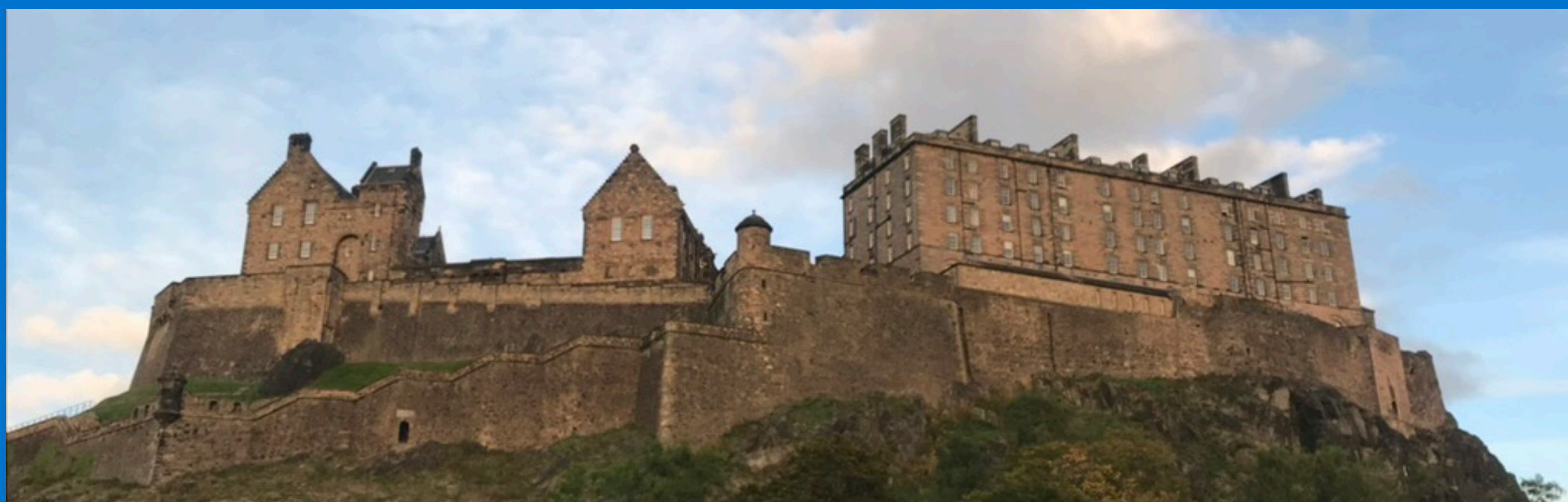
UNIVERSITY OF CAMBRIDGE

Murray Edwards College
University of Cambridge

FUTURE CIRCULAR COLLIDER

Overview of the Future Circular Collider



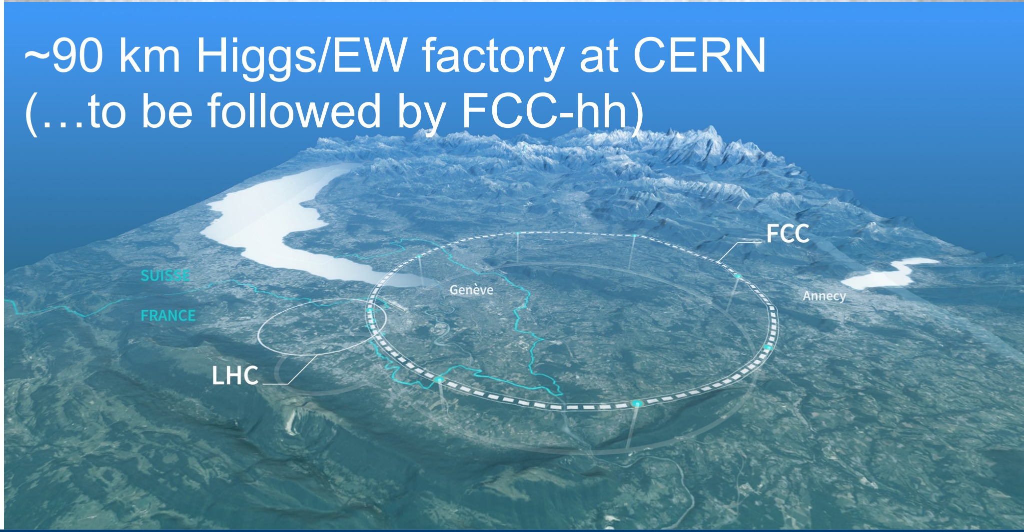
Dr Sarah Williams, on behalf of the FCC collaboration

Introduction

https://home.cern/science/accelerators/future-circular-collider

- Lots of synergies between CEPC and FCC (-ee).
- Today I'll discuss the FCC project and progress on the feasibility study, with a focus on FCC-ee.
- For more detailed overviews of the status see the slides at the London FCC week.

Thanks to the numerous collaborators whose slides/schematics have been used in these slides ☺



The 2020 European Strategy Update

Following ~ 2 years of concensus gathering within the community, the ESU made several key recommendations to the community:

1. 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

2. 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

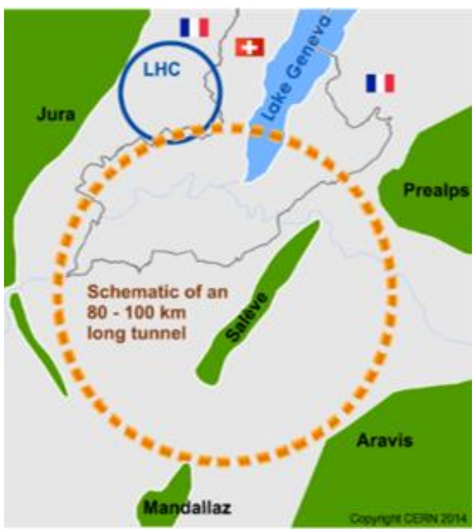
Following the 2020 ESU, the FCC feasibility study was launched in 2021, aiming to provide input by 2025 to feed into the next ESU…

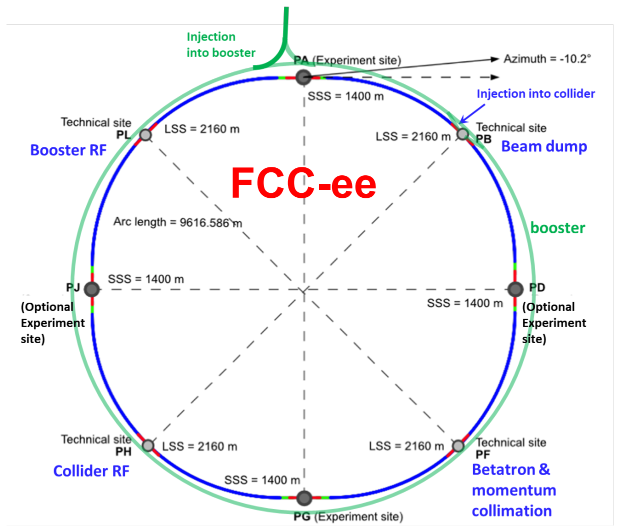
FCC integrated programme

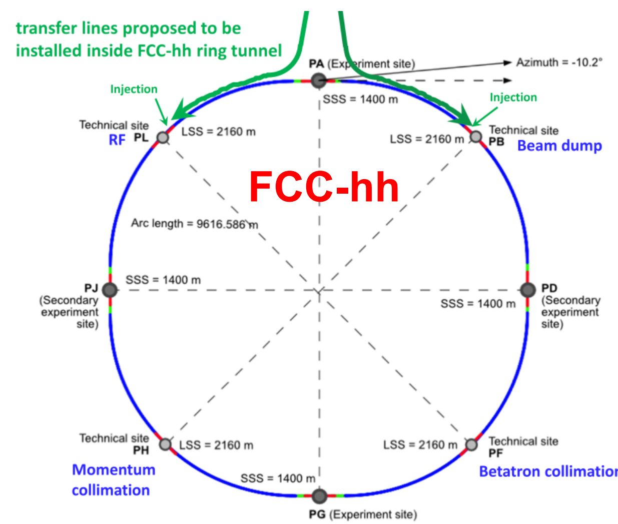
See slides by M. Benedikt at FCC week.

Comprehensive long-term programme maximises physics opportunities at the intensity and energy frontier:

1. FCC-ee (Z, W, H, $t\bar{t}$) as high-luminosity Higgs, EW + top factory.
2. FCC-hh (~ 100 TeV) to maximise reach at the energy frontier, with pp, AA and e-h options.

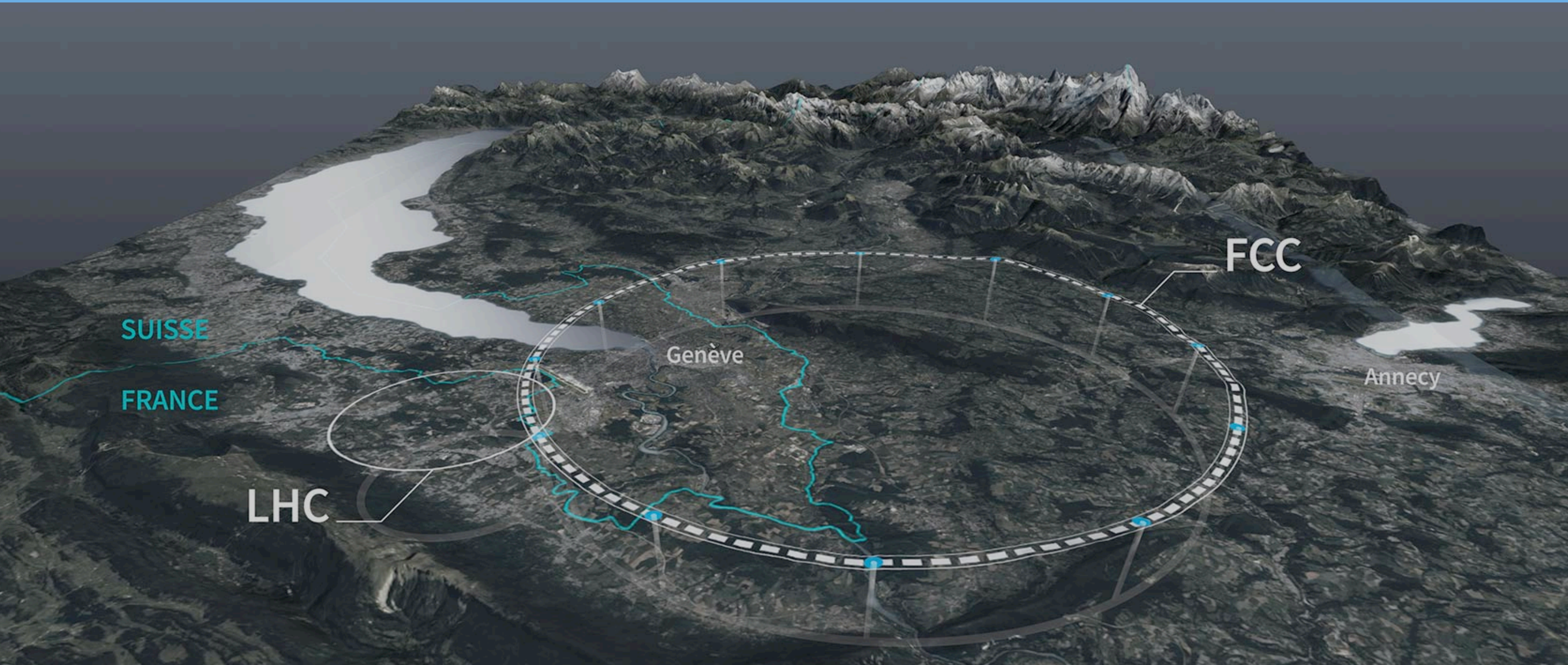






2020 - 2040 | 2045 - 2063 | 2070 - 2095

FCC-ee and -hh synergies



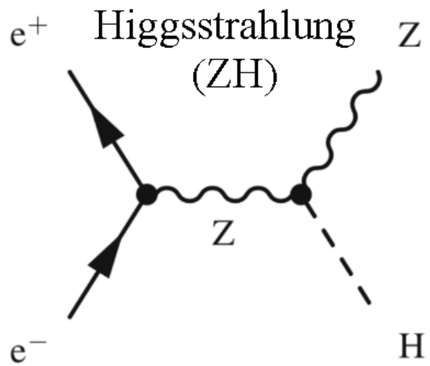
Integrated programme combines precision at the intensity frontier (FCC-ee) giving indirect sensitivity to a multitude of NP as well as unique direct sensitivity to low-mass and weakly interacting BSM physics, with discovery potential at the energy frontier (FCC-hh) that will extend the precision achieved at FCC-ee!

FCC-ee and -hh synergies - Higgs measurements

- FCC-ee can provide a model independent measurement of g_{HZZ} through measuring σ_{ZH}. This provide standard candle to normalize the measurement of other Higgs couplings.

- FCC-ee will measure ttZ couplings through $ee \rightarrow t\bar{t}$. This gives a second standard candle used to extract g_{ttH} and g_{HHH} at FCC-hh.

- FCC-hh will provide the statistics to access rarer Higgs decays ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$) and ~ 20 million HH events to give precise ultimate tests of the EWPT.

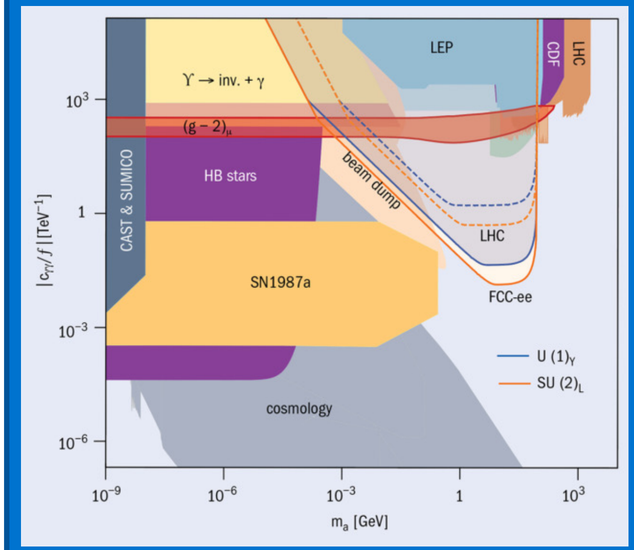


FCC-ee and -hh synergies - BSM

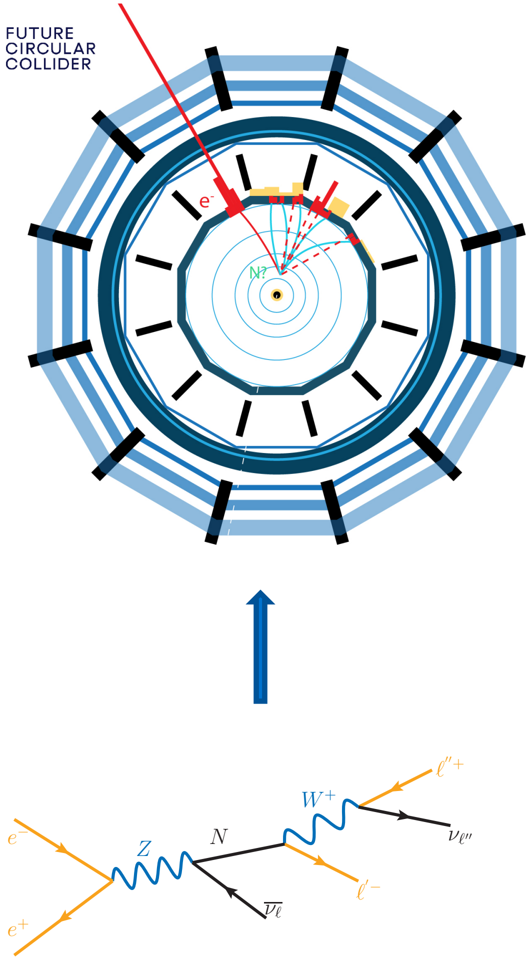
See slides by G. Salam at FCC week

Direct FCC-ee sensitivity

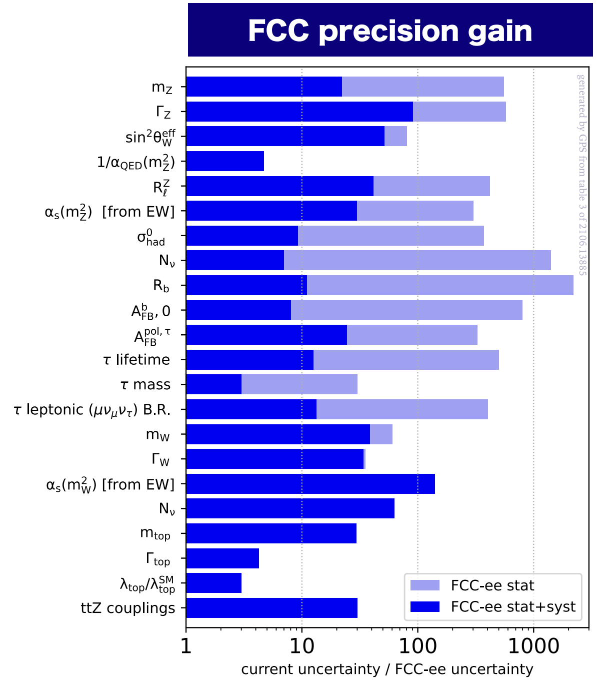
- HNLs
- Alps
- Exotic Higgs decays



m_a: ALP mass, $c_{\gamma\gamma}$: ALP-photon coupling



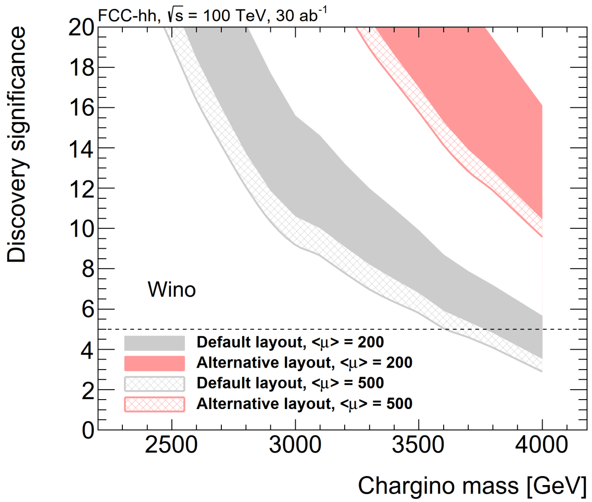
…plus **indirect access** to a range of BSM phenomena through ultra-precise measurements of SM parameters…

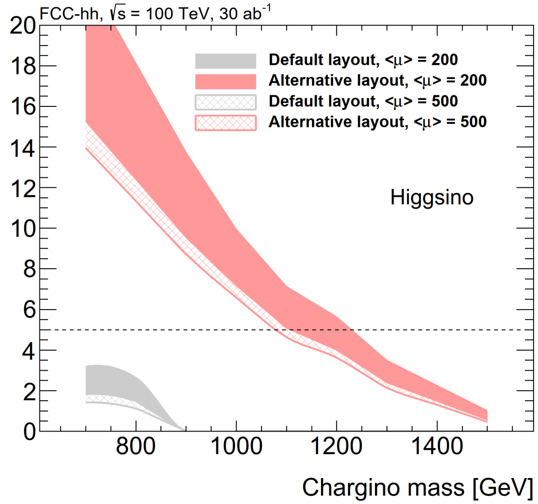


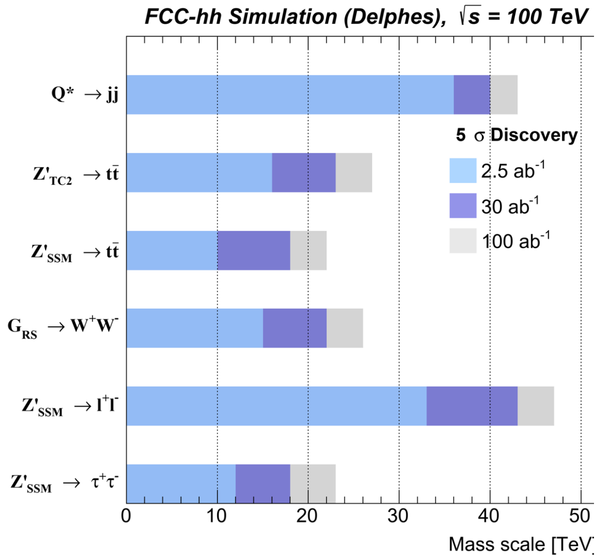
FCC-ee and -hh synergies - BSM searches

More details in FCC TDR and ESU submissions here

FCC-hh sensitivity to direct NP







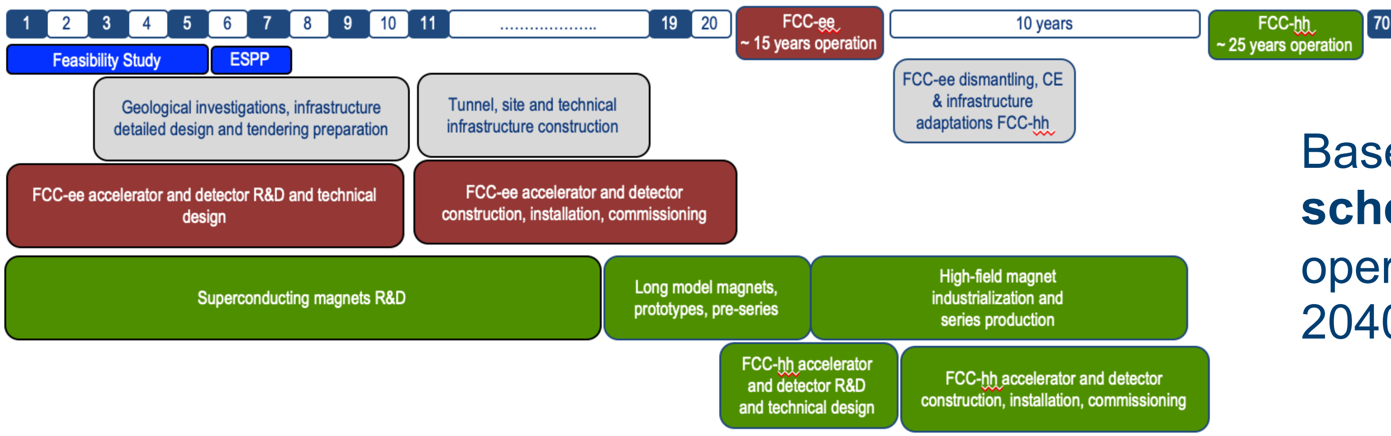
Cover full mass range for discovery of WIMP dark matter candidates

Substantial discovery reach for heavy resonances

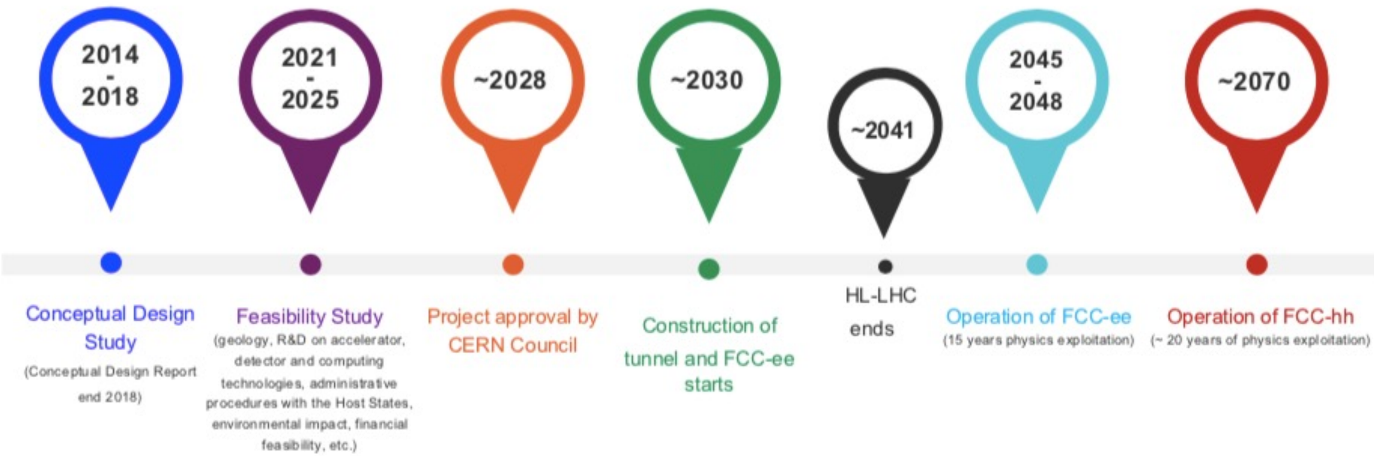
In summary- exciting possibilities to discover/characterize NP that could be indirectly predicted through precision measurements at FCC-ee

FCC timelines

Taken from slides by F. Gianotti at FCC week.



Based on **technical schedule**, FCC-ee operation could start in 2040 or earlier.

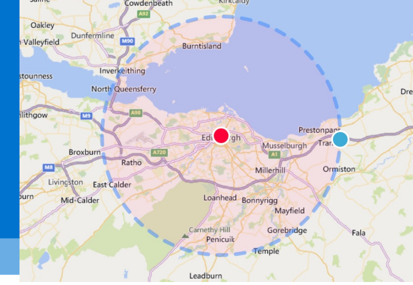


More **realistic schedule**, accounting for past experience of building colliders, approval timelines, HL-LHC operation…

FCC ring placement

Taken from slides by M. Benedikt at FCC week.

For scale, a ~ 100km ring centered on Edinburgh Waverley

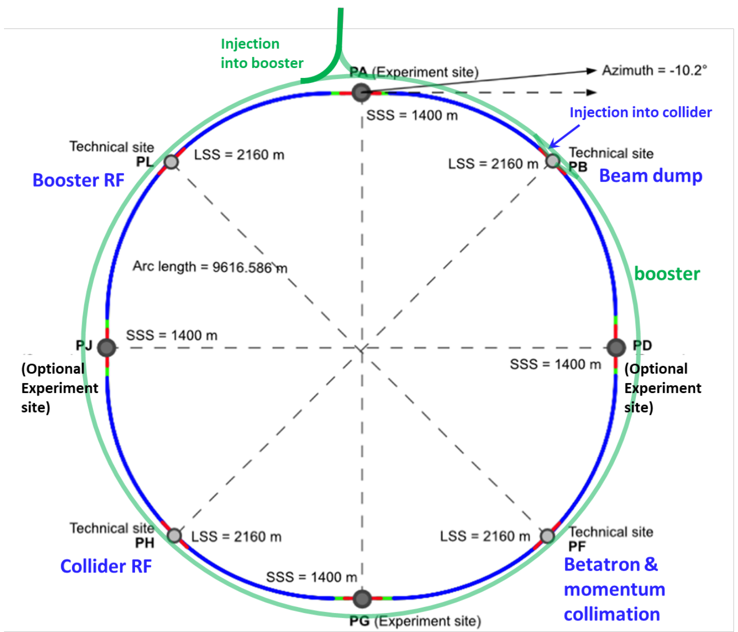


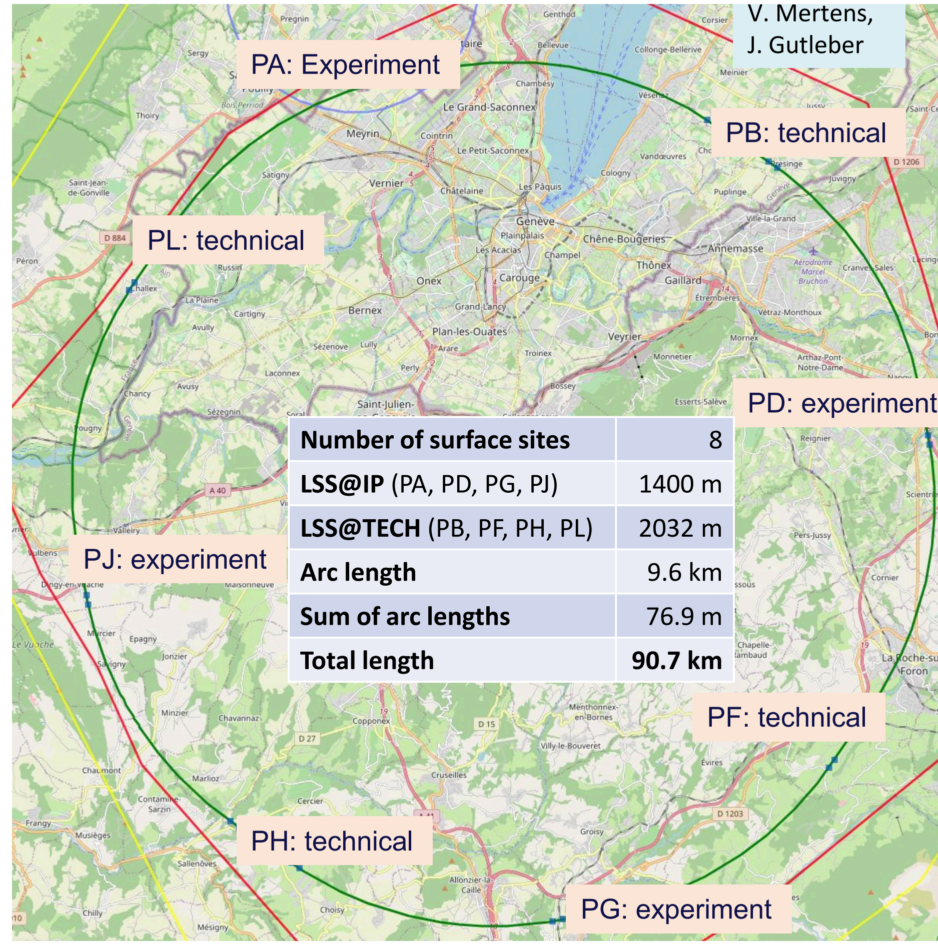
Major achievement: optimization of the ring placement

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), etc.
"Éviter, reduire, compenser" principle of EU and French regulations

Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs

Whole project now adapted to this placement

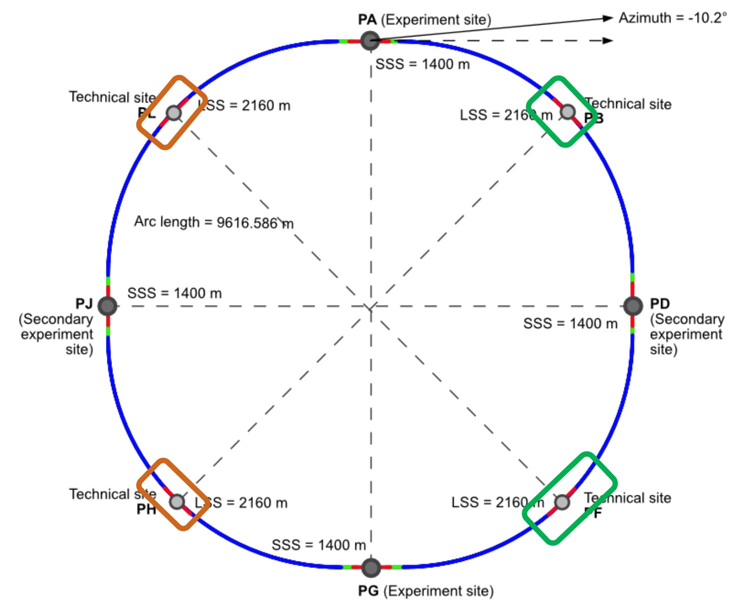




Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC-ee accelerators

- Separate rings for electrons and positrons and full-energy top-up booster ring in same tunnel.
- Max 50MW synchrotron radiation per collider ring across full operating range.
- Asymmetric IR layout limits photon synchrotron radiation 500m upstream of IP towards detectors, and generates large 30mrad crossing angle.
- Crab waist technique to optimize luminosity.



4 possible experimental sites at PA, PD, PG and PJ with RF stations at PH, PL and injection/extraction and collimation in PB/PF straights.

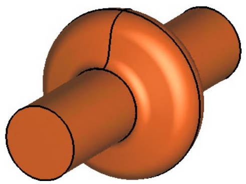
FCC-ee SRF system

Schematic taken from slides by F. Zimmerman at US Snowmass townhall

F. Peauger, O. Brunner

Z

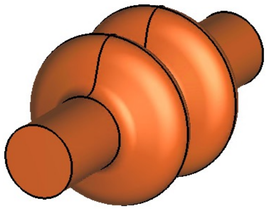
1-cell
400 MHz,
Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

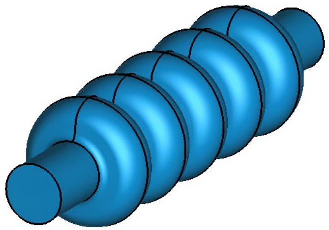
2-cell
400 MHz,
Nb/Cu



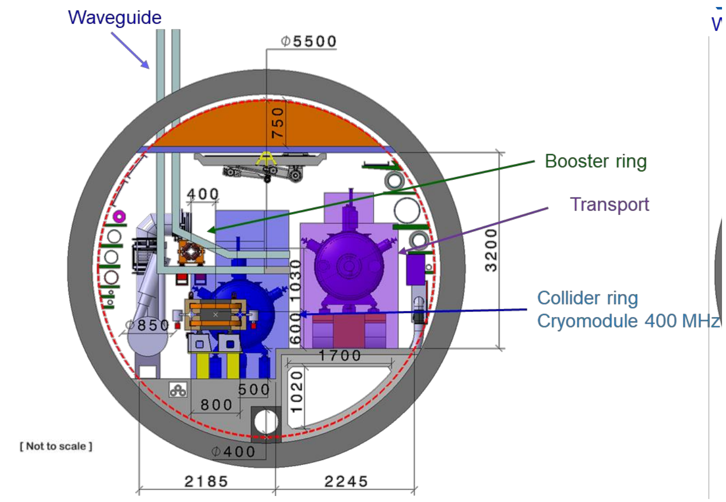
moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

ttbar, booster

5-cell
800 MHz,
bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

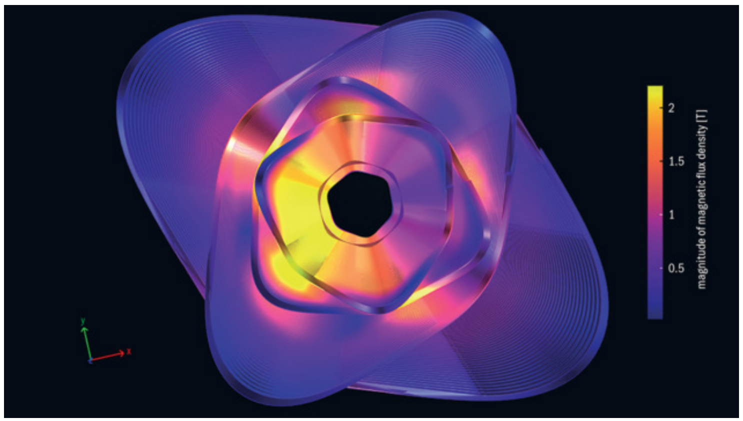


RF for collider and booster in separate sections (collider in PH- 400 & 800 MHz, booster in ML- 800 MHz only) with fully separated technical infrastructure (cryogenics)

FCC-ee beam optics

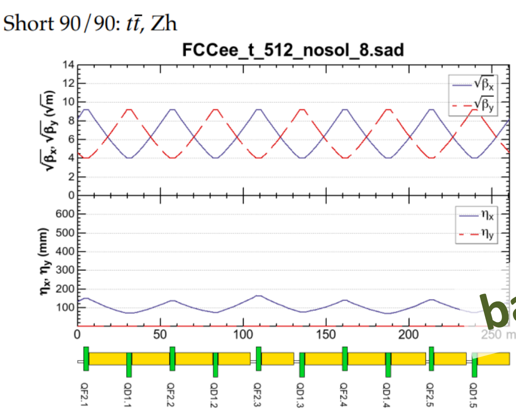
Two new projects backed by CHART aim to explore use of HTS to improve energy efficiency. See CERN courier article here

Maximising energy efficiency is a major factor!



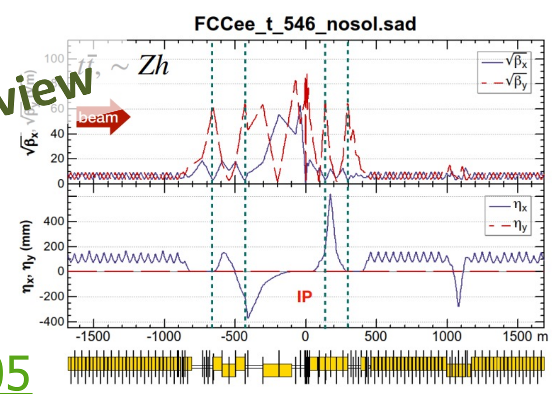
- Focussing and defocusing by ~3000 quadrupoles and ~ 6000 sextupoles.
- Designs being considered to reduce power consumption (single-cells vs super-cells).

arc



FODO lattice, many -*I* sext pairs; periodic unit cell length ~260 m

interaction region

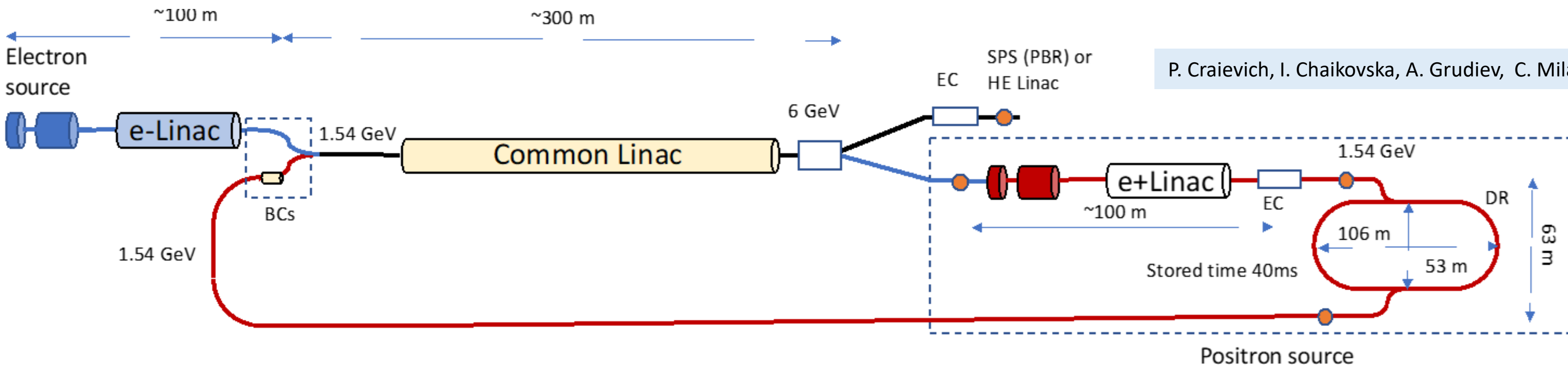


baseline for 2023 FCC "mid-term" review

Phys. Rev. Accel. Beams **19**, 111005

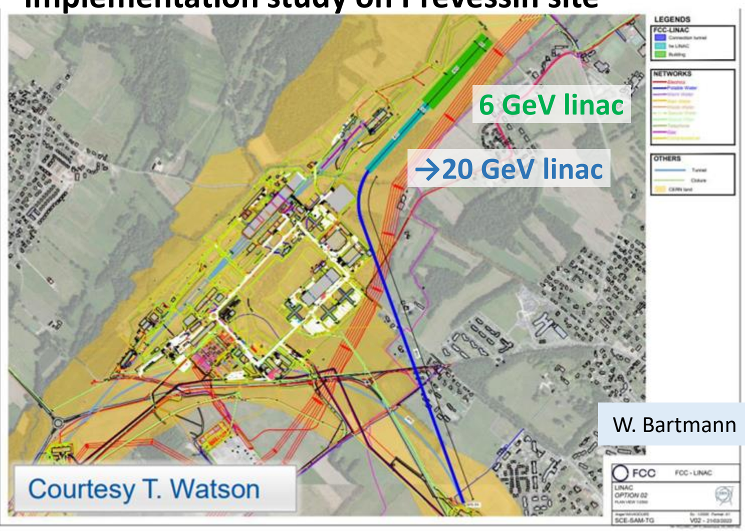
New FCC-ee injector layout

Taken from slides by M. Benedikt at FCC week

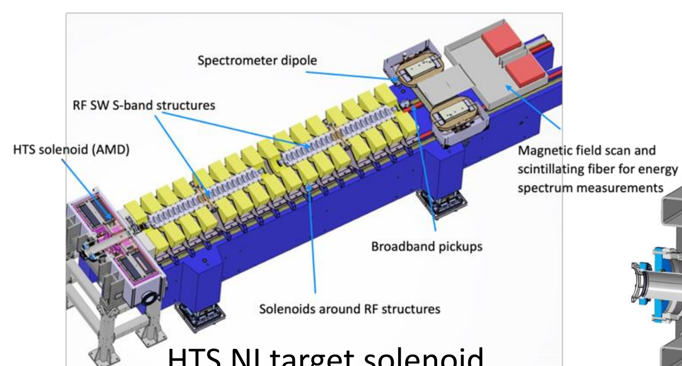


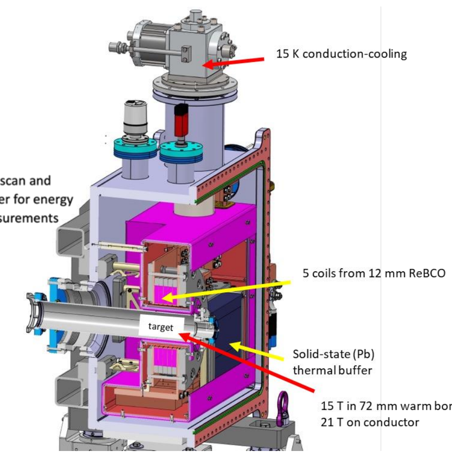
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

implementation study on Prevessin site



"Positron production experiment" at PSI's SwissFEL, beam tests from 2025/26





HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

Summary of FCC-ee beam parameters

Taken from slides by F. Gianotti at FCC week.

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years 5×10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs

Currently assessing technical feasibility of changing operation sequence (e.g. starting at ZH energy)

- 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 physics landscape

Schematics from slides by M. Selvaggi at FCC week

FCC-ee Physics landscape

Higgs
factory

m_H, σ, Γ_H
self-coupling
$H \rightarrow$ bb, cc, ss, gg
$H \rightarrow$ inv
ee$\rightarrow$H
$H \rightarrow$ bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \rightarrow \tau \nu$
$B_s \rightarrow D_s K/\pi$
$B_s \rightarrow K^* \tau \tau$
$B \rightarrow K^* \nu \nu$
$B_s \rightarrow \varphi \nu \nu$ ...

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

FCC-ee Detector requirements

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
"boosted" B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 µm

luminosity

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

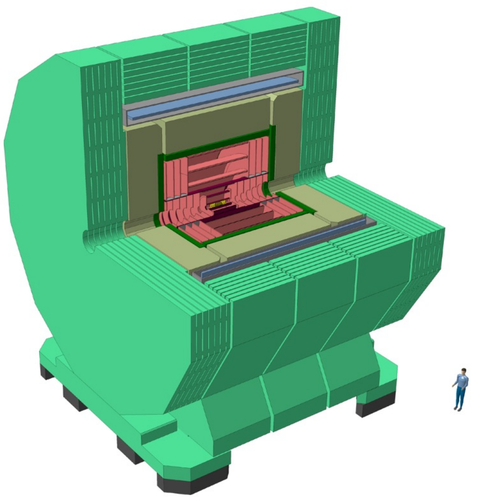
impact parameter resolution for large displacement

triggerless

- Broad landscape of physics opportunities, from precise measurements of Higgs/Top/EW parameters of SM, to unique flavour opportunities at tera-Z run, and direct+indirect BSM sensitivity.
- Significant effort ongoing to study detector concepts across range of physics analyses (including unconventional signatures from LLPs/FIPs).

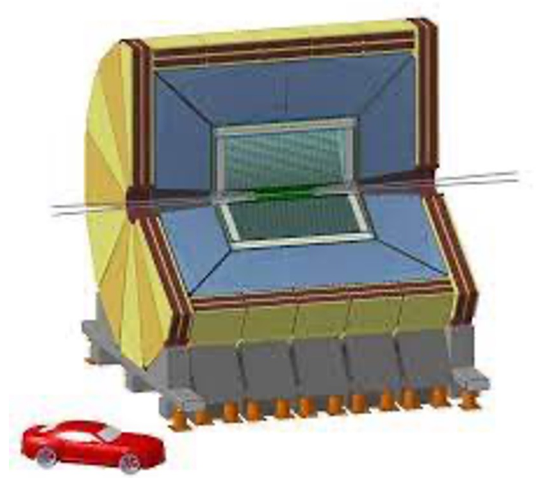
Detector concepts for FCC-ee

CLD ("CLIC-like Detector")



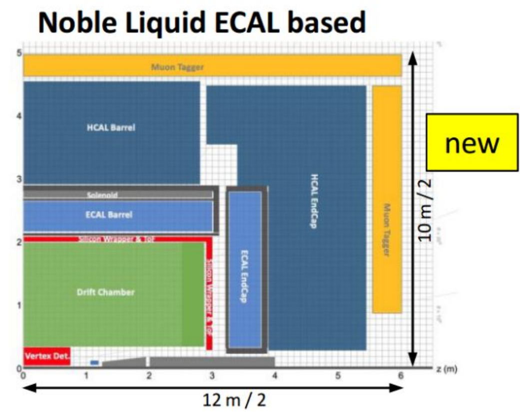
Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

IDEA ("Innovative Detector for Electron-positron Accelerator")



Silicon vertex detector
Short-drift chamber tracker.
Dual-readout calorimeter

…Plus new proposals …



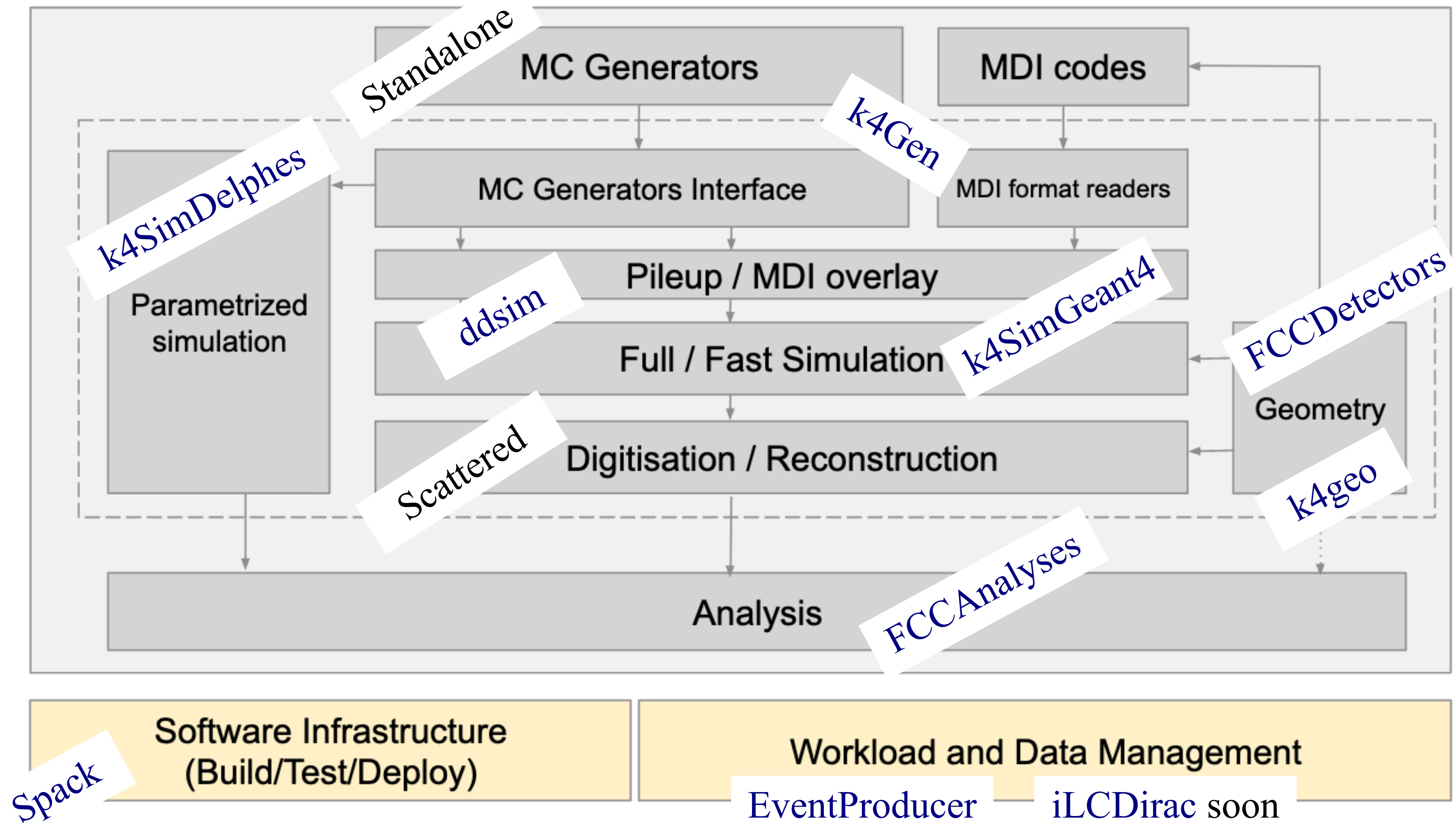
New proposal using liquid LAr calorimeter!

Easy to study impact of detector design on physics sensitivity through FCC software framework…

FCC analysis software

Schematic taken from slides by Brieuc Francois at FCC week

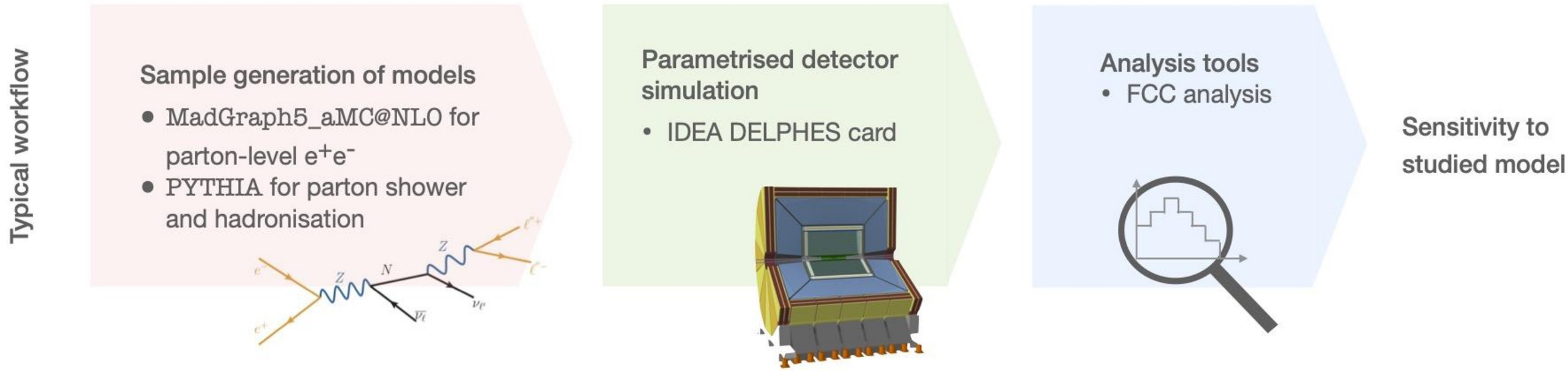
Sophisticated software ecosystem in place to perform simulations and physics/detector studies…



FCC analysis software

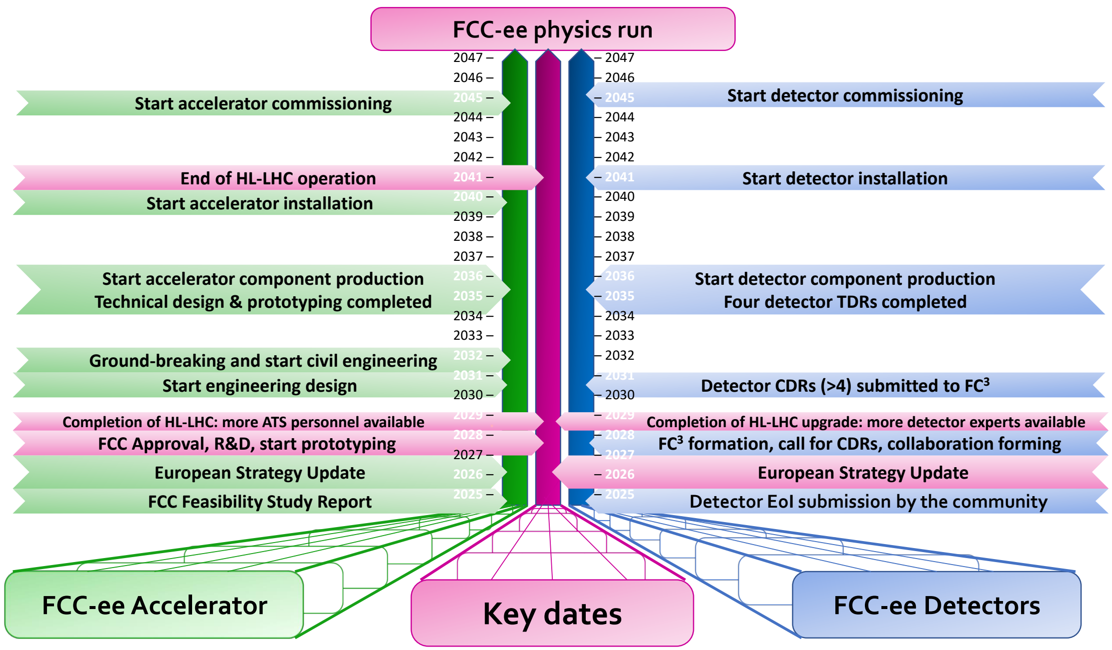
https://key4hep.github.io/key4hep-doc/

- Integrated in the Key4Hep ecosystem which also provides a common EDM for future collider studies.
- Central MC samples produced (in EDM4HEP format) to facilitate physics/detector studies.
- FCC Analysis software developed to analyse EDM4HEP files and support sensitivity/detector development studies.



Conclusions/outlook

- Mid-term review of FCC feasibility study being completed, with key milestones including ring placement.
- Lots of progress in defining accelerator layout + optics, studying detector concepts and physics sensitivity- with significant updates coming in the coming years.

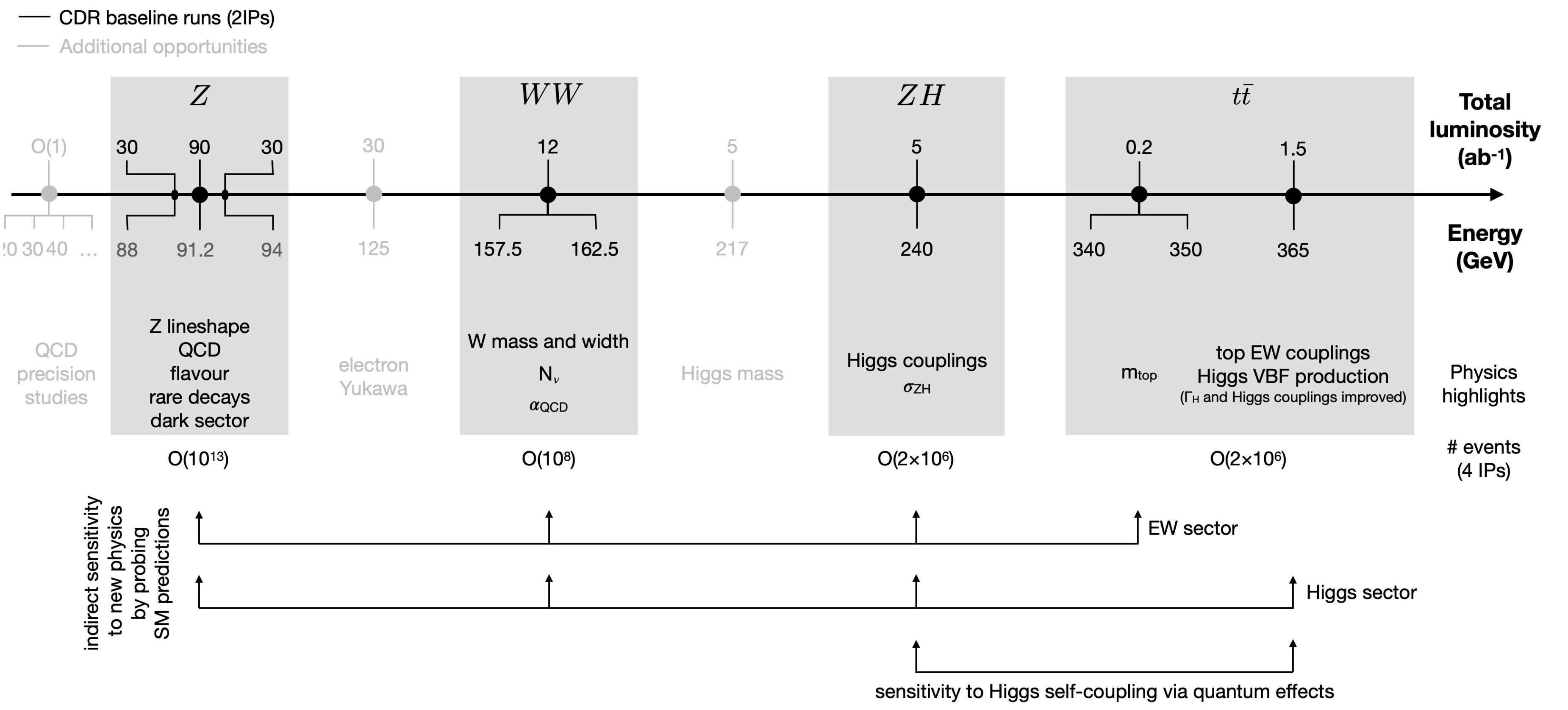


Thanks for listening- I am happy to take questions!

Backup

FCC-ee physics runs ordered by energy

Image credit: Christophe Grojean



FCC-ee updated operation schedule- 4 IPs

Updated for mid-term review 2023

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW $\rightarrow$ H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW $\rightarrow$ H	

CEPC Operation mode		ZH	Z	W^+W^-	ttbar
		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	***L* / IP [$\times 10^{34}$ cm^{-2}s^{-1}]**	3	32	10	-
	[ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	**1×10^{6}**	**7×10^{11}**	**2×10^{7}**	-
Run time [years]		10	2	1	5
Latest (50MW)	***L* / IP [$\times 10^{34}$ cm^{-2}s^{-1}]**	8.3	192	27	0.83
	[ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	**4×10^{6}**	**4×10^{12}**	**5×10^{7}**	**5×10^{5}**

Based on upgraded operation mode with 50MW power, more comparable with FCC-ee (more details in slides by João Guimarães da Costa in 2022 CEPC workshop).

Further details of integrated FCC programme

Taken from slides by F. Gianotti at FCC week.

	$\sqrt{s}$	L /IP ($cm^{-2}\,s^{-1}$)		Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top			2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV		20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

Higgs coupling measurements

Taken from briefing book for 2020 ESU- improvements on Higgs coupling measurements in "kappa" framework:

- Red= linear e+e- collider colliders.
- Blue= circular e+e- machines.
- Orange= integrated FCC programme.