FCC-eh – Status and CDR Plan

Baseline

Physics

Towards the CDR

FCC-eh
E_p =50 TeV

HE LHC
E_p=12.5 TeV

+ ERL electrons
E_e=60 GeV

Max Klein
University of Liverpool

For the electron-hadron study group

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

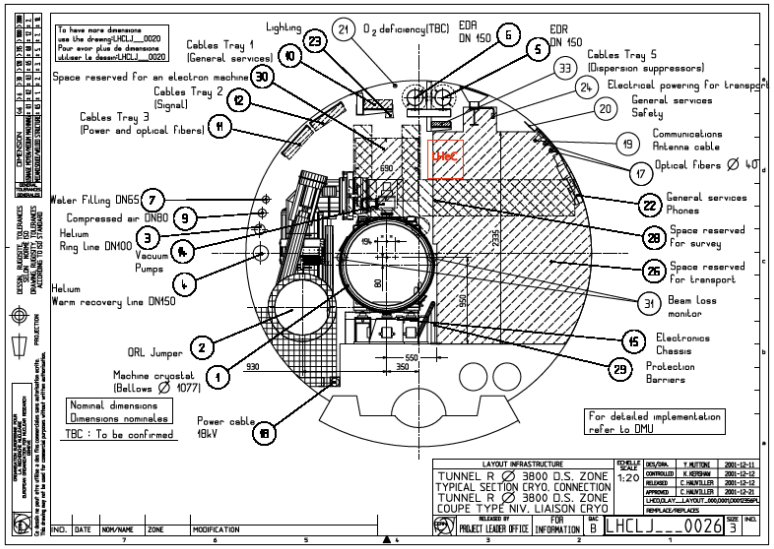
LHeC CDR
arXiv:1206.2913
J.Phys. G39 (2012) 075001

FCC Annual Workshop, Berlin, 29th of May 2017

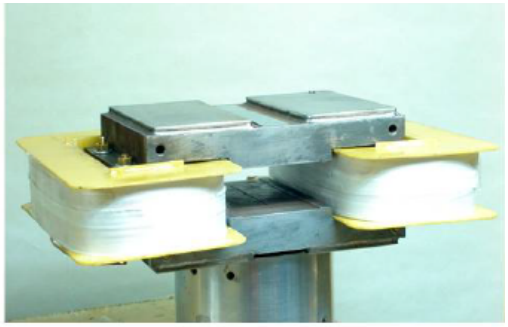
Introduction: $eh + hh$

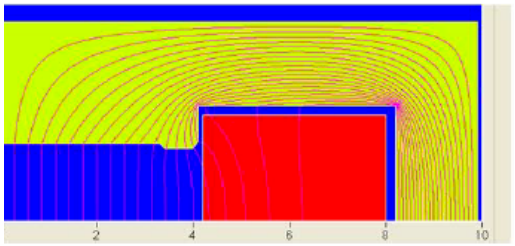
With the LHC, CERN has unique, highest energy and intensity hadron beams (p, Pb)
Obvious question, since Lausanne 1984, has been how to utilise these for eh + why.

CDR on $LHeC$: arXiv:1206.2913 (J.Phys.G)
600 refereed pages on ep/eA with LHC



Location of electron magnets in LHC tunnel

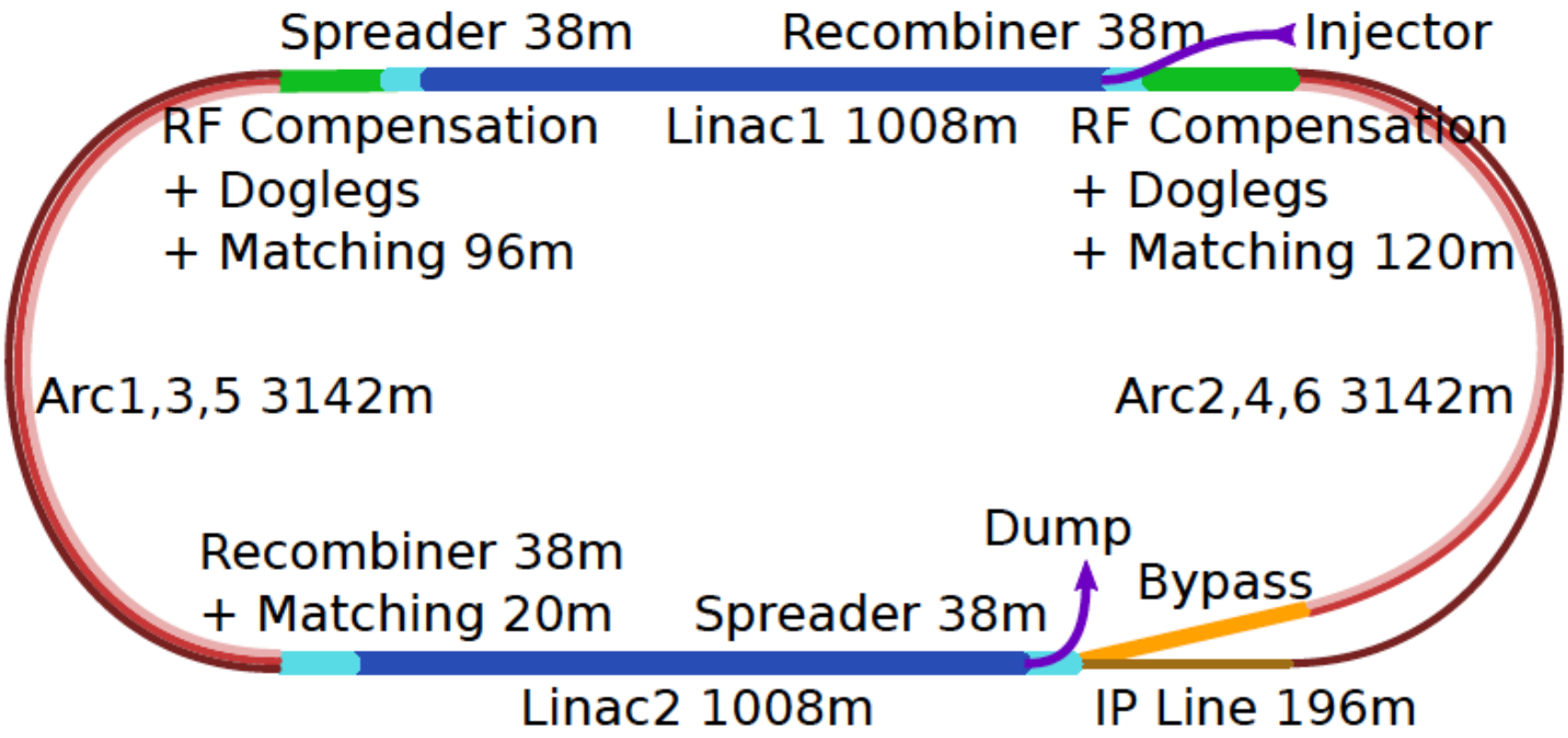




Dipole magnet prototypes built by BINP (foto) and CERN (also in LHeC CDR), all met spec's
→ Much lighter and slimmer than LEP dipoles

Conclusion for LH(e)C: electron accelerator better outside the main tunnel (HE LHC?)

ERL Baseline for *LHeC* and *FCC-eh*

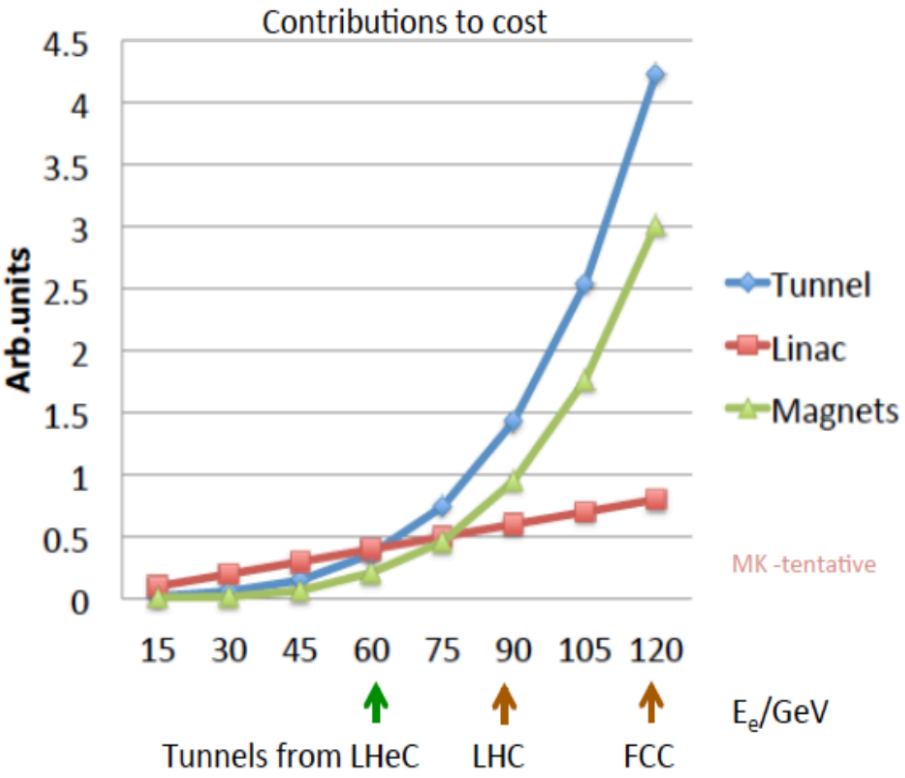


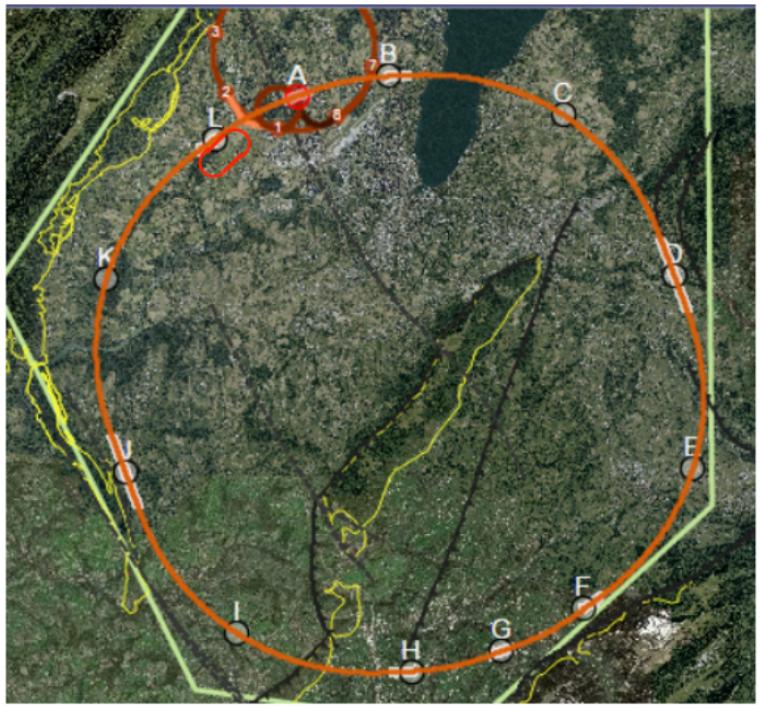
Concurrent operation to pp, LHC/FCC become 3 beam facility. P(e) < 100 MW

F Zimmermann Monday and O Bruening on Thursday (IR work in progress with BNL/CERN)

FCC-eh Default Configuration

With the *FCC-hh* (*HE LHC*) CERN, again, should have the world lead on *hh* beams





Jo Stanyard/J Osborne on Thursday

A rough extrapolation of a 3-turn *ERL* shows how the cost rises strongly with the electron beam energy. We therefore, currently stick to 60 GeV which maximizes physics return.

ERL is of modular, multi-use for eh at CERN

CE prefers the 9km circumference *ERL* to be placed to L, For HE LHC the *ERL* would be in place.

Conclusion for *FCC-eh*: consider the ERL as baseline for *eh*: for CDR, refer to *LHeC*

Five Major Themes of eh Physics

Cleanest High Resolution Microscopes

Joint ep and pp Physics

High Precision Higgs Exploration

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility

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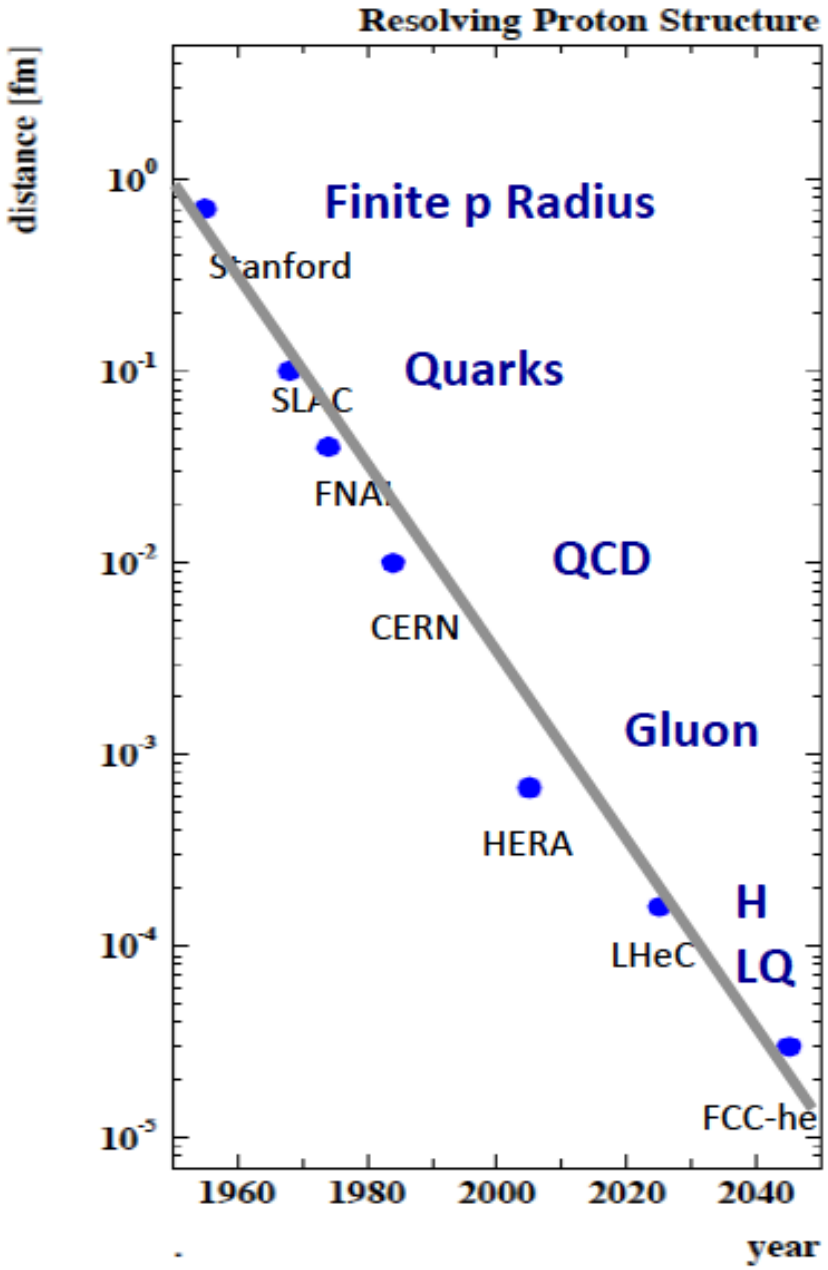


Microscope

Resolve with spectacular range (each high energy ep collider probes range down to SLAC's 0.1fm as scale varies) and precision:

Structure and Dynamics of

Proton, neutron, photon, pomeron, jets..

In momentum and transverse space

PDFs, TMDs, DVCS, generalised PDFs, ..

Here rely on CDR of LHeC + updates

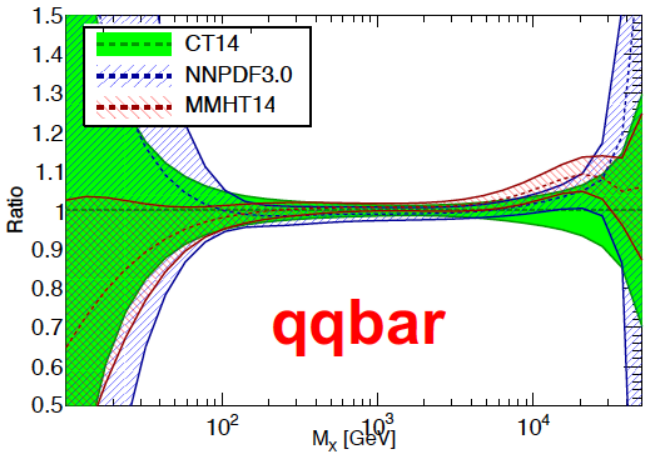
Prospect and challenge: Resolution up by 5 orders of magnitude in 100 years

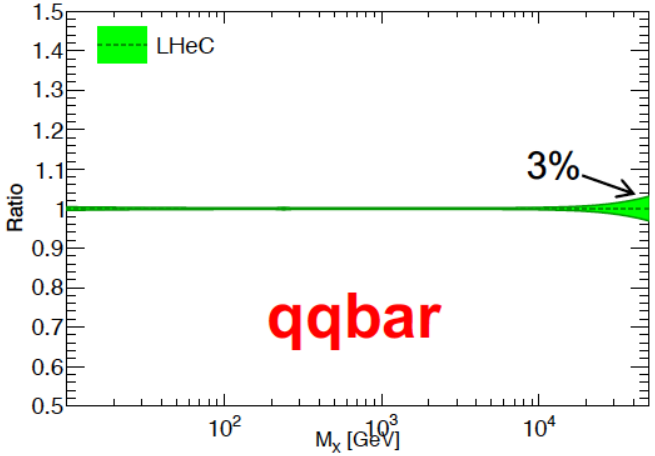
Unravelling structure of matter

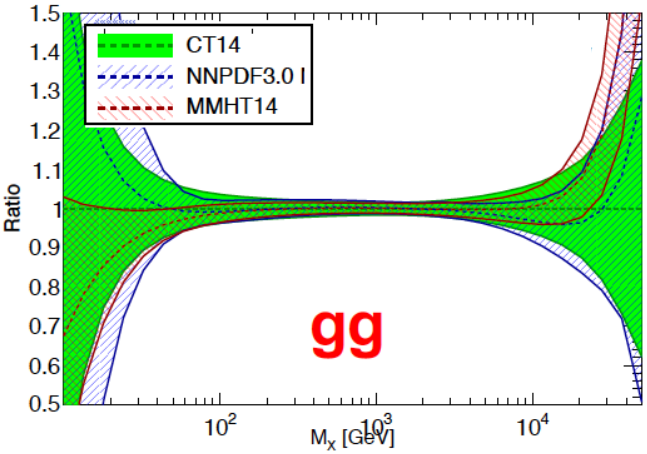
Resolve parton structure of the proton completely: u_v,d_v,s_v?,u,d,s,c,b,t and xg
Unprecedented range, sub% precision, free of parameterisation assumptions,
Resolve p structure, solve non linear and saturation issues, test QCD, N^{3}LO…

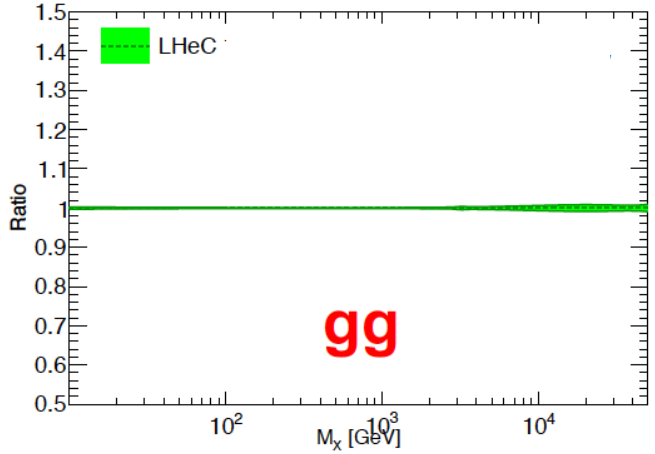
Strong Coupling in inclusive DIS to O(0.1)%

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









Completely new PDF Analysis under way for CDR(s)

D.Britzger
On Thursday

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

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Top Physics

Top electric charge

EDM and MDM

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

V_{tb}

Top spin

W-t-b

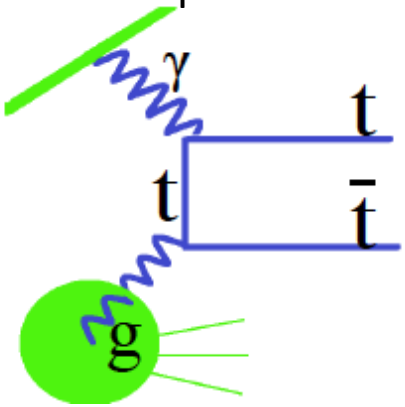
Top PDF

Top mass

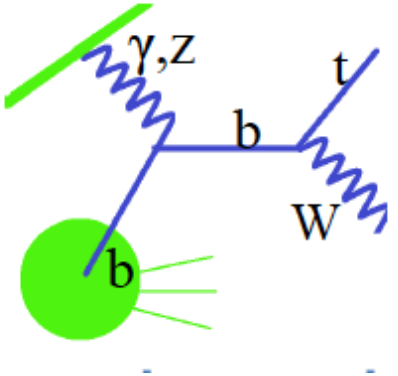
Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Pair production

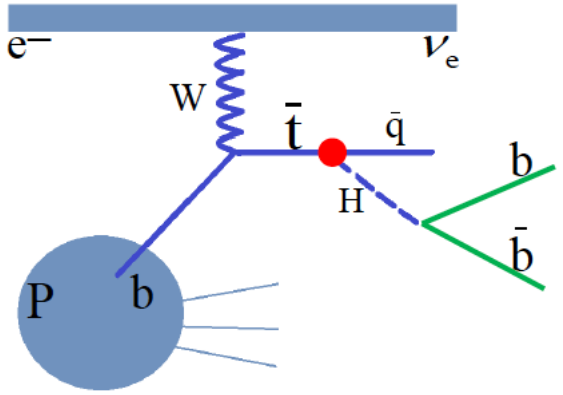


Single production



Huge rise of cross section from LHeC to FCC-eh
Very active, new studies
Complementarity in FCC
Unique sensitivity

FCNC top Higgs CC interaction



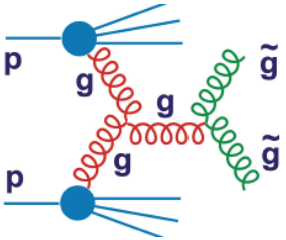
As we study find a huge potential of top physics in ep at high energies

Empowering pp Discoveries

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

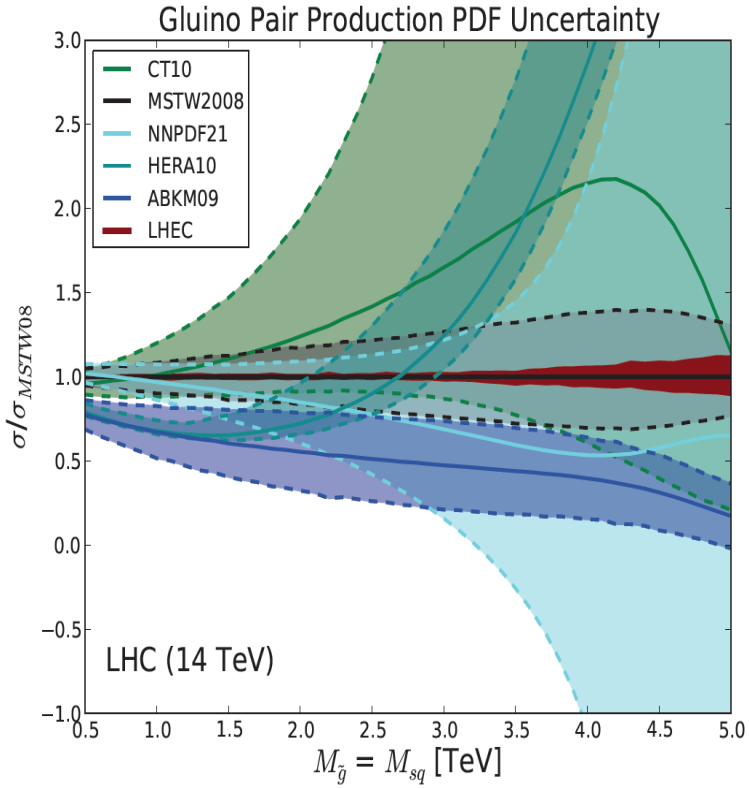
GLUON

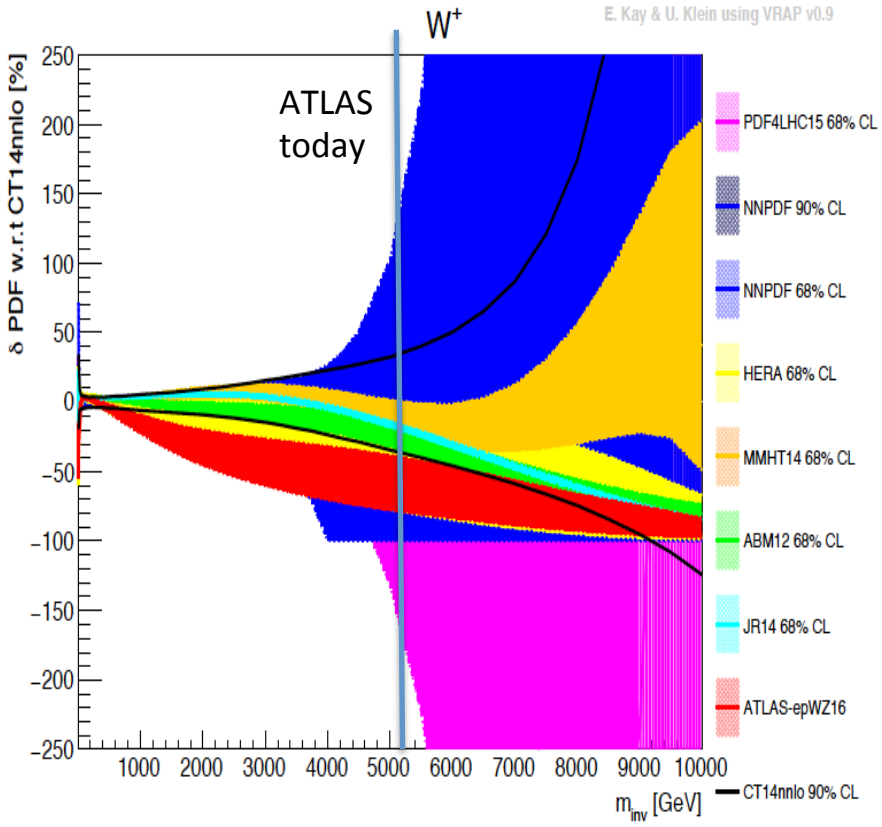
SUSY, RPC, RPV, LQS..



QUARKS

Exotic+ Extra boson searches at high mass





FCC-he: mass range:50/7 larger: eh vital to resolve high mass (x) region: "synergy" for CDR

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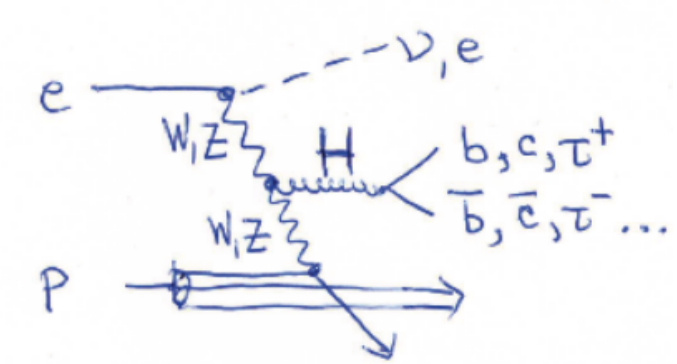
Higgs Physics with *ep*



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

ep when added to pp turns the pp colliders into high precision Higgs facilities. Removes gg-H QCD uncertainties (N^3LO) in pp

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

for CDR: complete SM (τ,W,g?) and add BSM Higgs studies, integrate with hh/ee

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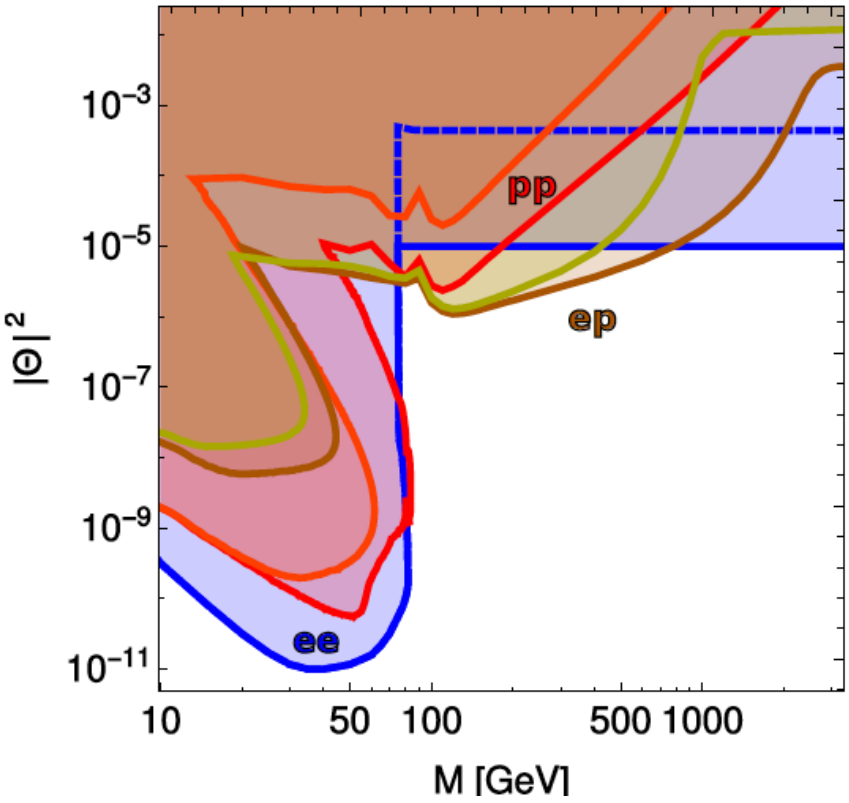
Possible Discoveries Beyond SM with eh

Search for Sterile Neutrinos
(LHC/FCChh **FCCee** **LHeC/FCCeh**)



O Fischer talk Tuesday

QCD:

(No) saturation of the gluon density

QCD radiation pattern (BFKL?) – hh!

New QCD states (instantons)

Higher symmetry embedding QCD

Electroweak:

EFTs, CI to 300 TeV, RPV SUSY

Exotic Higgs Decays (Dark Matter..)

Extension of Higgs Sector (H^{++}..)

Sterile Neutrinos . . .

K Wang
on Thursday

"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)

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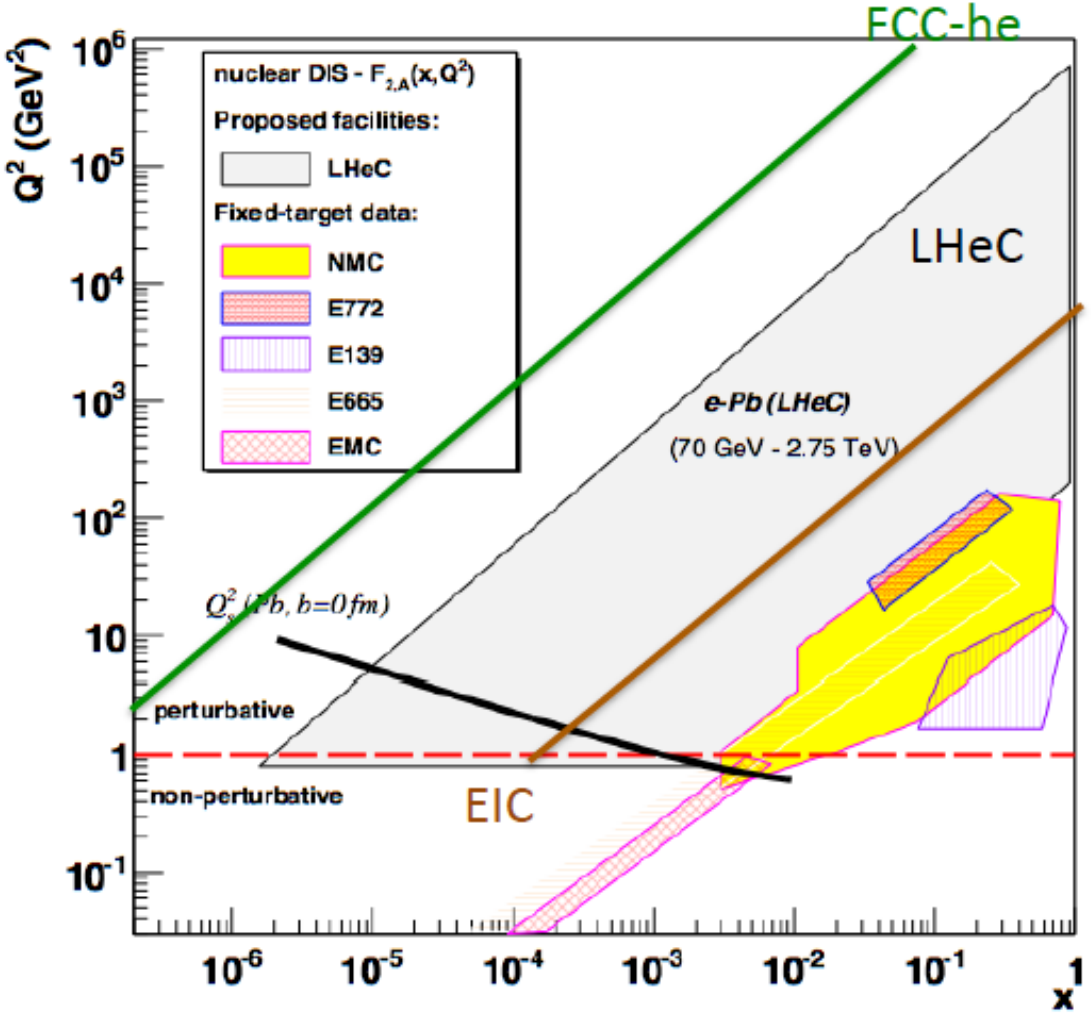
Electron-Ion Nuclear and Particle Physics



Extension of kinematic range by 4 orders of magnitude:
will change our view on nuclear structure and colour dynamics

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

May lead to genuine surprises

Saturation: non-linear gluon i.a.s
saturation needs very high energy:
Discovery in ep and verification eA

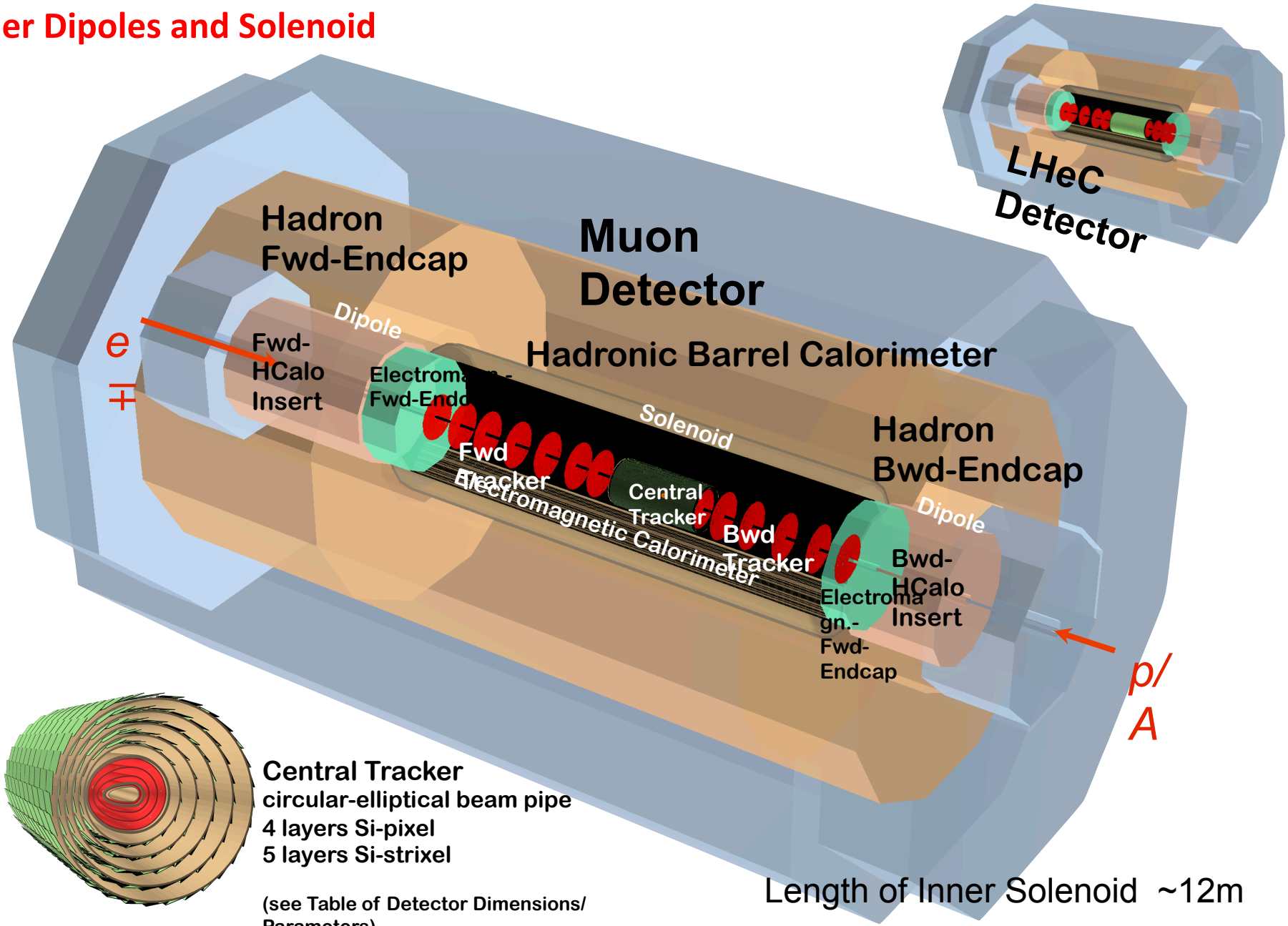
G Milhano on Thursday

For CDR: update in view of LHC (AA,pA) and new simulations, new ansatz to p+N PDFs..

Detector and ERL Development

FCC-he Detector Layout - Scaled Version of LHeC Detector

Inner Dipoles and Solenoid



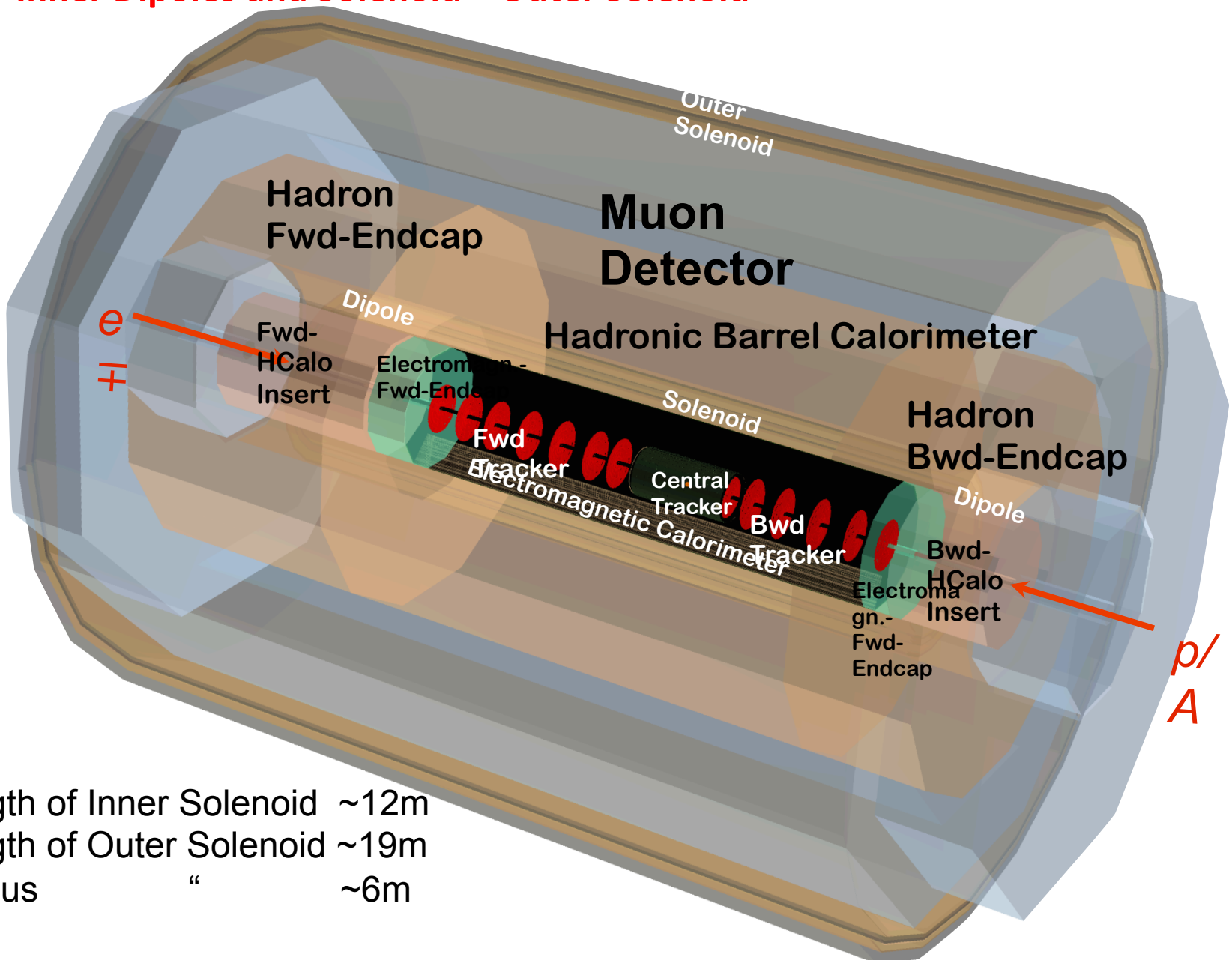
Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

(see Table of Detector Dimensions/ Parameters)

Length of Inner Solenoid ~12m

FCC-he Detector Layout - Scaled Version of LHeC Detector

Inner Dipoles and Solenoid + Outer Solenoid



Length of Inner Solenoid ~12m
Length of Outer Solenoid ~19m
Radius " ~6m

FCC-eh: Tracker, Calorimeters and Steps

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
$Si_{pix/strix}$ $[m^2]$	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
Volume $[m^3]$	13.2	3.1	28.8	407	1.98	7.0
Sum-Si $[m^2]$	461					

Input to detector design: HERA, ATLAS/CMS+their upgrades, CALICE, LHeC (CDR and update)

At FCC-eh unlike LHeC we think muon momentum measurement is vital (H-μμ)

Next steps: final choice of CDR technology, IR integration, joint eh-hh consideration, software

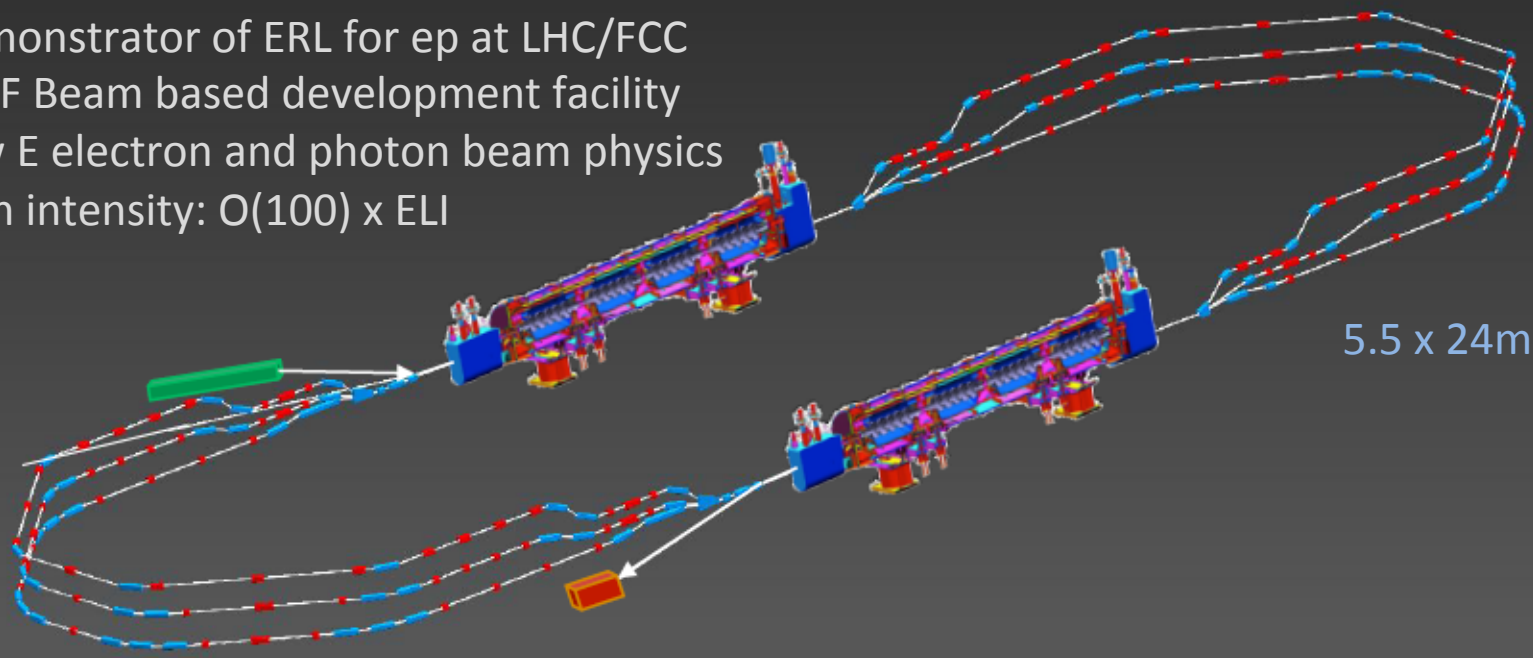
Powerful ERL for Experiments (ep,γp): PERLE at Orsay

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



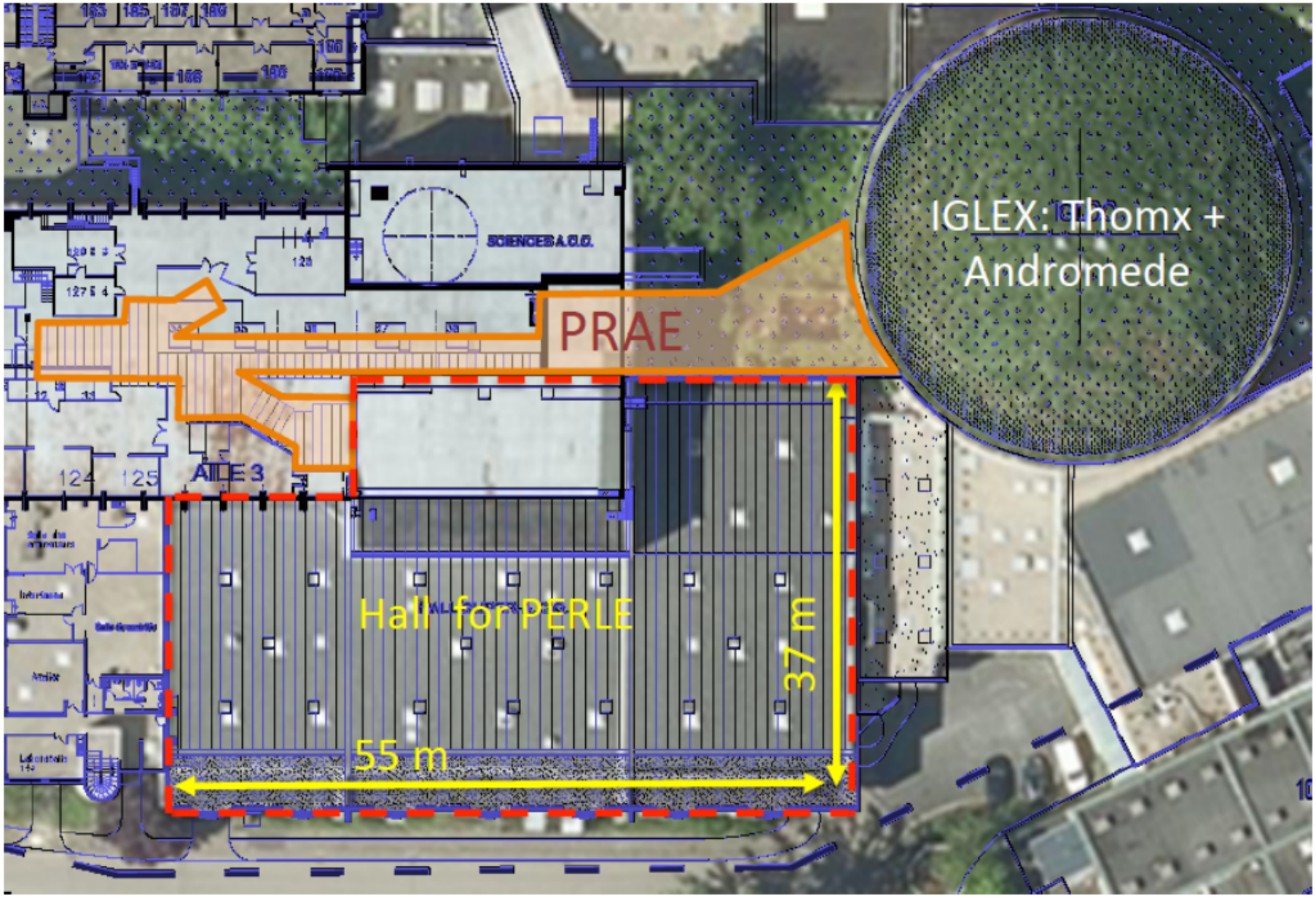
5.5 x 24m^2

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

See also https://indico.lal.in2p3.fr/event/3428/

A.Bogacz

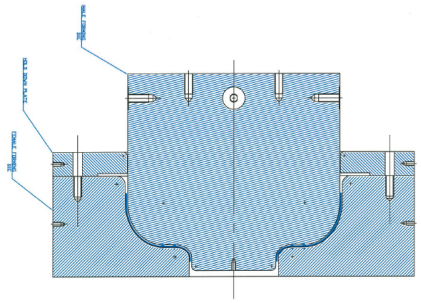
Site of PERLE at LAL/IPN Orsay



Described in PERLE CDR: arXiv:1705. 08783

802 MHz Cavity Fabrication Status

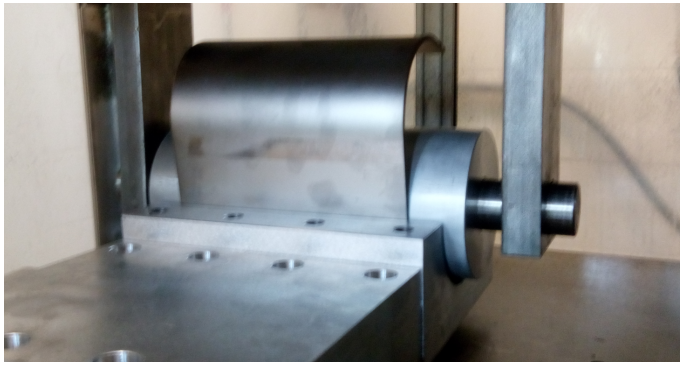
802 MHZ Nb and Cu prototype cavities progressing well

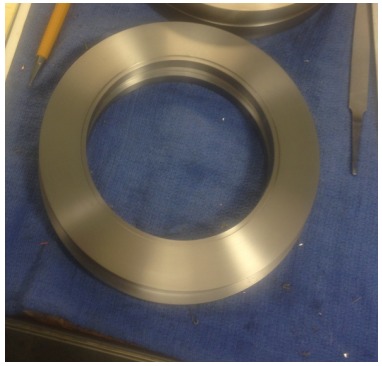


802 MHz deep-drawing die set and machining fixtures (completed)

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

Main eh Tasks for Completion of CDR

4 areas of activity

Accelerator: Update of the eh IR design for LHC/HE-LHC/FCC at 10^{34}

PERLE: Technical design and fabrication+test of an 802 MHz cavity

Detector: Update detector technology choice (collaboration with hh)

Physics: Update wrt LHC results and integration with hh+ee

Contributions to 4 FCC CDR Books (see M Benedikt today)

B1: Physics with the FCC (hh-he-ee)

B2: Summary of FCC-hh with integrated FCC-eh

B3: Details to B2

B6: HE LHC with eh (based on LHeC CDR Update B0)

a total of ~300 FCC pages

Electron-Hadron Scattering at the Energy Frontier – A Higgs Physics Facility Resolving the Substructure of Matter

Draft Table of Contents

Update of the LHeC CDR*) and input to EU strategy, reference document for FCC-eh + HE LHC

*) arXiv:1206.2913

Rolf Heuer at
Aix Les Bains
1. 10. 2013

Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (**ILC** or CLIC) ?)

Next decades

Rolf Heuer at
Aix Les Bains
1. 10. 2013

Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, FCC-hh/HE LHC)

lepton - hadron colliders (LHeC,FCC-eh)

lepton - lepton colliders (LC (**ILC** or CLIC) - FCC/SepC)

Modified MK

There is much to be discussed on the future of accelerator based particle physics

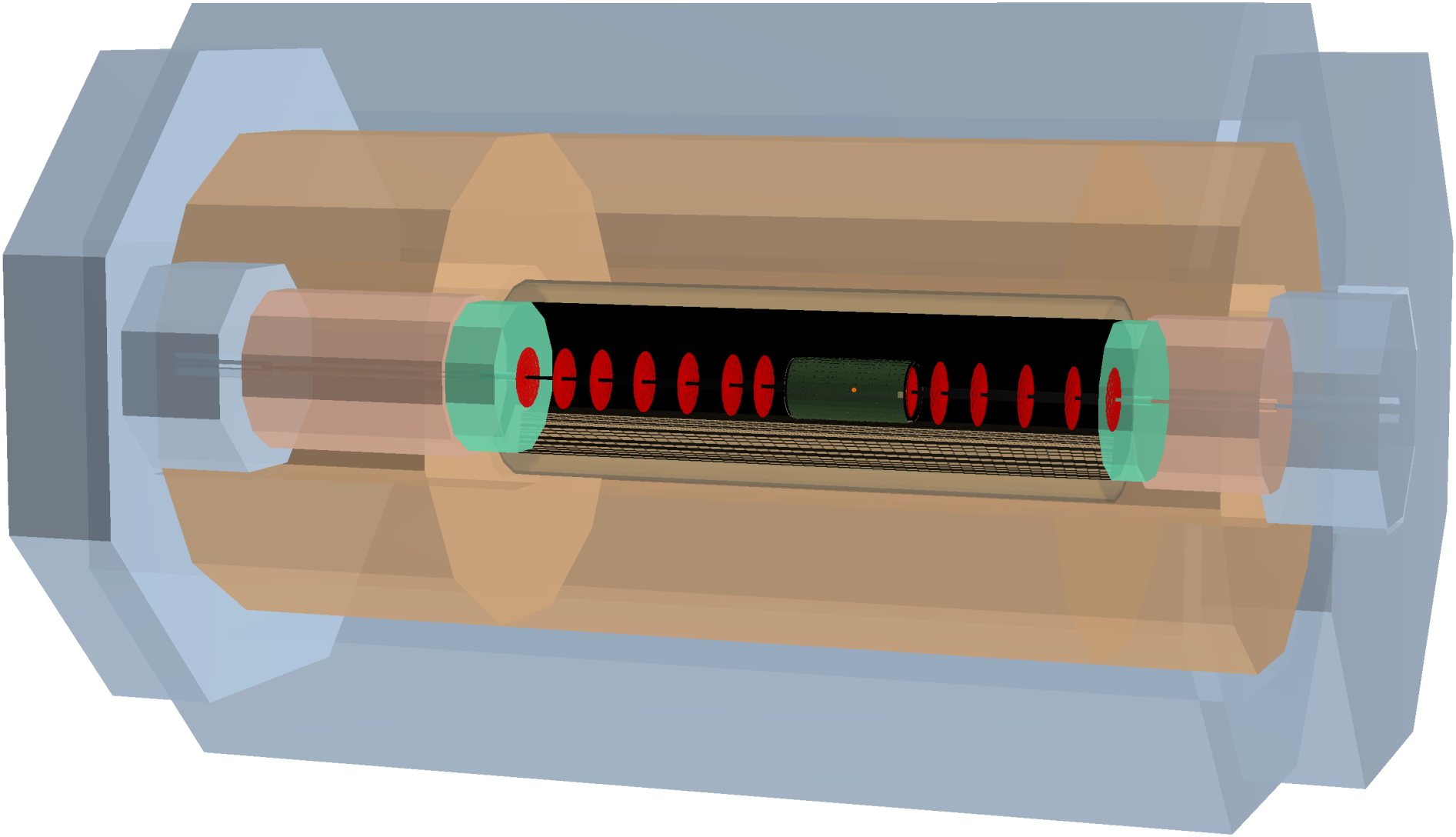
Energy frontier electron-proton and e-ion physics can make it substantially richer.

Many thanks to CERN for support and to my colleagues who share the pleasure and challenge to work on cinderella, the sister of the beautys hh and ee.

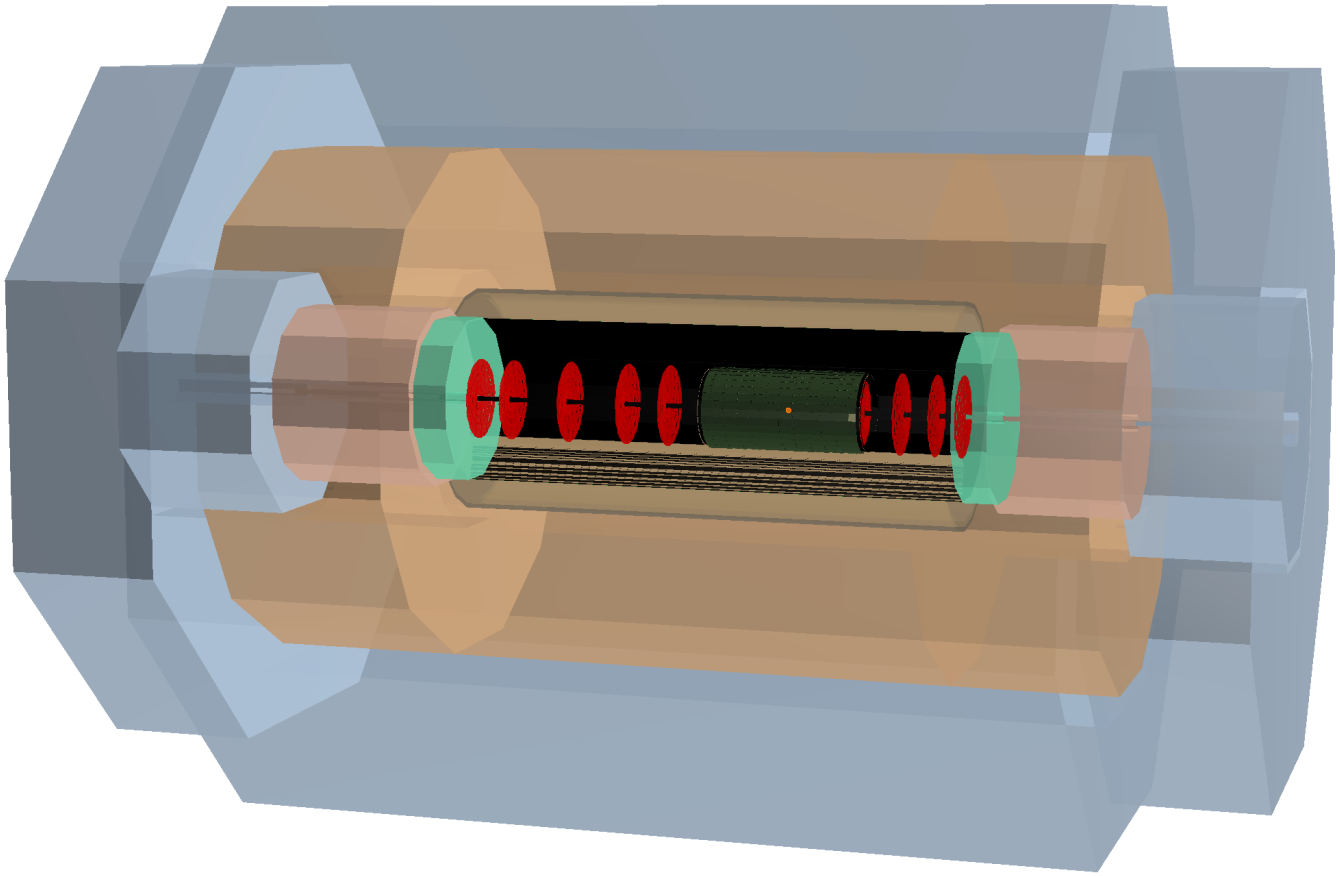
Thanks to Michael, Frank, Johannes and the FCC coordination group.

backup

FCC-eh Detector



FCC Detector is a scaled version of LHeC Detector



eh and *hh* Relations

Physics:

- **high precision** of ep essential for pp: Higgs, strong coupling (link to ee too)…

- **high Bjorken x**: resolve PDF uncertainties to enable searches at highest mass in pp

- **low Bjorken x**: clarify parton evolution (BFKL? gluon saturation?) to understand pp

- Complement **searches**: spectroscopy of leptoquarks, sterile neutrinos (ee-eh-hh),..

Detector: very smilar requirements in **forward (h) beam direction** as for hh
backward similar to ee

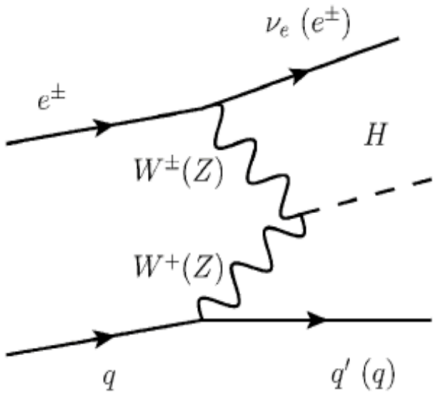
Accelerator:

Concurrent operation of pp and ep – no significant loss of pp luminosity

Development of **technologies**: SCRF for ep and ee, for example

Conclusion: *eh* is genuine part of *hh* and should occur in the *FCC-hh* CDR books

Higgs in ep beyond precision couplings

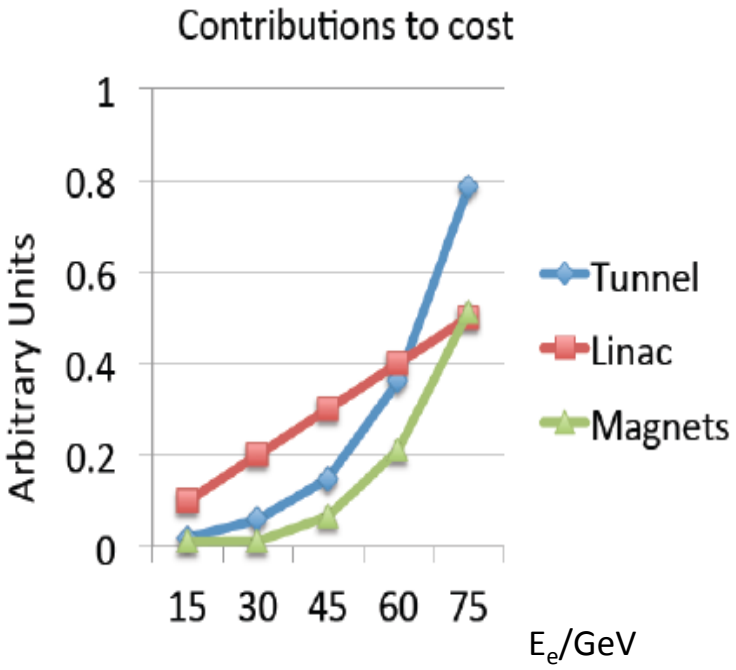


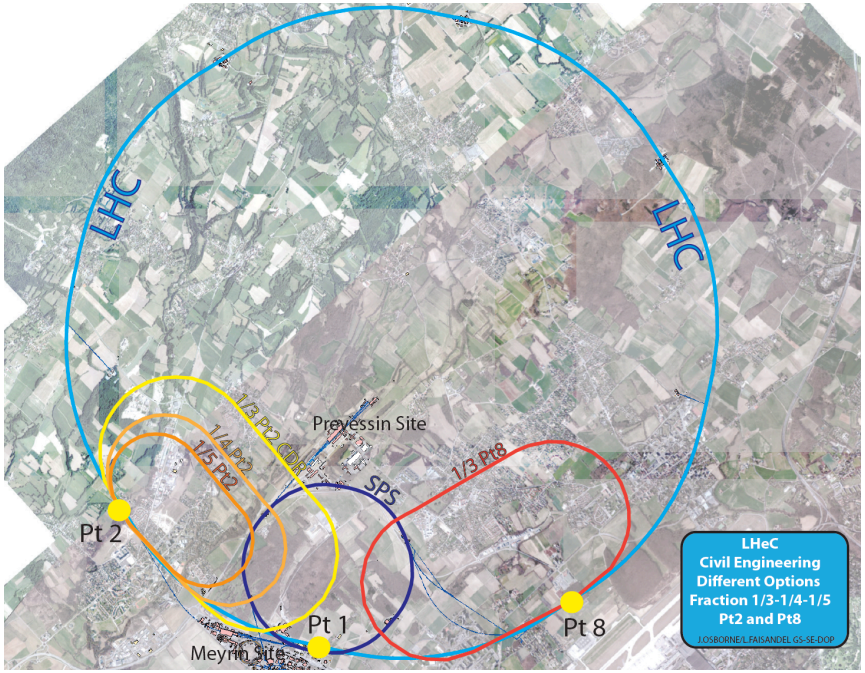
Higgs Physics with *ep*

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

- Higgs is produced via an EW process in ep collisions
  - **No involvement of ggF and no pile-up**
  - **Precise theoretical control of the cross-section**
- Superior sensitivity of ep with respect to pp in various aspects:
  - **h → bb,cc,tautau couplings, unique access to WW-H-WW**
    - **Access to h → gg?**
  - **Structure of hVV and top Yukawa couplings**
- Access to hh and invisible decays (dark matter) in ep collisions
- Removal of QCD uncertainties to gg → H calculation for LHC
- **With ep, pp becomes very high precision Higgs facility of important complementarity to ee (LH(e)C and FCC-pp+ep**

LHeC Default Configuration





A rough extrapolation of a 3-turn ERL shows how the cost rises non-linearly with the electron beam energy. Reliable cost estimate work in progress

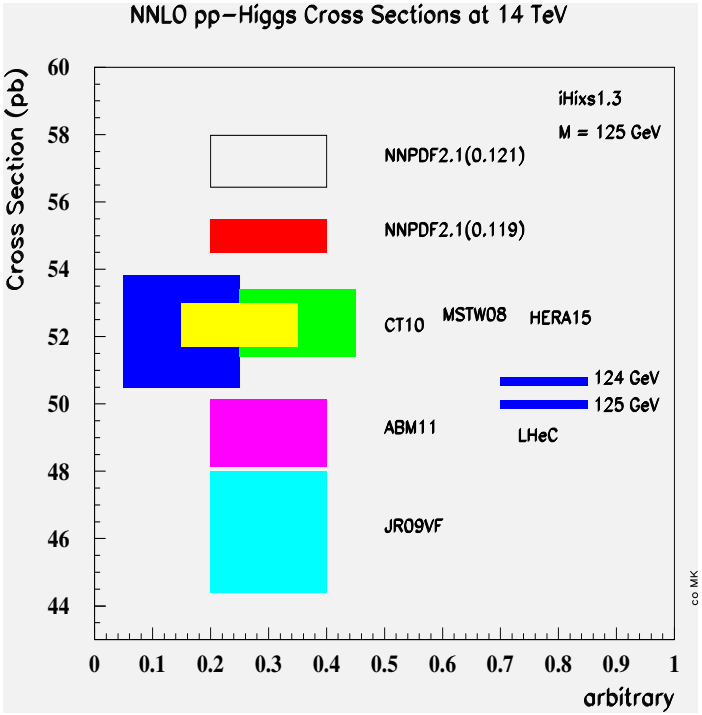
9km: 1/3 of U(LHC) leads to 60 GeV e energy
5.4km : 1/5 of LHC circumference: 51 GeV
energy driven by H, top, BSM and low x physics

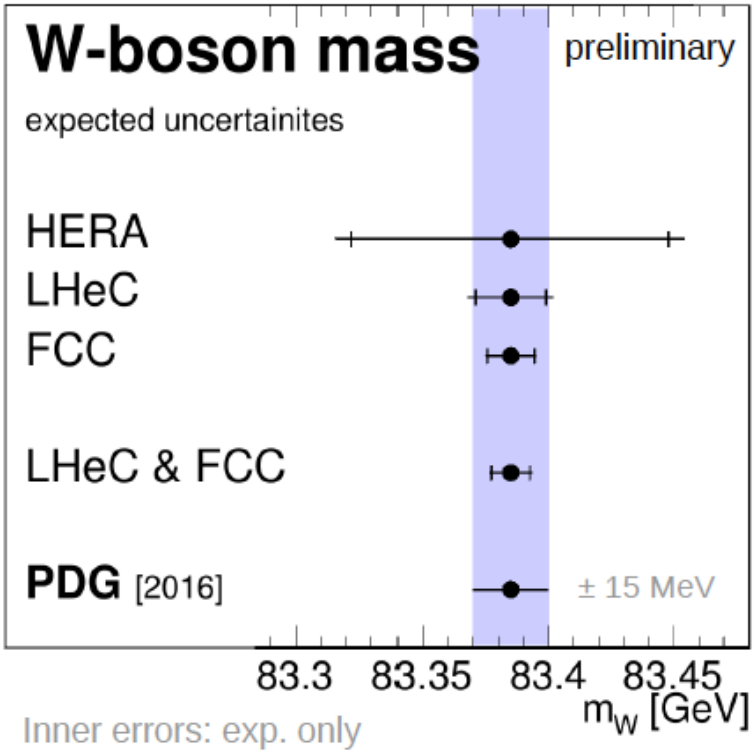
Conclusion on LHeC: may build an ERL tangential to LHC (HL and HE in sight). Choice of energy from optimization of physics, cost, effort, time schedule..

F Zimmermann on Monday

High Precision for the LHC

Higgs pp Cross Section





D.Britzger on Thursday

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

ep+pp deliver high precision of Higgs and qcd and electroweak physics − compl to ee

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 in pp