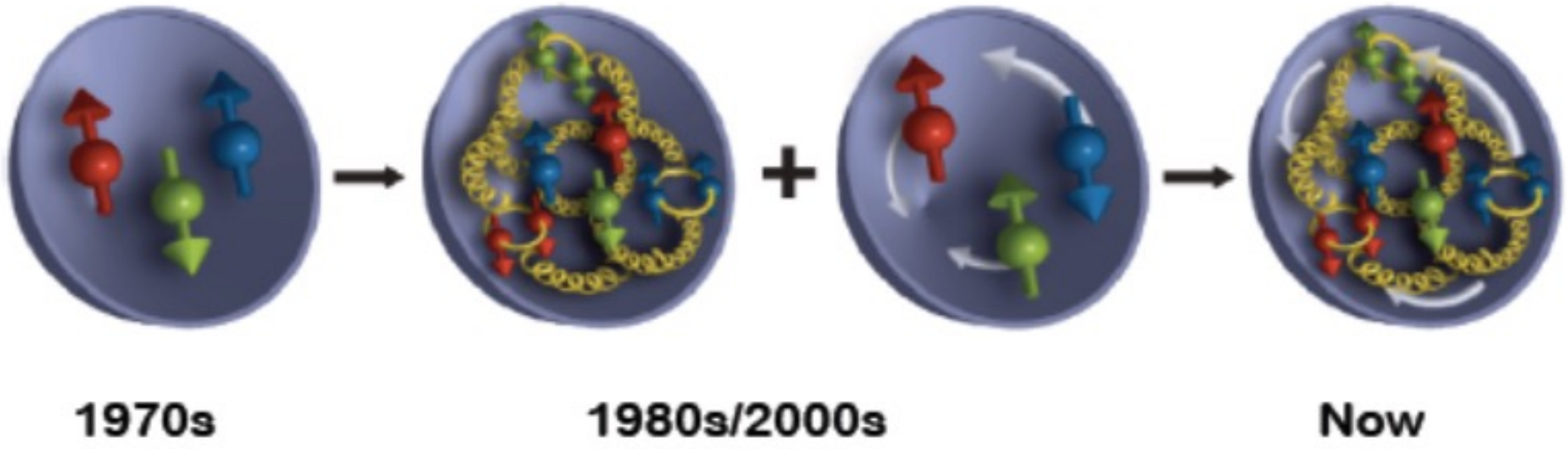
Study of nucleon structure and hadron physics at EicC

Aiqiang Guo (Institute of Modern Physics, Chinese Academy of Sciences)

On behalf of the EicC working group

Our understanding on nucleon



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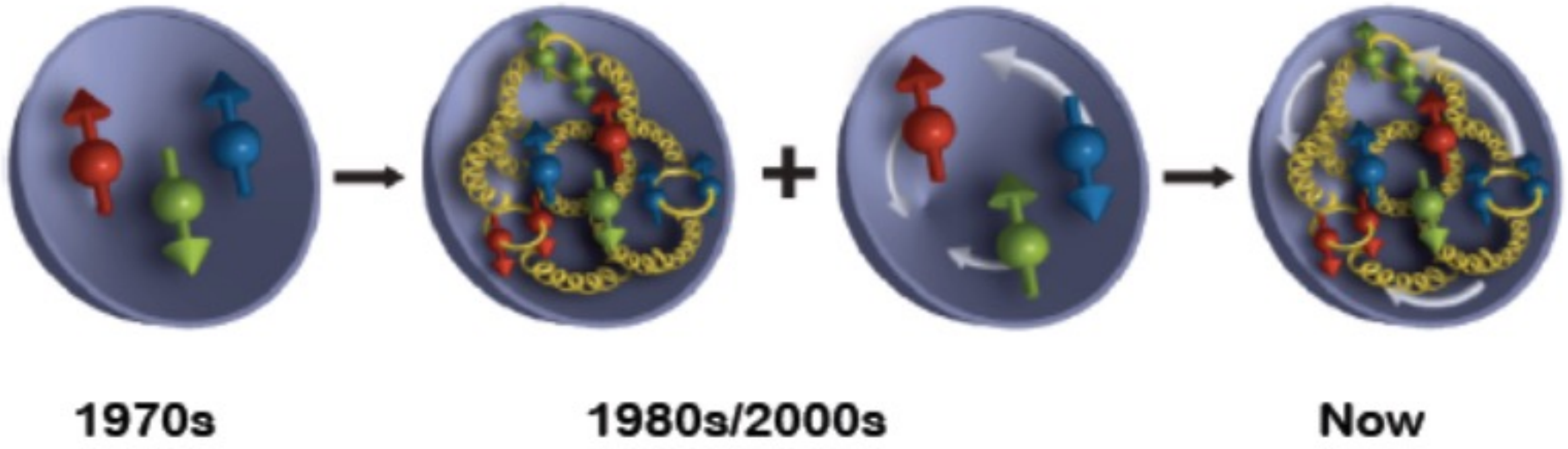
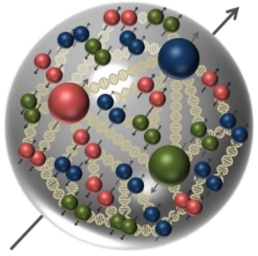
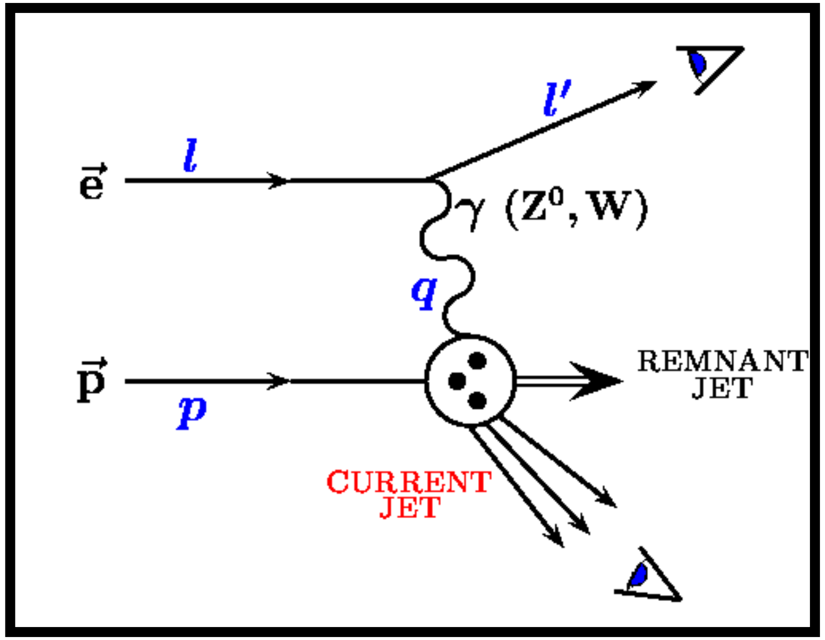




Origin of nucleon spin

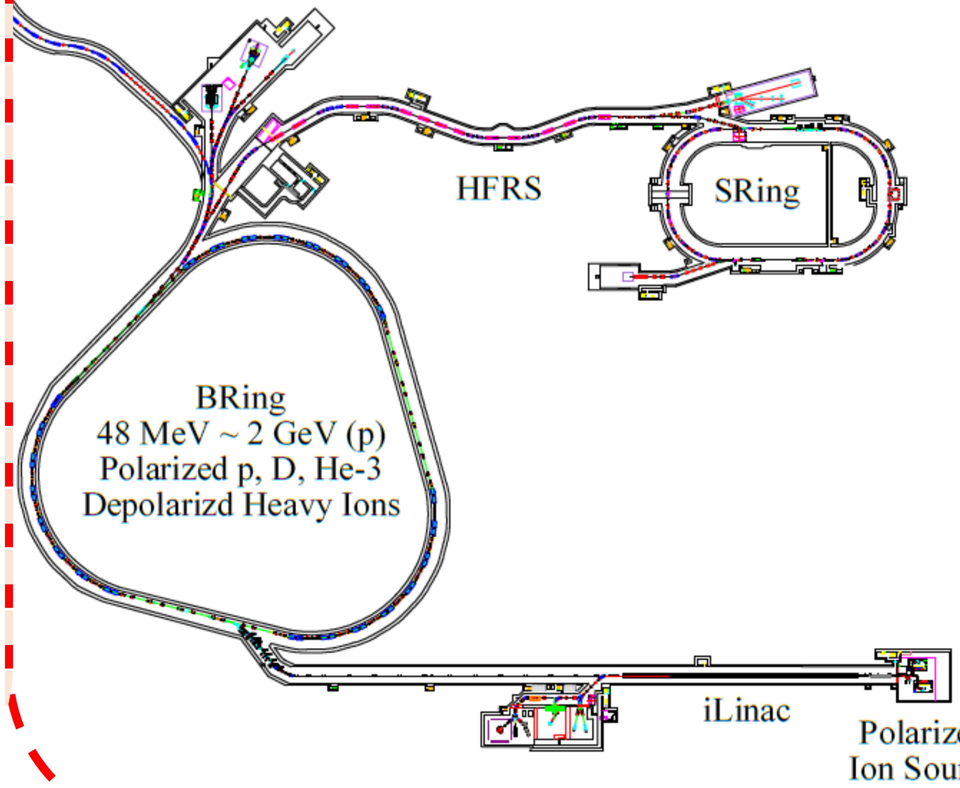
Origin of nucleon mass



EicC project introduction

Electron Ion Collider in China,

HIAF currently under construction
At Huizhou, Guangdong



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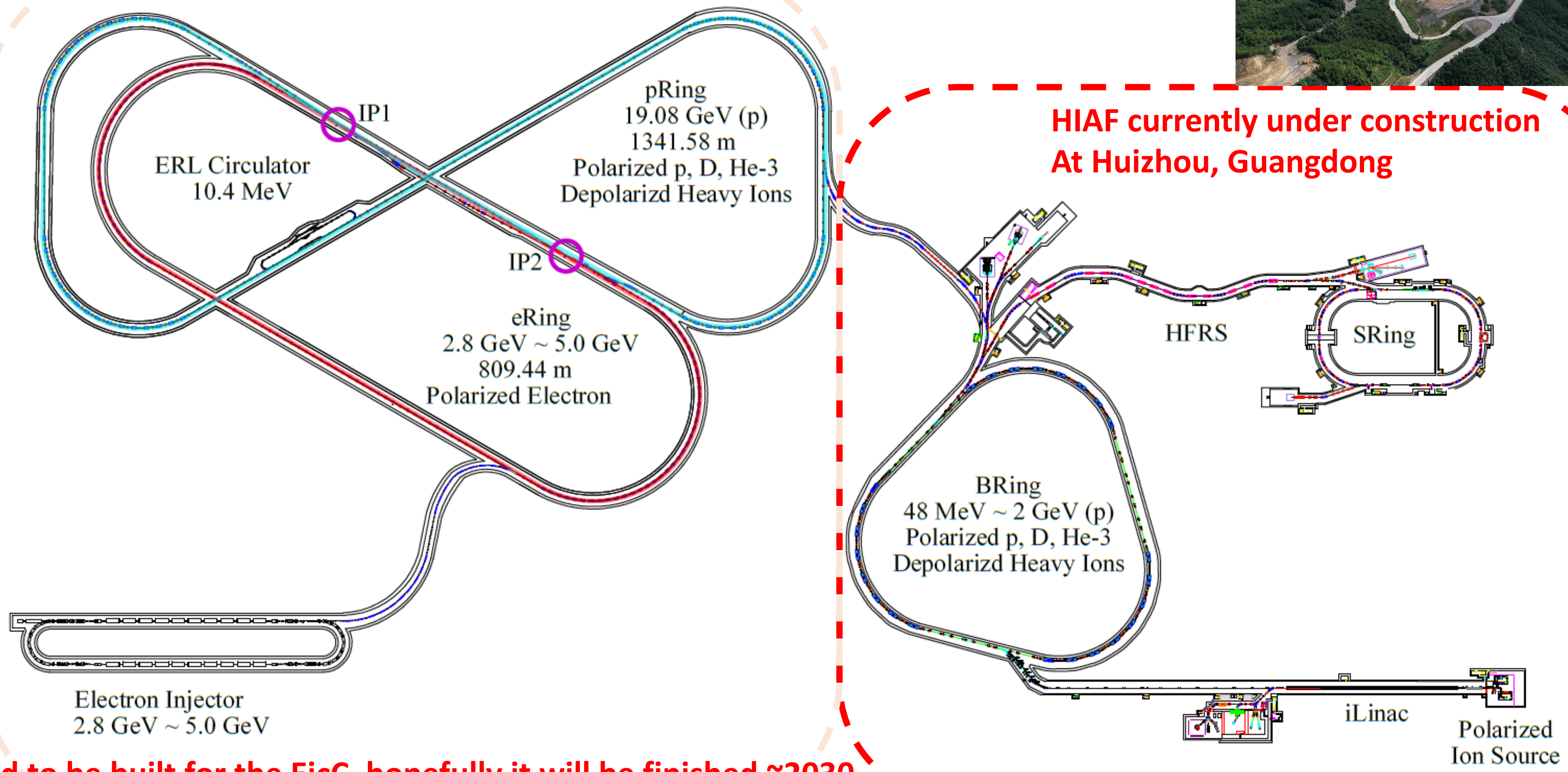

HIAF currently under construction At Huizhou, Guangdong

Need to be built for the EicC, hopefully it will be finished ~2030

EicC project introduction

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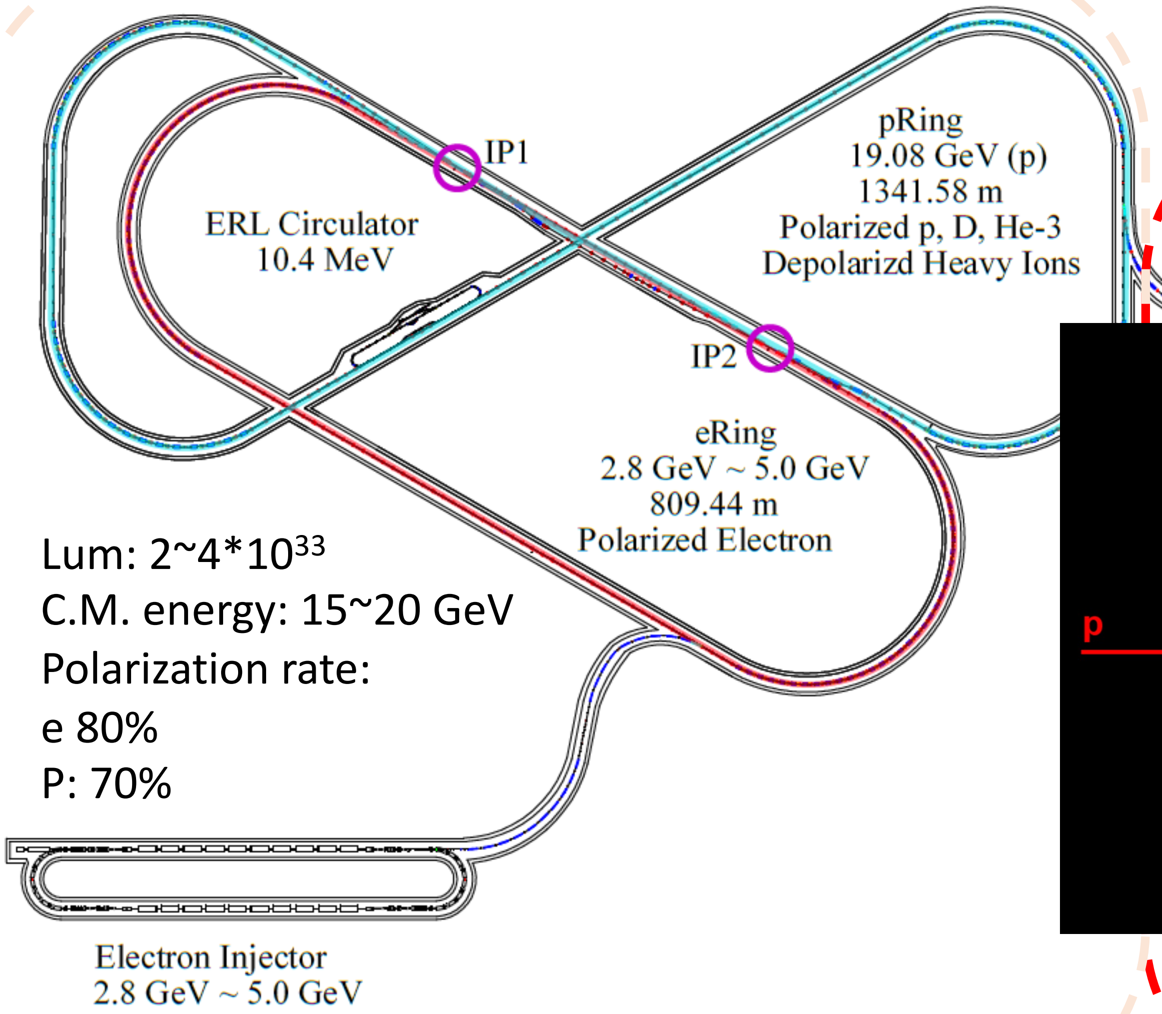
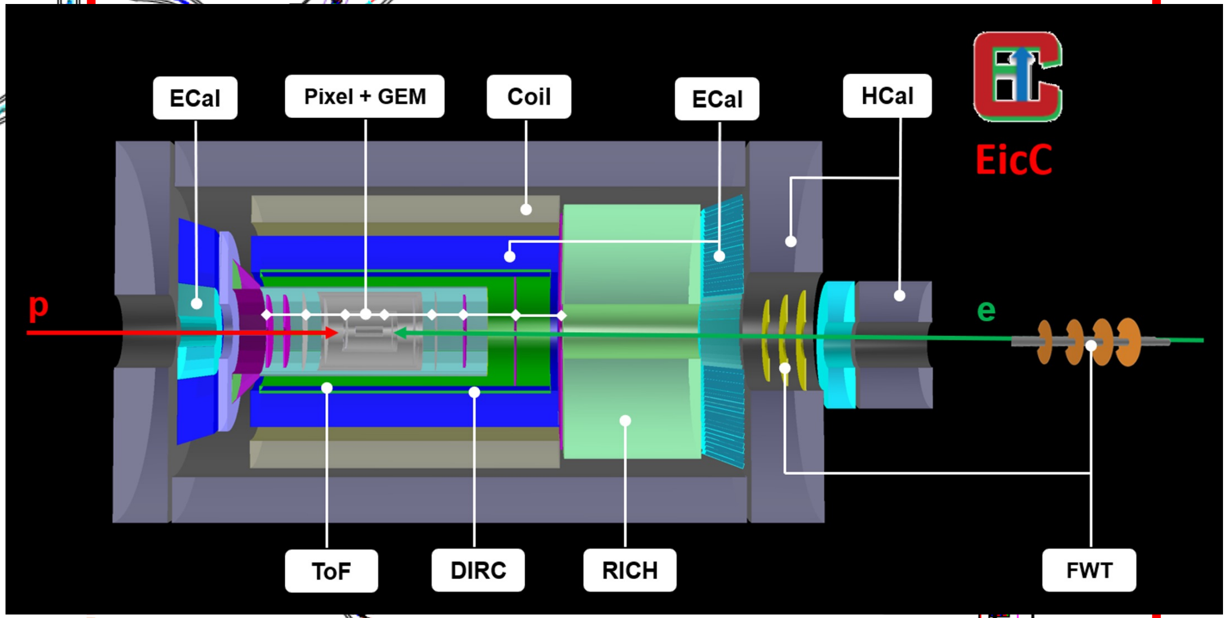


Lum: 2~4*10^{33}
C.M. energy: 15~20 GeV
Polarization rate:
e 80%
P: 70%

HIAF currently under construction
At Huizhou, Guangdong



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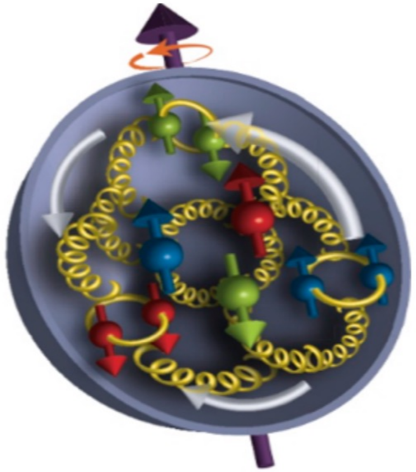
Highlighted physics topics

- Spin-dependent nucleon structure: 1D, 3D
  - Polarized structure function
  - Spin-dependent TMDs

- Exotic states with c/cbar, b/bbar
  - J/ψ and Υ production at EicC
  - Exotic states production at EicC

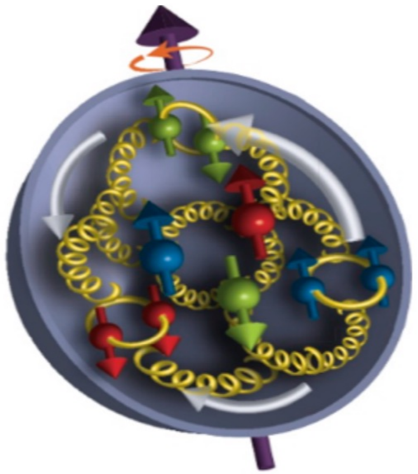
Spin decomposition



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)\,,$$

quarks gluon orbital angular momenta

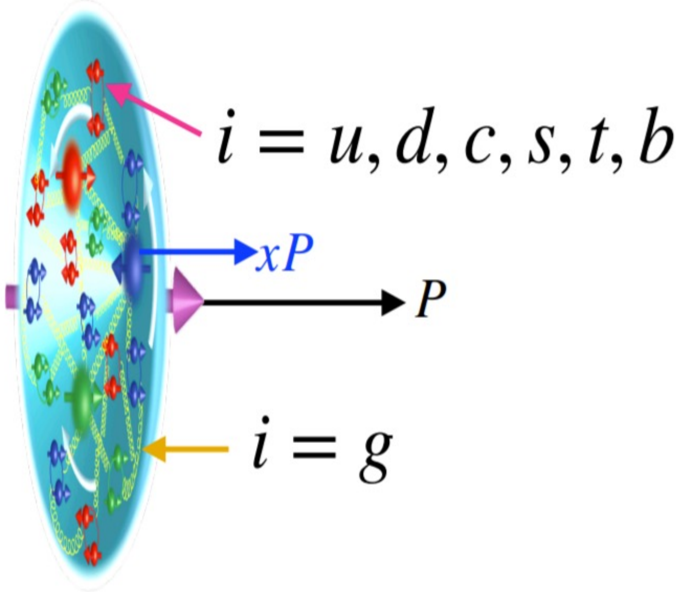
Spin decomposition

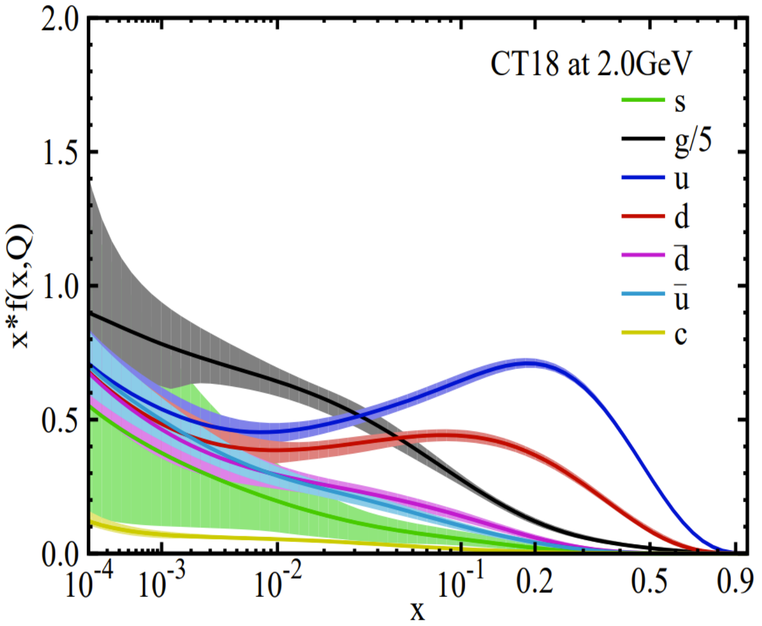


$$\frac{1}{2} = \boxed{\frac{1}{2}\Delta\Sigma(\mu)} + \Delta G(\mu) + L_{Q+G}(\mu)\,,$$

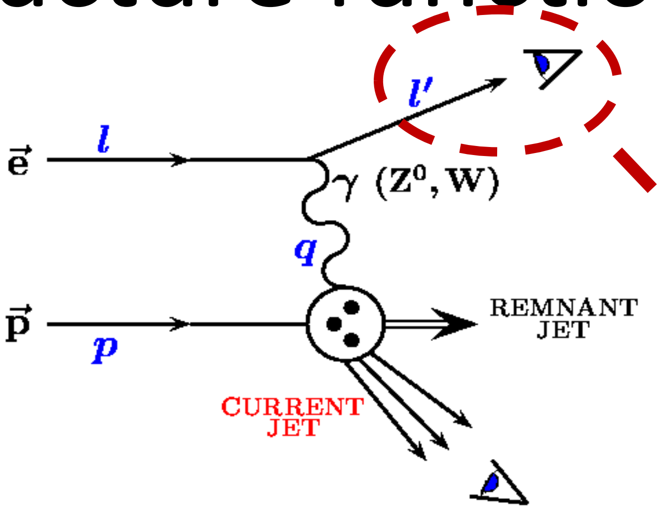
quarks gluon orbital angular momenta

- By DIS, we can measure the nucleon parton distribution function in momentum space: F(x)
- Similarly, to measure the $\Delta\Sigma(\mu)$, we need to know the parton distribution function in spin space: g(x)





Structure functions and PDFs : Polarized case



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

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

Only scattered leptons are detected

Experimental observables

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

$Q^2 << M_Z^2$

Polarized structure functions

g_1 , g_2

Quark-Parton Model
QPM

PDFs

Polarized pdfs

Helicity distribution

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

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q(x).$$

Flavor decompositions

- With pure γ exchange in inclusive DIS:

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

- Assumption: SU(3) flavor symmetry
  - ✓ Additional inputs from β-decay of neutron and hyperons

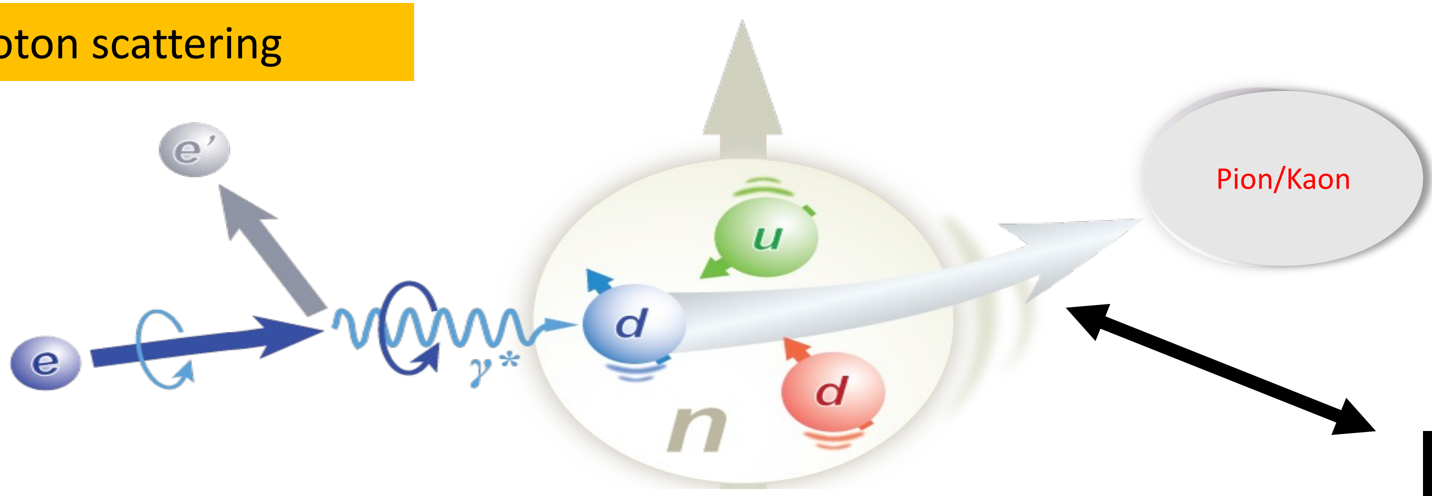
$\Delta u + \Delta d - 2\,\Delta s$ $\quad\quad$ $\Delta u + \Delta d$

A way out:

SIDIS measurements: with the initial quark flavor tagged
Fragmentation Functions needed

SIDIS processes for flavor decompositions

Electron-proton scattering



Fragmentation Functions

Experimental observable: polarized structure functions g1

input

input

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

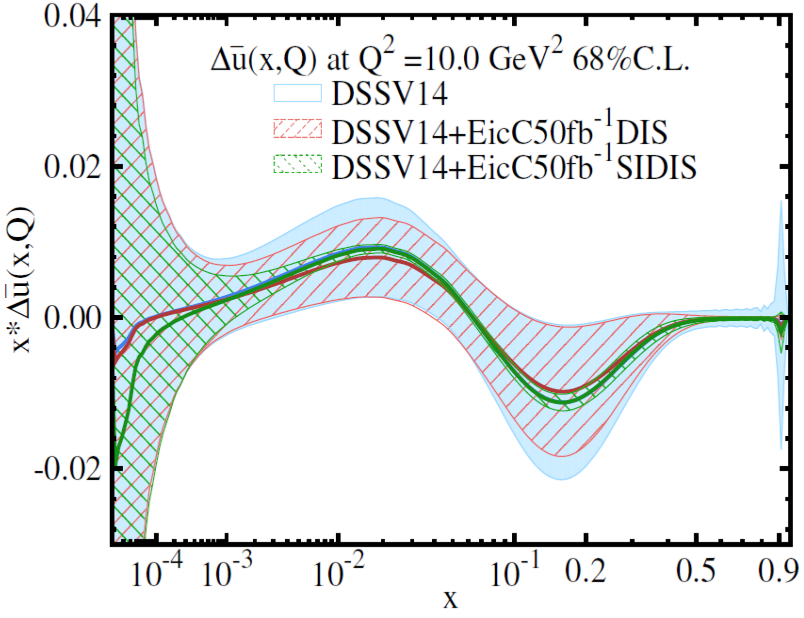
Leading Order picture

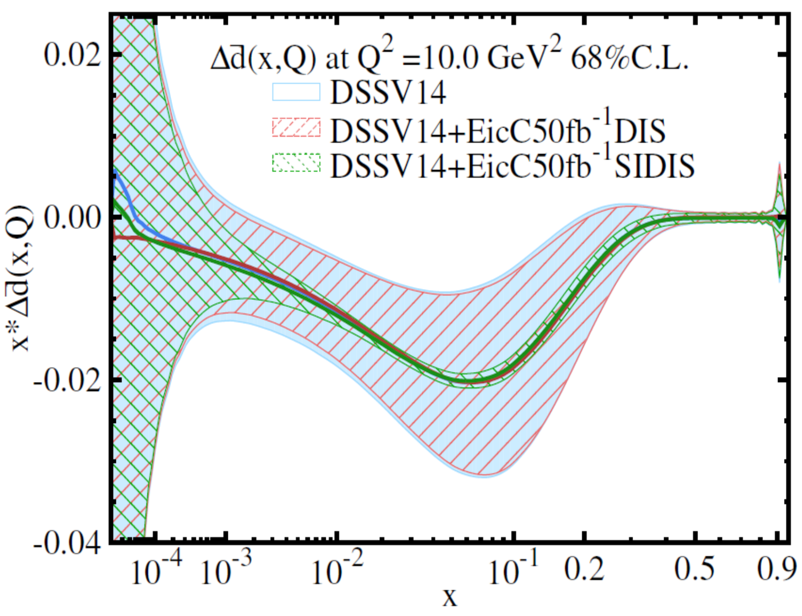
Extracted nucleon structure information: polarized PDFs (helicity distribution)

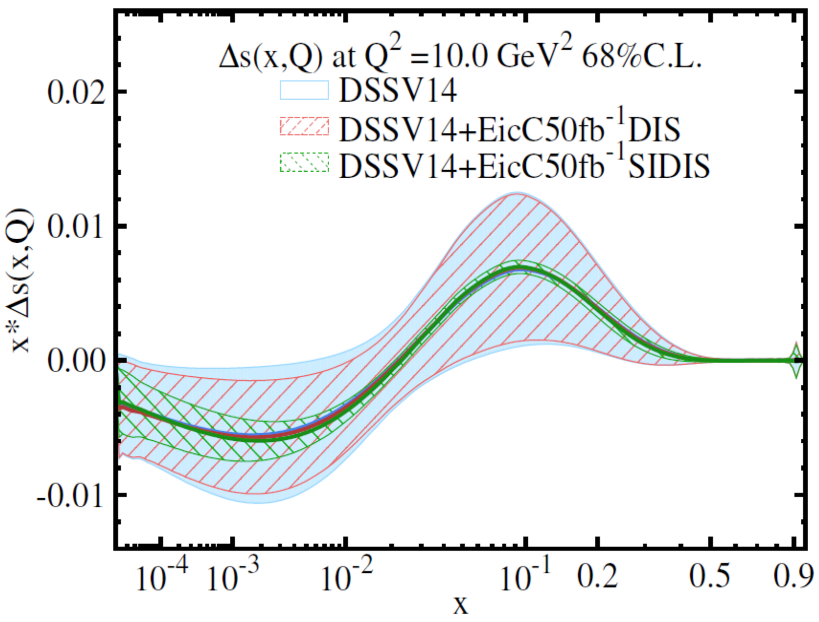
Spin of the nucleon-helicity distribution

A NLO impact study
See arXiv:2103.10276
JHEP08(2021)034

EicC white paper

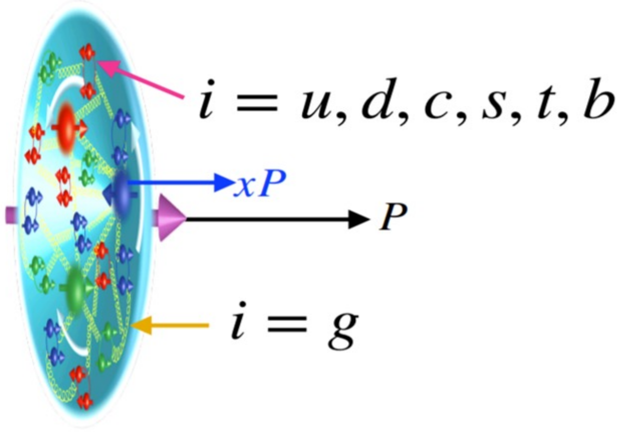




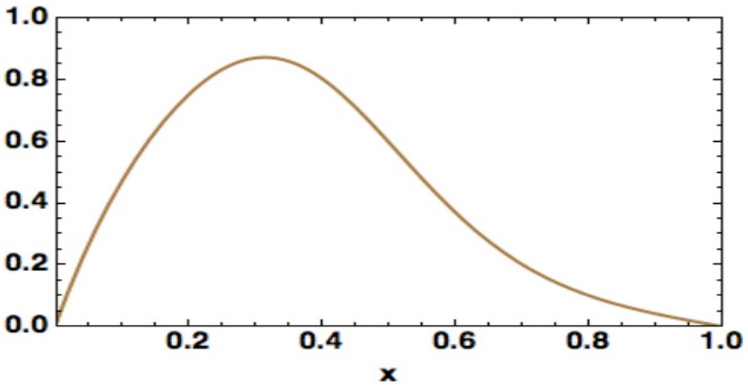


The TMDs

PDF 1D

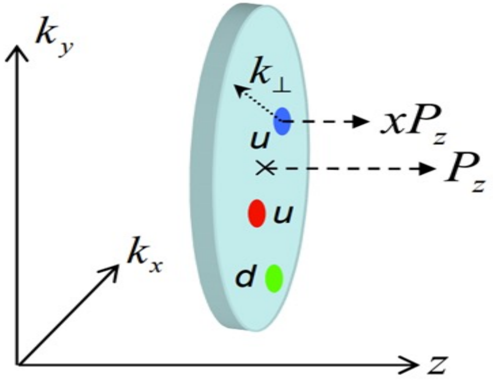


$xf_1^u(x)$

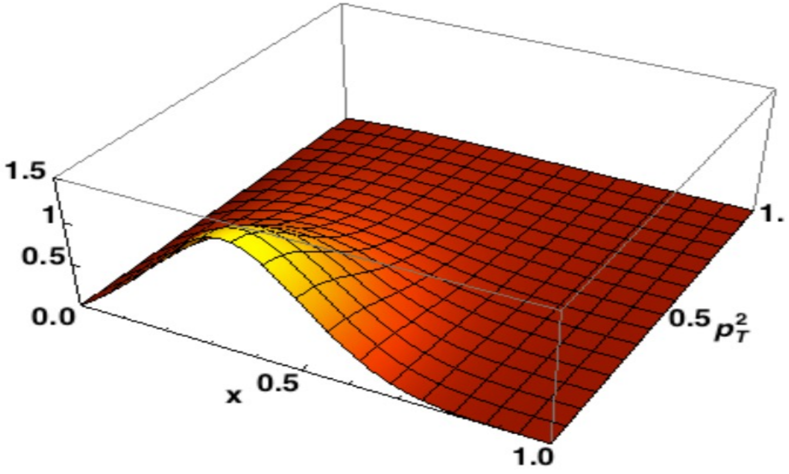


Standard collinear PDF

TMD PDF 3D



$xf_1^u(x, p_T^2)$



TMD

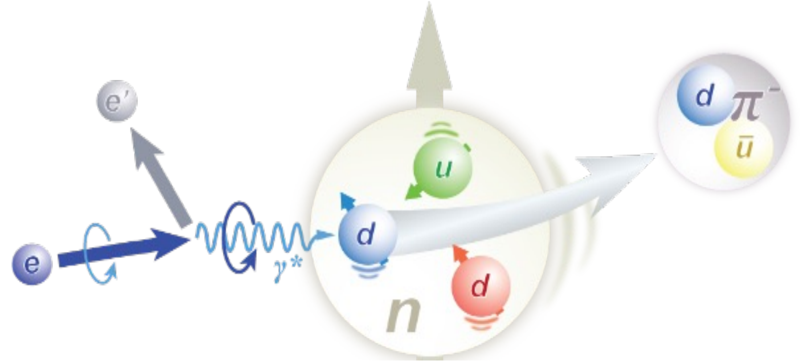
A. Bacchetta, F. Conti, M. Radici, Phys.Rev. D78 074010 (2008)

Spin-dependent TMDs (Leading-Twist)

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$		$h_1^{\perp} = \quad - \quad$ Boer-Mulders
L		$g_1 = \quad - \quad$ Helicity	$h_{1L}^{\perp} = \quad - \quad$ Worm Gear
T	$f_{1T}^{\perp} = \quad - \quad$ Sivers	$g_{1T} = \quad - \quad$ Worm Gear	$h_1 = \quad - \quad$ Transversity $h_{1T}^{\perp} = \quad - \quad$ Pretzelosity

Nucleon Spin *Quark Spin* Survive the k_T integration, yield 1D pdfs

TMDs in SIDIS Cross Section



$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\begin{aligned}
&\{F_{UU,T} + \ldots \\
&+ \varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots
\end{aligned}$$

Unpolarized

$$\begin{aligned}
&+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots] \\
&+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)} \\
&+ \sin(\phi_h-\phi_S)\cdot(F_{UT}^{\sin(\phi_h-\phi_S)} + \ldots) \\
&+ \varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]
\end{aligned}$$

Polarized Target

$$\begin{aligned}
&+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots] \\
&+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}
\end{aligned}$$

Polarized Beam and Target

f_1 =

Boer-Mulder $h_1^\perp$ =

$h_{1L}^\perp$ =

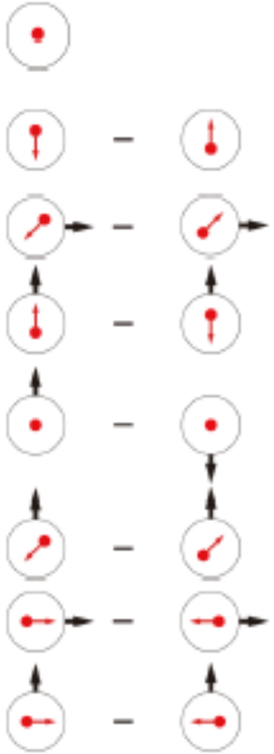
Transversity h_{1T} =

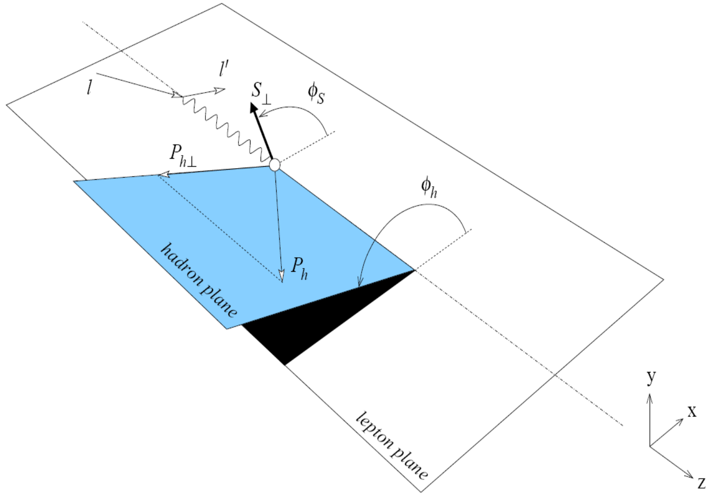
Sivers $f_{1T}^\perp$ =

Pretzelosity $h_{1T}^\perp$ =

g_1 =

$g_{1T}^\perp$ =





S_L, S_T: Target Polarization; λ_e: Beam Polarization

Target SSA, beam-target DSA measurements

Spin structure of the nucleon-TMDs

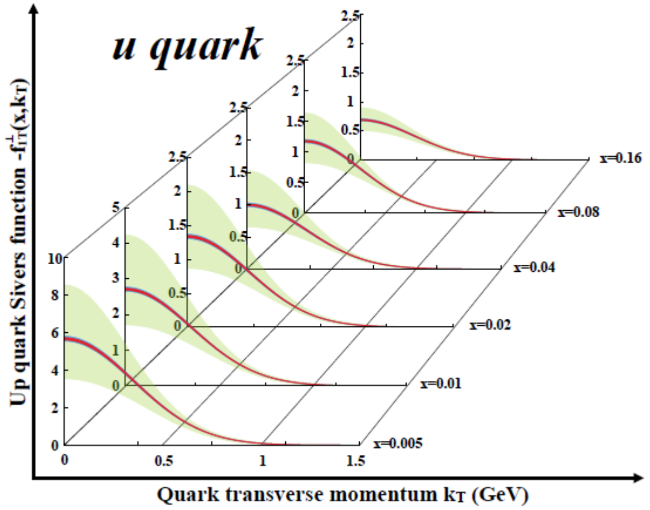
u/d Sivers EicC vs world data

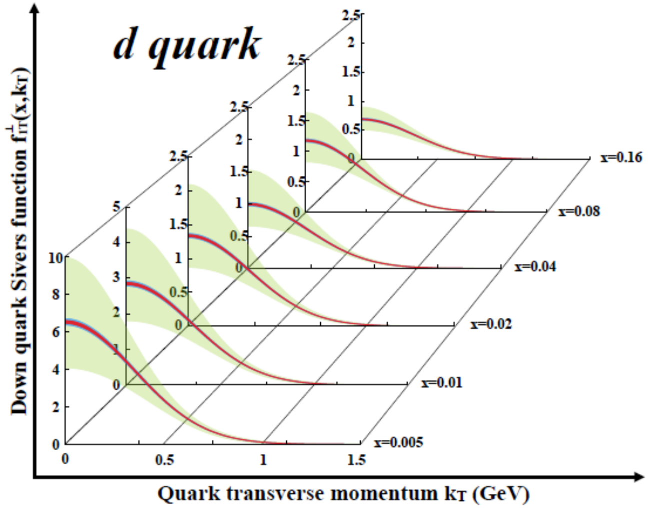
LO analysis

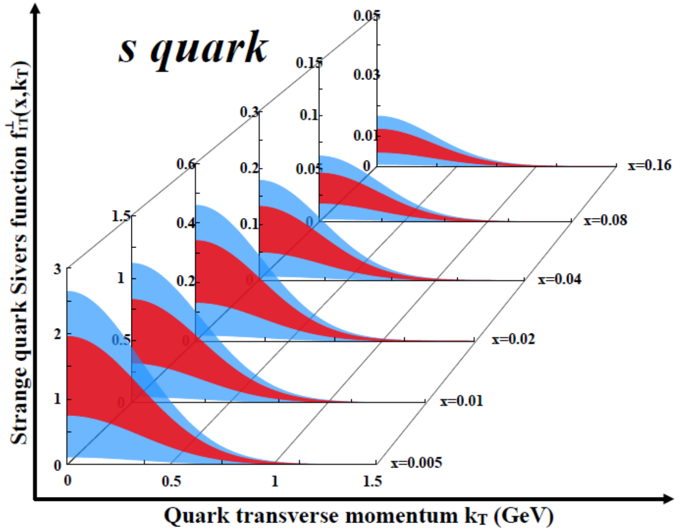
EicC SIDS data:

- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV X 20 GeV
- eHe-3: 3.5 GeV X 40 GeV
- Pol.: e(80%), p(70%), He-3(70%)
- Lumi: ep 50 fb^{-1}, eHe-3 50 fb^{-1}

EicC, precise measurements.







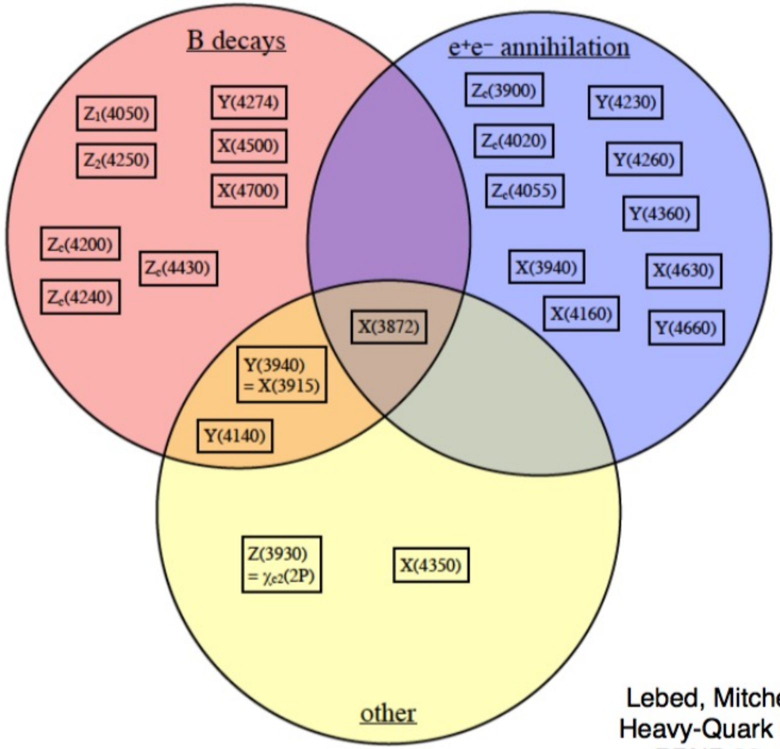
Green: Current accuracy
Red: stat. error only
Blue: sys. Error included

- sea quark Sivers function dynamically generated via Spin dependenent odderon
- leads to a unique predication for s-quark: quark and anit-quark Sivers functions flip sign

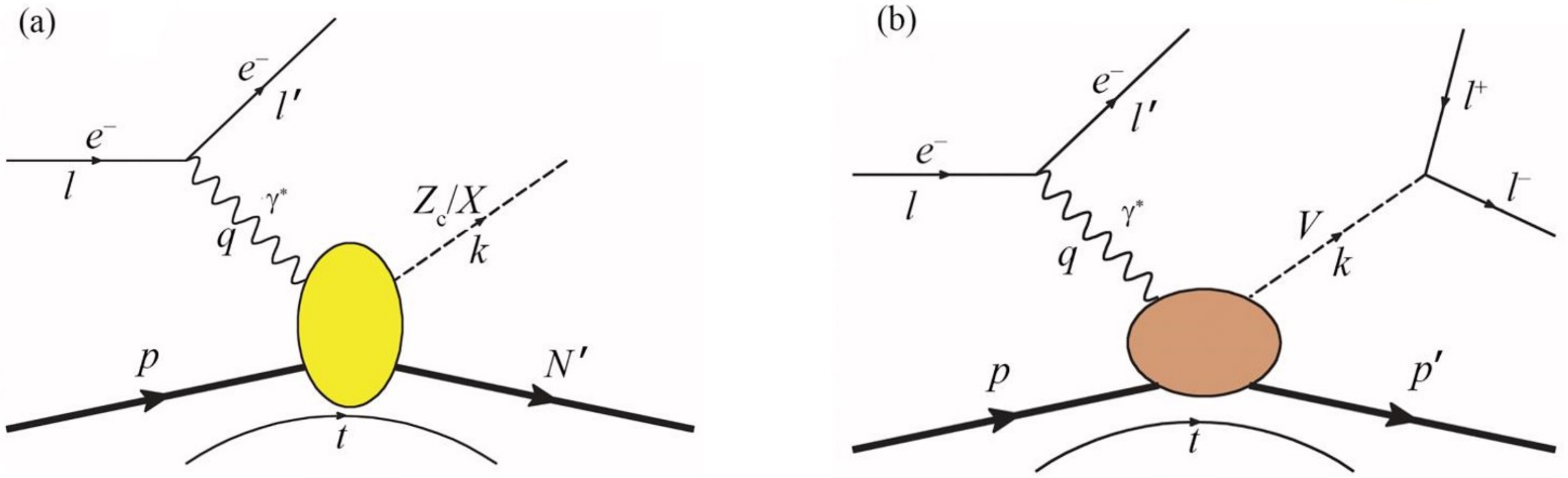
H. Dong, D. X. Zheng, J. Zhou, 2018

Study of quarkonium at EicC

- Study the exotic states from **new production mechanism** is crucial to pin down their nature
- EicC as a unique electron-ion collider has many advantages
  - ➢ Larger cross section compared to e^+e^- collision
  - ➢ Smaller background compared to pp and pp collisions
  - ➢ Polarized beams: pin down the quantum numbers J^P
  - ➢ **No triangle singularity**



Lebed, Mitchell, Swanson, Heavy-Quark QCD Exotica, PPNP 93, 143 (2017)



J/Psi production at EicC

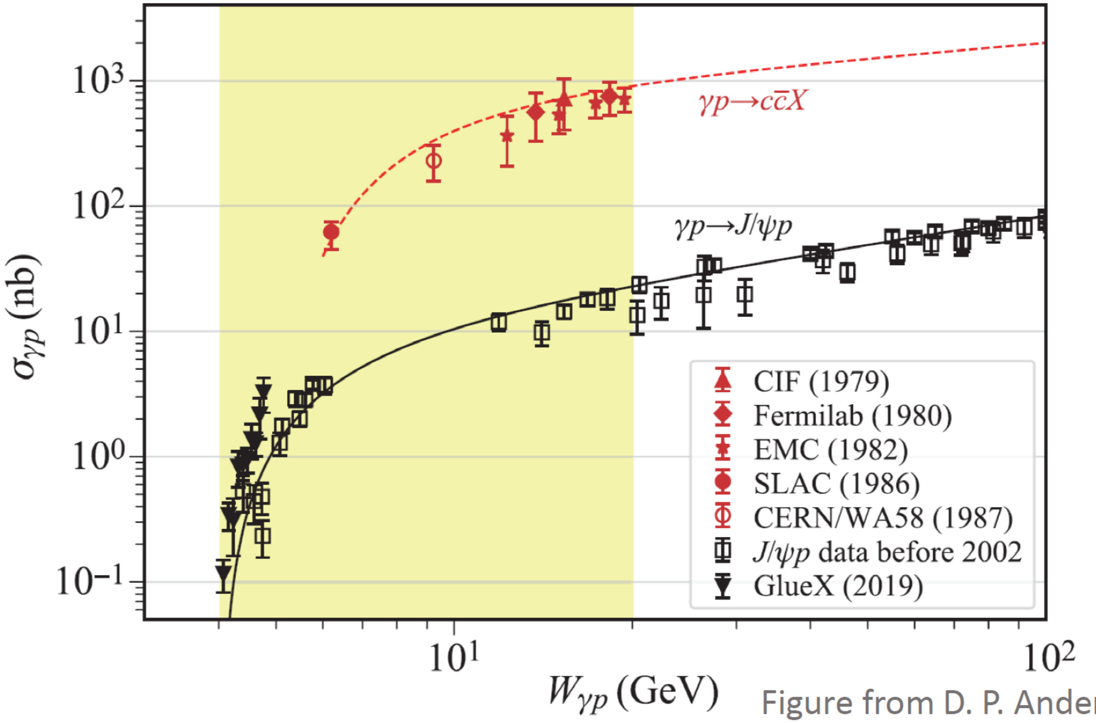


Figure from D. P. Anderle et al. Front.Phys.16(2021)64701

For W=10-20 GeV,

- Photoproduction: $\sigma(\gamma p \to J/\psi p) \sim O(10 \text{ nb})$, (no resonant enhancement considered), $\sigma(\gamma p \to c\bar{c}X) \sim 50\sigma(\gamma p \to J/\psi p)$
- Leptoproduction: cross sections are roughly two orders of magnitude (α) smaller
- For an integrated luminosity of 50 fb^{-1}, no. of J/ψ is $\sim O(10^7 - 10^8)$; many more open-charm hadrons D and Λ_c

Upsilon production at EicC

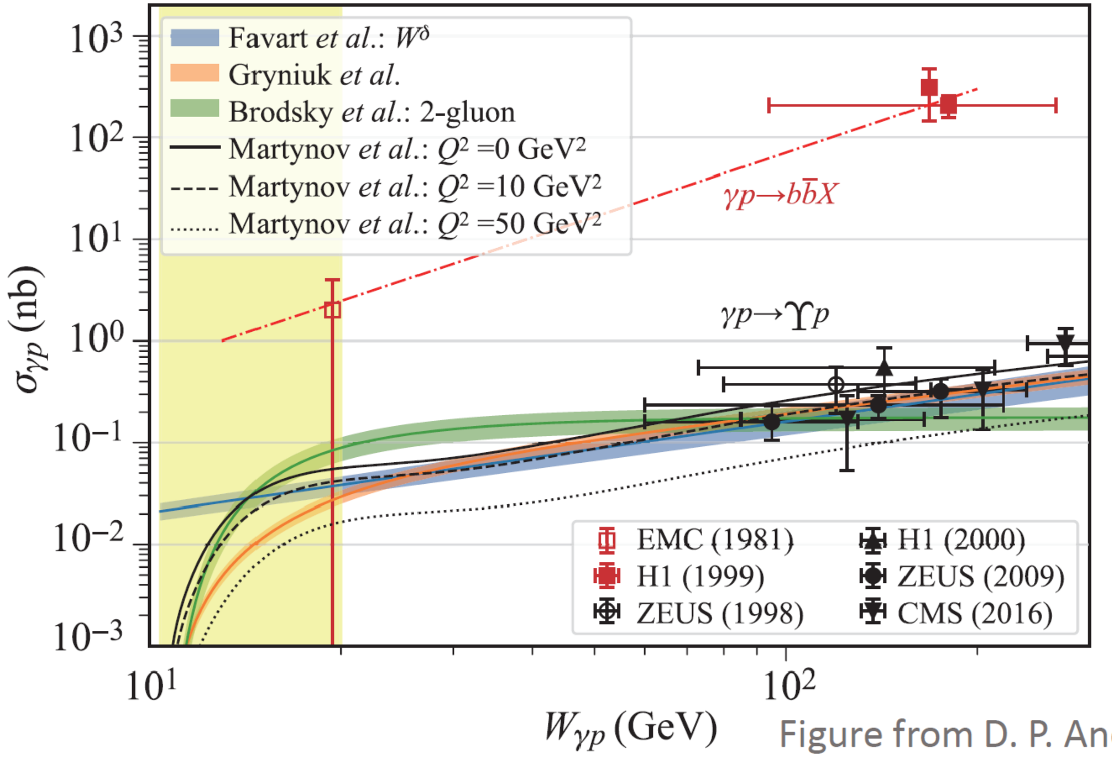


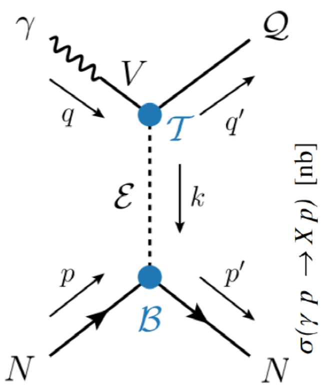
Figure from D. P. Anderle et al. Front.Phys.16(2021)64701

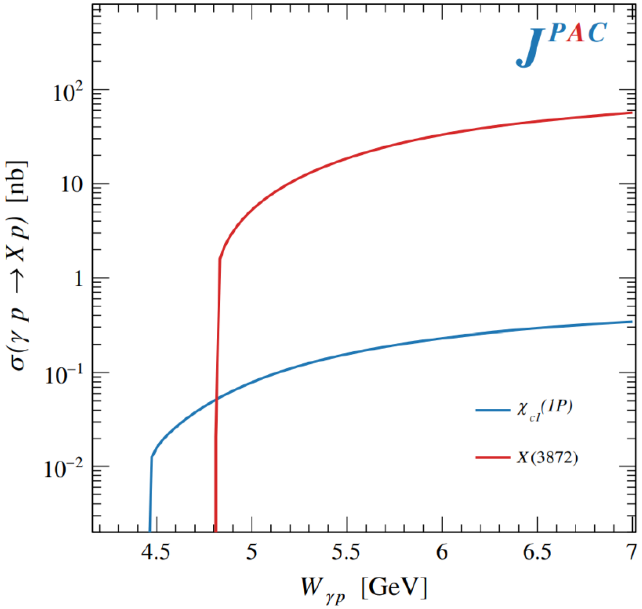
For W=15-20 GeV,

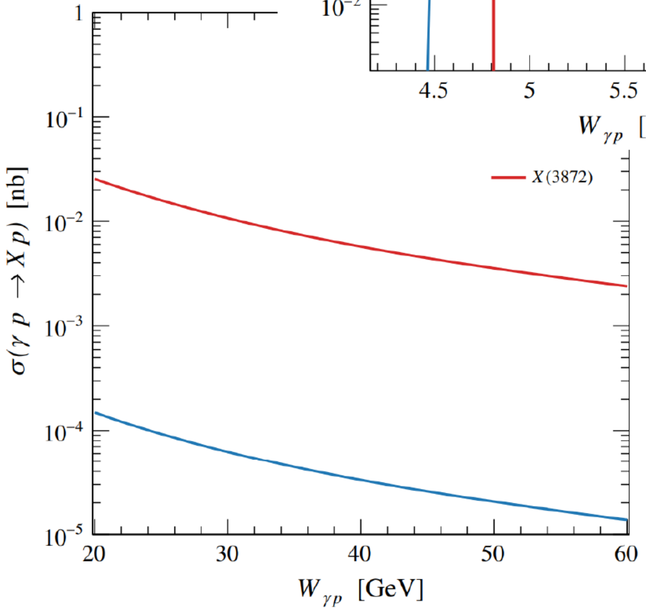
- Photoproduction: $\sigma(\gamma p \to \Upsilon p) \sim O(10\text{ pb})$ (no resonant enhancement considered), $\sigma(\gamma p \to b\bar{b}X)$ is about two orders higher
- Electroproduction: roughly two orders of magnitude (α) smaller, $\sim O(0.1\ pb)$
- For an integrated luminosity of 50 fb^{-1}, no. of Υ is $\sim O(10^4)$;

Exotic states production at EicC

- Cross section estimates for exclusive reactions assuming VMD (highly model-dependent)







- Estimated events for EicC (50 /fb)

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)	$ep \to eP_b(\text{narrow})$ $P_b(\text{narrow}) \to p\Upsilon$ $\Upsilon \to l^+l^-$	~30%	0–20
P_b(wide)	$ep \to eP_b(\text{wide})$ $P_b(\text{wide}) \to p\Upsilon$ $\Upsilon \to l^+l^-$	~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

JPAC, PRD102(2020)114010

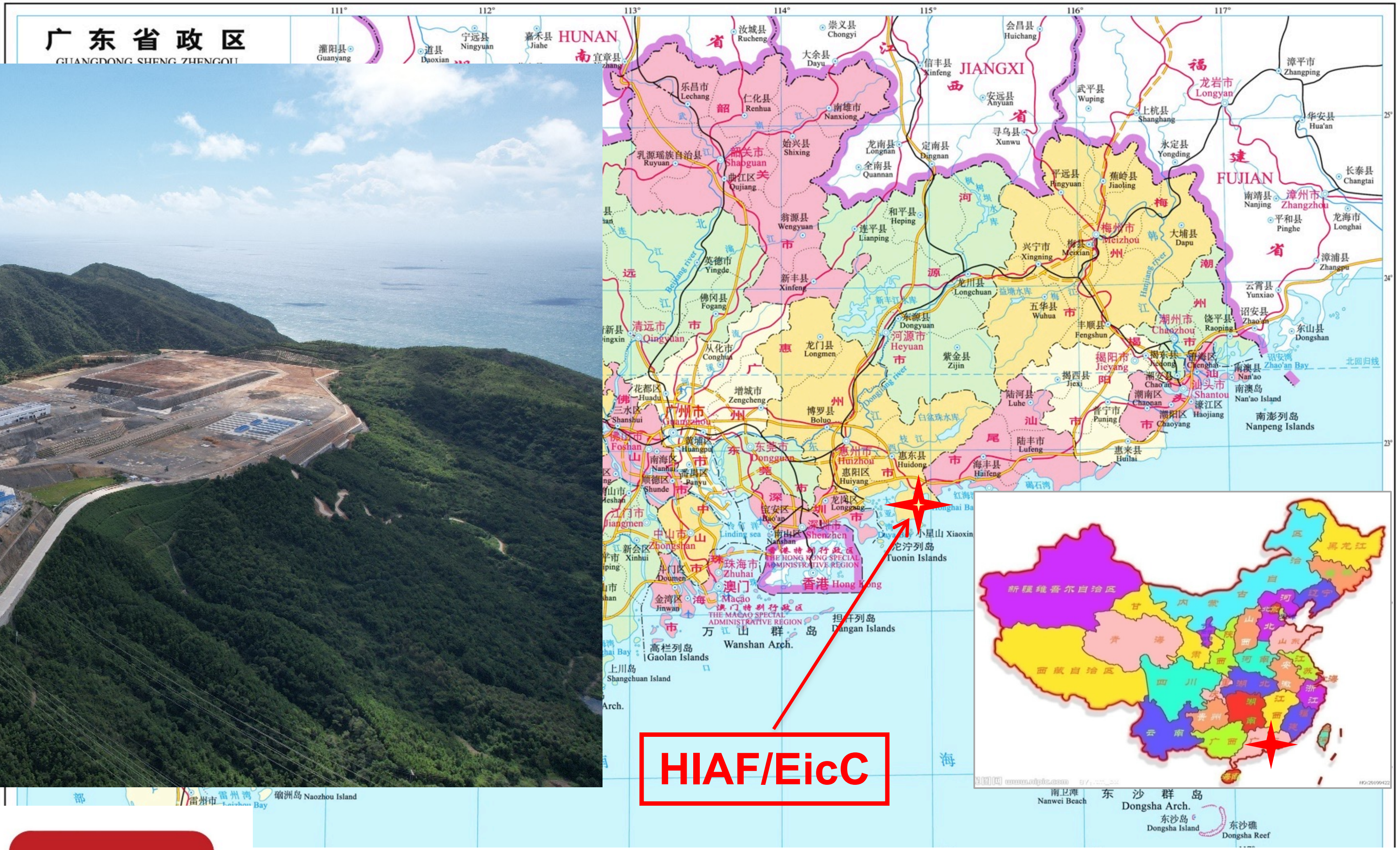
Summary

- EicC is a critical facility to study the nucleon structure and quarkonium
  - Polarized structure function
  - Spin-dependent TMDs
  - J/ψ , Υ and exotic states production
- Detector R&Ds are ongoing → CDR in 2023
- More physics topics are under study and development

Thanks!

Backup

Electron Ion Collider in China…Huizhou(惠州) in Guangdong province



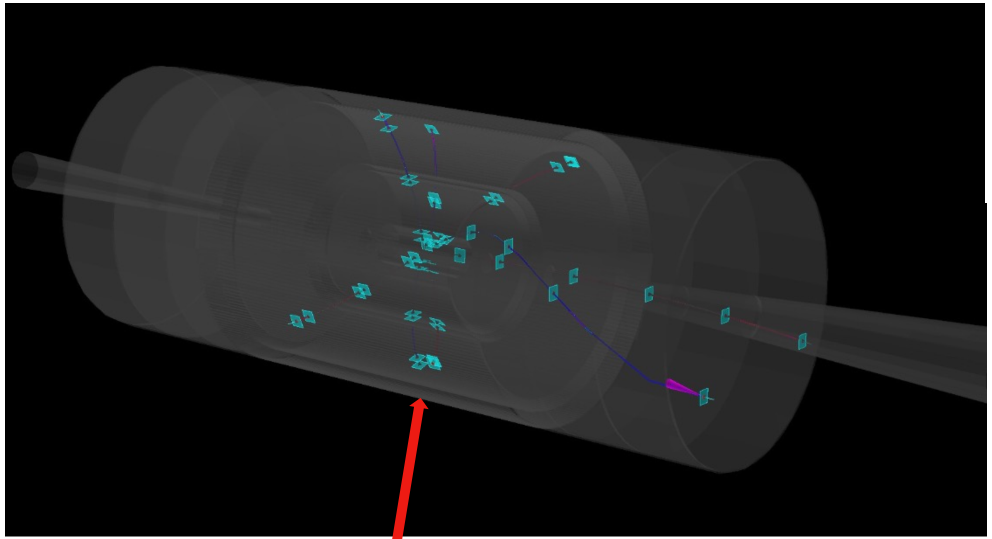
HIAF under construction

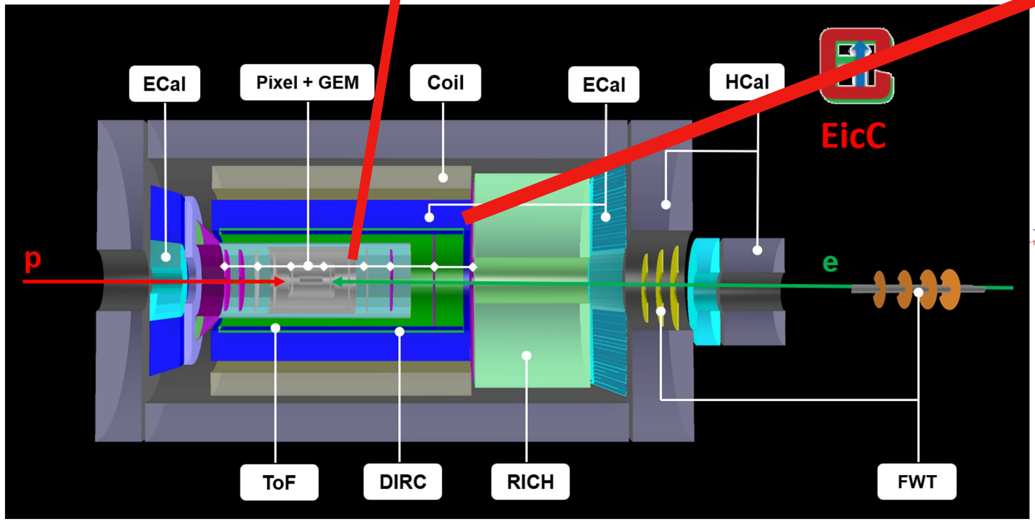
EIC in China

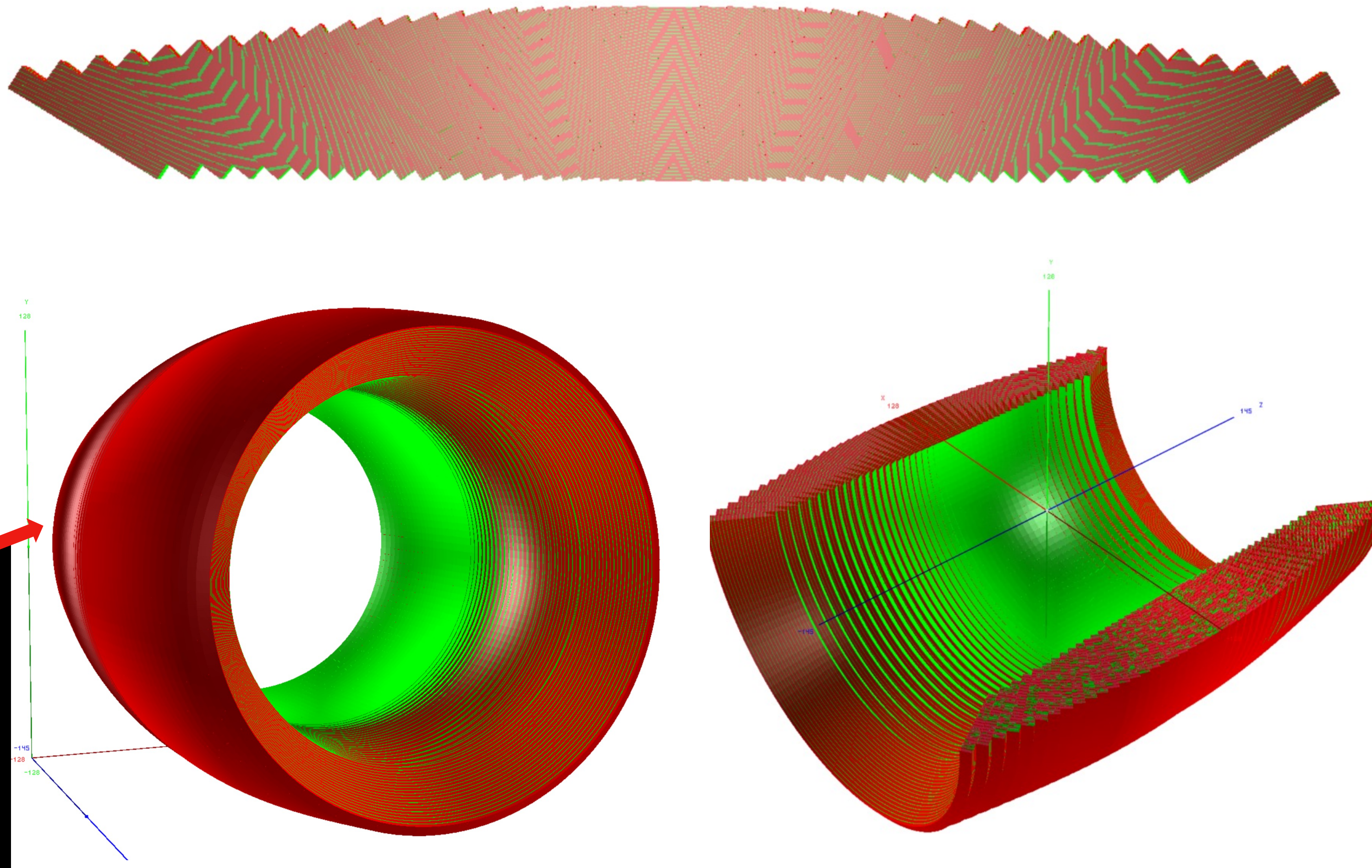
Electron Ion Collider in China, EicC

Detector simulations---an example

Tracking with all-silicon or Si+MPGD design



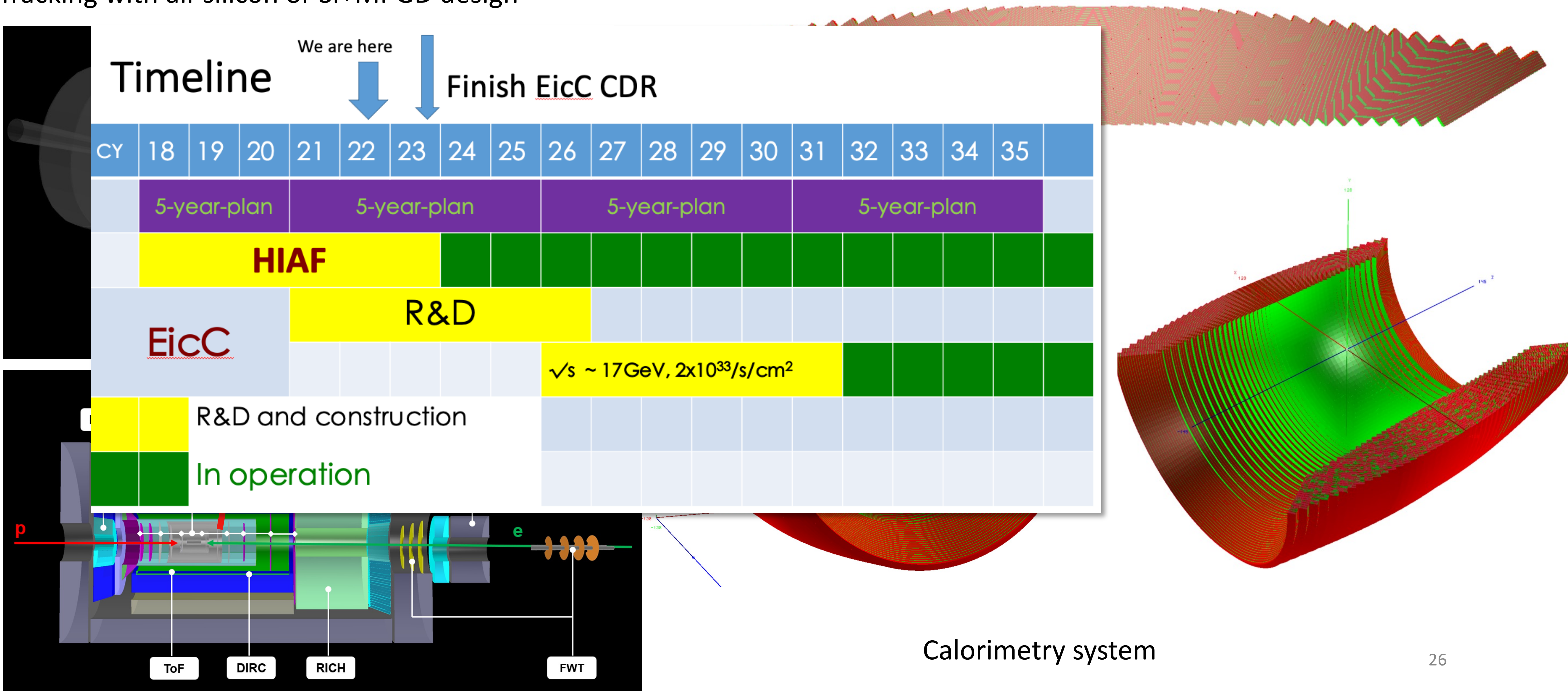




Calorimetry system

Detector simulations---an example

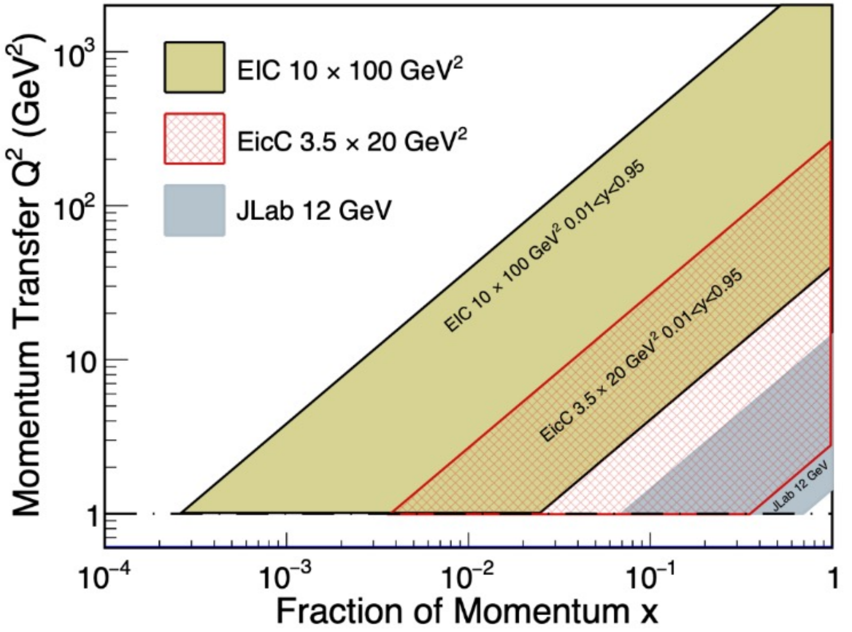
Tracking with all-silicon or Si+MPGD design

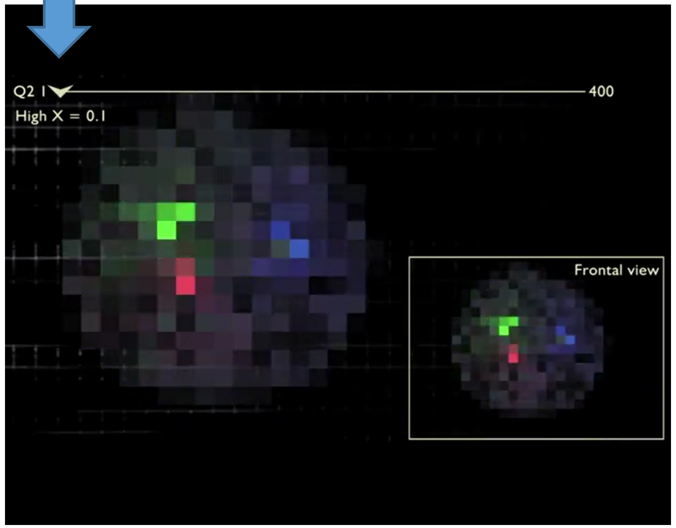


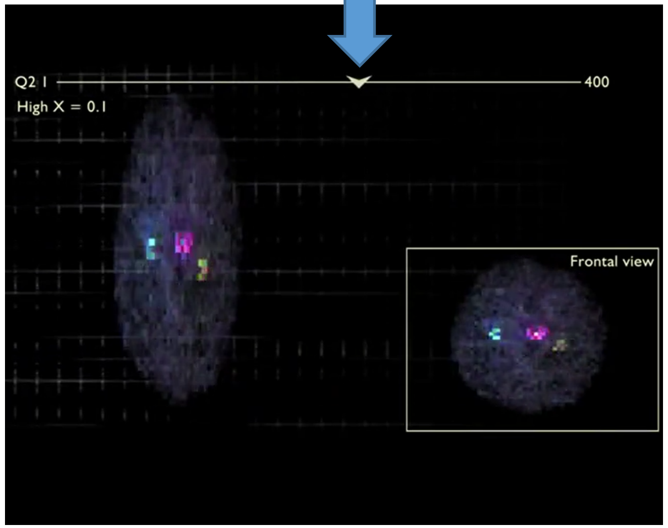
Calorimetry system

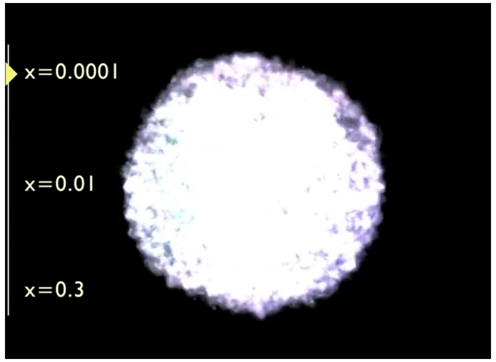
Kinematic region VS physics

See a video at:
http://eicug.org/

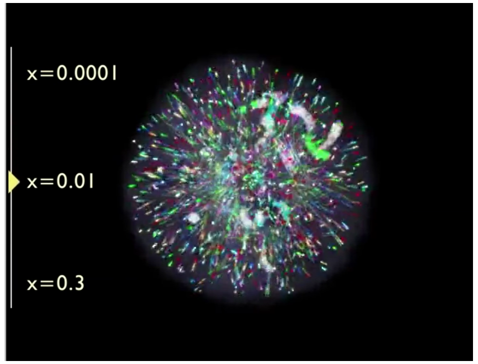




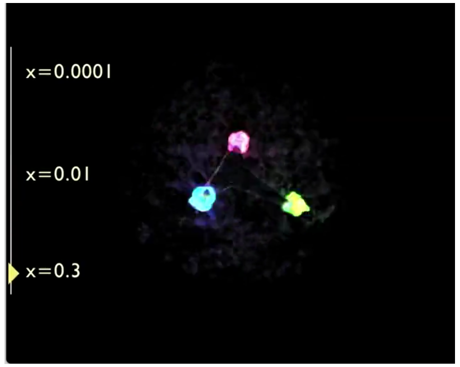




Gluon dominates



Gluon + sea quarks

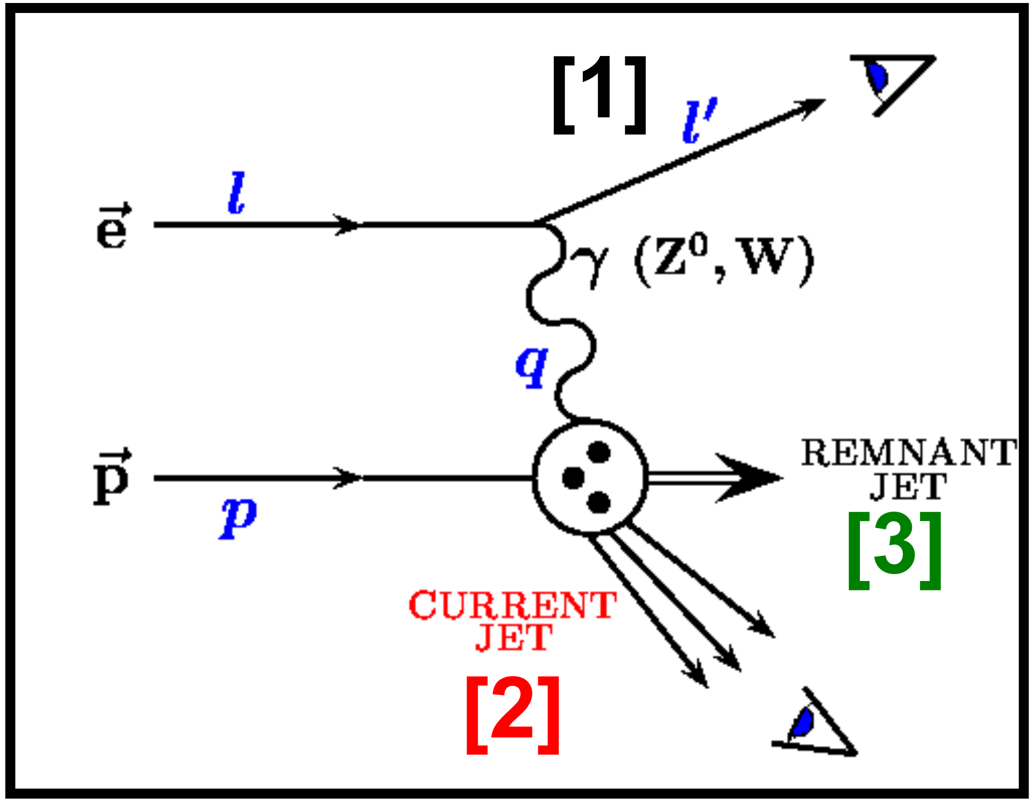


Valence quarks

- Different x → different picture
- Broad Q^2 coverage:
  - QCD evolution
  - Non-perturbative → perturbative

Lepton-Nucleon Scatterings

QED tool to study QCD nature of the nucleon



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

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

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

$$s = 4E_e E_p$$

$$W = (q+p)^2$$

- QED probe is clean
- α_{EM} ~1/137 with broad Q coverage
- One-photon exchange approximation: ~1% accuracy
- Detection scale is determined by Q^2: 1GeV^2 ~ nucleon size

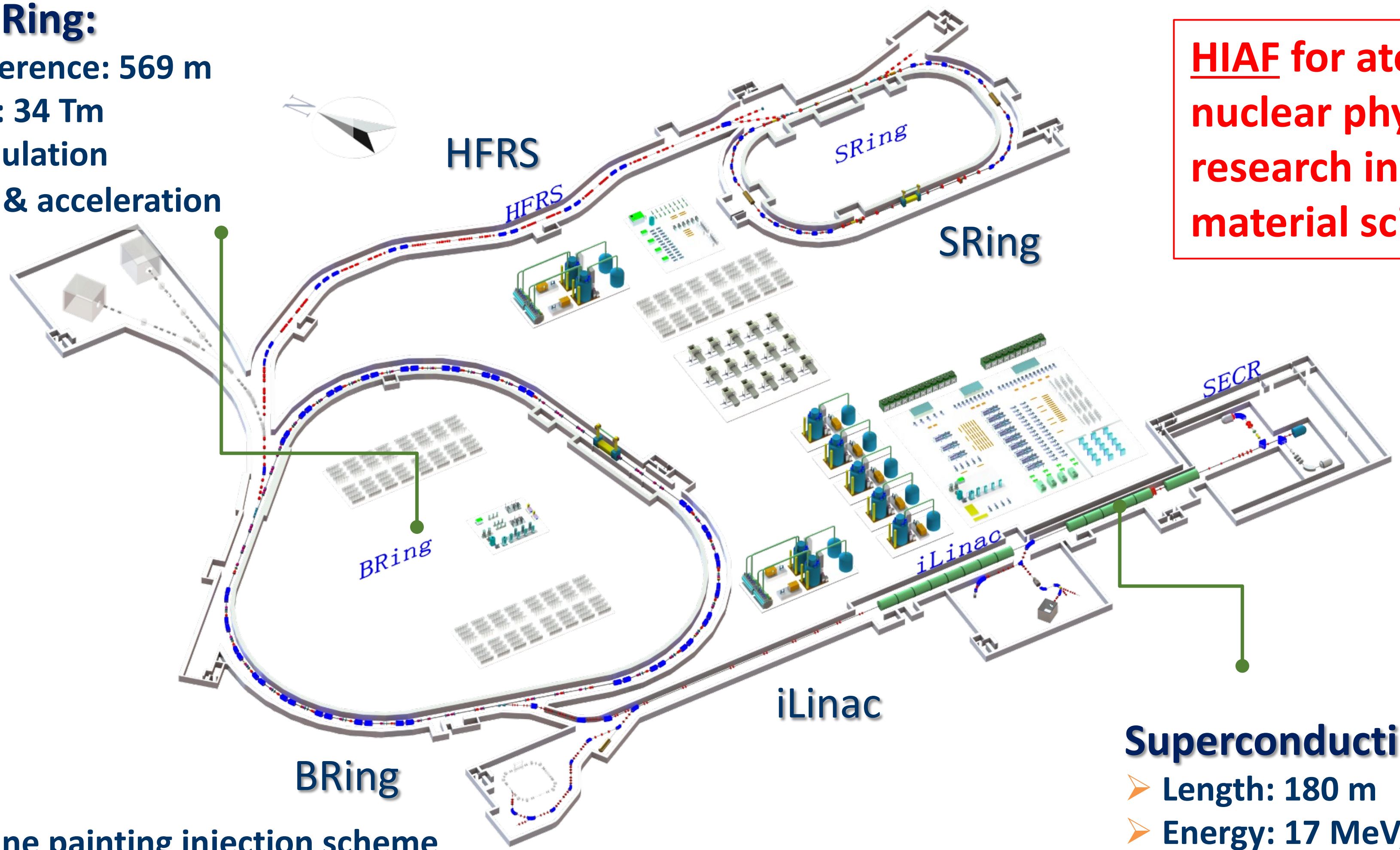
Observe scattered electron/muon	[1]	→ **inclusive**
Observe current jet/hadron	[1]+[2]	→ **semi-inclusive**
Observe remnant jet/hadron as well	[1]+[2]+[3]	→ **exclusive**

High Intensity heavy-ion Accelerator Facility (HIAF)

HIAF total investment: 2.5 billion RMB **(Funded)**

Booster Ring:

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



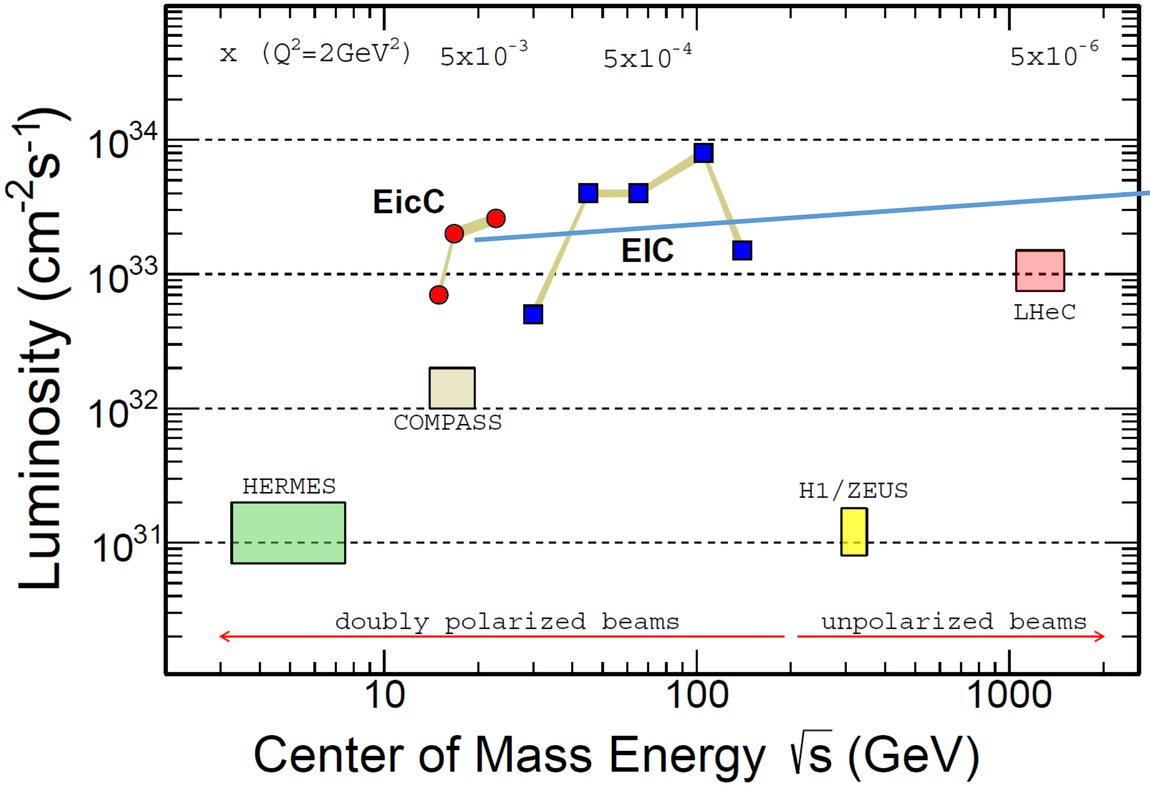
HIAF for atomic physics, nuclear physics, applied research in biology and material science etc.

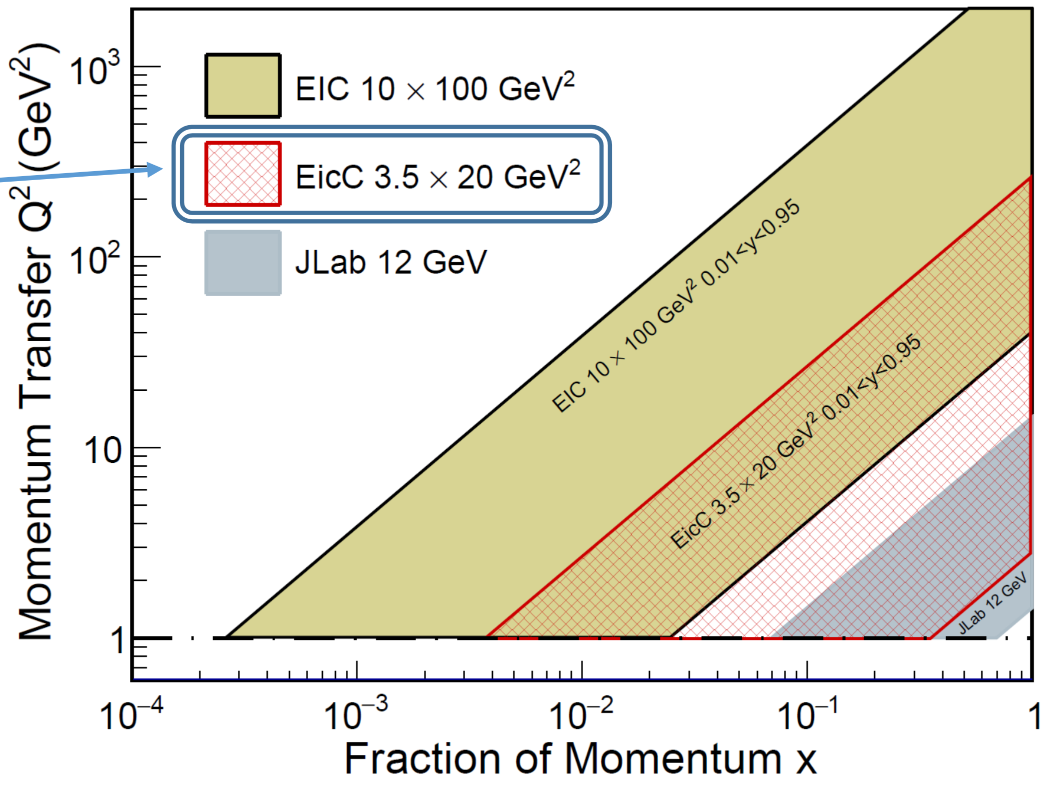
Superconducting Ion Linac:

- Length: 180 m
- Energy: 17 MeV/u (U^{34+})
- CW and pulse modes

- Two-plane painting injection scheme
- Fast ramping rate operation

EicC parameters



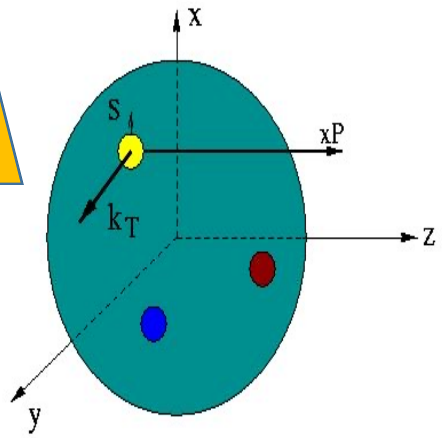


- EicC covers the kinematic region between JLab experiments and US-EIC
- EicC complements the ongoing scientific programs at JLab and future EIC project
- EicC focuses on moderate x and sea-quark region

Unified view of nucleon structure

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

5D Dist.



d^3r

$d^2k_T\,dr_z$

TMD PDFs

$f_1^u(x,k_T)$, ..

$h_1^u(x,k_T)$

GPDs/IPDs

3D imaging

dx & Fourier Transformation

d^2k_T

d^2r_T

PDFs

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

1D

Form Factors

$G_E(Q^2)$,

$G_M(Q^2)$

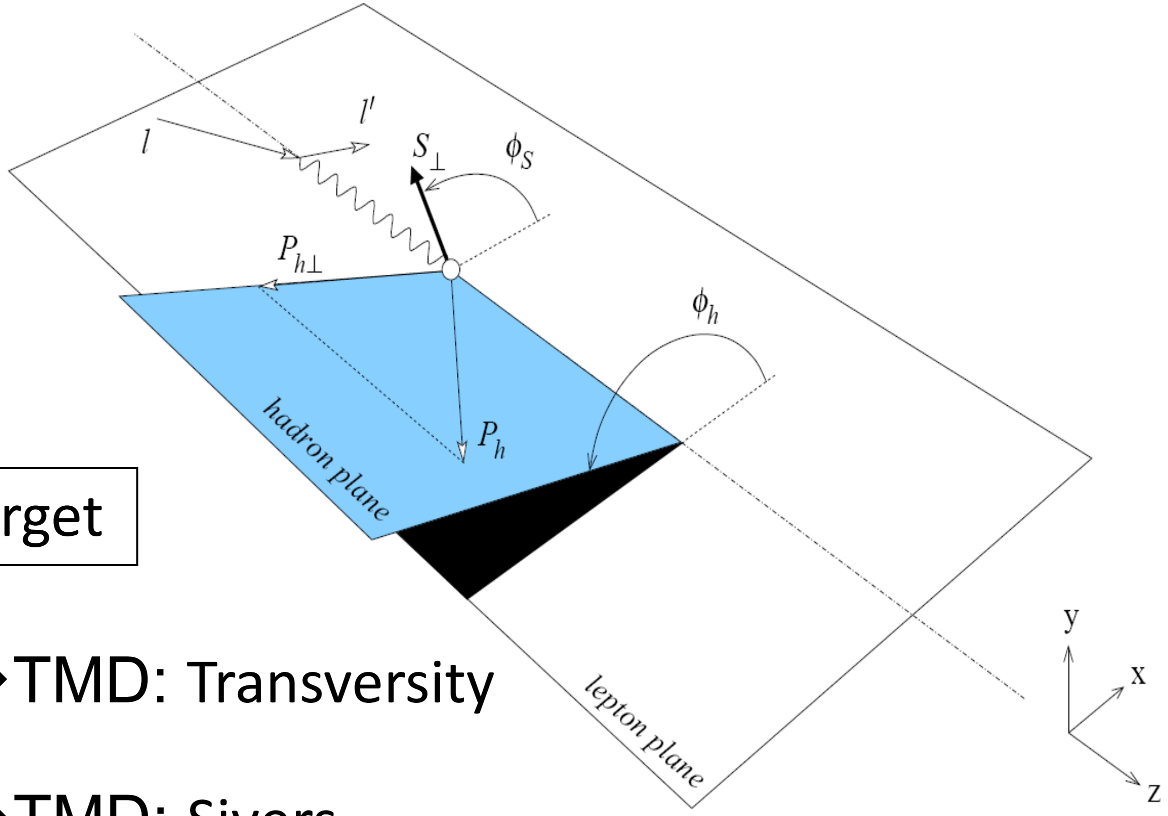
Experimentally

Separation of Collins, Sivers and Pretzelosity through azimuthal angular dependence

$$A_{UT}(\varphi_h^l,\varphi_S^l)=\frac{1}{P}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

$$=A_{UT}^{Collins}\sin(\phi_h+\phi_S)+A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

$$+A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S)$$



UT: **U**npolarized beam + **T**ransversely polarized target

$$A_{UT}^{Collins}\propto\left\langle\sin(\phi_h+\phi_S)\right\rangle_{UT}\propto h_1\otimes H_1^{\perp}$$ →TMD: Transversity

$$A_{UT}^{Sivers}\propto\left\langle\sin(\phi_h-\phi_S)\right\rangle_{UT}\propto f_{1T}^{\perp}\otimes D_1$$ →TMD: Sivers

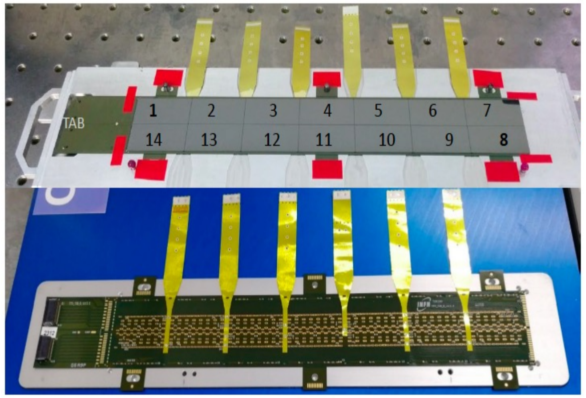
$$A_{UT}^{Pretzelosity}\propto\left\langle\sin(3\phi_h-\phi_S)\right\rangle_{UT}\propto h_{1T}^{\perp}\otimes H_1^{\perp}$$ →TMD: Pretzelosity

Detector R&Ds

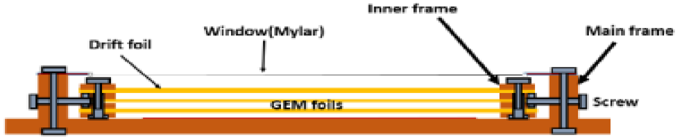
Clean rooms of ISO6 and ISO7 (in total of 200 m²) for detector assembling

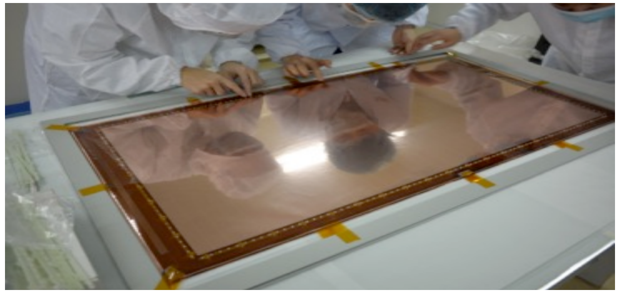
- **25cm x 25 cm Micromegas mass production**
- **R&D on 0.4m x 0.4m**

ALICE style ITS2 MAPS pixel detector



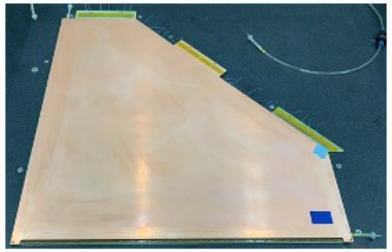
1m x 0.5 m GEM (self-stretching)

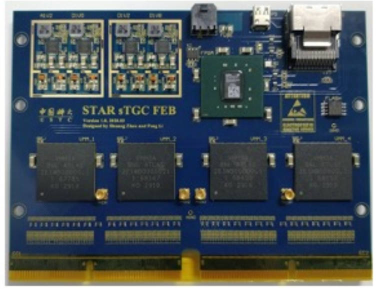




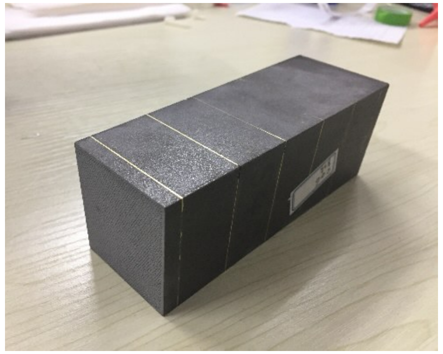
sTGC detector

~55cm * 55cm pentagon





Shashlyk and W-powder+ScFi EMCal



DIRC prototype