Electrons for the LHC

Future Deep Inelastic Lepton-Hadron Scattering at the Energy Frontier

Max Klein

UNIVERSITY OF LIVERPOOL

DIS

CDR

LHC

Physics

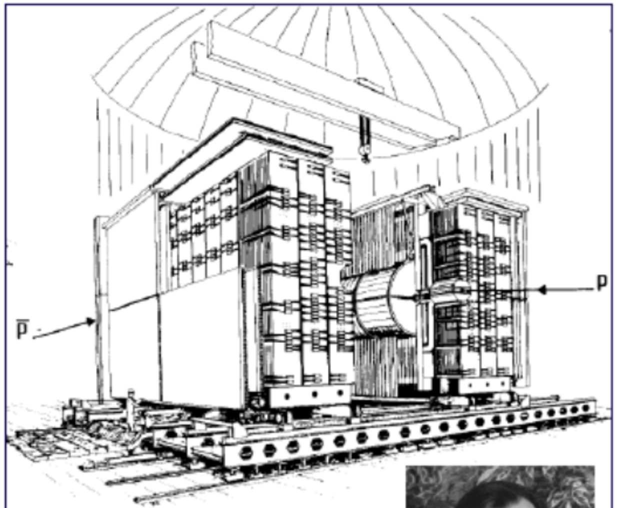
PERLE

Detector+

http://lhec.web.cern.ch
CDR 2012, Update 2018
ep (and eA) at the LHC

Seminar at Saclay, 24.03.2018

DIS and pp at CERN some 30-40 years ago



UA1

“ We have two tasks: kill Weinberg Salam, kill QCD”
Carlo Rubbia: 1978 BCDMS meeting at Dubna.
The failure to fulfill his task made Carlo famous…

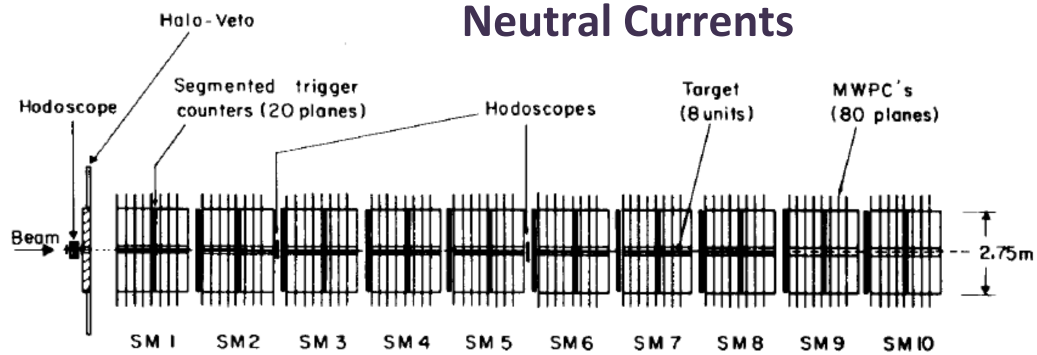
UA2

Pierre Darriulat

Charged Currents

BEBC, **CDHS(W)**, CHARM, CHORUS

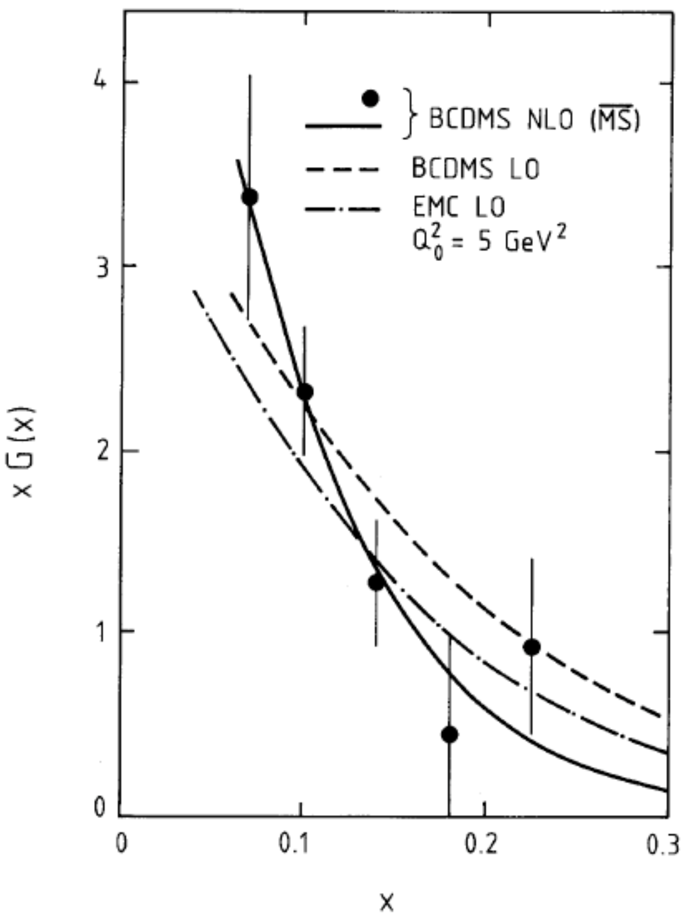
Neutral Currents



BCDMS, EMC, SMC, COMPASS

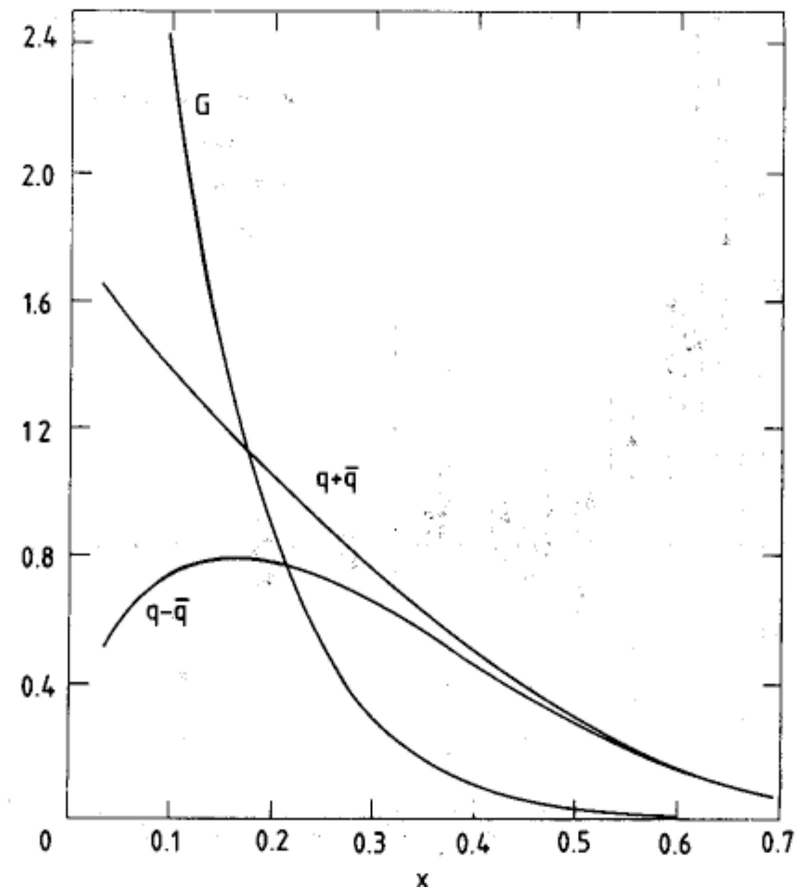
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



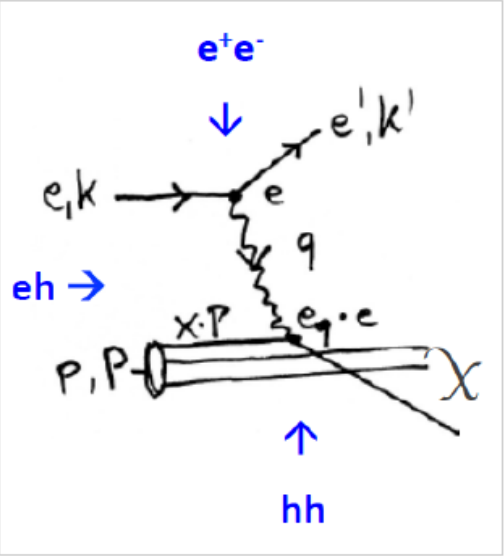
CERN-EP/89-07
January 17th, 1989

CDHS



CERN-EP/89-103
15 August 1989

Deep Inelastic Lepton-Hadron Scattering



ep Colliders:

Calculated to N^2LO
J Vermaseren et al,
and N^3LO to come

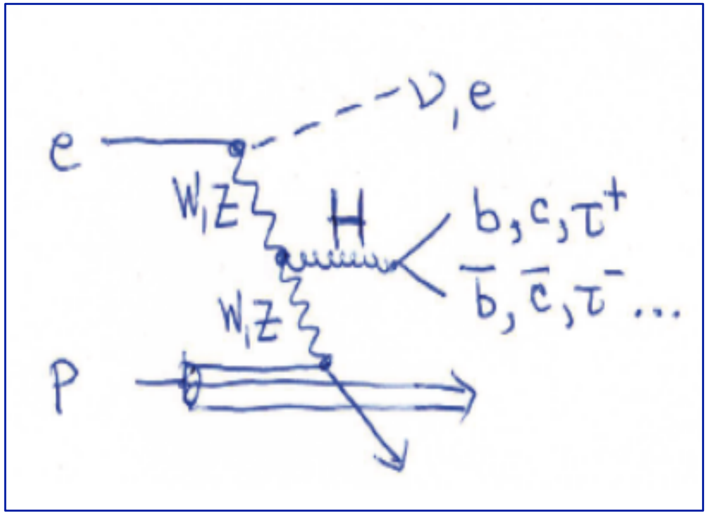
Redundant determination of the scattering kinematics: x, $Q^2 \leq 4E_eE_p=s$ → high precision

Resolution of substructure $d=1/\sqrt{Q^2}$ (protons and nuclei: the 'forgotten' task of HERA)
Proton, neutron, diffractive, nuclear, generalised, unintegrated partons. Much more than 'PDFs'.
Q^2=sxy varies by 7(8) orders of magnitude, 0.1-$10^{6(7)}$ GeV^2 for LHeC (FCCeh)
Small x > 1/s ($Q^2 > M_p^{\ 2}$): new parton dynamics, confinement, UHE neutrino scattering…

Electroweak γ,W,Z-parton scattering: clean final state, no pile-up (μ=0.1 at the LHeC), tag γ*p

The LHeC and the FCC-eh **are the cleanest high resolution microscopes the world can build.**

Deep Inelastic Lepton-Hadron Scattering

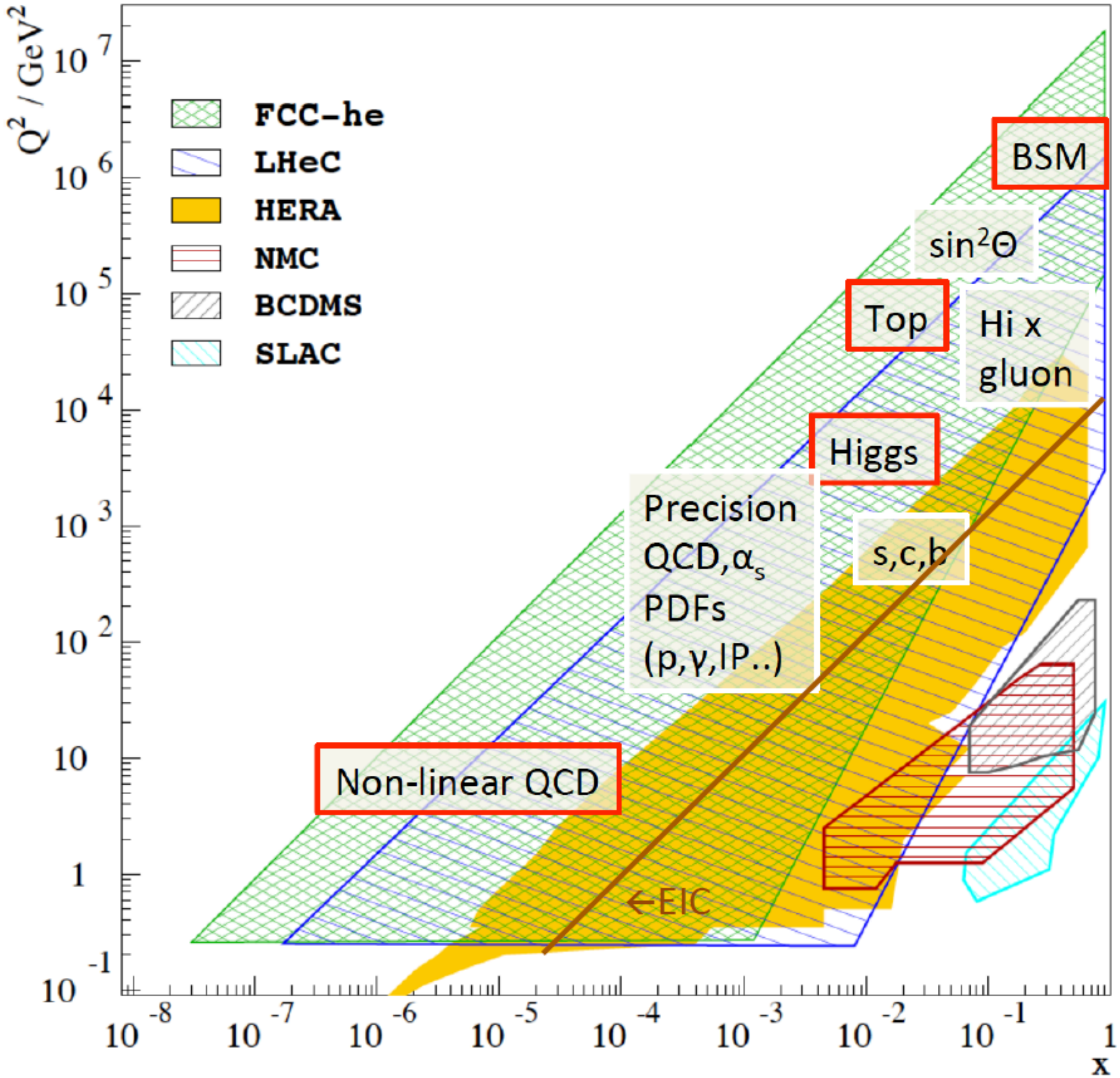


Can produce heavy new states (Higgs, 750 GeV ghost..) and reach to O(200) TeV by indirect constraints, such as high precision contact interaction measurements

pp, ep and ee are ordered in energy reach: $2E_p \gg 2\sqrt{(E_p E_e)} \gg 2E_e$
For the LH(e)C this translates to 14 TeV vs 1.3 TeV vs 0.25-0.35 TeV.

Drell-Yan production in pp of new states with mass M in pp: $M^2 = s\, x_1\, x_2$
Resolving high mass physics needs PDFs at high x. Note: Higgs at FCC will be low x physics
For pp need to separate new physics from QCD dynamics in the proton

Pursue **New Physics** of Deep Inelastic Scattering



.. and yet, ep is usually treated like the early Cinderella

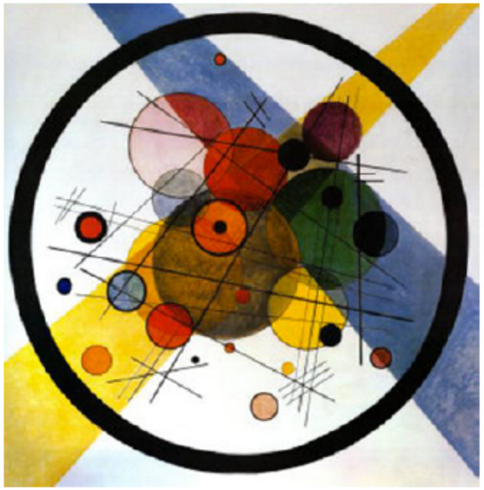
→ **Needs radiant appearance (lumi, physics, technology), readiness to work and a bit of luck..**

II The LHeC Conceptual Design Report

ep@LHC: Lausanne 1984
Aachen 1990
Rubbia: ICHEP Singapore 1990: pp in 1996 and ep in 1998

In 2007: the CERN SPC asks about ep: (r)ECFA+CERN Mandate

→ CDR in 2012



W.Kandinsky: "Circles in a circle" (1923) Philadelphia (USA) Museum of Art
First shown in LHeC context in a talk by A.S.Vera Workshop 2008

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Journal of Physics G

Nuclear and Particle Physics

arXiv:1206.2913

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

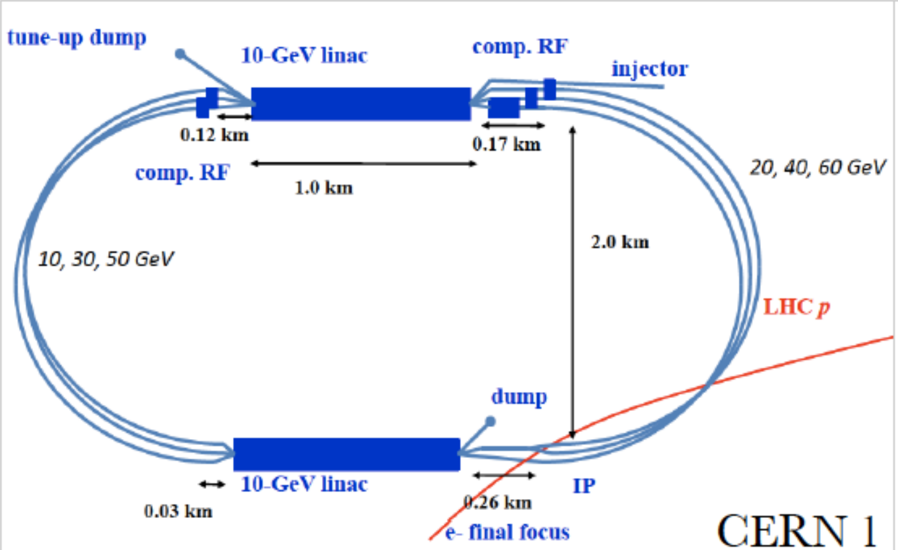
Journal of Physics G Nuclear and Particle Physics Vol 39, No 7 075001 July 2012

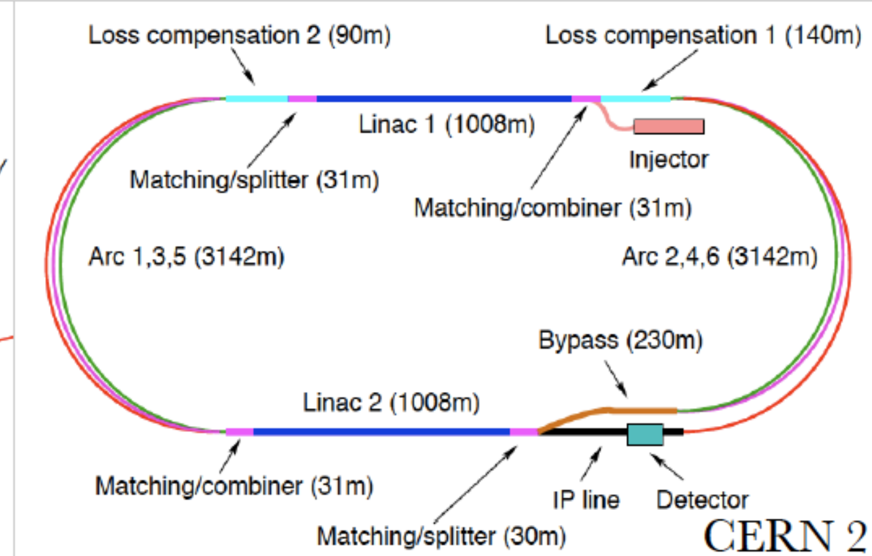
CERN Referees

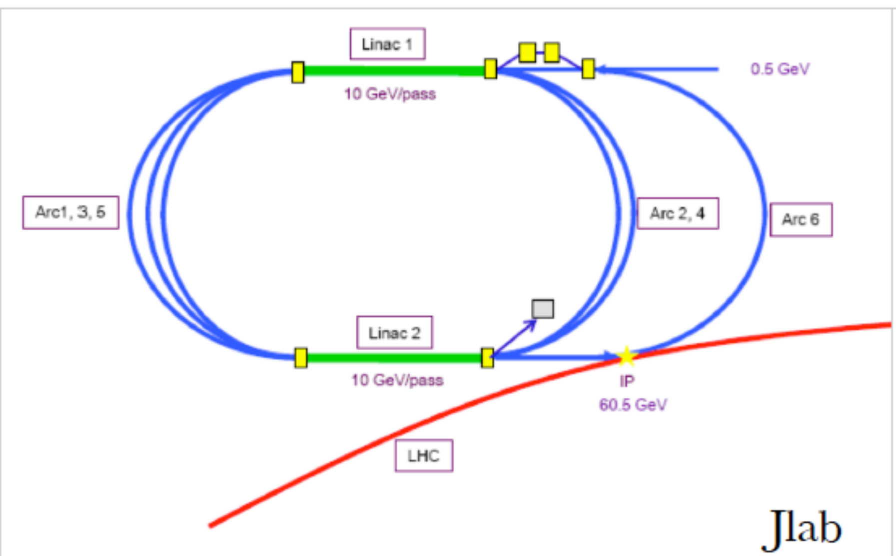
Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
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)

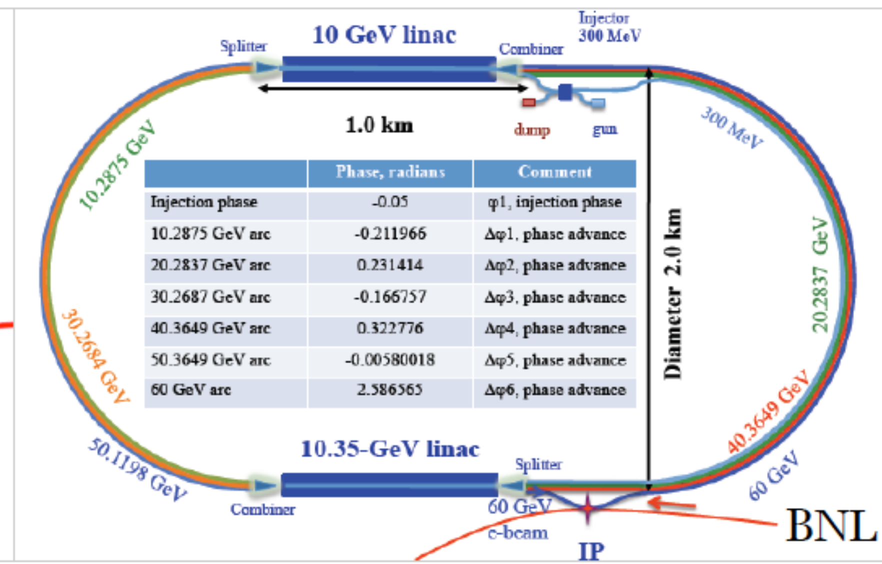
Published 600 pages conceptual design report (CDR) written by 200 authors from 60 Institutes and refereed by 24 world experts on physics, accelerator and detector, which CERN had invited.

60 GeV Energy Recovery Linac









	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

CDR: Default configuration, 60 GeV, 3 passes, 720 MHz, synchronous ep+pp, $L_{ep}=10^{33}$

Performance

Interaction Region

Optics

Ions

Polarisation (80-90%)

Positrons

CDR: VERY detailed design of the LHeC Linac (and Ring) – Ring Collider, + components, CE..

http://lhec.web.cern.ch

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 2014

"you never walk alone"

Physics Overview - CDR

LHeC Note 2012-004, arXiv:1211.5102

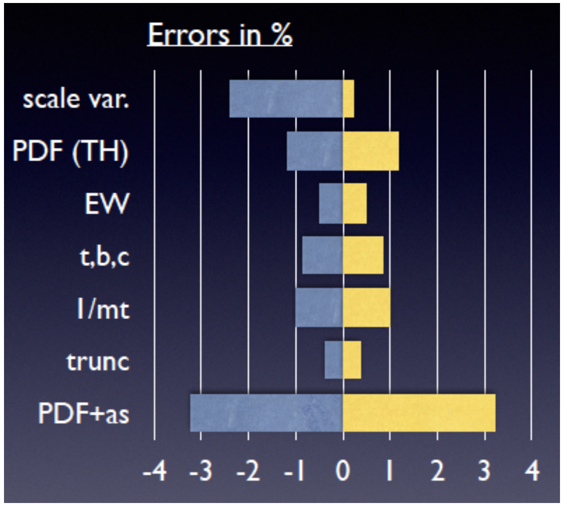
QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, 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, $x \simeq 1$, 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.

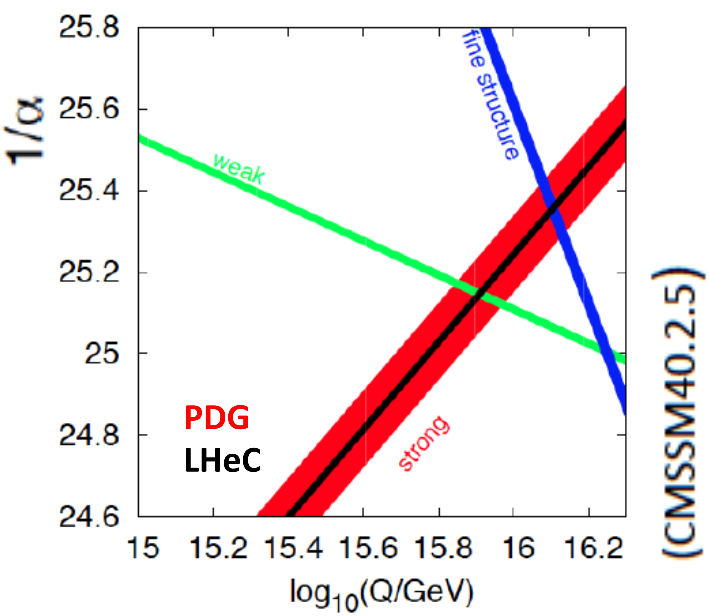
LHeC: 20 times 1/x and Q^2 and 100-1000 times luminosity as compared to HERA

→ **Very rich programme on DIS, ions, Higgs and new physics in much extended range**

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



- **α_s least known of coupling constants**
  Grand Unification predictions need smaller $\delta\alpha_s$
- **Is α_s(DIS) lower than world average (?)**
- **LHeC: per mille - independent of BCDMS!**
- **High precision from inclusive data – α_s(jets)??**
- **Challenge lattice QCD**

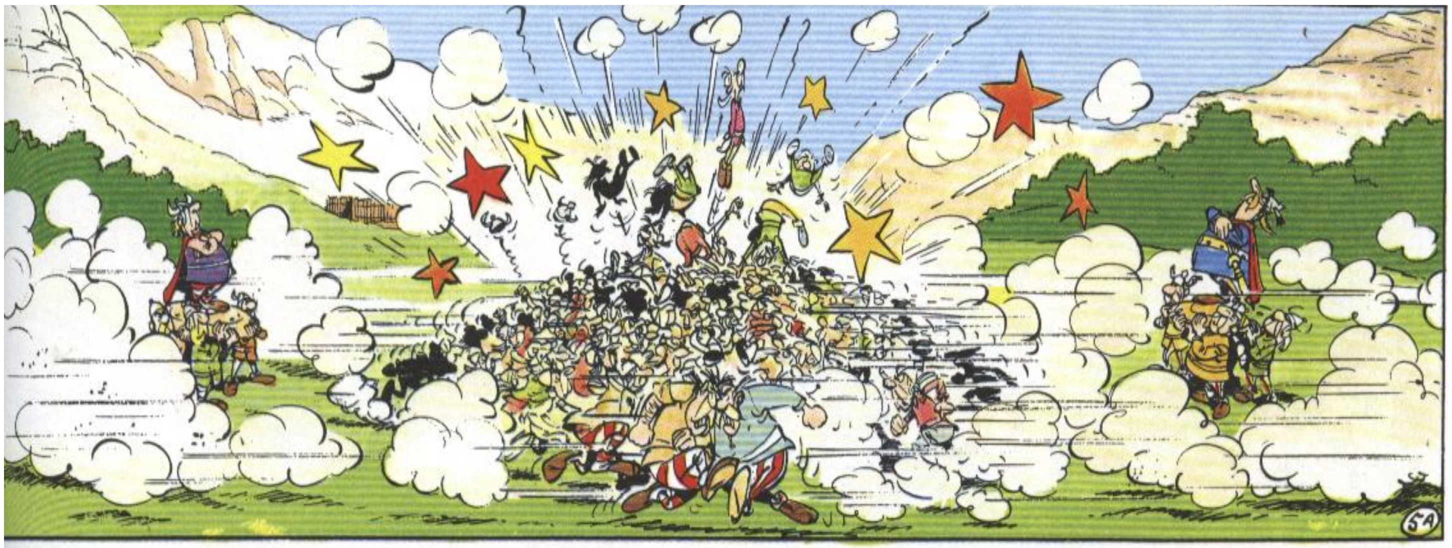
LHeC simulation, NC+CC inclusive, total exp error

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

III LHC Physics

Superb LHC performance, reliable detectors and great experimental art

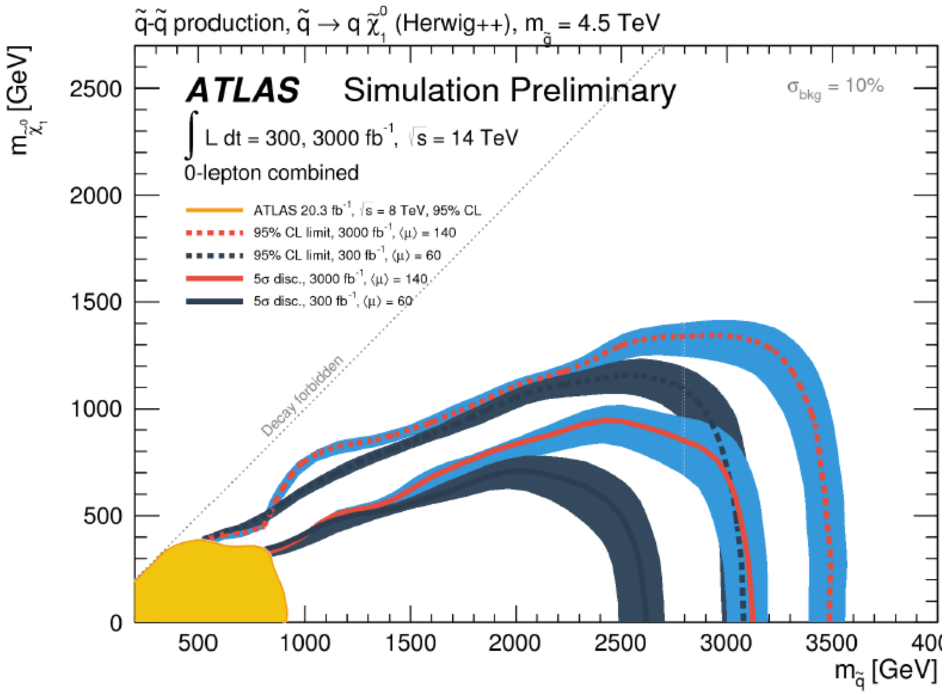


French artist's view on LHC physics − pileup at HL LHC 140-200

- 2000 LHC papers published (ATLAS 100/year). No BSM Physics observed
- Discovery of the Higgs Boson (Mass to W,Z,fermions + portal to BSM??)
- Surprisingly high precision (e.g. ATLAS Wmass to 19 MeV → 0.02%)

- The LHC exploits the large majority of HEP physicists, ATLAS: 1200 PhD's
- Programme HL LHC to operate until about/almost 2040

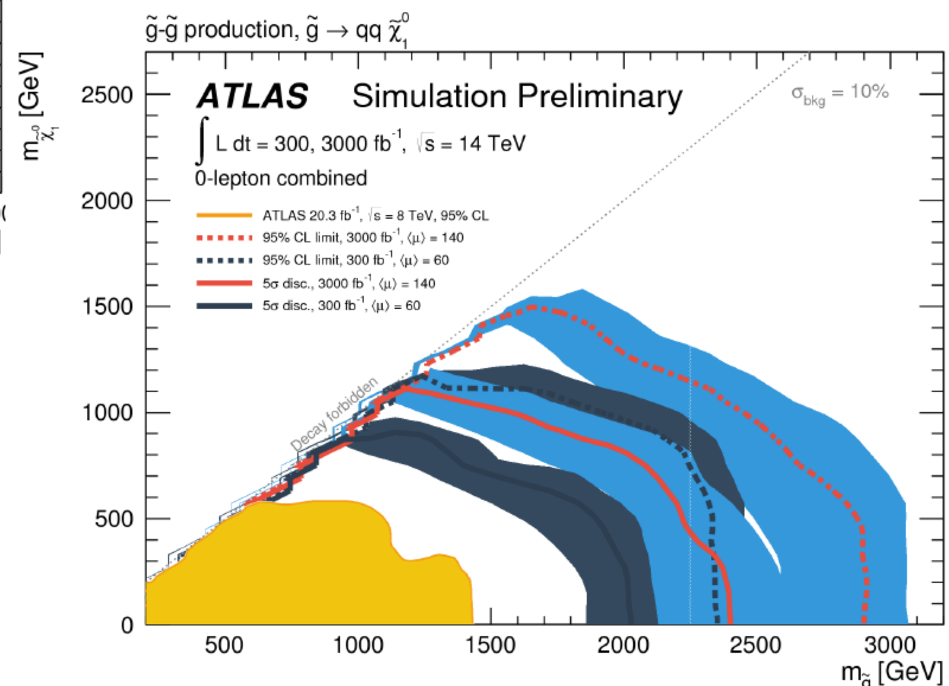
Extended Search Programme (SUSY?)



5σ up to ~2.5TeV gluinos

@ HL-LHC

ATLAS-PUB-2014-10



5σ up to ~3TeV squarks

5σ up to ~1.2 TeV stops

5σ up to ~1.3 TeV sbottoms

@ HL-LHC

SUSY is too beautiful to not exist but it is broken “heavier and heavier”

Physics studies of the HL LHC Potential: ongoing → **HL/HE LHC Workshop 17/18**

IV Recent LHeC Developments (mostly) past CDR

Particle Physics - a Sequence of Spectroscopies

- "Excitation of the 2536 Å Resonanc Line of Mercury"
  Franck /Hertz 1914
  Bohr $\longrightarrow$ ATOMIC SPECTROSCOPY

- "Disintegration of Elements by High Velocity Protons"
  Cockcroft / Walton 1932
  pLi $\longrightarrow \alpha\alpha$: NUCLEAR SPECTROSCOPY

- "Total Cross-Sections of Positive Pions in Hydrogen"
  Anderson/Fermi/Long/Nagle 1952
  $\Delta^{++} \longrightarrow p\pi$: HADRON SPECTROSCOPY

- The charming "November Revolution"
  Ting et al., Richter et al. 11.11.1974
  $\mathcal{J}/\Psi \longrightarrow c\bar{c}$: QUARK SPECTROSCOPY

Gustav Hertz: Nobel 1925

John Cockroft and Ernest Walton: Nobel 1951

Enrico Fermi: Nobel 1935

Sam Ting and Burt Richter: Nobel 1976

No new spectroscopy appeared – neither 1992 (LEP) nor 2012 (LHC), No SUSY, neither at 100 GeV nor at 1000 GeV → a major surprise

50 years ago

Robert Jungk (1966)
Die grosse Maschine
auf dem Weg in eine andere Welt
The big machine
on the road into a new world
A book on the Proton Synchrotron ..

Niels Bohr at 1st Council 1952
Council: highest level committee

ICHEP 1966

FUNDAMENTAL THEORETICAL QUESTIONS

M. Froissart, Rapporteur

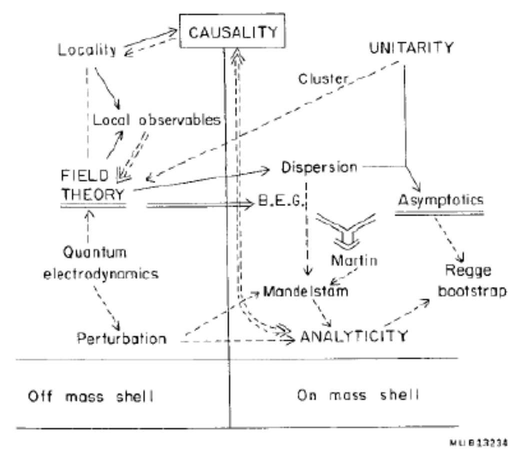


Fig. 1-1. Logical map of "Fundamental" concepts.

No Standard Model, Theory confused,
ECFA, Amaldi: SPS for CERN
Experiment paved the way:
Quarks (ep) → QCD, $SU_L(2)xU(1)$

MK, presented to UK PPAP, July 2017

Today in various aspects resembles 50 years ago:

- Some think our dreams are too ambitious
- Our scientific standards are kept maximally high
- and the theory is pointing to every- or nowhere

Our science is experiment driven, it can't be realised with pp alone

Framework of the Development

Following the CDR in 2012: Mandate issued by CERN:2014 (RH), confirmed in 2016 (FG)

Mandate to the International Advisory Committee

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, em. DG of CERN. IAC+CERN have invited four of its members to follow the study with special attention (Stefano Forte, Andrew Hutton, Leandro Nisati and Lenny Rifkin). Collaboration also with the FCC Review Committee chaired by Guenther Dissertori.

LHeC has been a development for and initiated by CERN, ECFA and NuPECC, so far, it's formal status is that of a community study, not a proposal, which holds for the FCC also, of which 'eh' is a part.

Organisation*)

International Advisory Committee

"..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
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 (ESS)

We miss Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

Nestor Armesto
Oliver Brüning – Co-Chair
Andrea Gaddi
Erk Jensen
Walid Kaabi
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(11) are members of the FCC coordination team

OB+MK: FCC-eh responsibles
MDO: physics co-convenor

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

*)September 2017

Luminosity for LHeC, HE-LHeC and FCC-ep

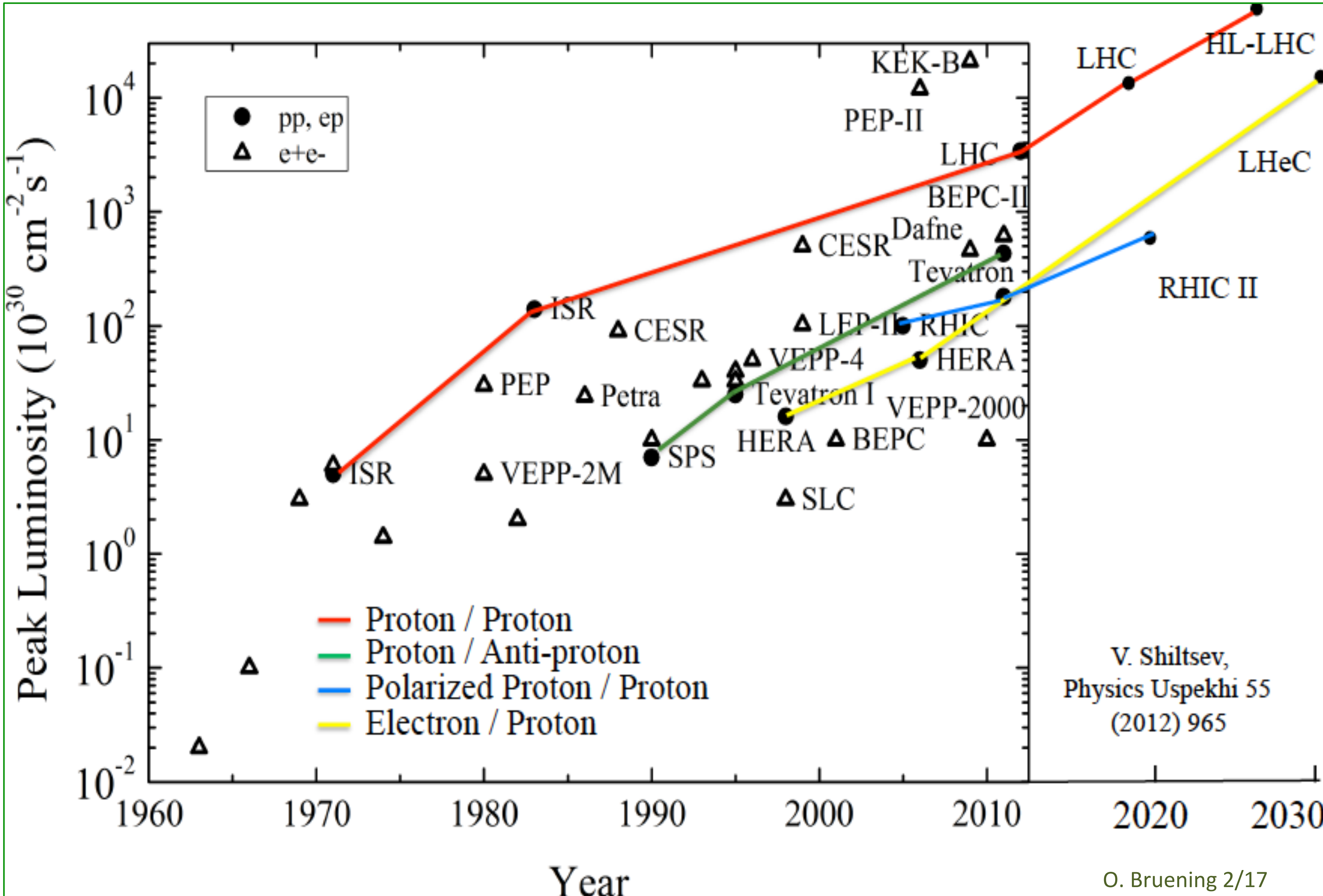
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

Contains update on eA:
6 10^{32} in e-Pb for LHeC.

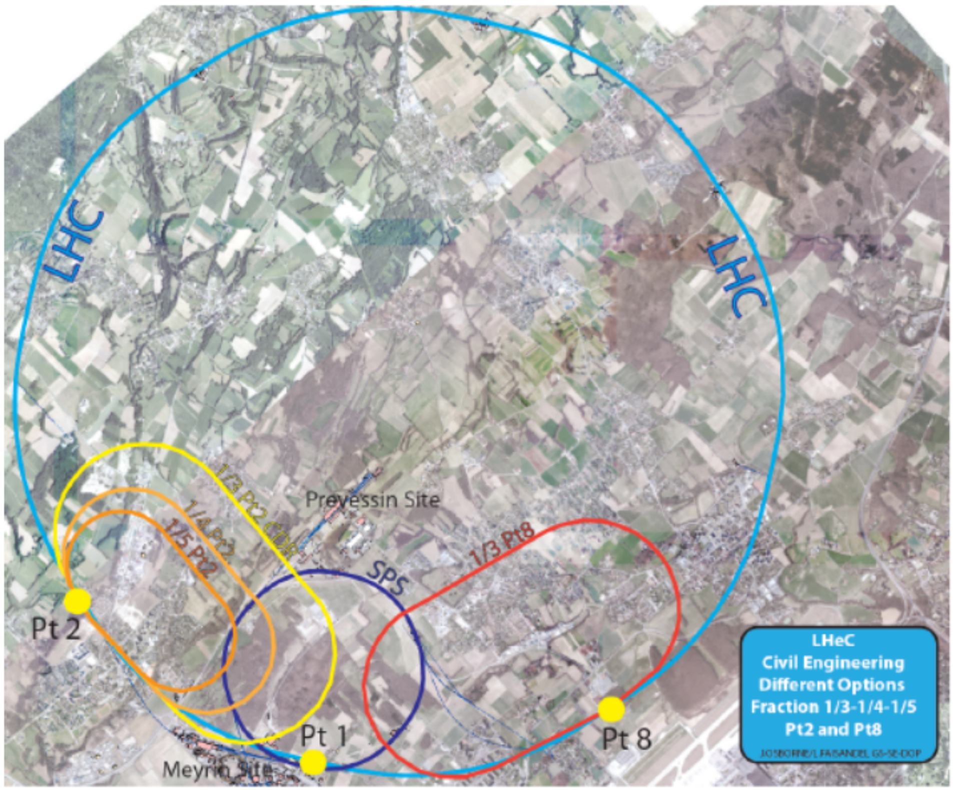
Collider Luminosities vs Year (pp and ep)

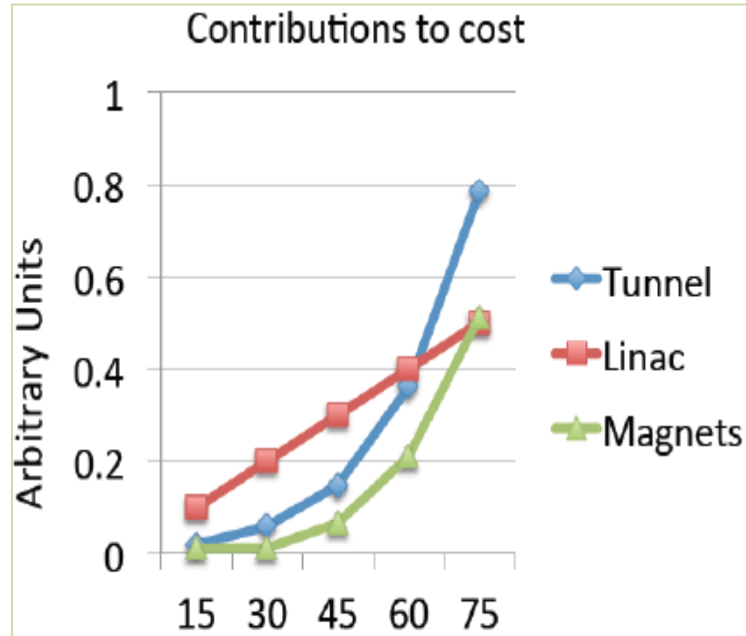


O. Bruening 2/17

Location, Footprint, Use of the Electron Racetrack

e beam external to LHC. Location suitable for both HL and HE LHC.





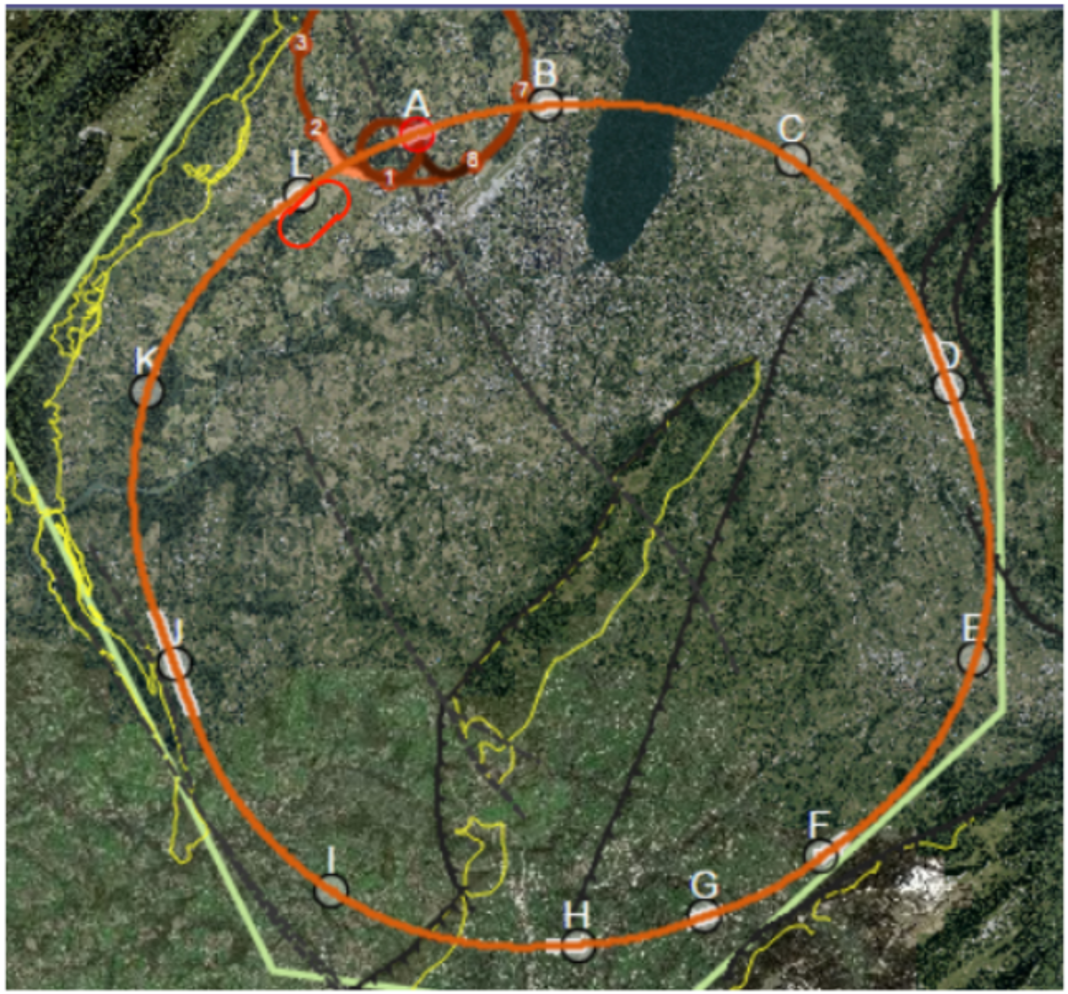
MK, F Zimmermann

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

Initial, **tentative**, rough scaling estimate of basic cost (tunnel, linac (XFEL), magnets

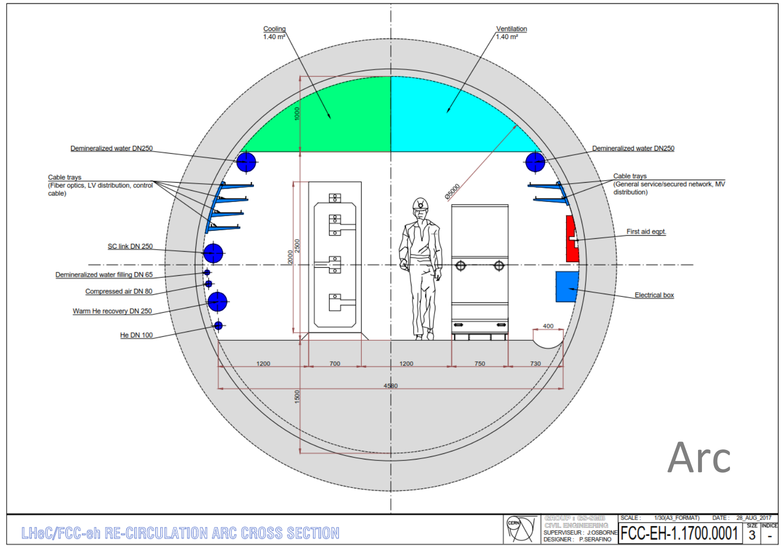
Energy – Cost – Physics – Footprint are being reinvestigated for EU strategy

FCC-eh

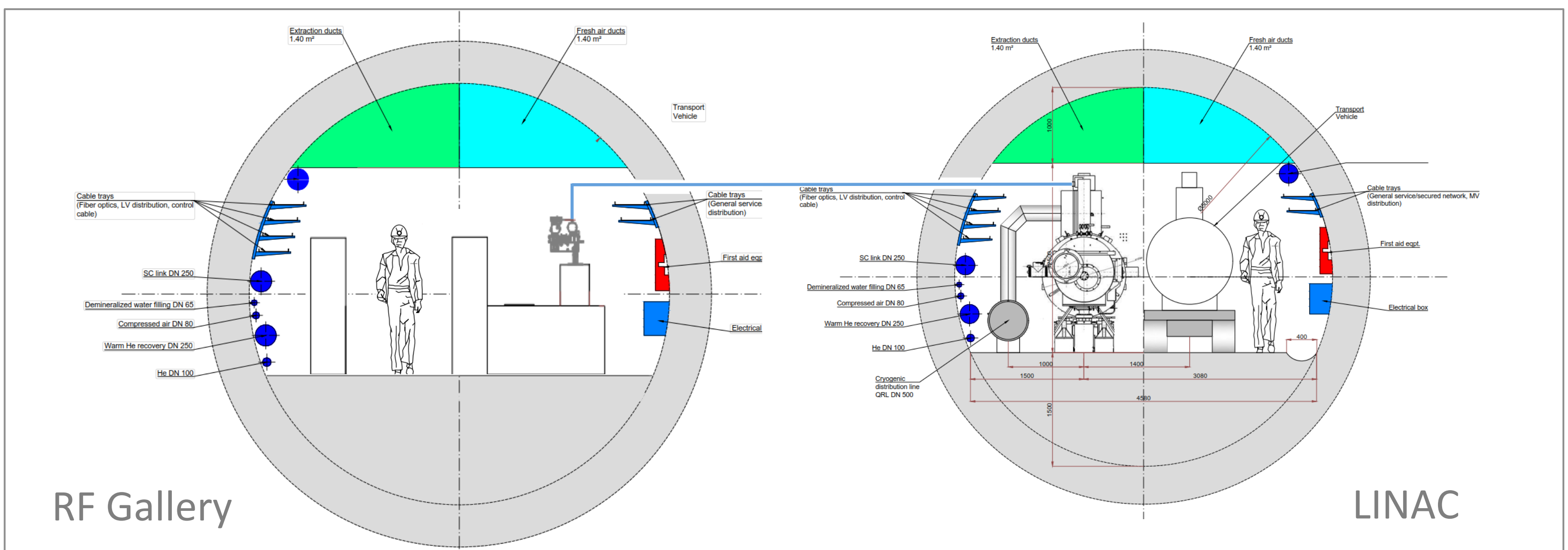


60 GeV ERL tangential to FCC-hh. IP: L for geological reasons. L= 1.5 10^{34} Higher s, Q^2, 1/x

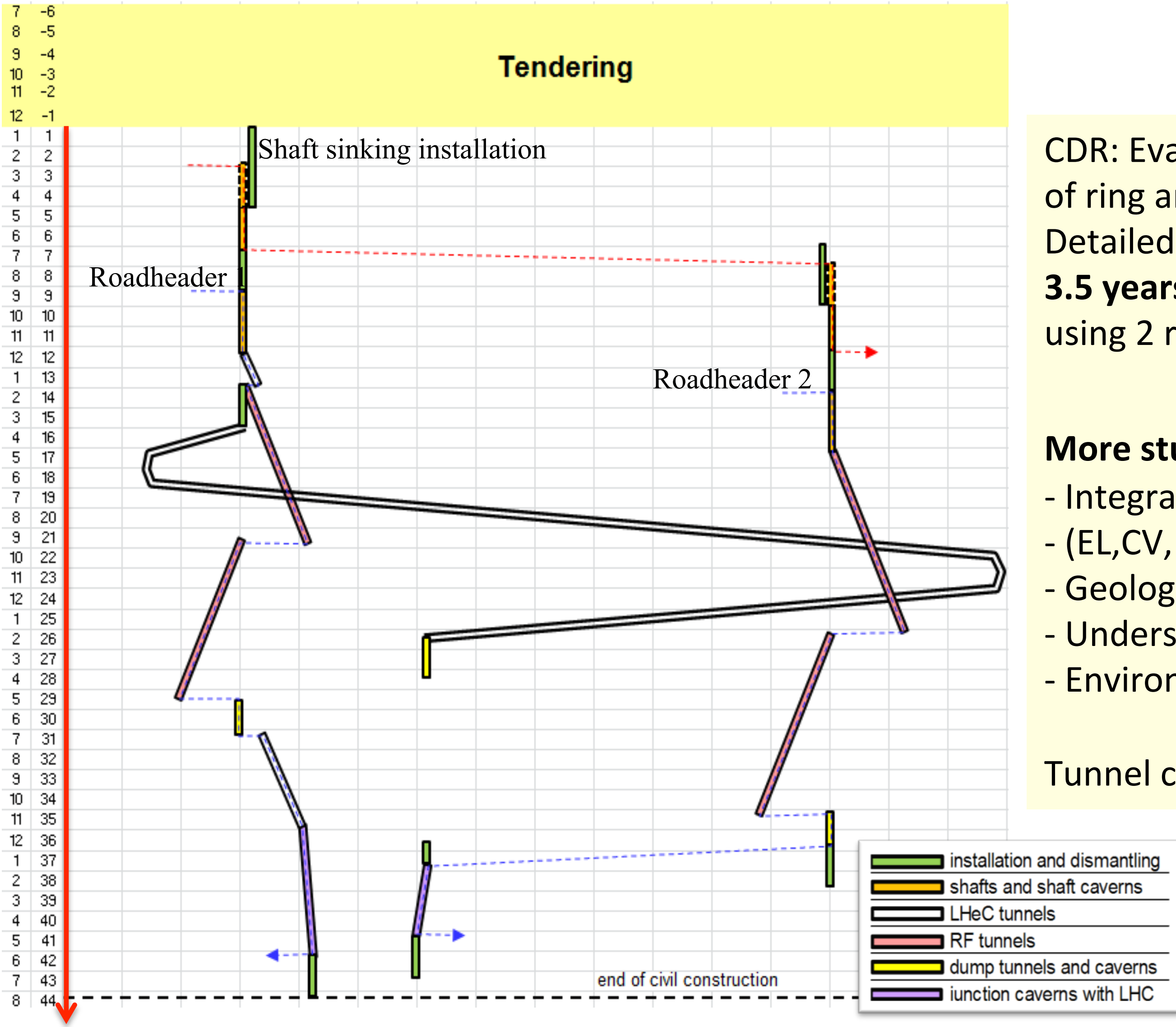
Tunnels: Triple Arc and LINACs



DRAFT: for ERL in any pp combi.
cf Matt Stewart et al. 12.9.17



Civil Engineering – full design made



CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich. Detailed estimate of cost and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

More studies will be needed for

- Integration with all services
- (EL,CV, transport, survey etc).
- Geology
- Understanding vibration risks
- Environmental impact assessment

Tunnel connection in IP2

J.Osborne et al.

Tentative

Physics Considerations on the Choice of E_e

SM Higgs Couplings

H→ bb (cc): 0.5 (4)% coupling uncertainty, for 1ab^{-1}, 60 GeV, polarised
This becomes 2(15)% for 0.5ab^{-1} and 30 GeV: **Under these conditions one looses high H precision and the ep portal to new physics potential and the neutral current Higgs programme disappears**

New Higgs+top Physics

Heavy new objects: Htt coupling: 17 → 31 % for 60 → 40 GeV (M Kumar)
Discovery potential for anomalous tqH: 0.5 – 3.2 -22% precision for 60 → 50 → 40 GeV (H Sun). **At 40 GeV the discovery potential is gone.**

Longitudinal Structure Function – THE path to saturation

Low x physics: **Saturation** requires 1% measurement of F_L. That needs y=0.9=1-E'/Ee. HERA: big complication: E' at high y too small for precision (eID, background, charge symmetry): needs ~twice E_e to be safe.

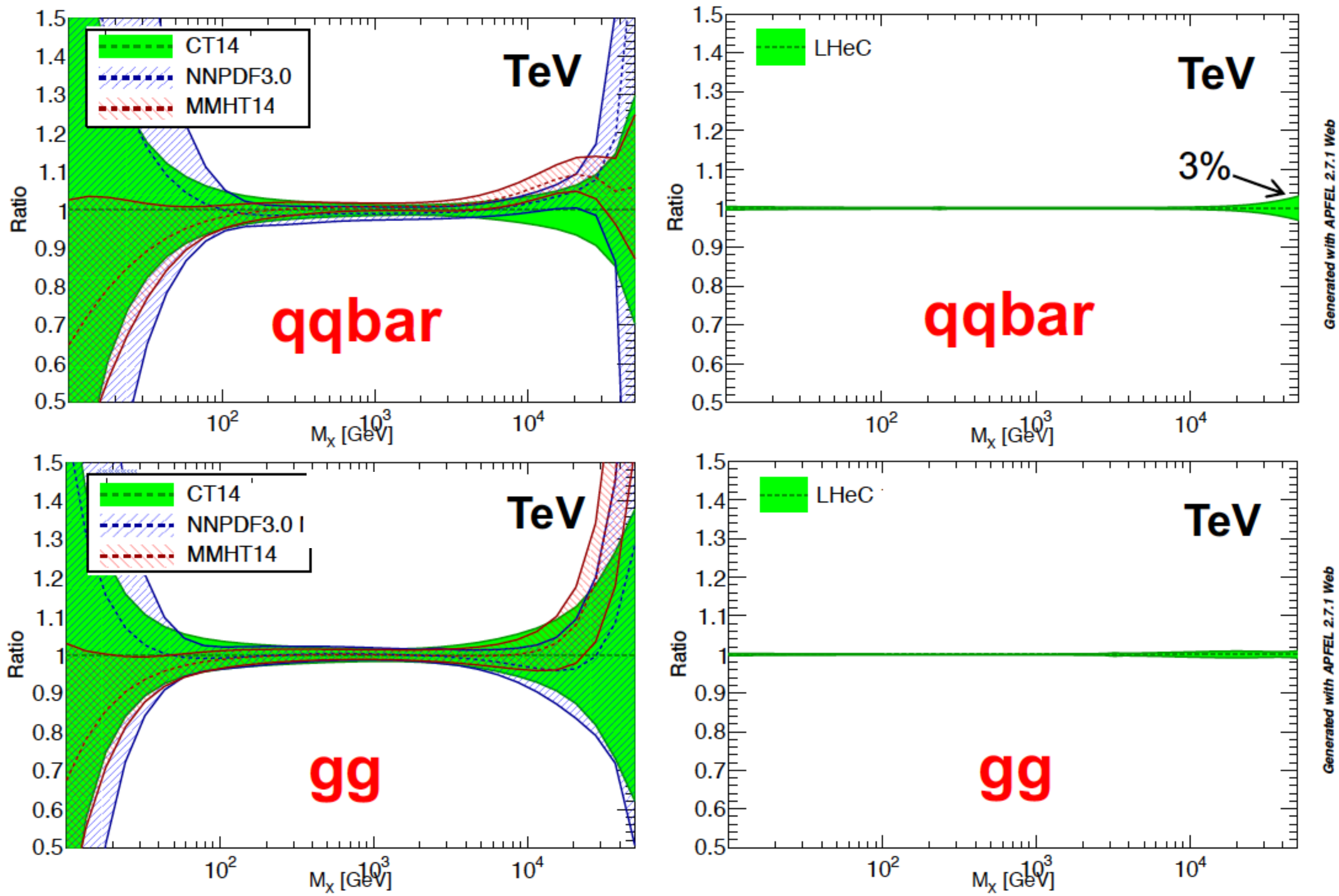
→ 50 GeV the programme stands, 40 GeV it looses BSM, t, 30 GeV: precision gone
→ Keep the electron energy as high as it can be afforded, and not lower than 50 GeV

The LHeC PDF Programme

Resolve parton structure of the proton completely: u_v,d_v,s_v?,u,d,s,c,b,t and xg
Unprecedented range, sub% precision, free of parameterisation assumptions,
Resolve p structure, solve non linear and saturation issues, test QCD, N^{3}LO…

Strong Coupling in inclusive DIS at LHeC to 0.1%

Lattice??
Jets??
BCDMS??
GUTs?
Higgs in pp



Solve the PDF issues for pp and test QCD with permille measurement of strong coupling

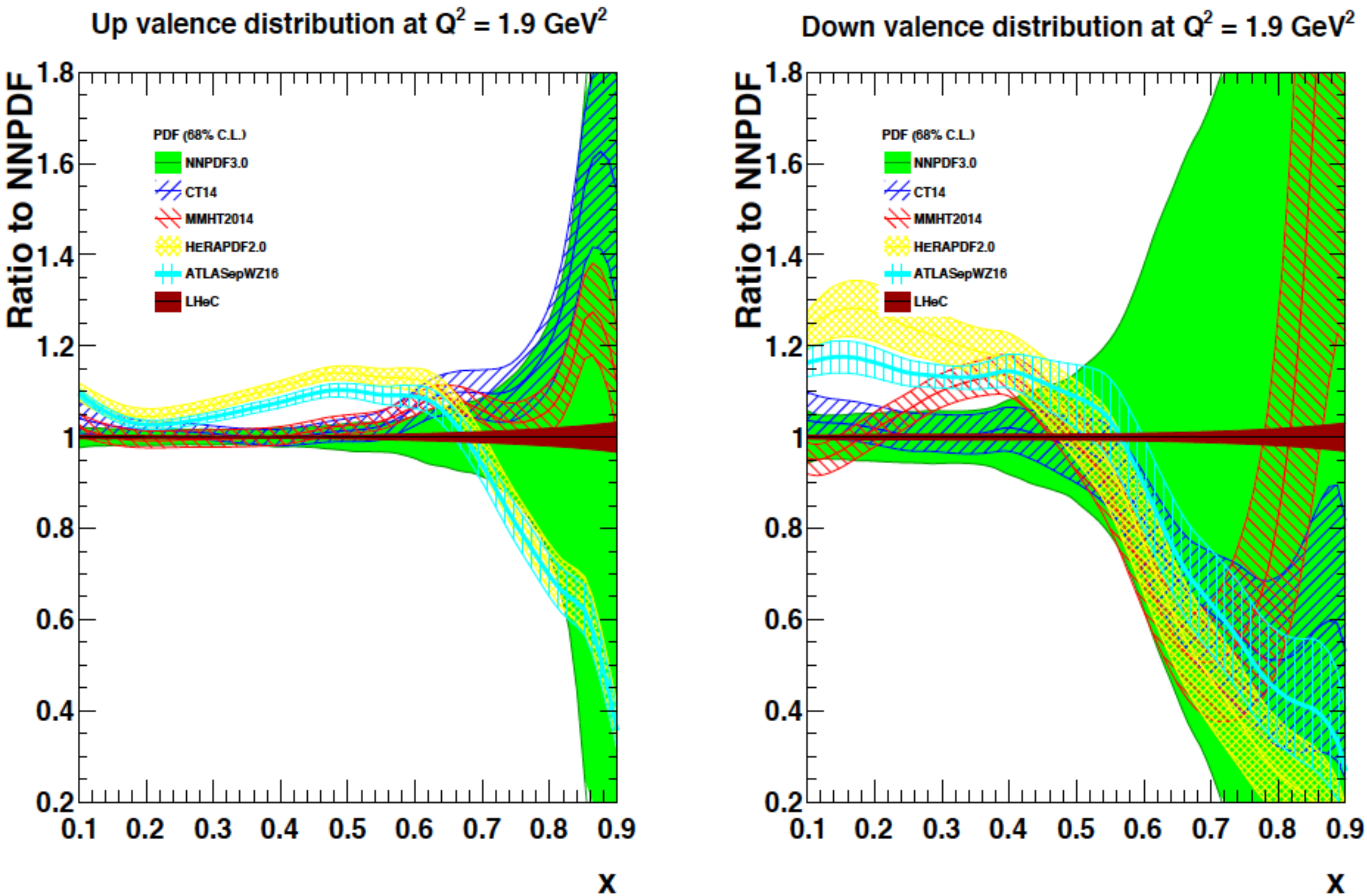


Figure 2: Determination of the valence quark distributions as functions of Bjorken x. Plotted are the ratios to the NNPDF result with uncertainties displayed as are provided by the individual sets, left for the up-valence quark and right the down-valence quark distribution. For the LHeC the total uncertainty is plotted and the central value assumed to agree with NNPDF. As non-singlet quantities, the valence quark distributions are approximately the same with varying Q^2.

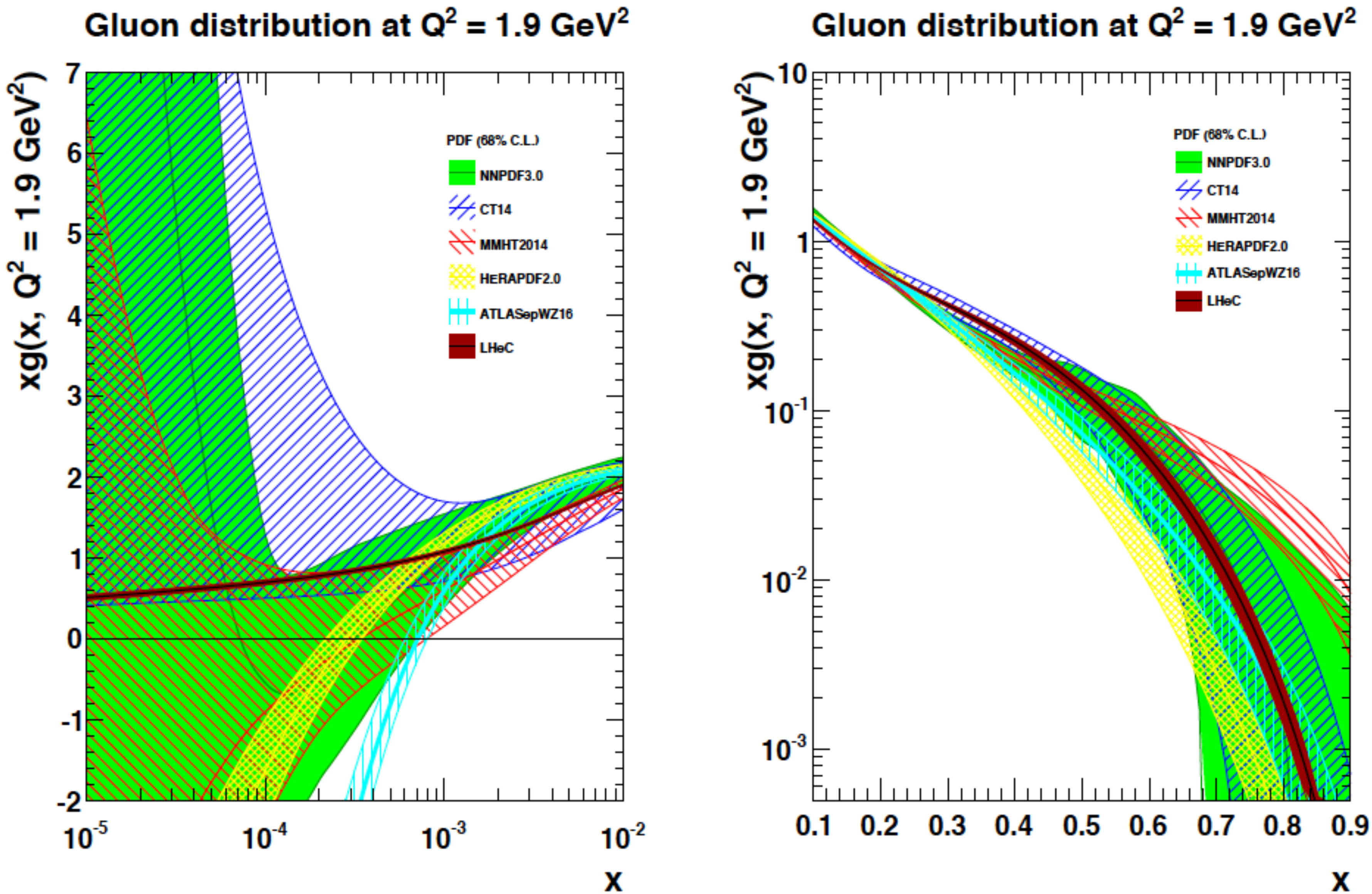
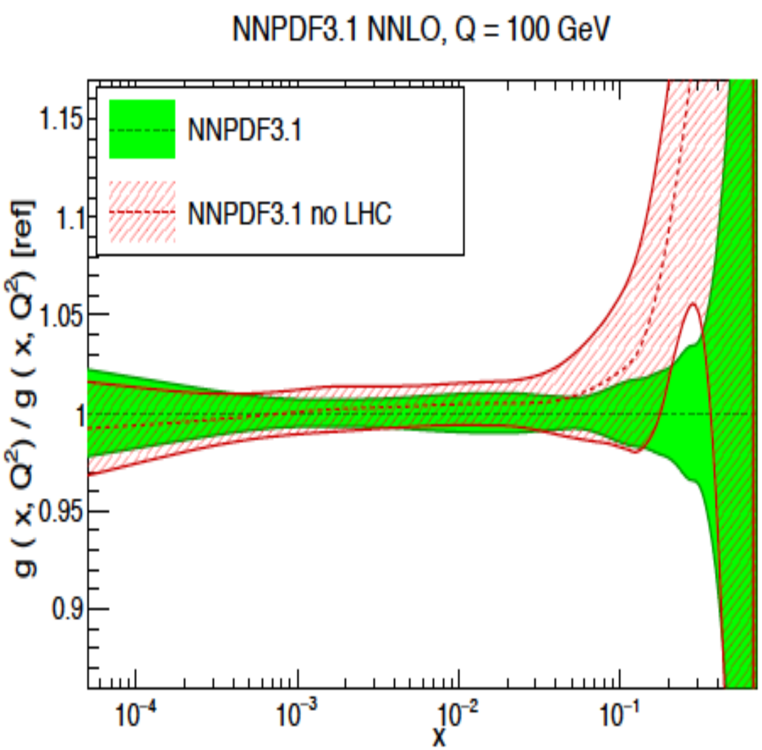


Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on xg from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for xg a range from $x \simeq 5\ 10^{-4}$ to $x \simeq 0.6$, and much of the LHC data from Run I. Left: xg at small x; Right at large x.

LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

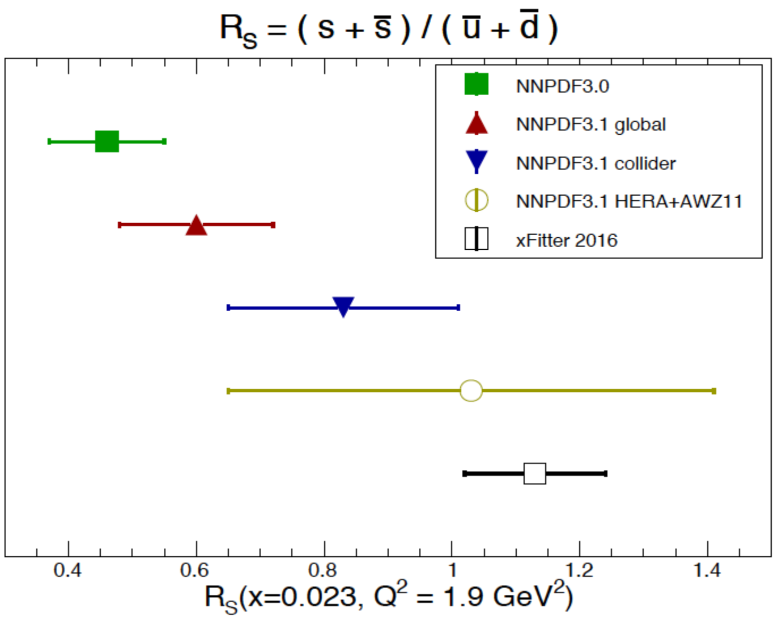
- Needs complete q_i,g unfolding (miss variety) at all x, as there are sum-rules
- Needs strong coupling to per mille precision, not in pp
- Needs stronger effects (miss Q^2 variation) cannot come from W,Z at $Q^2=10^4$ GeV^2
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour s,c,b,t measured and VFNS fixed
- Needs verification of BFKL at low x (only F_2-F_L)
- Needs N^3LO (as for Higgs)
- Needs external input to find QCD subtleties such as factorisation, resummation…to not go wrong
- Needs external precise input for subtle discoveries
- Needs data which yet (W,Z) will hardly be better
- Needs agreement between the PDfs and χ^2+1 ..

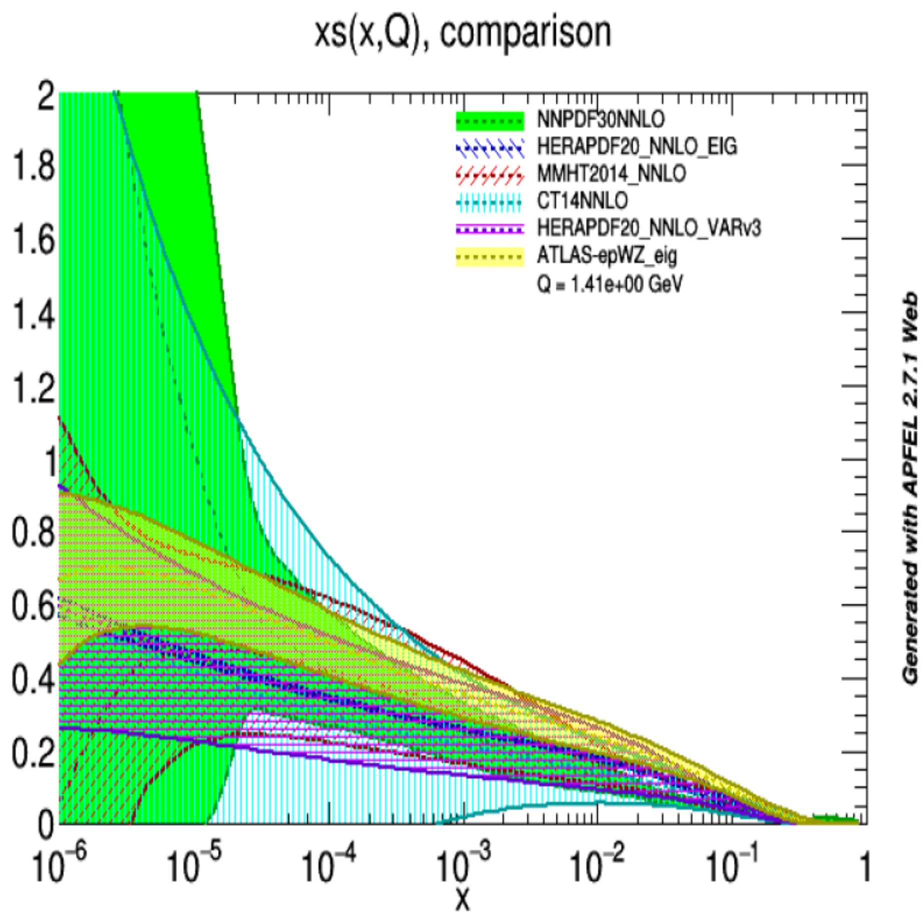
PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at x ~ 0.01 (nonsuppressed s/dbar). Can take low pileup runs, mitigate PDF influence .. − but can't do what is sometimes stated.

LHeC vs HERA: Higher Q^2: CC; higher s: small x/g saturation?; high lumi: x→ 1; s, c,b,t. …

Strange Strange

Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]



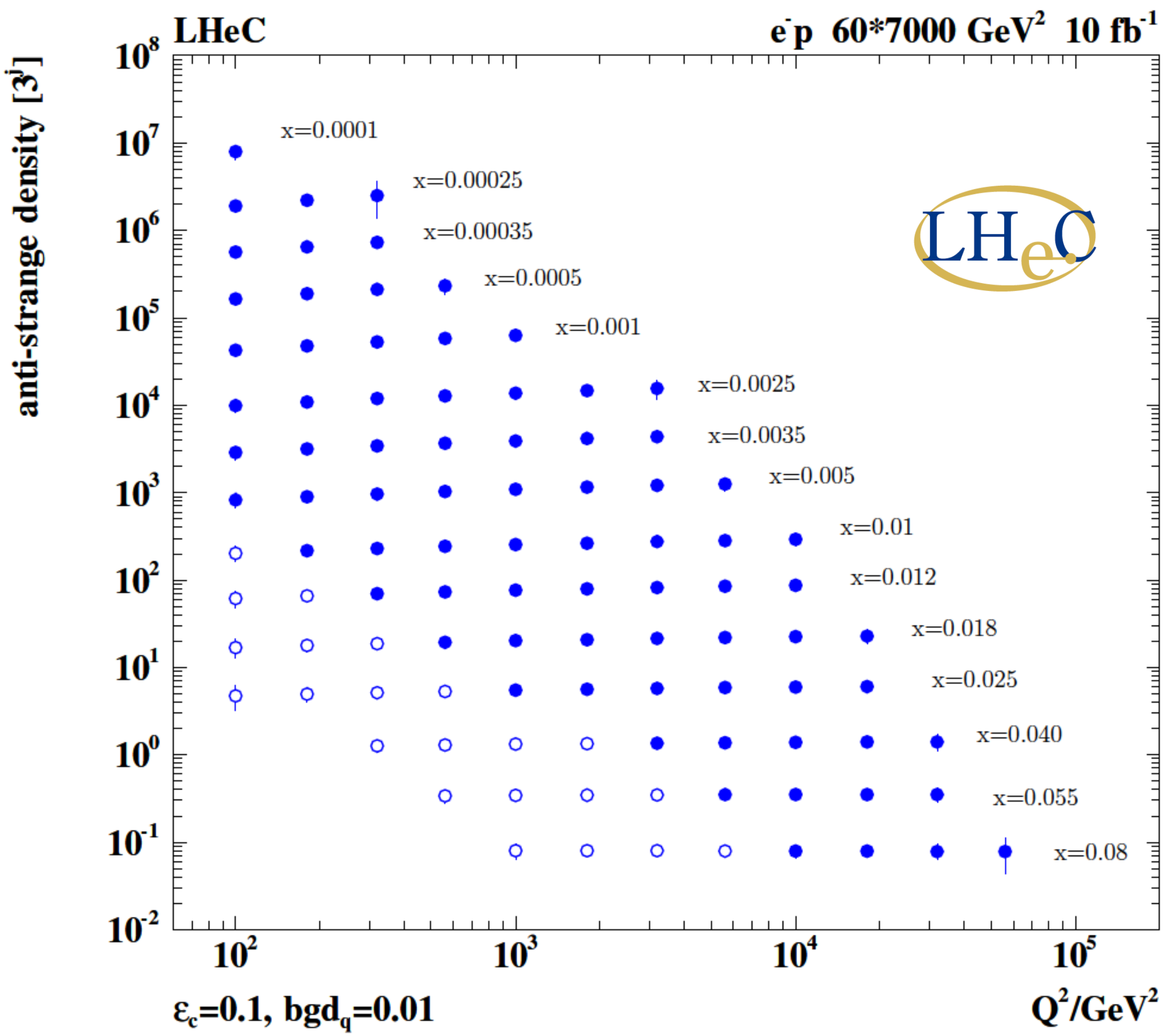


NNPDF3.1 arXiv:1706.00428, note:
“xFITTER16” = ATLAS: 1612.0301
Also look at MMHT and other results

A Cooper-Sarkar, DIS17

The strange quark density, after 60 years of DIS, has remained unknown. Is there a valence s?

Strange Quark Distribution from LHeC



High luminosity

High Q^2

Small beam spot

Modern Silicon

NO pile-up..

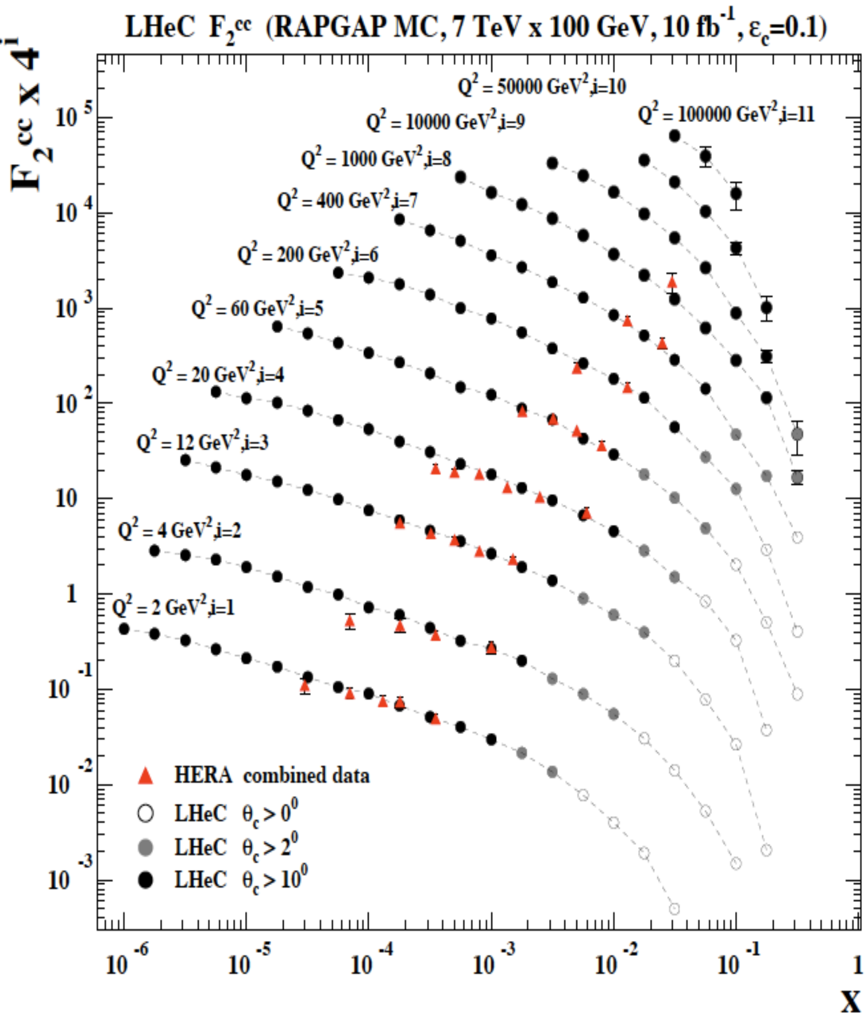
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4} .. 0.1$
$Q^2 = 100 – 10^5$ GeV^2

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

Charm F_2^{cc} and Mass

LHeC CDR arXiv:1206.2913



HERA 0.0005/2.5 .. 0.05/2000 GeV^2
LHeC 0.00001/1 .. 0.2/200000 GeV^2

ε(c) assumed 10%, 1% light background, ~3% δ(syst)

Heavy Flavour with LHeC

Beam spot (in xy): 7µm
Impact parameter: better than 10µm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

	HERA	LHeC
$m_c(m_c)$/GeV	1.26	?
δ(exp)	0.05	0.003
δ(mod)	0.03	~0.002
δ(par)	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

LHeC determines strong coupling to 0.1%
High precision PDF data will reduce the mod and par errors by a very large amount.

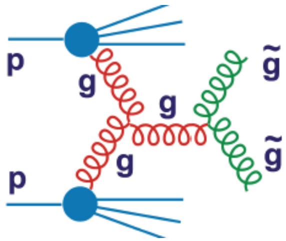
Determination of charm mass to 3 MeV: crucial for M_W in pp or H→ cc in ep
cf also NNPDF3.1 (arXiv:1706.00428) and refs

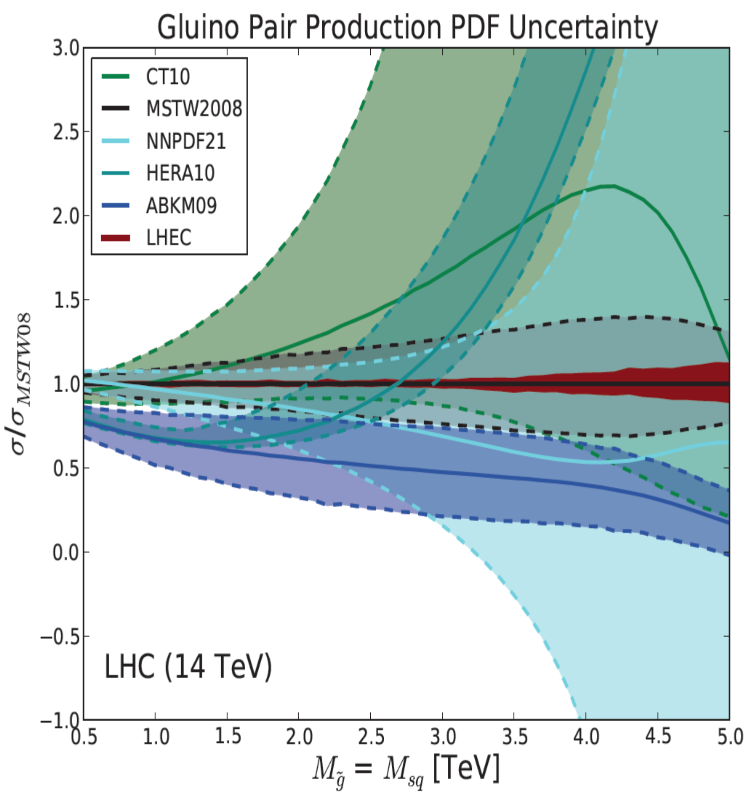
Empowering pp Discoveries

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

GLUON

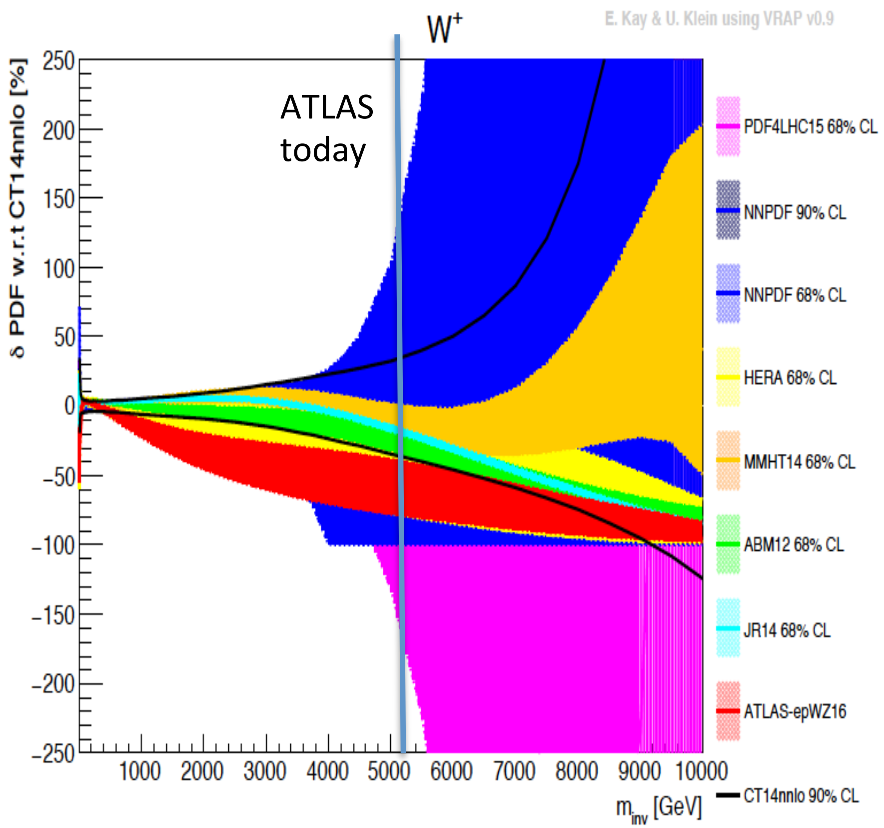
SUSY, RPC, RPV, LQS..



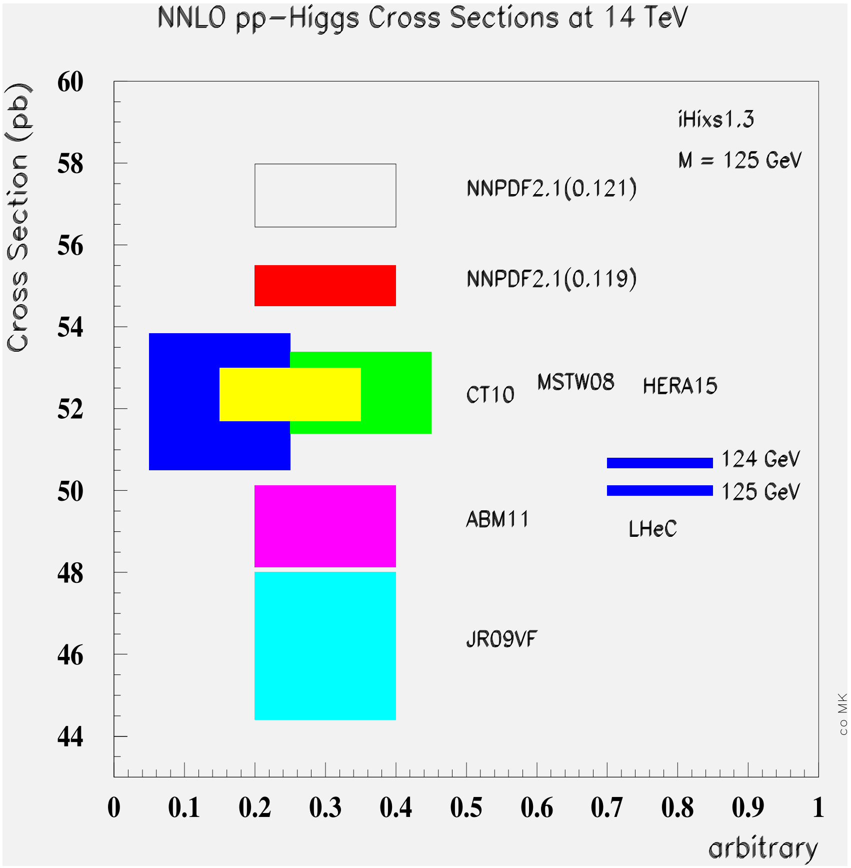


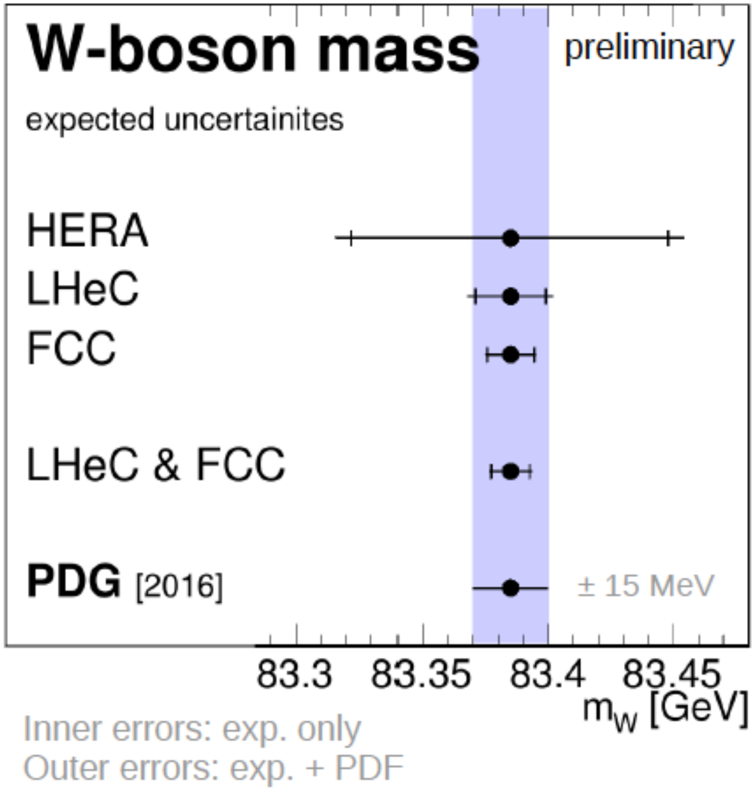
QUARKS

Exotic+ Extra boson searches at high mass



High Precision for the LHC



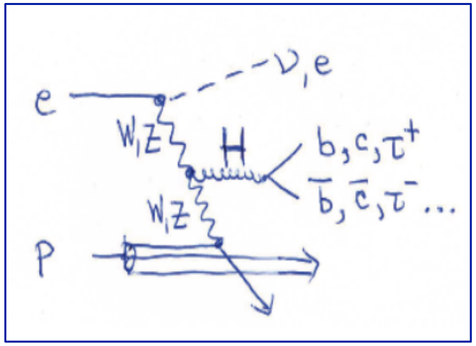


Predict the Higgs cross section in pp to 0.2% precision which matches the M_H measurement and removes the PDF error

Spacelike M_W to 10 MeV from ep
→ Electroweak thy test at 0.01% !

Predict M_W in pp to 2.8 MeV →
Remove PDF uncertainty on M_W LHC

LHeC Higgs Physics



High precision coupling measurements

Higgs as portal to new physics (in decay and production of non SM Higgses)

CC cross section: 200 fb. That is the 'same' value as for Z* → HZ in e^+e^-
NC cross section: 25 fb. ZZ → H (→ WW) and WW → H(→ ZZ) uniquely distinguishable.
VBF cross sections in pp at LHC are O(100) fb also.

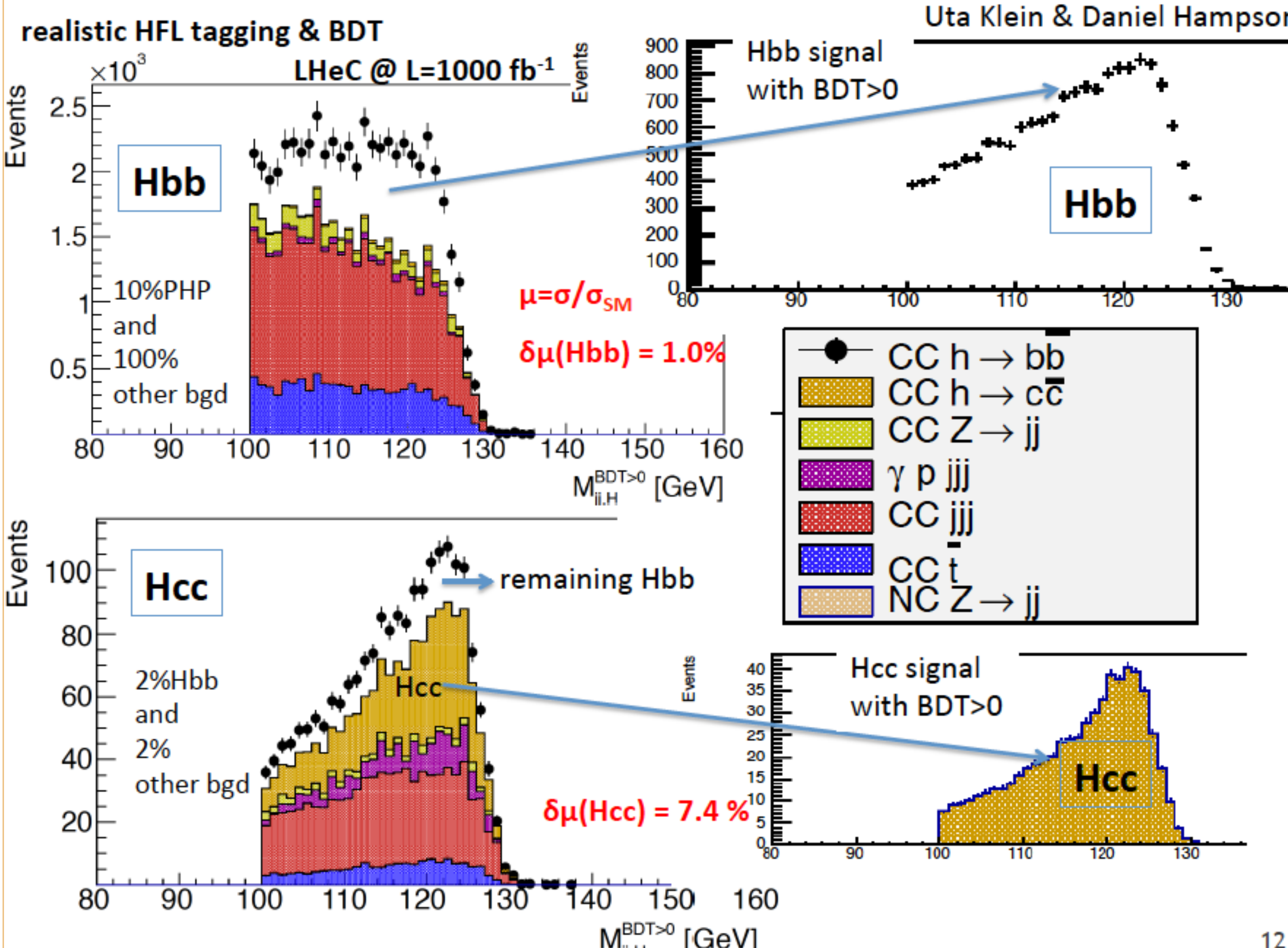
Final state in ep clean. Pileup 0.1 at LHeC. Theory clear. Luminosity to 0.5-1%.
Detector: full acceptance to η = 4.7 Requirement for high resolution hadron calorimeter

First studies: complete detector, S and B simulation and BDT for H→ bb and cc

New: MADGRAPH based extension to other channels using bb and cc experience

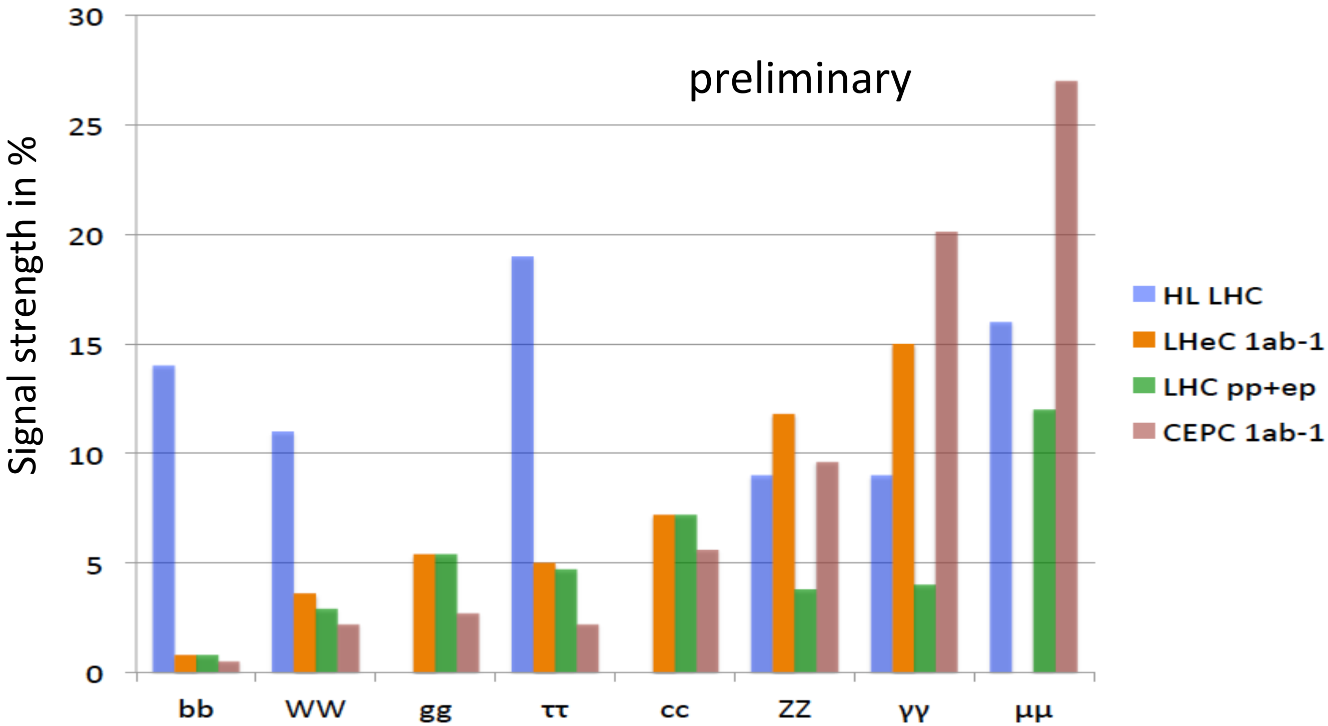
New also: various, often Chinese publications on exotic Higgs physics in ep, cf below
and talks by Uta Klein and Kechen Wang in January at FCC Physics at CERN

H-HH: very hard at LHeC, possible to ~30% at FCC-eh: see arXiv:1509.04016 M Kumar et al



realistic HFL tagging & BDT
Uta Klein & Daniel Hampson
LHeC @ L=1000 fb⁻¹
Hbb
10%PHP
and
100%
other bgd
μ=σ/σSM
δμ(Hbb) = 1.0%
Hbb signal
with BDT>0
Hbb
CC h → bb̄
CC h → cc̄
CC Z → jj
γ p jjj
CC jjj
CC t̄
NC Z → jj
Hcc
remaining Hbb
2%Hbb
and
2%
other bgd
δμ(Hcc) = 7.4 %
Hcc signal
with BDT>0
Hcc
Events
[GeV]

Comparison LH(e)C and CEPC



LHC: ATLAS 2014 (will be better)

LHeC: MK+UK FCC WS1/18

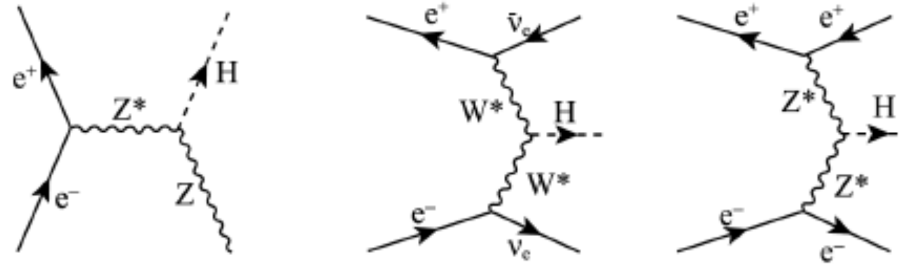
LHC: pp (no thy) + ep

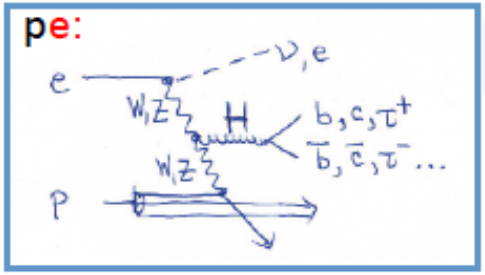
CEPC: M Ruan, 14.1.17
scaled to $1ab^{-1}$

The **ep** and the **e^+e^-** prospects of measuring Higgs decays are (about) the same for same L.
Note that $1ab^{-1}$ is 10 years of operation at 10^{34} , at high reliability.
J Gao: CEPC wants 3 10^{34} and hopes for 5 ab^{-1}. Theorists write about a 350 GeV operation.
LHeC NC: ZZ→H → bb at high precision which should fix the H-ZZ coupling to 2%.. Γ ??
Sum of all major decay channels: LHC 0.89+-0.12, LHeC 0.99 +- 0.02, LHCep+pp: 1.00+-0.01
In ep couplings are overconstrained. Fit to do. EFT analyses may then include ep.
The addition of the LHeC to the HL LHC transforms that into a high precision Higgs facility

Higgs in ee vs pe

ee: Dominant Higgs productions

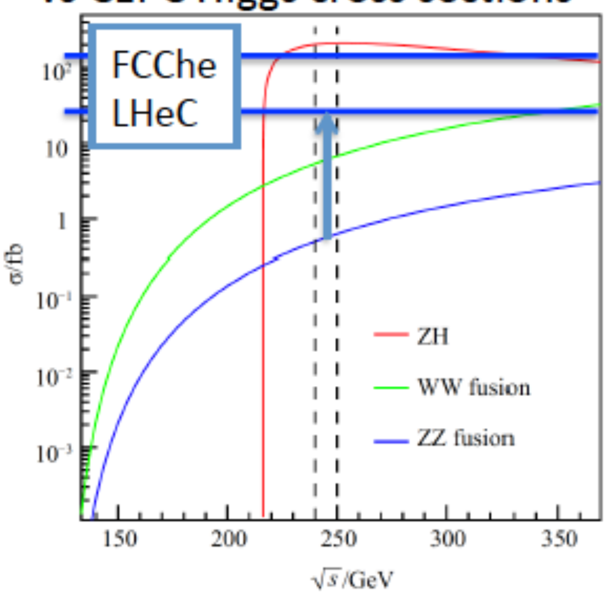


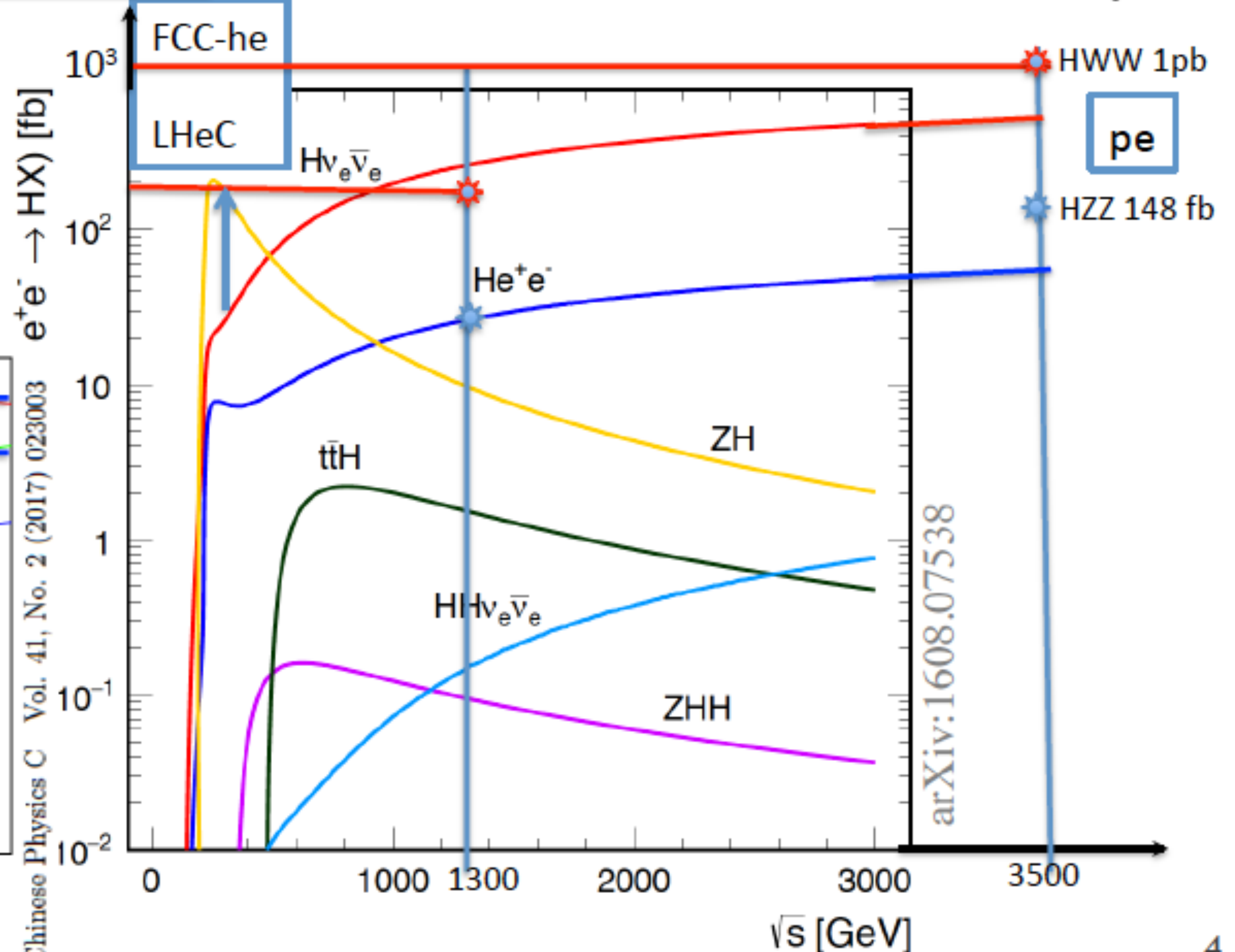


pe:WW Fusion

pe: ZZ Fusion

vs CEPC Higgs cross sections





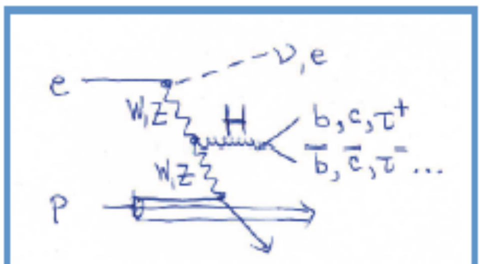
Uta Klein, Talk at FCC Workshop 16.1.18

Uta & Max Klein, Contribution to FCC Workshop, 16.1.2018, preliminary

CC DIS WWH → H

FCC-he L=2 ab^{-1}

	bb	WW	gg	ττ	cc	ZZ	γγ
BR	**0.577**	**0.215**	**0.086**	**0.0632**	**0.0291**	**0.0264**	**0.00228**
δBR_{theory}	3.2%	4.2%	10.1%	5.7%	12.2%	4.2%	5.0%
N	**1.15 10^6**	**4.3 10^5**	**1.72 10^5**	**1.26 10^5**	**5.8 10^4**	**5.2 10^4**	**4600**
f	2.86 $_{BDT}$	16	7.4	5.9	5.6 $_{BDT}$	8.9	3.23
δμ/μ [%]	**0.27**	**2.45**	**1.78**	**1.65**	**2.36**	**3.94**	**3.23**
$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$	0.14	0.61*	0.89	0.83	1.18	1.97	2.37



→ Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +- 0.02

FCChe: 0.9964 +- 0.01

pp: < 0.99 → cc? gg?

Further coupling constraints to be explored:

$$\sigma(WW \to H \to WW) \propto \kappa^4(HWW)$$

$$\sigma(WW \to H \to bb) \propto \kappa^2(HWW) \bullet \kappa^2(Hbb)$$

$$\sigma(WW \to H \to \tau\tau) \propto \kappa^2(HWW) \bullet \kappa^2(H\tau\tau)$$

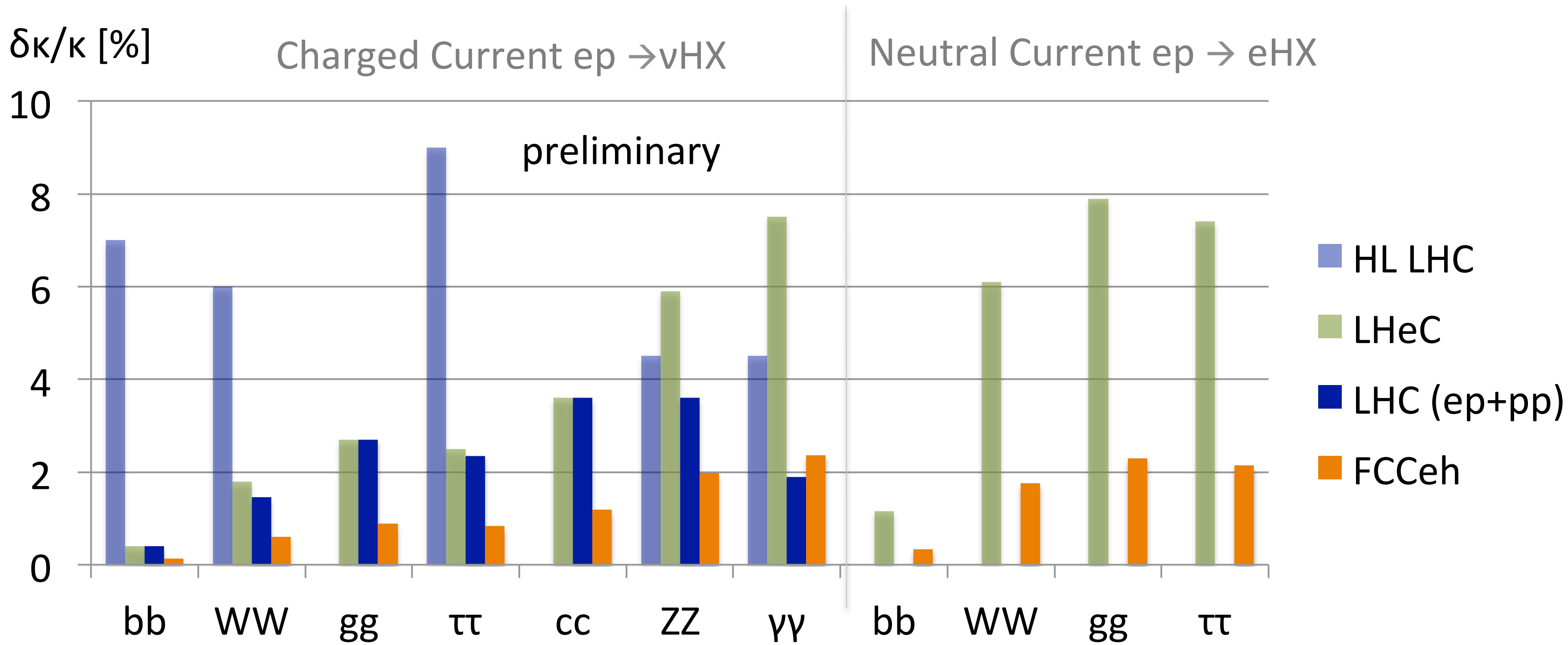
$$\sigma(WW \to H \to gg) \propto \kappa^2(HWW) \bullet \kappa^2(Hgg)$$

$$\sigma(WW \to H \to cc) \propto \kappa^2(HWW) \bullet \kappa^2(Hcc)$$

$$\sigma(WW \to H \to ZZ) \propto \kappa^2(HWW) \bullet \kappa^2(HZZ)$$

$$Note: \sigma(ZZ \to H \to WW) \propto \kappa^2(HZZ) \bullet \kappa^2(HWW)$$

FCCeh: Higgs SM Coupling Prospects

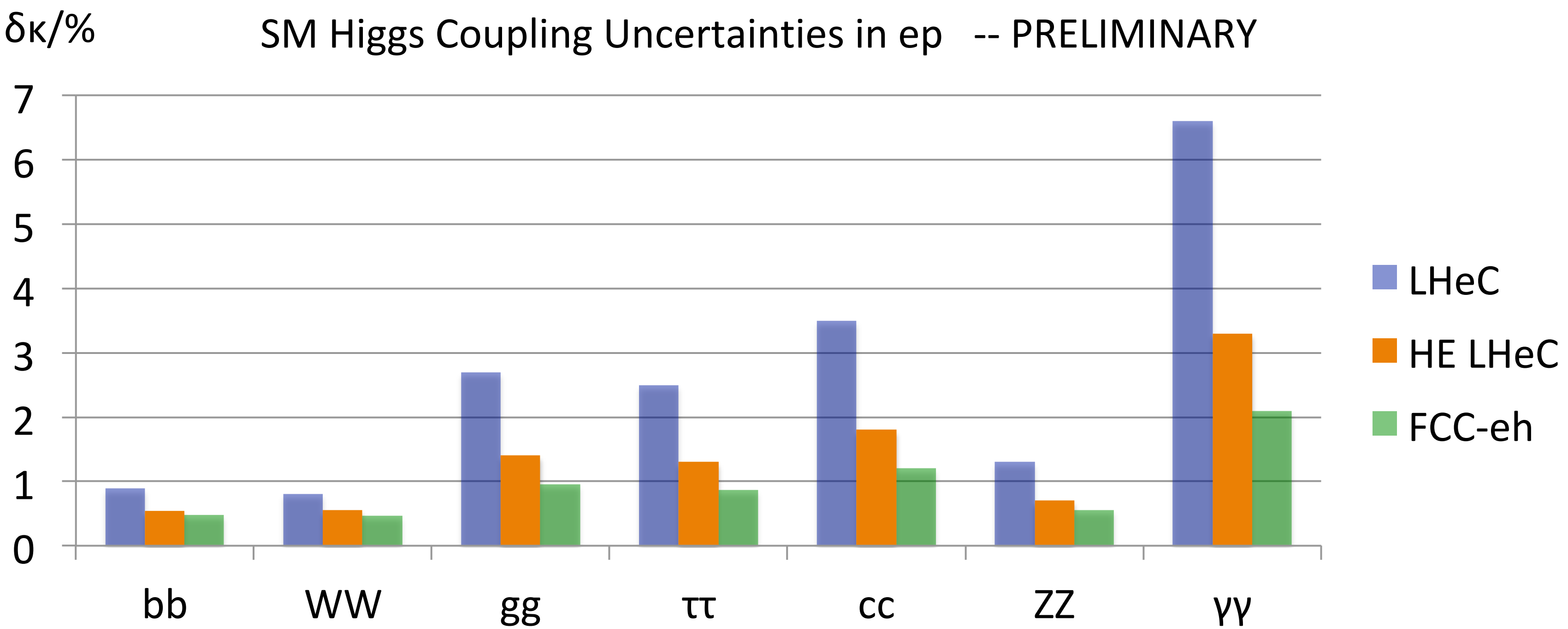


HL LHC: ATLAS-PUB-2014-016 14 TeV 3ab^{-1} – LHC has no gg, no cc, and poor bb, but rare channels as γγ
LHeC: 1ab^{-1}, 60 GeV x 7 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..
LHC (ep+pp): HL LHC with reduced theory uncertainty combined with LHeC
FCCeh: 2ab^{-1}, 60 GeV x 50 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..

Improvements: ATLAS 2014 conservative, no CMS. ep (LHeC/FCCeh) are overconstrained:
CC+NC, ratios, sum(br)=1.. → joint coupling determination: especially WW and ZZ should improve

U+M Klein, Contribution to FCC Workshop, 16.1.2018, preliminary. cf talk by Uta Klein

Couplings from Joint Fit to NC and CC Input



UK/MK 2/2018

Work in progress

BSM Higgs

- **Higgs invisible decays**
  - $h \to invisible$, see [Uta Klein's talk "*Higgs SM Couplings at FCC-ep*"]
- **Higgs exotic decays**
  - $h \to \tilde{\chi}_1^0 \, \tilde{\chi}_1^0 \to (3j)(3j)$ in RPV SUSY
  - $h \to 2\phi \to \left(b\bar{b}\right)(b\bar{b})$ [S. Liu, Y. Tang, C. Zhang, S. Zhu, 1608.08458]
- **Charged Higgs**
  - $H^{\pm\pm}$, in Vector Boson Scattering

    [H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D 96, 095003 (2017)]
  - $H^{\pm}$, in Vector Boson Scattering

    [Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505]
  - H^{+}, in 2HDM type III, $p\, e^- \to \nu j H^+ \to \nu j \left(c\bar{b}\right)$,

    [J. Hernández-Sánchez, etc. 1612.06316]

Triple Gauge Couplings (WWV, V = γ, Z)

[R. Li, X. Shen, K. Wang, T. Xu, L. Zhang and G. Zhu, 1711.05607]

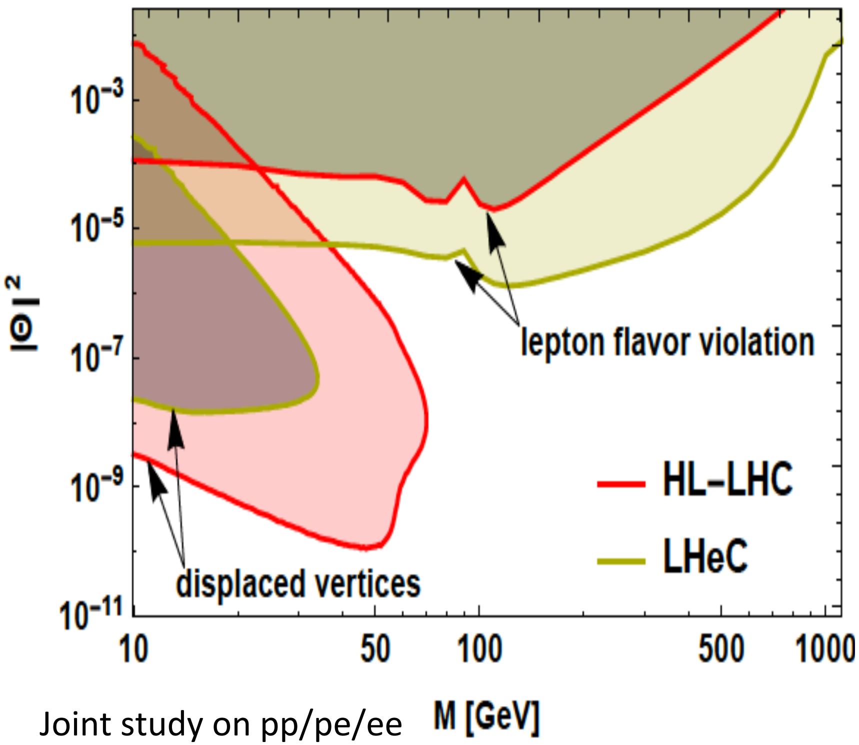
Impressive flow of new physics in ep studies is being digested for 2018

Kechen Wang, BSM in ep, FCC Workshop 1/2018 at CERN

Lots of important new papers on BSM in ep

Sterile (heavy) Neutrinos in ep → NX

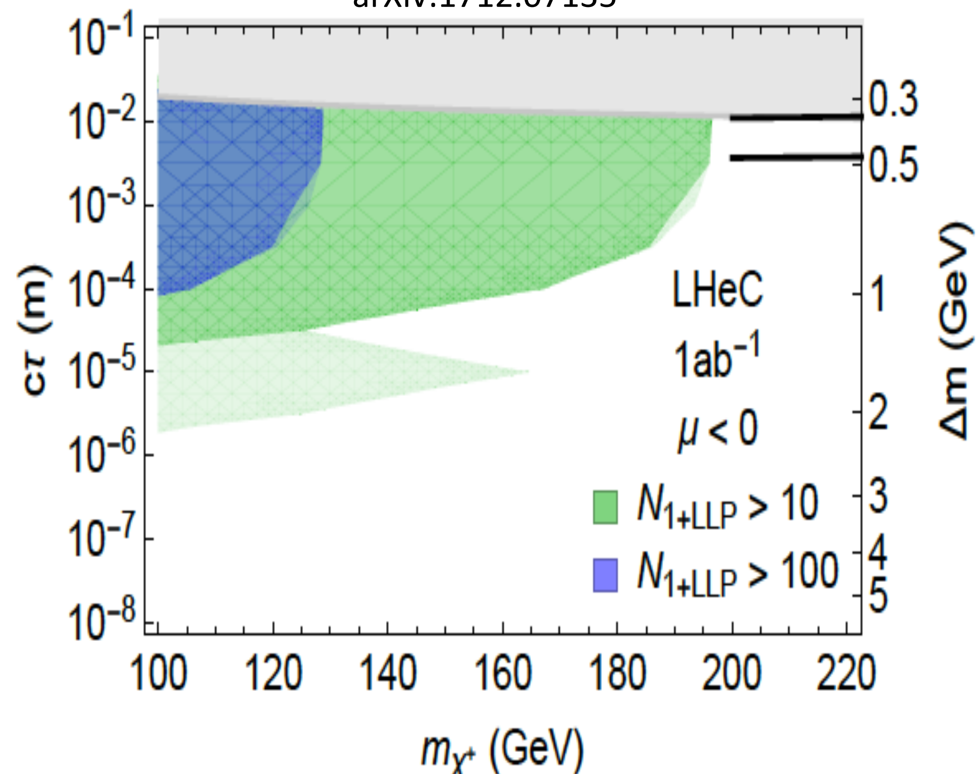
arXiv:1612.02728

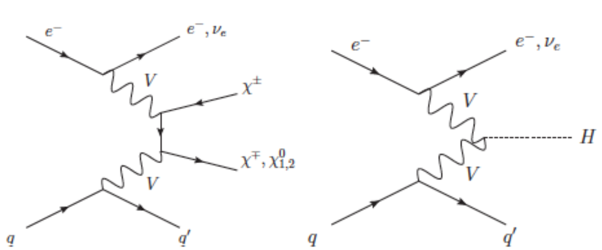


Joint study on pp/pe/ee

Search for Higgsino at LHeC

arXiv:1712.07135





This adds significant motivation for the construction of future e^-p colliders. Together with the invaluable proton PDF data, as well as precision measurements of EW parameters, top quark couplings and Higgs couplings, our results make clear that adding a DIS program to a pp collider is necessary to fully exploit its discovery potential for new physics.

QCD - Developments and Discoveries

AdS/CFT

Instantons

Odderons

Non pQCD

QGP

N^kLO

Resummation

Saturation and BFKL

Non-conventional PDFs …

Breaking of Factorisation

Free Quarks

Unconfined Color

New kind of coloured matter

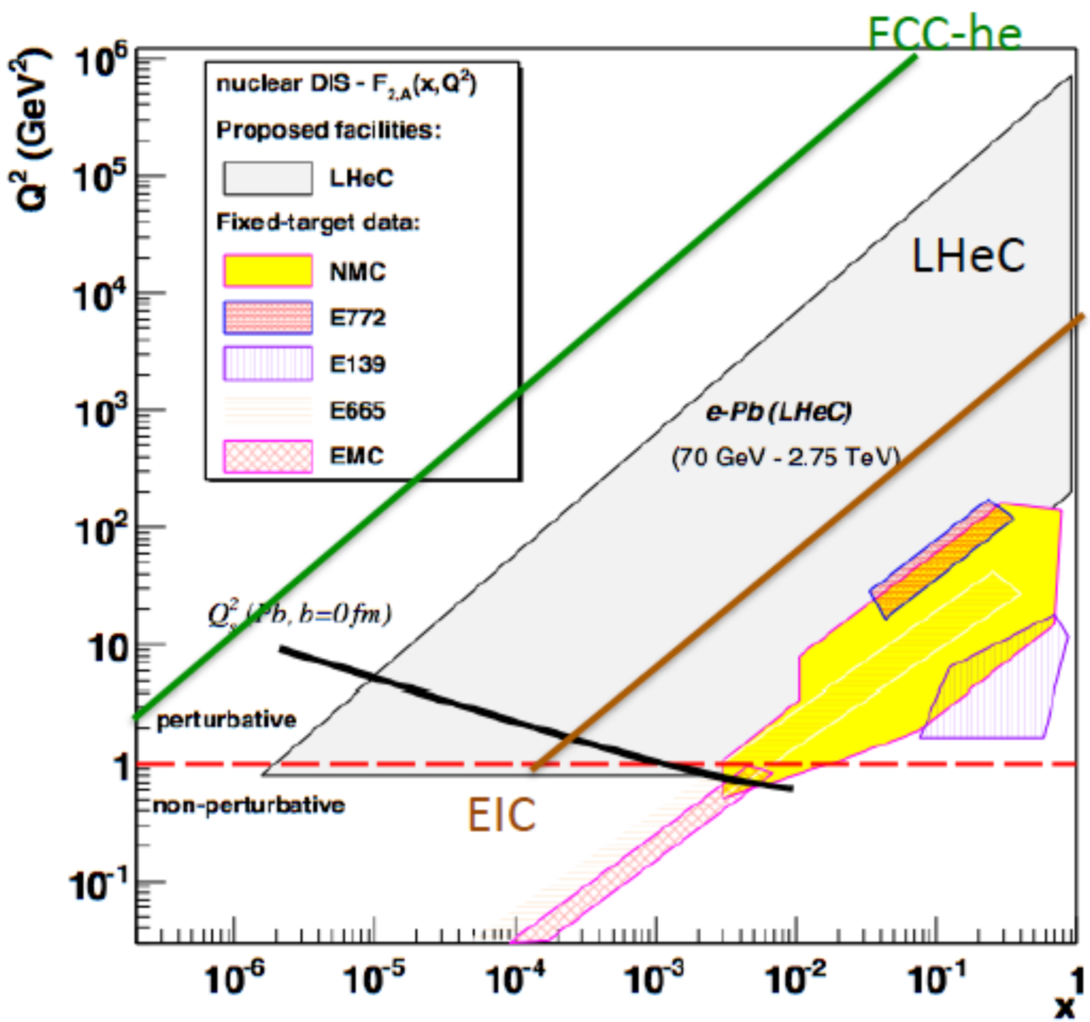
Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background.

Electron-Ion Nuclear and Particle Physics



Extension of kinematic range in lA by 4 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 ?

Relates to LHC Heavy Ion Physics

- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

Saturation: needs large xg at small x
ep and eA

Powerful Energy Recovery Linac for Experiments

PERLE

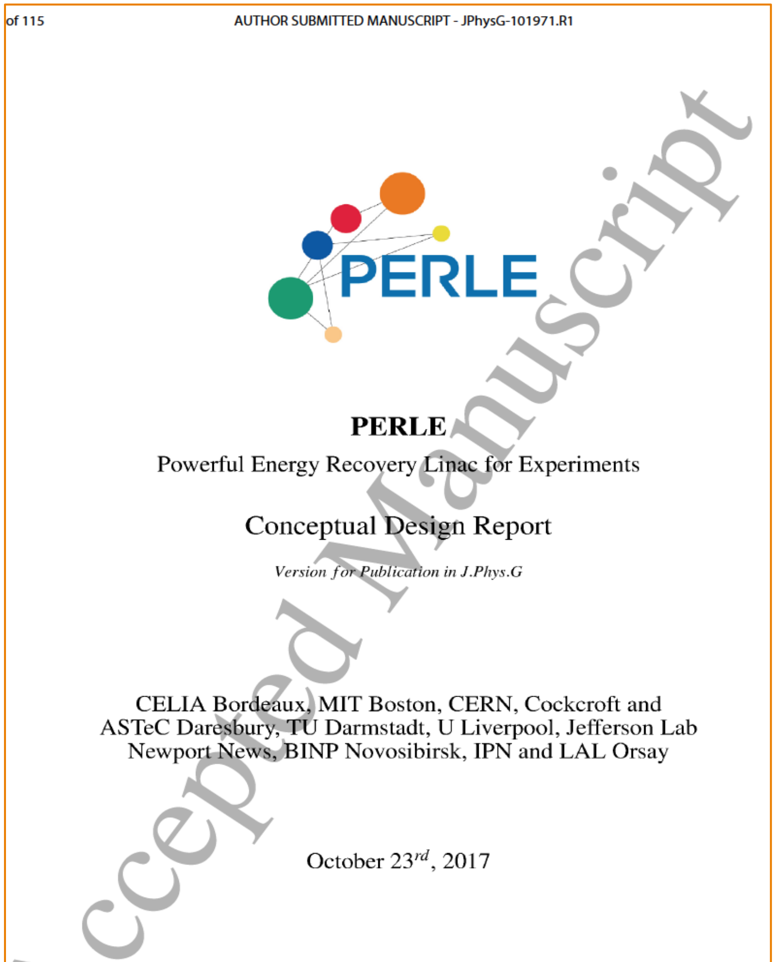
$$I_e = eN_e f = \frac{P}{E_e}$$

15mA and 60 GeV correspond to 900 MW power
This can only be realised using energy recovery.
New: high current, high energy, multi-pass: study!

BINP, CERN, Daresbury, Jefferson Laboratory, U Liverpool, Orsay (LAL+INP), + Collaboration

Powerful ERL for Experiments

Collaboration of BINP, CERN, Daresbury/Liverpool, Jlab, Orsay INP+LAL + : CDR 2016/17, TDR 2018/19 ..


of 115 AUTHOR SUBMITTED MANUSCRIPT - JPhysG-101971.R1

PERLE

PERLE

Powerful Energy Recovery Linac for Experiments

Conceptual Design Report

Version for Publication in J.Phys.G

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and ASTeC Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab Newport News, BINP Novosibirsk, IPN and LAL Orsay

October 23rd, 2017

arXiv:1705.08783

J Phys G in print

https://indico.cern.ch/event/680603/

ERL facility: high current and energy
low energy nuclear, particle and astro physics

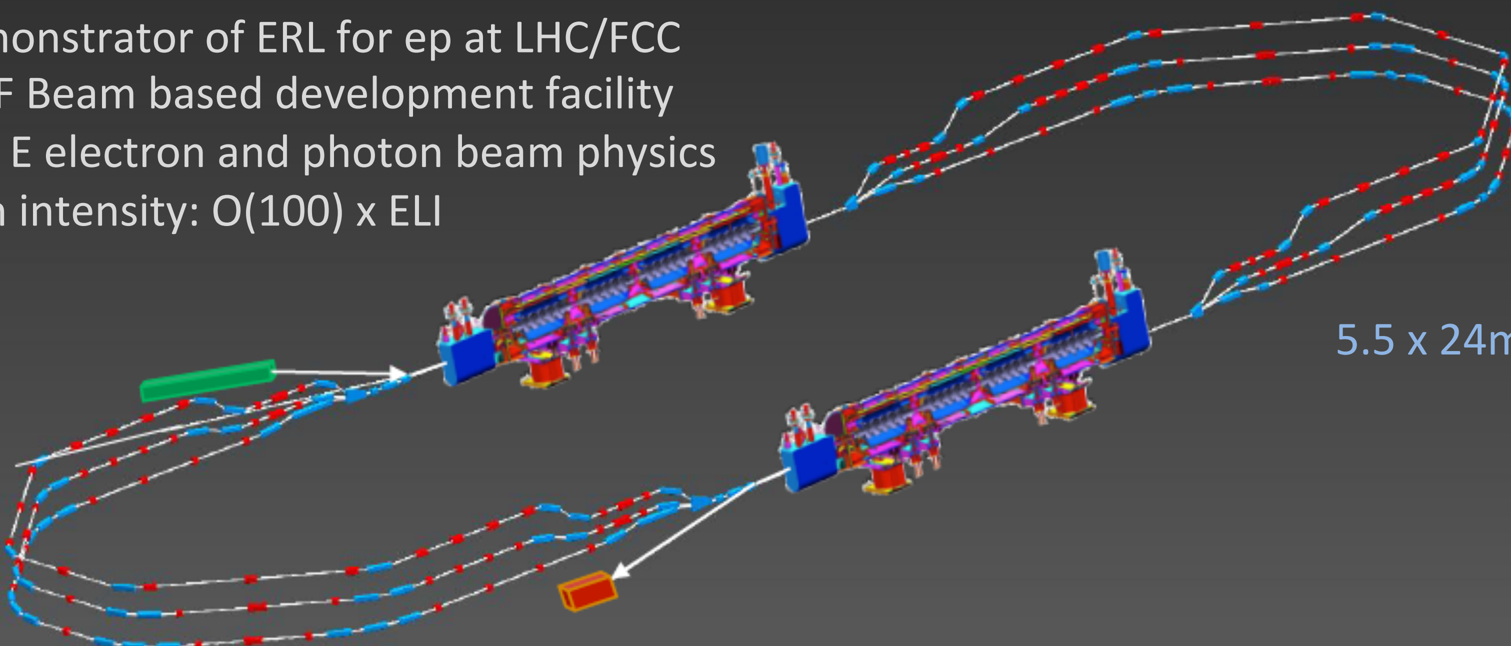
PERLE at Orsay

title

PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +

3 turns, 2 Linacs, 500 MeV, 20mA, 802 MHz, Energy Recovery Linac facility

-Demonstrator of ERL for ep at LHC/FCC
-SCRF Beam based development facility
-Low E electron and photon beam physics
-High intensity: O(100) x ELI



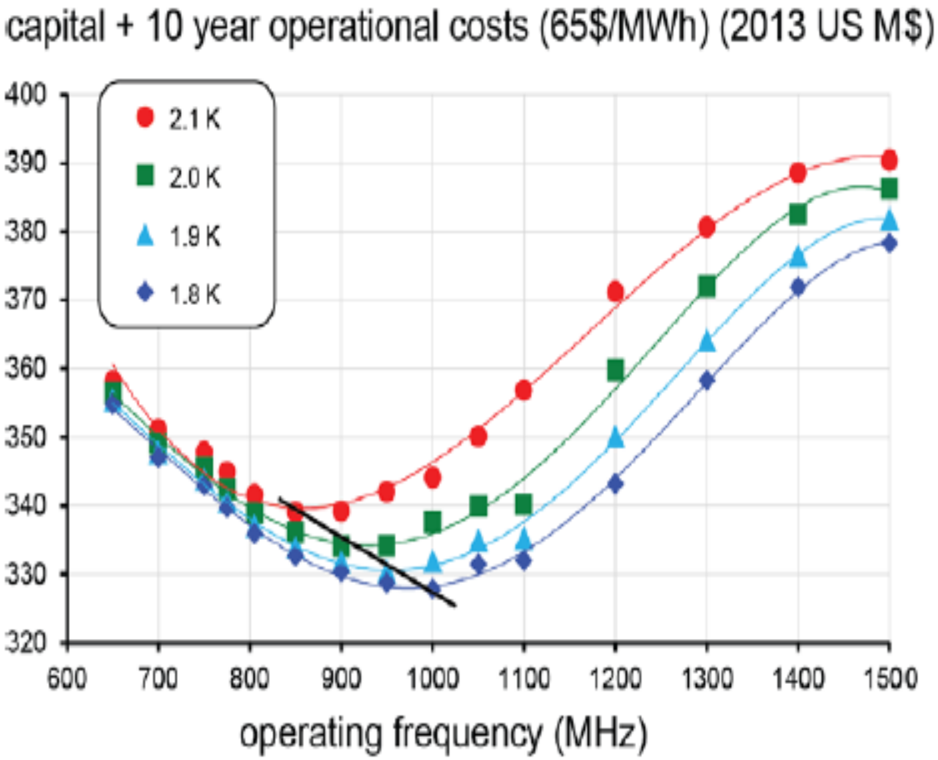
5.5 x 24m^2

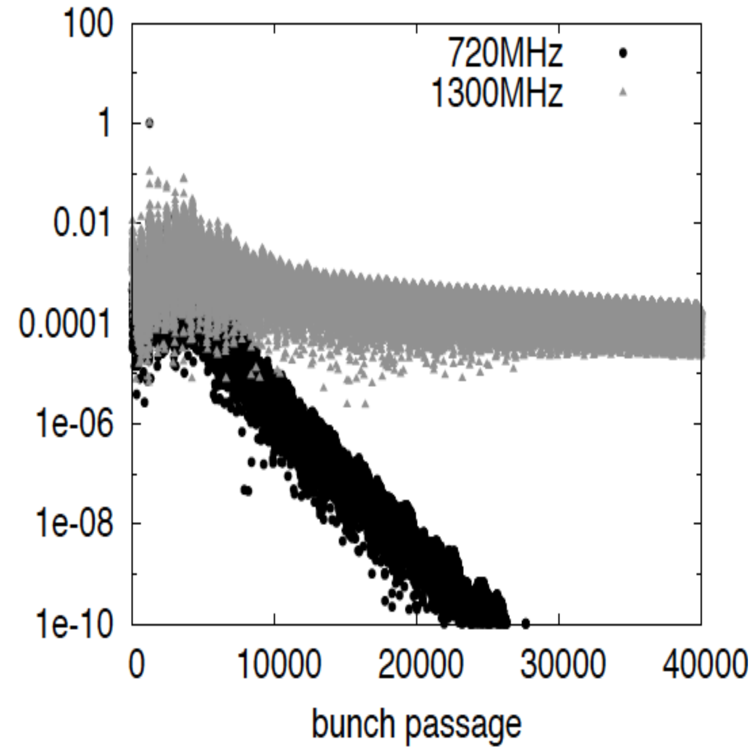
CDR to appear in J Phys G [arXiv:1705. 08783]

Strong low energy physics program:
p radius, sin2theta, dark photons, photon-nuclear physics, ..

A.Bogacz

Frequency Choice





Cost, dynamic heat losses, resistance, Q_0… point to f < 1 GHz (F Marhauser, Orsay 2/17)

Beam beam interactions unstable for f > 1 GHz (D Schulte, D Pellegrini March 2013)

Compatibility with LHC: **Decision for 802 MHz** (E Jensen CI Workshop 1/2015, FM input)

Why PERLE [as seen from LHeC]?

FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**

- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**
  ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no 'automatic' longitudinal phase stability, etc.)

- **Proof validity of fundamental design choices:**
  Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  Implications of high current operation (2 * 3 * [6mA – 25mA] → 30-150mA!!)

- **Verify and test machine and operation tolerances before designing a large scale facility**
  Tolerances in terms of field quality of the arc magnets and cavity alignment
  Required RF phase stability (RF power) and LLRF requirements
  Halo and beam loss tolerances

PERLE Magnets

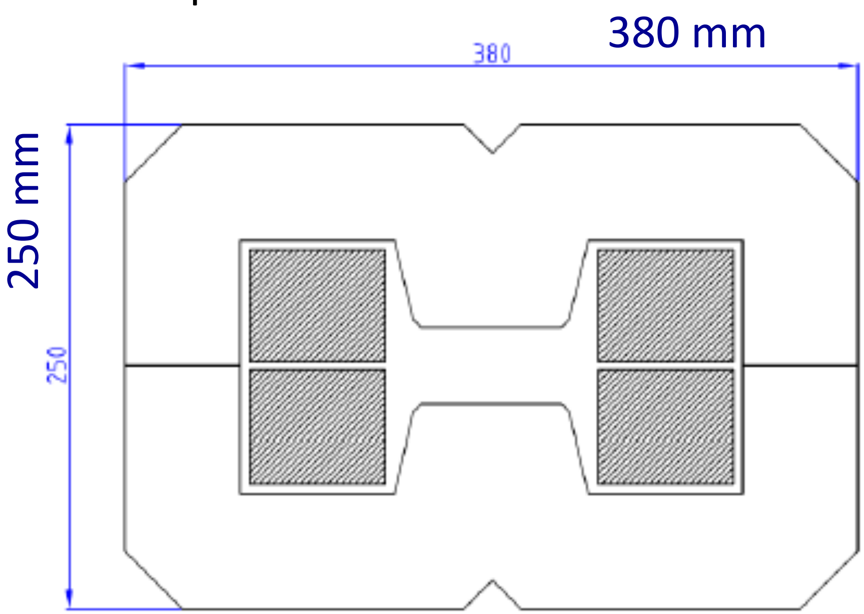
70 dipoles 0.45-1.29 T

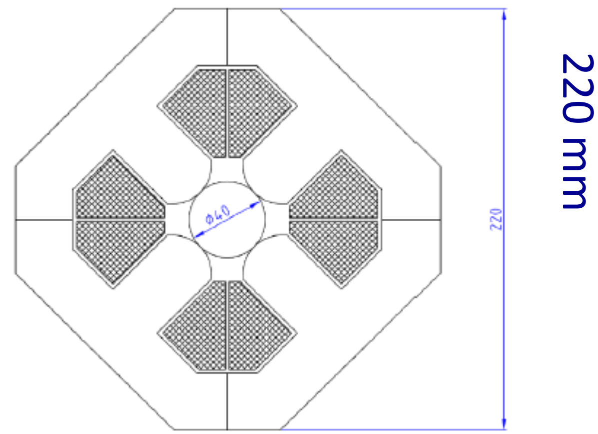
+- 20 mm aperture, l=200,300,400 mm

May be identical for hor+vert bend

7A/mm2 (in grey area) water cooled

DC operated





114 quadrupoles max 28T/m

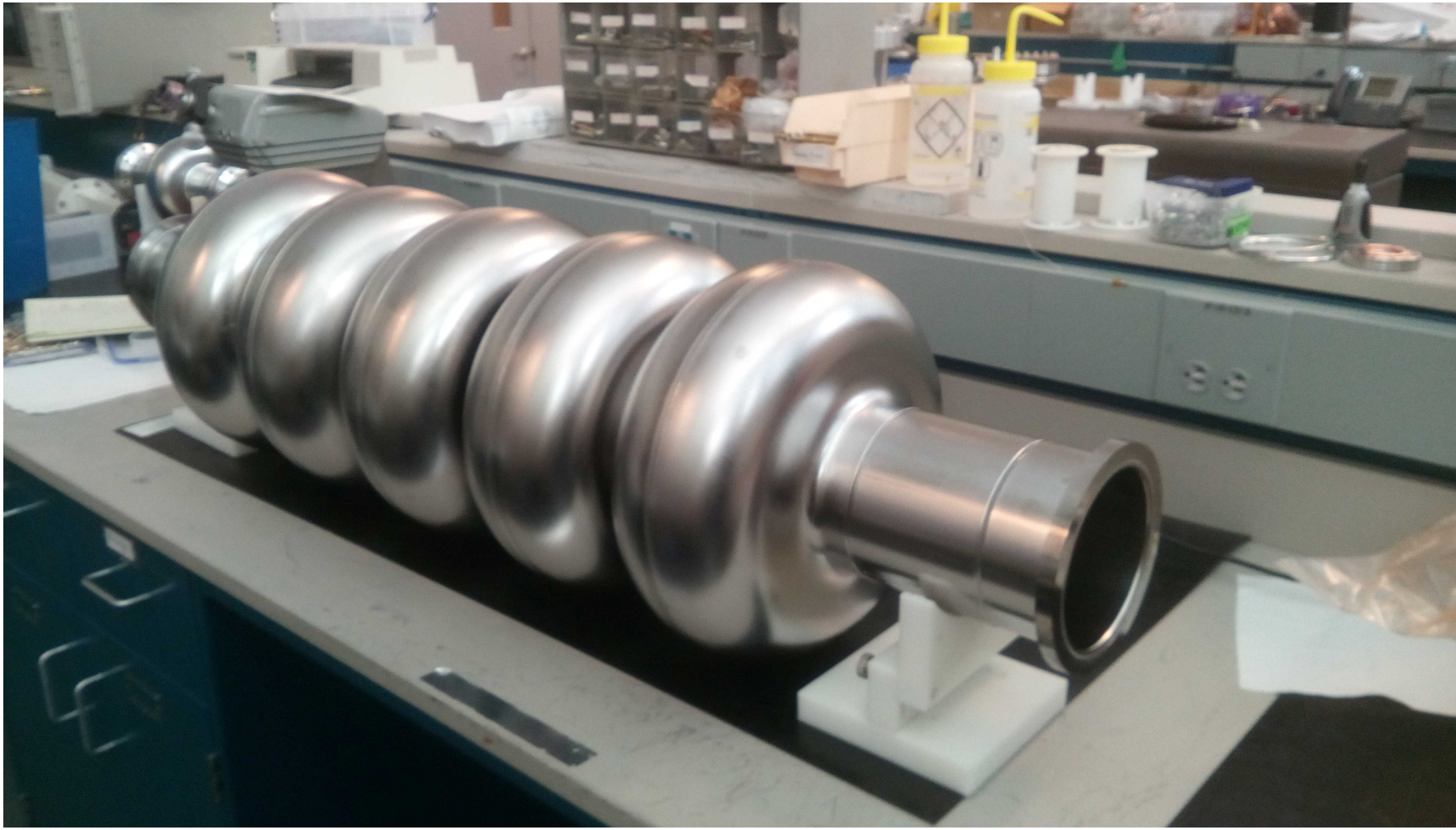
Common aperture of 40mm all arcs

Two lengths: 100 and 150mm

DC operated

P Thonet, A Milanese (CERN), C Vallerand (LAL), Y Pupkov (BINP)

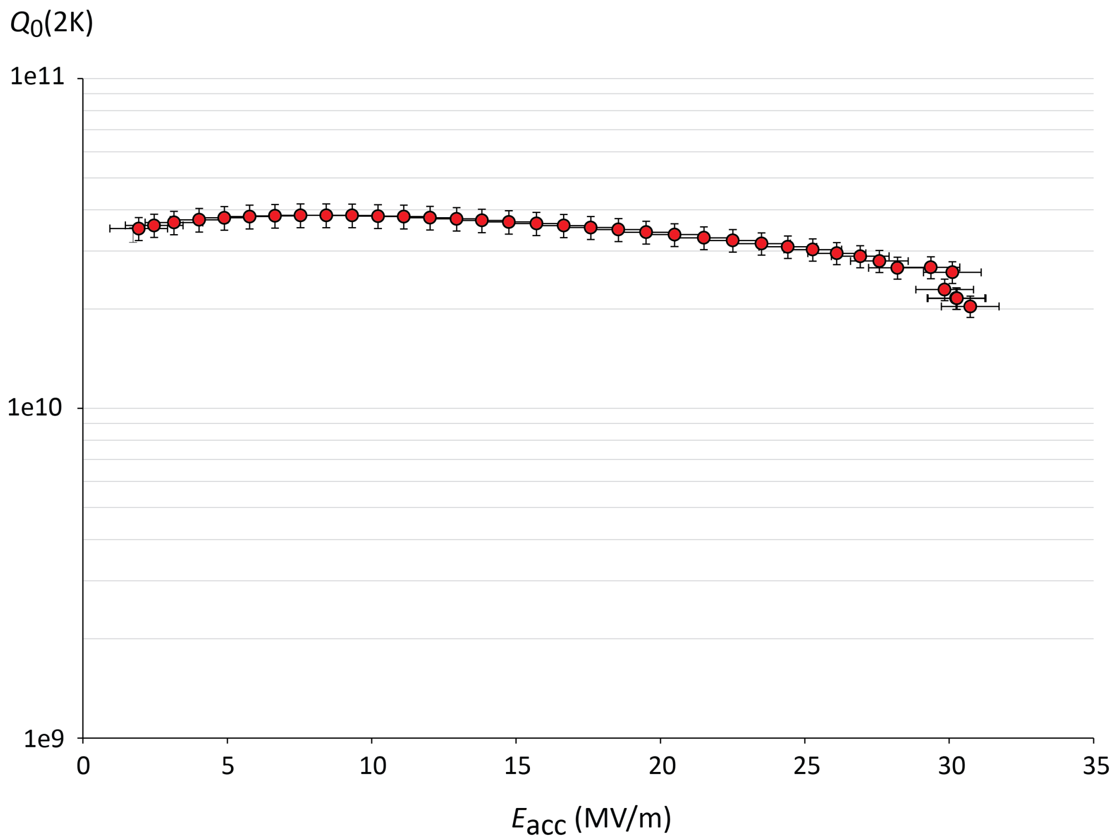
1st 802 MHz Cavity



Tests ongoing. CERN-Jlab design, produced at Jefferson Laboratory **November 2017**

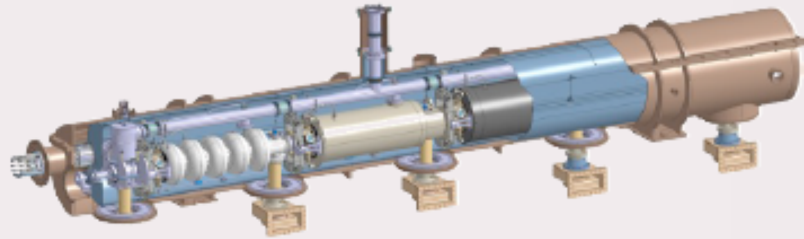
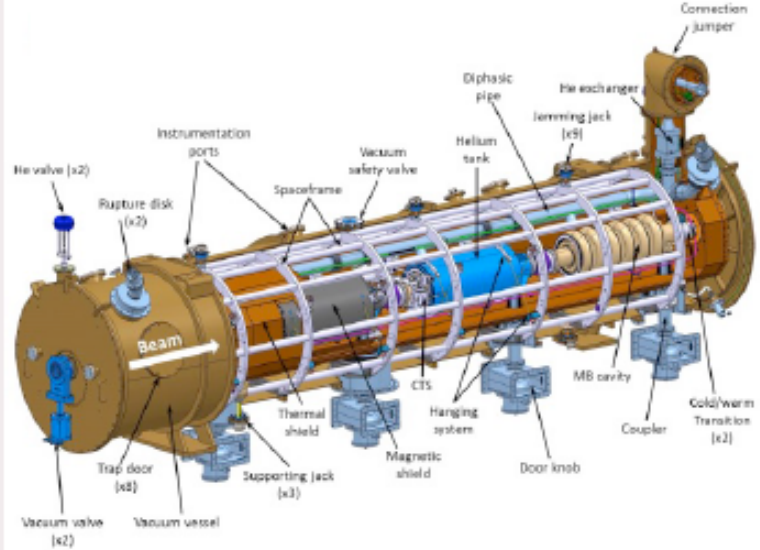
Goal: 16 MV/m, $Q_0 > 10^{10}$ operated in CW in the PERLE+LHeC ERLs, prototype also for FCC-ee

Initial 2K Test of 802 MHz Nb Cavity. **December 17**



High quality, CW: operation point at about 18 MV/m. Quench at 31 MV/m
Rerinsing for field emission suppression, observed at higher gradients.
Next: HOM adapter and cryomodule design − cavity production to proceed.

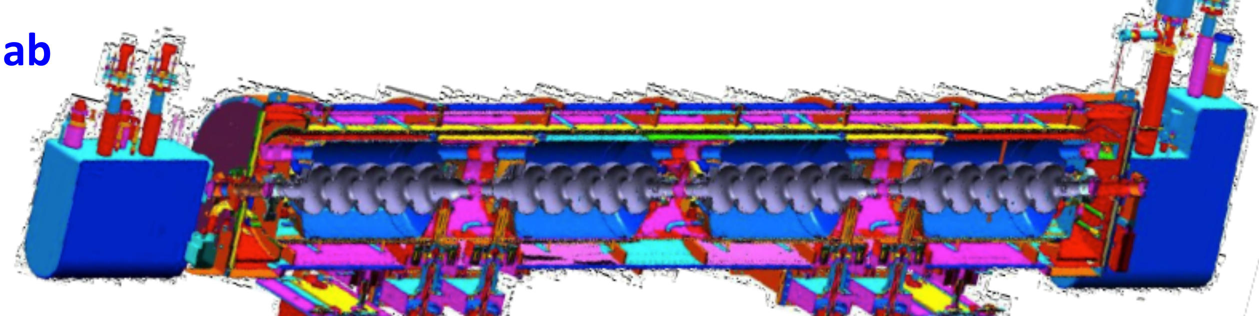
Next Step: Cryomodule

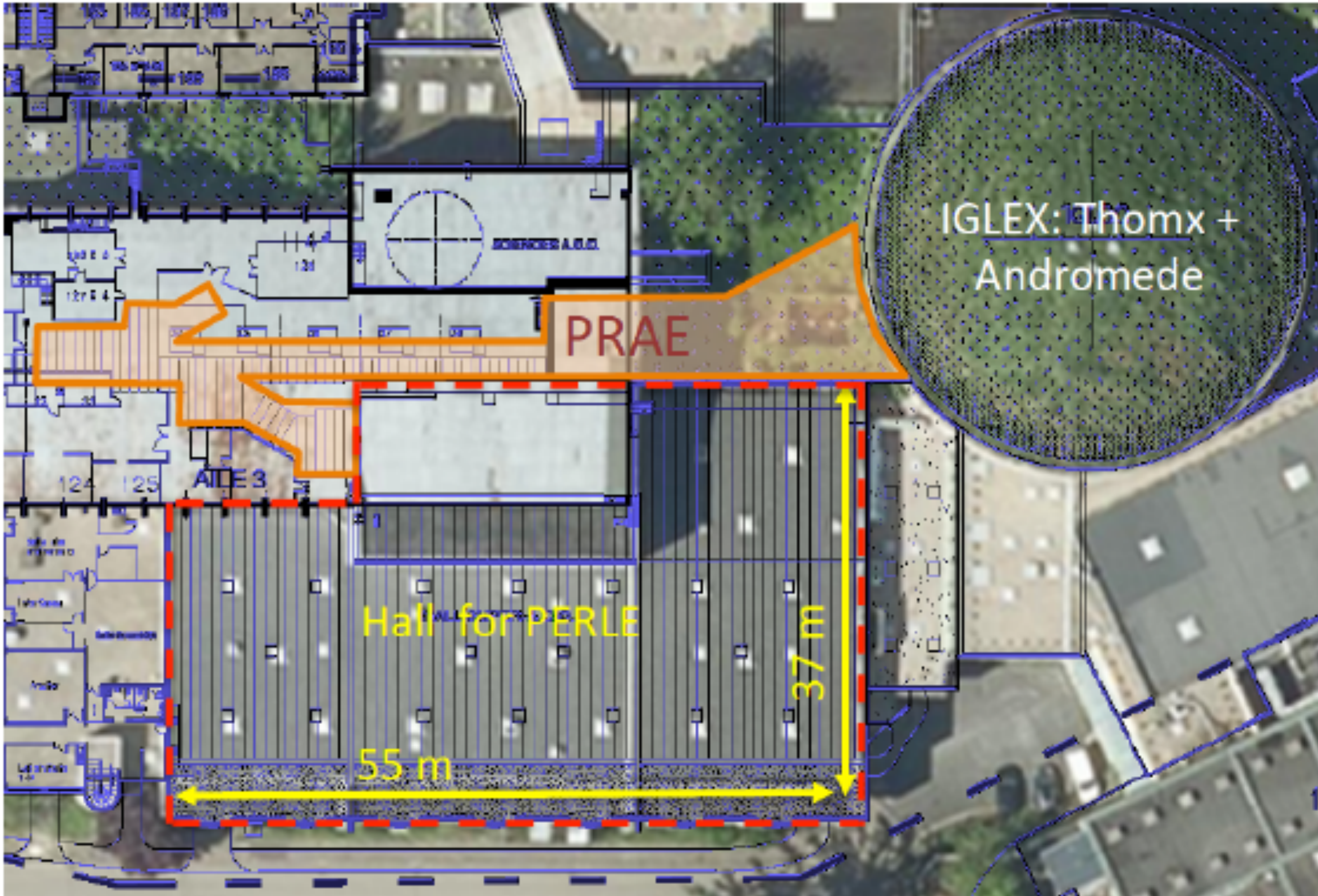
SPL « Short cryomodule »	5-cells Elliptical 700 MHz, β = 1.0 **X 4**	Full length top lid closure Cold mass supported by power couplers	
ESS Elliptical cryomodule(s)	5&6-cells Elliptical 700 MHz β = 0.67 & 0.86 **X 4**	Side loading Space frame	

Plan for production of PERLE cryomodules (2) by IPN Orsay in collaboration with Jlab+CERN

Jlab

SNS 805 MHz cryomodule

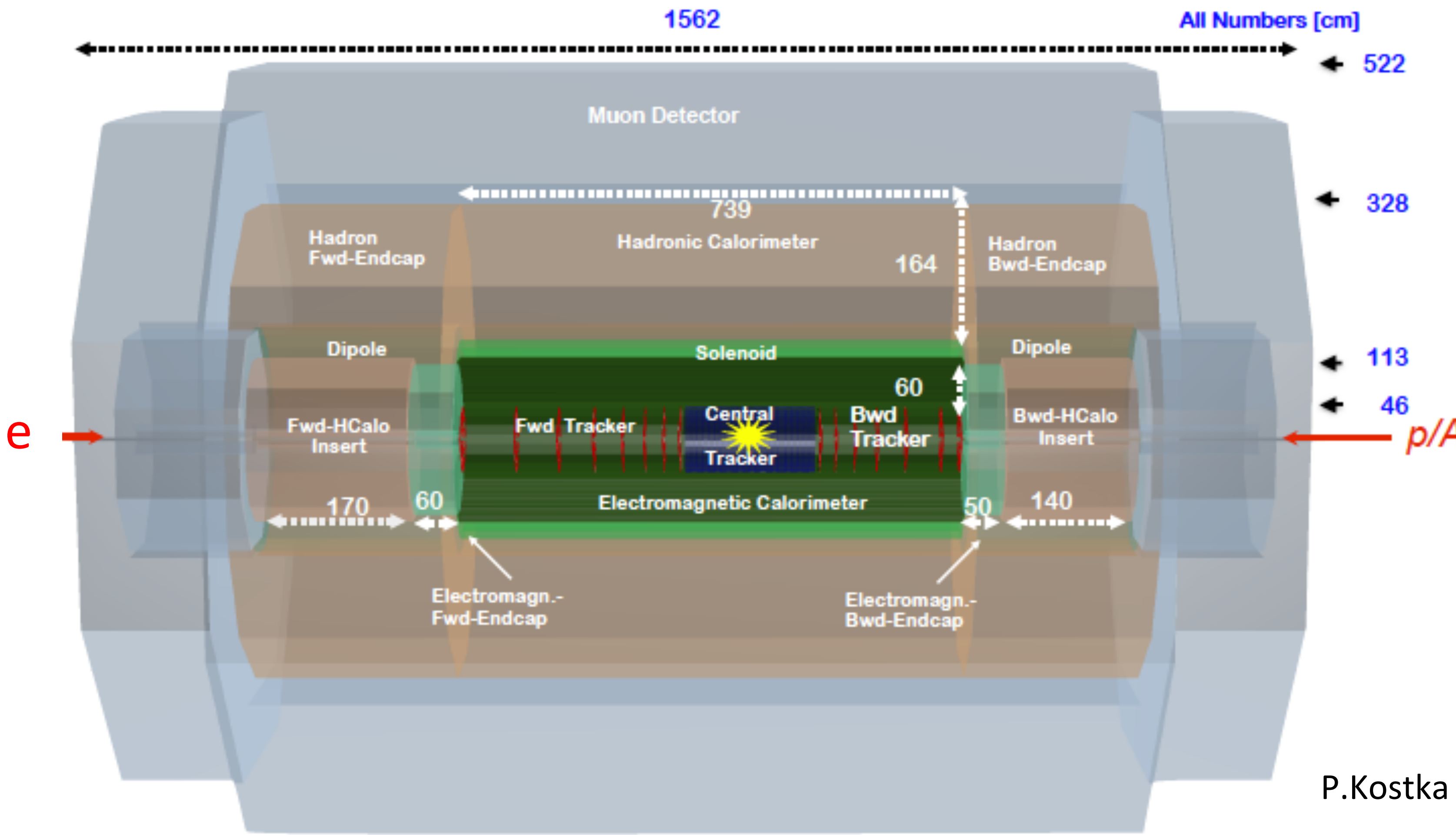




IGLEX: Thomx +
Andromede
PRAE
AILE 3
124
125
Hall for PERLE
37 m
55 m

VI Towards e for the LHC

LHeC Detector for the HL/HE LHC



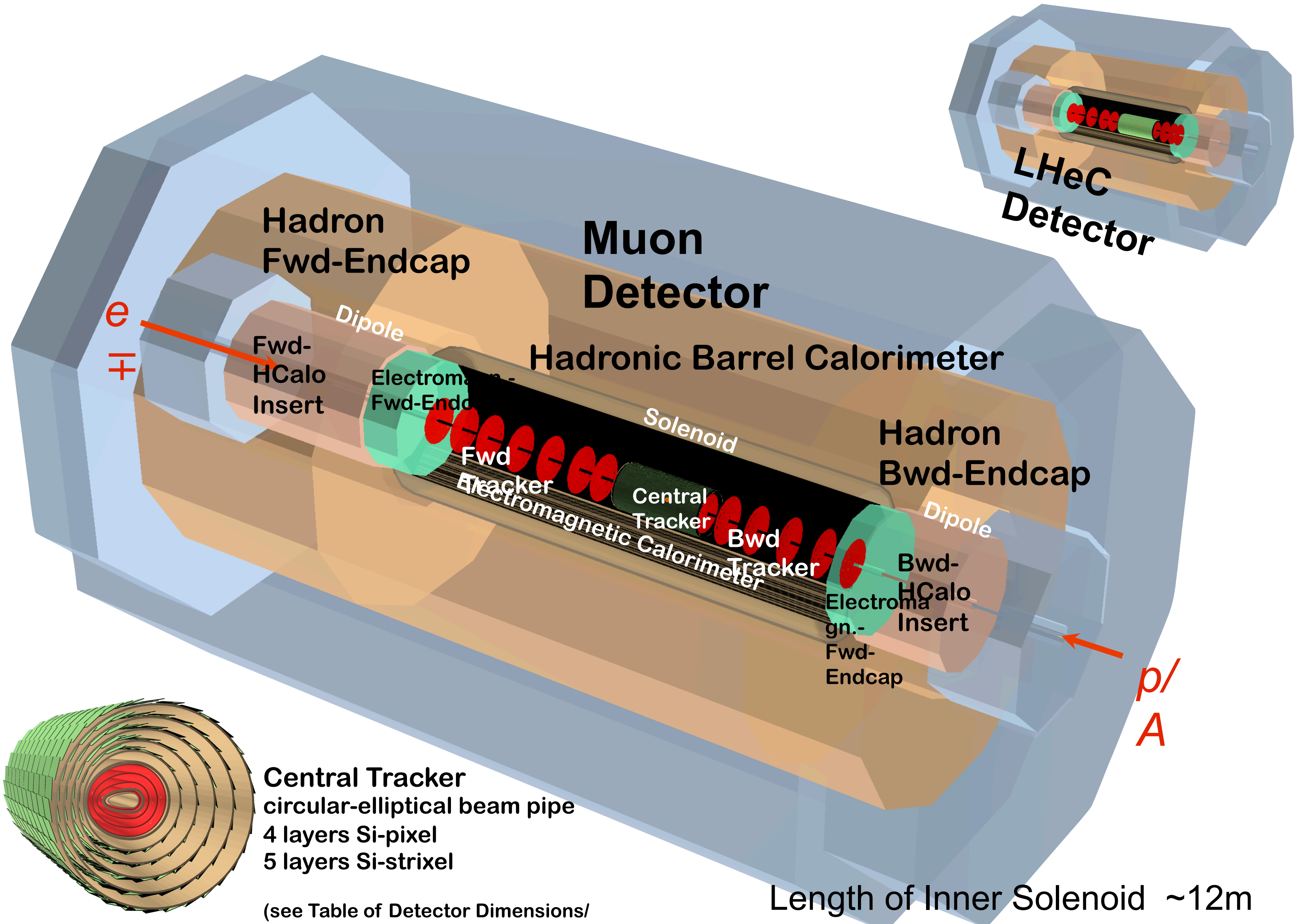
P.Kostka et al

Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)

ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

LHeC/FCC ep/eA detector - a test bed for new technology in the twenties

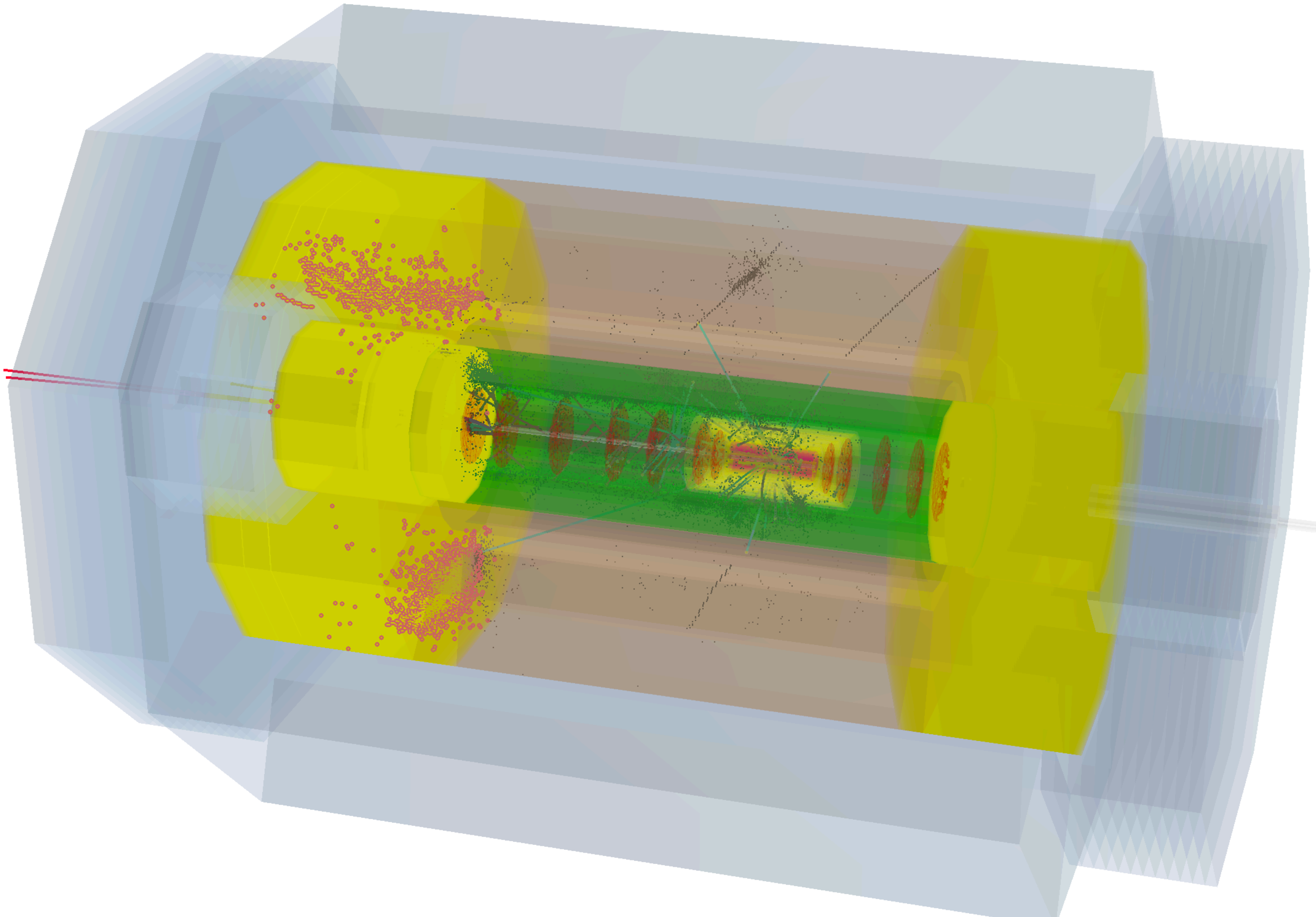


Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

(see Table of Detector Dimensions/
Parameters in backup)

Length of Inner Solenoid ~12m

H→ bb in LHeC Detector

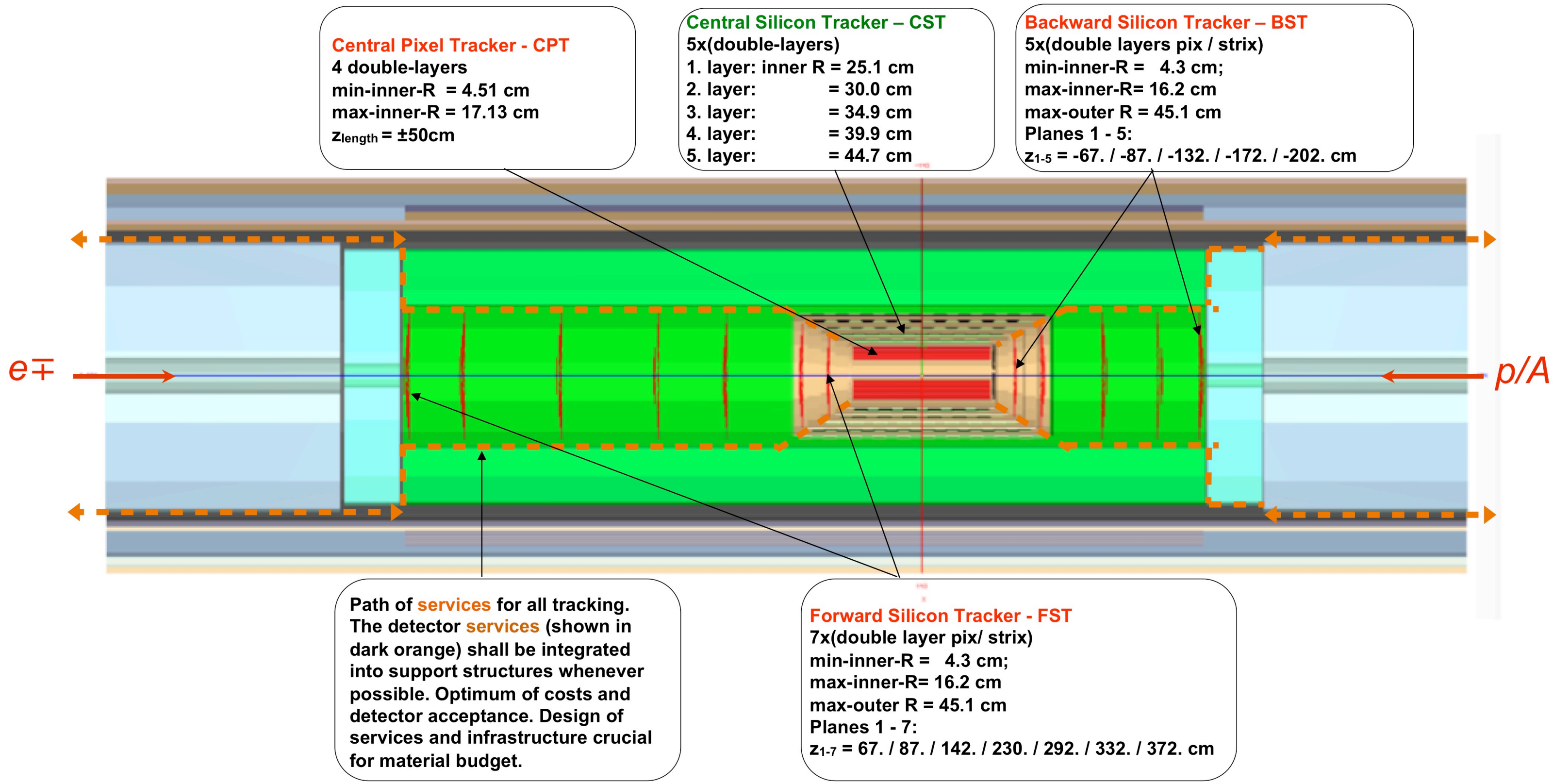


Dimensions and Multitudes - LHeC

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	5		2	–	–	2	3	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.7	3.8	3.0	5.1	24/155	177.8	173.1	178.7
$\eta_{max/min}$	5.1	3.4	3.6	$\pm$3.1	$\pm$1.4	-3.6	-2.8	-4.5
$Si_{pix/strix}$ $[m^2]$	6.9	9.5	2.8	5.4	33.7	2.8	5.7	4.1
Sum-Si $[m^2]$	70.9 double layers taken into account							

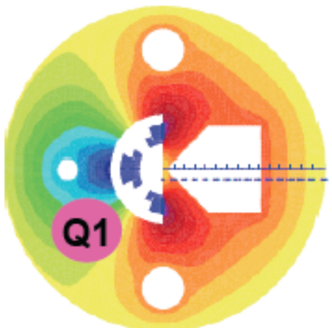
Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.61	0.68	8/166	14.2/160	178.7	178.9
$\eta_{max/min}$	5.2	5.1	2.7/-2.1	2.1/-1.7	-4.5	-4.7
Volume $[m^3]$	6.7	1.6	15.1	165	1.6	5.8
Sum-Si $[m^2]$	197.4					

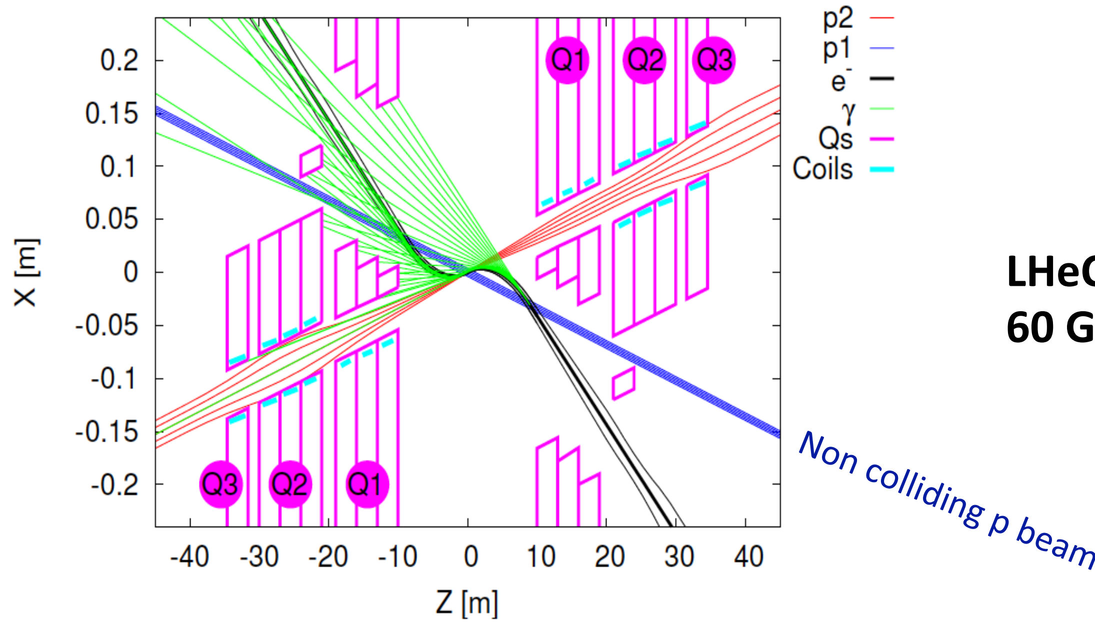
Detector design: Inner Silicon Tracker (status 3/16)



More detailed designs for other components too. DD4HEP software developments..
An opportunity for R+D and building a novel, challenging 4π detector in the twenties.
Profit from HL LHC detector upgrades, also ILC, with no pileup and small radiation load

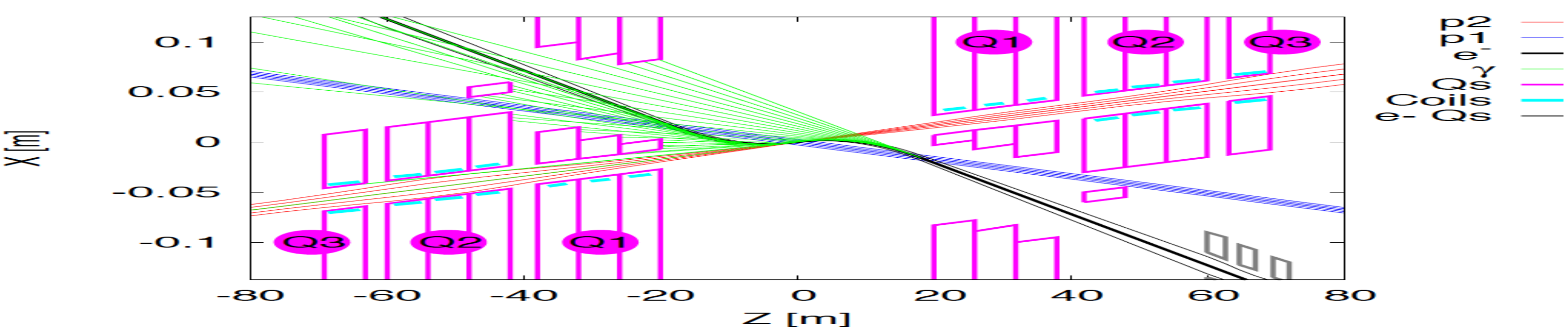
Interaction Regions for ep with Synchronous pp Operation





LHeC (CDR)
60 GeV * 7 TeV

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



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

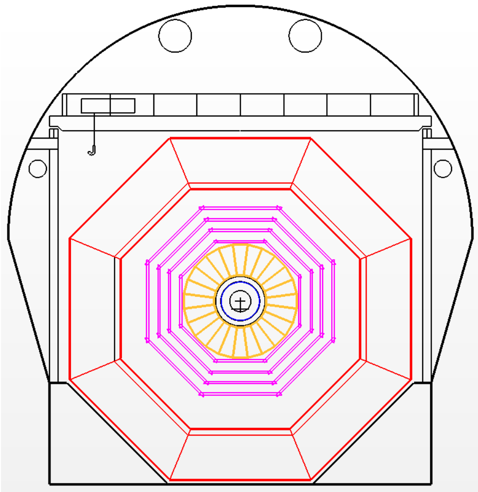
FCC-he (ERL)
60 GeV * 50 TeV

Rogelio Tomas et al

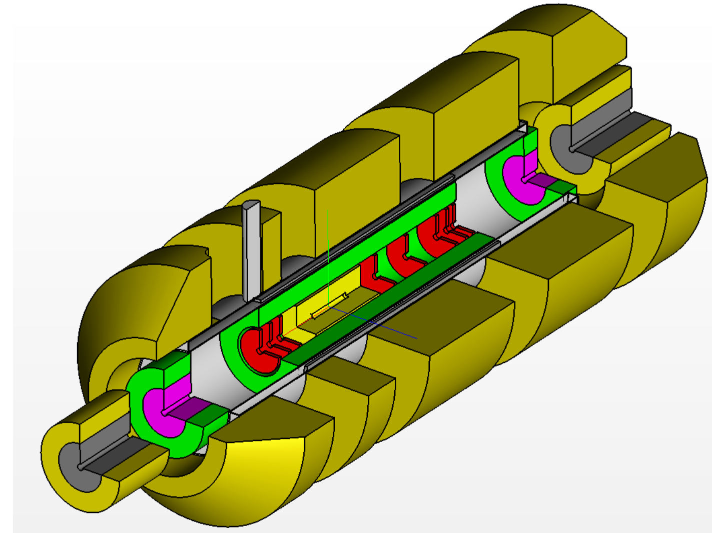
Installation Study

to fit into LHC shutdown needs directed to IP2

Andrea Gaddi et al

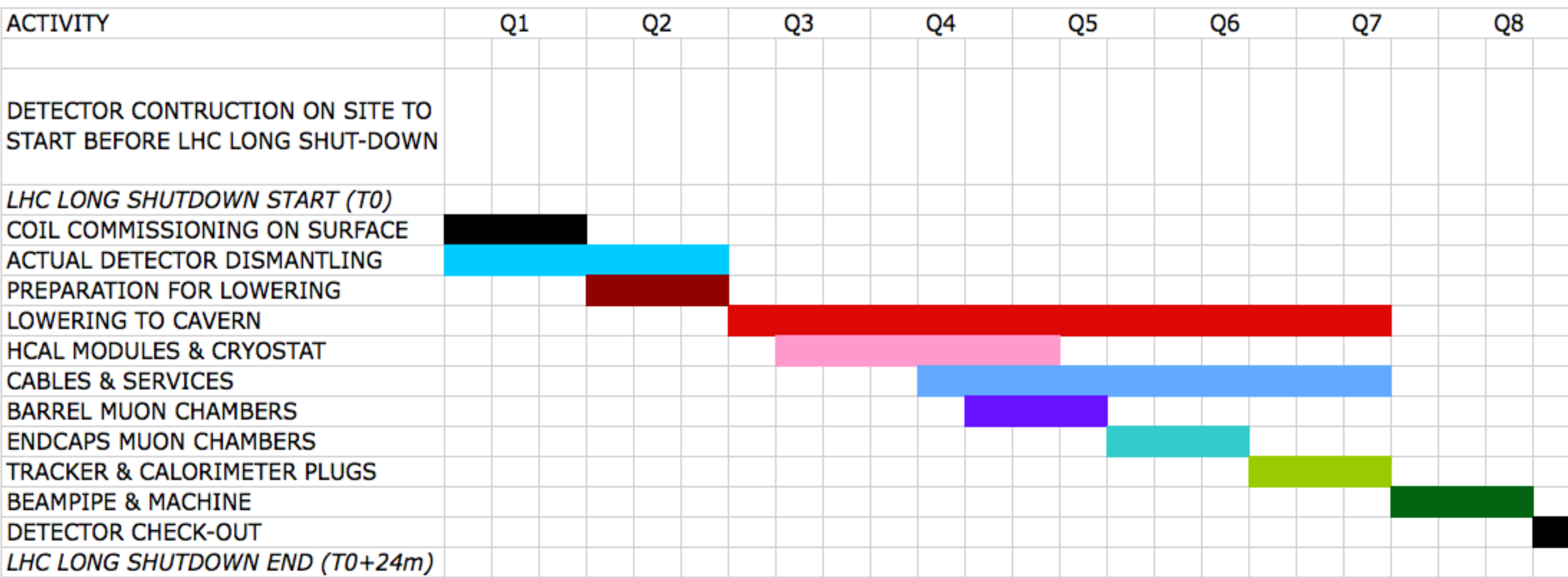


Detector fits in L3 magnet support

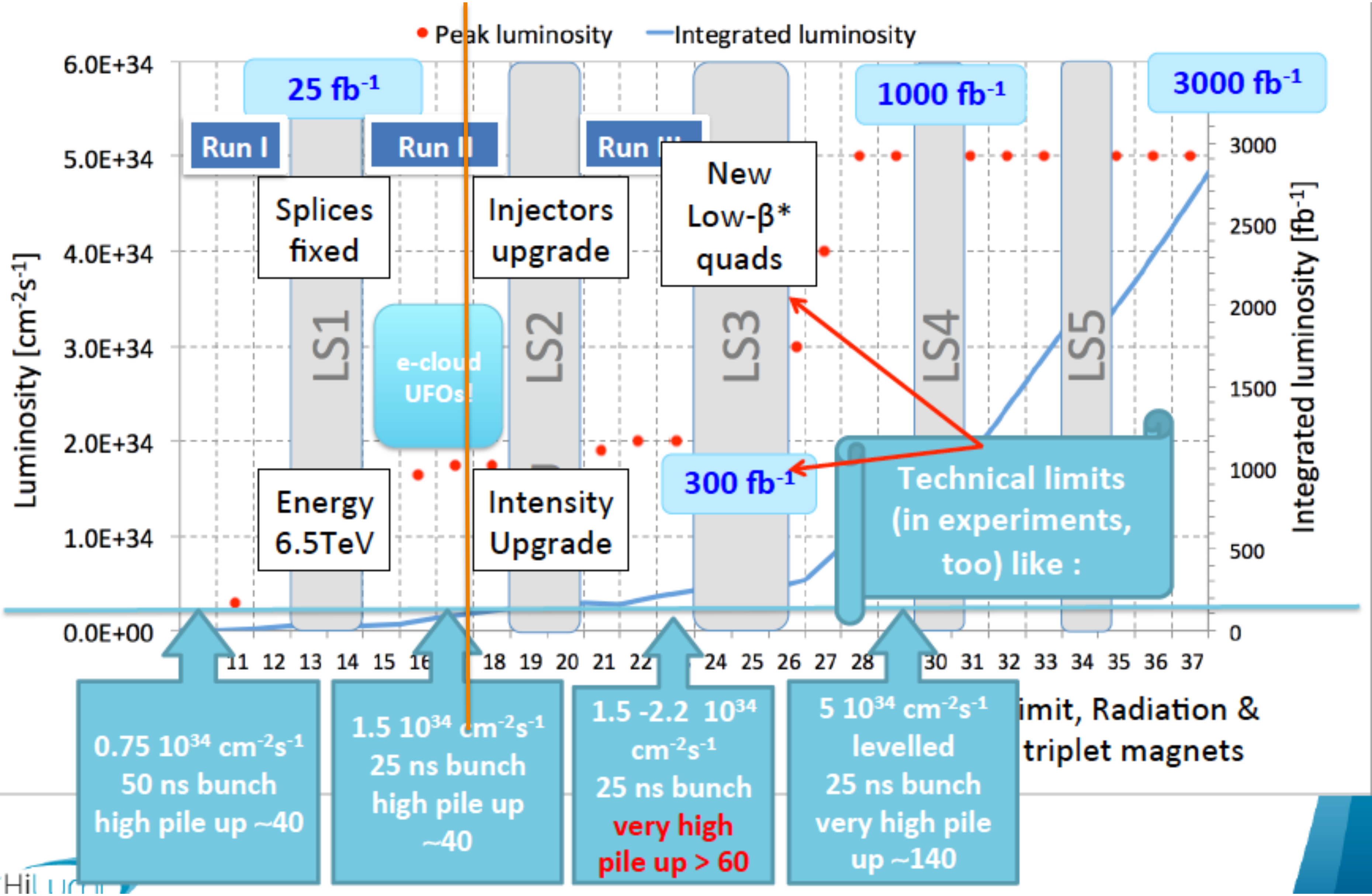


Modular structure

LHeC INSTALLATION SCHEDULE

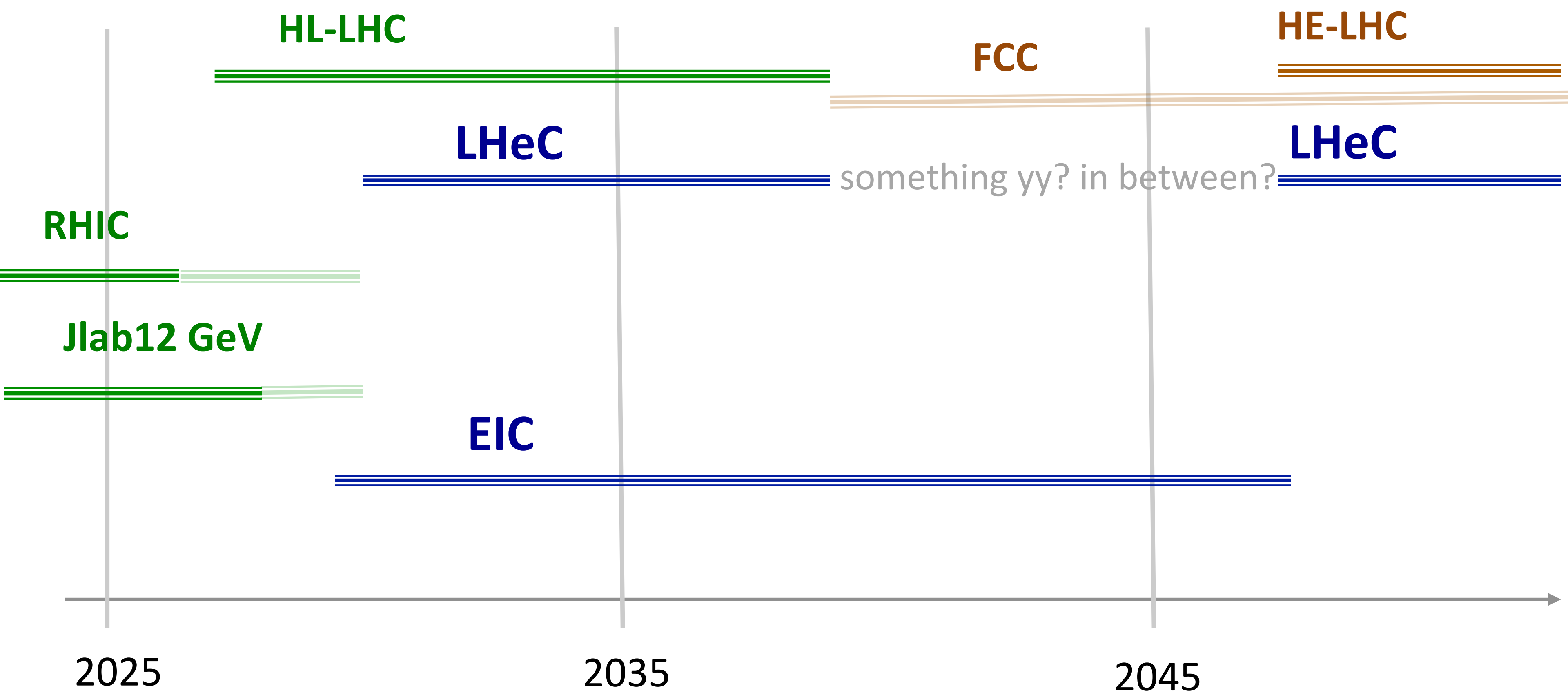


HL LHC offers unique opportunity for ep and eA detector in the 30ies



O Bruening, F Bordry

Projected Timelines for Future ep/eA Colliders



HERA: Proposal 1984, Data 1992-2007, Publications 1993-2018

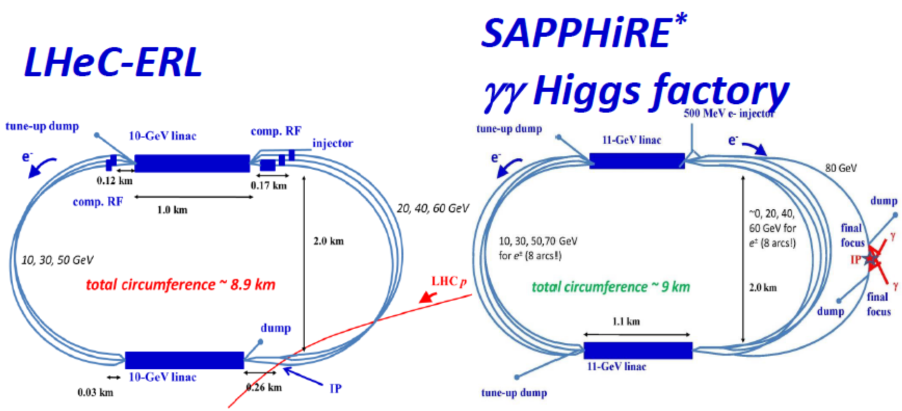
VHEep: Plasma e − LHC. **Chinese ep/A** projects: Lanzhou (low E) and CEPC/SPPC

Dislaimer: For discussion and illustration at DIS17 only MK+RY, April 7th, 2017, DIS at Birmingham

Further use of ERL in between HL and HE LHC

F.Zimmermann at LHeC WS 9/17

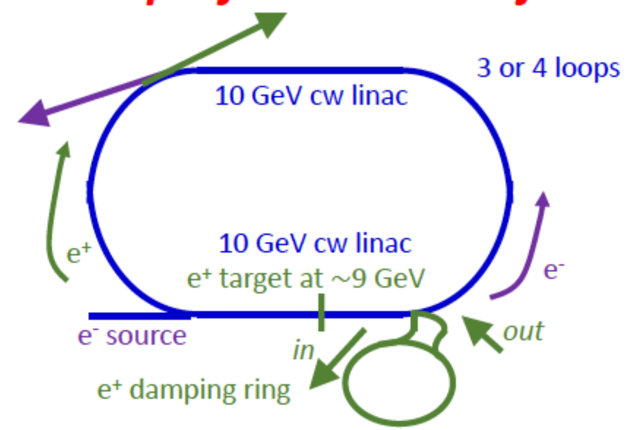
Reconfiguring *LHeC* → *SAPPHiRE*



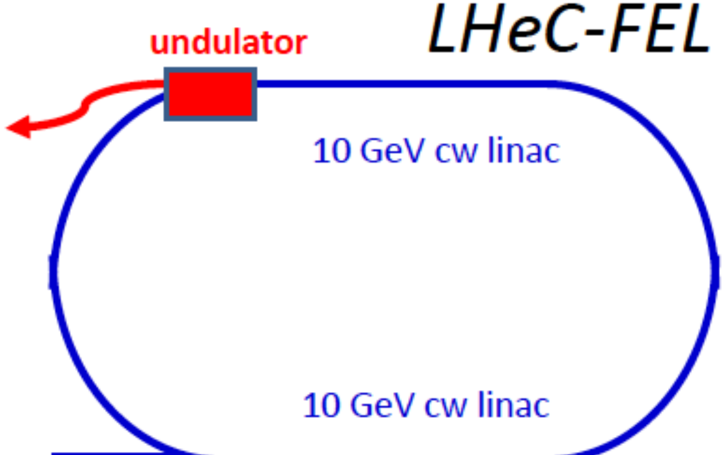
*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, 'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

LHeC: perfect FCC-ee injector!



LHeC-FEL



up to 60 GeV,
~25 mA,
1 MeV photons?

3-15x higher beam energy
(10-200x higher γ energies),
300-600x higher current

XFEL: 20GeV e, 0.03mA, 24keV photons. LCLSII: 4 GeV e, 0.06mA, 5 keV photons

Time Projections

Scientific activities

European Strategy ***2006***

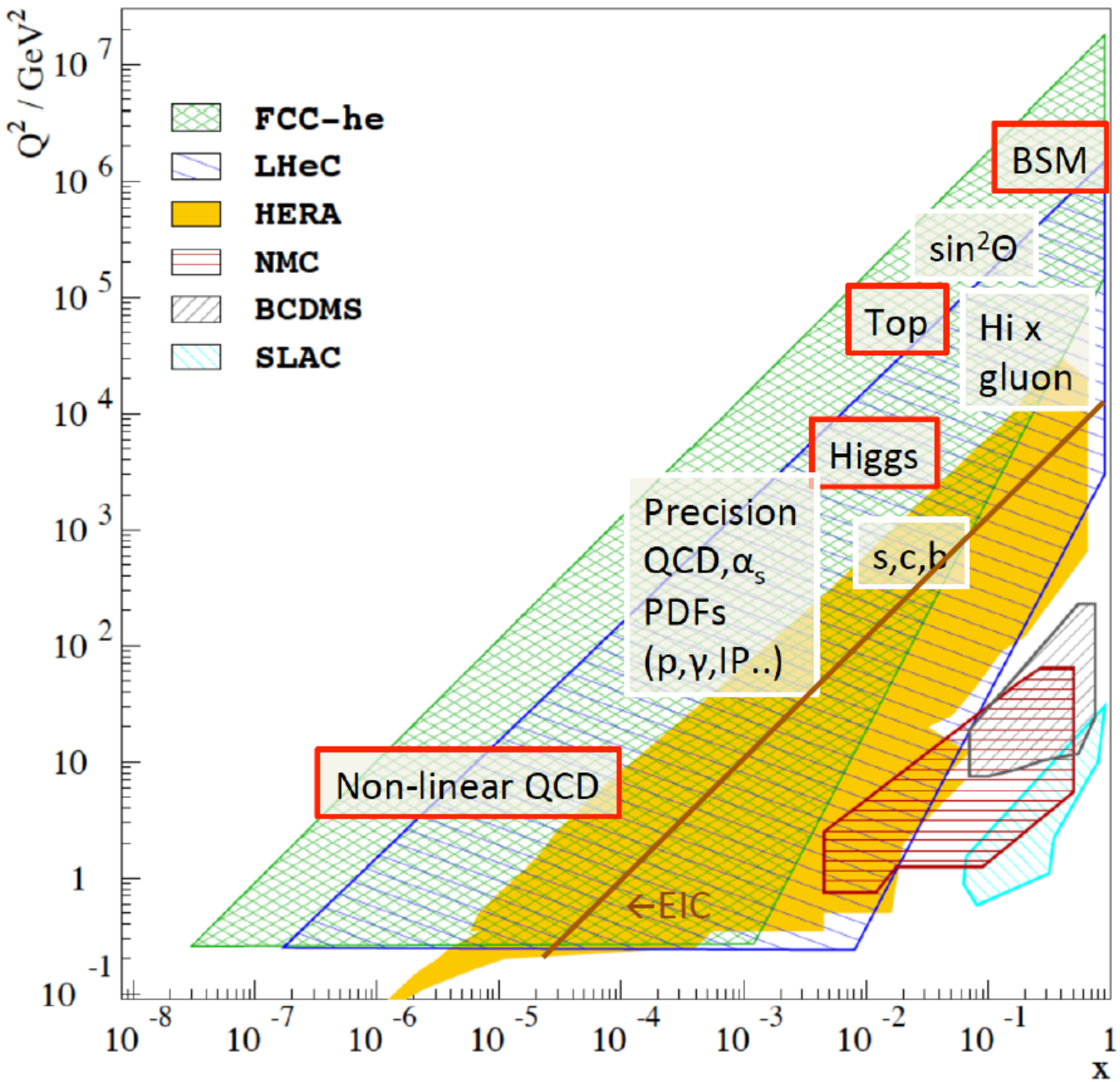
3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; *the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance.* A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; *to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.*

Most likely, the LHC will have been the main base for HEP for ~50 years…

Apparently we are unable to deliver reliable time projections

… and yet we need optimism in order to progress …

Pursue **New Physics** of Deep Inelastic Scattering



Five Major Themes of Electron-Hadron Physics

at the energy frontier

Cleanest High Resolution Microscope

Joint ep and pp Physics at LHC and FCC

High Precision Higgs Exploration

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility

CERN has the obligation to utilize its potential fully: the HL LHC programme can and should not "fade away", new discoveries have to be correctly interpreted, and the world's Collider future is with CERN. DIS has to be part of it, as Guido Altarelli and Lev Lipatov had taught us.

An electron–proton collider could bridge the gap between the LHC and its successor

Frédérick Bordry, CERN's director for accelerators and technology. The project needs more support from the particle-physics community, he notes. "The next European strategy for particle physics will be very important for the LHeC." The strategy recommendations are slated to come out in 2020, and decisions may be delayed beyond that. **Toni Feder**

- 7×why -

i) a huge step (in energy and luminosity) into the unknown of the space-like lepton-parton interaction which only CERN can make, a unique test bed for new physics, certainly in QCD;

ii) the continuation of a seminal tradition of particle physics in building high resolution microscopes, from Hofstadter to Wiik, for searching deeper into the substructure of matter;

iii) the next realistic option to study the Higgs boson and shed more light on its properties, by also making the LHC facility at large the first precision H factory;

iv) the necessary addendum for pp in resolving the largely unknown region of high mass (corresponding to large x_bj) where new particles or interactions may reside;

v) the real (QCD) base for physics of nuclear interactions (which is not just hydrodynamics but parton interactions, non-linear) - ways better than any low energy EIC;

vi) the next energy frontier collider which CERN could build in the twenties, boosting not only SCRF but also the arts of civil engineering, cryogenics, magnet or IR design to a new level, electrons back at CERN, prior to when the time will come for an even bigger enterprise;

vii) a convincing answer to the question as to which detector could one build next, which is becoming formulated more and more pressing, when one listens to detector builders we join in the ATLAS upgrade and elsewhere.

"The future belongs to those who believe in the beauty of their dreams."

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015

title

Particle Physics with pp-ee-ep

SM was completed with a series of pp, ee and ep machines exploring the 10 GeV scale (ISR,SppS − PETRA, Tristan − electron, muon and neutrino experiments) and the Fermi scale (Tevatron − LEP, SLC − HERA), **besides further dedicated experiments [ep SLAC78..].**

All three types of colliding experiments were instrumental in the SM establishment:
For example: LEP predicted the top mass and Tevatron found the top quark;
HERA measured the gluon distribution and LHC discovered gg→**Higgs**→ 4l, γγ.
Tevatron saw excess in high pt jets, yet attributed to PDFs with DIS etc

For the first time since decades we have NO definite guidance, no SM particle to find. Note, however, that the Tevatron, LEP and HERA proposals largely emphasised NOT the SM but the BSM (SUSY, LQ) physics. Rarely the SM was a funding argument before either and the theory was no less speculative . Theory only guides: e.g. Weinberg 1980 SU(5): end of colliders, go underground to see proton decay … to find neutrino oscillations ..

The LHC stands alone, it has no ep partner to explore the 1 TeV scale and it has no ee partner to study the Higgs boson. Can we build in time a 1 TeV ep collider (yes we could) and can we build a higher (than LEP) energy ee collider (for others to discuss)

The FCC study has hh, ee and eh: yet 5?: time, cost, technology, theory, detectors
+ the public acceptance of such a major step into the unknown and below Lac Leman

Three Lessons from HERA

HERA kept electron-proton scattering as an integral part of high energy particle physics. It demonstrated the richness of DIS physics and the feasibility of constructing and operating energy frontier *ep* colliders. It is a testimony of the vision and authority of Bjoern Wiik. What did we learn to take into a next higher energy *ep* collider design? Perhaps there were three lessons about i) the need for higher energy, for three reasons: to make charged currents a real, precision part of *ep* physics, for instance for the complete unfolding of the flavour composition of the sea and valence quarks, to produce heavier mass particles (Higgs, top, exotics) with favourable cross sections and, a third reason, to discover or disproof the existence of gluon saturation for which one needs to measure at lower $x \propto Q^2/s$ than HERA could; ii) the need for much, much higher luminosity: the first almost ten years of HERA provided just a hundred pb^{-1}. As a consequence, HERA could not accurately access the high x region, and it was inefficient and short of statistics in resolving puzzling event fluctuations; iii) the complexity of the interaction region design when a bent electron beam caused synchrotron radiation while the opposite proton beam generated quite some halo background through beam-gas and beam-wall proton-ion interactions. This we had not seen clearly enough prior to and during the initial phase of the HERA luminosity upgrade.

Need higher energy, higher luminosity and to carefully design the IR

MK Future Deep Inelastic Scattering with the LHeC, arXiv:1802.04317

The strong coupling constant in DIS (today)

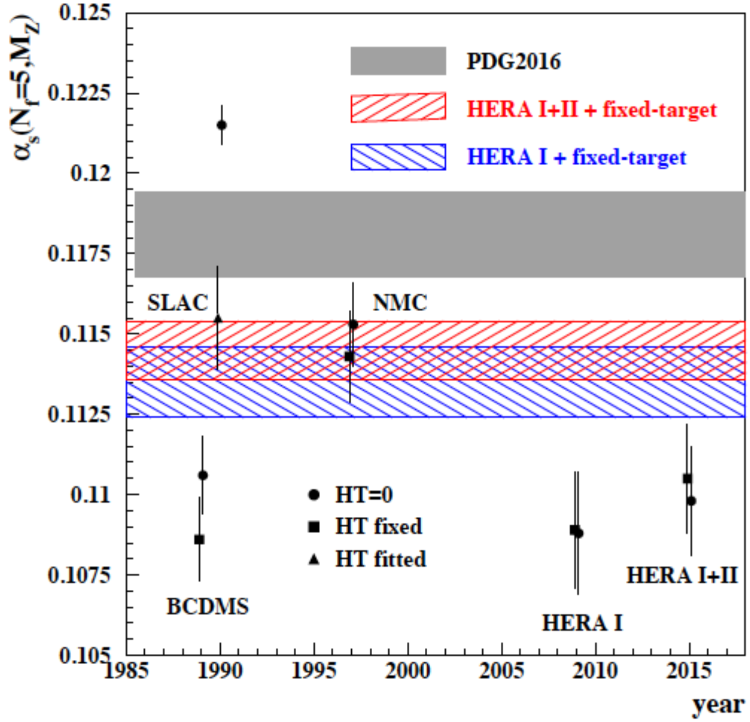


Figure 12: Determinations of α_s by the ABMP group [85]. One observes quite some spread and a final result (red dashed) below the PDG average value, which includes DIS. Results are shown with the higher twist terms set to zero (circles), HT terms fixed to the values obtained in the ABMP16 fit from considering all data sets (squares) and when fitting the HT terms to the individual data sets (triangles). The bands are obtained by using the combination of the SLAC, BCDMS and NMC samples together with the combined H1 and ZEUS data from HERA I (left-tilted hatches, blue) and from HERA I+II (right-tilted hatches, red).

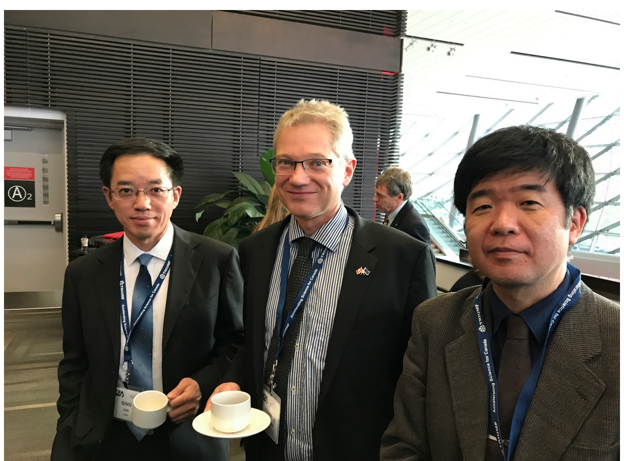
on “the strategy”

The next European strategy will hardly decide anything as it is five years before the 2 BSF HL upgrade takes place, and no one knows how to reach out to O(10)BSF. The demand to make HL LHC a success will be overriding, adding ep and eA is a golden key to this.

Directions may become visible in a global context (an asiatic e+e- machine decision would be important). HEP is remarkably in the hands of the J+Ch governments.

The ERL development and the detector+physics study has a long term future with CERN as we consider this accelerator as a modular addition to HL/HE LHC and the FCC hh.

MK remarks made in the LHeC Coordination June 2017



At ICFA Seminar in Canada 11/17

Quin Qin, Frank Zimmermann
and Shinichiro Michizono

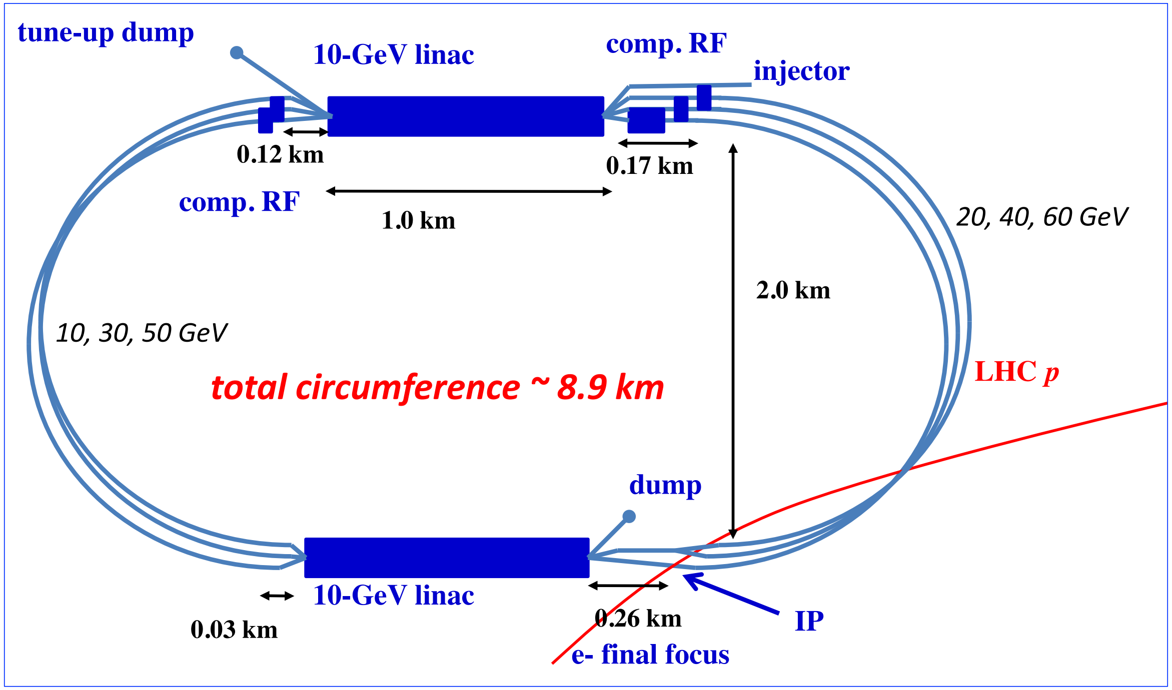
Summary and Complementary between ep and pp

slide based on [Georges Azuelos and Monica D'Onofrio]

Compositeness	• *4-fermion EFT: Lepton-quark compositeness scale* • *Quark radius*
Leptoquarks and RPV squark decay	• *Accessible range largely excluded, but not completely* • *Better measure of LQ characteristics, if they exist*
Anomalous Triple Gauge Couplings	• *Comparable to LHC*
Top FCNC couplings	• $tu\gamma, tc\gamma, tuH$ *couplings*
Vector-like leptons, heavy/excited leptons, bileptons, higher isospin lepton multiplets	• *No constraints on VLL, so far, at LHC* • *Extend sensitivity to eγ for lower masses*
Heavy neutrinos, Majorana neutrinos, sterile neutrinos	• *Symmetry-protected see-saw model*
SUSY EW: sleptons, Higgsino, (dark sector)	• *kinematical observables for compressed scenario* • *Long-lived neutral particles* • *Disppearing tracks*
Anomalous Quartic Gauge Couplings	• *Better control on background:* *no gluon exchange diagrams (mostly FCC?)*
Extended Higgs sector: higher isospin multiplet	• *Singly- and doubly- charged higgs by VBF (mostly FCC)*

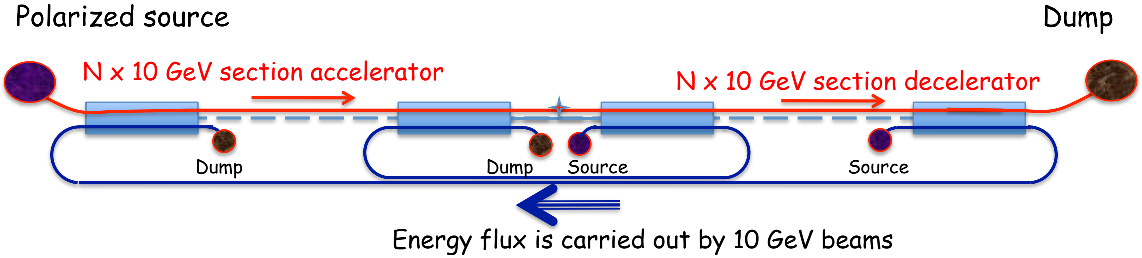
ep/A with the LHC

Conceptual Design Report: arXiv:1206.2913, published in JPhysG



LHeC: 60 GeV off 7 TeV, L(ep) $=10^{33\rightarrow 34}\ \mathrm{cm^{-2}\,s^{-1}}$ (1000 x HERA) in synchronous ep+pp operation

Non default: An expensive generalisation to achieve E_e= 500 GeV or more



III LHC

1000 papers:

Higgs Discovery

No BSM up to O(TeV) SUSY RPV/RPC, W', Z', Kaluza Klein gravitons, DarkMatter…

QCD to high orders well established in new range

Precision Measurements: W,Z to 1/2 %, MW to 2 10^{-4}

Some fluctuations

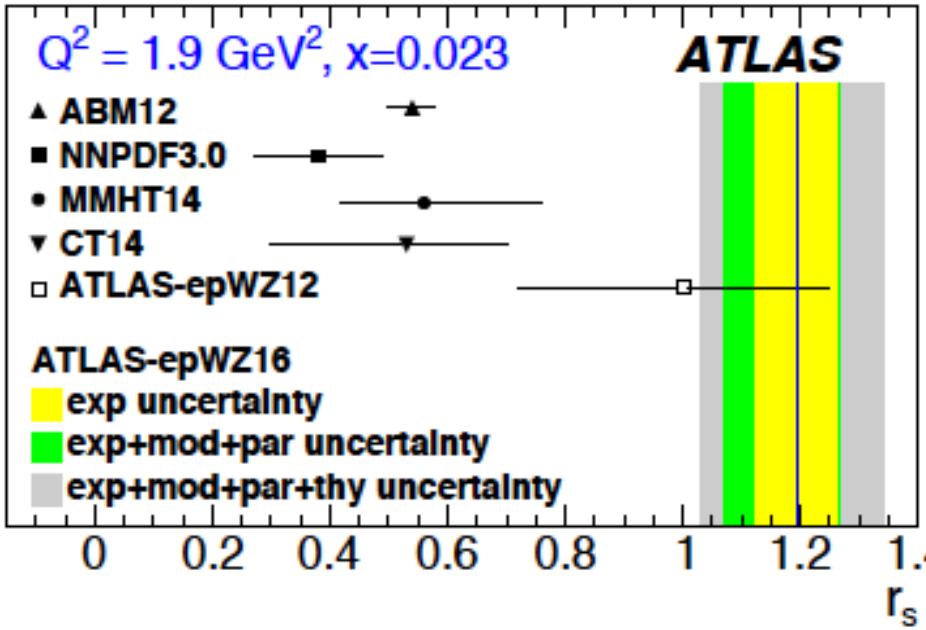
The LHC delivered now 100 fb^{-1} and is scheduled to deliver 3-4 ab^{-1} by 2040

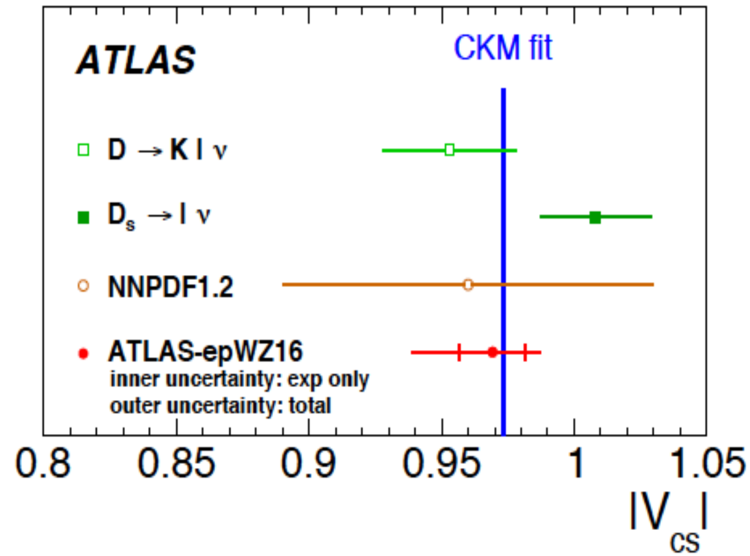
Amazing detector performances and innovative analyses by few 1000 people.

30 times more luminosity, slight energy increase. Pileup from 40 to 150, radiation ..
Major detector upgrades (completely new tracker for ATLAS. ITK, perhaps with HGTD)

Strange Strange

Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]





Confirmed with much higher precision

HERA+ATLAS → V_{cs}

ATLAS: 1612.0301, PRD

Expect LHeC+HL LHC to be 10 x better from +2-3% to surely 0.5% or below

Source: DC Photocathode

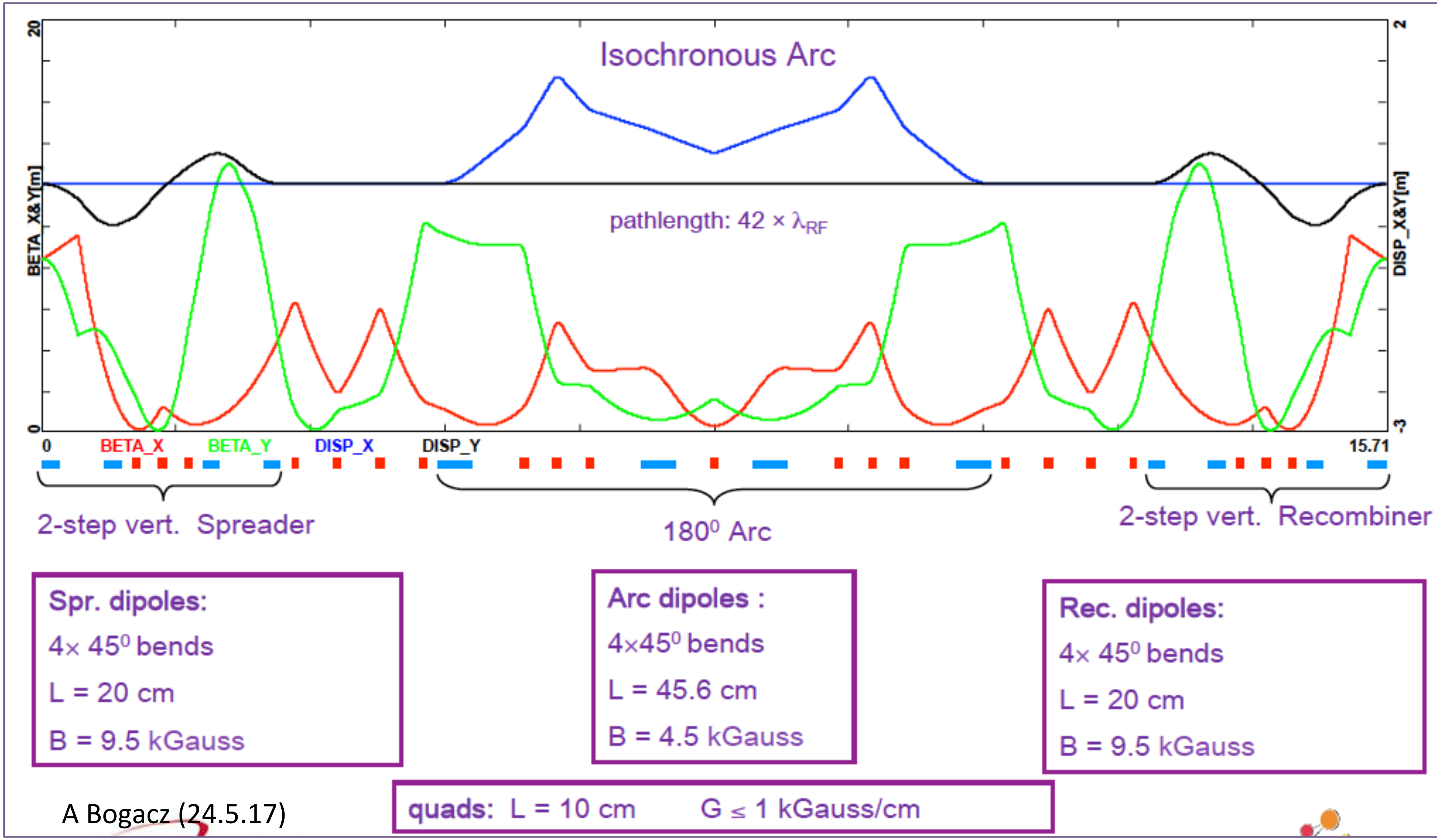
Material	Typical oper.λ	Work function	Observed Q.E.	Laser power for 20 mA	Observed max current	Obs. lifetime
Sb-based unpolarised	532 nm	1.5-1.9 eV	4-5%	4.7 W at Q.E.=1%	65 mA [Cornell]	Days rep.
GaAs-based polarised	780 nm	1.2 eV at NEA state	0.1-1.0%	31.8 W at Q.E.=0.1%	5-6 mA [JLAB]	Hours

Table 4.1: Characteristics of photocathode materials available for PERLE

← Boris Militsyn’s kukhnja at Daresbury

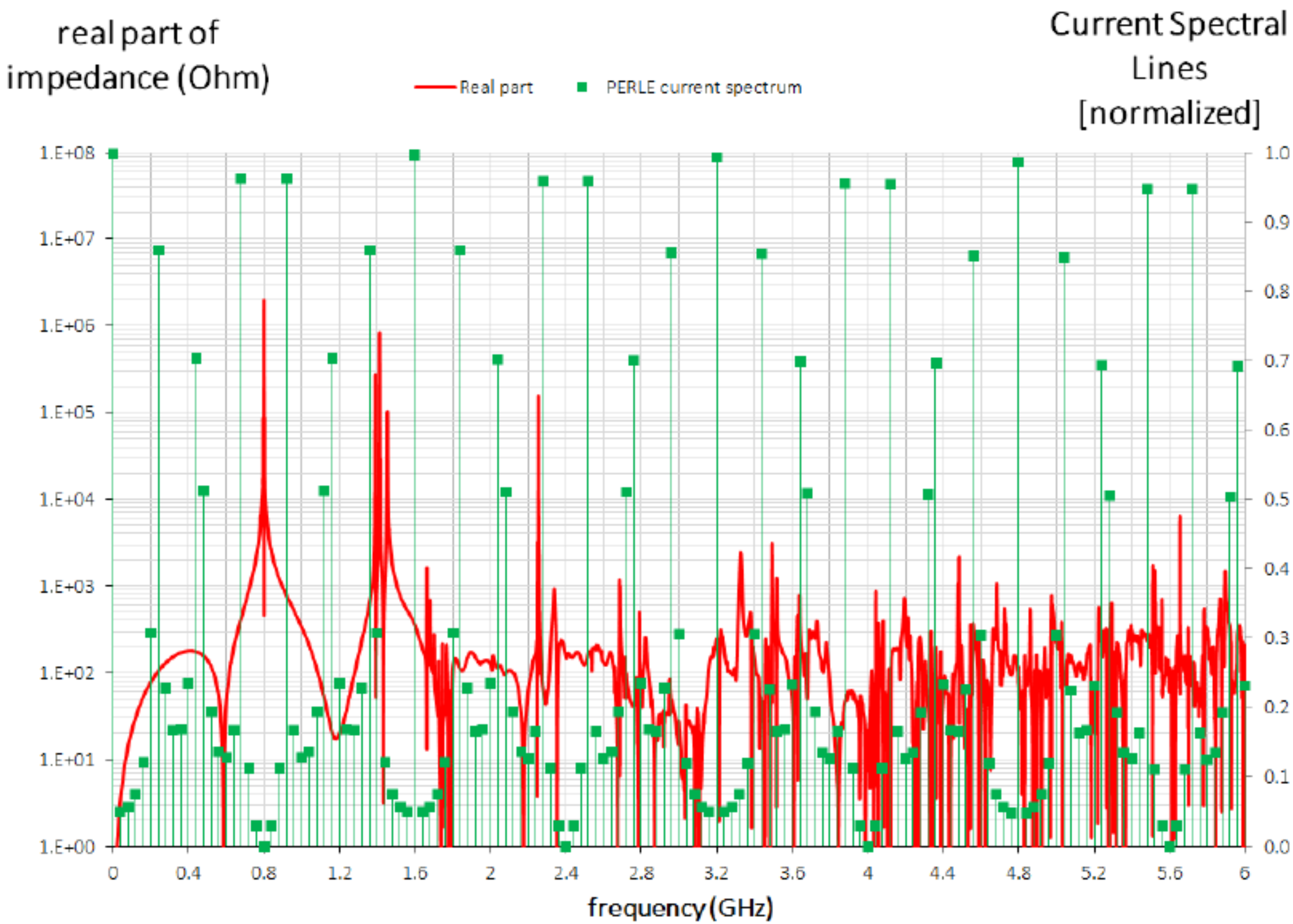
GaAs photocathode preparation facility designed for 4GLS and ALICE gun upgrade.

PERLE 3 turn optics (80 MeV Arc)



70 Dipoles and **114 Quadrupoles** **footprint 22 x 5.5 m2**

HOM Assessment



Impedance of cavities + oscillating modes (F Marhauser) ≠ Spectral content of PERLE beam (D Pellegrini)

Electrons for the LHC

There are various reasons to indeed build the LHeC

Physics (cf slide before)

The uncertainty of HEP and its experience demand pp+ep+ee

The LHC HL Phase physics program would be transformed with ep/eA

CERN needs to build a new machine 20 years after LHC was built and
20 years before a next big machine may indeed be realised.

An ep detector would be a welcome task following the HL LHC.

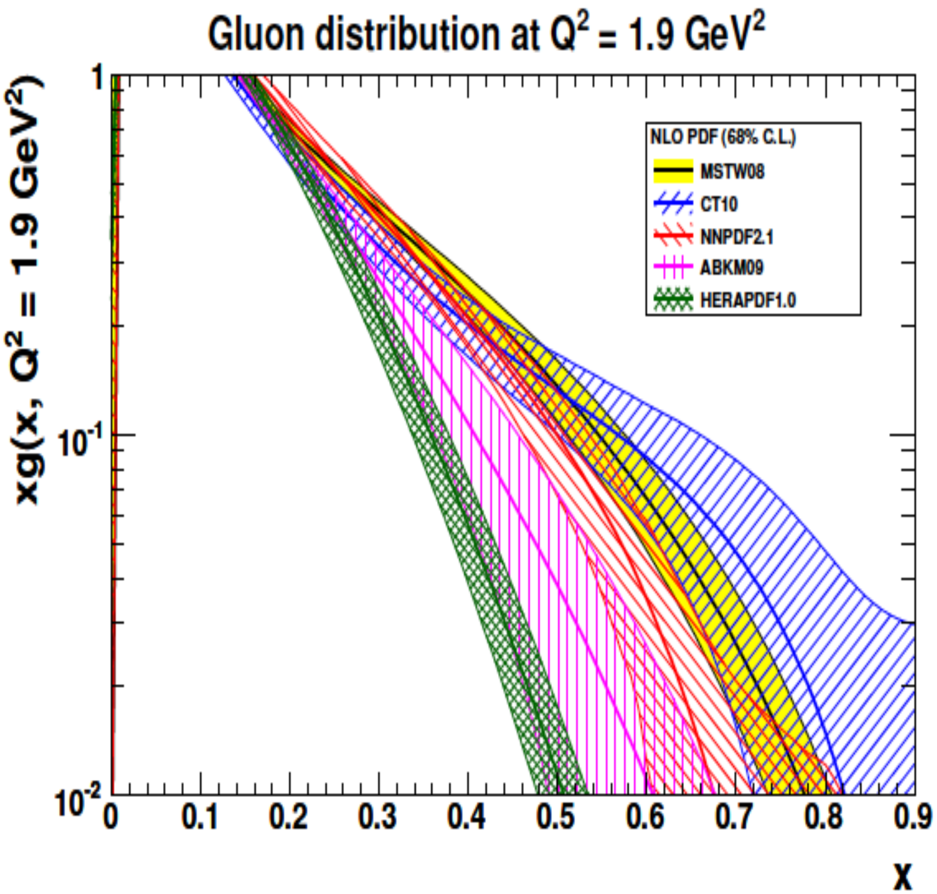
There is a window of opportunity with the LHC lifetime, AA ending etc.

The ERL is green, high tech, innovative accelerator technology, in line with XFEL..

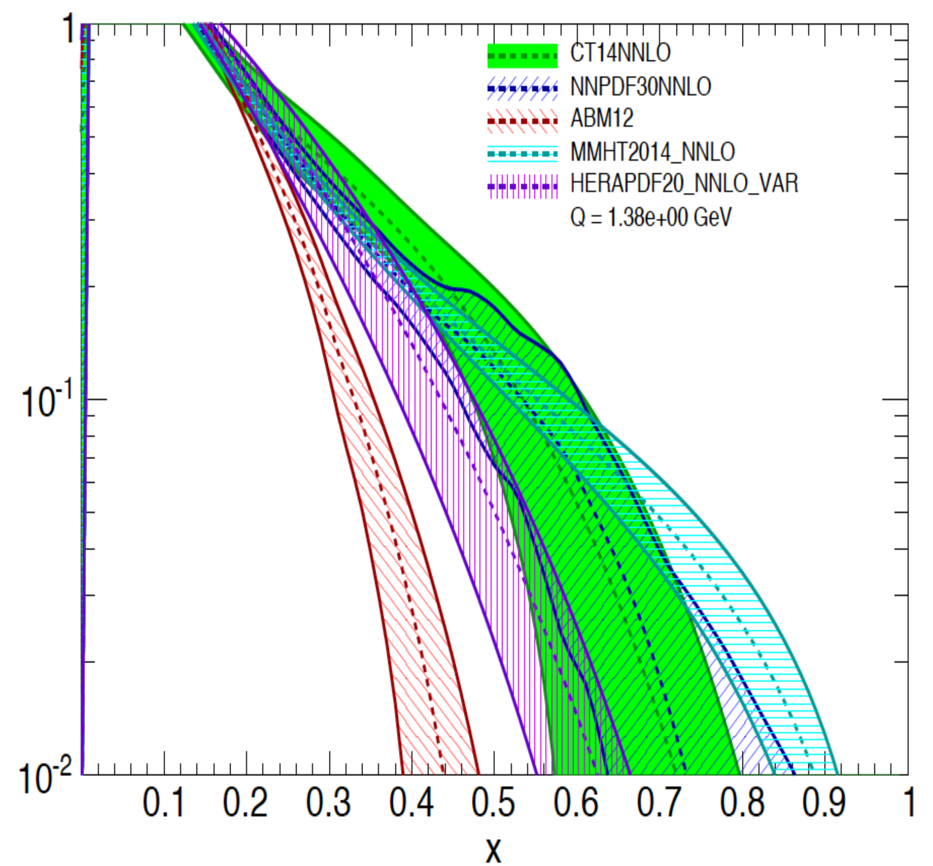
Veksler wanted one reason:
ep is the most precise and versatile microscope the world can build and CERN its place

High x Gluon Density Now

High x



Gluon prior to LHC data (2011)



Gluon with (first) LHC data (2015)

used by CT14,NNPDF,MMHT

Top Physics

Top electric charge

EDM and MDM

Anomalous t-q-γ and t-g-Z

V_{tb} and W-t-b

Top spin

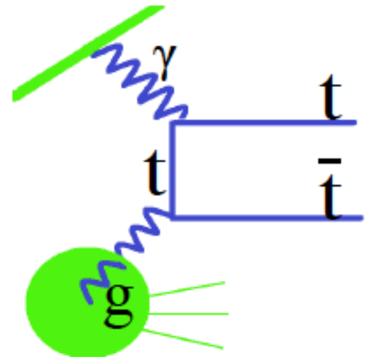
Top PDF

Top mass

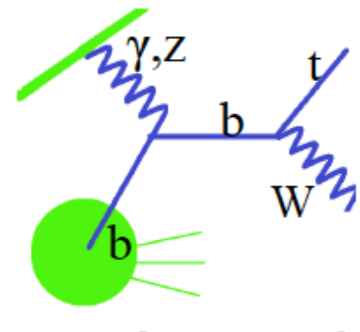
Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Pair production



Single production



σ=0.05pb @ LHeC
σ=1.14pb @ FCC-ep

σ=1.73pb @ LHeC
σ=15.3pb @ FCC-ep

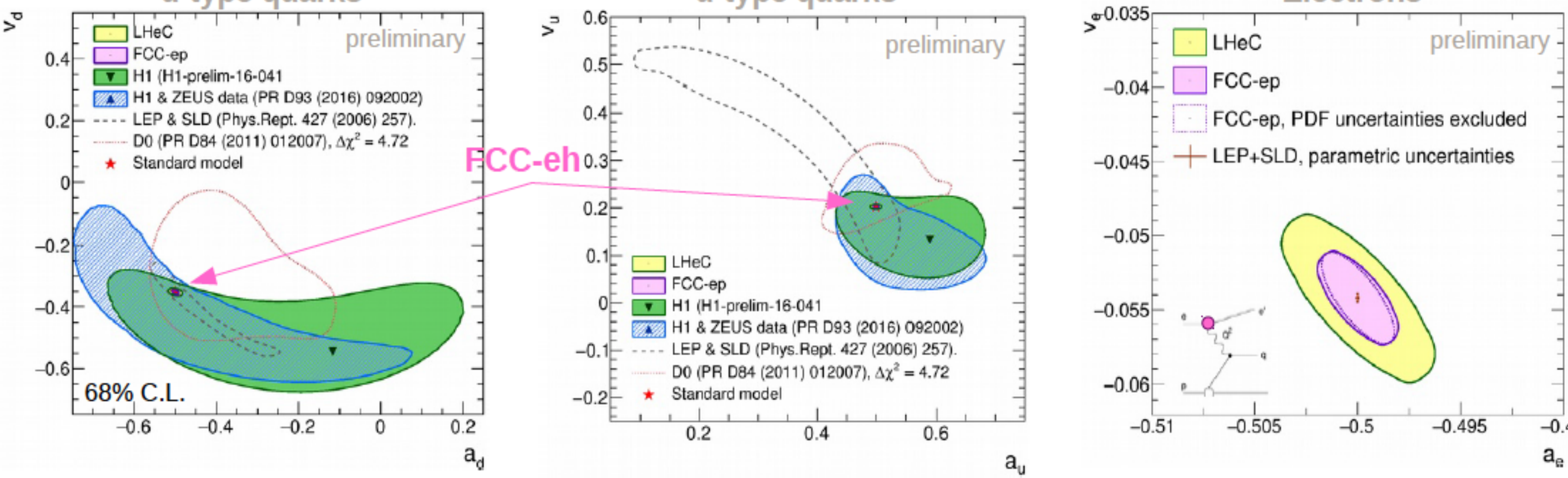
LHeC and even more FCC-eh **are top factories with huge BSM potential**
For top itself: maximise Ee. For t as background for Higgs: not too much

cf Christian Schwanenberger, Top in ep, Talk at FCC Physics Week 17.1.18

Electroweak Physics: LHeC and FCCeh

Weak neutral couplings: quarks, electrons

d-type quarks | u-type quarks | Electrons



Weak neutral quark couplings

- u- and d-quark couplings determined simultaneously
- Very precise measurements feasible

```
a_u =  0.5  +/- 0.003
a_d = -0.5  +/- 0.005
v_u =  0.20 +/- 0.002
v_d = -0.35 +/- 0.005
```

Electron couplings

- High precision
- Though:
  LEP with 'ulitmate' precision

High precision test of electroweak sector of Standard Model

Complementary test

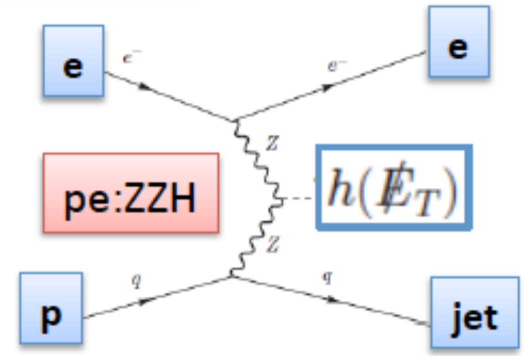
title

Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Update of values given in case of 2σ and L=1 ab^{-1}

Delphes detectors	LHeC 1.3 TeV	FCC-he 3.5 TeV
LHC-style	4.7%	1.9%
First 'ep-style'	5.7%	2.6%
+BDT Optimisation	5.5% (4.5%*)	1.7% (2.1%*)



- ✓ Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques*
- ✓ Results for full MG5+Delphes analyses look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 1.7% to 1.2% for 1 to 2 ab^{-1}

- ✓ We also checked LHeC ←→ FCC-he scaling with the corresponding cross sections (* results in table) : Downscaling FCC-he simulation results to LHeC would give 4.5%, while up-scaling of LHeC simulation to FCC-he would result in 2.1% → all well within uncertainties of projections of ~25%
- employ further synergies within LHC community and HL-LHC&FCC study group
  → **further detector and analysis details have certainly an impact on results**

Uta Klein, Higgs in ep, Talk at FCC Physics Week, 16.1.18