Future Circular Colliders

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CERN
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Corfu Summer Institute

17th Hellenic School and Workshops on Elementary Particle Physics and Gravity

Corfu, Greece 2017

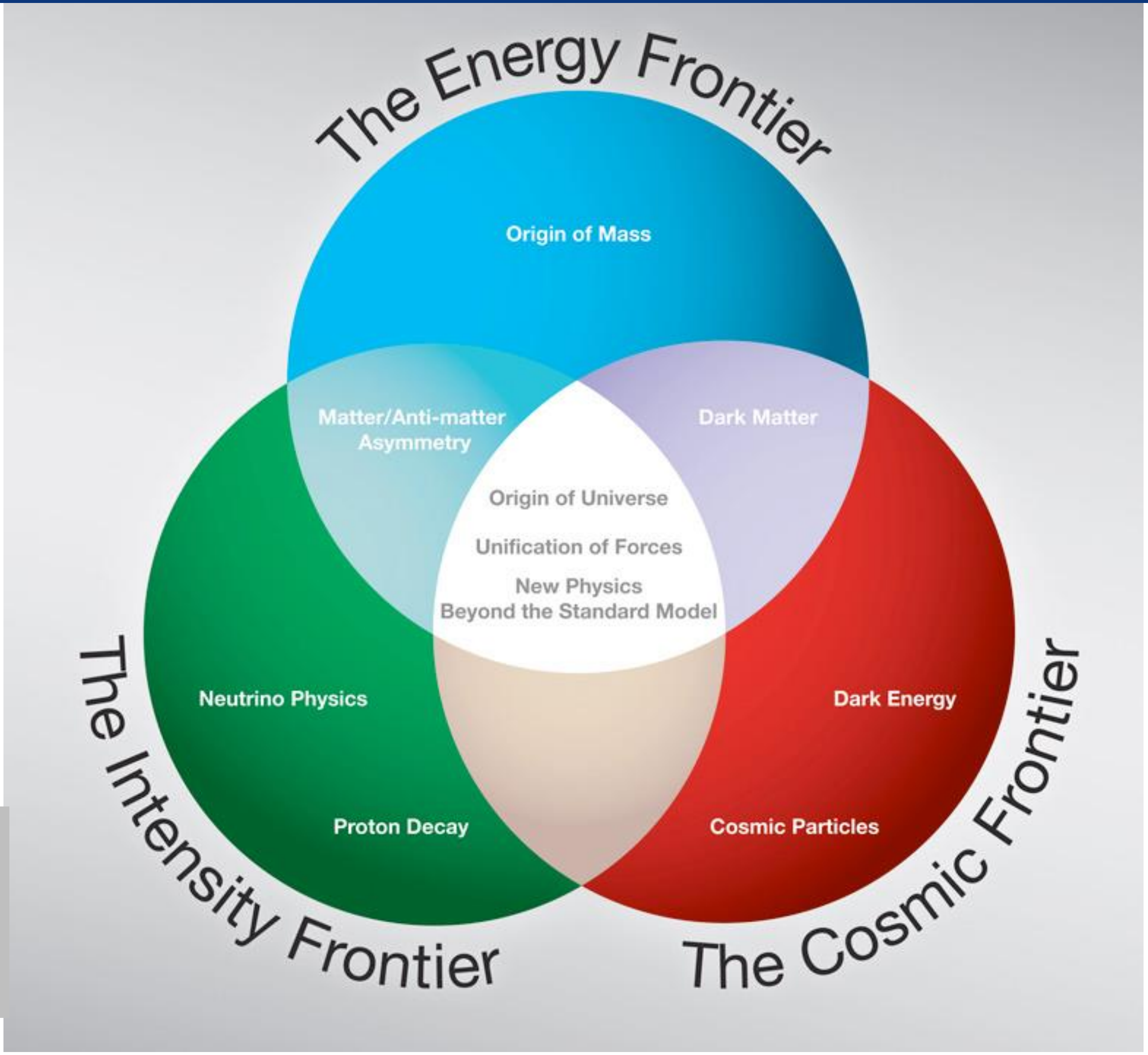
Future HEP: The Three Frontiers

After the Higgs discovery

2012-2014

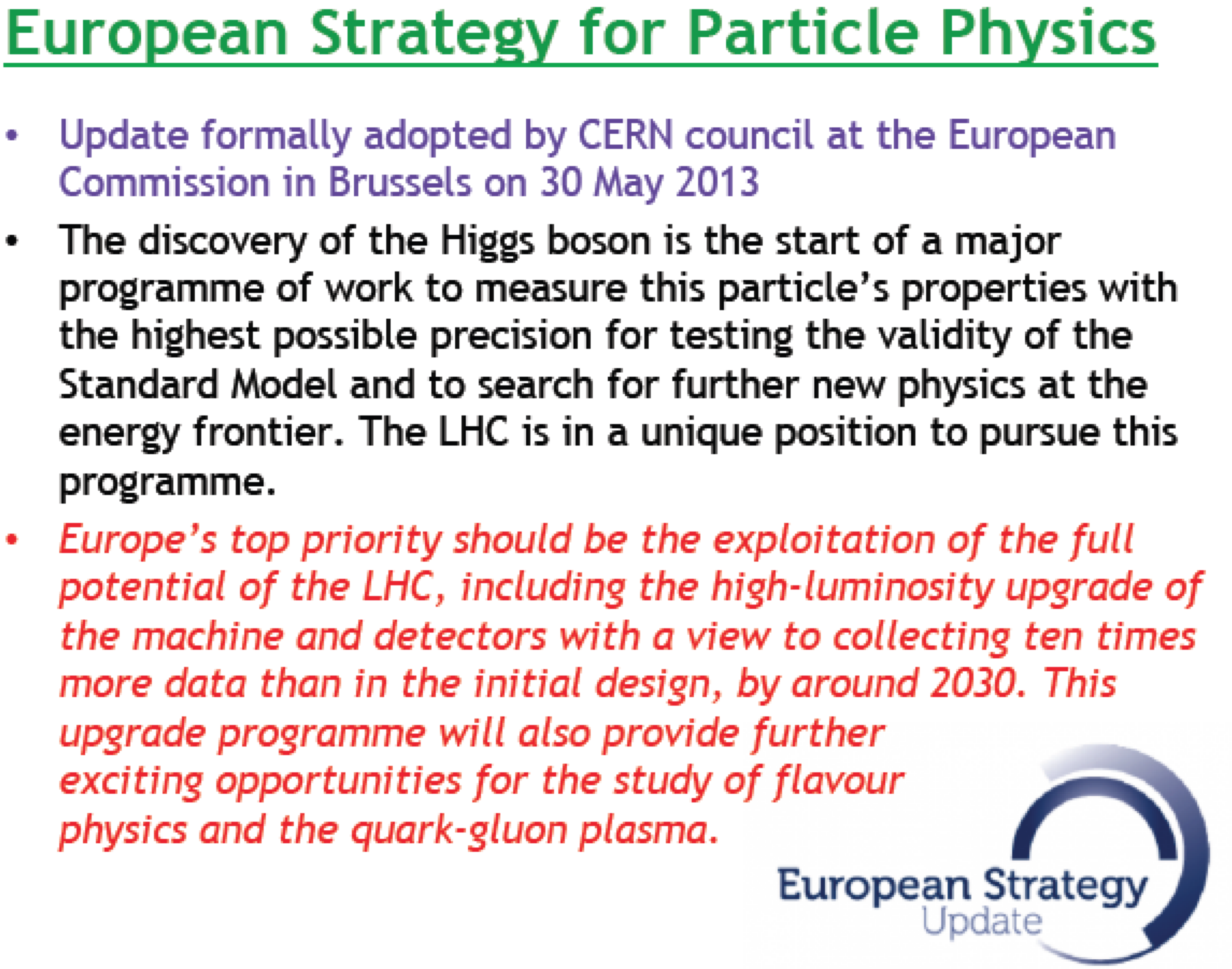
Evaluation in all regions: Europe Asia, the Americas

- European strategy group
- Snowmass study and IP5
- Japan strategy group



Will concentrate here on the Energy Frontier

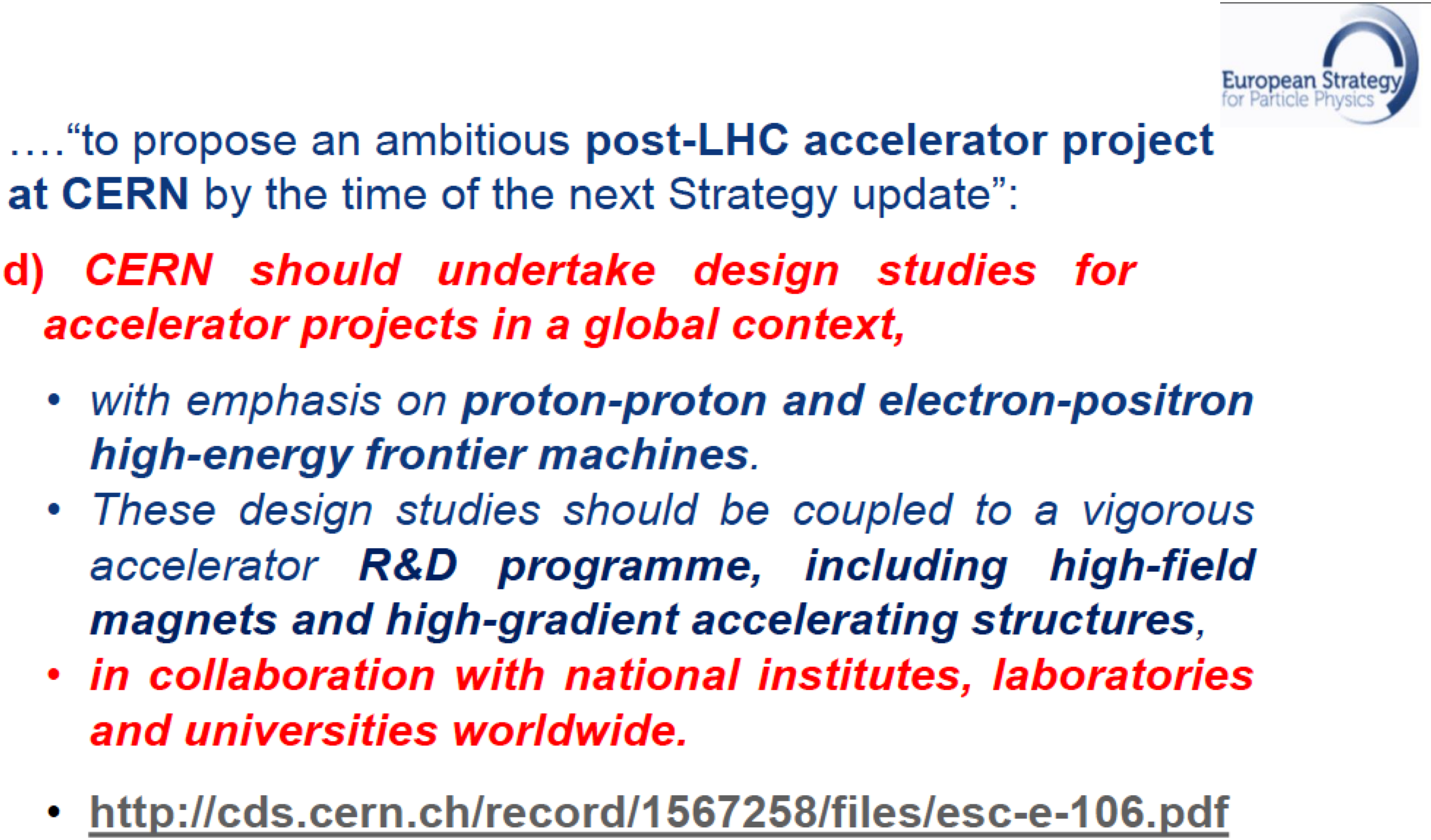
Europe Strategy Group



European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Europe Strategy Group



European Strategy for Particle Physics

….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

d) CERN should undertake design studies for accelerator projects in a global context,

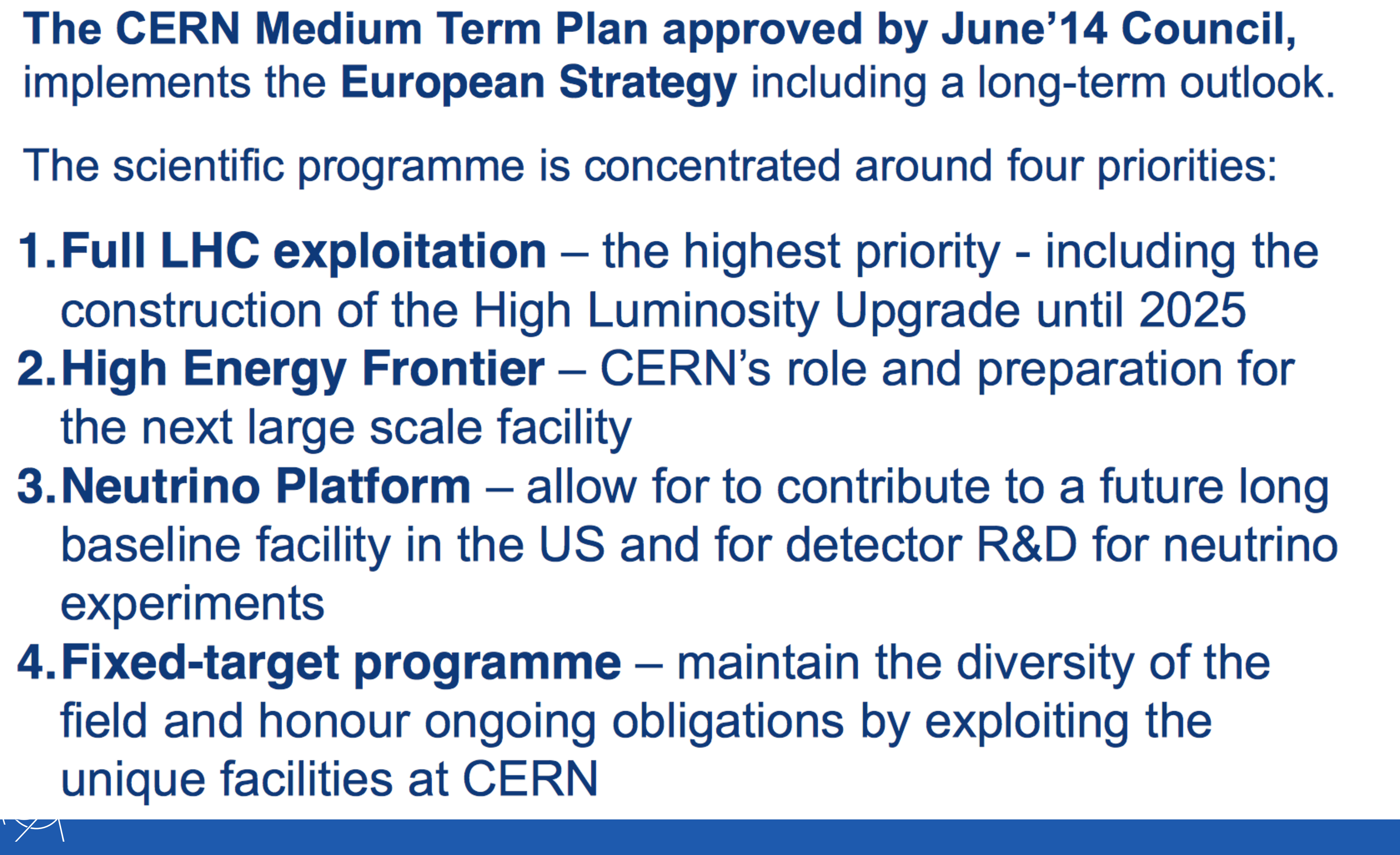
- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

Similar recommendation from the Snowmass studies in the US

=> The CERN Roadmap

F. Bodry , March 2015



The CERN Medium Term Plan approved by June'14 Council, implements the **European Strategy** including a long-term outlook.

The scientific programme is concentrated around four priorities:

1. **Full LHC exploitation** – the highest priority - including the construction of the High Luminosity Upgrade until 2025
2. **High Energy Frontier** – CERN's role and preparation for the next large scale facility
3. **Neutrino Platform** – allow for to contribute to a future long baseline facility in the US and for detector R&D for neutrino experiments
4. **Fixed-target programme** – maintain the diversity of the field and honour ongoing obligations by exploiting the unique facilities at CERN

FCC General Yearly Meeting May 2017

> 500 participants
147 institutes
a lot of young people
(>35% younger than 35)

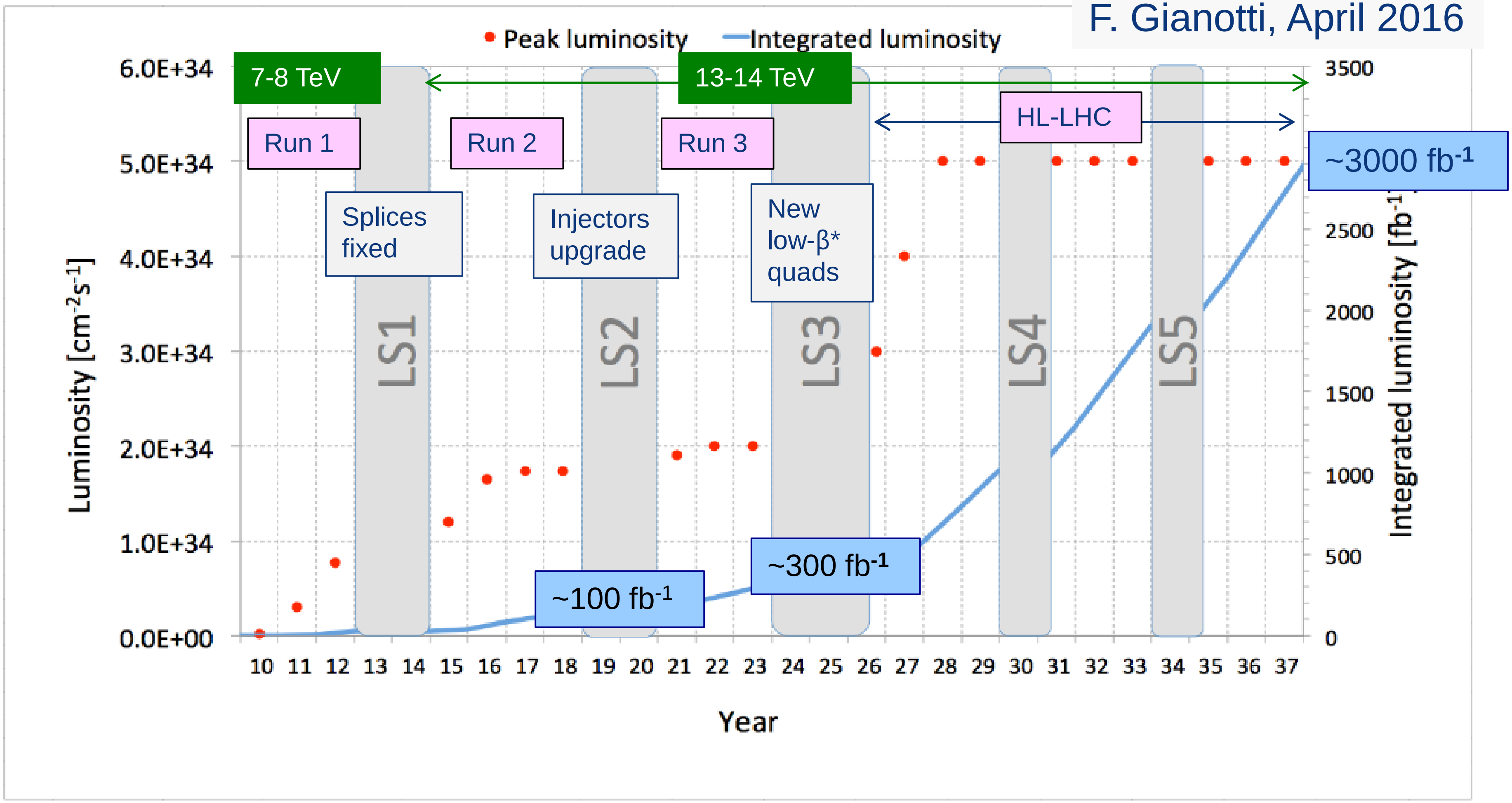
FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch

Slides from M. Benedikt, M. Mangano, W. Riegler, Y. Wang, F.Zimmerman, A Blondel

The LHC Upgrade

The LHC Approved LHC Roadmap

F. Gianotti, April 2016



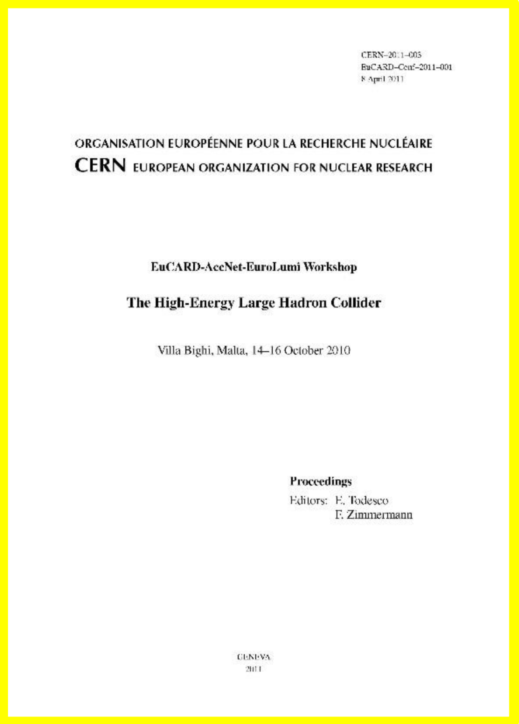
Approved program at CERN to collect 3000 fb^{-1} with the LHC (HL-LHC)

Maximize the reach for searches and for precision measurements (eg Higgs)

High-Energy LHC??

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1



CERN–2011–003
EuCARD–Conf–2011–001
8 April 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EuCARD-AccNet-EuroLumi Workshop

The High-Energy Large Hadron Collider

Villa Bighi, Malta, 14–16 October 2010

Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

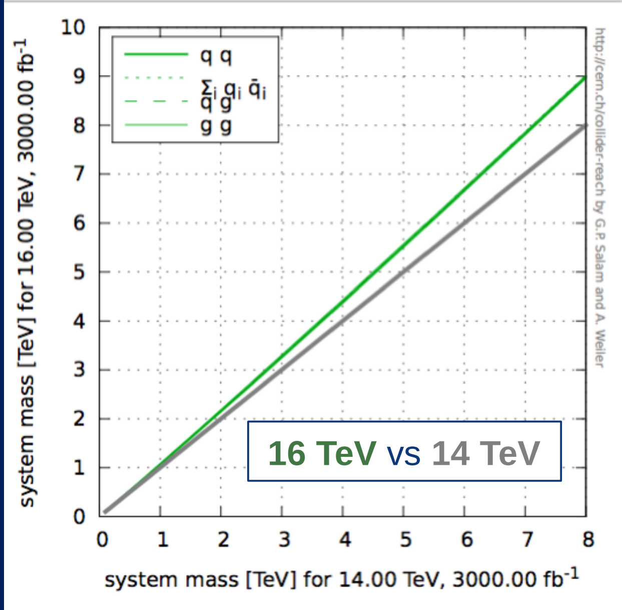
EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

- based on 16-T dipoles developed for FCC-hh
- extrapolation of other parts from the present (HL-)LHC and from FCC developments

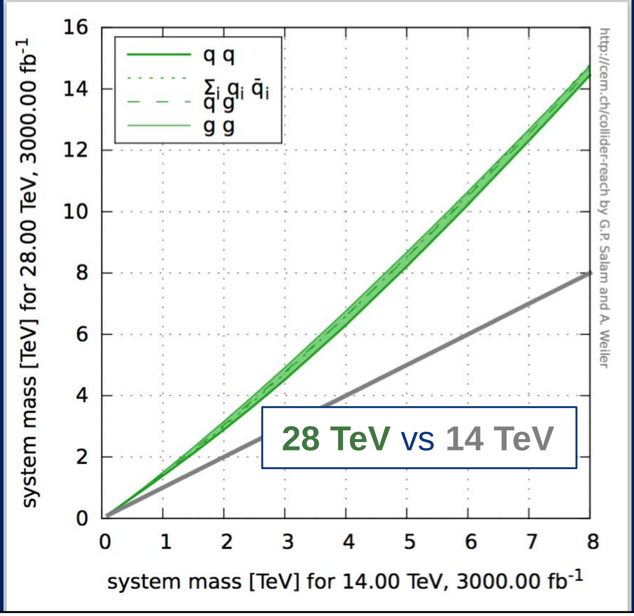
CM Energy 25-28 TeV

High-Energy LHC

F. Gianotti
FCC meeting
Rome April 2016



16 TeV vs 14 TeV



28 TeV vs 14 TeV

Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb_3Sn magnets)
→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
→ Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ √s~ 30 TeV)
☐ uses existing tunnel and infrastructure; can be built at fixed budget
☐ strong physics case if new physics from LHC/HL-LHC
☐ powerful demonstration of the FCC-hh magnet technology

Beyond the LHC

- Proton-proton machines at higher energy…
- Electron-positron machines for high precision…
- Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

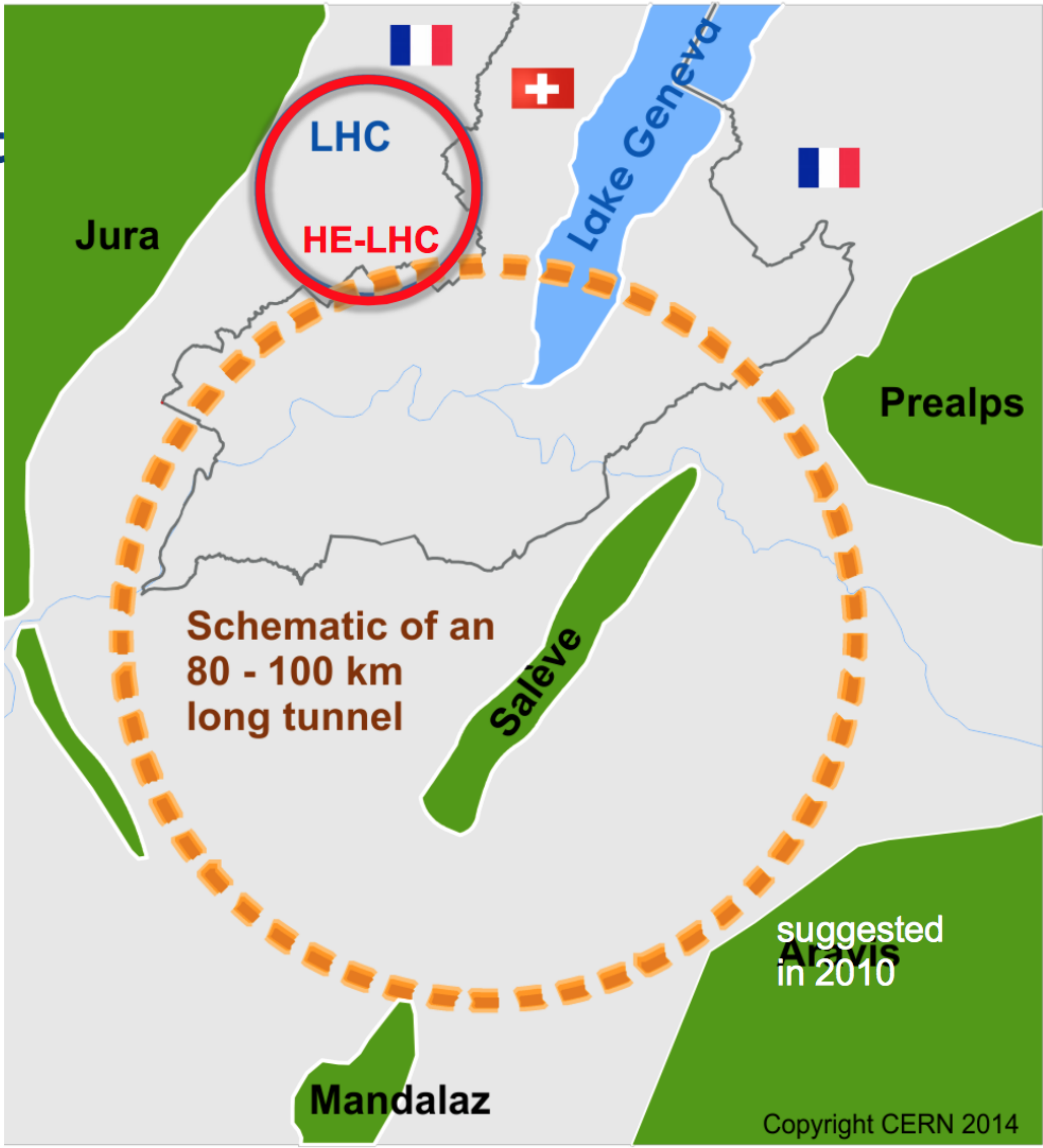
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to design:

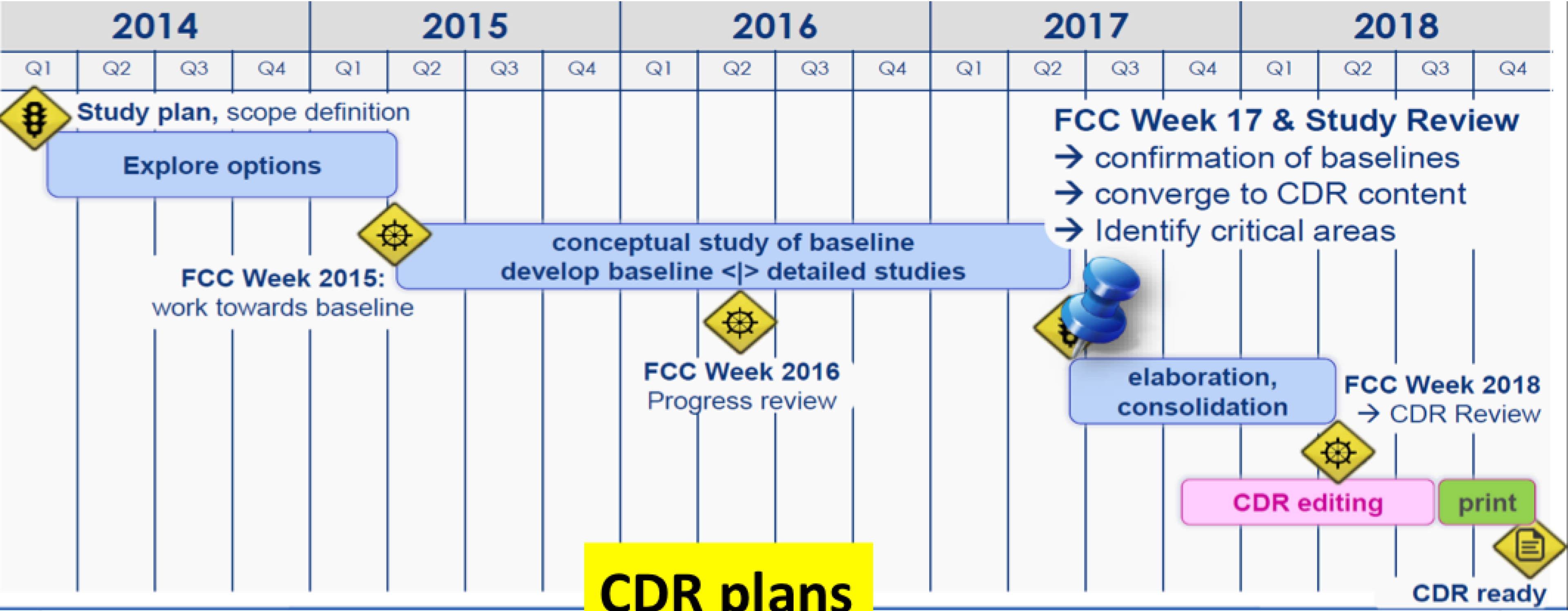
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology



CDR plans



2014 | 2015 | 2016 | 2017 | 2018

Q1 Q2 Q3 Q4 (each year)

Study plan, scope definition

Explore options

FCC Week 2015:
work towards baseline

conceptual study of baseline
develop baseline <|> detailed studies

FCC Week 2016
Progress review

FCC Week 17 & Study Review
→ confirmation of baselines
→ converge to CDR content
→ Identify critical areas

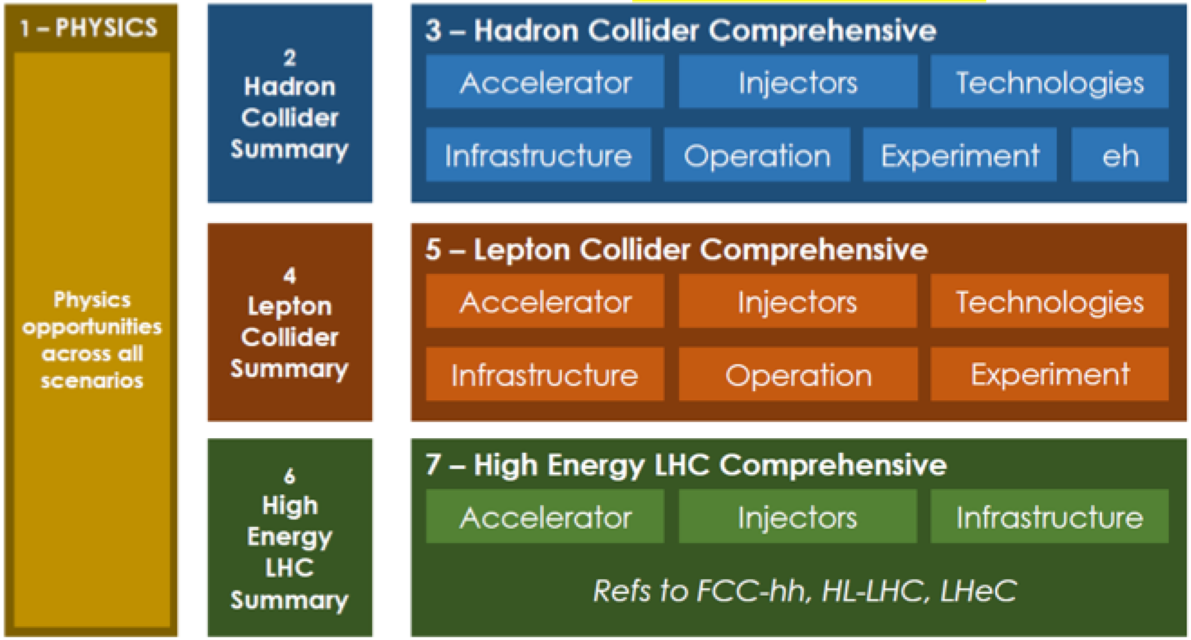
elaboration, consolidation

FCC Week 2018
→ CDR Review

CDR editing

print

CDR ready



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

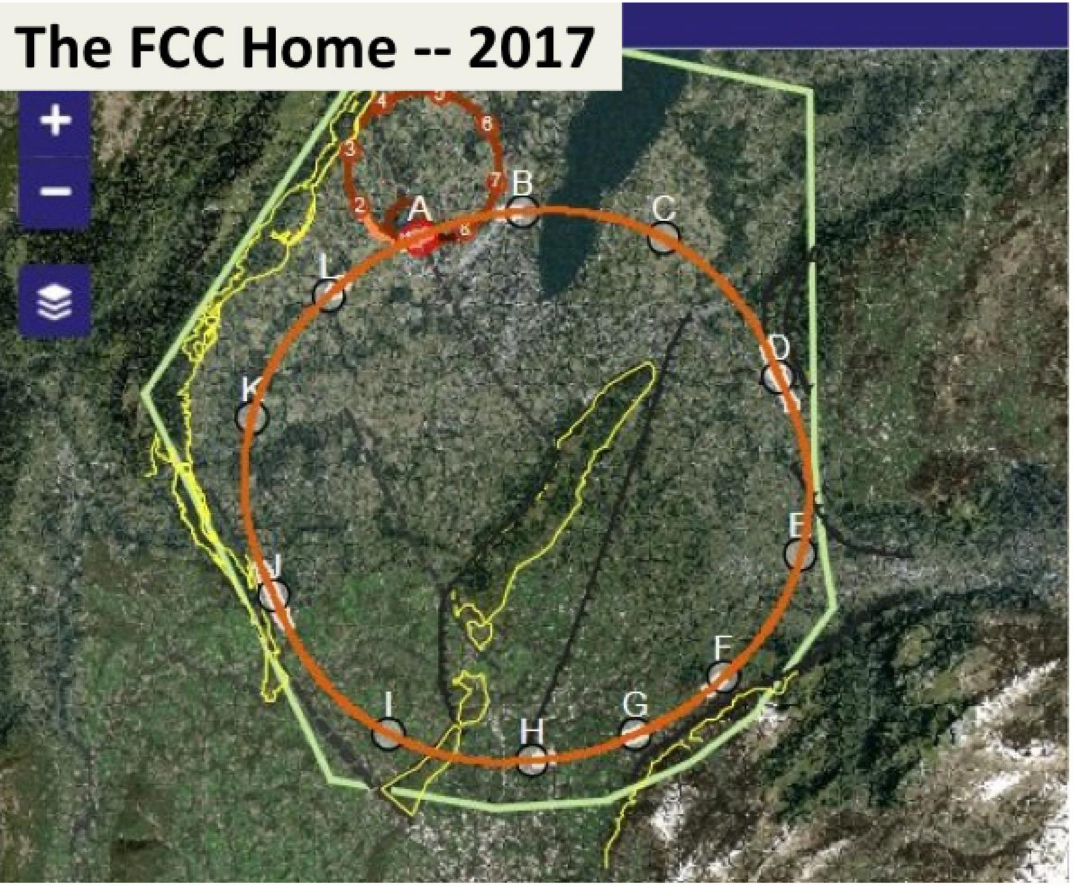
6 High Energy LHC Summary

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**

The FCC Home -- 2017



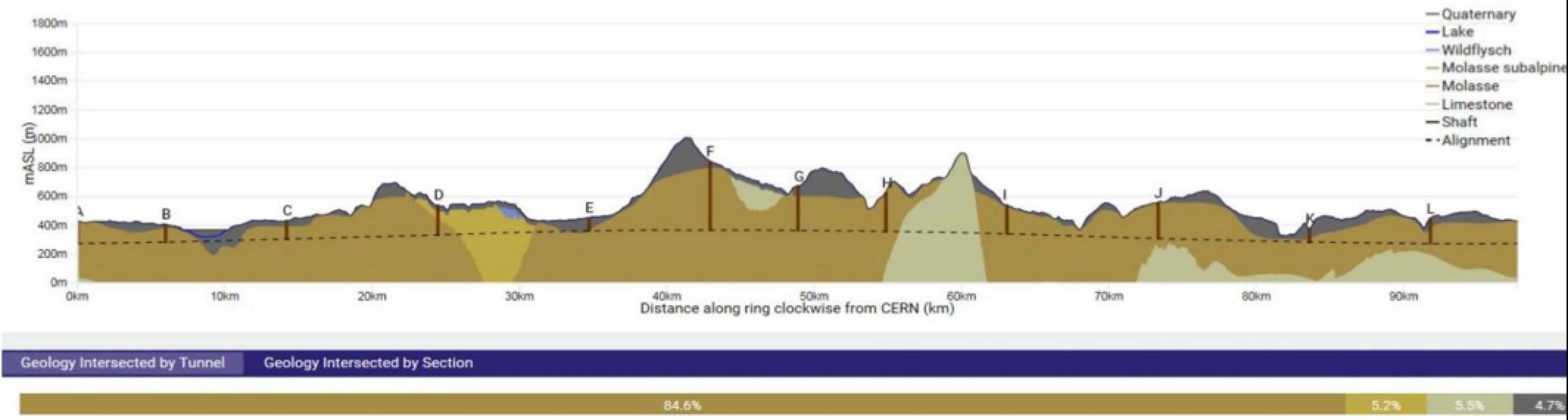
Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc. optimum: **97.5 km**

Tunneling

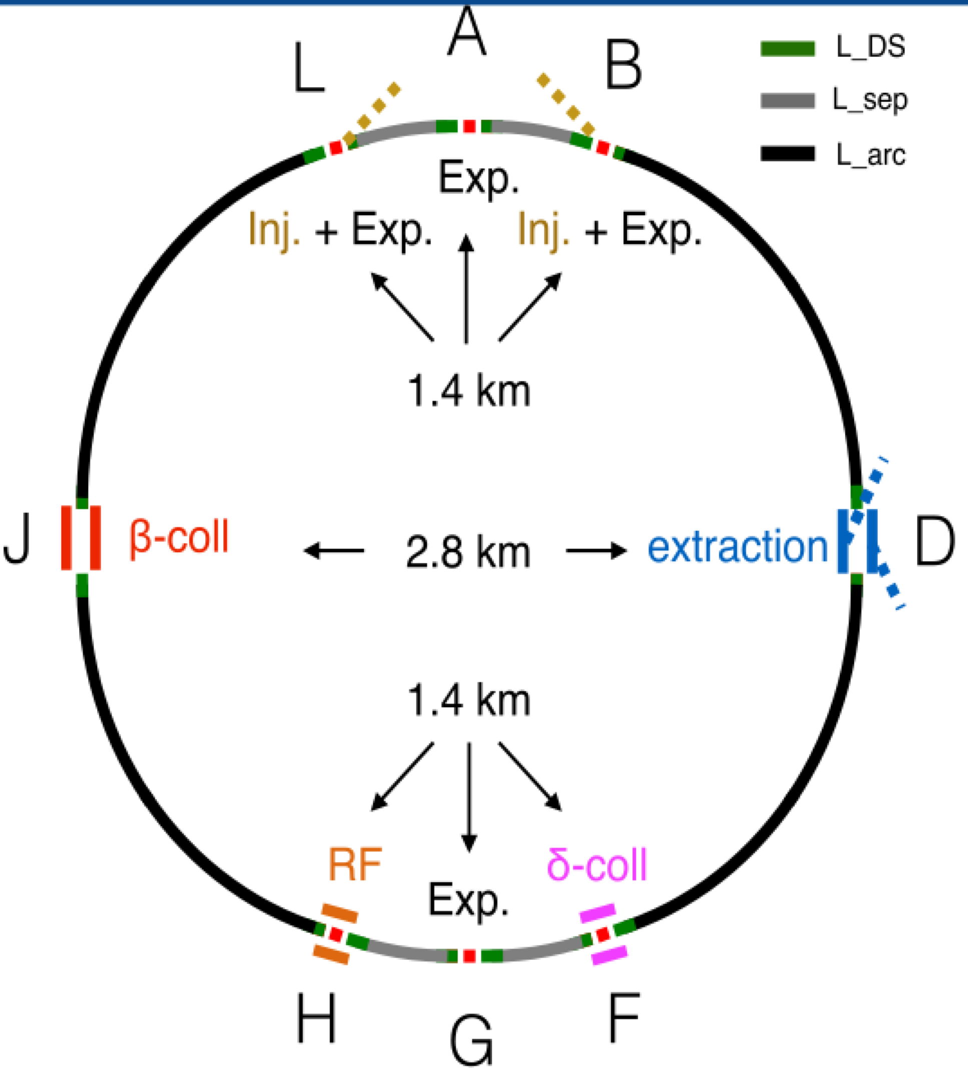
- Molasse 90% (good rock),
- Limestone 5%, Moraines 5% (tough)

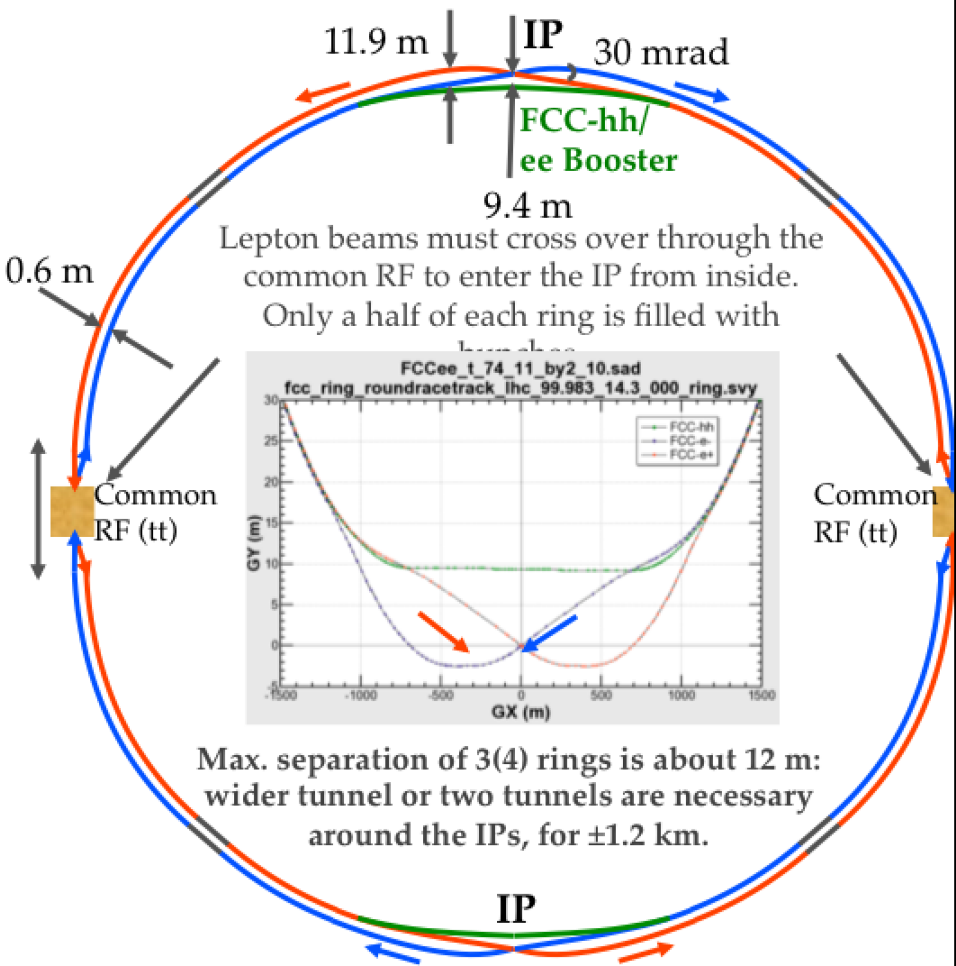
Shallow implementation

- ~ 30 m below Léman lakebed
- Reduction of shaft lengths etc...
- One very deep shaft **F** (476m) (RF or collimation), alternatives being studied, e.g. inclined access



common layouts for hh & ee





Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

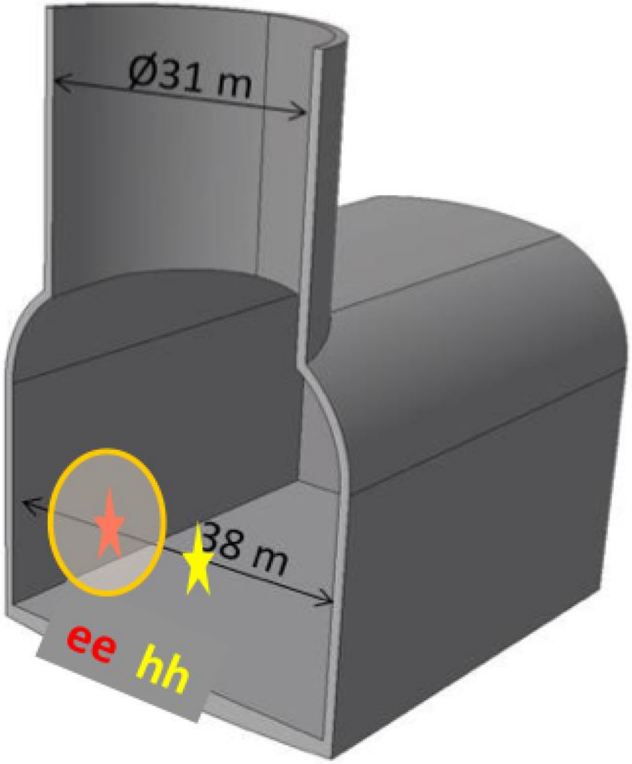
Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

2 main IPs in A, G for both machines

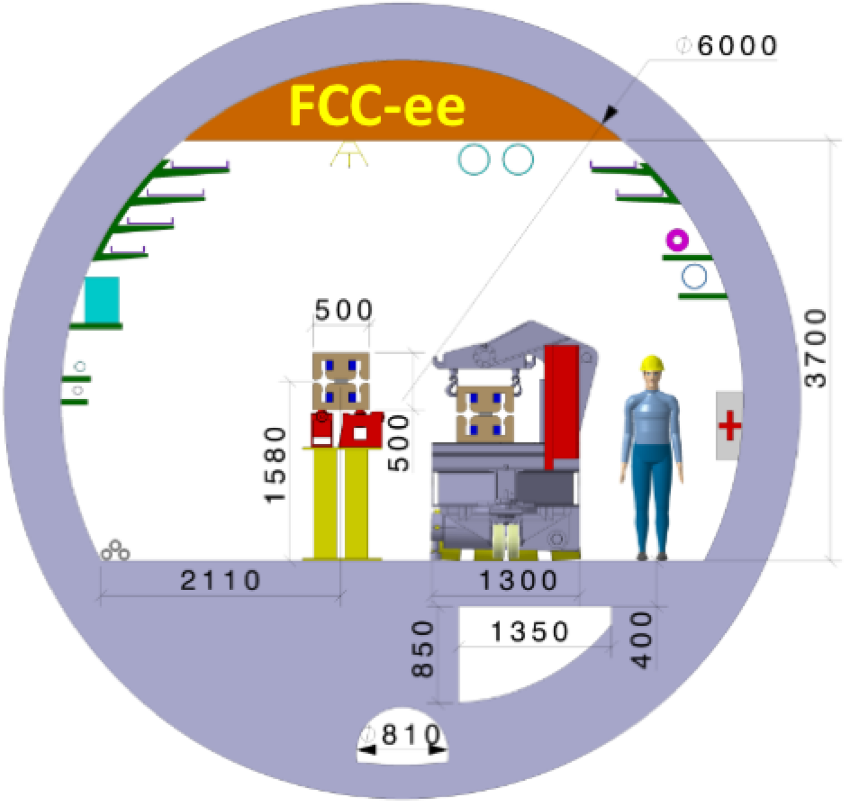
FCC-ee 1, FCC-ee 2,

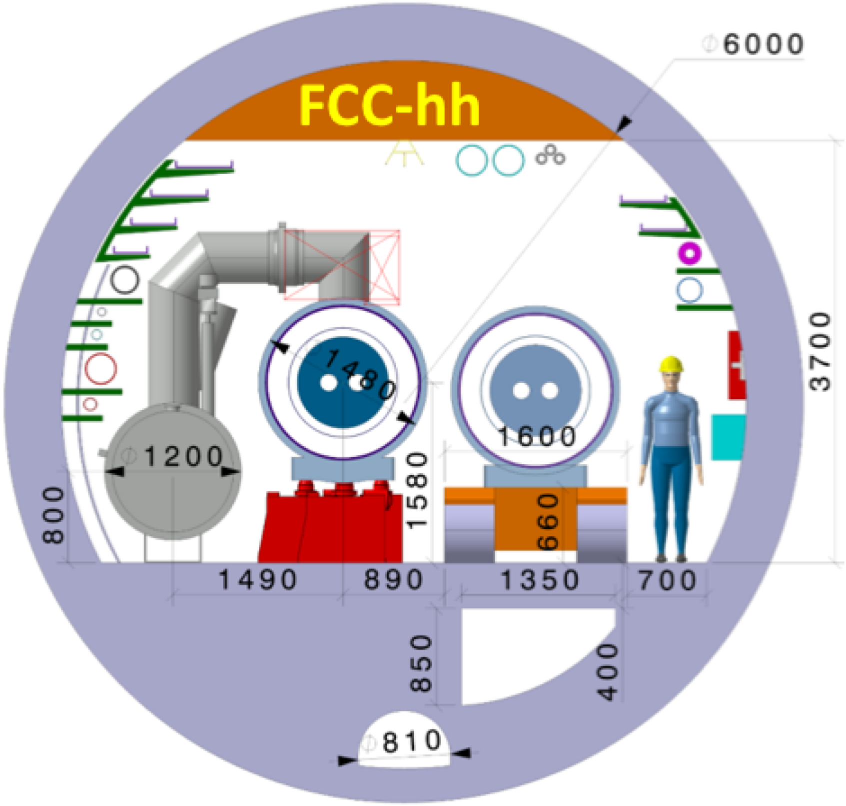
FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt



Sharing the FCC experimental caverns
(Prelim. layout as of FCC-Rome meeting)

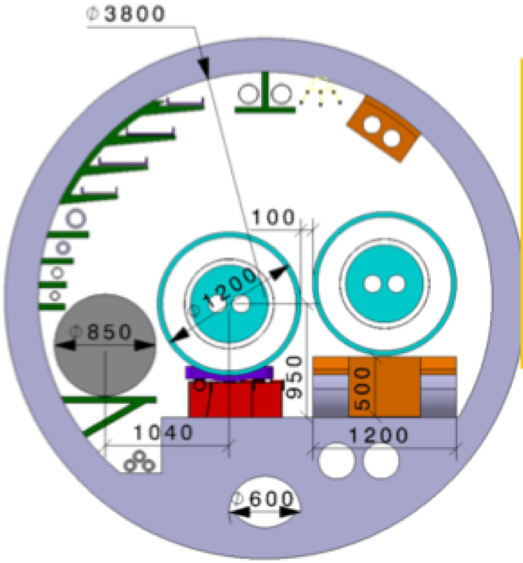




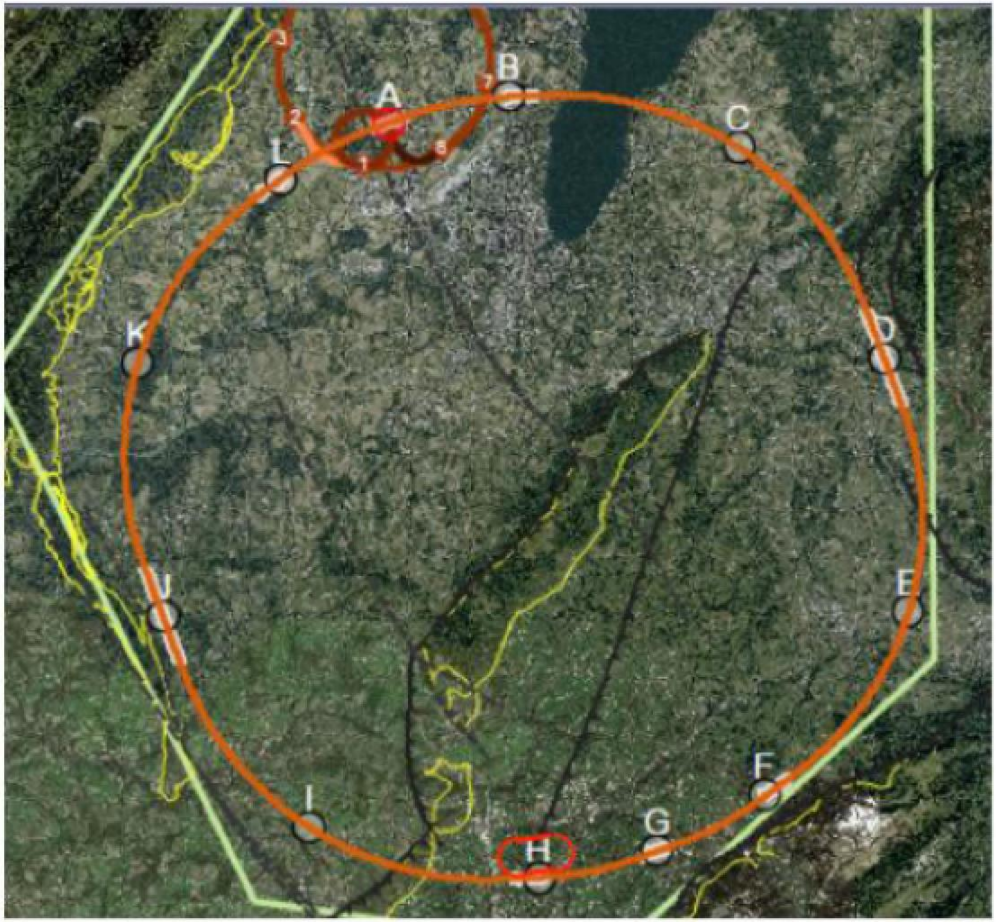
HE-LHC :
constraints:
No civil engineering, same beam height as LHC
→ Magnets OD ca. 1200 m max
QRL (shorter than FCC) OD ca. 850 mm (all included)

Magnet suspended during „handover“
from transport vehicle to installation transfer table

Compliant 16T magnet design ongoing
+ still many items to study!



If HE-LHC can work in 3.8m ∅ … it will feed-back to FCC tunnel design!



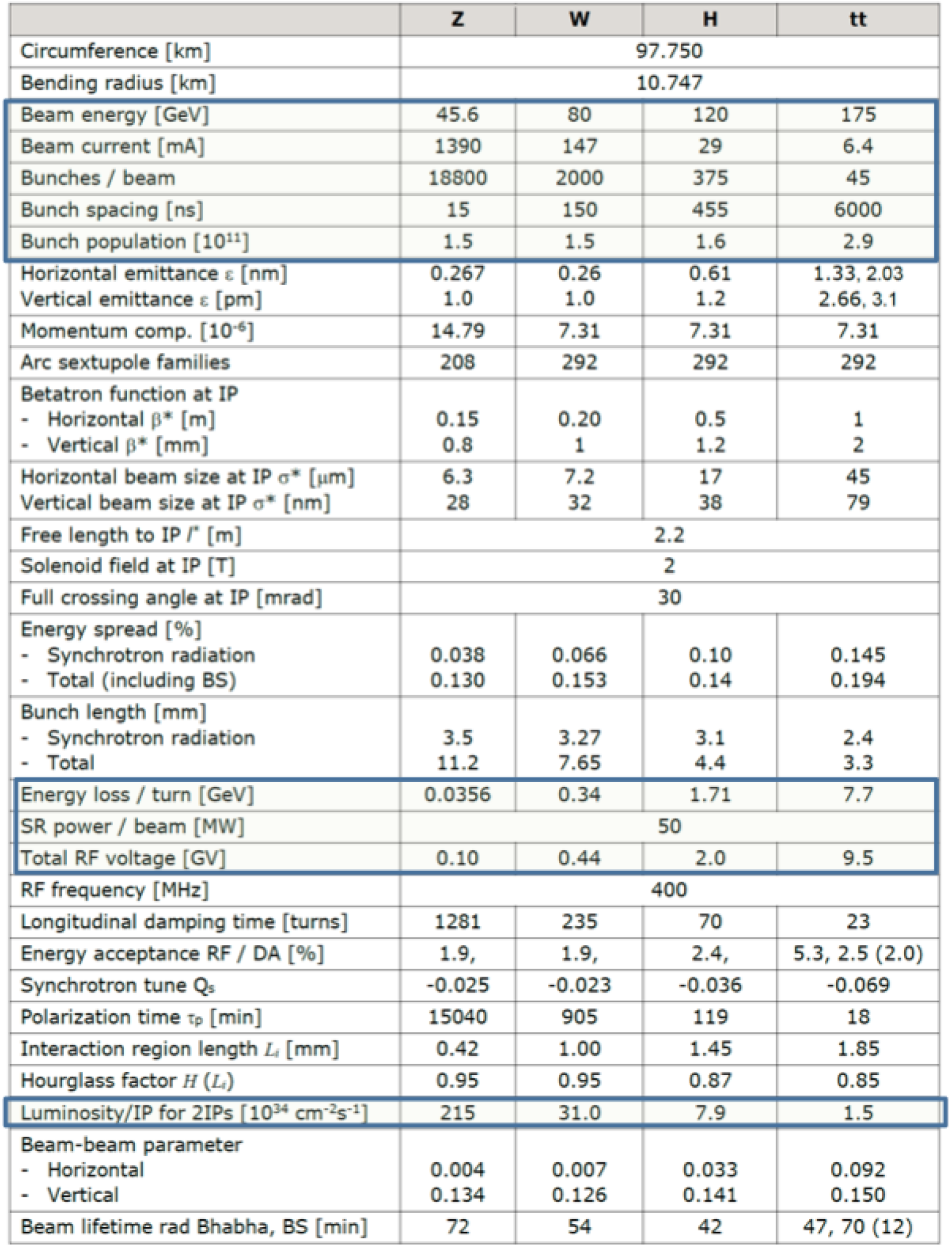
FCC-eh

LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively: additional 10km cicumference Electron Reciculating Linac ERL.

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study

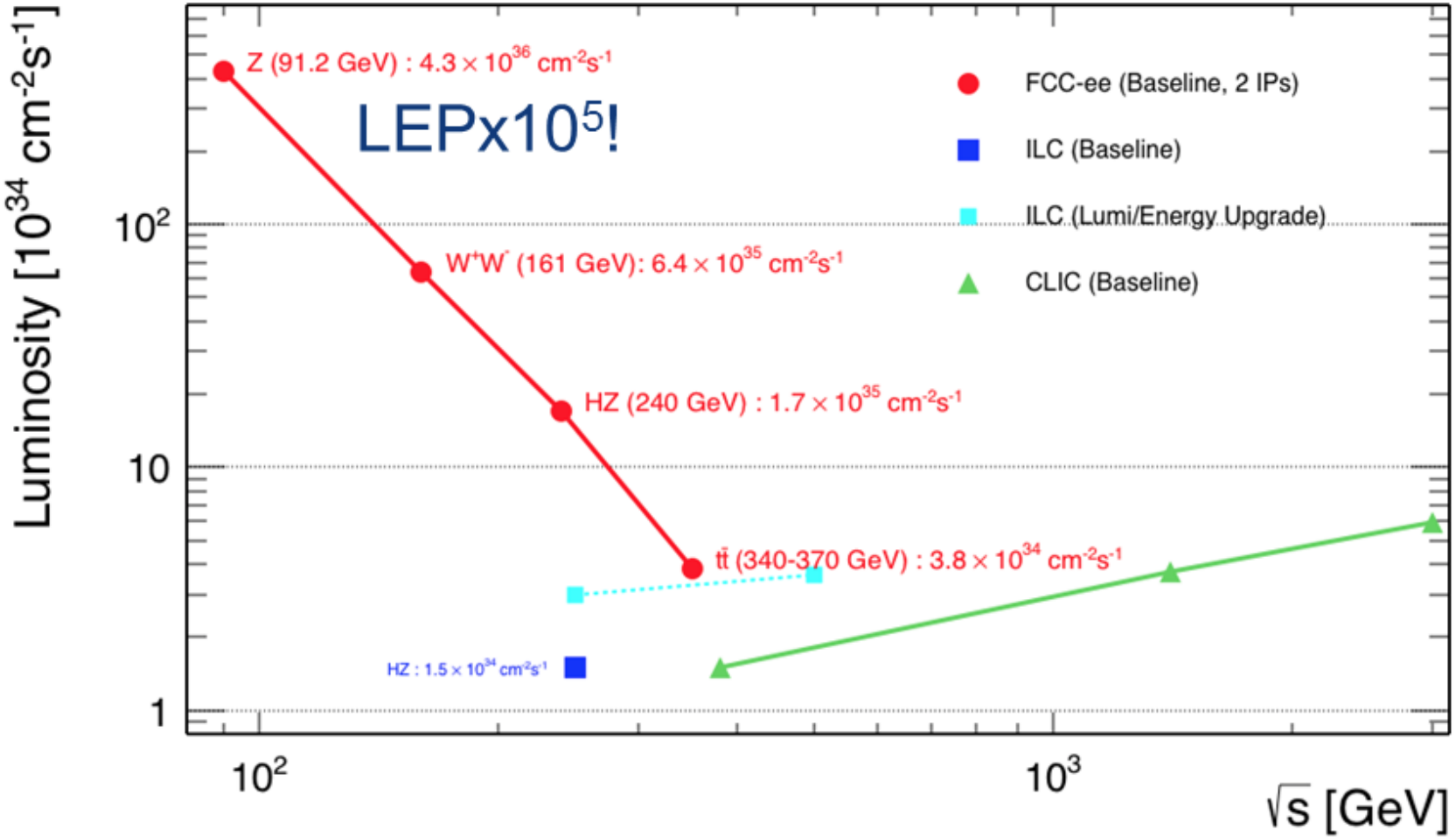
In the case of FCC-eh it could profit from the -- then existing -- FCC-hh, and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee

Recent FCC-ee parameter list



	Z	W	H	tt
Circumference [km]	97.750			
Bending radius [km]	10.747			
Beam energy [GeV]	45.6	80	120	175
Beam current [mA]	1390	147	29	6.4
Bunches / beam	18800	2000	375	45
Bunch spacing [ns]	15	150	455	6000
Bunch population [10^{11}]	1.5	1.5	1.6	2.9
Horizontal emittance ε [nm]	0.267	0.26	0.61	1.33, 2.03
Vertical emittance ε [pm]	1.0	1.0	1.2	2.66, 3.1
Momentum comp. [10^{-6}]	14.79	7.31	7.31	7.31
Arc sextupole families	208	292	292	292
Betatron function at IP				
- Horizontal β^* [m]	0.15	0.20	0.5	1
- Vertical β^* [mm]	0.8	1	1.2	2
Horizontal beam size at IP σ^* [μm]	6.3	7.2	17	45
Vertical beam size at IP σ^* [nm]	28	32	38	79
Free length to IP l^* [m]	2.2			
Solenoid field at IP [T]	2			
Full crossing angle at IP [mrad]	30			
Energy spread [%]				
- Synchrotron radiation	0.038	0.066	0.10	0.145
- Total (including BS)	0.130	0.153	0.14	0.194
Bunch length [mm]				
- Synchrotron radiation	3.5	3.27	3.1	2.4
- Total	11.2	7.65	4.4	3.3
Energy loss / turn [GeV]	0.0356	0.34	1.71	7.7
SR power / beam [MW]	50			
Total RF voltage [GV]	0.10	0.44	2.0	9.5
RF frequency [MHz]	400			
Longitudinal damping time [turns]	1281	235	70	23
Energy acceptance RF / DA [%]	1.9,	1.9,	2.4,	5.3, 2.5 (2.0)
Synchrotron tune Q_s	-0.025	-0.023	-0.036	-0.069
Polarization time τ_p [min]	15040	905	119	18
Interaction region length L_i [mm]	0.42	1.00	1.45	1.85
Hourglass factor $H(L_i)$	0.95	0.95	0.87	0.85
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	215	31.0	7.9	1.5
Beam-beam parameter				
- Horizontal	0.004	0.007	0.033	0.092
- Vertical	0.134	0.126	0.141	0.150
Beam lifetime rad Bhabha, BS [min]	72	54	42	47, 70 (12)

Luminosities for Future ee colliders

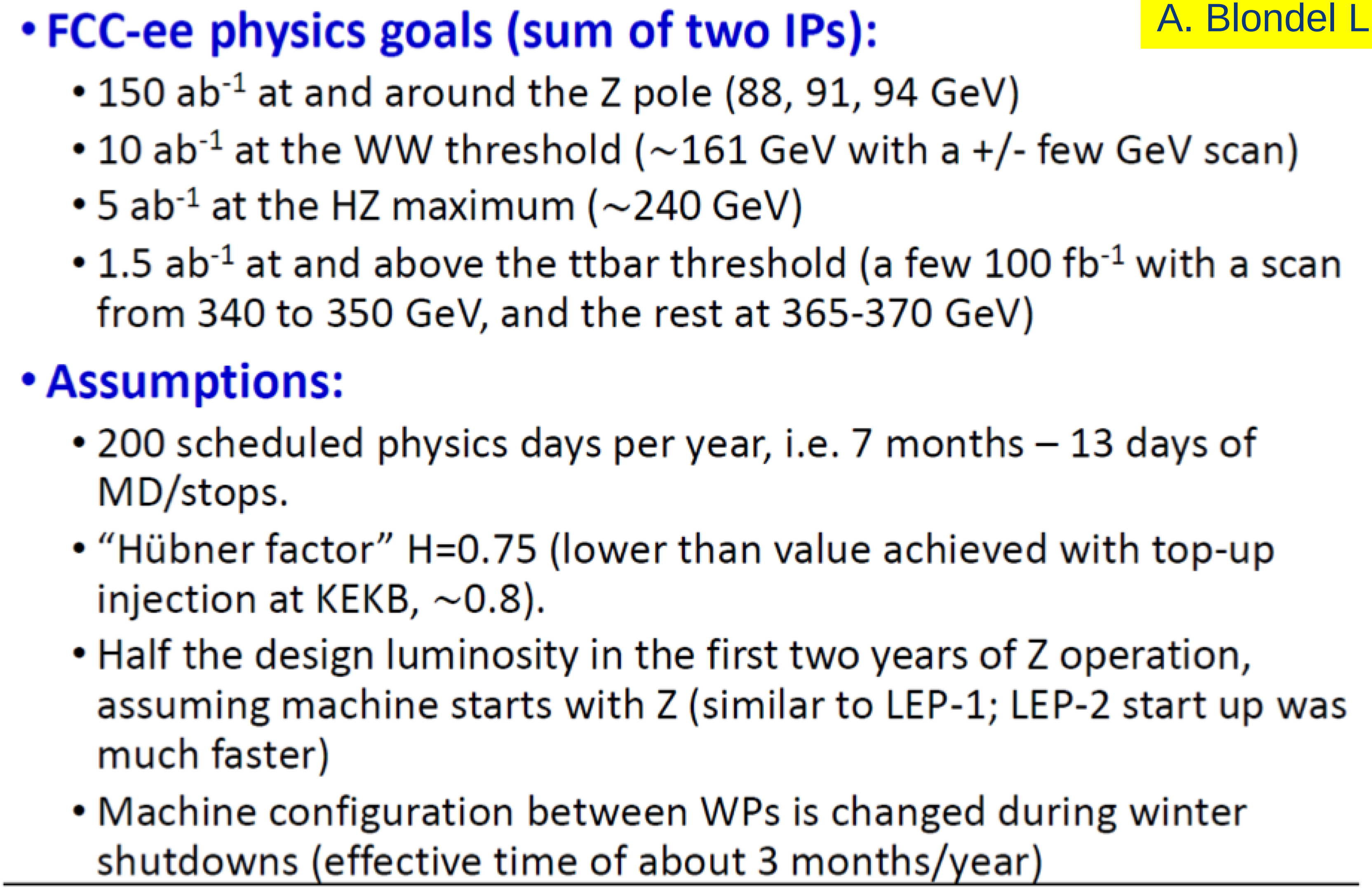


LEPx10^5!

A. Blondel, Lepton-Photon 2017

FCC-ee Physics Runs

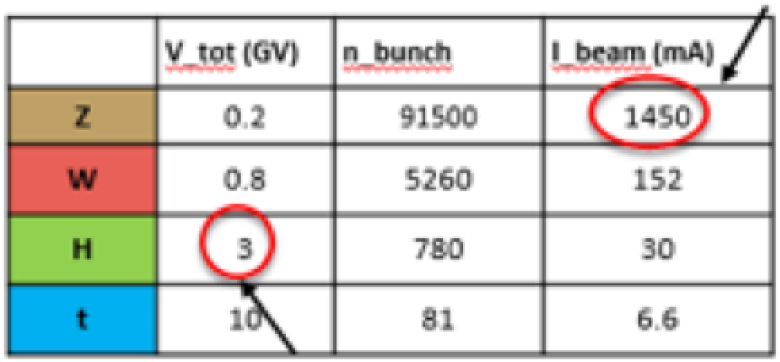
A. Blondel LP17



- **FCC-ee physics goals (sum of two IPs):**
  - 150 ab^{-1} at and around the Z pole (88, 91, 94 GeV)
  - 10 ab^{-1} at the WW threshold (~161 GeV with a +/- few GeV scan)
  - 5 ab^{-1} at the HZ maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the ttbar threshold (a few 100 fb^{-1} with a scan from 340 to 350 GeV, and the rest at 365-370 GeV)
- **Assumptions:**
  - 200 scheduled physics days per year, i.e. 7 months – 13 days of MD/stops.
  - “Hübner factor” H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  - Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)
  - Machine configuration between WPs is changed during winter shutdowns (effective time of about 3 months/year)

IMPLEMENTATION AND RUN PLAN

"Ampere-class" machine



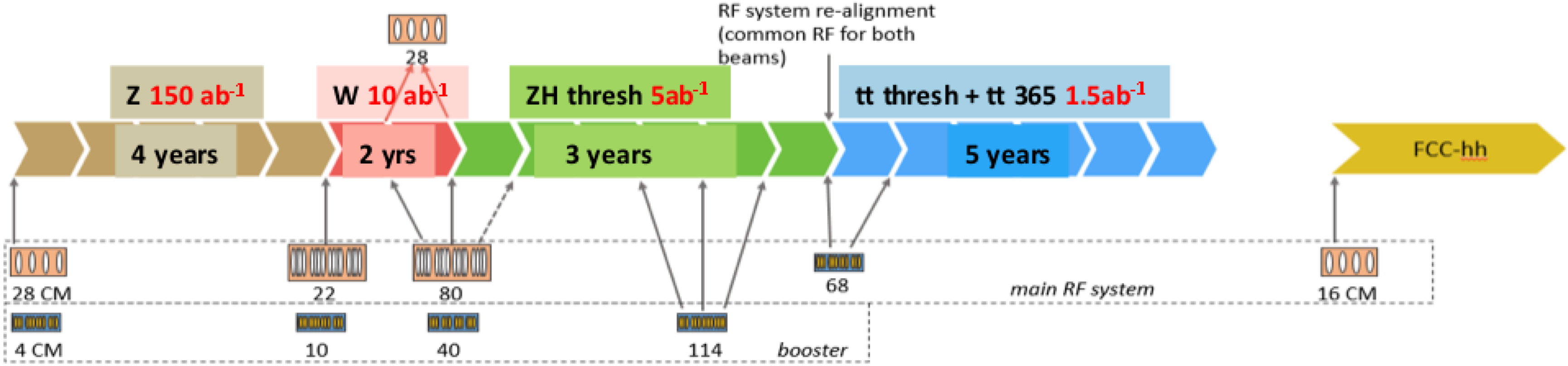
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

- Installation as LEP (≈30 CM/winter)
- high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source
- high energy (W, 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

➔ Spreads the funding profile



indicative: 2(comm) + 2 2 3 5 total ~14 years

FCC-ee Detectors

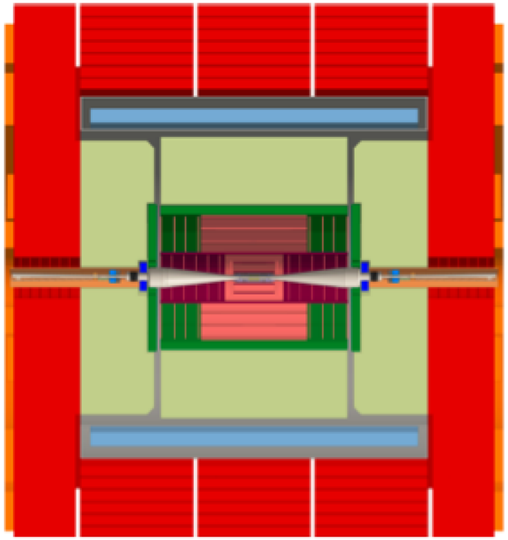
A. Blondel LP17

Two integration, performance and cost estimates ongoing:

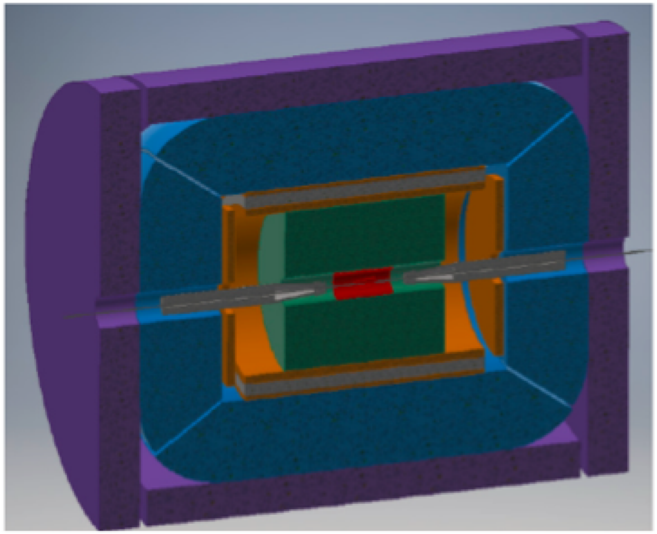
-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"

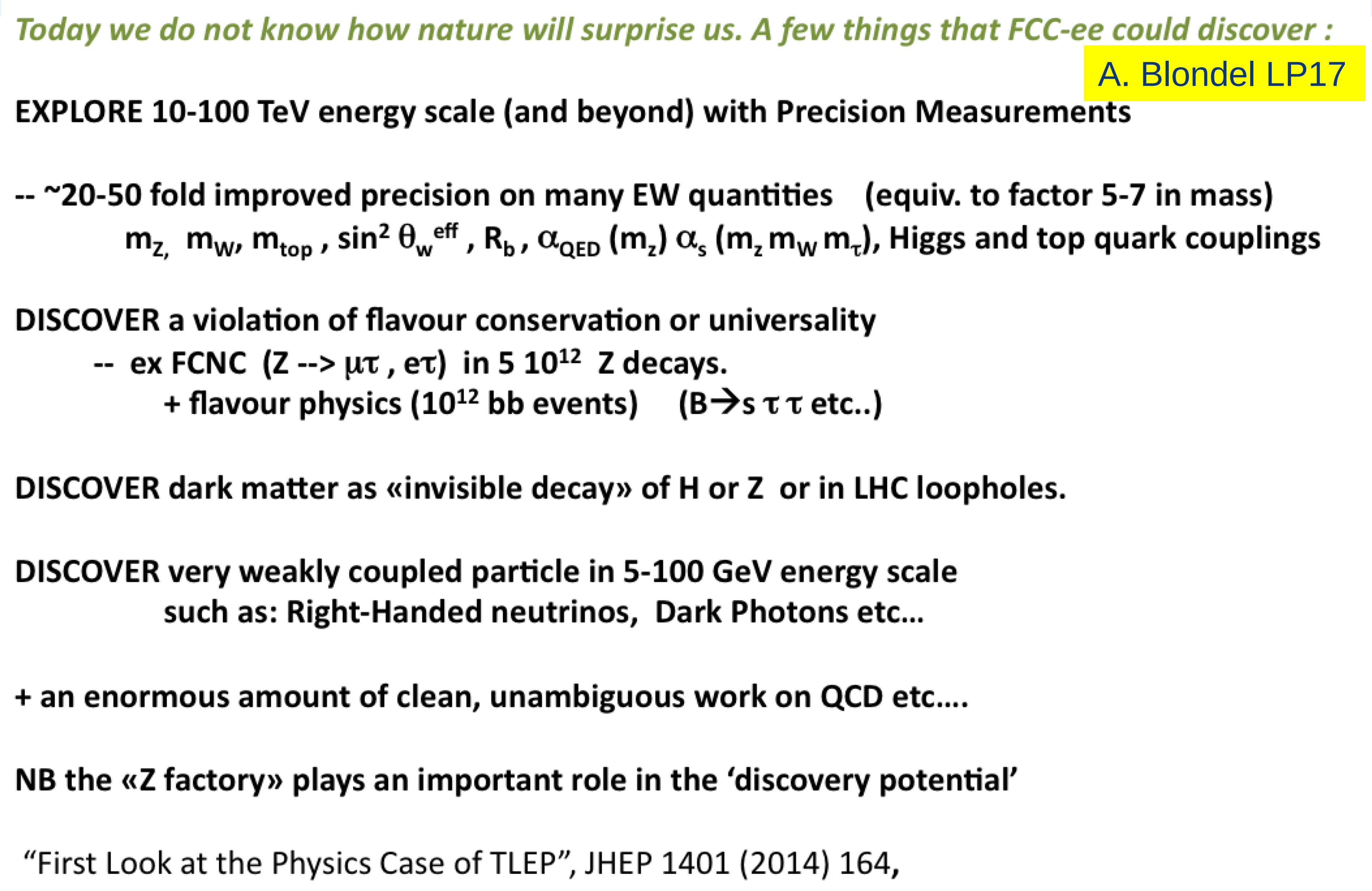


"IDEA"



- Vertex detector: ALICE MAPS
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

FCC-ee Discovery Potential



Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

A. Blondel LP17

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)

$m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality

-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.

+ flavour physics (10^{12} bb events) ($B \rightarrow s\, \tau\, \tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z or in LHC loopholes.

DISCOVER very weakly coupled particle in 5-100 GeV energy scale

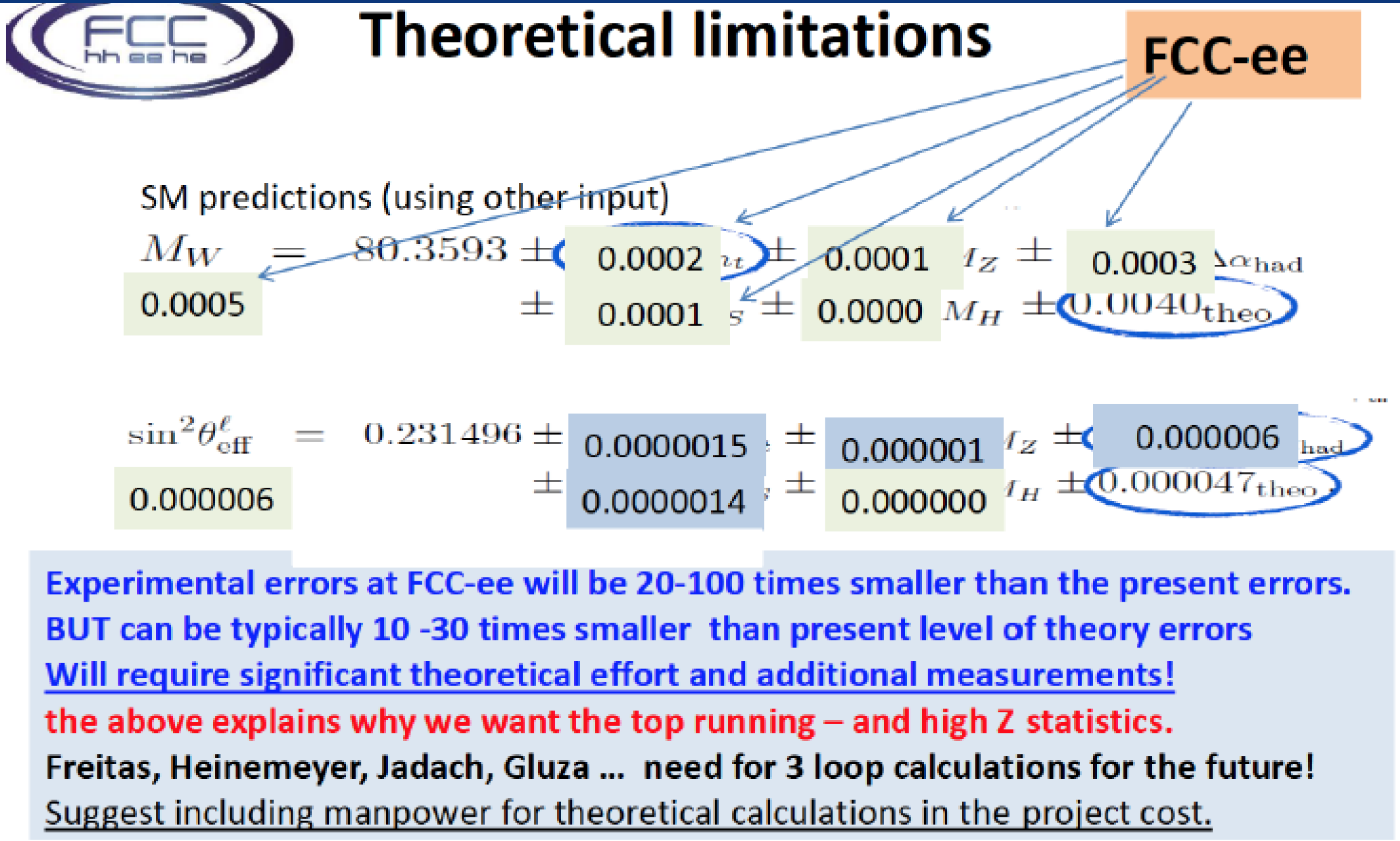
such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD etc….

NB the «Z factory» plays an important role in the 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164,

FCC-ee: Need for Precise Theory



Theoretical limitations

FCC-ee

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0002_{t} \pm 0.0001_{Z} \pm 0.0003_{\Delta\alpha_{\rm had}}$$

$$\pm 0.0001_{s} \pm 0.0000_{M_H} \pm 0.0040_{\rm theo}$$

0.0005

$$\sin^2\theta^\ell_{\rm eff} = 0.231496 \pm 0.0000015 \pm 0.000001_{Z} \pm 0.000006_{\rm had}$$

$$\pm 0.0000014 \pm 0.000000_{H} \pm 0.000047_{\rm theo}$$

0.000006

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.

BUT can be typically 10 -30 times smaller than present level of theory errors

Will require significant theoretical effort and additional measurements!

the above explains why we want the top running – and high Z statistics.

Freitas, Heinemeyer, Jadach, Gluza … need for 3 loop calculations for the future!

Suggest including manpower for theoretical calculations in the project cost.

hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.2)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (5)		25 (5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (0.44)		2.5 (0.5)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	25	(5) 1
peak #events/bunch crossing	170	1000 (200)	800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.6	(15) 40

16 Tesla Magnets

FCC goal is 16 T operating field

- Requires to use Nb_3Sn technology
- At 11 T used for HL-LHC

⇒ Strong synergy with HL-LHC

R&D on cables in test stand at CERN

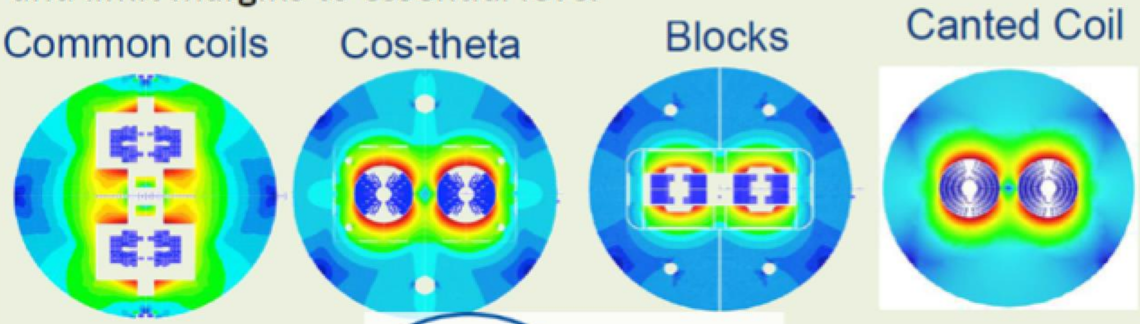
Target: $J_C > 2300$ A/mm² at 1.9 K and 16 T (**50% above HL-LHC**)

Industrial fabrication:
Target cost: 3.4Euro/kAm

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

Magnet design to **minimise material** use and limit margins to essential level

D. Tommasini at al.



CIEMAT, CEA, INFN

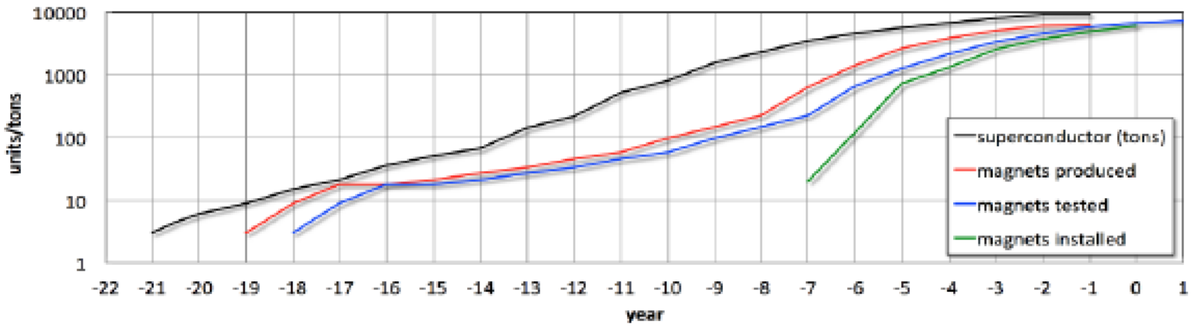
EuroCirCol
A key to New Physics

Swiss contribution
via PSI

D. Schulte, EPS'17

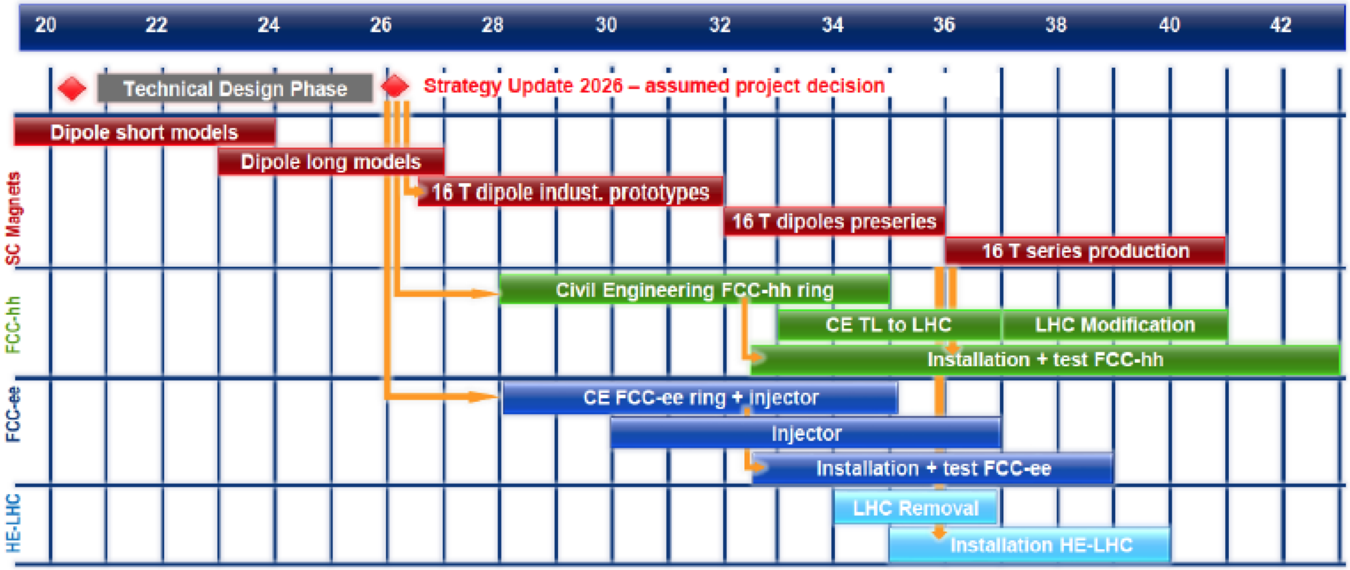
-- possible shorter term application SCSPS or HE-LHC
-- For longer timescale HTS is also studied → 20T

16 Tesla Magnets



Total duration of magnet program:

~20 years



Technical Design Phase

Strategy Update 2026 – assumed project decision

Dipole short models

Dipole long models

16 T dipole indust. prototypes

16 T dipoles preseries

16 T series production

Civil Engineering FCC-hh ring

CE TL to LHC

LHC Modification

Installation + test FCC-hh

CE FCC-ee ring + injector

Injector

Installation + test FCC-ee

LHC Removal

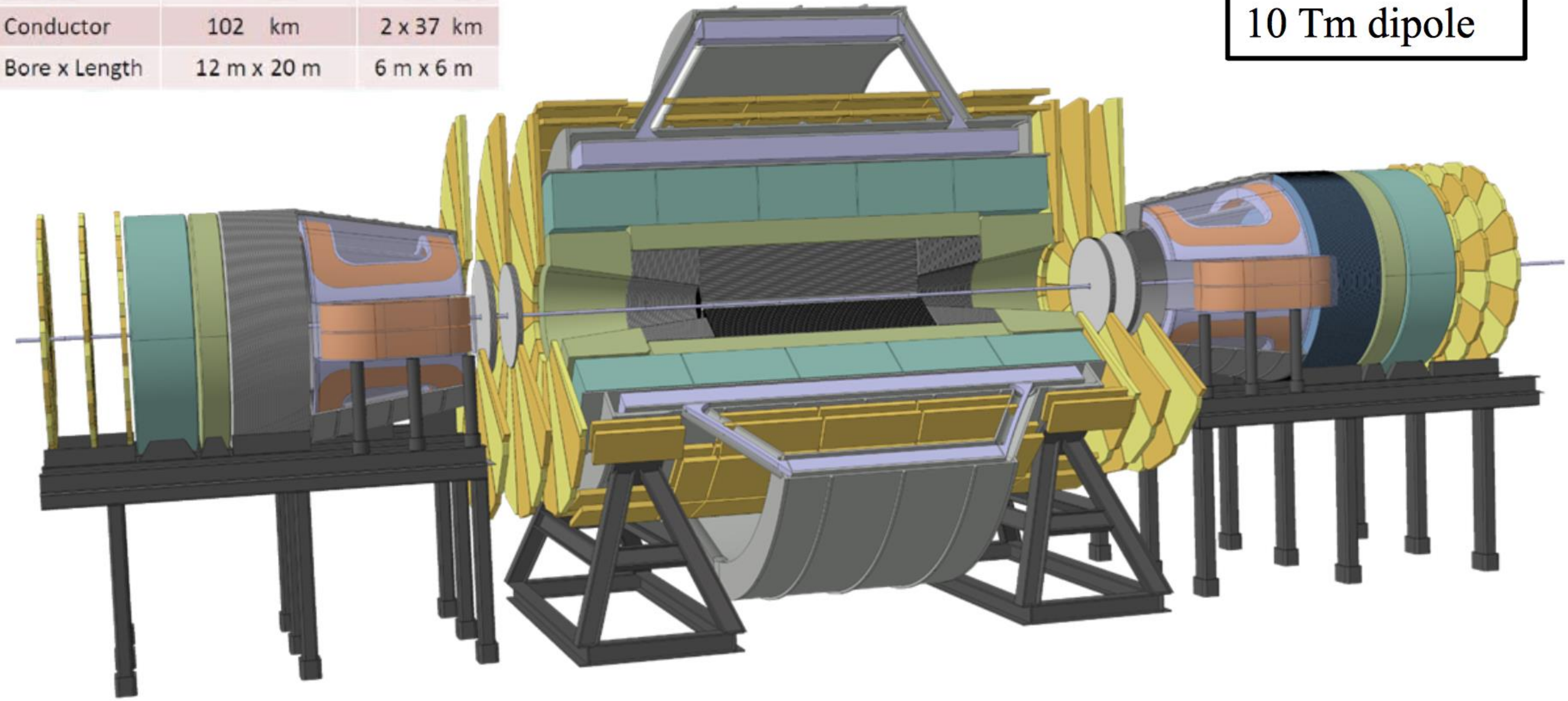
Installation HE-LHC

Baseline FCC-hh Detector 2016

	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

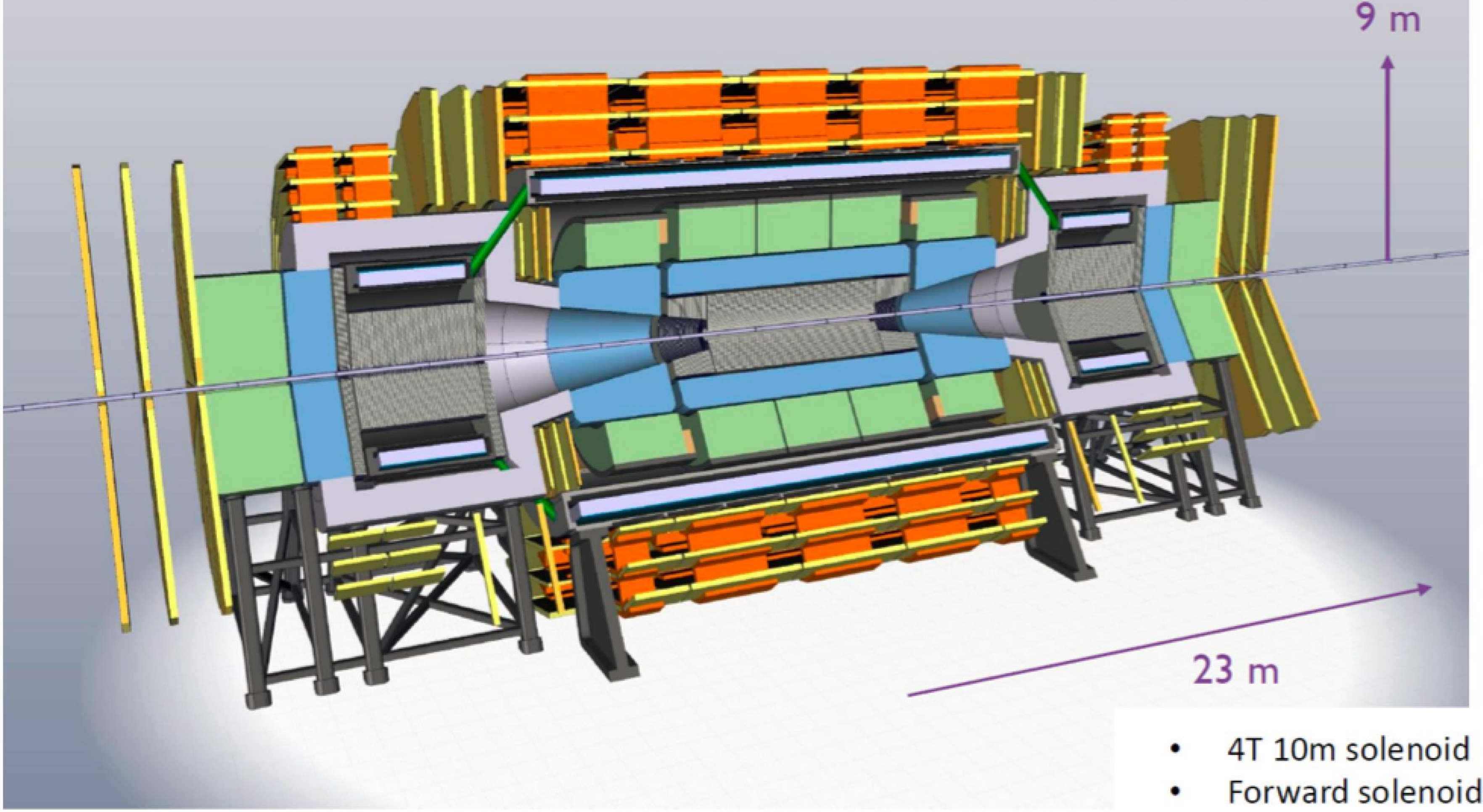
King Size Detector!
Diameter 27m
Length 60m

Twin solenoid
6 Tesla
12m bore
10 Tm dipole



But the detector would be a multi-Billion project. Reasonable?

FCC-hh Reference Detector 2017



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

New Design 2017

Solenoids in Central *and* forward areas no flux return.

FCC-hh Discovery Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!

- ex: strongly coupled new particle up to 50 TeV
  - Excited quarks, Z', W', up to ~tens of TeV
  - Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
  - Sensitivity to high energy phenomena in e.g. WW scattering

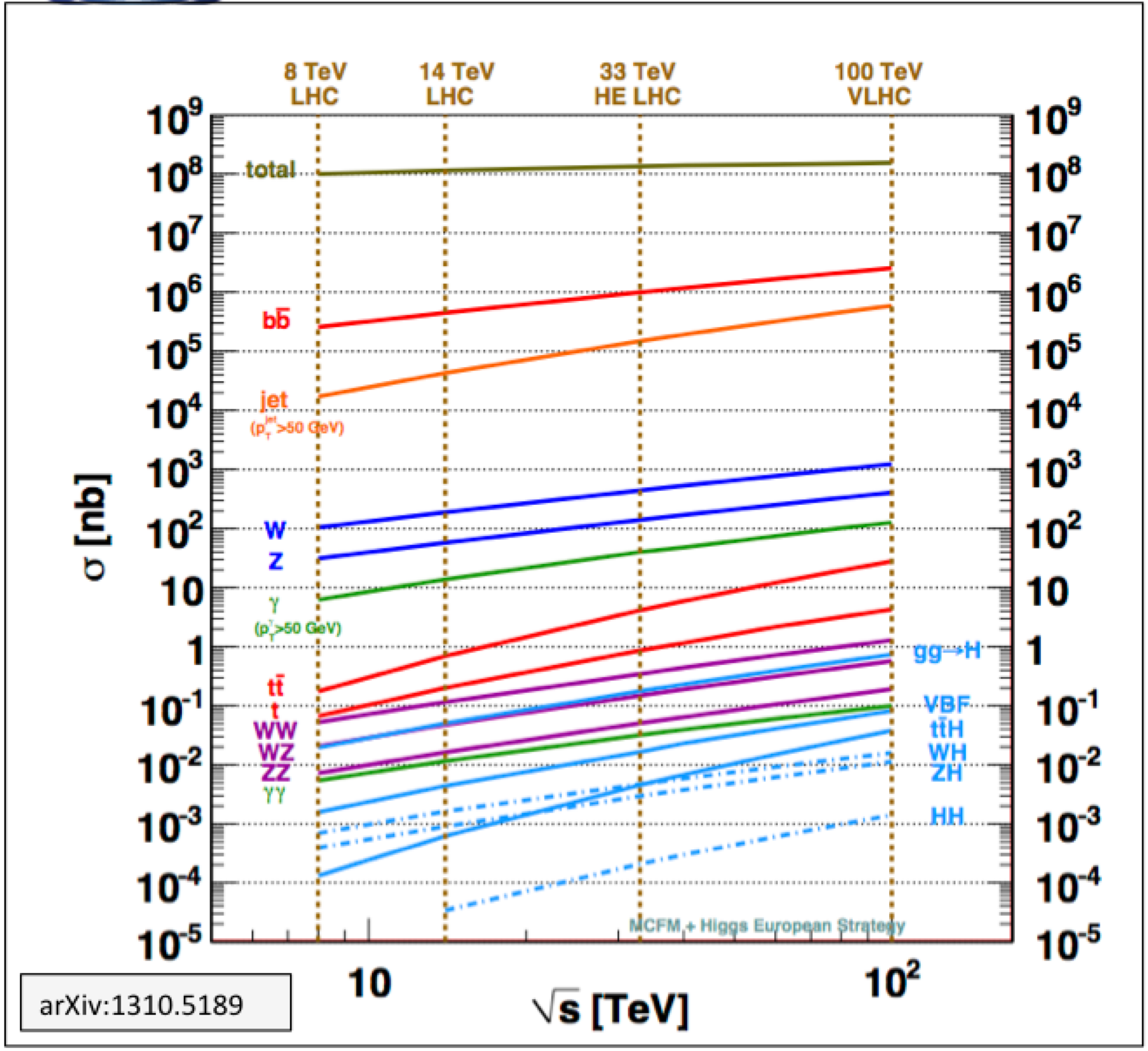
-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks

- -- Higgs precision tests using ratios to e.g. γγ/μμ/ ττ/ZZ, ttH/ttZ @% level
- -- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
- -- detection of rare decays H→ Vγ (V= ρ,φ,J/ψ,ϒ,Z…)
- -- search for invisibles (DM searches, RH neutrinos in W decays)
- -- renewed interest for long lived (very weakly coupled) particles.
- -- rich top and HF physics program

-- Cleaner signals for high Pt physics

- allows clean signals for channels presently difficult at LHC (e.g. H→ bb)

Hadron colliders: direct exploration of the "energy frontier"



arXiv:1310.5189

Gianotti

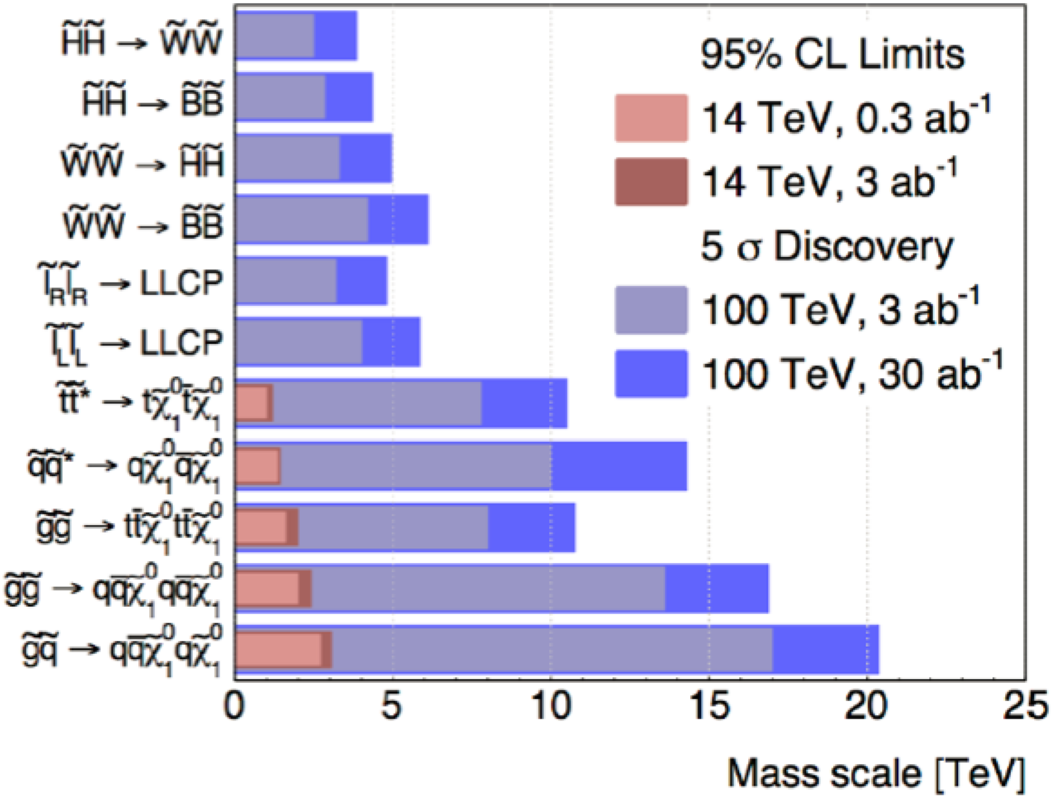
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

With 40/ab at √s=100 TeV expect: ~10^{12} top, 10^{10} H bosons, 10^5 m=8 TeV gluino pairs, …

If new (heavy) physics discovered at the LHC → completion of spectrum is a "no-lose" argument for future ~ 100 TeV pp collider: extend discovery potential up to m~50 TeV

Supersymmetry

Summary from FCC Report:



The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.

Physics Complementarity

Some examples

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling , (and many others)
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc...)
sensitive to heavy physics up to ... 100 TeV
-- FCC-hh gives access to direct observation at unprecedented energies
Also huge statistics of Z,W and top → rare decays

QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had})
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0002$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

Heavy Neutrinos -- ee: very powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
NB this is very much work in progress!!

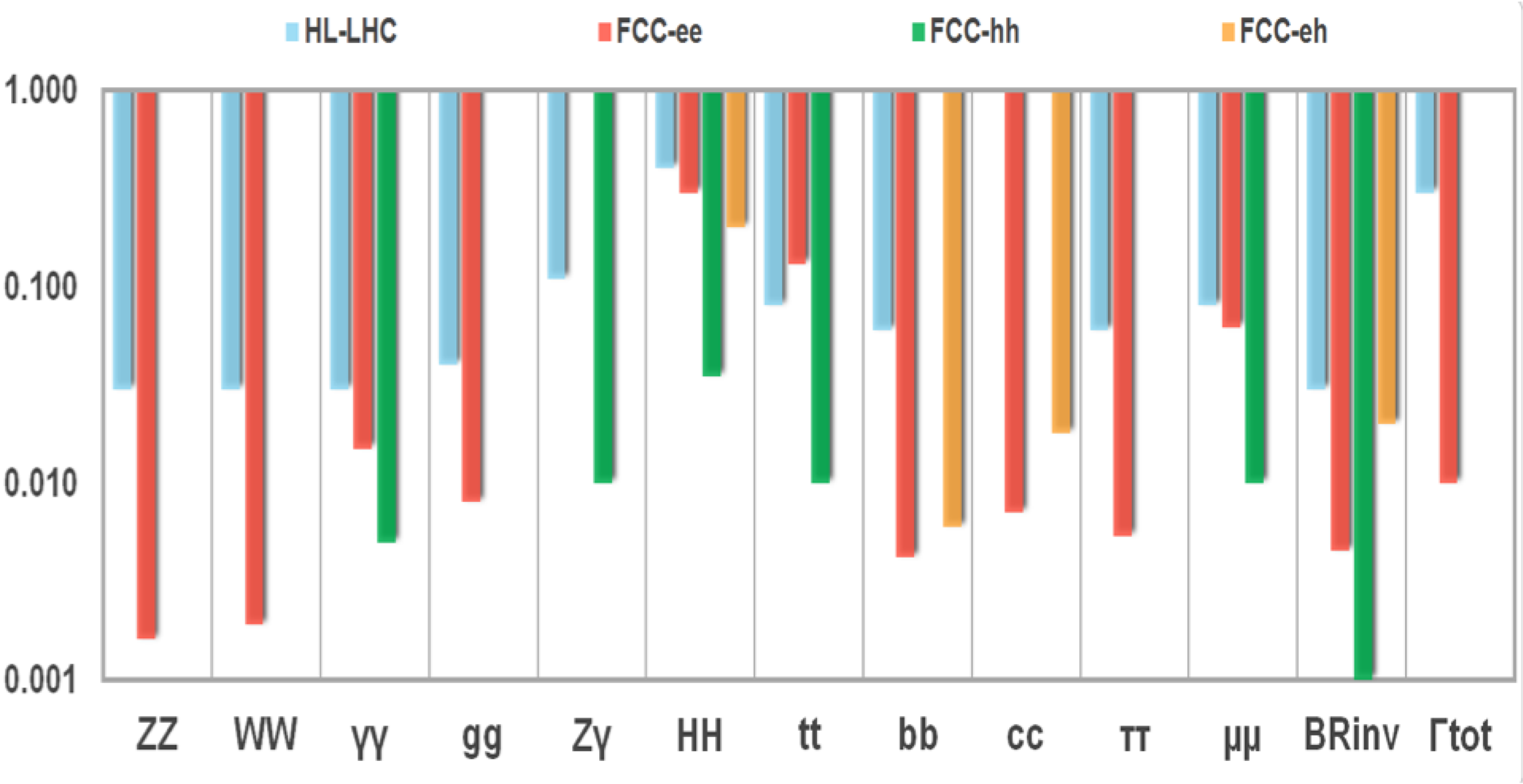
HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume
SM or ee measurements

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
γγ	1.5%	**<1%**	
Zγ	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
ττ	**0.5%**		
cc	**0.7%**		1.8%
μμ	6.2%	**2%**	
uu,dd	H→ ργ?	H→ ργ?	
ss	H→ φγ ?	H→ φγ ?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%

FCC Complementarity



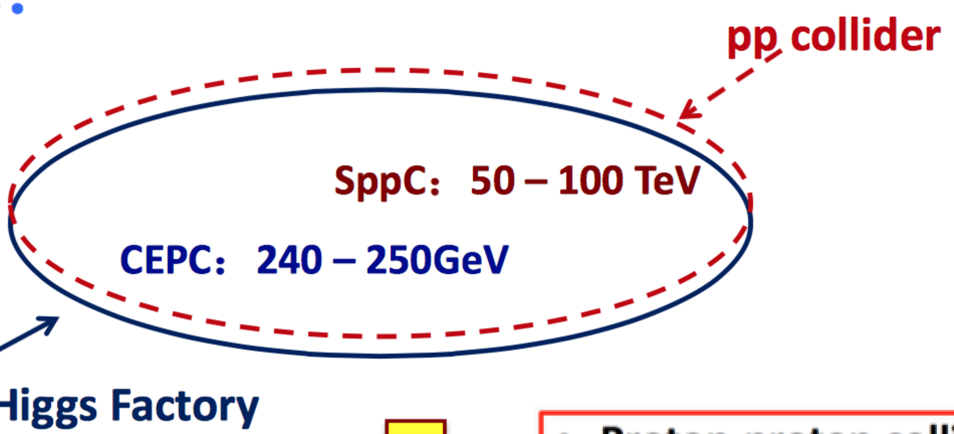
NB this is an ‘impression plot’ not the consistent result of a Higgs coupling fit!

hh, eh precisions assume SM or ee measurements!

The CEPC/SppC Design (China)

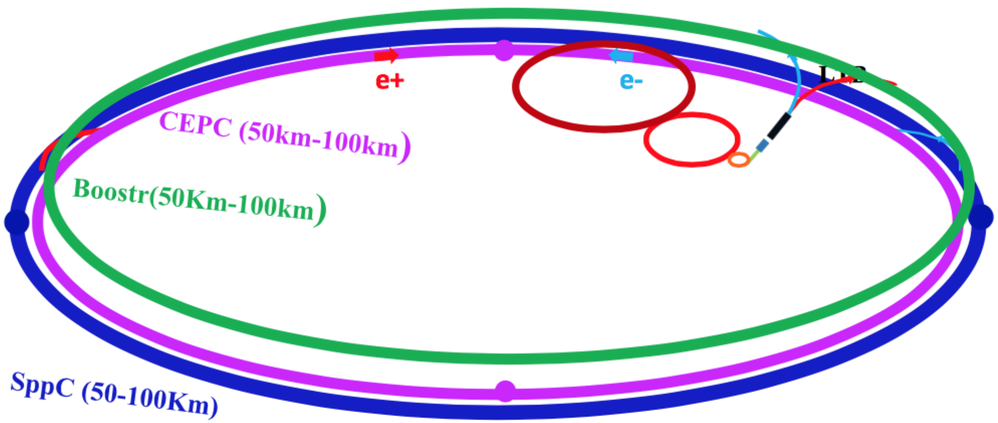
CEPC+SppC：

2012-2014: idea

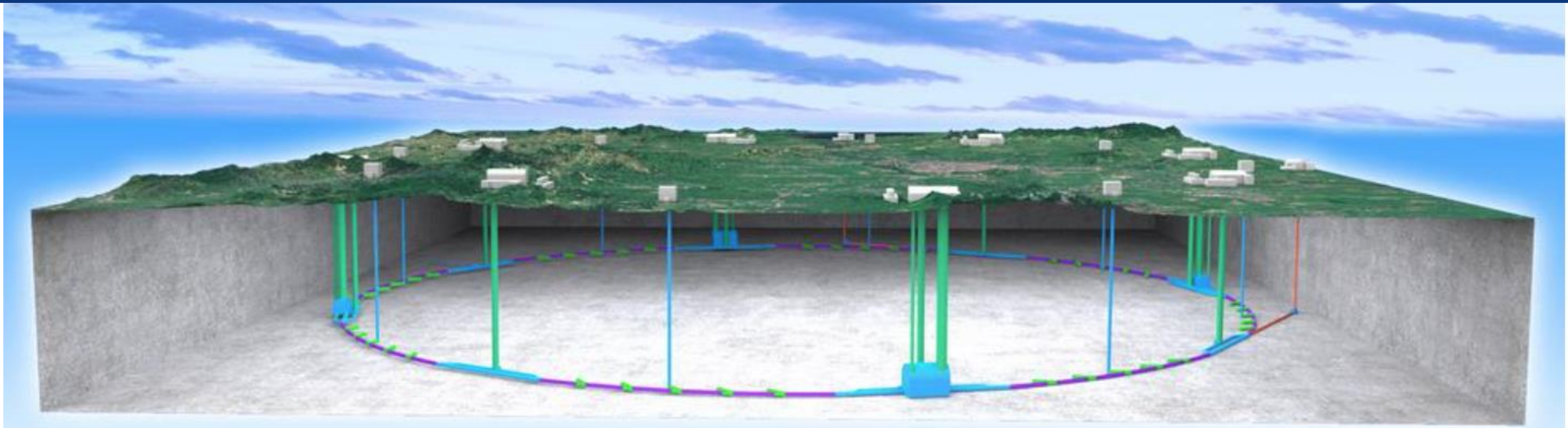


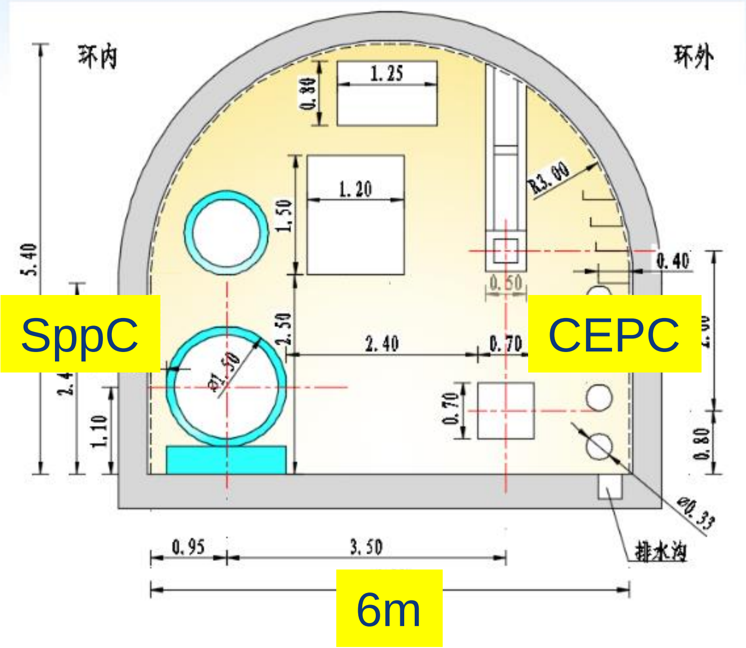
2015 pre-CDR

- **Proton-proton collider(~100 TeV)**
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings



The CEPC/SppC Civil Construction

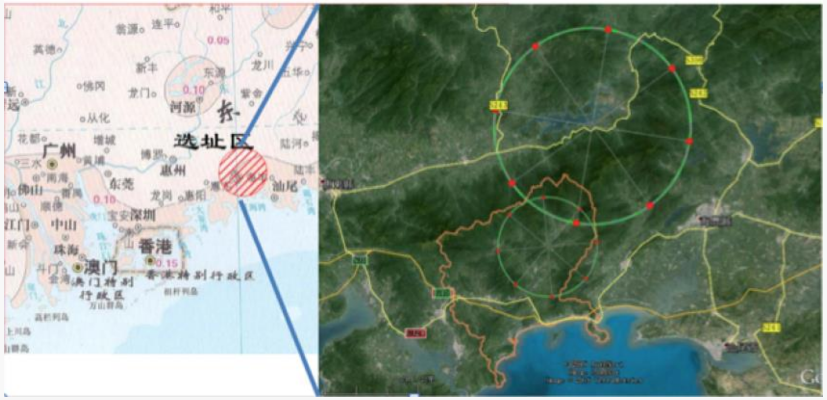




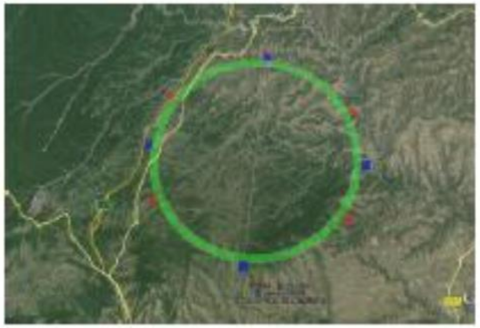
Site selection ongoing

Possibilities among others..

- Qinhuangdao (1 hr by train from Beijing)
- Close to Hong-Kong?...



Alternative CEPC Sites



1) Qinhuangdao

(site technical exloring done)

2) Shanxi Province

(under site technical exploring, started from Jan. 2017)

3) Near Shenzhen and Hongkong

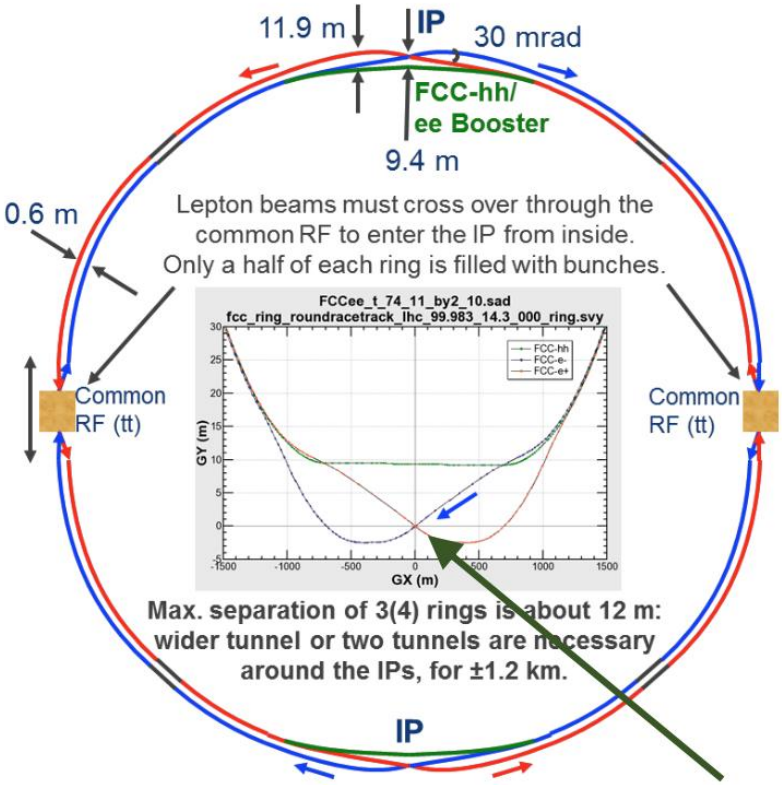
(site technical exloring done)

M. Koratzinos, HongKong

designs for future circular e^+e^- colliders are converging

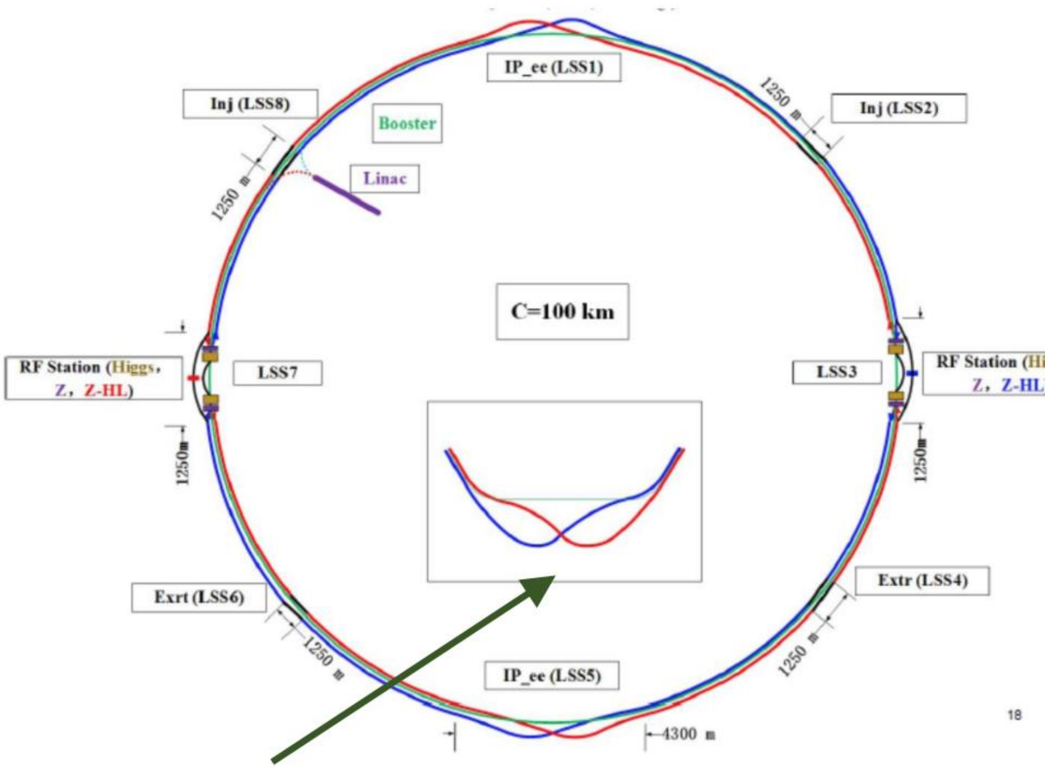
FCC-ee design

CEPC design



Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.



C=97.75 km

“bowtie” final focus
(M. Koratzinos,
A. Blondel, K. Oide)

C=100 km

CEPC Schedule (Ideal)

X. Lou LP17

design issues
R&D items
preCDR

design, funding
R&D program
Intl. collabration
site study

seek approval, site decision
construction during 14th
5- year plan
commissioning

- **CEPC data-taking starts before the LHC program ends**
- **Possibly con-current with the ILC program**

FCC WEEK 2018

AMSTERDAM, 9-13 April 2018

also: 2018 FCC Physics Workshop, 15-19 January 2018, CERN

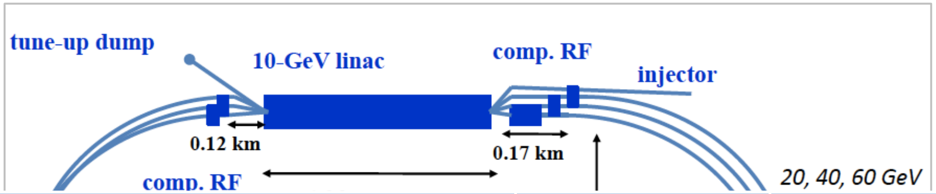
Future Circular Colliders: Summary

- FCC collider design is being developed as option for future flagship project at CERN for the world-wide high energy physics community. It includes hh-ee-eh options
  - Goal is to have CDR ready by end 2018 for European strategy update. No show stoppers so far
  - **https://indico.cern.ch/category/5153/**
- A High Energy LHC scenario is also being studied (again)
- SppC//CEPC in China is moving to a CDR phase
  - Detailed magnet R&D program ramping up for hh-mode
- Detailed physics studies for pp at 100 TeV, e+e- and ep at FCC in progress. Interested people are very welcome to join!

Using an Energy Recovery Linac

Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference →

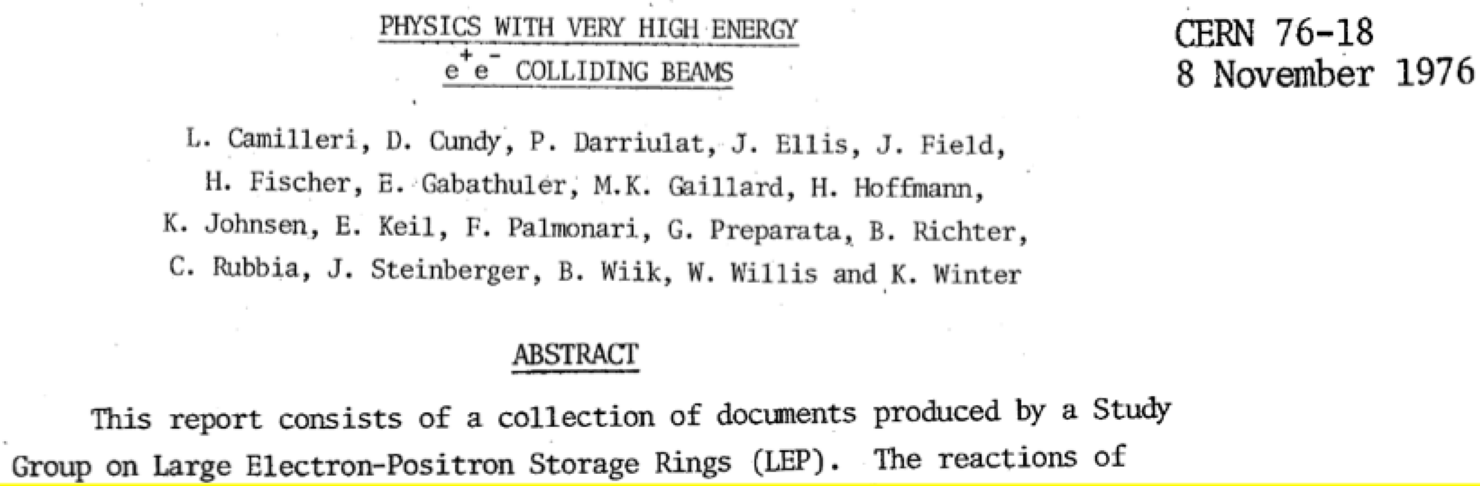


10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [µm]	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [µm]	4	4
rms Beam divergence σ□$^*_{x,y}$ [µrad]	80	40
Beam Current @ IP[mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

Two 1 km long, 10 GeV SC LINACs with 3 accelerating and decelerating passes in W operation

- SRF sees 6*current at the IP (≈ 4ns spacing)
- $Q_0 = 10^{10}$ requires cryogenic system comparable to LHC system! $Q_0 > 10^{10}$

A successful model!



CERN 76-18
8 November 1976

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

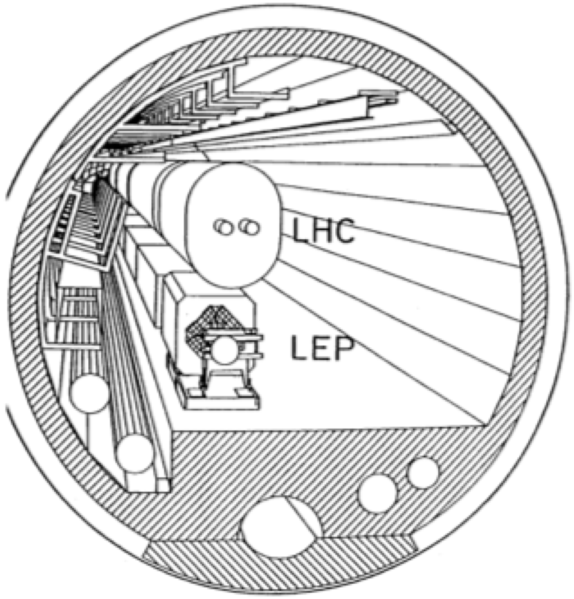
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel **>60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

p p 2009-2039

Let’s not be SHY!

SPPC main parameters

Parameter	Unit	SPPC			FCC	
		PreCDR	"CDR"	"Ultimate"		
Circumference	km	54.4	100	100	100	
c.m. energy	TeV	70.6	75	125-150	100	
dipole field	T	20	12	20-24	16	
injection energy	TeV	2.1	2.1	4.2	3.3	
#IPs		2	2	2	2	
luminosity per IP	10^{35} cm^{-2}s^{-1}	1.2	1.0	-	0.5	3.0
norm. emittance	μm	4.1	2.4	?	2.2 (0.44)	
IP beta function	m	0.75	0.75	-	1.1	0.3
beam current	A	1.0	0.7	-	0.5	
bunch separation	ns	25	25	-	25 (5)	25 (5)
bunch population	10^{11}	2.0	1.5	-	1.0 (0.2)	1.0 (0.2
SR power /beam	MW	2.1	1.1	-	2.5	
SR heat load/ap	W/m	45	13	-	30	

J. Tang

Parameters for CEPC double ring for CDR Goal

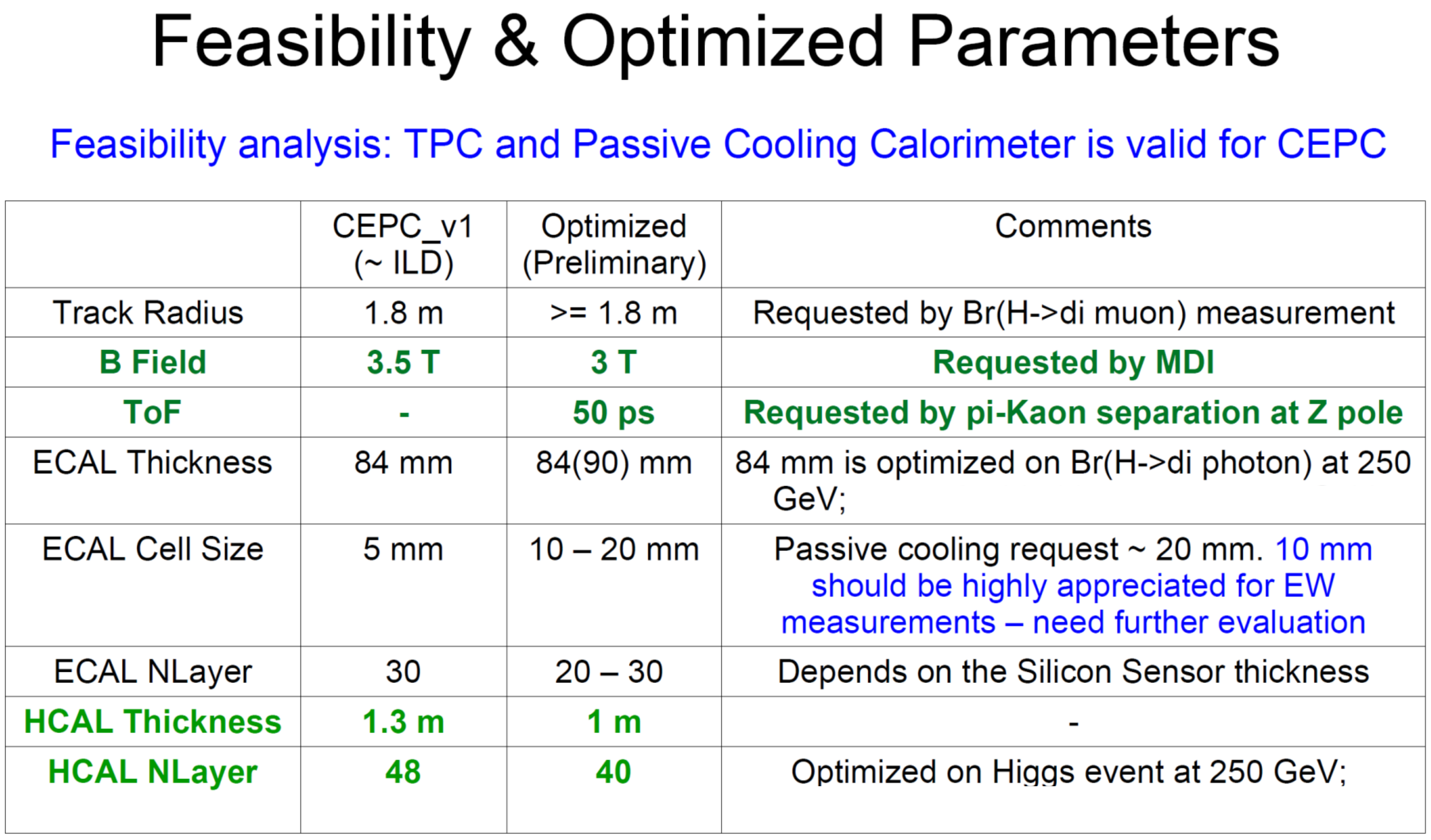
（wangdou20170426-100km_2mmβy）

	Pre-CDR	***Higgs***	***W***	***Z***	
Number of IPs	2	2	2	2	
Energy (GeV)	120	120	80	45.5	
Circumference (km)	54	100	100	100	
SR loss/turn (GeV)	3.1	1.67	0.33	0.034	
Half crossing angle (mrad)	0	16.5	16.5	16.5	
Piwinski angle	0	3.19	5.69	4.29	11.77
N_e/bunch (10^{11})	3.79	0.968	0.365	0.455	0.307
Bunch number	50	412	5534	21300	2770
Beam current (mA)	16.6	19.2	97.1	465.8	408.7
SR power /beam (MW)	51.7	**32**	**32**	**16.1**	**1.4**
Bending radius (km)	6.1	11	11	11	11
Momentum compaction (10^{-5})	3.4	1.14	1.14	4.49	1.14
β_{IP} x/y (m)	0.8/0.0012	0.171/0.002	0.171 /0.002	0.16/0.002	0.171 /0.002
Emittance x/y (nm)	6.12/0.018	1.31/0.004	0.57/0.0017	1.48/0.0078	0.18/0.0037
Transverse σ_{IP} (um)	69.97/0.15	15.0/0.089	9.9/0.059	15.4/0.125	5.6/0.086
ξ_x/ξ_y/IP	0.118/0.083	0.013/0.083	0.0055/0.062	0.008/0.054	0.006/0.054
RF Phase (degree)	153.0	128	126.9	165.3	136.2
V_{RF} (GV)	6.87	**2.1**	**0.41**	**0.14**	**0.05**
f_{RF} (MHz) (harmonic)	650	650	650 (217800)	650 (217800)	
Nature σ_z (mm)	2.14	**2.72**	**3.37**	**3.97**	**3.83**
Total σ_z (mm)	2.65	2.9	3.4	4.0	4.0
HOM power/cavity (kw)	3.6 (5cell)	0.41(2cell)	0.36(2cell)	1.99(2cell)	0.12(2cell)
Energy spread (%)	0.13	0.098	0.065	0.037	
Energy acceptance (%)	2	1.5			
Energy acceptance by RF (%)	6	2.1	1.1	1.1	0.68
n_γ	0.23	0.26	0.15	0.12	0.22
Life time due to beamstrahlung_cal (minute)	47	52			
F (hour glass)	0.68	0.96	0.98	0.96	0.99
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	2.0	5.15	11.9	1.1

Preliminary results shows **co-existence of Z/H programs** are possible

Reconfiguration of CEPC can lead to much better luminosity at the Z pole → **Z facto**

CEPC Detector: more compact & updated for CDR



Feasibility & Optimized Parameters

Feasibility analysis: TPC and Passive Cooling Calorimeter is valid for CEPC

	CEPC_v1 (~ ILD)	Optimized (Preliminary)	Comments
Track Radius	1.8 m	>= 1.8 m	Requested by Br(H->di muon) measurement
B Field	**3.5 T**	**3 T**	**Requested by MDI**
ToF	**-**	**50 ps**	**Requested by pi-Kaon separation at Z pole**
ECAL Thickness	84 mm	84(90) mm	84 mm is optimized on Br(H->di photon) at 250 GeV;
ECAL Cell Size	5 mm	10 – 20 mm	Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation
ECAL NLayer	30	20 – 30	Depends on the Silicon Sensor thickness
HCAL Thickness	**1.3 m**	**1 m**	-
HCAL NLayer	**48**	**40**	Optimized on Higgs event at 250 GeV;

CEPC Funding

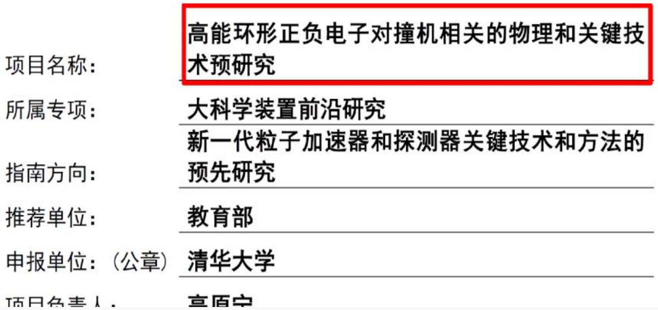
HEP seed money

11 M RMB/3 years (2015-2017)

国家重点研发计划
项目预申报书

FY 2016

Ministry of Science and Technology
Requested 45M RMB; 36M RMB approved



项目名称：高能环形正负电子对撞机相关的物理和关键技术预研究
所属专项：大科学装置前沿研究
指南方向：新一代粒子加速器和探测器关键技术和方法的预先研究
推荐单位：教育部
申报单位：（公章）清华大学
项目负责人：高原宁

R&D Funding - NSFC

Increasing support for CEPC D+RDby NSFC
5 projects (2015); 7 projects(2016)

CEPC相关基金名称（2015-2016）	基金类型	负责人	承担单位
高精度气体径迹探测器及激光校正的研究 (2015)	重点基金	李玉兰/ 陈元柏	清华大学/ Tsinghua 高能物理研究所 IHEP
成像型电磁量能器关键技术研究(2016)	重点基金	刘树彬	中国科技大学 USTC
CEPC局部双环对撞区挡板系统设计及螺线管场补偿(2016)	面上基金	白莎	高能物理研究所
用于顶点探测器的高分辨、低功耗SOI像素芯片的若干关键问题的研究(2015)	面上基金	卢云鹏	高能物理研究所
基于粒子流算法的电磁量能器性能研究 (2016)	面上基金	王志刚	高能物理研究所
基于THGEM探测器的数字量能器的研究(2015)	面上基金	俞伯祥	高能物理研究所
高粒度量能器上的通用粒子流算法开发(2016)	面上基金	阮曼奇	高能物理研究所
正离子反馈连续抑制型气体探测器的实验研究(2016)	面上基金	祁辉荣	高能物理研究所
CEPC对撞区最终聚焦系统的设计研究(2015)	青年基金	王逗	高能物理研究所
利用耗尽型CPS提高顶点探测器空间分辨精度的研究 (2016)	青年基金	周扬	高能物理研究所
关于CEPC动力学孔径研究(2016)	青年基金	王毅伟	高能物理研究所

~60M RMB CAS-Beijing fund, talent program

~500M RMB Beijing fund (light source)

year 2017 funding request (45M) to MOST and other agencies under preparation

funding needs for carrying out CEPC design and R&D should be fully met by end of 2018

Physics Requirements (FCC-hh)

Higgs boson physics: 125 GeV object at 100 TeV can be highly boosted + need for optimal sensitivity to multi-Higgs and VBF processes.

- Precision tracking (momentum spectroscopy) and ECAL up to η=4
- Tracking and highly granular calorimetry for jets up to η=6.
- Sensitivity to low *pT* tracks vital for broad physics acceptance.

Searches require excellent performance at the highest energies.

- Calorimetry: hermetic and 1-2% constant term (shower containment needs 12 λ).
- Tracking: high momentum resolution ~10% at pT=10 TeV.

Pile-up for 30x10^34 and 25ns would reach ~1000 events/bunch crossing.

- Calorimeter granularity of ΔR ≤ 0.05x0.05 or 0.025x0.025 to mitigate pile-up and measure jet substructure and boosted objects.
- Precision track association with primary vertex, timing for pileup rejection etc. …

Efficient b, c, τ -tagging despite intense radiation levels at low radii.

e-mail-list:fcc-experiments-hadron@cern.ch
Contact: Werner.Riegler@cern.ch