Future pp/hh and ep/h Colliders

Preface

HL LHC and its ep/A complement

FCC-hh with its associated eh option

HE LHC

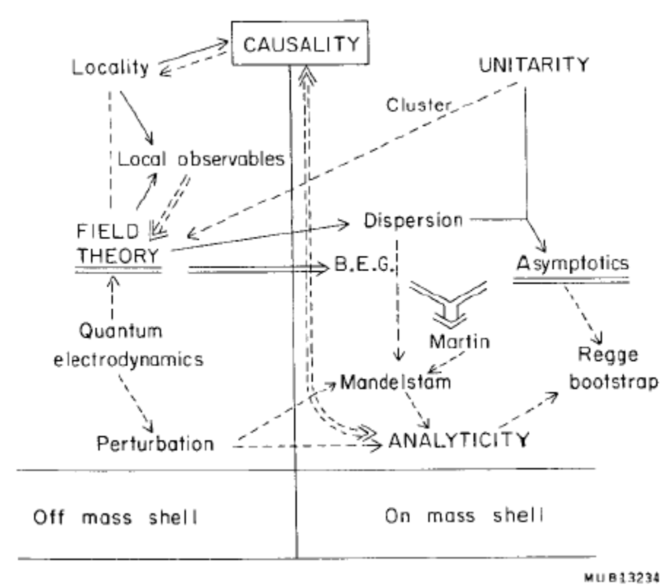
Personal Remarks on the Physics, Accelerator and Projects

Max Klein (U Liverpool)
ATLAS, H1, LHeC and FCC-eh

Invited Talk at the UK PPAP Meeting, Rutherford Laboratory, 20th of July, 2017

50 years ago

ICHEP 1966


FUNDAMENTAL THEORETICAL QUESTIONS

M. Froissart, Rapporteur

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

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

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

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

Funding HEP

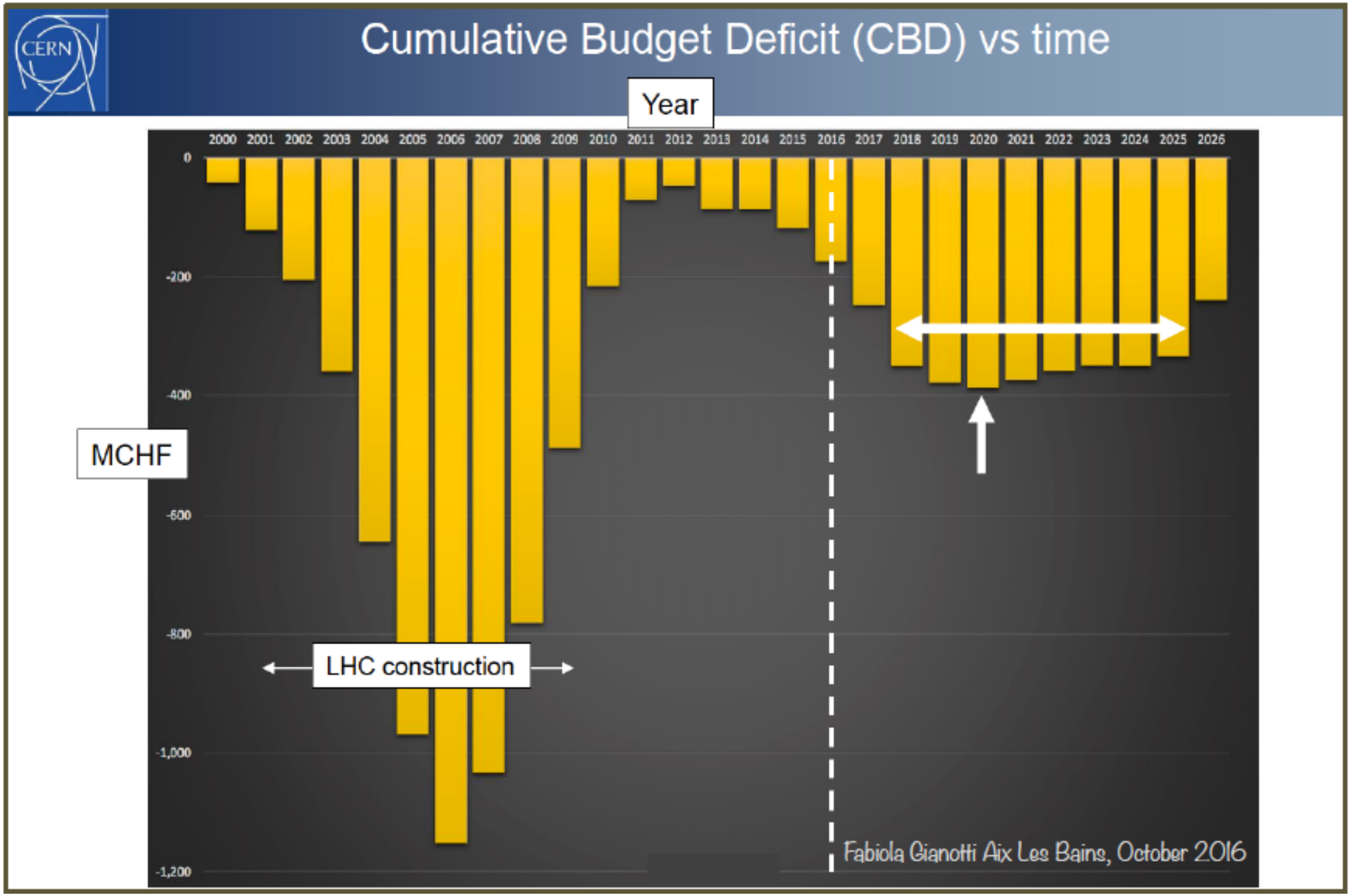
Softened but hard
Brexit from SPS in 68
→ repeal shortly after

E.Amaldi to ECFA, 10.7.1968

In the Council meeting of 19 June, the United Kingdom delegation announced the decision of the British Government not to participate in the 300 GeV project. This decision was essentially based on economical considerations; the scientific and technical merits of the project were not questioned. The British delegate added a personal statement endorsed by the competent scientific authorities in his country in which as a physicist he regretted the decision of his Government and hoped that it would be possible at a later time to come back on it.

convincing us, the academic and the public society – necessary, not always sufficient

The Current Major HEP Funding Resource is -CERN



CERN has O(200)MSF free money annually → 100 years to fund a 20 BSF project this way.

Time Projections

Scientific activities

European Strategy ***2006***

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

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

Apparently we are unable to deliver reliable time projections

… and yet we need optimism in order to progress …

Particle Physics - a Sequence of Spectroscopies

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

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

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

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

Gustav Hertz: Nobel 1925


John Cockroft and Ernest Walton: Nobel 1951


Enrico Fermi: Nobel 1935


Sam Ting and Burt Richter: Nobel 1976

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

The Standard Model is (formally) complete

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..].**

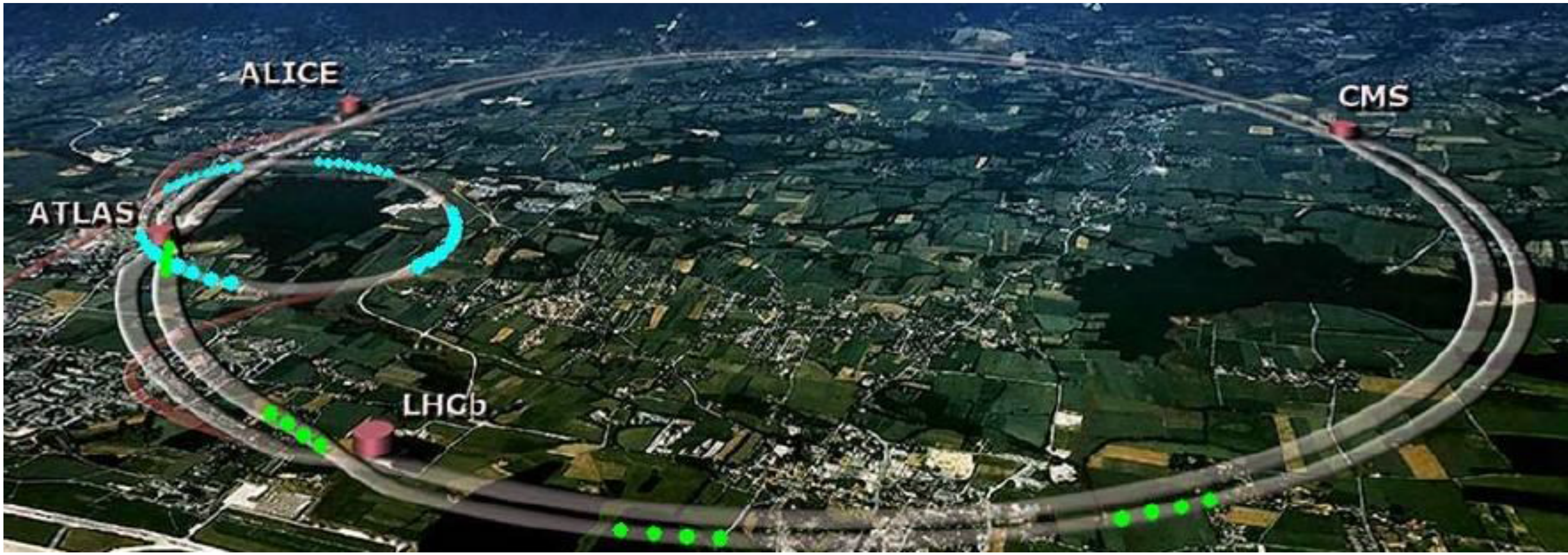
All three types of colliding experiments were instrumental in the SM establishment:
For example: LEP predicted the top mass and Tevatron found the top quark;
HERA measured the gluon distribution and LHC discovered gg→**Higgs**→ 4l, γγ.
Tevatron saw excess in high pt jets, yet attributed to PDFs with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

HL LHC



Machine: 950 MSF [170 CE, 120 in kind], LIU 180 MSF; 1800 CERN person years + 1100 FTE
ATLAS: major detector upgrade and tracker replacement; CMS: major upgrades, fwd calo..

Total cost may be close to 2 BSF and involves 10k physicists in experiment and accelerators

The first priority of the 2020 strategy update will no doubt be the HL LHC, for 2 decades hence

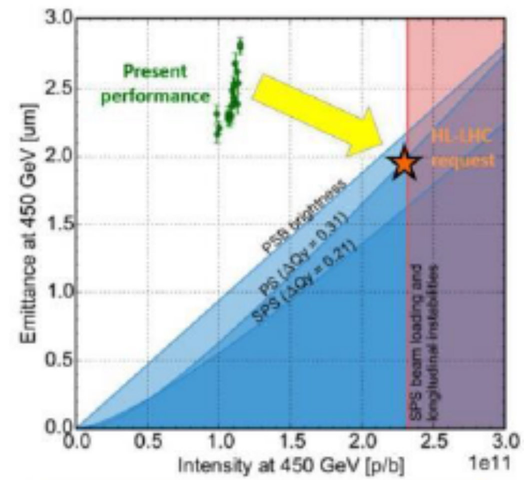
LIU project

Increase injector reliability and lifetime to cover HL-LHC run (until ~2040) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)
⇒ Improve radioprotection measures (shielding, ventilation…)

Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)
⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal



	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
LIU Baseline	2.3	2.2
HL-LHC	2.3	2.1

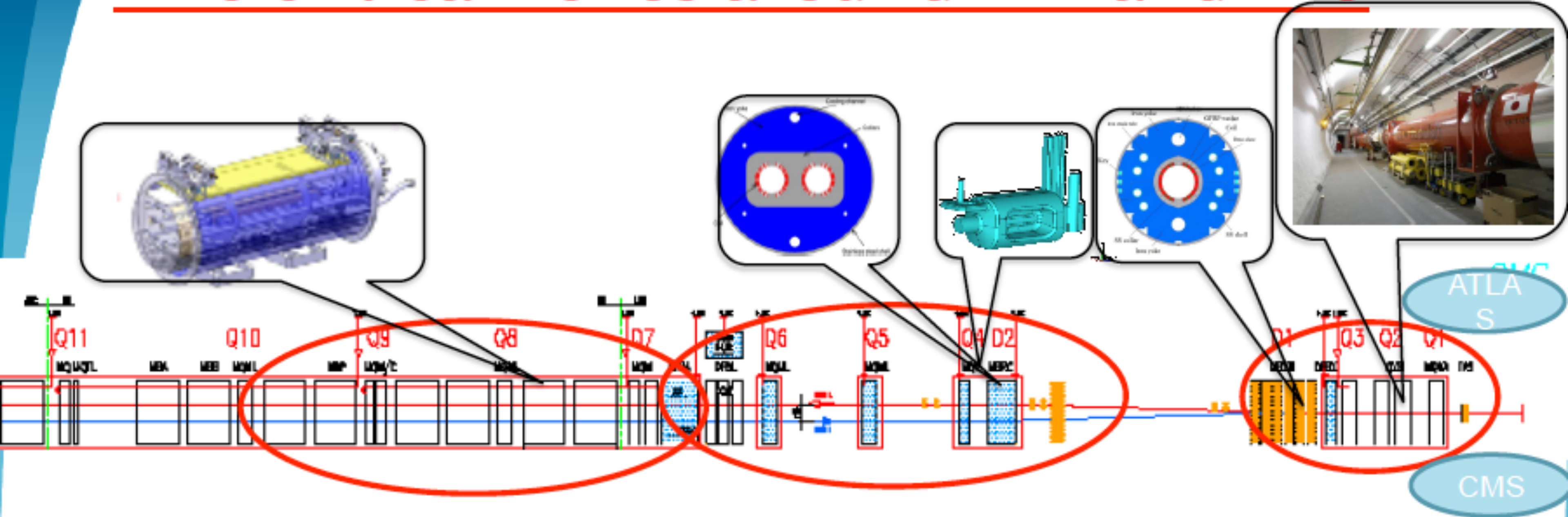
LHC Upgrade Goals: Performance optimization

- Luminosity recipe (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

- ➔1) maximize bunch intensities ➔ Injector complex
- ➔2) minimize the beam emittance Upgrade LIU
- ➔3) minimize beam size (constant beam power); ➔ triplet aperture
- ➔4) maximize number of bunches (beam power); ➔ 25ns
- ➔5) compensate for 'F'; ➔ Crab Cavities
- ➔6) Improve machine 'Efficiency' ➔ minimize number of unscheduled beam aborts

The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat in IR7: 11T Nb_3Sn dipole

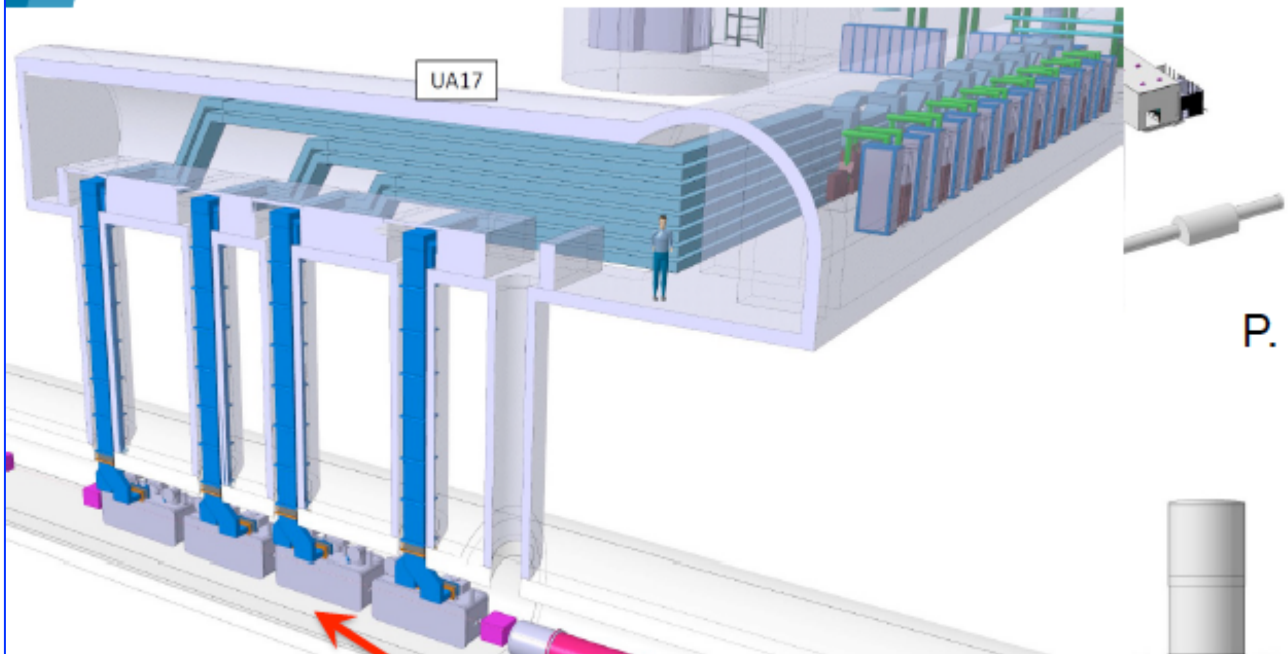
2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2

1. New triplet Nb_3Sn required due to:
-Radiation damage
-Need for more aperture

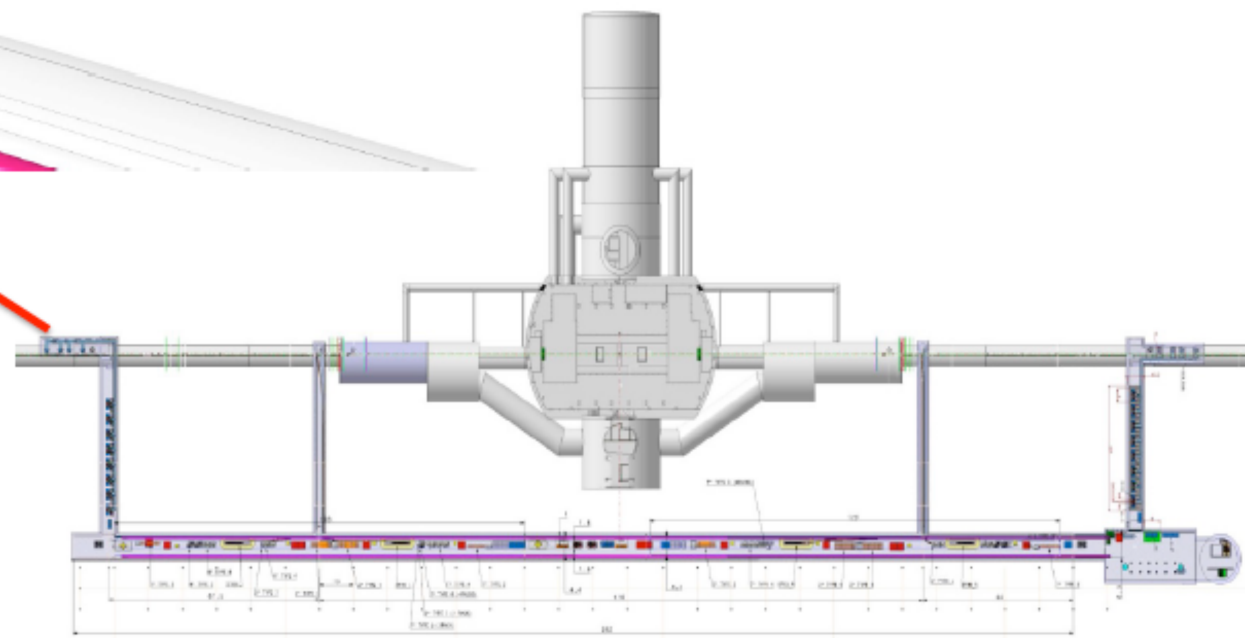
Changing the triplet region is not enough for reaching the HL-LHC goal!

→ More than 1.2 km of LHC !!
→ Plus technical infrastructure (e.g. Cryo and Powering)!!

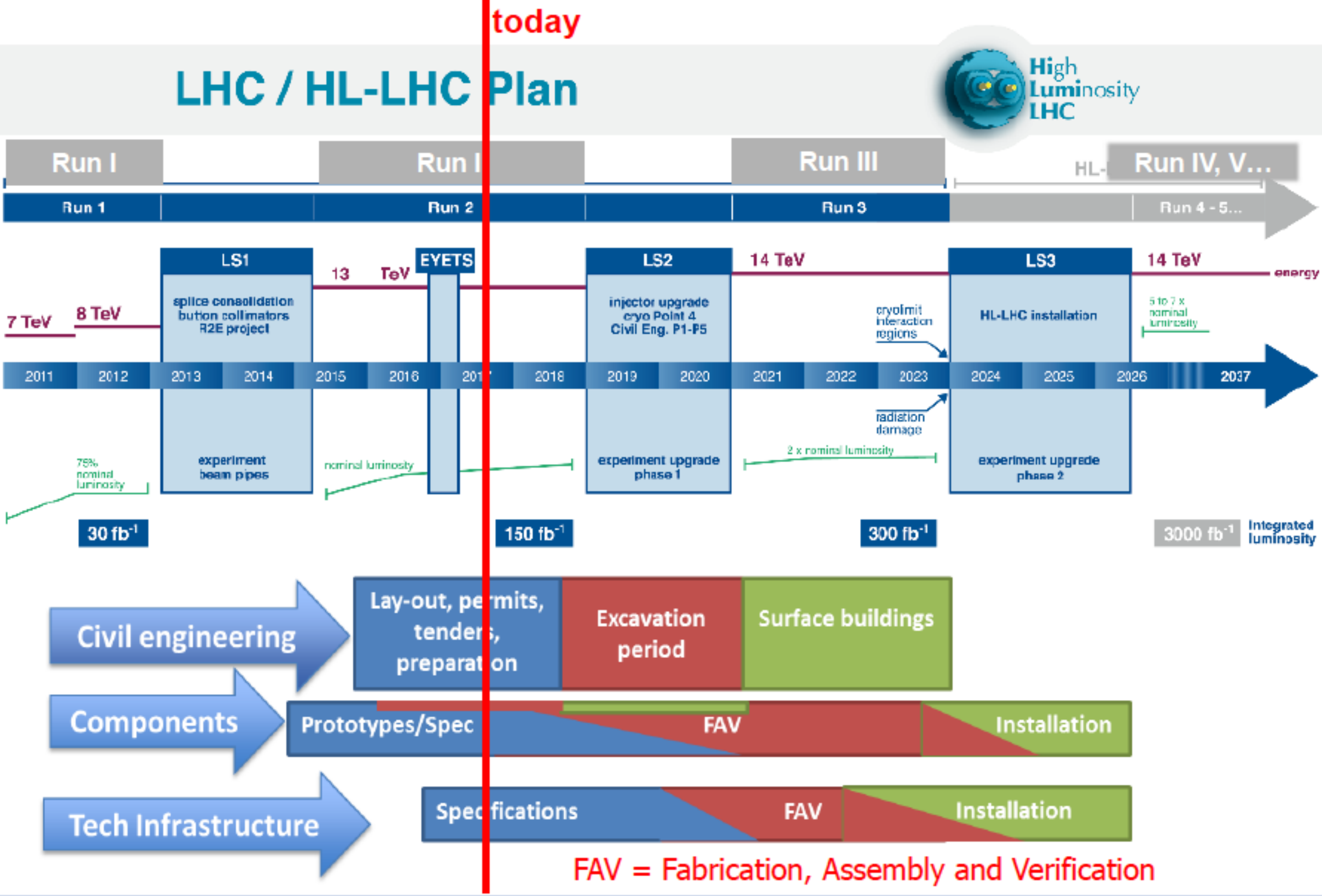
IR1 & IR5 Underground Civil Engineering:



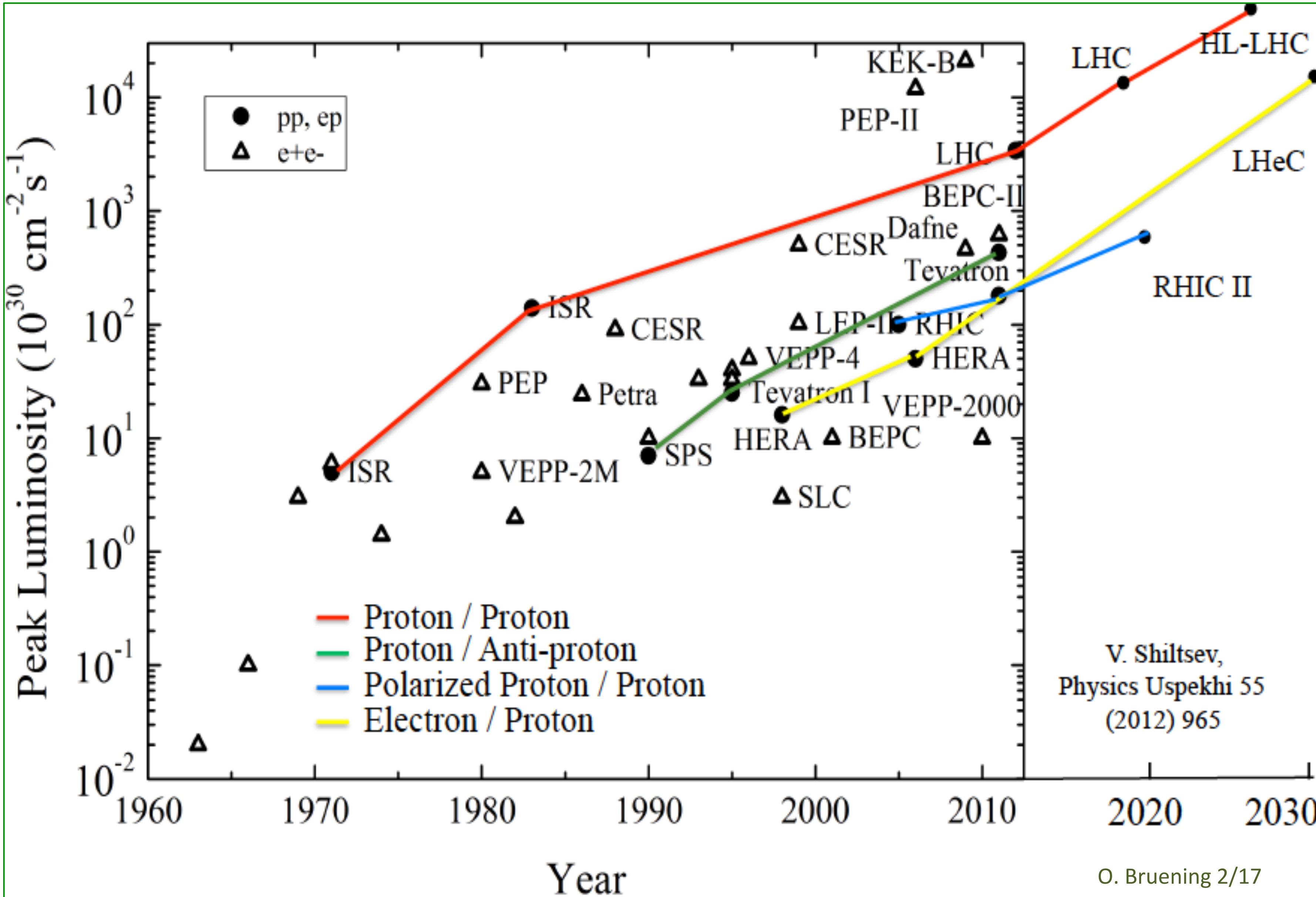
P. Fessia, HL-LHC TDR



LHC / HL-LHC Plan



Collider Luminosities vs Year (pp and ep)



O. Bruening 2/17

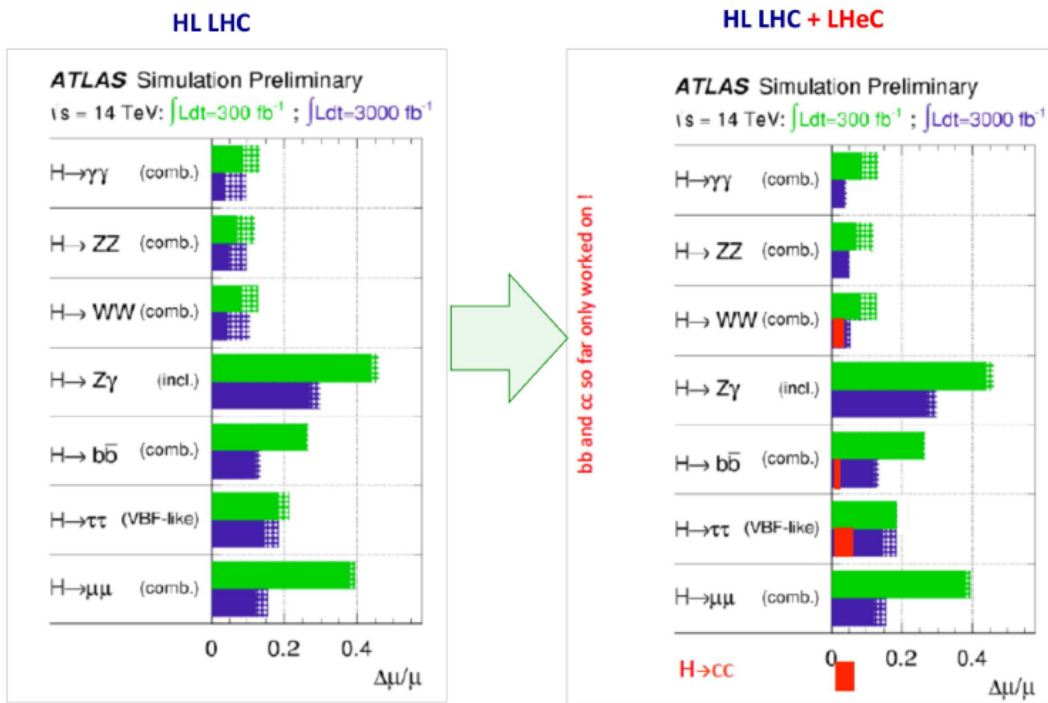
Parameters of CERN pp Colliders

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

F Zimmermann, June 2017

Precision Measurement Programme with HL LHC (High Precision with ep)

HIGGS PHYSICS AT THE LHEC
SUMMARY

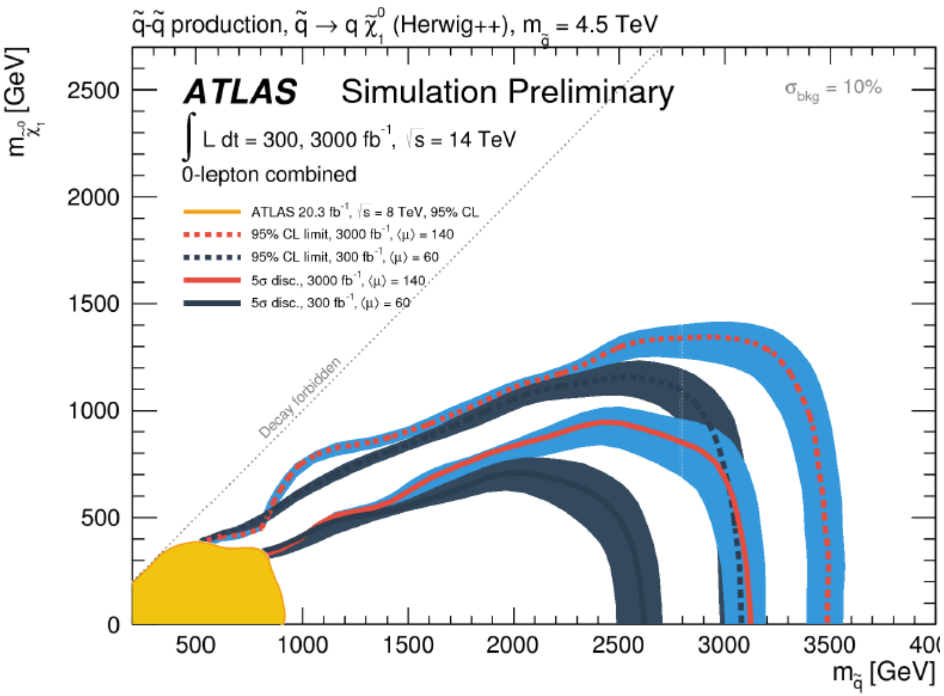


- GLUON FUSION AND W FUSION $\Rightarrow$ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

S.Forte ECFA 11/15

The exp. error on the Higgs cross section calculated with LHeC PDF is 0.3% → sensitive to mass

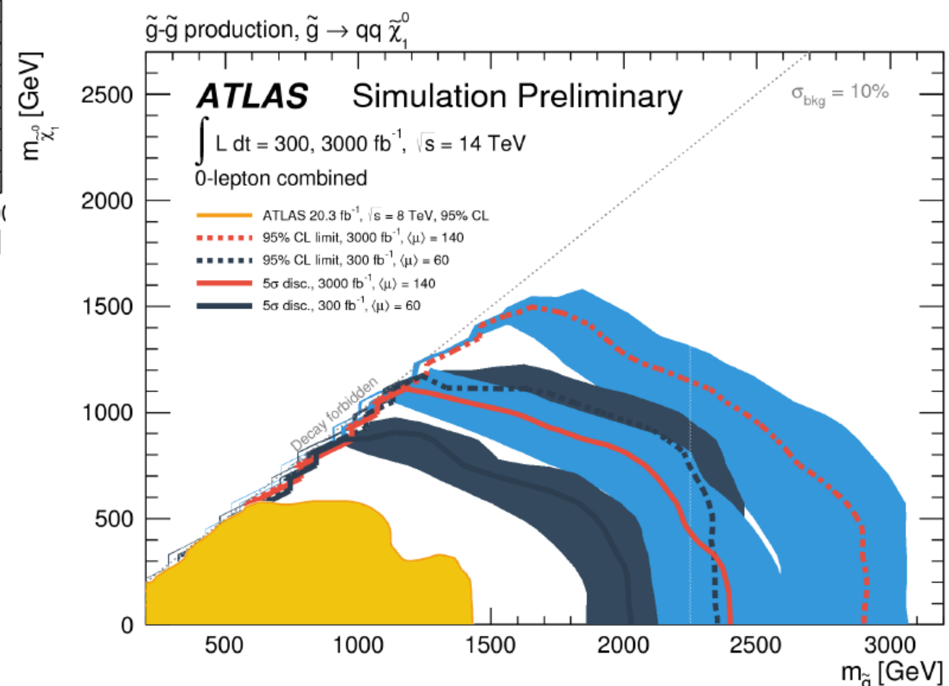
Extended Search Programme (SUSY?)



5σ up to ~3TeV squarks
5σ up to ~1.2 TeV stops
5σ up to ~1.3 TeV sbottoms
@ HL-LHC

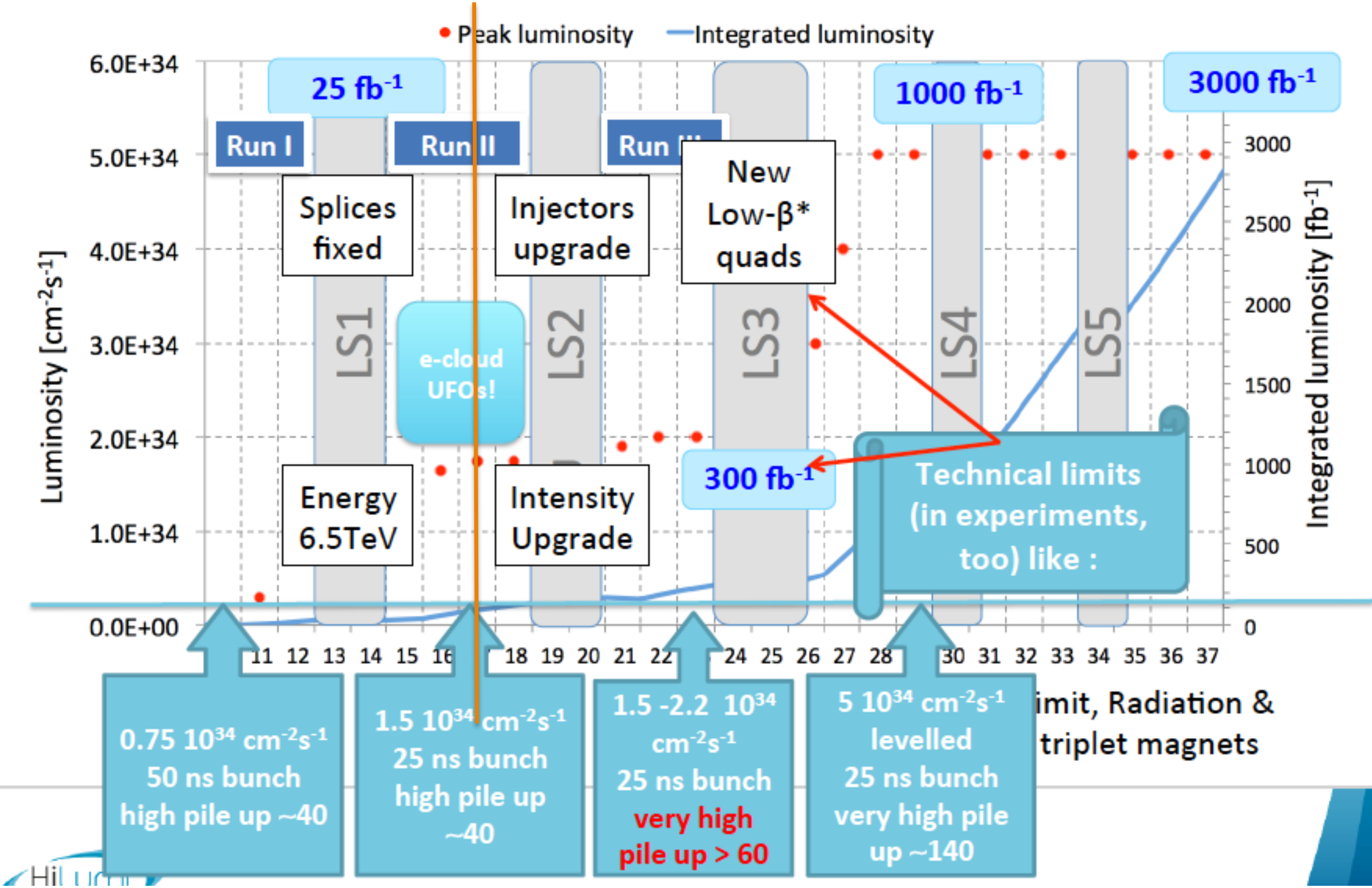
5σ up to ~2.5TeV gluinos
@ HL-LHC

ATLAS-PUB-2014-10



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

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



How can we make HL LHC sustainable if nature persists to hide new physics?

LHC Full Energy Exploitation:

- Operation beyond ultimate beam energy: E > 7.56TeV

Proposal to replace 1/3 of all MB magnets with 11T Nb_3Sn magnets

➔ Major interventions [opening of all MB interconnects]

➔ Not clear other magnets can be scaled up in energy e.g. insertion quadrupoles and triplet magnets

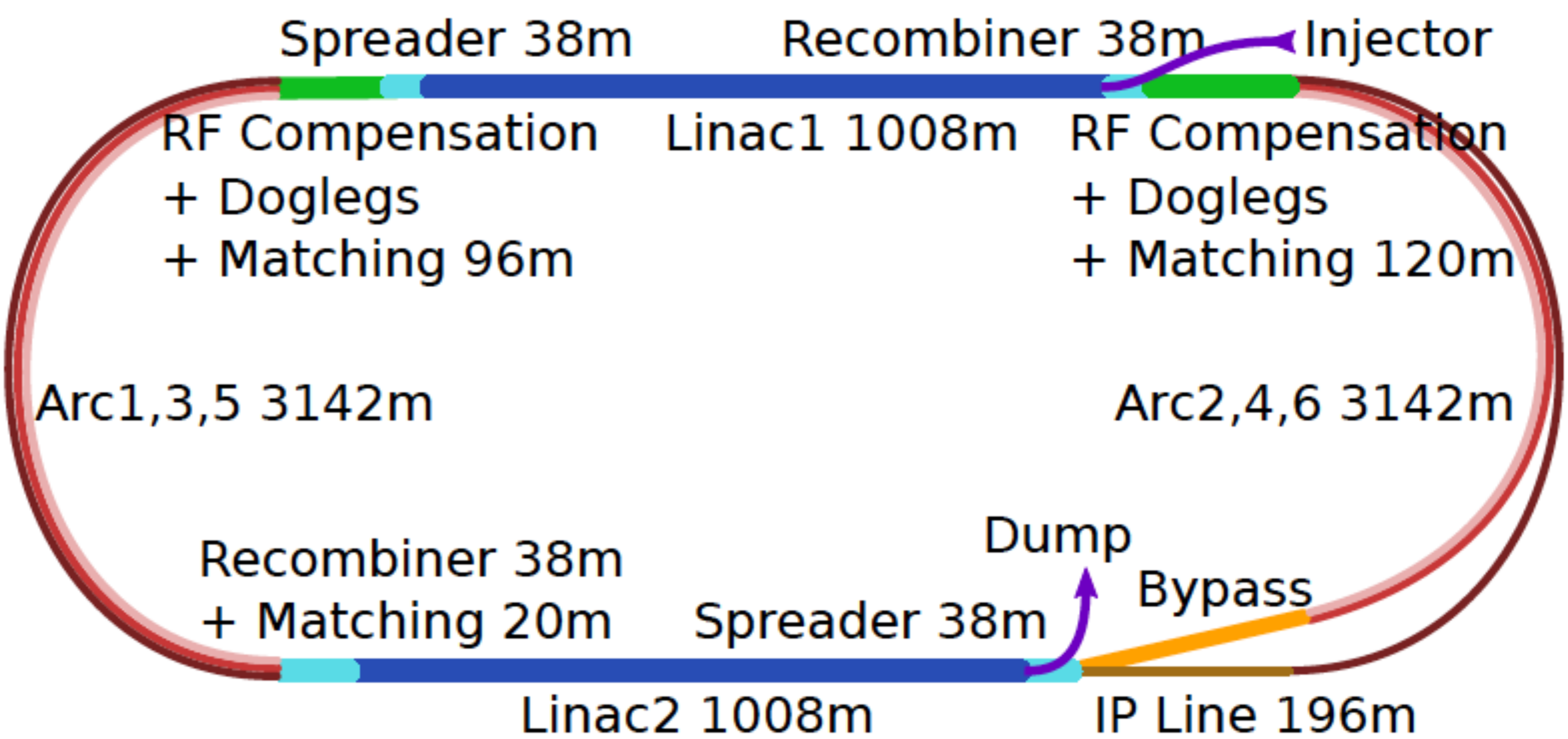
➔ Not clear other systems [e.g. beam dump system] can be easily upgraded

Study ongoing and results expected for end 2018 / beginning 2019

Could perhaps be envisaged as a second LHC upgrade at the end of the HL-LHC exploitation period. But investment [time and capital] will be substantial

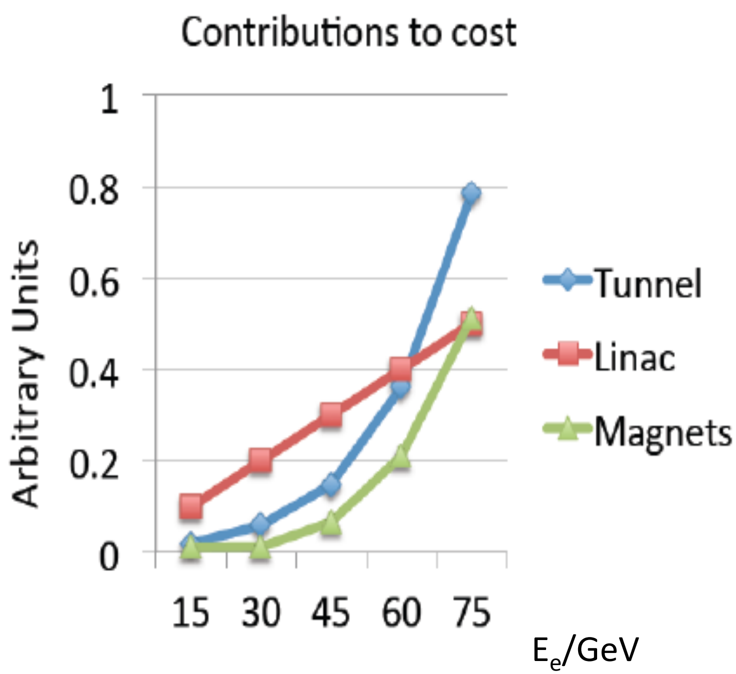
Add an Electron Beam (ERL) to LHC (+FCC)

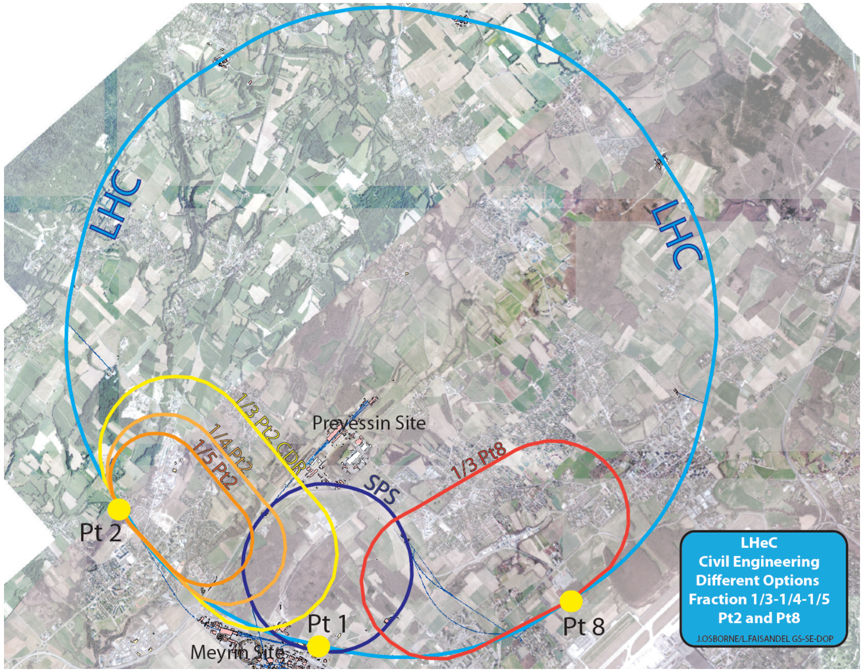
Conceptual Design Report (2012), Update for next European Strategy



Concurrent operation to pp, LHC/FCC become 3 beam facilities. P(e) < 100 MW
10^{34} luminosity and factor of 20 (LHC) extension of Q^2, 1/x reach vs HERA

Optimize Cost vs Physics and Time





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

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..

Five Major Themes of electron-hadron Physics

Cleanest High Resolution Microscopes

Joint ep and pp Physics

High Precision Higgs Exploration

Discovery Beyond the Standard Model

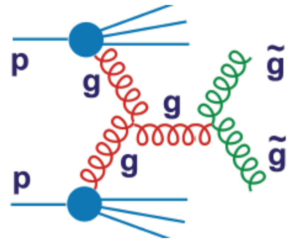
A Unique Nuclear Physics Facility

Empowering pp Discoveries

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

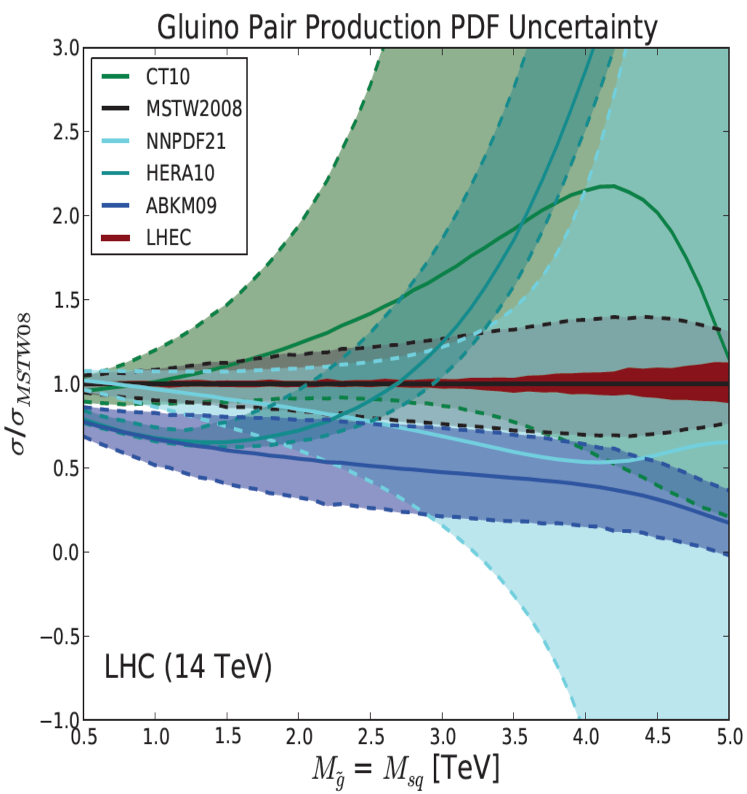
GLUON

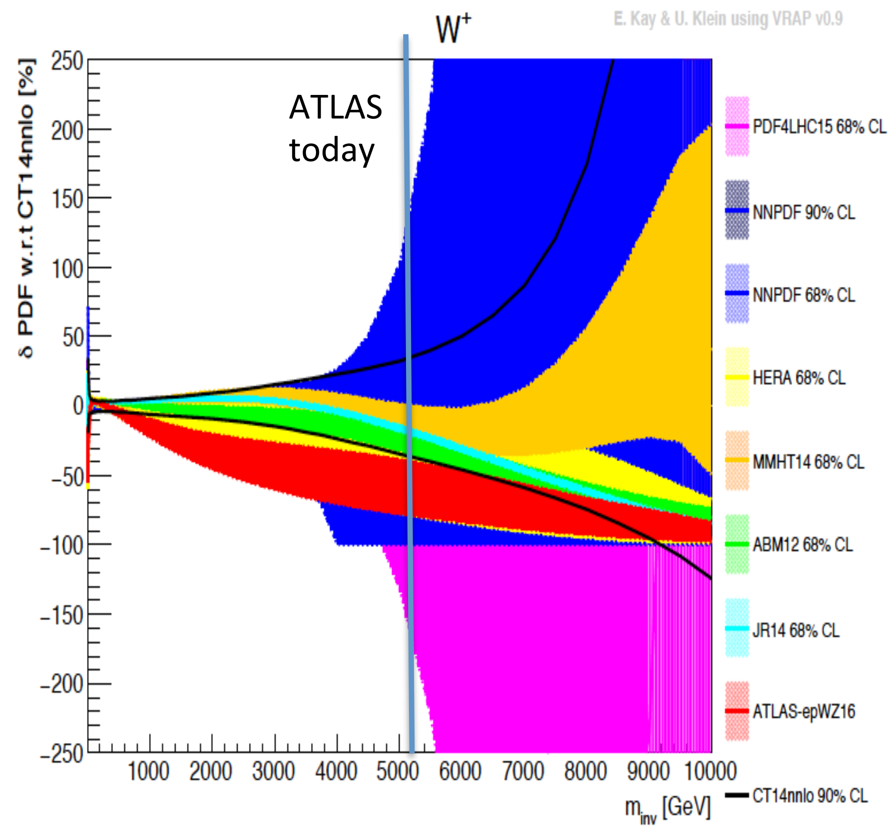
SUSY, RPC, RPV, LQS..



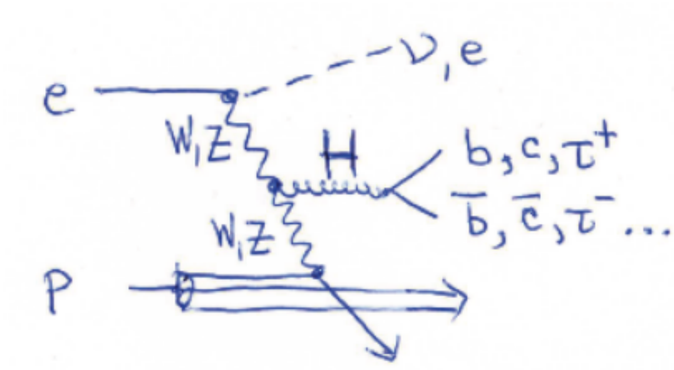
QUARKS

Exotic+ Extra boson searches at high mass





Higgs Physics with ep



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

Electroweak production, uniquely CC vs NC

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

No pileup, clean theory, challenging simulations

SM coupling measurement expectations

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

Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

DLHC (~35,000 H→bb events)

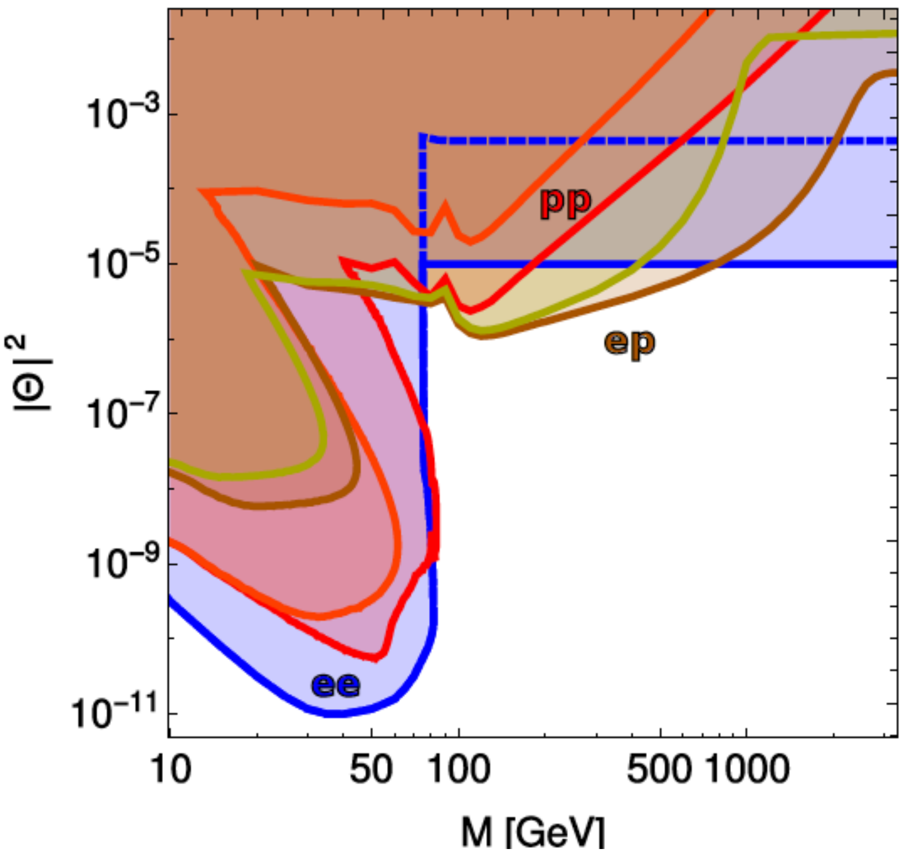
LHeC (~15,000 H→bb events)

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

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

Possible Discoveries Beyond SM with eh

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



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 …

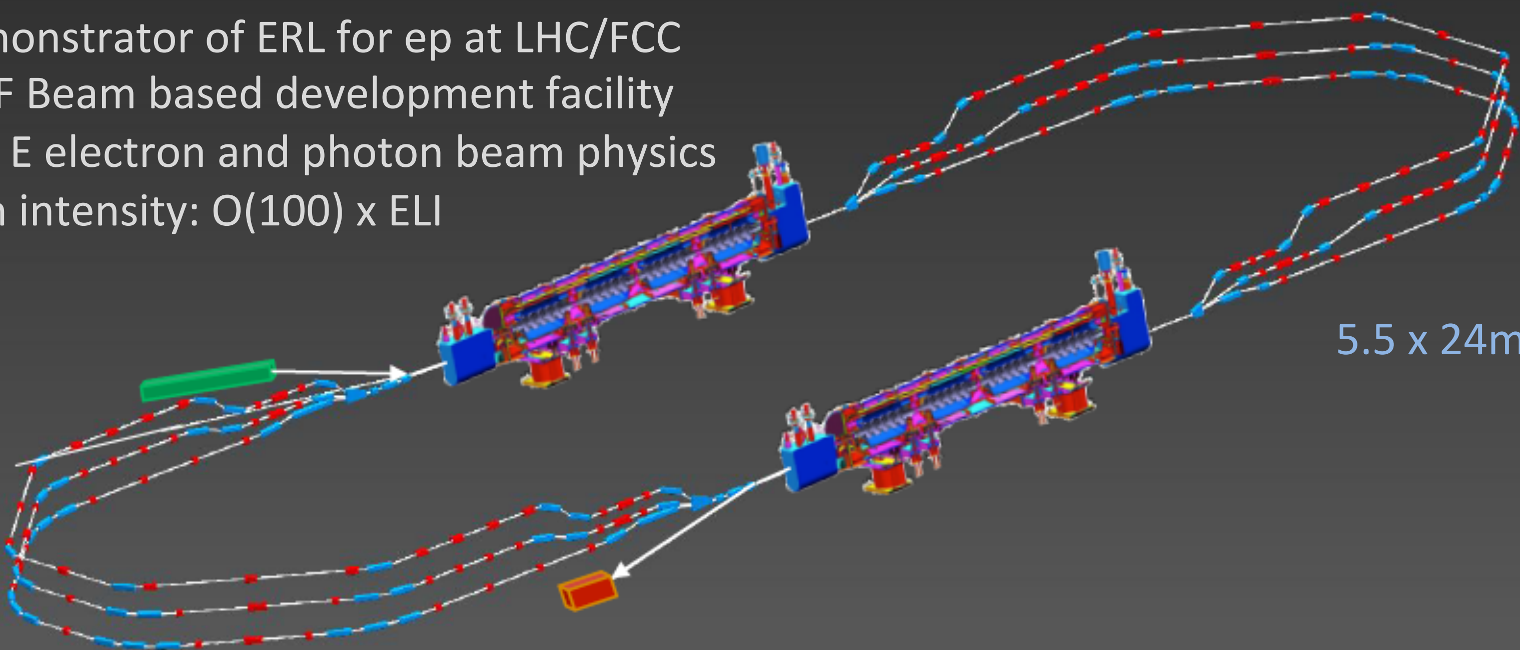
Powerful ERL for Experiments (ep,γp): PERLE at Orsay

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

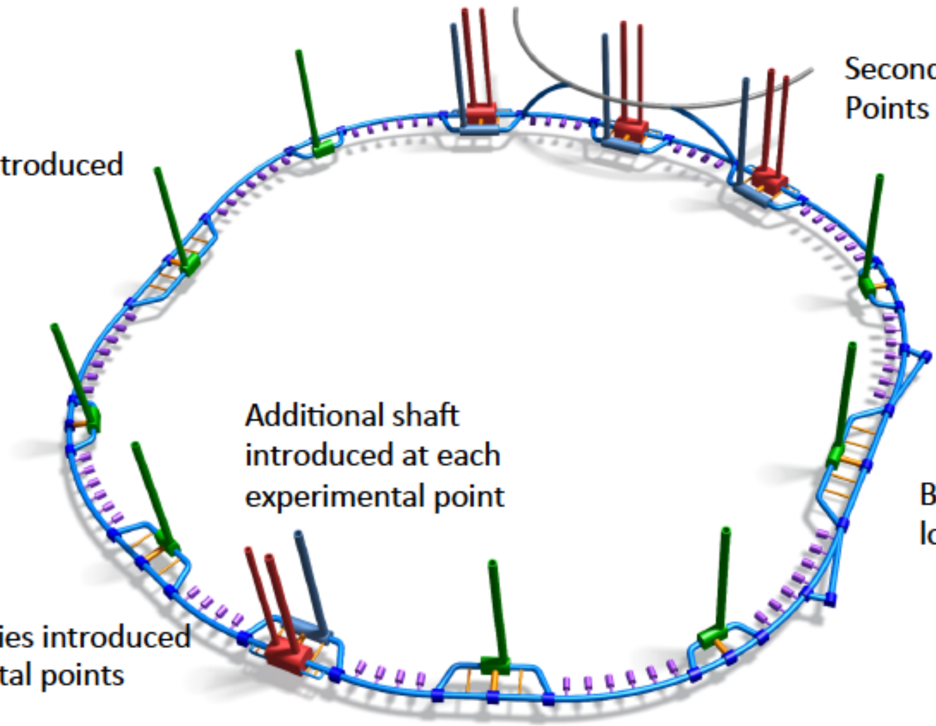


CDR to appear in J Phys G [arXiv:1705. 08783]

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

A.Bogacz

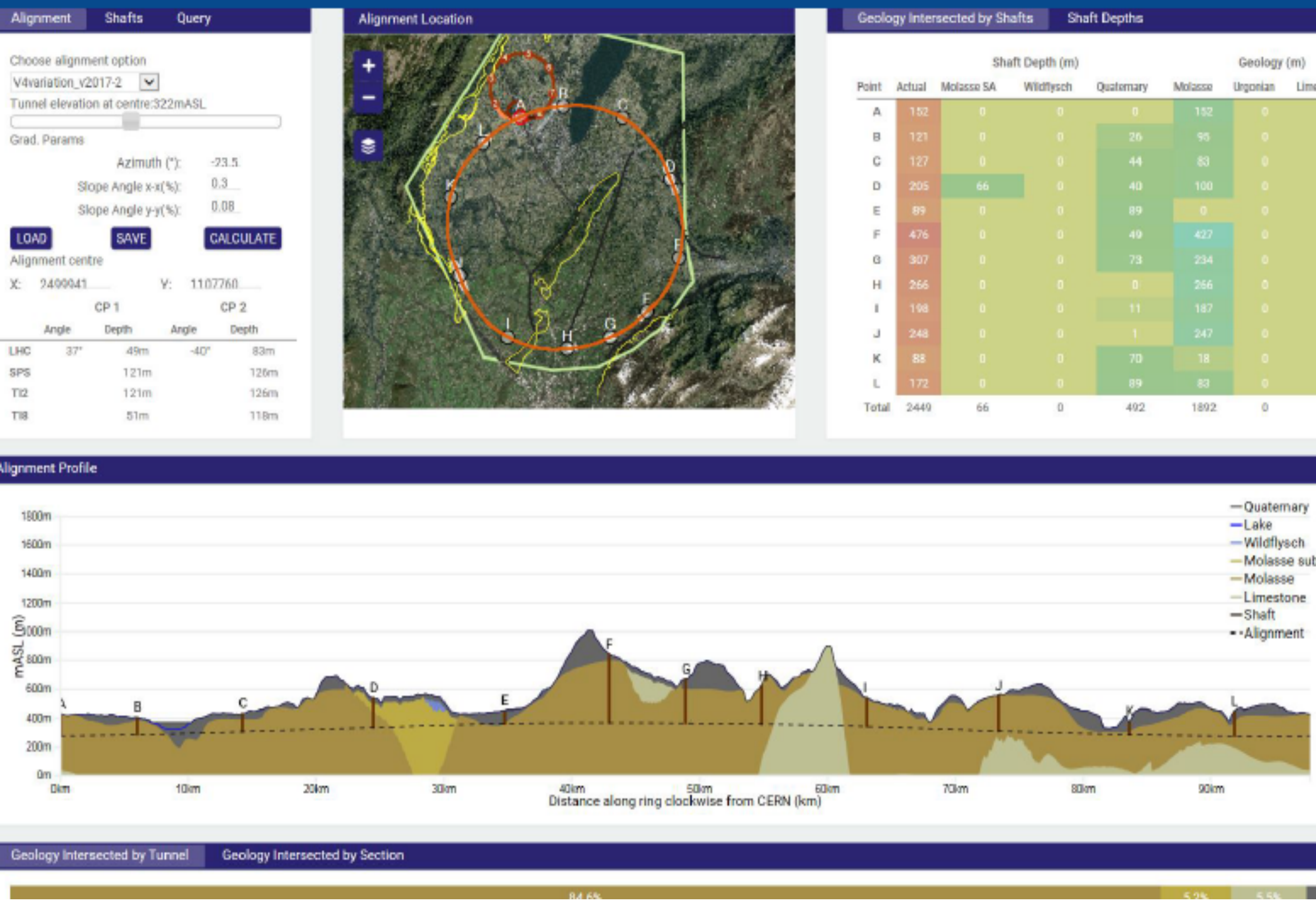
FCC



- First two sectors complete in 4 years, 11 months.
- Construction complete in 6 years, 5 months.

+ power, ventilation, logistics, cryogenics, turn around, safety, radioprotection, survey..

Implementation - new footprint baseline



Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc.

Tunneling

- Molasse 90%, Limestone 5%, Moraines 5%

Shallow implementation

- ~ 30 m below lakebed
- Reduction of shaft length and technical installations
- One very deep shaft **F** (RF or collimation), alternatives being studied, e.g. inclined access

Designing the FCC-hh

- synchrotron radiation power → associated cryogenics power (after various technological improvements and mitigation – higher beam-screen temperature etc.) limits maximum number of protons (e.g. 10^{15} p/beam or beam current of ~0.5 A for 100 km ring at 100 TeV c.m.)
- maximum beam current + "turnaround time" (FCC + inj.) constrain integrated luminosity
- maximum peak pile up ~1000 or ~200 limits peak luminosity at 25 ns and 5 ns bunch spacing, respectively
- maximum acceptable beam-beam tune shift 0.01 or 0.03 + optics (minimum β^* ~0.3-1.1 m) also limits peak luminosity

F.Zimmermann 1/17

The potential of a Future Circular Collider

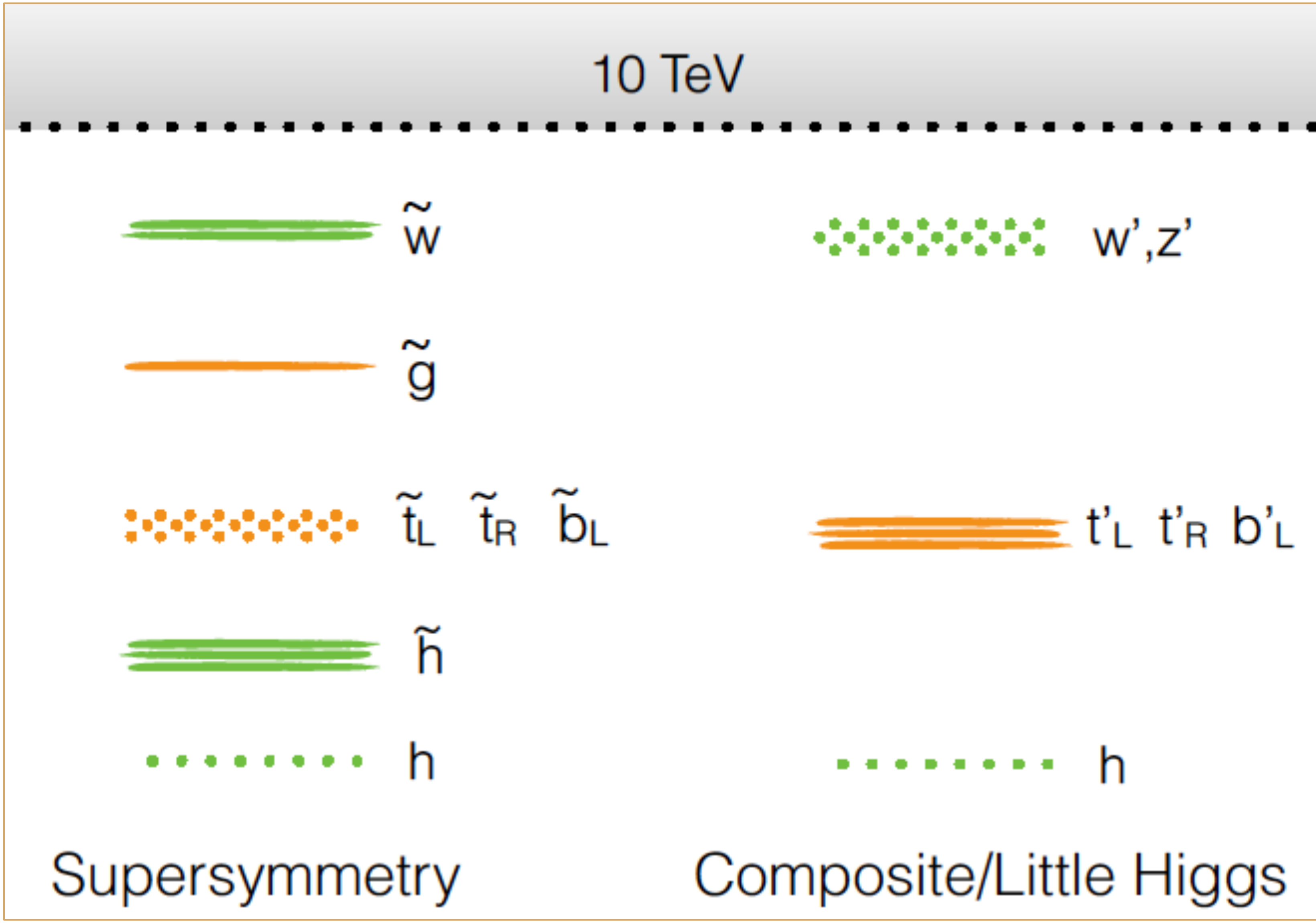
- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable precision and sensitivity

- Exploration potential:
  - mass reach enhanced by factor ~ E / 14 TeV (will be **5–7** at 100 TeV, depending on integrated luminosity)
    - *statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC*
  - benefit from both direct (large Q^2) and indirect (precision) probes

- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?

M Mangano 17.7.17

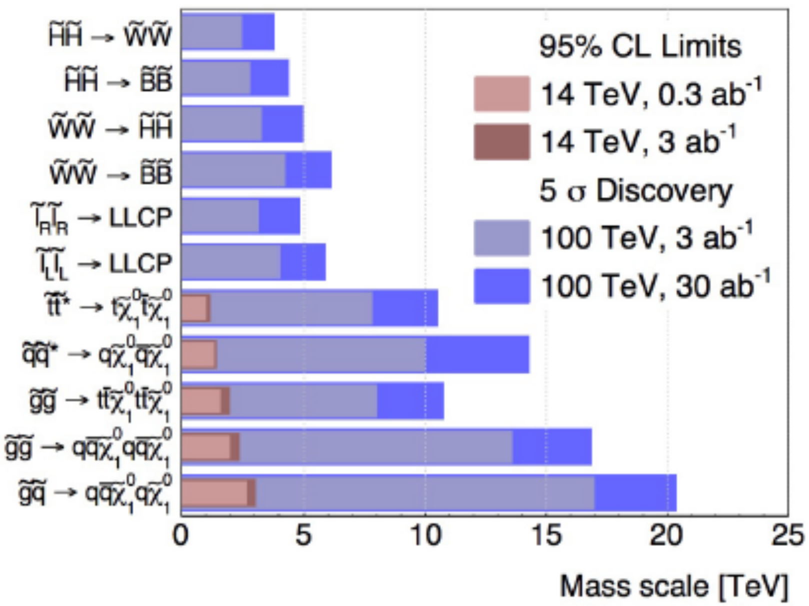
Theory to pave new ways

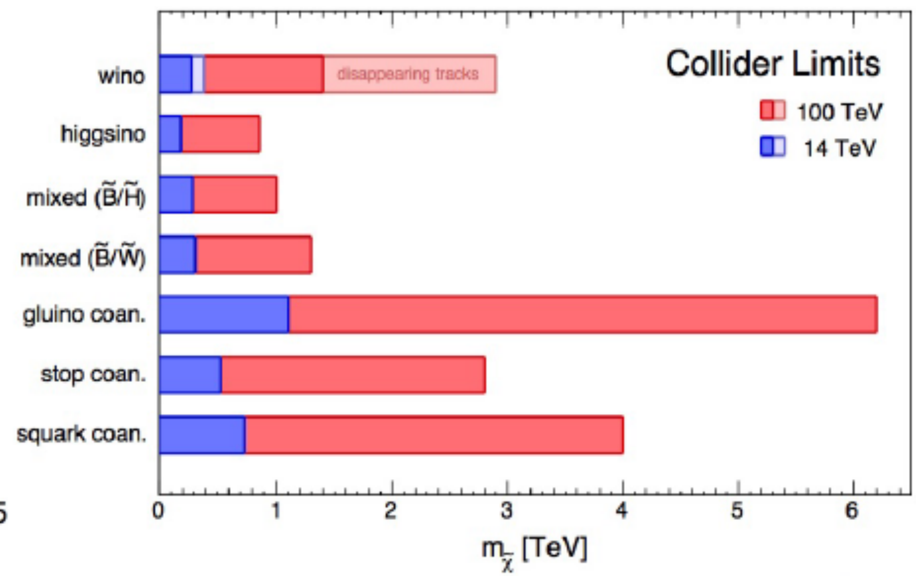


"Colored" Naturalness N.Craig Aspen 1/15

Direct Discovery Potential of the FCC (pp)

Eg SUSY and DM reach at 100 TeV





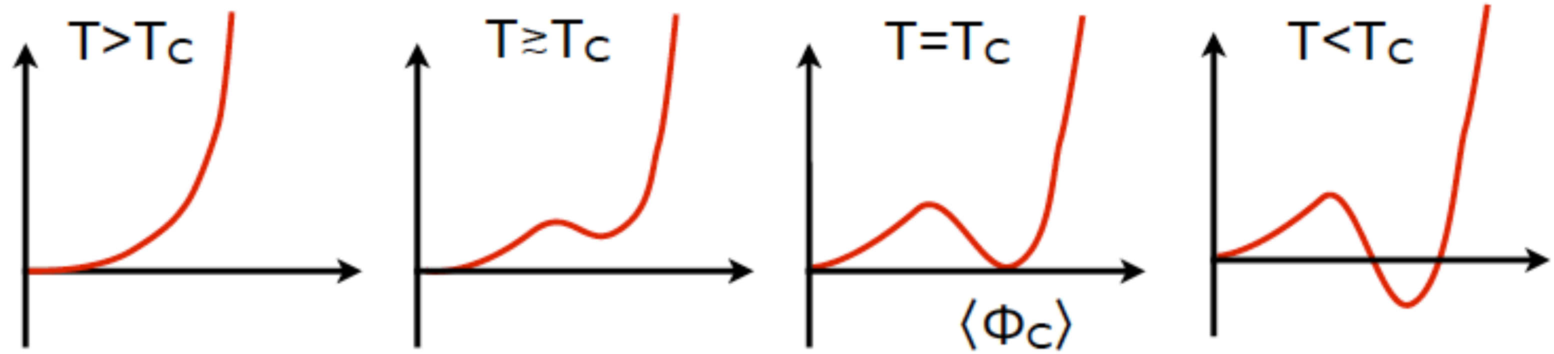
$$M_{\rm WIMP} \leq 1.8\ \text{TeV}\ \left(\frac{g^2}{0.3}\right)$$

First preliminary findings:

- possibility to find (or rule out) thermal WIMP DM candidates
- possibility to support (or exclude) EW baryogenesis

Searching for no-lose items..

Strong 1st order phase transition required to generate and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking



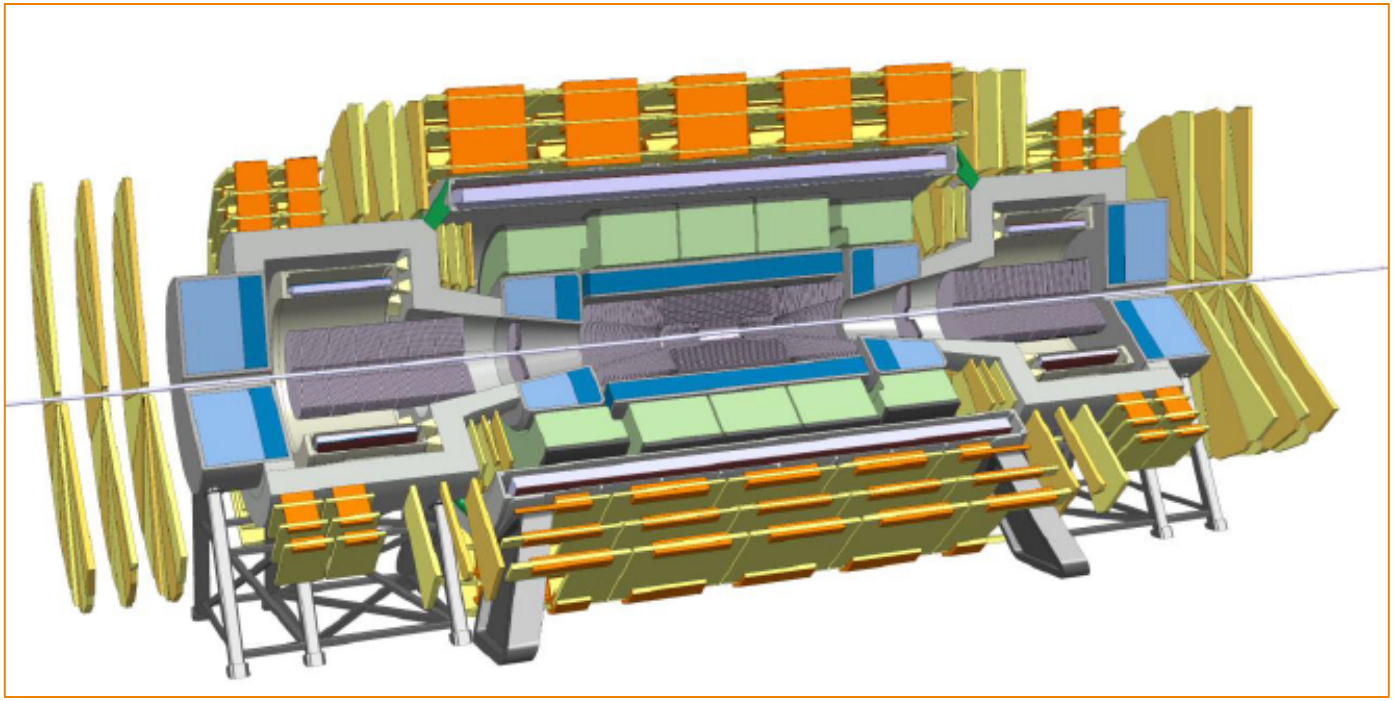
Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV.

Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

See D Curtain et al 1409.0005

FCC-hh Detector Study

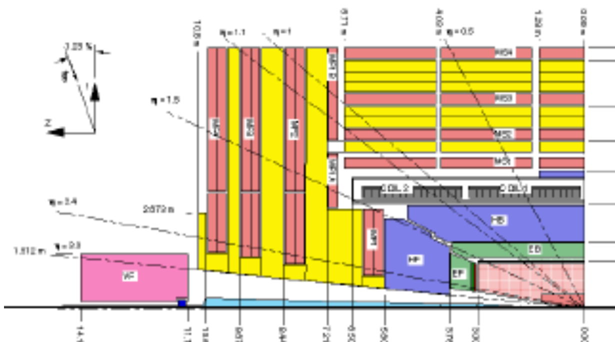


70m cavern
18m shaft
“only 1 BSF”

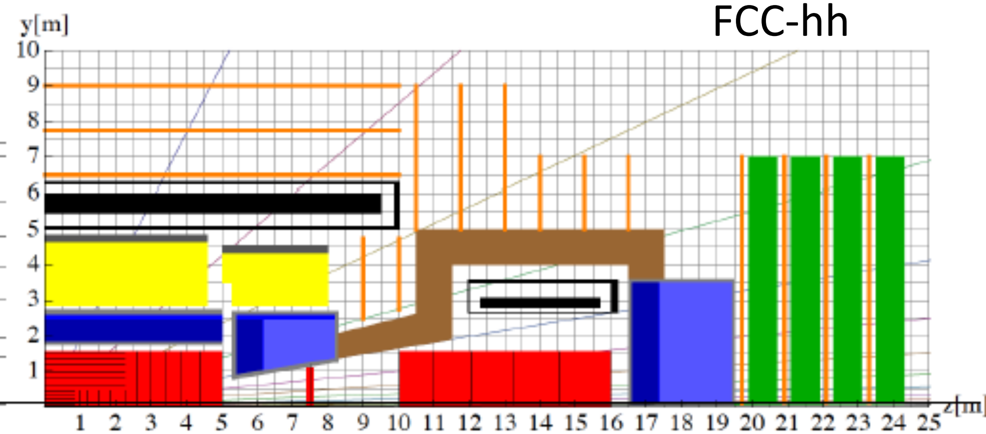
4T 10m solenoid
Forward solenoids
Silicon tracker
Barrel ECAL Lar
Barrel HCAL Fe/Sci
Endcap HCAL/ECAL LAr
Forward HCAL/ECAL LAr

W Riegler et al
June 2017

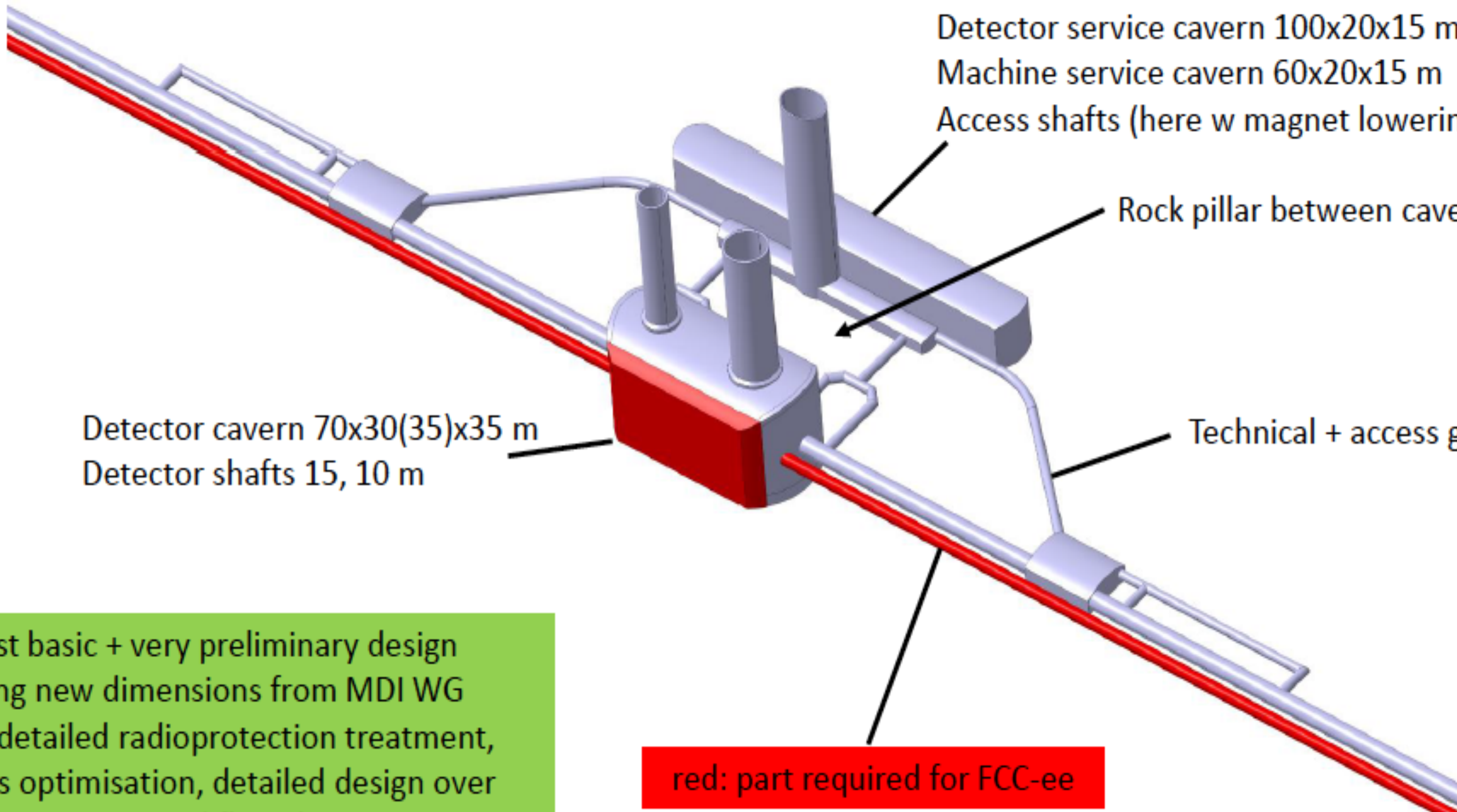
CMS



FCC-hh

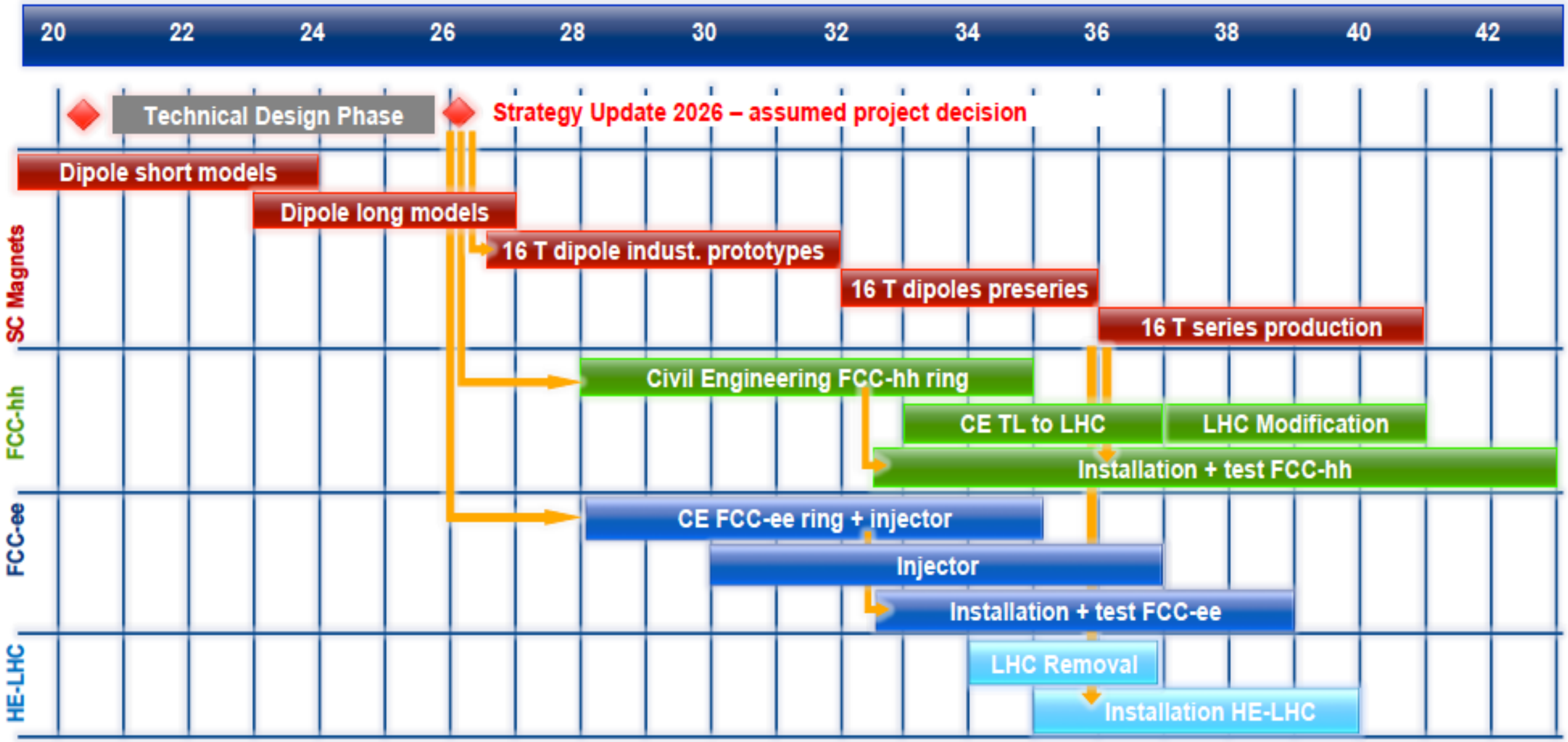


Underground structures



First basic + very preliminary design using new dimensions from MDI WG (w/o detailed radioprotection treatment, access optimisation, detailed design over several floors)

Draft Schedule Considerations



FCC-ee RF staging scenario

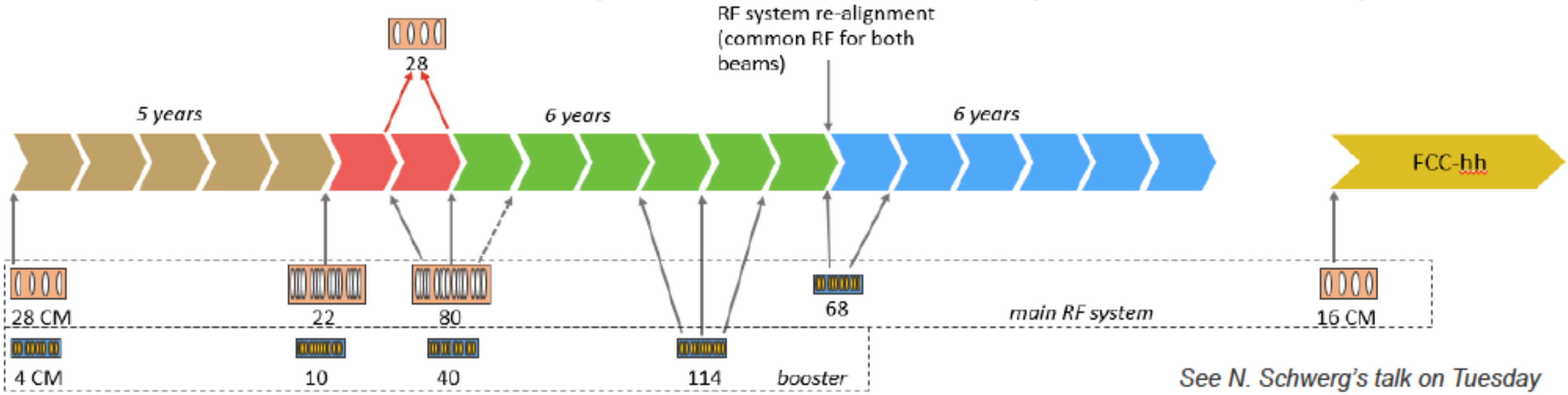
"Ampere-class" machine

	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities to cover all options FCCee & Booster:

- Installation sequence comparable to LEP (≈30 CM/shutdown)
- high intensity (Z, FCC-hh): 400 MHz mono-cell cav, ≈ 1MW source
- high energy (H, t): 400 MHz four-cell cavities, also for W machine
- booster and t machine complement: 800 MHz four-cell cavities
- Adaptable 100MW, 400MHz RF power distribution system



See N. Schwerg's talk on Tuesday

FCC-ee count on seminal luminosity for el.weak and only later H measurements
FCC-ee as "a first step" would defer the hadron-hadron collider to in +50 years..
If we were now at Lausanne 1984, the LHC started operating 2009: +25 years

Conceptual Design Report

1 – PHYSICS
Physics opportunities across all scenarios

2 Hadron Collider Summary

3 – Hadron Collider Comprehensive
- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment
- eh

4 Lepton Collider Summary

5 – Lepton Collider Comprehensive
- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment

6 High Energy LHC Summary

7 – High Energy LHC Comprehensive
- Accelerator
- Injectors
- Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

- Required for end 2018, as input for European Strategy Update
- Common physics summary volume
- Three detailed volumes FCChh, FCCee, HE-LHC
- Three summary volumes FCChh, FCCee, HE-LHC

he civil engineering studies : preferred location

Why is experimental point L preferred?

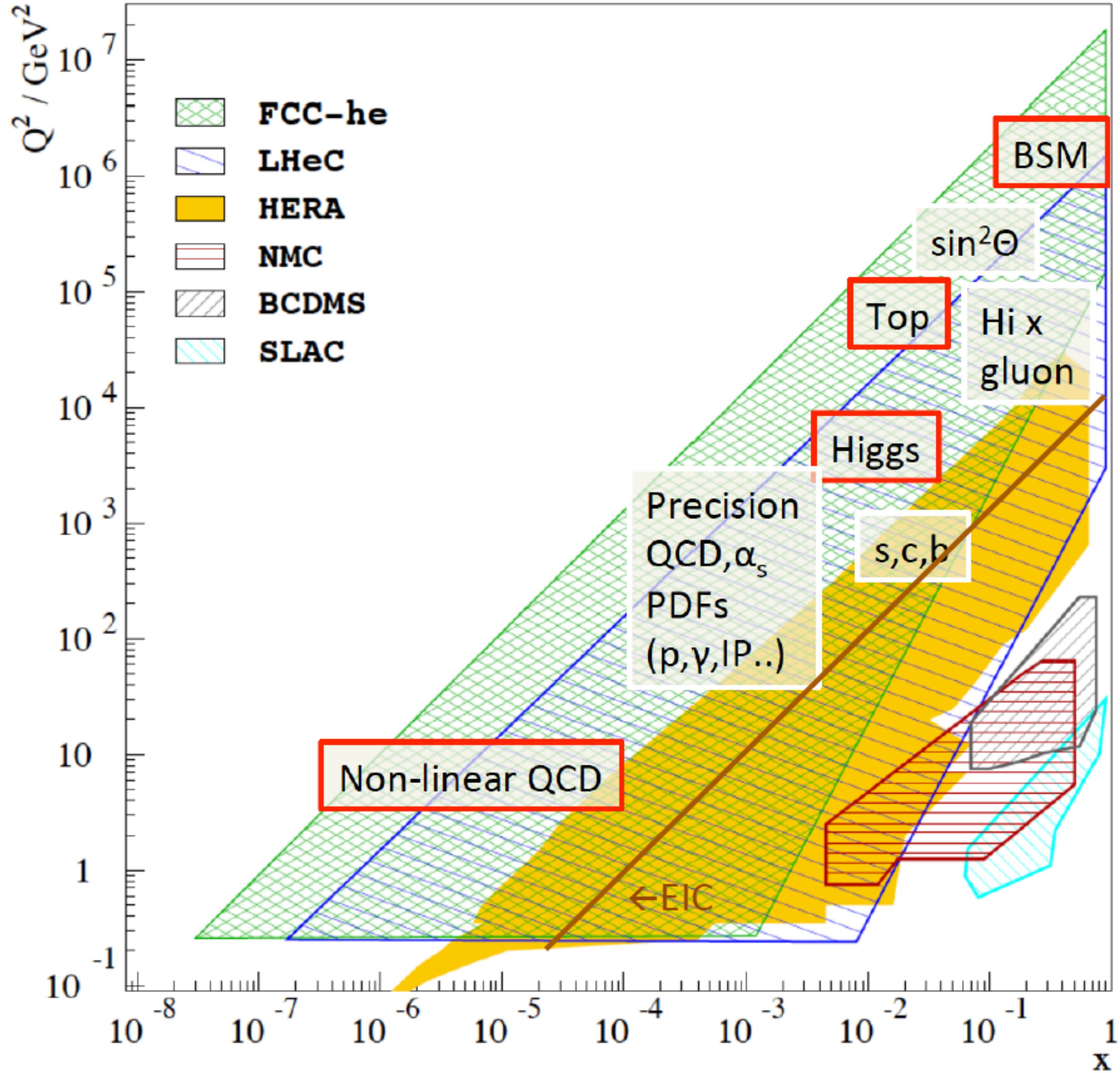
Positives:

- Low geological risk compared to other locations, anticipated tunnelling in molasse only.
- Close to current CERN site.
- FCC ring relatively shallow at this point, therefore shallower shafts.

Remaining problems:

- Potential clash with injection lines needs to be studied.
- Located inside the FCC ring so integration with other structures to be studied.
- Depth below Rhone to be evaluated.

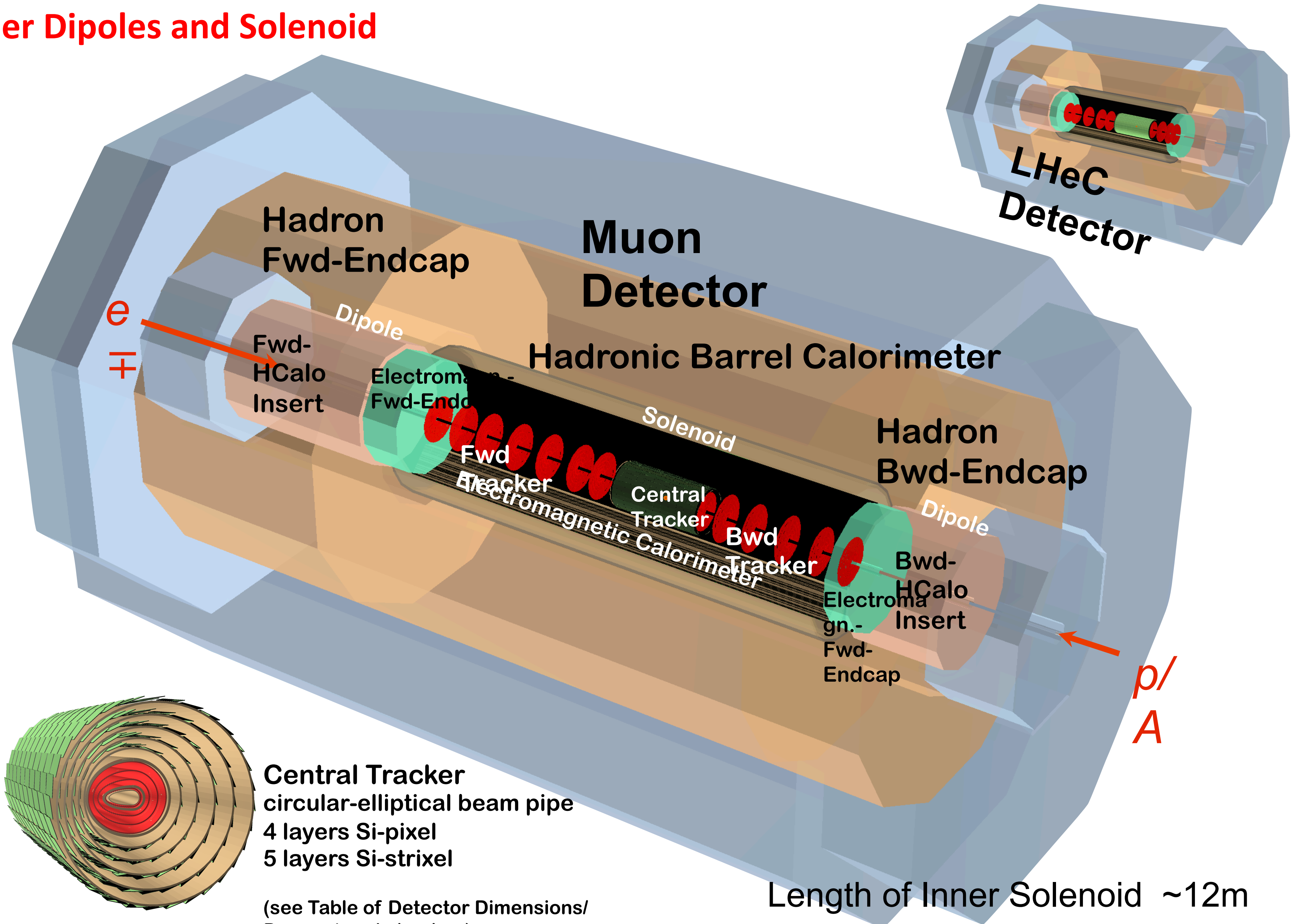
Civil engineering optimisation for FCC-he (J. L. Stanyard)



Q^2 / GeV^2
FCC-he
LHeC
HERA
NMC
BCDMS
SLAC
BSM
$sin^2Θ$
Top
Hi x
gluon
Higgs
Precision
QCD,$α_s$
PDFs
(p,γ,IP..)
s,c,b
Non-linear QCD
←EIC
x

FCC-he Detector Layout - Scaled Version of LHeC Detector

Inner Dipoles and Solenoid



HE LHC

many aspects extrapolated/copied from HL-LHC or FCC-hh

exceptions:

tunnel integration and magnet technology

- push for **compact 16 T** magnets (magnetic cryostat, shielding)
- **HE-LHC Nb_3Sn magnets must be bent** - 5 mm horizontal orbit shift over 14 m

arc optics

- higher dipole filling factor to reach energy target → different arc optics
- relaxed strength of quadrupoles and sextupoles → different arc optics

straights

- low-beta insertions, longer triplet than HL-LHC, β^* reach
- collimation straights, FCC-hh scaling not applicable,
  warm dipole length increases w.r.t. to LHC; new approach needed?!
- extraction straights – length of kicker & septum sections

injector

- determined by extraction system, physical & dynamic aperture, impedance…

Parameters of CERN pp Colliders

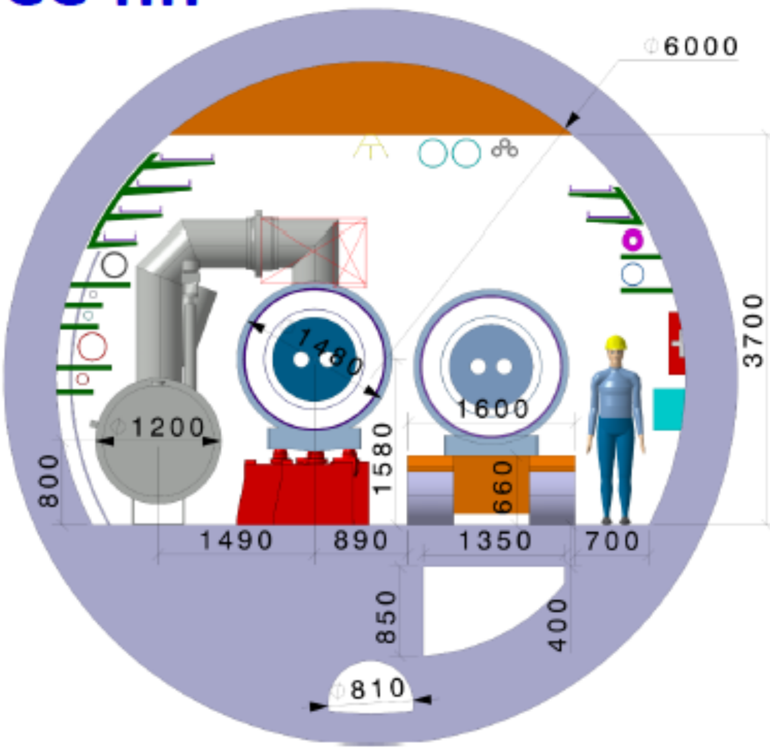
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

F Zimmermann, June 2017

tunnel integration

V. Mertens et al.

FCC-hh

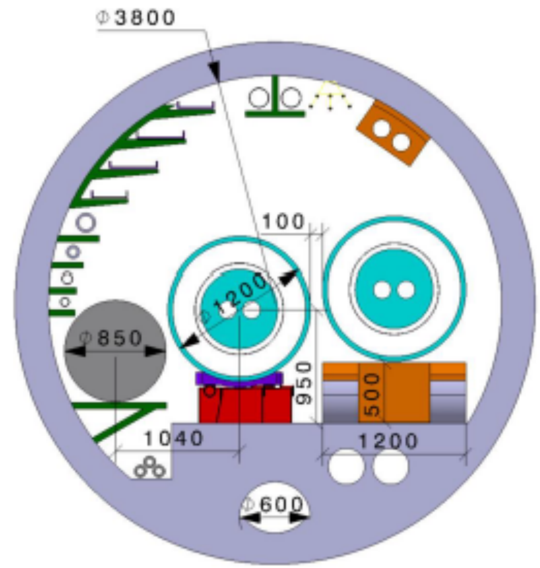


6 m inner tunnel diameter

main space allocation:

- 1200 mm cryo distribution line (QRL)
- 1500 mm installed cryomagnet
- 1600 cryomagnet magnet transport
- >700 mm free passage.

HE-LHC



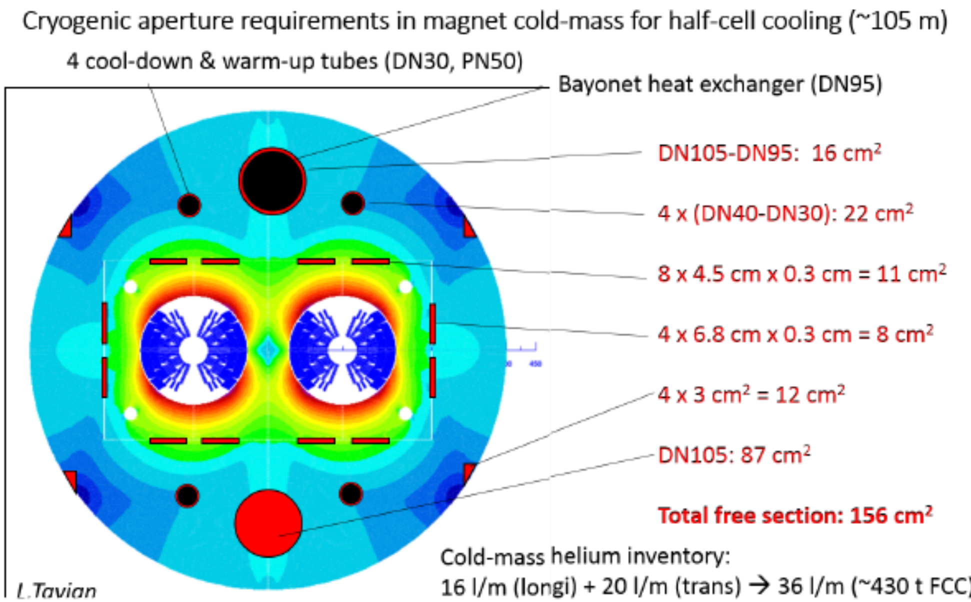
3.8 m inner tunnel diameter

main space allocation:

- 850 mm cryo distribution line (QRL)
- 1200 mm installed cryomagnet
- 1200 cryomagnet magnet transport

challenging

Nb_3Sn Magnet Development – 16 T



- How close is the best of today to the FCC specification (irrespective of $d_{effective}$ or RRR)?
- The best is actually not too far away: 1675 A/mm² versus 1850 A/mm²

Also strong SC RF developments and progress (cf E Jensen Berlin)

- The present cost is > 20 Euro/kAm @ 4.2 K, 16 T (FCC target is 5 Euro/kAm)
- Large production (~7-10 kt for FCC-hh, 2-3 kt for HE-LHC)
  - ITER : ~500 tons in total, 100 tons/year, 8 companies
  - HL-LHC : ~ 20 tons in total, initially 2 companies, now 1 company)

Development

Collaboration agreement with **KEK- Japan.** Development of Nb_3Sn wire at **Jastec** and **Furukawa**

Collaboration agreement with **KAT – Korea**. Development of Nb_3Sn wire.

Collaboration agreement with **Bochvar Inst.– Russia**. Development of Nb_3Sn wire at **TVEL**

See also Luca Bottura summary at Berlin FCC

From D Tommassini (June 17)

HE LHC Time Schedule

Remark

We recall that the US Nb_3Sn conductor program started in 1999 aiming at the same target cost as the one set for the FCC. After 5 years the program stopped: the target cost was not achieved, remaining about three times higher than the target (presently we are exactly in the same situation, with no advancement with respect to the outcome of that US program). However the program was very successful and resulted in practically doubling the critical current and decreasing the cost of the conductor by more than a factor of 2.

This is to say that a vigurous R&D program, probably over 5-10 years, will be necessary before a massive production for a HE-LHC or a FCC can start.

D Tommassini (June 17)

Production of HE LHC Components: O(10) years.

Injector: Currently scSPS disfavoured and SPS 450 GeV considered. 80 years old by 2050

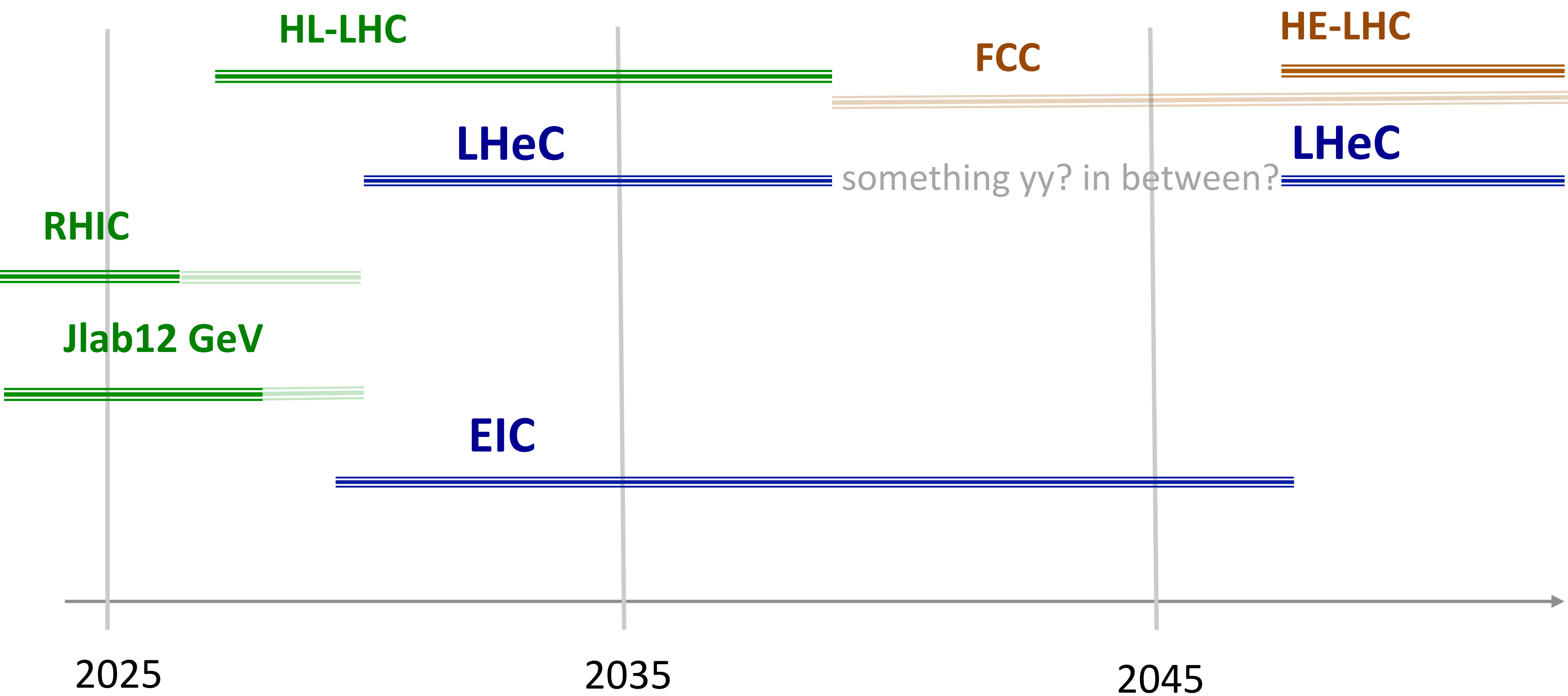
Detectors: ATLAS and CMS at twice the proton beam energy − major upgrades to study

HL LHC: $3ab^{-1}$ estimated duration: until 2038 − 2040

Dismantling LHC, Installing HE LHC O(10) years: **HE LHC in 2050** maybe a bit earlier.

Total cost O(5) BSF: 25 years of 200 MSF. Magnet cost crucial to reduce. **Physics ?**

Projected Timelines for Future ep/eA Colliders



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

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

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

Luminosity for LHeC, HE-LHeC and FCC-ep

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

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

ep at CERN: 1000 times the luminosity of HERA
< 100 MW wall plug

Summary

A summary is personal and not straightforward. CERN has major opportunities and skills to drive the pp energy frontier higher + BSM. This can be substantially enriched by adding an ERL electron beam, at relatively low cost, for concurrent pp+ep (as well as AA+eA) operation, with the LHC, the HE LHC and the FCC.

The FCC appears as a vision while HL LHC is the next program. Working on the vision is important (infrastructure, magnets, RF, detectors…). We shall invest in theoretical physics for without convincing guidance (no loose no-lose..) one will not be able to attract the world's attention + means for making that vision real.

In between, the HE LHC offers a next major step, based at large on FCC technology. That step is neither easy nor cheap and will be real hardly before 2050 unless the HL LHC programme will be substantially shortened, with an overriding justification..

Many thanks to many colleagues: M Benedikt, S Bertolucci, O Bruening, G Dissertori, E Jensen, P Kostka, U Klein, M Mangano, V Radescu, D Schulte, H Schopper, A Stocchi, F Zimmermann, + many others, the LHeC + FCC teams, my colleagues at Liverpool and on ATLAS − all who join, tolerate or/and support thinking about the future.

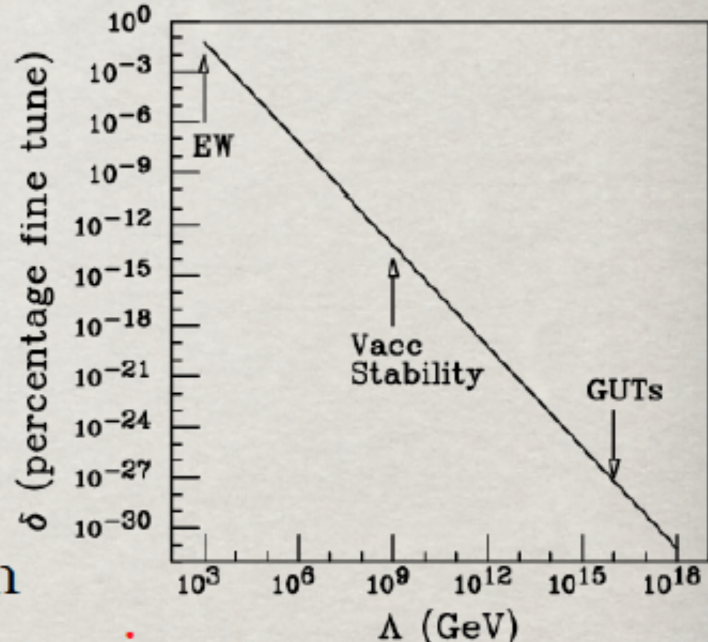
Sources and Events 2017

FCC Physics Week January, FCC at Berlin May, IAC FCC Review June, LHeC/FCCeh workshop September 11-13 (CERN), HL/HE LHC Workshop November 2017 .. 2018 (CERN)

title

T Han Aspen

- With the Higgs discovery, the SM is healthier than ever, valid to a scale up to Λ ~ ?
  But the Higgs sector fine-tuned δ :
- VLHC will take the lead for searches:
  $\tilde{g}, \tilde{t}, \tilde{b}, \chi^{\pm,0}$, …$H^{\pm}$, A^0; $W^{\pm\prime}$, Z' …



The *top, W, Z, H* may hold the key for discovery!

- Searching for new physics starts from understanding old physics in the new regime:
  - *top, W, Z* may behave as partons to produce new heavy states;
  - *top, W, Z, H* may serve as new radiation sources; and may help reveal new heavy states.
  - Thus, need precise understanding of the dynamics/kinematics

Future SUSY

Assuming a massless LSP

Model	Limit [TeV]	Discovery Reach [TeV]	
	8 TeV	14 TeV	100 TeV
	20 fb^{-1}	3000 fb^{-1}	3000 fb^{-1}
$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$	1.4 (ATLAS)	2.3	**11**
$pp \to \tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$	1.4 (ATLAS)	2.0	**6.0**
$pp \to \tilde{q}\tilde{q}^* \to q\tilde{\chi}_1^0 \bar{q}\tilde{\chi}_1^0$	1.0 (CMS)	1.0	**7.8**
$pp \to \tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0 \bar{t}\tilde{\chi}_1^0$	0.7 (CMS)	1.2[a]	**6.5**

[a] ATLAS projection

M. Hance Aspen 15

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

For the FCC to be built we need overriding reasons which the society can accept for the project to go ahead. Magnets and theory are the main challenges of the FCC.

Report of the SSC Collider Dipole Review Panel

June 1989

SSC-SR-1040

G. Voss
Deutsches Elektronen-Synchrotron, DESY
Hamburg, Germany

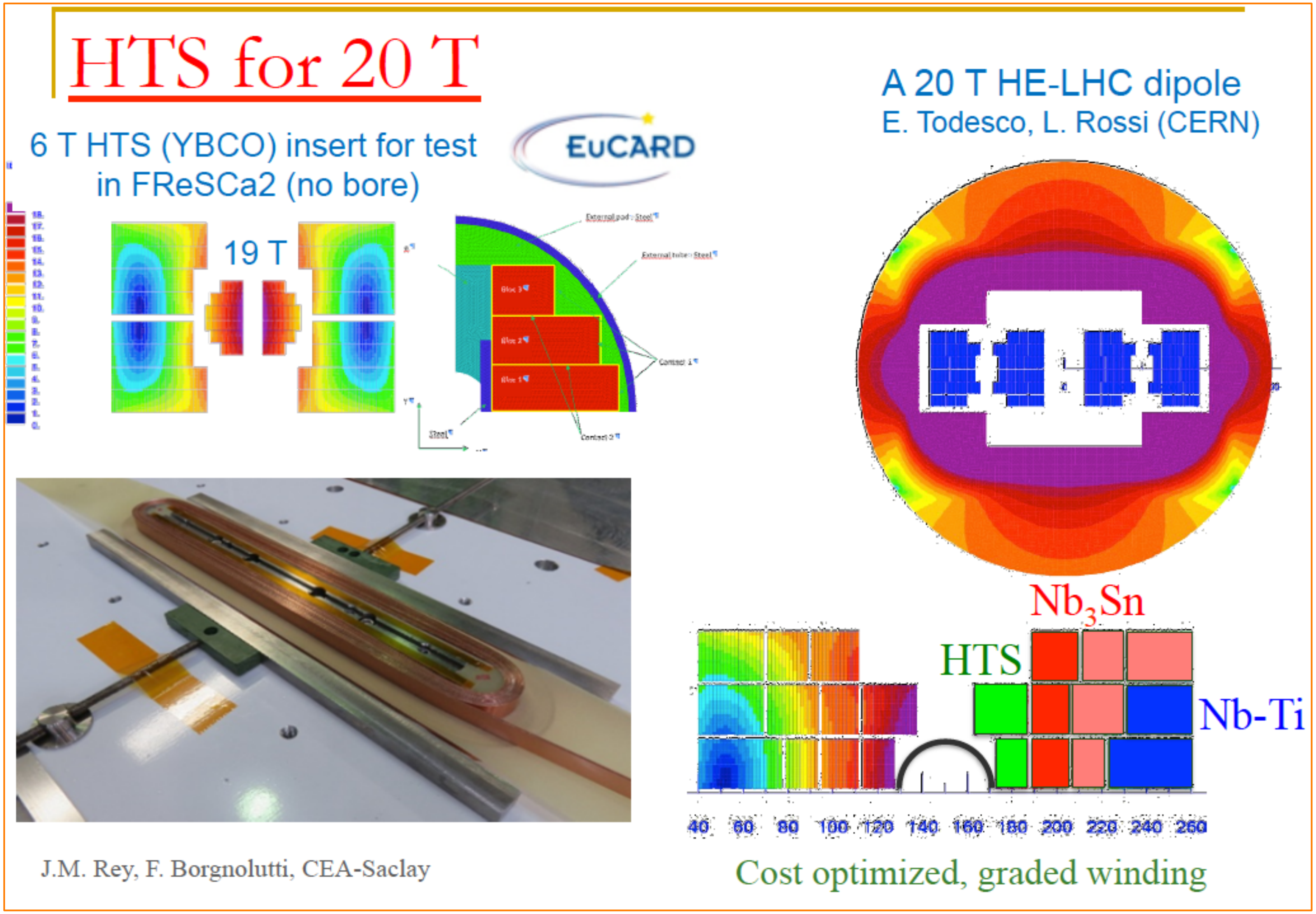
and

T. Kirk
SSC Central Design Group*
c/o Lawrence Berkeley Laboratory
Berkeley, CA

design. The evaluation was based upon information provided in the scheduled topic presentations, comments and discussion from various Magnet Program personnel, and a set of documents provided by the SSC Magnet Systems Division head: *SSC Magnet R&D Plan 1988*, edited by E. L. Goldwasser; *Development Status for SSC Magnets*, December 1988; *SSC Magnet R&D Plan Update*, January 1989; and the SSC Magnet Program presentations given at the DOE SSC Annual Review, 30 January 1989.

The program goal is to provide a mature design for a 17-m-long magnet that is capable of producing a uniform dipole field with an intensity of 6.6 T at a temperature of 4.35 K and which satisfies all system requirements but is not yet optimized for industrial production. Further

Development of High Field Dipoles



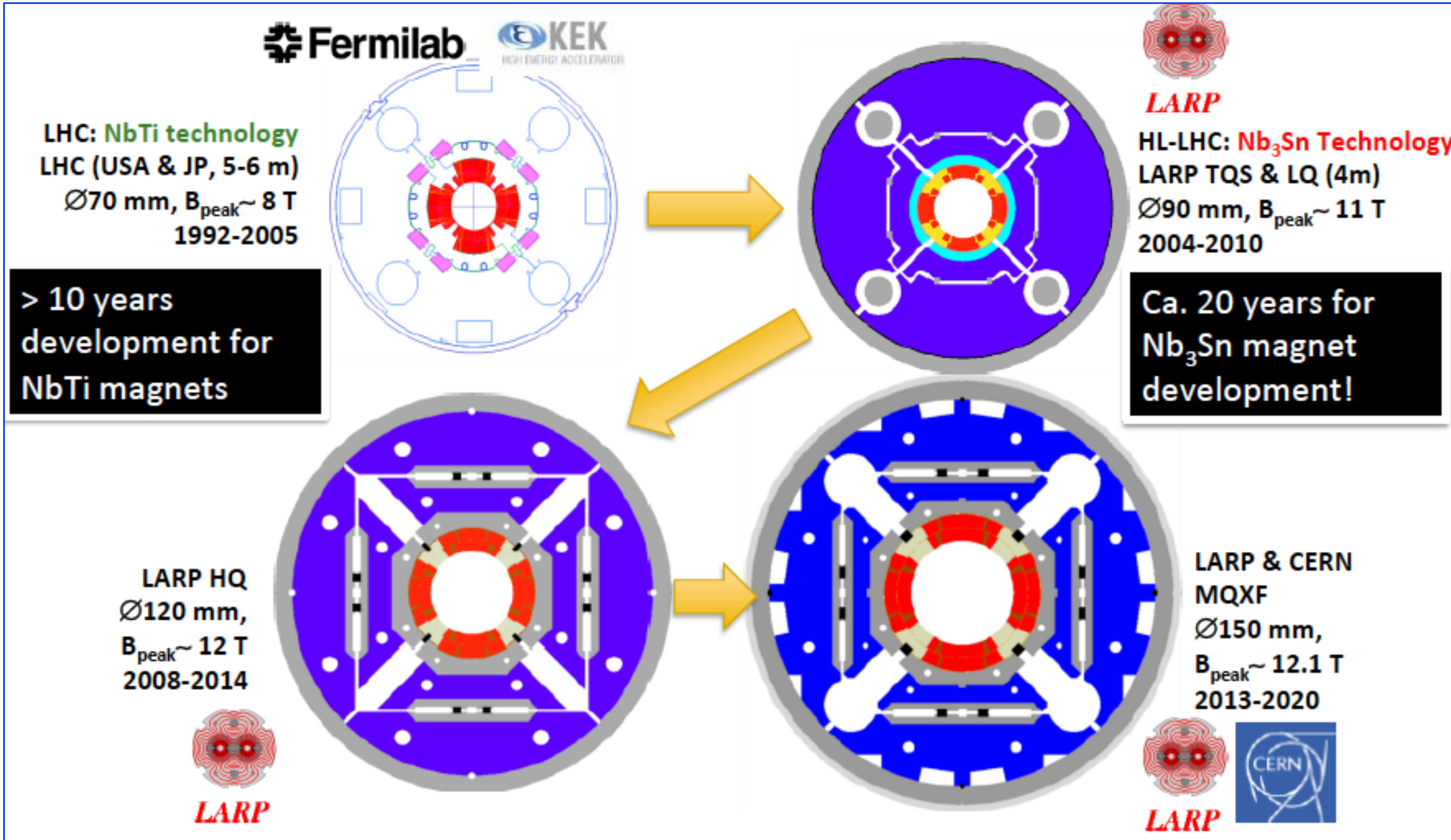
Sc wire: higher current, higher field. Reduced losses. NbTi: 15T at 10K, Nb_3Sn: 25Tat4K, HTC inserts YBCO

Cost is a major factor: today: Nb_3Sn is 5 times the NbTi cost and HTC is 10 times Nb_3Sn (O.Bruening at KET 2/17)

HE LHC needs about 4500 tons of Nb_3Sn, ITER needs 500 t

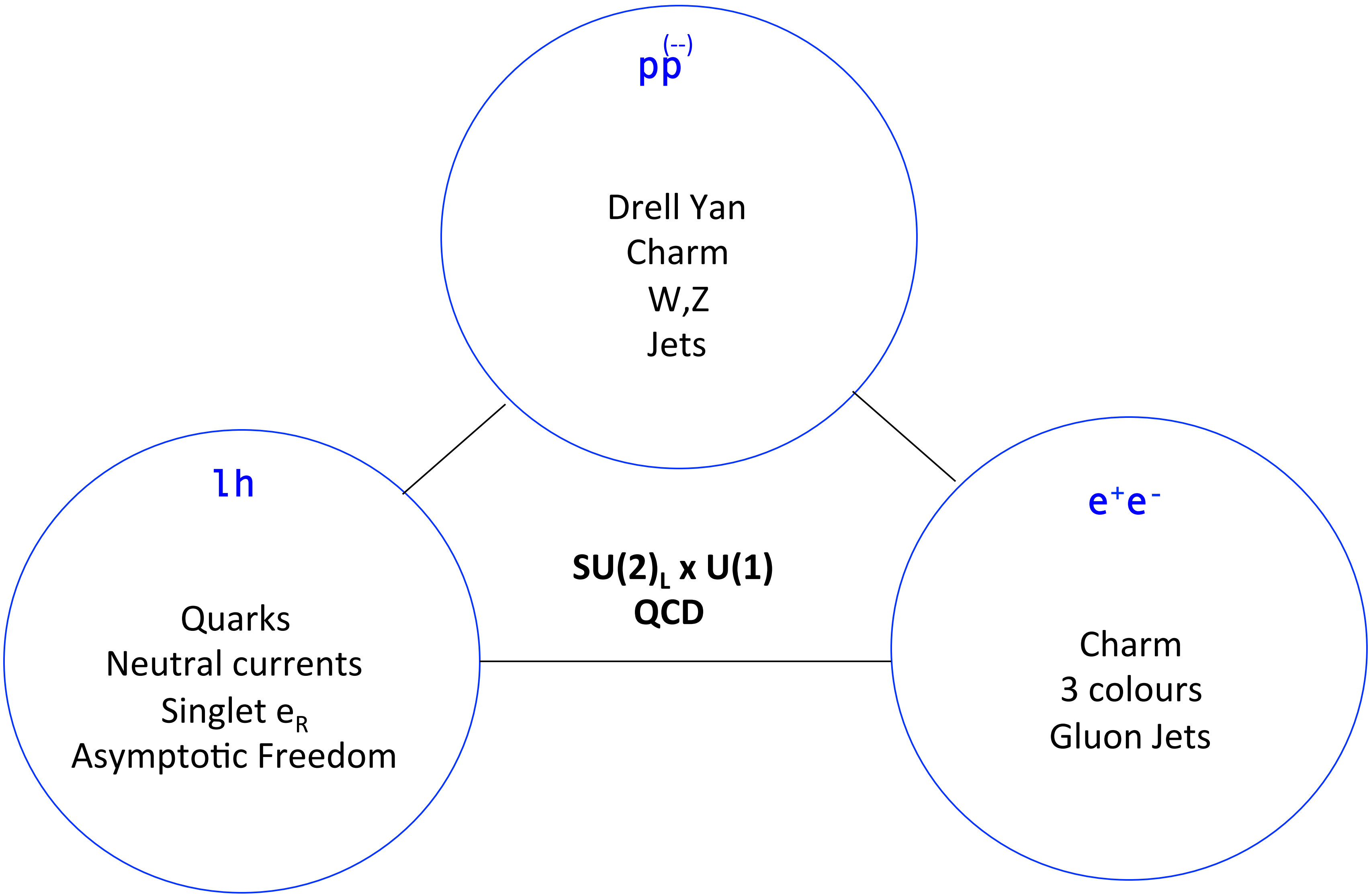
HL LHC – Replacement of Inner Quadrupoles

Inner triplet quadrupoles receive 25MGy of radiation from 300fb^{-1} of pp at the LHC → Larger aperture, larger field to ensure high luminosity performance: 1-2 decades of design

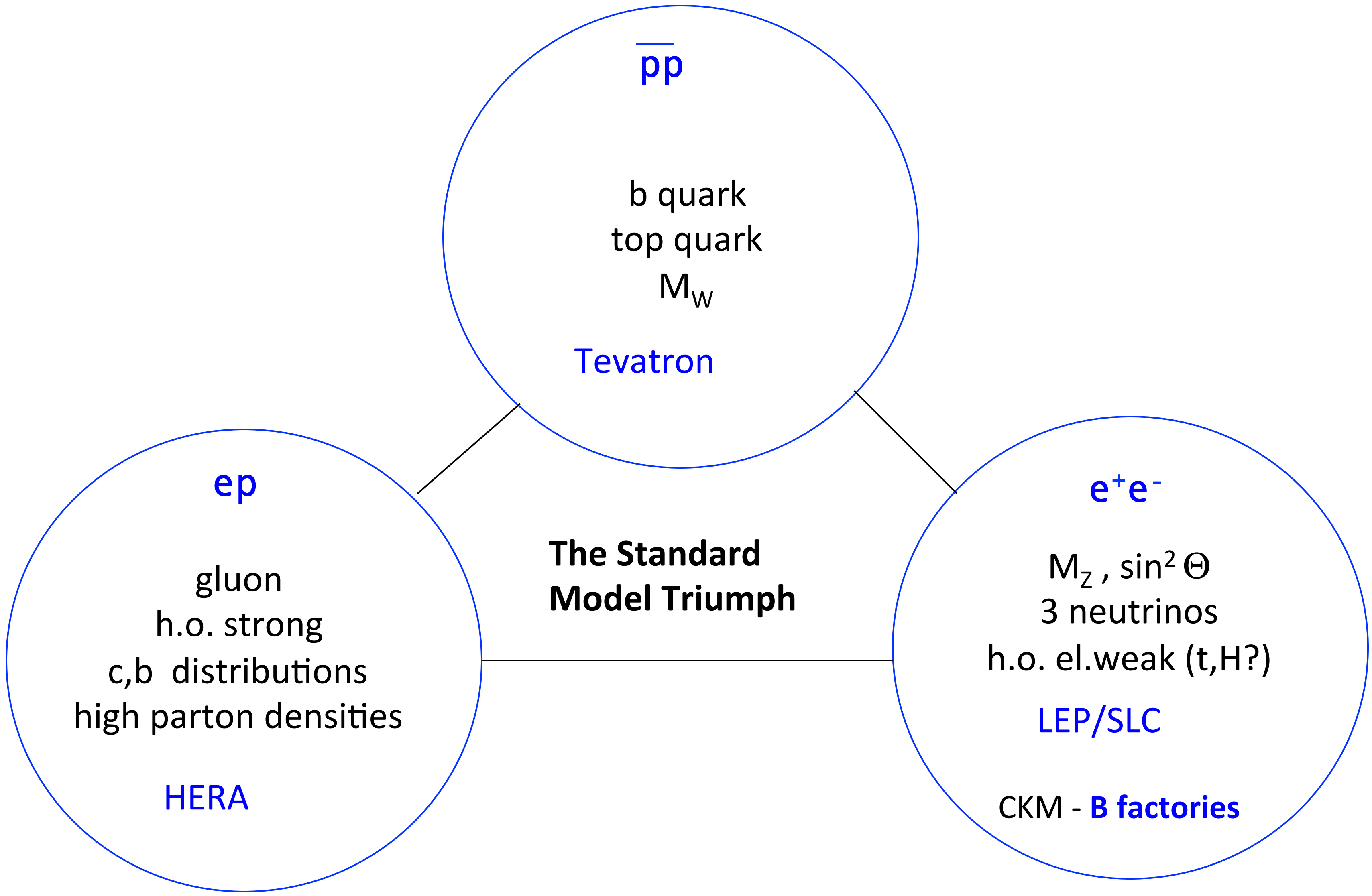


title

The 10-100 GeV Energy Scale [1968-1986]



The Fermi Scale [1985-2010]



Three conditions for prosperity of HEP

Staff

Positions for next generations: CERN staff + visitors: *1960* 1166 → *1965* 2530
A major new step will depend on how we can keep HEP attractive for life plans.

Accelerators

L.D. Landau:
Accelerators have the advantage to control the initial conditions

Europe's big machines

???
LHC
LEP, HERA
SppS, PETRA
SPS
time →

Accelerators need sites and major institutions. CERN should better have strong European partners DESY, Frascati, RAL, Saclay,.. and global challenges too.

Robert Jungk (1966)

Die grosse Maschine
-auf dem Weg in eine andere Welt

The big machine
-on the road into a new world

5. Big Questions

- Do we have too many particles? 12 leptons, 36 quarks, 12 mediators, 1 Higgs = 61
- Is there a further layer of structure (preons?)
- How can we unify the 3 + 1 interactions (SU(5) failed in 1980 but established neutrino physics)
- Why are leptons and quarks different?
- Can one restore the boson-fermion symmetry (SUSY since 1972)
- Why do we have 3 families?
- Neutrino puzzles: Majorana, sterile neutrinos – Oscillations (98), Pontecorvo (57)
- Is the proton stable?
- …
- And: what is "behind" dark matter.. ? Not sure that is a particle physics question?

New: We lost the SM guidance
Reminds on Kelvin, Planck ~1900
Note: 500 ATLAS papers

1. The increase of energy and luminosity often led to discoveries

Substructure discovered at Stanford

Hofstatter et al: 1957: ep → ep E_e=200 MeV beam: proton finite radius of 1fm

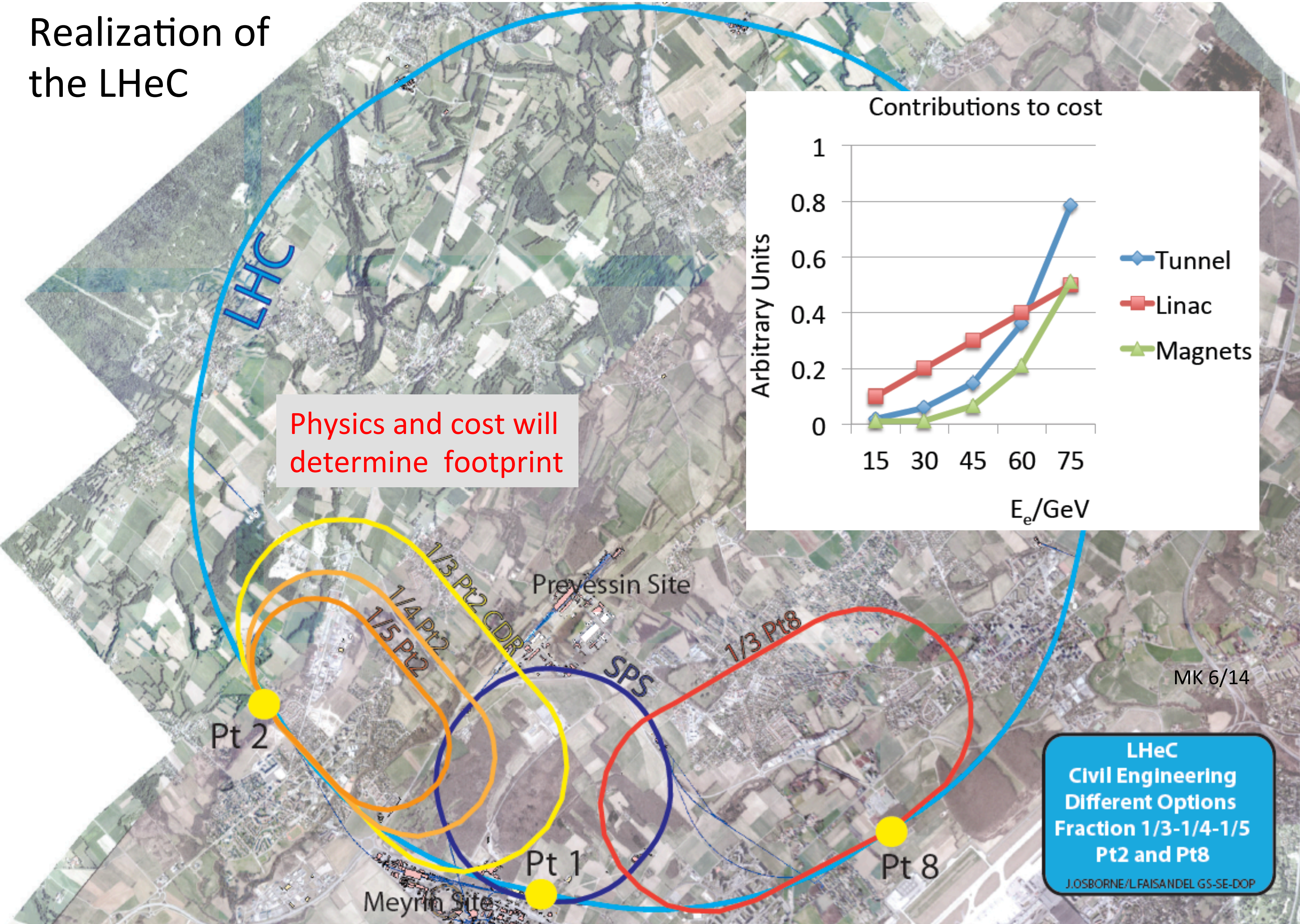
Taylor et al: 1968: ep → eX E_e=1-20 GeV beam (2 mile linac): partons at 0.1fm

W,Z Bosons discovered at CERN

ISR in 1970,
SPS in 1974 Ep=450 GeV (fixed target lh, hh experiments, injector for LHC)
transformed to SppS Collider L=10^{30-31} cm^{-2} s^{-1} by van der Meer + Rubbia
UA1, UA2: first full acceptance pp detectors to catch W → lnu and MET

Partons came unexpected - despite the Quark Model
W,Z were predicted in $SU_L(2)xU(1)$ electroweak theory

Realization of the LHeC



title

2015
2016
2017
2018
2019
2020
2021
2022
2023
EYETS
LS2
Shutdown/Technical stop
Protons physics
Commissioning
Ions
2024
2025
2026
2027
2028
2029
2030
2031
2032
LS3
LS4
2033
2034
2035
2036
2037
LS5

Concluding Remarks

1. Electron-hadron scattering has **five big themes** (Microscope, Higgs, Joint to pp, BSM, Nuclei)
   → It thus has a unique place in High Energy Physics (reaching beyond these themes too..)

2. **ep empowers pp**: searches and high precision (e.g. Higgs in pp+ep – an especially rich mix)
   → ep and pp can operate concurrently: should be seen, studied and understood together

3. QCD deserves major new development through novel exp input (ep + pp) and theory
   → **QCD may fail and lead BSM**: non-linear evolution, higher/grand symmetry, breaking of factorisation, valence components of heavy quarks, free colour, instantons, substructure..

4. ions: **eA at CERN is to revolutionise nuclear dynamics** and structure physics
   → chromodynamic understanding of QGP, an EIC requires highest energy to be of highest value

5. Detector: one in LR, two in RR (HE-LHC?) **novel experimental opportunity post HL LHC upgrade**

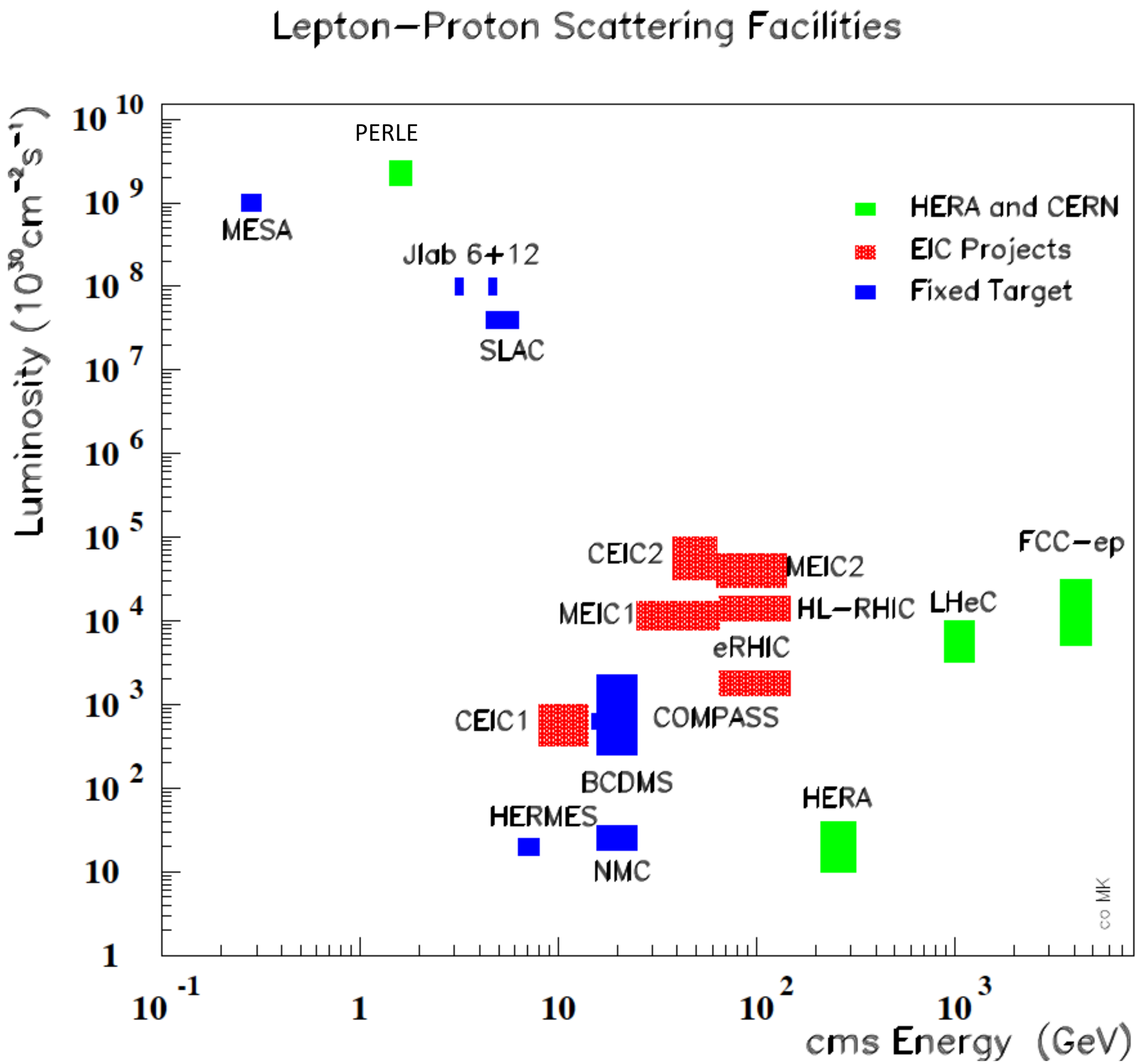
6. **PERLE**: in time and scope to learn how to build and operate the ERL at high energy

→ Electron-hadron configuration: genuine, high, added + crucial, **unique value for HEP**

→ The ERL at the HL/HE/FCC **is affordable, i.e. it does NOT affect larger scale decisions** but possibly provides time until those may be taken. The electron energy is a function of available cost (in building and operating the ERL). The ep cms energy is much higher than that of ILC/CepC or FCCee (even CLIC in the FCC-eh case)

→ **ep is an exciting, realistic option for a next energy frontier collider for particle physics**

Intensity and Energy Frontier of Future DIS



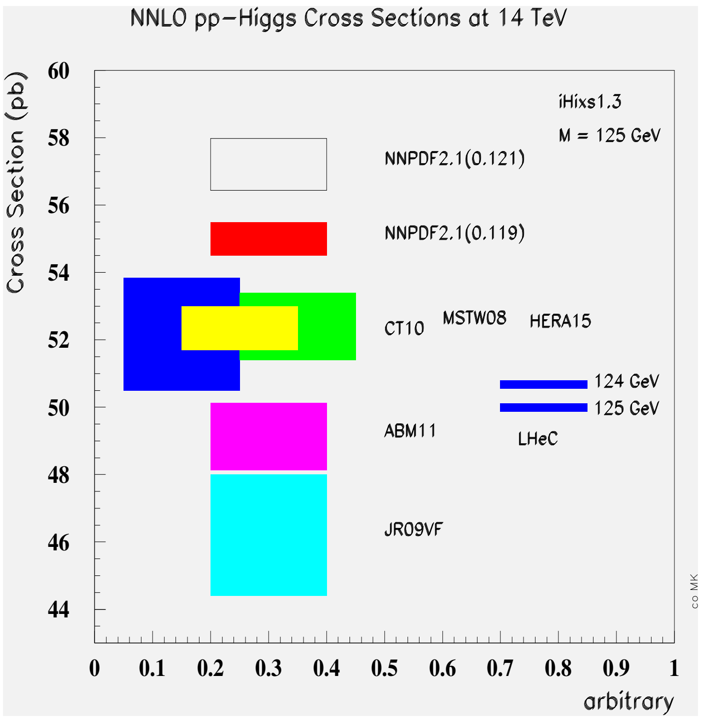
From CERN Courier
MK, H.Schopper
June 2014

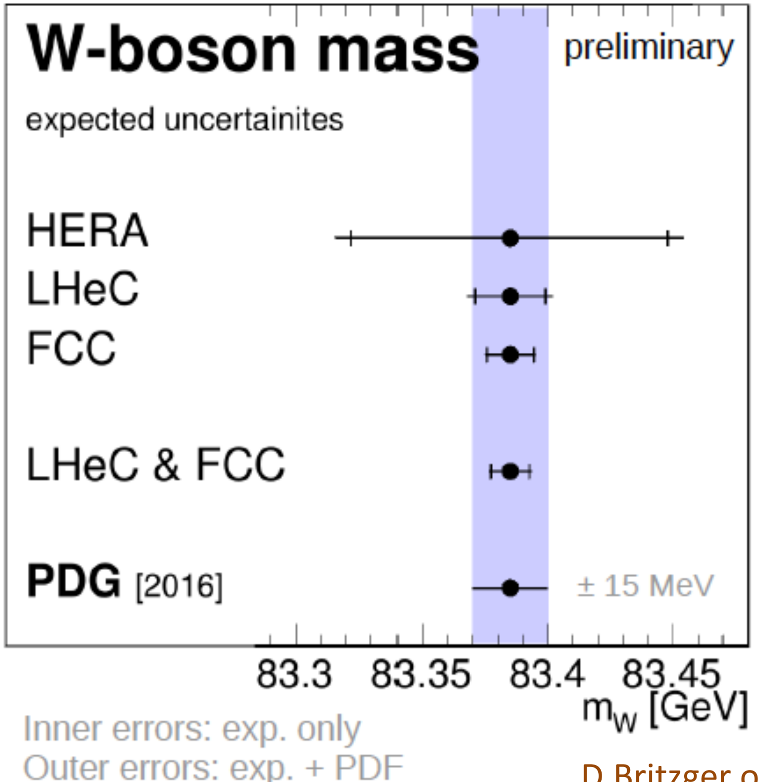
With input from
A.Hutton, R.Ent,
F.Maas, T.Rosner

CERN: LHC+FCC: the only realistic opportunity for energy frontier deep inelastic scattering
Huge step in energy (Q^2,1/x) and 2-3 orders of magnitude higher luminosity than HERA

High Precision for the LHC

Higgs pp Cross Section





D.Britzger on Thursday

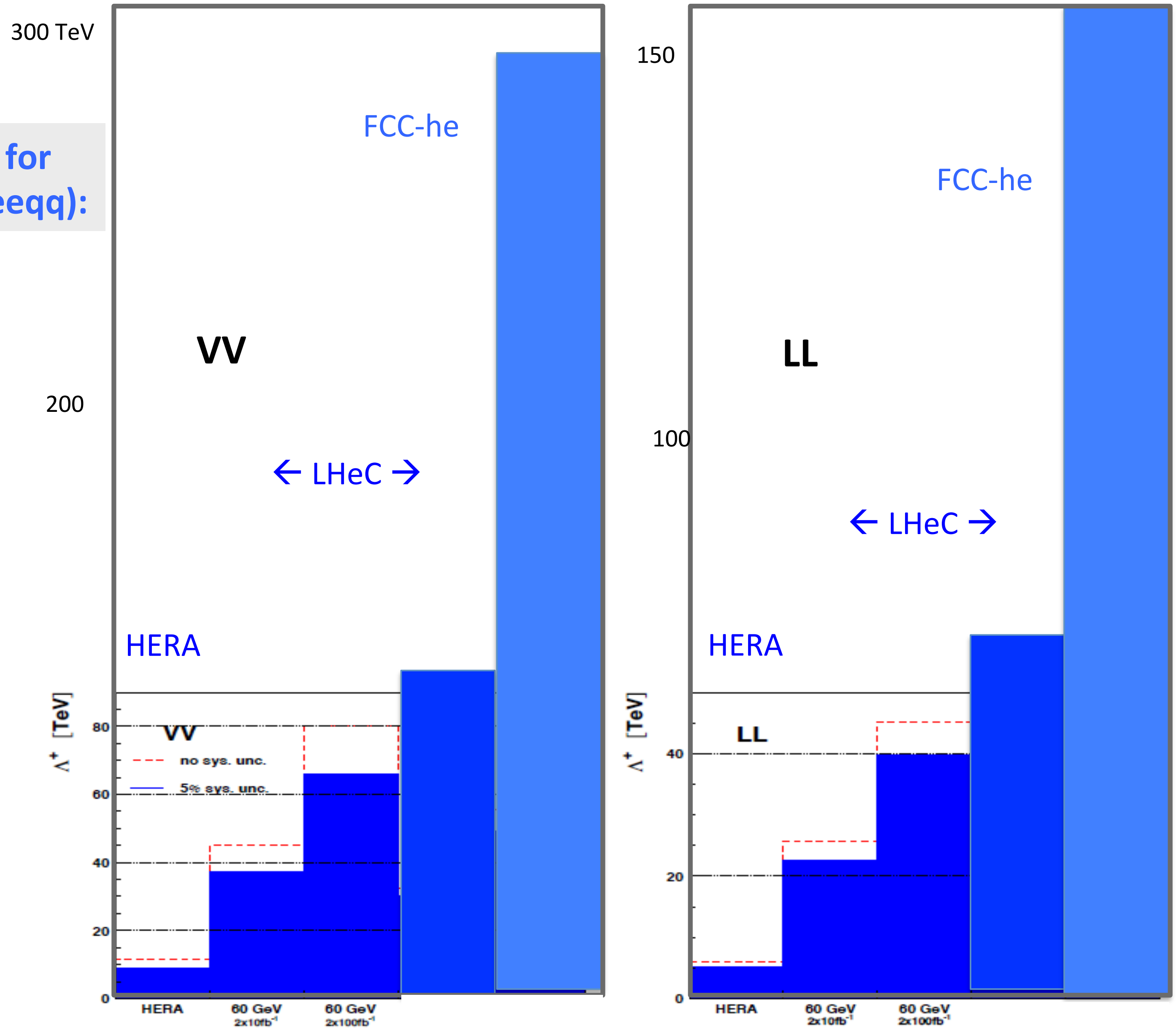
Predict the Higgs cross section in pp to 0.2% precision which matches the M_H measurement and removes the PDF error

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

Reach for Λ (CI eeqq):



LHeC: see CDR 2012

FCC - rough scaling only – very preliminary