ePa/eA Facilities Complimentary to the US EIC: from JLab12 to Low-energy EIC in China

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INT18-3: Probing Nucleons and Nuclei in High Energy Collisions, October 22, 2018

- Introduction
- Jefferson Lab: 12 GeV Energy Upgrade/SoLID Program
- Nucleon Mass, Spin and 3-d Structure Study
- Low-energy EIC in China
- Summary

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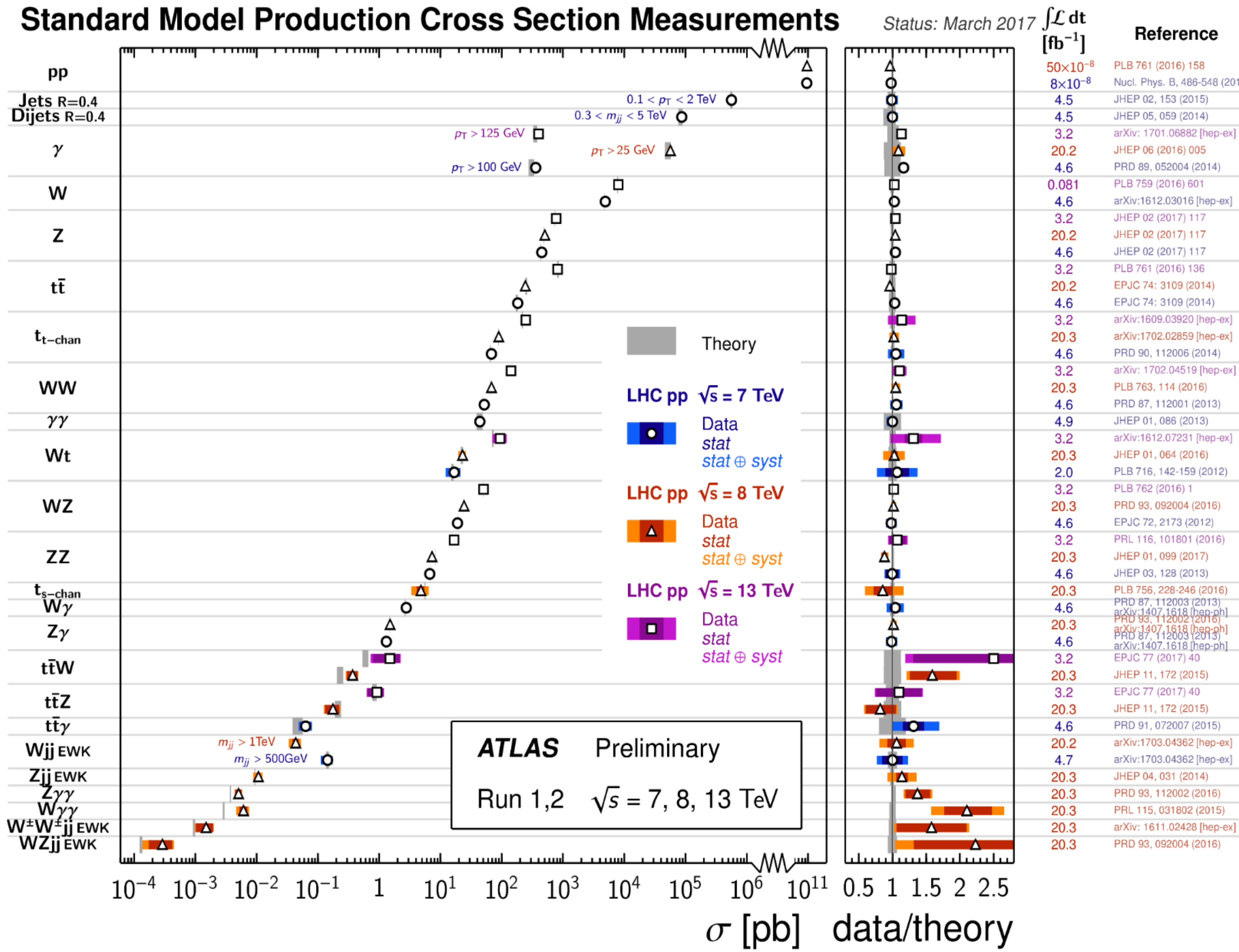
Introduction

Nucleon Structure and Strong Interaction (QCD)

Successes of the Standard Model

- **EW tested to high precision**
- **LHC:** *Higgs found*
  no evidence of BSM
  so far!
- **QCD tested at high energy**
  perturbative region
  pQCD works
  over a large range
  for many channels
- **Main remaining challenge:**
  "Strong" (non-perturbative) QCD/ Confinement
  - ***hadron Structure***

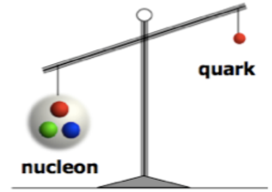


Nucleon Structure and QCD

- Nucleon: proton =(uud) ,   neutron=(udd)   *+ sea quarks + gluons (**QCD vacuum**)*
- Nucleon: ***99% of the visible mass in universe***

➢ **Proton mass "puzzle":**

Quarks carry ~ a few % of proton's mass?

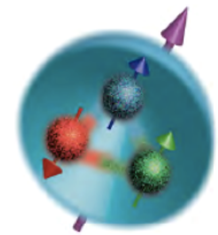


m_q ~ 10 MeV

m_N ~ 1000 MeV

How does glue dynamics generate the energy for nucleon mass?

➢ **Proton spin "puzzle":**   Quarks carry ~ 30% of proton's spin



How does quark and gluon dynamics generate the rest of the proton spin?

➢ **3D structure of nucleon: 3D in momentum or (2D space +1 in momentum)**

Color Confinement   Asymptotic freedom

Q (GeV)

200 MeV (1 fm)   2 GeV (1/10)   Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?
Can we scan the nucleon to reveal its 3D structure?
How does the nuclear force arise from QCD

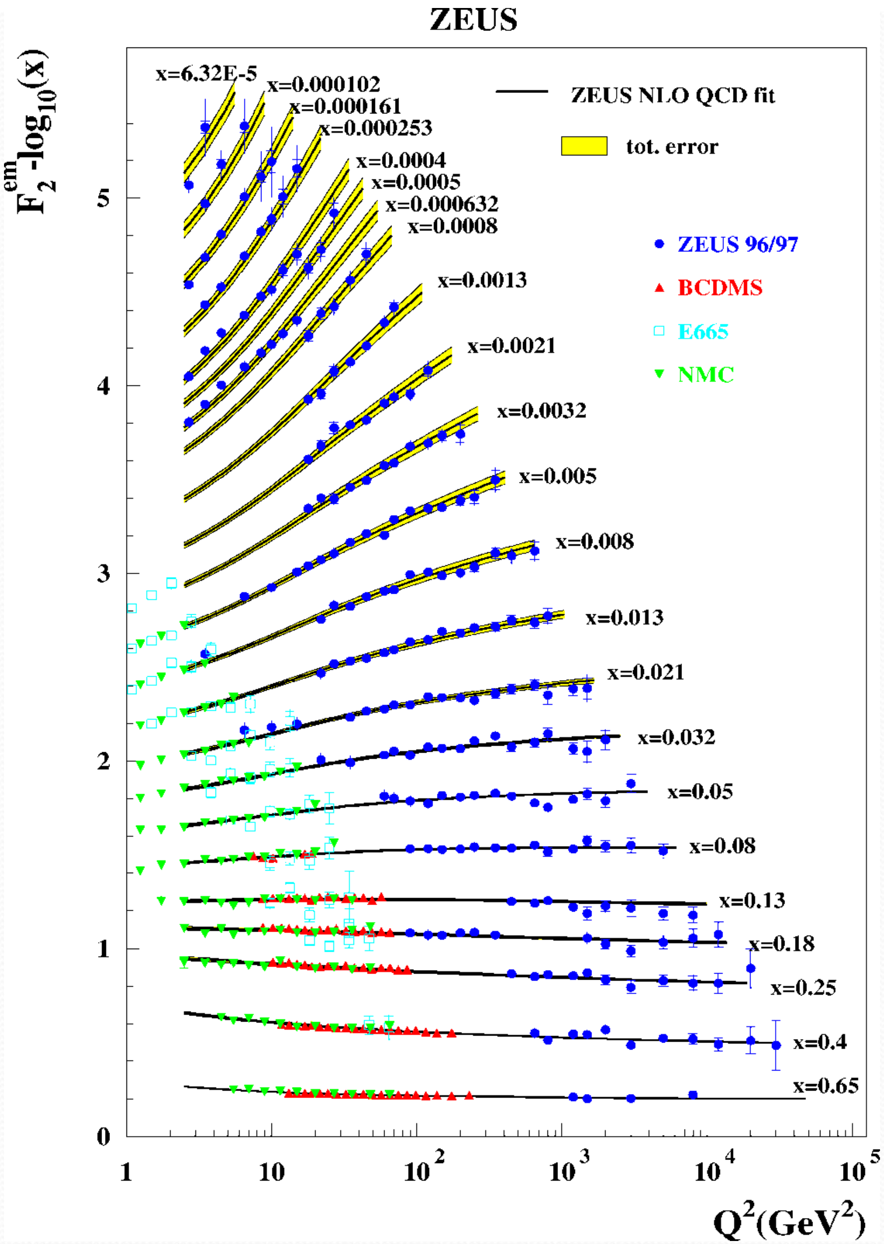
DIS: Powerful Tool to Probe Nucleon Structure

- Unpolarized Structure Function F_2
- Bjorken Scaling

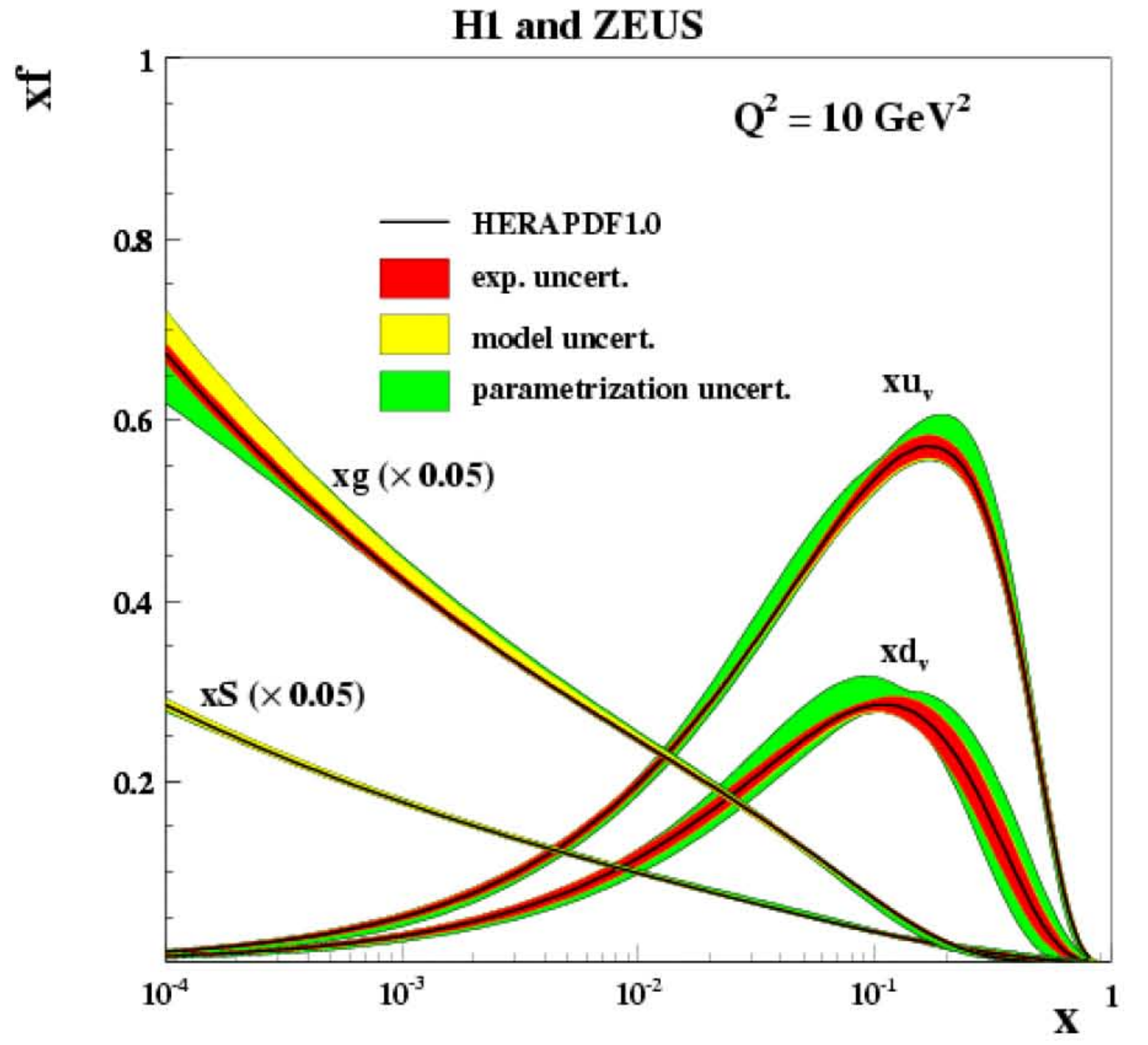
  and Scaling Violation
- Gluon radiation –

  QCD evolution

  NLO: Next-to-Leading-Order
- One of the best experimental tests of QCD



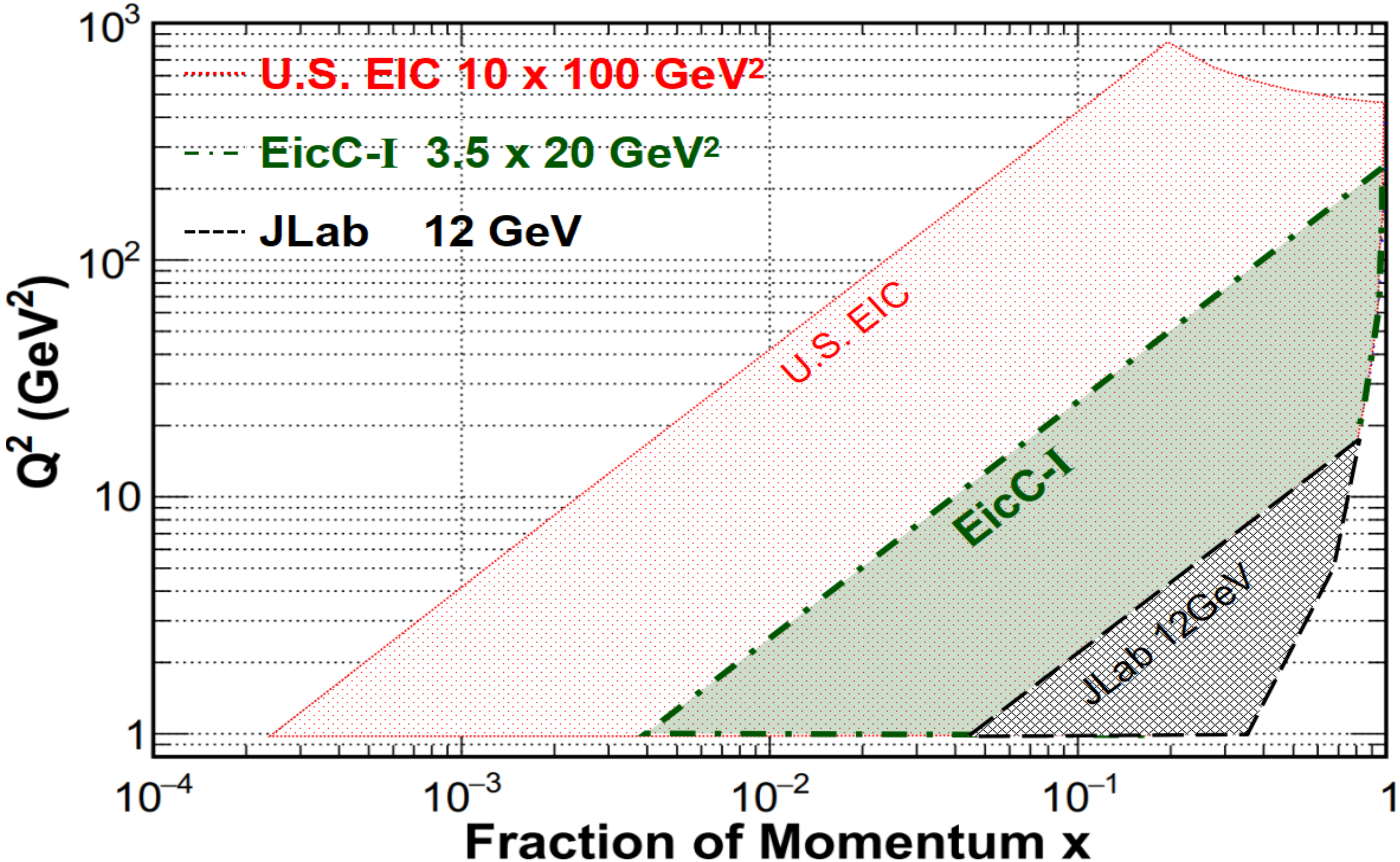
Parton Distribution Functions (CTEQ6)



Experimental Facilities for e-N (e-A)

- SLAC: Fix target, 20/50 GeV (polarized) electron beam,, polarized p, d and ^{3}He
- CERN: EMC/NMC/SMC/COMPASS
  Fixed target, ~200 GeV polarized μ beam on polarized p, d
- DESY: HERA, unpolarized e-p collider. 27.5 GeV x 920 GeV
  HERMES, fixed target, polarized e-/e+ 27 GeV beam,
  polarized internal p, d, ^{3}He
- **JLab: fixed target, 6/12 GeV polarized e beam, polarized targets (p,n/^{3}He,d)**
  highest luminosity 10^{39} (10^{36} for polarized)
- Low energy facilities: Mainz, MIT-Bates, Saclay, NIKHEF, …
- **Future EIC: e-RHIC, JLEIC, EicC: EIC@China, LHeC, …**

Kinematics Reach



JLab12: **a few x 10^{-2} < x < ~ 1** → valence quark region

EicC-I: **a few x 10^{-3} < x < ~ 1** → light sea and valance quark region

US EIC: **few x 10^{-4} < x < ~1** → gluon and sea quark regions

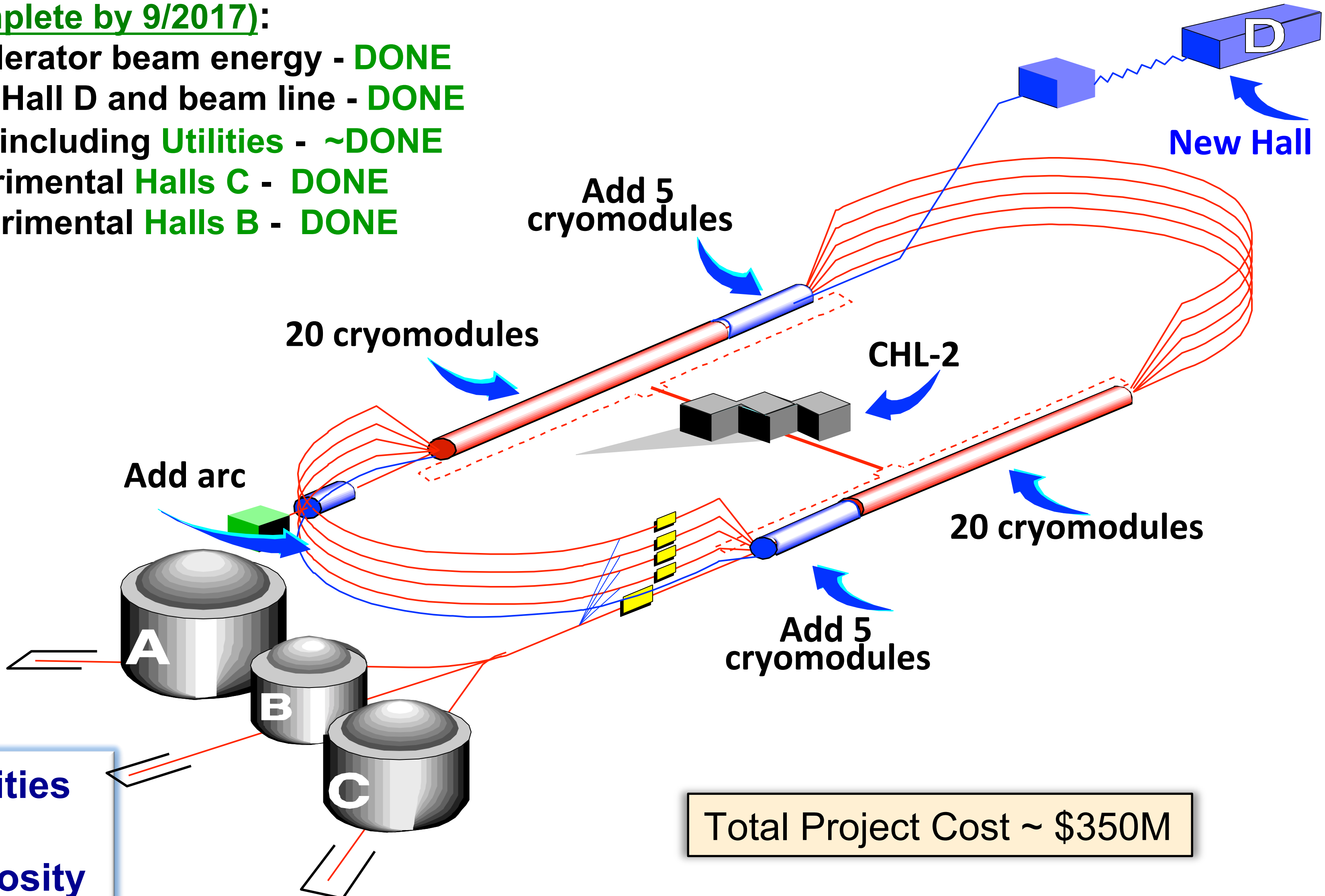
JLab 12 GeV Energy Upgrade

JLab12 / SoLID Program

12 GeV Upgrade Project

Project Scope (complete by 9/2017):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - ~DONE
- Upgrades to Experimental Halls C - DONE
- Upgrades to Experimental Halls B - DONE

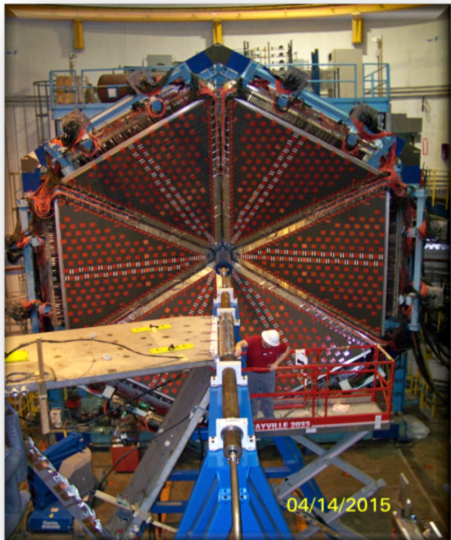


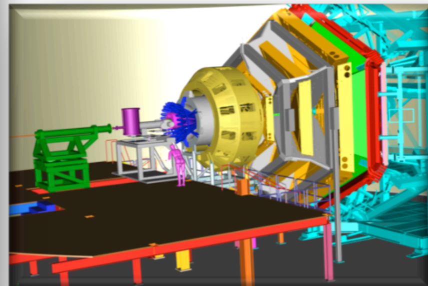
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - $\sim10^{39}$ $cm^{-2}s^{-1}$

Total Project Cost ~ $350M

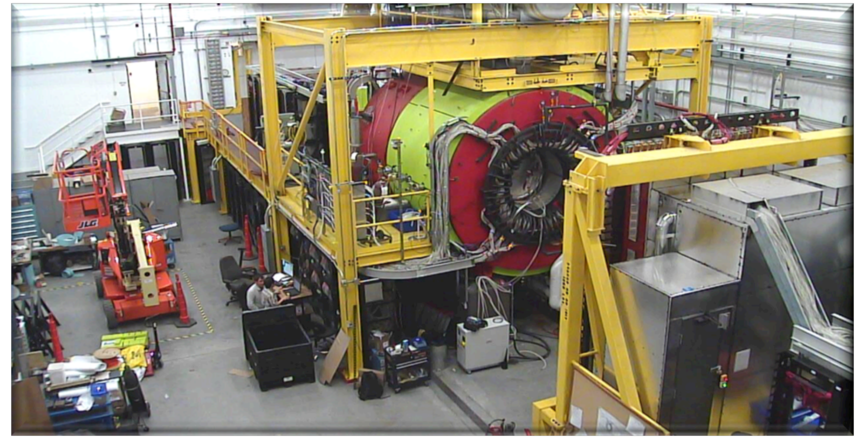
12 GeV Scientific Capabilities

Hall B** – understanding **nucleon structure** via **generalized parton distributions

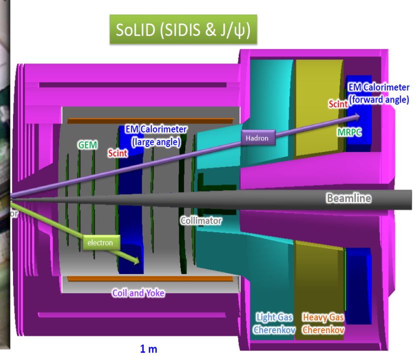




Hall D** – exploring origin of **confinement** by studying **exotic mesons



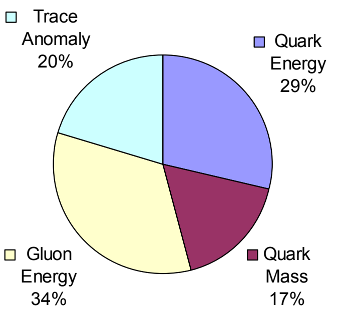
***Hall A** – form factors, future new experiments (e.g., **SoLID** and MOLLER)*



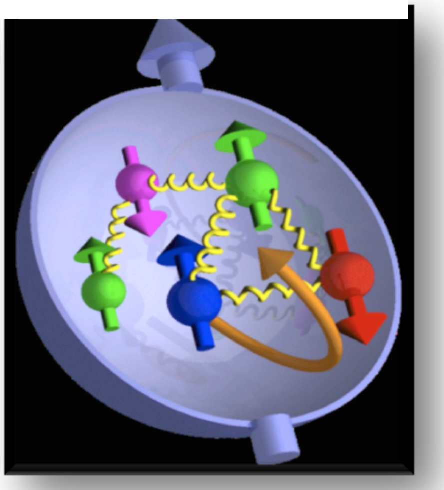
***Hall C** – precision determination of **valence quark** properties in nucleons/nuclei*

Jefferson Lab @ 12 GeV Science Questions

- What's the origin of the proton mass?
 How can measurements help?

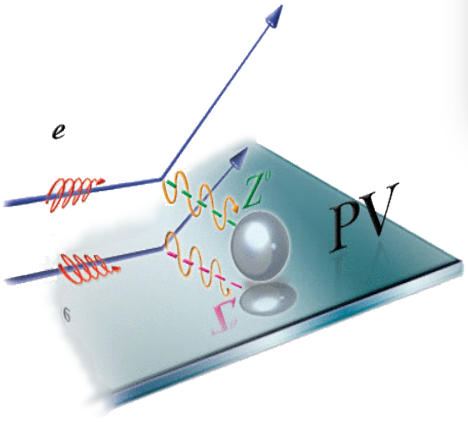


- Where is the missing spin in the nucleon?
Role of orbital angular momentum?

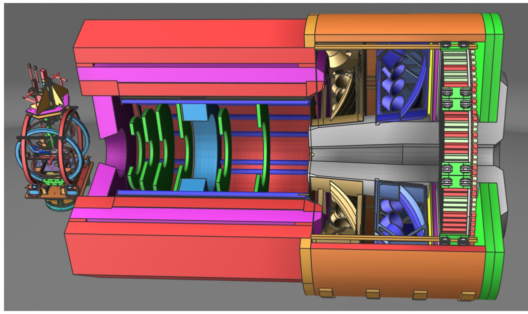


- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?

- Can we discover evidence for physics
beyond the standard model
of particle physics?



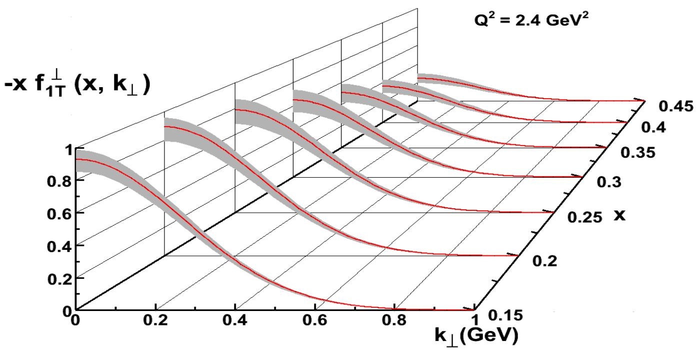
Solenoidal Large Intensity Device (SoLID)

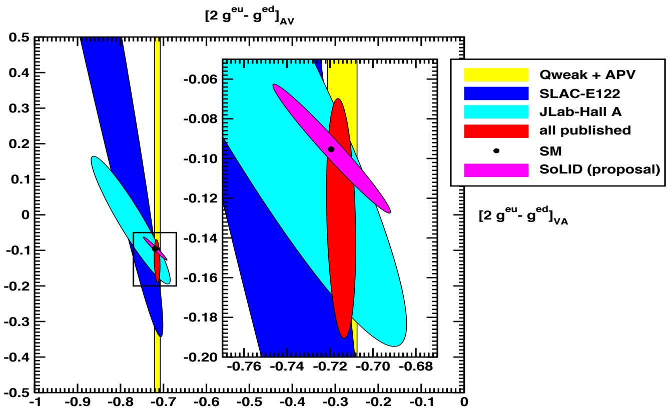


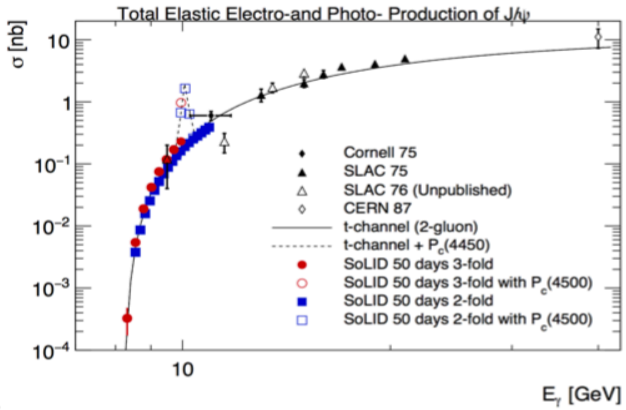
- *Full exploitation of JLab 12 GeV Upgrade to maximize scientific return*

A Large Acceptance Detector AND Can Handle High Luminosity (10^{37}-10^{39})

  - *Reach ultimate precision for tomography of the nucleon*
  - *PVDIS in high-x region - providing sensitivity to new physics at 10-20 TeV*
  - *Threshold J/Psi - probing strong color fields in the nucleon and the origin of its mass (trace anomaly)*





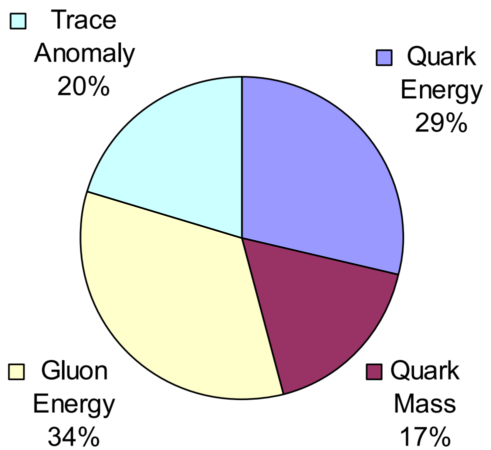


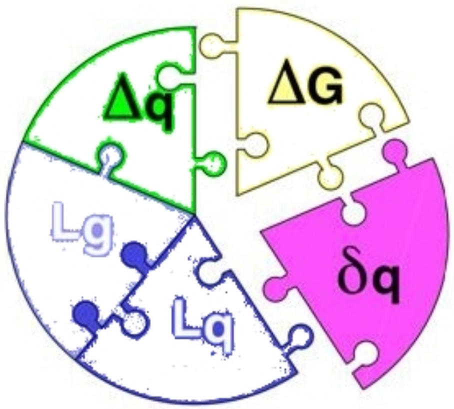
- *Strong collaboration (300 collaborators from 72 institutions, 13 countries)*
  - *Significant international contributions*
  - *Strong theoretical support*

- *2015 LRP recommendation IV*
  - *We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories –*
  - *SoLID – Strongly endorsed mid-scale project*

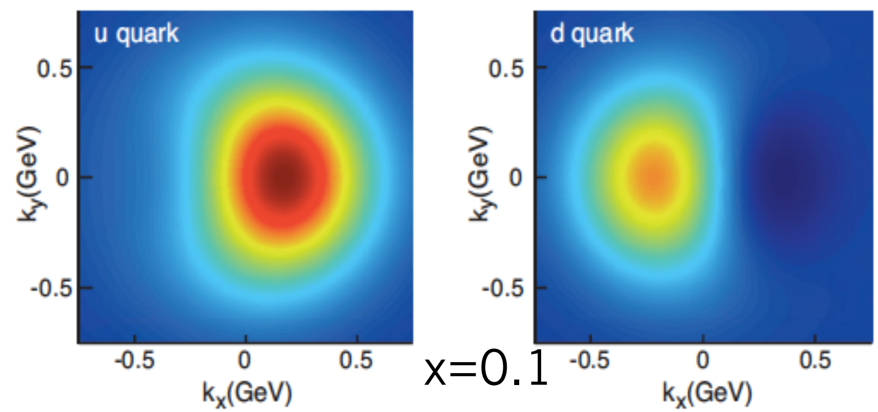
Nucleon Mass, Spin and 3-D structure

Mass and Spin Decomposition





Nucleon Femtography



Proton Mass Decomposition

❑ Roles of quarks and gluons?

✧ **QCD energy-momentum tensor:**

$$T^{\mu\nu} = \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}}$$

Traceless term: $\overline{T^{\mu\nu}} \equiv T^{\mu\nu} - \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\ \alpha}$

Trace term: $\widehat{T^{\mu\nu}} \equiv \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\ \alpha}$

with $T^{\alpha}_{\ \alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q (1+\gamma_m) \bar{\psi}_q \psi_q$

Vacuum expectation breaks chiral symmetry

QCD trace anomaly $\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

✧ **Invariant hadron mass (in any frame):**

$$\langle p | T^{\mu\nu} | p \rangle \propto p^\mu p^\nu \;\Rightarrow\; \langle p | T^{\mu\nu} | p \rangle (g_{\mu\nu}) \propto p^\mu p^\nu (g_{\mu\nu}) = m^2$$

$$m^2 \propto \langle p | T^{\alpha}_{\ \alpha} | p \rangle \;\Rightarrow\; \frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$$

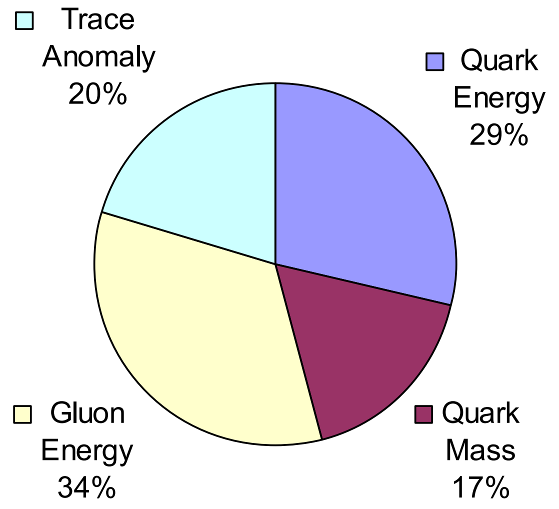
➡ **At the chiral limit, the entire mass is from gluons!**

Proton Mass: QCD energy

X. Ji, PRL741071(1995)

- At proton rest frame

One can calculate the proton mass through the expectation value of the QCD Hamiltonian



$$H_{\rm QCD} = H_q + H_m + H_g + H_a .$$

$$H_q = \int d^3\vec{x}\ \bar{\psi}(-i\mathbf{D}\cdot\alpha)\psi,$$ ← ***Quark energy***

$$H_m = \int d^3\vec{x}\ \bar{\psi}m\psi,$$ ← ***Quark mass***

$$H_g = \int d^3\vec{x}\ \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2),$$ ← ***Gluon energy***

$$H_a = \int d^3\vec{x}\ \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2).$$ ← ***Trace anomaly (Dark Energy)***

Relating to Measurements

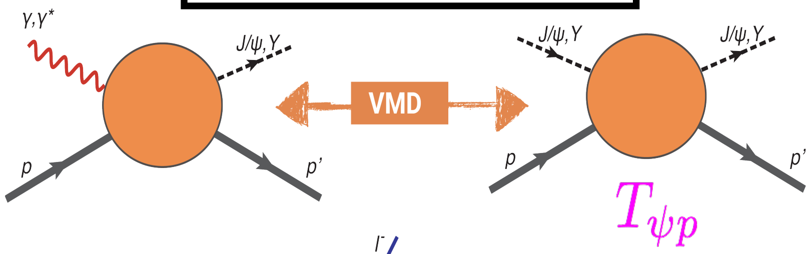
- **Traceless part** at rest frame becomes ***quark kinetic energy and gluon energy***
  can be extracted from **parton distribution functions**
  scheme and scale dependent

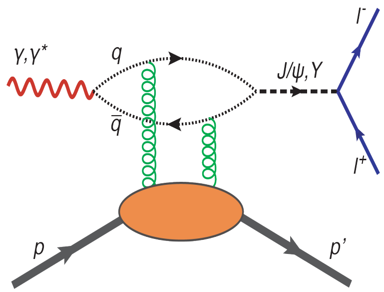
- ***Quark mass***: u and d quark contribution obtain from **pi-nucleon sigma term**
  s quark from **Chiral Purturbation Theory for baryon octet**
  or LQCD, …

- ***Trace Anomaly***: **analogous to the cosmological constant (dark energy)**
  Heavy Quark (J/ψ and Upsilon) threshold production may provide access?

Charm @ SoLID and Beauty @ EIC

$$\gamma^* + N \rightarrow N + J/\psi$$





Heavy quark – dominated by two glu

Proton Mass:

$$\langle P|T^\alpha_\alpha|P\rangle = 2P^\alpha P_\alpha = 2M_p^2$$

Covariant Decomposition of the Energy Momentum Tenso

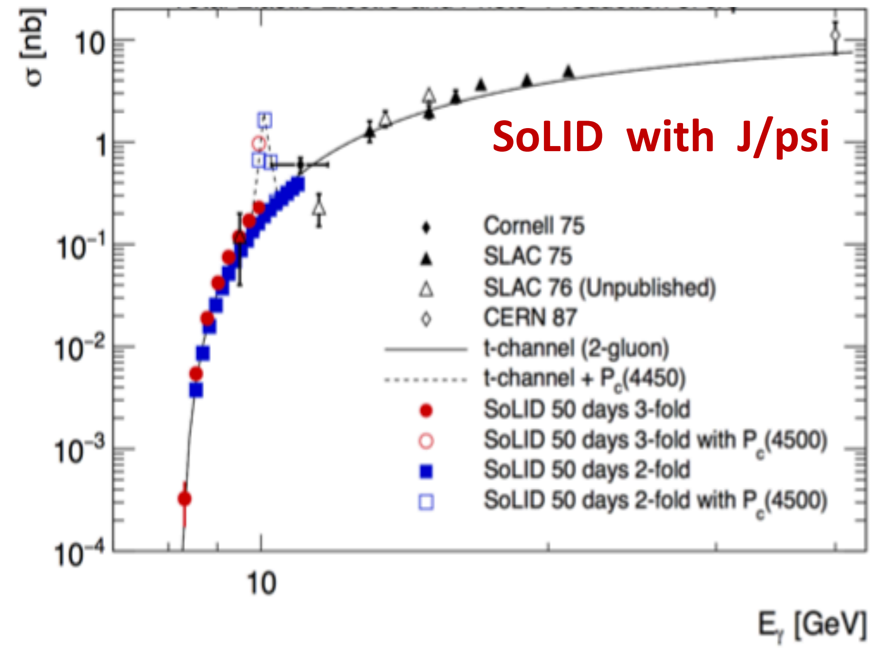
$$T^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} F^{\mu\nu,a}F^a_{\mu\nu} + \sum_{q=u,d,s} m_q(1+\gamma_m)\bar{\psi}_q\psi_q$$

QCD trace anomaly — Light quark mass

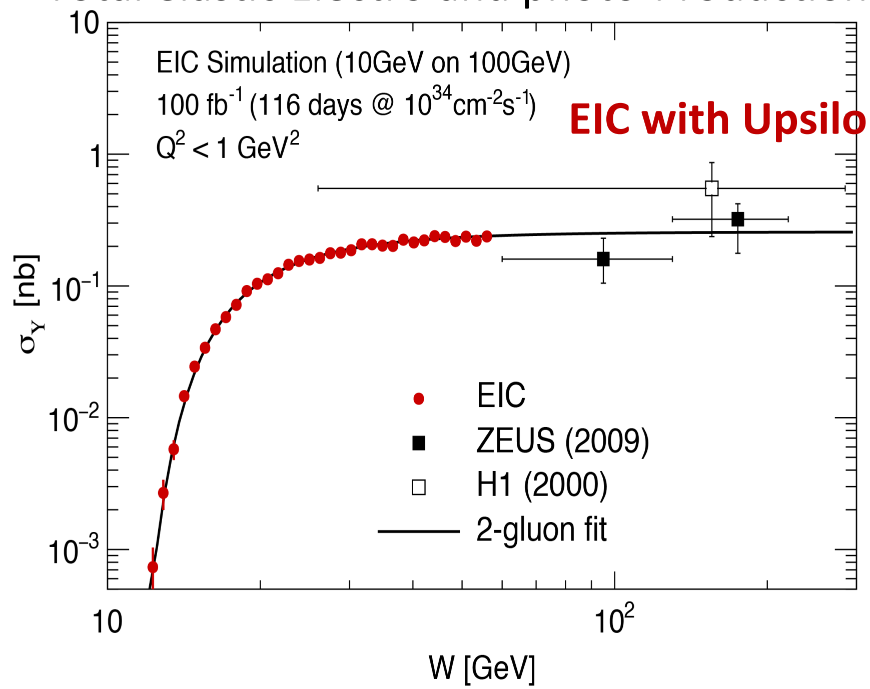
Trace of EMT proportional to Quarkonium-proton scatterir

$T_{\psi p}$ to be measured at JLab with J/psi at SoLID or Upsilon a

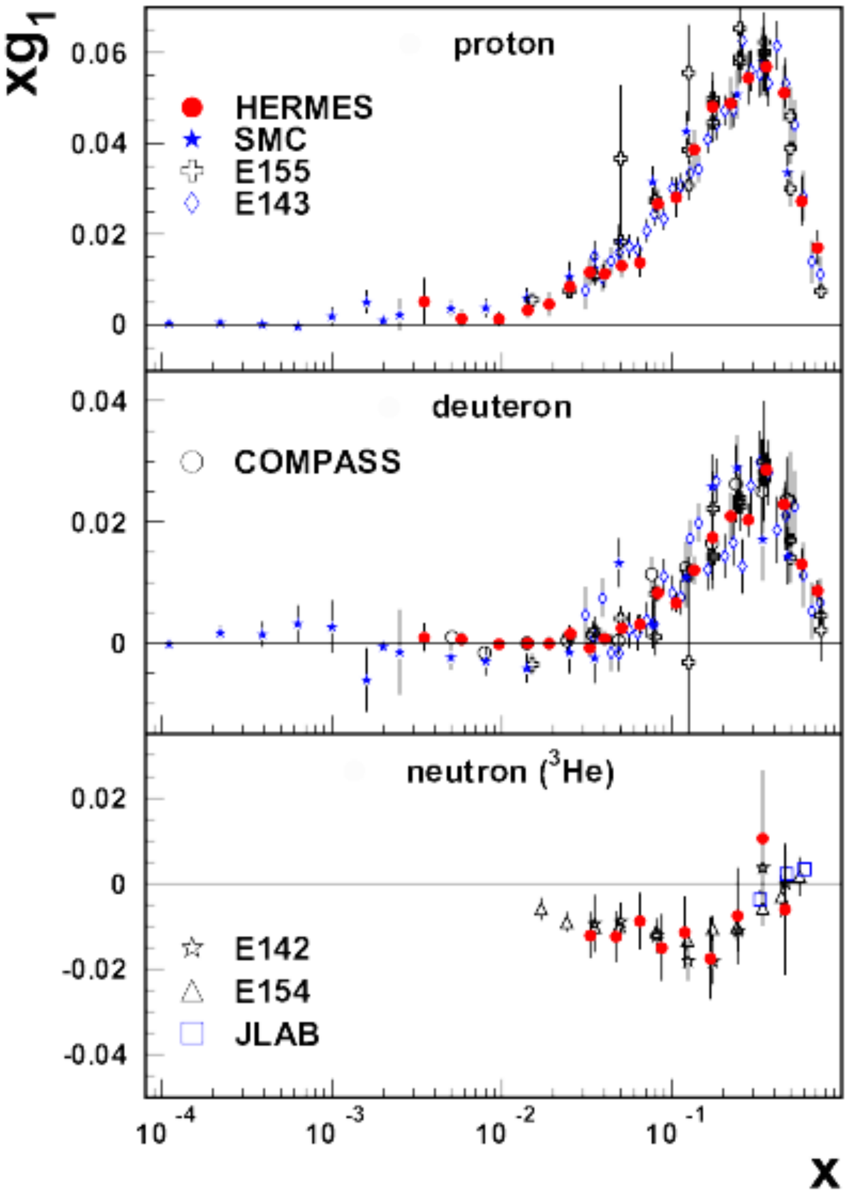
Total elastic Electro and photo-Production

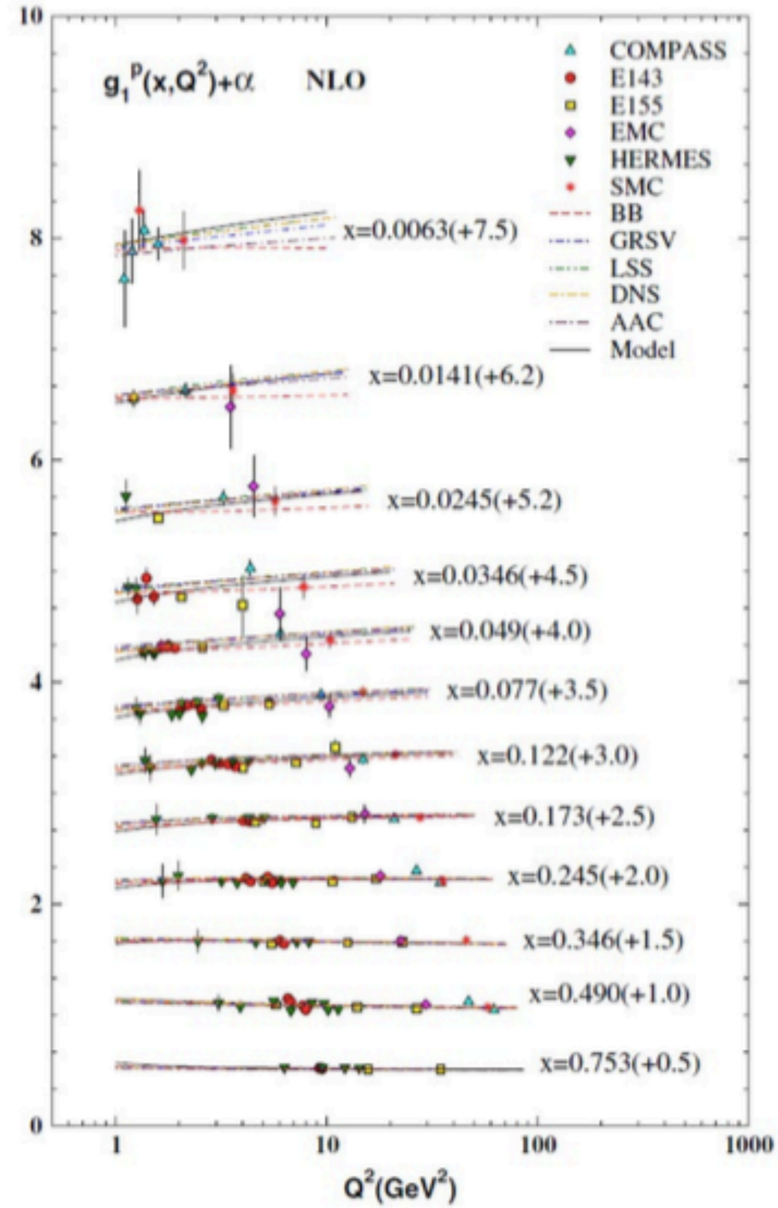


Total elastic Electro and photo-Production o

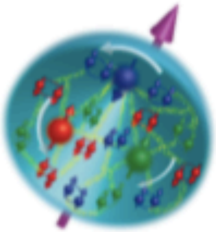


Polarized Structure functions





Nucleon Spin Decomposition



Proton spin puzzle

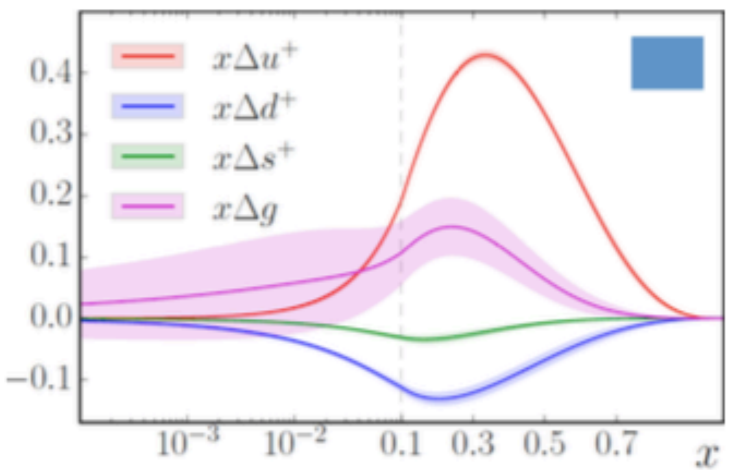
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

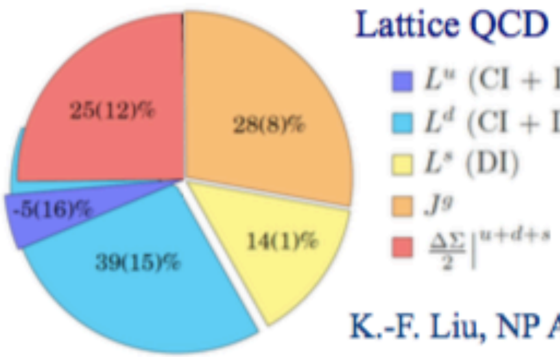
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PRD (2016).



K.-F. Liu, NP A928, 99 (2014).

Gluon spin: STAR and PHENIX (pp collisions)
Lattice: Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017)

5

Access to $L_{q/g}$

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

Sea Quark Spin-Flavor Study with EIC

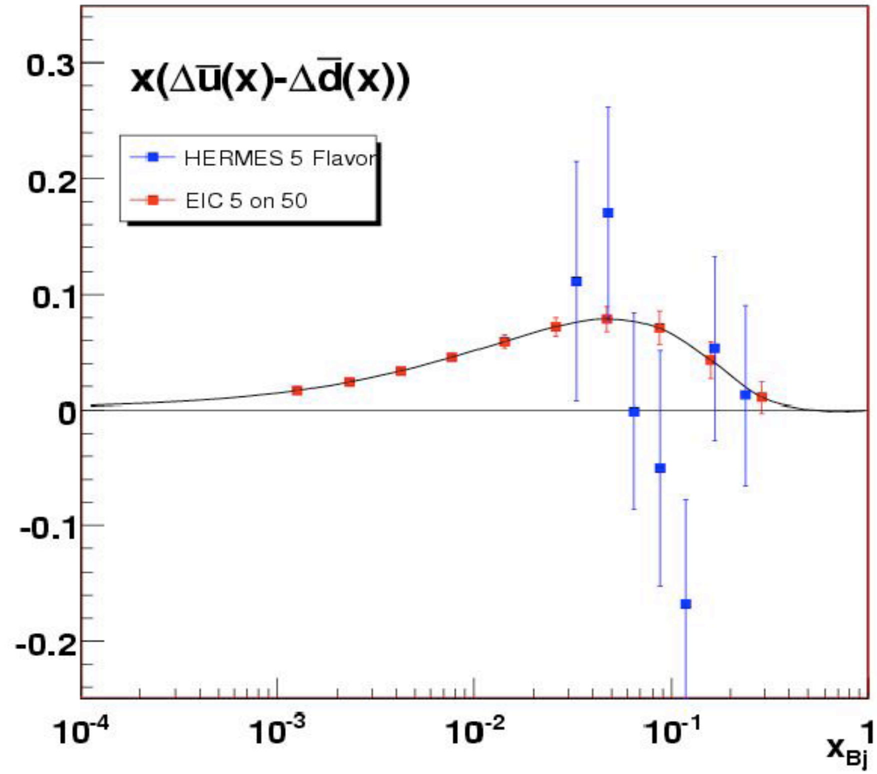
- Unique opportunity for Δs

energy reach current fragmentation region for Kaon tagging in SIDIS

- Significant improvement for Δu_bar, Δd_bar from SIDIS

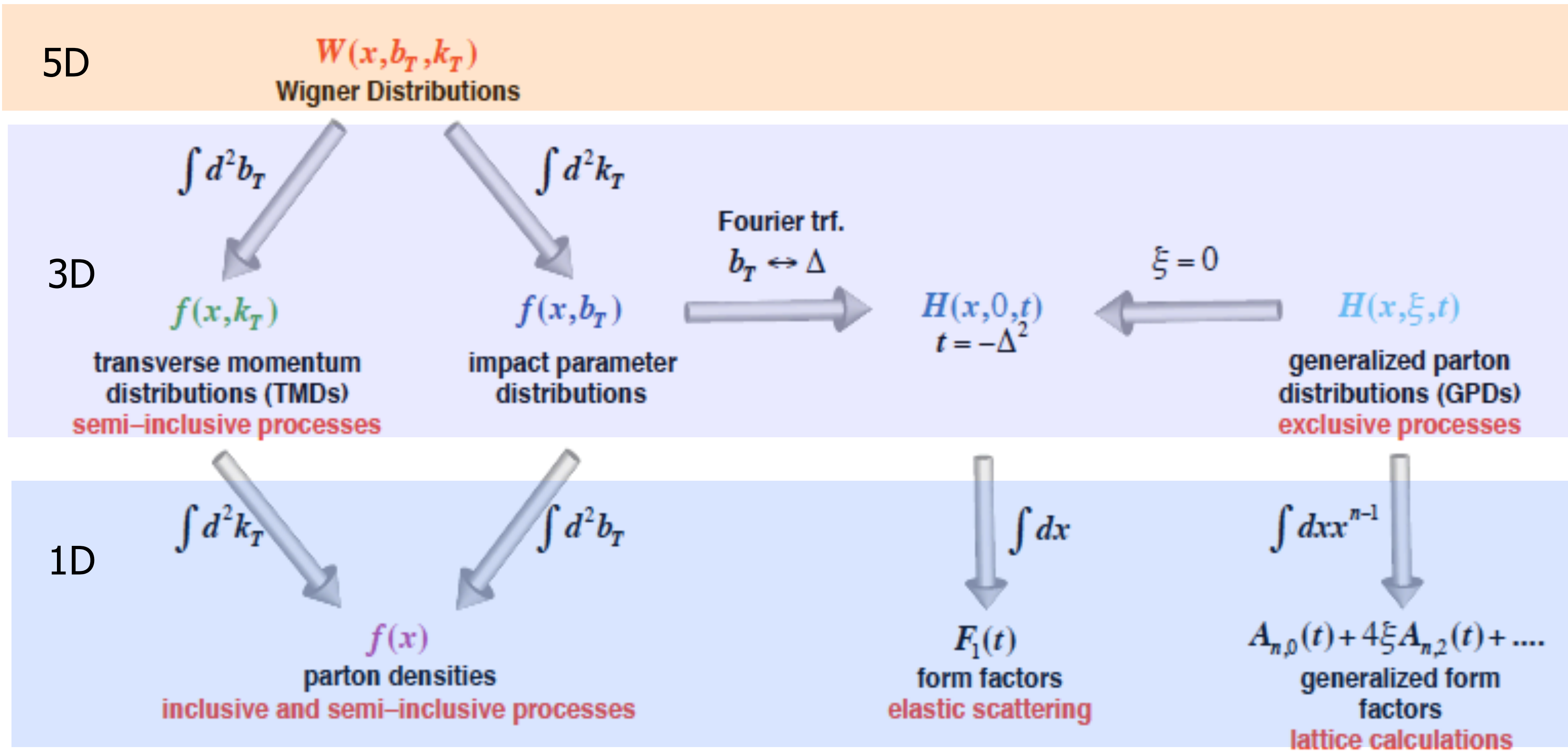
- Increase in Q^2 range/precision for g_1 (and g_2)

constraint on Δg.



Unified View of Nucleon Structure

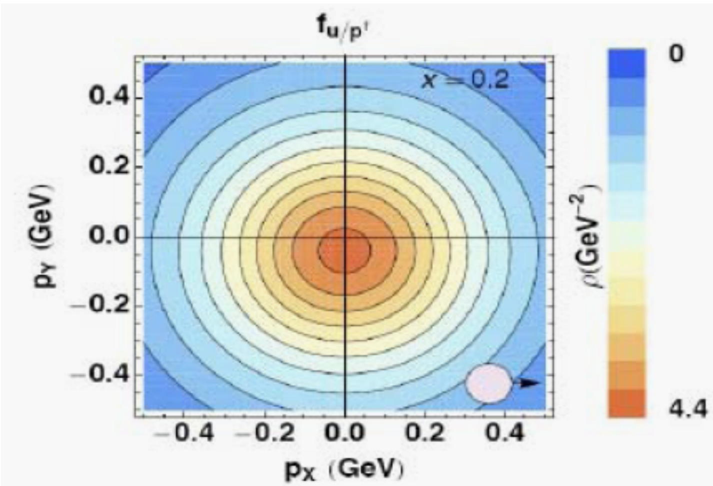
- Wigner distributions



Towards Imaging - Two Approaches

TMDs

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

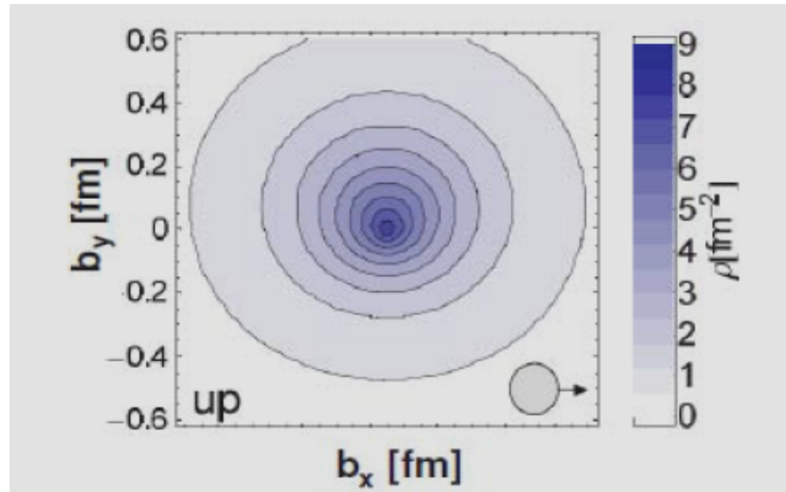


Bacchetta, Conti, Radici

- 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**



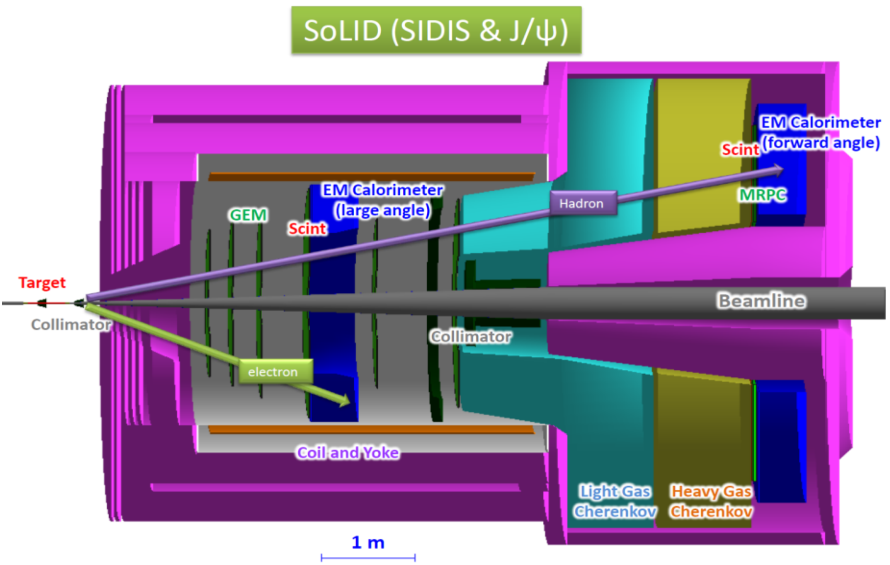
QCDSF collaboration

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

JLab 12 GeV: Precision Study of TMDs

- From exploration to precision study with 12 GeV JLab
- Transversity: fundamental *PDF*s, tensor charge
- *TMD*s: 3-d momentum structure of the nucleon
- → Quark orbital angular momentum
- Multi-dimensional mapping of *TMD*s
  - 4-d ($x,z,P_\perp,Q^2$)
  - Multi-facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

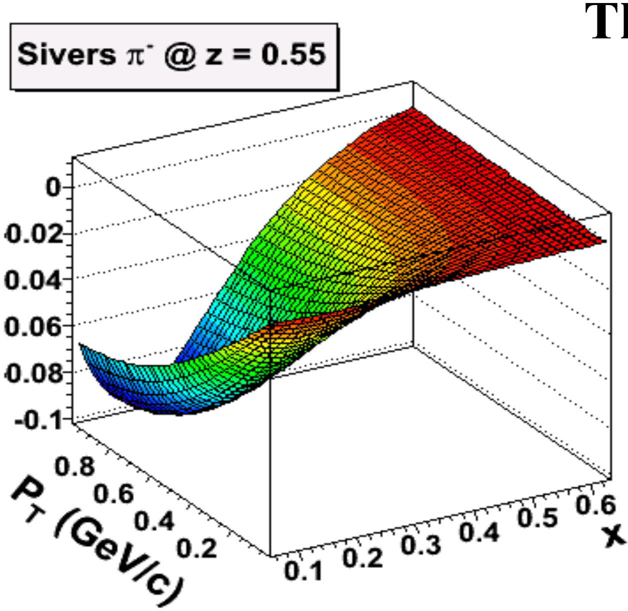


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

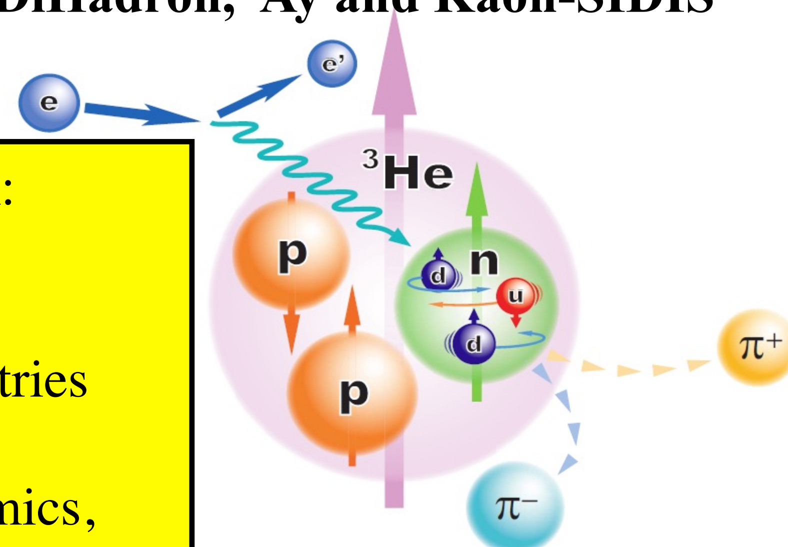
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

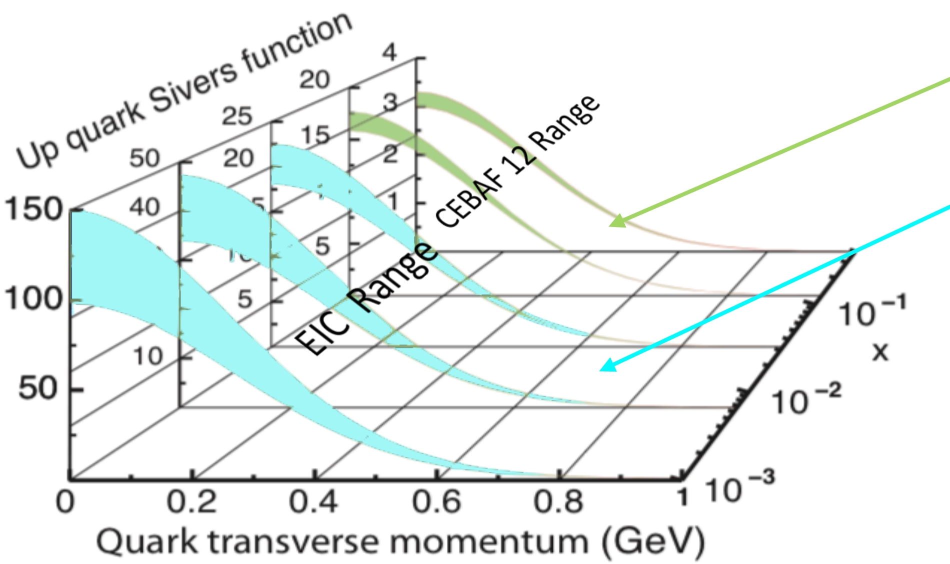
Three run group experiments DiHadron, Ay and Kaon-SIDIS



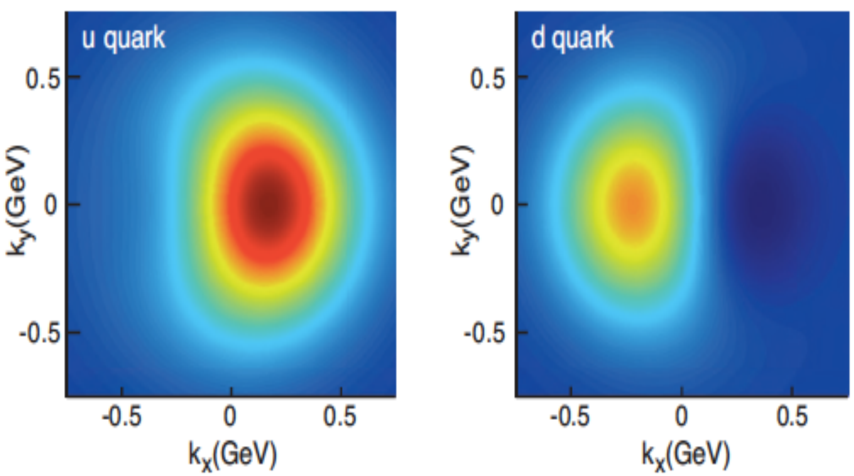
Key of SoLID-Spin program:
Large Acceptance
\+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Quark Orbital Angular Momentum, Imaging in 3-D momentum space.



SoLID and EIC: full imaging of nucleons and study QCD



Polarized Quark 3D Momentum distributions



SoLID - high precision extraction of Sivers function in the valence quark region – complementary to EIC Sivers measurement

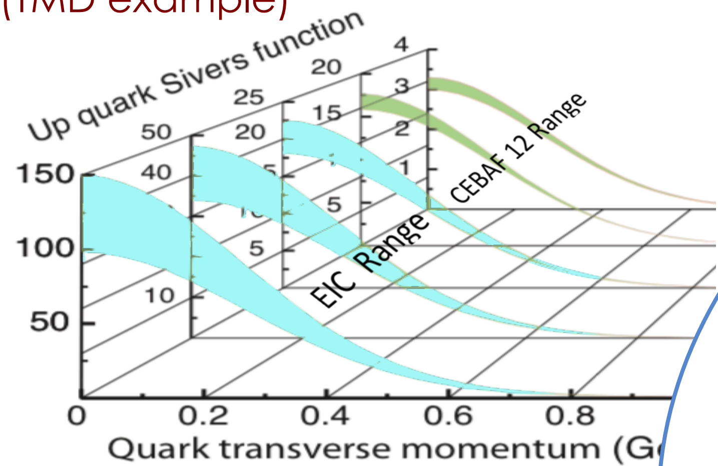
Transversity distribution (valence quark dominant) and tensor charge – unique SoLID contribution

$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x) \right] dx$$

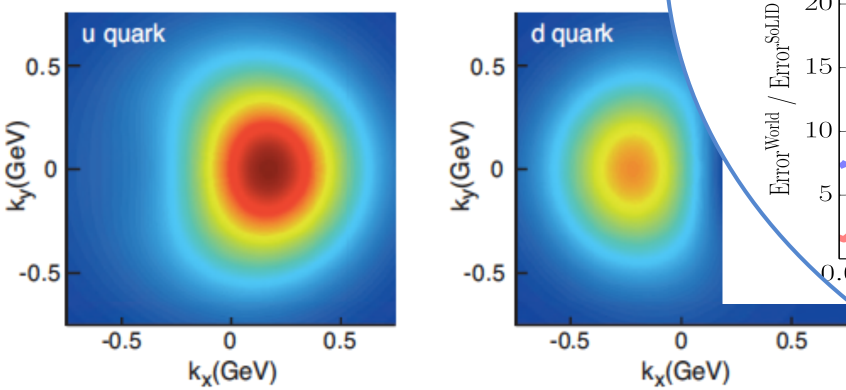
1. A fundamental QCD quantity
2. Matrix element of local operators
3. Calculable in lattice QCD.
4. Connects to quark electric dipole moment and sensitive to new physics beyond SM

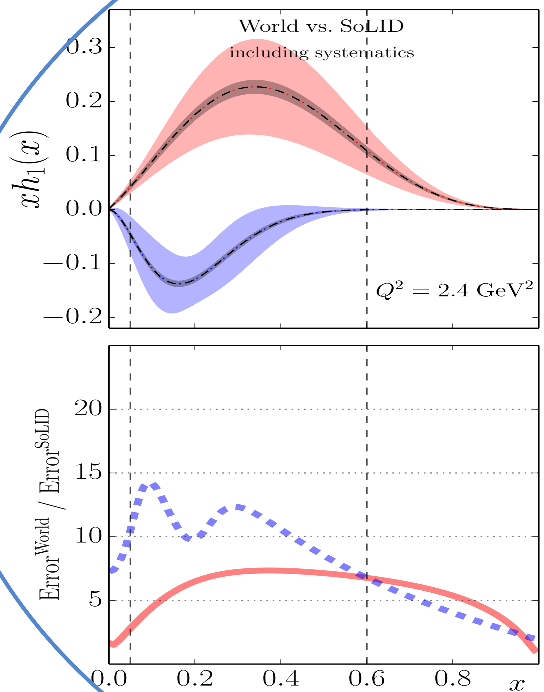
SoLID and EIC: full imaging of nucleons and study QCD

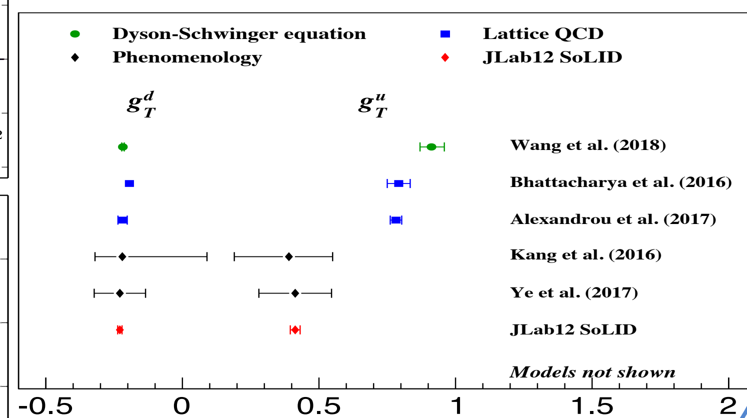
(TMD example)



Polarized Quark 3D Momentum distributions







Transversity: valence quark effect

Electron Ion Collider

Future QCD Facility:
Study QCD Sea and Gluons

Electron Ion Collider

NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

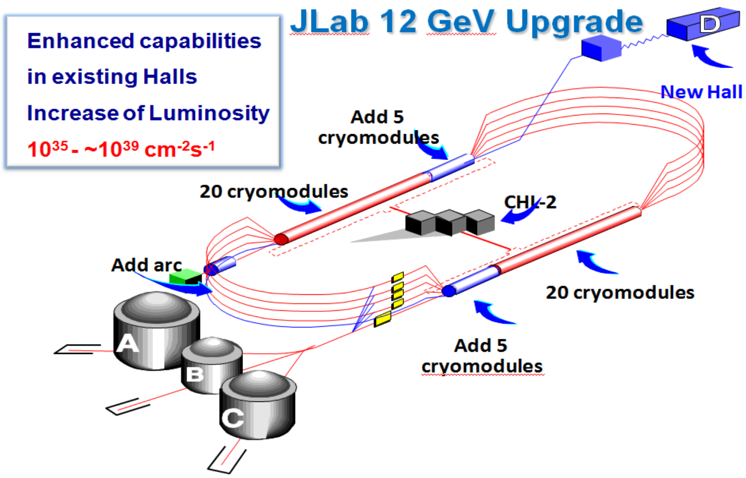
NSAC 2015 Long-Range Plan:

We recommend a high-energy high-luminosity polarized **EIC as the highest priority for new facility construction** following the completion of FRIB.

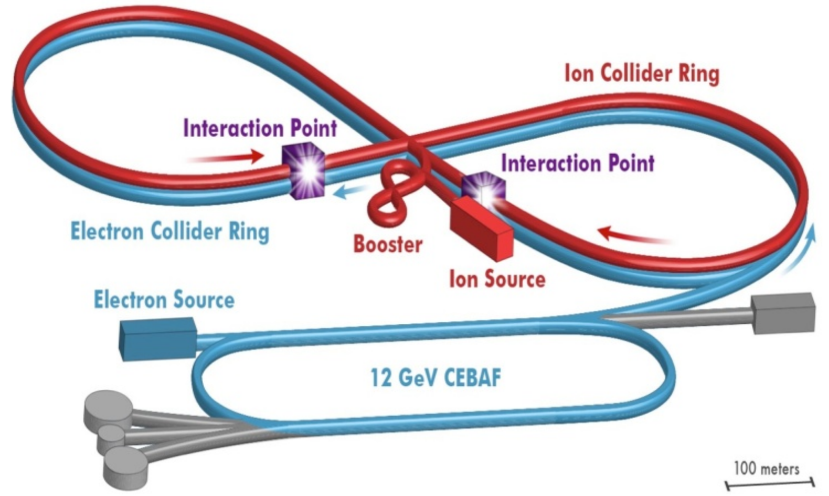
EIC Community White Paper arXiv:1212.1701v2

Academy of Sciences Review Report

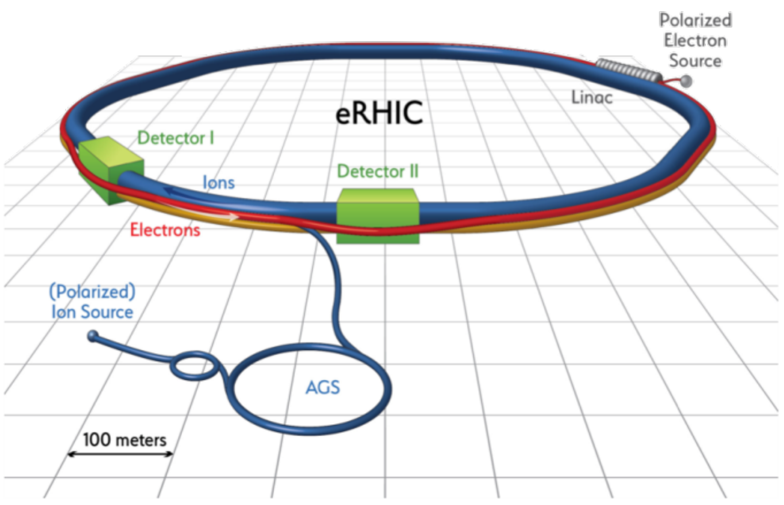
JLab 12 and Future EIC Plan



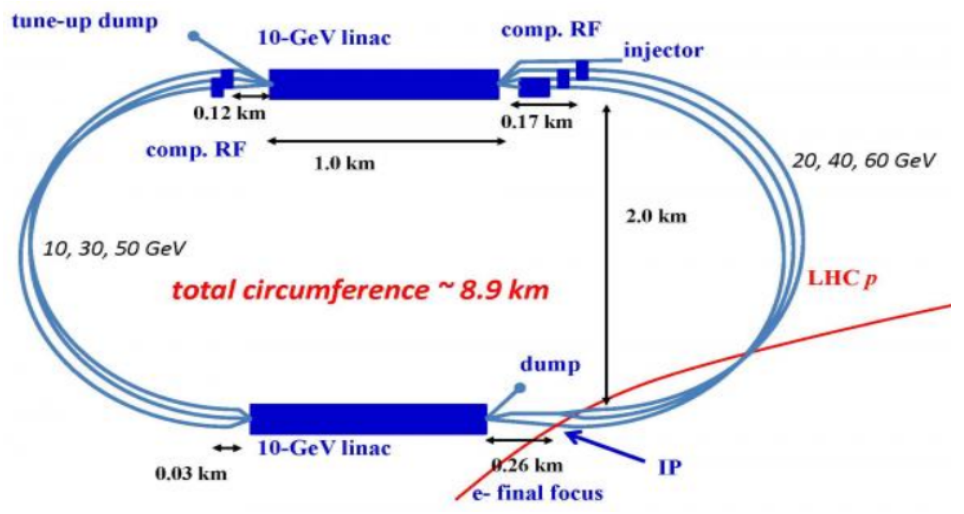
Jlab 12 upgrade (Fixed target)



JLEIC √s ~ 50 GeV



eRHIC, √s ~ 100 GeV



LHeC, √s : 1.3~3.5 TeV

Overview of EIC Experiments

Key Questions for EIC:

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

- Spin and Flavor Structure of the Nucleon
- 3-d Structure in Momentum Space and Confined Motion of Partons inside the Nucleon
- 3-d Structure in Coordinator Space and Tomography of the Nucleon
- Proton Mass

Other Important Questions:

“Where does the saturation of gluon densities set in?

How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?”

Opportunity for Low Energy Search of Physics Beyond SM

- Parity Violating e-N

Electron Ion Collider in China

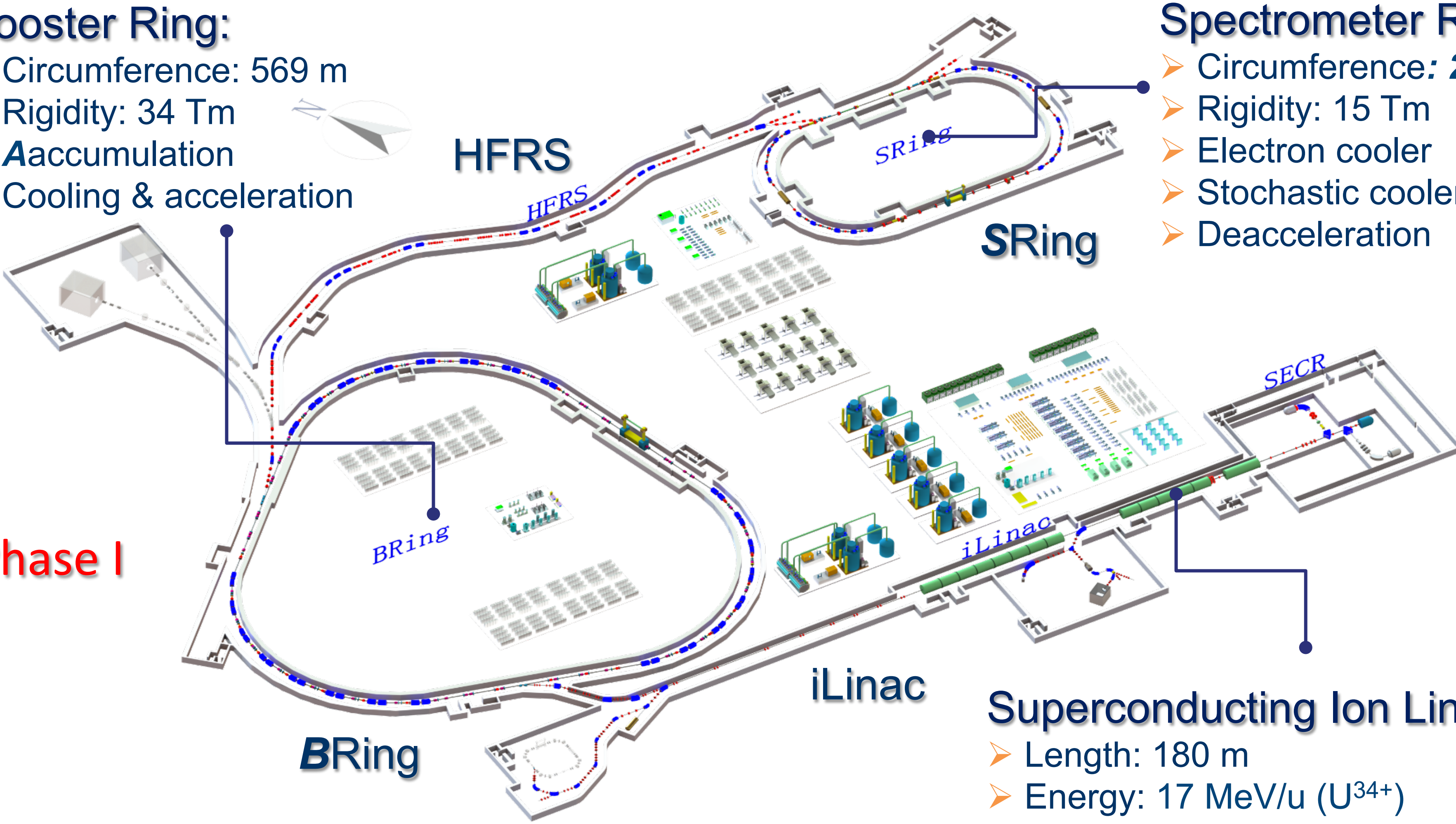
EicC: EIC@HIAF

High Intensity Heavy-ion Accelerator Facility (HIAF)

lead by Institute of Modern Physics, Academy of Sciences, China

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- ***A**accumulation*
- Cooling & acceleration

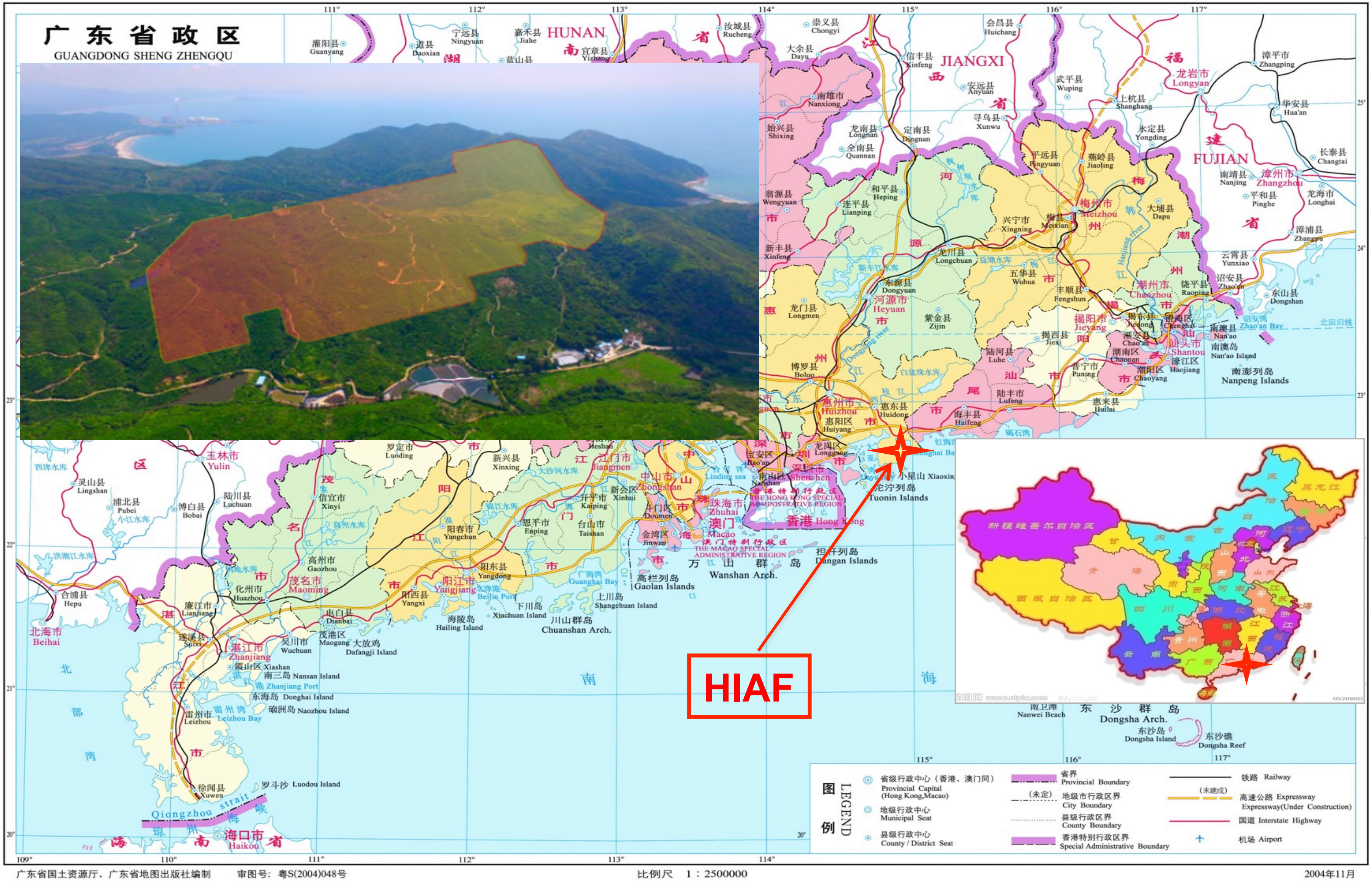
Spectrometer Ring:
- Circumference***: 270.5 m***
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler
- Deacceleration



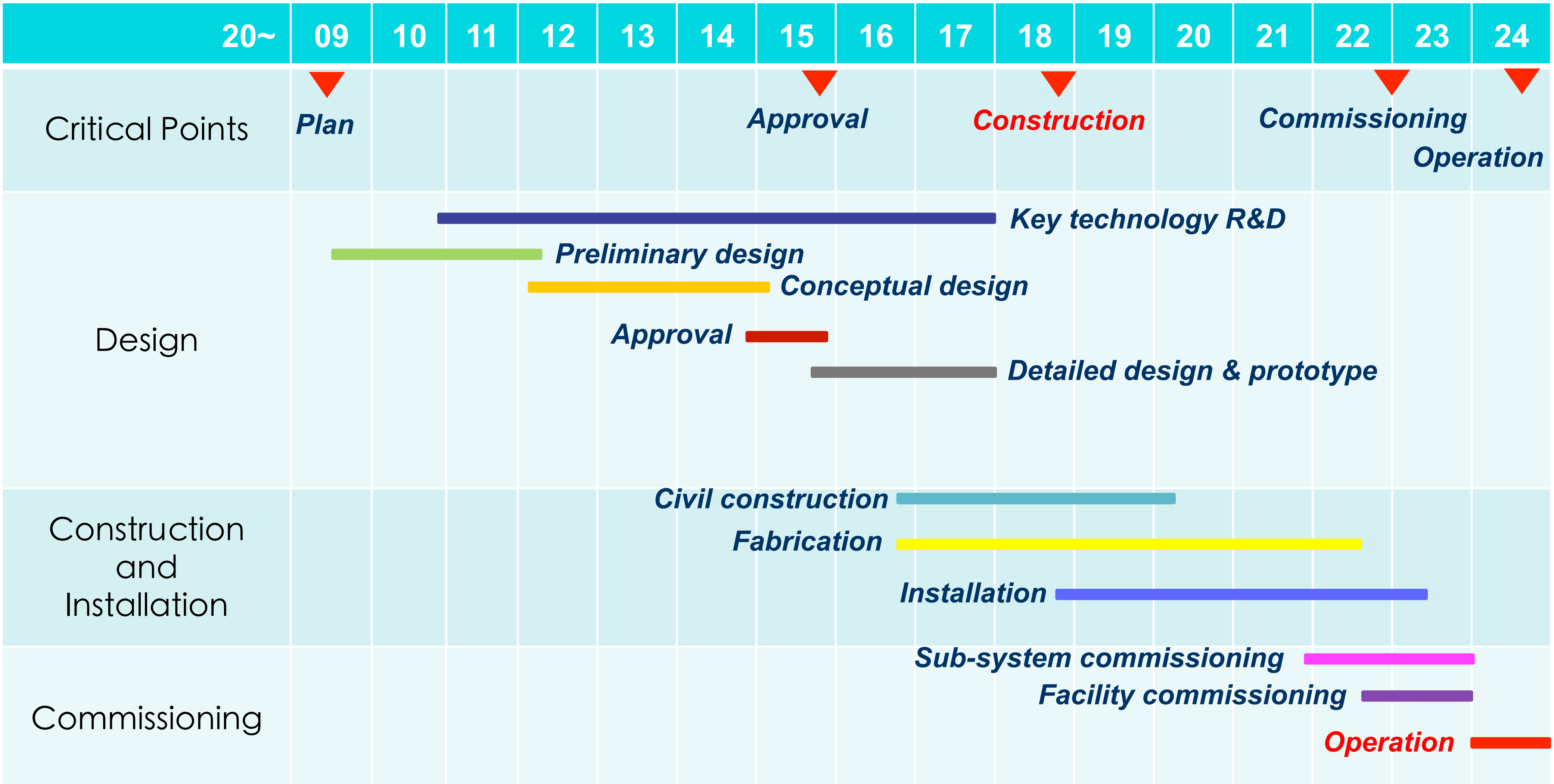
Superconducting Ion Linac:
- Length: 180 m
- Energy: 17 MeV/u (U^{34+})
- CW and pulse modes

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

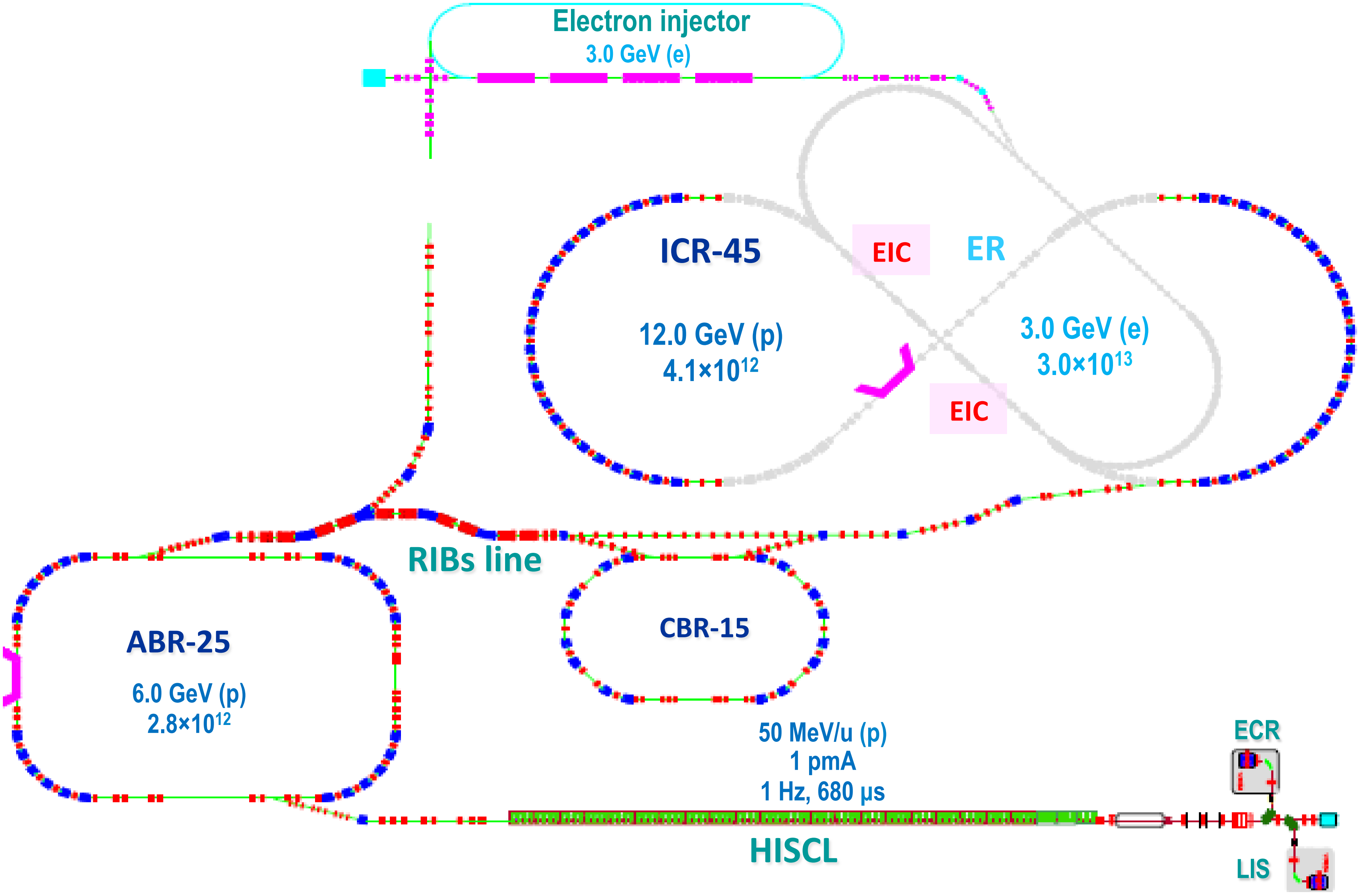
HIAF and Its Location



HIAF Timetable

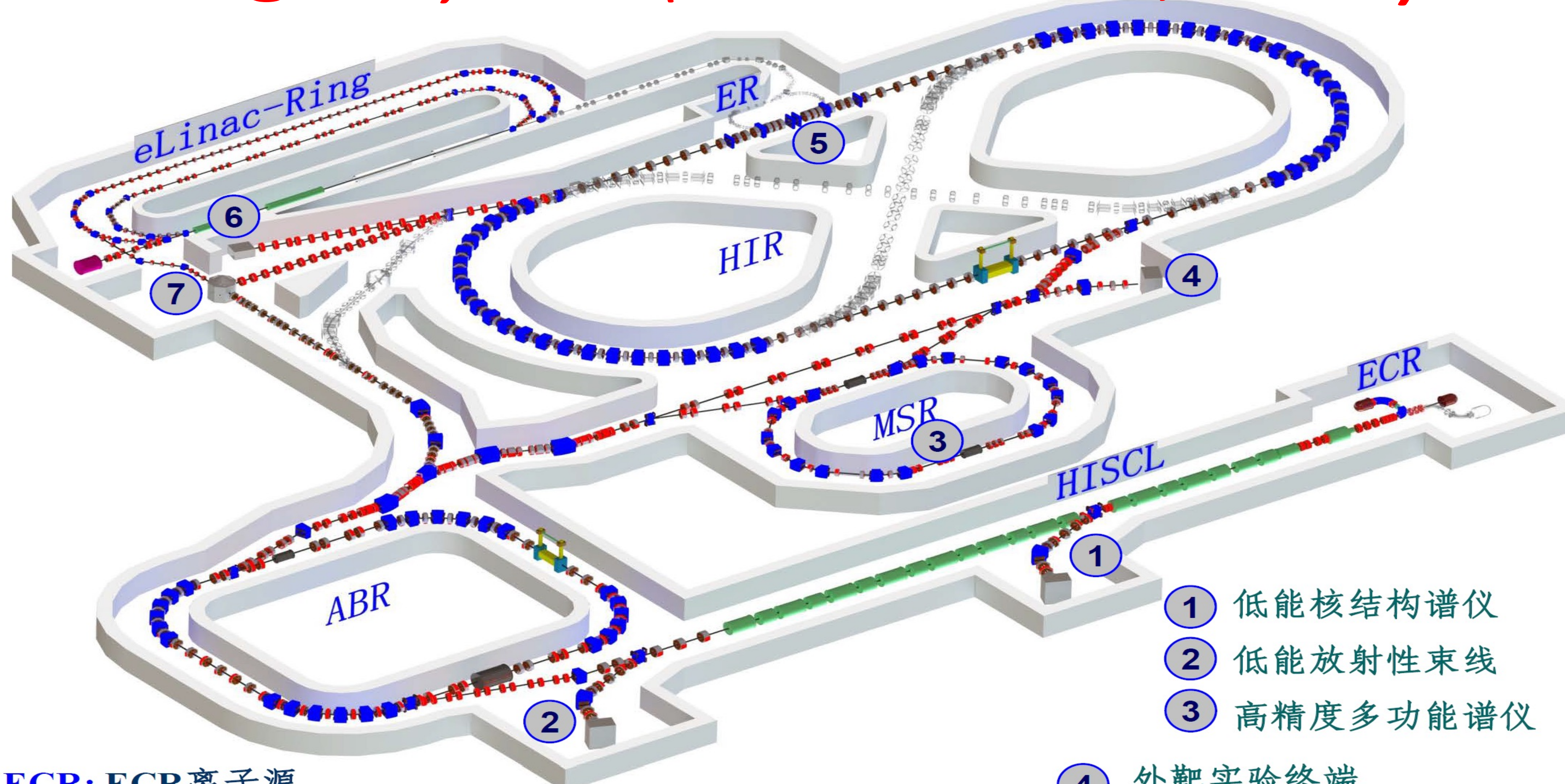


EIC@HIAF, China (2013 Version, 3x12 GeV)



HIAF总体布局和结构

EIC@HIAF, China (Another 2013 Version, 3x12 GeV)



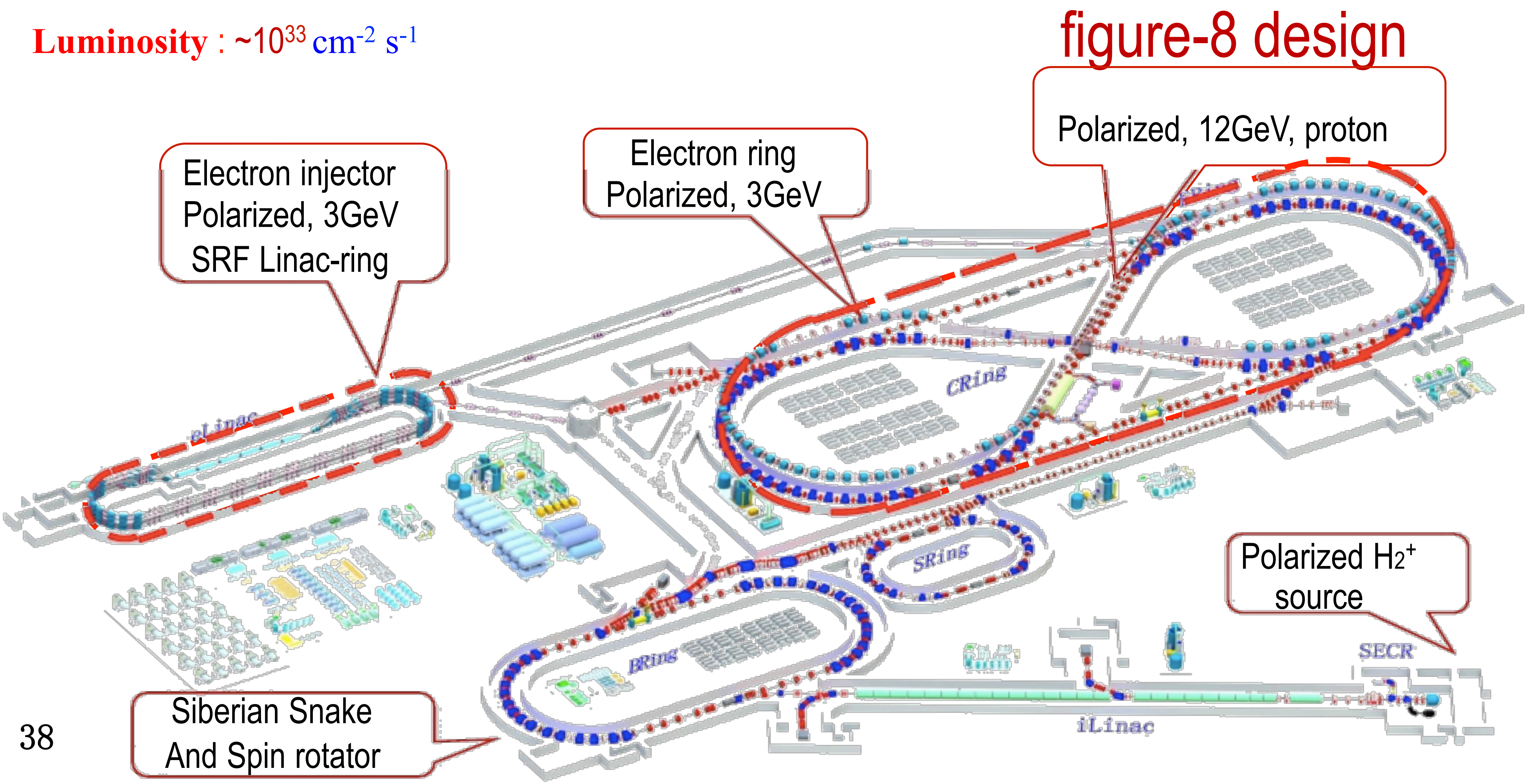
① 低能核结构谱仪
② 低能放射性束线
③ 高精度多功能谱仪
④ 外靶实验终端
⑤ 电子-离子对撞谱仪
⑥ 高能综合辐照终端
⑦ 高能量密度物质实验终端

ECR: ECR离子源
HISCL: 强流超导直线加速器
ABR: 多功能同步加速环
HIR: 高能离子储存环
e Linac-Ring: 电子注入器
ER: 电子储存环
MSR: 高精度多功能谱仪

Second phase for HIAF: EIC in China (3 x 12 GeV)
2016 Version

See W. L. Zhan's talk@The 8th Workshop on Hadron Physics in China and Opportunities Worldwide (2016)

Luminosity : ~10^{33} cm^{-2} s^{-1}

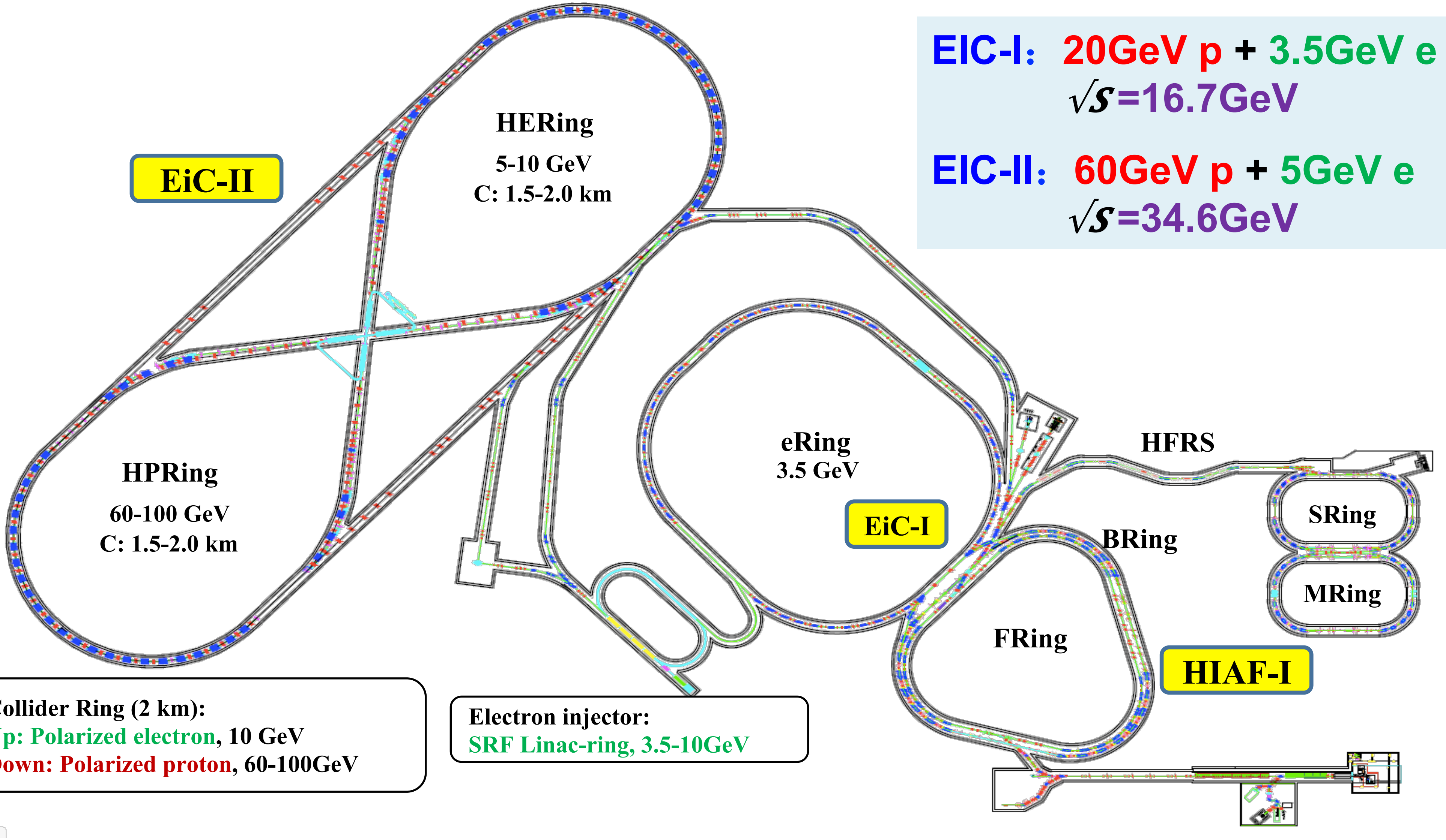


HIAF-EicC (2018 version)

J. Yang

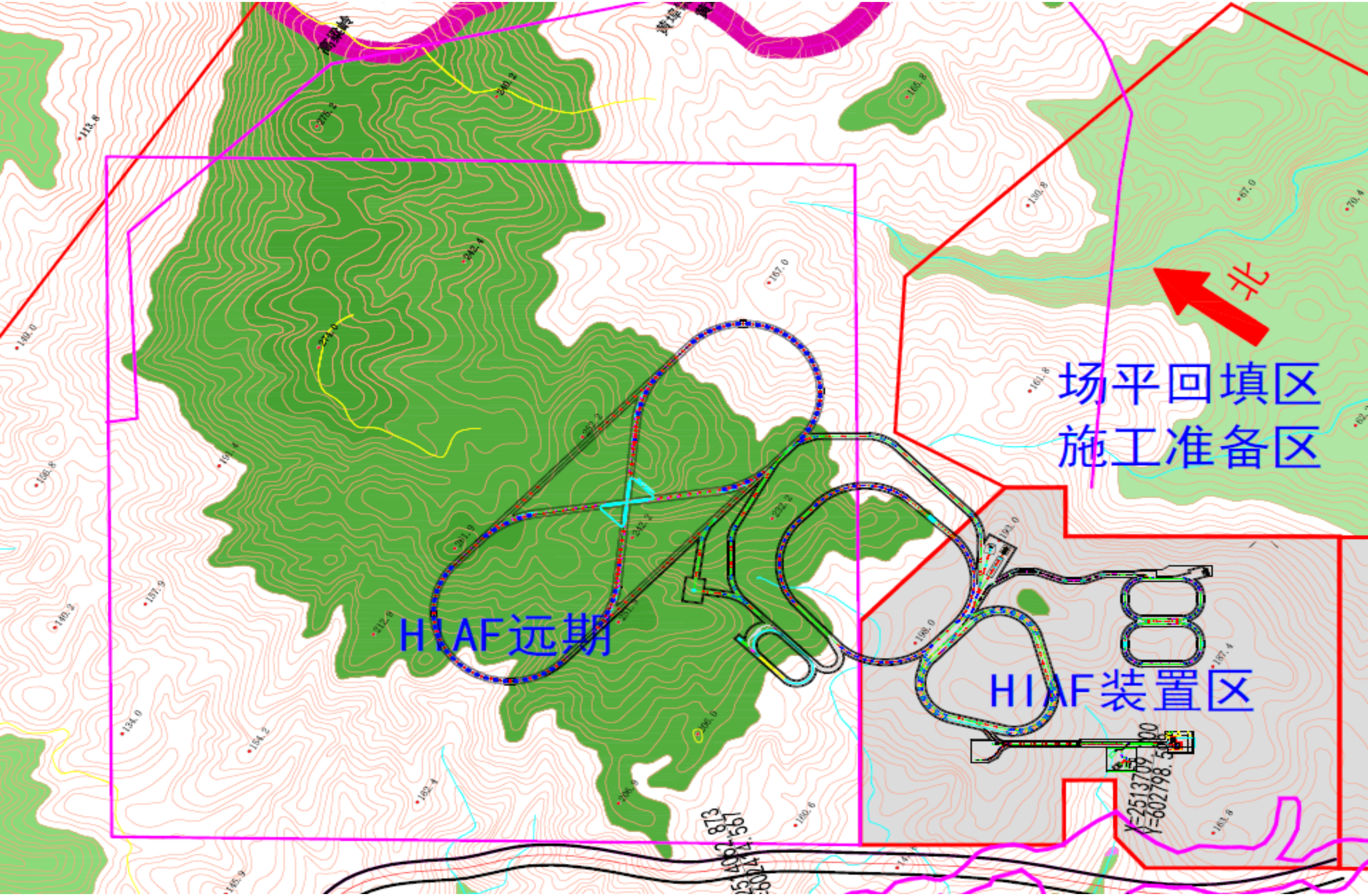
EIC-I: 20GeV p + 3.5GeV e
$\sqrt{s}$=16.7GeV

EIC-II: 60GeV p + 5GeV e
$\sqrt{s}$=34.6GeV



Collider Ring (2 km):
Up: Polarized electron, 10 GeV
Down: Polarized proton, 60-100GeV

Electron injector:
SRF Linac-ring, 3.5-10GeV

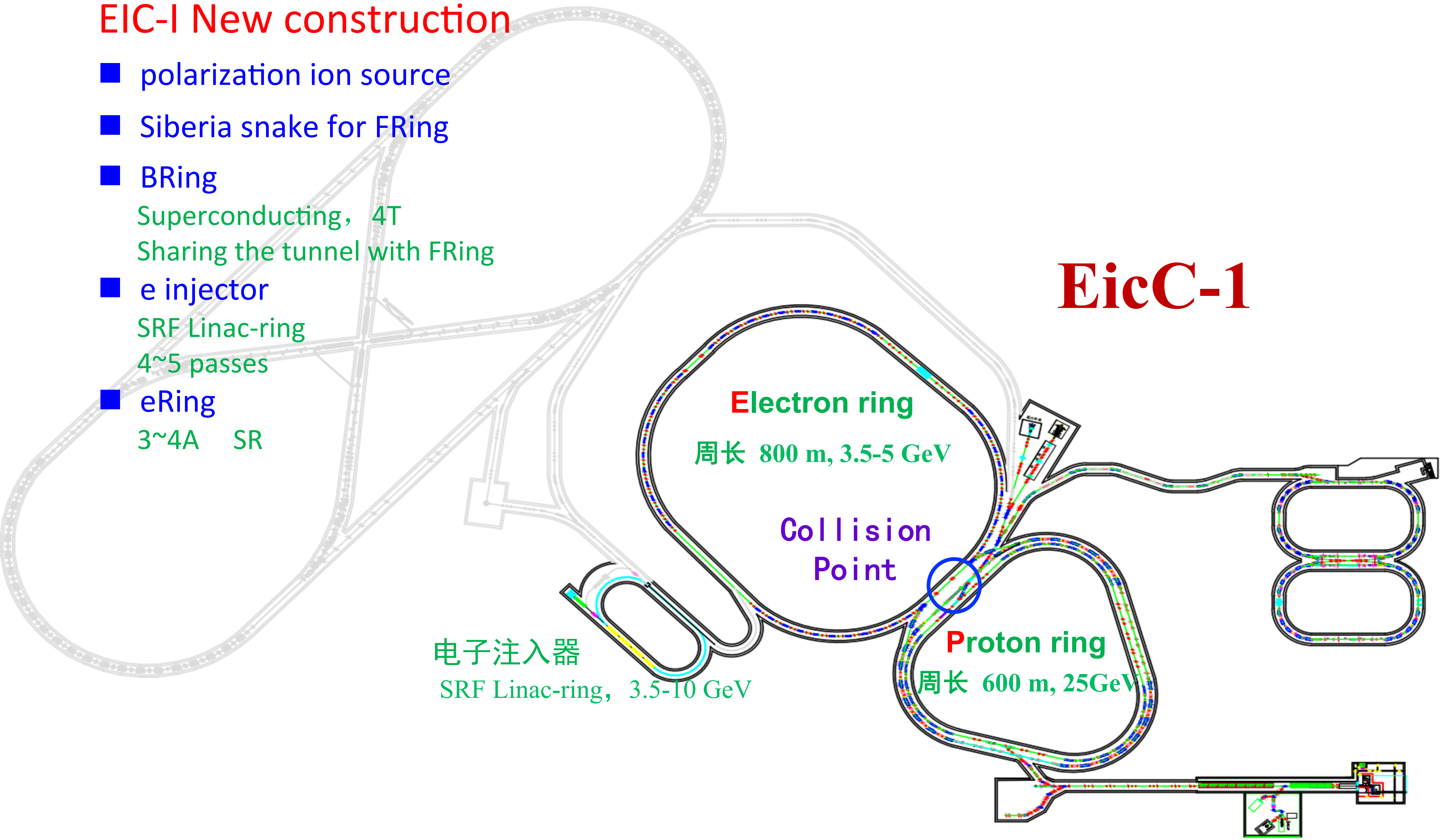

北
场平回填区
施工准备区
HIAF远期
HIAF装置区

EicC-1 Layout

J. Yang

EIC-I New construction

- polarization ion source
- Siberia snake for FRing
- BRing
  Superconducting， 4T
  Sharing the tunnel with FRing
- e injector
  SRF Linac-ring
  4~5 passes
- eRing
  3~4A SR



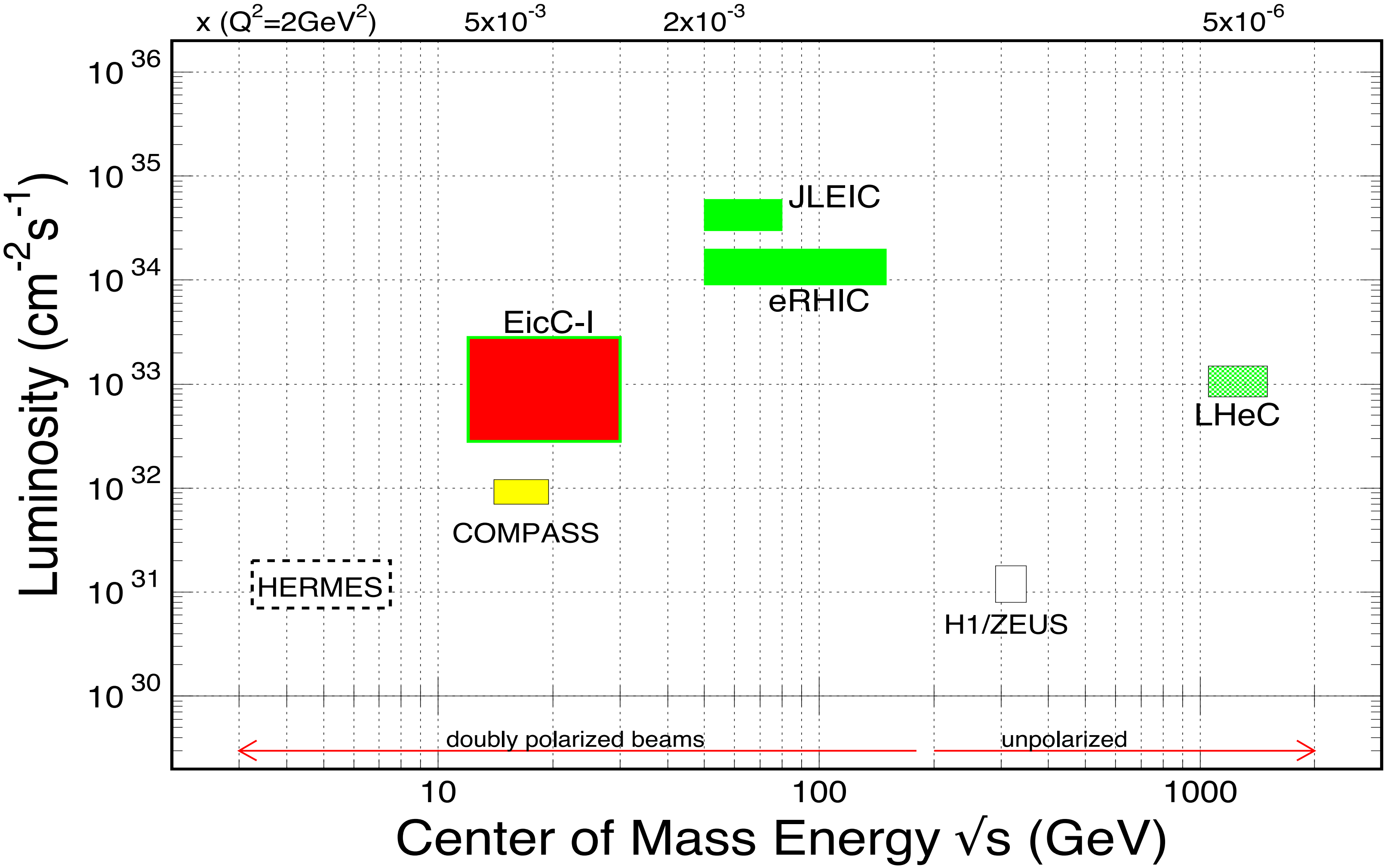
J. Yang

Luminosity estimation

	p	e
circumference(m)	600	800
energy(GeV)	20	3.5
Bρ(T·m)	87	11.7
$f_{collision}$(MHz)	750	750
particles per bunch($\times 10^{10}$)	0.5	3.2
ε_x, ε_y(nm·rad, rms)	100(50)	10
β^*_x/β^*_y (m)	0.02/0.01	0.2/0.1(0.1/0.05)
IBS rate	0.0003(H,V),0.0018(L) 0.002(H,V),0.005(L)	—
bunch length(m)	0.03	0.01
dp/p	3e-4	
Beam-Beam Parameter ξ_y	0.0015(0.003)	0.01
Laslett tune shift	0.005(0.01)	—
energy loss per turn(MeV)	—	0.33
total SR power(MW)	—	1.3
SR linear power density(kW/m)	—	5.2
current(A)	0.6	3.9
crossing angle(mrad)	50	
hourglass	0.75	
Luminosity($cm^{-2}s^{-1}$)	$0.5(1.0)\times 10^{33}$	

Designed Energy and Luminosity

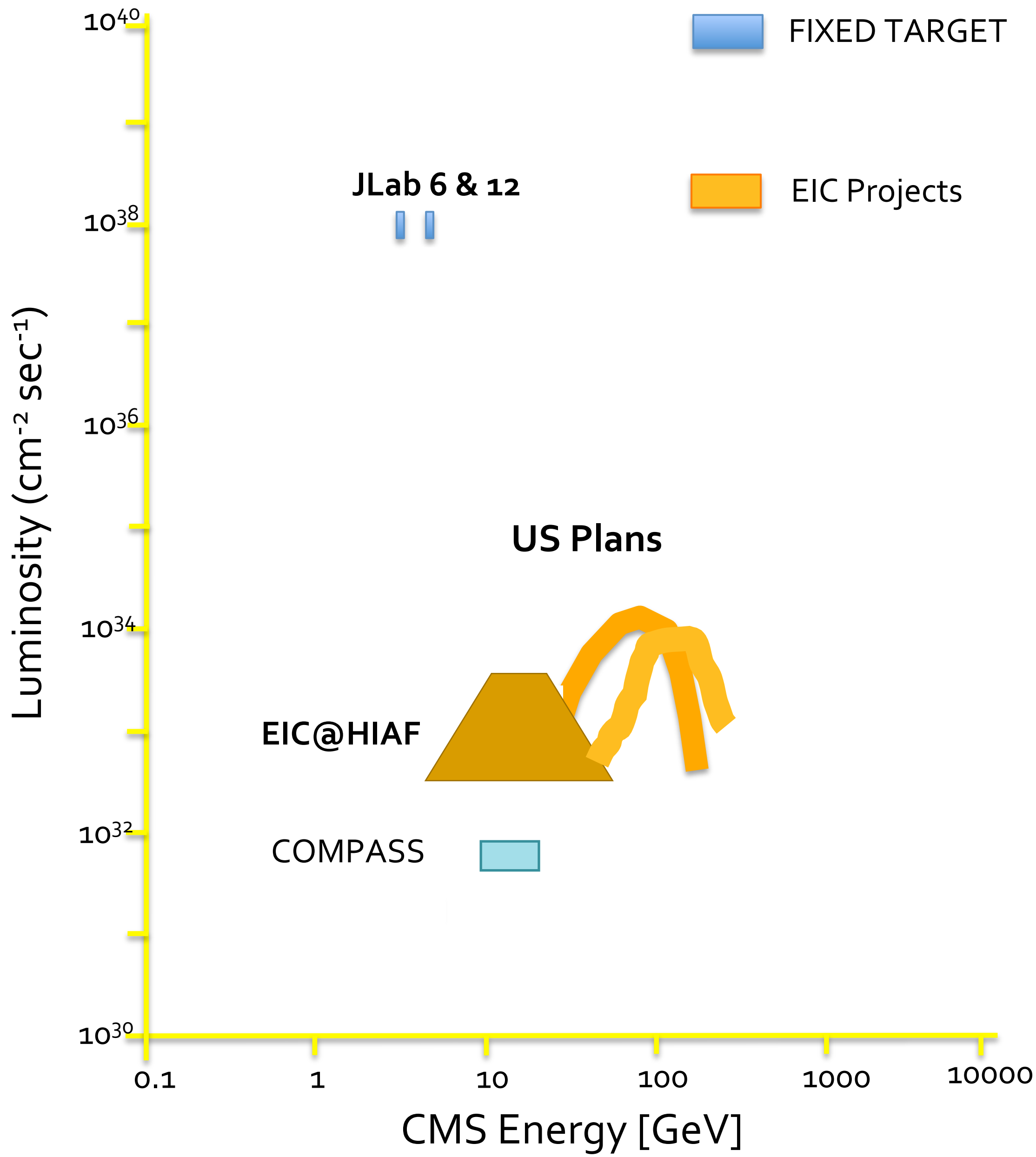
X. Chen

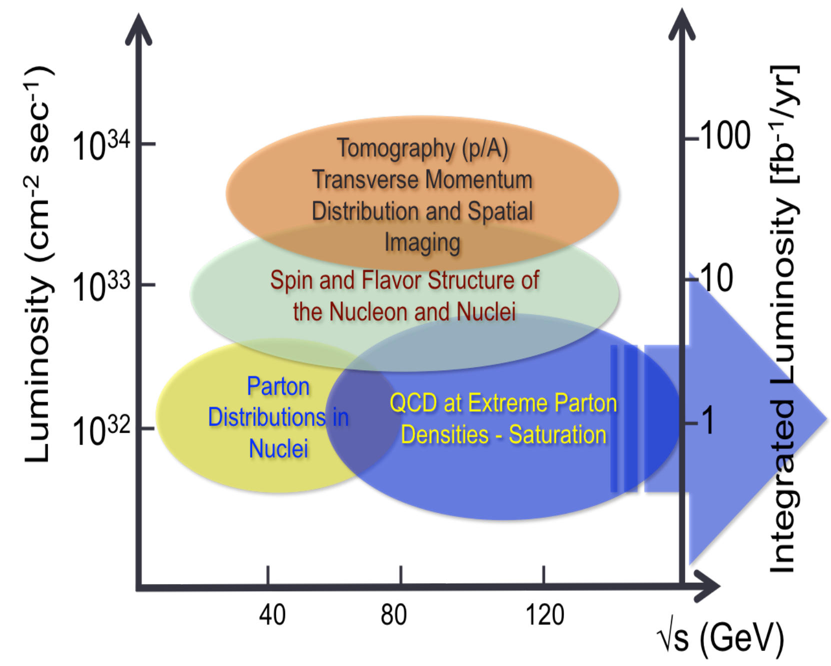


EicC-I: will be constructed around √s ~ 20 GeV region

1) ***Focus on nucleon structure/nuclear physics problems***
2) ***B-quark hadron production***

Polarized EICs and Current DIS facilities

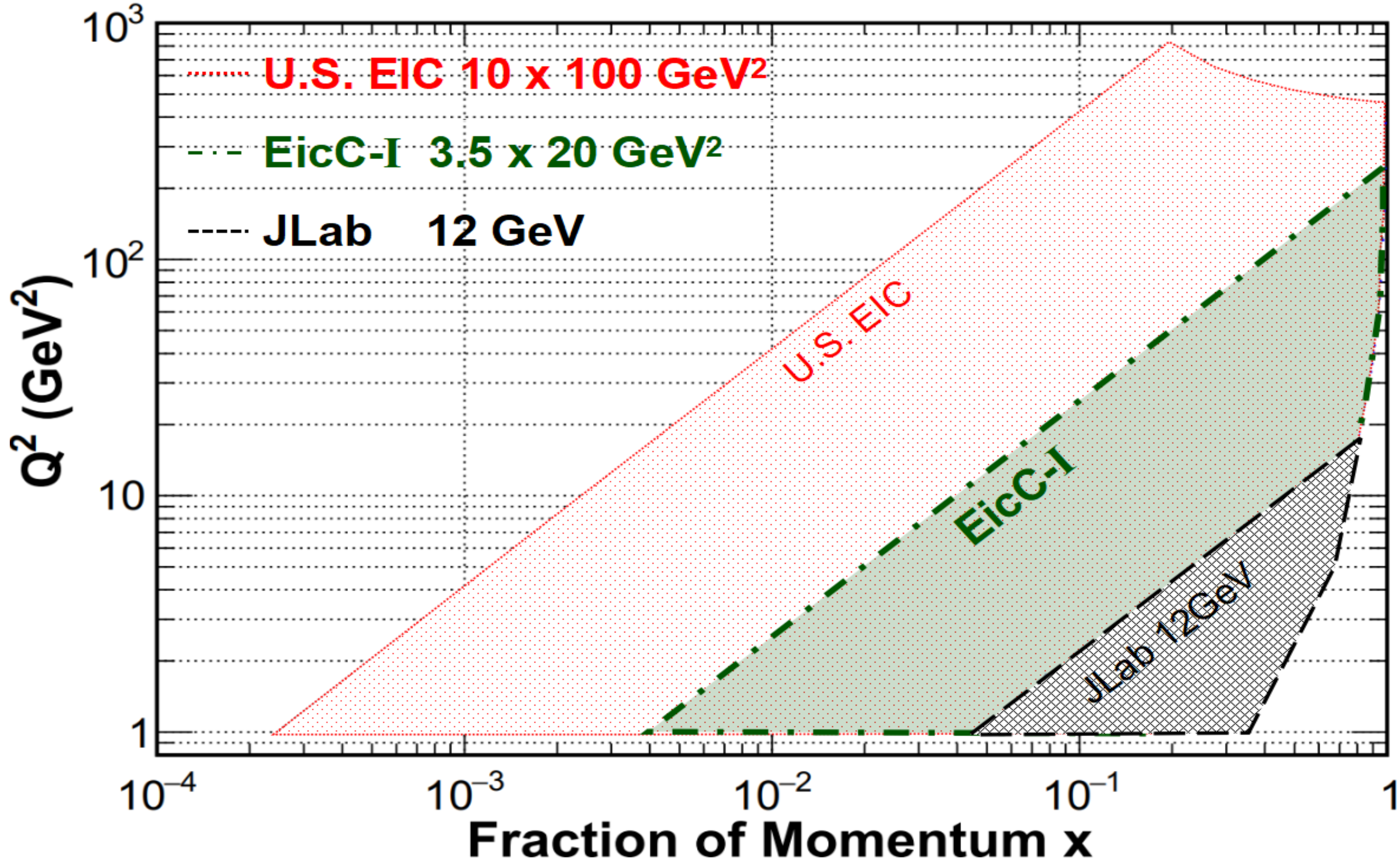




US-EIC:
Spin, ion species together with its luminosity and √s coverage makes it a completely unique machine.

Polarized luminosities:
collider advantage over fixed target due to dilution factor ~ 50 for e-p

Kinematics Reach



EicC-I: **$4x10^{-3} < x < \sim 1$** region

Valance- and sea-quark

EicC-I Working Groups

WGs	Interested People	Topics
Accelerator Group (AWG)	M. Bai, L.J. Mao, G.D. Shen, Y.C. Yang, H.Y. Zhang, H.W. Zhao, …	1) Conceptual design ($\geqslant 10^{33}$/s cm^2) 2) Cooling 3) IR design
Detector/Simulation Group (DWG)	J.P. Chen, X.R. Chen, H.Y. Gao, F. Liu, A. Deshpande, N. Xu, Z.H. Ye, L. Zhang, Y. Zhao, Z.W. Zhao,…	1) Physics Requirements 2) Conceptual design
Physics Group (PWG)	Z.T. Liang, B.Q. Ma, J.P. Ma, Q. Wang, J.J. Xie, B.W. Xiao, F. Yuan, J. Zhou, Q. Zhao, B.S. Zou,…	1) Science cases 2) Observables
- Contact - Monthly working group meeting (video meeting) - General meeting every three-month (video meetings + annual IMP meeting)		

Goal: first draft of EicC-I Whitepaper by the end of 2019

Overview of EIC (EicC-I) Experiments

Key Questions for EIC:

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

- Spin and Flavor Structure of the Nucleon → **light sea polarization**
- 3-d Structure in Momentum Space and Confined Motion of Partons inside the Nucleon → **TMDs with pion and Kaon**
- 3-d Structure in Coordinator Space and Tomography of the Nucleon
  → **DVCS, DVMP(pi/Kaon)**
- Proton Mass → **Upsilon Threshold Production**
- **Pion/Kaon structure**

Other Important Questions:

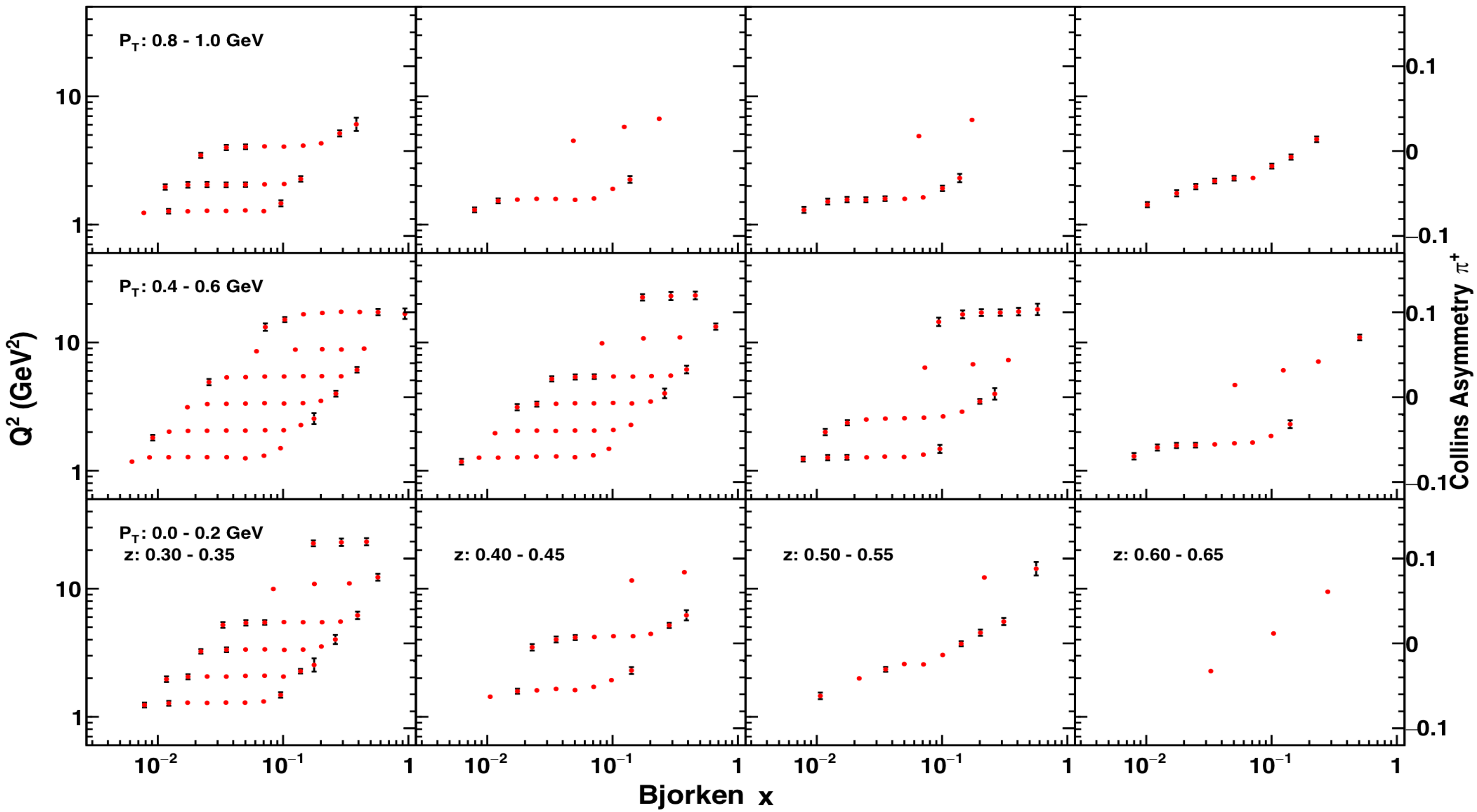
"Where does the saturation of gluon densities set in?

How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?"

Opportunity for Low Energy Search of Physics Beyond SM

- Parity Violating e-N

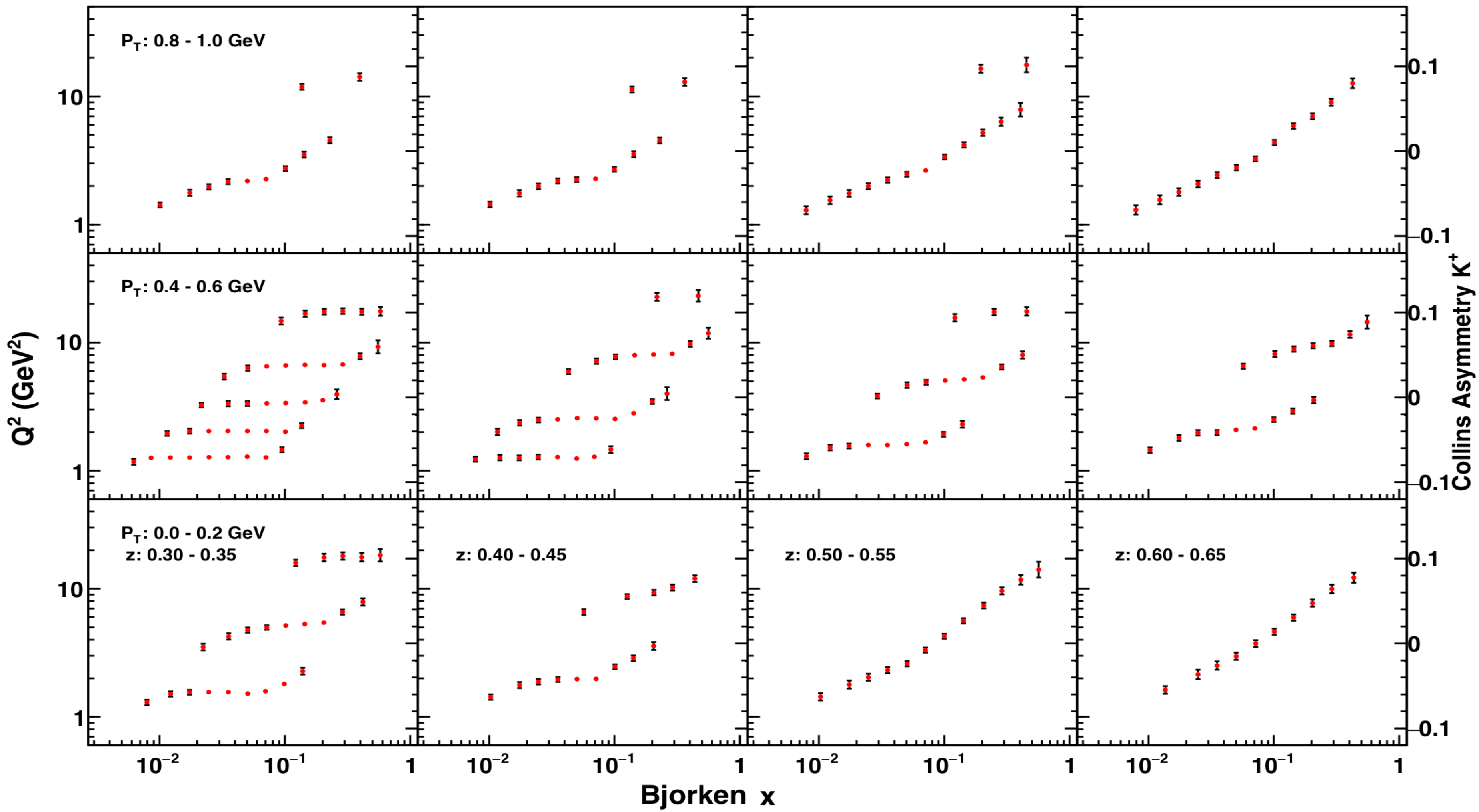
EicC-I Projection :TMD Collins asymmetry for Pions



EicC-I: Precision measurement TMD for pion production
(Very Preliminary)

Z. Yang

EicC-I Projection: TMD Collins asymmetry for **Kaons**

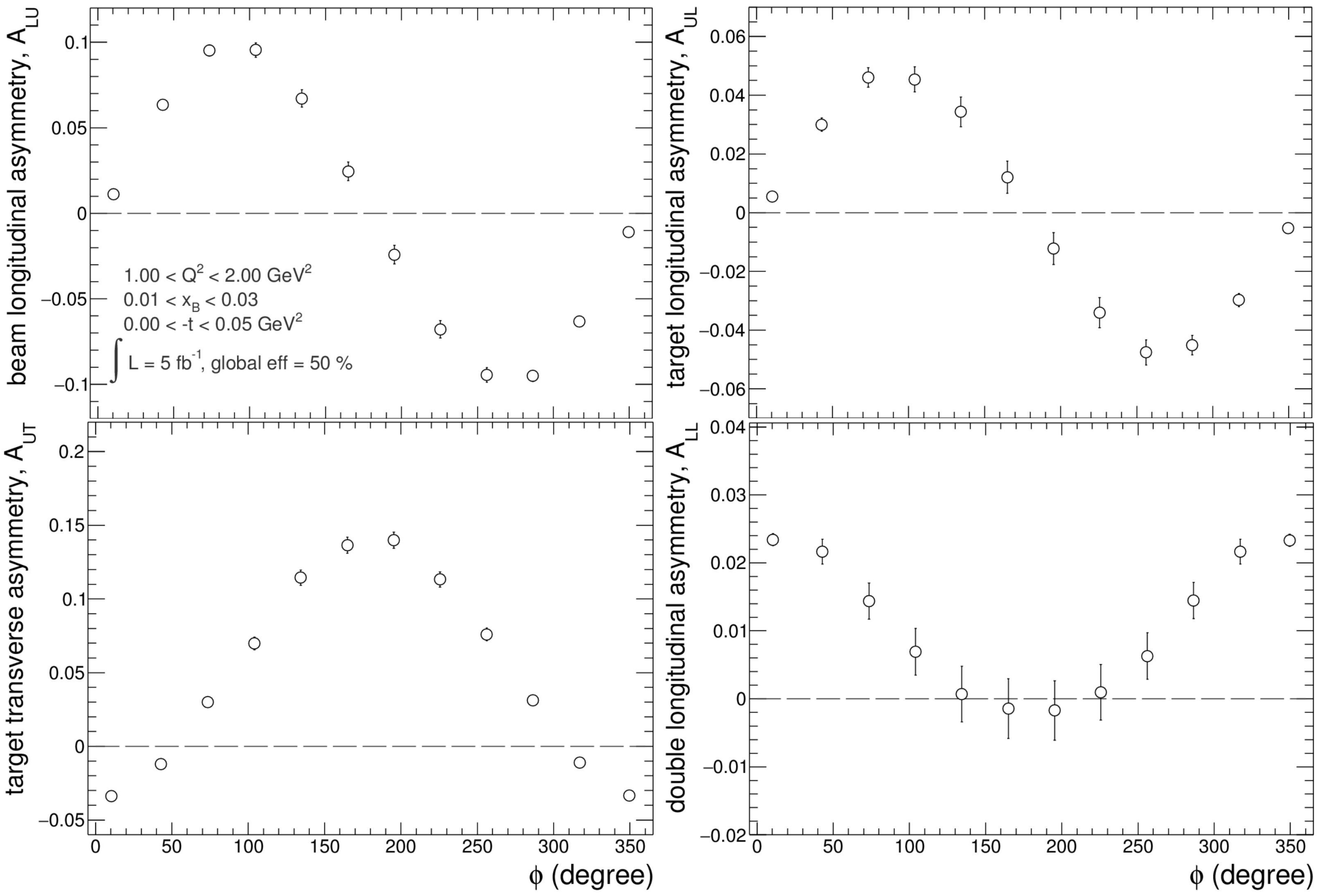


Kaon is one of key measurements at EicC-I.
(Very Preliminary)

Z. Yang

EicC-I: Projection for DVCS

Q.Fu



Projection of DVCS at EicC-I 3.5 x 20 GeV,

Single Electron Beam Spin Asymmetry and Single Transverse Proton Spin Asymmetry

(Very Preliminary)

The 3rd EicC Discussion Meeting

Date: November 9-10(Friday-Saturday), 2018
Location: Kunshan Duke University
Kunshan, China

Topics to be covered:

i) Science cases for EicC
ii) Detector and physics simulations
iii) Machine design and simulations

Contact: Xurong Chen: xchen@impcas.ac.cn
Nu Xu: nxu@impcas.ac.cn

Meeting secretary: Ms. Yali Zhao
Phone: +86 181 3999 7361
eMail: zhaoyali@impcas.ac.cn

EicC Timetable

	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	
	十三五			十四五					十五五					十六五					
	HIAF																		
EicC-I				R&D															
									$\sqrt{s}$ ~ 20GeV, ~10^{33}/sec cm^2										

R&D and construction

In operation

Summary

- Understand strong interaction/nucleon structure: A challenge
- Physics program with JLab 12 GeV upgrade / SoLID Project

  focusing on valence quark region:

  Proton Mass and J/ψ production

  Nucleon spin structure

  3-d Structure: GPDs and TMDs

- EIC in China: EicC-I, 3.5 x 20 GeV → sqrt(s) ~ 20 GeV, L~ 10^{33}

  light sea and valence quark regions for spin, TMDs and GPDs

  B-quark threshold, proton mass

- Complimentary to US Electron-Ion Collide:

  leads to a much better understanding of gluons, sea and valence quark structure of nucleon/nuclei and strong interaction