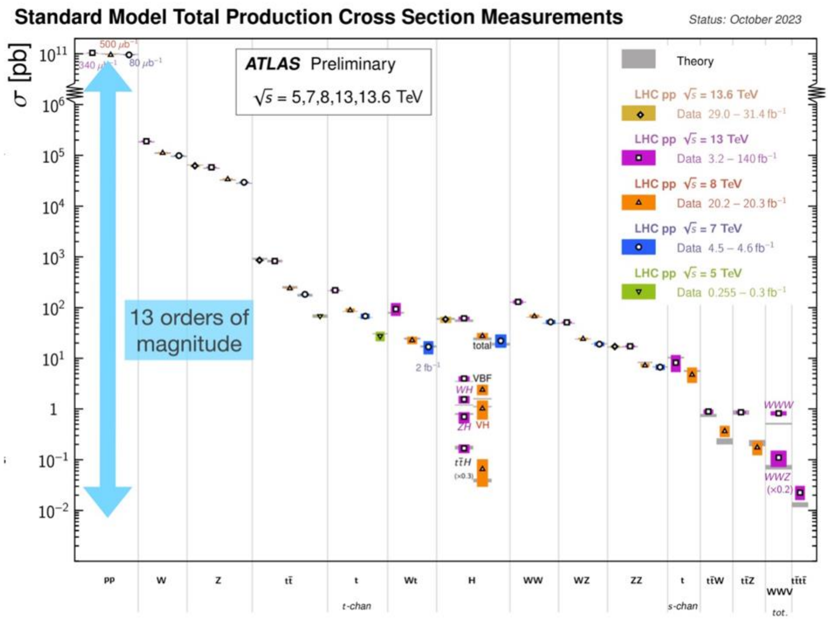
FCC - THE 2040: PARTICLE PHYSICS ODYSSEY

Marcin Chrząszcz (IFJ PAN)

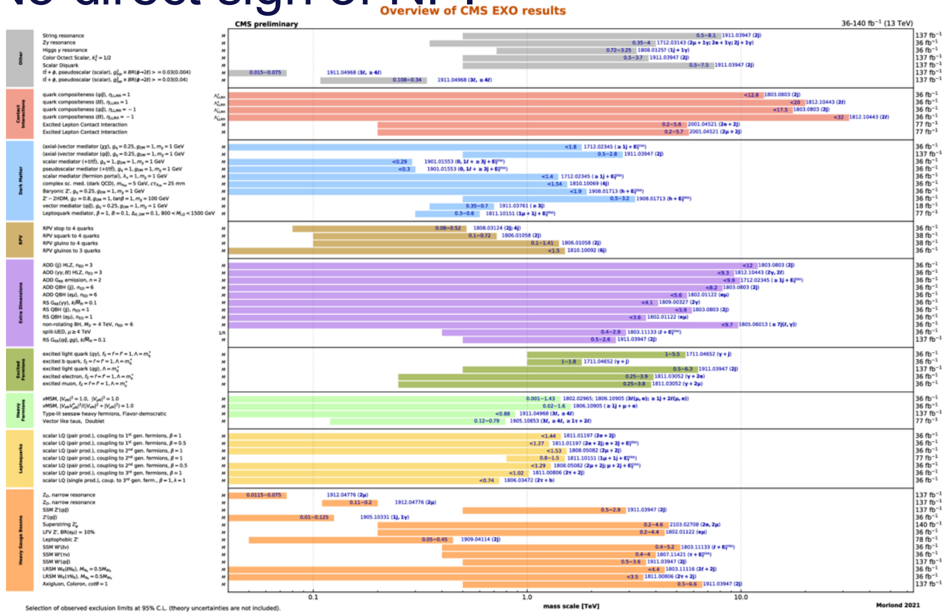
Where are we?

LHC entering the precision area



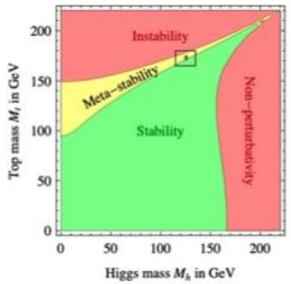
Extraordinary agreement with SM predictions.

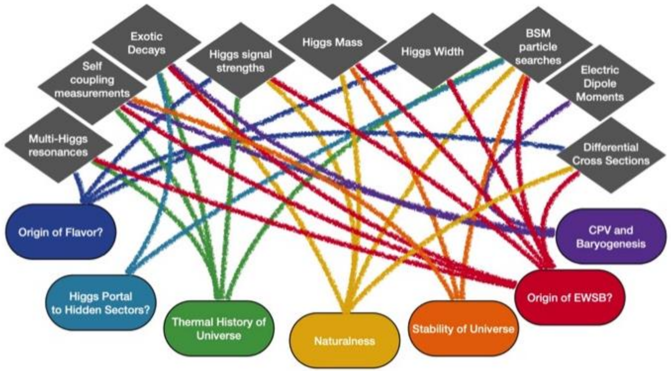
No direct sign of NP!

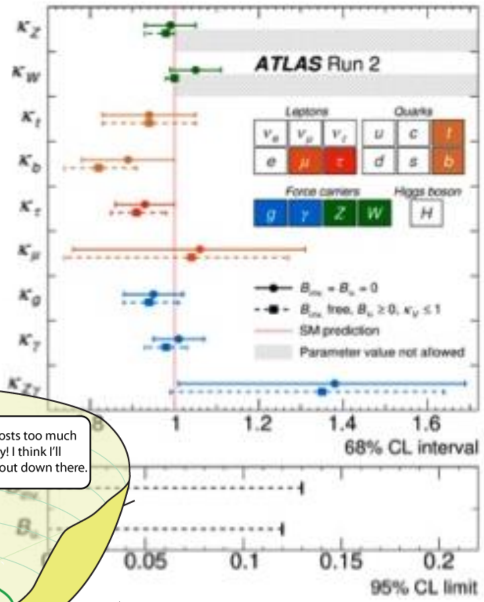


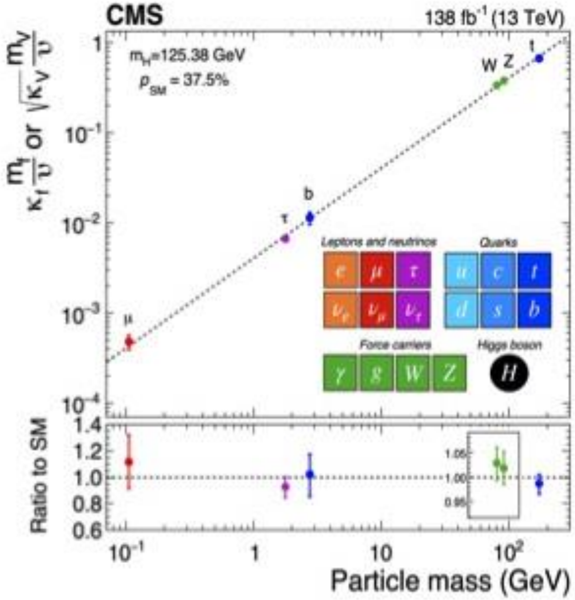
Higgs

LHC is measuring the Higgs potential up to the 2nd generation.
Higgs is in the meta-stable region.

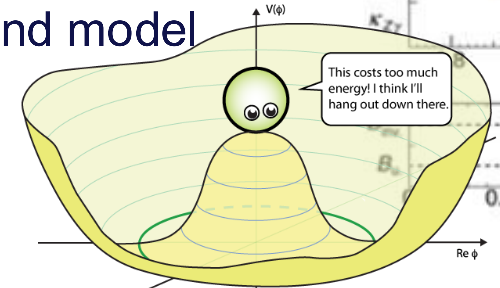






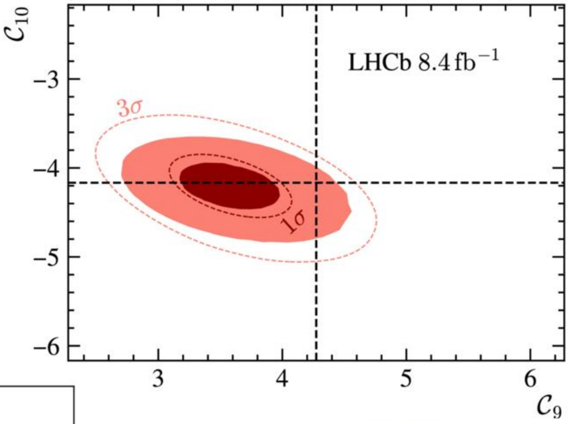


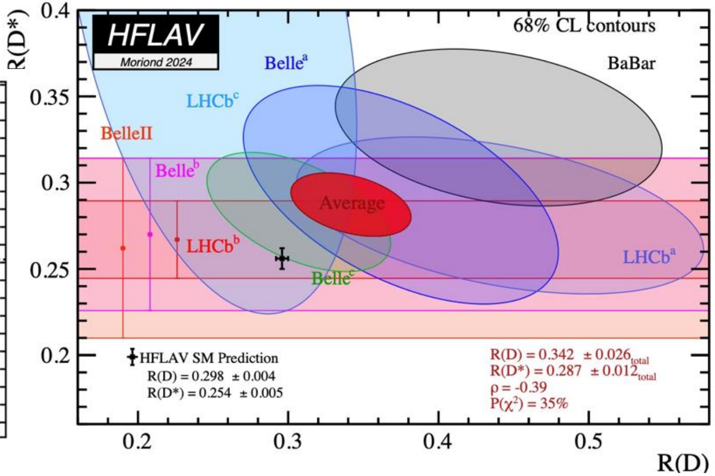
Need to measure Higgs with high precision and model independently

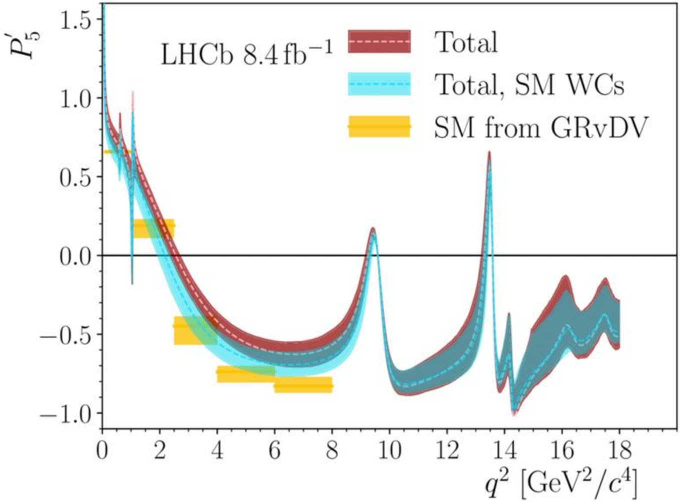


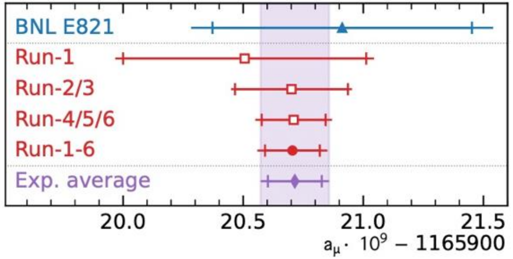
What remains?

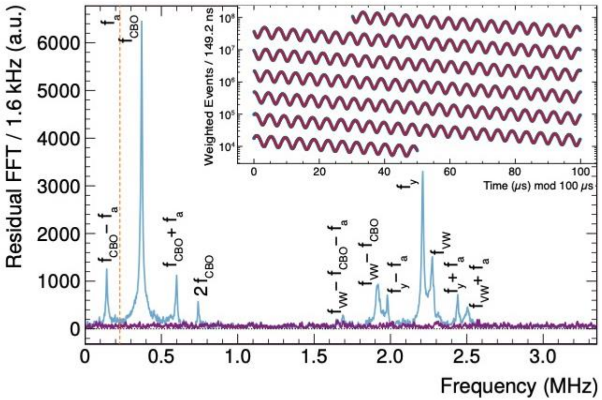
There are still couple of Flavour anomalies flying around





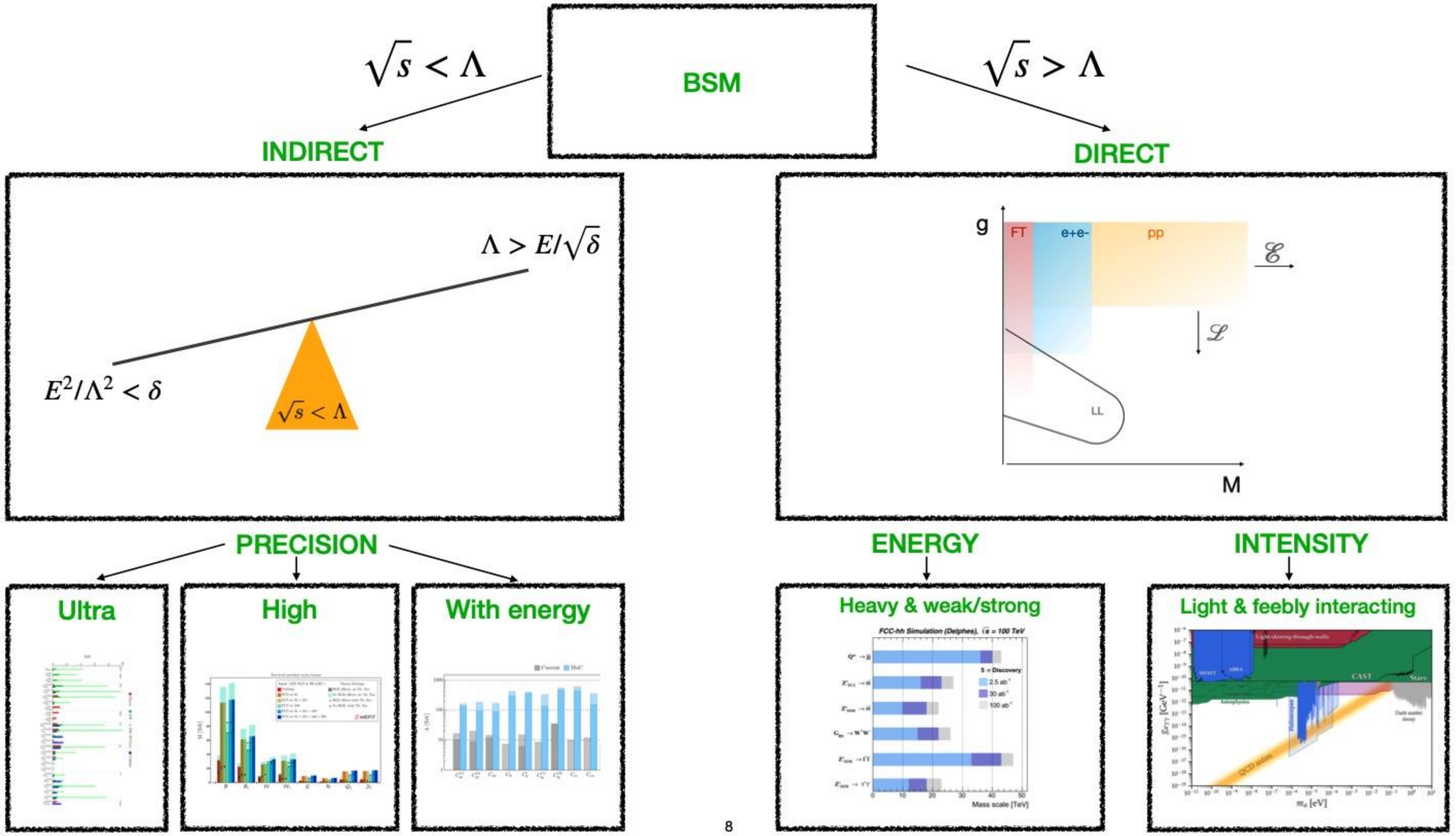


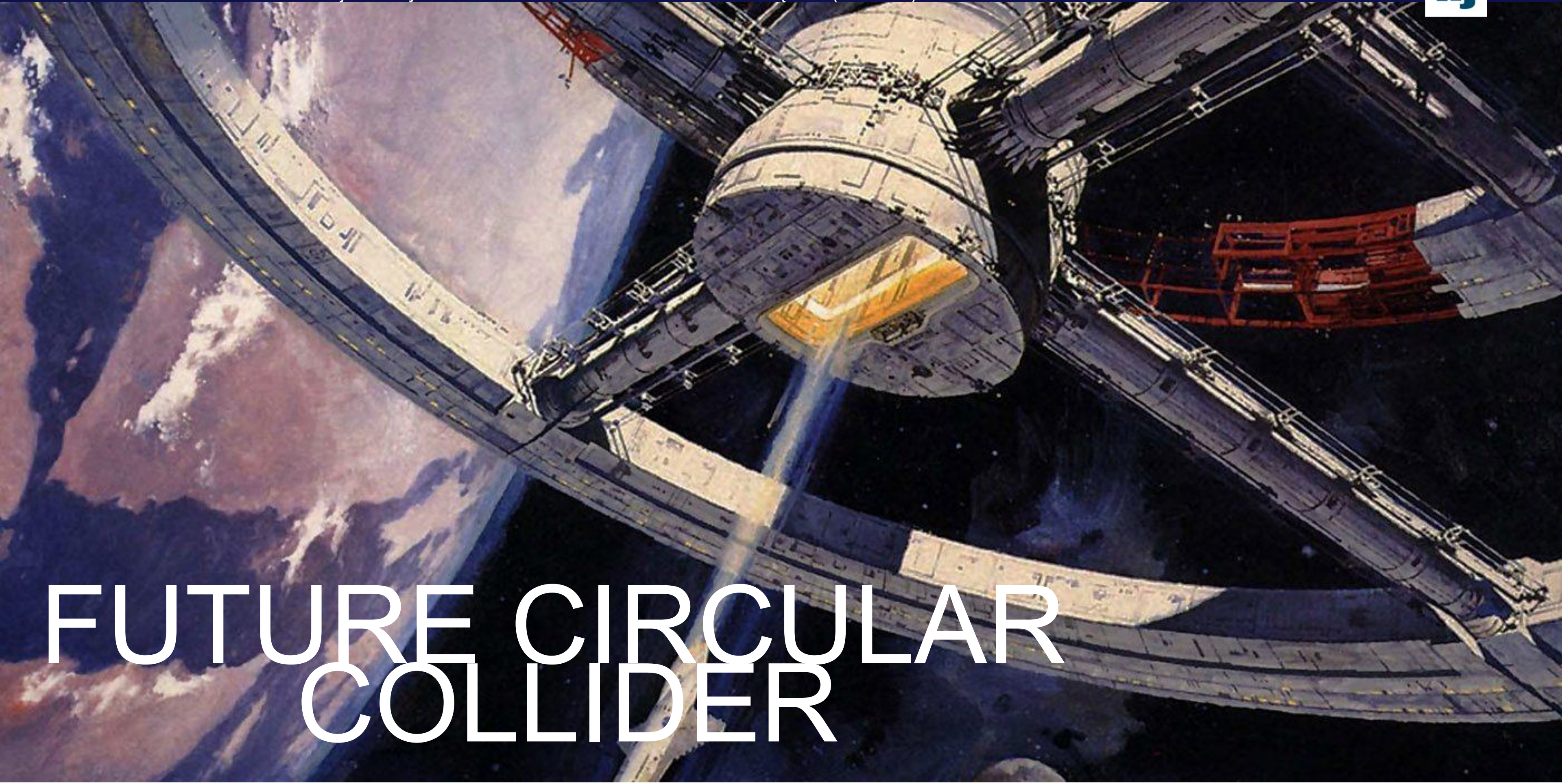




Open big questions

Why are there so many kinds of particles?
What is dark matter? What is dark energy?
Why is there matter and no antimatter?
Why is CP Violation absent in QCD?
Why CKM is so different then PMNS?
Why only 3 generations?
Are there extra dimensions?
Do the forces unify?
What is the nature of neutrinos?
What stabilizes the Higgs mass?

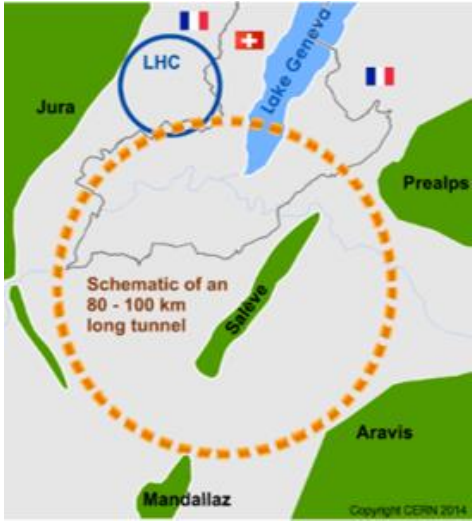

BSM
$\sqrt{s} < \Lambda$
$\sqrt{s} > \Lambda$
INDIRECT
DIRECT
$\Lambda > E/\sqrt{\delta}$
$E^2/\Lambda^2 < \delta$
$\sqrt{s} < \Lambda$
g
FT
e+e-
pp
$\mathscr{E}$
$\mathscr{L}$
LL
M
PRECISION
ENERGY
INTENSITY
Ultra
High
With energy
Heavy & weak/strong
Light & feebly interacting
FCC-hh Simulation (Delphes), $\sqrt{s}$ = 100 TeV
5 σ Discovery
Mass scale [TeV]

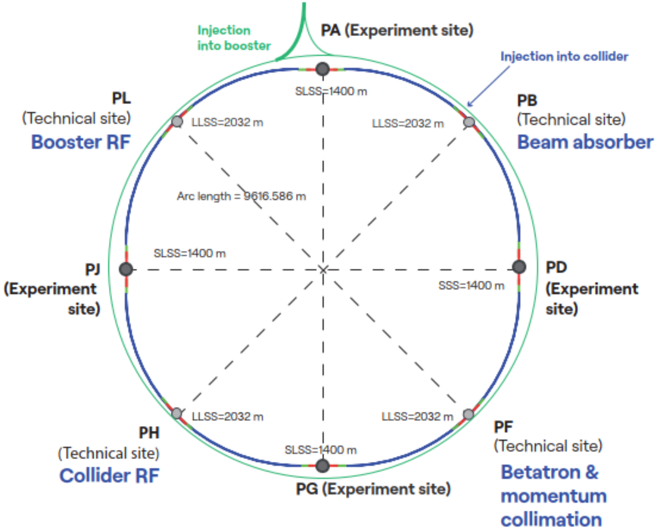


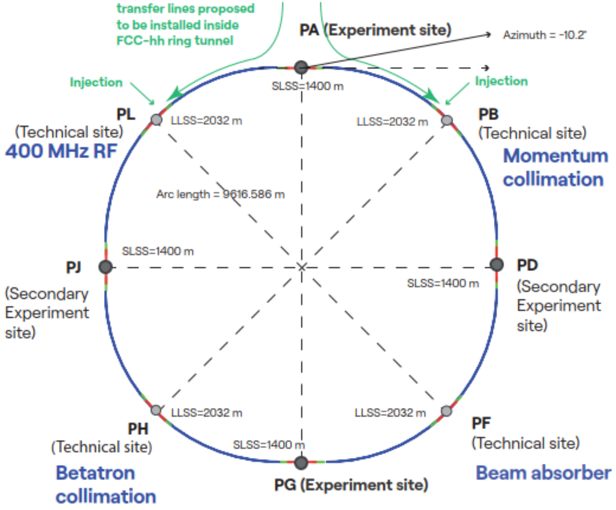
FUTURE CIRCULAR COLLIDER

FCC integrated program – scope

- 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
- 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 few years of the end of HL-LHC exploitation

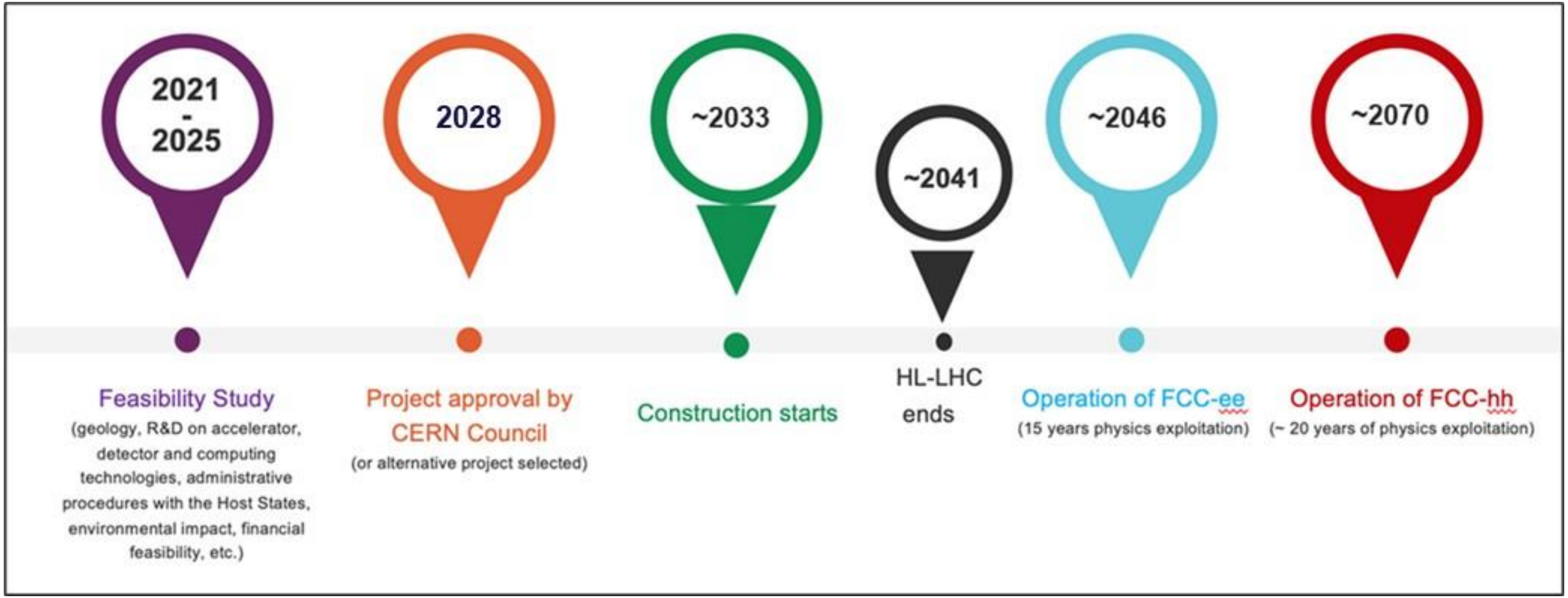






2020 - 2045 | 2046 - 2065 | 2070 - 2100

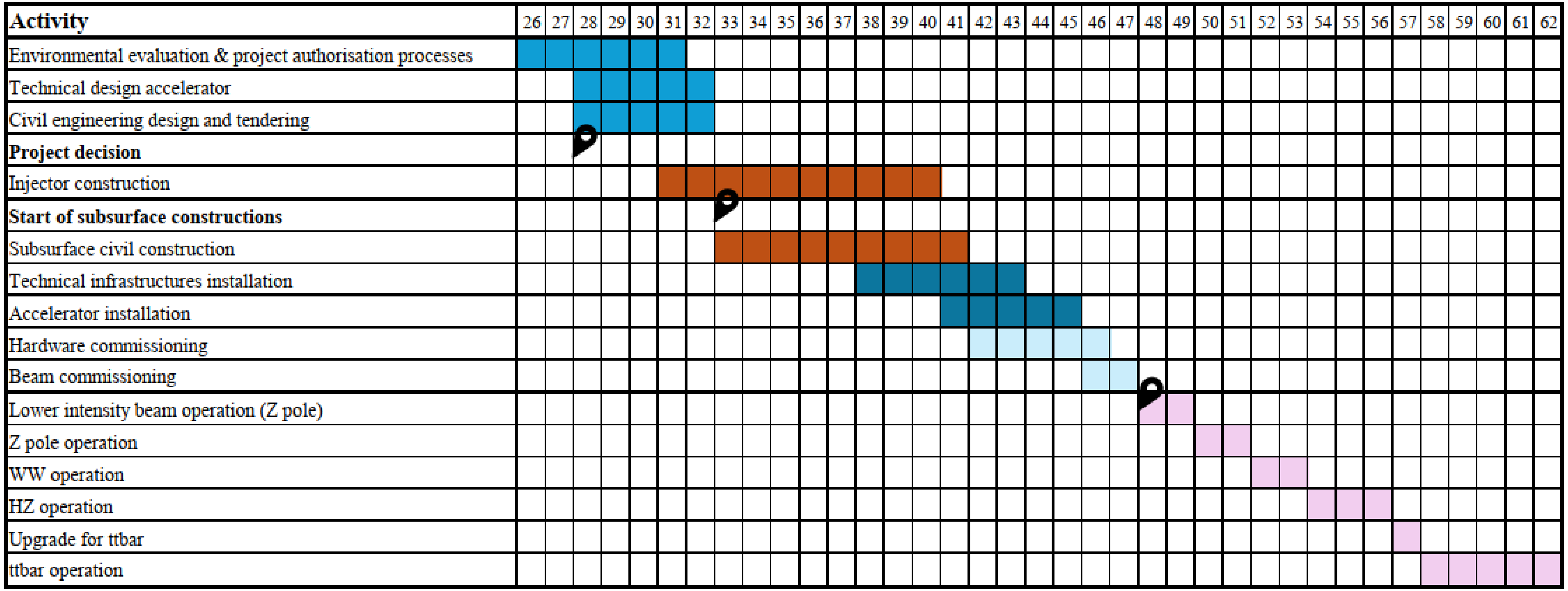
FCC integrated program - timeline



Ambitious schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041
- ❑ **project preparatory phase with adequate resources immediately after Feasibility Study**

FCC-ee construction schedule



- **01/2028** **assumed project approval by CERN Council**
- **01/2033 – 06/2041** **CE construction work**
- **07/2039 – 12/2043** **technical infrastructure installation**
- **07/2041 – 06/2045** **accelerator installation**
- **07/2046** **start of beam commissioning and operation**
- **01/2048** **nominal beam operation**

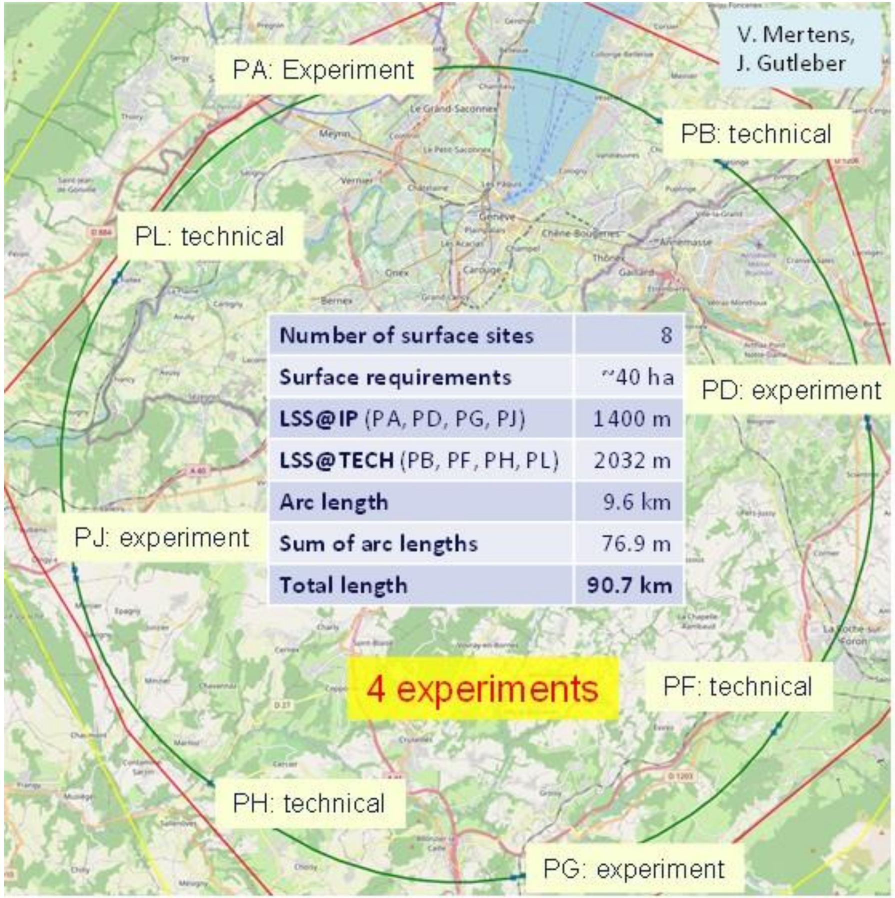
Reference layout and implementation: PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on several criterias:

- **geology,**
- **surface constraints** (land availability, urbanistic, etc.),
- **environment,** (protected zones),
- **infrastructure** (electricity, transport),
- **machine performance**

"Avoid-reduce-compensate" principle of EU and French regulations.

Overall lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold symmetry



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**

Surface site locations 7 sites in FR and 1 site in CH

Optimisation done with municipalities, land plot needs communicated to Host States

PA

PB

PD

PF

PG

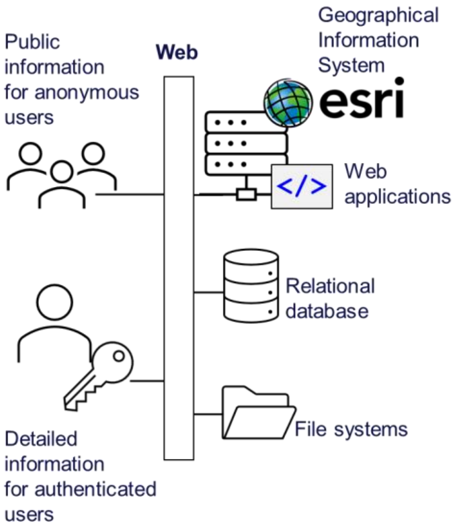
PH

PJ

PL

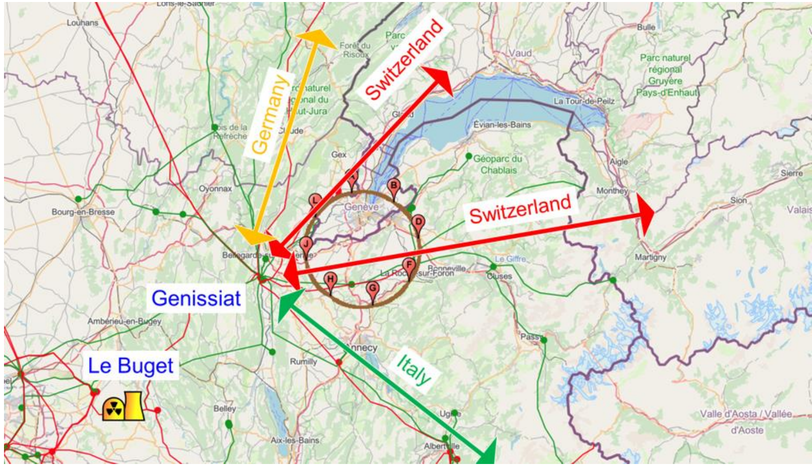
Environmental initial state analysis

Environmental information system



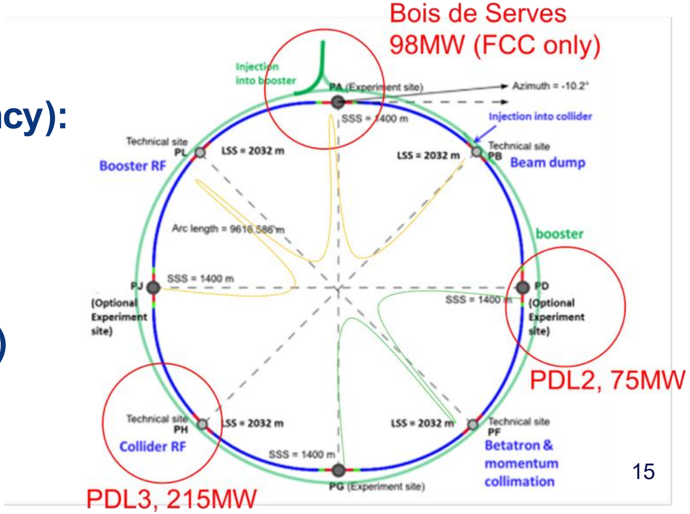
- The environmental **initial state analysis** at the eight surface site locations (~600 ha covered) **did not reveal principal showstoppers for the project.**
- **Basis for detailed optimisation of surface sites.**
- **Reference for the environmental impact assessment.**

Electrical energy consumption, Connections to high-voltage grid



FCC-ee elecrtical energy consumption	Z	W	H	TT
Beam energy [GeV]	45.6	80	120	182.5
Peak power during beam operation [MW]	**250**	**275**	**297**	**381**
Total FCC-ee yearly consumption [TWh]	**1.2**	**1.3**	**1.4**	**1.85**

Various R&D towards further reduction of electrical consumption



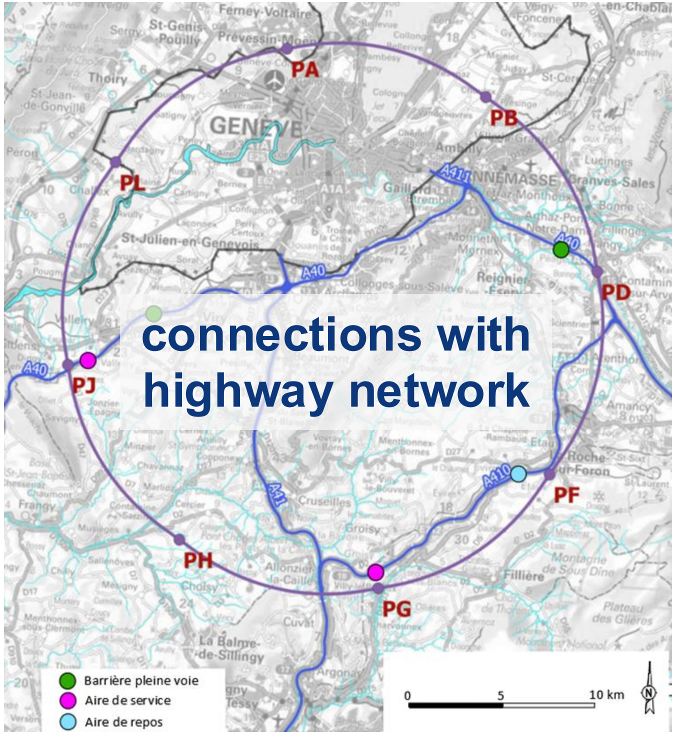
Loads distributed on three main sub-stations (providing redundancy):

- **Point A with existing CERN station** covering PA – PB – PL – PJ
- **Point D with a new sub-station** covering PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF

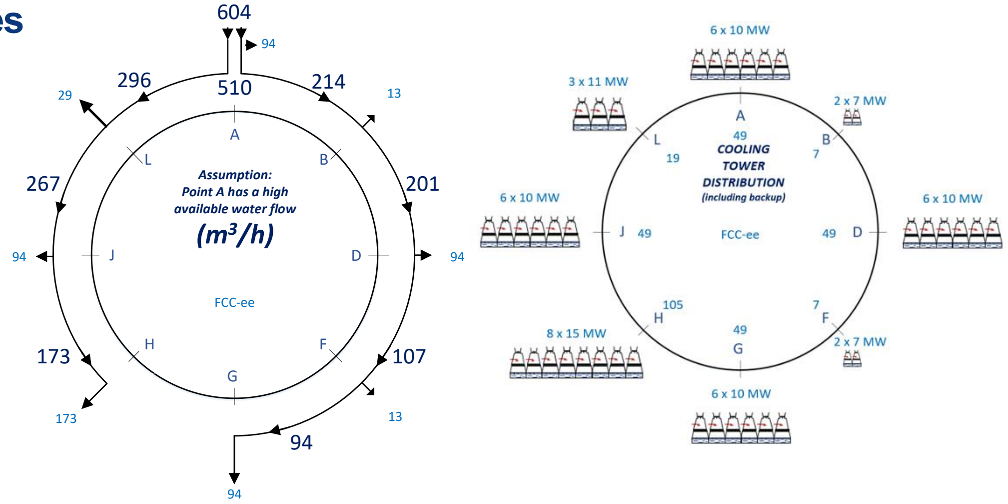
- **Connection concept confirmed by RTE (French el. grid operator)**
- **➔ requested loads have no significant impact on grid**
- Powering concept and rating of the three sub-stations compatible with FCC-hh

Road access

- **Road accesses developed for all 8 surface sites**
- **Four possible highway connections defined**
- **Less than 4 km of new roads required**



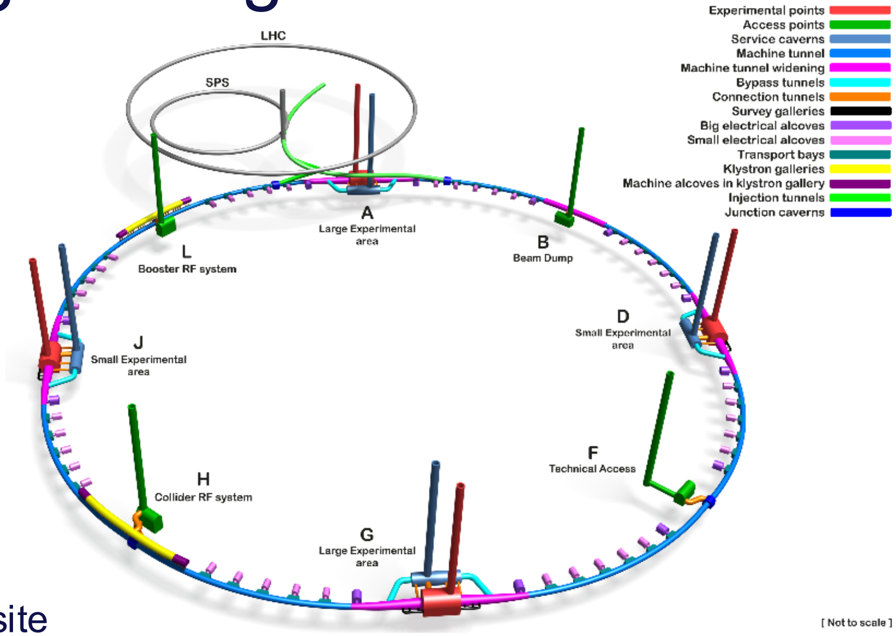
Cooling water supply concept



- **Potential source of cooling water is lake Geneva (PA).**
- **The existing supply line with lake water provided by SIG to CERN LHC P8 (LHCb) is sufficient for FCC-ee.**
- **Maximum yearly consumption (ttbar): 3 Mm^3 (~CERN today)**
- **Pipework in the tunnel will connect to the remaining points.**
- **Main cooling towers placed at experiment points (PA, PD, PG, PJ), and RF sites (PL, PH).**

Key Features of the Civil Engineering

- 90.7 km main tunnel with an internal diameter of 5.5 m.
- Depth varies between 50m and 560m.
- 12 shafts up to 400 m deep and 18 m in diameter.
- 2 larger experiment caverns (35m span).
- 2 smaller experiment caverns (span 25m).
- >70 small caverns.
- 5 km transfer tunnel from the surface.
- 3 km of klystron gallery tunnels.
- Technical buildings on 8 surface sites
- Injector FCC-ee: high-energy linac at CERN Prevessin site



Schematic Layout of the FCC ee Underground Structures

CE Construction carbon footprint estimate (A1 – A5):

Total CE: 530 000 - 1 184 000 $tCO_2(eq)$

Assessed according to European Norms, (EN 17472, EN15804+A2)

FCC-ee main parameters and operation plan

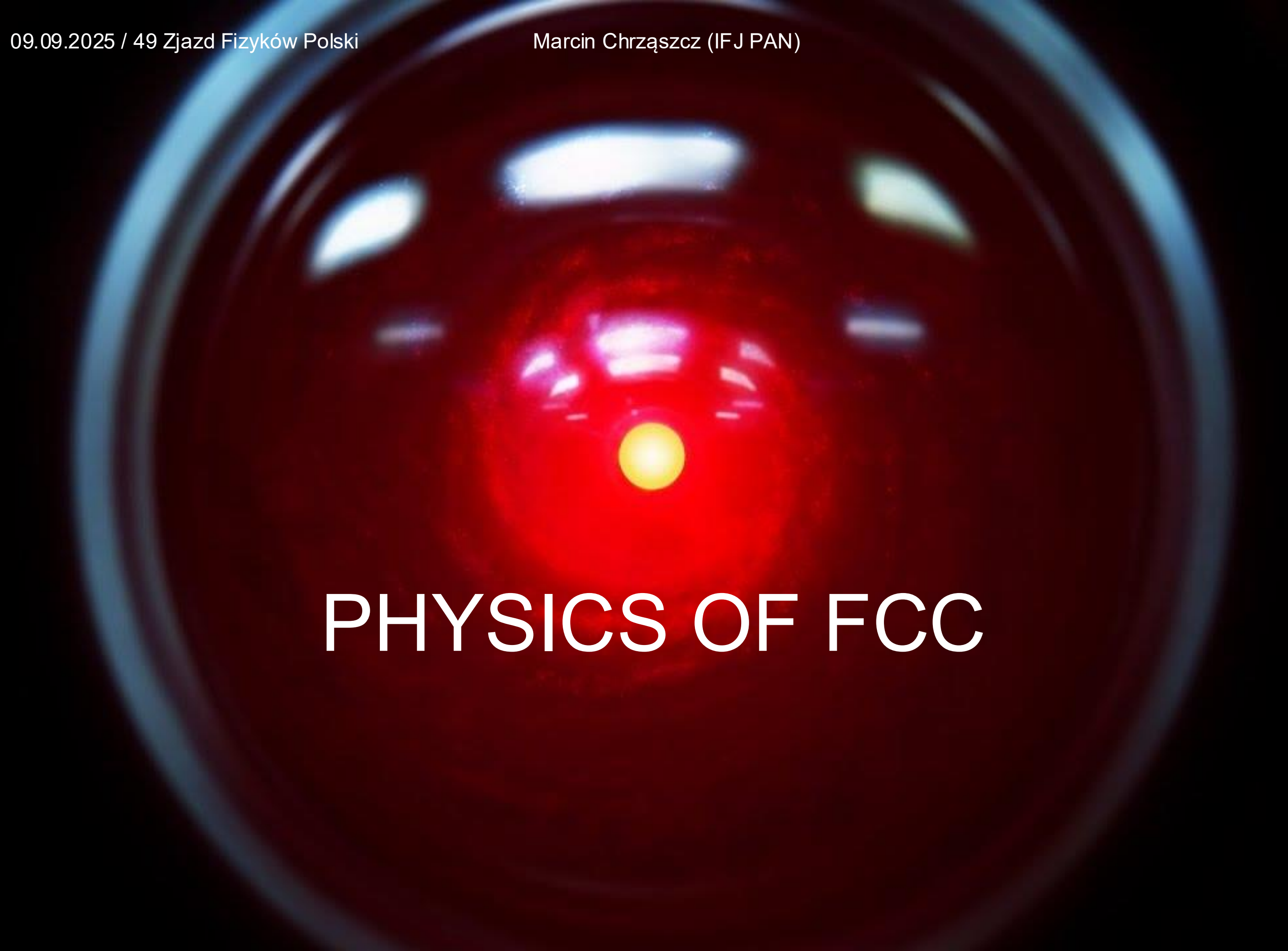
parameter	Z	WW	H (ZH)	$t\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340-350	365
synchrotron radiation/beam [MW]	50	50	50	50	50
beam current [mA]	1294	135	26.8	6.0	5.1
number bunches / beam	11200	1852	300	70	64
total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	144	20	7.5	1.8	1.4
luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
run time (including lumi ramp-up) [years]	4	2	3	1	4
total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
total number of events	$6\ 10^{12}$ Z	$2.4\ 10^{8}$ WW (incl. WW at higher $\sqrt{s}$)	$2.2\ 10^{6}$ ZH 65k WW → H	$2\ 10^{6}$ $t\bar{t}$ + 370k ZH + 92k WW → H	

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF.

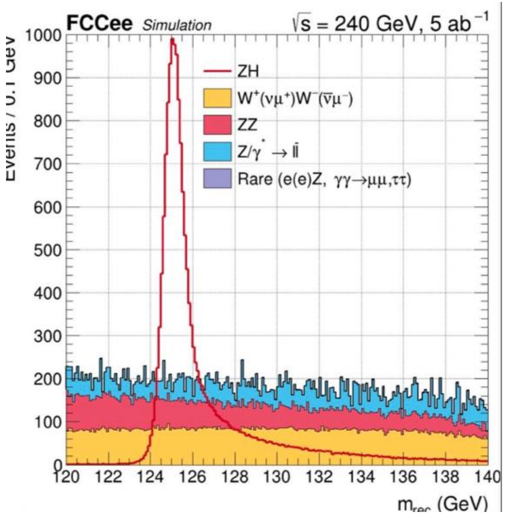


PHYSICS OF FCC

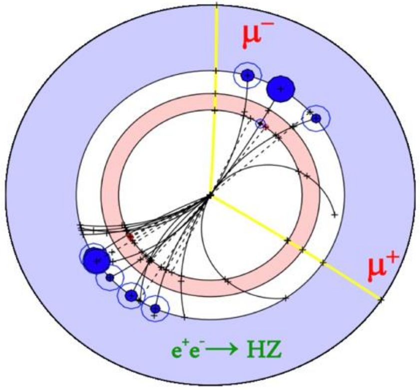
Higgs program @ FCC

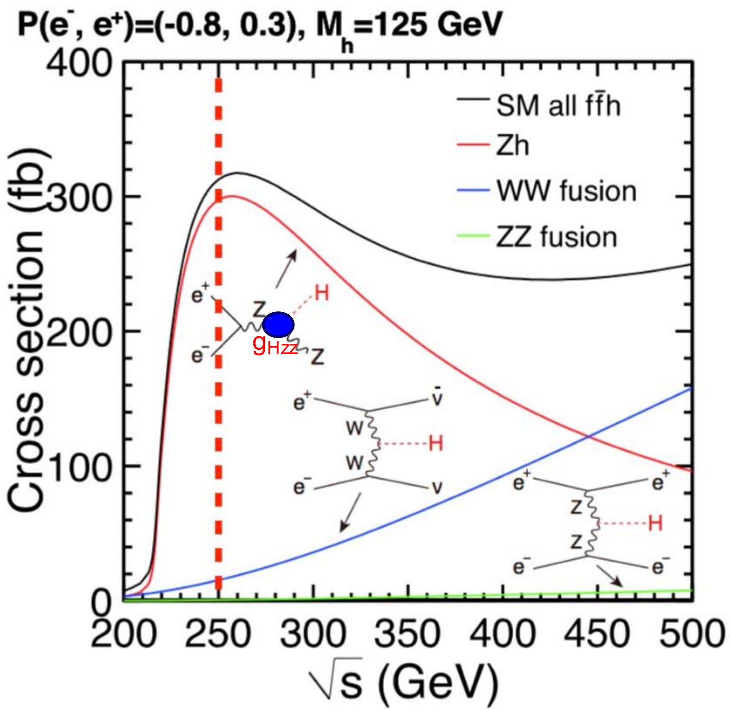
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**

$$M^2_{\text{rec.}} = s - 2E_Z\sqrt{s} + M_Z^2$$



$\sigma(ZH) \sim g^2_{HZZ}$





Measurement of $\sigma(ZH)\sim O(\%)$ and $\frac{\delta g_{ZHH}}{g_{ZHH}} \sim 0.2\%$

Higgs mass ~ $O(MeV)$

Higgs program @ FCC

Once we measure g_{ZHH} we have access to all other couplings:

$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

$$\frac{\sigma(e^+e^- \to ZH)}{BR(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{SM} \times \Gamma_H$$

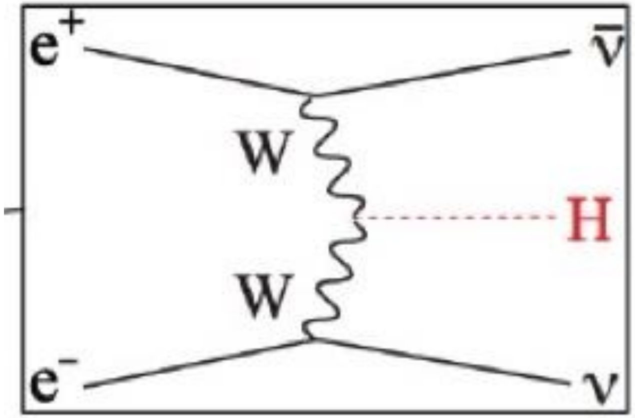
Select events with $H \to bb, cc, gg, WW, tt, \mu\mu, Z\gamma$ ... and get $g_{Hbb}, g_{Hcc}, g_{Hgg}, g_{HWW}, g_{Htt}, g_{H\mu\mu}, g_{HZ\gamma}$ ...

Additional observables at higher energies:

$$\sigma_{H\nu_e\bar{\nu}_e} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HWW} \times g^2_{HXX}}{\Gamma_H}$$

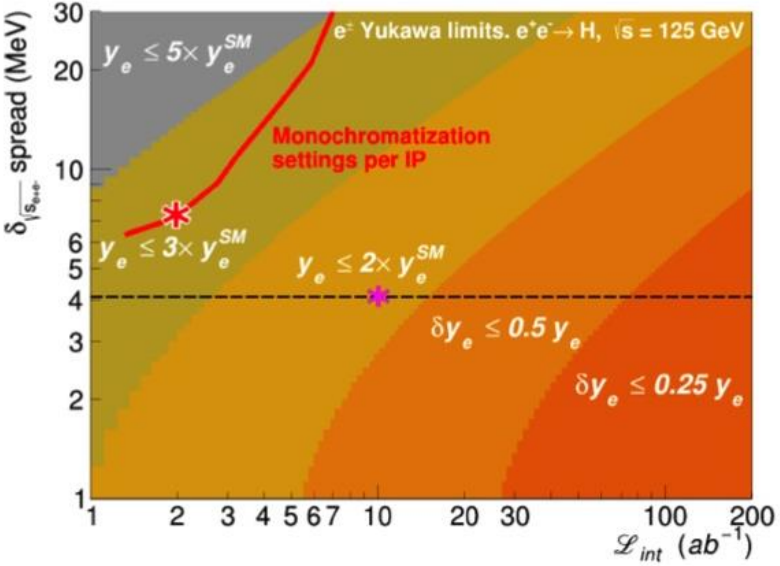
Need a global fit in the Kappa or SMEFT framework for

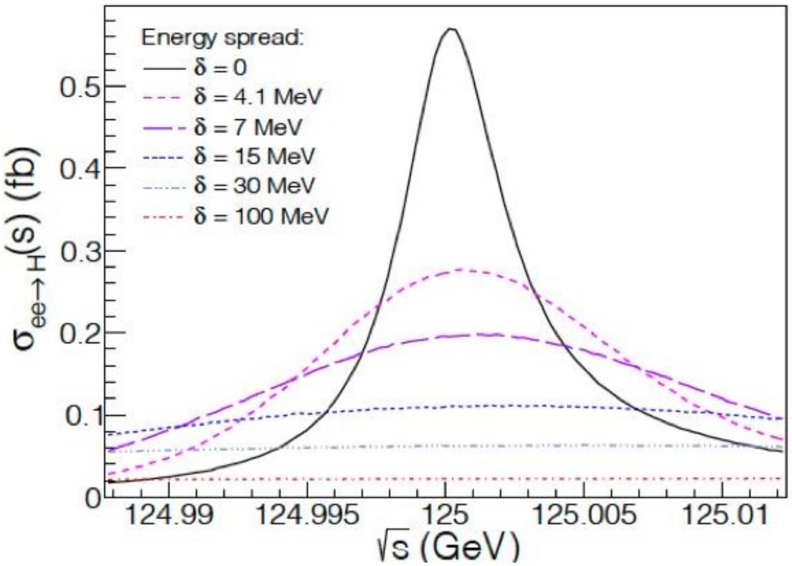
ultimate determination of the parameters



Higgs program @ FCC

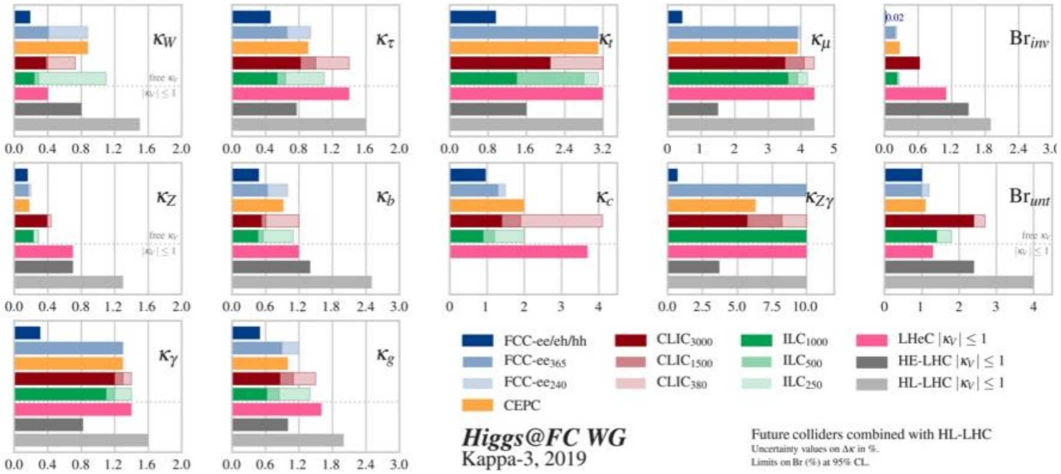
arXiv:2107.02686



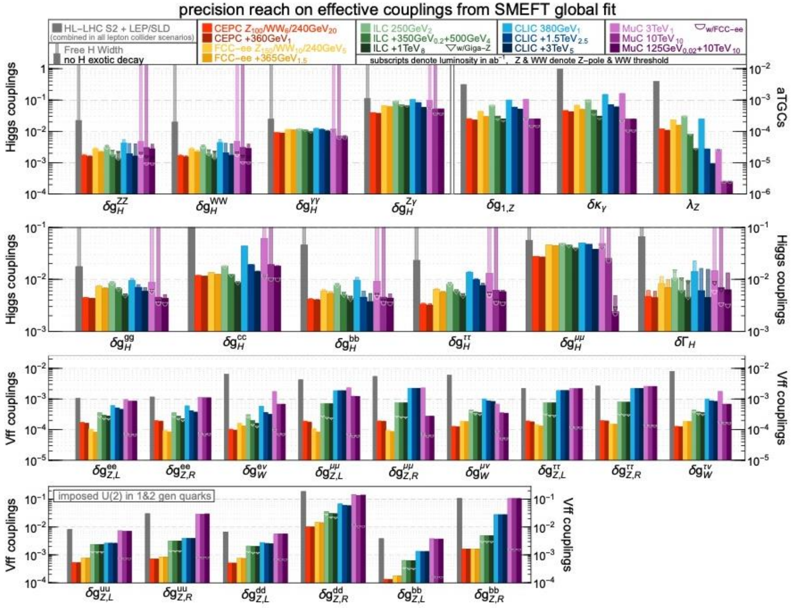


$H \to gg$	$H \to WW^* \to \ell\nu\ 2j;\ 2\ell\ 2\nu;\ 4j$	$H \to ZZ^* \to 2j\ 2\nu;\ 2\ell\ 2j;\ 2\ell\ 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

Higgs program @ FCC

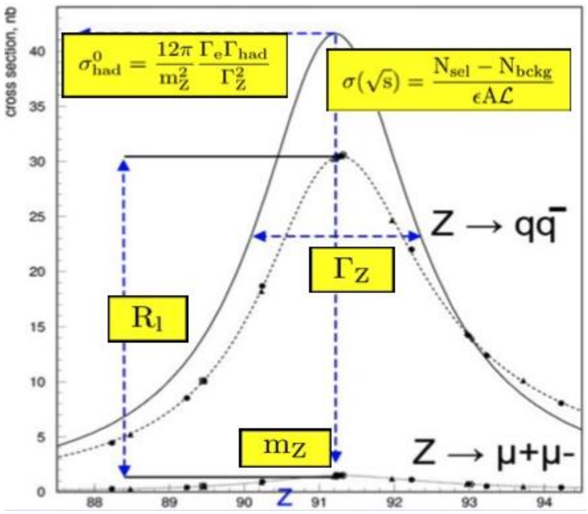


arXiv:2206.08326



Combined FCC is ahead!

EW program @ FCC



LEP: 2 x 10^7 Z

FCCee: 6 x 10^{12} Z

The crucial factor limiting factor: uncertainty on the collision energy: continuous ECM calibration (resonant depolarization of the transversely polarized beams)

Experimental (big) challenge: match the detector capabilities to the statistical power the detector capabilities to the statistical power

Theoretical challenges: improved precision on predictions used for lumi measurement, deconvolution of QED effects; EW/QCD corrections

Δ[keV]	LEP	FCC – ee		
		Total	stat	syst
Z mass	2100	100	10	100
Z width	2300	25	4	25

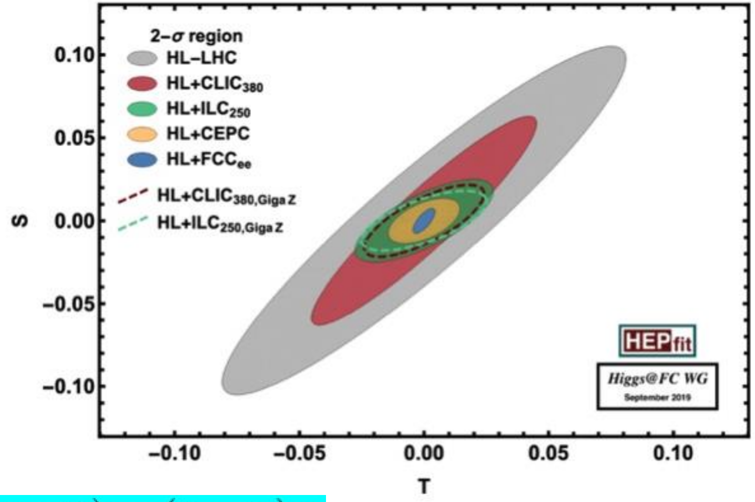
$\times 10^{-6}$	PDG (LEP) rel. precision	FCC – ee Total	stat	syst
R_e	2400	10	3.6	10
R_μ	1600	10	2.6	10
R_τ	2200	10	3.1	10
R_b	3100	300	1.4	300
R_c	17000	1500	150	1500

$$R_q = \frac{\Gamma_{\bar{q}q}}{\Gamma_{had}} \qquad R_l = \frac{\Gamma_{\bar{l}l}}{\Gamma_{had}}$$

Last but not least α_s can be measured with $0.1 - 0.2\%$ precision.

EW program @ FCC

Observable	unit	Present value	± error	FCC-ee (stat.)	FCC-ee (syst.)
m_Z	[keV]	91 186 700	2 200	4	100
Γ_Z	[keV]	2 495 200	2 300	4	25
$\sin^2\theta_W^{\rm eff}$	$[\times 10^6]$	231 480	160	2	2.4
$1/\alpha_{\rm QED}(m_Z^2)$	$[\times 10^3]$	128 952	14	3	small
R_l^Z	$[\times 10^3]$	20 767	25	0.06	0.2-1
$\alpha_S(m_Z^2)$	$[\times 10^4]$	1 196	30	0.1	0.4-1.6
$\sigma^0_{\rm had}$	$[\times 10^3$ nb$]$	41 541	37	0.1	4
N_ν	$[\times 10^3]$	2 996	7	0.005	1
R_b	$[\times 10^6]$	216 290	660	0.3	< 60
$A_{\rm FB}^{b,0}$	$[\times 10^4]$	992	16	0.02	1-3
$A_{\rm FB}^{{\rm pol},\tau}$	$[\times 10^4]$	1498	49	0.15	< 2
τ lifetime	[fs]	290.3	0.5	0.001	0.04
τ mass	[MeV]	1776.86	0.12	0.004	0.04
τ leptonic BR	[%]	17.38	0.04	0.0001	0.003
m_W	[MeV]	80 350	15	0.25	0.3
Γ_W	[MeV]	2 085	42	1.2	0.3
$\alpha_S(m_W^2)$	$[\times 10^4]$	1 170	420	3	small
$m_{\rm top}$	[MeV]	172 740	500	17	small
$\Gamma_{\rm top}$	[MeV]	1 410	190	45	small



$$A_{FB}^{\tau} = \frac{(\sigma_r - \sigma_l)_F - (\sigma_r - \sigma_l)_B}{(\sigma_r + \sigma_l)_F + (\sigma_r + \sigma_l)_B}$$

$$\sin^2\theta^f_{\rm W,eff} = \frac{1}{4}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

$\Delta\sin^2\theta^f_{W,\rm eff}(\times 10^6)$	current	total	stat	syst
from muon FB	160	3.1	2.0	2.4

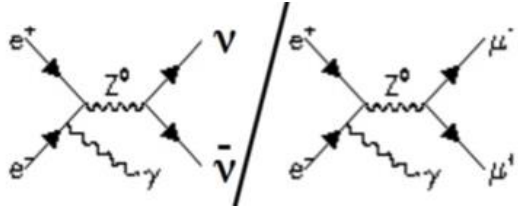
EW program @ FCC

Number of neutrinos: $N_\nu = 2.996 \pm 0.007$

$$N_\nu = \frac{\Gamma_\ell}{\Gamma_\nu} \cdot \left(\sqrt{\frac{12\pi R_\ell^Z}{m_Z^2 \sigma_{had}^0}} - R_\ell - 3 \right).$$

FCC will reach 5 x10^{-5} level

Monophoton events:



$$N_\nu = \left| \left(\frac{e^+e^- \to \gamma Z_{\text{inv}}}{e^+e^- \to \gamma Z_{\text{lept}}} \right)^{\text{meas}} \right| / \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\text{lept}}} \right)^{\text{SM}}$$

Stat dominated

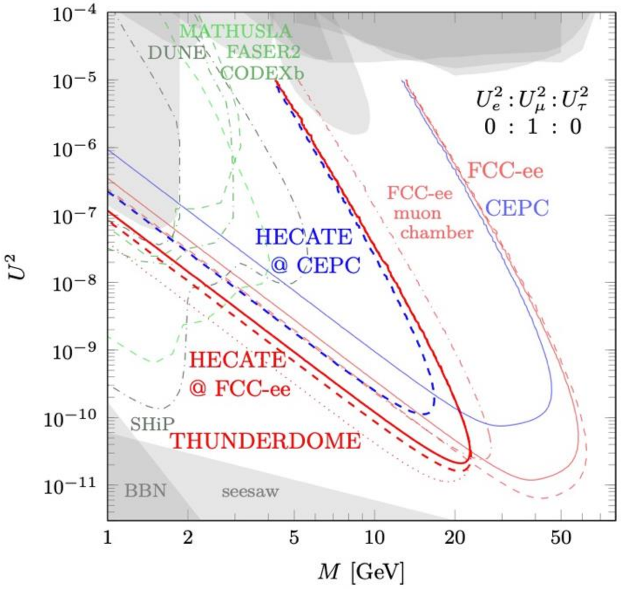
LEP : 2.98 ± 0.05

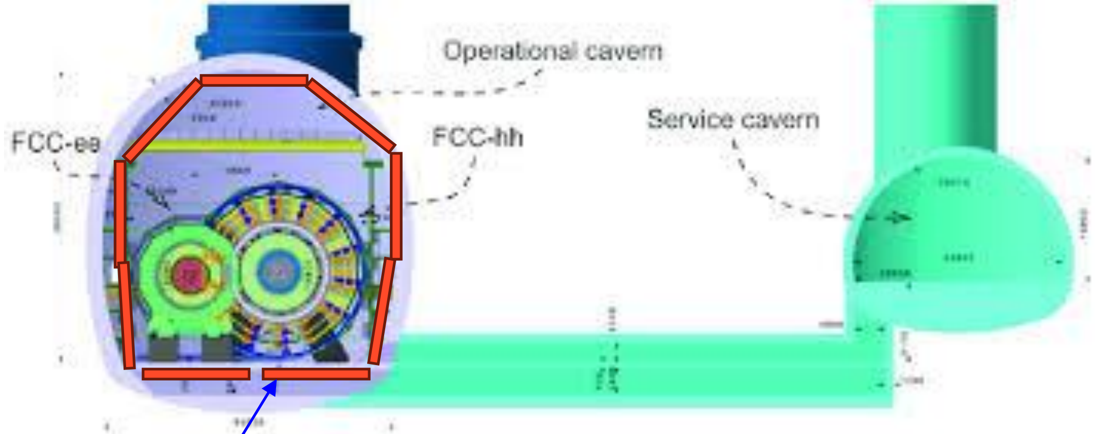
Lumi error cancel out!!! Systematic cancels OUT!!!

Can be measured in different $\sqrt{s}$

FCC will reach 4 x10^{-5} level

Neutrinos @ FCC





HErmetic CAvern TrackEr HECATE

$$N_{\rm obs} \simeq L\sigma_N \left[\exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right)\right].$$

ESPP 2025 – FIRST IMPRESSIONS

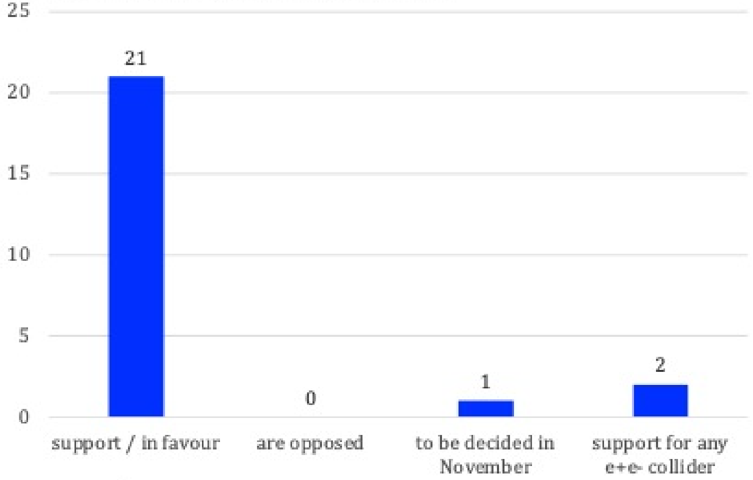
ESPP 2020

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.

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.

a) Which is the preferred next major/flagship collider project for CERN?

- **Broad consensus** among CERN Member States in support of the Future Circular Collider (FCC) as a key long-term project to maintain Europe's leadership in particle physics.



Support for FCC	Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland, United Kingdom
Opposed	None
To be finalized in November	Netherlands
Support for any e^+e^- collider	Austria, Bulgaria 6

@ Calin Alexa ESPP

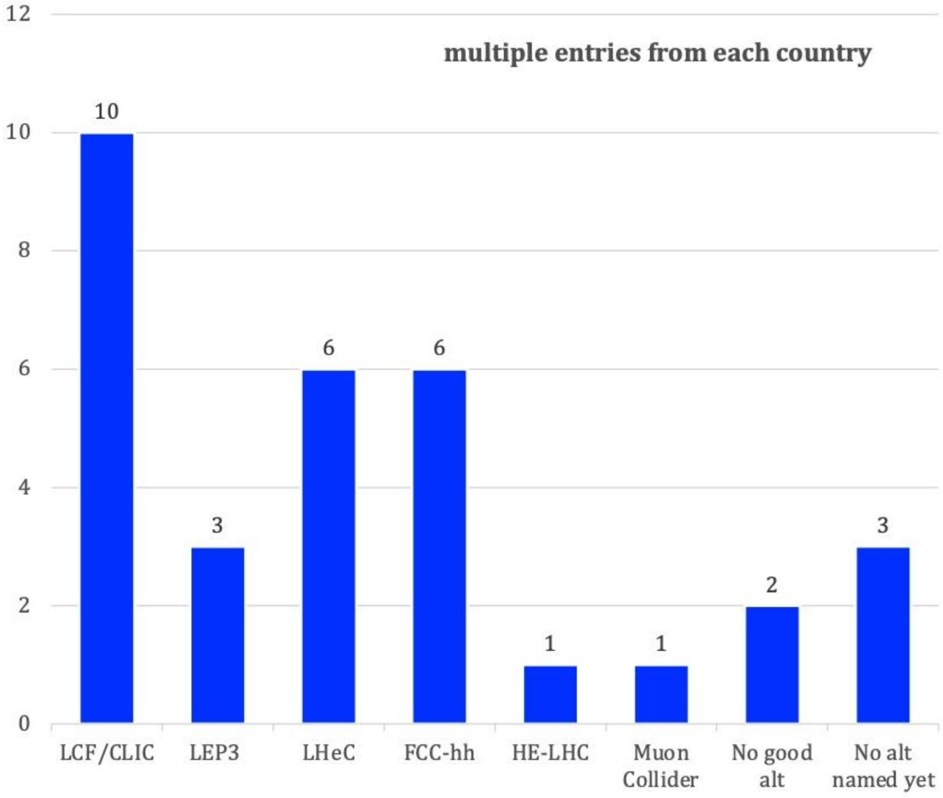
e) What is the prioritised list of alternative options if the preferred option is not feasible?

- Ten countries (DE, ES, FI, FR, NO, PL, PT, SE, RS, SK) list a linear collider at CERN as the second-best choice, with one (FI) mentioning the need for it to be affordable and another (UK) highlighting it as a viable strategic alternative. Two (DE, ES) of these countries highlight the benefits of polarized beams, the potential for two interaction points, and its ability to be upgraded.

- Two countries (CH, HU) see no reason for another option, as they would be equally costly.

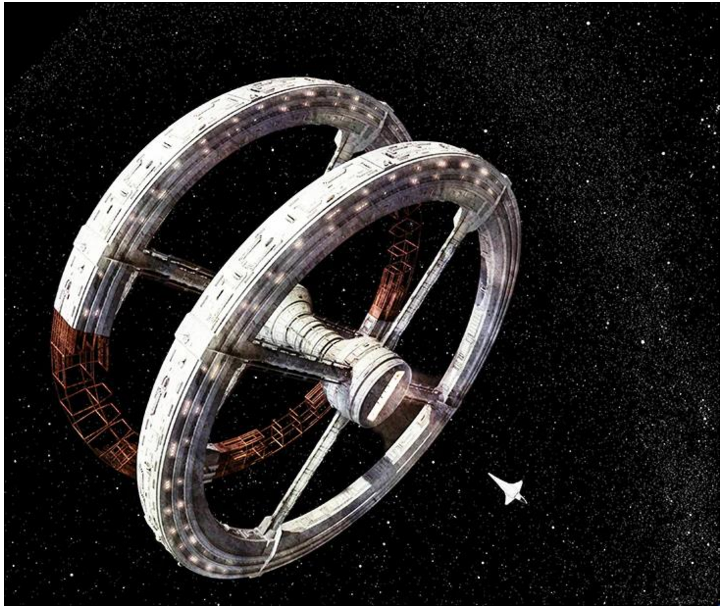
- Three countries (BE, GR, UK) mention LEP3 as a genuinely less costly alternative to the FCC-ee.

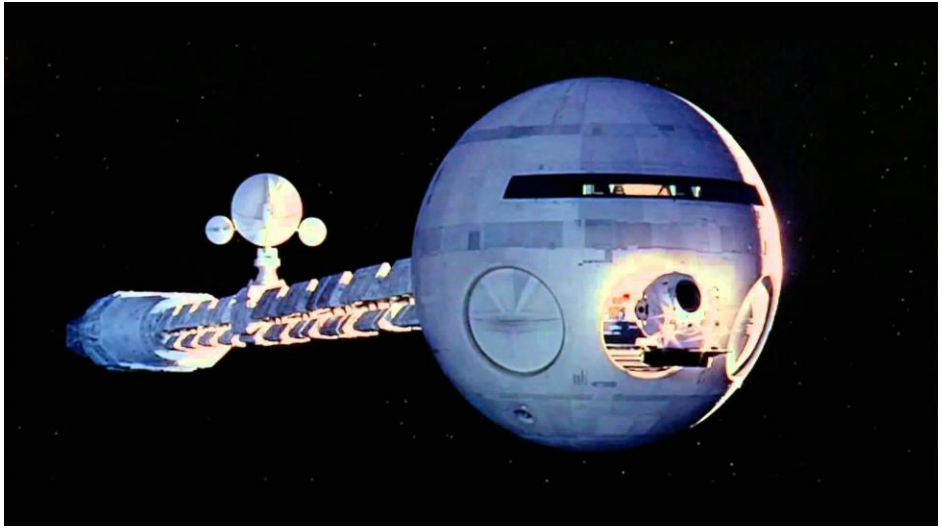
- No prioritised alternatives have been named yet by three other countries (CZ, DK, SK). The U.S. national input did not express a prioritized list.



@ Calin Alexa ESPP

The discussion between linear and circular colliders starts to become obsolete…

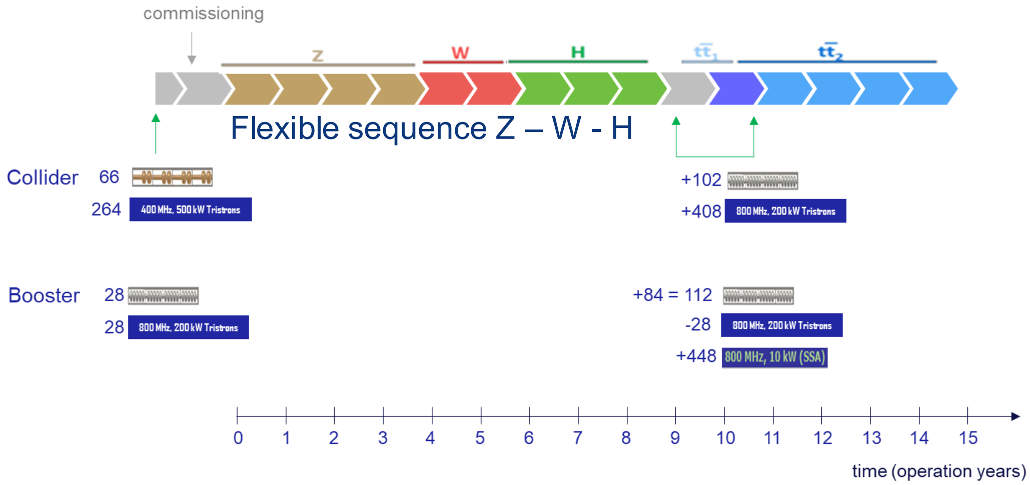




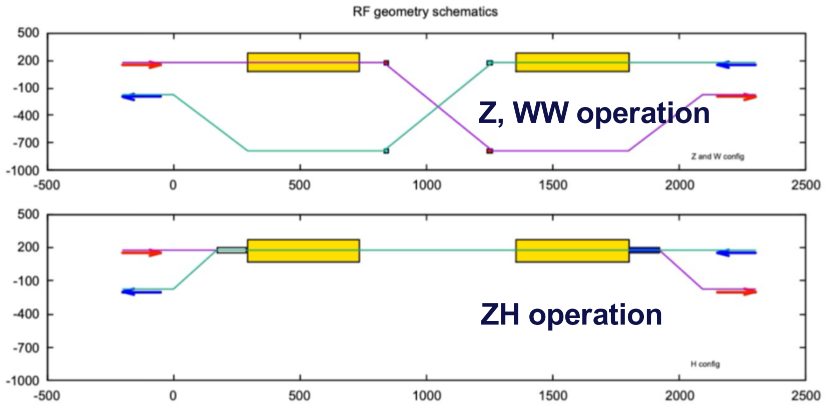
FCC

Thank you for your attention.

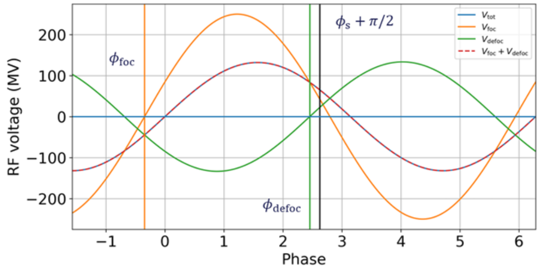
FCC-ee operation sequence and SRF concept



400 MHz RF layout and beam switching



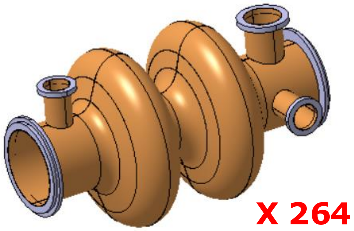
- **2-cell 400 MHz SRF system for Z, W and ZH**, entire system installed at operation start
  - flexibility for switching between Z, WW, ZH operation
  - reverse phase operation at Z allows constant cavity coupling
  - suppression of the single-cell 400 MHz system
  - reduced R&D, installation, commissioning, etc…



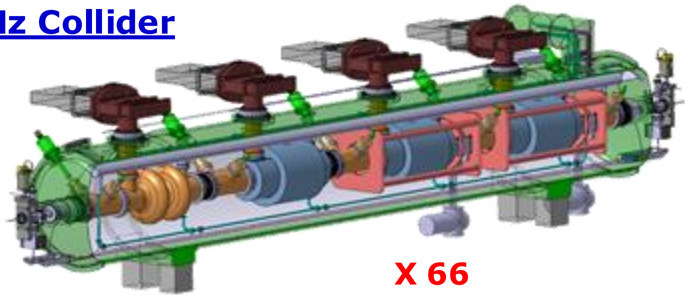
- **6-cell 800 MHz SRF system for collider ttbar operation and booster at all energies**

FCC-ee RF system – key technology

400 MHz Collider



X 264



X 66

Superconducting elliptical cavity

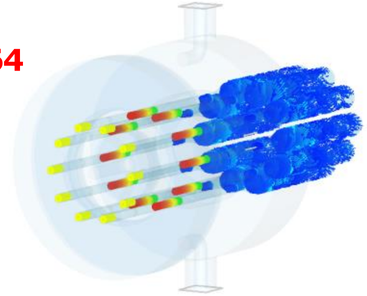
- 400 MHz, 2-cell, copper Nb coated
- 1.5 m. long

400 MHz Cryomodule

Power source: Multibeam Tristron

- **Very efficient ~90 % ! <<OPEX**
- 3 m long
- 50 kV
- 500 kW, CW

X 264



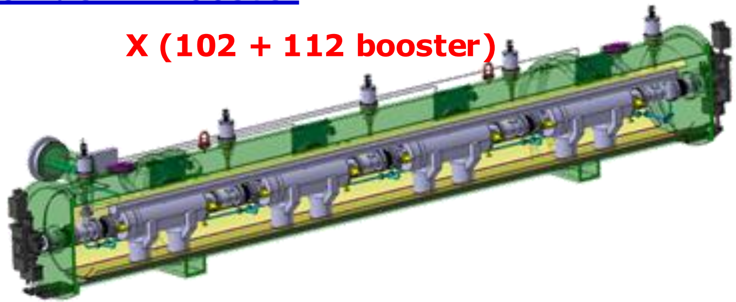
X 204

+ 448 x 10 kW SSA booster

800 MHz Collider + Booster

X (408 + 448 booster)

X (102 + 112 booster)



Superconducting elliptical cavity

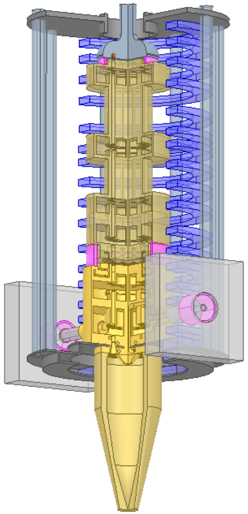
- 800 MHz, 6-cell, bulk Nb
- Nb_3Sn if R&D is successful

800 MHz Cryomodule

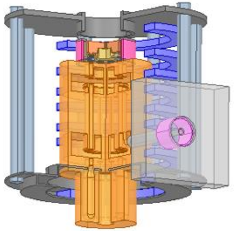
RF power source R&D – operation efficiency, sustainability, etc.

- For Z, W, ZH operation: 100 MW RF required via 264 klystron + 2-cell cavity units, 400 MHz CW.
- New 380 kW klystron prototype built with industry (HL-LHC) η = 70%, as design simulation.
- Two-stage klystron design made for η = 86%, similar to CLIC drive-beam and ILC klystrons.
- Concept for multi-beam tristron developed, η = 93% over wider range of powers → prototype 2027.
- Assumption for present FCC-ee power consumption is η = 80%.

HL-LHC (relevant prototype)



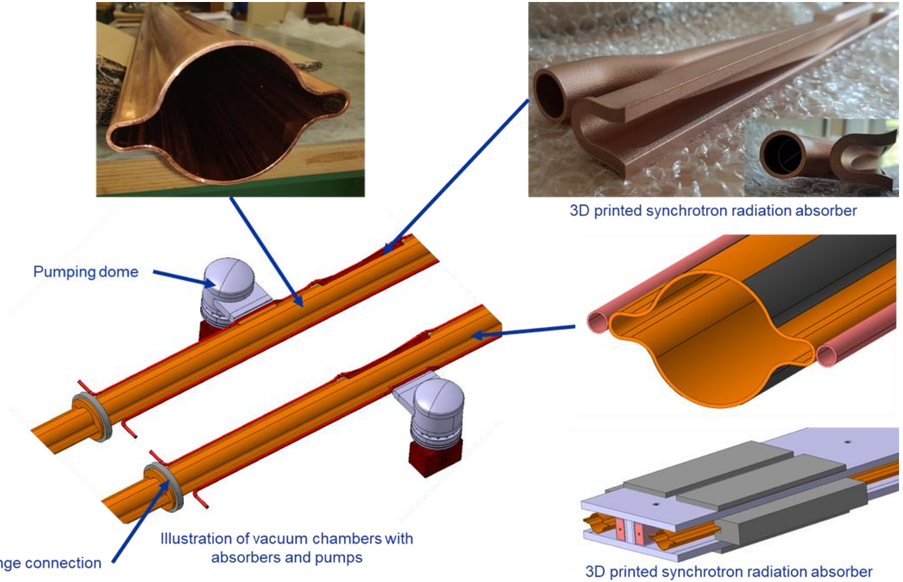
Two-stage klystron (design)



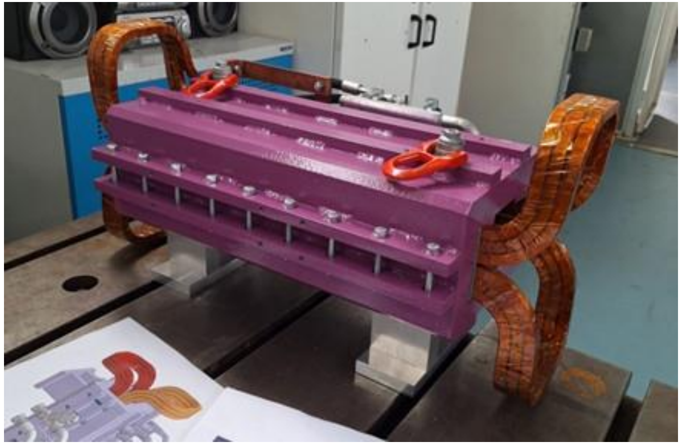
Tristron (concept)

R&D topics – energy and operational efficiency, industrialisation

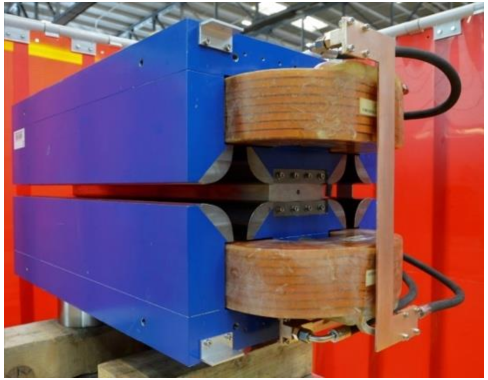
3 * 92km of beam vacuum chamber
NEG-coated technology for collider
synchrotron radiation absorbers and shielding
Prototyping started



Booster dipole
low-field
cycling magnet

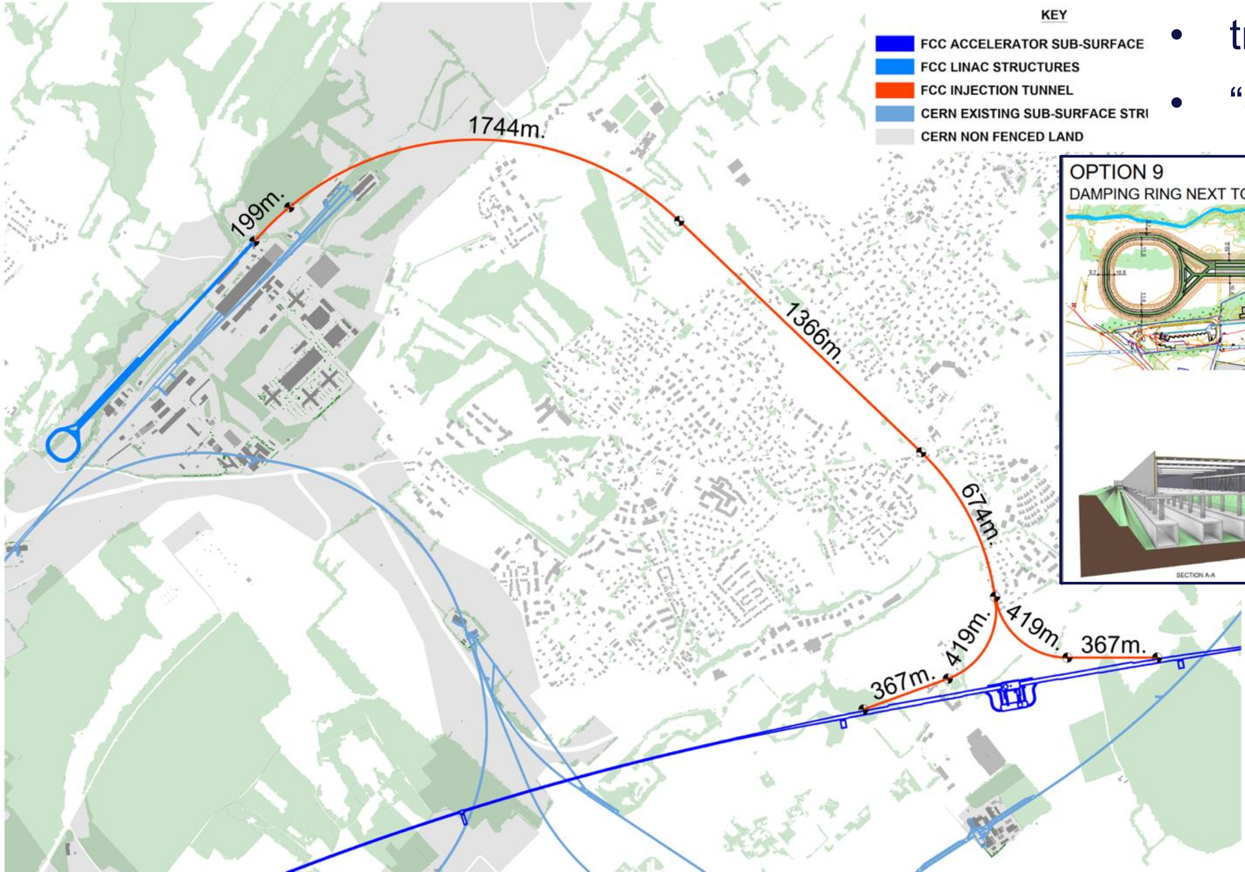


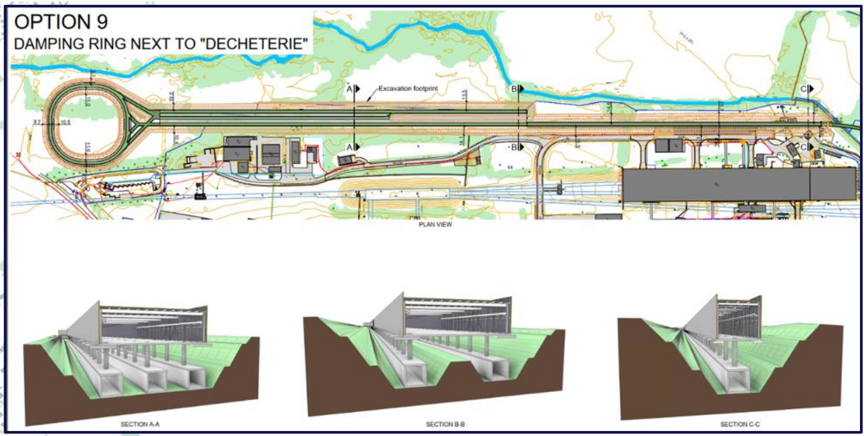
Twin F/D arc
quad design with
2× power saving
25 MW (at 175
GeV), with Cu
conductor



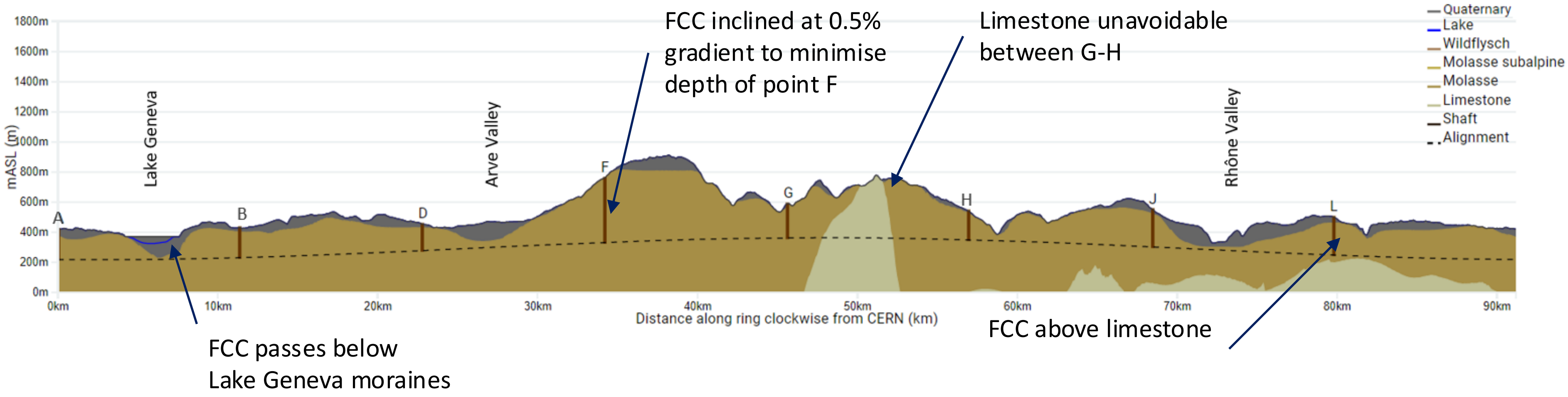
FCC-ee injector with HE Linac

- Located on CERN Prévessin site
- possible connection to North Area
- transfer line to FCC PA (LHC P8)
- “cut and cover” construction





Optimum placement of FCC tunnel and geology



Tunneling mainly in molasse layer (soft rock), well suited for fast, low-risk TBM construction.

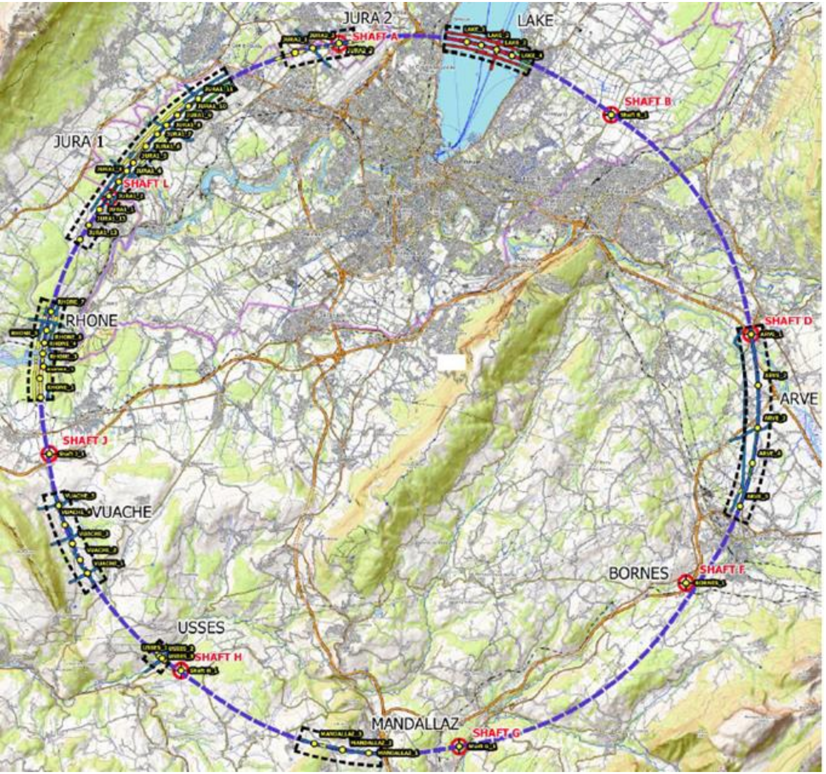
6 million m^3 excavated volume → 8.5 million m^3 excavation material on surface

CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

Site investigation

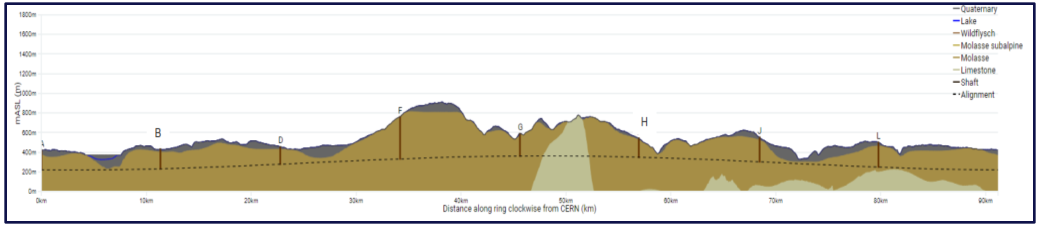


Site investigations to identify exact location of geological interfaces:

- Molasse layer vs moraines/limestone
- ~30 drillings and ~100 km seismic lines
- Start in July 2024

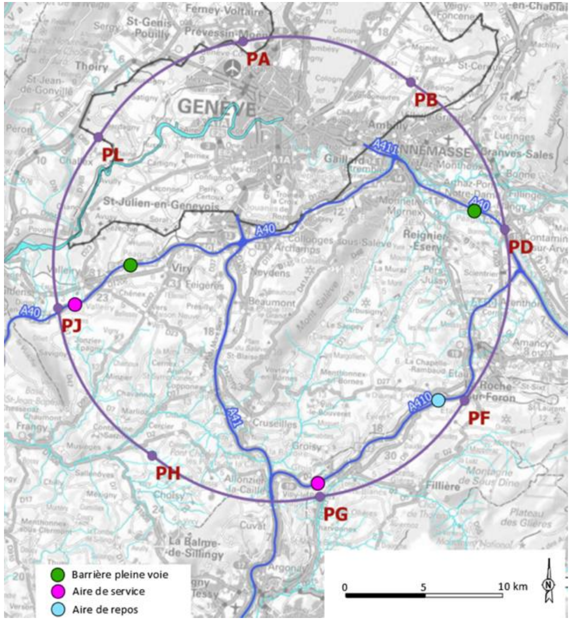
→ Vertical position and inclination of tunnel

Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)

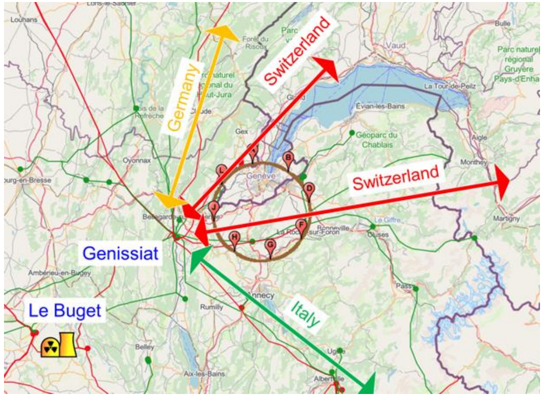


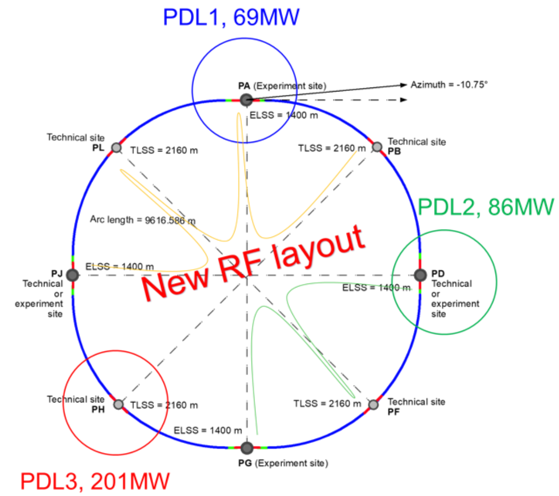
Site investigation

- Road accesses developed for all 8 surface sites
- Four possible highway connections defined
- Less than 4 km of new roads required



connections to French electricity grid





- Electrical connection concept developed with RTE (French electricity grid operator)
- Three HV supply points, two new stations & CERN Prevessin
  ➔ requested loads have no significant impact on grid
- R&D efforts aiming at reduction of the energy consumption of FCC-ee and FCC-hh

FCC Collaboration

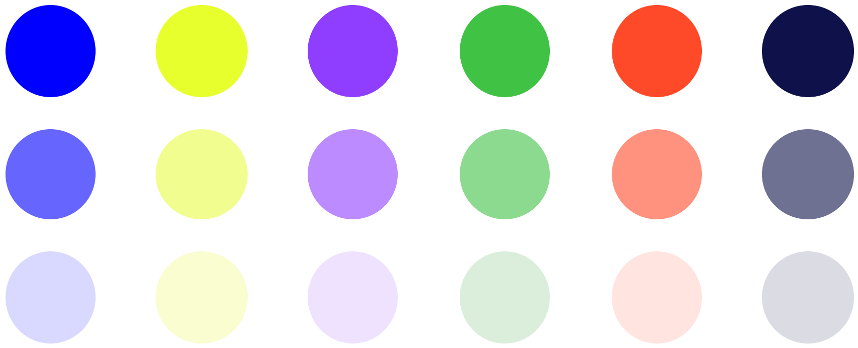
FCC Feasibility Study:
Aim is to increase further the collaboration,
on all aspects, in particular on Accelerator and Particle/Experiments/Detectors

141 Institutes

32 countries + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

COLORS



Radian t Blue

Flash

Energy

Green

Red

Deep Blue

BACKGROUNDS

Background Blue

Background Purple

Background Yellow

Background Grey

Use for Layout