ep/eA in Europe: LHeC, FCCeh, …

Deep Inelastic Scattering at the Energy Frontier

LHeC:
E_e=60 GeV
E_p= 7 TeV

Introduction
Motivation + Opportunity
Highlights
Status
PERLE

FCC_eh:
E_e =60 GeV
E_p =50 TeV

HE LHC:
E_p=12.5 TeV

For references, please consult
lhec.web.cern.ch

LHeC CDR
arXiv:1206.2913
J.Phys. G39 (2012) 075001

Max Klein
University of Liverpool

for the LHeC+FCC-eh Study Group

. . .

KET Workshop at DESY, 15.12.2017

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, yy.
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

MK, presented to UK PPAP, July 2017

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

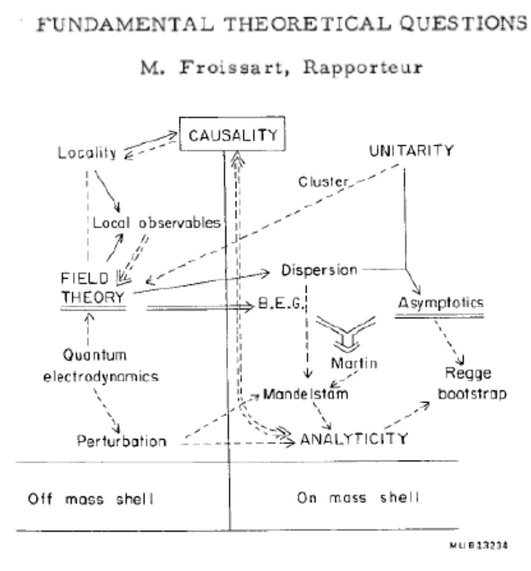


Fig. 1-1. Logical map of "Fundamental" concepts.

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

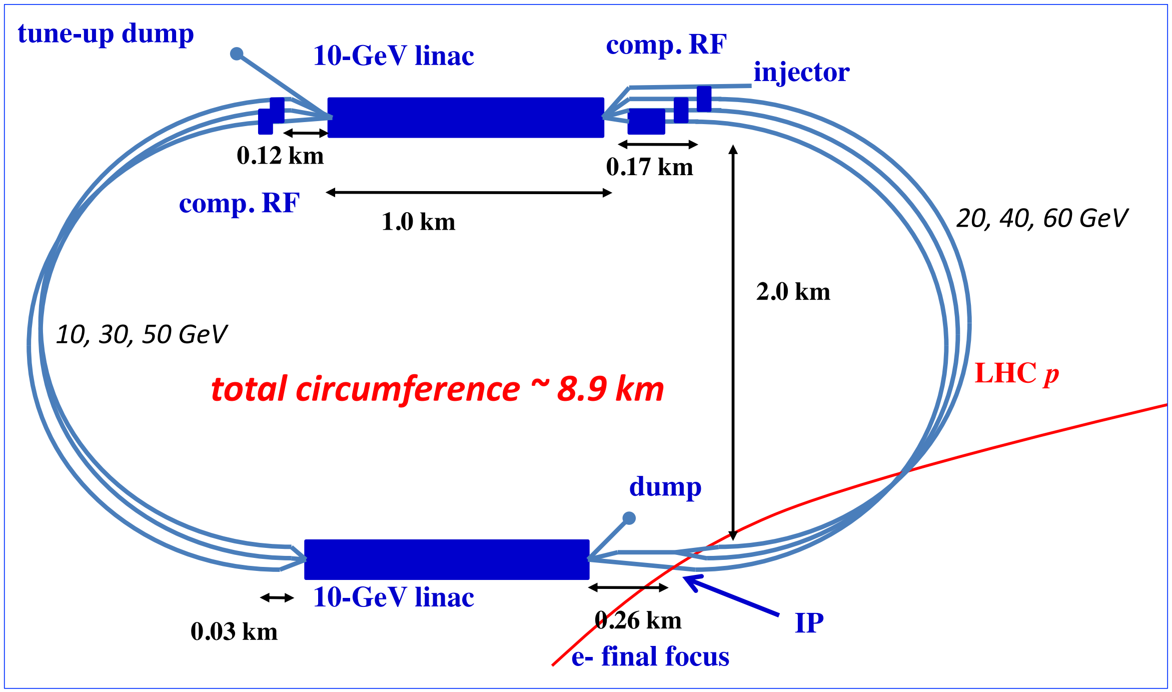
MK, presented to UK PPAP, July 2017

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

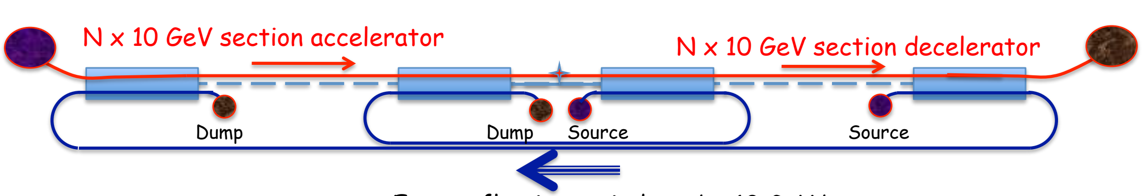
ep/A with the LHC

Conceptual Design Report: arXiv:1206.2913, published in JPhysG – 20 referees..



LHeC: 60 GeV off 7 TeV, L(ep) =10^{34} 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



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

You never walk alone

Motivation

Mandate (ECFA, NuPECC, CERN, PP Community)

HERA's success which is DESY's legacy to a major extent

Technology (ERL – green, high tech accelerator technology, SCRF)

An affordable accelerator for CERN to build, not only design.

Detector (a high tech detector challenge following the lumi upgrade)

New Physics in QCD + BSM, BLHC and ultra high precision (for ep AND pp)

The cleanest high resolution microscope the world can build!

Exploitation of our largest particle physics infrastructure

It can be done (think of 2m SLAC Linac 50 years ago and XFEL at DESY)

… in one word
develop energy frontier collider physics and technology *comme il faut*

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

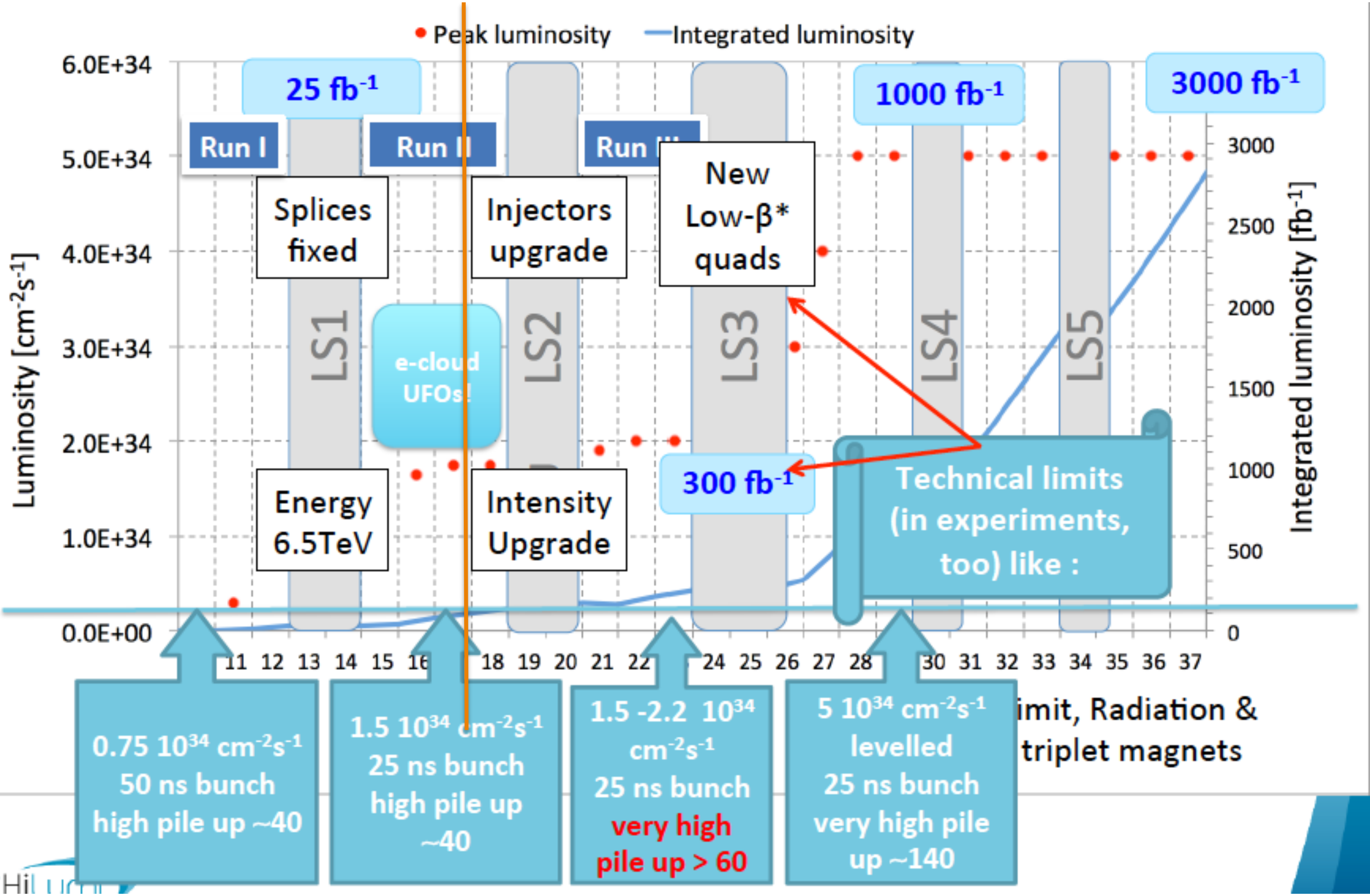
OB+MK: FCC-eh responsibles
MDO: physics co-convenor

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

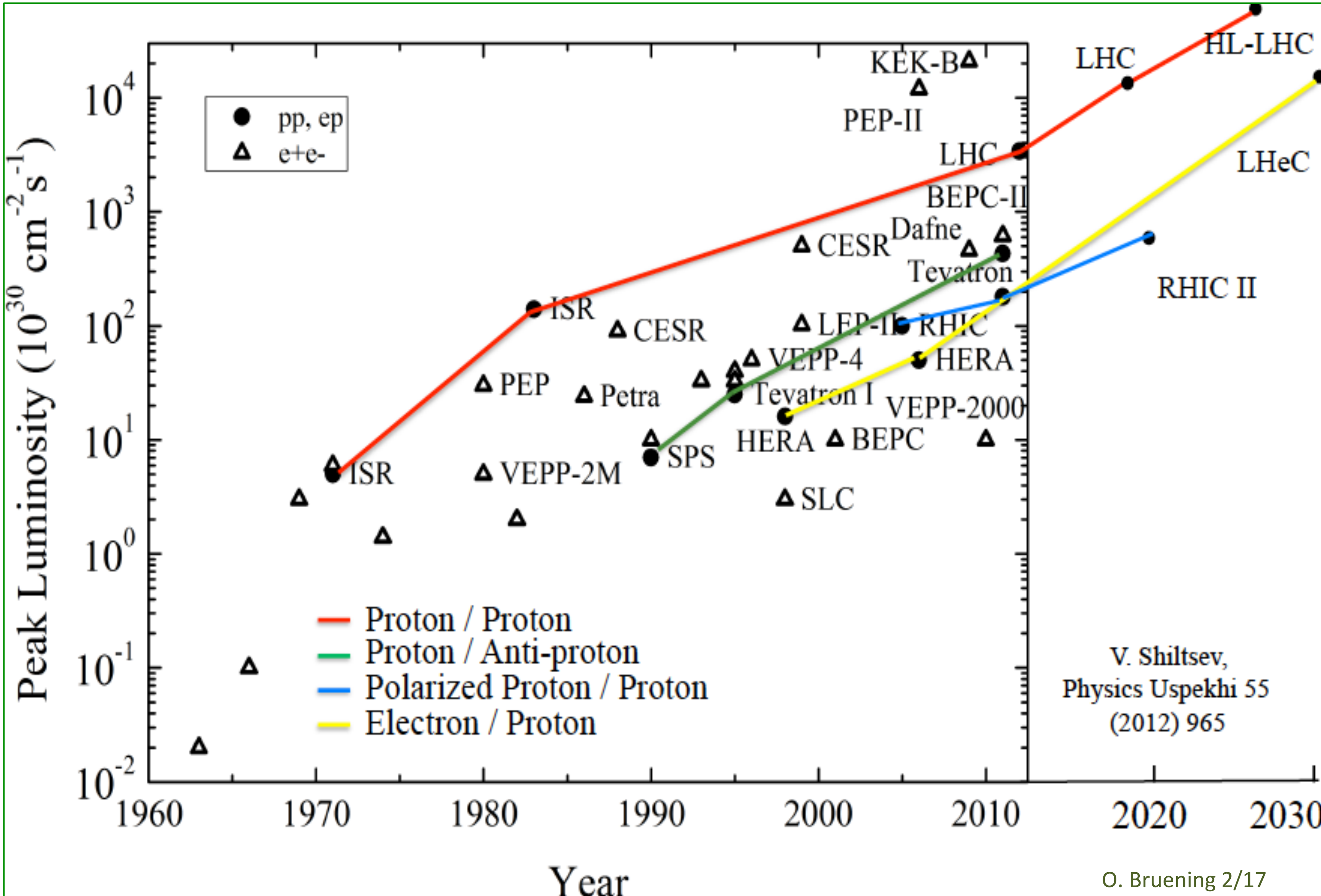
*)September 2017

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



O Bruening, F Bordry

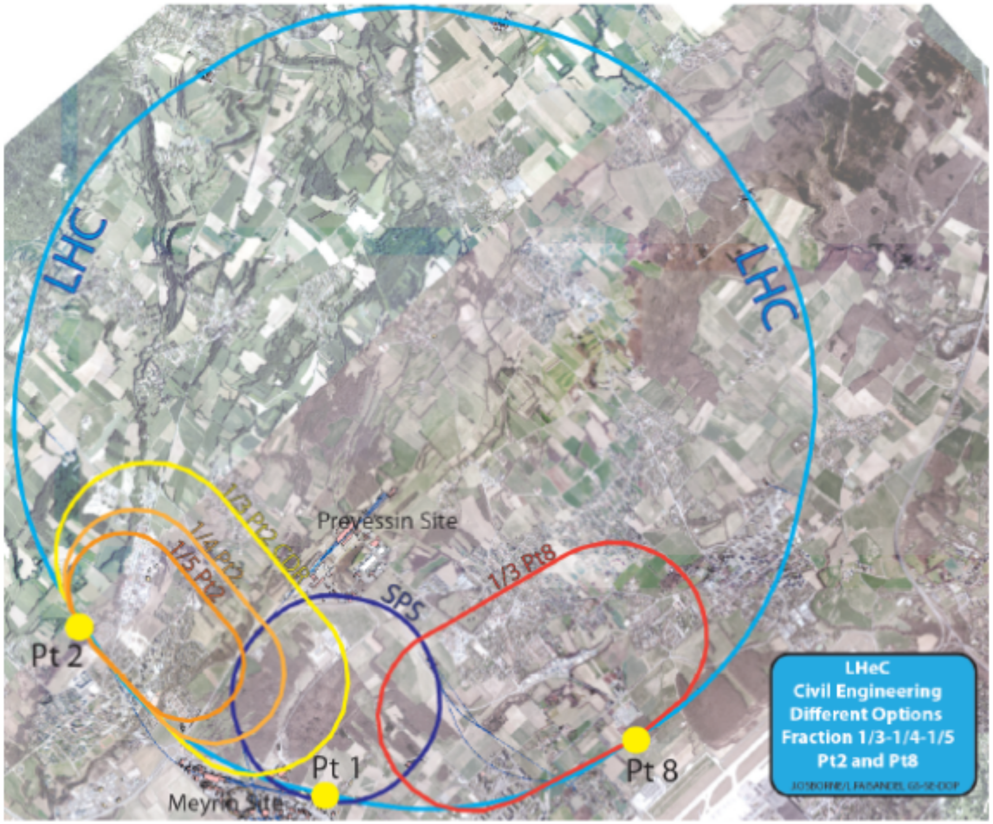
Collider Luminosities vs Year (pp and ep)

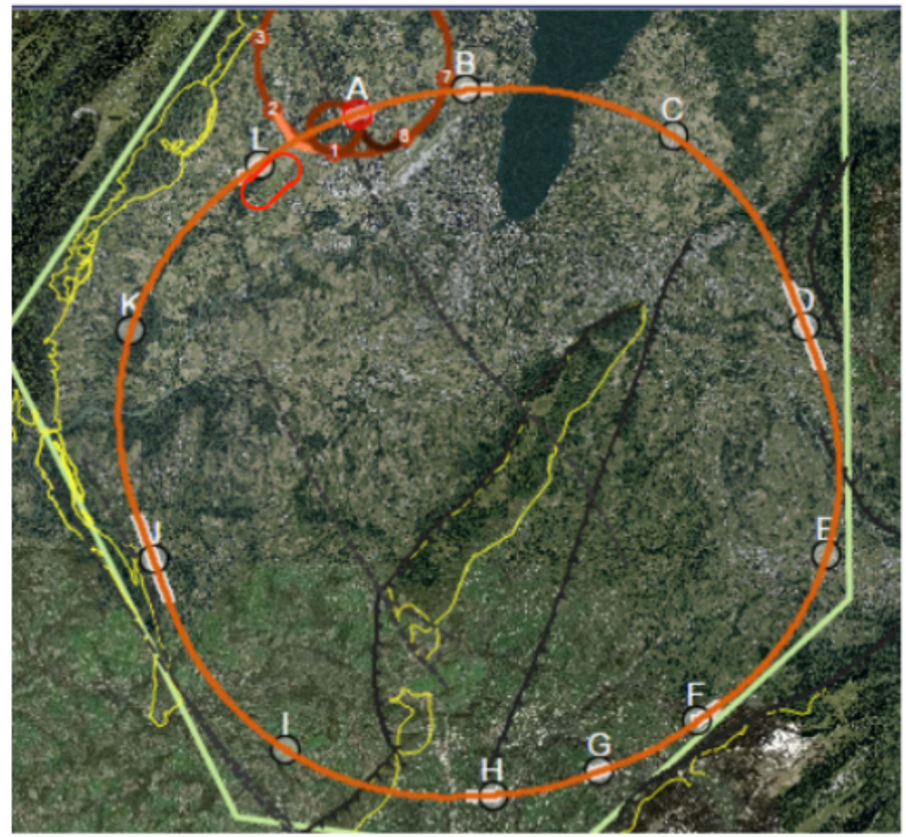


Location + Footprint of the **electron ERL**

LHC (HL and HE)

FCC



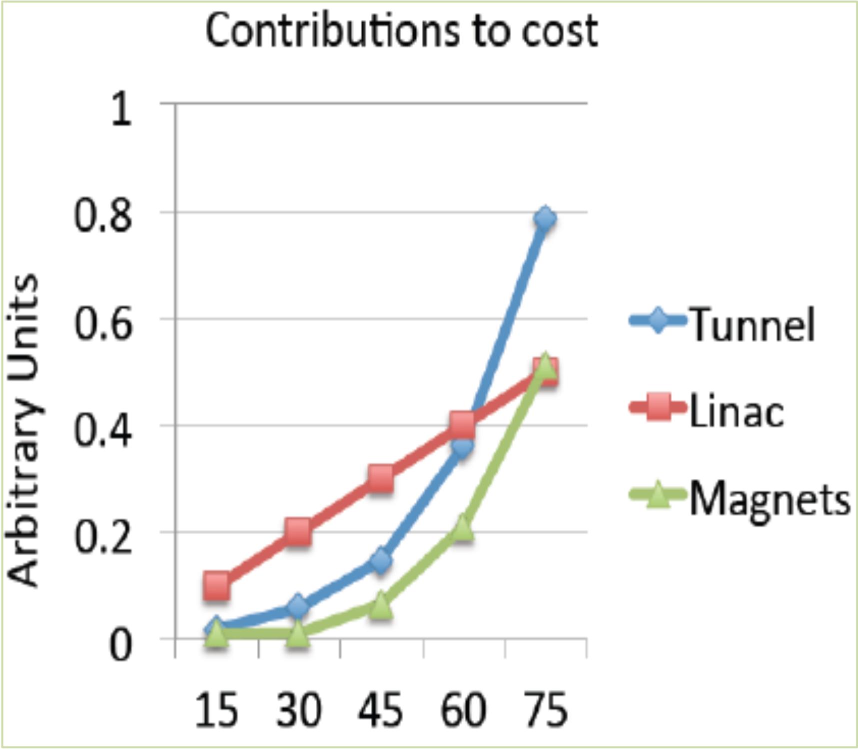


Energy – Cost – Physics – Footprint
are being reinvestigated

A 9km ERL is a small add-on for the FCC
Doubling the energy to 120 GeV hugely increases cost and effort.

Considerations on the Choice of E_e

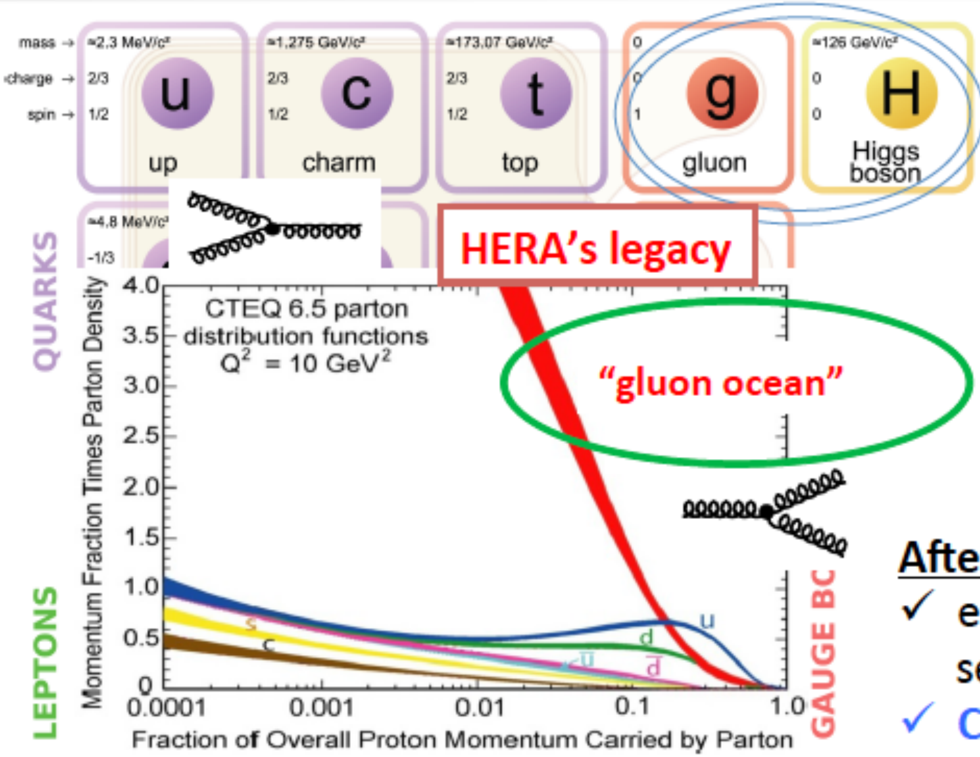
Chosen 60 GeV and U(LHeC)=U(LHC)/3 as a supposedly realistic first choice.



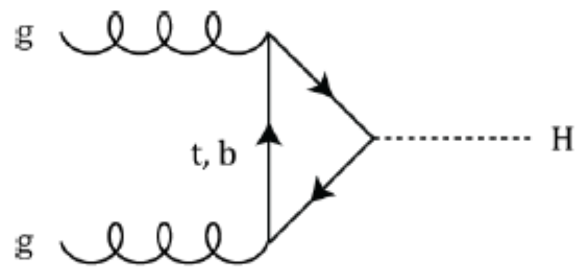
MK, F Zimmermann

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

SM, Higgs and QCD



Higgs discovery at LHC via gluon-gluon fusion

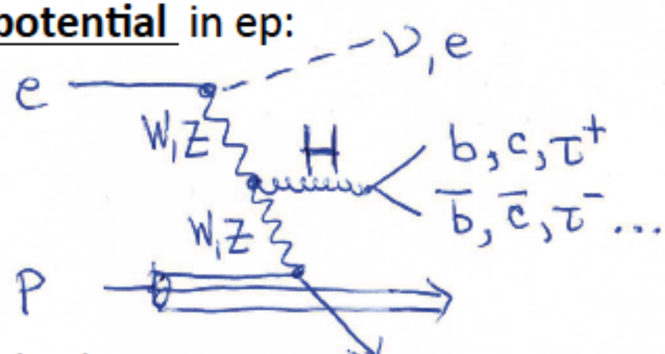


After the Higgs discovery:

✓ ep : High precision quark-gluon dynamics for sensitive searches; top & Higgs physics

✓ Concurrent running of pp and ep : Compelling synergy for exploring the EW and QCD sector to unprecedented precision.

Higgs potential in ep:



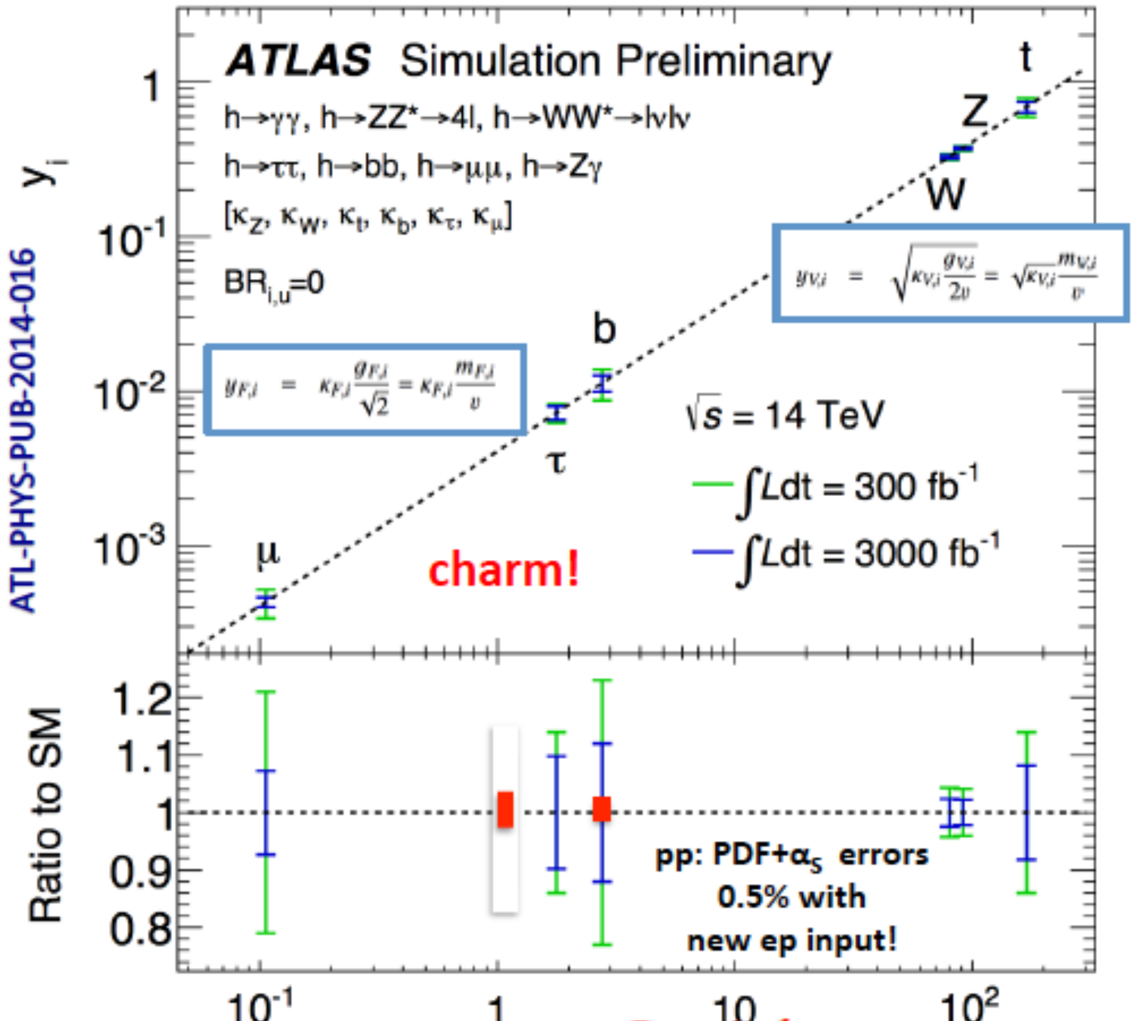
Higgs physics & EW symmetry breaking:

① High precision coupling measurements

② Higgs as the portal for new physics, DM etc.

Higgs Couplings at pp + ep

running concurrently



LHeC @1ab^{-1}

results in 2038 …

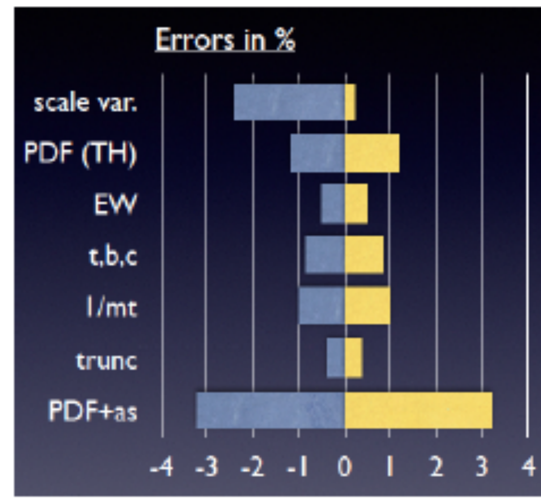
concurrent with HL-LHC end

Uncertainty on pp Higgs cross section

Giulia Zanderighi, Vietnam 9/16,

from C.Anastasiou et al, 1602.00695

who also discuss the ABM alpha_s..

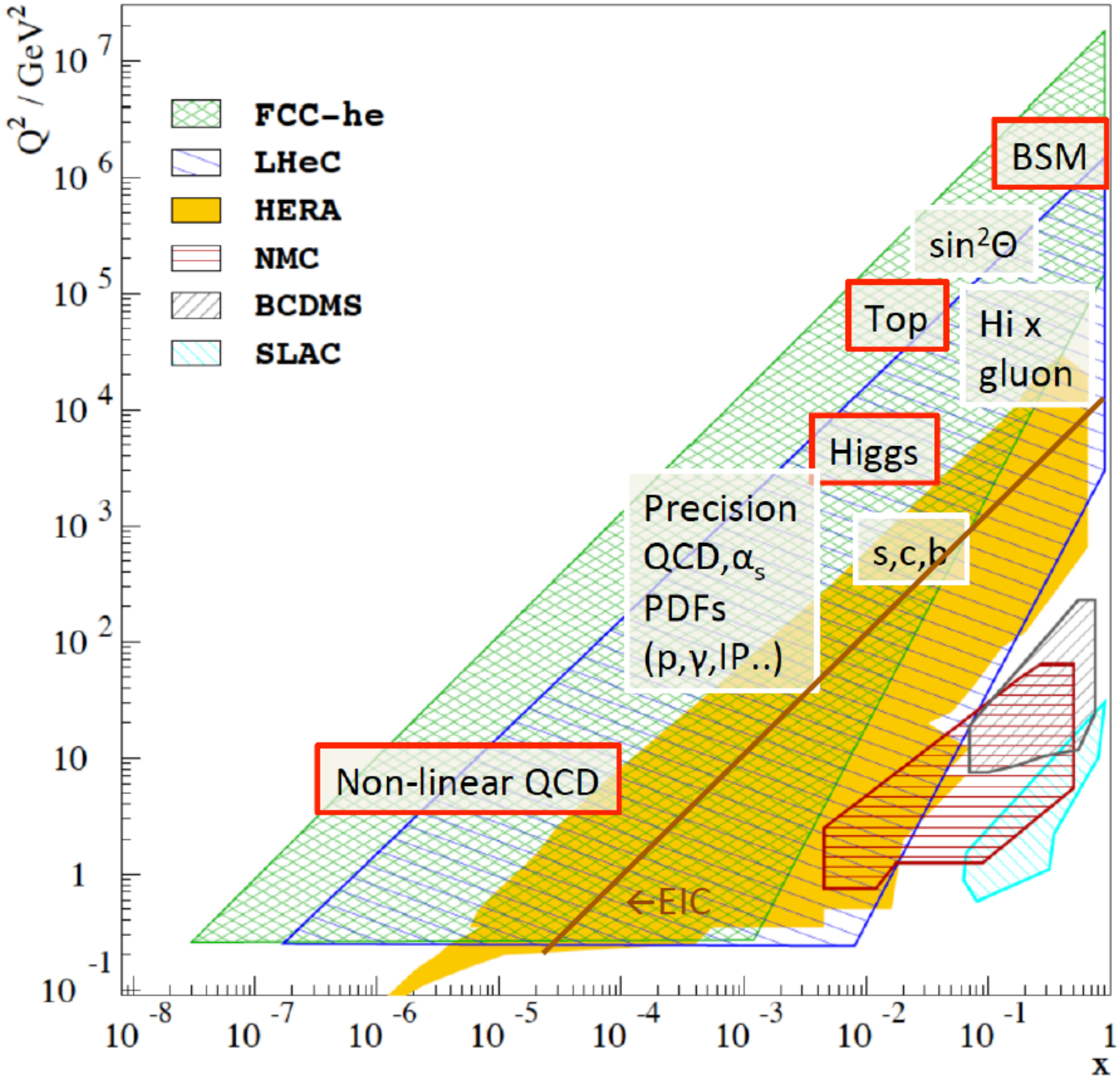


→ use ep as the 'near' detector for pp to beat those α_s and PDF uncertainties to <~0.5%, δm_b to 10 MeV; δm_{charm} to 3 MeV

Physics Programme

cf Nestor Armesto at this Workshop

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.

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.

V.N. Gribov, L.N. Lipatov, *Gluboko neuprugoe ep-rasseyanie v teorii vozmushchenii*, Yadernaya fizika, 15(4), 781-807 (1972).

2.5.1940 Leningrad
4.9.2017 Dubna

The Pomeranchuk Singularity in Nonabelian Gauge Theories: E.A.**K**uraev, **L**, V.S.**F**adin, SJNP 45(77)199
The Pomeranchuk Singularity in QCD: Ya.Ya.**B**alitsky, L **L**ipatov: SJNP 28 (78) 822

Small x Physics in perturbative QCD Physics Reports 286 (1997)131, hep-ph/9610276

More recently Lipatov has taken these ideas into the hot, new field in theoretical physics: **the anti-de Sitter/conformal-field theory correspondence (ADS/CFT)** – a hypothesis put forward by Juan Maldacena in 1997. This states that there is a correspondence – a duality – in the description of the maximally supersymmetric N=4 modification of QCD from the standard field-theory side and, from the "gravity" side, in the spectrum of a string moving in a peculiar curved anti-de Sitter background – a seemingly unrelated problem. However, Lipatov's experience and deep understanding of re-summed perturbation theory has enabled him to move quickly into this new territory where he has developed and tested new ideas, considering first the BFKL and DGLAP equations in the N=4 theory and computing the anomalous dimensions of various operators. The high symmetry of this theory, in contrast to standard QCD, allows calculations to be made at unprecedented high orders and the results then compared with the "dual" predictions of string theory. It also facilitates finding the integrable structures in the theory (Lipatov 2009).

D Diakonov, CERN Courier July 2010

A Millenium Prize Question

QCD, as much as it seems to work for the description of high energy interactions as at the LHC, still has a very fundamental problem that is the explanation of the confinement of partons inside the proton. This caused Jaffe and Witten, in 2000, to propose including Quantum Yang-Mills Theory as one of the seven millenium prize questions, in which they indicated that QCD indeed shall be a consistent non-perturbative Quantum Field Theory which has to have three features: i) a mass gap between confined massless gluons and their massive bound states, ii) confinement of partons compatible with SU(3) invariant free hadrons and iii) chiral symmetry breaking to incorporate current algebra [25]. Thus there is much more behind the strong interaction theory than is naively known. Deep inelastic scattering is ideally suited to approach the confinement puzzle by i) studiing the stunning phenomenon DIS diffraction where the proton remains intact despite a hugely energetic collision, and ii) by exploring the process of hadronisation, i.e. the propagation of partons in space-time, their interaction and the coalescence into colour-singlet states. The role the LHeC can play in these investigations has been discussed in the CDR, see also [26]. The LHeC allows to follow the particle formation, sketched in Fig. 4, over a long distance which can be prescribed with the scattering kinematics. Measurements of Deeply Virtual Compton Scattering (DVCS) processes can establish a

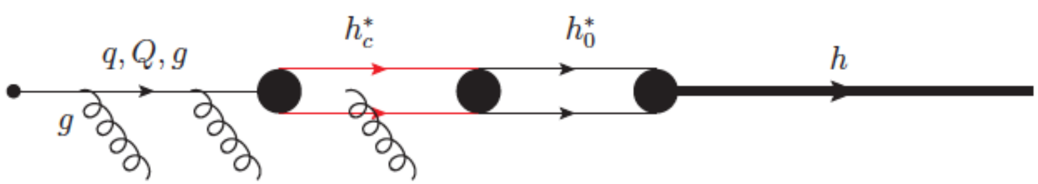


Figure 4: Time evolution of hadronisation from a parton created in an interaction on to the formation of coloured and white states preceding the emission of a hadron, from [26].

dynamic picture of the 3D structure of the proton as is entailed in Generalised Parton Distributions.

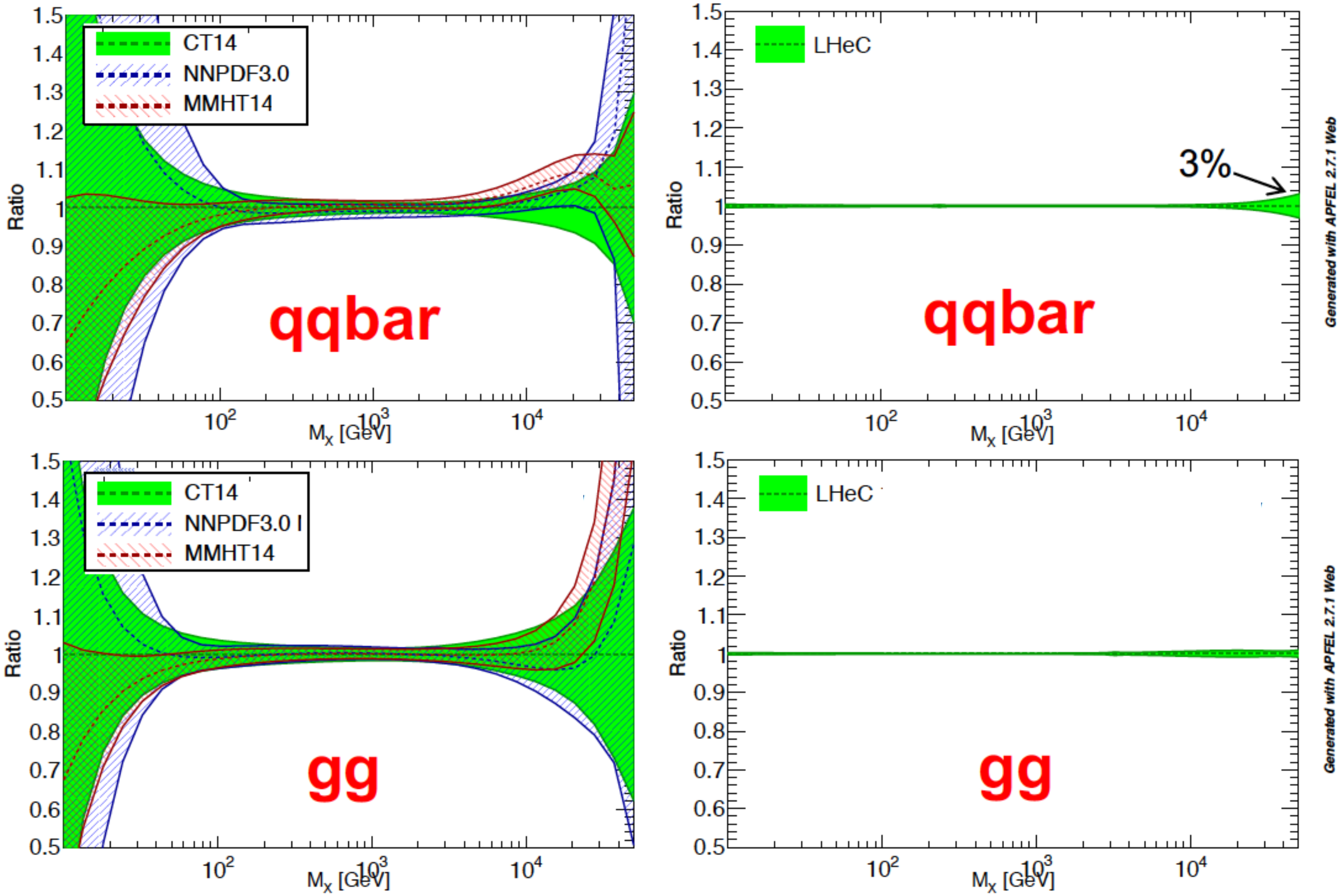
MK The Future of DIS and the LHeC: Contribution to a Book in Memory of Guido Altarelli, 2018

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^3LO…

Strong Coupling in inclusive DIS at LHeC to 0.1%

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



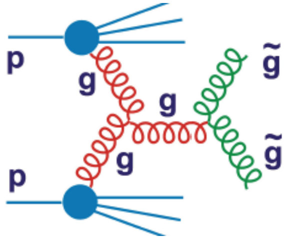
Note that LHC is about to reach its own limits on PDFs. pp is NOT DIS, cf ATLAS W,Z to 0.5%

Empowering pp Discoveries

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

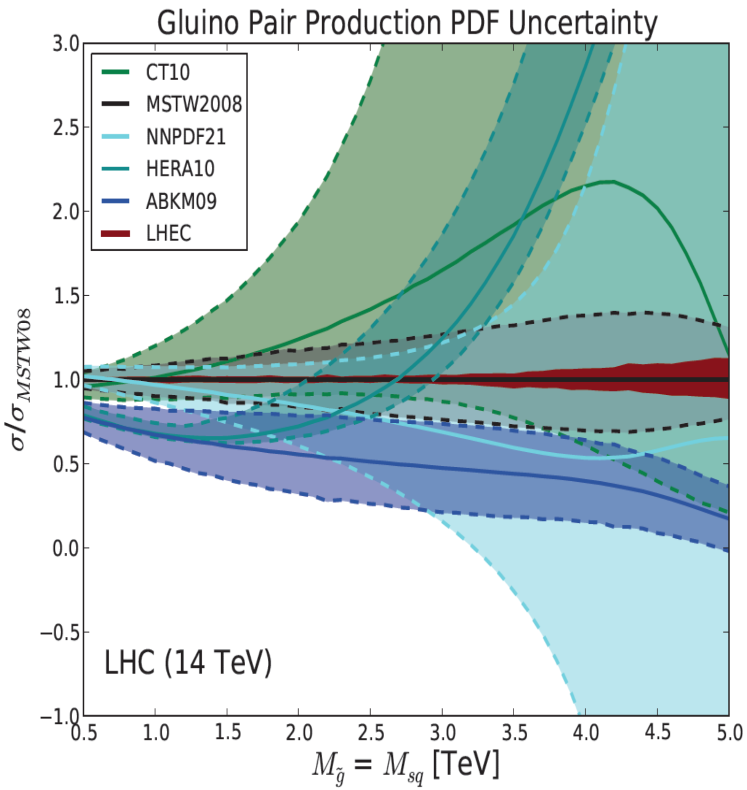
GLUON

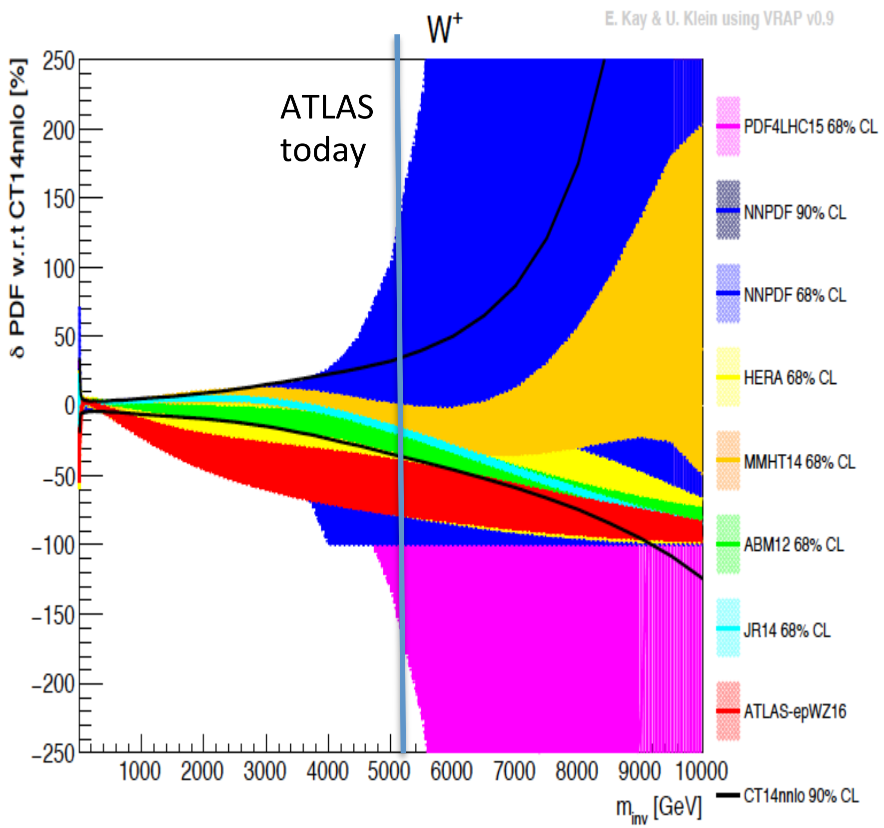
SUSY, RPC, RPV, LQS..



QUARKS

Exotic+ Extra boson searches at high mass





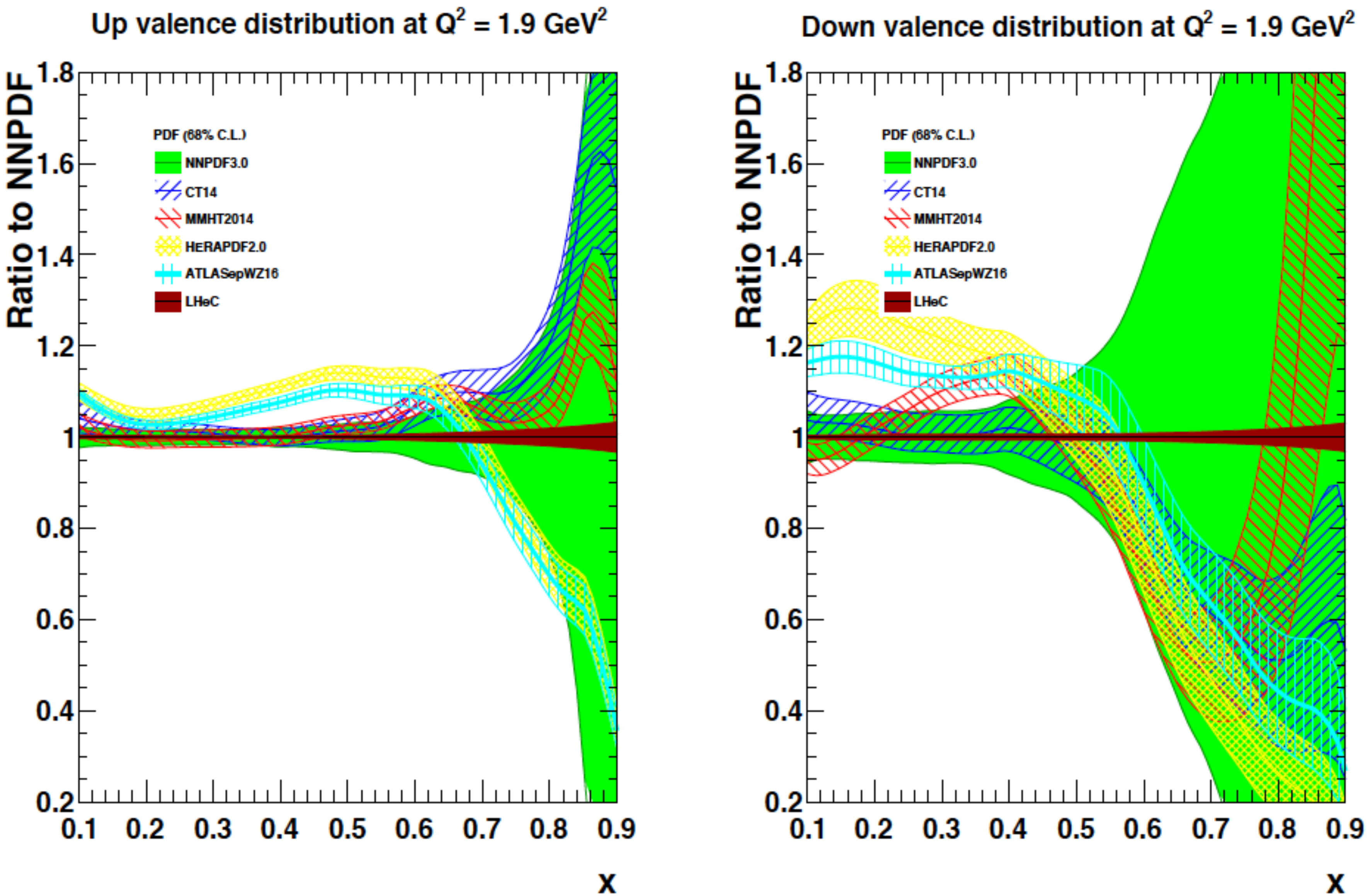


Figure 2: Determination of the valence quark distributions as functions of Bjorken x. Plotted are the ratios to the NNPDF result with uncertainties displayed as are provided by the individual sets, left for the up-valence quark and right the down-valence quark distribution. For the LHeC the total uncertainty 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.

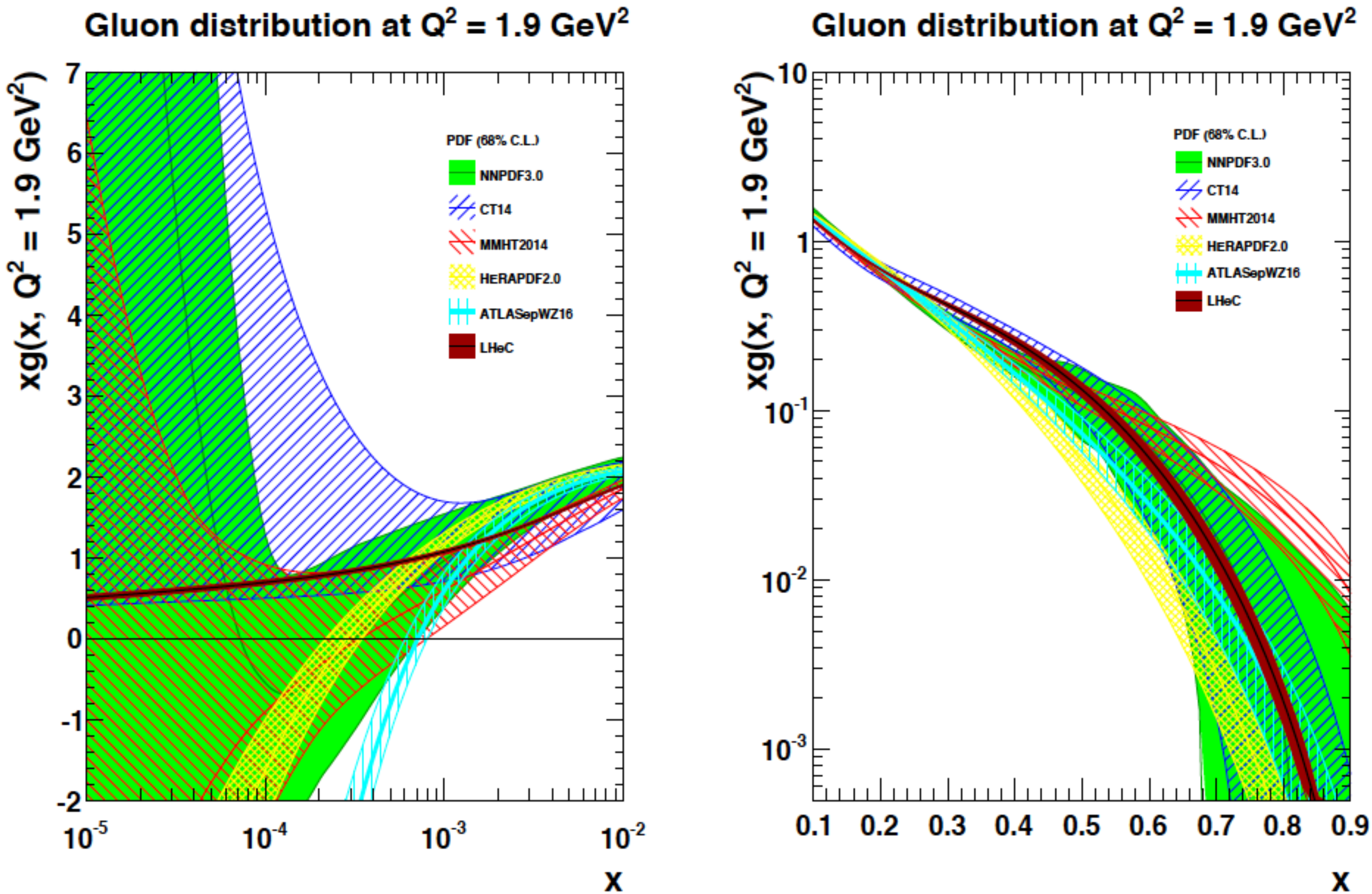
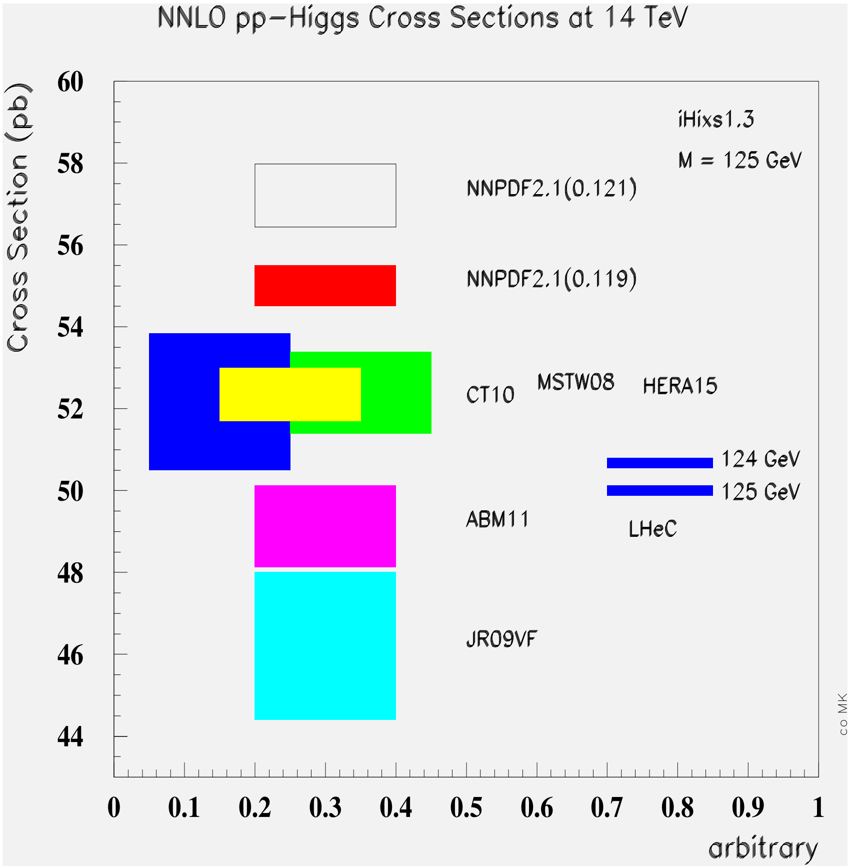
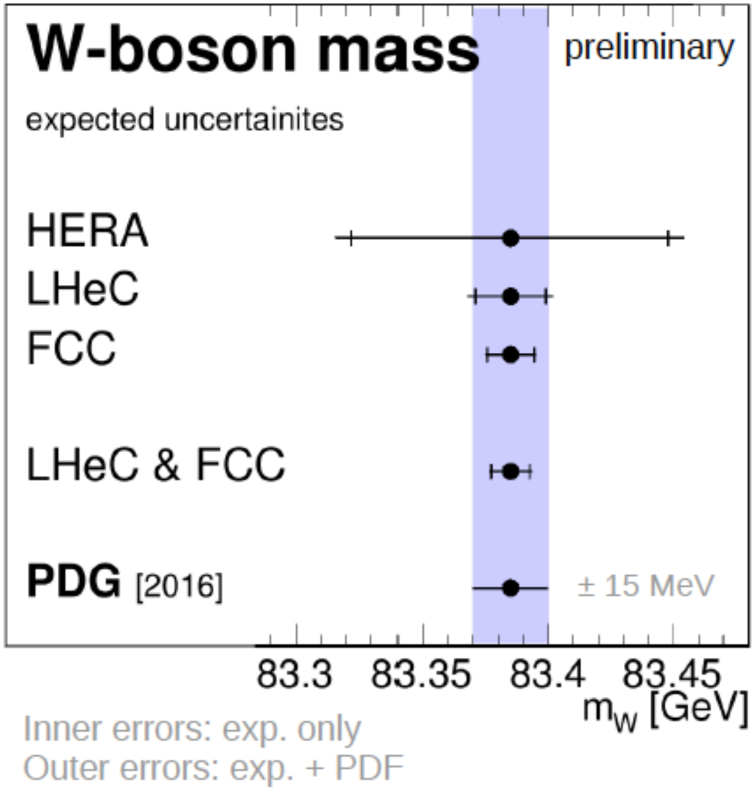


Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on xg from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for xg a range from $x \simeq 5\ 10^{-4}$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

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

Top Physics

Top electric charge

EDM and MDM

Anomalous t-q-y and t-g-Z

V_{tb}

Top spin

W-t-b

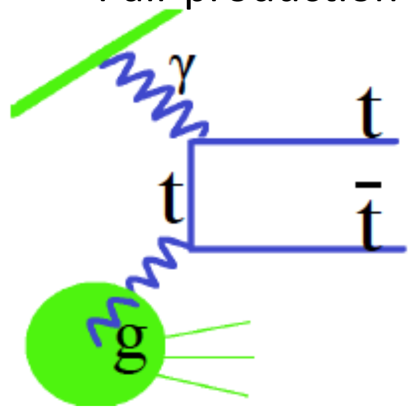
Top PDF

Top mass

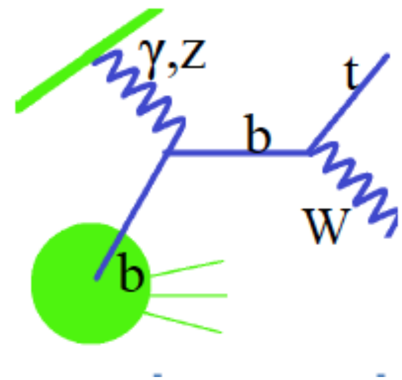
Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

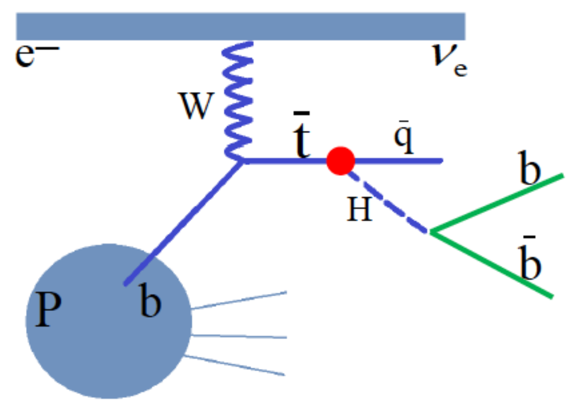
Pair production



Single production



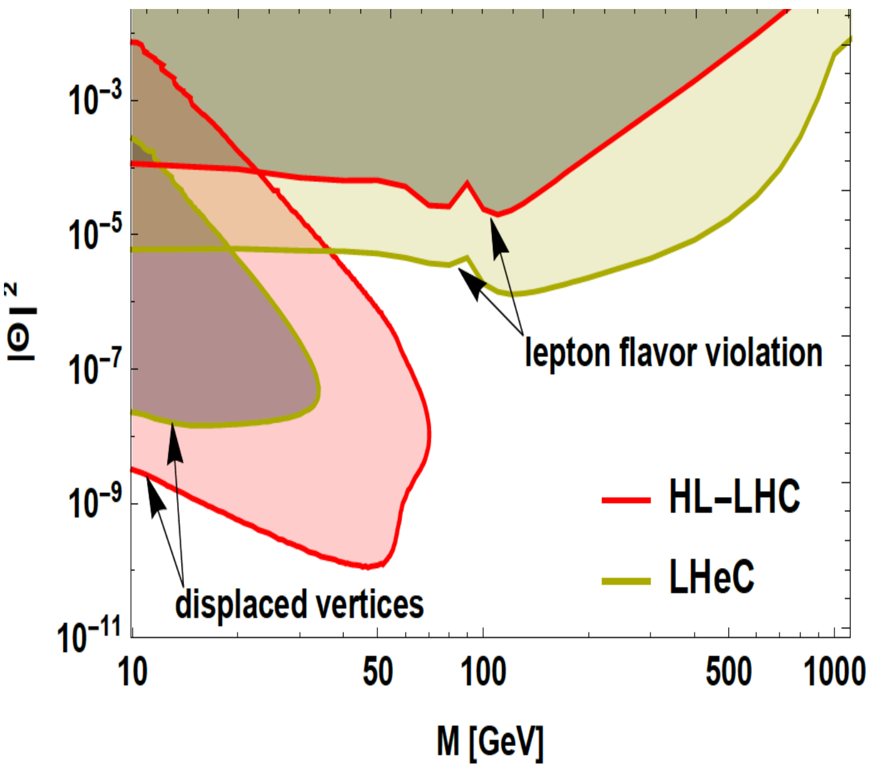
FCNC top Higgs CC interaction



Just started to fully see the huge potential of top physics in ep at high energies

Possible Discoveries Beyond SM with LHeC

Search for Sterile Neutrinos (LHC LHeC)



It is a wasted p that does NOT collide with an e beam
(Oliver Fischer - 2017)

QCD:

No saturation

BFKL

Instantons

Higher symmetry embedding QCD

Electroweak:

EFTs

Exotic Higgs Decays

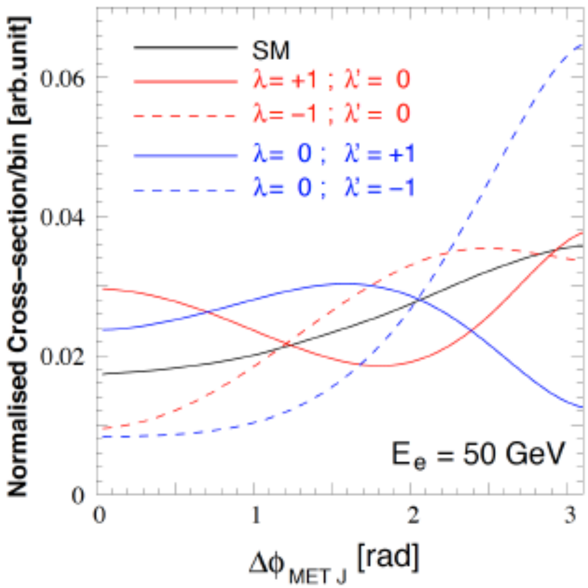
Extension of Higgs Sector

Sterile Neutrinos …

It would be a waste not to exploit the 7 TeV beams for ep and eA physics at some stage during the LHC time (Guido Altarelli – 2008)

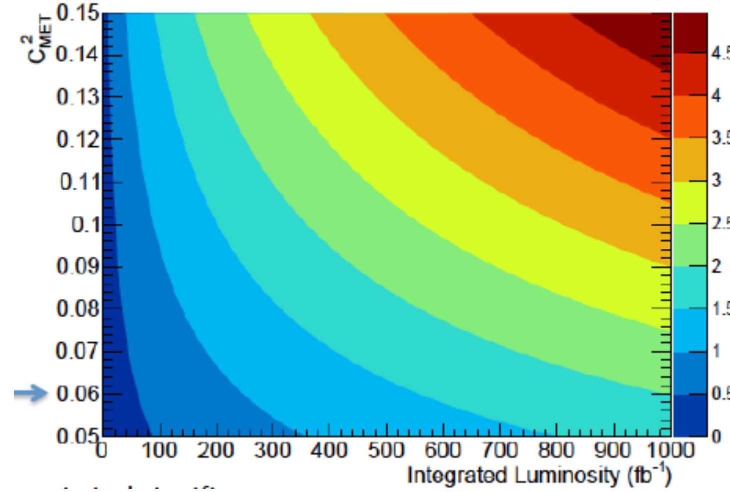
BSM Higgs in ep

CP Properties of H-VV vertex



Higgs to Dark Matter

$$C^2_{\mathrm{MET}} = \kappa_Z^2 \times \mathrm{Br}(h \to \not{E}_T)$$



Branching for invisible Higgs

Values given in case of 2σ

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Delphes detectors	LHeC 1.3 TeV	DLHeC 1.8 TeV	FCC-eh 3.5 TeV
LHC-style	4.7%	3.2%	1.9%
First 'ep-style'	5.7%		2.6%
+BDT Optimisation	5.5% (4.5%*)		1.7% (2.1%*)

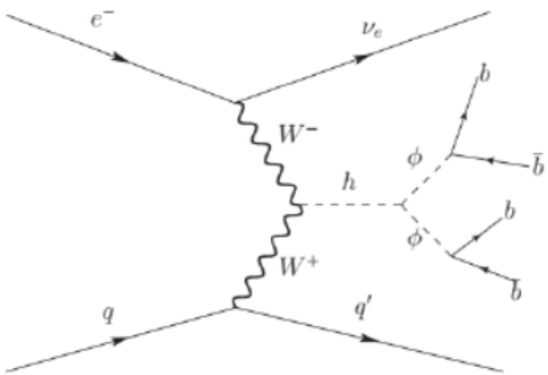
Cf talk by U Klein at September 2017 LHeC/FCCeh Workshop

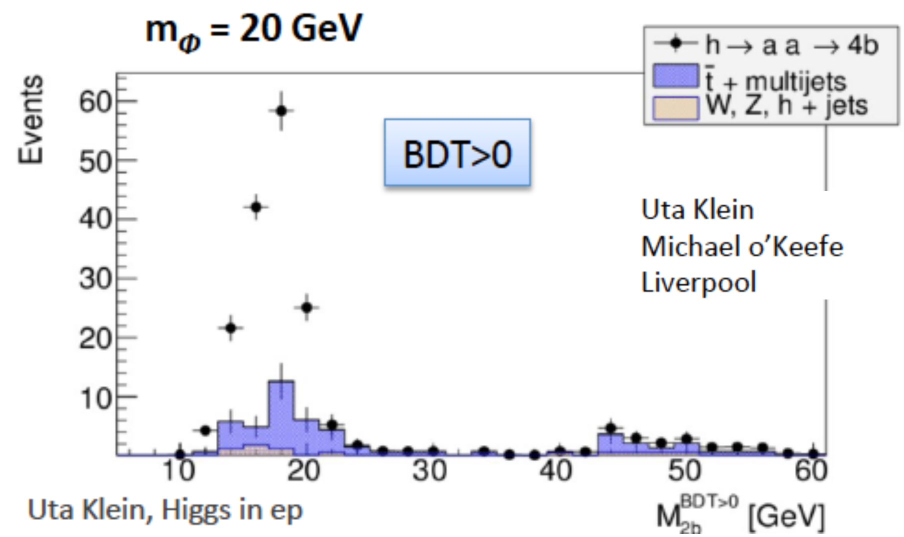
Exotic Higgs Decays

$$h \to \phi\phi \to 4b$$

ϕ: a spin-0 particle from new physics.

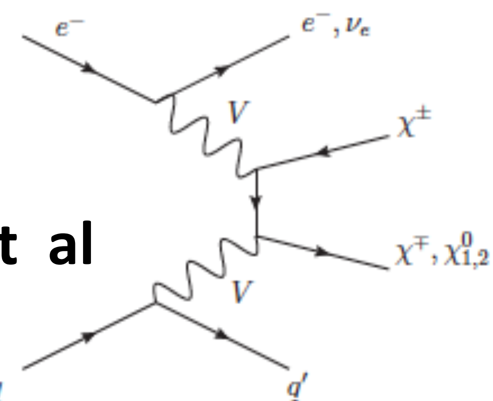
$$eq \to \nu_e h q' \to \nu_e \phi\phi q' \to \nu_e b\bar{b}b\bar{b}q'$$





1% branching with 1ab^{-1} at FCC-eh (prel)

S. Liu, Y. L. Tang, C. Zhang, S. Zhu, 1608.08458

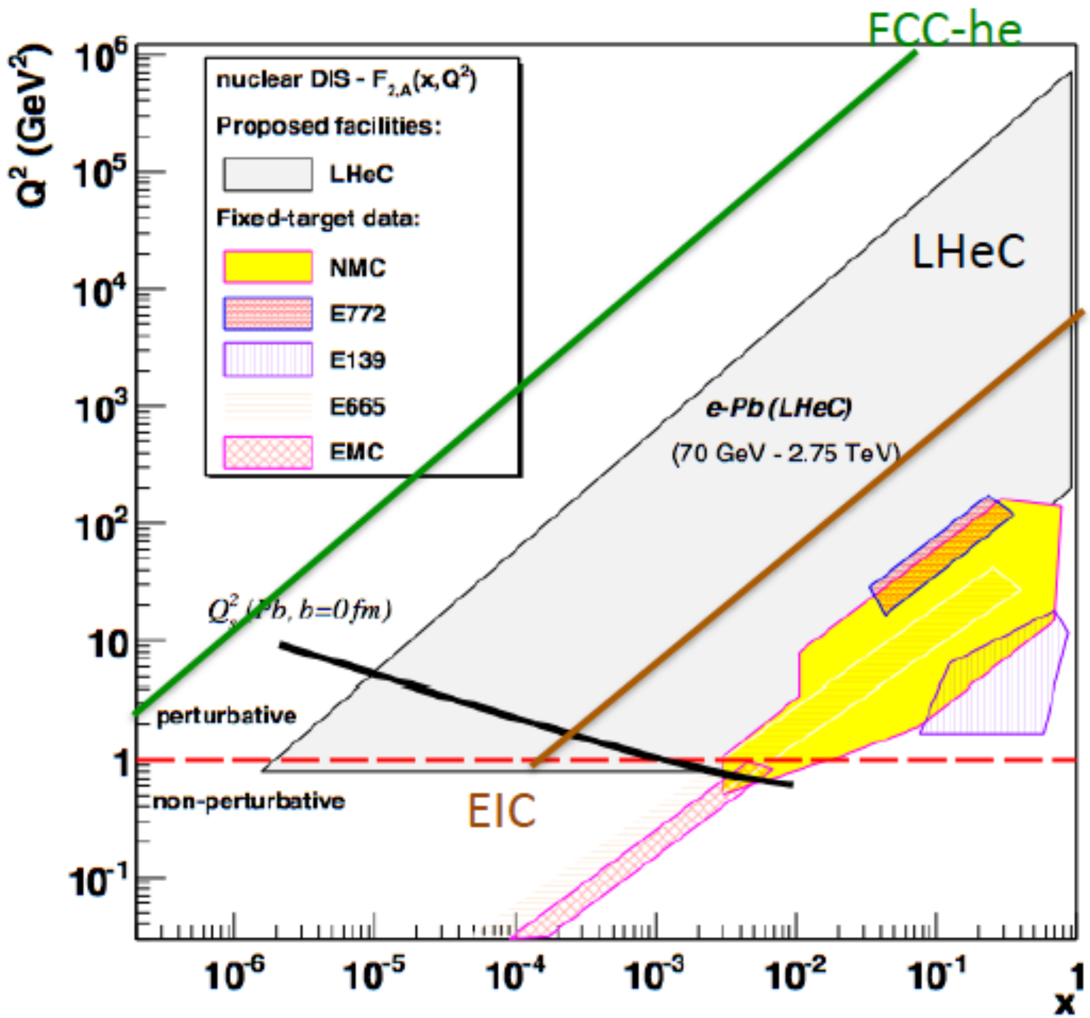


Search for Higgsinos. D Curtin et al

To appear next week

LLP: ep unique: energy higher than in ee, much cleaner than pp

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 ?

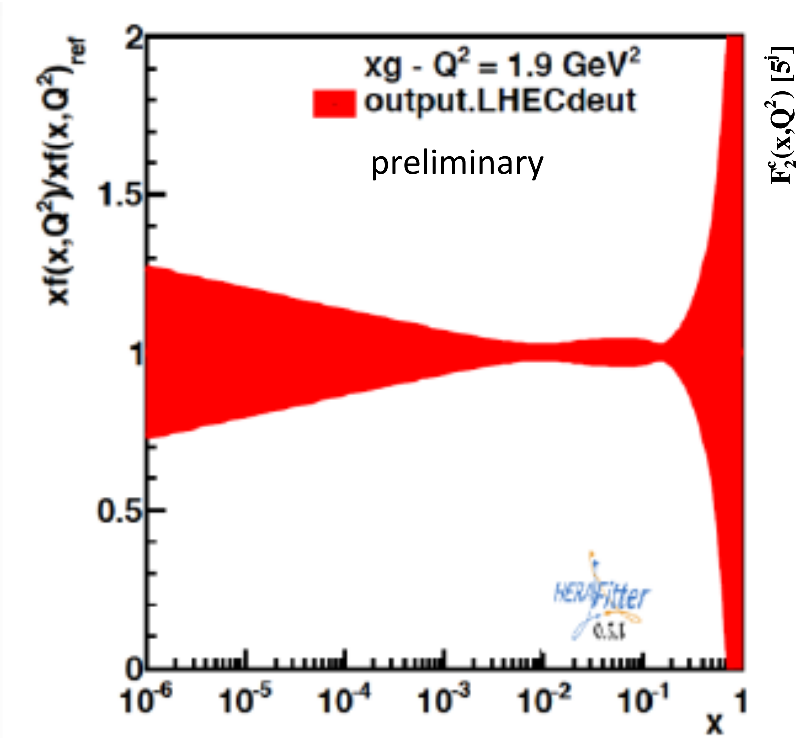
Relates to LHC Heavy Ion Physics
- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

Saturation: needs large xg at small x
ep and eA

Future Nuclear PDFs with LHeC

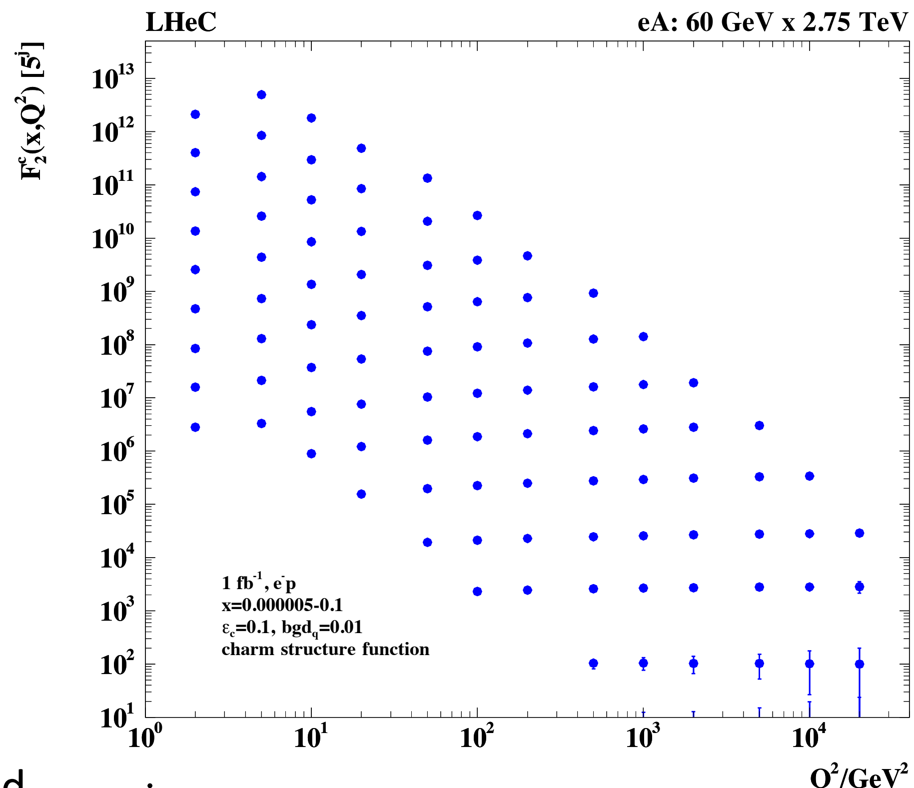
From an eA collider one can determine nuclear PDFs in a novel, the classic way.
Currently: use some proton PDF base and fit a parameterised shadowing term R.
Then: use the NC and CC eA cross sections directly and get $R(x,Q^2;p)$ as p/N PDFs.

Gluon density uncertainty in eA



1fb^{-1} of sole eA isoscalar data fitted

Charm density in nuclei



Impact parameter measurement in eA

Status December 2017

LHeC design RR+LR published in 2012 (10^{33}, 1 TeV) − 600 pages CDR

Since then:

Luminosity to 10^{34} in ep and 6 10^{32} in eA

Detector Design for LHeC, HE-LHeC and FCCeh

Installation Sequence to comply with LHC Shutdowns

IR work in progress

Civil Engineering

Physics and its integration in pp at HL/HE LHC and the FCC

ERL Development Facility (PERLE) in progress

Work in 2018 towards:
LHeC: Update of CDR, FCC: CDR. 10 pages on ep/eA at CERN

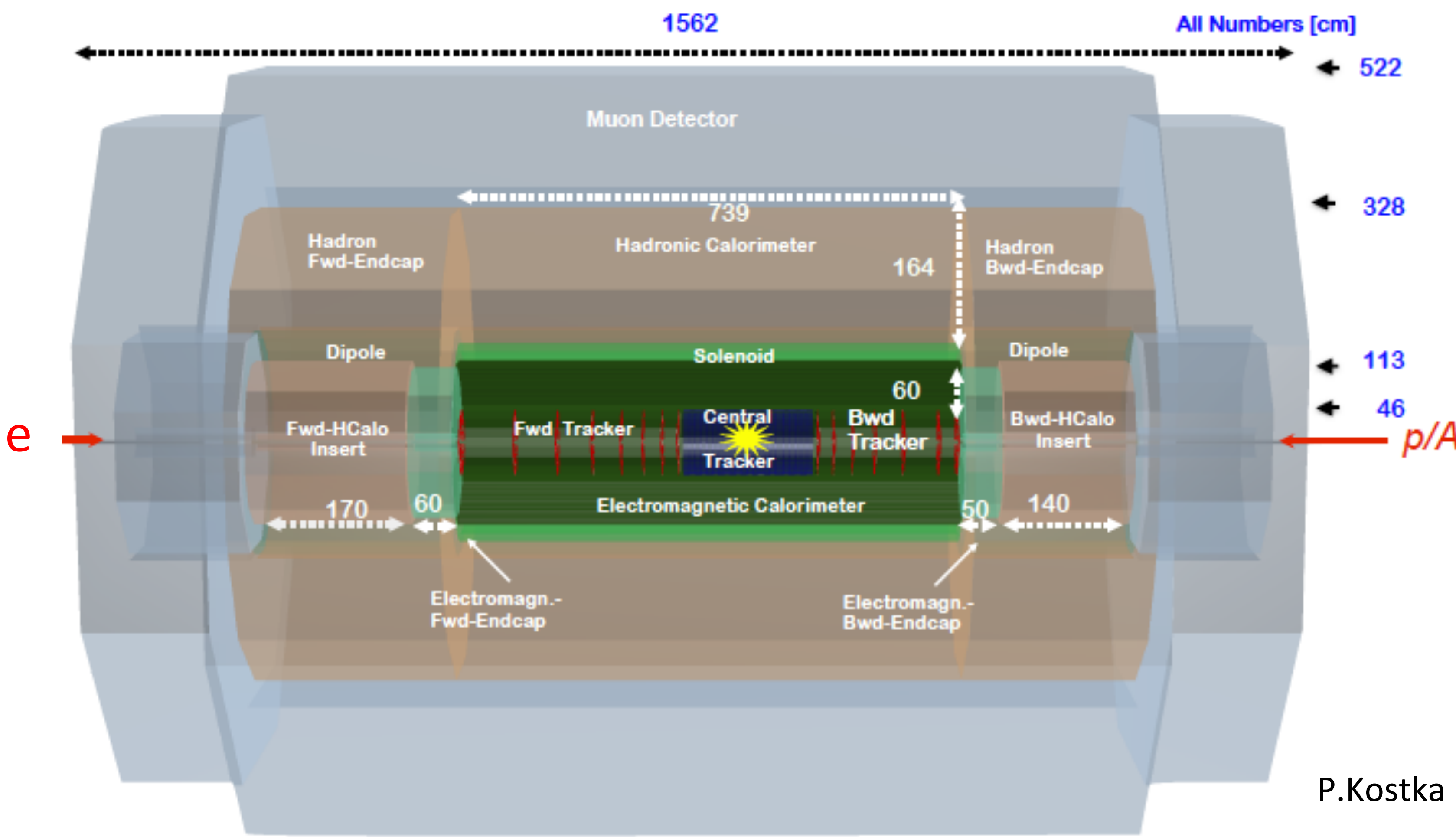
Luminosity for LHeC, HE-LHeC and FCC-ep

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}cm^{-2}s^{-1}]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
April 6^{th}, 2017

10^{34} in ep, simulated
6 10^{32} in eA

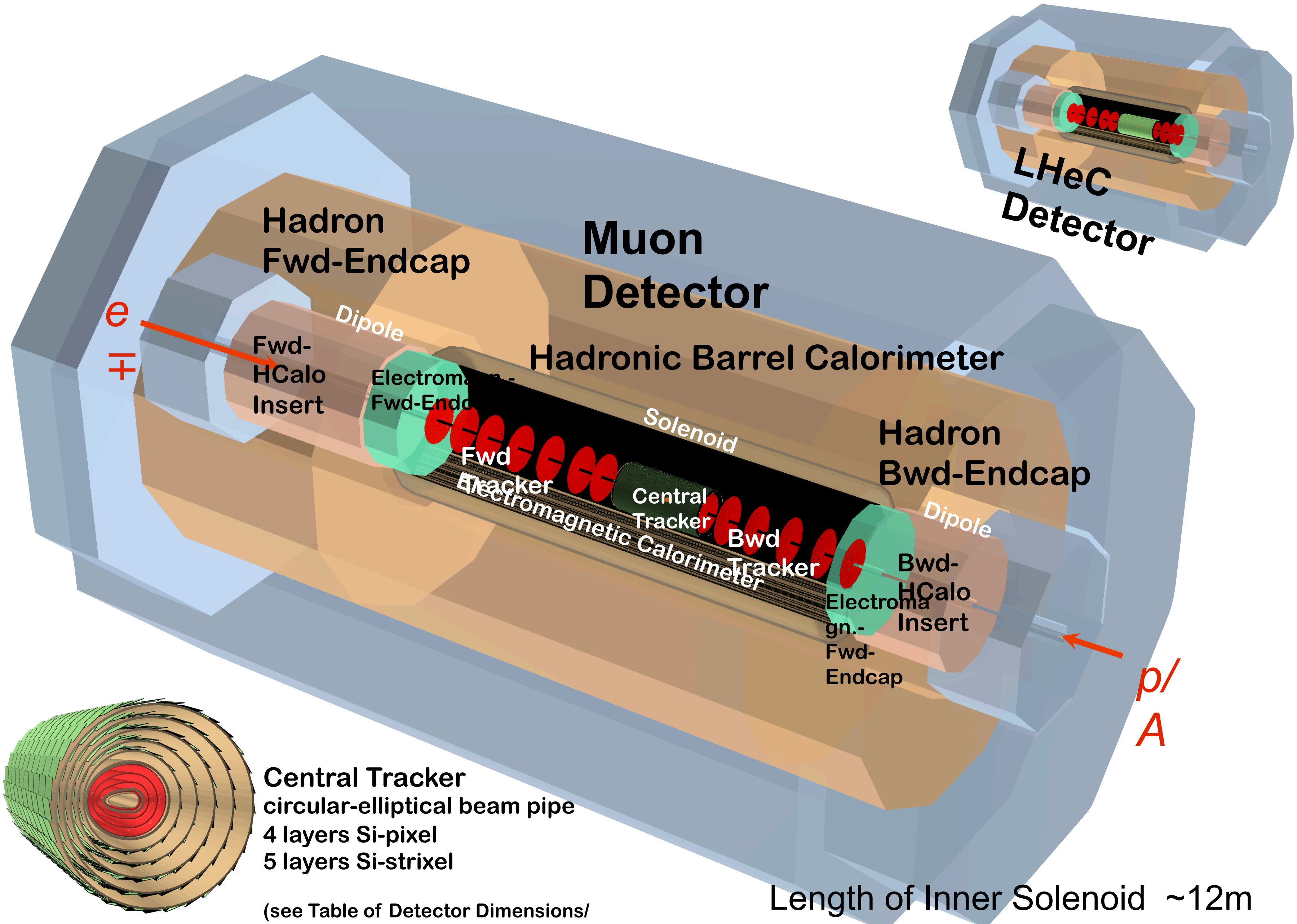
LHeC Detector for the HE LHC



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

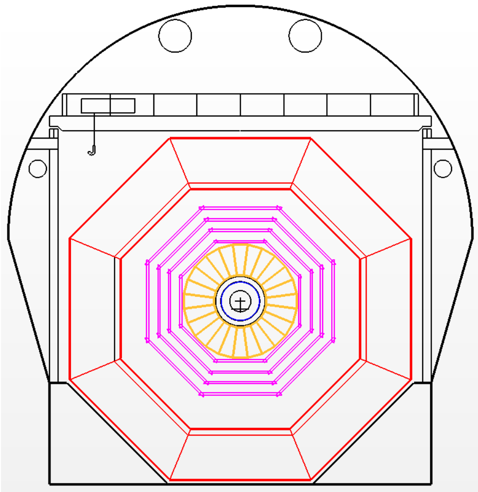
LHeC/FCC ep/eA detector - a test bed for new technology in the twenties



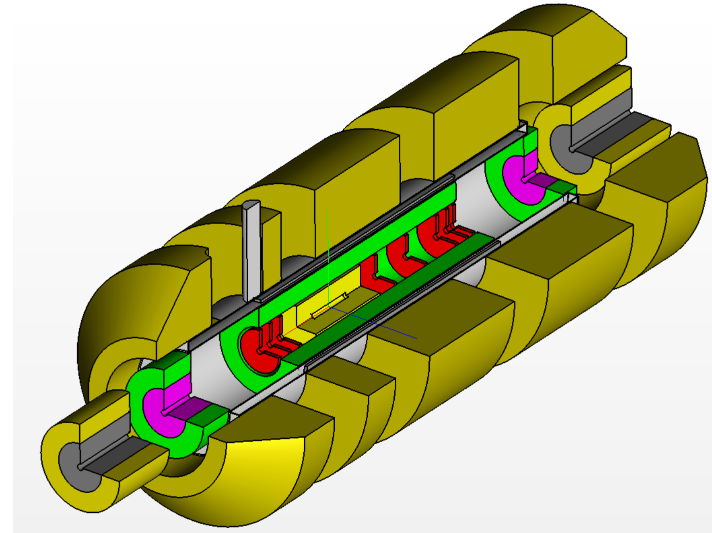
Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

(see Table of Detector Dimensions/ Parameters in backup)

Installation Study

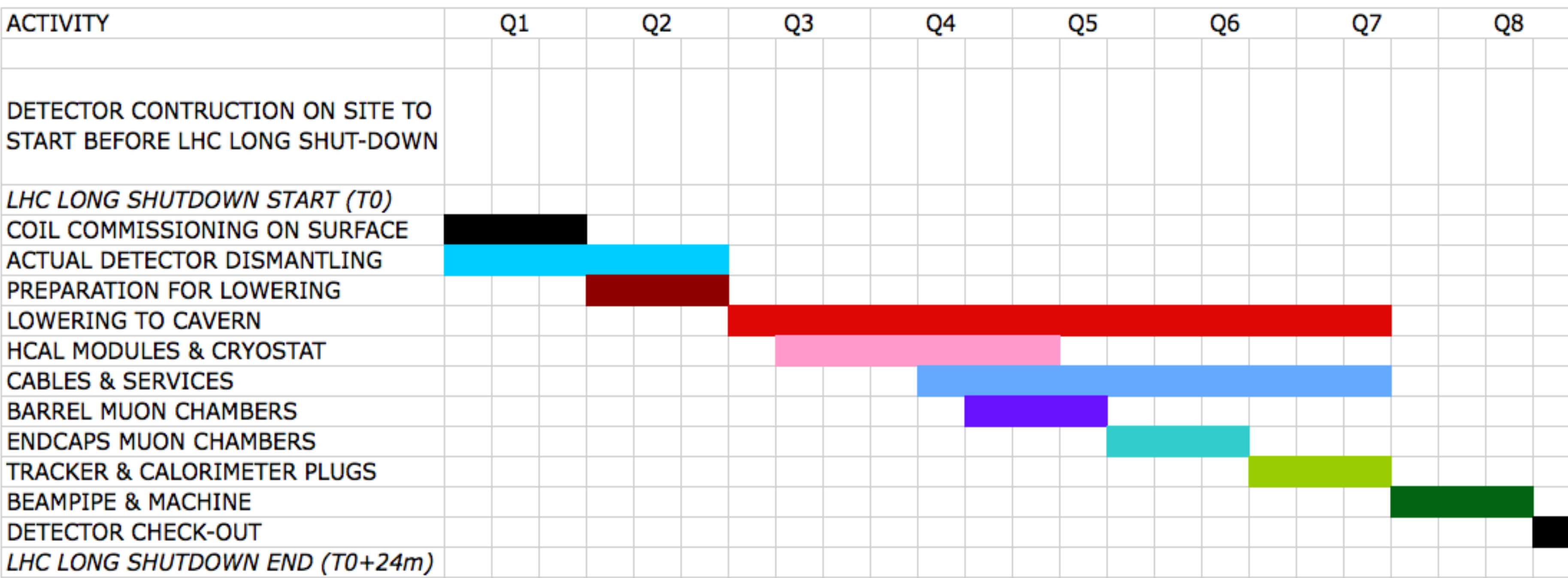


Detector fits in L3 magnet support

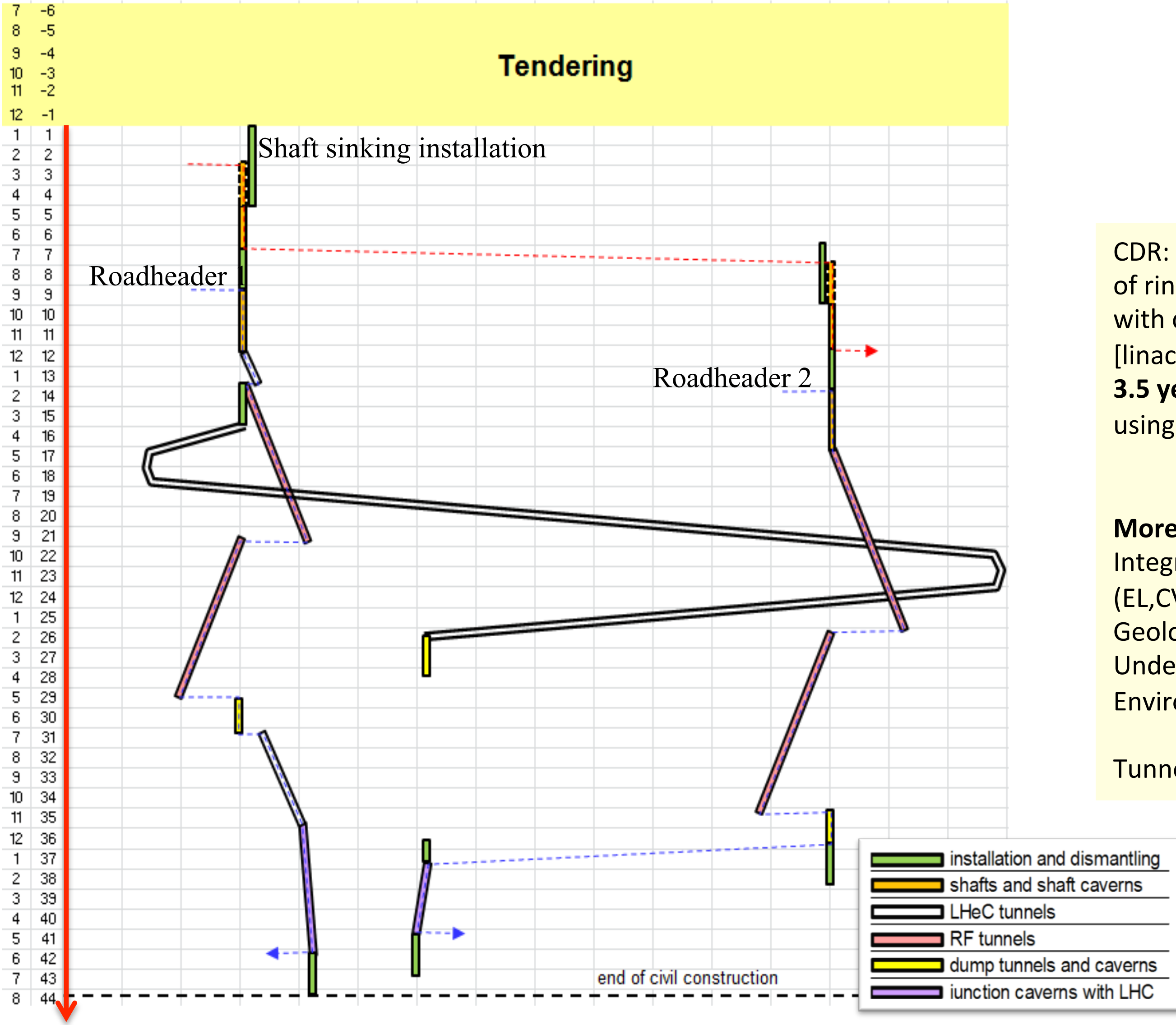


Modular structure

LHeC INSTALLATION SCHEDULE



Civil Engineering – full design made



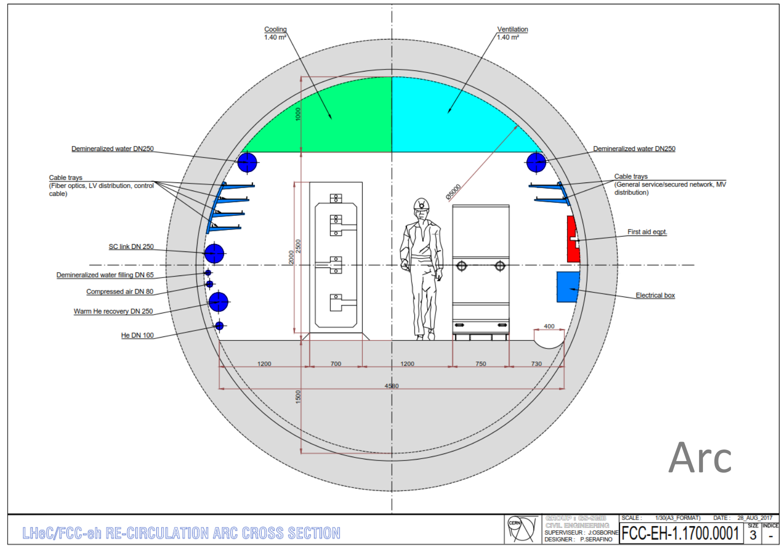
CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich with detailed cost estimate [linac CE: 249,928 kSF..] and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

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

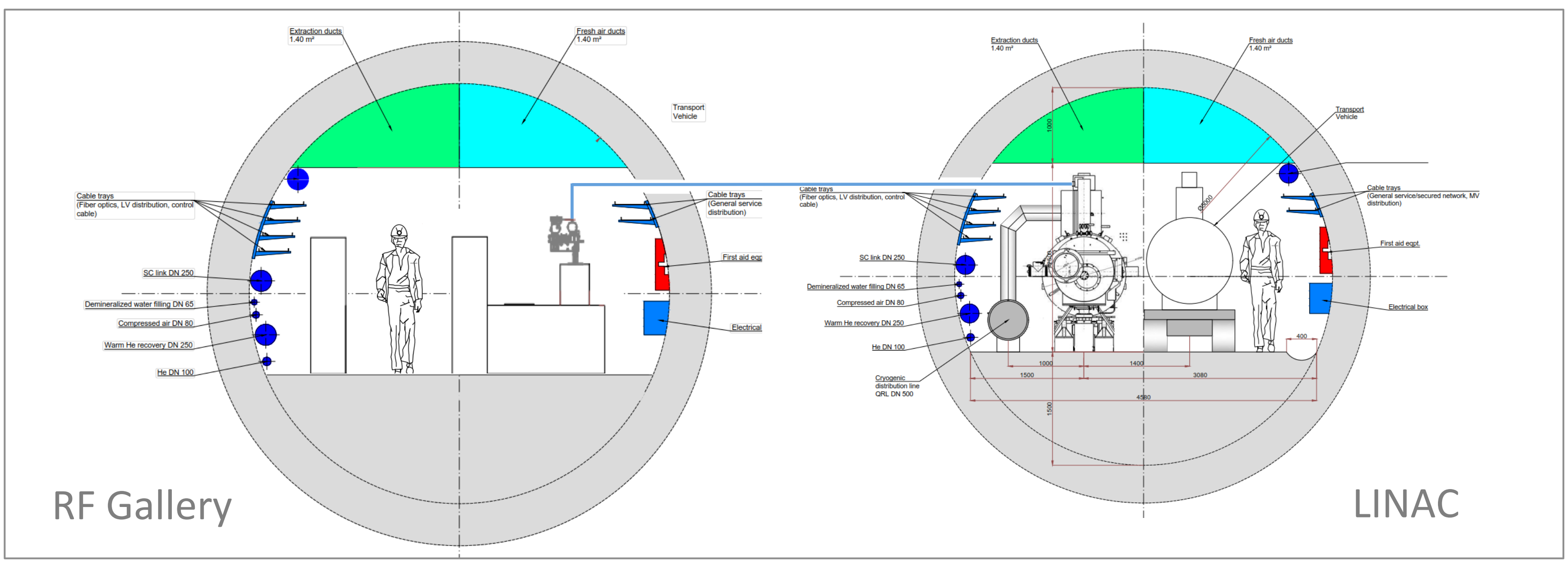
Tunnel connection in IP2

J.Osborne et al.

Tunnels: Triple Arc and LINACs



DRAFTs
cf Matt Stewart et al. 12.9.



PERLE

Development of ERL and SCRF Technology. Demonstrator for LHeC. Physics Facility

400 MeV, CW, 20mA current, 802 MHz, 3 turns.

arXiv:1705.08783

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 23^{rd}, 2017

arXiv:1705.08783

J Phys G in print

WHY PERLE?

An Accelerator Test Facility
Supporting the LHeC

University of Liverpool, November 2017

Steve Benson, Alex Bogacz, David Douglas, and *Chris Tennant*

for the Jlab PERLE Study Group

Saturday, November 11, 2017

Jefferson Lab

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

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

PERLE TDR Kickoff Meeting, Orsay, February 22-24, 2017. PERLE CDR published in JPhysG

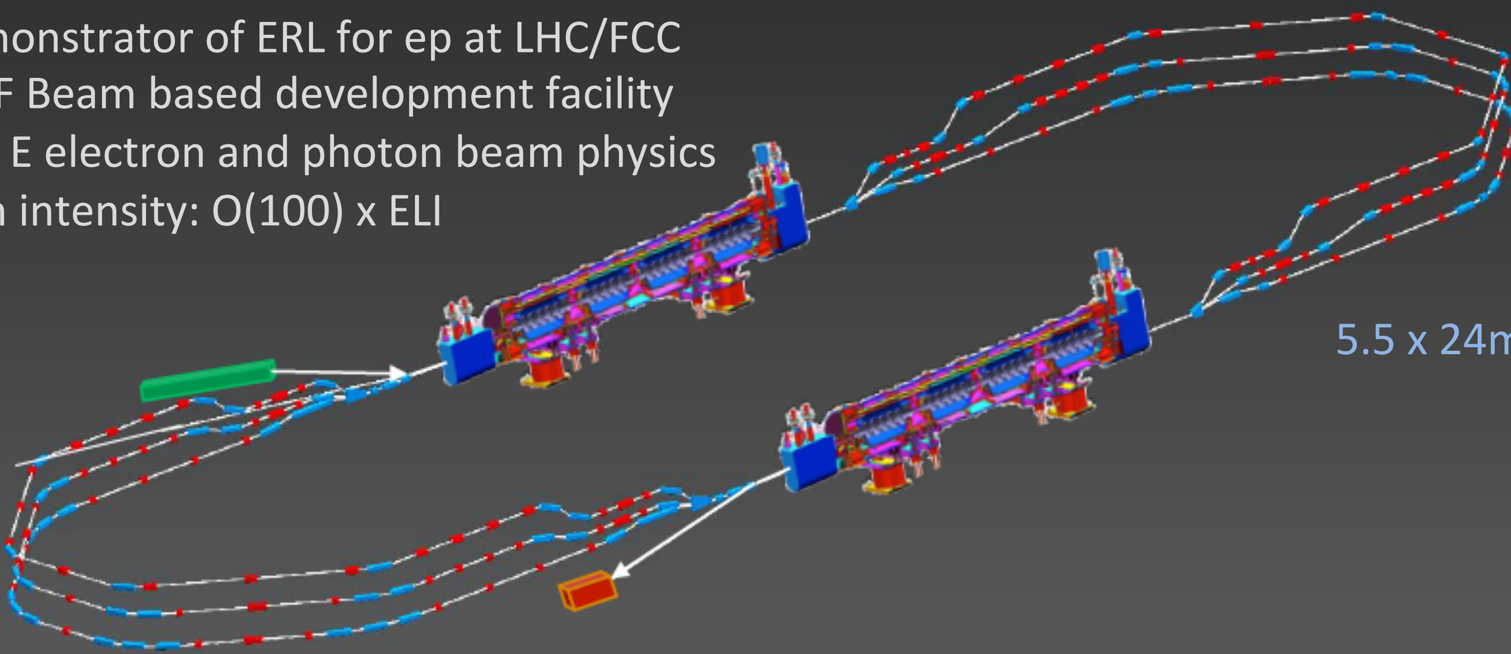
PERLE at Orsay

title

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

3 turns, 2 Linacs, 400 MeV, 15mA, 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



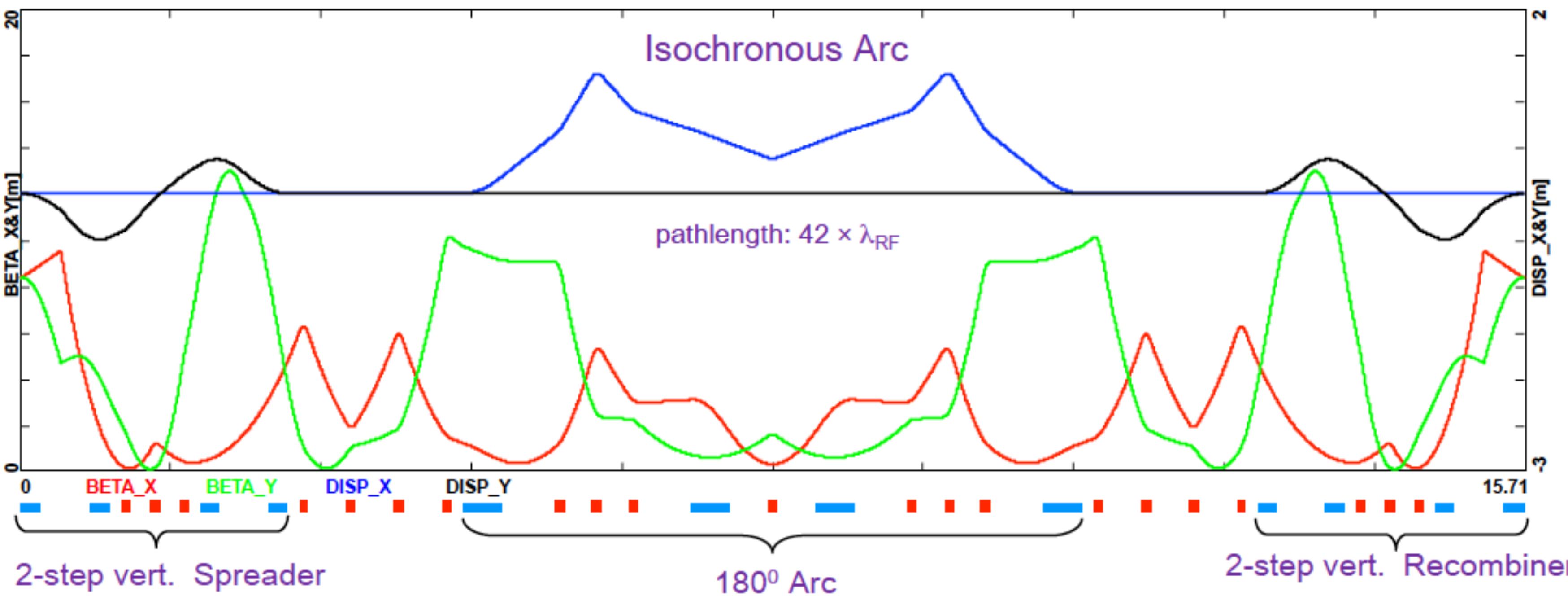
5.5 x 24m^2

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

PERLE 3 turn optics (80 MeV Arc)



Spr. dipoles:

4× 45^0 bends

L = 20 cm

B = 9.5 kGauss

Arc dipoles :

4×45^0 bends

L = 45.6 cm

B = 4.5 kGauss

Rec. dipoles:

4× 45^0 bends

L = 20 cm

B = 9.5 kGauss

A Bogacz (24.5.17)

quads: L = 10 cm G ≤ 1 kGauss/cm

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

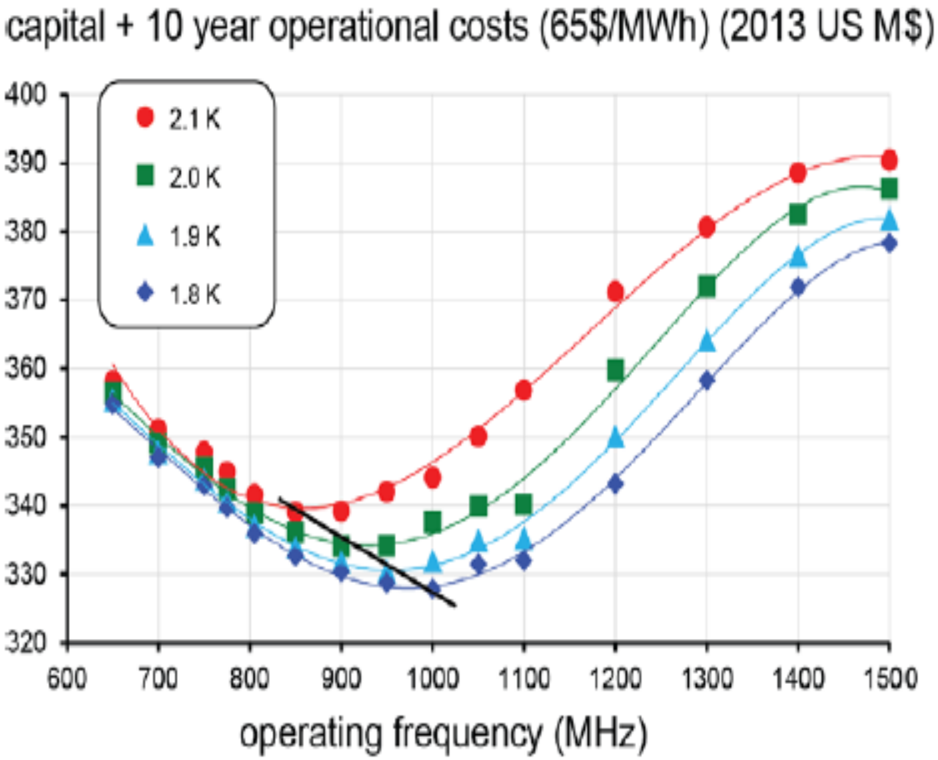
RELEVANT DYNAMICS/TECHNOLOGY R&D/VALIDATION

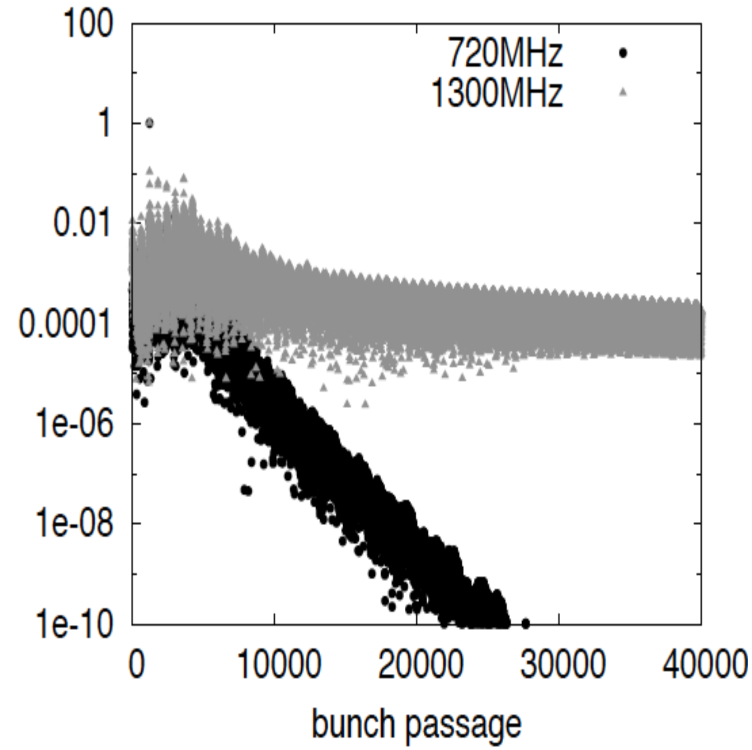
PERLE moves the community to the 10 MW level in several areas!

- High charge/brightness bunch
  - Beam quality preservation with space charge/LSC, CSR, mBI…
- High current/charge/power beam ⇔ beam stability
  - BBU, other impedance/wake effects
- High current/power beam ⇔ power flow management
  - Halo formation and control
  - High power THz, RF heating, resistive wall,…
- Machine operations:
  - Choice of working point
  - Control algorithms for common transport & halo control
  - Diagnostic & Control in new beam power regime
    - Large dynamic range (LDR) diagnostics, measurement methods

David Douglas (Jlab)

Frequency Choice





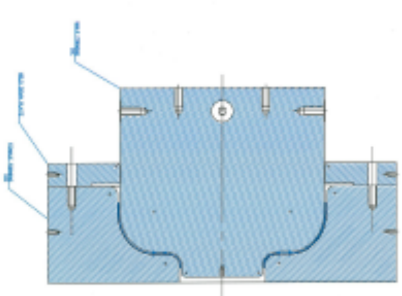
Cost, dynamic heat losses, resistance, Q_0… point to f < 1 GHz (F Marhauser, Orsay 2/17)

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)

802 MHz Cavity Fabrication Status

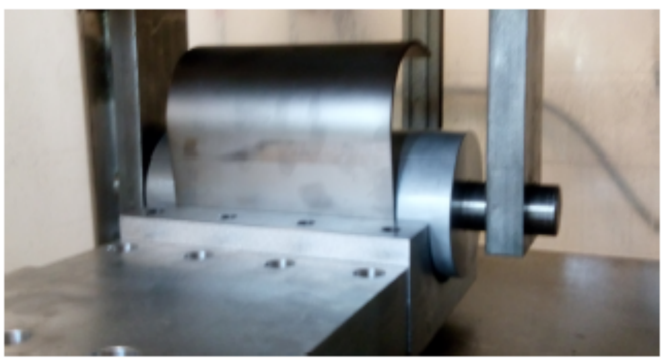
802 MHZ Nb and Cu prototype cavities progressing well

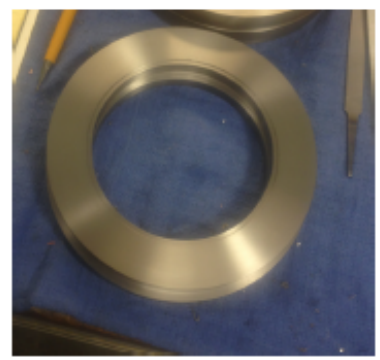



802 MHz deep-drawing die set and machining fixtures (completed)

F. Marhauser
Status 05-25-2017

Deep-drawn 802 MHz Nb and Cu half-cells (Status April '17)



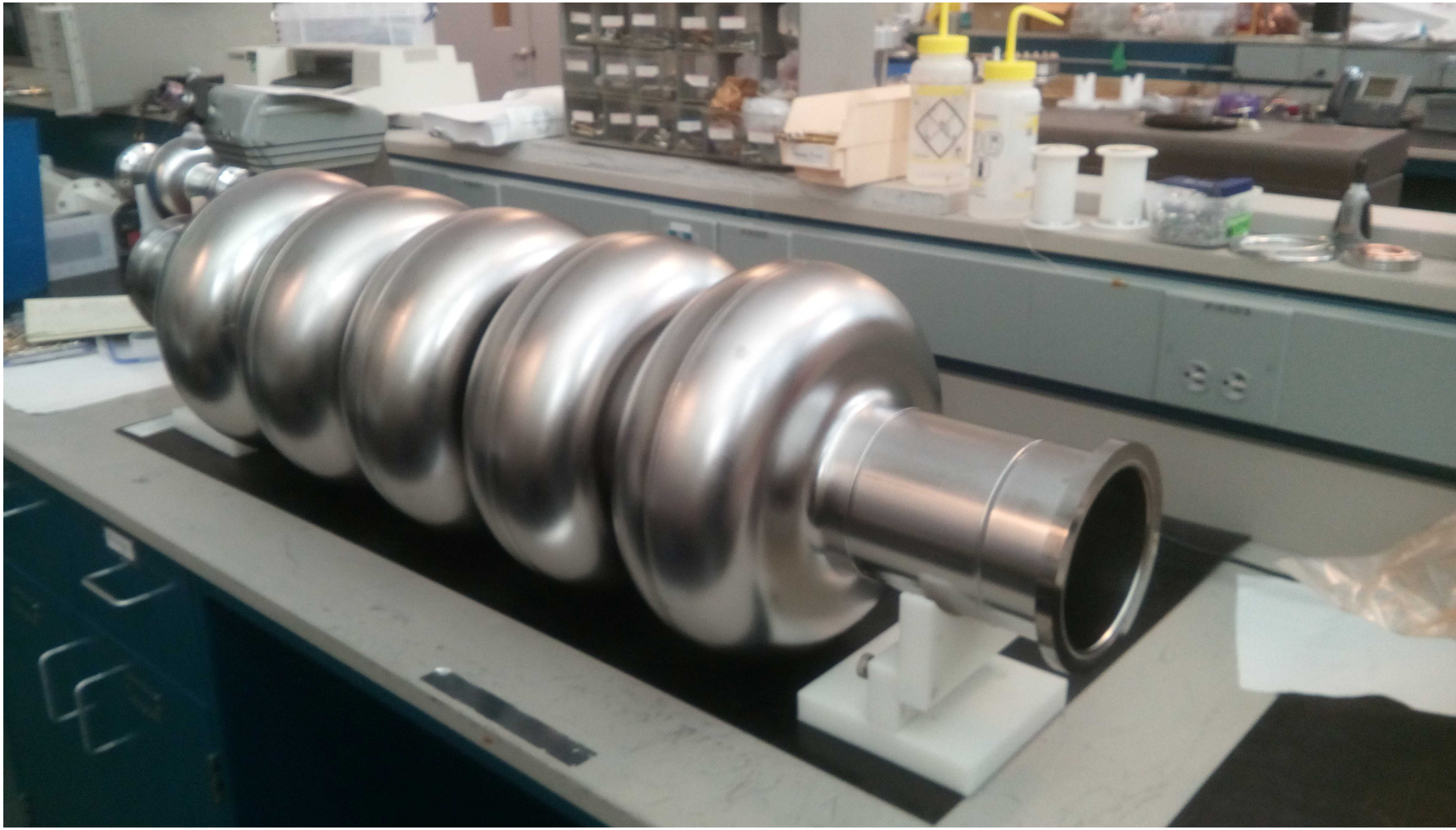


NbTi flanges (completed)

Rolling of beam tubes and EBW before machining (completed), beam tubes are being machined (to be completed soon, 05/17)

RF test hardware for OD = 6.5" flanges available

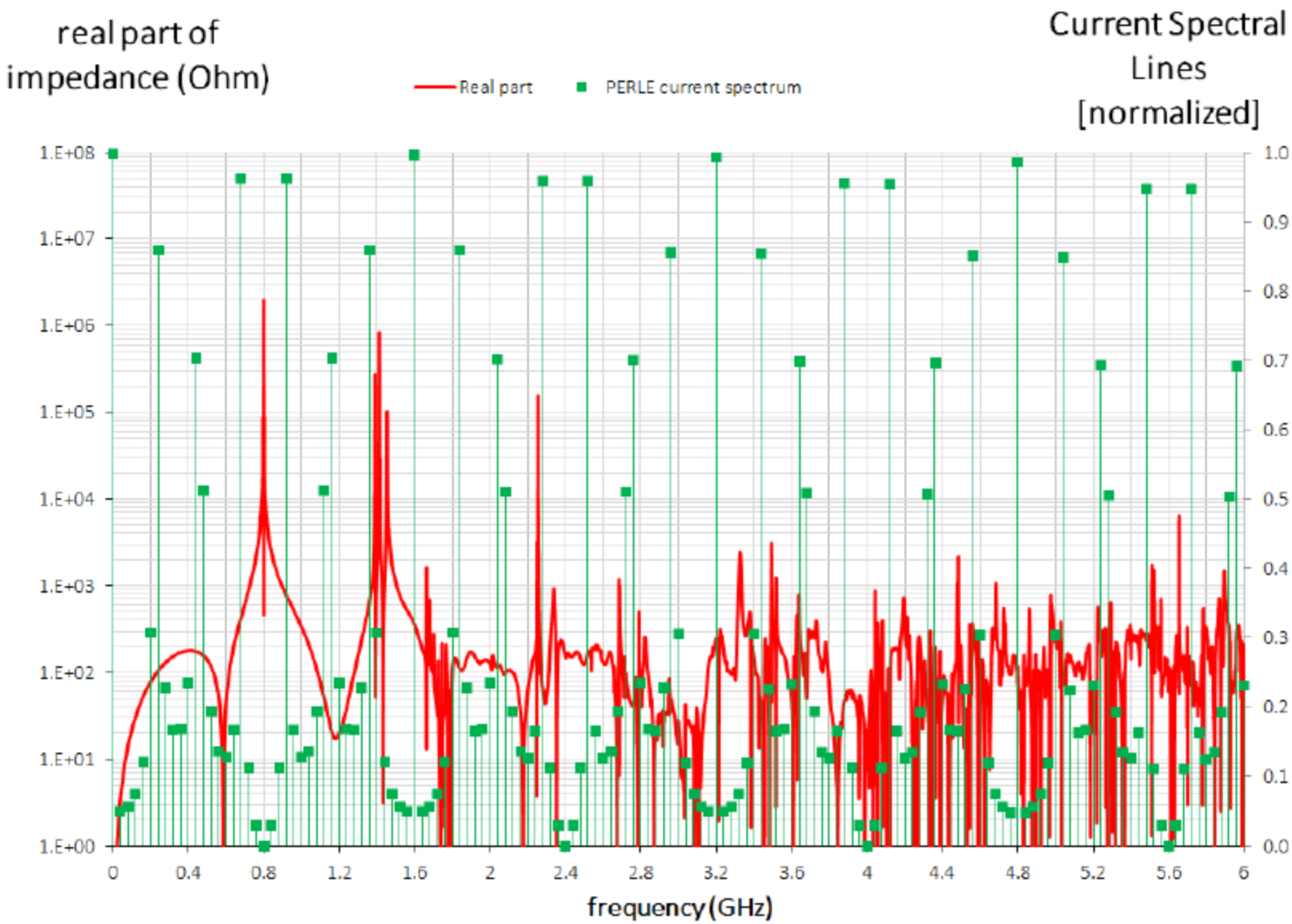
1^{st} 802 MHz Cavity



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

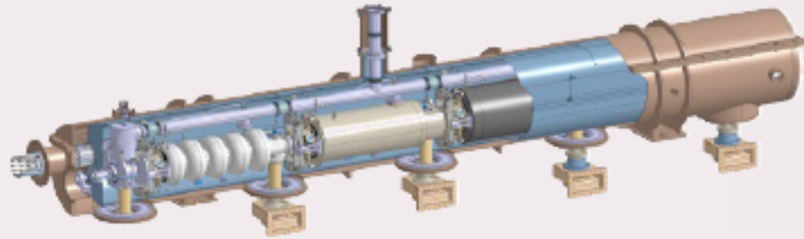
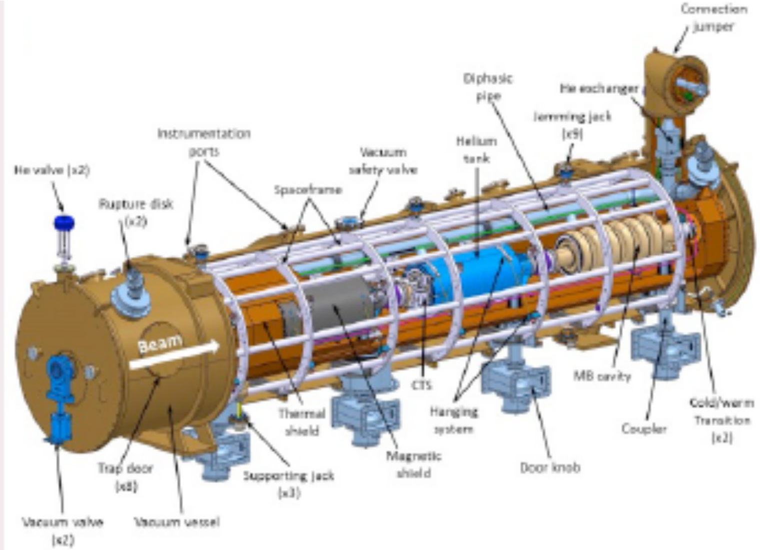
Goal: 16 MV/m, $Q_0 > 10^{10}$ operated in CW in the PERLE+LHeC ERLs, prototype for FCC-ee

HOM Assessment



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

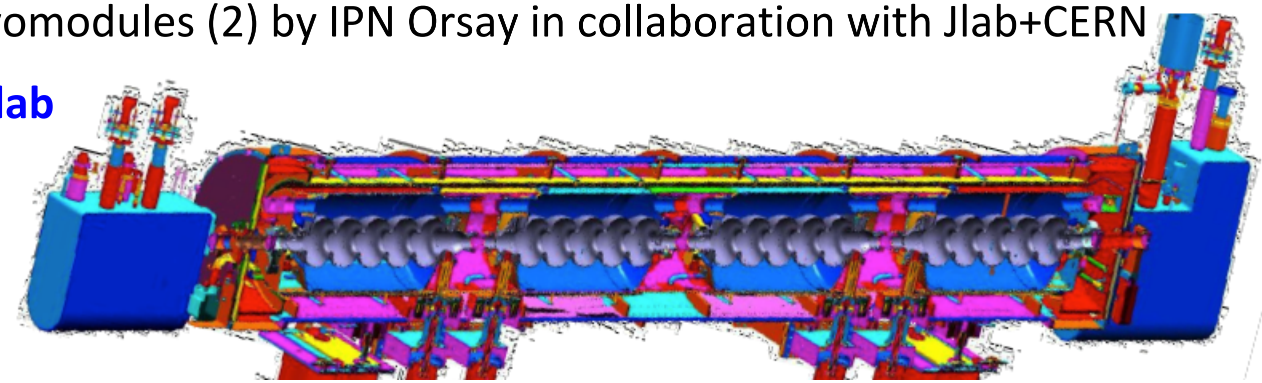
Next Step: Cryomodule

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



PERLE Magnets

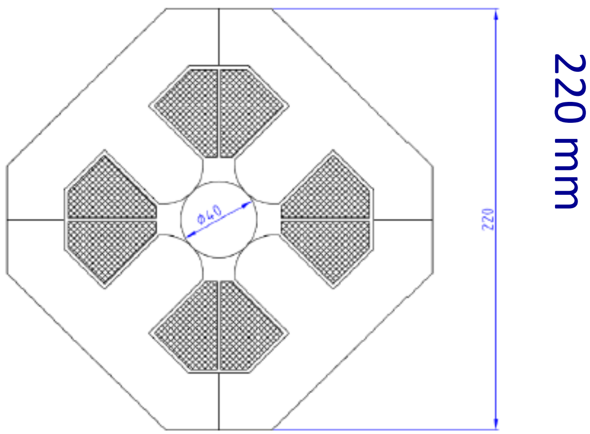
70 dipoles 0.45-1.29 T

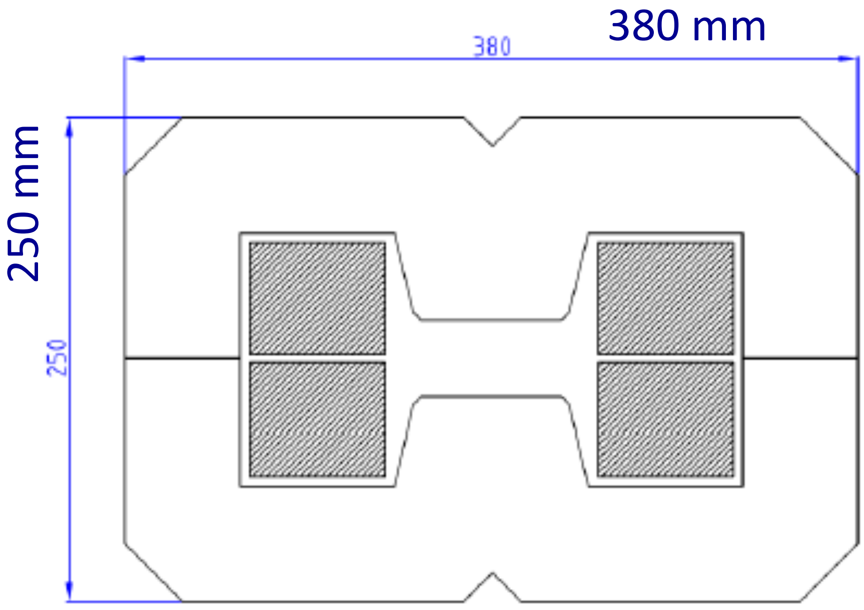
+- 20 mm aperture, l=200,300,400 mm

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)

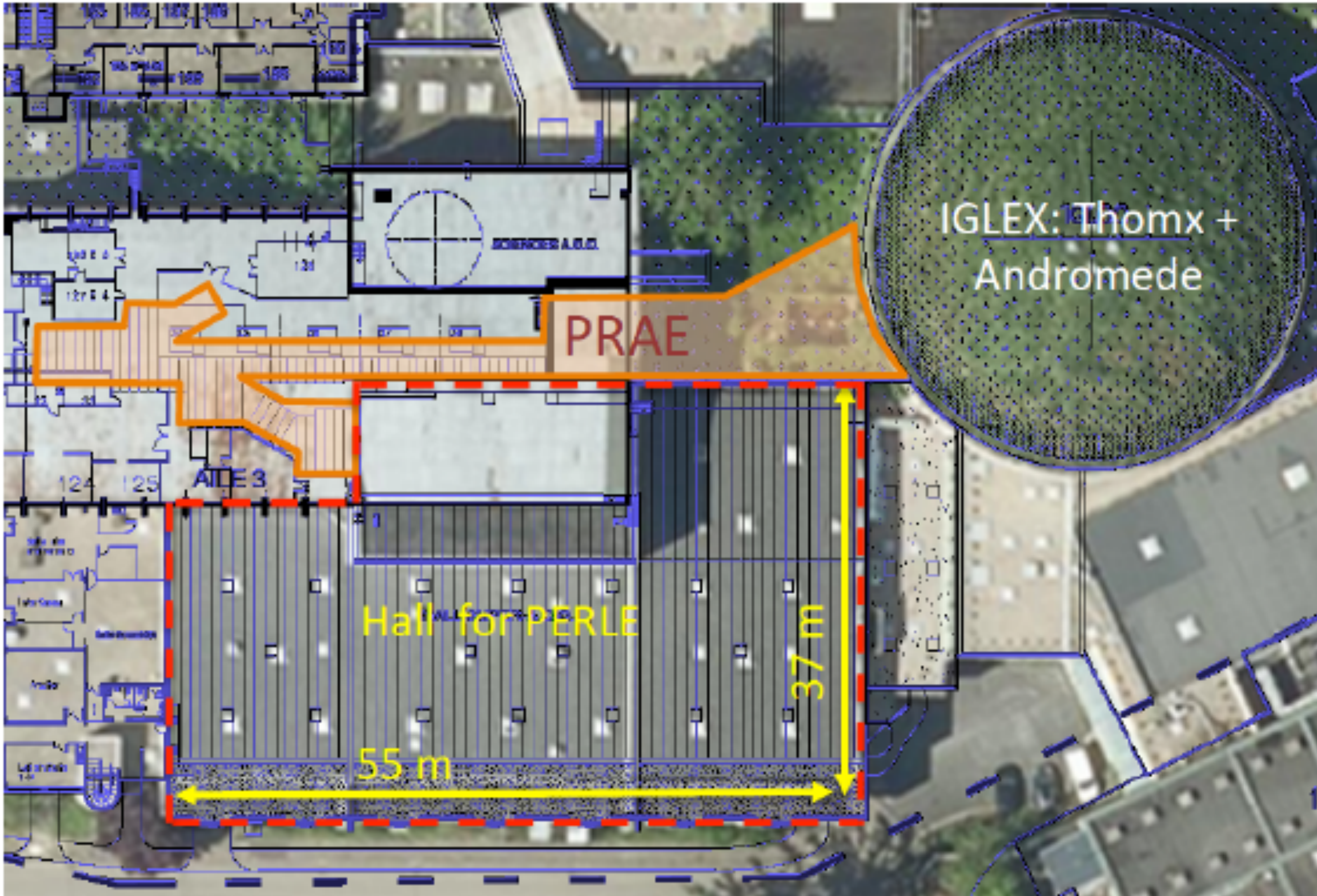
Source

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 home

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

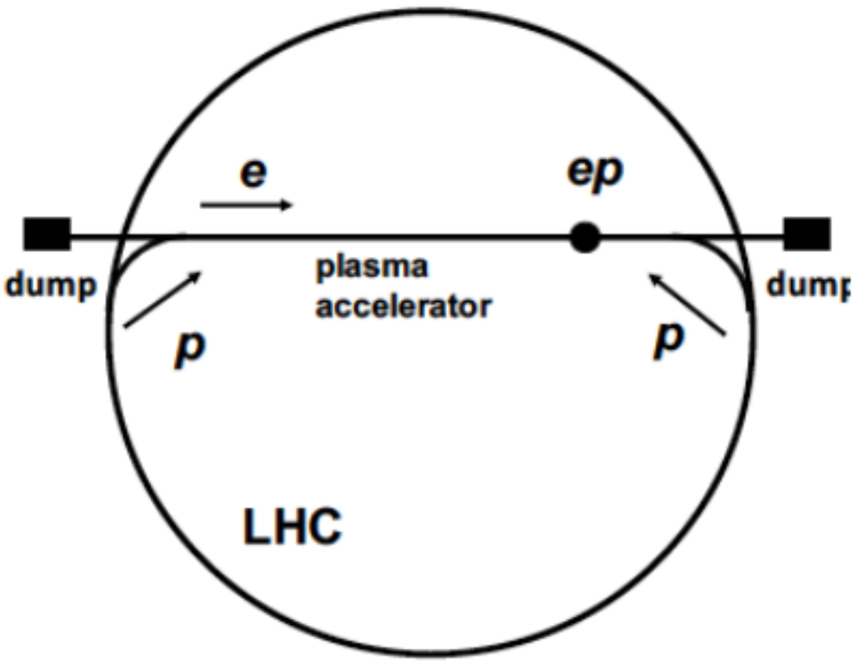

IGLEX: Thomx +
Andromede
PRAE
AILE 3
124
125
Hall for PERLE
37 m
55 m


8105

Concluding Remarks

VHEeP

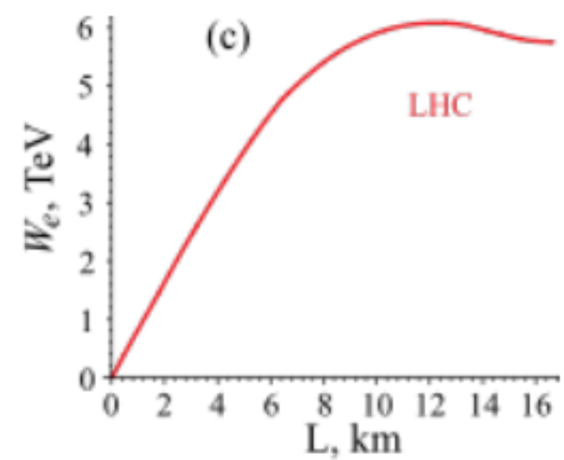
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with other proton beam

Luminosity ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Electron energy from wakefield acceleration by LHC bunch



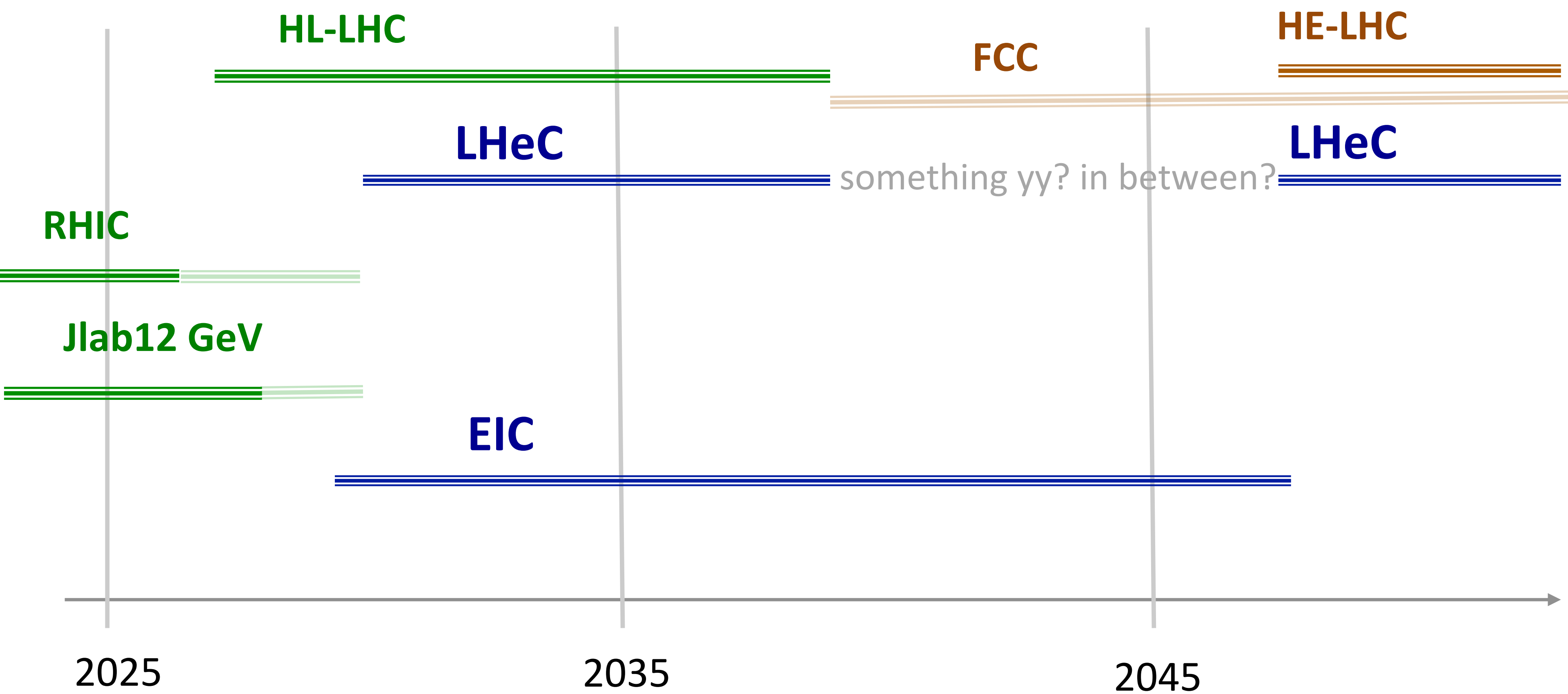
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Choose E_e = 3 TeV as a baseline for a new collider with E_p = 7 TeV yields √s = 9 TeV. Can vary.

- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

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

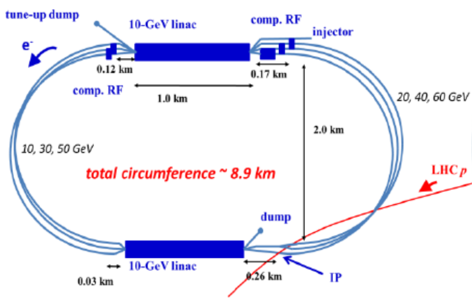
Dislaimer: For discussion and illustration at DIS17 only MK+RY, April 7th, 2017, DIS at Birmingham

Further use of ERL in between HL and HE LHC

Reconfiguring *LHeC → SAPPHiRE*

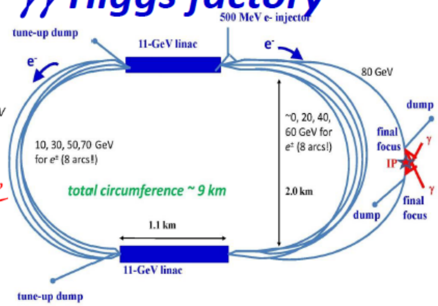
F.Zimmermann at LHeC WS 9/17

LHeC-ERL



*SAPPHiRE**

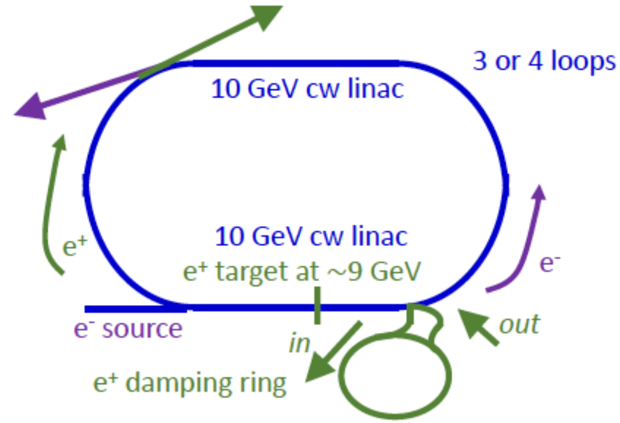
γγ Higgs factory



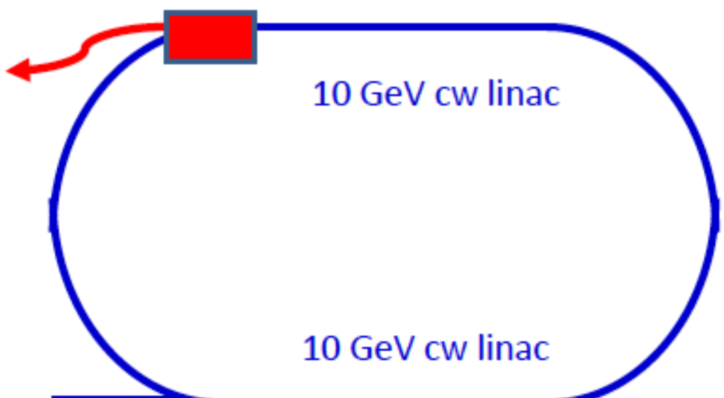
*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

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

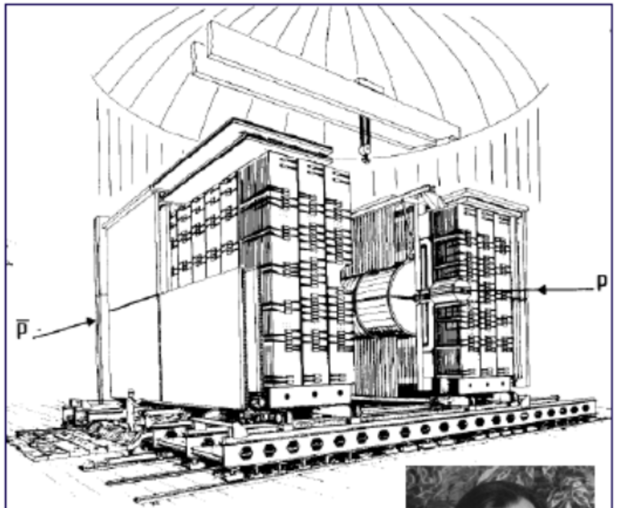
An Important Remark

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**

Can CERN host pp and DIS at once?

.. in the 80ies it successfully did



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…

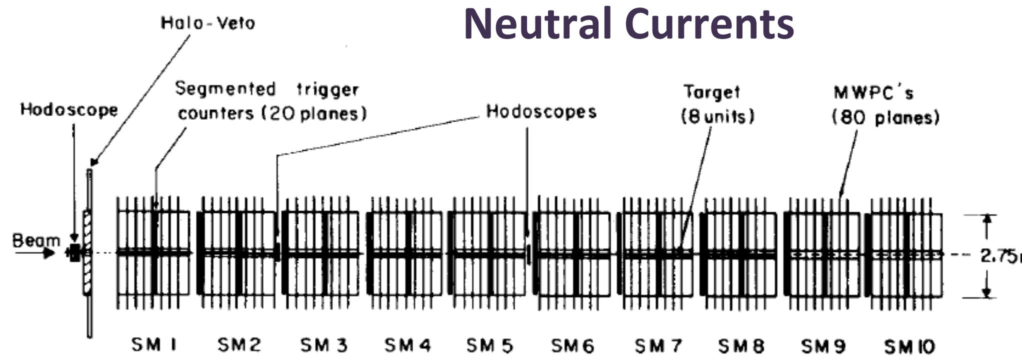
UA2

Pierre Darriulat

Charged Currents

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

Neutral Currents



BCDMS, EMC, SMC, COMPASS

Poster by Vassili, Celine and Audrey

Workshops

← September 2017
https://indico.cern.ch/event/639067/

Next: 27-29 June 2018 Orsay
Preparation for strategy:
Physics, Accelerator, Detector, PERLE

Also FCC workshops
cf M Benedikt (Jan+April)
POETIC in March
DIS in April

and HL-HE LHC Physics 17/18
which includes ep/eA
.
https://lhec.web.cern.ch

Logo of the CDR

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

Many thanks to the LHeC/FCC-eh collaborators, the IAC, to CERN and our labs

https://lhec.web.cern.ch

Five Major Themes of Electron-Hadron Physics

at the energy frontier

Cleanest High Resolution Microscope

Joint ep and pp Physics at LHC and FCC

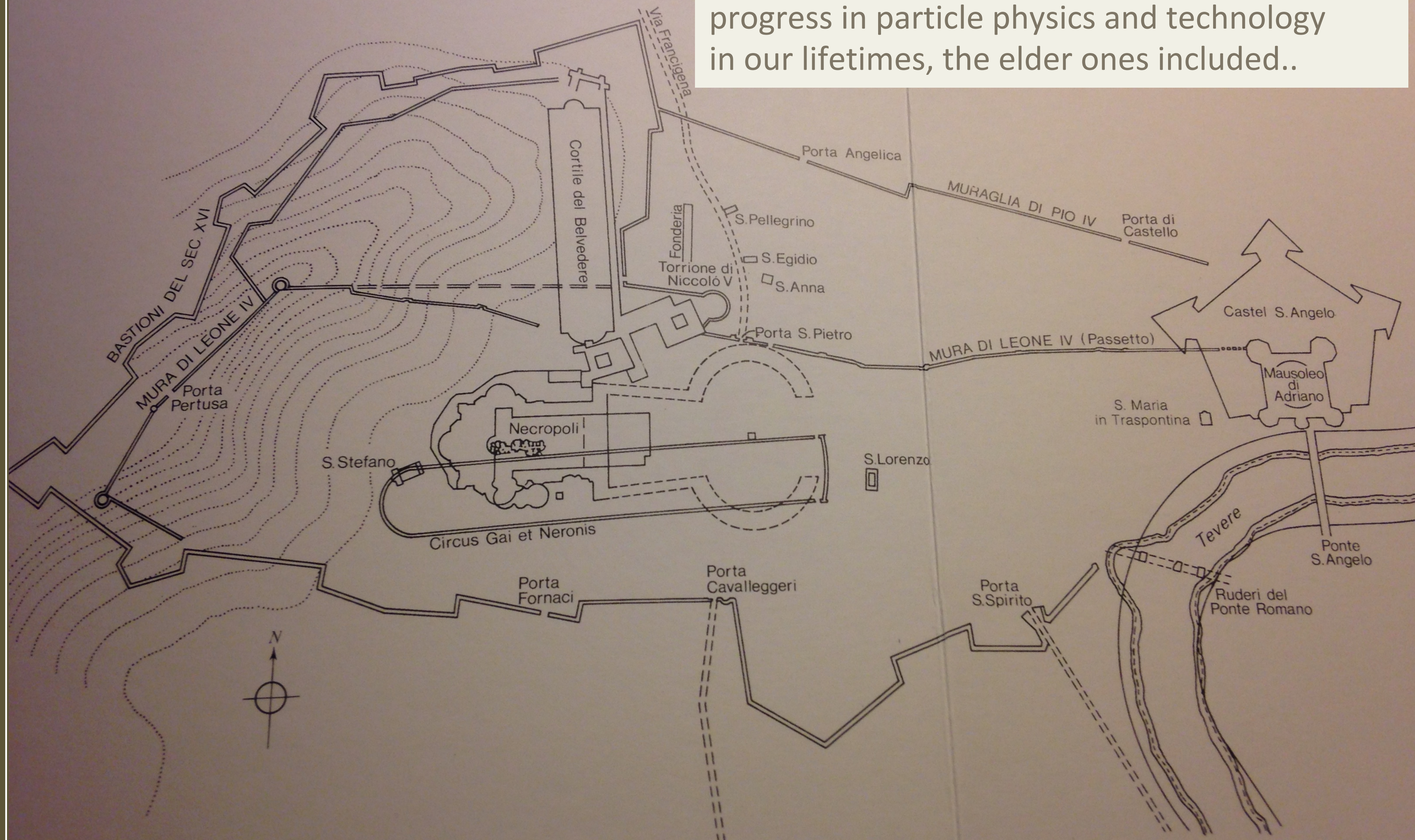
High Precision Higgs Exploration

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.

The LHeC is not the first racetrack of the world. It can be built and will lead to fundamental progress in particle physics and technology in our lifetimes, the elder ones included..



An early racetrack embedded in the Vatican (XV century)

title

Towards 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

Accelerator Design: Participating Institutes

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU
Norwegian University of Science and Technology

ECFA

CLIC

The Cockcroft Institute of Accelerator Science and Technology

Jefferson Lab
Thomas Jefferson National Accelerator Facility

ANKARA ÜNİVERSİTESİ

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

DESY

LAL Physique des accélérateurs

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

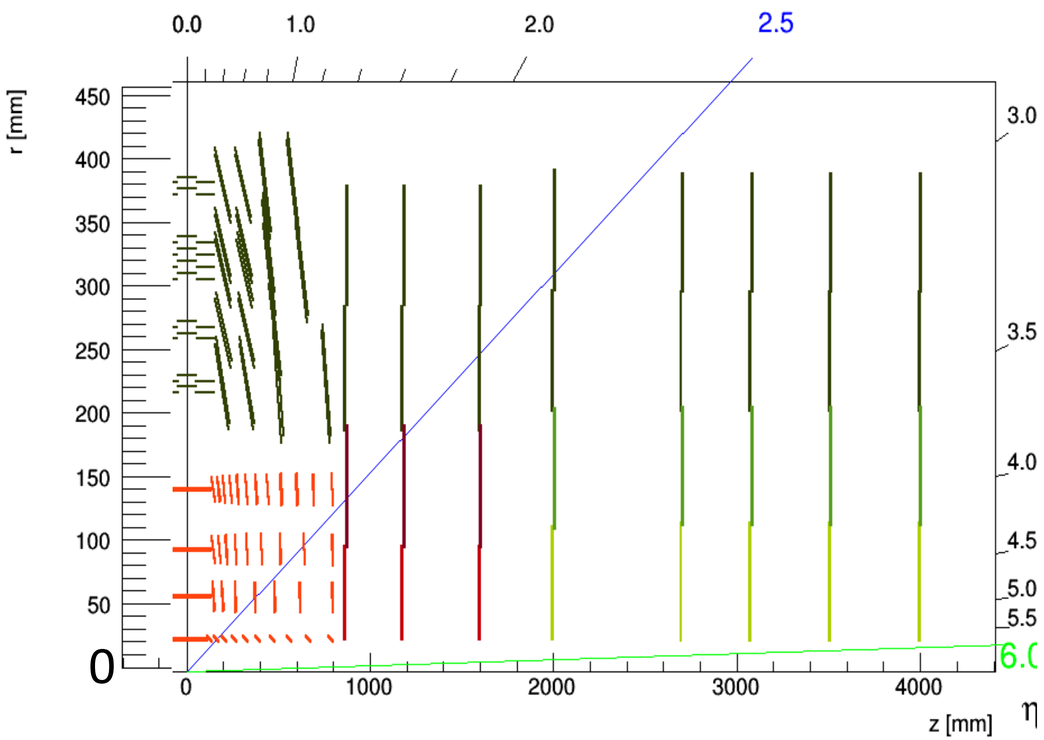
KEK

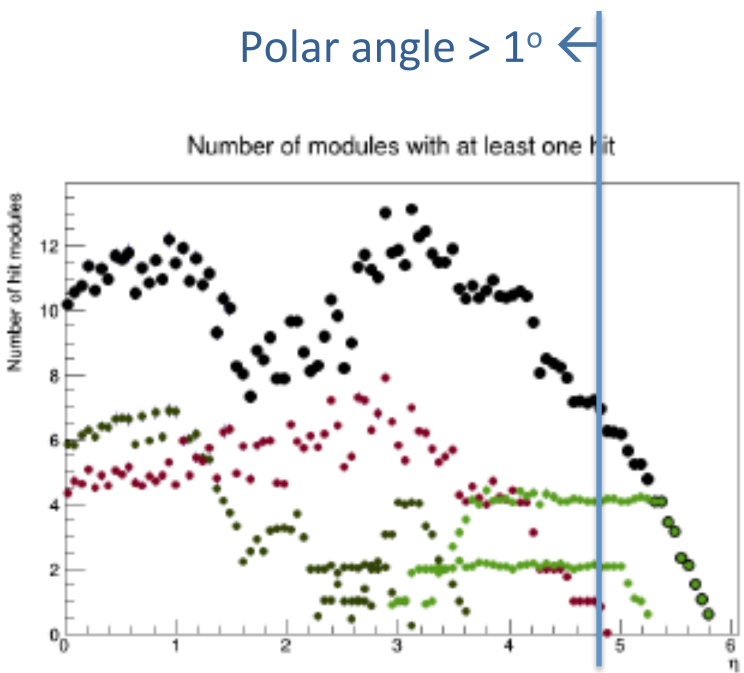
BROOKHAVEN NATIONAL LABORATORY

СИБИРСКОЕ ОТДЕЛЕНИЕ РАН
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И.Будкера
630090 Новосибирск

Source	Power [MW]
Cryogenics (linac)	21
Linac grid power	24
SR compensation	23
Extra RF cryopower	2
Injector	6
Arc magnets	3
Total	**78**

Forward Tracking at LHeC





Work in progress, on tracker layout, with emphasis on forward acceptance, and technical issues as asymmetric beam pipe and material budget.

cf talks by A Pollini, P Kostka and A Gaddi

September LHeC workshop : https://indico.cern.ch/event/639067

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.

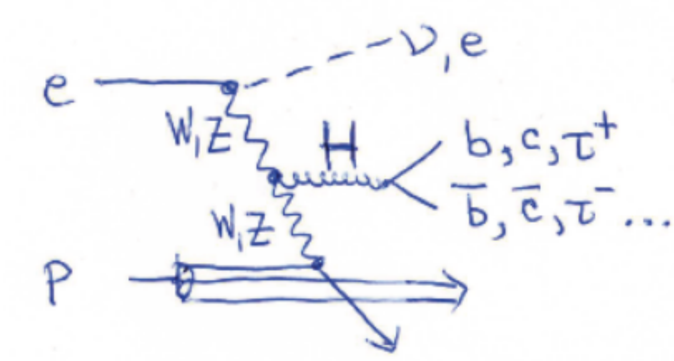
→ 50 GeV the programme stands, 40 GeV it looses BSM, t, 30 GeV: precision gone
→ Keep the electron energy as high as it can be afforded, and not lower than 50 GeV

FCCeh Detector Parameters

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
Pitch $[\mu m]$	30 x 30	37.5 x 1750	30 x 30	30 x 30	37.5 x 1750	30 x 30	37.5 x 1750	30 x 30
ReadOut-Pitch $[\mu m]$	30	75	30	30	75	30	75	30
X_0 per layer [%]	0.3	0.8	0.3	0.3	0.8	0.3	0.8	0.3
$Si_{pix/strix}$ $[m^2]$	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si $[m^2]$	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
ReadOut-Pitch $[mm]$	20 x 20	10 x 10			20 x 20	20 x 20
Volume $[m^3]$	13.2	3.1	28.8	407	1.98	7.0
Sum-Si $[m^2]$	461					

Higgs Physics with ep



High cross section (cc: LHeC 200fb, FCC-eh 1pb)

Electroweak production, uniquely CC vs NC

Access to WW-H-WW and ZZ-H-ZZ

No pileup, clean theory, challenging simulations

SM coupling measurement expectations

κ in %	HL LHC	LHeC HL	LHeC HE	FCC-eh
H → bb	10?	0.5	0.3	0.2
H → cc	50??	4	2.8	1.8

Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

DLHC (~35,000 H→bb events)

LHeC (~15,000 H→bb events)

Recent Higgs-in-ep studies for CDR: Higgs self coupling from FCC-eh associated top-Higgs production, Higgs into invisible (dark matter), Exotic Higgs physics: H into light scalars, H^{--} and others

cf U Klein at FCC Berlin for references and summary

ep when added to pp turns the pp colliders into high precision Higgs facilities.
Removes PDF and coupling constant uncertainties in pp gg fusion process.

Parameters for FCC-eh Detector

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ [^{0}]	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
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Pitch [μm]	30 x 30	37.5 x 1750	30 x 30	30 x 30	37.5 x 1750	30 x 30	37.5 x 1750	30 x 30
ReadOut-Pitch [μm]	30	75	30	30	75	30	75	30
X_0 per layer [%]	0.3	0.8	0.3	0.3	0.8	0.3	0.8	0.3
$Si_{pix/strix}$ [m^2]	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si [m^2]	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
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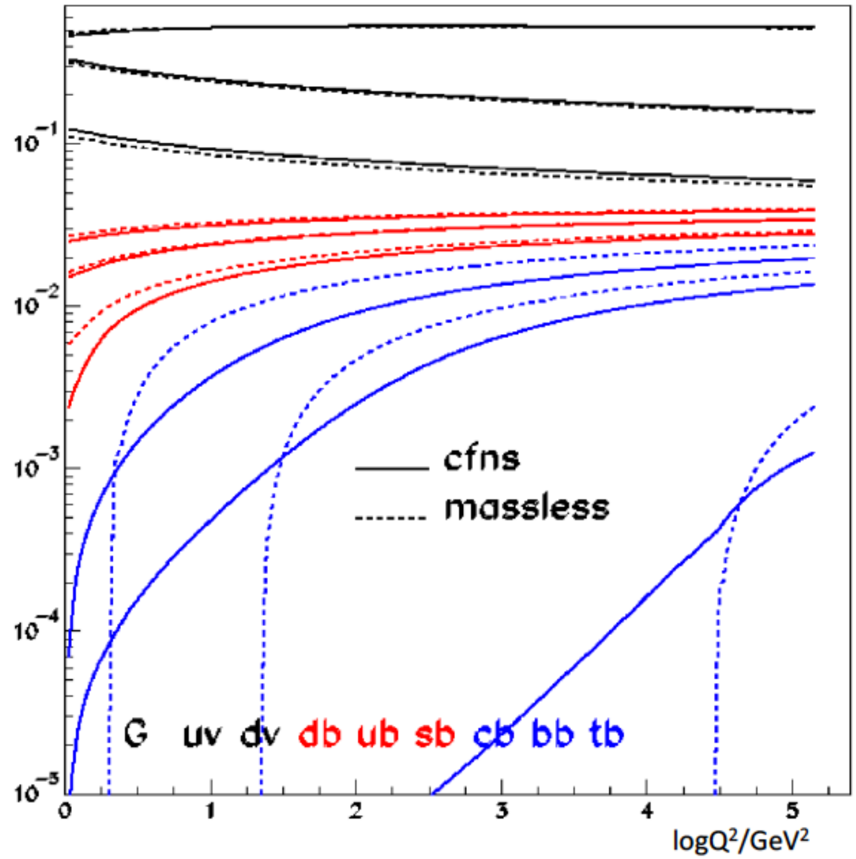
ReadOut-Pitch [mm]	20 x 20	10 x 10			20 x 20	20 x 20
Volume [m^3]	13.2	3.1	28.8	407	1.98	7.0
Sum-Si [m^2]	461					

Top

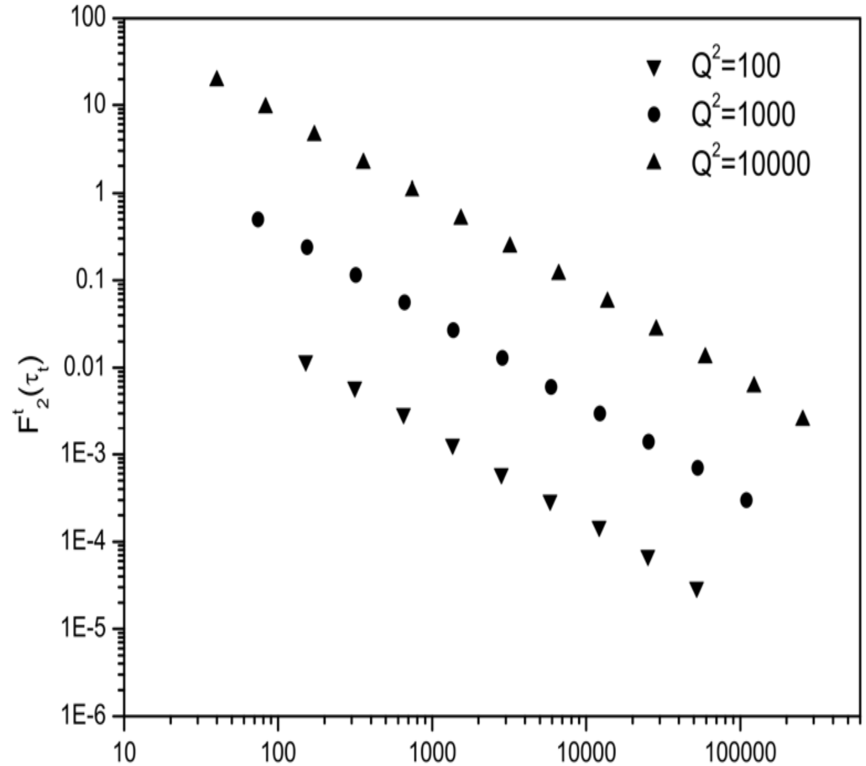
Cross sections and kinematic range base of unique SM and BSM top physics program in ep

See for example talk by U Klein today and by H Sun at DIS2017 at Birmingham. Here a note on the "top PDF"

LHeC CDR arXiv:1206.2913



At high $Q^2 \sim m_t^2$ top demands a fraction of proton's momentum – need to understand what a "top PDF" is. Scheme dependence

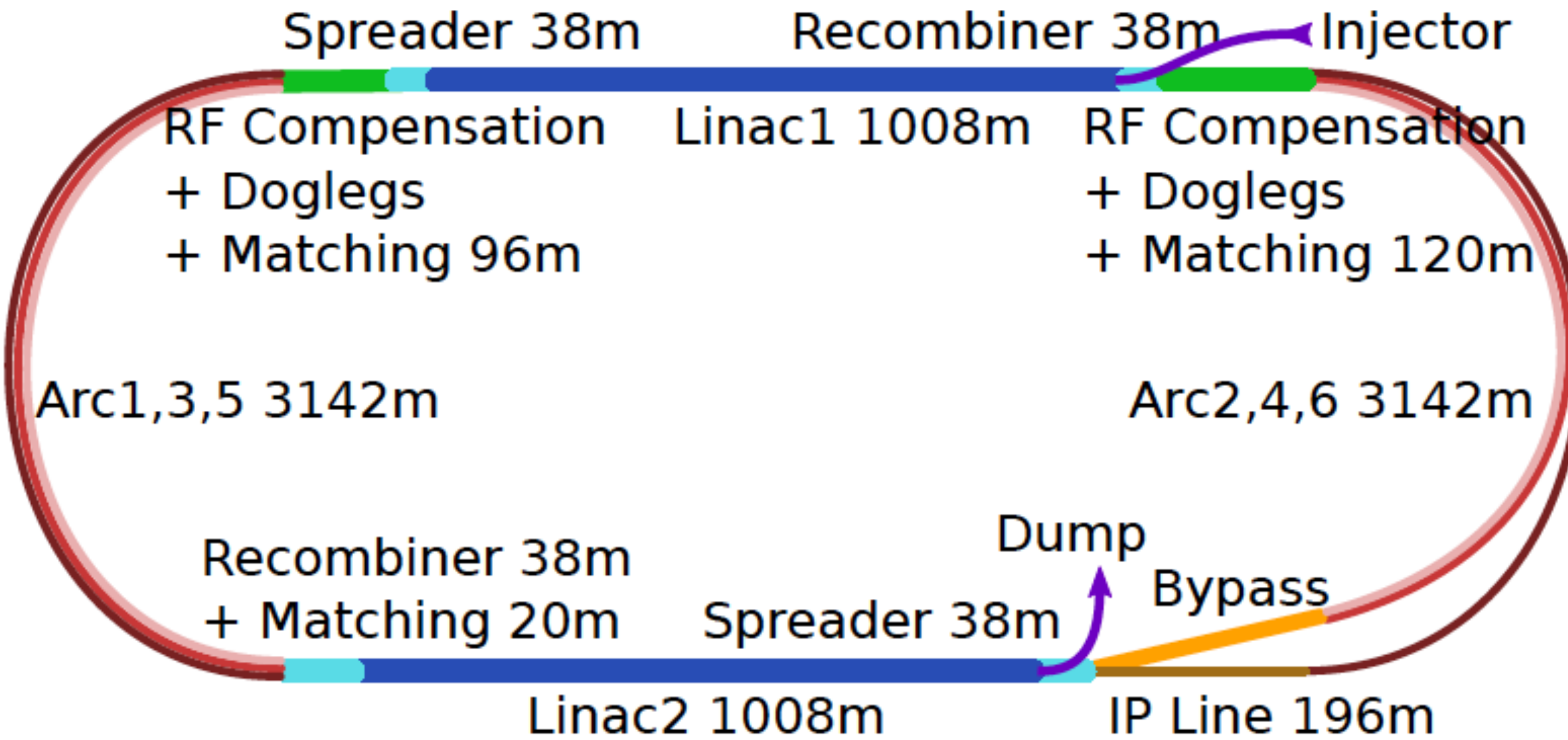


Boroun, Phys. Lett. B744, 142 (2015)

$$\tau_t = (1 + \frac{4m_t^2}{Q^2})^{1+\lambda}\frac{Q^2}{Q_0^2}(\frac{x_B}{x_0})^\lambda$$

Add an Electron Beam (ERL) to LHC (+FCC)

Conceptual Design Report (2012), Update for next European Strategy

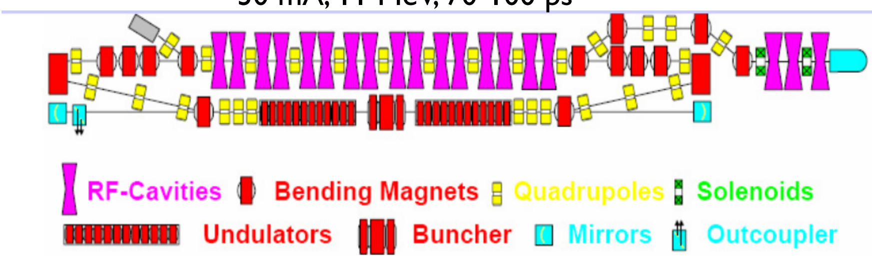


Concurrent operation to pp, LHC/FCC become 3 beam facilities. P(e) < 100 MW
10^{34} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach vs HERA

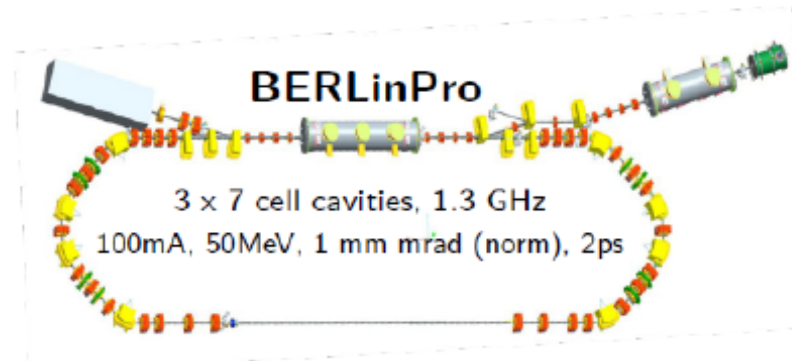
Other Facilities

Normal Conducting 180 MHz + DC Gun

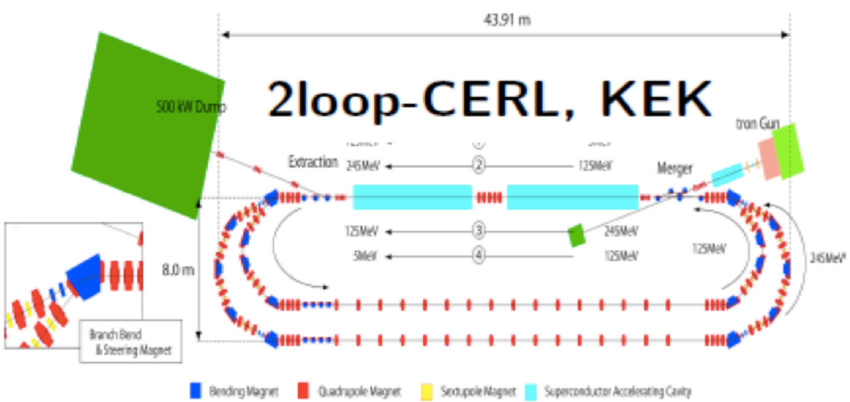
30 mA, 11 MeV, 70-100 ps



BINP, Novosibirsk

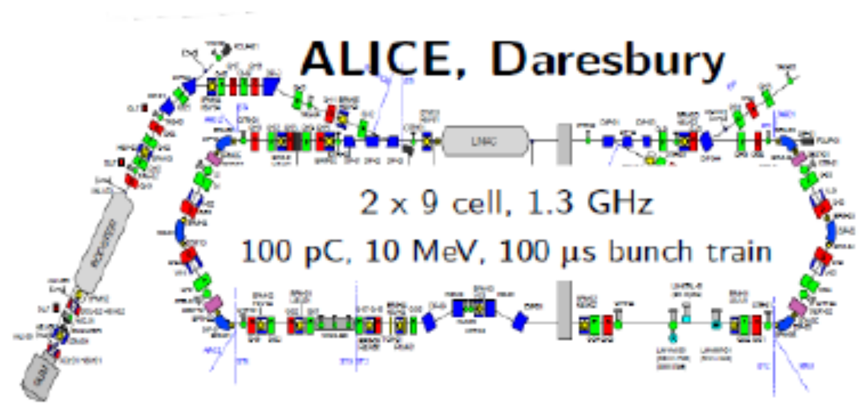


+D: MESA at Mainz and S-Dalinac Darmstadt



9 cell, 1.3 GHz cavities, 4 modules

77 pC, 245 MeV, 1-3 ps



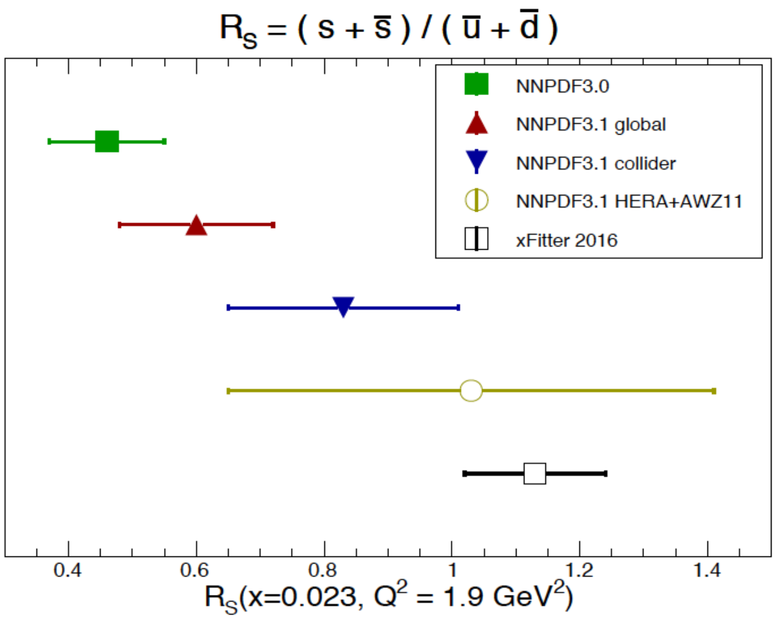
Also: **CEBAF** (single pass, 5 GeV, ..

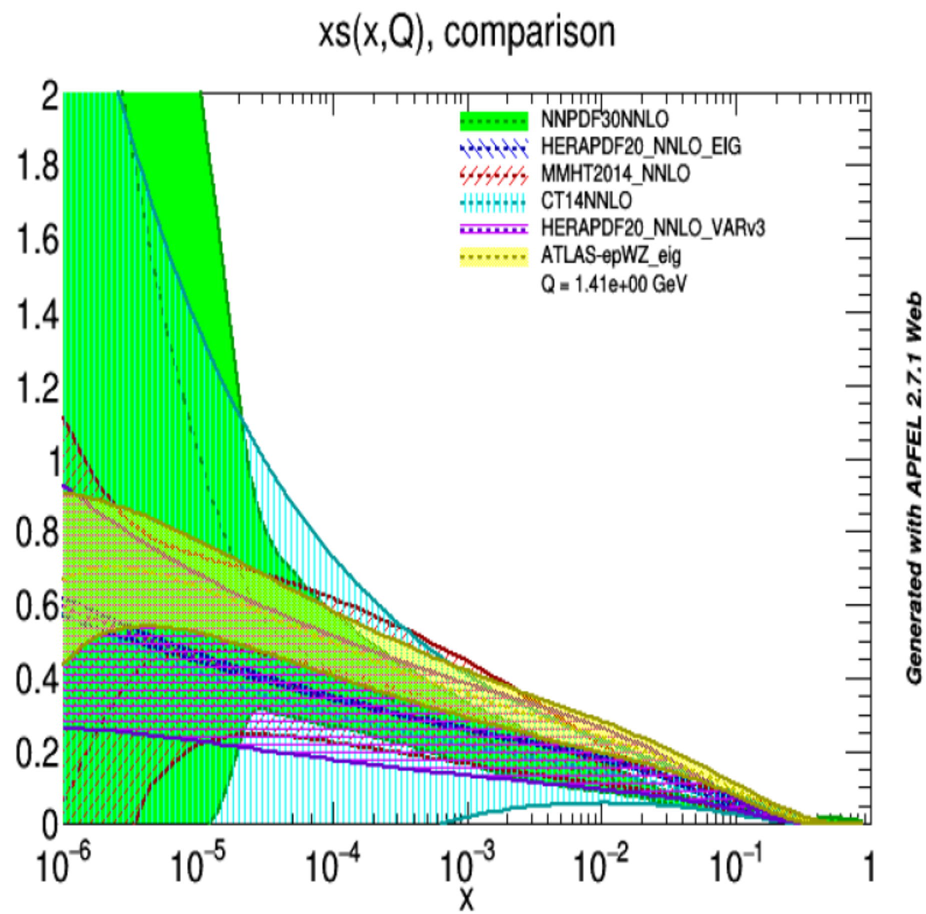
CBETA (50mA, 3 pass, FFAG, 1.3GHz)

Strong possibilities for collaboration (ERL workshop 19-23.6.2017 at CERN, E Jensen et al)

Strange Strange

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



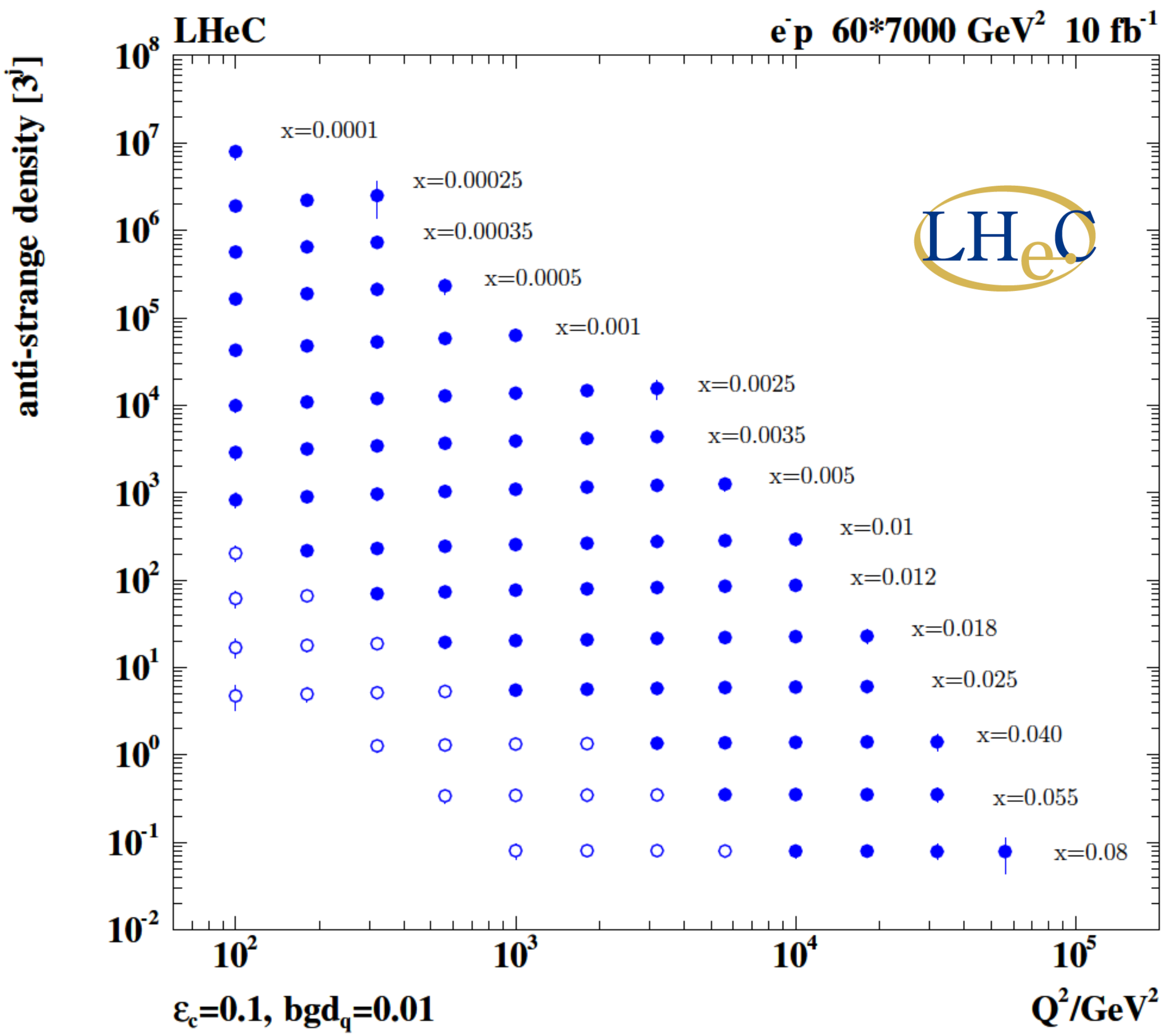


NNPDF3.1 arXiv:1706.00428, note:
"xFITTER16" = ATLAS: 1612.0301
Also look at MMHT and other results

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

The LHC can NOT measure PDFs but constrains some, the LHeC PDF programme is complete
You want reliable external input to examine standard and new phenomena in pp

Exploring SM EFT & New Physics

M. Trott @ LHeC Workshop 2014
http://lhec.web.cern.ch

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:

Four fermion operators with leptons and quark fields:

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

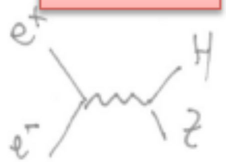
$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

➔ 59 operators or 2499 parameters experimentally to constraint!

➔ where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks

Kinematics and M_H : ee vs ep

ee: ZZH



e^+e^-

ee: Z→ νν contribution!

$$(p_{e^-}+p_{e^+})^2 = s = (p_H+p_Z)^2 = M_H^2+M_Z^2+2(E_H E_Z - \vec{p}_H \vec{p}_Z)$$

$$p_{e^+} = (E_e, -E_e, \vec{0}_\perp), \quad p_{e^-} = (E_e, E_e, \vec{0}_\perp)$$

$$\curvearrowright \quad 2E_e = E_H + E_Z, \quad \vec{p}_H = -\vec{p}_Z$$

$$s = M_H^2 + M_Z^2 + 2(E_Z\cdot(2E_e - E_Z)) + 2p_Z^2$$

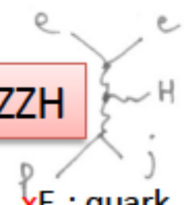
$$s = M_H^2 + M_Z^2 - 2M_Z^2 + 4E_Z\cdot E_e$$

$$s = M_H^2 - M_Z^2 + 2\sqrt{s}\cdot E_Z$$

$$\rightarrow M_H^2 = s + M_Z^2 - 2\sqrt{s}\cdot E_Z$$

ee: x=1 no PDF or from factor involved

ep:ZZH



ep

$J_e := (e+j)$

ep: no Z→ νν contribution!

xE_p: quark in DIS carries fraction x of initial proton energy

$$(p_e+p_p)^2 = s = 4E_eE_p\, x \quad M_H^2 + M_{J_e}^2 + 2(E_H\cdot E_{J_e} - \vec{p}_H\cdot\vec{p}_{J_e})$$

$$p_e = (E_e, -E_e, \vec{0}), \quad p_p = (xE_p, xE_p, \vec{0})$$

$$E_e + xE_p = E_H + E_{J_e} \quad ; \quad (\vec{p}_H + \vec{p}_{J_e})_z = xE_p - E_e$$

$$s = M_H^2 + M_{J_e}^2 + 2E_{J_e}\cdot(E_e + xE_p - E_{J_e}) - 2\vec{p}_{J_e,z}[(xE_p - E_e) - \vec{p}_{J_e,z}]$$

$$= M_H^2 + M_{J_e}^2 - 2M_{J_e}^2 + 2E_{J_e}(E_e+E_p) - 2\vec{p}_{J_e,z}(E_p - E_e)$$

$$\rightarrow M_H^2 = s + M_{J_e}^2 - 2(E_e + xE_p)\cdot E_{J_e} + 2(xE_p - E_e)\cdot \vec{p}_{J_e,z}$$

for $xE_p = E_e$, $J_e = Z$ this is equivalent to M_H in e^+e^-

12.8.17.

→ x in DIS can be determined via electron angle and energy or inclusive hadron kinematics or combinations of it

From a talk on EIC and LHeC Side by Side

In time: - The EIC and the LHeC will not be operational before 2030
[cf B. Mueller on eRHIC Monday and LH(e)C time schedule (LS4),
HERA took 8 years to build: approval in 1984 data 1992 → 2007. XFEL ~9 years]
- They should be considered to be operational together, not sequential *)
- EIC needs decades for spin, ep and eA data, much beyond the Trump time
- LHeC will be terminated with the LHC but may reappear with HE LHC (FCC)

In their technology choice:
- currently (BNL?) both the two US EICs and the LHeC use ERLs for the e beam
- they have similar challenges (multi-turn, high current ERL)
- all luminosity goals are very ambitious and need R+D:
a common problem is a high current polarised e^- source (LHeC 15, BNL 50mA)
- they almost certainly will have 100 times less or no positrons, P=0

In their kinematics: $Q^2_{max} = s = 10^4$ GeV^2 (EIC) 10^6 GeV^2 (LHeC), $x > 1$ GeV^2 /s in DIS

In their role: seen from the perspective of genuine deep inelastic scattering:
- EIC will "replace BCDMS/NMC (suspicious at high x) and HERMES/COMPASS"
- LHeC will "replace HERA (uncertain at high x and no CC x > 0.5)"

*) Predicting is difficult, in particular if it concerns the future (V. Weisskopf)

MK at POETIC 2016, Philadelphia


8105

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

MK at Ephiphany, Cracow January 2015

A low energy EIC cannot replace the high energy LHeC. The LHeC cannot measure p spin composition and is not set to study hadron structure at medium x. Like H1/ZEUS and HERMES/Compass, both have a task while NOT being the same.

Magnets, Spreaders, Combiners