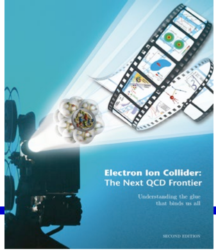
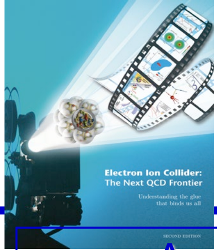


Prospects for Electron-Ion Colliders

S. Dalla Torre

INFN - TRIESTE

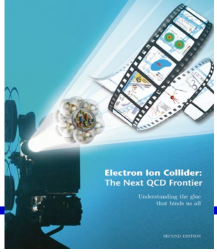


MAJOR CREDITS

- A. Accardi et al., Electron-Ion Collider: The next QCD frontier, Eur. Phys. J. A52 (2016) 268.
- A. Caldwell, R. Ent, A. Levy, P. Newman and F. Olness, “The "DIS and Related Subjects Strategy Document: Fundamental Science from Lepton-Hadron Scattering”, submitted to EPPSU 2018-2020
- Talks at DIS2019:
  - A. Stasto, “Overview of physics possibilities at future DIS facilities”
  - B. Surrow, “Status and Perspectives of a US-based Electron-Ion Collider (EIC)”
  - M. Klein, “The Large Hadron-electron Collider: status and plans”
  - Y. Zhao, “An EIC proposed in China (EicC)”
  - C. Gwenlen, “Precision QCD with the LHeC and FCC-eh”
- Tasks at EPPSU Open Symposium 2019:
  - N. Armesto, “Strong interaction physics at future eA colliders”
  - T. Galatyuk, “Emerging facilities around the world for strong interaction physics”
  - U. Klein, “Opportunities and challenges for QCD physics in high-energy ep collisions at future facilities”
  - J. D'Hondt, “Strong Interactions (perturbative and non-perturbative QCD, DIS, heavy ions)”
- Talk at Strategia Europea-giornate della Comunita’ INFN, 2018:
  - A. Bressan, “Prospettive per fisica adronica e collisionatori e-adronici”
- & many more sources of updated information …

The rich bibliography also tests of the interest of the scientific community

Thank you



THE FUTURE WORLD-WIDE PANORAMA

2000 physicists worldwide !

- **A panorama astonishing wide !**

A. Caldwell, R. Ent, A. Levy,
B. P. Newman and F. Olness

- **testing the <u>first-class scientific value</u> of these facilities**
- **all projects consider also eA options**
- **variety of energy and luminosity <u>parameters</u>**
- **<u>polarization</u> as a key tool in part of the projects**
- **<u>world-wide effort</u> (USA, China, CERN)**
- **Extremely <u>different maturity level</u> of the various proposals**
  - ***technological aspects, strategy definition***

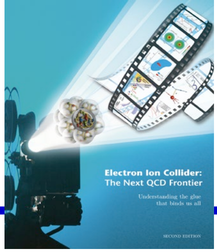
Table 1: Overview of proposed electron-hadron colliders.

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	20 - 100 $\rightarrow$ 140	2 - 30	p $\rightarrow$ U	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	1 $\rightarrow$ 100	p $\rightarrow$ Pb	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	530 $\rightarrow$ 1400	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

CERN (LHeC, PEPIC, VHEeP, FCC-eh)

A. Caldwell, R. Ent, A. Levy, P. Newman and F. Olness

Optimistic lower limits ?



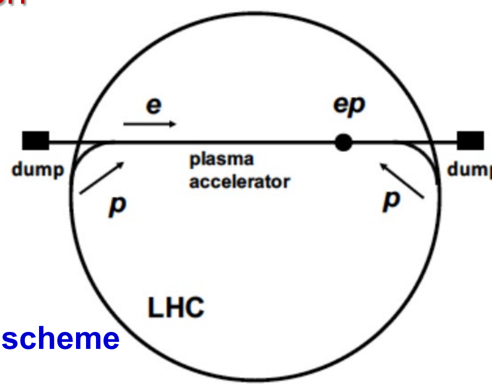
"FAR" PROPOPSALS

Table 1: Overview of proposed electron-hadron colliders.

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	20 - 100 → 140	2 - 30	p → U	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	1 → 100	p → Pb	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	530 → 1400	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

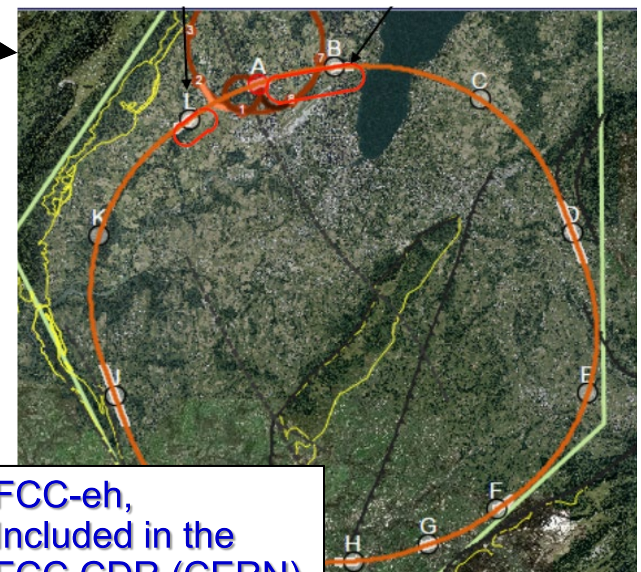
making use of the concept of proton-driven plasma wakefield acceleration

PEPIC: eP/eA using SPS driver
VHEeP: eP/eA using LHC driver

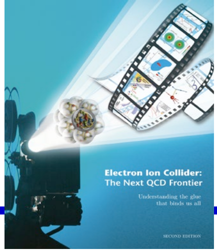


VHEeP scheme

A. Caldwell, M. Wing at DIS2018



FCC-eh, Included in the FCC CDR (CERN) Jan. 2019



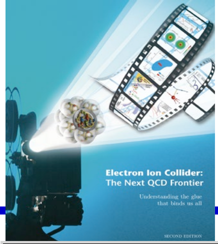
"NEARER" PROPOPSALS

Table 1: Overview of proposed electron-hadron colliders.

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	$20 - 100 \rightarrow 140$	2 - 30	$p \rightarrow U$	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	$1 \rightarrow 100$	$p \rightarrow Pb$	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	$530 \rightarrow 1400$	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

The nearest:
- **positive decisions expected in 2019**
- **Technology well advanced**
- **R&D supported**
- **A strong international community**

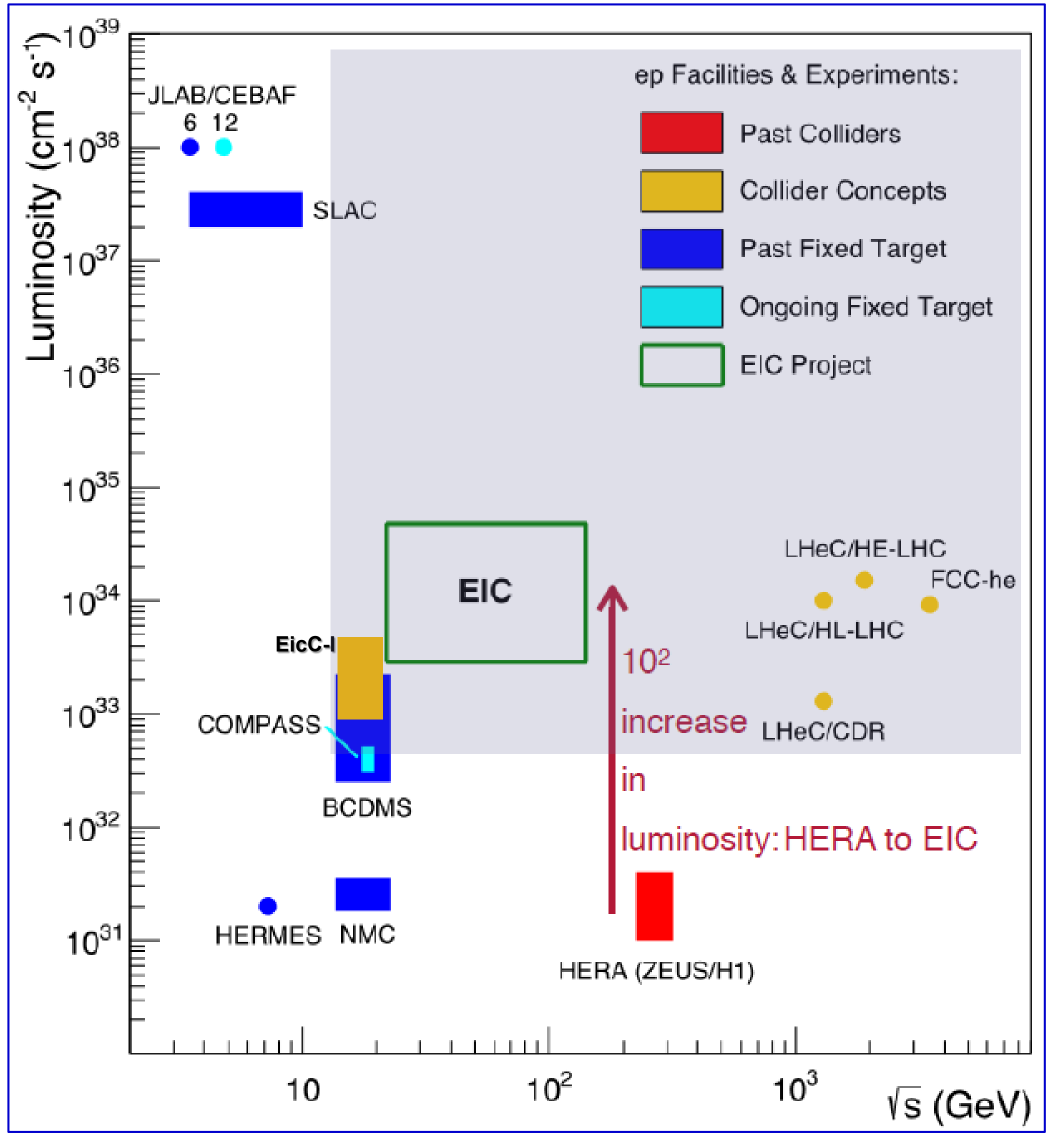
These are the proposals discussed in this talk



ENERGY & LUMINOSITY, future vs past

PAST

FIXED TARGET, e BEAM				
SLAC	concluded	high $\mathscr{L}$	polarization	
CEBAF	active	high $\mathscr{L}$	polarization	
HERMES	concluded	limited $\mathscr{L}$	polarization	internal gas jet target
FIXED TARGET, HIGH ENERGY μ BEAM				
BCDMS	concluded	high $\mathscr{L}$		access to small x & large Q2 range
EMC	concluded	limited $\mathscr{L}$	polarization	access to small x & large Q2 range
NMC	concluded	limited $\mathscr{L}$		access to small x & large Q2 range
SMC	concluded	limited $\mathscr{L}$	polarization	access to small x & large Q2 range
COMPASS	active	high $\mathscr{L}$	polarization	access to small x & large Q2 range
COLLIDER ep				
HERA	concluded	limited $\mathscr{L}$		high energy, access to very small x & very large Q2 range



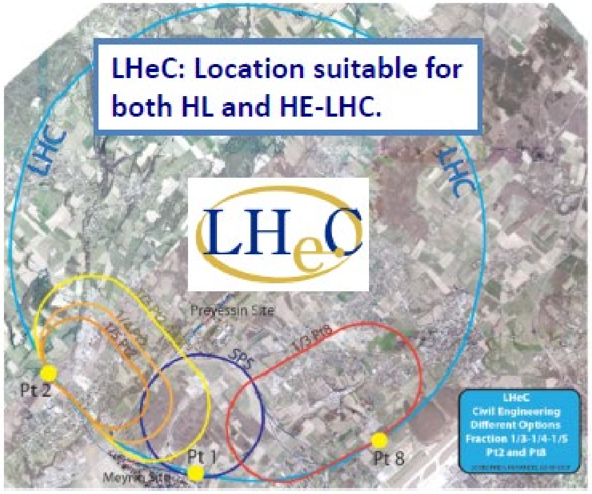
FUTURE:

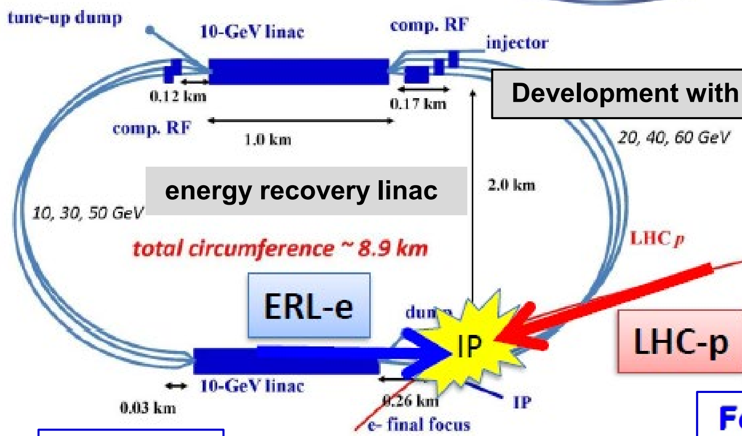
Filling the high E - high $\mathscr{L}$ region:

- **precision**
- **wide kinematic range**
  - **also access to high x-region**

LHeC

LHeC electrons for hh : ERL + LHC/FCC





U.Klein, EPPSU open symposium

Concurrent eh and LHC operation!
Same *Twin Collider* idea holds for HE-LHC and FCC-hh

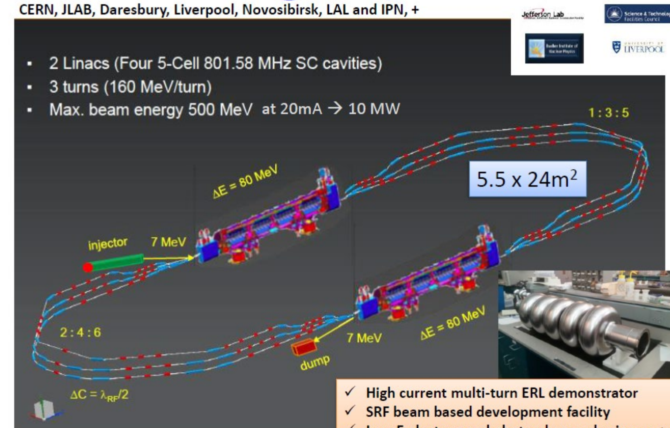
Nominal: 60 GeV e-ERL external to pp rings

LHC	pp@14 TeV &	**ep@1.3 TeV : LHeC**
HE-LHC	pp@27 TeV &	ep@1.8 TeV : HE-LHeC
FCC	pp@100 TeV &	**ep@3.5 TeV : FCC-eh**

- LHeC realization could be in LS4
- **For full QCD programme: L= 50 fb^{-1} total collected in first 3 years** → 100X HERA luminosity!

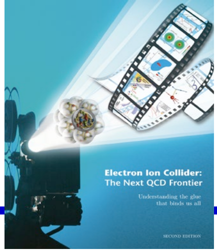
For ERL: PERLE @ Orsay

CERN, JLAB, Daresbury, Liverpool, Novosibirsk, LAL and IPN, +

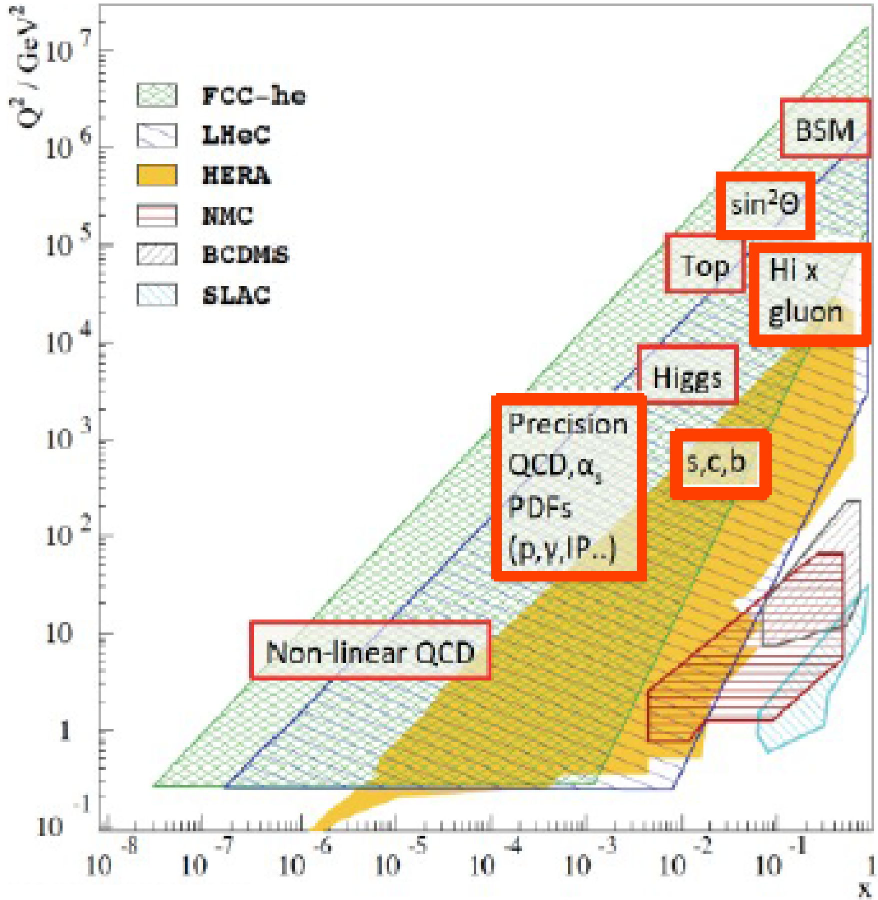


- ✓ High current multi-turn ERL demonstrator
- ✓ SRF beam based development facility
- ✓ Low E electron and photon beam physics: proton radius, sin2theta, photo-nuclear physics
- ✓ High intensity: O(100) x ELI

- ep lumi → $10^{34}\ cm^{-2}\ s^{-1}$
  ⇒ 100 fb^{-1} per year-1 ab^{-1} in total
- eD and eA collision always been integral to the programme
- e-nucleon lumi estimates ~10^{31} (3×10^{32}) $cm^{-2}\ s^{-1}$ for eD (ePb)



THE CASE FOR LHeC



Raison(s) d'etre of the LHeC

- Cleanest High Resolution Microscope: **QCD Discovery**
- Empowering the LHC Search Programme
- Transformation of LHC into high precision Higgs facility
- Discovery (top, H, heavy ν's..) Beyond the Standard Model
- A Unique **Nuclear Physics Facility**

Generalised Parton Distributions [DVCS] – "proton in 3D - tomography"
Unintegrated Parton Distributions [Final State] – DGLAP/BFKL?
Diffractive Parton Distributions [Diffraction] – pomeron, confinement??
Photon Parton Distribution [Photoproduction Dijets,QQ; F2,L] - fashionable..
Neutron Parton Distributions [Tagged en (eD) Scattering] – ignored at HERA

A. Bressan, "Prospettive per fisica adronica e collisionatori adronici"

THE CASE FOR LHeC

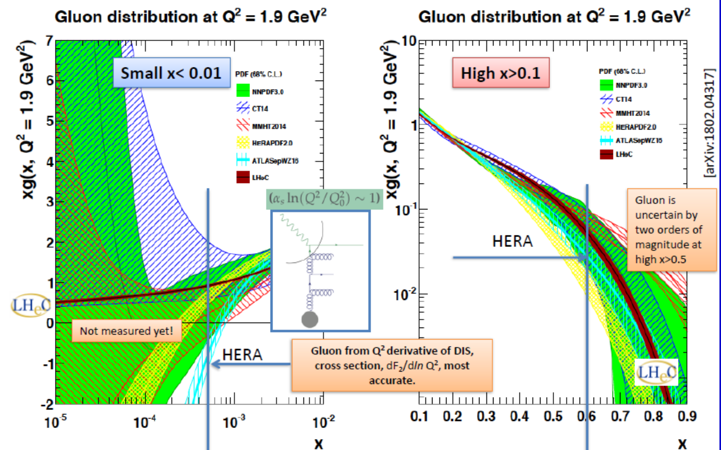
U.Klein, EPPSU open symposium

Understanding the Gluon

Hera's ep legacy and limitation

DGLAP approach

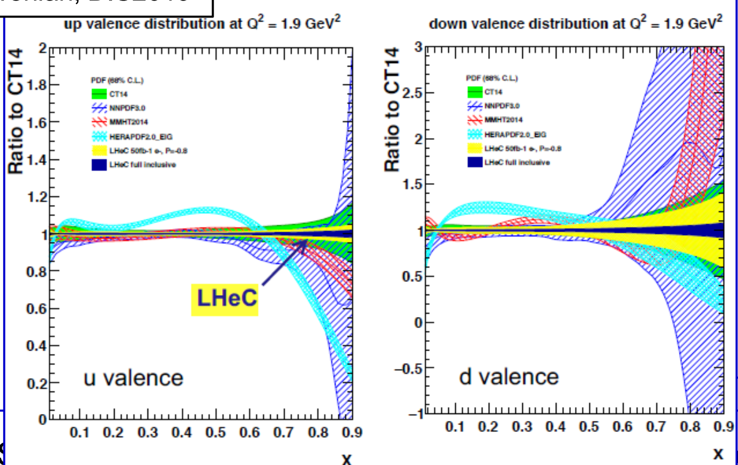
Low and high x parton distributions are intertwined by momentum sum rules!



Deeper understanding of the N structure

valence quarks from LHeC

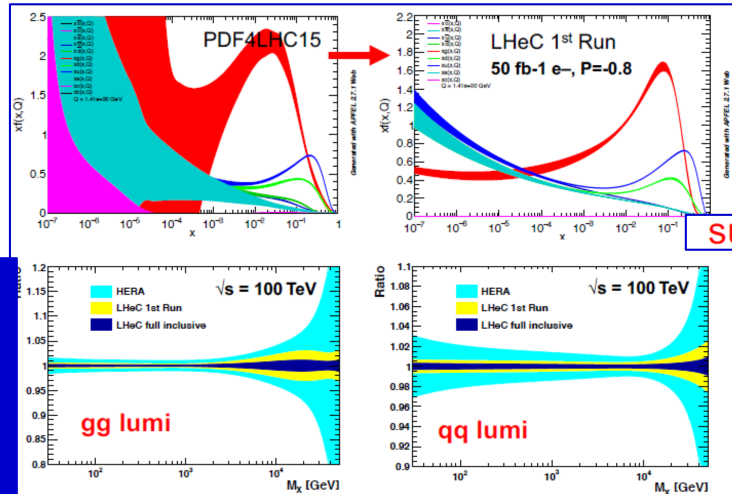
C. Gwenlan, DIS2019



Empowering high energy hh colliders

PDF precision set limits on

- searches of new physics at LHC, especially at high x
- the Higgs precision at medium x
- …

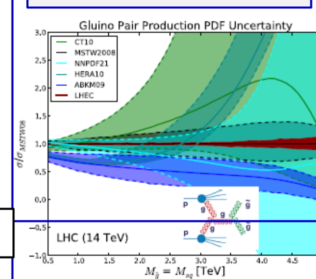


summary of LHeC pdfs

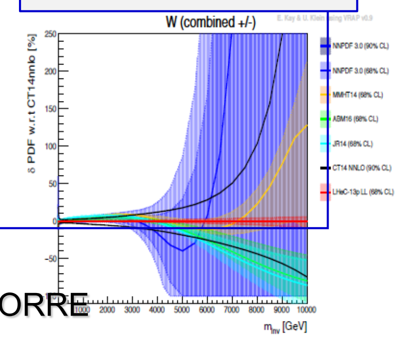
C. Gwenlan, DIS2019

external, reliable **pdfs** needed for range extension and interpretation

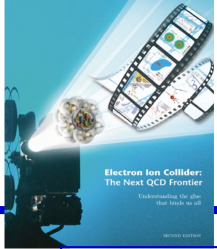
Gluons: Gluino pair production



Quarks: High mass exotic and extra bosons

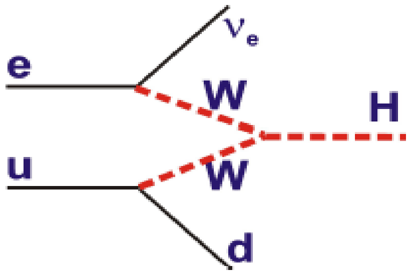


C. Gwenlan, DIS2019



THE CASE FOR LHeC

- **ep as a Higgs factory (LHeC and other options)**

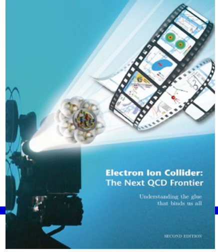


Future Colliders in a chart

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\rm inst}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

M. Cepeda, EPPSU Open Symposium 2019

- The values for $\sqrt{s}$ are approximate: when a scan is proposed: included in the closest value
- When the entire programme is discussed, the highest energy value label is used inclusively



EIC

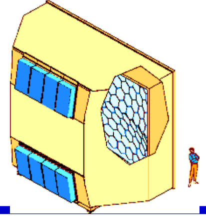
"SPECIFICATION":

World First
- polarized e-p/light A collider
- eA collider

- spanning a wide kinematical range
  - **ECM: 20 – 100 GeV, extendable up 140 GeV**
- High luminosity
  - **up to 10^{34} cm^{-2} s^{-1}**
- **highly polarized e (~ 80%) beams**
- **highly polarized light A (~70%) beams**
- wide variety of ions: **from H to Pb/U**
- **True 4π-coverage**
  - **Fully integrated detector-IR**
- **Experiments with high acceptance PID systems (e/h, h identification)**
- **Tagging all nuclear fragments**

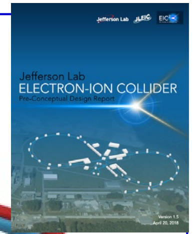
collider design

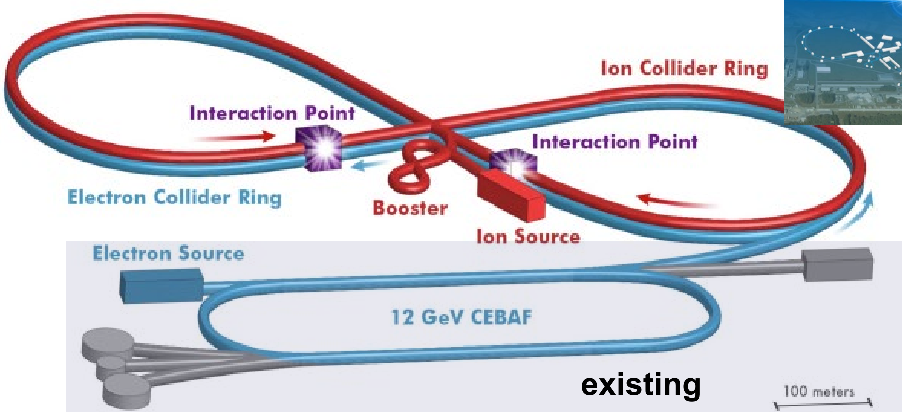
experiment design



THE 2 OPTIONS FOR THE EIC

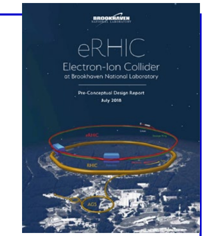
▪ JLEIC @ Jlab

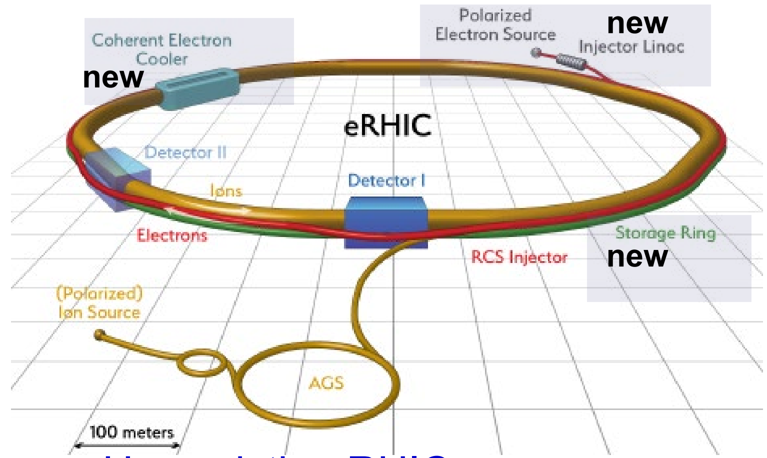




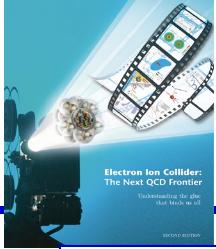
- Use existing CEBAF as polarized e injector
- Figure 8 Layout: Optimized for high ion beam polarization
- • Energy Range: √s : 20 to 65 – upgradable to 140 GeV (magnet technology choice)
- Full luminosity from the beginning
- Staging in energy, with technology choice determining initial one, and upgraded energy reach

▪ eRHIC @ BNL





- Use existing RHIC: up to 275 GeV polarized p
  - tunnel, detector halls & hadron injector complex
  - Strong p cooling needed for full luminosity
- Add
  - 400 MeV, 10 nC guns at 1Hz linear injector
  - 18 GeV injector in the same tunnel
  - 5-18 GeV electron storage ring in the same tunnel
- Energy range: √s 29-140 GeV
- Full energy range from the beginning
- Staging for the full luminosity reach

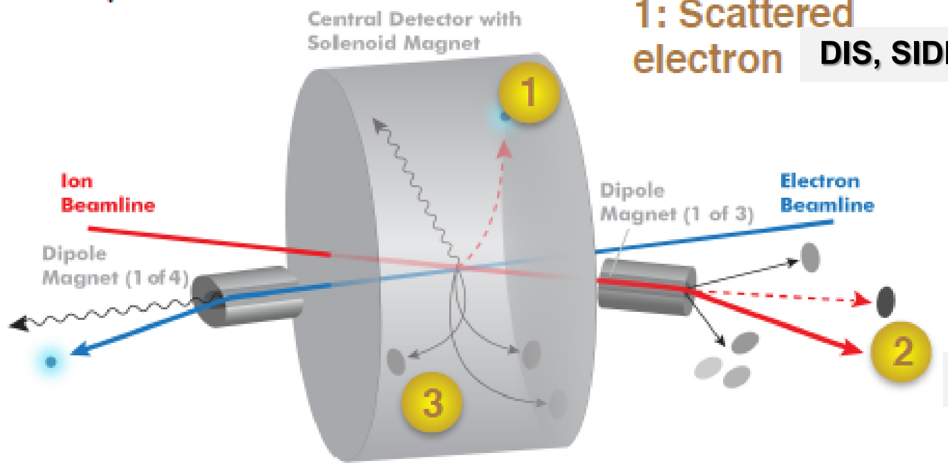


EIC DETECTOR CONCEPTS

❑ Overview of general requirements

arXiv:1212.1701

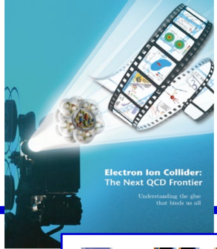
3: Nuclear and nucleonic fragments / scattered proton
exclusive



1: Scattered electron
DIS, SIDIS, exclusive

2: Fragmented particles (e.g. π, K, p) of struck quark
SIDIS, exclusive

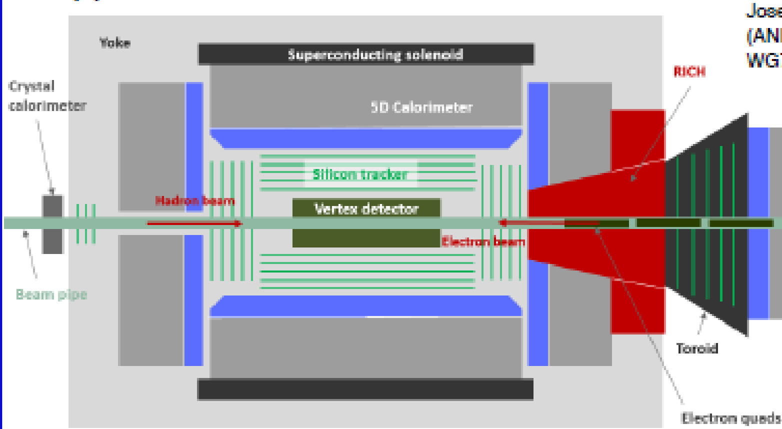
- Acceptance: Close to 4π coverage with a η-coverage (η = -ln(tan(θ/2)) of approximately η < |3.5| combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage
- Low dead material budget in particular in rear direction (~5% X/X_0)
- Good momentum resolution Δp/p ~ few %
- Electron ID for e/h separation varies with θ / η at the level of 1:10^4 / ~2-3%/√E for η<-2 and ~7%/√E for -2<η<1
- Particle ID for π/K/p separation over wide momentum range (Forward η up to ~50GeV/c / Barrel η up to ~4GeV/c / Rear η up to ~6 GeV/c)
- High spatial vertex resolution ~ 10-20μm for vertex reconstruction
- Low-angel taggers:
  - Forward proton / A fragment spectrometer (Roman pots)
  - Low Q^2 tagger
  - Neutrons on hadron direction
- Luminosity (Absolute and relative) and local polarization direction measurement



EIC DETECTOR CONCEPTS

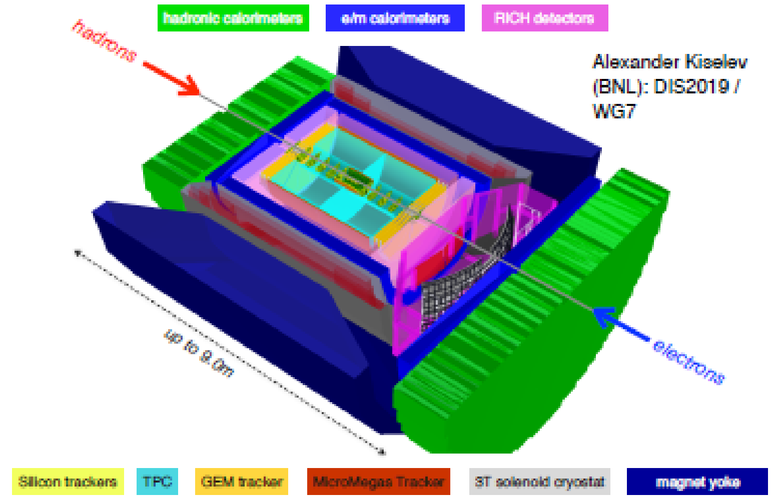
❑ EIC detector design at JLab and BNL

(a) TOPSIDE at JLab:



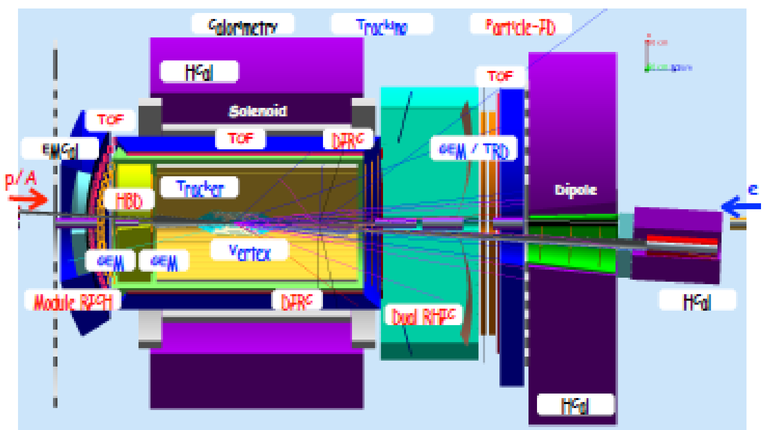
Jose Repond (ANL): DIS 2019 / WG7

(c) BEAST detector design at BNL:

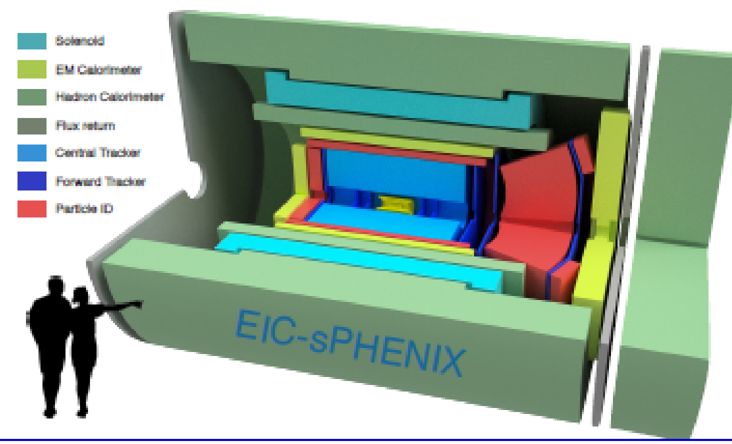


Alexander Kiselev (BNL): DIS2019 / WG7

(b) JLEIC detector design at JLab:



(d) sPHENIX-EIC detector design at BNL:

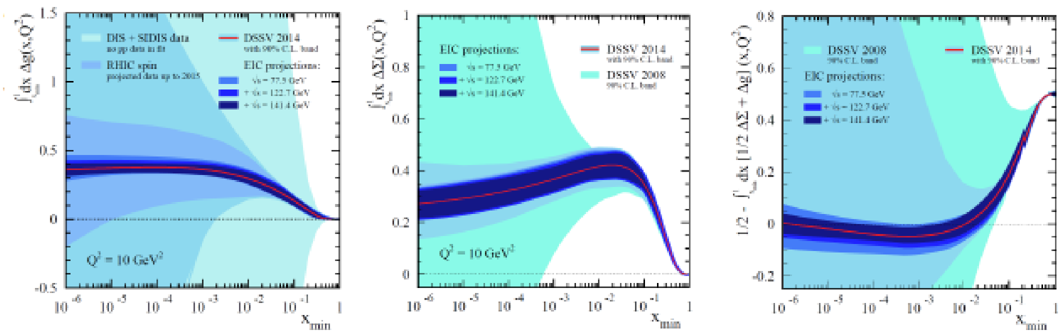


THE CASE FOR EIC

It is more than the number ½ ! It is the interplay between
the intrinsic properties and interactions of quarks and gluons

What do we know:

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\left| J^z_{QCD} \right| P,\frac{1}{2}\right\rangle = \underbrace{\frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)}_{\text{total quark spin}} + \underbrace{\int_0^1 dx\Delta G(x,Q^2)}_{\text{gluon spin}} + \underbrace{\int_0^1 dx\left(\sum_q L_q^z + L_g^z\right)}_{\text{angular momentum}}$$

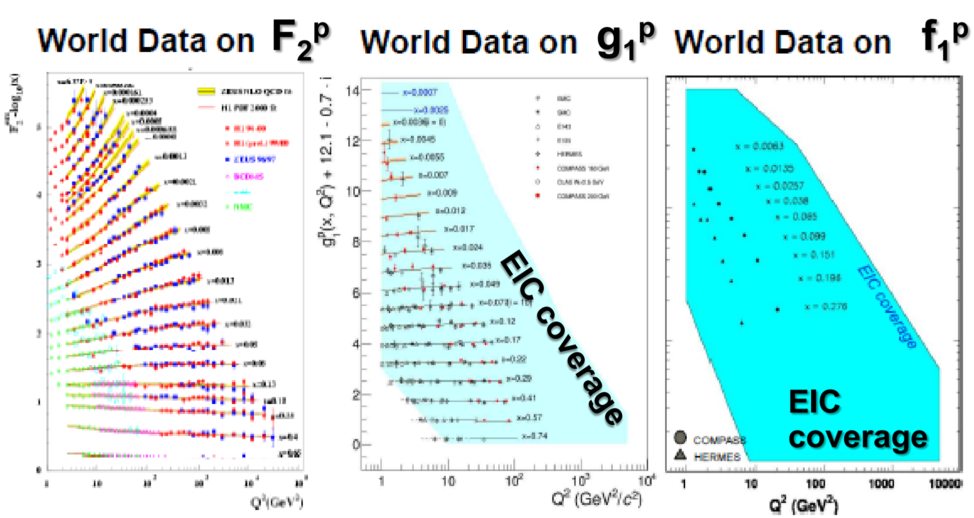


1/2 - Gluon $_{40\%}$ - Quarks $_{30\%}$ = orbital angular momentum

Understanding the N spin

A. Bressan, "Prospettive per fisica adronica e collisionatori adronici"

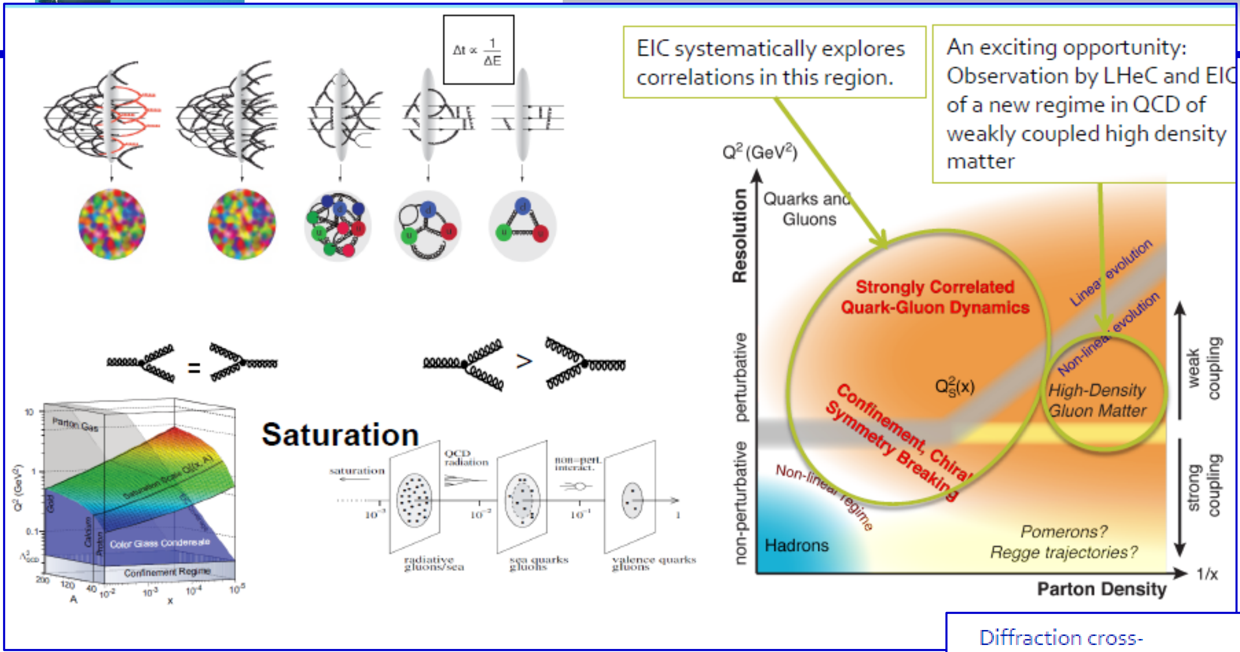
transverse momentum dependent (TMD) distributions



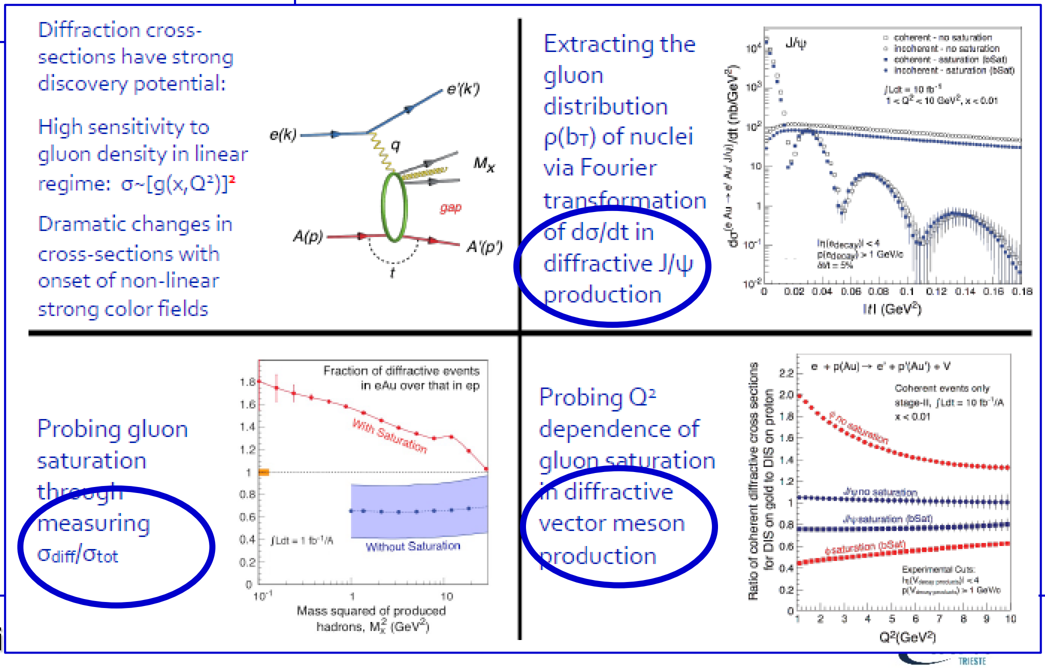
momentum

spin

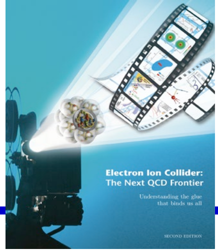
transverse spin ~ angular momentum



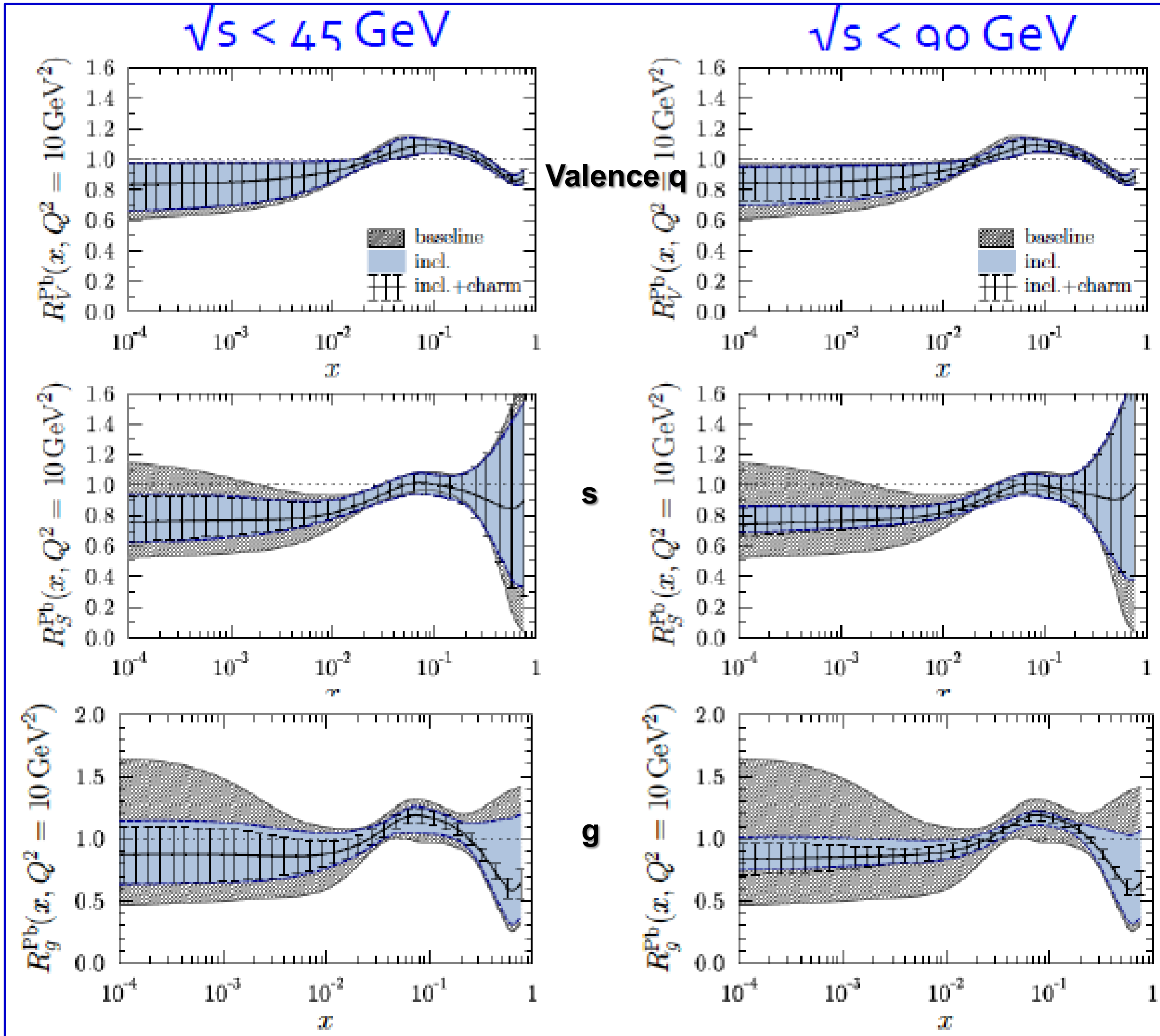
Evolution of the N see



Diffraction cross-section as a powerful tool to access gluon saturation

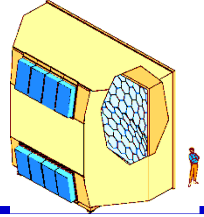


EIC – IMPACT on NUCLEAR PDFs



Ratio of PDF of Pb over Proton

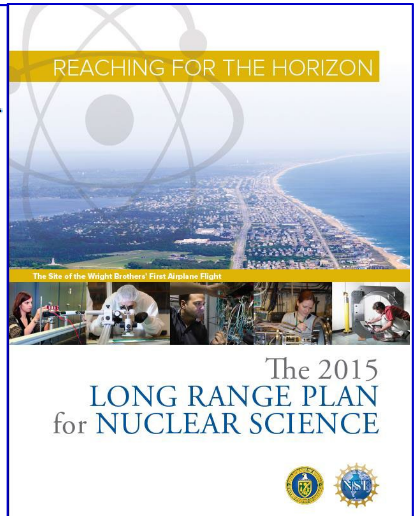
- ❑ Without EIC, large uncertainties
  → With EIC significantly reduced uncertainties
- ❑ Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- ❑ Does the nucleus behave like a proton at low-x?
  → relevant to very high-energy cosmic ray studies
  → critical input to AA



EIC – the "nearest" COLLIDER

The project is strongly supported by the nuclear physics community.

Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.



An Assessment of
U.S.-Based Electron-Ion Collider Science

Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

NAS report, July 2018

The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely.

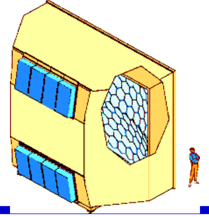
- **Next step: CD0 (Critical Decision)**
- **CD0 by 2019 ? a realistic option**

https://www.energy.gov/cfo/downloads/fy-2020-budget-justification

Volume 4 - DOE/CF-0154: EIC development part of the most recent DOE FY2020 Congressional Budget Request:

Pg. 10: "Funding is requested in FY 2020 for the start of R&D and conceptual design for a proposed U.S.-based Electron Ion Collider."

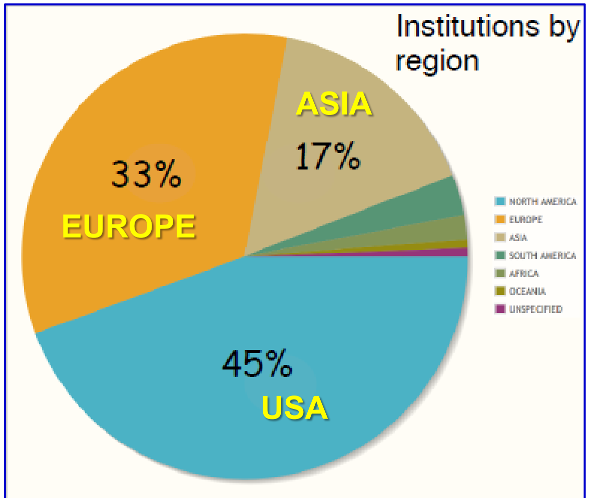
Pg. 276: "Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. Critical Decision-0, Approve Mission Need, is planned for FY 2019."



EIC – the "nearest" COLLIDER

A STRONG INTERNATIONAL COMMUNITY

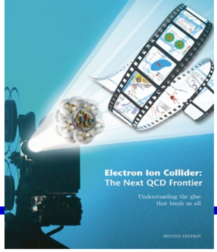
The EICUG (User Group)



supported R&D activities:

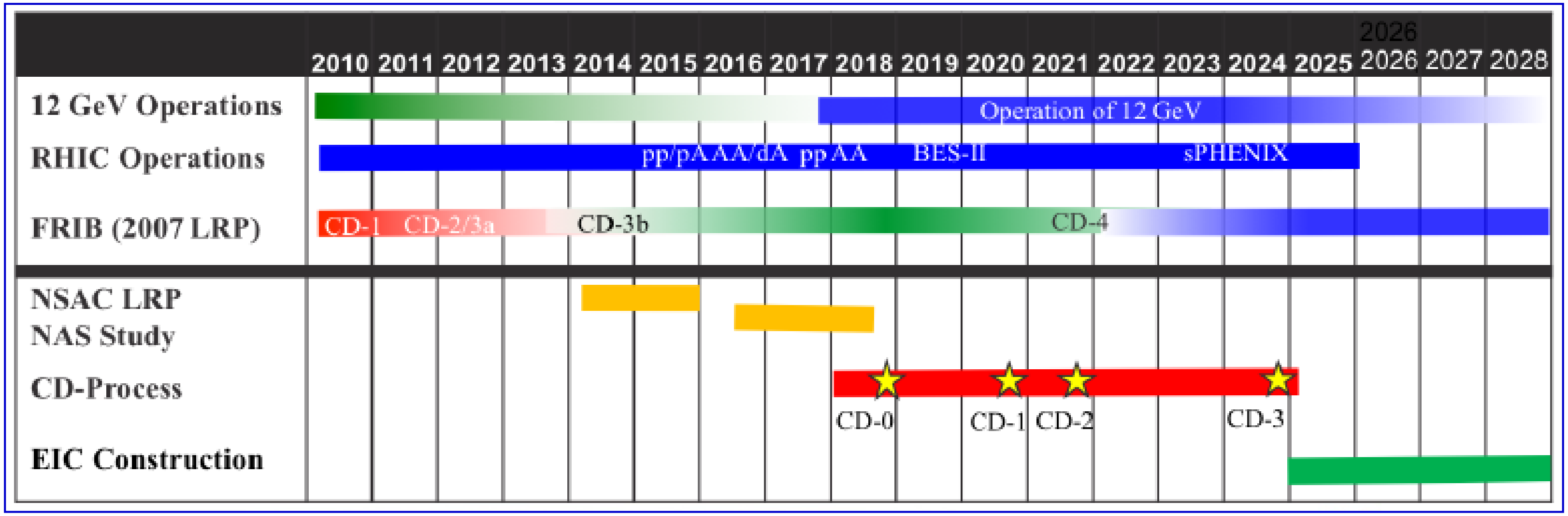
- **1M $ / y for detectors**
- **7M $ / y for accelerators**

- **Intense community activities**
  - Annual EICUG meetings
  - The annual dedicated conference (POETIC - Physics Opportunities at an ElecTron-Ion Collider)
  - And more …



EIC – the "nearest" COLLIDER

TIMELINES



Operation in about 10 y !

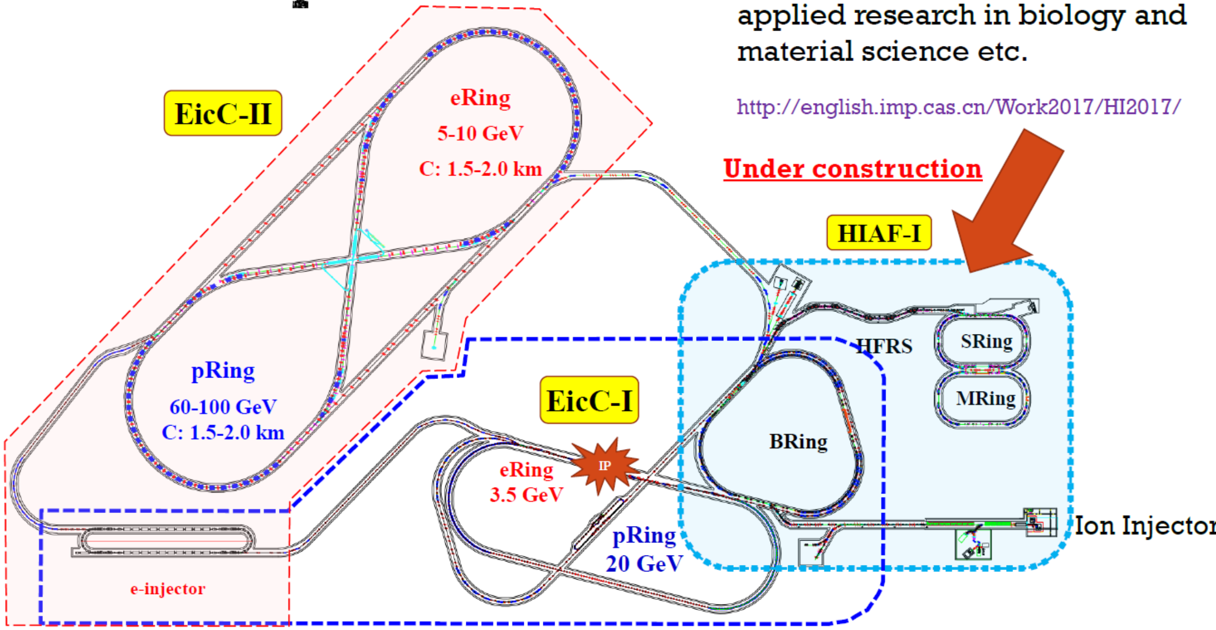
EicC (Chinese EIC)

Huizhou in Guangdong province

Accelerator complex overview

High intensity ion beams for atomic physics, nuclear physics, applied research in biology and material science etc.

http://english.imp.cas.cn/Work2017/HI2017/



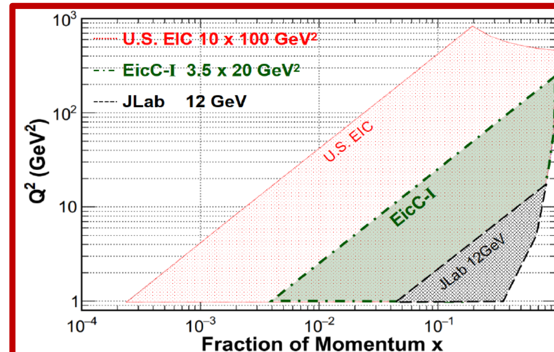
High-Intensity Heavy Ion Accelerator Facility (HIAF)

EicC white paper will be submitted to the government by the end of 2019

EicC-I:
Beam energy: 3.5 GeV e + 20 GeV P
Polarization: e 80%, P 70%
Inst. Lumi.: (1-5)×10^{33} $cm^{-2}s^{-1}$

Also D, He-3, heavy nuclear beam

EicC-II:
Beam energy: 10 GeV e + (60-200) GeV P
Polarization: e 80%, P 70%
Inst. Lumi.: up to 5×10^{34} $cm^{-2}s^{-1}$



Timeline for the project

CY	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
	5-year-plan			5-year-plan					5-year-plan					5-year-plan				
	HIAF																	
EicC-I				R&D														
									√s ~ 17GeV, $2x10^{33}/s/cm^2$									

R&D and construction (yellow)

In operation (green)

CONCLUSIONS

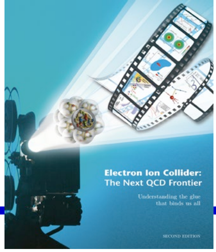
Perspectives for the Electron-Ion Colliders by the main facts

- **A large and active community at work**
  - **As also tested by the several projects all over the world**

- **Broad physics reach**
  - **Main center in understanding QCD**
  - **Key ingredients for high energy h colliders**
  - **And more (discovery opportunities)**

- **US EIC now very near to the real axis**
  - **Perspectives for CD0 in 2019**
- **Prospects exists also for other projects**
  - **The different projects are intrinsically complementary**

→ **A future where key issues in physics are accessed by Electron-Ion Colliders is in front of us**


Electron Ion Collider:
The Next QCD Frontier
Understanding the glue
that binds us all

THANK YOU