Physics Program with the Electron-Ion Collider in China

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Outline

- **Introduction**
- **Electron-Ion Collider in China (EicC)**

  1st stage: 3.5 ~5 GeV (pol. e) X 20 GeV (pol. p), L= 2- 4x10^{33}

  EicC construction : 2030 – 2038
- **EicC Physics Highlights**

  Spin-Flavor Structure (sea quark polarization)

  3-d Structure of the Nucleon (GPDs,TMDs)

  Proton Mass

  pi/kaon structure, Hadronization/EMC/SRC
- **Conclusions**

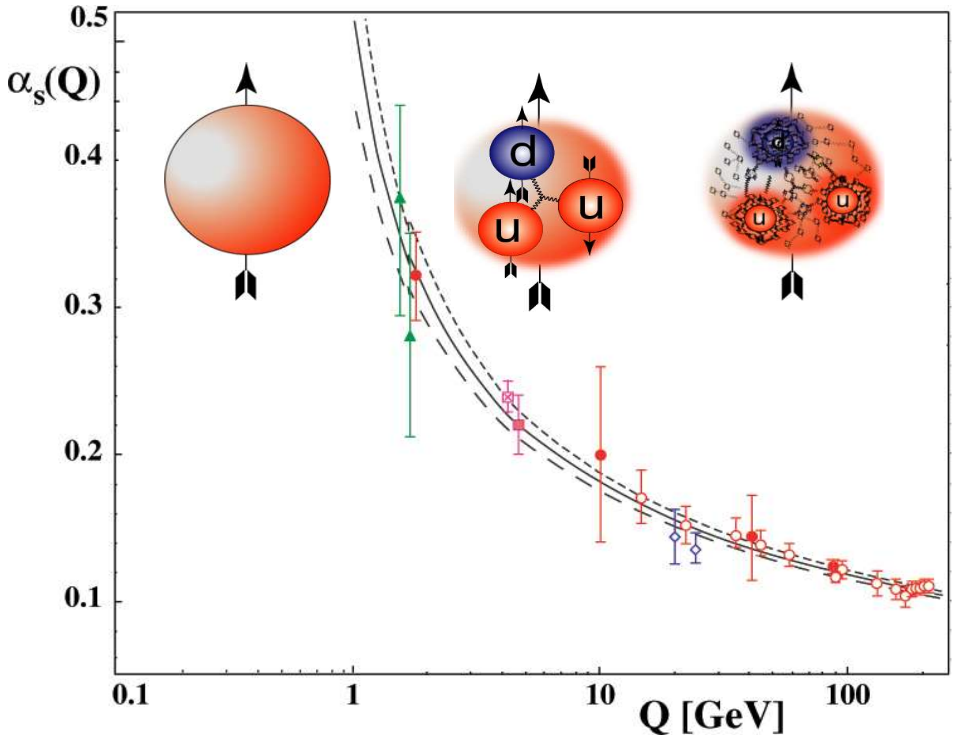
Introduction

QCD, *Standard Model* Parton model

Strong Interaction and QCD

- Strong interaction, running coupling ~1
  -- asymptotic freedom (2004 Nobel)
  perturbation calculation works at high energy
  -- interaction significant at intermediate energy
  quark-gluon correlations
  -- interaction strong at low energy
  confinement
  -- gluons self interacting

running coupling "constant"



- A major challenge in fundamental physics:
  -- Understand QCD in all regions, including strong (confinement) region

- Fundamental degrees of freedom:
  quarks, gluons
  Natural effective degrees of freedom:
  hadrons
- Nucleon/Nucleus: ideal lab to study QCD

What are the challenges?

- Success of the Standard Model

  Electro-Weak theory tested to very good level of precision

  Discovery of Higgs (like) particle at LHC

  QCD tested in the high energy (short distance) region

- Major challenges:

  Test QCD at long distance (non-perturbative)

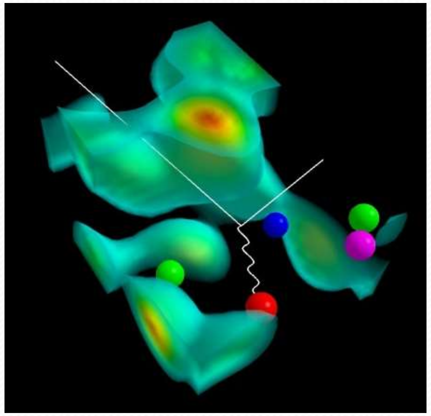
  Understand quark-gluon structure of the nucleon

  Confinement

- Beyond Standard Model

  Intensity (precision) frontier: test Standard Model at low energy

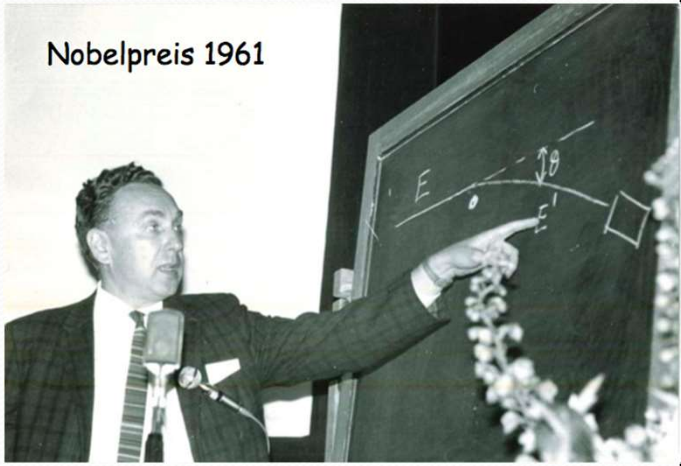
Nucleon Structure: A Universe Inside



- Nucleon: proton =(uud) , neutron=(udd)
  + sea + gluons
- Global properties and structure: full of surprises
  - Mass: 99% of the visible mass in universe
    - ~1 GeV, but u/d quark mass only a few MeV each!
    - Lattice QCD: vacuum condensation **(1 of top 10 discoveries in 2008)**
  - Charge and magnetic distributions: very different!
  - Proton charge radius: muonic hydrogen Lamb shift result! **(Nature 466, 213 (2010))**
  - Momentum: quarks carry ~ 50%
  - Spin: ½, but total quarks contribution only ~30%! — Spin Sum Rule
  - Magnetic moment: large part is anomalous, >150%! — GDH Sum Rule
  - Axial charge — Bjorken Sum Rule
  - Tensor charge
  - Orbital angular momentum
  - Transverve (3-d) structure: TMDs and GPDs
  - …

Electron Scattering and Nucleon Structure

- Clean probe to study nucleon structure
  only electro-weak interaction, well understood



Robert Hofstadter,
Nobel Prize 1961

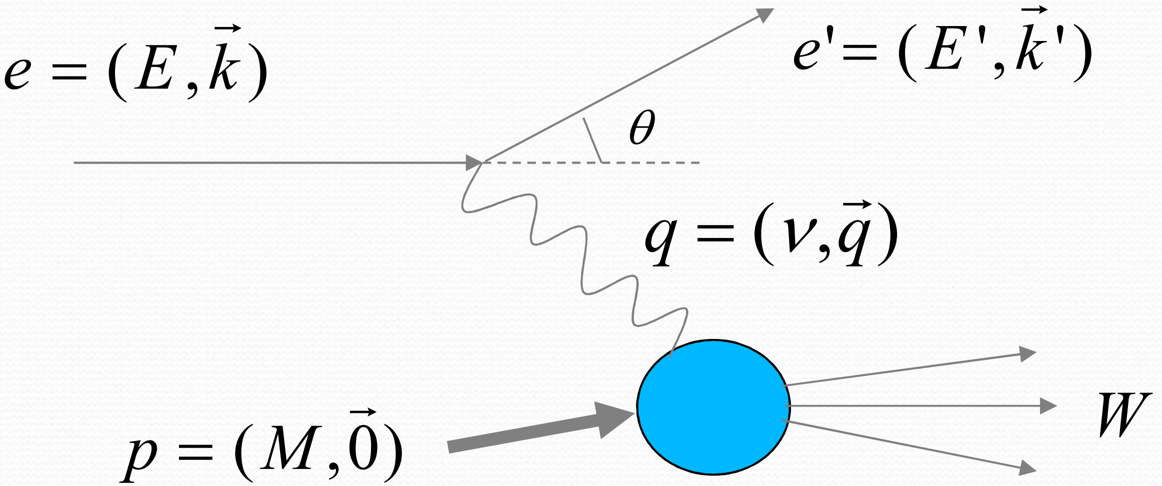
- Elastic Electron Scattering: Form Factors
  → 60s: established nucleon has structure (Nobel Prize)
  electrical and magnetic distributions

- Resonance Excitations
  → internal structure, rich spectroscopy (new particle search)
  constituent quark models

- Deep Inelastic Scattering
  → 70s: established quark-parton picture (Nobel Prize)
  parton distribution functions (PDFs)
  polarized PDFs : Spin Structure

J.T. Friedman ***R. Taylor*** ***H.W. Kendall***
Nobel Prize 1990

Inclusive Electron Scattering



4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

Invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

Unpolarized:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_M \left[\frac{1}{\nu} F_2(\nu, Q^2) + \frac{2}{M} F_1(\nu, Q^2) \tan^2\tfrac{\theta}{2} \right]$$

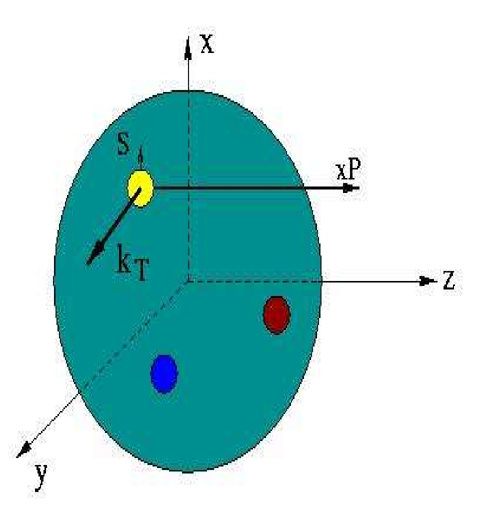
$$\sigma_M = \frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)}$$

F_1 and F_2: information on the nucleon/nuclear structure

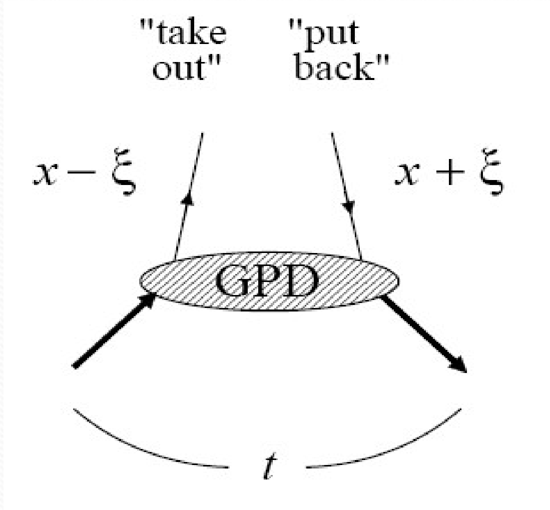
Unified View of Nucleon Structure

$W_p^u(x,k_T,r)$ *Wigner distributions* **(X. Ji)**

6D Dist.



d^3r $\qquad$ $d^2k_T\,dr_z$



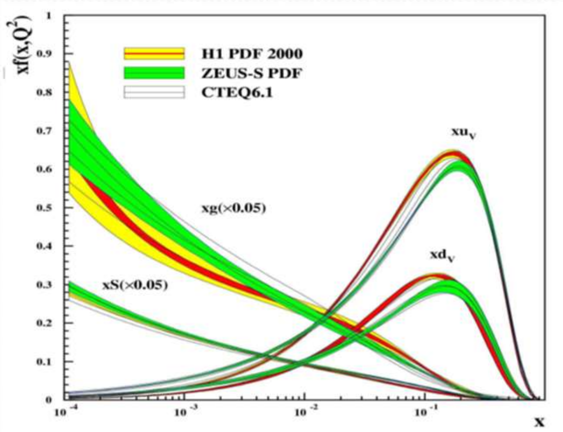
TMD PDFs
$f_1^u(x,k_T)$, ..
$h_1^u(x,k_T)$

GPDs/IPDs

3D imaging

d^2k_T $\qquad$ d^2r_T

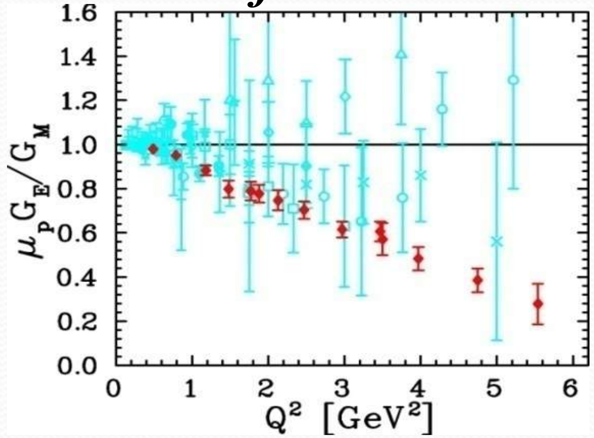
dx &
Fourier Transformation



PDFs
$f_1^u(x)$, .. $h_1^u(x)$

1D

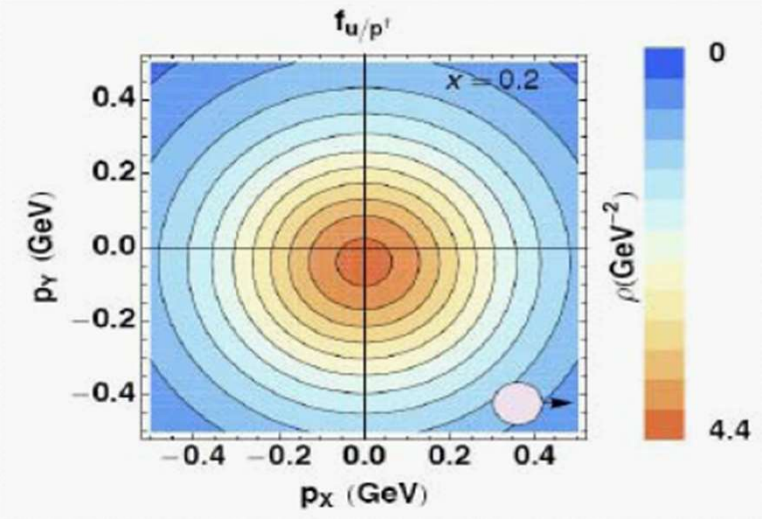
Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$



3-D Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

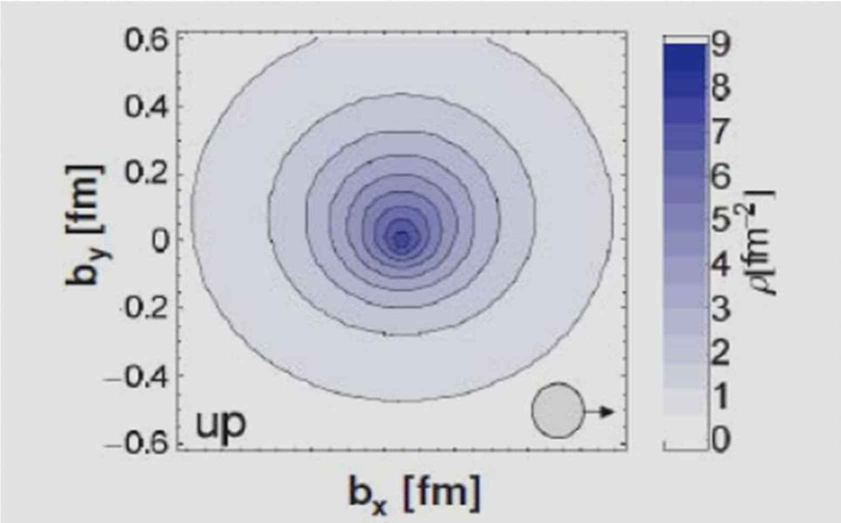


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations- relate to OAM
- non-trivial factorization
- accessible in SIDIS (and Drell-Yan)

GPDs

2+1 D picture in **impact-parameter space**



QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

Electron-Ion Collider Project in China (EicC)

A future facility to study sea quark and nuclear physics

EIC: Science Motivation

A High Luminosity, High Energy Electron-Ion Collider:
A New Experimental Quest to Study the Sea and Glue
How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

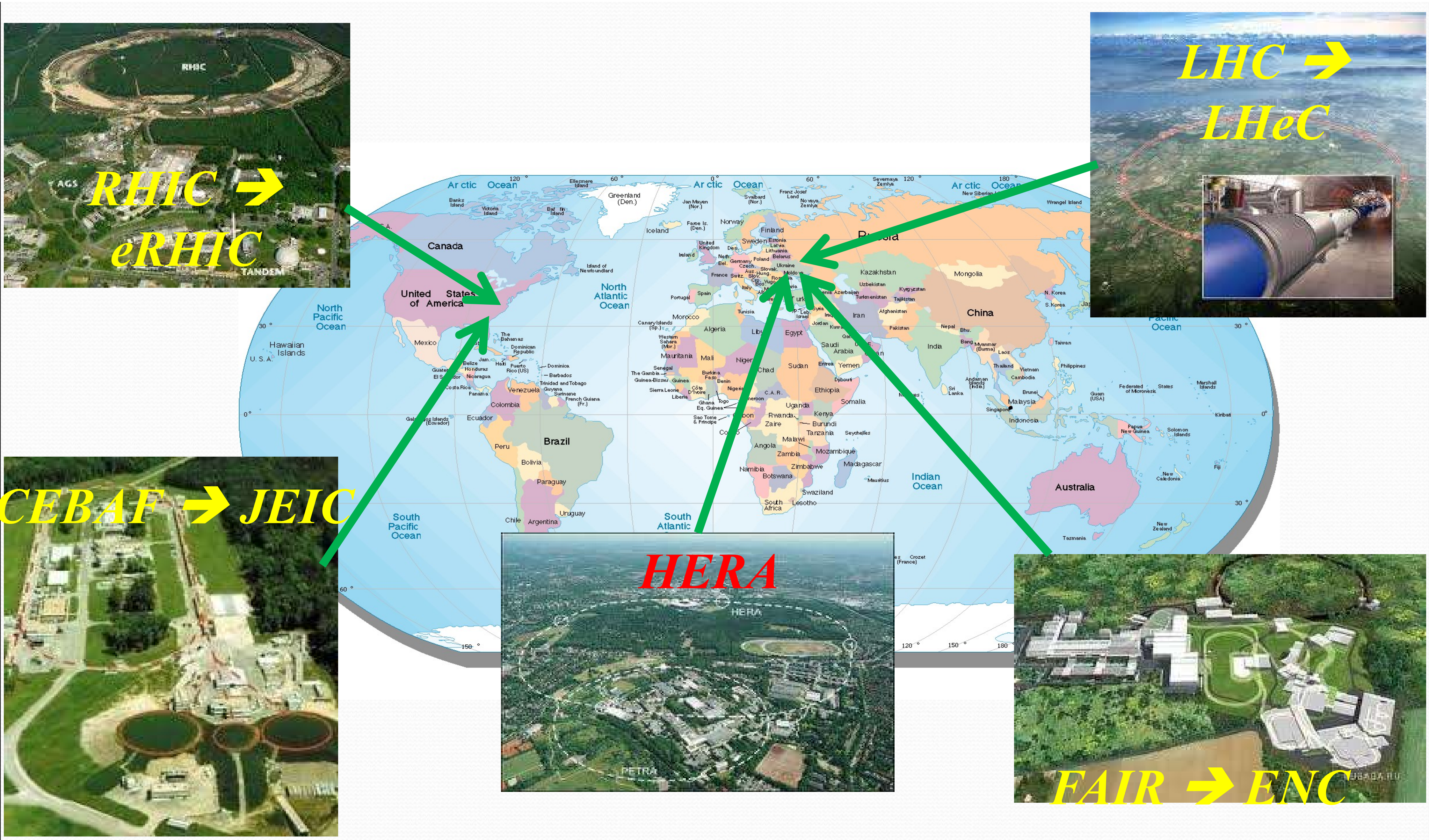
Precisely image the sea-quarks and gluons in the nucleon:

- How do the gluons and sea-quarks contribute to the spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do hadronic final-states form in QCD?

Explore the new QCD frontier: strong color fields in nuclei:

- How do the gluons contribute to the structure of the nucleus?
- What are the properties of high density gluon matter?
- How do fast quarks or gluons interact as they traverse nuclear matter?

Electron Ion Colliders on the World Map

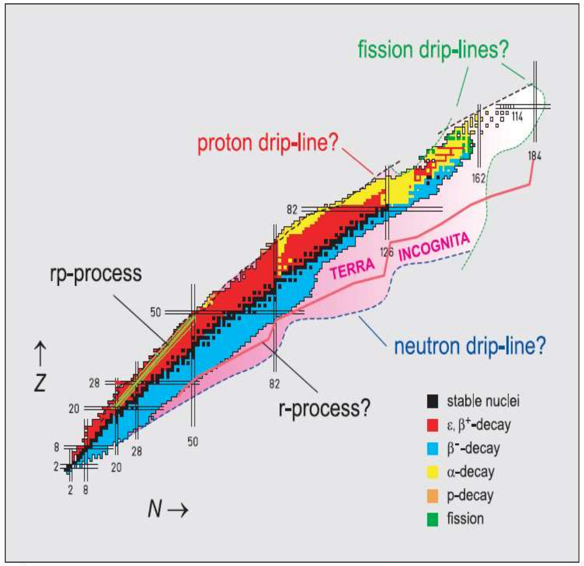


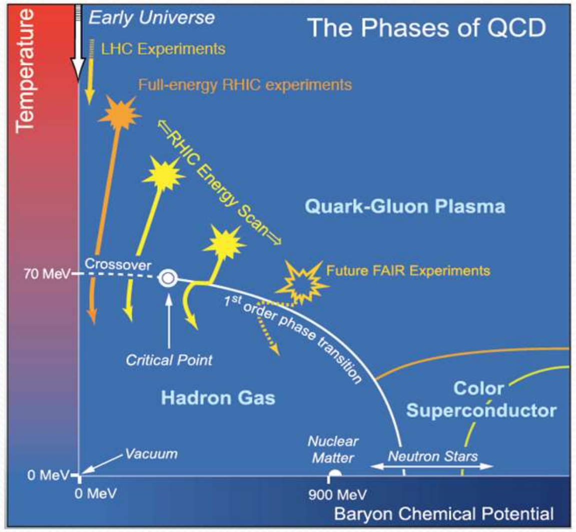
Nuclear Physics Facilities in IMP

Nuclear Structure

QCD Phase digram

Nucleon Structue





CSR

CEE (CSR External Target)
HIAF

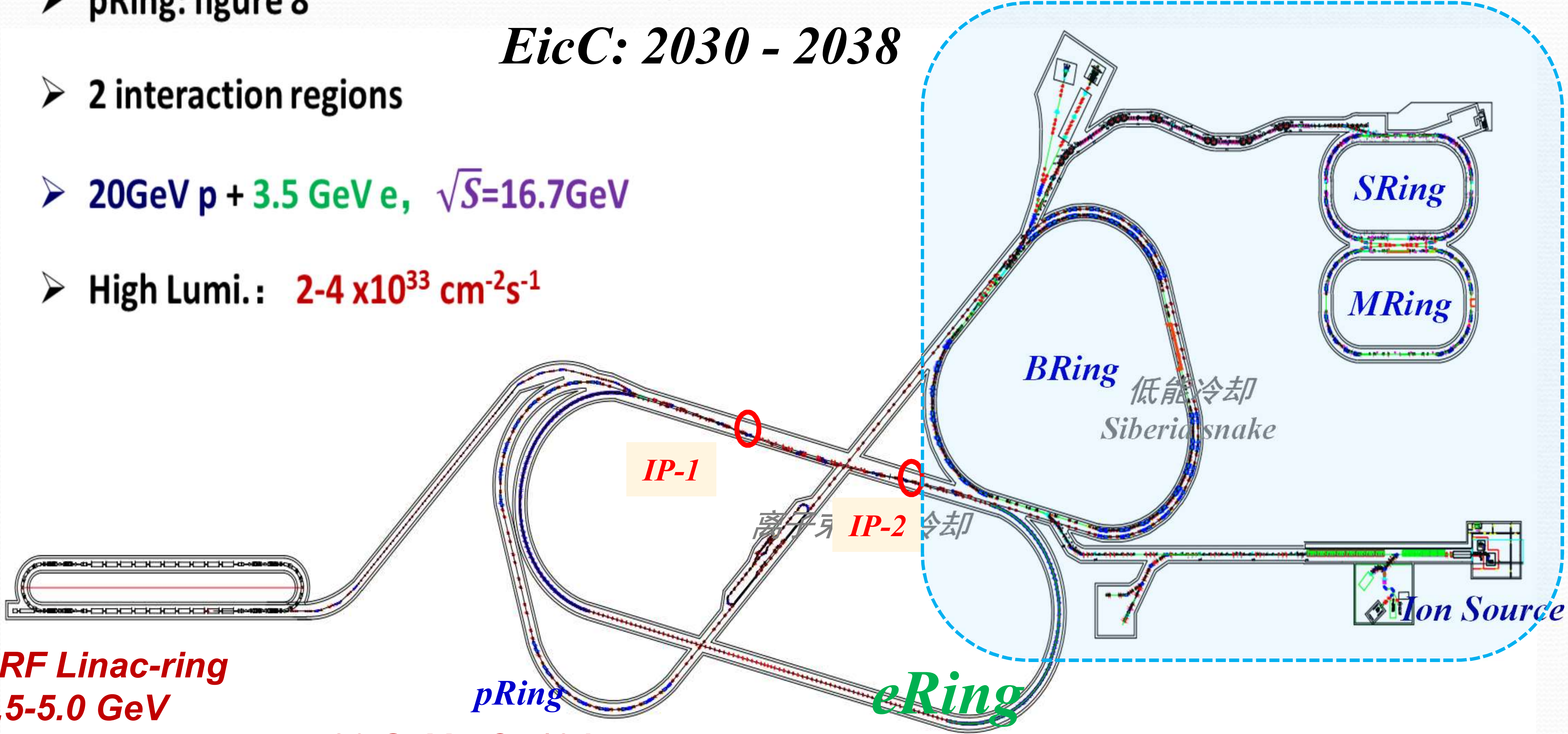
EicC: Eic in China

High Intensity heavy-ion Accelerator Facility (HIAF)

EicC accelerator complex overview

HIAF: constructing
HIAF-U: 2025-2032
EicC: 2030 - 2038

- pRing: figure 8
- 2 interaction regions
- 20GeV p + 3.5 GeV e, $\sqrt{S}$=16.7GeV
- High Lumi.: 2-4 x10^{33} $cm^{-2}s^{-1}$

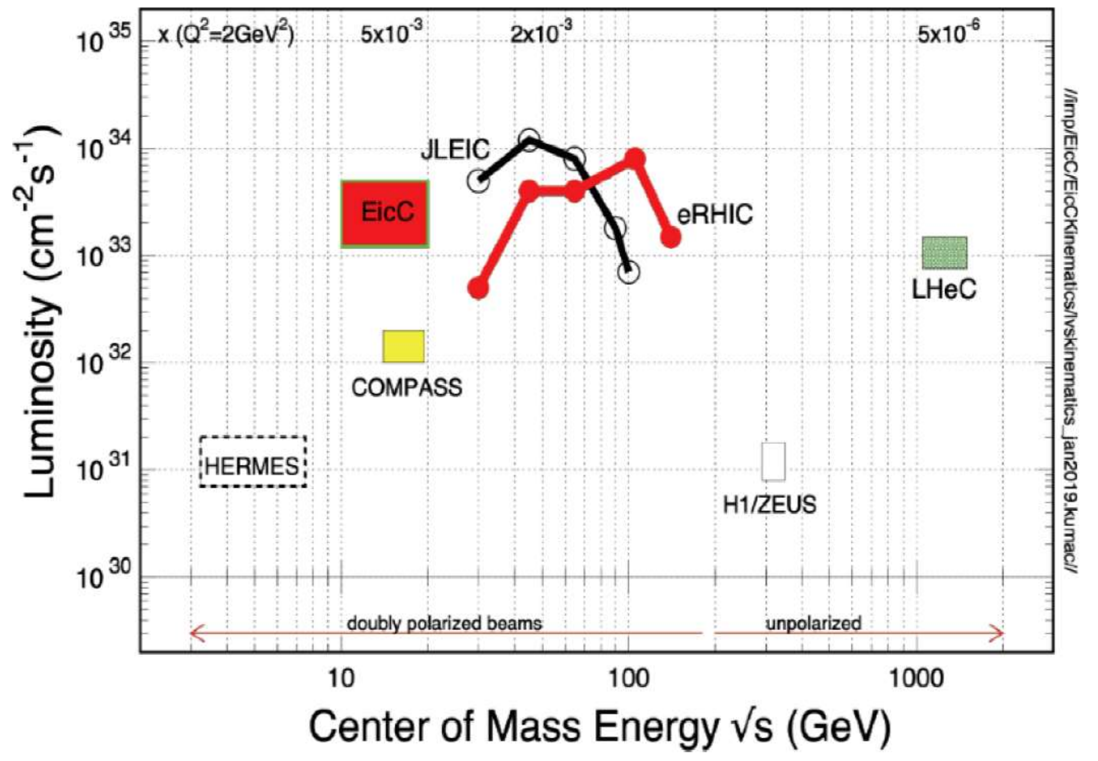


SRF Linac-ring
3.5-5.0 GeV
Top-up

20 GeV，C: 1347 m
Polarized proton

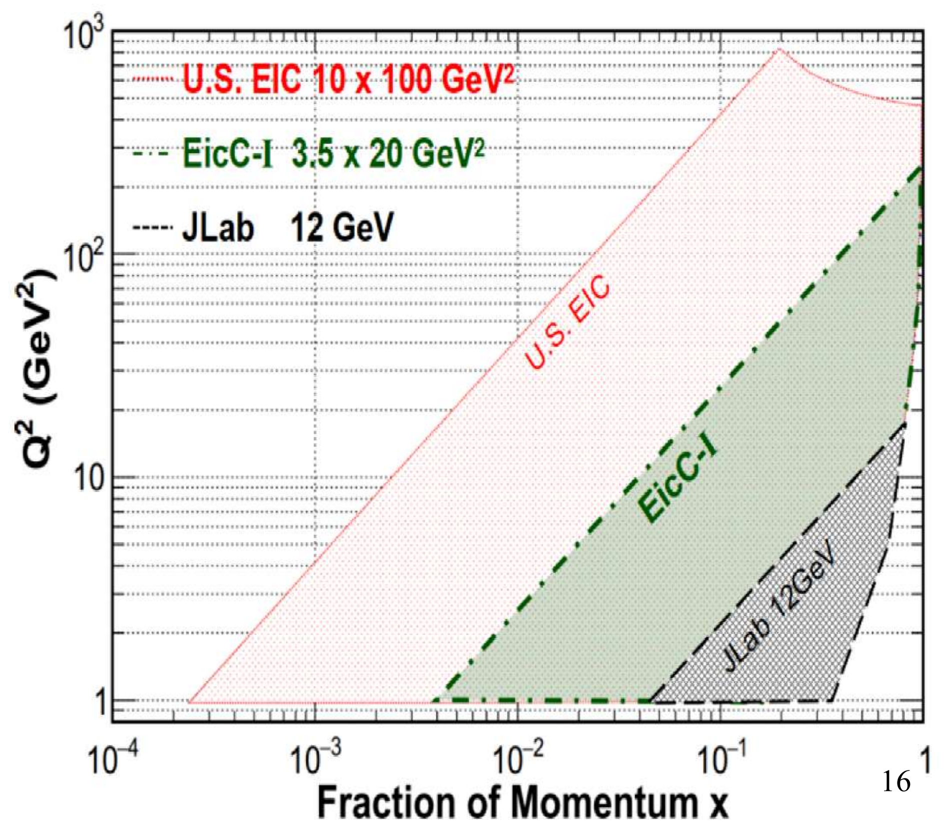
3.5 -5.0 GeV，C: 822 m
Polarized electron

EIC Kinematics



EicC, √s : 15 ~ 20 GeV

- ***Focus on nuclear physics***
- ***B-quark hadron production***



Facilities	Main goals
JLab 12 GeV	Valence quark
EicC	Valence and Sea
US and Europe EIC	gluon

EicC Physics Highlights

Nucleon structure 1D and 3D, pi/k structure, proton mass

Case 1:Longitudinal Spin Structure

Spin puzzles and surprises

Spin Milestones (Nature)

- 1896: Zeeman effect (milestone 1)
- 1922: Stern-Gerlach experiment (2)
- 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
- 1928: Dirac equation (4)
-             Quantum magnetism (5)
- 1932: Isospin(6)
- 1935: Proton anomalous magnetic moment
- 1940: Spin–statistics connection(7)
- 1946: Nuclear magnetic resonance (NMR)(8)
- 1971: Supersymmetry(13)
- 1973: Magnetic resonance imaging(15)
- 1980s: “Proton spin crisis”
- 1990: Functional MRI (19)
- 1997: Semiconductor spintronics (23)
- 2000s: Breakthrough in nucleon spin physics?
- 2000s: Application of nucleon spin physics?

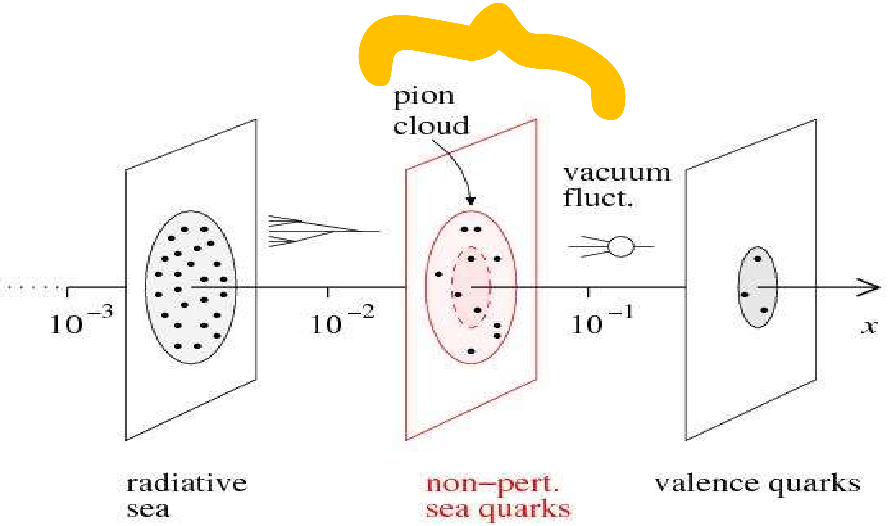
Pauli and Bohr watch a spinning top

Sea Quarks 1D Structure

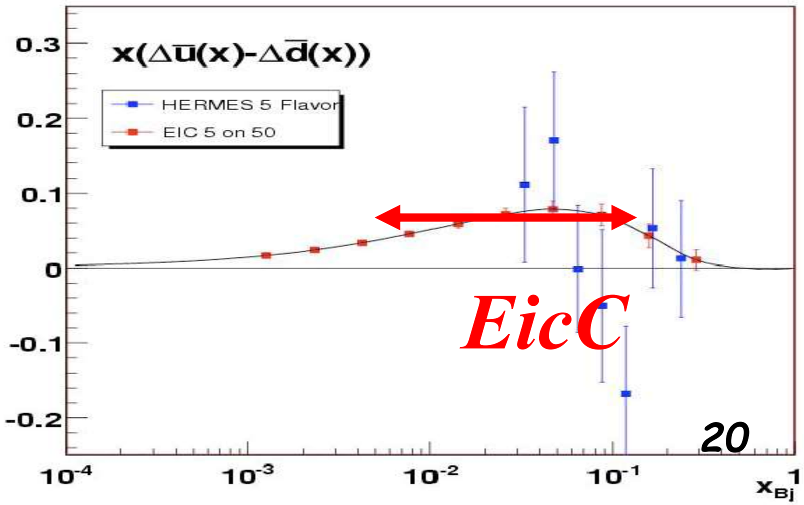
- Sea quarks are poorly known!
- Without EIC: large uncertainties in nuclear sea quarks and gluons
- With EIC: significantly reduces uncertainties: Wide coverage in x,Q2
- EicC, combination of energy and luminosity

Significant improvement for Δubar, Δdbar from SIDIS

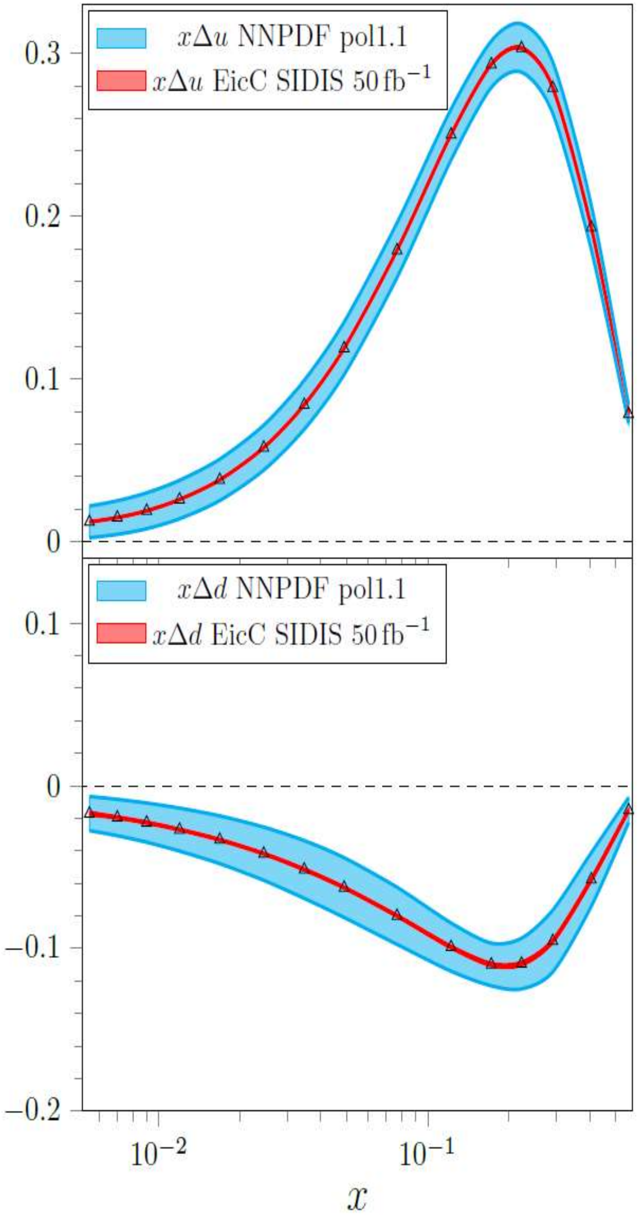
Unique opportunity for Δs

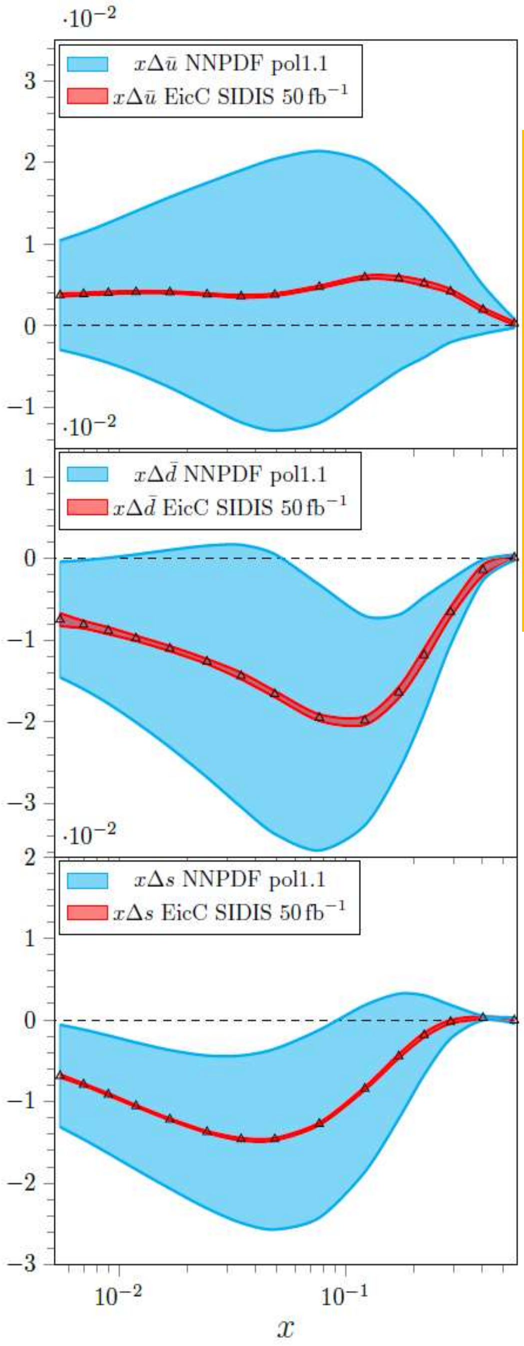


Sea Quark Polarization



Projections on helicity distributions (EicC)





EicC SIDIS data:

- ✓ *e x p 3.5GeV x 20 GeV*
- ✓ *e x he3 3.5GeV x 40 GeV(He3)*

Lumi:

- ✓ *Ep 50 fb^{-1}*
- ✓ *eHe3 50 fb^{-1} (per nucleus)*

Pion, Kaon SIDIS measurements

Fragmenation functions used: DSS

Preliminary

Case 2: GPD 3D Structure

Generalized Parton Distributions

GPD Study at EicC

- Unique opportunity for DVMP (pion/Kaon)

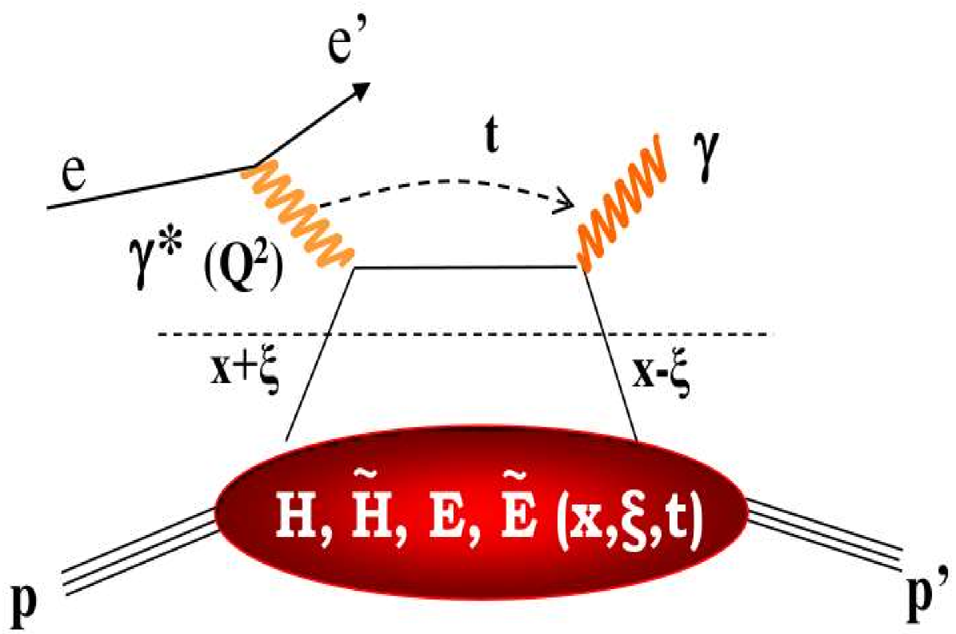
  flavor decomposition needs DVMP

  energy reach $Q^2 > 5\text{-}10\ GeV^2$, scaling region for exclusive light meson production

  (JLab12 energy not high enough to have clean meson deep exclusive process)

- Significant increase in range for DVCS

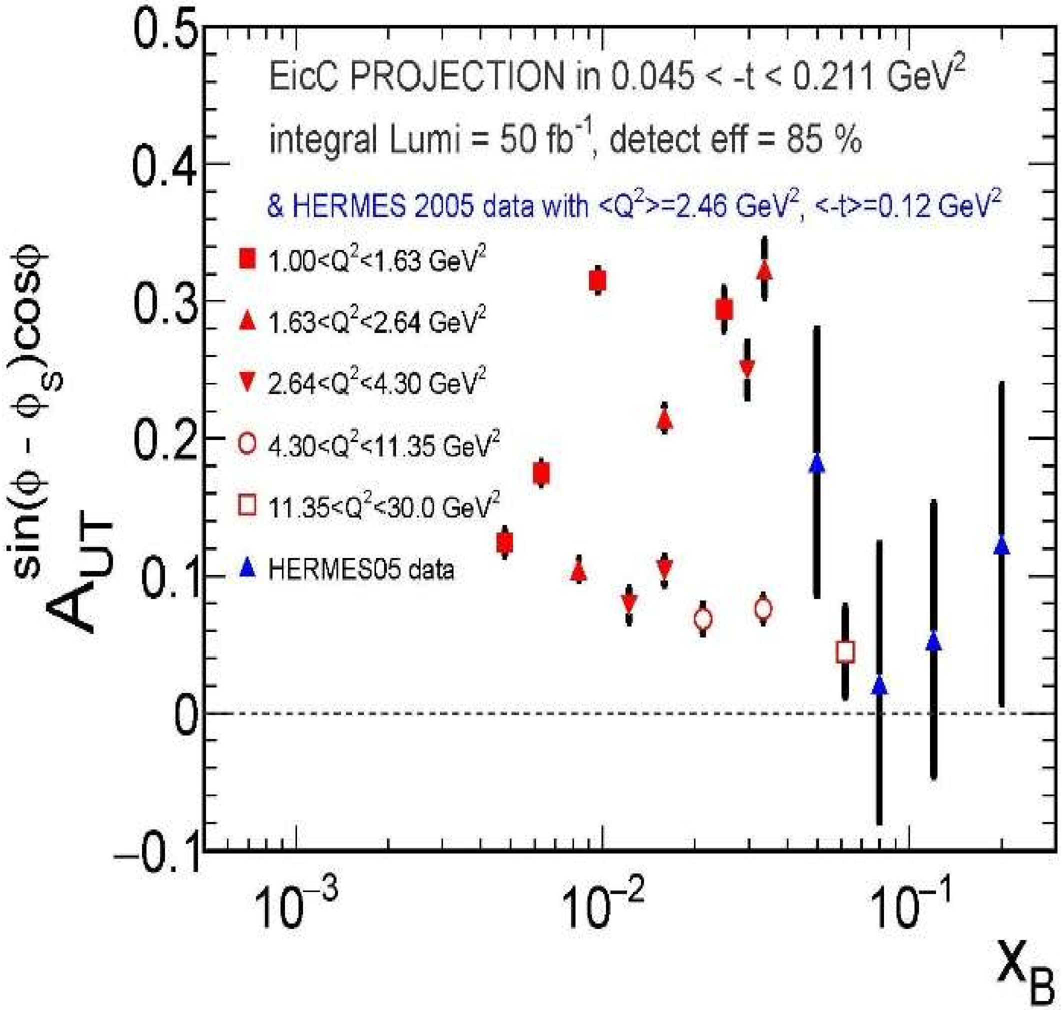
  combination of energy and luminosity



Exclusive reactions, such as DVCS, can get access to GPDs.

EicC simulations on GPDs

EicC，Statistic error only



Projection with multi-dimensional binning: t, Q^2, x_B

EicC: significantly increase the range for DVCS; Unique opportunity for DVMP (pion/Kaon)

Case 3: TMD 3D Structure

Transverse Momentum-Dependent Distributions

TMD Study at EicC

TMDs via SIDIS	Quark Polarization		
	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization: U	$F_{UU} \propto f_1 \otimes D_1$ *Unpolarized*		$F_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp} \otimes H_1^{\perp}$ *Boer-Mulders*
Nucleon Polarization: L		$A_{LL} \propto g_1 \otimes D_1$ *Helicity*	$A_{UL}^{\sin(2\phi_h)} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$ *Long-Transversity*
Nucleon Polarization: T	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$ *Sivers*	$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T} \otimes D_1$ *Trans-Helicity*	$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1 \otimes H_1^{\perp}$ *Transversity* $A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$ *Pretzelosity*

- **JLab12: Semi-incl DIS in valence region**

  Precise observables, but limited phase space

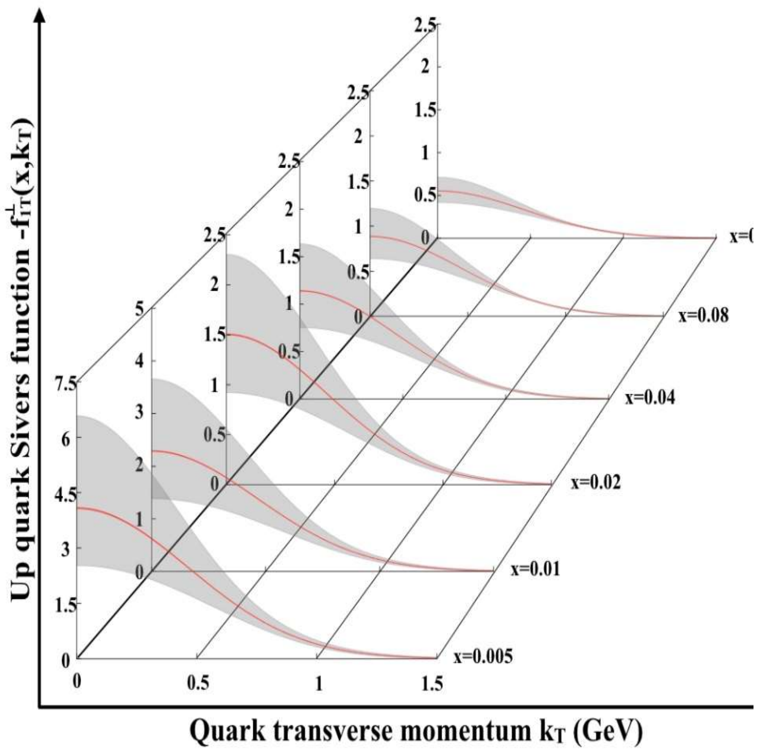
- **EicC: Wide kinematic range for SIDIS**

1. High precision quantitative measurements of all the quark TMDs in the valence region
2. Significant increase in Q^2 range for valence region: energy reach Q^2 ~40 GeV^2 at x ~ 0.4
3. Unique opportunity for TMD in "sea quark" region: reach x ~ 0.01

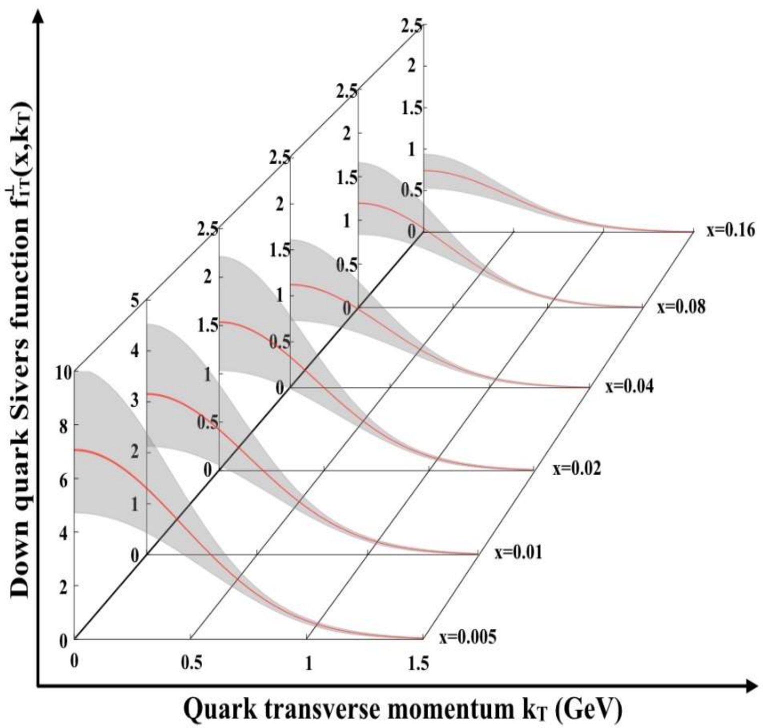
EicC projections on Sivers TMD

sivers EicC VS world data

U quark



d quark



Current & target fragmentation un-distinguished clearly yet:
$W > 2.3$ GeV
$W' > 1.6$ GeV
$0.3 < z < 0.7$
$Q^2 > 1$ GeV^2

Preliminary

LO study: Only u,ubar, d, dbar included

Case 4: Proton Mass

Visible mass in universe

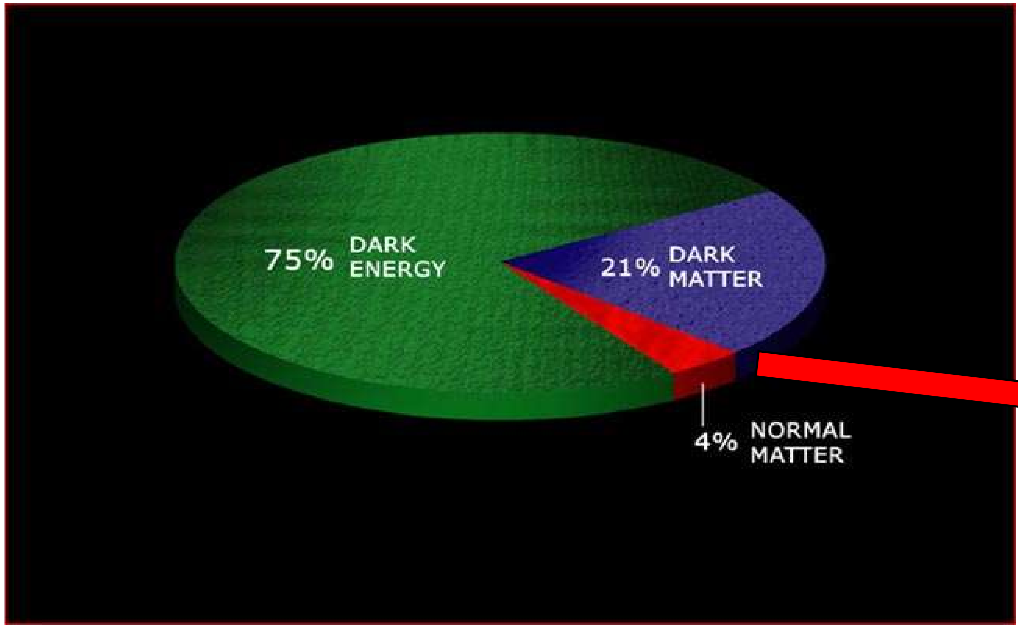
Explore Proton Mass

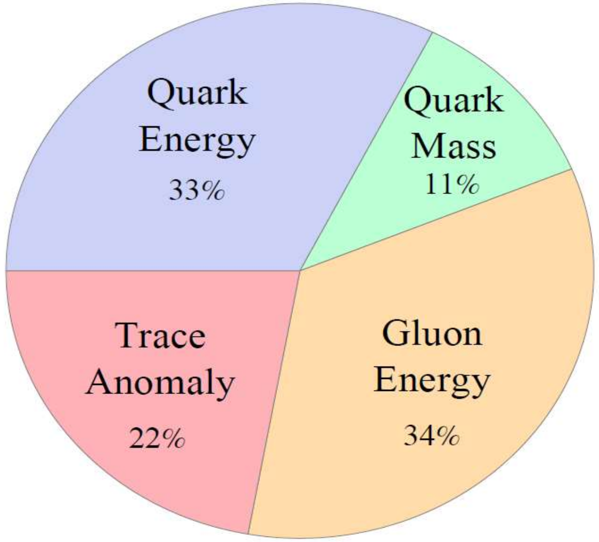
- ***Proton Mass Ji's decomposition:*** **: *parameters a and b***

X. Ji, PRL 74, 1071 (1995) & PRD 52, 271 (1995)

- ***Proton mass budget: about 22% comes from trace anomaly***
- ***We know very little about it***

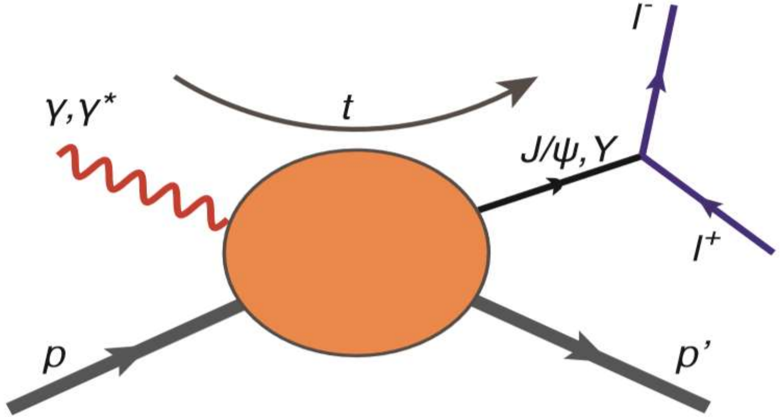
$$
\begin{aligned}
M_q &= \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right)M, \\
M_g &= \frac{3}{4}(1-a)M, \\
M_m &= \frac{4+\gamma_m}{4(1+\gamma_m)}bM, \\
M_a &= \frac{1}{4}(1-b)M,
\end{aligned}
$$





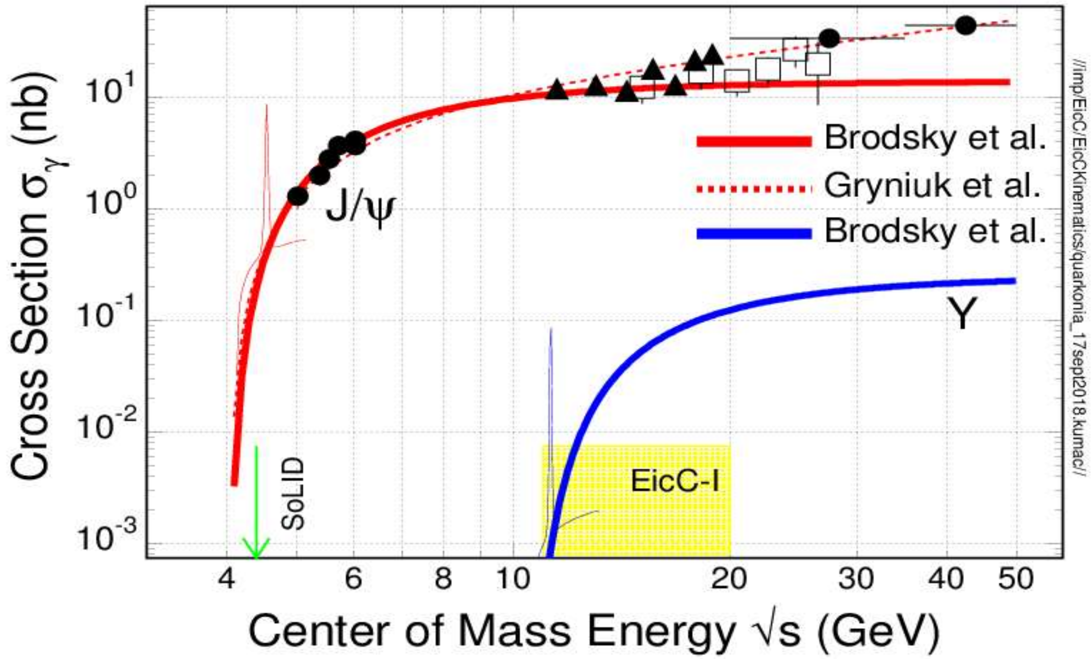
Quarkonium in electro- and photo-production

- **Parameter *a*：** related to PDFs, well constrained
- **Parameter *b*：** related to quarkonium-proton scattering amplitude $M_{\psi p}$ near-threshold
- **Quarkonium as a probe to study the gluonic structure of the nucleon**



VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude

EicC: Upsilon production cross-sections



● Jlab 12: J/ψ production near threshold

- ➢ Shed light on the low energy J/ψ-nucleon interaction (color Van der Waals force): Prediction of J/ψ-Nuclei bound state
- ➢ Shed light on the 'conformal anomaly': proton mass

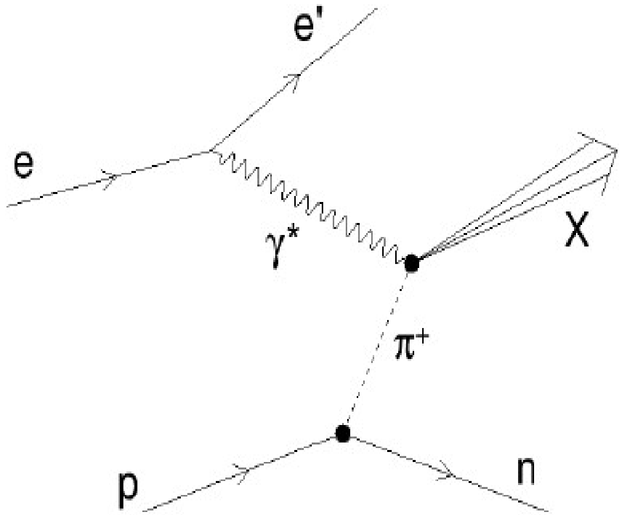
● EicC: precision measurement Upsilon near threshold

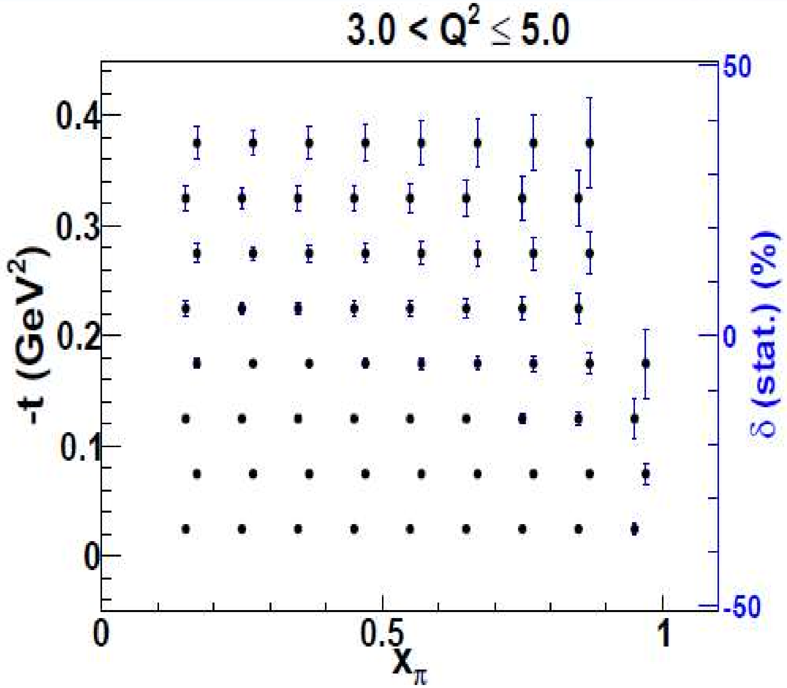
EicC will offer unique opportunity for precision measurement Upsilon near threshold: the heavier mass of the bottom should help suppress the theoretical systematic uncertainties

O. Gryniuk and M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)

Other interesting topics

- ***Pion/Kaon structure***





- ***Nuclear medium effect (Hadronization, EMC-SRC ….)***

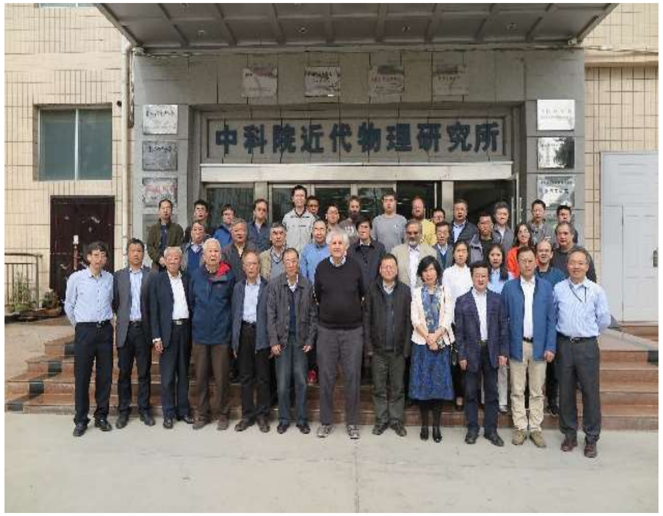
- ***Hadron Spectroscopy (b-quark hadron)***

- ***And more…***

Conclusions

Design, Schedule, R&D, Location, Summary

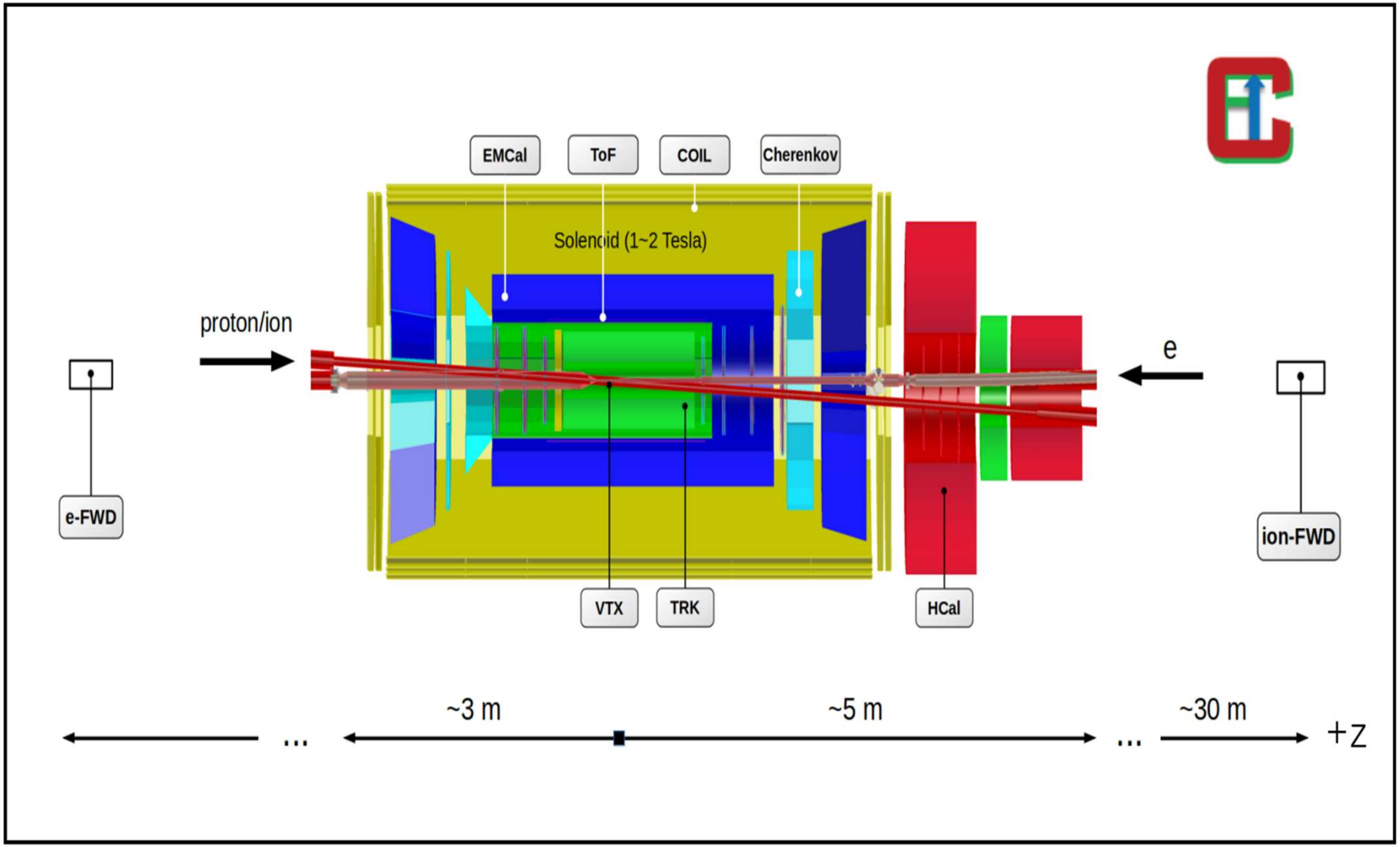
EicC Status



- **4 pre-Collaboration meetings up to now.**
- **Discussions on: physics programs, simulations, accelerator, detector**

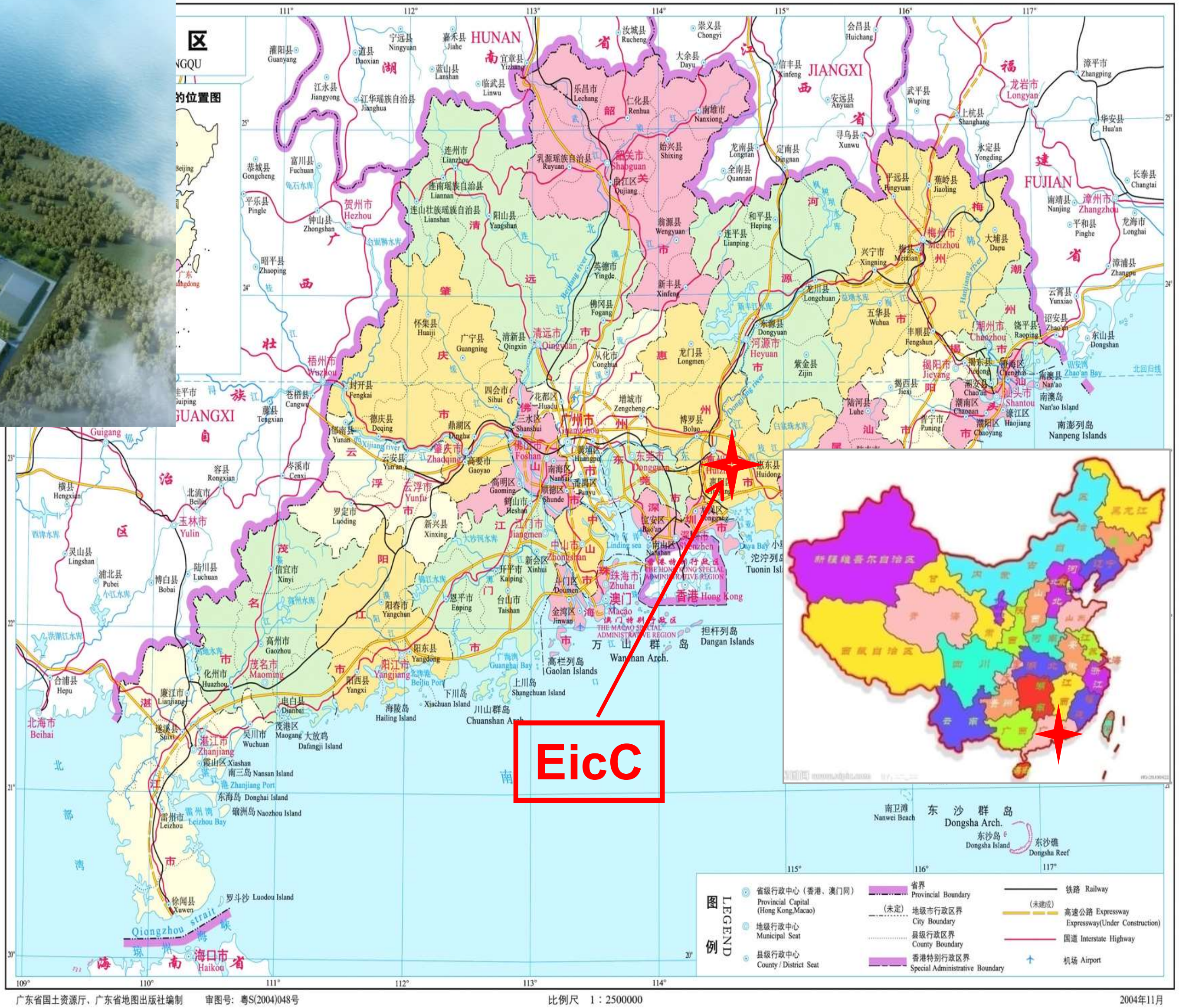
1) **2019 – 2020 : EicC Whitepaper (Chinese and English)**
2) **14th-Five-Year Plan (2021 – 2025): National funding for EicC R&D efforts**
3) **2020-2050 CAS near- & long-term plan for mega-science projects**

EicC detector conceptual design



Very preliminary design; detector options are open.

Where we are talking about…Huizhou in Guangdong province



- ***Huizhou: Coast city***
- ***Strong support from local government***

Summary

- EicC the facility to fully study/understand sea quark structure and crucial for 3D spin-flavor structure and proton mass
- Examples of "Golden Experiments"

  Nucleon spin-flavor structure (polarizd sea, Δs)

  3-d Structure: GPDs (DVMP) and DVCS

  3-d Structure: TMDs (sea, range in Q^2, P_T)
- Other interesting physics topics will be delivered as well, not mentioned here in details
- EicC focuses on nuclear physics: Complimentary to the US EIC with higher center-of-mass and JLab 12 GeV
- EicC opens up a new window to study/understand nucleon structure, especially the sea

Will be at the forefront of hadron physics in the world

Exciting new opportunities → lead to breakthroughs?

Please contact us at Email: EicC@impcas.ac.cn

Thank You !