Future Electron-Hadron Colliders

at the energy frontier

LHeC: ep at √s = 1.3 TeV

FCC-eh and eh in China at ~4 TeV

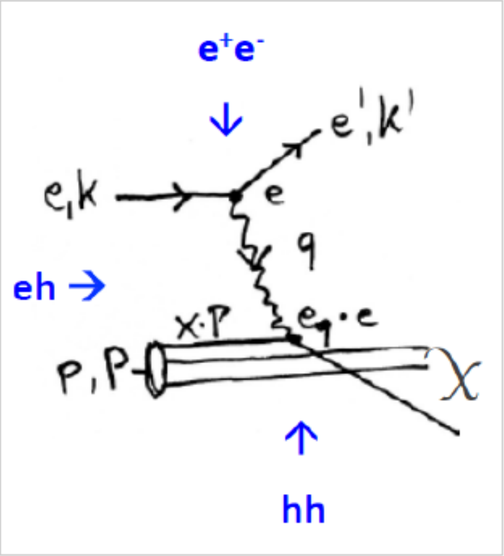
Remarks on projects, accelerator, detector and (selected) physics prospects

Max Klein
University of Liverpool, H1 and ATLAS

For the LHeC and FCC-eh Study Groups and the PERLE Collaboration

Talk at the IAS Hongkong Conference on High Energy Physics, 24.1.2018

Deep Inelastic Lepton-Hadron Scattering



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

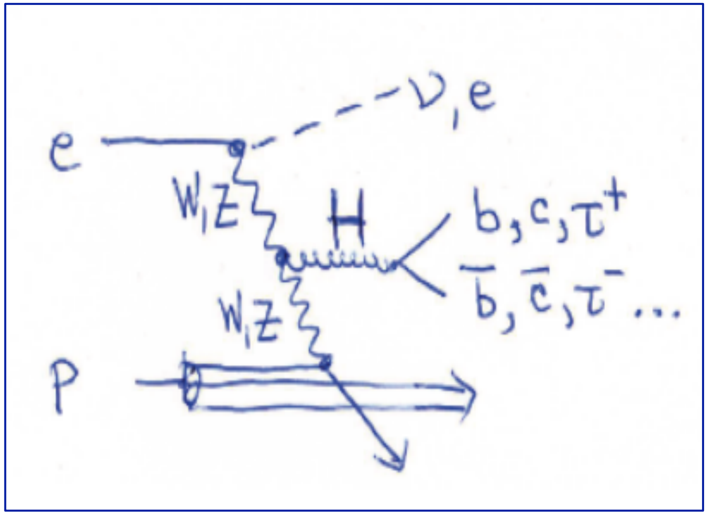
Redundant determination of the scattering kinematics: x, $Q^2 \leq 4E_eE_p=s$ → high precision

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

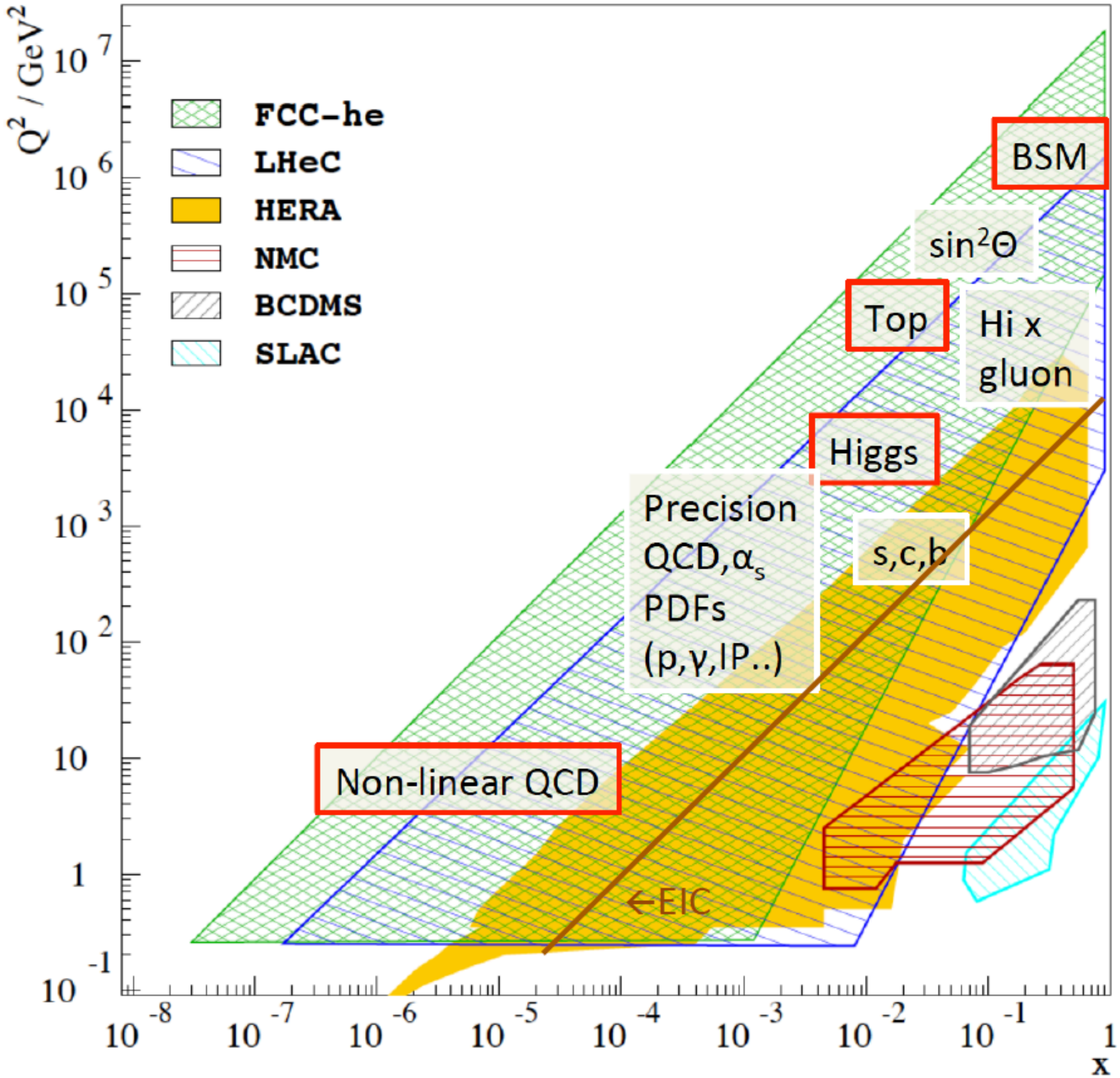


Can produce heavy new states (Higgs, 750 GeV ghost..) and reach to O(200) TeV by indirect constraints, such as high precision contact interaction measurements

pp, ep and ee are ordered in energy reach: $2E_p >> 2\sqrt{(E_pE_e)} >> 2E_e$
For the FCC this translates to 100 TeV vs 3.5 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..**

Outline

0. Bits of Information

1. Parameters and Configuration of the LHeC

2. PERLE Testfacility for Energy Recovery Physics and SCRF

3. Detector Development for LHeC and Installation Issues

4. Selected Physics Highlights (PDFs, Higgs, BSM)

5. Extension to the multi TeV range (FCCeh and in China)

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

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

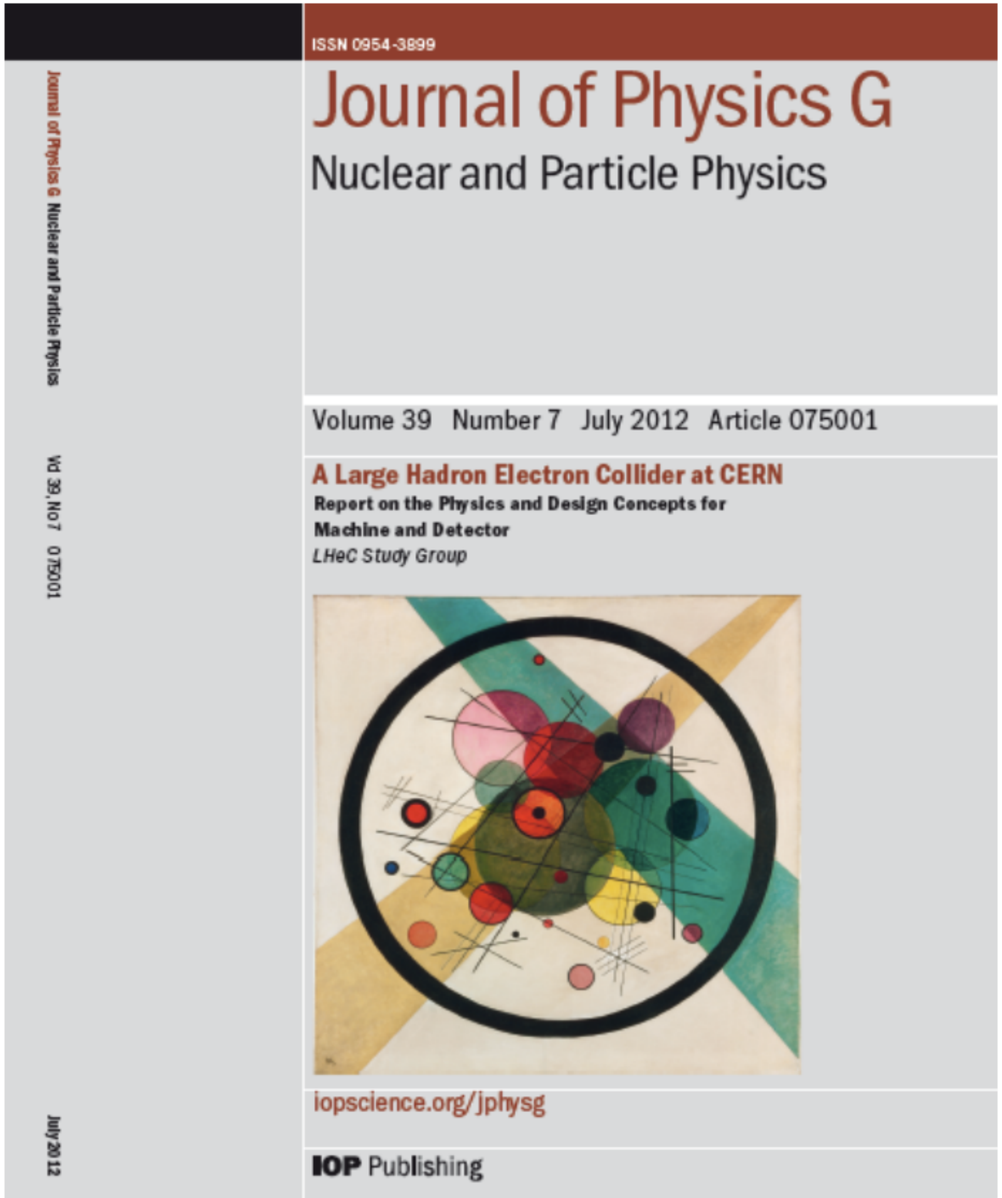
5(11) are members of the FCC coordination team

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



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.

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"

Information on LHeC

Conceptual Design Report: arXiv:1206.2913

Discussion of move to 10^{34}: O. Bruening, MK: arXiv:1305.2090 published MPLA

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

Toni Feder

Citation: Physics Today **70**, 5, 29 (2017);
View online: https://doi.org/10.1063/PT.3.3551

Future Deep Inelastic Scattering with the LHeC

Contribution to a Book dedicated to the Memory of Guido Altarelli, January 21, 2018

MK: To be submitted to the arXiv

Increasing number of papers (e.g. D Curtin et al, 1712.07135) **and talks: https://lhec.web.cern.ch**

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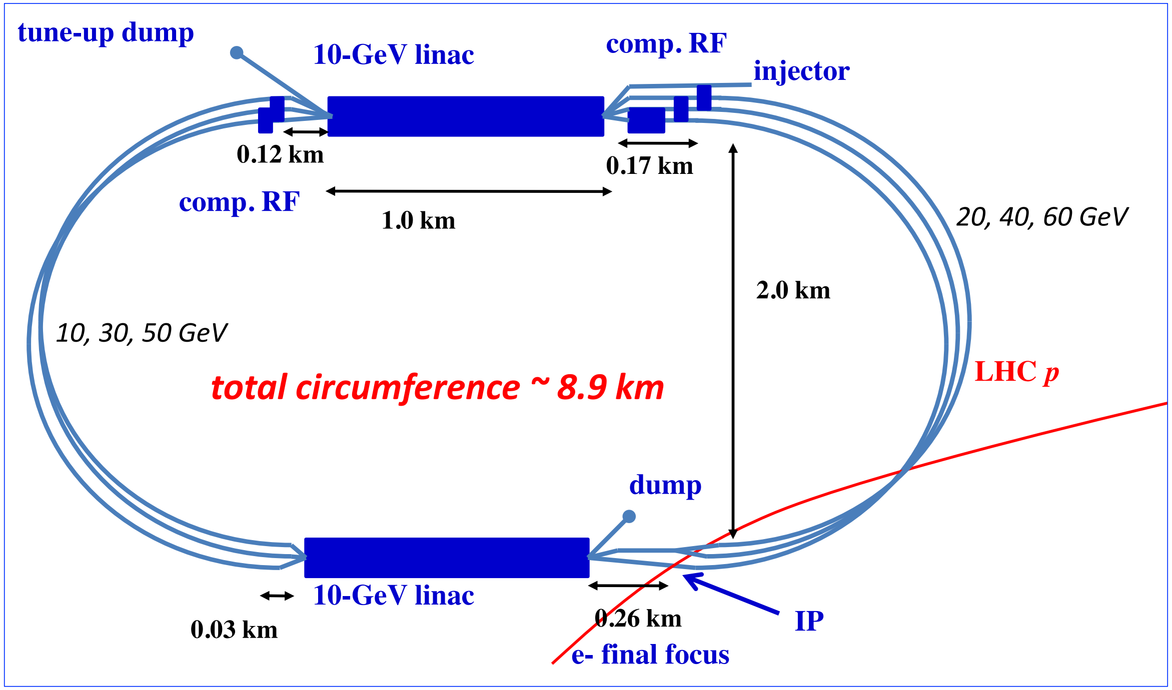
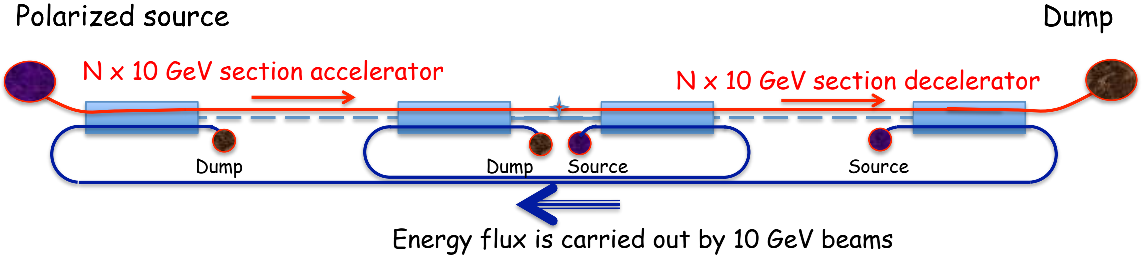
ep/A with the LHC

Conceptual Design Report: arXiv:1206.2913, published in JPhysG



LHeC: 60 GeV off 7 TeV, L(ep) =$10^{33 \rightarrow 34}$ 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



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Performance

Interaction Region

Optics

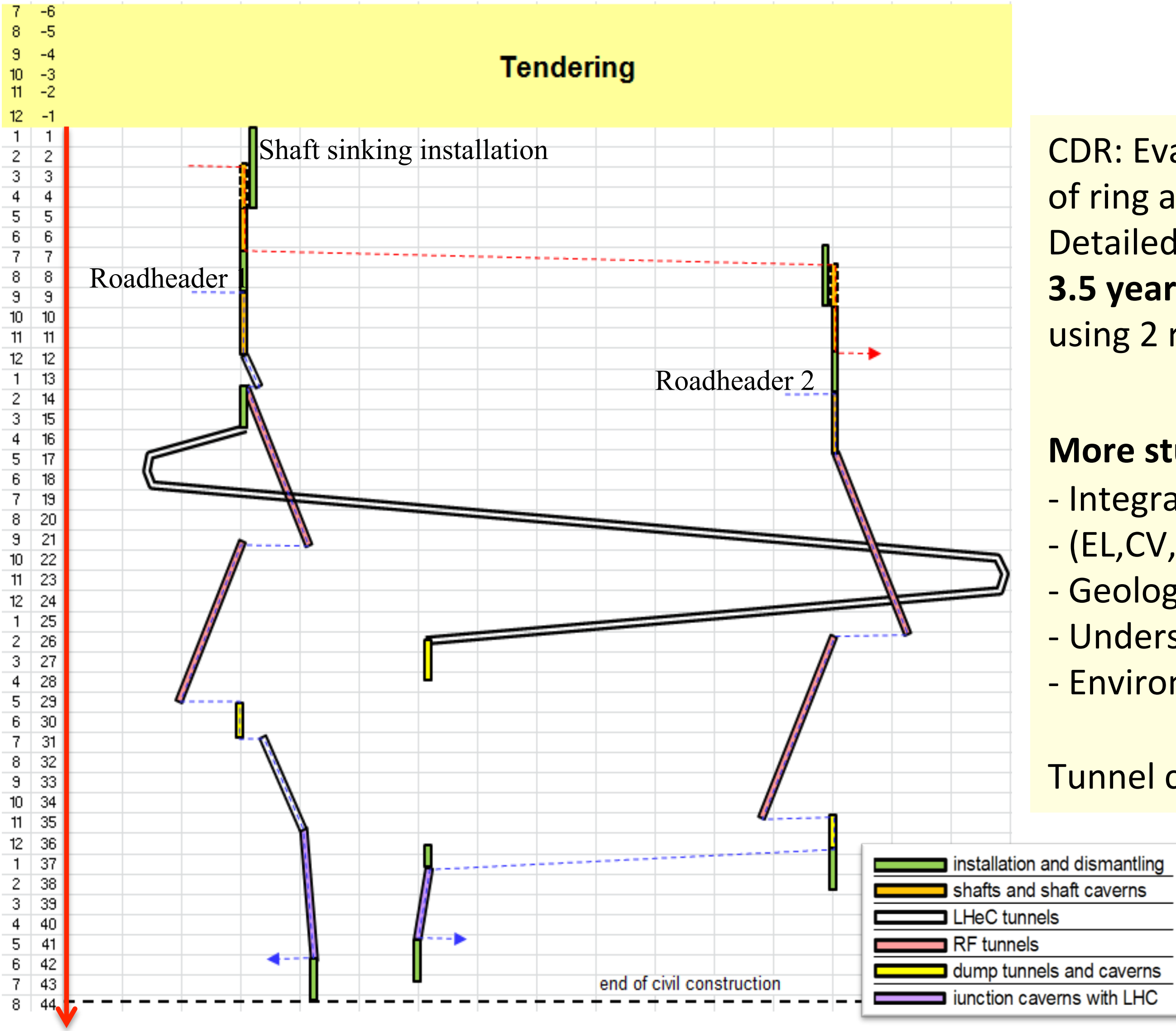
Ions

Polarisation (80-90%)

Positrons

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

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

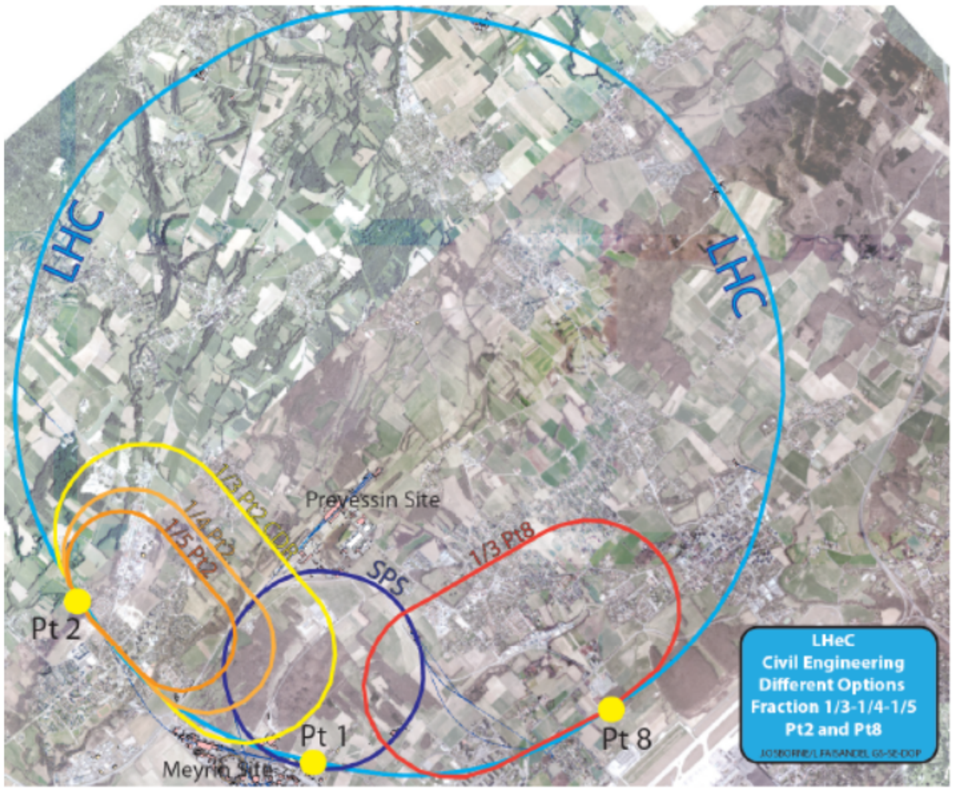
More studies will be needed for
- Integration with all services
- (EL,CV, transport, survey etc).
- Geology
- Understanding vibration risks
- Environmental impact assessment

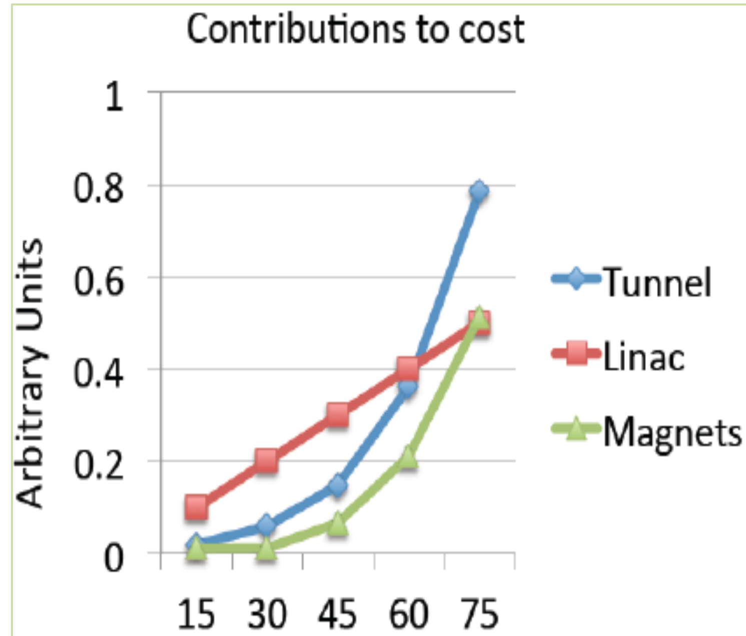
Tunnel connection in IP2

J.Osborne et al.

Location, Footprint, Use of the Electron Racetrack

e beam external to LHC. Location suitable for both HL and HE LHC. Program in the transition: yy collider, high energy FEL, fixed target





MK, F Zimmermann

- We don't have six sites as the CEPC..
- 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

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.**

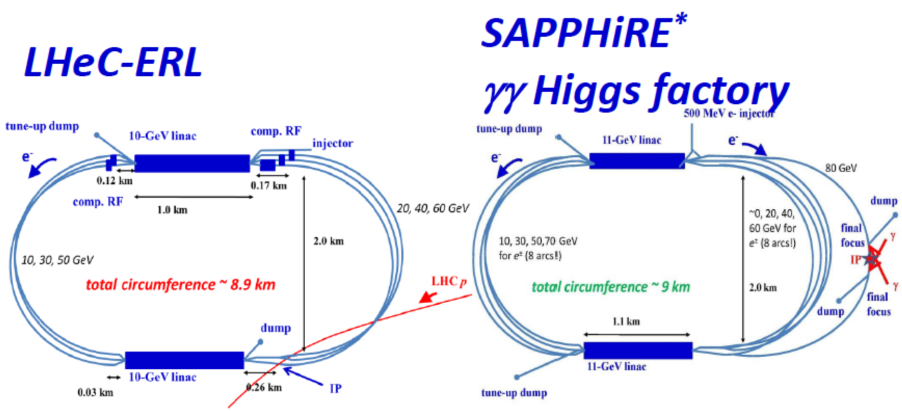
Longitudinal Structure Function – THE path to saturation

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

Further use of ERL in between HL and HE LHC

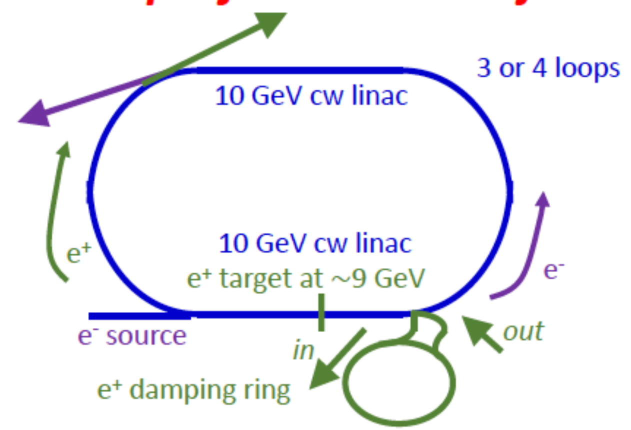
Reconfiguring *LHeC* → *SAPPHiRE*



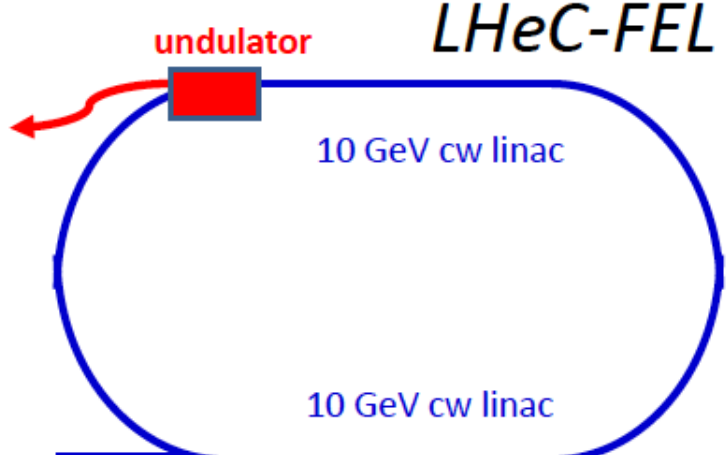
*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons
S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, 'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

F.Zimmermann at LHeC WS 9/17

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

Luminosity for LHeC, HE-LHeC and FCC-ep

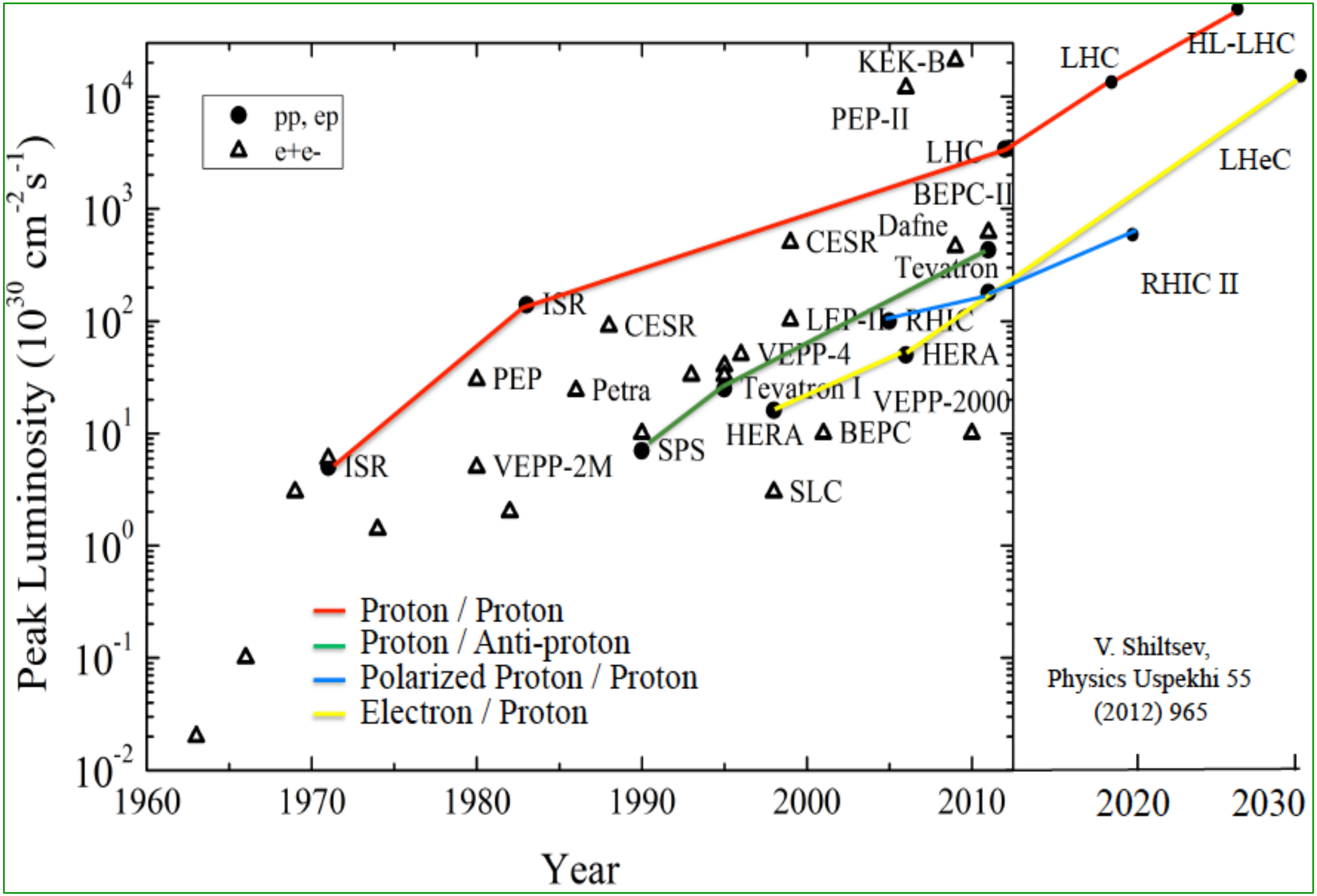
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [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[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.

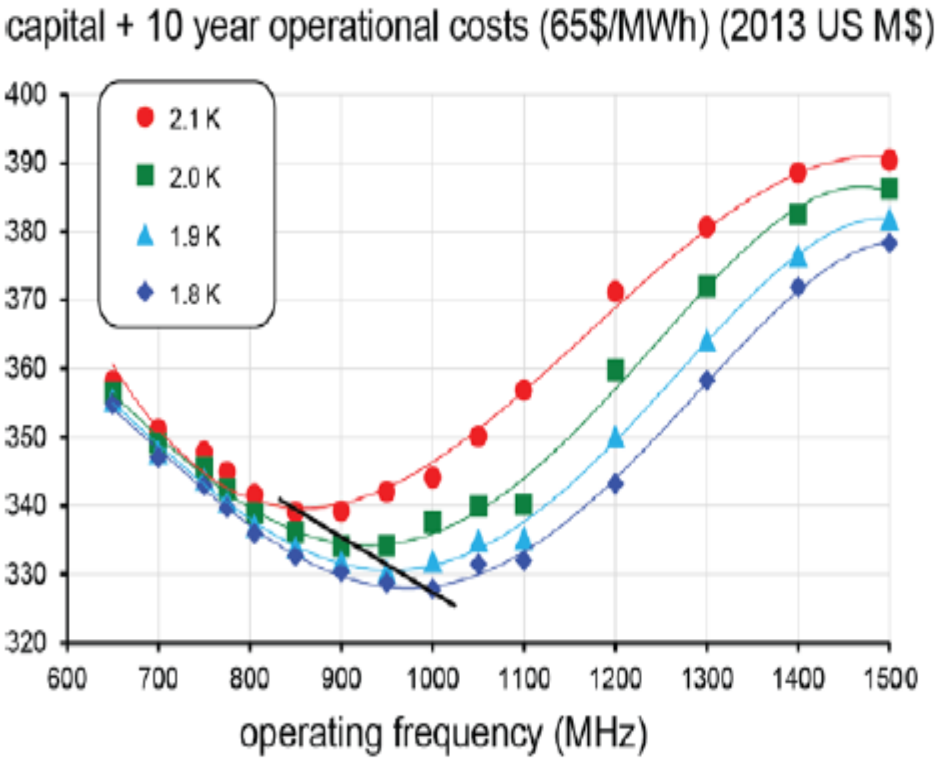
Collider Luminosities vs Year (pp and ep)

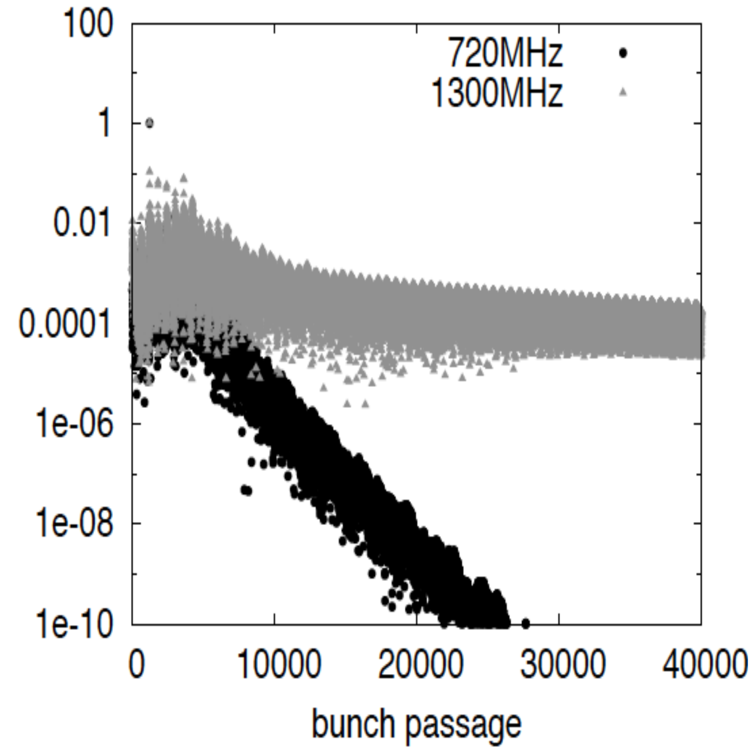


O. Bruening 2/17

HL LHC programme: 3ab^{-1} (in pp scattering) in 10 years of operation: LHC until almost 2040

Frequency Choice: 801.58 MHz





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)

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Powerful Energy Recovery Linac for Experiments

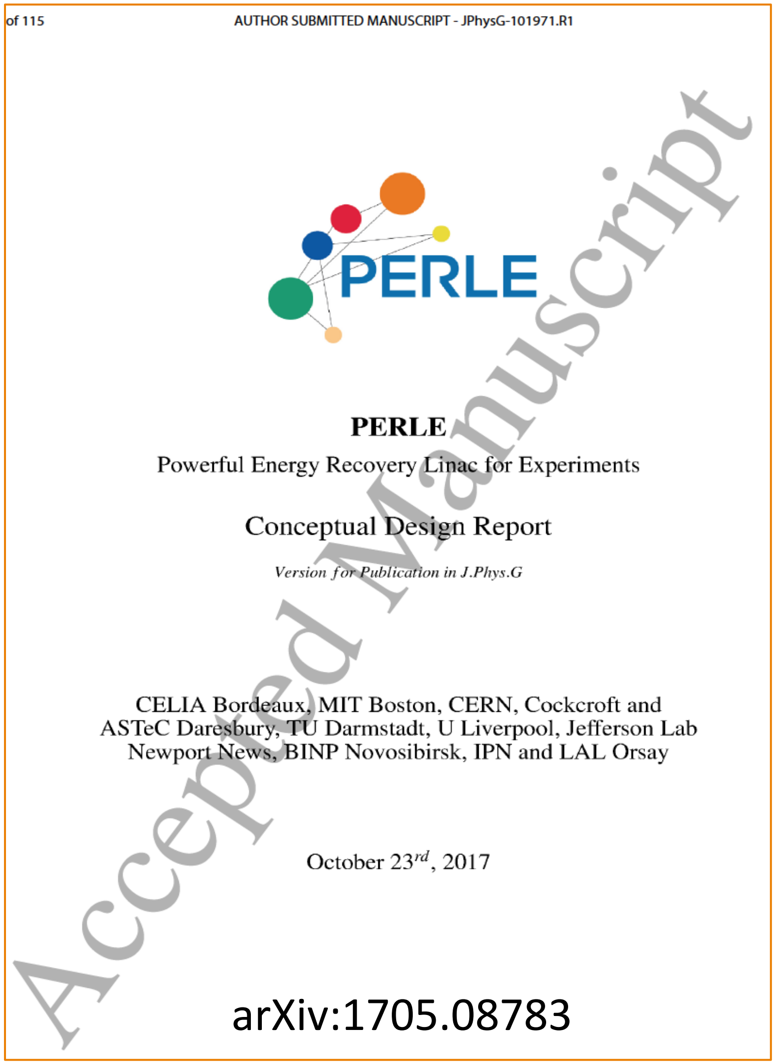
$$I_e = eN_e f = \frac{P}{E_e}$$

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 **E**xperiments

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

Accepted Manuscript

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

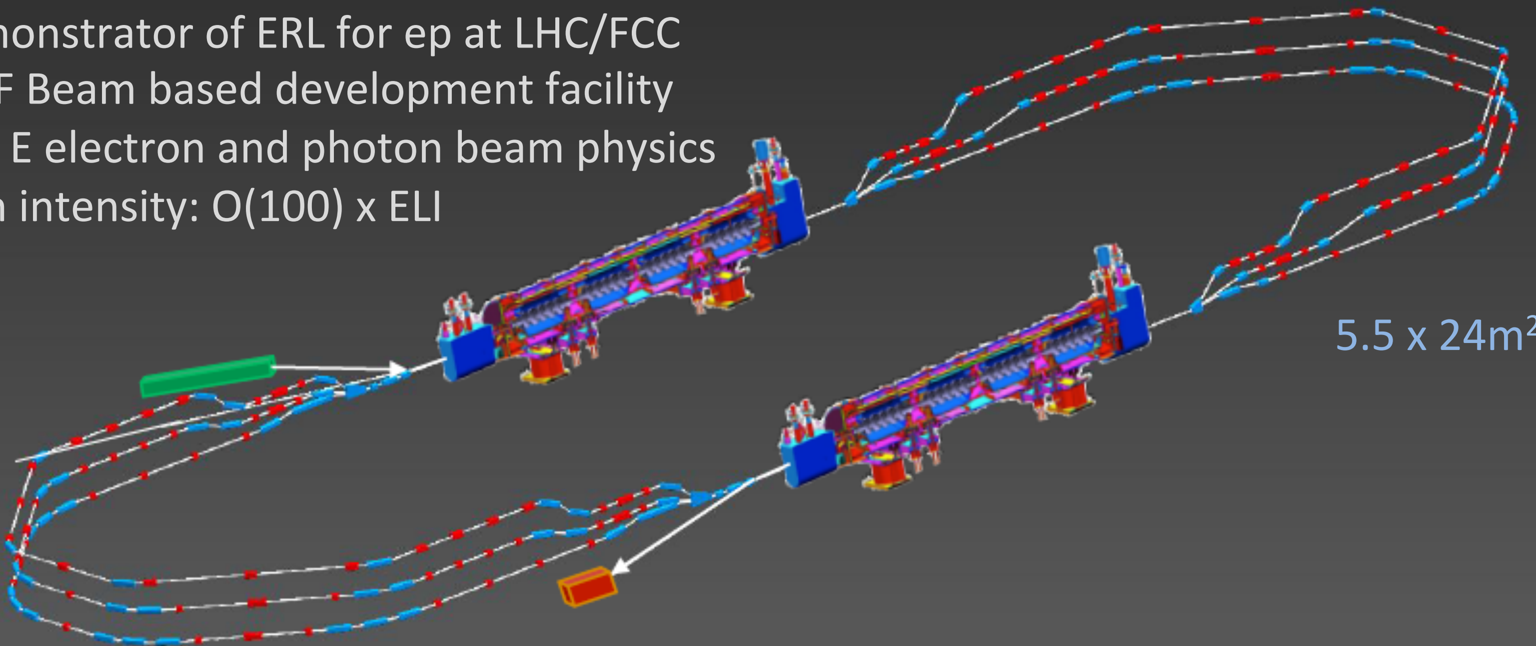
PERLE at Orsay

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



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

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

Source: DC Photocathode

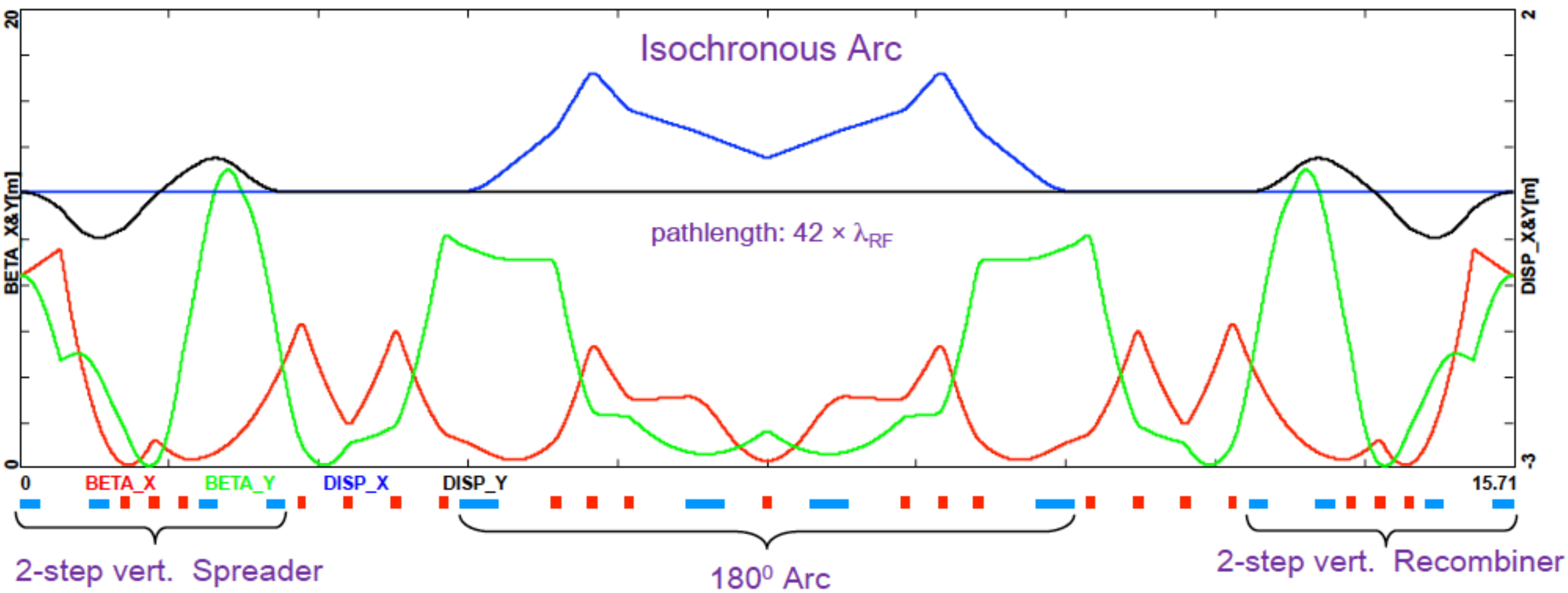
Material	Typical oper.λ	Work function	Observed Q.E.	Laser power for 20 mA	Observed max current	Obs. lifetime
Sb-based unpolarised	532 nm	1.5-1.9 eV	4-5%	4.7 W at Q.E.=1%	65 mA [Cornell]	Days rep.
GaAs-based polarised	780 nm	1.2 eV at NEA state	0.1-1.0%	31.8 W at Q.E.=0.1%	5-6 mA [JLAB]	Hours

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)



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 $\leq$ 1 kGauss/cm

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

PERLE Magnets

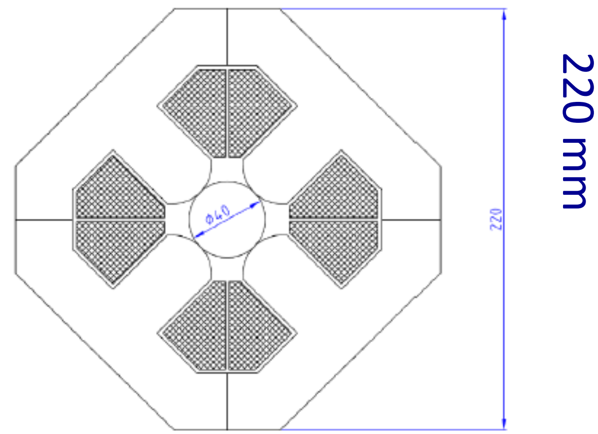
70 dipoles 0.45-1.29 T

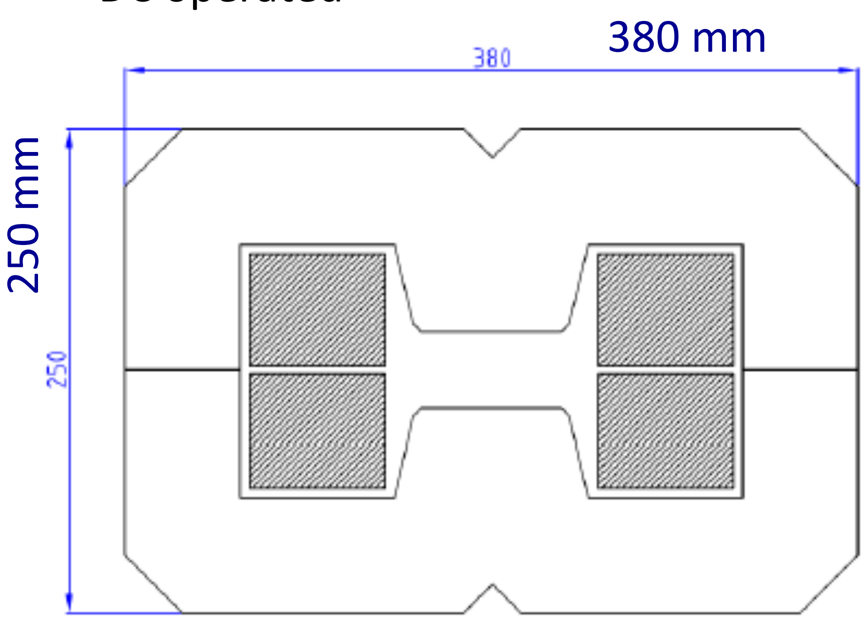
+- 20 mm aperture, l=200,300,400 mm

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

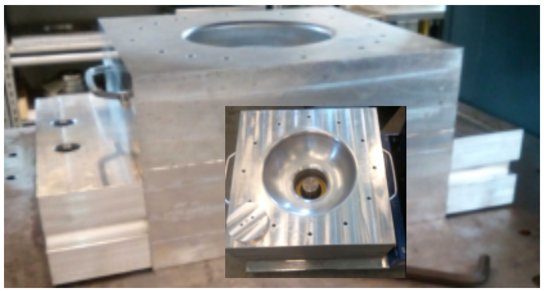
Two lengths: 100 and 150mm

DC operated

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

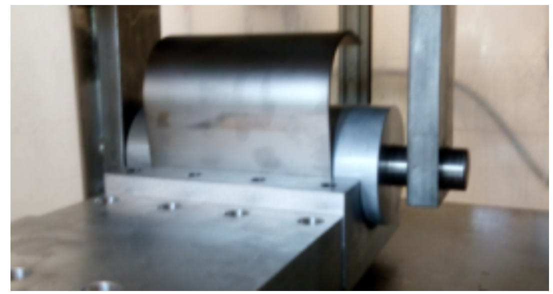
Cavity Fabrication

- We developed all tooling for cavity fabrication

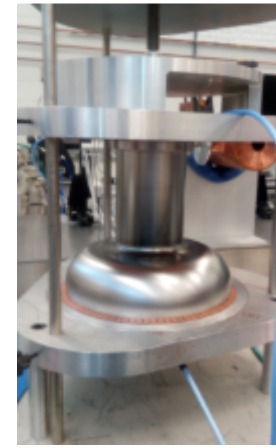


Fixture for female die with blank holder

Male die

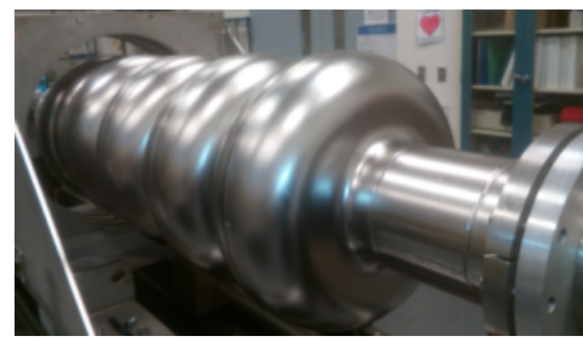


Beam tube rolling die



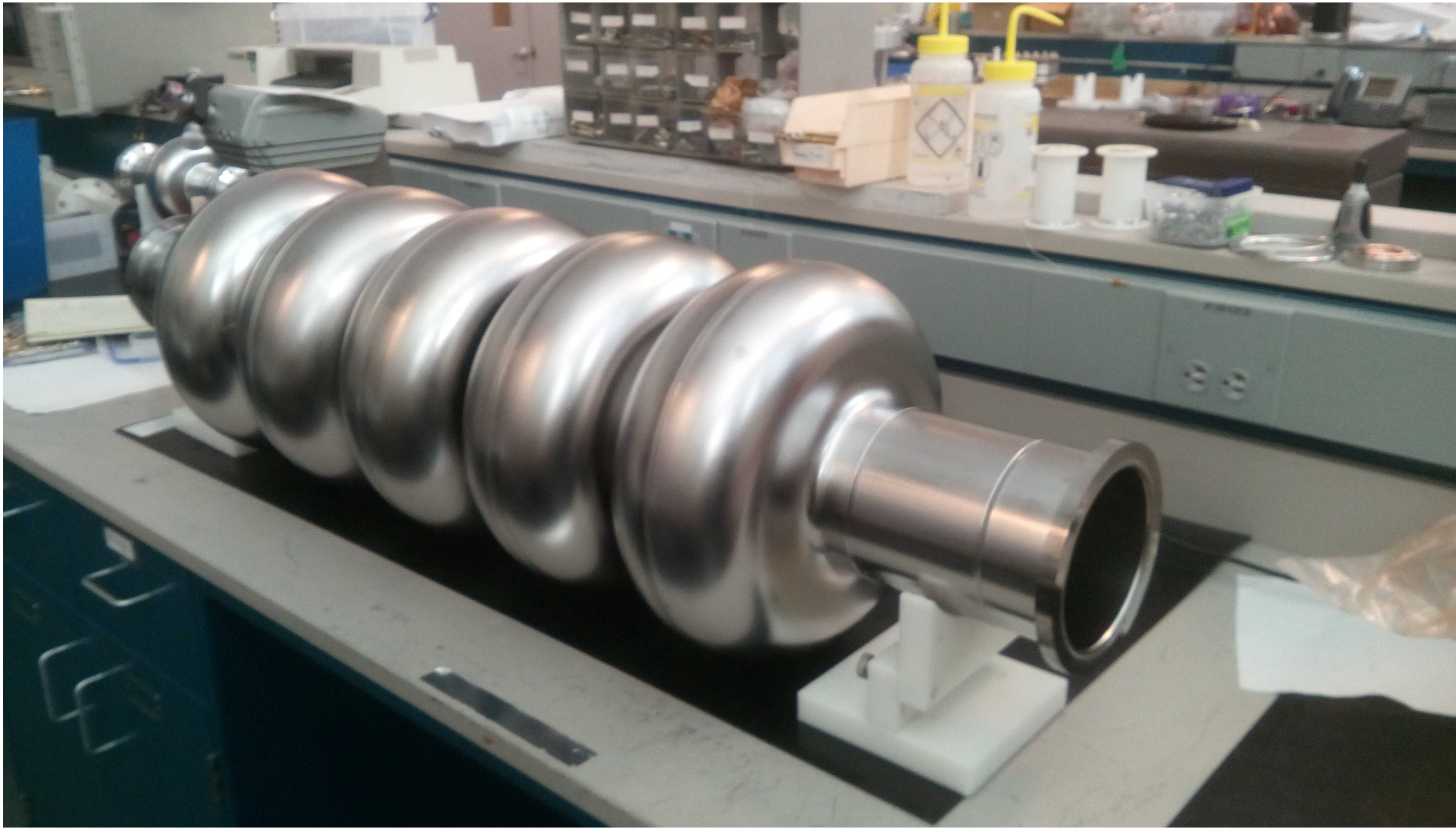
RF half cell/dumbbell measurements fixture

Five-cell cavity in EBW machine prepared for subsequent dumbbell and endgroup welding with both outside and inside welds in tilted position



Five-cell cavity on tuning bench

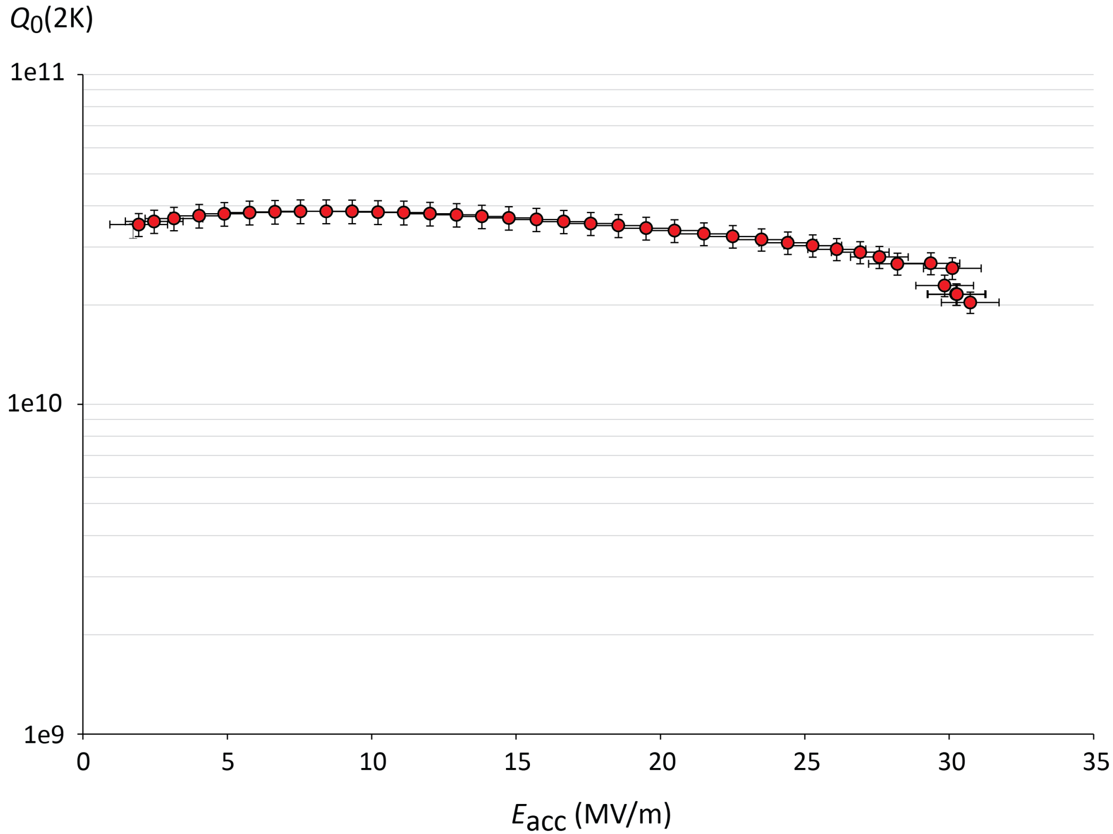
1^{st} 802 MHz Cavity



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

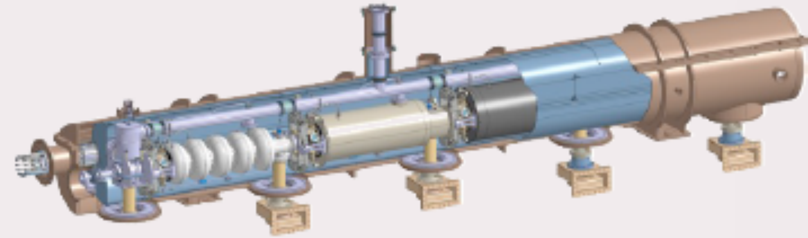
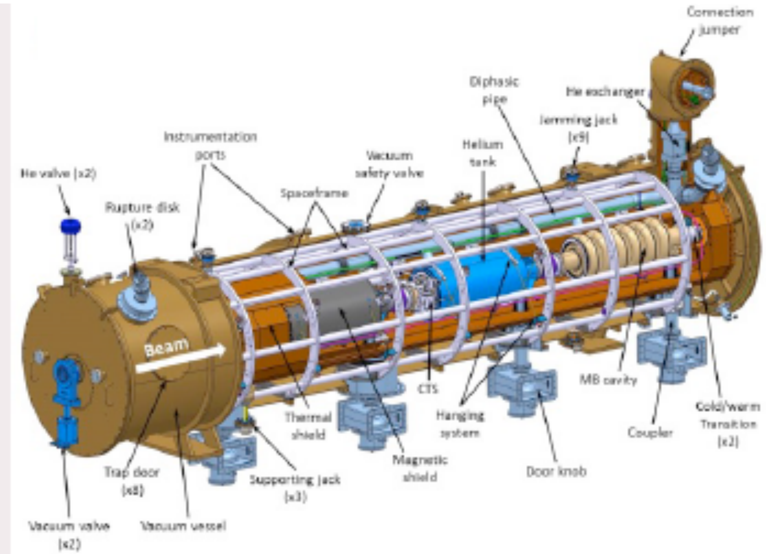
Goal: 16 MV/m, $Q_0 > 10^{10}$ operated in CW in the PERLE+LHeC ERLs, prototype also for FCC-ee

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.

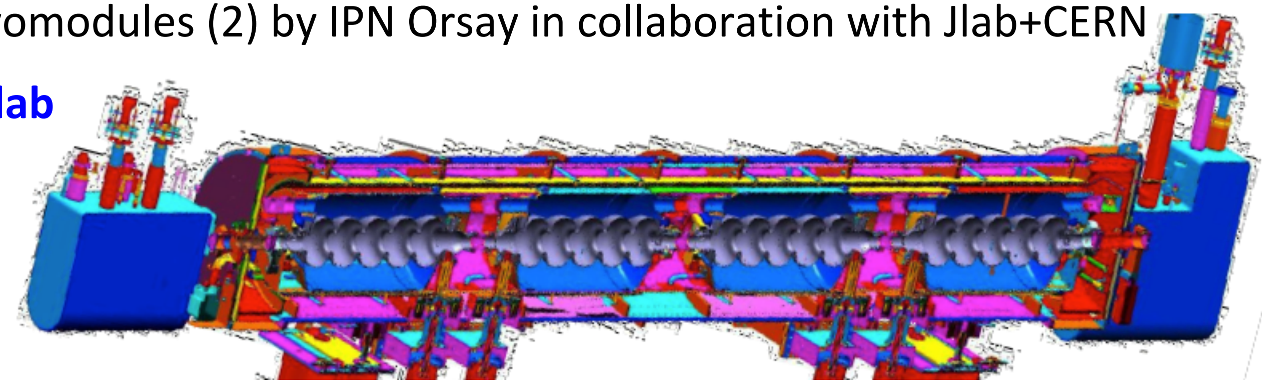
Next Step: Cryomodule

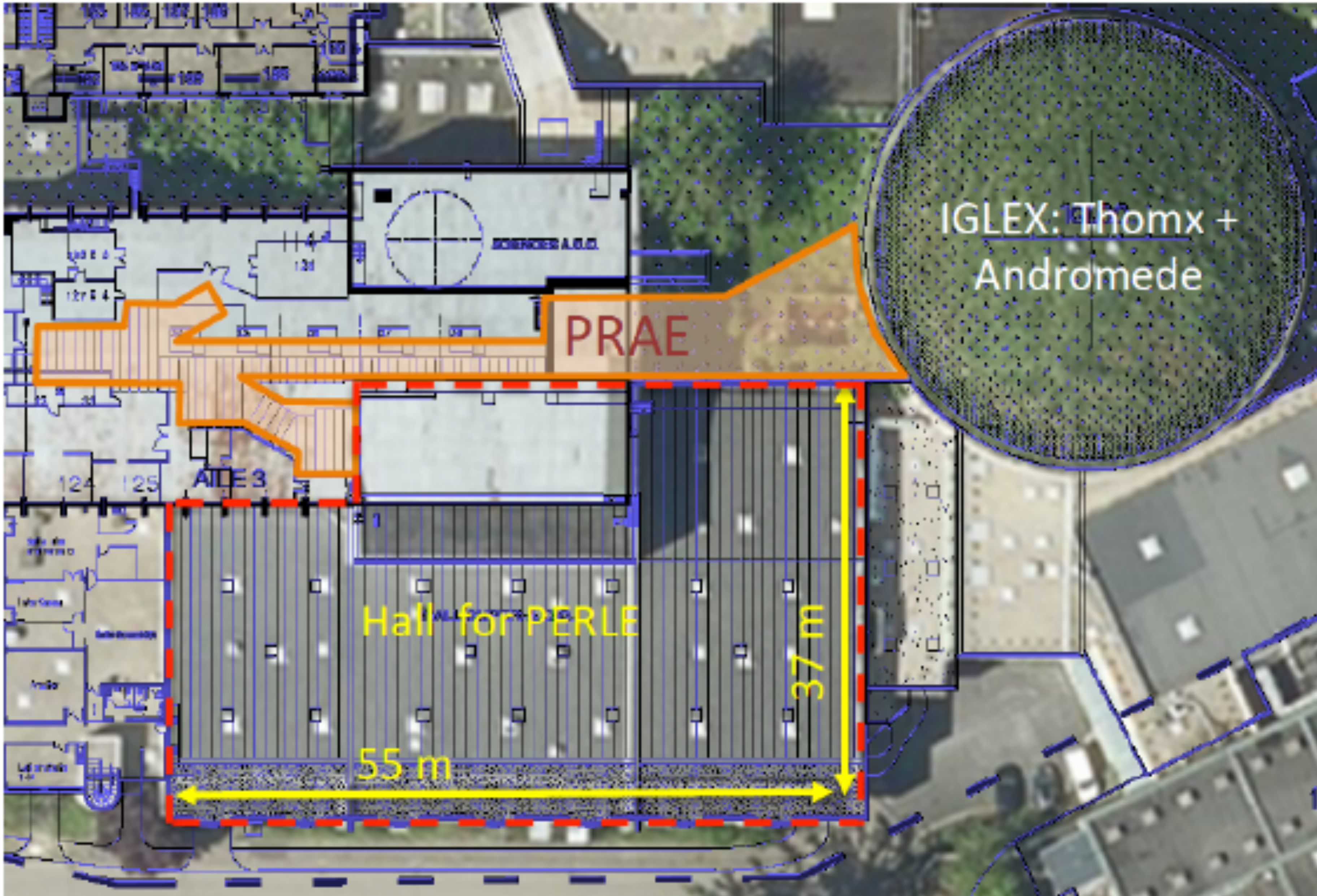
SPL « Short cryomodule »	5-cells Elliptical 700 MHz, β = 1.0 **X 4**	Full length top lid closure Cold mass supported by power couplers	
ESS Elliptical cryomodule(s)	5&6-cells Elliptical 700 MHz $\beta = 0.67$ & 0.86 **X 4**	Side loading Space frame	

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

Jlab

SNS 805 MHz cryomodule




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


8105

Outline

0. Bits of Information

1. Parameters and Configuration of the LHeC

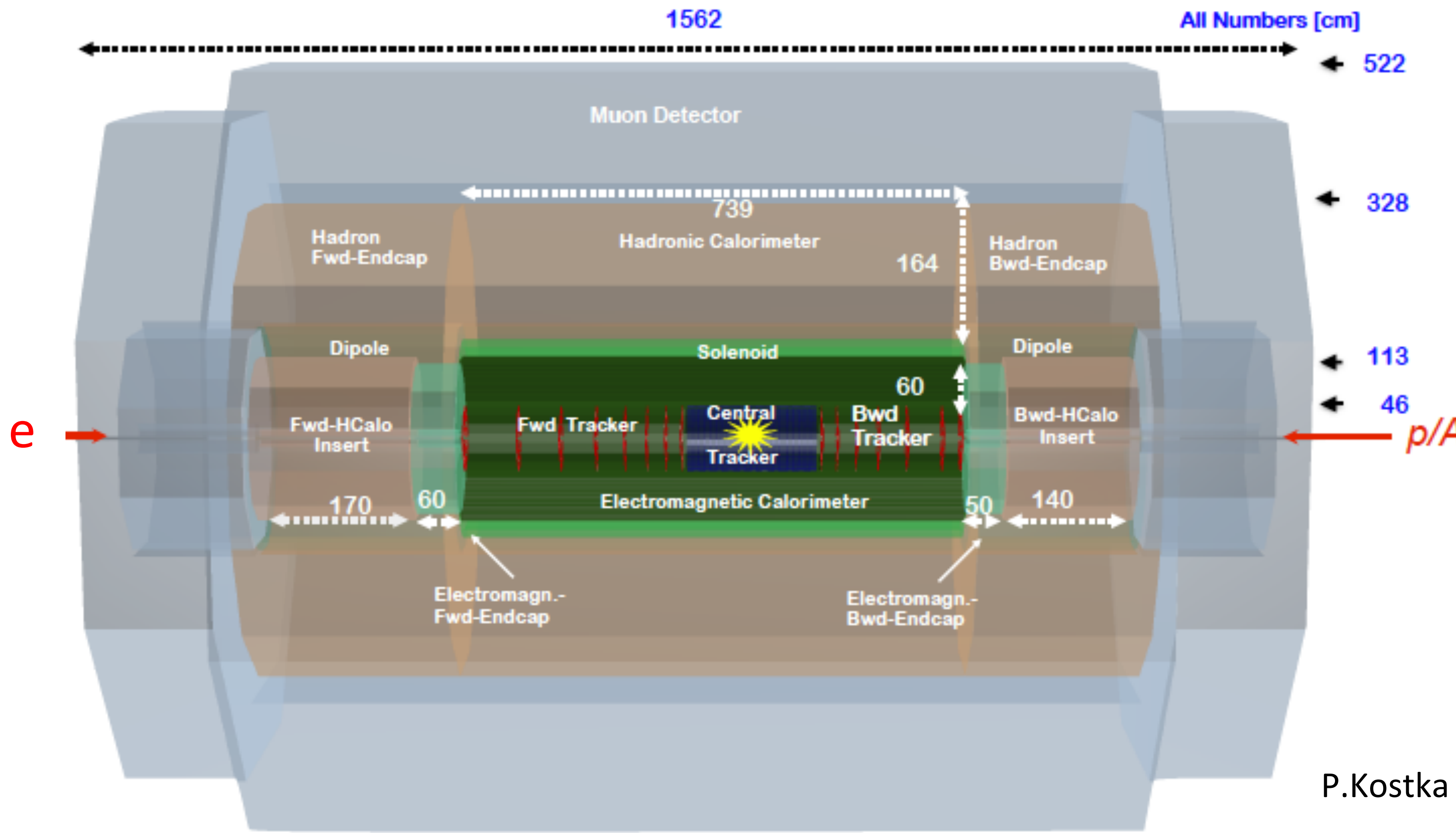
2. PERLE Testfacility for Energy Recovery Physics and SCRF

3. Detector Development for LHeC and Installation Issues

4. Selected Physics Highlights (PDFs, Higgs, BSM)

5. Extension to the multi TeV range (FCCeh and in China)

LHeC Detector for the HE LHC



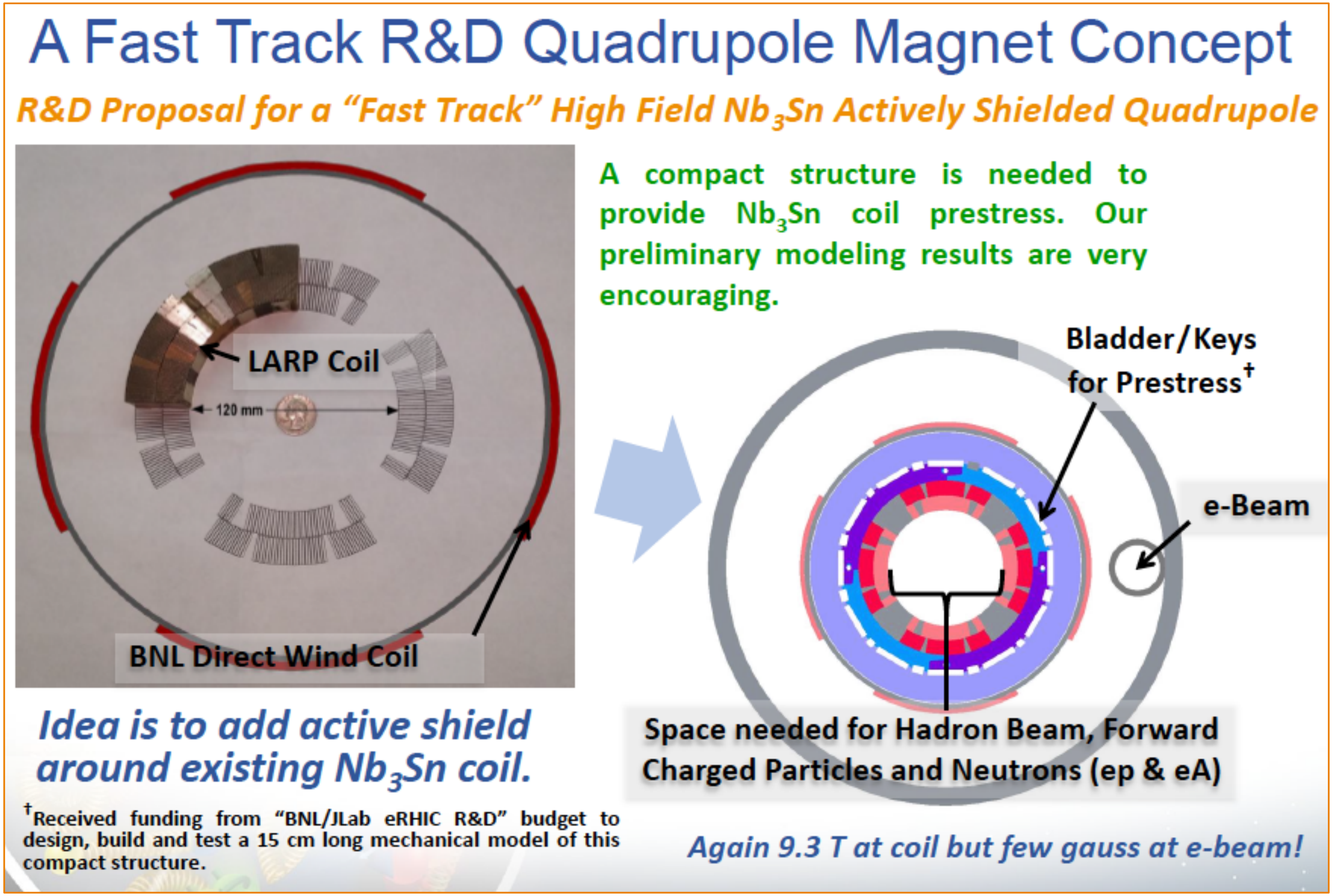
P.Kostka et al

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

Concluding Work on IR (3 beams, cf CDR)

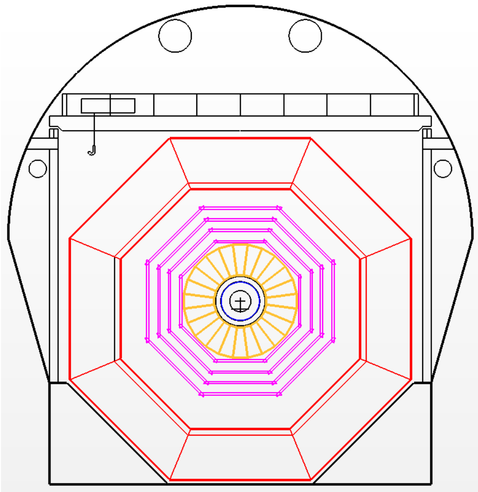


Brett Parker at September 2017 LHeC Workshop. Replace Q1 of CDR by another design

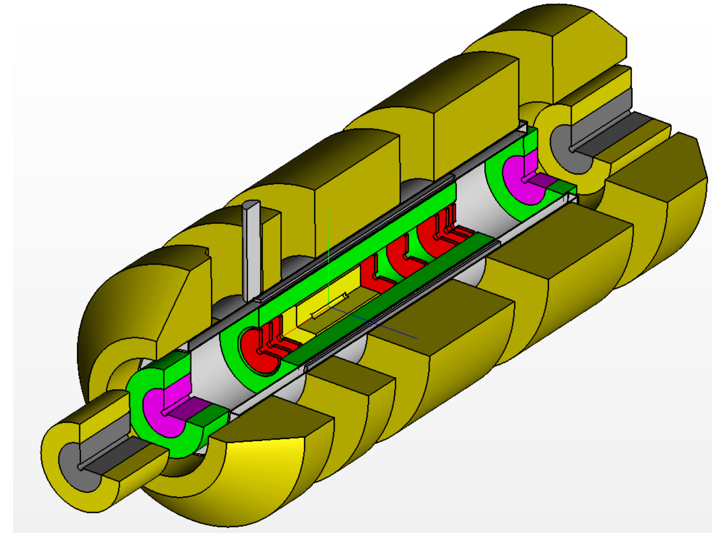
Installation Study

to fit into LHC shutdown needs directed to IP2

Andrea Gaddi et al

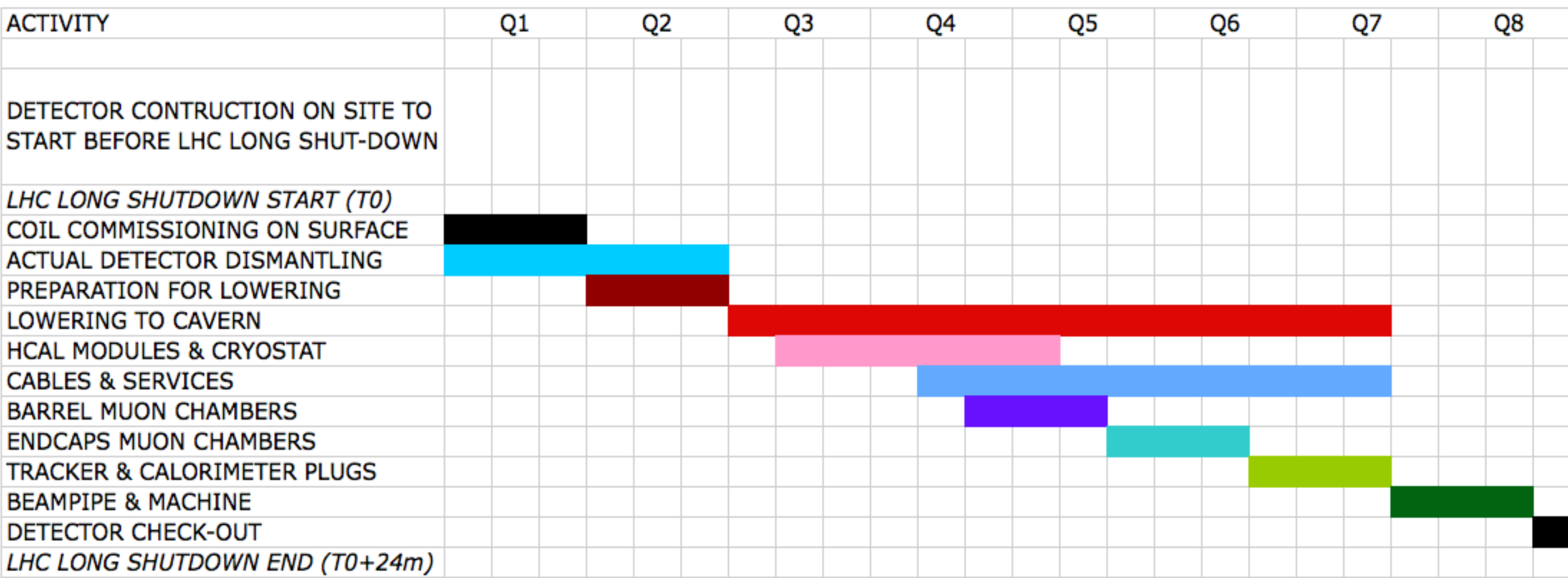


Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE



Outline

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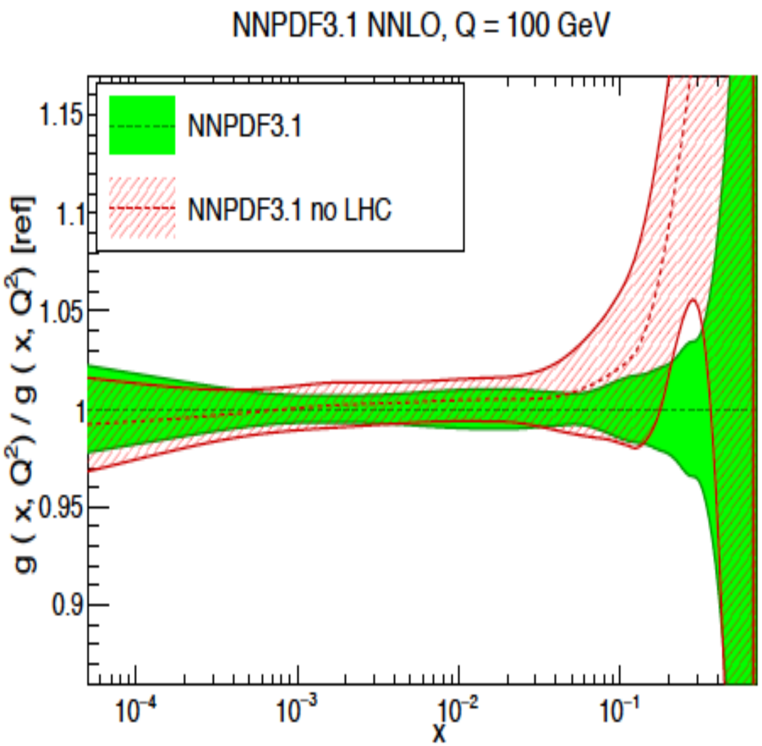
LHC Folklore: PDFs come from pp



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 sumrules
- Needs strong coupling to permille 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.

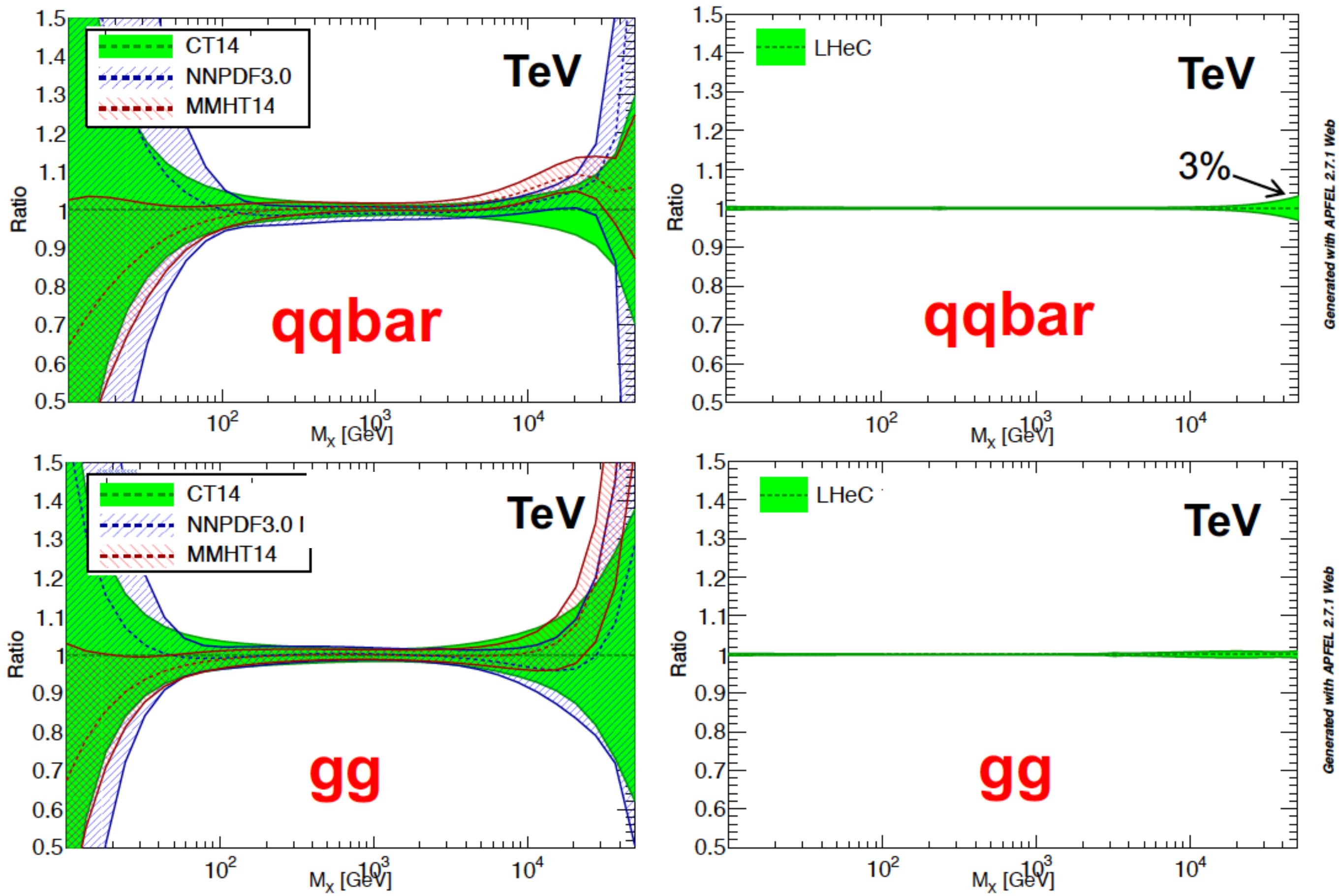
LHeC vs HERA: Higher Q^2: CC; higher s: small x/g saturation?; high lumi: x→ 1; s, c,b,t. …

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

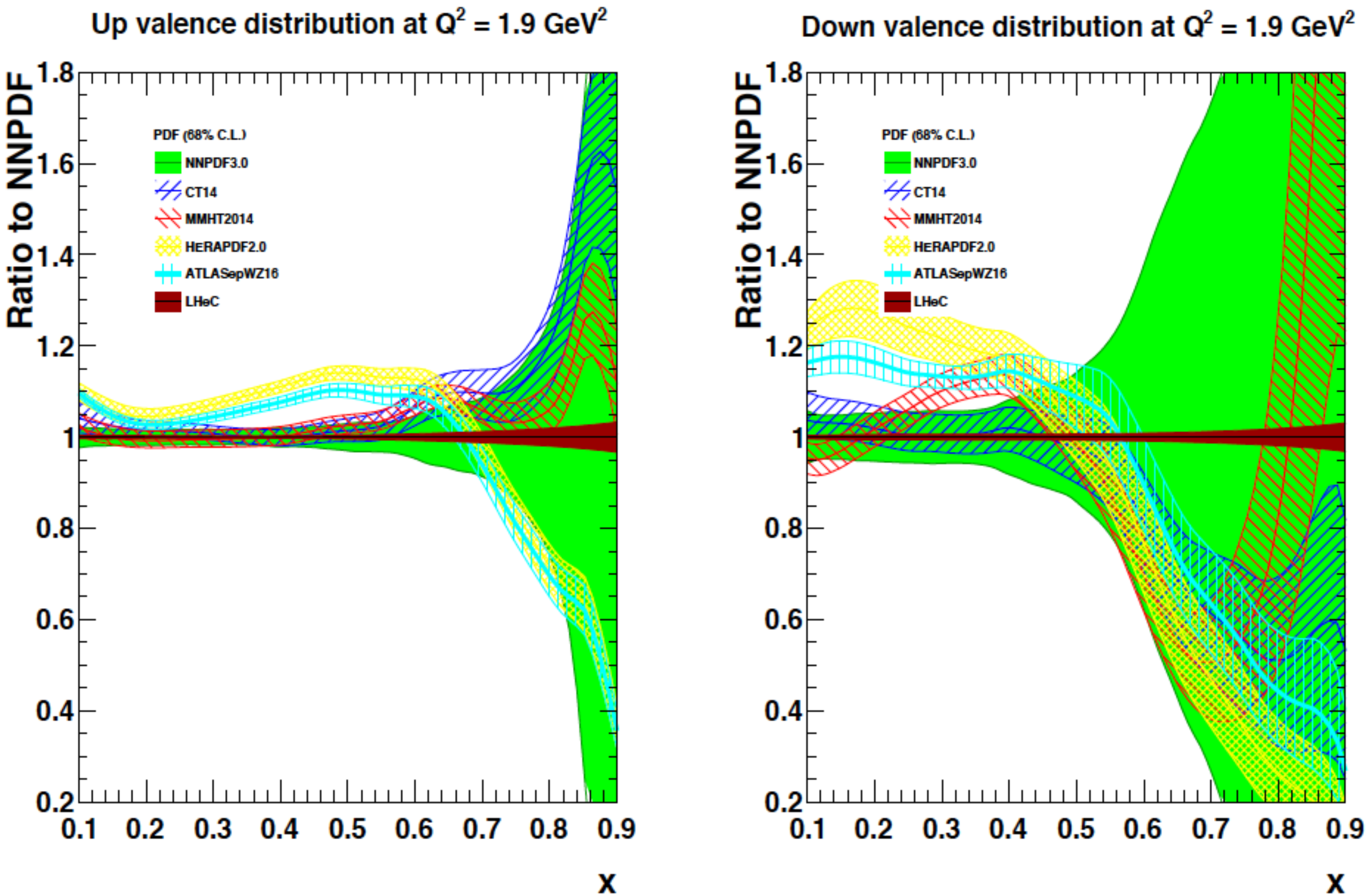


Figure 2: Determination of the valence quark distributions as functions of Bjorken x. Plotted are the ratios to the NNPDF result with uncertainties displayed as are provided by the individual sets, left for the up-valence quark and right the down-valence quark distribution. For the LHeC the total uncertainty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

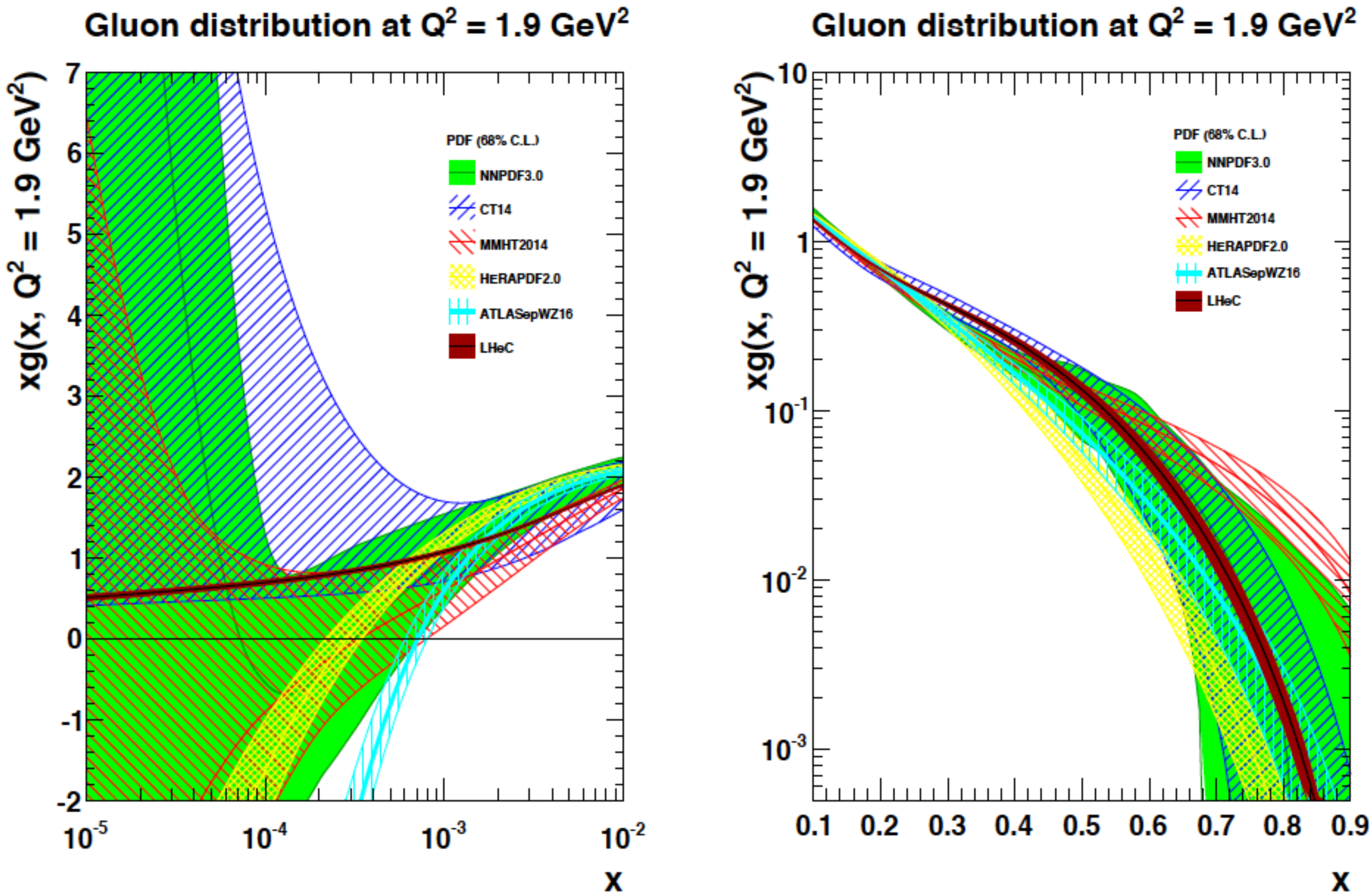


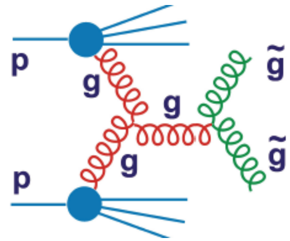
Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on xg from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for xg a range from $x \simeq 5\ 10^{-4}$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

Empowering pp Discoveries

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

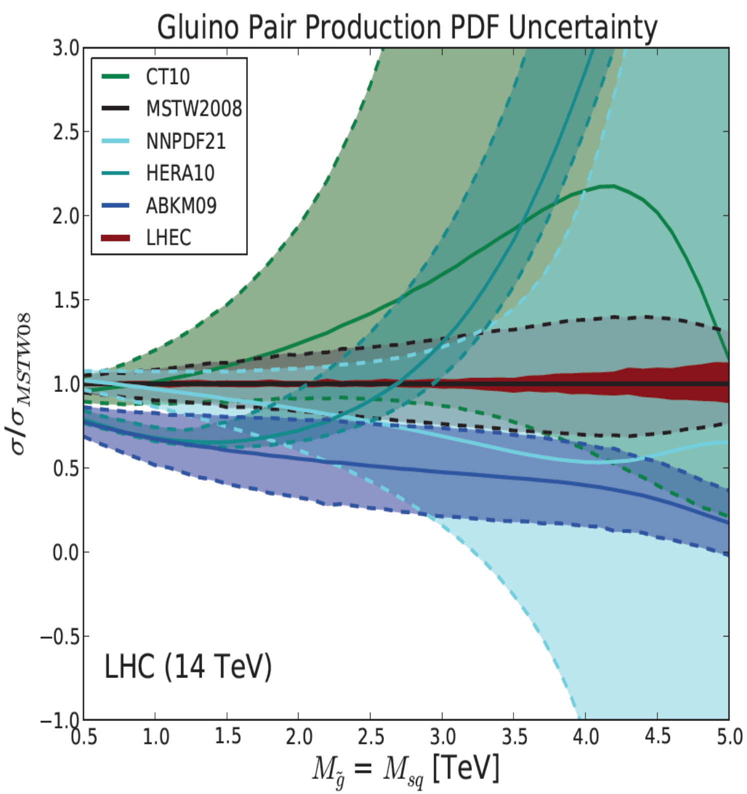
GLUON

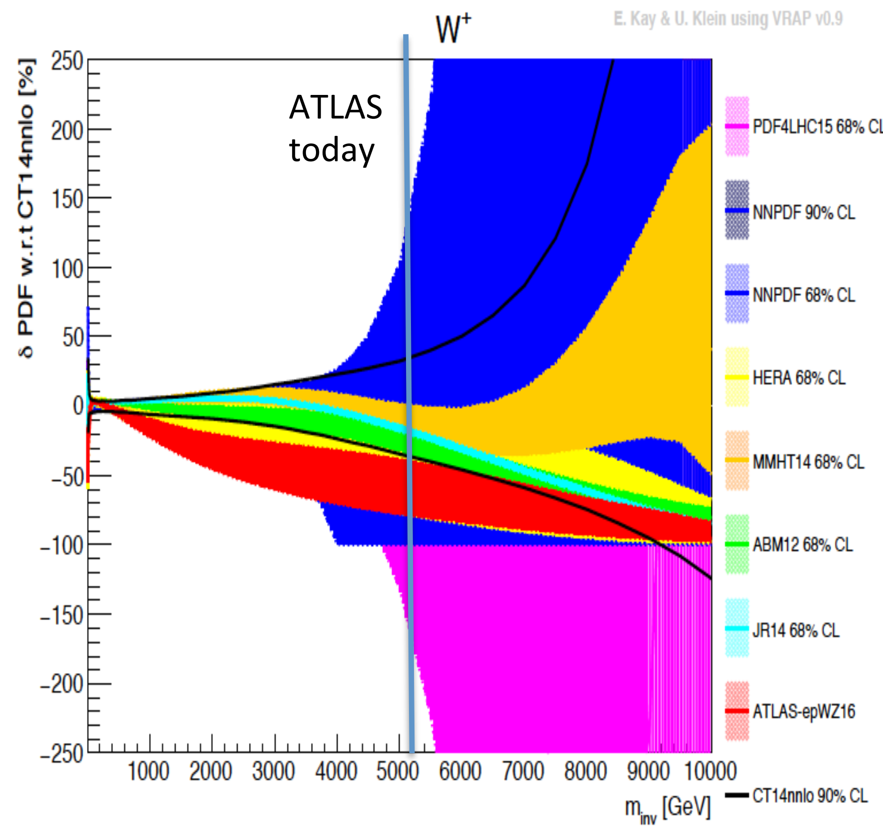
SUSY, RPC, RPV, LQS..



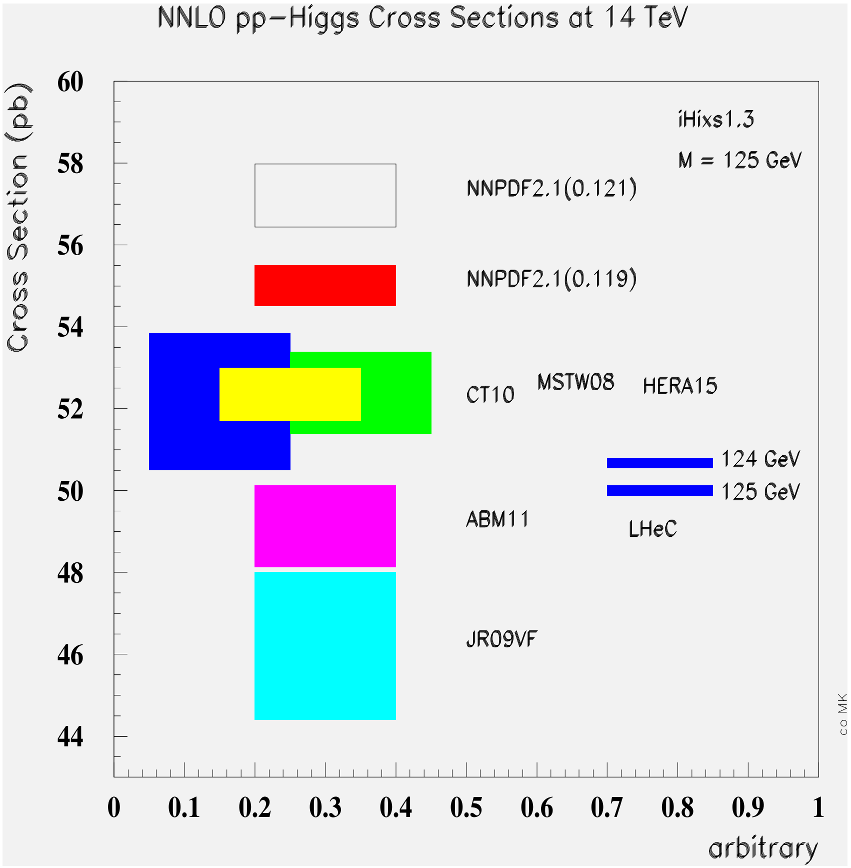
QUARKS

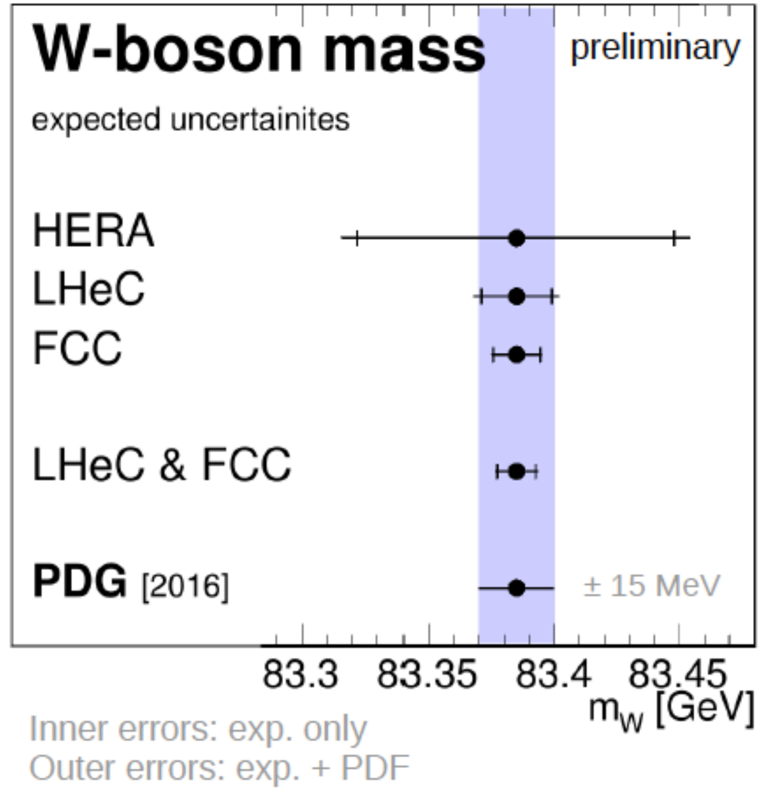
Exotic+ Extra boson searches at high mass





High Precision for the LHC



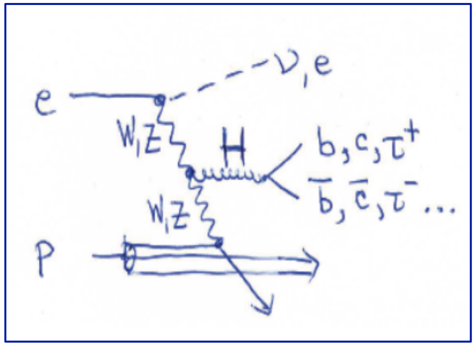


Predict the Higgs cross section in pp to 0.2% precision which matches the M_H measurement and removes the PDF error

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

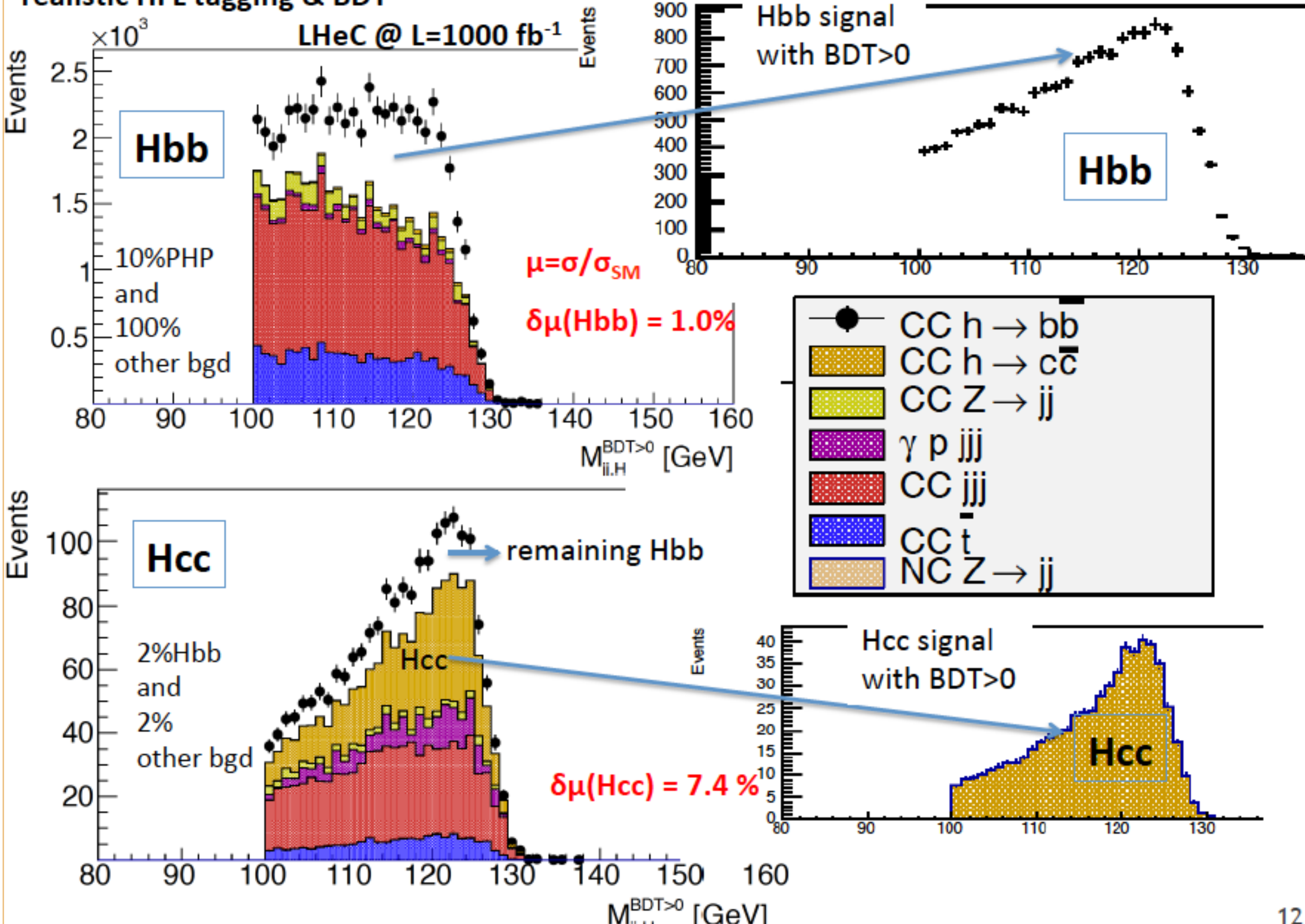
New: MADGRAPH based extension to other channels using bb and cc experience

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

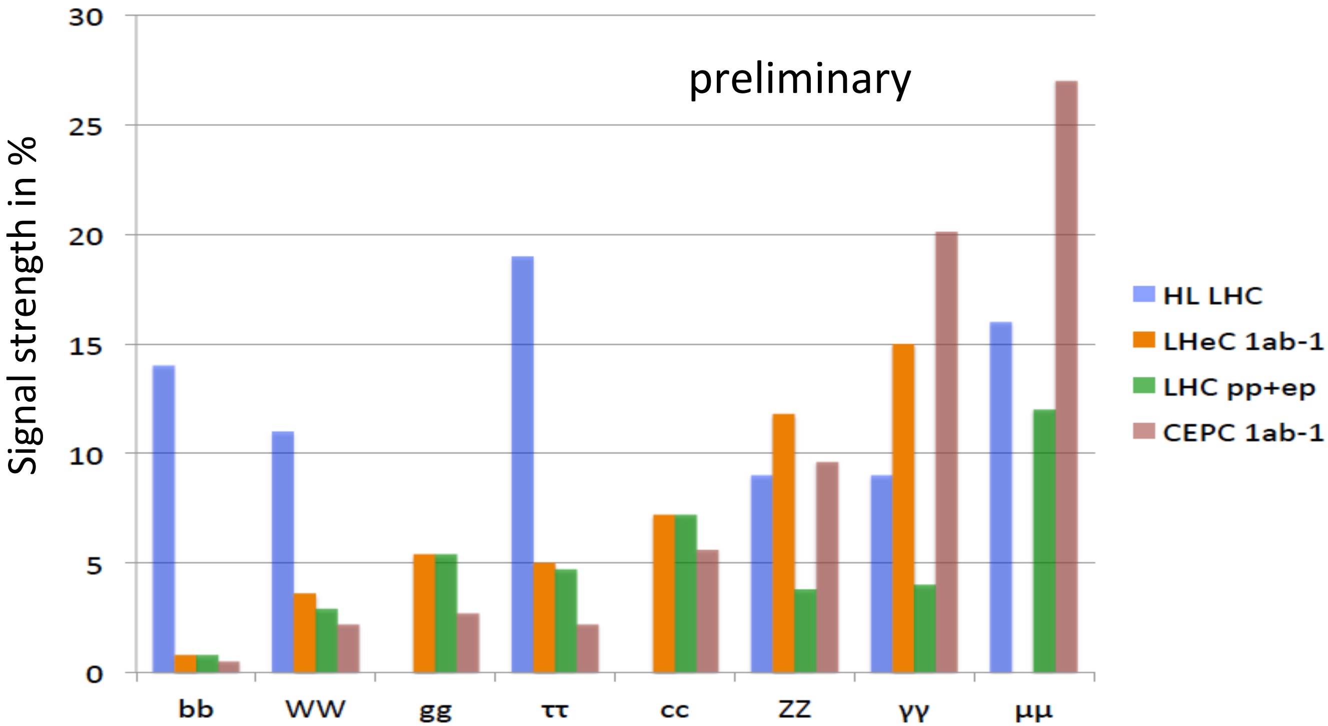
H-HH: very hard at LHeC, possible to ~30% at FCC-eh: see arXiv:1509.04016 M Kumar et al

realistic HFL tagging & BDT

Uta Klein & Daniel Hampson



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

Top electric charge

Top Physics

EDM and MDM

Anomalous t-q-γ and t-g-Z

V_{tb} and W-t-b

Top spin

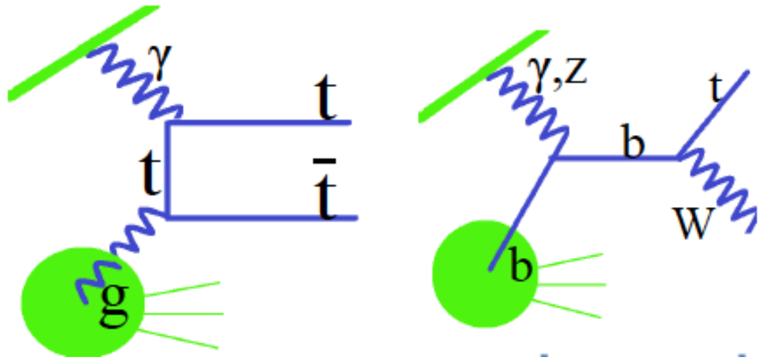
Top PDF

Top mass

Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Pair production Single production



σ=0.05pb @ LHeC **σ=1.73pb @ LHeC**

σ=1.14pb @ FCC-ep **σ=15.3pb @ FCC-ep**

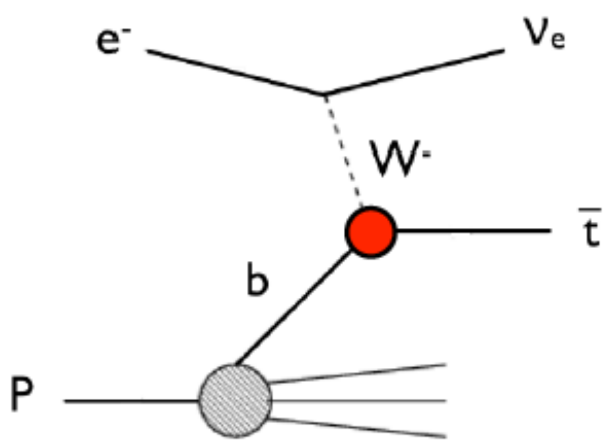
LHeC and even more FCC-eh are top factories with huge BSM potential

For top itself: maximise Ee. For t as background for Higgs: not too much

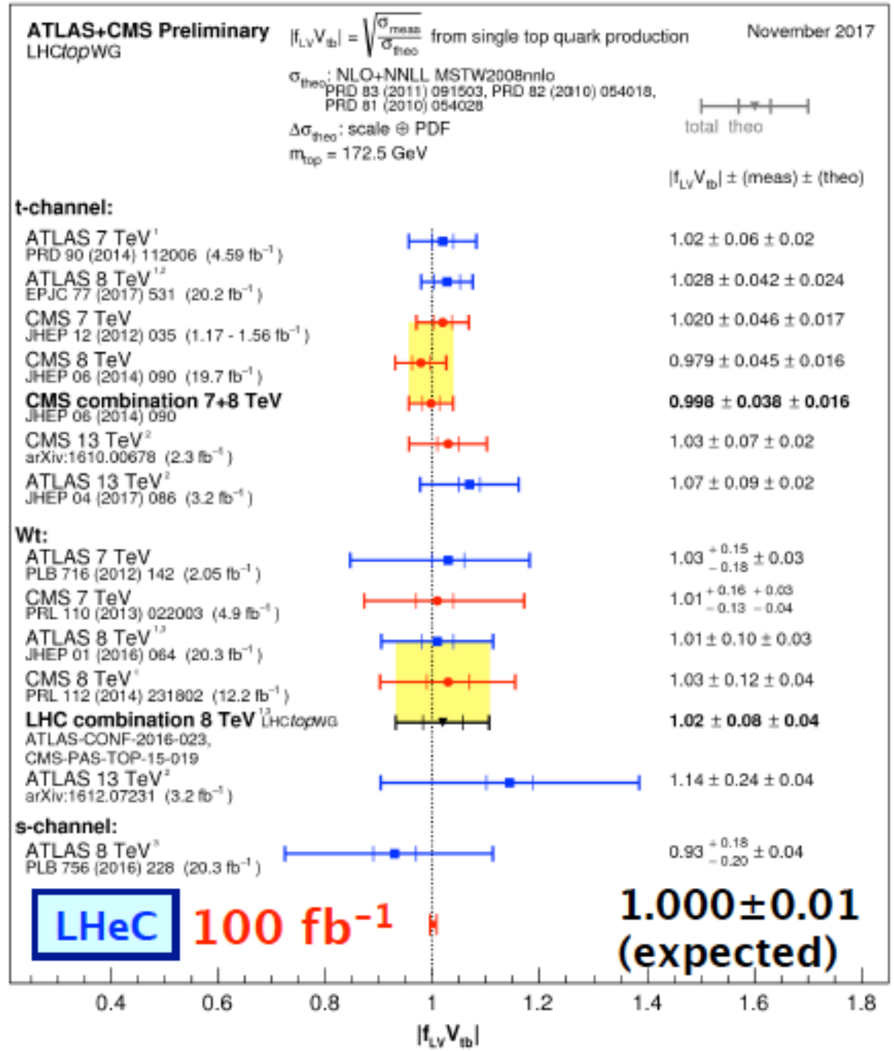
cf Christian Schwanenberger, Top in ep, Talk at FCC Physics Week 17.1.18

Direct Measurement of $|V_{tb}|$

[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO PDF4LHC11 NPPS205 (2010) 10, CPC191 (2015) 74
[3] including beam energy uncertainty



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

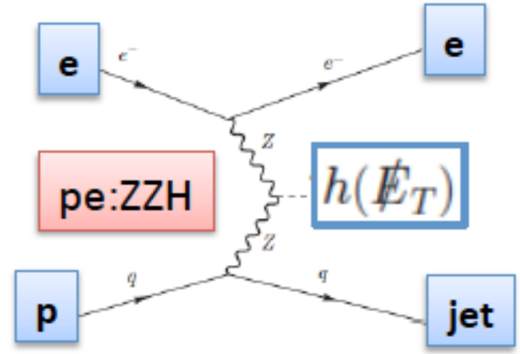


Branching for invisible Higgs

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

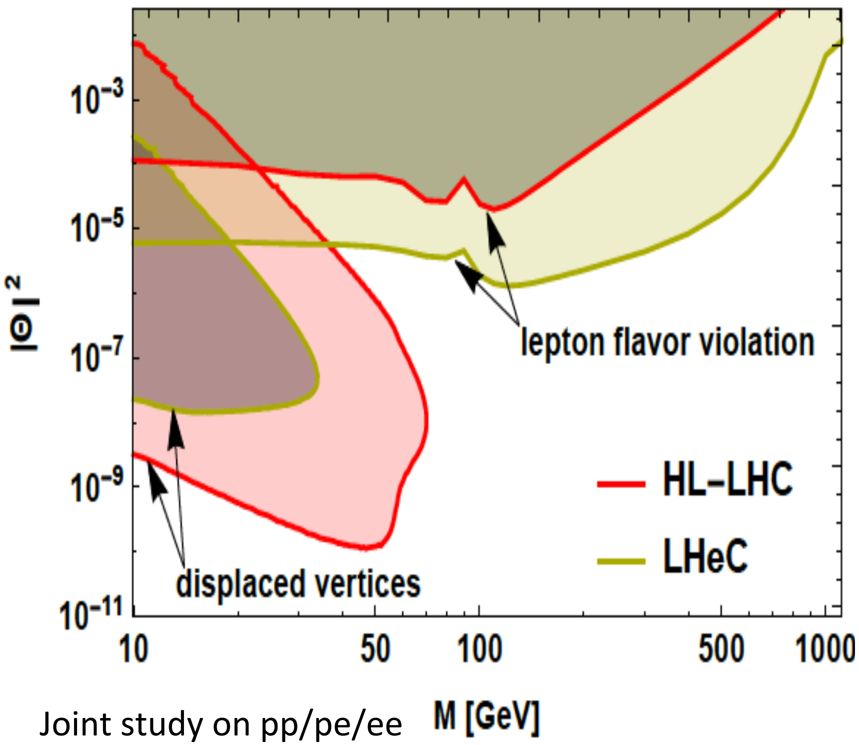
→ **further detector and analysis details have certainly an impact on results**

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

Lots of important new papers on BSM in ep

Sterile (heavy) Neutrinos in ep → NX

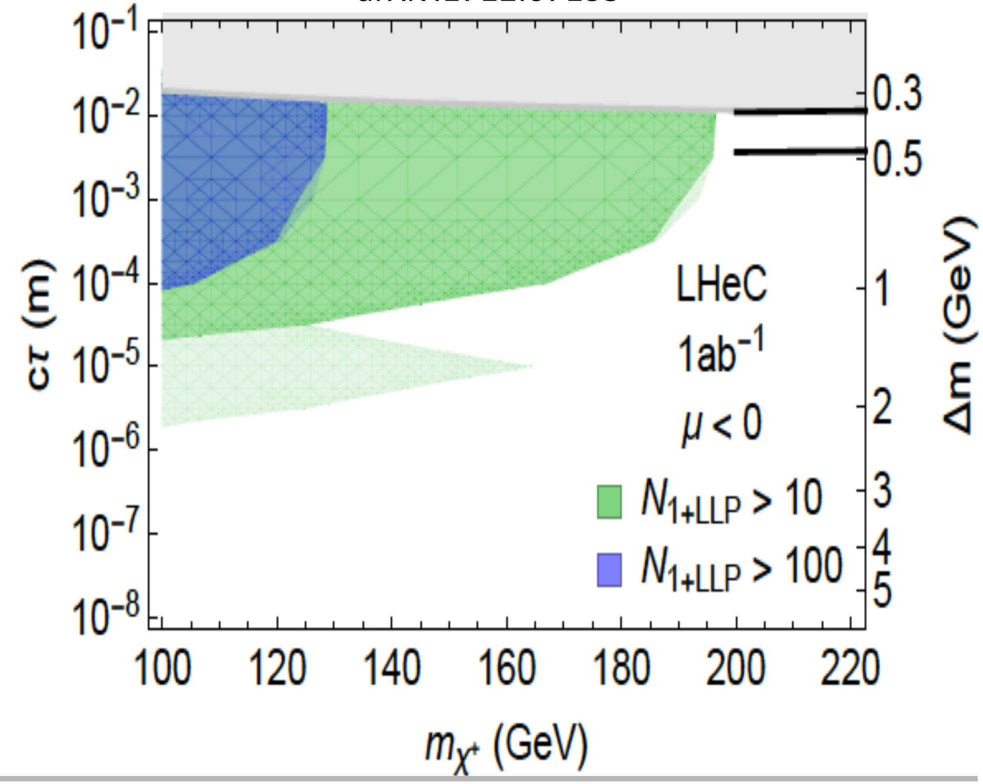
arXiv:1612.02728

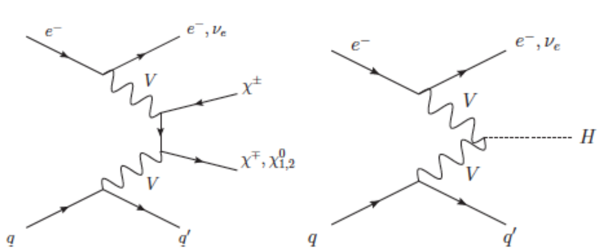


Joint study on pp/pe/ee

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

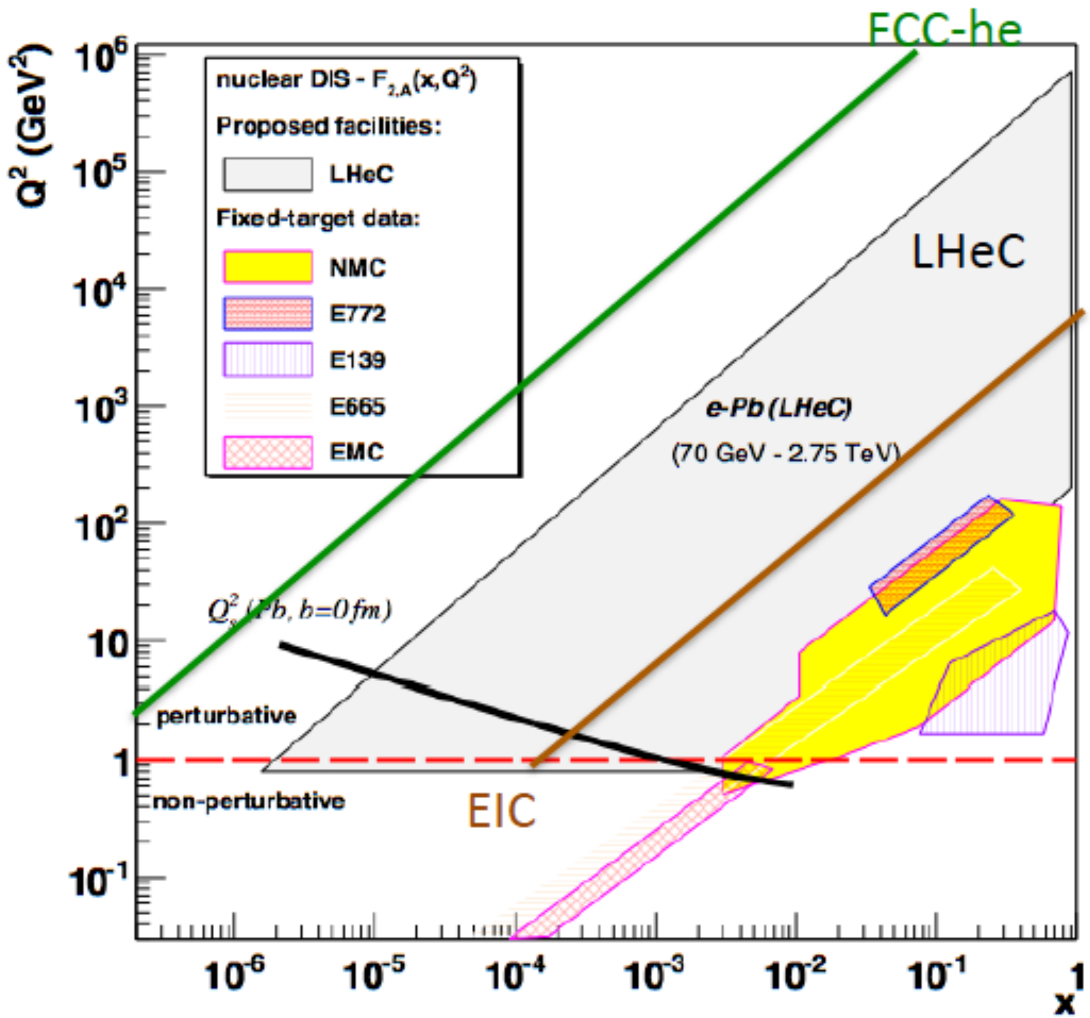
Quark substructure

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

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.

Outline

0. Bits of Information

1. Parameters and Configuration of the LHeC

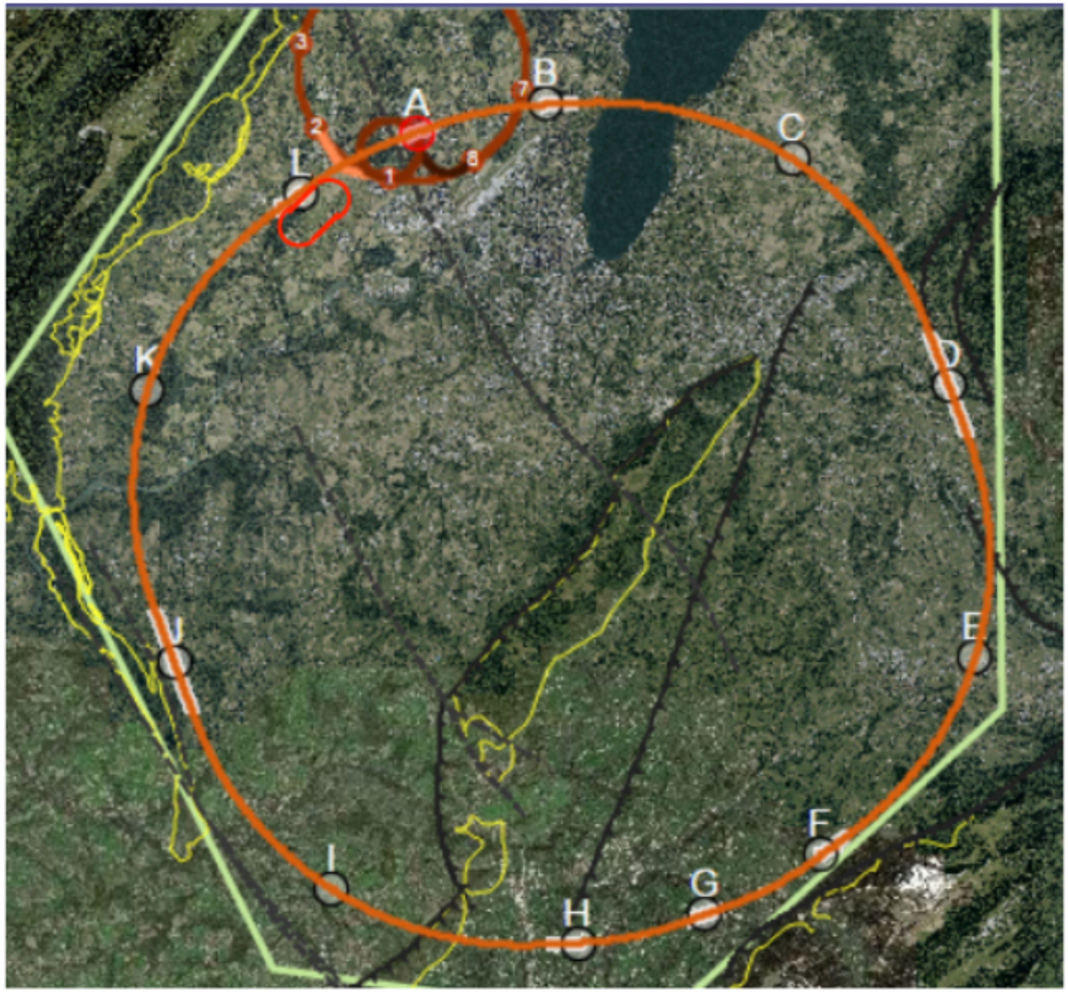
2. PERLE Testfacility for Energy Recovery Physics and SCRF

3. Detector Development for LHeC and Installation Issues

4. Selected Physics Highlights (PDFs, Higgs, BSM)

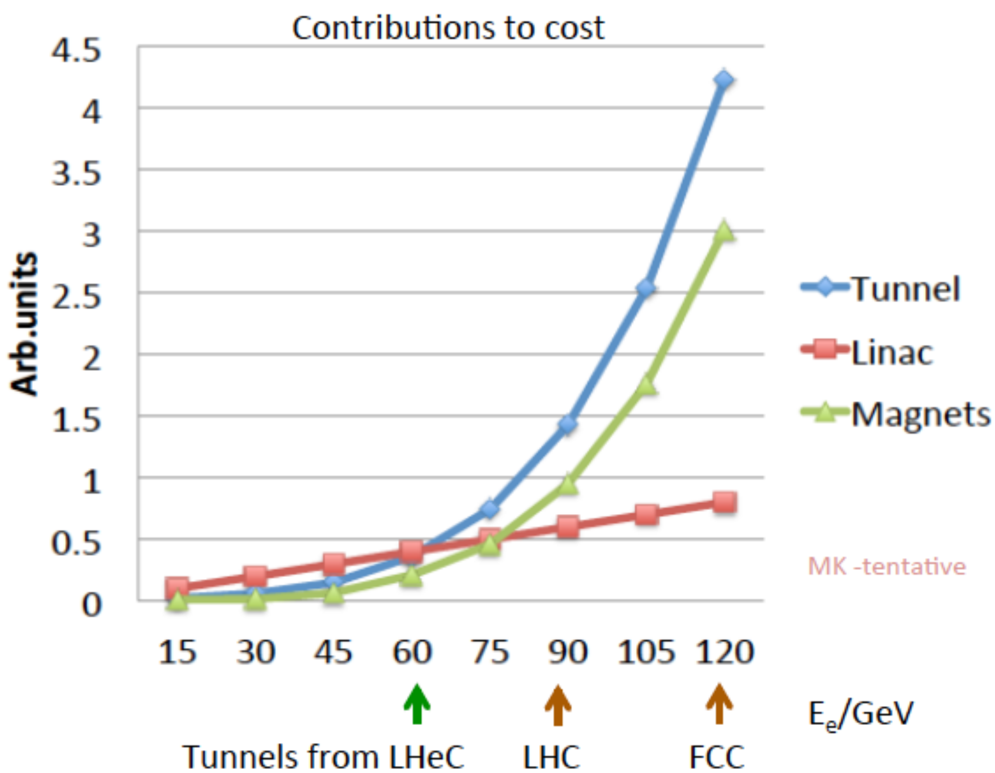
5. Extension to the multi TeV range (FCC-eh and in China)

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

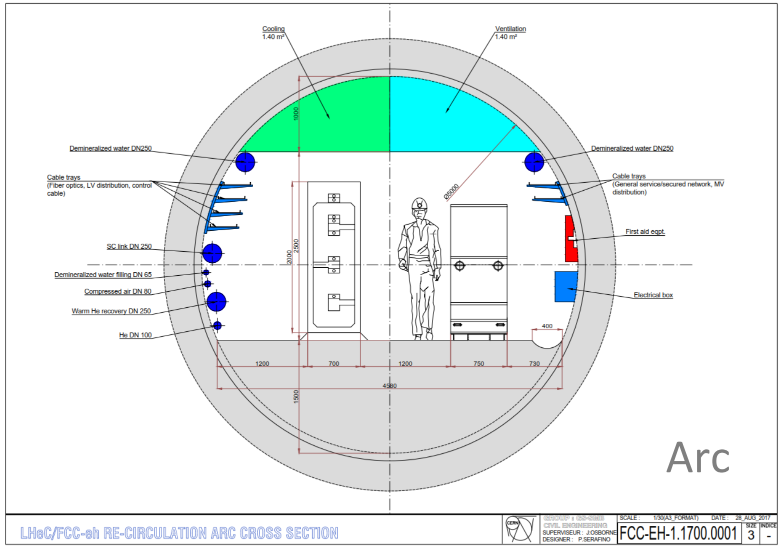
More than 60 GeV E_e? Not for the FCC CDR



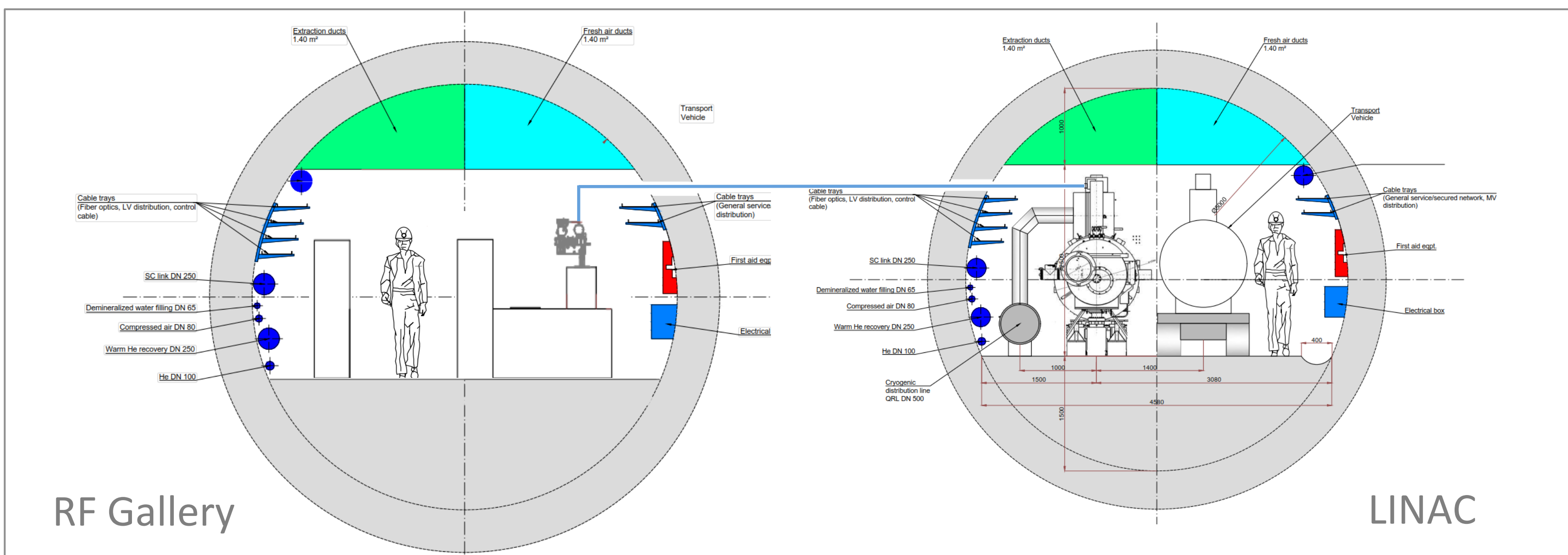
Higher E_e is desirable for BSM, LQ, RPV SUSY.., hhh, forward angular coverage.
It could be thought of with the LHC or FCC tunnels, or an e-p linac (Litvinenko)

Still: plan for synchronous ep and pp operation and appropriate cost, power, effort..
It thus appears most natural to consider the LHeC ERL as the electron beam for *eh*

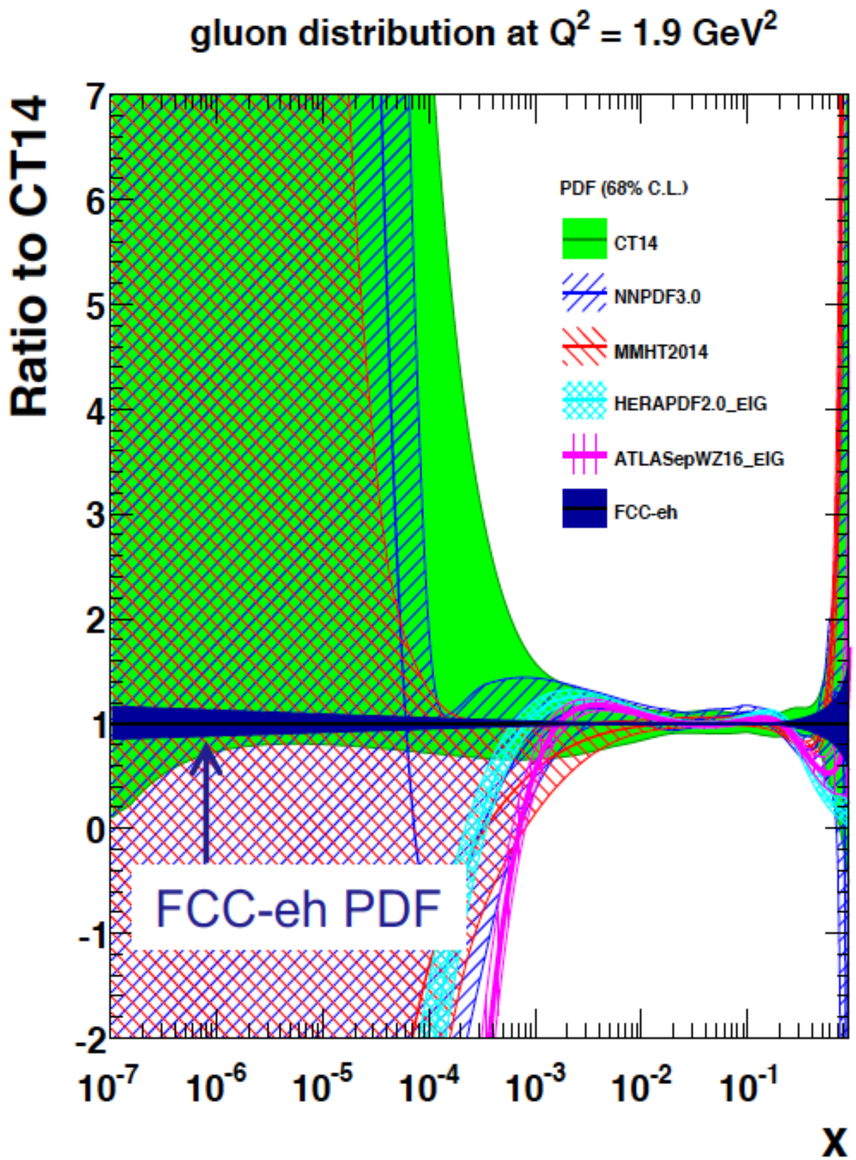
Tunnels: Triple Arc and LINACs



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



gluon at low x



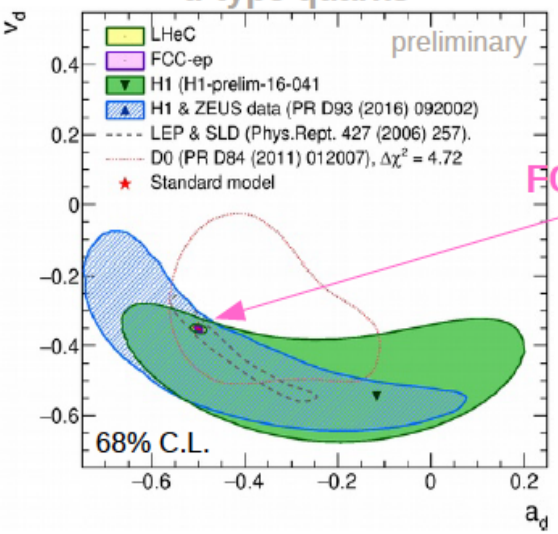
gluon at low x:
recall – no current data much below $x=5\times10^{-5}$ to directly constrain; so even this is an extrapolation for current PDFs at low x

FCC-eh would provide single, precise and unambiguous dataset
(explore low x QCD, DGLAP vs BFKL, non-linear evolution, gluon saturation; implications also for ultra high energy neutrino cross sections)

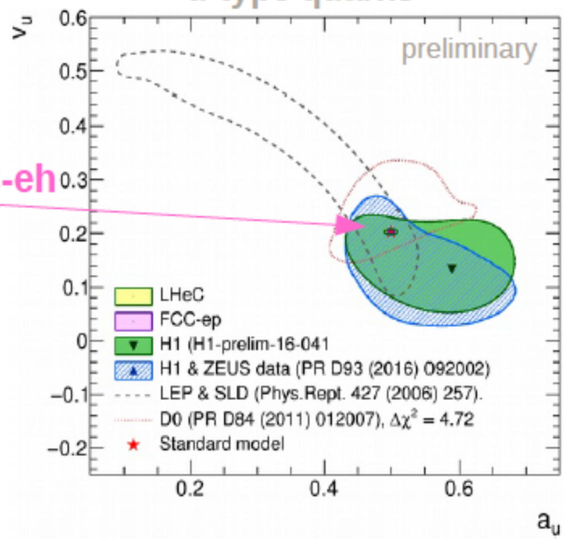
Electroweak Physics: LHeC and FCCeh

Weak neutral couplings: quarks, electrons

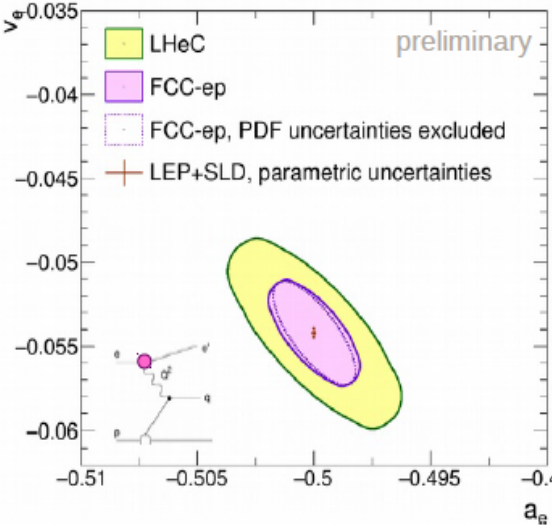
d-type quarks



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

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
  - $h \to 2\phi \to (b\bar{b})(b\bar{b})$ [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, $p\, e^- \to \nu j H^+ \to \nu j\, (c\bar{b})$,

    [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]

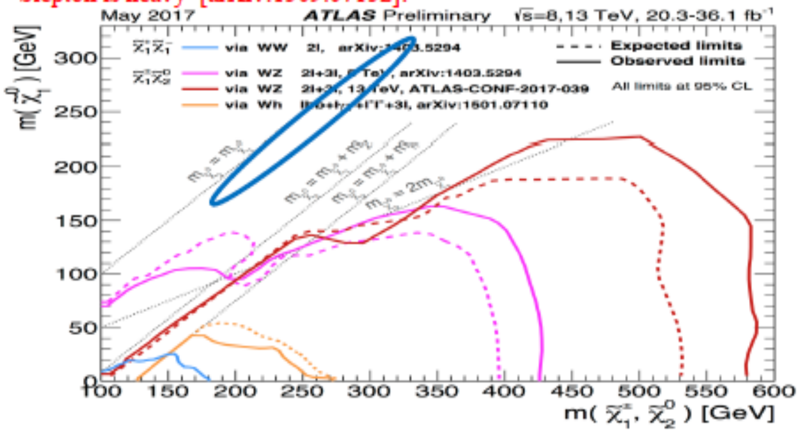
Impressive flow of new physics in ep studies is being digested for 2018

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

R-Parity Conserving SUSY

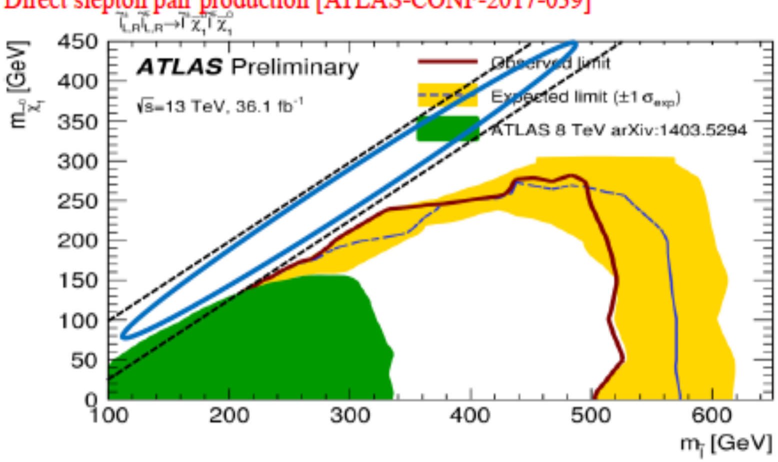
Current LHC limits on SUSY DM:

Slepton is heavy [arXiv:1509.07152]:



Current LHC limits on SUSY sleptons

Direct slepton pair production [ATLAS-CONF-2017-039]



Complementary at ep:

(a) Compressed Scenarios:
- → decay products are very soft, challenging @ pp
- → fwd j/e, low bkg, feasible @ ep

(b) Light sleptons:
- → can be motivited by the "muon g-2"
- → DM production can be enhanced by the slepton decays.

Signal scenarios:

Bino: $M_{\tilde{\chi}_1^0}$

Wino: $M_{\tilde{\chi}_1^\pm} \sim M_{\tilde{\chi}_2^0} = M_{\tilde{\chi}_1^0} + 1\,\mathrm{GeV}$

(1) Slepton slightly heavier (light slepton case)

Slepton: $M_{\tilde{l}_L} = M_{\tilde{\chi}_1^\pm}$ + 35 GeV

Sneutrino: $M_{\tilde{\nu}} \sim M_{\tilde{l}_L}$ – 9 GeV

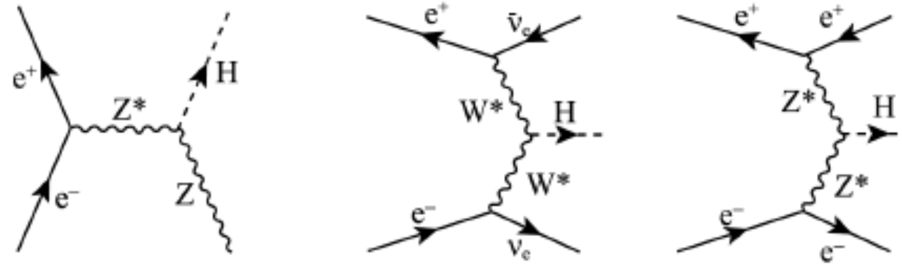
(2) Slepton & Sneutrino heavy and decoupled (heavy slepton case)

ep combines: high energy, high luminosity with clean final state: unique BSM potential
see the discussion in D Curtin et al on Higgsino search: 1712.07135

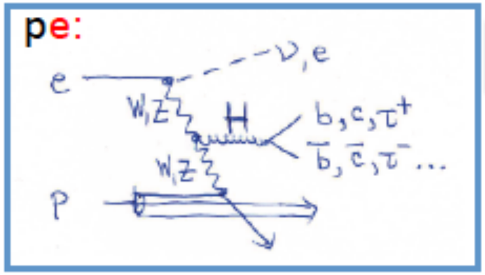
Kechen Wang, BSM in ep, FCC Workshop 1/2018 at CERN

Higgs in ee vs pe

ee: Dominant Higgs productions



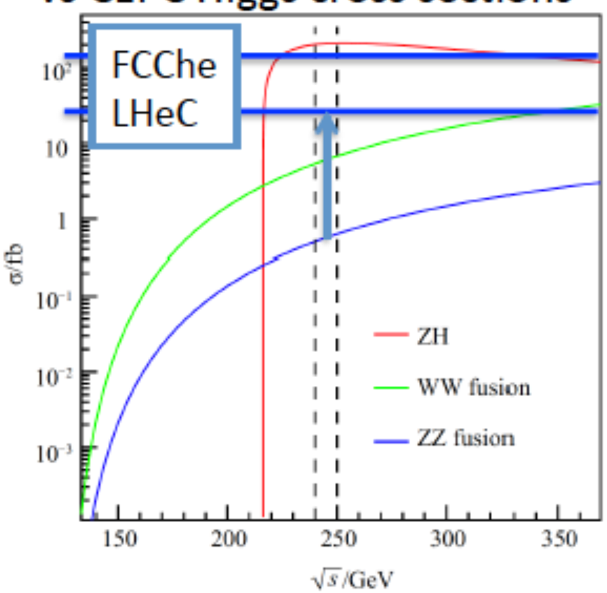
pe:

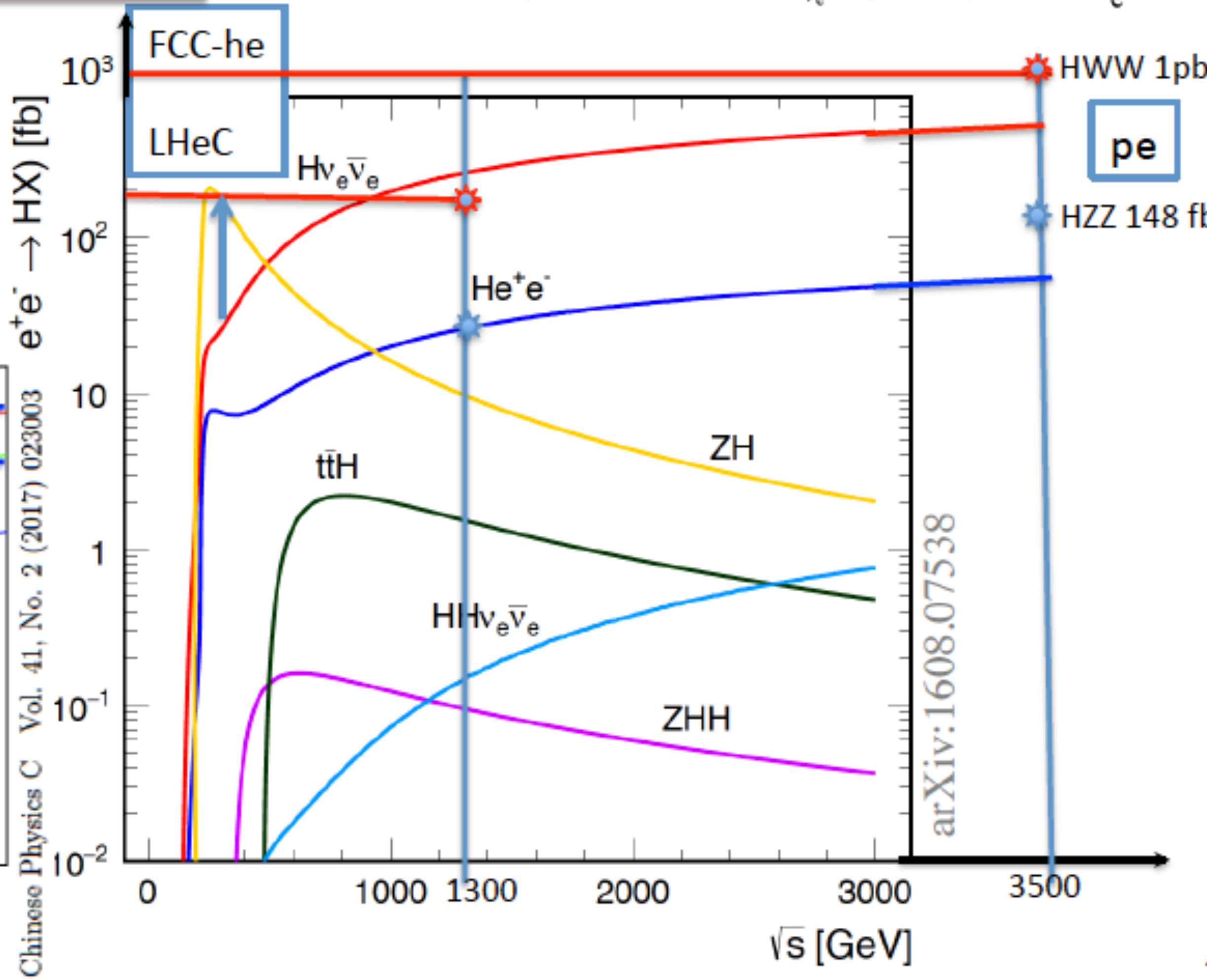


pe:WW Fusion

pe: ZZ Fusion

vs CEPC Higgs cross sections



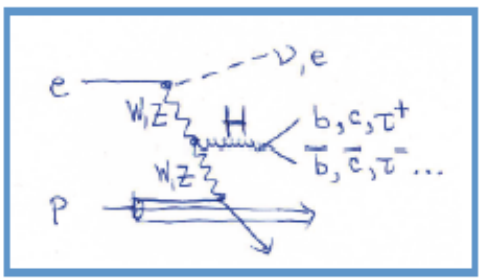


Uta Klein, Talk at FCC Workshop 16.1.18

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:

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

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

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

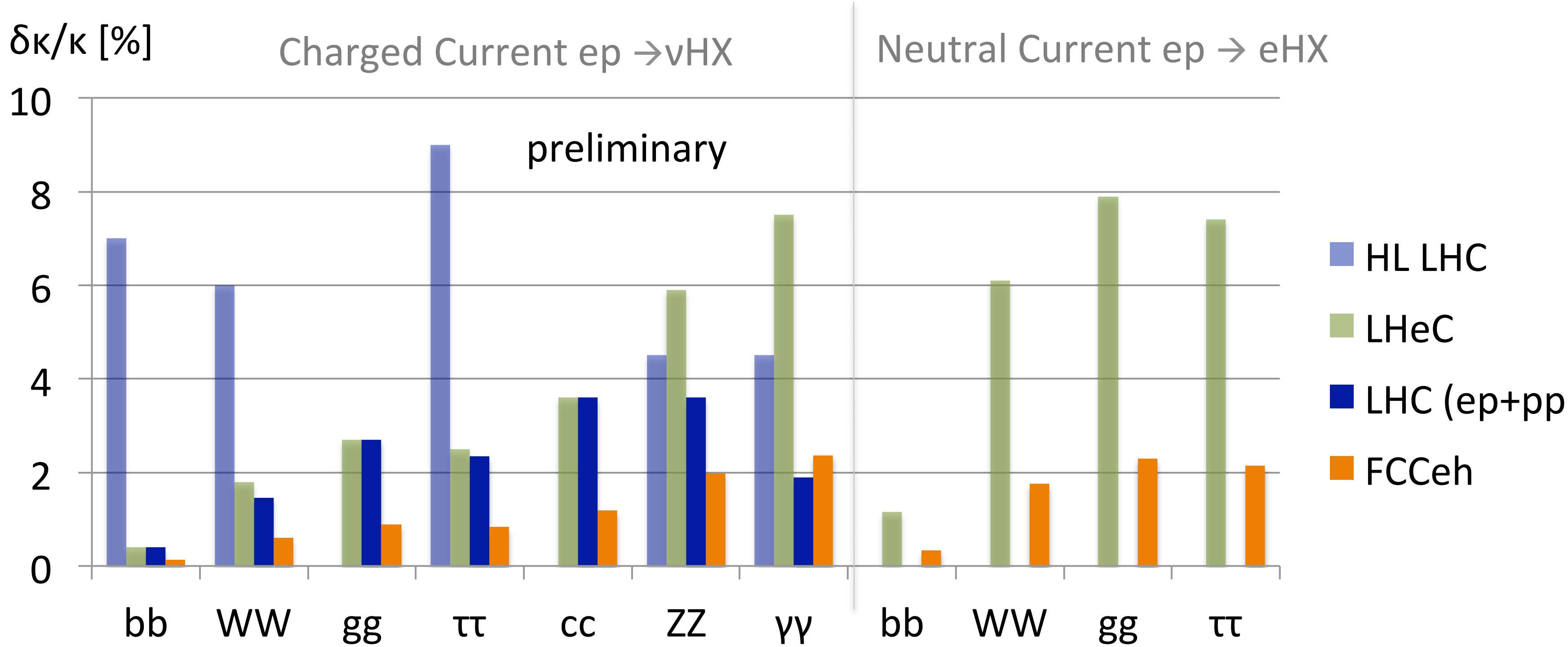
$$\sigma(WW \to H \to gg) \propto \kappa^2(HWW) \bullet \kappa^2(Hgg)$$

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

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

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

FCCeh: Higgs SM Coupling Prospects

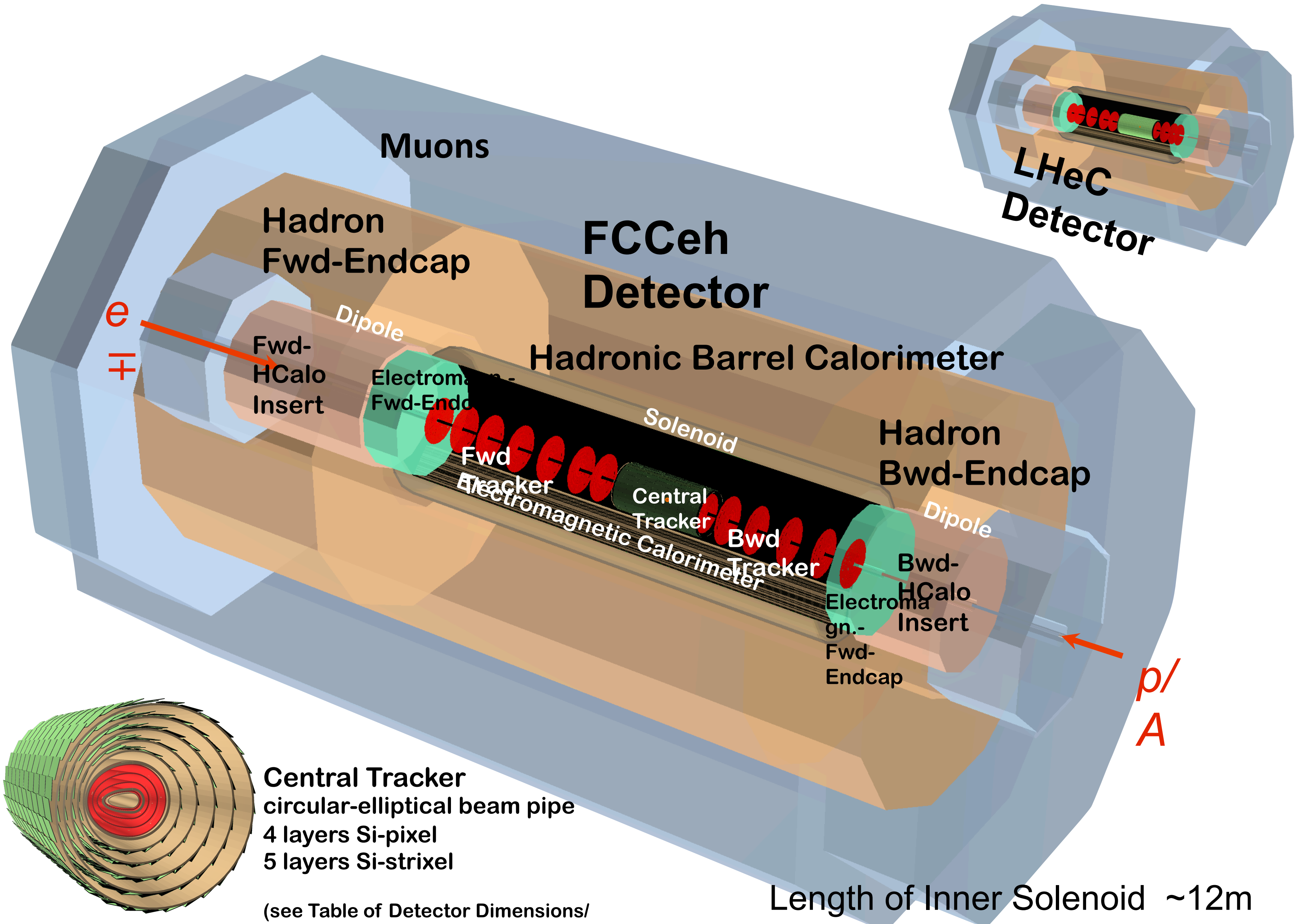


HL LHC: ATLAS-PUB-2014-016 14 TeV 3ab^{-1} – LHC has no gg, no cc, and poor bb, but rare channels as γγ
LHeC: 1ab^{-1}, 60 GeV x 7 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..
LHC (ep+pp): HL LHC with reduced theory uncertainty combined with LHeC
FCCeh: 2ab^{-1}, 60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

LHeC/FCC ep/eA detector



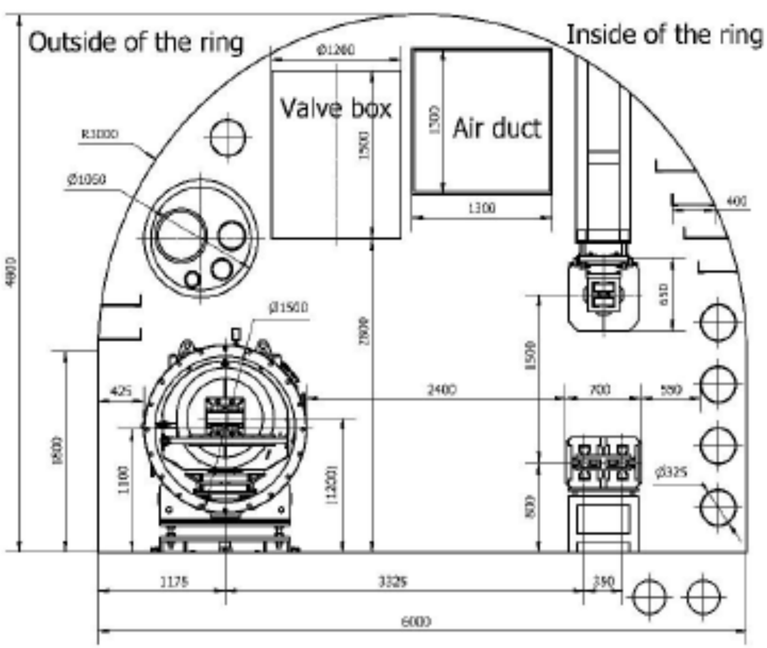
Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

(see Table of Detector Dimensions/ Parameters in backup)

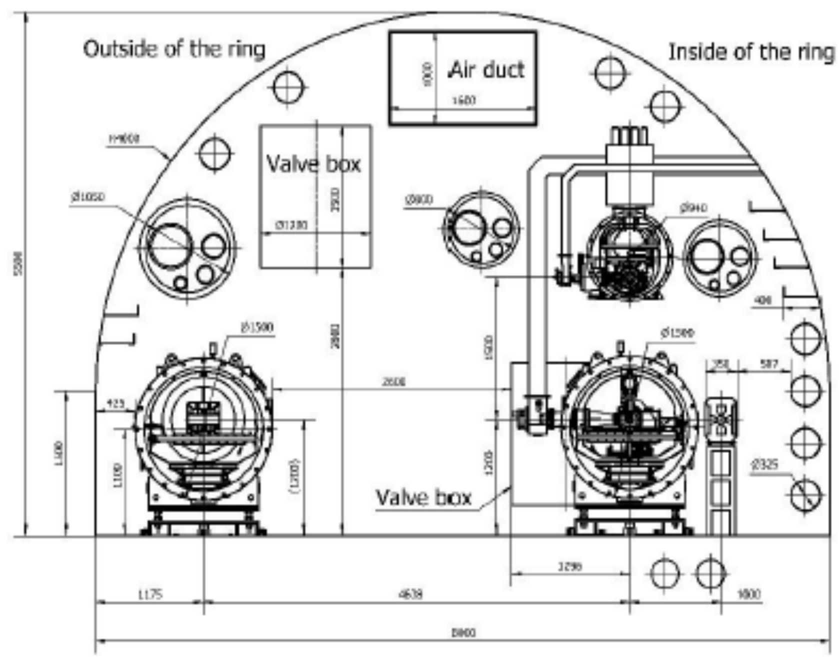
CEPC-SppC Tunnel Cross Sections

J.L. Wang

Tunnel cross section at arc-section
Width: 6,000 mm. Height: 4,800 mm.



Tunnel cross section at RF-section
Width: 8,000 mm. Height: 5,500 mm.



CEPC e-p and e-A Options

Y.H. Zhang

CEPC-SPPC *e-p* and *e-A* Design Parameters

Particle		Proton	Electron	Lead ($^{208}Pb^{82+}$)	Electron
Beam energy	TeV	37.5	0.12	14.8	0.12
CM energy	TeV	4.2		2.7	
Beam current	mA	730	34.8	730	34.8
Particles per bunch	10^{10}	15	0.72	0.18	0.72
Number of bunch		10080		10080	
Bunch filling factor		0.756		0.756	
Bunch spacing	ns	25	25	25	25
Bunch repetition rate	MHz	40	40	40	40
Norm. emittance, (x/y)	μm rad	2.35	282	0.22	282
Bunch length, RMS	Cm	7	0.5	7	0.5
Beta-star (x/y)	Cm	75	3.7	75	0.88
Beam spot size at IP (c/y)	Mm	6.6	6.6	3.25	3.25
Beam-beam per IP(x/y)		0.0004	0.12	0.0016	0.12
Crossing angle	mrad	~0.95		~0.95	
Hour-glass (HG) reduction		0.77		0.34	
Luminosity/nuclei per IP, with HG reduction	10^{33}/cm²/s			1.0	
Luminosity/nucleon per IP, with HG reduction	10^{33}/cm²/s	4.5		23.6	

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

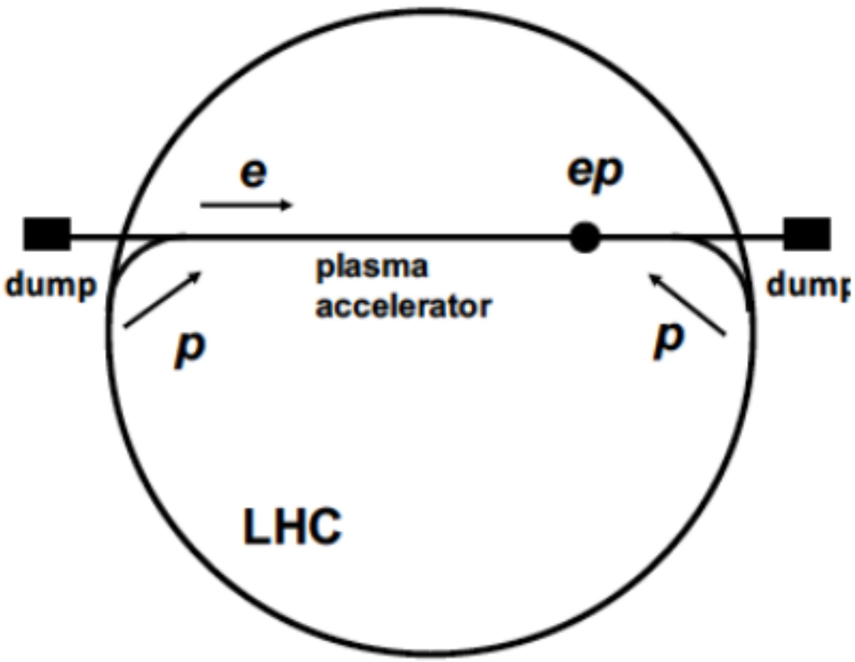
Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

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

VHEeP

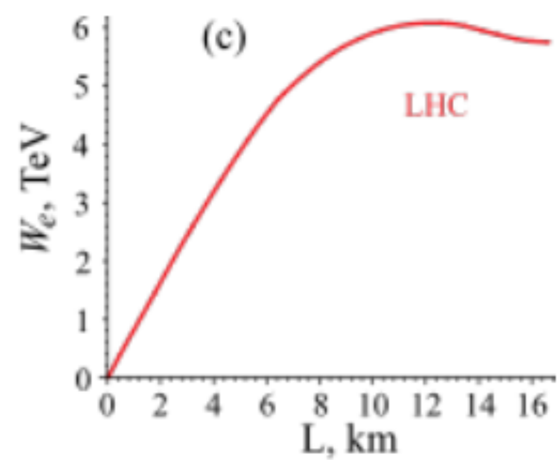
(Very High Energy electron-Proton collider)



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

Final Remarks

ep physics at the energy frontier has 4 big themes:

- Cleanest high resolution microscope on the substructure of and dynamcis inside matter
- Empowering the search and precision measurement potential of the LHC/FCC
- Transformation of LHC (HE LHC+ FCC-hh) into high precision Higgs facility/ies
- Discovery beyond the SM, through high precision and direct discovery, also QCD

eA at the energy frontier is a unique NP facility to establish QCD of QGP + nuclear structure

eh and hh belong and can operate together.

Luminosities beyond 10^{34} are crucial to achieve (1000 x HERA), ERL is **a green technology**

The CERN electron beam solution is unique: 3 pass, 802 MHz, high current ERL, its test opens new horizons for SCRF and low energy physics and other applications (I:100 x ELI), the ERL facilities can be turned to next generation FEL labs, huge potential impact

The LHeC opens the opportunity to **build a new, high tech detector in the twenties**, with high resolution, precise tracking and large acceptance needs, at no pile-up and low radiation

Next steps: PERLE TDR, Brief input to the European strategy, Workshop 27-29.6. Paris, Update of the LHeC CDR towards a new experiment at the LHC, summary for FCC CDR
You are welcome to join any or all of these activities. Cinderella's life is not so bad.

Workshops

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

Next: 27-29 June 2018 Orsay
https://indico.cern.ch/event/698368/
Preparation for strategy:
Physics, Accelerator, Detector, PERLE

Many eh related workshops
FCC: Last week Physics (CERN)
and in April (Amsterdam)
POETIC in March (Regensburg)
DIS in April (Kobe)
HL-HE LHC Physics 17/18 (CERN)
which includes ep/eA

https://lhec.web.cern.ch

Logo of the CDR

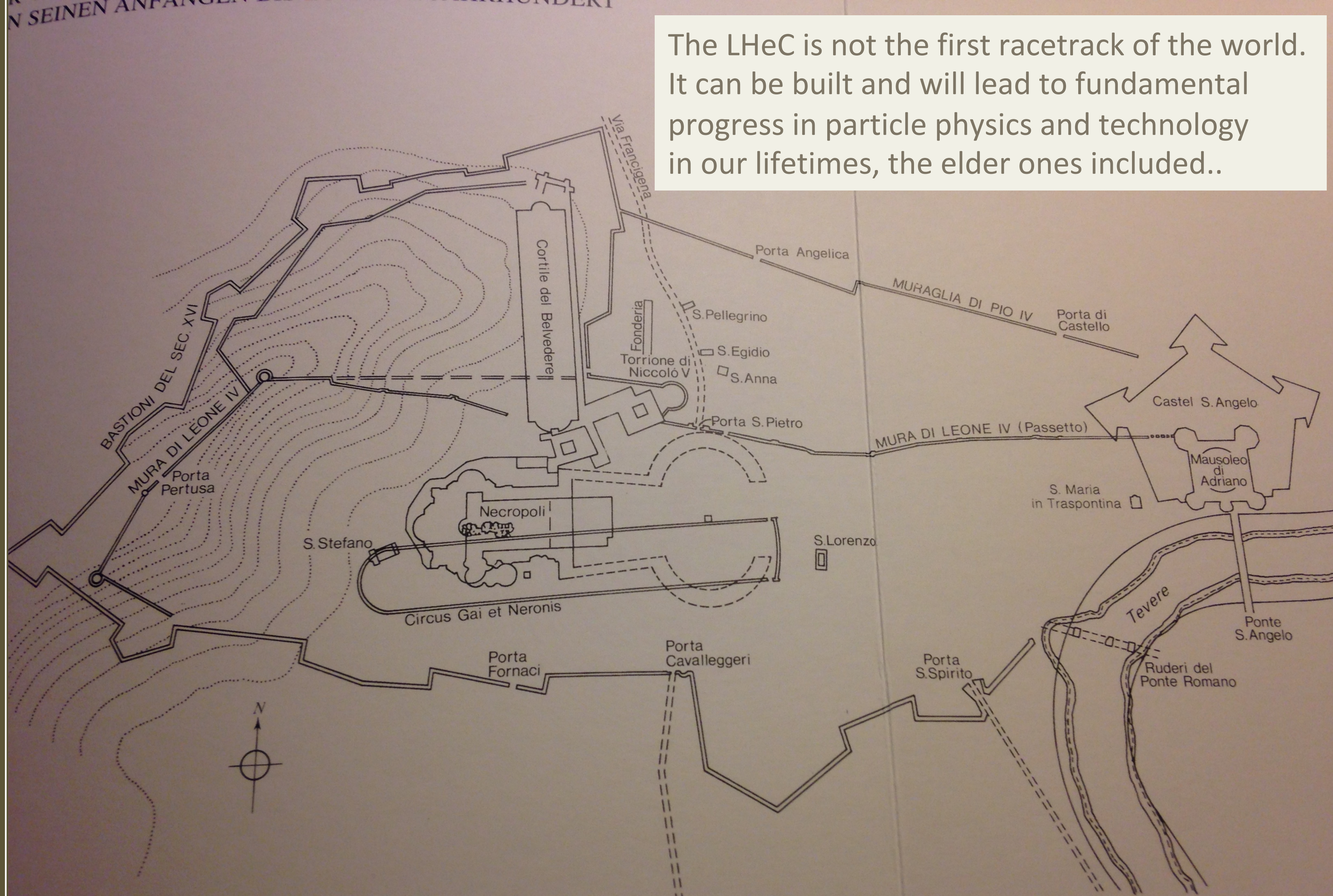
W.Kandinsky: “Circles in a circle” (1923) Philadelphia (USA) Museum of Art

First shown in LHeC context in a talk by A.S.Vera Workshop 2008

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

https://lhec.web.cern.ch

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)

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

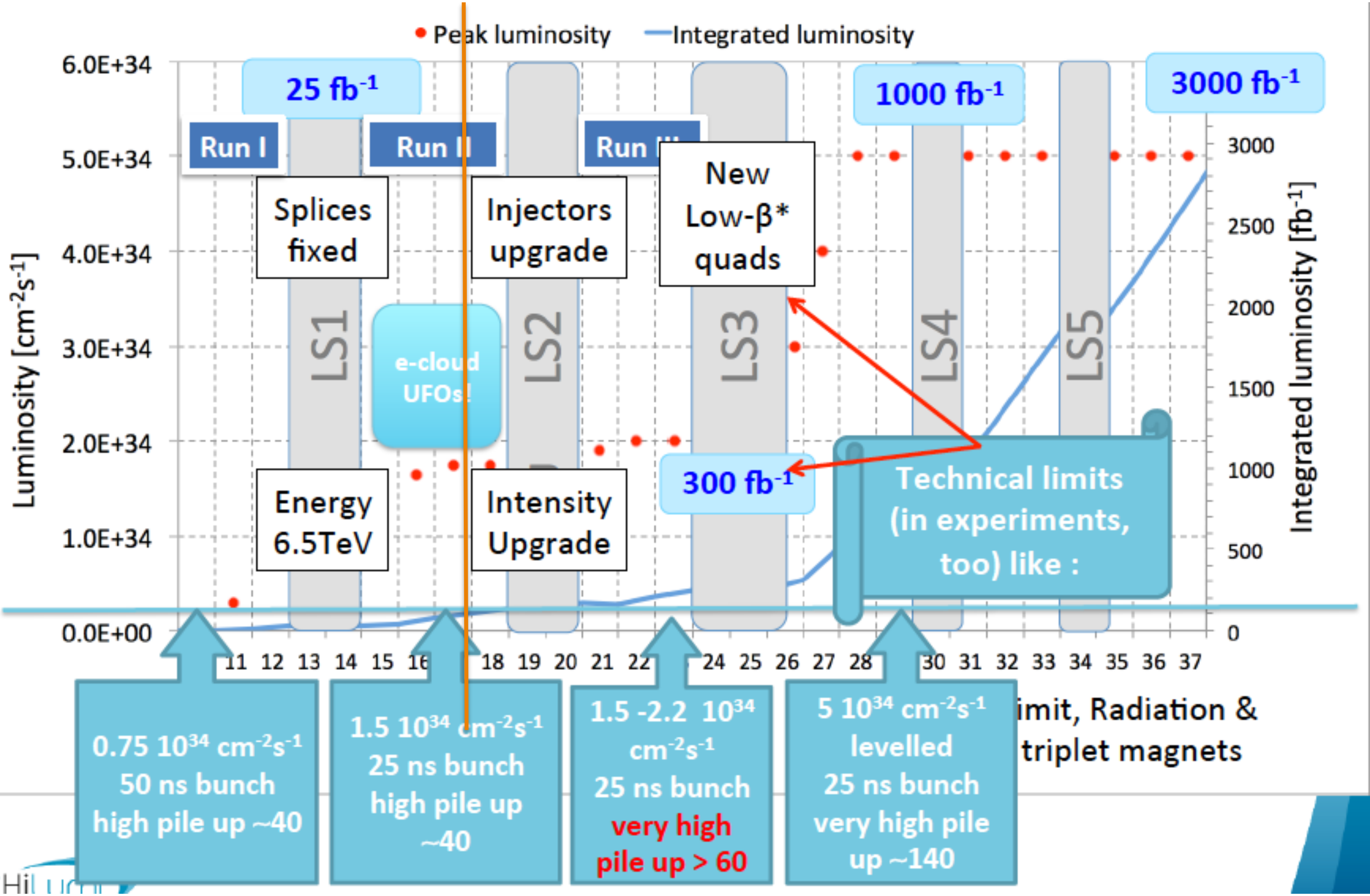
Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

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

title

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



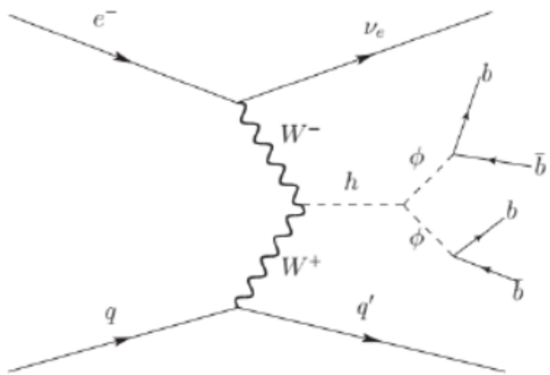
O Bruening, F Bordry

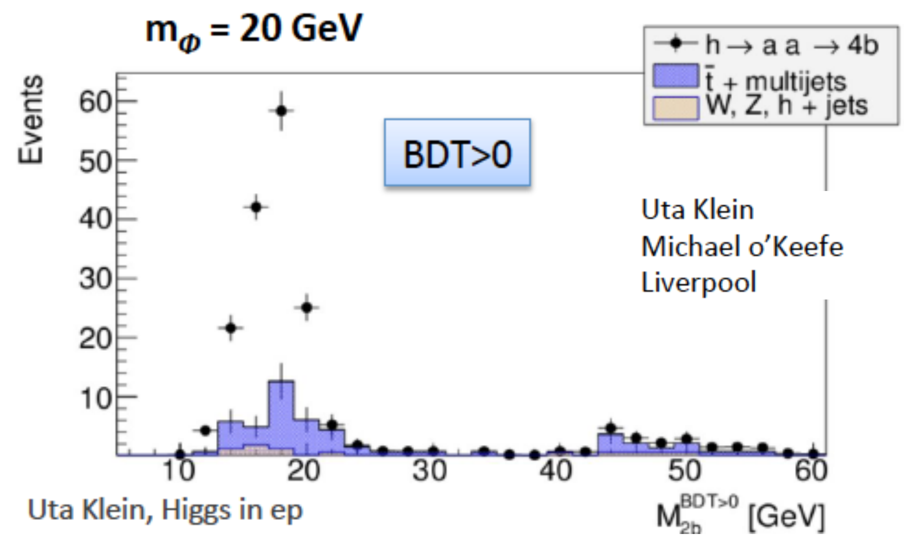
Exotic Higgs Decays

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

ϕ: a spin-0 particle from new physics.

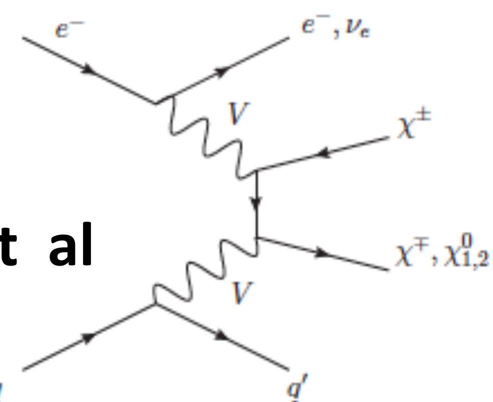
$$eq \to \nu_e h q' \to \nu_e \phi\phi q' \to \nu_e b\bar{b}b\bar{b}q'$$





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

New: Estimates of Higgs Prospects

- Use LO Higgs cross sections **σ_H for M_H=125 GeV, in [fb],** and branching fractions BR(H→XX from Higgs Cross Section Handbook (c.f. appendix)
- Apply further branching, BR(X→FS) in case e.g. of W→ 2 jets and use acceptance, Acc, estimates based on MG5, for further decay
- Use reconstruction efficiencies, ε, achieved at LHC Run-1, see e.g. prospect calculations explored in arXiV:1511.05170
- Use fully simulated LHeC Hbb and Hcc results as baseline for S/B ranges
- Use fully simulated Higgs to invisible for 3 ep c.m.s. scenarios as guidance for extrapolation uncertainty (~25%)
- Estimate HIggs events per decay channel for certain Luminosity in [fb^{-1}]

$$N = \sigma_H \bullet BR(H \to XX) \bullet BR(X \to FS) \bullet L$$

- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

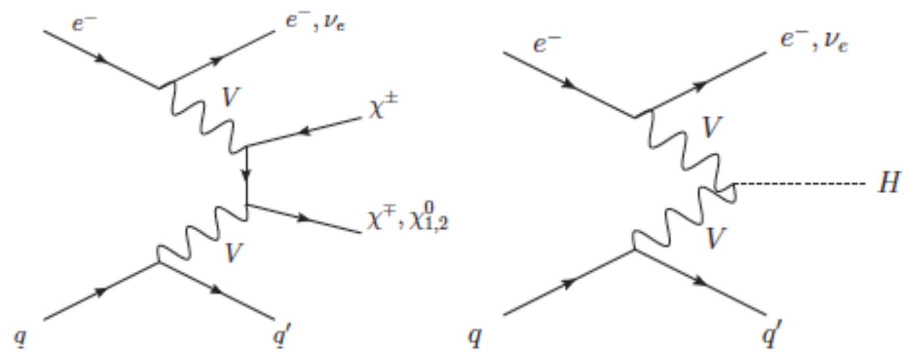
$$\frac{\delta\mu}{\mu} = \frac{1}{\sqrt{N}} \bullet f \quad \text{with} \quad f = \sqrt{\frac{1 + 1/(S/B)}{Acc \bullet \varepsilon}}$$

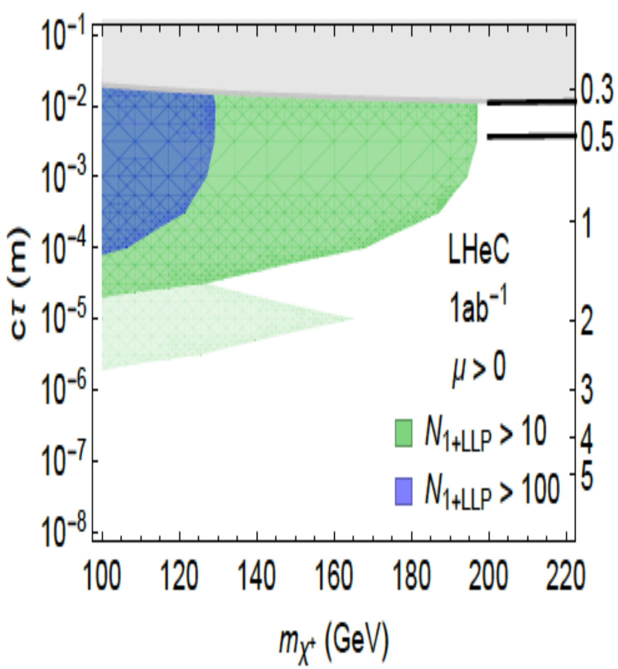
FCC-eh Detector Parameters

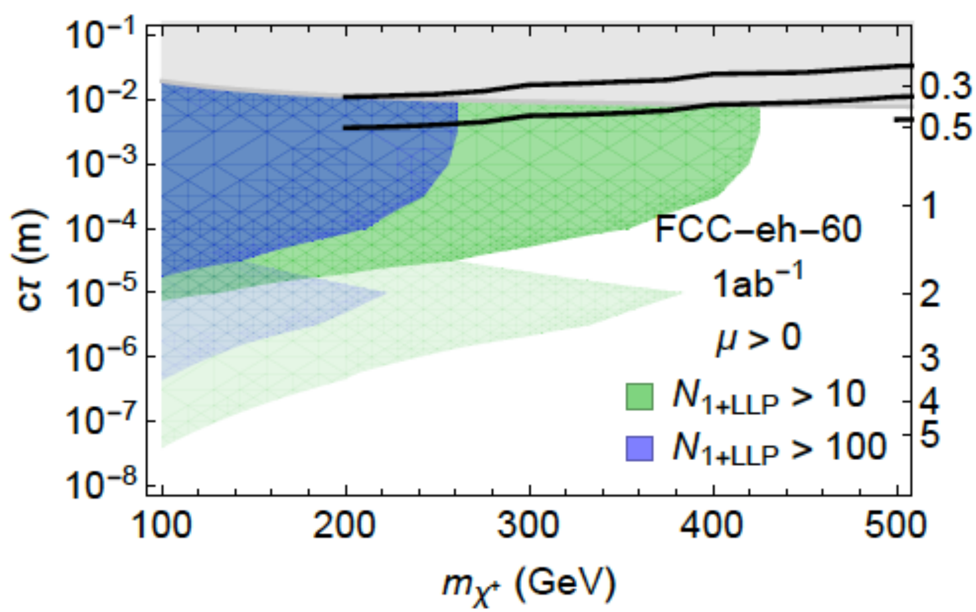
Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ [^{0}]	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
Pitch [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}
$\theta_{min/max}$ [^{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					

Search for Higgsino in ep







How it developed - DGs

1984 Herwig Schopper: Lausanne Meeting on LHC

1990 Carlo Rubbia at ICHEP Singapore: pp 1996, ep 1998 ..

1997 Chris Llewellyn Smith: LHC approval, with ‘ions and ep as a bonus’

2007 Robert Aymar, rECFA: Mandate to develop LHeC → CDR in 2012

2013 Rolf Heuer: “SM developed through synergy of pp,ee and ep” − new IAC

2016 Fabiola Gianotti: Reconfirmation of that Mandate for the IAC → update 2018

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* $e\gamma$ *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)*

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

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

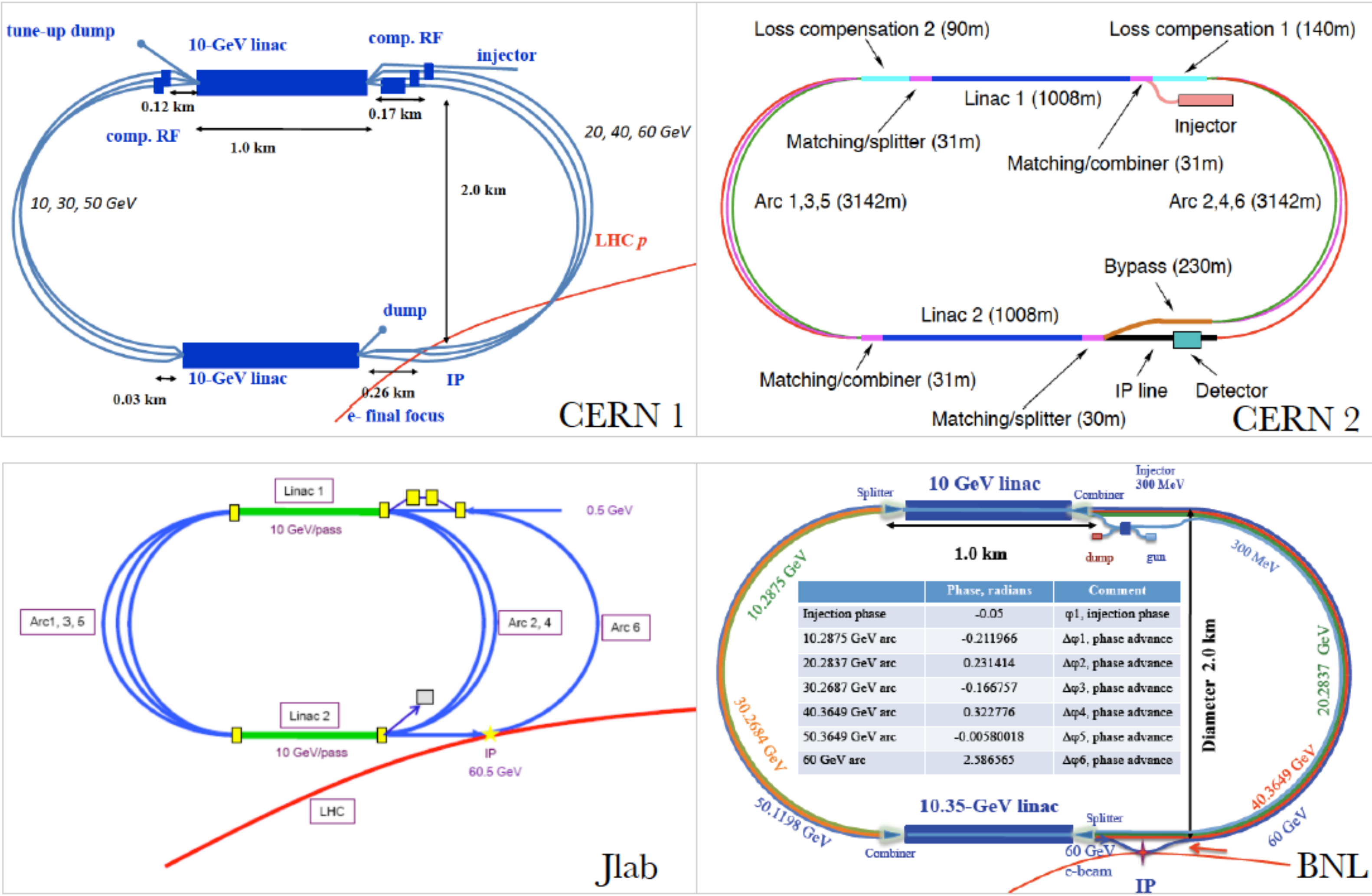
The Pomeranchuk Singularity in Nonabelian Gauge Theories: E.A.**K**uraev, **L**, V.S.**F**adin, SJNP 45(77)199
The Pomeranchuk Singularity in QCD: Ya.Ya.**B**alitsky, L **L**ipatov: SJNP 28 (78) 822

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

60 GeV Energy Recovery Linac

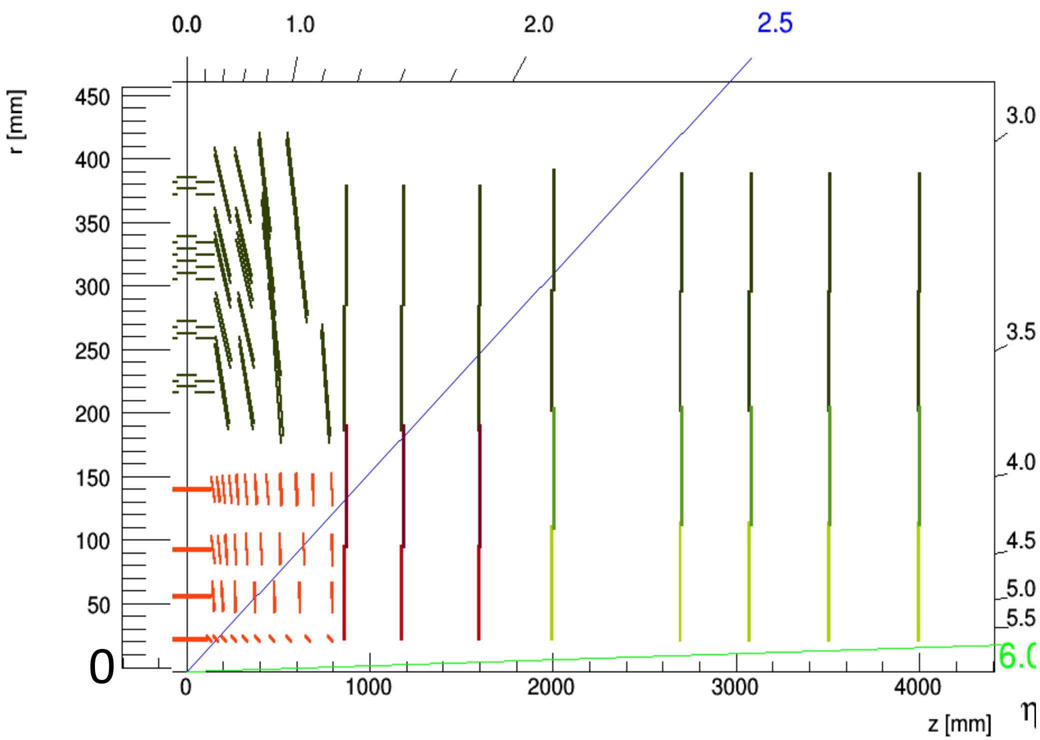


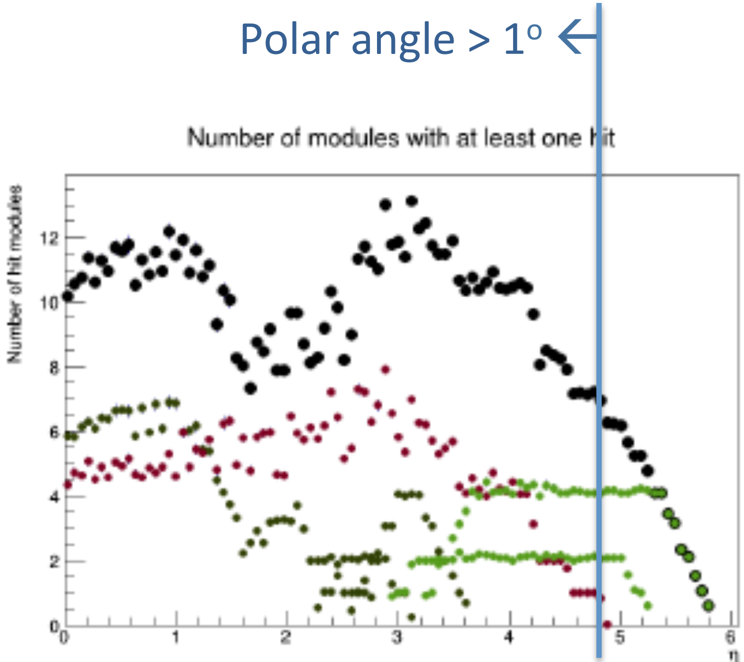
	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc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

CDR: Default configuration, 60 GeV, 3 passes, 720 MHz, synchronous ep+pp, $L_{ep}=10^{33}$ cm^{-2} s^{-1}

→Update in 2018 (to be published in the fall): 60 GeV + staging, 802 MHz, joint ep+pp, 10^{34}

Forward Tracking at LHeC

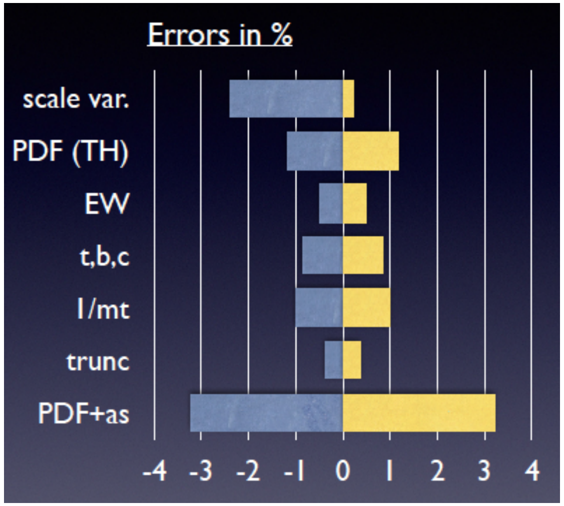




Work in progress, on tracker layout, with emphasis on forward acceptance, and technical issues as asymmetric beam pipe and material budget.

cf talks by A Pollini, P Kostka and A Gaddi

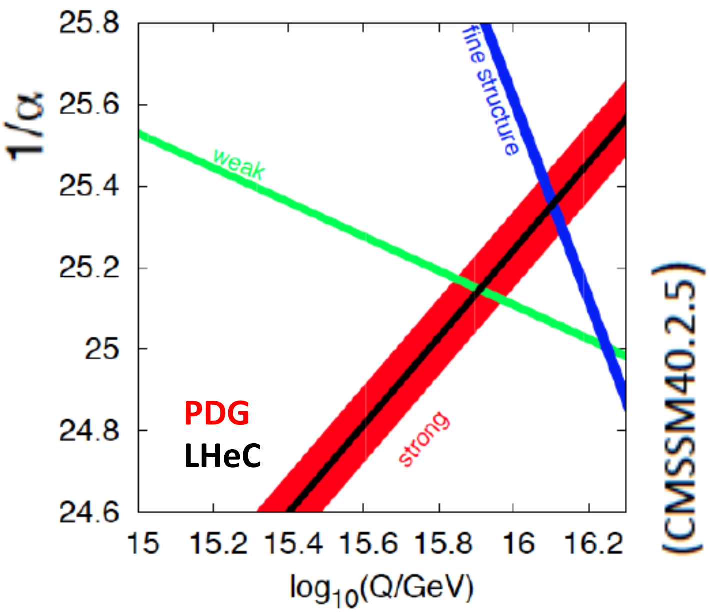
September LHeC workshop : https://indico.cern.ch/event/639067



Strong Coupling Constant

- 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

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



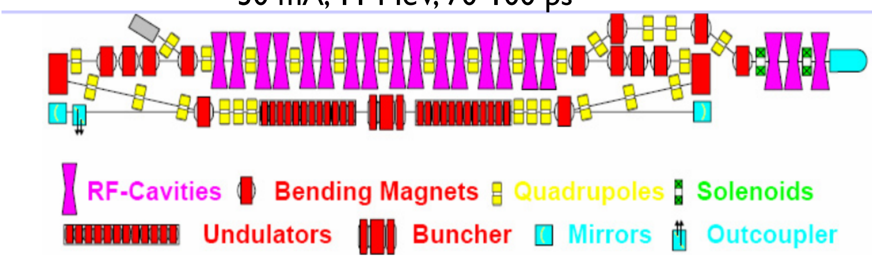
LHeC simulation, NC+CC inclusive, total exp error

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

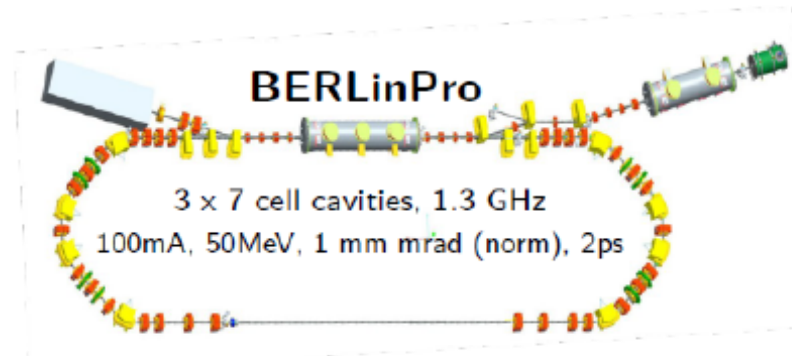
Two independent QCD analyses using LHeC+HERA/BCDMS

Other Facilities

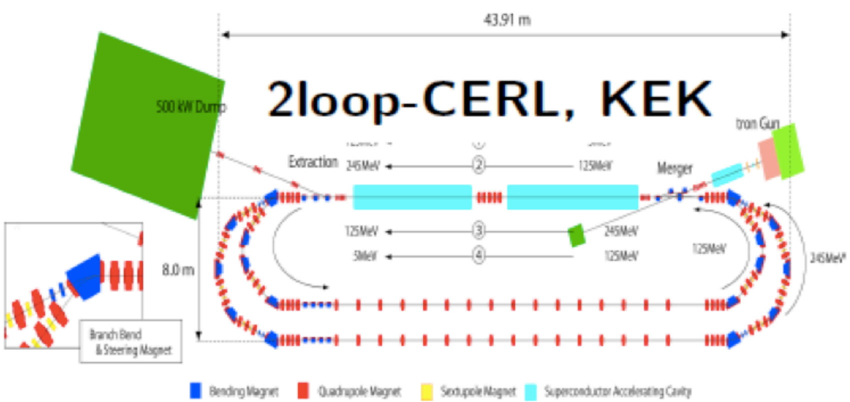
Normal Conducting 180 MHz + DC Gun
30 mA, 11 MeV, 70-100 ps



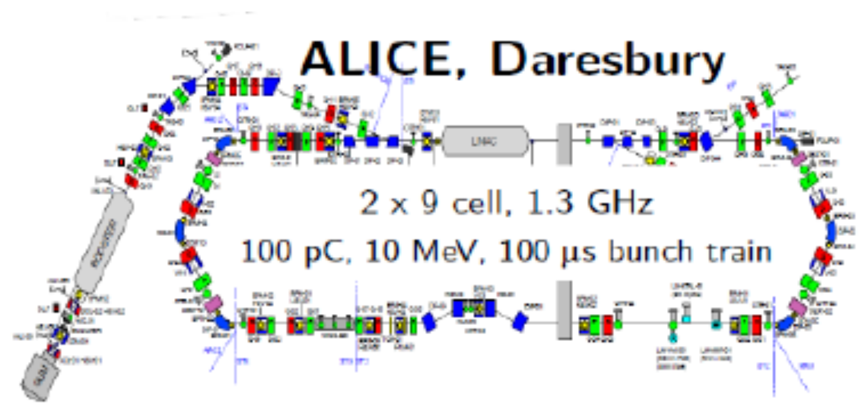
BINP, Novosibirsk



+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)

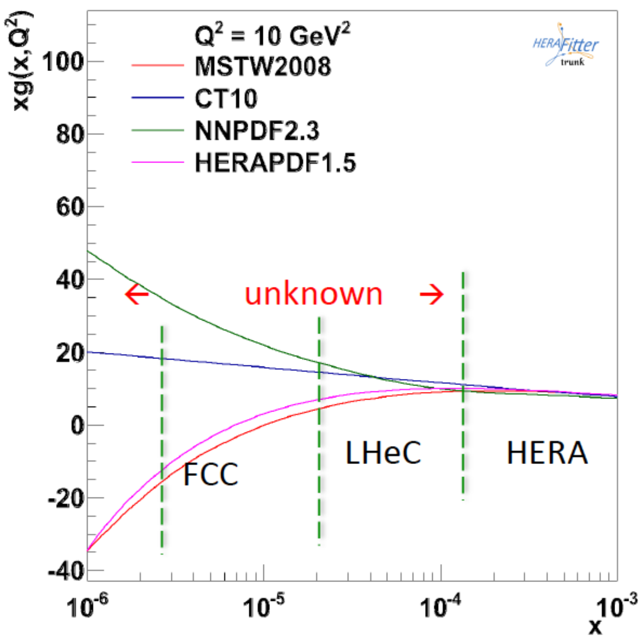
Strong possibilities for collaboration (ERL workshop 19-23.6.2017 at CERN, E Jensen et al)

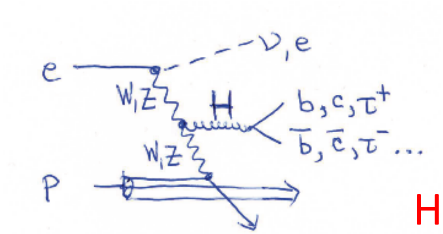
Energy frontier eh Physics

BSM

Rise or fall of xg
Non-linear QCD
Nuclear structure
UHEν physics..

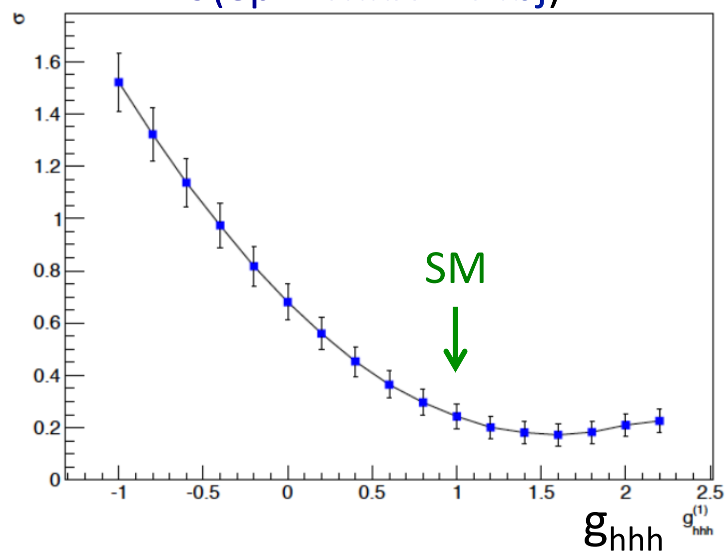
Low x ~ 1/s





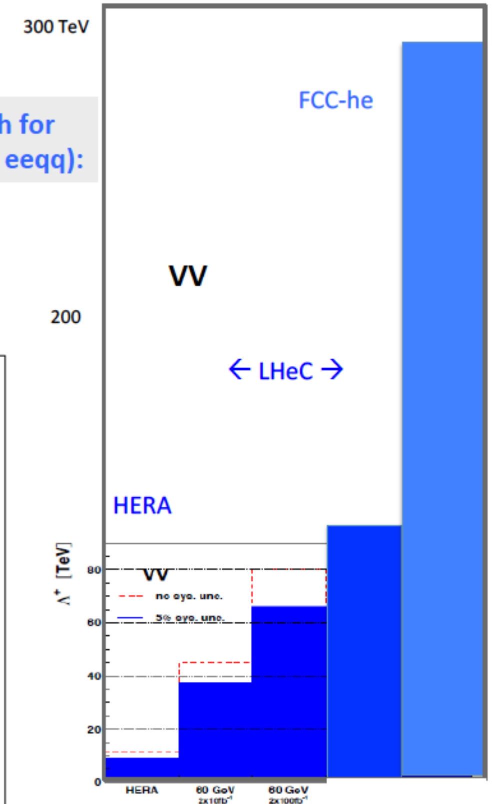
Higgs

σ(ep→νhhX→ν4bj)



Higgs couplings bb to 0.2%
h-hh in 4b, cut based: 5-8σ
ep - cost effective Higgs facility

Reach for
Λ (CI eeqq):



LHeC: see CDR 2012

CI to 300 TeV
LQ to 4 TeV
Compositeness
??

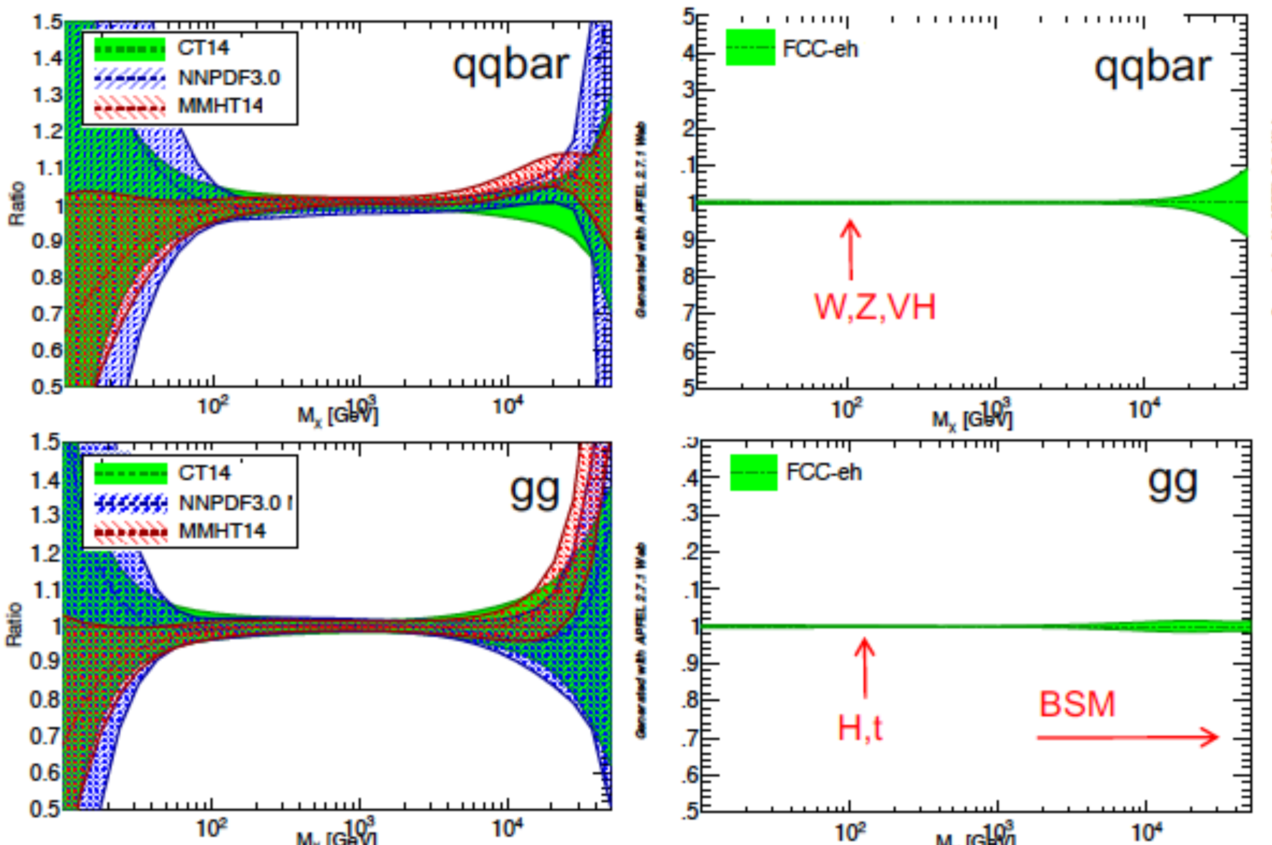
FCC-eh PDF program

completely resolve parton structure of proton: u_v, d_v, u, d, s, c, b, t and xg

unprecidented kinematic range, sub% precision, free of parameterisation assumptions, N^3LO;

solve non-linear and saturation issues, test QCD, …

today… FCC parton luminosities (100 TeV) **… then, with FCC-eh**

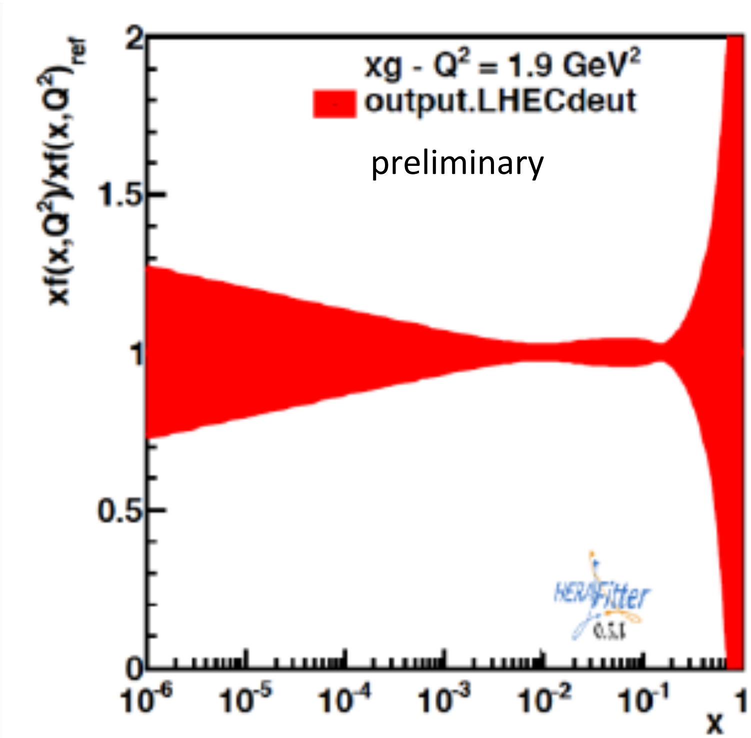


Claire Gwenlan PDFs at FCCeh – FCC Week 1/2018

Future Nuclear PDFs with LHeC

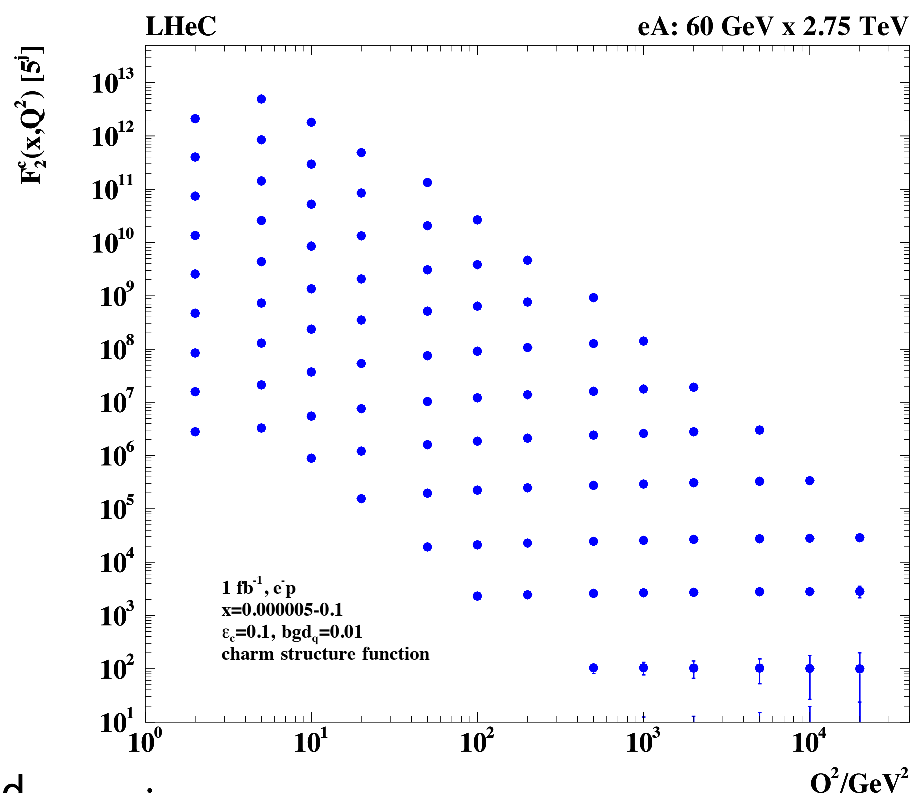
From an eA collider one can determine nuclear PDFs in a novel, the classic way.
Currently: use some proton PDF base and fit a parameterised shadowing term R.
Then: use the NC and CC eA cross sections directly and get $R(x,Q^2;p)$ as p/N PDFs.

Gluon density uncertainty in eA



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

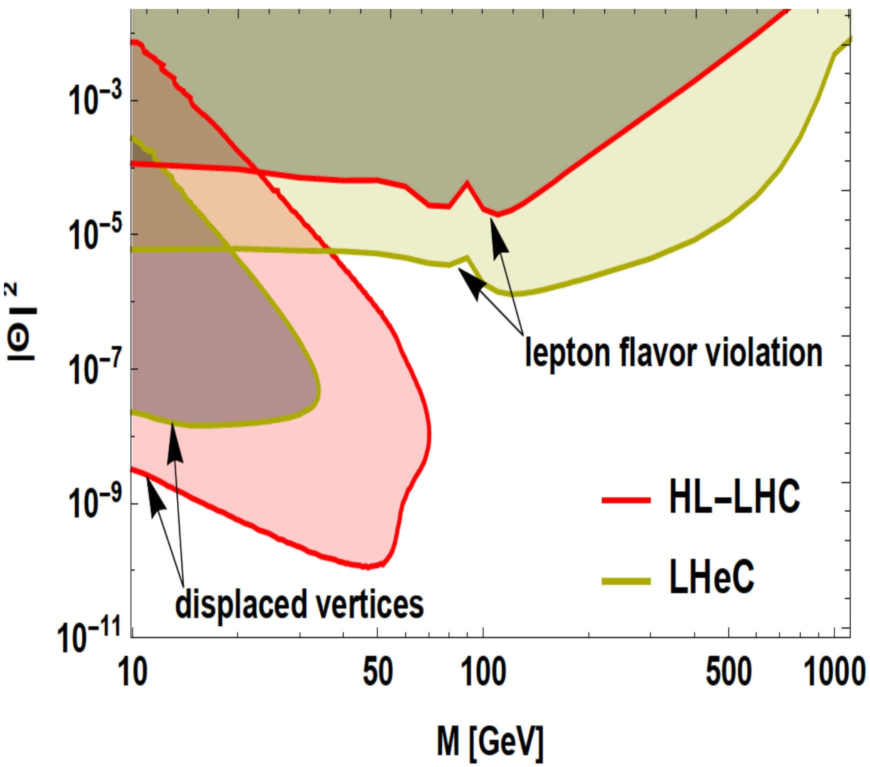
Charm density in nuclei



Impact parameter measurement in eA

Possible Discoveries Beyond SM with LHeC

Search for Sterile Neutrinos (LHC LHeC)



QCD:

No saturation

BFKL

Instantons

Higher symmetry embedding QCD

Electroweak:

EFTs

Exotic Higgs Decays

Extension of Higgs Sector

Sterile Neutrinos …

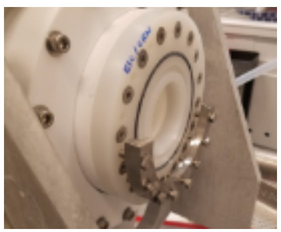
It is a wasted p that does NOT collide with an e beam
(Oliver Fischer - 2017)

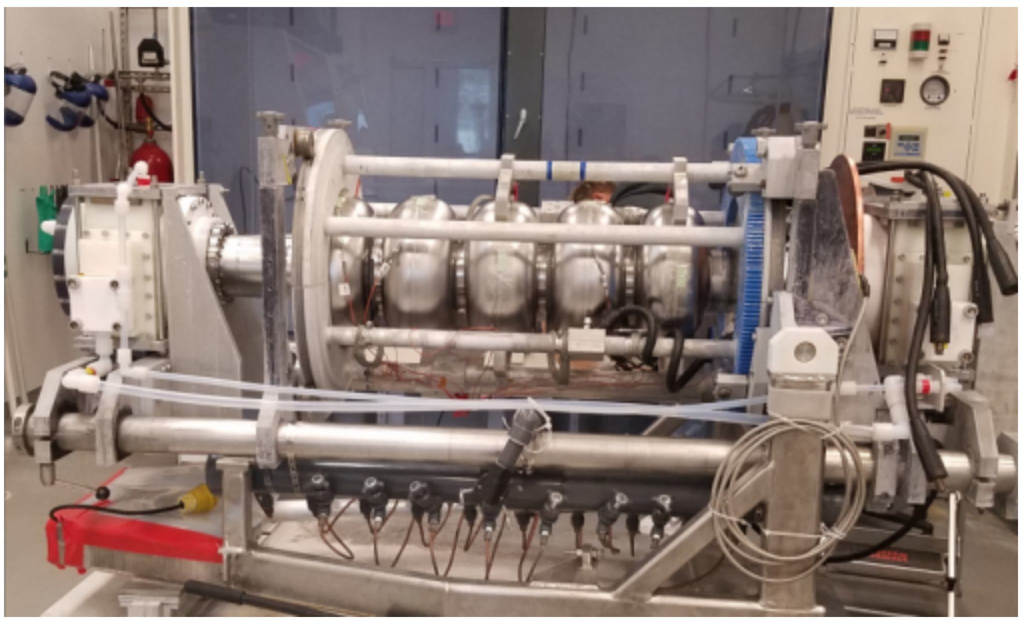
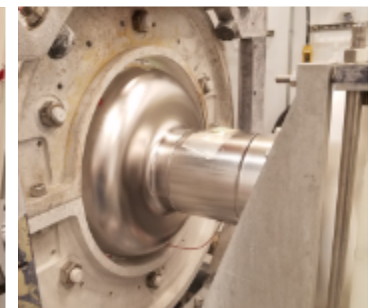
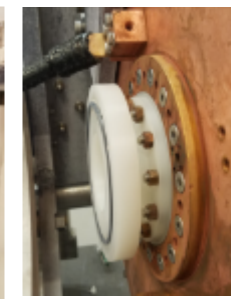
It would be a waste not to exploit the 7 TeV beams for ep and eA physics at some stage during the LHC time (Guido Altarelli – 2008)

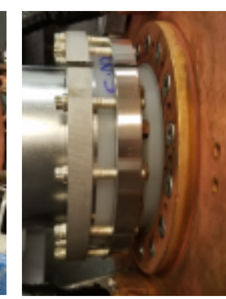
FCCeh

Post-Processing - Electropolishing (EP)

- New flange adapters were required to enable electropolishing with existing machine
  - Cavity just fits into system (largest cavity so far eletropolished at JLab)
- Electropolishing carried out successfully with outside temperature control (water spraying, cavity walls < 25 deg. C)

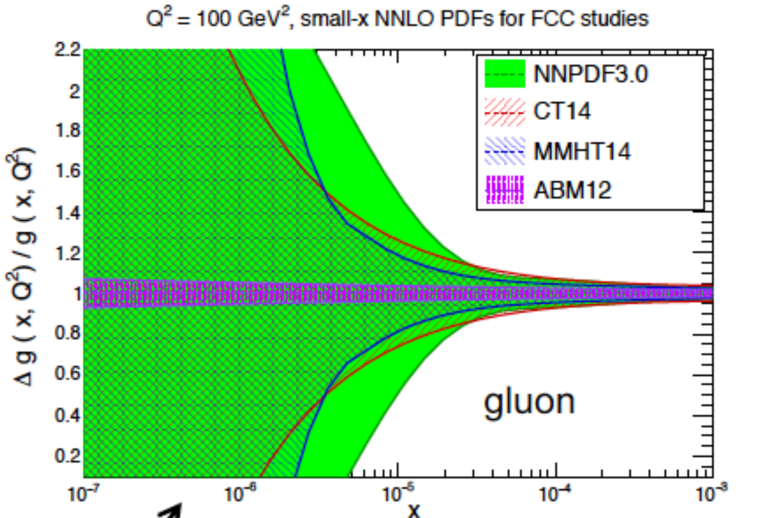


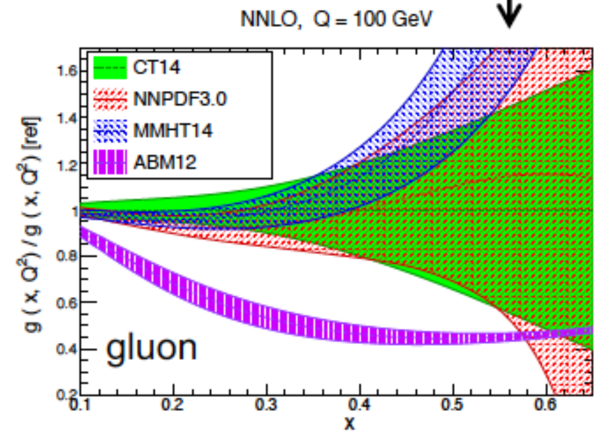




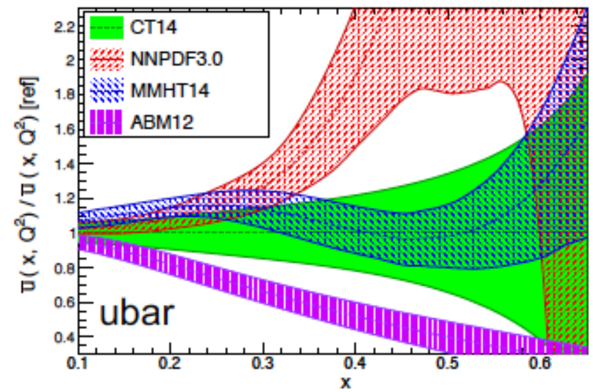


situation today

zoom in on large x







- **small x:** no current data constrain $x \leq 5\times10^{-5}$
- … and DGLAP will break down at small x
  (evidence for onset of BFKL dynamics recently demonstrated in HERA inclusive data, R. Ball et al. arXiv:1710.05935)
- FCC: small x becomes relevant even for W, Z, H, t
- **large x:** crucial for new physics searches in extended kinematic regime

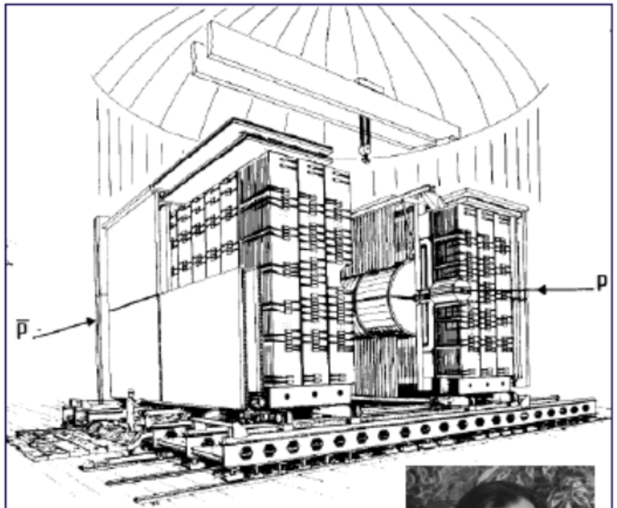
(plots from arXiv:1607.01831)

Dissidents are normally excluded → PDF or α_s uncertainty diminished
perhaps tolerable for average use,
not for precision, not for searches

Claire Gwenlan at FCC Week, January 2018, CERN

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…

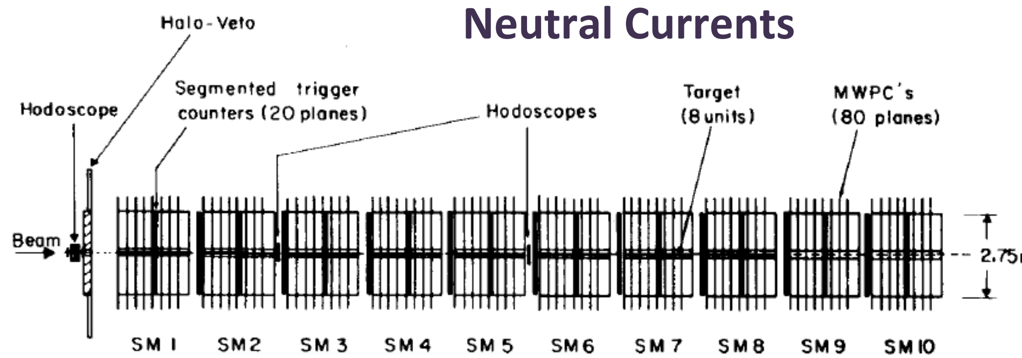
UA2

Pierre Darriulat

Charged Currents

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

Neutral Currents



BCDMS, EMC, SMC, COMPASS