Development of the FCC-he Study

Max Klein
U Liverpool and CERN
for the FCC-he Study Group

DIS
Accelerator
Physics
Detector and IR
Test Facility
Project Status

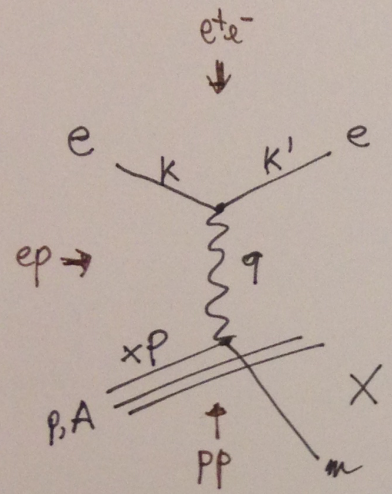
Istanbul, 11th of March, 2016

http://lhec.web.cern.ch

An invitation to join the study (acc, det, phys)

max.klein@cern.ch

Preface on "eh"



$q = k - k'$

$Q^2 = -q^2$

$(xP + q)^2 = m^2$

$$x = \frac{Q^2}{2P \cdot q}$$

$$d \approx 1/\sqrt{Q^2}\,, \quad Q^2 \leq \underbrace{4E_e E_p}_{s} \sim 10^7\,\text{GeV}^2$$

- microscope with resolution down to 10^{-20} m, variation by 4 orders of magnitude
- $x = \frac{Q^2}{sy}$: $10^{-7} \ldots 1$ fixed by e (or ν)

PDFs not calculable from first principles.

- very low $x \lesssim 10^{-5}$: non-linear g-g interactions. end of linear (DGLAP) evolution, sum rules $\int x g\,dx \sim 1/2$ → novel QCD and requirement to master "hh" !

  UHE ν interactions : very low x
- high x ↔ high mass in pp Drell-Yan scattering

  $M = S \cdot x_1 x_2$ need to control search / BSM regime
- Higgs sets scale for luminosity, with high x, Q^2: 10^{34}
- ∃ fundamental difference pp - ep - ee :

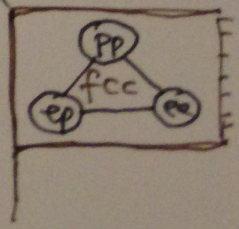
  FCC : $E_p \simeq 50$ TeV, $E_e \sim 100$ GeV ↷

$$\sqrt{s_{pp}} = 2E_p \gg \sqrt{s_{ep}} = 2\sqrt{E_e \cdot E_p} \gg \sqrt{s_{ee}} = 2E_e$$

- HERA no low x, no high x, E too low, $\mathcal{L} = 1\text{-}4\ 10^{31}\,\text{cm}^{-2}\text{s}^{-1}$
- pp : high energy frontier discovery machine

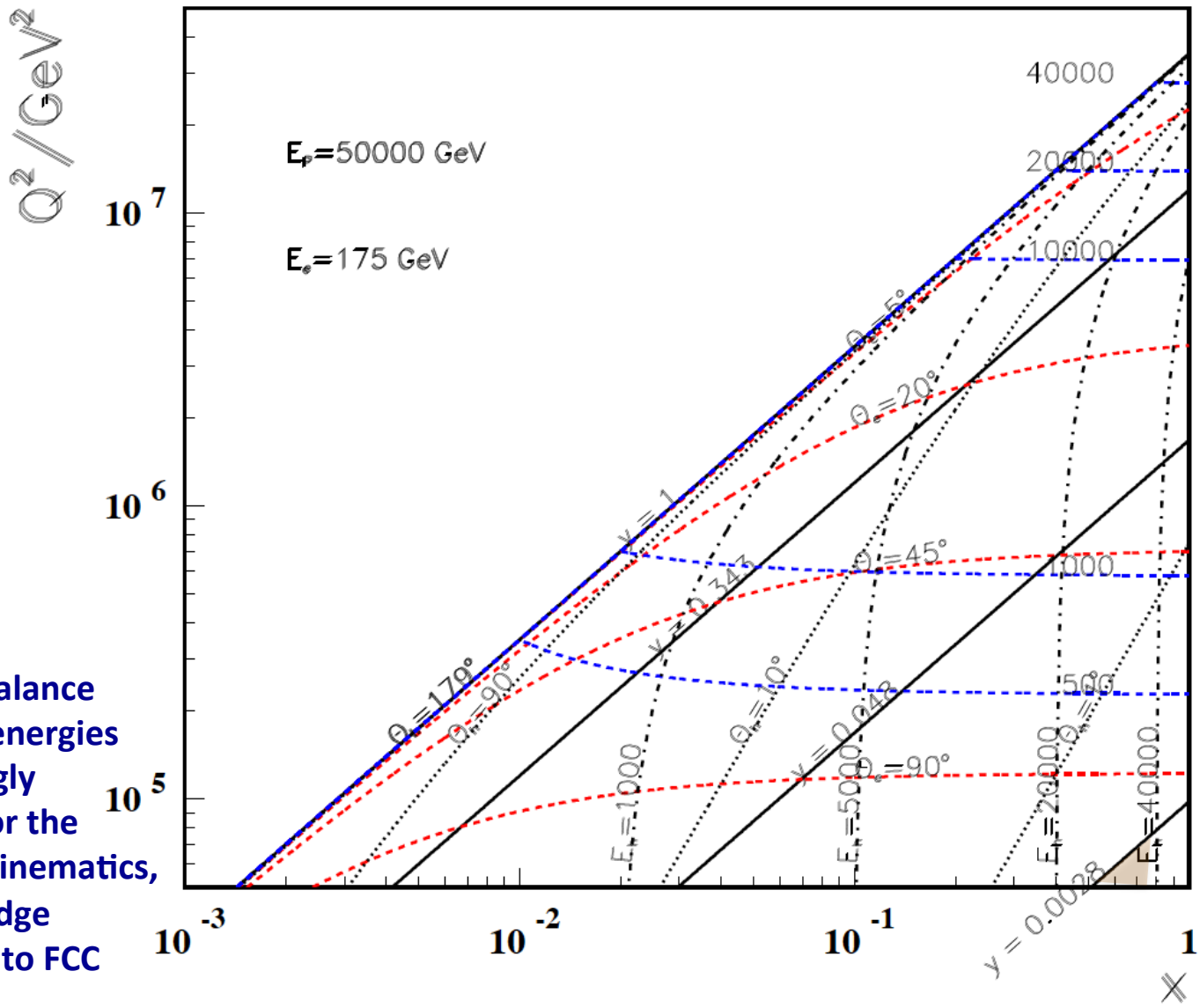
  ep : complements pp with own discovery and precision measurement potential

  ee : low energy, high precision.



High Q^2

Rutherford backscattering
of dozens of TeV e- energy



FCC-he
175 GeV
60 GeV

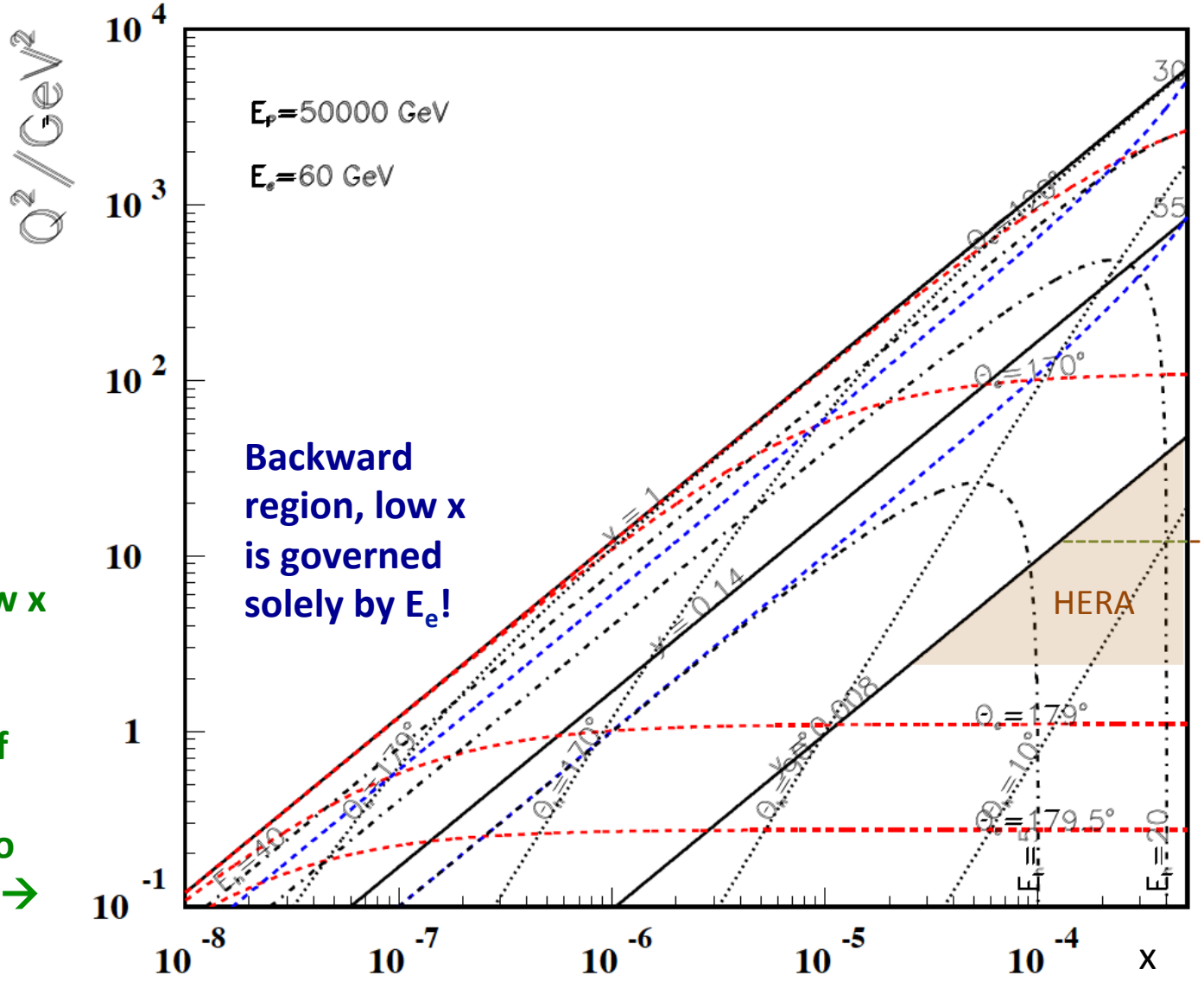
LHeC

← ϑ_h=1°

← HERA

Large imabalance of e and p energies is surprisingly tolerable for the high Q^2, x kinematics, LHeC to bridge from HERA to FCC

Low x



FCC-he
60 GeV

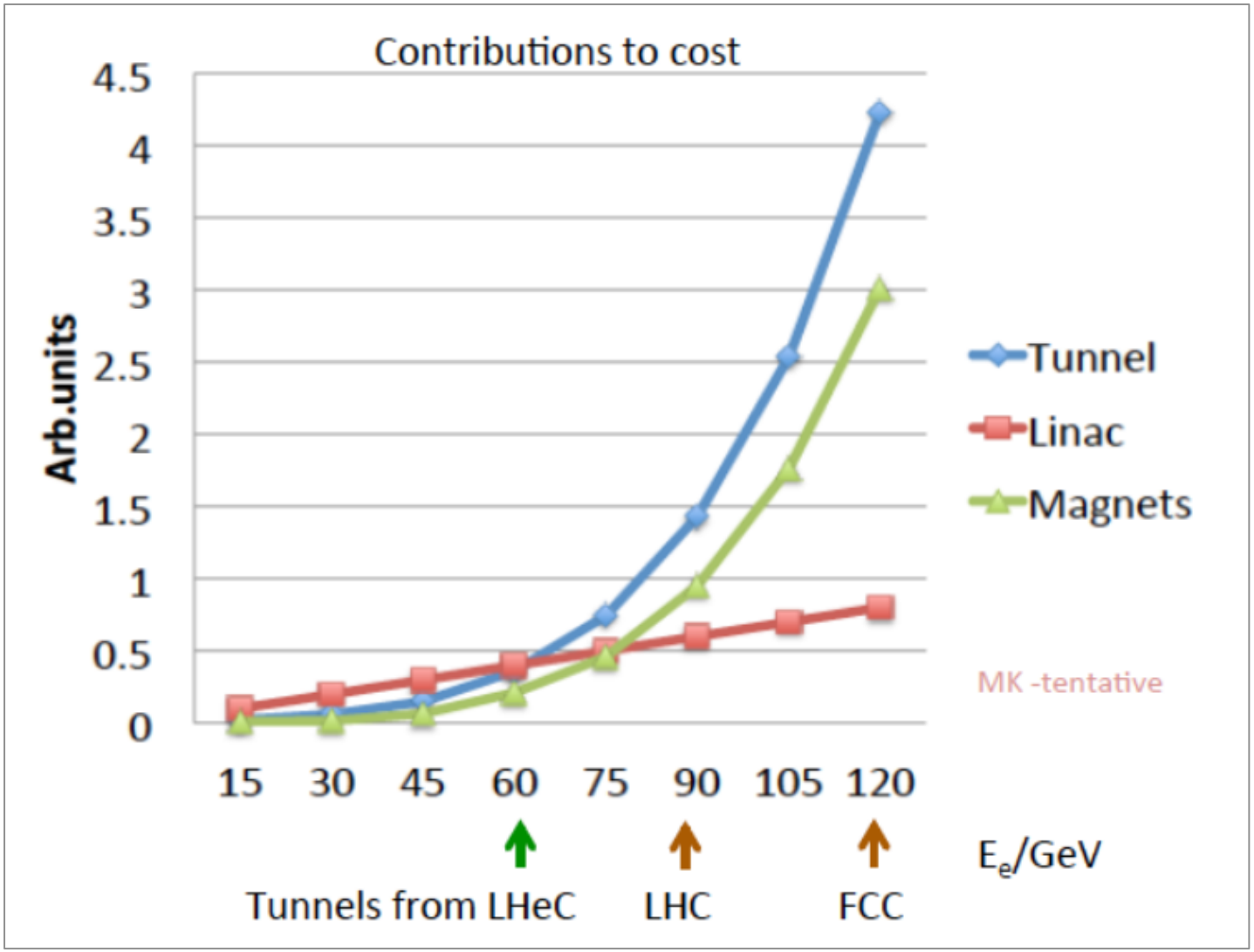
LHeC

← 179°
@ 180 GeV
.. very low x requires not the maximum of E_e

Very low x reaches direct range of UHE neutrino physics →

For $x < 10^{-3}$ no (average) energy deposition exceeding the electron beam energy

Choice of Baseline Configuration = f(cost,E_e,s)



→ Cost strongly rising with tunnel circumference. Presently stick to LHeC default.

→ Maximise independence of ring installation, design for synchronous ep and pp OP

Baseline Electron Beam Configuration*)

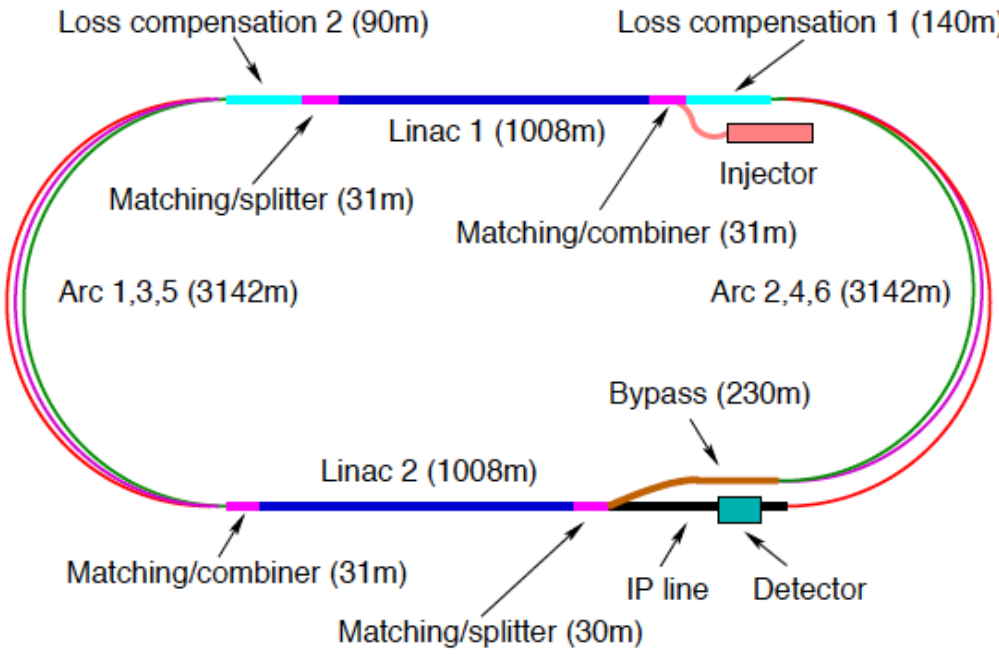


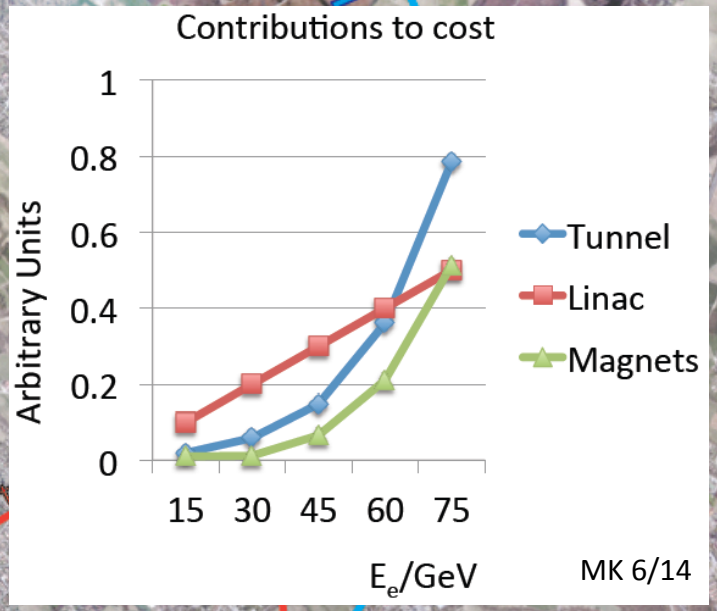
Figure 2: Schematic view of the default LHeC configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the interaction point after three passes through the opposite lying linac structures made of 60 cavity-cryo modules each. The arc radius is about 1 km and the circumference chosen to be 1/3 of that of the LHC. The beam is decelerated for recovering the beam power after having passed the IP.

*) LHeC CDR, arXiv:1206.2913

Civil Engineering Footprint

LHeC construction planning	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

7 years for 9km Civil Engineering



LHC

1/3 Pt2 CDR

1/4 Pt2

1/5 Pt2

Prevessin Site

SPS

1/3 Pt

Pt 2

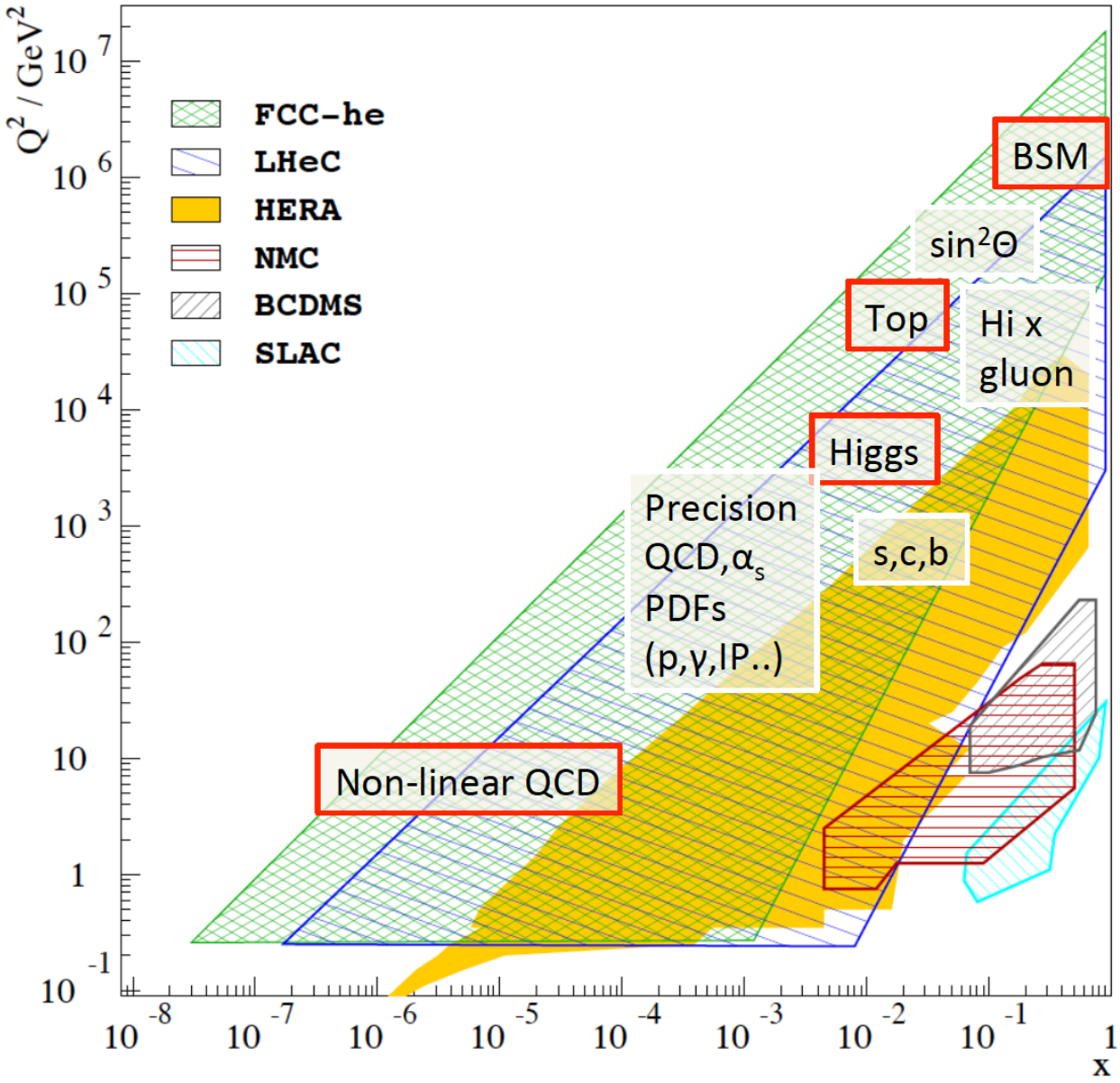
Pt 1

Meyrin Site

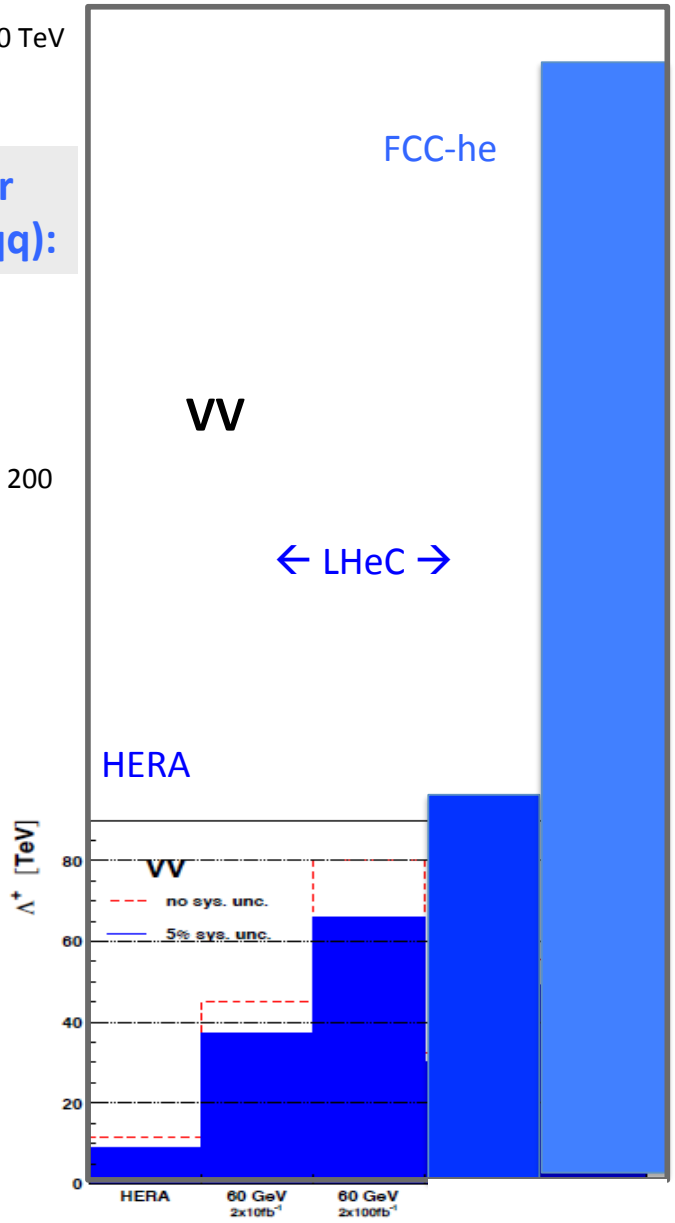
Pt 8

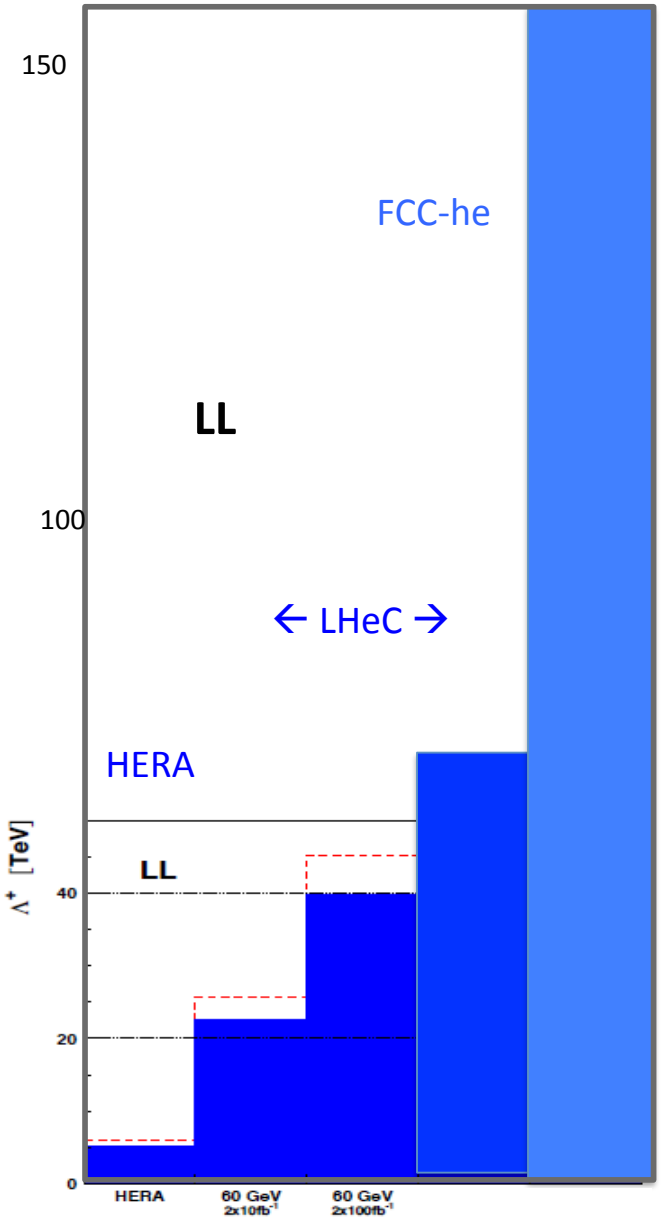
LHeC
Civil Engineering
Different Options
Fraction 1/3-1/4-1/5
Pt2 and Pt8
J.OSBORNE/L.FAISANDEL GS-SE-DOP

Summary of ep Physics



Reach for Λ (CI eeqq):





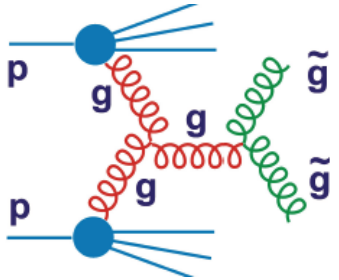
FCC - rough scaling only – very preliminary

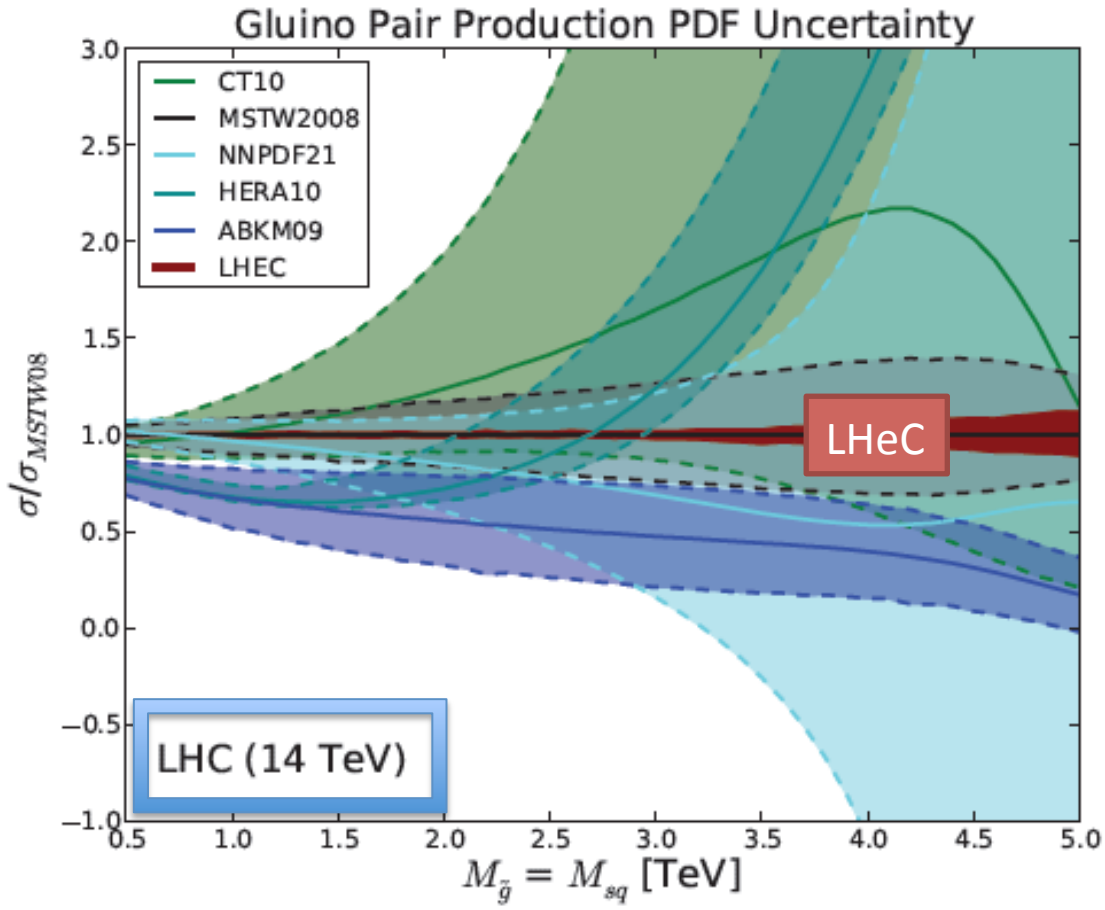
LHeC: see CDR 2012

Search for + verification of Contact Interactions into O(100)TeV. eq Fusion: Leptoquarks M<√s

Precision PDFs for BSM Searches

Gluons for SUSY



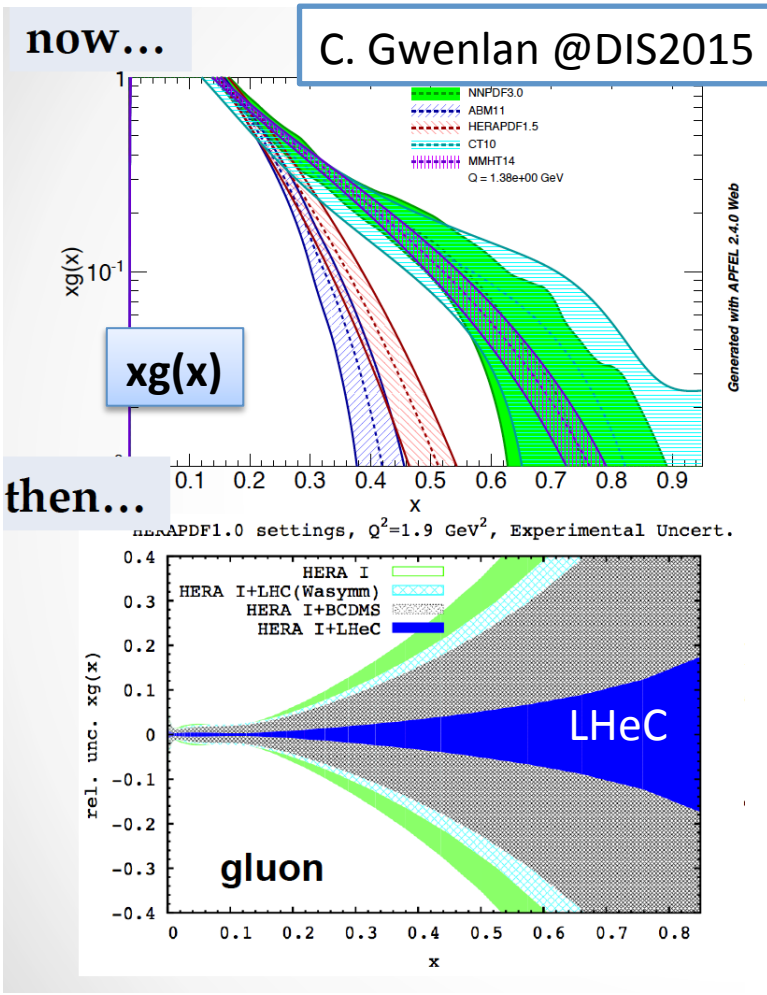


Using 2012 NLO PDFs

LHeC Note 2012-005 [arXiv:1211.5102]

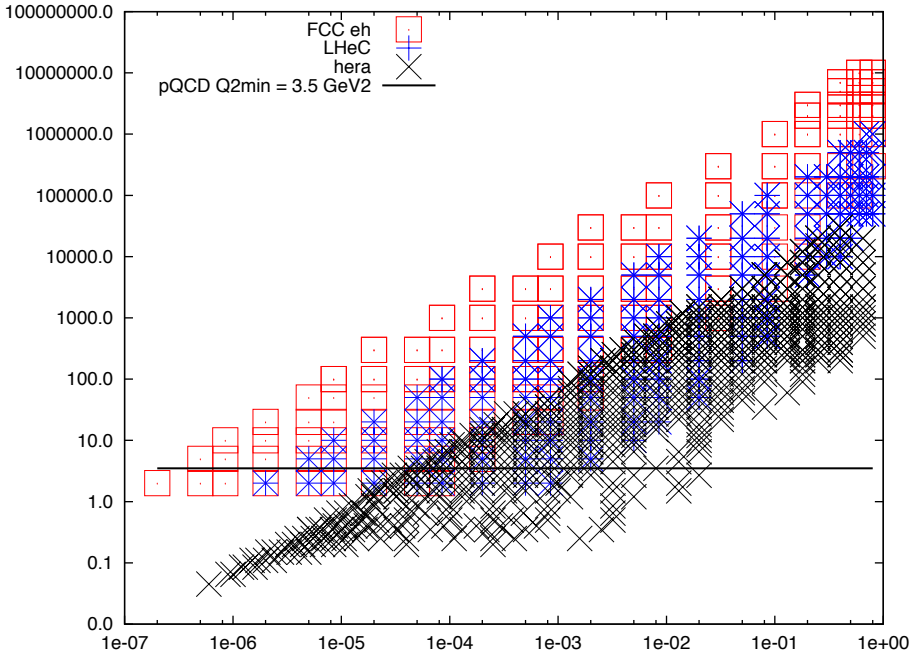
LHeC-PDF accessible via LHAPDF, MK, V.Radescu

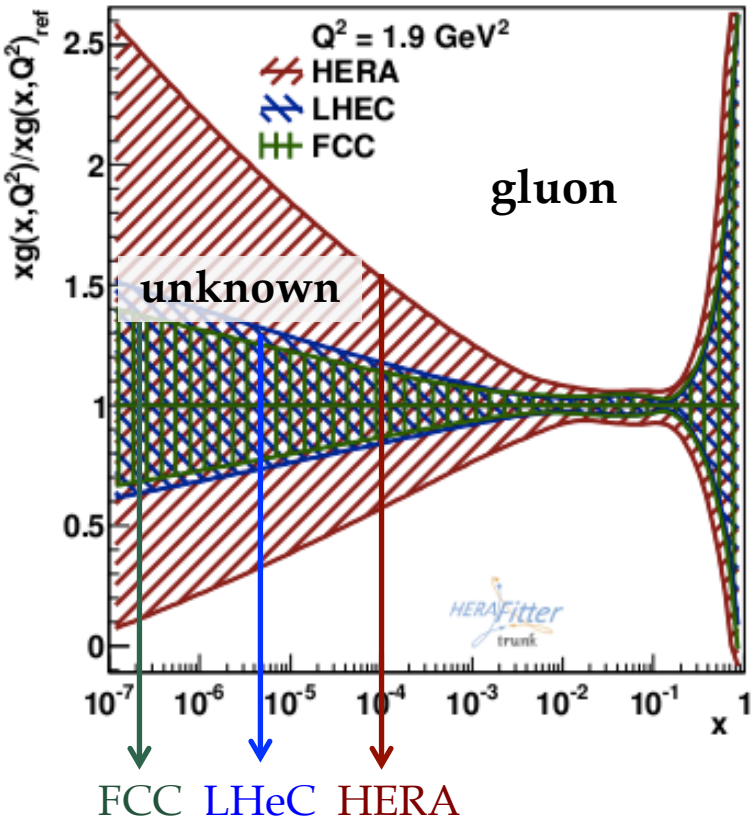
C. Gwenlan @DIS2015



Using 2014 NNLO PDFs

FCC-eh vs LHeC vs HERA





FCC-eh: Ep=50 TeV, Ee=100 GeV

NC and CC: e-p, P=80%, 1000 fb^{-1}

stat: 0.1 – 30%, uncor 0.7%, syst 1 – 5%

coverage down to x=2×10-7, up to $Q^2 = 10^7$ GeV^2

need FCC to constrain much below x=10^{-5}

FCC-eh can further improve, and explore low-x phenomenology

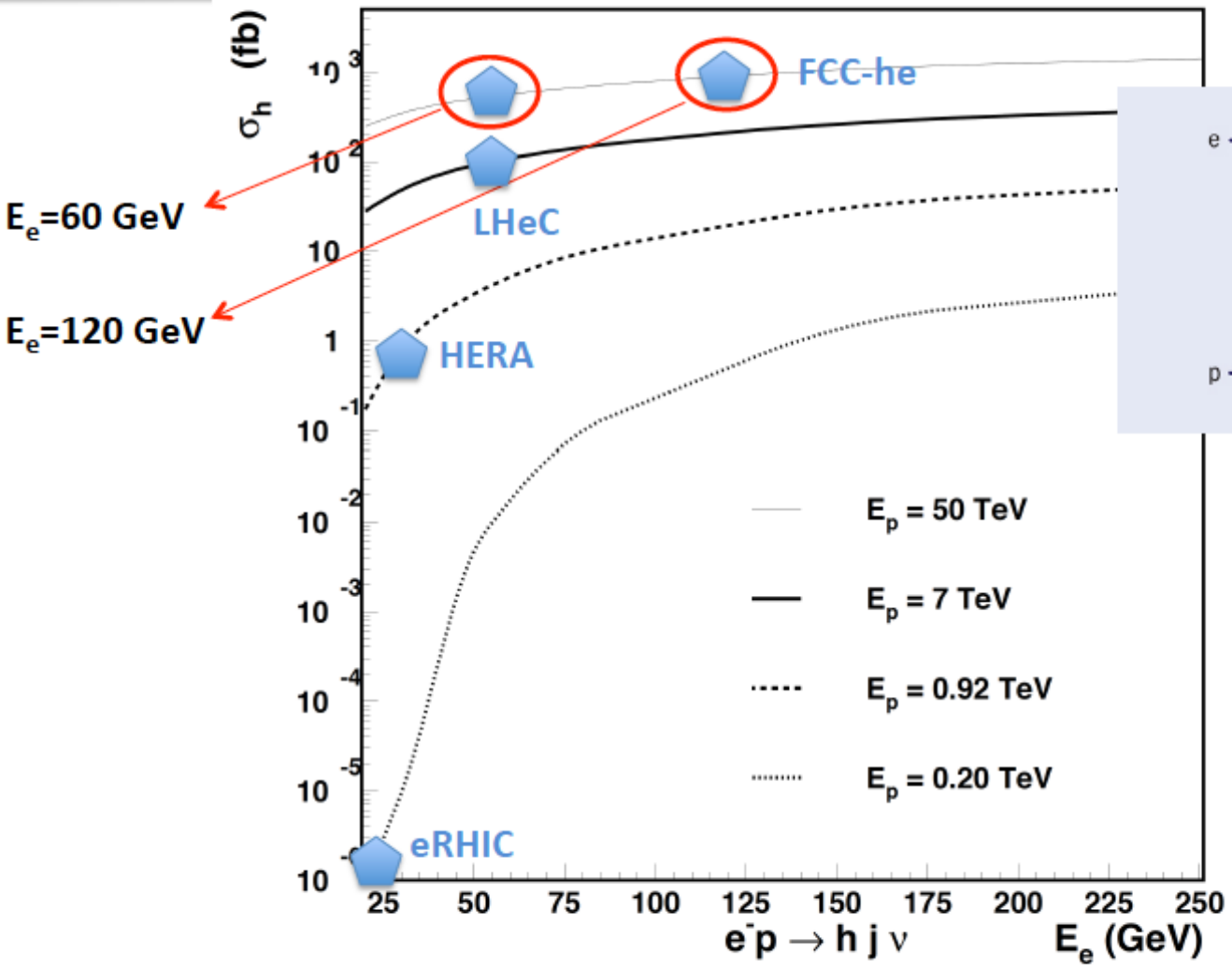
Electron Ion Physics

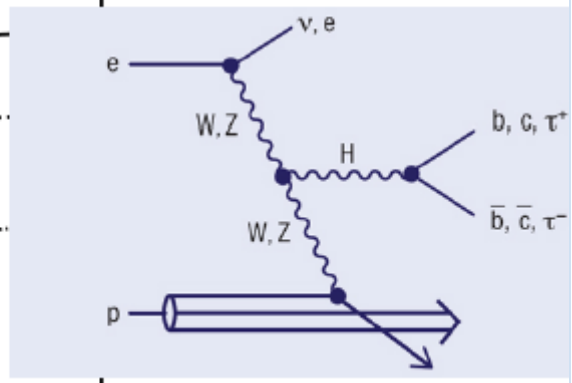
item	HKN07	EPS09	DSSZ	nCTEQ	LHeC
Reference	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv: 1509.00792	Workshops + this talk PRD(2030+)
Order pQCD	LO & NLO	LO & NLO	NLO	NLO	NNLO
NC e+A / e+d DIS	√	√	√	√	NC
Drell-Yan ll in p+A / p+d	√	√	√	√	--
RHIC pions in d+Au / p+p		√	√	√	--
Neutrino-nucleus DIS			√		CC
√Q^2 cut in DIS	1 GeV	1.3 GeV	1 GeV	2 GeV	free
# of data points	1241	929	1579	740	many
Free parameters	12	15	25	17	O(20)
Error sets available		√	√	√	(y)
Error tolerance $\Delta\chi^2$	13.7	50	30	35	1
Baseline	MRST98	CTEQ6.1	MSTW08	CTEQ6M	None – or ep+eD+eA
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS	s,c,b data

HERA had no eA phase. Thus the LHeC (FCC-eh) extends the Q^2,1/x range of nuclear DIS by 4(5) orders of magnitude → a revolution of understanding nuclear dynamics+structure

Cf recent talks on LHeC web page and paper (M.K.) in POETIC2015

SM Higgs in ep





Clean production
High xsection (5xee)
Clean final state
No pile-up in ep
→ Unique and complementary H lab
High Precision → Window to BSM, DM

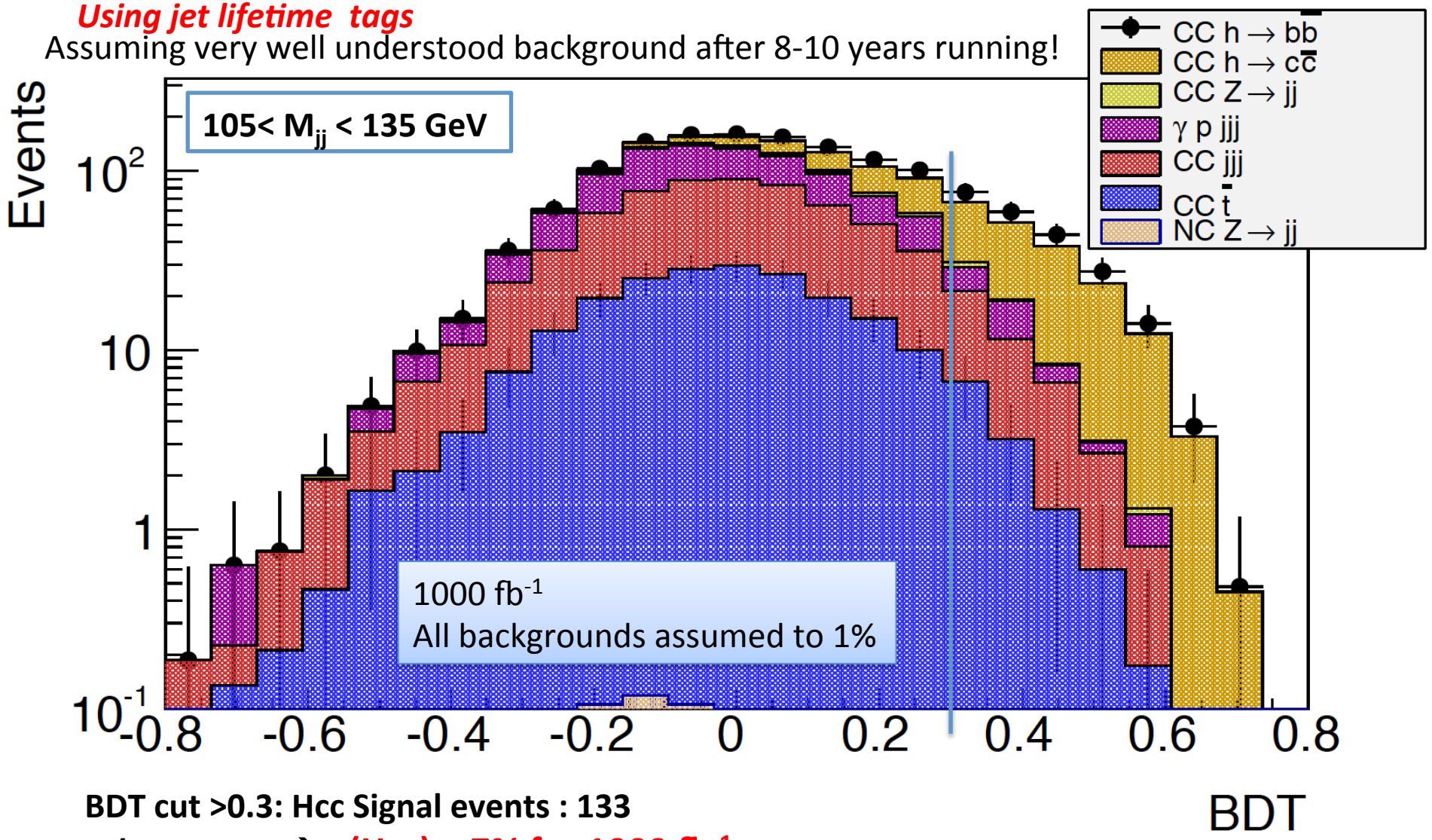
LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

[P=-0.8, BR=0.029]

Very first BDT results : Higgs→ cc

Using jet lifetime tags

Assuming very well understood background after 8-10 years running!



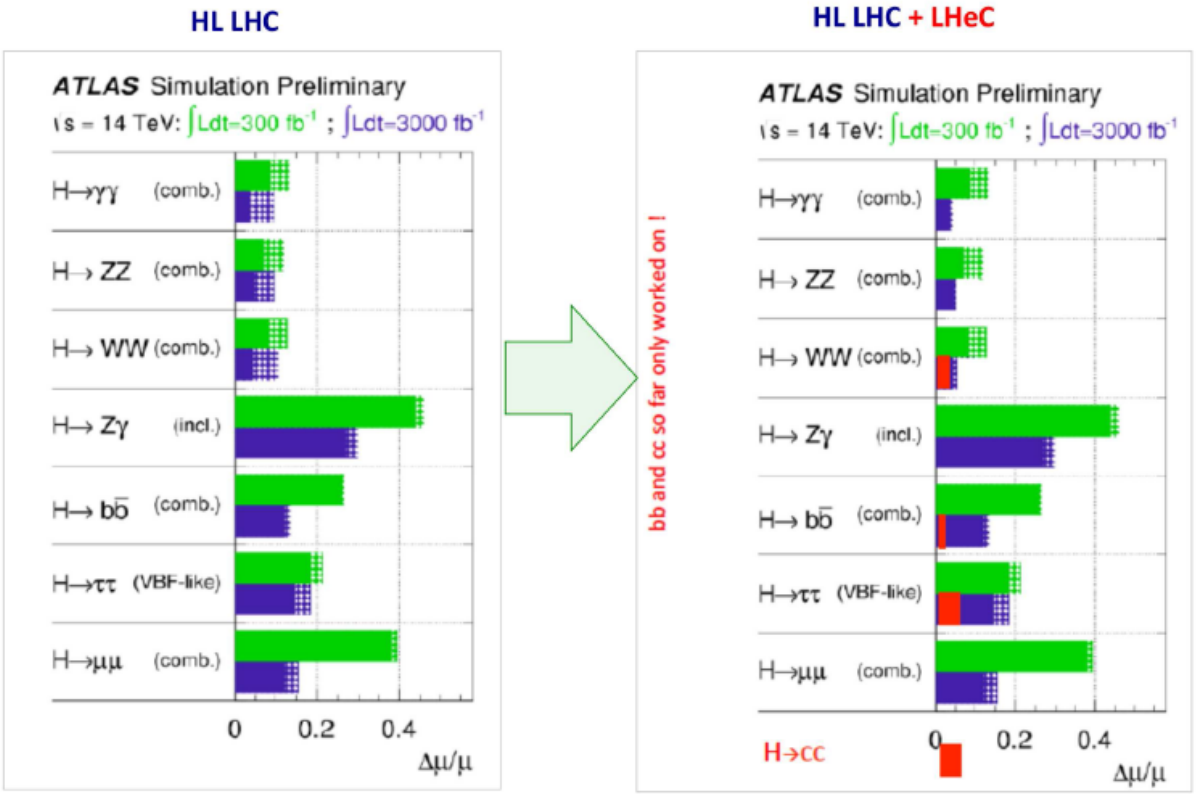
BDT cut >0.3: Hcc Signal events : 133

S/√S+B=1.5 → κ(Hcc) = 7% for 1000 fb^{-1}

→ There is a clear potential to measure Hcc at LHeC

→ Further optimisation ongoing, e.g. using R=0.7 jets will double statistics

HIGGS PHYSICS AT THE LHEC
SUMMARY



- GLUON FUSION AND W FUSION $\Rightarrow$ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

Turn LHC into precision Higgs facility: add PDFs add ep channels (bb,cc.)

S.Forte ECFA 9/15

Further Recent Studies on Higgs in ep

BSM Higgs with LHeC

Invisible Higgs Decay at the LHeC

Yi-Lei Tang,[1,*] Chen Zhang,[2,†] and Shou-hua Zhu[1,2,3,‡]

arXiv:1508.01095, 2015

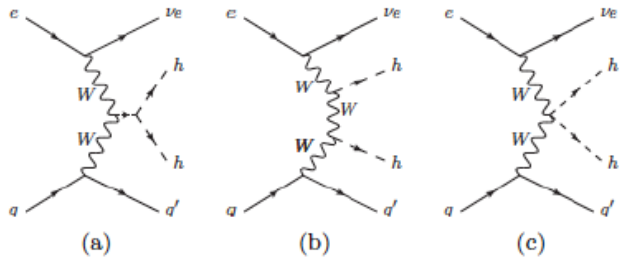
Our study clearly justifies a luminosity upgrade to 1 ab^{-1} for the LHeC to become a Higgs boson factory [46] and demonstrates its huge potential on study of exotic Higgs decays. Besides the invisible Higgs decay, the LHeC is suited to the study of those exotic Higgs decays which suffer from large backgrounds, trigger or p_T threshold problem at the (HL-)LHC such as $h \to 4b$, $h \to 2b2\tau$, $h \to 4j$, $h \to b\bar{b} + \not{E}_T$ [73], $h \to \gamma + \not{E}_T$, $h \to Z + \not{E}_T$ [74]. Work on these directions is in progress [75]. The

H-HH with FCC-he (√s=3.5 TeV vs 0.3 at FCC-ee)

Higgs cross section at FCC-ep is O(1pb) →striking potential being explored

Probing anomalous couplings using di-Higgs production in electron-proton collisions

Mukesh Kumar,[1,*] Xifeng Ruan,[2,†] Rashidul Islam,[3,‡] Alan S. Cornell,[1,§] Max Klein,[4,¶] Uta Klein,[4,**] and Bruce Mellado[2,††]



arXiv:1509.04016, 2015.

Overview for Physics after (?) the Higgs

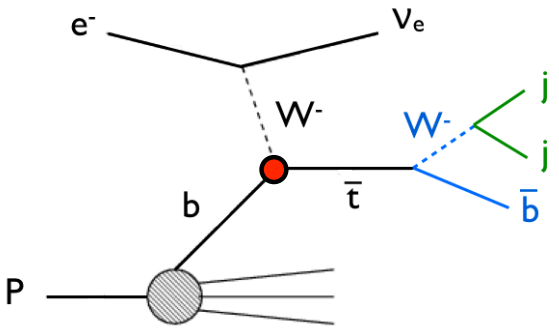
Deep Inelastic Scattering at the Energy Frontier

Max Klein (University of Liverpool and CERN)

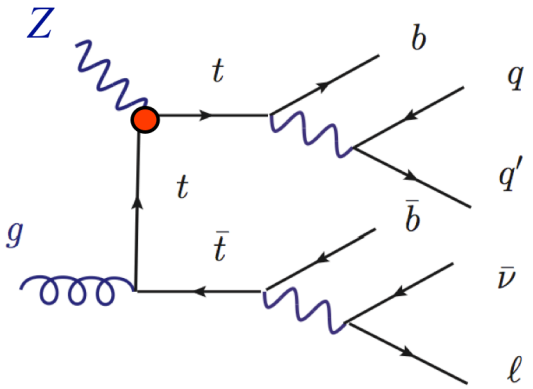
Physics summary artiicle - Published in Annals of Physics 1/16

top quark electroweak interactions

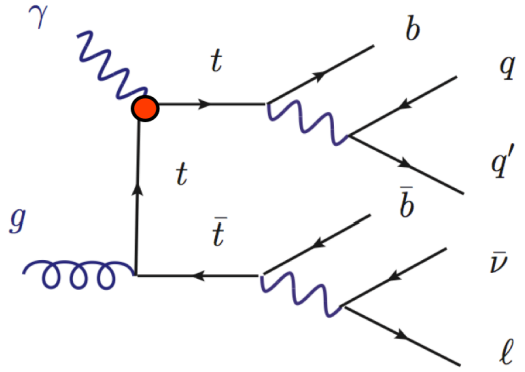
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



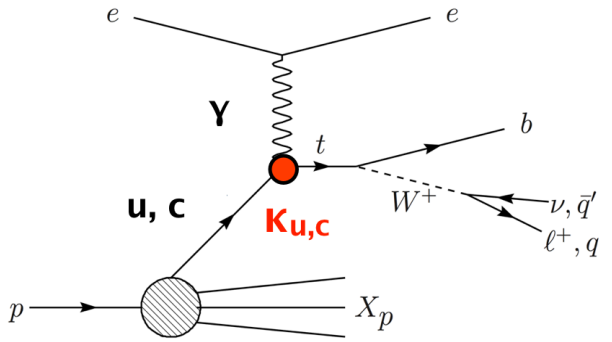
- high precision measurements of Vtb and search for anomalous Wtb couplings



- measurement of top isospin and search for anomalous ttbarZ couplings (eg. EDM, MDM)



- direct measurement of top quark charge and search for anomalous ttbarγ couplings (eg. EDM, MDM)



- sensitive search for FCNC couplings will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

A Baseline for the FCC-he

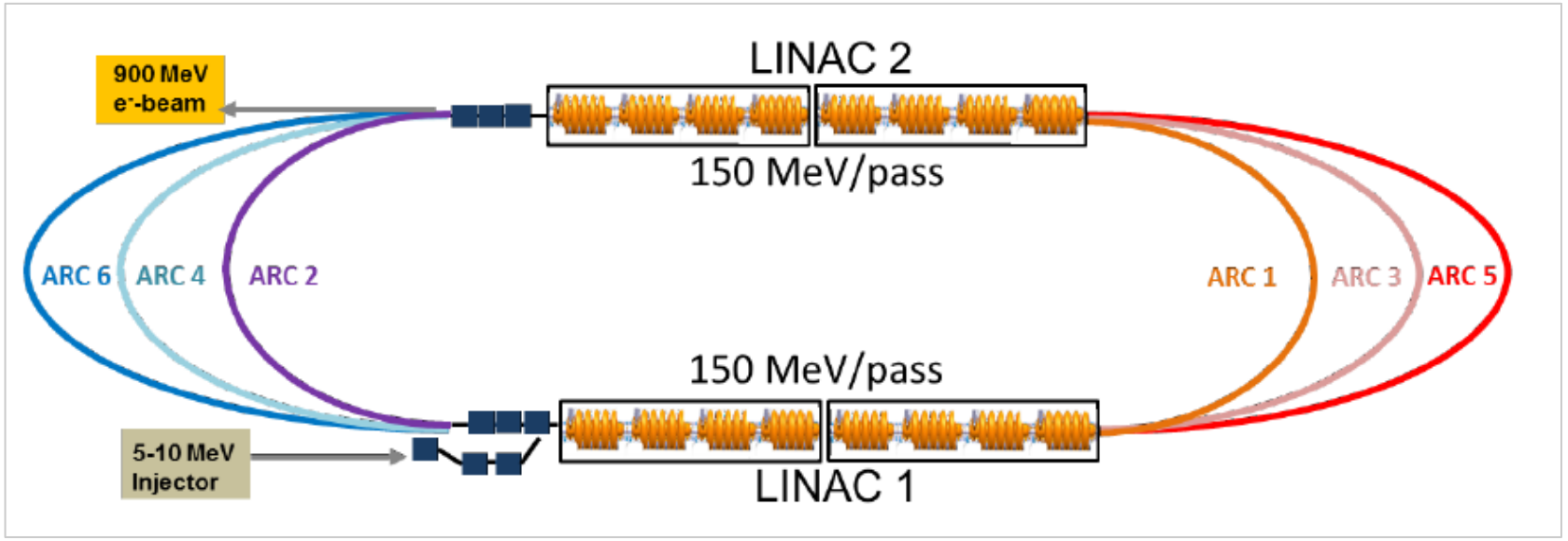
Oliver Brüning[1] Max Klein[1,2], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
March 3rd, 2016

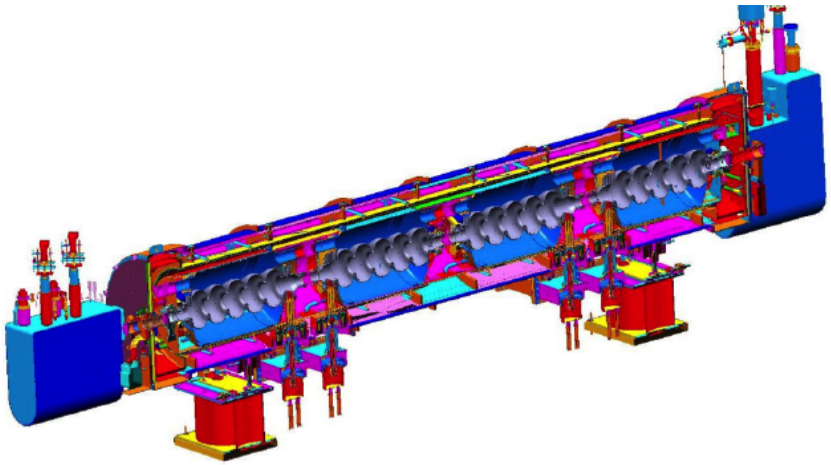
Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

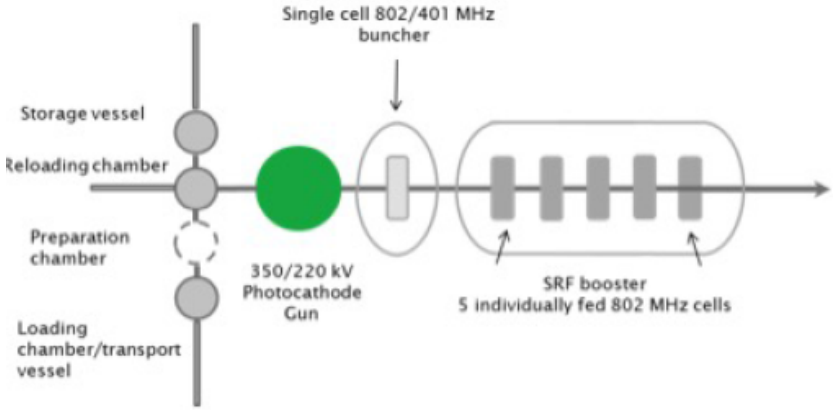
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.3	10.1	15.1	9.2

4.3.2016 - *work in progress* Study value of dedicated operation O(10^{35} cm^{-2} s^{-1}), also eA

Test and Physics Facility







Source (Boris Mlytsin, CI)

Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

ICFA BeamNewsletter68 (1/16) and to be published

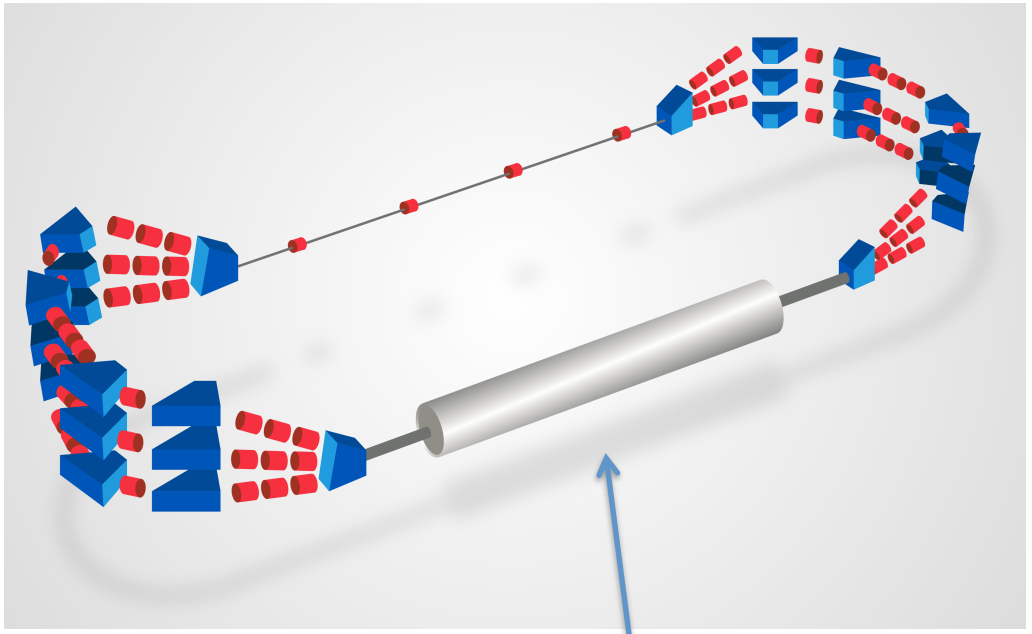
ERL Demonstrator

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

E_e = 200 (400) MeV with 1(2) module

A.Valloni 2/16



Parameter	Value
Dipoles per arc Dipole length Max B Field	3/4 50 cm 1.1 T
Quadrupoles per arc Quadrupoles in straight lines	5 4
Dipoles in Spreader/Combiner Quads in Spreader/Combiner	1-3 3
Dipoles for Injection-Extraction	6

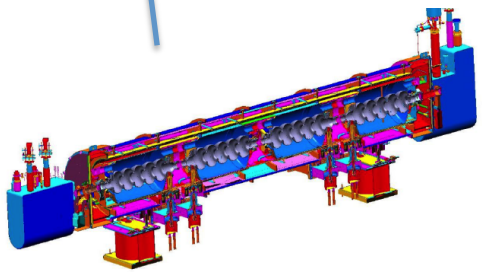
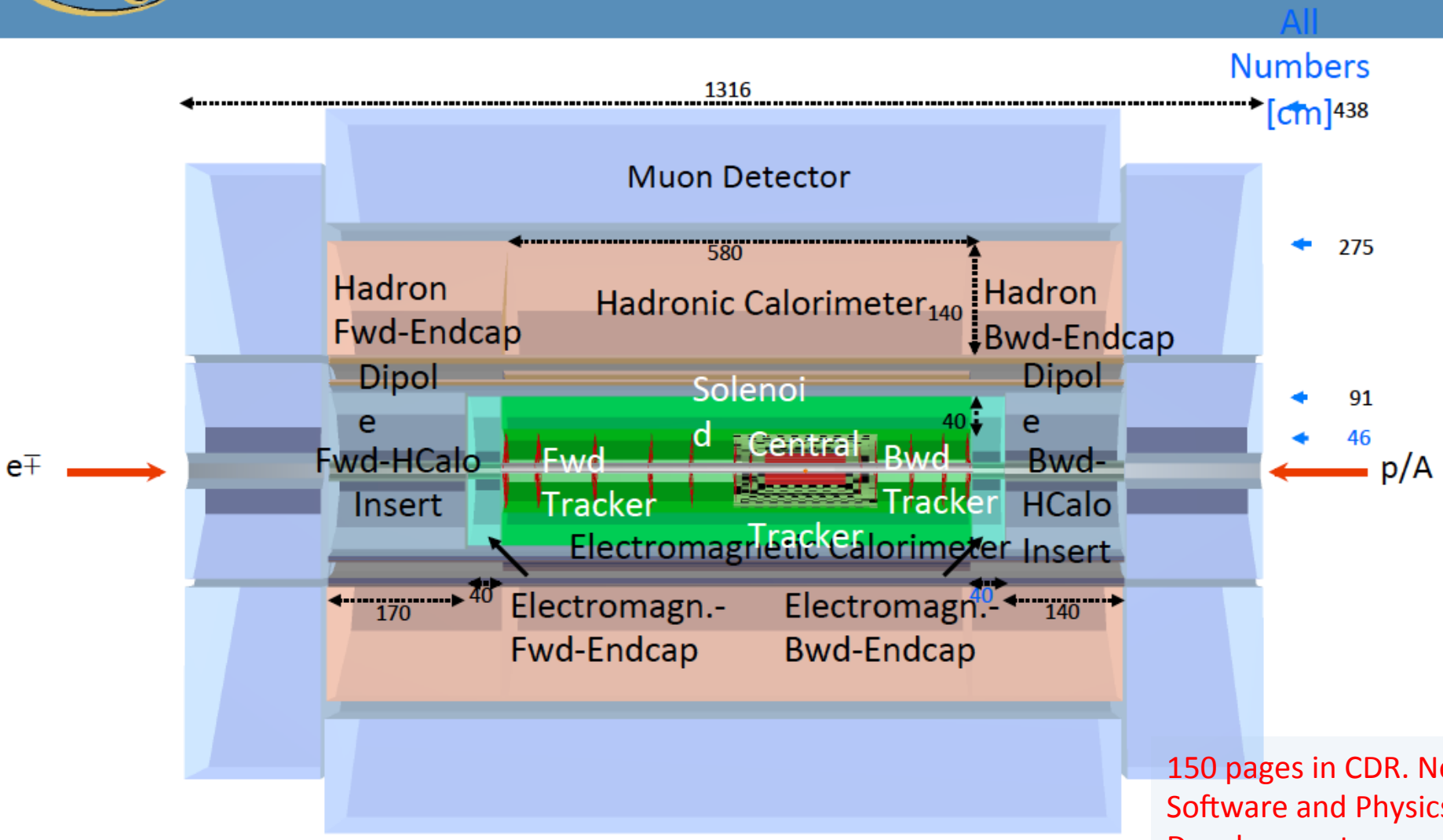


Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

Work in progress

LHeC ep/A Detector

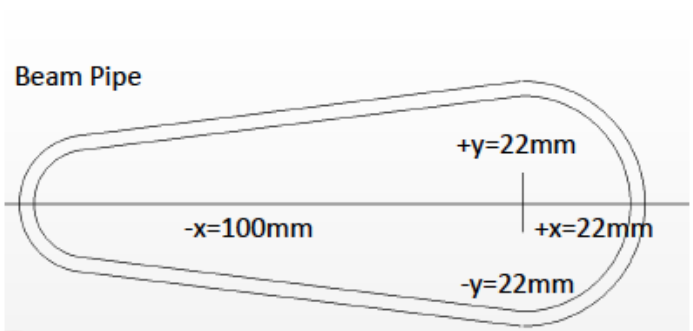


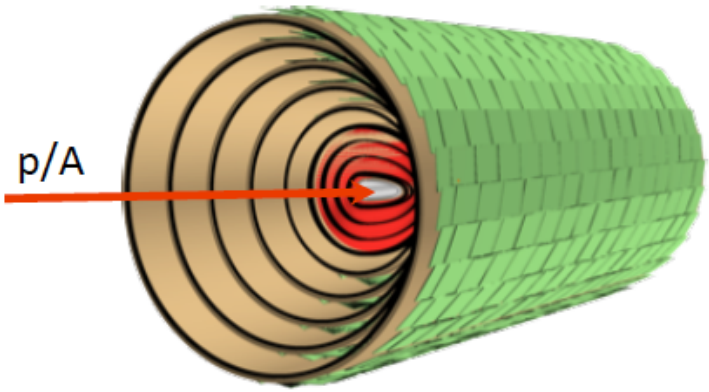
150 pages in CDR. New Software and Physics Developments

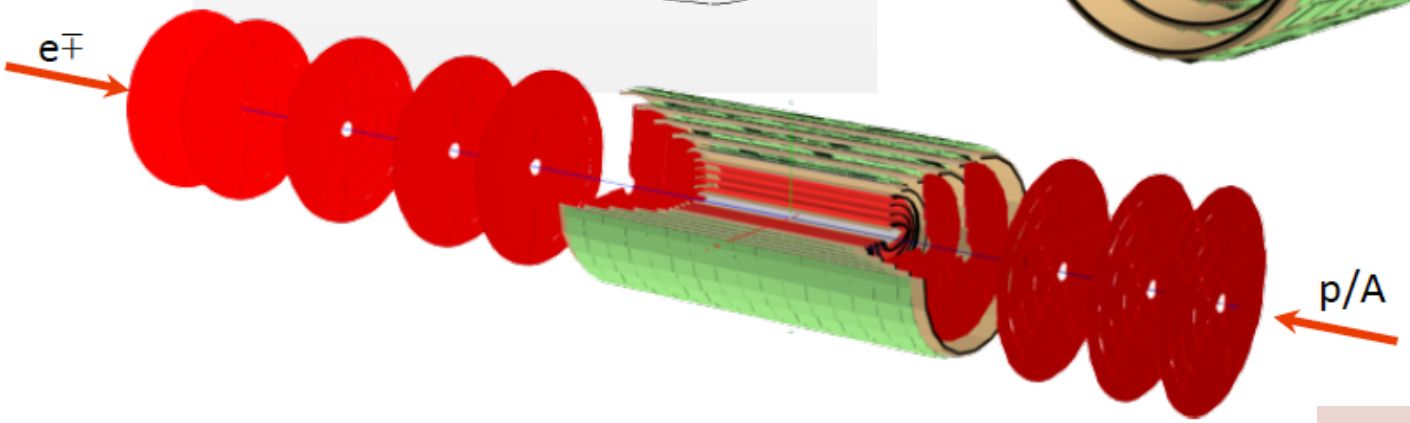
3 beams: $e^{\mp}$ + proton1 + proton2 (also heavy ions A)

Dipole magnets to guide the e-beam in and out, for making electrons to collide head-on with p-beam1; 0.3 T transverse field along 2 x 9 m

Tracker







Interaction region design - Impact of Synchrotron Radiation

Elliptical Beam Pipe and Vertex Pixel Detector placement around

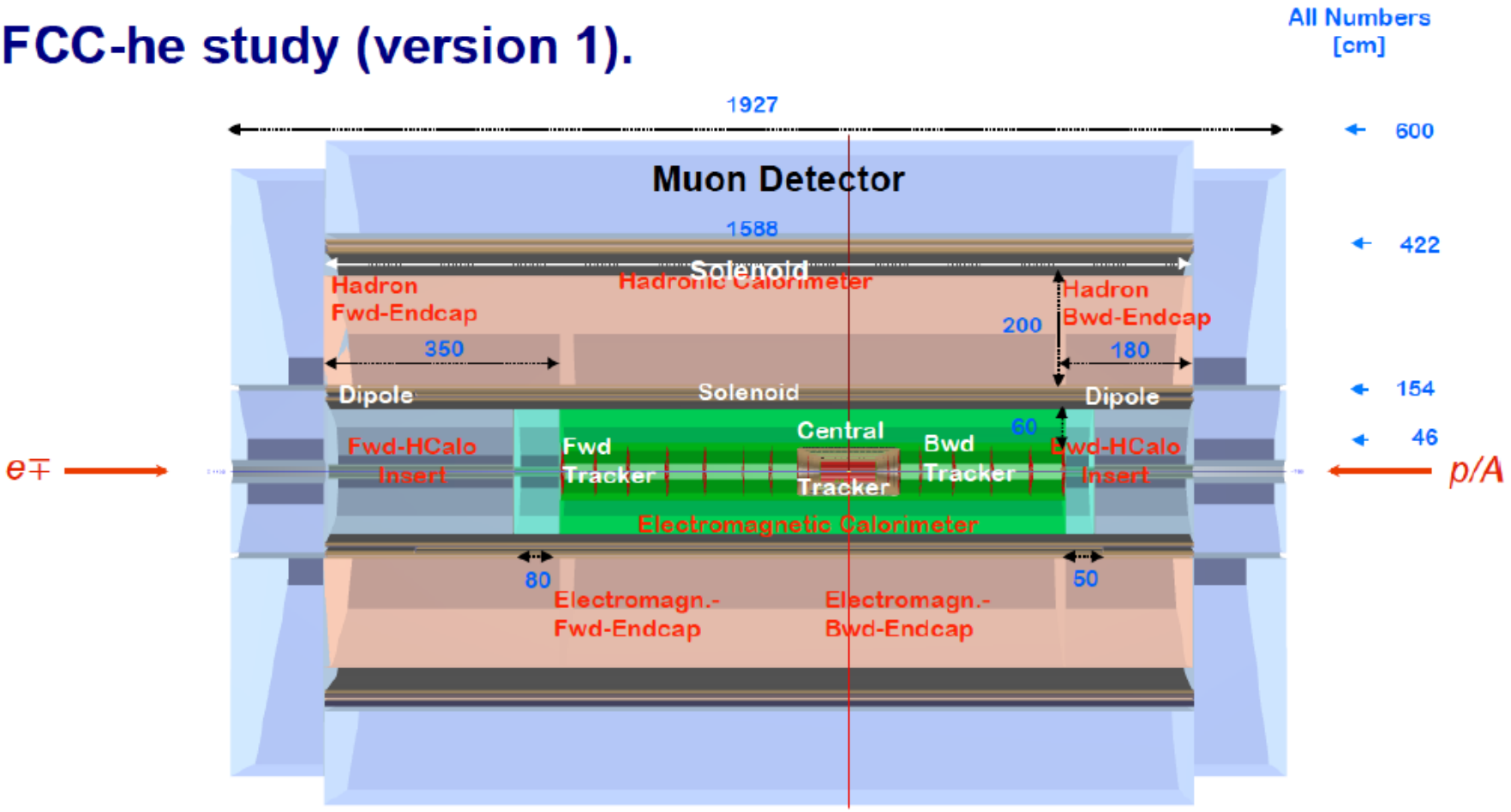
1st version describes sensitive / passive elements
(sensors / support structure / I-O elements)
Many details to be solved

LHeC/FCC-he design differ in fwd/bwd wheels placement only (currently)

Direct synergy
LHeC and FCC-eh
Common study.
Note huge progress
in thin Si technology
post HL LHC!

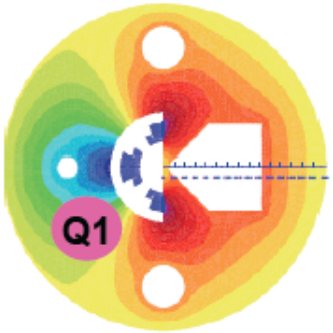
FCC-he Detector

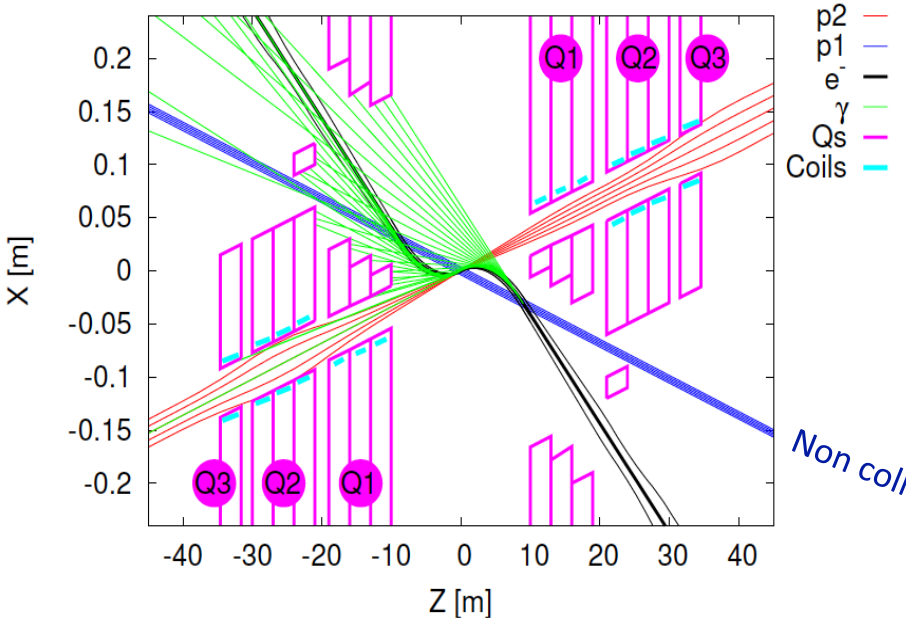
FCC-he study (version 1).



Solenoids 1 or 2, muons, fwd acceptance to enlarge, IR !

Interaction Regions for ep with Synchronous pp Operation

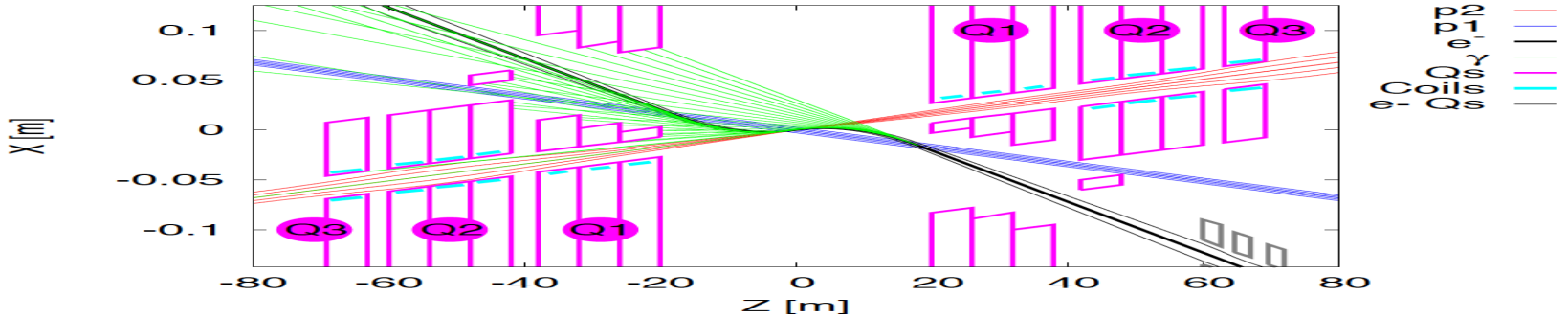




Non colliding p beam

LHeC (CDR)
60 GeV * 7 TeV

Still work in progress: may not need half quad if L*(e) < L*(p)



FCC-he (ERL)
60 GeV * 50 TeV

Tentative: ε_p=2μm, β*=20cm → σ_p=3μm ≈σ_e matched! ε_e=5μm ..

Rogelio Tomas et al

Remarks on the Project Status

LHeC: CDR in 2012 (300 authors, 600 pages). 2014: CERN Mandate to continue the study:

Mandate to the International Advisory Committee 2014-2017

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

Chair: Herwig Schopper

Next major goals:
Development of SC RF (802 MHz) with Jlab. Design of Test Facility (10mA, 3 turn, ERL)
Update of the CDR by 2018: LHC physics, 10^{34} lumi, detector and accelerator updates

FCC-eh: Utilize the LHeC design study to describe baseline ep/A option.
Emphasis: 3 TeV physics, IR and Detector: synchronous ep-pp operation.
Open to other configurations and new physics developments (750..)

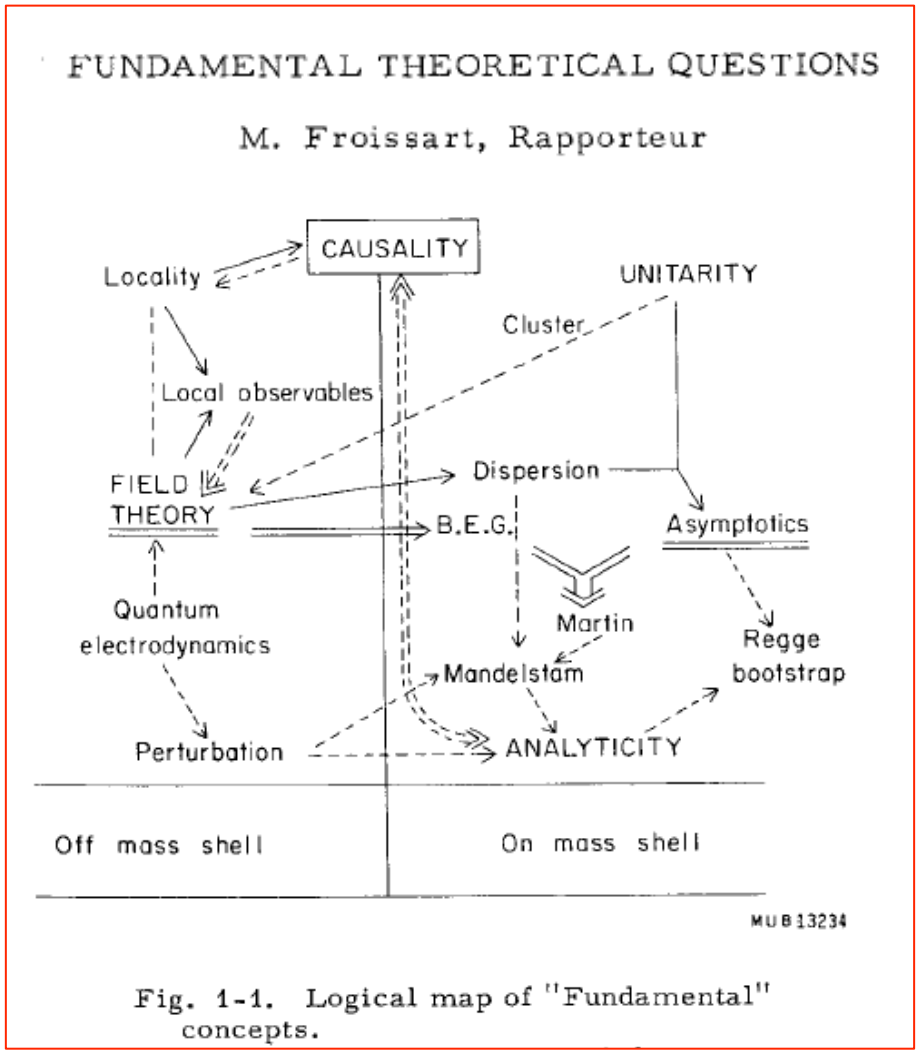
A Revival of electron-proton (ion) colliders following HERA

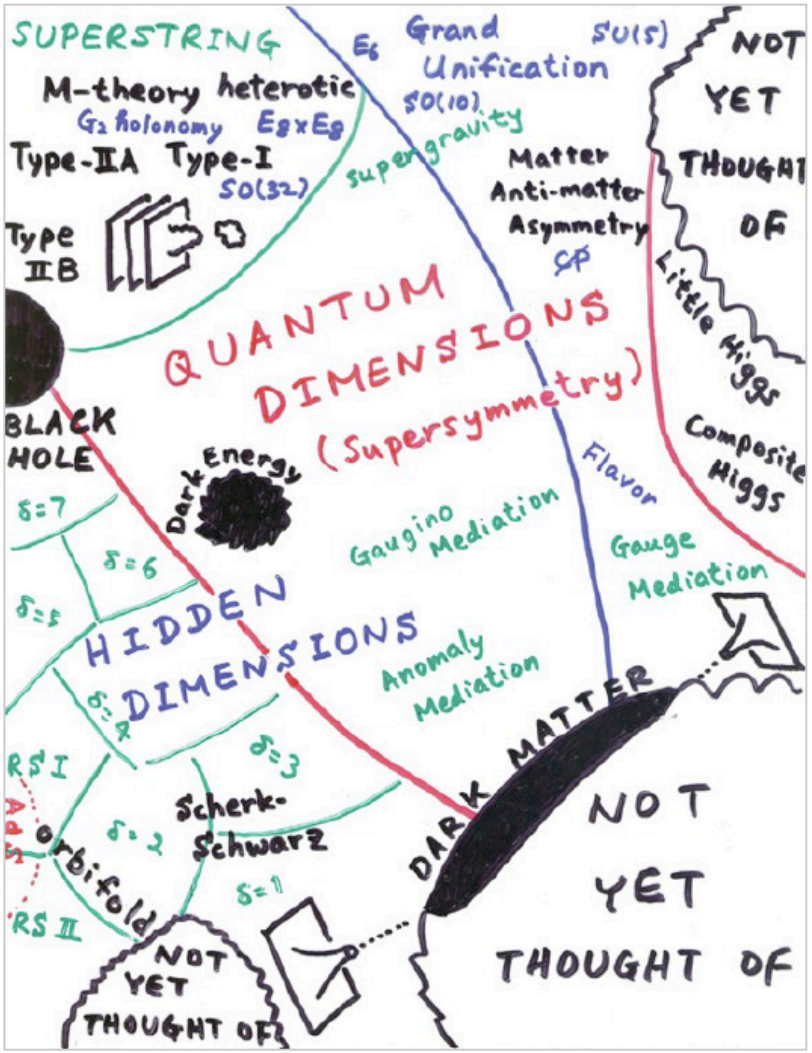
ep colliders 11.2014 Max Klein	CEPC	MEIC	eRHIC	HERA 92-07	CepC	LHeC	SepC	FCC-he
√s/GeV	**13**	**35**	**122**	**319**	**1000**	**1300**	**3375**	**3464**
$L/10^{33}$ $cm^{-2}s^{-1}$	0.4	5.6	1.5	0.04	4.8	16	8.9	10
E_e/GeV	3	5	15.9	27.6	120	60	80	60
E_p/GeV	15	60	250	920	2100	7000	35600	50000
f /MHz	500	750	9.4	10.4	20	40	40	40
$N_{e/p}10^{10}$	3.7/0.54	2.5/0.42	3.3/3	3/7	1.3/16.7	0.4/22	3.3/5	0.5/10
$\varepsilon_{e/p}$ /μm	.03/.15	54/.35	32/.27	4.6/.09y	250/1	20/2.5	7.4/2.4	10/2
$\beta^*_{e/p}$/cm	10/2	10/2	5/5	28/18 y	4.2/10	10/5	9.3/75	9/40
comment	Lanzhou	full acc.	"Day1"	HERA II	Booster	ERL (H)	$E_e = M_W$	ERL (HH)
source	X.Chen July 14	McKoewn POETIC14	Litvinenko S.Brook 14	B.Holzer at CERN 2008	Y.Peng Oct. 2014	Frank Z. LHeC 2014	Y.Peng Oct. 2014	Frank Z. IPAC 2014

M.Froissart ICHEP ("Rochester") 1966

THEORY

H.Murayama – ICFA11



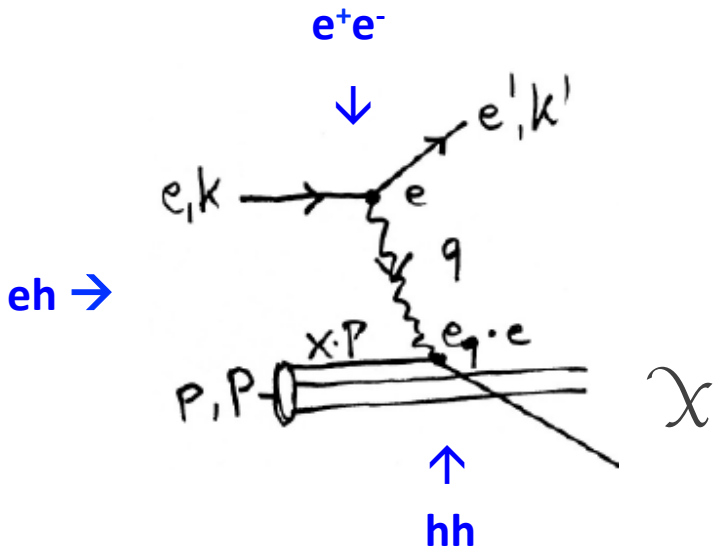


→ Quarks in 1969

→ ?in 2015+?

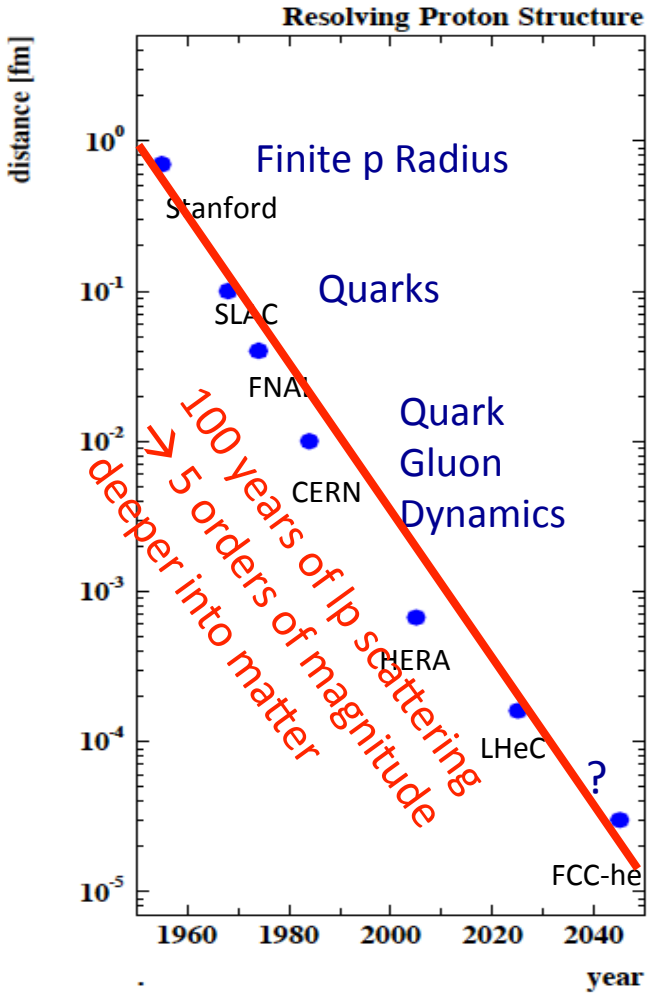
We like to see particle physics as driven by experiment … Burt Richter

Deep Inelastic Scattering [eh → e'X]



Parton momentum fixed by electron kinematics
Incl. NC (γ,Z) and CC ($W^{\pm}$) independent of hadronisation
Rigorous theory: Operator expansion (lightcone)
Parton momentum distributions to be measured in DIS
Collider- as at HERA: $y_h = y_e$: Redundant kinematics

→ DIS is an ideal laboratory for the development of particle physics into the multi TeV energy scale era. The CERN hadron beams are the unique base for building the "Hubble" equivalents to explore the inner structure and pursue novel measurements leading to discovery. In this quest, hh, eh and ee are a unity.



POETIC VI Workshop, 7.-11.9.2015, Paris
http://poetic6.sciencesconf.org
Michael Benedikt, Lepton Photon Conference, 15.08.2015, Ljubljana
http://indico.cern.ch/event/325831/session/18/contribution/60/attachments/1143145/1638099/150822-MBE_FutureCircularColliders_ap.pdf
Fabiola Gianotti, EPS 2015, 29.07.2015, Vienna
https://indico.cern.ch/event/356420/timetable/#20150729.detailed
LHeC Workshop, CERN (24 June) and Chavannes-de-Bogis (25-26 June)
https://indico.cern.ch/event/356714/
DIS2015, 27. April -1 May 2015, Dallas, Texas
https://indico.cern.ch/event/341292/
First Annual FCC Meeting, 23-29 March 2015, Washington, U.S.A.
http://indico.cern.ch/event/340703/
Higgs & BSM at 100 TeV, 11-13 March 2015, CERN
http://indico.cern.ch/event/352868/
Nima Arkani-Hamed, SUSY2013, Trieste
https://www.youtube.com/watch?v=xNVZg694ct8
M. Mangano, "Future Colliders", UK Forum 11/2014
http://conference.ippp.dur.ac.uk/event/394/
11th ICFA Seminar in Beijing, 27.-30.10.14
http://indico.ihep.ac.cn/conferenceOtherViews.py?view=standard&confId=3867
"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]