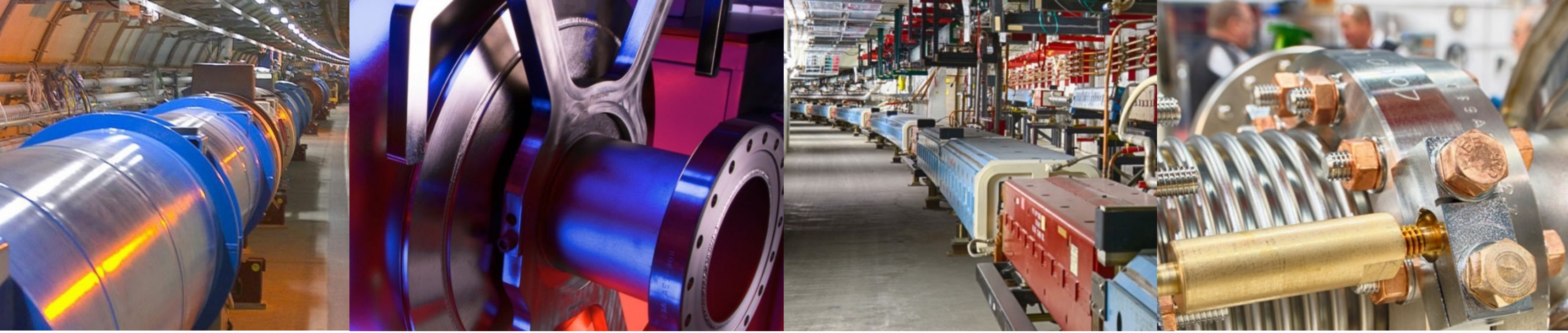
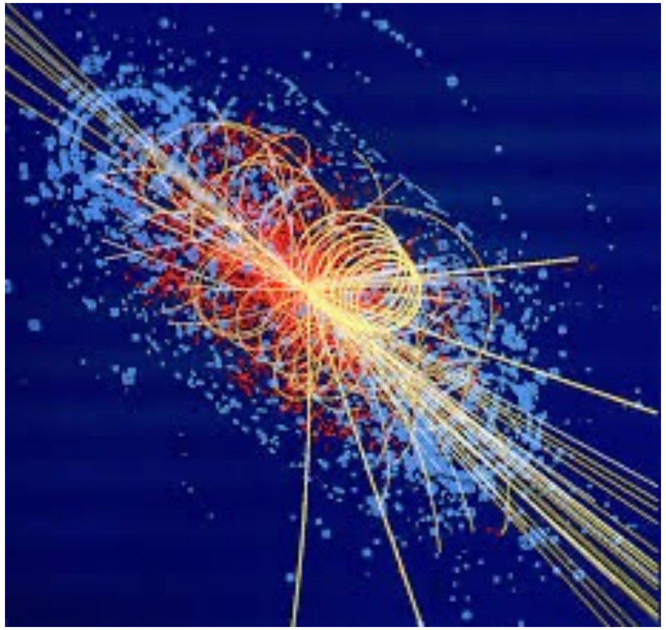


Current physics landscape: motivations and future collider projects

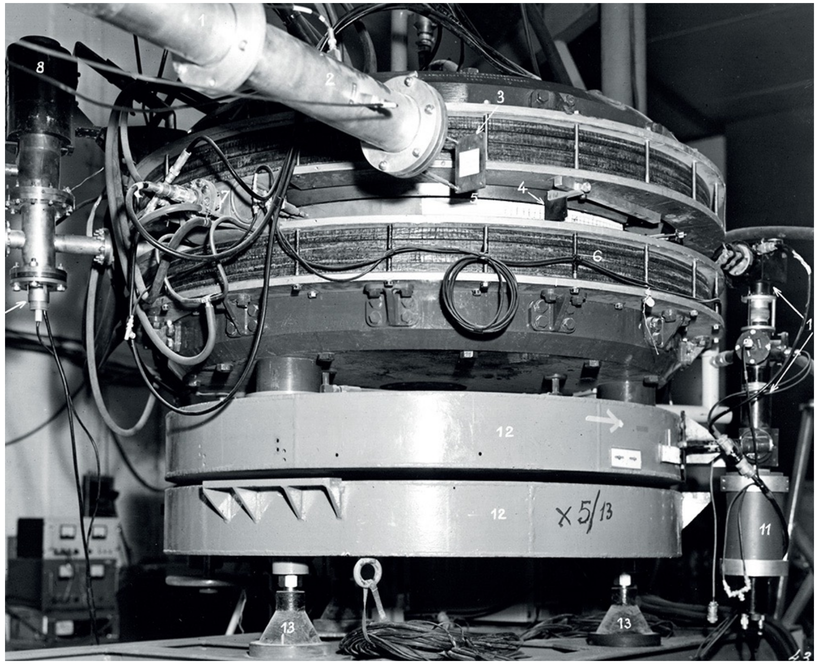
P. Campana, LNF-INFN

INFN ECR meeting, Frascati, Sep. 30, 2024



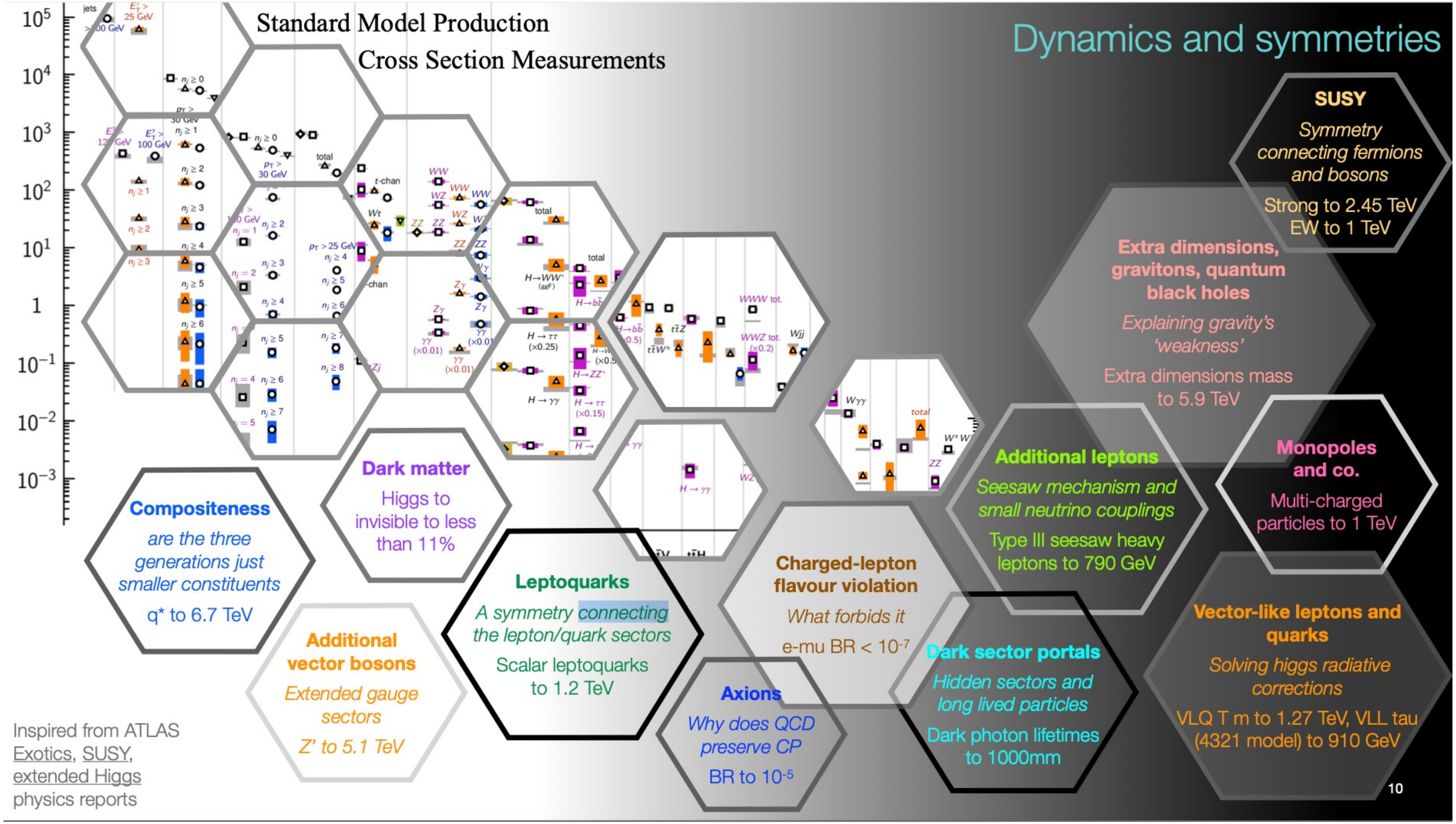
Talk outlook:

- What after LHC and why
- The near term collider landscape: technologies ready
- The longer perspective: technological challenges
- International Science Policies
- Governance, funding models, sustainability
- Societal impact & HEP sociology
- Take-away messages



1. What after LHC, and why

LHC: the SM in full swing



Standard Model Production

Cross Section Measurements

Dynamics and symmetries

SUSY

Symmetry connecting fermions and bosons

Strong to 2.45 TeV
EW to 1 TeV

Extra dimensions, gravitons, quantum black holes

Explaining gravity's 'weakness'

Extra dimensions mass to 5.9 TeV

Compositeness

are the three generations just smaller constituents

q* to 6.7 TeV

Dark matter

Higgs to invisible to less than 11%

Leptoquarks

A symmetry connecting the lepton/quark sectors

Scalar leptoquarks to 1.2 TeV

Additional vector bosons

Extended gauge sectors

Z' to 5.1 TeV

Charged-lepton flavour violation

What forbids it

e-mu BR < 10^{-7}

Axions

Why does QCD preserve CP

BR to 10^{-5}

Additional leptons

Seesaw mechanism and small neutrino couplings

Type III seesaw heavy leptons to 790 GeV

Monopoles and co.

Multi-charged particles to 1 TeV

Dark sector portals

Hidden sectors and long lived particles

Dark photon lifetimes to 1000mm

Vector-like leptons and quarks

Solving higgs radiative corrections

VLQ T m to 1.27 TeV, VLL tau (4321 model) to 910 GeV

Inspired from ATLAS Exotics, SUSY, extended Higgs physics reports

10

Monica Dunford ICHEP2024

LHC: no anomaly, fo far, in Higgs model

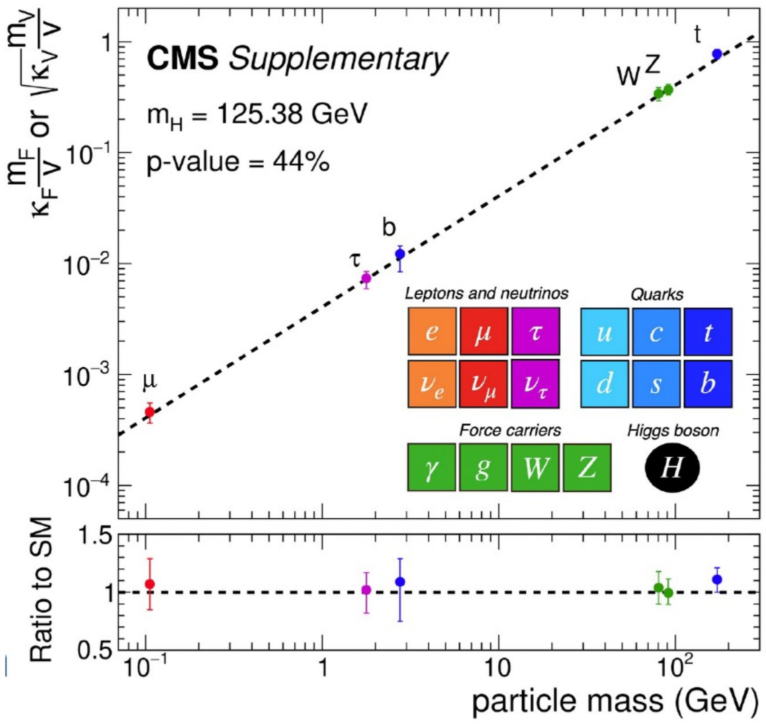
Higgs physics is still in its nascence. Pions were discovered in the early 1940's. Their fundamental origin, QCD, was developed theoretically in the early 1970's and only experimentally established in the late 1970's.

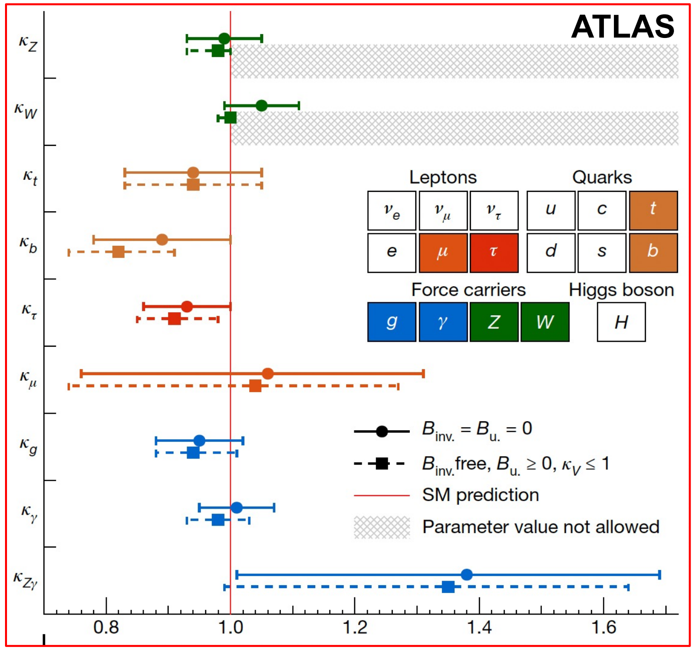
Twelve years since discovery of the Higgs boson.

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

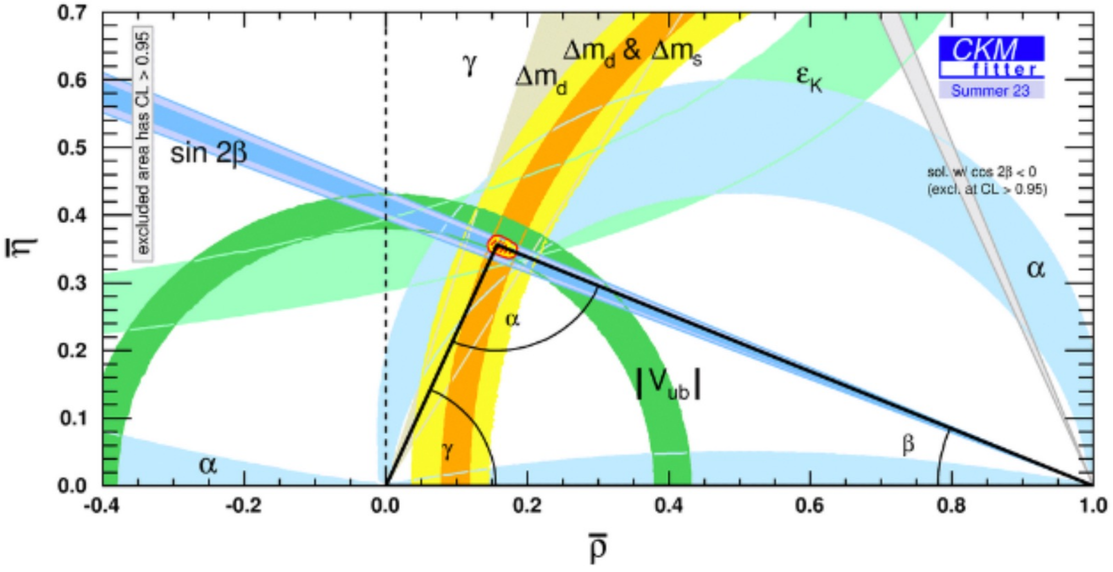
We must be patient and determined to uncover its origins.

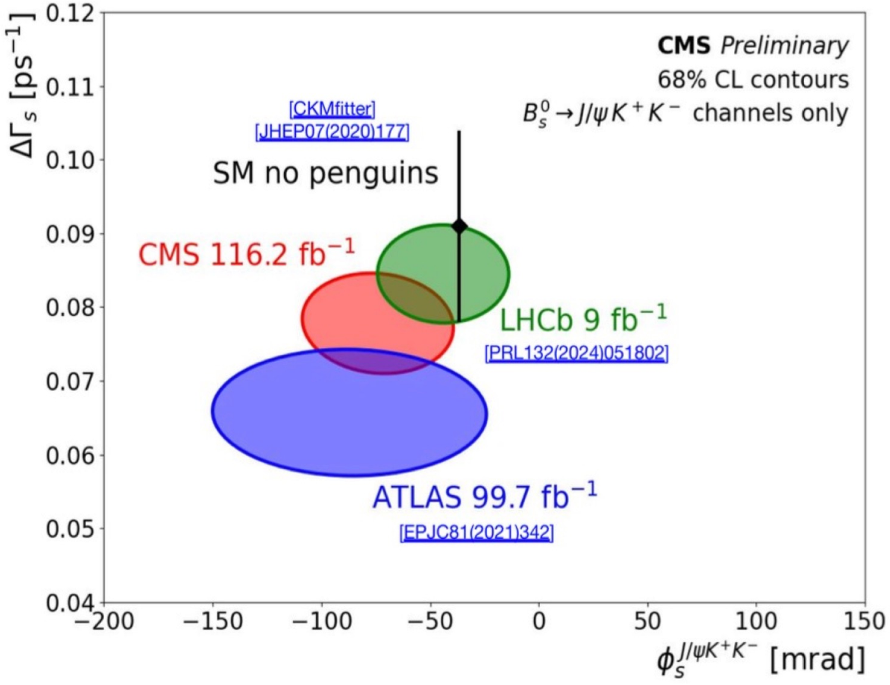
M. McCullogh ICHEP2024

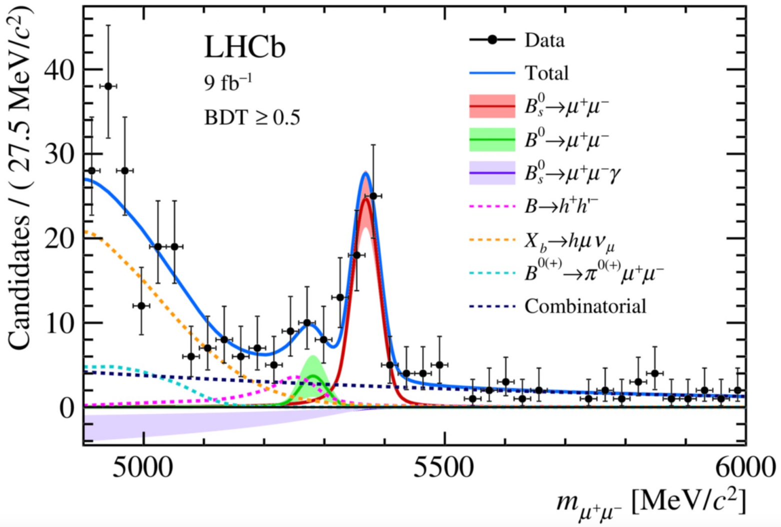


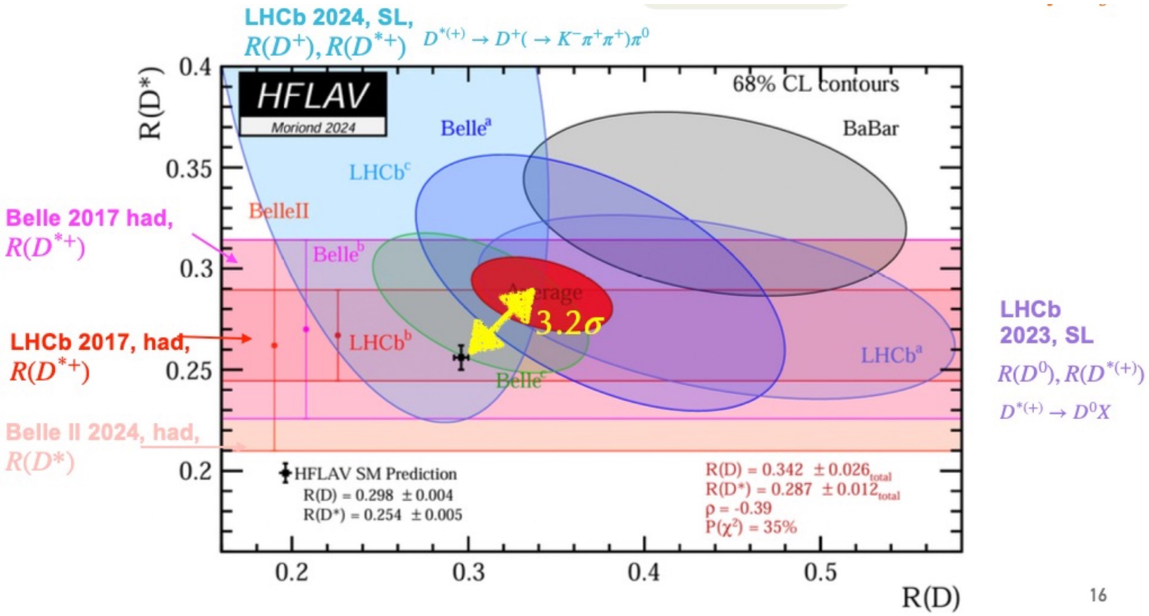


LHC: flavor, business as usual

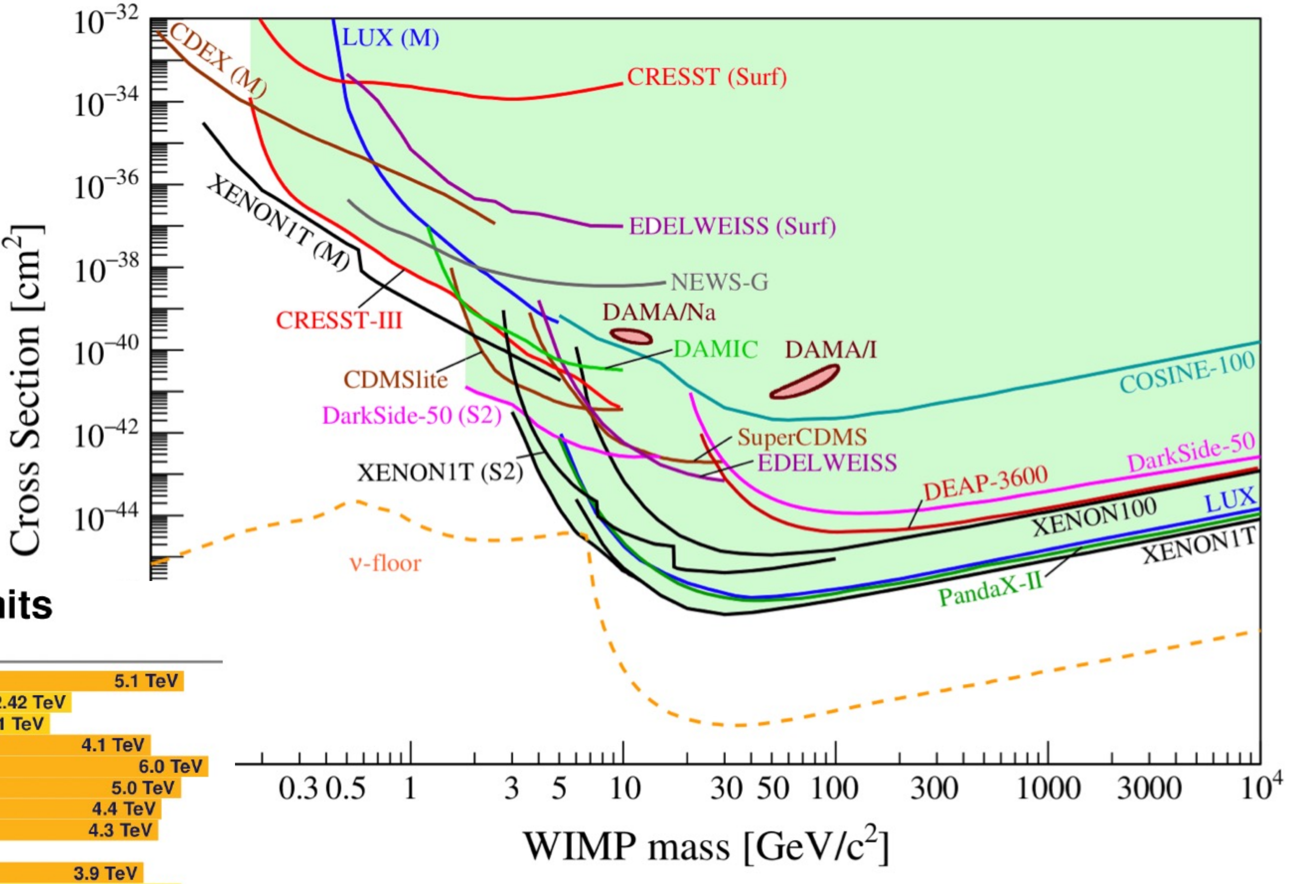






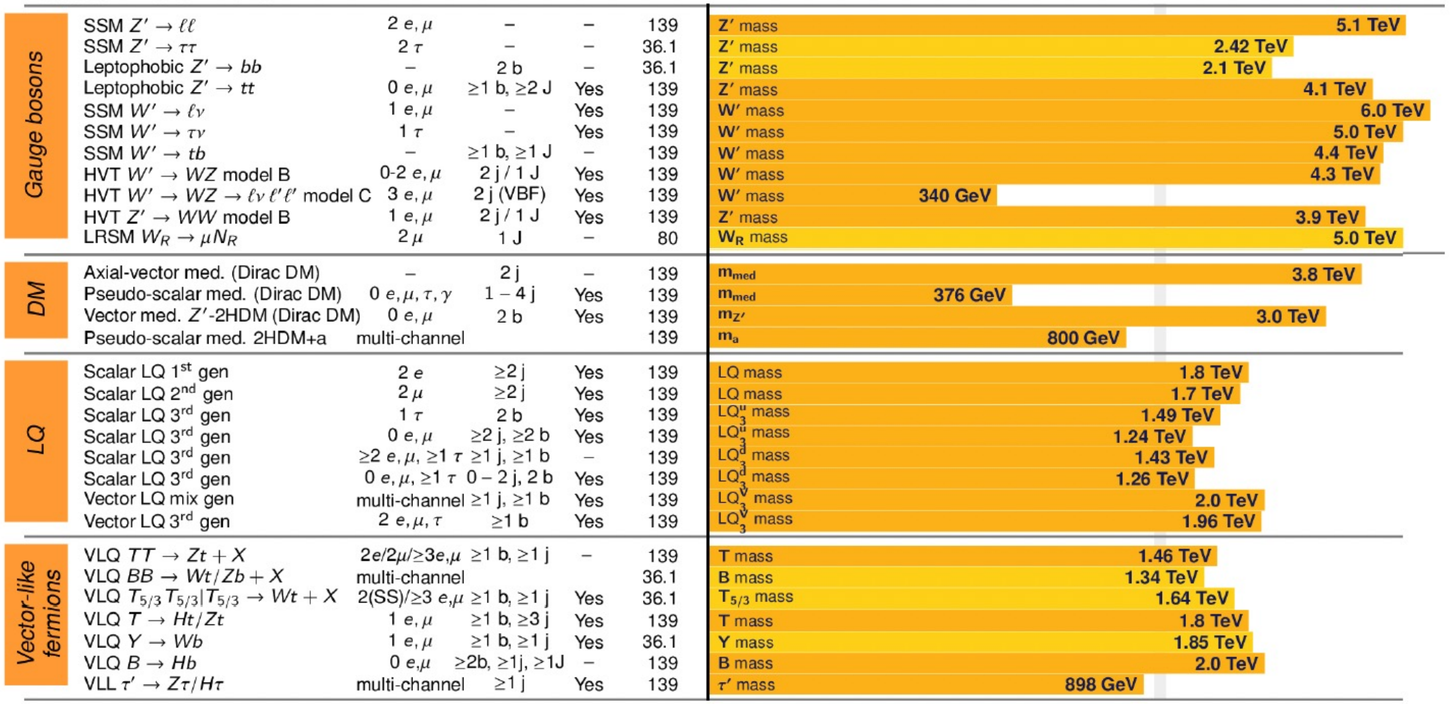


BSM and DM (LHC & co.): no signs

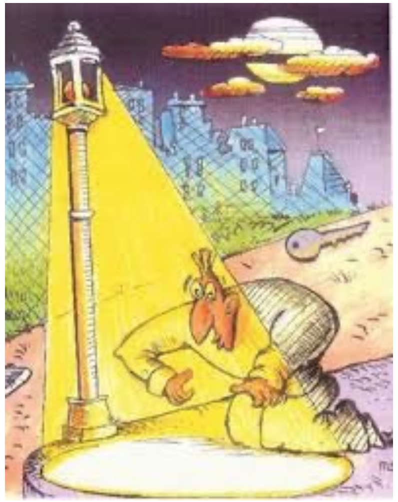


ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

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 $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$	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



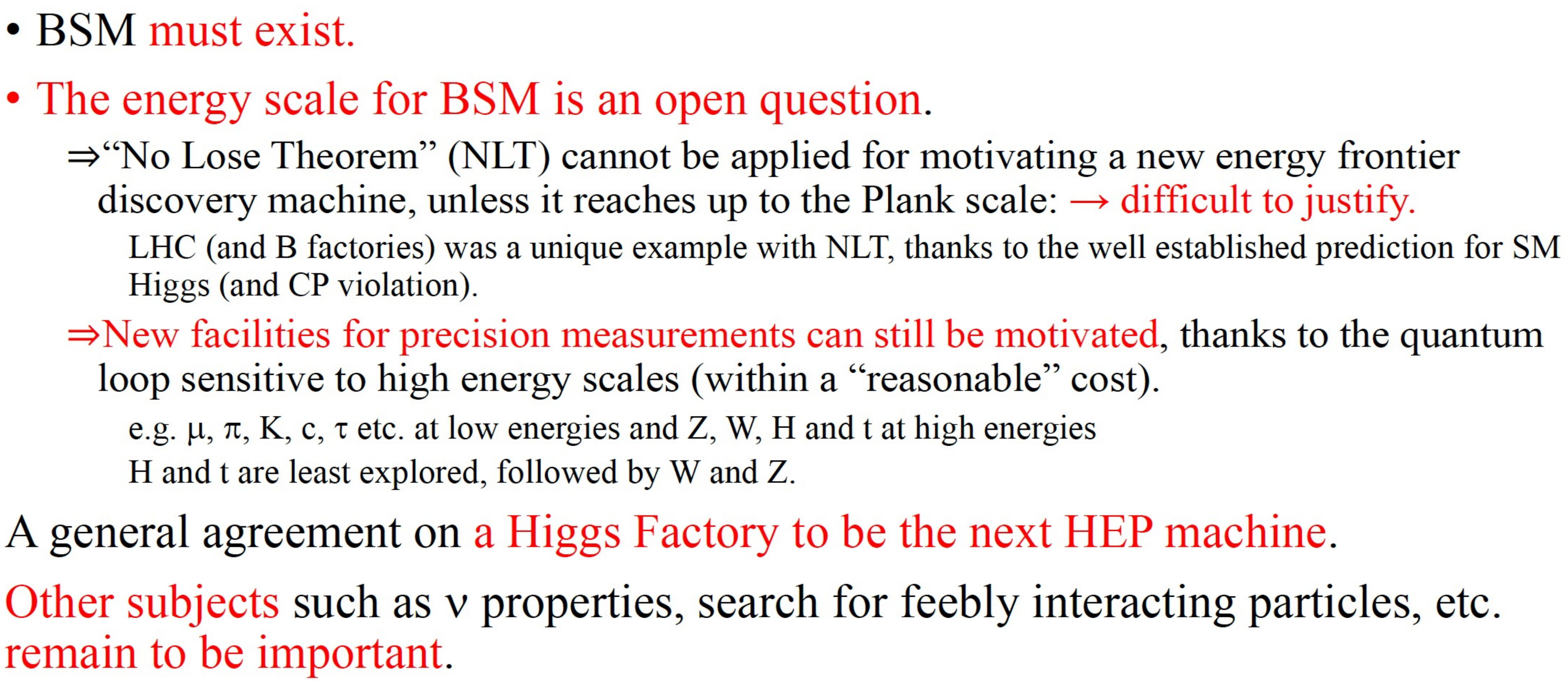
Current situation of physics

- 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 μ(g–2) from the SM predictions~~
  - ~~Flavour anomaly in semileptonic B meson decays~~
  - …

TH: Lattice vs e+e- data analysis

- 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.

T. Nakada, ECR 2023, CERN



- BSM must exist.
- The energy scale for BSM is an open question.

  ⇒"No Lose Theorem" (NLT) cannot be applied for motivating a new energy frontier discovery machine, unless it reaches up to the Plank scale: → difficult to justify.

  LHC (and B factories) was a unique example with NLT, thanks to the well established prediction for SM Higgs (and CP violation).

  ⇒New facilities for precision measurements can still be motivated, thanks to the quantum loop sensitive to high energy scales (within a "reasonable" cost).

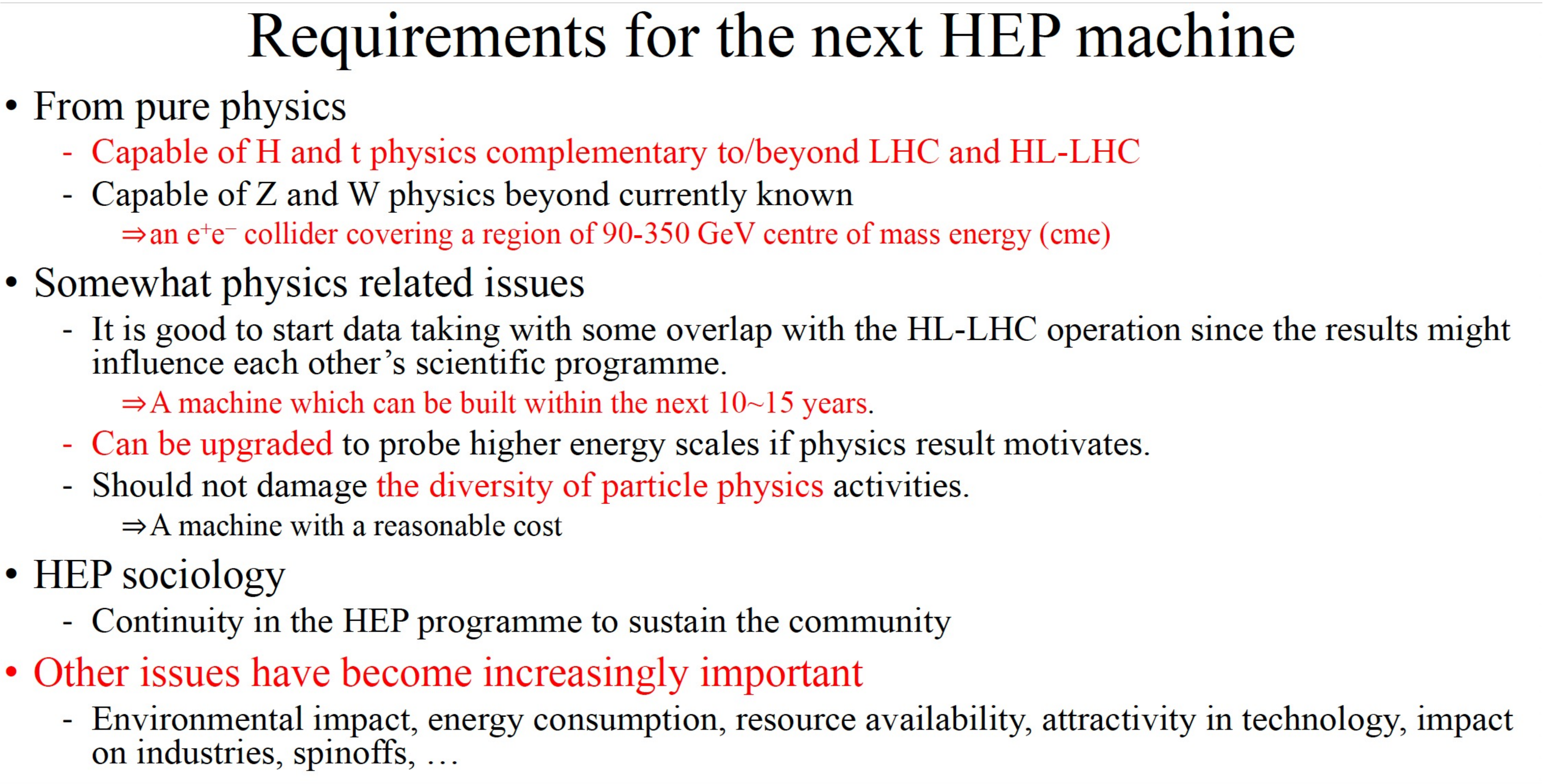
  e.g. μ, π, K, c, τ etc. at low energies and Z, W, H and t at high energies

  H and t are least explored, followed by W and Z.

A general agreement on a Higgs Factory to be the next HEP machine.

Other subjects such as ν properties, search for feebly interacting particles, etc. remain to be important.

T. Nakada, ECR 2023, CERN



Requirements for the next HEP machine

- From pure physics
  - Capable of H and t physics complementary to/beyond LHC and HL-LHC
  - Capable of Z and W physics beyond currently known
    - ⇒an e^+e^- collider covering a region of 90-350 GeV centre of mass energy (cme)
- Somewhat physics related issues
  - It is good to start data taking with some overlap with the HL-LHC operation since the results might influence each other's scientific programme.
    - ⇒A machine which can be built within the next 10~15 years.
  - Can be upgraded to probe higher energy scales if physics result motivates.
  - Should not damage the diversity of particle physics activities.
    - ⇒A machine with a reasonable cost
- HEP sociology
  - Continuity in the HEP programme to sustain the community
- Other issues have become increasingly important
  - Environmental impact, energy consumption, resource availability, attractivity in technology, impact on industries, spinoffs, …

T. Nakada, ECR 2023, CERN

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:

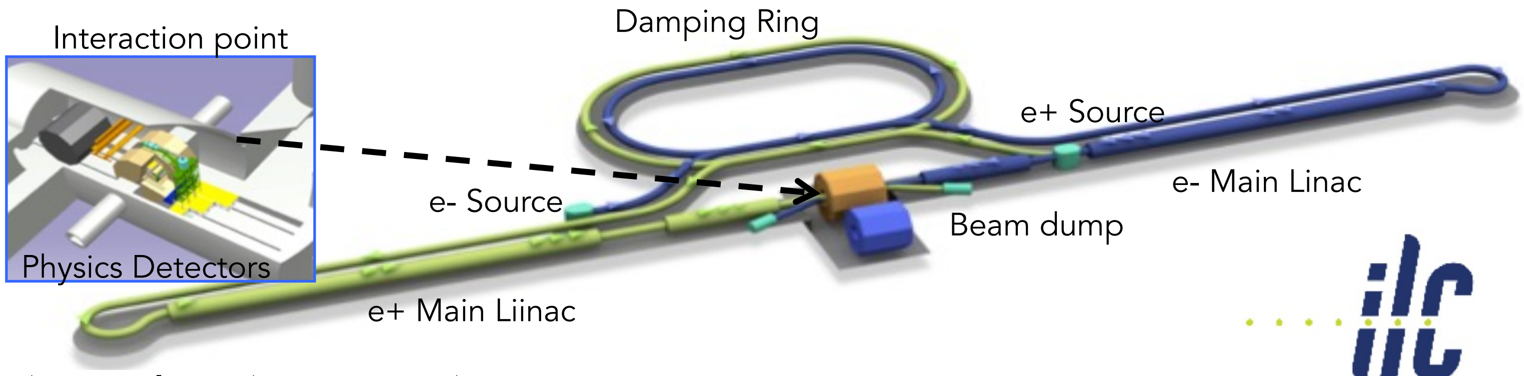
- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***
- ***Europe, together with its international partners, should investigate the technical 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.

2. The near term collider landscape: Technologies ready

ILC, CLIC, FCC-ee, CEPC

Technologies ready (I)



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)

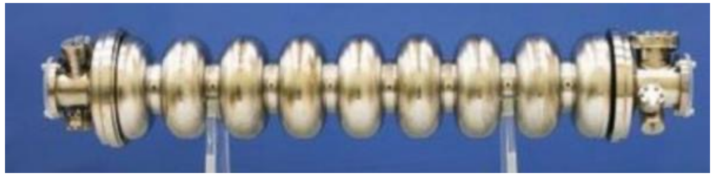
Item	Parameters
C.M. Energy	250 GeV
Length	20 km
Luminosity	**1.35 x10^{34} $cm^{-2}s^{-1}$**
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity Gain Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}

A. Yamamoto, 2014/02/05

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

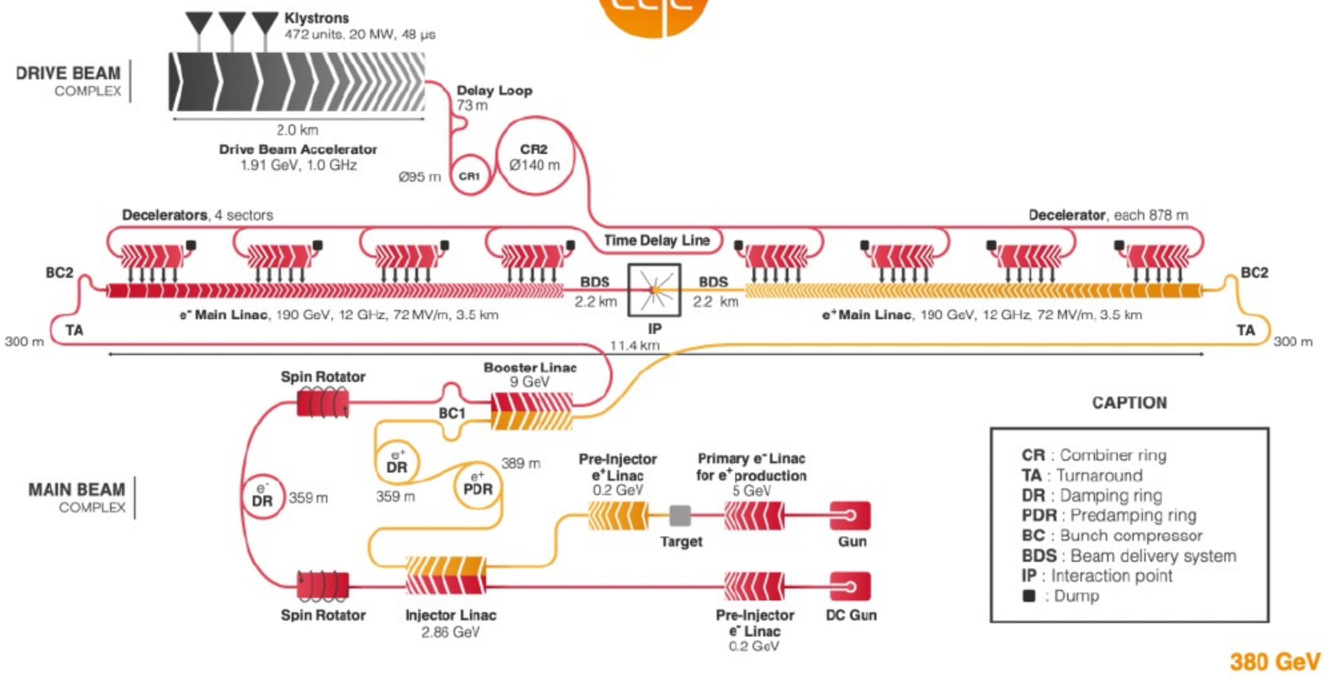
If moved at CERN, cost to be re-evaluated



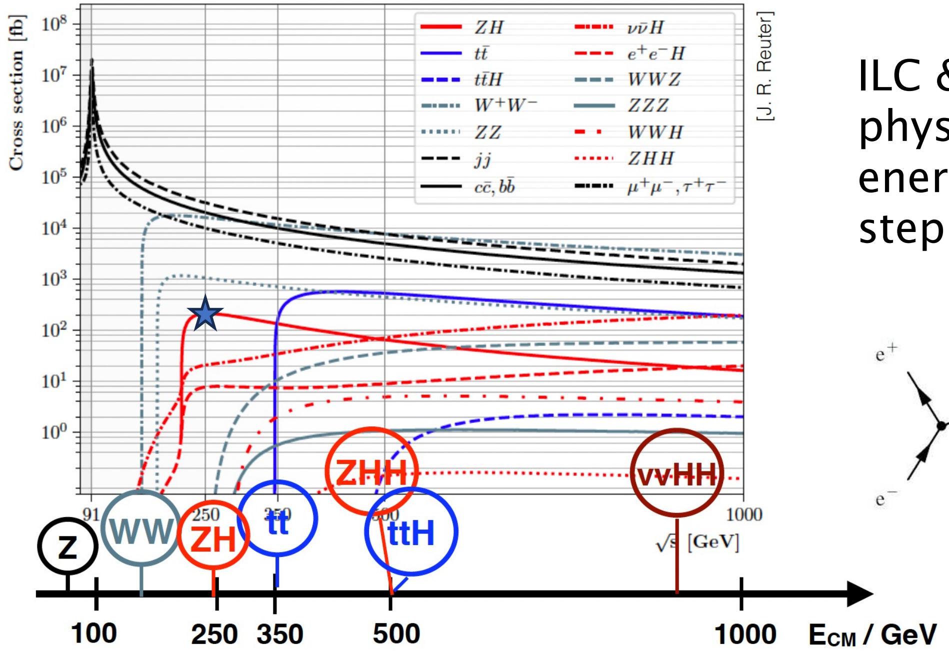
Technologies ready (2)

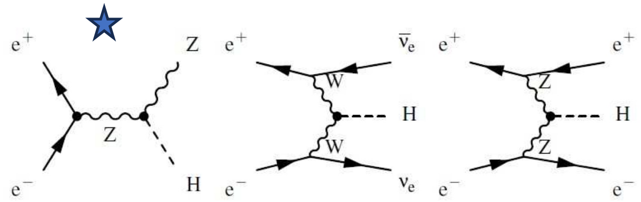
CLIC (pre-TDR in 2018)
Based on RF warm technology: 2 acc. options
– 2 GeV e⁻ drive beam
– X band klystrons
Both aiming at ~70 MV/m

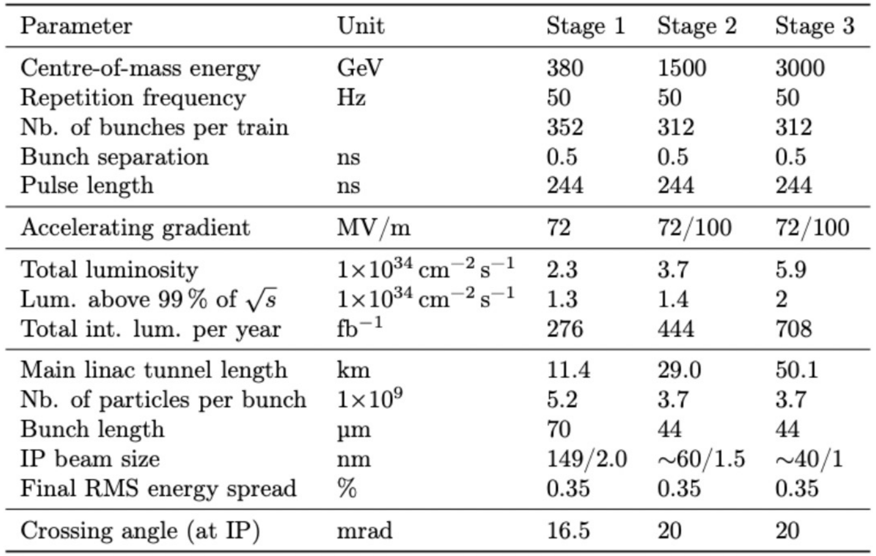
Baseline 380 GeV, L=11 km, **6.0 BSF** (2018)
Scalable up to 3 TeV (50 km !)



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

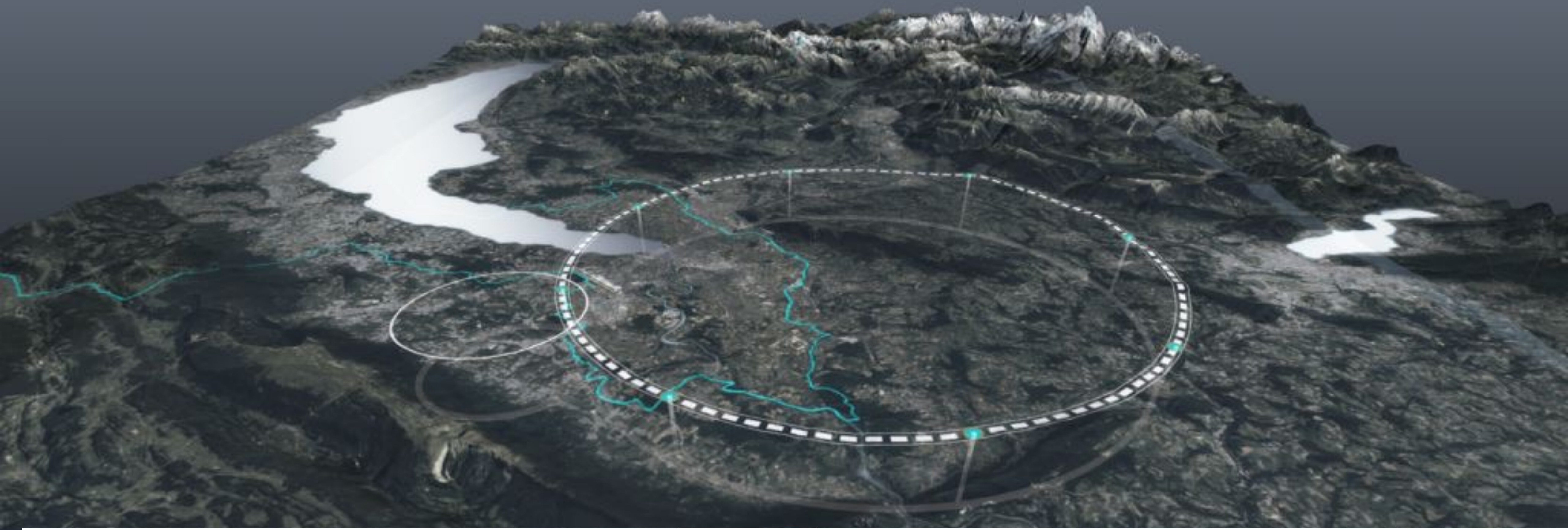






Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	1×10^{34} cm^{-2}s^{-1}	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	1×10^{34} cm^{-2}s^{-1}	1.3	1.4	2
Total int. lum. per year	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

Status of the FCC Feasibility Study



FUTURE CIRCULAR COLLIDER Innovation Study

EuroCirCol A key to New Physics

EASITrain

iFAST

E-JADE

EAJADE

CHART Swiss Accelerator Research and Technology

http://cern.ch/fcc

CERN

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **iFAST**, grant agreement 101004730, **FCCIS**, grant agreement 951754; **E-JADE,** contract no. 645479; **EAJADE**, contract number 101086276; and by the Swiss **CHART** program*

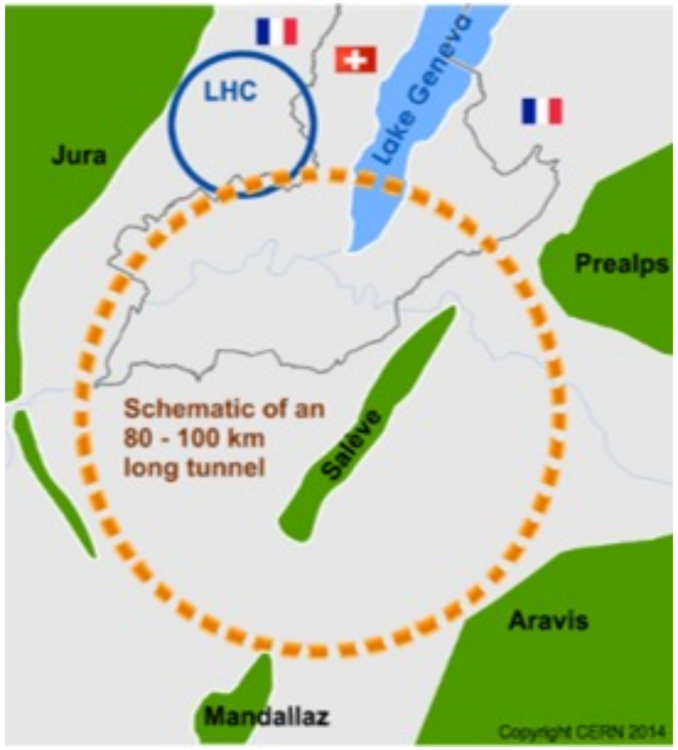
European Commission | Horizon 2020 European Union funding for Research & Innovation

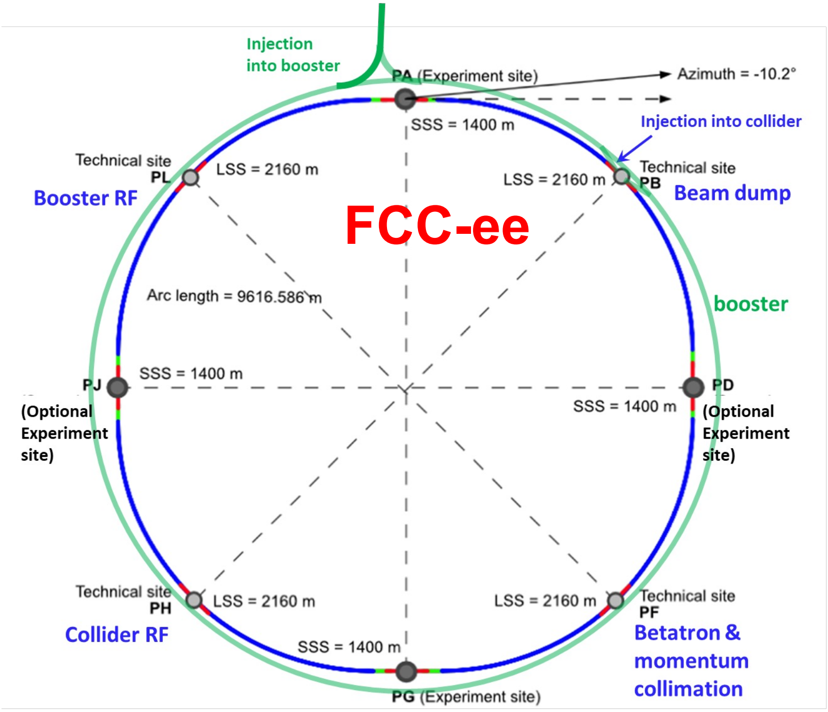
photo: J. Wenninger

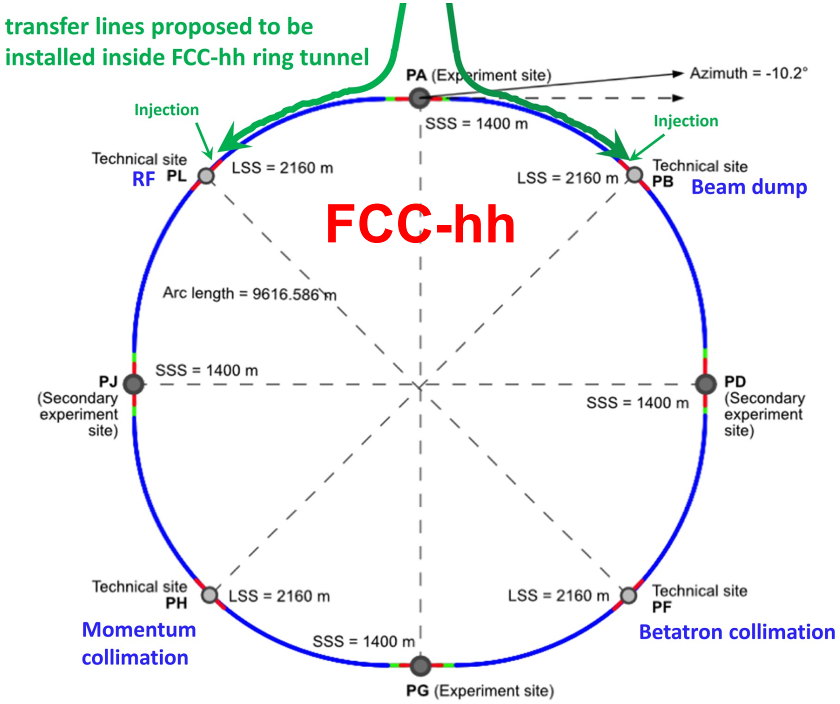
FCC integrated program

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







FUTURE
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COLLIDER

FCC Feasibility Study (2021-2025): high-level objectives

- ☐ demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- ☐ pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- ☐ optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- ☐ elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- ☐ development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- ☐ identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- ☐ consolidation of the physics case and detector concepts for both colliders.

Results will be summarised in a Feasibility Study Report to be released by March 2025

Main goals for 2024/begin 2025

- **Completion of technical work for Feasibility Study until end 2024**
    - Implementation of recommendations of the mid-term review
    - Focus on “feasibility items” and items with important impact on cost/performance
    - Develop a risk register
    - Update cost estimate to reach cat 3 level on cost uncertainty.
    - Further develop the funding model based on discussions with the Council

- **Complete FS by March 2025 as input for ESPP update.**

- **In parallel, continue work with host states on project definition and responsibilities, authorization procedures, excavation material strategy and regional implementation development.**

Pre-TDR phase from April 2025 until end 2027

- Main goal is to provide all information to Council to allow taking a decision on the project **at the end of 2027 or mid-2028**
    - further develop the civil engineering and the technical design all major components, so as to provide a **more detailed cost estimate** with reduced uncertainties
    - Continuation ot **technical R&D activities**.
    - Continuation of site investigations and perform an **overall integration study to specify requirements of technical infrastructure, accelerators and detectors** for subsequent civil engineering design in case the project goes ahead.
    - Launch of **environmental impact study in 2026**
    - Work with host states on **regional implementation development** and authorization procedures.

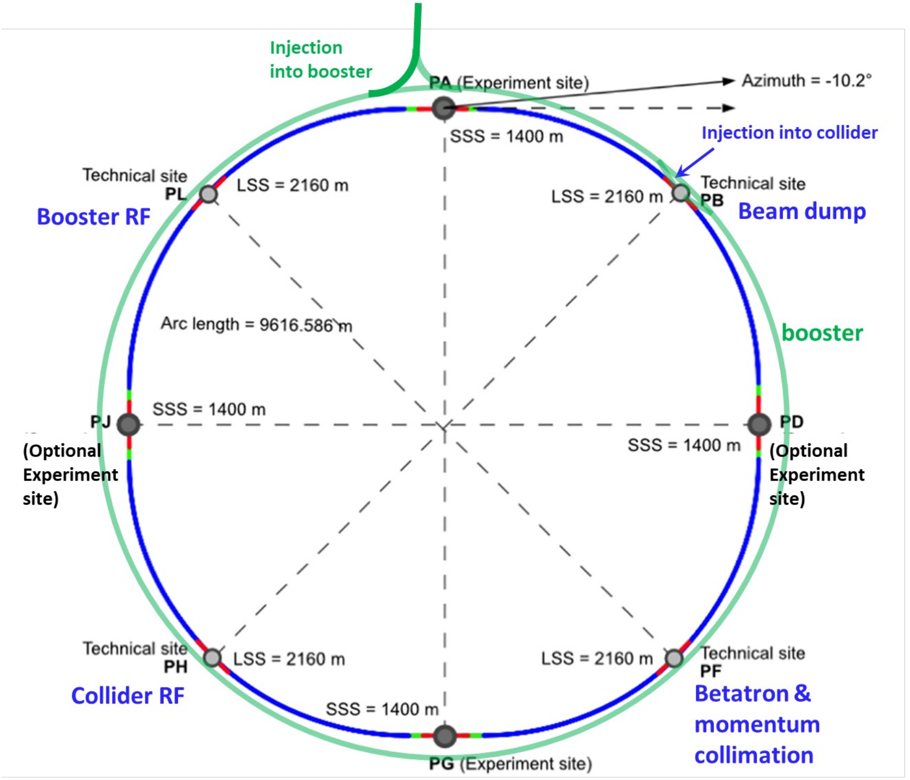
FUTURE CIRCULAR COLLIDER

Optimized placement and layout for feasibility study

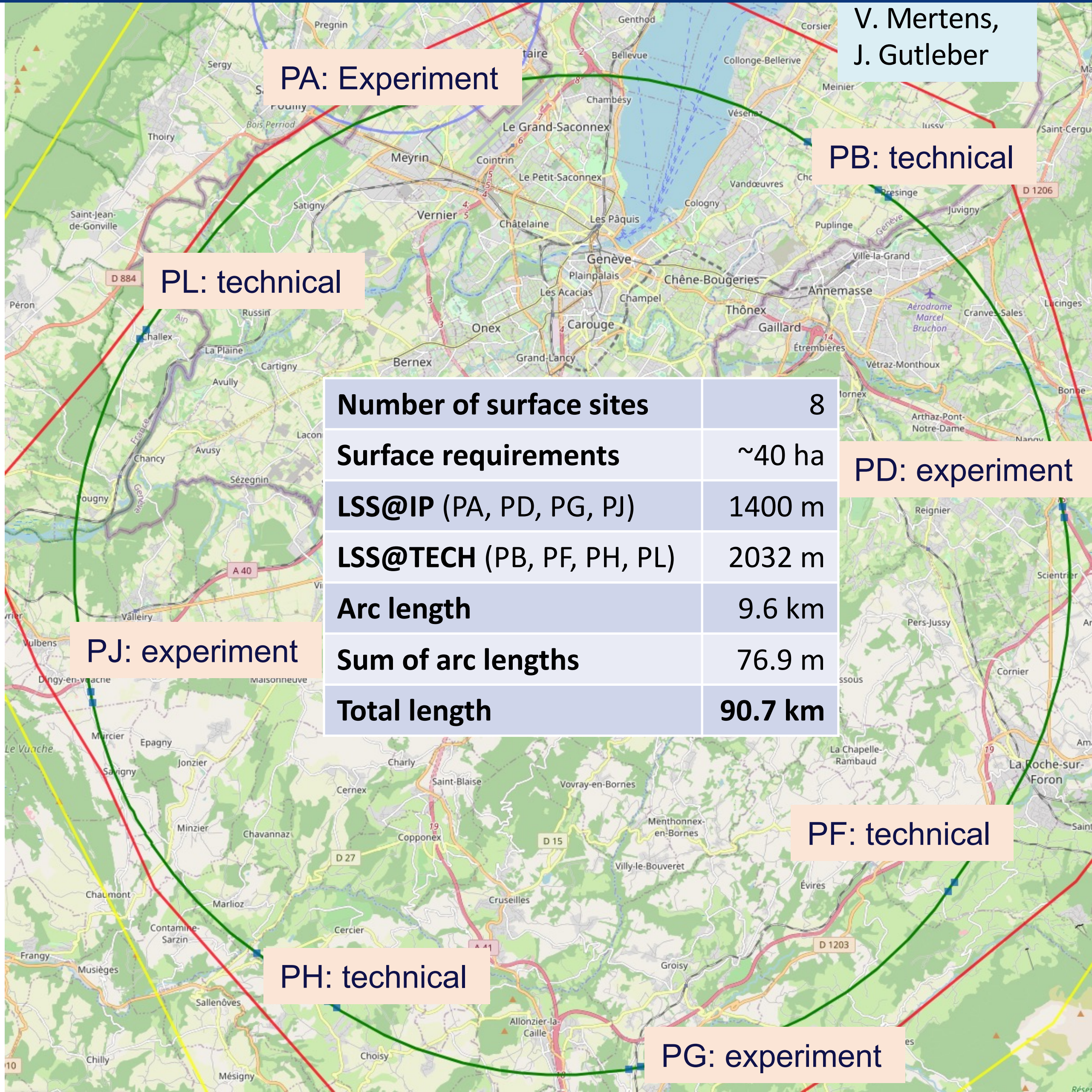
Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce-compensate” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement



V. Mertens,
J. Gutleber



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

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FCC-ee: main 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
	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

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

- ☐ 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

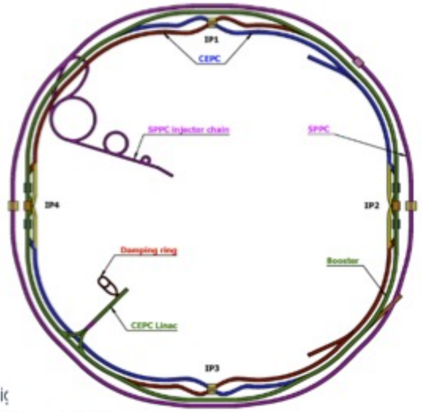
Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

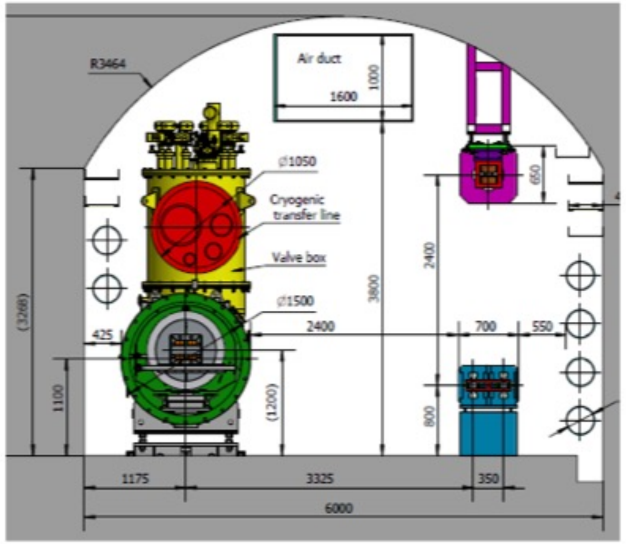
F. Gianotti

CEPC Layout and Design Essentials

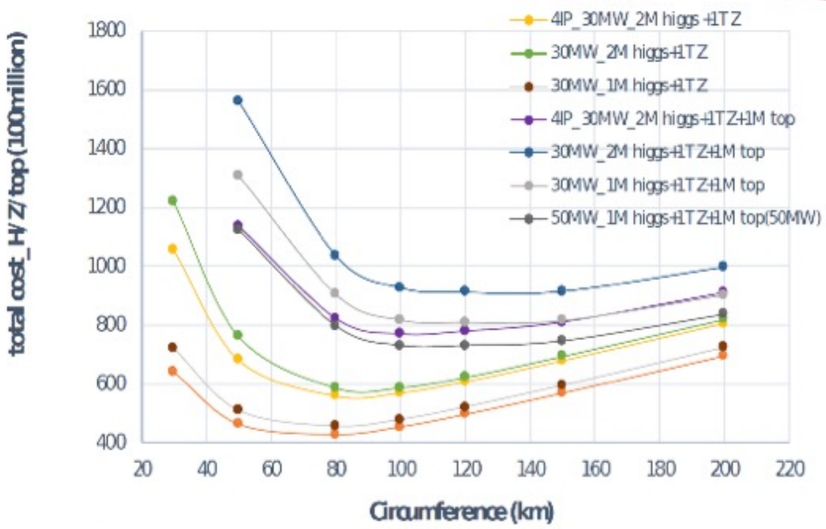
Main Design considerations:

- **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

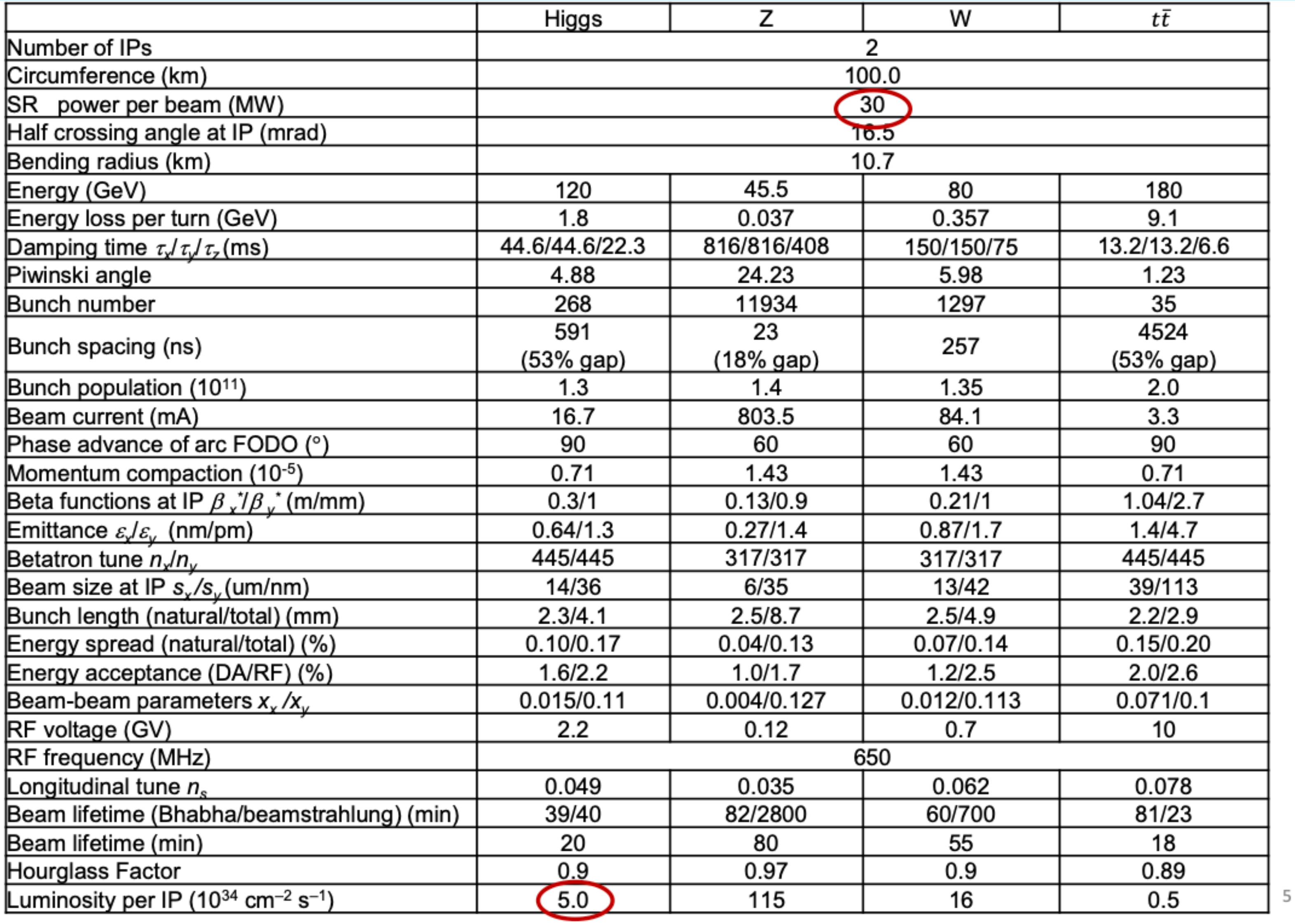


Cost optimization v.s. circumference

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

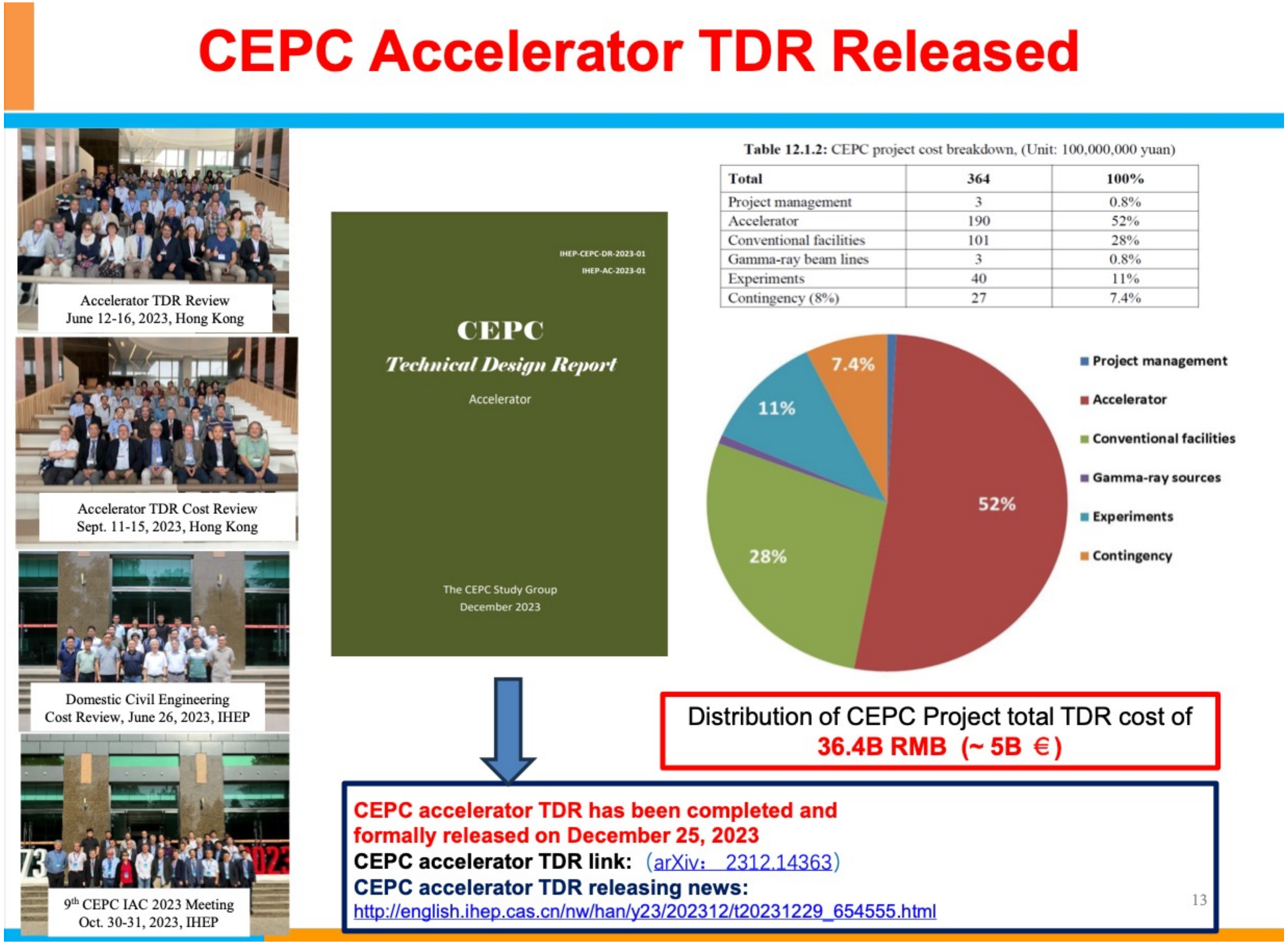
Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar

Machine Parameters



	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune n_x/n_y	445/445	317/317	317/317	445/445
Beam size at IP s_x/s_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.7	1.2/2.5	2.0/2.6
Beam-beam parameters x_x/x_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune n_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	39/40	82/2800	60/700	81/23
Beam lifetime (min)	20	80	55	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5

5



CEPC Accelerator TDR Released

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

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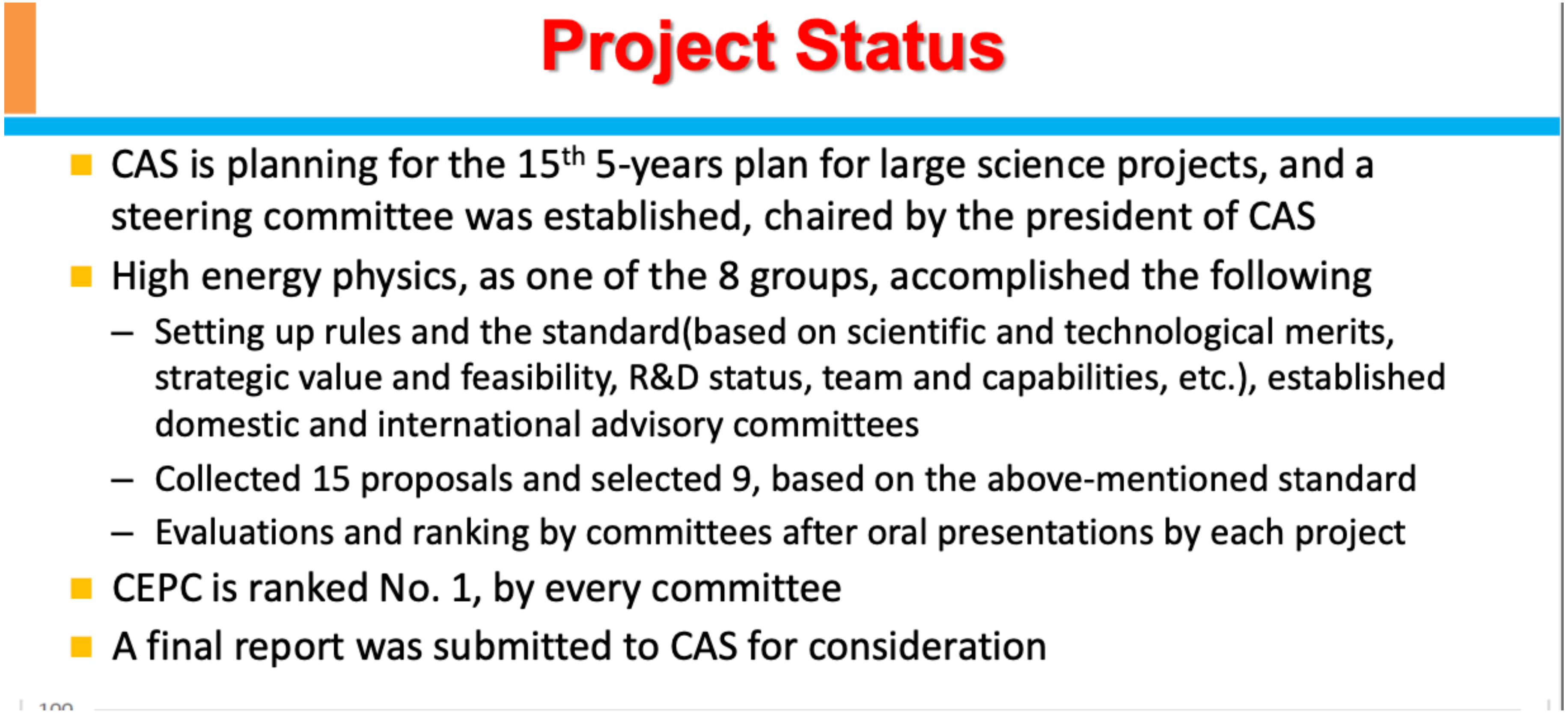
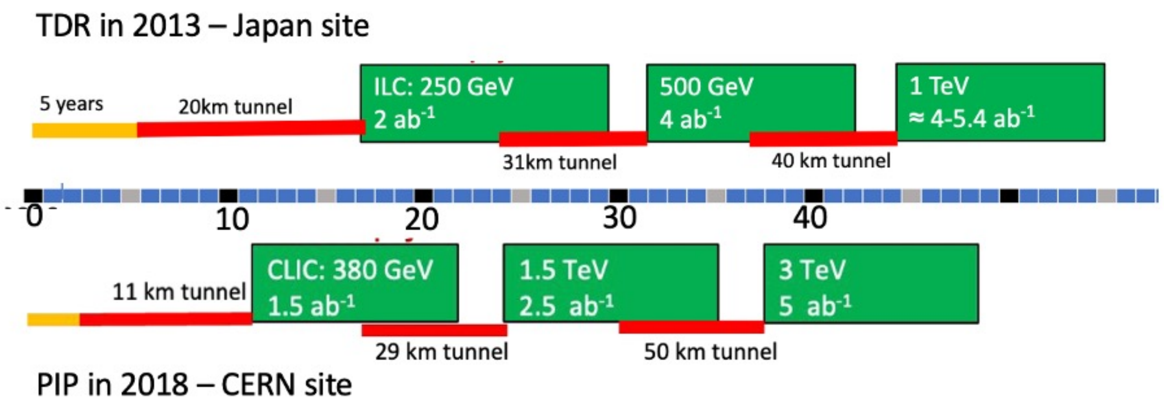


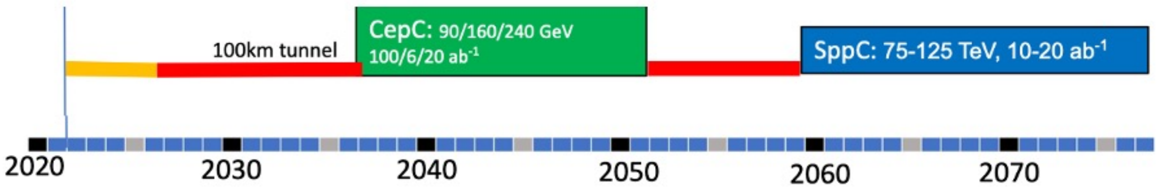
Project Status

- CAS is planning for the 15th 5-years plan for large science projects, and a steering committee was established, chaired by the president of CAS
- High energy physics, as one of the 8 groups, accomplished the following
  - Setting up rules and the standard(based on scientific and technological merits, strategic value and feasibility, R&D status, team and capabilities, etc.), established domestic and international advisory committees
  - Collected 15 proposals and selected 9, based on the above-mentioned standard
  - Evaluations and ranking by committees after oral presentations by each project
- CEPC is ranked No. 1, by every committee
- A final report was submitted to CAS for consideration

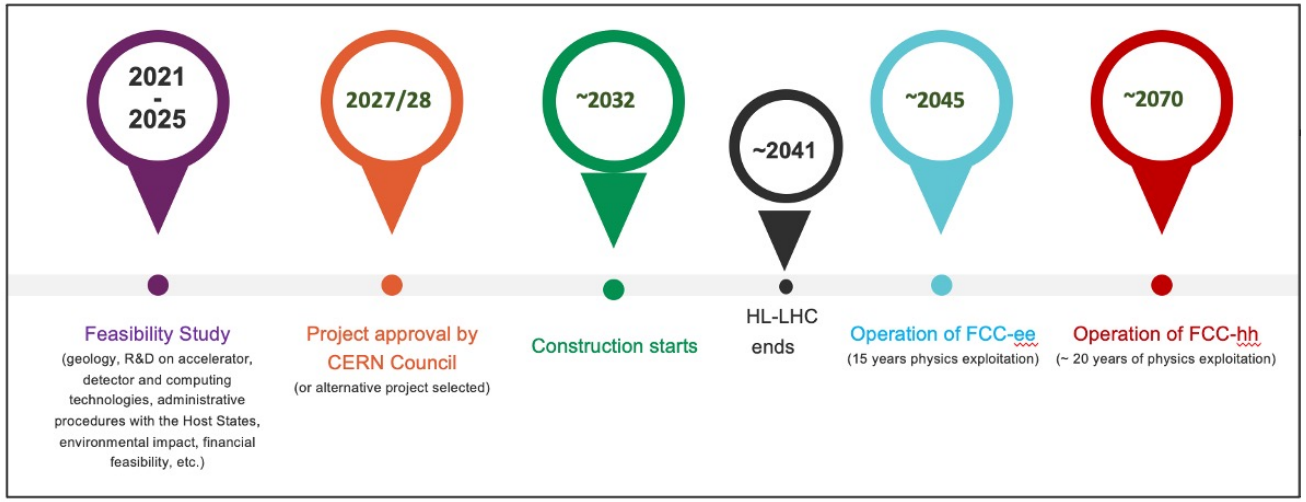
CECP is primarily a national Chinese project lead by IHEP.
International participation expected on one of the two detectors.
Several candidate sites being studied but none is at IHEP, Beijing (“green field” infrastructure, probably additional costs).
Strong capabilities by Chinese industries (SRFs, magnets, mechanics, etc…)
Some R&D budget has been allocated and waiting for a decision (early 2026 ?)

Dates of possible approval still to be defined



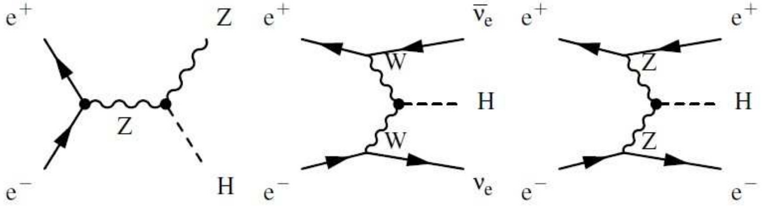


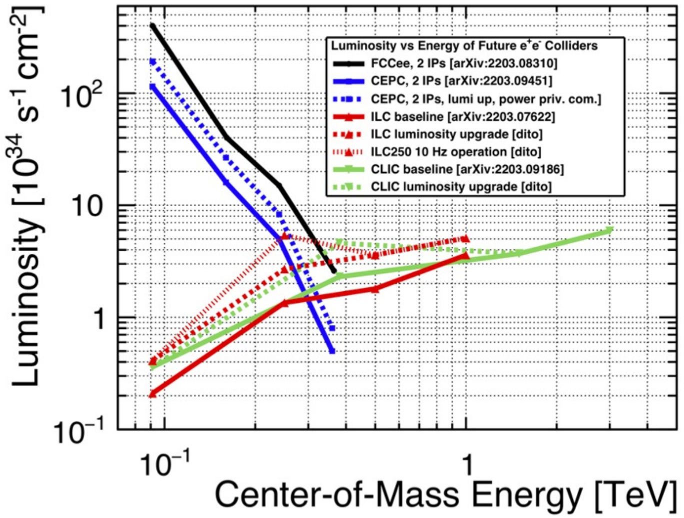
Re-elaborated from Snowmass EF 2021



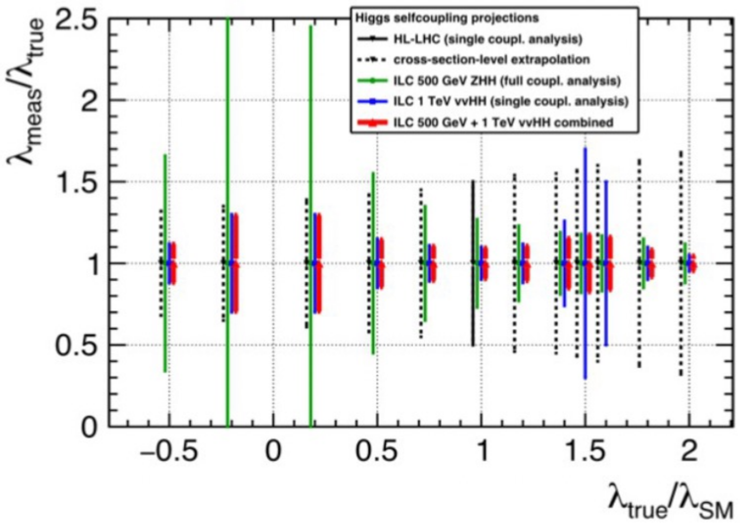
- **2021 - 2025** Feasibility Study (geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)
- **2027/28** Project approval by CERN Council (or alternative project selected)
- **~2032** Construction starts
- **~2041** HL-LHC ends
- **~2045** Operation of FCC-ee (15 years physics exploitation)
- **~2070** Operation of FCC-hh (~ 20 years of physics exploitation)

Wrap-up (1)





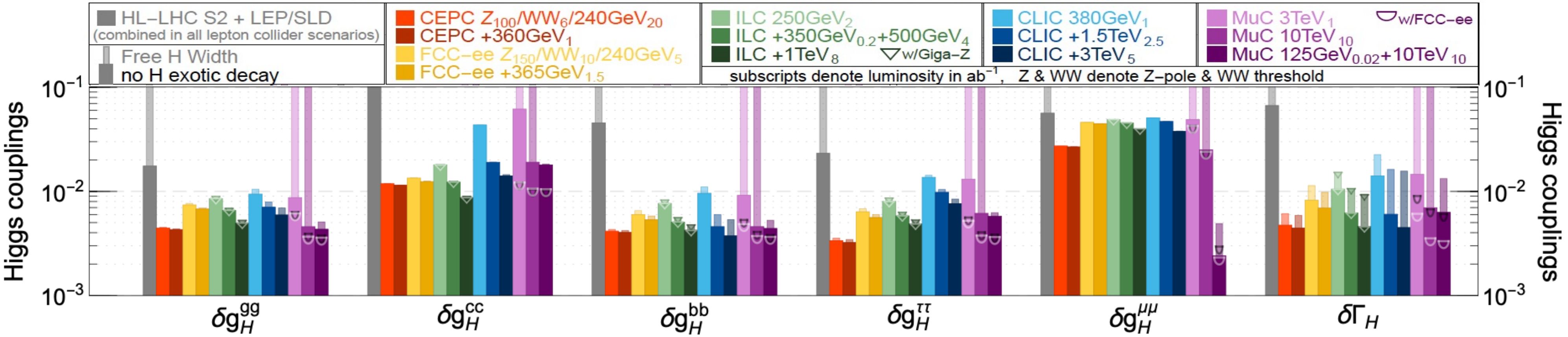
Higgs self-coupling measurement

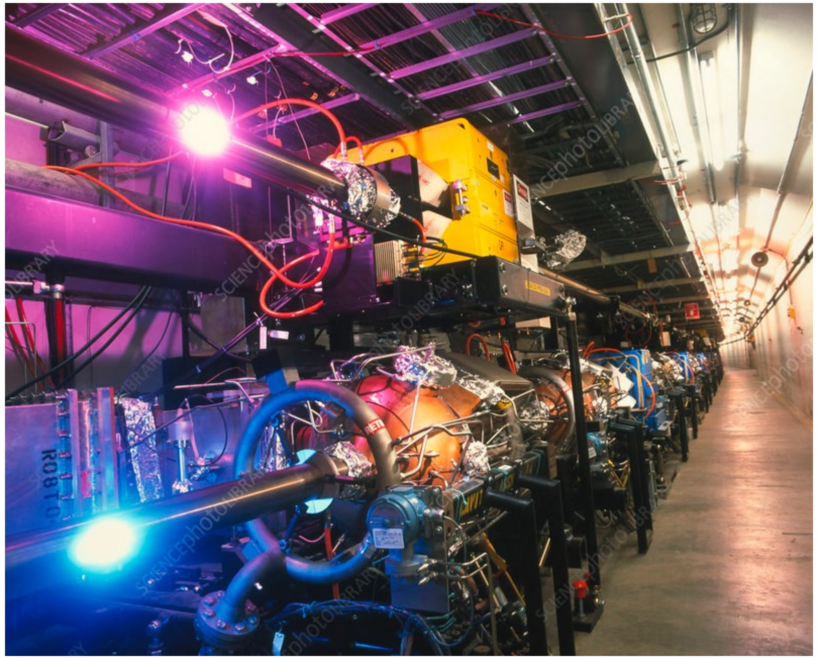


- All planned e+e- machines will deliver O(1%) precision on Higgs couplings
  - Beam polarisation at LC catches up for smaller luminosity
- Higher energies increase the precision and allow for measuring the Higgs self-coupling
- Linear colliders largely less performant at Z pole (1:1000 in stat.), partial recovery with polarization
- Circular colliders statistics slight better as Higgs factory (3:1)

precision reach on effective couplings from SMEFT global fit

ArXiv:2206.08326

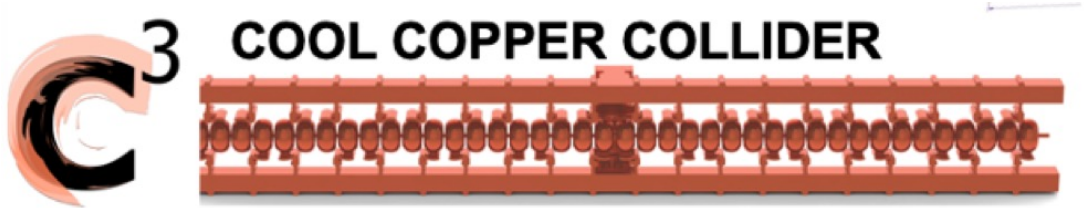




3. The longer perspective: Technological challenges

C3, plasma (ILC vision); muon collider; FCC-hh & SppC

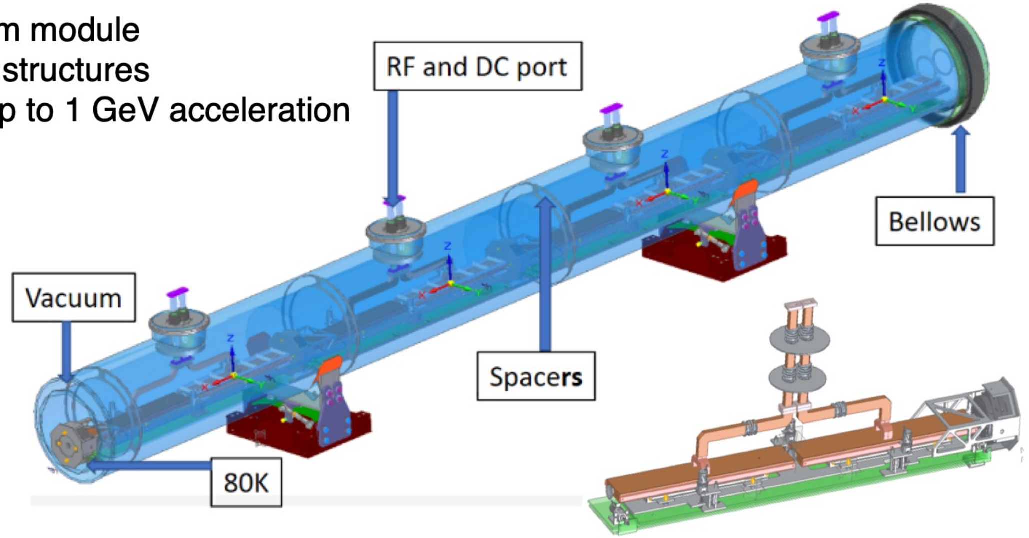
COOL COPPER COLLIDER

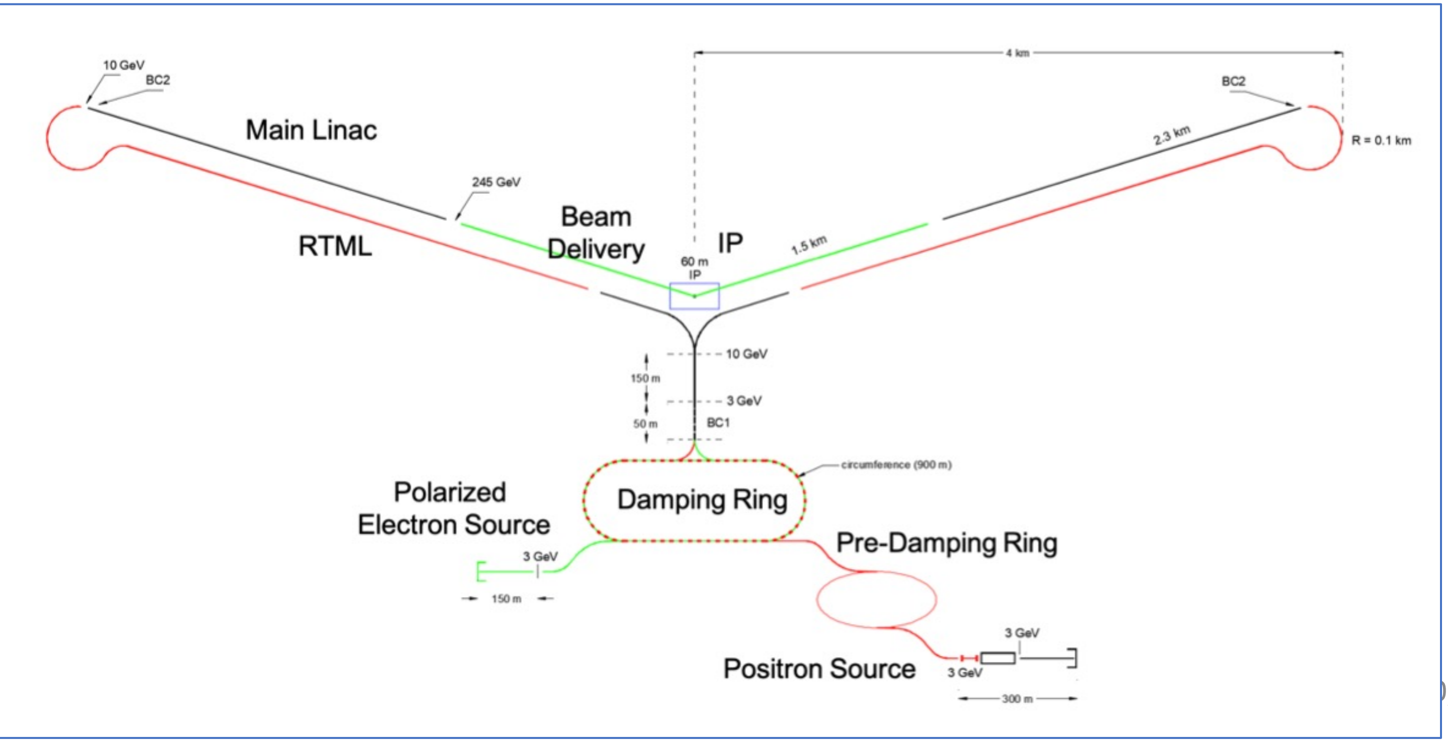


- Planning for operations at high gradient **at 550 GeV, 120 MeV/m**
  - **Start at 70 MeV/m for C^{3}-250 8 km footprint**

C-band well established techology, obtaining higher gradient (x2) using N2 cryogenic cooling of Cu RF cavities

9m module
8 structures
Up to 1 GeV acceleration



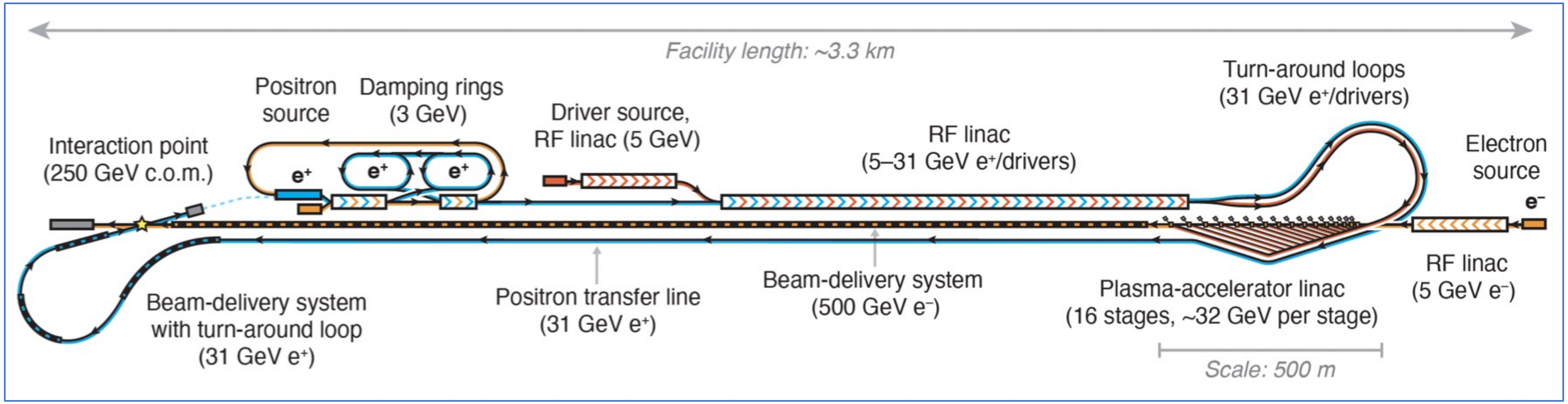


Challenges:
- achieve an maintain over a large no. of cavities w/high gradient standards
- integration level of cryo-structures with the rest of the machine's elements.

A demonstrator of C3 technology will be needed in future years (as XFEL, ESS, etc… were for SRFs).
An option for future ILC upgrades

Hybrid Asymmetric Linear Higgs Factory (HALHF)

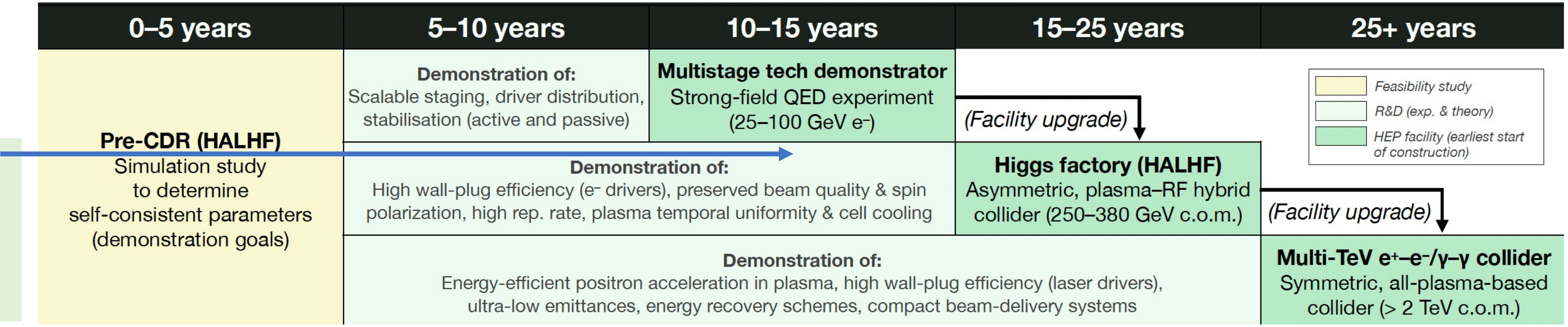
To obtain Ecm=250 GeV (ZH)
500 GeV e- beam driven plasma x **31 GeV e+** RF



Energy upgrade to ttbar (380 GeV) => 47.5 GeV positrons / 760 GeV electrons

Challenges: RF linac (high power, high stability), positron source, multi-stage plasma acceleration at low emittance/low E spread beam quality. An option for future ILC upgrades

FEL plasma based @ LNF could play a role as demonstrator of technologies for Linear Colliders



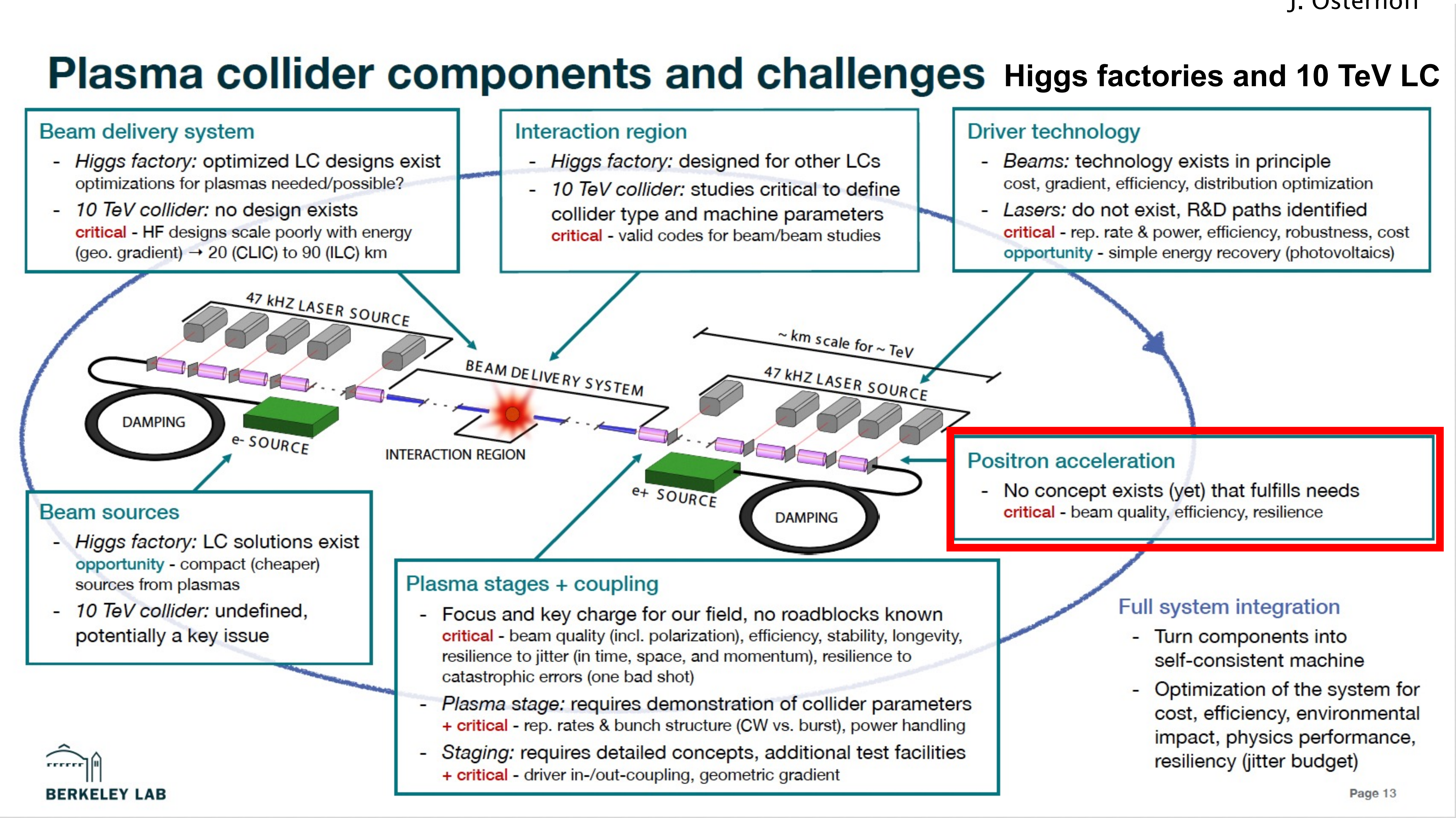
0–5 years	5–10 years	10–15 years	15–25 years	25+ years
Pre-CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e−)	*(Facility upgrade)*	
	Demonstration of: High wall-plug efficiency (e− drivers), preserved beam quality & spin polarization, high rep. rate, plasma temporal uniformity & cell cooling		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	*(Facility upgrade)*
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e+–e−/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

🟨 *Feasibility study*
⬜ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

J. Osterhoff

Plasma collider components and challenges

Higgs factories and 10 TeV LC



Beam delivery system

- *Higgs factory:* optimized LC designs exist
  optimizations for plasmas needed/possible?
- *10 TeV collider:* no design exists
  critical - HF designs scale poorly with energy (geo. gradient) → 20 (CLIC) to 90 (ILC) km

Interaction region

- *Higgs factory:* designed for other LCs
- *10 TeV collider:* studies critical to define collider type and machine parameters
  critical - valid codes for beam/beam studies

Driver technology

- *Beams:* technology exists in principle
  cost, gradient, efficiency, distribution optimization
- *Lasers:* do not exist, R&D paths identified
  critical - rep. rate & power, efficiency, robustness, cost
  opportunity - simple energy recovery (photovoltaics)

Positron acceleration

- No concept exists (yet) that fulfills needs
  critical - beam quality, efficiency, resilience

Beam sources

- *Higgs factory:* LC solutions exist
  opportunity - compact (cheaper) sources from plasmas
- *10 TeV collider:* undefined, potentially a key issue

Plasma stages + coupling

- Focus and key charge for our field, no roadblocks known
  critical - beam quality (incl. polarization), efficiency, stability, longevity, resilience to jitter (in time, space, and momentum), resilience to catastrophic errors (one bad shot)
- *Plasma stage:* requires demonstration of collider parameters
  + critical - rep. rates & bunch structure (CW vs. burst), power handling
- *Staging:* requires detailed concepts, additional test facilities
  + critical - driver in-/out-coupling, geometric gradient

Full system integration

- Turn components into self-consistent machine
- Optimization of the system for cost, efficiency, environmental impact, physics performance, resiliency (jitter budget)

BERKELEY LAB

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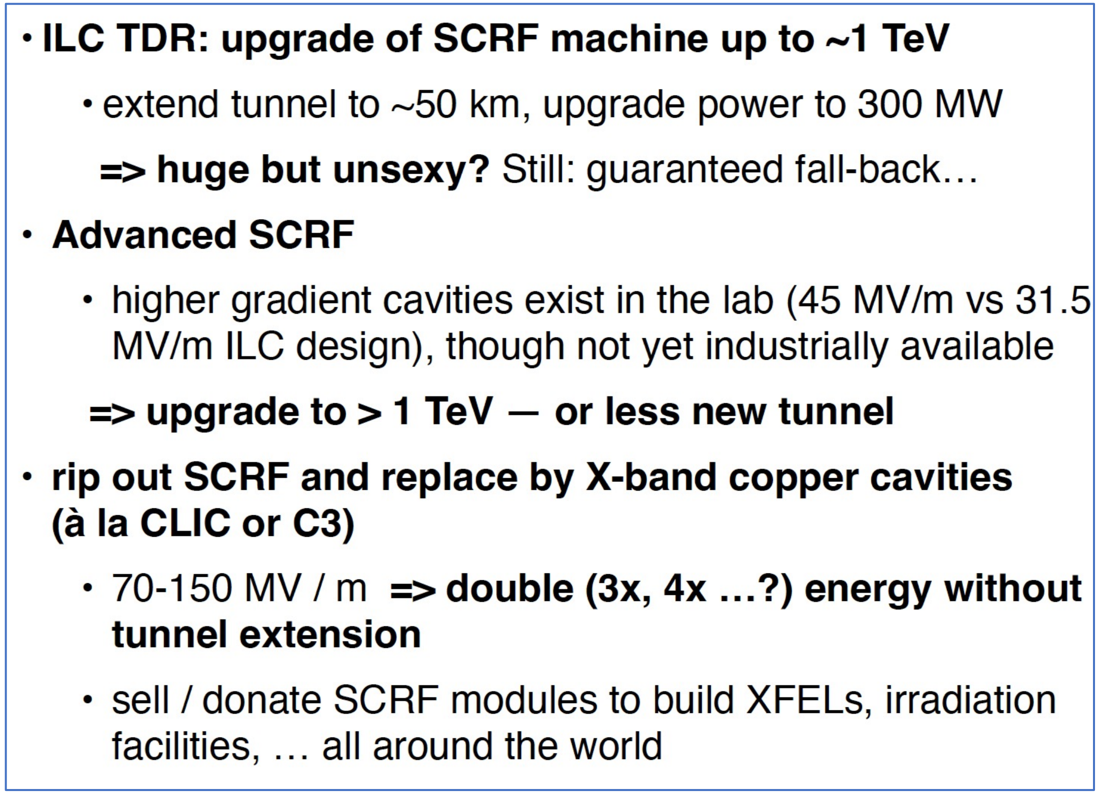
J. List et al.

"LC vision" = ILC & upgrades at CERN

Upgrade Options - Higher Energy "conventional"

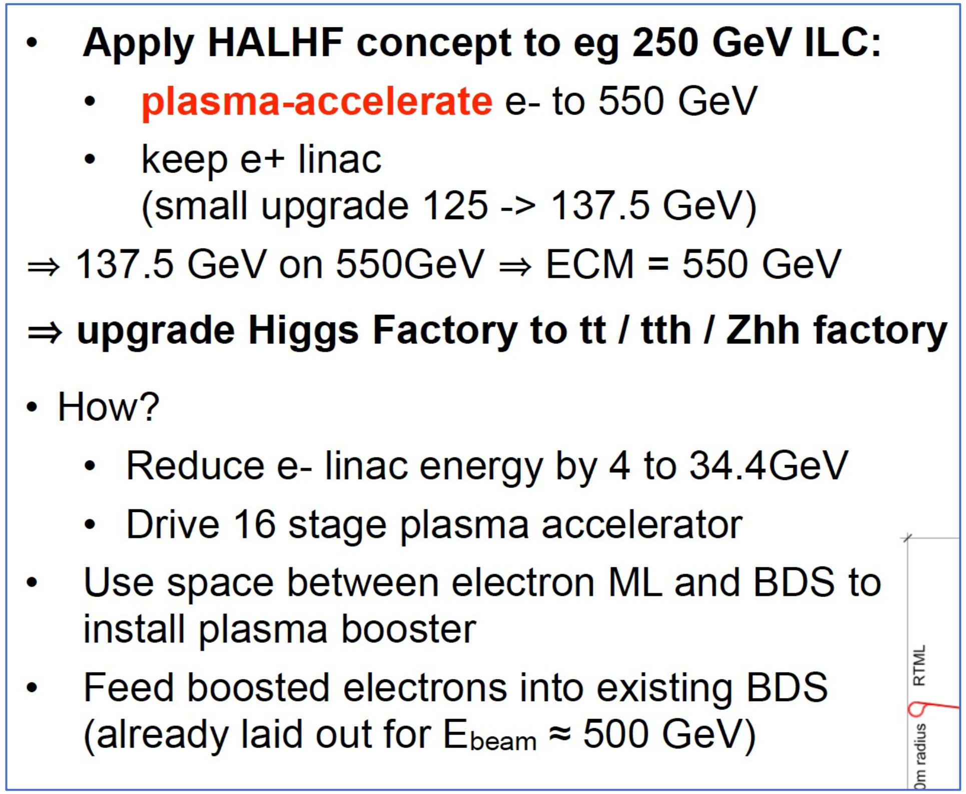


- **ILC TDR: upgrade of SCRF machine up to ~1 TeV**
  - extend tunnel to ~50 km, upgrade power to 300 MW

  => huge but unsexy? Still: guaranteed fall-back…
- **Advanced SCRF**
  - higher gradient cavities exist in the lab (45 MV/m vs 31.5 MV/m ILC design), though not yet industrially available

  => upgrade to > 1 TeV — or less new tunnel
- **rip out SCRF and replace by X-band copper cavities (à la CLIC or C3)**
  - 70-150 MV / m **=> double (3x, 4x …?) energy without tunnel extension**
  - sell / donate SCRF modules to build XFELs, irradiation facilities, … all around the world

Upgrade Options - Double ECM by "HALHFing" LCF



- **Apply HALHF concept to eg 250 GeV ILC:**
  - **plasma-accelerate** e- to 550 GeV
  - keep e+ linac
    (small upgrade 125 -> 137.5 GeV)

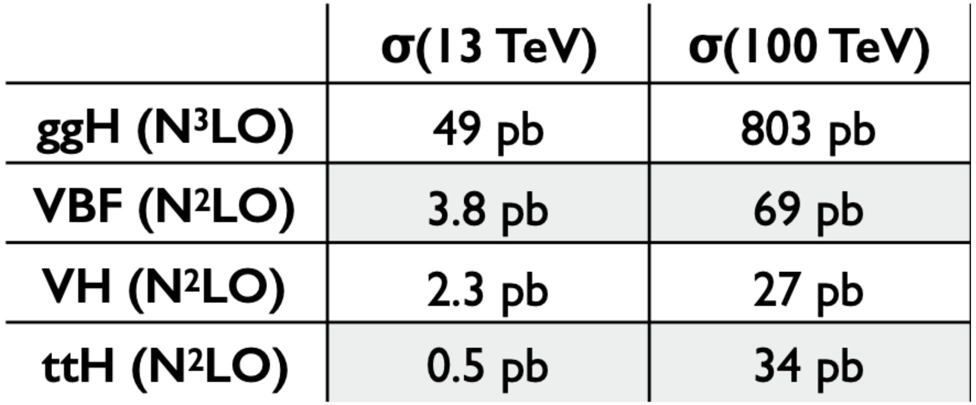
⇒ 137.5 GeV on 550GeV ⇒ ECM = 550 GeV

⇒ upgrade Higgs Factory to tt / tth / Zhh factory

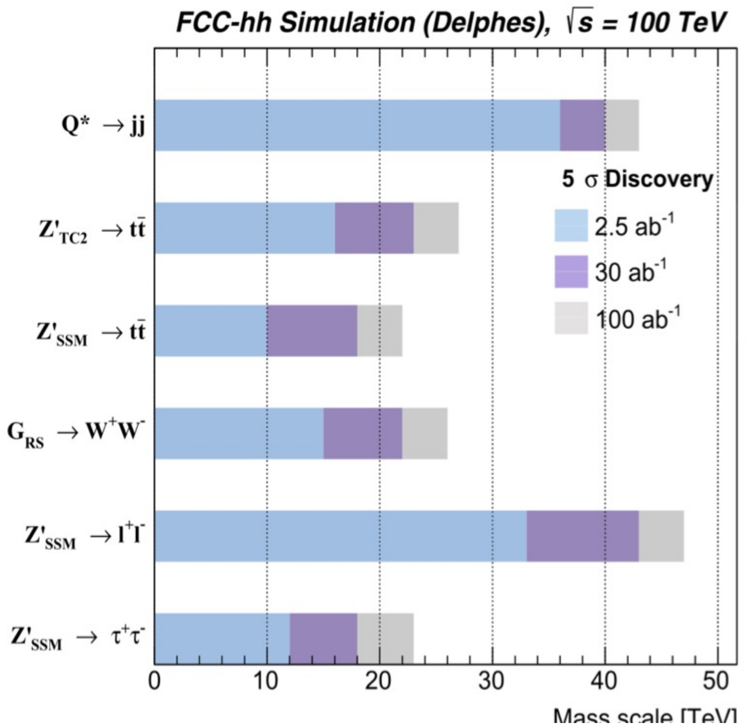
- How?
  - Reduce e- linac energy by 4 to 34.4GeV
  - Drive 16 stage plasma accelerator
- Use space between electron ML and BDS to install plasma booster
- Feed boosted electrons into existing BDS (already laid out for E_{beam} ≈ 500 GeV)

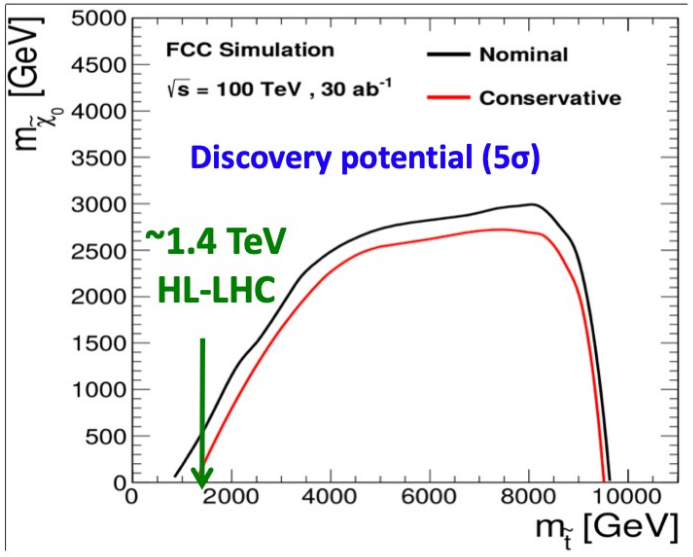
FCC-hh & SppC: the big smashers

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

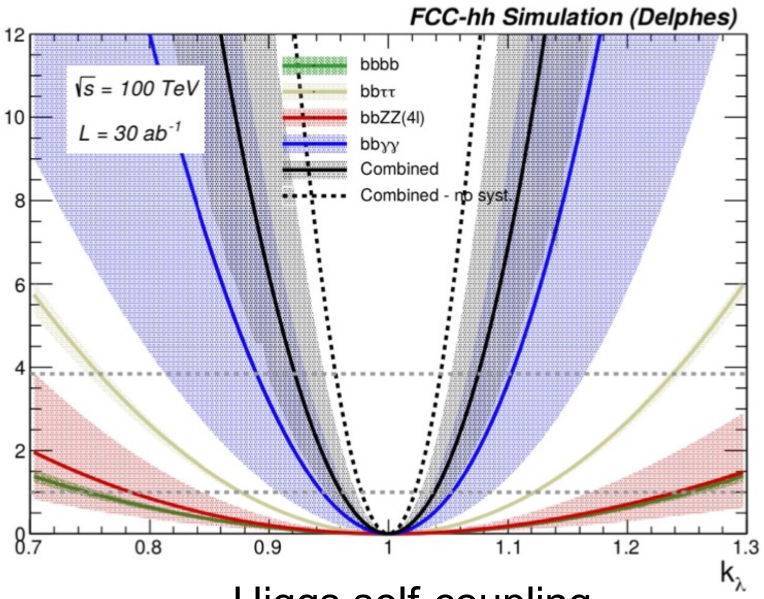


	σ(13 TeV)	σ(100 TeV)
ggH (N^3LO)	49 pb	803 pb
VBF (N^2LO)	3.8 pb	69 pb
VH (N^2LO)	2.3 pb	27 pb
ttH (N^2LO)	0.5 pb	34 pb





Discover scalars up to O(10) TeV



Higgs self-coupling

FCC-hh parameters

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

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:

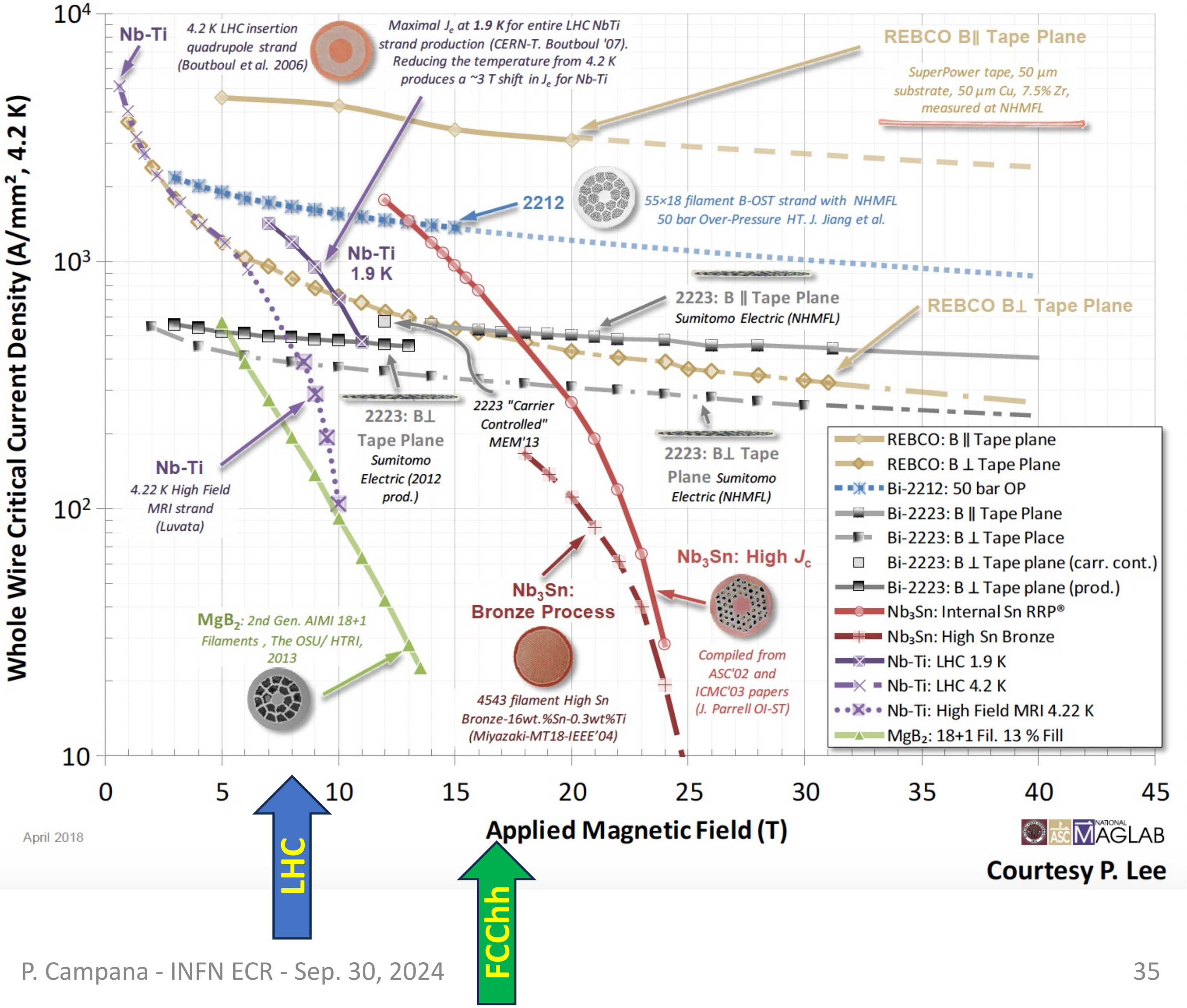
☐ Direct discovery potential up to ~ 40 TeV
☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
☐ Final word about WIMP dark matter

HFM, HTS and the quest for high critical currents

For suitable applications, it is the whole-wire current density that counts!

Assuming a threshold of 300 A/mm² @1.9-4.5K, we see:

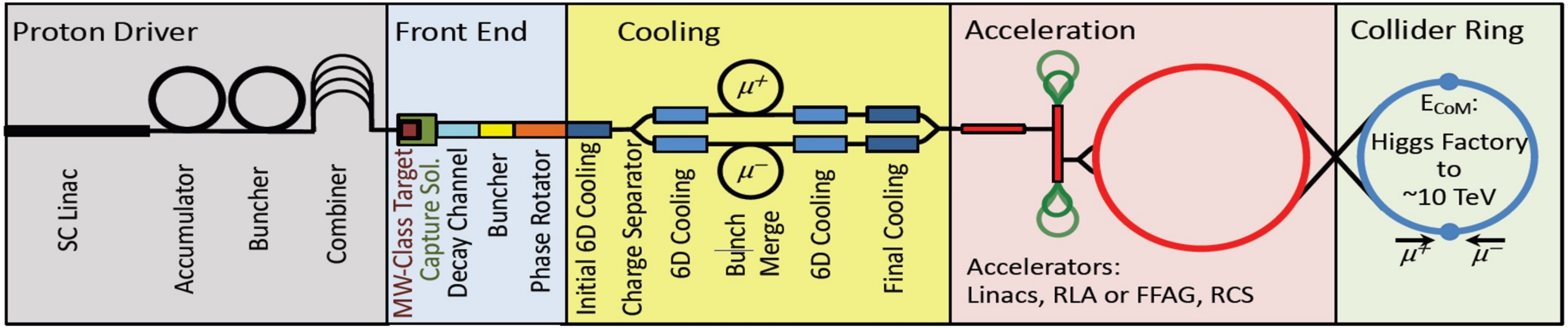
- MgB$_2$ up to 5 T
- NbTi up to 10-11 T @1.9 K
- Nb$_3$Sn up to 20 T @1.9 K
- **Only HTS: Bi-2212, Bi-2223 and ReBCO can go >>20 T up to the conductor YS limit!**



Courtesy P. Lee

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

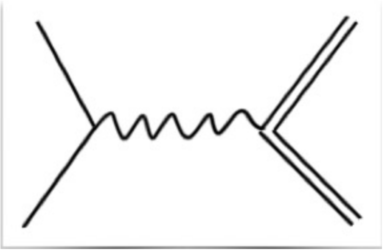
6D cooling
High Mag Field Solenoids +
RF cavities in HFM (!)

Acceleration to collision energy

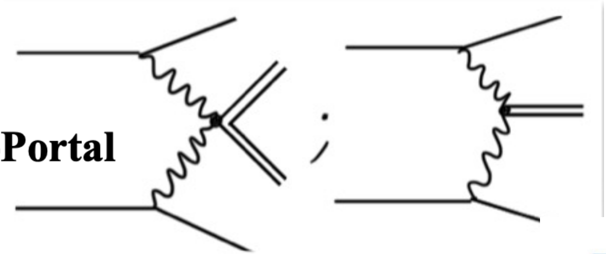
Collision

High background at IR
Radiological neutrino flux

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

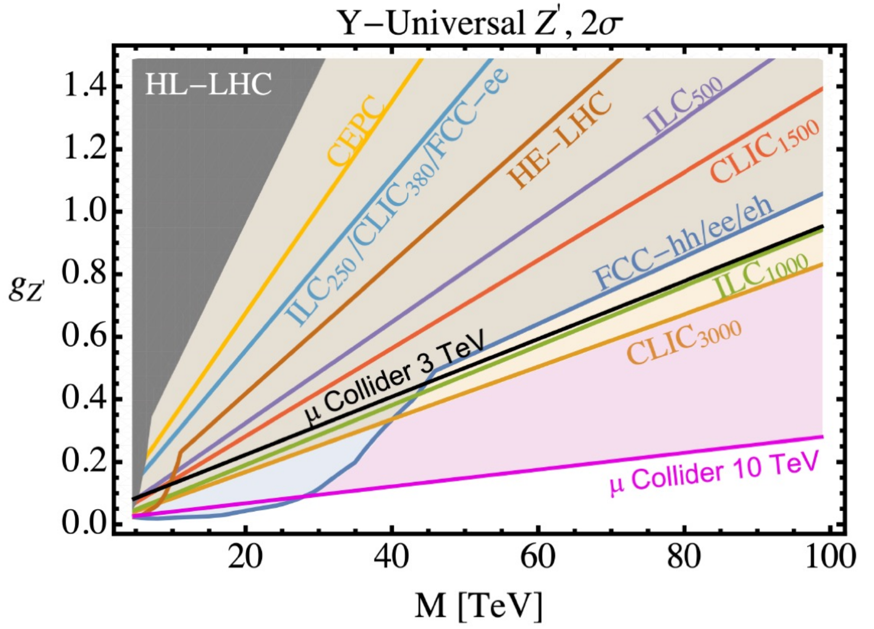


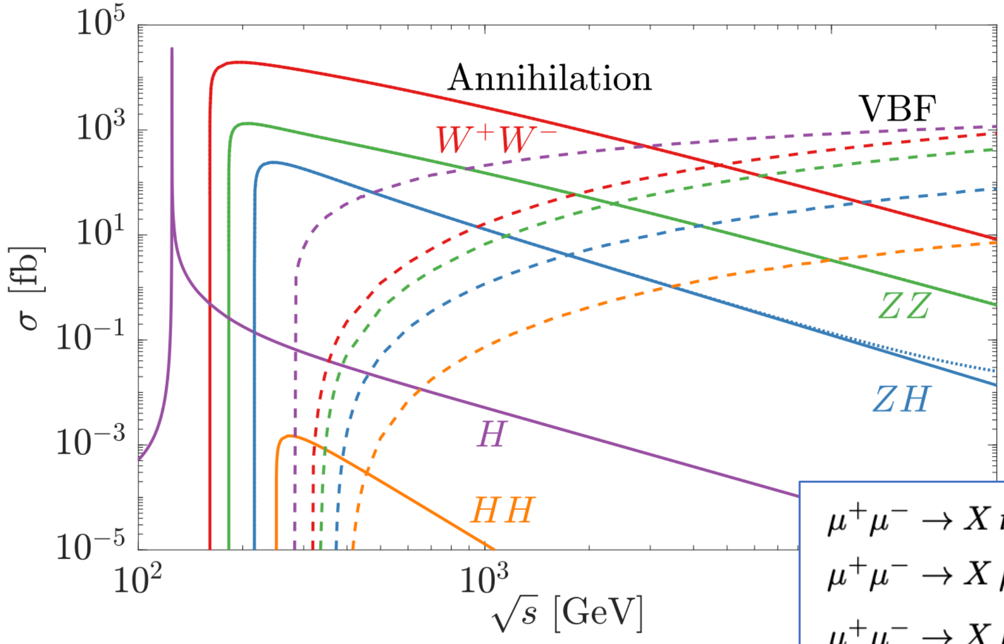
μμ annihilation: production of **EW-charged particles**



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

Huge rates due VBF rising cross section

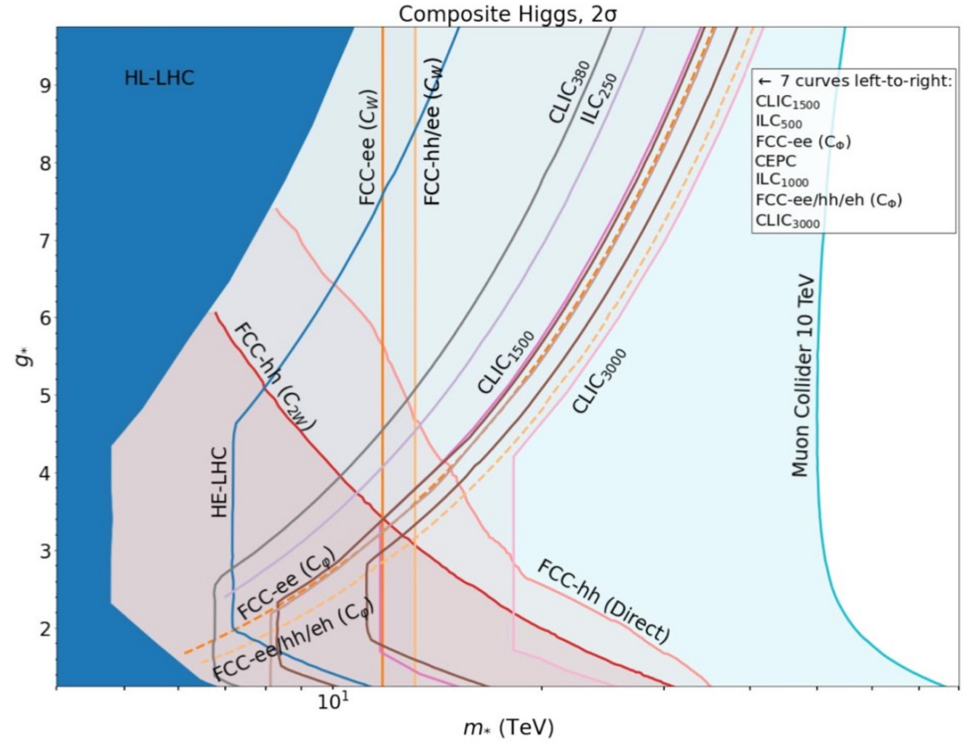




$\mu^+\mu^- \to X\,\nu_\mu\bar{\nu}_\mu$ (WW fusion),

$\mu^+\mu^- \to X\,\mu^+\mu^-$ (ZZ/Zγ/γγ fusion).

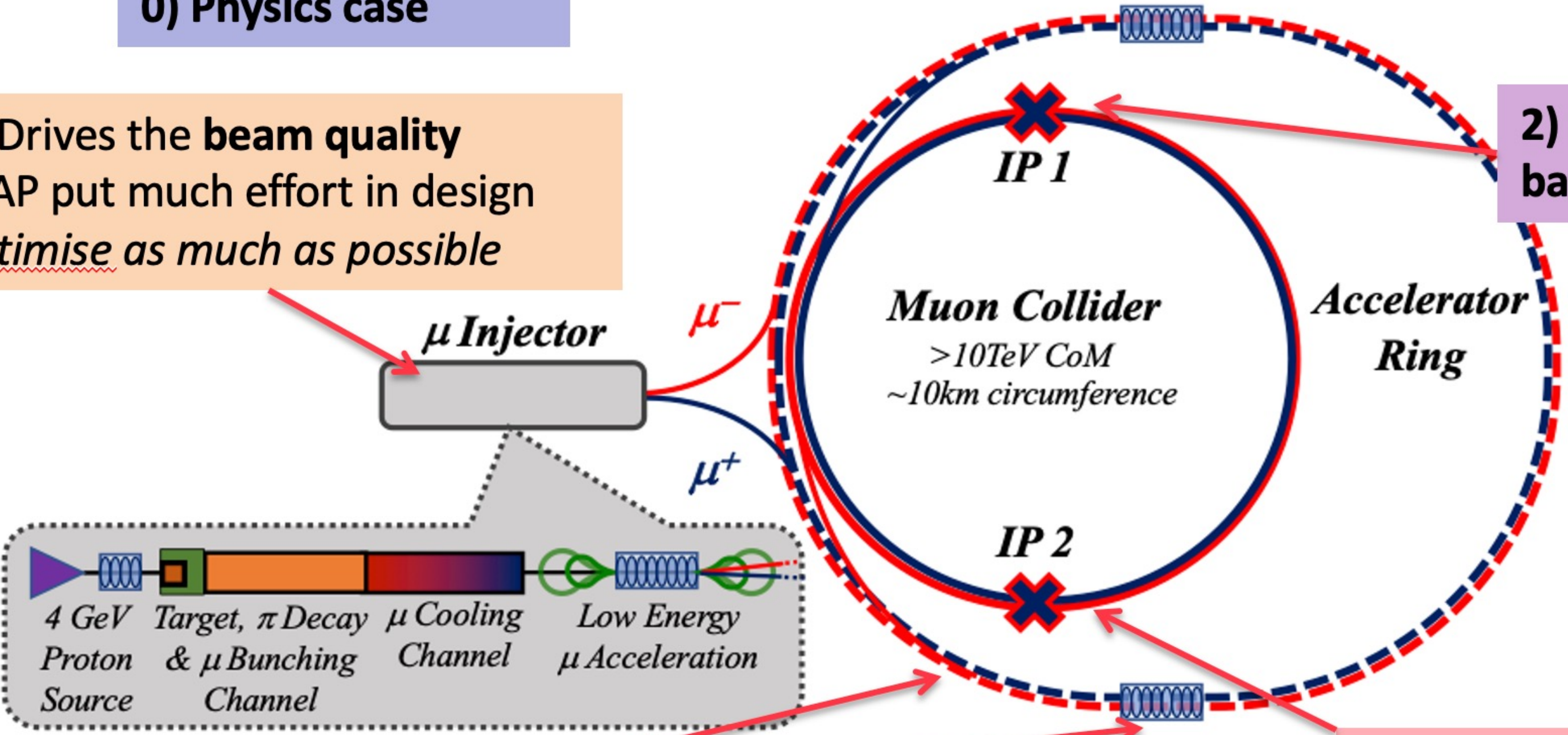
$\mu^+\mu^- \to X\,\mu^\pm\overset{(-)}{\nu}_\mu$ (WZ fusion),



Key Challenges

0) Physics case

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

Wrap-up (2)

Options for the next HEP machine

T. Nakada, ECR 2023, CERN

An e^+e^- collider covering a region of 90-350 GeV cme

- A circular collider (CC): e,g, FCC(CERN) and CECP(IHEP)
  - Double storage rings of 90-100 km circumference, L~ $10^{35} cm^{-2}s^{-1}$
  - Well established technology. Many CC's have been built, the largest one LEP with 27 km circumference at 207 GeV cme, the highest luminosity achieved by SuperKEKB at 10 GeV cme, 3.8×10^{34} $cm^{-2}s^{-1}$
  - Upgrade path: installing pp collider 100 TeV cme accessing 10 TeV physics
- A linear collider (LC): e.g. CLIC, C^3, HALHF and ILC
  - Colliding e^+ e^- accelerated by lineacs, with a total length of ~3 km to 20 km depending on the acceleration gradient of the technology used with L~ $10^{34} cm^{-2}s^{-1}$
  - CLIC: normal conducting room temperature X-band Cu RF cavities, 72 MeV/m
  - C^3: normal conductive liquid N_2 temperature X-band Cu RF cavities, 70 MeV/m
  - HALHF: Plasma wake-field accelerated 500 GeV e^- (1.2 GeV/m) against 31 GeV e^+ conventional lineac,
  - ILC: super conducting L-band RF cavities (series production experience @European XFEL), 32 MeV/m
  - There has been only one LC built, SLAC Linear Collider 100 GeV cme with L~3×10^{30} $cm^{-2}s^{-1}$ (end of 90's)
  - Upgrade path: increasing the cme energy: multi-TeV to ~10 TeV, by improving the acceleration gradient, ultimately fully wake-field acceleration and extending the tunnel in needed.

FCC-hh & Muon collider: long pathways toward technological maturity

4. International Science Policies

Update of the European Strategy

- In March 2024, the CERN Council approved the timeline for the next update of the European Strategy for Particle Physics with a completion date in June 2026

- The proposed timeline is determined by physics (LHC, HL-LHC, results from other colliders) and strategic considerations:

  - **Physics landscape**: physics results from the LHC and other colliders, HL-LHC upgrades ongoing, exploration of the Higgs sector remains central

  - **Excellent progress at CERN and beyond on the preparation for future colliders**

    *** FCC Feasibility Study**
    (mid-term report presented, excellent progress on the technical side - no showstoppers identified for an FCC-ee as a first stage of an integrated FCC programme)
    Planned to complete the study in March 2025

    *** Clearer view on the international landscape for future colliders**
    - ILC in Japan as a global project; so far no commitments
    - P5 process in the US (→ participation in an off-shore Higgs factory (ILC, FCC-ee)
    - Technical Design Report for CEPC in China released in Dec 2023;
      Aim for adoption of the project in the next 5-year funding cycle(s) in 2025

- *In addition:*

  - ***Long timescales, long-term community engagement***

    * The gap between the end of the HL-LHC and the start of the next collider project should be minimised, to ensure continuity of expertise and commitment.

    * Wish of the young generation of physicists to have a clear vision of the future of our research field, as well as a credible timeline for the realisation of any future collider project

  - **Strategy recommendations on the complementary physics programme** at CERN and beyond are important for establishing / upgrading relevant facilities

- *In June 2024, the CERN Council established and approved the* ***remit of the European Strategy Group***

  "The aim of the Strategy update should be to develop a ***visionary and concrete plan*** *that greatly advances human knowledge in fundamental physics through the* ***realisation of the next flagship project at CERN****. This plan should attract and value* ***international collaboration*** *and should* ***allow Europe to continue to play a leading role in the field."***

- *The Strategy update should include the* ***preferred option*** *for the next collider at CERN and* ***prioritised alternative options*** *to be pursued if the chosen preferred plan turns out not to be feasible or competitive.*

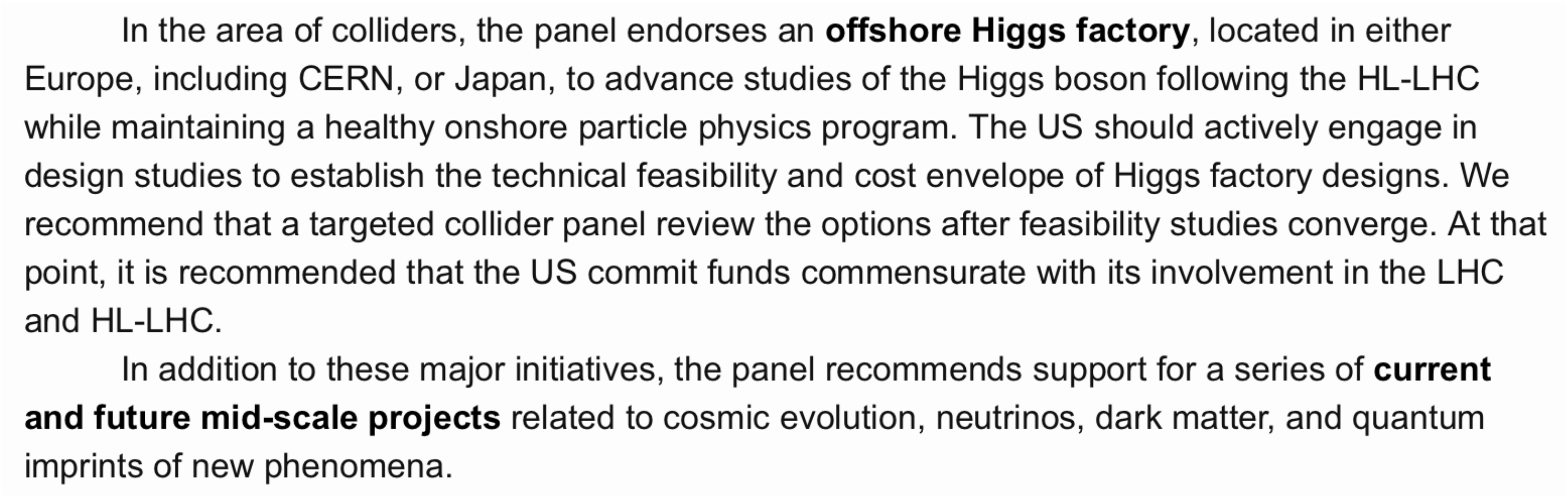
Exploring the Quantum Universe

P5 Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

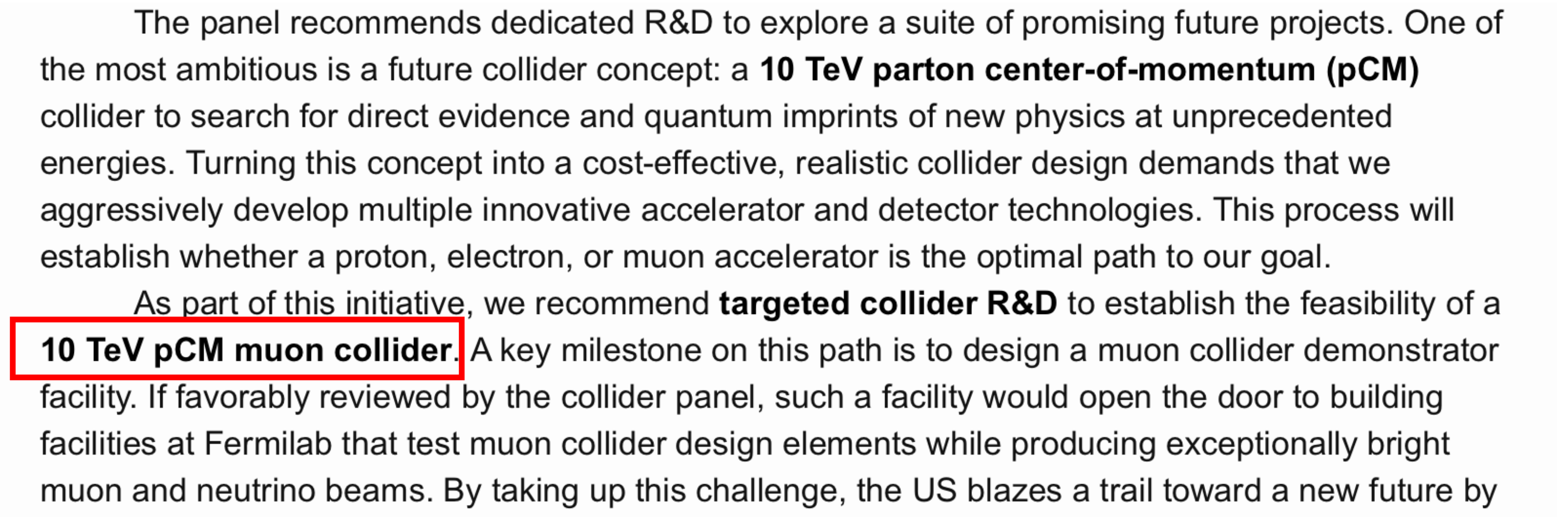
U.S. DEPARTMENT OF ENERGY

U.S. National Science Foundation



In the area of colliders, the panel endorses an **offshore Higgs factory**, located in either Europe, including CERN, or Japan, to advance studies of the Higgs boson following the HL-LHC while maintaining a healthy onshore particle physics program. The US should actively engage in design studies to establish the technical feasibility and cost envelope of Higgs factory designs. We recommend that a targeted collider panel review the options after feasibility studies converge. At that point, it is recommended that the US commit funds commensurate with its involvement in the LHC and HL-LHC.

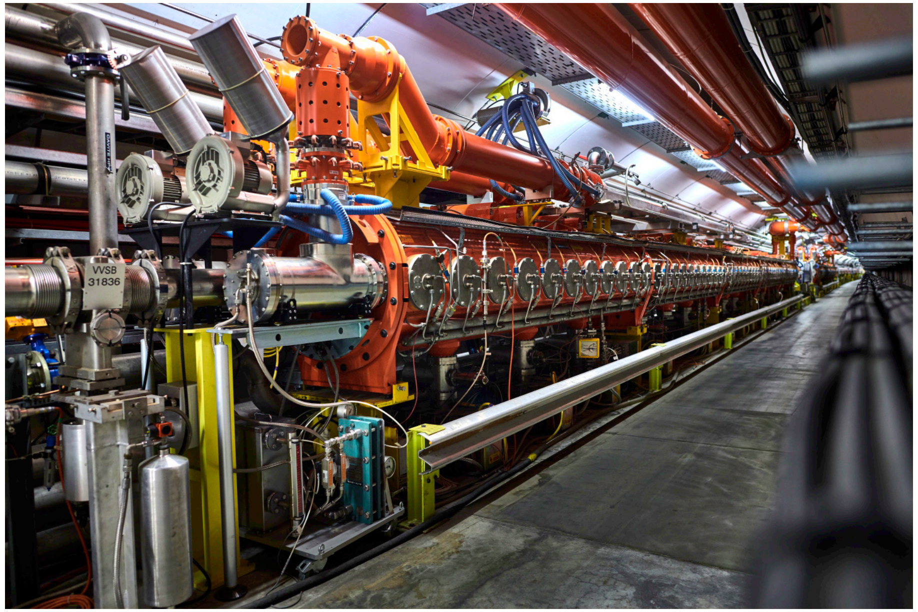
In addition to these major initiatives, the panel recommends support for a series of **current and future mid-scale projects** related to cosmic evolution, neutrinos, dark matter, and quantum imprints of new phenomena.



The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM)** collider to search for direct evidence and quantum imprints of new physics at unprecedented energies. Turning this concept into a cost-effective, realistic collider design demands that we aggressively develop multiple innovative accelerator and detector technologies. This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.

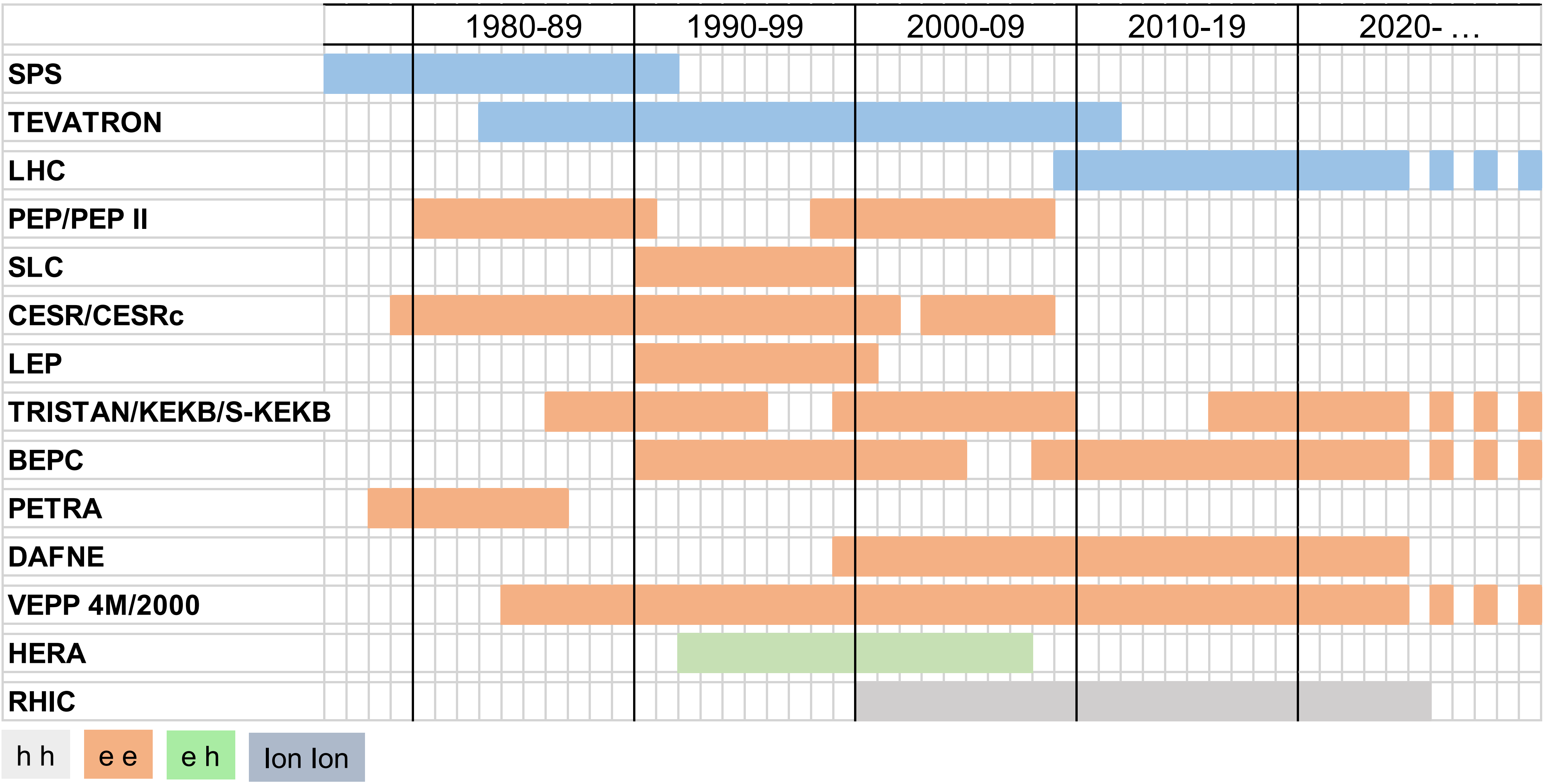
As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by

Snowmass
- Physics Report arXiv:2211.11084
- Accelerator Report arXiv:2209.14136



5. Governance, funding models, sustainability

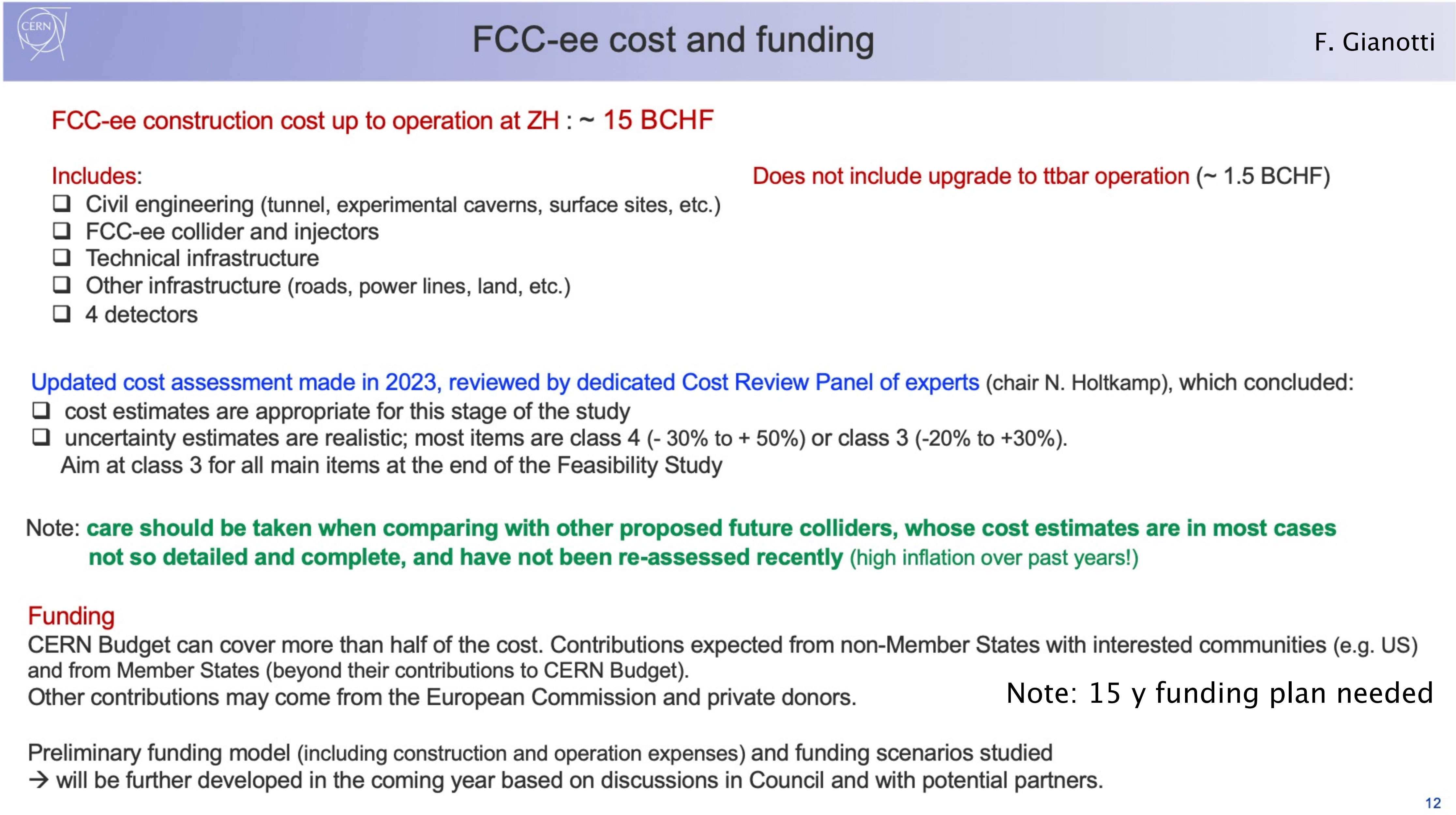
The Golden Age of Colliders



Looking "global" to projects: scaling costs

					COST/GDP
HERA	cost	0.7 G$	FRG GDP 1984 (const. starts)	0.7 T$	10 x 10^{-4}
~20% non-German contributions					
LEP	cost	1.4 G$	(EU+CH) GDP 1984 (const. starts)	2.7 T$	5 x 10^{-4}
LHC	cost	5 G$	(EU+CH) GDP 1998 (approval year)	8 T$	6 x 10^{-4}
benefitting of LEP tunnel + 15% NMS contributions					
FCCee	cost	12 G$	(EU+CH+UK) GDP 2023	22 T$	6 x 10^{-4}
CEPC	cost	5 G$	China GDP 2023	18 T$	3 x 10^{-4}
ILC	cost	7 G$	Japan GDP 2023	4.2 T$	17 x 10^{-4}

"Globalisation" of the Research Infrastructures are further assets in project conception, providing possibility of in-kind contributions. Current time span of RI is bigger (funding dilution)



FCC-ee cost and funding

F. Gianotti

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.

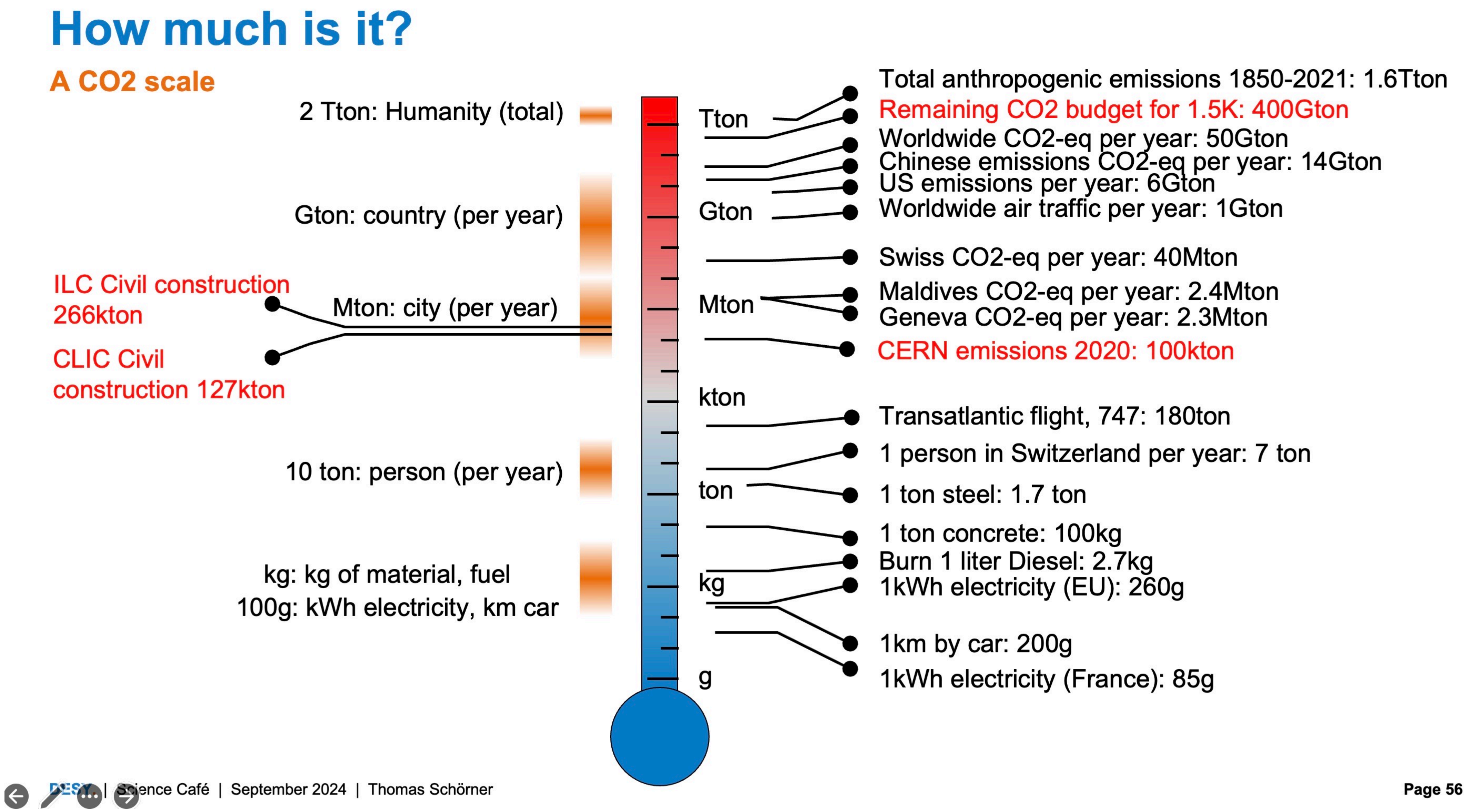
Note: 15 y funding plan needed

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.

Governance models

- **An international project** is a project hosted by a particular laboratory ("host lab") on the initiative of an individual country, a group of countries, or an organization. Other partnering participants ("partners") provide contributions – mainly in-kind – as agreed upon with the host lab, or its funding agency, through bilateral or multilateral agreements. The host lab is responsible for operating the facility or infrastructure and bears all possible risks, it takes the final decisions relating to the operation of the facility, with inputs from its partners through various fora – e.g. councils, review boards, etc. – prior to making its decisions.

- **A global project** is a project in which partnering states or organizations, and their funding agencies, work together to develop the project from the outset. The project is collaborative and all partners participate in the decision making. This can include determining the cost-sharing model and governance and organization. The project may be located in one or more states. The partners work together to solicit potential hosts and then collectively decide where the site should be located. All partners share, in a balanced manner, the running of the facility. The partners in the project therefore make all decisions concerning each of these project phases collectively, by means of a vote.
- **A national project, with international participation** is a project hosted by a national laboratory ("host lab") in which international support (typically in-kind) is seeked on specific items (accelerator and/or experiments). The host lab is responsible for operating the facility or infrastructure and bears all possible risks partnering states or organizations, and supports operation costs.



How much is it?

A CO2 scale

2 Tton: Humanity (total)
Gton: country (per year)
Mton: city (per year)
10 ton: person (per year)
kg: kg of material, fuel
100g: kWh electricity, km car

ILC Civil construction 266kton
CLIC Civil construction 127kton

Total anthropogenic emissions 1850-2021: 1.6Tton
Remaining CO2 budget for 1.5K: 400Gton
Worldwide CO2-eq per year: 50Gton
Chinese emissions CO2-eq per year: 14Gton
US emissions per year: 6Gton
Worldwide air traffic per year: 1Gton
Swiss CO2-eq per year: 40Mton
Maldives CO2-eq per year: 2.4Mton
Geneva CO2-eq per year: 2.3Mton
CERN emissions 2020: 100kton
Transatlantic flight, 747: 180ton
1 person in Switzerland per year: 7 ton
1 ton steel: 1.7 ton
1 ton concrete: 100kg
Burn 1 liter Diesel: 2.7kg
1kWh electricity (EU): 260g
1km by car: 200g
1kWh electricity (France): 85g

DESY. | Science Café | September 2024 | Thomas Schörner

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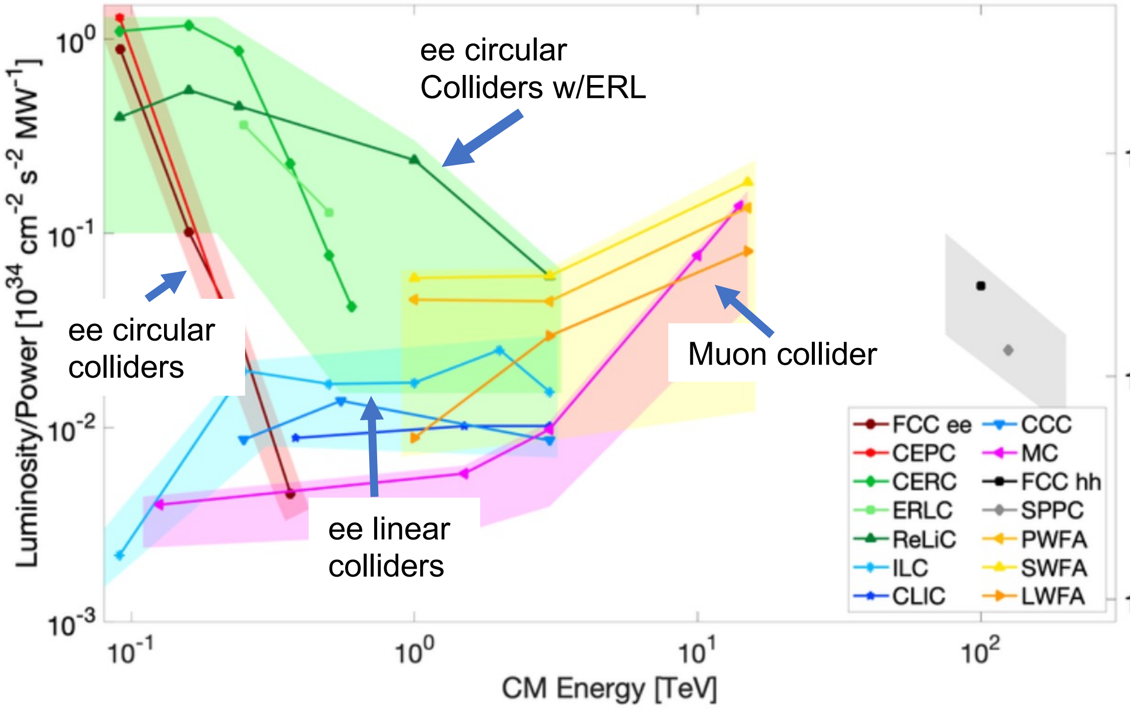
Sustainability (construction & operation)

A quite complex assessment: material impact (eg. concrete for tunnels), operation costs of various technologies, CO2/produced Higgs, …

This evalution will be more and more element of discrimination among choices

Energy Recovery Linacs (ERL) could become important



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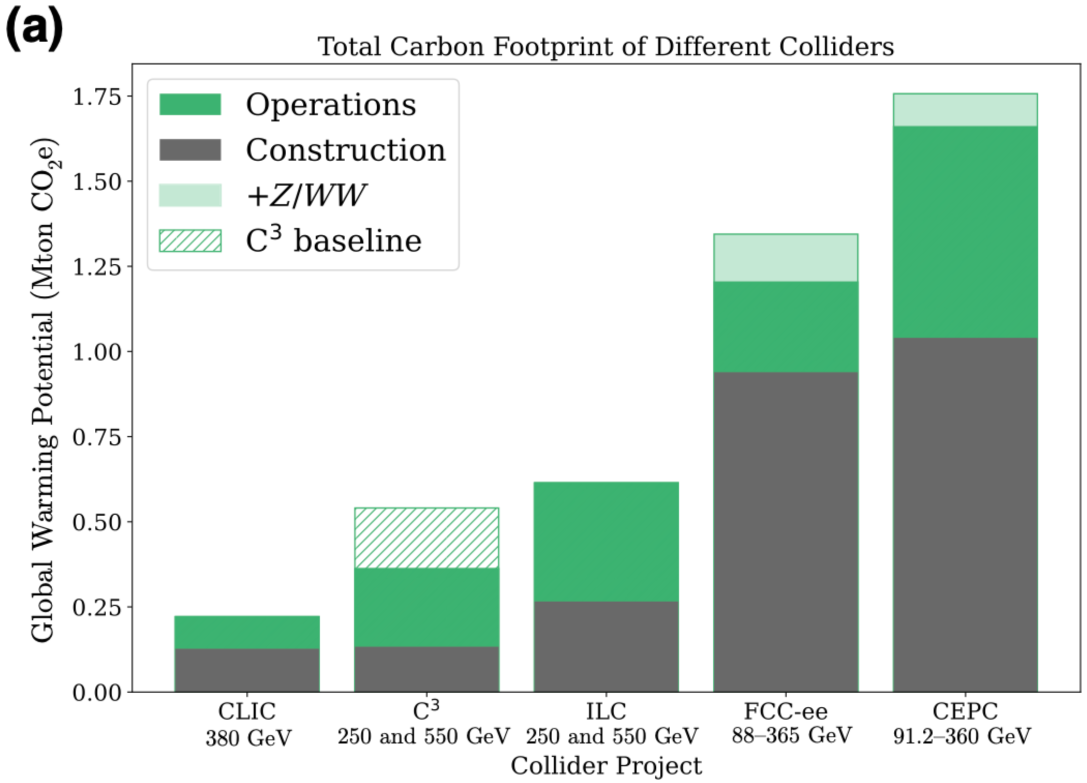


6. Impact on society & sociology of HEP

Societal acceptance of a new collider

Le Monde

Le futur accélérateur de particules géant du CERN : est-ce bien raisonnable ?

Dans une tribune au « Monde », des politiques français et suisses, ainsi que des membres d'un collectif et d'ONG questionnent le projet du futur collisionneur sur les plans éthique et politique.

Publié le 21 mars 2024 à 08h00, modifié le 21 mars 2024 à 12h32 | ⏱ Lecture 3 min.

Wednesday, June 19, 2019

Sabine Hossenfelder

No, a next larger particle collider will not tell us anything about the creation of the universe

A few days ago, Scientific American ran a piece by a CERN physicist and a philosopher about particle physicists' plans to spend $20 billion on a next larger particle collider, the Future Circular Collider (FCC). To make their case, the authors have dug up a quote from 1977 and ignored the 40 years after this, which is a truly excellent illustration of all that's wrong with particle physics at the moment.

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

In the past, it was possible to promote large colliders (strong relationships with politics, see LEP example, cold war still favorable to HEP).

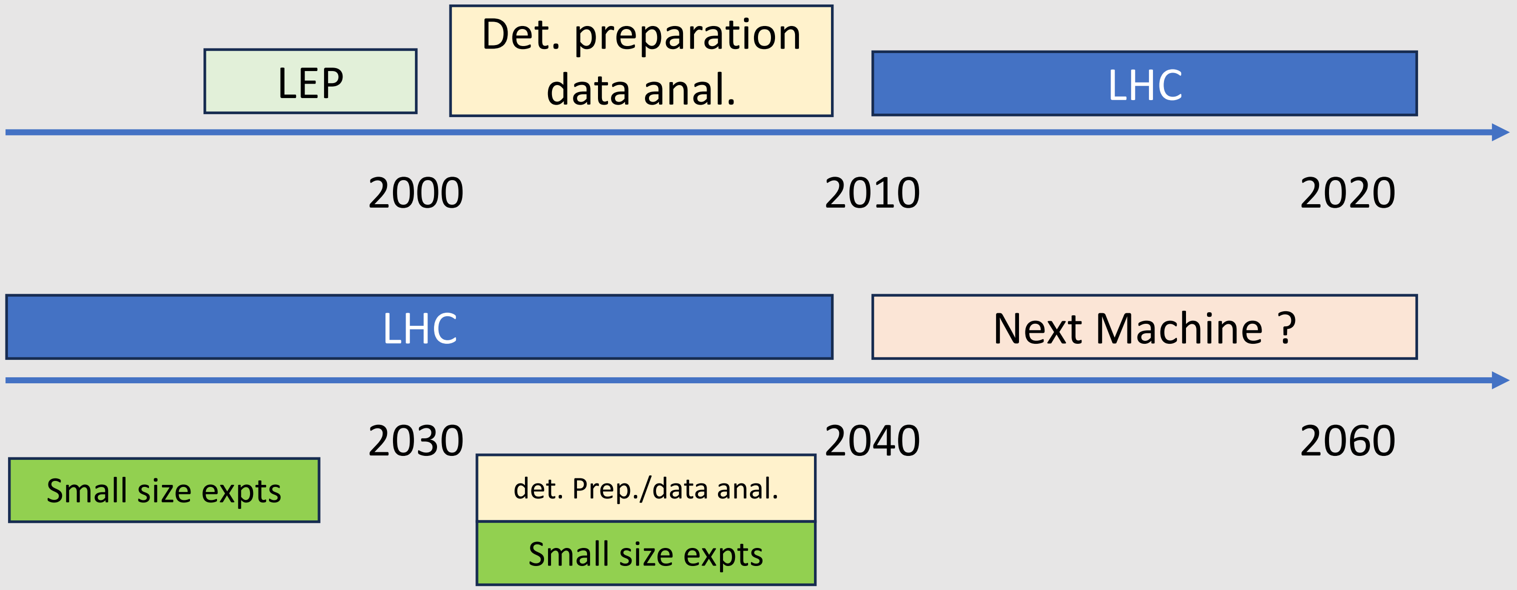
Several new actors entering science arena: bio-medical, IT, quantum, GW …

Still CERN is a flagship RI, generating large societal impact (see also Draghi's recent report), holding European stewardship in several areas

Justifying FCC/ILC … increasingly complex … but we should not give up

Sociological aspects of HEP

ECR career (PhD in “80s”)



ECR career (PhD in “20s”)

mitigation

+ …

20 k CERN users: ILC/CLIC 1 experiment, FCC 2 experiments.
Can future colliders host the whole community ?
Diversification needed

7. Take-away messages

The choice of the next collider is a complex choice, dictated not only by science, but also from a long list of other relevant issues:

economic resources
international political situation
technological feasibility
sustainability and societal acceptance
…

Next project should be **global** to have some chance of success, considering the resources needed. If done at CERN, suitable adjustments to its governance should be envisaged.
As of today, a global infrastructure not located in Europe seems unlikely.

Nevertheless the current ignorance about SM deficits is "exciting" …

- We had a good time of "everything, everywhere at the same time". We had to change to "certain things, everywhere at the same time", or "everything at different places at the same time", or "everything at everywhere at different time". Are we heading toward "one thing at one place taking forever"?

T. Nakada, ECR 2023, CERN