The ePIC experiment and physics highlights

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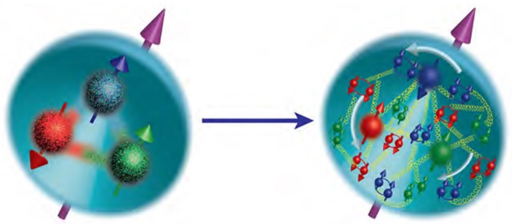
INFN
Gruppo Collegato di Cosenza
Istituto Nazionale di Fisica Nucleare


2nd workshop on advancing the understanding of non-perturbative QCD using energy flow
Stony Brook University - November 6-9, 2023

Most compelling physics GOALS

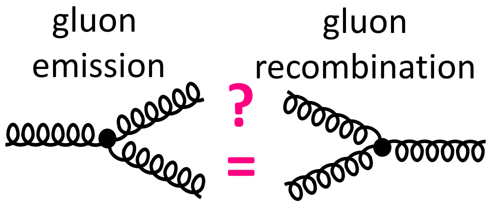
How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

- How do the nucleon properties (spin, mass) emerge from them and their interactions?



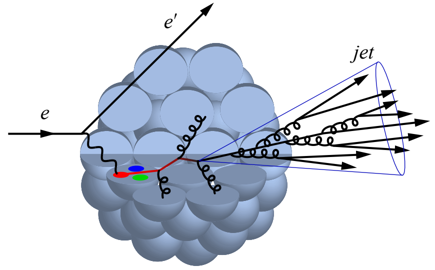
What happens to the gluon density in nuclei?

- Does it saturate at high energy?
- Does this saturation give rise to a gluonic matter with universal properties in all nuclei, even proton?

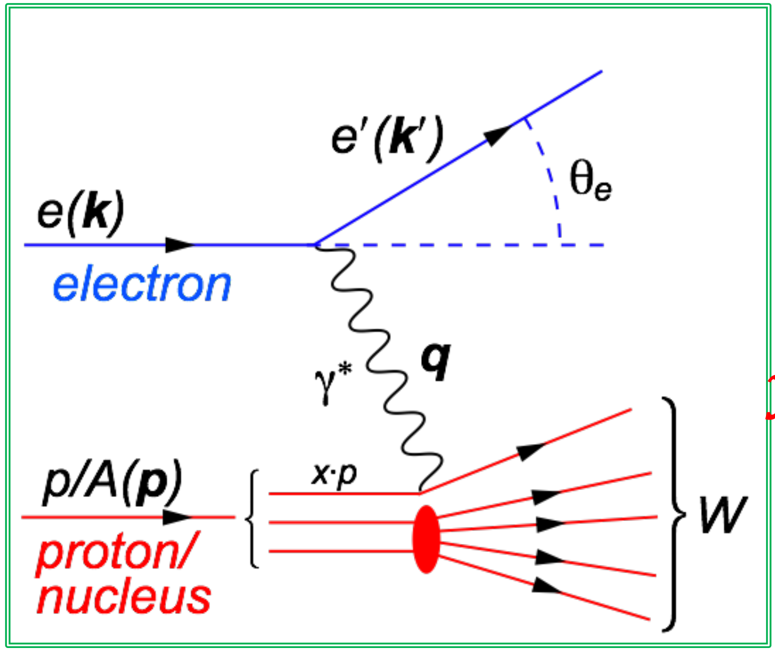


How does a dense nuclear environment affect the quarks and gluons, their correlations and interactions?

- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?



Our Tool – Deep Inelastic Scattering



Kinematics:

$$Q^2 = 2E_e E'_e(1-\cos\theta_{e'}) = -(k-k')^2 = -q^2$$

Measure of resolution power

$$y = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq}$$

Measure of momentum fraction of struck quark

$$\sqrt{s} = 2\sqrt{E_e E_p}$$

Center-of-mass energy of electron-hadron system

All variables are correlated: $Q^2 = s \cdot x \cdot y$

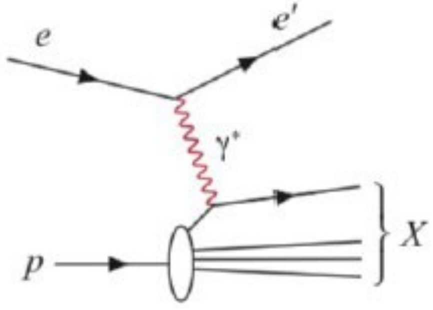
DIS:

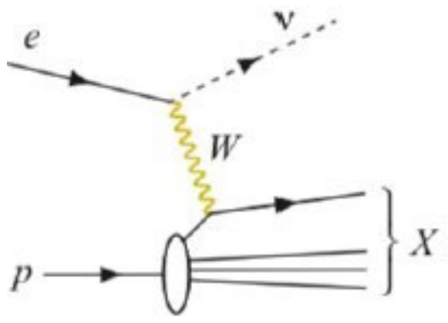
- ✧ As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- ✧ Direct, model independent, determination of kinematics of physics processes

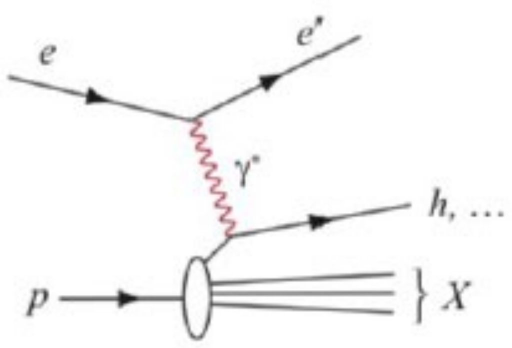
What process must be measured?

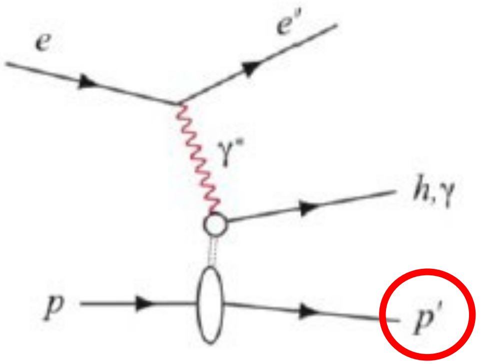
Parton Distributions in nucleons and nuclei / QCD at Extreme Parton Densities - Saturation / Spin and Flavor structure of nucleons and nuclei / Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation / Tomography Spatial Imaging







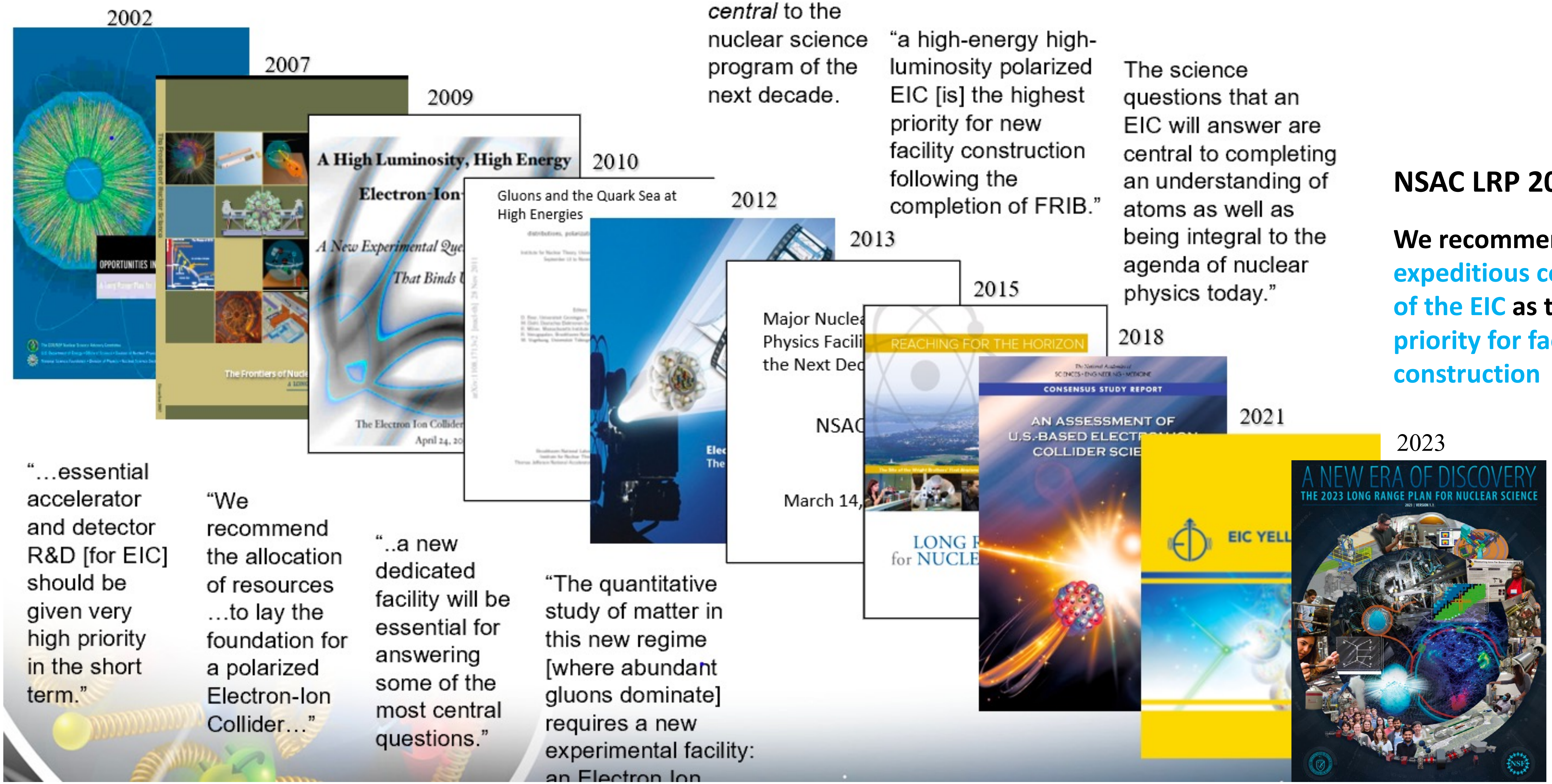


NC & CC Inclusive DIS	Semi-Inclusive DIS	Exclusive Reactions
$\sim 1\ \mathrm{fb}^{-1}$	$\sim 10\ \mathrm{fb}^{-1}$	$\sim 100\ \mathrm{fb}^{-1}$

$\int \mathcal{L} dt$:

Hadronic Jets: B. Page

> 20 years long pathway!



"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion

central to the nuclear science program of the next decade.

"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

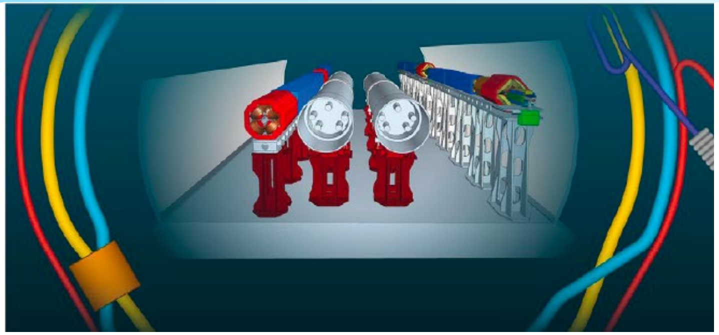
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

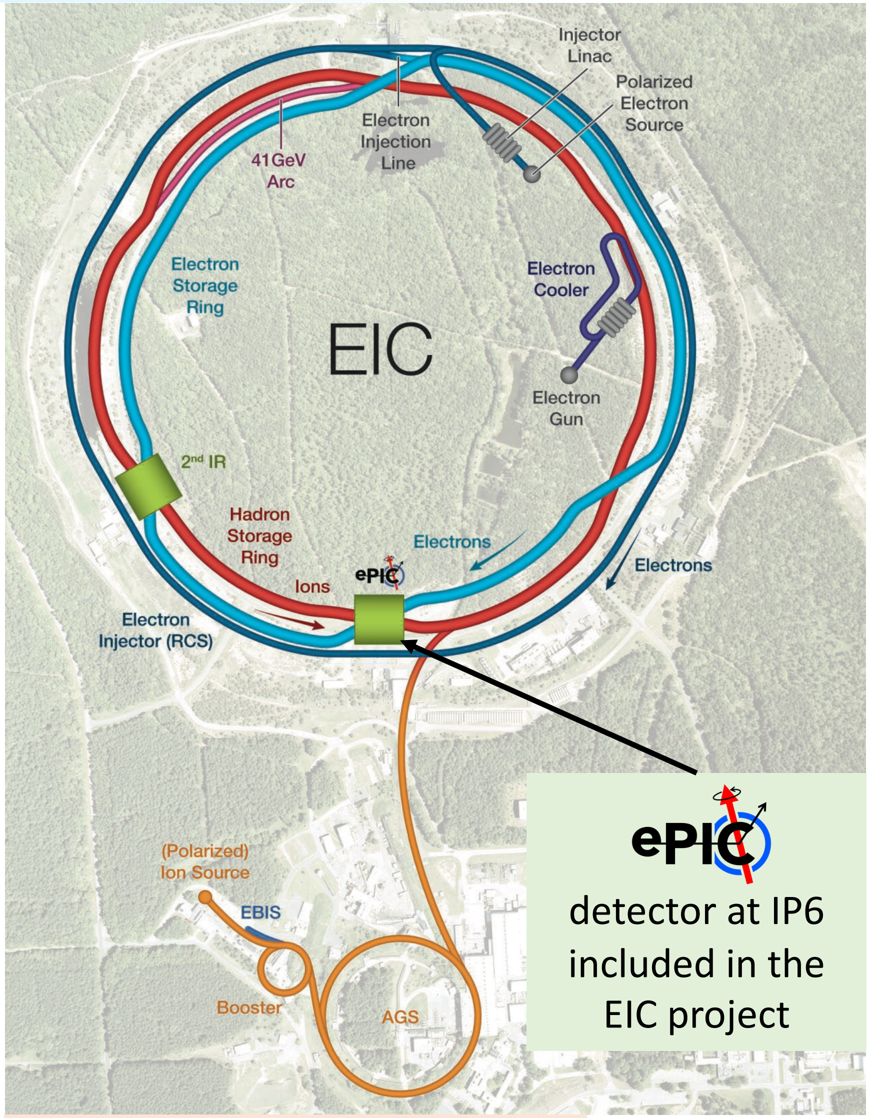
NSAC LRP 2023:

We recommend the expeditious completion of the EIC as the highest priority for facility construction

The Electron-Ion Collider

A DOE approved project!
Could be the only new collider in the coming ~20-30 years





ePIC detector at IP6 included in the EIC project

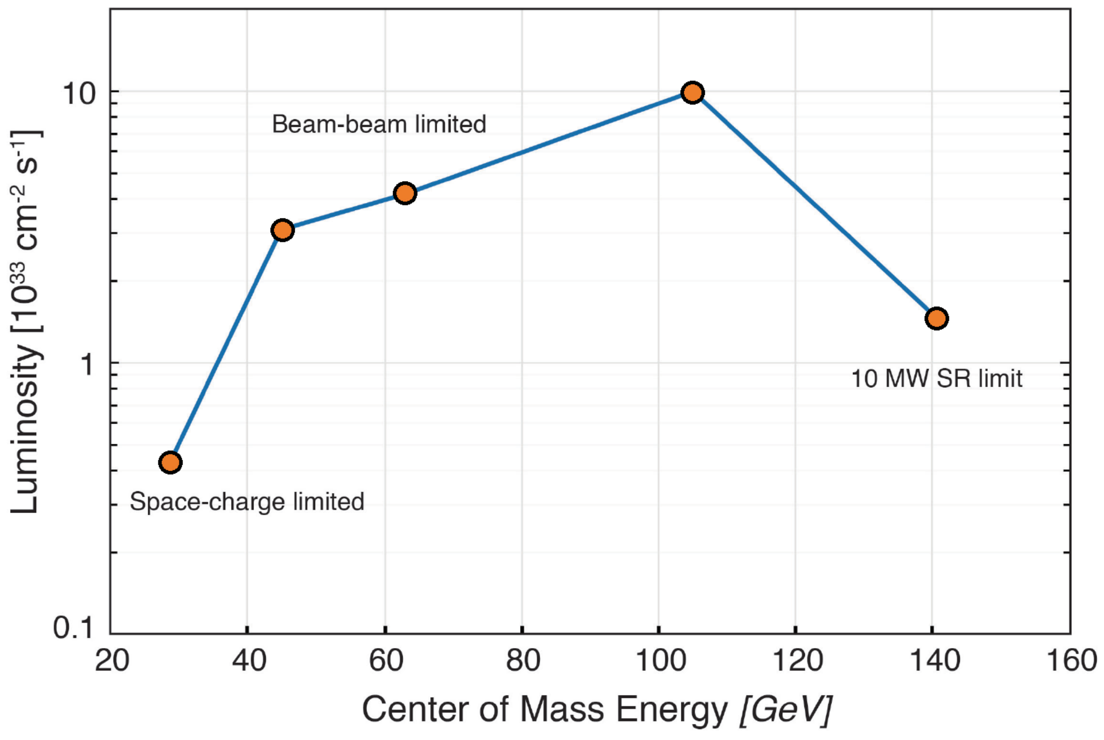
- ✓ Add a 5 to 18 GeV electron storage ring (same tunnel) & its injector complex to the RHIC facility
- ✓ Two interaction regions, IP6 and IP8
- ✓ High Luminosity: 10^{33} -10^{34} cm^{-2}s^{-1} (~10^2-10^3 times HERA)
- ✓ Flexible √s = 29-141 GeV (per nucleon)
- ✓ Highly polarized (~70%) $e^{\uparrow}, p^{\uparrow}, d^{\uparrow}, He^{\uparrow}$, flexible spin pattern
- ✓ Wide variety of nuclear beams: (D to U)

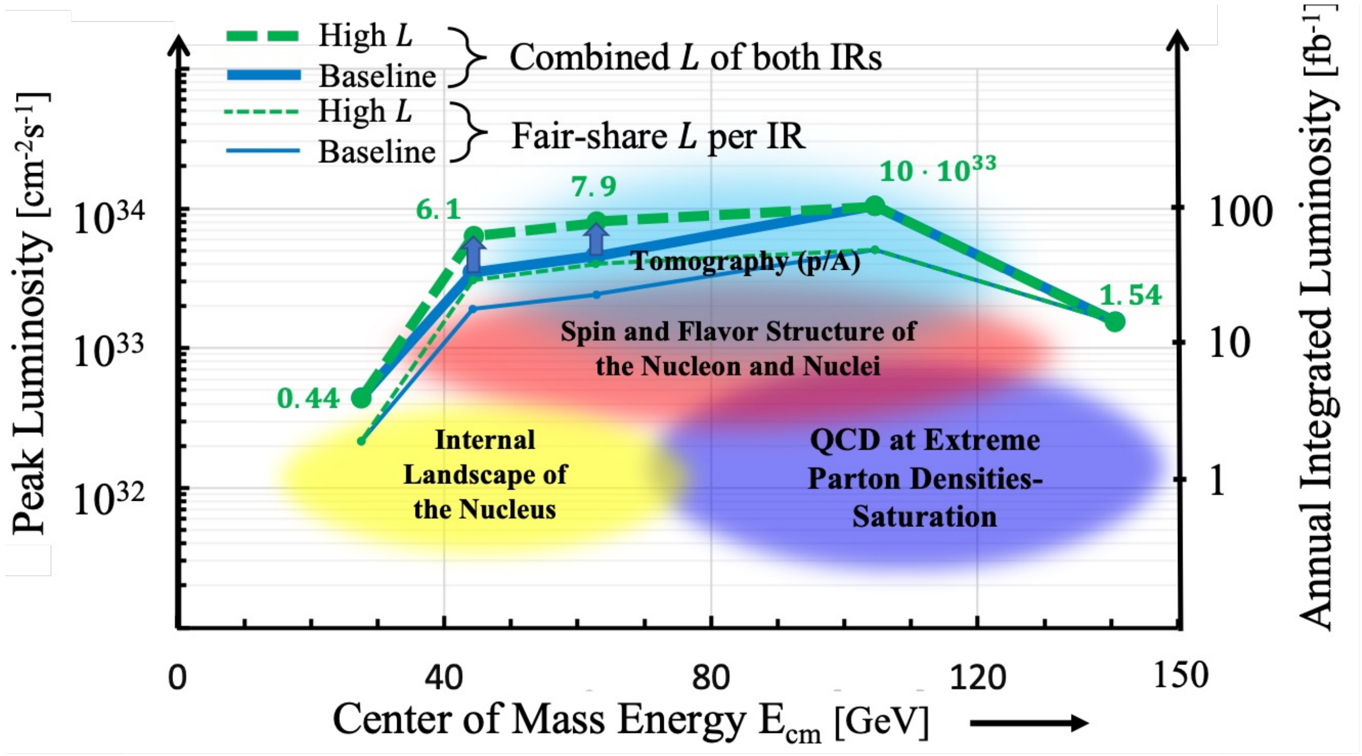
World's first Polarized electron-proton/light ion and electron-Nucleus collider

2^{nd} detector concept: Bill Li

Polarimeters: Z. Zhang

The EIC Luminosity





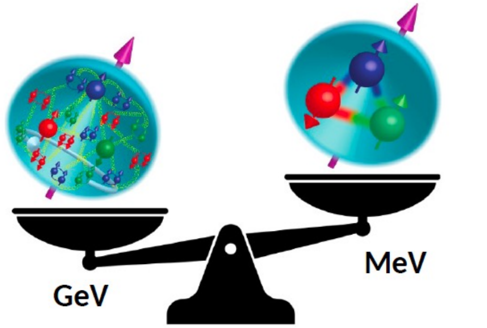
- $e-p$ collisions luminosity vs center-of-mass energy
  - achieves expected physics needs
- $e-A$ collisions luminosity is similar within a factor of ~2 to 3

Scientific goals: origin of the mass of visible matter

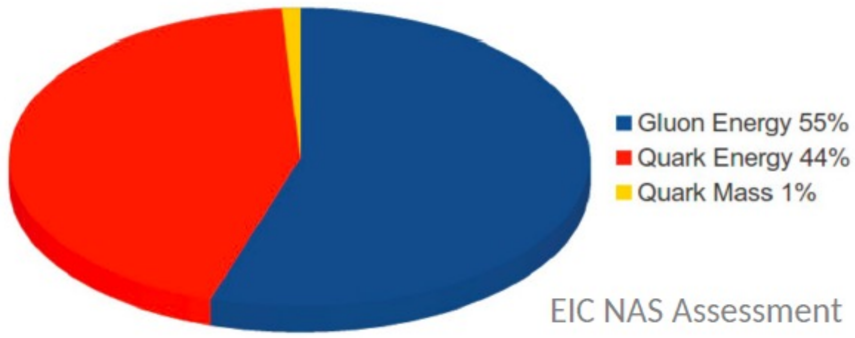
- Gluons have no mass and quarks are very light, but nucleons and nuclei are heavy, making up for most of the visible mass in the Universe
- Visible matter only made of constituents of light mass: masses emerge from quark-gluon dynamics

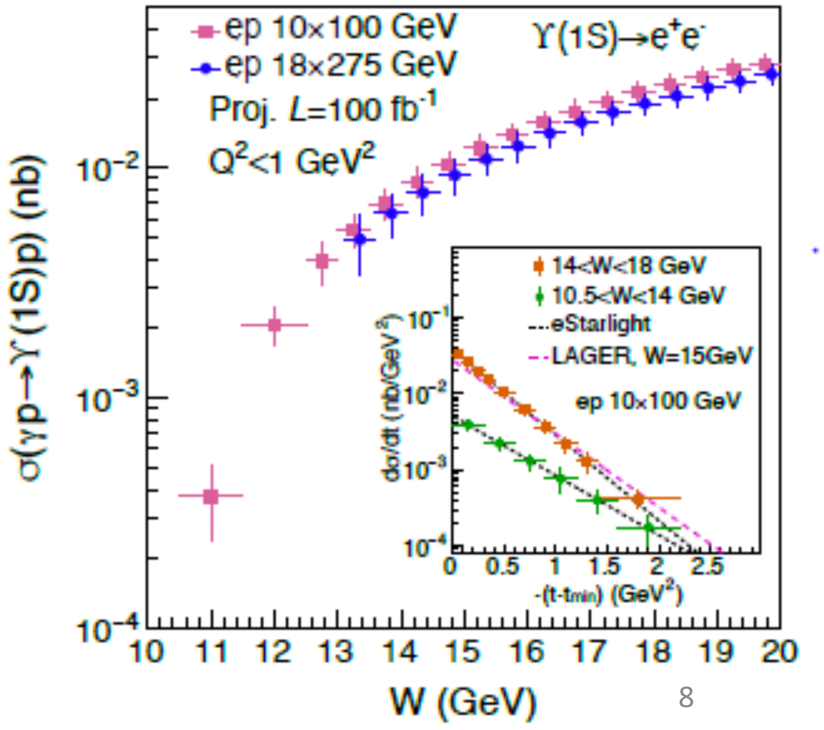
Proton (valence quarks: uud) → $m_p = 940$ MeV

- The mass is dominated by the energy of highly relativistic gluonic field
- EIC can determine an important contribution term to the proton mass, the so-called "QCD trace anomaly" ⟼ accessible in exclusive reactions (e.g. Υ photoproduction near threshold)

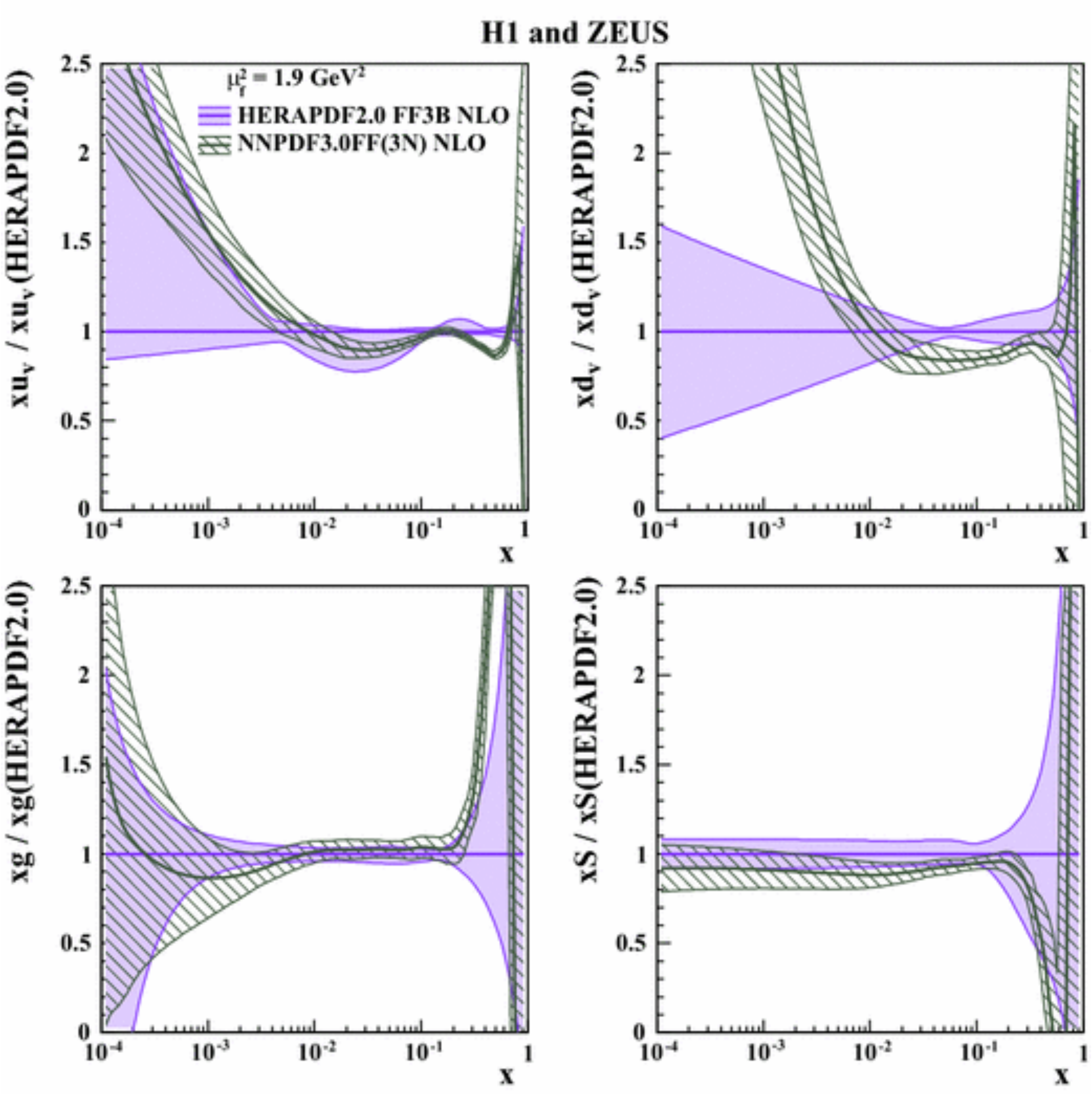


Contributions to the total mass of the nucleon





Scientific goals: proton PDFs

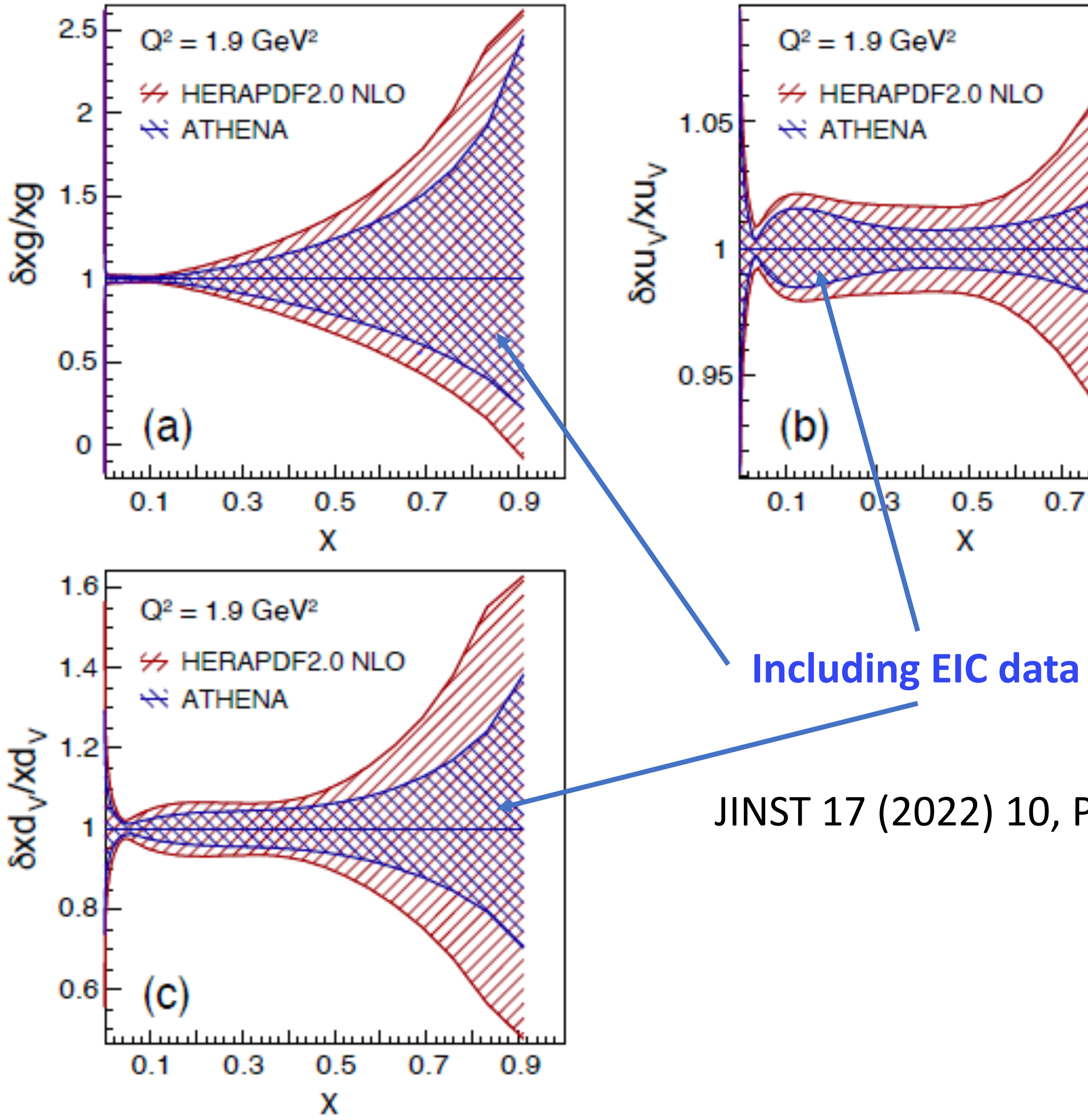


Eur. Phys. J. C 75 (2015) 580

- $F_2(x, Q^2)$ **largely studied at HERA**
- Nevertheless, a better precision often needed for precise calculations!

  --> explore specific kinematics
- Valence quark PDFs can be improved at small x
- Gluon PDFs need further exploration at large x

Scientific goals: proton PDFs



JINST 17 (2022) 10, P10019

Proton PDFs @ EIC

- EIC impact on HERA + LHC global fits
  - as estimated at the times of detector proposals in 2022
- EIC constrains the high-*x* region of both gluons and flavor-separated *u* and *d* valence quarks

Key detector performance:

- Electron ID
- Fine resolution in *y* over a large phase space

Scientific goals: nuclear PDFs

Inclusive DIS on e+A analog to e+p:

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark (F_2)

gluons (or tag on F_2-charm) (F_L)

DGLAP evolution model:
predicts Q^2 but not A-dependence and x-dependence

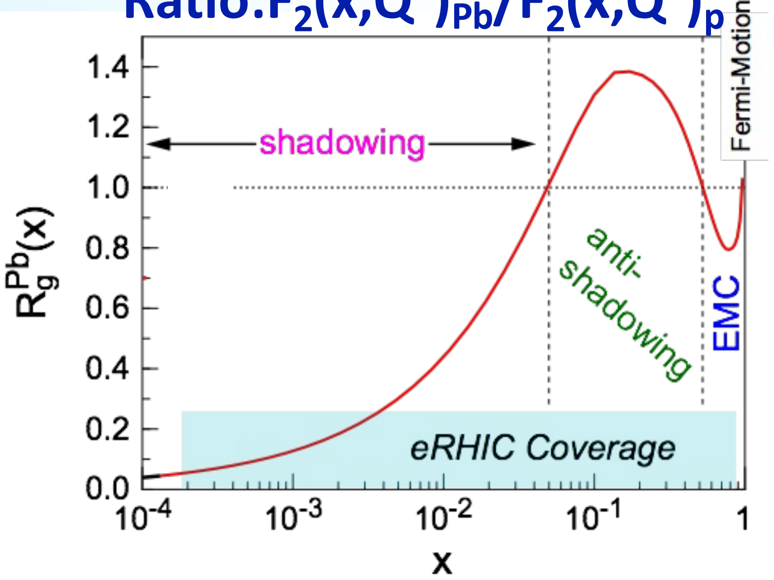
Saturation models:
predict A-dependence and x-dependence but not Q^2

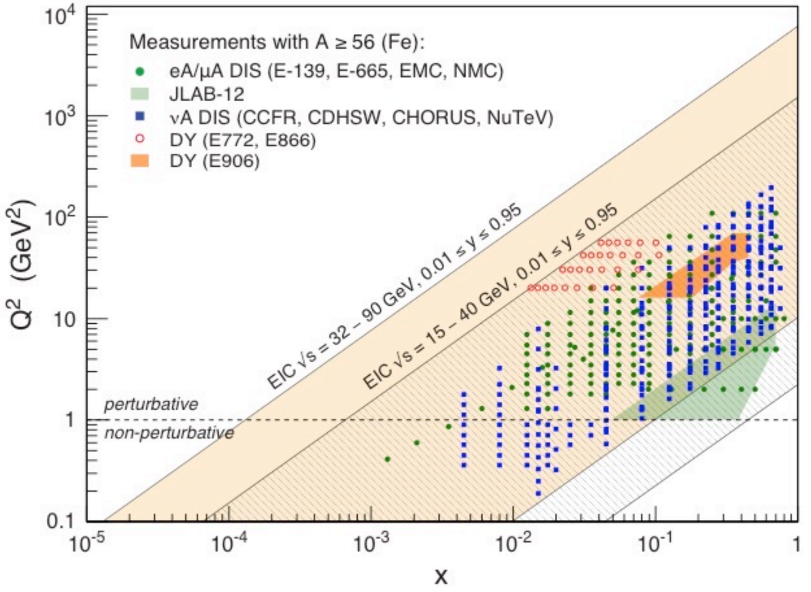
→ Need: large Q^2 lever-arm for fixed x, A-scan

- Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge ⇒ different evolution

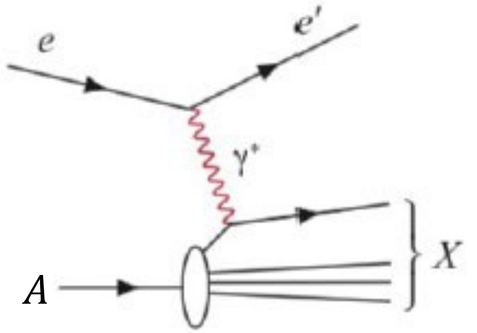
The EIC provides a factor ~10 larger reach in Q^2 and at low-x compared to available data

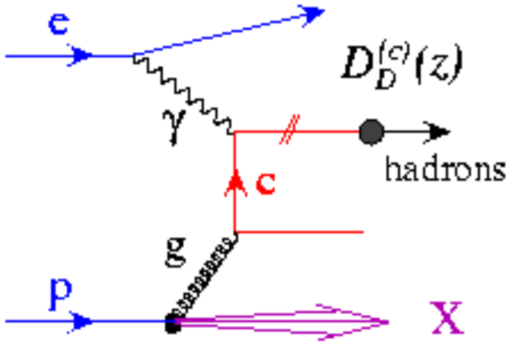
Ratio: $F_2(x,Q^2)_{Pb}/F_2(x,Q^2)_p$

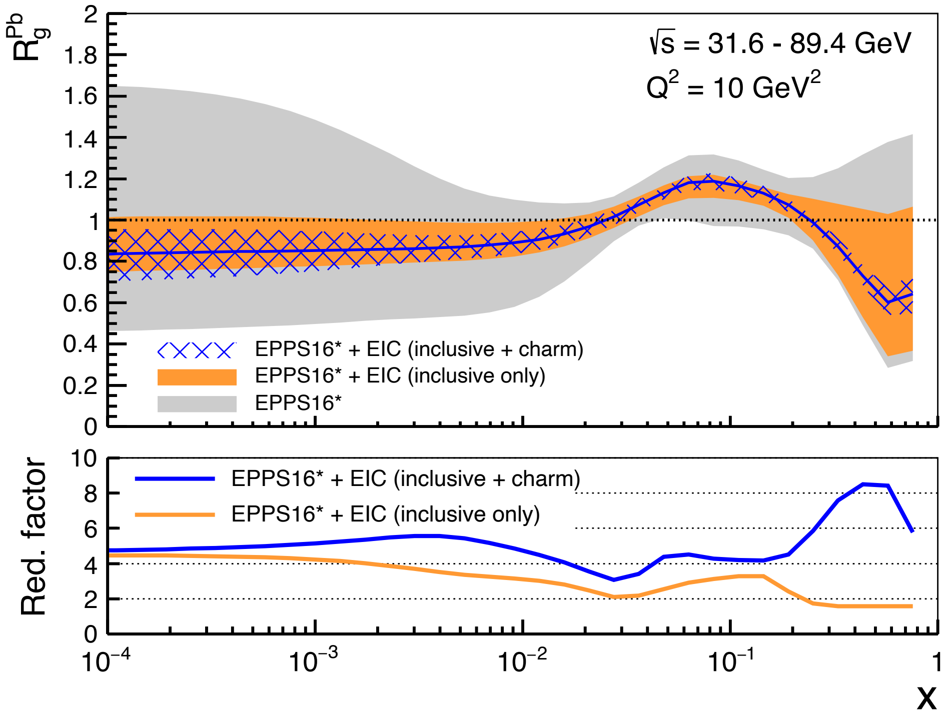




Scientific goals: nuclear PDFs







E.C. Aschenauer, S. F., M.A.C. Lamont, H. Paukkunen, P. Zurita
[Phys. Rev. D 96, 114005 (2017)]

- **Inclusive DIS in e+A**
  - tag the scattered electron
- **Charm production:**
- Direct access to gluons at medium to high *x* by tagging **photon-gluon fusion**

- Higher $\sqrt{s}$ energy constrains gluons at mid- and low-*x*
- charm has a dramatic effect at high-*x*

Key detector performance:

- Vertexing (for charm tagging)
- Electron ID
- Fine resolution in *y* over a large phase space

Multidimensional imaging of quarks and gluons

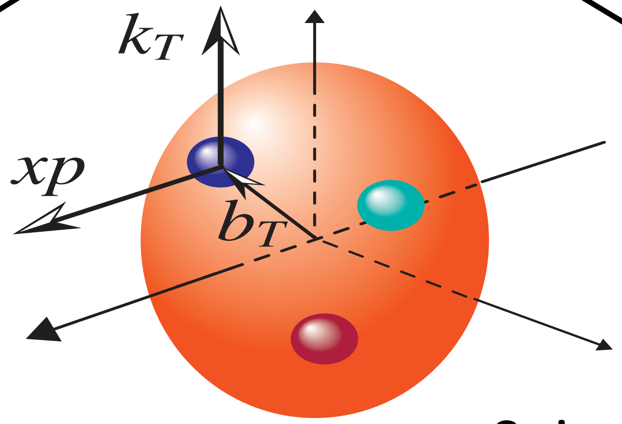
Wigner functions

offer unprecedented insight into confinement and chiral symmetry breaking

$W(x,b_T,k_T)$

Momentum space $\int d^2b_T$ → $f(x,k_T)$

$\int d^2k_T$ → $f(x,b_T)$ *Coordinate space*

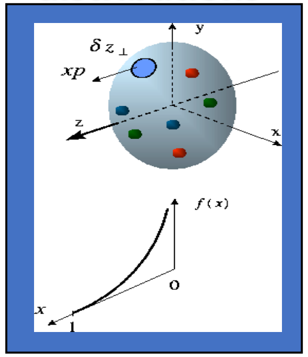


Spin-dependent 3D **momentum space** images from **semi-inclusive scattering** → Transverse-Momentum Depentent distributions (**TMDs**)

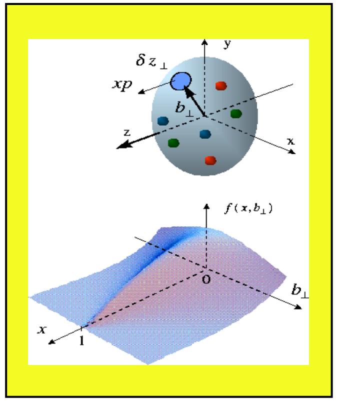
Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from **exclusive scattering** →Generalized Parton Distributions (**GPDs**)

Scientific goals: GPDs

Longitudinal momentum & helicity distributions

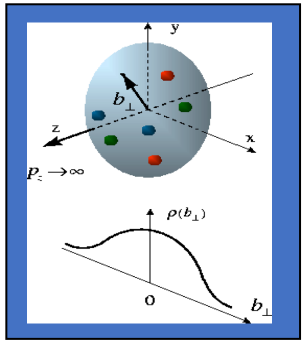


$f(x)$
parton densities



$H(x,\xi,t)$
GPDs

transverse charge & current densities



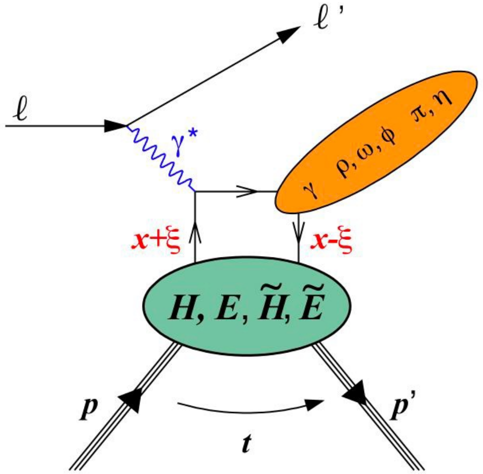
$F(t)$
form factors

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

Spin-½ hadron: **4 chiral-even** (H, E and their polarized-hadron versions $\tilde{H}$, $\tilde{E}$) and **4 chiral-odd** ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$) quark and gluon **GPDs at leading twist**

Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of parton operators**:

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0}$$
$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$



- Experimental access to GPDs via Compton Form Factors (CFFs)

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

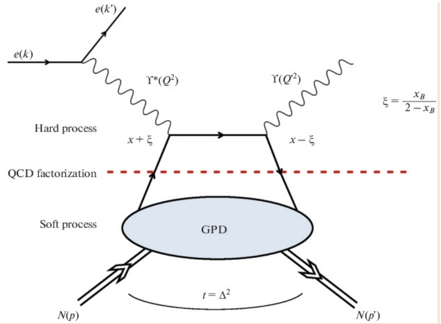
Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x[H^q(x,\xi,t) + E^q(x,\xi,t)]$ $\qquad J_q = \frac{1}{2}\Delta\Sigma + L_q$

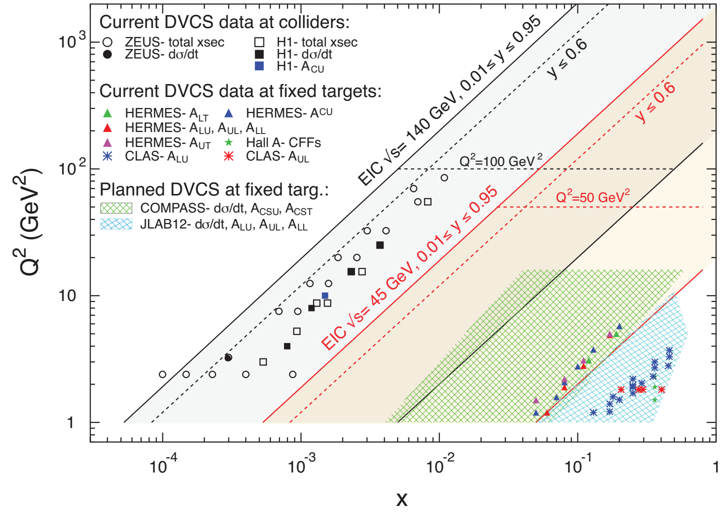
[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

Accessing GPDs in exclusive processes

Real photon (DVCS):

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Access to the whole set of GPDs
- Sensitive to both quarks and gluons [via Q^2 dependence of xsec (scaling violation)]





Only possible at EIC:
from valence quark region, deep into the sea!

Hard Exclusive Meson Production (HEMP):

- Uncertainty of wave function
- Hard scale provided by $Q^2 + M^2$
- J/Psi, Υ → direct access to gluons, $c\bar{c}$, or $b\bar{b}$ pairs produced via $q(g) - g$ fusion
- Light VMs → quark-flavor separation
- Psedoscalars → helicity-flip GPDs

H^q E^q

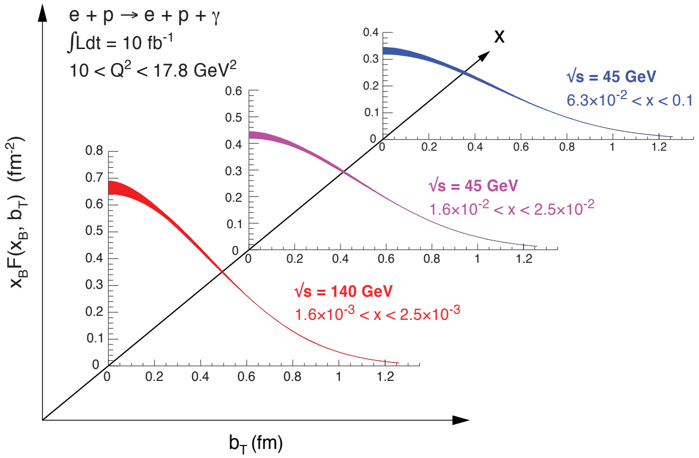
ρ⁰	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ⁺	u−d
J/ψ, Υ	g

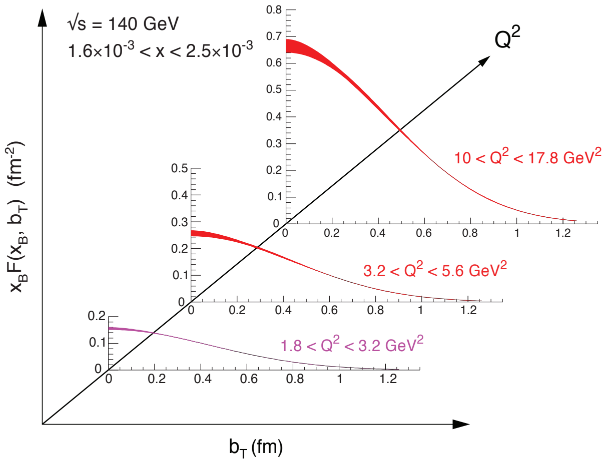
$\widetilde{H}^q$ $\widetilde{E}^q$

π⁰	2Δu□Δd
η	2Δu−Δd

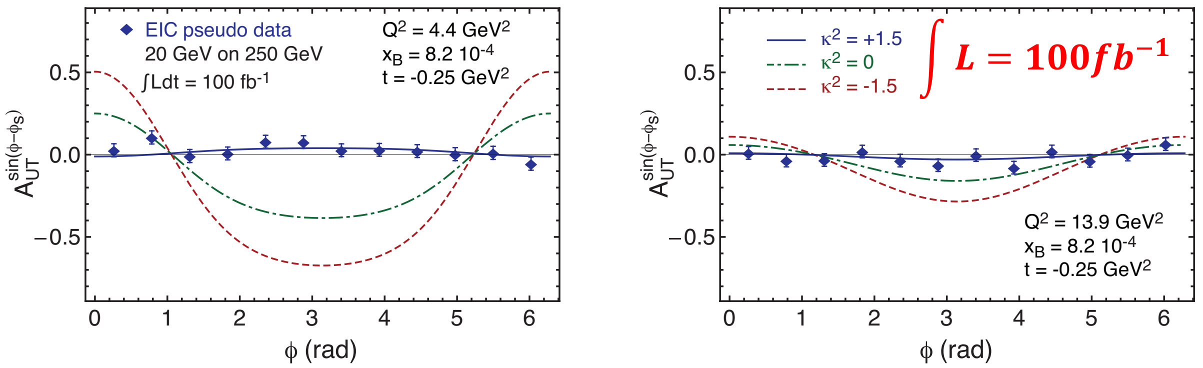
Accessing GPDs in exclusive processes

DVCS: $ep \to \gamma$



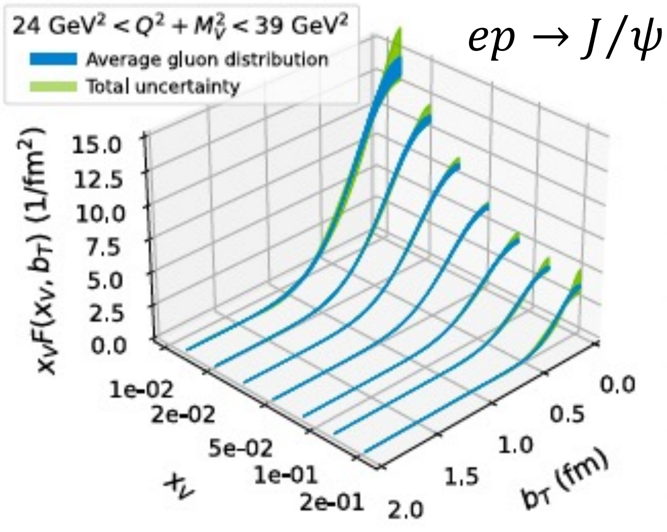


E.C. Aschenauer, S. F., K. Kumerički, D. Müller [JHEP09(2013)093]

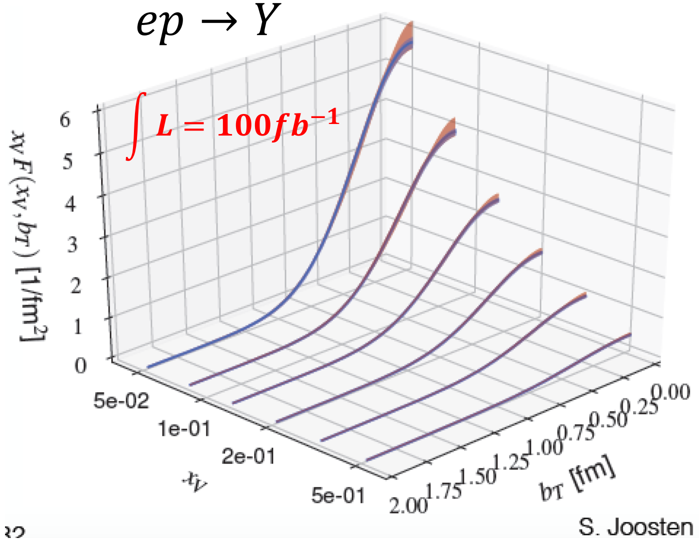


Theory curves show different assumptions for E

$ep \to J/\psi$



$ep \to \Upsilon$



Key detector performance:

- γ/π^0 separation in ECAL for DVCS
- Acceptance and low material for VM decay leptons
- Resolution of lepton pair inv. mass
- Muon id
- Scattered electrons over full kinem.
- t- lever arm in FF spectrometers

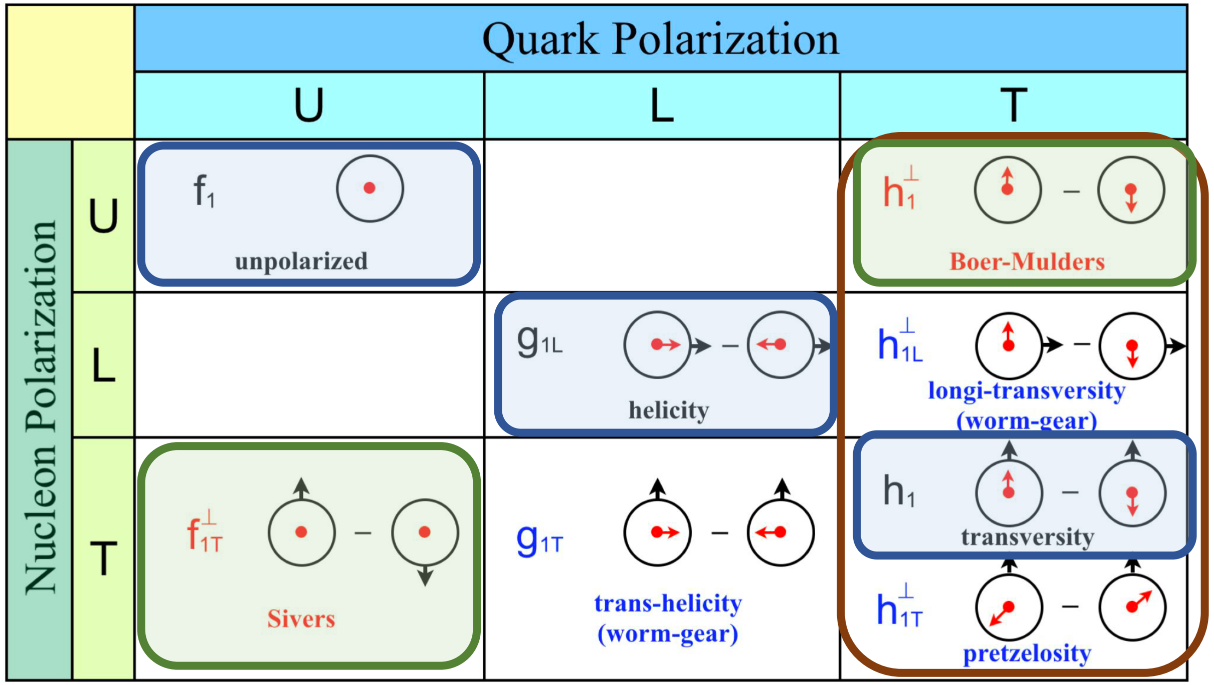
Scientific goals: TMDs

TMDs surviving integration over k_T

Time-reversal odd TMDs describing **strength of spin-orbit correlations**

Chiral odd TMDs

Note: off-diagonal part vanishes without parton's transverse motion



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

- **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

Scientific goals: TMDs

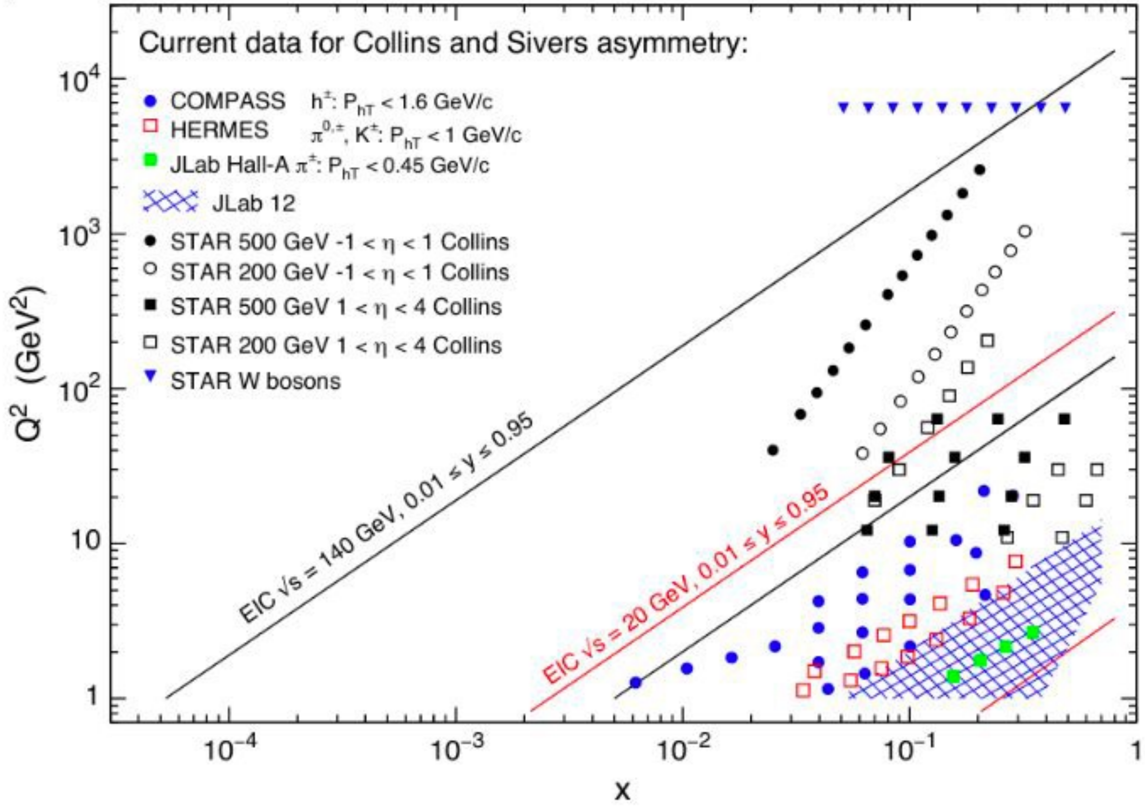
EIC will access TMDs primarily through SIDIS for single hadrons, as well as other semi-inclusive processes with the production of di-hadrons and jets

What we want to measure:

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

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

EIC Yellow Report: kin. reach for Sivers and Collins



EIC envisions a 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

- Extends the SiDIS kinematic coverage of an order ~2 in both x and Q^2

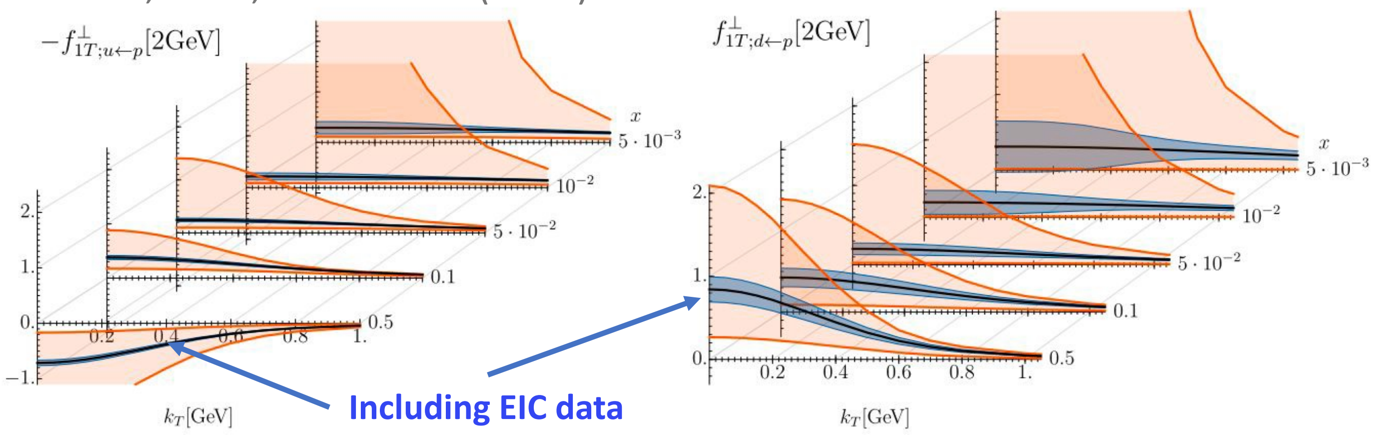
Key detector performance:

- Azimuthal acceptance
- PID
- Acceptance
- Vertexing (heavy flavor)
- Quality of tracking
- HCal (for jets)

Scientific goals: TMDs

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

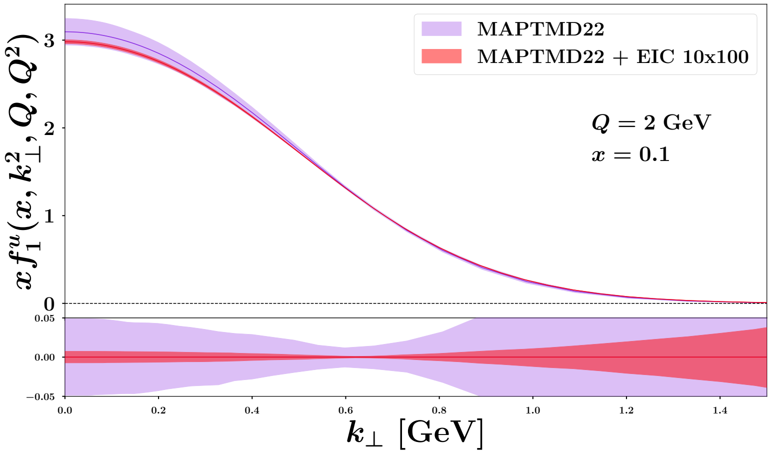
R. Seidl, et al., NIMA 1049 (2023) 168017

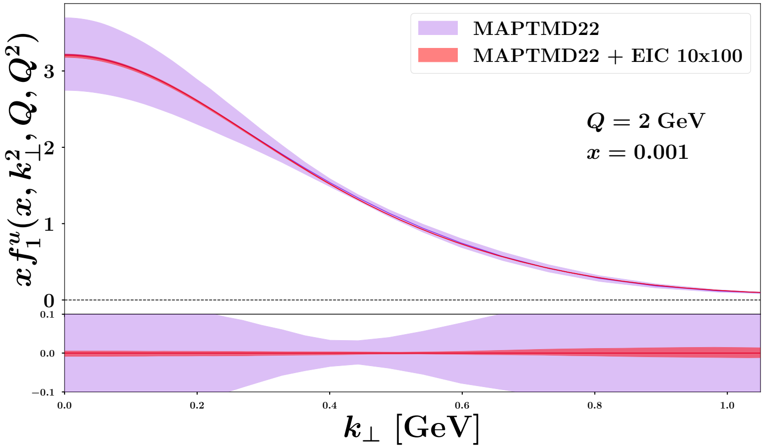


Expected impact unpolarized *u* quark

Map Collaboration impact studies

Courtesy of A. Bacchetta & M. Radici





Impact Studies on TMDs

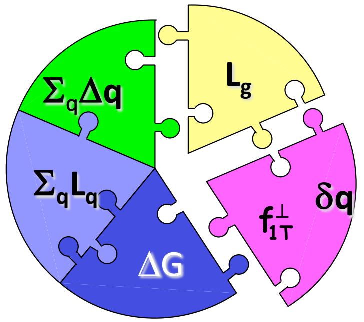
- Valence region TMDs still have significant uncertainties
- Severe lack of experimental data for sea quarks and gluons

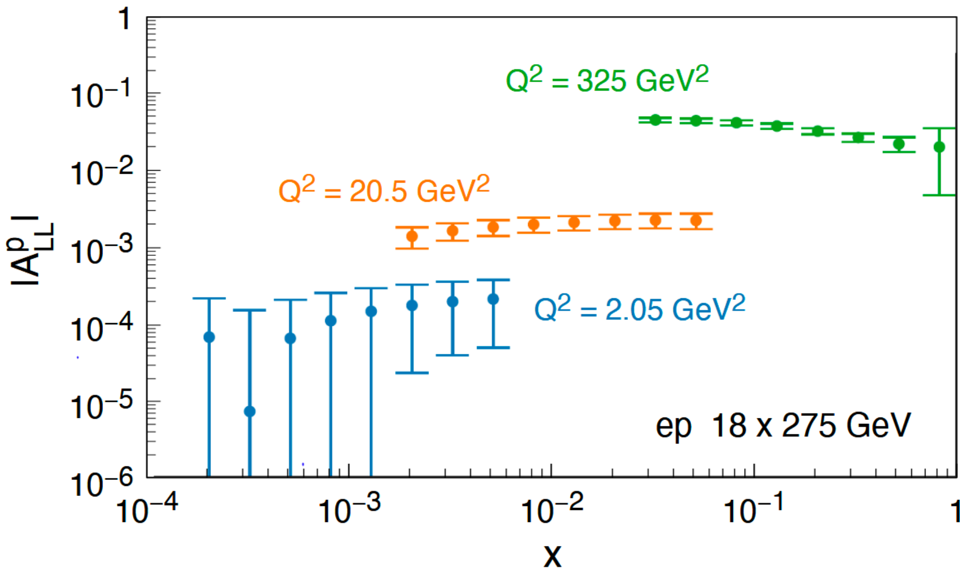
- **EIC has transformative potential for understanding the proton's 3D structure in momentum space**

Scientific goals: source of the proton's spin

Jaffe and Manohar "sum rule" [Nucl. Phys. B337, 509 (1990)]

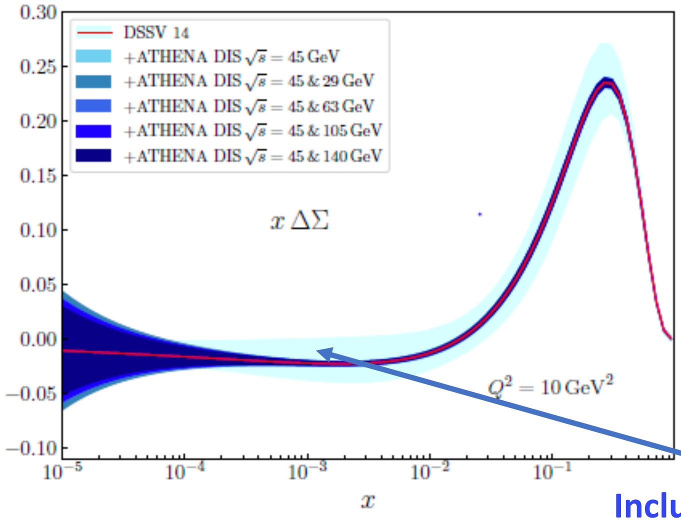
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\,|\,J^z_{QCD}\,|\,P,\frac{1}{2}\right\rangle = \underbrace{\sum_q \frac{1}{2}S^z_q}_{\text{total u+d+s quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \underbrace{\sum_q L^z_q + L^z_g}_{\text{angular momentum}}$$

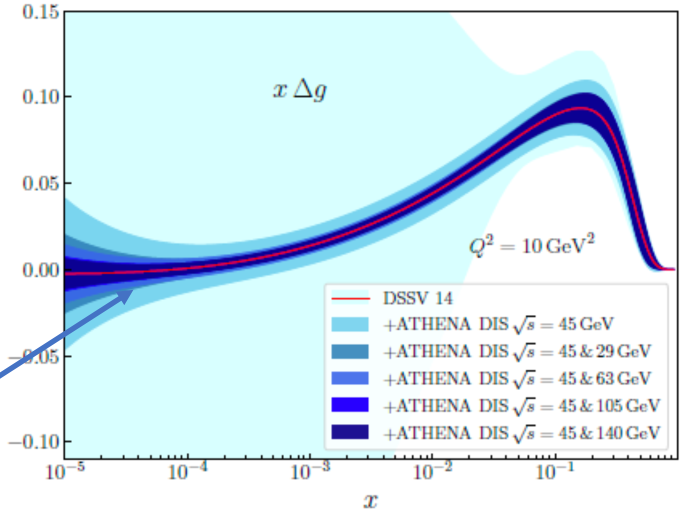




- **Observable:** Longitudinal double spin asymmetries (A_{LL})
- **DIS** scaling violations determine **gluons** at small *x*

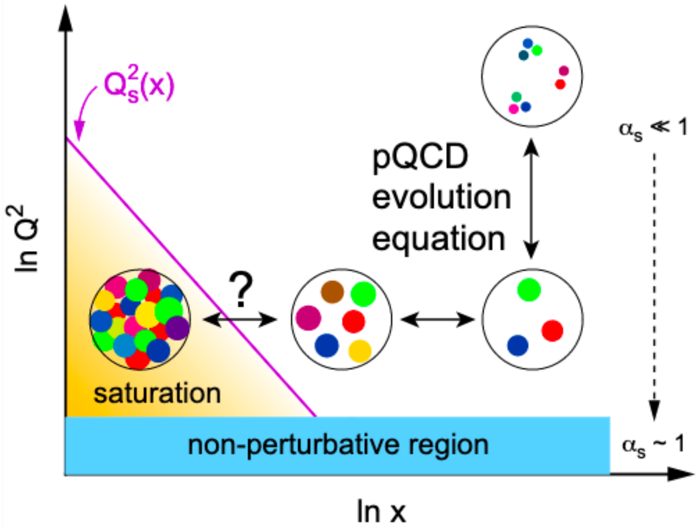
1/2 - Quarks - Gluons = orb. angular momentum

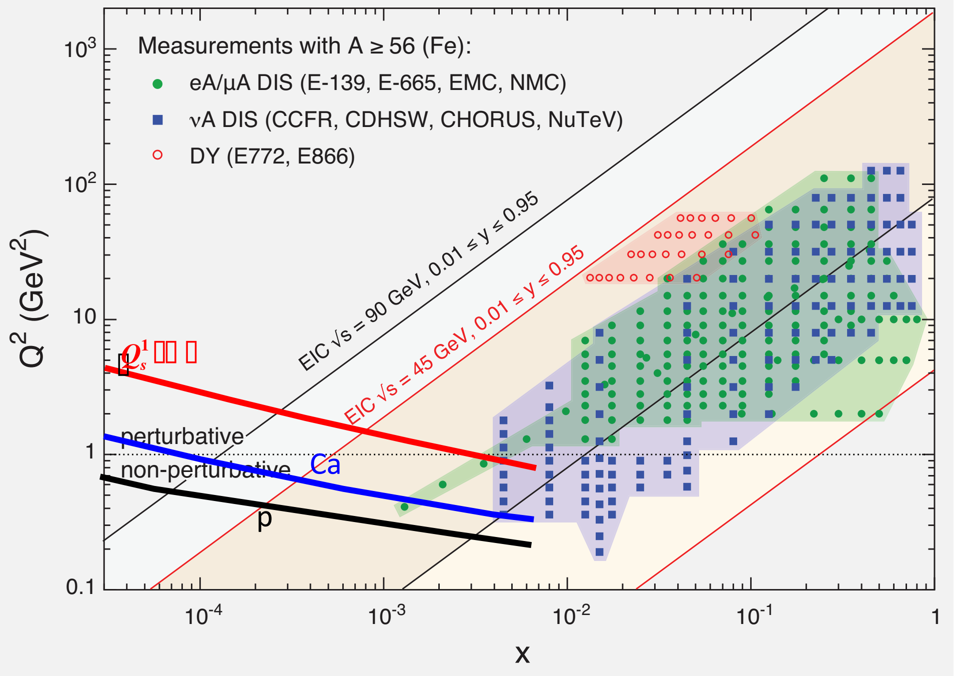


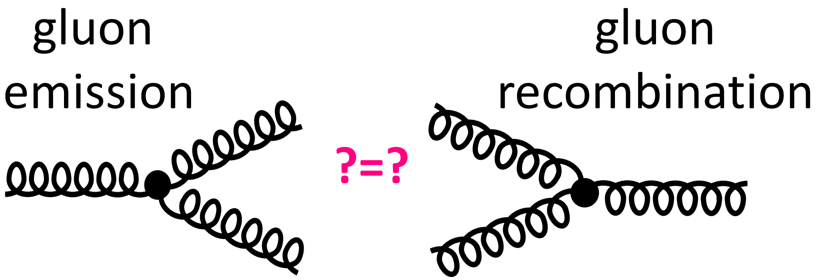


Including EIC data

A window into the Gluon Saturation regime

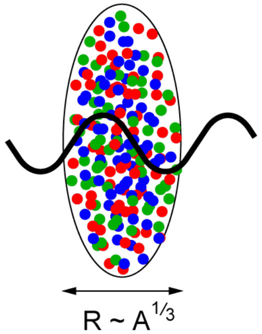






$$(Q_s^A)^2 \sim c Q_o^2 \left(\frac{A}{x}\right)^{1/3}$$

$L \sim (2m_N x)^{-1} > 2 R_A \sim A^{1/3}$



Probe interacts coherently with all nucleons

Gold: 197 times smaller effective x !

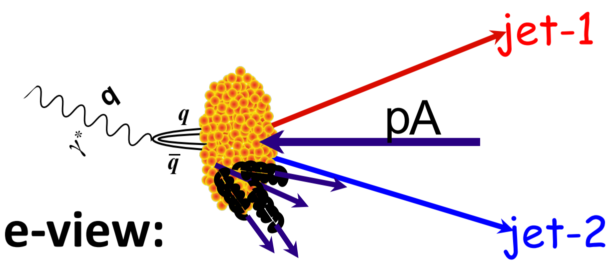
→ EIC will map the transition between a non-saturated and a saturated regime with high precision, by making use of a large range of nuclei and spin

→ With its flexible ion source, we will be able to measure the A-dependence of the saturation scale $Q_s(x)$

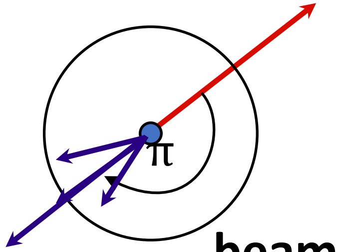
→ a fundamental landmark of QCD

Scientific goals: gluon saturation

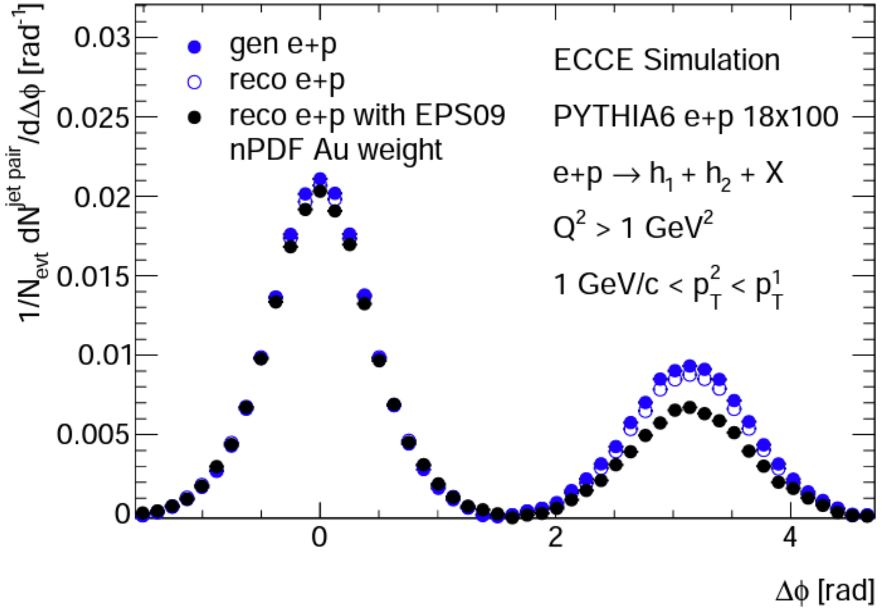
Di-hadron correlations



side-view:



beam-view:



Low gluon density (ep):

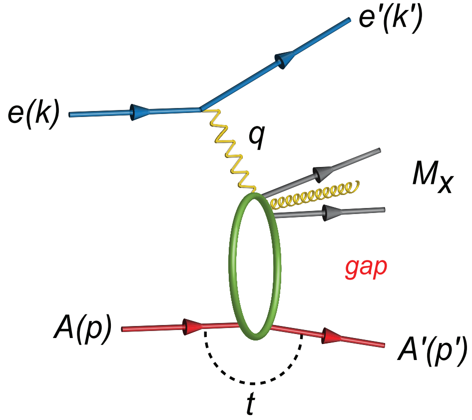
pQCD predicts 2→2 process

⇒ back-to-back di-jet

High gluon density (eA):

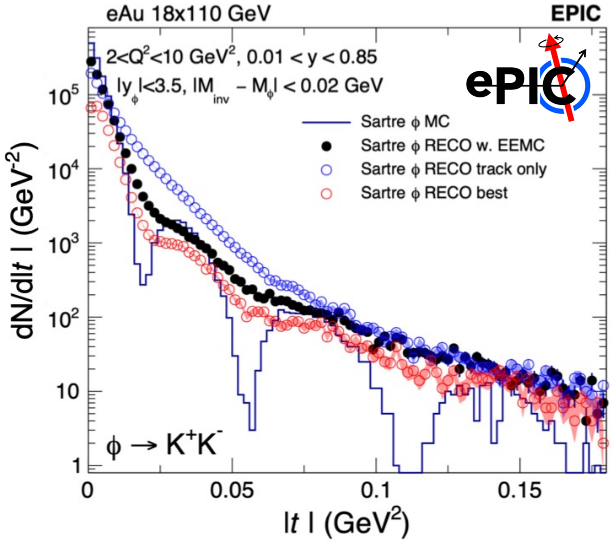
2 → many process

⇒ expect broadening of away-side



Diffraction

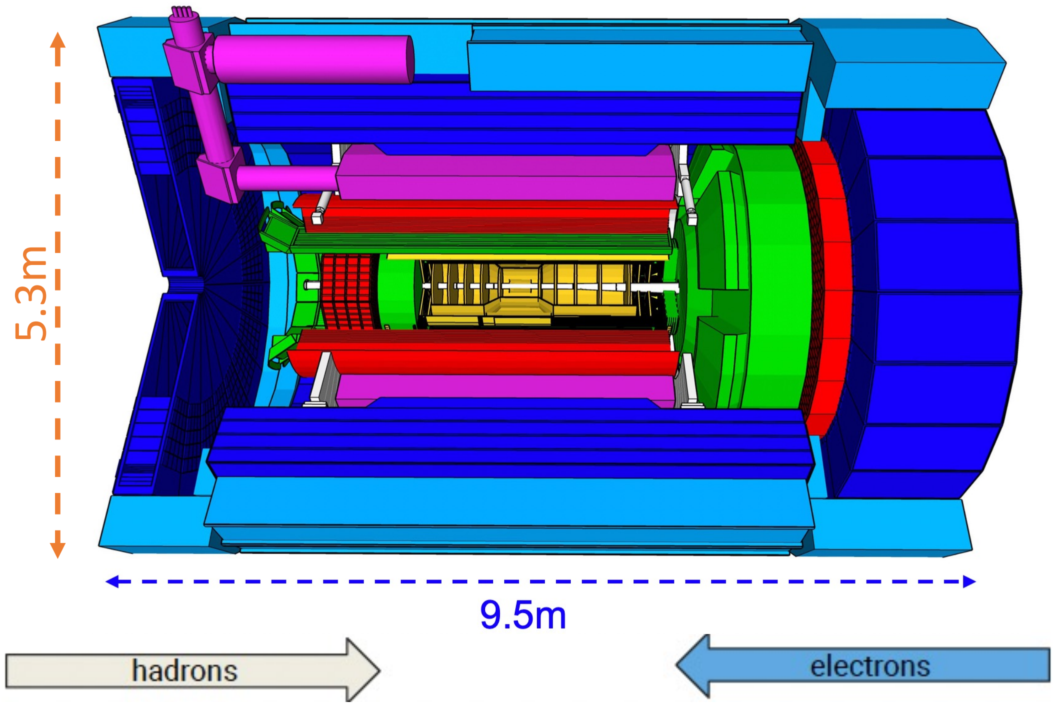
High sensitivity to gluon density in linear regime $\sigma \sim [g(x,Q^2)]^2$

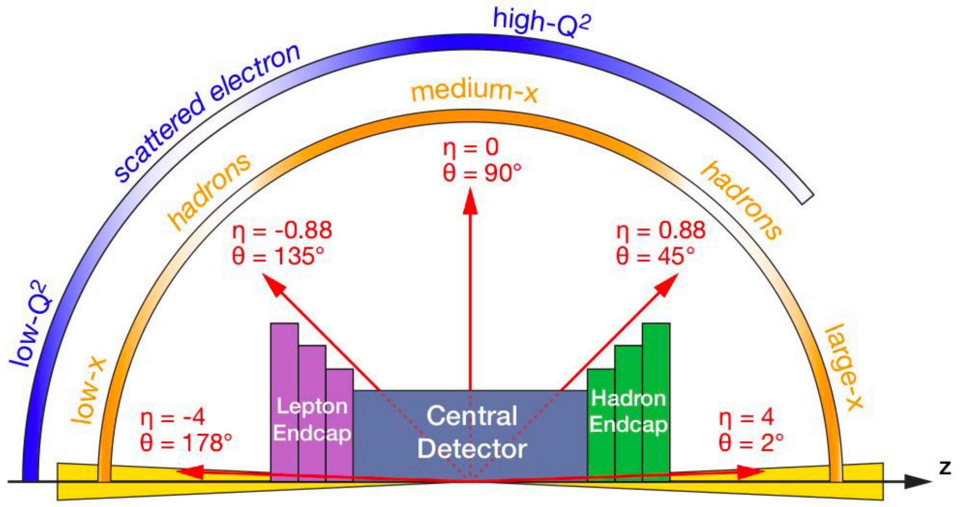


Key detector performance:

- Quality of detection at mid rapidity
- Reconstruction of dijets (dihadron)
- Particle ID

The ePIC detector





Tracking

- New 1.7 T solenoid
- Si MAPS (vertex, barrel, forward, backward disks)
- MPGDs (μRWELL/μMegas) (barrel, forward, backward disks)

Particle identification

- High performance DIRC (barrel)
- Dual radiator (aerogel+gas) RICH (forward)
- Proximity focusing RICH (aerogel) (backward)
- TOF (~30ps): AC-LGAD (barrel and forward)

E.M. Calorimetry

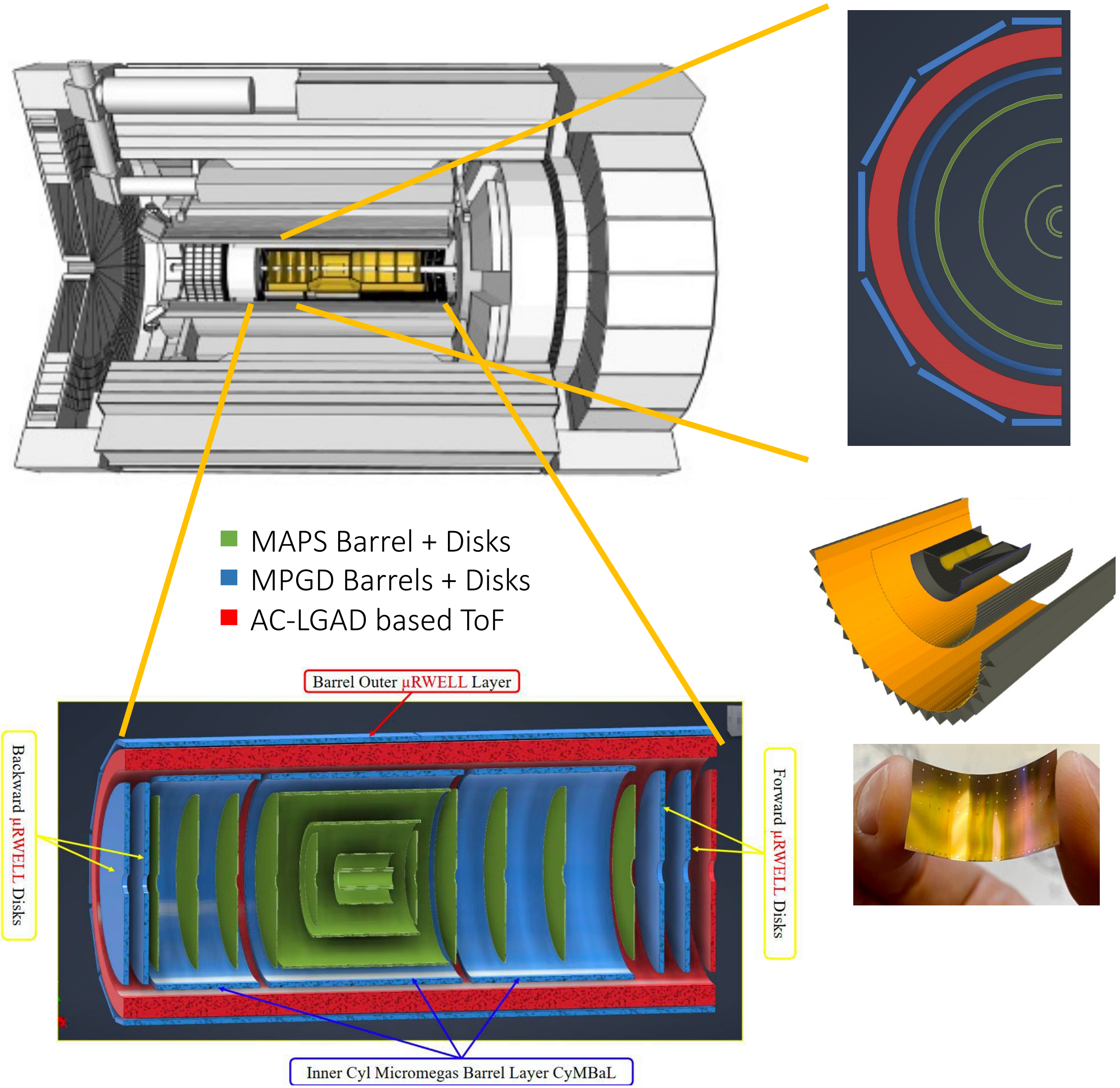
- Imaging EMCAL (barrel)
- W-powder/ScFi (forward)
- $PbWO_4$ crystals (backward)

Hadronic Calorimetry

- Fe/Scint reuse from sPHENIX (barrel)
- Steel/Scint - W/Scint (backwards/forward)

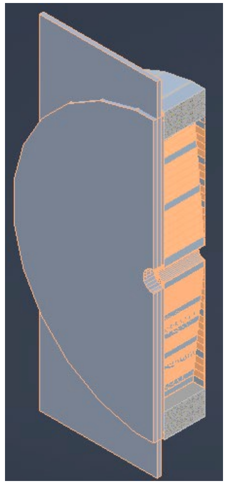
DAQ: streaming/triggerless with AI

Tracking

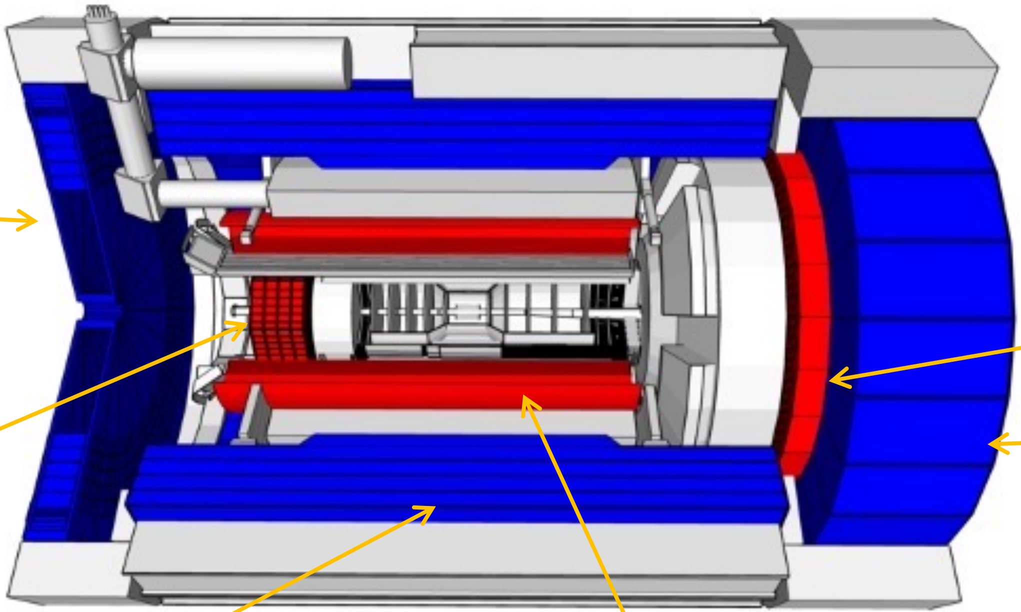


- MAPS Tracker:
  - Small pixels (20 μm), low power consumption (<20 mW/cm^2) and low material budget (0.05% to 0.55% X/X_0) per layer
  - Based on ALICE ITS3 development
  - Vertex layers optimized for beam pipe bake-out and ITS-3 sensor size
  - Forward and backward disks
- MPGD Layers:
  - Provide timing and pattern recognition
  - Cylindrical μMEGAs
  - Planar μRWell's before hpDIRC - Impact point and direction for ring seeding
- AC-LGAD TOF and AstroPix (BECAL):
  - Additional space point for pattern recognition / redundancy
  - Fast hit point / Low p PID

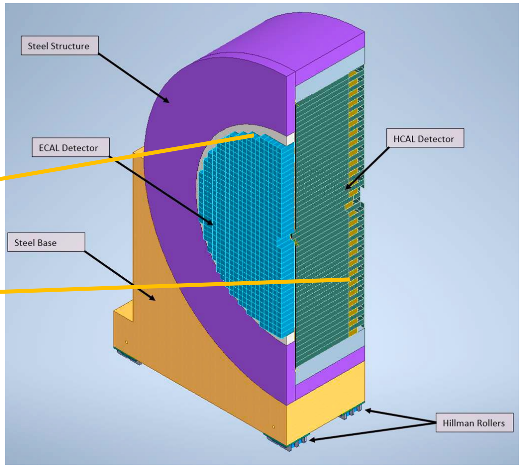
Calorimetry



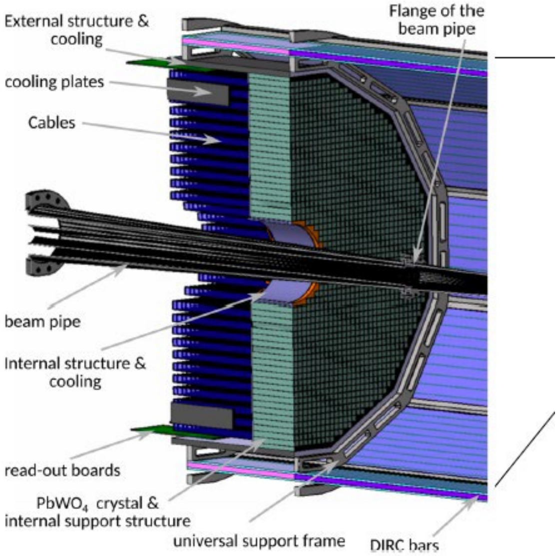
Backwards HCal
Steel/Sc
Sandwich
tail catcher



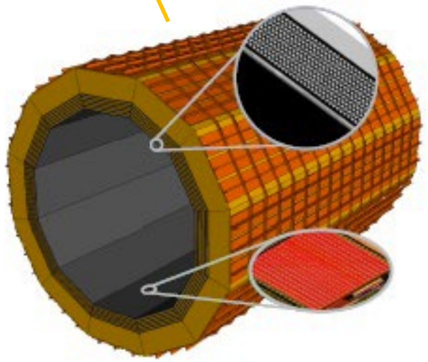
Forward EMCal
High granularity W/SciFi
a unique technology allowing to achieve e/h ~1 (response to hadrons)



Backwards EMCal
PbW04 crystals, SiPM photosensors

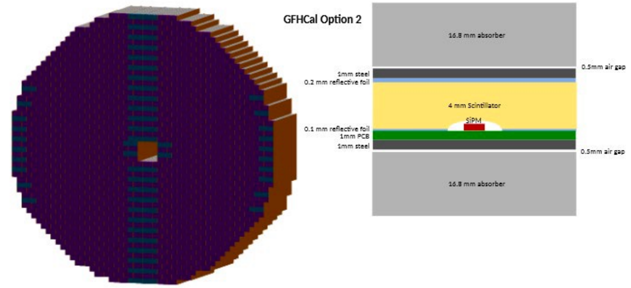


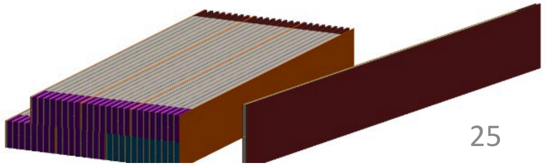
Barrel HCAL
Fe/Sc sandwich, ~3.5λ
(sPHENIX re-use)



Barrel EMCAL
4 (6) layers of imaging calorimetry by Astropix MAPS,
and sampling calorimetry by Pb/SciFi

Forward Hcal
SiPMs on tile

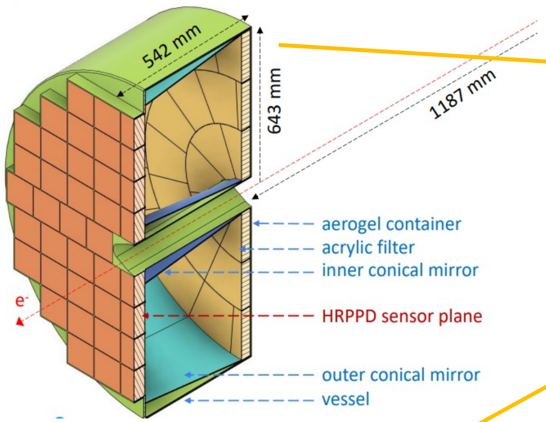


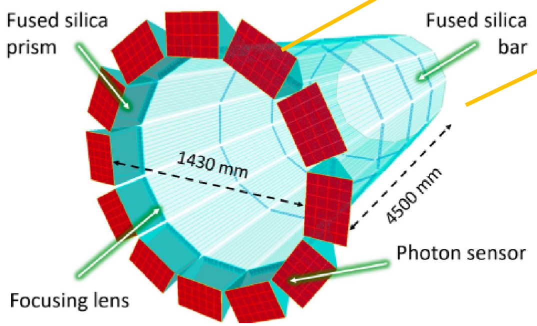


Particle ID

Proximity Focused (pfRICH)

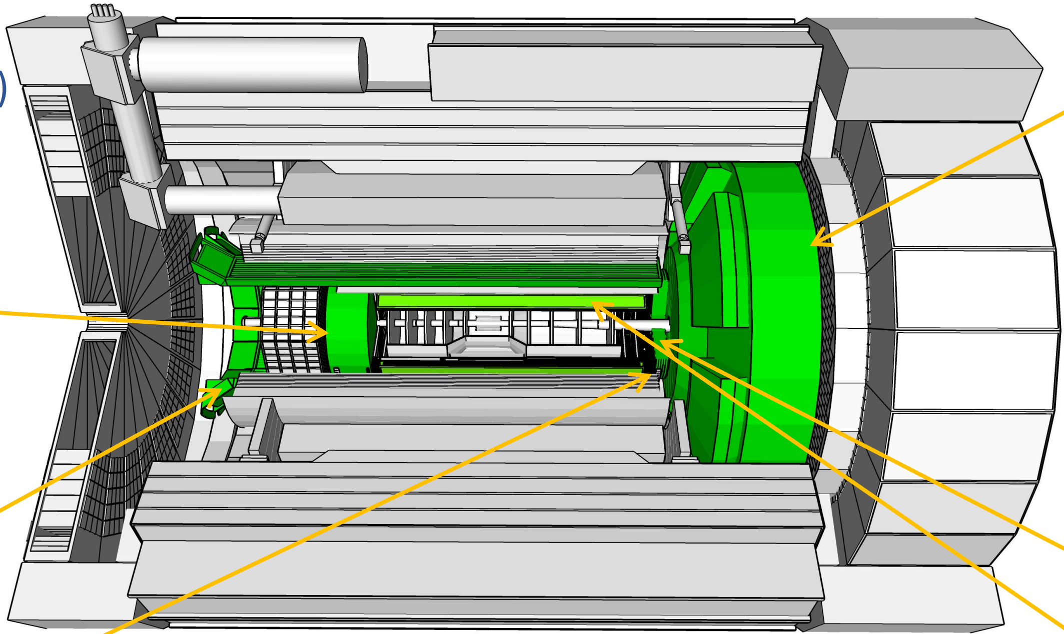
- Aerogel with Long proximity gap (~40 cm)
- Sensor: HRPPDs
- 3σ π/K sep. up to 9 GeV/c

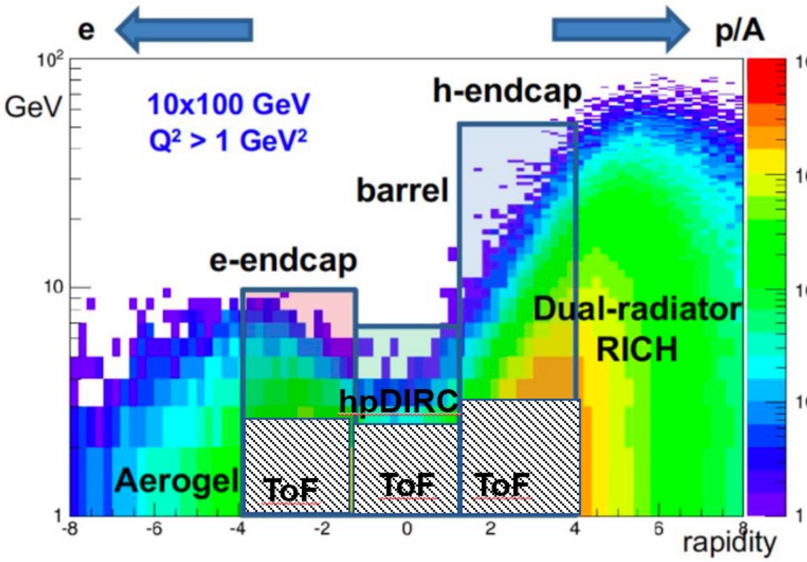


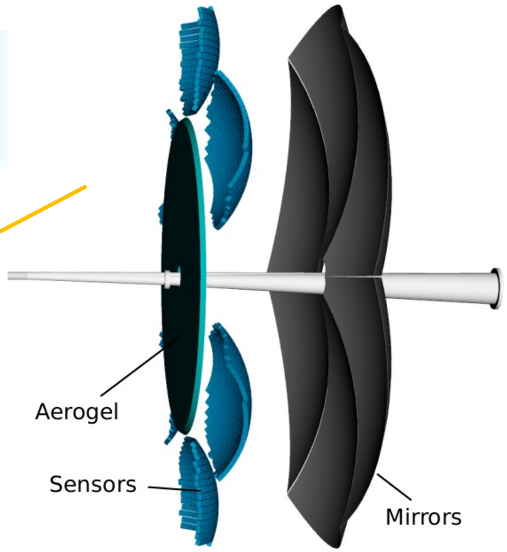


High-Performance DIRC

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

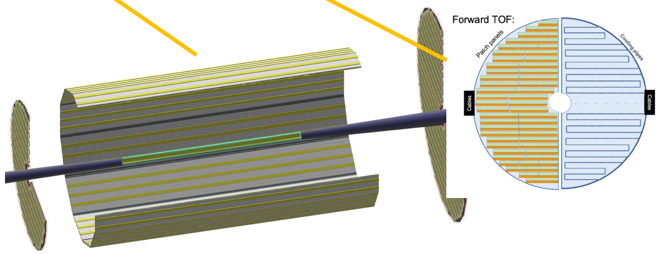






Dual-Radiator RICH (dRICH)

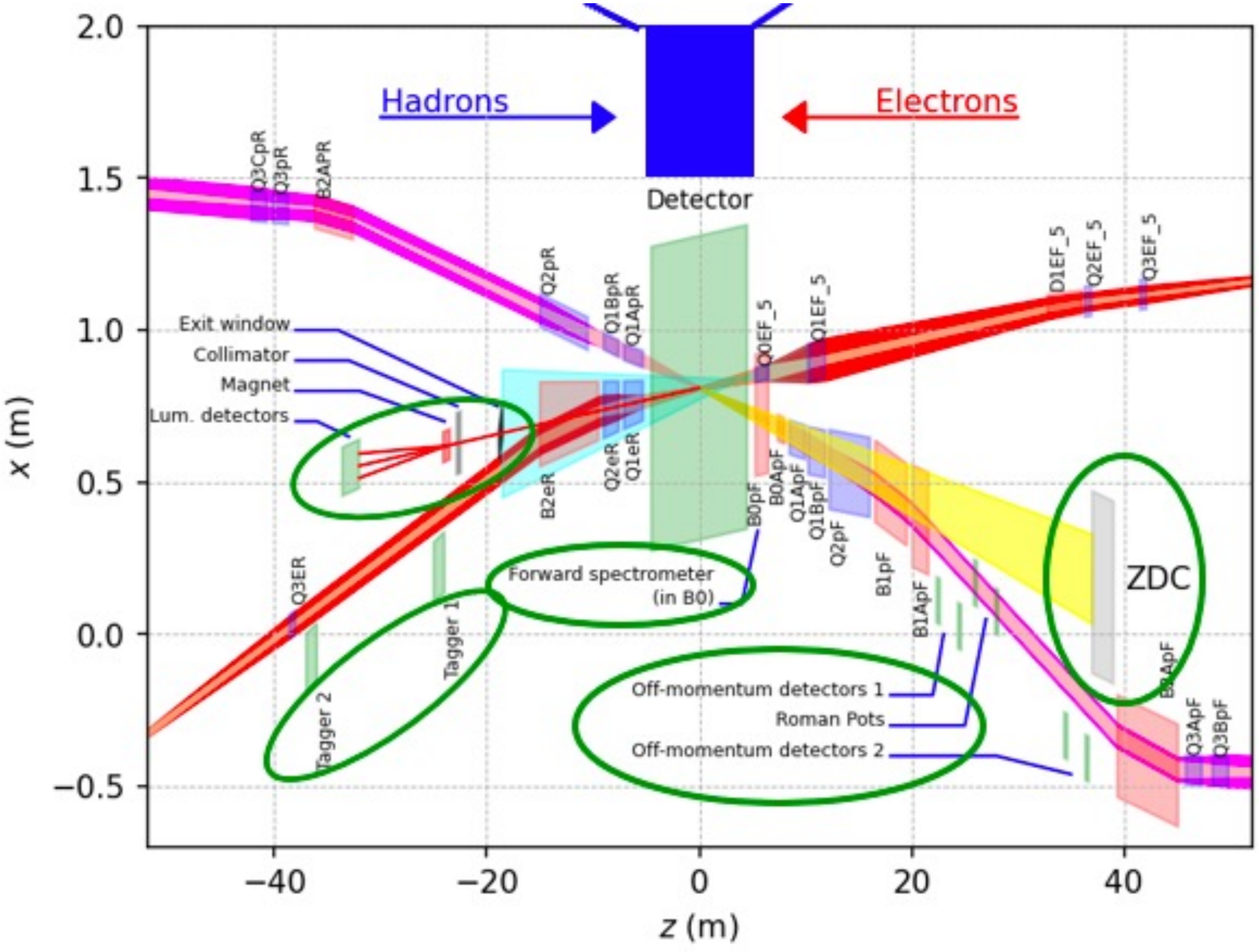
- C_2F_6 Gas Volume and Aerogel
- Single photon sensors (SiPMs)
- π/K 3σ sep. at 50 GeV/c



AC-LGAD TOF (~30ps)

- Accurate space point for tracking / Low p PID
- Forward disk and central barrel

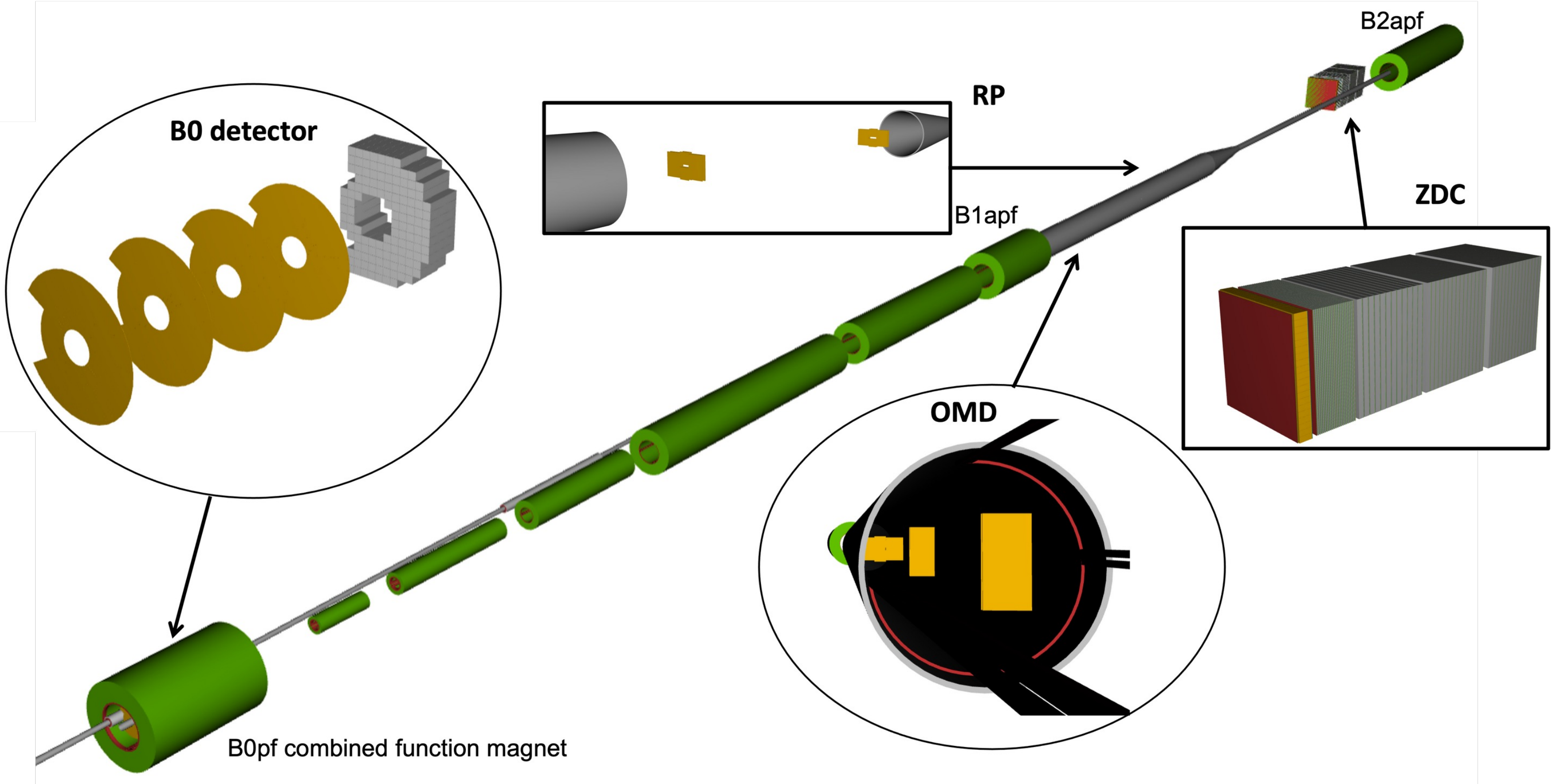
Auxiliary detectors



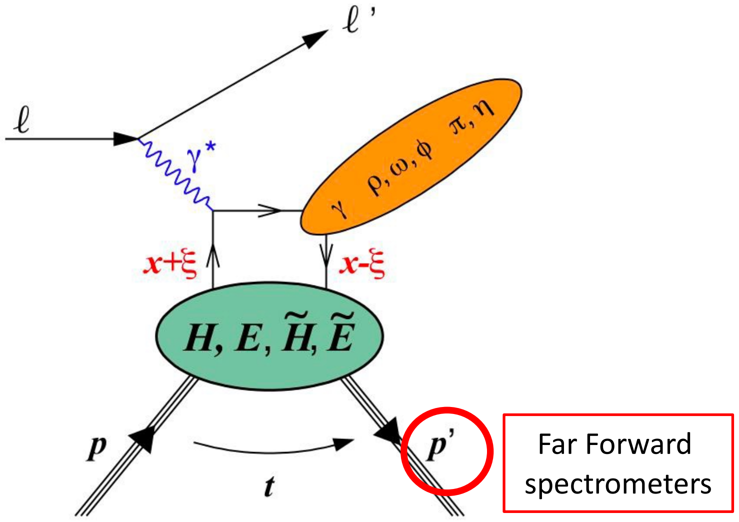
Needed to tag particles with very small scattering angles both in the outgoing lepton and hadron beam direction

- B0-Taggers
- Off-momentum taggers
- Roman Pots
- Zero-degree Calorimeter
- low Q2-tagger
- Luminosity detector

Far forward detectors



See talk by: A. Jentsch



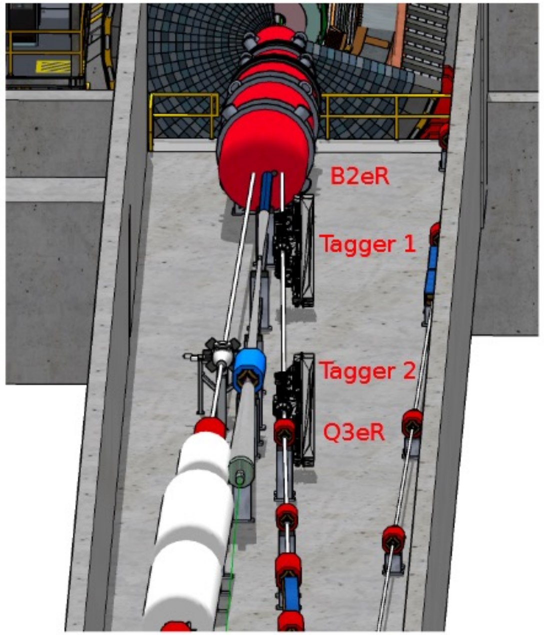
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$\theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)

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

- Require accurate measurement of t across a wide range in ep collisions
- Scattered protons measured by
  - Roman Pots (low t)
  - B0 (higher t)

Far backward detectors

Figure: Low-Q^2 taggers



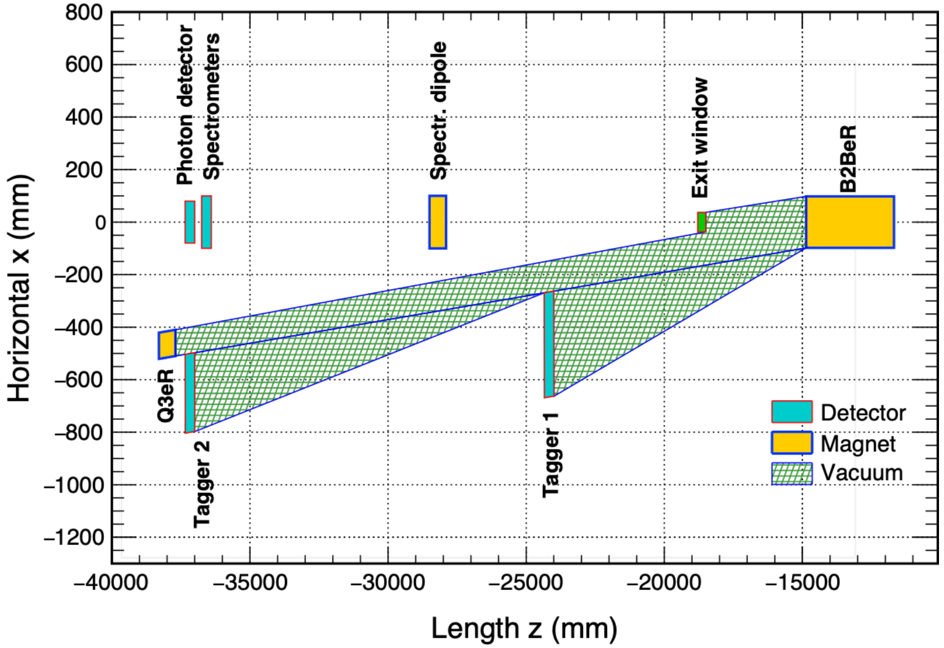
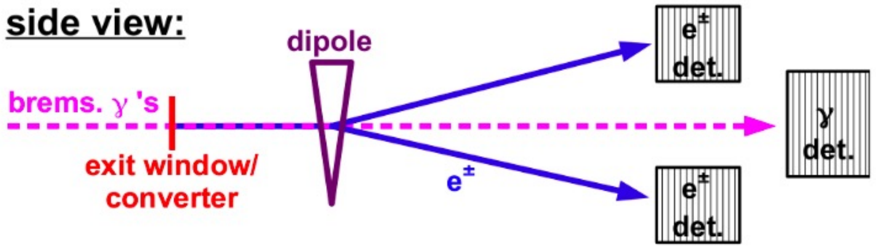
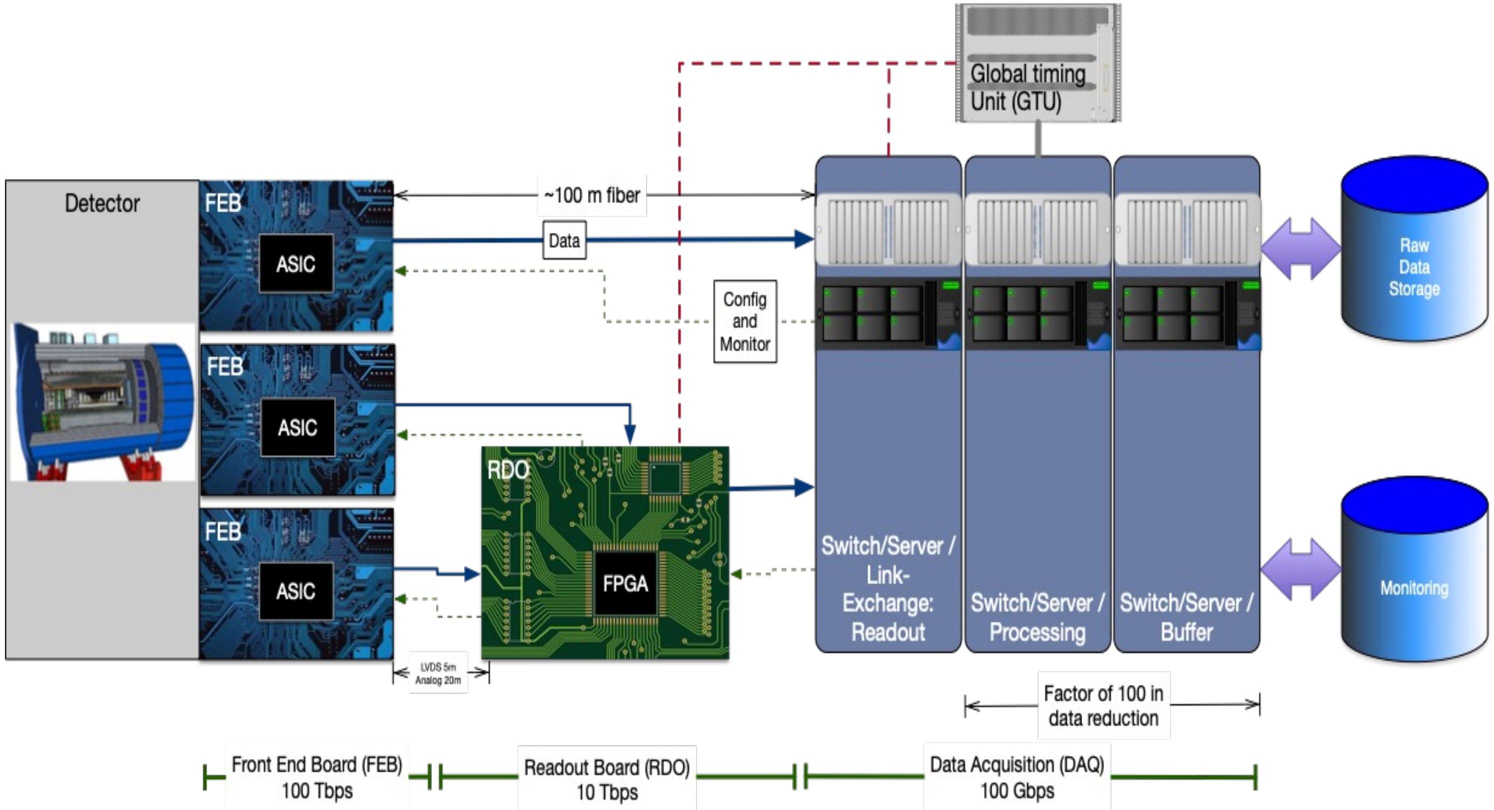


Figure: Luminosity detector



- High precision luminosity measurement at 1% level for absolute luminosity and 0.01% for relative luminosity measurement using several methods based on the Bremsstrahlung process:
  1. Counting photons converted in thin exit window using dipole field and measuring e^+e^- pairs
  2. Energy measurement of unconverted photons
  3. Counting of unconverted photons
- Low Q2 taggers - PHP tagger

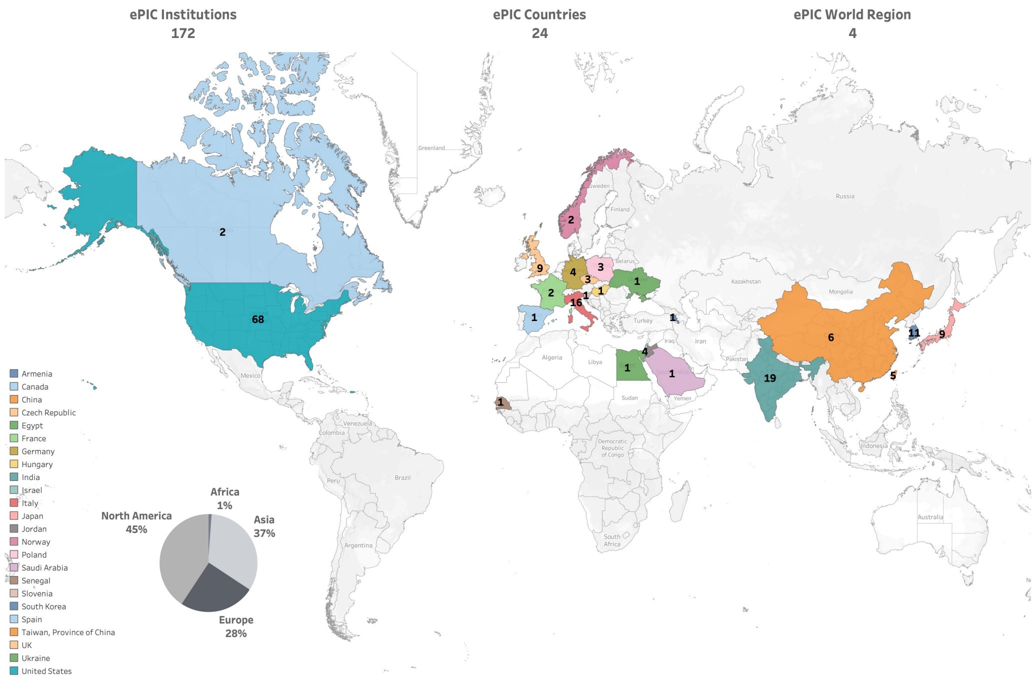
Streaming DAQ



- No External trigger
- All collision data digitized, but zero suppressed at FEB
- Low / zero dead-time
- Event selection can be based on full data from all detectors (in real-time, or later)
- Collision data flow is independent and unidirectional

  → no global latency requirements
- Avoiding hardware triggers avoids complex custom hardware and firmware

The ePIC Collaboration

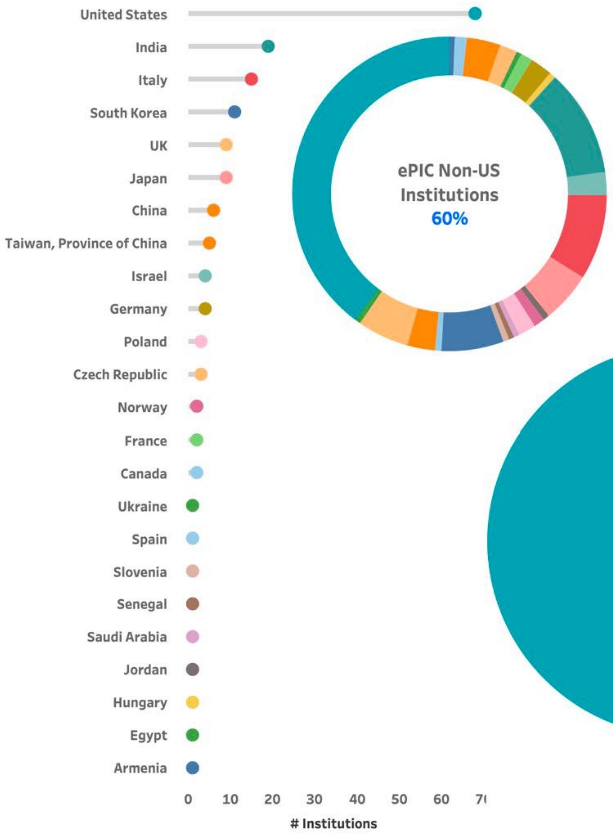


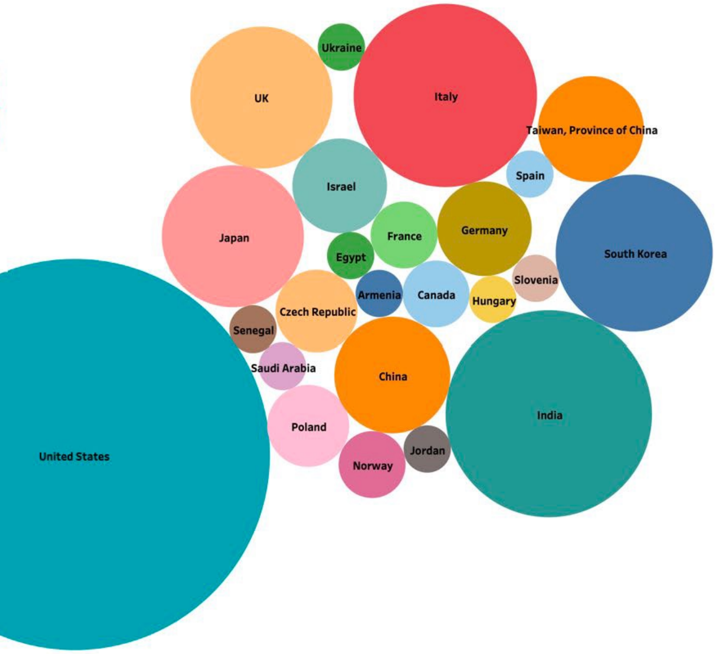
A truly global pursuit for a new experiment at the EIC

24 Countries

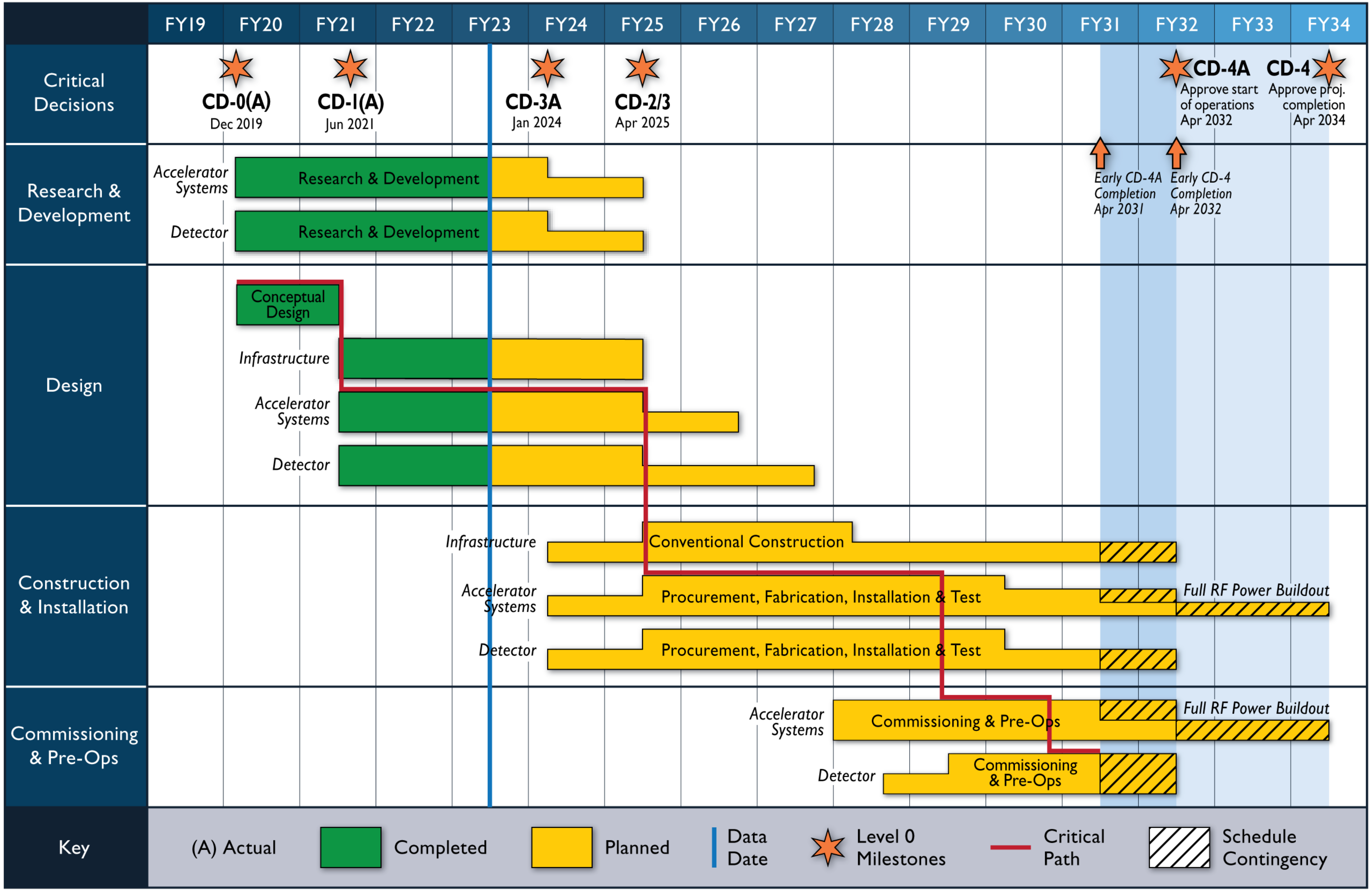
171 Institutions and counting!

500+ scientists and counting!





Schedule for the ePIC project-detector



Summary

- ✓ The EIC provides an unprecedented opportunity for the ultimate understanding of QCD
  - ❖ Over two decades, the nuclear physics community has developed the scientific and technical case for the Electron-Ion Collider
  - ❖ It might be the only new collider in the world for the next decades
- ✓ The ePIC experimental Collaboration was formed in Spring 2022 after a successful merging of several proposal efforts
  - ❖ ePIC is approved as part of the EIC project, and progressing according to schedule
  - ❖ The ePIC detector is an enormous undertaking that will require participation and expertise from both the US (Labs and Academia) communities, as well as the international contributions (60% of Institutions from abroad world-wide)

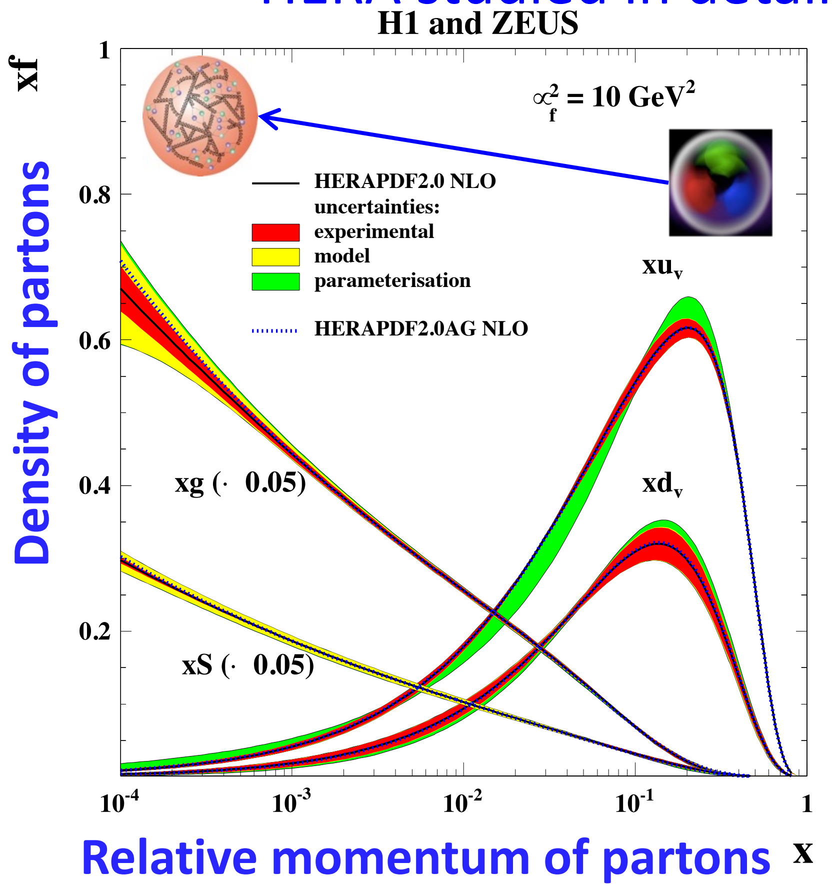
New excitement ahead

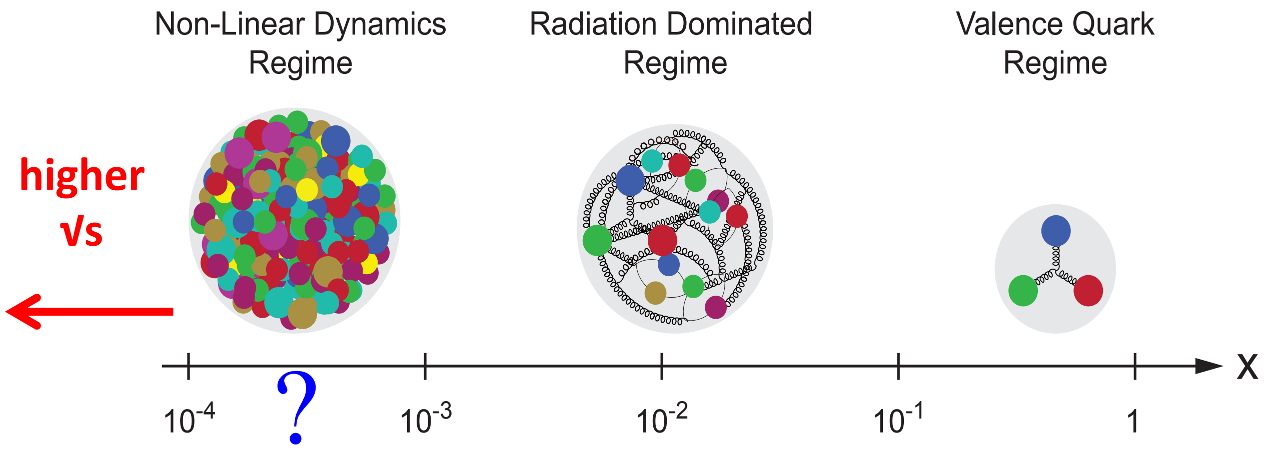
- Event reconstruction at the ePIC experiment being finalized & novel analysis tools being developed
  - New, more realistic, impact studies
- Exciting perspectives with designing and building detectors and producing science!
- It is NOW the right time to join the efforts and get involved!


BACKUP

What did HERA found?

HERA studied in detail the one-dimensional picture of a free proton





HERA discovery:
Gluon density dominates at x < 0.1

Limits of HERA: Low luminosity; no nuclei; no polarization of the proton beam

Need a high lumi, highly polarized e+p(A) collider to resolve quark and gluon spatial, momentum and spin structure in multi-dimensions in both protons and nuclei → **EIC**

Recipe for an Electron-Ion Collider

Large center-of-mass coverage:

Access to wide kinematic range in x and Q^2

Polarized electron and hadron beams:

- access to spin structure of nucleons and nuclei
- Spin vehicle to access the 3D spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

Nuclear beams:

- Accessing the highest gluon densities → amplification of saturation phenomena

High luminosity:

- Detailed mapping the 3D spatial and momentum structure of nucleons and nuclei
- Access to rare probes

All these requirement can be addressed by the future **Electron-Ion Collider**