Nucleon Structure and Hadron Physcis on EicC

Dexu Lin
(On behalf of the EicC working group)

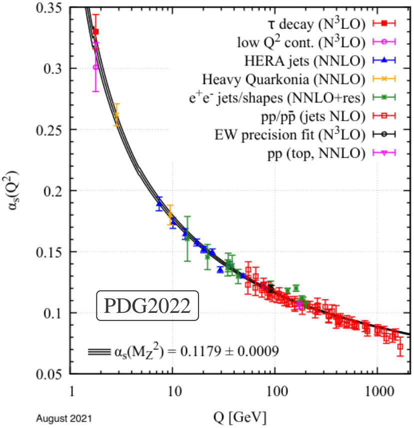
Quark Matter Research Center,
Institute of Modern Physics

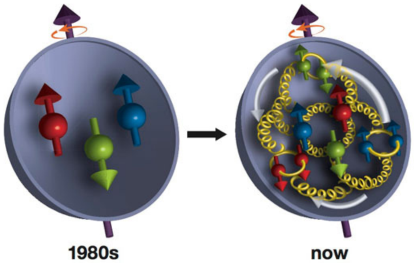
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Università di Genova, Italia
Jun. 05 - Jun. 09, 2023

Outline

Introduction



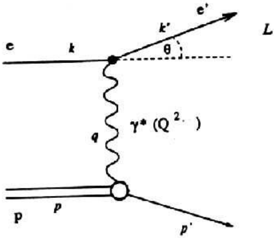


- More than 90% of visible matter in nature governed by strong interaction, which is described by QCD successfully (in general),
- pQCD (perturbative) at high energy scale vs non-pQCD in the low energy regime.

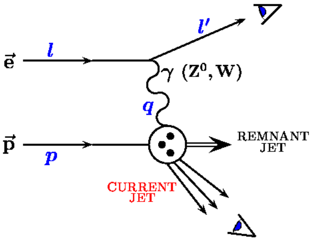
- Total mass of three valence quarks is only $\sim$ 10% of proton mass
  $\Longrightarrow$ **origin of proton mass**?
- Only $\sim$ 30% of proton spin from quark spin
  $\Longrightarrow$ **origin of proton spin**?

➥ **The internal structure of proton (nucleon)?**

Introduction – Nucleon Structure Research



Elastic Scattering



Deep Inelastic Scattering

Proton has internal structure (not point like particle)

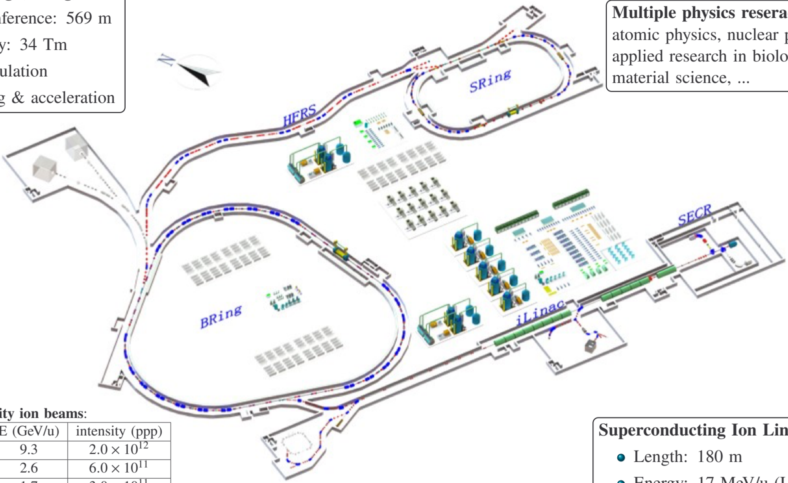
- Elastic scattering of electon-proton at low energy:
  - Electromagnetic form factors of proton,
  - Size of the proton: charge and magnetization distributions,
  - Four-momentum transfer squared: Q^2;
- Deep inelastic scattering of electron-nucleon at high energy:
  - **Parton distribution** (PDF) inside the nucleon,
  - One-dimensional **spin structure** of nucleons,
  - **Three-dimensional tomography** of nucleons,
  - ......
- Electron-Ion Collider (EIC), as a "Super Three Dimention Computed Tomography", can research the clearest structure inside the nucleon.
- EicC (Electron-Ion Collider in China) is considered, based on HIAF at IMP.

High Intensity Heavy-Ion Accelerator Facility (HIAF)

Layout of the accelerator complex of HIAF

Booster Ring (BRing)

- Circumference: 569 m
- Rigidity: 34 Tm
- Accumulation
- Cooling & acceleration



Multiple physics reseraches: atomic physics, nuclear physics, applied research in biology and material science, ...

High intensity ion beams:

beam	E (GeV/u)	intensity (ppp)
p	9.3	2.0×10^{12}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{35+}$	0.835	1.0×10^{11}

Superconducting Ion Linac:

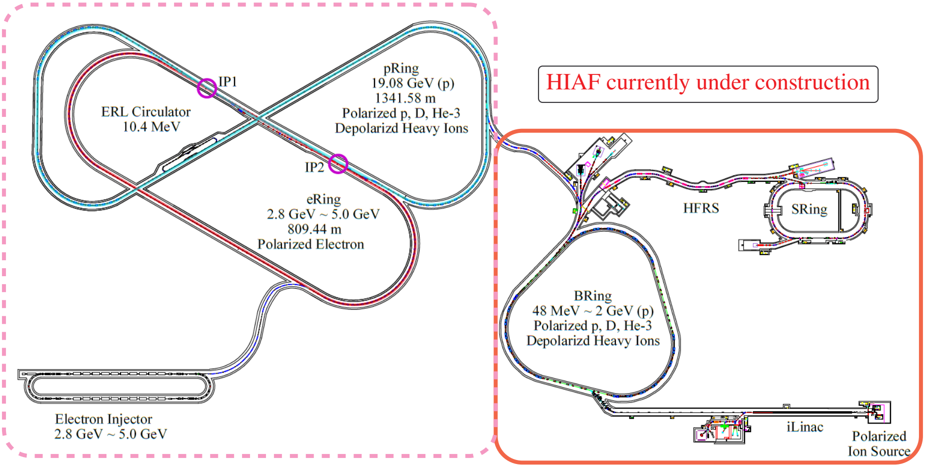
- Length: 180 m
- Energy: 17 MeV/u (U^{35+})
- CW and pulse modes

Location of HIAF

The facility is under construction at Huizhou of Guangdong Province.

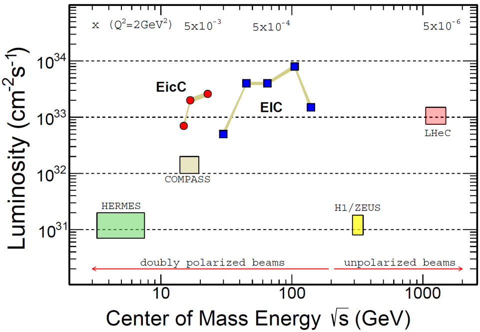
by Dr. Yutie Liang

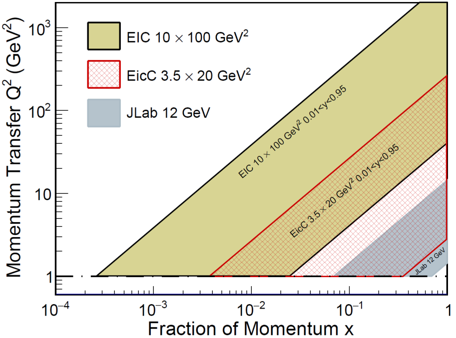
Electron-Ion Collider in China



EicC is considering based on the upgrade of HIAF
R&D for accelerator, detectors are in progress!

Parameters of EicC

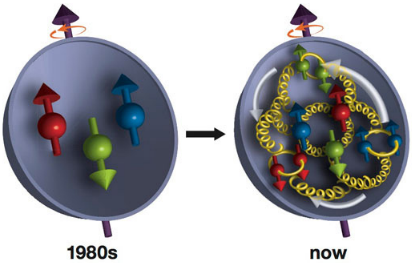




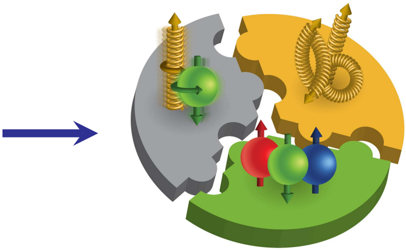
- Luminosity of EicC is up to 2.0×10^{33} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ (for proton),
- Center-of-mass energy ($\sqrt{s}$) of EicC ranged between 15 and 20 GeV,
- EicC focuses on moderate x and sea-quark regions,
- EicC covers the kinematic region between JLab experiments and us-EIC.

Spin Decomposition of Proton

picture by S. B. Shea (BNL)



picture by K. M. Walsh (BNL)



- In the late 1980s, experiment revealed that the constituent quarks contribute only 14% of proton's helicity
  ⇒ proton spin puzzle.
- Now we know that the proton's spin has different contributions from quarks, gluons and their interactions
  but how?

Spin Decomposition

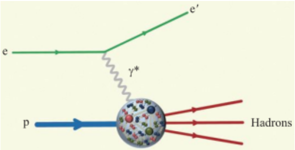
$$\frac{1}{2} = \underbrace{\boxed{S_q + S_g}}_{\text{helicities}} + \underbrace{\boxed{L_q + L_g}}_{\text{orbital angular momenta}}$$

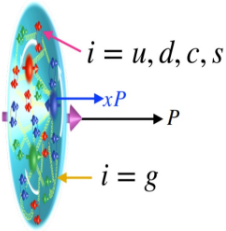
$$S_q(Q^2) = \frac{1}{2}\int_0^1 \Delta\Sigma(x, Q^2)dx,$$

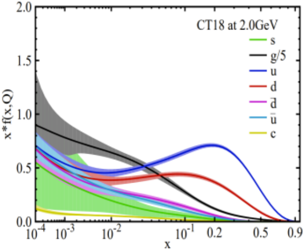
$$S_g(Q^2) = \int_0^1 \Delta G(x, Q^2)dx,$$

$\Delta\Sigma$ and ΔG are quark and gluon helicity PDF (hPDF), respectively

Nucleon Structure by Electron-Nucleon Scattering

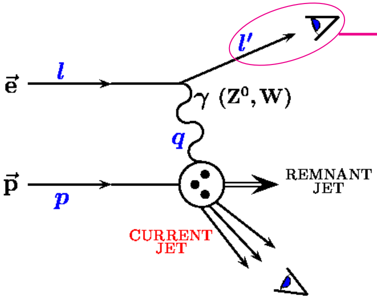






- Through deep inelastic scattering (DIS), the nucleon **parton distribution function (PDF)** ($F(x)$) can be measured in momentum space,
- To measure quark contributions (S_q), the **parton distribution function (PDF)** ($g(x)$) has to be known in spin space.

Structure Function and PDFs from Polarized Case



Only scattered leptons are detected

beam/target helicity flips: $d\sigma = d\bar{\sigma} \pm d\Delta\sigma$

$$\frac{d\Delta\sigma}{dx\,dy} = \lambda \cdot \frac{e^4}{4\pi^2 Q^2} \cdot \left[\left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2\right) \cdot g_1 - \frac{y}{2} \cdot \gamma^2 \cdot g_2\right]$$

Experimental Observables

A_{LL}, A_{LT} (A_1, A_2)

$Q^2 \ll m_Z^2$

Polarized structure functions
g_1 and g_2

QPM
(Quark-Parton Model)

PDFs

Polarized PDFs
Helicity distribution

$$\Delta q = q^{\uparrow}(x) - q^{\downarrow}(x)$$

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \left[\Delta q(x) + \Delta \bar{q}(x)\right]$$

Flavor Decomposition

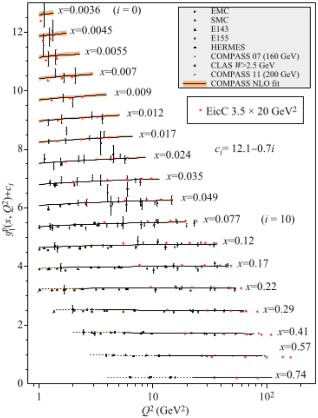
- Generally, g_1 is measured through the inclusive DIS process, assuming one photon exchange:

$$g_1^p = \frac{1}{2}\left(\frac{4}{9}(\Delta u + \Delta\bar{u}) + \frac{1}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right)$$

$$g_1^n = \frac{1}{2}\left(\frac{1}{9}(\Delta u + \Delta\bar{u}) + \frac{4}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right)$$

- Based on assumption of $SU(3)$ flavor symmetry, to extract the polarized distribution functions of of quarks of various flavors,
- But, this method has a strong model dependence, and it mixes the contributions from quarks of different flavors.

➥ **SIDIS** (Semi-Inclusive DIS) measurements: with the initial quark flavor tagged fragmentation functions needed.

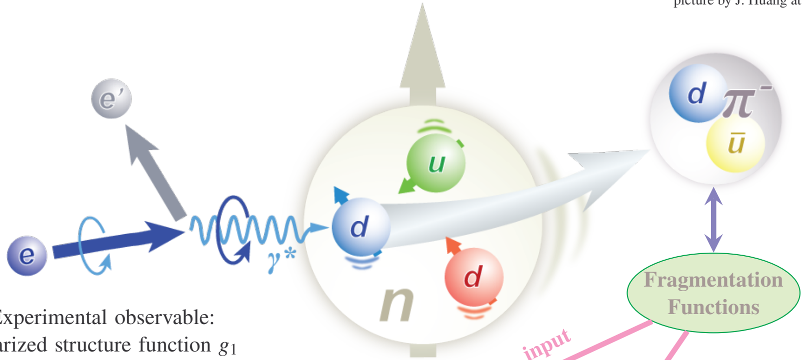


Global data of proton g_1 from inclusive DIS measurements compared with 50 fb^{-1} projected EicC data.

Flavor Decomposition from SIDIS Progress

double polarized electron-neutron scattering

picture by J. Huang at JLab



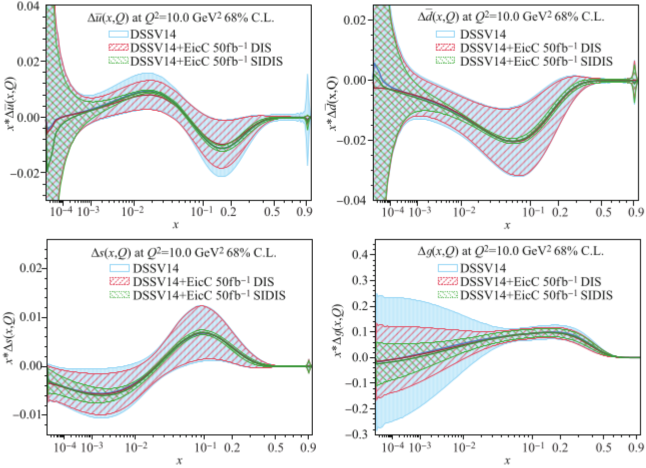
Experimental observable:
polarized structure function g_1

Leading Order

$$g_1^h(x, Q^2, z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x, Q^2) D_q^h(z, Q^2) + \Delta\bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2)\right]$$

Extracted nucleon structure information: polarized PDFs (helicity distribution)

Impact Expected from Future EicC Data



EicC white paper

Front. Phys. 16(6), 64701 (2021)

- DSSV14 global fit including EicC pseudodata,
- EicC $e-p$ (3.5 GeV + 20 GeV) and $e-^3$He (3.5 GeV + 40 GeV) collisions,
- Pseudodata analysis has requirements:
  $Q^2 > 2$ GeV^2,
  $W^2 > 12$ GeV^2,
  $0.05 < y < 0.8$ and
  $0.05 < z < 0.8$.

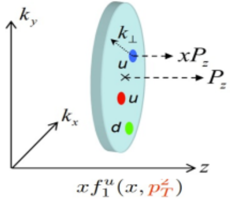
- Expecting to improve the precision of helicity distributions of see quarks and gluons with the future EicC data,
- Integrated luminosity of 50 fb^{-1} will be around 10 months EicC running with the designed instantaneous luminosity.

Three-Dimentional Tomography of Nucleon

leading-twist quark TMD distributions

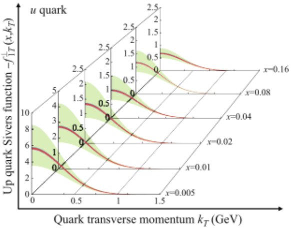
TMDs		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally polarized (L)	Quark polarization: Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^\perp$ Boer–Mulders
	L		g_{1L} Helicity	$h_{1L}^\perp$ Longi-transversity
	T	$f_{1T}^\perp$ Sivers	g_{1T} Trans-helicity	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

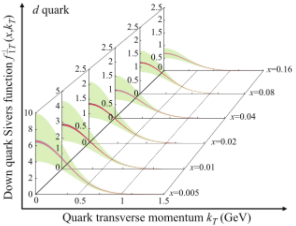
Nucleon spin   Quark spin



- **TMDs**: transverse momentum (k_{T}) dependent parton distributions,
- Eight independent leading twist quark/gluon TMDs can be defined by introducing the spin degrees of freedom,
- Rich information of the nucleon structure revealed from spin-dependent TMDs, especially for parton orbital motions and spin-orbit correlations.

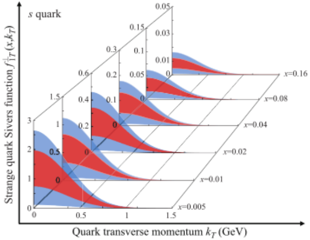
Spin Structure of Nucleon TMDs





EicC SIDIS pseudodata:

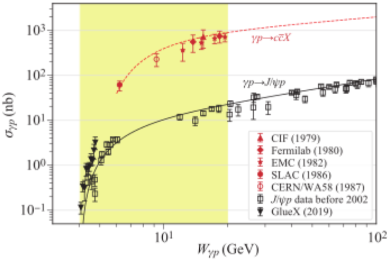
- LO analysis with $\pi^{\pm}$, $K^{\pm}$,
- $e-p$: 3.5 GeV $\times$ 20 GeV,
- $e-{}^3$He: 3.5 GeV $\times$ 40 GeV,
- Pol.: $e(80\%)$, $p/{}^3$He(70%),
- $\mathcal{L}_{\text{int}}$: 50 fb^{-1} ($e-p/e-{}^3$He).

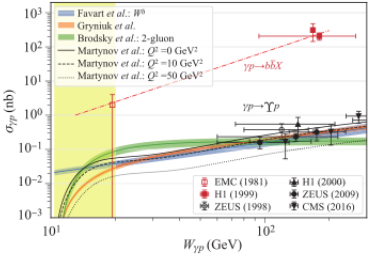


quark (u, d and s) Sivers function

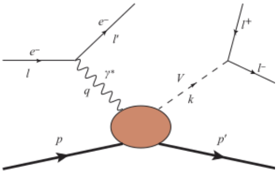
From available SIDIS data currently:
green: current accuracy
Including EicC pseudodata: red: statistical uncertainty only
blue: part of systematic uncertainties inlcuded

Quarkonium Studies at EicC



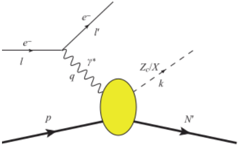


pictures from EicC white paper

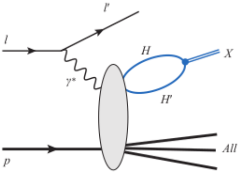


- Quarkonium ($c\bar{c}$, $b\bar{b}$) from electroproduction process,
- The cross section is ~2 orders of magnitude smaller than the photoproduction process,
- In EicC energy region:
  $\sim \mathcal{O}(100)$ pb for $ep \to epJ/\psi$ and
  $\sim \mathcal{O}(0.1)$ pb for $ep \to ep\Upsilon$,
- Many open- and hidden-charm hadrons,
- Hidden-bottom pentaquark states expected from decays of $N\Upsilon$, $B^{(*)}\Lambda_b$ and $B^{(*)}\Sigma_b$.

Exotic States at EicC



Exotic states	Production/decay processes	Detection efficiency	Expected events
$P_c(4312)$	$ep \to eP_c(4312)$ $P_c(4312) \to pJ/\psi$ $J/\psi \to l^+l^-$	~30%	15−1450
$P_c(4440)$	$ep \to eP_c(4440)$ $P_c(4440) \to pJ/\psi$ $J/\psi \to l^+l^-$	~30%	20−2200
$P_c(4457)$	$ep \to eP_c(4457)$ $P_c(4457) \to pJ/\psi$ $J/\psi \to l^+l^-$	~30%	10−650
P_b(narrow)	$ep \to eP_b$(narrow) P_b(narrow) $\to p\Upsilon$ $\Upsilon \to l^+l^-$	~30%	0−20
P_b(wide)	$ep \to eP_b$(wide) P_b(wide) $\to p\Upsilon$ $\Upsilon \to l^+l^-$	~30%	0−200
$\chi_{c1}(3872)$	$ep \to e\chi_{c1}(3872)p$ $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ $J/\psi \to l^+l^-$	~50%	0−90
$Z_c(3900)^+$	$ep \to eZ_c(3900)^+n$ $Z_c^+(3900) \to \pi^+ J/\psi$ $J/\psi \to l^+l^-$	~60%	90−9300



	Channel	$\Lambda = 0.5$ GeV	$\Lambda = 1.0$ GeV
$\chi_{c1}(3872)$	$D\bar{D}^*$	21	89
$Z_c(3900)^0$	$(D\bar{D}^*)^0$	0.3×10^3	1.1×10^3
$Z_c(3900)^+$	$(D\bar{D}^*)^+$	0.4×10^3	1.3×10^3
$X(4020)^0$	$(D^*\bar{D}^*)^0$	0.1×10^3	0.5×10^3
$P_c(4312)$	$\Sigma_c\bar{D}$	0.8	4.1
$P_c(4440)$	$\Sigma_c\bar{D}^*$	0.7	4.7
$P_c(4457)$	$\Sigma_c\bar{D}^*$	0.5	1.9
$P_c(4380)$	$\Sigma_c^*\bar{D}$	1.6	8.4
$P_c(4524)$	$\Sigma_c^*\bar{D}^*$	0.8	3.9
$P_c(4518)$	$\Sigma_c^*\bar{D}^*$	1.2	6.9
$P_c(4498)$	$\Sigma_c^*\bar{D}^*$	1.2	9.8

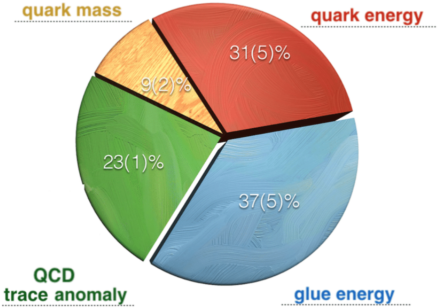
- Different models estimate the cross sections (expected events) for exotic states produced at EicC,
- Polarized beams help to pinpoint the quantum numbers (J^P) of exotic states.

Proton Mass Study at EicC

Proton mass decomposition [Ji (1995, 2021)]:

$$M = \underbrace{M_q + M_m}_{\text{Quark}} + \underbrace{M_g + M_a}_{\text{Gluon}}$$

M_q: quark energy
M_m: quark mass (condensate)
M_g: gluon energy
M_a: trace anomaly

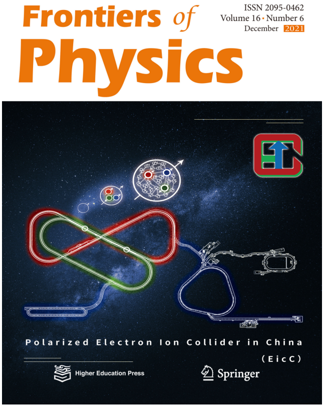


➡EPJ WoC **175** (2018) 14002

- M_q and M_g constrained by PDFs,
- M_m via πN scattering at low energy region,
- M_a via quarkonium (J/ψ, Υ) threshold production,
- EicC can delivery precision in the study of Υ production. ➡ EicC White Paper

Towards Conceptual Design Report

EicC white paper (2021) → Eicc **CDR** preparation



Volume I: Accelerator

Contents

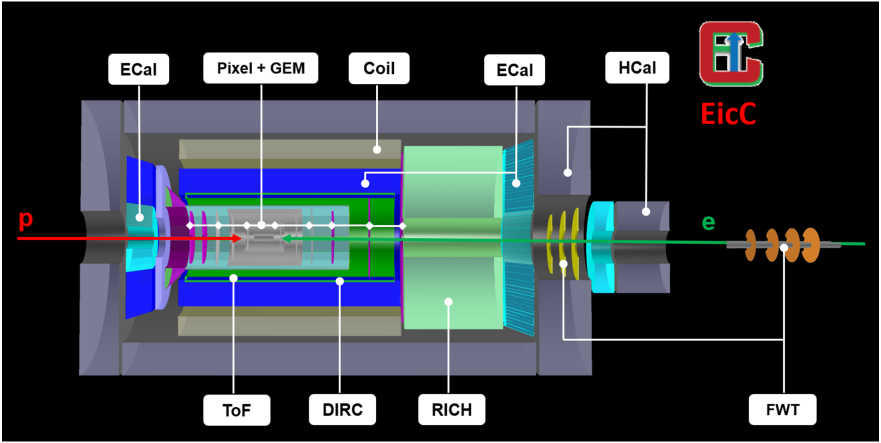
1

Volume II: Physics and Detectors

Contents

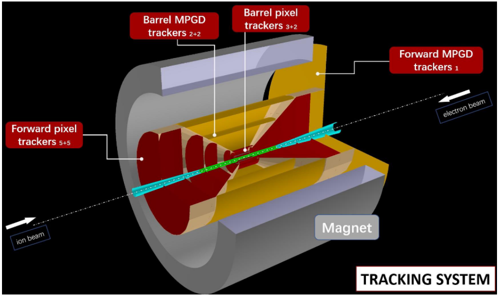
1

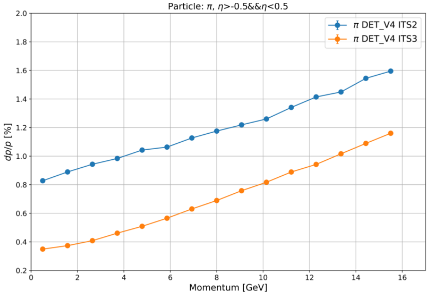
Spectrometer of EicC

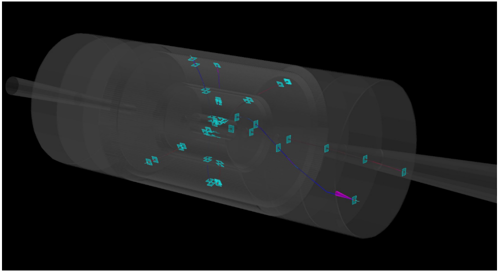


- Baseline design of EicC: 3.5 GeV electron beam and 20 GeV proton beam,
- Mian parts of the spectrometer: Vertex, Tracking, PID, Calorimeter, FWT, ...,

Vertex and Tracking Detector

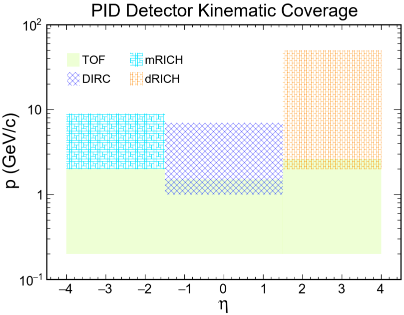


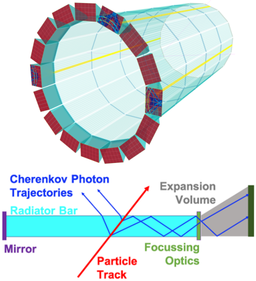




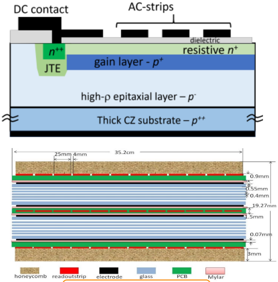
- Tracking system with all-silicon design,
- ITS3 based vertex detector,
- ITS3 based cylindrical layers and disk-like layers,
- MPGD gaseous laysers (cylinder and disk),
- Good performance for the momentum resolution.

Detector for Particle Identification



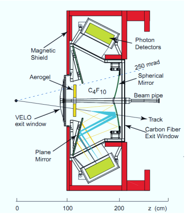


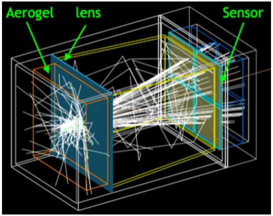
DIRC for barrel



LGAD and MPRC

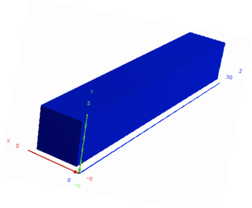
- PID system designed based on different coverages,
- DIRC for barrel: $\delta\theta \sim 1$ mrad, δT <100 ps,
- RICH (dual and module) for endcaps: π/K separation $\sim 3\sigma$ @15 GeV/c,
- MRPC and LGAD for low momentum particle identification, ~ 30 ps @0.1-2.0 GeV/c.



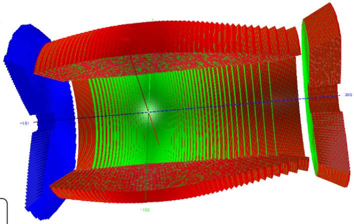


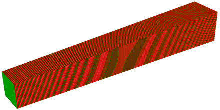
dual-RICH and module-RICH for endcaps

Electromagnetic Calorimeter



Crystal module for ef-EMC



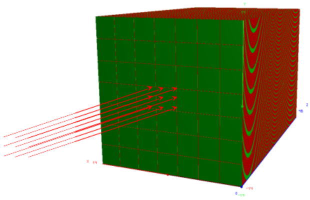


Shashlik module for br- and hf-EMC

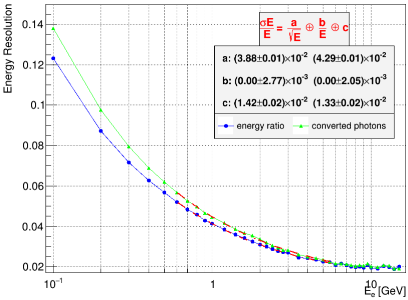
part	type	z/r [m]	L [cm]	coverage [cm]	pseudora-pidity (η)	tower size [cm×cm]
ef-EMC	CsI	z=-1.5	30.0 (16.1 X_0)	15.0<r<127.6	(-3.0, -1.0)	4.0×4.0 (front)
br-EMC	Shashlik	r=0.9	44.4 (15.8 X_0)	-105.8<z<187.5	(-1.0, 1.5)	4.0×4.0 (front)
hf-EMC	Shashlik	z=2.4		24.0<r<115.2	(1.5, 3.0)	

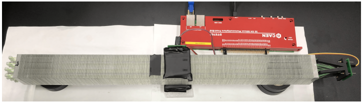
- Different technology in different acceptance region to satisfy the detection requirements,
- Homogeneous design with crystal in electron forward endcap (ef-EMC), **measuring the scattering electron precisely**,
- Sampling design with Shashlik type in barrel (br-EMC) and hadron forward endcap (hf-EMC).

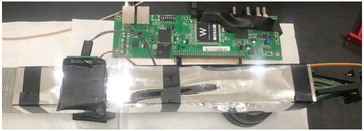
Shashlik Module of EMC



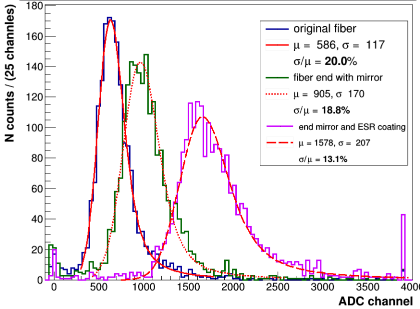
Simulation with 7 × 7 array



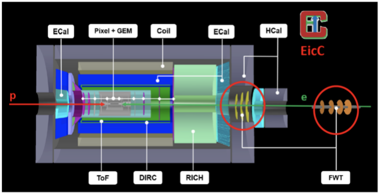




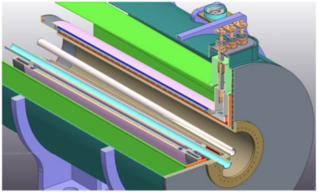
Shashlik module measuring with cosmic ray

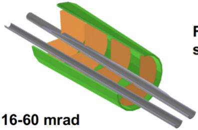


Design and Simulation of Far Forward Detectors

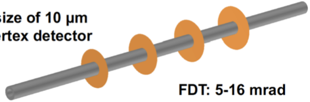


B0pf magnet





Four disks with pixel size of 10 μm
same as the central vertex detector

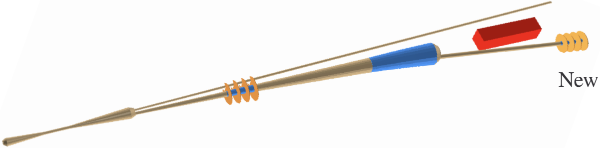


EDT: 16-60 mrad

FDT: 5-16 mrad

EDT (Endcap Dipole Tracking)

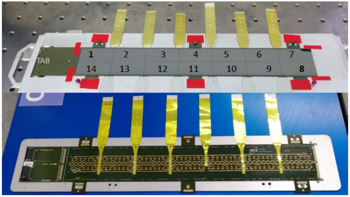
FDT (Forward Dipole Tracking)



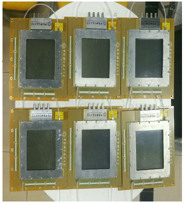
New Beam Design for ZDC

Detector R&D for EicC

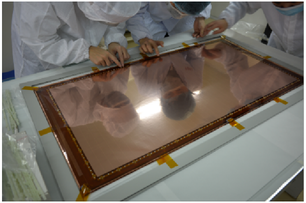
Clean room of ISO6/7



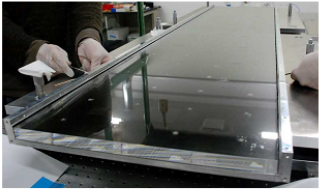
Pixel detector



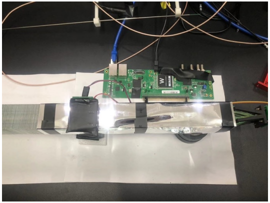
Micromegas



GEM detector



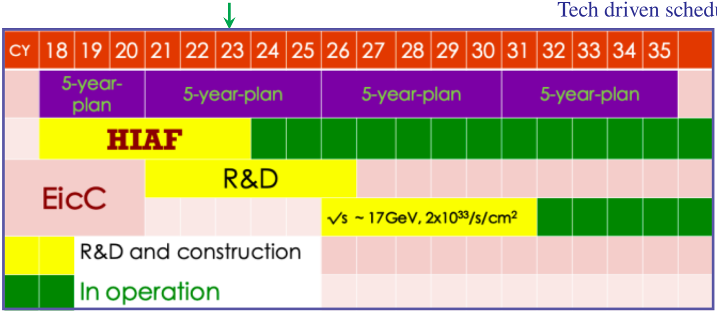
DIRC prototype



Shashlik module

Preliminary Timeline of EicC

Tech driven schedule



- **HIAF** is half way through its construction,
- 2021: EicC white paper published,
- 2023: Aim to finish the Conceptual Design Report (CDR) of EicC,
- 2021-2025: Simulations and R&D for physics and detectors,
- 2026-2030: Hope to get support by the next five-year plan.

Summary and Outlook

- An **electron-ion collider** has been proposed in China, based on the futhure **upgrade of HIAF**,
- **High precision** measurements of **nucleon structures** and study **quarkonium** with the **heavy flavors**,
- Moderate energy (electron beam **3.5 GeV**, proton beam **20 GeV**) covers the region (x) between us-EIC and JLab,
- Many interesting physics topics are under development and studying,
- **Research and deveopment** of the EicC **detectors** are ongoing,
- The **Concept Design Repor**t (CDR) is expected in 2023.

Thanks!

Welcome to join
eicc@impcas.ac.cn


thank you
gracias
danke
merci
obrigado
teşekkür ederim
ngiyabonga
謝謝
go raibh maith agat
mochchakkeram
dziękuję
sukriya
kop khun krap
terima kasih
grazie
arigatô
dakujem
мерси
спасибо
Баярлалаа
рахмат
bedankt
감사합니다
ありがとう
ευχαριστώ
xiexie
dank je
tack
mersi
tapadh leat
хвала
asante
mahalo
misaotra
paldies
grazzi
trugarez
shukriya
blagodaram
vinaka
faafetai lava
köszönöm
hvala
dankie
kiitos
enkosi
dhanyavad
chnorakaloutioun
gracies
sobodi
mesi
najis tuke
kam sah hamnida
tanemirt
rahmet
dziekuje
matondo
welalin
barka
дякую
djiere dieuf
dhanyavadagalu