# The EIC: A New Machine to Unlock the Secrets of the Strong Force


EIC User Group

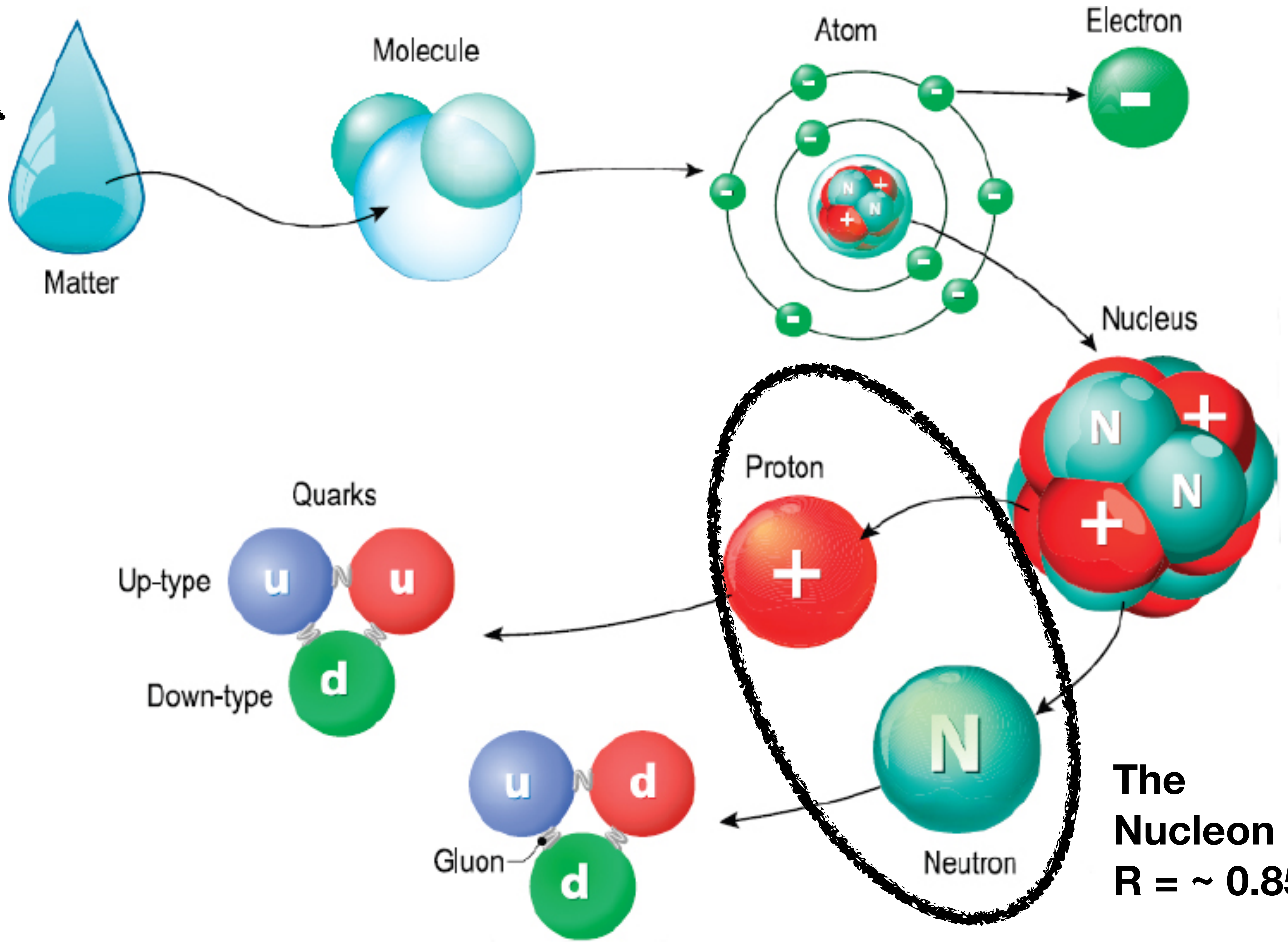
ePIC

*Rachel Montgomery*
*University of Glasgow*

*IJCLab, Orsay, 9/12/24*

*On behalf of work performed by many from EICUG and ePIC Collaborations*

# What are we made of?




The Nucleon
R = ~ 0.85 fm

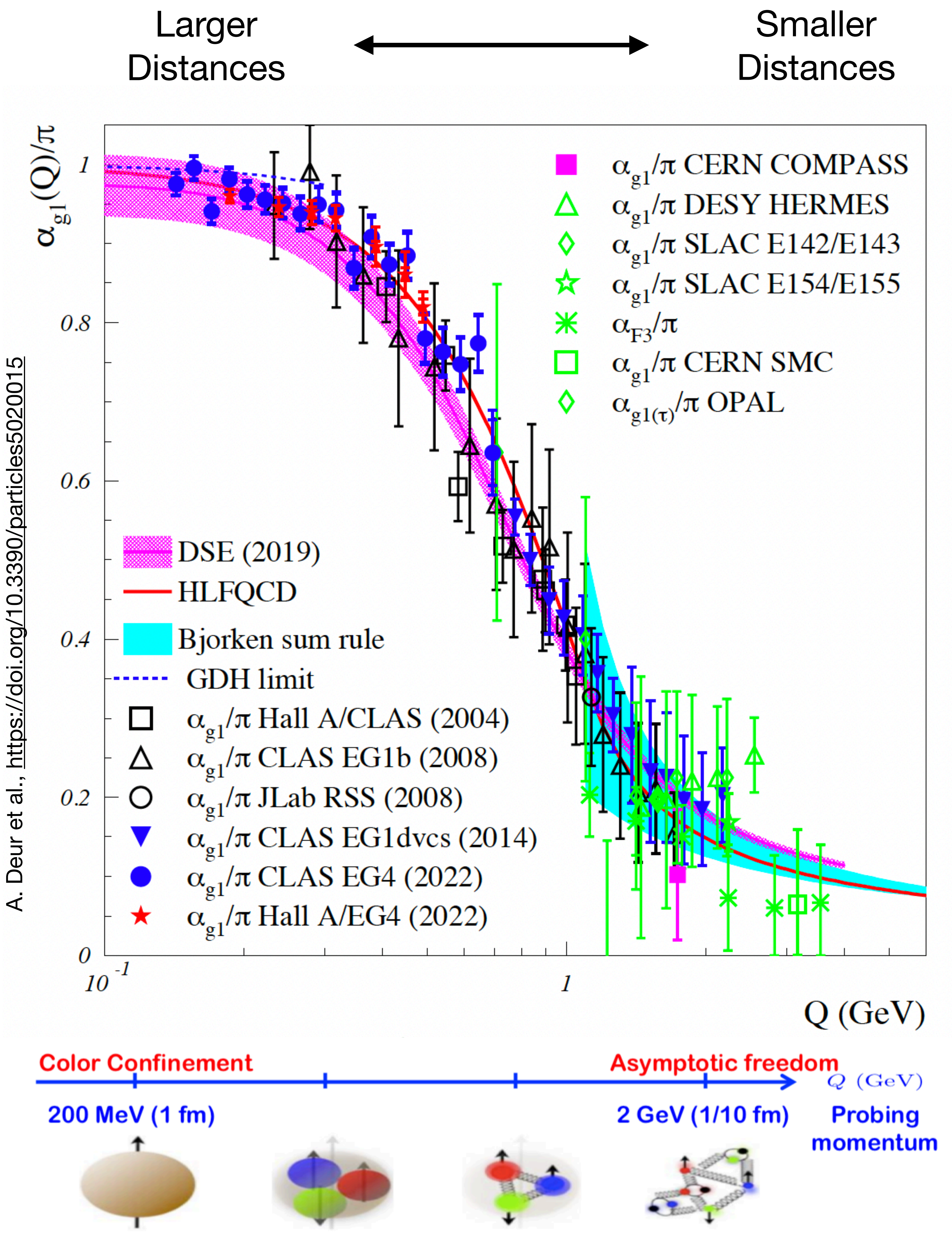
1 fm = 0.000 000 000 000 001 m

Nuclei responsible for almost all visible matter in Universe

We still strive to fully understand how quarks and gluons are arranged inside the nucleon

EIC will be like a powerful microscope to help us understand this further via “femtography”!

# How Are We Held Together?



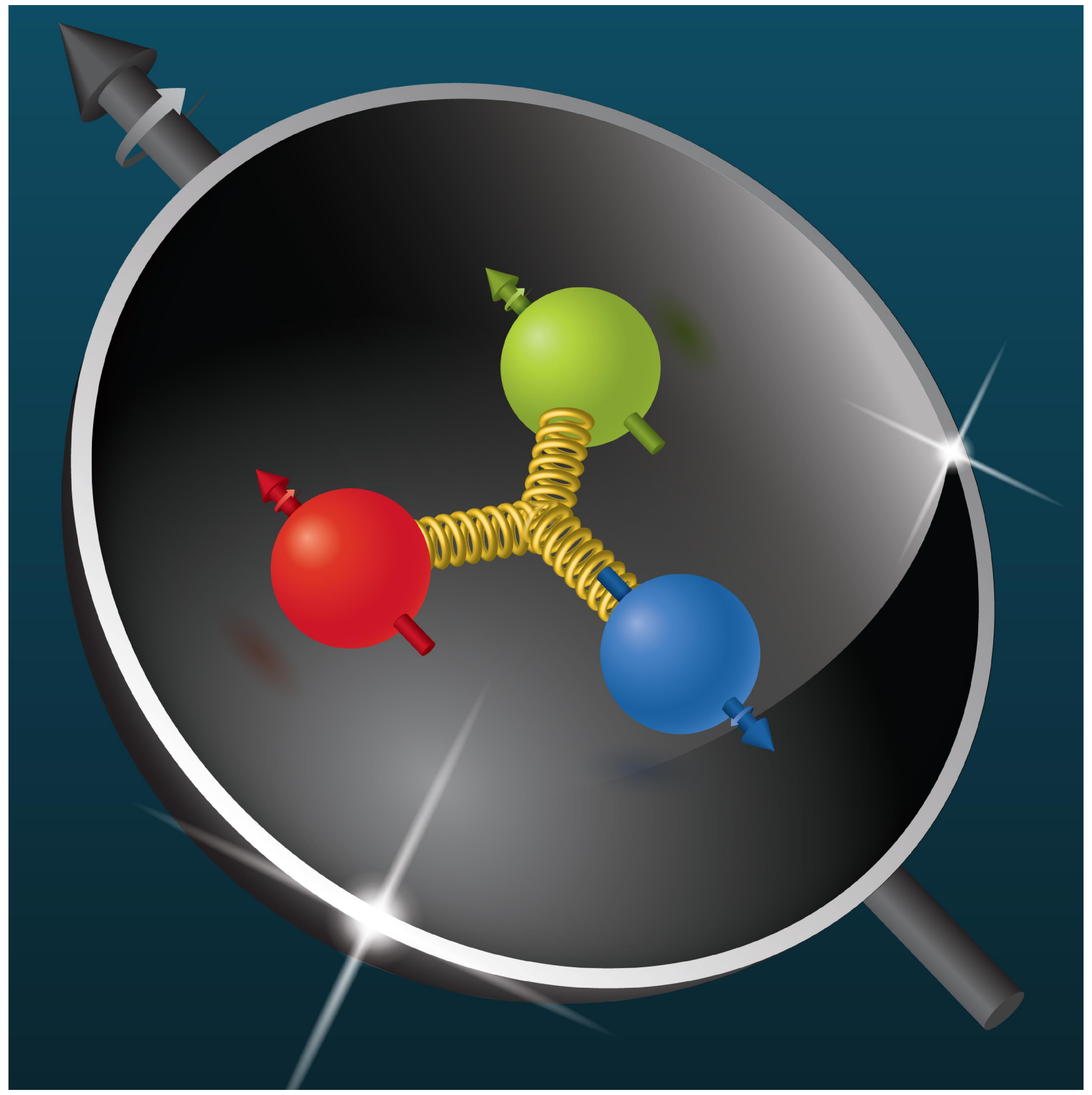

- Quarks and gluons are confined in nuclear matter by strong force, which is mediated by gluons

- Many aspects of strong force not understood
  - E.g. confinement

- EIC will transform our understanding of the force keeping our visible world together!

# The Microcosm of the Nucleon

3 valence quarks
Proton = uud



Sea of transient quark/antiquark pairs and gluons

Proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ +…

- Strong force responsible for complex microcosm of nucleon
- Everyday properties emerge from the nature of the strong interaction
  - mass (mass spectrometry in pharmaceutics)
  - spin (magnetic moment in MRI machines)
- We want to understand the observed properties in terms of the quark/gluon *dynamics*
  - We need the EIC

# A Long Time Coming…

2002

2007

2009

2010

2012

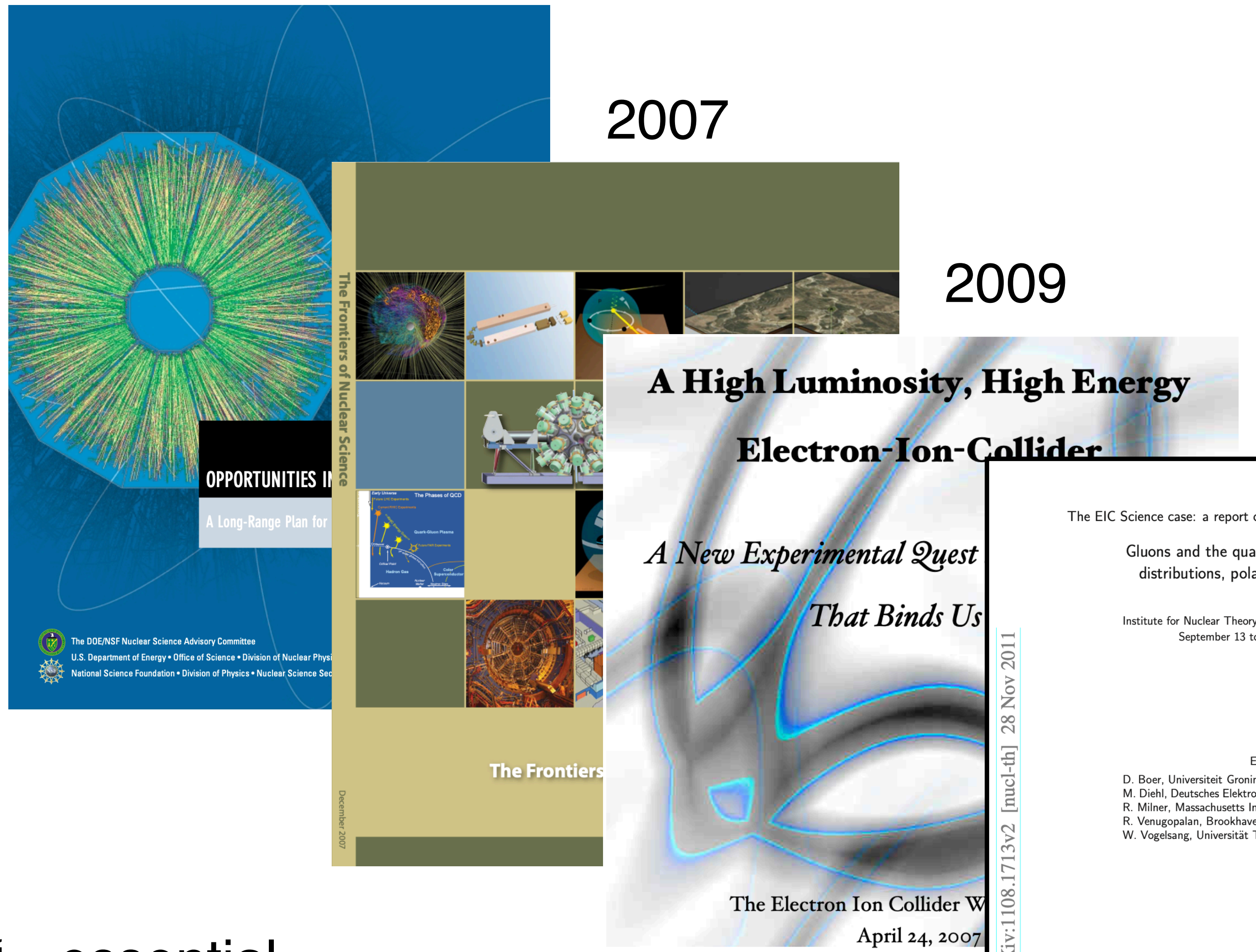
2013

2015

2018

2021

2023






"Central to the nuclear science program of the next decade"

"A high-energy high-luminosity polarised 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

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

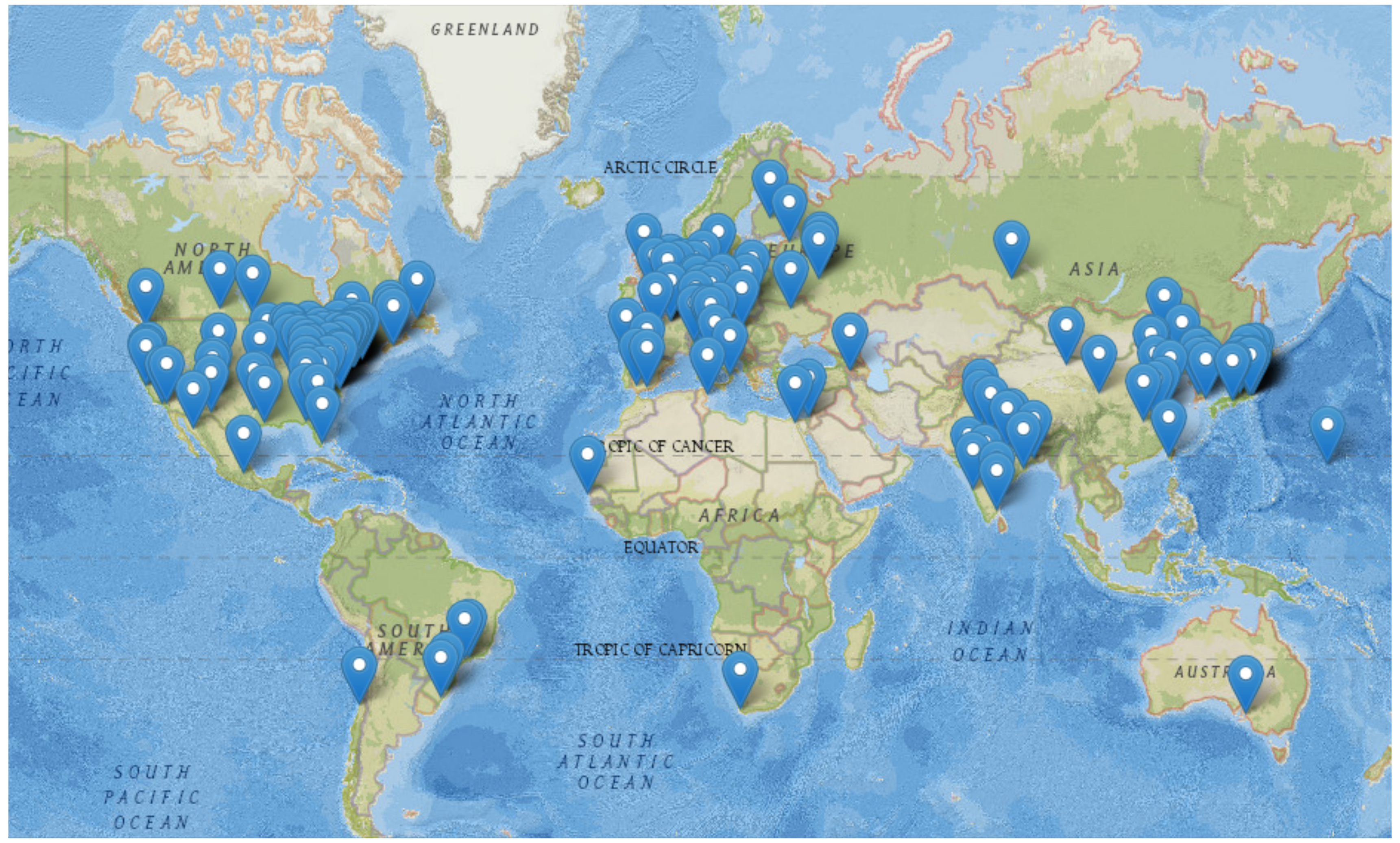
"We recommend the allocation of resources…to lay the foundation for a polarised Electron-Ion Collider…"

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

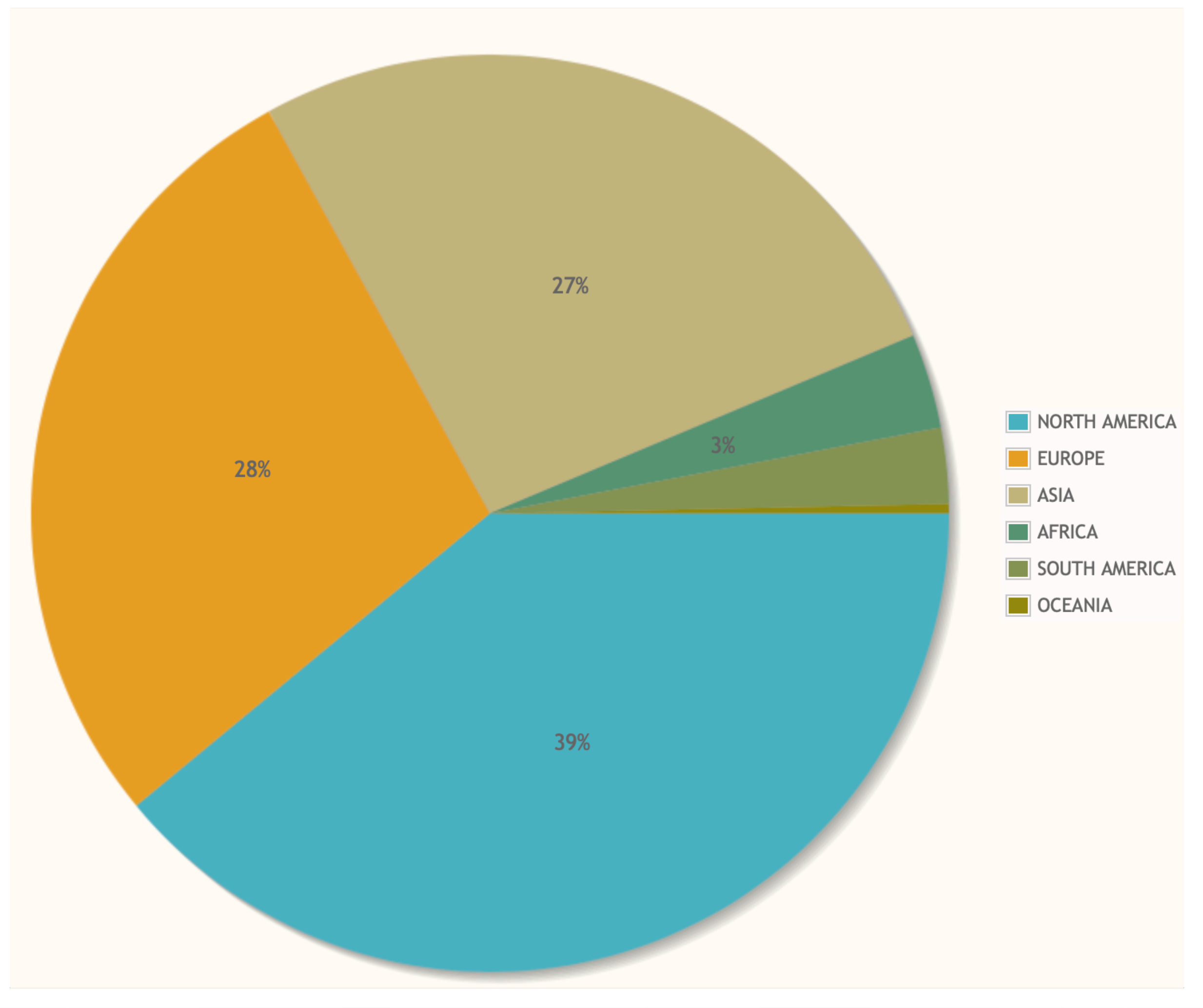
"The quantitative study of matter in this new regime [where abundant gluing dominate] requires a new experimental facility: an Electron-Ion Collider"

**Extensive EIC program has been developed by a large international community over two decades**

# A Long Time Coming…




- An ever-growing international community has been developing science case
  - more collaborators always welcome
- EIC Users Group (https://www.eicug.org)
- Formed 2016
- Set out the science requirements and detector concepts in Yellow Report




Current stats:

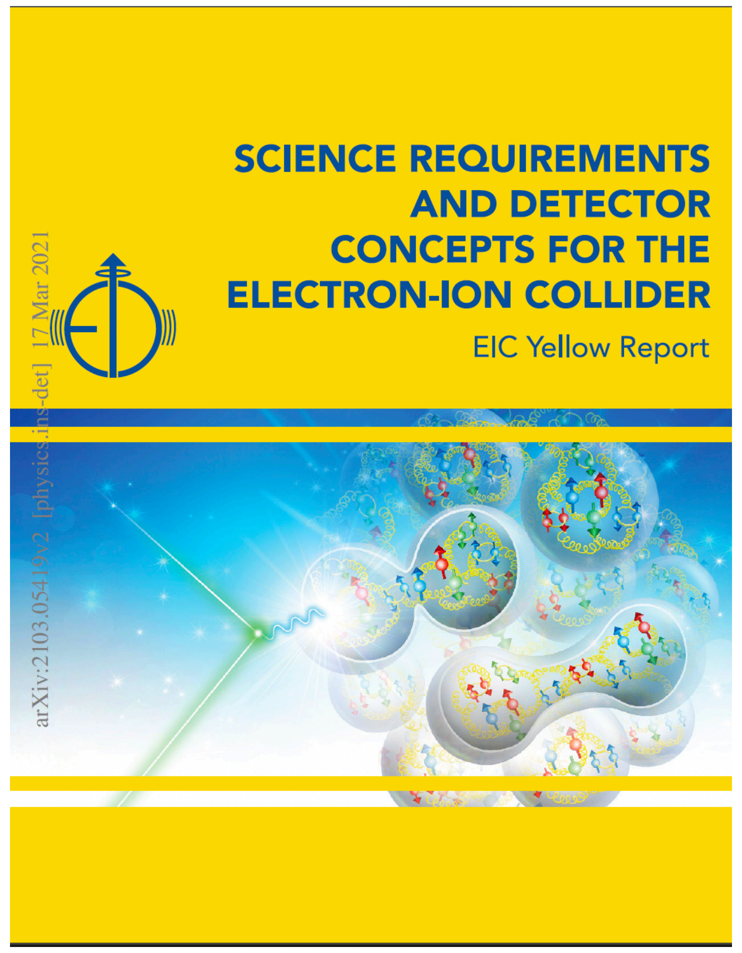
1552 members;

300 institutions;

40 countries (6 world regions)

1032 Experimentalists; 374 Theorists; 130 in Accelerator

2021



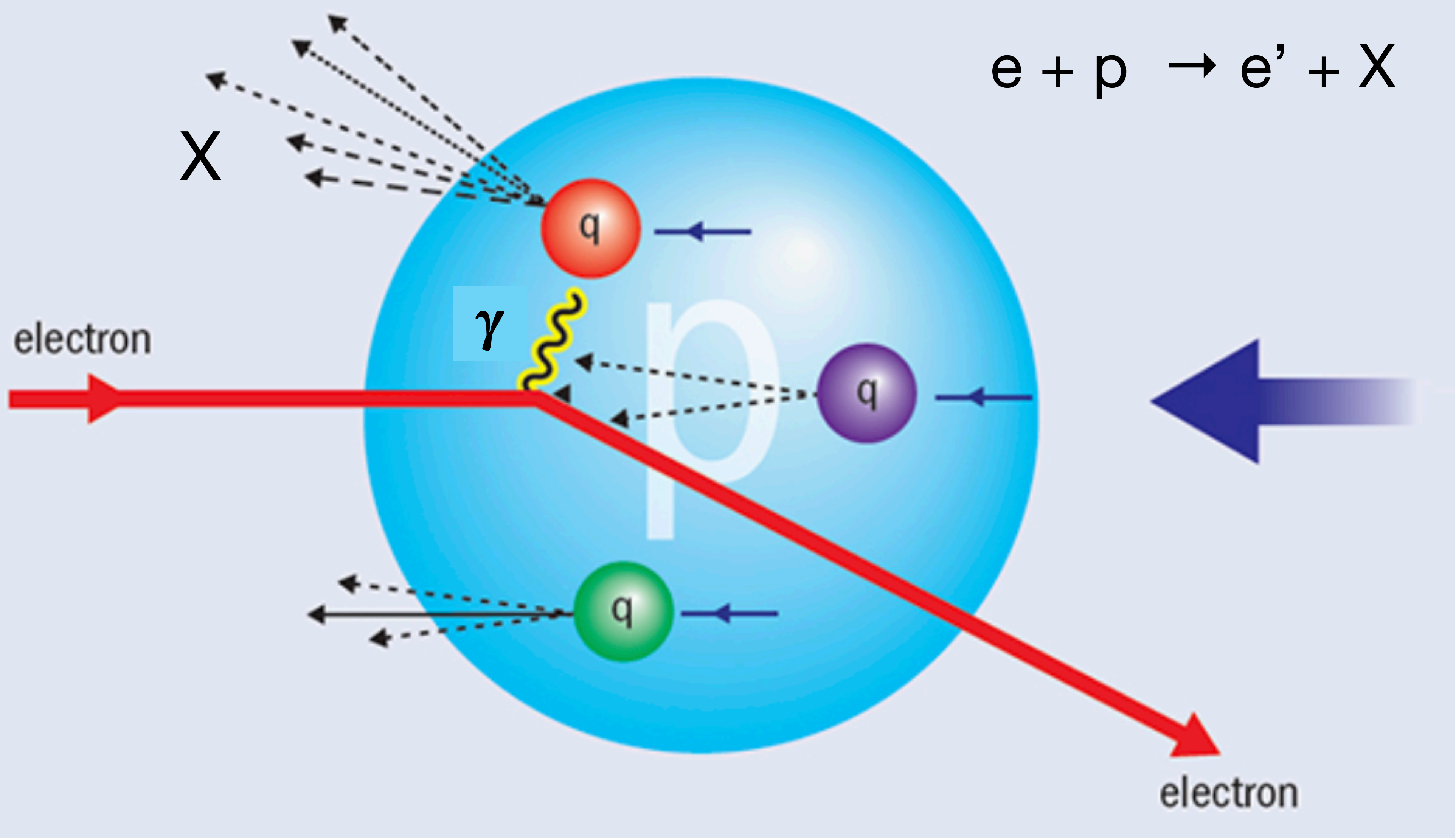

Yellow Report arXiv:2103.05419v2 [physics.ins-det]

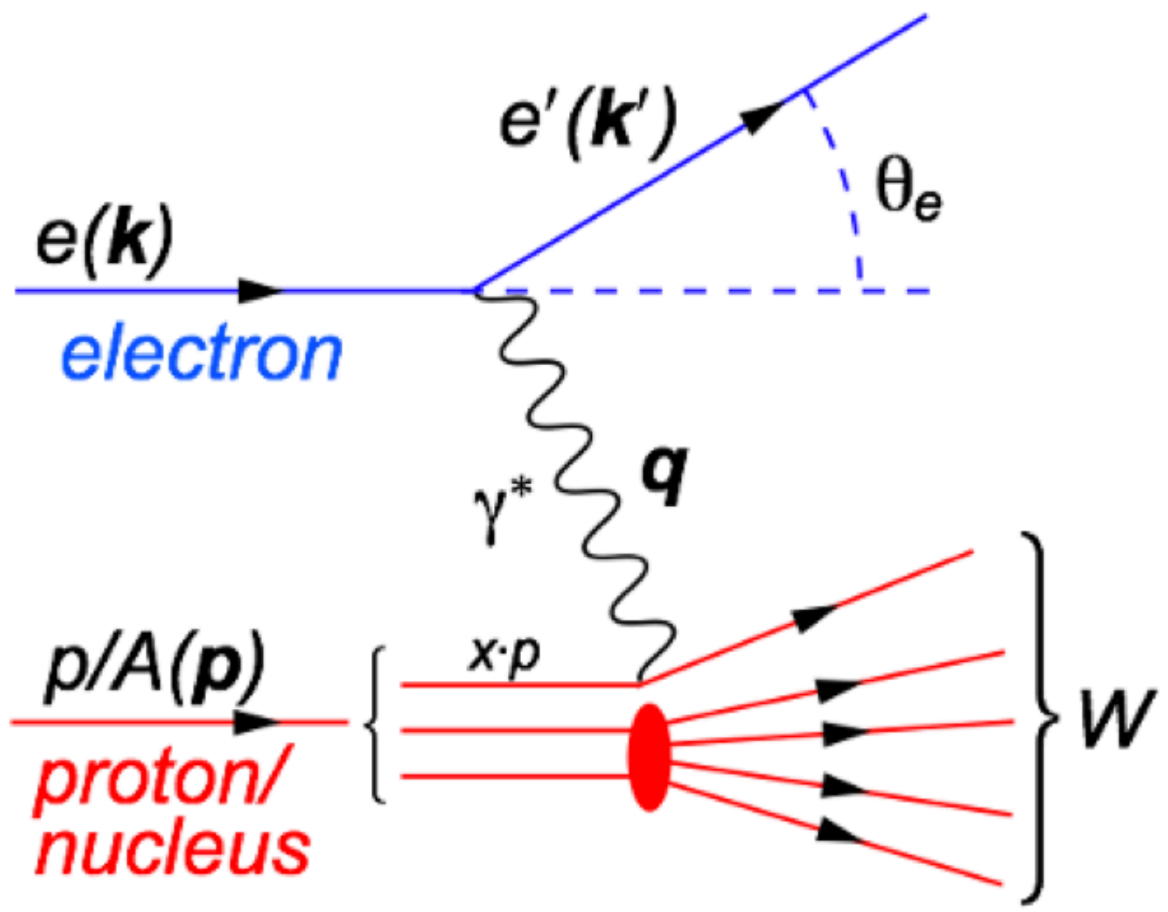
How can this science program be realised?

# How Will the EIC Peer Inside Nuclear Matter?

## Deep Inelastic Scattering (DIS) - Golden Process

Electrons → electromagnetic interaction → unmatched precision of QED




e-p $E_{CM}^2$

$$s = (k+p)^2$$

Photon virtuality - by detecting e

$$Q^2 = -q^2$$

$$y = \frac{p \cdot q}{p \cdot k}$$

*Inelasticity*

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

*Bjorken x*

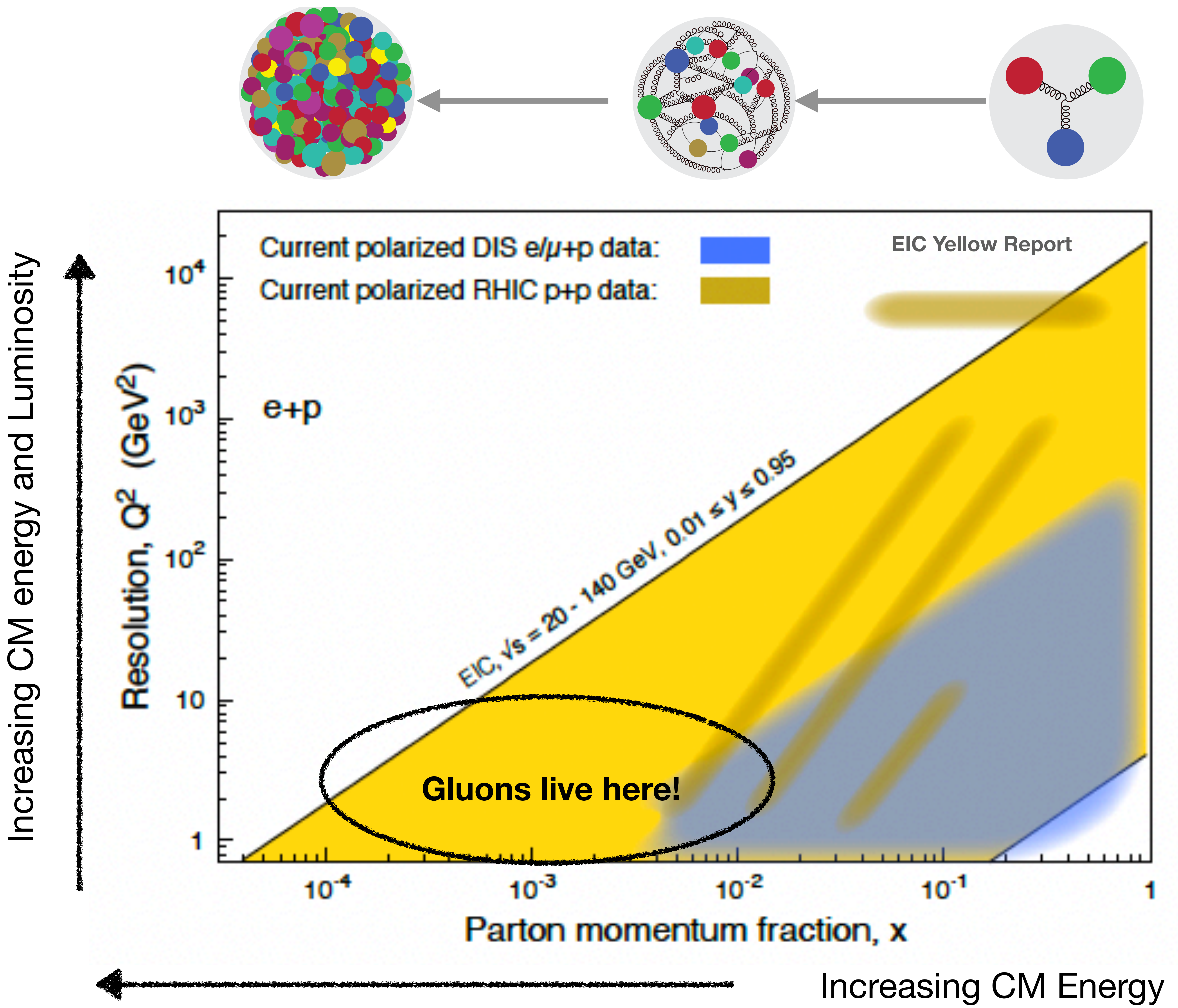
- Complete control of partonic kinematics event by event
- Initial and final states can be disentangled

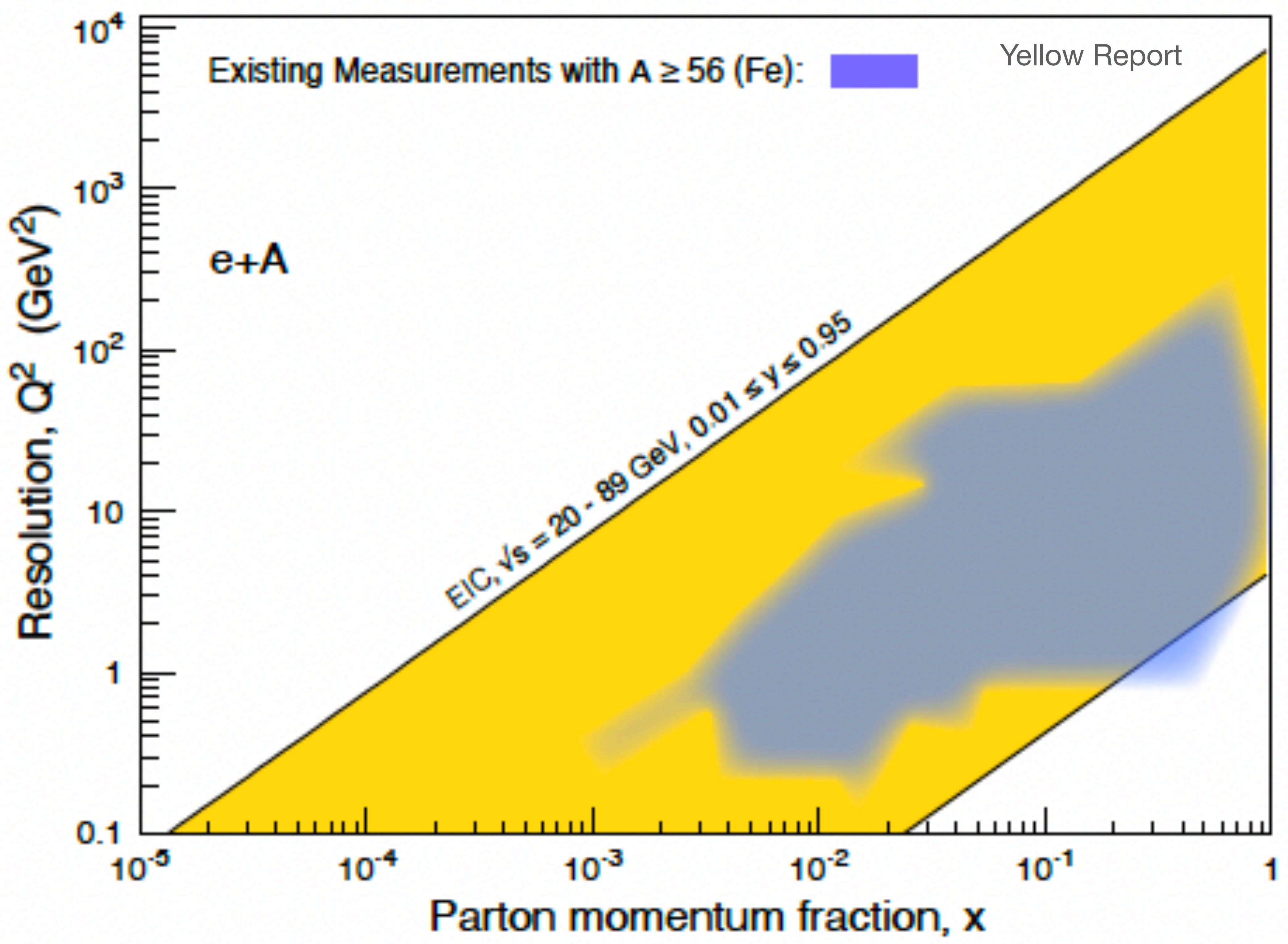
- Complimentary to e+e-, pp/pA/AA (eg test universality)

$$\boxed{Q^2 = s \cdot x \cdot y}$$

$Q^2$ = Resolution power
s = Centre-of-mass energy squared
x = Fraction of nucleon's momentum that the struck quark carries (0<x<1)
y = Inelasticity

# Probing Unchartered Territory



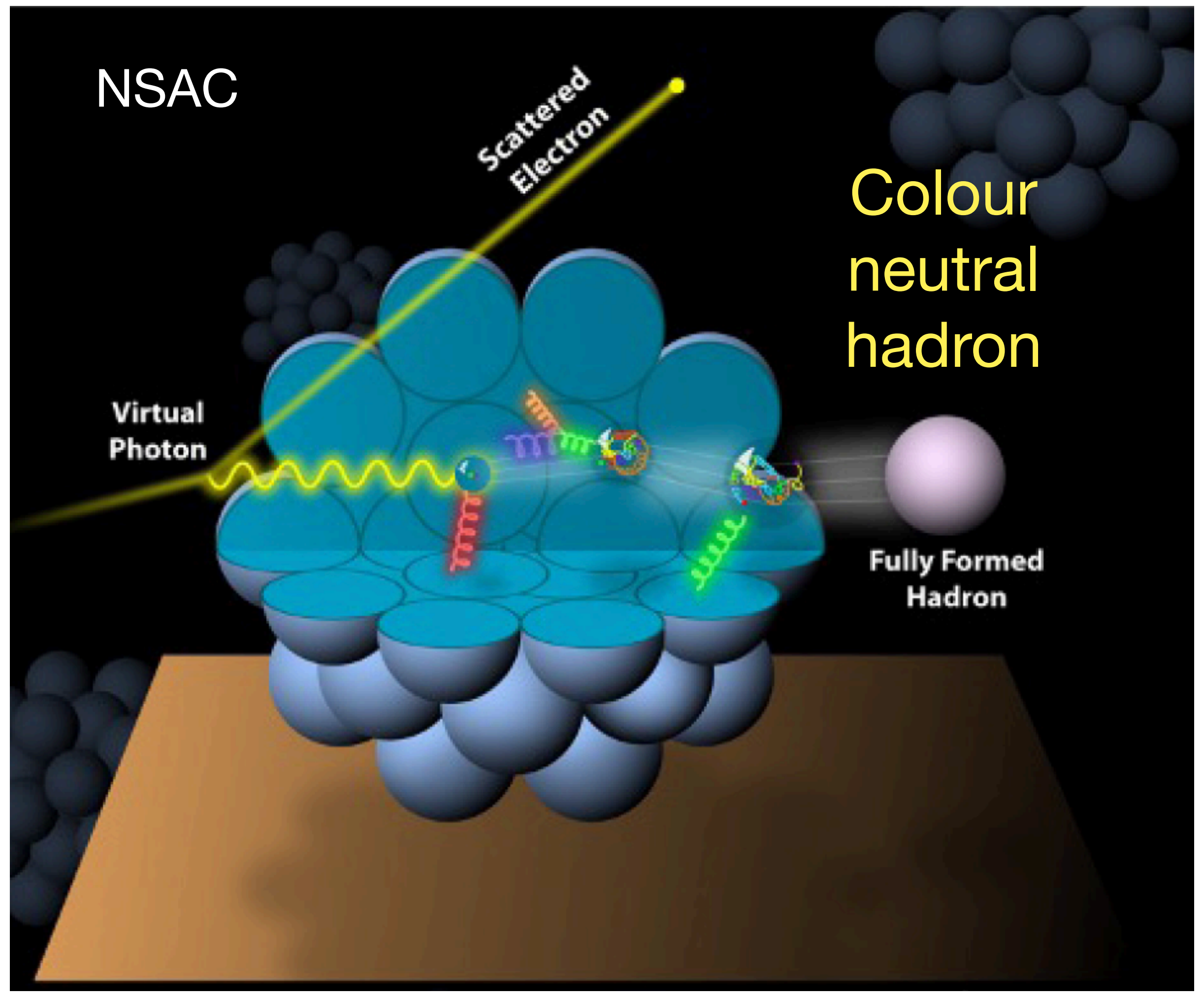




Vast QCD landscape in resolution ($Q^2$) and quark/gluon density (1/x)

Overlaps with existing data and provides access to unchartered regions in x and $Q^2$

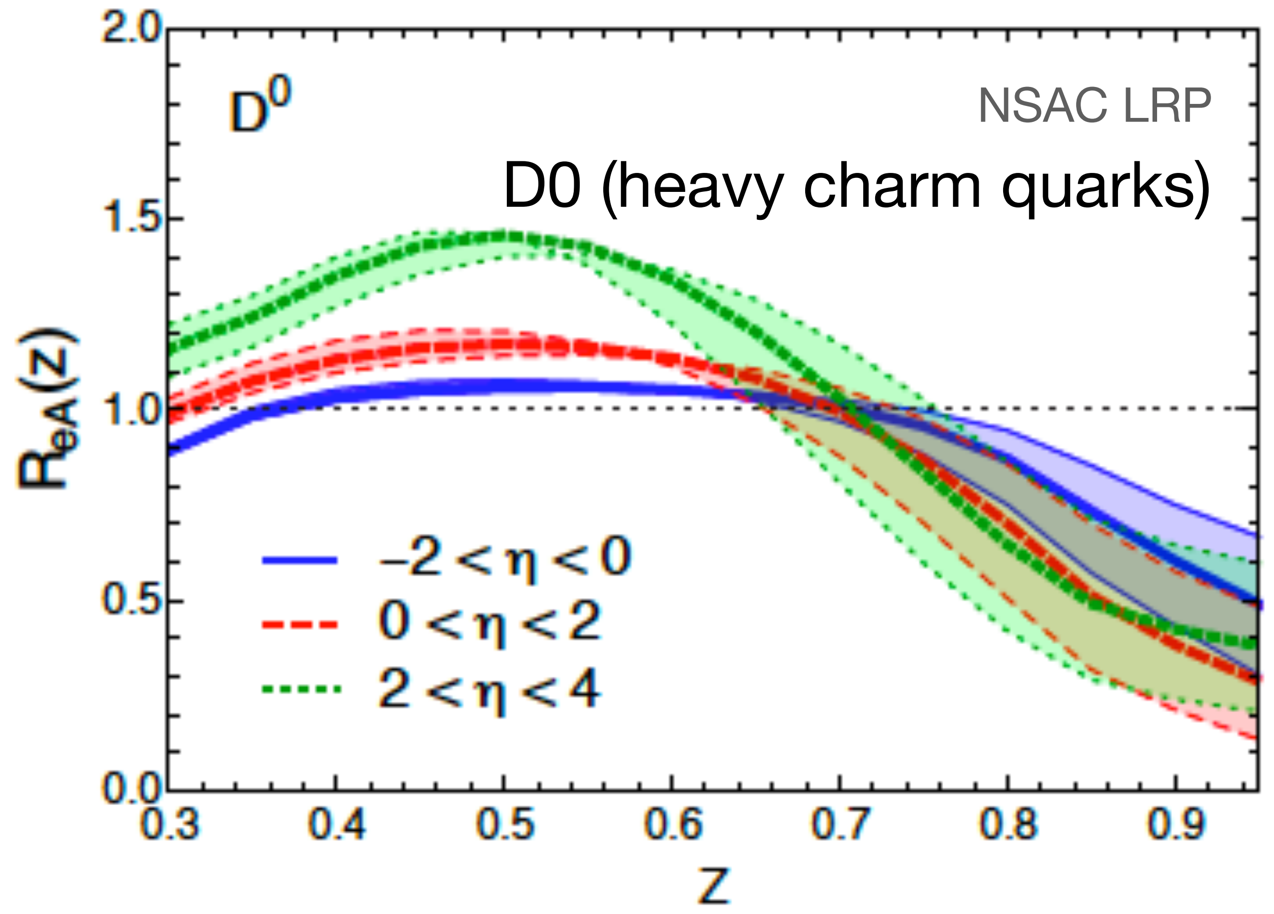
The only facility in the world uniquely designed to probe the ocean of gluons and sea quarks!

# Nuclei as a Laboratory for the Strong Force




How do hadrons emerge? What's the nature of confinement?

How do colour charged quarks, gluons and colourless jets interact with nuclear medium?

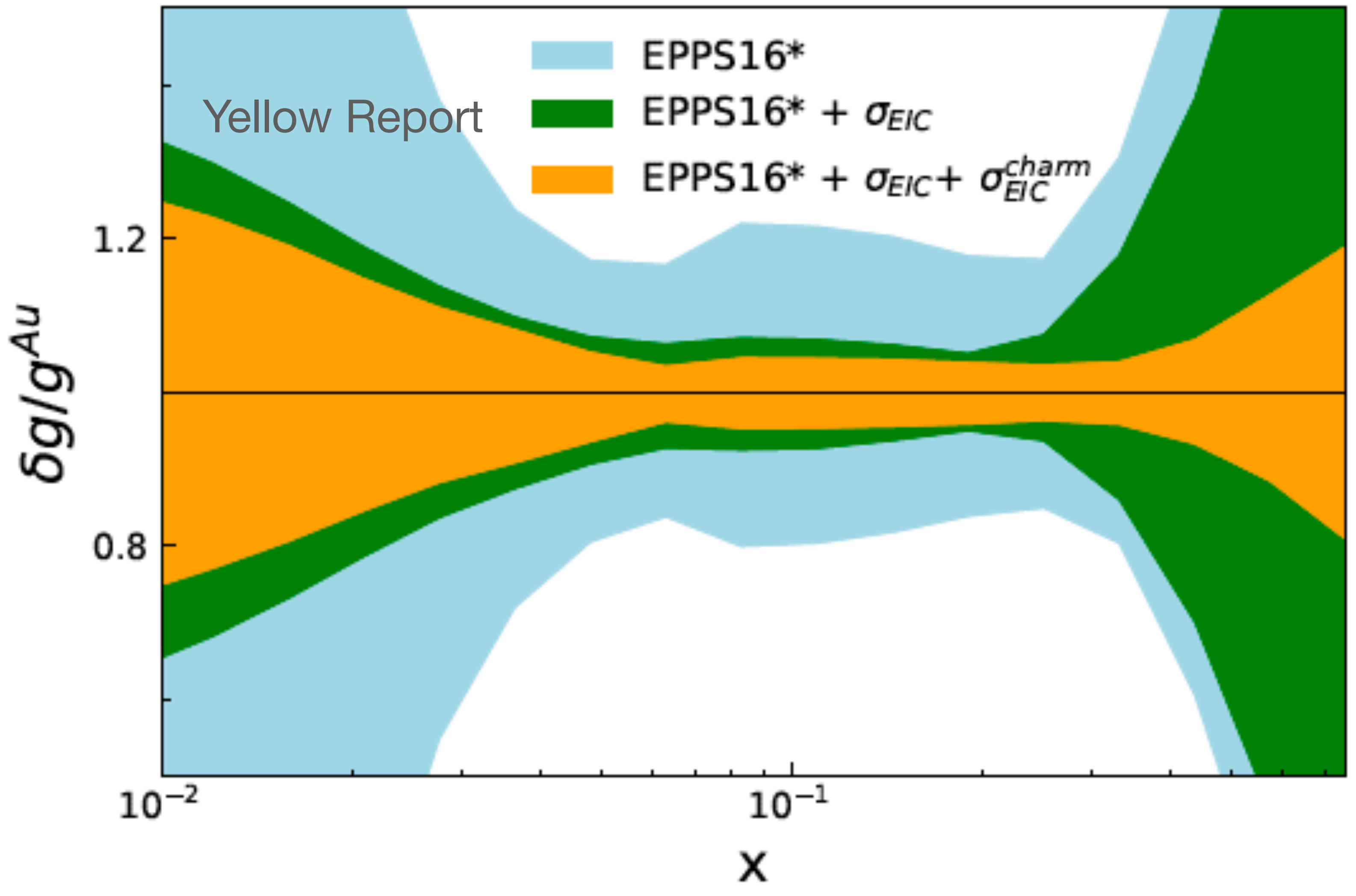



Predicted ratios of relative particle production in eA over ep

Substantial modification → differentiate models of hadronisation

EIC will compare jets of particles created in e+p vs e+A
Wide $Q^2$ range, high luminosity, excellent particle identification
Range of nuclei to study how different nuclear mediums affect different quarks types

Relative uncertainties of gluon densities in Au

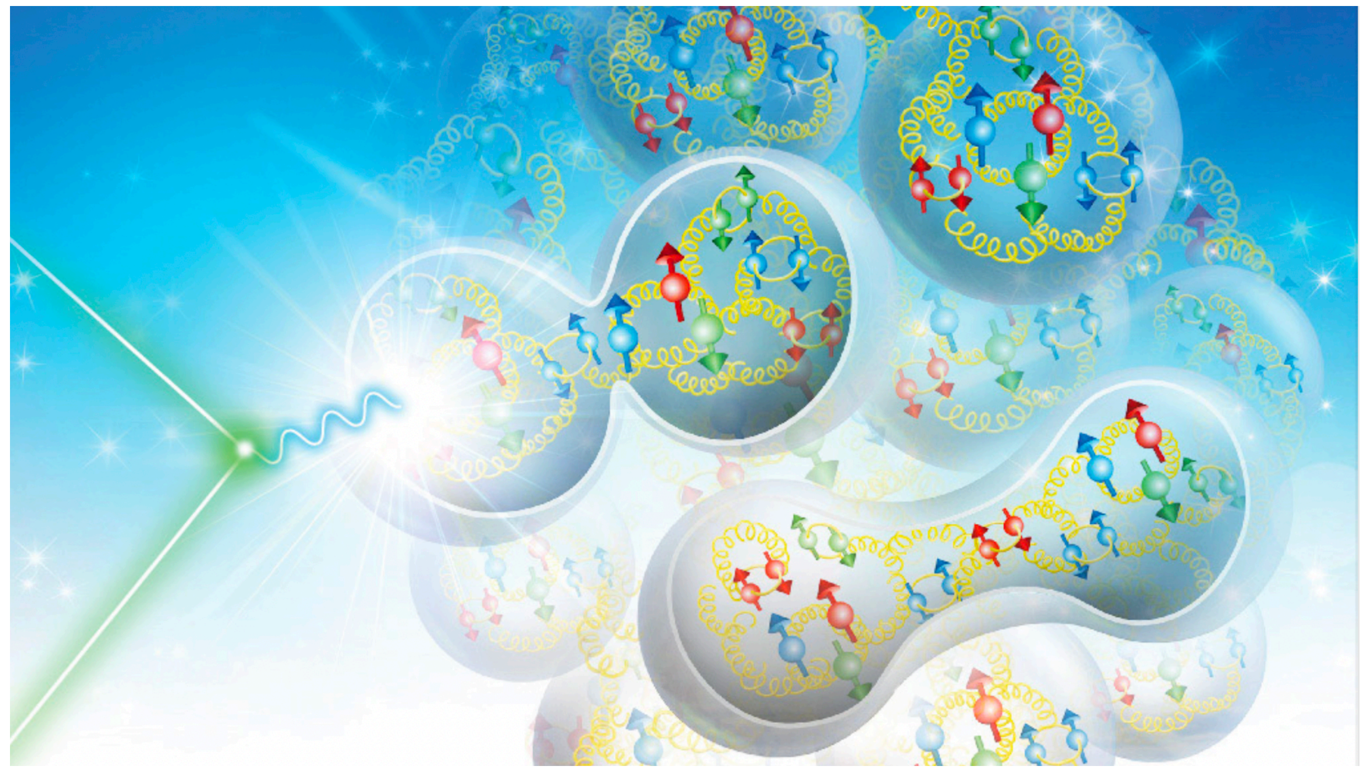



Access to heavy charm quarks will help pin down gluon contributions to nuclear modifications

Picture inside an un-bound proton changes when that proton is bound inside a nucleus. How? Why?

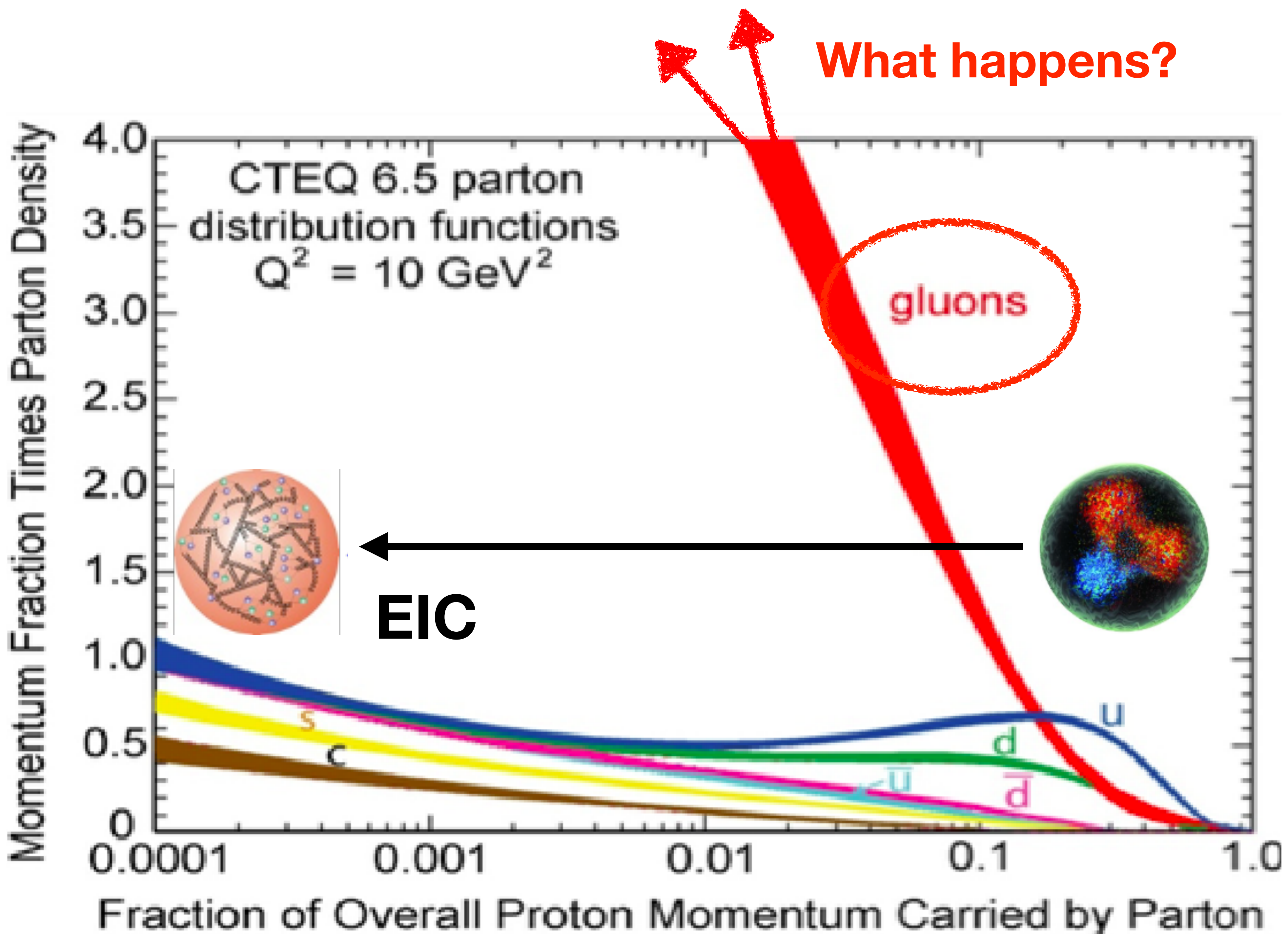
EIC will compare unbound proton with nuclear PDFs via inclusive DIS on nuclei

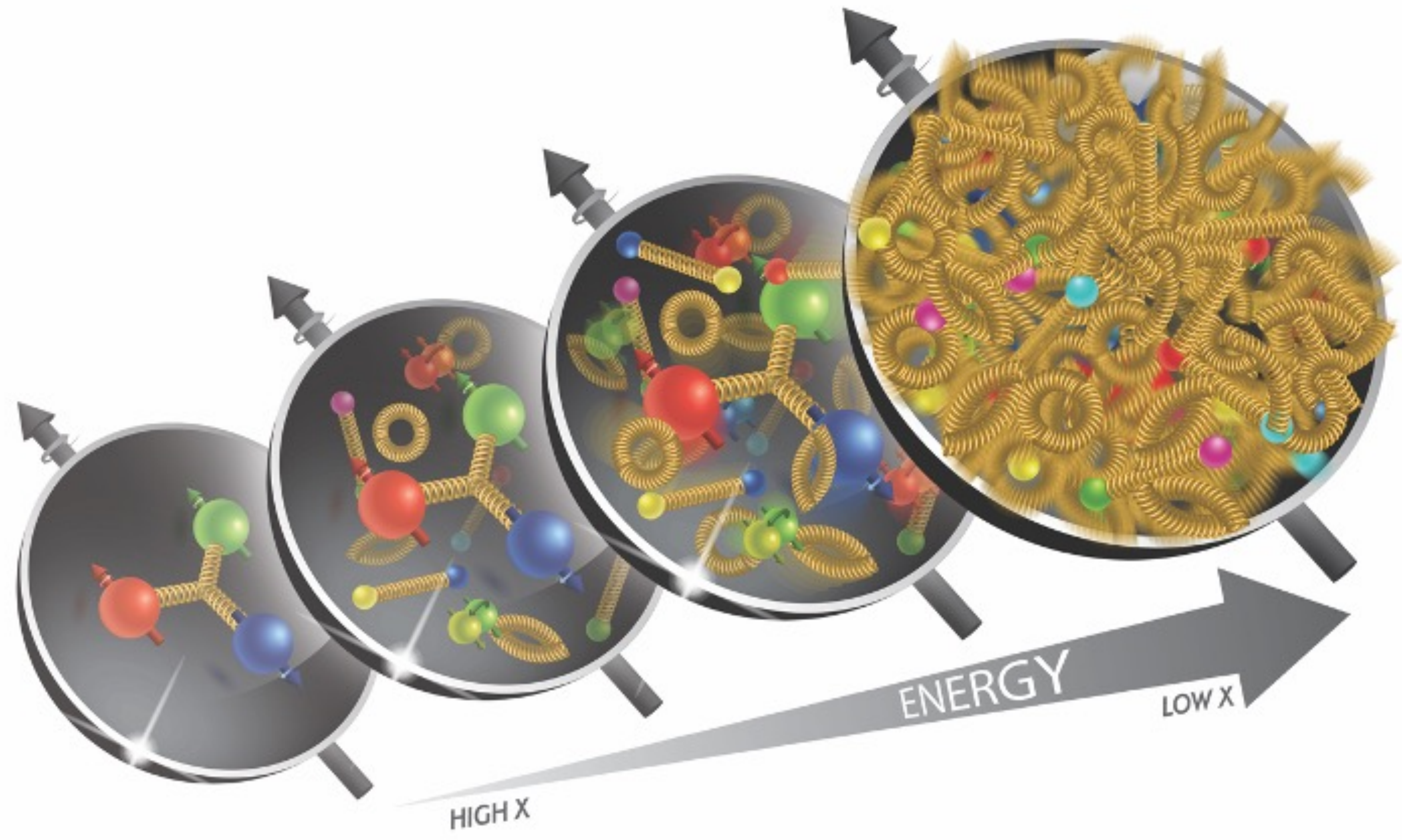
- unrivalled precision over very wide landscape



Tagging nucleons knocked out from DIS on light nuclei will shed light on how protons and neutrons interact with each other inside nuclei
How does this influence nuclear binding?

# Deep Dive into Gluon Territory



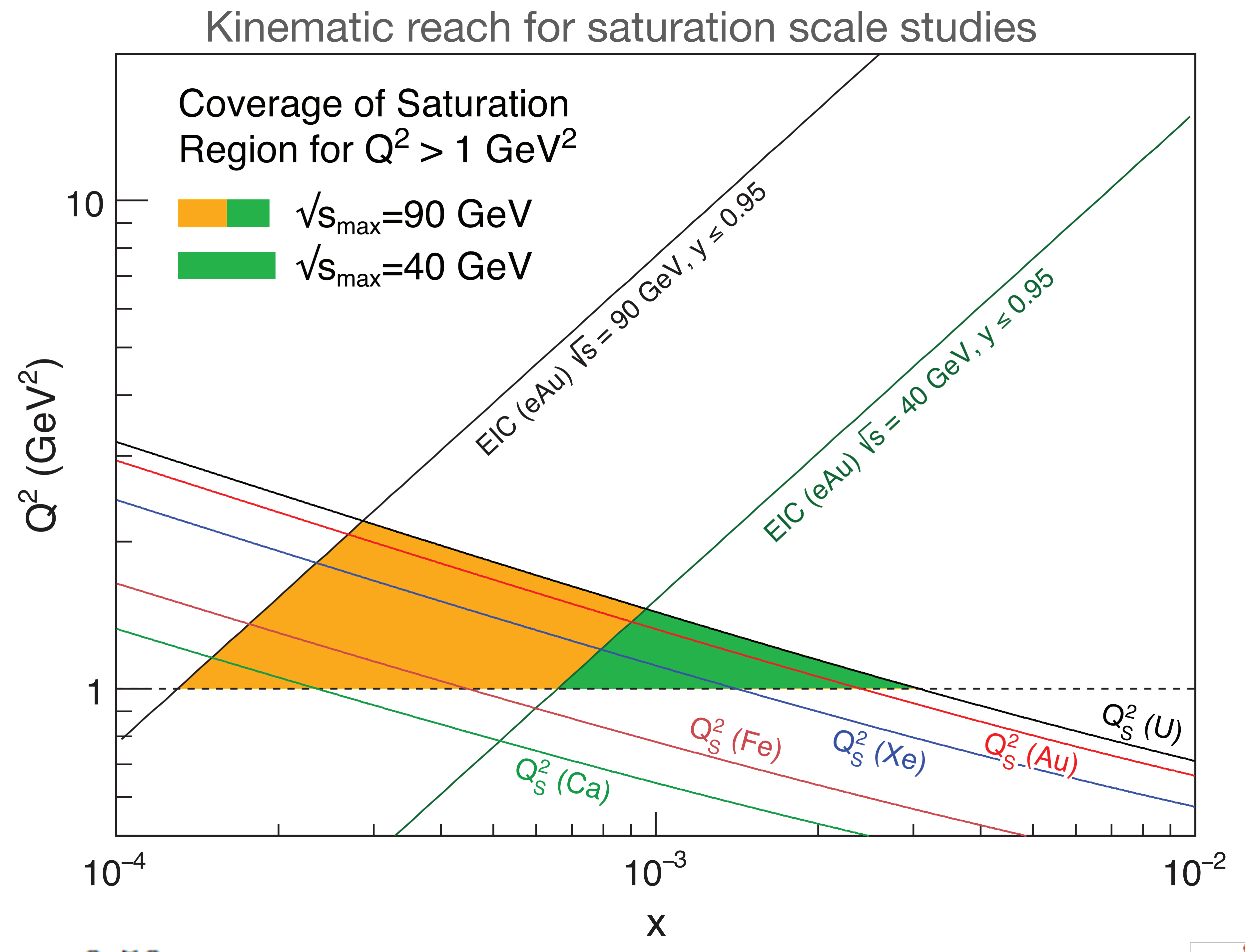

Is the proton a runaway popcorn machine?

Previous *1D* studies show explosion of gluons
Gluons are self interacting

What happens to gluons?
Does gluon density saturate? When?

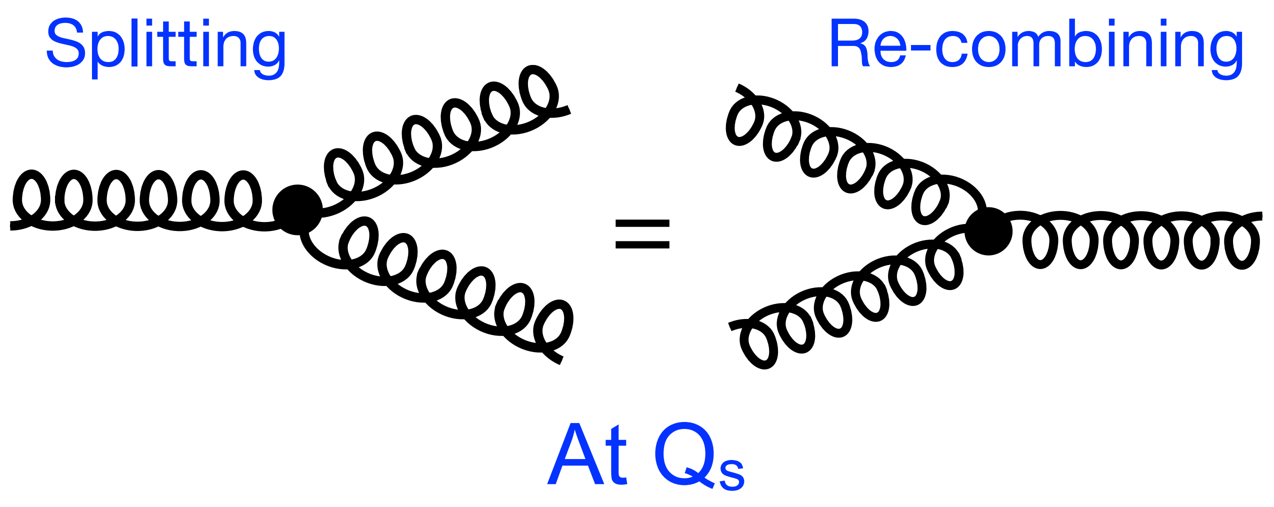
Does this give rise to a new phase of matter with universal properties in the nucleon and nuclei?

# Deep Dive into Gluon Territory

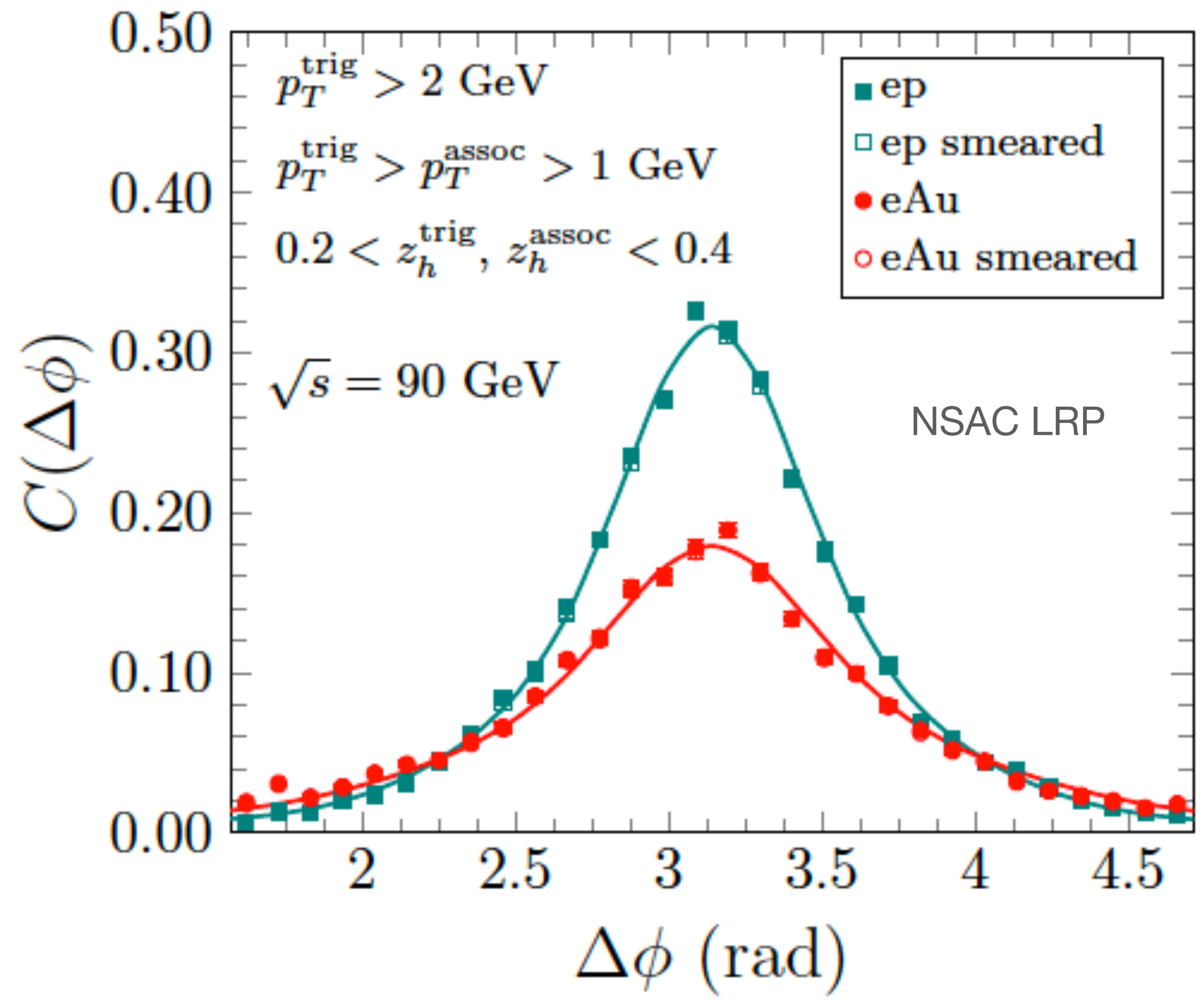


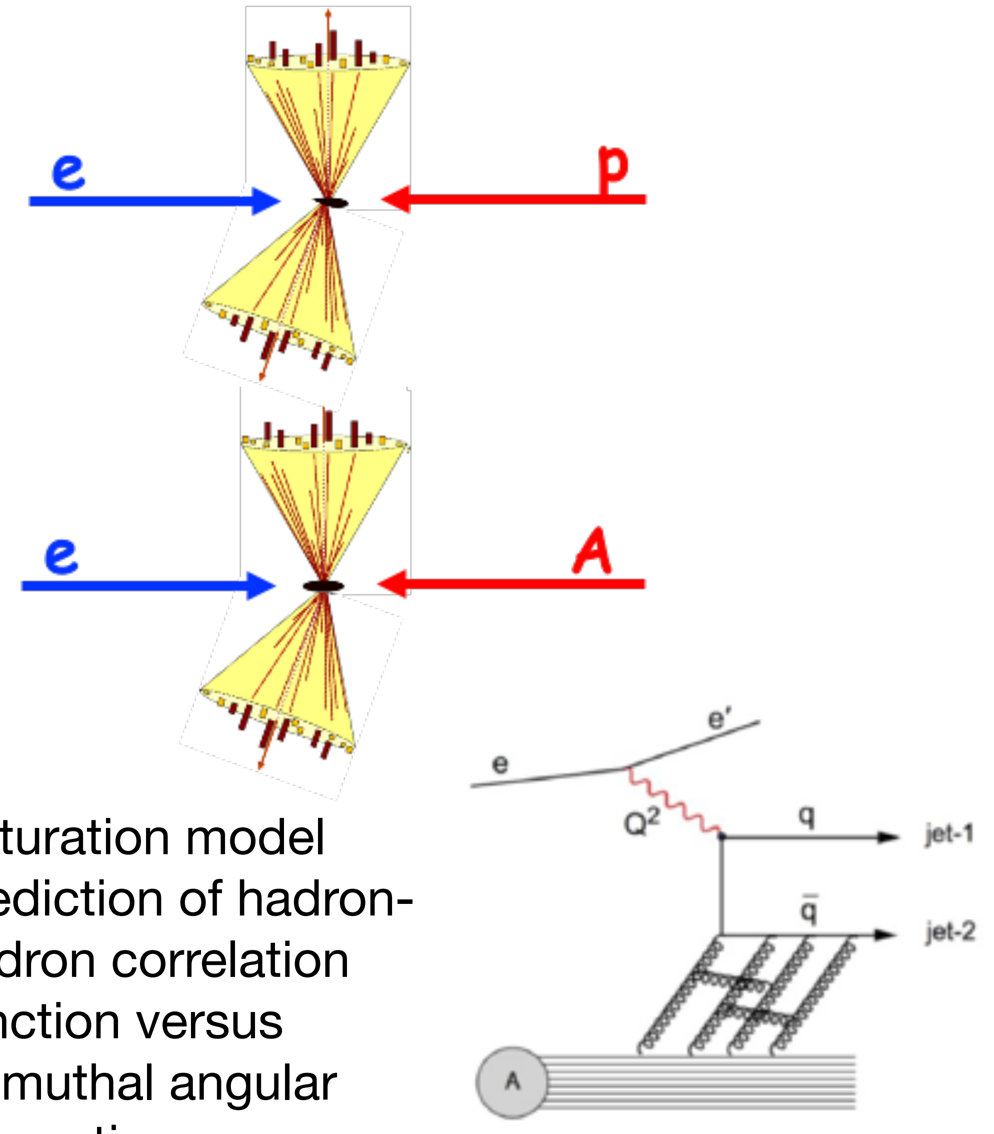

Gluons have a spatial extent which we probe with Q²

When we no longer "see" individual gluons we have reached domain of saturation




$$\boxed{Q_S^2 \propto A^{\frac{1}{3}}}$$



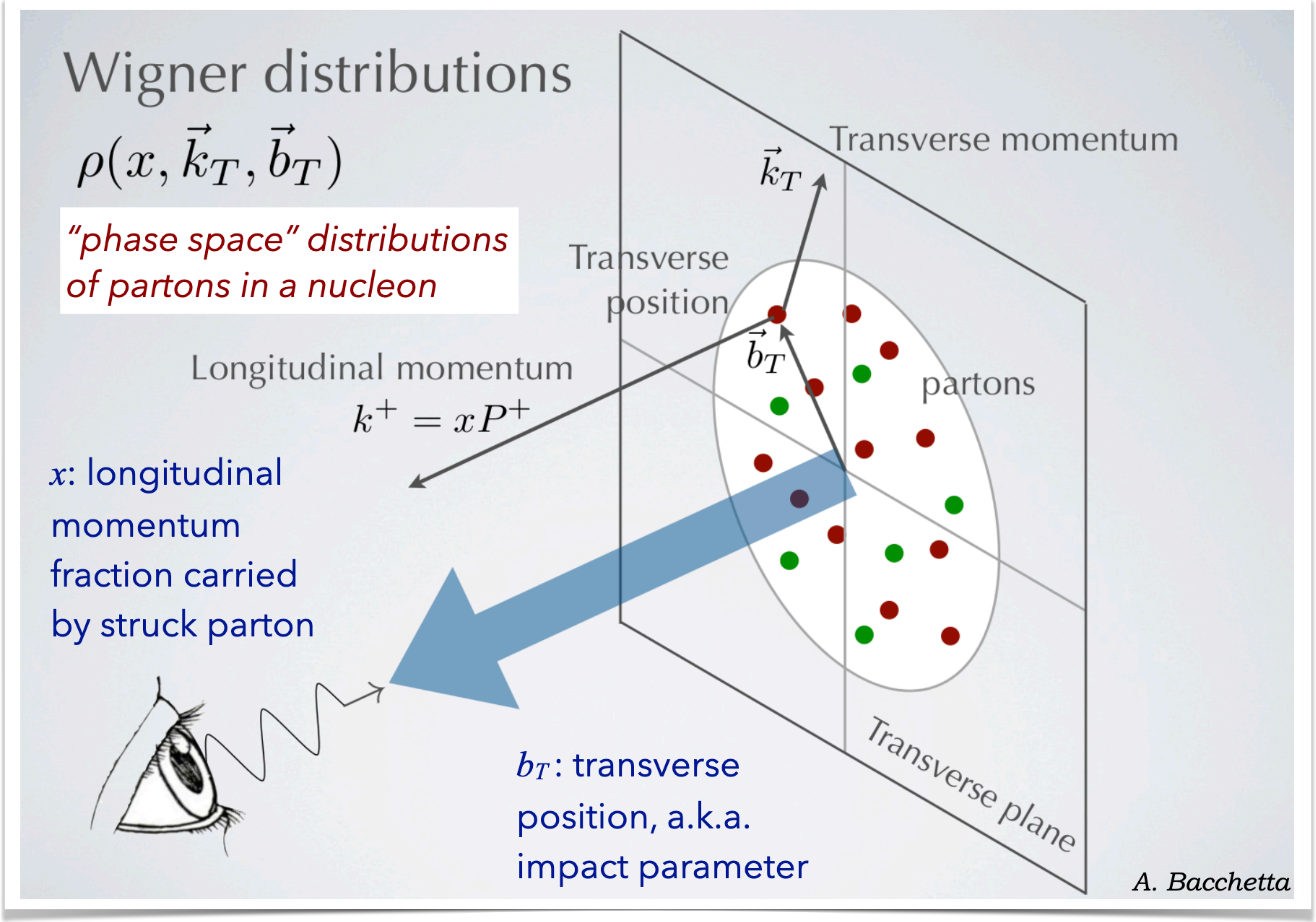

Saturation model prediction of hadron-hadron correlation function versus azimuthal angular separation

- EIC → large suite of measurements to study onset of saturation and map transition from linear to non-linear QCD regime
- Characterised by saturation scale, $Q_S$
- EIC: high energies, low reach in x, range of nuclei
- Very large gluon densities uniquely available (eg e-Pb)
- $Q_S$ can be reached at lower energies with heavier nuclei

- Measurements: coherent diffractive scattering of nuclei; nuclear vs nucleon PDFs; angular correlations in production of di-jets in ep vs eA … and more …

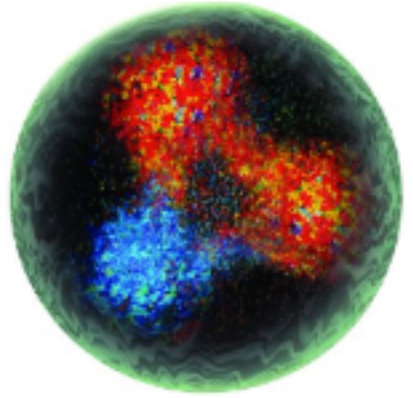
# How are the partons distributed inside the nucleon?

Another tool to improve our understanding of quark/gluon densities is tomography

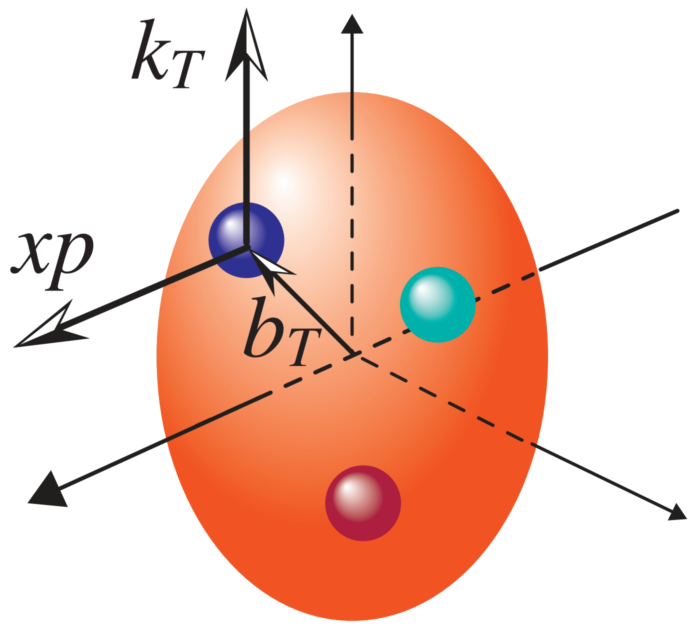



Our goal: understand how quarks and gluons are distributed in space and momentum inside hadrons

# Tomography for 3D Structure



**Wigner Function W(x, $b_T$, $k_T$)**
**Full phase space parton distribution of the nucleon**



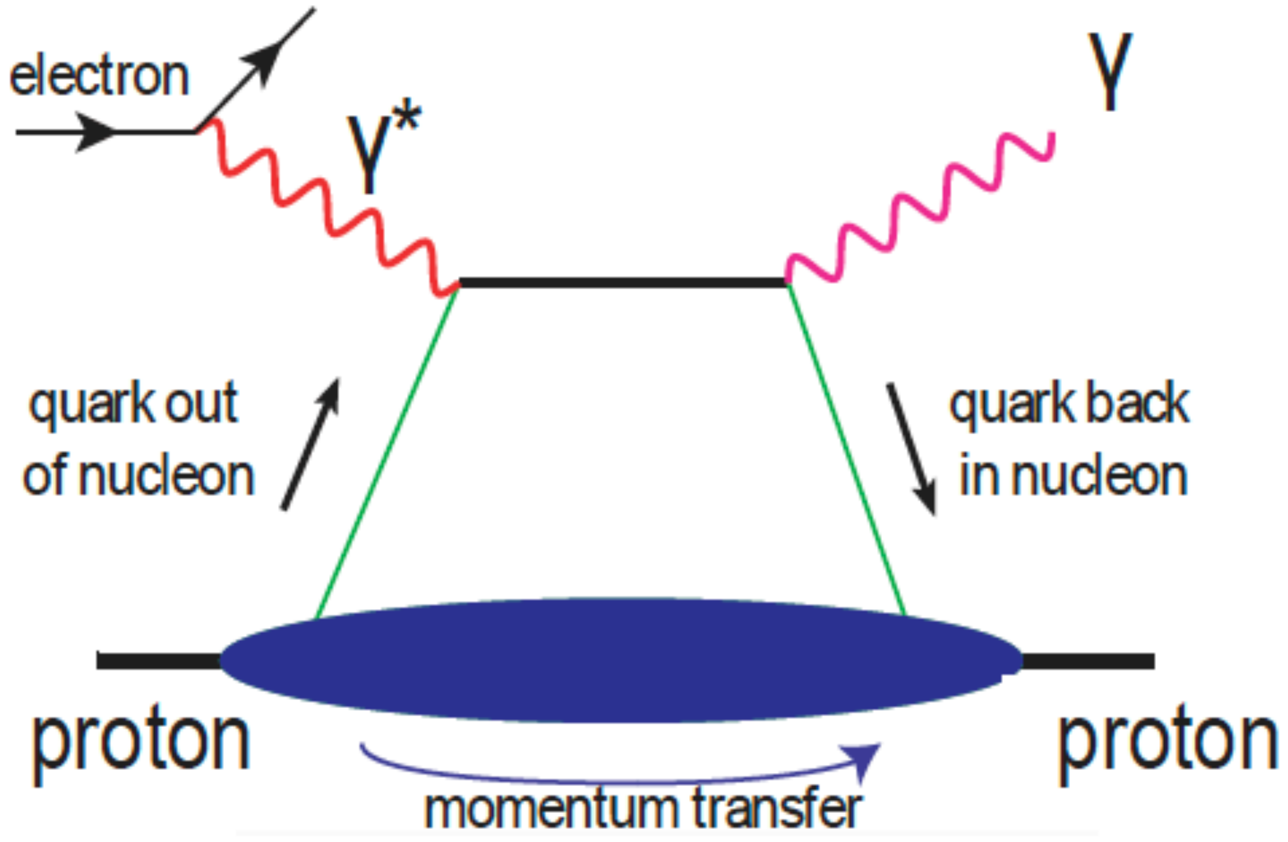

**$\int d^2k_T$**

**$\int d^2b_T$**

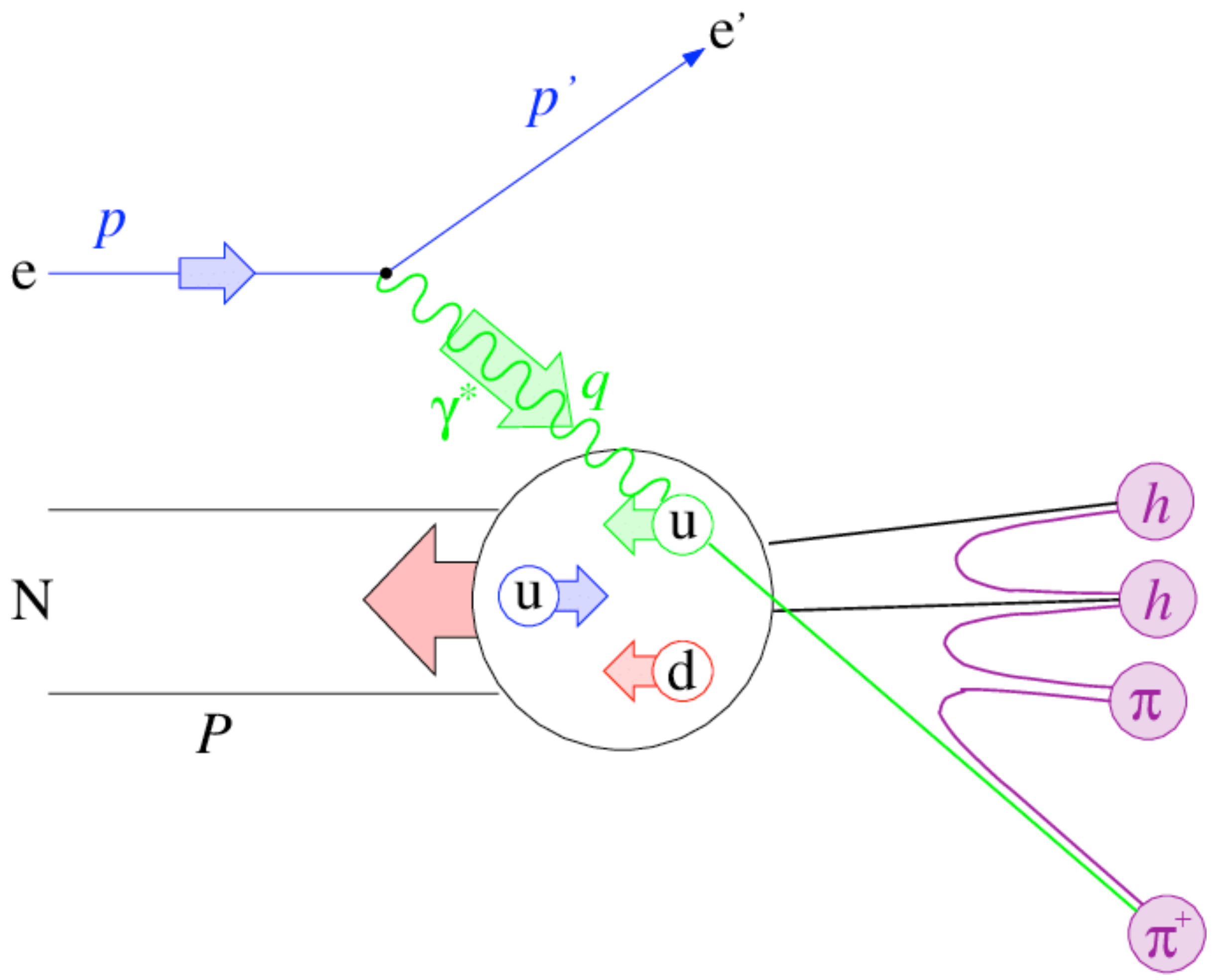
**Coordinate Space**
**f(x,$b_T$)**

**Momentum Space**
**f(x,$k_T$)**

Exclusive reactions e.g. electroproduction of photons (γ) or mesons ($q\bar{q}$)

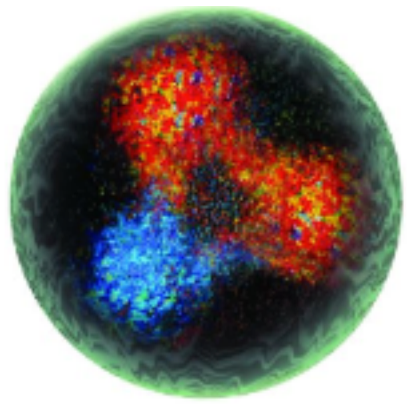



"Deeply Virtual Compton Scattering"




Semi-inclusive deep inelastic scattering

# Tomography for 3D Structure



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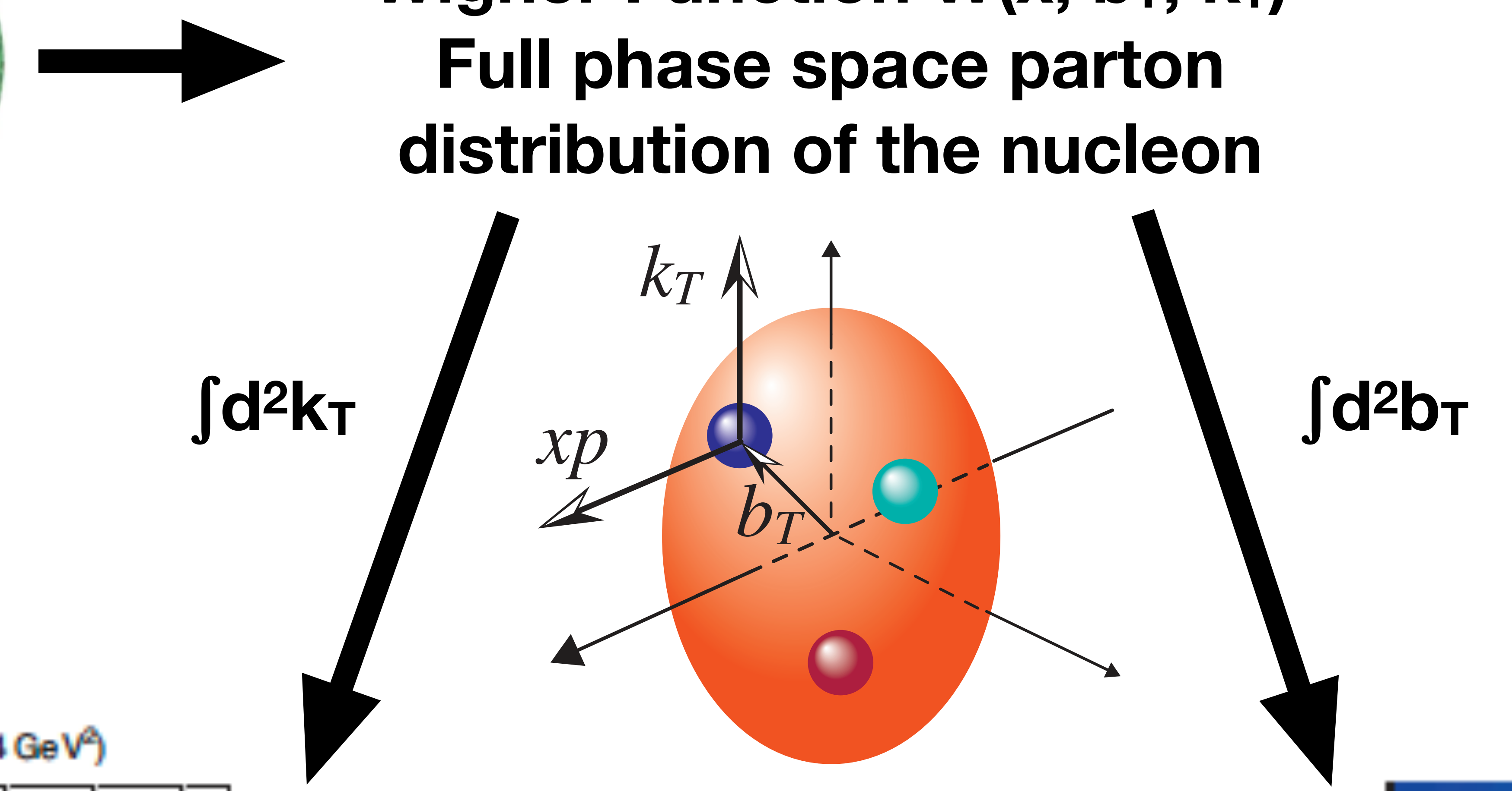


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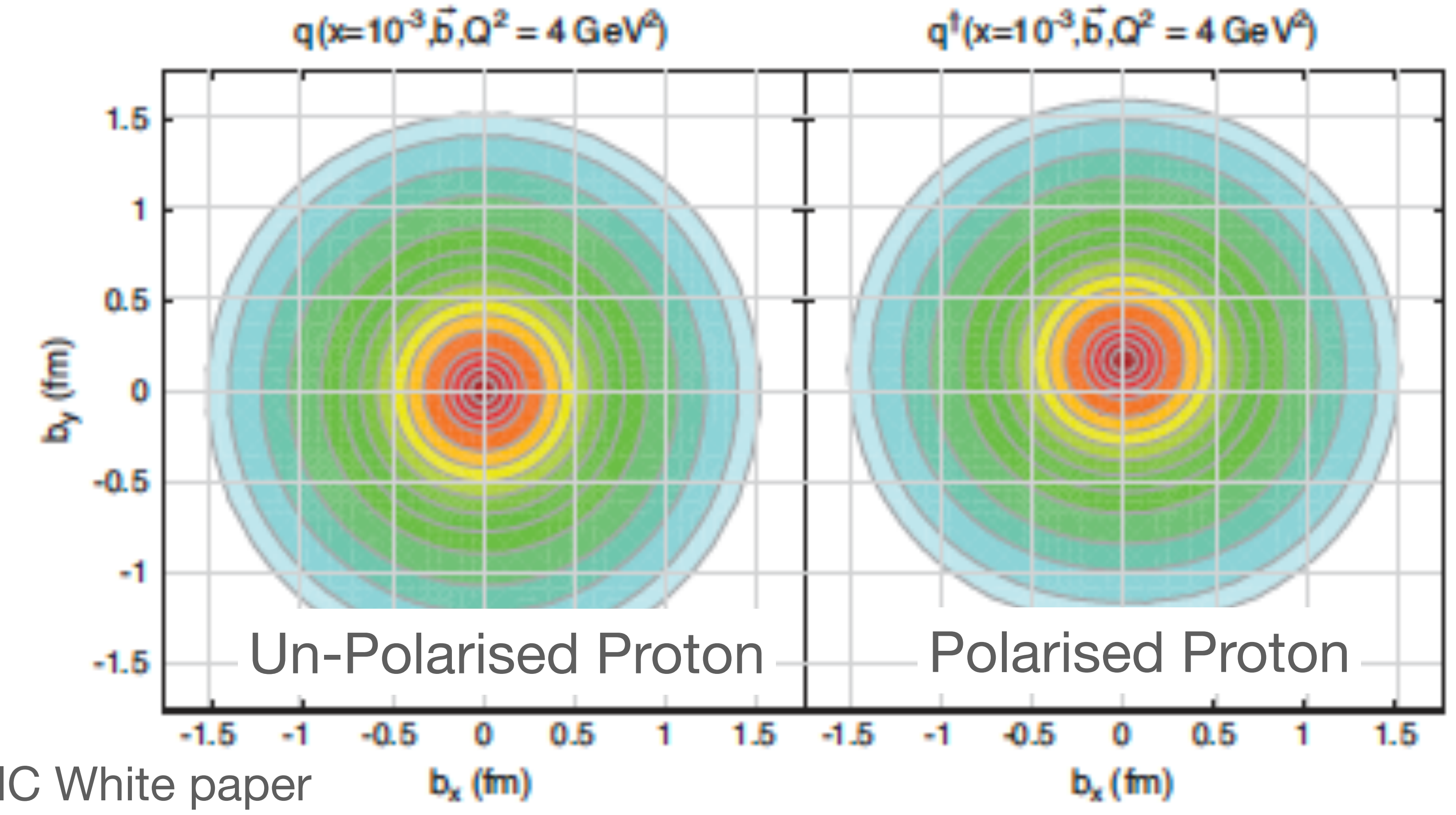



EIC White paper

Density of quarks in transverse space plane

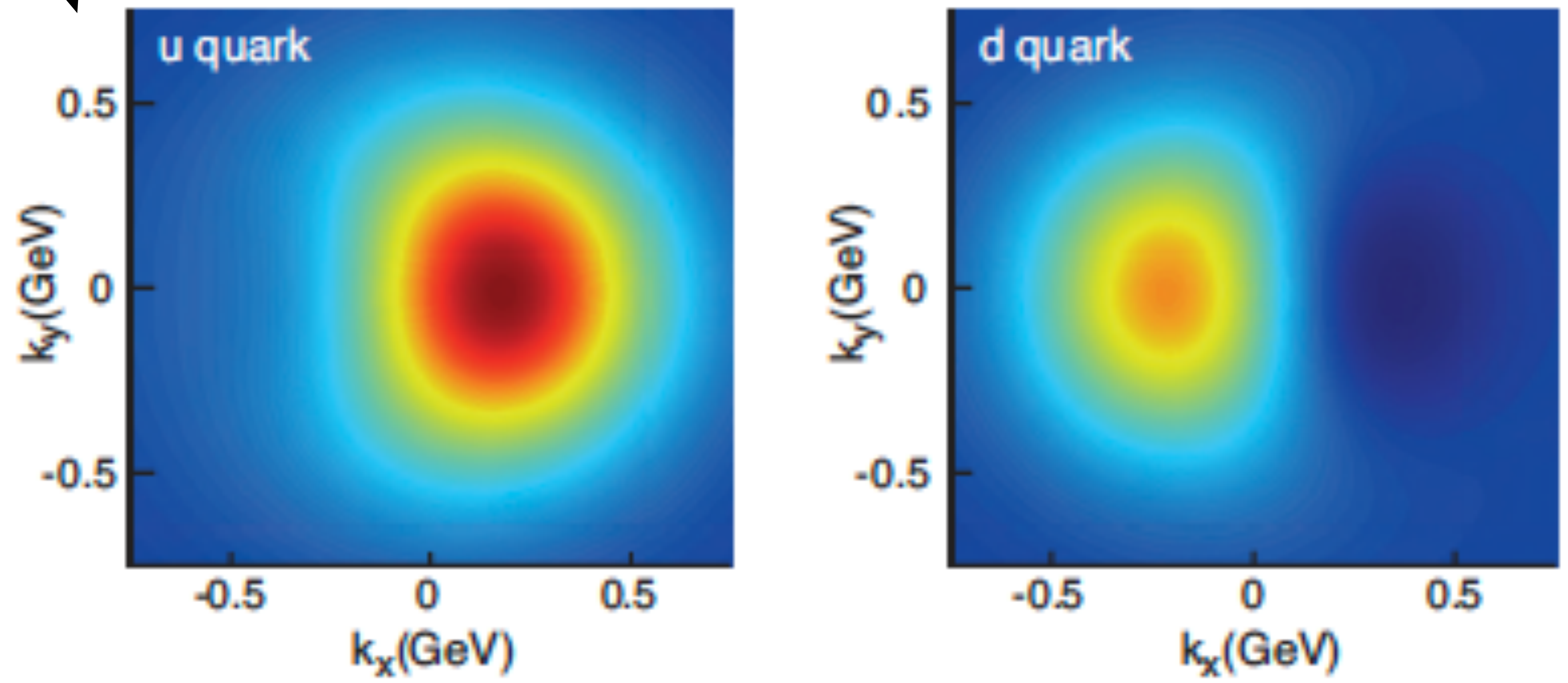
**Spin-dependent Generalised Parton Distributions Function (GPDs)**

2D coordinate space (transverse) + 1D momentum (longitudinal) images

**Momentum Space**
**f(x, $k_T$)**

Polarised Nucleon, x=0.1
x $f_1(x, k_T, S_T)$

EIC White paper



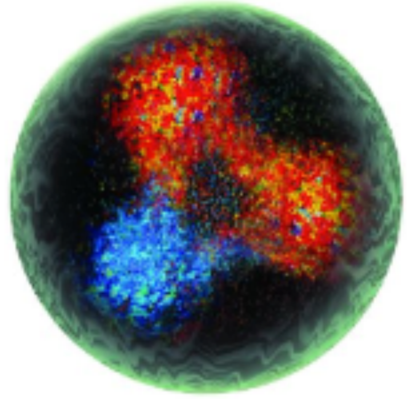

Density of un-polarised quarks in transverse momentum plane

**Spin-dependent Transverse Momentum Dependent Distribution Functions (TMDs)**

3D momentum space images

# Tomography for 3D Structure

Nucleon



Wigner Function: full phase space parton distribution of the nucleon

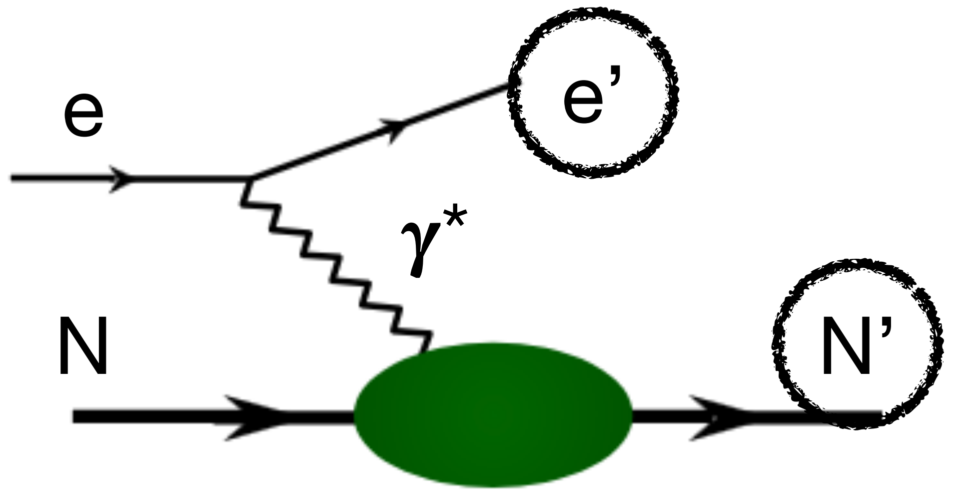
$\int d^2k_T$

**Generalised Parton Distributions (GPDs)**

$\int dx$

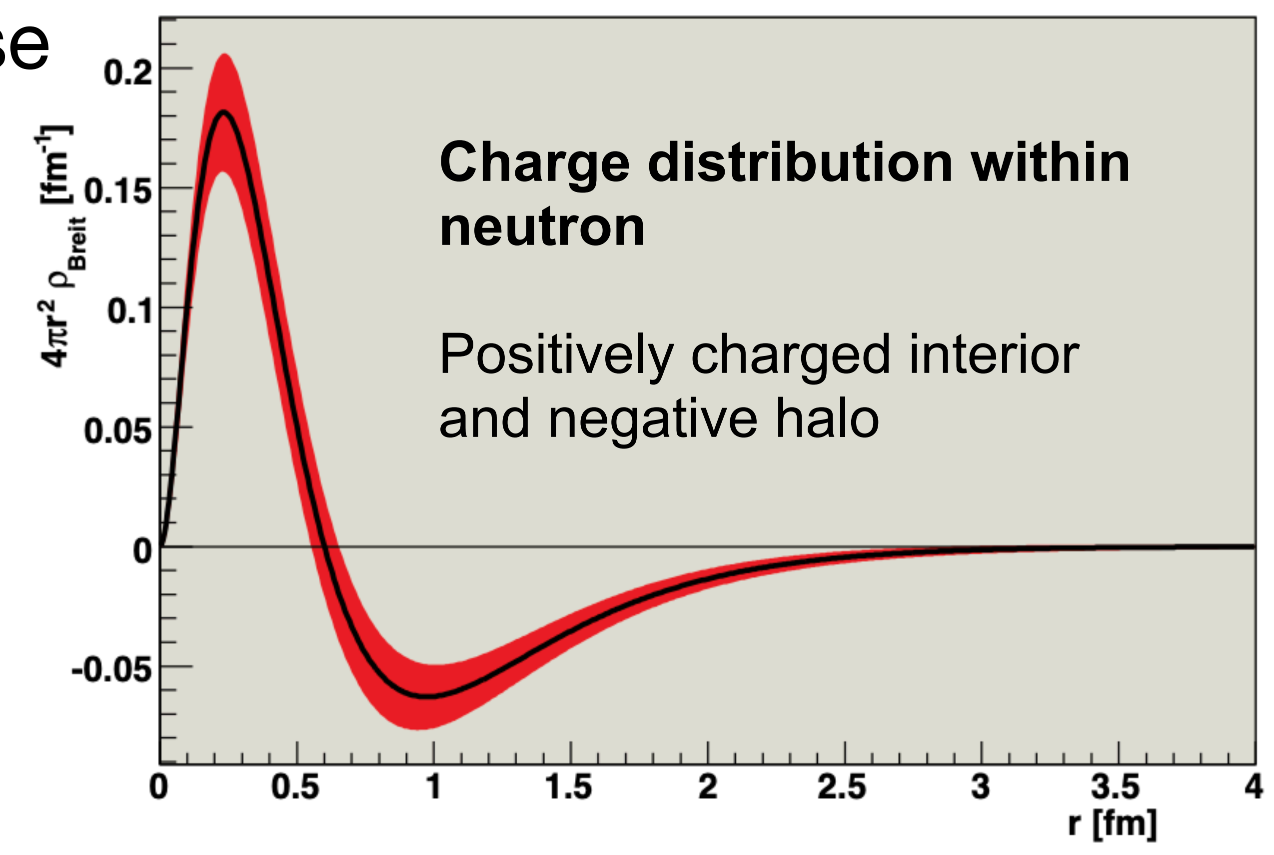
**Electromagnetic Form Factors eg $G_E$, $G_M$**

Fourier transform of transverse charge/current densities




Elastic scattering

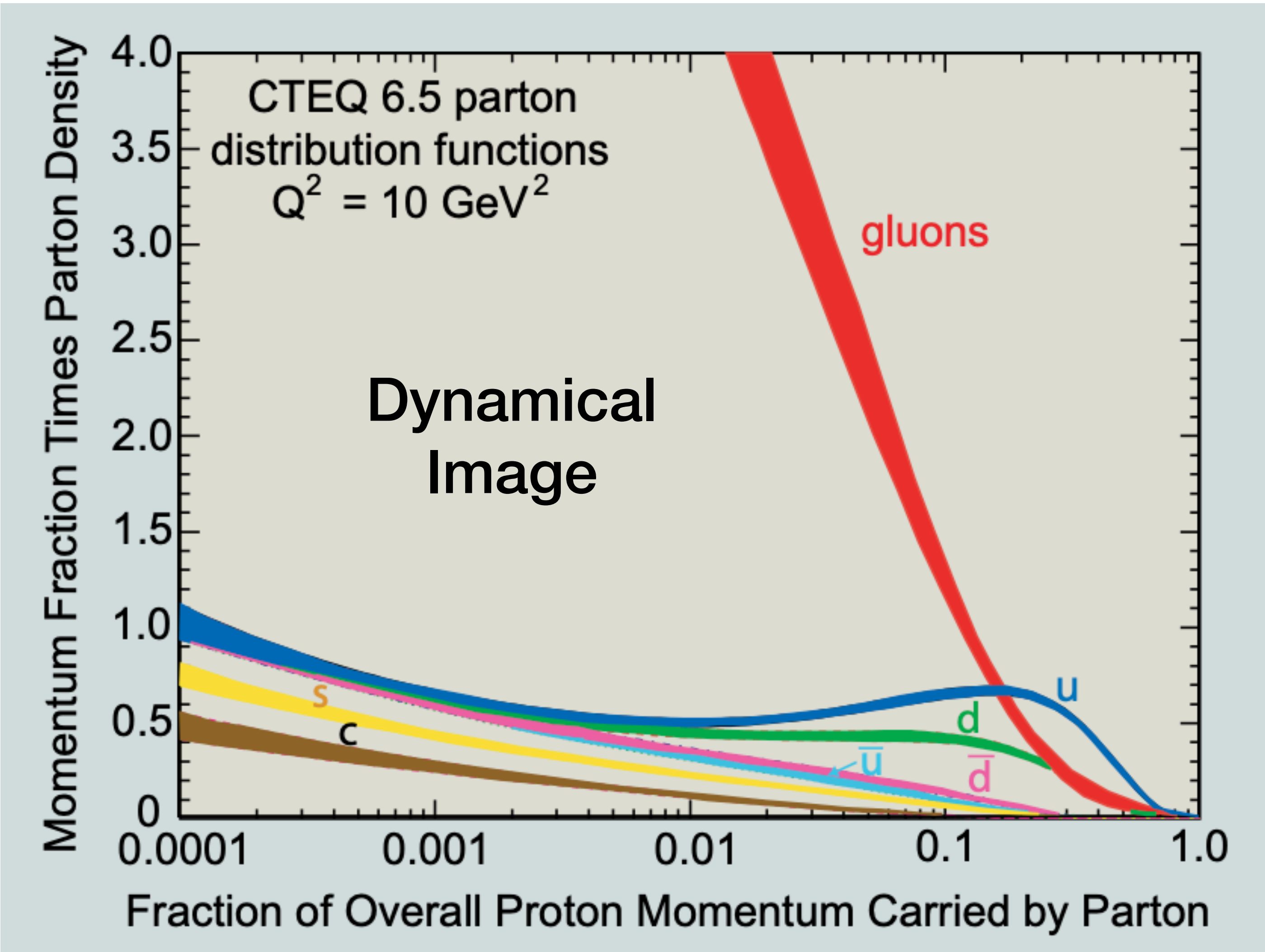
DOE/NSF NSAC, arXiv:0809.3137v1




$\int d^2b_T$

**Transverse Momentum Dependent Distribution Functions (TMDs)**

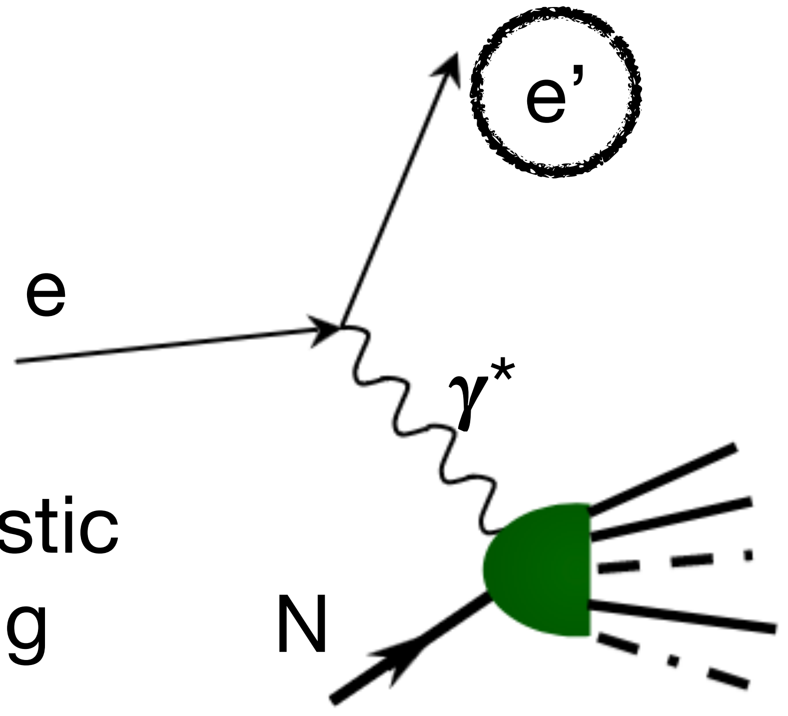
arXiv:0809.3137v1 [nucl-ex]




$\int k_T$

**Parton Distribution Functions**

Number densities of different partons as a function of x




Deep Inelastic Scattering

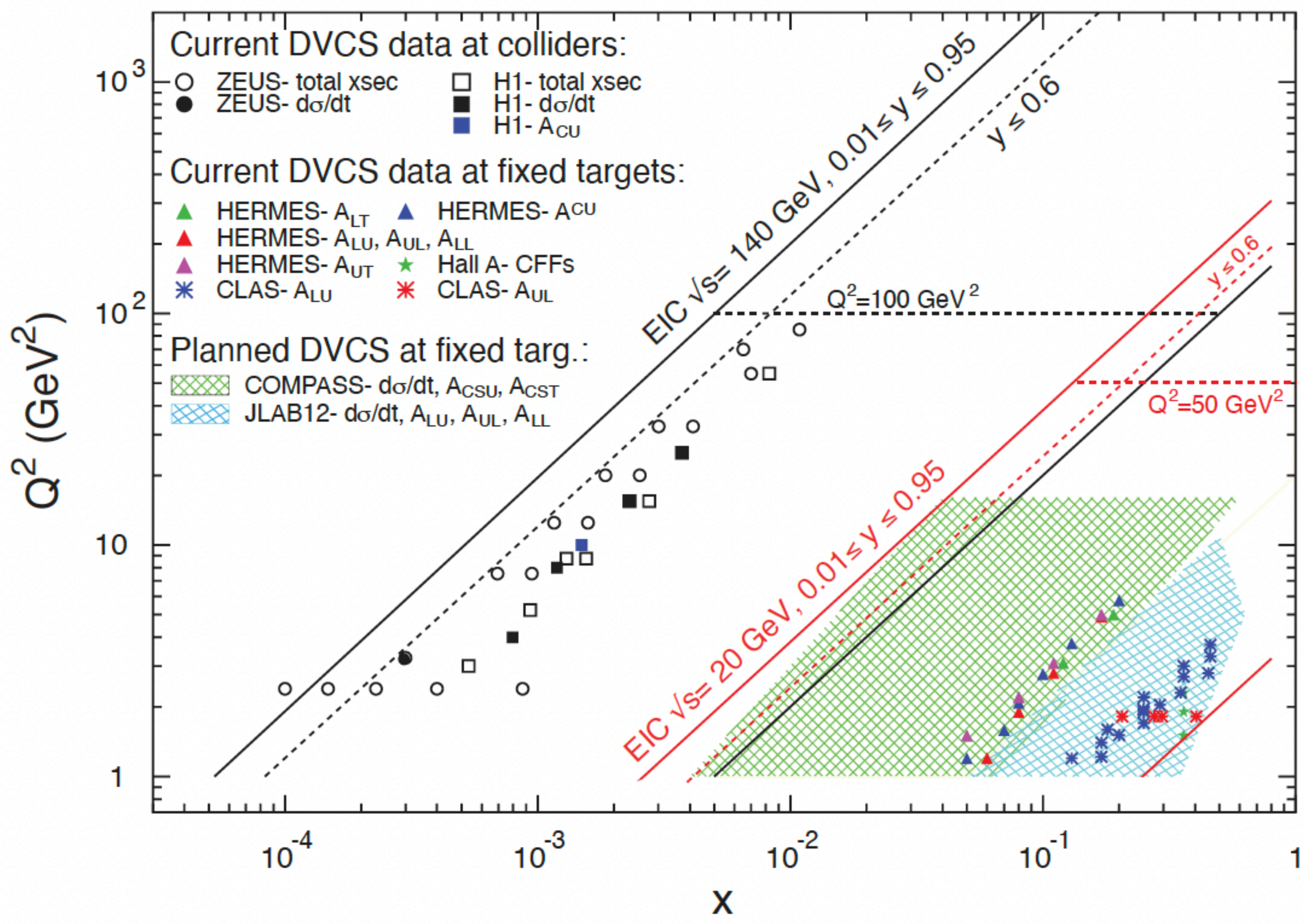
# Tomography for 3D Structure

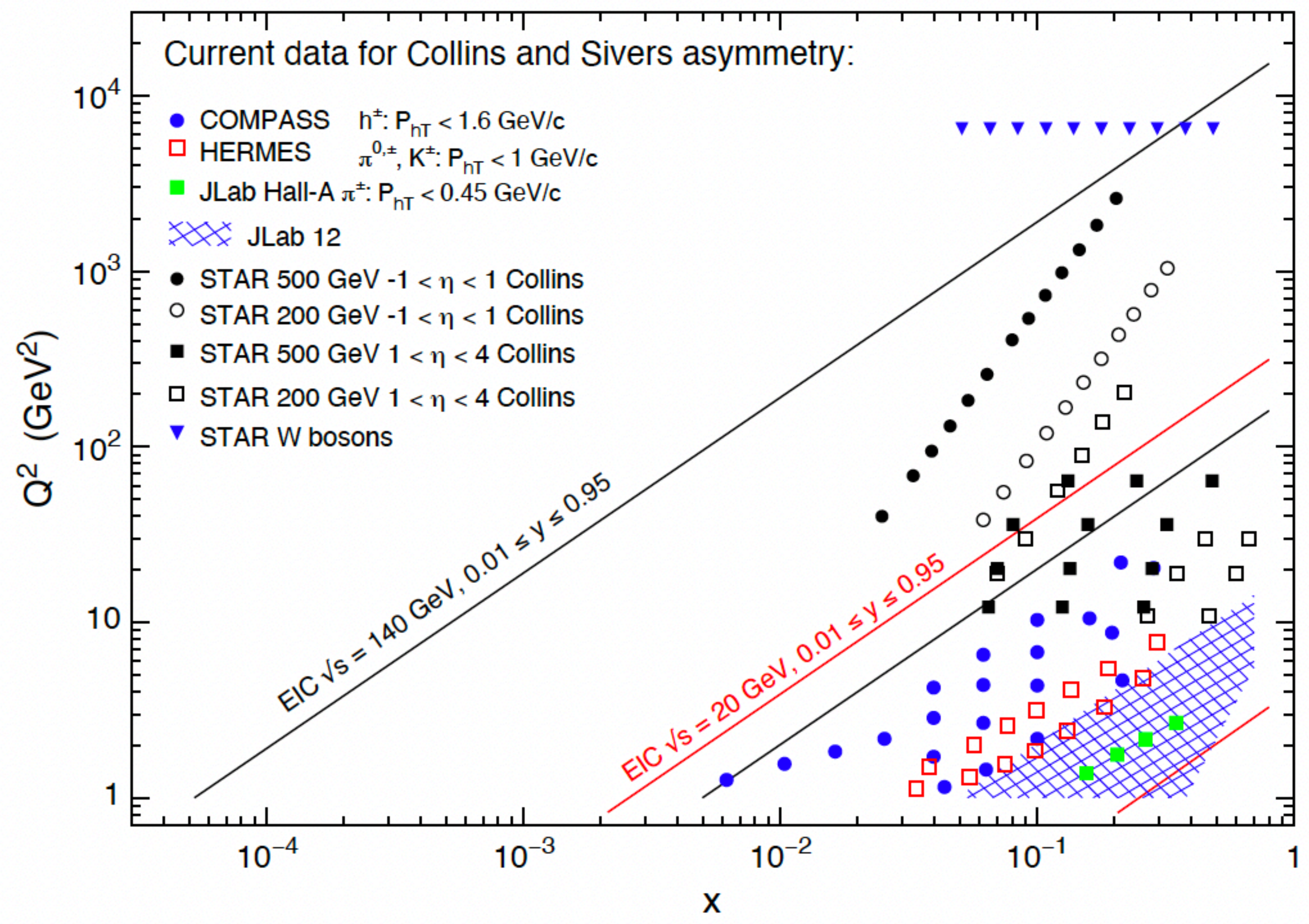

- EIC will revolutionise our picture inside the nucleon to deliver a 3D imaging program:
  - collect “images” of position and momentum densities for several x-slices
  - build up multi-dimensional pictures

- EIC will provide unrivalled precision in tomography, extending into the high density regime of sea quarks and gluons

# EIC Will Unlock a Vast Landscape for Tomography

Two example EIC energy configurations shown




Two orders in x and $Q^2$ compared to existing/planned polarised data for GPD studies

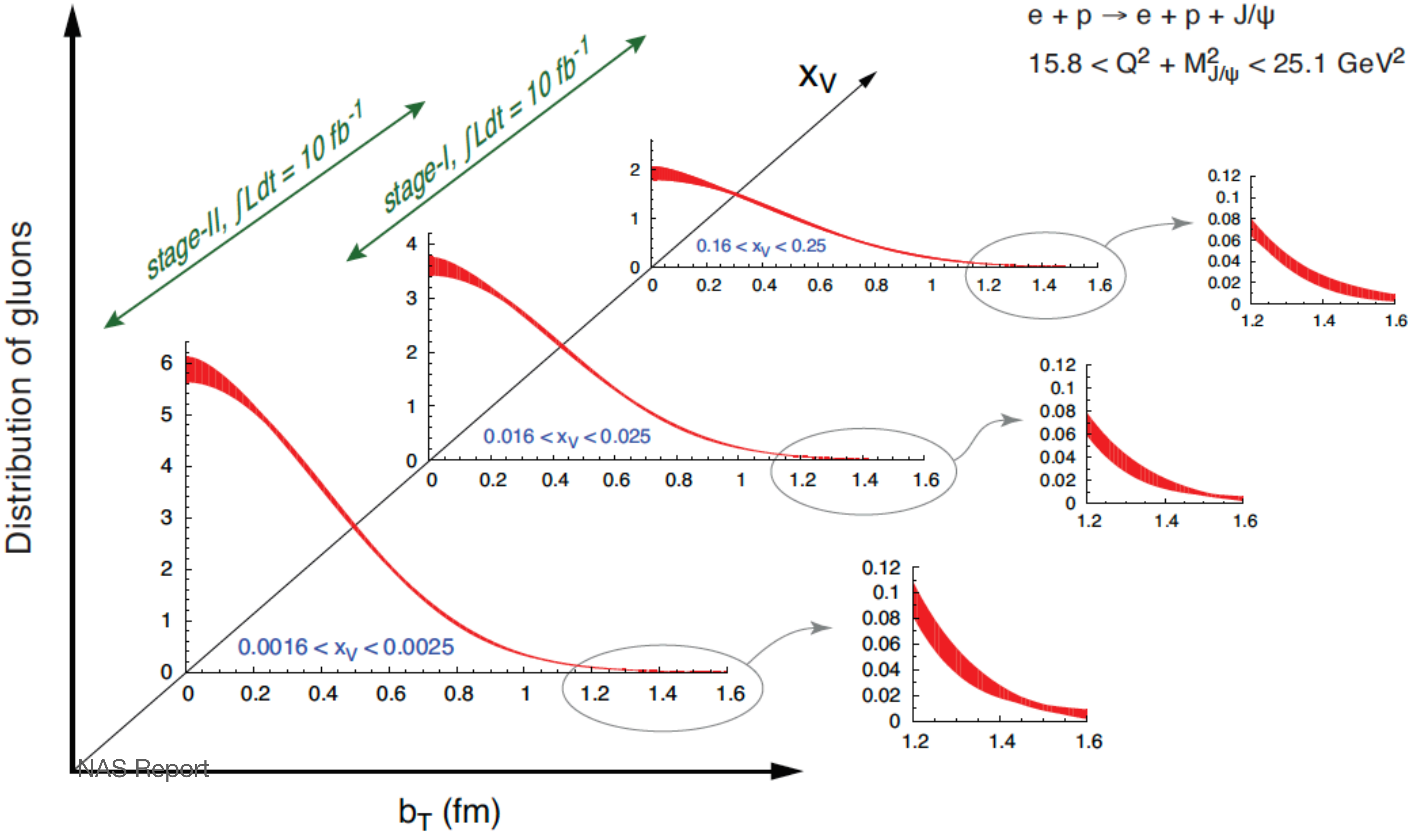
Two to three orders of magnitude in luminosity for unpolarised data

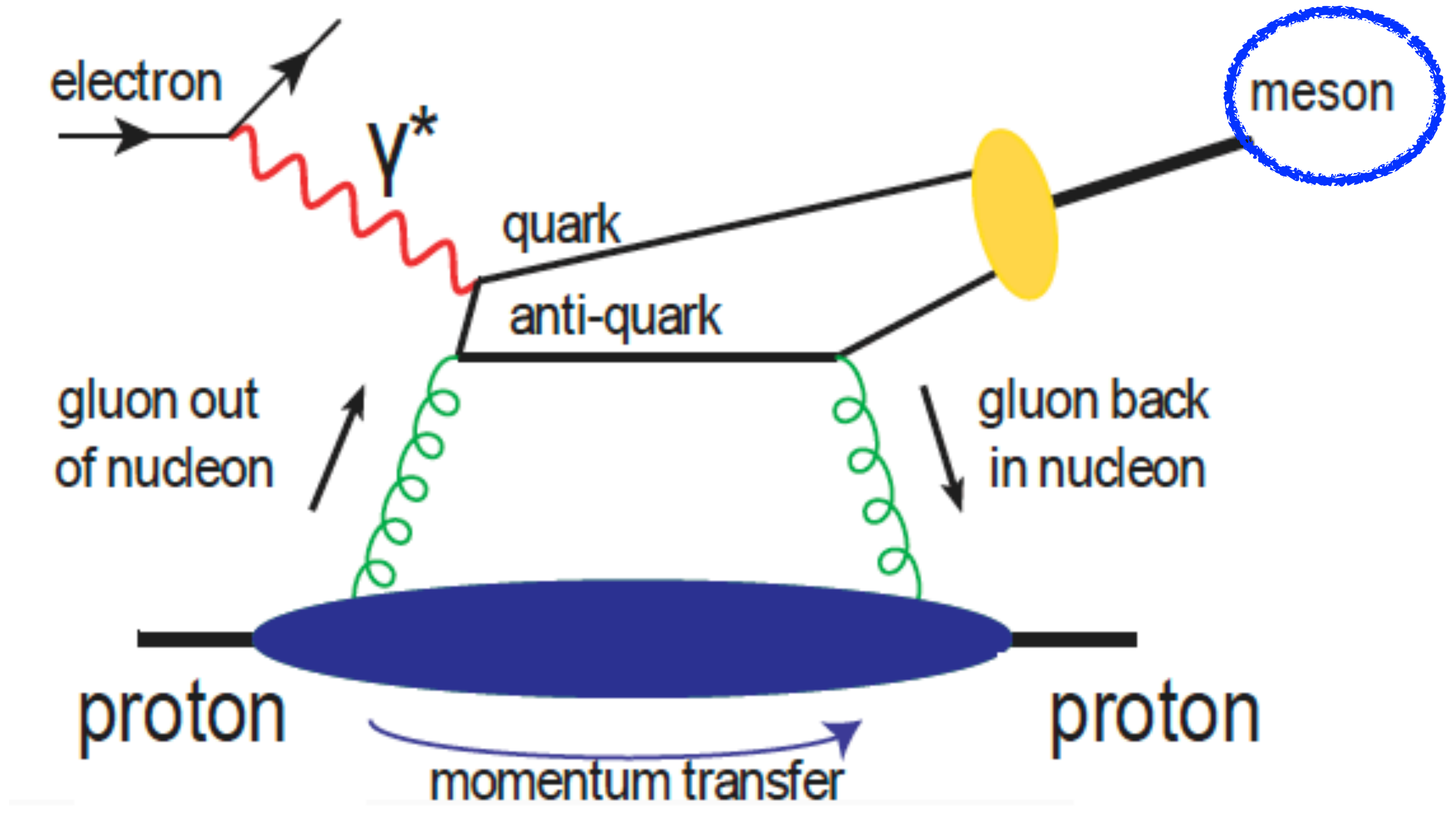
Two orders in x and $Q^2$ compared to existing/planned SIDIS data for TMD studies

# Plus Tomography of Gluons!

Gluon spatial densities in proton for the first time!

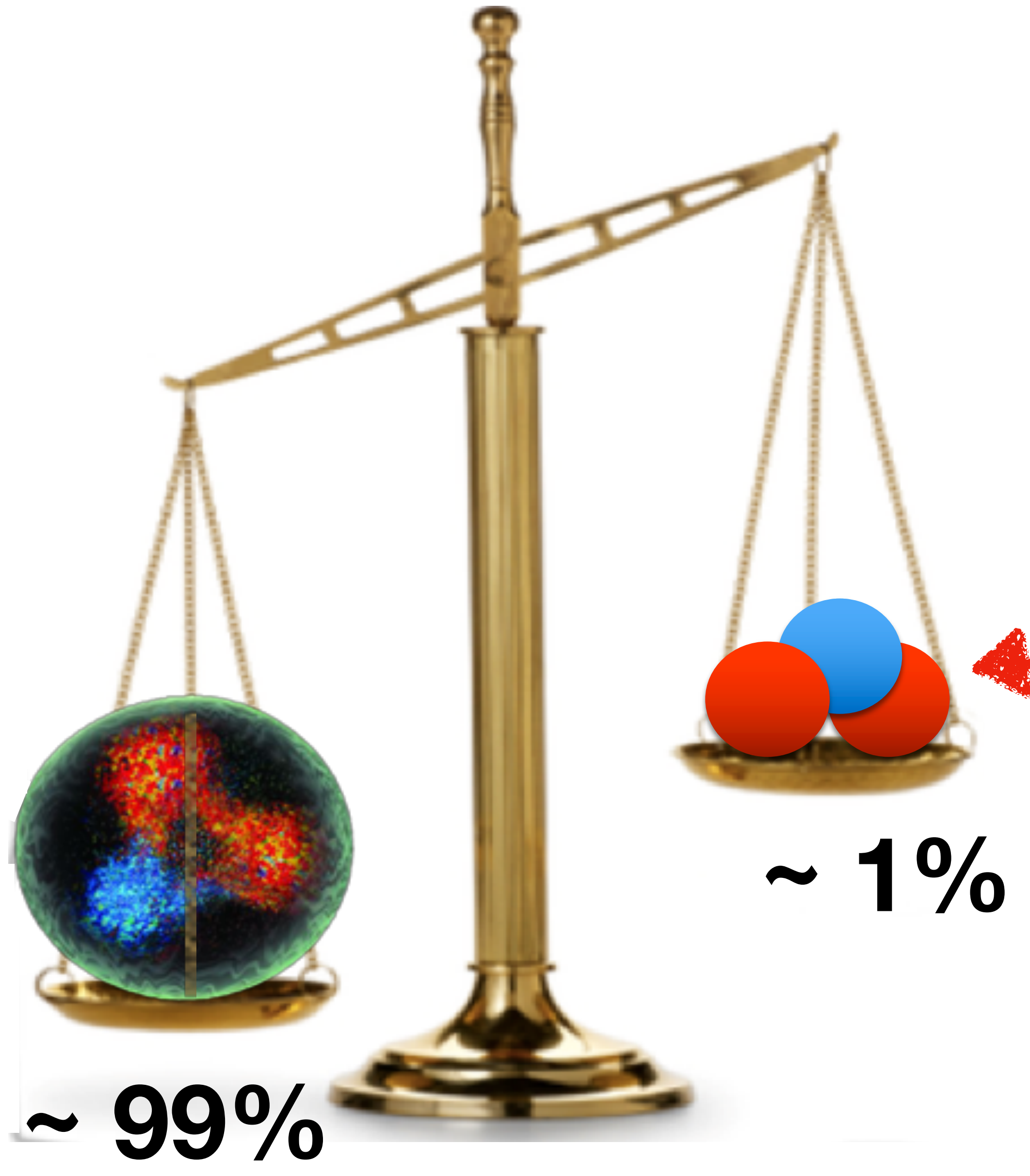
**Only possible at the EIC**

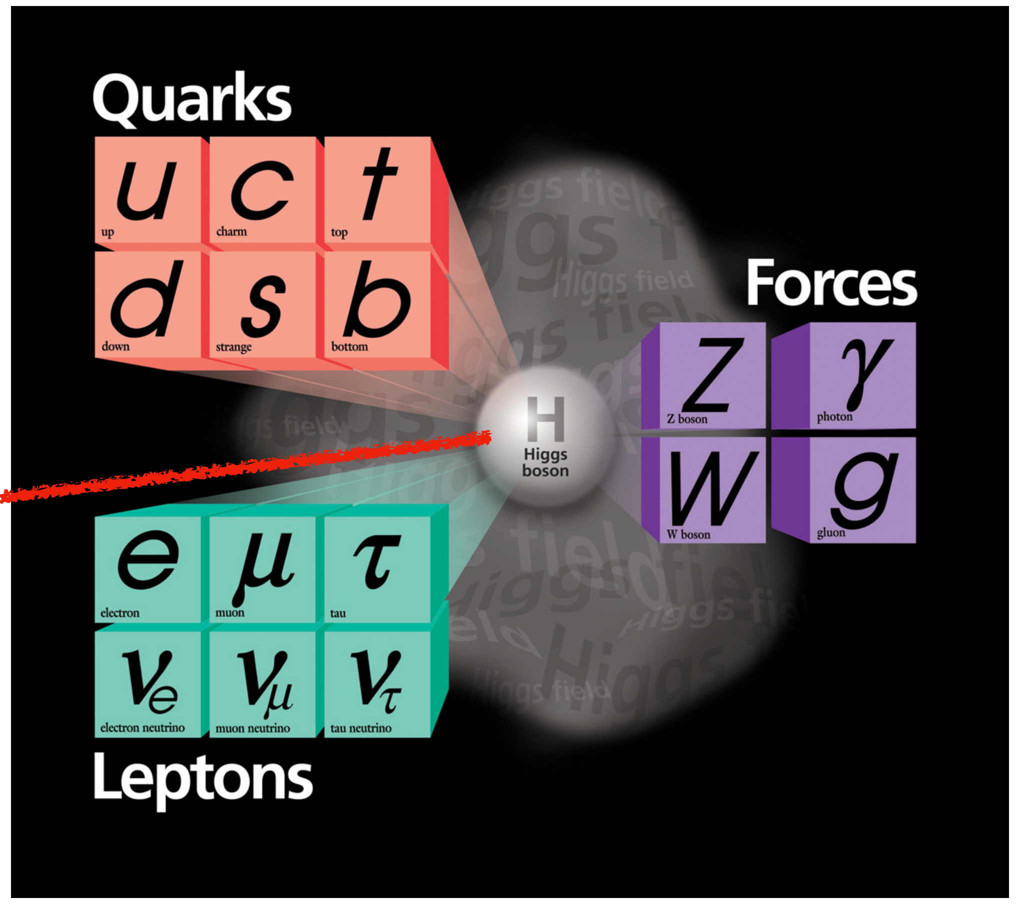


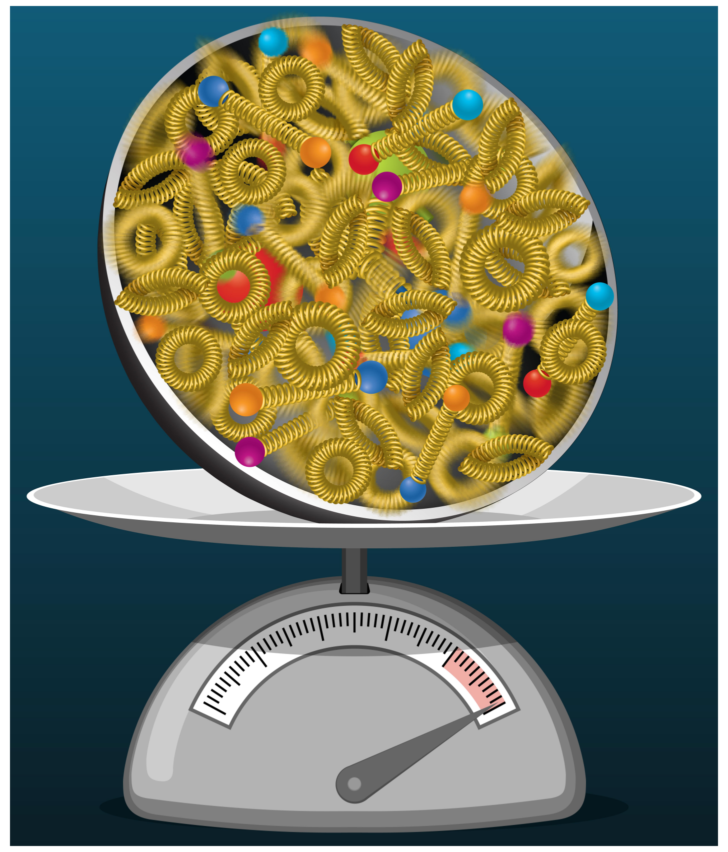

- Exclusive production of certain mesons in e+p at the EIC e.g. J/Ψ ($c\bar{c}$), will provide tomography of gluons in the nucleon
- In e + A scattering, ions scatter
  - coherently (ion stays in-tact)
  - incoherently (ion breaks apart)
- Mesons produced in coherent scattering of ions can probe the gluon spatial distribution of a nucleus
- → might give hints about confinement

# Nucleon Mass Enigma




| | Observed Mass | Higgs Mass |
|---|---|---|
| Proton (uud) | ~ 1000 MeV | ~10 MeV |



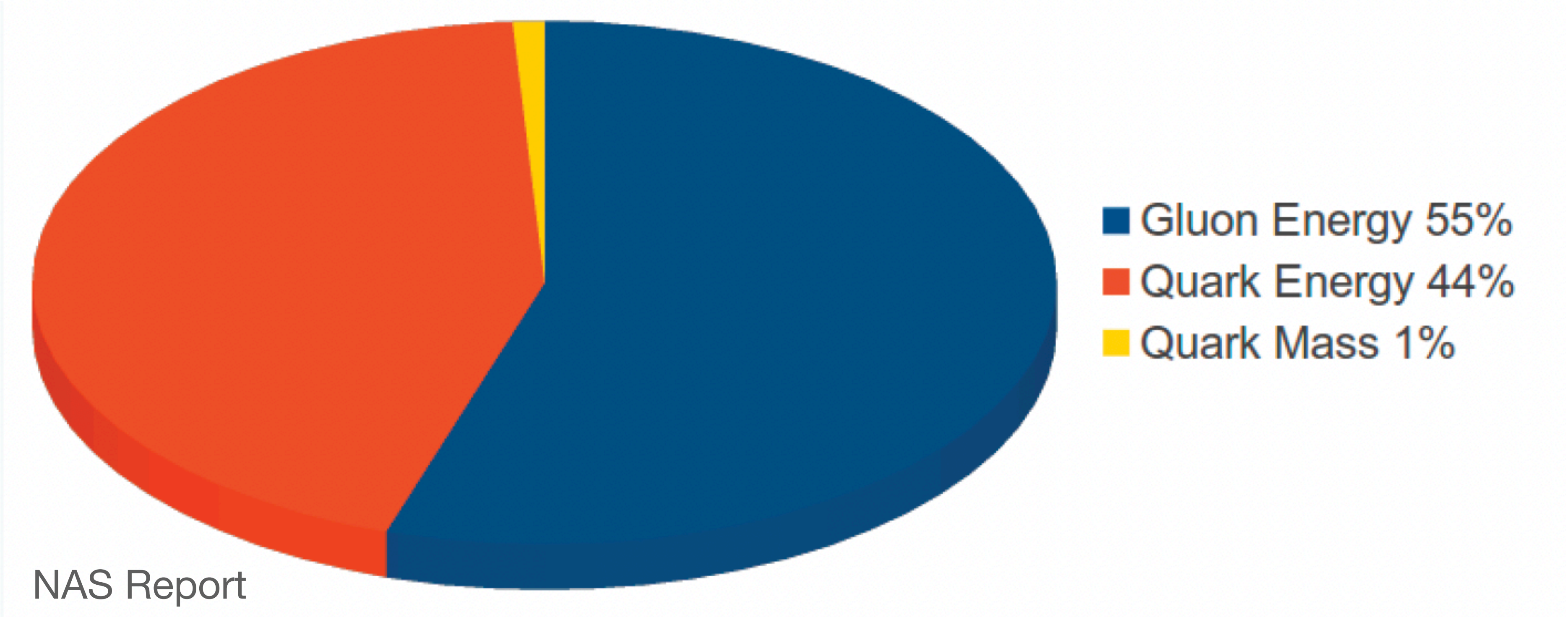
- Mass - intrinsic property of a particle

- Gluons are massless
- Quark masses generated by Higgs ~1% nucleon mass!
- Nucleon is unexpectedly *heavy*

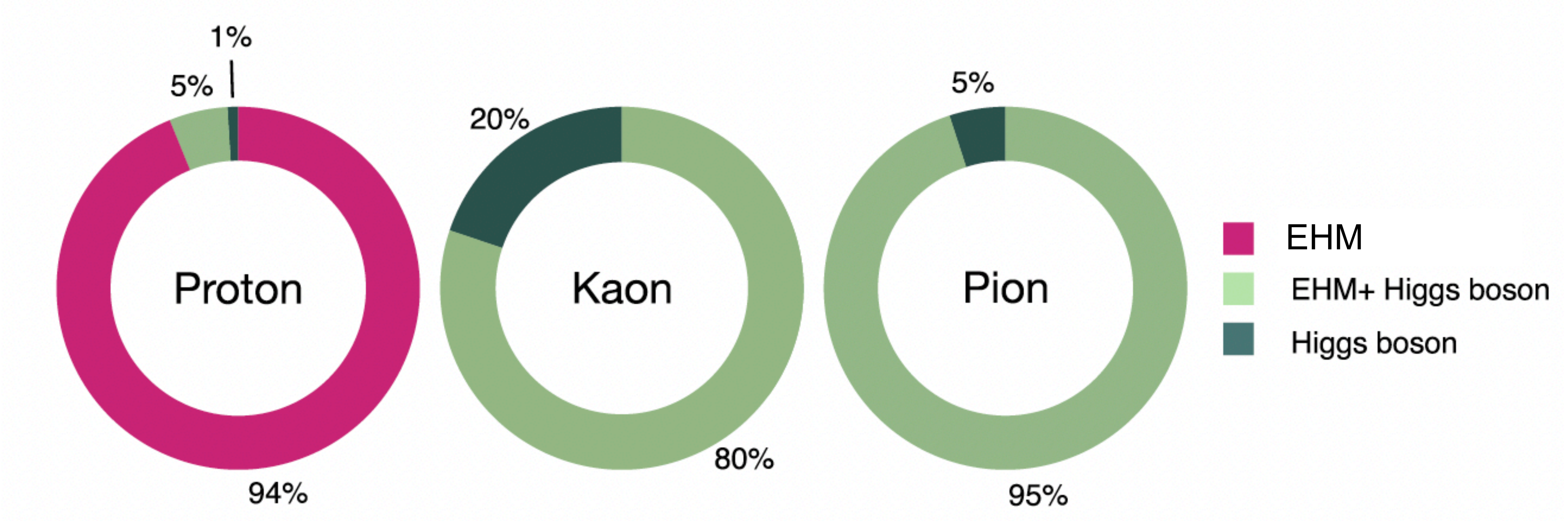
- The up and down valence quarks in the nucleon are surrounded by sea quarks ($q\bar{q}$) and gluons

- *~99% of nucleon's mass is due to quantum fluctuations of $q\bar{q}$ pairs, gluons, and energy associated with quarks moving close to speed of light within it*

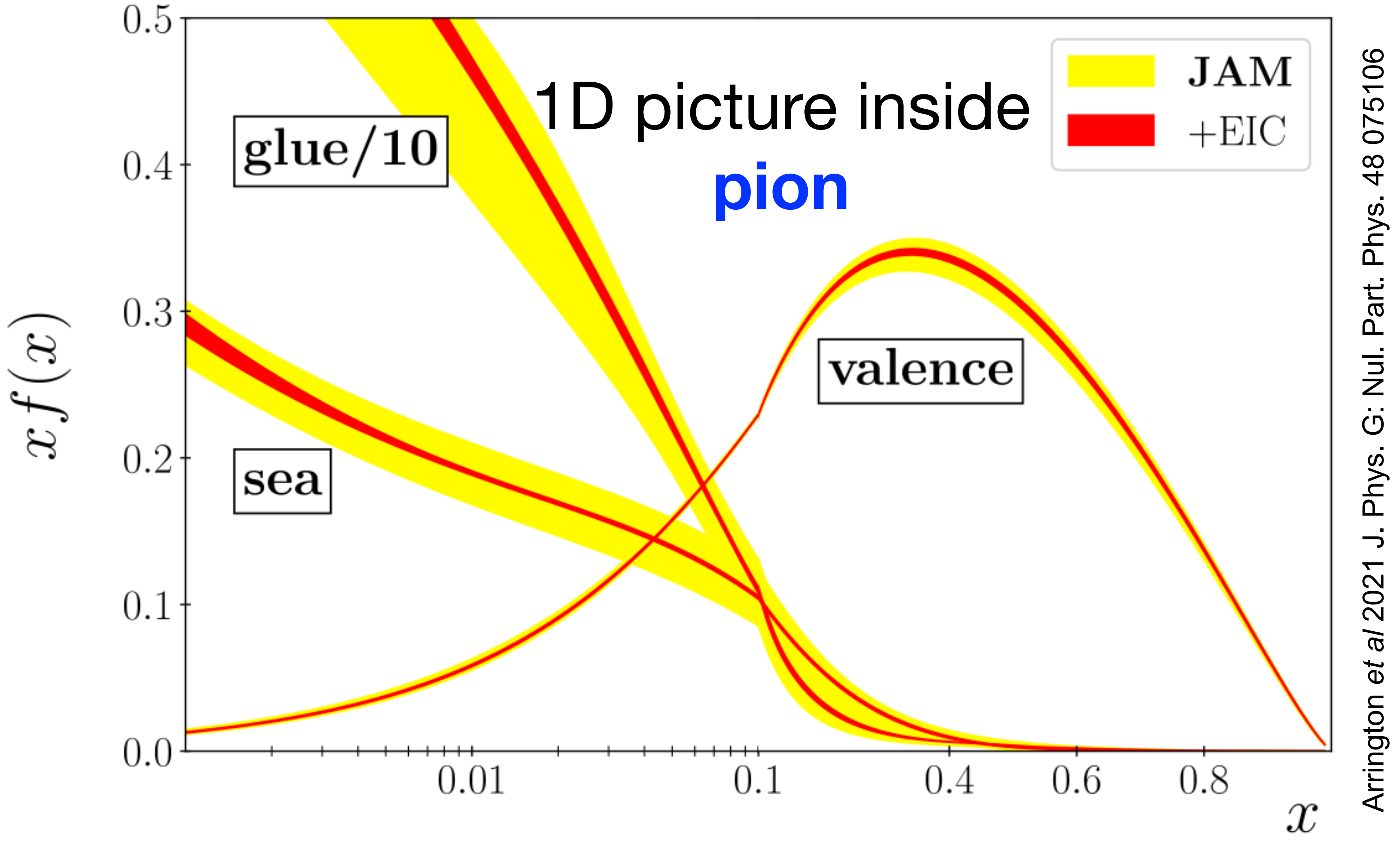
**Nucleon mass budget**



# Nucleon Mass Enigma




D. Binosi, DOI: 10.1007/s00601-022-01740-6




EIC will get comparable data for pions/ kaons compared to the proton

- Pions ($u\bar{d}$) and kaons ($u\bar{s}$) appear unexpectedly light
- Gluon contents expected to be different within pions, kaons and nucleon
- What can this tell us? We need more data!

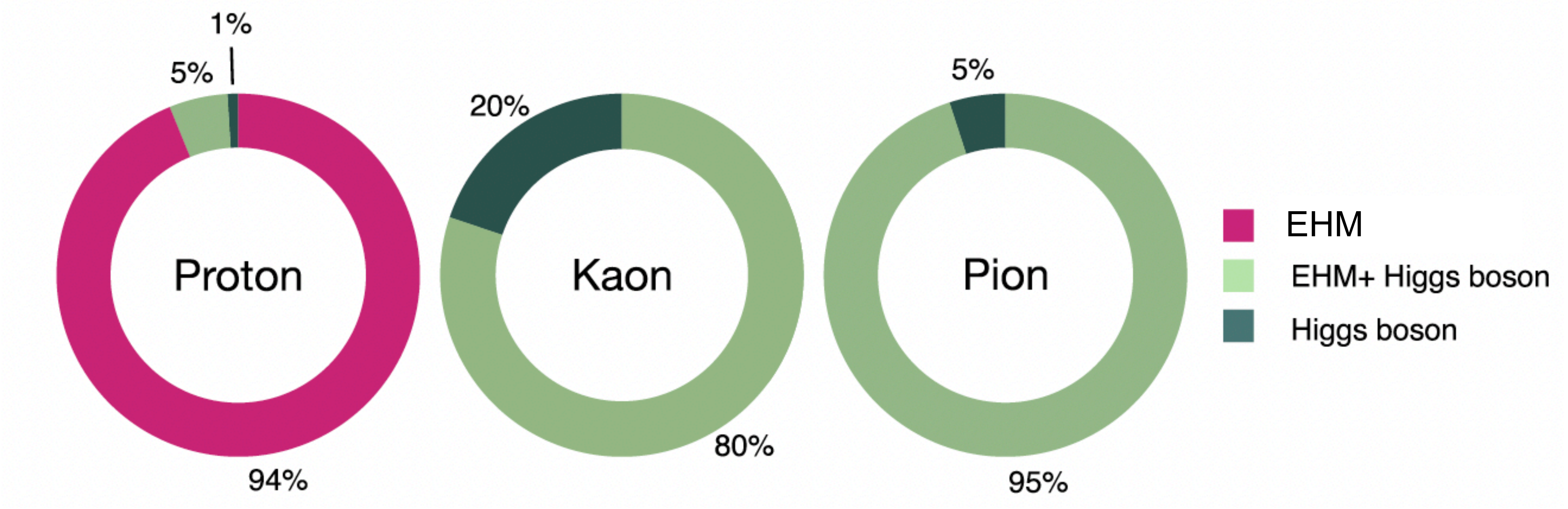
- EIC will compare inner structures of pions and kaons with nucleon to shed light on mass enigma
  - e.g. form factor and structure function measurements

- Heavier mesons will also be measured
  - e.g. J/Ψ ($c\bar{c}$), ϒ ($b\bar{b}$)
  - These mesons interact primarily with gluons in nucleon

- Tomography and GPD studies with J/Ψ and ϒ can be related to distribution of mass inside nucleon via gravitational form factors

- Production near threshold offers new information on an important quantity for decomposition of nucleon mass
  - trace anomaly of QCD energy-momentum tensor (mass contribution from vacuum)

# Nucleon Mass Enigma

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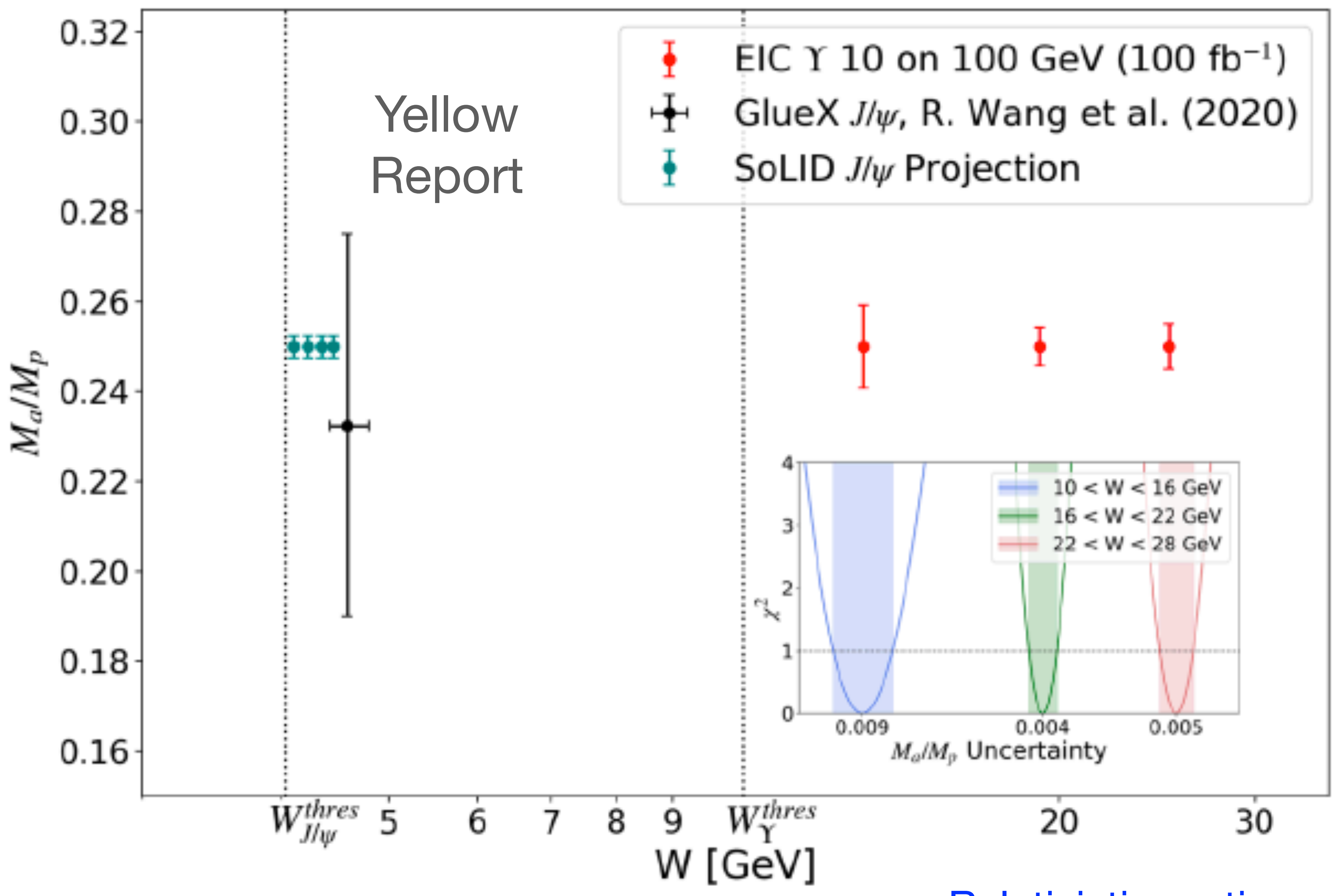


Trace anomaly contribution to proton mass

$$M = \underbrace{\boxed{E_q + E_g}}_{\text{Relativistic motion}} + \underbrace{\boxed{\chi m_q + T_g}}_{\text{Quantum Fluctuation}}$$

Quark energy, Gluon energy, Quark mass, Trace Anomaly

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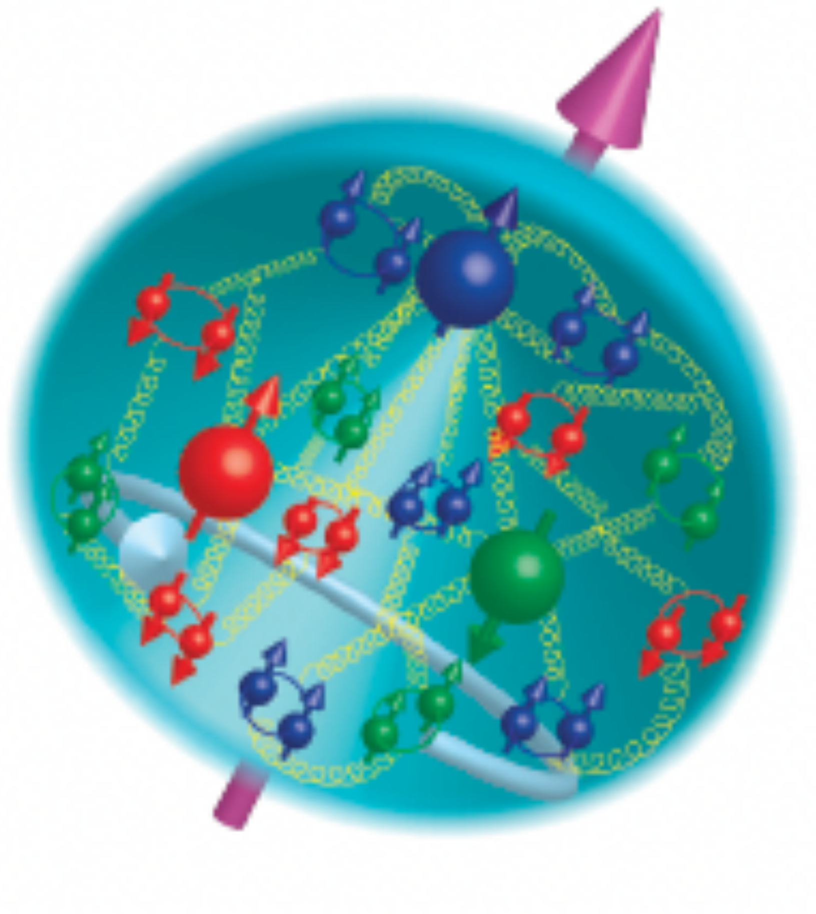
  - e.g. J/Ψ ($c\bar{c}$), ϒ ($b\bar{b}$)
  - These mesons interact primarily with gluons in nucleon

- Tomography/GPD studies with J/Ψ and ϒ can be related to distribution of mass inside nucleon via gravitational form factors

- Production near threshold offers new information on an important quantity for decomposition of nucleon mass
  - trace anomaly of QCD energy-momentum tensor (mass contribution from vacuum)

# Nucleon Spin Puzzle

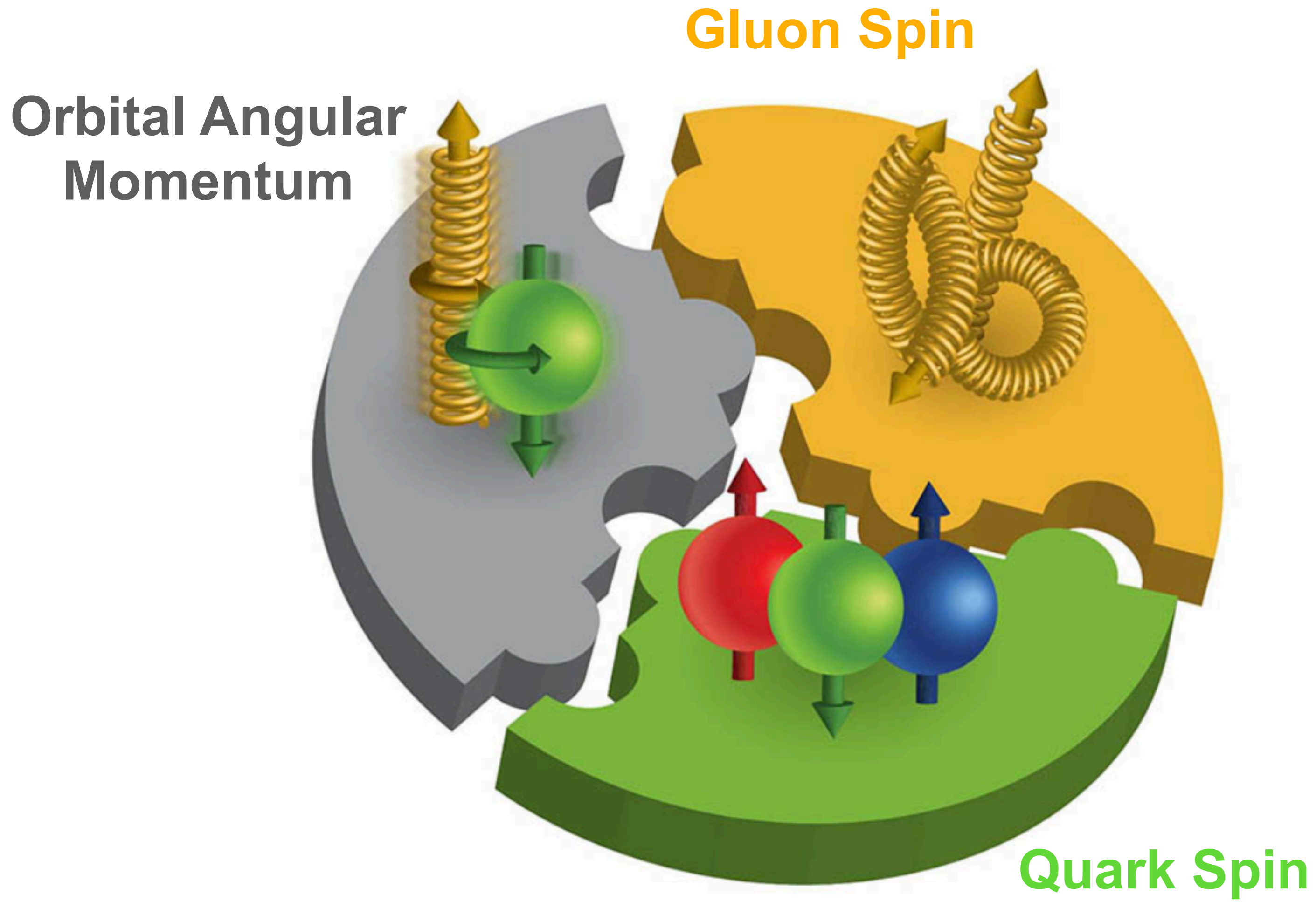
For a proton with 3 valence quarks, is it the sum or valence quark spins?



What about the sea?

- Proton spin appears as 1/2
- The spins of its components should sum to this
- Only a small fraction is carried by valence quarks

- How does the nucleon's spin originate from quarks and gluons, and their interactions?



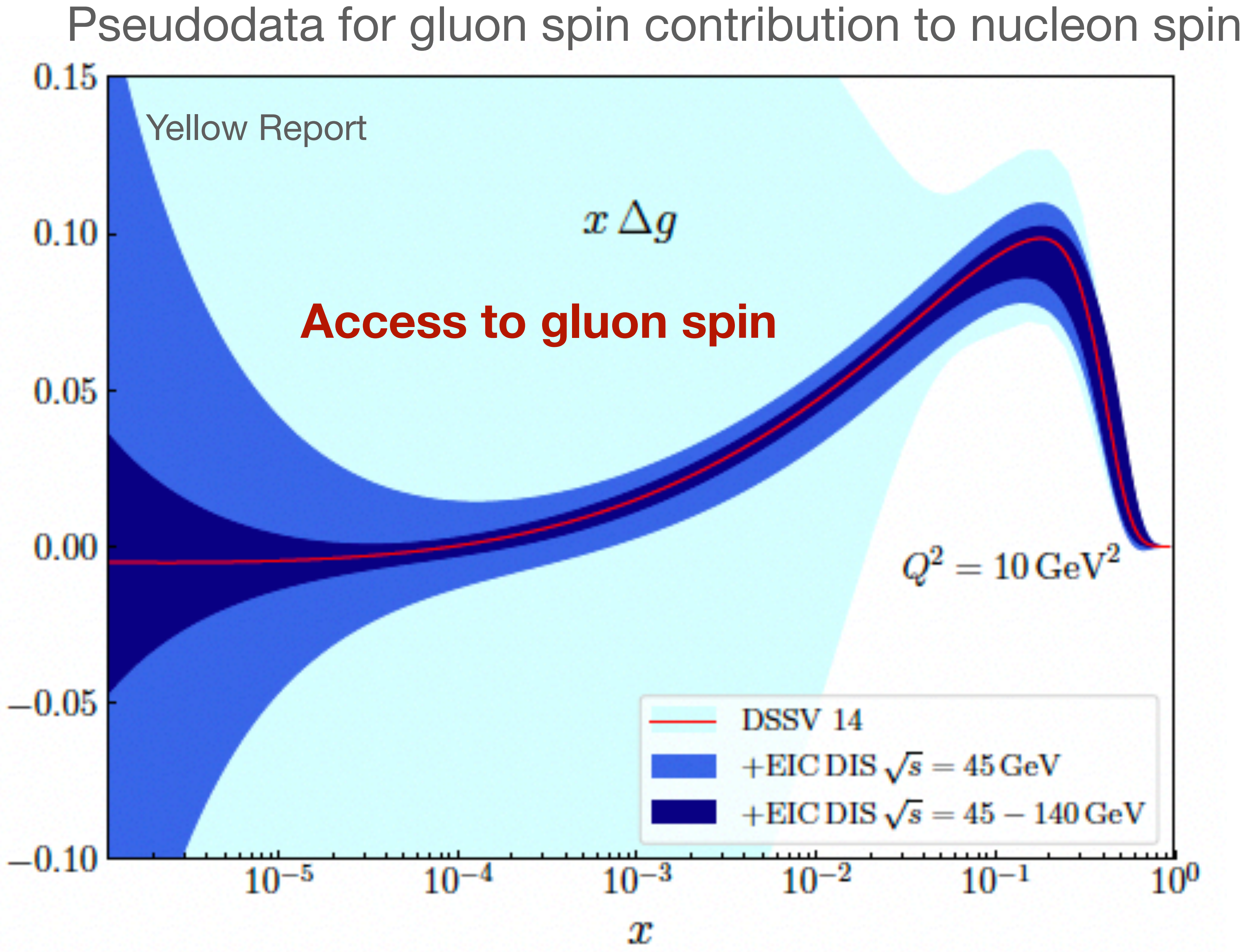

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \left(\sum L_q^z + L_g^z\right)$$

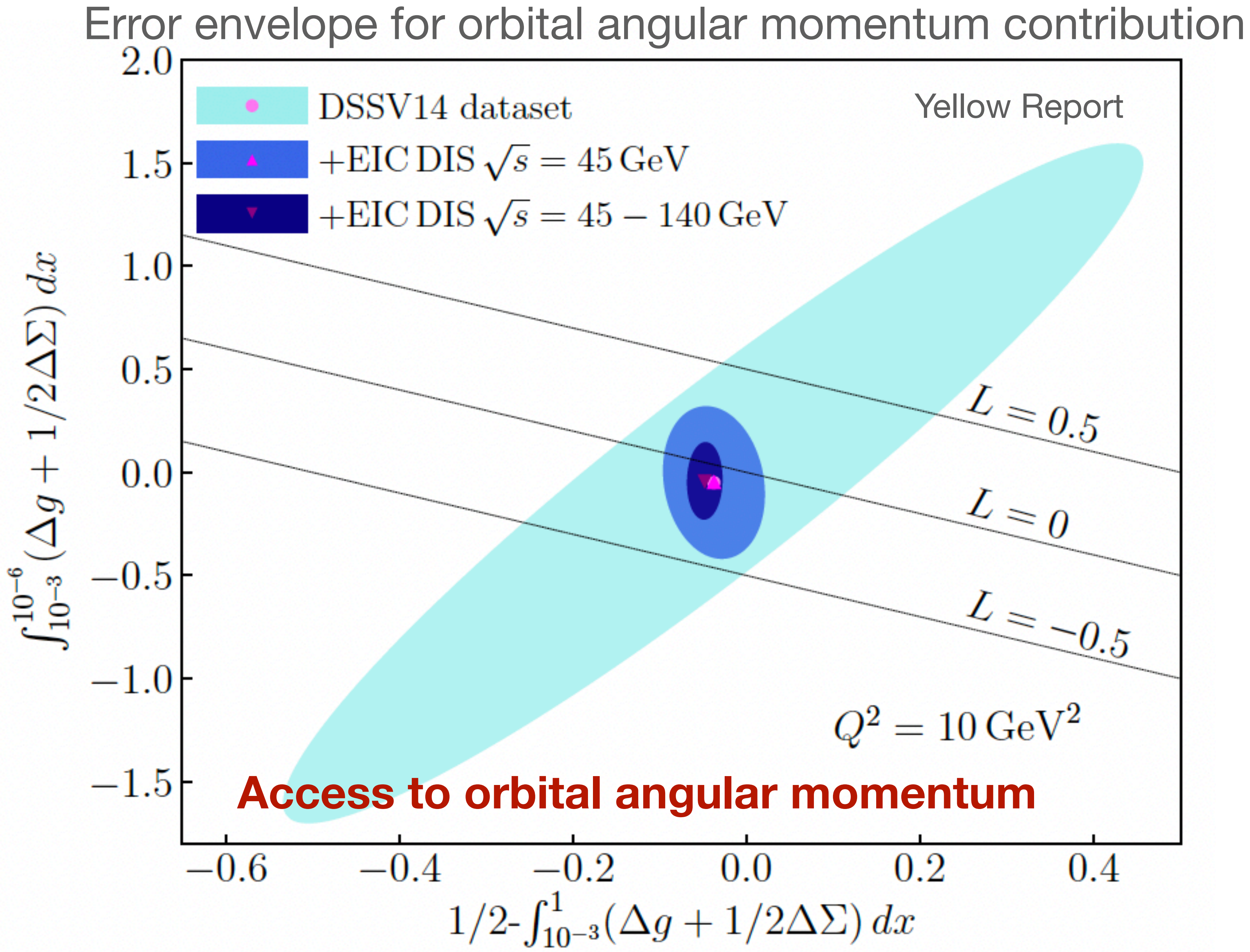
Quark Spin | Gluon Spin | Orbital Angular Momentum

We need to pin down:

- Gluon spin
- Orbital angular momentum
- Improve existing quark spin measurements

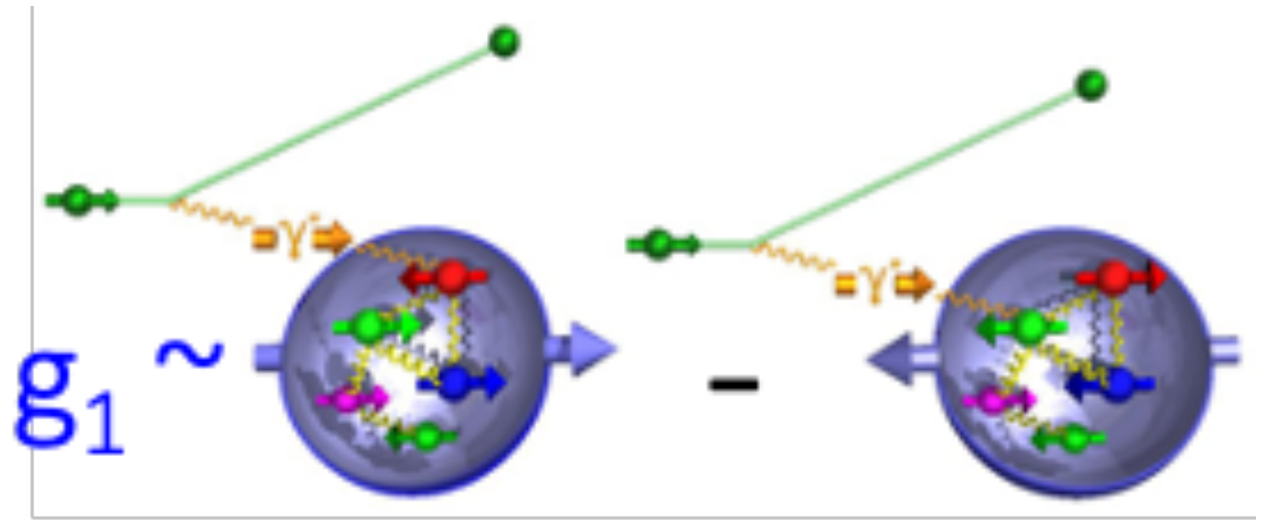
# Nucleon Spin Puzzle




EIC:

- Unprecedented DIS program with spin polarised beams
- High precision mapping of different spin contributions across vast landscape
- Unchartered territory of small x
  - (currently not much known precisely for x<0.01)
- Pioneering measurements of gluon contributions




EIC can align spins of beams to enable measurements like this for protons and light nuclei (ie neutrons)!

- Measurements of cross-section differences according to spin alignment
  - Spin structure function g1

- Tomography and GPD studies will also offer new insights on:
  - Quark flavour contributions
  - Angular momentum

# Numerous Final States… (not exhaustive)

Parton distributions in nucleons and nuclei

QCD at extreme parton densities - saturation

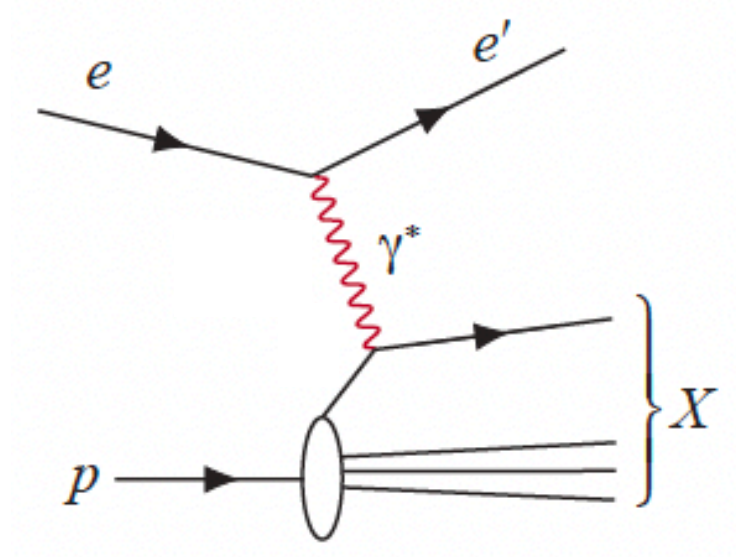
Spin and flavour structure of nucleons and nuclei

Tomography and transverse momentum distributions

QCD at extreme parton densities - saturation

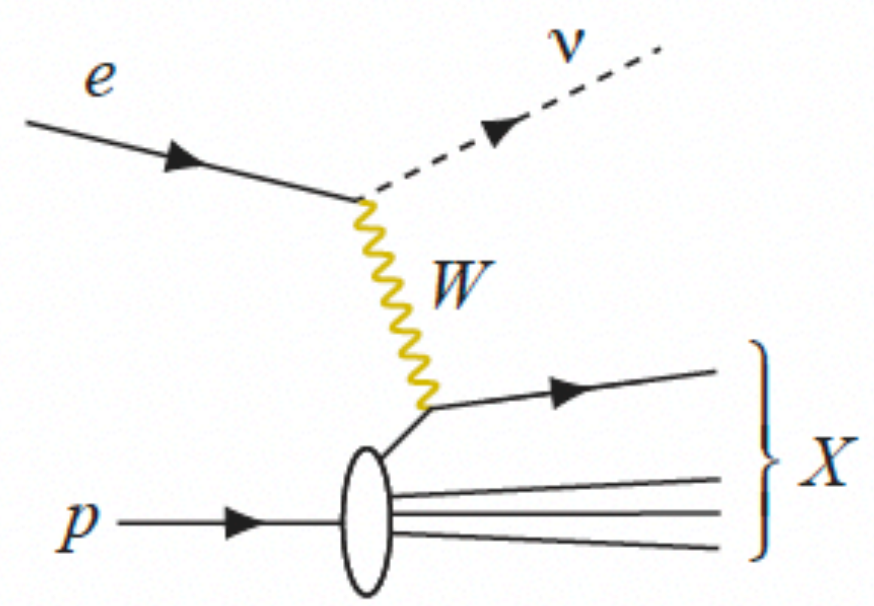
Tomography and spatial imaging

## Neutral current inclusive




$$e + p/A \to e' + X$$

## Charged current inclusive

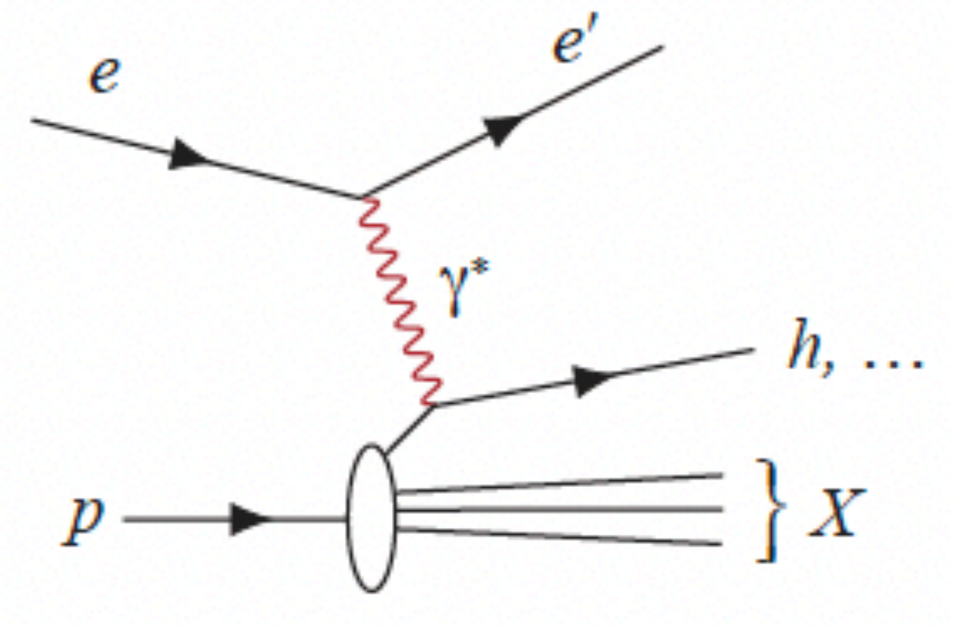



$$e + p/A \to \nu + X$$

**$\int \mathcal{L}dt$ ~ 1fb$^{-1}$**

Measure e’
→e/h PID, eCAL calorimetry

## Semi-inclusive

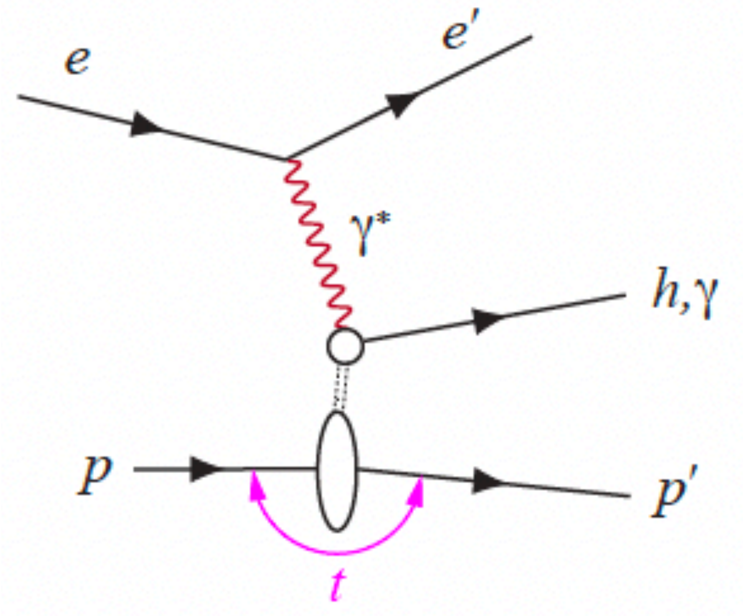



$$e + p/A \to e' + h^{\pm,0} + X$$

**$\int \mathcal{L}dt$ ~ 10 fb$^{-1}$**

Measure e’ and hadrons
→hadron PID

## Exclusive




$$e + p/A \to e' + p'/A' + \gamma/h^{\pm,0}/VM$$

**$\int \mathcal{L}dt$ ~ 10 - 100 fb$^{-1}$**

Measure all particles
→hermiticity

EIC YR

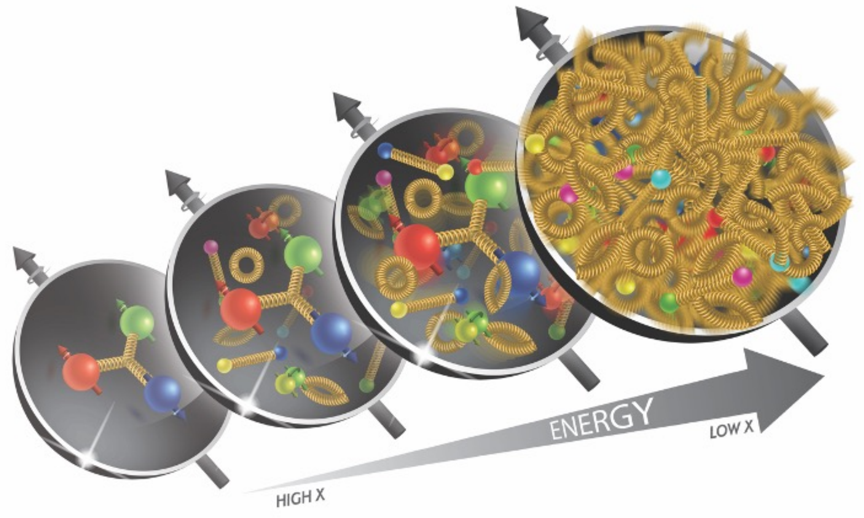
| Processes / Topics | Inclusive | Semi-Inclusive | Jets, Heavy Quarks | Exclusive | Diffractive, Forward Tagging |
|---|---|---|---|---|---|
| Global properties & parton structure | incl. SF | h, hh | jet, Q | excl. $Q\bar{Q}$ | incl. diffraction, tagged DIS on D/He |
| Multidimensional Imaging | | h | jet, di-jet, jet+h, Q, $Q\bar{Q}$ | DVCS, DVMP, elast. scattering | |
| Nucleus | incl. SF | h, hh | jet, di-jet, Q, $Q\bar{Q}$ | coh. VM, di-jet, h, hh, D/He FF | diffr. SF, incoh. VM, di-jet, h, hh, nucl. fragments |
| Hadronization | | h, hh, jet+h | jet, Q, $Q\bar{Q}$ | | |
| Other fields | incl. SF with $e^+$, $\sigma^{tot}_{\gamma A}$ | charged curr. DIS, $\sigma_{\gamma A \to hX}$ | | $\sigma^{elast}_{\gamma A}$ | $\sigma^{diffr}_{\gamma A}$ |

…Plus jets, diffraction, forward tagging…

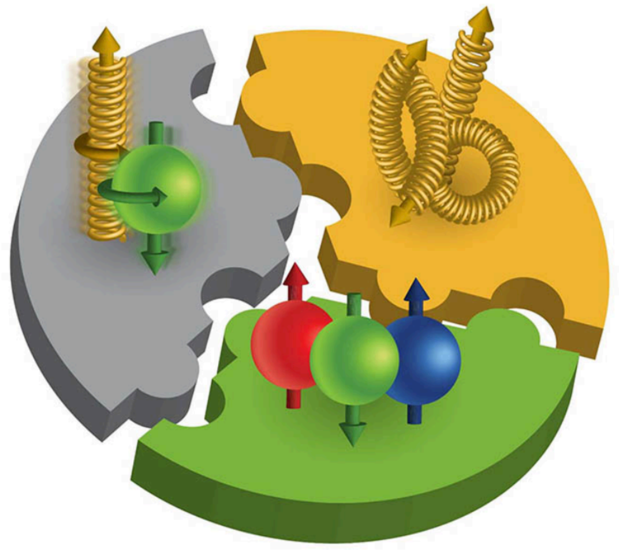
*Need a new facility to realise such a uniquely broad physics program*

SF = structure function; FF = form factor; h = identified hadrons, Q = heavy quarks, QQbar = heavy quark-bound states (quarkonium), VM = vector mesons

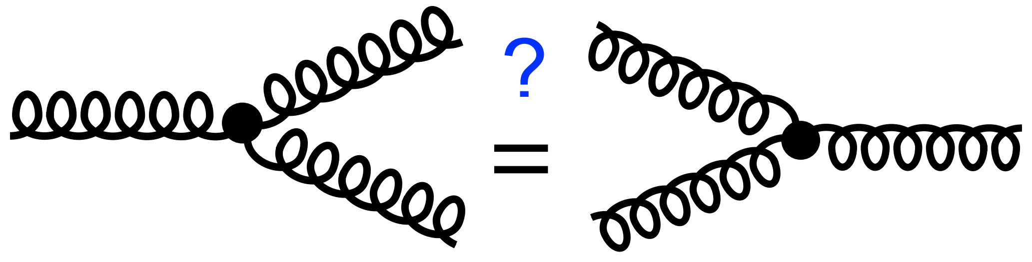
# What Kind of Facility Does the Physics Need?



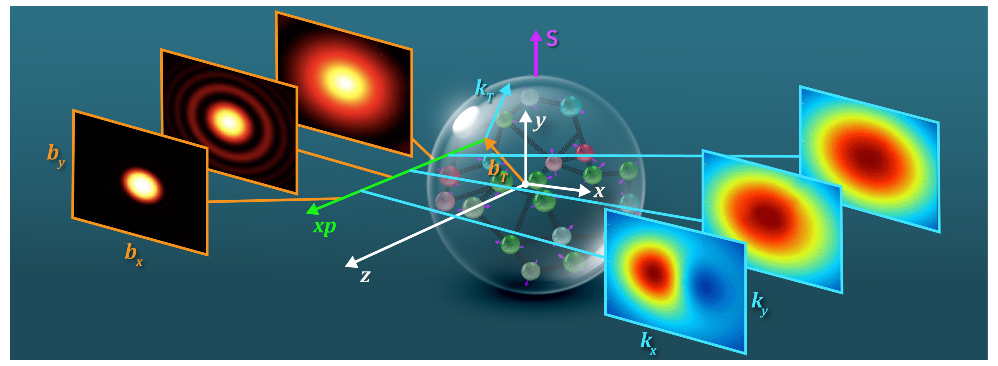

- Wide centre of mass energies
  - Map nucleon/nuclei structure over wide kinematic range in x and $Q^2$



- Polarised e and hadron beams
  - Access to spin structure of nucleons/nuclei
  - Access to 3D spatial and momentum structures
  - Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

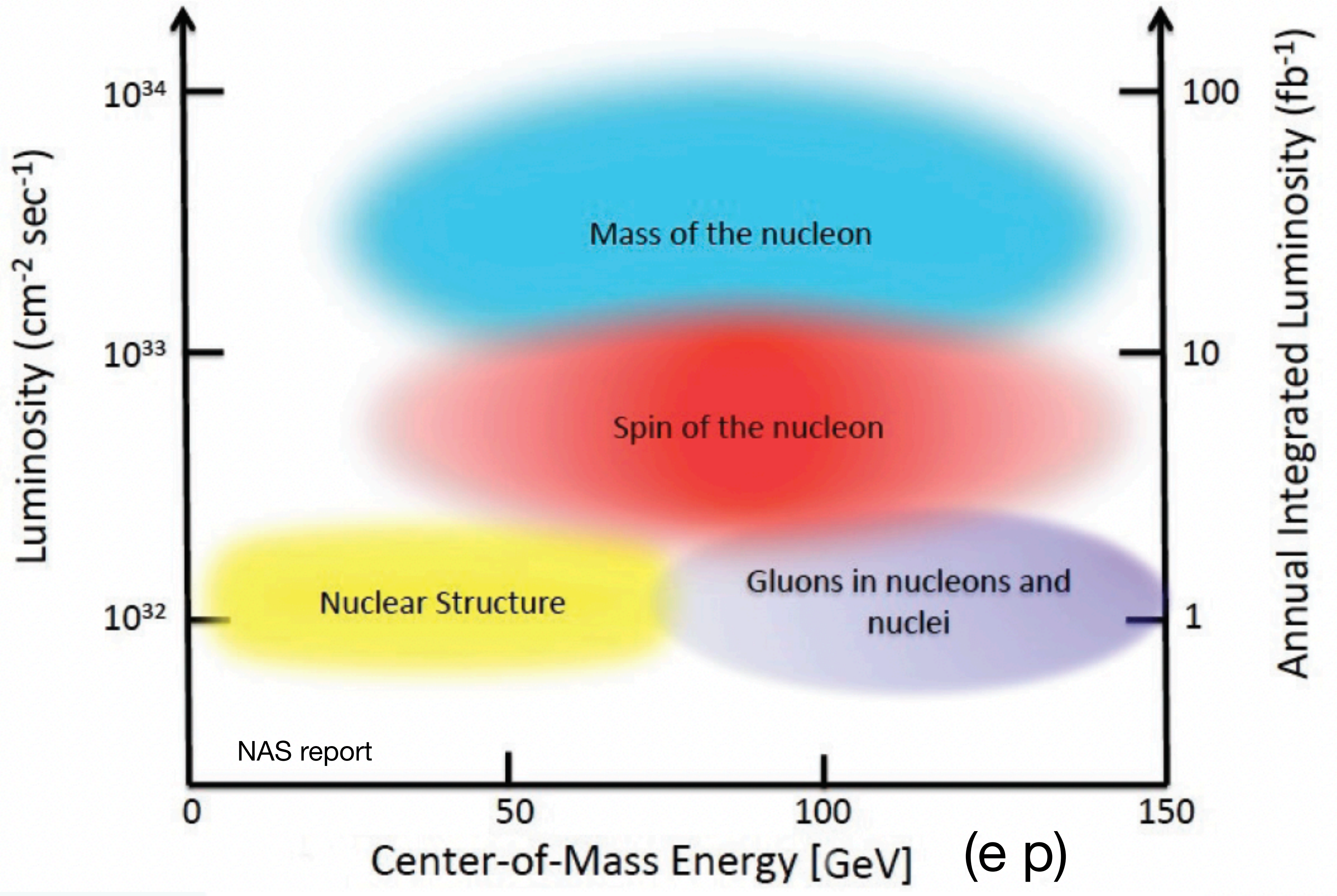


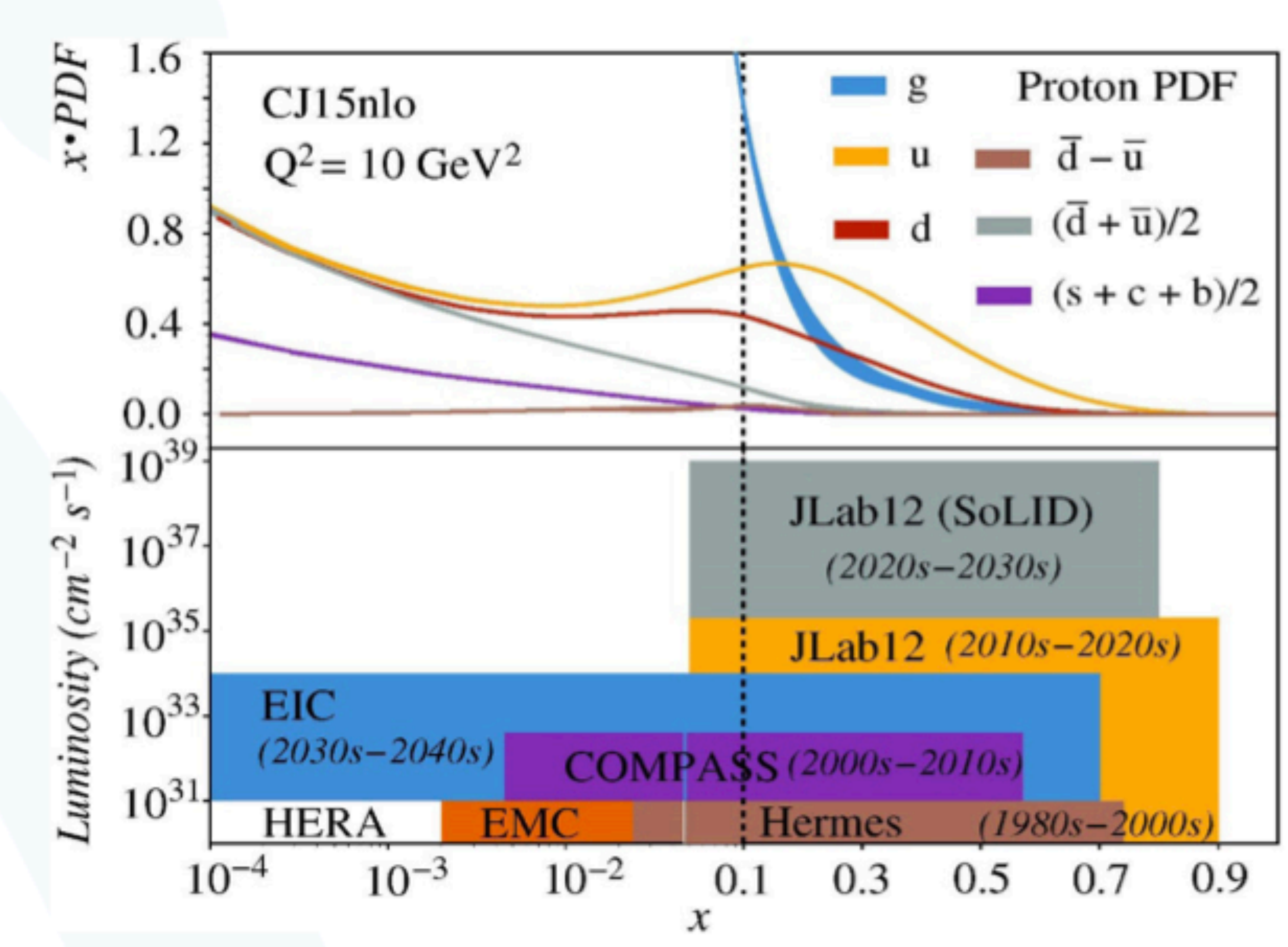

- Wide range of nuclear beams
  - Access highest gluon densities to probe saturation
  - Study quark and gluon interaction with nuclear medium



- High luminosities
  - Multi-dimensional kinematic binning of cross sections to map 3D spatial and momentum structures
  - Access to rare reactions (e.g. W's)
- Large detector acceptance
  - Exclusive and semi inclusive measurements for 3D spatial and momentum imaging of nucleons/nuclei

# First-Of-A-Kind Facility




QCD landscape, NSAC 2023 LRP

- World's first polarised electron-proton/light ion and electron-nucleus collider
  - Ranging from protons, light nuclei, up to uranium
- High polarised beams: 70%
- High-luminosity, up to $10^{34}$ cm$^{-2}$s$^{-1}$
  - 10 - 100 fb$^{-1}$/year
  - 100 - 1000 x HERA luminosity
- Large and variable centre of mass energy:
  - 30 < $E_{CM}$ < 140 GeV
- At least >2 decades increase in ($x$,$Q^2$) landscape compared to fixed target facilities
- ePIC general-purpose collider detector and beam line detectors to reconstruct all particles with high precision
- State-of-the-art, multi-purpose facility

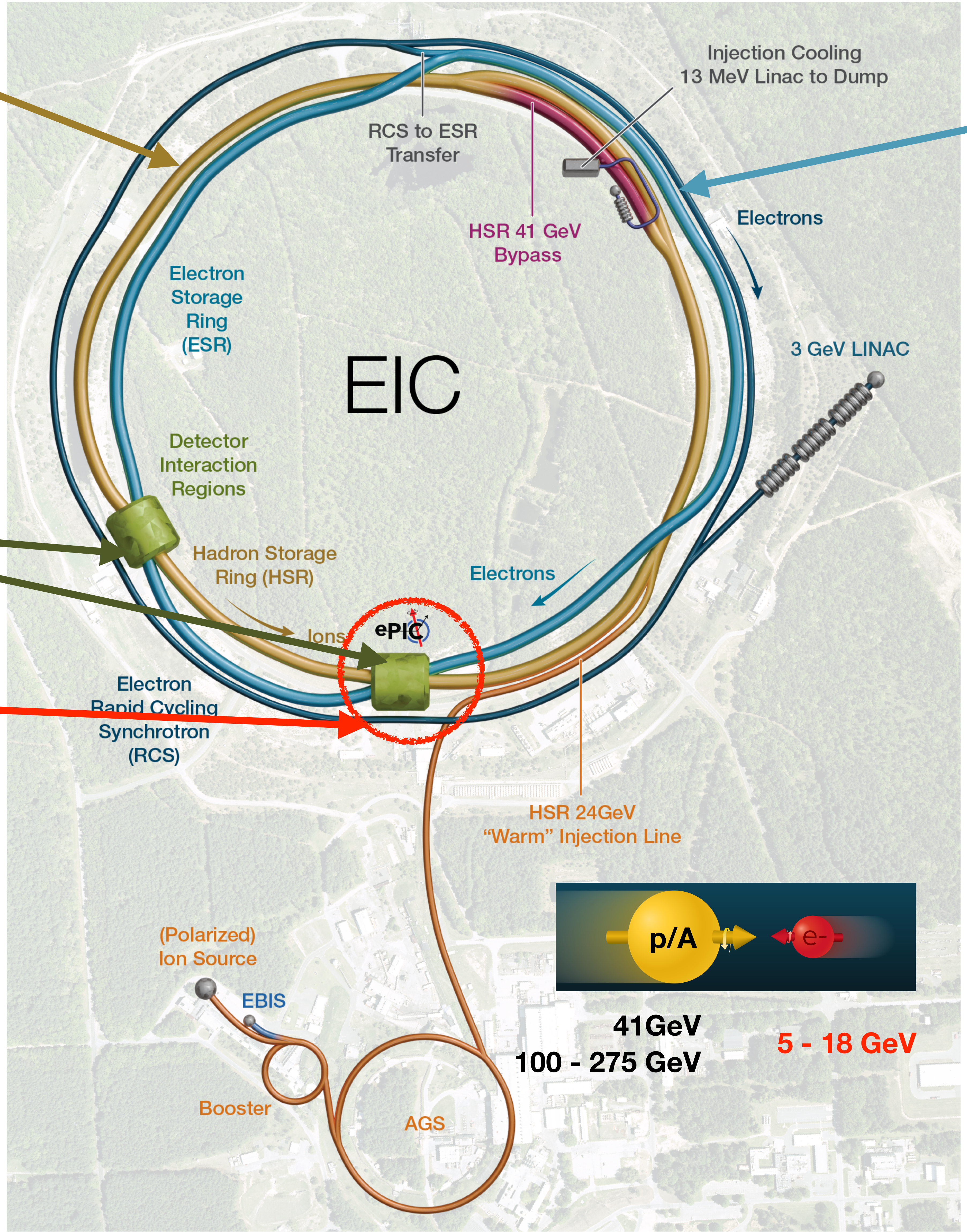
# First-Of-A-Kind Facility

**Hadron** storage (RHIC)
- 41, 100-275 GeV
- Many bunches
- 1A current
- Needs strong cooling
- Light ion beams (p, d, $^{3}$He) polarised >70%
- Unpolarised nuclear beams d to U

High Luminosity **interaction region(s)**
- Superconducting magnets

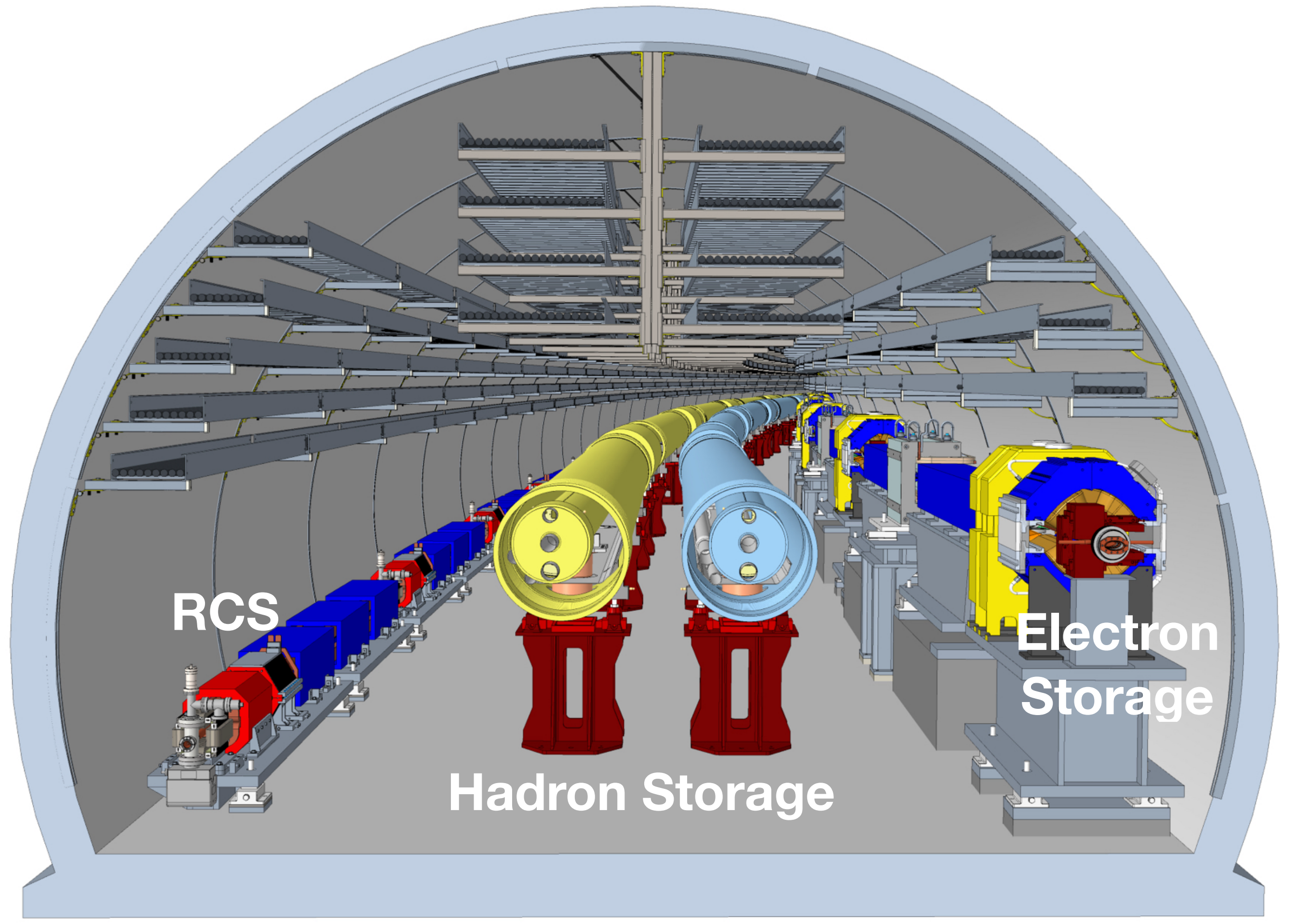
- **ePIC detector for first IR under construction (IP6)**
- Buch crossing ~10ns/ 98.5MHz

- Second IR (IP8) not included in DOE project, but IR, detector and physics under study by EIC community




**Electron** rapid cycling synchrotron (new)
- 1 - 2 Hz
- Spin transparent due to high periodicity

**Electron** storage ring (new), 5 - 18 GeV
- >70% polarisation
- Many bunches
- 9MW synchrotron radiation
- Large beam current (2.5 A)
- Superconducting RF cavities

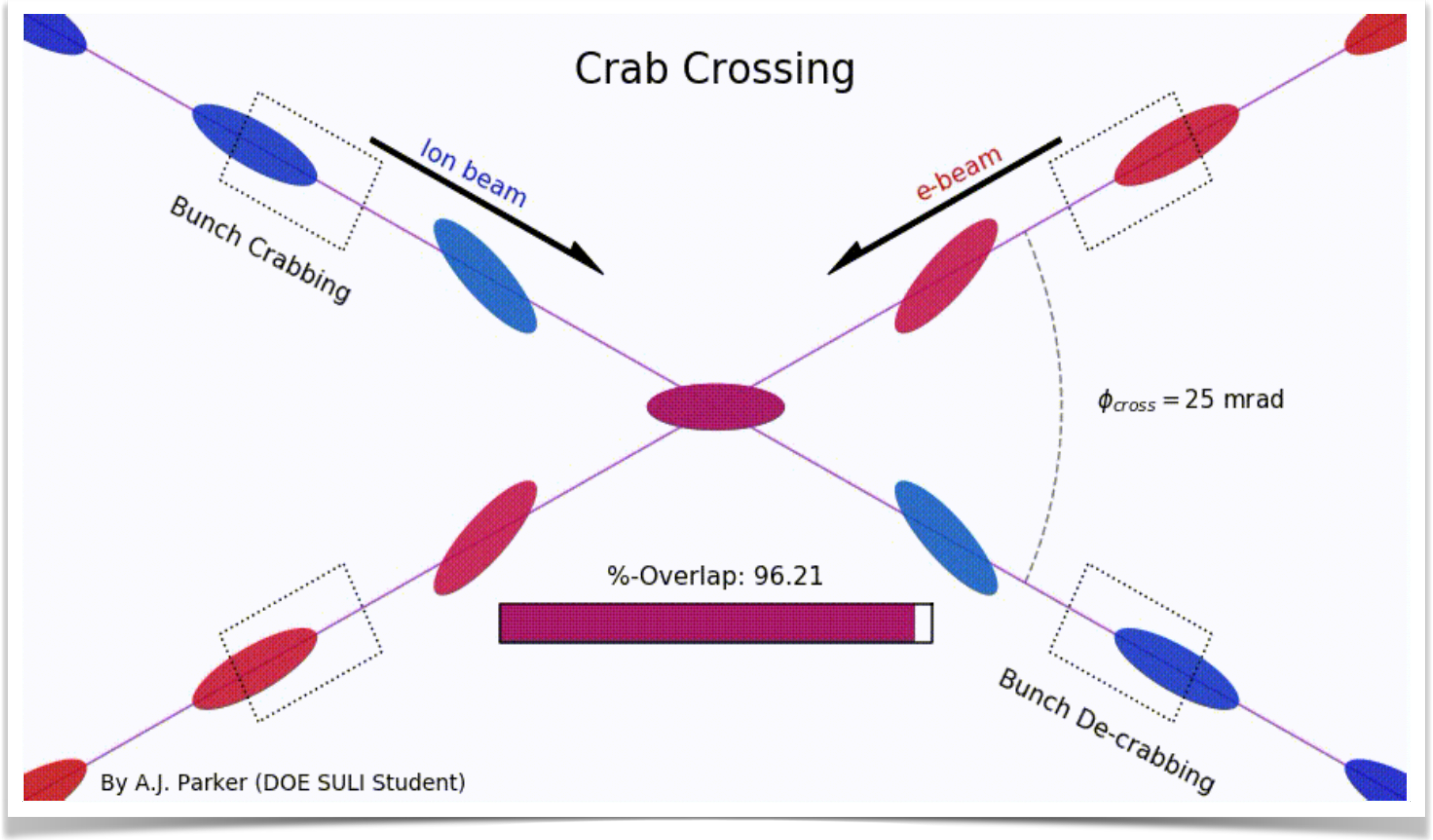


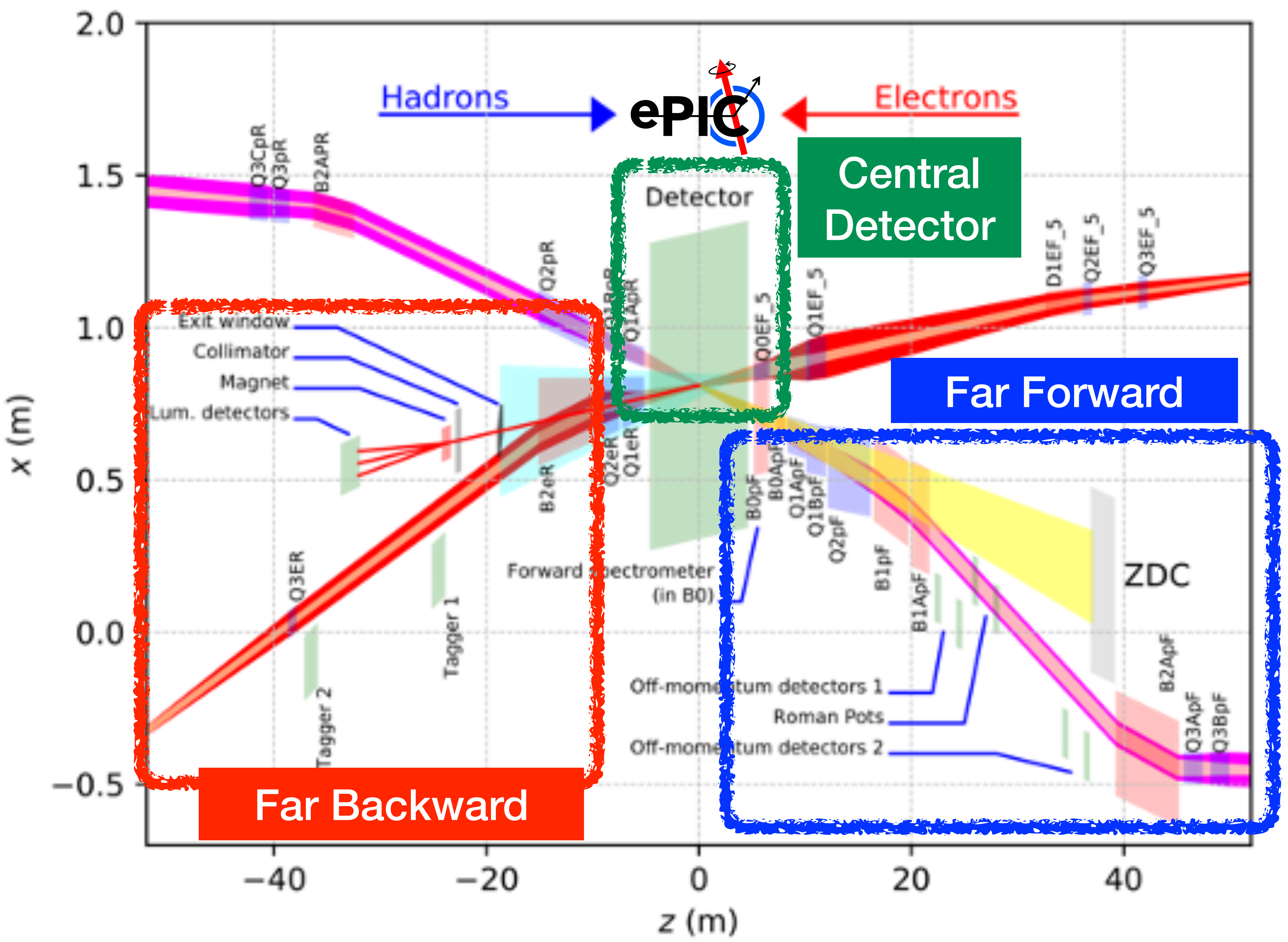

To be built at BNL, on RHIC complex
Partnership between BNL and JLab

US DOE Project currently successfully ongoing for construction of collider, first IR and first general purpose detector, total project cost $2.4B

Only new collider in next decade → EIC is at frontier of accelerator technology

# IR Layout for ePIC




**High Luminosity**

- 25 mrad crossing angle
- Head-on collisions “restored” by crab cavities - crab cavities rotate beam bunches for near full overlap at interaction point
- Small β*, ie small beam size and high luminosity with limited IR chromaticity contributions
- Large final focus quadrupole aperture

**Interface with machine**

- No magnets within -4.5/+5 m from IR
- Far forward and backward regions equipped with instruments integrated with beamlines → near complete acceptance of final state particles

# Considerations for ePIC Detector

- Hermetic detector, as close to full acceptance as possible
- Electron measurement and jets in $-4 < \eta < 4$

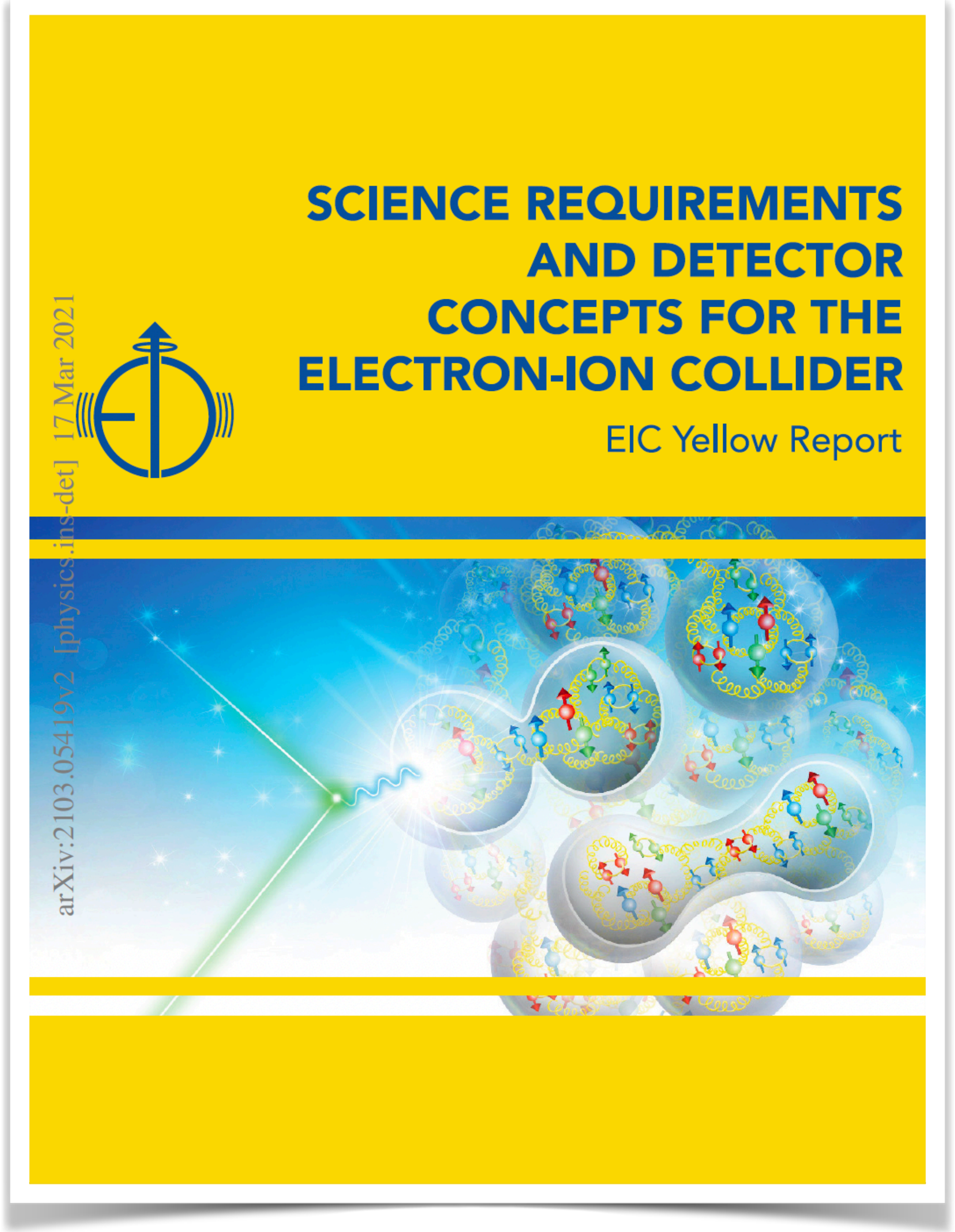
- Large centre of mass energy range

- Low mass inner tracking

- Momentum resolution
  - Central: $\sigma(p)/p = 0.05\%p \oplus 0.5\%$ to $0.05\%p \oplus 1.0\%$
  - Forward/Backward: $\sigma(p)/p = 0.05\%p \oplus 1.0\%$ to $\sigma(p)/p = 0.1\%p \oplus 2.0\%$

- EM Calorimetry resolution
  - Central: $\sigma(E)/E = 10\%/\sqrt{E}$
  - Backward : $\sigma(E)/E < 2\%/\sqrt{E}$
- Hadronic Calorimetry resolution
  - Forward: $\sigma(E)/E = 50\%/\sqrt{E}$

- Hadron PID ($\pi$/K/p)
  - Forward: up to 50GeV/c
  - Central: up to 8GeV/c
  - Backward: up to 7GeV/c



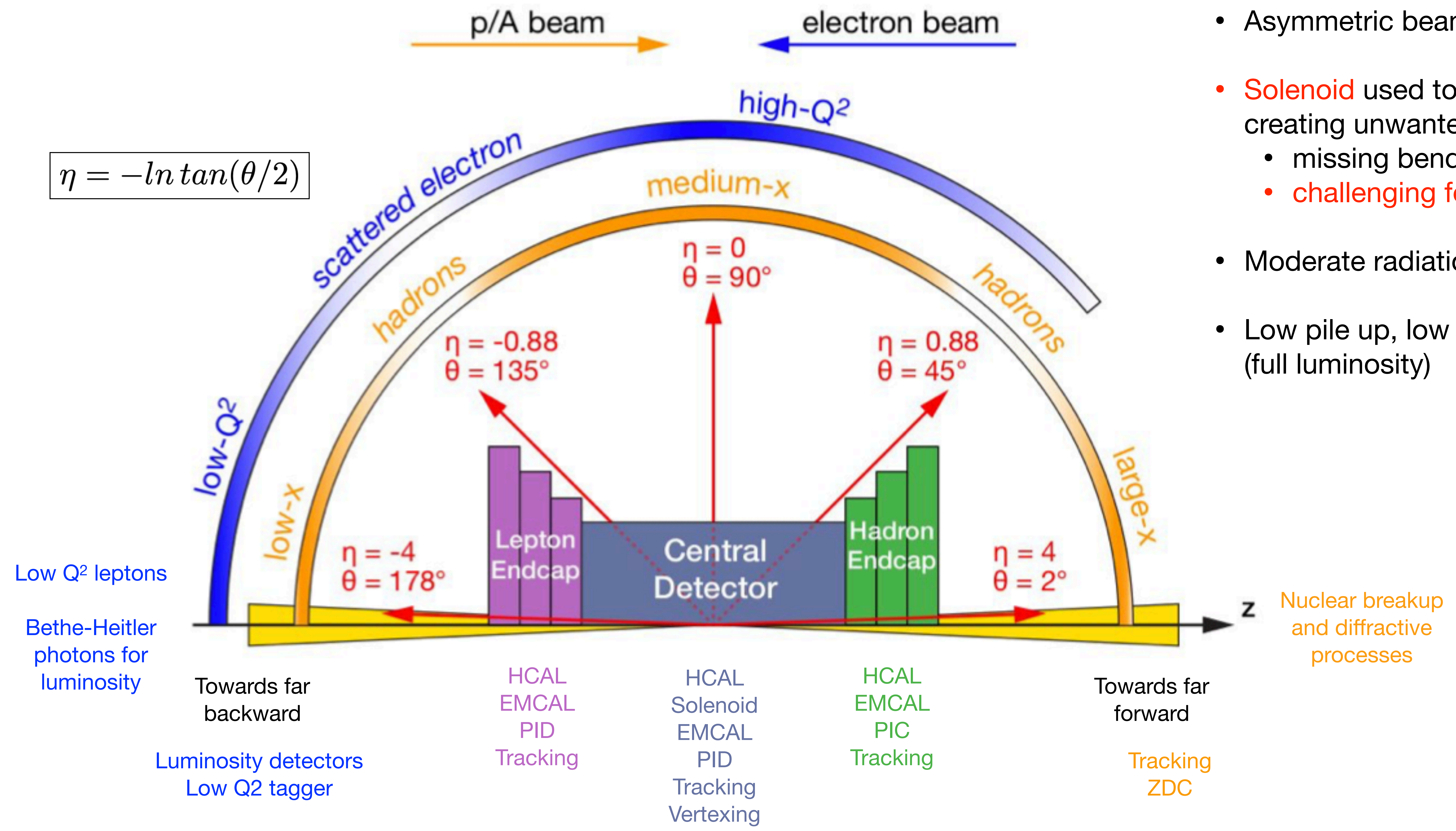

EIC YR published by EICUG laid out the detector requirements for realising an EIC physics program

arXiv:2103.05419v3 [physics.ins-det]

Challenging detector design driven entirely by physics requirements

# Considerations for ePIC Detector

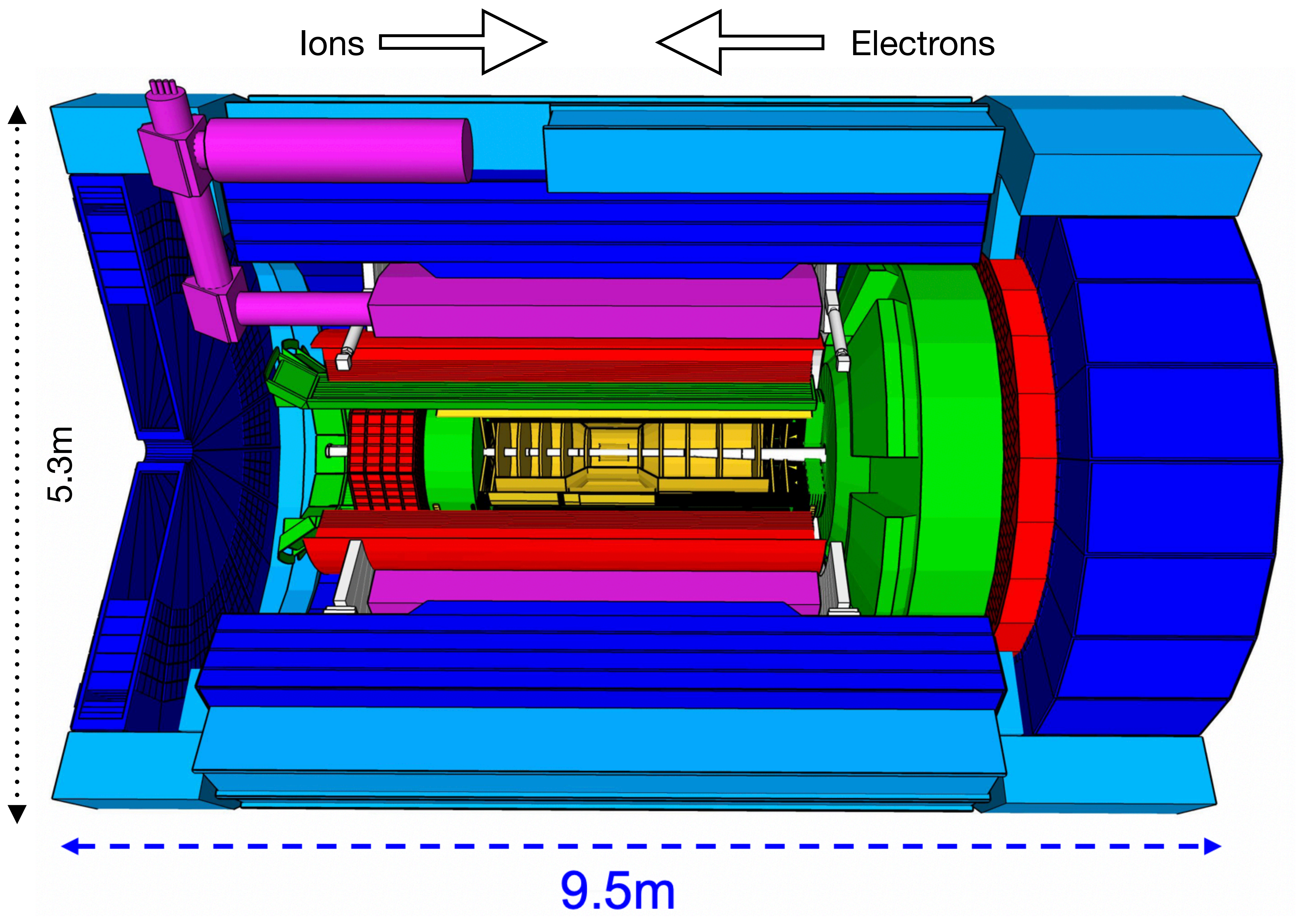
$$\eta = -ln\, tan(\theta/2)$$




- Asymmetric beams → asymmetric detector
- Solenoid used to avoid affecting e-beam and creating unwanted synchrotron radiation
  - missing bending power in endcaps
  - challenging for tracking and calorimetry
- Moderate radiation hardness
- Low pile up, low multiplicity, data rate ~500kHz (full luminosity)

# ePIC Detector

electron-proton/ion collider (ePIC) experiment




Hermetic central detector: $0^\circ \le \phi \le 360^\circ$; $\mathbf{-4 \le \eta \le 4}$

## E/M Calorimetry

- Imaging EMCal (Pb+SciFi) with imaging Astropix layers (barrel)
- High granularity W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

## Hadronic Calorimetry

- Steel/Scint from sPHENIX (barrel)
- Steel/Scint - W/Scint (backward/forward)

## Particle Identification

- High performance DIRC, hpDIRC (Quartz/MCP-PMT) (barrel)
- Dual radiator RICH, dRICH (aerogel+$C_2F_6$ gas/SiPM) (forward)
- Proximity focussing RICH, pfRICH (aerogel/HRPPD) (backward)
- TOF (~30ps, AC-LGAD), also for tracking (barrel and forward)

## Solenoid

- MARCO magnet. New 1.7T (1.5 - 2T), superconducting, 2.8m bore diameter

## Vertexing and Tracking

- Si MAPS (vertex, barrel, forward and backward disks)
- MPGD (μRWELL; micromegas) (barrel, forward and backward disks)

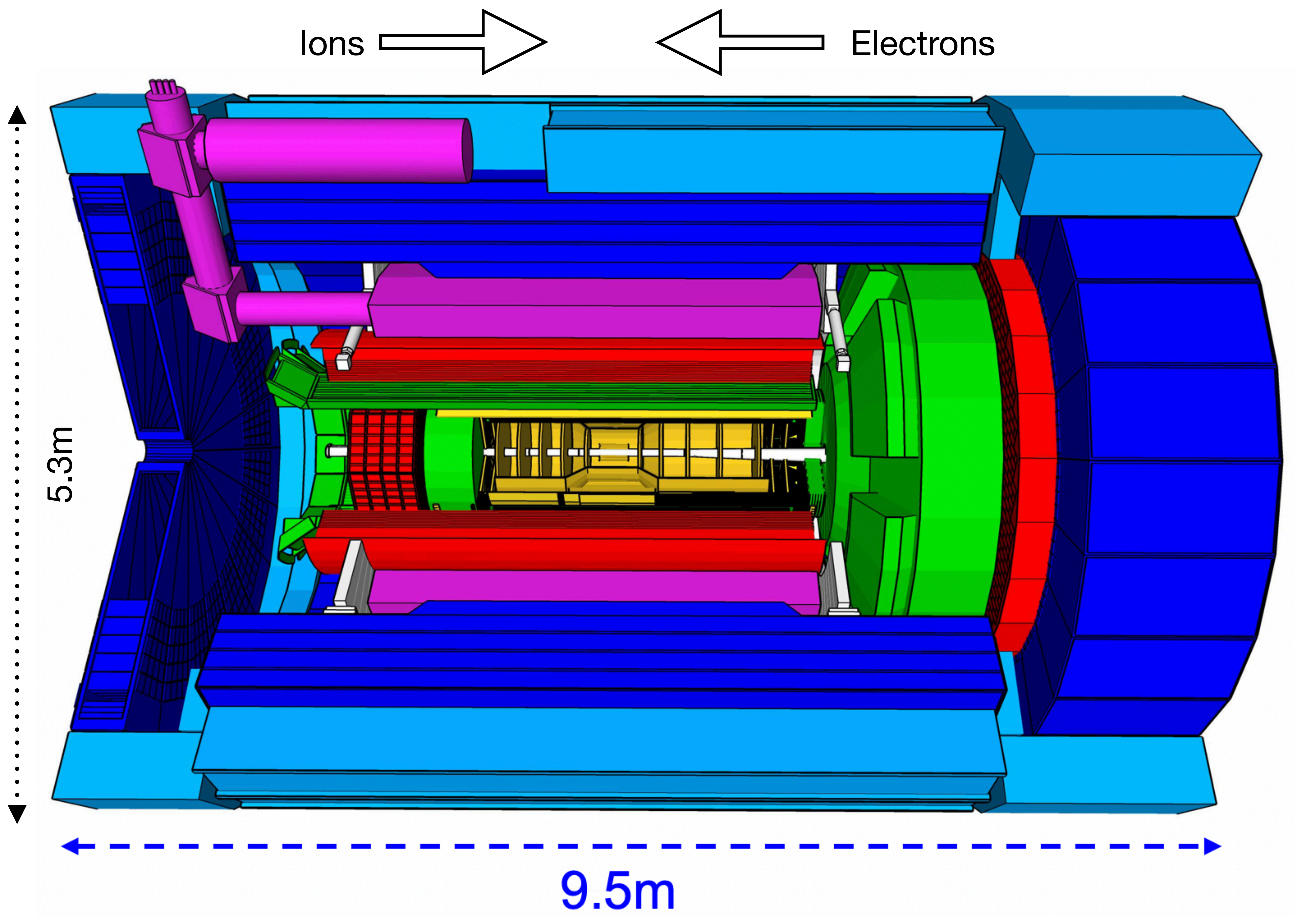
## DAQ

- Streaming/trigger-less, inclusion of AI

Plus services, e.g. power, cooling, data for many subsystems within constrained volume!

# ePIC Detector

electron-proton/ion collider (ePIC) experiment

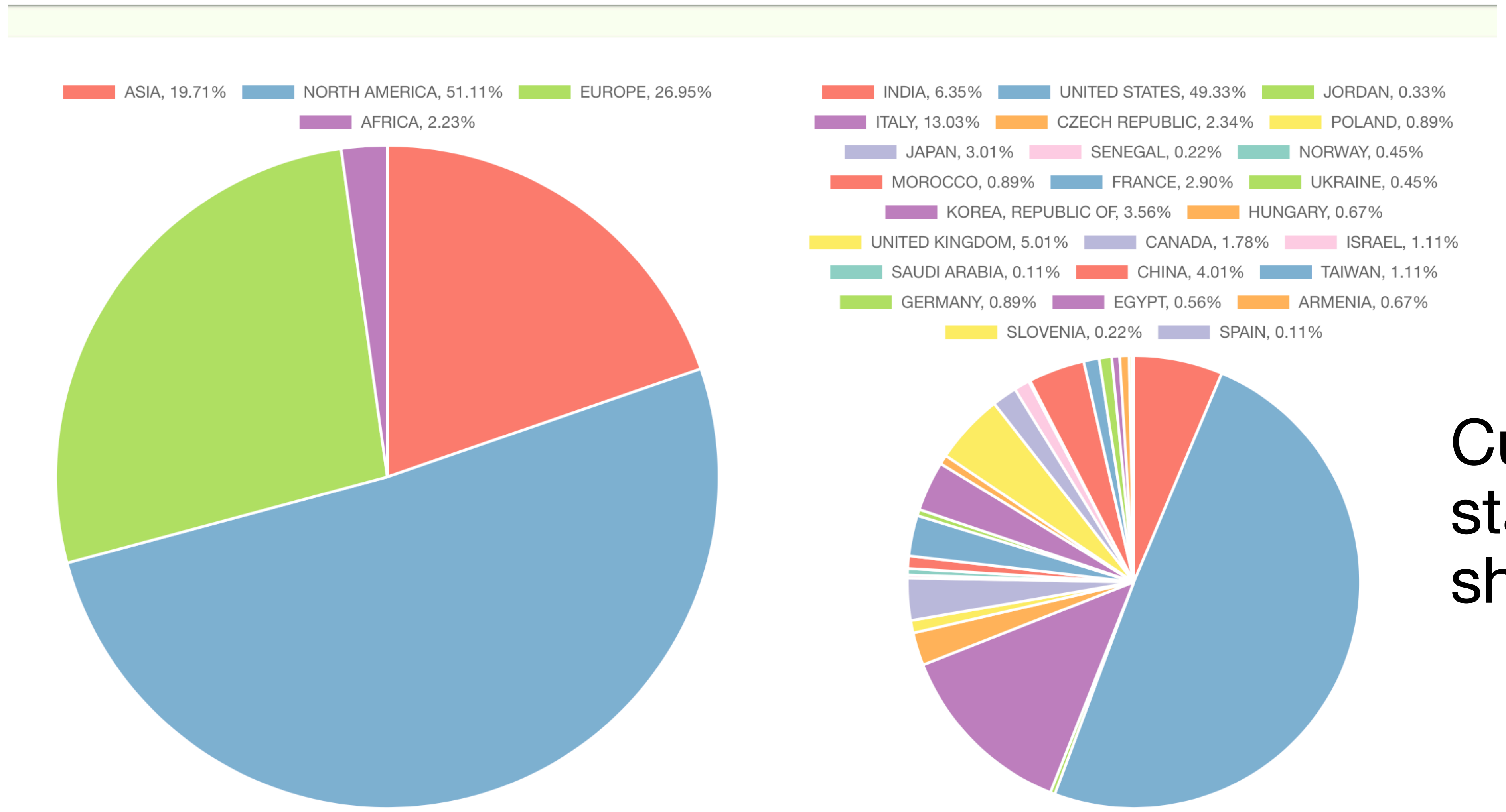



ePIC Collaboration formed in 2022 to realise first detector

(https://www.epic-eic.org/public/overview.html)

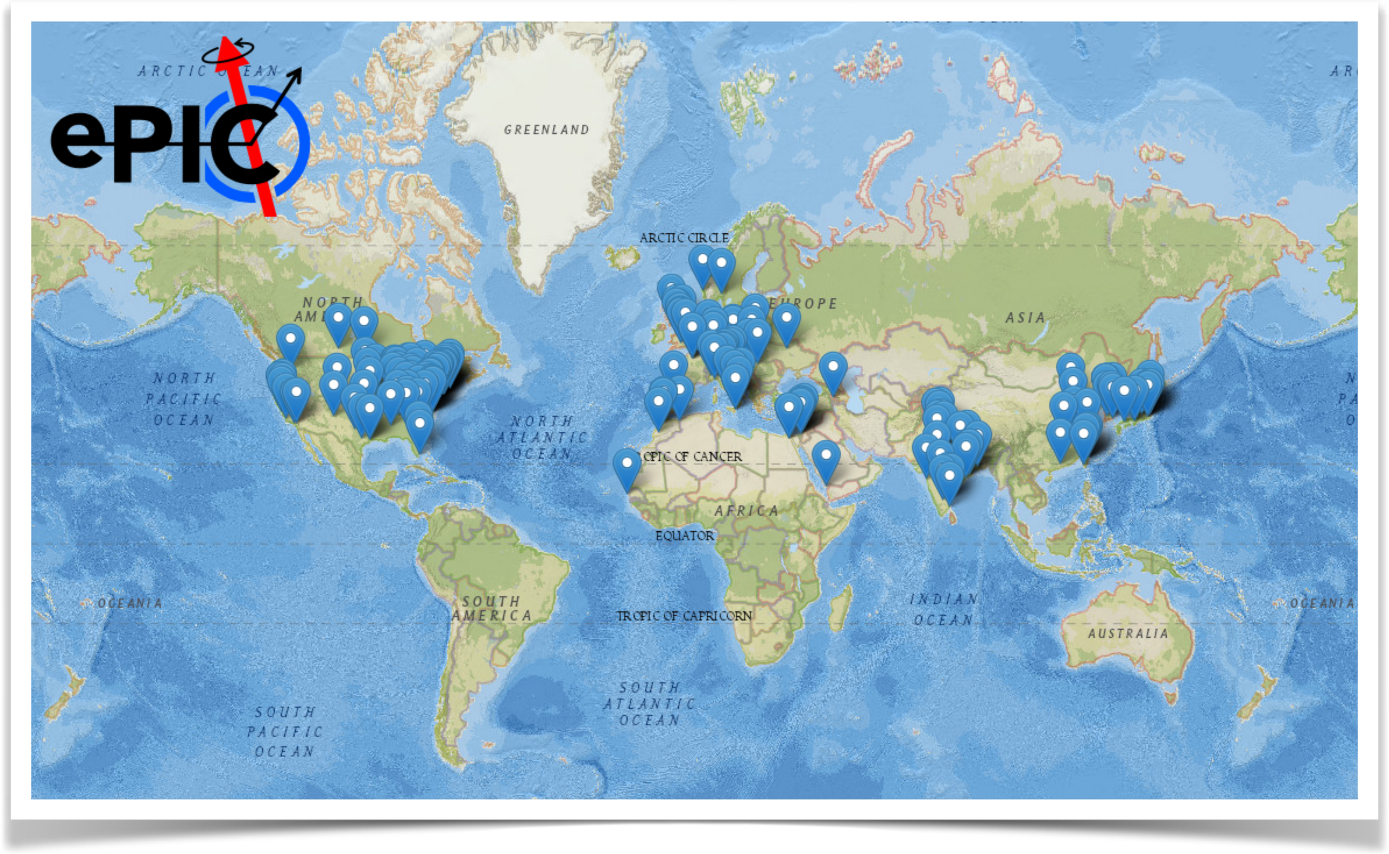
Currently working towards TDR

| 898 MEMBERS | 177 INSTITUTIONS | 25 COUNTRIES | 4 WORLD REGIONS |
|---|---|---|---|

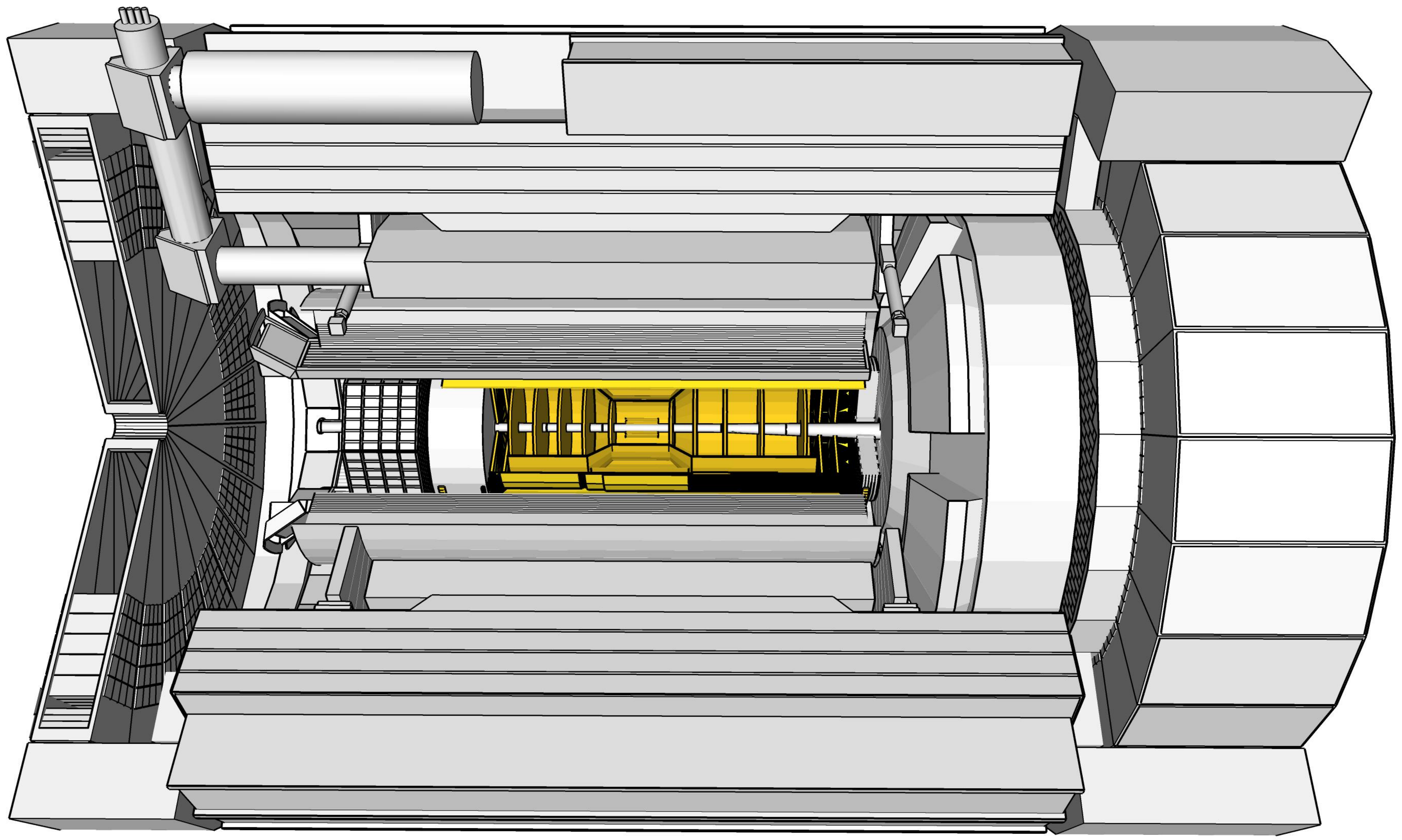



Current stats shown

Very welcoming collaboration for new members!



# Tracking



- Precisely measure e' and charged hadrons produced in collisions
  - (scattered ions (or breakup) outside of acceptance)
- Decay particles eg from hadrons containing heavy quarks, or VM
- Aid PID through primary and secondary vertexing, and by providing directional and impact information on charged-particle trajectories through to outer PID systems

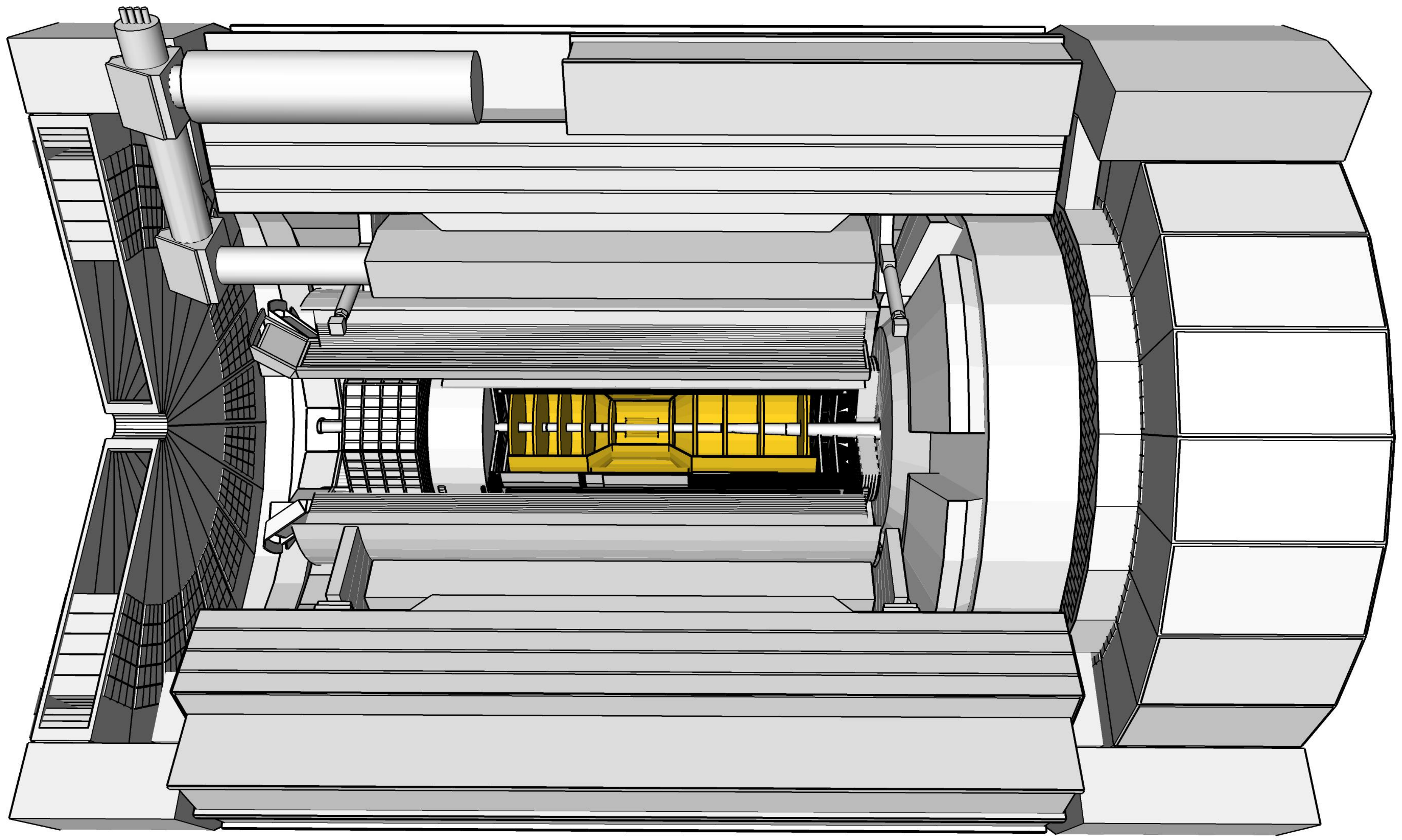
**Requirements:**

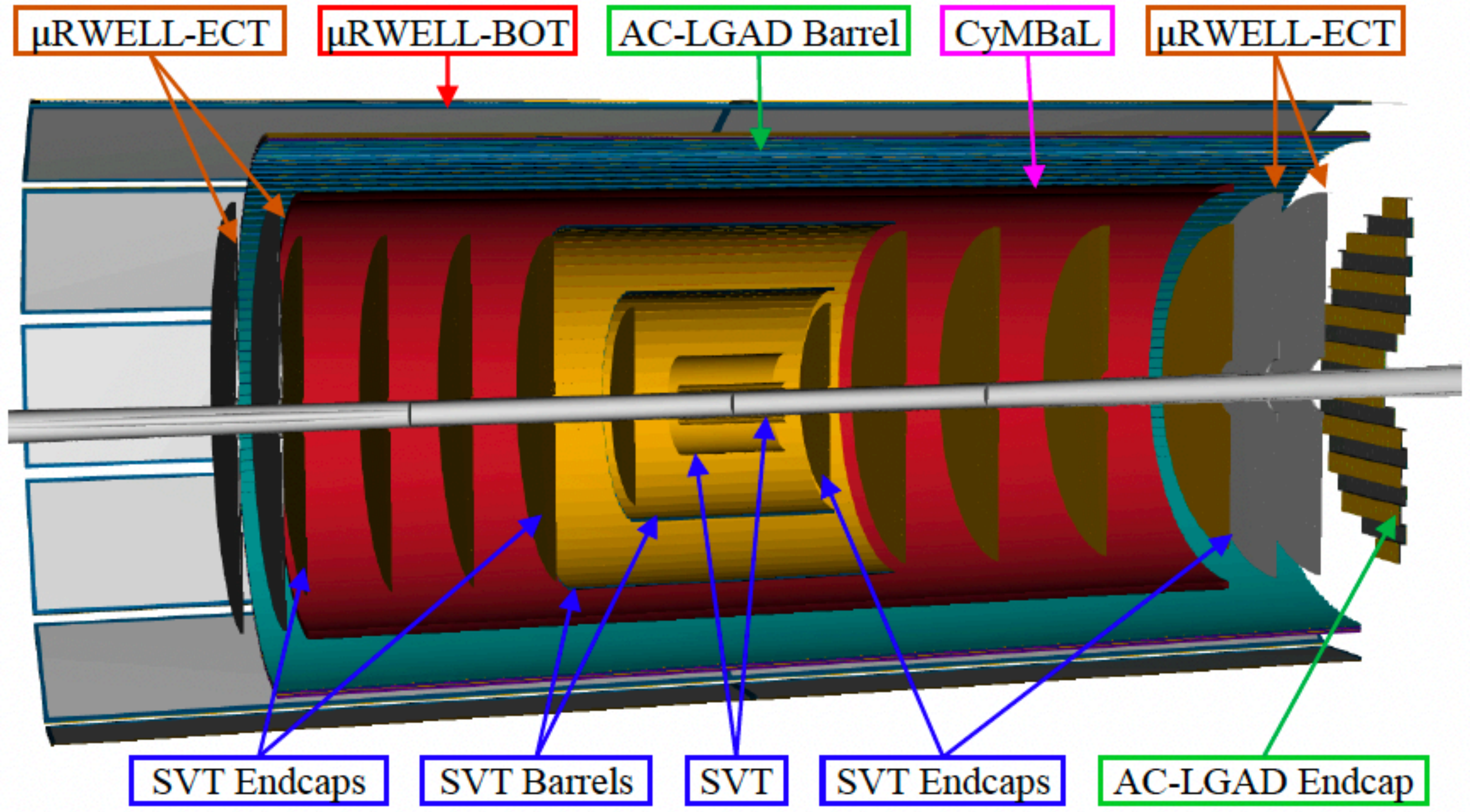
- Low-mass tracking
- High spatial resolution and efficiency over large area
- High pixel granularity
- Very low material budget constraints, including at large η
  - challenging for services

| Rapidity Range | Momentum Resolution | Spatial Resolution |
|---|---|---|
| Backward (-3.5 to -2.5) | $\sim 0.10\% \times p \oplus 2.0\%$ | $\sim 30/pT\ \mu m \oplus 40 \mu m$ |
| Backward (-2.5 to -1.0) | $\sim 0.05\% \times p \oplus 1.0\%$ | $\sim 30/pT\ \mu m \oplus 20 \mu m$ |
| Barrel (-1.0 to 1.0) | $\sim 0.05\% \times p \oplus 0.5\%$ | $\sim 20/pT\ \mu m \oplus 5 \mu m$ |
| Forward (1.0 to 2.5) | $\sim 0.05\% \times p \oplus 1.0\%$ | $\sim 30/pT\ \mu m \oplus 20 \mu m$ |
| Forward (2.5 to 3.5) | $\sim 0.10\% \times p \oplus 2.0\%$ | $\sim 30/pT\ \mu m \oplus 40 \mu m$ |

At extreme |η|, momentum resolution complemented by calorimetric resolutions → physics requirements are met

# Tracking






## Silicon Vertex Tracker (SVT)

- Monolithic Active Pixel Sensor (MAPS)
  - 20µm pixel pitch, ~6µm point resolution, low power consumption (<20mW/cm$^2$)
- Synergistic efforts with CERN ALICE-ITS3 MOSAIX developments
  - Some necessary design modifications for EIC
- 3 inner barrels
  - ITS3-curved wafer-scale sensors, 0.05% $X/X_0$
  - Bent around beam line
  - Large surface area (8m$^2$)
- 2 outer barrels
  - ITS3 based Large Area Sensors (EIC-LAS), 0.25% (innermost), 0.55% (outermost) $X/X_0$
  - EIC-LAS are a modification of ITS3 sensors — World First
- 5 endcap disks each in forward/backward directions
  - EIC-LAS 0.25% $X/X_0$ — World First

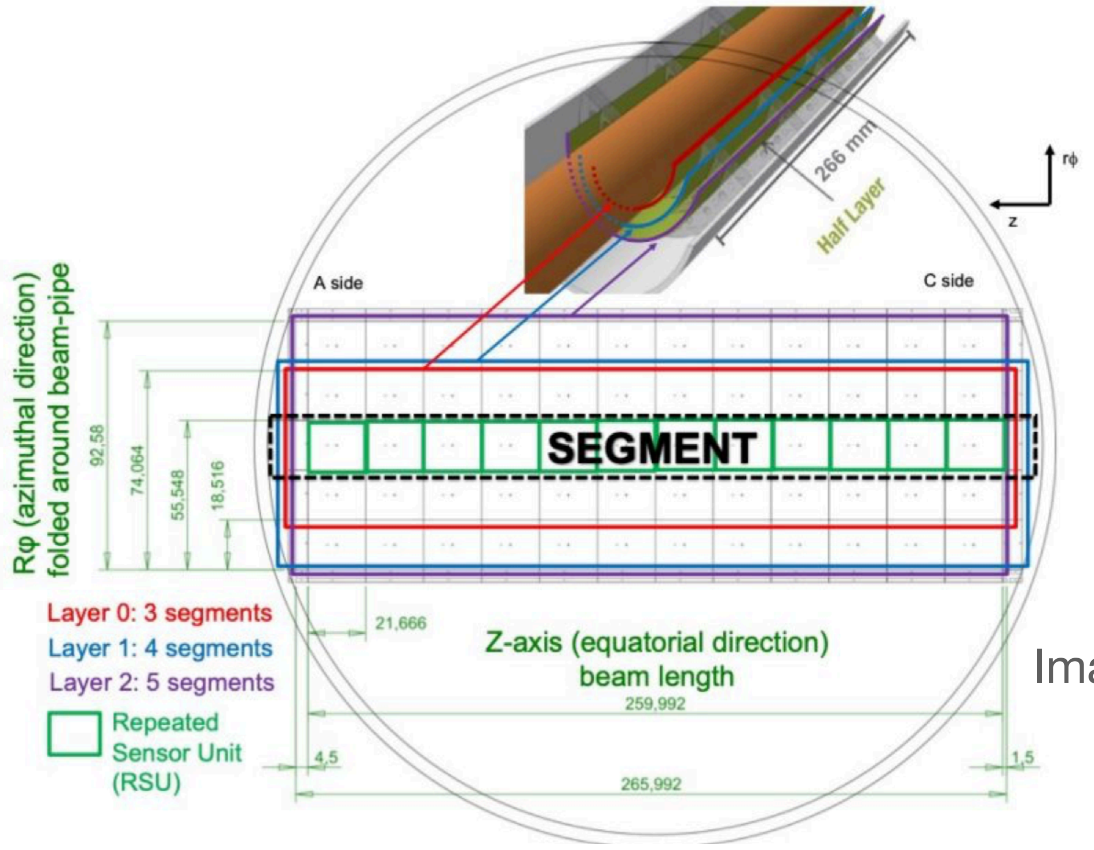
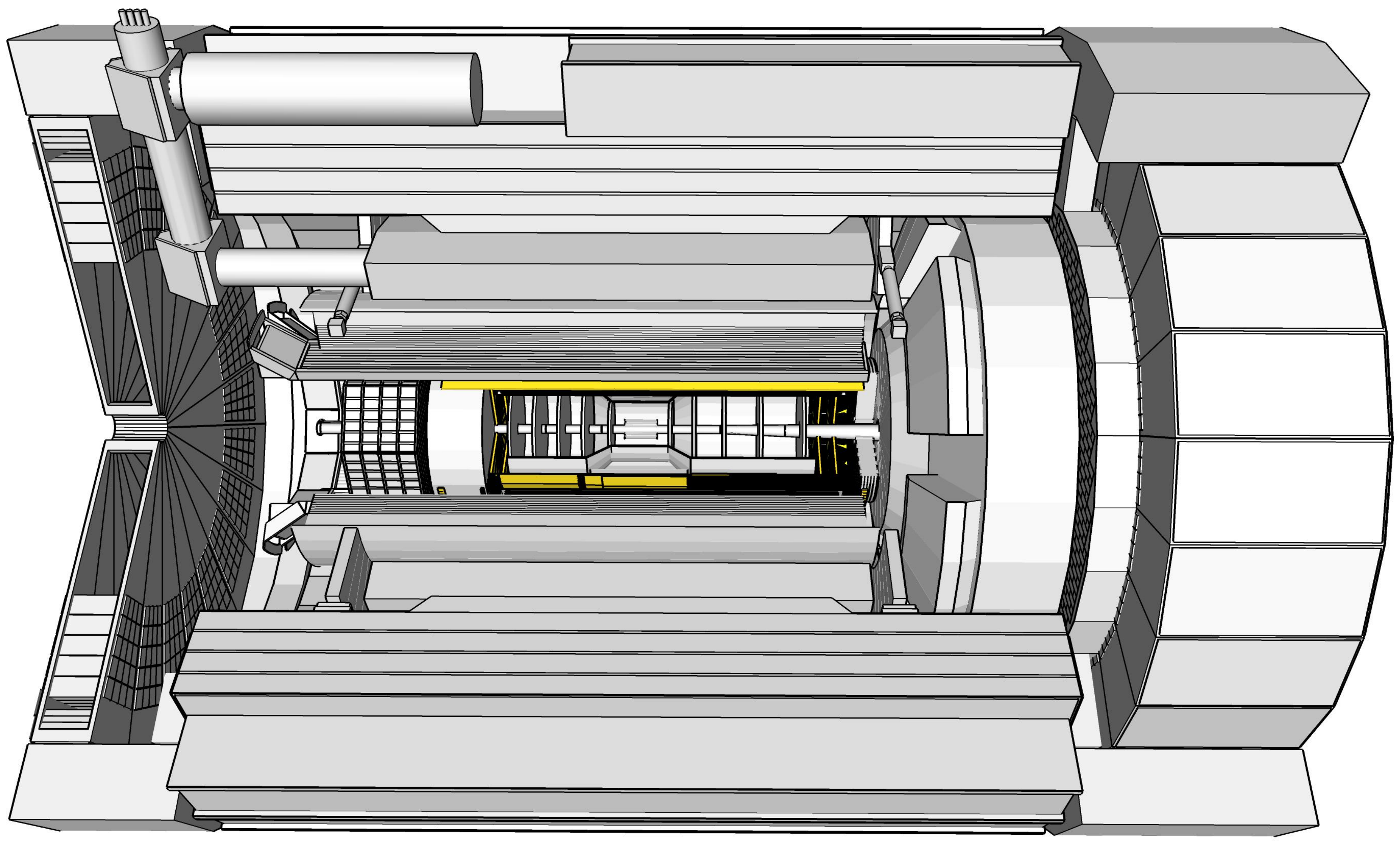
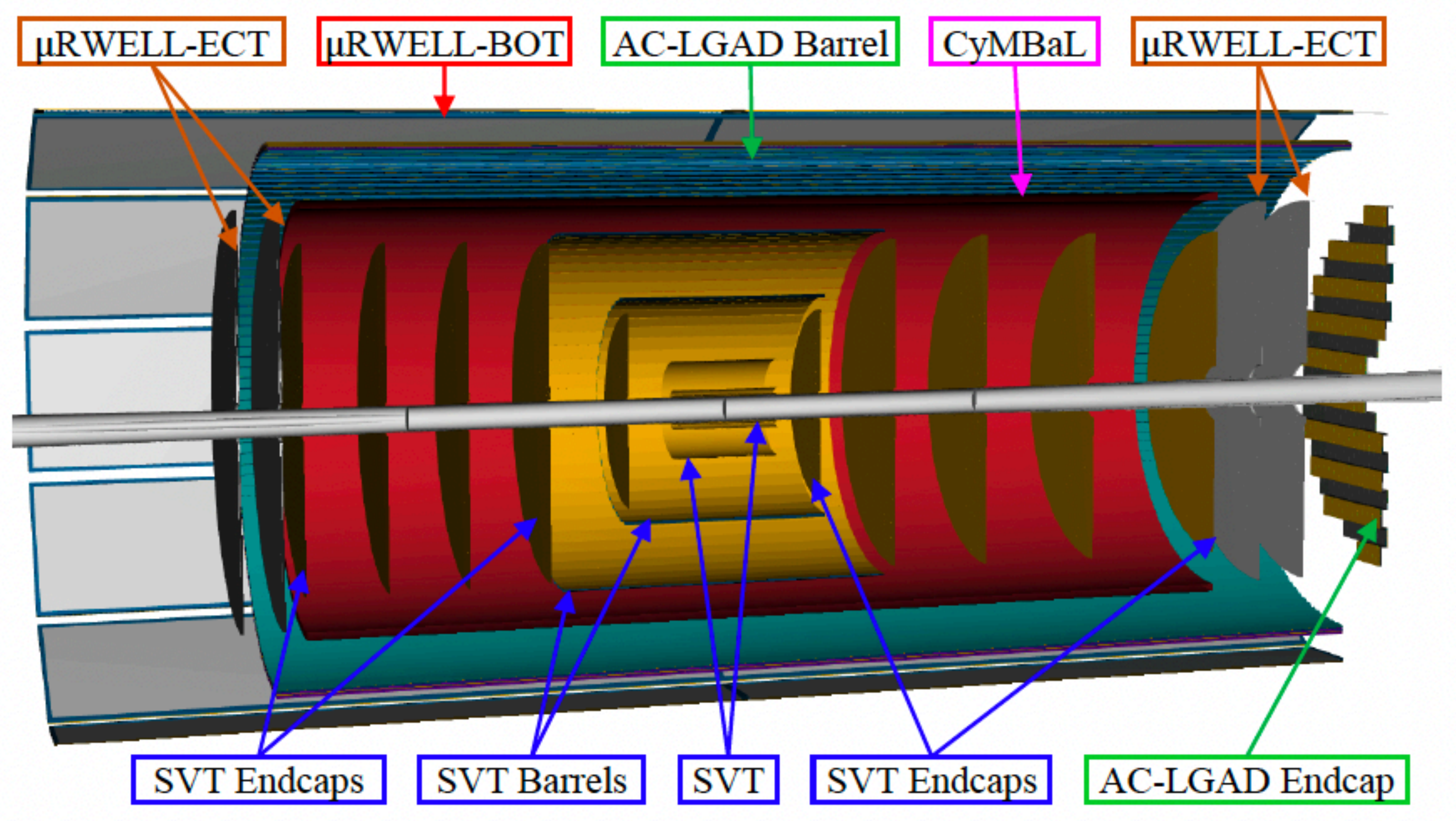



Image: I. Sedgwick (RAL)

# Tracking

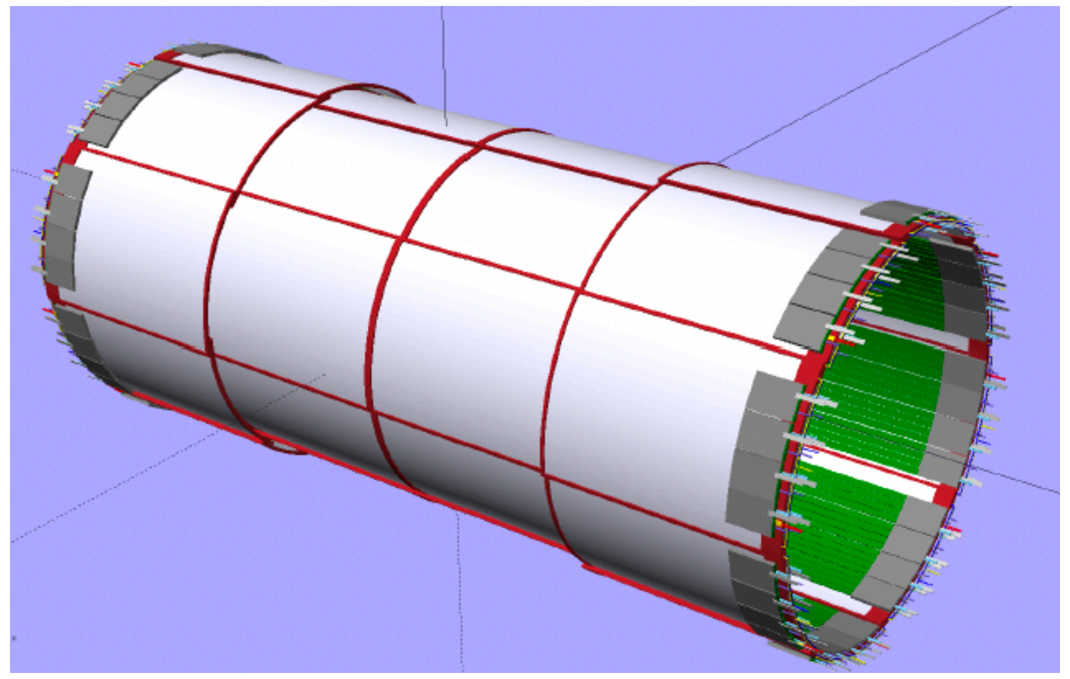




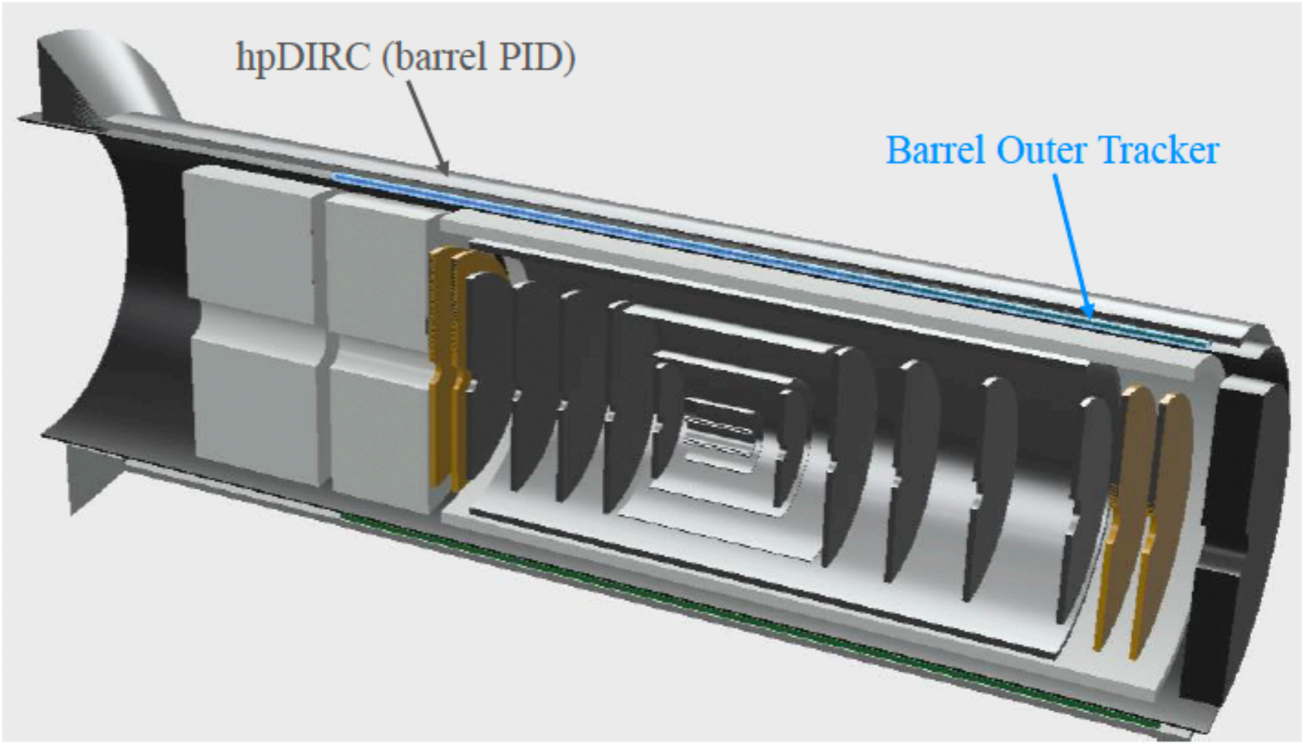

## Micro Pattern Gaseous Detectors (MPGD)

- Resolutions:
  - Timing (10ns) for pattern recognition
  - Additional space points (150µm) for redundancy and improved pattern recognition

- 2 x 2 endcap discs: GEM-µRwell hybrid detectors, 1-2% $X/X_0$ **World First**
- One inner barrel layer: cylindrical micromegas 0.5% $X/X_0$
- One outer barrel layer: thin-gap GEM-µRwell hybrid detectors **World First**
  - Will also help angular and space point resolution in barrel PID (hpDIRC)

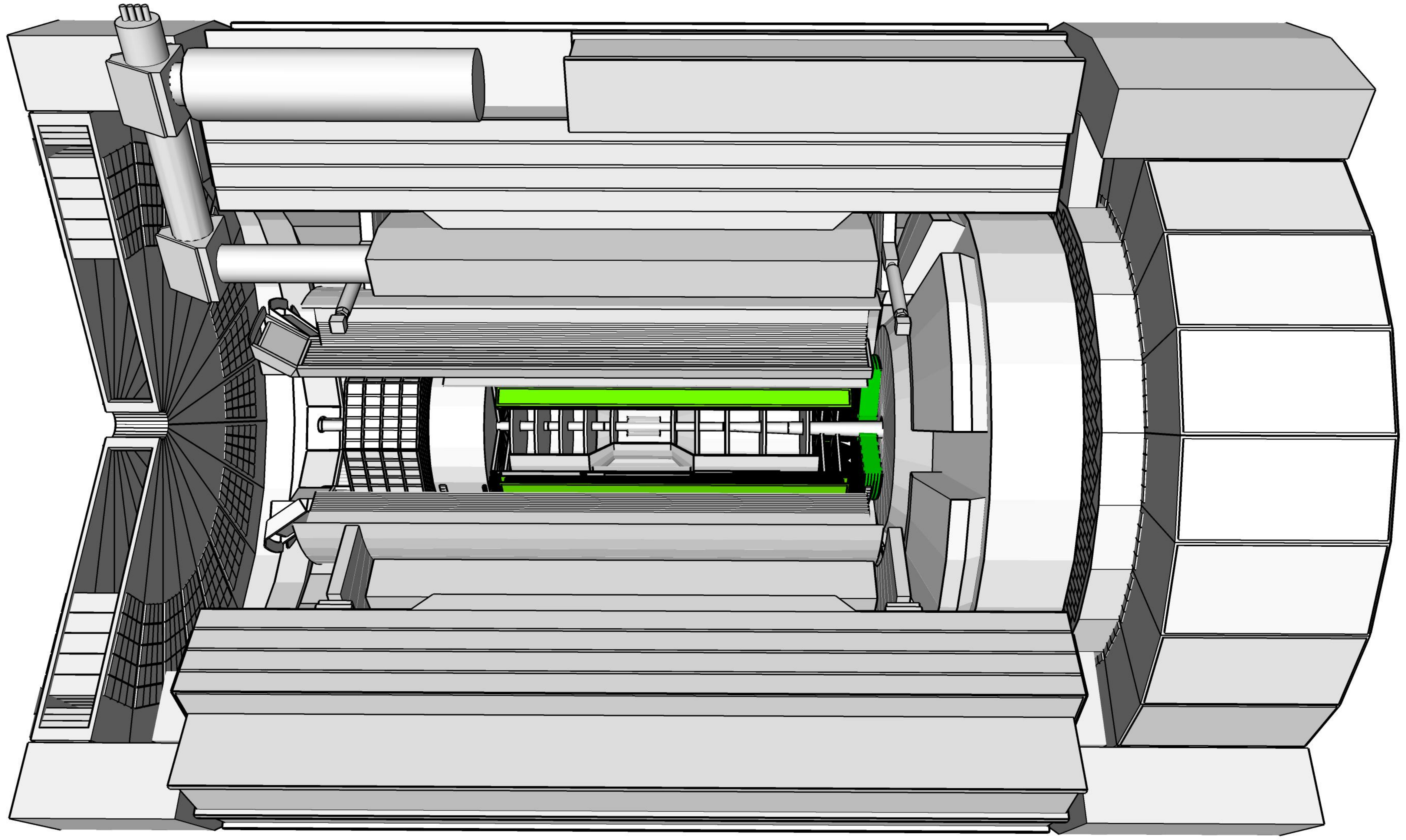


Micromegas (CyMBaL)




µRwell-BOT

Images from ePIC pre-TDR



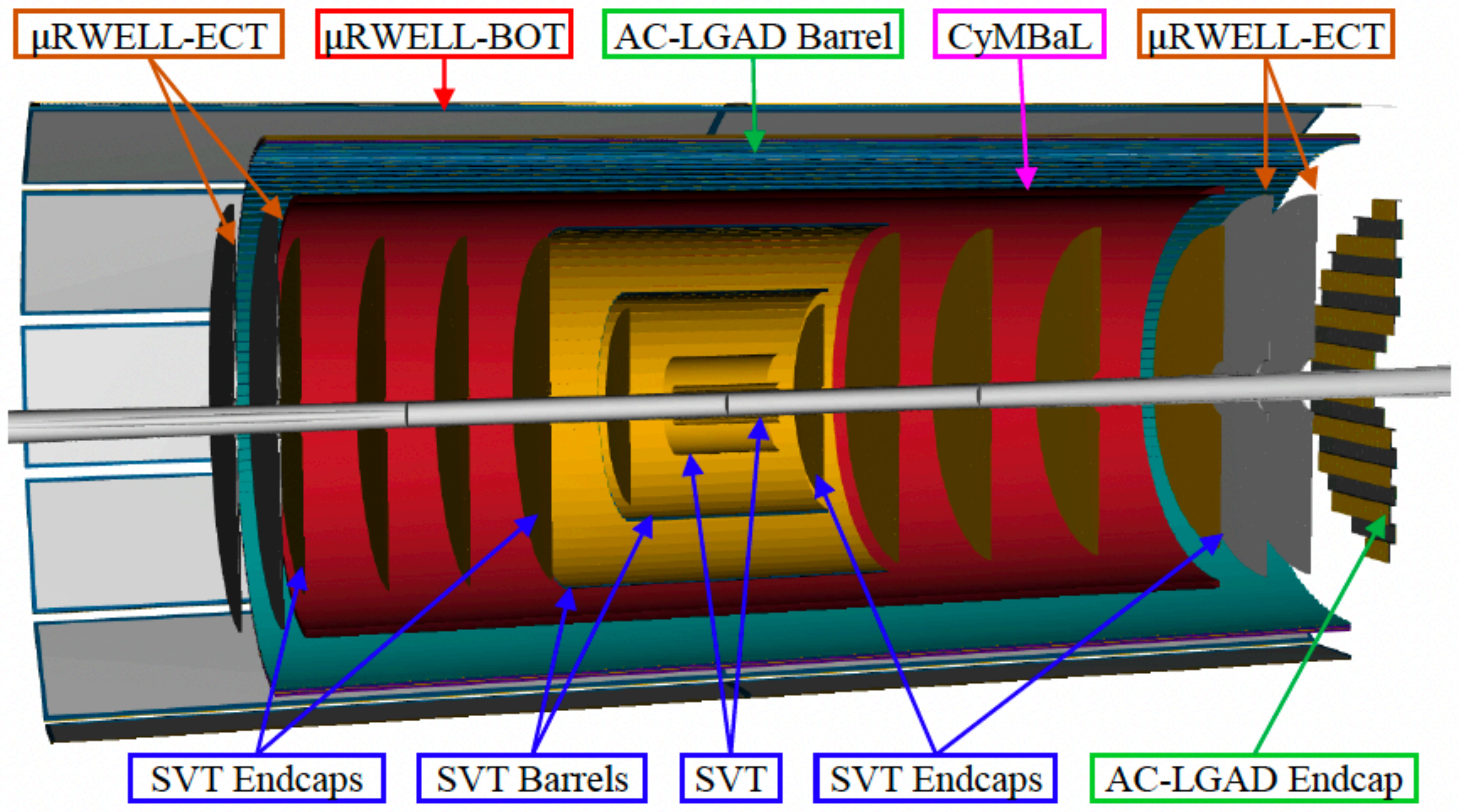
### AC-coupled Low Gain Avalanche Diode (AC-LGAD)

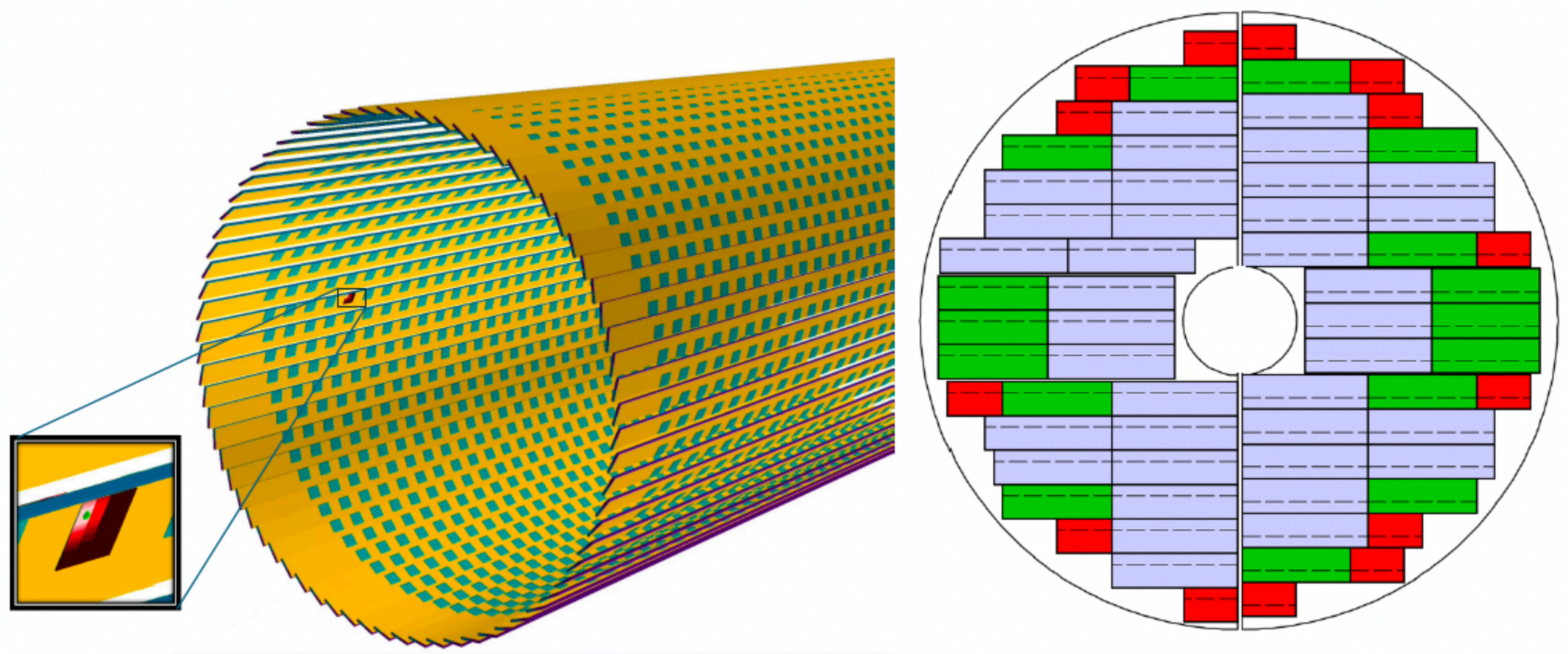
- Silicon sensor technology
- Resolutions:
    - ~30ps, 30μm

- Provides TOF to cover PID at low $p_T$
- Can also provide time and additional spatial information/ redundancy for tracking

- Barrel: 0.05 cm x 1 cm strips, 1% $X/X_0$
- Endcap: 0.05 cm x 0.05 cm pixels, 2.5% $X/X_0$

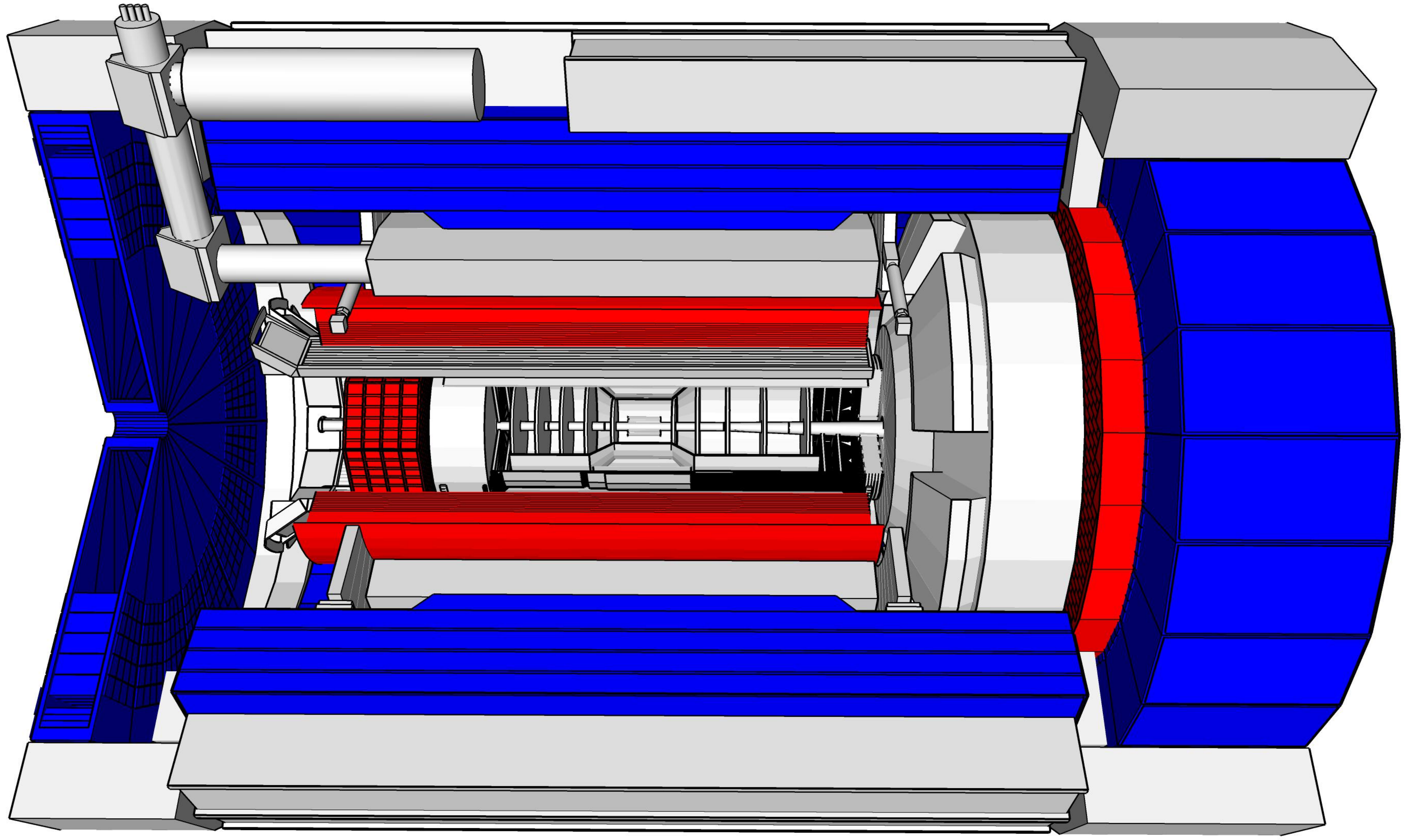
World First



Images from ePIC pre-TDR

# Calorimetry



Electromagnetic (ECal)
Hadronic (HCal)

- Detect e' and provide e'/π separation (up to 104 suppression factor in backward and barrel ECals)
- Improve electron momentum resolution at backward rapidities (2-3%/$\sqrt{E} \oplus$(1-2)% for backward ECal)
- ECals should provide spatial resolution for disentangling two photons sufficient to identify $\pi^0 \rightarrow \gamma\gamma$ at high energies
- Contain the highly energetic hadronic final state and separate clusters in a dense hadronic environment in forward ECal and HCal

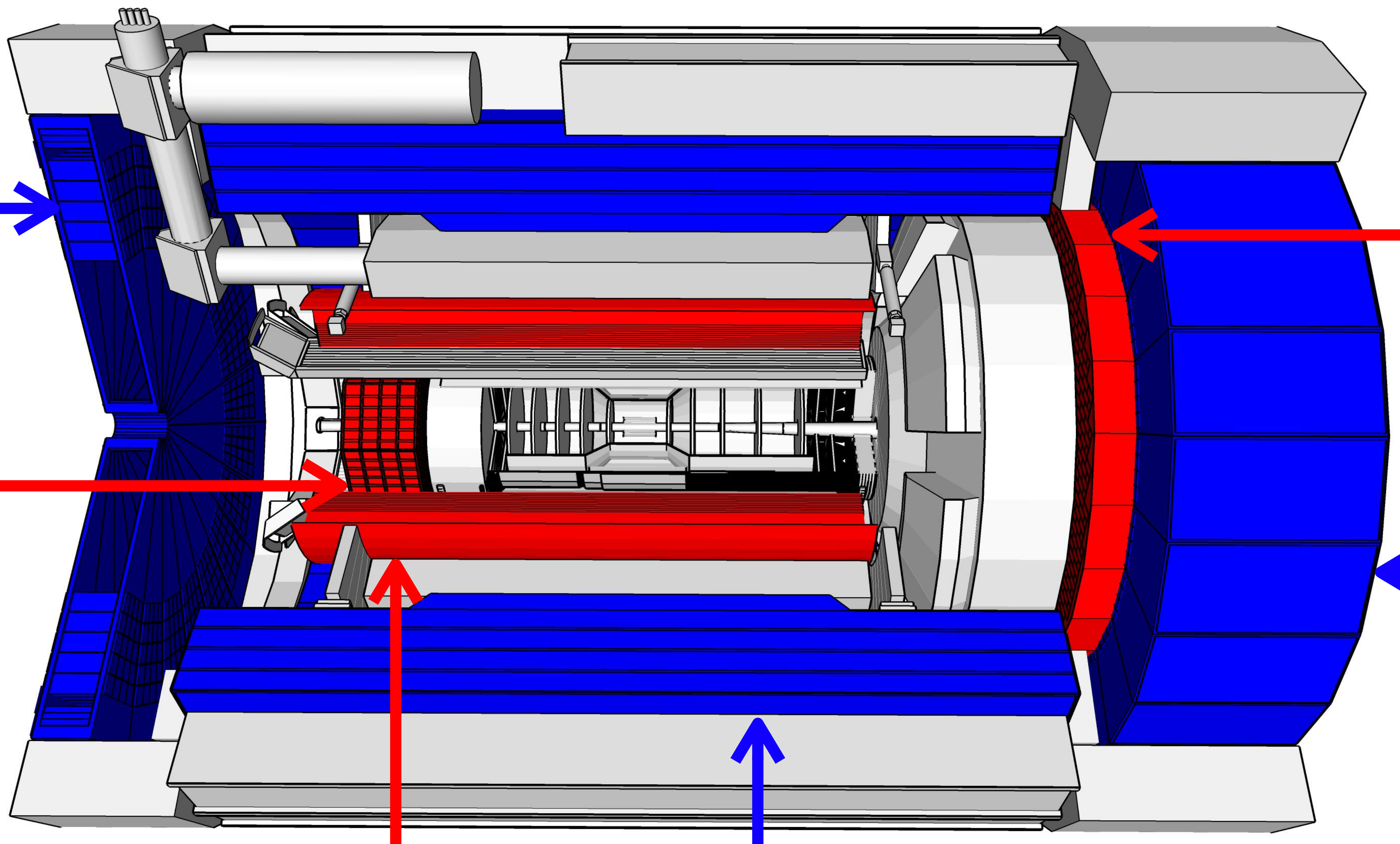
# Calorimetry

Electromagnetic (ECal)
Hadronic (HCal)

*Calorimeters with wide range of acceptances and different technologies used to meet broad physics requirements*

Backward HCal:
Muon and neutral detection →improved jet energy reconstruction

Backward ECal:
Scattered lepton detection → very high precision



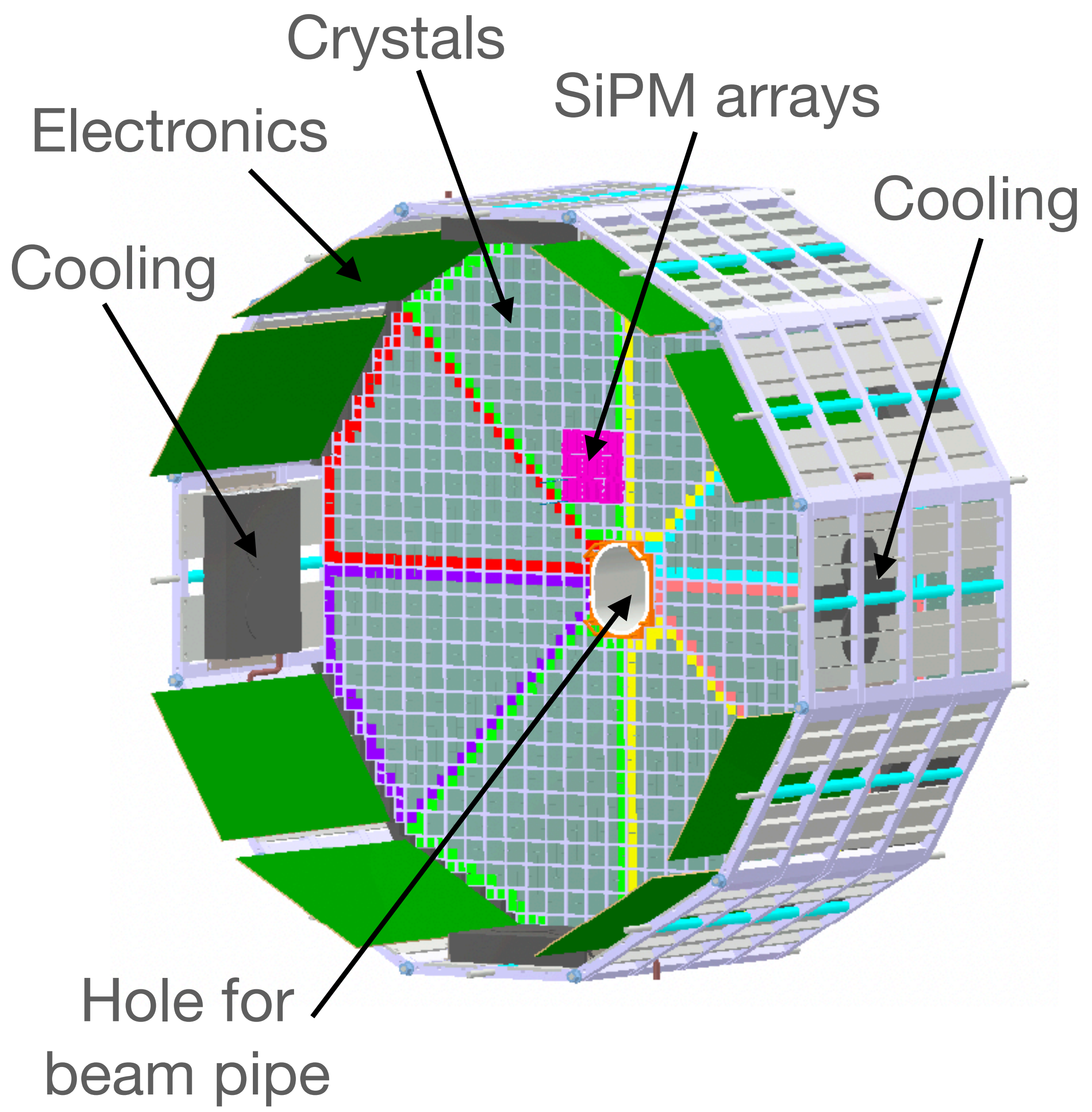
Forward ECal:
Lepton and $\gamma$ detection, hadronic final state characterisation, $\pi^0 \rightarrow \gamma\gamma$ separation

Forward HCal:
Particle flow measurements

Barrel ECal:
Scattered lepton and $\gamma$ detection, hadronic final state characterisation

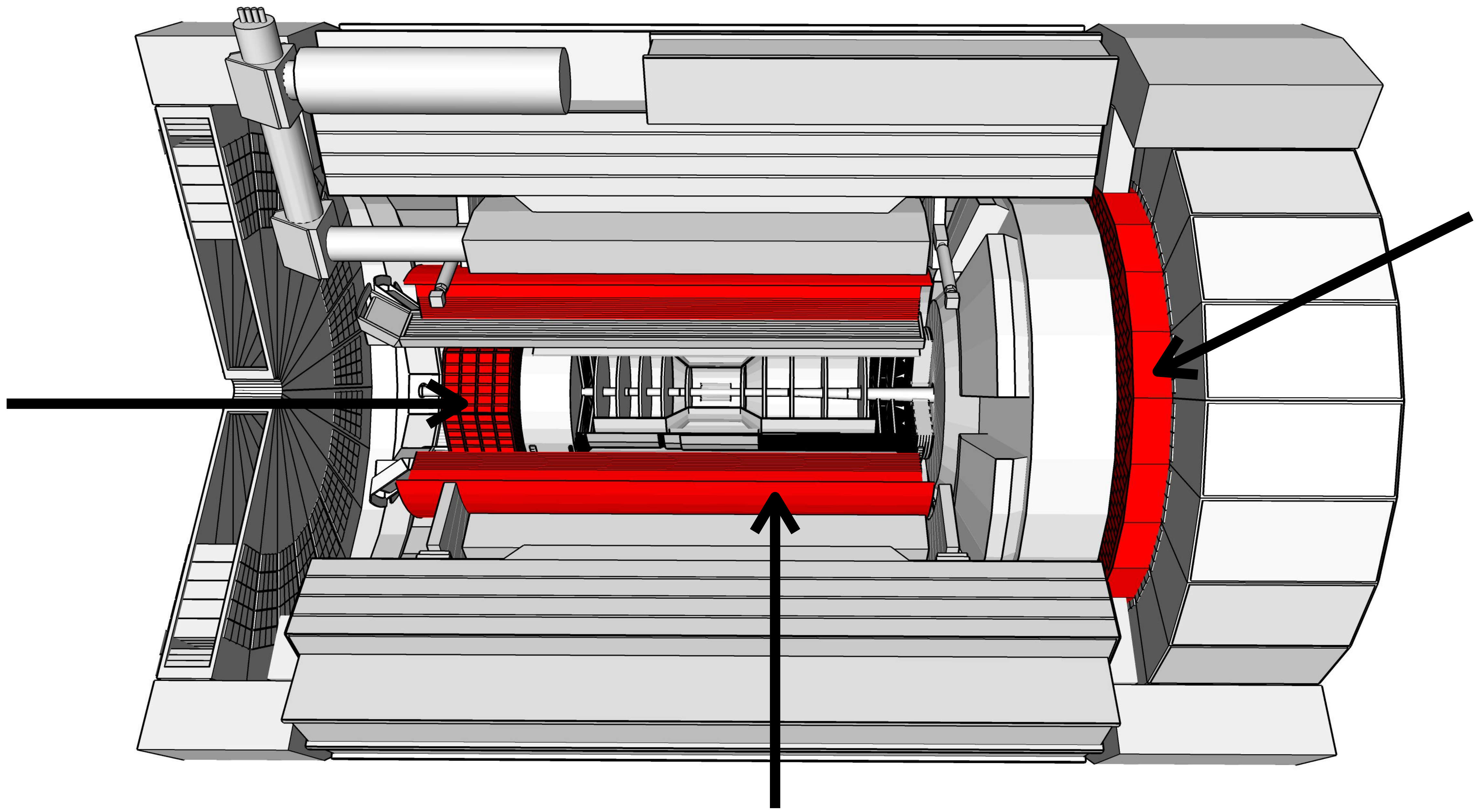
Barrel HCal:
Muon and neutral detection →improved jet energy reconstruction

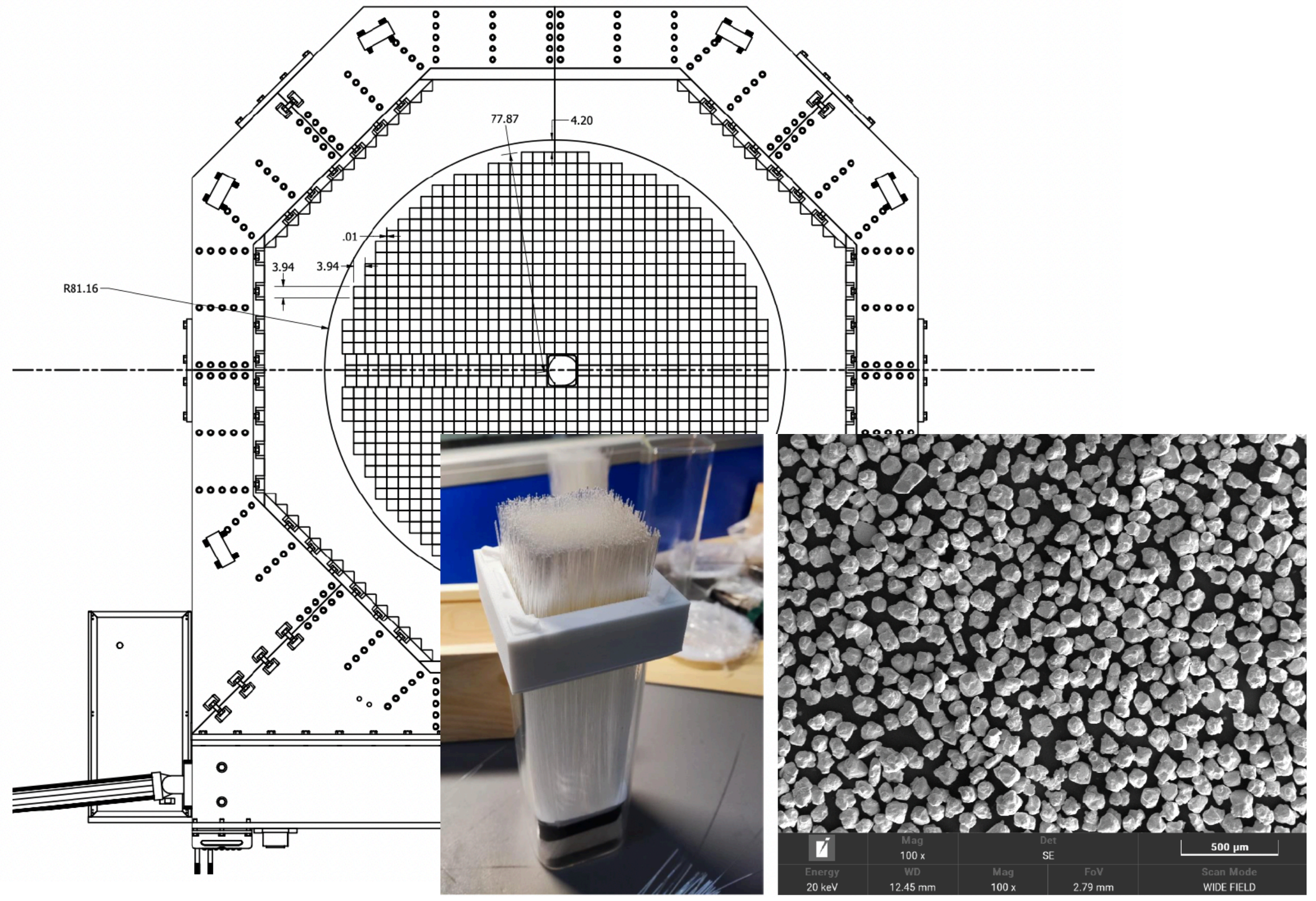
# Electromagnetic Calorimetry




## Backward Endcap EMCal

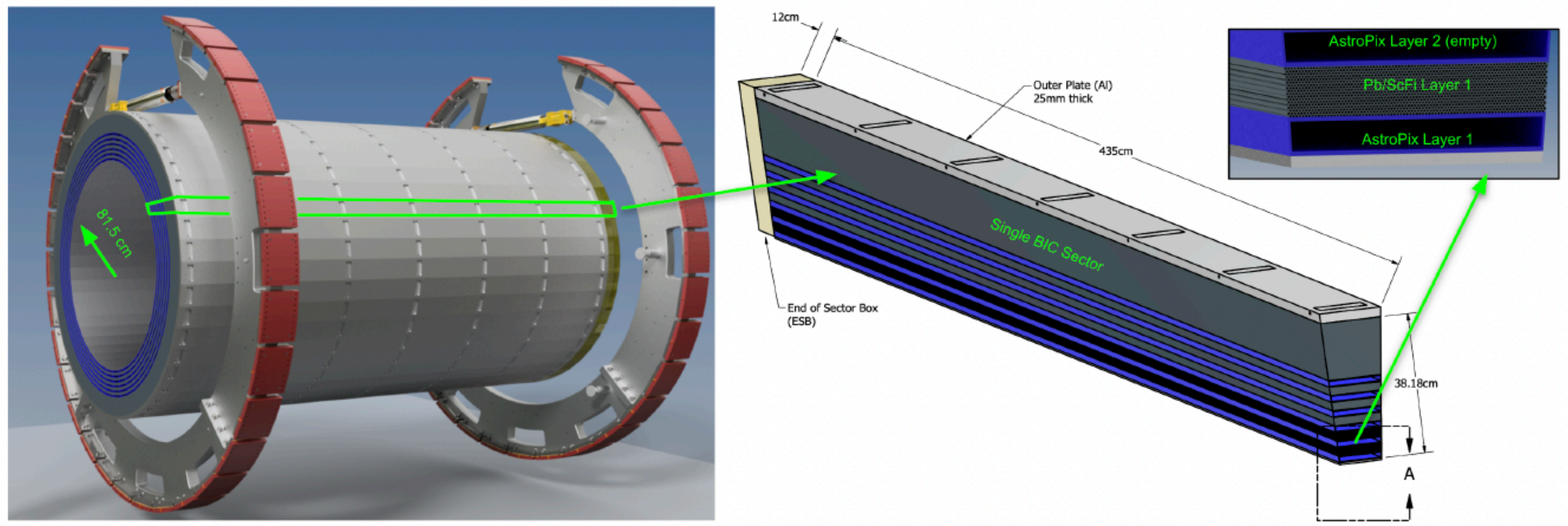
- 2 x 2 x 20 cm³ $PbWO_4$ crystals
- SiPM readout **World First**
- Depth ~20 $X_0$
- Cooling to keep temperature stable within ±0.1C°





## Forward Endcap EMCal

- High granularity W/SciFi (tungsten powder mixed with epoxy and scintillating fibres)
- 5 x 5 x 17cm blocks
- 4 independent towers per block
- SiPM readout
- Depth ~23 $X_0$

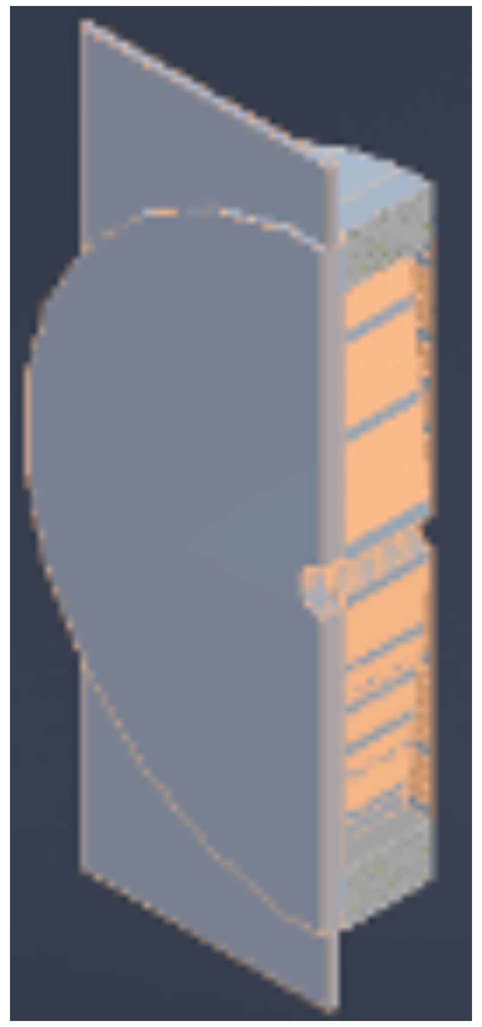



## Imaging Barrel Calorimeter **World First**

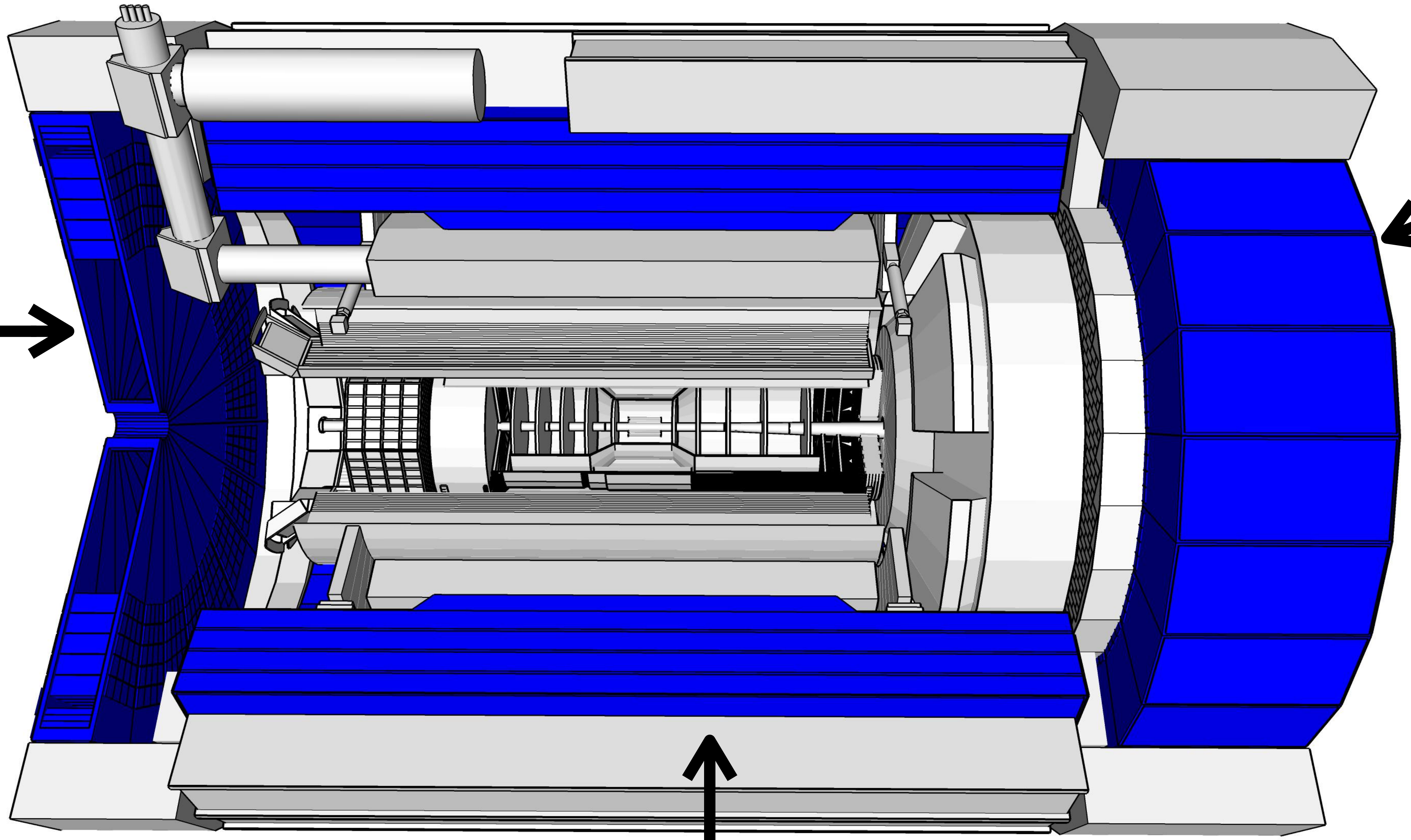
- 4(+2) layers of AstroPix MAPS sensor, 500 x 500 μm
- Interleaved with scintillating fiber/Pb layers
- Dual end SiPM readout
- Depth ~17.1 $X_0$ at $\eta$=0

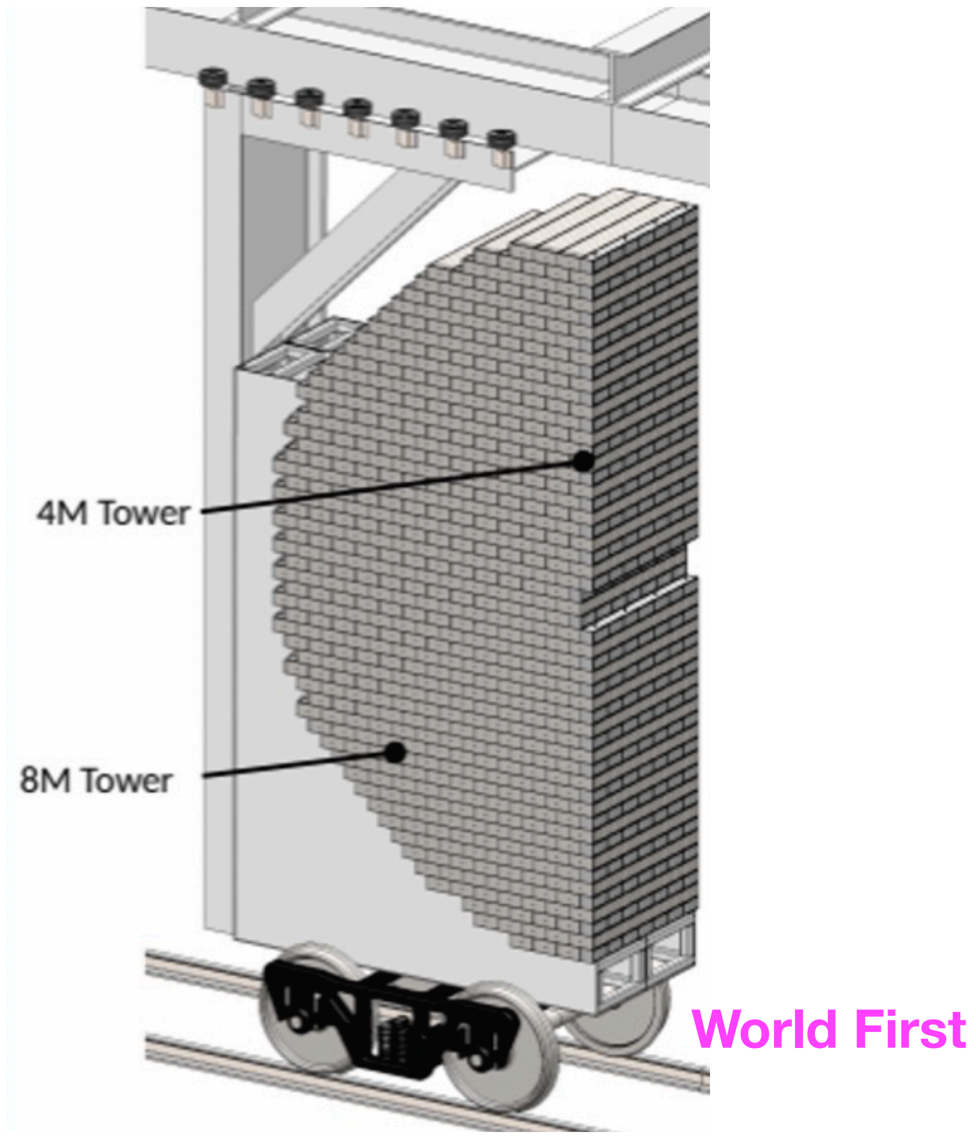
Images from ePIC pre-TDR

# Hadronic Calorimetry



**Backward Endcap HCal**
- Steel and large scintillator tiles sandwich tail catcher
- SiPM readout

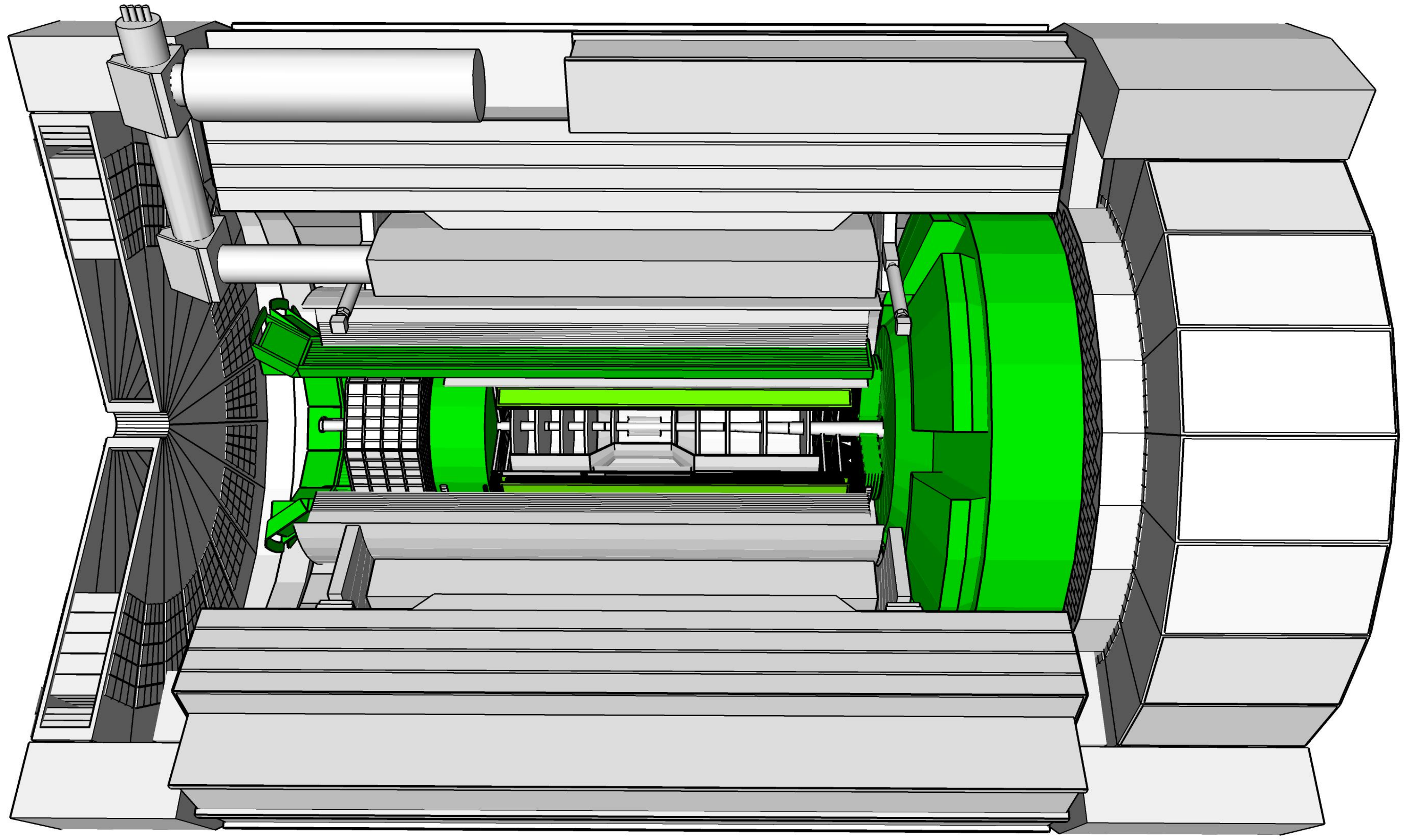





**Forward Endcap HCal**
- Longitudinally separated HCal with high-η highly segmented insert
- Steel and scintillator with SiPM on-tile
- Highly segmented longitudinally
- 65 layers per tower
- > 565k SiPMs
- Stackable for easier construction

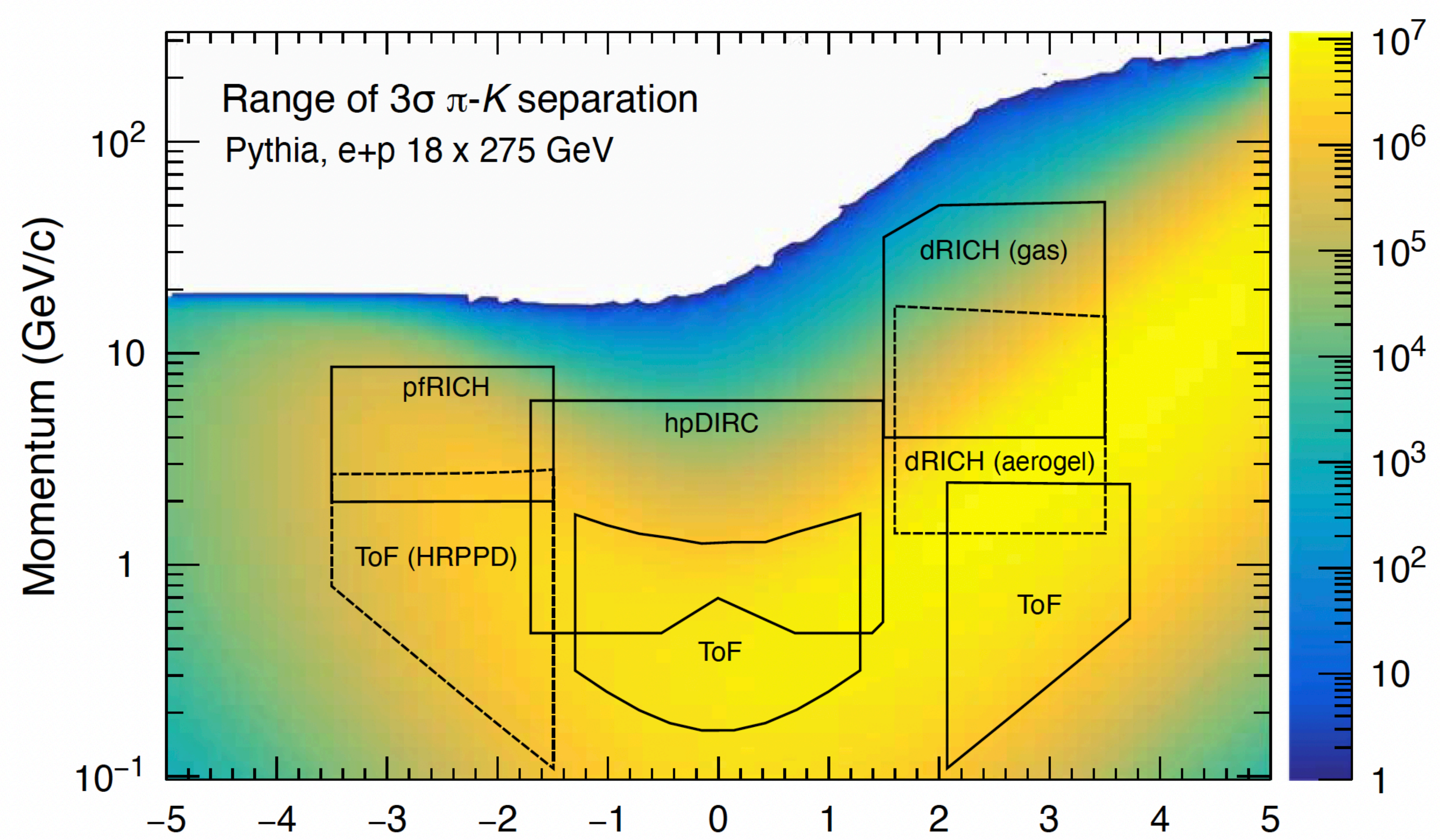
**Barrel HCal (sPHENIX re-use)**
- Tilted steel/scintillator plates with SiPM readout
- Needs refurbished for ePIC
- Minor radiation damage → replace SiPMs
- Upgrade electronics (to HGCROC)
- Read out each tile individually

# Particle Identification



*General separation requirements:*
- Electrons from photons →4π coverage in tracking
- Electrons from charged hadrons → mostly provided by calorimetry and tracking, with PID detectors for low p
- Charged π/K/p on track level → Cherenkov detectors
- Cherenkov detectors complimented by other technologies, dE/dx or TOF, at low momenta

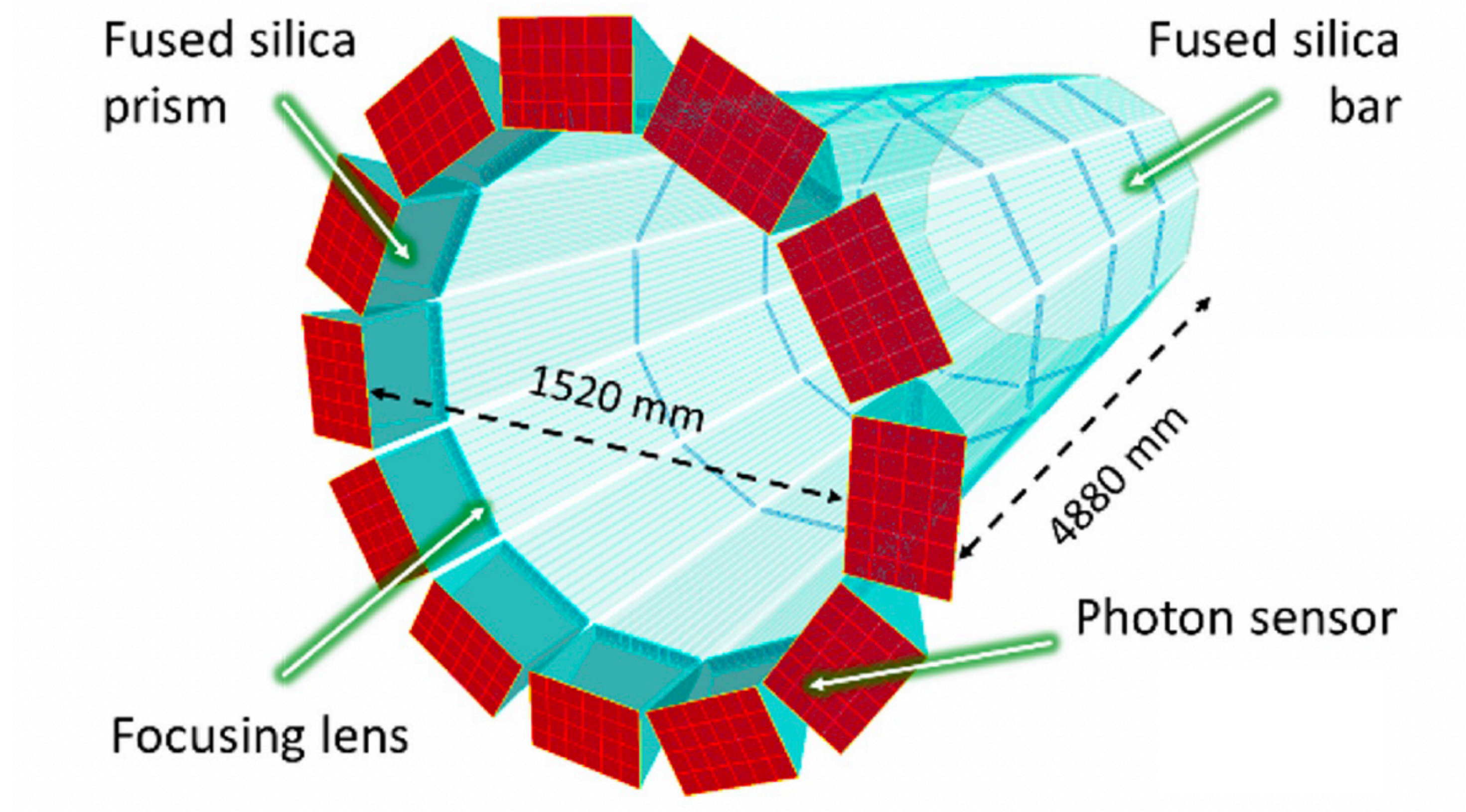
- Demands on PID are unique to EIC
  - Unprecedented coverage over wide range of momenta and η
  - Combination of technologies needed




Example from ePIC preTDR

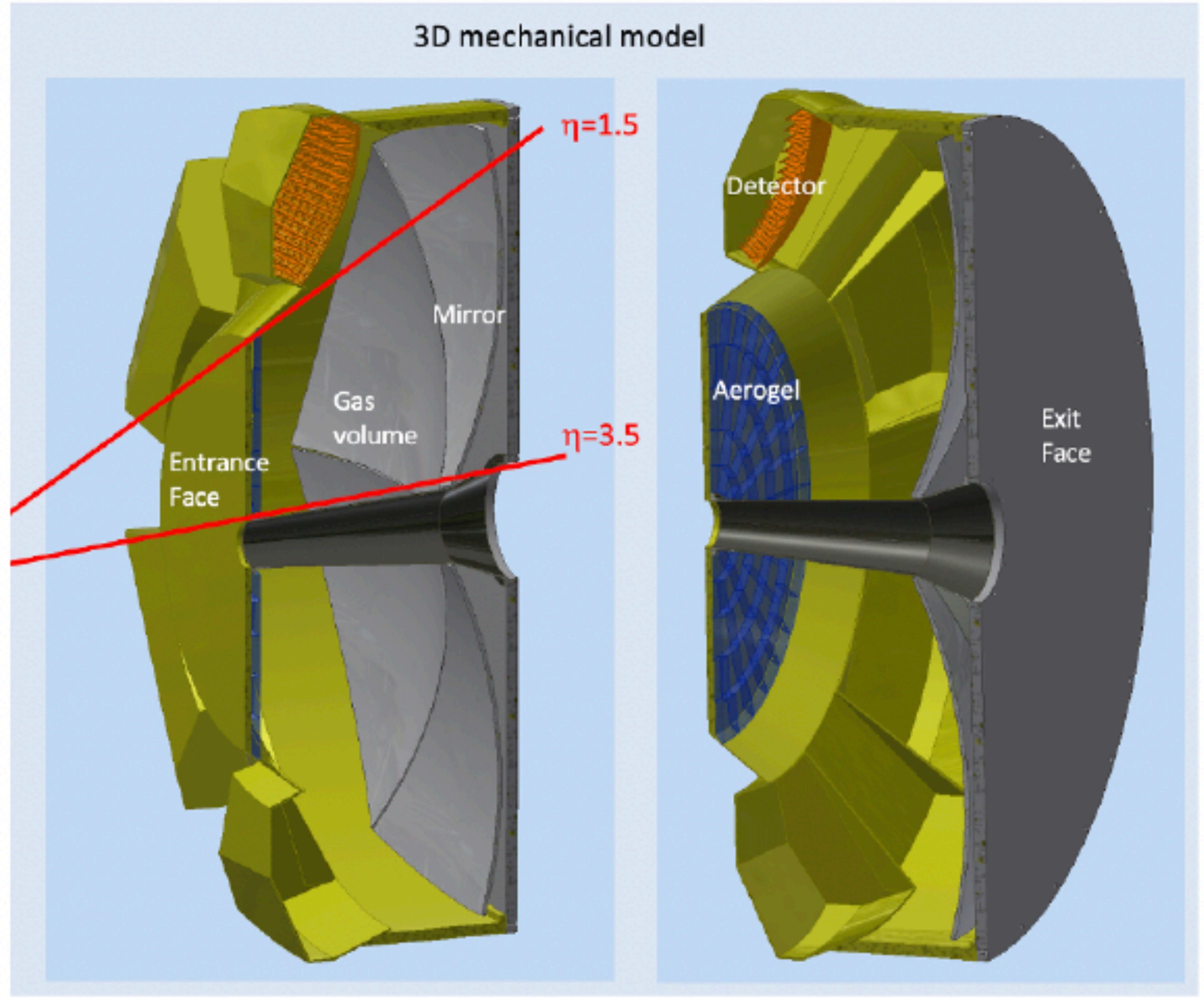
| η | π/K/p and $\pi^0/\gamma$ | e/h | Min $p_T$ (E) |
|---|---|---|---|
| **-3.5 - ~1.0** | 7 GeV/c | 18 GeV/c | 100 MeV/c |
| **-1.0 - 1.0** | 8 - 10 GeV/c | 8 GeV/c | 100 MeV/c |
| **1.0 - 3.5** | 50 GeV/c | 20 GeV/c | 100 MeV/c |

# Particle Identification



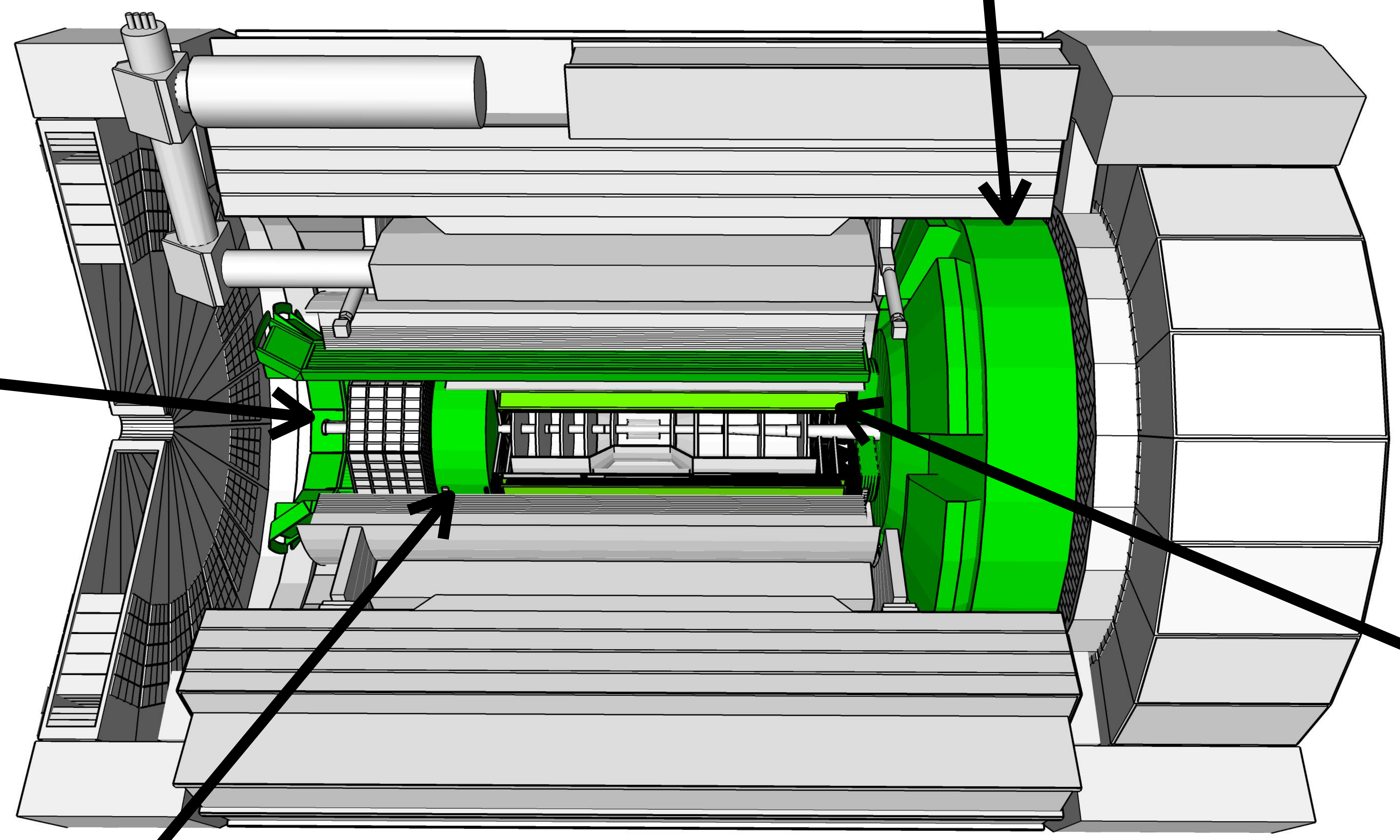

## Dual Radiator RICH (dRICH)

- C2F6 gas volume and aerogel
- SiPM with cooling and annealing — World First
- π/K separation at 3σ up to 50 GeV/c



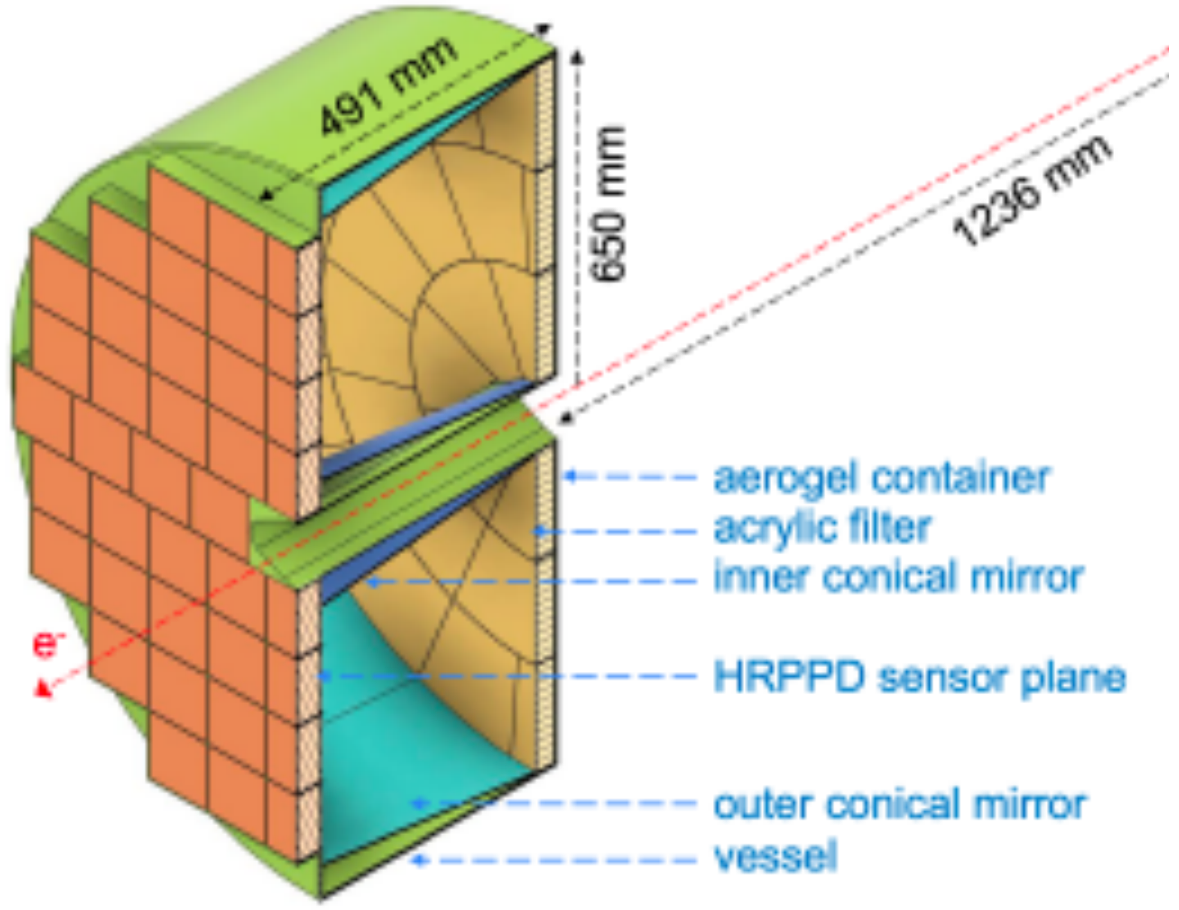

## High-performance DIRC (hpDIRC)

- Quartz radiator bars (reuse BaBar)
- Focussing optics
- MCP PMT photosensors (or HRPPD in future)
- π/K separation at 3σ up to 6 GeV/c



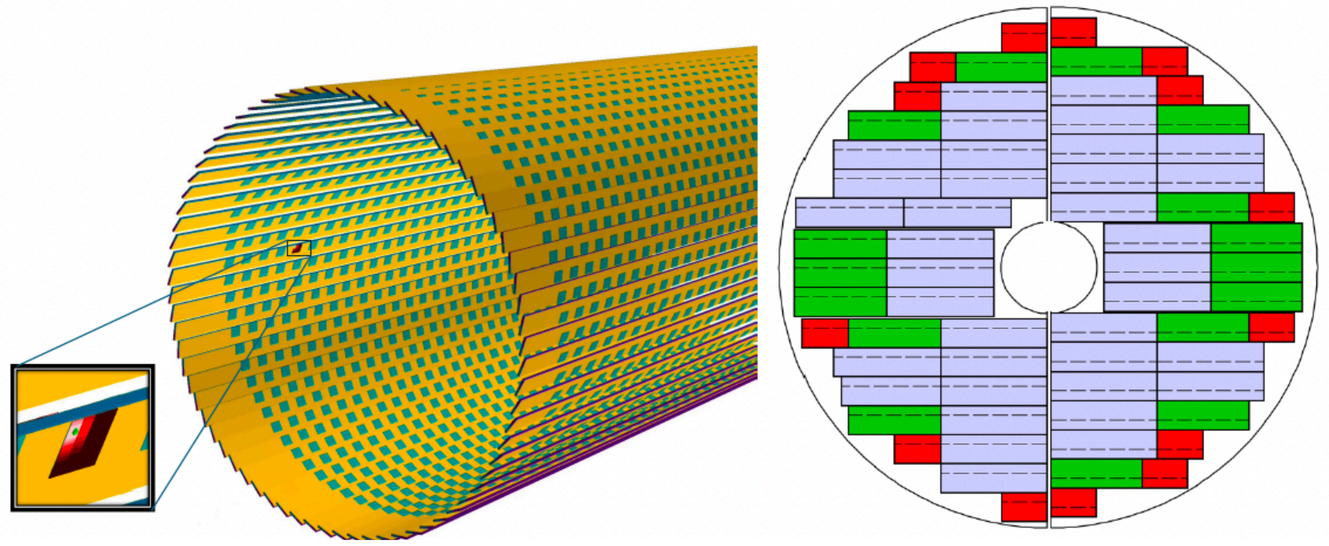
## AC-LGAD based TOF

- Resolution ~30ps — World First
- Space point for tracking 30μm
- Forward disc and barrel geometries
- Assists in PID at low momenta




## Proximity Focused RICH (pfRICH)

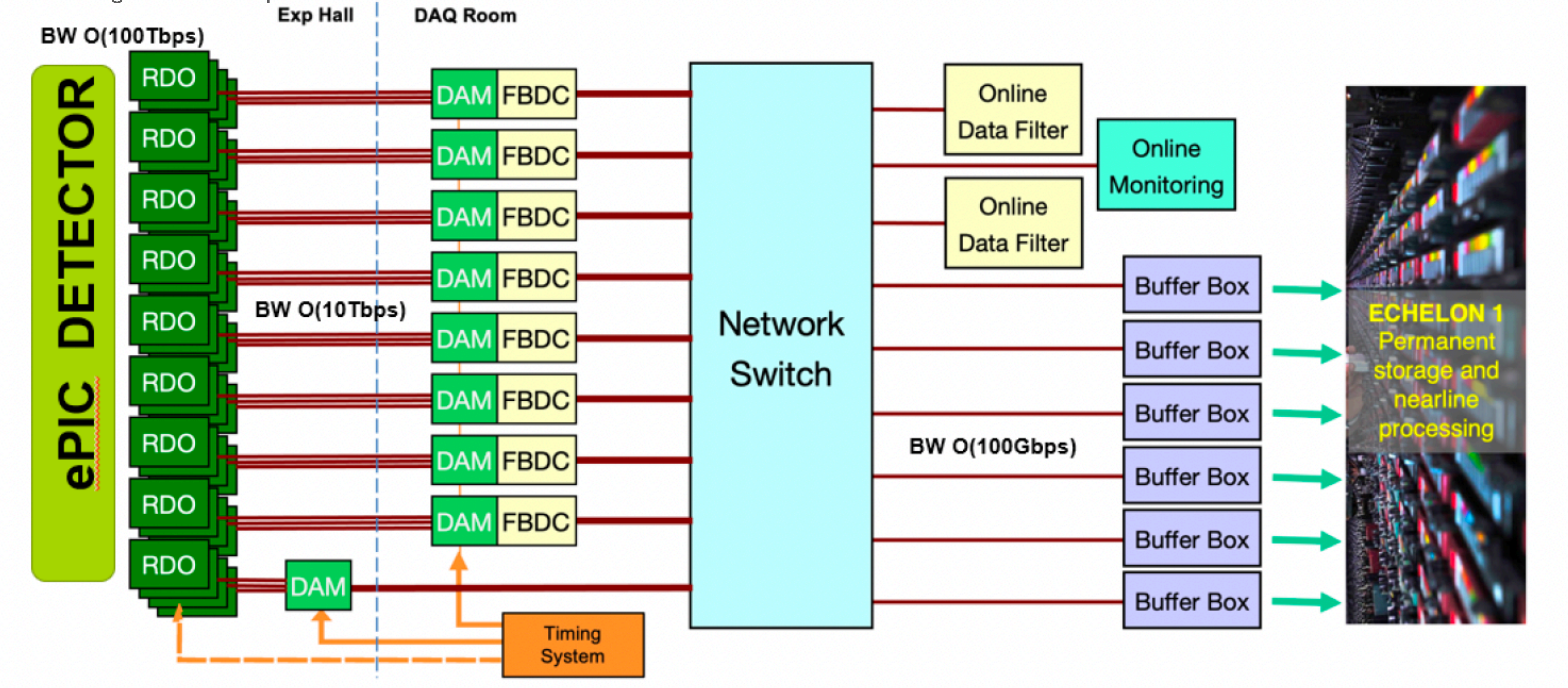
- Proximity gap >40cm
- HRPPD photosensors (also provides reference time for TOF and ePIC barrel start time, ~20ps) — World First
- π/K separation at 3σ up to 10 GeV/c
- e/π separation at 3σ up to 2.5 GeV/c



Images from ePIC pre-TDR

# Streaming Readout

Image from ePIC pre-TDR

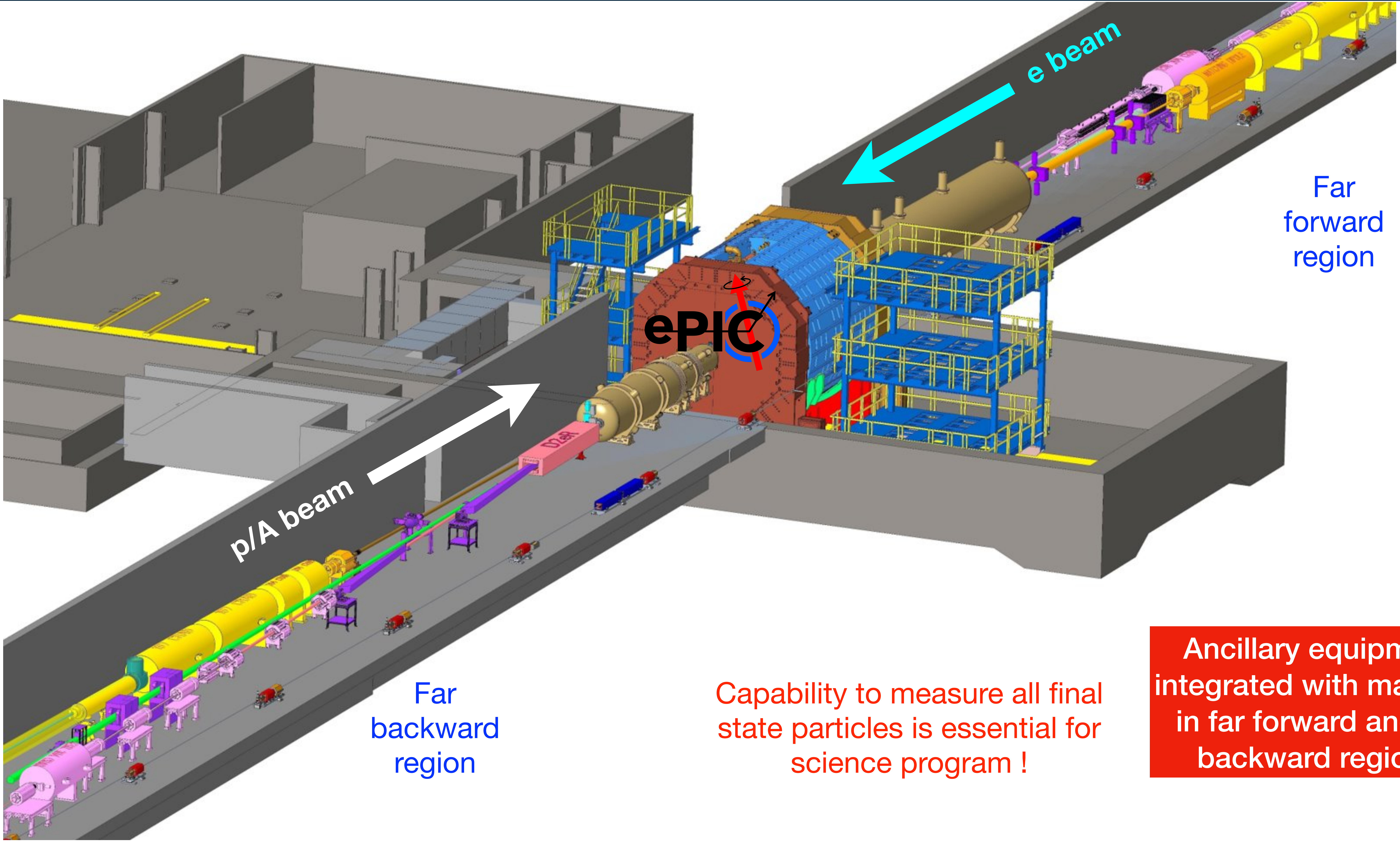



GTU/Distributed clock (jitter ~5ps)

At full luminosity ~0.5MHz interaction rate

- Triggerless streaming architecture → more flexibility for physics
- Avoids complex custom hardware and firmware triggers
- Event selection can be based upon full data from all detectors (in real time or later)
- All collision data digitised and aggressively zero suppressed at front end
- Benefits from low multiplicity/low occupancy, even in eA
- Low/zero dead time
- Collision data flow independent and unidirectional
  - No global latency requirements
- Data volume reduced as much as possible at each stage

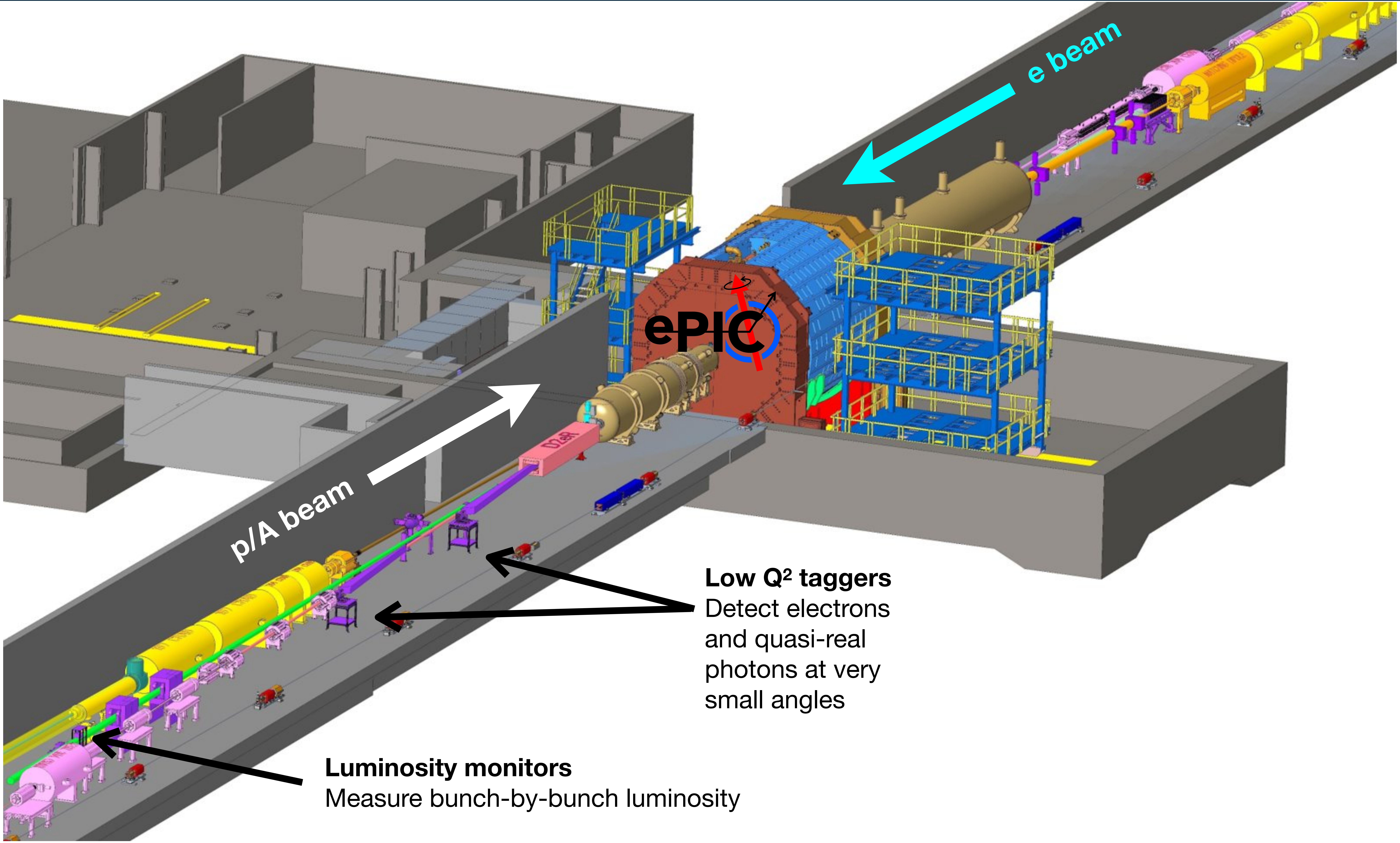
# And More!




Capability to measure all final state particles is essential for science program !

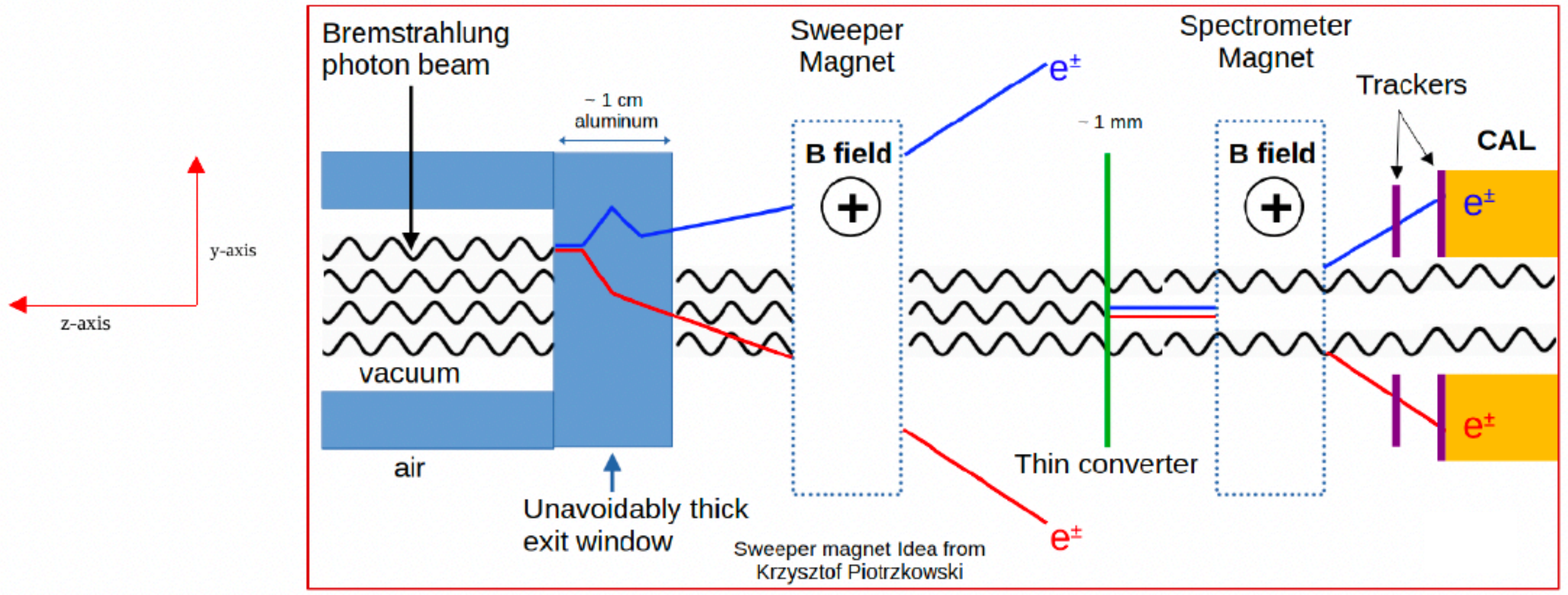
Ancillary equipment integrated with machine in far forward and far backward regions

# Far Backward system

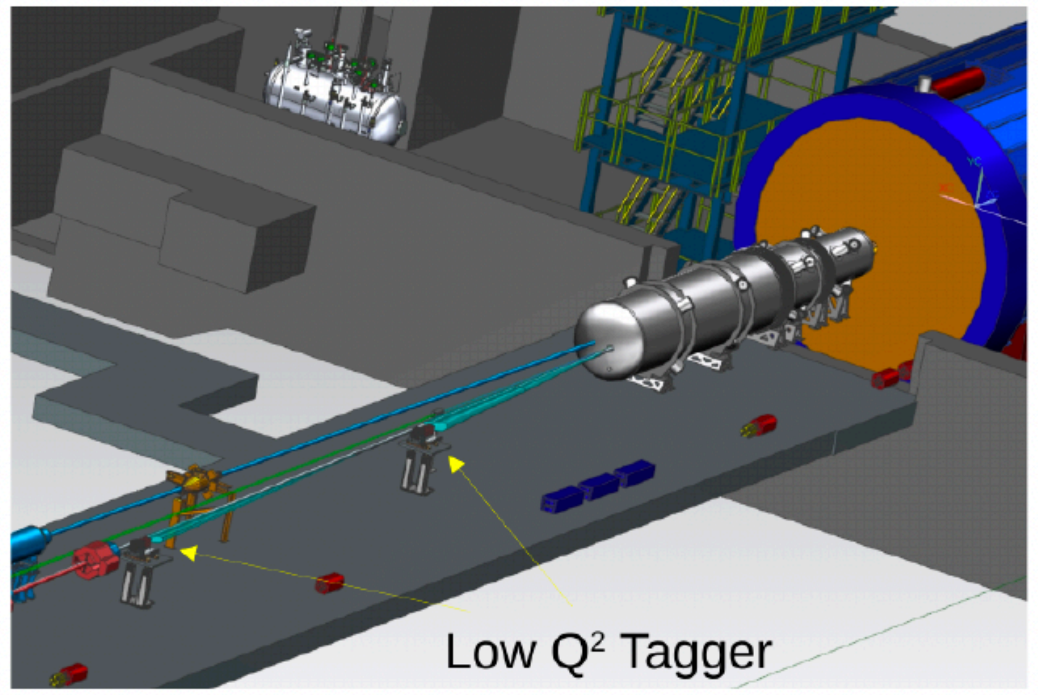


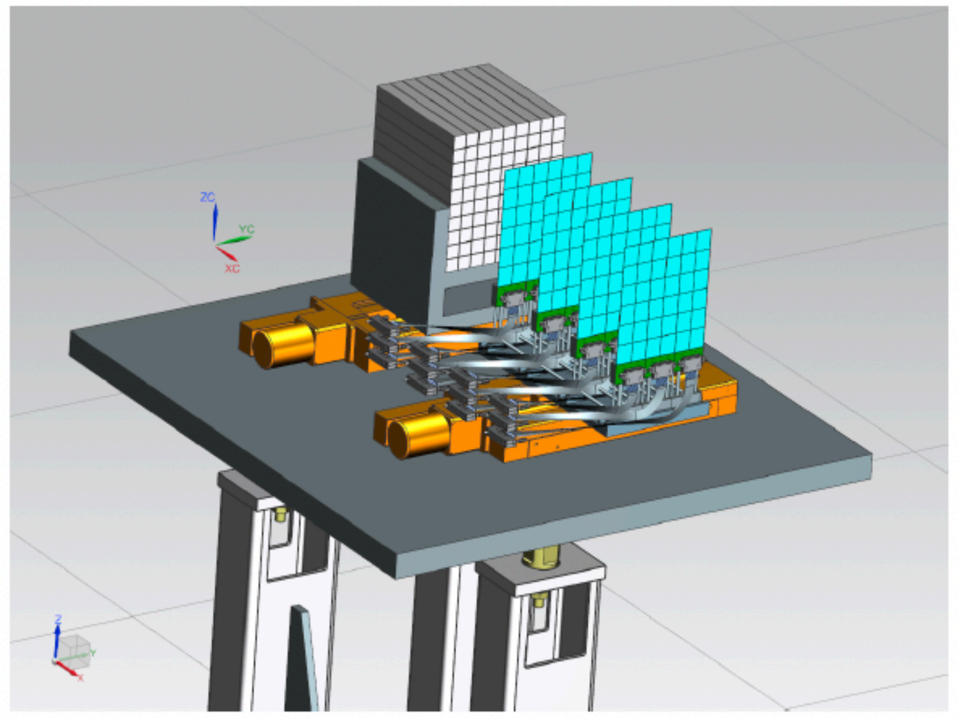

**Low $Q^2$ taggers**
Detect electrons and quasi-real photons at very small angles

**Luminosity monitors**
Measure bunch-by-bunch luminosity



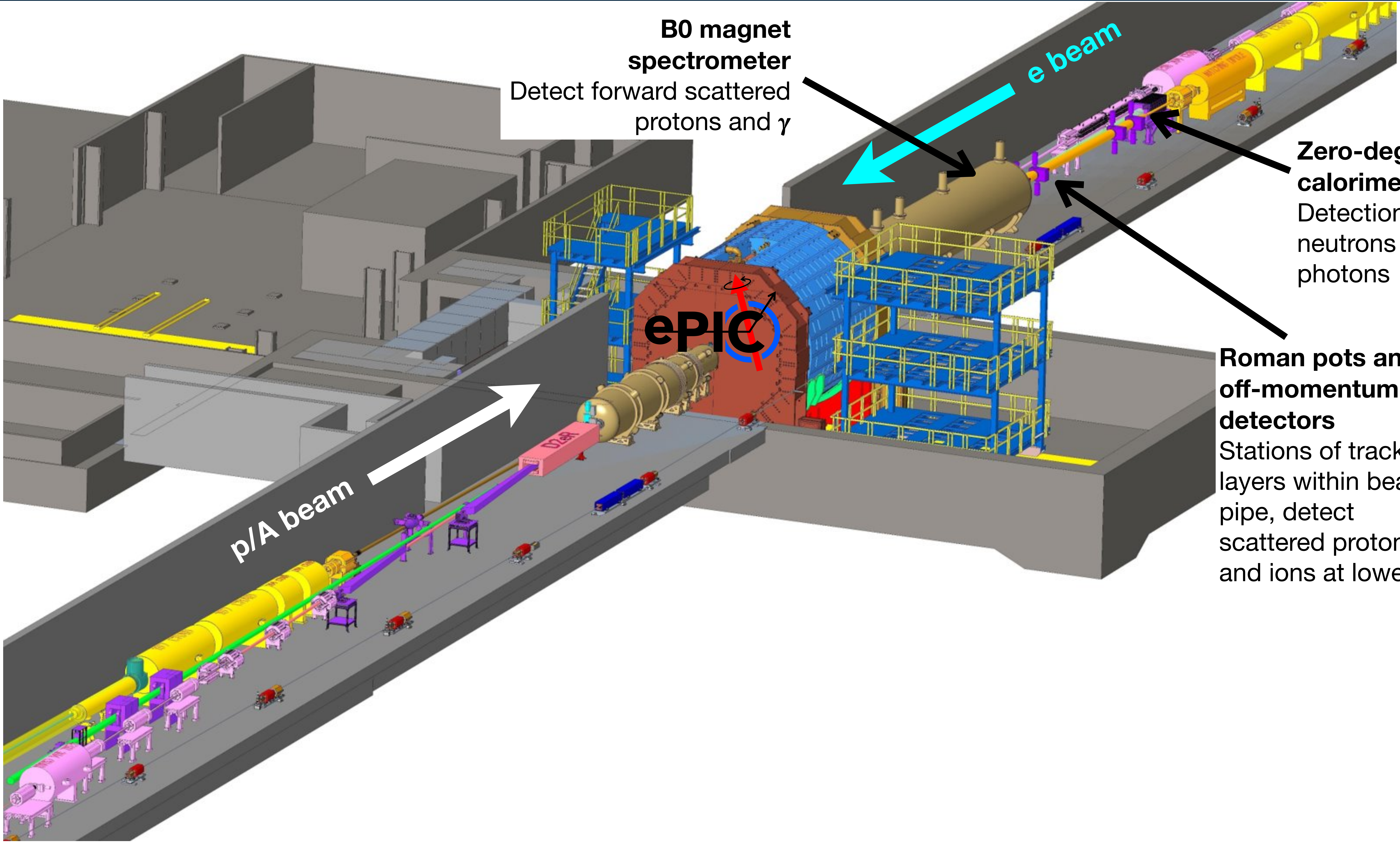

- Bunch by bunch luminosity monitoring required for physics normalisations
  - Absolute $\delta L/L <\sim 1\%$
  - Relative up to $10^{-4}$ - $10^{-5}$
- Direct photon detector (c.f. HERA)
  - Downstream of Bremsstrahlung photon beam
  - Also in acceptance of synchrotron radiation
- Pair spectrometer
  - Converts Bremsstrahlung $\gamma$ to $e^+e^-$
  - Out of way of synchrotron radiation
  - AC-LGAD and scintillating fibre 23 X0 ECal



- Low Q2 electron tagging
  - Can verify luminosity measurements
  - Extends physics kinematic range for electrons or quasi real photons ($Q^2$<<1) at very small angles
  - 2 stations with 4 pixel-based Timepix4 ASIC silicon tracking layers (each 16 cm x 18cm)
  - Rate capability >10 tracks per bunch

# Far Forward system

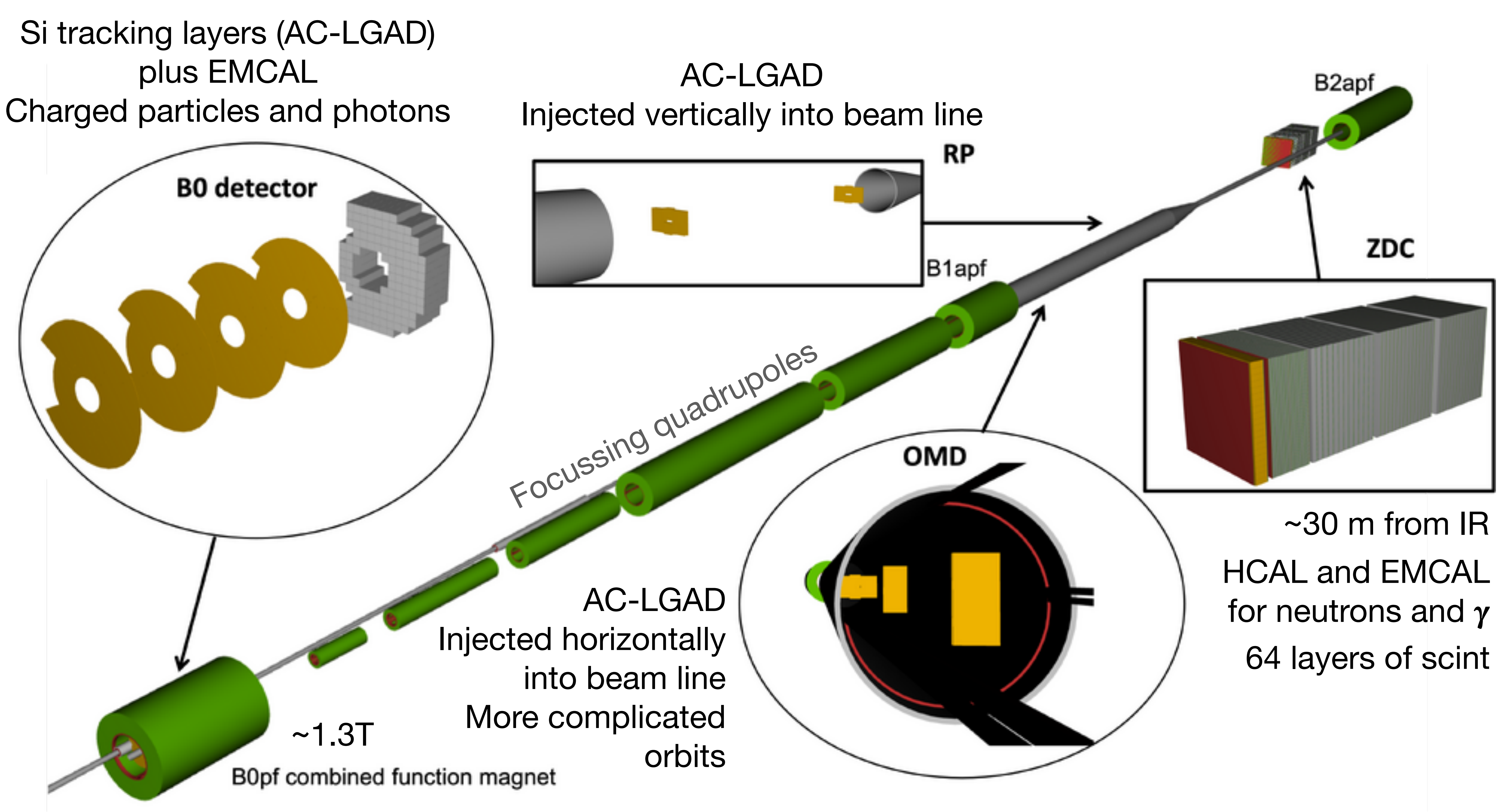



**B0 magnet spectrometer**
Detect forward scattered protons and $\gamma$

**Zero-degree calorimeter**
Detection of neutrons and photons

**Roman pots and off-momentum detectors**
Stations of tracking layers within beam-pipe, detect scattered protons and ions at lowest t

# Far Forward




| Detector | Acceptance |
|---|---|
| Zero-degree calorimeter (ZDC) | θ < 5.5 mrad (η > 6 ) |
| Roman pots (RP) (2 stations) | 0.0 < θ < 5.0 mrad (η > 6 ) |
| Off-Momentum Detectors (OMD) (2 | 0.0 < θ < 5.0 mrad (η > 6 ) |
| B0 | 5.5 < θ < 20.0 mrad (4.6 < η < 5.9 ) |

- Tagging at very small scattering angles η>4.5
- Charged hadrons or neutrals particles, as well as nuclei with different magnetic rigidity from beam
- Variety of final states
- Wide range of beam/particle/ion energies

- **B0:** charged particles and photons
- **Off-momentum detectors:** charged spectators from light nuclei breakup
- **Roman pots:** charged particles near beam
- **Zero-degree calorimeter:** neutral particles at small angles

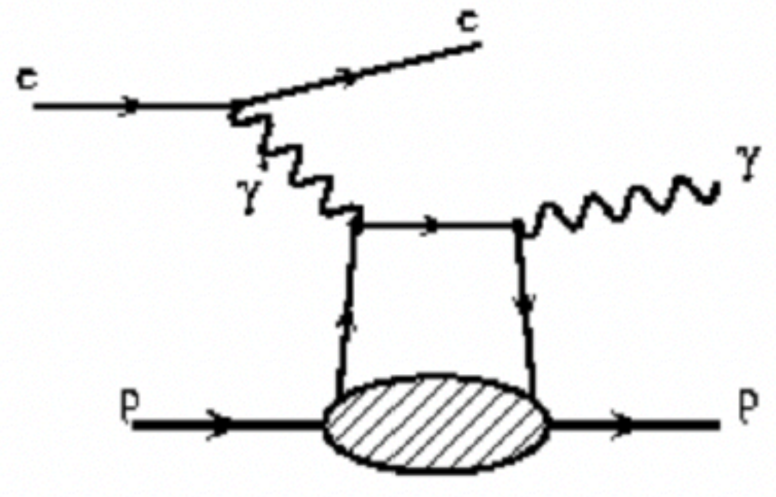
- Essential for exclusive physics program
  - e.g. tagging; nuclear breakup/incoherent vetoing; -t reconstruction and reaching to very low -t values…

# Exclusive, Diffractive, Tagging Topics

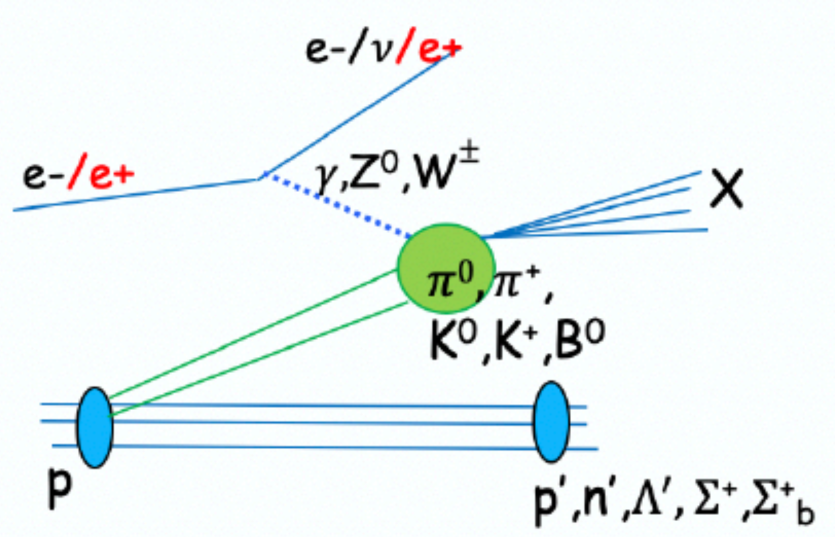
*Far Forward/Far Backward regions are crucial for realising the exclusive/diffractive/tagging program of the EIC*

Imaging, spin, orbital angular momentum

e+p DVCS



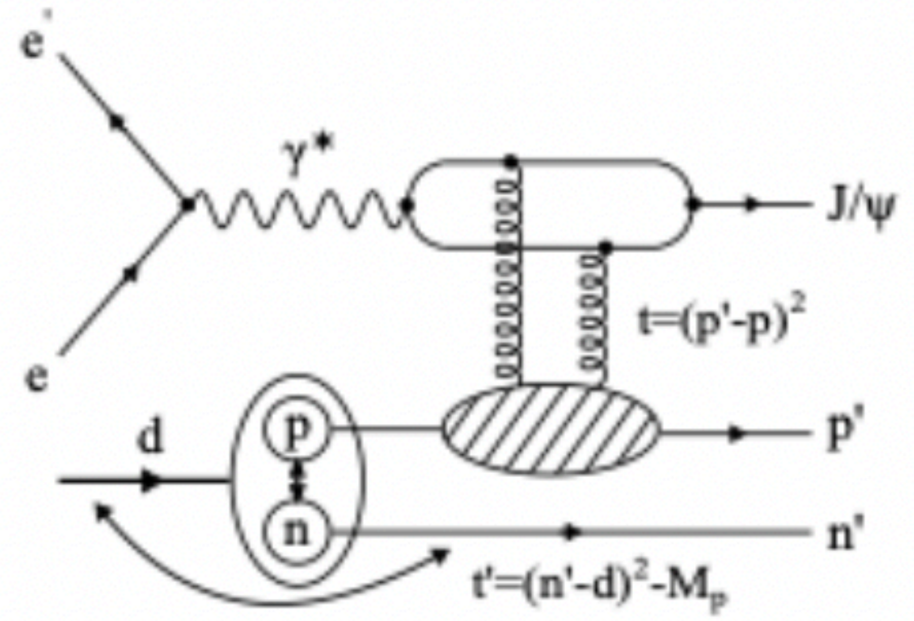

Meson structure:
- ➢ ep→ ($\pi$) →e' n X
- ➢ $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$



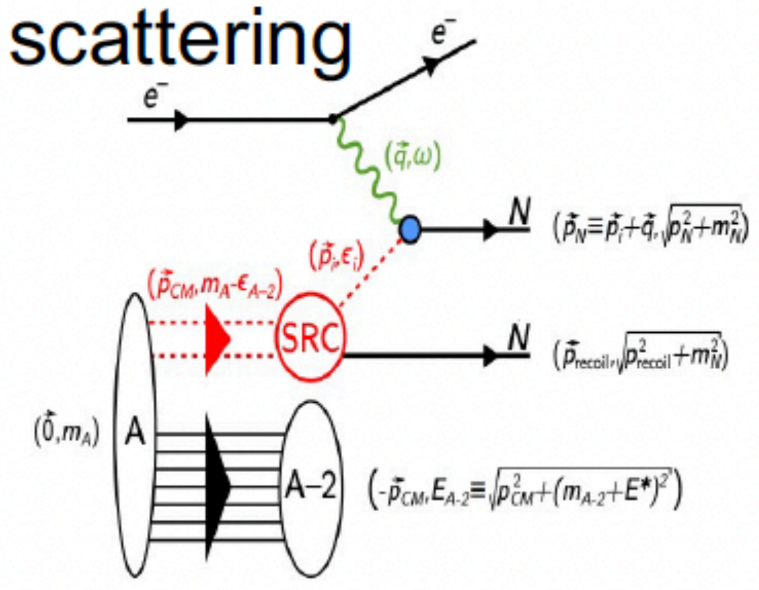

Emergent Hadronic Mass

Short-range correlations

e+d exclusive J/Psi with p/n tagging



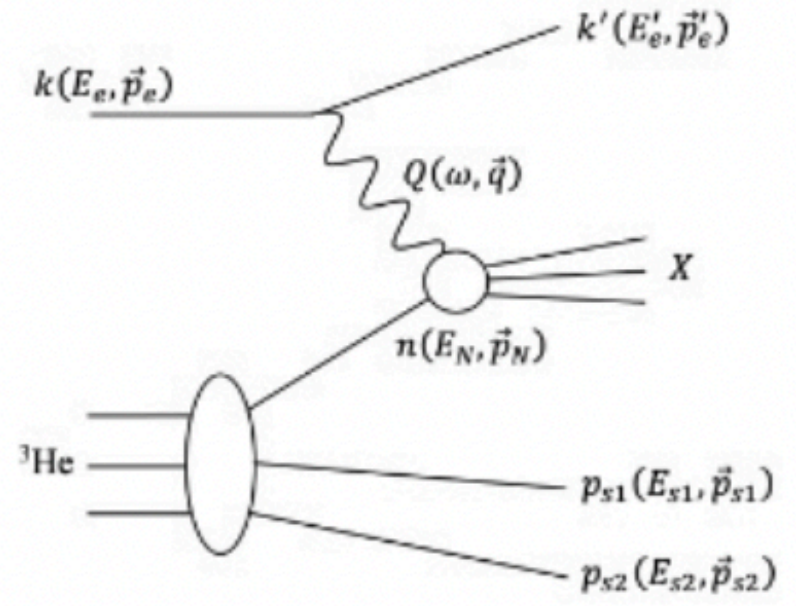

Quasi-elastic electron scattering



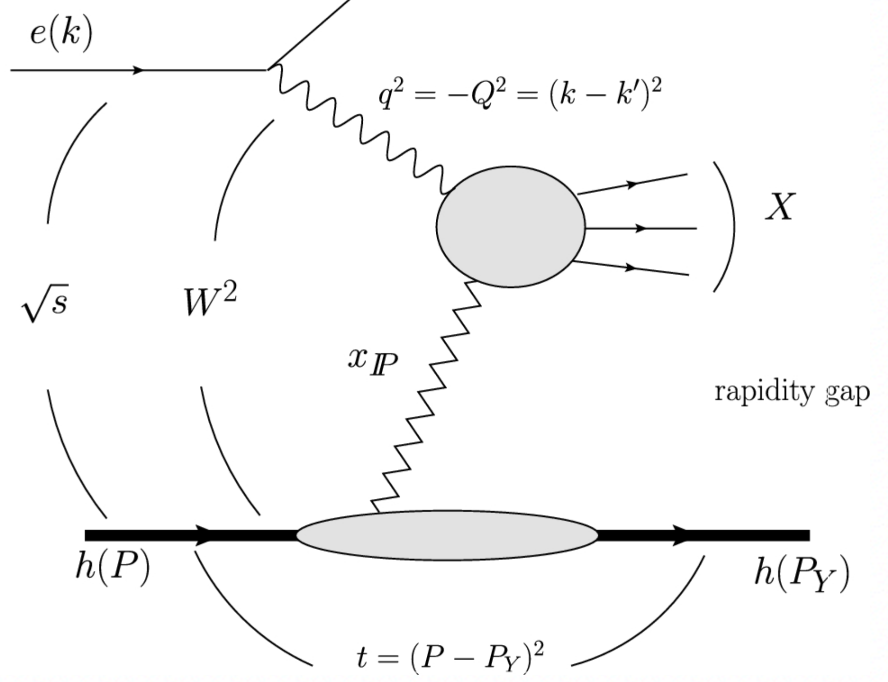

Short-range correlations

Neutron Spin Structure

e+He3 spectator tagging



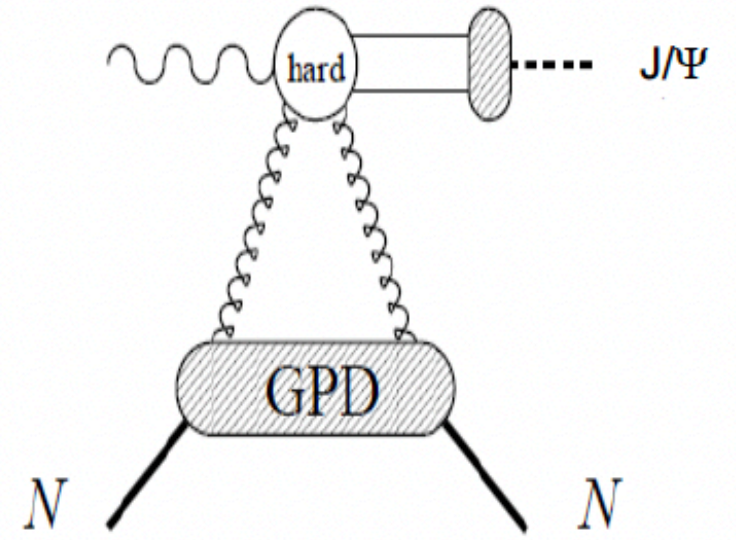

Diffraction



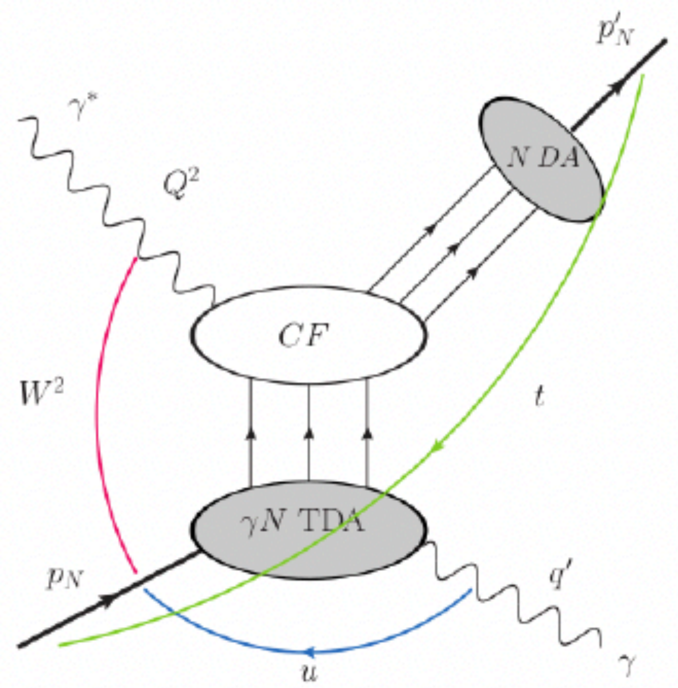

Saturation
Nucleon/nuclei structure

Gluon Saturation

coherent/incoherent $J/\psi$ production in e+A




u-channel backward exclusive electroproduction




Baryon transport in small systems

Capability to measure numerous reactions offers access to many physics topics!

And many more…!

# Exclusive, Diffractive, Tagging Topics

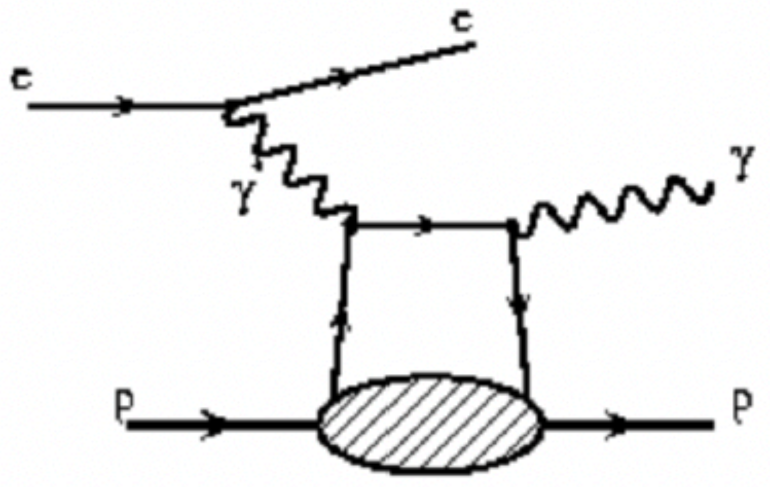
Imaging, spin, orbital angular momentum

Short-range correlations

Neutron Spin Structure

Gluon Saturation

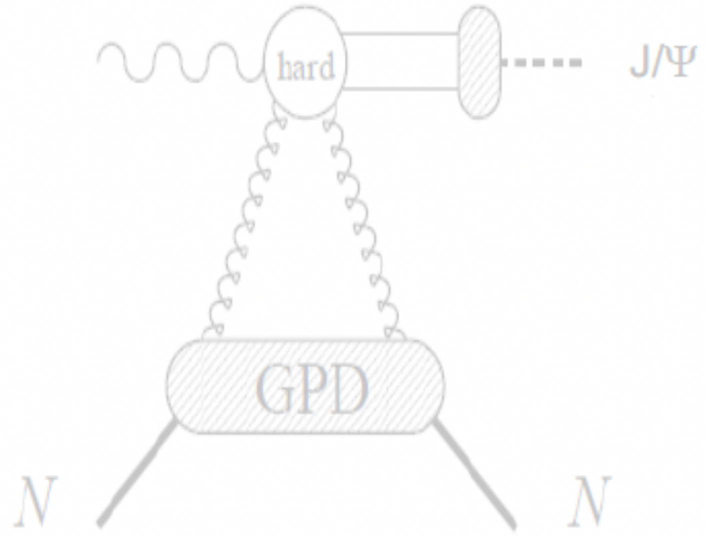
e+p DVCS



e+d exclusive J/Psi with p/n taggi

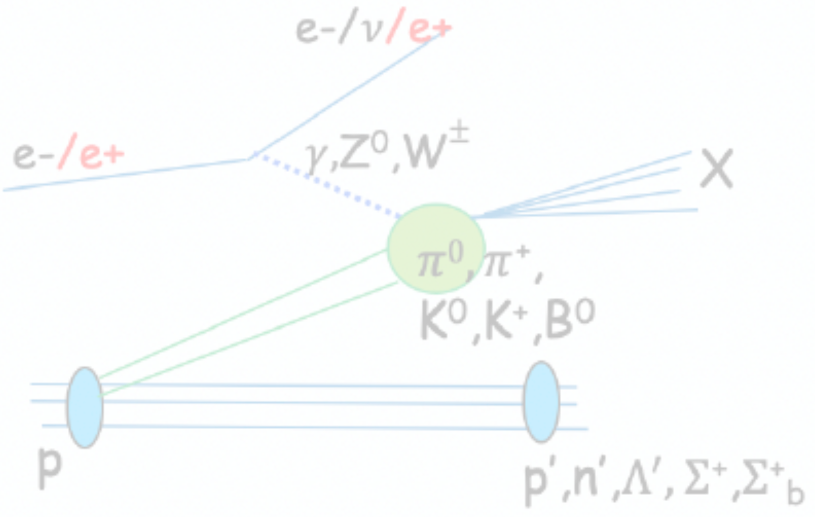
e+He3 spectator tagging

coherent/incoherent $J/\psi$ production in e+A

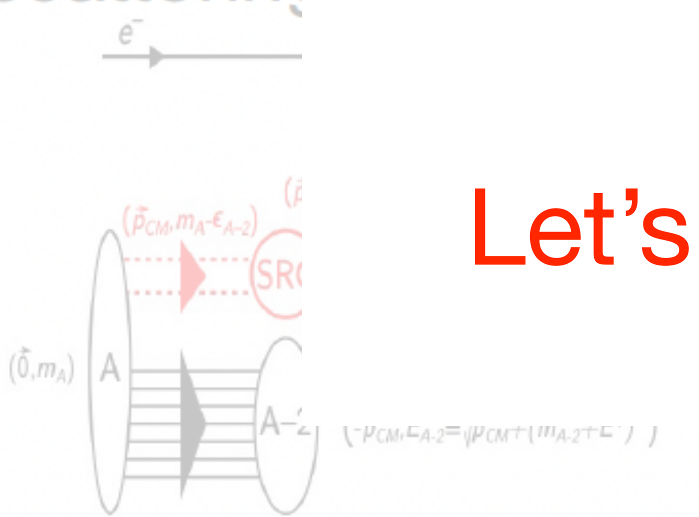



Meson structure:

- ep→ ($\pi$) →e' n X
- $\Lambda \to p\pi^-$ and $\Lambda \to n\pi^0$



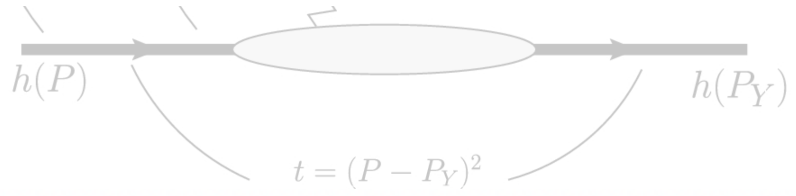

Quasi-ela scattering



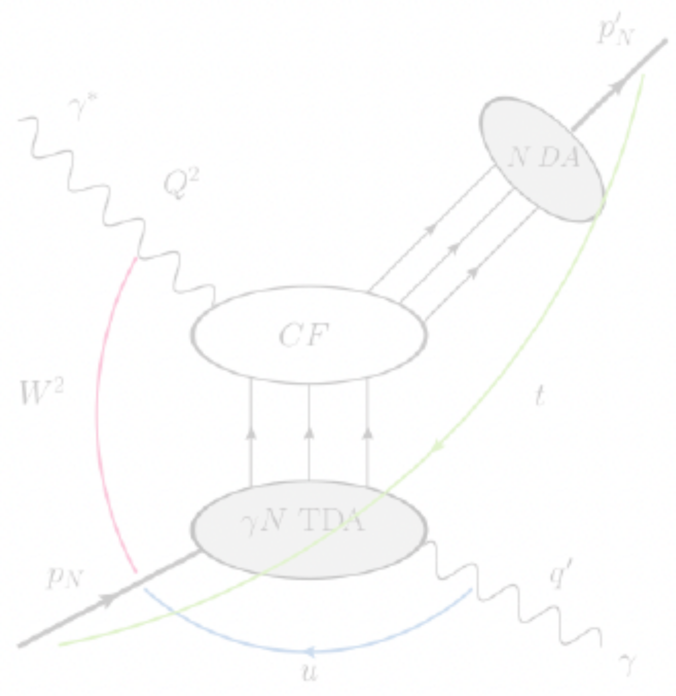
Numerous studies into several of these reactions are on-going by ePIC collaborators within the EDT physics working group

Studies use full Geant4 simulation of ePIC and aim to benchmark physics capabilities

Let's look at a couple of current examples



hannel backward lusive electroproduction



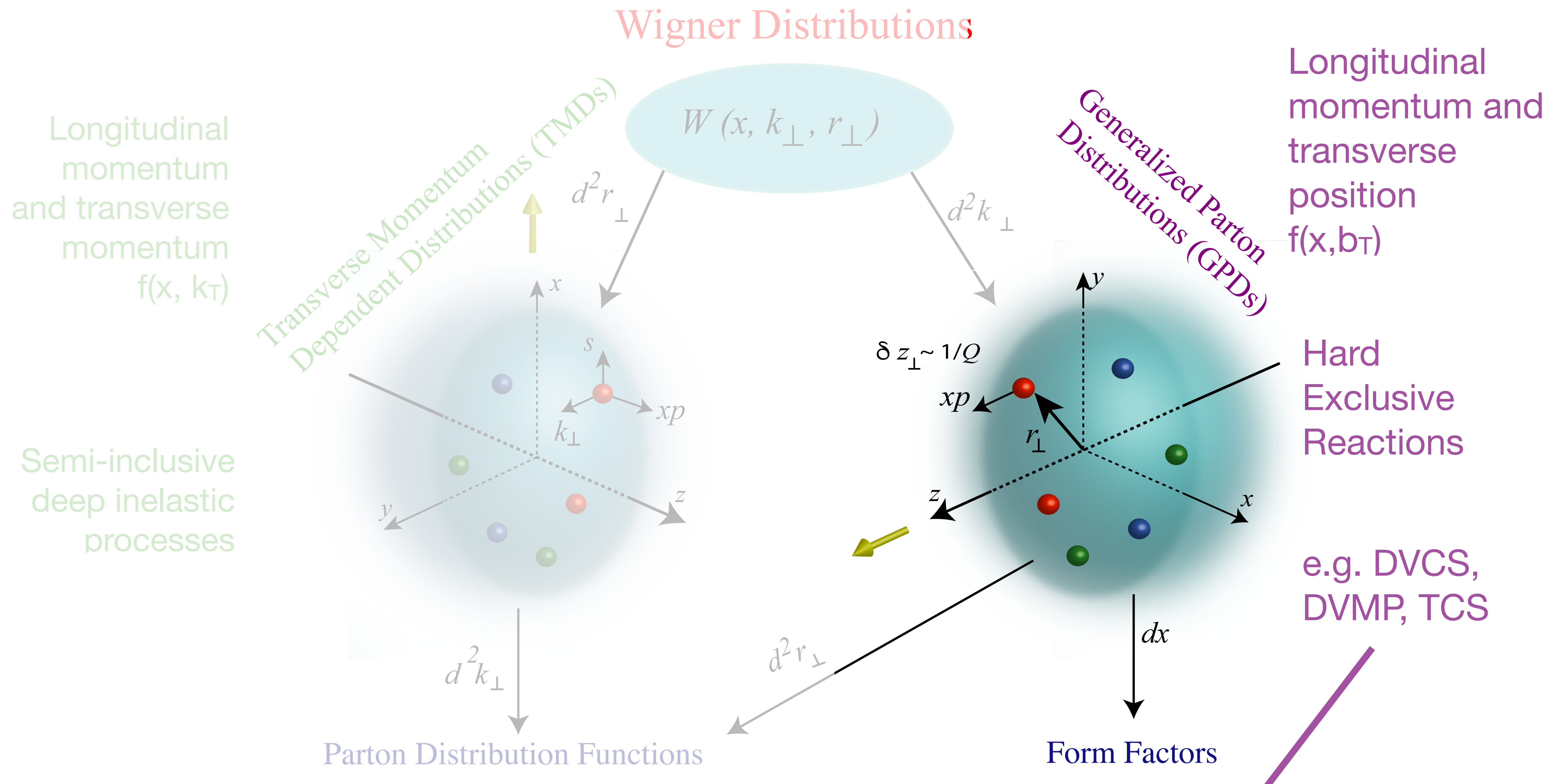
Emergent Hadronic Mass

Short-range correlations

Saturation Nucleon/nuclei structure

Baryon transport in small systems

# Deeply Virtual Compton Scattering (DVCS)



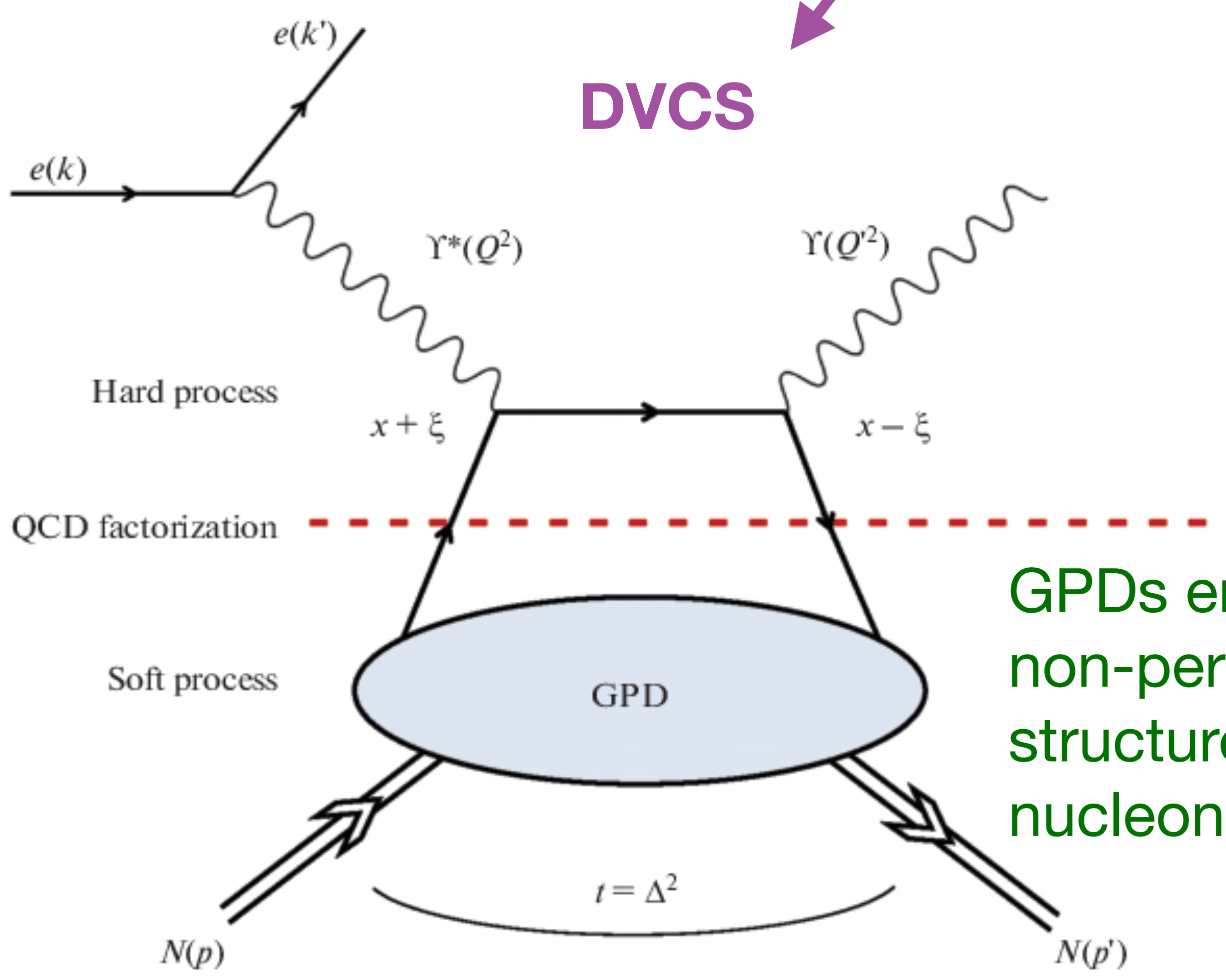

DVCS

$Q^2 = -(\mathbf{k} - \mathbf{k}')^2 \quad t = (\mathbf{p}'_\mathbf{n} - \mathbf{p}_\mathbf{n})^2$

Bjorken variable $\quad x_B = \dfrac{Q^2}{2\mathbf{p}_\mathbf{n} \cdot \mathbf{q}}$

Longitudinal momentum fractions of struck parton $\quad x \pm \xi$

Skewness $\quad \xi = \dfrac{x_B}{2 - x_B}$




GPDs encode non-perturbative structure of nucleon

| 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 1/2 hadron: **4 chiral-even** ($H$, $E$ and their polarised-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**

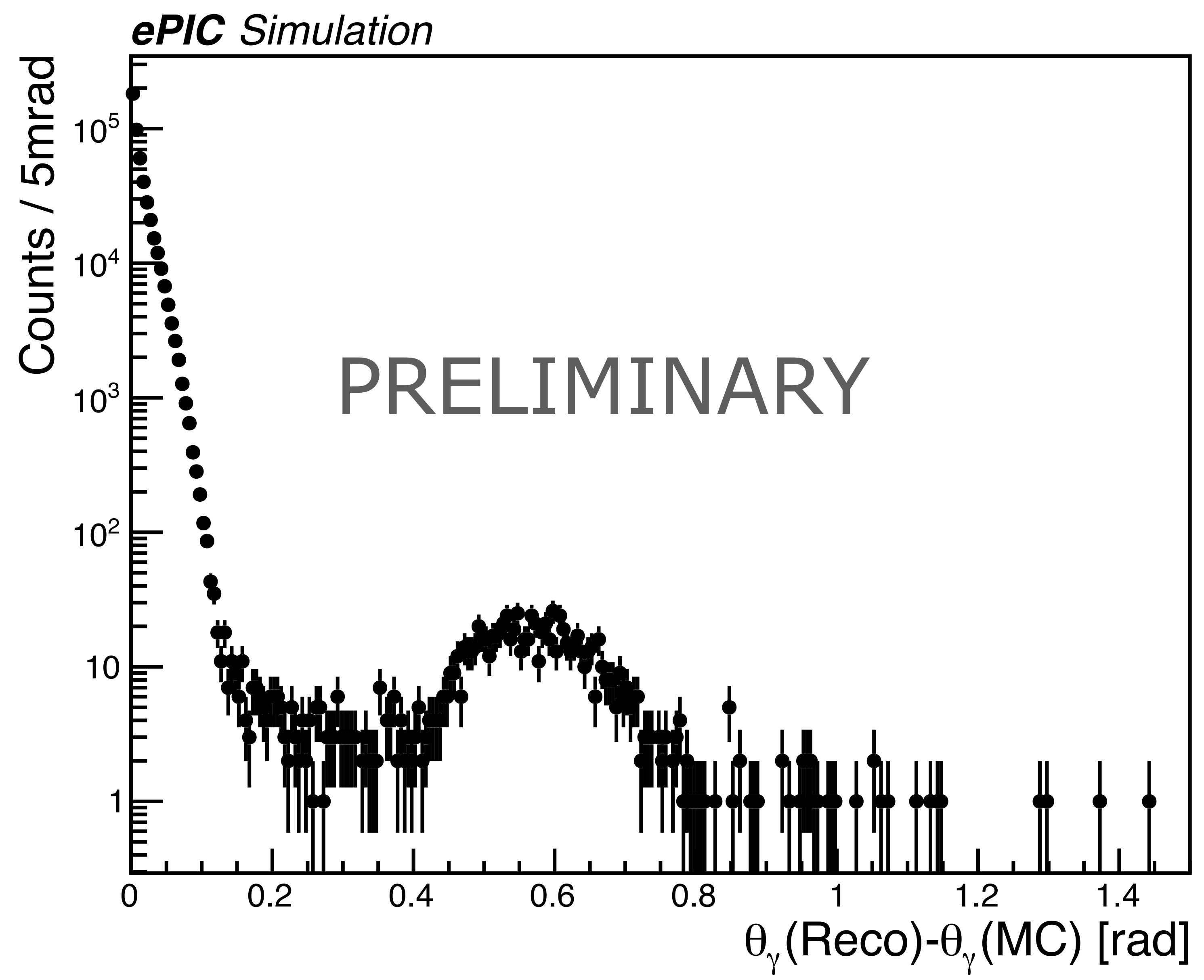
- DVCS at high $Q^2$, low t → sensitivity to four parton helicity-conserving chiral-even GPDs:

$$E^q, \tilde{E}^q, H^q, \tilde{H}^q(x, \xi, t)$$

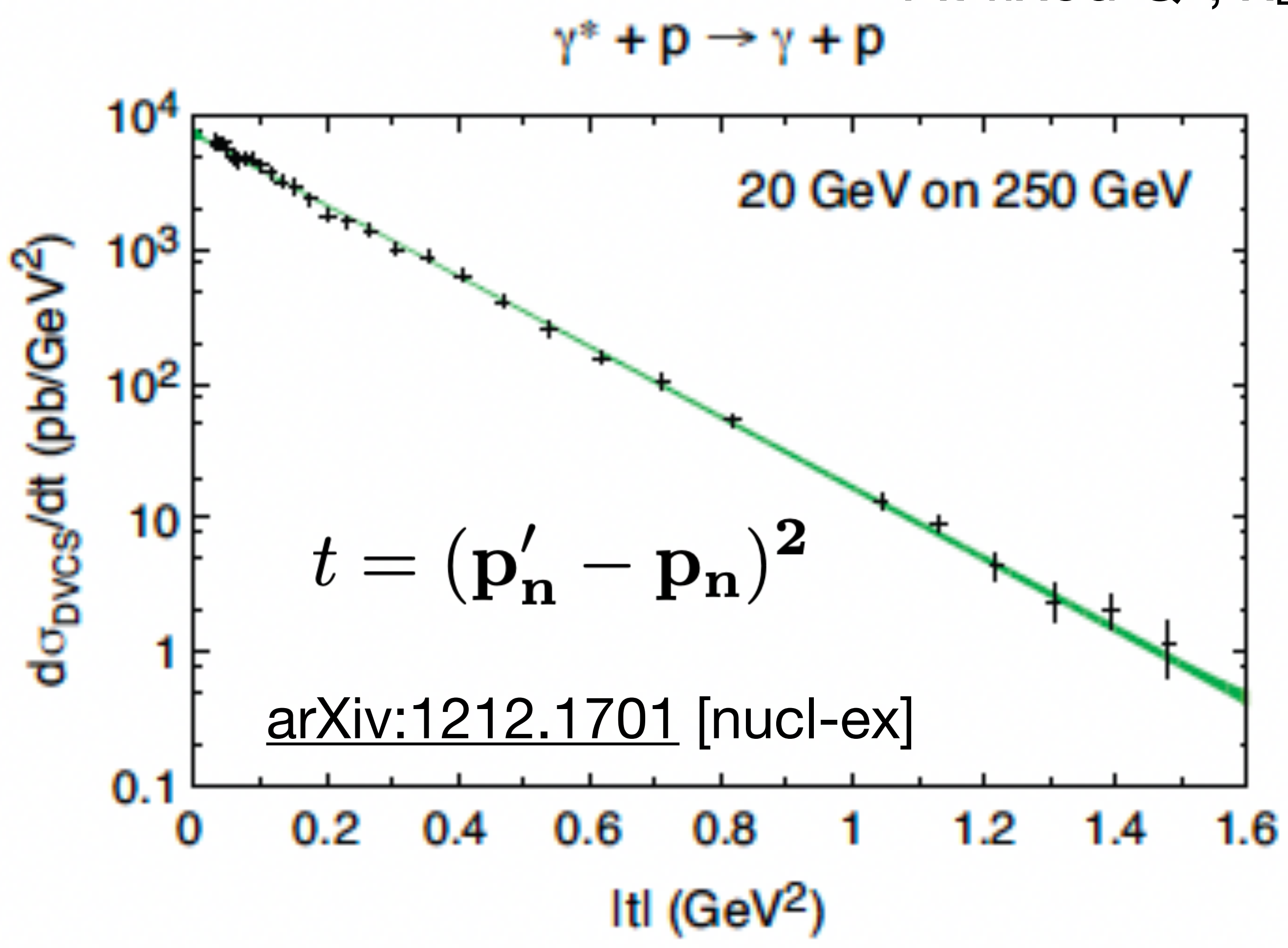
- Transverse spatial positions in longitudinal momentum space
- Quark orbital angular momentum
  - First moments of GPDs enter Ji's sum rule for angular momentum carried by partons

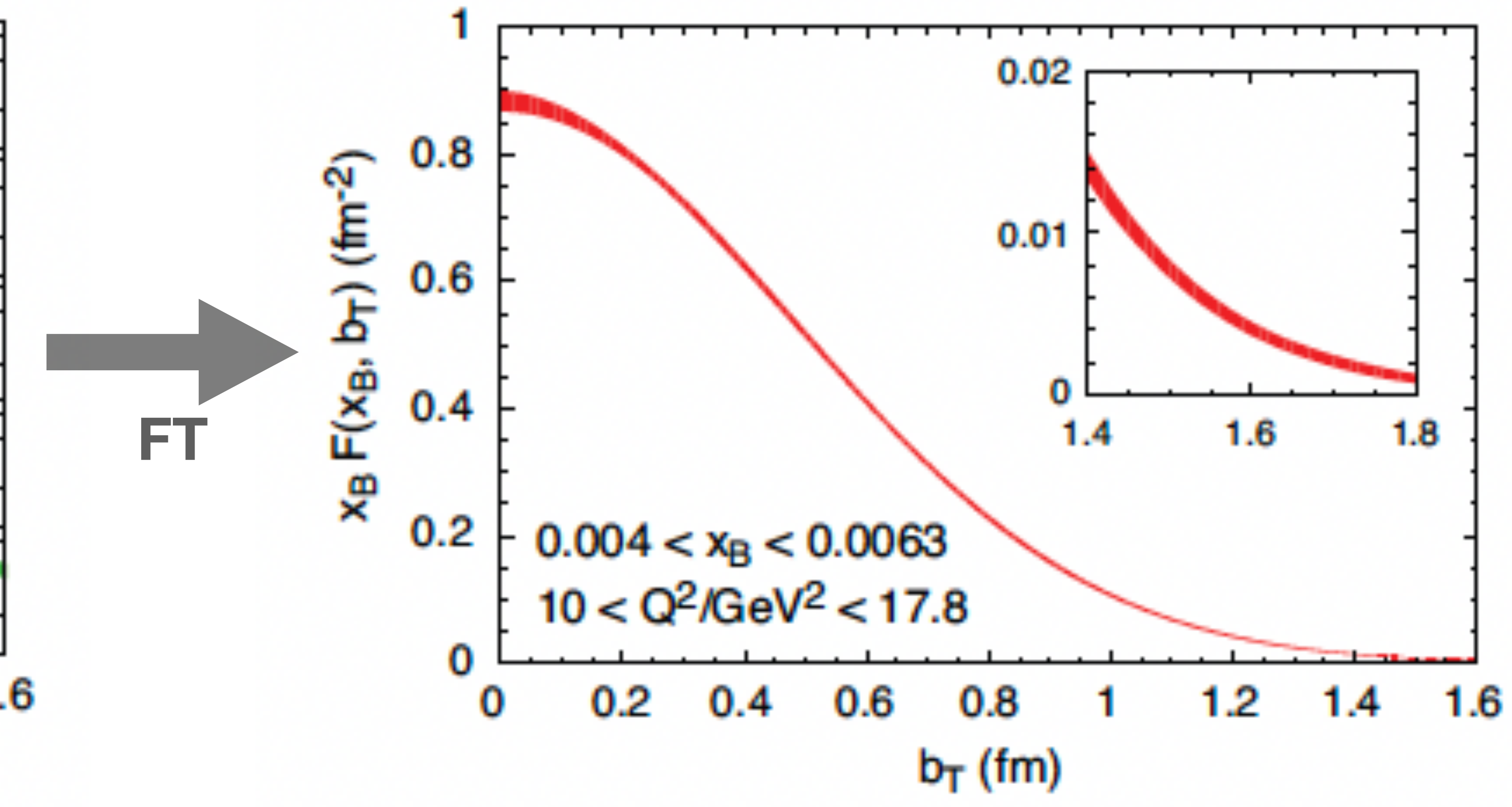
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x dx \{H^q(x,\xi,0) + E^q(x,\xi,0)\}$$

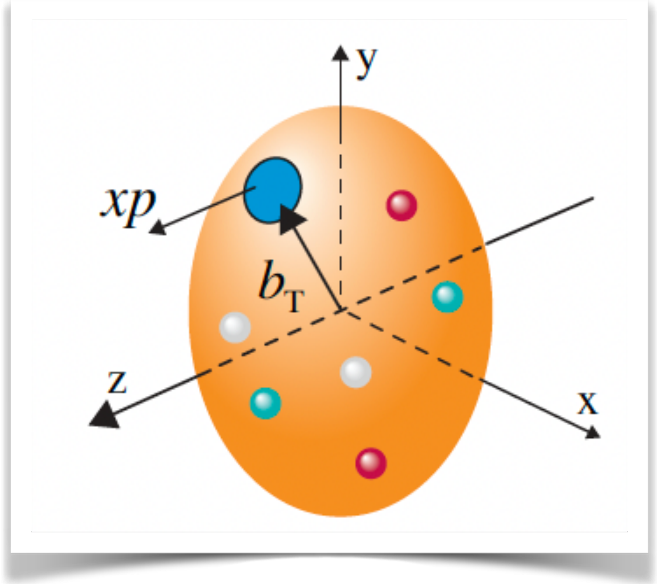
- Gravitational form factors and mechanical properties, e.g. pressure distributions (indirectly);

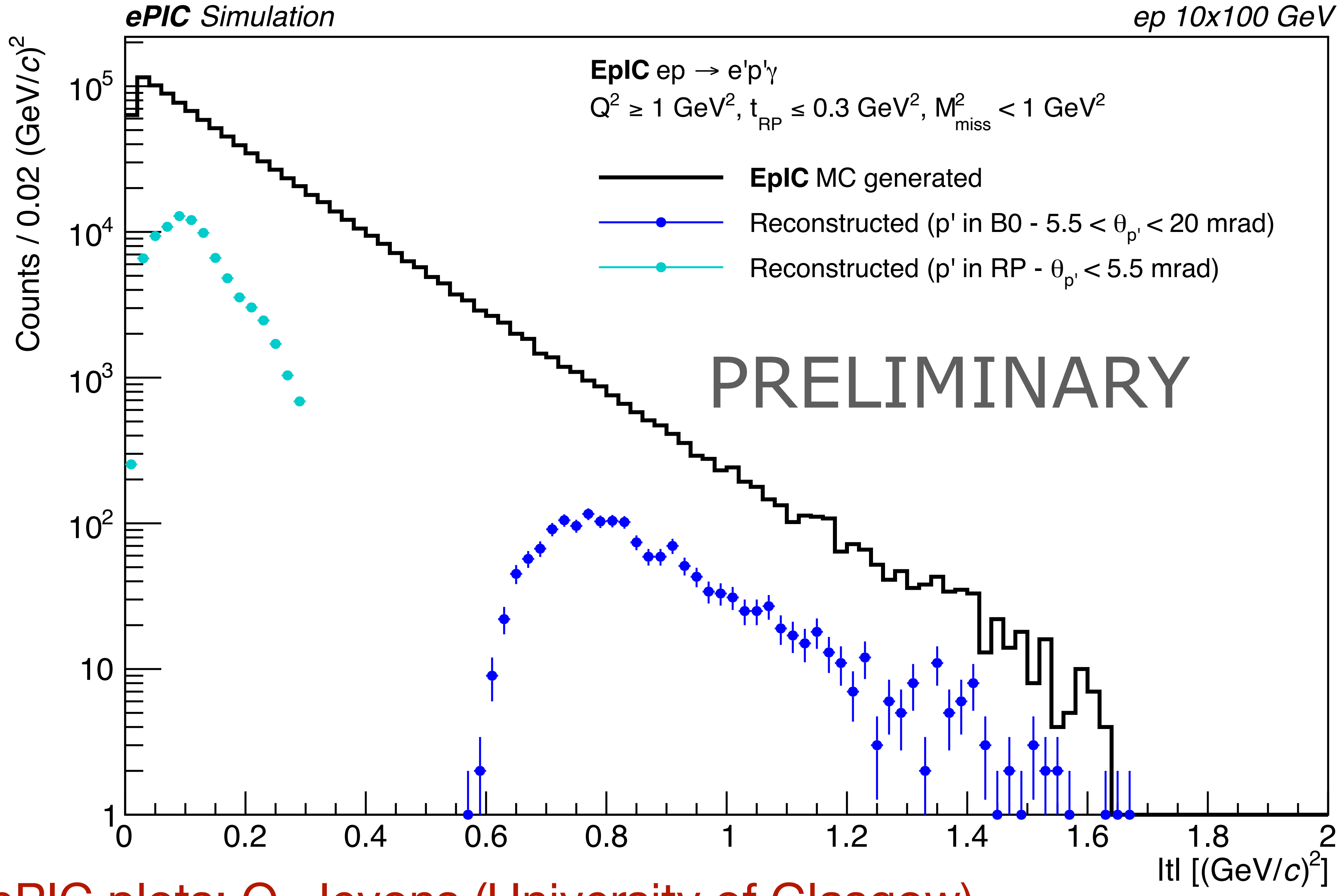



At fixed $Q^2$, $x_B$ and Ɛ=0, slope of cross section related to transverse spatial distributions of quarks inside nucleon




- e' in central detector, p' in FF, photon in central detector

- Different FF detectors come into play at different beam energies
- e.g. p' detected in B0 for lower energies, and RP for higher energies

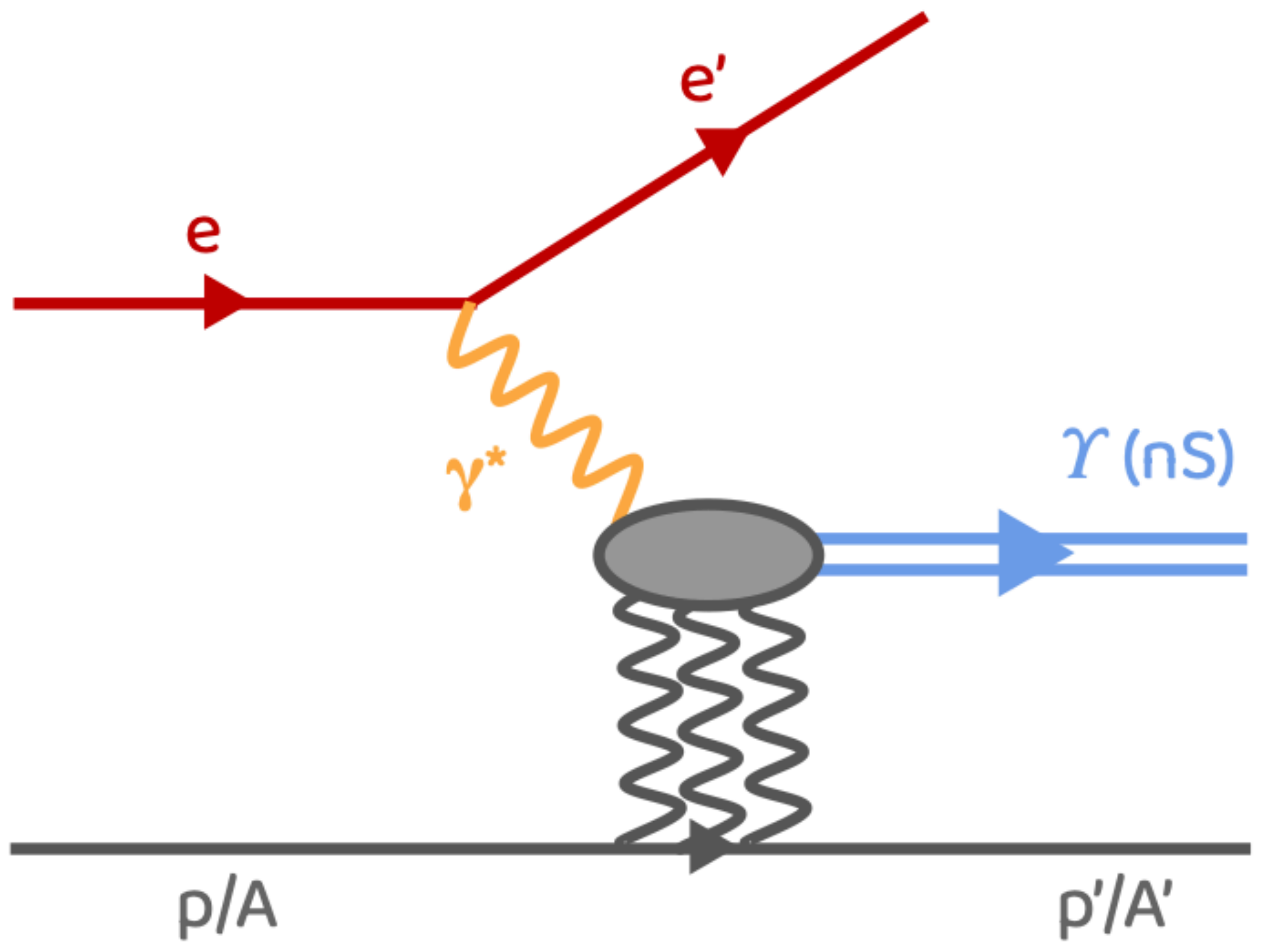
- Reconstruction of t in FF region is crucial for physics, e.g. related to impact parameter information
- Need to measure t over wide range and reach as close to 0 as possible

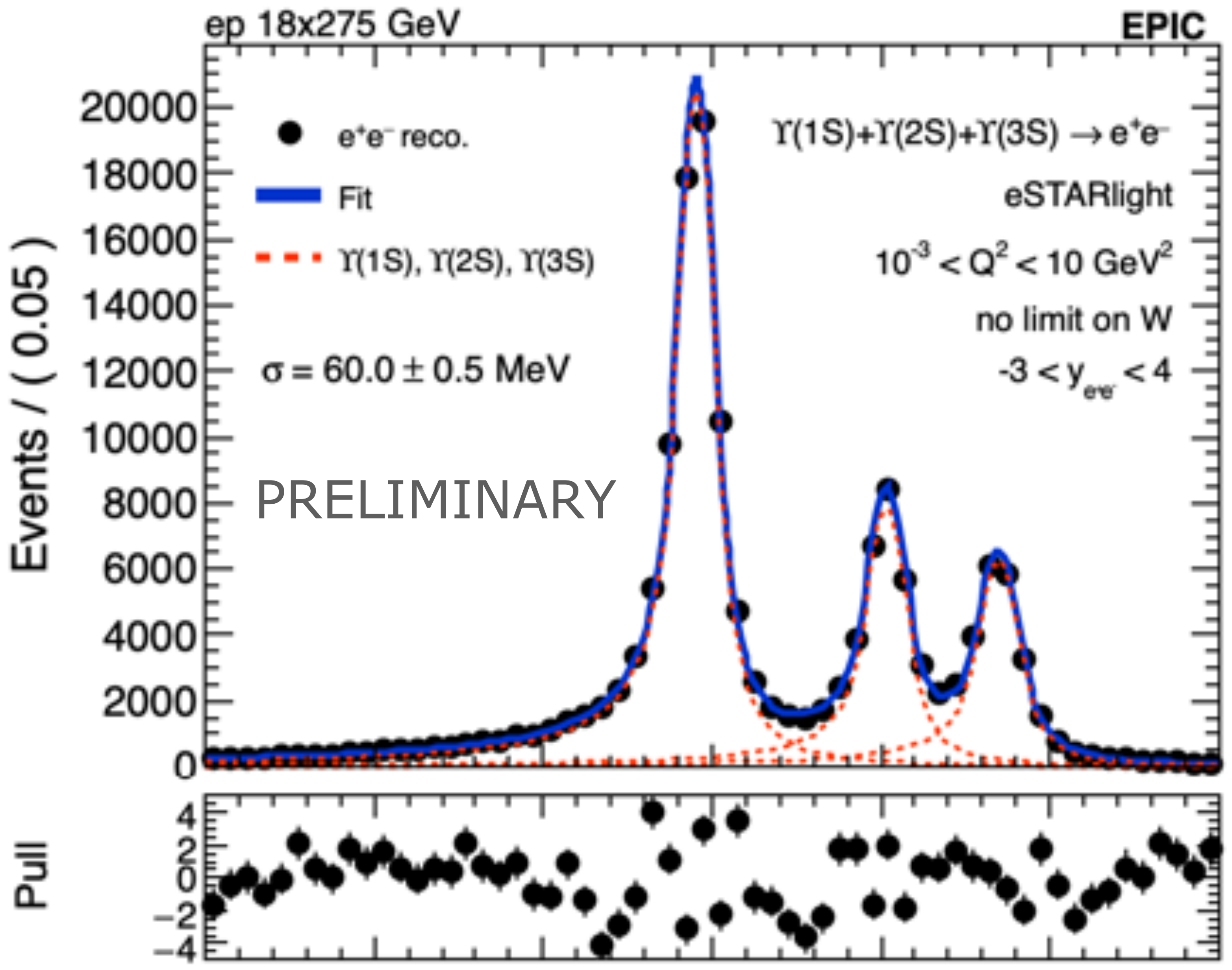
- Real photon reconstruction allows to separate main background ($\pi^0 \to \gamma\gamma$)

ePIC plots: O. Jevons (University of Glasgow)

Simulations shown use EpIC generator (EPJ C **82**, 819 (2022))

# Upsilon Production




- Exclusive heavy quarkonia production → sensitivity to gluon distributions in nucleon/nuclei and access to gluon GPDs
- Near threshold production can provide new inputs to trace anomaly studies

- Resolution study underway for ϒ(1S), ϒ(2S), ϒ(3S) → $e^+e^-$ in ep
  - (S. Yoo (UC Davis), M. Kim (Berkeley Lab), S. Klein (Berkeley Lab), D. Cebra (UC Davis)

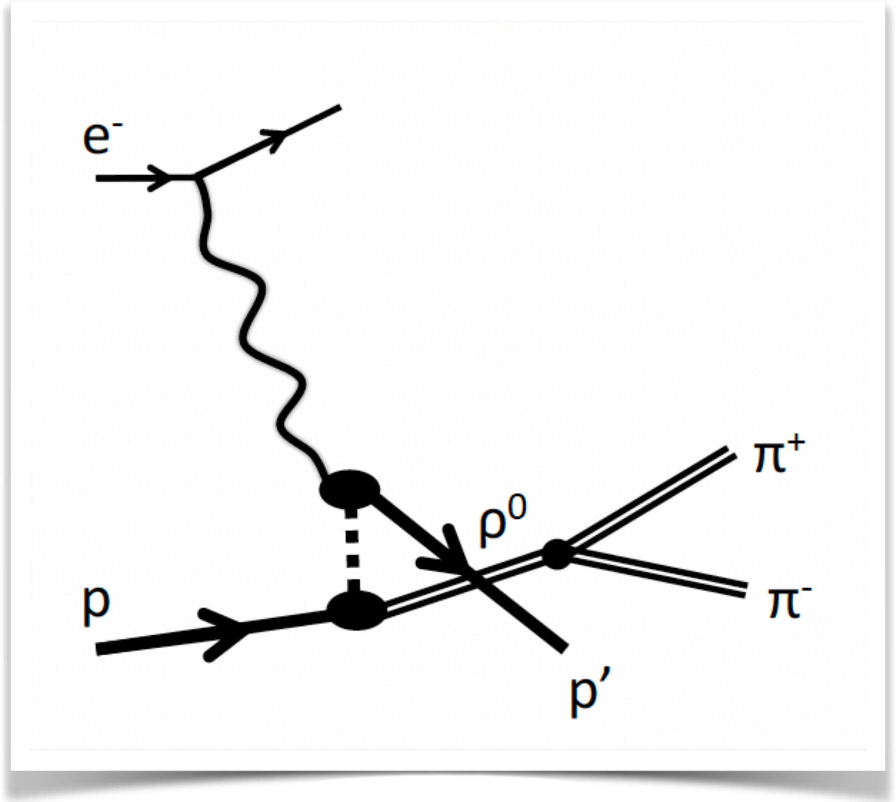
- ϒ($b\bar{b}$) heaviest vector meson states accessible at EIC
- Quark contribution to ϒ production smaller than for J/Ψ($c\bar{c}$)
- Comparing all three states (each with different wave functions) reduces systematic uncertainties in gluon distribution extractions

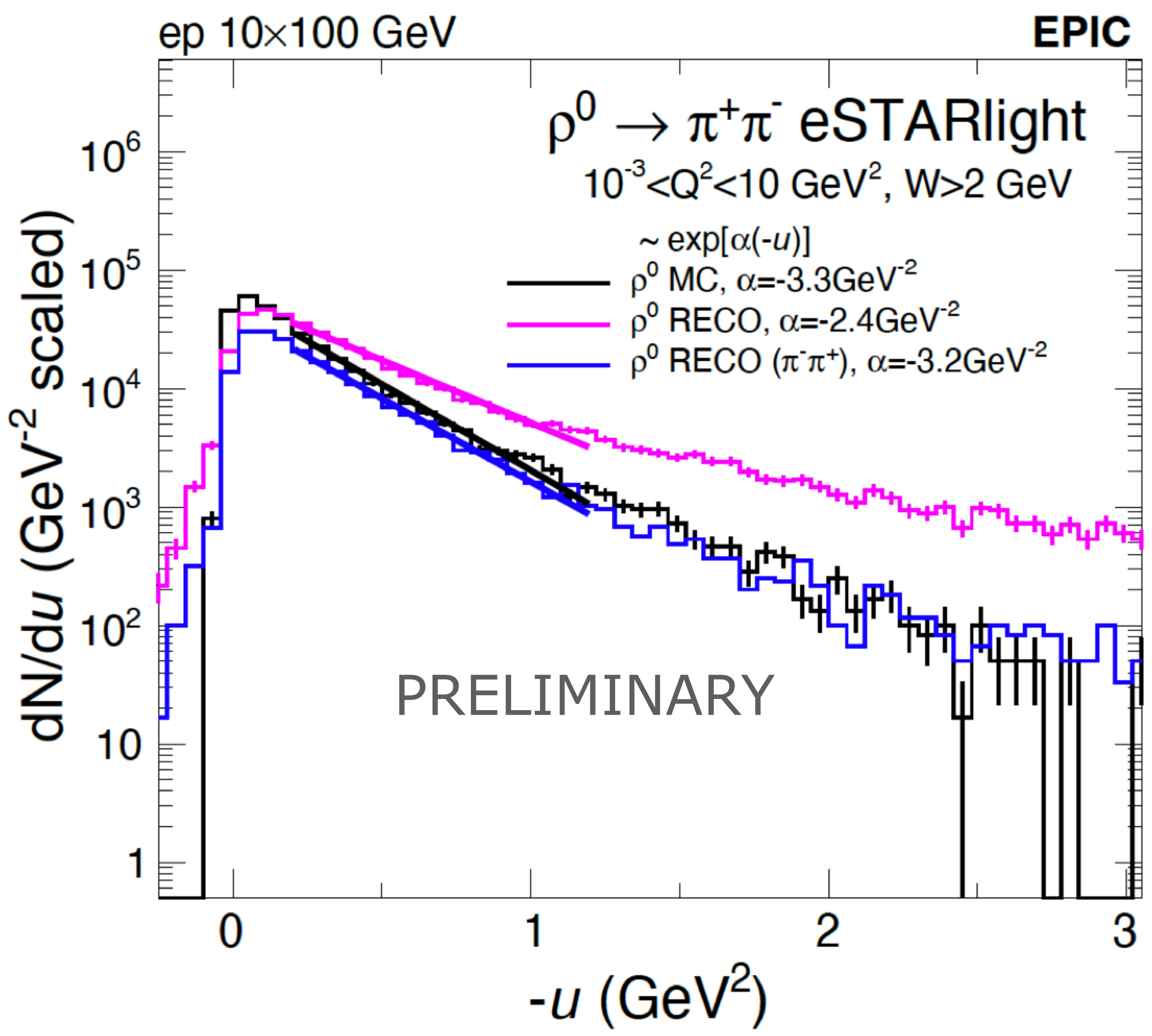
- Momentum resolution of tracking crucial to reconstruct $e^+e^-$
- Good separation achieved through vast majority of rapidity regions
- Muon decay channel also under study, especially for most forward rapidities ($2<\eta<4$)

ePIC plots: S. Yoo (UC Davis)

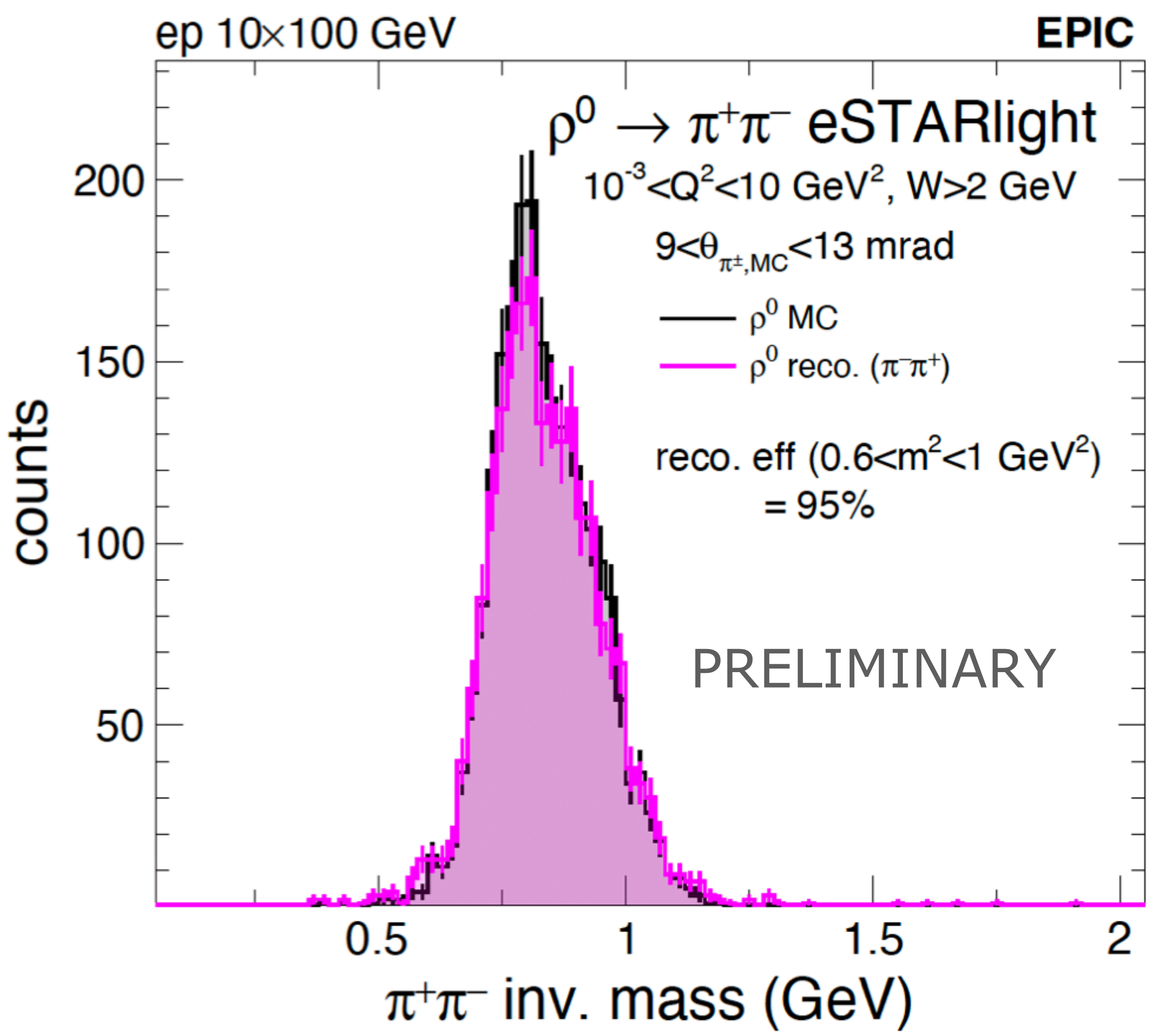
# Backward (u-channel) Production of Rho

- Nucleon/nuclear tomography
- Forward (t-channel) cross-sections → parton distributions in transverse plane via GPDs
- Backwards (u-channel) cross-sections → quark clusters and baryon number distributions in transverse plane via transition distribution amplitudes (TDAs)
- TDAs → describe mechanism by which a baryon transitions into a meson
  - Sensitive to di-quark clustering in nucleon and helicity of correlated quarks
  - FT gives info on spatial parton distributions (impact parameter plane)
- Connections with baryon stopping powers




u-channel cross-section slope reconstruction




$\rho^0$ reconstruction efficiency

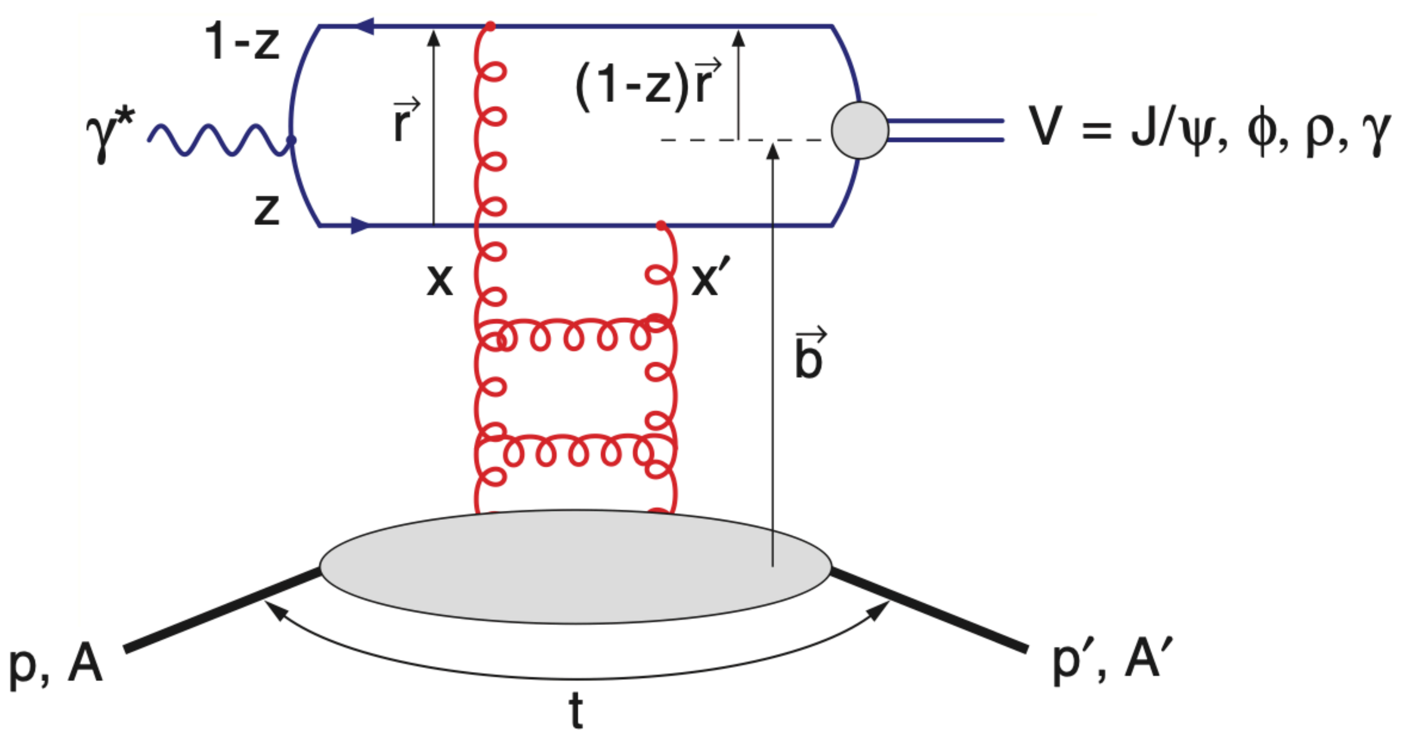
- Produced meson takes most of momentum of struck nucleon → ends up in FF
- Nucleon shifts by several units in rapidity to mid-rapidity (central detector)
- Z. Sweger (UC Davis) et al
- Backwards $\rho^0$ meson production
  - $ep \to e'p'\rho^0 \to e'p'\pi^+\pi^-$
  - Low Mandelstam u, high t

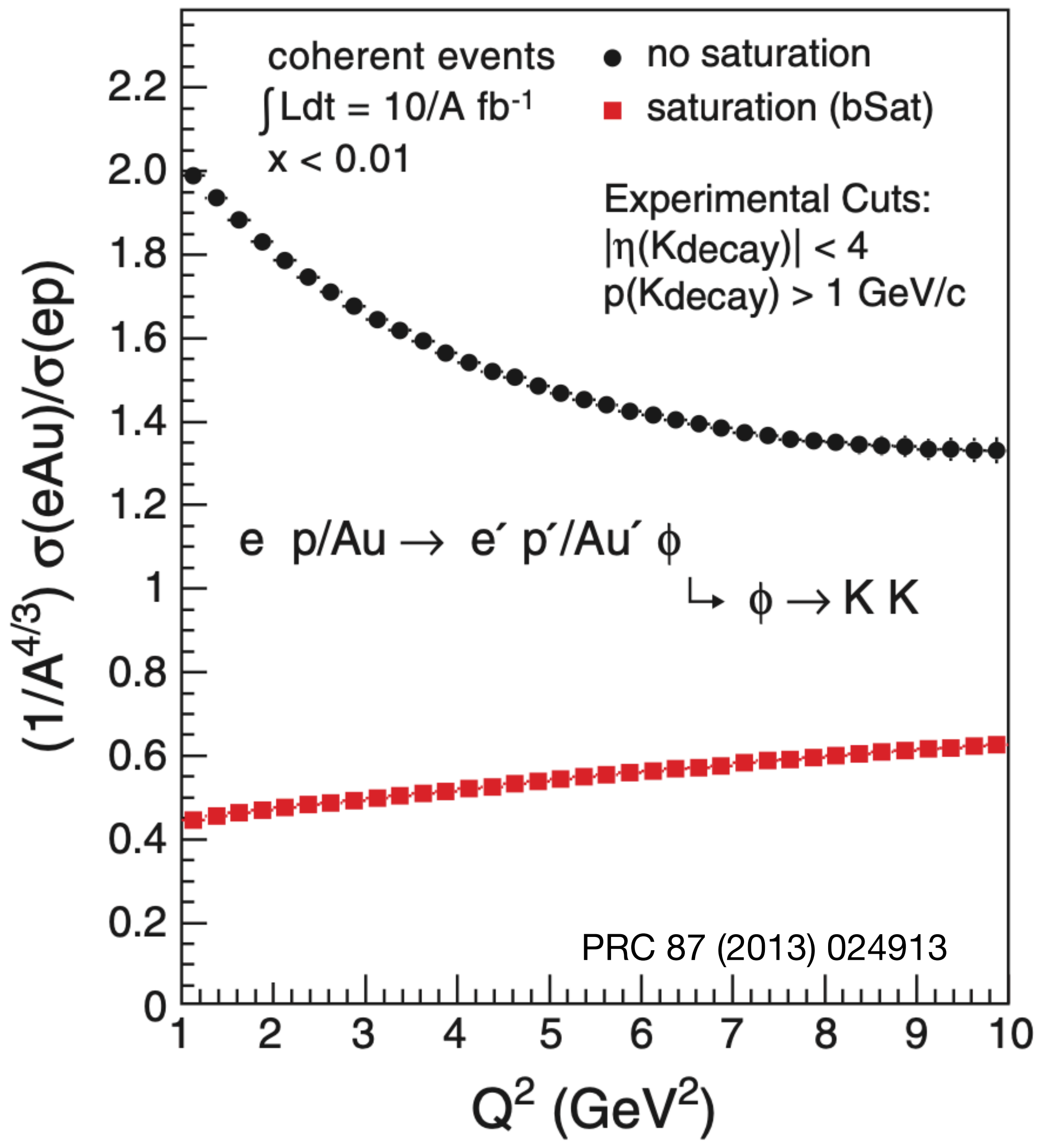
More info on this physics: Phys. Rev. C 106, 015204 (2022)

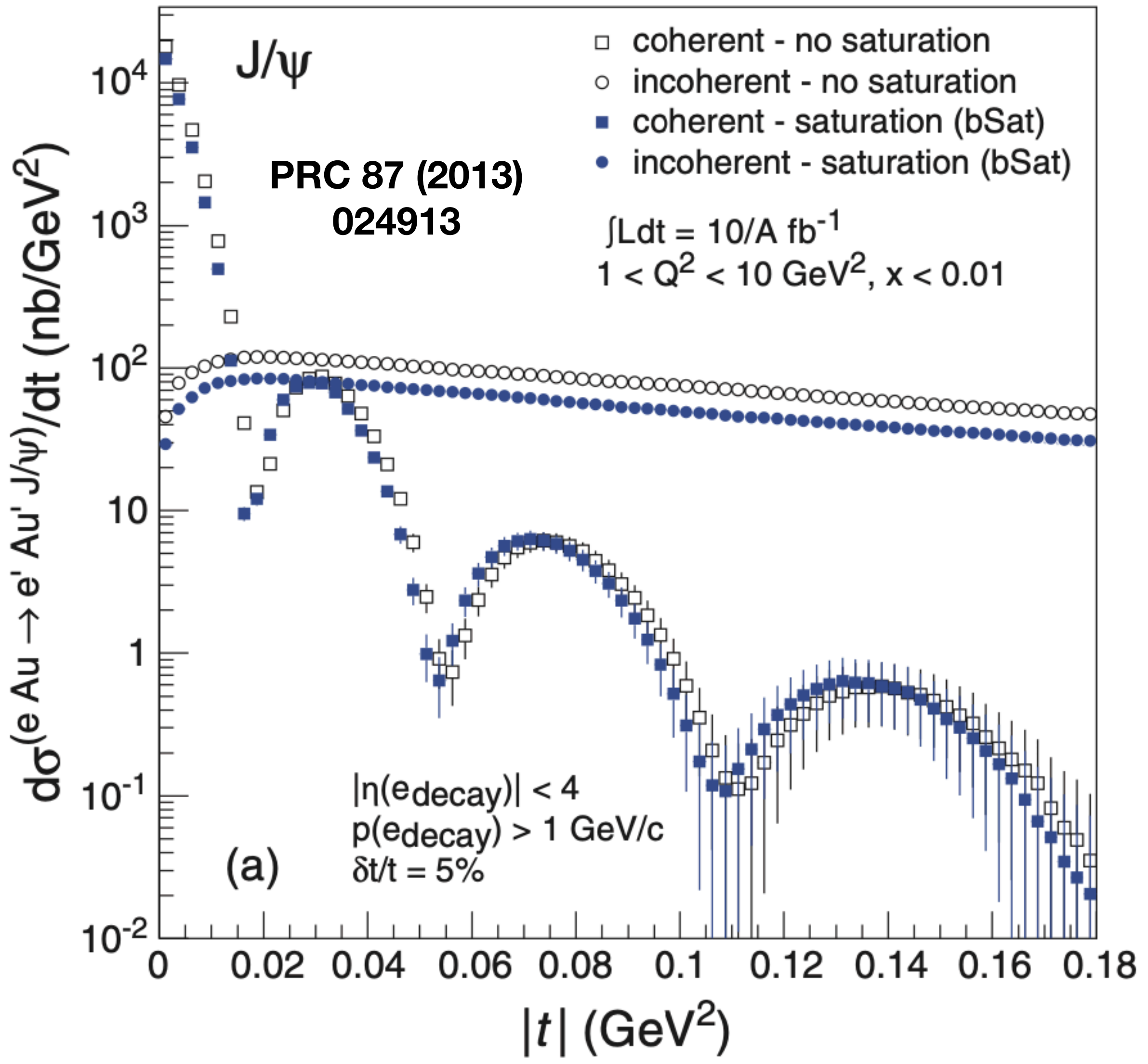
ePIC plots: Z. Sweger (UC Davis)

# Diffractive VM Production in eA

**Toll, Ulrich, PRC 87 (2013) 024913**

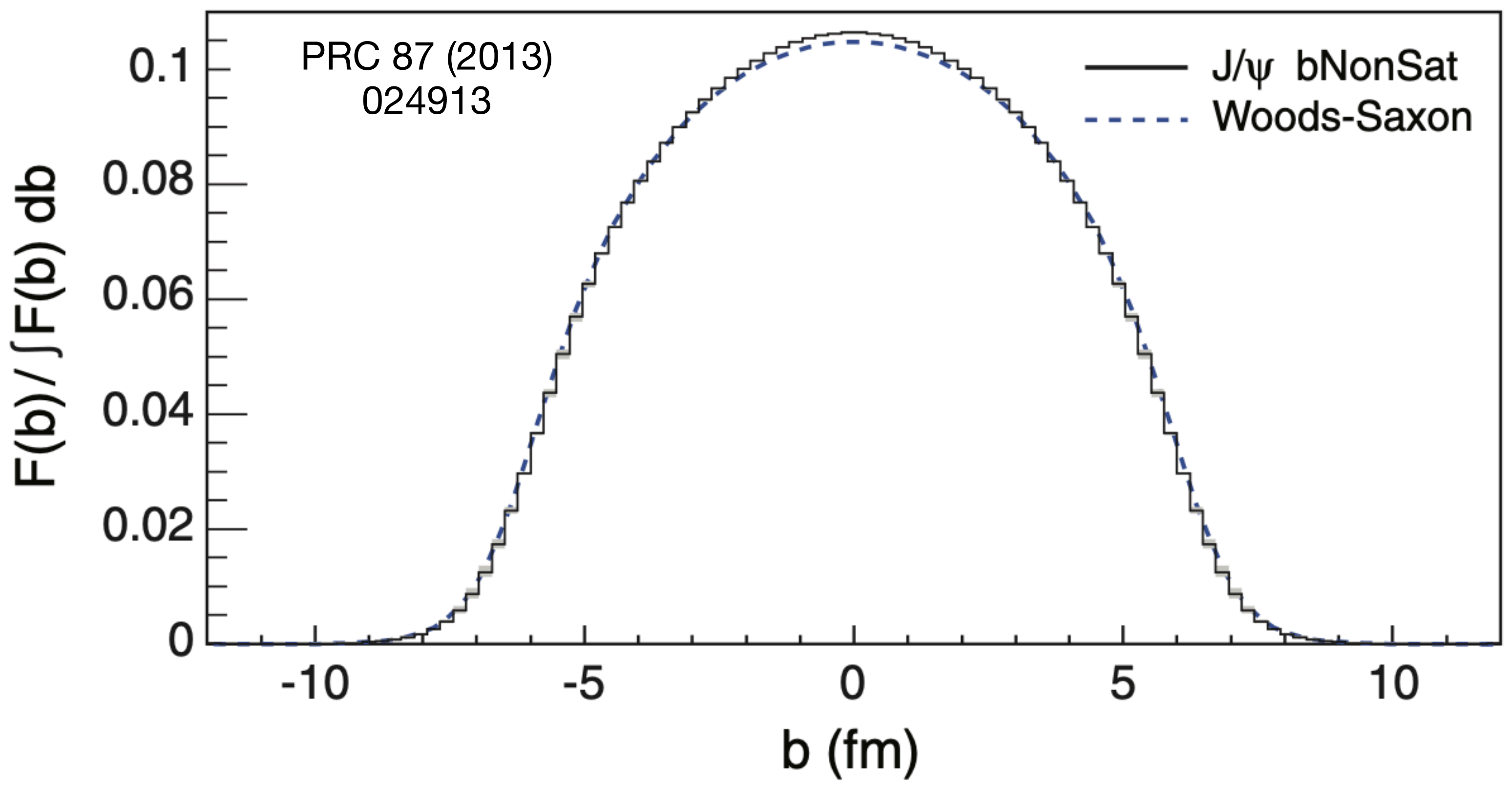



**Fourier Transform Coherent**

|t| conjugate $p_T$



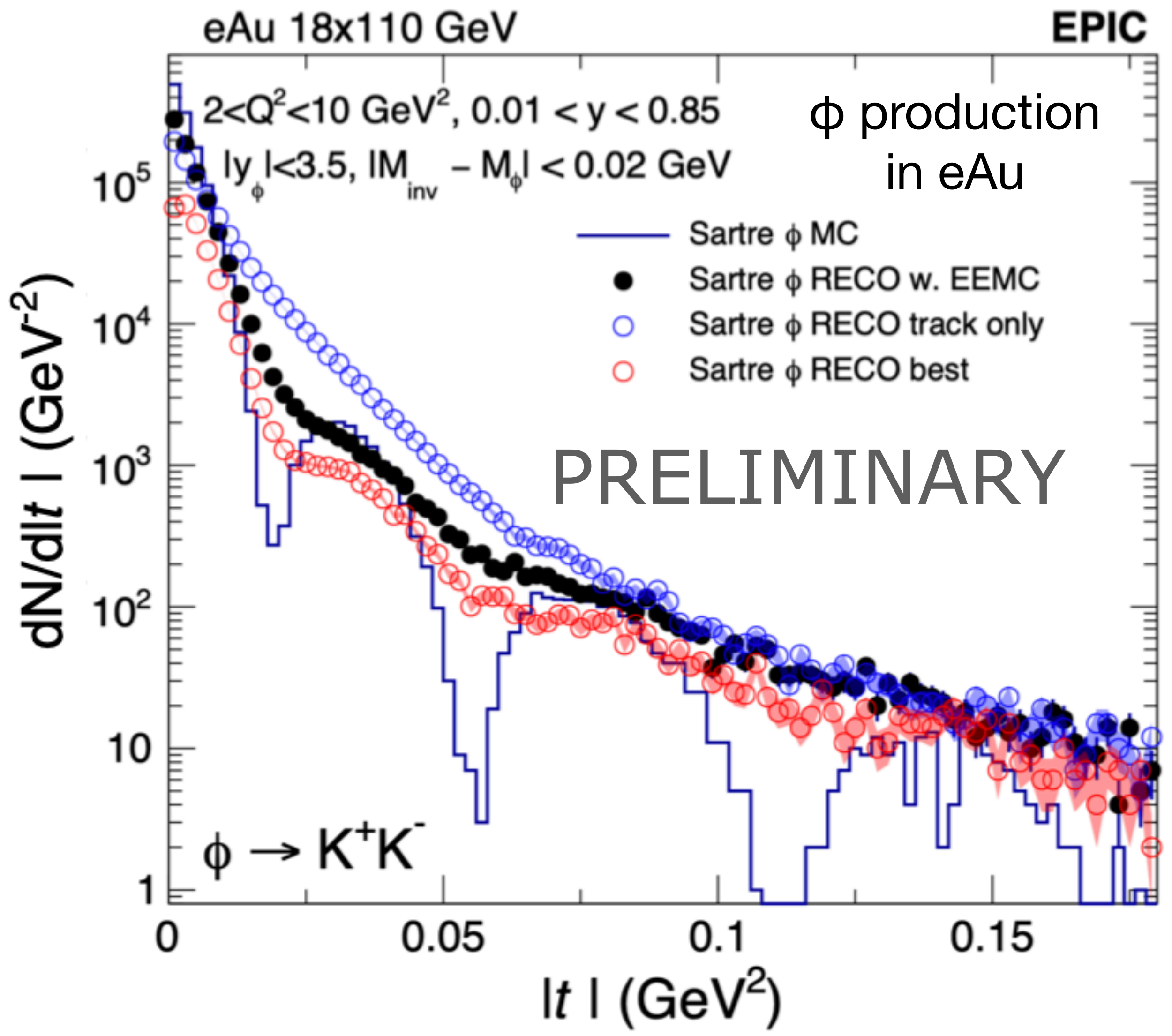

- e + A → e’ + A’ + VM
- Cross section sensitive to gluon spatial distributions within nuclei
- Probe gluon saturation
- Coherent - sensitive to average nuclear geometry
  - 1st minima → info on nuclear parton density

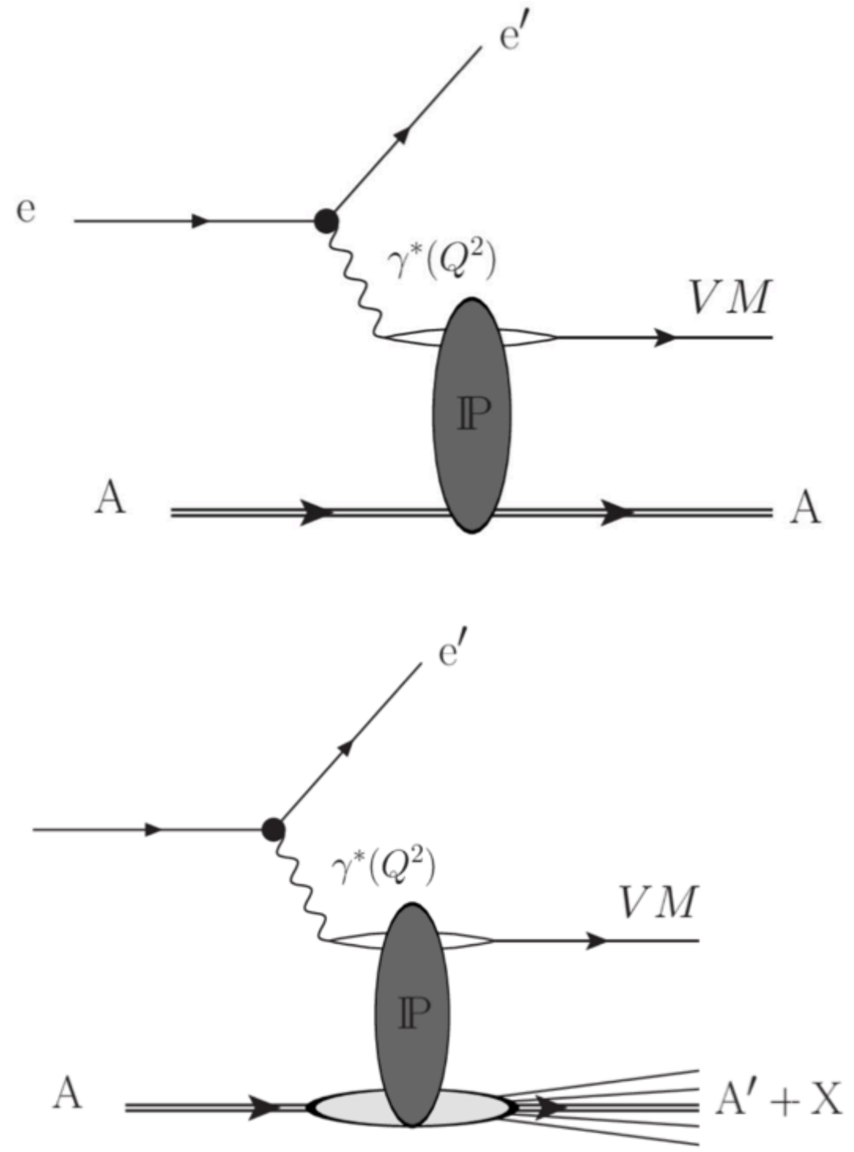
- EIC: range of mesons, several ions, wide range $Q^2$
  - e.g. J/Ψ, ϕ, ρ, ω, ϒ under study
- |t| resolution crucial for pattern - very challenging
- Need to remove breakup from incoherent scattering

- A’ escapes down beam pipe
  - Reconstructed from decay products and exclusive kinematics
  - Need high resolution for e’ and VM decay

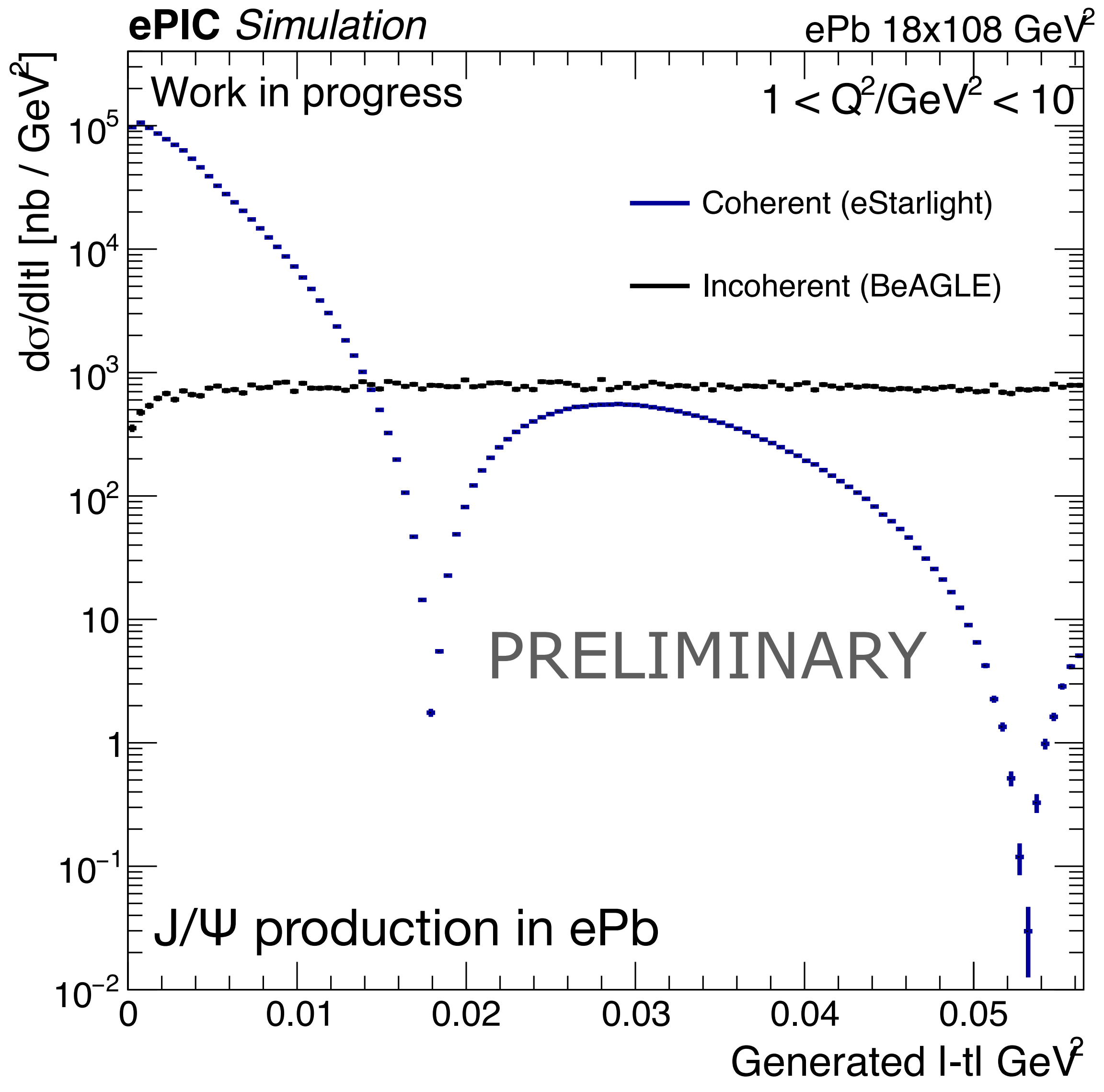
# Diffractive VM Production in eA

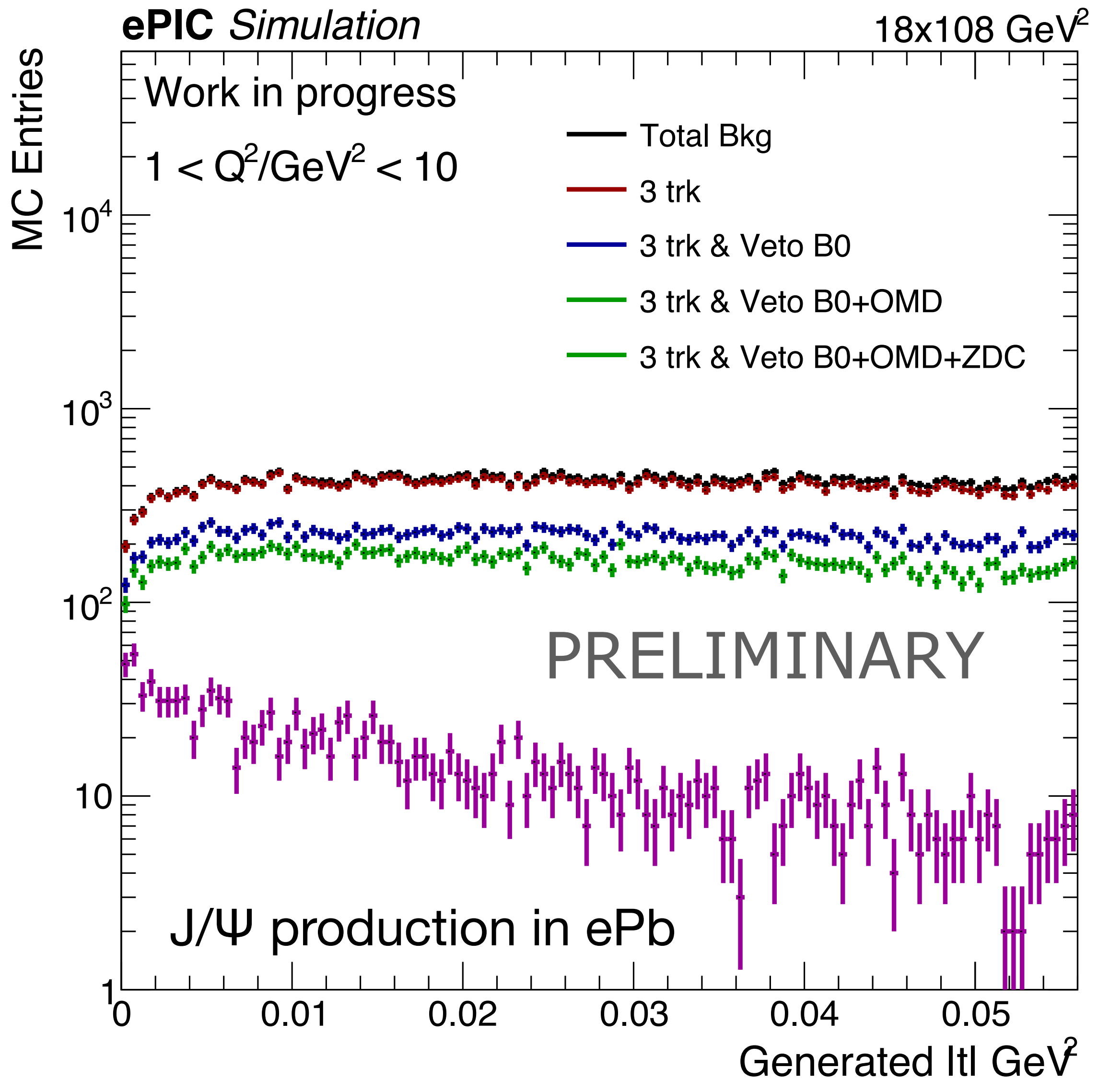
ePIC Coherent plot: Z. Tu (BNL)




- Coherent e + Au → e' + Au + ϕ → e' + $K^+K^-$
  - e' central detector, $K^+K^-$ (very soft) central detector
  - Au' escapes down beam pipe
- Detector challenge: reconstruct |t|
- e' in backward calorimeter and $K^+K^-$ reconstructed with tracking in central detector
- Optimised reconstruction event by event shows some improvement



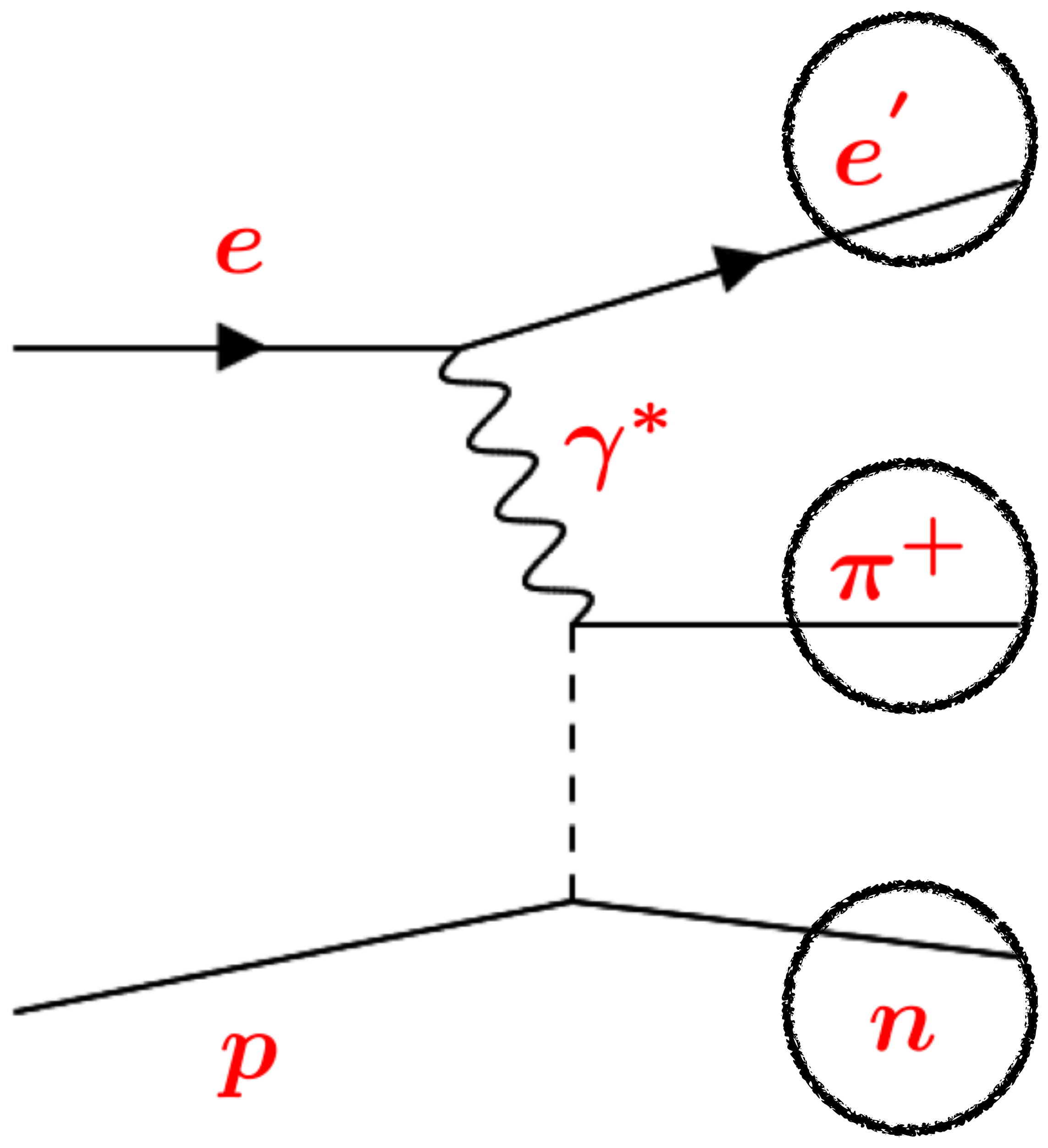



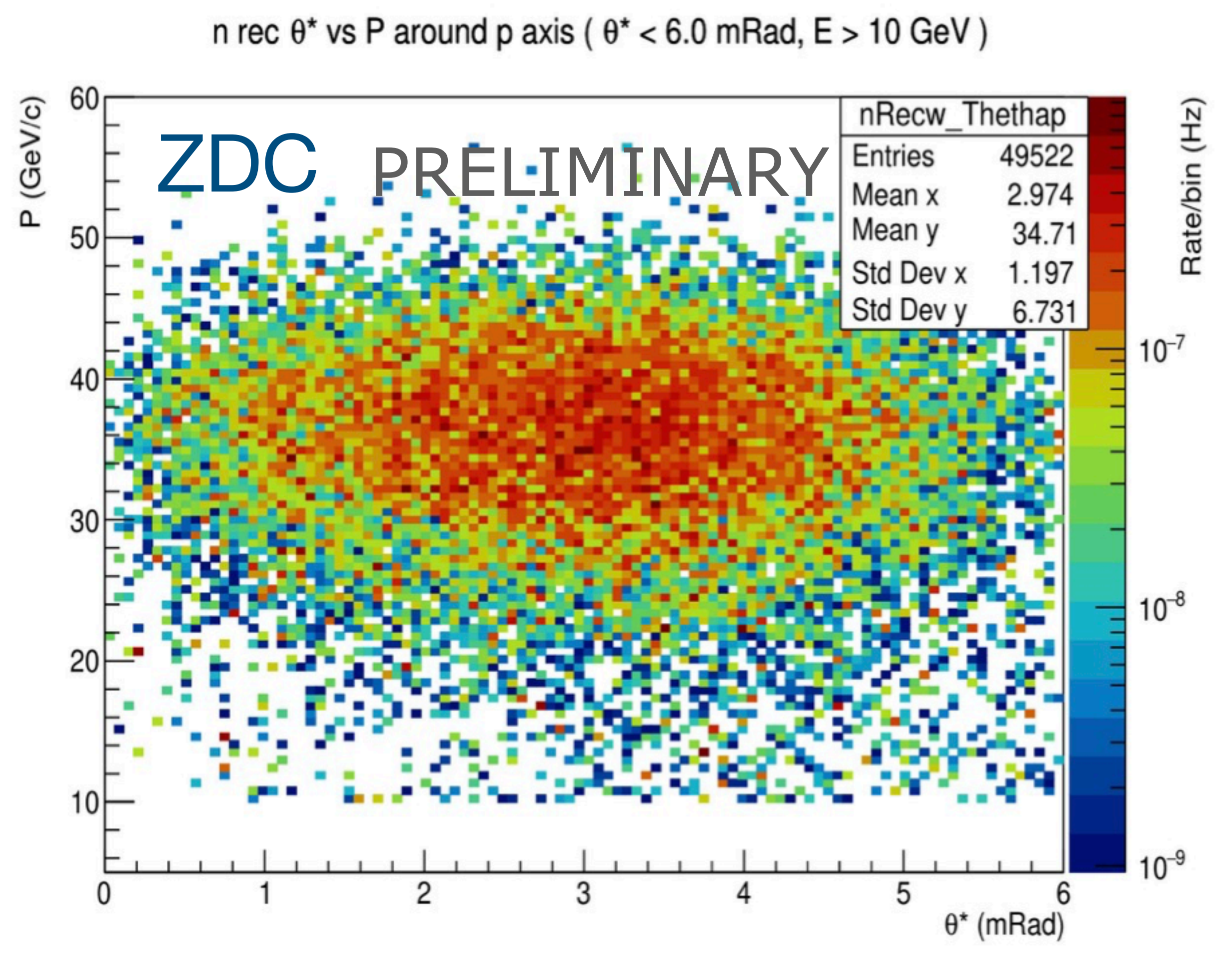

- Incoherent is interesting in its own right → info on partonic fluctuations and gluons hot spots
- Also biggest background for coherent (except at small |t|)
- Event by event tagging in far forward region detectors to veto incoherent
- ePIC studies with most up-to-date FF detectors on-going

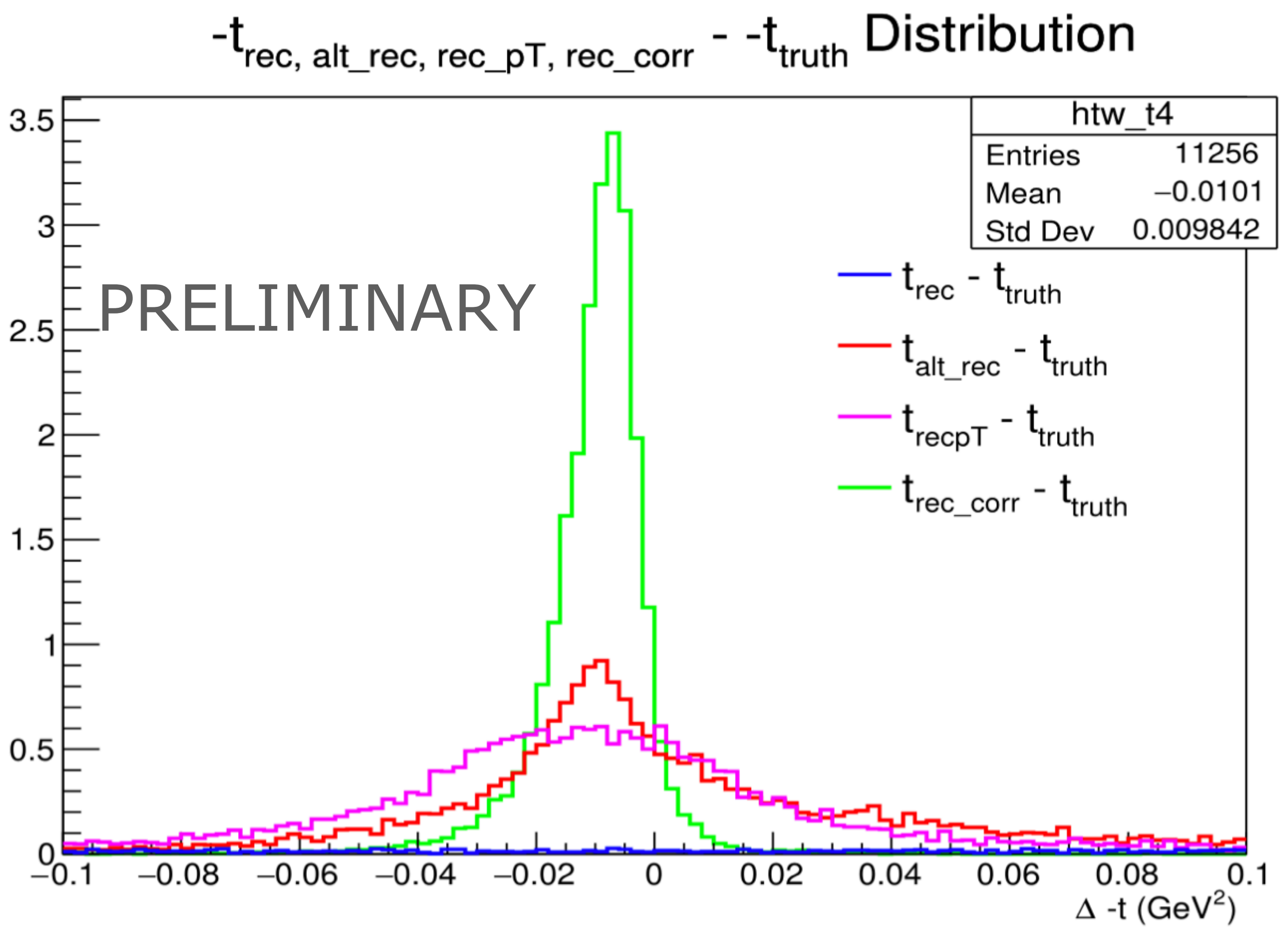
ePIC incoherent plots: M. Pitt et al, Ben Gurion University of the Negev

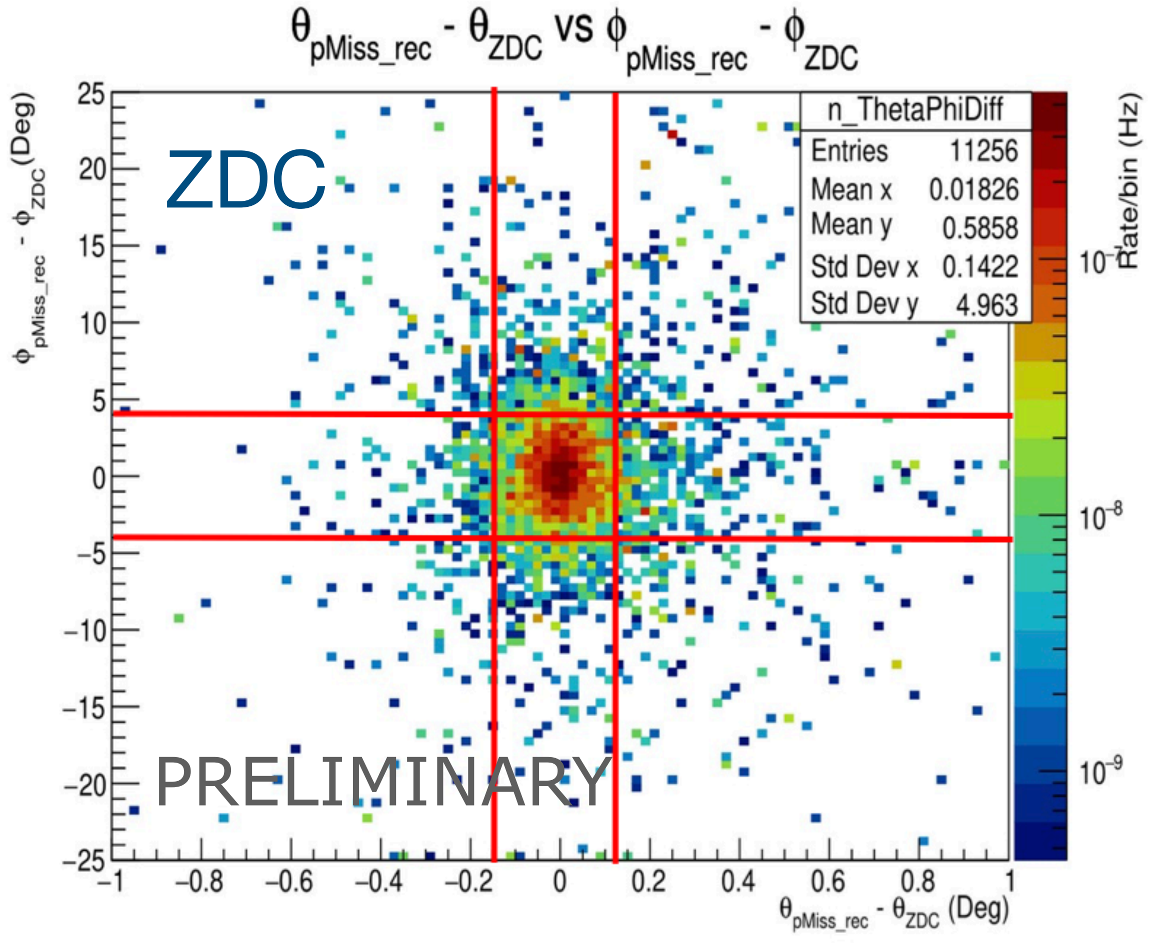
# Light Meson Form Factors

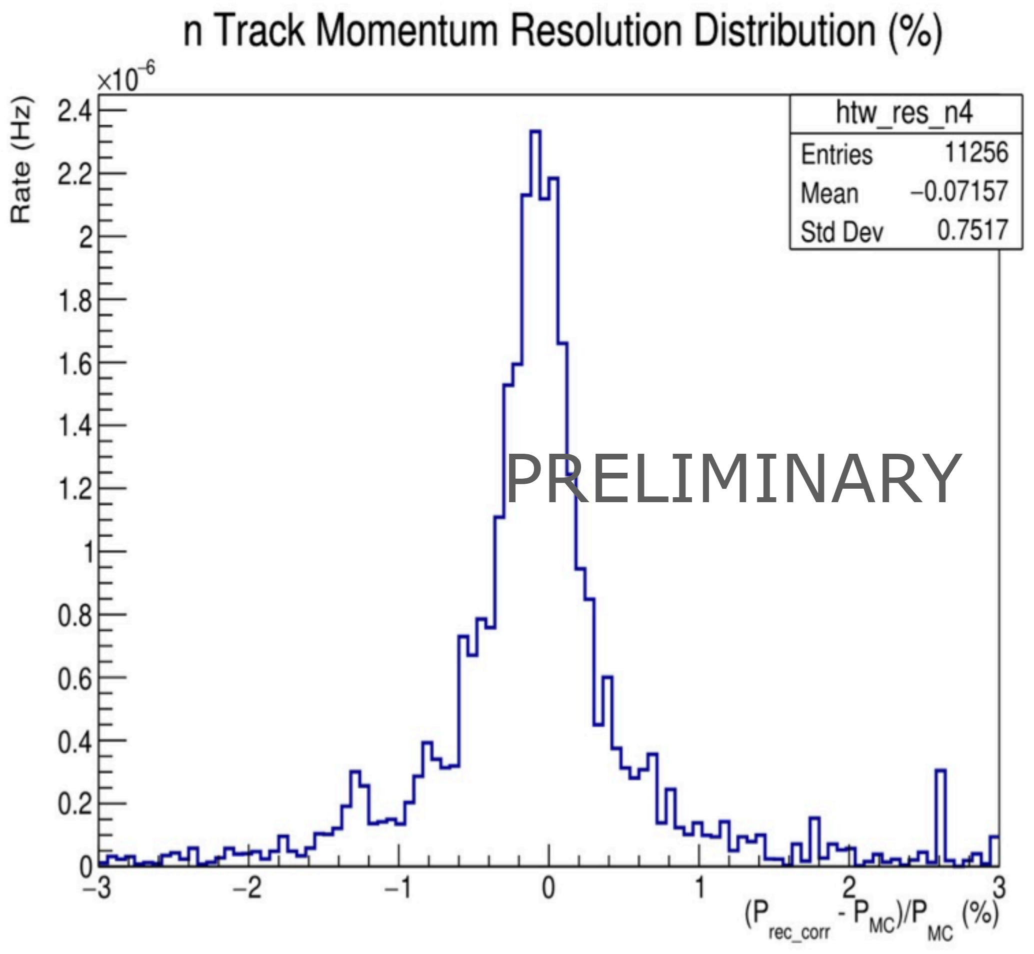
- Pion and kaon form factors can shed light on emergent hadronic mass
- Pion form factor extracted in exclusive elastic scattering ep→e’$\pi^+$n
- Studies underway by L. Preet, G. Huber et al. (U. of Regina), S. Kay (U. of York)



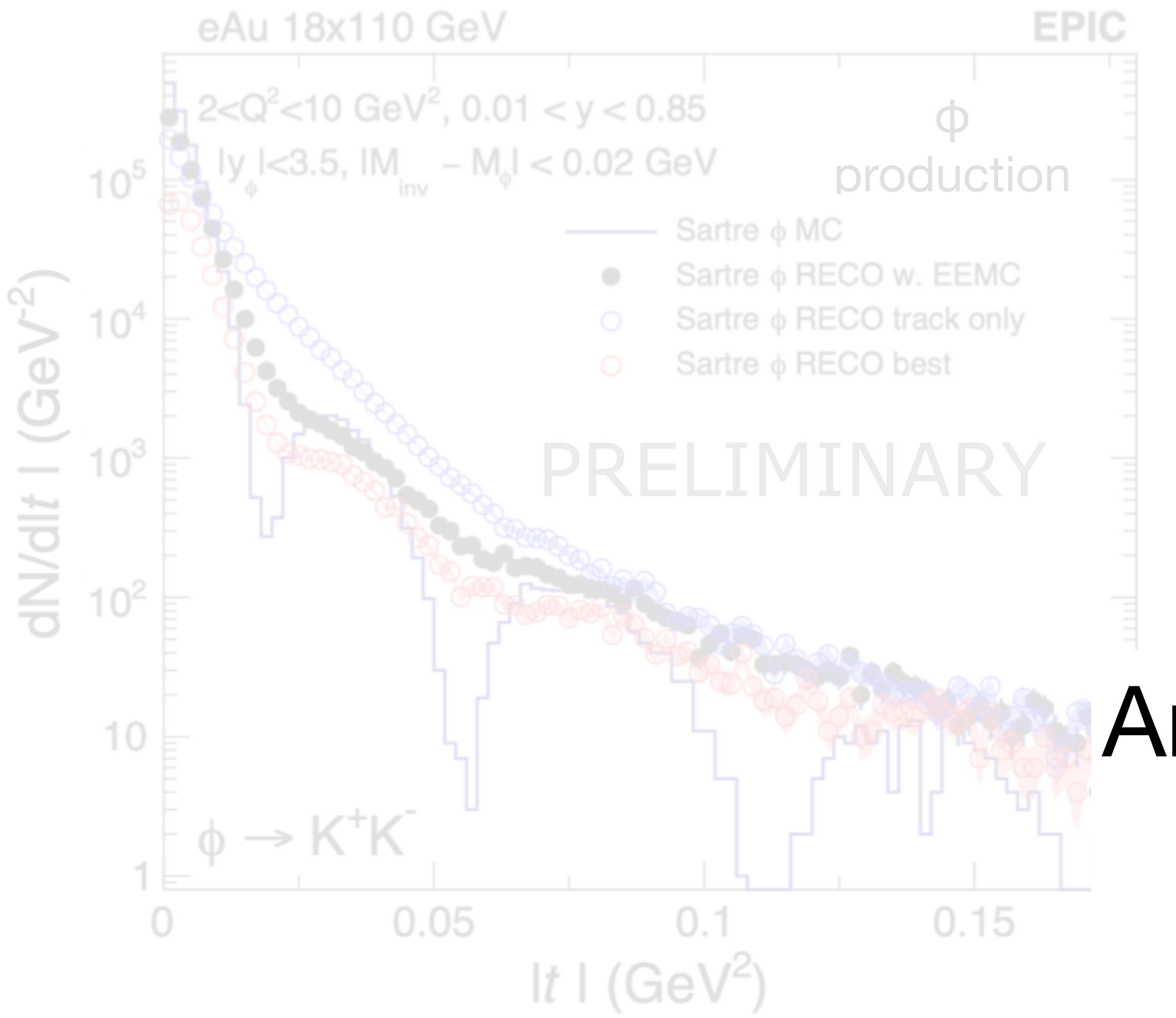




- All final state particles reconstructed
- e’ and $\pi^+$ central detector, n in FF (mainly ZDC)
- Neutron track angle and momentum resolutions as expected
- t-reconstruction working well
- $F_\pi(Q^2)$ projections underway
- Further plans to extend to kaons (more challenging)

ePIC plots: L. Preet (University of Regina) ePIC Coherent plot: Z. Tu (BNL)







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  - e' central detector, $K^+K^-$ (very soft) central detector
  - Au' escapes down beam pipe
- Detector challenge: reconstruct |t|
- e' in backward calorimeter and $K^+K^-$ reconstructed with tracking in central detector
- ...ent shows some

And ***many*** more physics studies ongoing not covered today

If interested in getting involved please join us







- Incoherent is interesting in its own right → info on partonic fluctuations
- Also biggest background for coherent (except at small |t|)
- Event by event tagging in far forward region detectors to veto incoherent
- ePIC studies with most up-to-date FF detectors on-going

ePIC incoherent plots: M. Pitt et al, Ben Gurion University of the Negev

# Summary

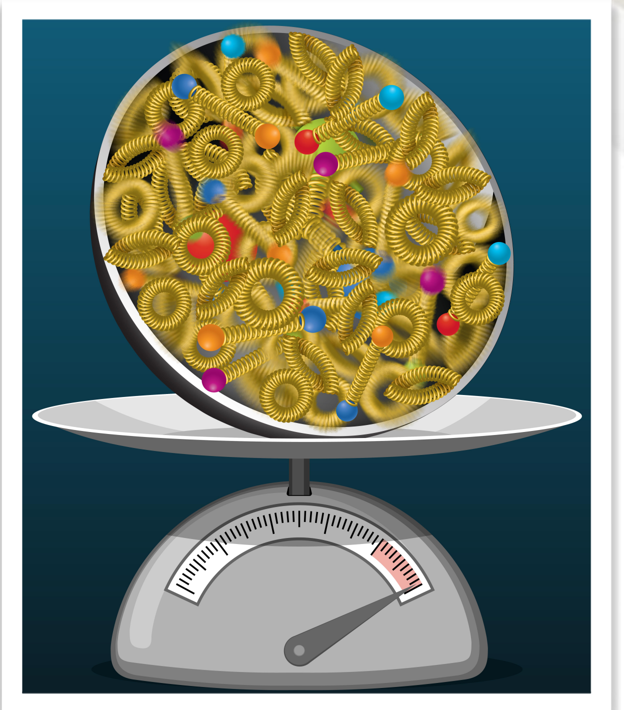
- Nuclear matter is governed by gluons and the dynamics of the strong interaction

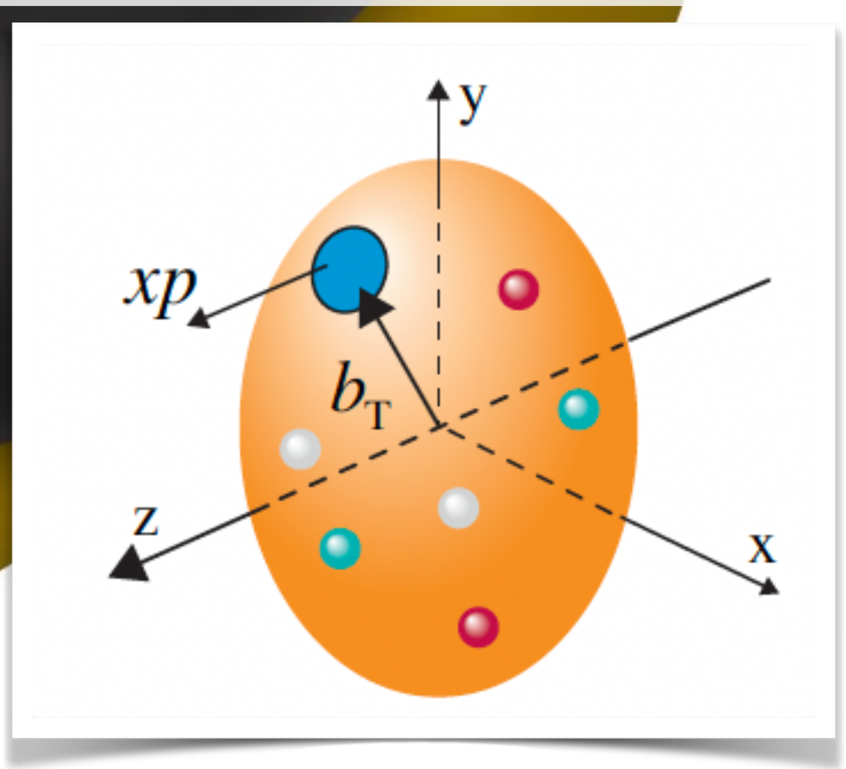
- EIC will delve deep into the building blocks of our visible Universe to revolutionise our understanding of the nucleon, nuclei and the strong interaction

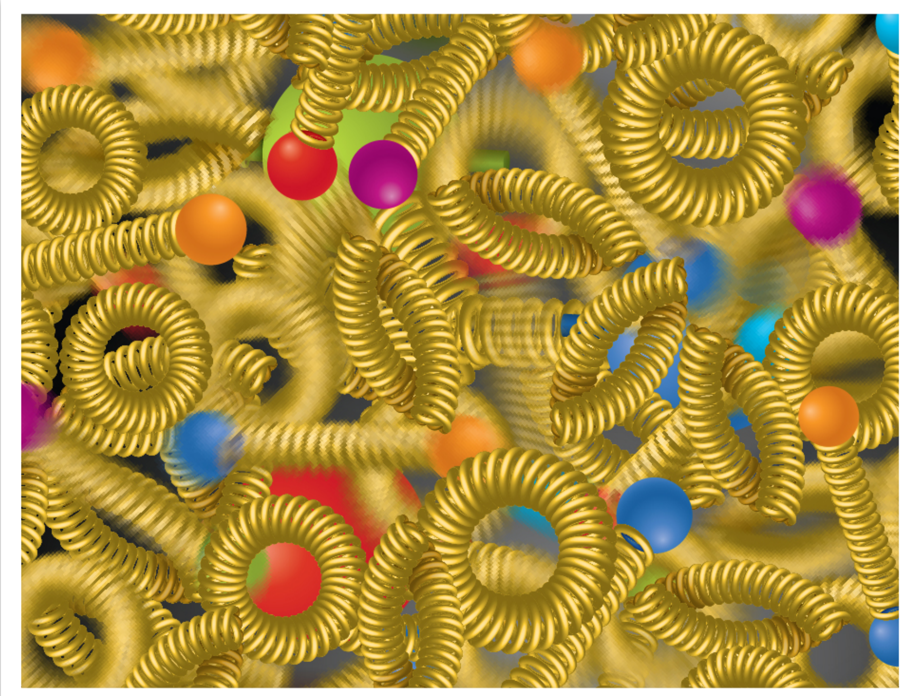
- The EIC will be one of the world's most sophisticated particle accelerators and use the cutting edge ePIC detector
- Its instrumentation is designed to realise an exciting and wide science program which only the EIC can uniquely address
- ePIC collaboration are currently working hard towards realising this

- Specific physics topics include
  - Origins of mass and spin
  - Nucleon and nuclei tomography
  - Dense systems of gluons in the nucleon/nuclei
  - More…

- EIC will push the frontiers of nuclear science unlike anything before!





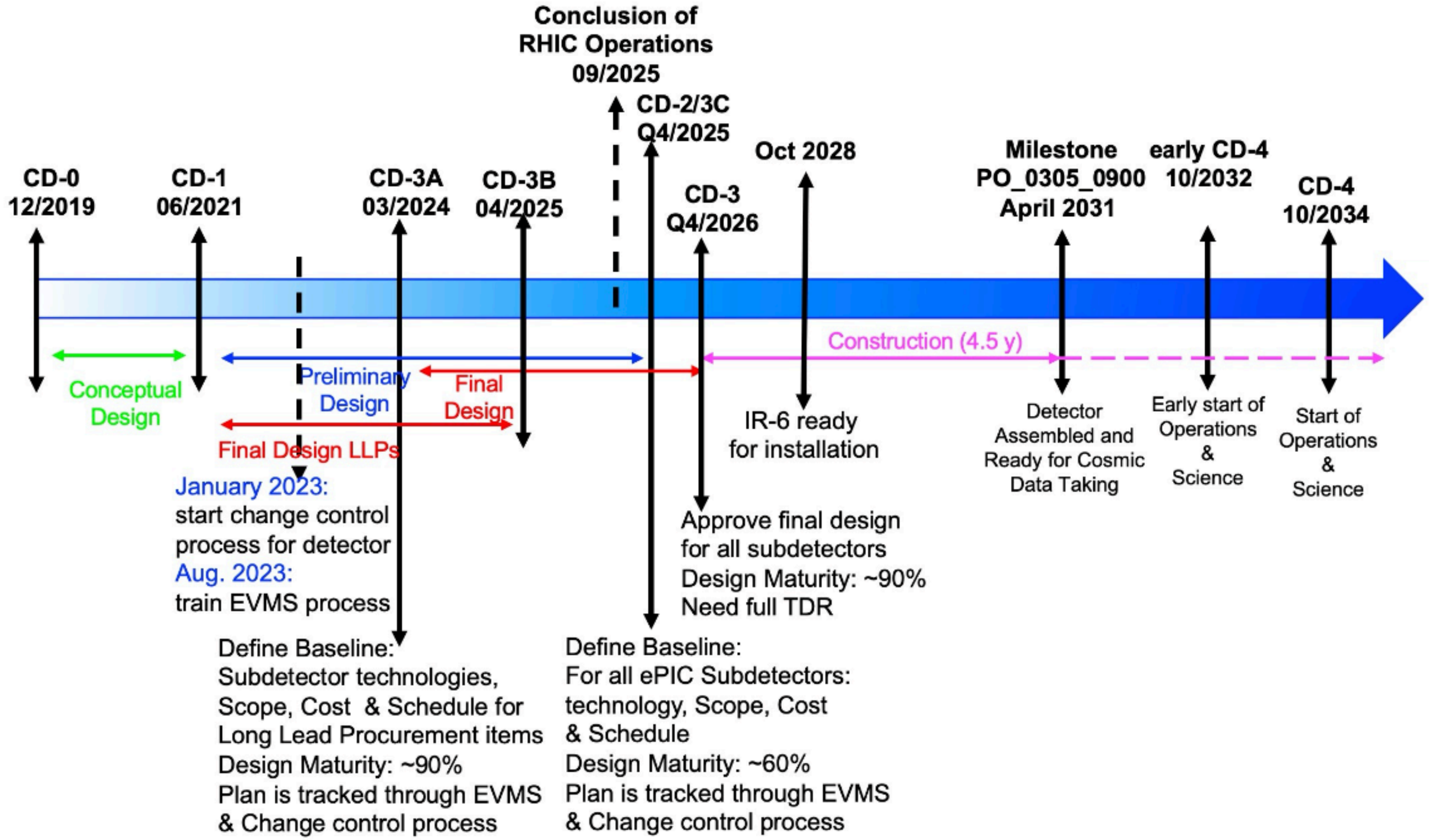



Backup Follows

# Where Are We?


ePIC Collaboration currently working towards TDR

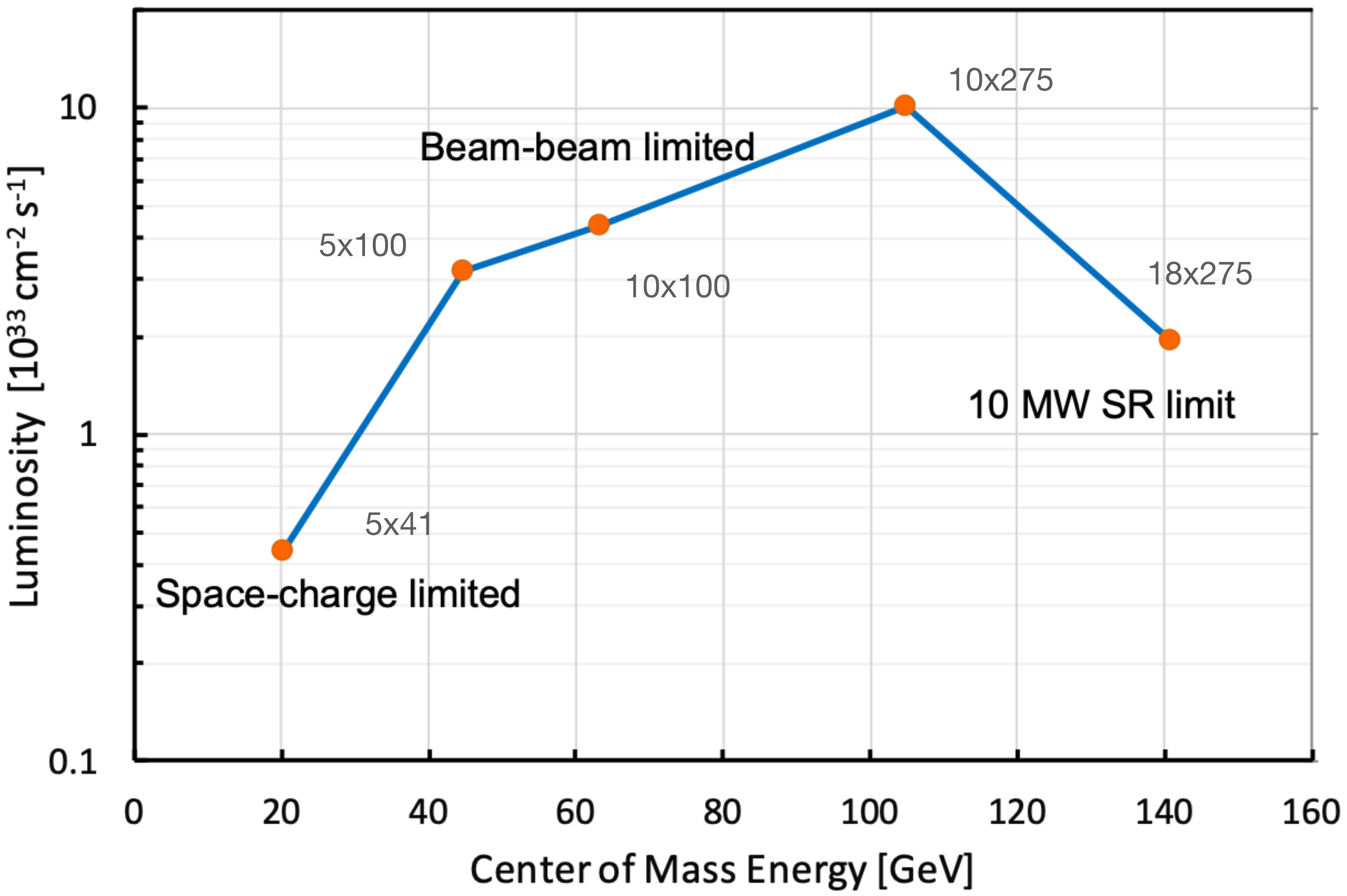
# Where Are We?



Conclusion of
RHIC Operations
09/2025
CD-2/3C
Q4/2025
Oct 2028
Milestone
PO_0305_0900
April 2031
early CD-4
10/2032
CD-0
12/2019
CD-1
06/2021
CD-3A
03/2024
CD-3B
04/2025
CD-3
Q4/2026
CD-4
10/2034
Construction (4.5 y)
Conceptual
Design
Preliminary
Design
Final
Design
Final Design LLPs
January 2023:
start change control
process for detector
Aug. 2023:
train EVMS process
IR-6 ready
for installation
Detector
Assembled and
Ready for Cosmic
Data Taking
Early start of
Operations
&
Science
Start of
Operations
&
Science
Approve final design
for all subdetectors
Design Maturity: ~90%
Need full TDR
Define Baseline:
Subdetector technologies,
Scope, Cost & Schedule for
Long Lead Procurement items
Design Maturity: ~90%
Plan is tracked through EVMS
& Change control process
Define Baseline:
For all ePIC Subdetectors:
technology, Scope, Cost
& Schedule
Design Maturity: ~60%
Plan is tracked through EVMS
& Change control process

# Luminosity Design

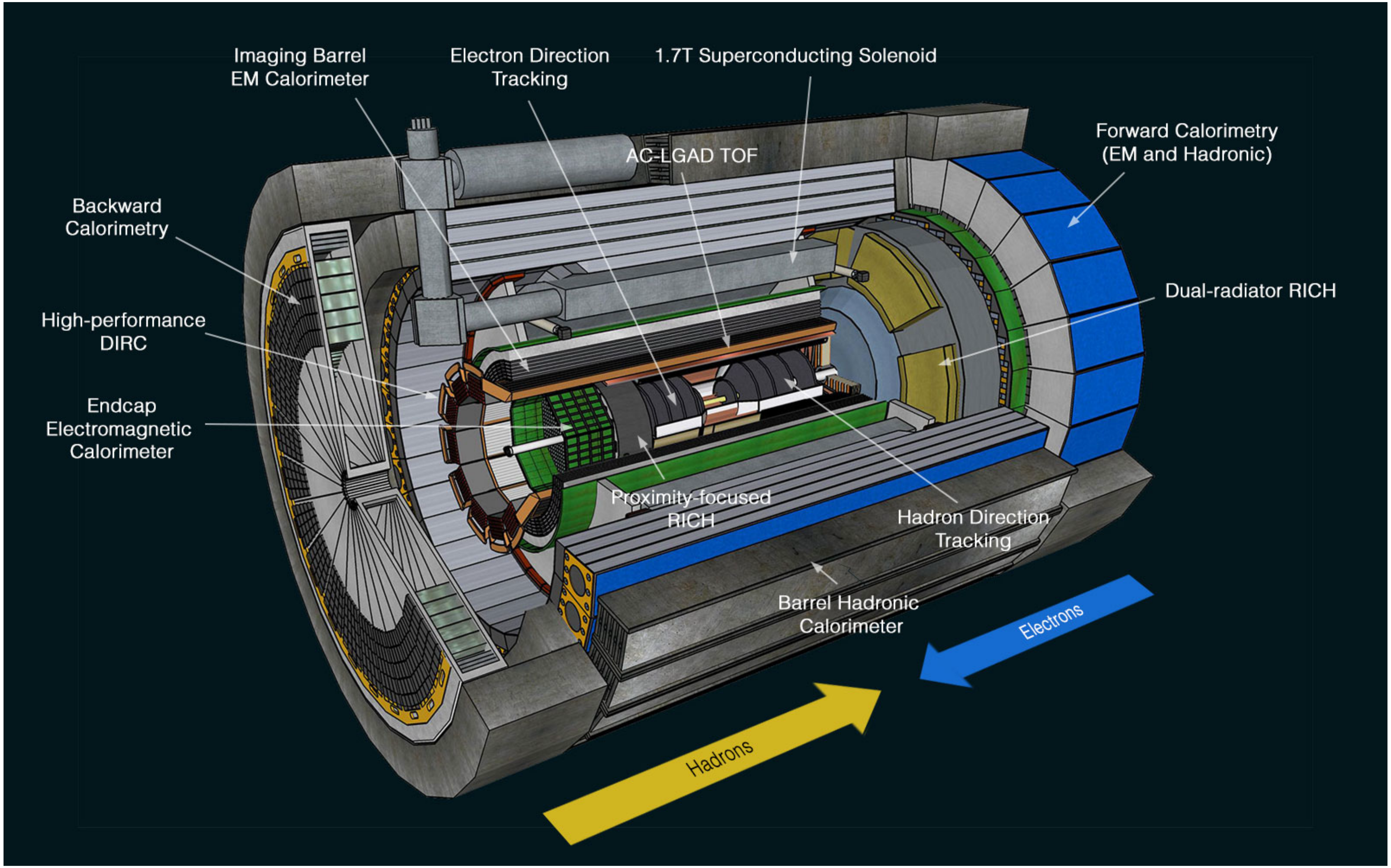
From CDR: https://www.bnl.gov/ec/files/eic_cdr_final.pdf




e-p shown

e-N luminosities in e-A collisions similar within factor of 2 - 3

# ePIC


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