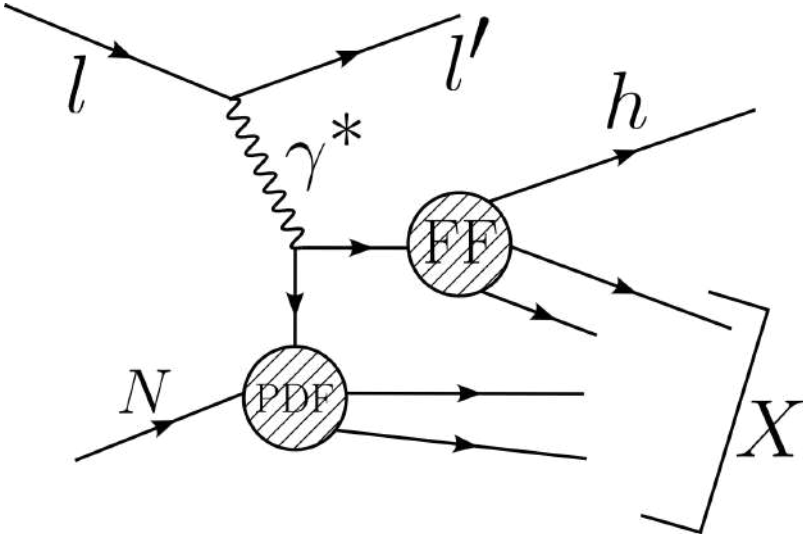
Polarization measurements will be covered next week by Oleg Eyser

Flavor Separation

Flavor Separation

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 $z = E^h/\nu$



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

Flavor Separation

Photon-nucleon asymmetry for SIDIS

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

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

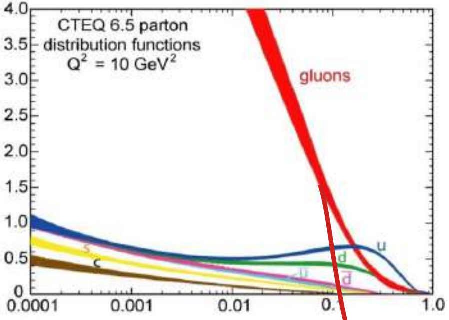
Experimental access through double spin asymmetries (analogous to DIS)

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

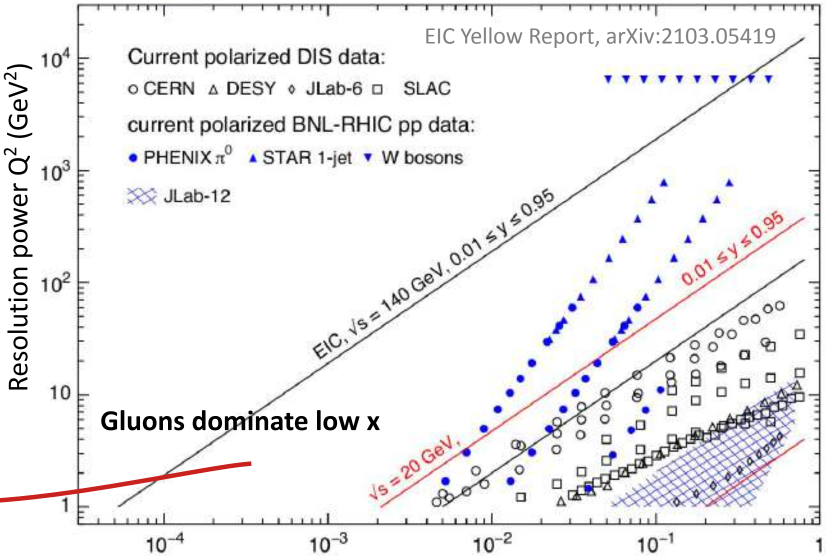
Kinematics

What Kinematics Do We Access?

Quarks and gluons momentum fraction times their density inside the proton



Parton momentum fraction x



Parton momentum fraction x

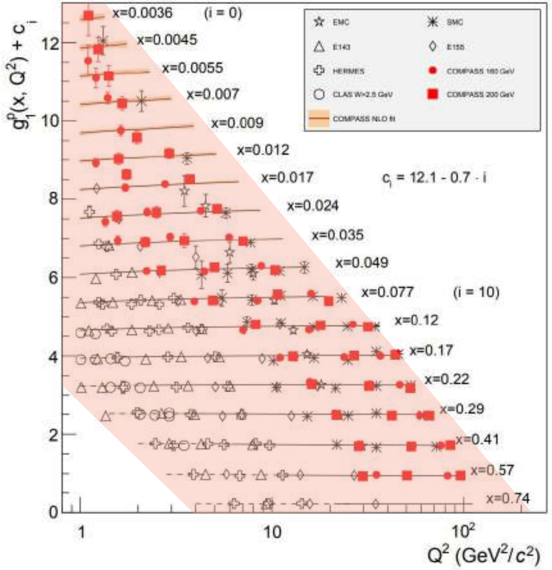
Larger center of mass energy

Larger center of mass energy and luminosity

Pictures: adapted from Brookhaven National Laboratory

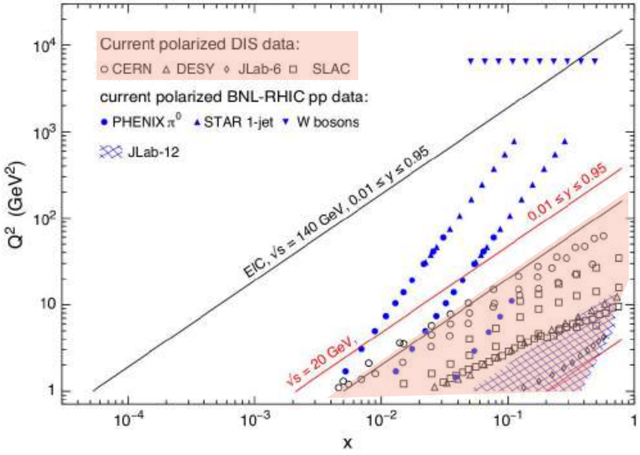
What Kinematics Do We Access?

COMPASS, PLB 753 (2016) 18



Current DIS Data:
Down to x ≈ 0.005
Q^2 ≈ 1-100 GeV^2

EIC, Yellow Report



EIC:
Down to x ≈ 10^{-4}
Q^2 ≈ 1-10^3 GeV^2 !

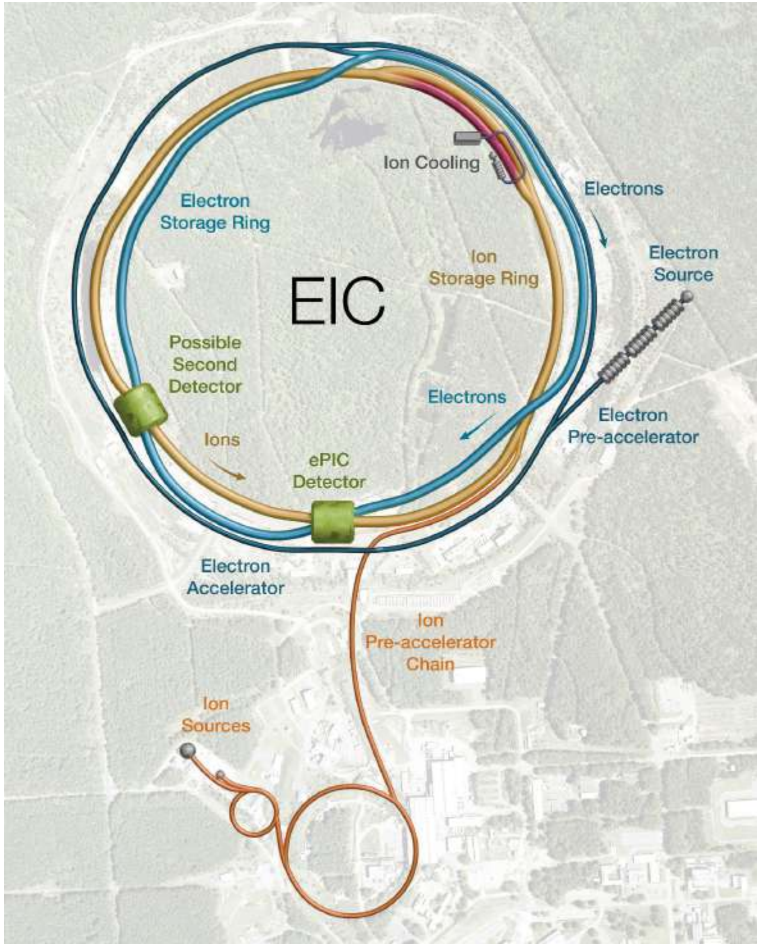
- Access to gluon spin through g_1 scaling violation
- different √s settings to maximize kinematic coverage

M. Żurek

Experimental Requirements

The EIC Facility

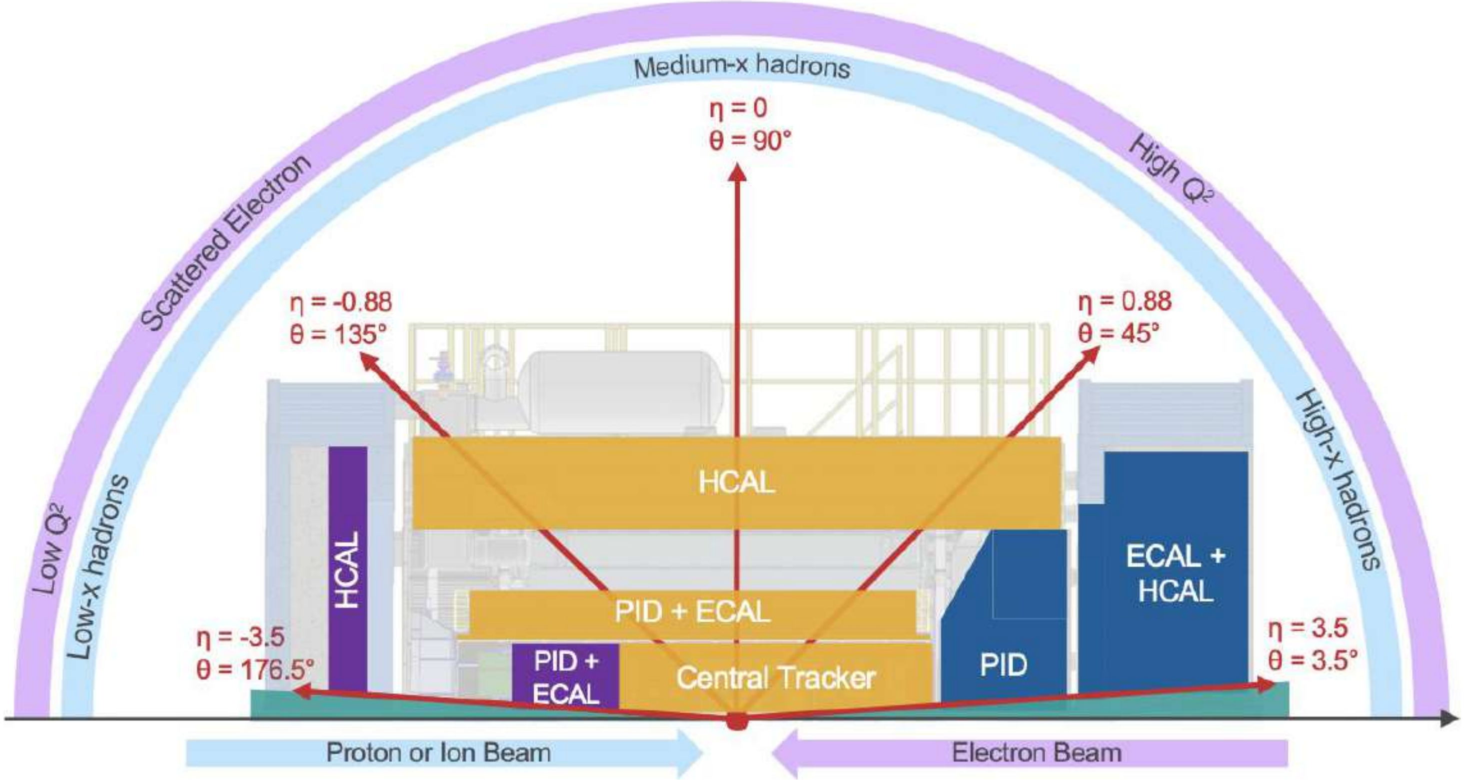
- The **only collider project anticipated in the near term**, ensuring cutting-edge exploration for years to come
- **Breakthrough precision**: Delivers luminosities 100 to 1000 times greater than HERA
- Explore QCD landscape over **large range of Q^2 and quark/gluon density (1/x)**

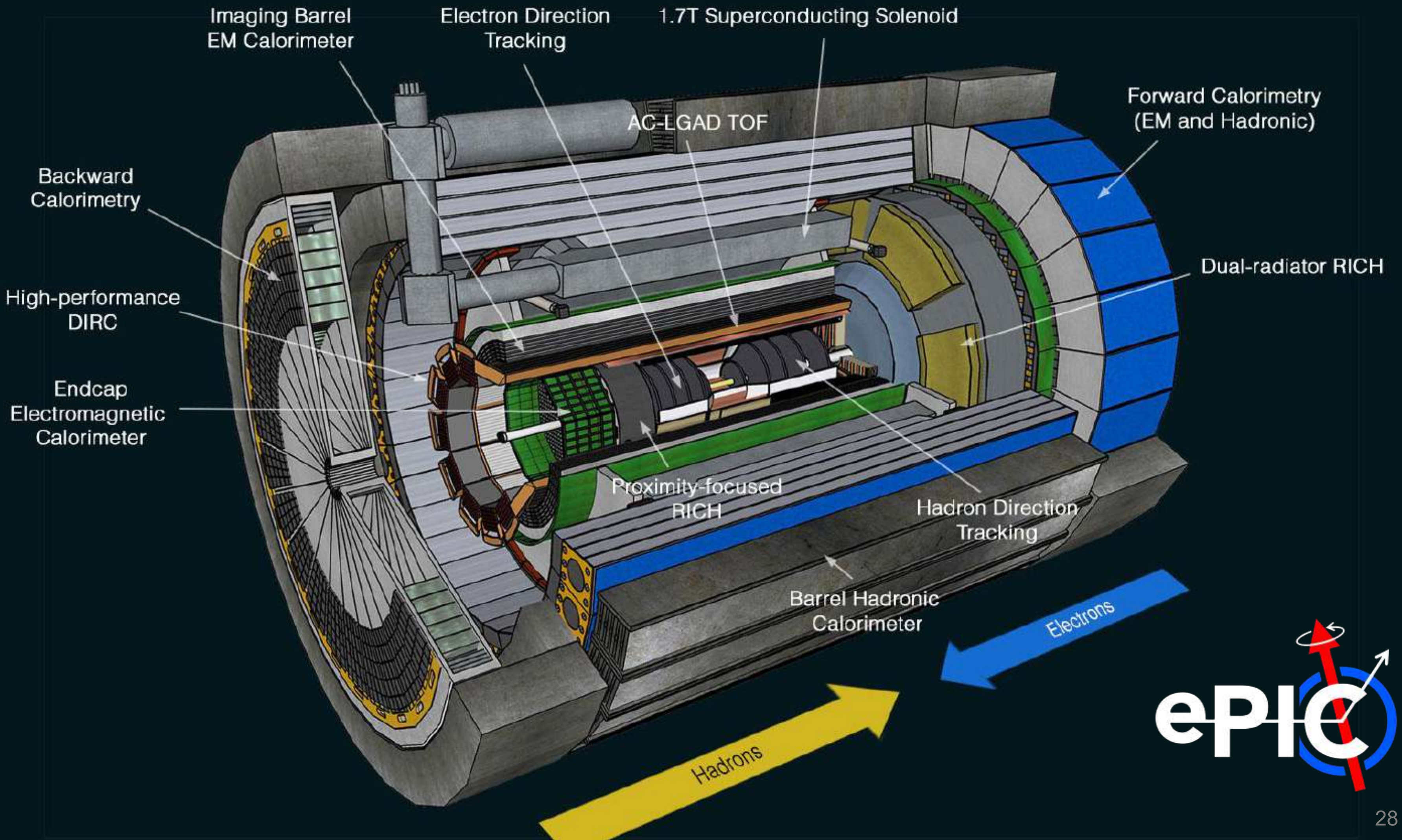


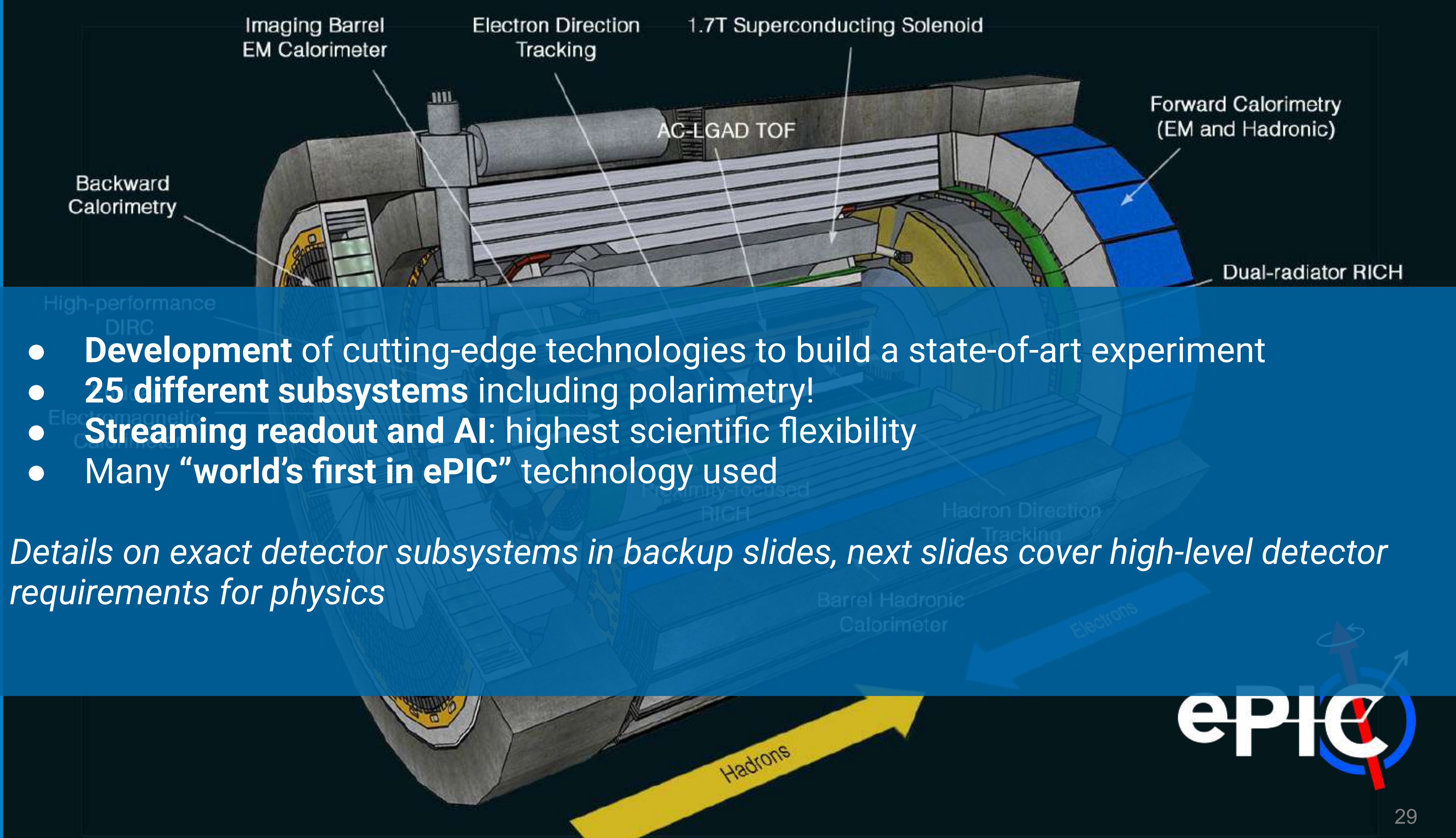
- **Spin-controlled collisions**: Both electrons and protons/light nuclei can be polarized, enabling unique spin-related studies
- Handles **nuclear beams** from light nuclei like deuterium up to heavy ions such as U
- Equipped with a **cutting-edge detector**, designed for high-precision data collection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

Picture: EIC Project Sharepoint

Proton Spin and ePIC Detector Requirements




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
ePIC



- **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

Proton Spin and ePIC Detector Requirements

Information on $\Delta\Sigma$ and ΔG

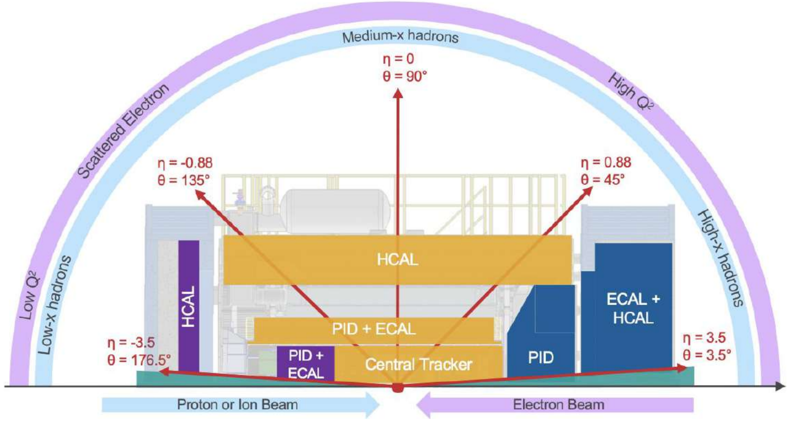
Longitudinally polarized e^- and p for over a wide range in center-of-mass energy (x-Q^2 coverage)

Low-x performance:

- Good EM calo in barrel region
- Superior in backward region
- 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)

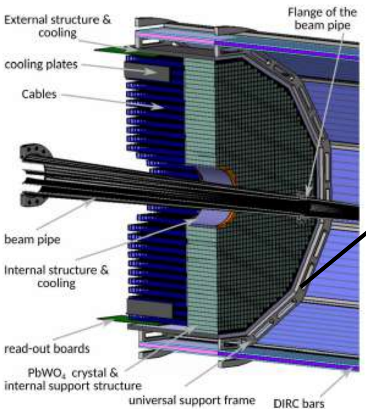
Access to Orbital Angular Momentum - GPD measurements

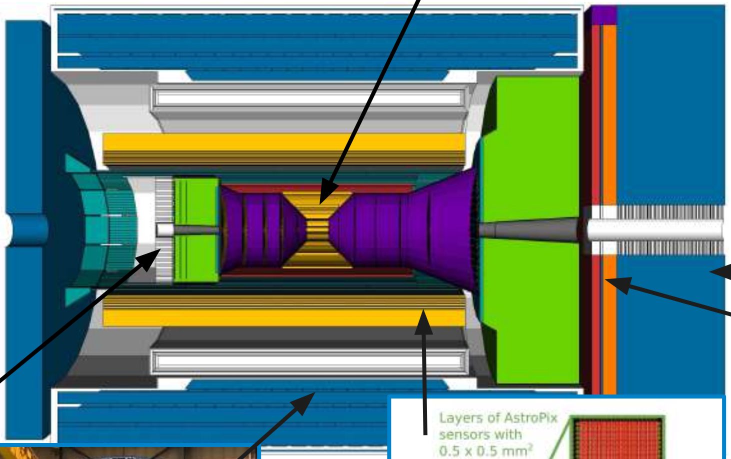
- Demanding program requiring high luminosity and detection of the forward-going protons scattered under small angles (*Forward-Backward Detectors discussed yesterday by Thomas*)

Calorimetry Requirements

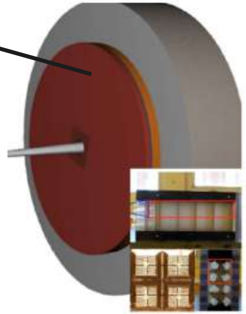
Electron momentum resolution - dominated by tracker in central region: Si MAPS Trackers + Micro Pattern Gas Detectors

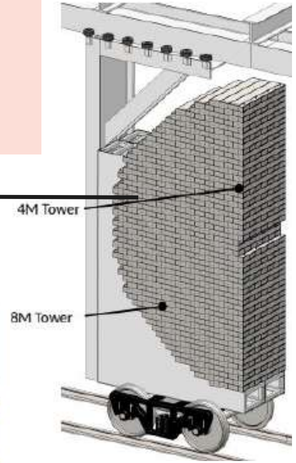
Superior EM energy resolution from Backwards EMCal - $PbWO_4$ crystals



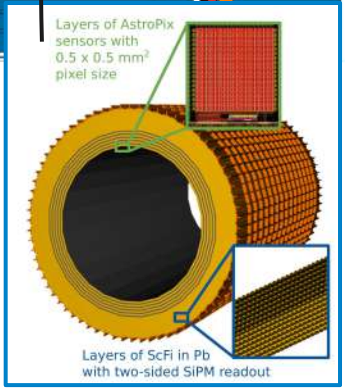


High granularity W/SciFi EMCal and longitudinally separated HCAL with high-η insert for high precision jet (hadronic remnant) reconstruction





Barrel HCAL (sPHENIX re-use)

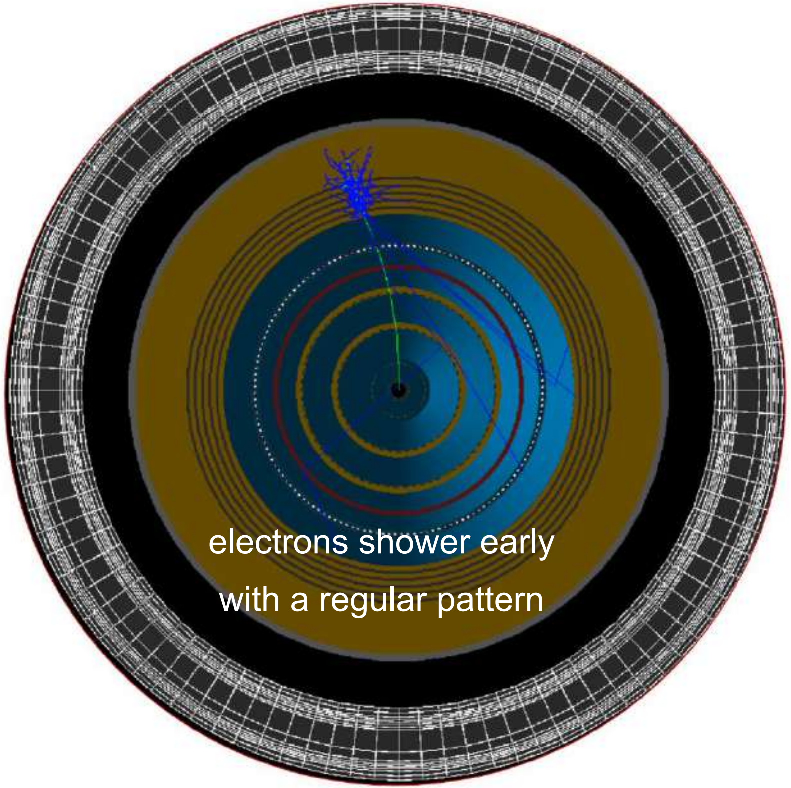


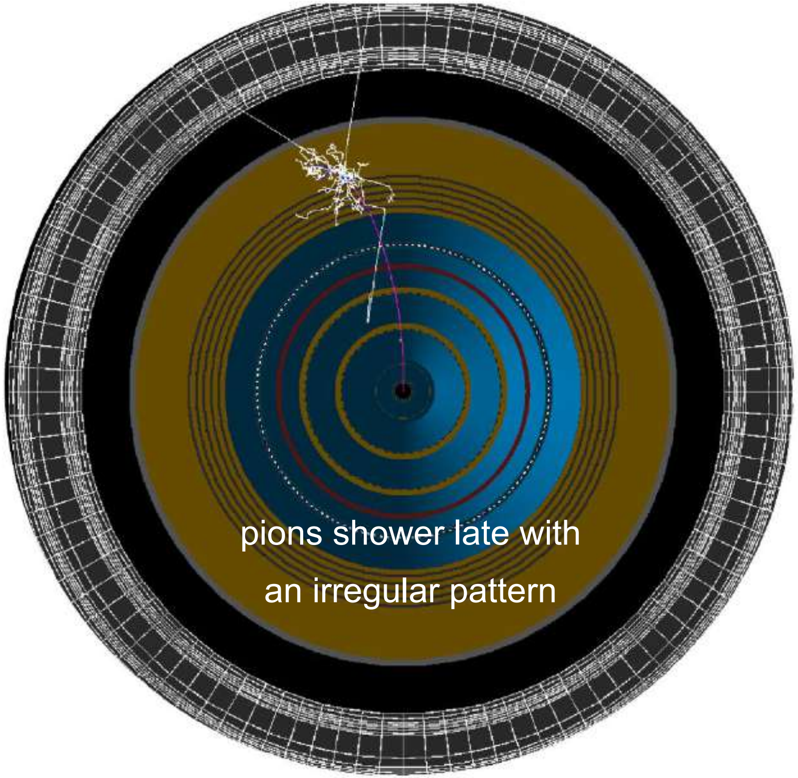
Barrel Imaging ECAL with good energy resolution from SciFi/Pb and high e/π separation supported by Si layers

M. Żurek

Particle Identification in Barrel

electron-pion: method





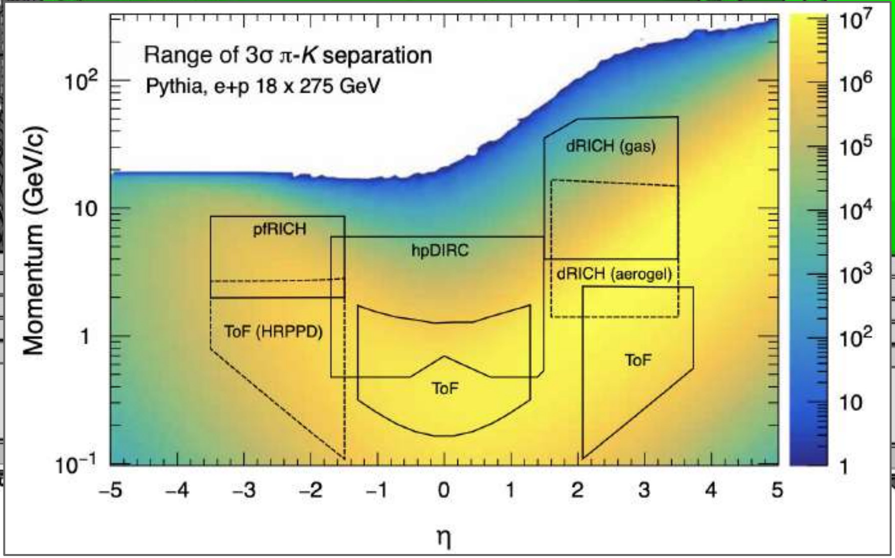
*BIC geometry rendering with an electron and pion shower from simulations with **SciFi/Pb** and **AstroPix layers***

Particle Identification Requirements

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

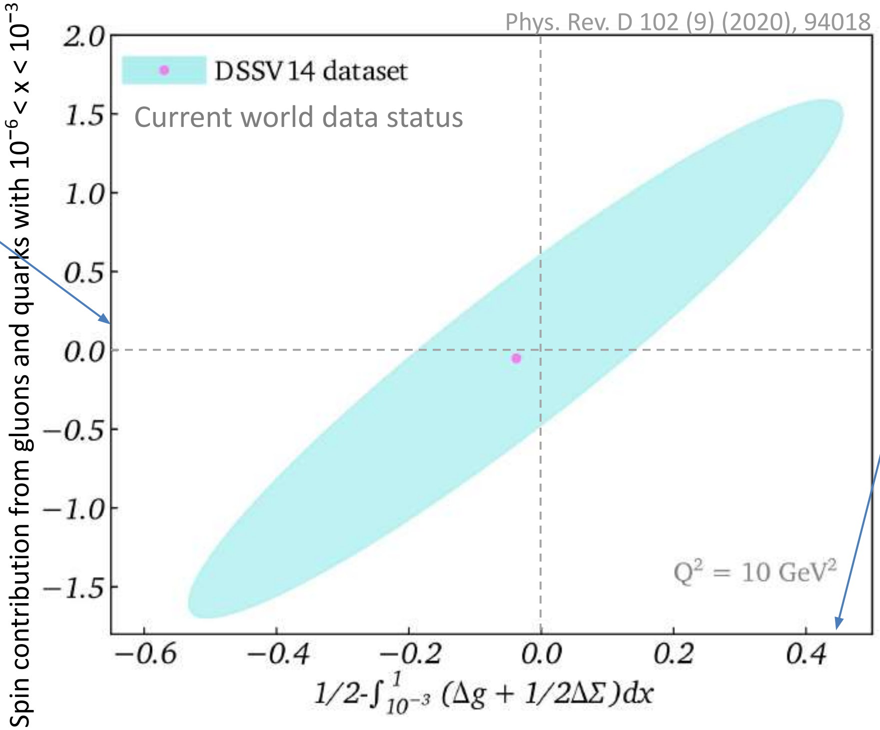


Impact

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?

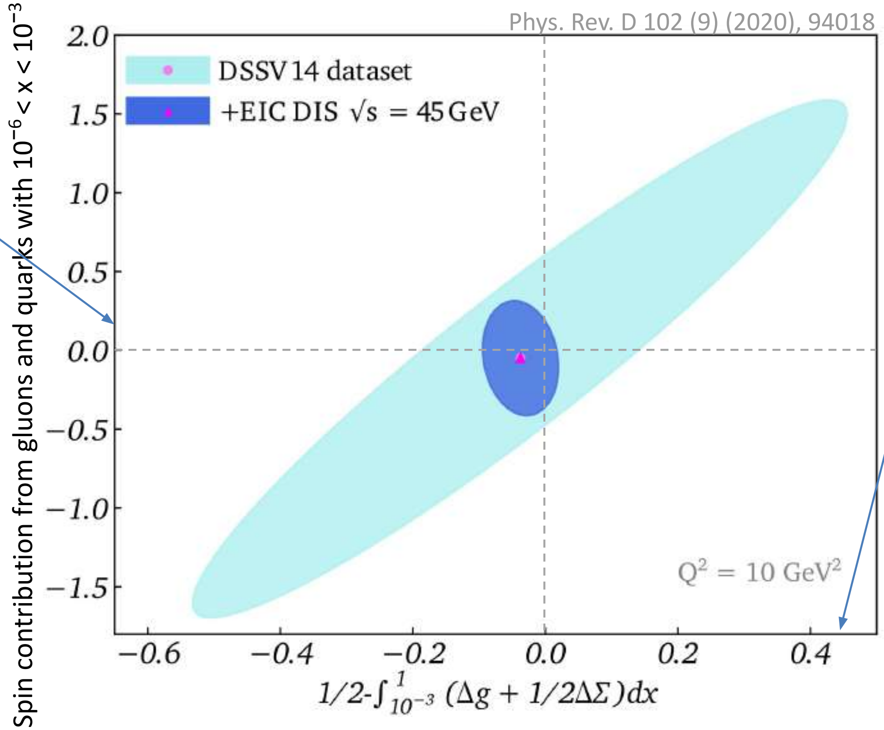
Close to zero—but with a huge uncertainty ranging from -100% to +80% of the total proton spin!

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?

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



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?

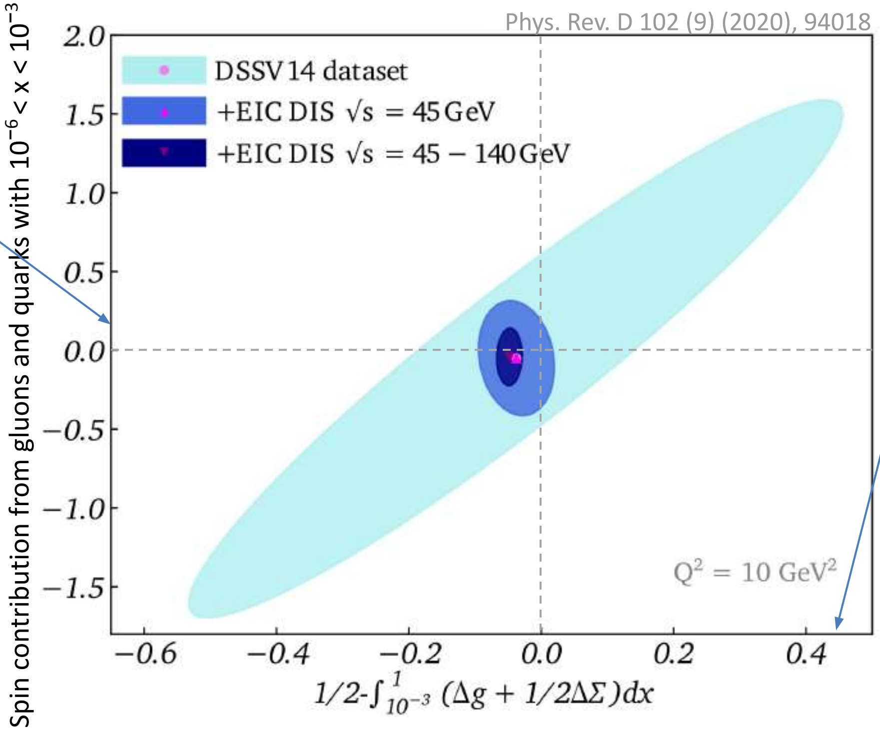
Pictures: adapted from arXiv:2007.08300

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!

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



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

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 ~ 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

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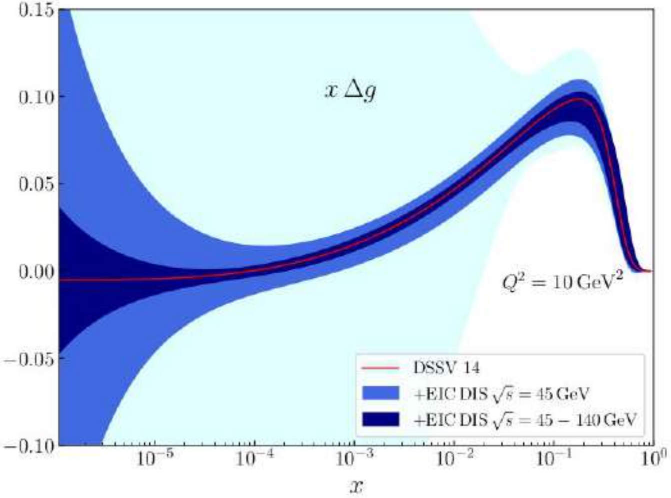

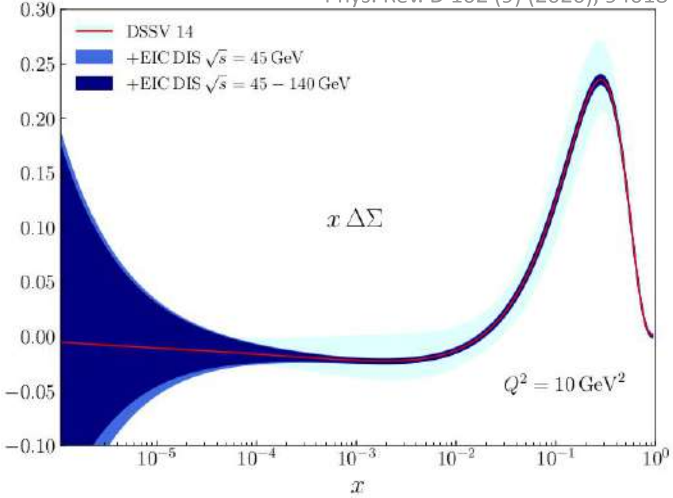

Impact of the projected EIC DIS A_{LL} pseudodata ($L = 10\ \mathrm{fb}^{-1}$) on the gluon helicity and quark singlet helicity

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

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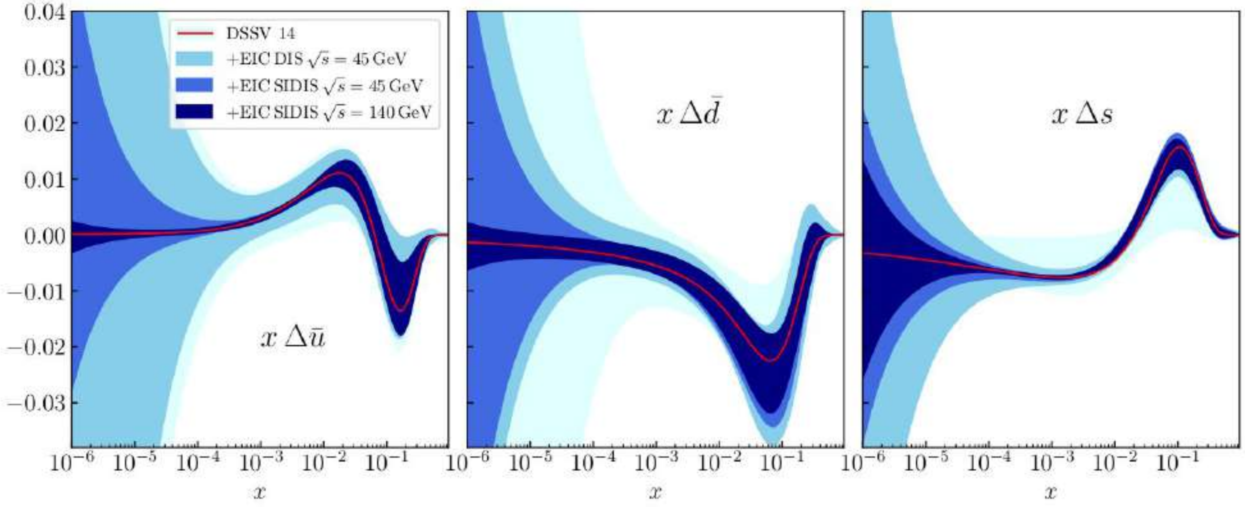


The EIC Is a Candystore of Physics Opportunities

The EIC Is a Candystore of Physics Opportunities

- Today we focused on a **few case studies**
- But this is just the beginning...
- The EIC will enable insight into glue that binds us all:
  - 3D **momentum-space imaging** (TMDs)
  - 3D **spatial imaging** (GPDs, DVCS)
  - Precision studies of **nuclear effects** and **saturation**
  - Mapping **gluon and sea quark** distributions at small x
  - Explorations of **color charge propagation**, **hadronization**, and more

Summary

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

Our current knowledge about the structure of matter is a **mysterious dark room** even after decades of studies

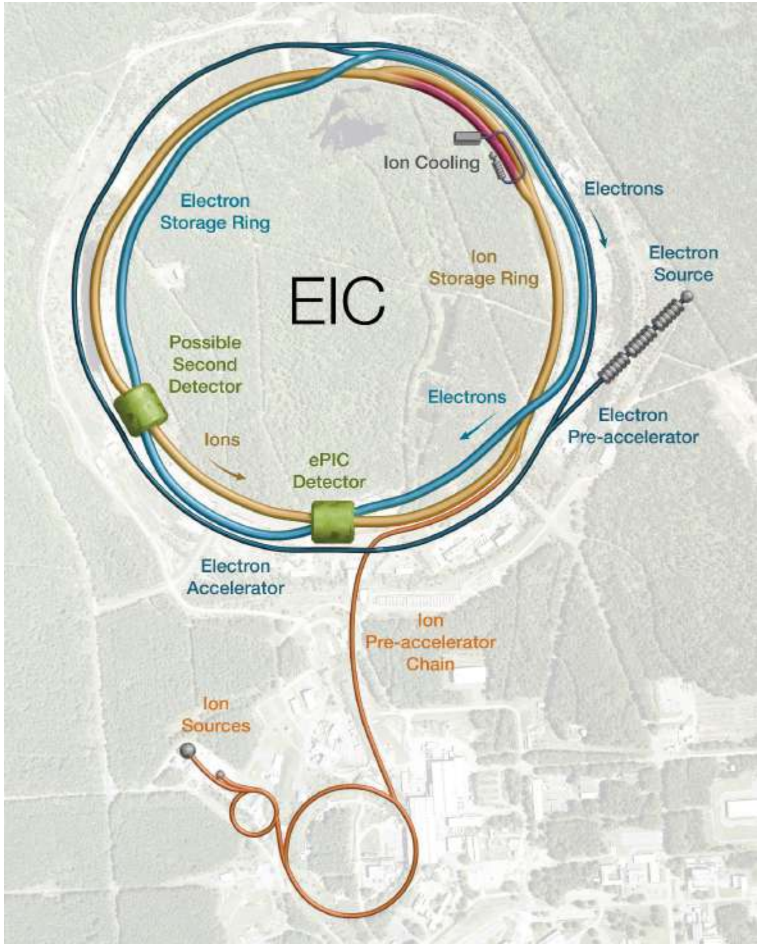
- We can see shadows and shapes with some important bright spots with existing tools
- With the EIC, we can turn on the light and reveal the hidden details inside

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 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

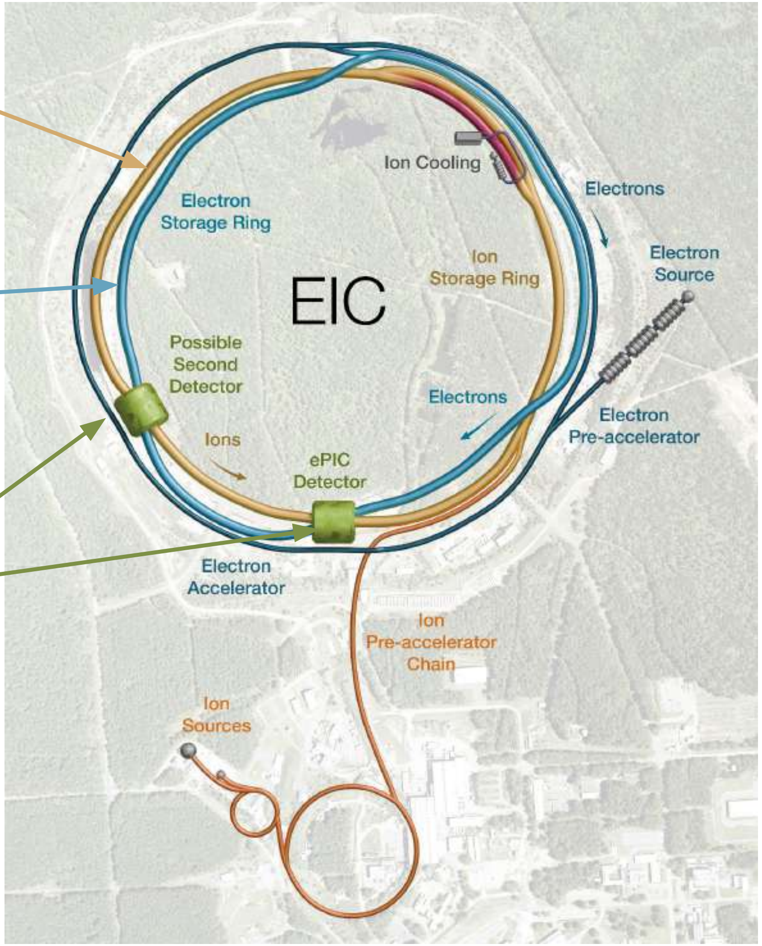
Hadron Storage Ring (RHIC Rings)
41, 100-275 GeV

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



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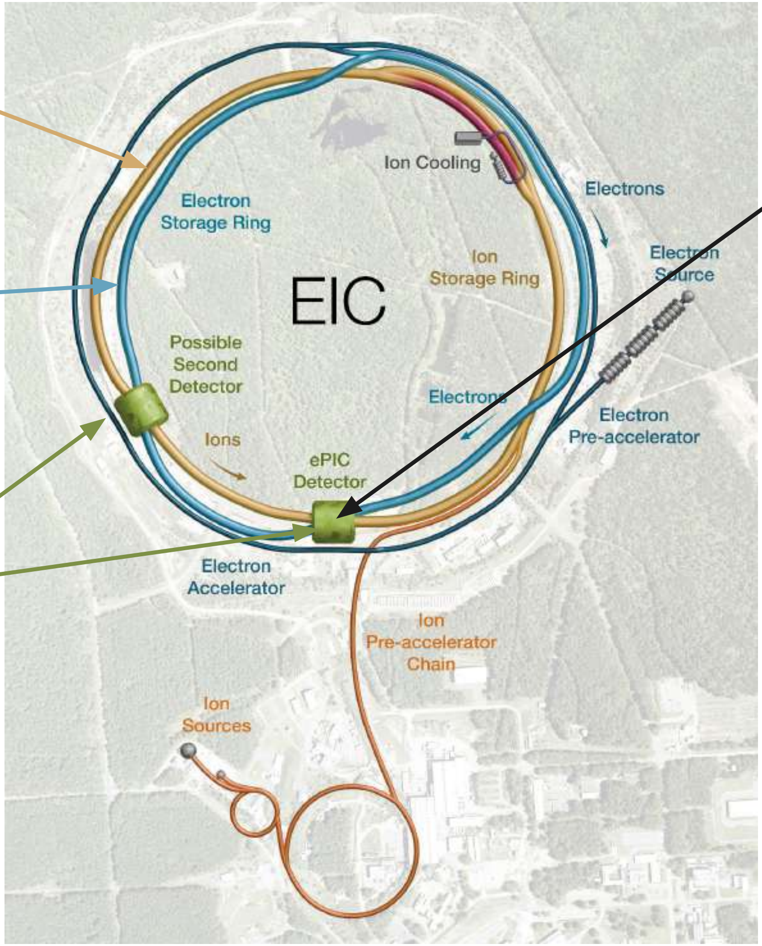


Detector located at 6 o'clock of the EIC Ring

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

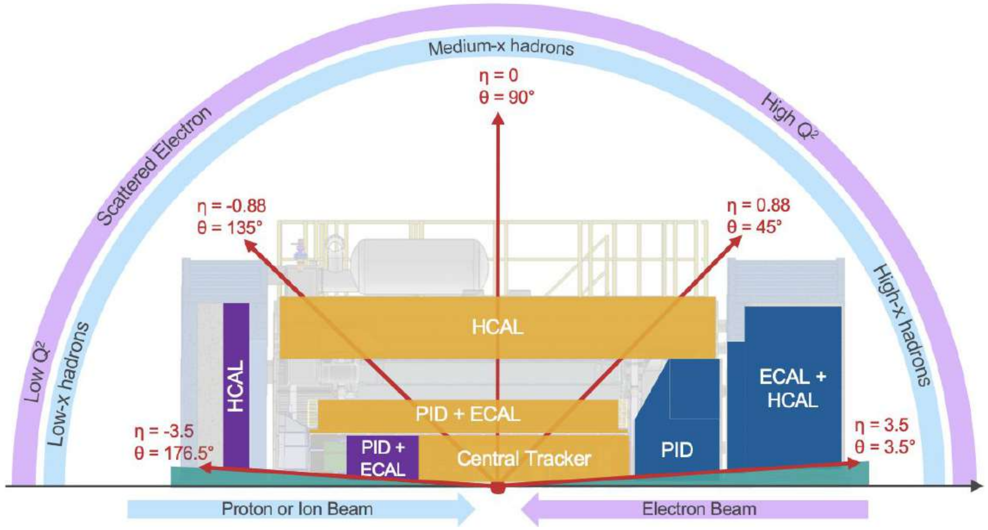
- 177 Institutions, 26 countries, 4 world's region
- Currently: > 850 collaborators (from 2024 survey)

M. Żurek

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

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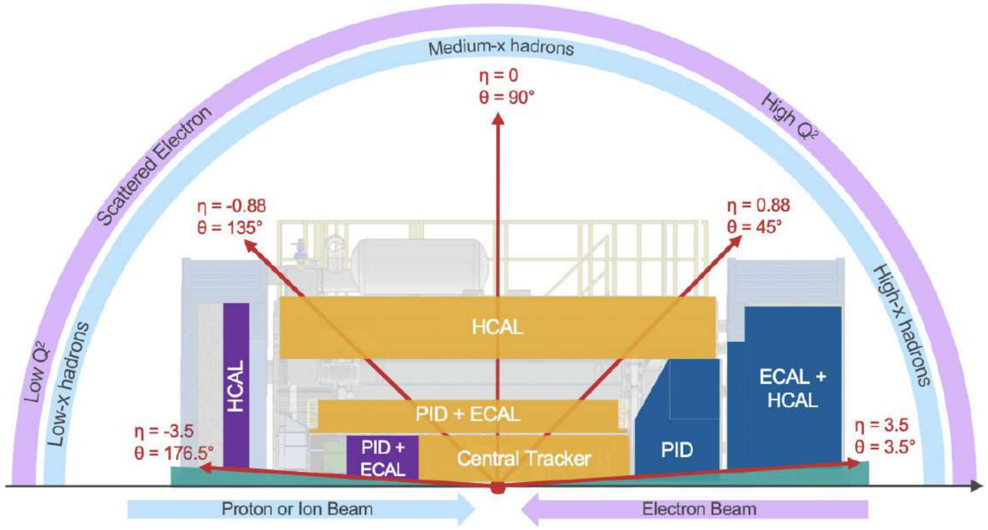


Large center-of-mass energy range: 29-140 GeV

- Large detector acceptance

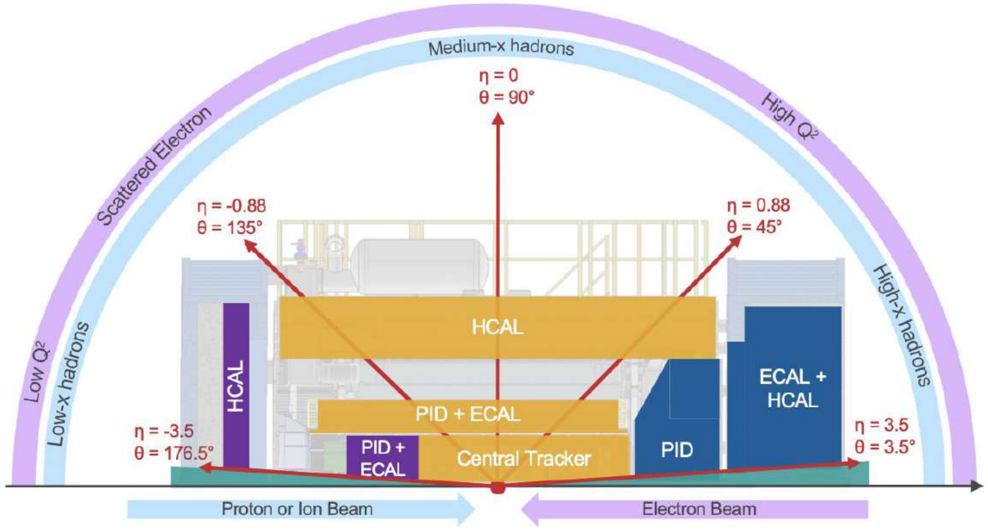
Asymmetric beams

- **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

Picture: Yellow Report

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

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- Large detector acceptance

Asymmetric beams

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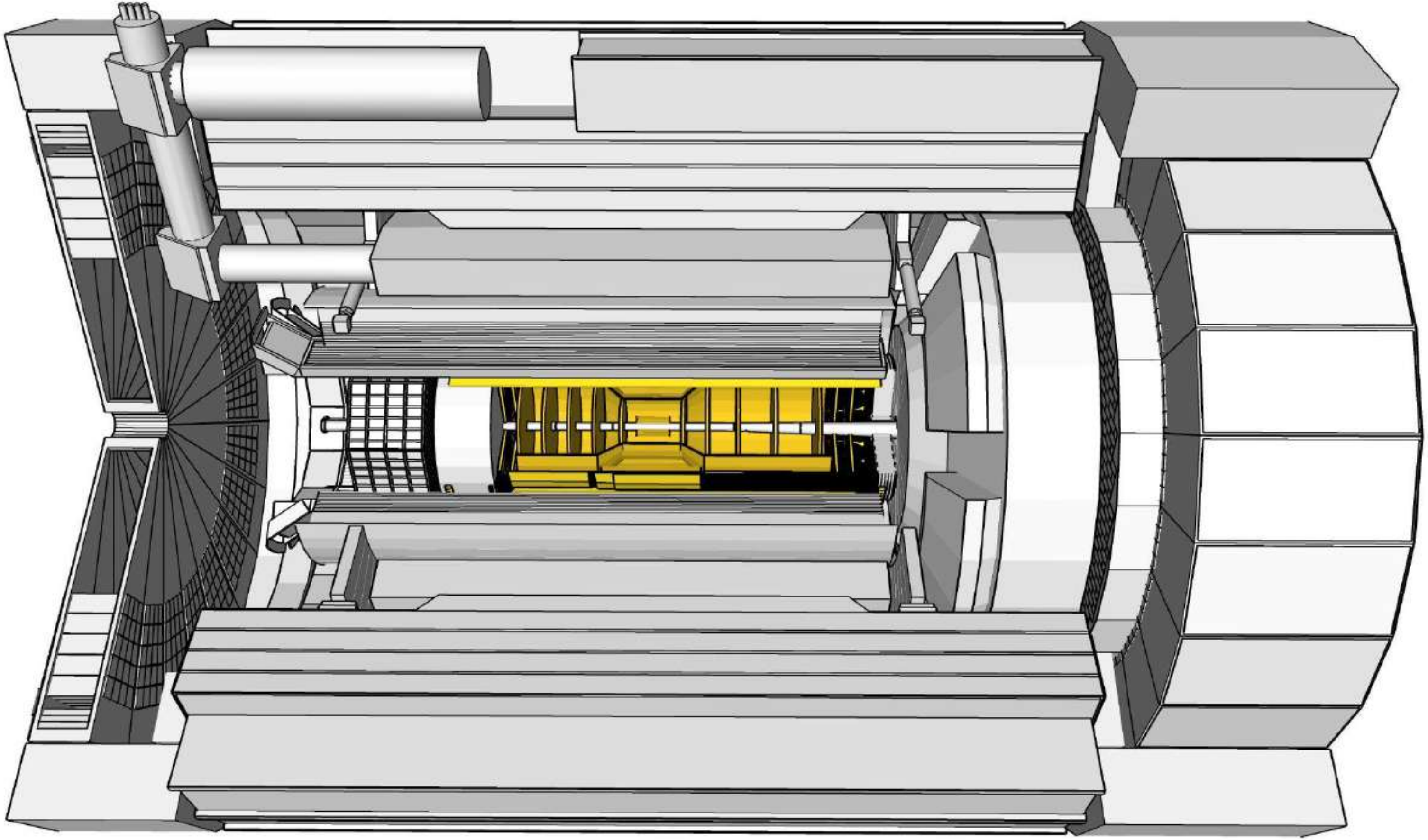
Imaging science program with large ion species range: protons-U

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

Picture: Yellow Report

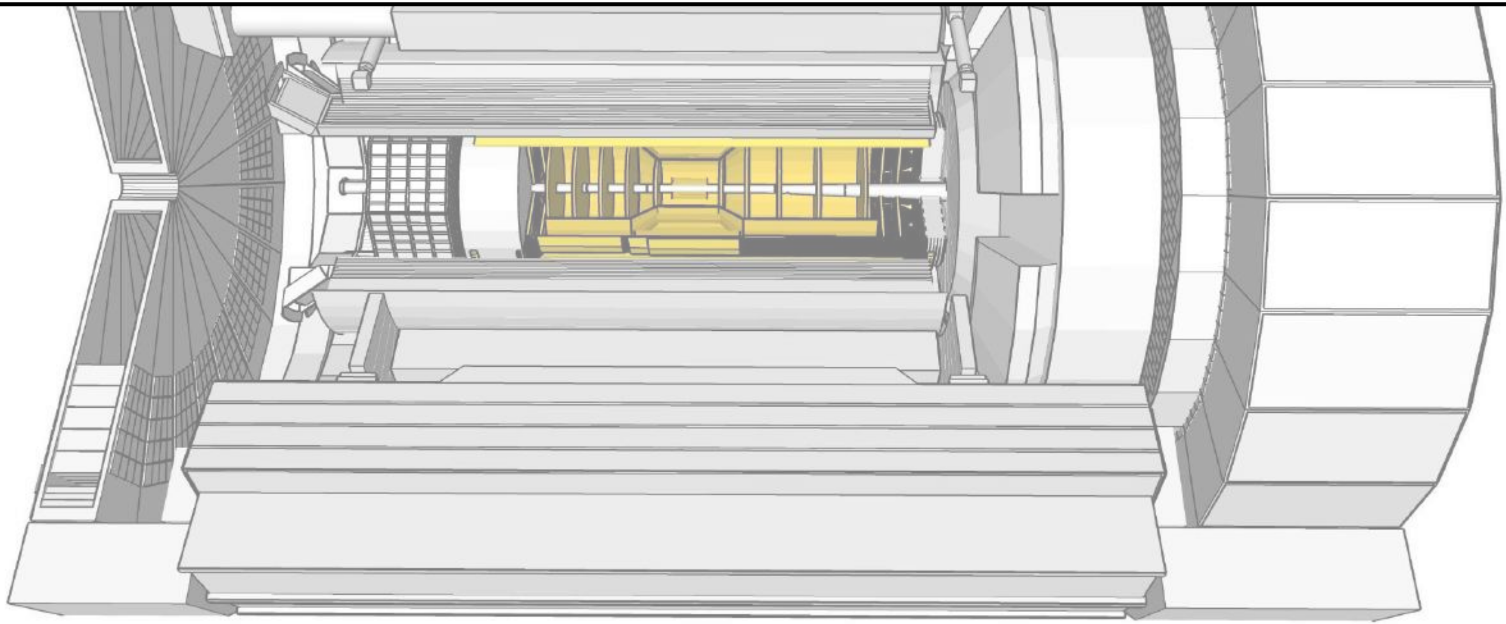
Tracking



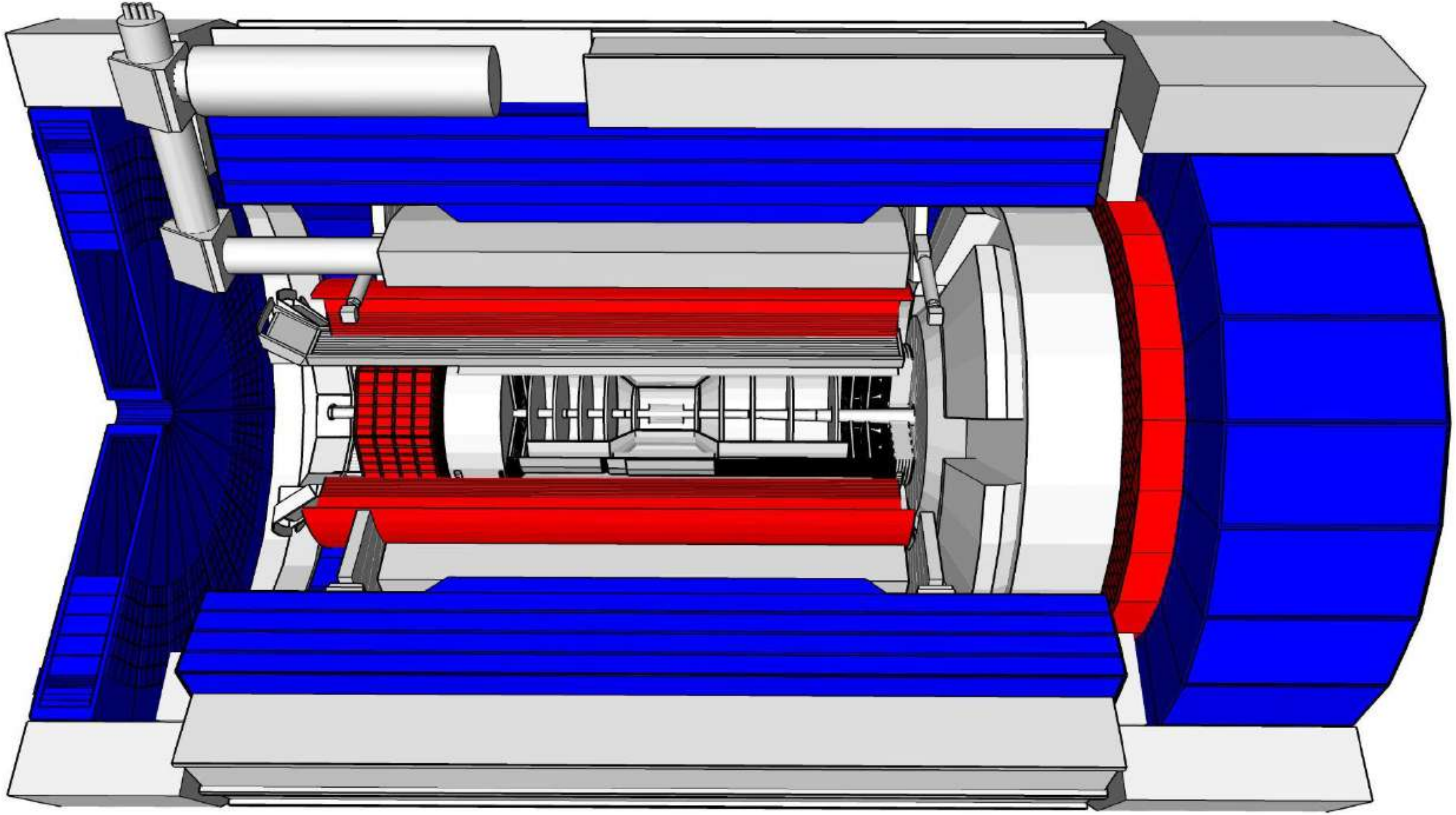
Tracking

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)



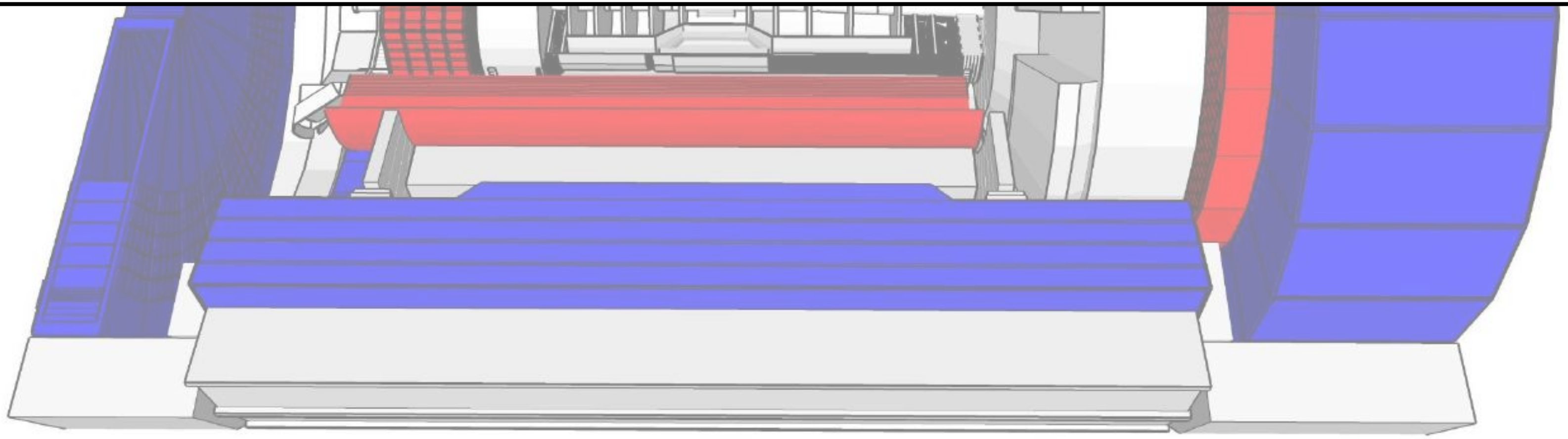
Calorimetry



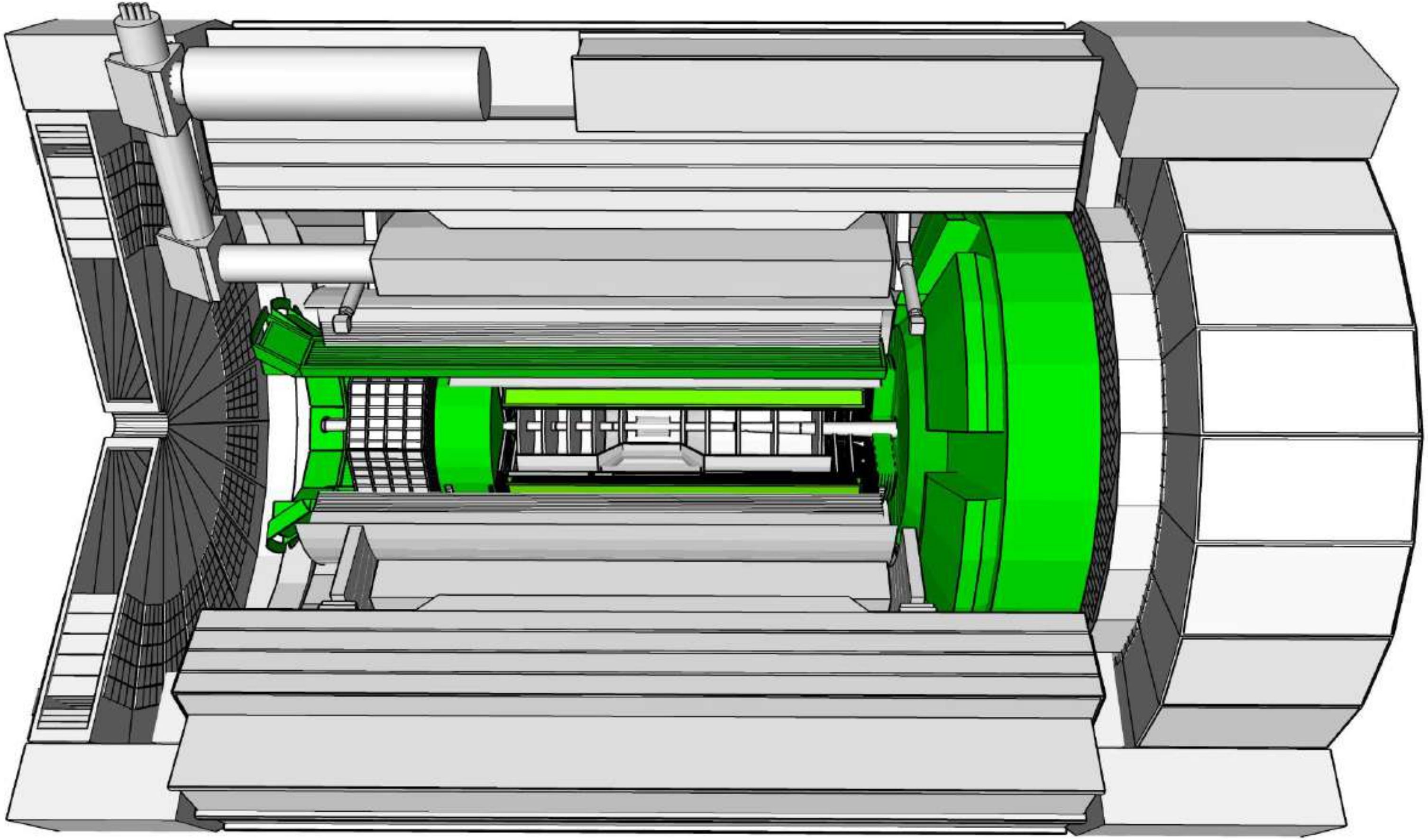
Calorimetry

Challenges:

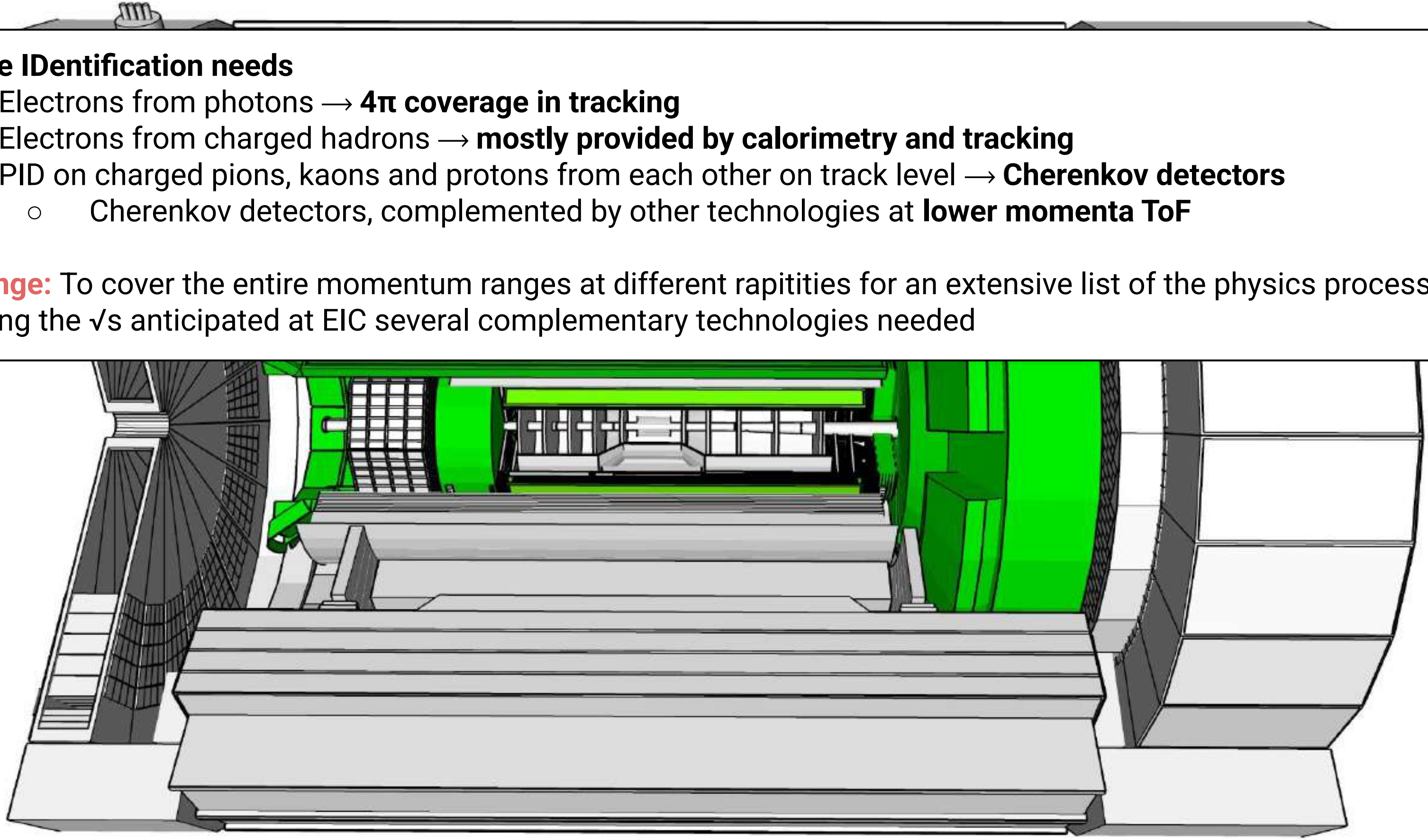
- Detect the **scattered electron** and **separate them from π** (up to 10^{-4} suppression factor in backward and barrel ECal)
- Improve the electron **momentum resolution at backward rapidities** (2-3% $/\sqrt{E} \oplus (1-2)\%$ for backward ECal)
  - e.g., DIS, SIDIS, …
- Provide **spatial resolution of two photons sufficient to identify decays $\pi^0 \rightarrow \gamma\gamma$** 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

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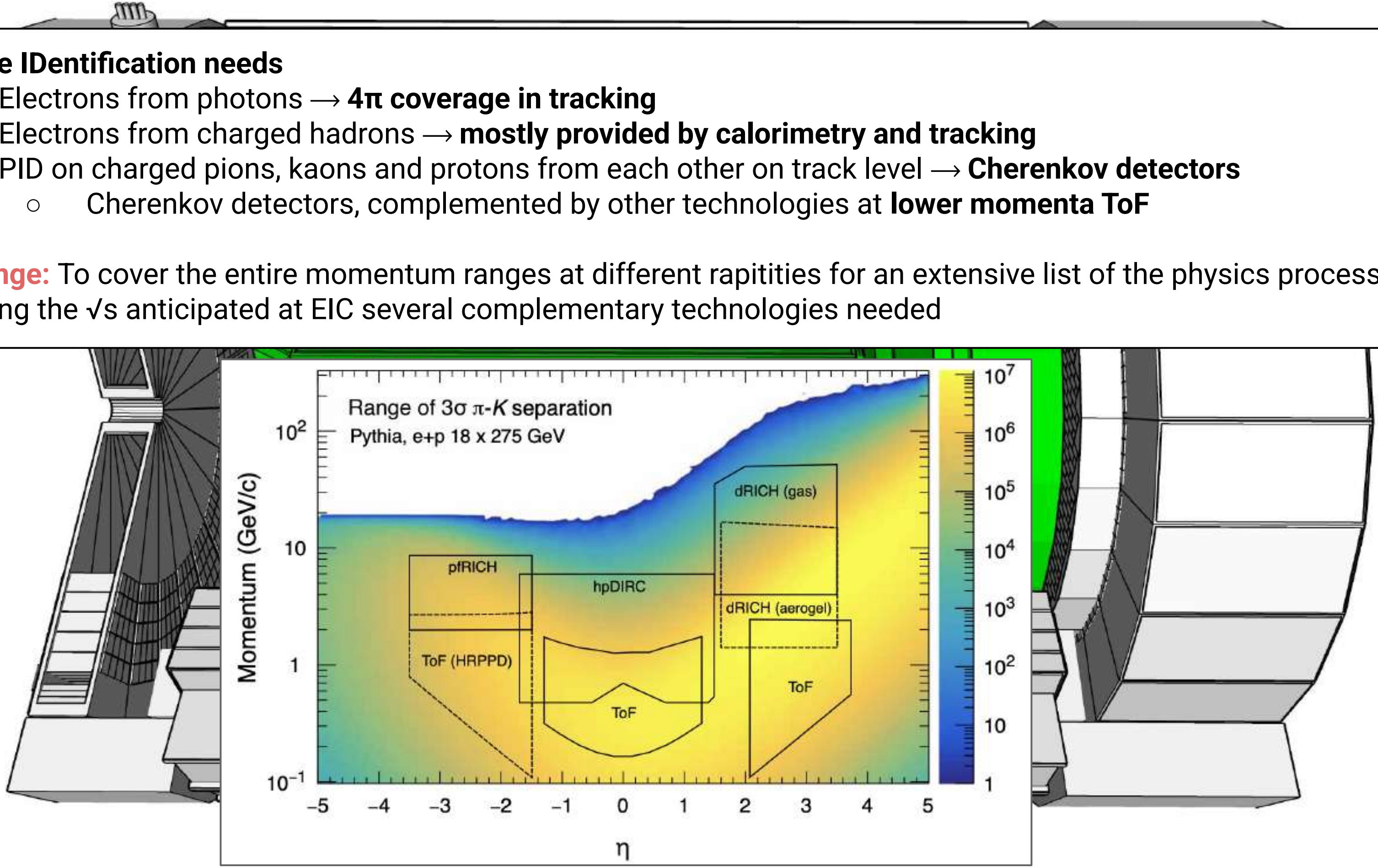
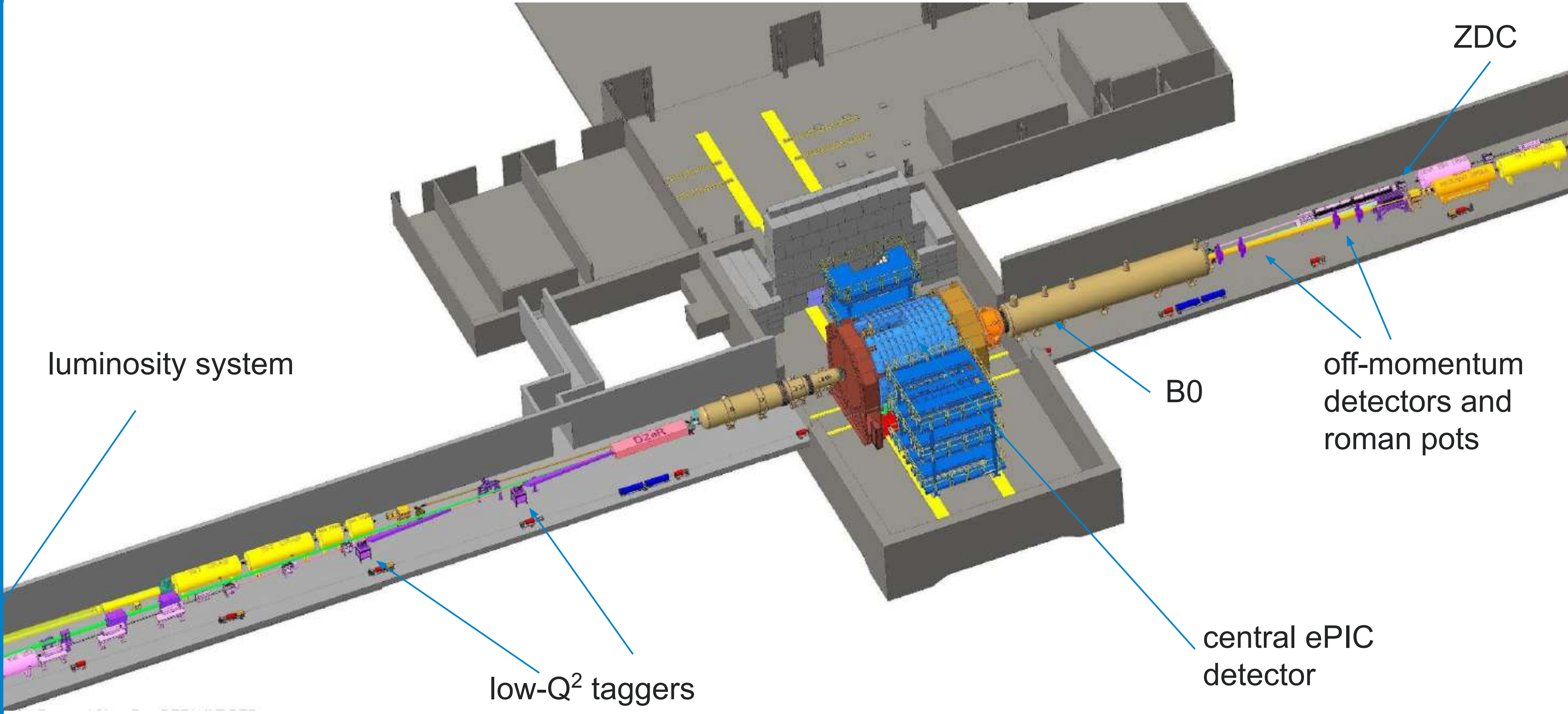
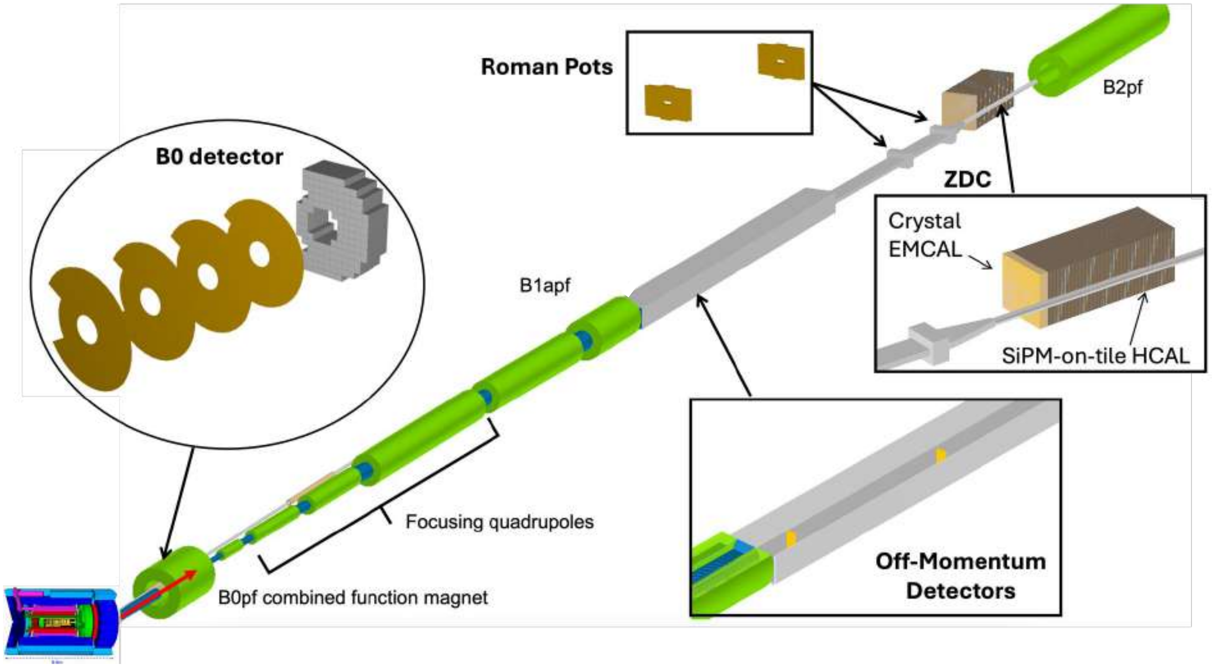


ePIC is more than 80 m long...



Pictures: EIC Project Sharepoint

Far-Forward Detectors



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

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

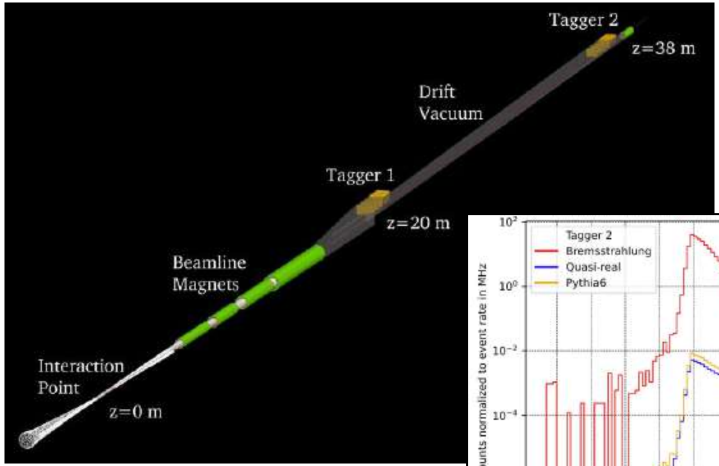
Far-Backward Detectors

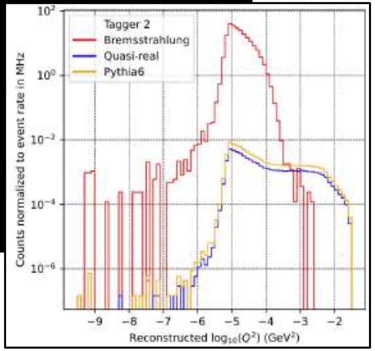
Low-Q^2 tagger

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



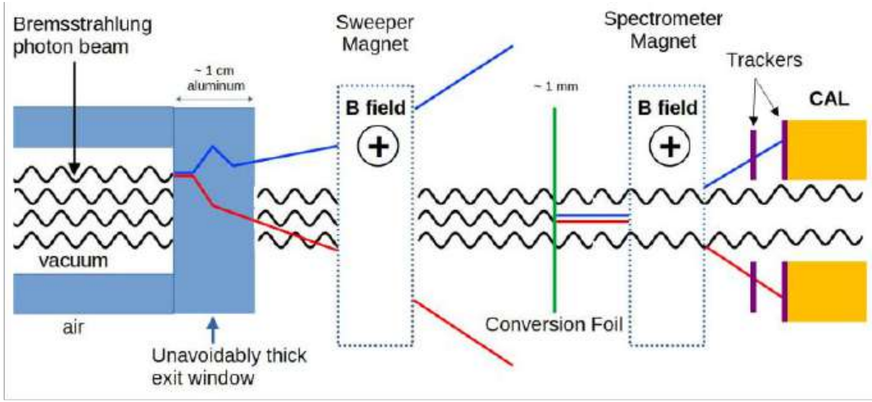


Luminosity Spectrometer

Challenge: Precise luminosity determination (<1%)

From Bremsstrahlung processes
$e+p \to e\,\gamma\,p$
$e+Au \to e\,\gamma\,Au$

AC-LGAD and Scintillating Fiber $23X_0$ ECal



Longitudinal Spin Structure - Experimental Overview

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:

$$\boxed{\Delta\Sigma/2} + \boxed{L_q} + \boxed{J_g} = \hbar/2$$

Quark helicity

Quark orbital angular momentum

Gluon helicity and orbital angular momentum

- **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:

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

Quark helicity

Gluon helicity

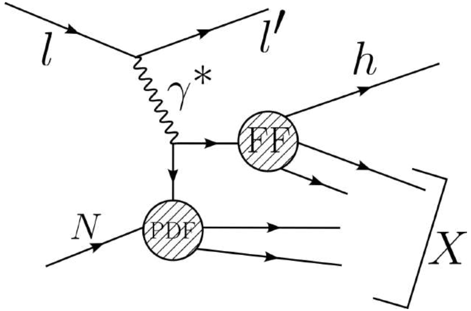
Quark canonical orbital angular momentum

Gluon canonical orbital angular momentum

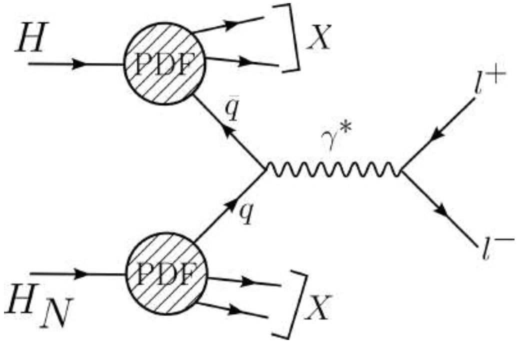
- All terms have **partonic interpretation**
- In infinite-momentum frame
- **ℓq and ℓg** (Twist-3 quantities) can be extracted **from GPDs**
- Nucl. Phys. B 337, 509−546 (1990)

Complementary Experimental Probes

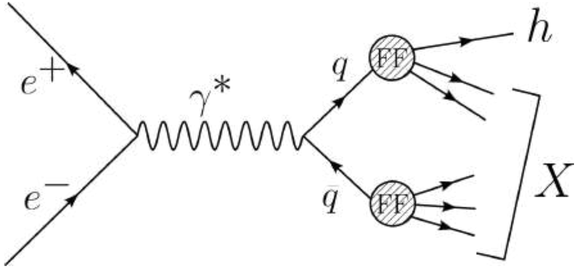
(Semi-Inclusive) Deep Inelastic Scattering

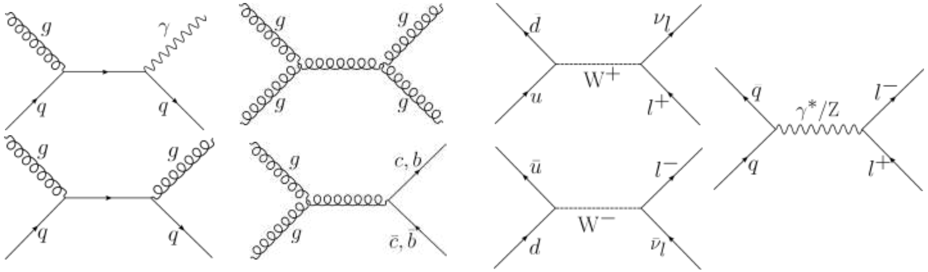


Hadron-hadron interactions



e+e- annihilation (access to FF)





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)

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

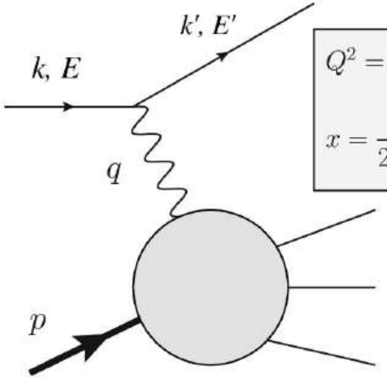
$\nu = E - E'$

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

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

In (LO QCD) Quark Parton Model

Quark helicity distribution



$Q^2 = -q^2$

$x = \frac{Q^2}{2\,p \cdot q}$

Experimental access through double spin asymmetries

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

D - Depolarization factor

η - kinematic fator

A_1 - photon-nucleon asymmetry

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

Longitudinal Spin Structure

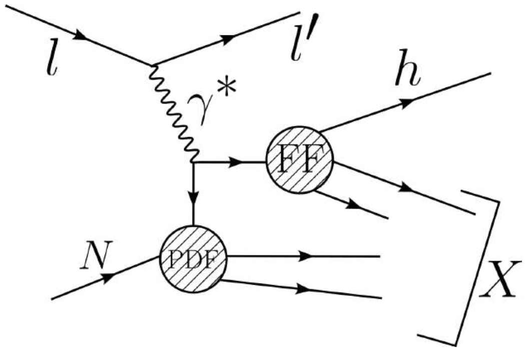
- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- Semi-Inclusive Deep Inelastic Scattering with charged pions and kaons adds **sensitivity to flavor-separated quark helicities** via the fragmentation functions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

Photon-nucleon asymmetry for SIDIS

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

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

Experimental access through double spin asymmetries (analogous to DIS)



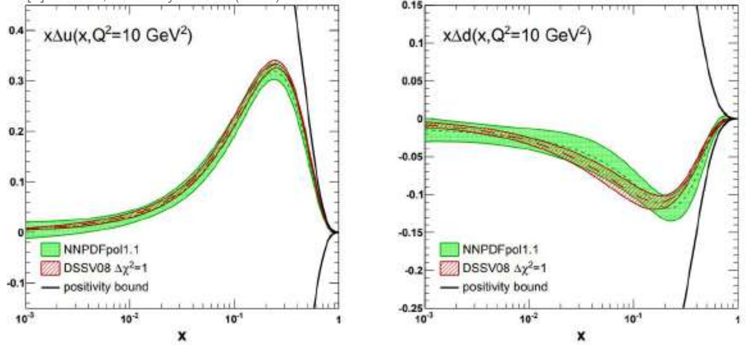
- Sensitivity to sea quarks at low x from $A_1^{\pi-}$ $(\Delta\bar{u})$, $A_1^{\pi+}$ $(\Delta\bar{d})$, A_1^{K} (Δs)

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

Longitudinal Spin Structure - Where Are We?

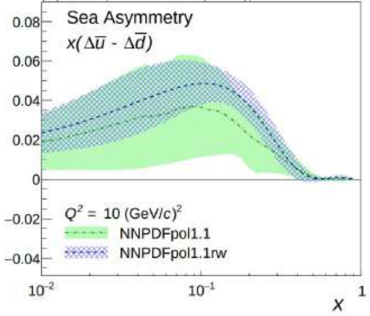
u and d quark helicities

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

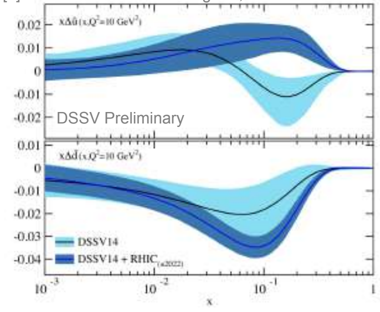


Sea-quark polarization asymmetry

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

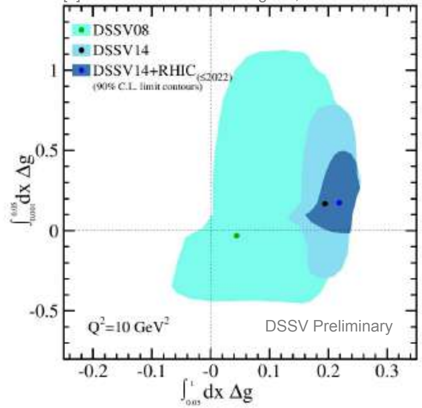


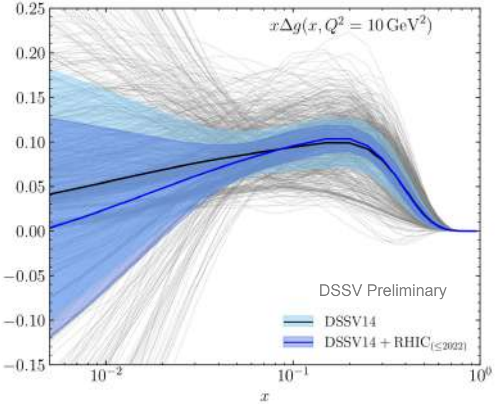
[2] The RHIC Cold QCD Program, arXiv:2302.00605



Gluon Helicity

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





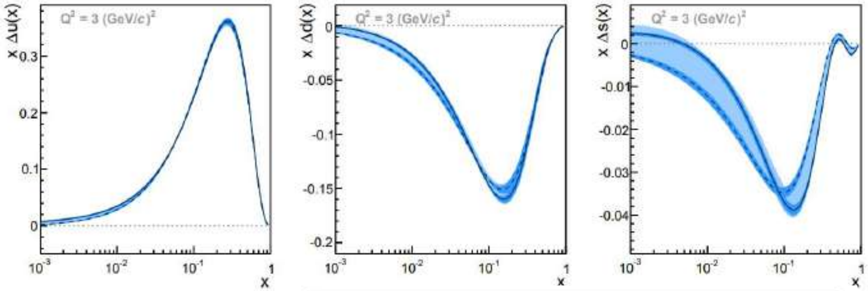
	NNPDF1.1[1]	DSSV08[1]
x	(0.001, 1)	
$\Delta\Sigma$	$+0.25 \pm 0.10$	$+0.366^{+0.042}_{-0.062}\ (+0.124)$

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

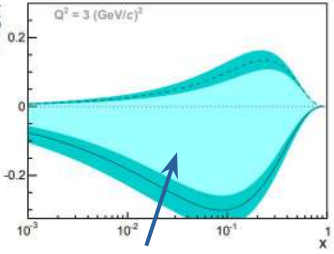
Insights from DIS

QCD fit to g_1 world data

COMPASS, PLB 753 (2016) 18

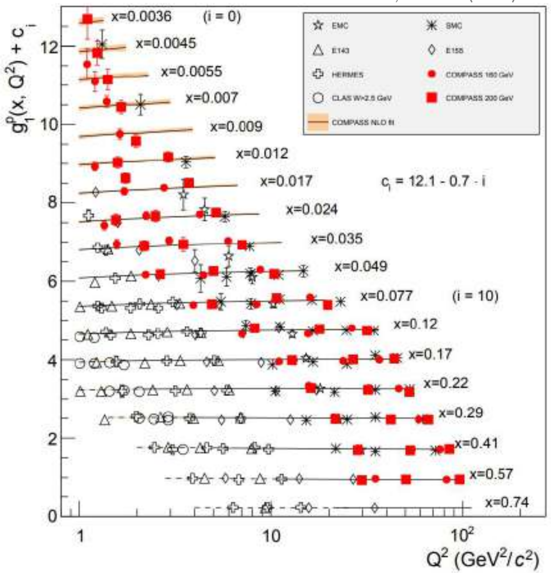


First moment	Value range at $Q^2 = 3\ (\mathrm{GeV}/c)^2$
$\Delta\Sigma$	[0.26, 0.36]



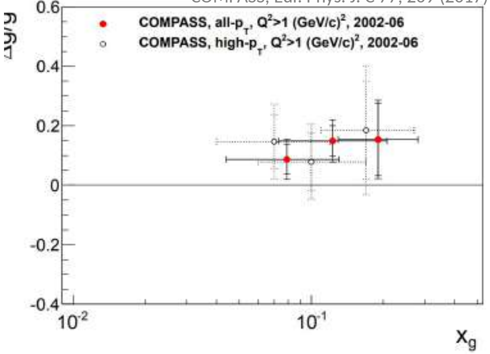
Indirect way to access gluon spin

COMPASS, PLB 753 (2016) 18

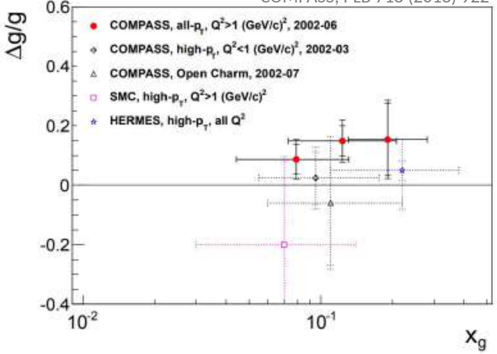


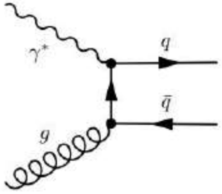
Direct access to Δg from SIDIS

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

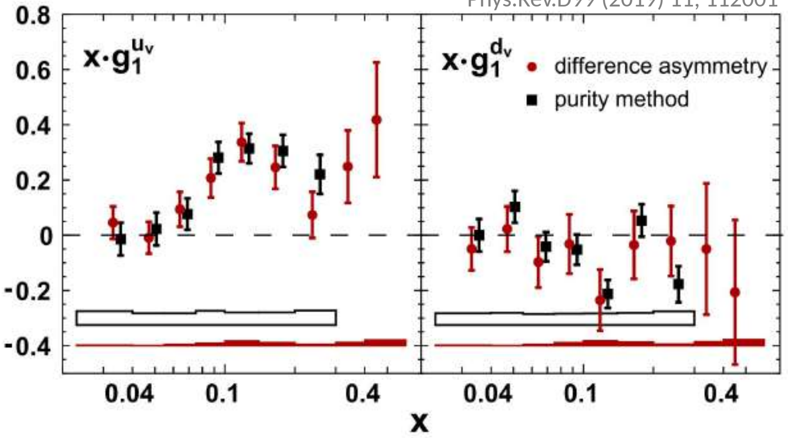
- Enhanced contribution of higher-order processes

Insights from DIS

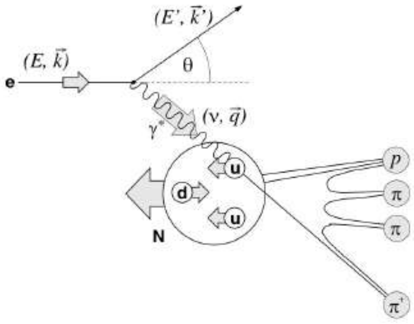
Flavor-separated valence-quark helicities from SIDIS (HERMES, COMPASS)

- 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



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

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

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

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)

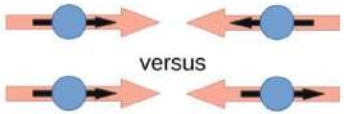
$$A_1^{\mathrm{h}}(x, Q^2, z) = \sum_q \mathcal{P}_q^{\mathrm{h}}(x, Q^2, z) \cdot \frac{\Delta q(x, Q^2)}{q(x, Q^2)}$$

Gluon spin from pp collisions

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

LO for illustration

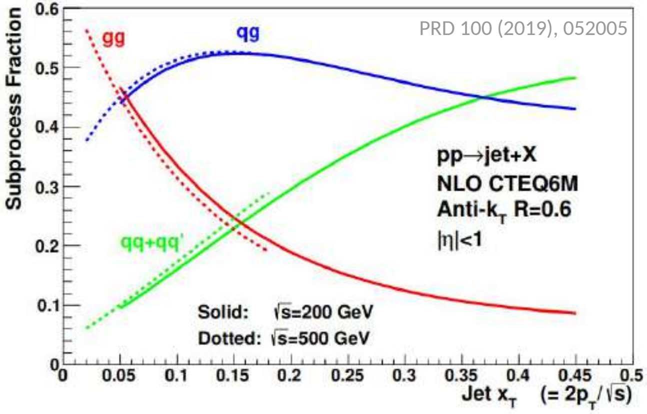
$$\vec{p} + \vec{p} \to \mathrm{jet/dijet/hadrons} + X$$



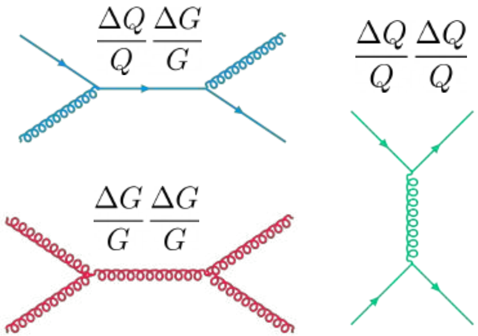
At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**

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

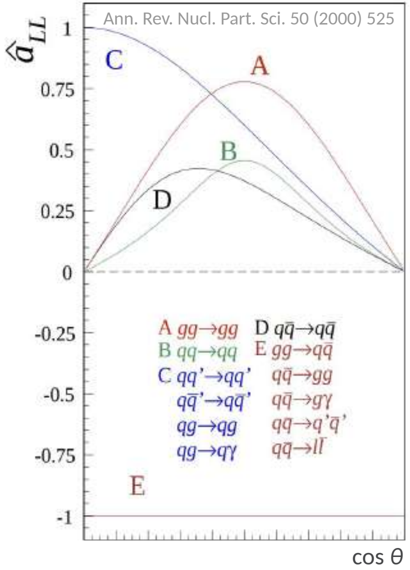
Which processes dominate at RHIC?



Subprocess fraction in central jet production

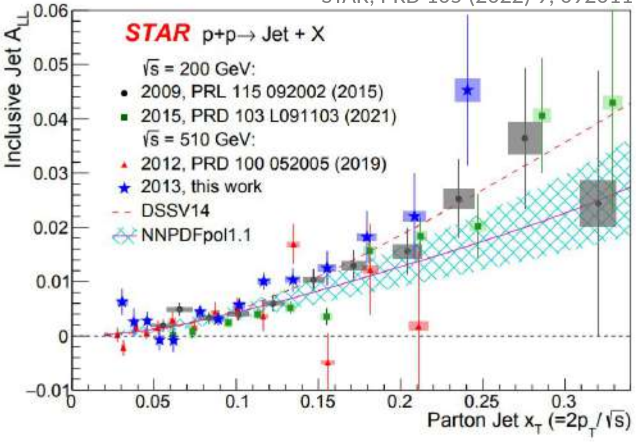


What are a_{LL} for these processes?

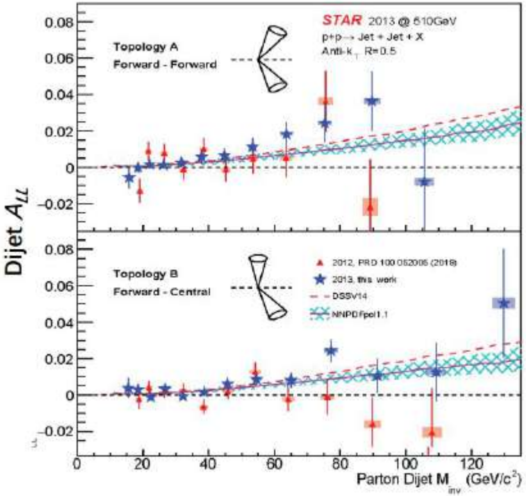


Gluon spin from pp collisions

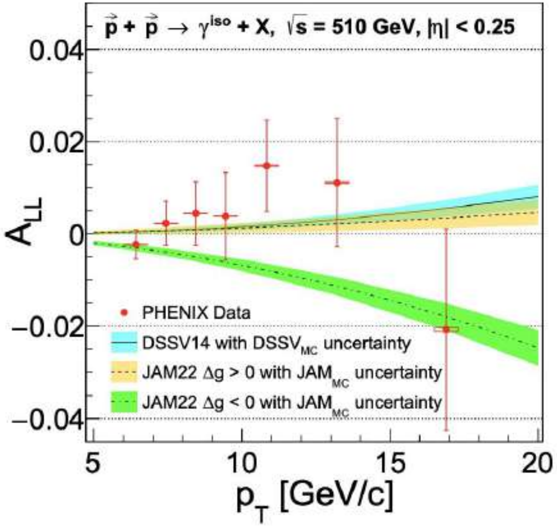
STAR, PRD 105 (2022) 9, 092011



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

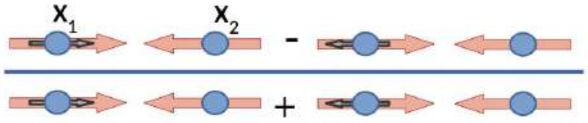
- Down to ~0.004 with STAR Endcap (η < 1.8) dijets at 510 GeV
- **Dijets** provide constraints to underlying partonic kinematics - **better constraints on functional form of ΔG(x)**
- **Direct photon** sensitive to gq → γq LO process; **clean access to Δg(x)** (no hadronization)
- **Consistent results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

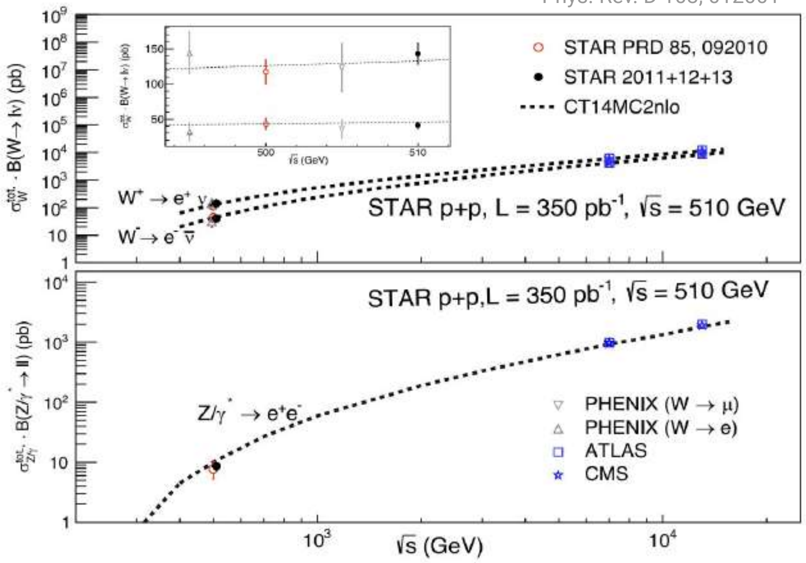
Maximal parity violation

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

The decay process is calculable

- Free from fragmentation function

Phys. Rev. D 103, 012001

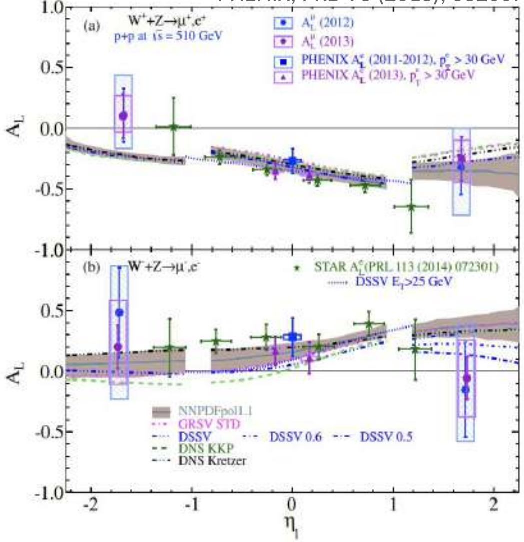


$W^{+/-}$ and Z cross section

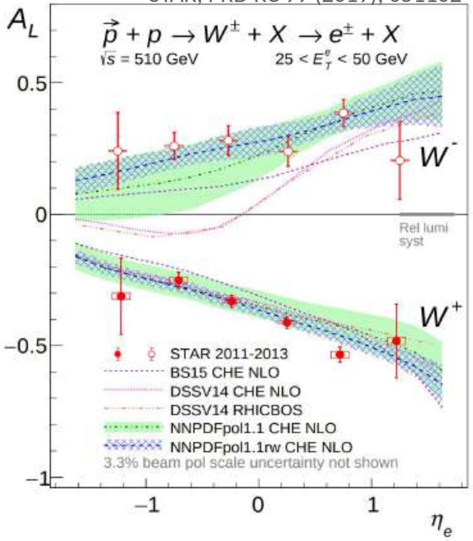
- Agreement between theory and experiment
- Support for the NLO pQCD interpretation of asymmetry measurements

Sea-quark spin from pp collisions

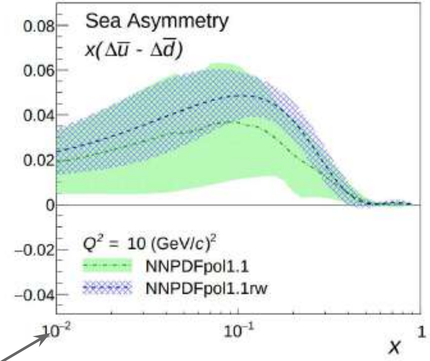
PHENIX, PRD 98 (2018), 032007



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

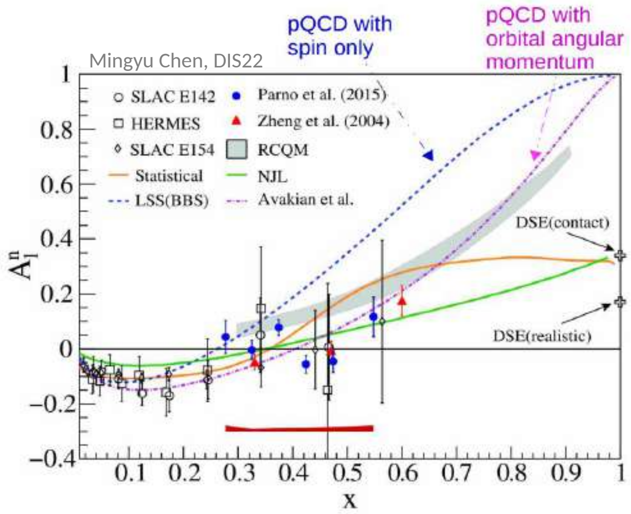
Nucleon spin structure at high-x

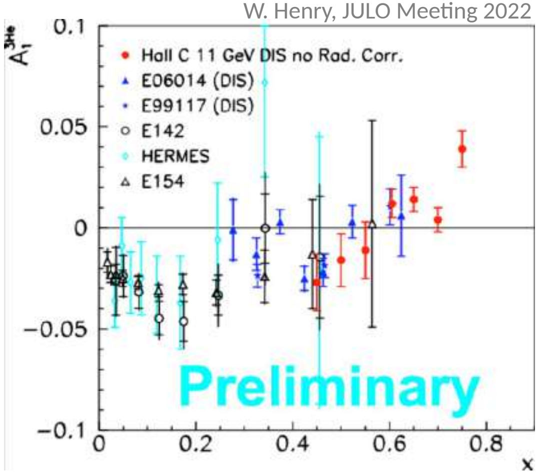
Hall C A1n experiment with polarized ^{3}He target (E12-06-110)

- Measurement of the virtual-photon-nucleon asymmetry A_1 on polarized neutron (^{3}He) target

  $\mathbf{A_1(x) \approx g_1(x)/F_1(x)}$ 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

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

Nucleon spin structure at high-x

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- Measurement of the virtual-photon-nucleon asymmetry A_1 on polarized neutron (^{3}He) target

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- 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

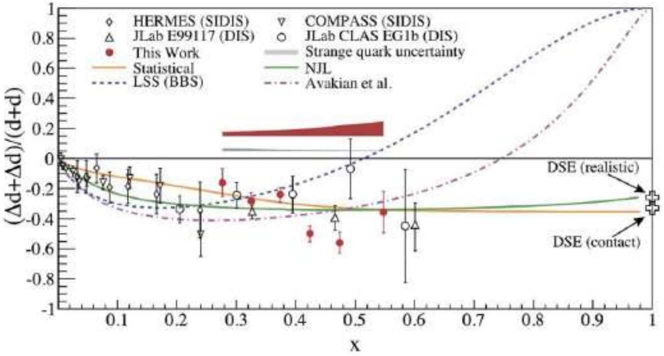
$$\frac{\Delta u + \Delta\bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + R^{du}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4R^{du}\right)$$

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

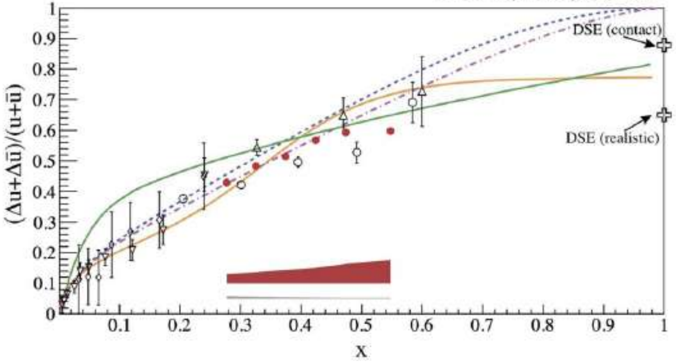
where $R^{du} \equiv (d + \bar{d})/(u + \bar{u})$ and is taken from the CJ12

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



PLB 744, 2015, 309-314



Proton Spin and ePIC Detector Requirements

DIS Kinematics

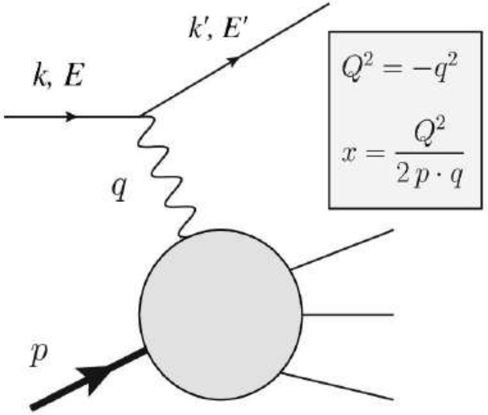
Reconstructed from **scattered electron** or **hadronic final state**

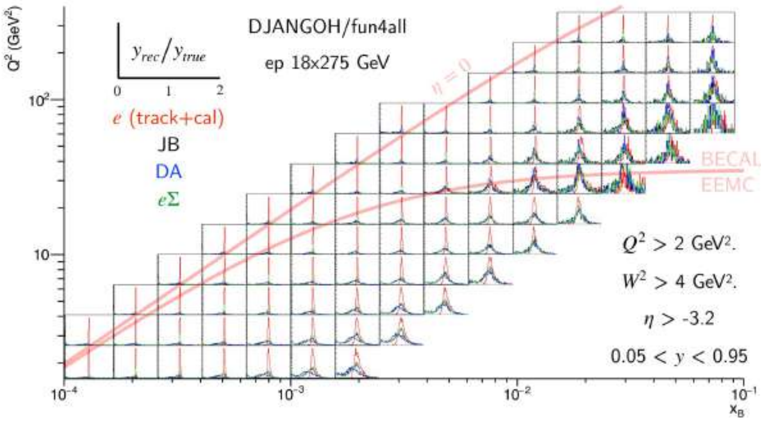
Inclusive NC: leveraging the overconstraint of kinematics to maximize the resolution

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 $\Delta\Sigma$ and ΔG

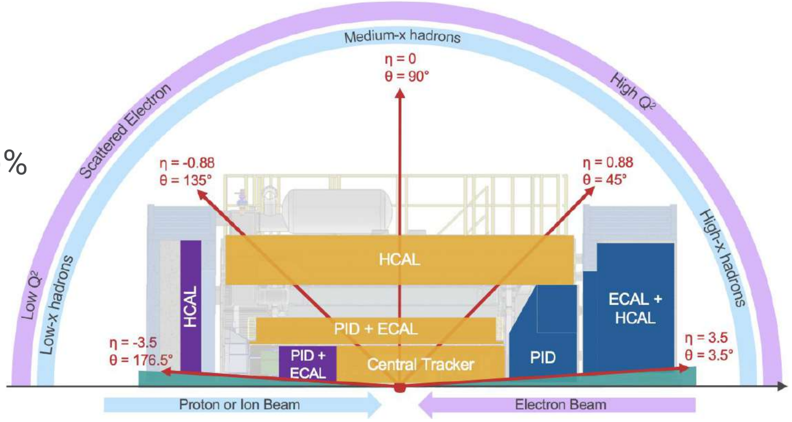
Longitudinally polarized e^- and p for over a wide range in center-of-mass energy (x-Q^2 coverage)

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)

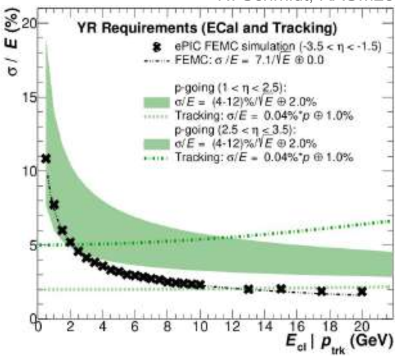
Access to Orbital Angular Momentum - GPD measurements

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

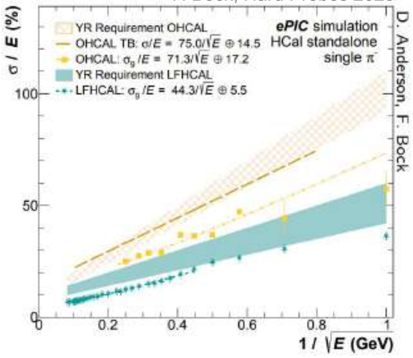
Proton Spin and ePIC Detector Requirements

p-going

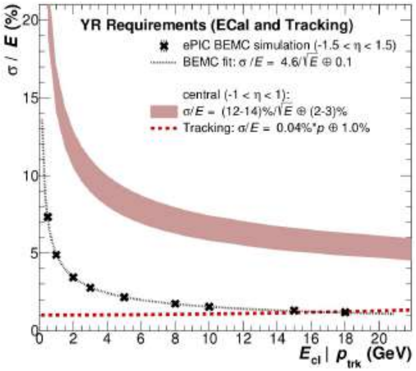
N. Schmidt, RAUM23



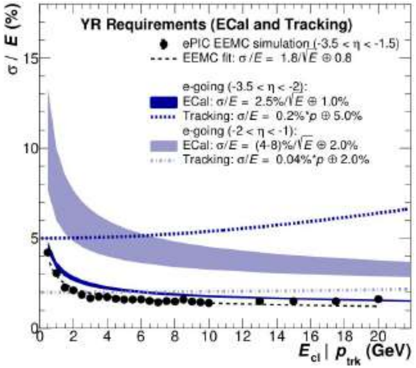
F. Bock, Hard Probes 2023



barrel



e-going

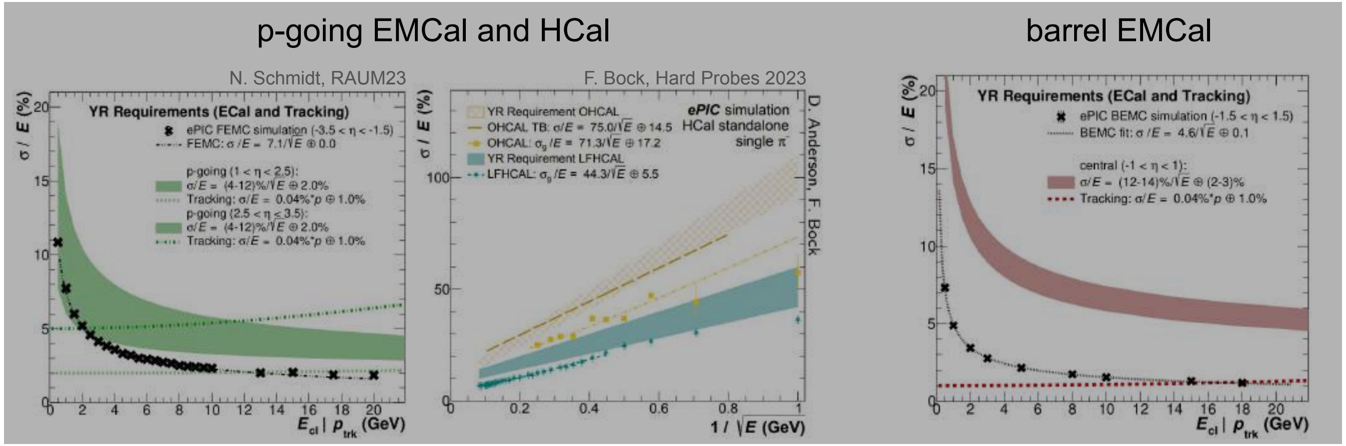


Performance of energy resolution

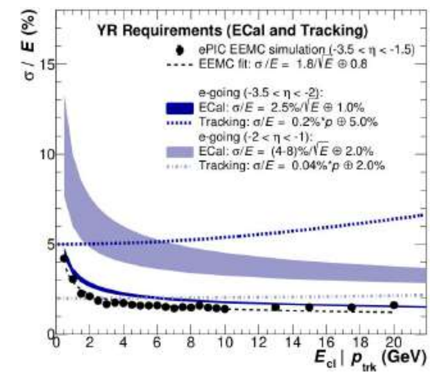
- Technologies fulfill YR requirements on energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry, tracking and reconstruction algorithms

- **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

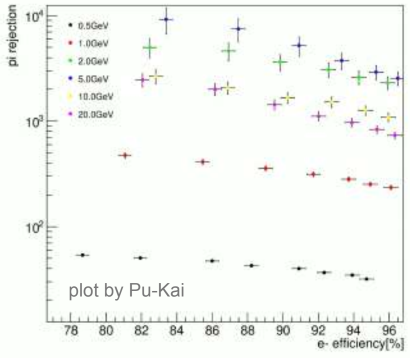
Example Backward e/π Performance for 10 x 100 GeV



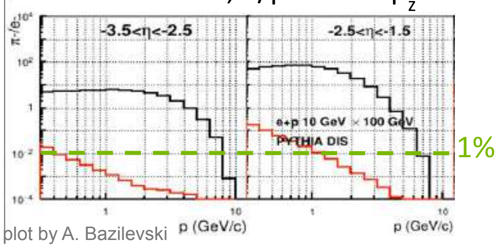
e-going EMCal



ePIC Simulation, E/p cut only



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

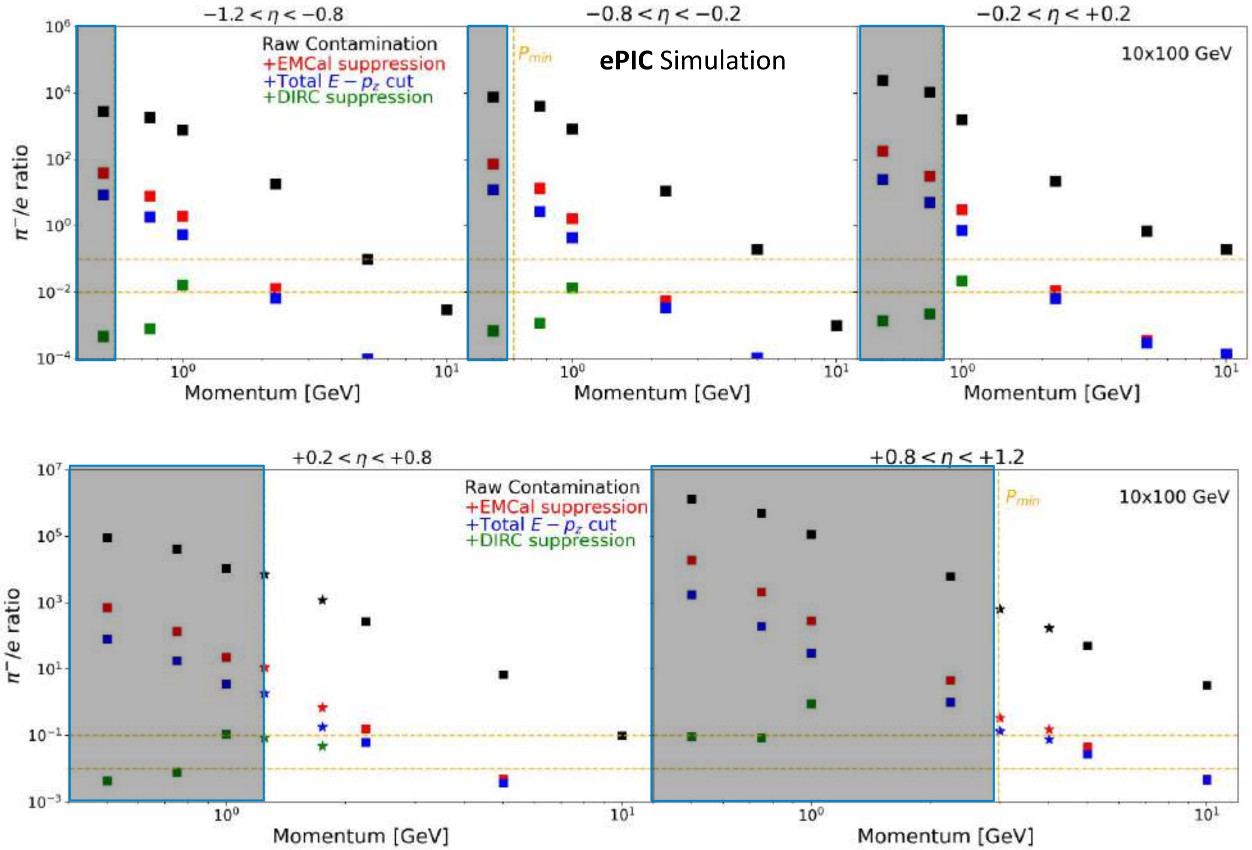


< 1% pion contamination expected for the DIS electron reconstruction

- 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)

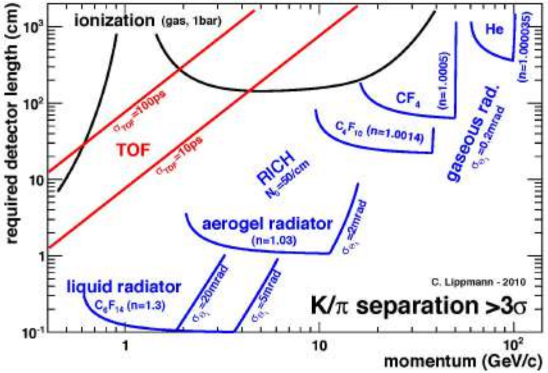
Requirement fulfilled in all η ranges

SIDIS and ePIC Detector Requirements

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

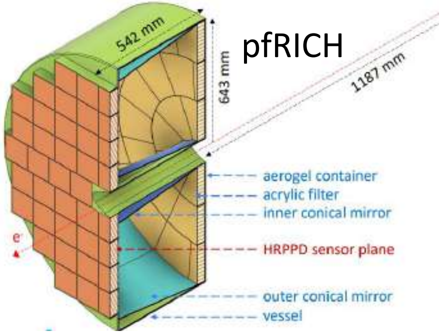
On top of the inclusive DIS requirements ⟶ Particle IDentification needs

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

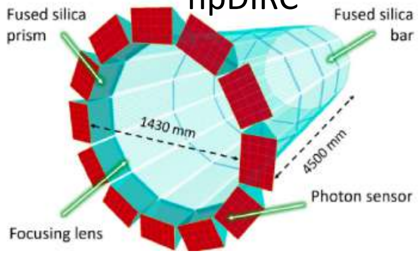


Region	Momentum	ePIC Technology
forward	< 50 GeV/c	dual-radiator RICH
central	< 6 GeV/c	high performance DIRC, AC-LGAD ToF
backward	< 10 GeV/c	proximity focusing RICH

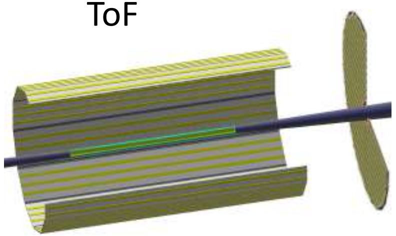
pfRICH



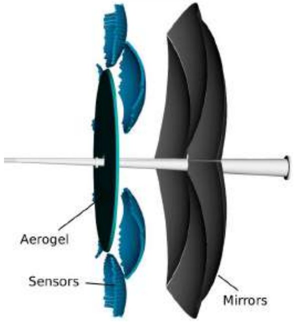
hpDIRC



ToF



dRICH



GPDs and Angular Orbital Momentum

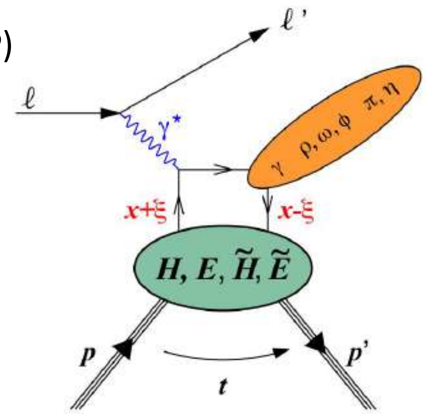
Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$ $\quad J_q = \frac{1}{2}\Delta\Sigma + L_q$

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

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

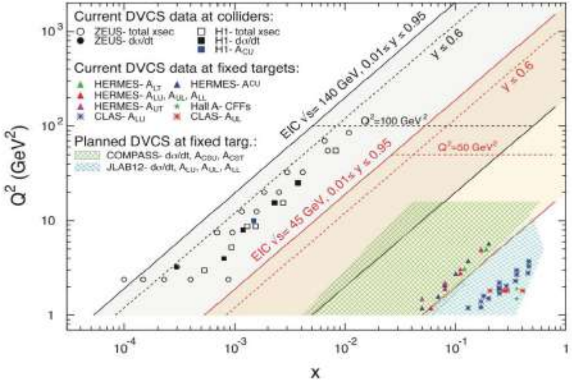
- Experimental access to GPDs via Compton Form Factors
- Different configurations: p and e polarization, beam charge → different CFFs
- proton + neutron DVCS → flavor separation of GPDs

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

GPDs at EIC: Snapshot

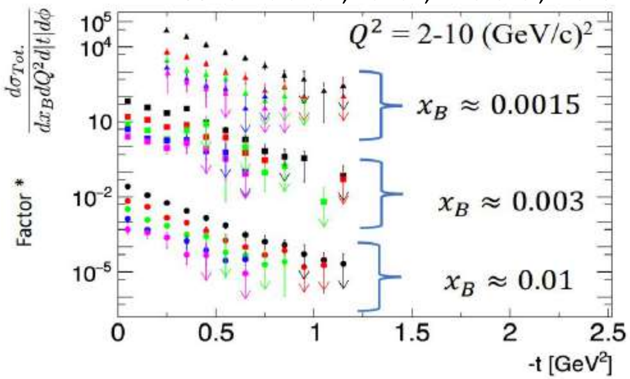
EIC kinematic reach: DVCS

EIC, Yellow Report



Projected DVCS cross-sections

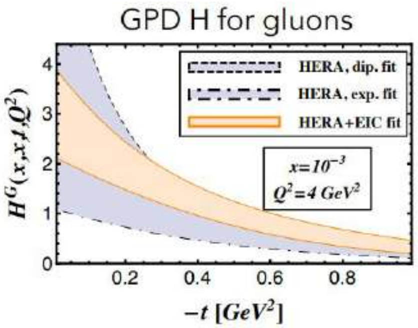
ECCE Simulation, 10 fb^{-1}, I. Korover, DIS23

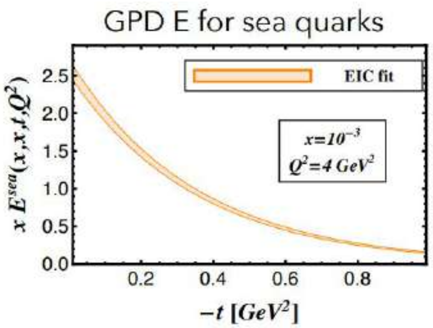


- ▲ e+p 18+275 GeV
- ■ e+p 10+100 GeV
- ● e+p 5+41 GeV

Strong constraints on extraction of Compton Form Factors from multidimentional binning

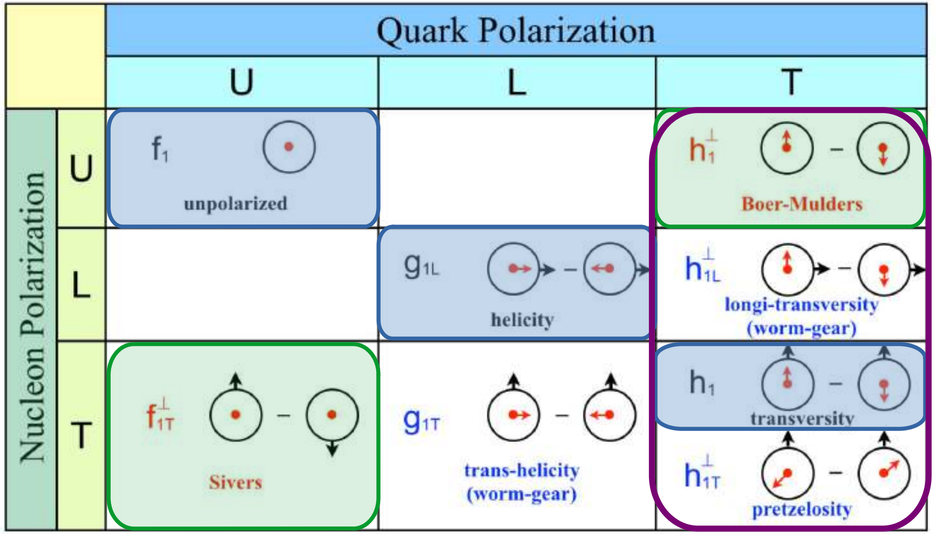
Anticipated constrain on GPDs H and E from EIC





- 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

TMDs and Spin-Orbit Correlations



TMDs surviving integration over k_T

Naive time-reversal odd TMDs describing strength of **spin-orbit correlations**

Chiral odd TMDs

Off-diagonal part vanishes without parton's transverse motion

TMDs describing strength of spin-orbit correlations non-zero → indication of parton OAM

- No quantitative relation between TMDs & OAM identified yet

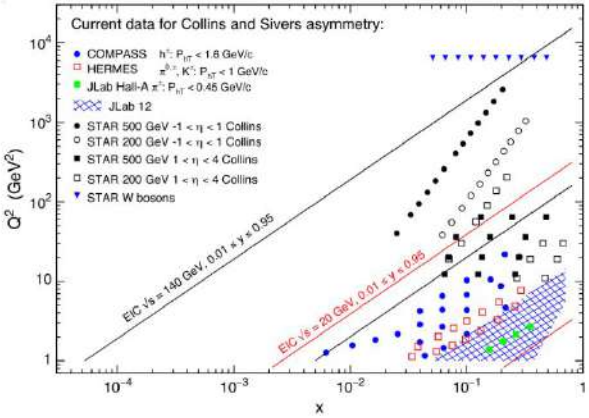
- **Sivers:** correlations of transverse-spin direction and the parton transverse momentum
- **Boer-Mulders:** correlations of parton transverse spin and parton transverse momentum
- **Collins:** fragmentation of a transversely polarized parton into a final-state hadron

TMDs at EIC: Snapshot

See plenary talks and in TMD session:
C. Dilks, Future studies of dihadron production in SIDIS
A. Mukherjee, Probing gluon TMDs in back-to-back production of a D meson and jet at the EIC
A. Prokudin, Three-dimensional nucleon structure

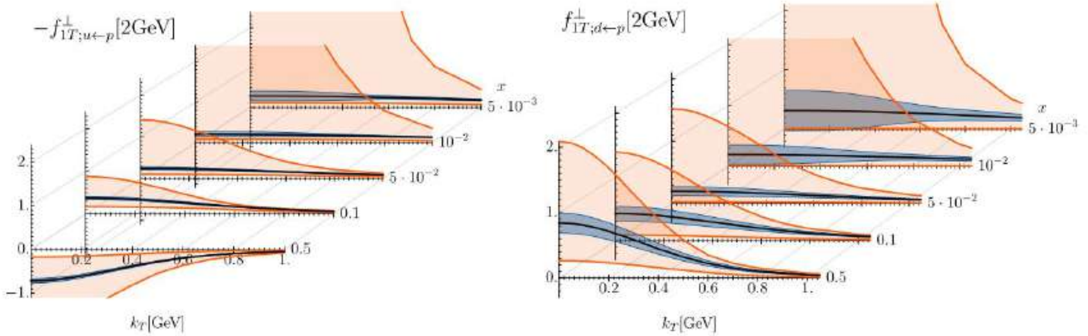
EIC kinematic reach: Collins and Sivers

EIC, Yellow Report



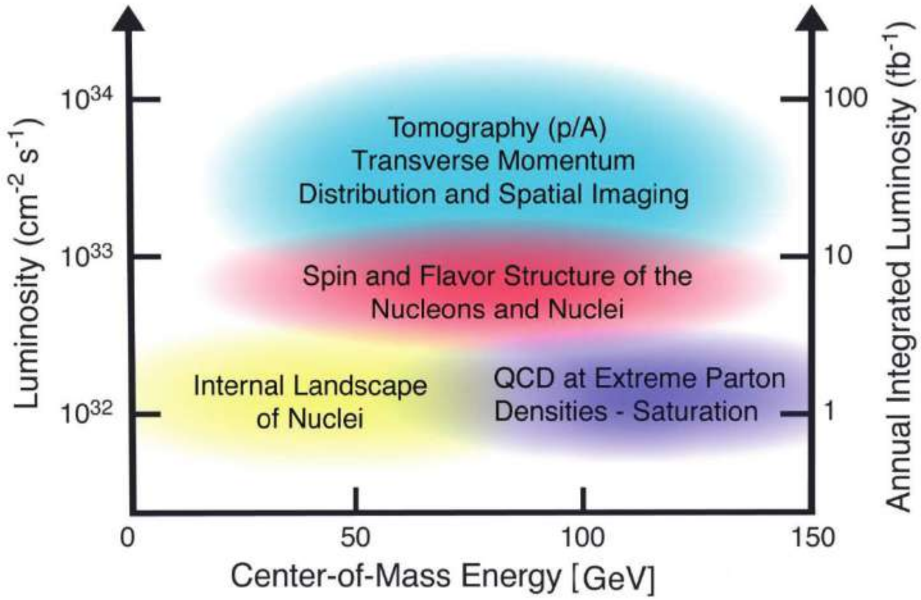
Example: expected impact on u and d quark Sivers distributions

R. Seidl, et al. (ECCE), Nucl.Instrum.Meth.A 1049 (2023) 168017



- Rich program to probe spin-orbit effects within the proton and during hadronization, and explore the 3D spin structure of the proton in momentum space
- Access TMDs primarily through **SIDIS for single hadrons**, as well as other semi-inclusive processes with **di-hadrons and jets**
- **EIC has transformative potential for understanding the proton's 3D structure in momentum space**
  - Valence region TMDs still have significant uncertainties (see the Sivers function example)
  - Severe lack of experimental data for sea quarks and gluons

Experimental Access to EIC Physics



Access to EIC Physics through

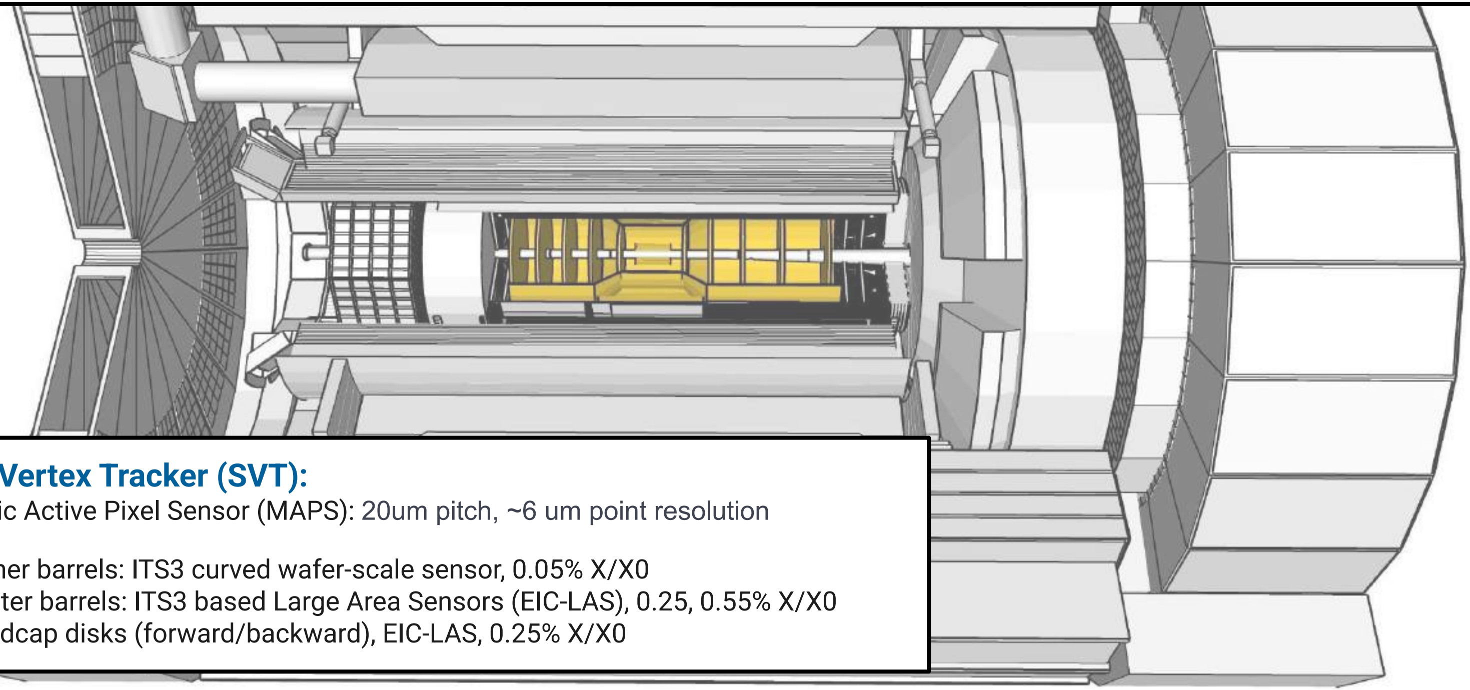
- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

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

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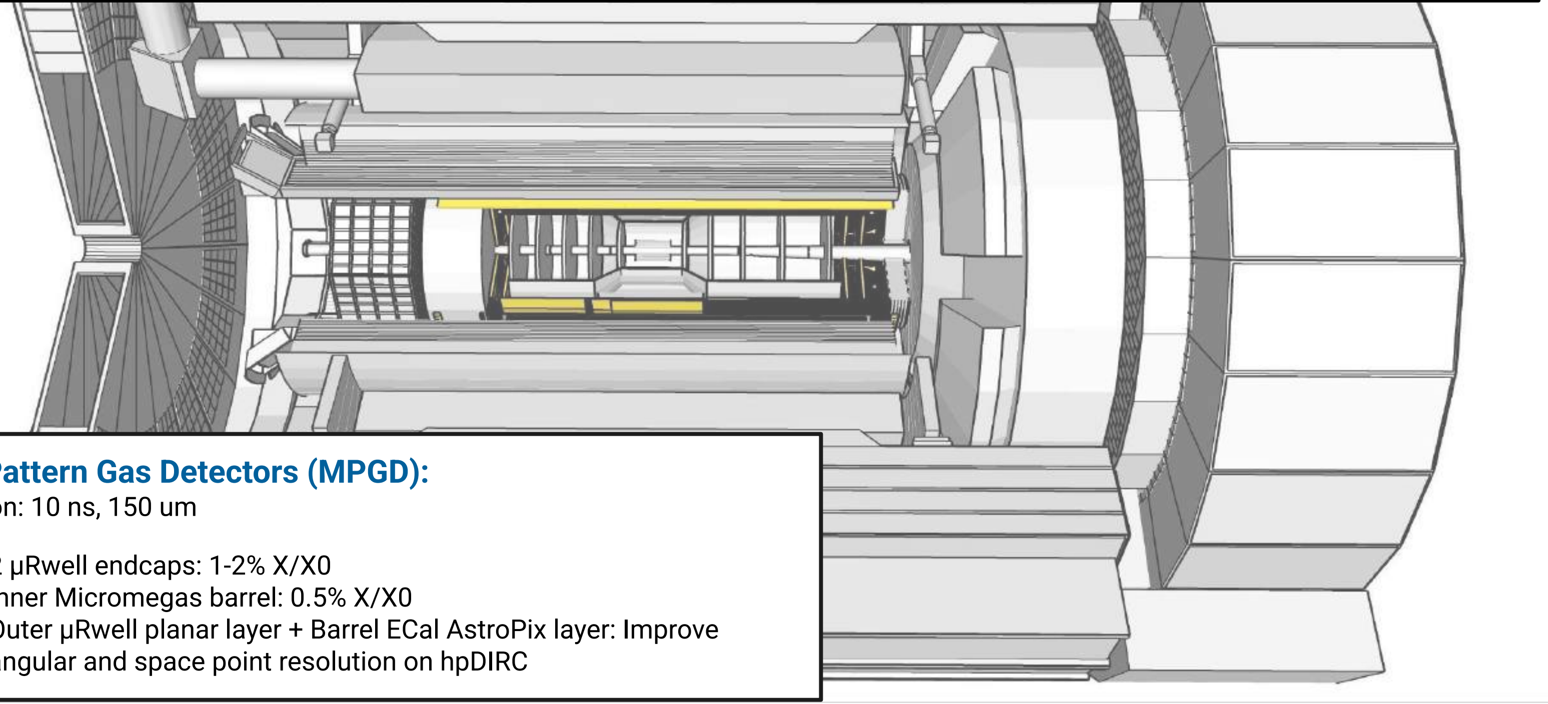

Micro Pattern Gas Detectors (MPGD):
Resolution: 10 ns, 150 um

- 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

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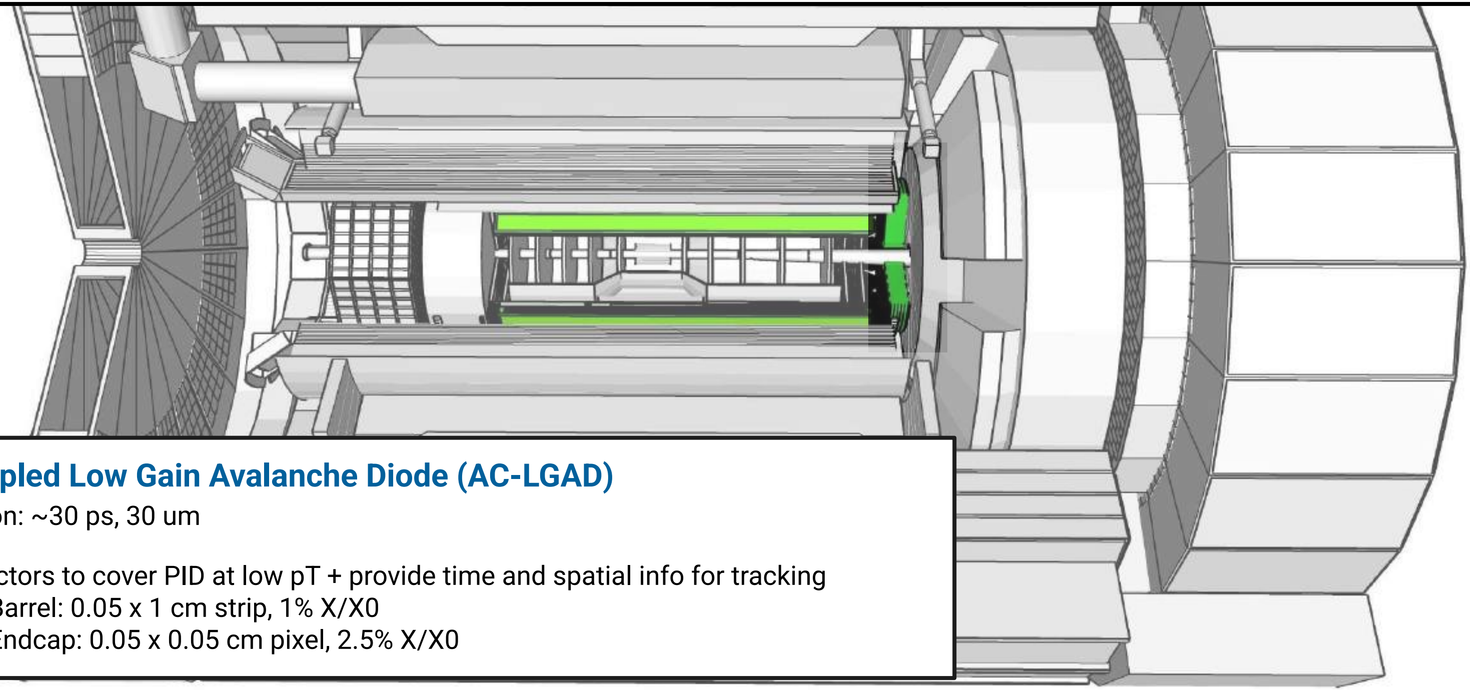


AC-coupled Low Gain Avalanche Diode (AC-LGAD)

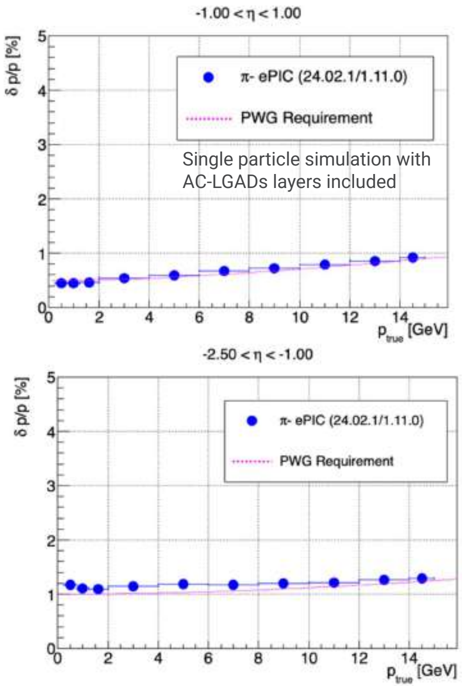
Resolution: ~30 ps, 30 um

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

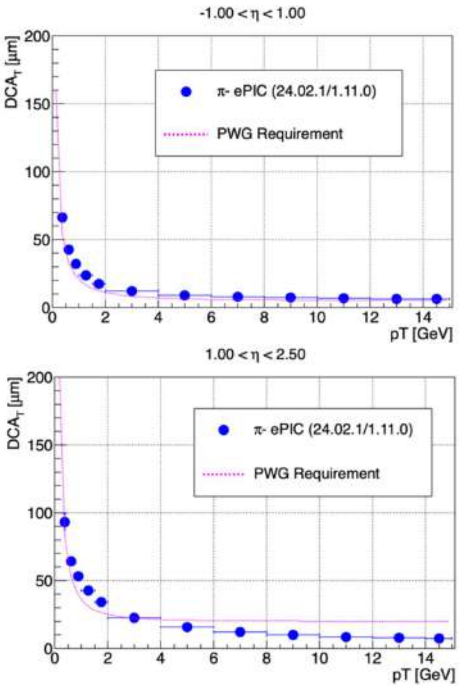
- Barrel: 0.05 x 1 cm strip, 1% X/X0
- Endcap: 0.05 x 0.05 cm pixel, 2.5% X/X0

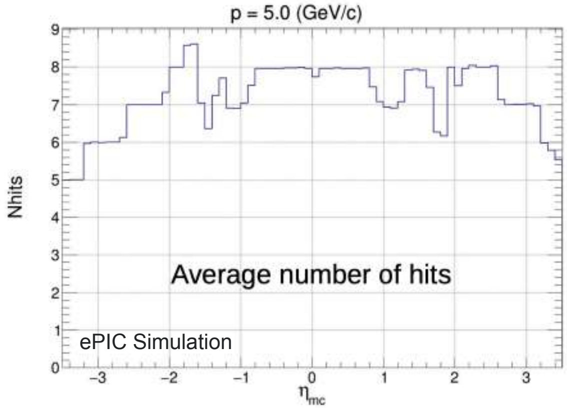
Tracking Performance

Momentum



Distance of Closest Approach (DCA_T)

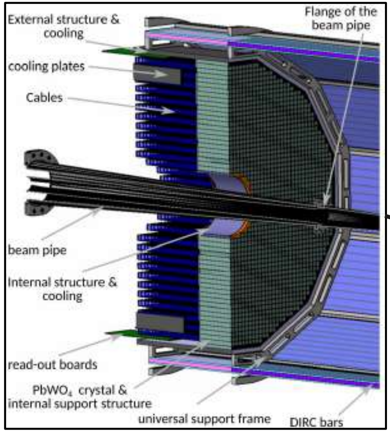


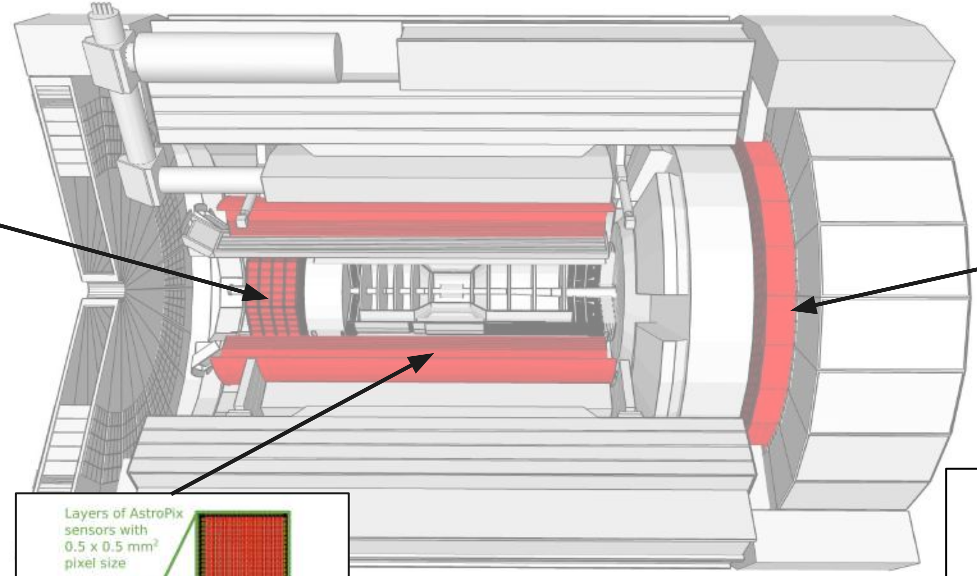


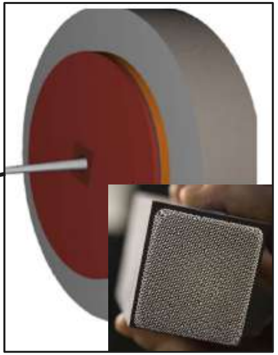
	Momentum Resolution	Spatial Resolution
Backward (-3.5 to -2.5)	~0.10%×p⊕2.0%	~ 30/pT µm ⊕ 40 µm
Backward (-2.5 to -1.0)	~ 0.05%×p⊕1.0%	~ 30/pT µm ⊕ 20 µm
Barrel (-1.0 to 1.0)	~0.05%×p⊕0.5%	~ 20/pT µm ⊕ 5 µm
Forward (1.0 to 2.5)	~0.05%×p⊕1.0%	~ 30/pT µm ⊕ 20 µm
Forward (2.5 to 3.5)	~0.10%×p⊕2.0%	~ 30/pT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

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

Electromagnetic Calorimetry

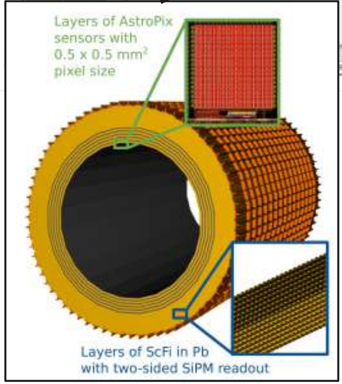






Backward EMCal $PbWO_4$ crystals

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



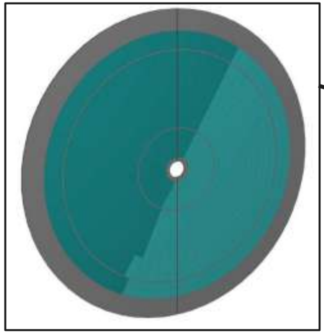
Imaging Barrel Calorimeter

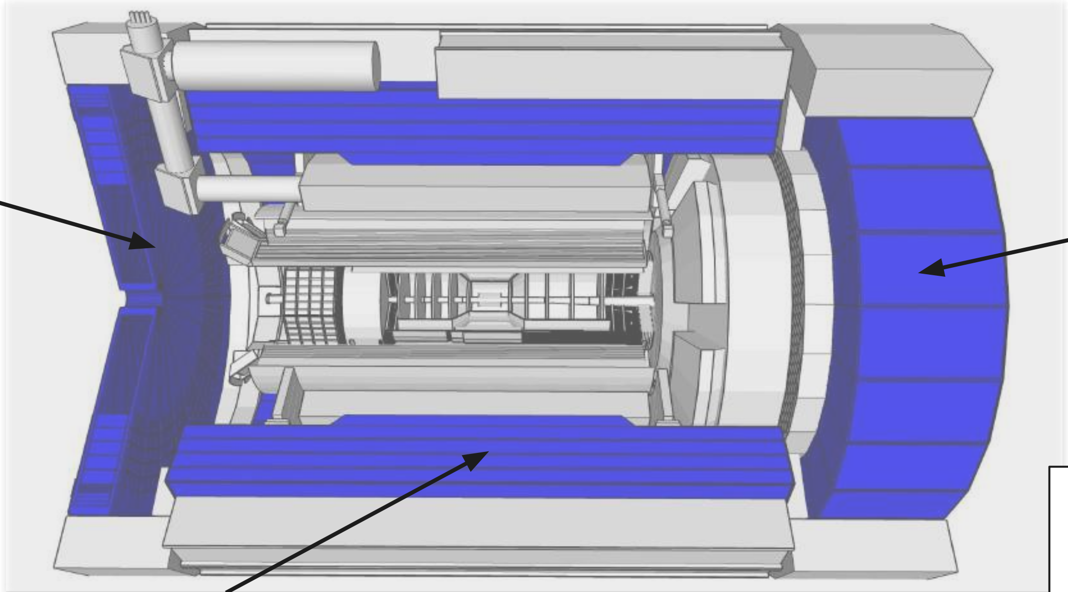
- 4(+2) layers of AstroPix MAPS sensor, 500x500 μm
- Interleaved with scintillating fiber/Pb layers
  - 2-side SiPM readout, 50 μm pixel
- Depth: ~17.1 X0

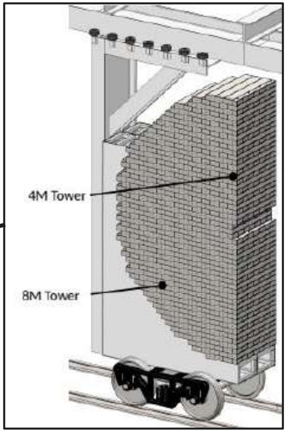
High granularity W/SciFi EMCal

- 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

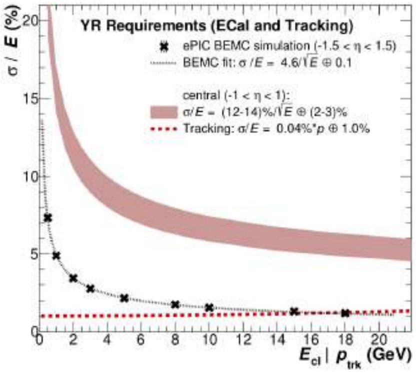
- Minor radiation damage replace SiPMs
- Upgrade electronics to HGCROC
- Reading out each tile individually

Longitudinally separated HCAL with high-η insert

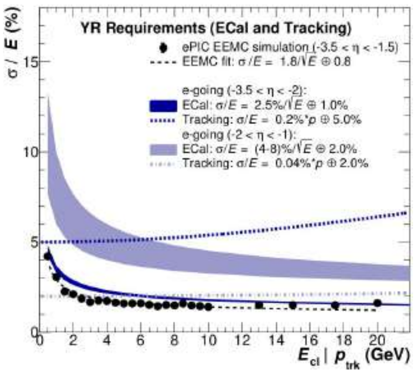
- Steel + Scintillator SiPM-on-tile
- Highly segmented longitudinally
- 65 layers per tower
  - 565,760 SiPMs
- Stackable for “easy” construction
- Highly segmented insert

Calorimetry Performance

Barrel

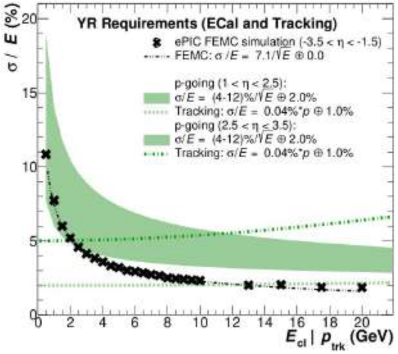


Endcap (e-going)

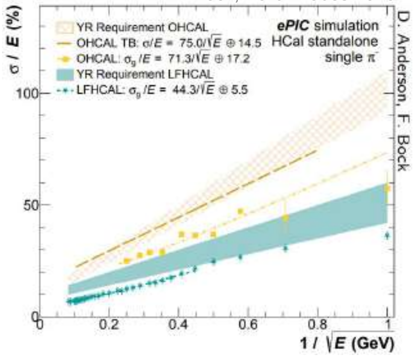


Endcap (p-going)

N. Schmidt, RAUM23

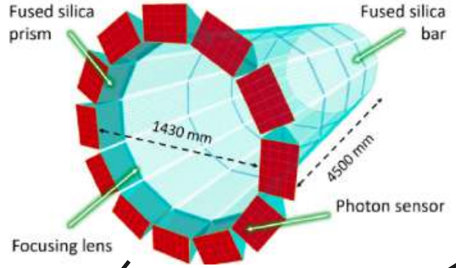


F. Bock, Hard Probes 2023

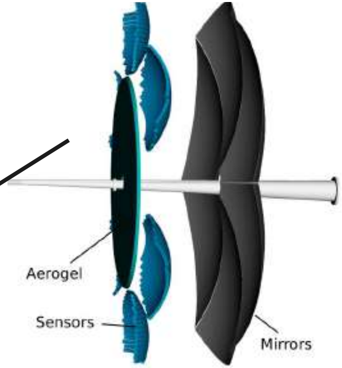


D. Anderson, F. Bock

Particle Identification



Dual-Radiator RICH (dRICH)

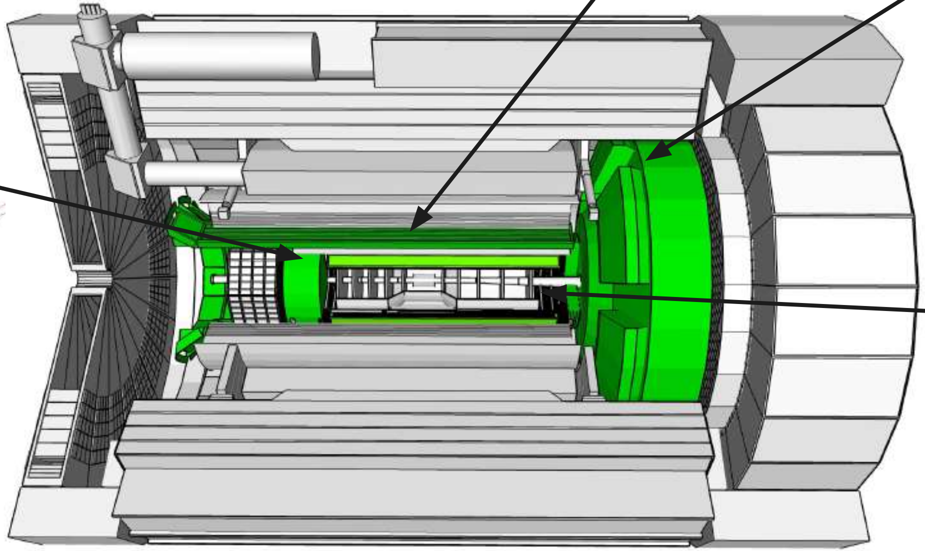


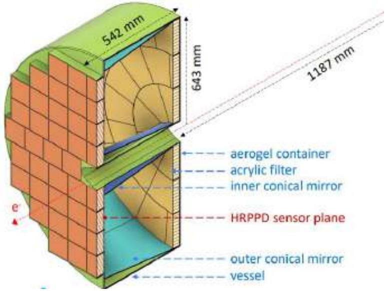
High-Performance DIRC

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

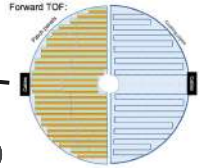
Proximity Focusing RICH

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

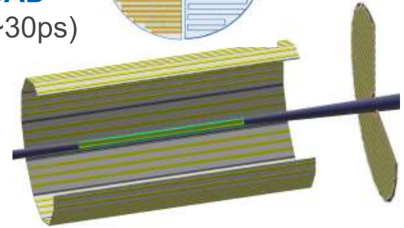




- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3σ sep. at 50 GeV/c



AC-LGAD TOF (~30ps)



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