Andrea Bressan
University of Trieste and INFN

Prospettive per fisica adronica e collisioni e-adroni

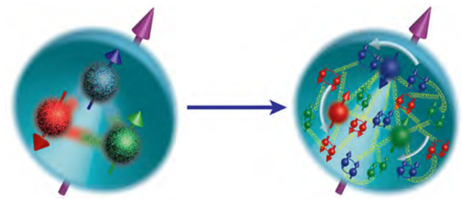
Disclaimer

- I will not cover the full hadron physics. In particular, I will :
  - Nor discuss the importance of the CERN fixed target program with extracted beams and the support that this deserves
  - Nor discuss the very interesting future/proposed fixed target measurement in the LHC
  - Nor cover FAIR or NICA
- I will elaborate over the progress in the knowledge that eventual new machines under discussion that can be in operation in a decade from now will bring to us
- Mainly I will concentrate on QCD In the low-energy region, it represents an extremely relativistic, strongly coupled, quantum many-body problem—one of the daunting challenges in theoretical physics

1 of 7 millennium prize problems, Clay Math. Institute, Cambridge, MA

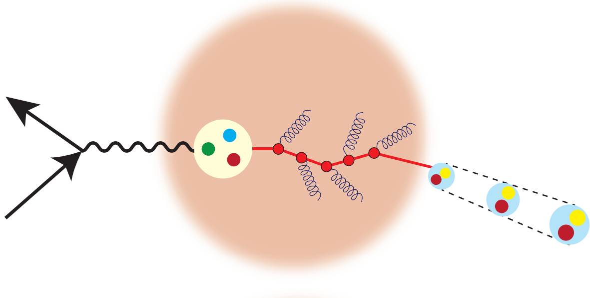
$1M prize to solve QCD! (E. Witten)

Hot Question in Cold QCD



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

How do the nucleon properties emerge from them and their interactions?



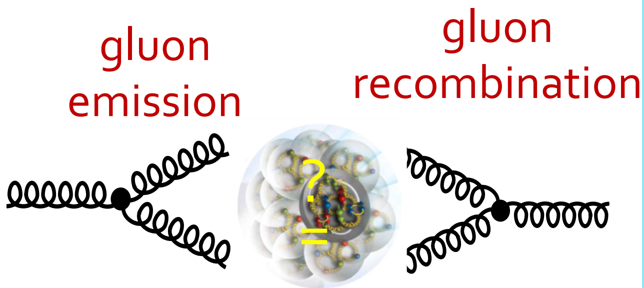
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

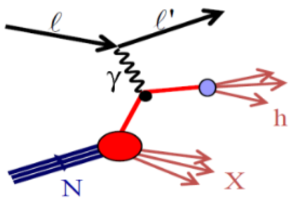
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



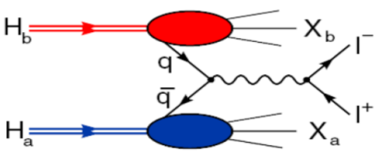
FACTORISATION

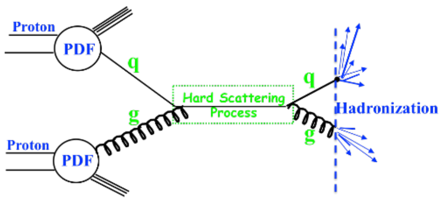
- DIS/SIDIS off polarized p, d, n targets



Cern/Hera/Jlab
future: ***eN colliders?***

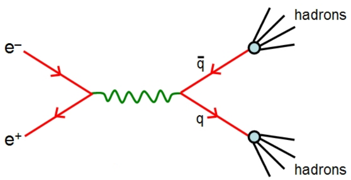
- Drell-Yan/W/jets in Hadron Hadron





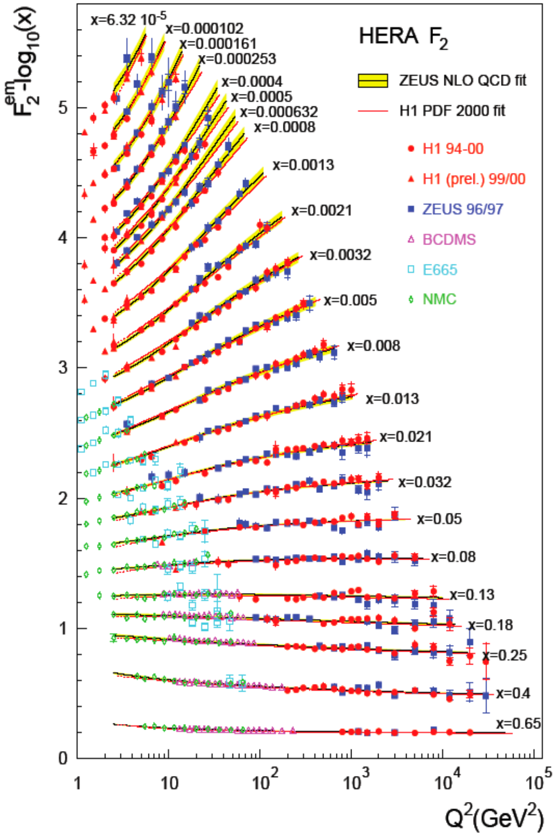
CERN(COMPASS/LHC)/RHIC/*FNAL*
future: ***FAIR, JPark, NICA***

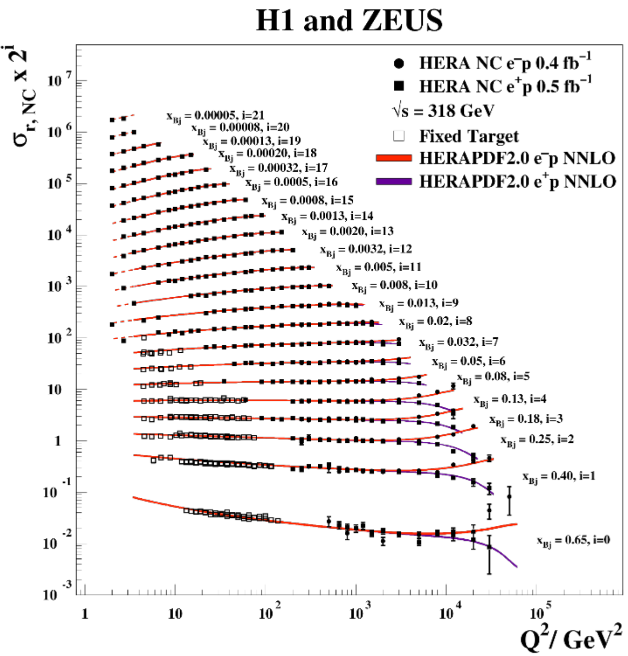
- $e^+ e^- \to h_1 h_2$

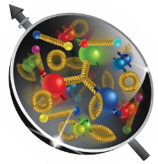


LEP/SLAC/BELLE/BES

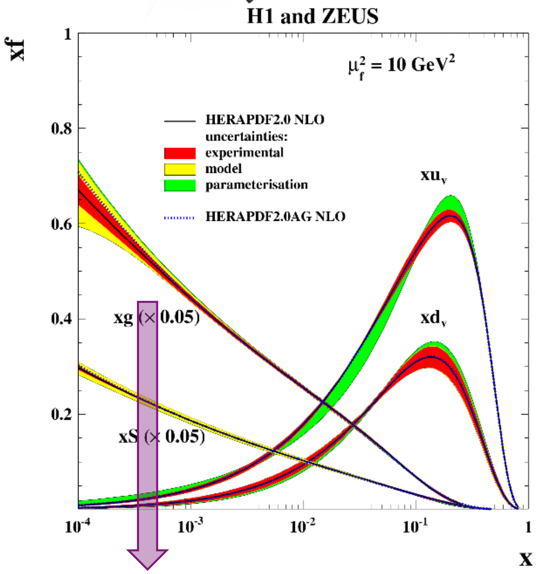
DIS – Hera Legacy







Gluons and "sea" quarks



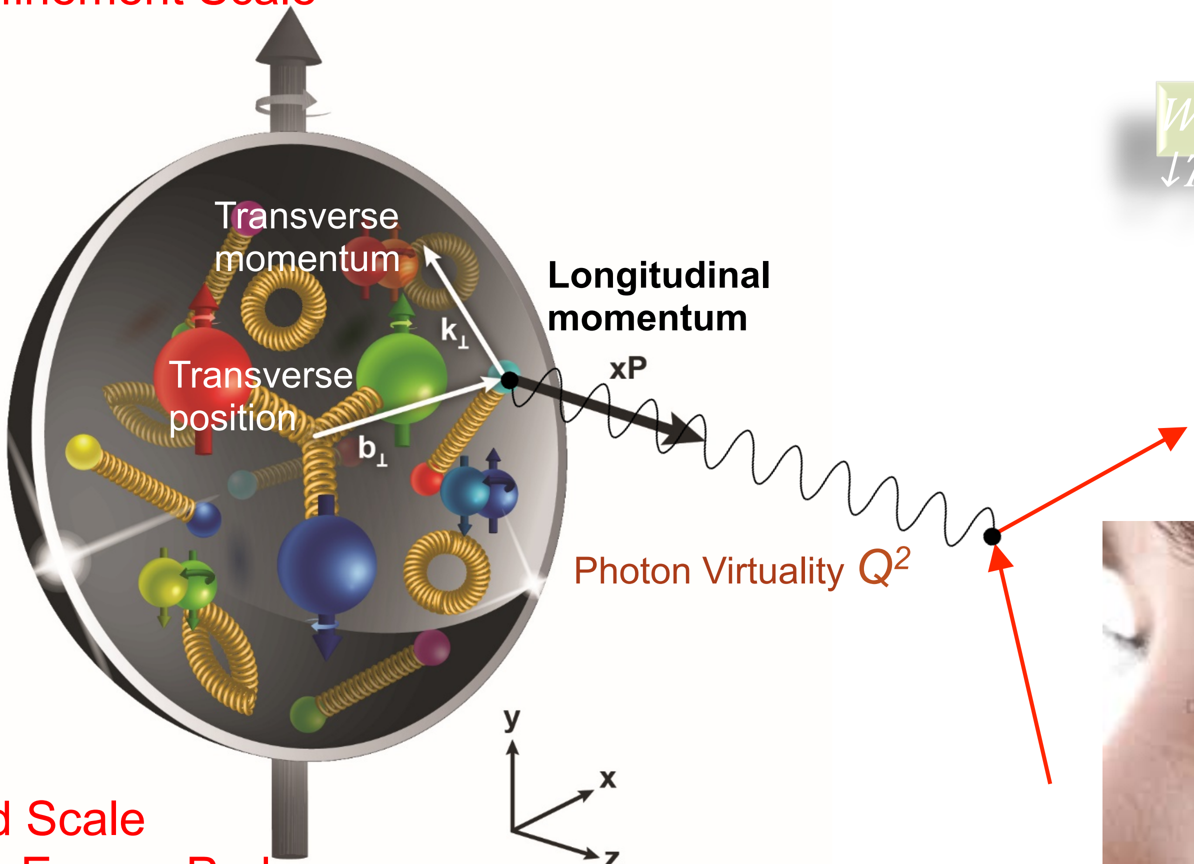
The proton at high energies (small) is dominated by glue!

Evolution from DGLAP (Dokshitzer–Gribov–Lipatov–*Altarelli–Parisi*)

Transverse structure of the Nucleon

Confinement Scale

$W_{p}^{q}(x, k_{\perp}, b_{T})$



Hard Scale
High Energy Probe

Unified view of the Nucleon

- Wigner distributions (Belitsky, Ji, Yuan)

5D $W_p^q(x, k_\perp, b_T)$
Wigner distributions

$\int d^2b_T$ $\int d^2k_\perp$

(X. Ji, D. Mueller, A. Radyushkin)

3D $f_p^q(x, k_\perp)$
TMD PDFs: SIDIS

$f_p^q(x, b_T)$
Impact Parameter Ds

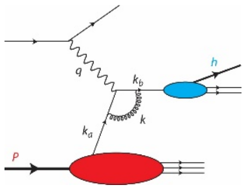
F.T. $b_T \Leftrightarrow \Delta$ → $H_p^q(x,0,t)$, $\xi=0$, $t=-\Delta^2$ ← $H_p^q(x,\xi,t)$
GPDs: Exclusive

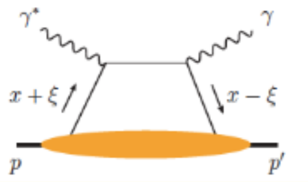
$\int d^2k_\perp$ $\int d^2b_T$ $\int dx$ $\int x^{n-1} dx$

1D $f_p^q(x)$
PDFs: DIS and SIDIS

$F(t)$
FFs: Elastic Scattering

$A_{n,0}(t)+4\xi^2 A_{n,2}(t)$
GFFs: Lattice

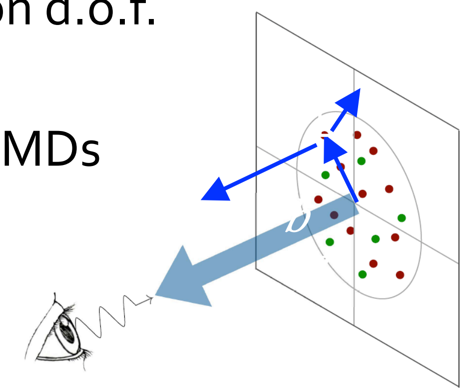




Confined parton motion in a hadron

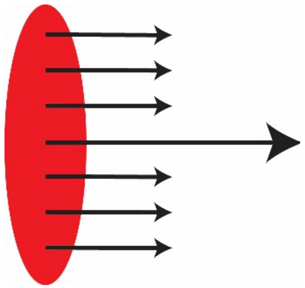
- Scattering with a large momentum transfer
  - Momentum scale of the hard probe $Q \gg 1/R \sim 1\ \text{fm}^{-1} \sim \Lambda_{QCD}$
  - Combined motion $\sim 1/R$ is too week to be sensitive to the hard probe
  - Collinear factorization – integrated into PDFs

- Scattering with multiple momentum scales observed
  - Two-scale observables (such as low P_{hT} SIDIS, low p_T Drell-Yan) $Q \gg q_T \sim 1/R \sim \Lambda_{QCD} \sim 1\ \text{fm}$
  - “Hard” scale Q localizes the probe to see the quark or gluon d.o.f.
  - “Soft” scale q_T could be sensitive to the confined motion
  - TMD factorization: the confined motion is encoded into TMDs

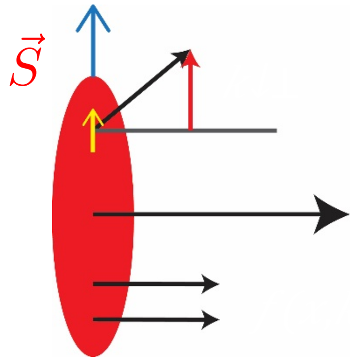


Structure of proton

- Transverse Momentum Dependent parton distribution (TMDs)



Longitudinal motion only



Longitudinal + transverse motion

- Sivers function: an asymmetric parton distribution in a transversely polarized nucleon ($k_{\perp}$ correlated with the spin of the nucleon)

- Boer-Mulders function: an asymmetric parton distribution in an unpolarised nucleon ($k_{\perp}$ correlated with the spin of the quark)

TMD evolution:

- QCD evolution of TMDs in Fourier space (solution of equation)

$$C\otimes F(x, c/b^*)\exp\{-\int_{c/b^*}^{Q_f} d\mu/\mu \,(A\ln Q_f^2/\mu^2 + B)\}\times$$
$$\text{non-pert}\,(b,Q)]$$

Evolution of longitudinal/ collinear part

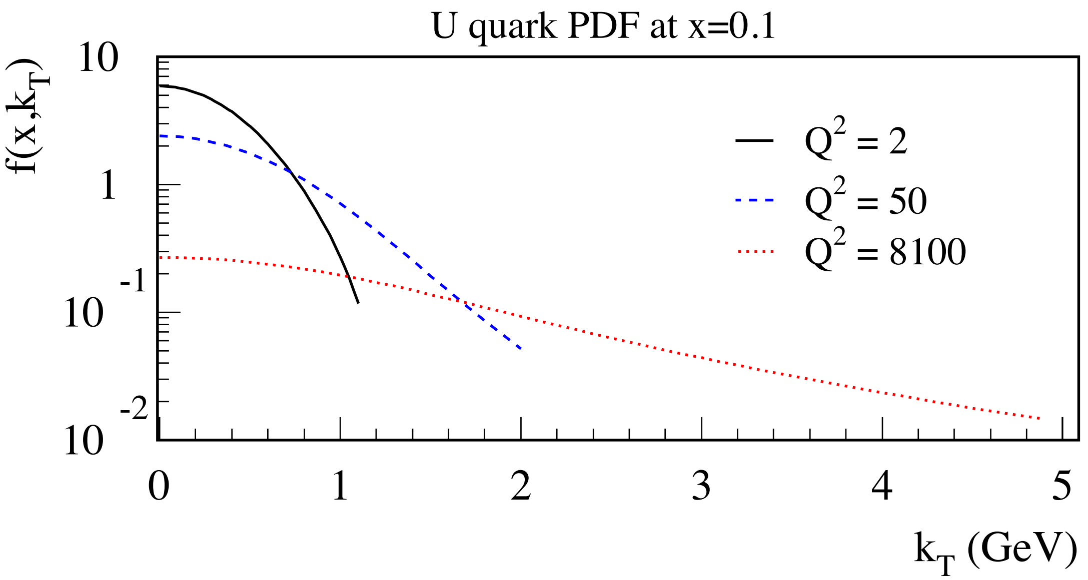
Evolution of transverse part (Sudakov form factor)

Non-perturbative part has to be fitted to experimental data
The key ingredient is spin-independent

- Polarized scattering data comes as ratio: e.g. $A_{UT}^{\sin(\phi_h-\phi_s)} = F_{UT}^{\sin(\phi_h-\phi_s)} / F_{UU}$
- Unpolarized data is very important to constrain/extract the key ingredient for the non-perturbative part

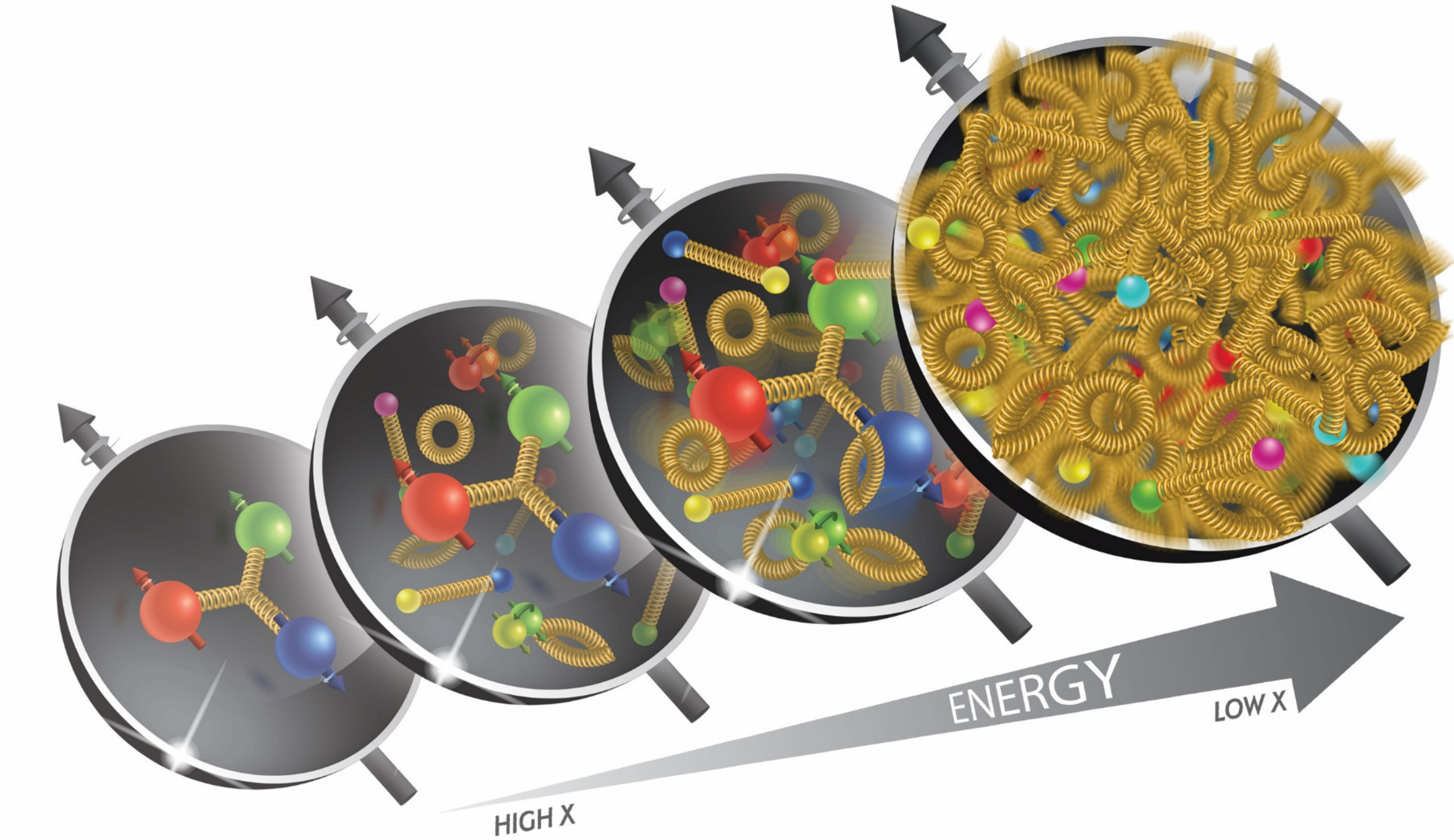
Effect of QCD evolution

- What evolution does
  - Spread out the distribution to much larger $k_\perp$. At low $k_\perp$, the distribution decreases due to this spread

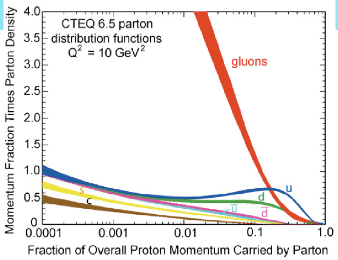


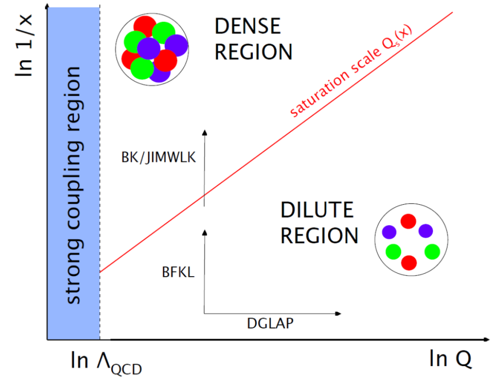
Echevarria, Idilbi, Kang, Vitev. Kang, Prokudin, Sun, Yuan

What is happening at low-x?



What do we learn from low-x studies?





What tames the low-x rise?

- New evolution eqn.s @ low x & moderate . Saturation Scale where gluon emission and recombination comparable

gluon emission

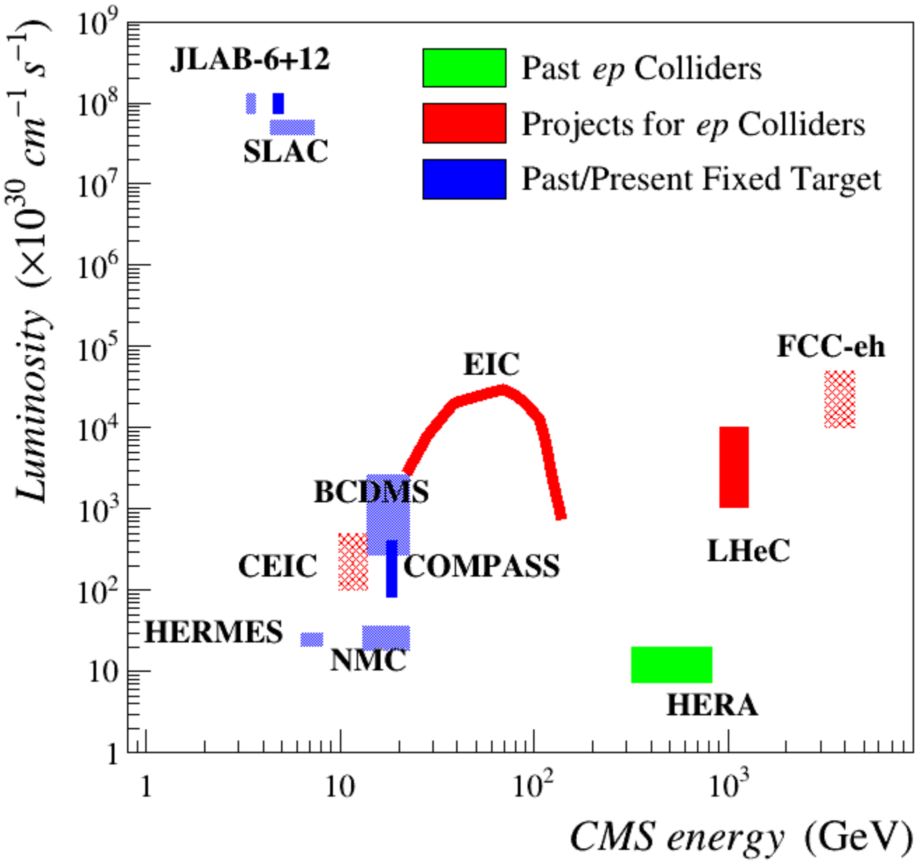
at Q_S

gluon recombination

Observation/study of gluon recombination effects in nuclei:
➔leading to a collective gluonic system!

→ Is this a universal property?
→ Is the Color Glass Condensate an appropriate effective theory?

DIS around the world



New QCD facility at CERN M2

https://arxiv.org/abs/1808.00848

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

August 3, 2018

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS

O.Yu. Denisov
on behalf of the working group:
"A New QCD Facility at the M2 beam line of the CERN SPS"*

Contents

*The final author list of the LoI will be finished in October 2018. Please send e-mail to NQF-M2@cern.ch for questions and requests.

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pr. H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified PT magnet
Input for DMS	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\overline{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisi-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

The Case for the LHeC

From the CDR 2012 to the time ahead 2018+

Particle Physics

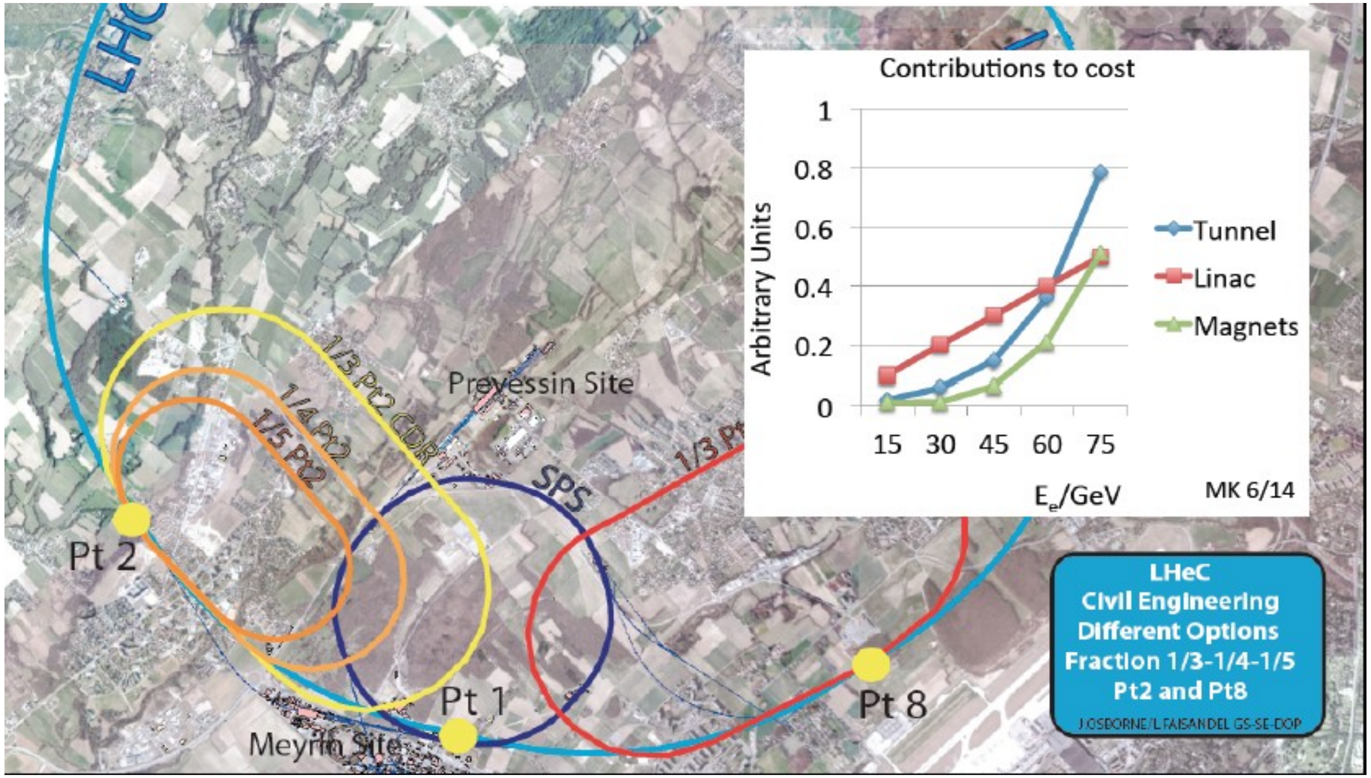
Physics Case

Preparations

http://lhec.web.cern.ch

Possibles LHeC locations

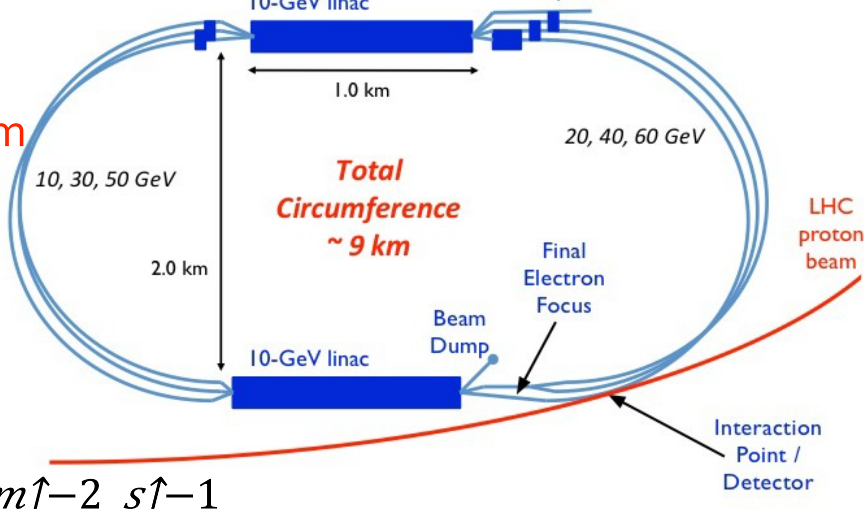
- Default design is 1/3 at Point 2 (currently ALICE)
- Point 8 (currently LHCb) has also been considered



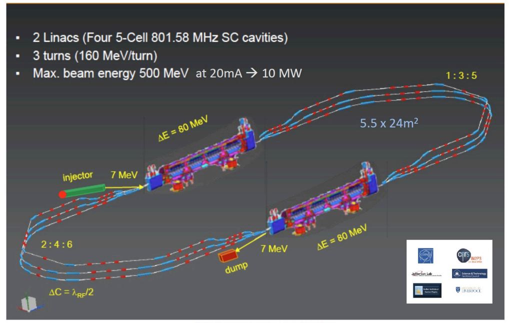
Baseline Design (Electron "Linac")

- LHeC CDR, July 2012 [arXiv:1206.2913]
- Design constraint: power consumption < 100 MW $\Rightarrow E_e = 60$ GeV

- Two 10 GeV linacs,
  - 3 returns, 20 MV/m
- Energy recovery in same structures



Powerful ERL for Experiments at Orsay



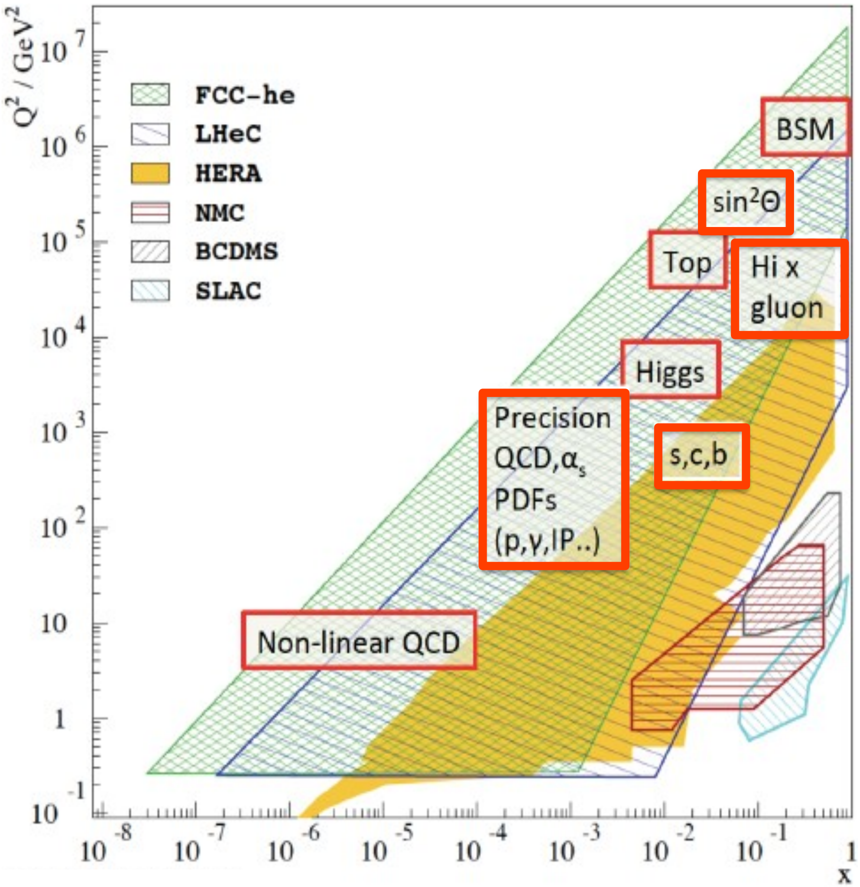
cf Walid Kaabi at Amsterdam FCC

New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

- ep lumi $\rightarrow 10^{34}\ cm^{-2}\ s^{-1}$

  $\Longrightarrow 100\ fb^{-1}$ per year - $1\ ab^{-1}$ in total
- eD and eA collision always been integral to the programme
- e-nucleon lumi estimates $\sim 10^{31}\ (3\times 10^{32})\ cm^{-2}\ s^{-1}$ for eD (ePb)
- Alternative design based on electron ring and on higher energy, lower lumi linac also exist

A Classic DIS Programme with the LHeC



Raison(s) d'etre of the LHeC

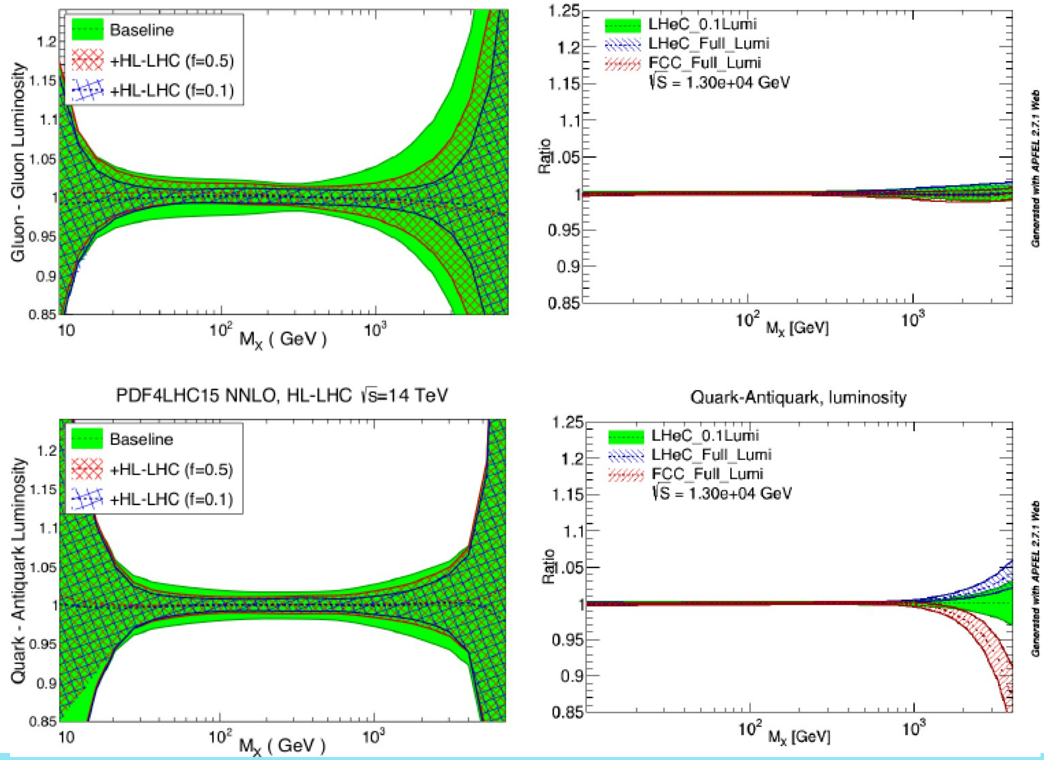
- Cleanest High Resolution Microscope: **QCD Discovery**
- Empowering the LHC Search Programme
- Transformation of LHC into high precision Higgs facility
- Discovery (top, H, heavy ν's..) Beyond the Standard Model
- A Unique **Nuclear Physics Facility**

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

PDF precision

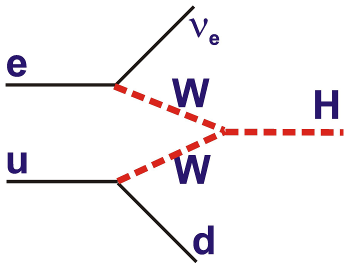
- Limits to the search of new physics at LHC will be dominated by the PDF uncertainty especially at high x, while f.i. medium x limit Higgs precision etc

Current data + LHC ‘ultimate Current data + LHeC



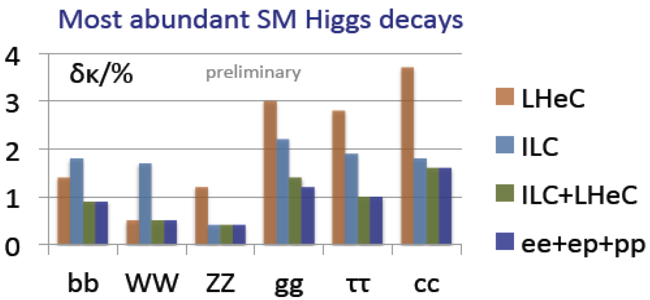
LHeC Standalone Higgs Sensitivity

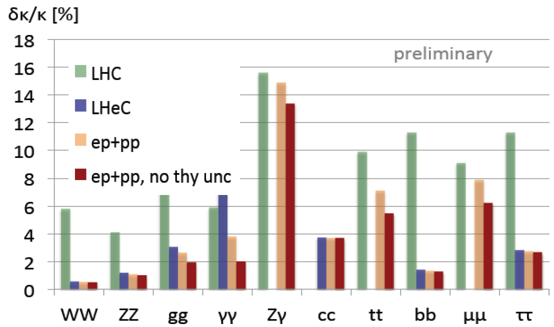
- Estimated integrated yields



Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

- Known production mode each event via WW(CC) or ZZ (NC)
- Detailed studies of bb, cc, extrapolations of LHC performance for other modes





Large Hadron Electron Collider on 1 page

E_e = 10-60 GeV, E_p =1-7 TeV: √s = 200 – 1300 GeV. **Kinematics**: $0 < Q^2 < s$, $1 > x \geq 10^{-6}$ (DIS)
Electron Polarisation P=±80%. Positrons: significantly lower intensity, unpolarised
Luminosity: $O(10^{34})$ $cm^{-2} s^{-1}$. integrated O(1) ab^{-1} for HL LHC and 2 ab^{-1} for HE LHC/FCCeh
e-ions 6 10^{32} $cm^{-2} s^{-1}$ O(10)fb^{-1} in ePb . O(1)fb^{-1} for ep F_L measurements

Physics: QCD: develop+break? The worlds best microscope. BSM (H, top, ν, SUSY..)
Transformations: Searches at LHC, LHC as Higgs Precision Facility, QCD of Nuclear Dynamics
The LHeC has a deep, unique QCD, H and BSM precision and discovery physics programme.

Time: Determined by the Large Hadron Collider (HL LHC needs till ~2040 for 3 ab^{-1})
LHeC: Detector Installation in 2 years, earliest in LS4 (2030/31).
HE LHC: re-use ERL. In between HL-HE, 10 years time of ERL Physics (laser, γγ..)
Very long term: FCC-eh

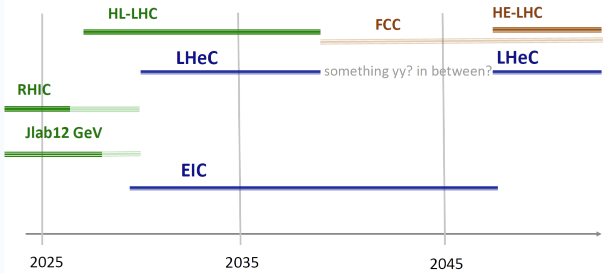
Challenges: Development of ERL Technology (high electron current, multi-turn)
Design 3-beam IR for concurrent ep+pp operation, New Detector with Taggers - in 10 years.

The LHeC is a great opportunity to sustain deep inelastic physics within future HEP.
The cost of an ep Higgs event is O(1/10) of that at any of the 4 e^+e^- machines under consideration
It can be done: the Linac is shorter than 2 miles and the time we have longer than HERA had.

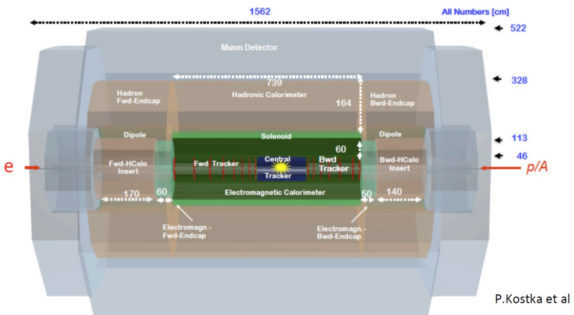
CERN and world HEP: Vital to make the High Luminosity LHC programme a success.

Max Klein Kobe 17.4.18

Projected Timelines for Future ep/eA Colliders



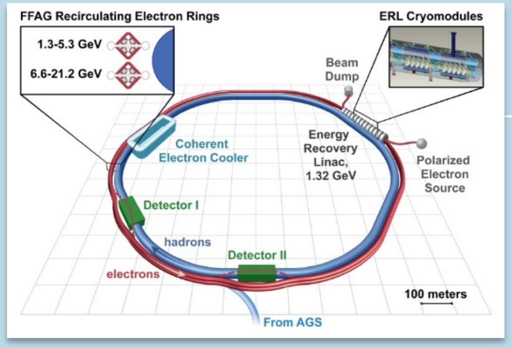
LHeC Detector for the HL/HE LHC

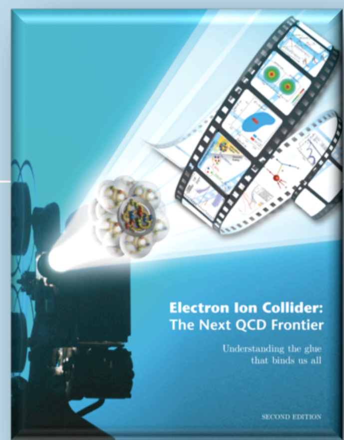


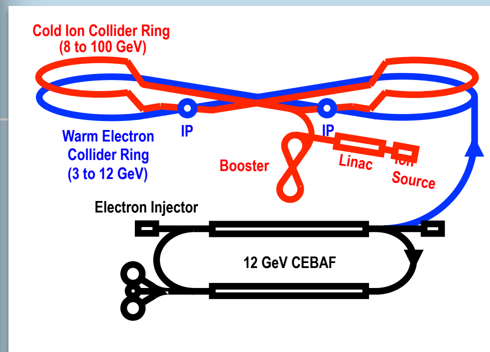
P.Kostka et al

Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)
ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

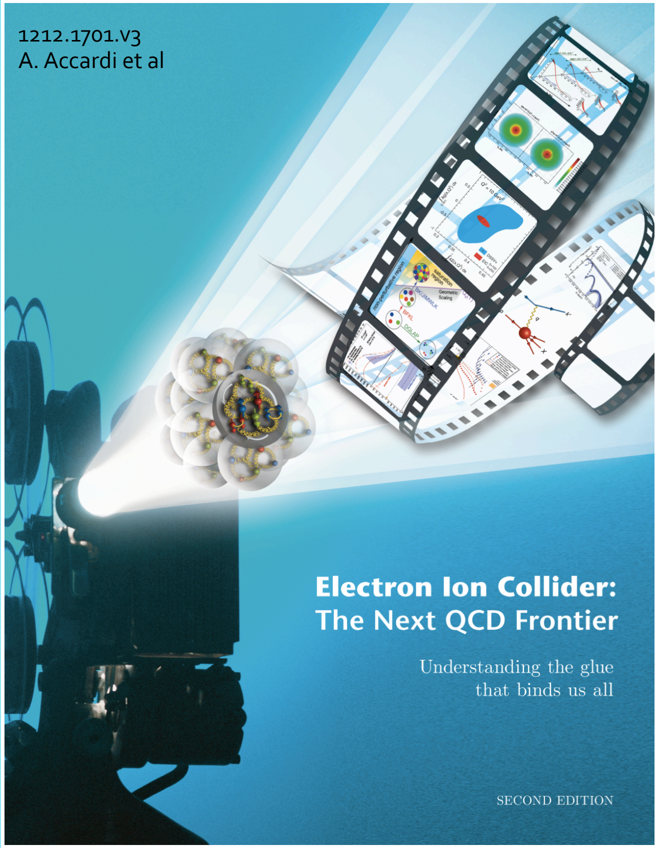
The Case for the EIC







The Electron Ion Collider



For e-N collisions at the EIC:

- ✓ Polarized beams:
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity

100-1000 times HERA

20-100 (140) GeV Variable CoM

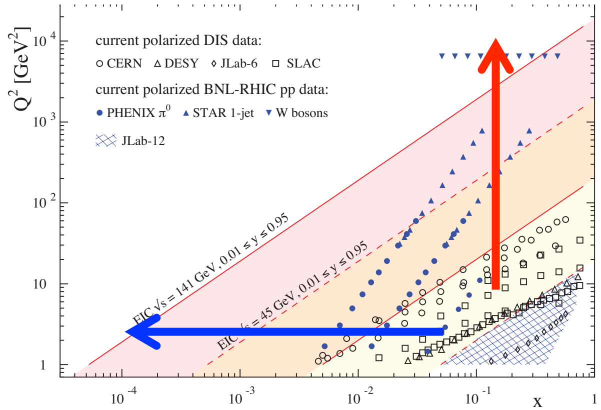
For e-A collisions at the EIC:

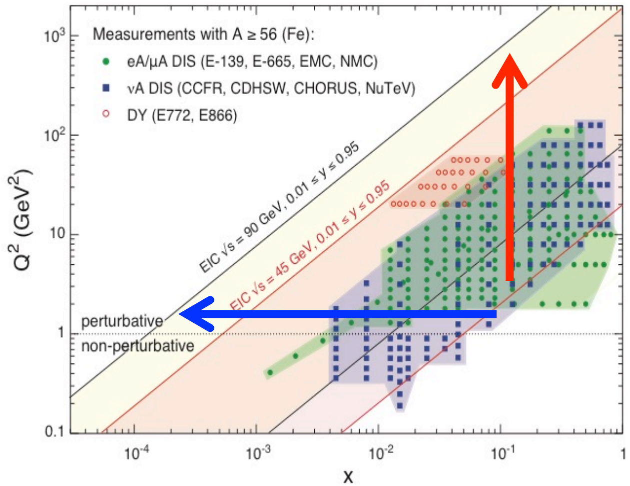
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as
- ✓ Variable center of mass energy

World's <u>first</u>

Polarized electron-proton/light ion

and electron-Nucleus collider





EIC Requirements

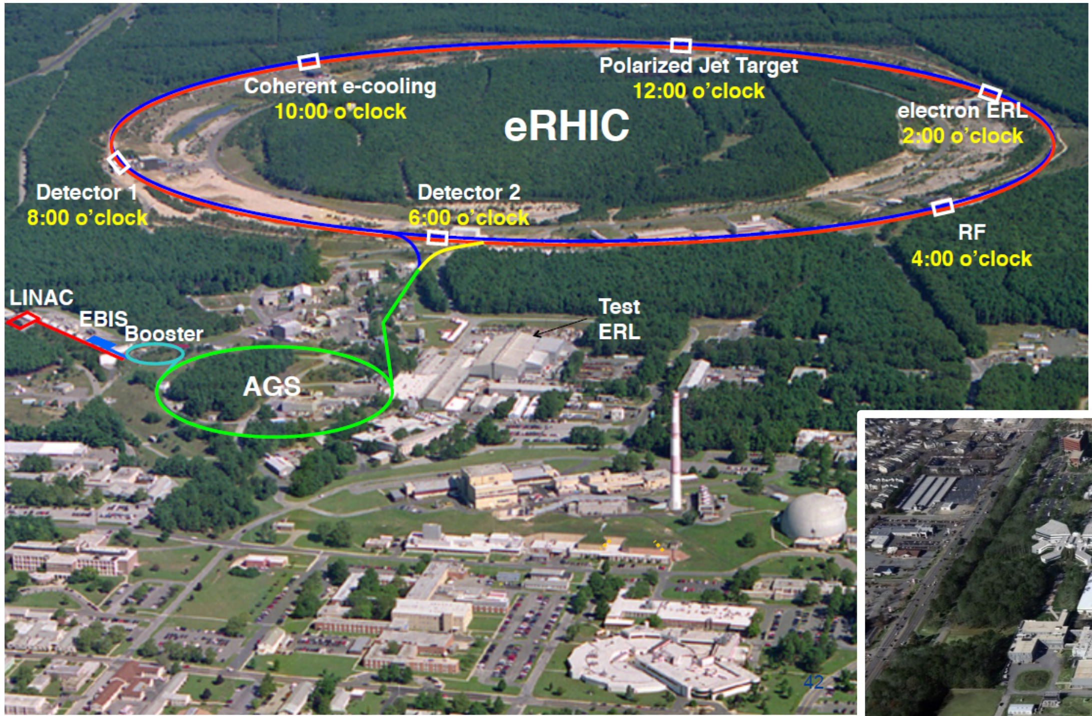
Requirements from Physics:

- ❑ High Luminosity: 10^{33-34} cm^{-2}s^{-1} and higher → nucleon/nuclei imaging
- ❑ Flexible center of mass energy → wide kinematic reach
- ❑ Electrons (0.8) and protons/light nuclei (0.7) highly polarized → study of spin structure
- ❑ Wide range of nuclear beams (D to Pb/U) → high gluon densities
- ❑ Room for a wide acceptance detector with good PID (e/h & π, K, p) → flavor dependence
- ❑ Full acceptance for tagging, exclusivity, protons from elastic reactions, neutrons from nuclear breakup → target/nuclear fragments

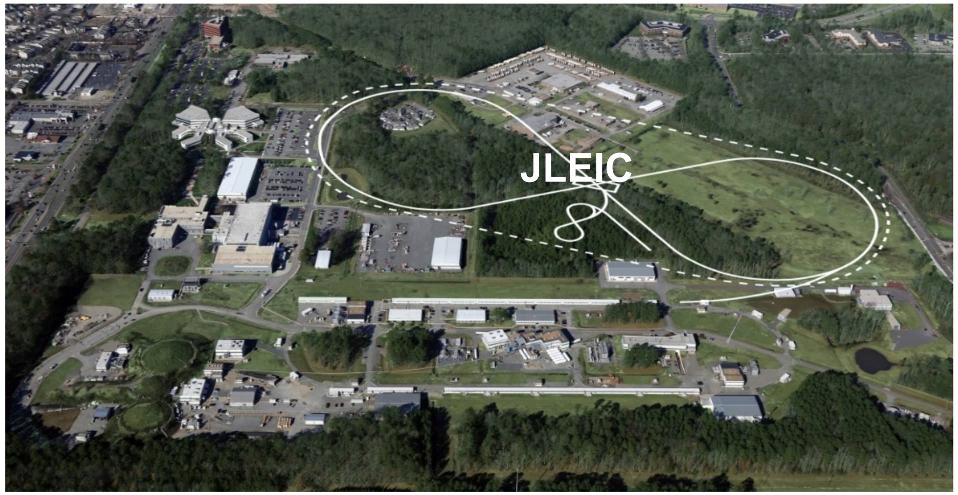
The "sweet spot" for the EIC parameters is a balance of

- High enough energies to reach high Q^2 (up to ~1000 GeV^2)
- Low enough proton energy to measure transverse scale of ~100 MeV well.
- High enough energy to explore collective effects towards saturation.
- High enough luminosity and good resolution for the nucleon/nuclei imaging.
- IR and Detector with acceptance and performance to fully measure the processes of relevance → **Polarized luminosity and the capability to measure physics of interest is what counts**

US-Based EICs

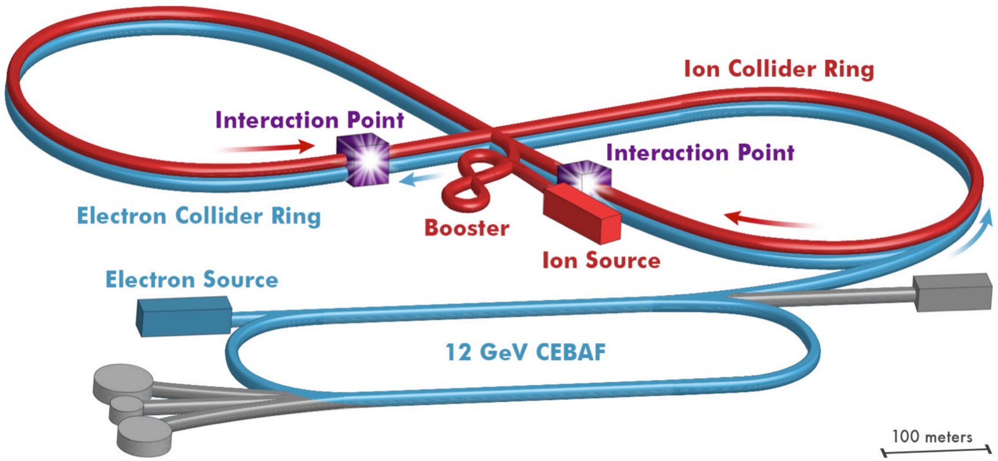


Brookhaven Lab
Long Island, NY



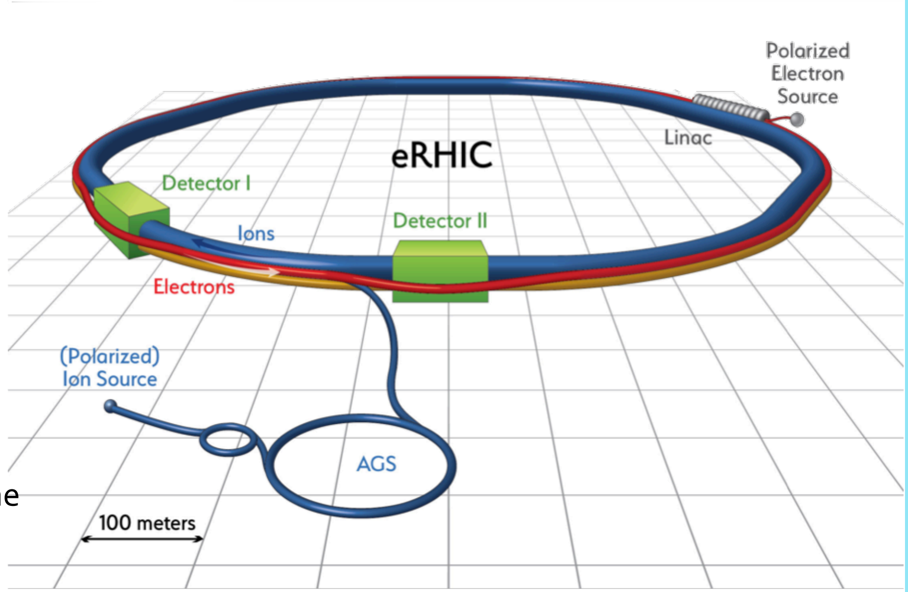
Jefferson Lab
Newport News, VA

JLEIC Realization



- Use existing CEBAF for polarized electron injector
- Figure 8 Layout: Optimized for high ion beam polarization → polarized deuterons
- Energy Range: $\sqrt{s}$: 20 to 65 - 140 GeV (magnet technology choice)
- Fully integrated detector/IR
- 50 mrad crossing
- Full luminosity from the beginning. Staging in energy, with technology choice determining initial and upgraded energy reach

eRHIC Realization



- Use existing RHIC
  - Up to 275 GeV protons
  - Existing: tunnel, detector halls & hadron injector complex
  - Proton cooling needed for full luminosity
- Add 10-18 GeV electron accelerator in the same tunnel
  - Use high intensity Electron Storage Ring (up to 2.5 A)
  - 400 MeV, 10 nC guns at 1Hz reversing polarization each time
  - 18 GeV on energy injector
- Achieve high luminosity, high energy e-p/A collisions with full acceptance detector
- Bunch frequency: 58 MHz to 115MHz
- 22 mrad crossing angle
- Full energy range covered from the beginning. Staging for the full luminosity reach

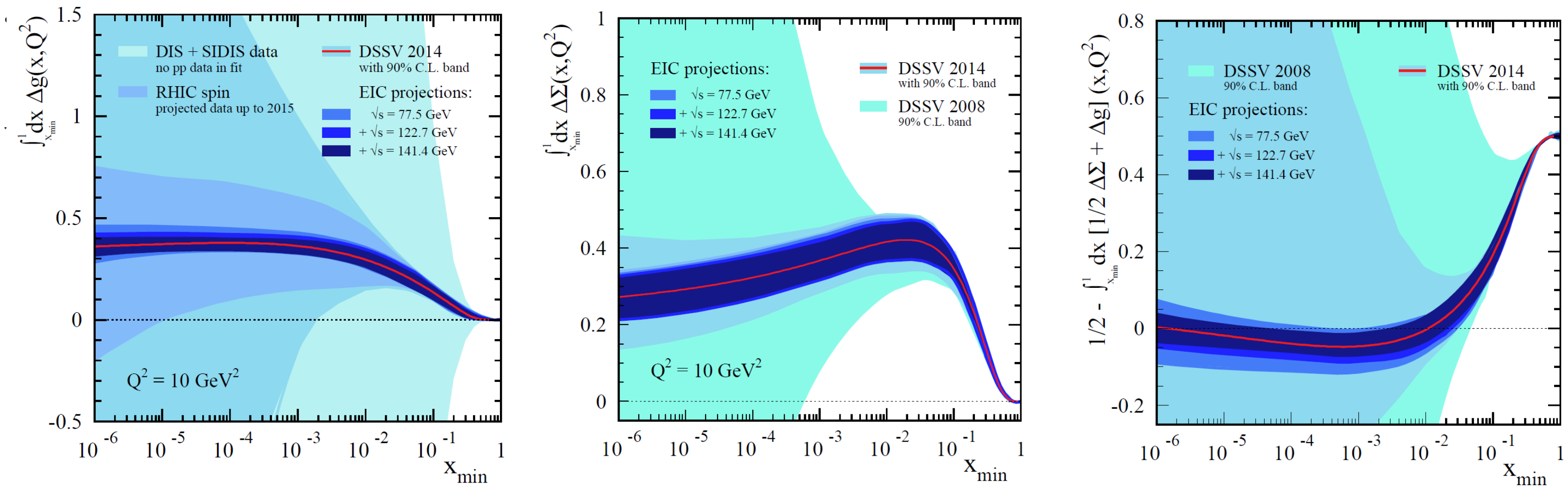
What forms the Spin of the Proton

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:

total quark spin — gluon spin — angular momentum

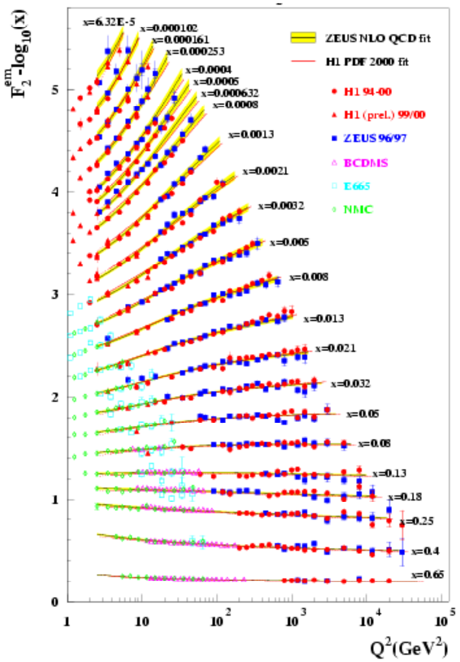
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle = \underbrace{\frac{1}{2}\int_0^1 dx \Delta\Sigma(x,Q^2)}_{\text{total quark spin}} + \underbrace{\int_0^1 dx \Delta G(x,Q^2)}_{\text{gluon spin}} + \underbrace{\int_0^1 dx \left(\sum_q L_q^z + L_g^z\right)}_{\text{angular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



1/2 - Gluon 40% - Quarks 30% = orbital angular momentum

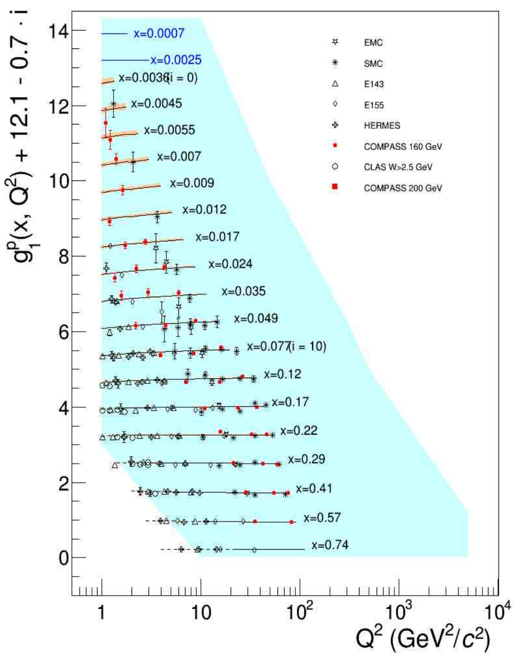
TMDs

World Data on



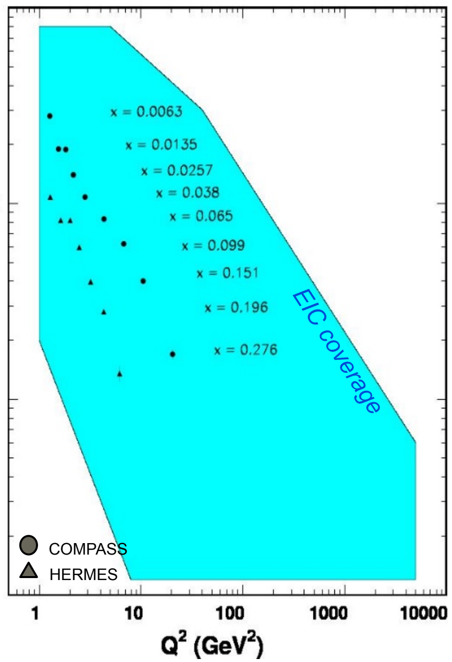
momentum

World Data on



spin

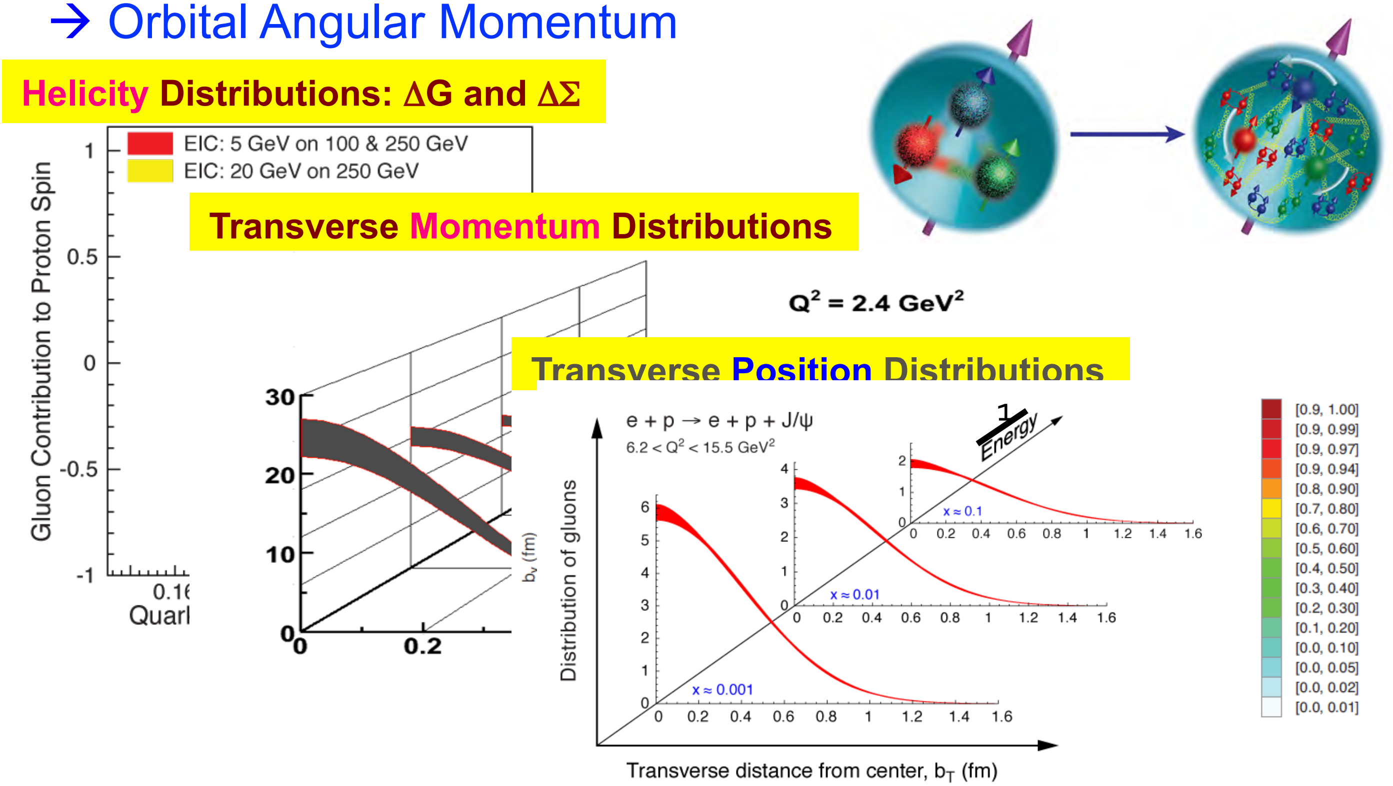
World Data on



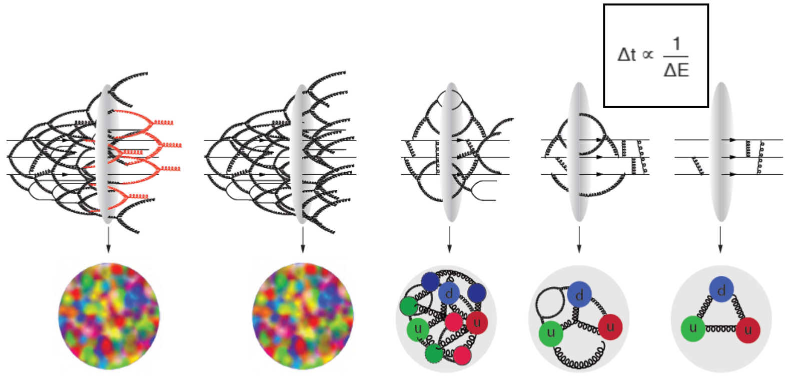
transverse spin ~ angular momentum

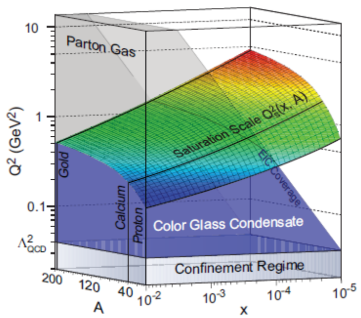
2+1 D partonic image of the proton

Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum

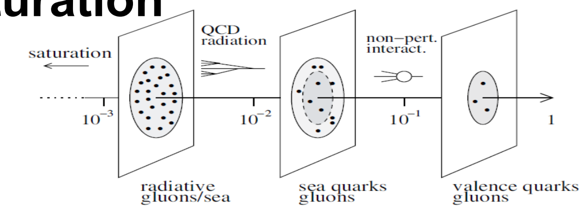


Evolution of a Proton – Deep into the Sea



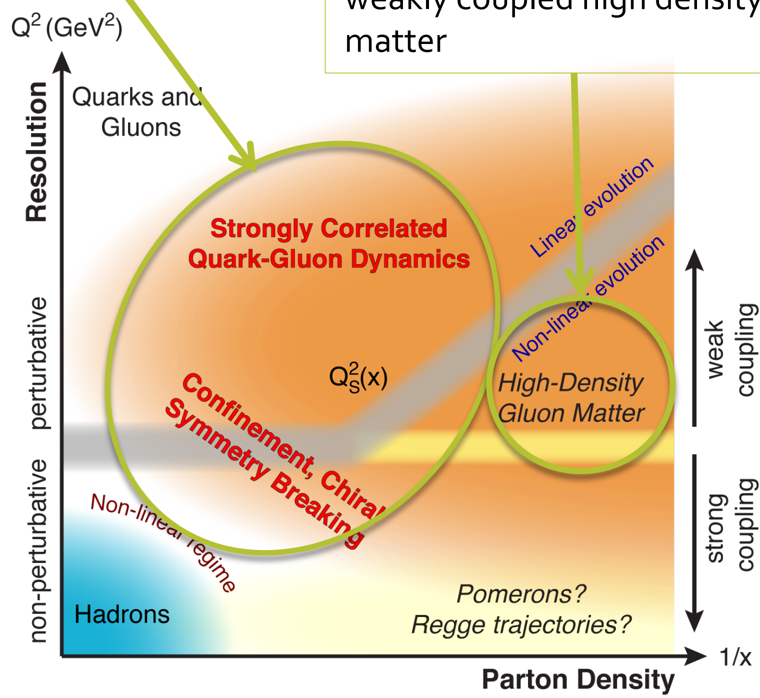


Saturation



EIC systematically explores correlations in this region.

An exciting opportunity: Observation by LHeC and EIC of a new regime in QCD of weakly coupled high density matter

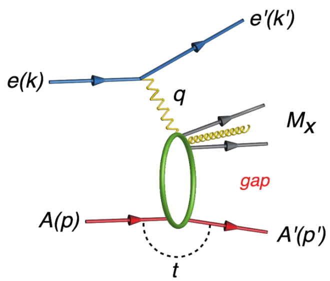


Diffraction: a signature of gluon saturation

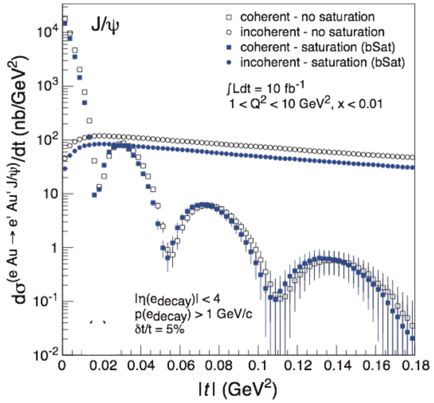
Diffraction cross-sections have strong discovery potential:

High sensitivity to gluon density in linear regime: σ~[g(x,Q²)]²

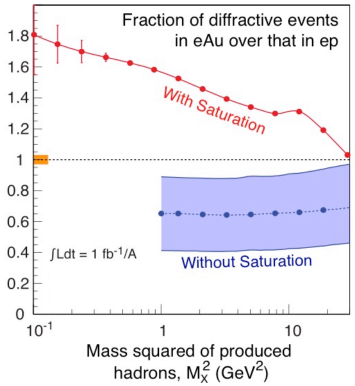
Dramatic changes in cross-sections with onset of non-linear strong color fields



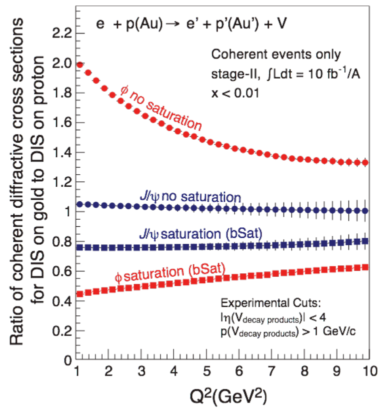
Extracting the gluon distribution ρ(b_T) of nuclei via Fourier transformation of dσ/dt in diffractive J/ψ production



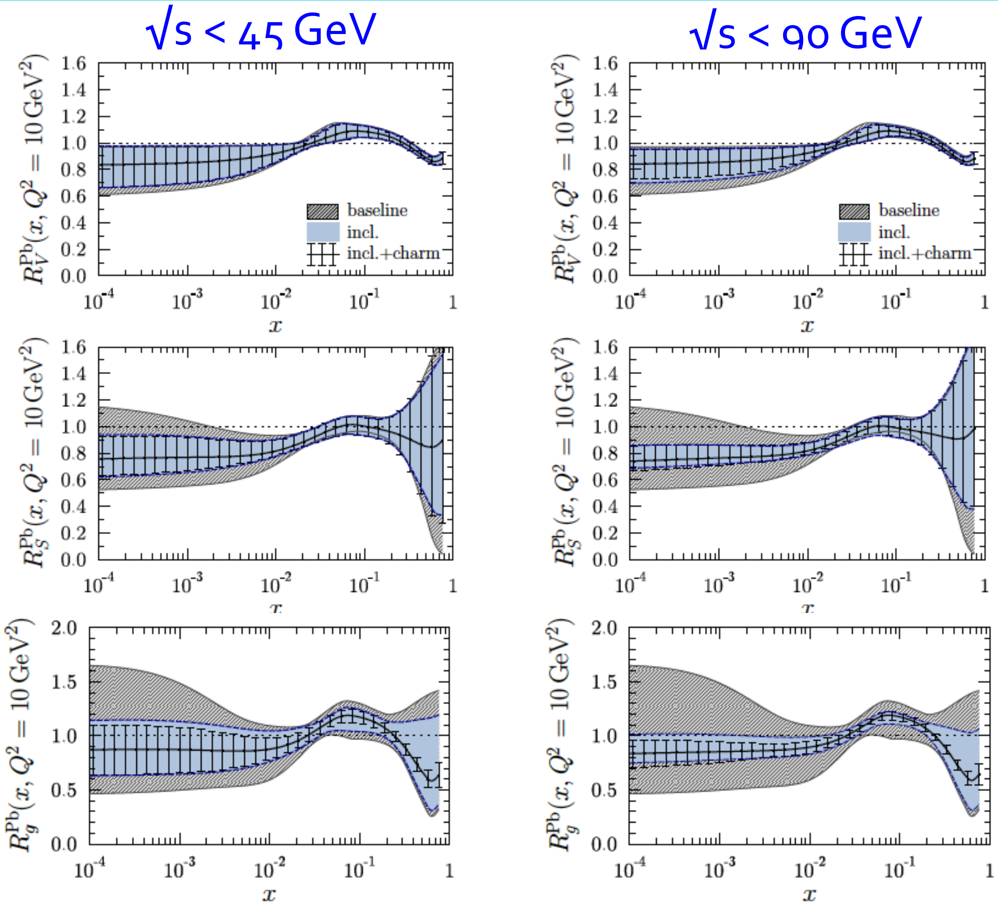
Probing gluon saturation through measuring $\sigma_{diff}/\sigma_{tot}$



Probing Q² dependence of gluon saturation in diffractive vector meson production



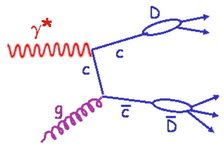
EIC: Impact on 1D Nuclear PDFs



Ratio of PDF of Pb over Proton

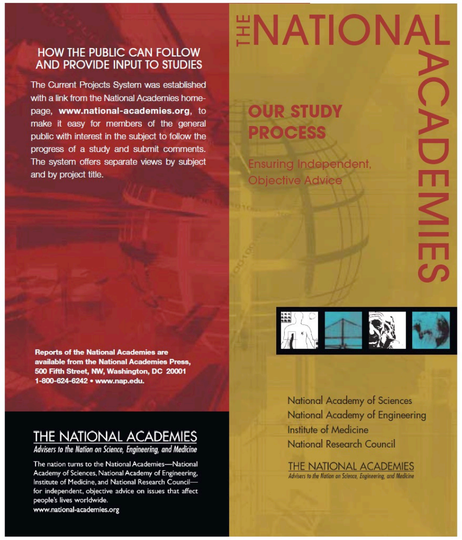
- Without EIC, large uncertainties
  → With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x?
  → relevant to very high-energy cosmic ray studies
  → critical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

Direct Access to gluons at medium to high x by tagging photon-gluon fusion through charm events



https://www.jlab.org/conferences/eicugm18/index.html

Academy of Science report



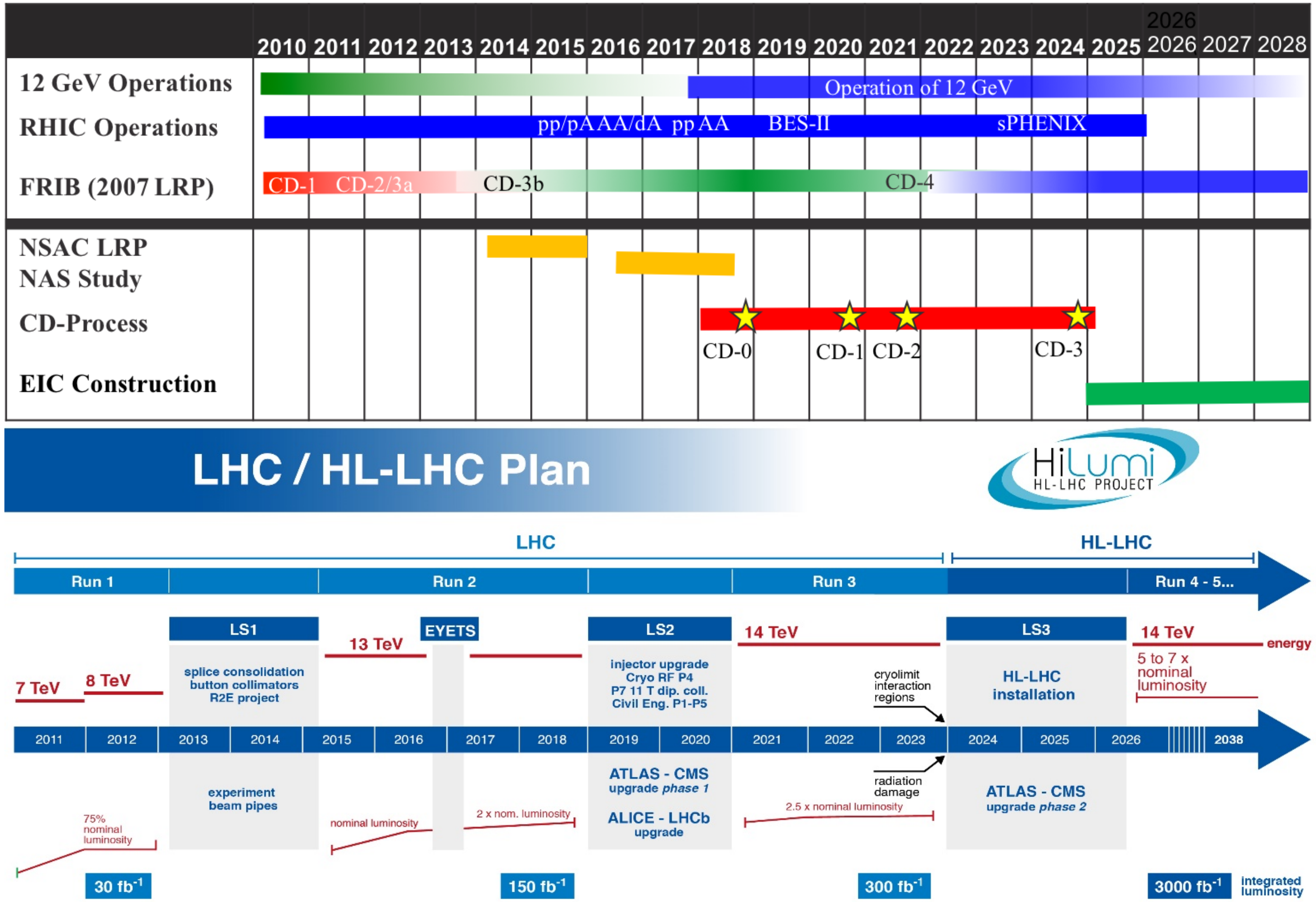
The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely.

The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be a unique facility in the world that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.

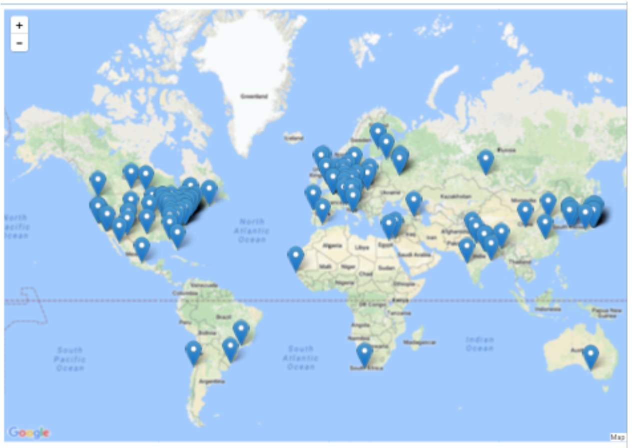
The project is strongly supported by the nuclear physics community.

The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

EIC Timeline



EIC User Community



Currently ~817 members from 173 institutions from 30 countries from 7 world regions
US: 45% Europe: 34% [Italy 10%] Asia: 16%

→ continuously growing
http://www.eicug.org

- Very active generic EIC detector R&D program: https://wiki.bnl.gov/conferences/index.php/EIC_R%25D
  37 groups collaborate in tracking, calorimeter, PID consortia and …….
- EIC Conference series: POETIC (Physics Opportunities at an ElecTron-Ion Collider)
  19th – 22nd of March 2018: Regensburg Germany
- Last EIC user group meeting: July 30 – August 3, 2018 at Catholic University Washington, DC
- INT-Program: Probing Nucleons and Nuclei in High-Energy Collisions (INT-18-3), October 1 – November 18, 2018.

Outlook

- There is a clear program of QCD studies outline already in 2012 both for EIC and LHeC
- Both machines are not cheap also but not very expensive “add-ons” over existing complex, optimizing the physics reach
- There is complementarity between LHeC and EIC. One is focused at the high energies that can be reach in conjunction with the LHC (now) and FCC in future. The other one have choosen a suit spot between the phase space coverage and the spin, TMD e GPD measurements
- There is a large community (more than 800, only staffs) and a strong support for the realization of the EIC in the US. The very positive outcome of the NAS review has paved (at least we hope) the way for the next formal steps toward the approval
- LHeC was supported at the level of R&D but it’s future is strongly linked to the this udate of the European Strategy


Back up

Findings

- Finding 1: An EIC can uniquely address three profound questions about nucleons —neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - *How does the mass of the nucleon arise?*
  - *How does the spin of the nucleon arise?*
  - *What are the emergent properties of dense systems of gluons?*
- Finding 2: These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.
- Finding 3: An EIC would be a unique facility in the world, and would maintain U.S. leadership in nuclear physics.
- Finding 4: An EIC would maintain U.S. leadership in the accelerator science and technology of colliders, and help to maintain scientific leadership more broadly.
- Finding 5: Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

Findings

- Finding 6: The current accelerator R&D program supported by the Department of Energy is crucial to addressing outstanding design challenges.

- Finding 7: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and further, to glean the fundamental insights into QCD that an EIC can reveal.

- Finding 8: The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high luminosity polarized Electron Ion Collider (EIC) as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

- Finding 9: The broader impacts of building an EIC in the U.S. are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.