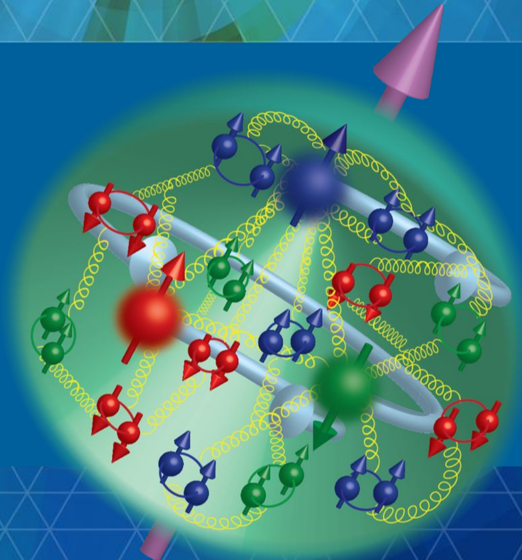
September 25th 2023
25th International Spin Symposium (SPIN 2023)

Proton Spin at EIC

Joint Helicity and Future Experiments Session



Maria ŻUREK
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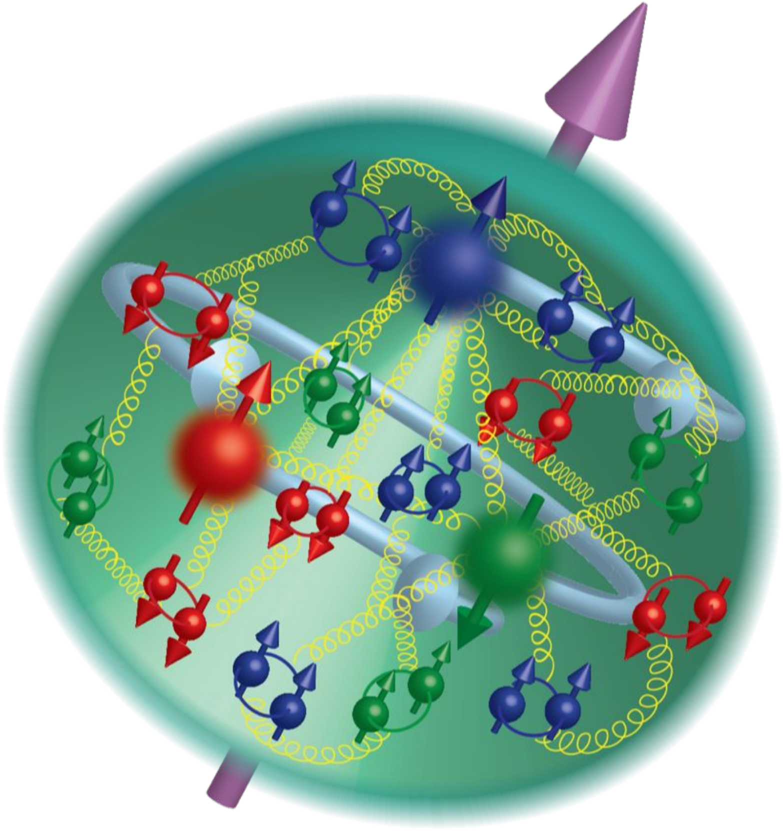
ePIC

Argonne NATIONAL LABORATORY



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

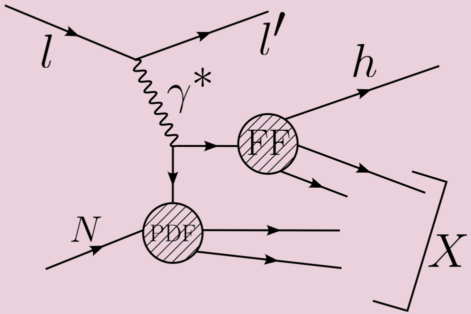
Gluon canonical orbital angular momentum

- 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)

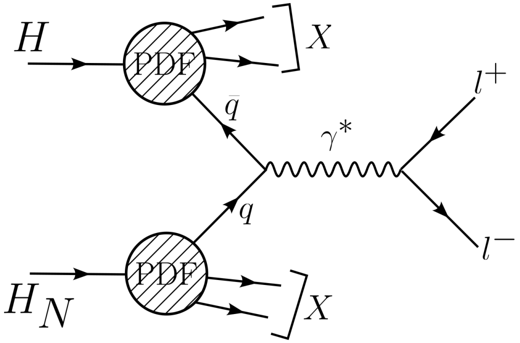
How to access proton spin structure?

Complementarity of experimental probes

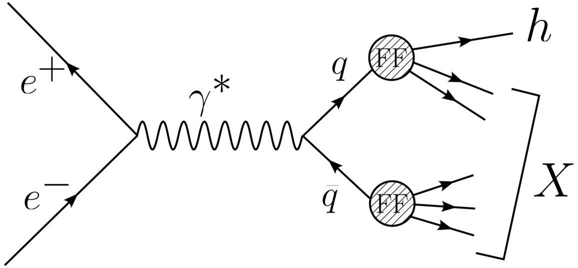
(Semi-Inclusive) Deep Inelastic Scattering

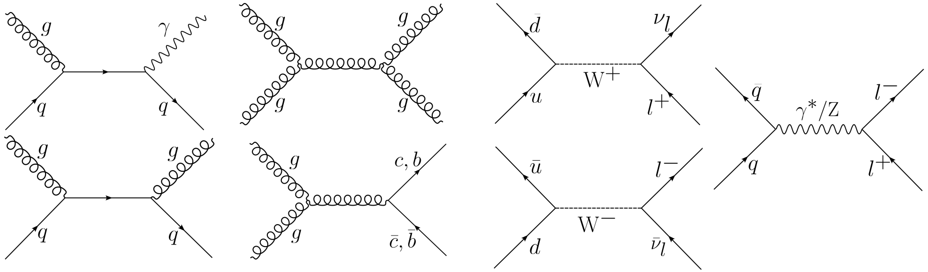


Hadron-hadron interactions



e+e- annihilation (access to FF)





Physics Question

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:

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

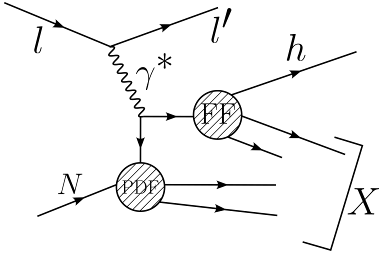
Quark helicity

Gluon helicity

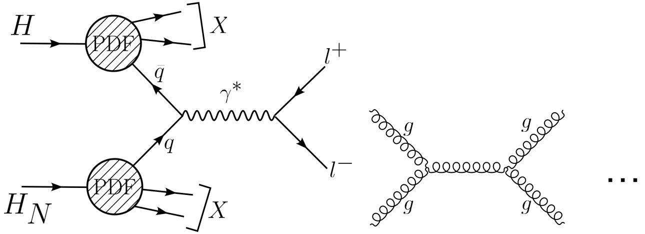
Quark canonical orbital angular momentum

Gluon canonical orbital angular momentum

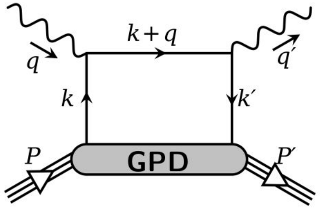
(SI)DIS



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)

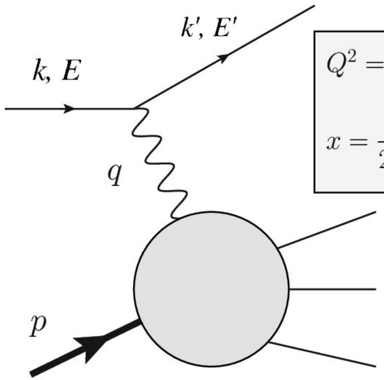
$$\frac{\mathrm{d}^2\sigma_{\mathrm{LL}}(x,Q^2)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{8\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{y^2}{4}\gamma^2\right)\boxed{g_1(x,Q^2)} - \frac{y}{2}\gamma^2 g_2(x,Q^2)\right]$$

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

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

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

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

D - Depolarization factor
η - kinematic fator
A_1 - photon-nucleon asymmetry

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

Longitudinal Spin Structure

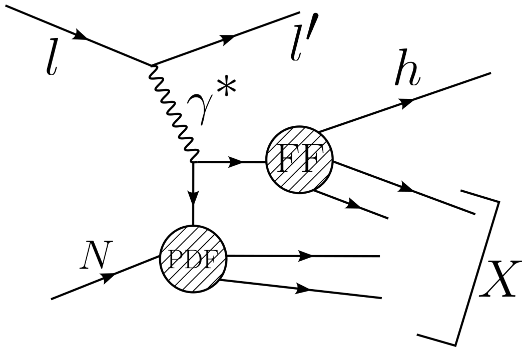
- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- Semi-Inclusive Deep Inelastic Scattering with charged pions and kaons adds **sensitivity to flavor-separated quark helicities** via the fragmentation functions $D_q^h(z,Q^2)$
  - 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

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

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

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)

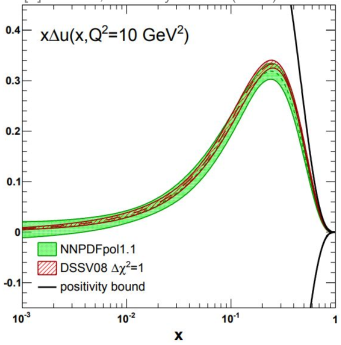
$\sigma^{SIDIS} = \hat{\sigma} \otimes \text{PDF} \otimes \text{FF}$

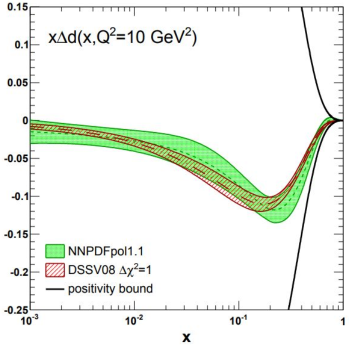
See talk by W. Vogelsang: News on the nucleon's helicity structure

Longitudinal Spin Structure - Where Are We?

u and d quark helicities

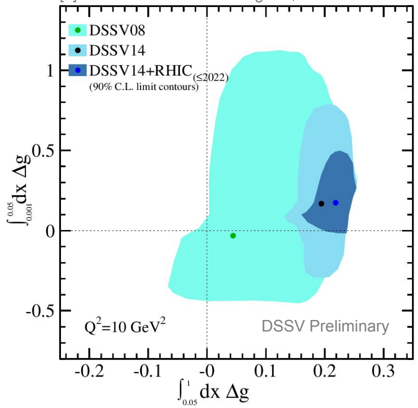
[1] NNPDF, Nucl.Phys.B 887 (2014) 276-308

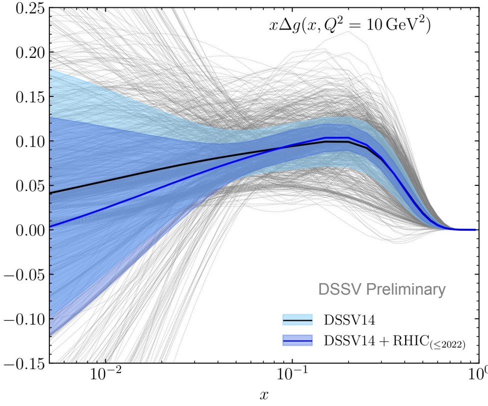




Gluon Helicity

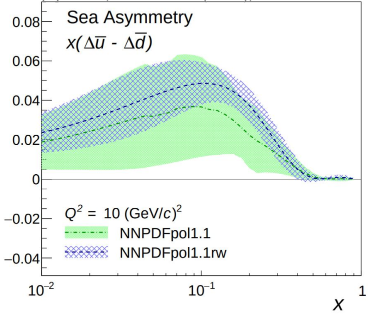
[2]The RHIC Cold QCD Program, arXiv:2302.00605



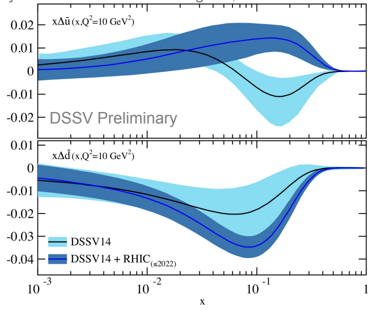


Sea-quark polarization asymmetry

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



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

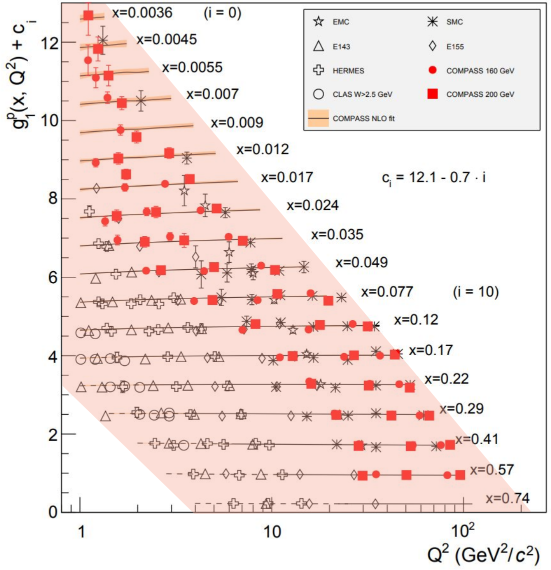


	NNPDF1.1[1]	DSSV08[1]
x	(0.001, 1)	
ΔΣ	$+0.25 \pm 0.10$	$+0.366^{+0.042}_{-0.062}\,(+0.124)$

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

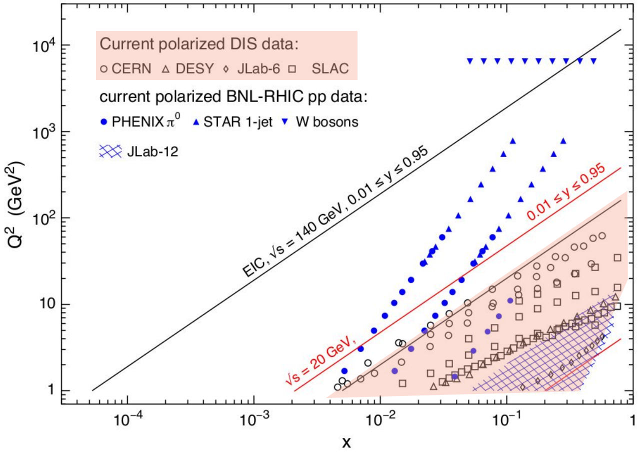
Longitudinal Spin Structure - Where Are We Going?

COMPASS, PLB 753 (2016) 18



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

EIC, Yellow Report

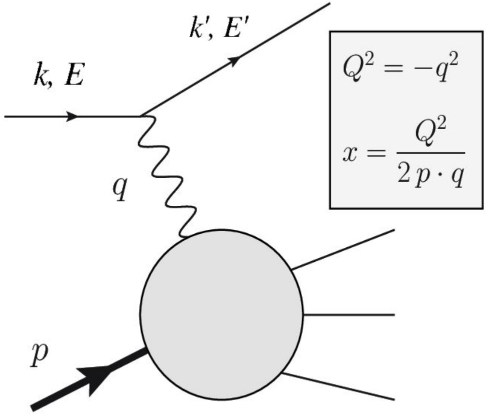


EIC:
Down to x ≈ 10^{-4}
Q^2 ≈ 1-10^3 GeV^2 !

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

DIS Kinematics

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

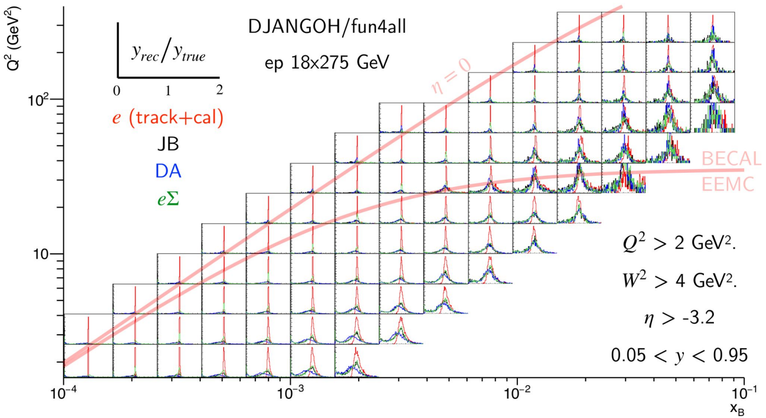


Inclusive NC: leveraging the overconstraint of kinematics to maximize the resolution

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)
- Particle flow for hadronic final state (see, e.g., M. Diefenthaler et al., Eur.Phys.J.C 82 (2022) 11, 1064, C. Pecar, AI4EIC22)

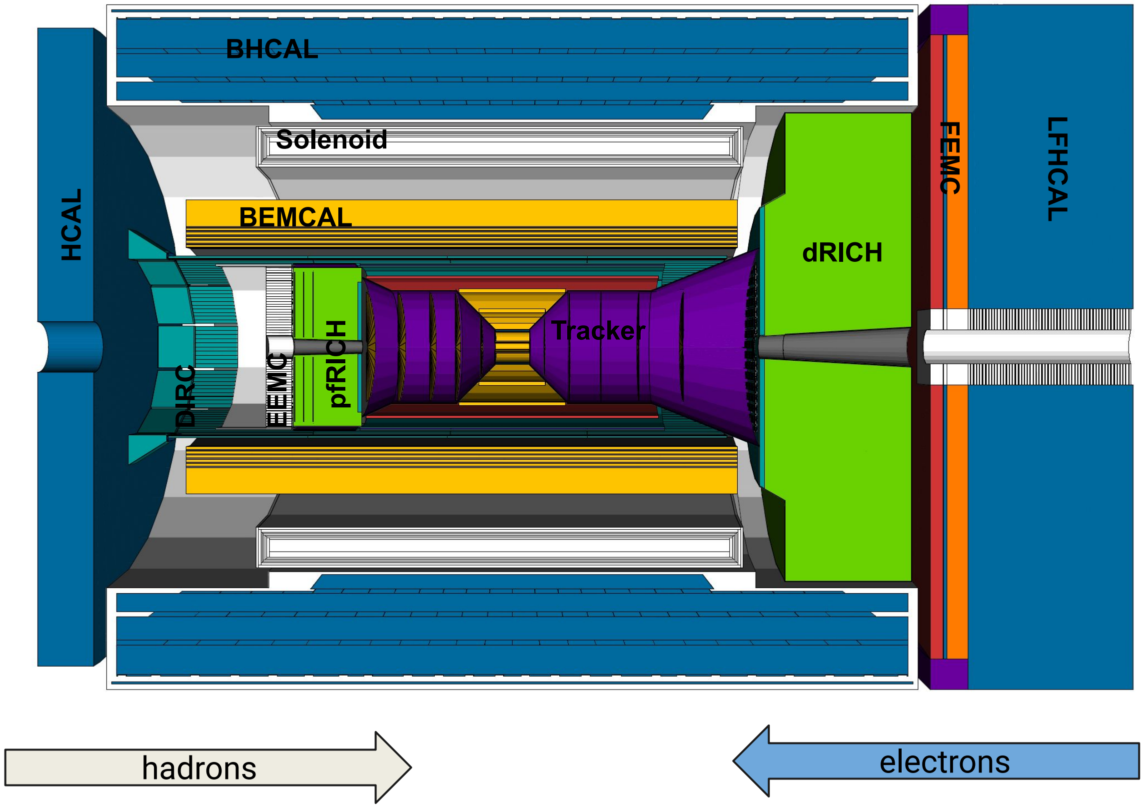


Assessment of relative performance of reconstruction methods for measured phase space for ECCE and ATHENA

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

ePIC Detector Design

See ePIC Overview talk by B. Schmookler



Tracking:
- New 1.7 T solenoid
- Si MAPS Trackers
- MPGDs (mRWELL/mMegas)

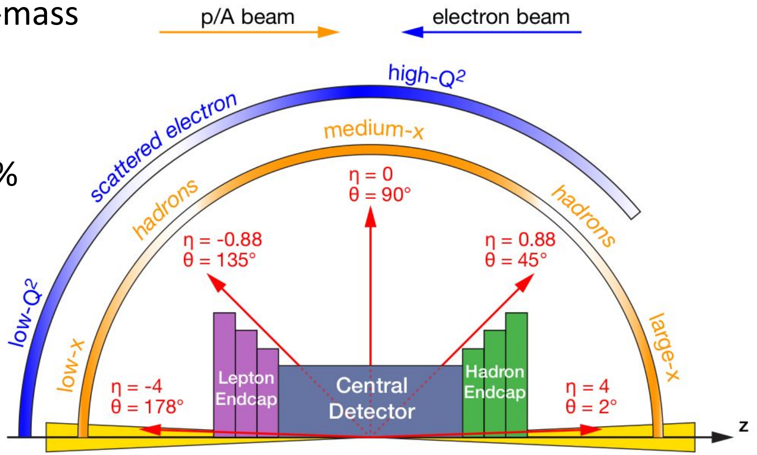
Particle ID:
- DIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- Si and Pb/ScFi Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal + HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

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)

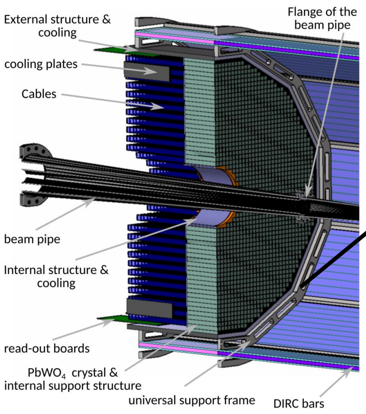
Access to Orbital Angular Momentum - GPD measurements

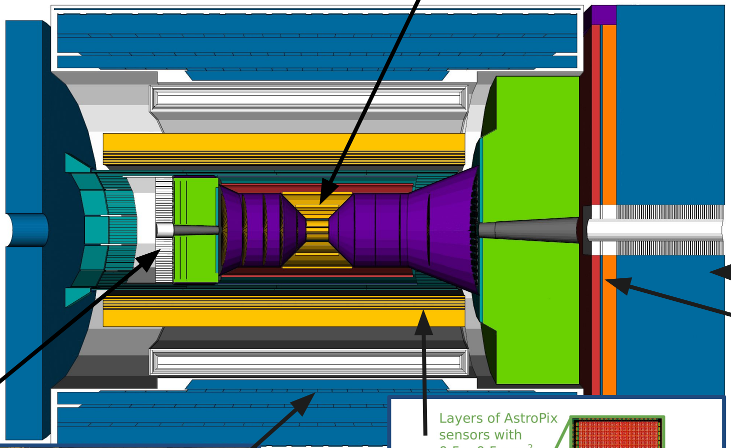
- Demanding program requiring high luminosity and detection of the forward-going protons scattered under small angles

Proton Spin and ePIC Detector Requirements

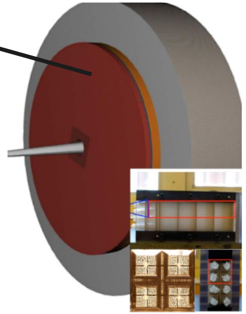
Electron momentum resolution - dominated by tracker in central region: Si MAPS Trackers + µMega (see backup for more details)

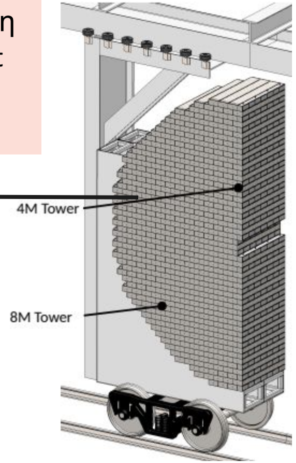
Superior EM energy resolution from Backwards EMCal - $PbWO_4$ crystals

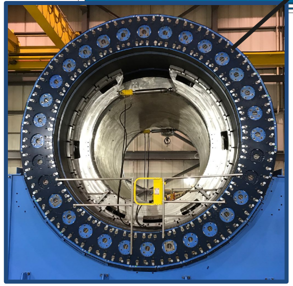




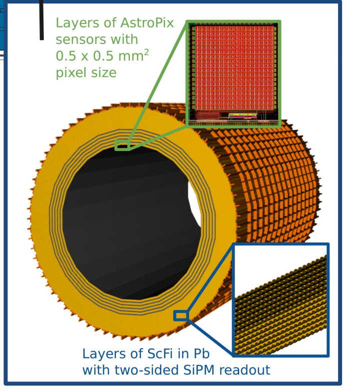
High granularity W/SciFi EMCal and longitudinally separated HCAL with high-η insert for high precision jet (hadronic remnant) reconstruction





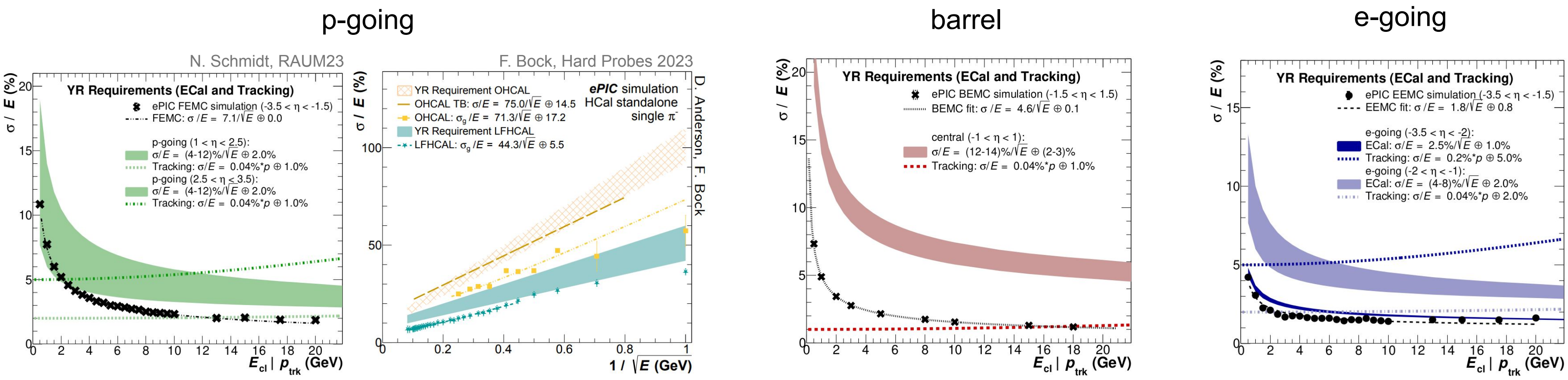


Barrel HCAL
(sPHENIX re-use)



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

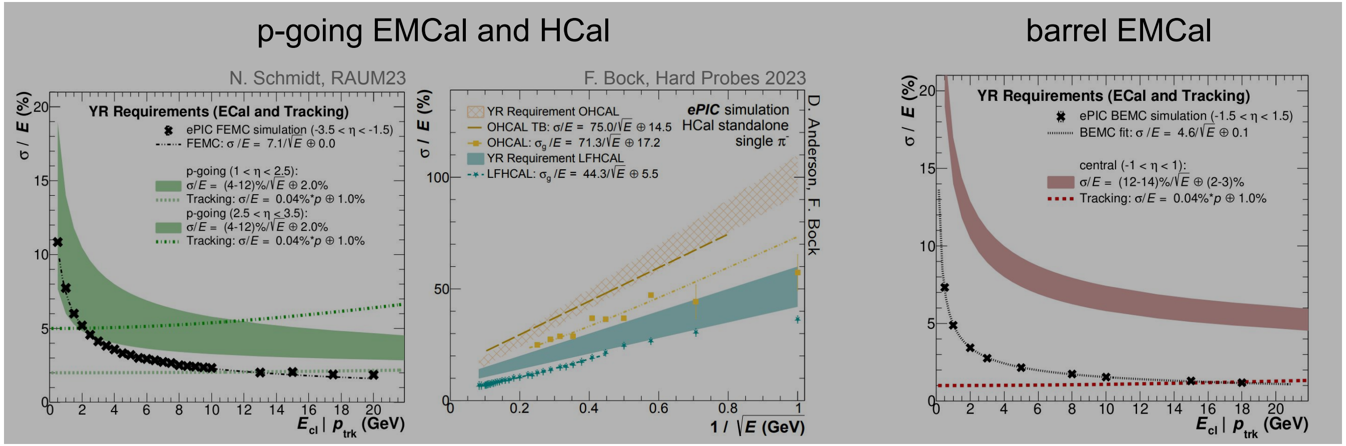
Proton Spin and ePIC Detector Requirements

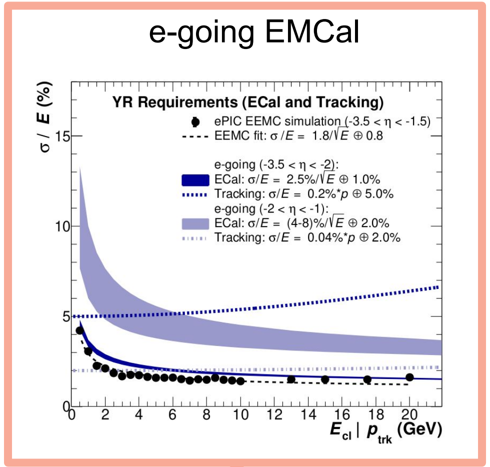


Performance of energy resolution

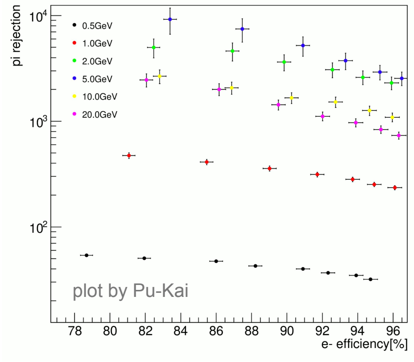
- Technologies fulfill YR requirements on energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry, tracking and reconstruction algorithms
- **Barrel:** electron momentum measurement predominantly from tracker, but e/π separation critical (EMCal for 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

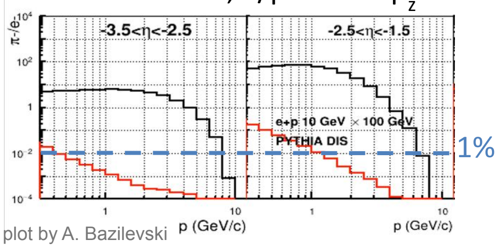




ePIC Simulation, E/p cut only



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

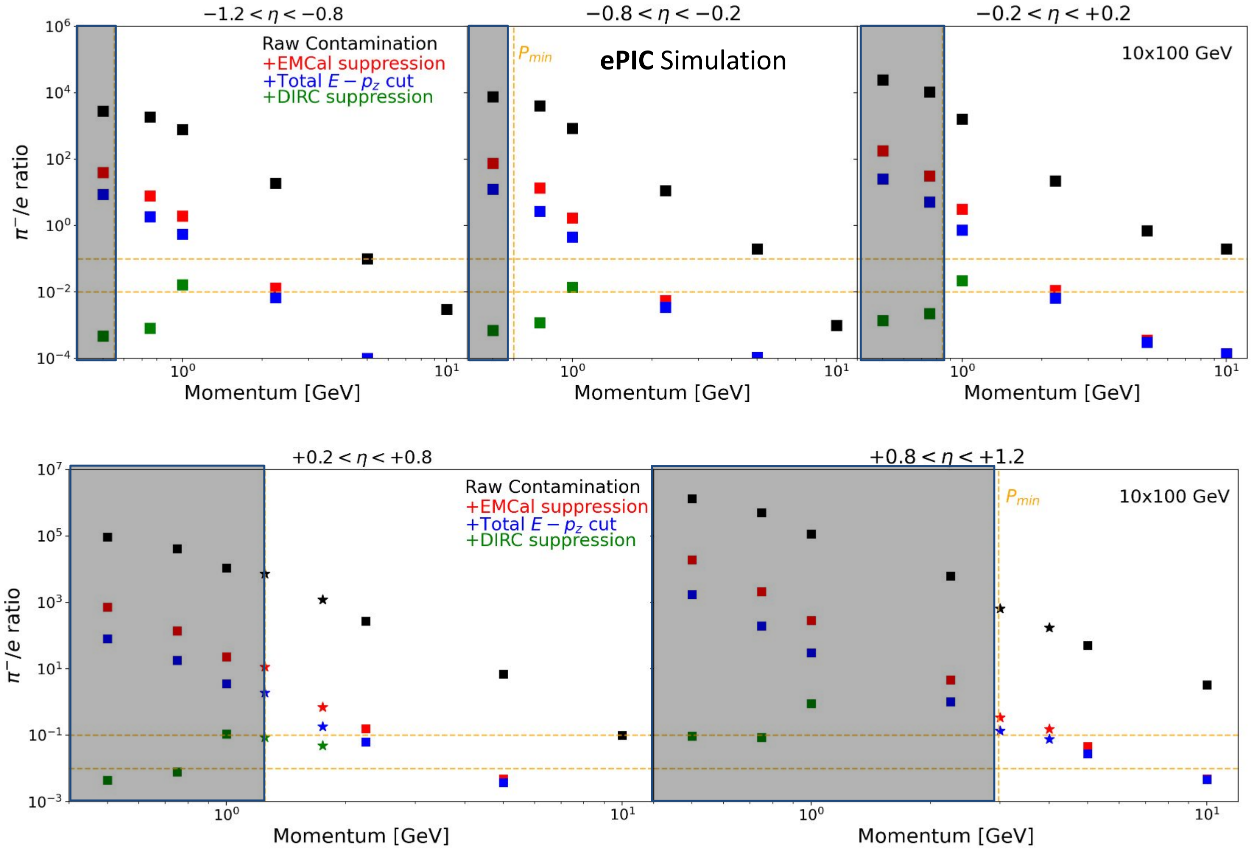


< 1% pion contamination expected for the DIS electron reconstruction

- 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

$\Delta\Sigma$ and ΔG Projections

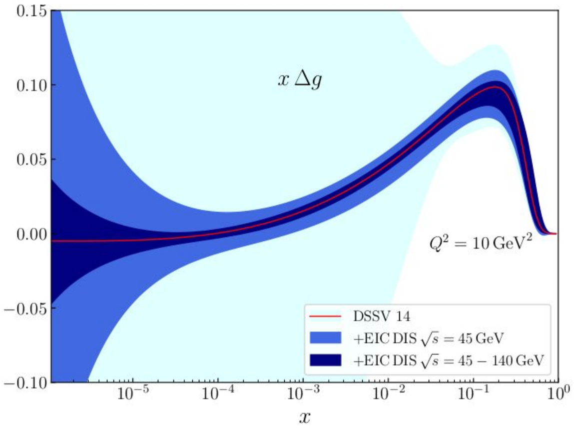
Current world data

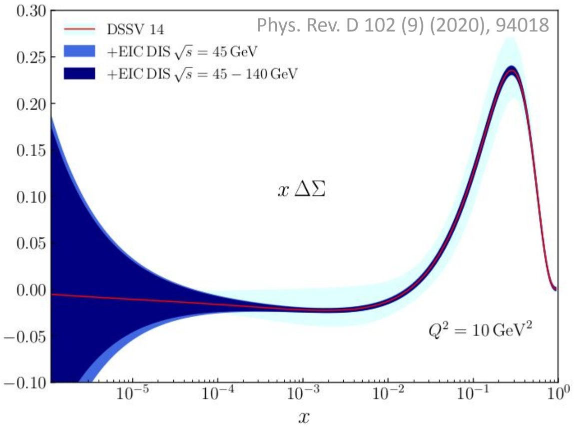
- Helicity distributions known for **x > ~0.01** with good precision

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



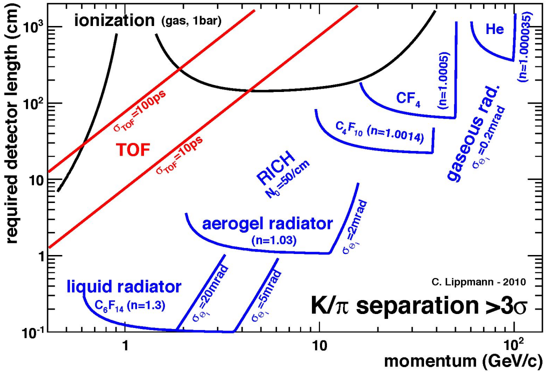


SIDIS and ePIC Detector Requirements

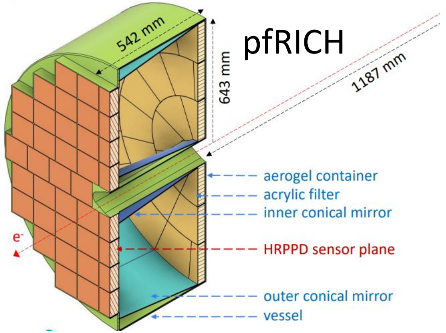
SIDS Measurements to probe fragmentation functions and flavor-separated quark helicities:

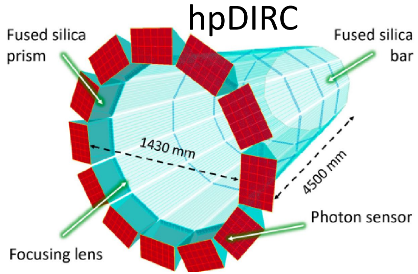
On top of the inclusive DIS requirements ⟶ Particle IDentification needs

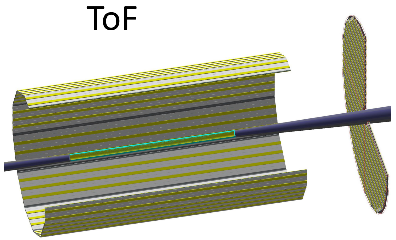
- Charged pions, kaons and protons separation on track level ⟶ **Cherenkov detectors** complemented by **ToF** at lower momenta

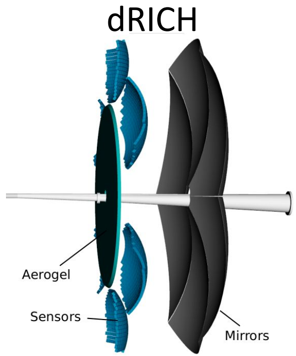


Region	Momentum	ePIC Technology
forward	< 50 GeV/c	dual-radiator RICH
central	< 6 GeV/c	high performance DIRC, AC-LGAD ToF
backward	< 10 GeV/c	proximity focusing RICH







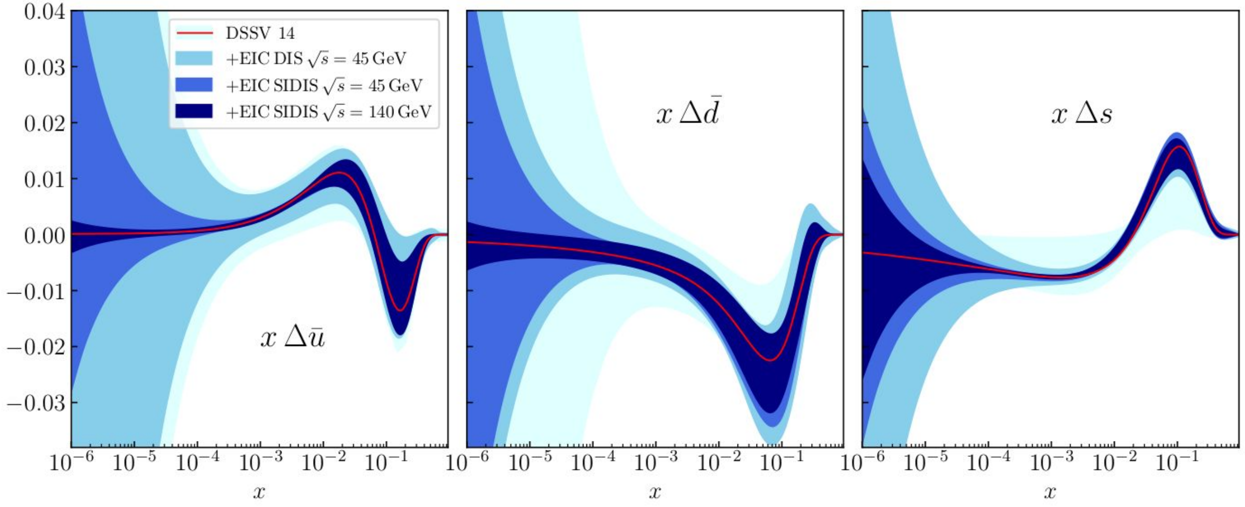


Sea Quark Helicities Projections

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



GPDs and Angular Orbital Momentum

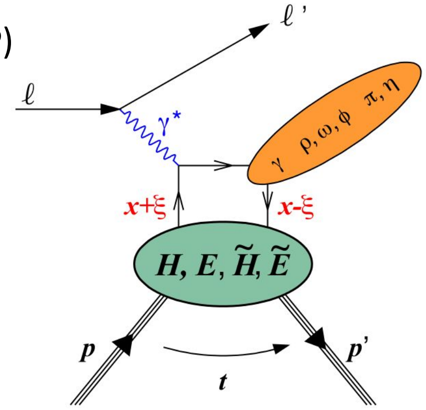
Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t)+E^q(x,\xi,t)]$ $\quad J_q = \frac{1}{2}\Delta\Sigma + L_q$

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

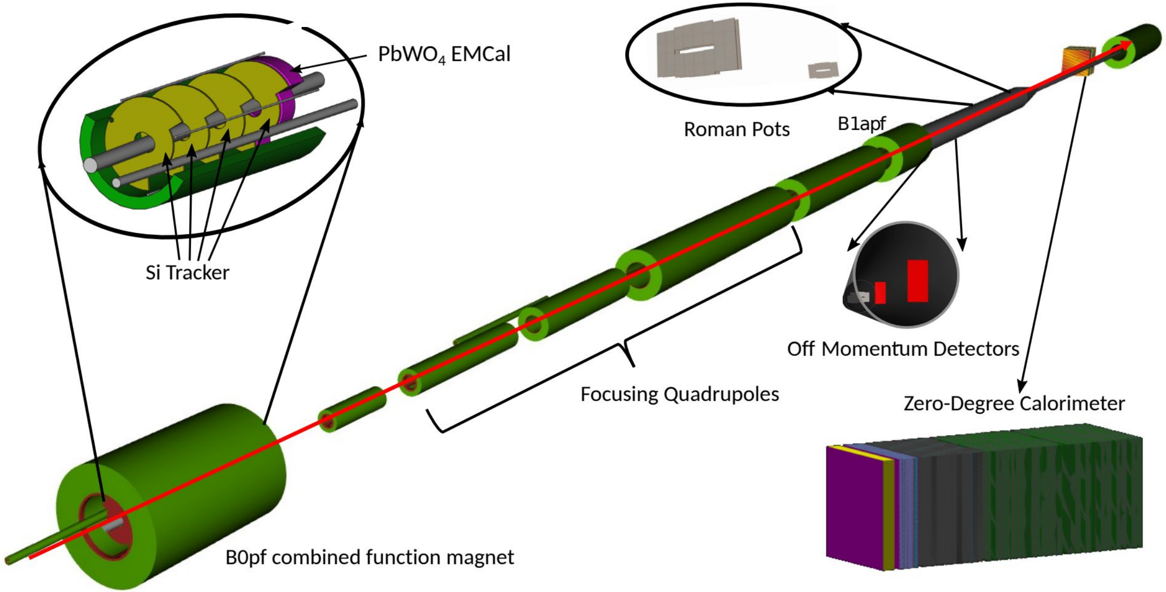


DVCS and access to GPDs

- 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

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

Far-Forward Detectors



The impact parameter information is encoded in $t = (p' - p)^2$

- Require accurate measurement of t across a wide range in ep collisions
- Scattered protons measured at Roman Pot (low t) detectors and B0 (higher t)

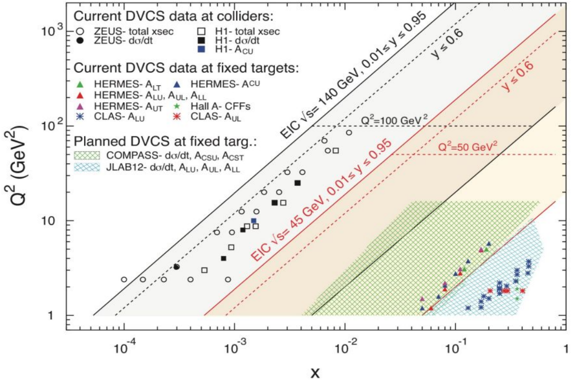
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$\theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)

See talks plenary and in GPD session:
V. Martinez-Fernandez, Can we measure Double DVCS at JLab and the EIC?
S. Klein, Probing parton distributions in ep and ultra-peripheral collisions
FX Girod: GPDs at future JLab, complementarity with EIC

GPDs at EIC: Snapshot

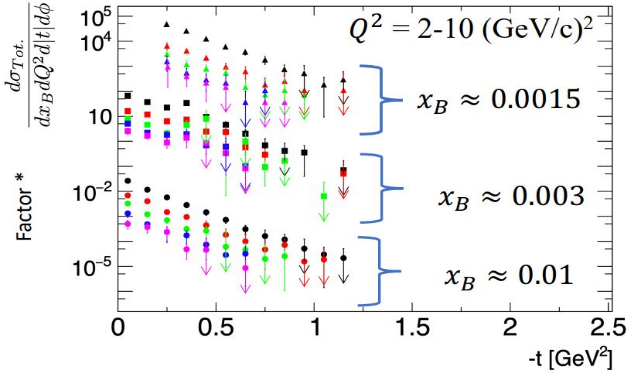
EIC kinematic reach: DVCS

EIC, Yellow Report



Projected DVCS cross-sections

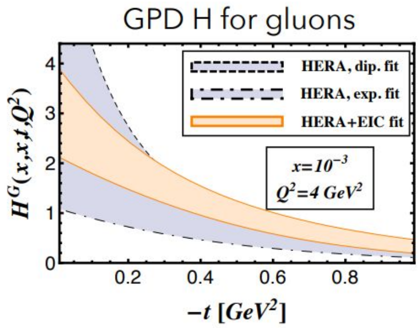
ECCE Simulation, 10 fb^{-1}, I. Korover, DIS23

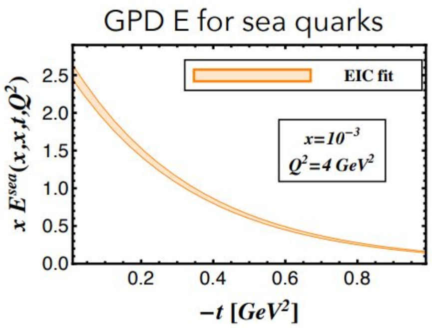


- ▲ e+p 18+275 GeV
- ■ e+p 10+100 GeV
- ● e+p 5+41 GeV

Strong constraints on extraction of Compton Form Factors from multidimentional binning

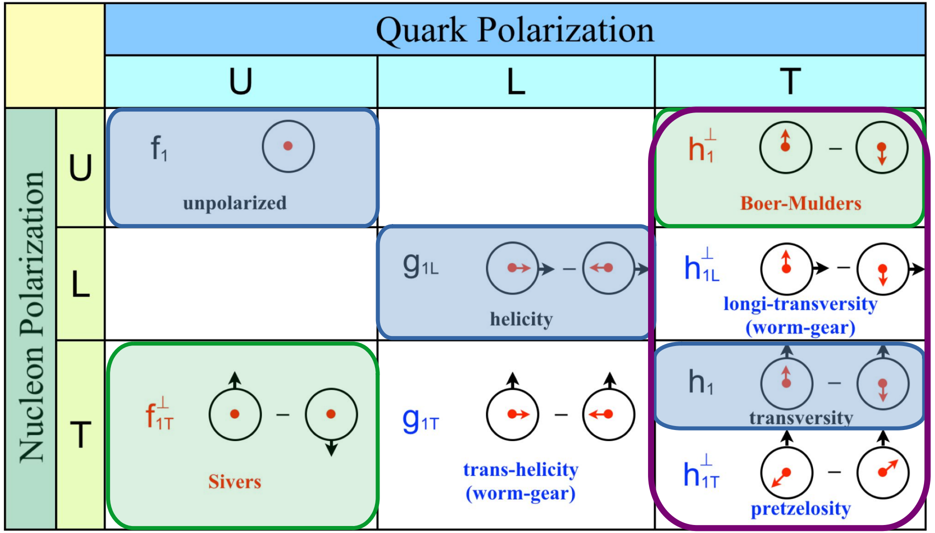
Anticipated constrain on GPDs H and E from EIC





- 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

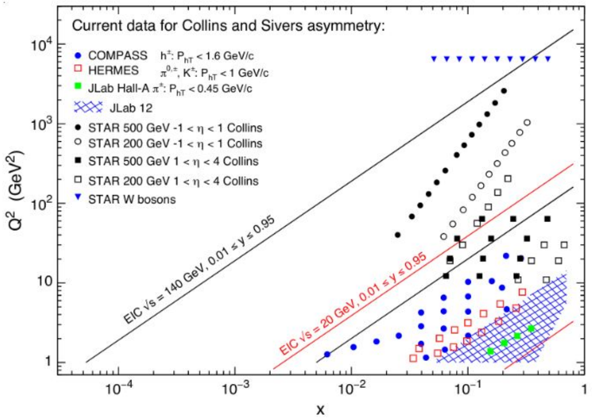
- **Sivers:** correlations of transverse-spin direction and the parton transverse momentum
- **Boer-Mulders:** correlations of parton transverse spin and parton transverse momentum
- **Collins:** fragmentation of a transversely polarized parton into a final-state hadron

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

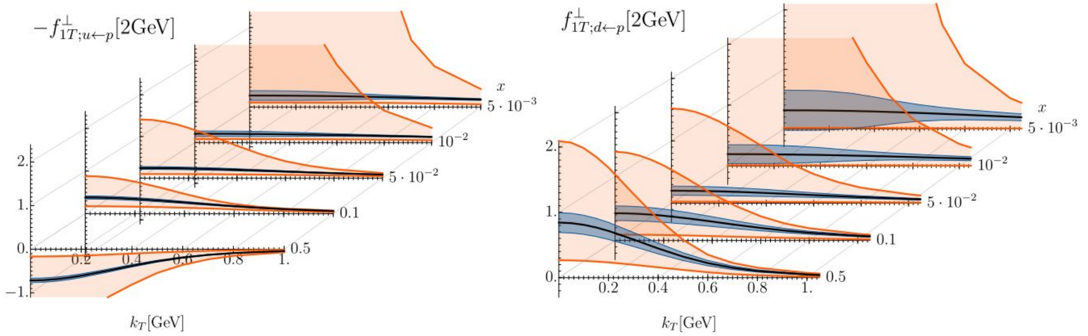
EIC kinematic reach: Collins and Sivers

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

Summary

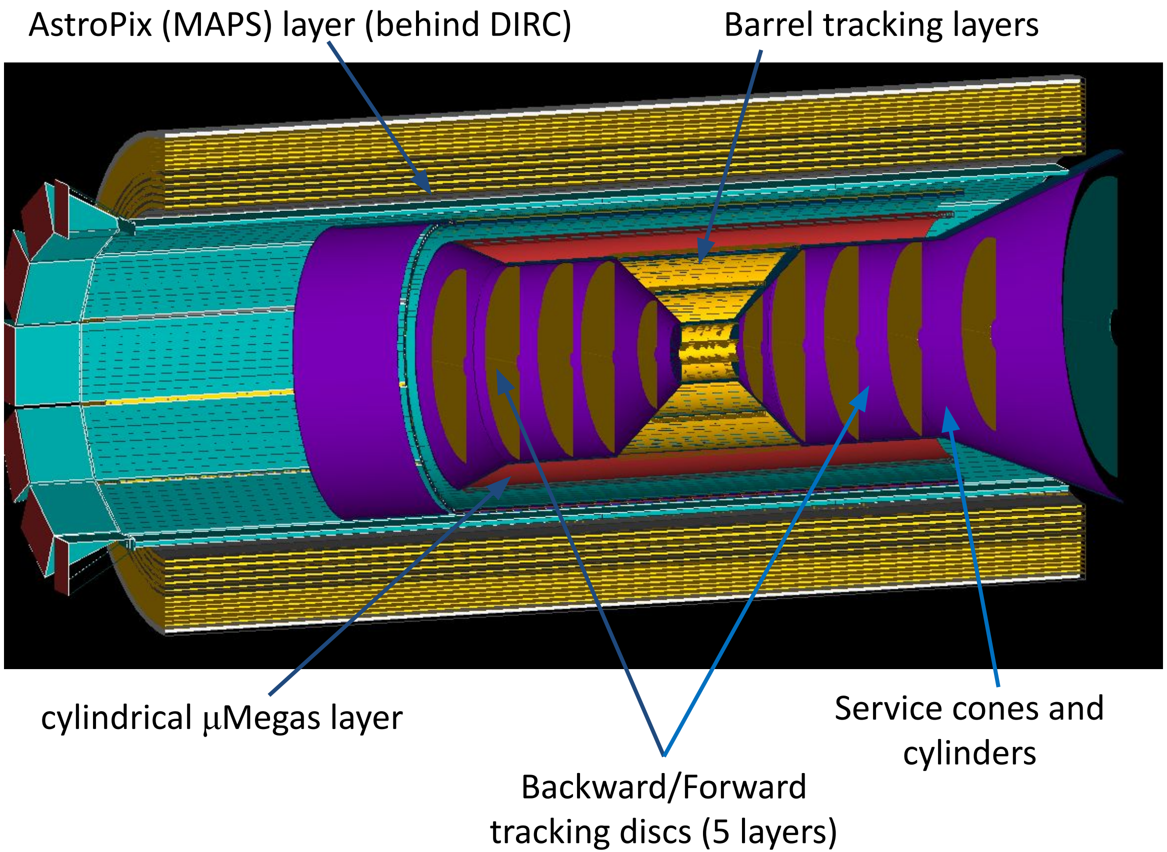
- Experiments employing both **lepton scattering processes** and **hadron-hadron interactions** have unveiled the intricate nucleon spin structure.
    - Decades of research encompassing **Deep Inelastic Scattering, Semi-Inclusive Deep Inelastic Scattering, and proton-proton collisions have paved the way**.
- **The Electron-Ion Collider promises precision** in probing the longitudinal spin structure of nucleons across a wide range of x and Q^2.
    - Polarized DIS measurements provide insight into **gluon and quark spin contributions** to proton spin via g_1.
    - SIDIS measurements involving pions and kaons shed light **on sea quark helicities**.
    - Access to **OAM** through Generalized Parton Distributions.

Progress Update:

- Extensive studies within the ePIC detector simulation framework have demonstrated alignment with Yellow Report requirements for the proton-spin program.
- Advanced reconstruction studies are currently underway.

Backup

ePIC Tracking



- **Inner two vertex layers** optimized for beam pipe bakeout and ITS-3 sensor size
- Third layer dual-purpose (vertex + sagitta) - **5 layers total**
- **Five discs in forward/backwards** direction (ITS-3 based large area sensor design)
- **Cylindrical μMega** provide pattern recognition redundancy
- **1st AstroPix layer of Barrel ECal** provides ring seed direction, space point for pattern recognition

ePIC Tracking

Technology

ITS3 MAPS based Si-detectors:

- O(10μm) pitch, X/X^0 ~ 0.05 – 0.55%/ layer

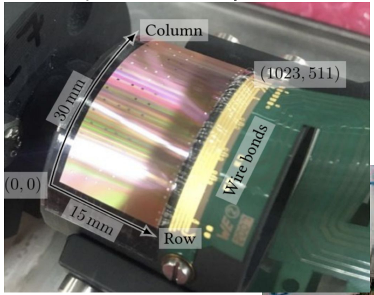
Gaseous tracker:

- σ = 55 μm, X/X_0 ~ 0.2%/layer

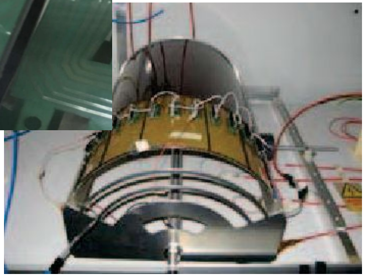
AstroPix outer tracker layer:

- 500μm pixel pitch (σ = 144 μm)

First “μITS3” assembly at CERN

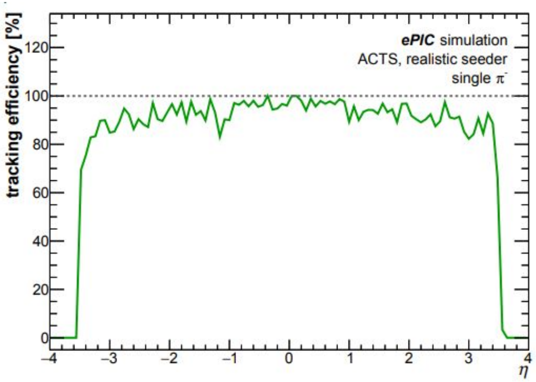


Cylindrical μMega



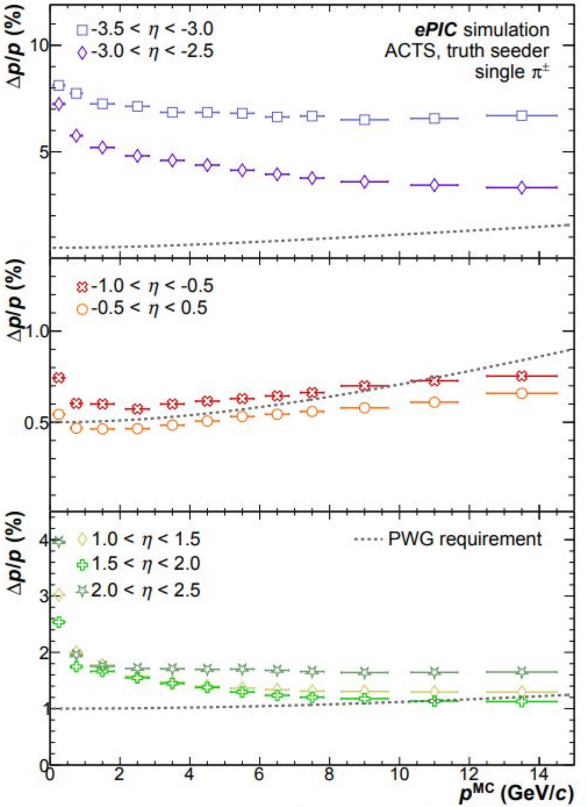
Simulated performance

F. Bock, Hard Probes 2023



- Meets EICUG Yellow Report design requirements
- Backward momentum resolution complemented by calorimetric resolution

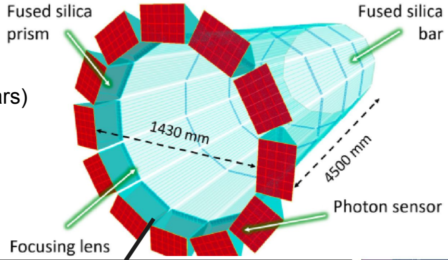
F. Bock, Hard Probes 2023



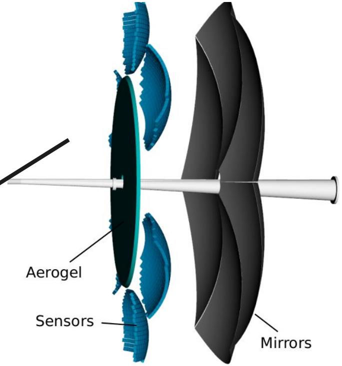
E. Yeats, R. Cruz-Torres, N. Schmidt, S. Maple

ePIC Particle ID

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

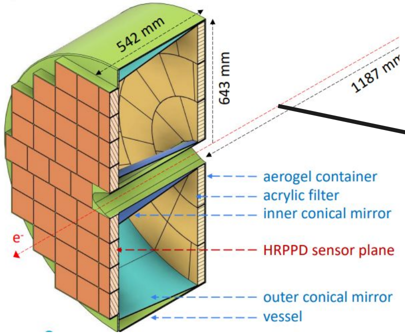


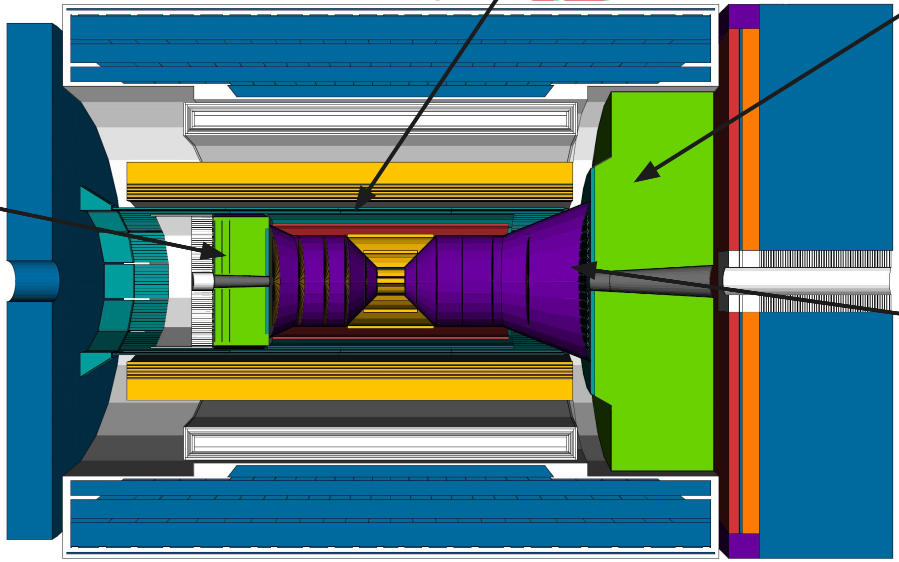
Dual-Radiator RICH(dRICH)



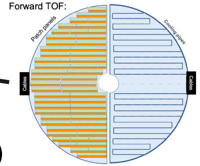
- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3σ sep. at 50 GeV/c

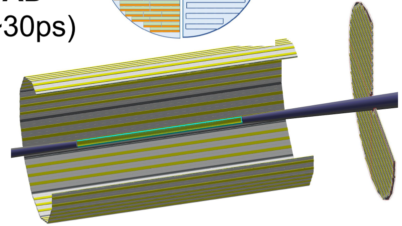
Proximity Focused (pfRICH)
- Proximity gap >40 cm
- Sensor: LAPPDs
- up to 9 GeV/c 3σ π/K sep.





AC-LGAD TOF (~30ps)



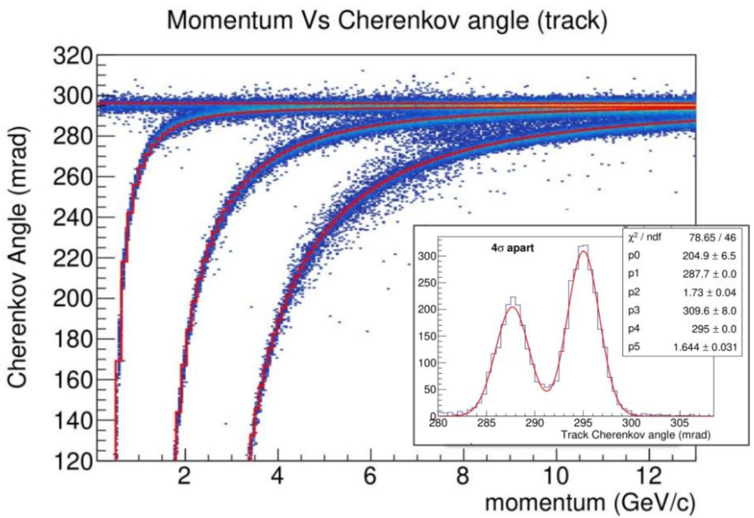


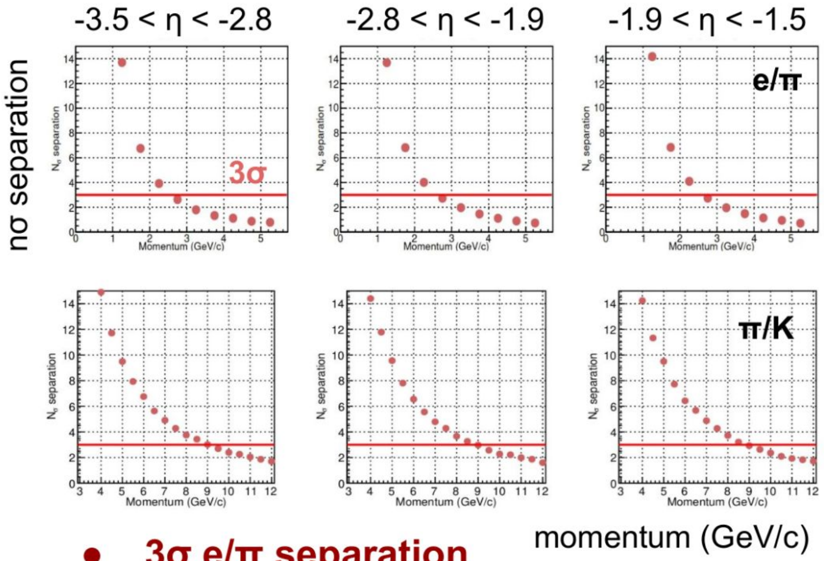
- Accurate space point for tracking
- forward disk and central barrel

pfRICH Simulated Performance

Roberto Preghenella, DIS23

complete Geant4 simulation, event-level digitisation and reconstruction





- **direct and reflected photon hits**
  - reconstruction algorithm capable of handling complex categories
  - angles in agreement with expectations
- **3σ e/π separation**
  - up to ~ 2.5 GeV/c
- **3σ π/K separation**
  - up to ~ 9.0 GeV/c

EIC Projections

ATHENA Detector Proposal, JINST 17 (2022) 10, P10019

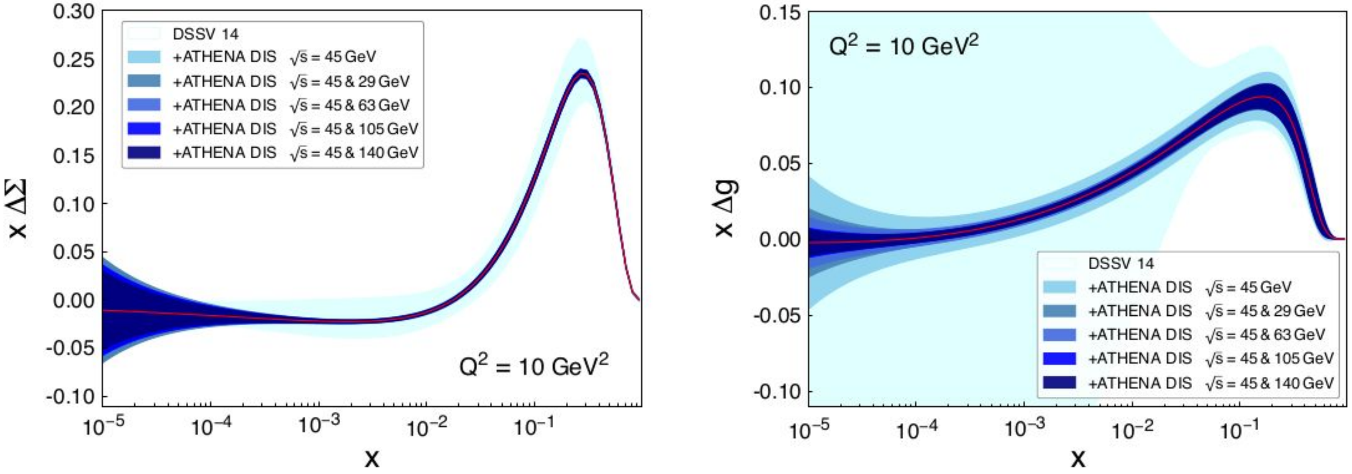


Figure 3.9: Impact of DIS inclusive A_{LL}^{p} pseudodata from ATHENA (FastSim) on the understanding of the proton spin, as expressed through helicity distributions at $Q^2 = 10\ \mathrm{GeV}^2$ in the DSSV14 fitting framework. Left: singlet quark helicity distribution. Right: gluon helicity distribution. The outermost bands correspond to the uncertainties in DSSV14. The inner bands show the results of additionally including simulated ATHENA data at different center-of-mass energy combinations, as indicated.

EIC Projections

ECCE Simulation, NIM Volume 1056, November 2023, 168563

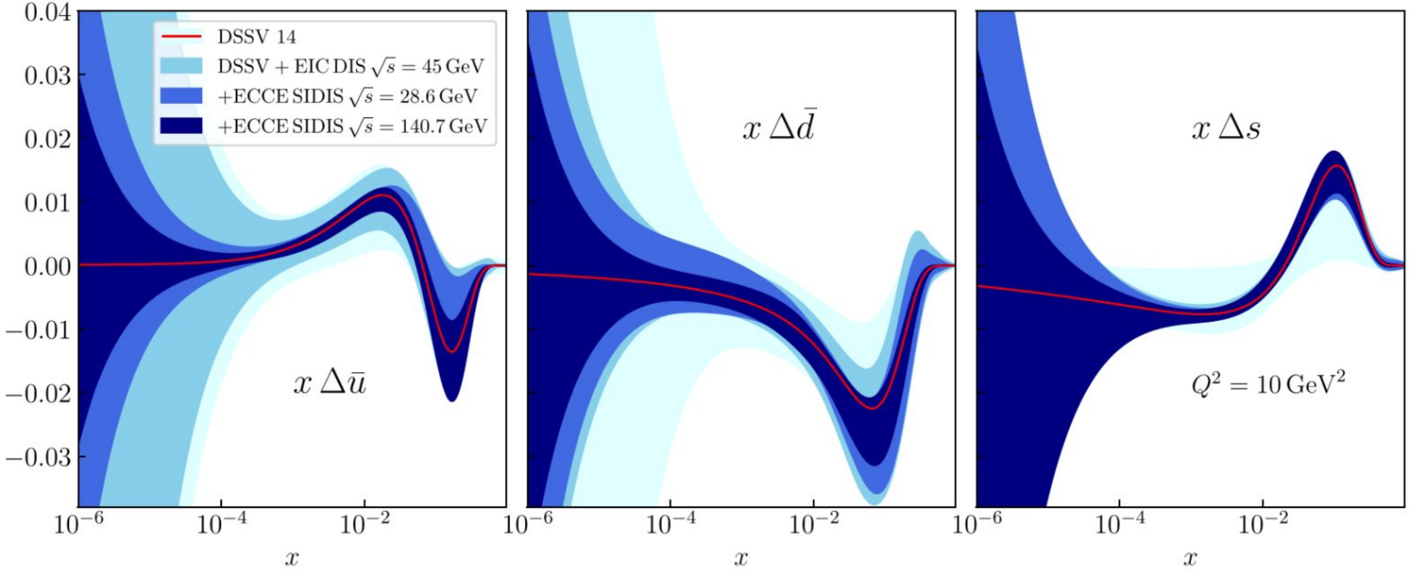


Fig. 10. Figures showing the impact of the projected ECCE semi-inclusive DIS data on the determination of the sea-quark helicity distributions for $\bar{u}$ (left), $\bar{d}$ (middle) and s (right), evaluated at $Q^2 = 10$ GeV^2. Together with the DSSV14 estimate, the uncertainty bands resulting from the fit that includes the $\sqrt{s} = 45$ GeV simulated inclusive DIS data and the reweighting with simulated ECCE semi-inclusive DIS data at $\sqrt{s} = 28.6$ GeV and $\sqrt{s} = 140.7$ GeV are presented.