Deep Inelastic ep/eA Scattering at the Energy Frontier

Introduction
Physics
Preparations
Outlook

lhec.web.cern.ch

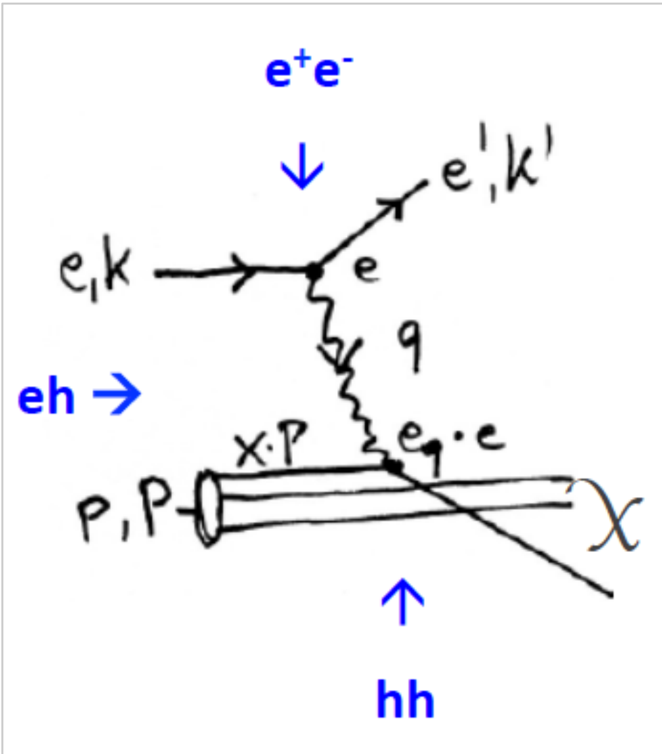
A 60 GeV e beam added to the LHC scattered off 7 TeV

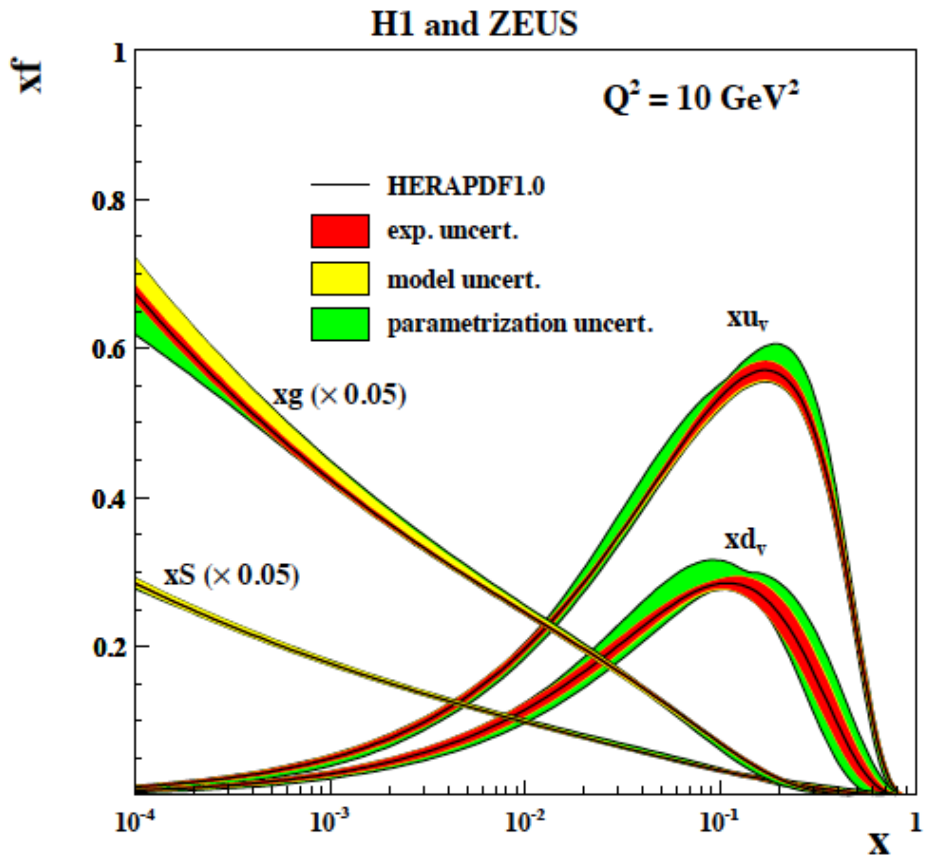
60 GeV from ERL or 120 GeV from e ring scattered off 50 TeV

Max Klein (University of Liverpool and CERN)

Epiphany Conference Cracow, 10th of January 2015 - for the LHeC/FCC_he Study Group

HERA (1984 →1992-2007→2017)

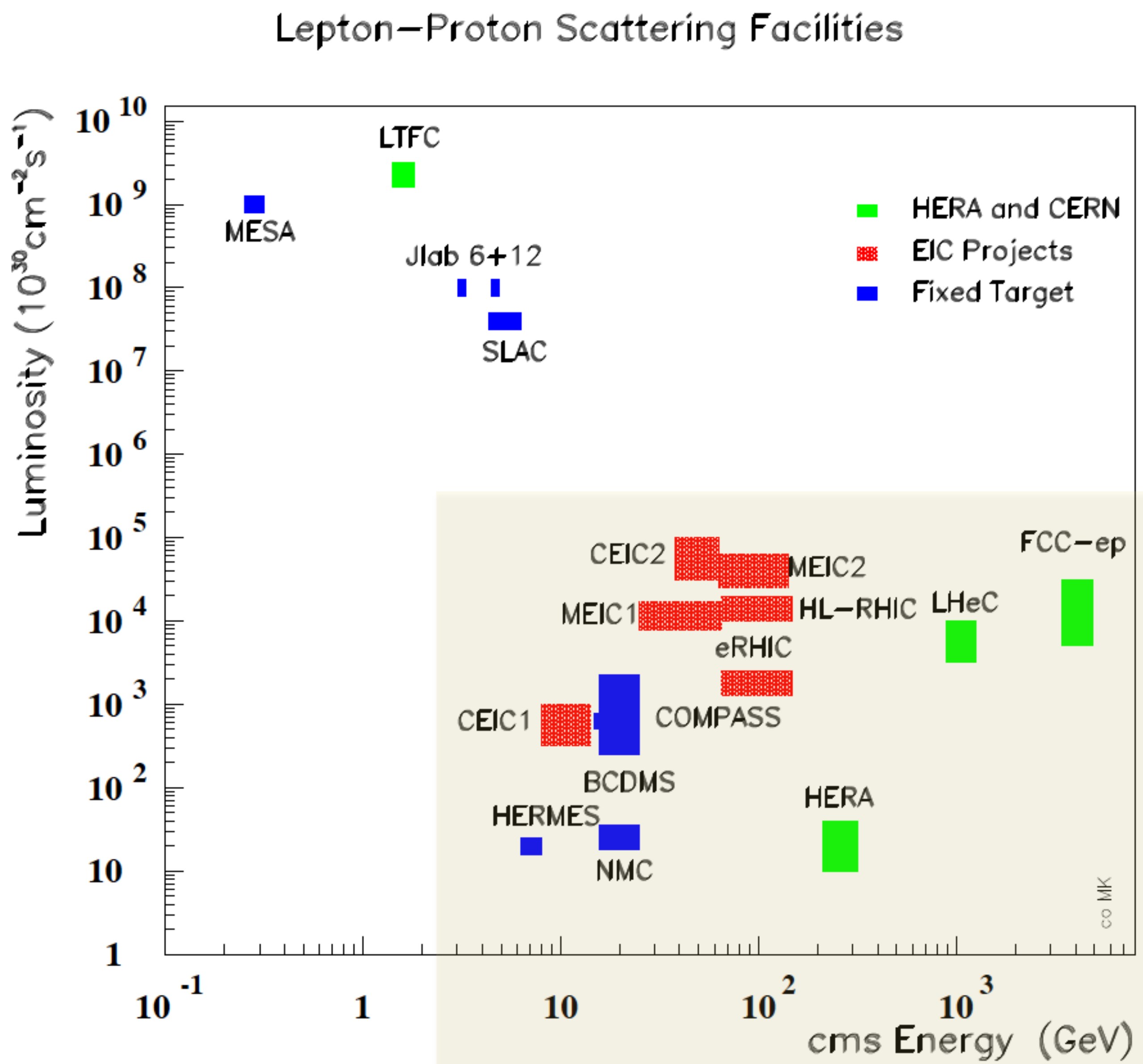




HERA was the first ep collider. L = 1-4 10^{31} cm^{-2} s^{-1} with E_e=27 GeV and E_p=920 GeV

It discovered the non-saturating rise of sea and gluon densities towards low x, DGLAP, and no Leptoquarks. It observed 10% of diffractive events and NC/CC approaching 1. It has been essential for interpreting Tevatron (hi Et excess) and LHC (Higgs) results…

New ep and eA Colliders are being developed



From CERN Courier
MK, H.Schopper
June 2014

With input from
A.Hutton, R.Ent,
F.Maas, T.Rosner

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

Main physics goals of new DIS Colliders*)

Substructure of nucleons
Development of QCD, Discoveries
Structure of γ, Pomeron, n, D, A..
Precision eweak measurements ..

Low energy (smaller HERA)

Nuclear structure
Electroweak below Z
p Spin composition
Spin structure
"Proton Holography 3d" ...

High Energy (bigger HERA)

Unfolding of *all* partons (NC+CC)
New physics (Higgs, DM, RPV SUSY, LQs..)
Electroweak below and beyond Z
Non linear QCD in ep and eA (QGP)
Top physics ...

FCC-he: 10 times higher H-HH cross section
10 times lower x
4 times larger mass range for NP ..
as compared to LHeC
but the FCC is later + more expensive.

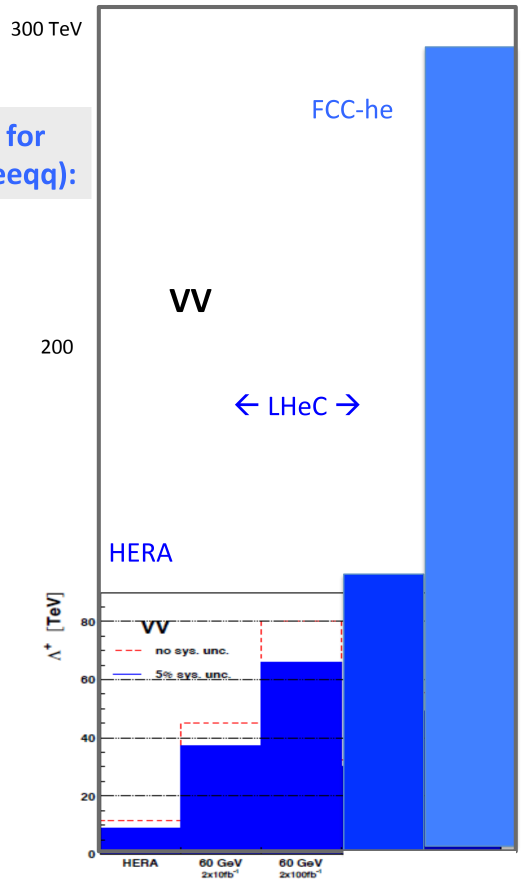
Why are quarks and leptons different?
Salam 1976

*) incomplete

High Energy ep Physics

High mass and Q^2 region

Reach for Λ (CI eeqq):

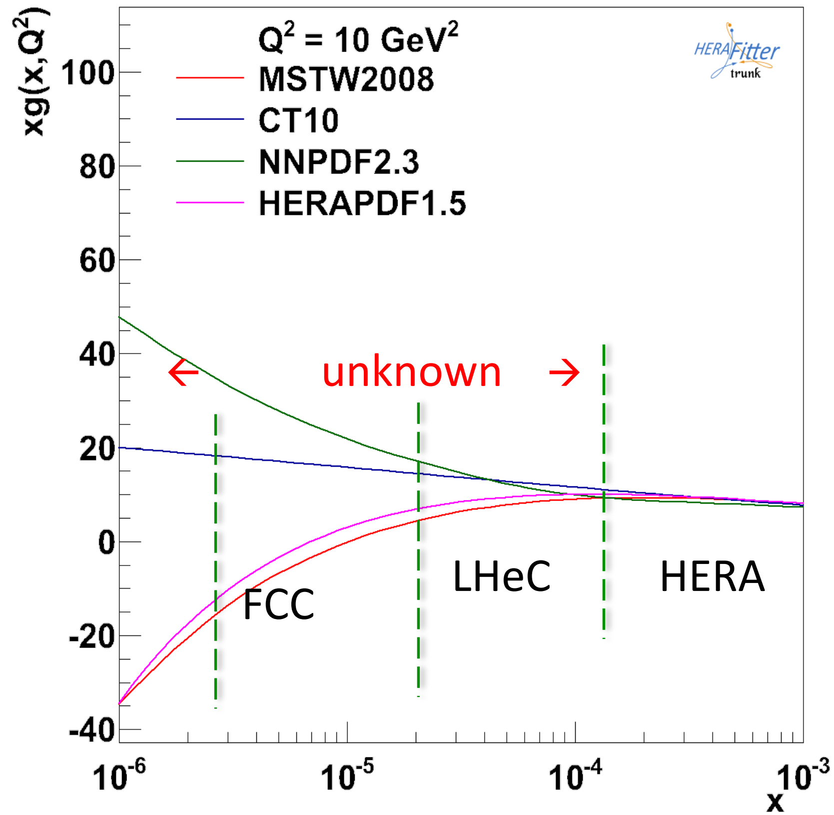


LHeC: see CDR 2012

Huge extension of reach for new physics

Leptoquark reach to √s ≈ 4 TeV

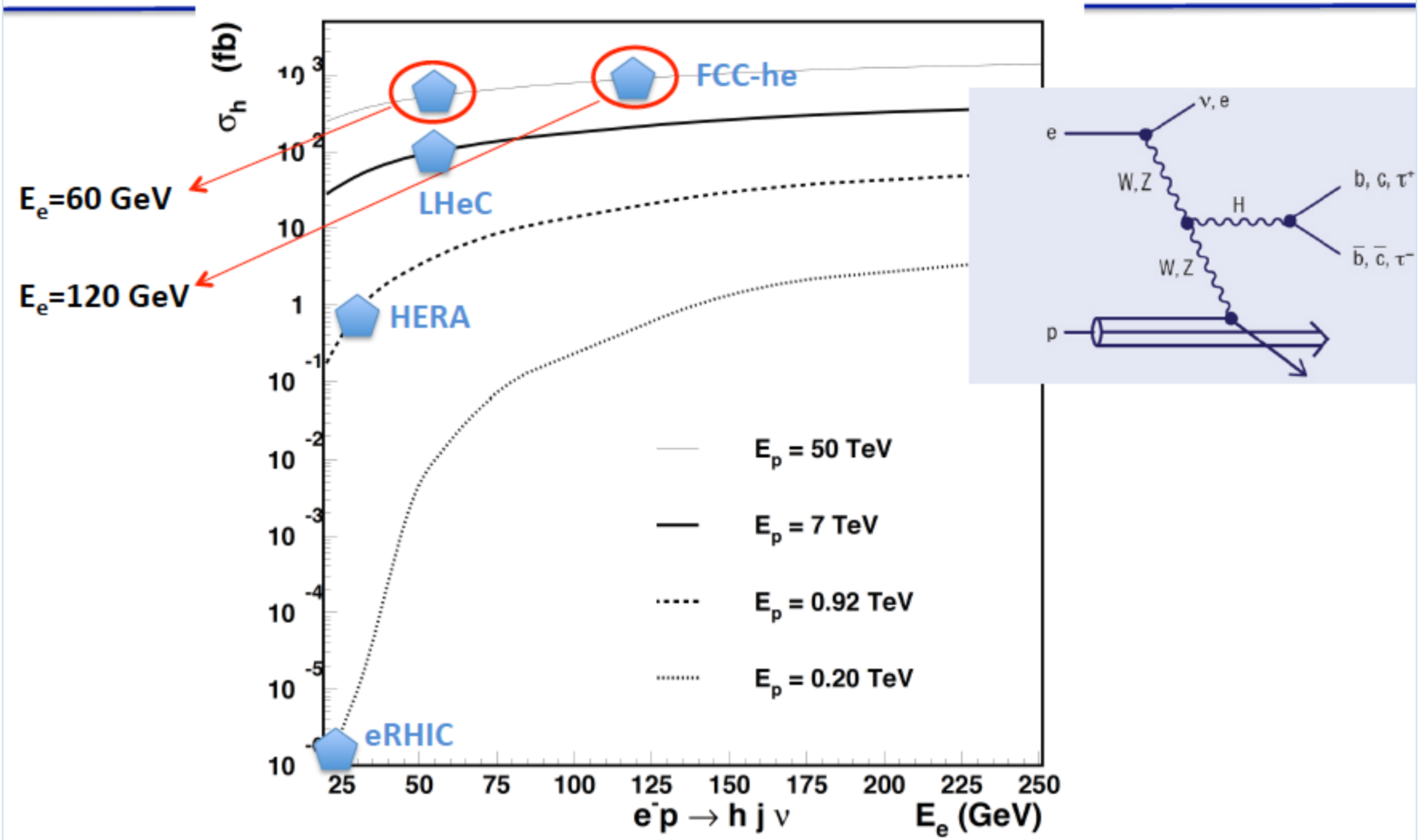
Low x Physics



Very low x – close to UHEν region, BFKL?

Need energies and L beyond HERA for being of interest for HEP and the search for and interpretation of new physics.

SM Higgs in ep



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

International Advisory Committee + Mandate

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – **Chair**
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

IAC Composition June 2014, plus
Oliver Brüning Max Klein ex officio

The IAC was invited in 12/13 by the DG with the following

Mandate 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.

2.Physics Examples

PDFs and Folklore

(we know them , we get them from pp, we do not need them..)

ep-pp

Heavy Ion QCD

Higgs Physics with ep

(no time for top, sin2theta(Q), v,a, jets, photoproduction..)

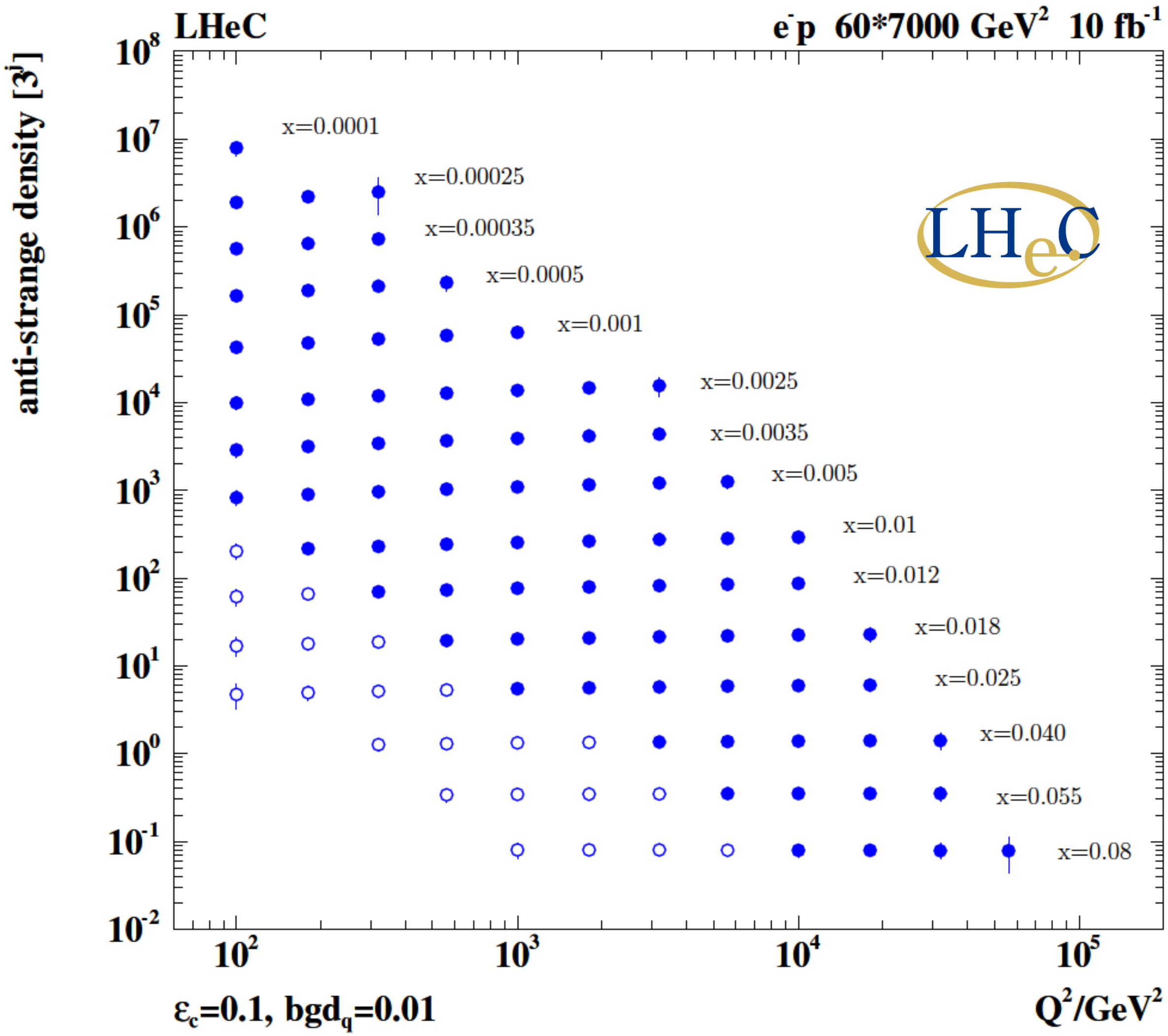
A new ep collider facility is a rich new physics lab. It is yet not competitive with the huge ee and pp collider projects since by construction it it is an add-on to LHC/FCC.

Parton (Quark and Gluon) Distributions

	PDF	comment	LHeC/FCC-he
	u valence d valence	after 40 years still do no know d/u at high x	CC free of nuclear effects
*	up sea down sea	not distinguished at HERA	NC and CC
*	strange	unknown basically (neutrinos, W,Z)	Ws → c : CC at high Q^2
	charm	HERA to ~5%, threshold, intrinsic (sea=anti??)	NC
	beauty	HERA ~20%. bb→ A ? HQ treatment in QCD	NC
	top	takes % of p momentum	CC at LHeC [first time]
*	gluon	low x saturation?, medium x Higgs, high x BSM	df2/dlnQ^2

LHeC: extended kinematic range: low x, high x, high Q^2 → the ONLY way to unfold all PDFs
ep/eA further determine neutron, photon, pomeron, nuclear densities – HUGE potential

Strange Quark Distribution from LHeC



High luminosity

High Q^2

Small beam spot

Modern Silicon

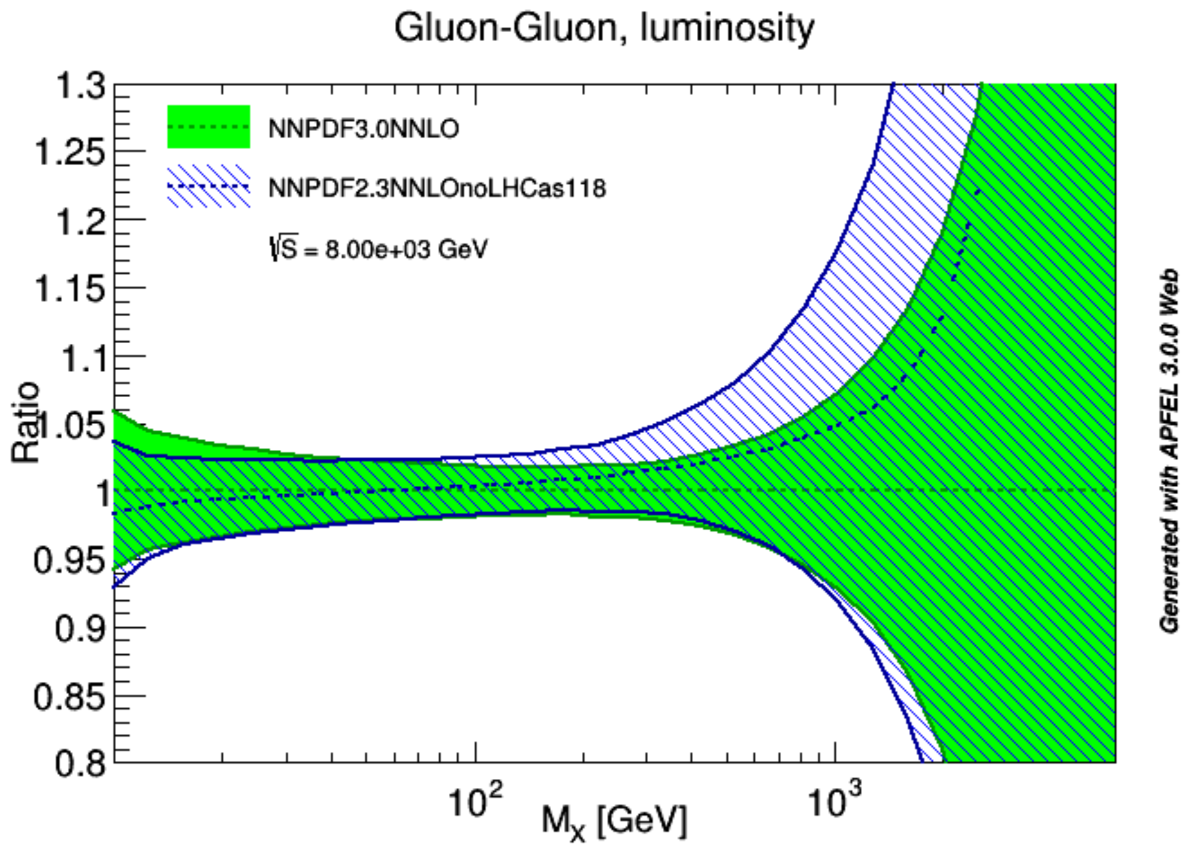
NO pile-up..

→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4}$ .. 0.05
$Q^2 = 100 – 10^5$ GeV^2

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

Sensitivity of PDFs to LHC - Gluon



No LHC
With LHC
NNPDF3.0
(Oct. 2014)
S.Forte et al

Large uncertainties at high mass

- γγ induced proc.s
- k factors
- eweak corrections

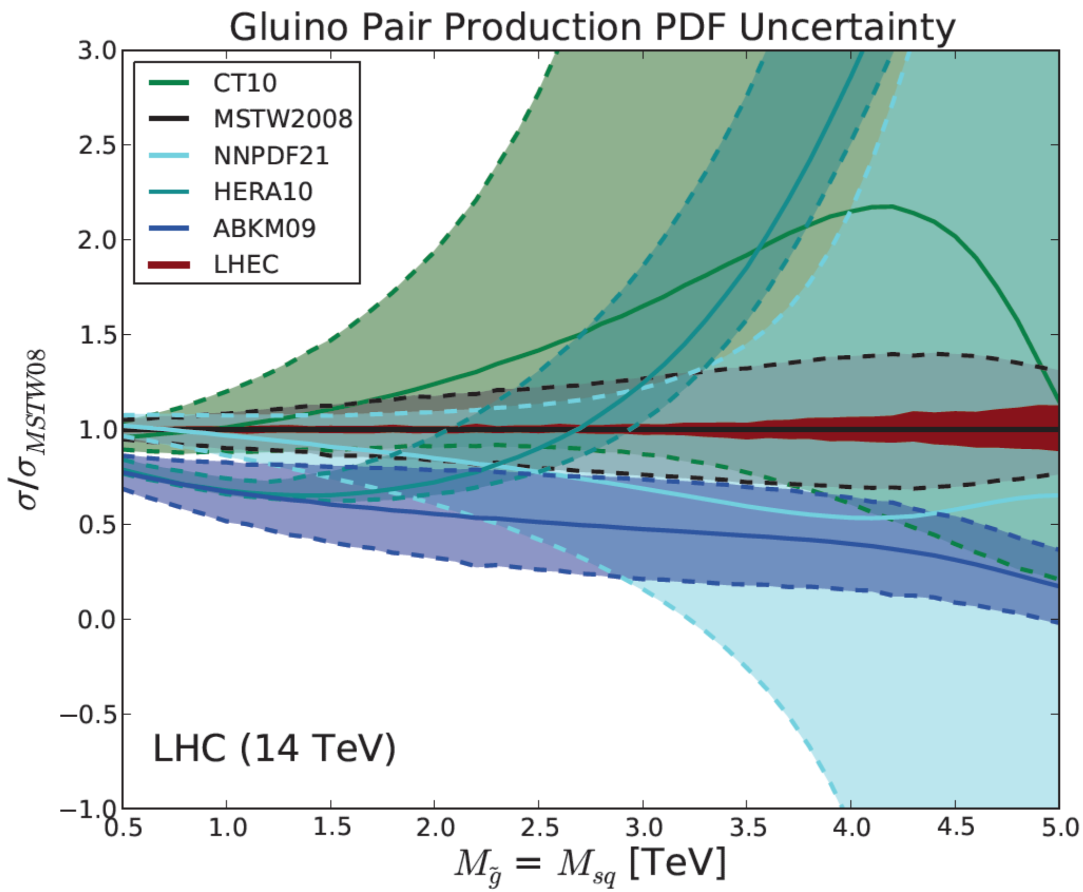
…

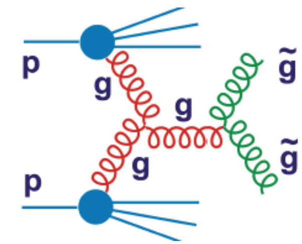
U.Klein LesHouches
arXiv:1405.1063

LHC: W+c, P_T(W), top, double differential W,Z data + previous input to NNPDF

New physics appearing as contact interaction would be confused with PDFs
Long range onset effects of new resonances: new physics or PDFs ??
High luminosity, high mass searches requires independent, precise PDFs ep--pp

Gluon-Gluon Luminosity with LHeC





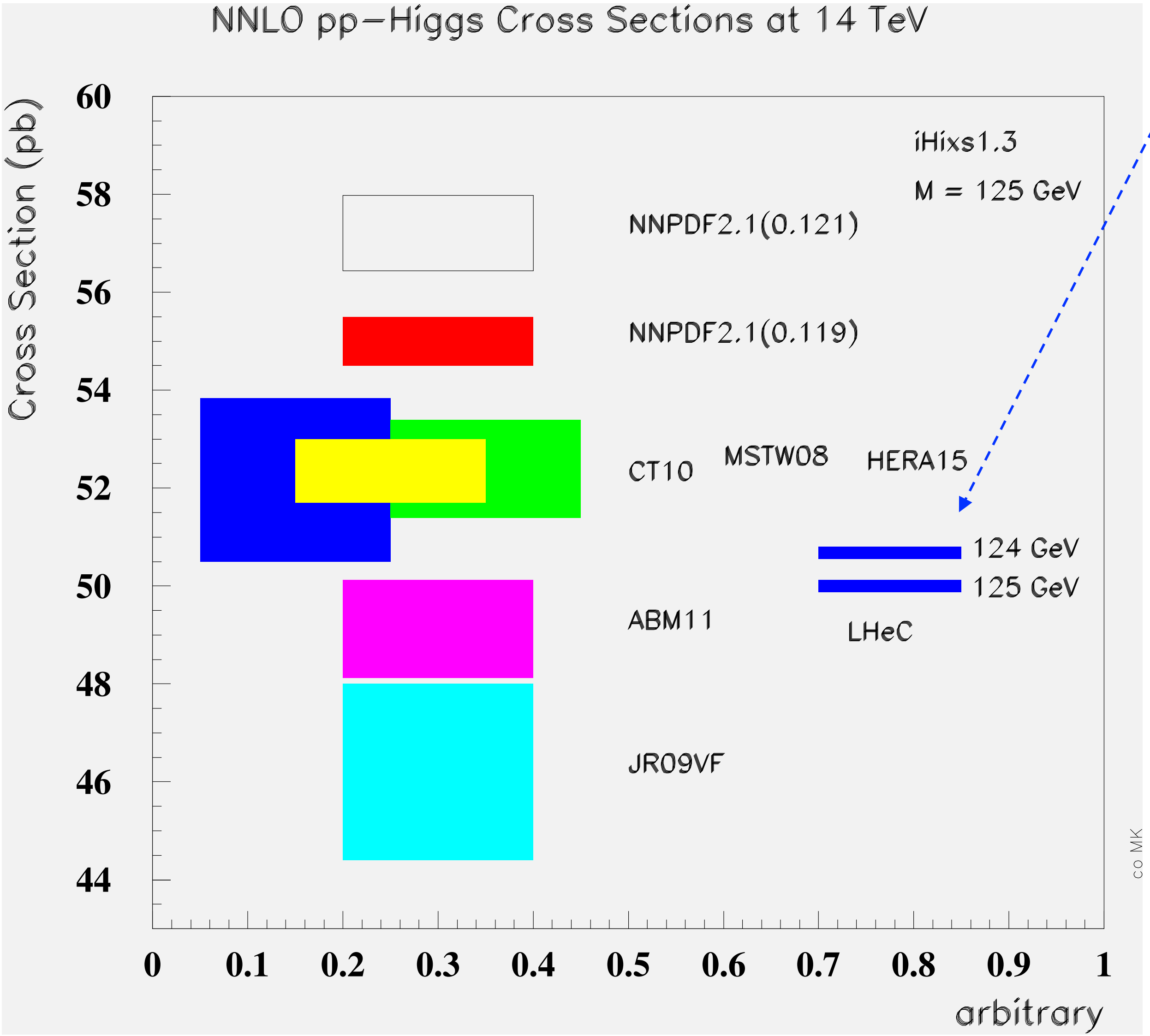
LHeC Note 2012-005
arXiv:1211.5102

LHeC PDFset on LHAPDF
V.Radescu, MK

Full detector simulation (CDR of LHeC) reveals high precision on gluon from LHeC alone.

With the LHC moving to high luminosity we conquer the few TeV mass region and need to know the partons at high x in order to take advantage of the luminosity upgrade.

Precision PDFs for Higgs at the LHC



O.Brüning and M.K. arXiv:1305.2090, MPLA 2013

LHeC:

Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 → 10%). LHeC: 0.0002 !

Needs N^3LO

HQ treatment important …

Strong Coupling Constant – GUT?

α_s least known of coupling constants

Grand Unification predictions suffer from $\delta\alpha_s$

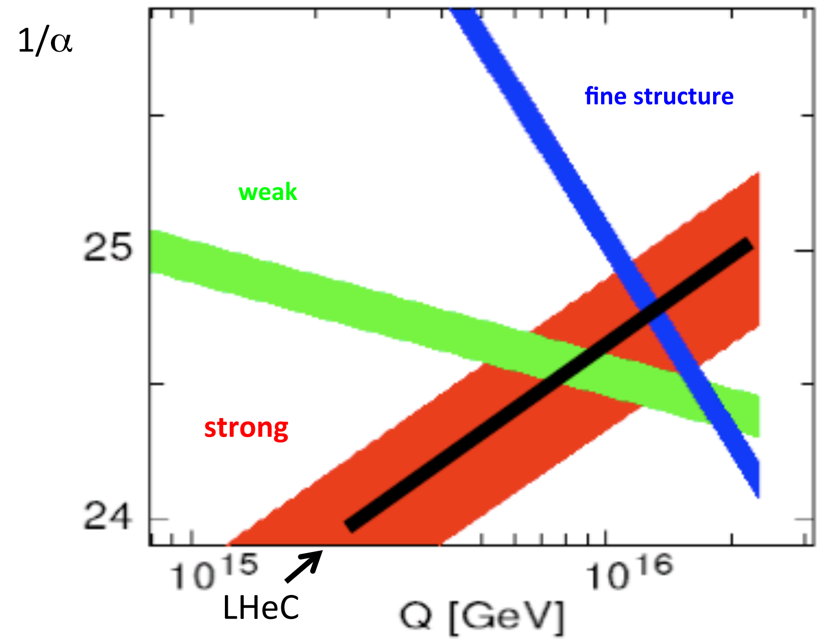
Is DIS lower than world average (?)

LHeC: per mille - indep. of BCDMS.

Challenge to experiment and to h.o. QCD →
A genuine DIS research programme rather than one outstanding measurement only.

More or as accurate as lattice QCD

(cf Les Houches 2013)

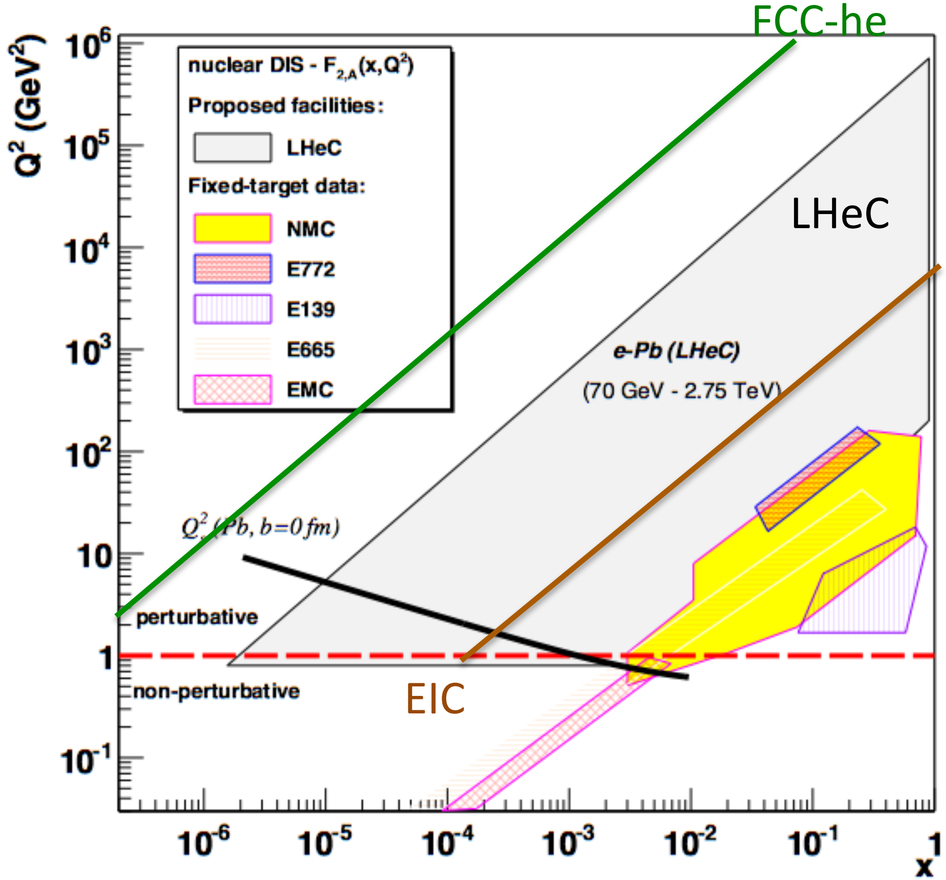


case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Two independent QCD analyses using LHeC+HERA/BCDMS

DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

LHeC-FCC-he as Electron Ion Collider(s)



LHeC is part of NuPECCs long range plan since 2010
$L_{eN} \sim 10^{32}$ cm^{-2} s^{-1}

Extension of kinematic range in lA by 4-5 orders of magnitude will change QCD view on nuclear structure and parton dynamics

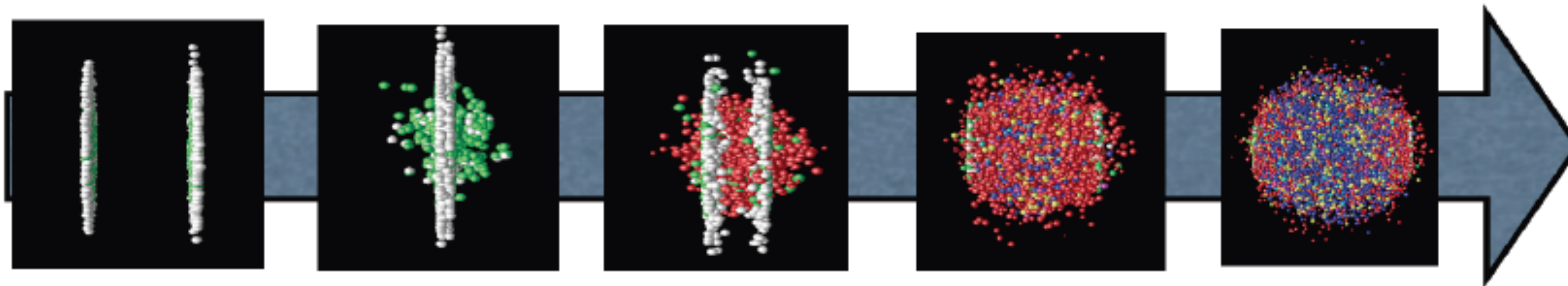
May lead to genuine surprises…

- No saturation of xg (x,Q^2) ?
- Small fraction of diffraction ?
- Broken isospin invariance ?
- Flavour dependent shadowing ?

Expect saturation of rise at
$\mathbf{Q^2_s \approx xg\,\alpha_s \approx c\,x^{-\lambda}A^{1/3}}$

Precision QCD study of parton dynamics in nuclei
Investigation of high density matter and QGP
Gluon saturation at low x, in DIS region.

LHeC Relevance for the HI program:



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x: nuclear structure functions.

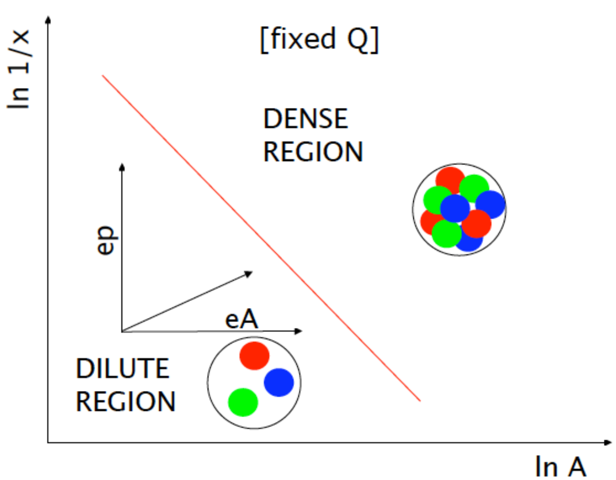
- Particle production at the very beginning: which factorisation in eA?

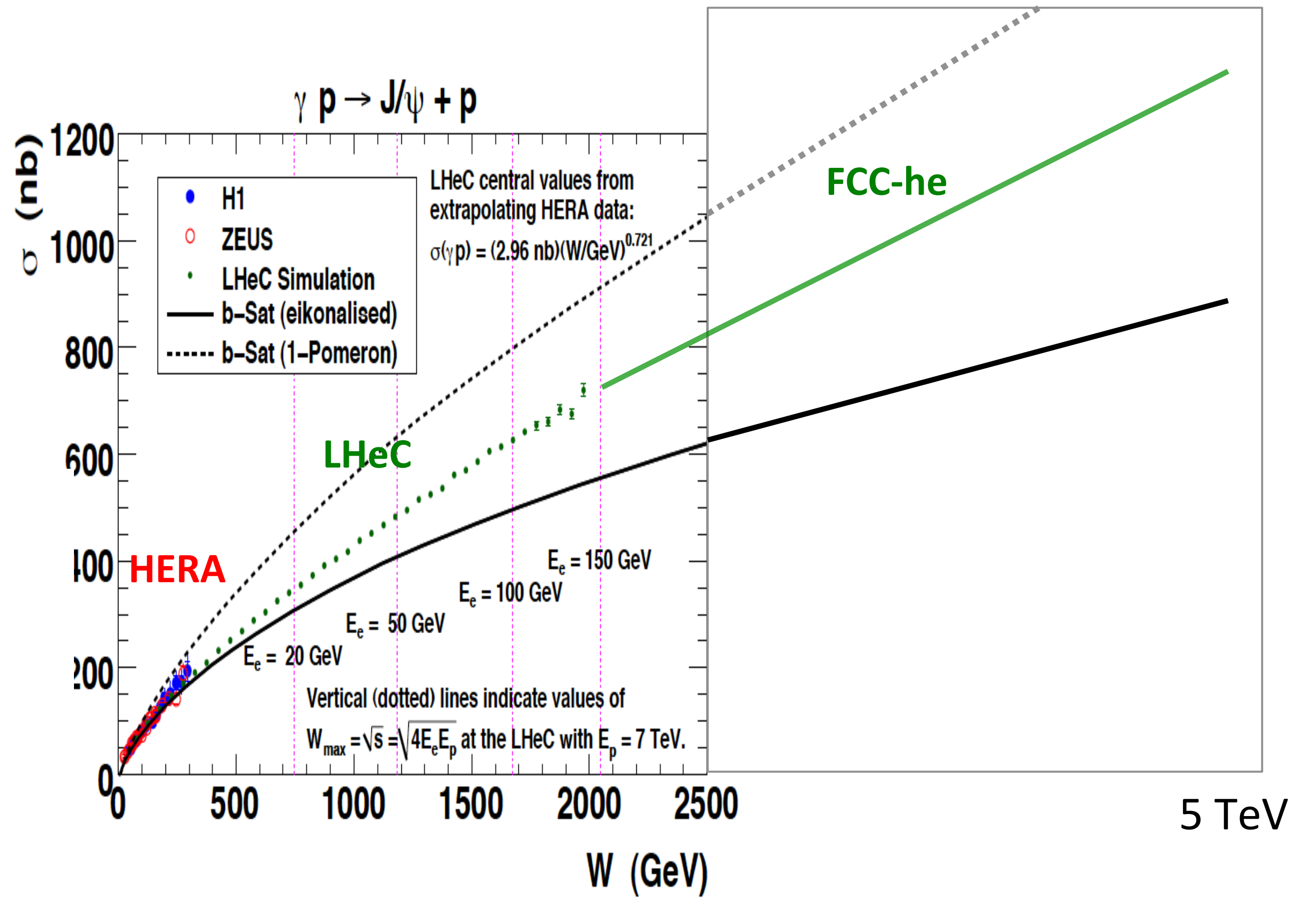
- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

modification of QCD radiation and hadronization in the nuclear medium.

Vector Mesons

Precision Measurements of vector mesons and diffraction to very high $M_X \sim xg^2$



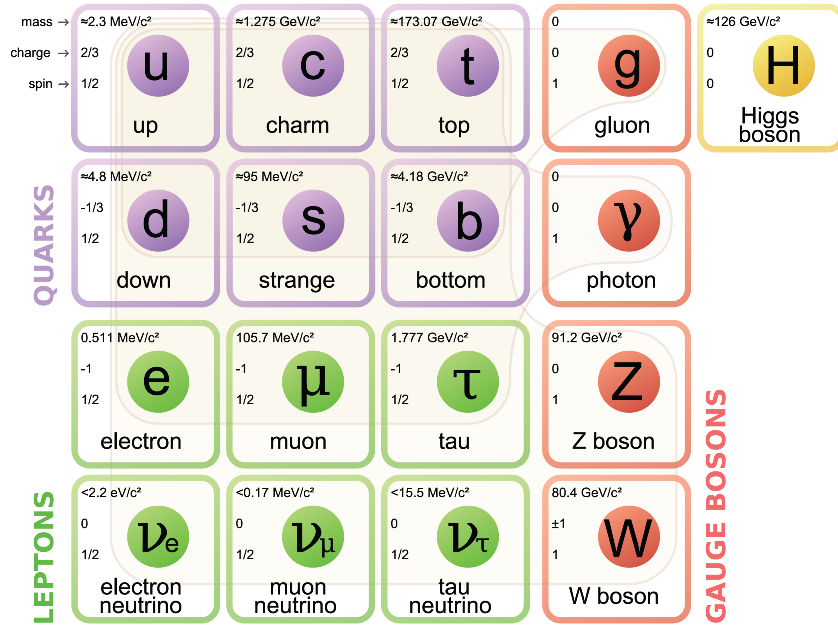


Higher energy (1/x), higher A

W = √ (ys) extends to ~ 4 TeV at FCC-he

Black body limit, interference pattern of σ

Remarks on the Higgs

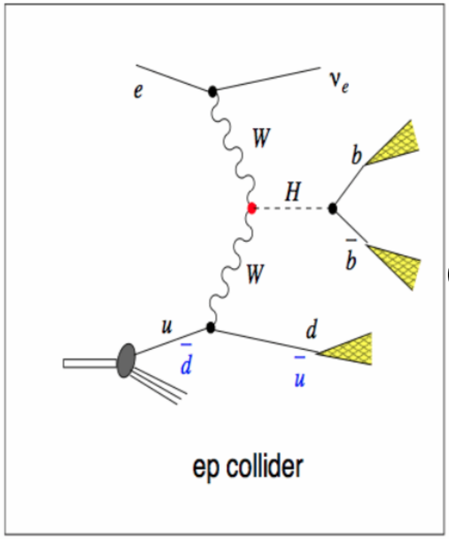


High precision measurements for access to new physics (new heavy particles in loops)
Dark matter: Higgs decay to invisible, DM in loop, Higgs + MET
Extended Higgs sector (scheme above not supersymmetric ..)

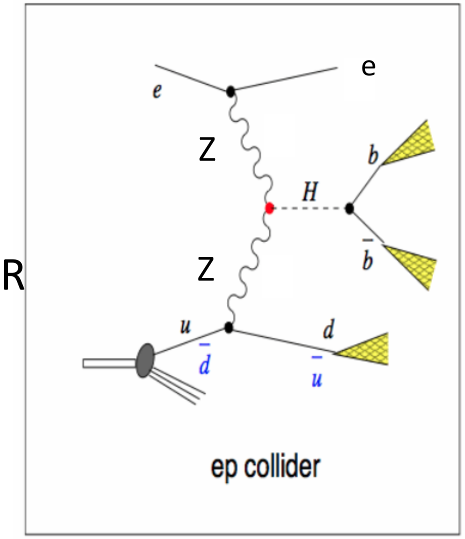
LHC: will address all these questions, it is the prime facility we have! **LHeC vital addition**: gg → H needs more precise xg, cross section: PDFs, alphas; H-HH hard to impossible

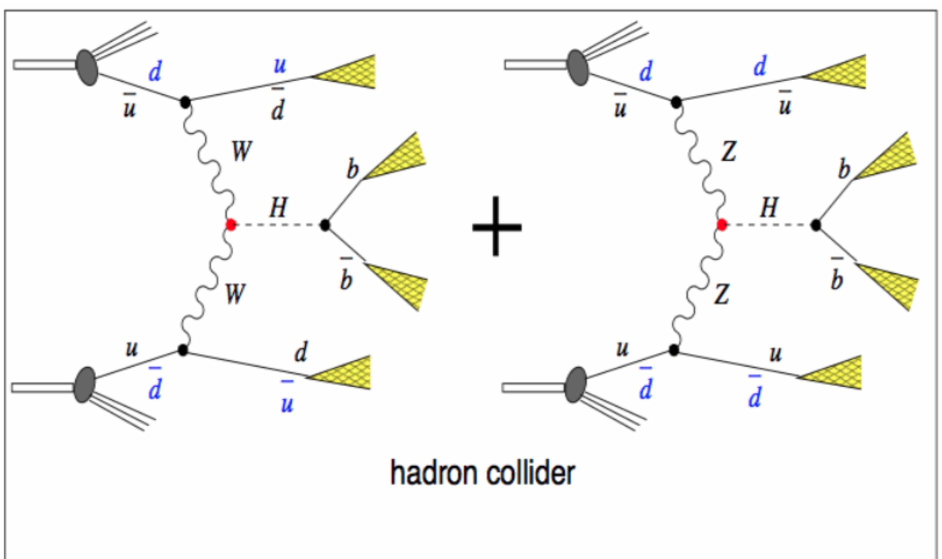
Need independent, complementary and more precise Higgs facilities, ep is one of them

VBF Higgs Production at the LH(e)C



OR





Higgs production in ep comes uniquely from either CC or NC

Cross section at LHeC ~200fb (about as at the e^+e^- colliders).

Pile-up in ep at 10^{34} is 0.1, 25ns

Clean(er) bb final state, S/B ~ 1

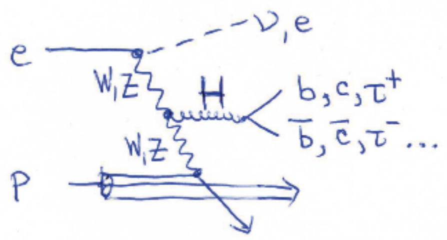
e-h Cross Calibration → Precision

Higgs production in pp comes predominantly from gg→ H

VBFC cross section about 200fb (about as at the LHeC).

Pile-up in pp at 5 10^{34} is 150, 25ns

S/B very small for bb

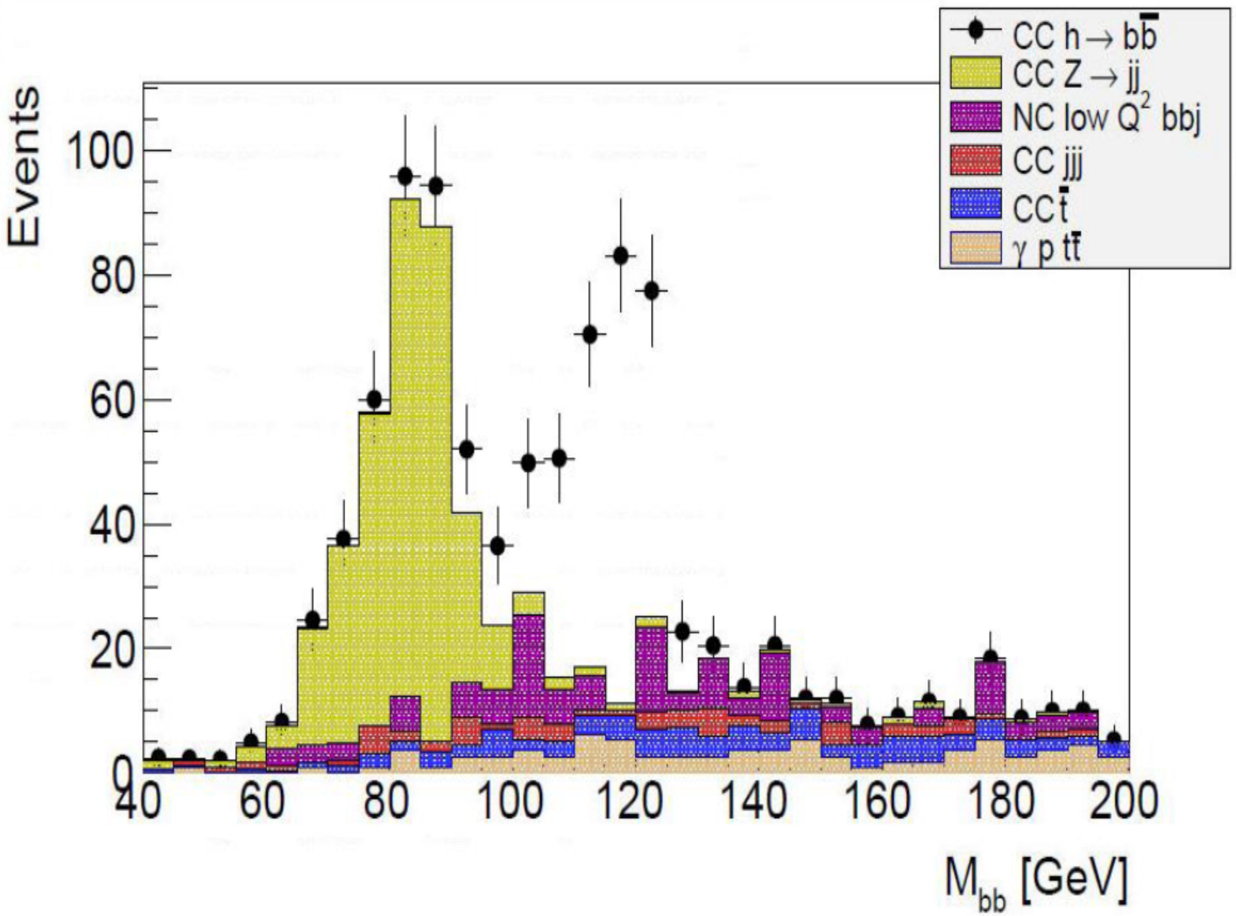


Higgs in ep → vHX

Simulation of H→ bb Measurement at the LHeC, $100fb^{-1}$

ep→ vH(bb)X
charged currents
σBR~120 fb
μ=0.1
S/B ~1-2
Cut based only

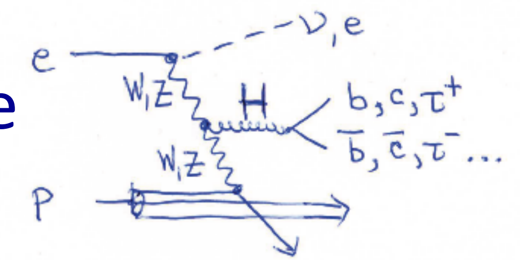
[LHC: VH - BDT's
σ(VH) ~ 130fb 8 TeV
arXiv:1409.6212]



LHeC Higgs Group U.Klein et al.

This reconstructs 60% of H in ep with very comfortable S/B ~1 , in CC and NC
→ Enables BSM Higgs (tensor structure of HVV, CP, dark H?) and H-HH at FCC-he
→ O(1)% precision on H-bb couplings with small thy uncertainty [high lumi crucial!]
→ Further decay channels will reflect branching ratio in their expected precision

Higgs Physics in DIS at the LHeC and FCC-he



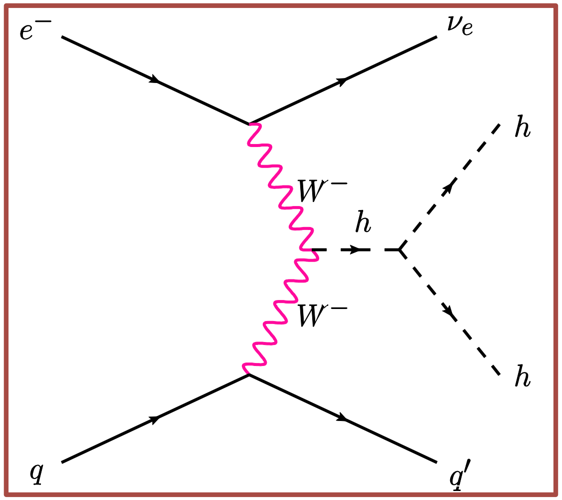
Higgs in e^-p	CC - LHeC	NC - LHeC	CC - FHeC
Polarisation	-0.8	-0.8	-0.8
Luminosity [ab^{-1}]	1	1	5
Cross Section [fb]	196	25	850
Decay BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$ 0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$ 0.029	5 700	700	123 000
$H \to \tau^+\tau^-$ 0.063	12 350	1 600	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

Cross section
at FCC-he
1pb ep→ vHX

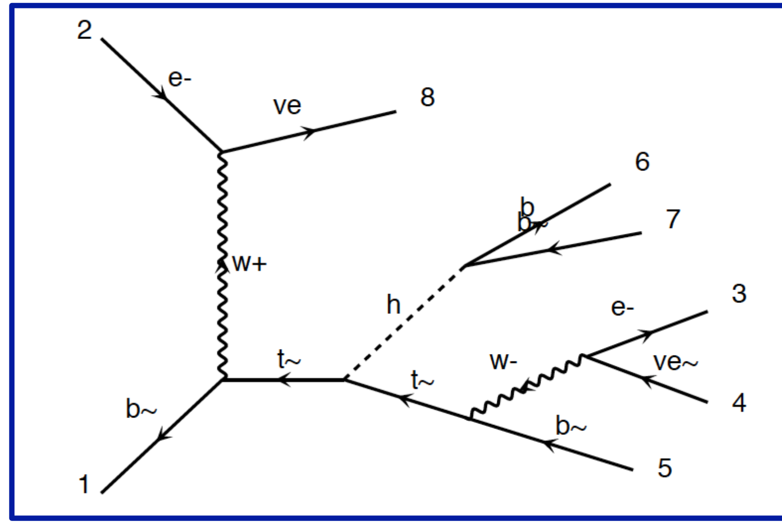
Luminosity
O(10^{34}) is
crucial for
H → HH [0.5 fb]
and rare H decays

Event rates for 1ab^{-1}. Note the LHeC WW-H cross section is as large as the Z*→ ZH cross section at the ILC or FCC- or CEPC, but it is much larger at the FCC-he

HH and tHt in ep



New Tentative Studies



<u>FCC-he unpolarised</u>
<u>Cross section at 3.5 TeV:</u>

total : 0.7 fb
fiducial : 0.2 fb
using pt(b,j)>20 GeV
ΔR(j.b)>0.4
η(j) <5
η(b) < 3

Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e hhj, h \to b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

Polarisation, max lumi, tuning cuts, bb and WW decays may provide O(10%) precision - tentative

Require time for reliable result (detector, analysis, backgrounds..)

Uta Klein, Masahiro Khuze, Bruce Mellado et al

3.Preparations

ERL

SCRF 802 MHz and Test facility

Synchronous high luminosity ep

Cost and Size

Interaction region (LHeC and FCC-he)

Detector LHeC

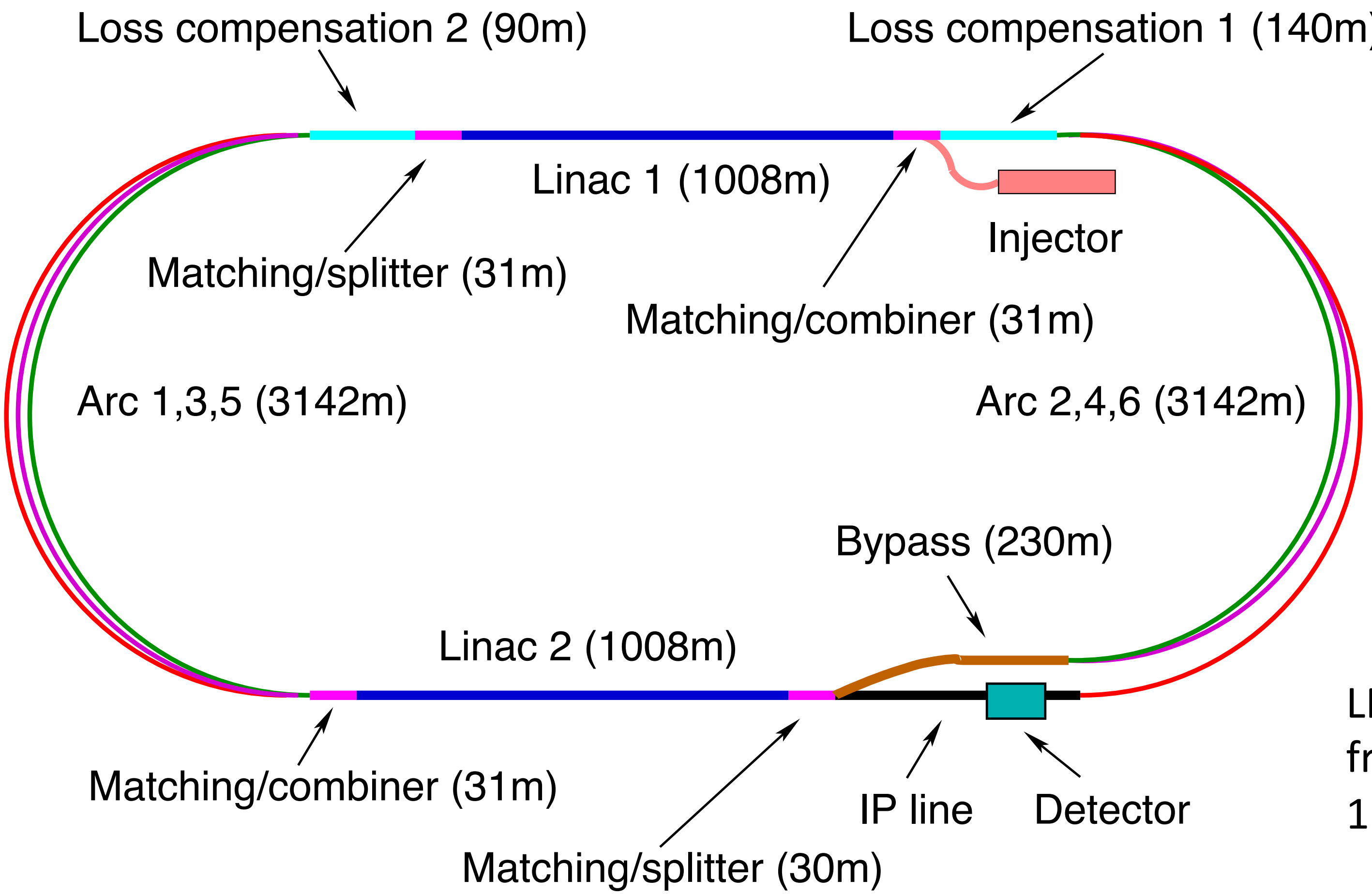
Extension to FCC-he

(no time for any detail

See also CDR of LHeC published in 2012)

Goals: Testfacility design by end of 2015, Update of Physics and Detector vs LHC, FCC-he (hh,ee)

Large Hadron Electron Collider for synchronous ep and pp OP @ LHC

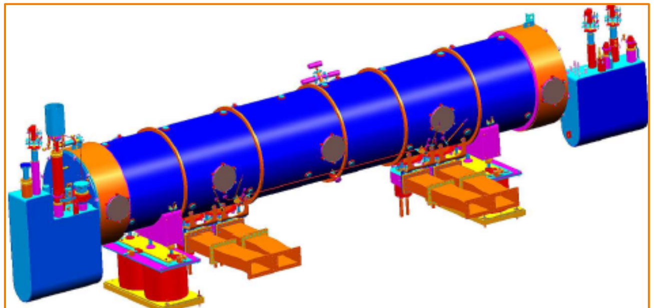


LR option from CDR 1206.2913

60 GeV electron beam energy, L= 10^{33} $cm^{-2}s^{-1}$, √s=1.3 TeV: Q^2_{max}= 10^6 GeV^2, 10^{-6} < x< 1
Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, ERL, < 100MW, 1/3 LHC)

SCRF and LTFC

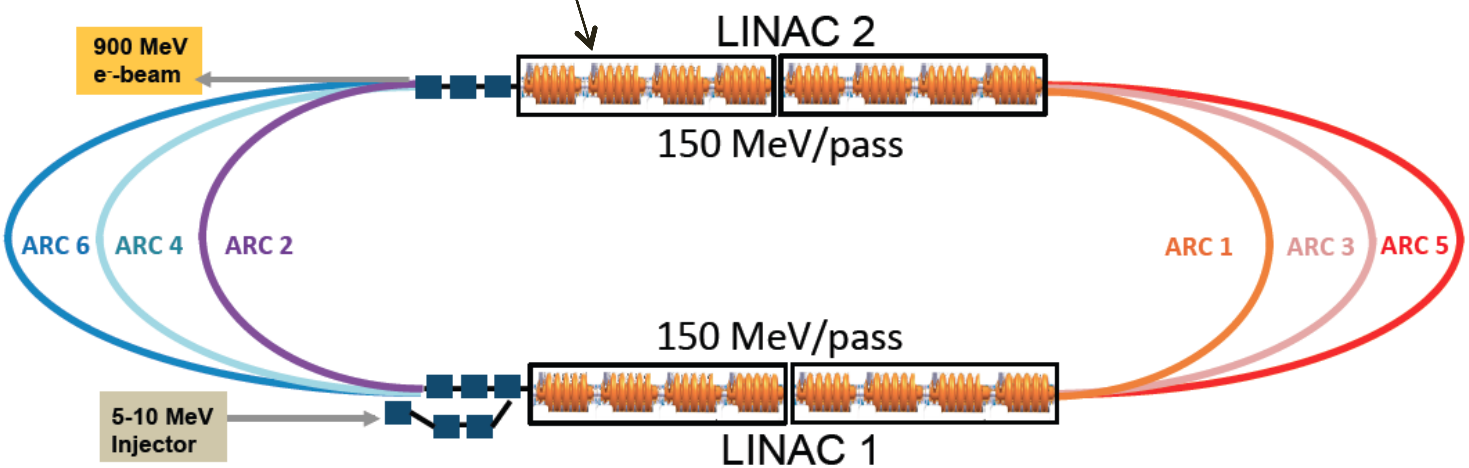
Superconducting RF and ERL Test Facility Design at CERN



R.Calaga, A.Hutton, B. Rimmer, E.Jensen et al.

Frequency 802 MHz
Design and built of 2 Modules (CERN+Jlab+)
Conceptual Design of the LTFC – end of 2015:
SCRF under beam conditions, applications,
high quality, high current, multipass, ERL

Interest for participation expressed by
BINP, BNL, CORNELL, IHEPBj, JLAB ..



Arc optics, Multipass linac optics, Lattice, Magnet specification, ... first passes done

A. Bogazc, A.Valloni, A.Milanese et al.

Areas of Study Post-CDR *)

More realistic with dedicated or new tools and evaluation of high luminosity prospect

Choice of RF Frequency – 802 MHz
Optimisation of IR Design [L*(e) < L*(p), inner triplet half? quad…]
Integration of p optics into HL-LHC
Integration of e optics into HL-LHC
Beam-beam effects (phase space deformation)
Multi-bunch beam break up
Wakefield effects on multi-bunch instability at IP
Emittance growth
Coherent synchrotron radiation
Fast beam-ion instability (1/3 gap compensated by 1.3 from pinch effect)
Arc optics FODO vs FMC (flexible momentum compaction)
Lattice design
Spreader and combiner
Civil engineering
…

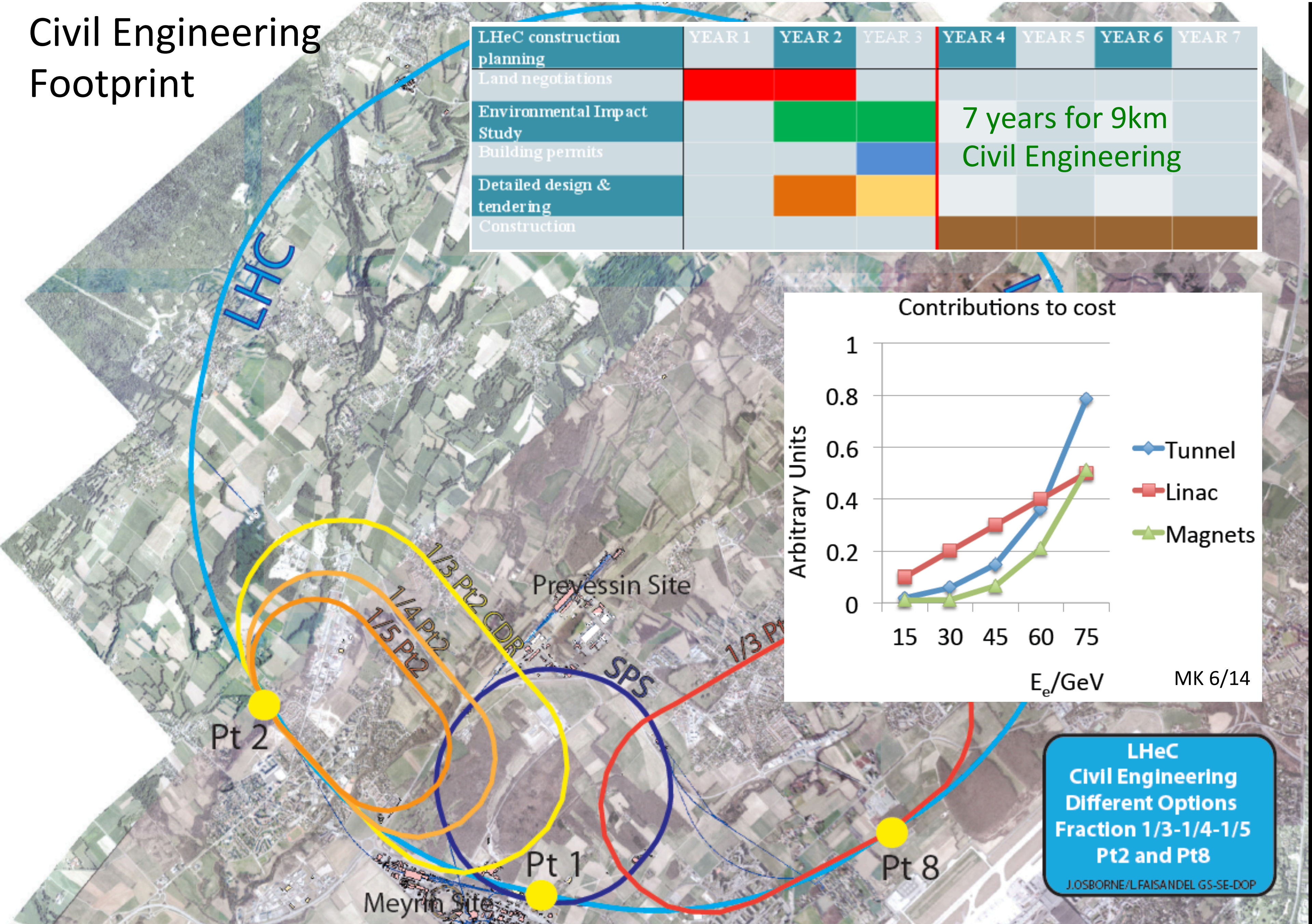
So far no showstopper found for O(10^{34})$cm^{-2}\,s^{-1}$: it requires further serious study and the development of SCRF within a Testfacility

*) Recent presentations by A.Bogacz, O.Bruening, E.Cruz, E.Jensen, D.Schulte, A.Valloni – see Webpage
Work by E.Cruz, M.Korostelev, E.Nissen, J.Osborne, D.Pellegrini, A.Letina, A.Milanese, A.Valloni and others

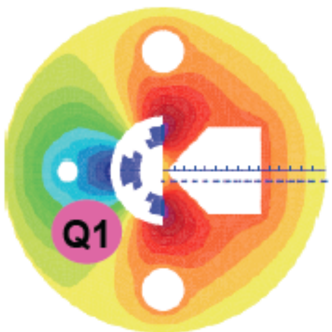
Civil Engineering Footprint

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				■	■	■	■

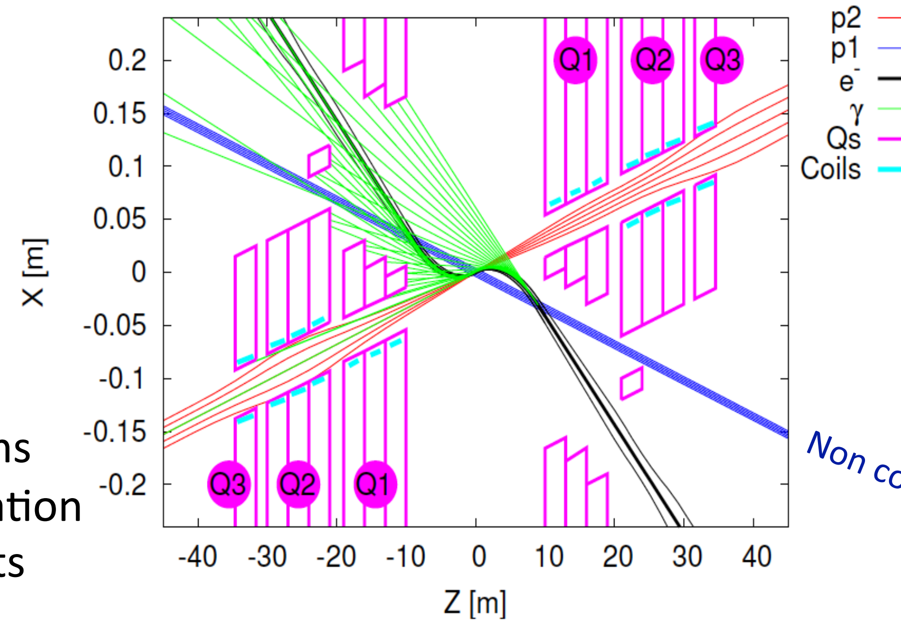
7 years for 9km Civil Engineering



Interaction Regions for ep with Synchronous pp Operation

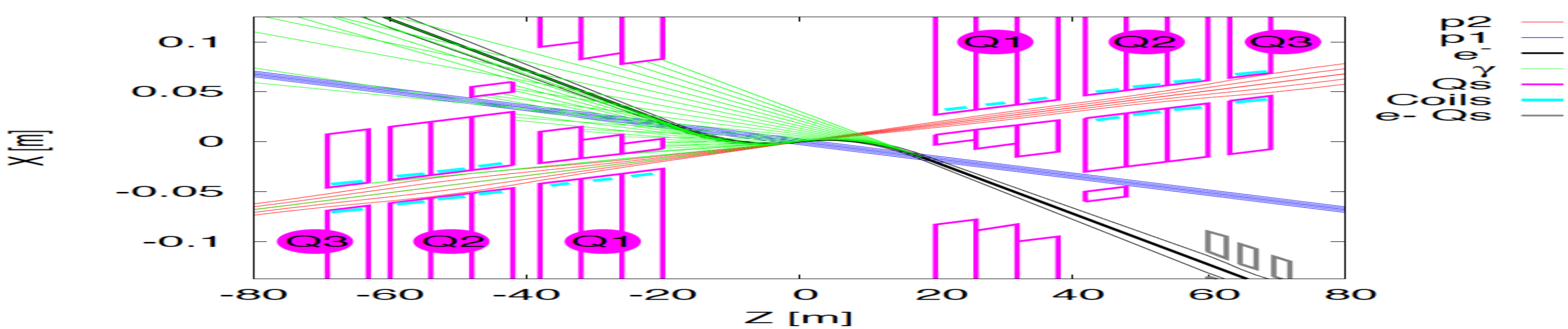


Likely one IR.
Matching e and p beams
Limit synchrotron radiation
Design of inner magnets
Beam-beam effects ....



Non colliding p beam

LHeC (CDR)
60 GeV * 7 TeV

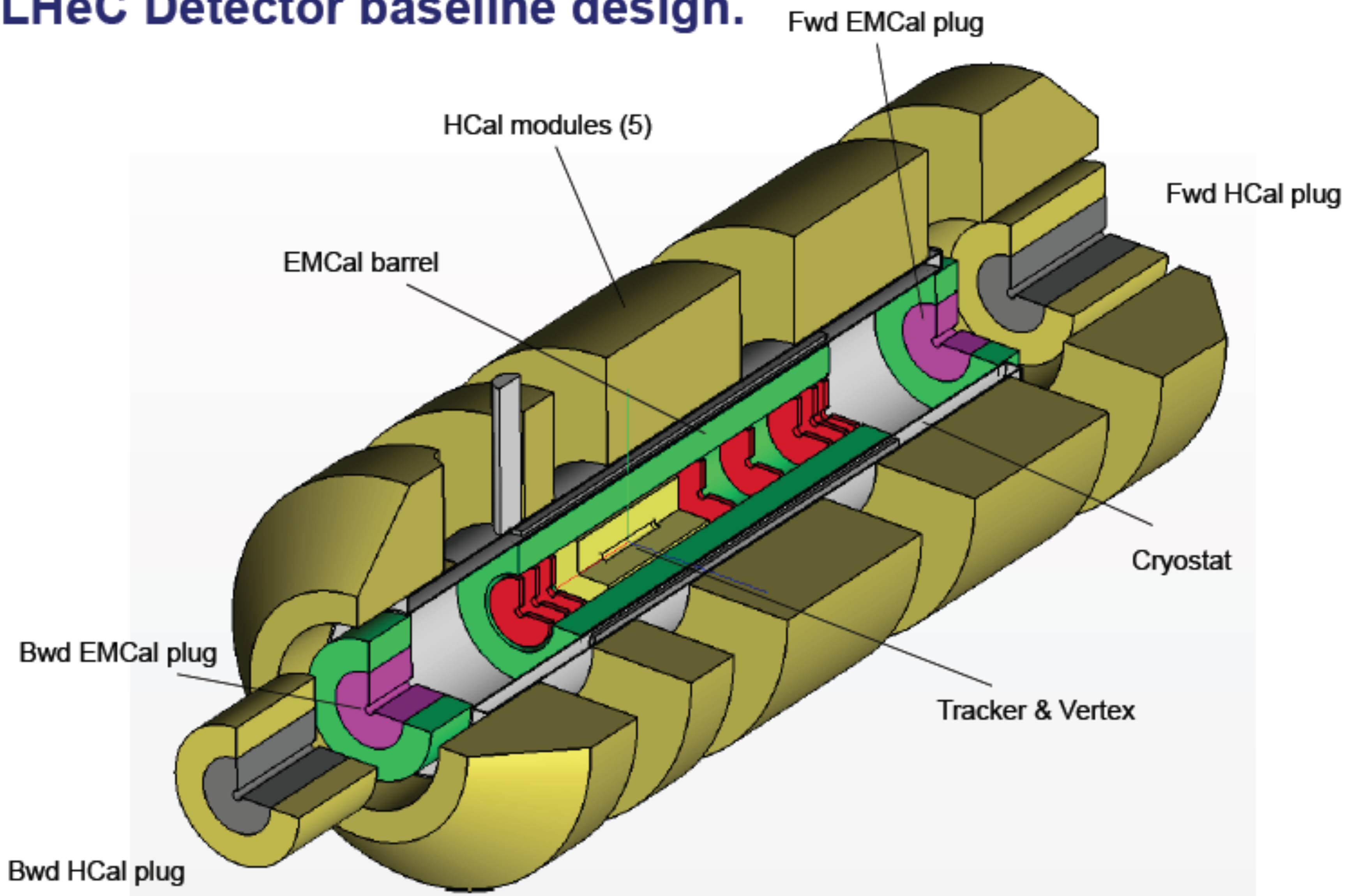


Tentative: ε_p=2μm, β*=20cm → σ_p=3μm ≈σ_e matched! ε_e=5μm ..

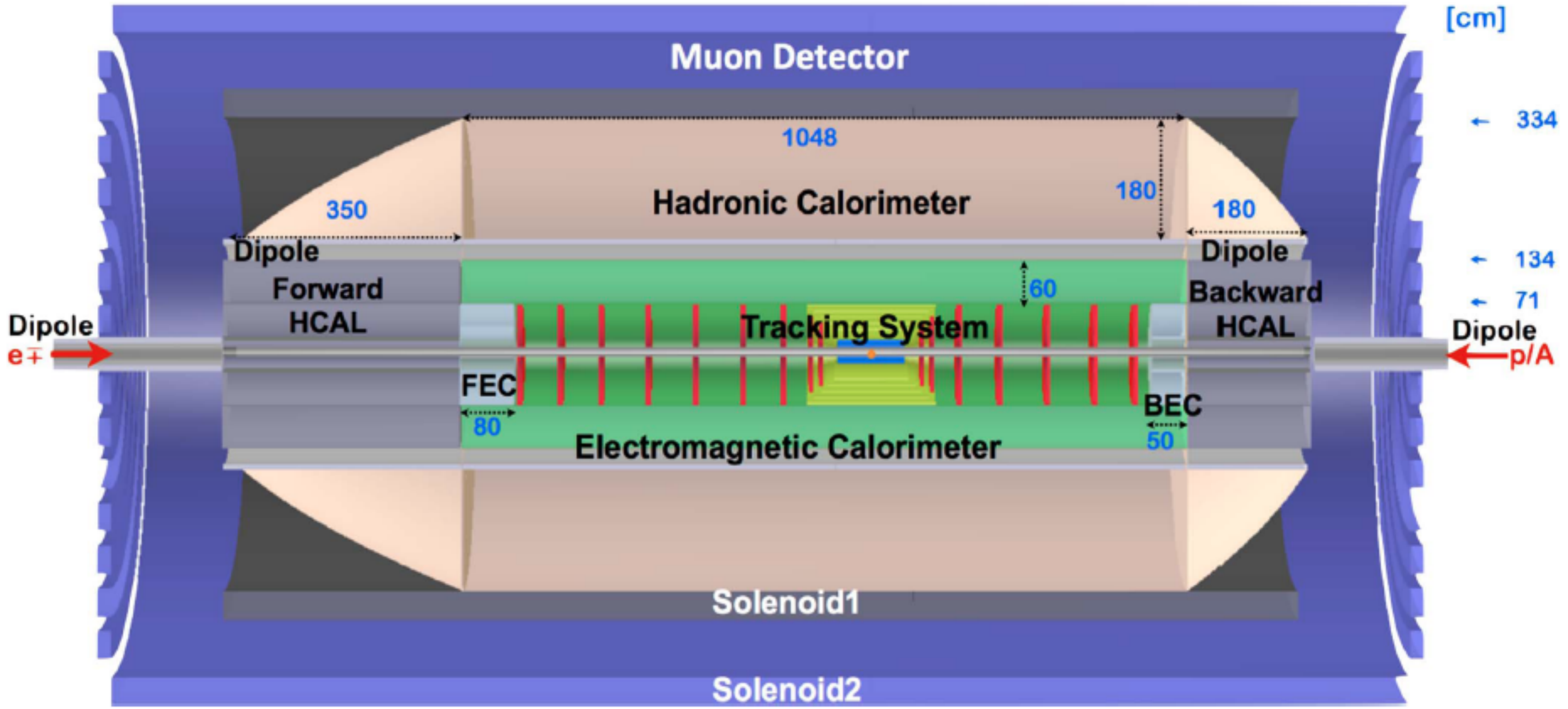
FCC-he (ERL)
60 GeV * 50 TeV

Rogelio Tomas, Max Klein, ICHEP14

LHeC Detector baseline design.



FCC-he Detector (B) – 0.1



Crab cavities for p instead of dipole magnet for e bend to ensure head on collisions
1000 H → μμ may call for better muon momentum measurement
H→ HH → 4b (and large/low x) call for large acceptance and optimum hadr. E resolution
Detector for FCC scales by about ln(50/7) ~2 in fwd, and ~1.3 in bwd direction
Full simulation of LHeC and FCC-he detectors vital for H and H-HH analysis

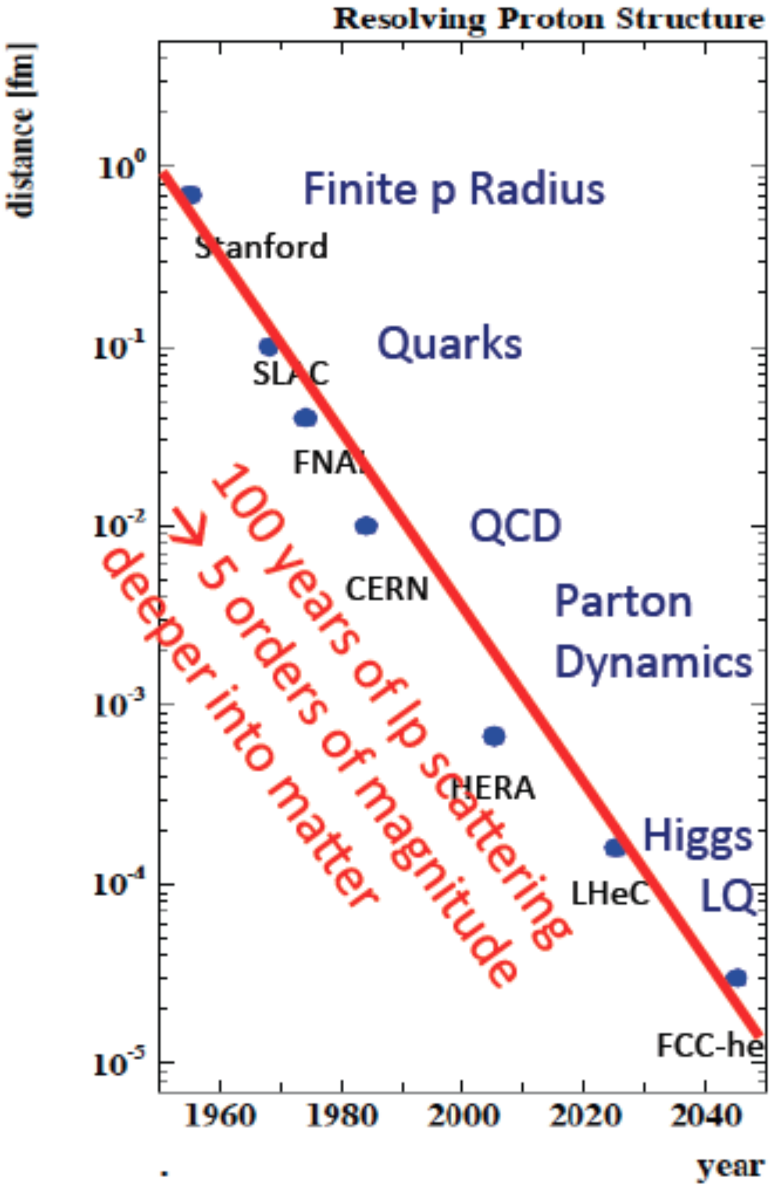
P.Kostka et al.

collider parameters	FCC ERL	FCC-ee ring		protons
species	e^- (e^+?)	$e^\pm$	$e^\pm$	p
beam energy [GeV]	60	60	120	50000
bunches / beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (*x*)	0.94 (*x*)	0.04 [0.02 *y*]
$\beta_{x,y}$*[mm]	94	8, 4	17, 8.5	400 [200 *y*]
$\sigma_{x,y}$* [μm]	4.0	4.0, 2.0		equal
beam-b. parameter ξ	(D=2)	**0.13**	**0.13**	0.022 (0.0002)
hourglass reduction	0.92 (H_D=1.35)	**~0.21**	~0.39	
CM energy [TeV]	3.5	3.5	4.9	
luminosity[$10^{34}cm^{-2}s^{-1}$]	**1.0**	**6.2**	**0.7**	

F.Zimmermann
ICHEP14, June

PRELIMINARY
L is 1000*HERA

Outlook



Perhaps then we know why quarks and leptons differ

ep/eA's Big Questions

- Structure of the Visible Matter
- Lepton-Quark Symmetry
- BSM (Higgs, DM, CI's, RPV SUSY..)
- BSM (Free colour, low x QCD)

ep/eA's Prominent Contributions

- Resolving the Proton PDFs
- Photon,Pomeron, GPDs, Neutron, A
- Higgs in WW and ZZ
- QCD of HI physics (NPDFs)
- Electroweak Physics beyond Z and H
- Surprises…

The LHeC is a new DIS collider of unprecedented precision and reach, an affordable precision Higgs facility leading to new accelerator and detector technologies/applications. **The FCC** leads into a very long and exciting future for ee, hh and eh.

M.Froissart ICHEP ("Rochester") 1966

THEORY

H.Murayama – ICFA11

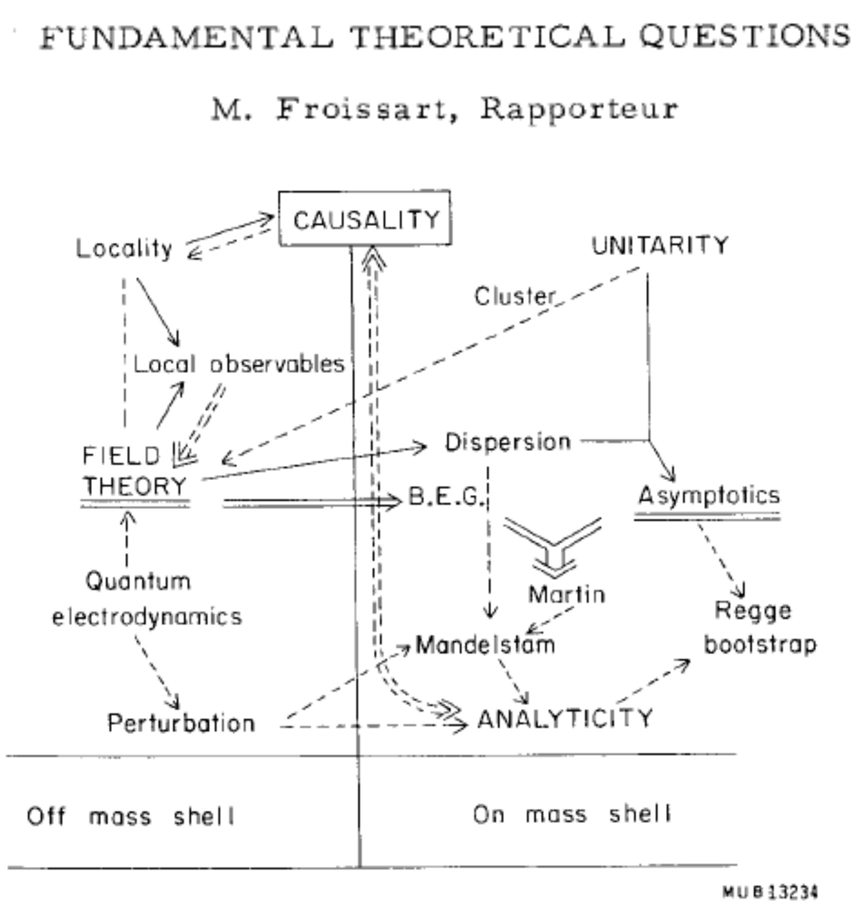
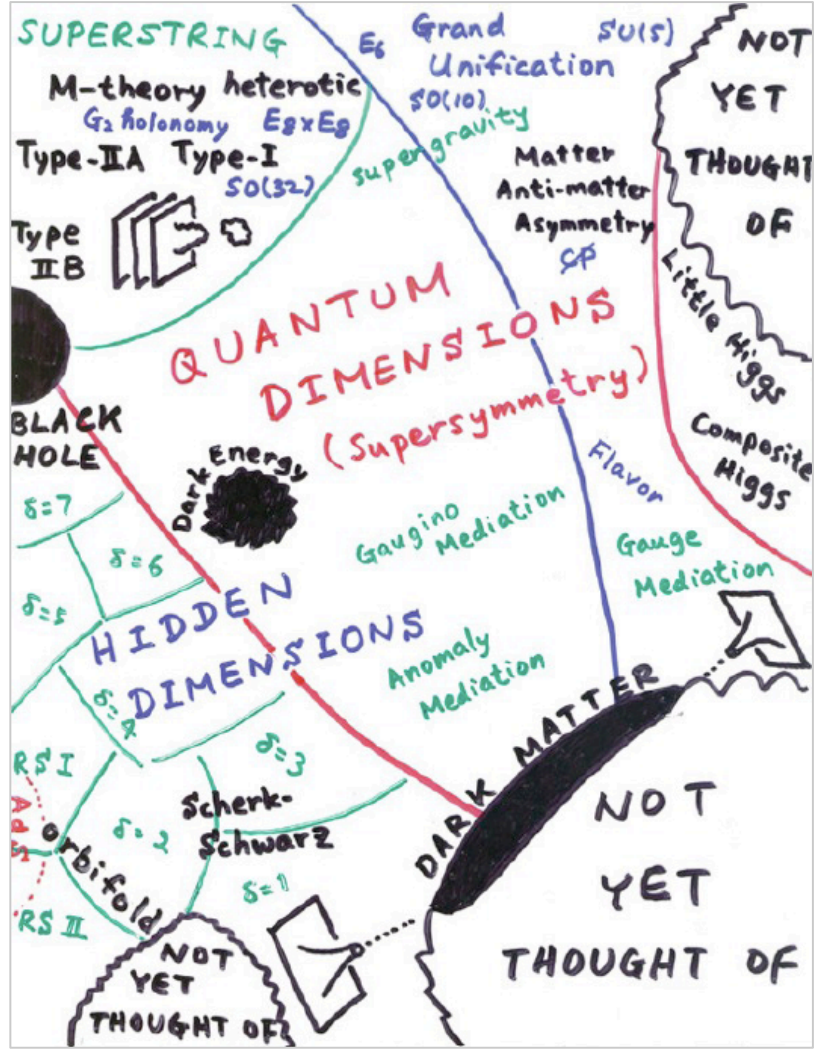


Fig. 1-1. Logical map of "Fundamental" concepts.



→ Quarks in 1969

→ ?in 2015+?

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

http://cern.ch/lhec

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

LHeC Study group and CDR authors [May13]

Workshop at Chavannes, I/14

Coordination Group

Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Gaddi
Erk Jensen
Max Klein
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

Thanks

to the whole
LHeC
Study
Group
to the FCC
team
and

www.lhec.cern.ch

Referees for Design Report

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

Physics Study Groups (Convenors)

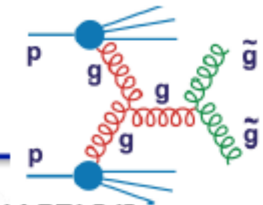
PDFs, QCD	Fred Olness, Voica Radescu
Higgs	Uta Klein, Masahiro Khuze
BSM	Georges Azuelos, Monica D'Onofrio
Top	Olaf Behnke, Christian Schwanenberger
Nuclei	Nestor Armesto
Small x	Paul Newman, Anna Stasto

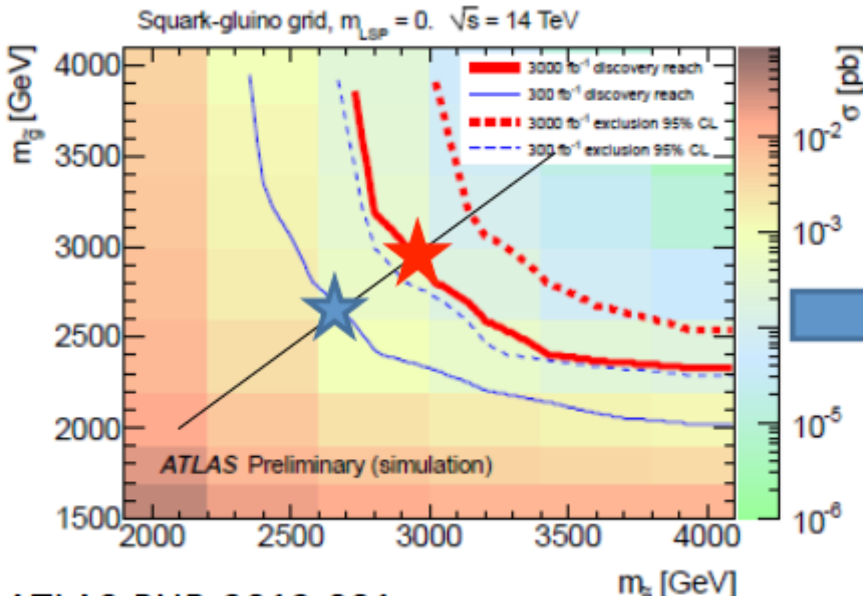
The LHeC design has been a strong community effort
Welcome to join us: Washington 23-27 March 15
CERN and Chavannes 24-27. June 2015 (thy, acc, exp)

CDR: arXiv:1206.2913

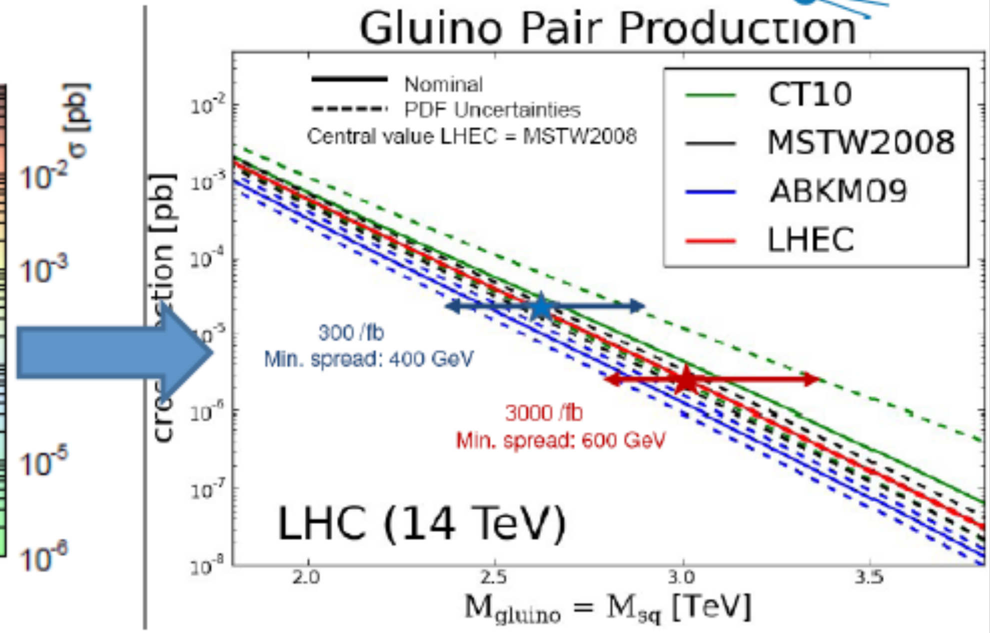
backup

LHeC and the HL-LHC (SUSY searches)





ATLAS-PUB-2012-001



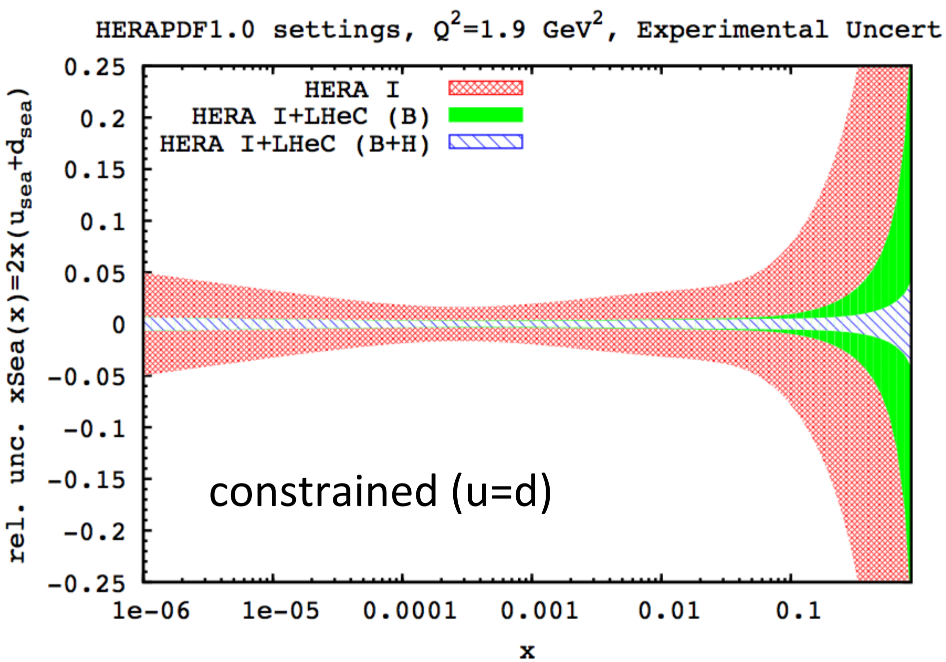
With high energy and luminosity, the LHC search range will be extended to high masses, up to 5 TeV in pair production → PDF uncertainties easily > 100% for high mass searches
➔ gluon density from LHeC (10% at x=0.6, ~4TeV)]

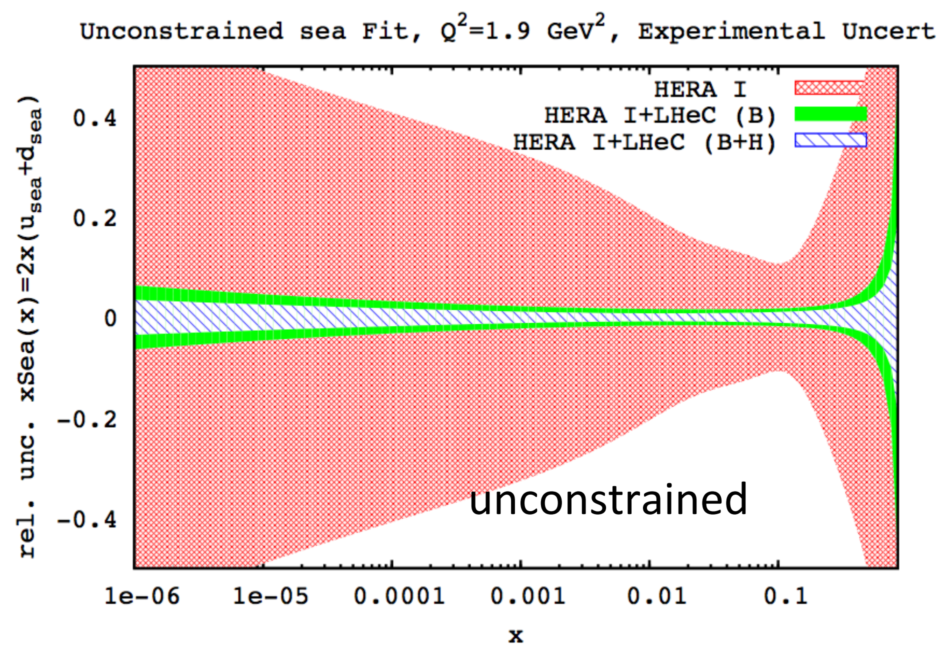
The HL-LHC and FCC-hh search programme requires a much more precise understanding of QCD, which the LHeC could provide (strong coupling, gluon, valence, factorisation, saturation, diffraction..)

Cf M D'Onofrio at ICFA Beijing 2014

Resolving Partonic Structure free of symmetry assumptions

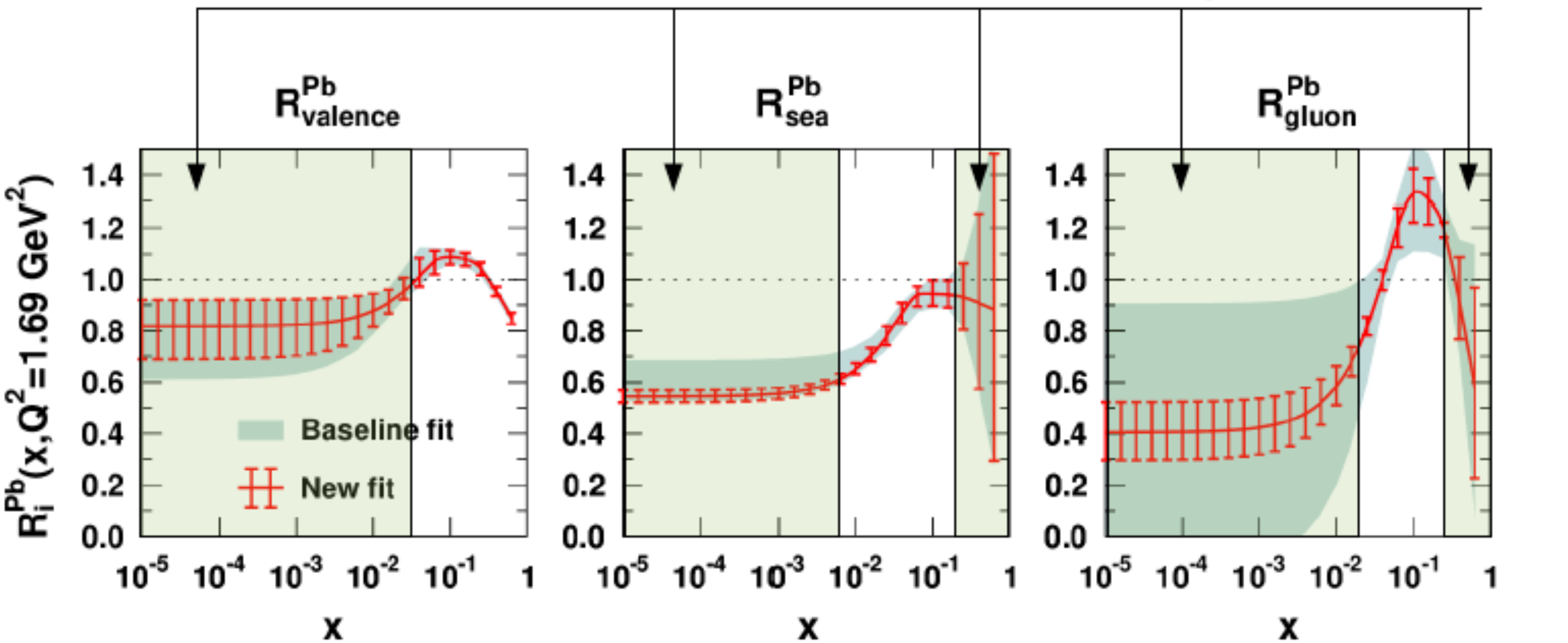
- Usual assumptions for light quark decomposition at low x may not necessary hold.
- **Relaxing the assumption at low x that u=d , we observe that uncertainties escalate**:





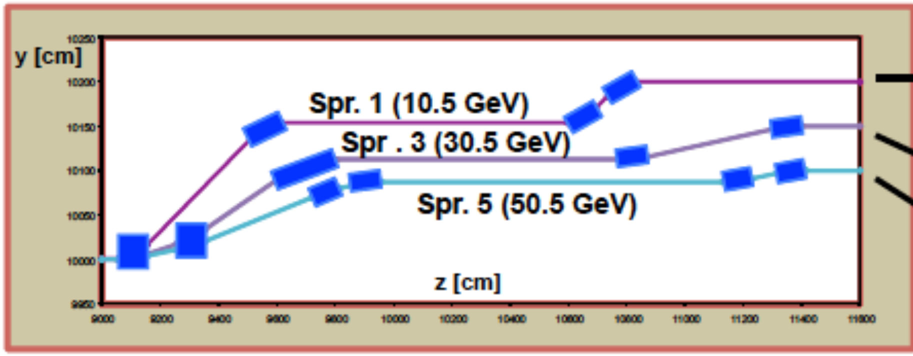
- One can see that for HERA data, if we relax the low x constraint on u and d,the errors are increased tremendously!
- However, when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing with diffraction…

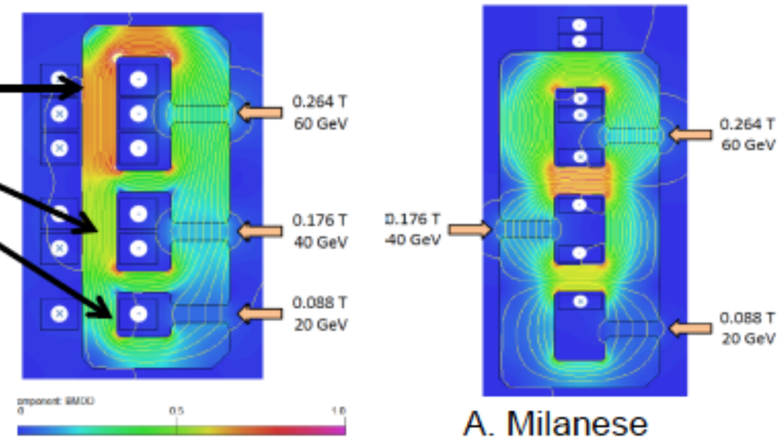
Effects in nPDFs, LHeC



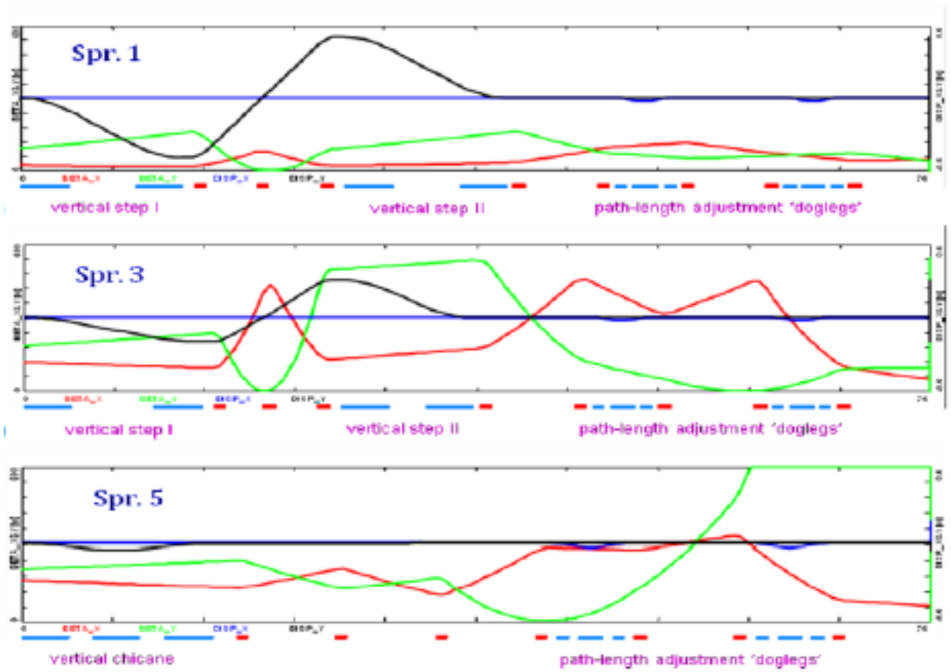
- A drastic reduction in the small-x gluon and sea quark uncertainties
- More freedom in the fit function should be allowed – the baseline uncertainty probably underestimated
- Addition of charged-current data should give a handle on the flavor dependence, which is currently (practically) unconstrained

Switchyards





A. Milanese



- Two-step-achromat spreaders and mirror symmetric recombiners
- Arcs are separated into 1m high vertical stack
- Very compact switchyard system (~20 m long)
- Horizontal doglegs used for path-length adjustment

A.Bogasz (Jlab), A.Milanese, A.Valloni (CERN) et al

Higgs Parameter List "H-LHeC"

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Beam Current [mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2 \cdot 10^{11}$	$4 \cdot 10^{9}$
Bunch charge [nC]	35	0.64

HL-LHC proton beam parameters

1000 times HERA Luminosity and 4 times cms Energy

Clarification and Tradition

Herwig Schopper at Chavannes 1/14 in the Panel Discussion with the CERN Directorate

My clarifying remark:

Any ep/eA project **cannot be a major CERN flagship project**
Essentially only one experiment,
cannot satisfy > 8000 users

not in competition with main projects (HL-LHC, HE-LHC, CLIC, FCC)
complementary (in time, resources)

International collaboration will be essential

- **for experiments (detectors, intersections)**
- **accelerator design (parameters, optimisation)**
- **preparing necessary technology (SC rf cavities, possibly ERL test facility)**

As in the tradition of CERN

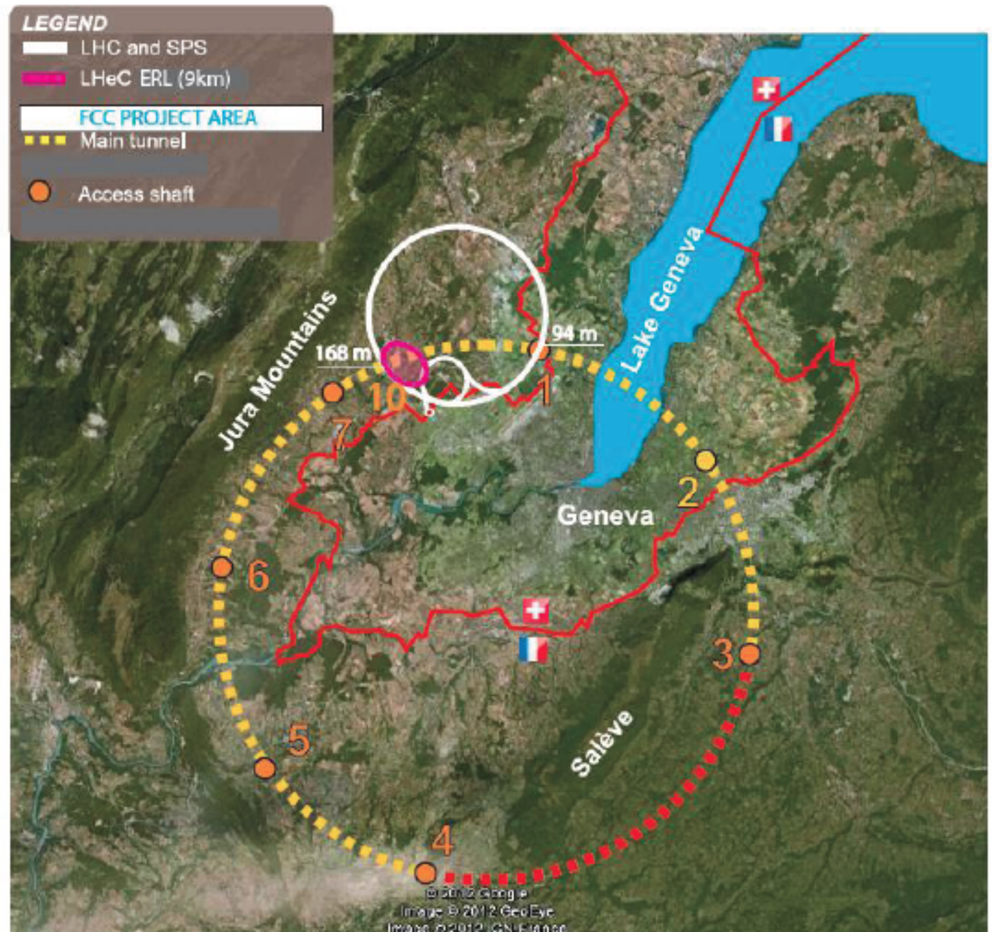
H.Schopper, M.K. CERN Courier June 2014

LHeC and the Future Circular Collider (FCC)

Version 230 mASL

	SPS	LHC	FCC	Between LHC/FCC
Point 1	40m	96m	190m	94m
Point 10	40m	50m	218m	168m

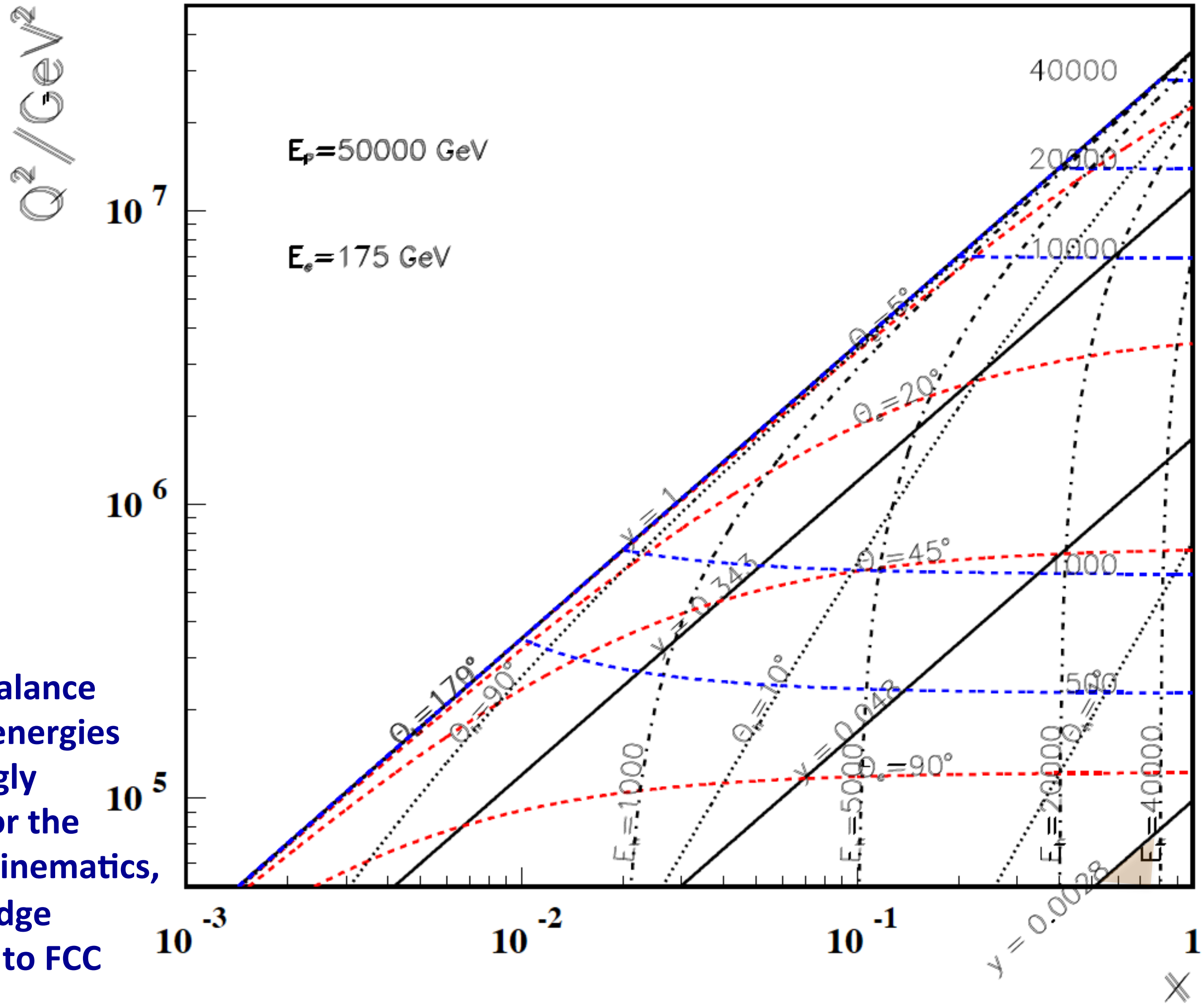
- **<u>Phase 1</u>** : ep collisions at LHC P2
- **<u>Phase 2</u>** : ep collisions in FCC near LHC P2
- European Strategy Paper (2012), the ‘plan’ position for passes under the LHeC ERL
- However, FCC is 150m deeper than ERL
- FCC tunnel location/depth still to be optimised



J Osborne at IAC Meeting 6/14

High Q^2

Rutherford backscattering of dozens of TeV e- energy



FCC-he
175 GeV
60 GeV

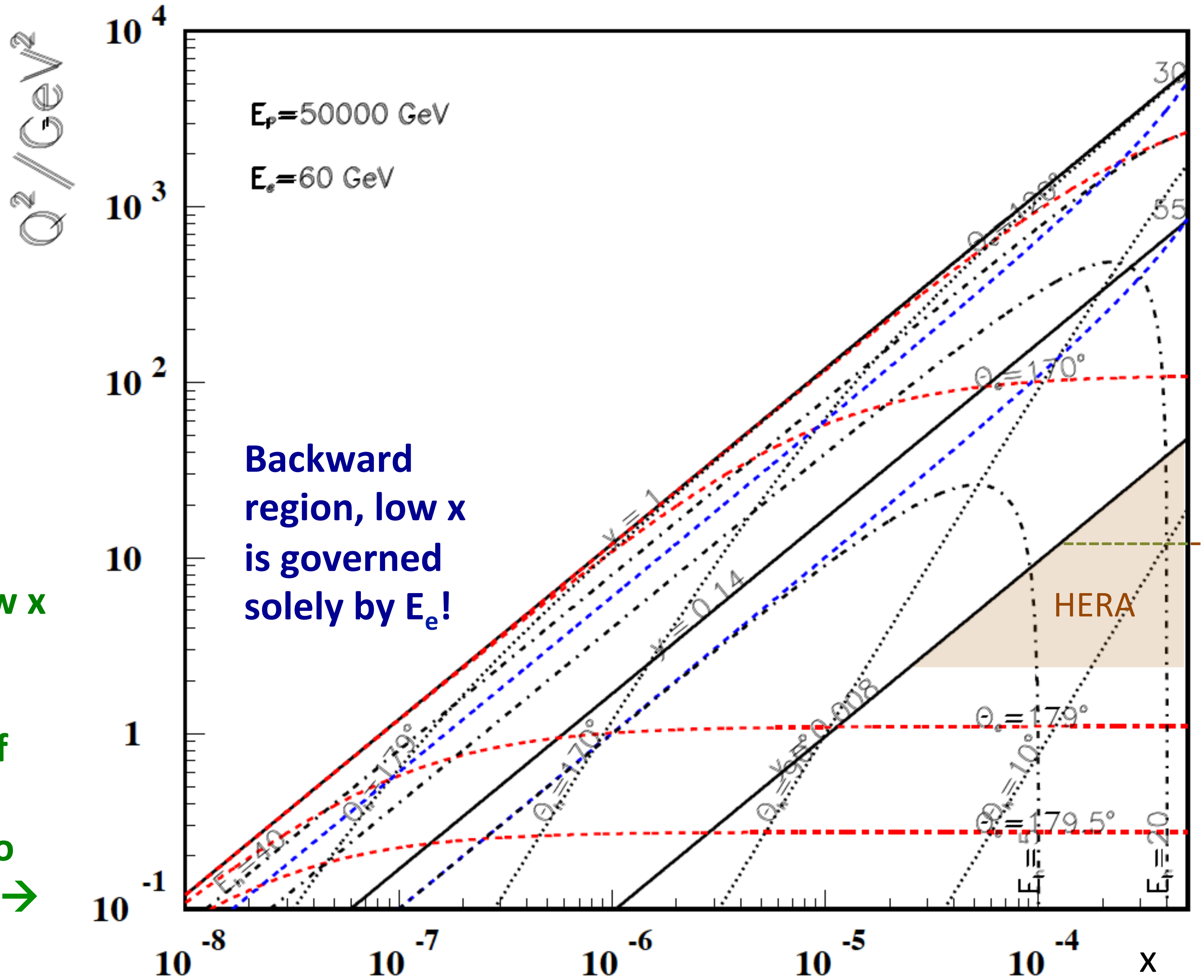
LHeC

← $\vartheta_h=1^o$

← 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

Future Circular Collider (FCC) study ; goals: CDR and cost review for the next European Strategy Update (2018)

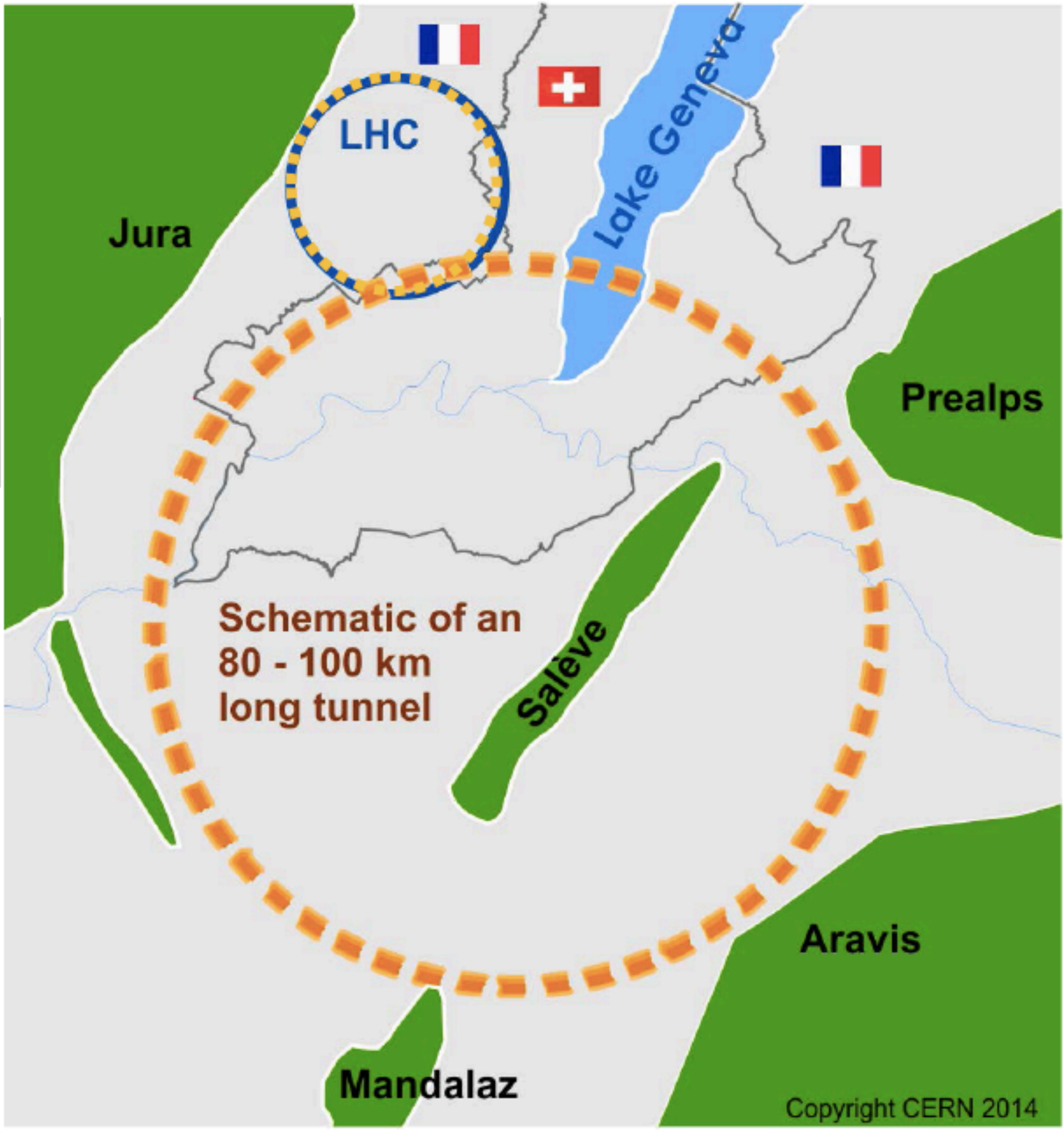
International collaboration :

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV in 100 km
~20 T ⇒ 100 TeV in 80 km

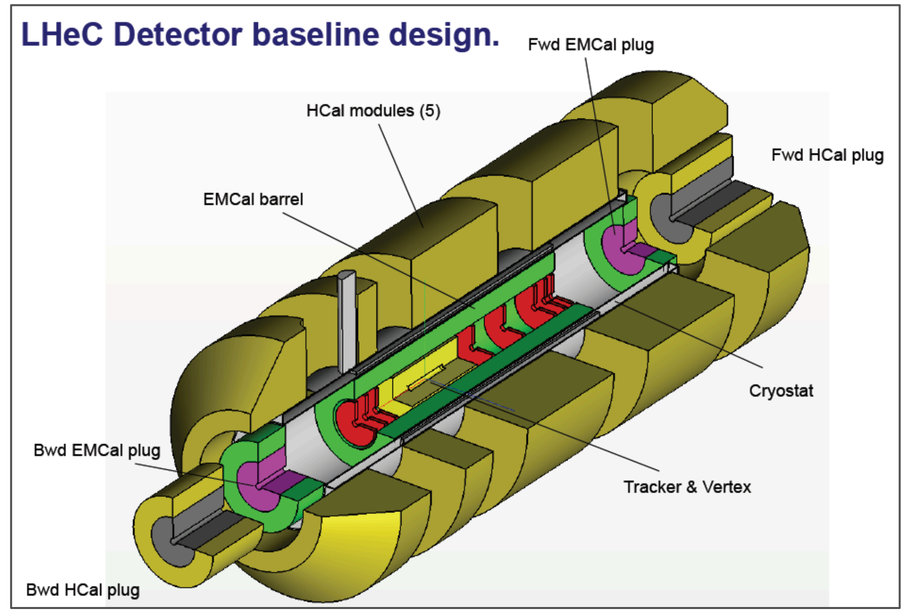
- including ***HE-LHC*** option: 16-20 T in LHC tunnel
- ***e^+e^-* collider (*FCC-ee/TLEP*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **100 km infrastructure** in Geneva area

M. Benedikt

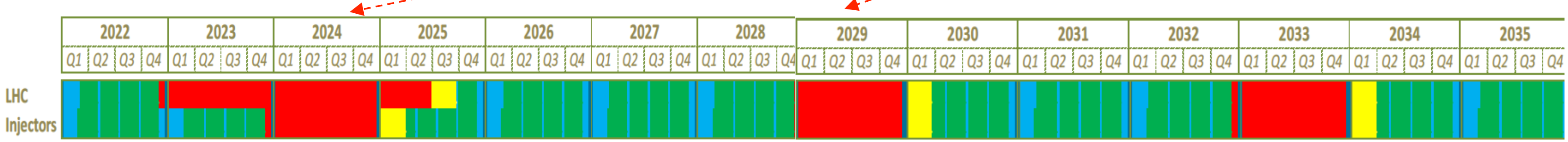


Time Schedule – 2 – Detector

A.Gaddi Chavannes 1/14



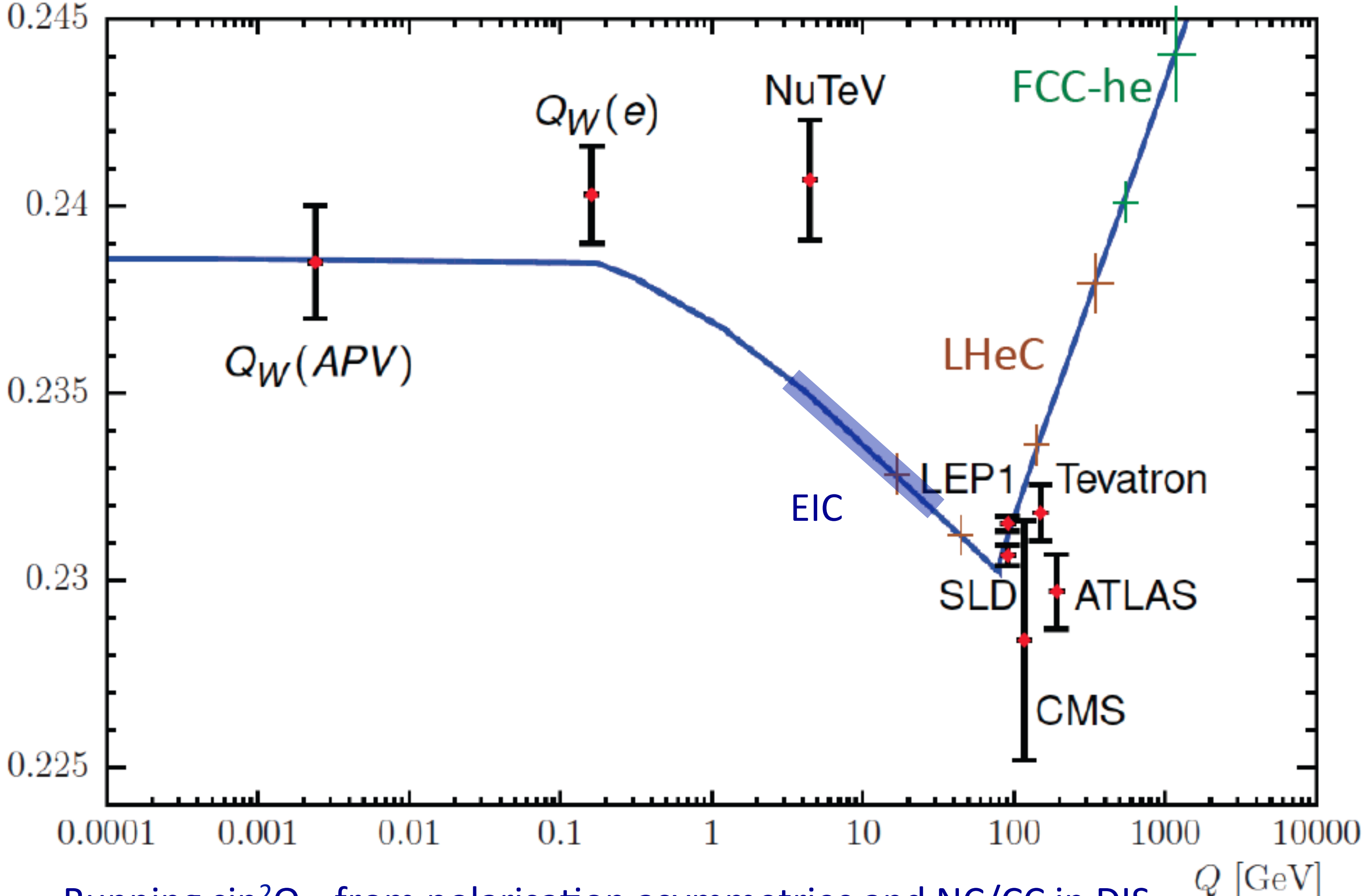
Pre-mounting at the surface of a modular detector – independent of LHC
Lowering (7), Installation (2), Connection (6), Field Map (1), Pipe (1) … min of 15 Month
which would be compliant with LS3 and may be with LS4 – depends on the LHC



Goals of a CERN ERL-Test Facility

- Main goal: **Study real SRF Cavities with beam** – not interfering with HEP!
  - citing W. Funk ("Jefferson Lab: Lessons Learned from SNS Production", ILC Workshop 2004 http://ilc.kek.jp/ILCWS/):
    - **All problems will not be experienced until the complete subsystem is tested under realistic conditions. Be prepared to test, with full rf power systems and beam, all of the pre-production prototypes.**
- In addition, it would allow to study **beam dynamics & operational aspects** of the advanced concept ERL (recovery of otherwise wasted beam energy)!
- Exploration of the ERL concept with multiple re-circulations and high beam current operation
- Additional goals:
  - Gun and injector studies
  - Test beams for detector R&D,
  - Beam induced quench test of SC magnets
  - … later possibly user facility: $e^{\uparrow -}$ test beams, CW FEL, Compton γ-ray source …
- At the same time, it will be fostering international collaboration (JG|U Mainz and TJNAF collaborations being formalized)

Scale dependence of $\sin^2\theta_W$



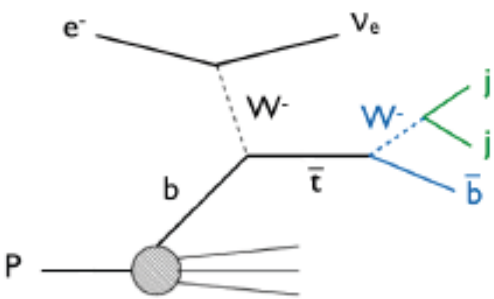
Running $\sin^2\Theta_W$ from polarisation asymmetries and NC/CC in DIS

Low scales from MAMI, Jlab and possibly the CERN Testfacility

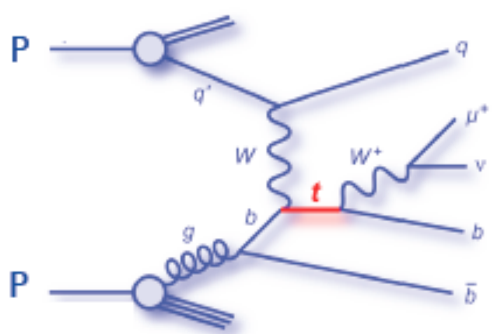
Search for Anomalous Wtb Couplings

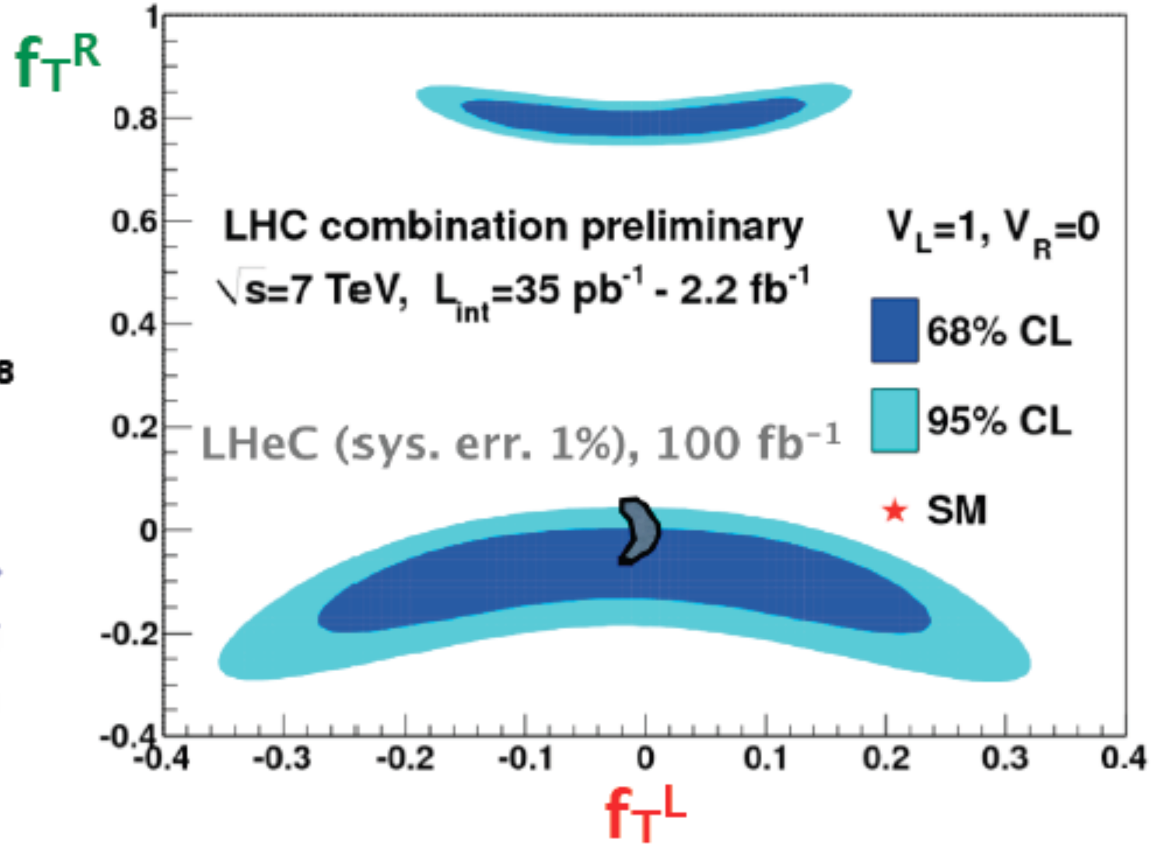
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

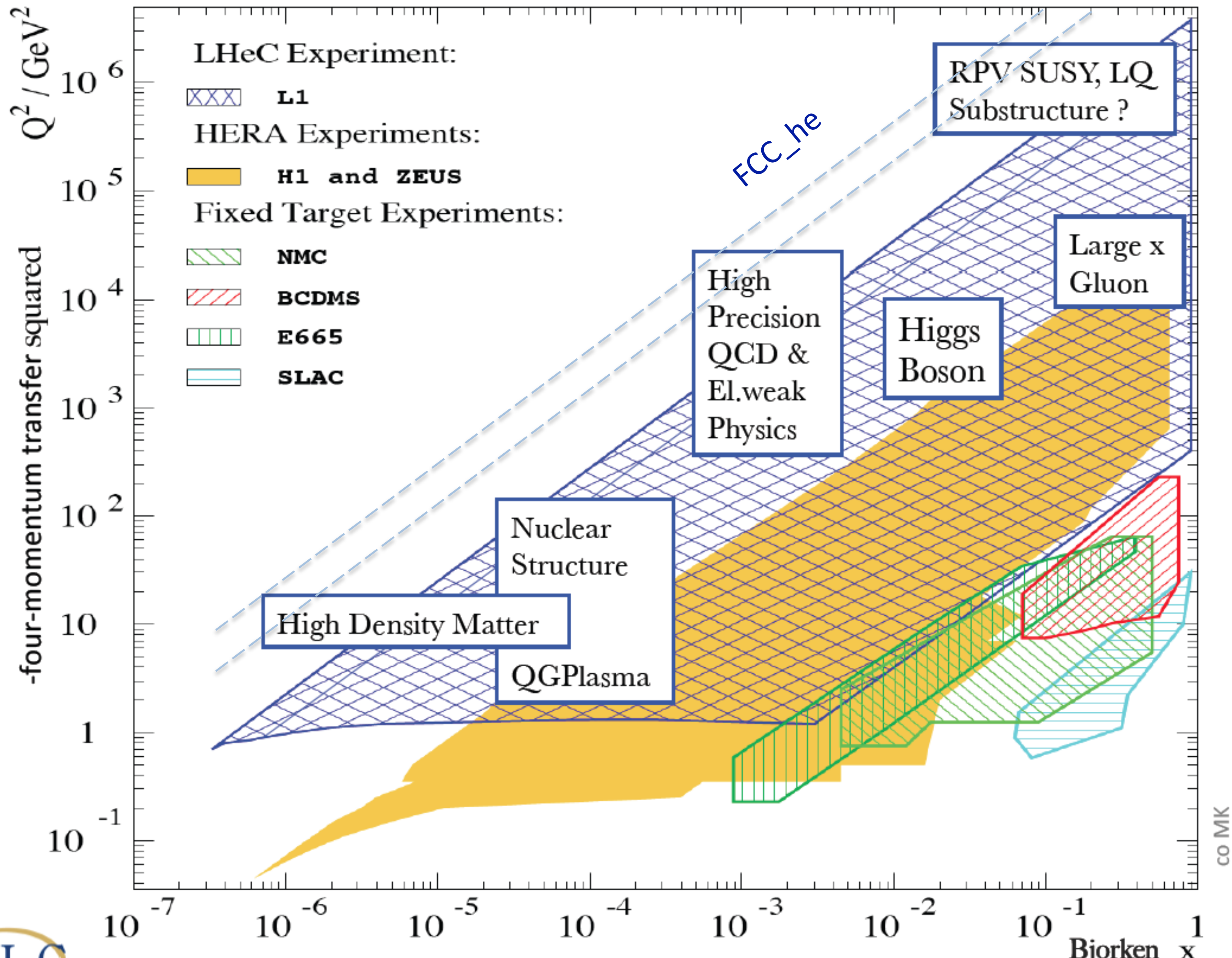
= 1 in SM



Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688






LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
FCC_he
RPV SUSY, LQ
Substructure ?
Large x
Gluon
High
Precision
QCD &
El.weak
Physics
Higgs
Boson
Nuclear
Structure
High Density Matter
QGPlasma
co MK
Q^2 / GeV^2
-four-momentum transfer squared
Bjorken x
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Physics Overview

LHeC Note 2012-004, arXiv:1211.5102

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H? leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top $\mathrm{N^3LO}$, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronization inside media, black limit, saturation PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Table 3: Schematic overview on key physics topics for investigation with the LHeC.

LHeC: 20 times 1/x and Q^2 and 100-1000 times luminosity as compared to HERA
→ **Very rich programme on DIS, ions, Higgs and new physics in much extended range**