GPDs and TMDs at Electron-Ion Collider

Workshop on hadron tomography at J-PARC and KEKB

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KEK, Tsukuba, Japan

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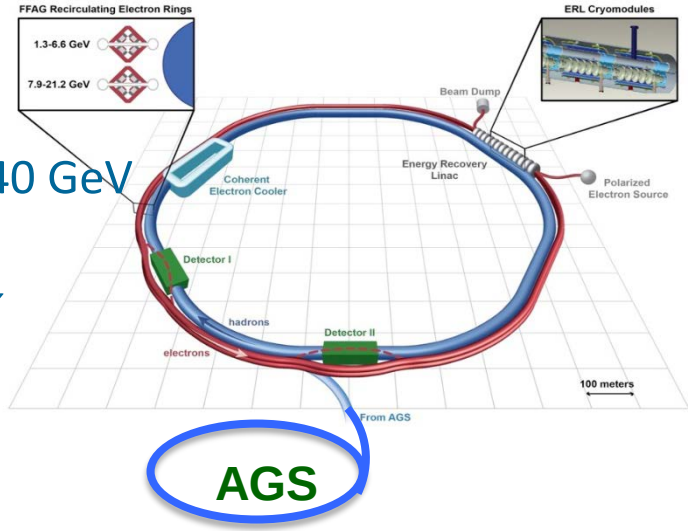
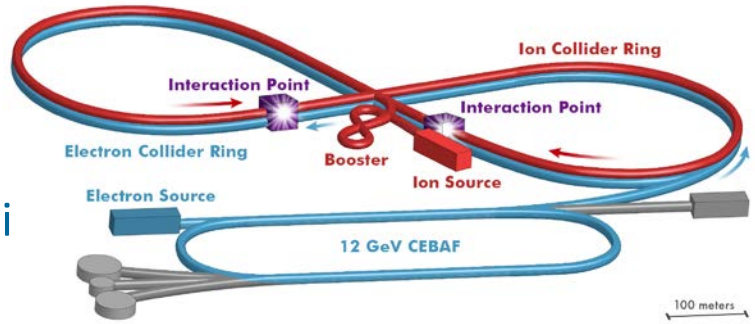
Electron-Ion Collider

- World's first polarized electron + proton / light-ion / heavy-ion collider to be constructed in US
  - QCD frontier machine for nucleon / nuclear structure in quark + gluon picture
    - Extending QCD science at JLab / RHIC
  - Wide range of kinematics
    - Variable center of mass energy $\sqrt{s}$ = 20 - 140 GeV
    - Wide Q^2 range for evolution study
    - Wide x range for covering valence to low-x physics
  - High beam polarization
    - e, p, d/^{3}He
  - High luminosity
    - $10^{33\text{-}34}$cm^{-2}s^{-1}
    - 100 - 1000 times HERA
  - Beam species
    - Polarized e, p, d/^{3}He, wide range in nuclei



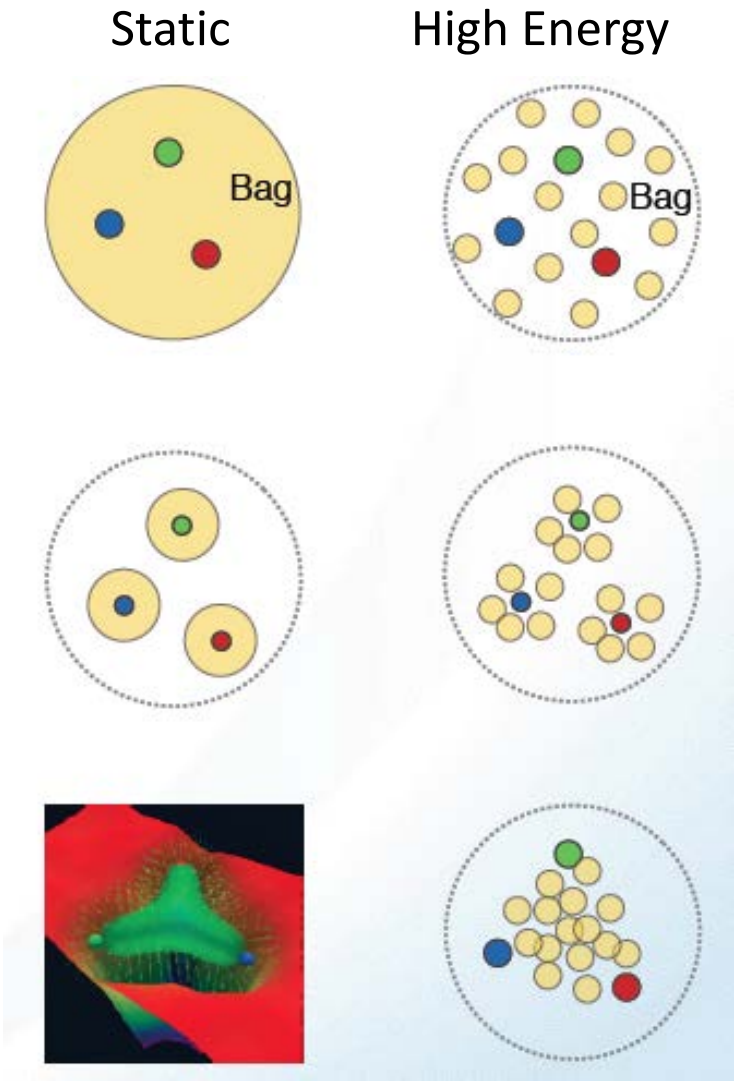


Electron-Ion Collider

- Physics at EIC
  - 3D structure of the nucleon / nucleus
    - TMDs / GPDs
    - Orbital motion
    - Gluon distribution (radius etc.)
  - Spin puzzle
    - Gluon polarization
    - Orbital angular momentum from GPDs
  - Gluon saturation
  - Hadronization

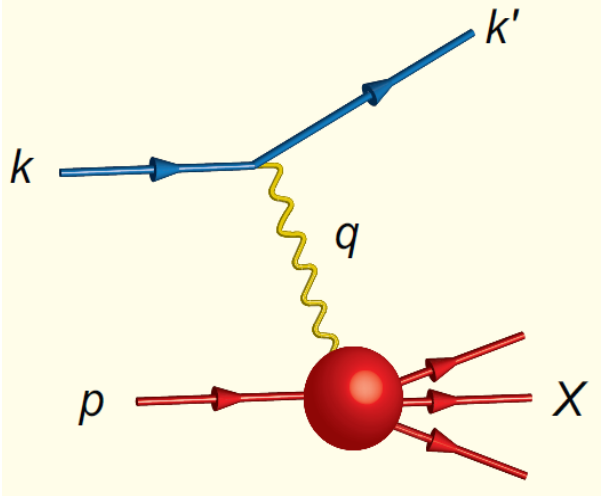
3D structure of the nucleon

- Bag model
  - Gluon field distribution is wider than the fast moving quarks
    - gluon radius > charged radius
- Constituent quark model
  - Gluons and sea quarks hide inside massive quarks
    - gluon radius ~ charged radius
- Lattice gauge theory (with slow moving quarks)
  - Gluons more concentrated inside the quarks
    - gluon radius < charged radius
- Need measurement of transverse images of the quarks and gluons in the nucleon



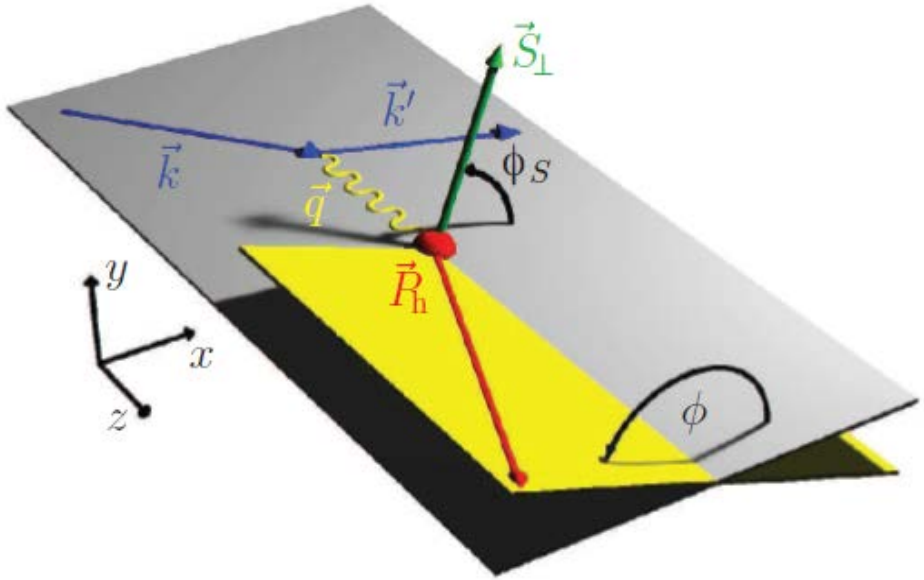
DIS

- Inclusive measurement of scattered lepton
- Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- 1D longitudinal motion of partons
  - Spin and flavor structure of the nucleon
    - e.g. gluon polarization



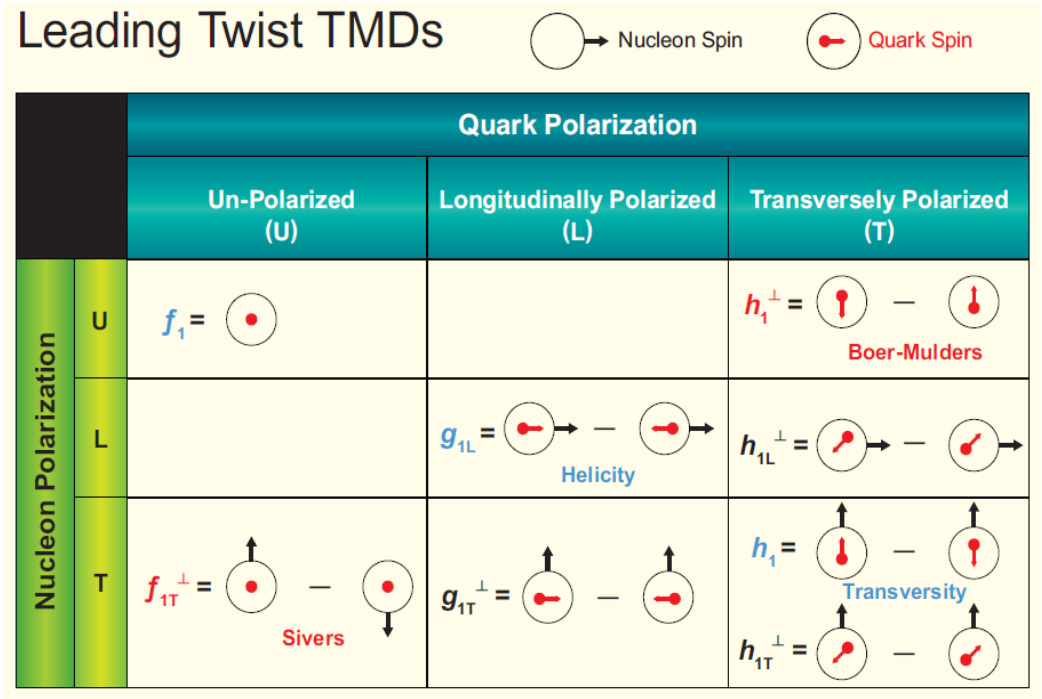
SIDIS

- Two momentum scales
  - Large Q^2: hard scale for spatial resolution
  - Small p_T: motion of confined partons
- TMD (Transverse-Momentum Dependent) parton distribution function (PDF)
  - Confined motion of partons inside the nucleon

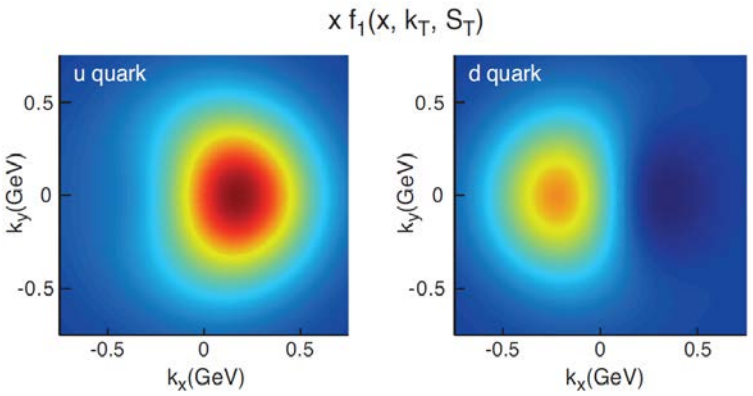


TMDs

- Correlation between the (orbital) motion and spin of partons, and the spin of the nucleon
  - Transversity: spin of the nucleon and spin of partons
  - Sivers: spin of the nucleon and orbital motion of partons
  - Boer-Mulders: orbital motion and spin of partons

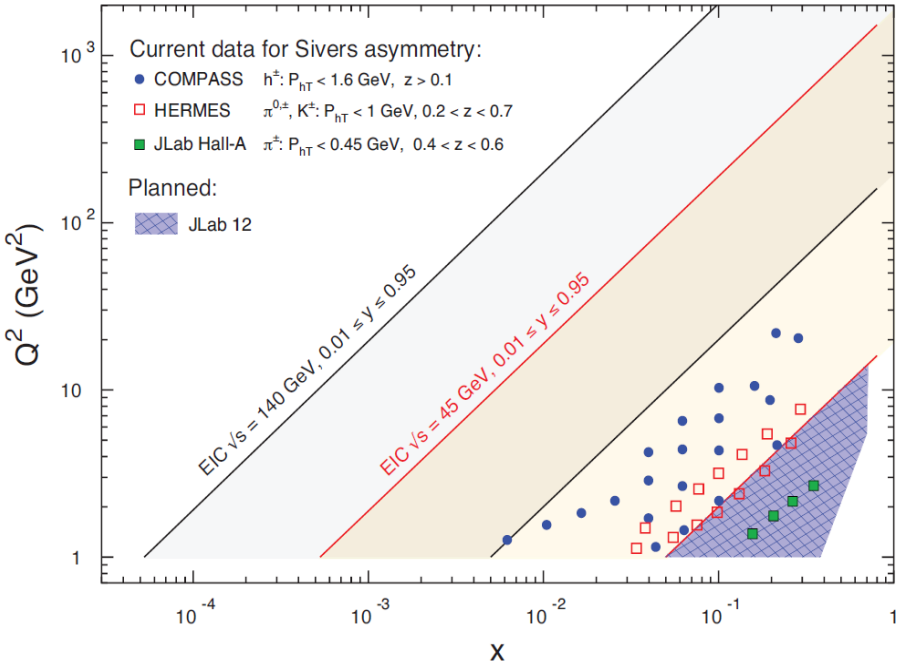


Sivers function at $x = 0.1$

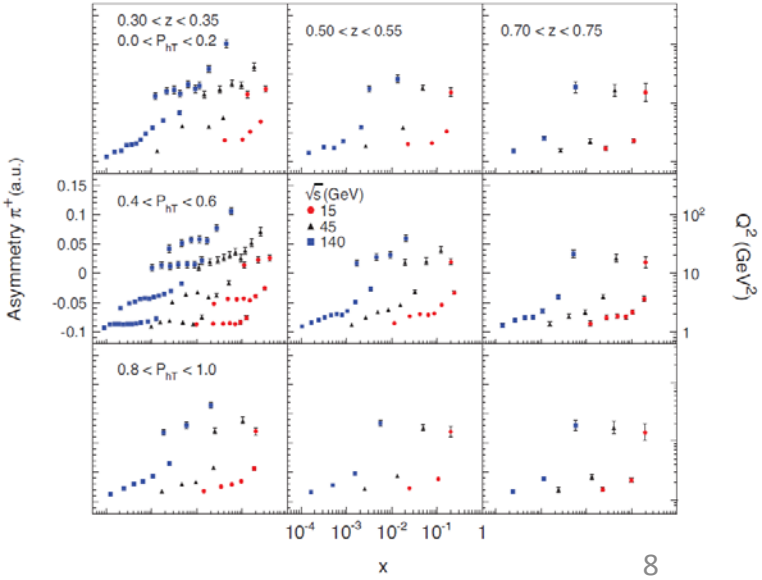


TMDs at EIC

- High precision measurement of all the quark TMDs in the valence region
  - Large Q^2 to suppress potential higher twist contamination
- First measurement of the TMDs for anti-quarks and gluons
- Studies of QCD evolution properties of TMDs

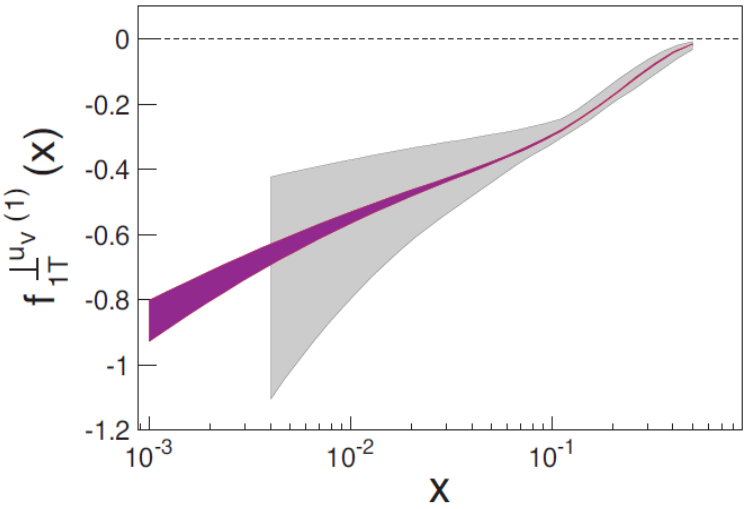


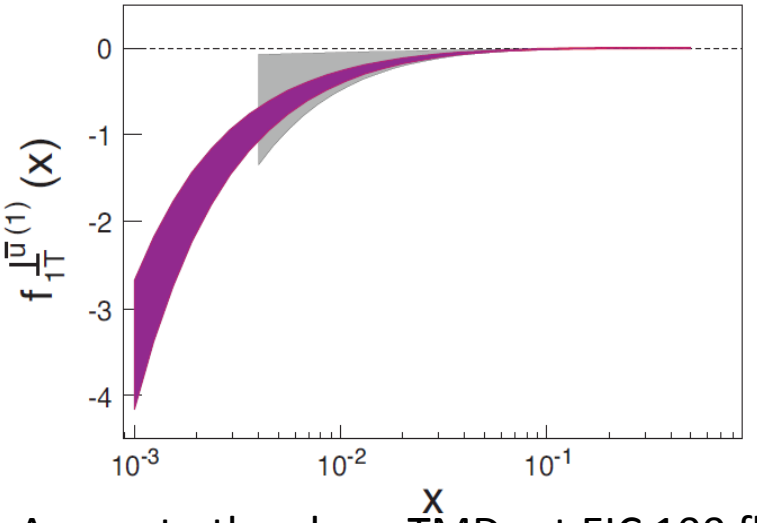
Accuracy for π^+ production in SIDIS off the proton at EIC 10 fb^{-1}



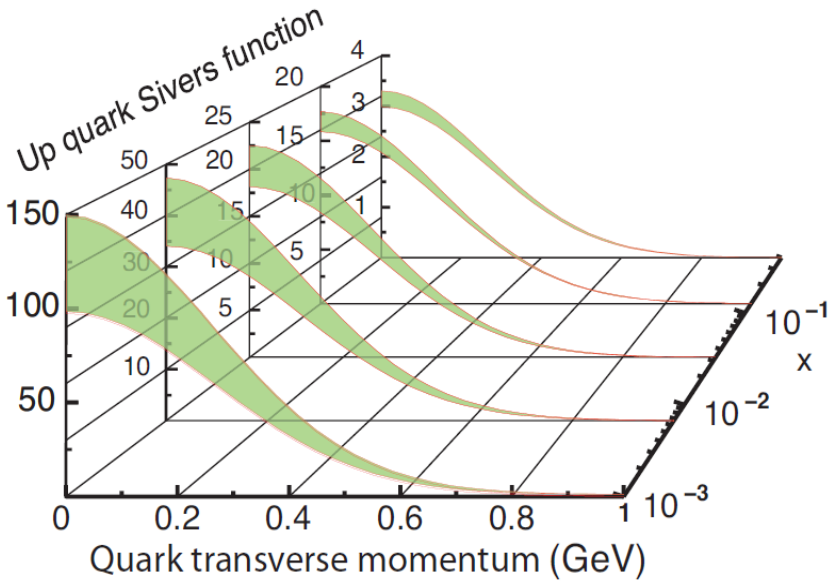
TMDs at EIC

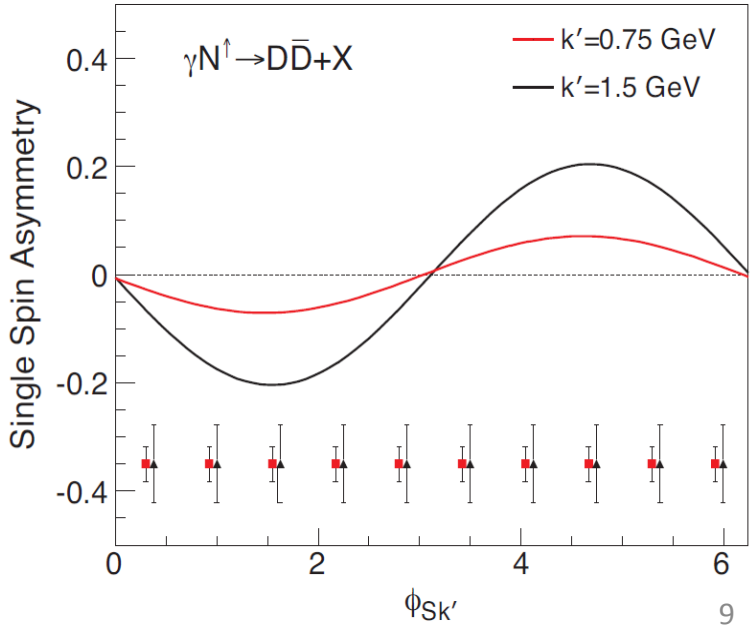
Sivers function extracted for valence (left) and sea (right) up quarks from (grey) currently available data and (purple) projection at EIC $\sqrt{s}$ = 45 GeV, 10 fb^{-1}





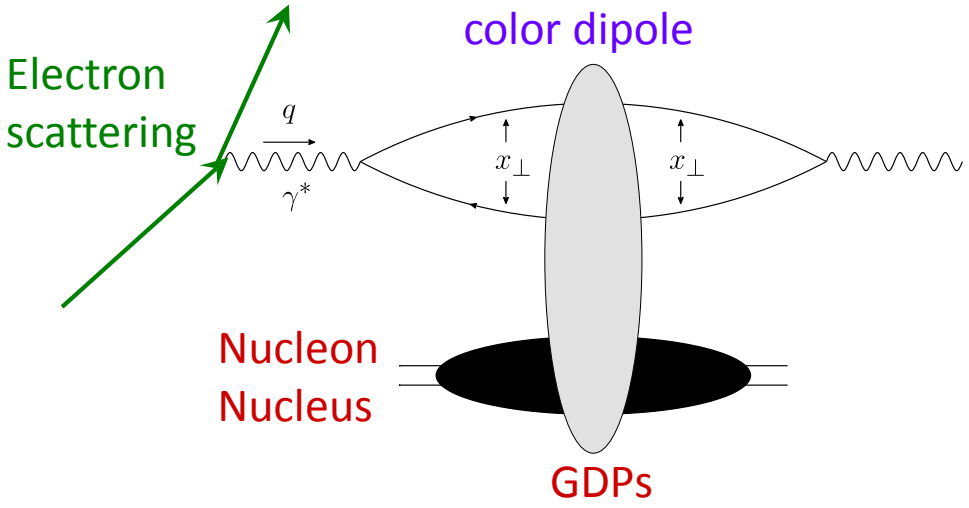
Access to the gluon TMDs at EIC 100 fb^{-1}



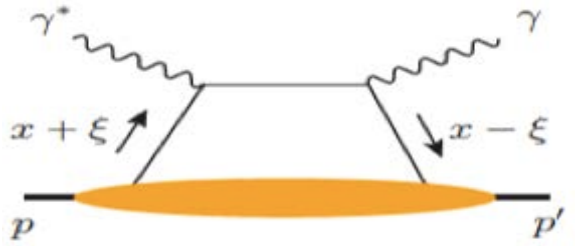


Exclusive processes

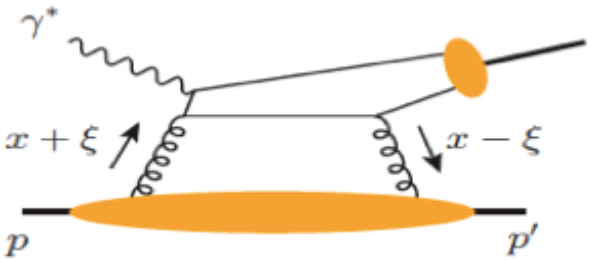
- Tomography of the nucleon / nucleus
- Spatial imaging of gluons and sea quarks
  - 2D (spatial) + 1D (longitudinal moment) coordinate space image



DVCS (Deeply Virtual Compton Scattering)



Meson Production

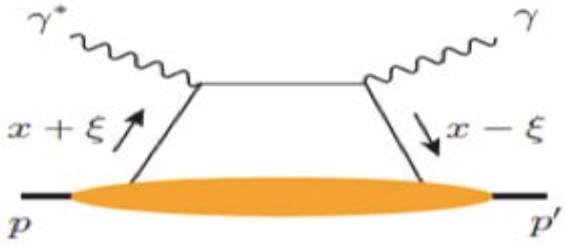


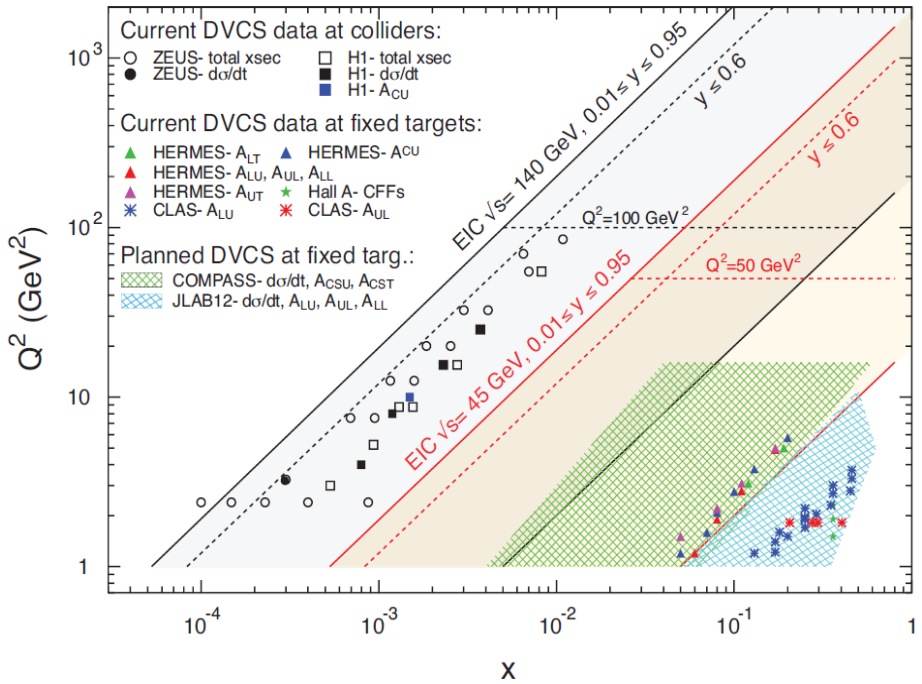
J/ψ, ϕ, ρ, etc.

GPDs

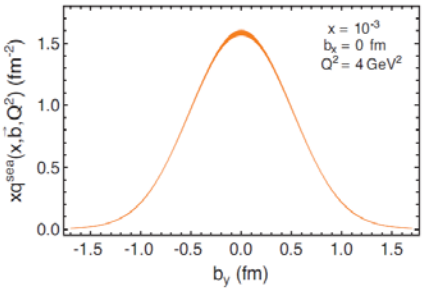
- DVCS

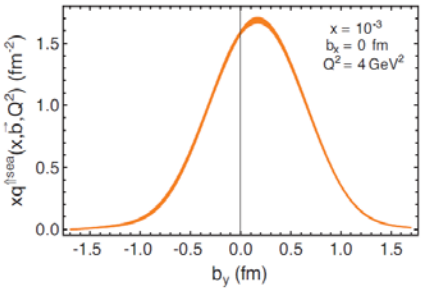
DVCS (Deeply Virtual Compton Scattering)

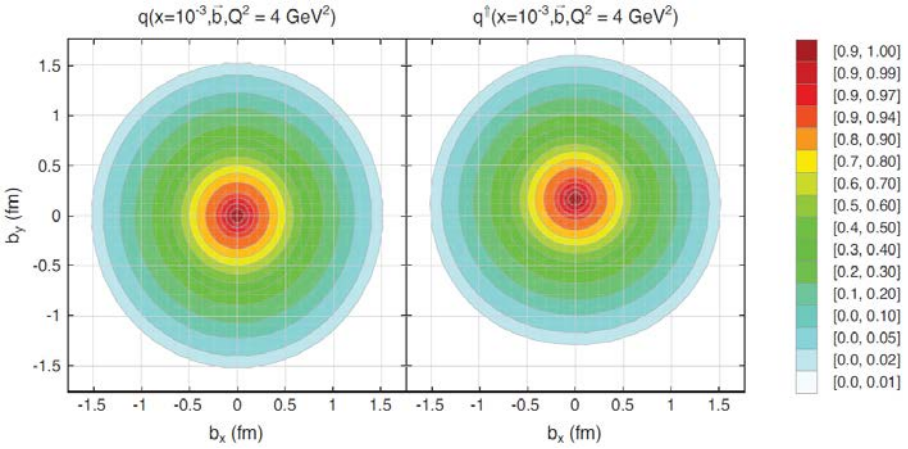




Spatial distribution of sea quarks in unpolarized proton (left) and polarized proton (right) at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane



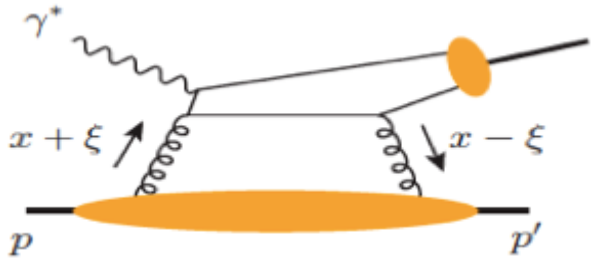




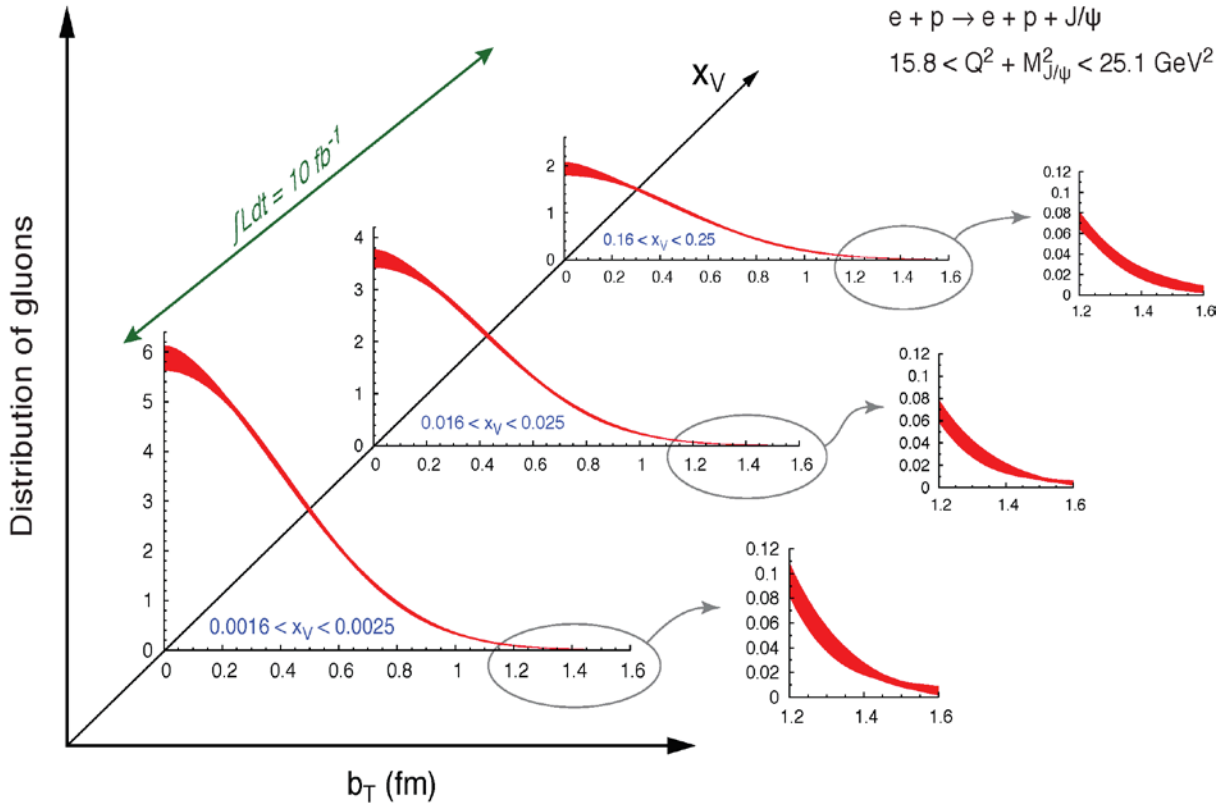
GPDs

- Meson production
  - Gluon GPDs from J/ψ production at EIC

Meson Production



J/ψ, ϕ, ρ, etc.



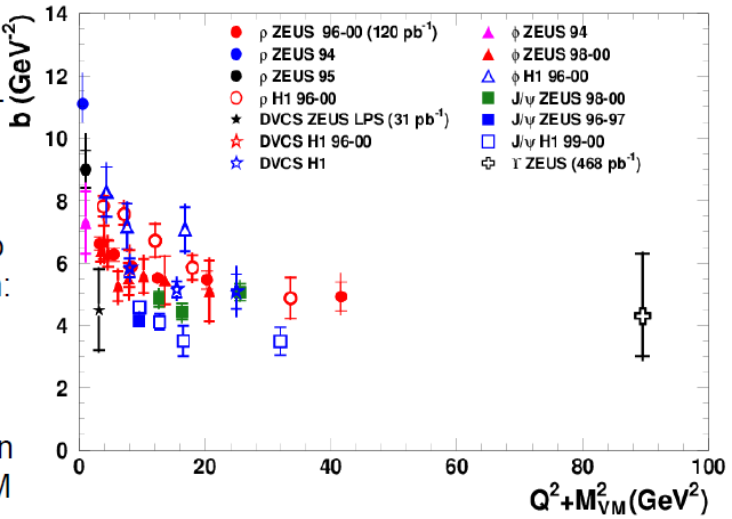
GPDs

- Gluon GPDs at HERA

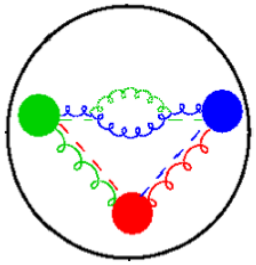
VM production and DVCS: t-dependence, $b(Q^2+M^2_{VM})$

- $d\sigma/dt \sim e^{-b|t|}$
- Data show b decreasing vs $Q^2 + M^2_{VM}$ up to an asymptotic value
- In optical model approach, via Fourier transform, b is related to the size of the interaction region:

  $b \sim (R^2_p + R^2_{VM})/4$
- For b~4.5 GeV^{-2} → radius of interaction ~ 0.6 fm, smaller than the radius of proton tested in EM interactions to be 0.8 fm



size of interacting gluons within the protons is smaller than the size of the quarks in the proton and is getting smaller with $Q^2 + M^2_{VM}$



Alessia Bruni | Exclusive processes at HERA | HESZ 201

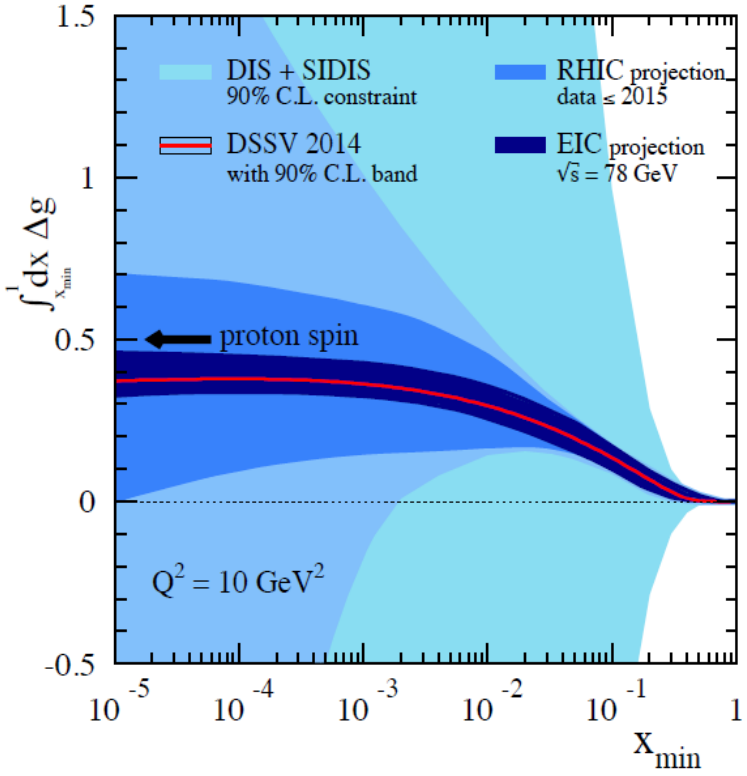
Spin puzzle

- Orbital angular momentum
  - Ji's sum rule in GPD

$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q^z$$

$$J_q^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^q + E^q\right)\right)_{t\to 0}$$

- Gluon polarization
  - DIS at EIC



$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin

L_Q = Quark Orbital Ang. Mom

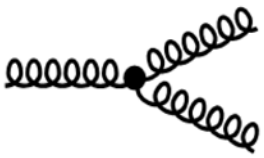
Δg = Gluon contribution to Proton Spin

L_G = Gluon Orbital Ang. Mom

Gluon saturation

- Gluon density saturated where gluon emission and recombination comparable
  - Color glass condensate (CGC)
  - First observation of a collective gluonic system

gluon emission



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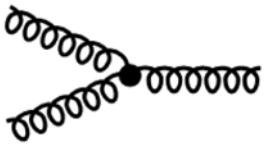
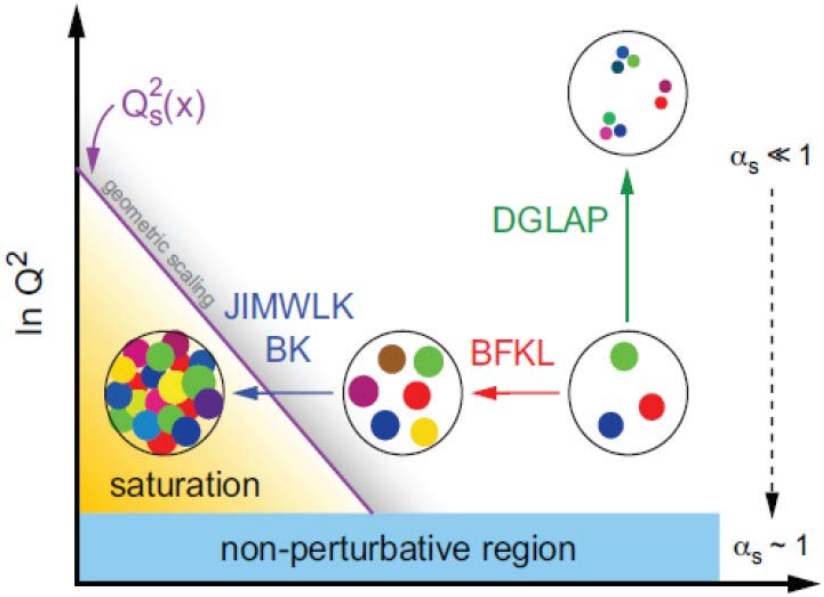
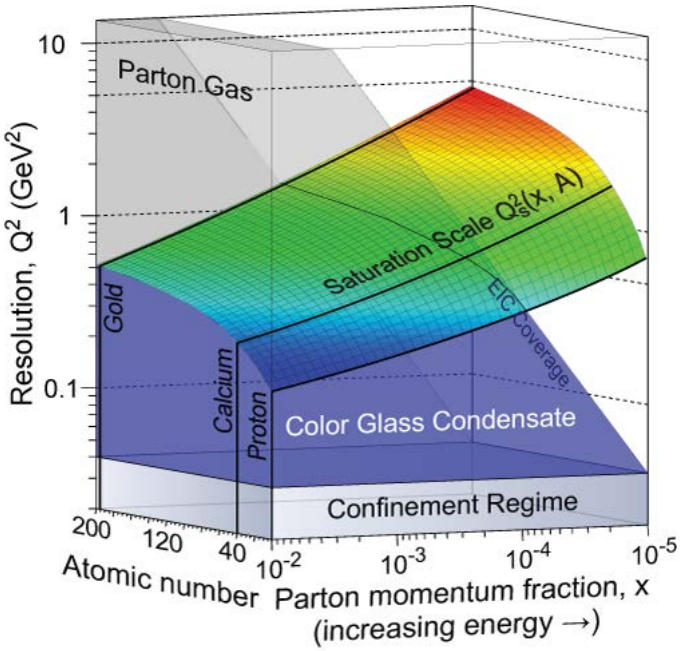
gluon recombination



At Q_S

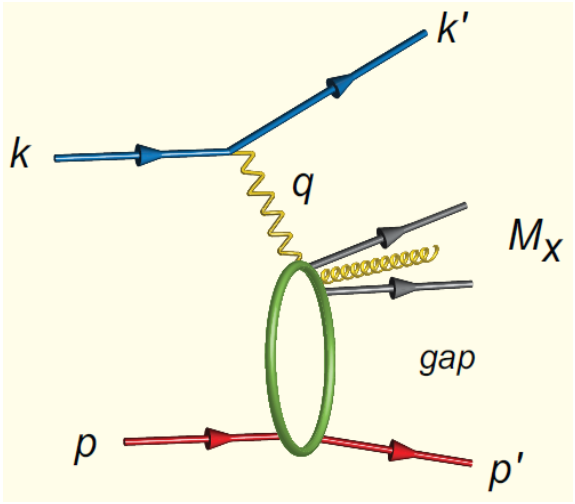
- Enhancement with nucleus
  - Saturation at significantly lower energy in e+A collisions at EIC

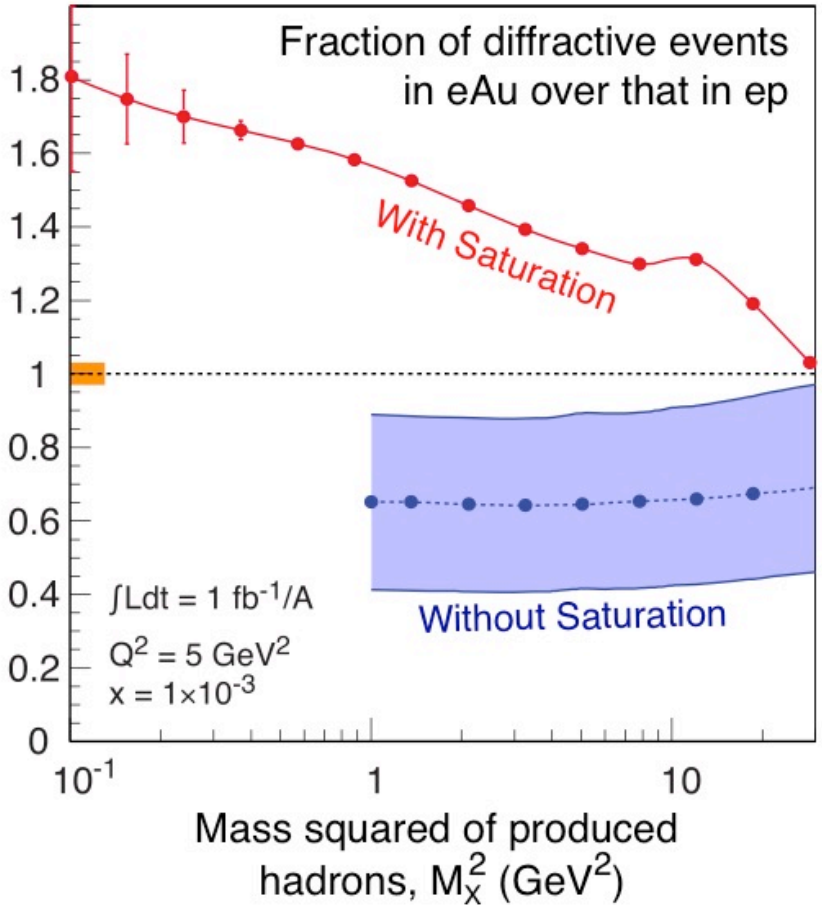




Diffractive process

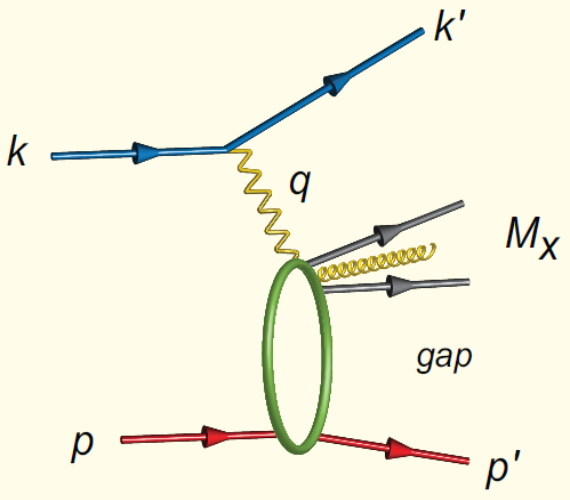
- Gluon saturation
  - Diffraction is the most sensitive way
  - More diffraction if saturation/CGC at EIC e+A

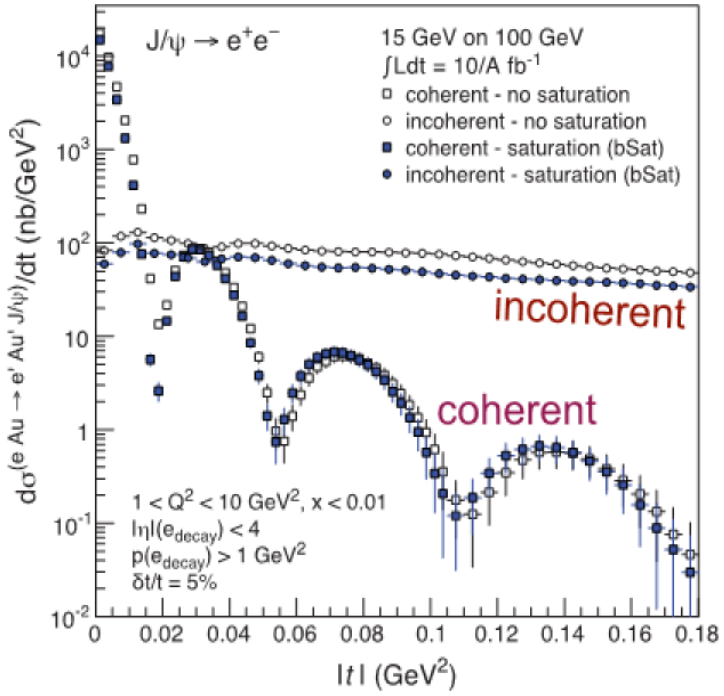


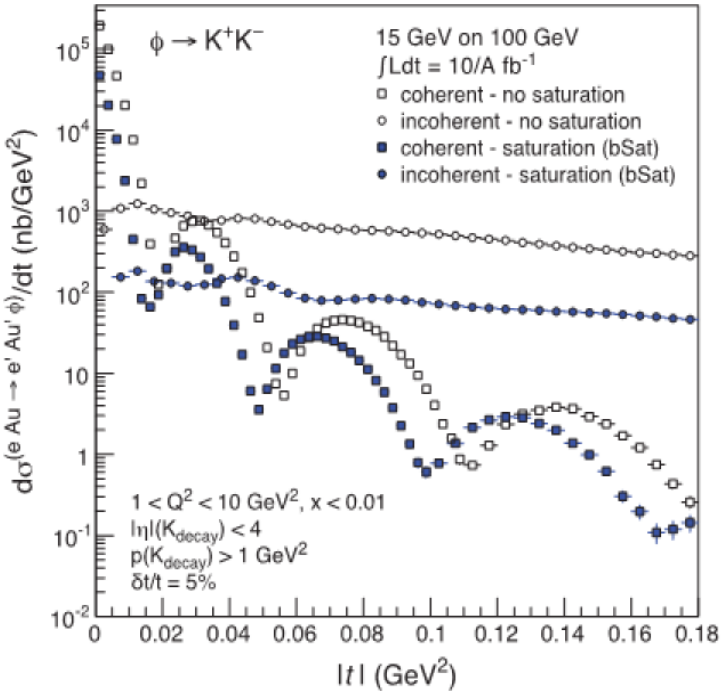


Diffractive process

- 3D structure of nucleus

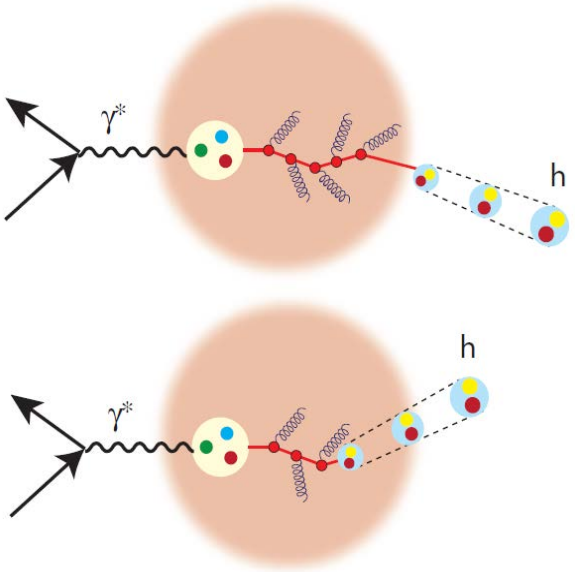


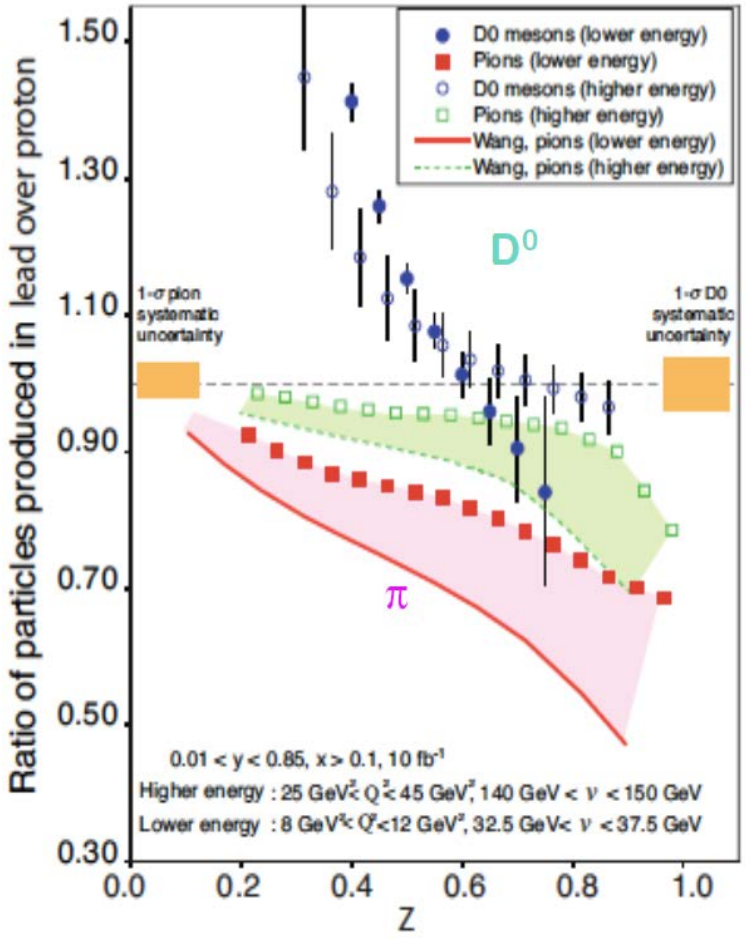




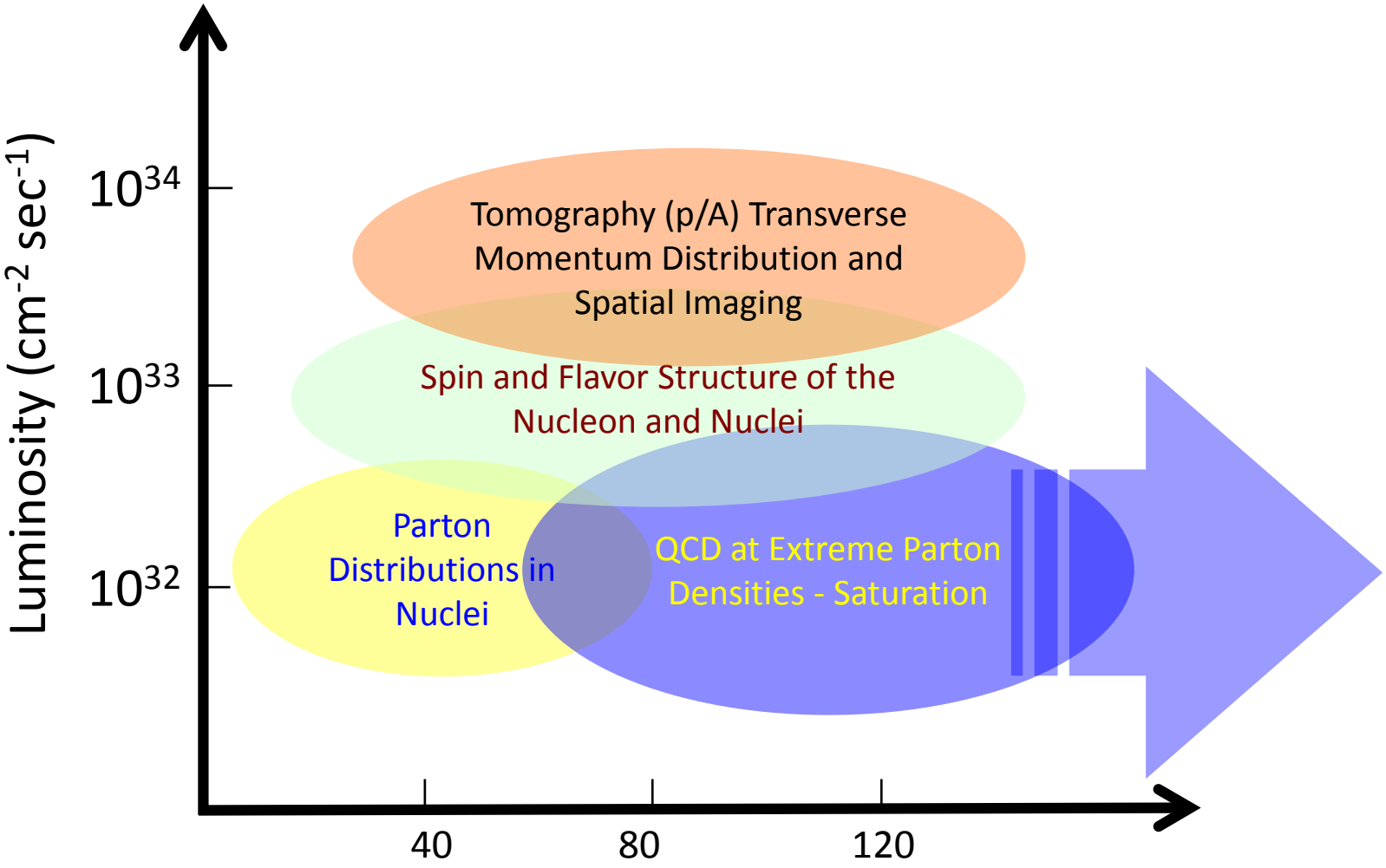
Hadronization

- Response of nuclear matter to fast moving color charge passing through it



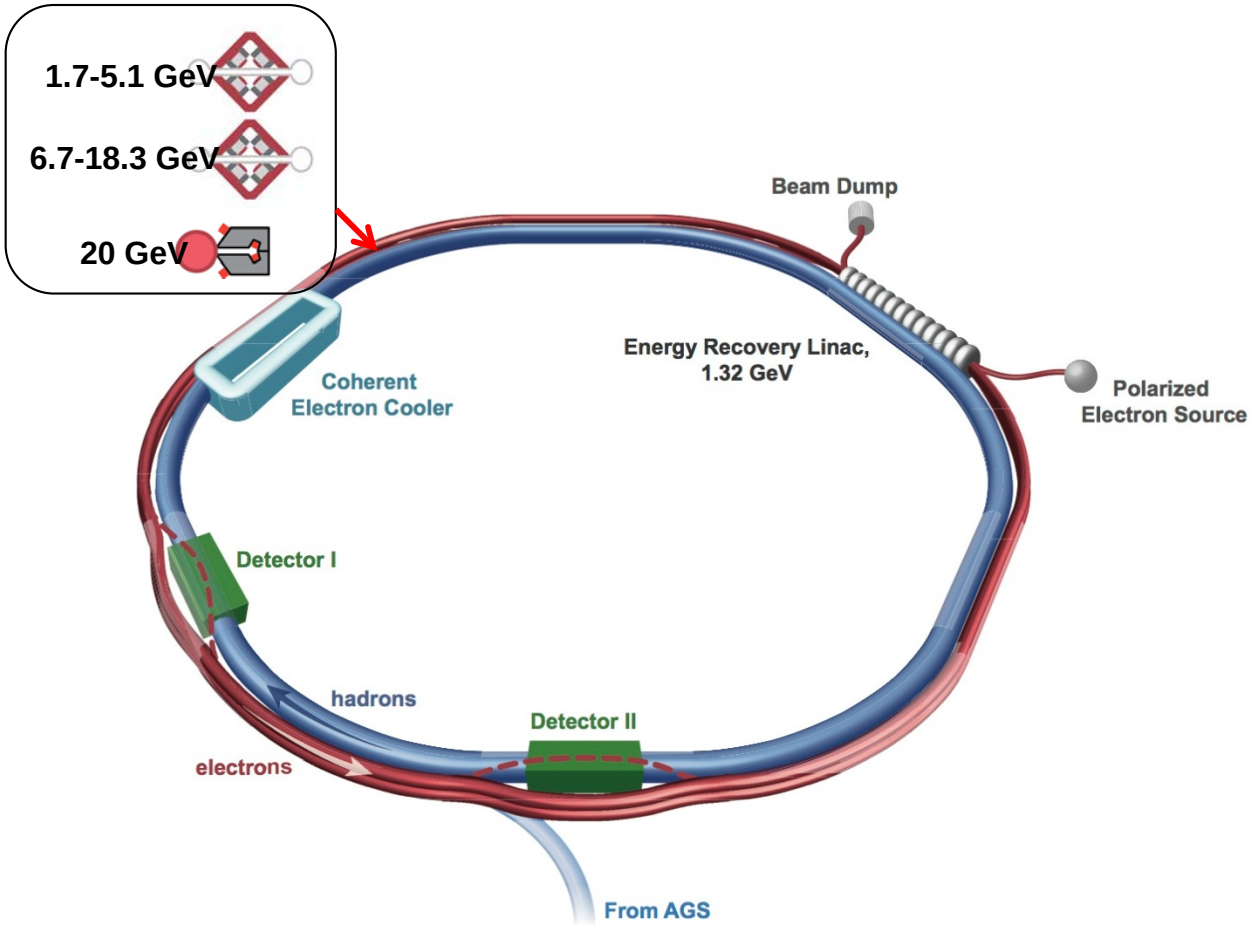


EIC Physics vs luminosity & energy



eRHIC at BNL

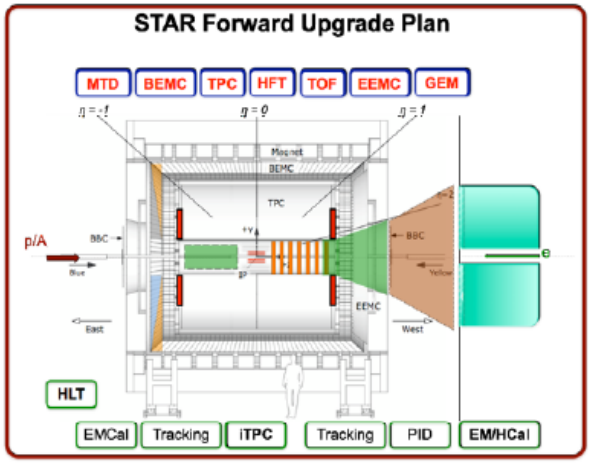
- 1.67 GeV main Energy Recovery Linac
- 2 FFAG beamlines used for re-circulations of 11 (12) beam energies
- Individual beamline to transport highest energy electrons



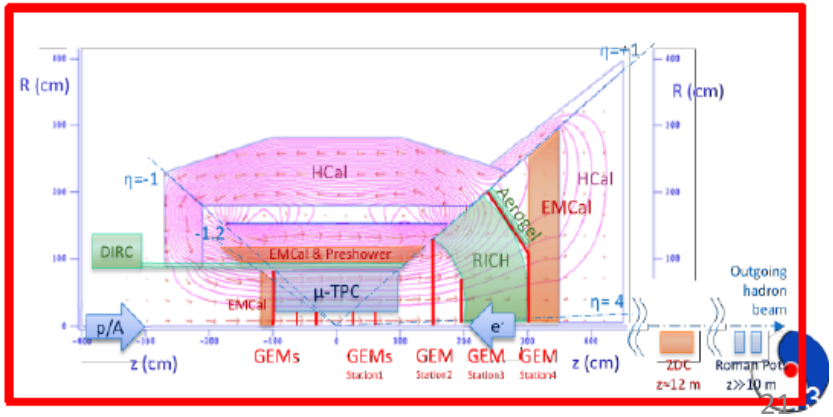
eRHIC at BNL

EIC Detectors & IR

Field-free electron pass thru hadron triplet magnets ⇒ minimize Sync Rad



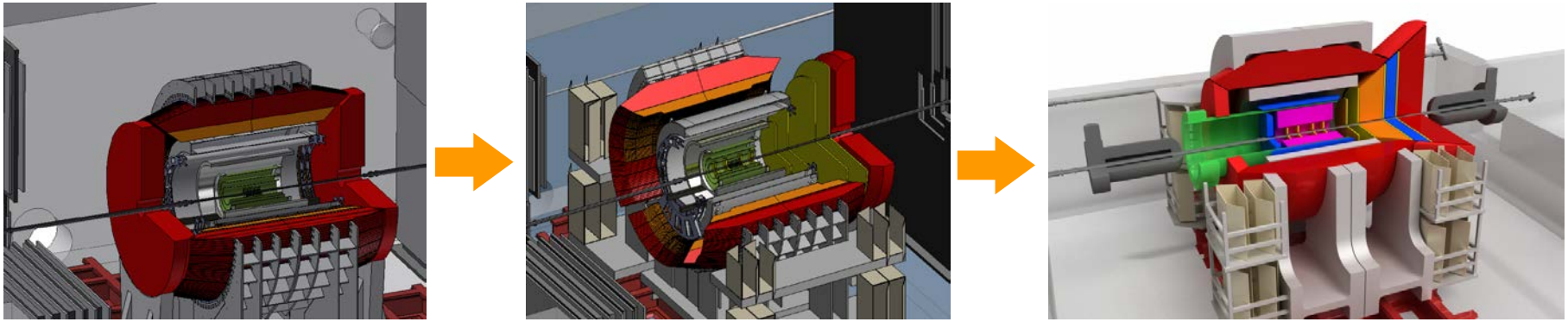
"eSTAR"



"ePHENIX"

ePHENIX

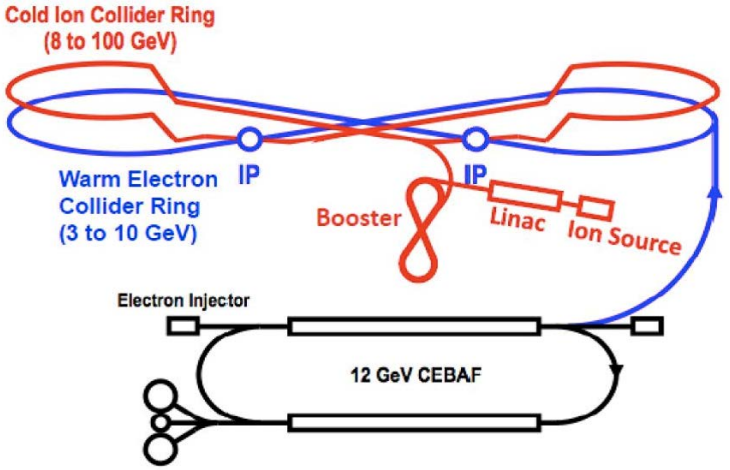
- ePHENIX as an initial detector at eRHIC
  - Feasible scenario for EIC

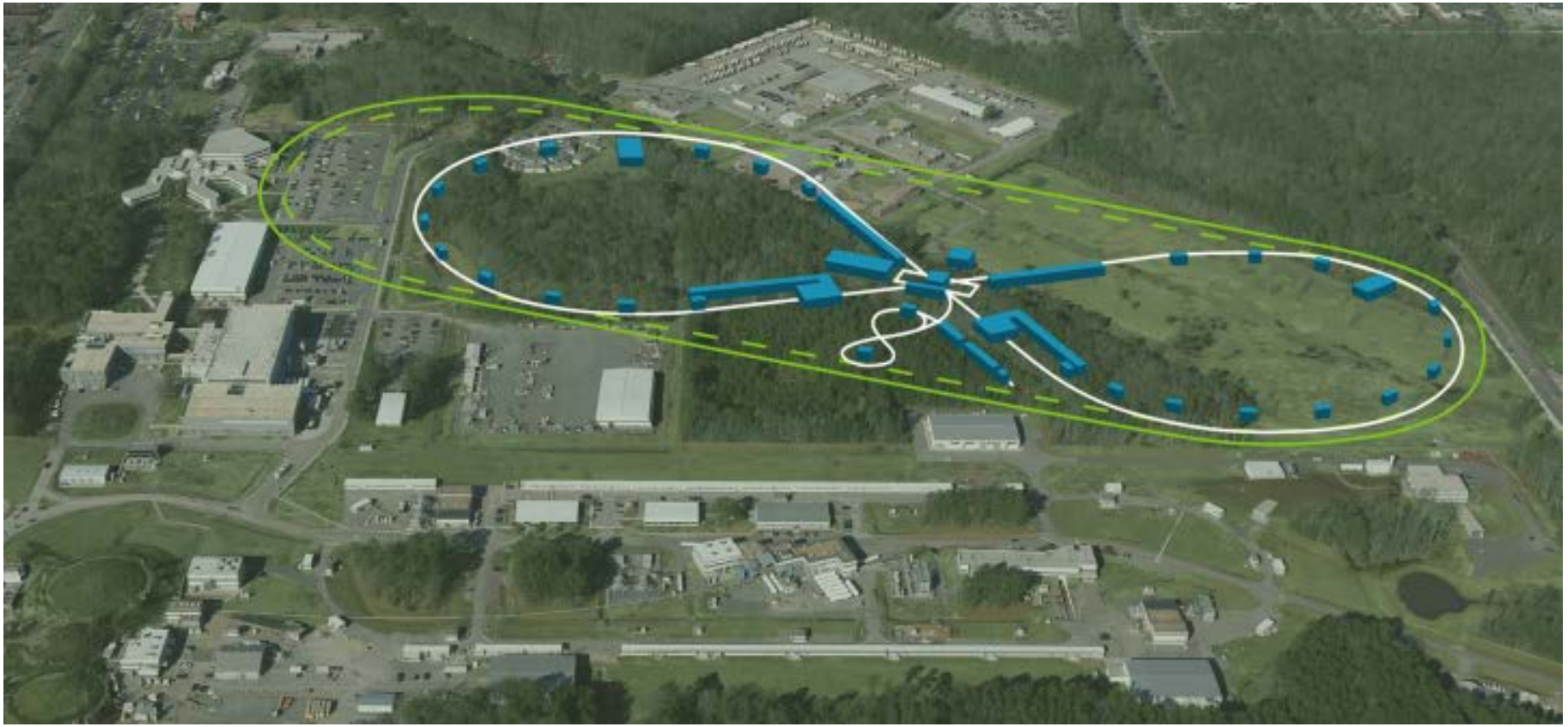


- sPHENIX (2022-23)
  - A new large-acceptance jet and Upsilon detector around the BaBar megnet
  - Probe QGP with precision measurements of jet quenching and Upsilon suppression
- forward sPHENIX (fsPHENIX)
  - Possible extension of sPHENIX for transverse spin physics
  - p+A and p$\uparrow$+A physics for CNM effects
- ePHENIX (2025 or later)
  - Central arm detector based on sPHENIX
  - Hadron arm detector possibly base on fsPHENIX
  - Electron arm detector

JLEIC at JLab

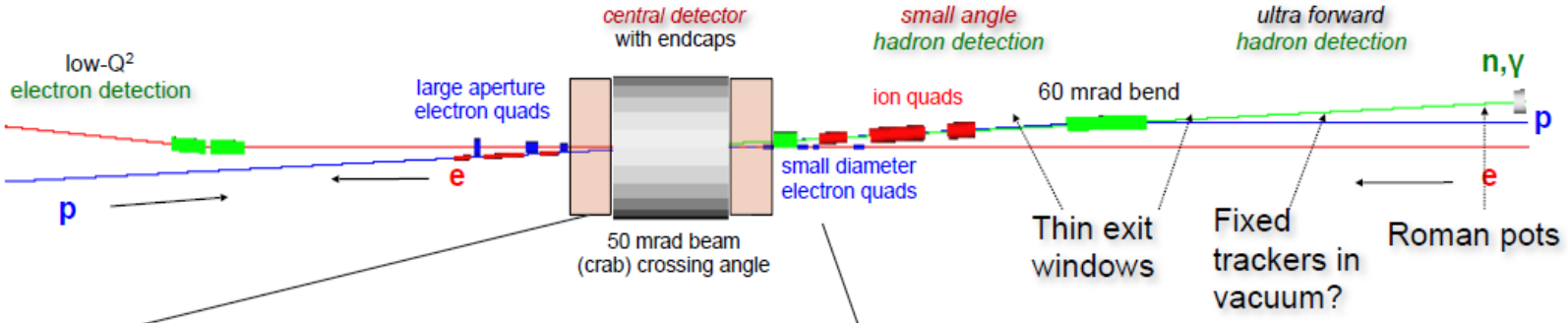
- Electron 3 – 10 GeV
- Proton 20 – 100 GeV
- Ion 12 – 40 GeV/u
- Collision energy $\sqrt{s}$ = 15 – 65 GeV

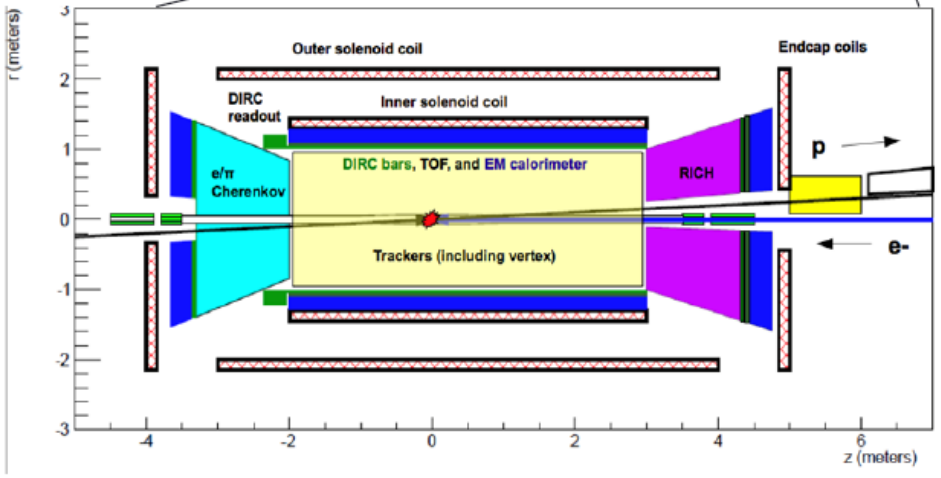




JLEIC at JLab

EIC at JLab: Integrated IR & Detector

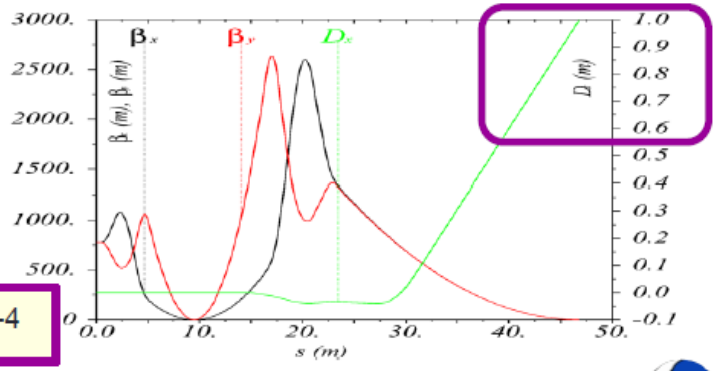




Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

Hadron/Ion detection in 3 stages

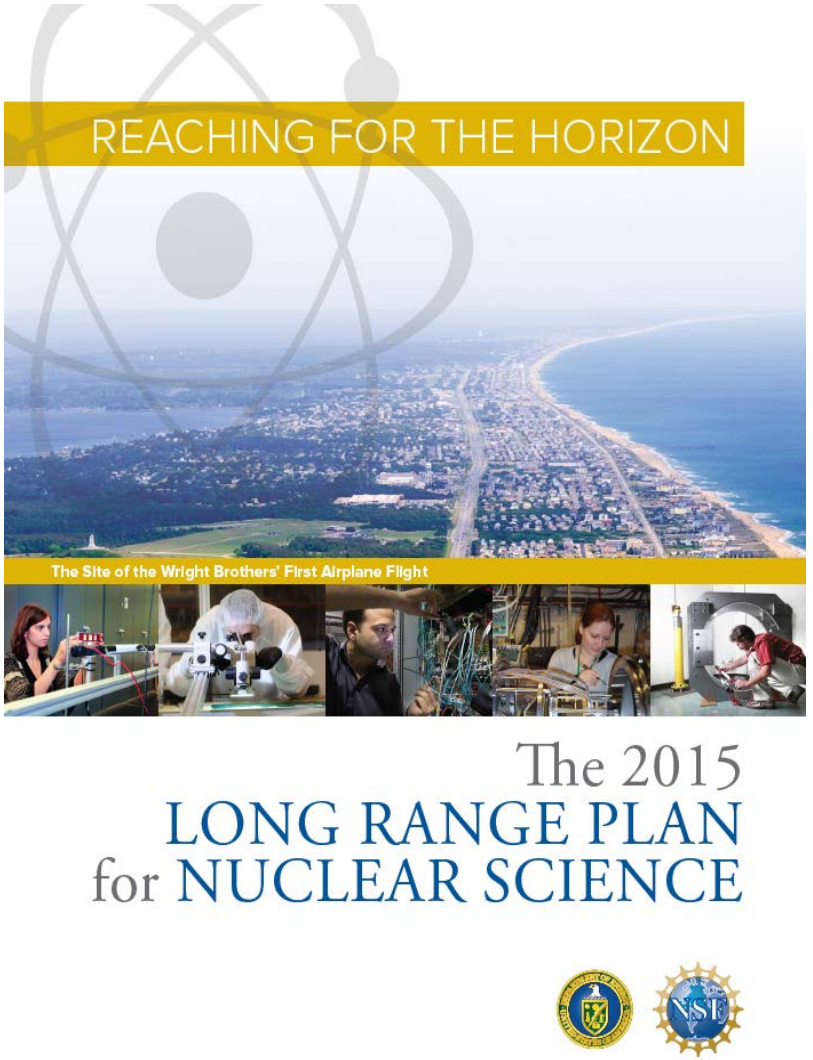
- Endcap with 50 mrad crossing angle
- Small dipole covering angles to a few degrees
- Ultra-forward up to one degree, for particles passing accelerator quads



Beamline functions as spectrometer: dp/p < 3x10^{-4}

EIC project

- NSAC 2015 Long Range Plan
  - We recommend a high-energy high luminosity polarized Electron Ion Collider as the highest priority for new facility construction after the completion of FRIB.
- CD3 (Start of construction) by 2022/23



EIC User Group (EUCUG)

- EIC Users
  - More than 600 collaborators, 26 countries, 101 institutions (March, 2016)
- From Japan
  - Experimentalists
    - RIKEN (Akiba, Goto, Nakagawa, Seidl, Mitsuka)
    - Tokyo Tech. (Shibata, Nakano)
    - Yamagata Univ. (Iwata, Miyachi, Doshita, Horikawa)
  - Theorists
    - Juntendo Univ. (Tanaka)
    - KEK (Kumano)
    - Kyorin Univ. (Ohtani)
    - Kyoto Univ. (Kunihiro, Hatta)
    - Niigata Univ. (Koike)
    - RIKEN (Hatsuda, Doi)
    - Tohoku Univ. (Sasaki)
    - Tokyo Univ. of Science (Saito)

Summary

- Physics at EIC
  - 3D structure of the nucleon / nucleus
    - TMDs / GPDs
    - Confined motion and distribution of partons inside the nucleon
  - Spin puzzle
    - Gluon polarization at low x region
    - Orbital angular momentum from GPDs
  - Gluon saturation
    - Discovery of collective gluonic system
  - Hadronization
- EIC project
  - Recommendation by NSAC 2015 Long Range Plan as the highest priority for new facility construction after FRIB
  - eRHIC at BNL
    - sPHENIX $\rightarrow$ ePHENIX
  - JLEIC at Jefferson Lab
  - Development of EIC User Group