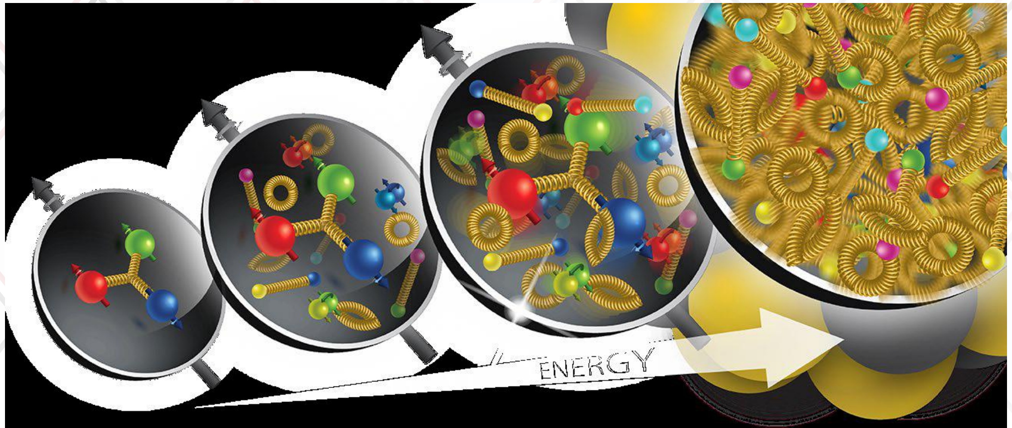
The Electron Ion Collider

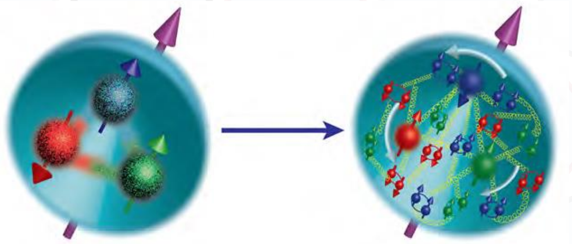
Tokyo University IPMU/ILANCE/ICRR seminar,
October 26, 2022,
Ralf Seidl (RIKEN)

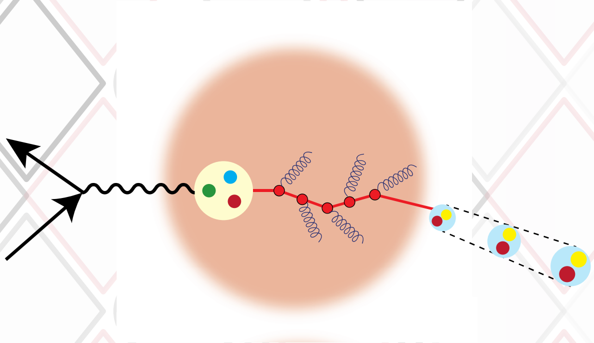


Questions, EIC wants to answer

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

How do the nucleon properties emerge from them and their interactions?

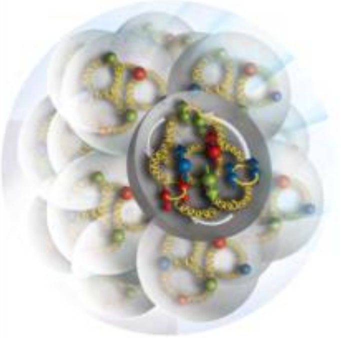




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

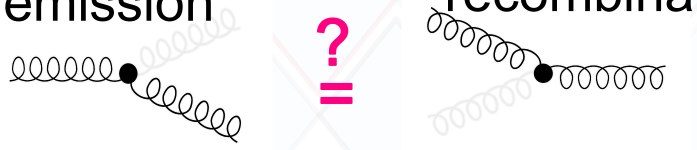
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



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

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



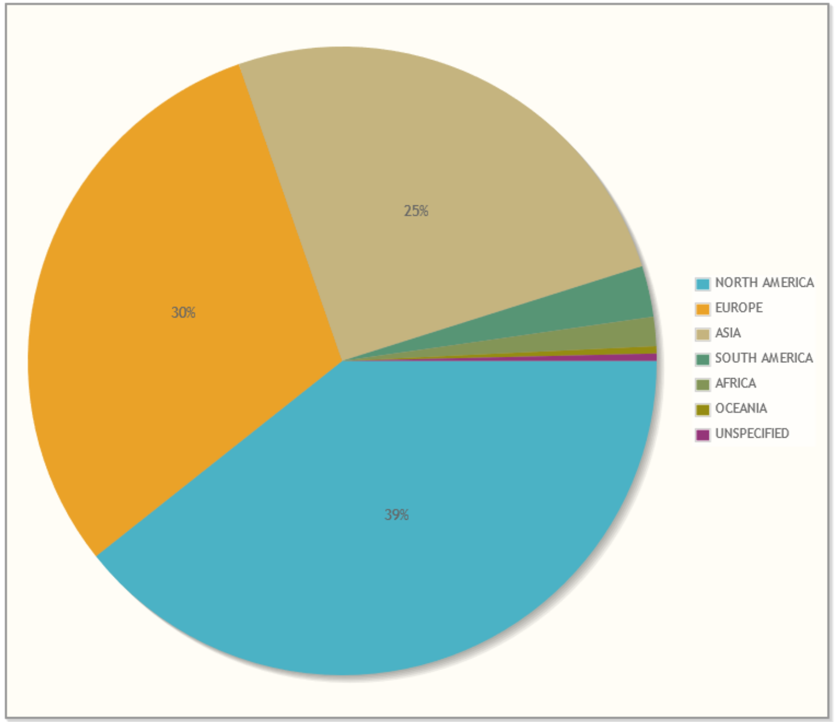
EIC timeline + DOE process

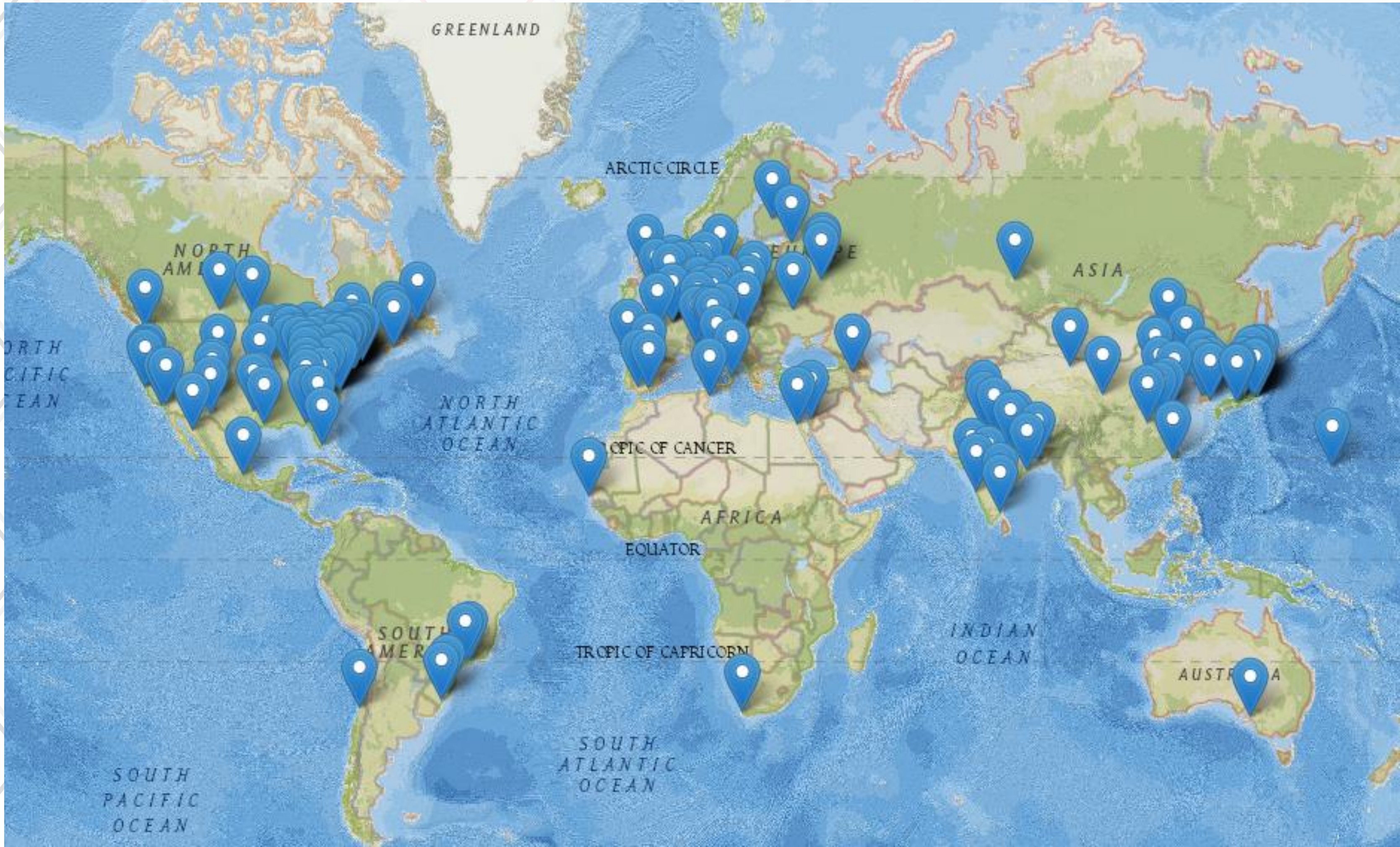
- 2011 INT write-up: Gluons and the quark sea at high energies: Distributions, polarization, tomography ,Daniel Boer *et al.*
- 2012 EIC White paper: Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all , A. Accardi *et al.*
- 2015 NSAC Long range plan: EIC top priority new construction project
- 2018 BNL, JLAB pre-CDRs
- 2019 DOE CD-0 Approved (Mission need). Site Selection →BNL
- 2020 EICUG Yellow Report: Physics and detector requirements
- 2020 EIC CDR
- 2021 DOE CD-1 Approved (alternate selection, cost range)
- 2021/2022 EIC Project Detector proposals → ECCE proposal, ePIC collaboration being formed

The EIC User group

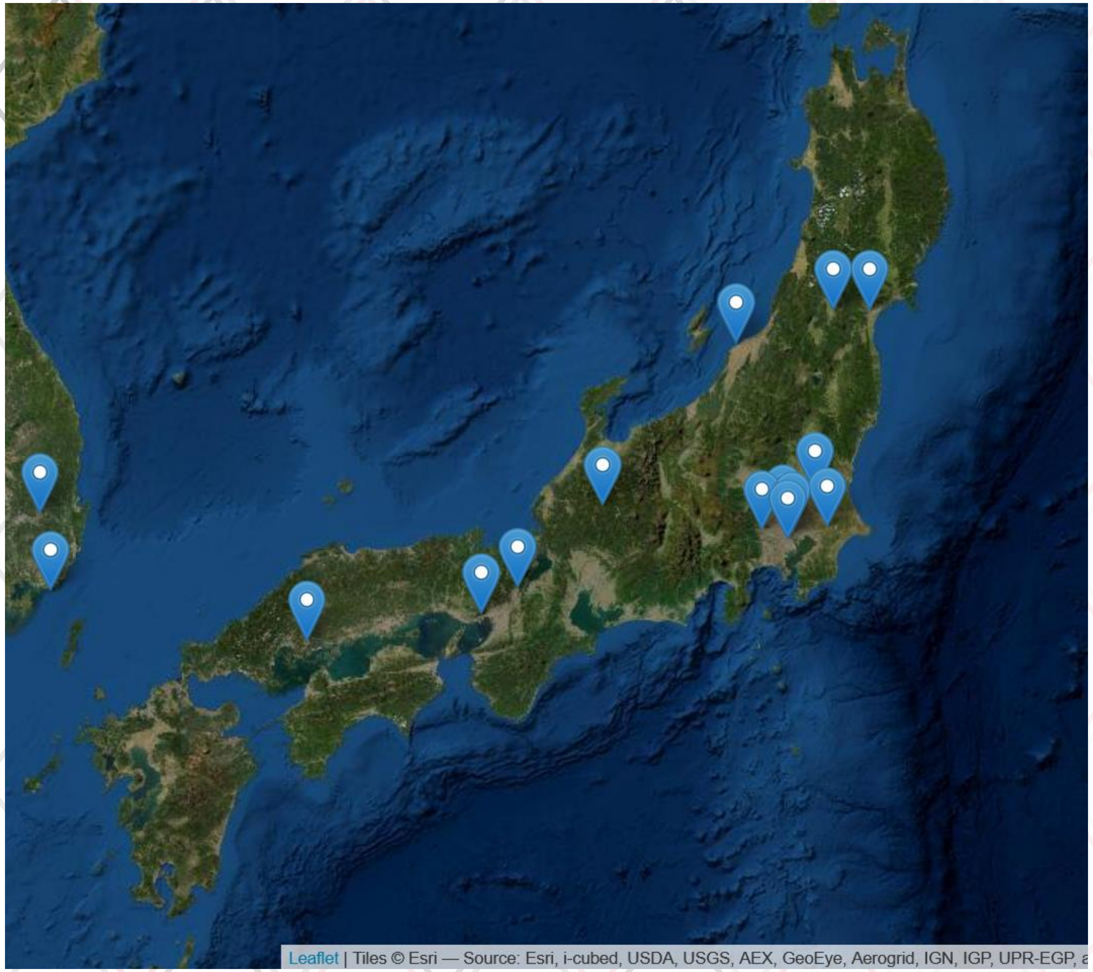
EIC User Group web page: http://www.eicug.org

- **1300** members (experimentalists, theorists, accelerator, etc)
- **>260** institutions
- **36** countries





Japanese groups participating in EIC User group


Leaflet | Tiles © Esri — Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Aerogrid, IGN, IGP, UPR-EGP, a

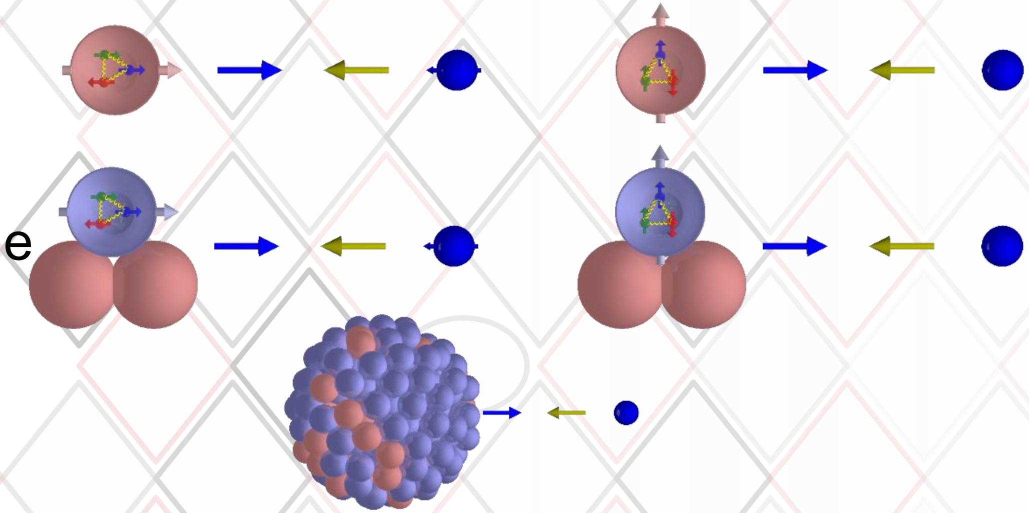
- Yamagata University
- RIKEN
- Kobe University
- KEK
- Hiroshima University
- Niigata University
- TiTech
- Tohoku
- Tokyo University of Science
- Shinshu University
- Kyorin University
- Juntendo University

EIC accelerator to be build at BNL

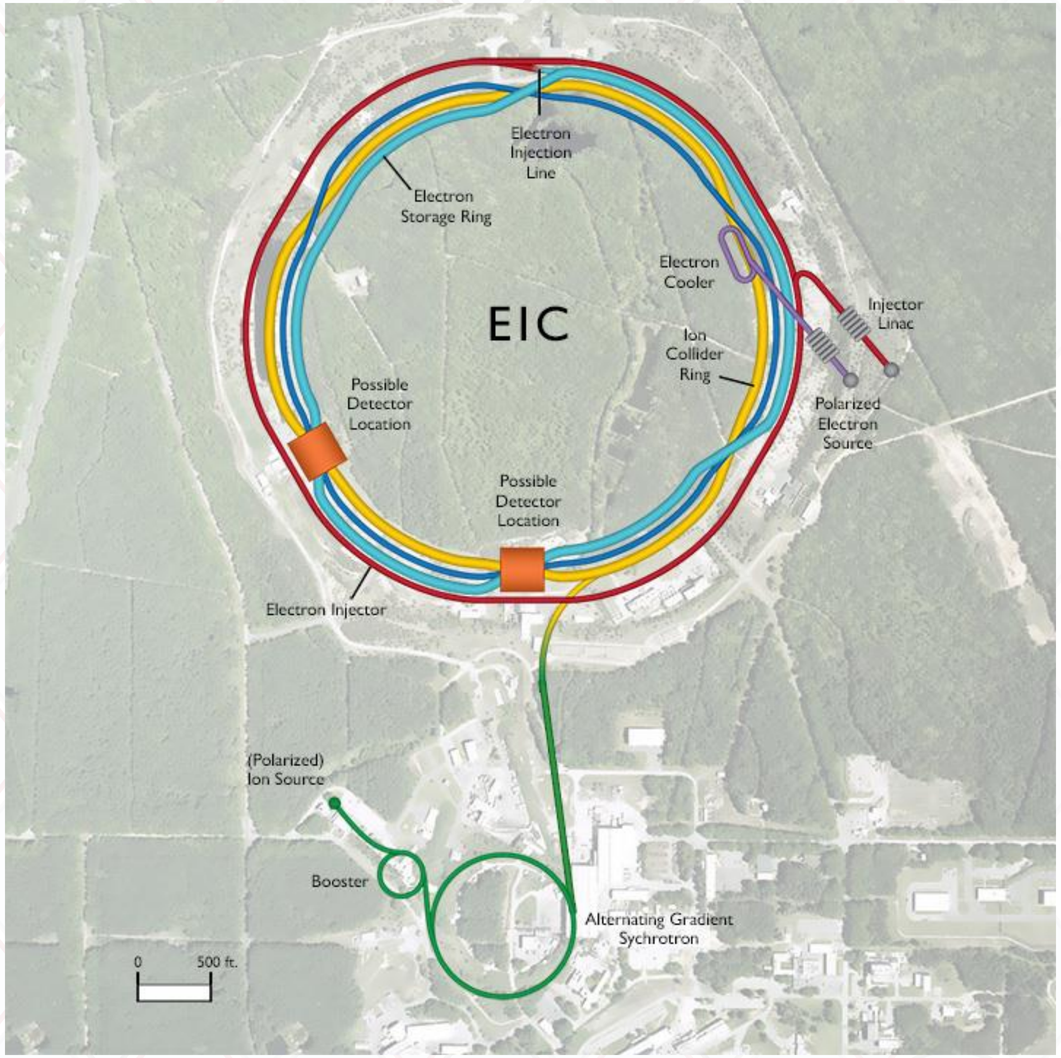
e+p

e+^{3}He

e+A



- 80% polarized electrons from 5-18 GeV
- 70% polarized protons from 40-275 GeV
- Ions from 40-110 GeV/u
- Polarized light ions 40 -184 GeV (^{3}He)
- CMS energies $\sqrt{s}$ = 29 – 140 GeV
- 1000x HERA luminosities: 10^{33}-10^{34} cm^{2}s^{-1}
- CD1 obtained in July 2021



EIC Goals:

Spin of the nucleon:

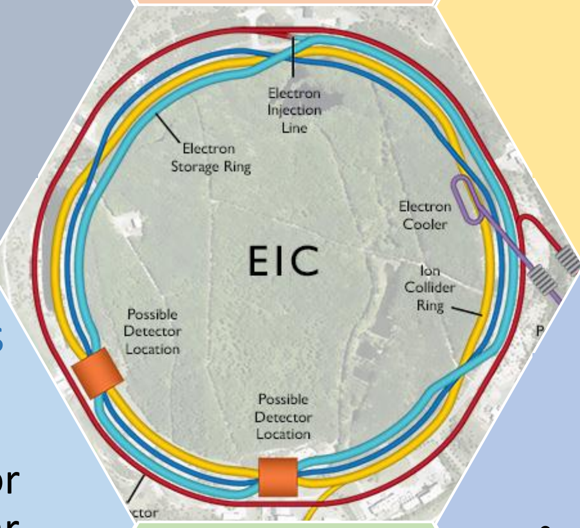
- Gluon spin
- Role of Sea quarks

QCD at high gluon densities

- Saturation effects

Tomography :

- 3D momentum structure (q, g Sivers, Tensor charge, TMD Evolution)
- 3D spatial structure



Nucelar effects

- Nuclear PDFs
- Passage of color through nuclear matter (nFFs, p_T broadening)

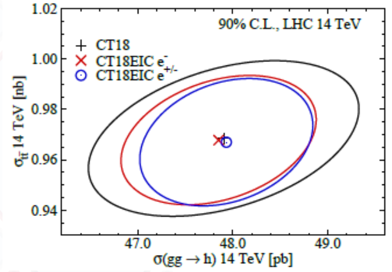
Origin of the Mass

- Axial anomaly contributions
- Hadron structure

Other

- Spectroscopy (XYZ)
- EW physics
- Fragmentation
- Unpol PDFs

Direct EIC benefits for the HEP/ASTRO community



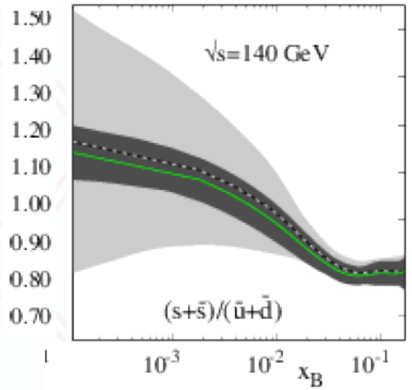
- PDFs at higher x and moderate Q^2 → searches
- K_t-dependent (unintegrated) PDFs → Higgs/heavy boson P_t spectra, searches

→ low-x physics

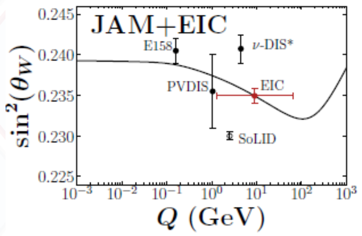
- e-A collisions (nPDFs, nFFs) → Astro-particle (air, ν)

→ Heavy Ion physics cold baseline

→ low-x physics



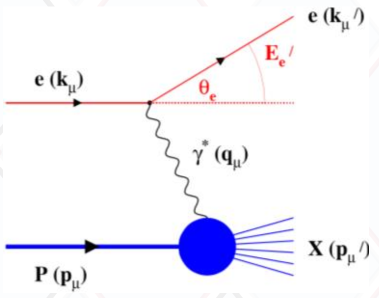
- Flavor decomposed PDFs via SIDIS → strange suppression mystery (Atlas<->CMS)
- Tensor charge measurements → indirect BSM searches



Tools at an EIC and basic requirements

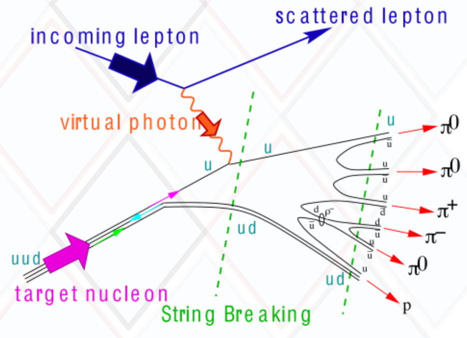
Inclusive Reactions in ep/eA:

- Physics: Structure Fcts.: g_1, F_2, F_L
- Very good electron id → identify scattered lepton
- Momentum/energy and angular resolution of e' critical
- scattered lepton → kinematics of event (x,Q^2)



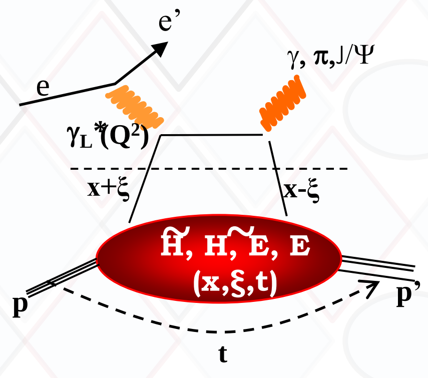
Semi-inclusive Reactions in ep/eA:

- Physics: TMDs, Helicity PDFs, FF → flavor separation, dihadron-corr.,…
  → Pion, Kaon asymmetries, cross sections
- Excellent particle ID: $\pi^\pm$,$K^\pm$,$p^\pm$ separation over a wide range in $-3<\eta<3$
  → excellent p resolution at forward rapidities
- TMDs: full Φ-coverage around γ^*, wide p_t coverage
- Excellent vertex resolution → Charm, Bottom separation



Exclusive Reactions in ep/eA:

- Physics: DVCS, excl. VM/PS prod. → GPDs, parton imaging in $b_{T;}$ $g(x,Q^2,b_T)$
- Exclusivity → large rapidity coverage → rapidity gap events
  ↘ reconstruction of all particles in event
- high resolution, wide coverage in t → b_t → Roman pots
- eA: veto nucleus breakup, determine impact parameter of collision
  → acceptance for neutrons in ZDCs



DIS Kinematics

- easiest case via scattered lepton l' (other methods include hadronic final state)
- Calculate DIS variables: x, y, Q^2, W^2
- Typical DIS events : Q^2>1 GeV^2, W^2>10 GeV^2, 0.01<y<0.95

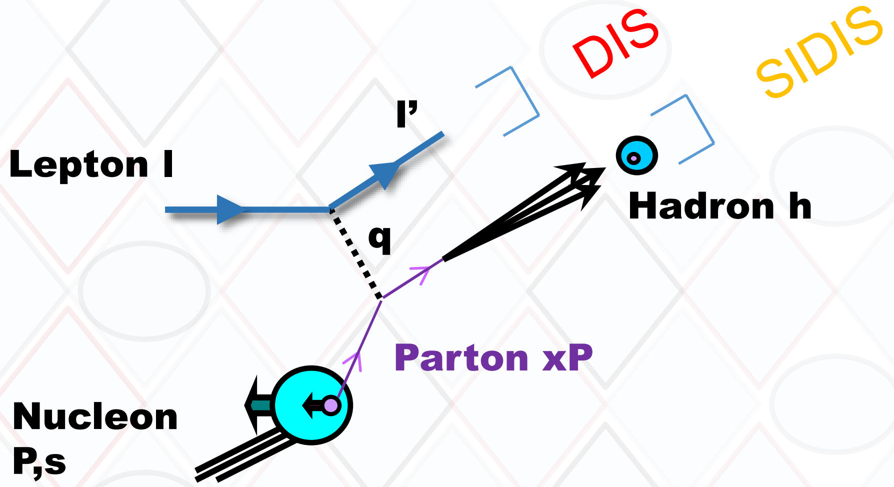
$$\frac{d^2\sigma^i}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\eta^i\left[Y_+F_2^i \pm Y_-xF_3^i - y^2F_L^i\right]$$

$$F_L^i = F_2^i - 2xF_1^i$$

$$\boxed{F_2^\gamma = x\sum_q e_q^2\left(q(x,Q)+\overline{q}(x,Q)\right)}$$

$$\frac{d^2\Delta\sigma^i}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\eta^i\left[Y_+2g_5^i - g_L^i \mp Y_-2xg_1^i + y^2g_L^i\right]$$

$$\boxed{g_1^\gamma = x\sum_q e_q^2\left(\Delta q(x,Q)+\Delta\overline{q}(x,Q)\right)}$$



$$q = l - l'$$

$$Q^2 = -q^\mu q_\mu$$

Momentum transfer

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

Parton momentum fraction*

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

Inelasticity

$$W^2 = M_p^2 + (1-x)Q^2/x$$

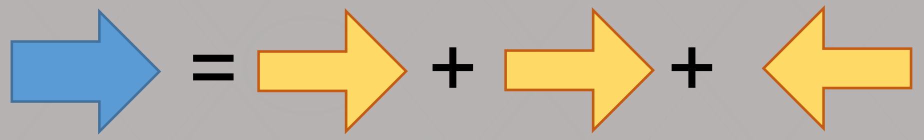
Mass of had final state

$$z = \frac{p\cdot P_h}{p\cdot q}$$

SIDIS hadron momentum fraction

The Spin sum rule

Naïve Quark Model picture: 3 valence quarks make up the spin of the nucleon:



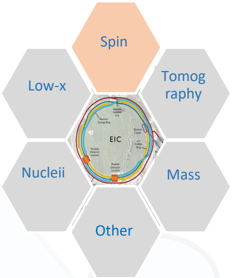
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$ Jaffe, Manohar

Quark spin Gluon spin Orbital angular momentum

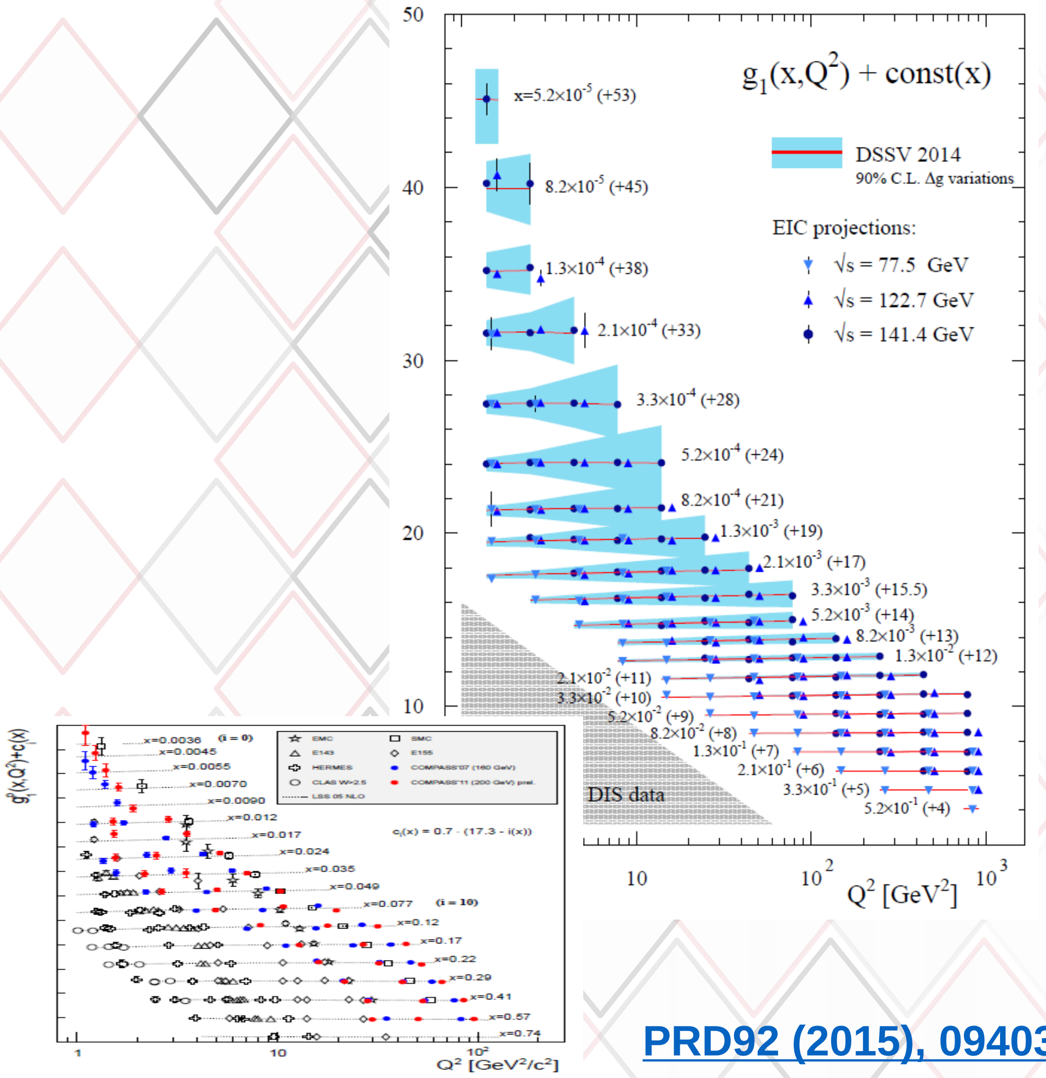
$$\Delta\Sigma = \int dx \left[(\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))\right]$$

- Spin Crisis (1980s): Quark spin contributes only little
- ΔΣ and ΔG can be accessed in longitudinally polarized (SI)DIS and pp collisions (currently for x>0.01)
- Where is the rest of the spin? Gluons? Lower momentum fractions? Orbital angular momentum?

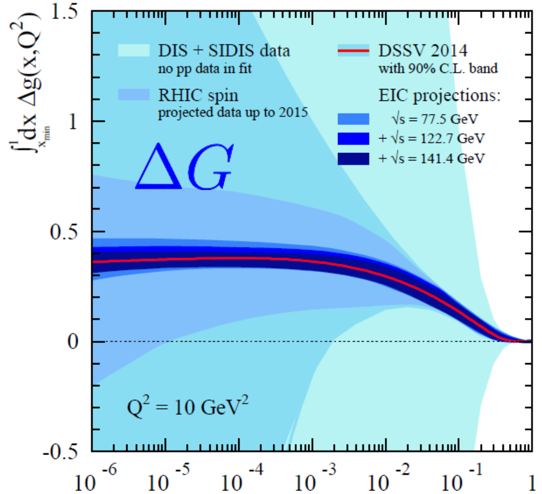
Inclusive DIS and Δg(x)



- Currently no lever arm to access gluon helicities via DIS (lepton-proton scattering)
- Nonzero gluon polarization found from 200/510 GeV RHIC data
- EIC: Several orders of magnitude of Q^2 at same x allows to determine gluon helicity via DGLAP (scale) evolution



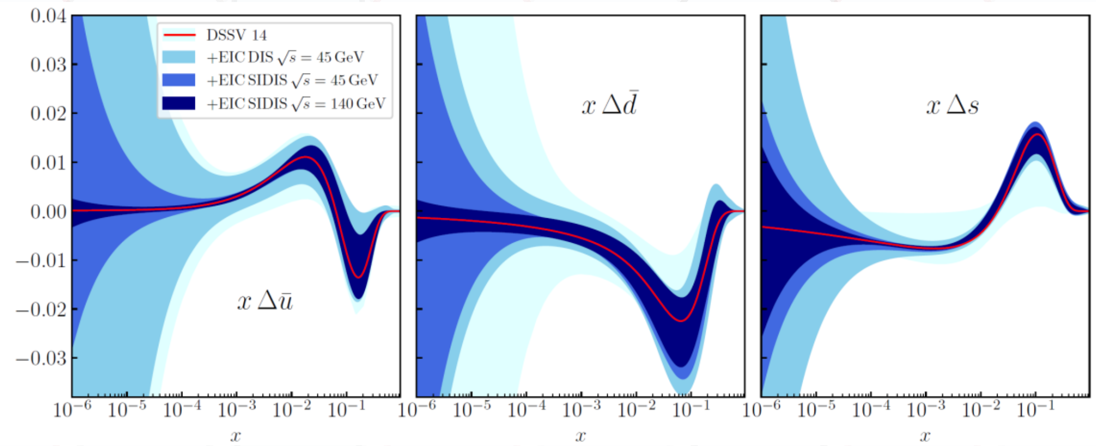
PRD92 (2015), 094030

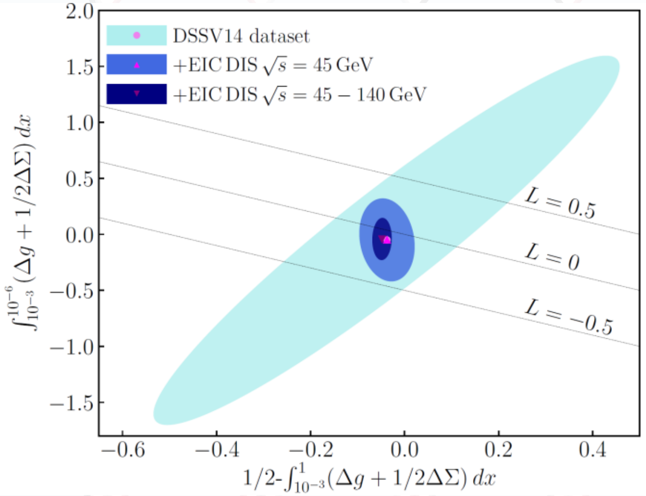


PRD92 (2015), 094030

Gluon and sea polarization

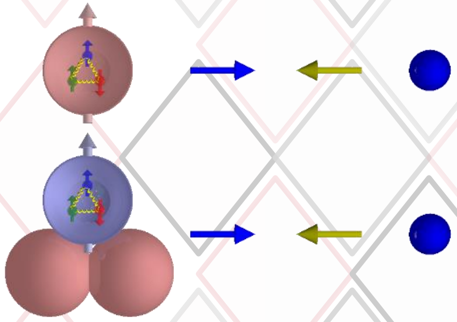
- 1 year of EIC running will pin down gluon polarization
- Using SIDIS: precise determination of sea quark helicities, especially strange contribution of interest
- Indirect determination of orbital angular momentum via sum rule
- Also interesting access to flavor via charged current reactions

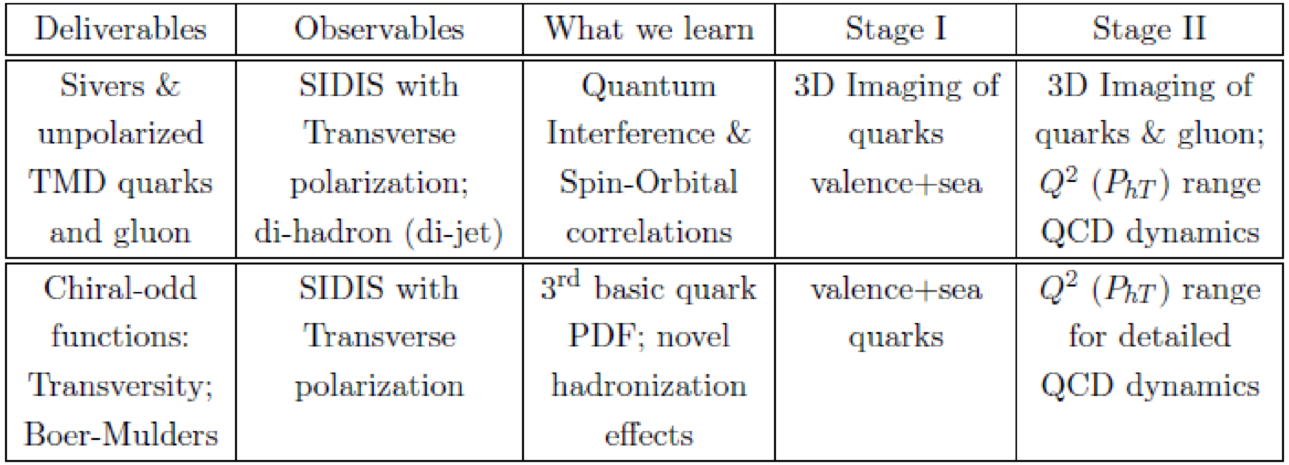




PRD 102 (2020), 094018

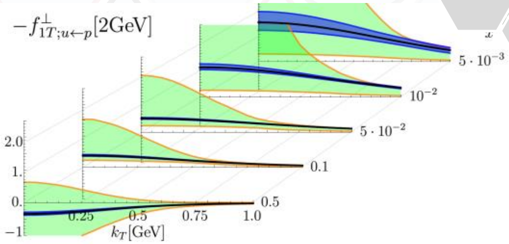
Motivation: 3D Transverse spin and momentum structure

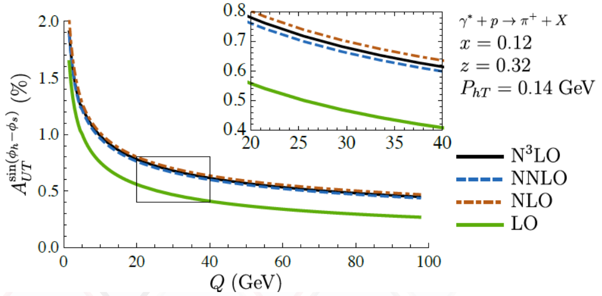


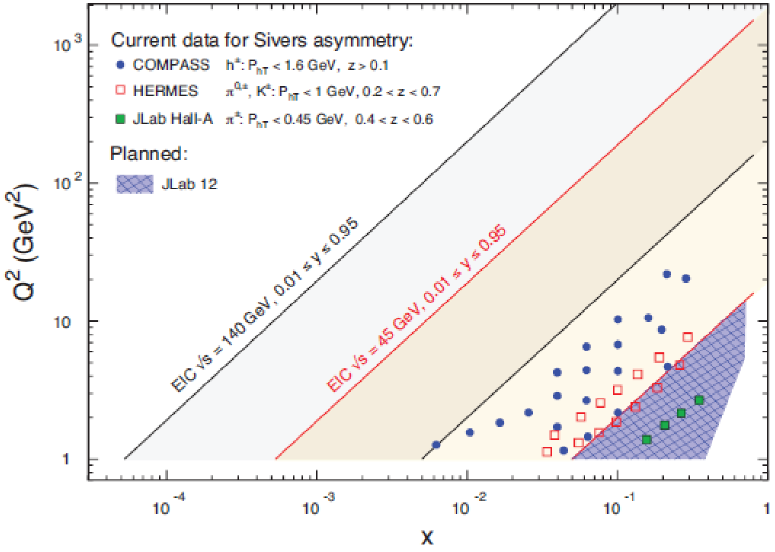


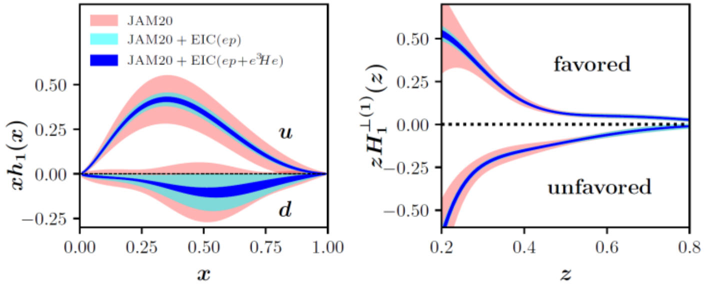
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3^{rd} basic quark PDF; novel hadronization effects	valence+sea quarks	Q^2 (P_{hT}) range for detailed QCD dynamics

Tables from original EIC white paper

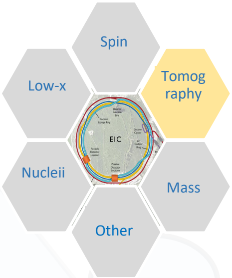






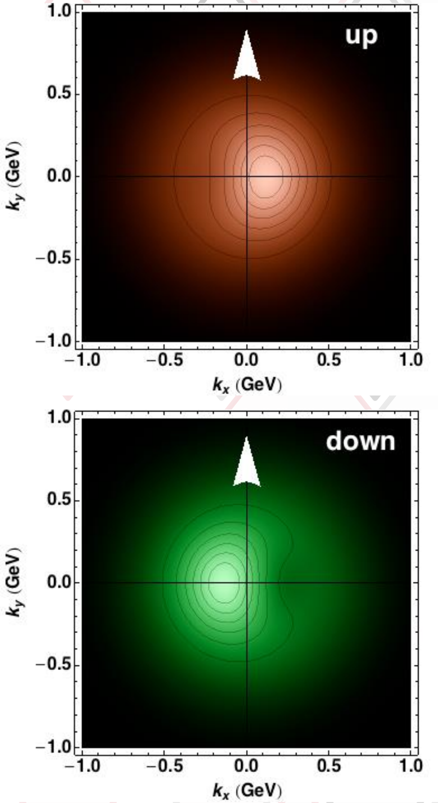


Current coverage for transverse spin related measurements

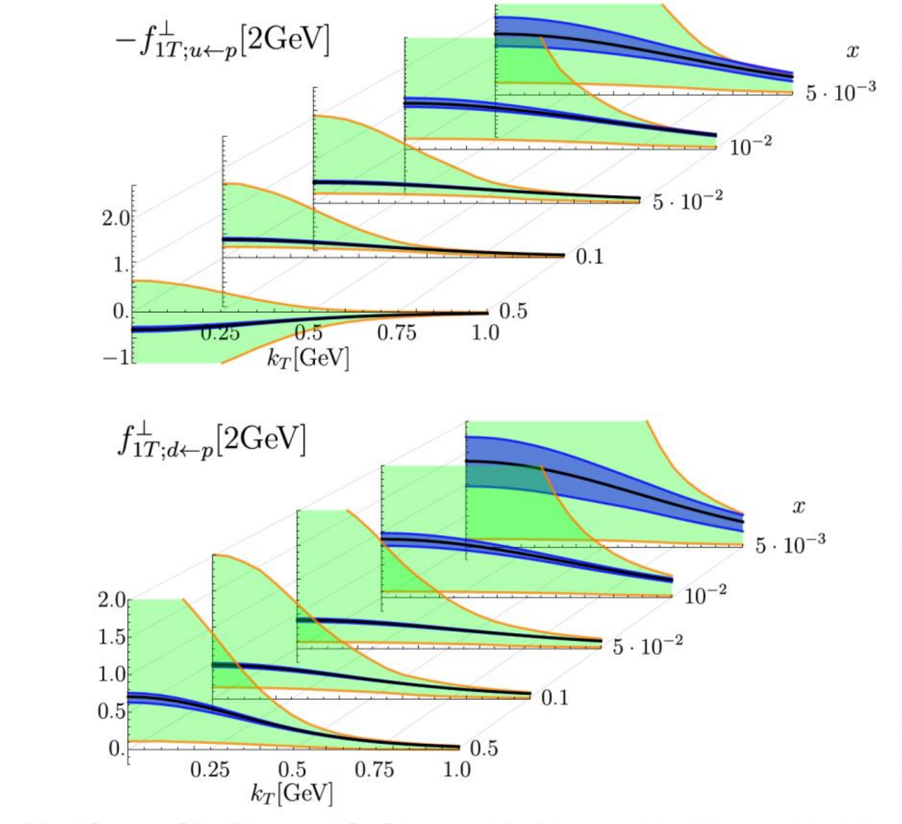


EIC impact for Sivers Functions

Transverse momentum imbalance of unpolarized partons in a transversely polarized nucleon <-> model dependent relation to orgbital angular momentum

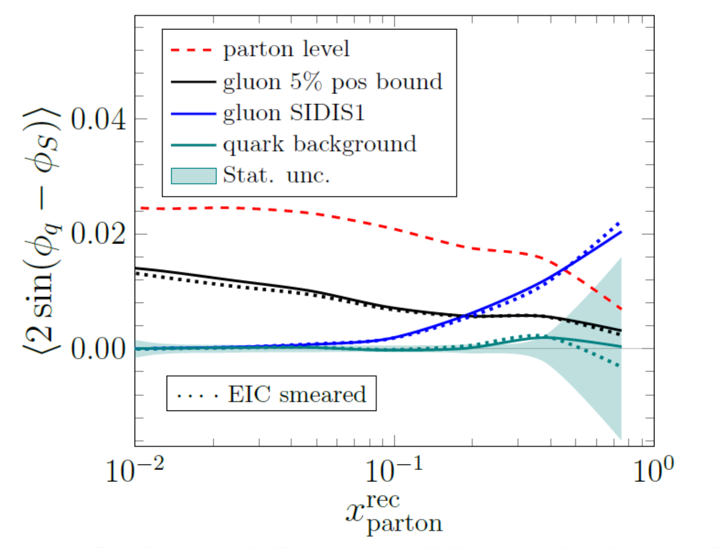


Bacchetta, Radici,
PRL 107 (2011) 212001



YR: Fig 7.53
Vladimirov, et al

- Precise nucleon image in momentum space for quarks, sea-quarks and gluons



YR Fig 7.55
Xiao, et al

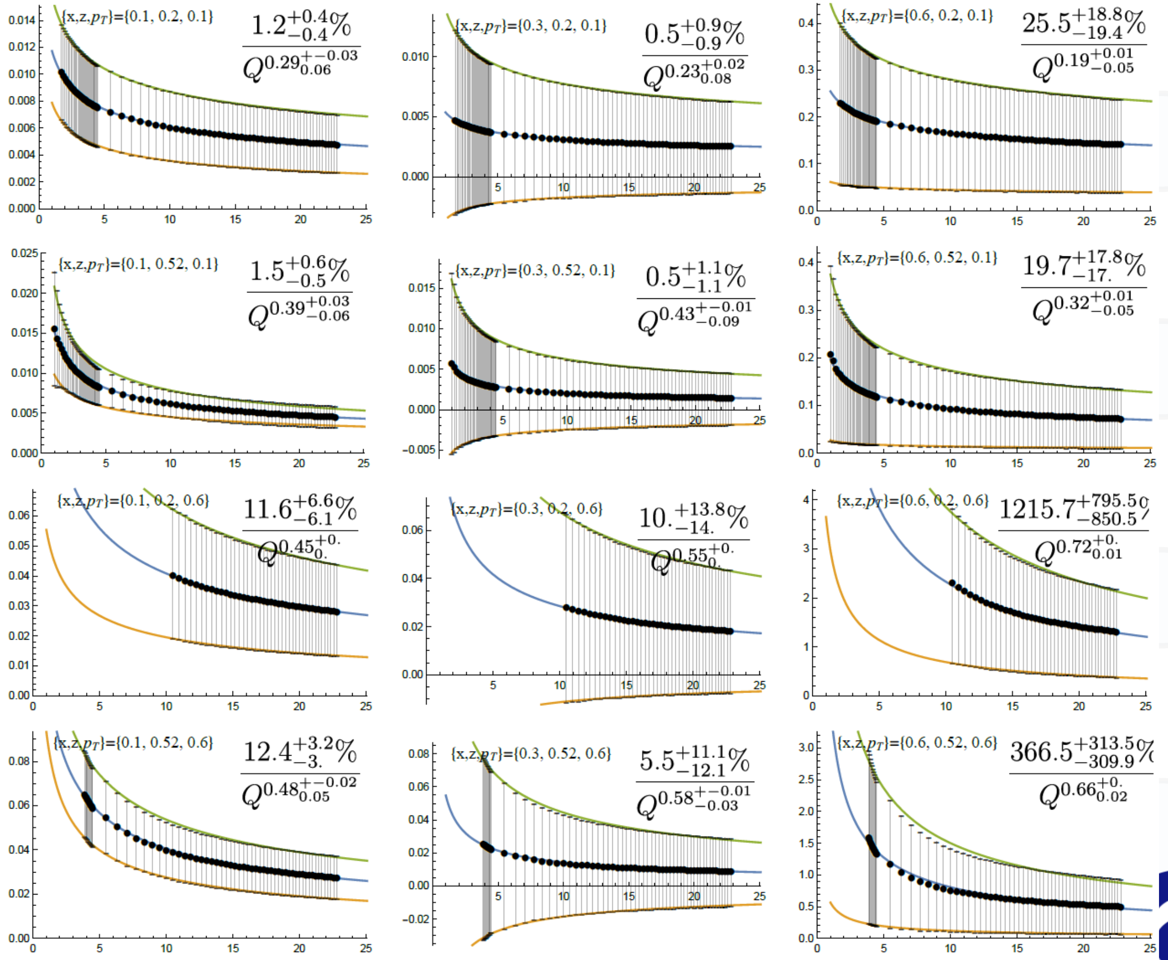
EIC access to TMD evolution

- Very important aspect is the study of TMD evolution
- Sivers asymmetries are expected to decrease at higher scales, but only logarithmically (ie they do NOT "disappear")
- At higher x Asymmetries of several % expected

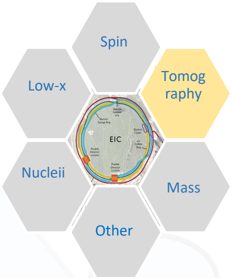
➔Well accessible with EIC over wide range in x and Q^2

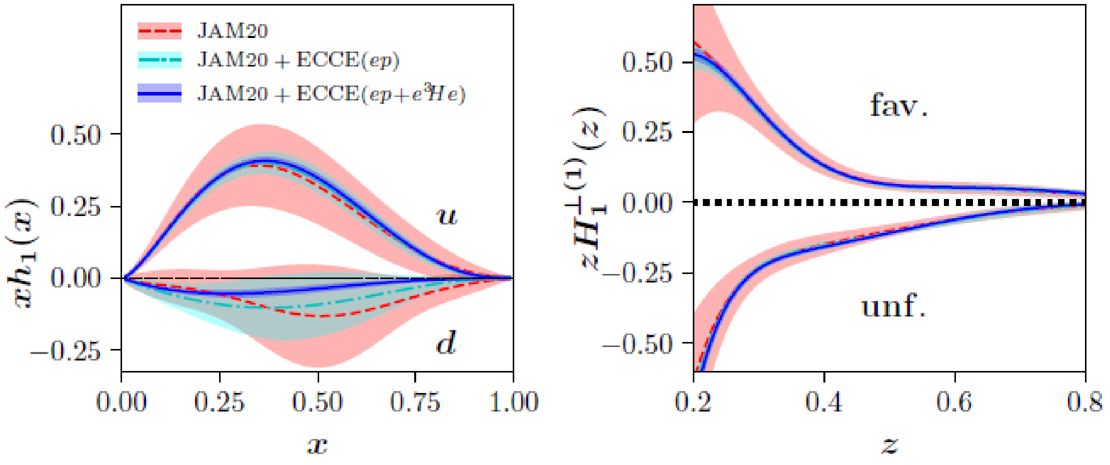
➔Lower x to study sea and glue (both mostly unknown)

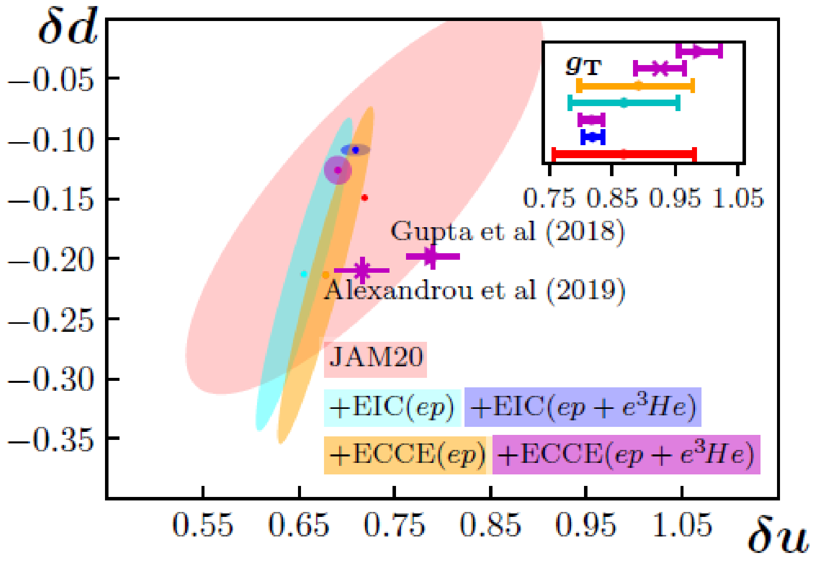
Vladimirov et al.



Tensor charges



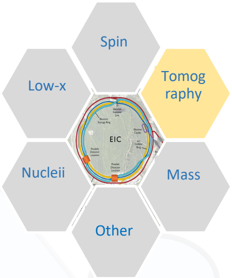




hep-ex:2207.10890

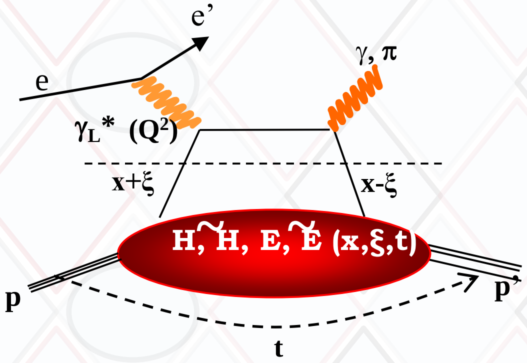
- Precise determination of tensor charges via Collins and di-hadron channels
- Better precision than lattice → potential access to BSM physics in case of discrepancies
- Preform full integrals, study role of sea quark transversity

Similarly:
Single hadron channel (YR : Fig 7.54 Gamberg et al *Phys.Lett.B* 816 (2021) 136255)
Di-hadron channel (YR : Fig 7.56, Radici)



Spatial imaging of quarks →DVCS

Deeply virtual Compton scattering:



- Access to generalized parton distributions and orbital angular momentum (OAM)
- Ji sum rule allows access to J_q (total angular momentum) via exclusive reactions:

$$J^q = \frac{1}{2}\int dx\, x\left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right]$$

- GPDs related to regular PDFs and form factors:

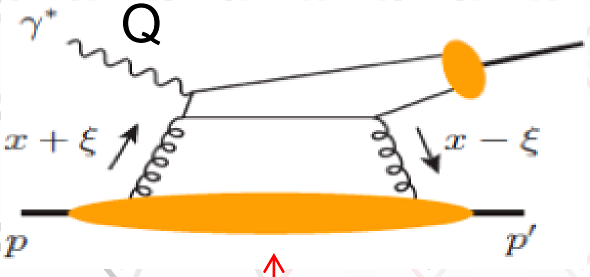
H→ q, $\widetilde{H}$ →Δq for ξ →0

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1^p(t)\,, \qquad \sum_q e_q \int dx\, E^q(x,\xi,t) = F_2^p(t)$$

- Any access to gluon OAM only via Twist 3
- t-dependence as FT of impact parameter →spatial imaging

Spatial imaging of gluon density

- **Exclusive vector meson production:**



J/Ψ, Φ, …

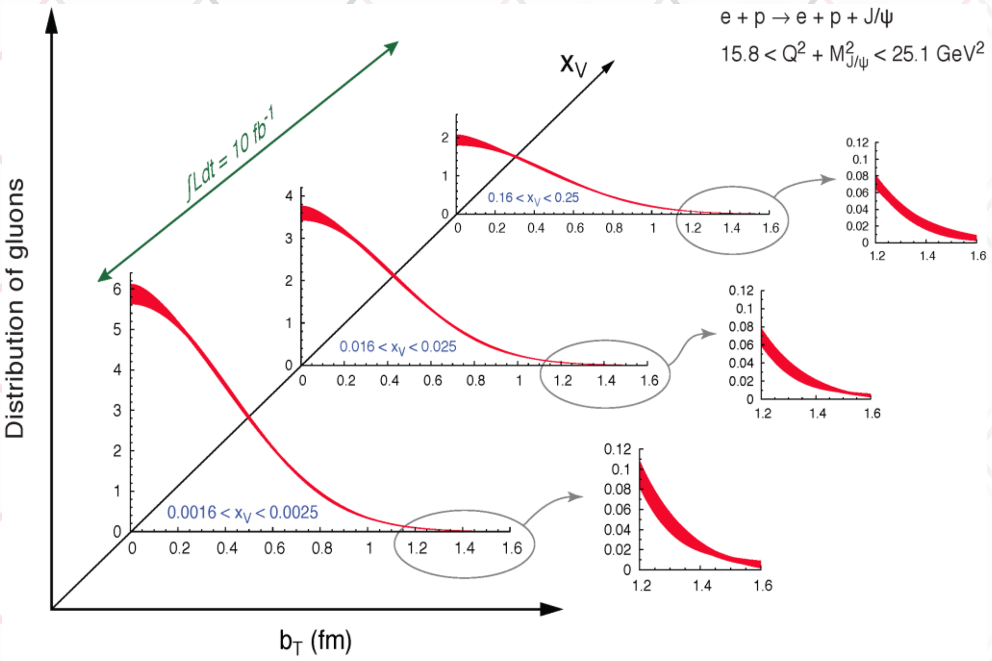
↑ t-dep

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

Fourier transform of the t-dependence

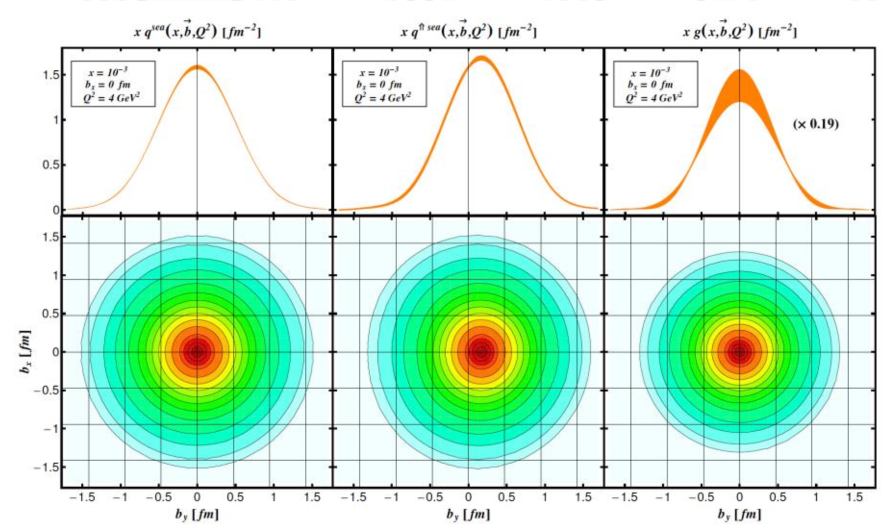
→ Spatial imaging of glue density

- **Gluon imaging from simulation:**

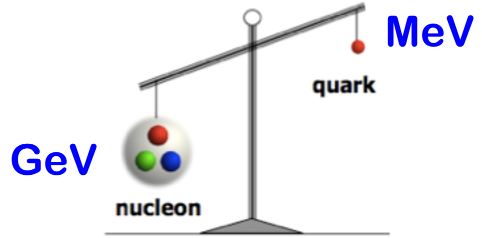


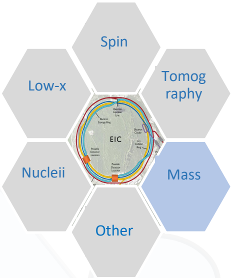
Images of gluons from exclusive J/ψ production

Only possible at the EIC: From the valence quark region deep into the sea quark region



Understanding Mass of Hadrons





Relativistic motion **χ Symmetry Breaking** **Quantum fluctuation**

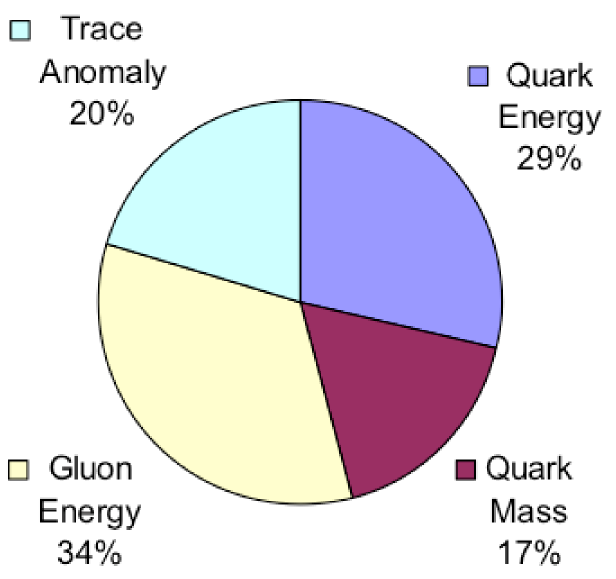
$$M = \overbrace{E_q + E_g} + \chi_{m_q} + T_g$$

Quark Energy **Gluon Energy** **Quark Mass** **Trace Anomaly**

> "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

The 2015 Long Range Plan for Nuclear Science

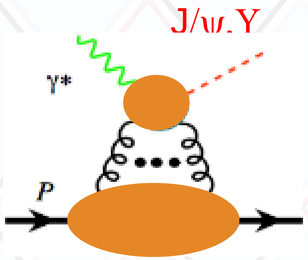
❑ Preliminary Lattice QCD results:



❑ EIC projected measurements:

- ✧ Trace anomaly:

  Upsilon production near the threshold

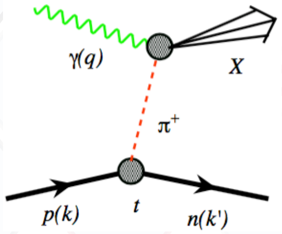


- ✧ Quark-gluon energy:

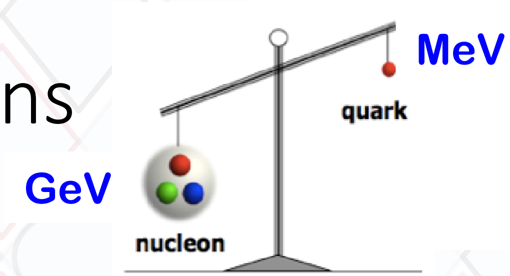
  ∝ *quark-gluon momentum fractions*

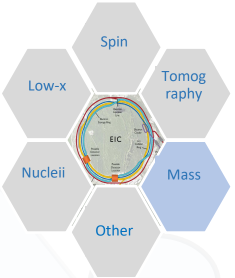
  In nucleon with DIS and SIDIS

  In pions and kaons with Sullivan process



Understanding Mass of Hadrons

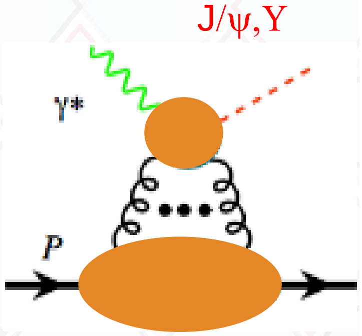


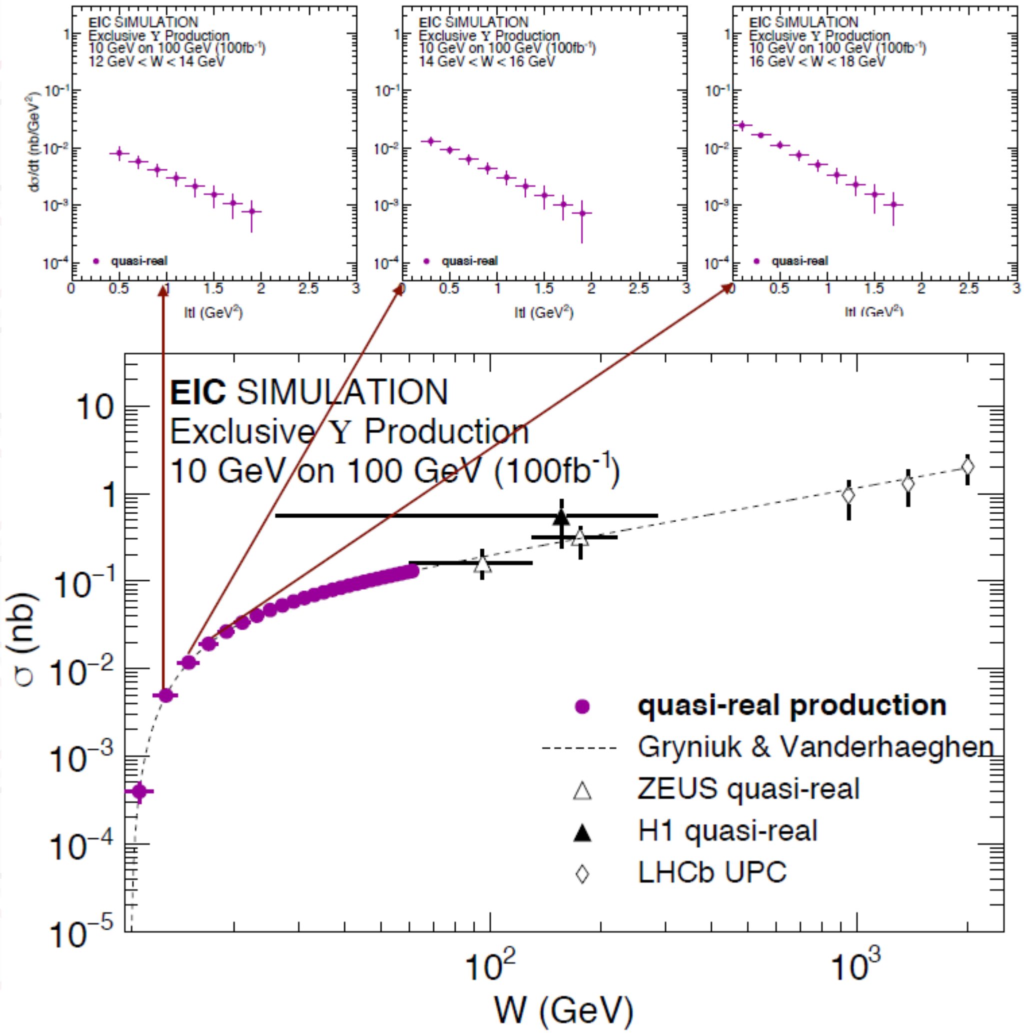


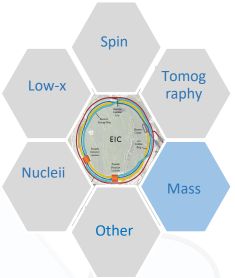
> “… The vast majority of the nucleon’s mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …”

The 2015 Long Range Plan for Nuclear Science

- Access at the EIC:
  - Study trace anomaly contribution via J/Psi/Υ production at threshold

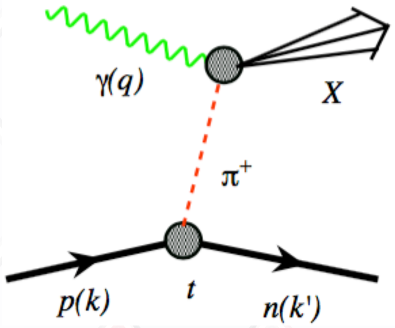


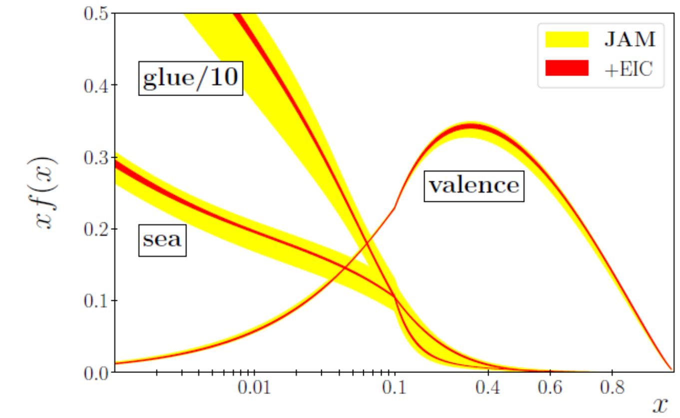


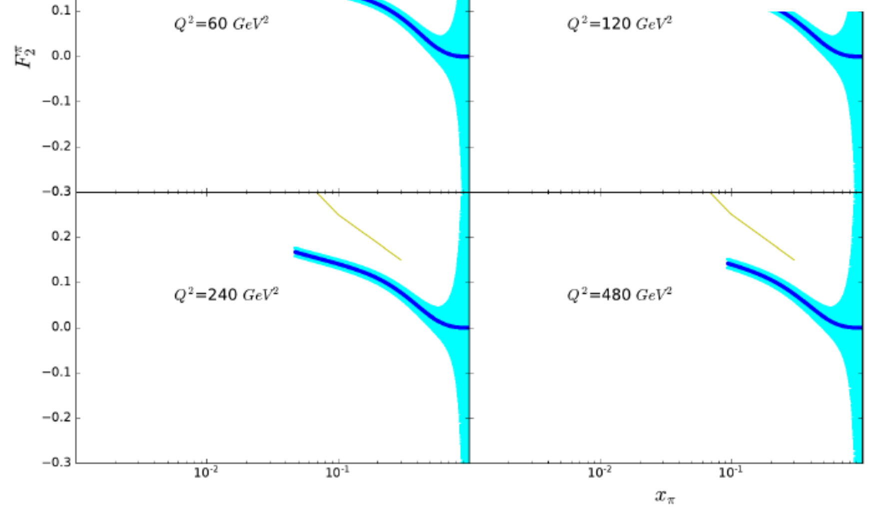


Pion/Kaon structure

- Quark-gluon energy contribution to mass: Use Sullivan process (scattering on virtual meson emitted from nucleon) to extract pion/Kaon Form Factors and PDFs

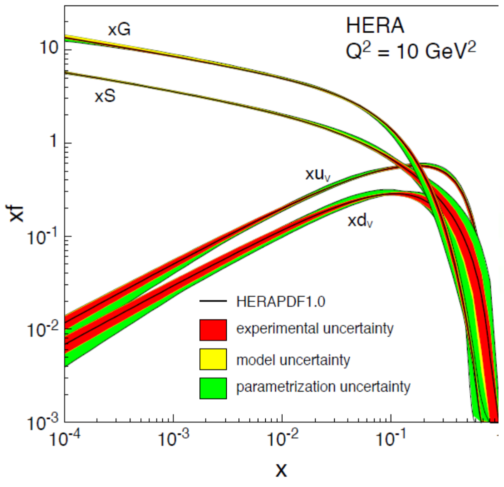


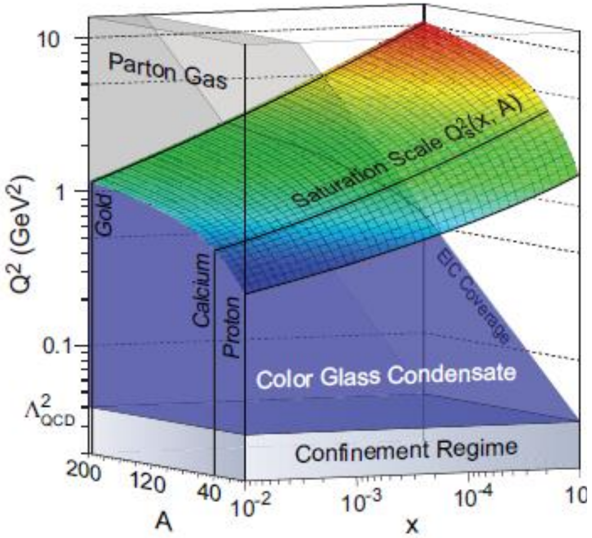


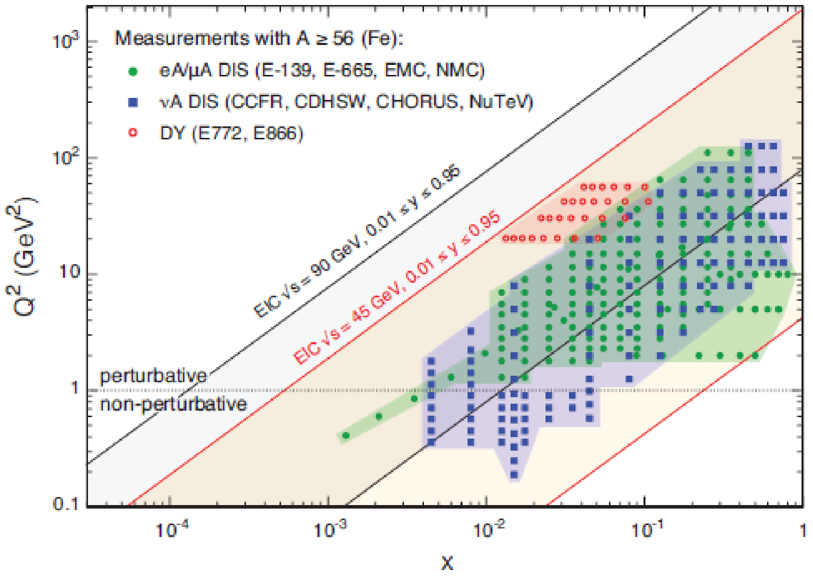


Nuclei at high gluon densities

Deliverables	Observables	What we learn	Stage-I	Stage-II
Integrated gluon momentum distributions $G_A(x, Q^2)$	$F_{2,L}$	Nuclear wave function; saturation	Gluons at $10^{-3} \lesssim x \lesssim 1$	Exploration of the saturation regime
k_T-dependent gluons $f(x, k_T)$; gluon correlations	Di-hadron correlations	Non-linear QCD evolution/universality; saturation scale Q_s	Onset of saturation; Q_s measurement	Non-linear small-x evolution
Spatial gluon distributions $f(x, b_T)$; gluon correlations	Diffractive dissociation $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ vector mesons & DVCS $d\sigma/dt$, $d\sigma/dQ^2$	Non-linear small-x evolution; saturation dynamics; black disk limit	saturation vs. non-saturation models	Spatial gluon distribution; Q_s vs centrality

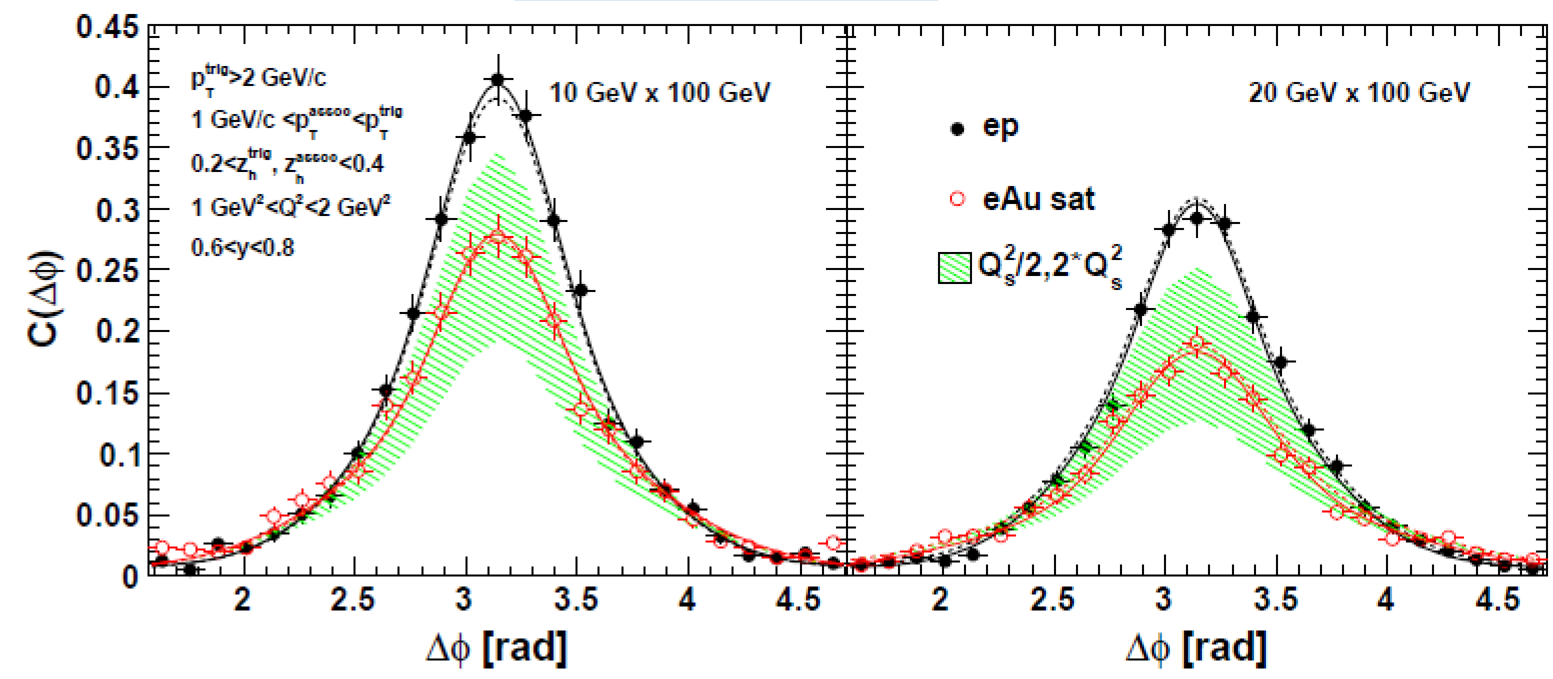


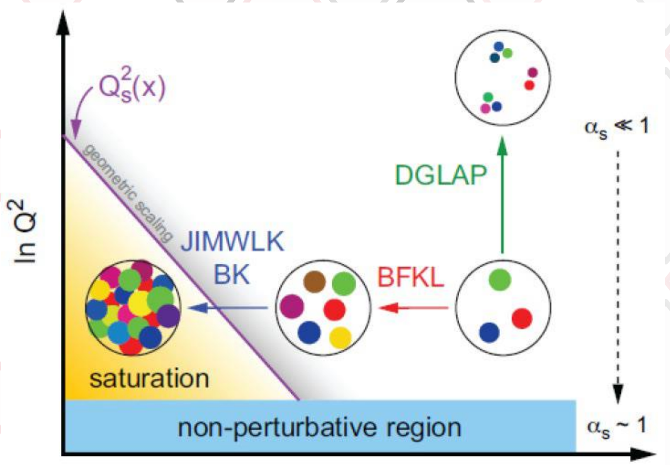




Di-hadron de-correlations to cleanly probe saturation

PRD89 (2014) 074037

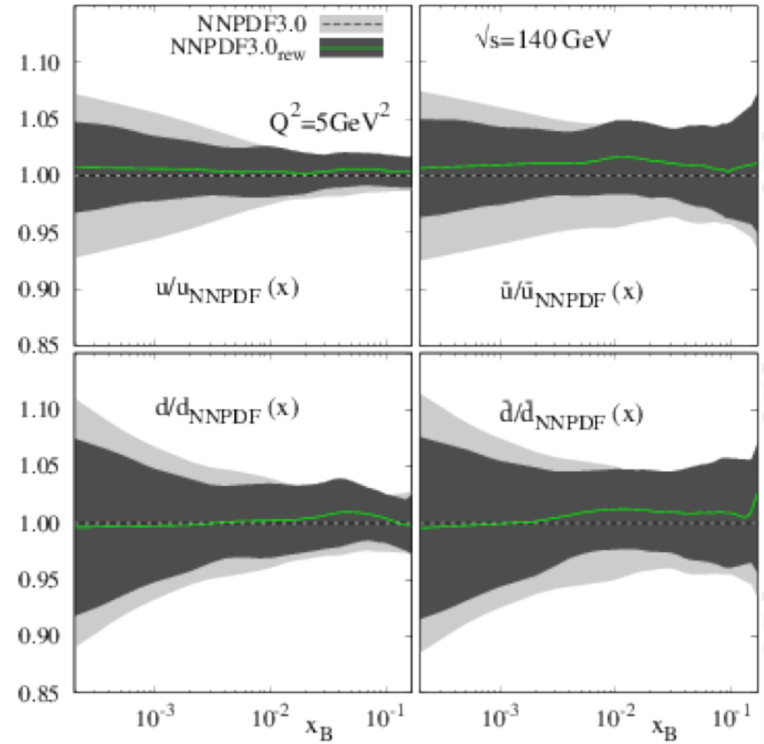


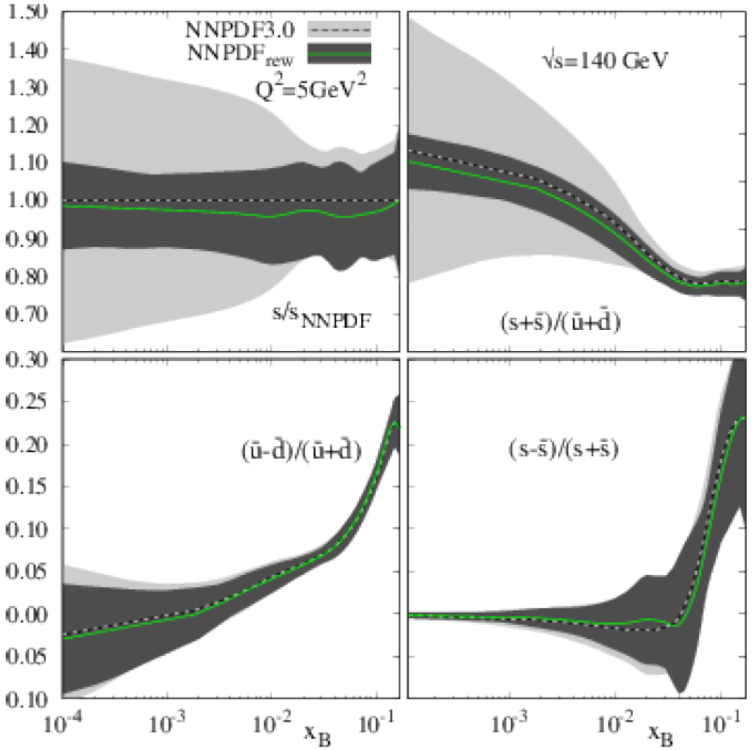


- Measure back-to-back hadron(jet) - hadron or hadron(jet) - photon correlations
- Suppression of away peak as indication for saturation
- Different probes to access different low-x gluon TMDs

Unpolarized PDFs

- Impact on unpolarized PDFs from plain (NC) DIS, PV (CC) DIS and SIDIS
- SIDIS (flavor sensitivity)→Sea quarks, especially strangeness suppression
- Also potential access to intrinsic charm?

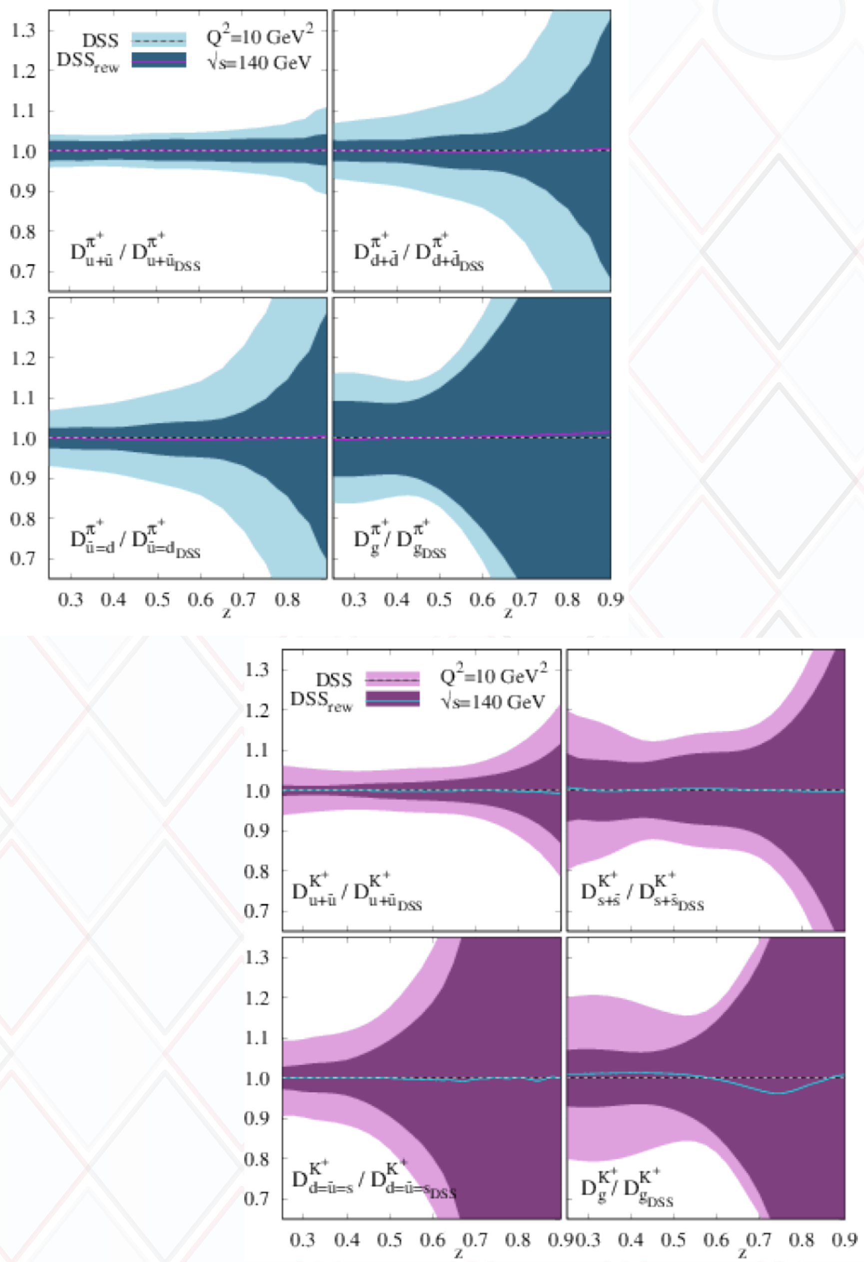




YR Figs 7.8, Aschenauer

FFs

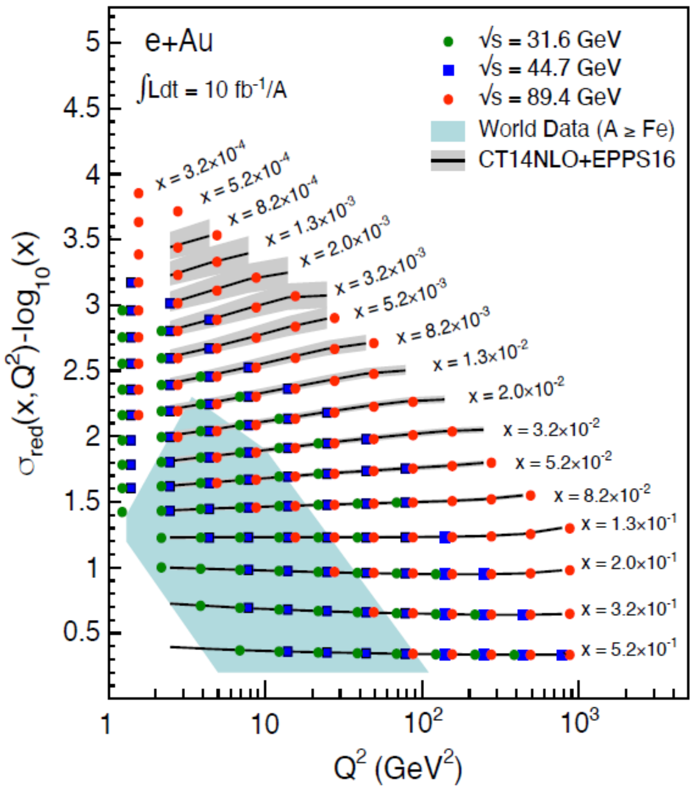
- Fragmentation functions provide information on struck parton, its flavor and spin
- They are a staple of all SIDIS measurements
- Also their understanding will improve further with the EIC



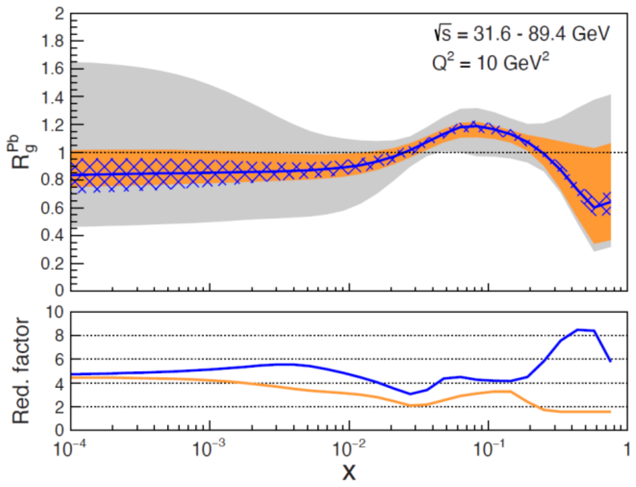
YR Fig 7.84, Aschenauer

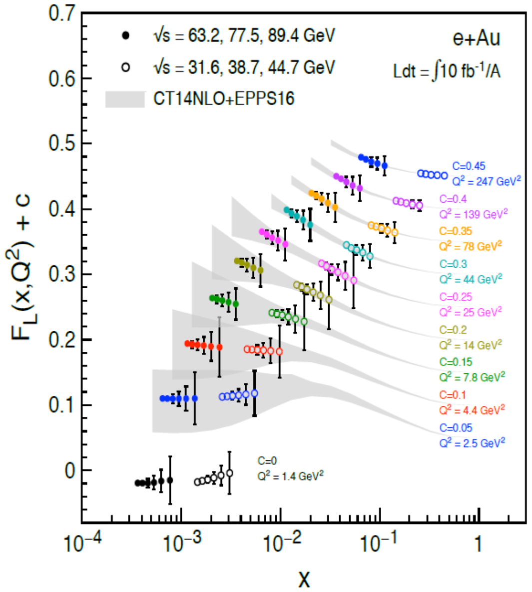
Nuclear PDFs

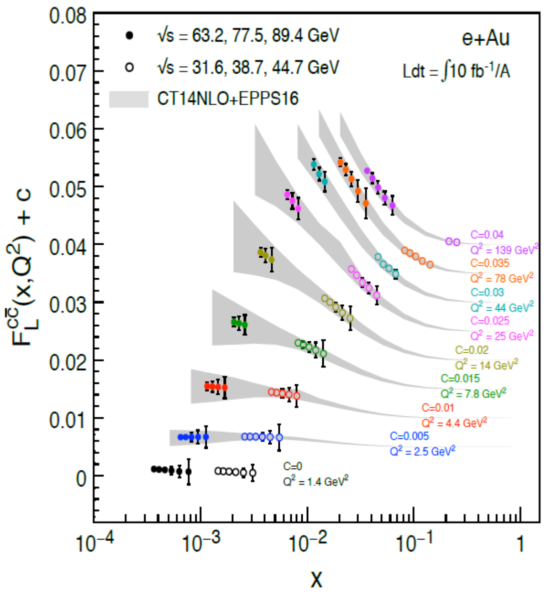
- Very precise nuclear PDFs will open way to quantitative HI physics
- Also F_L and $F_{L,charm}$ for nuclei will be extracted



EPPS16*

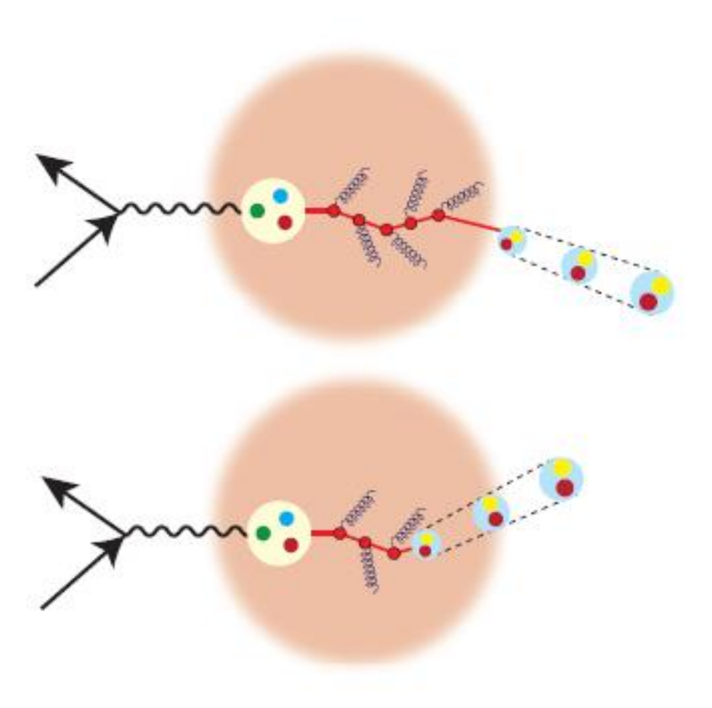


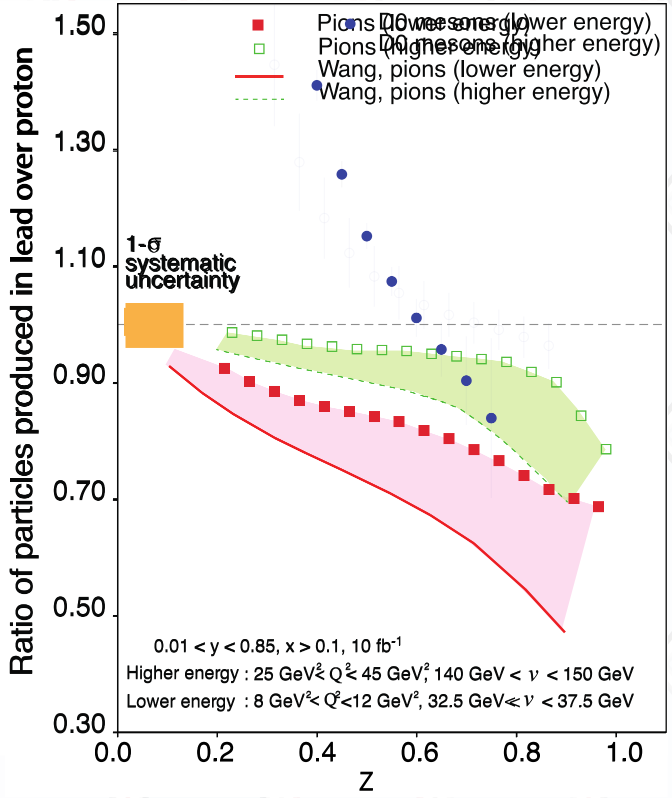




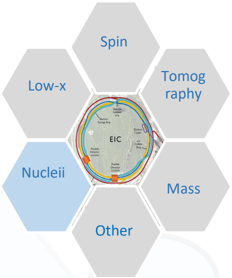
Fragmentation in the nucleus

Does the it affect hadron/quark mass?



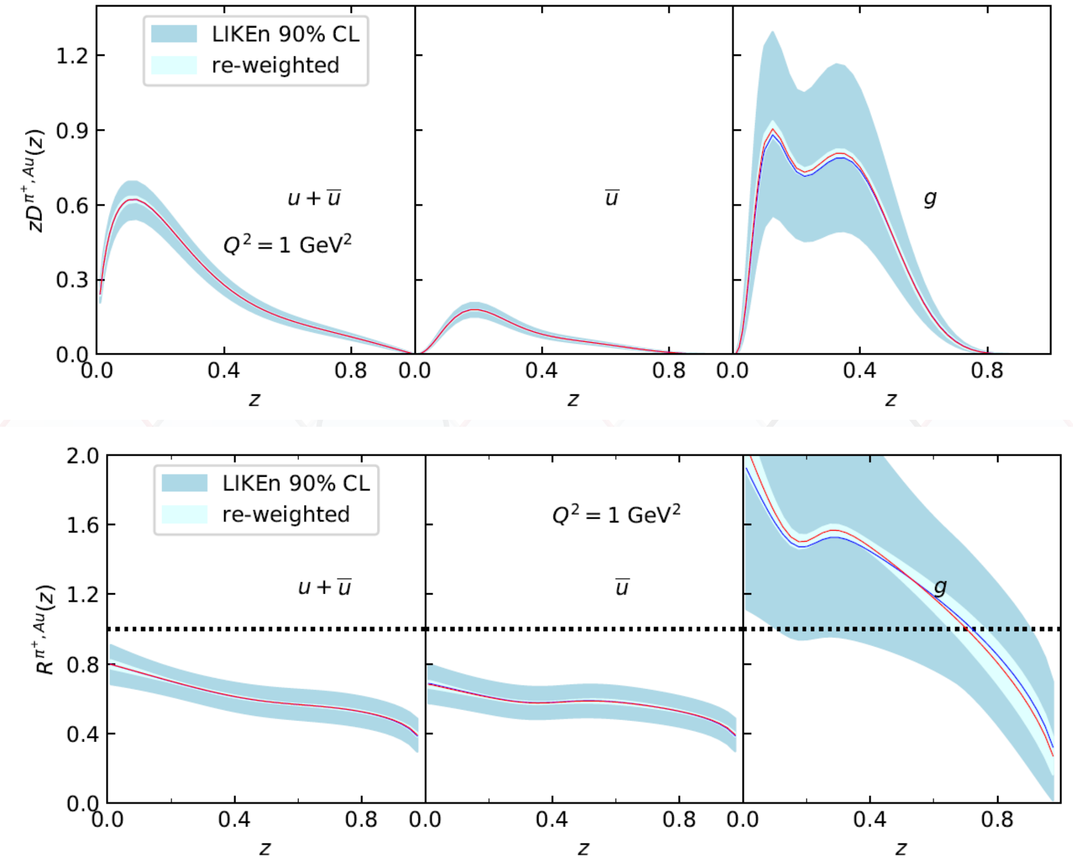


Comparison of Multiplicity ratios for light and heavy hadrons and various parton energies ν



nFFs

- Expected impact from EIC on light hadron nuclear FFs
- Also more sophisticated studies ongoing (transverse momentum broadening, nu dependence, etc)
- Similar studies for heavy flavor



YR Figs 7.90, 7.91, Zurita

EIC Project detector

- EIC user group yellow report (https://arxiv.org/abs/2103.05419) effort summarized most detector requirements to perform the physics goals
- Early 2021: Call for detector proposals by the EIC Project
- Fall 2021: 3 proposals submitted (Ecce, Athena and Core), reviewed by external panel
- Spring 2022: Ecce proposal chosen as baseline for project detector
- Since 2022 formation of ePIC detector from members of all three proposals, Collaboration being formed:

ePIC

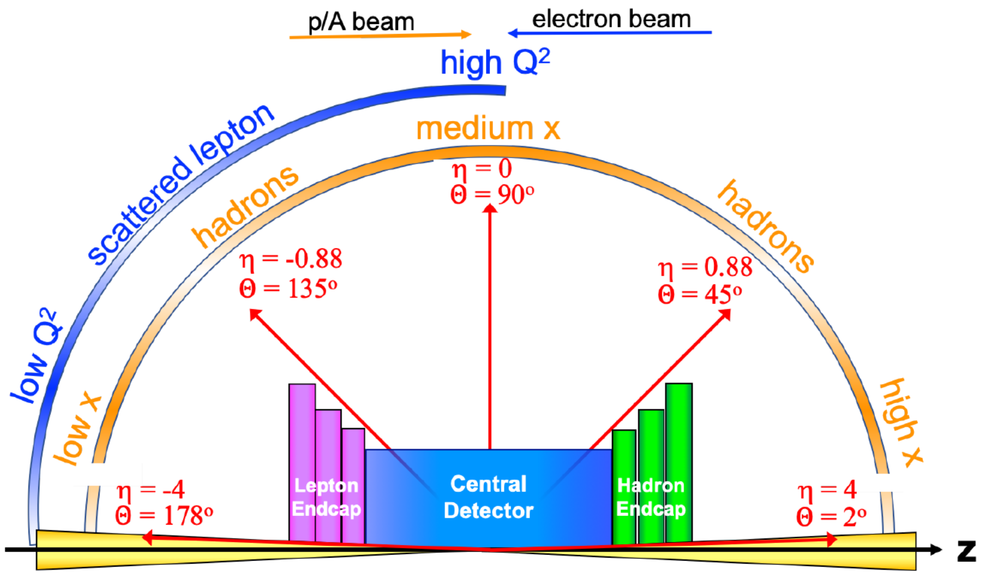
ePIC EXPERIMENT

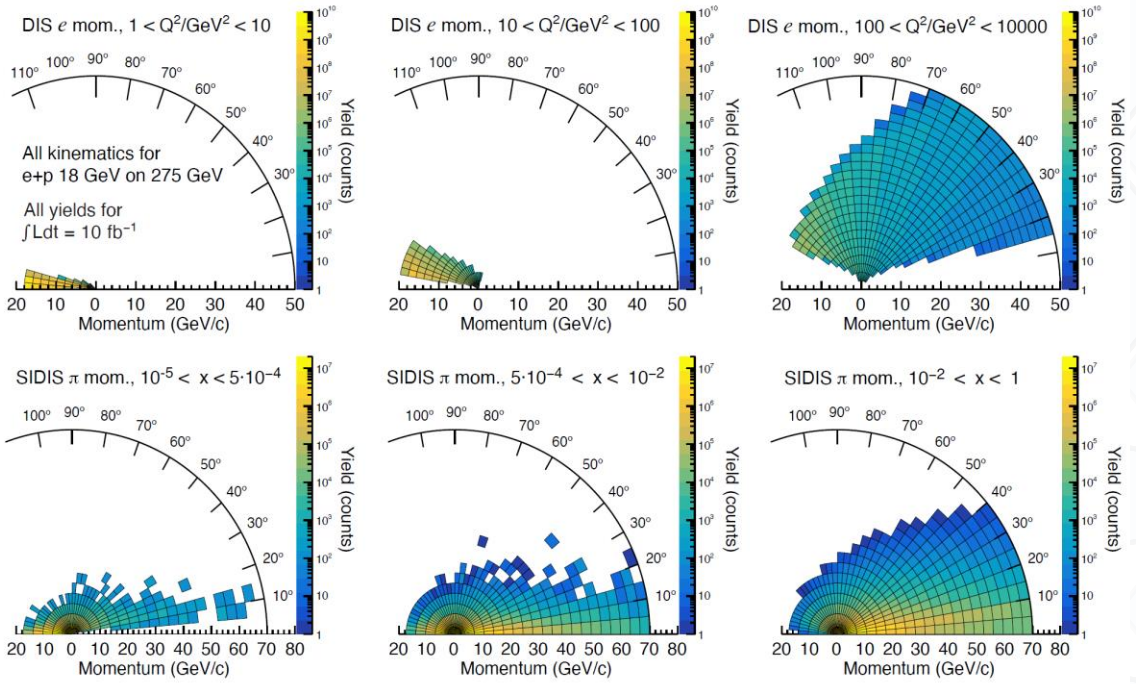
ePIC

EPIC
Electron Proton-Ion
Collider Experiment

General (SI)DIS kinematic

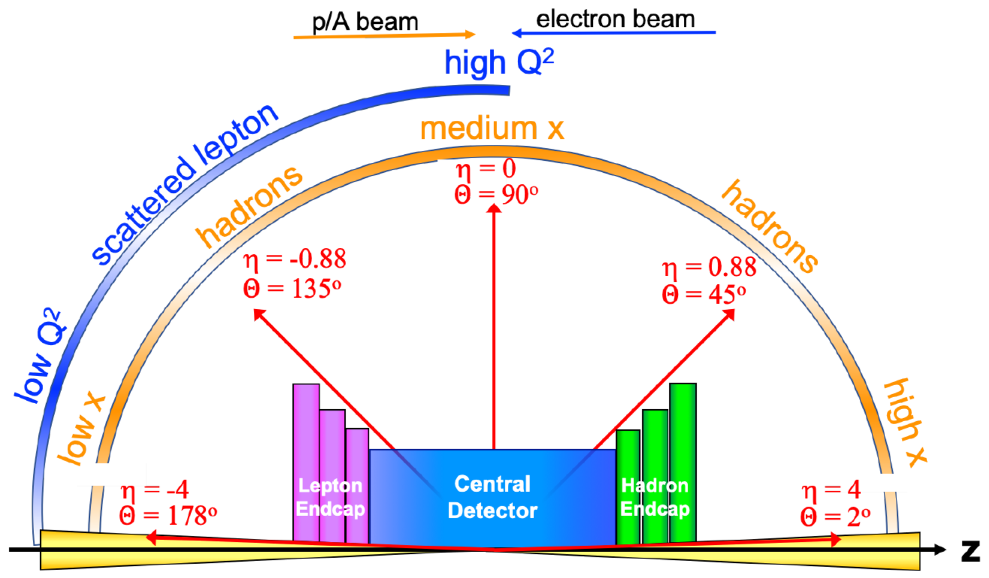
- Scattered lepton:
  - Low Q^2: Backward
  - Med Q^2: central
  - High Q^2: slightly forward
- SIDIS hadrons:
  - Low x: Backward-central
  - Med x: central-forward
  - High x: Forward

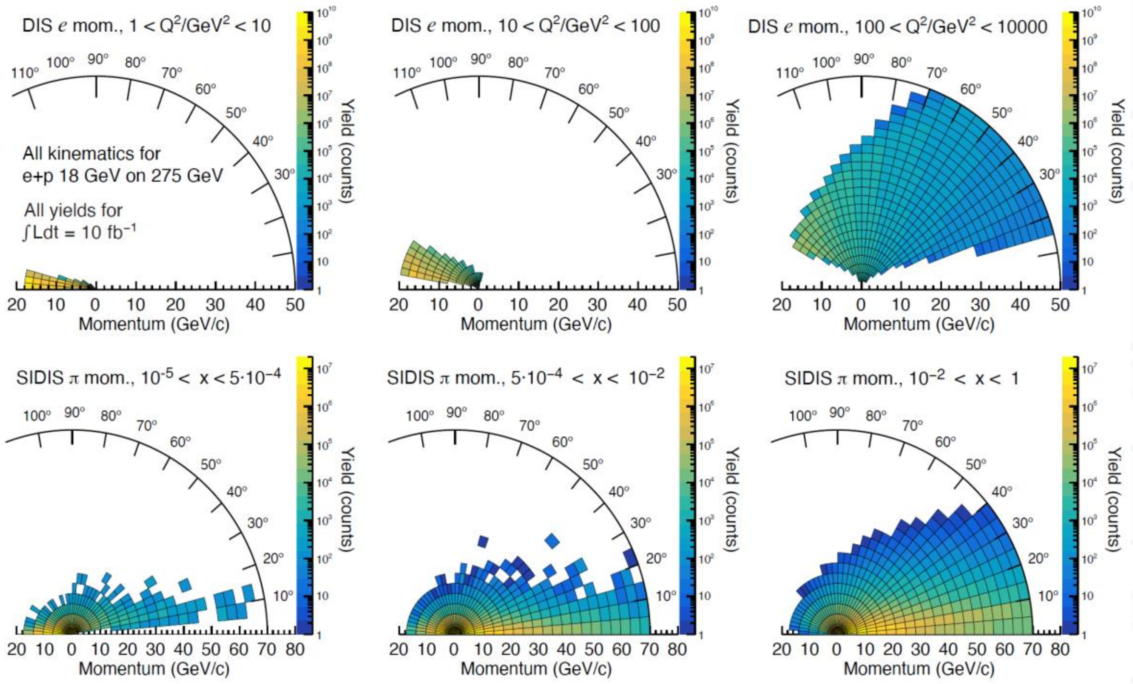




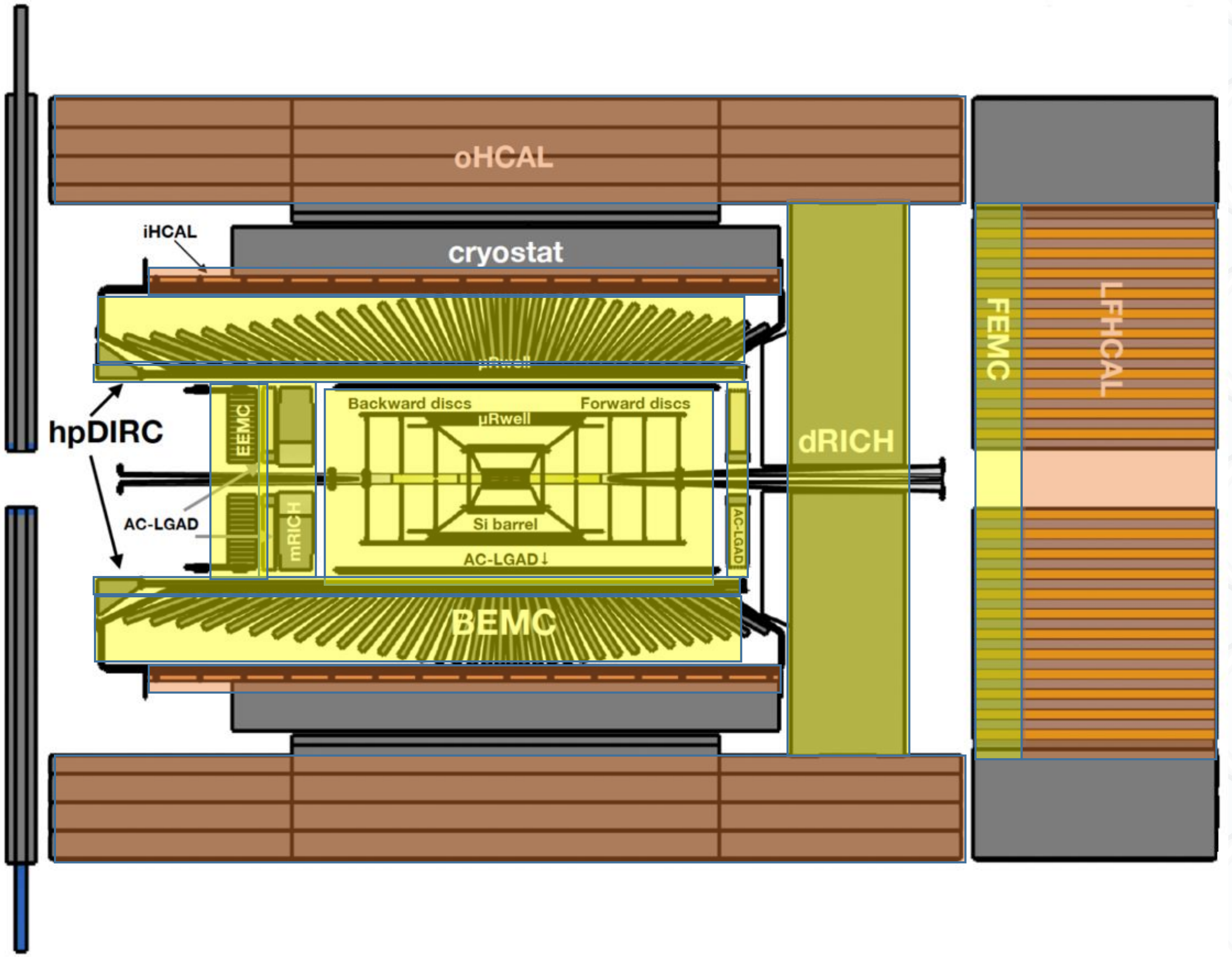
Detector requirements

- Need full coverage over a large range of rapidities
- Precise lepton kinematic measurements in backward/central/forward rapidities
- Precise hadron kine and PID in the forward/central region
- Auxiliary detectors far forward (ZDCs, roman pots)
- Auxiliary detectors far backward (low Q^2 tagger)
- Dedicated polarimetry/luminosity detectors





ePIC Detector Design (Current)



Tracking:

- Si MAPS (65nm)
- µRWELL/µMegas

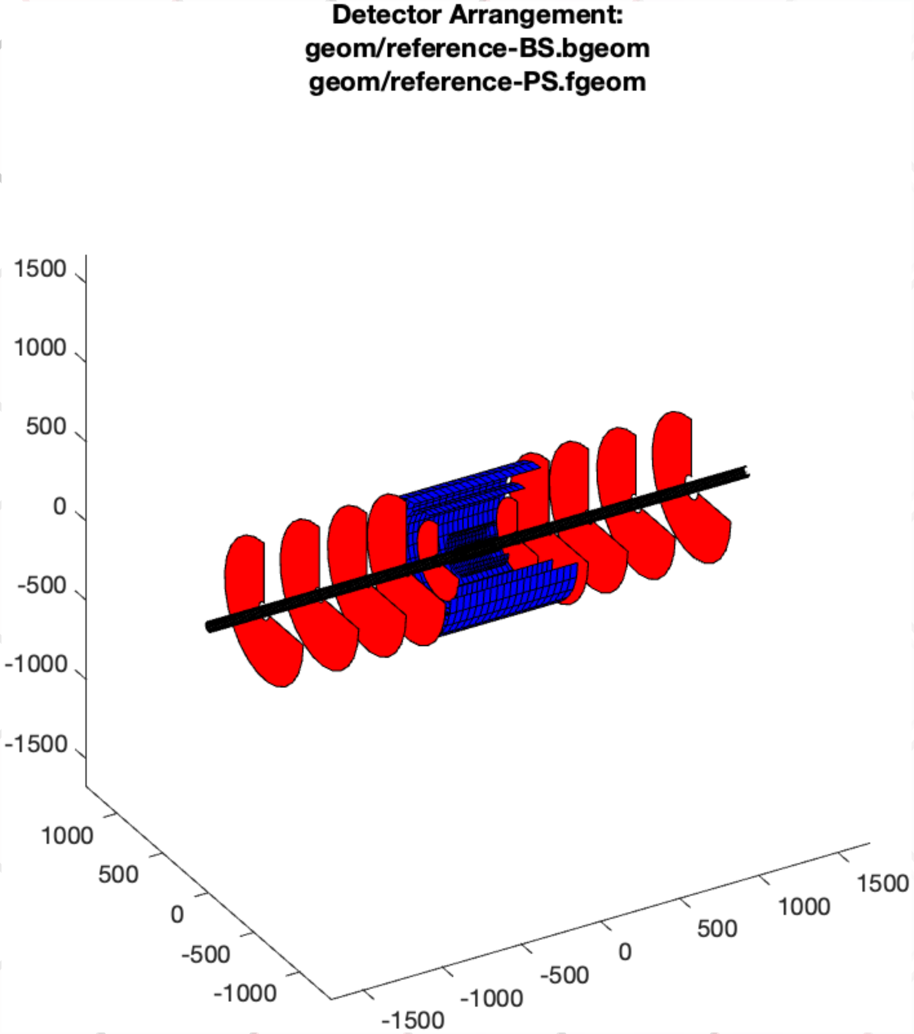
PID:

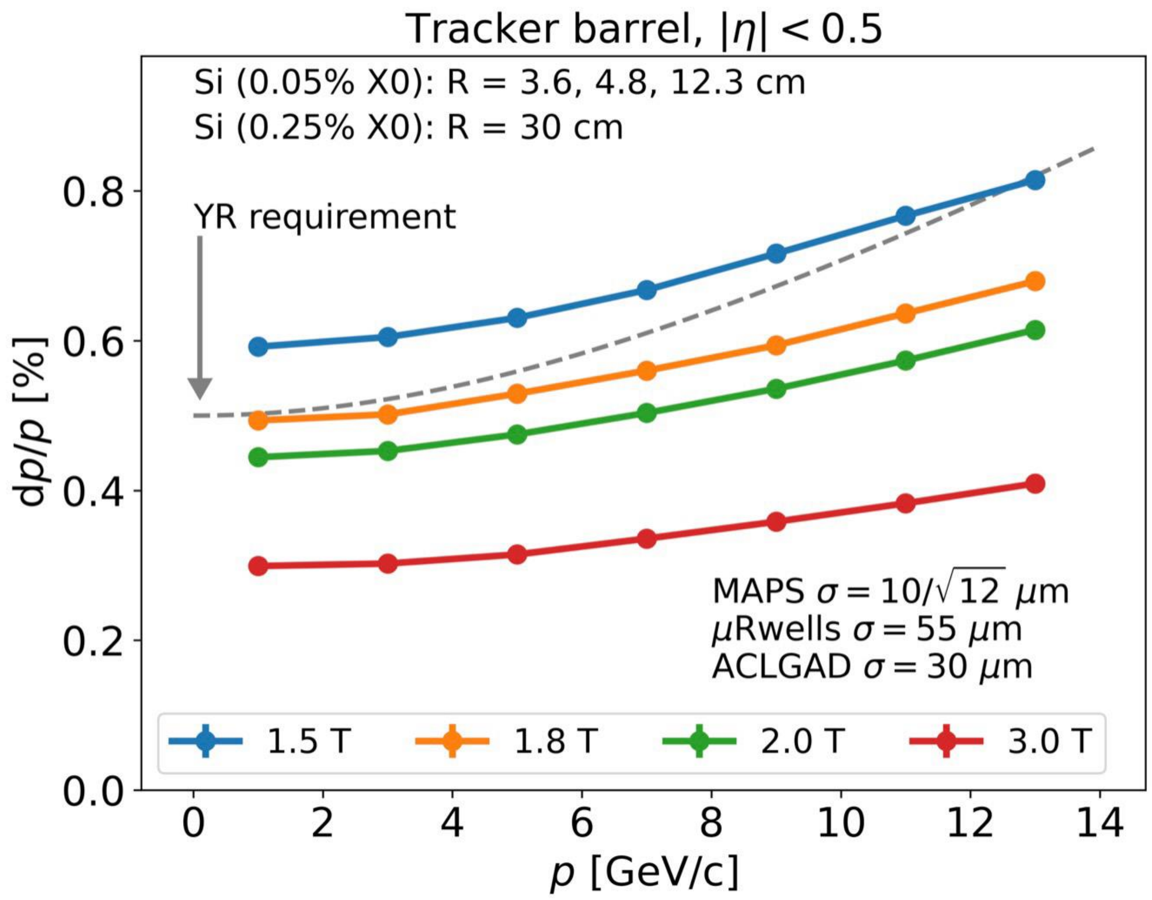
- hp-DIRC
- mRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:

- SciGlass Barrel EMCal
- PbWO EMCal in backward direction
- Longitudinally segmented EM+HCal in forward direction
- Outer HCal (sPHENIX re-use)

Tracking


Detector Arrangement:
geom/reference-BS.bgeom
geom/reference-PS.fgeom
1500
1000
500
0
-500
-1000
-1500
1000
500
0
-500
-1000
-1500
-1000
-500
0
500
1000
1500


Tracker barrel, |η| < 0.5
Si (0.05% X0): R = 3.6, 4.8, 12.3 cm
Si (0.25% X0): R = 30 cm
YR requirement
MAPS σ = 10/√12 μm
μRwells σ = 55 μm
ACLGAD σ = 30 μm
1.5 T
1.8 T
2.0 T
3.0 T
dp/p [%]
0.0
0.2
0.4
0.6
0.8
p [GeV/c]
0
2
4
6
8
10
12
14

Calorimetry

Backward ECAL (EEMC)

Homogeneous calorimeter based on high-resolution $PbWO_4$ crystals

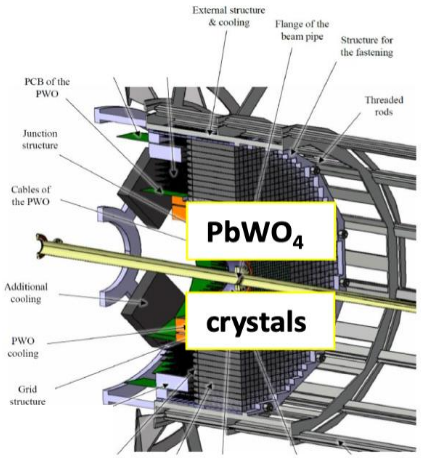


Figure from the EIC EEEMCAL Consortium design report

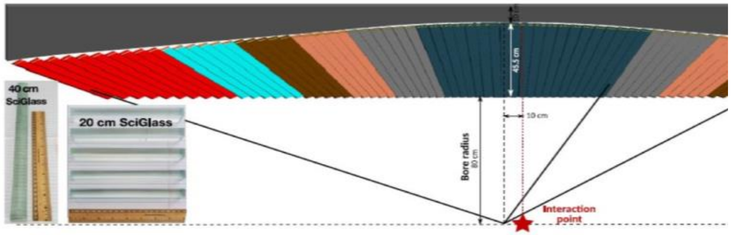
Backward ECAL

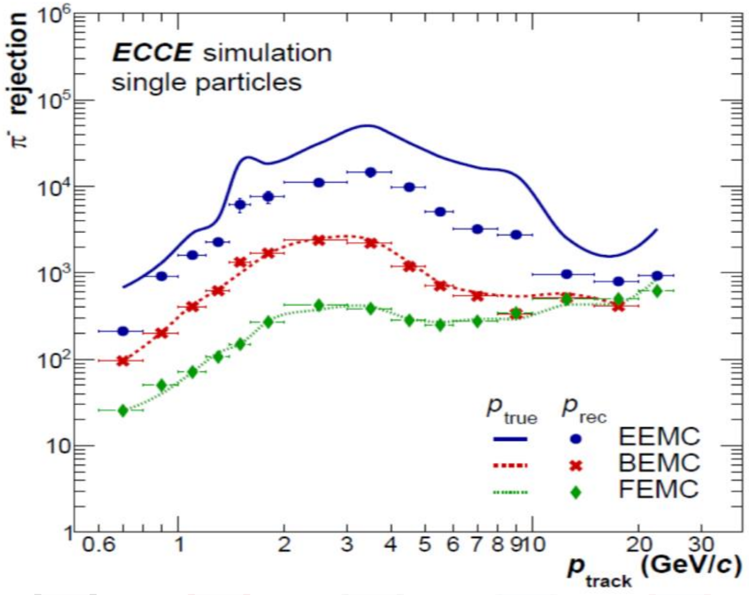
η	[-4 .. -1.8]
σ_E/E	2%/√E+1%*

*Based on prototype beam tests and earlier experiments

Barrel ECAL (BEMC)

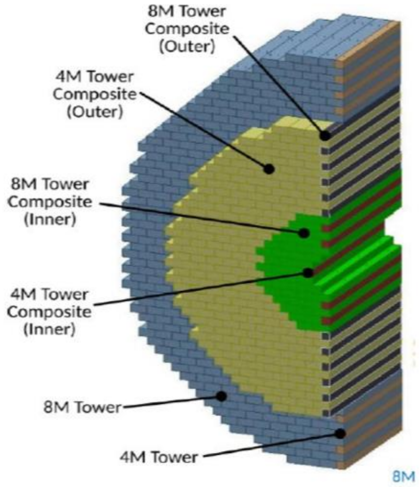
Homogeneous, projective calorimete based on SciGlass, cost-effective alternative to crystals

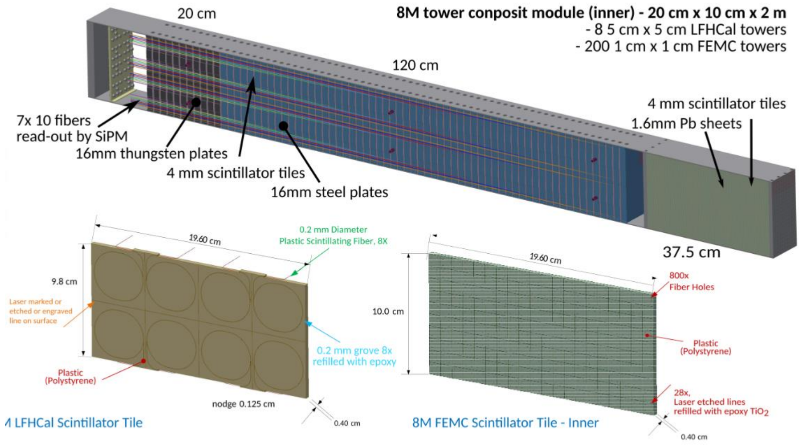




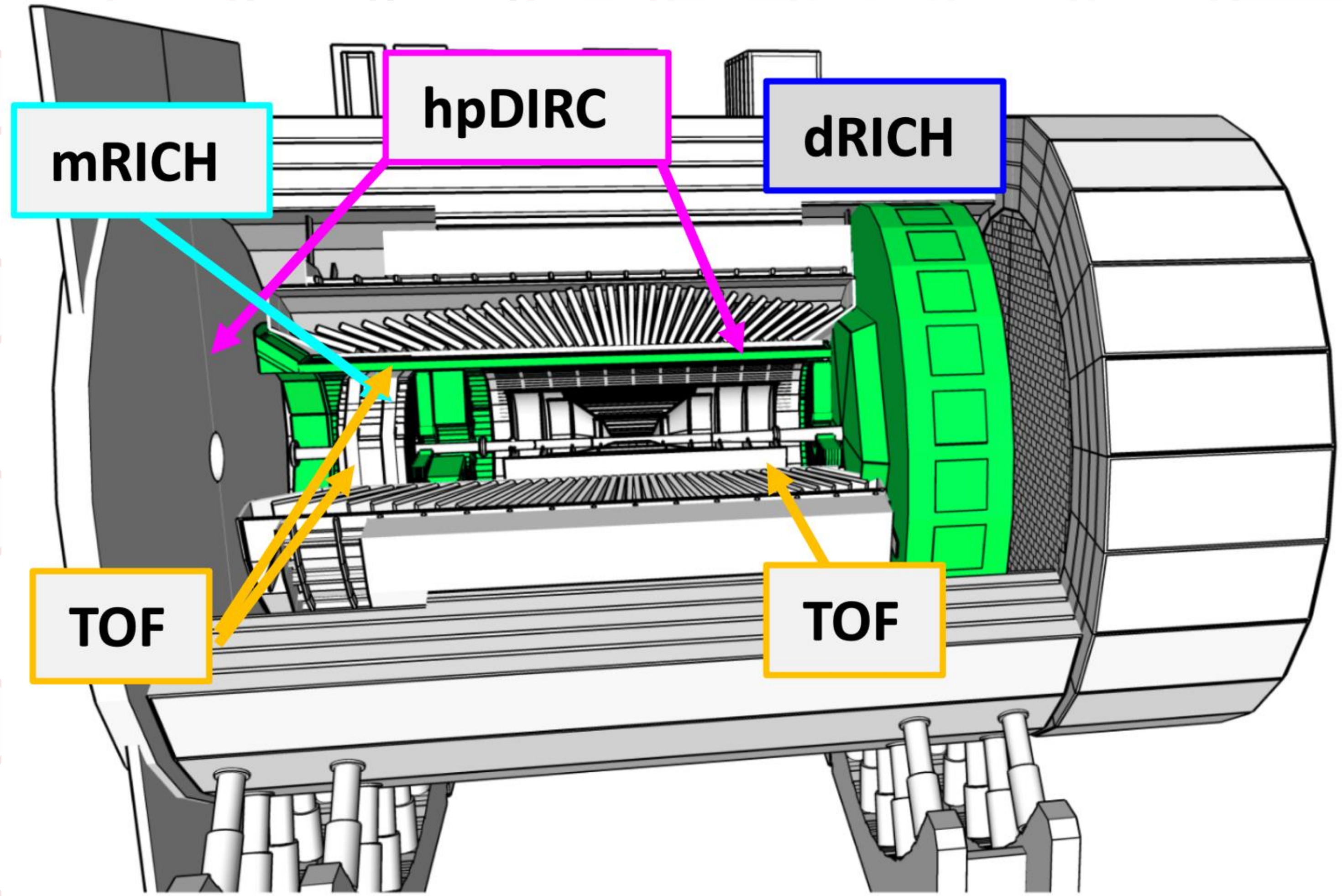
Forward ECAL (FEMC)

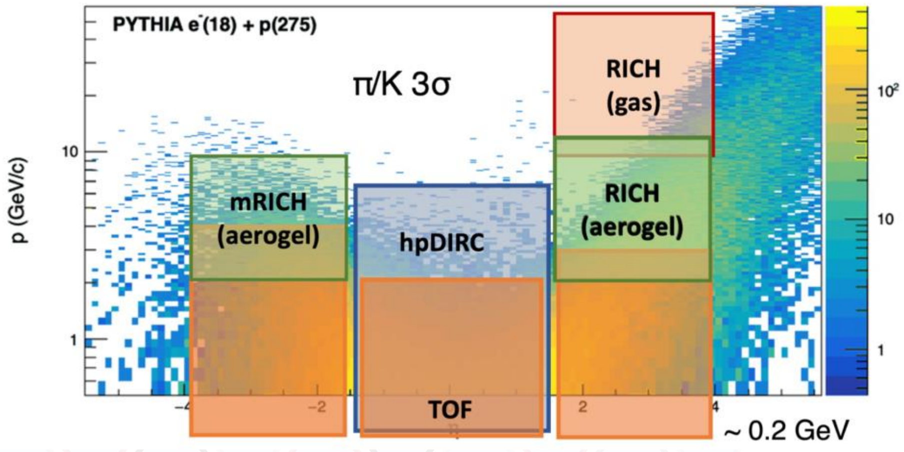
Highly-granular shashlik sampling calorimeter based on Pb/SC



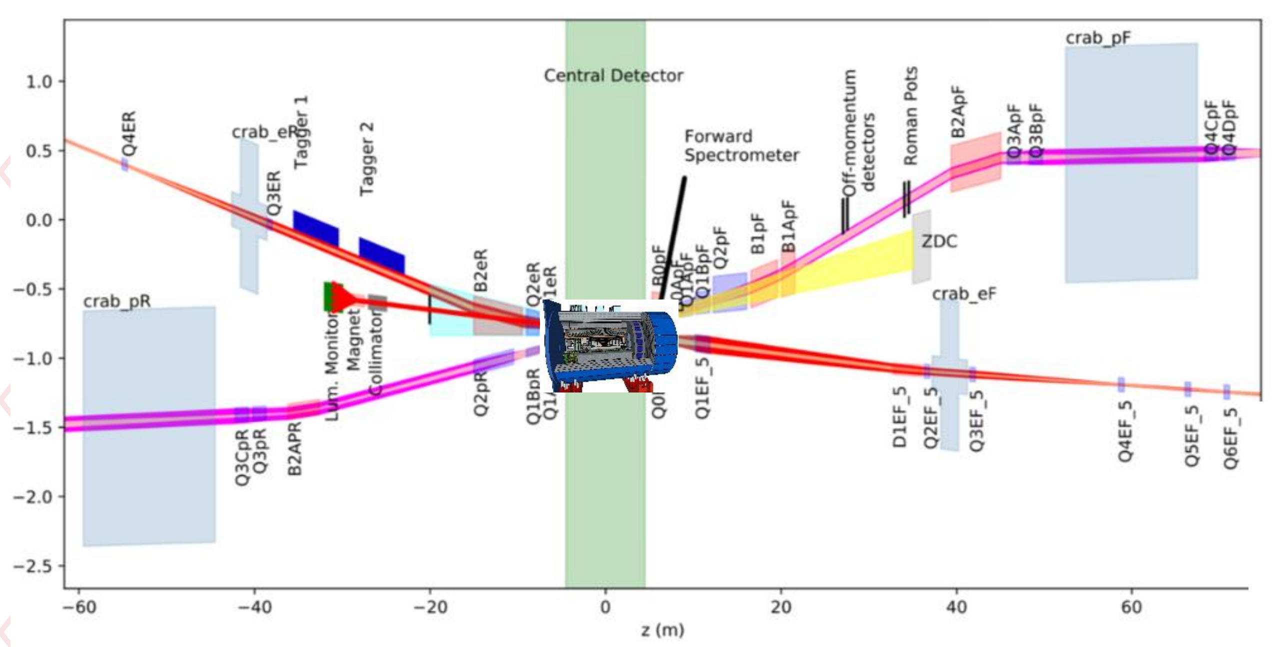


Particle ID


mRICH
hpDIRC
dRICH
TOF
TOF

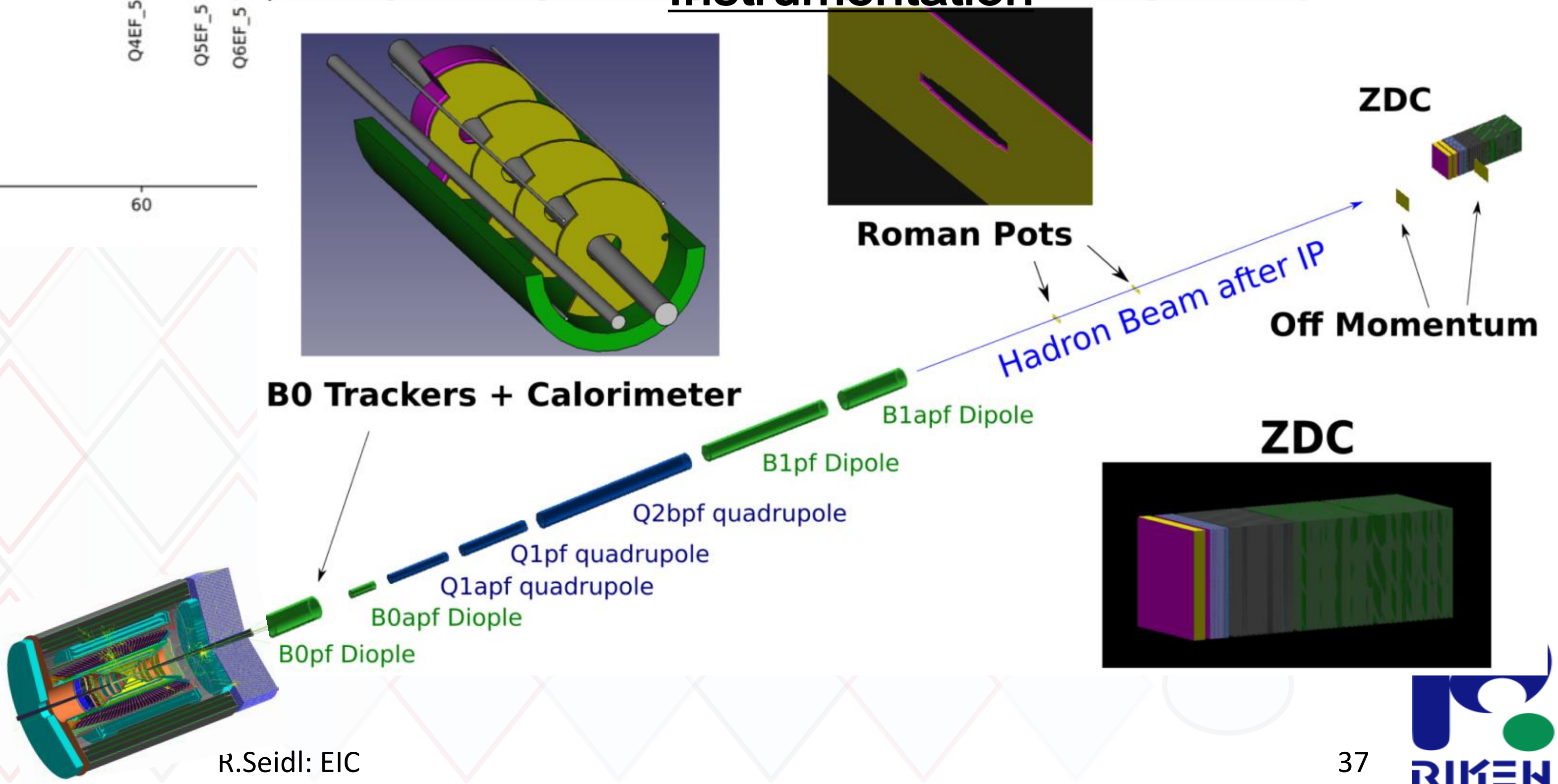

PYTHIA e⁻(18) + p(275)
π/K 3σ
RICH (gas)
mRICH (aerogel)
hpDIRC
RICH (aerogel)
TOF
p (GeV/c)
10
1
−4
−2
2
4
10²
10
1
~ 0.2 GeV

Far-Forward / Backward Instrumentation



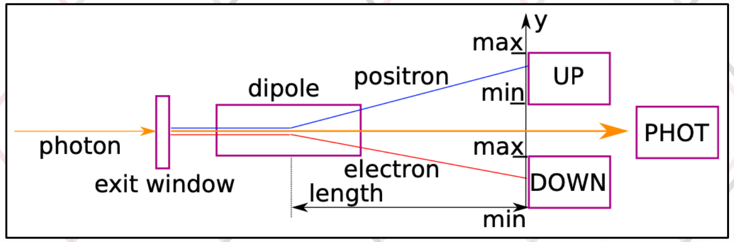
EIC detectors are highly integrated with the accelerator – extensive cooperation required to achieve science goals!

Far-Forward Instrumentation

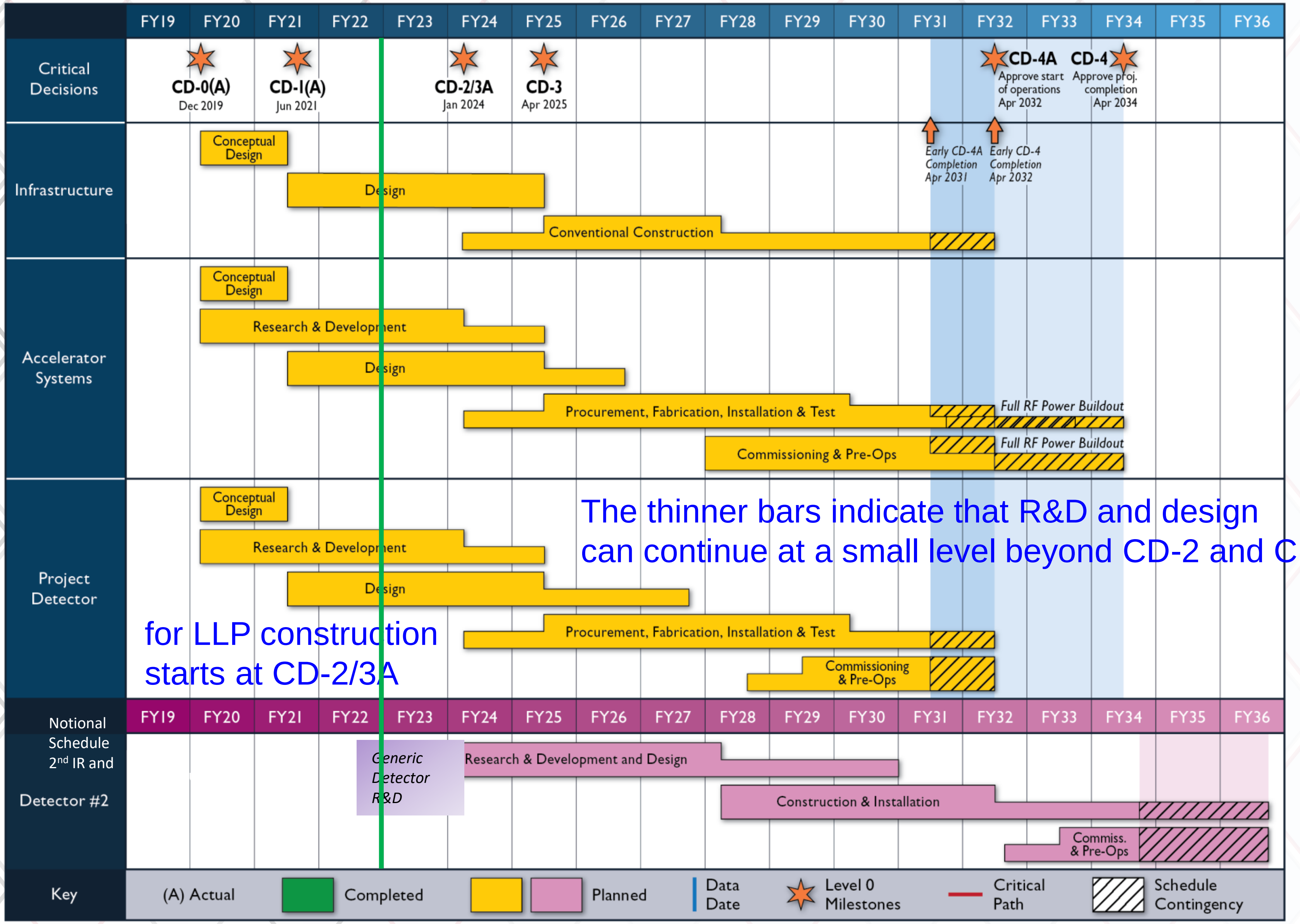


Far-Backwards

- Low-Q^2 tagger
- Luminosity



EIC Project High Level Reference Schedule



The thinner bars indicate that R&D and design can continue at a small level beyond CD-2 and CD-3

for LLP construction starts at CD-2/3A

Summary

- EIC CD1 received in 2021
- ECCE Detector proposal submitted in December 2021, chosen as 1st/project detector → ePIC collaboration now being formed
- A large variety of physics goals can be addressed:
    - Understanding the mass of the visible universe
    - spin sum rule
    - 3D imaging of the nucleon
    - QCD had high gluon densities
    - Strange puzzle
    - BSM searches (Tensor charge, Weinberg angle, etc)
- Full Geant studies show that ECCE/ePIC successfully addresses planned measurements of the EIC Yellow Report