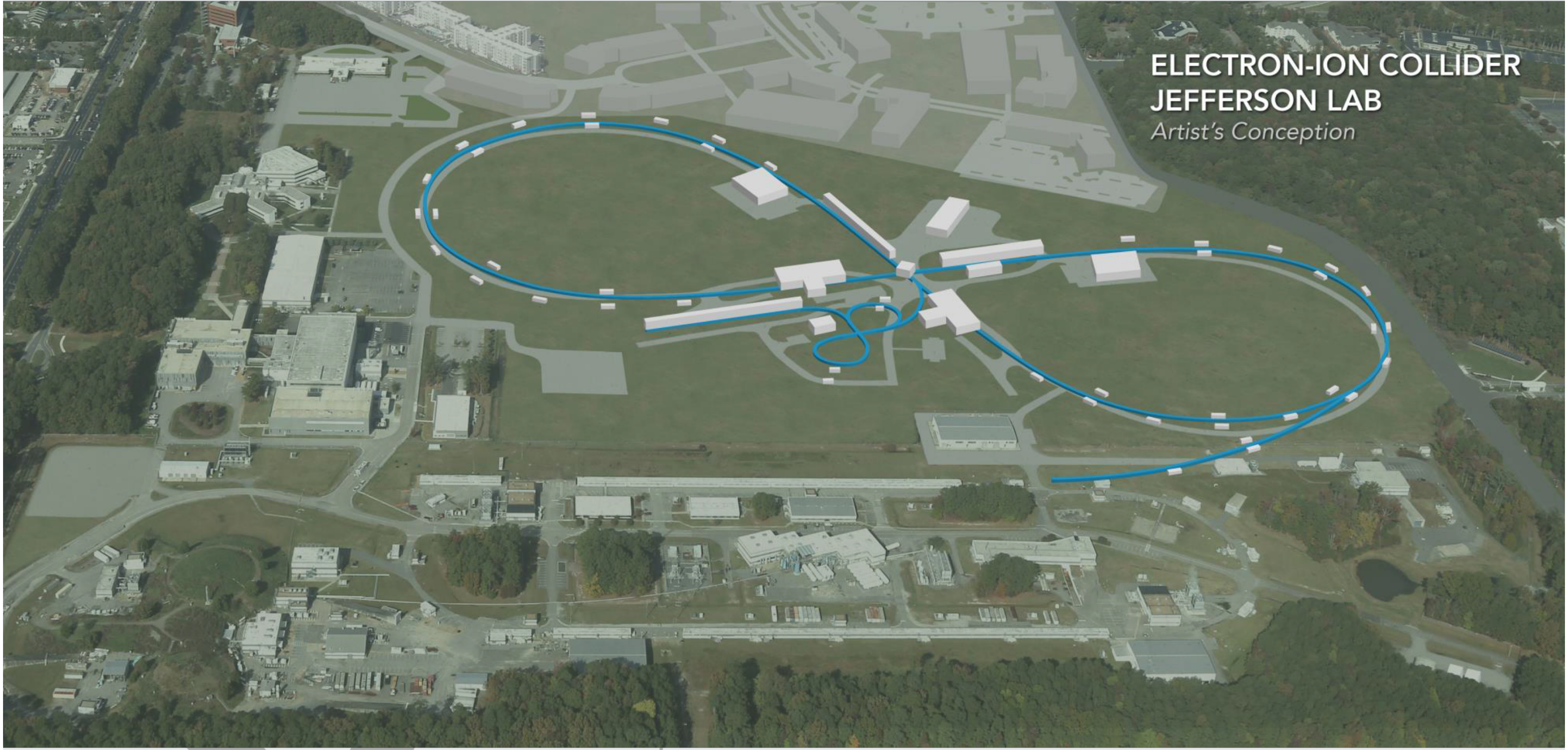
The EIC physics program at JLab



Patrizia Rossi

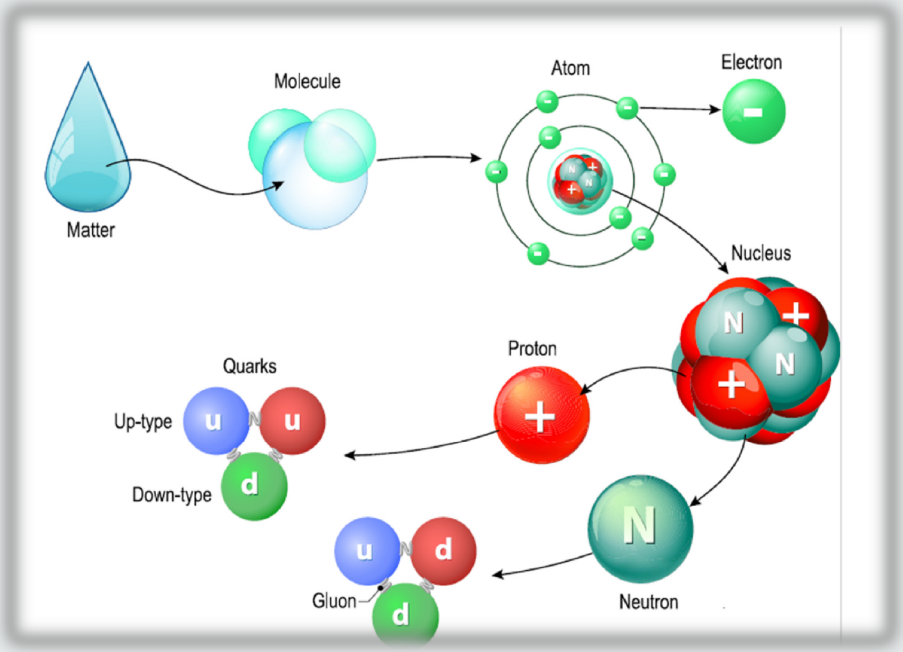
Jefferson Lab

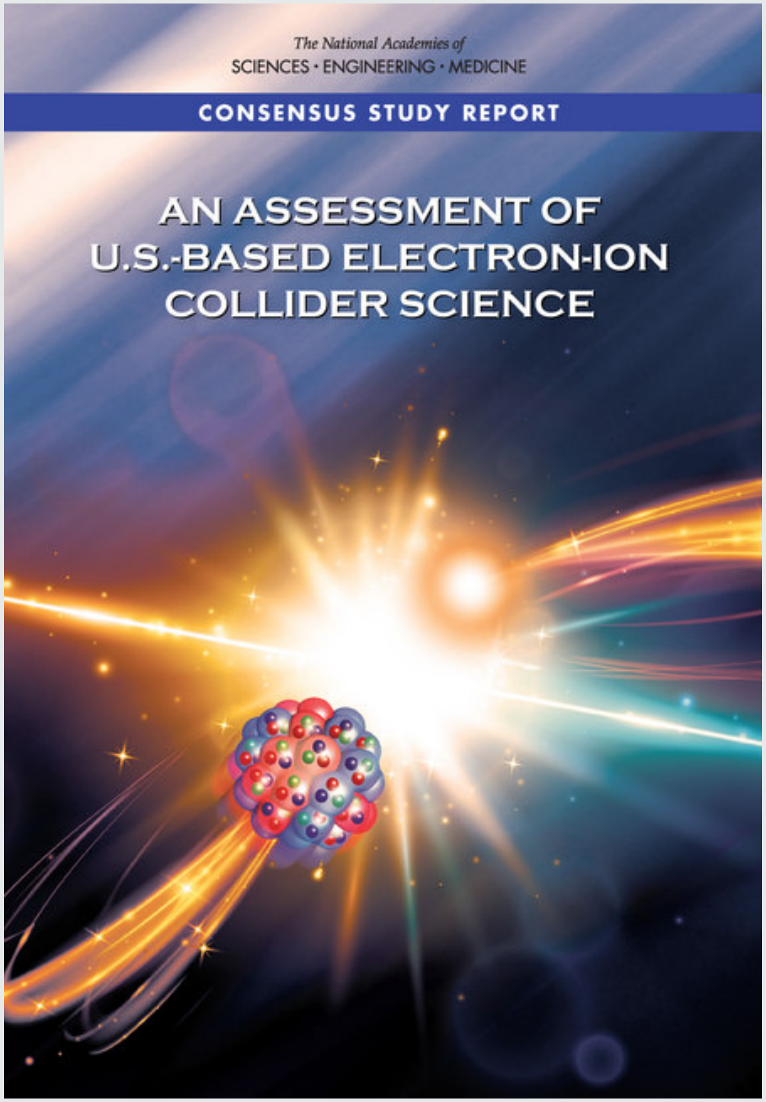
The Spectroscopy Program at EIC and future accelerators

ECT* Trento, December 21, 2018

Compelling Physics Questions

The primary aim of an EIC is to understand how up and down quarks, sea quarks, and gluons create the building blocks of the nuclei of atoms, neutrons, and protons, and furthermore how neutrons and protons in nuclei are held together by the color force.




The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

Compelling Physics Questions

From the NAS report:

An EIC is needed to address the picture of nucleons and nuclei as complex interacting many-body systems, and in particular to address three immediate and profound questions about neutrons and protons and how they are assembled to form the nuclei of atoms

How does the mass of the nucleon arise?
In other words, how do the constituents of the nucleon, the valence quarks, the sea quarks, and the gluons, and importantly their interactions, lead to a mass some 100 times larger than the sum of the three constituent quarks alone?

How does the spin of the nucleon arise?
While nucleons are made of three quarks, each with spin ½ the spins of these quarks constitute only a small fraction of the nucleon’s spin, the rest seemingly carried by the gluon spins, the sea quarks, and the orbital motion of the quarks.

What are the emergent properties of dense systems of gluons?
Two questions concerning the gluons arise when nucleons are combined into nuclei: How is the gluon field modified in a nucleus to accommodate the binding of nucleons? And does a novel regime of nuclear physics emerge in the high-energy limit, a regime in which the complicated structure of the nucleus is radically simplified, leading to a state in which the whole nucleus becomes a dense gluon system?

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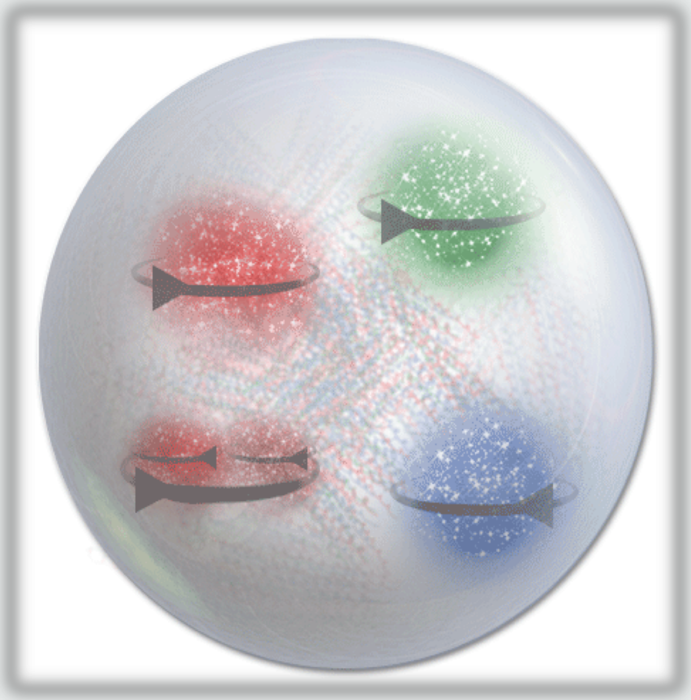
Interrelated Questions



Mass
Spin
NN interactions
…

→ Arise out of **quarks and gluons interacting** through Quantum Chromodynamics

- Mass of the proton’s constituents is negligible or even null

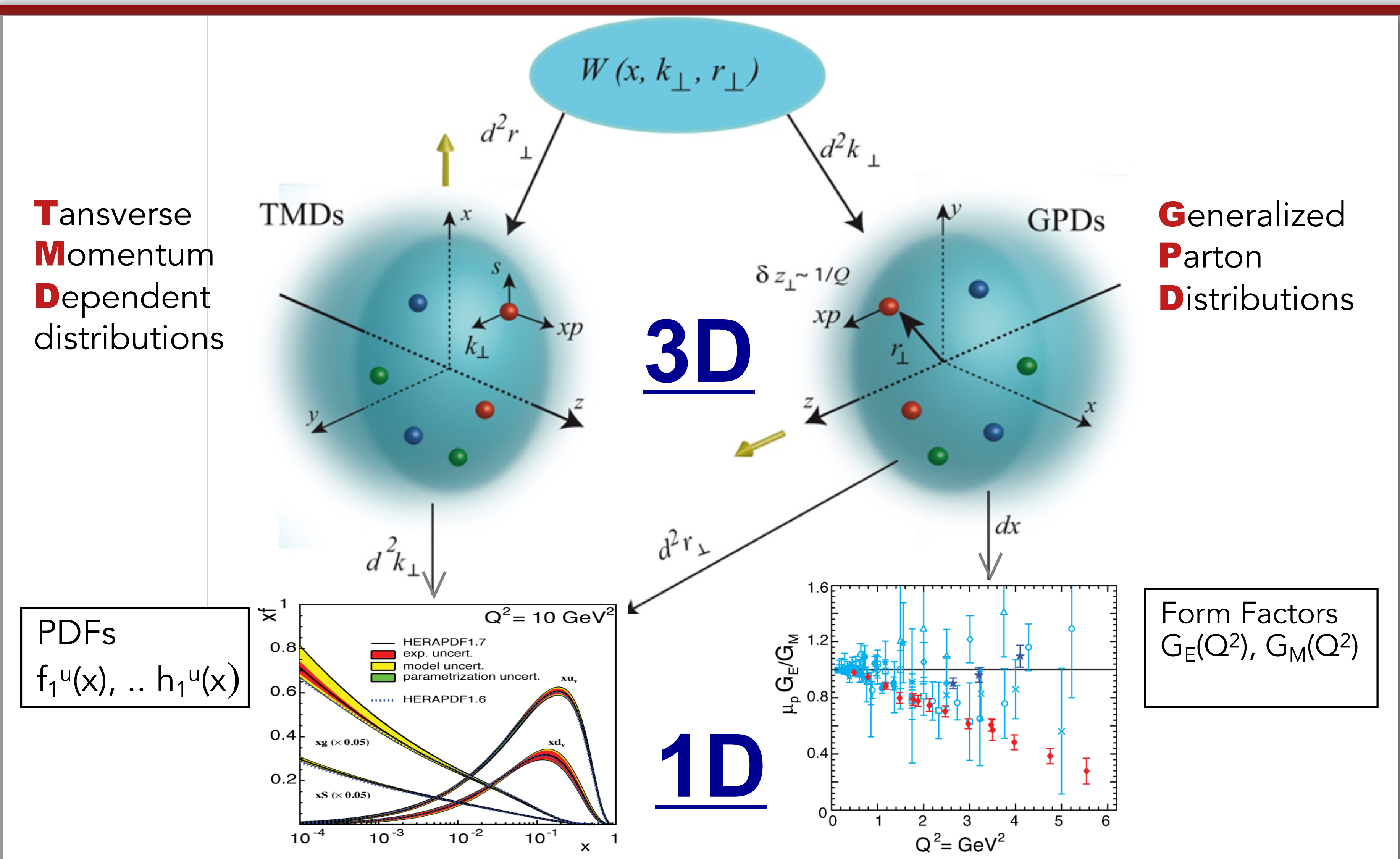
→ **Dynamics** of gluons: key point to understand the origin of the mass

- Spin of the proton’s constituents account only for a small fraction of the proton spin

→ **Spin – orbit correlations** : key point to understand the origin of the spin

  - Map the nucleon’s constituents both in space and in momentum
  - Study the interplay of quark and gluon distributions
  - Study the coupling between spin and orbital angular momentum

The Tool: Unified View of the Nucleon Structure



Tansverse
Momentum
Dependent
distributions

Generalized
Parton
Distributions

3D

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

1D

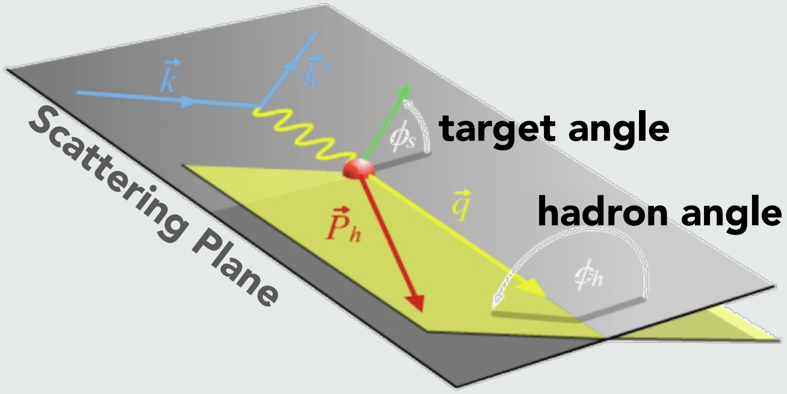
Form Factors
$G_E(Q^2)$, $G_M(Q^2)$

A NEW eye to study the nucleon: Nucleon Femtography & comprehensive description of its Internal Dynamics

Transverse Momentum Dependent PDF

$$\mathbf{ep \to e'hX}$$

$$\mathbf{d\sigma^h \propto \Sigma f^q(x, k_\perp) \otimes d\sigma^q(y) \otimes D^{(q\to h)}(z, p_\perp)}$$



Leading Order – Leading Twist

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

$$\mathbf{h_1^{\perp q}(x, k_T^2)\frac{(P \times k_T)\cdot S_q}{M}}$$

- correlations of spin q/n and transverse momentum of quarks

Higher Twist

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

- Interpretation as transferse force
- Quark-gluon correlations ➔ Interactions

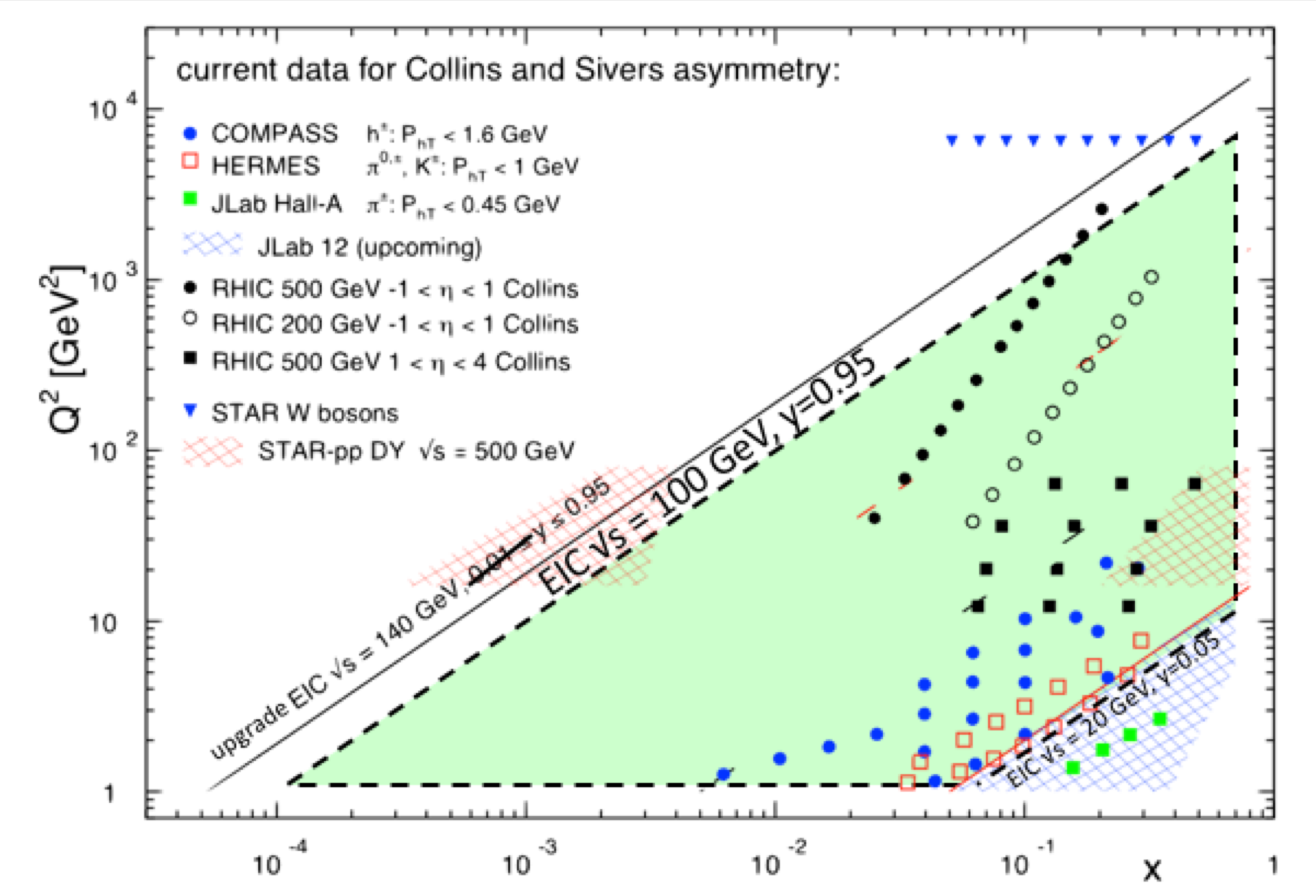
x= $Q^2/2M\nu$
$\nu = E_e - E_{e'}$
z = E_h/ν
y= ν/E_e

$$\langle \mathbf{P_{hT}^2} \rangle = \mathbf{z^2} \langle \mathbf{k_\perp^2} \rangle + \langle \mathbf{p_\perp^2} \rangle$$

Spin –Orbit Correlations manifest themselves through azimuthal asymmetries

- Collins Asymmetry in the Fragmentation Process
- Sivers Asymmetry in the Parton Distributions

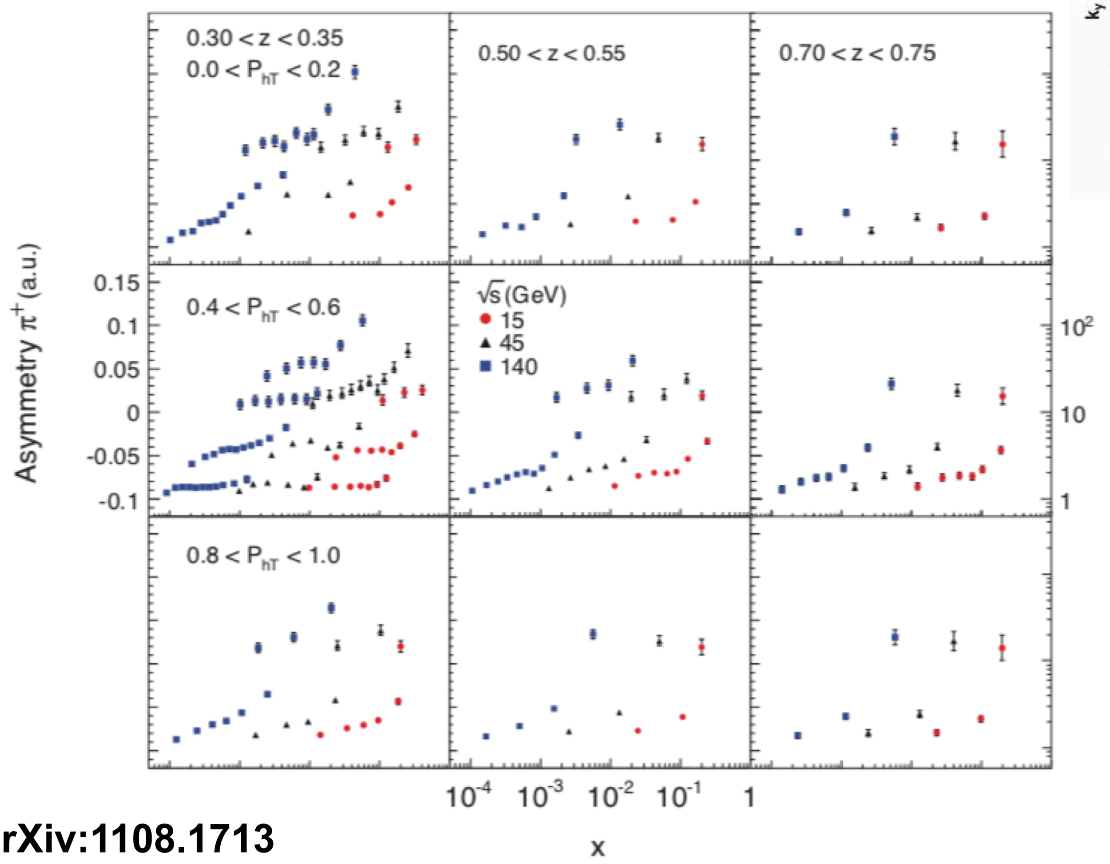
Sivers & Collins Asymmetries with EIC



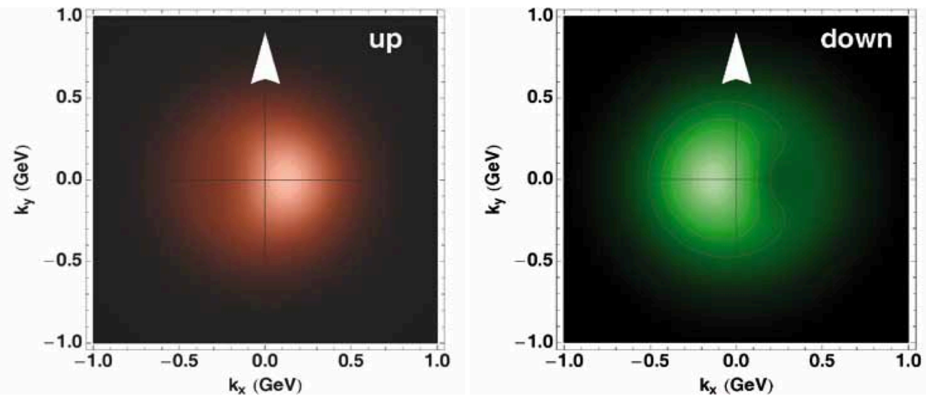
Sivers Function

EIC configurations

■ √s = 140 GeV ▲√s = 50 GeV ● √s = 15 GeV

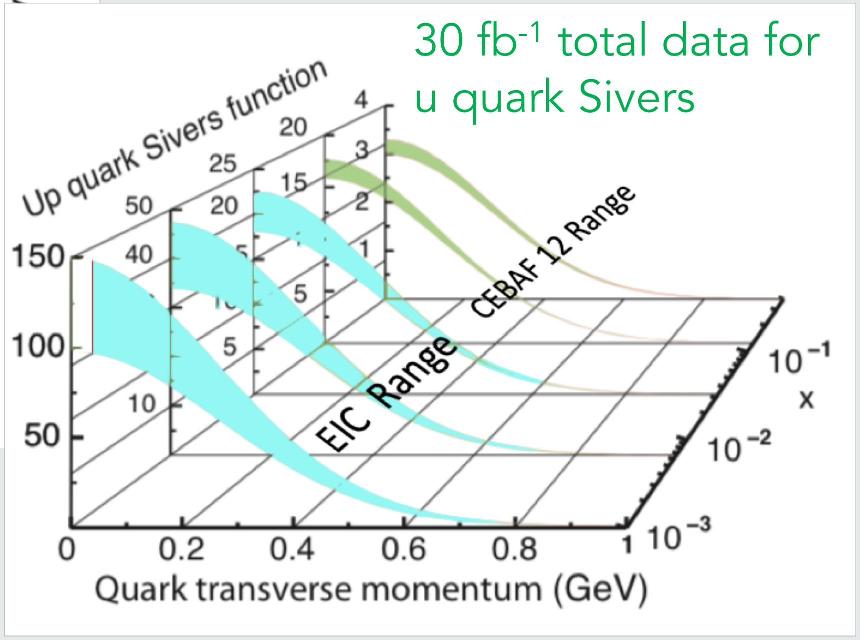


arXiv:1108.1713



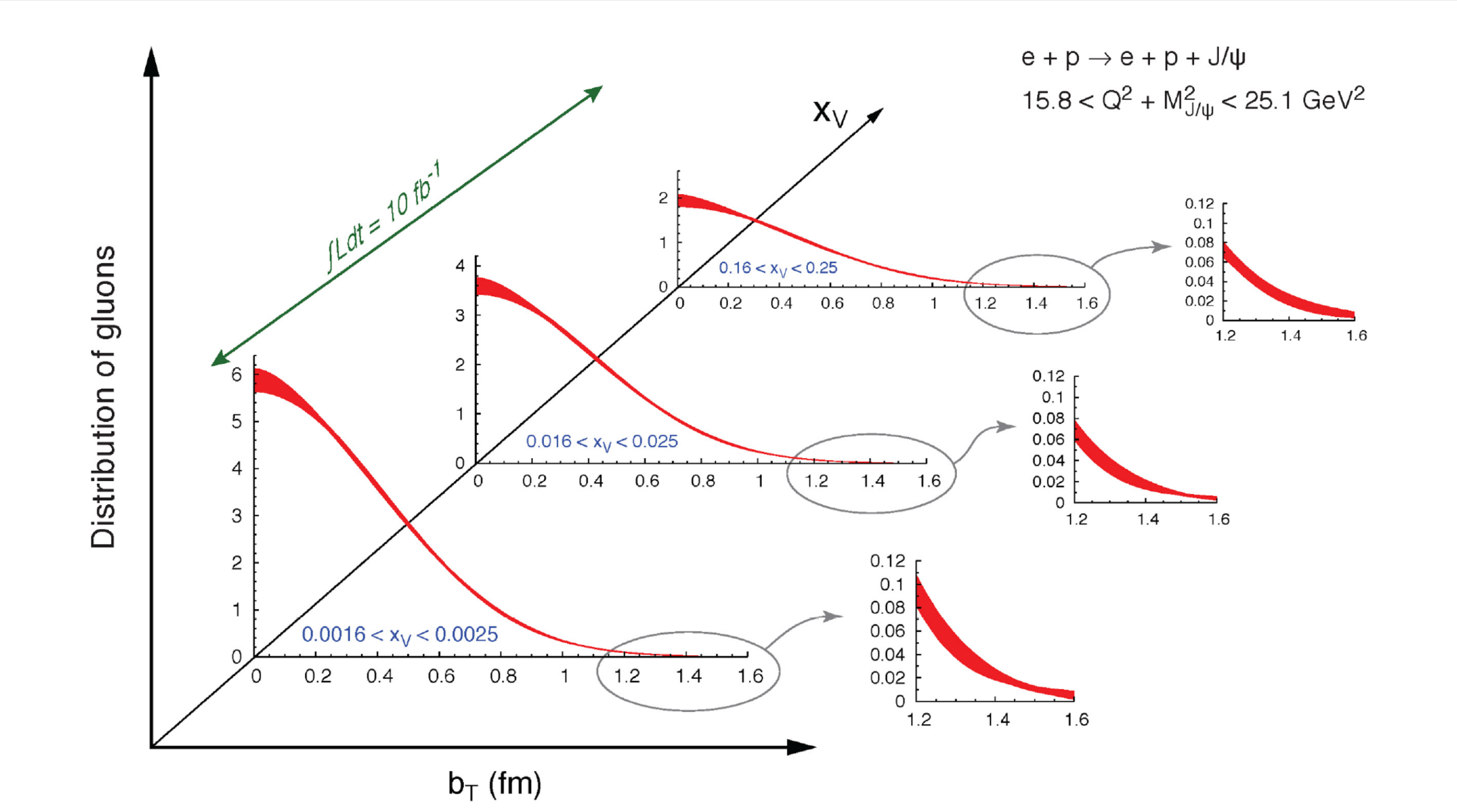
Bacchetta: Images elaborated from real data

EPJA (2009) 89 – PRL107 (2011) 212001


30 fb^{-1} total data for u quark Sivers

Large acceptance and energy range of EIC makes it ideal place to study the contributions of sea quarks to Sivers asymmetry

Transverse Gluon Profile



Transverse gluon profiles that can be obtained from J/ψ production using an integrated luminosity of 10 fb-1.

TMDs in Nuclei

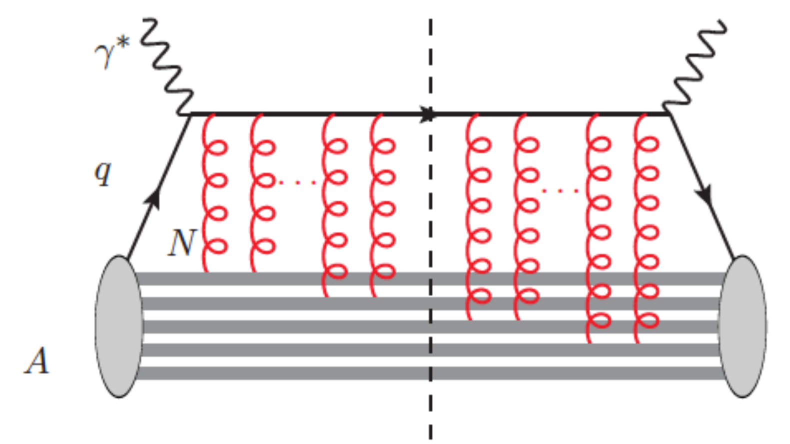
Orbital motion modifies in medium

Liang,Wang & Zhou
Phys.Rev.D77:125010,2008

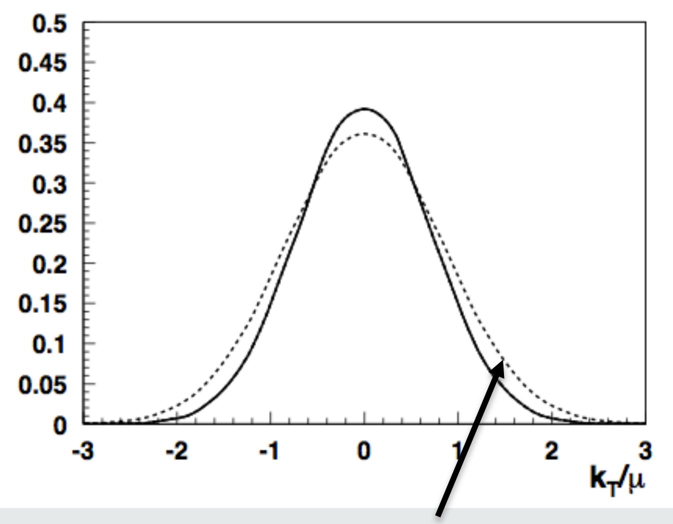
➜ studies of SSA in medium will provide important complementary information on 3D proton structure (study the A dependence)

$$f_q^N(x,\vec{k}_T)$$

$$f_q^A(x,\vec{k}_T) = \frac{A}{\pi\Delta_{2F}}\int d^2l_T e^{-(\vec{k}_T-\vec{l}_T)^2/\Delta_{2F}} f_q^N(x,\vec{l}_T)$$



Total transverse momentum broadening squared



- The intrinsic transverse momentum of partons arises naturally from multiple soft gluon interaction inside the nucleon or nucleus.

k_T-distributions wider in nuclei?

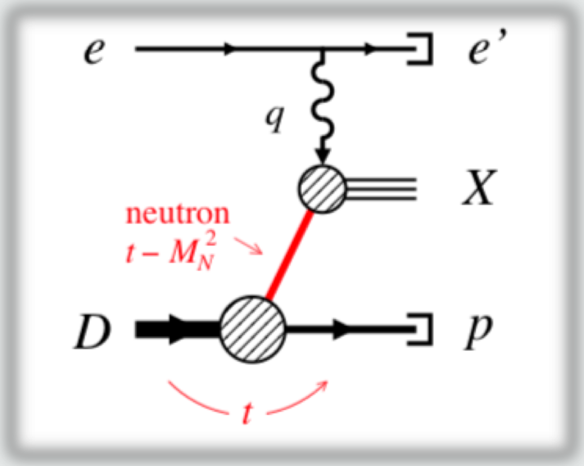
Femtography Center

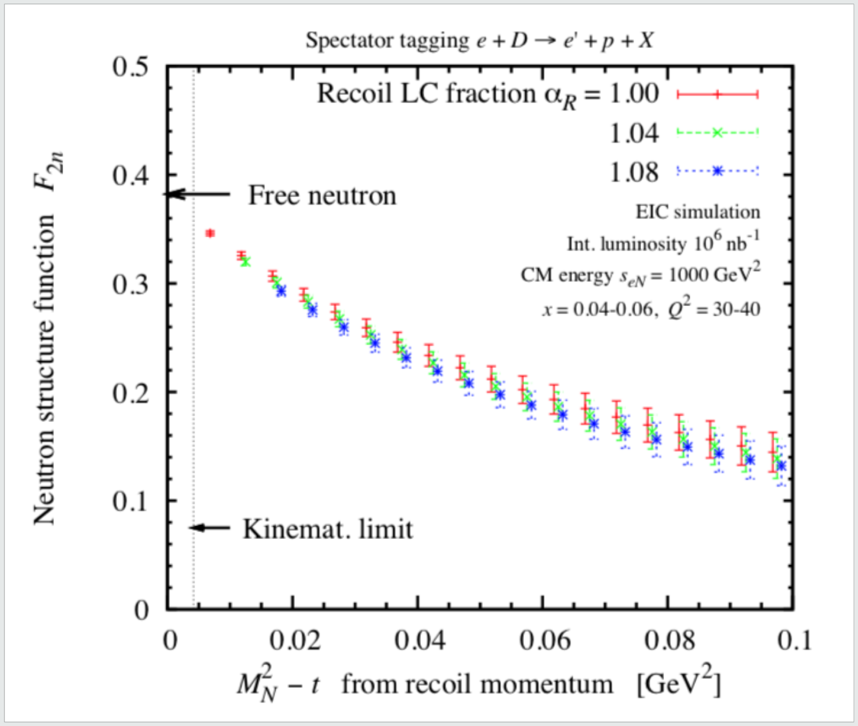
Pave the way…

Symposium on Imaging and Visualization in Science
December 10-11, 2018, University of Virginia

- The Commonwealth of Virginia has funded the establishment of a Center for Nuclear Femtography (CNF) to facilitate the application of modern developments in data science to the problem of imaging and visualization of sub-femtometer scale structure of protons, neutrons, and atomic nuclei.
- Consortium of VA universities
- Theoretical physics, experimental physics, computation, statistics – broad involvement
- Initial request of \$.5M for pilot study, funding of ~\$2M/year envisioned

Deuteron DIS with Spectator Tagging





e + D (pol)→ e′ + p + X

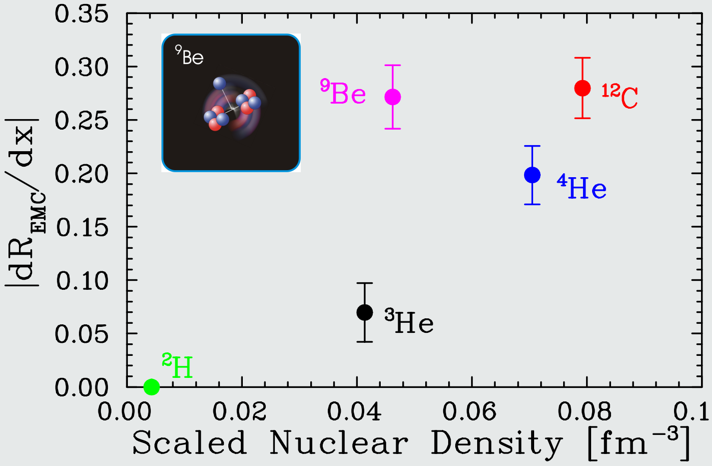
- "Free" neutron structure functions F2n, g1n from on-shell extrapolation t → M_N^2
- Nuclear modification as function of nucleon virtuality (EMC effect)

- Unique measurement for collider: No target material→ No dilution factor
- Requires integrated forward detectors with complete coverage for protons with low recoil momenta →The JLEIC interaction region and forward detection system have been designed for this purpose and provide fully sufficient capabilities.

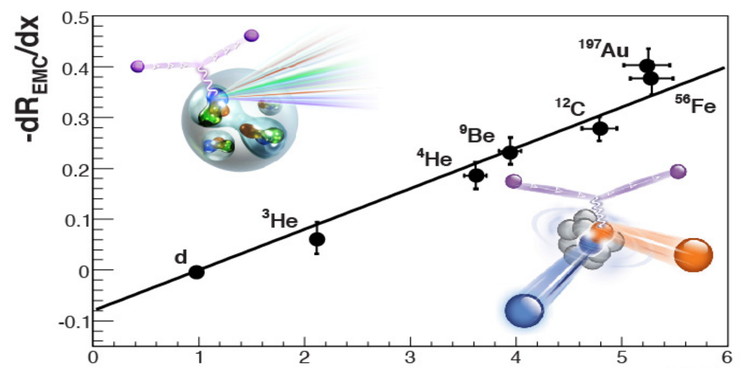
LDRD Project (C. Weiss PI)
"Physics potential of polarized light ions with EIC@JLab

Short Range Correlation (SRC)

- How the nuclear environment affects the quark-structure of nucleons ?



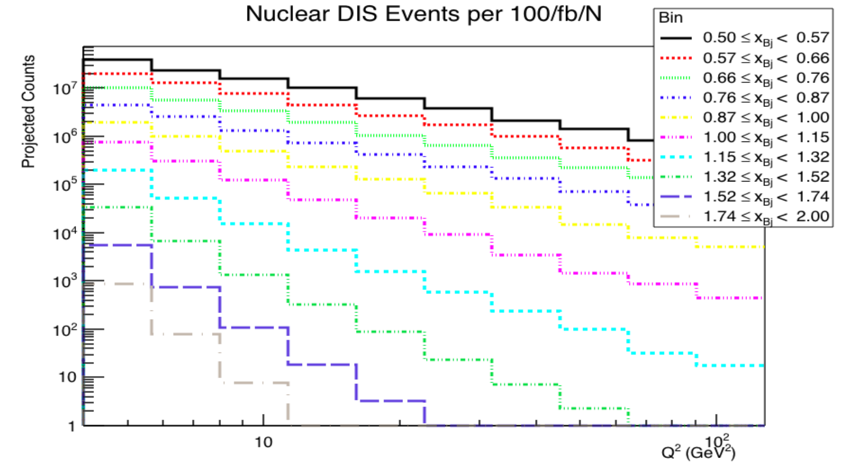
- Plot shows the slope of the EMC effect in light nuclei → the fairly "dilute" nucleus of ^{9}Be behaves more like the dense C than the similarly dilute 3He
  - → the quark distributions depend on the local rather than the average nuclear environment.



L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.

- The number of two-nucleon correlated pairs found in a given nucleus appears to be directly proportional to the magnitude of the EMC effect in that same nucleus

- SRCs @ an EIC present exciting possibilities to resolve long standing questions about the EMC effect and nucleons in the nucleus

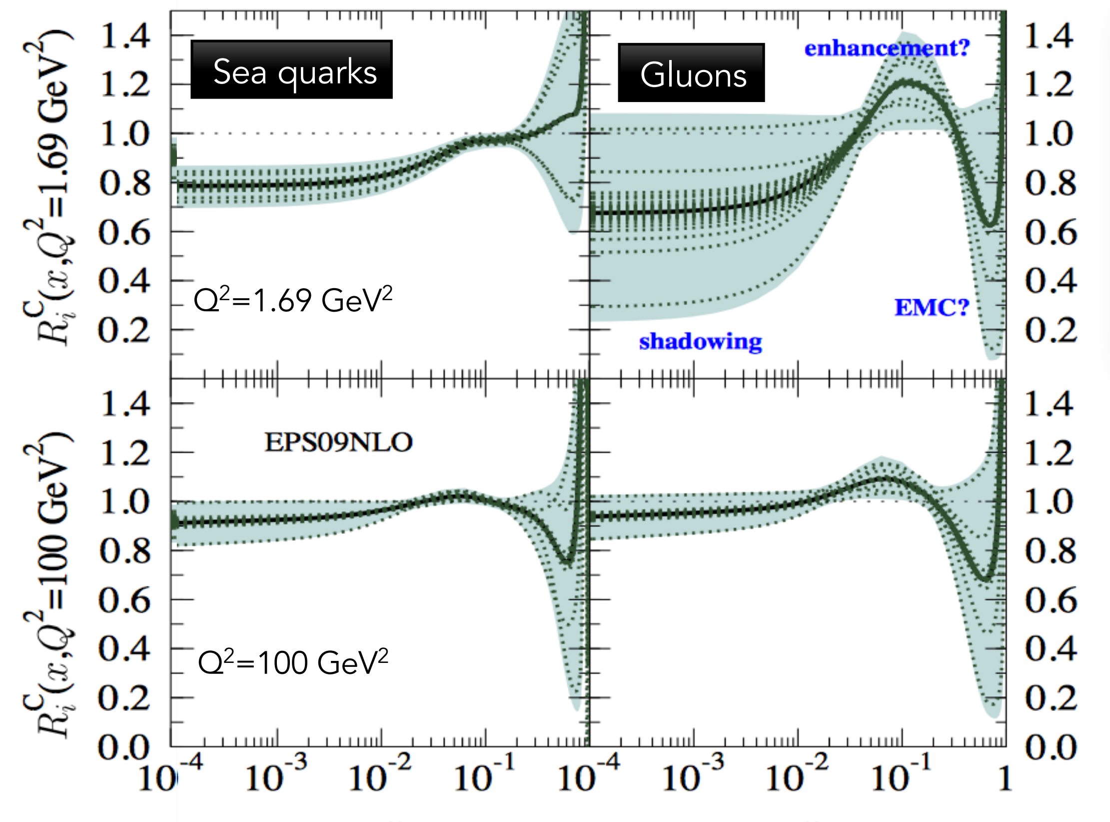


5x50 GeV e+C JLEIC with 6 weeks @ 100% efficiency

LDRD Project
" Tagged Short-Range correlations for medium to heavy ions at JLEIC"

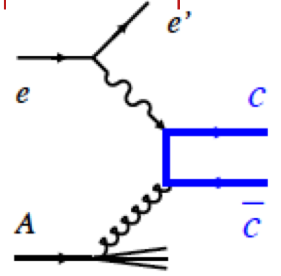
Nuclear gluons and sea quarks with EIC

- Modification of the nucleon quark-gluon structure in a nucleus

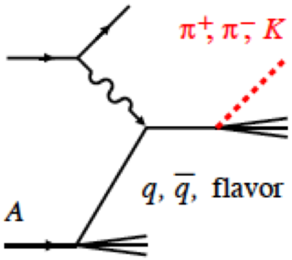


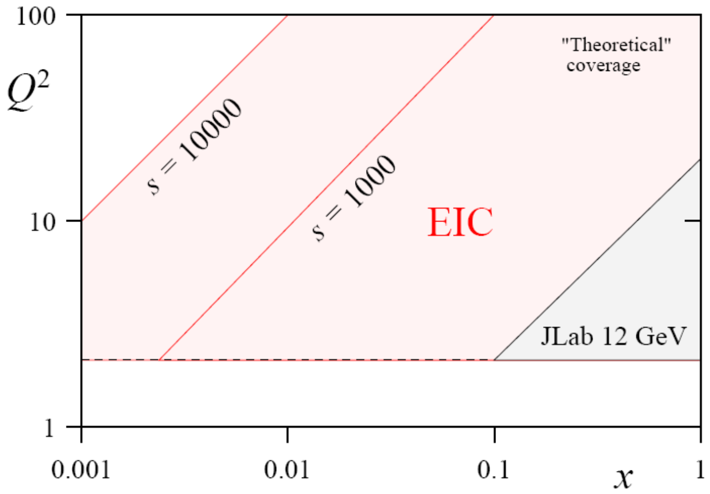
EPS09: arXiv:1209.1546

Open-charm production



Semi-inclusive DIS





- Sea quarks enhanced at x ~ 0.1?
- Flavor decomposition?

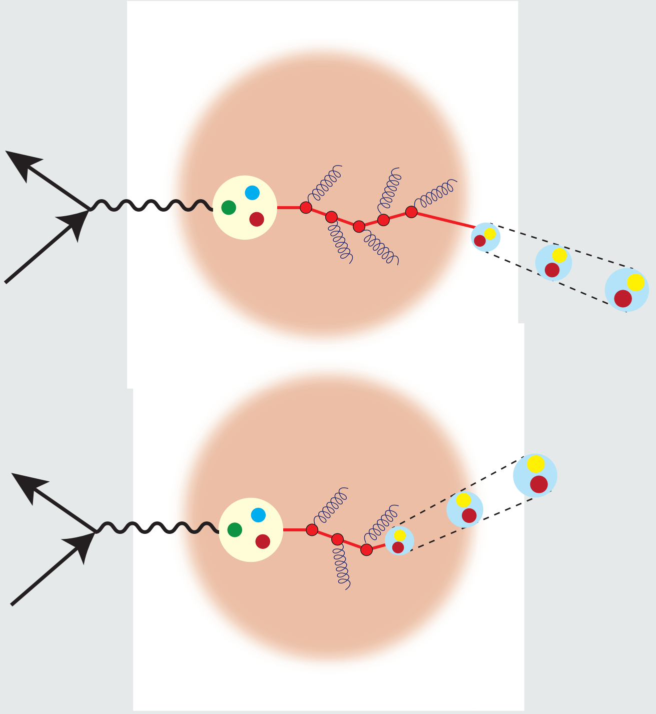
- Gluons suppressed at x > 0.3?
- Enhanced at x 0.1?

<u>LDRD Project (C. Weiss PI)</u>
"Nuclear gluons with charm at EIC"

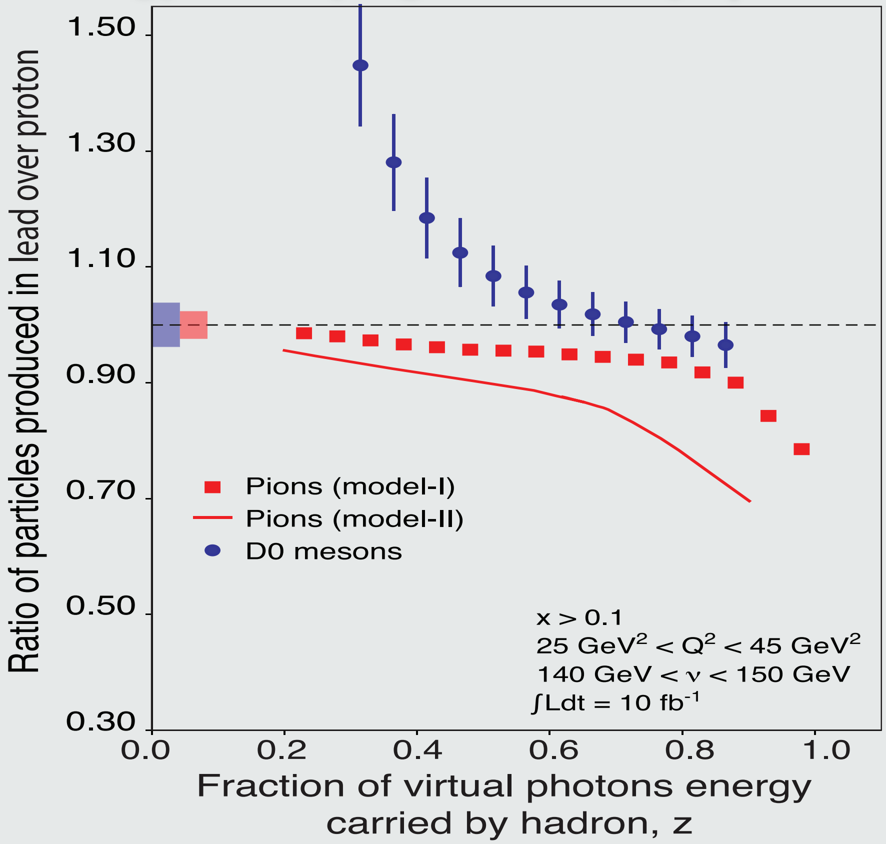
Energy into Matter

- How do hadrons emerge from quarks and gluons?
- What is nature telling us about confinement?

Anser these questions by using cold QCD matter as a “detector”



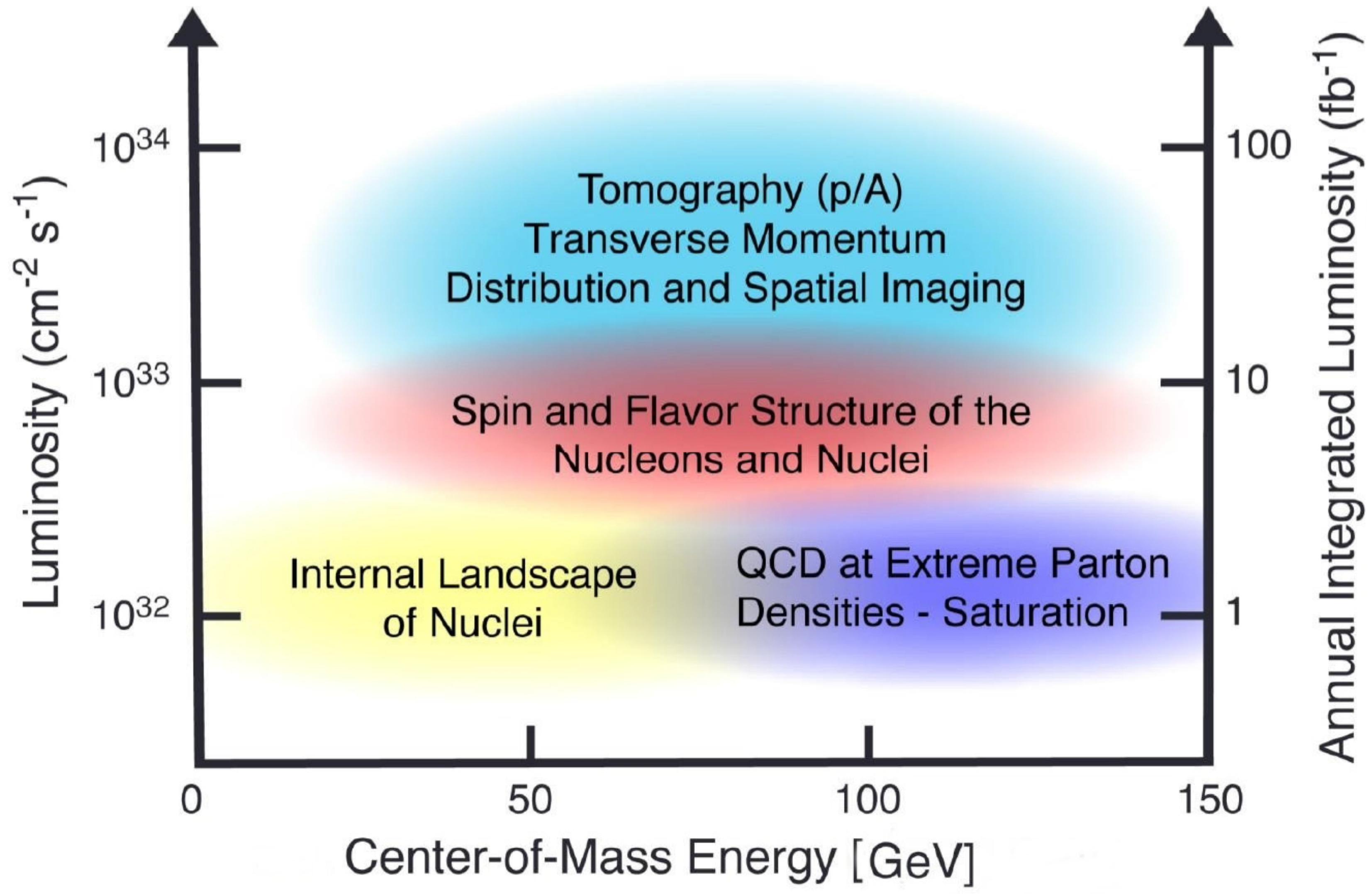
Energy loss by light vs. heavy quarks



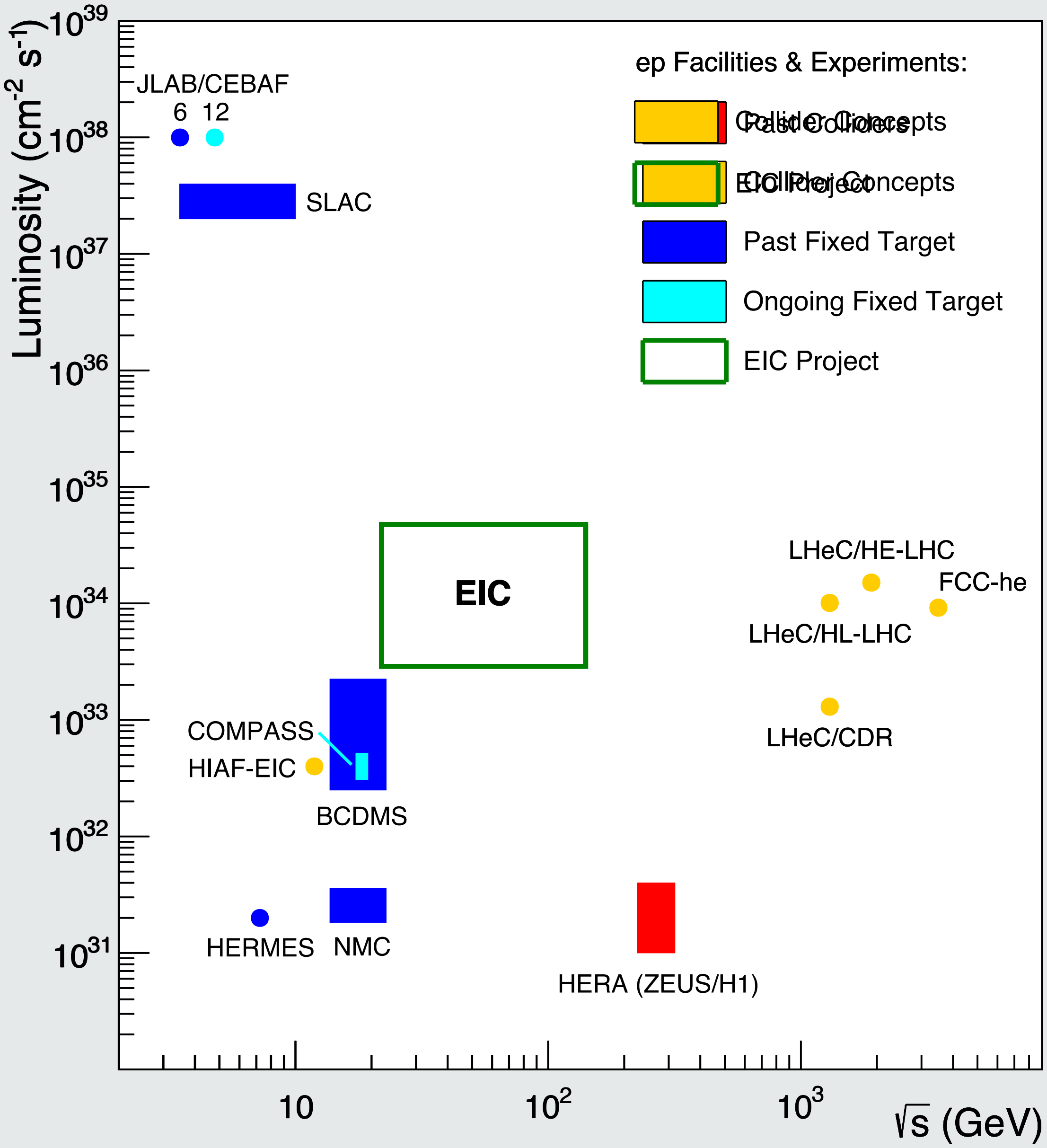
$$\nu = \frac{Q^2}{2mx}$$

With EIC: Unprecedented precision and control on parton kinematics & control of length-in-medium by selecting appropriate nuclei.

Luminosity Requirements



EIC Performance Requirements

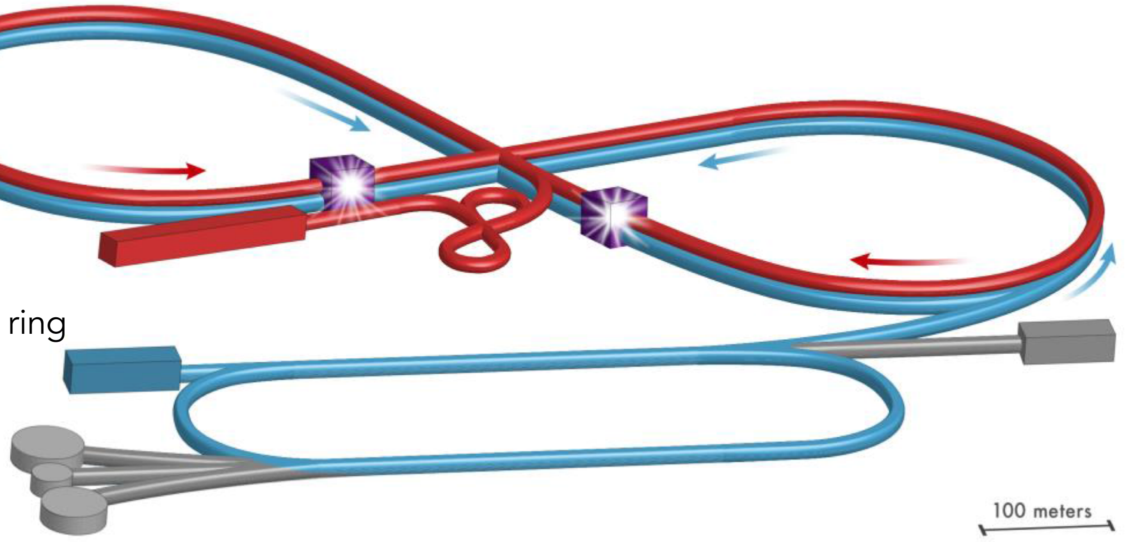


- $\sqrt{s_{ep}}$ = ~20 ÷ ~100 GeV upgradable to ~140 GeV
- Ion beams from D to heaviest stable nuclei
- 100 to 1000 times HERA luminosity
- At least ~70% polarization for electrons, protons and light ions
- One or more IR with integrated detector with high acceptance

EIC is unique

JLEIC Design

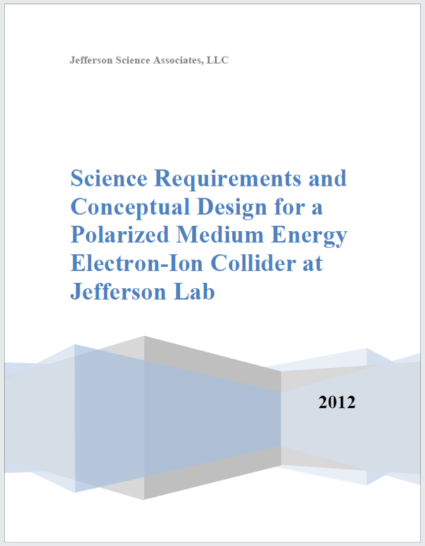
Design Concept – Figure 8 – unchanged over the years



- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring

Figure-8 concept
spin precession in one arc is exactly cancelled in the other

Polarization >80%
proton, light ions, electrons


Jefferson Science Associates, LLC

Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

2012

2012: arXiv:1209.0757

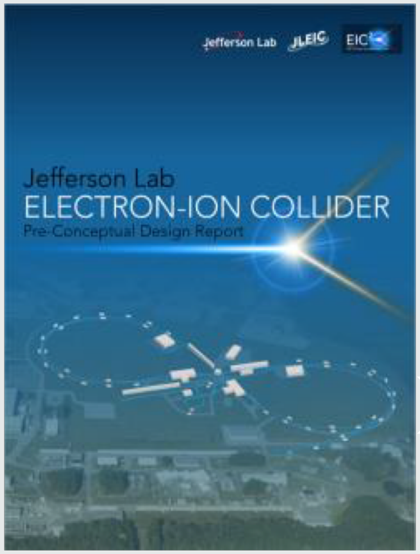

MEIC Design Summary

January 20, 2015

Author List

Author Institutions

2015: arXiv:1504.07961



Jefferson Lab
ELECTRON-ION COLLIDER
Pre-Conceptual Design Report

2018: Latest Update under development

Beam energy range
E_e = 3÷12 GeV (same as before)
E_p = 30 ÷ 200GeV (CHANGED by increasing ion ring dipole from 3T → 6T)

$\sqrt{s}$ = 20 ÷100 GeV (upgradable to 140 GeV)

JLEIC: Key Design Concepts

High luminosity: high collision rate of short modest-charge low-emittance bunches

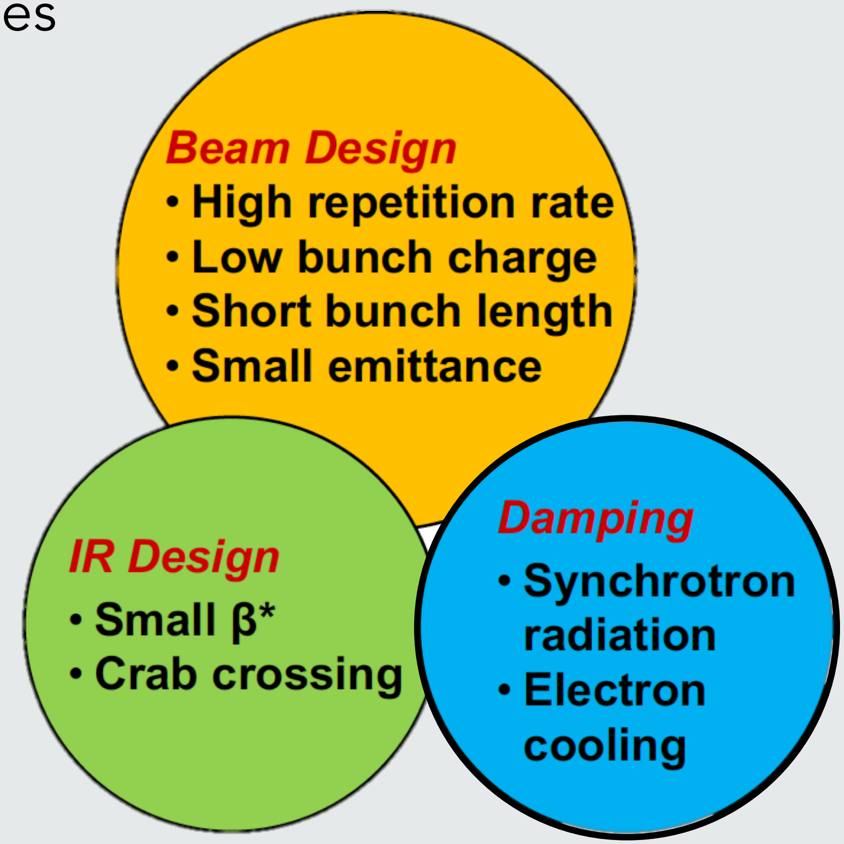
- Small beam size

• Small **β*** ➞ Short bunch length ➞ Low bunch charge, high repetition rate

• Small emittance ➞ Cooling

- Similar to lepton colliders such as KEK-B with L > 2x10^{34} cm^{-2}s^{-1}

$$L = f\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*} \sim f\frac{n_1 n_2}{\epsilon\beta_y^*}$$



Beam Design
- **High repetition rate**
- **Low bunch charge**
- **Short bunch length**
- **Small emittance**

IR Design
- **Small β***
- **Crab crossing**

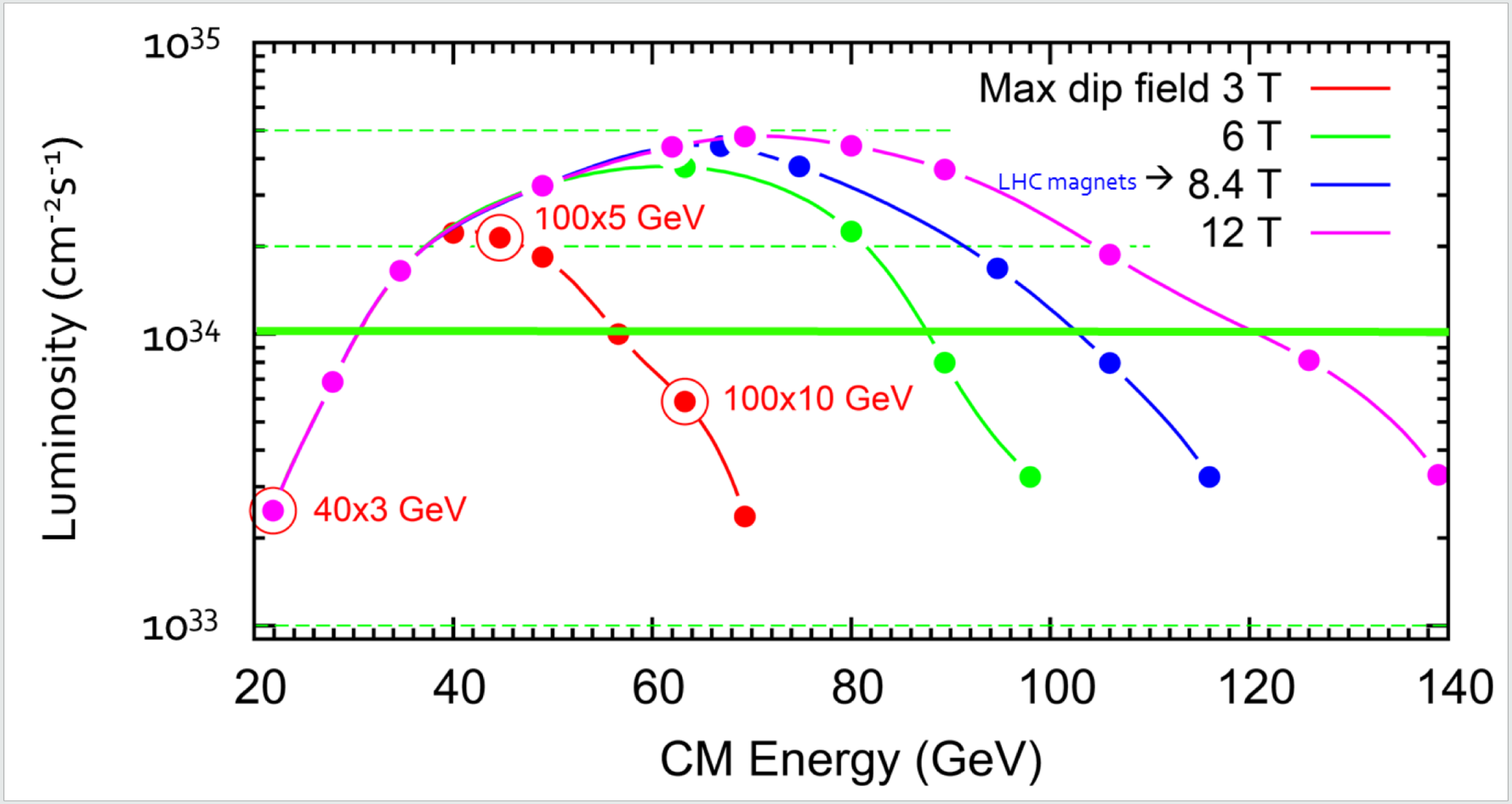
Damping
- **Synchrotron radiation**
- **Electron cooling**

• High polarization: figure-8 ring design

- Net spin precession zero
- Spin easily controlled by small magnetic fields for any particle species

• Full acceptance primary detector including far-forward acceptance

Luminosity and Energy Reach



- Our goal: 0.6 fb^{-1} to 6 fb^{-1}/week of running.
- Or average luminosity (while running):**10^{33} to $10^{34}cm^{-2}s^{-1}$**

↳(not instant, not peak, etc.)

Average luminosity (while running) is quoted for JLEIC

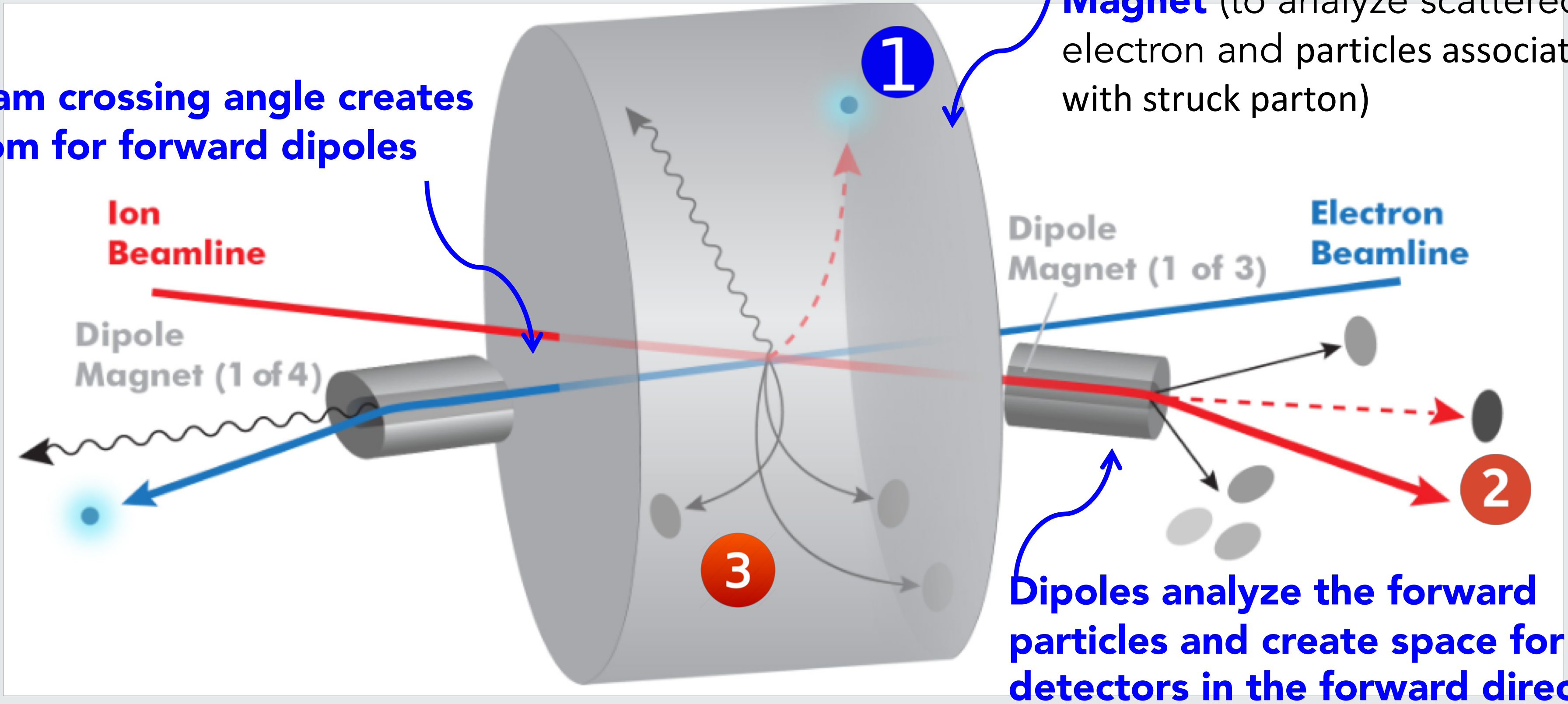
6 fb^{-1}/week

→ 100 fb^{-1}/year

Assuming running ~1/3 year

Interaction Region Concept @ JLEIC

- The goal is to get ~100% acceptance for all final state particles, and measure them with good resolution.
- Experimental challenges: a) beam elements limit forward acceptance, b) central Solenoid not effective for forward



Central Detector with Solenoid Magnet (to analyze scattered electron and particles associated with struck parton)

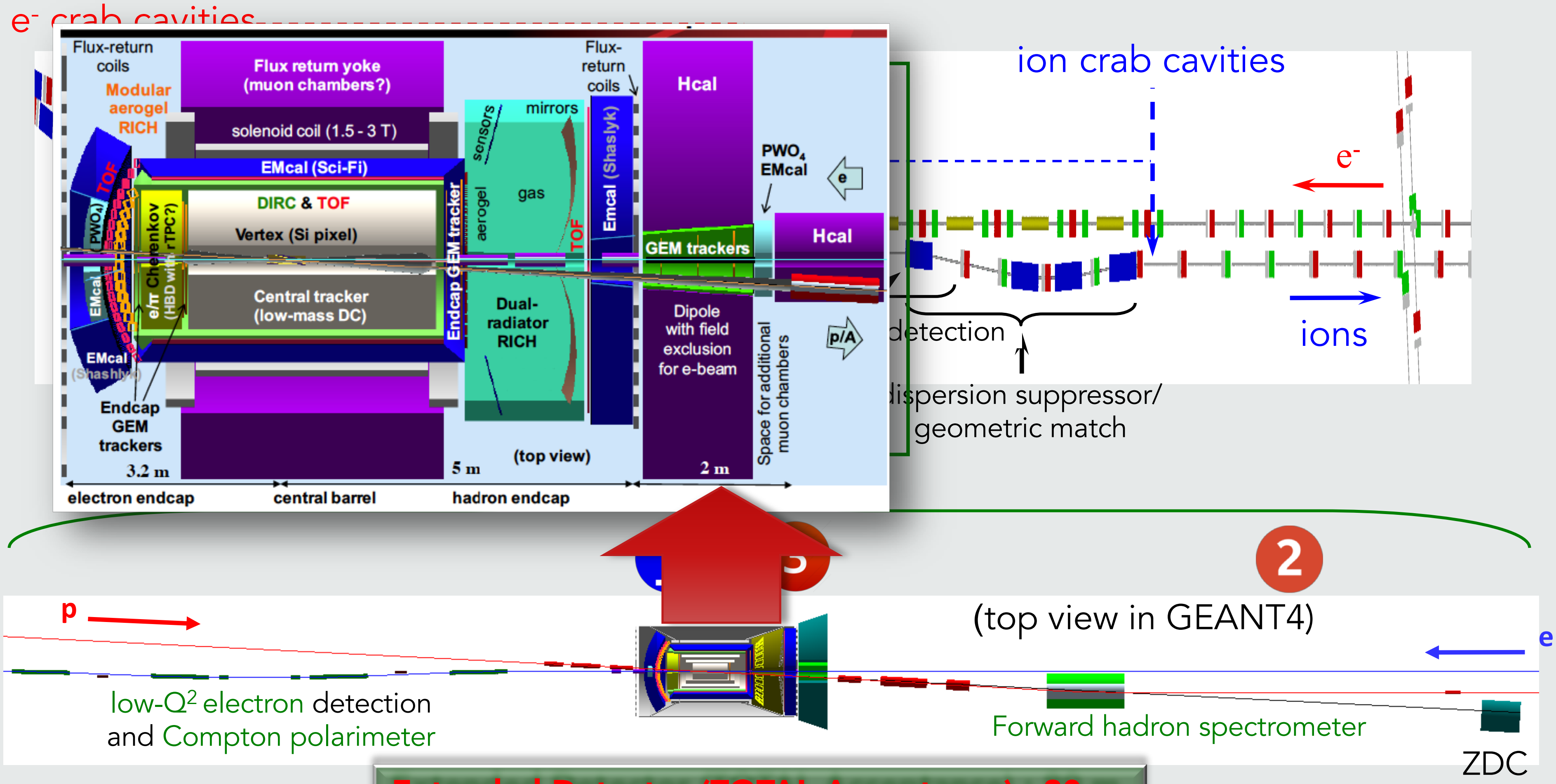
Beam crossing angle creates room for forward dipoles

Dipoles analyze the forward particles and create space for detectors in the forward direction (Particles associated with Initial Ion)

Courtesy of R. Yoshida

Detector and Interaction Region @ JLEIC

- Integrated detector region design developed satisfying the requirements of
  - Detection – Beam dynamics – Geometric match
- GEANT4 detector model developed, simulations in progress



Extended Detector (TOTAL Acceptance) : 80 m

EIC Center

Jefferson Lab EIC Realization Concept

EIC Center at Jefferson Lab

The Electron-Ion Collider Center at Jefferson Lab (EIC^2@JLab) is an organization to advance and promote the science program at a future electron-ion collier (EIC) facility. Particular emphasis is on the close connection of EIC science to the current Jefferson Lab 12 GeV CEBAF science program.

Group Leader: Rik Yoshida

Timeline

- NAS report released on July 24, 2018: Very positive!
- Various accelerator R&D questions will not be answered until ~2019
- EIC facility construction has to start after FRIB (Facility for Rare Isotope Beams) completion, with anticipated FRIB construction to ramp down around 2020
- Most optimistic scenario: EIC funds start in FY20, More realistically one: begin of construction funds in FY22/FY23
- Best guess for completion of EIC facility construction: around 2025-2030 - in roughly a decade from now

Conclusions & Outlook

- EIC goal is to revolutionize the understanding of nucleon and nuclear structure and associated dynamics.

- JLab program builds a strong foundation for future studies at EIC

- JLEIC fulfils the basic scientific requirements for such a facility. The basis of the design (ring-ring, high luminosity by high rep-rate, high polarization with Figure-8, full event coverage, and minimization of technical risk) has remained constant since 2005

- The energy reach is $\sqrt{s}$ =20 to 100 GeV upgradable to 140 GeV

- The conceptual design is nearly complete

- NAS review completed: waiting for CD0 mission statement

- EIC facility construction after FRIB completion

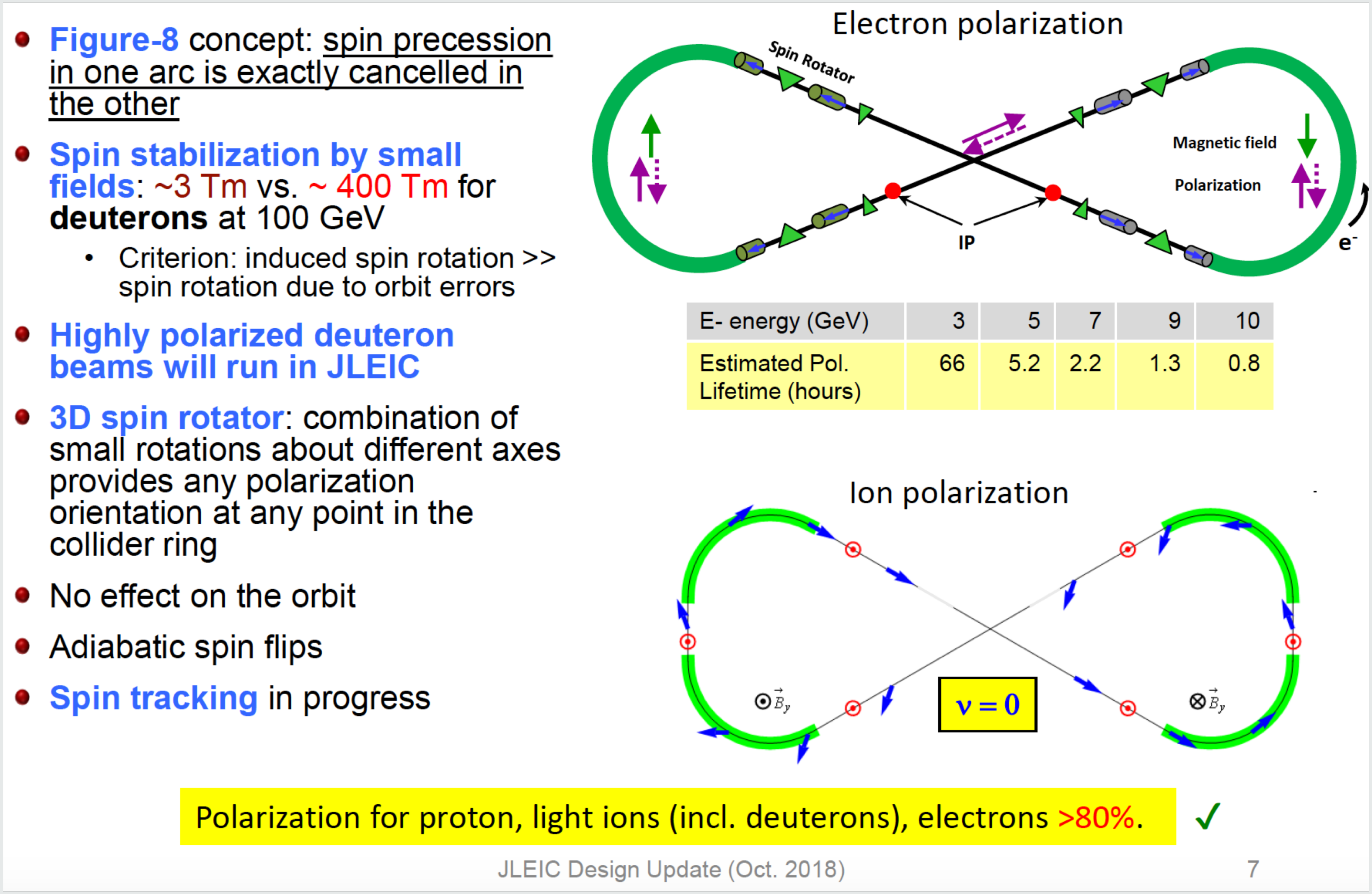
- EIC facility completion in 2025-2030: in roughly a decade from now!

Backup Slides

JLEIC Parameters (3T Options)

CM energy	**GeV**	**21.9 (low)**		**44.7 (medium)**		**63.3 (high)**	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	**0.98**	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	**80%**	**80%**	**80%**	**80%**	**80%**	**75%**
Bunch length, RMS	cm	3	1	**1**	1	2.2	1
Norm. emittance, hor / ver	µm	0.3/0.3	24/24	**0.5/0.1**	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β*	cm	8/8	13.5/13.5	**6/1.2**	5.1/1.0	10.5/2.1	4/0.8
Ver. beam-beam parameter		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7x10^{-4}	0.055	6x10^{-4}	0.056	7x10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**2.5**		**21.4**		**5.9**	

High Polarization: Figure 8



- **Figure-8** concept: <u>spin precession in one arc is exactly cancelled in the other</u>
- **Spin stabilization by small fields**: ~3 Tm vs. ~ 400 Tm for **deuterons** at 100 GeV
    - Criterion: induced spin rotation >> spin rotation due to orbit errors
- **Highly polarized deuteron beams will run in JLEIC**
- **3D spin rotator**: combination of small rotations about different axes provides any polarization orientation at any point in the collider ring
- No effect on the orbit
- Adiabatic spin flips
- **Spin tracking** in progress

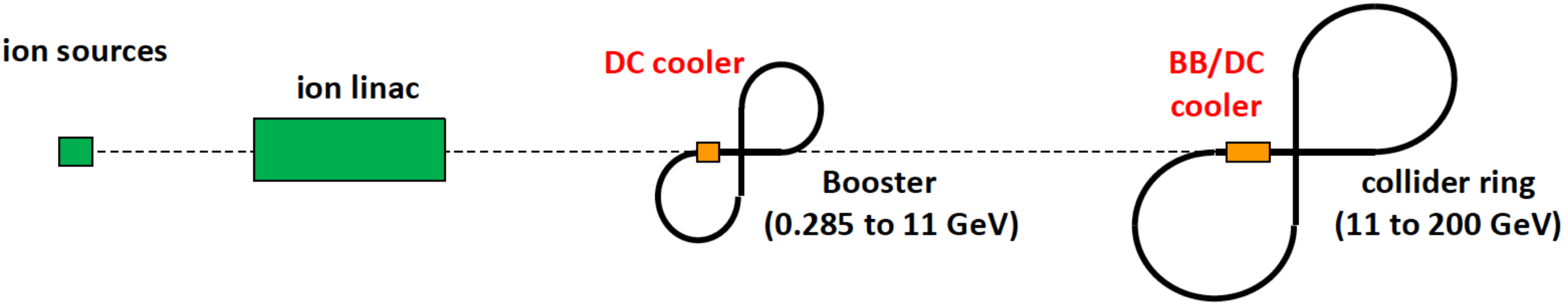
Electron polarization

E- energy (GeV)	3	5	7	9	10
Estimated Pol. Lifetime (hours)	66	5.2	2.2	1.3	0.8

Ion polarization

Polarization for proton, light ions (incl. deuterons), electrons >80%. ✓

High Luminosity: multi-phased cooling

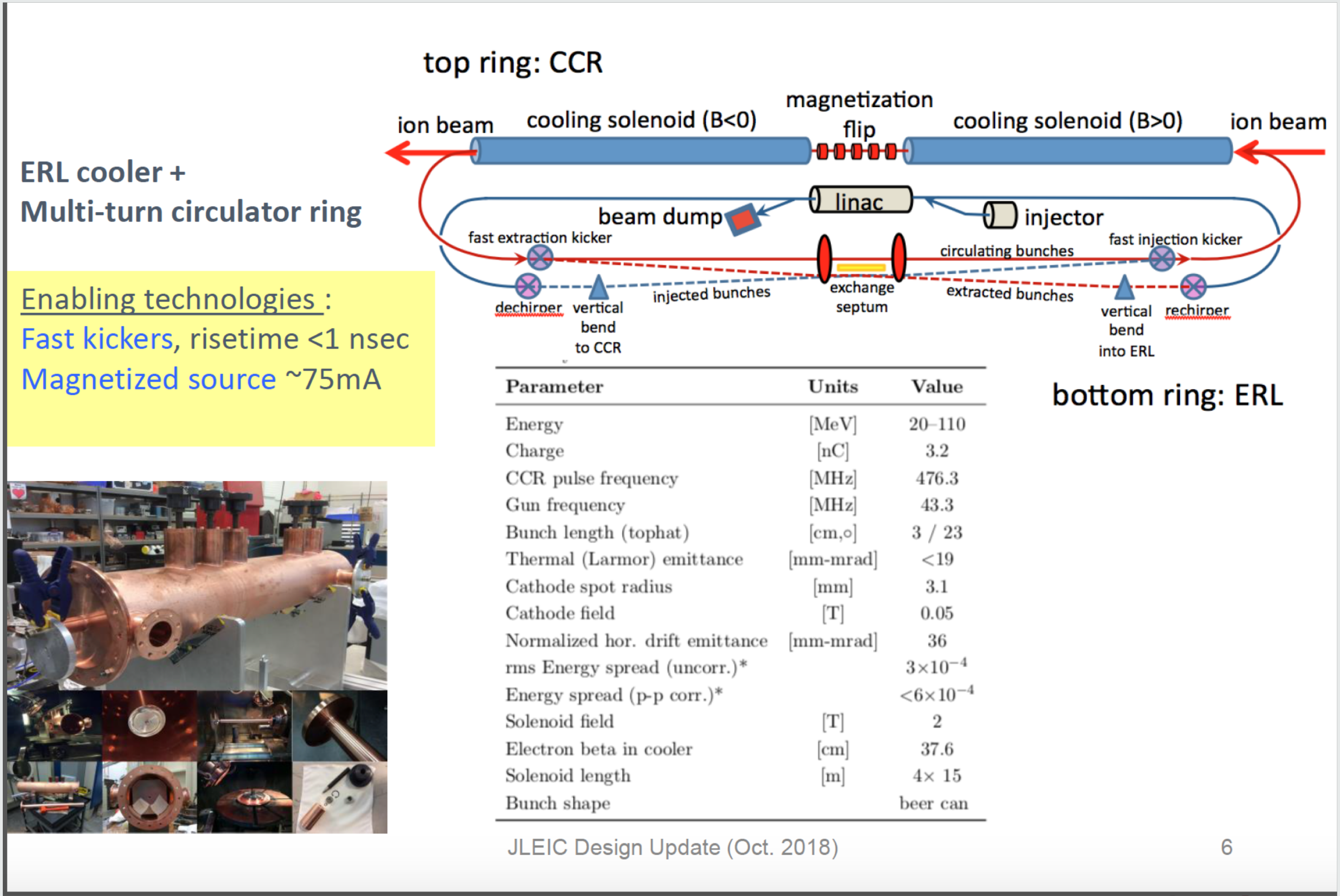


Ring	Functions	Kinetic energy (GeV / MeV)			Cooler type
		Proton	Lead ion	Electron	
booster ring	Accumulation of positive ions		0.1 (injection)	0.054	DC
collider ring	Maintain emitt. during stacking	11 (injection)	3 (injection)	6.0 (proton) 1.6 (lead)	DC
	Pre-cooling for emitt. reduction	11 (injection)	11 (ramp to)	6.0	DC
	Maintain emitt. during collision	Up to 200	Up to 78.3	Up to 109	BBC/ERL

4.3 MeV DC Cooler @Fermilab

- DC cooling for emittance reduction
- BBC cooling for emittance preservation against intra-beam scattering

Bunched Beam Cooling



ERL cooler +
Multi-turn circulator ring

Enabling technologies :
Fast kickers, risetime <1 nsec
Magnetized source ~75mA

Parameter	Units	Value
Energy	[MeV]	20–110
Charge	[nC]	3.2
CCR pulse frequency	[MHz]	476.3
Gun frequency	[MHz]	43.3
Bunch length (tophat)	[cm,°]	3 / 23
Thermal (Larmor) emittance	[mm-mrad]	<19
Cathode spot radius	[mm]	3.1
Cathode field	[T]	0.05
Normalized hor. drift emittance	[mm-mrad]	36
rms Energy spread (uncorr.)*		3×10^{-4}
Energy spread (p-p corr.)*		$<6\times10^{-4}$
Solenoid field	[T]	2
Electron beta in cooler	[cm]	37.6
Solenoid length	[m]	4× 15
Bunch shape		beer can

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