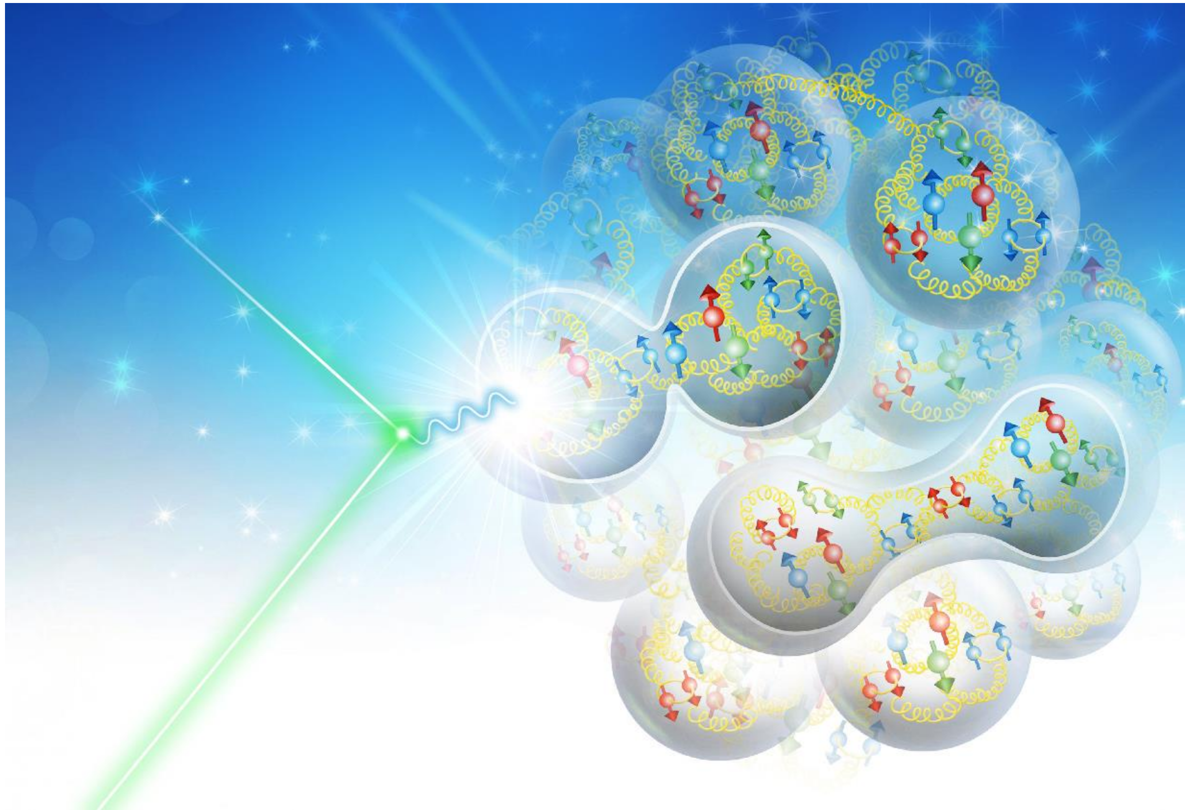
From HERA to the Future of DIS



Rik Yoshida

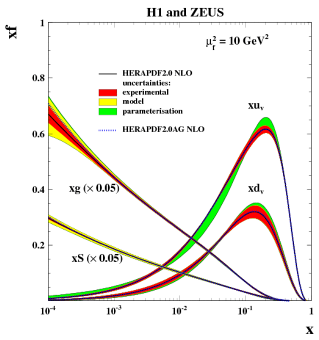
8 April, 2019

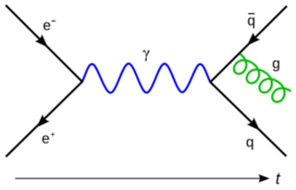
OUTLINE

- Introduction
- Structure and Interaction
  - A history of investigation of structure of matter
  - QCD and collinear factorization: investigation of interaction rather than structure
  - Return of structure as transverse quantities.
  - DIS as a eq collider
- Proposed DIS colliders
  - Capabilities
  - Timelines
  - Status
- Summary

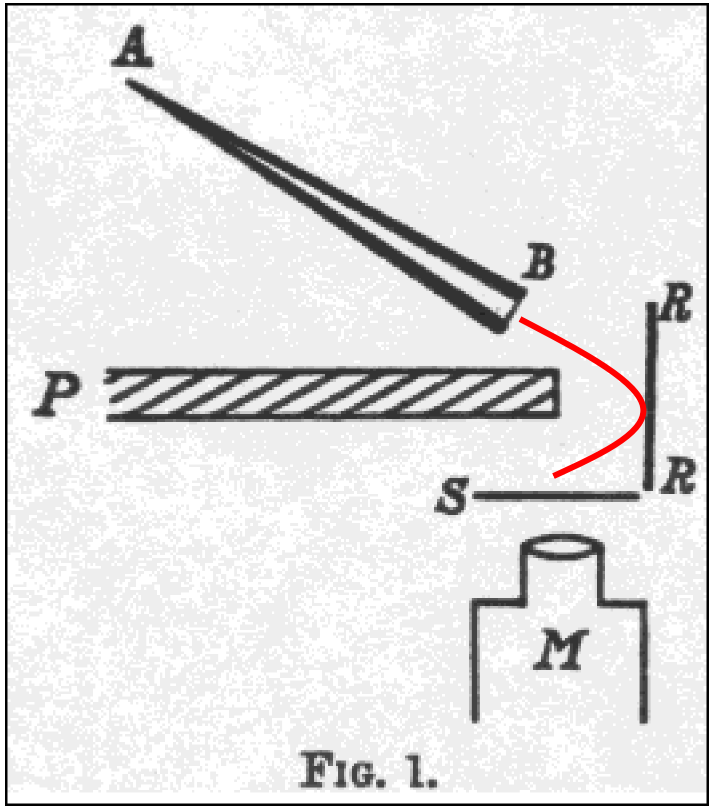
Introduction

- Deep Inelastic Scattering appears to cover many different arenas
  - Parton distributions, pQCD, resummations
  - Low-x and saturation
  - Heavy Flavors
  - Spin physics, transverse quantities, TMDs, GPDs
  - EW, BSM searches, Higgs physics
- Two approaches to thinking about nature
  - Structure: what are things made of?
  - Interactions: fundamental forces
  - Obviously you need both, but emphasis has gone back and forth in DIS.
    - Some parting of the strands have occurred.
  - Some strands are coming back together.
- Discuss history and future in this light. (DIS Colliders)

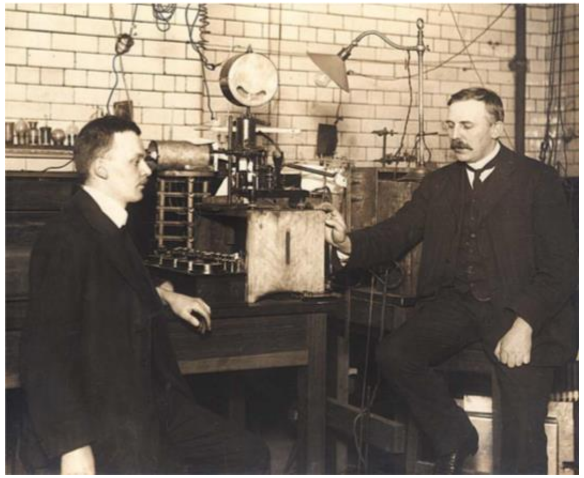


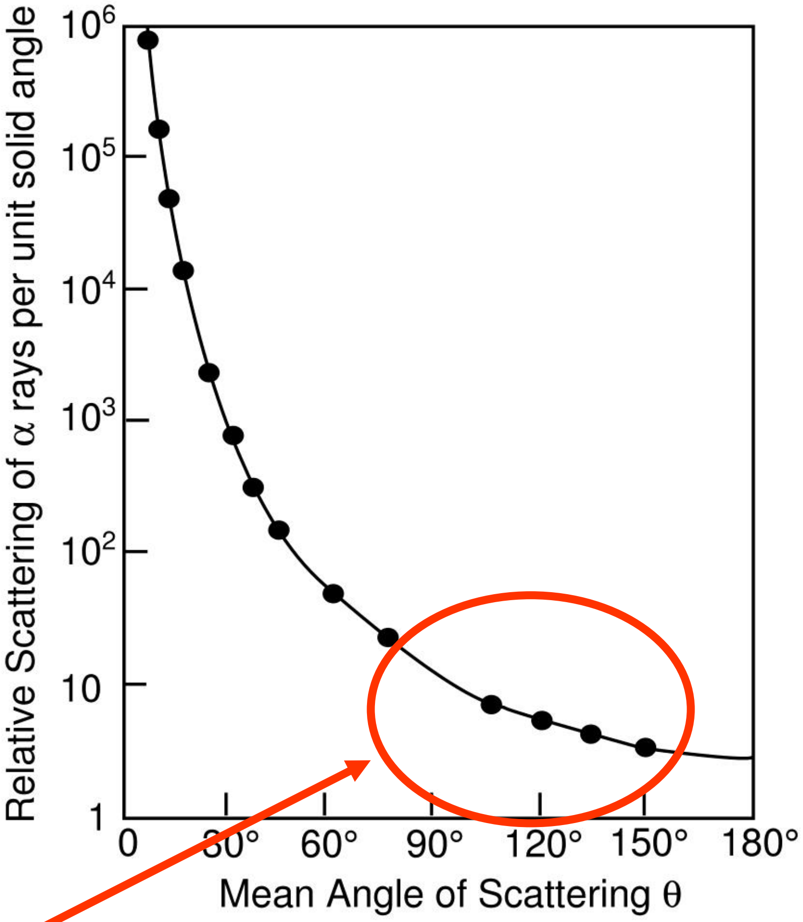


Rutherford Scattering: Discovering the nucleus



$$\sigma(\theta) = \frac{z^2 Z^2 e^4}{16E^2} \frac{1}{\sin^4 \frac{1}{2}\theta}$$

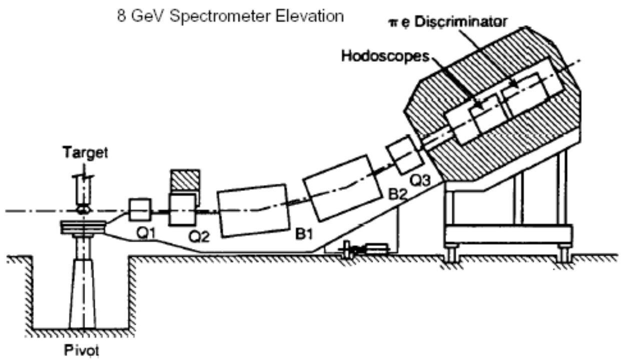


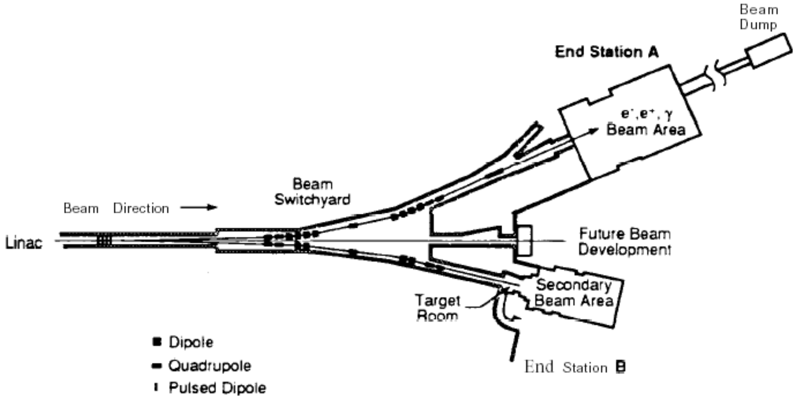


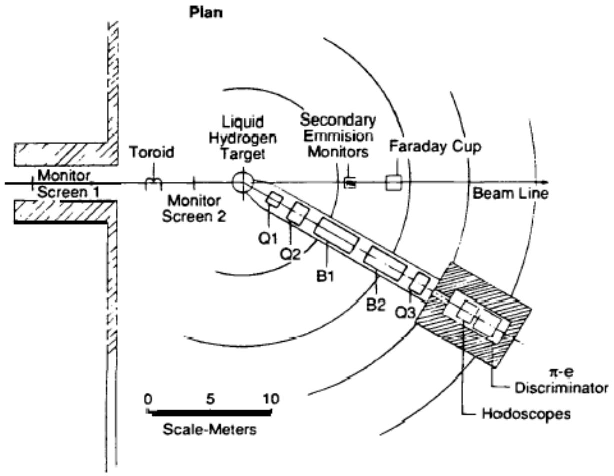
Discovery of atomic nucleus

→ N. Bohr Old Quantum theory…

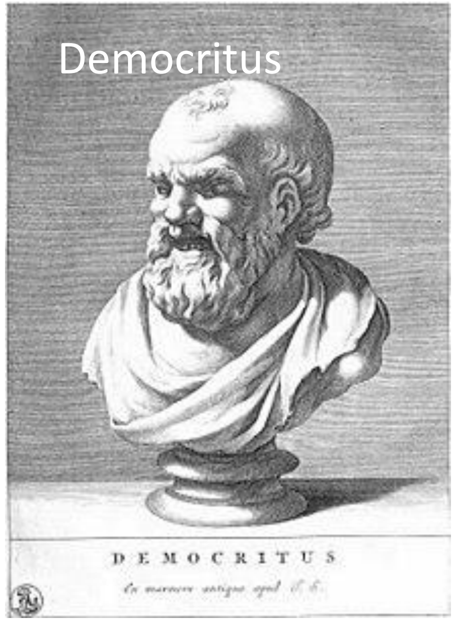
SLAC-MIT Experiment: Discovering the quark (50 years!)

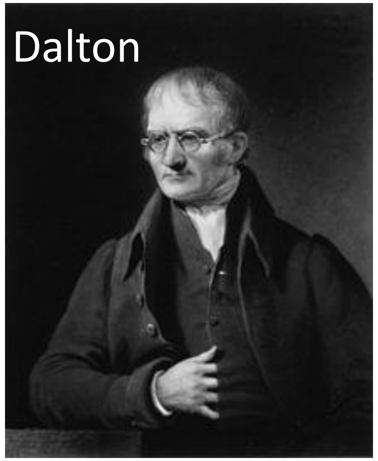




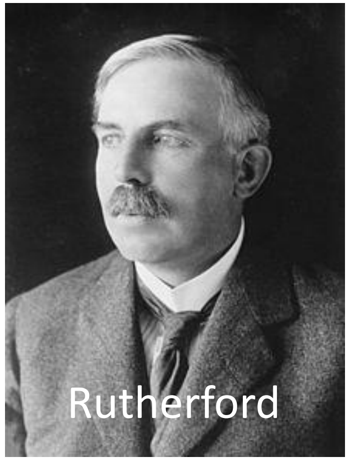


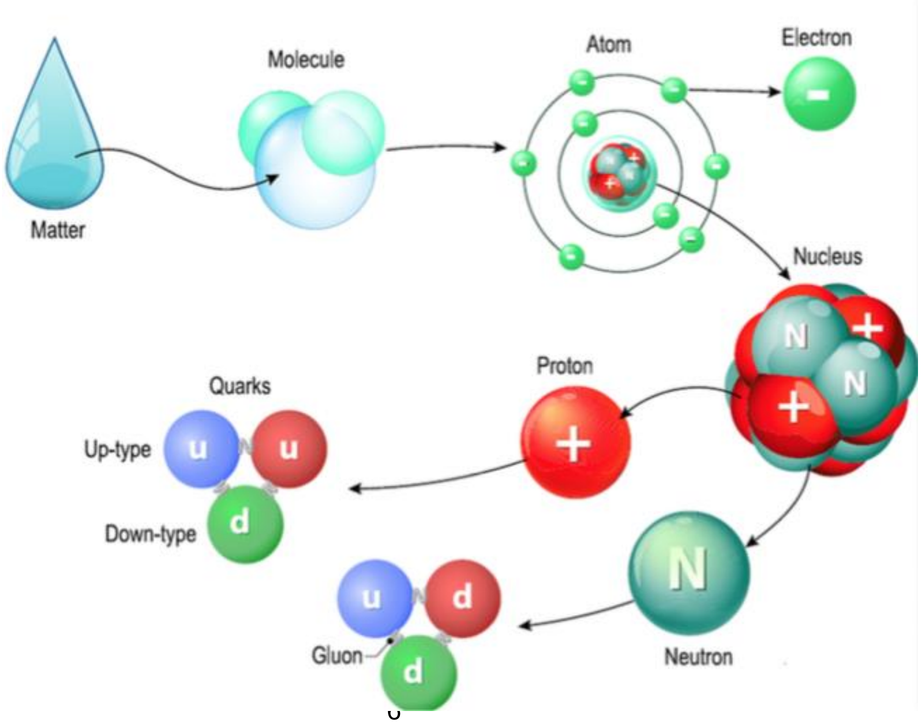
Investigating structure of matter

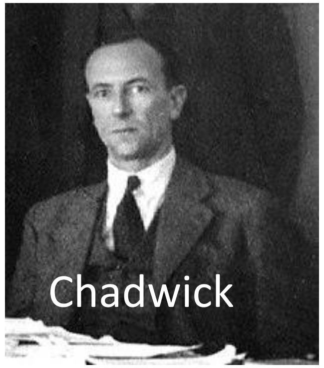




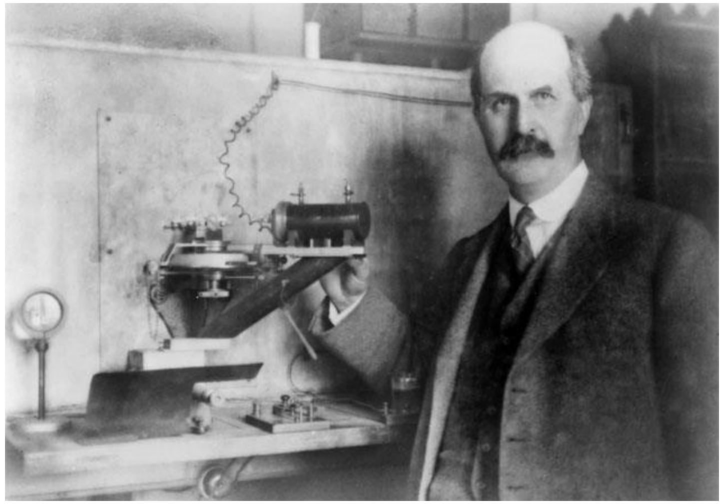
Trying to understand characteristics of matter in terms of their constituents

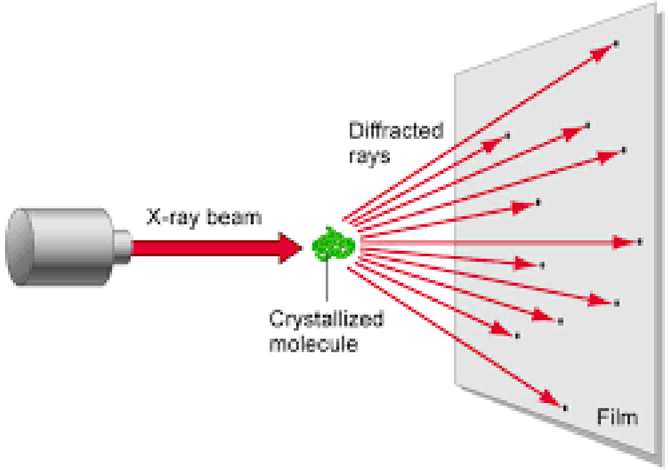


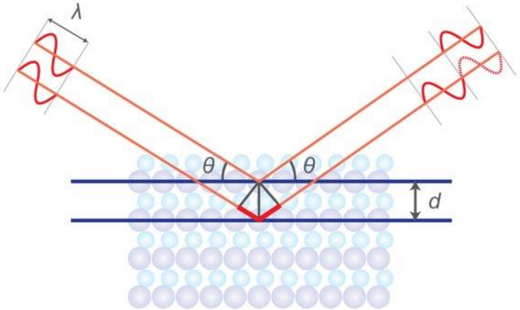




Atoms and X-ray Diffraction

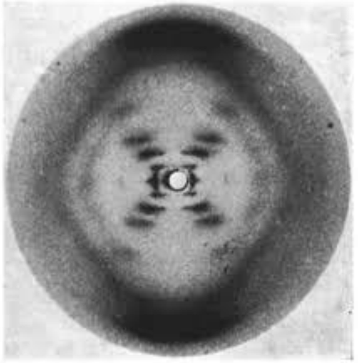






Understanding atomic structure of matter (together with EM) leads to new sciences and much of modern technology.

Condensed matter, molecular biology.. are emergent phenomena.
(i.e. new degrees of freedom arises from fundamental ones)



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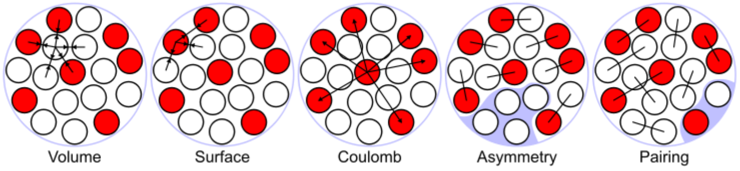
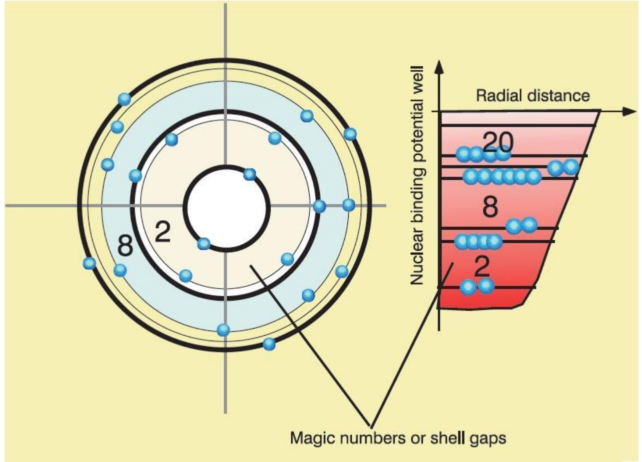
Beginnings of Nuclear Structure Theory (after neutron discovery)

- How do the properties of the nuclei emerge from the protons and neutrons that make them up?
- Liquid Drop model (Weizsacker 1935)
- Nuclear Shell model (Wigner, Mayer, Jensen 1949)

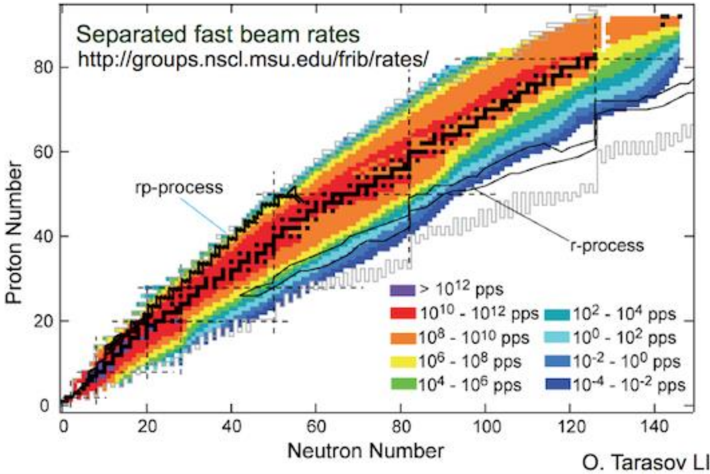


(semi-classical fluid made of p and n)



Highly successful description of nuclei

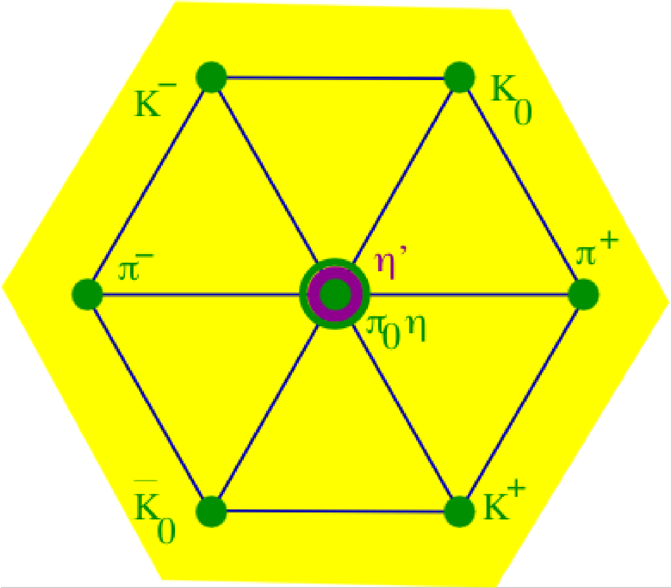
FRIB



O. Tarasov LISE++

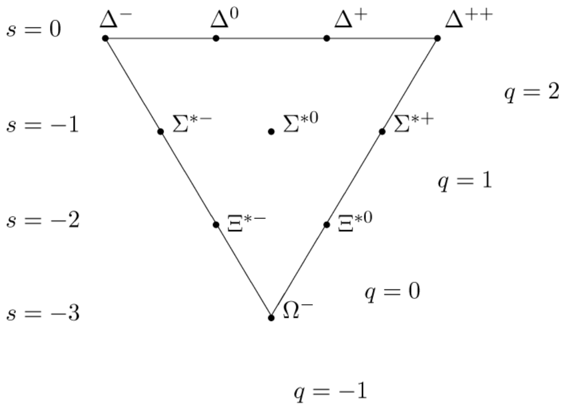
Jefferson Lab

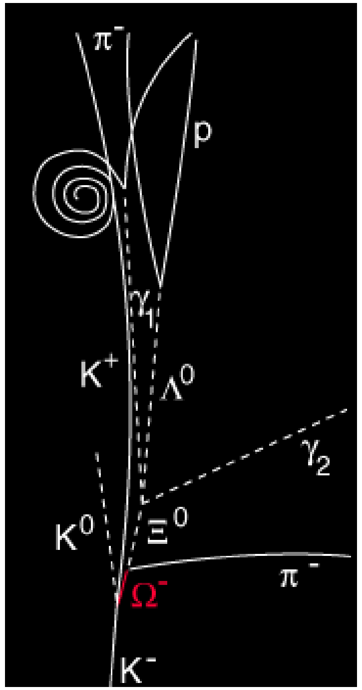
Trying to make sense of hadrons and their structure



Quark model, too arises out of desire to explain the characteristics of hadrons.

Eight-fold way → quark model

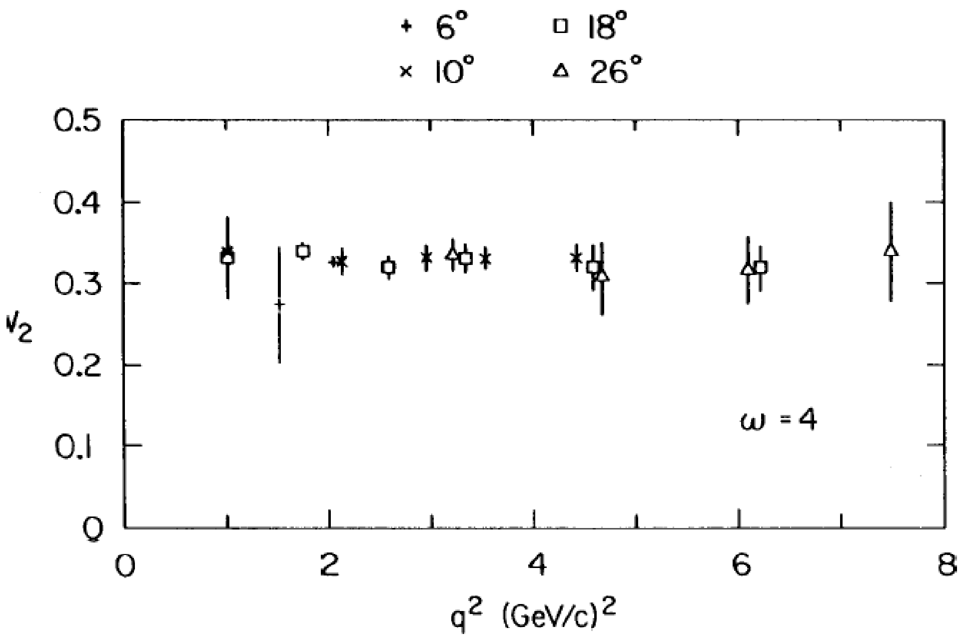




CERN conference 1962

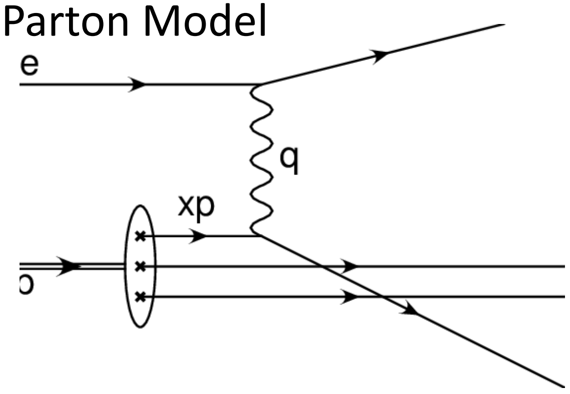
Scaling and Collinear factorization

Results from SLAC-MIT experiment



Scaling, partons and asymptotic freedom

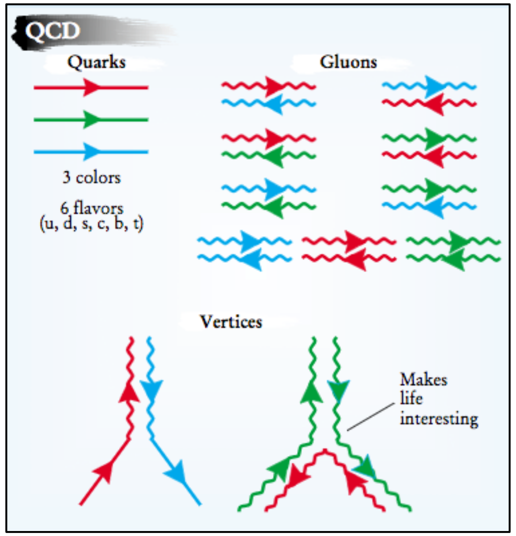
Parton Model



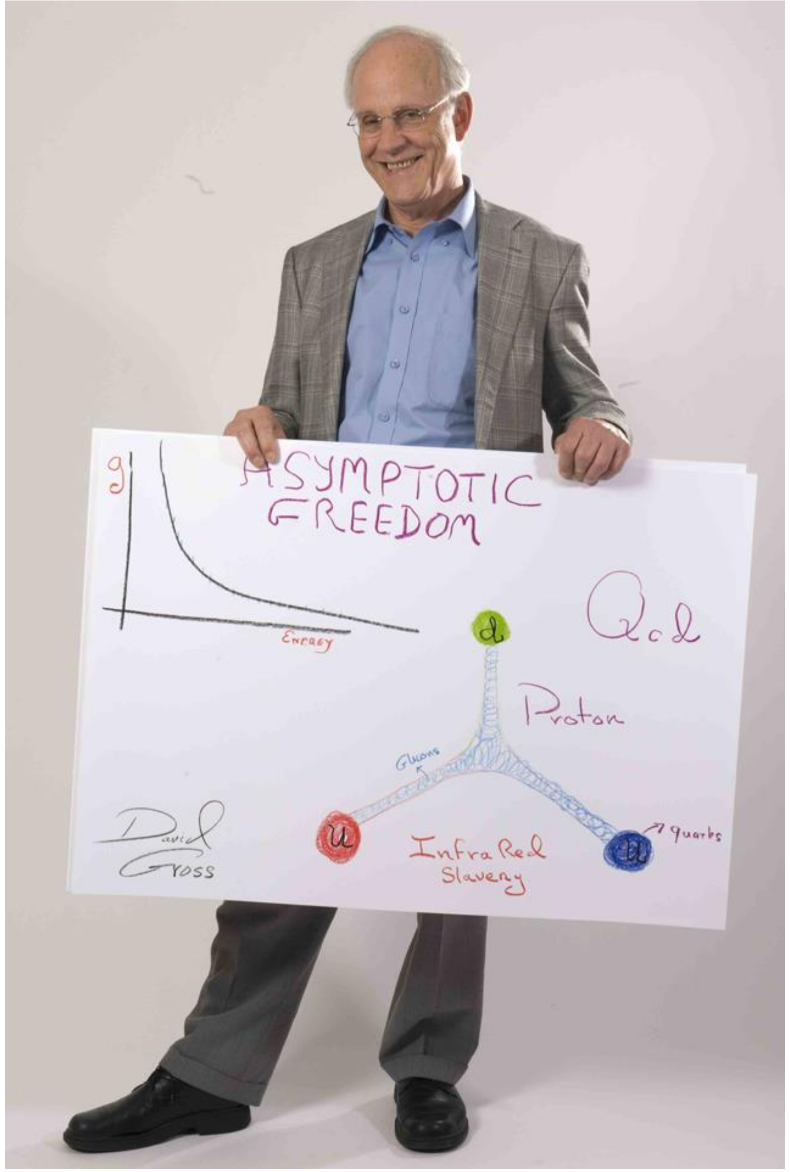
Leads to QCD improved parton model and Parton Distribution Functions.

Co-linear factorization meant the we determined parton distribution in terms of Bjorken-x (and Q^2).

DGLAP equations showed us how to handle evolution



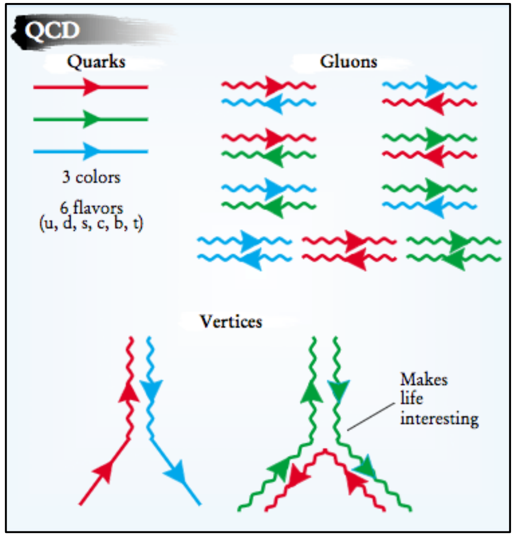
Structure and Interaction (QCD)

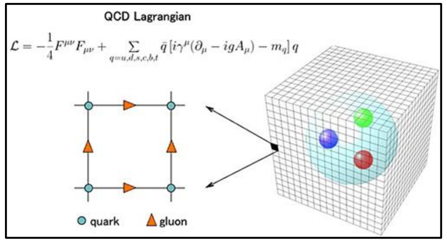


QCD→Asymptotic Freedom → partons = quarks and gluons → collinear factorization → DGLAP evolution → PDFs

In the end Infrared Slavery meant that we had enormous difficulty in the hadronic region eventually leading to:

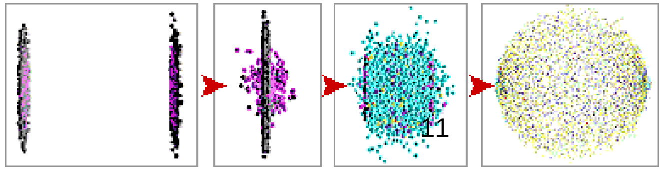
LQCD





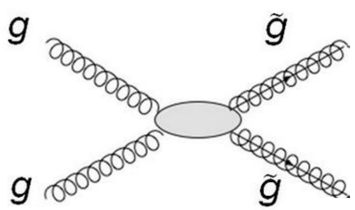
Somewhere here NP and HEP points of view begins to diverge..

Also implies quark-gluon plasma

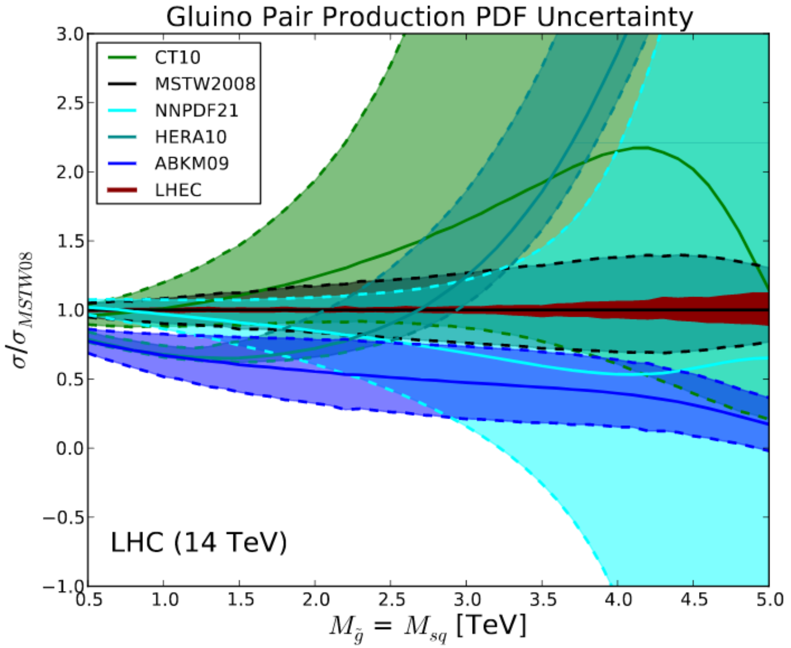


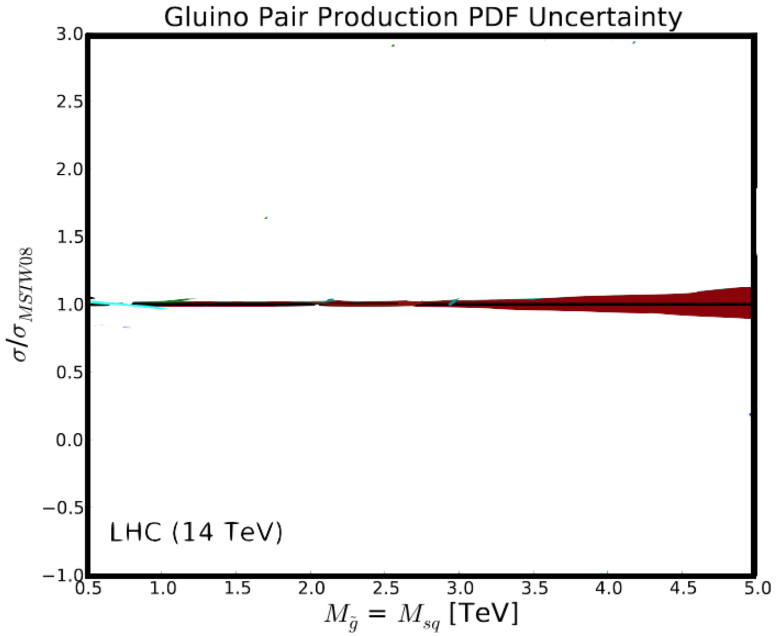
Parton Densities: Energy Frontier needs parton luminosities

HL-LHC gluino production



LHeC projection

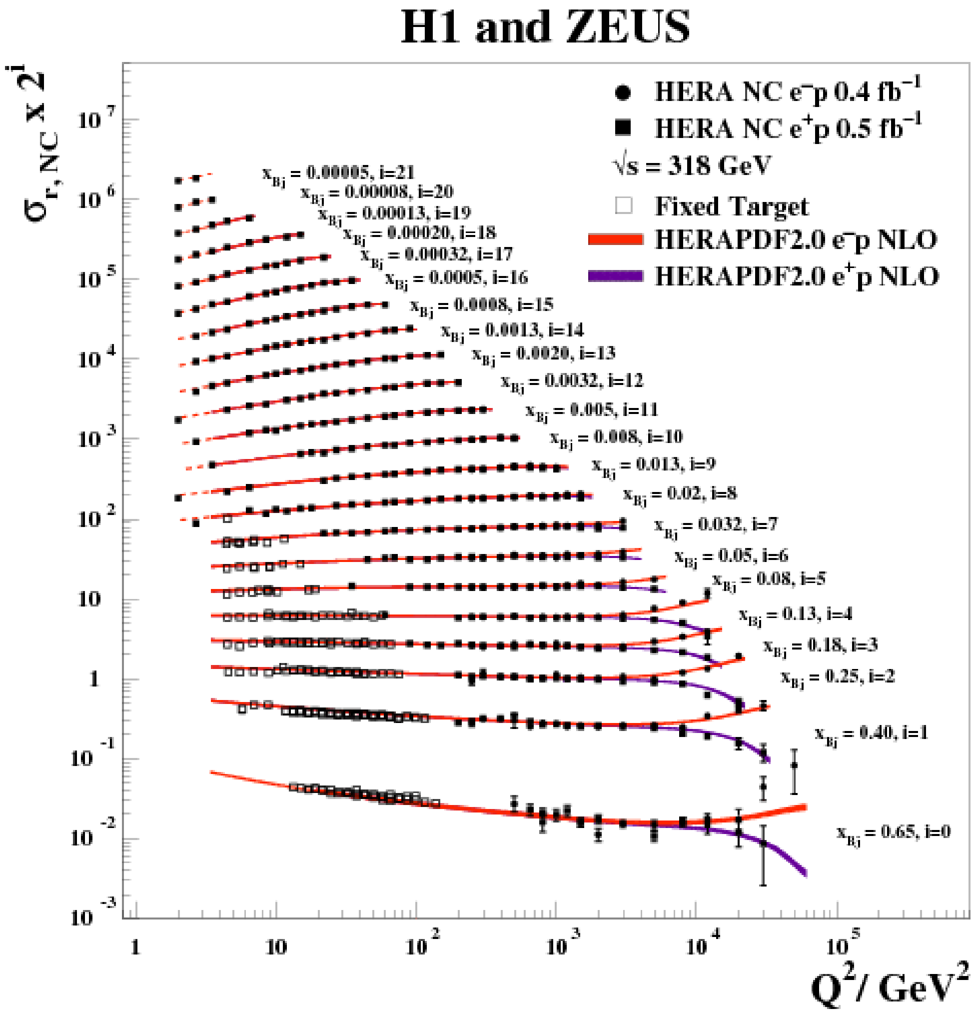


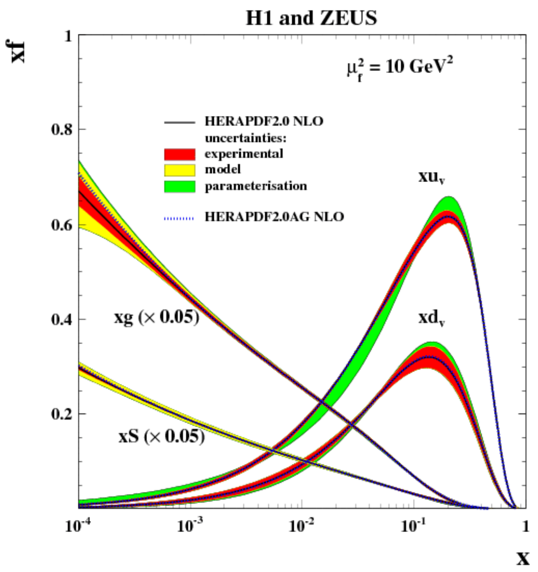


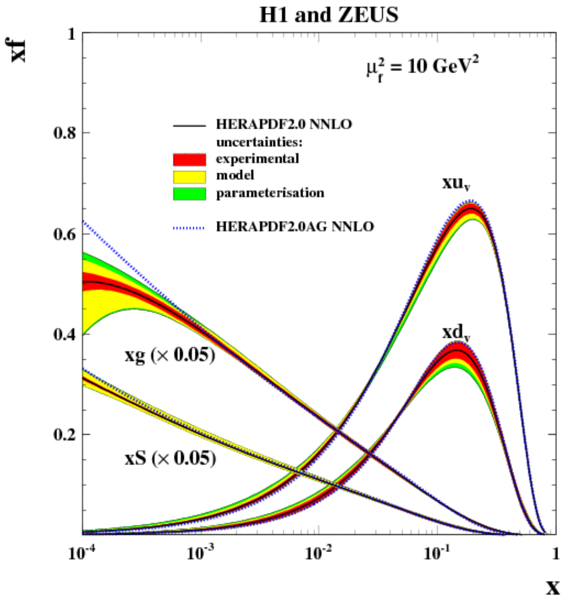
LHeC projection: arXiv: 1211.5102

Investigating pQCD (NLO and NNLO)

EPJC 75 (2015) 12, 580



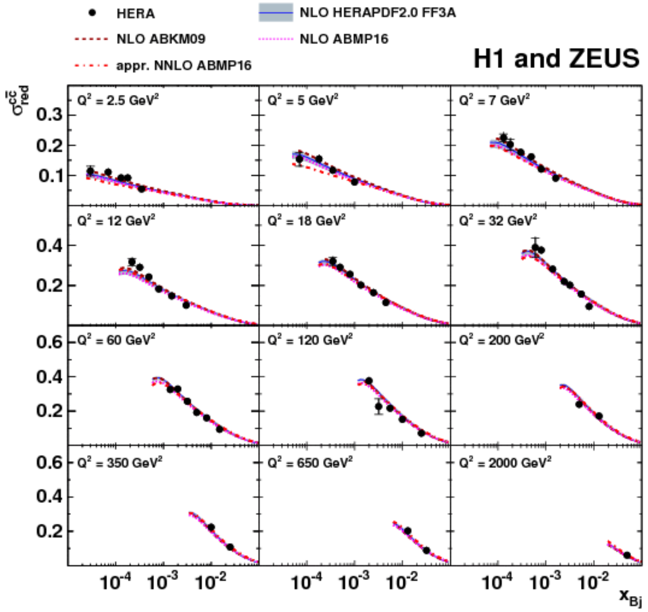


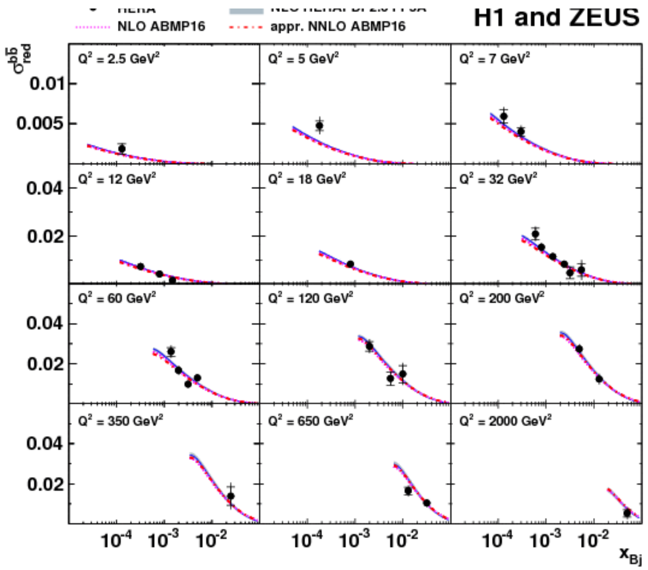


Now proton could be decomposed into their constituent quarks and gluons.

We could investigate, e.g. effect of using higher order terms in the analysis of the data.

Investigating pQCD (Heavy Quark production)

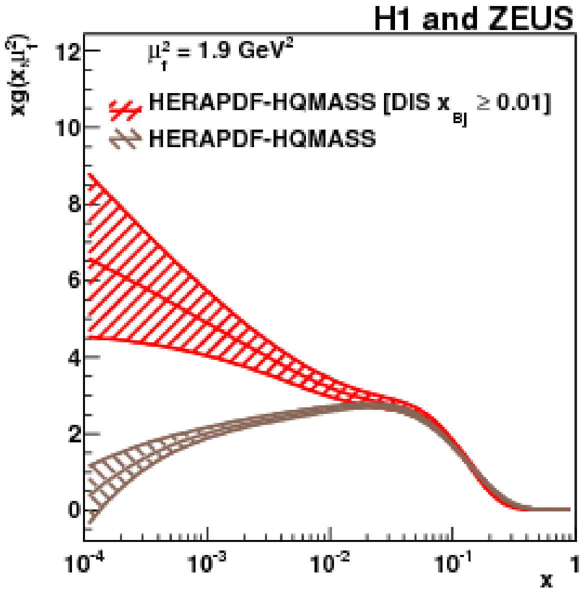




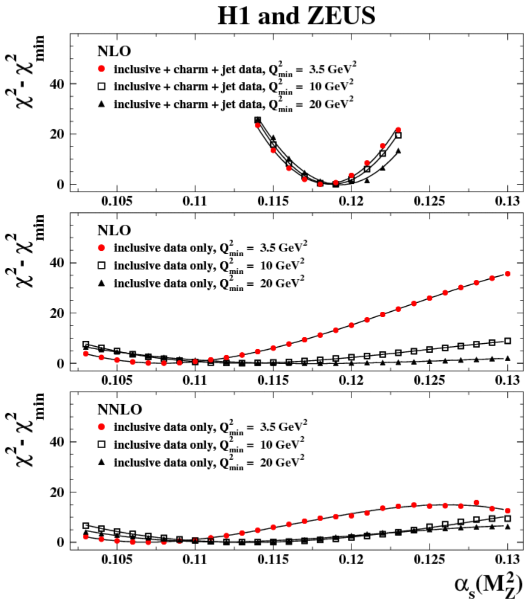
Eur.Phys.J.C78 (2018), 473

Investigating pQCD, example: Heavy Quarks and jets
Looking at compatibility/complementarity using different probes

Tension between scaling violation and HQ production in DIS

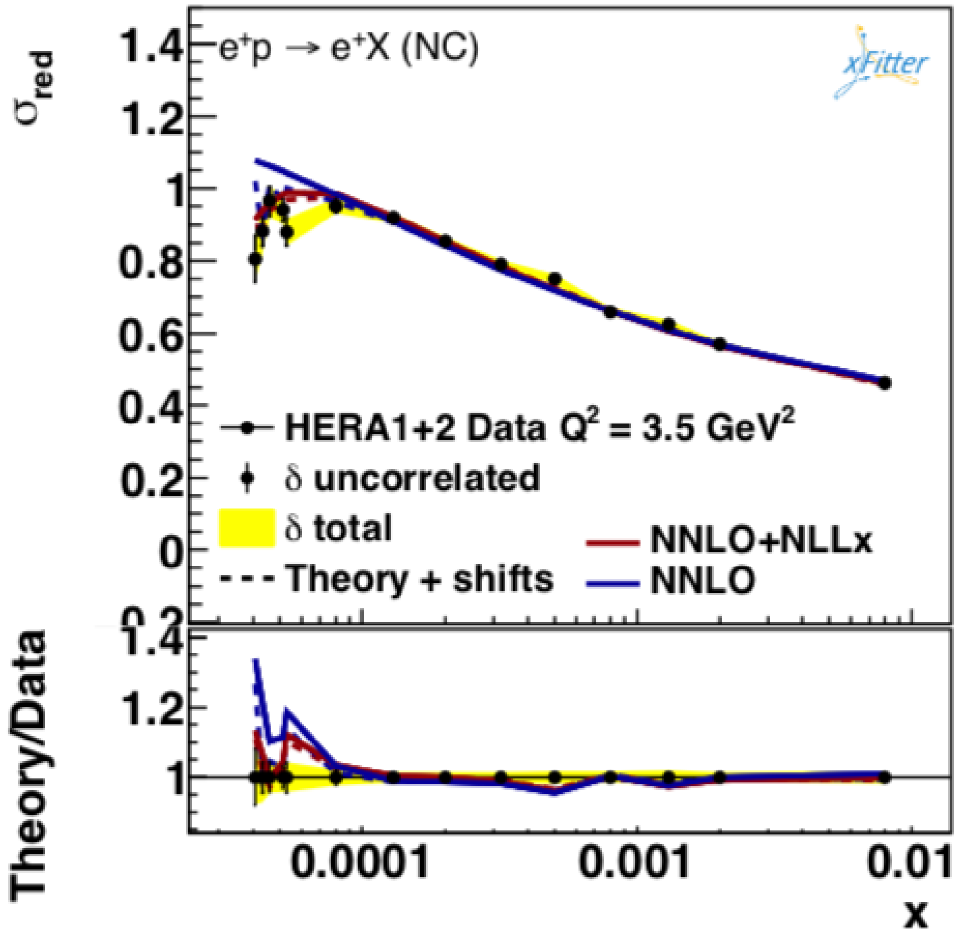


Using HQ and jets to constrain strong coupling

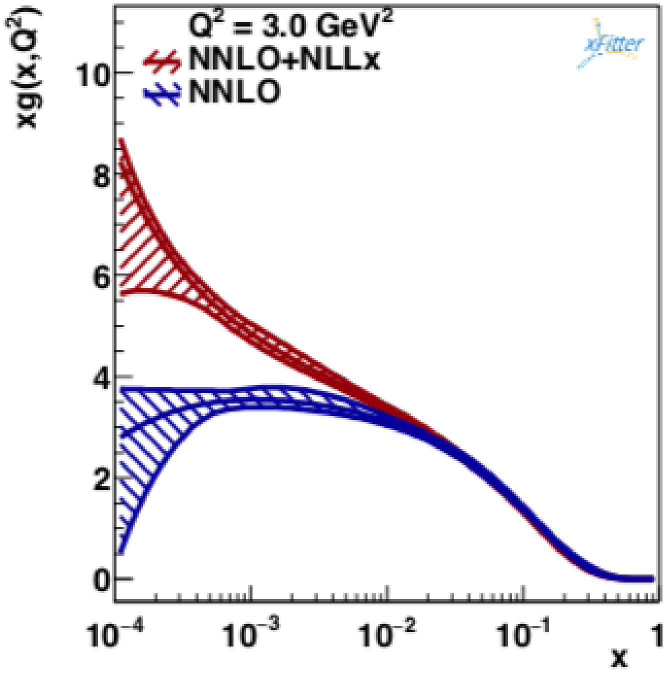


Investigating pQCD (low-x resummation)

x-Fitter developers EPJC 78 (2018) 8, 621



Is the low-x HERA data telling us something about 1/x terms? If so what are the implications?



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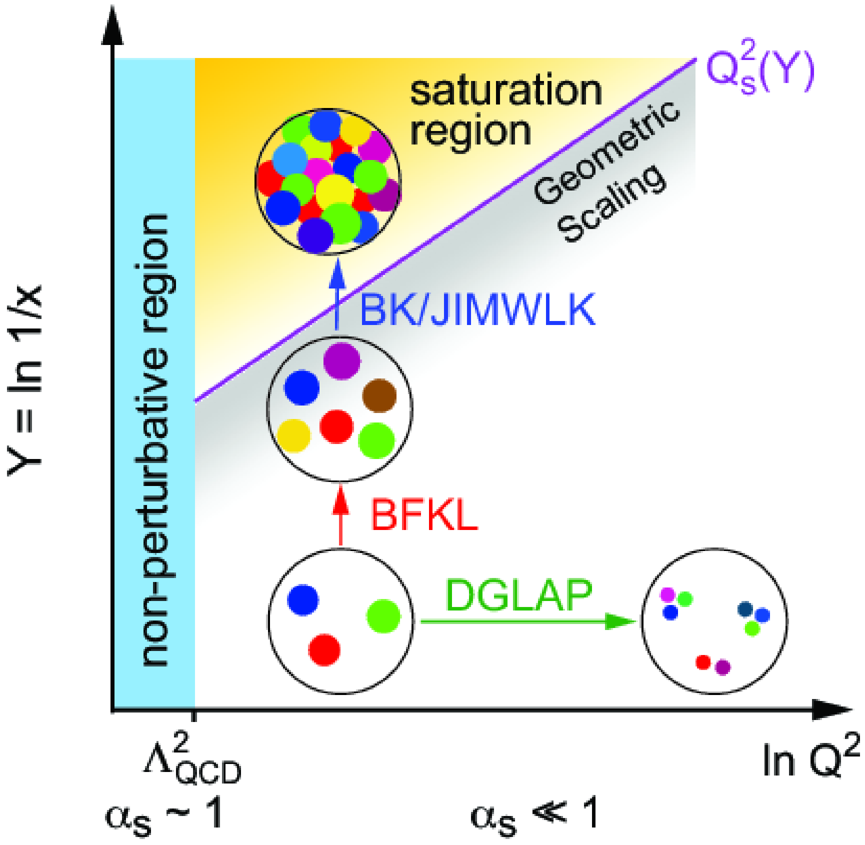
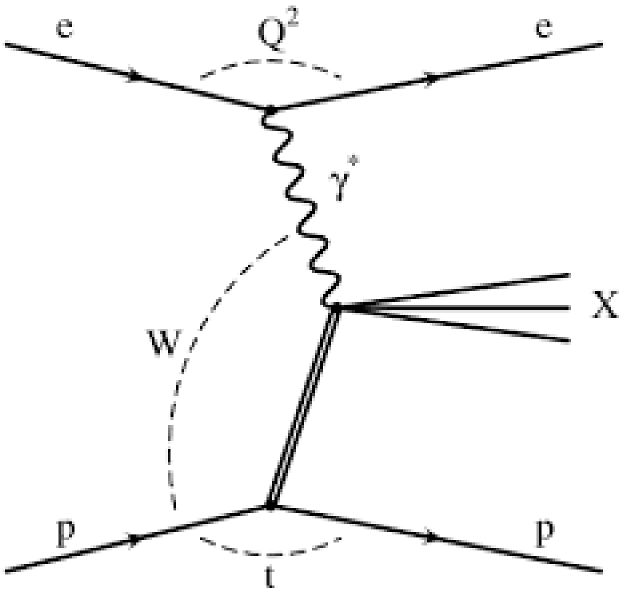
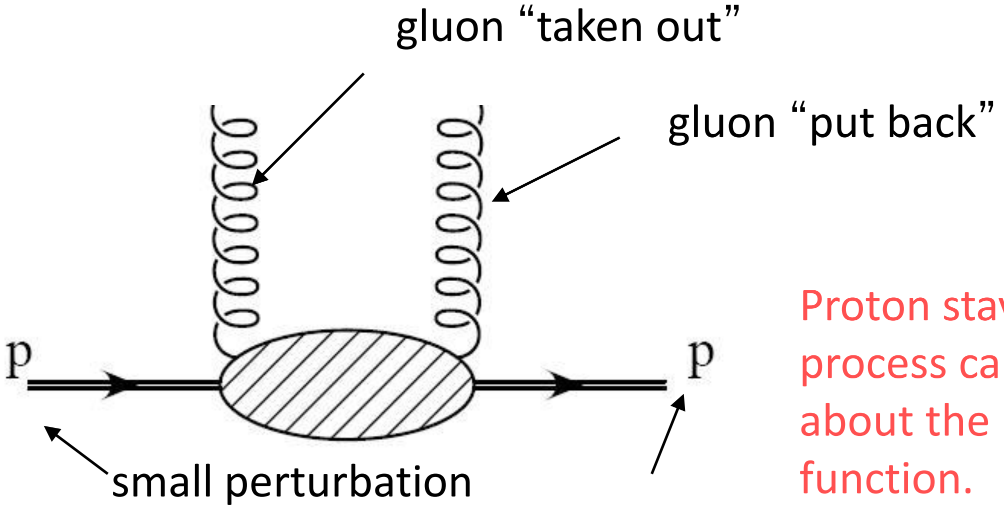
Shadow of the protons.. Saturation? Diffraction



What sets the saturation scale?

DIS diffraction discovered at HERA





Proton stays intact: this process carries information about the proton wave function.

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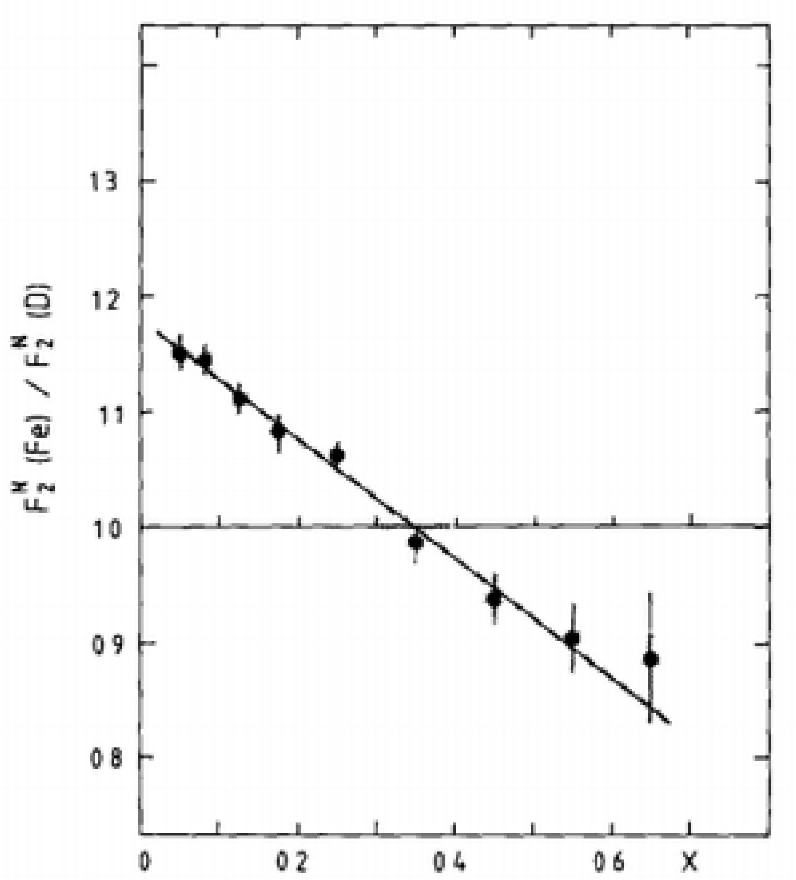
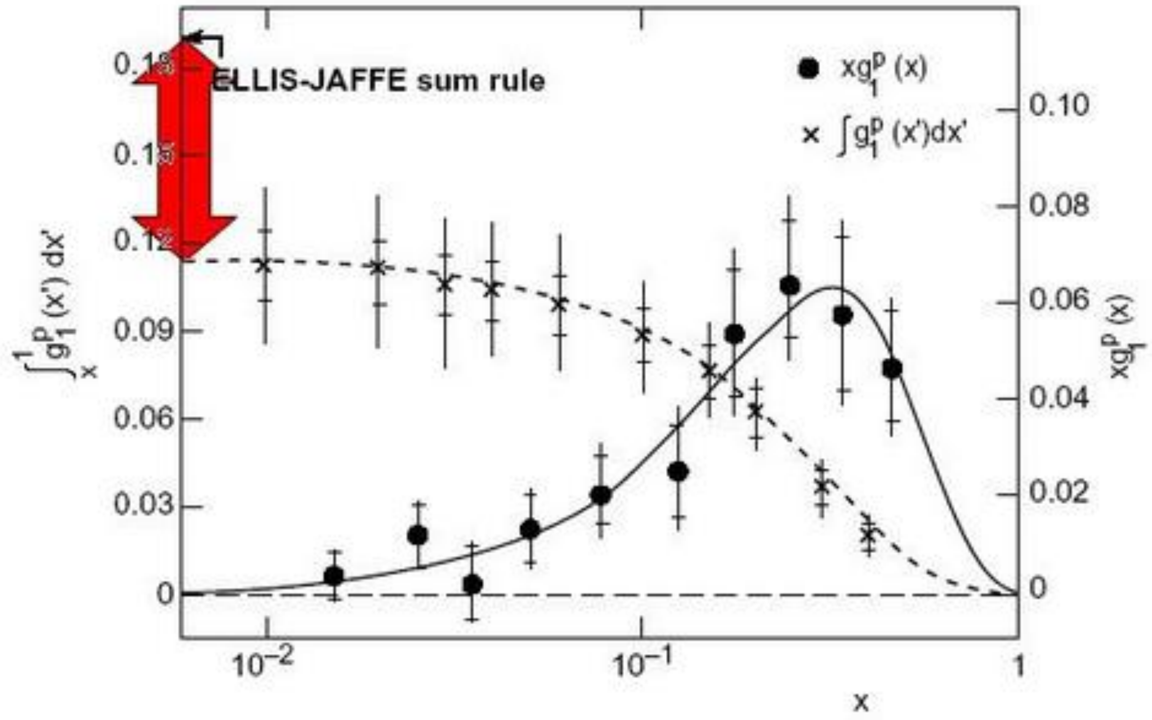
Quark/Gluon structure and Nucleon/Nuclear characteristics

EMC Experiment

EMC Effect



Quark and gluon structure has something to do with nucleon spin and but what?



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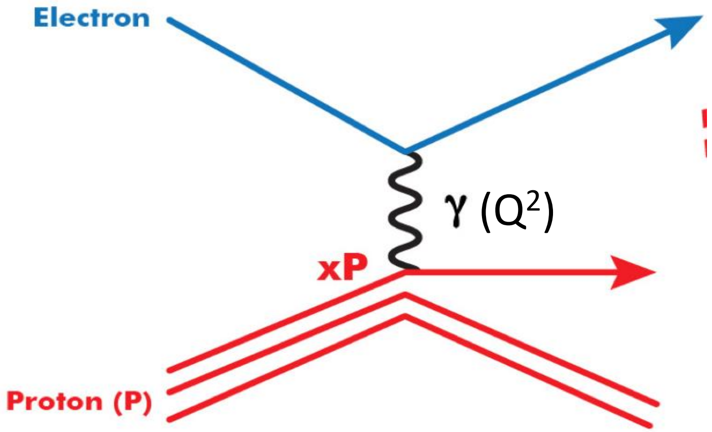
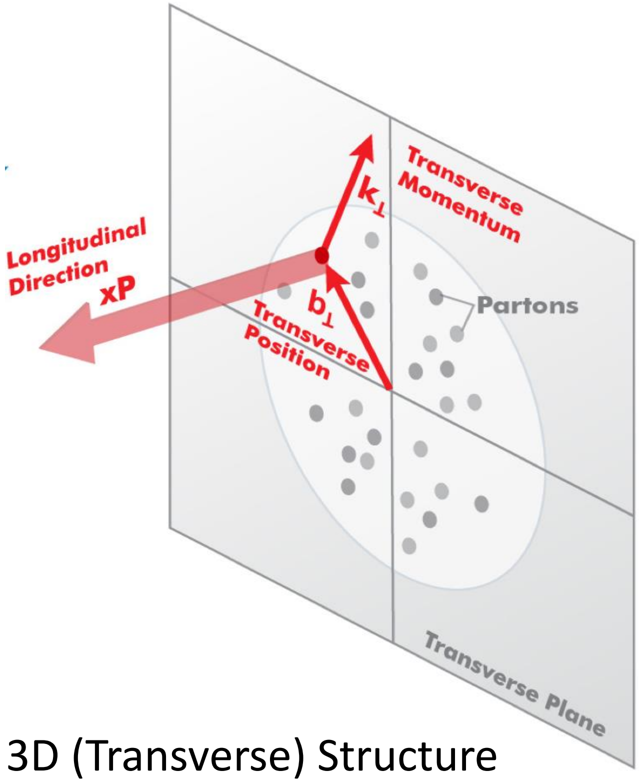
Towards Combining Structure and Interaction

Factorization II





Parton Distribution Functions:
Longitudinal only—
No way to interpret nucleon partonic structure in rest frame

3D (Transverse) Structure
TMD's, GPD's—
Now we know what to measure to understand the 3D structure of nucleons

Transverse Momentum Dependent Distributions (TMD): k_t
Generalized Parton Distributions (GPD): b_t

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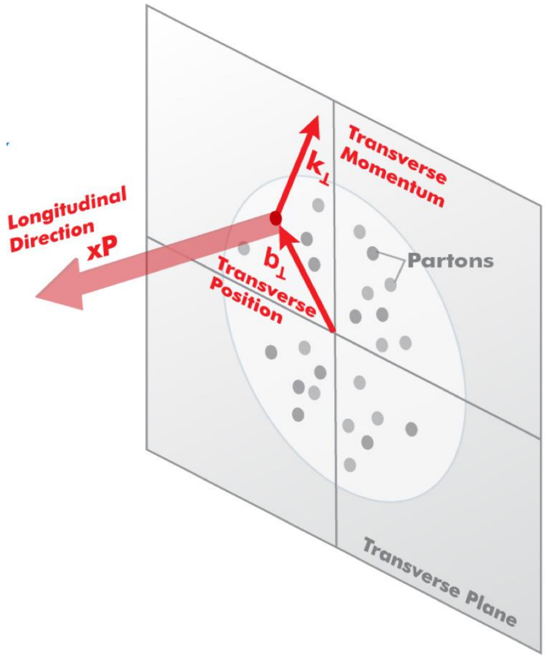
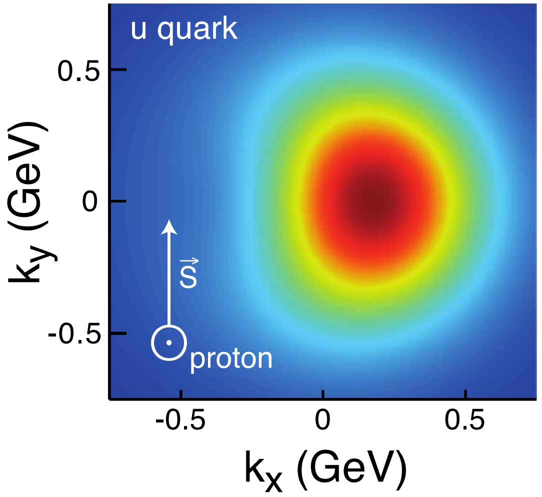
From 1D structure to 3D structure → EIC



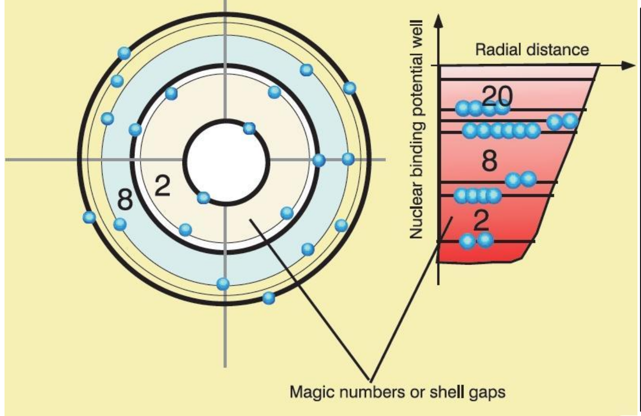


also for nuclei…

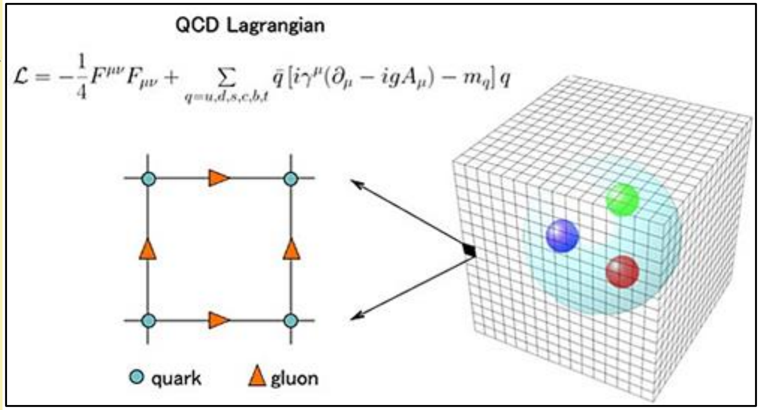
EIC Challenge

Can we relate this to what we understand from:

Traditional Nuclear Structure



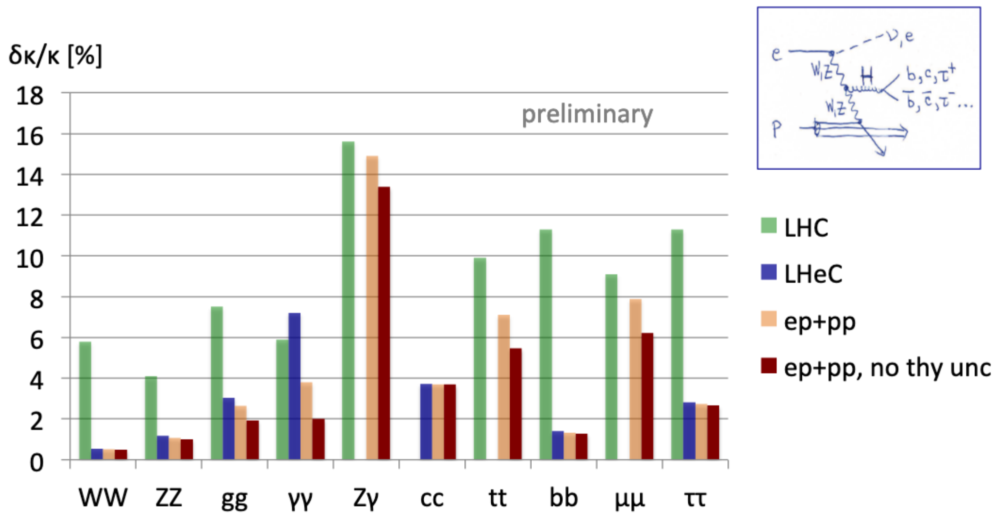
LQCD



The other extreme: LHeC as a Higgs Factory:

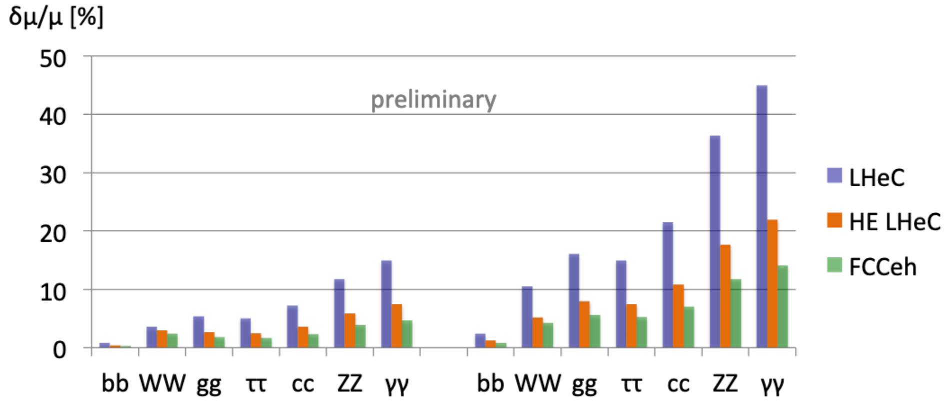
Max Klein

Transformation of the LHC into a High Precision Higgs Facility



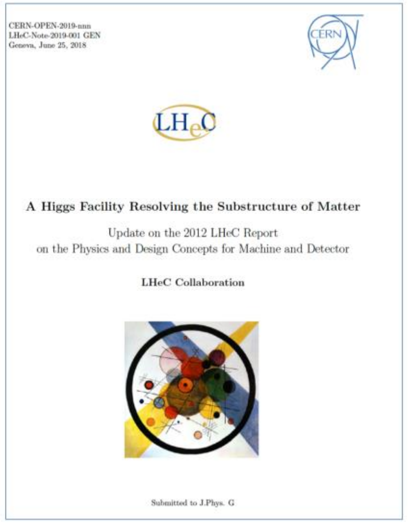
J. De Blas, M.+U. Klein, 16.4.2018

LHC: ATLAS prospects PUB Note 2014-016



M+U.Klein, 6.3.18

ttH at LHeC to 15%



CERN-OPEN-2019-nnn
LHeC-Note-2019-001 GEN
Geneva, June 25, 2018

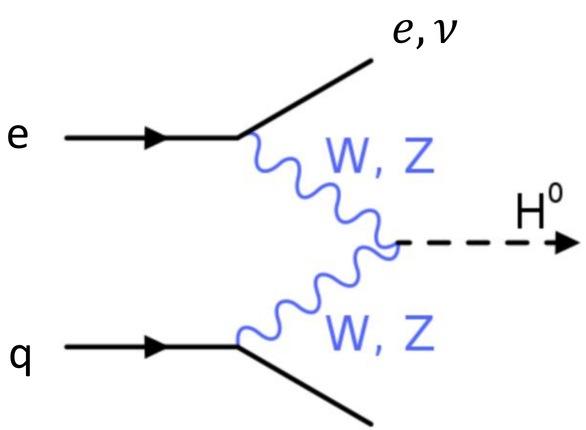
LHeC

A Higgs Facility Resolving the Substructure of Matter

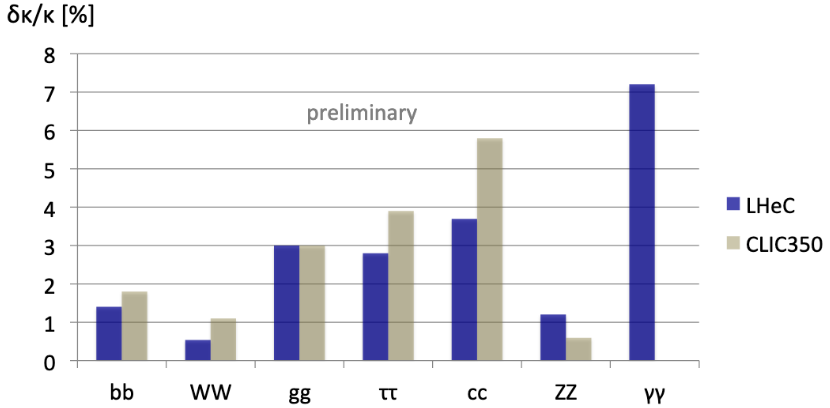
Update on the 2012 LHeC Report
on the Physics and Design Concepts for Machine and Detector

LHeC Collaboration

Submitted to J.Phys. G



Comparison of LHeC and CLIC Prospects

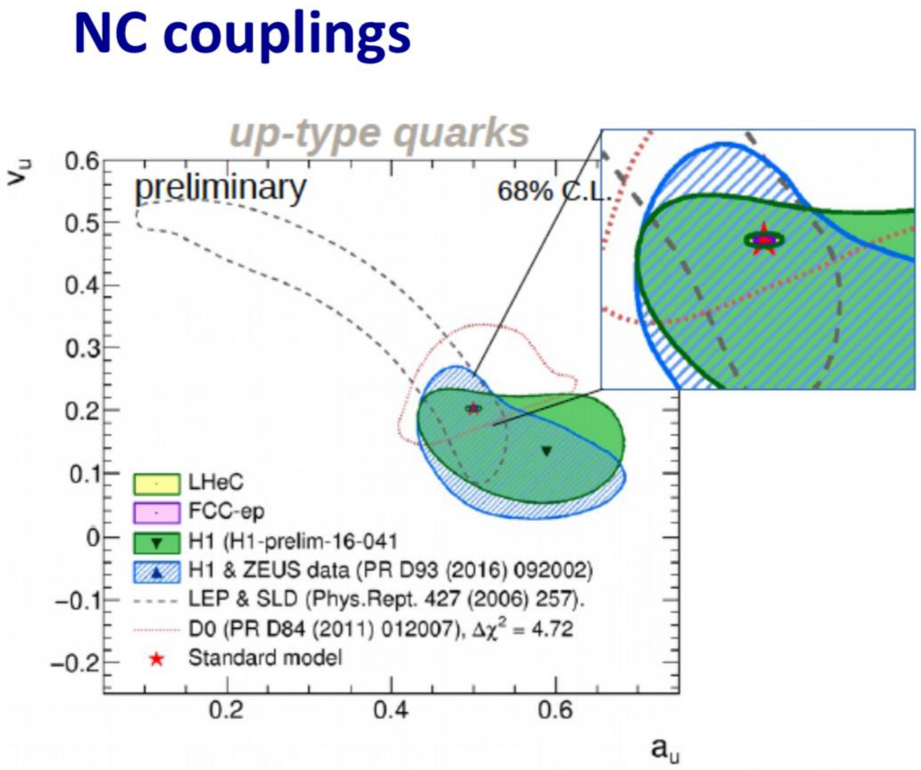


M+U Klein 3.4.18

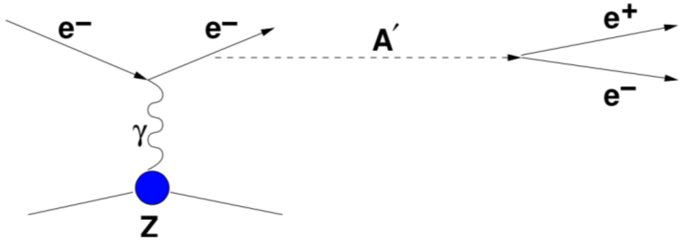
LHeC: 60 GeV x 7 TeV. **CLIC: 350 GeV** [arXiv:1608.07538, "model dependent fit", 0.5ab^{-1}]

BSM, Precision EW

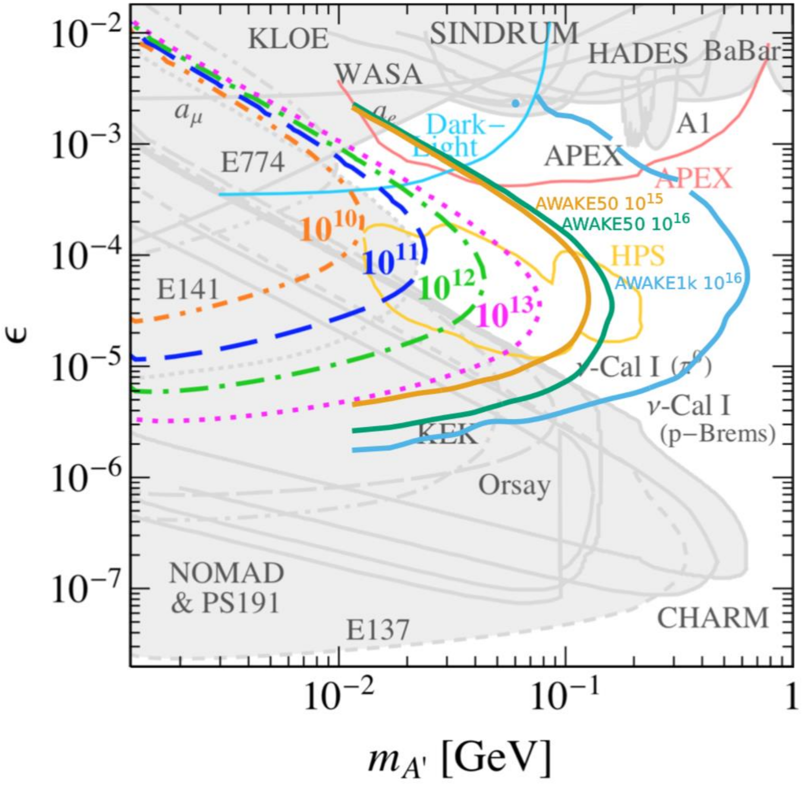
LHeC projection



Britzger, MK, Spiessberger, Zhang – work still in progress



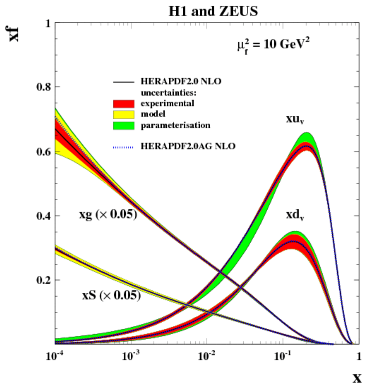
Dark Photon search with AWAKE fixed target

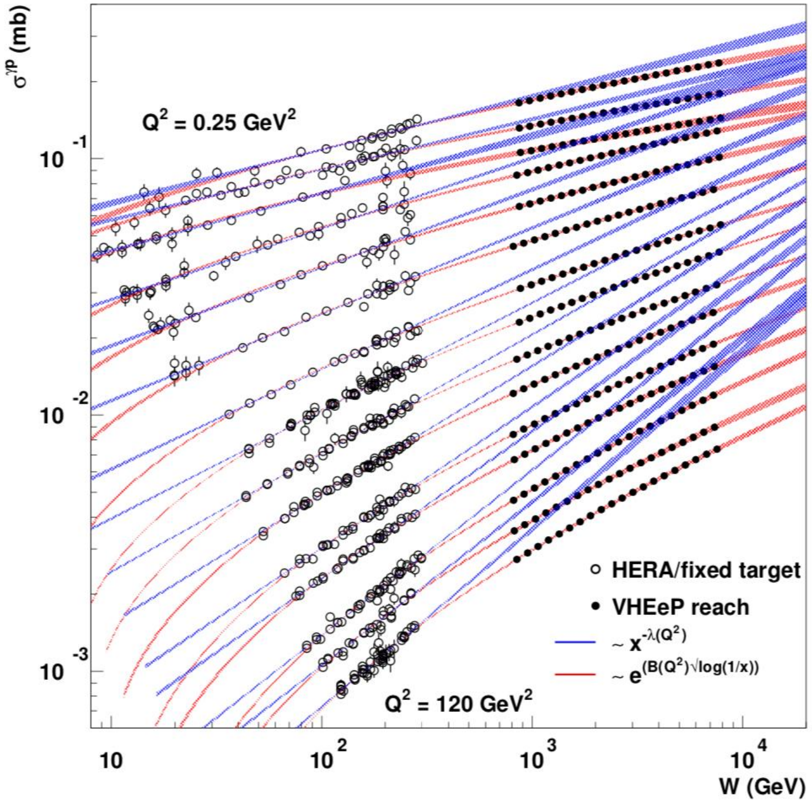


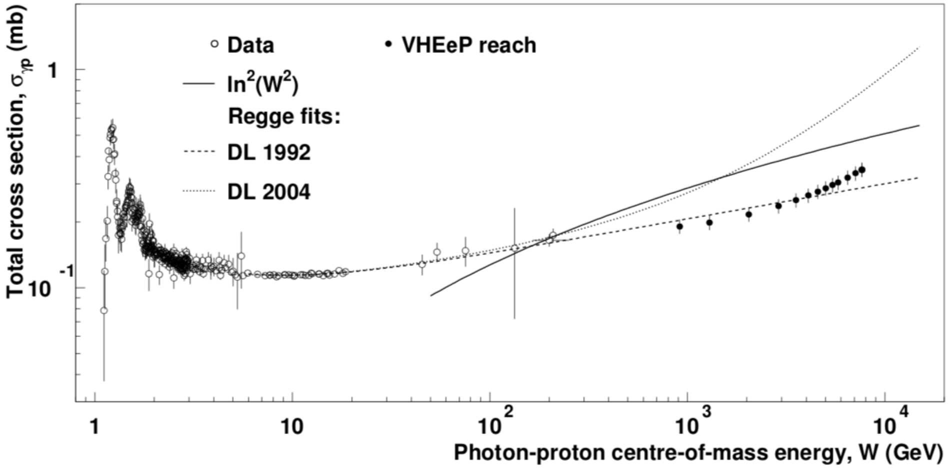
Approaching the hadron from the high energy limit

LHeC projections

Hadron-hadron scattering







What is the relation between rise of F_2 at low-x, saturation and the high energy limit of $\sigma_{\gamma p}$

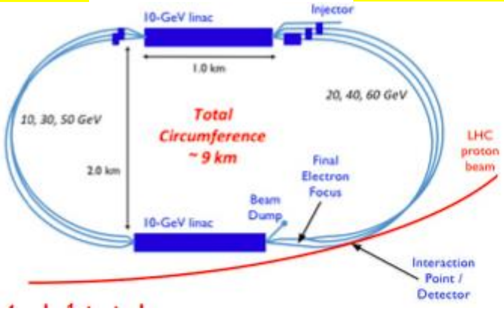
Planned DIS Colliders around the world

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

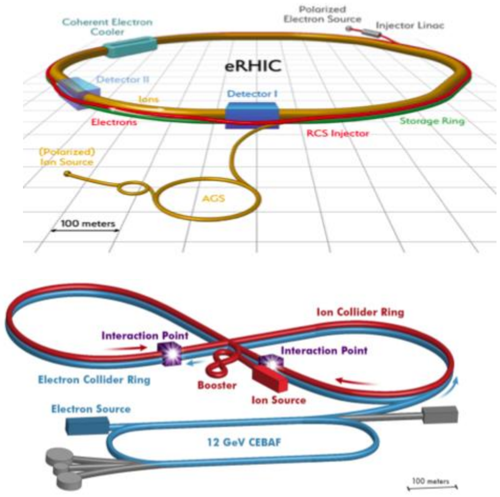
EPPSU DIS Input

LHeC

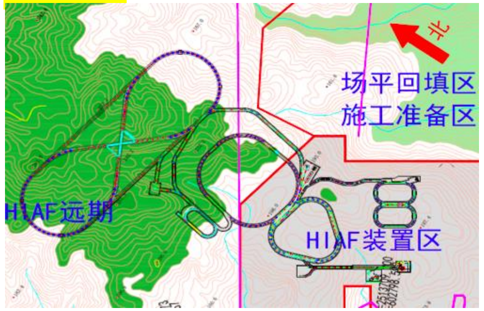
FCC-eh



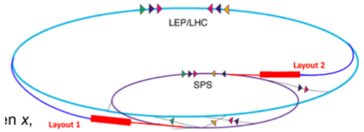
EIC



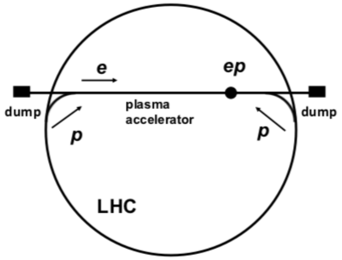
EicC



PEPIC

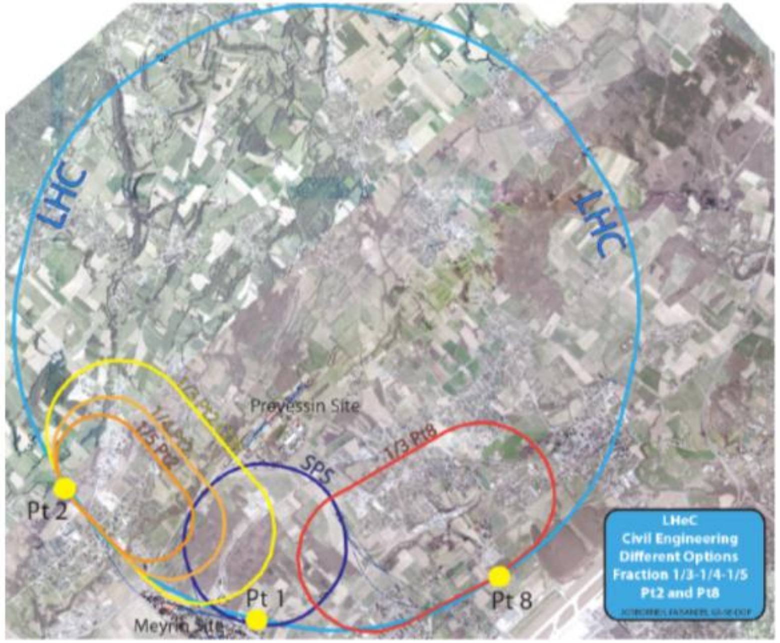


VLEeP



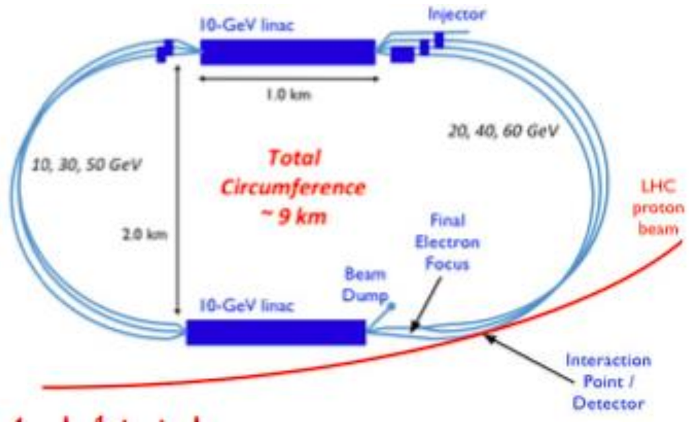
LHeC (also with HE-LHC) and FCCeh

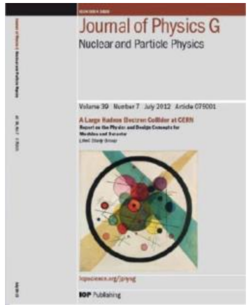
Max Klein



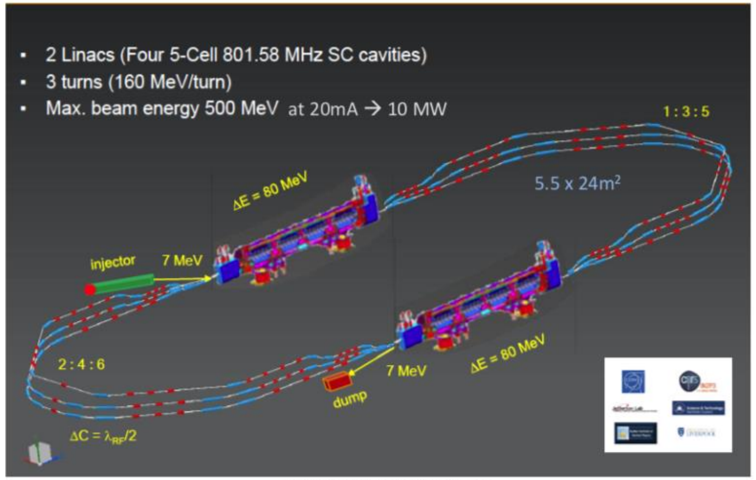
- U(ERL) = 1/n U(LHC): 60 GeV: 1/3
- BSM, top, Higgs, Low x all want maximum E_e
- Cost goes almost linearly down with E_e

For FCC can realise ep/A collisions
With IR at point L, not far from CERN
U(ERL) = 1/11 U(FCC)





Powerful ERL for Experiments at Orsay



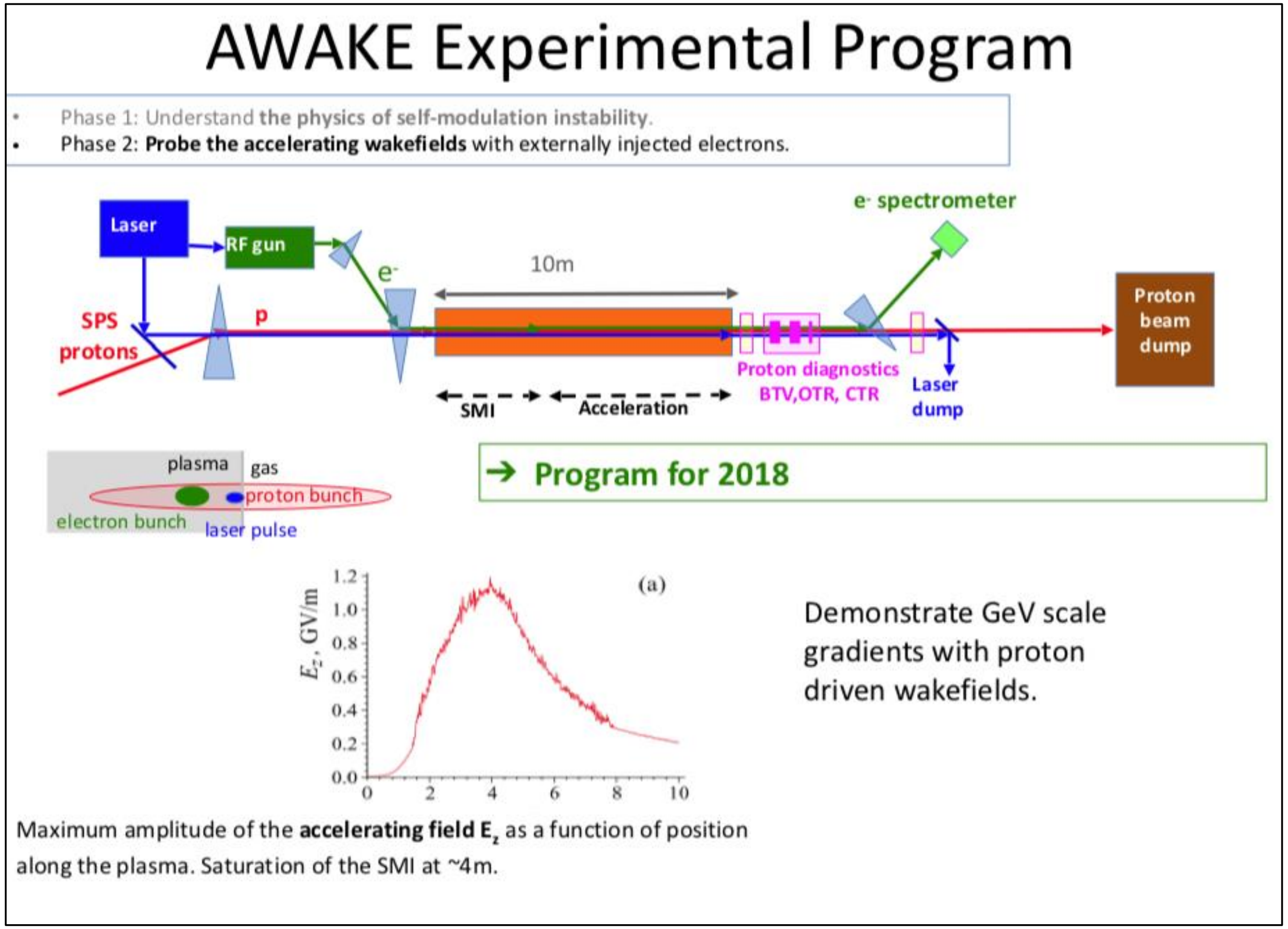
cf Walid Kaabi at Amsterdam FCC

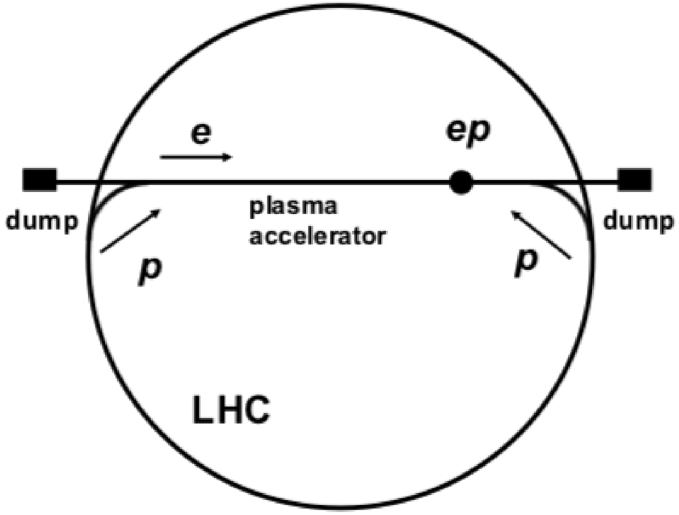
New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

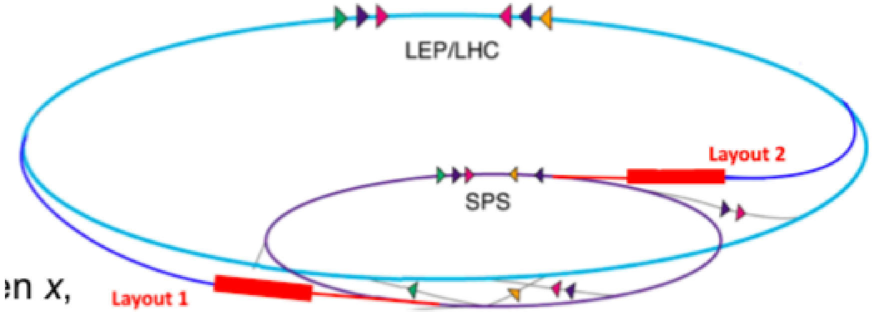
60 GeV e-beam from ERL and 7 TeV proton beam (for LHeC)

AWAKE (VHEeP, PEPIC)

Allen Caldwell, DIS 2018







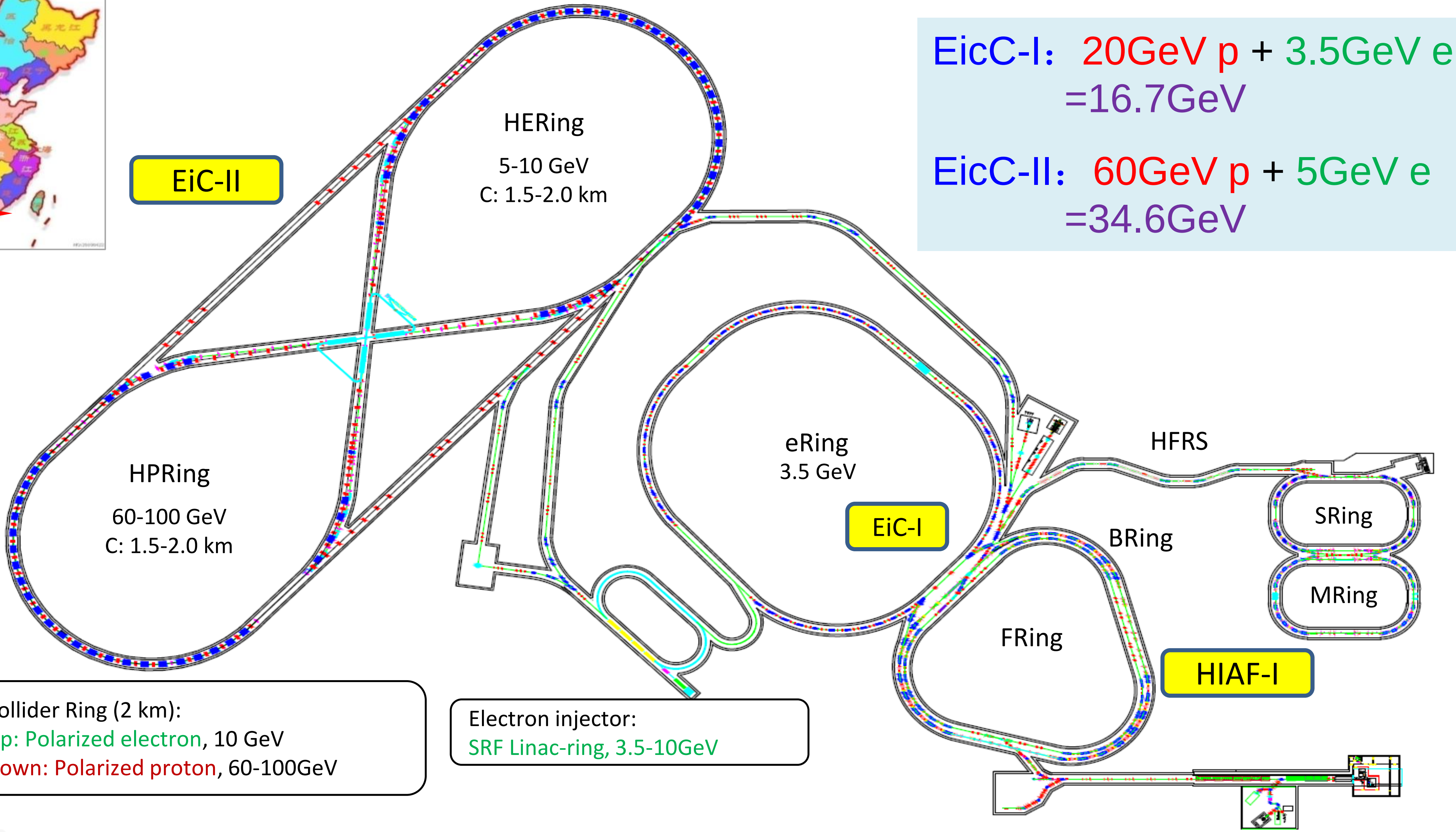
Create multi-TeV electron beam using proton wakefield in plasma

EicC (China)

From JP Chen,
INT-18, 2018

EicC-I：20GeV p + 3.5GeV e
=16.7GeV

EicC-II：60GeV p + 5GeV e
=34.6GeV

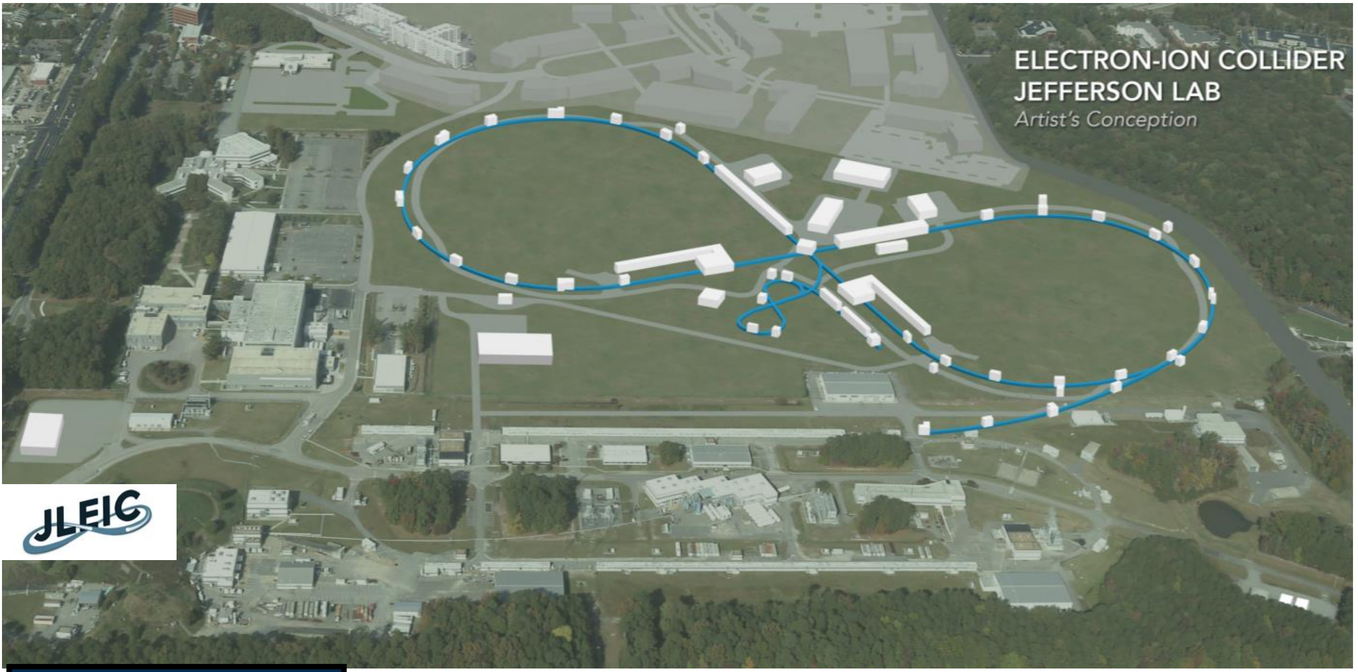


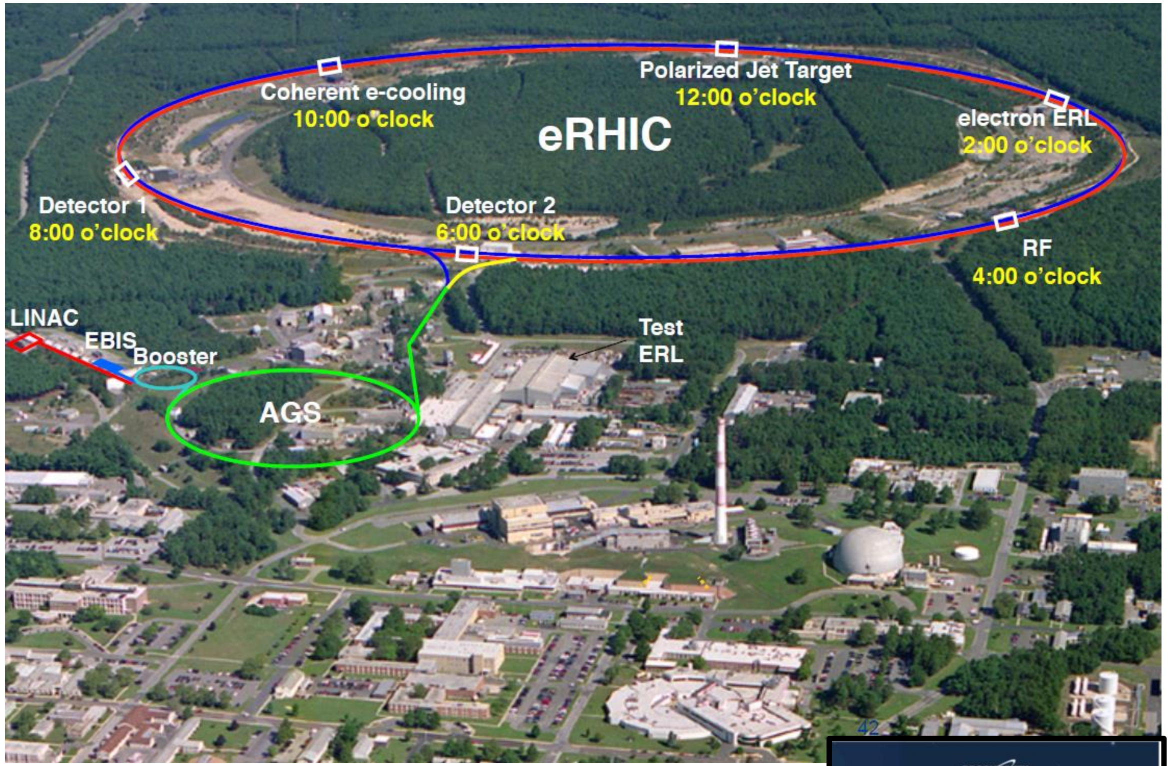
Collider Ring (2 km):
Up: Polarized electron, 10 GeV
Down: Polarized proton, 60-100GeV

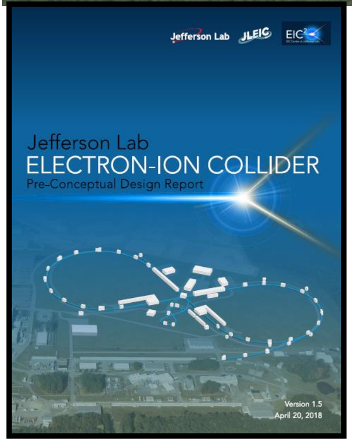
Electron injector:
SRF Linac-ring, 3.5-10GeV

Follow on to High Intensity Heavy Ion Accelerator Facility (HIAF) under construction

US EIC

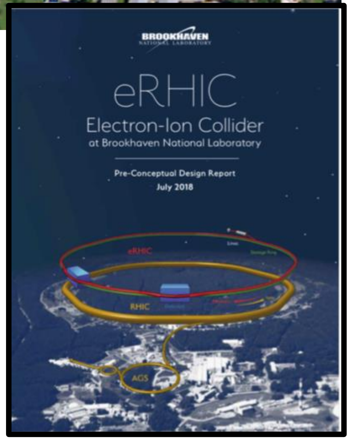






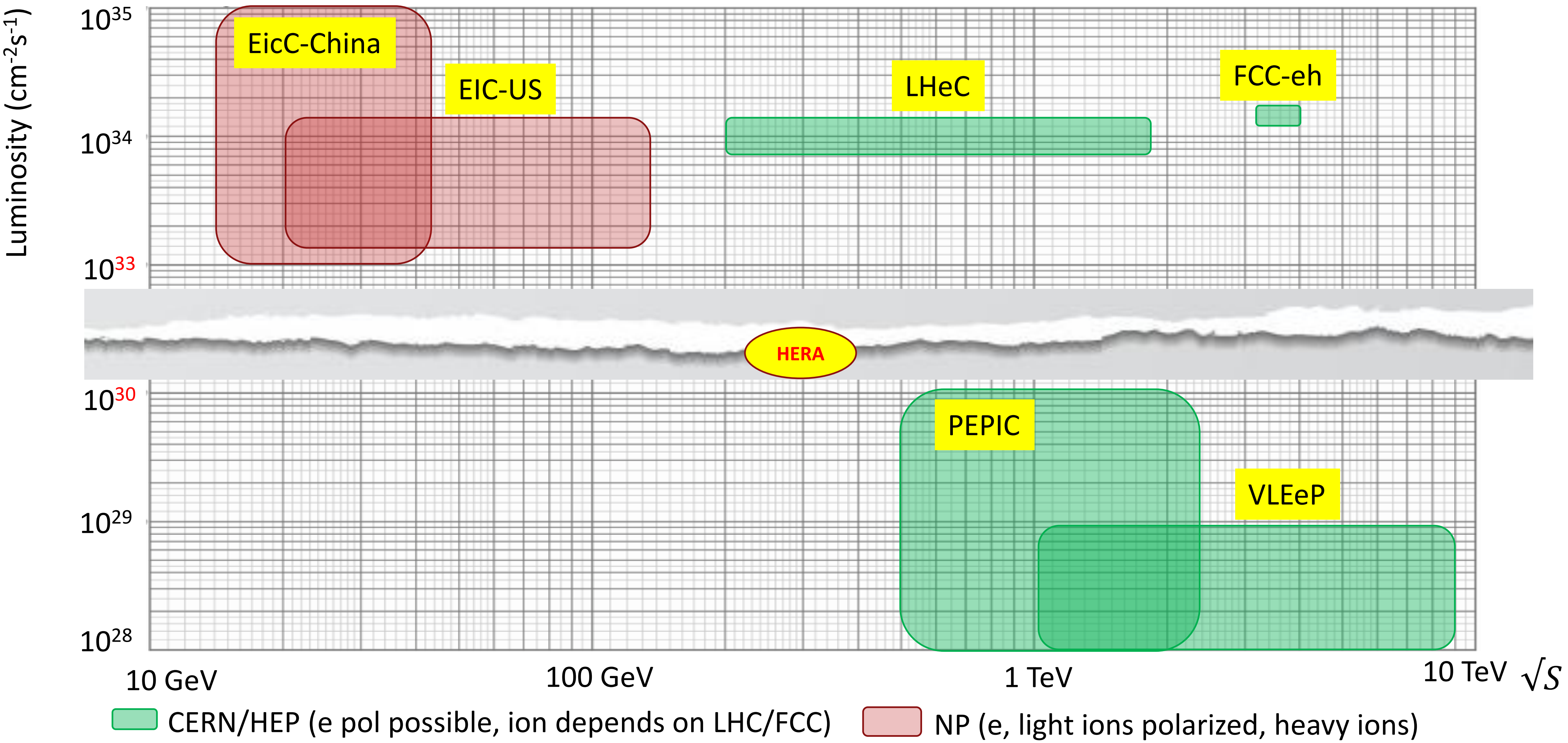
JLEIC Parameters Updated April, 2019

- Highly polarized (~ 70%) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~ 20 – ~100 GeV, upgradable to ~140 GeV
- High collision luminosity $\sim 10^{33-34}$ $cm^{-2}s^{-1}$
- Possibilities of having more than one interaction region

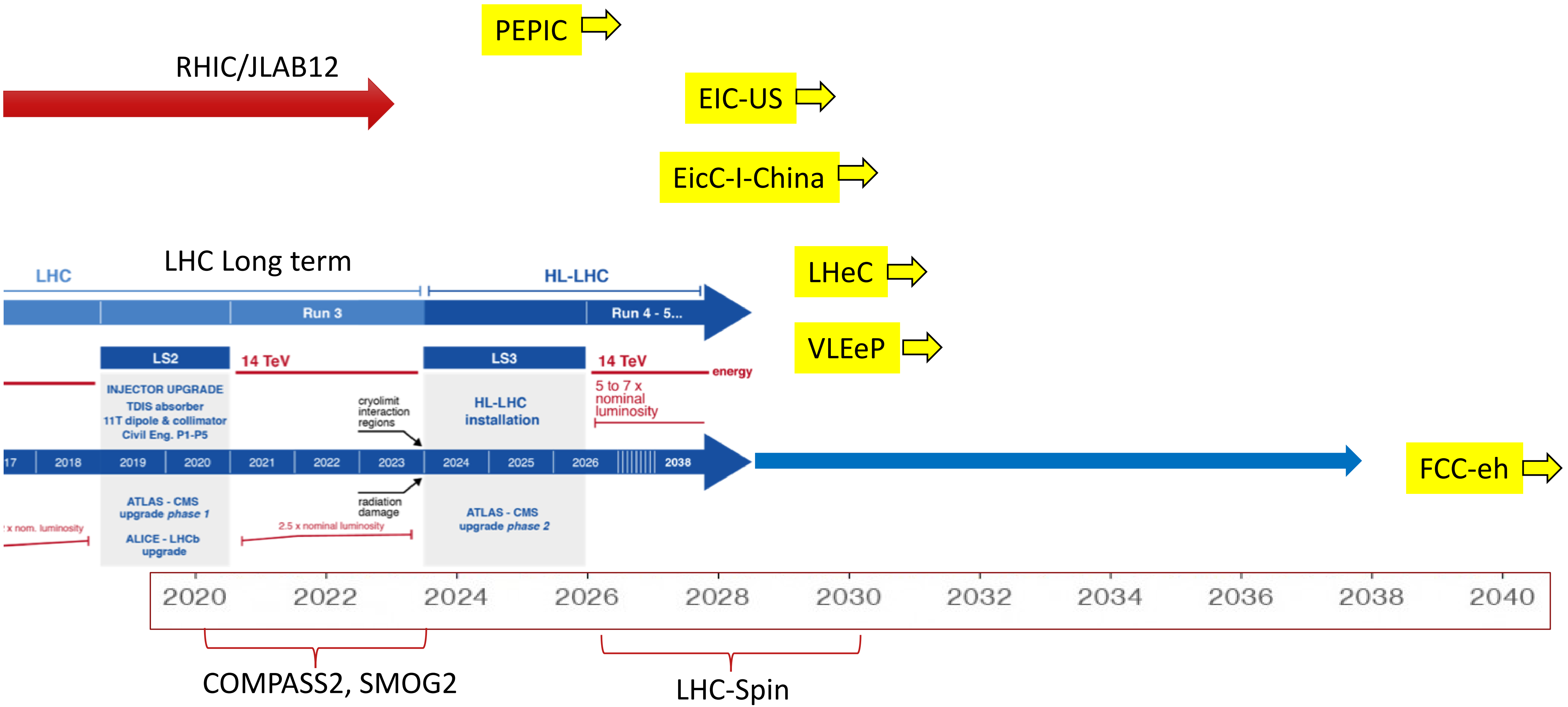


Two realization concepts being developed

DIS Collider Plan Comparison (from EPPSU DIS document)



DIS Collider Earliest Possible Timelines (EPPSU DIS Document)



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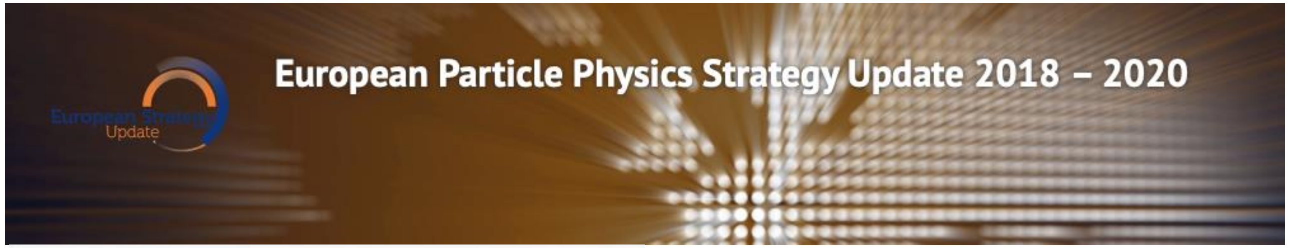
CERN/HEP proposals next steps



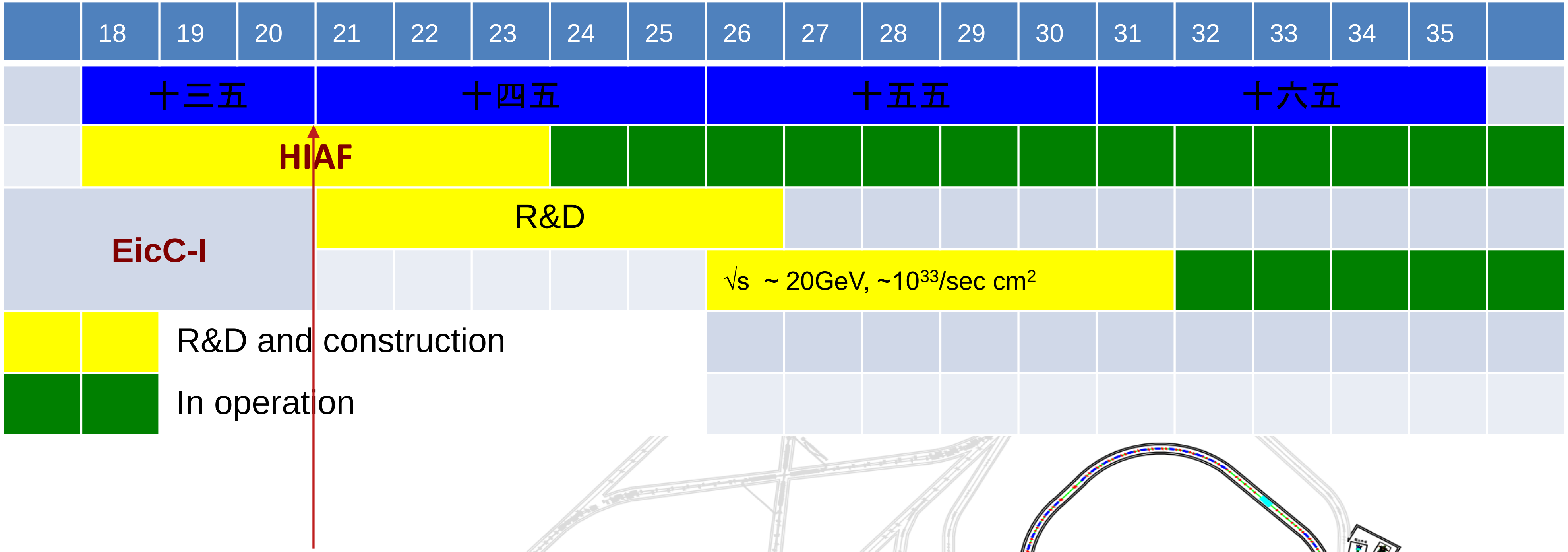
May 2019 Open Symposium

May 2020, Update document to be approved by CERN Council

10-page submissions to EPPSU (there are 160)

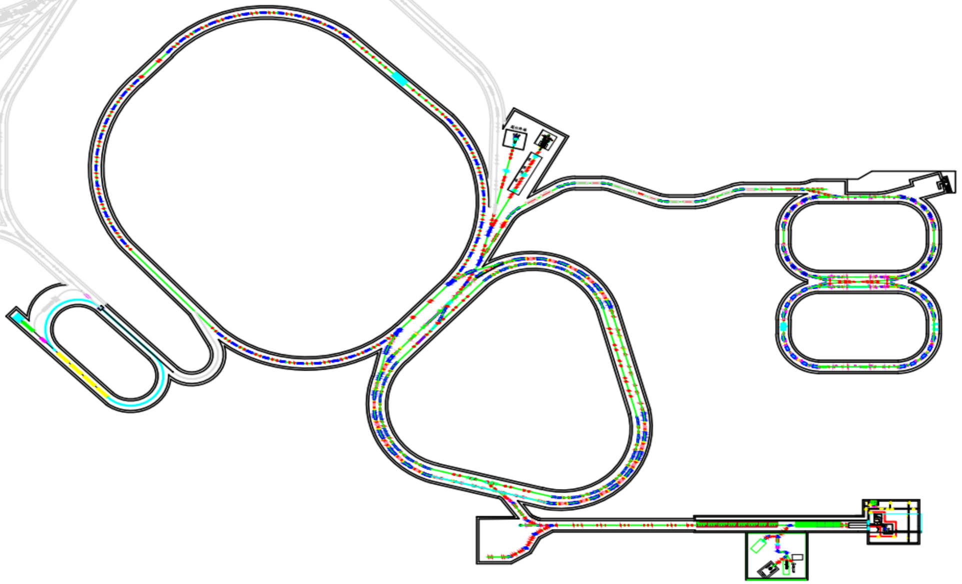
- DIS Collider submissions (ref #)
  - DIS document: EIC, LHeC, FCC-eh, VHEeP (103)
  - Electron-Ion colliders: LHeC (159), FCCeh (140), AWAKE (VHEeP, PEPIC) (58,35,50) US EIC (99,74)
- Related submissions (probably there are others)
  - QCD Theory 163
  - Heavy Ion Program: 110, 48, 37, 47
  - Hadron physics program: COMPASS 143, LHC Spin 111, Fixed Target program 67, [Nuclear Structure: Isolde 39]
  - Accelerator: PERLE 147

EicC (China)



From JP Chen, INT-18, 2018

Start of the next 5 year plan



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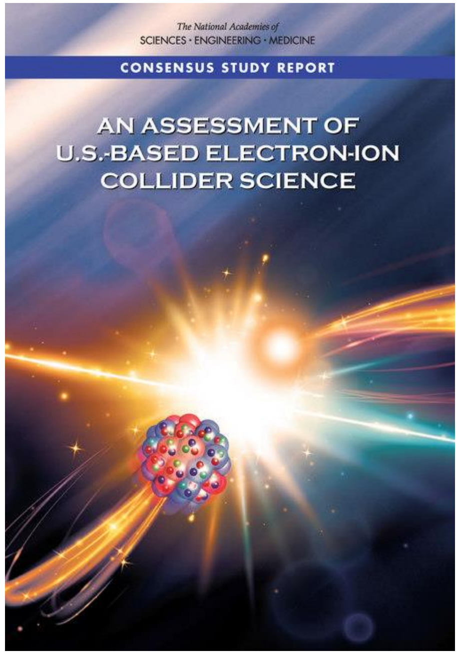
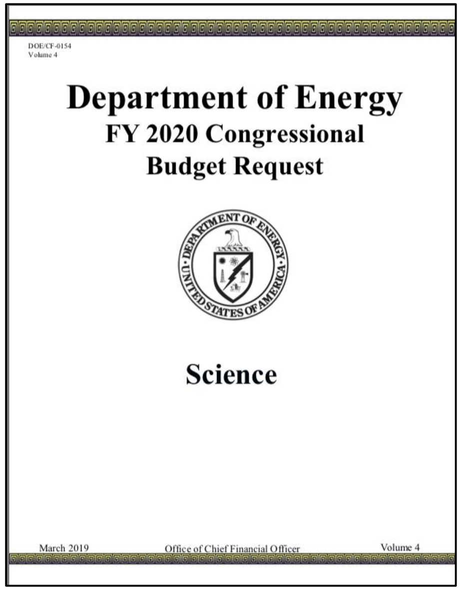
US EIC



National of Academy of Sciences : 2018 Assessment of US EIC

In summary, the committee finds a **compelling scientific case for such a facility**.

FY2020 US Budget Justification


DOE/CF-0154
Volume 4

Department of Energy
FY 2020 Congressional
Budget Request

Science

March 2019 | Office of Chief Financial Officer | Volume 4

Volume 4, Page 272:

"The Request for Construction and Major Items of Equipment (MIEs) includes:"

…

"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."

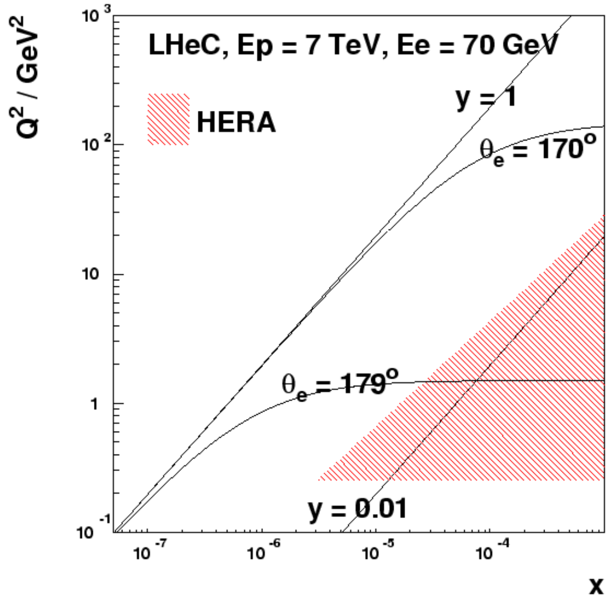
Approval needed in FY2019 to justify budget in FY2020

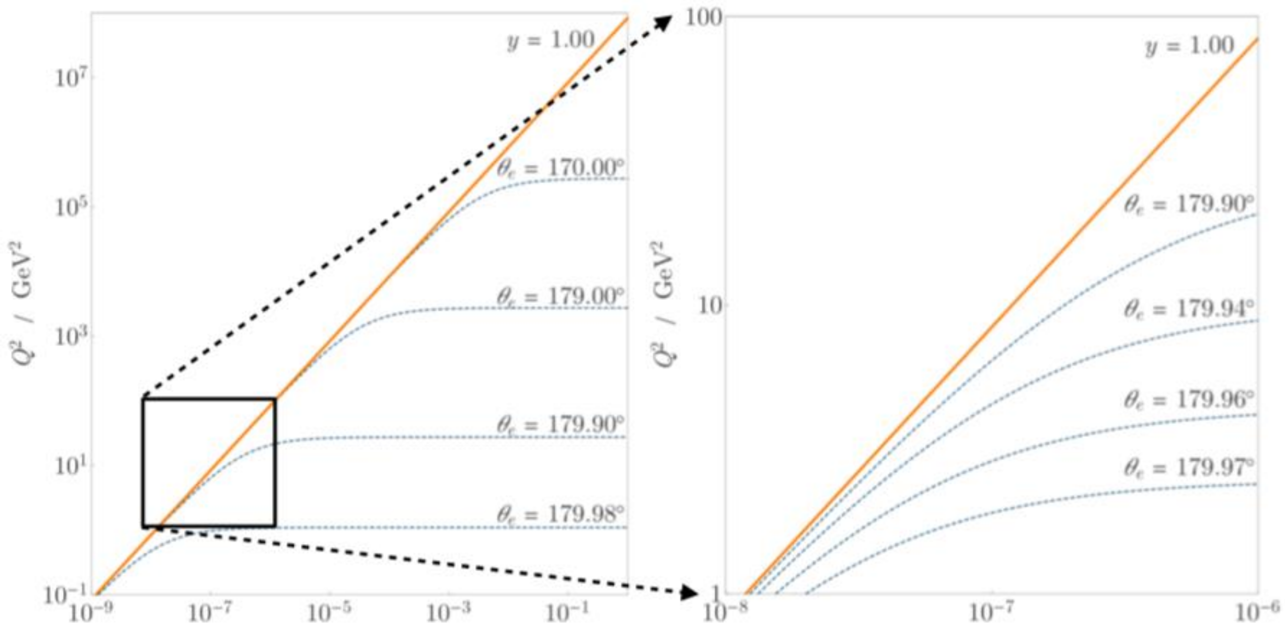
Summary

- Discussed the history of DIS in terms of
  - Investigation of structure
  - Investigation of interactions
  - Where they intersect
- These ideas can be thought of as driving the various direction of DIS research
- And the current proposals for new facilities.
- The DIS collider proposals on the table are very much complementary in capability
  - The next step for the CERN based proposals is the EPPSU 2020 process.
  - For EicC it is the next 5 year plans beginning 2021
  - DOE in US plans to make the EIC a project in FY2019

Extra

VHEeP





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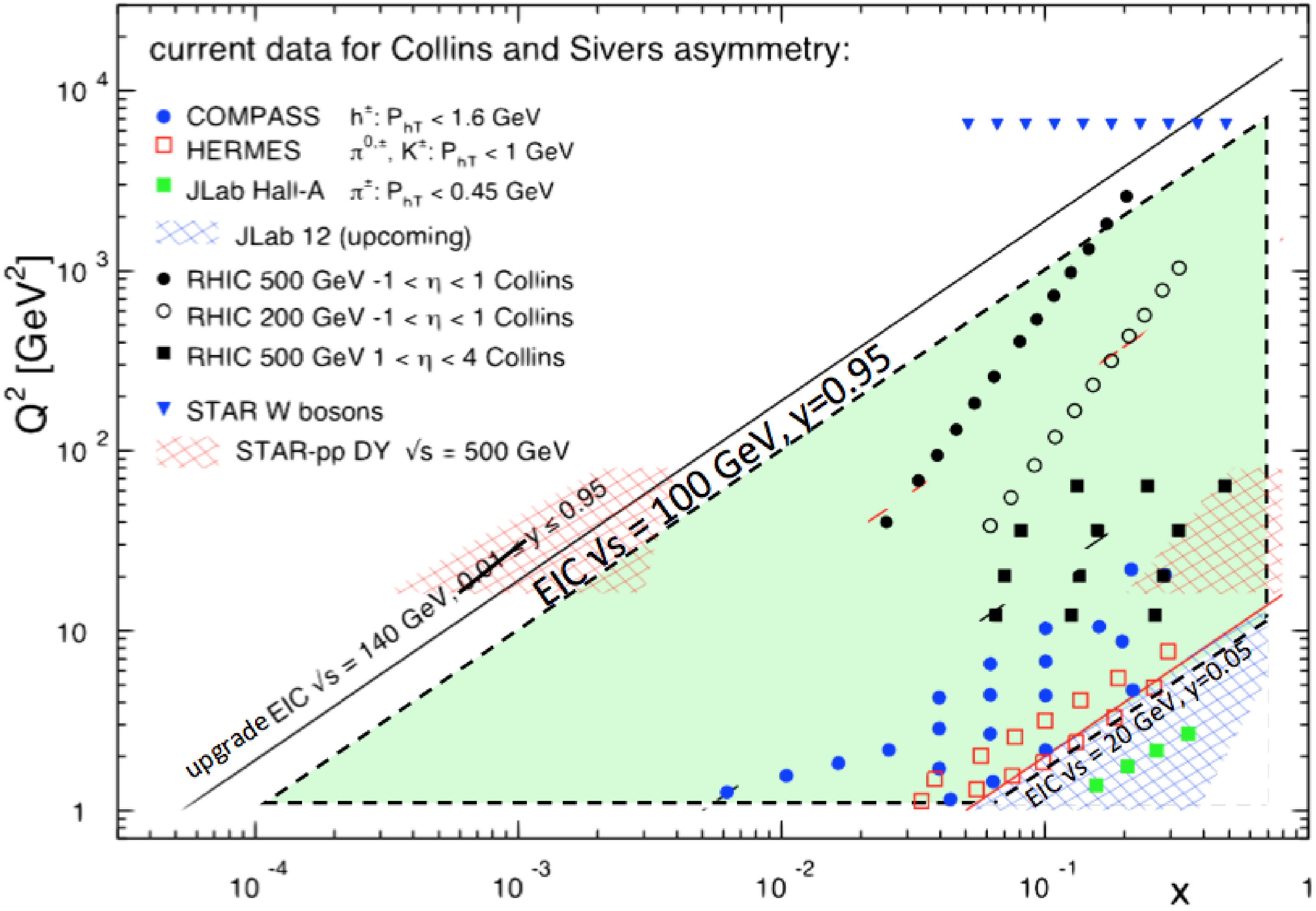

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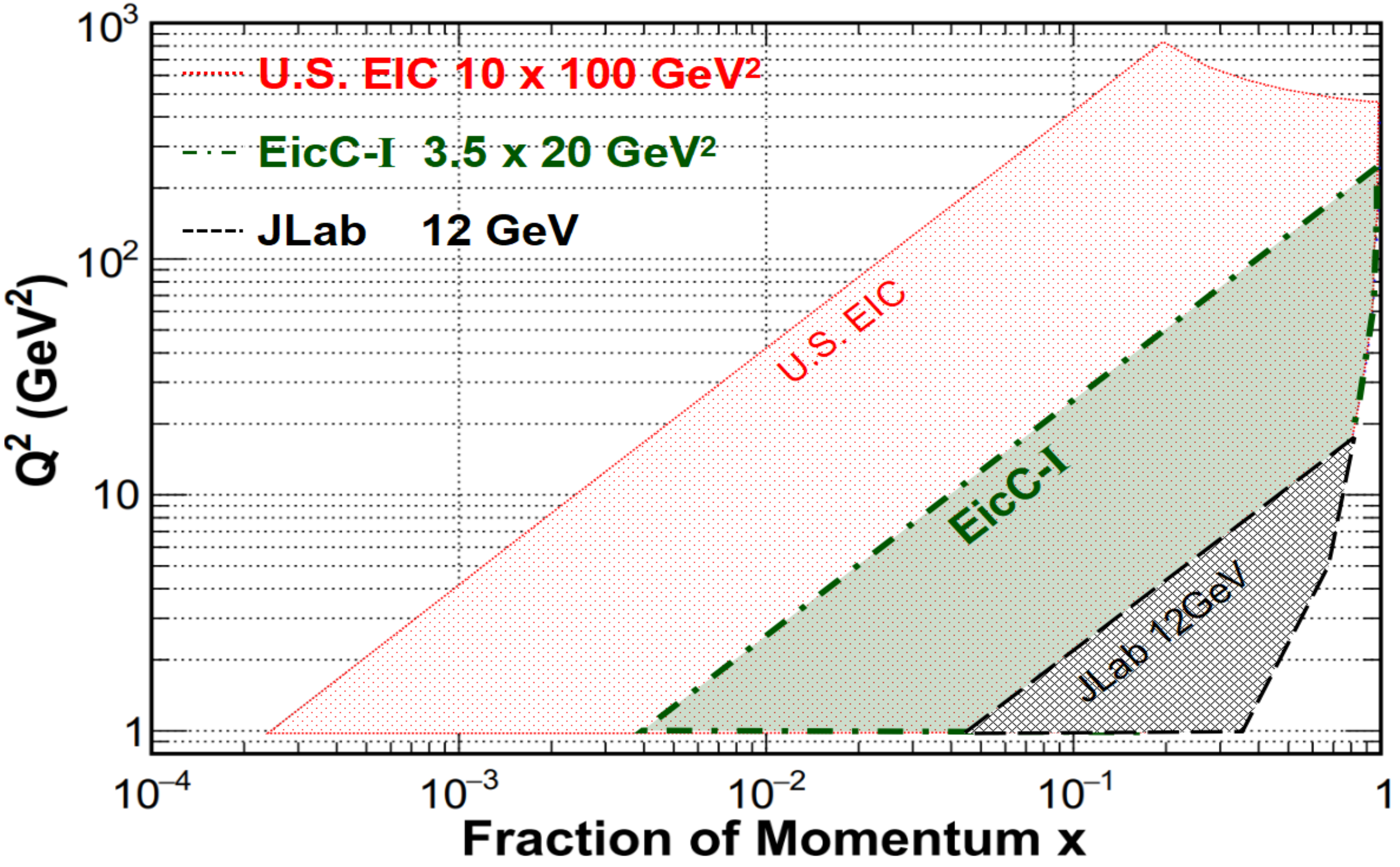

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