Gli acceleratori futuri: i progetti in discussione

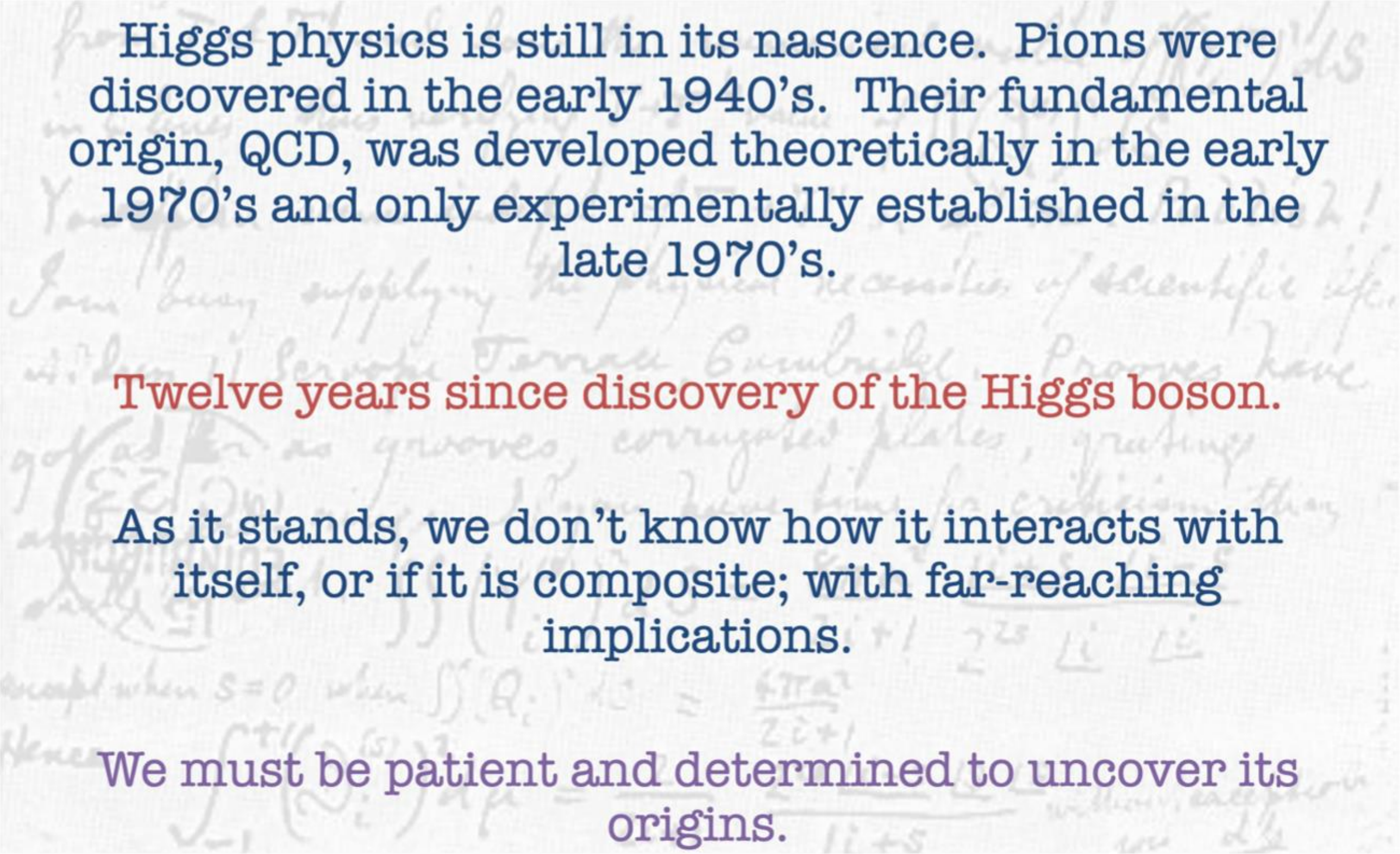
Una raccolta di informazioni dalle seguenti presentazioni:

- *P. Campana* *"Future collider projects"*
- *L. Rossi* *"Accelerator challenge"*

tenute al Workshop on High Luminosity LHC and Hadron Collider,
Frascati ottobre 2024

Riunione CSN1/RM2, 6 novembre 2024

LHC: no anomaly so far in Higgs model



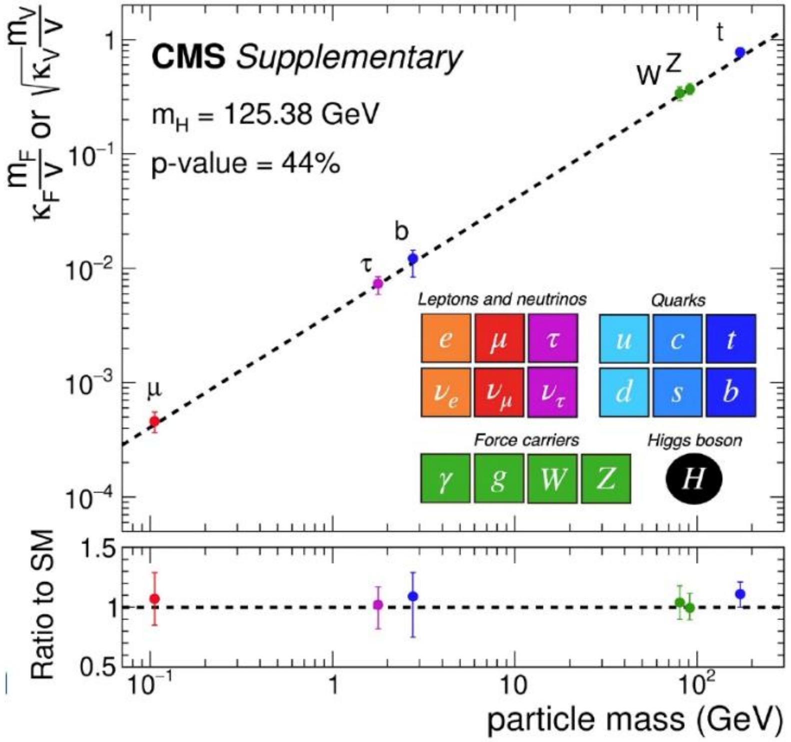
Higgs physics is still in its nascence. Pions were discovered in the early 1940’s. Their fundamental origin, QCD, was developed theoretically in the early 1970’s and only experimentally established in the late 1970’s.

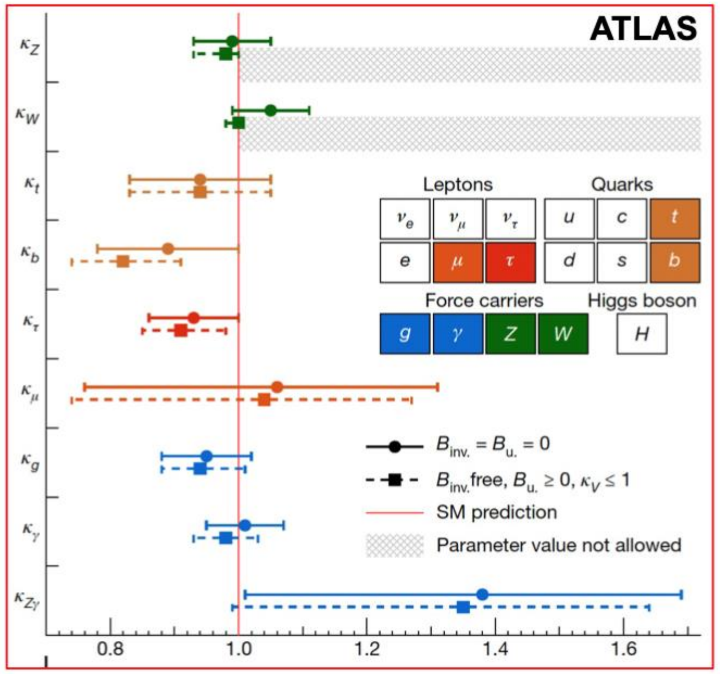
Twelve years since discovery of the Higgs boson.

As it stands, we don’t know how it interacts with itself, or if it is composite; with far-reaching implications.

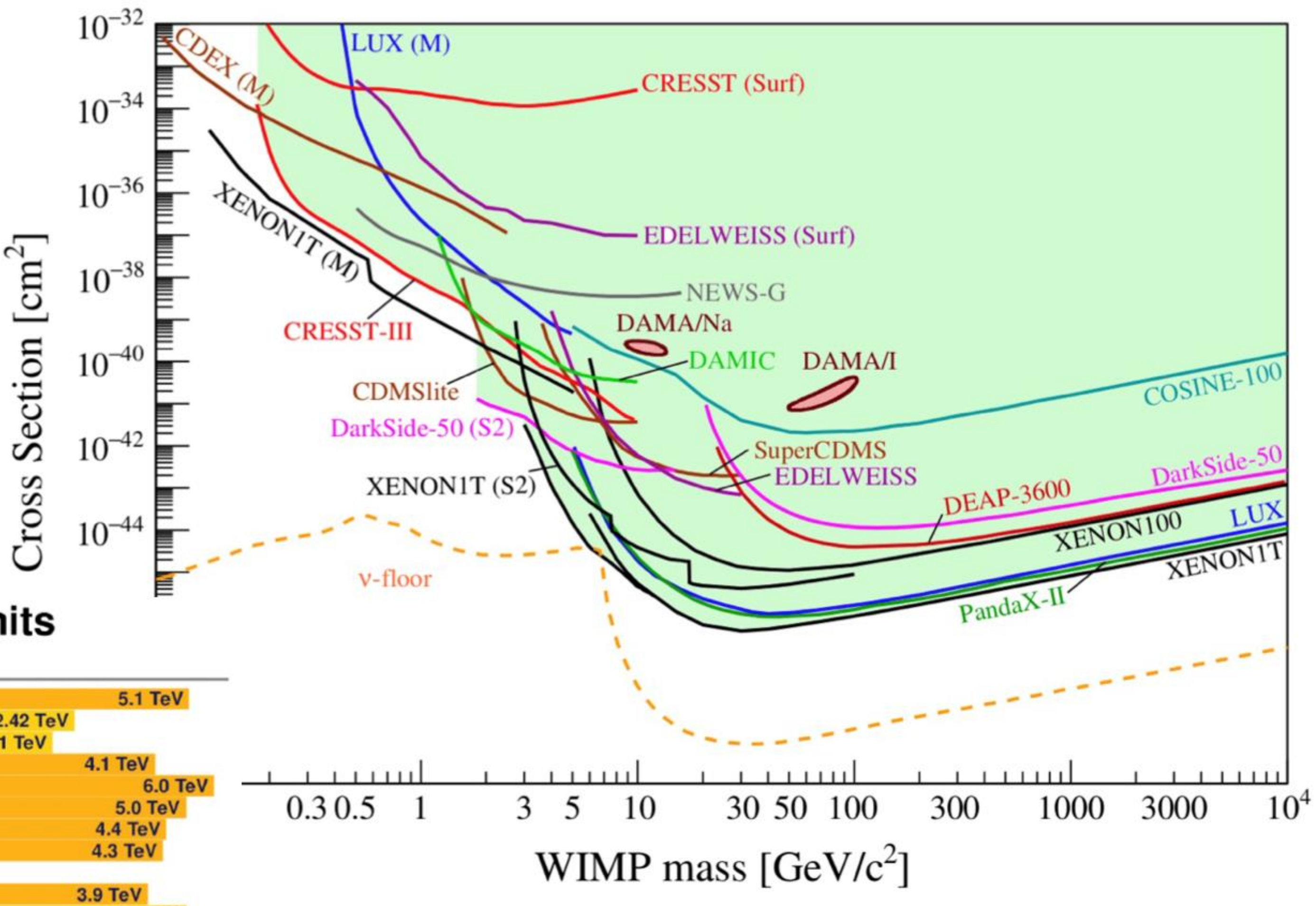
We must be patient and determined to uncover its origins.

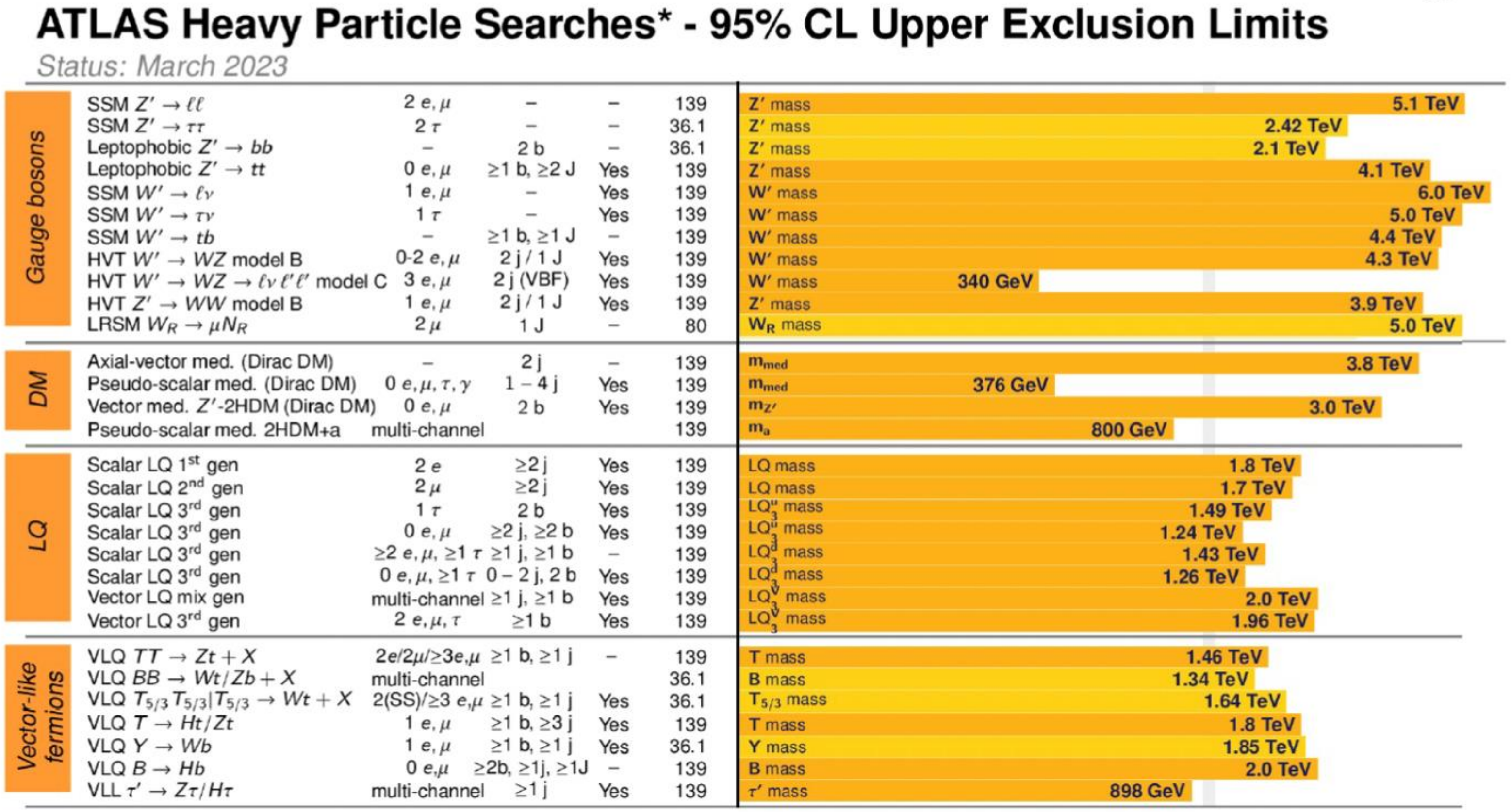
M. McCullogh ICHEP2024





BSM and DM: no signs



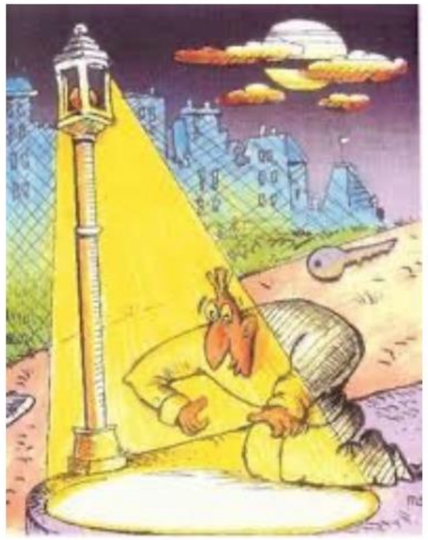


ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

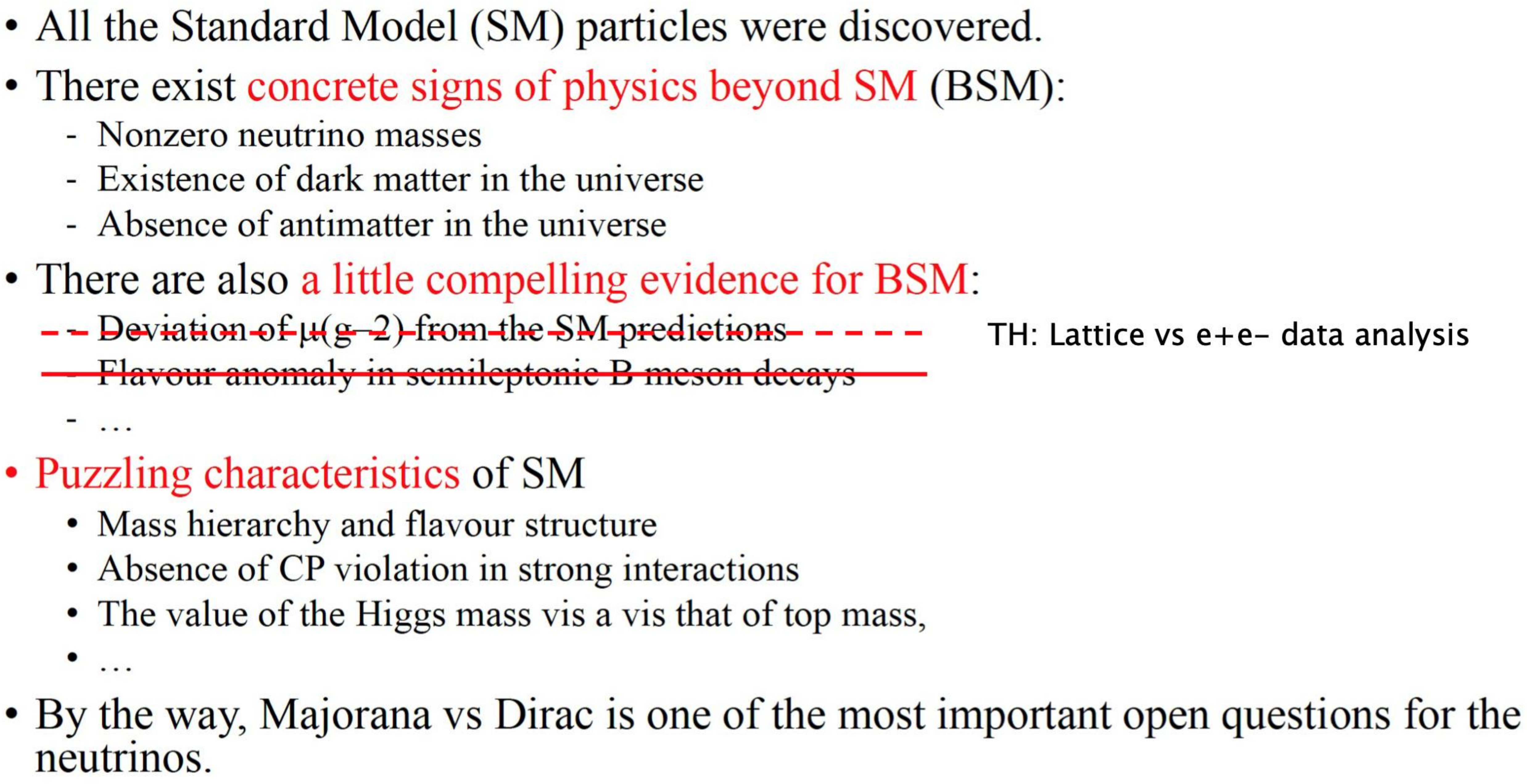
Status: March 2023

Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass	6.0 TeV
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass	5.0 TeV
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV
	HVT $W' \to WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass	340 GeV
	HVT $Z' \to WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass	3.9 TeV
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med}	3.8 TeV
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med}	376 GeV
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$	3.0 TeV
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a	800 GeV
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass	1.8 TeV
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass	1.7 TeV
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass	1.49 TeV
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass	2.0 TeV
	Vector LQ 3rd gen	2 e, μ, τ	≥1 b	Yes	139	LQ_3^V mass	1.96 TeV
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.46 TeV
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV
	VLQ $T_{5/3}T_{5/3} \| T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV

24



Current situation

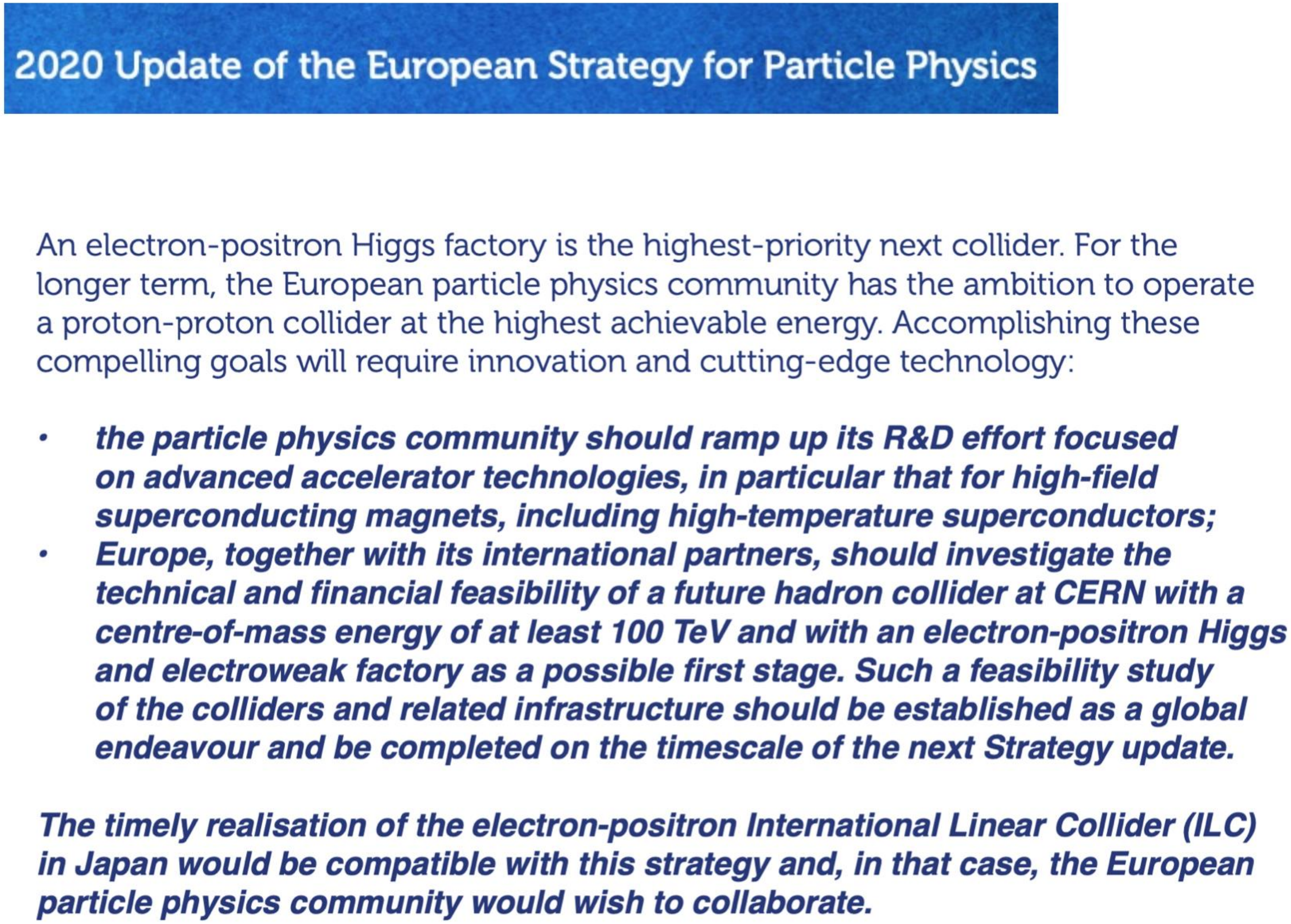


- All the Standard Model (SM) particles were discovered.
- There exist concrete signs of physics beyond SM (BSM):
  - Nonzero neutrino masses
  - Existence of dark matter in the universe
  - Absence of antimatter in the universe
- There are also a little compelling evidence for BSM:
  - ~~Deviation of $\mu(g-2)$ from the SM predictions~~
  - ~~Flavour anomaly in semileptonic B meson decays~~
  - …
- Puzzling characteristics of SM
  - Mass hierarchy and flavour structure
  - Absence of CP violation in strong interactions
  - The value of the Higgs mass vis a vis that of top mass,
  - …
- By the way, Majorana vs Dirac is one of the most important open questions for the neutrinos.

TH: Lattice vs e+e− data analysis

T. Nakada, ECR 2023, CERN

European strategy 2020 proposal



2020 Update of the European Strategy for Particle Physics

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

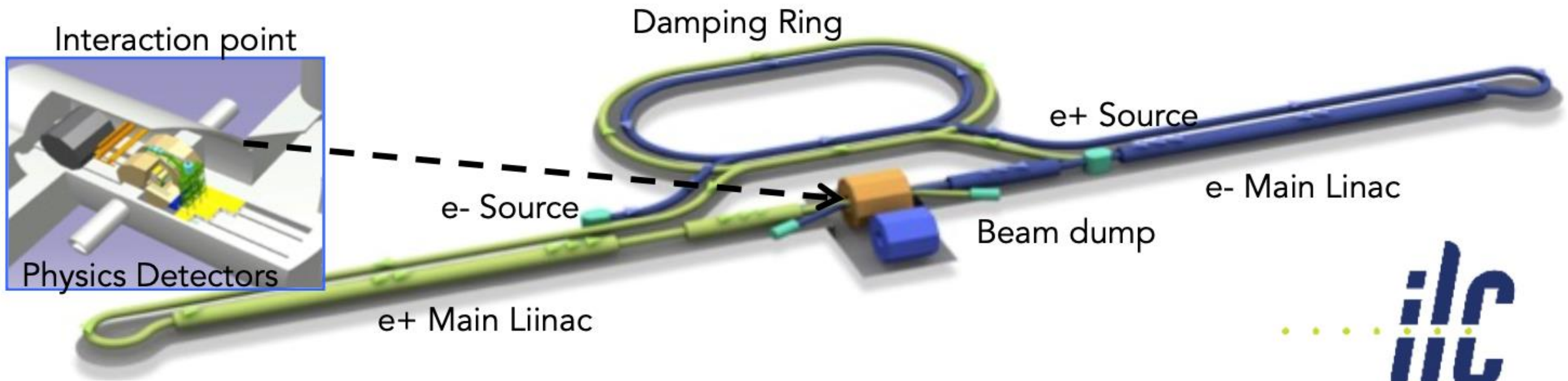
- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***
- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

The near term collider landscape: technology ready

ILC, CLIC, FCC-ee, CEPC

International Linear Collider (ILC)



ILC (TDR completed in 2013)
Baseline footprint L=20 km (250 GeV), 31 km (500 GeV)

Weel tested superconducting RF technology ~ 30 MV/m
(XFEL, ESS, LCLS2, PIP II)

Item	Parameters
C.M. Energy	250 GeV
Length	20 km
Luminosity	**1.35 x10^{34} cm^{-2}s^{-1}**
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity Gain Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}

Located in Tohoku province (Japan).
International based project, currently organized through an International Development Team (Japan, US, Europe)
Negotiation between partners still ongoing

Cost (250 GeV, 2017) ~ **5.2 B$**
to adjust for inflation 2017-24 ~ x 1.3

If moved at CERN, cost to be re-evaluated

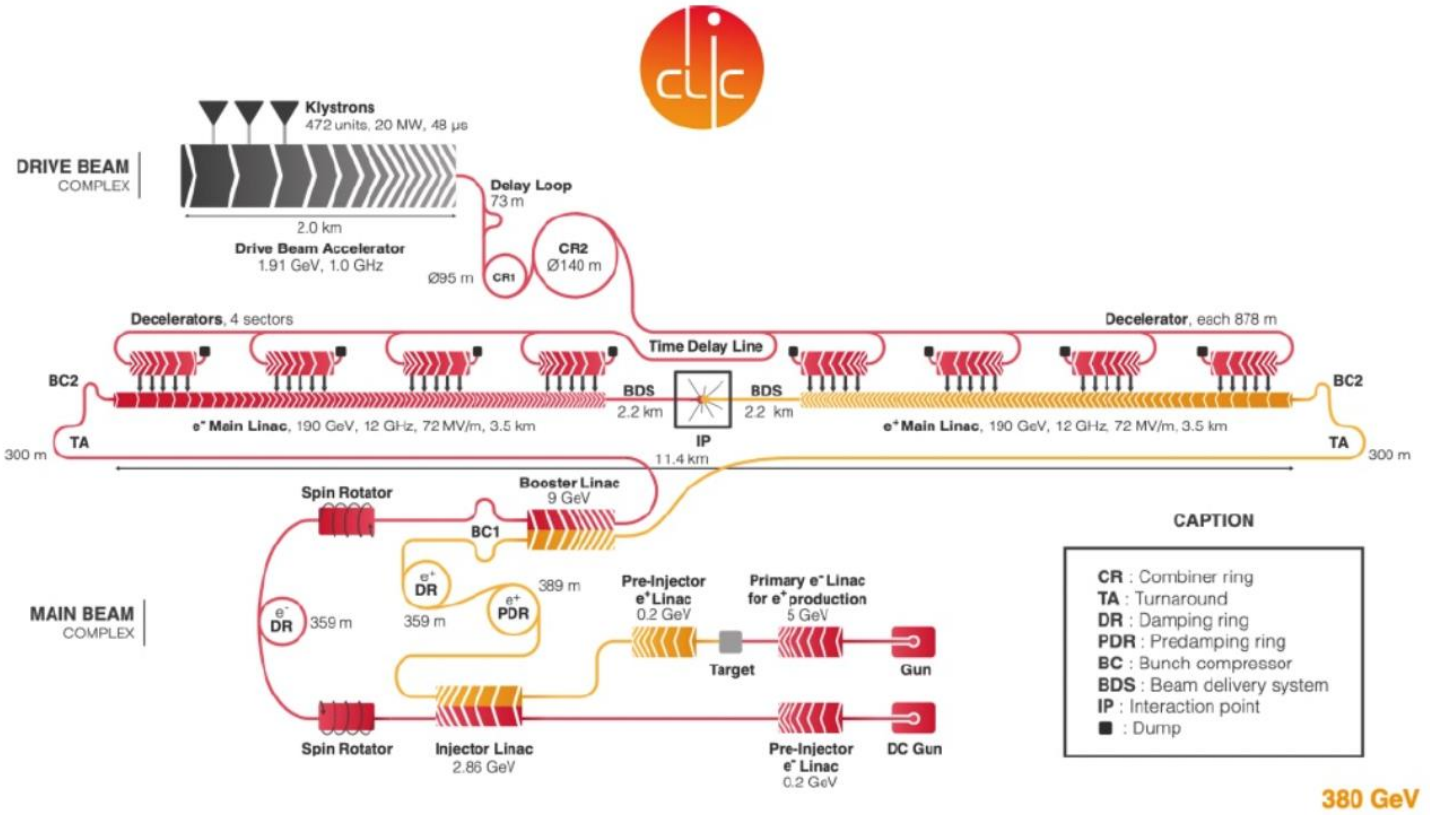
13

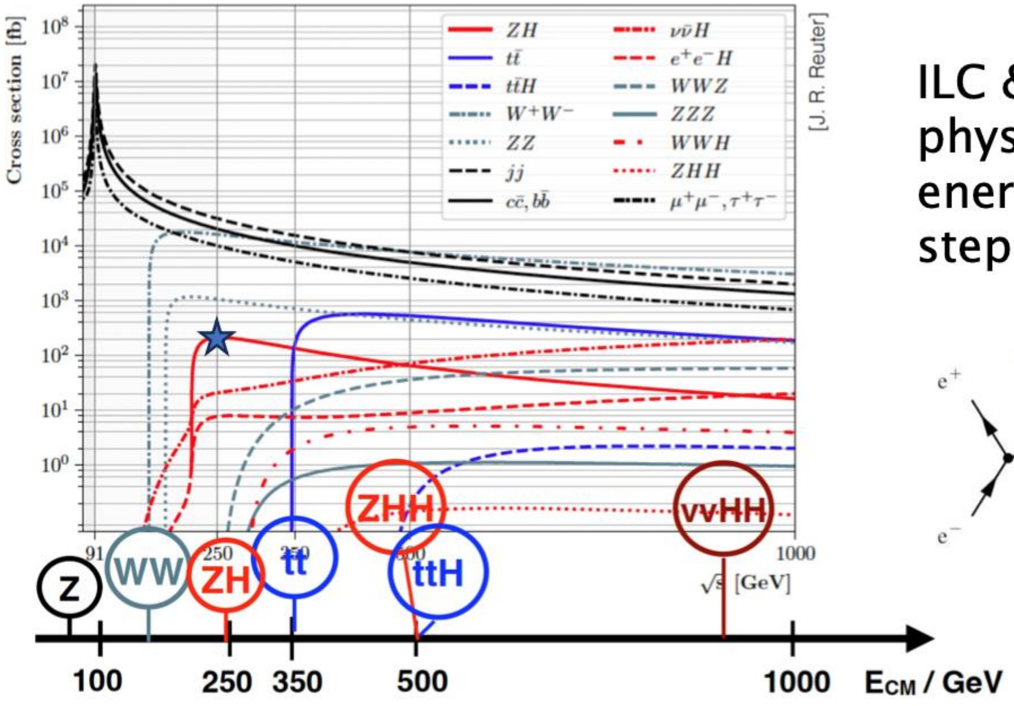
Compact Linear Collider (CLIC)

.

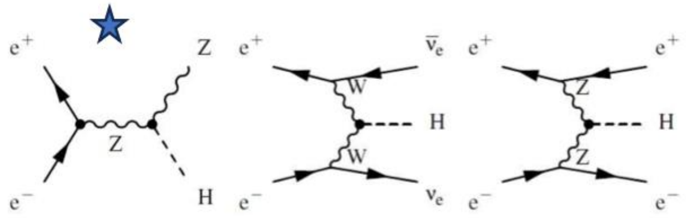
CLIC (pre-TDR in 2018)
Based on RF warm technology: 2 acc. options
- 2 GeV e⁻ drive beam
- X band klystrons
Both aiming at ~70 MV/m

Baseline 380 GeV, L=11 km, **6.0 BSF** (2018)
Scalable up to 3 TeV (50 km !)





ILC & CLIC share the same physics. Difficult to achieve TeV energies without technological step in acc. gradients

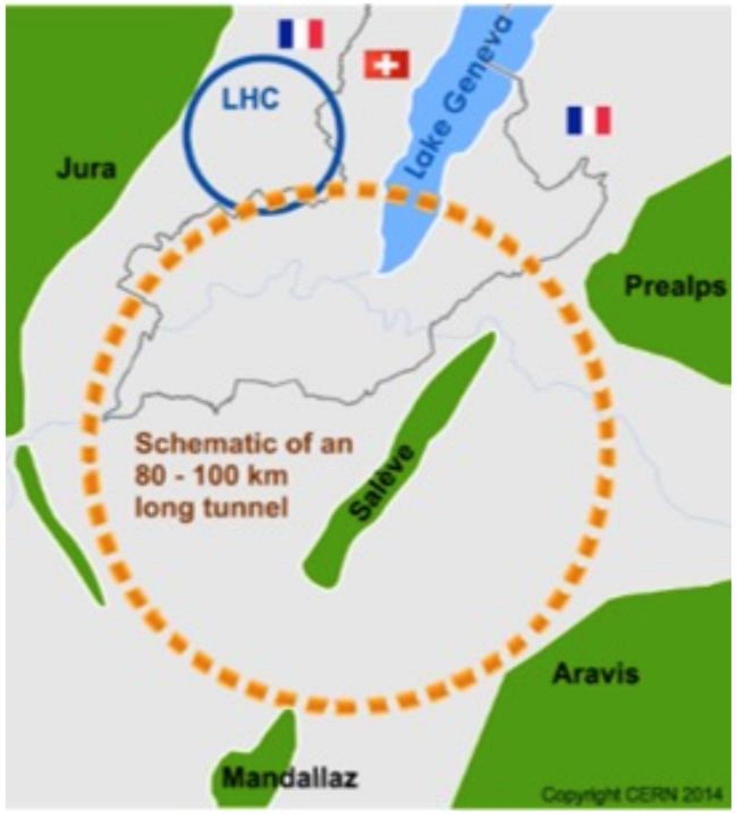


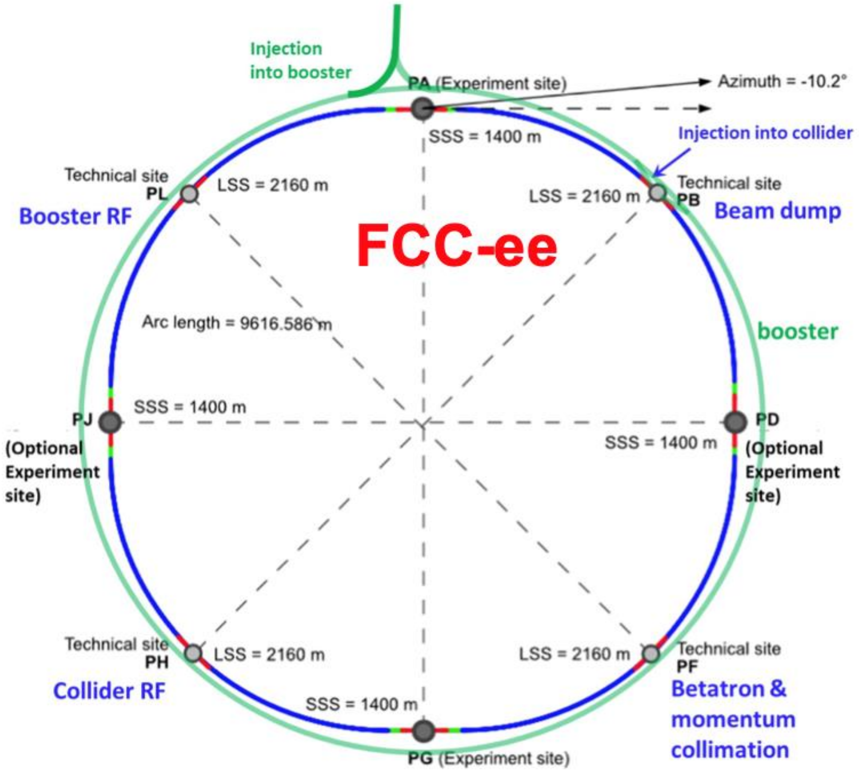
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	1.3	1.4	2
Total int. lum. per year	$\mathrm{fb^{-1}}$	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^9	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

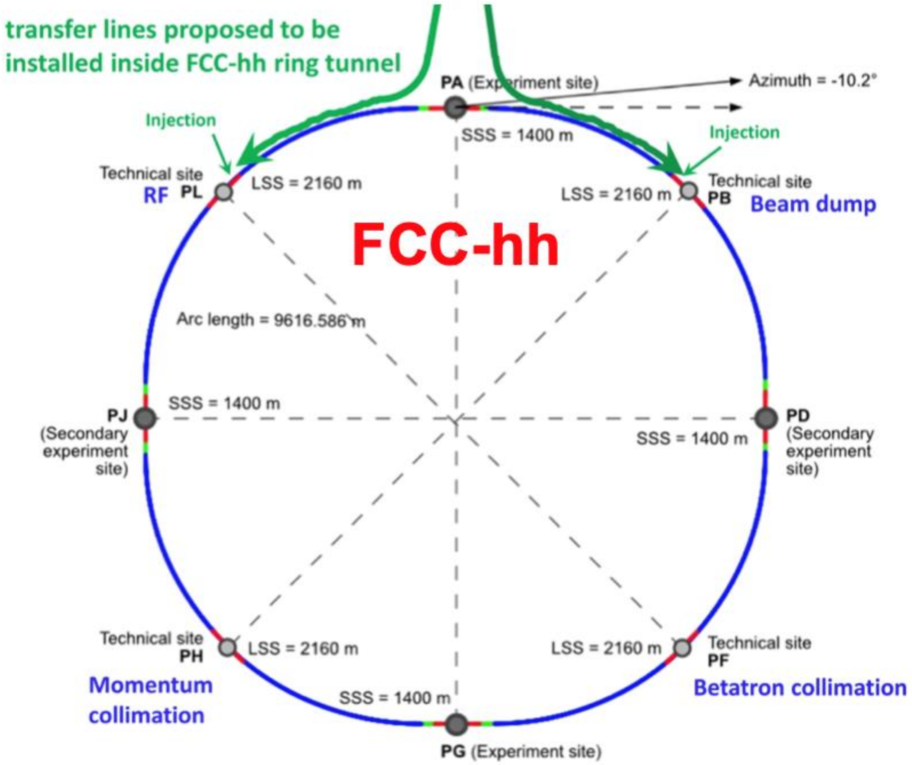
FCC integrated programme at CERN

Comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC

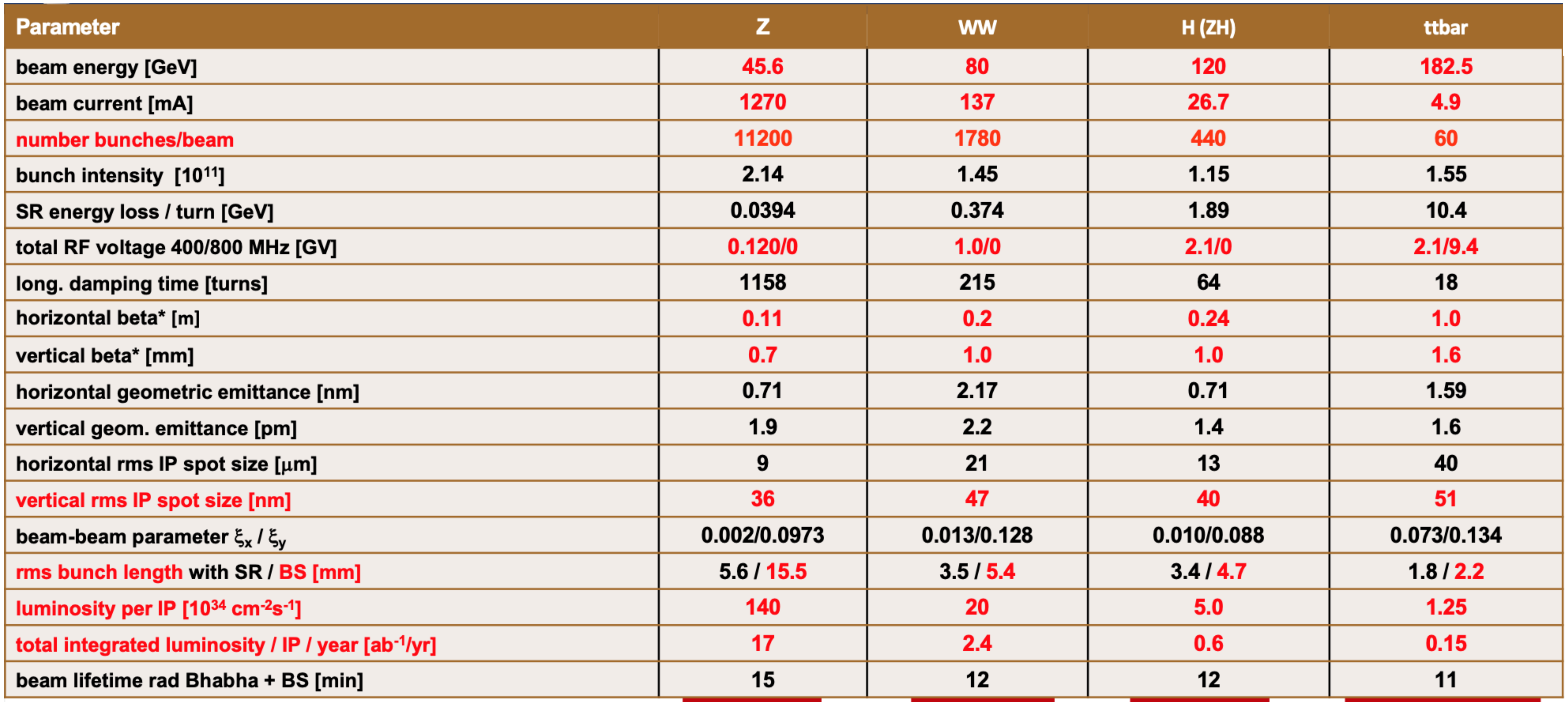






→ feasibility study for tunnel + FCC-ee ready in March 2025

FCC-ee machine parameters



Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

4 years
5 x 10^{12} Z
LEP x 10^5

2 years
> 10^8 WW
LEP x 10^4

3 years
2 x 10^6 H

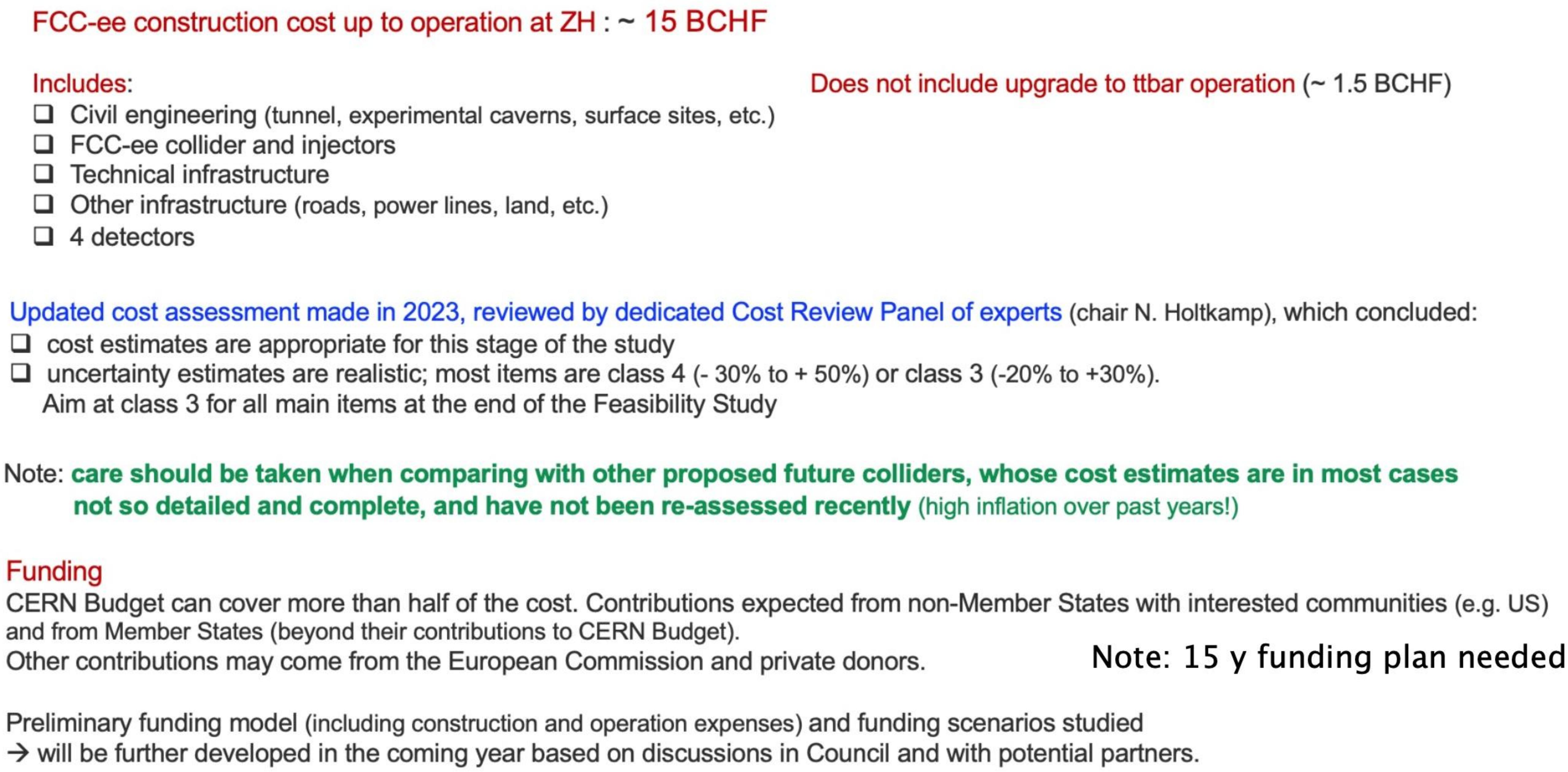
5 years
2 x 10^6 tt pairs

- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ❑ x10 Belle II statistics for b, c, τ
- ❑ indirect discovery potential up to ~ 70 TeV
- ❑ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

FCC-ee cost and funding



FCC-ee construction cost up to operation at ZH : ~ 15 BCHF

Includes:
- ❑ Civil engineering (tunnel, experimental caverns, surface sites, etc.)
- ❑ FCC-ee collider and injectors
- ❑ Technical infrastructure
- ❑ Other infrastructure (roads, power lines, land, etc.)
- ❑ 4 detectors

Does not include upgrade to ttbar operation (~ 1.5 BCHF)

Updated cost assessment made in 2023, reviewed by dedicated Cost Review Panel of experts (chair N. Holtkamp), which concluded:
- ❑ cost estimates are appropriate for this stage of the study
- ❑ uncertainty estimates are realistic; most items are class 4 (- 30% to + 50%) or class 3 (-20% to +30%). Aim at class 3 for all main items at the end of the Feasibility Study

Note: **care should be taken when comparing with other proposed future colliders, whose cost estimates are in most cases not so detailed and complete, and have not been re-assessed recently** (high inflation over past years!)

Funding

CERN Budget can cover more than half of the cost. Contributions expected from non-Member States with interested communities (e.g. US) and from Member States (beyond their contributions to CERN Budget).
Other contributions may come from the European Commission and private donors.

Note: 15 y funding plan needed

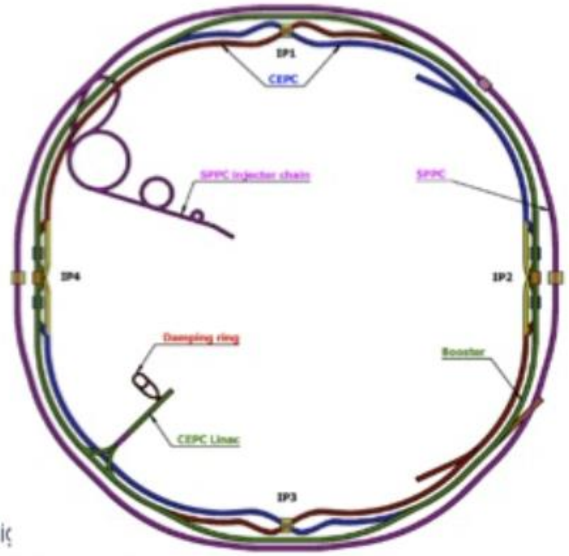
Preliminary funding model (including construction and operation expenses) and funding scenarios studied
→ will be further developed in the coming year based on discussions in Council and with potential partners.

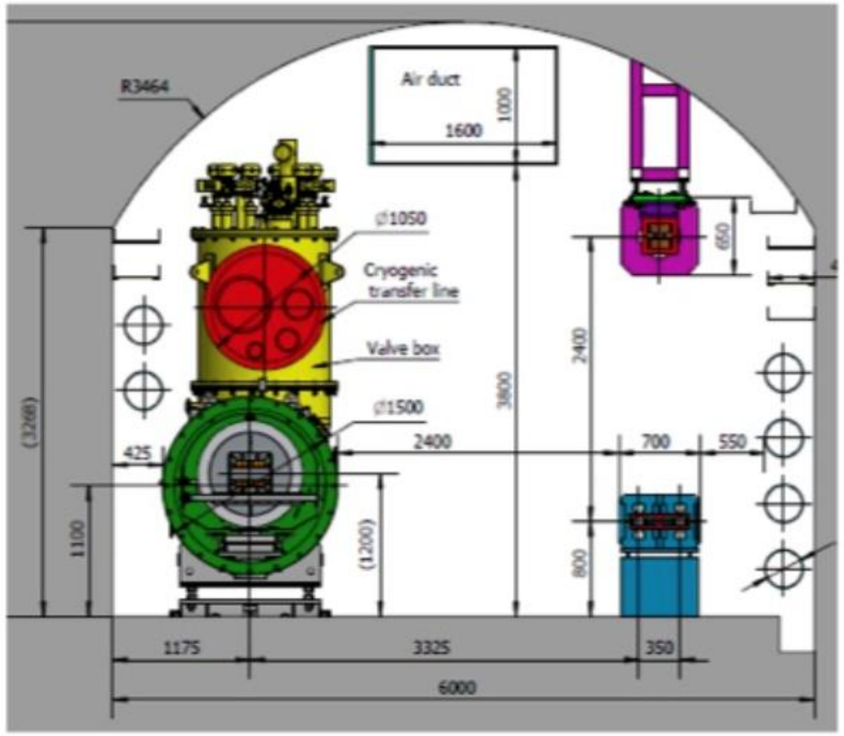
F. Gianotti

Chinese project: CEPC+SppC

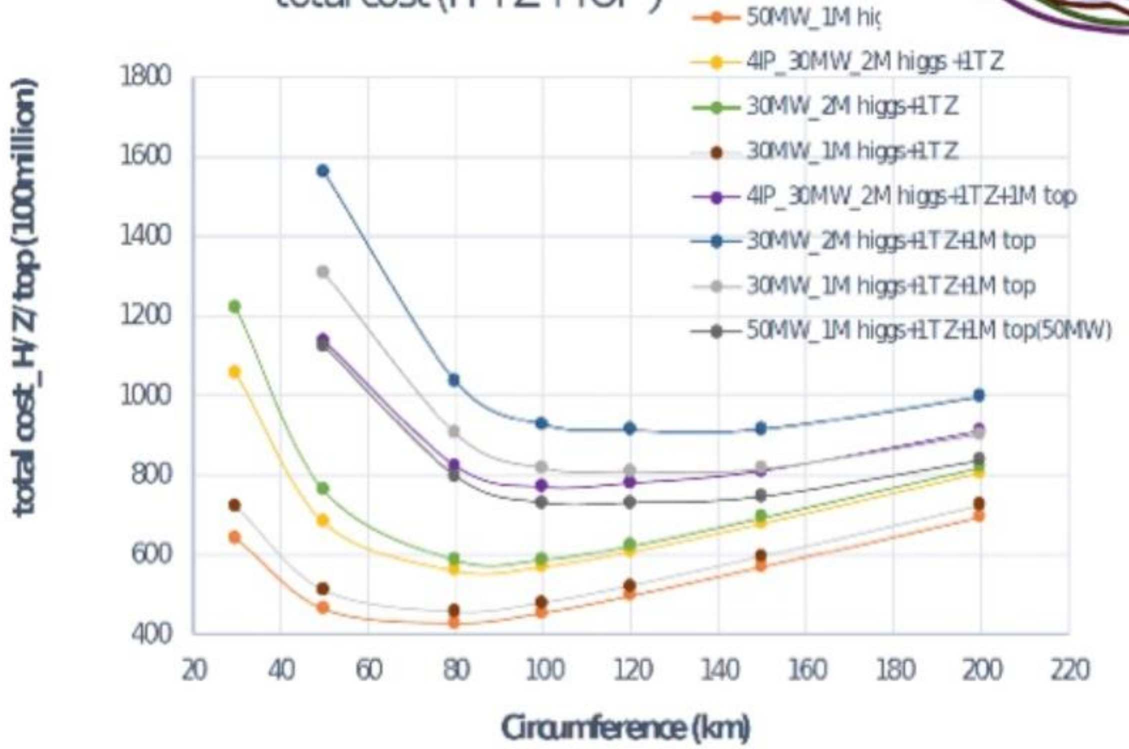
Main Design considerations:

- **100km circumference**: **Optimum total cost**
- **Shared tunnel**: **Compatible design for CEPC and SppC**
- **Switchable operation**: **Higgs, W/Z, top**





Common tunnel for booster/collider & SppC

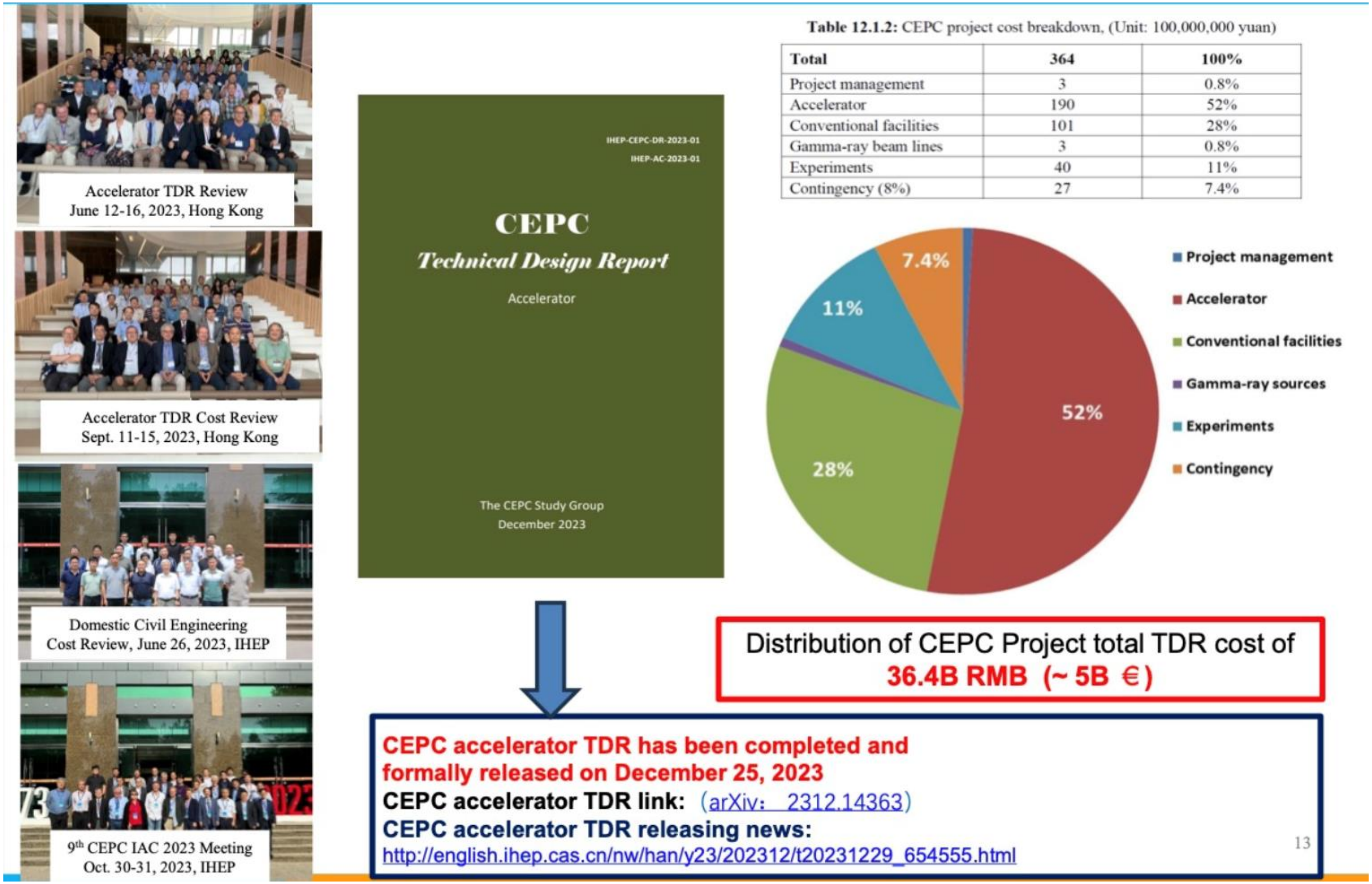


Cost optimization v.s. circumference

D. Wang *et al* 2022 *JINST* **17** P10018

Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar

CEPC accelerator TDR realised



Accelerator TDR Review
June 12-16, 2023, Hong Kong

Accelerator TDR Cost Review
Sept. 11-15, 2023, Hong Kong

Domestic Civil Engineering
Cost Review, June 26, 2023, IHEP

9th CEPC IAC 2023 Meeting
Oct. 30-31, 2023, IHEP

IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

CEPC
Technical Design Report
Accelerator

The CEPC Study Group
December 2023

Table 12.1.2: CEPC project cost breakdown, (Unit: 100,000,000 yuan)

Total	**364**	**100%**
Project management	3	0.8%
Accelerator	190	52%
Conventional facilities	101	28%
Gamma-ray beam lines	3	0.8%
Experiments	40	11%
Contingency (8%)	27	7.4%

Distribution of CEPC Project total TDR cost of
36.4B RMB (~ 5B €)

CEPC accelerator TDR has been completed and formally released on December 25, 2023
CEPC accelerator TDR link: (arXiv: 2312.14363)
CEPC accelerator TDR releasing news:
http://english.ihep.cas.cn/nw/han/y23/202312/t20231229_654555.html

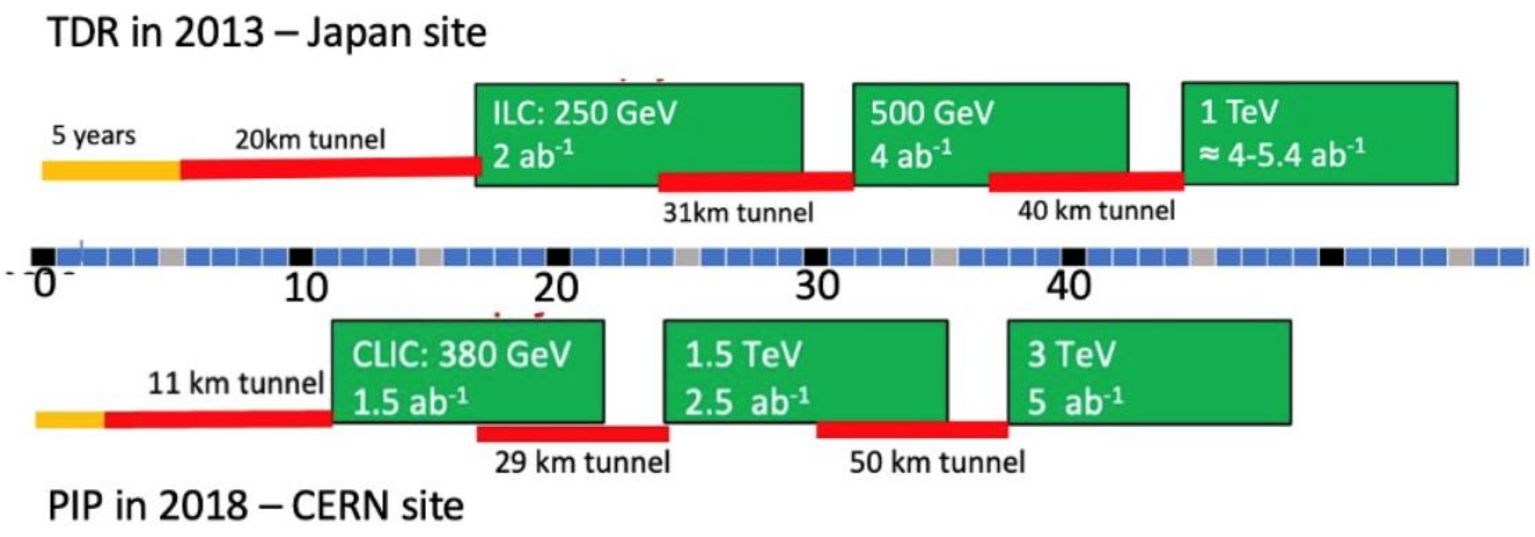
→ project to be approved within the framework of the 15th Five-Year Plan

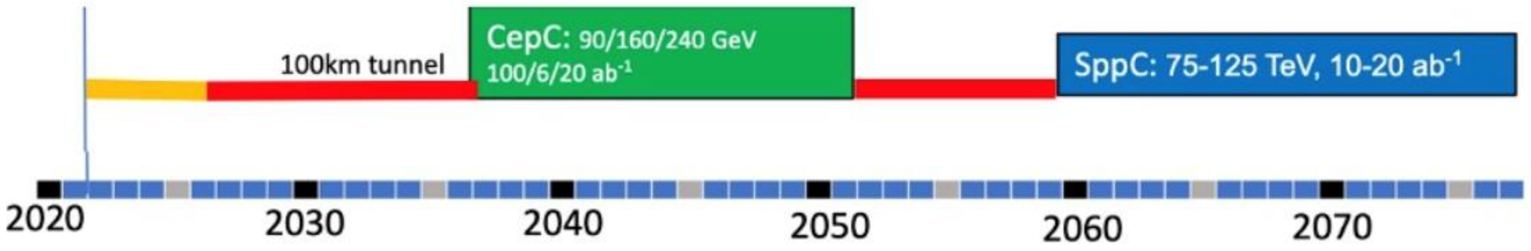
Preparation for China's 15th Five-Year-Plan (2026-2030)

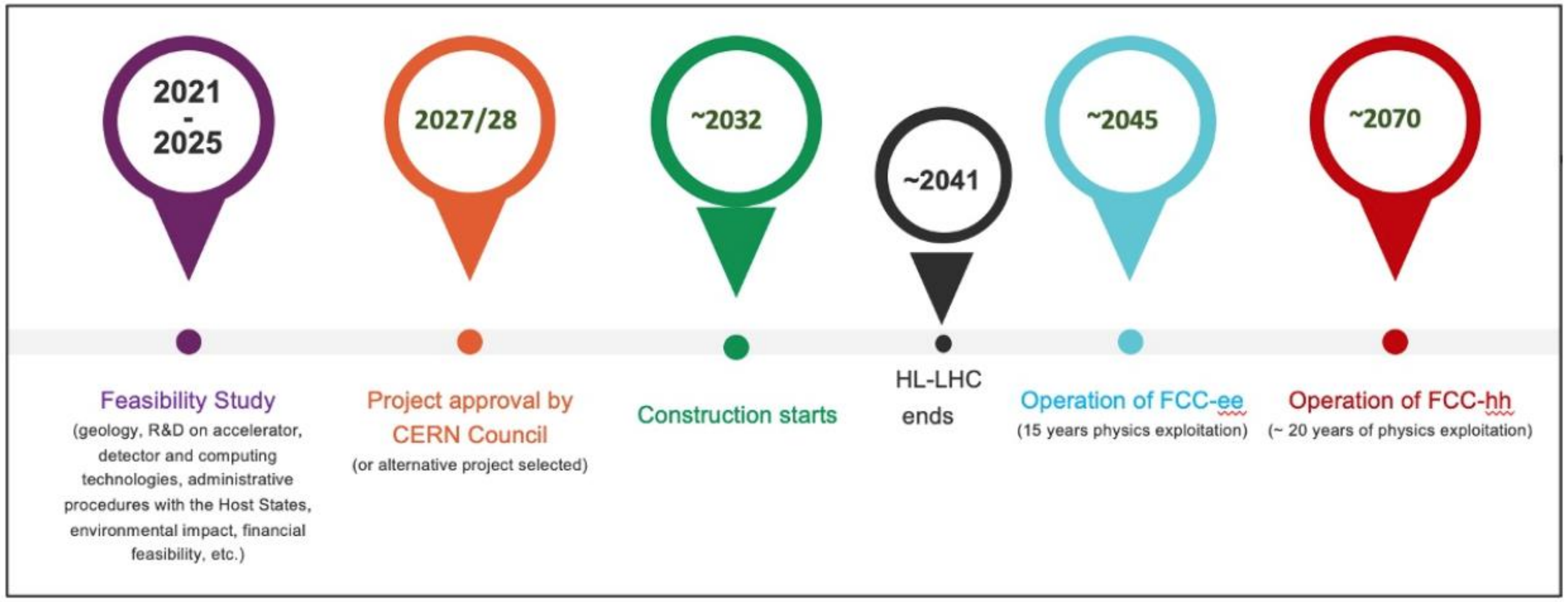
- Preparation is beginning....
- Procedure not clear yet
- The overall funding not known yet
- Coordination among IHEP, CAS, local and national governments expected
- CEPC aims at a start date in 2027-8, in the middle of the 15th Five-Year-Plan

Comparing timelines

Dates of possible approval still to be defined







Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

Project approval by CERN Council
(or alternative project selected)

Construction starts

HL-LHC ends

Operation of FCC-ee
(15 years physics exploitation)

Operation of FCC-hh
(~ 20 years of physics exploitation)

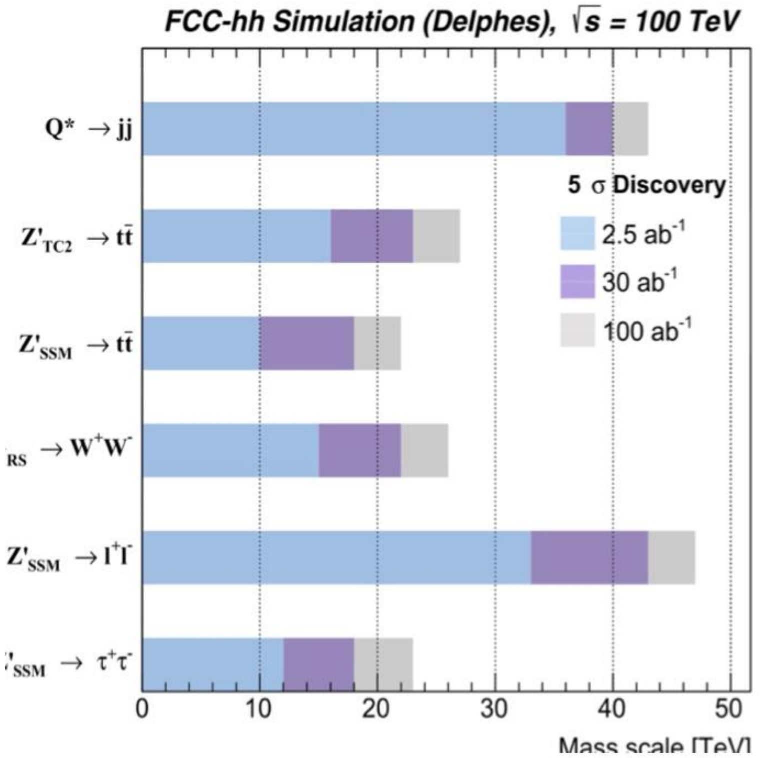
The longer perspective: technological challenge

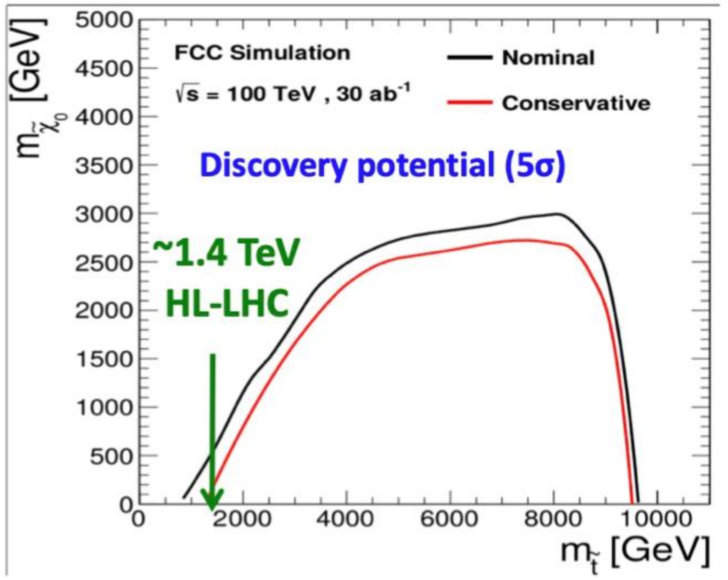
FCC-hh and SppC, muon collider

FCC-hh and SppC: the big smashers

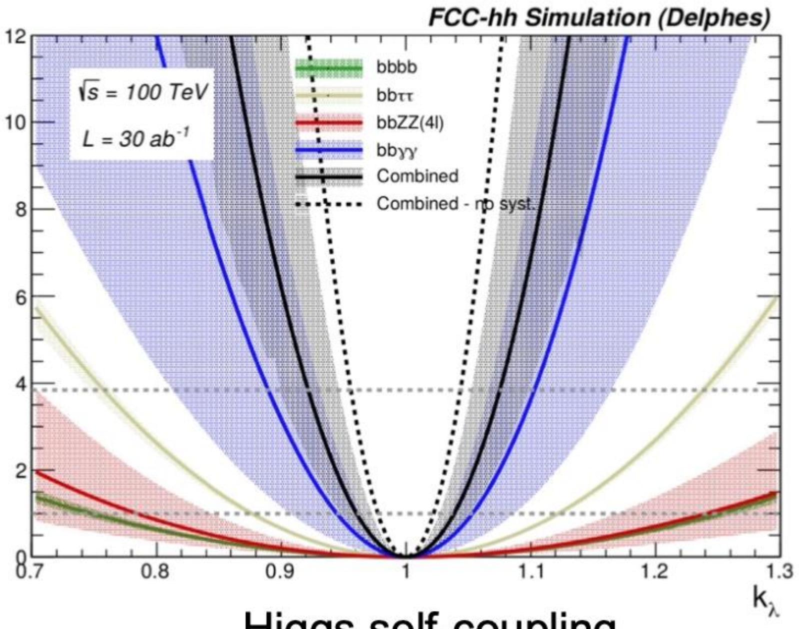
Huge cross sections for H, HH, HHH production
O(>10 TeV) reach for several exotica
No discovery guaranteed (swimming in open waters …)

	σ(13 TeV)	σ(100 TeV)
ggH (N^3LO)	49 pb	803 pb
VBF (N^2LO)	3.8 pb	69 pb
VH (N^2LO)	2.3 pb	27 pb
ttH (N^2LO)	0.5 pb	34 pb





Discover scalars up to O(10) TeV



Higgs self-coupling

FCC-hh machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity $[10^{11}]$	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP $[\mathrm{fb}^{-1}]$	20000	3000	300

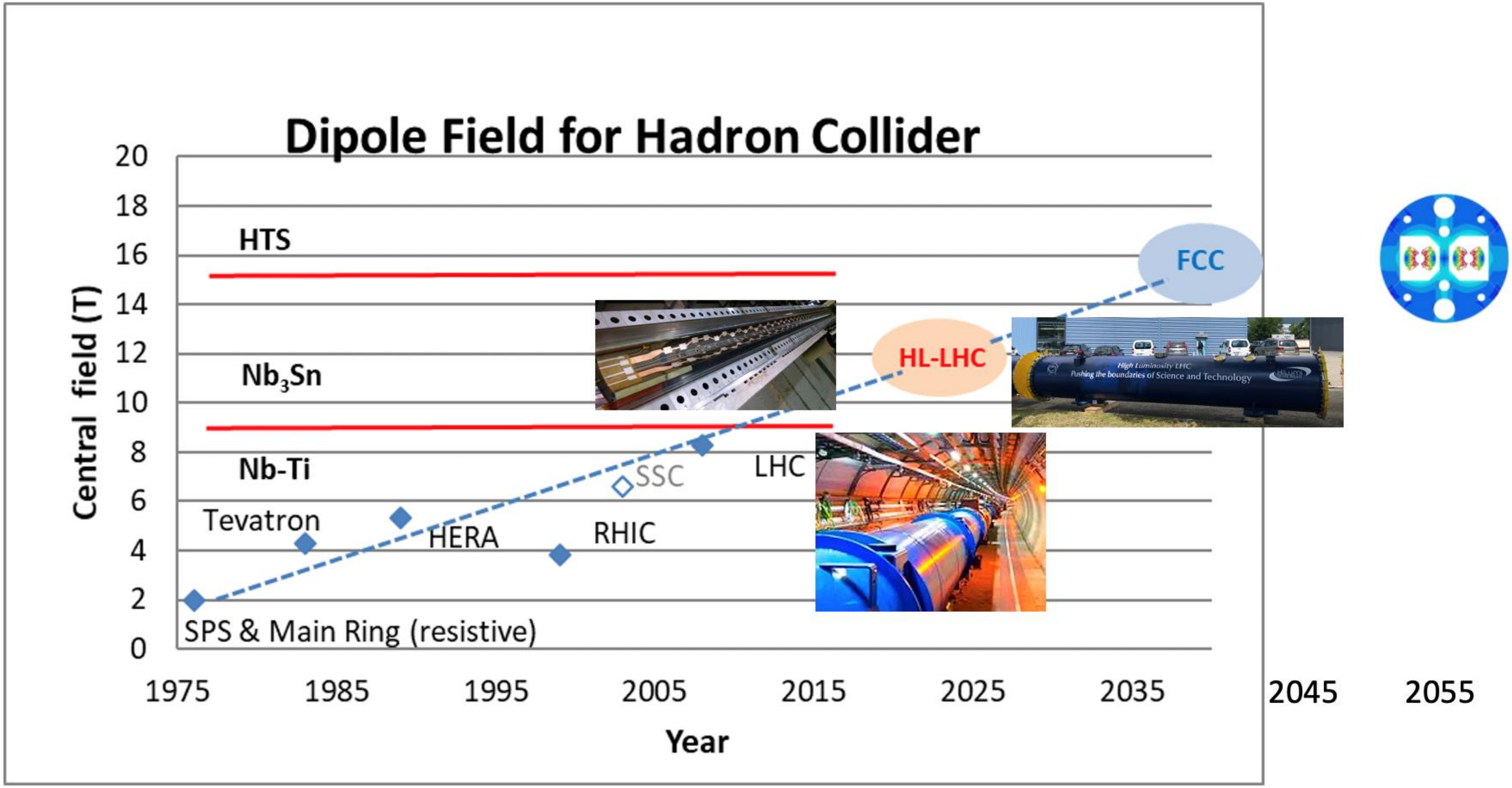
With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:
- ☐ high-field superconducting magnets: 14 - 20 T
- ☐ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ☐ stored beam energy: ~ 9 GJ → machine protection
- ☐ pile-up in the detectors: ~1000 events/xing
- ☐ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:
- ☐ Direct discovery potential up to ~ 40 TeV
- ☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays (γγ, Zγ, μμ)
- ☐ Final word about WIMP dark matter

High-field dipole magnets

L. Rossi



FCC-hh needs 16T magnets to reach 100 TeV,
with 14 TeV and better fill-factor can reach ~90 TeV

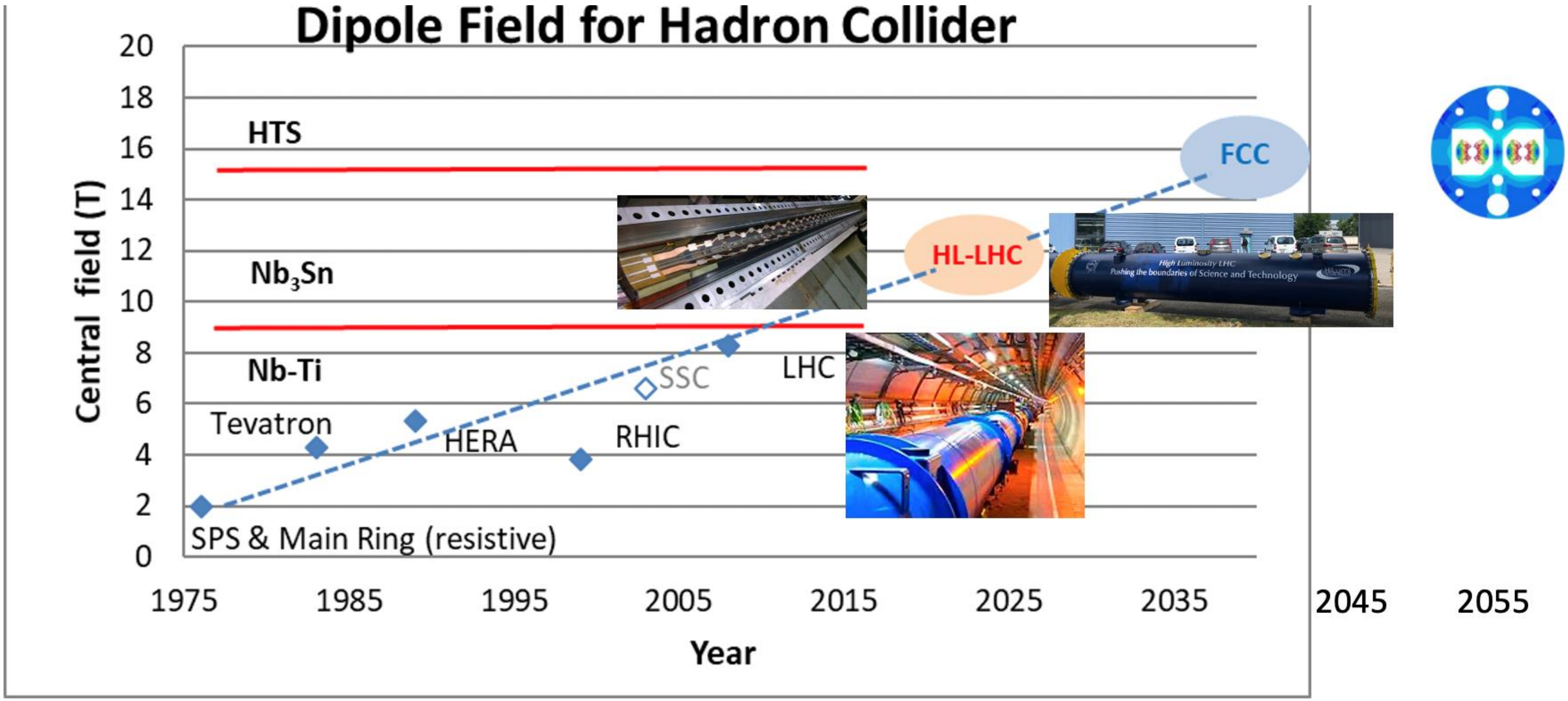
cost ~20B€

FCC-ee first to gain time (mandatory for the HTS option)

L. Rossi

Can we go faster?

Shorten timeline by ~10 years, so to fit the 2045 date for FCC-hh right after HL-LHC

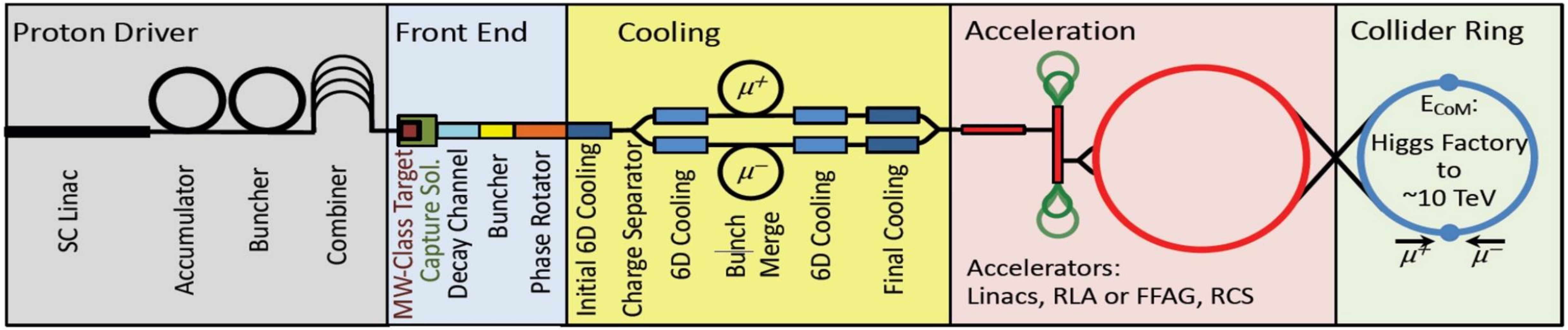


1) Easier technology target + ~100km tunnel: with 7 T magnets can reach ~45 TeV c.o.m., with 12 T magnets can reach ~85 TeV

2) More challenging technology + LHC tunnel: with 14T magnets can reach ~25 TeV c.o.m.

Muon collider overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

5 GeV, 2MW p beam, challenging target and trasport system

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

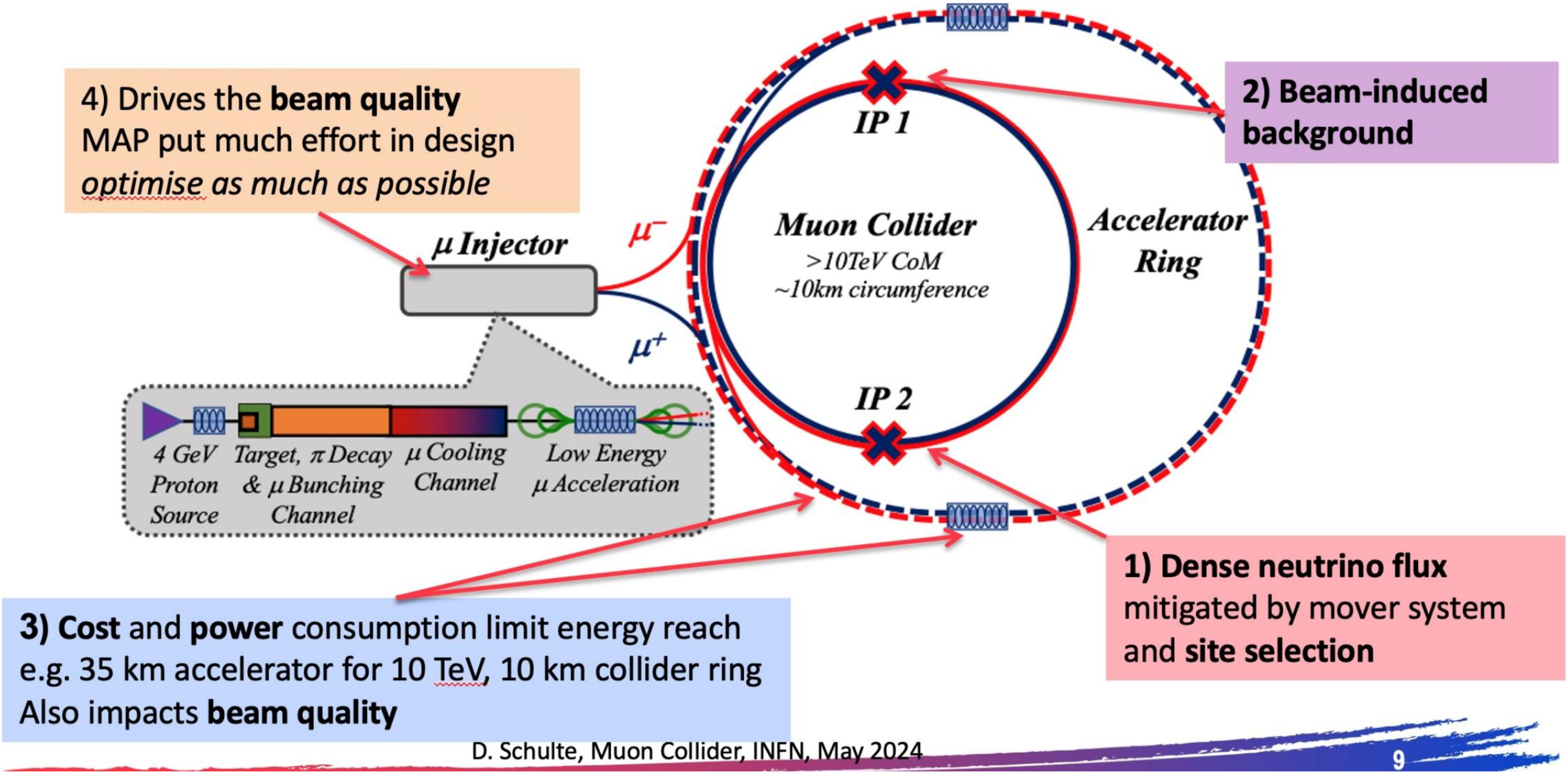
6D cooling
High Mag Field Solenoids +
RF cavities in HFM (!)

Acceleration to collision energy

Collision

High background at IR
Radiological neutrino flux

Key challenges



4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible

2) Beam-induced background

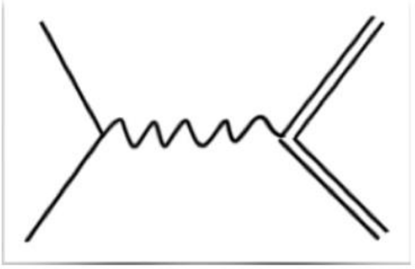
1) Dense neutrino flux
mitigated by mover system
and **site selection**

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

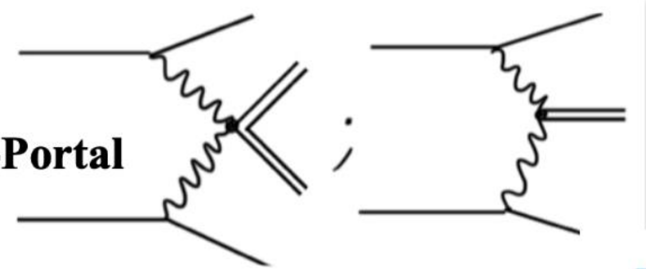
D. Schulte, Muon Collider, INFN, May 2024

Physics case

Self-evident elemental Physics at O(3-10 TeV) level

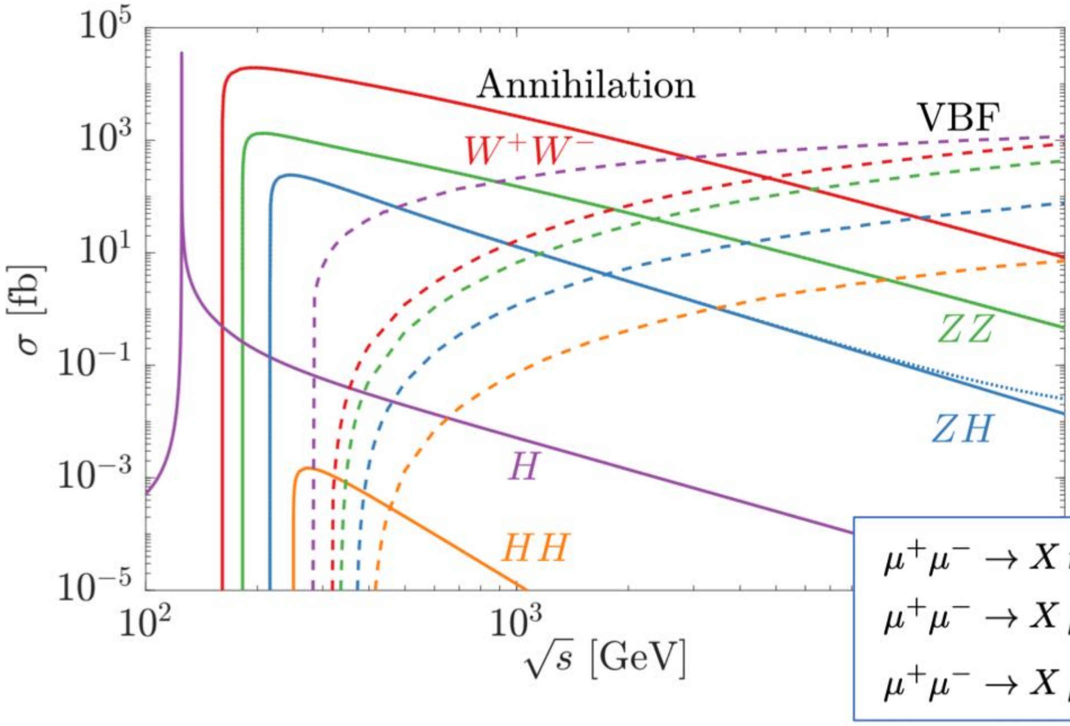


μμ annihilation: production of **EW-charged particles**

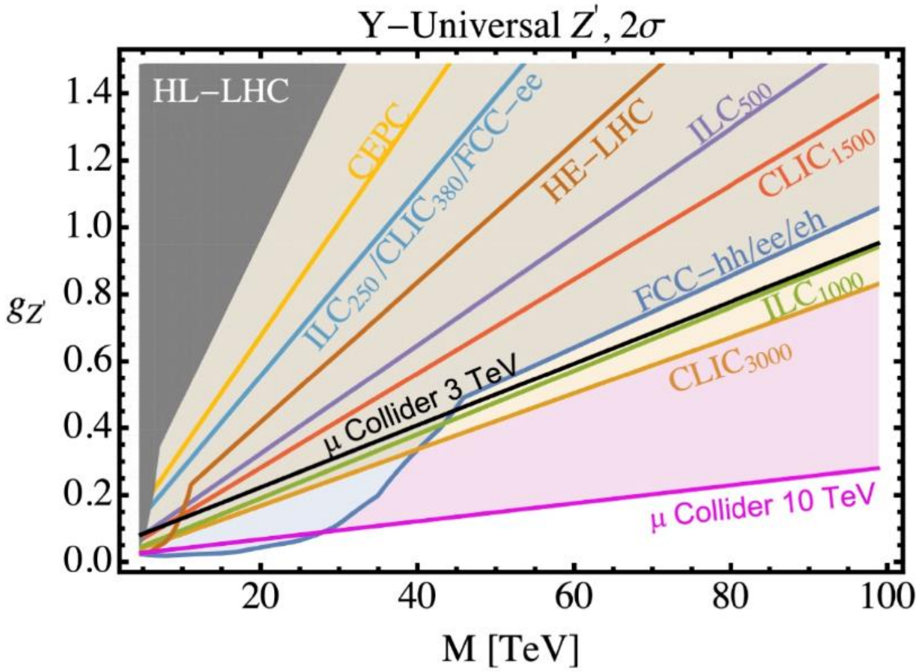


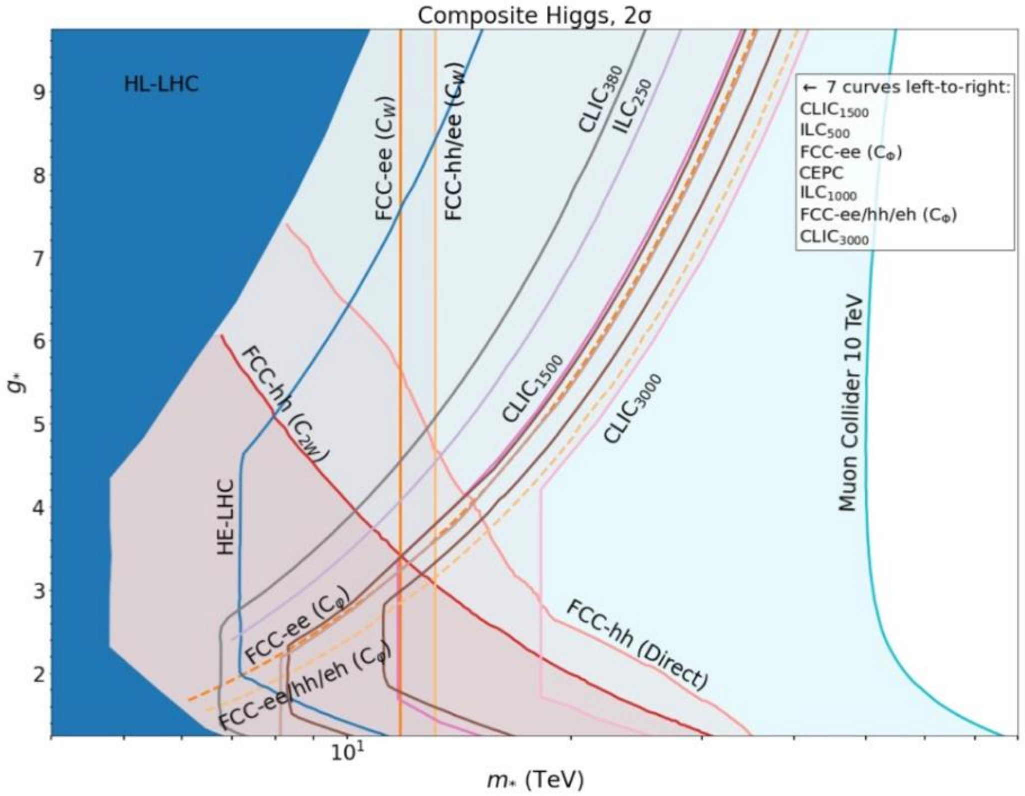
Vector Bosons Fusion: sensitive to EW-neutral **Higgs-Portal**

Huge rates due VBF rising cross section

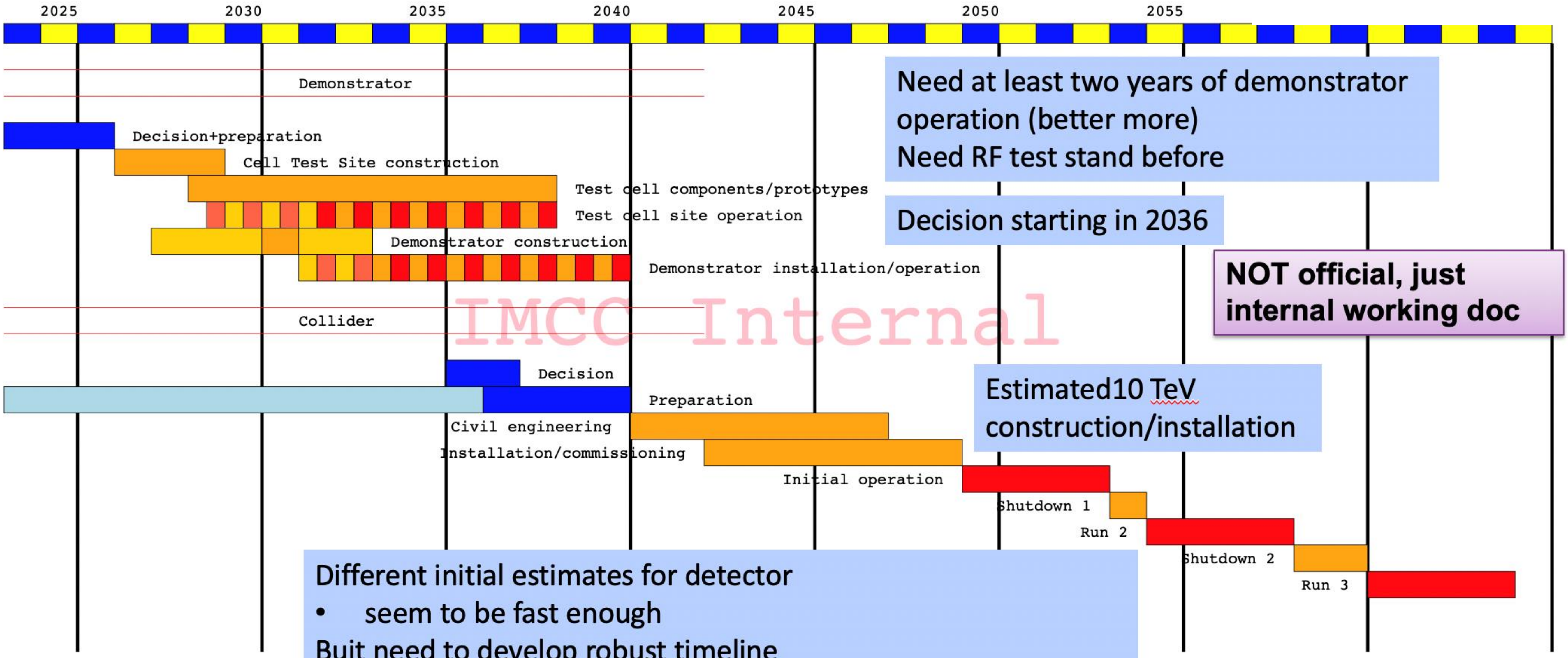


$$\mu^+\mu^- \to X\,\nu_\mu\bar{\nu}_\mu \quad (WW\ \text{fusion}),$$
$$\mu^+\mu^- \to X\,\mu^+\mu^- \quad (ZZ/Z\gamma/\gamma\gamma\ \text{fusion}).$$
$$\mu^+\mu^- \to X\,\mu^\pm\overset{(-)}{\nu}_\mu \quad (WZ\ \text{fusion}),$$





Tentative timeline



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

NOT official, just internal working doc

Estimated10 TeV construction/installation

Different initial estimates for detector
- seem to be fast enough

Buit need to develop robust timeline

Very important to build a demonstrator of the muon injector

L. Rossi

Conclusions 1 : FCC and CCEP/CSSP

- FCC: most complete road, coupling precision with discovery potential
  - Builds on decades of experiences of leptons and hadron rings
  - **FCC-ee has no technical showstoppers.** Cost & acceptability are the key issues
  - **For FCC-hh the 14T magnet Target is realistic (shorten the time) for 90 TeV**
HE-LHC (at 25 TeV): only better than nothing?
A viable project, 5-6 BCHF range… Maybe preceeded by a LEPIII (250 GeV)…
  - High intensity beams, high luminosity demonstrated for circular colliders, no big extrapolation, technology improvement needed, but no showstopper
  - Key issues:
    - Cost means also a growth of the infrastructure (tunnel, shafts), people, operation
    - Acceptability in a densely populated area
    - Power/energy consumption FCC-ee: 100 MW wasted in the vacuum…;
FCC-hh (almost) prohibitive cryogenic consumption key issue
→ HTS magnets @ 20 K may be the key but need to be demonstrated yet (5-8 y)

Conclusion 2 : ee linear colliders

- ILC
  - Mature design, solid concept, main technology (SRF) demonstrated by EU-XFEL
  - 250 GeV ready to start from technical point of view (organization and politics…)
  - Nice upgrade plan (500 GeV maybe does not require much R&D or size increase). 1 TeV seems brute force unless something happens in SRF performance
- CLIC
  - Step toward maturity
  - Swiss FEL is a first step demonstrator; medical and other applications push MV/m
  - Reasonable alternative to ILC. Or best upgrade of a first phase ILC (accelerator design must be revised… but possible)
  - Big progress in energy saving, but concerns for the 3 TeV option, hardly expandable…

3 – The “new” players: High risk – high gain?

- Muon-Collider
  - It is based on “classical” technologies, Magnets & RF
  - Integration and beam physics are challenging,
  - Needs **further serious advance in many technologies**: Magnets, RF, remote handling, absorbers: all VERY difficult, no apparent showstopper
  - Weak point is that those advances are required in many different fields…
  - **Needs cruelly a coling demonstrator, imperative in 2-3 years for this project.**
- Plasma
  - Game-changer
  - Certainly a fantastic tools for a variety of applications
  - **Missed basic demonstration that can work for a HEP collider:** positive charges, beam quality, multibunch, stability, energy efficiency…