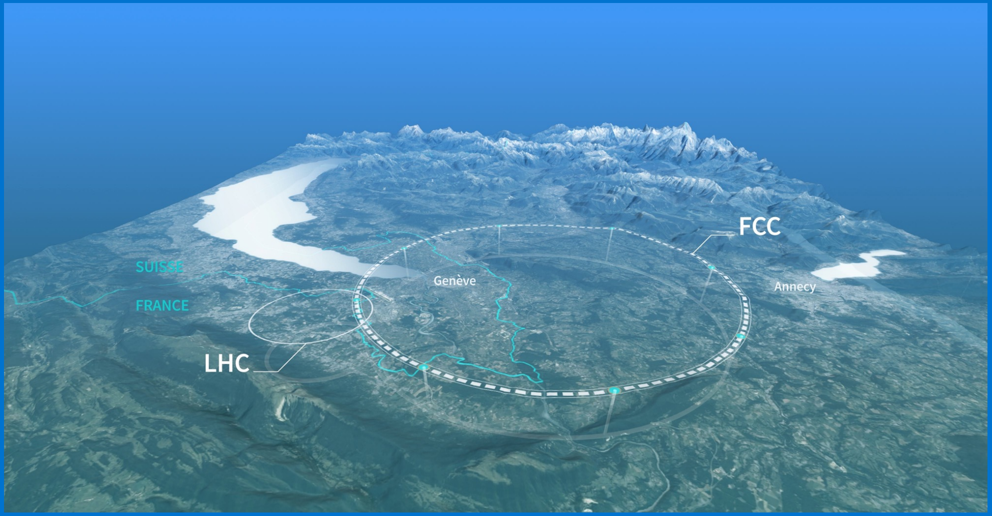
The Future Circular Collider as a Higgs/top/EW Factory: Status and plans for FCC-ee



Dr Sarah Williams, University of Cambridge

Introduction

- Thank you for inviting me to speak today- its great to be here.
- In the next ~ 45 minutes I'll aim to:

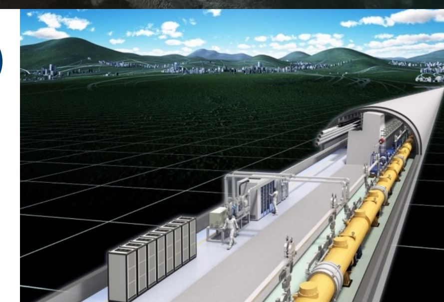
1. Convince you of the **importance** of thinking about future colliders now.
2. Provide an overview of **the Future Circular Collider** (FCC) integrated project.
3. Discuss the **opportunities** and **challenges** associated with the first stage of this project- the lepton collider.

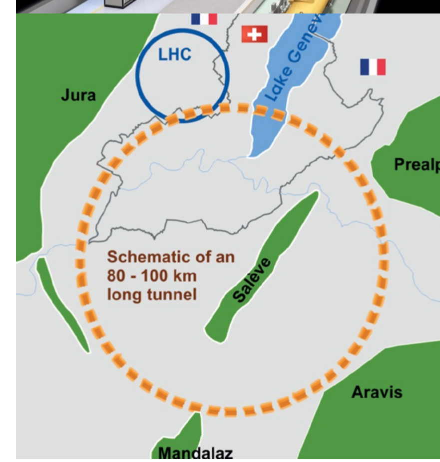
What should come after the HL-LHC?

In the aftermath of the Higgs discovery, lots of discussion on what machine should follow the LHC…

What should come after the LHC?

- e^+e^- machine?
  - Linear collider?
    - **CLIC** (CERN?)
    - **ILC** (Japan?)
  - Circular collider?
    - **CepC** (China)
    - **FCC-ee/hh** (CERN)
- Hadron collider?
  - **FCC-ee/hh** (CERN)
- Muon collider?





How might Europe fit into the global context?

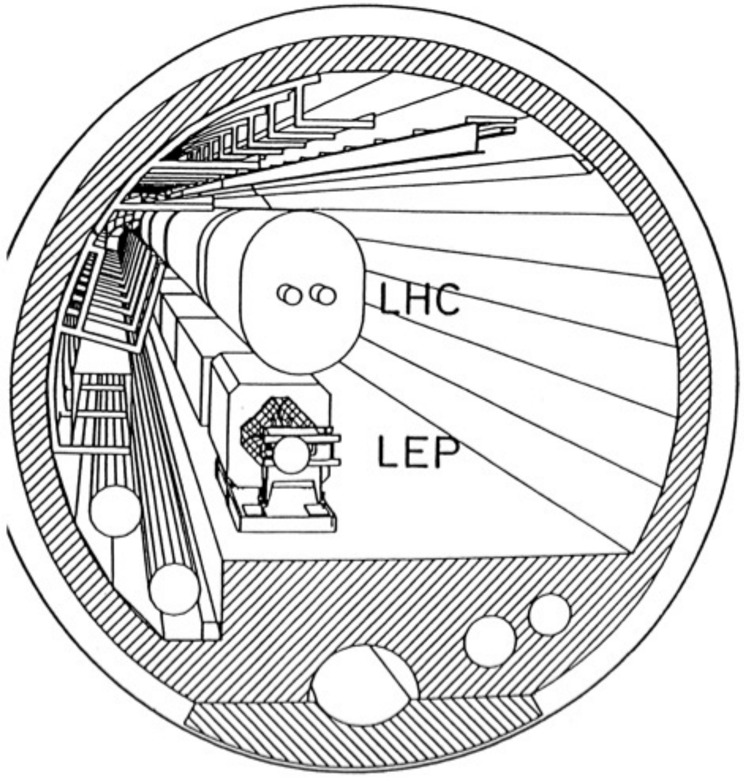
Timescales in particle physics

…are long…

1984: LHC proposed
1995: LHC approved
2012: Higgs discovery

ECFA-84-085-V-2

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

11. SUMMARY AND CONCLUSIONS

A theoretical consensus is emerging that new phenomena will be discovered at or below 1 TeV. There is no consensus about the nature of these phenomena but it is interesting that many of the ideas which have been suggested can be tested in experiments at an LHC. Although many, if not all, of these ideas will doubtless have been discarded, disproved or established by the time an LHC is built, this demonstrates the potential virtues of such a machine.

22 years later in 2006…

The European strategy for particle physics

Particle physics stands on the threshold of a new and exciting era of discovery. The next generation of experiments will explore new domains and probe the deep structure of space-time. They will measure the properties of the elementary constituents of matter and their interactions with unprecedented accuracy, and they will uncover new phenomena such as the Higgs boson or new forms of matter. Long-standing puzzles such as the origin of mass, the matter-antimatter asymmetry of the Universe and the mysterious dark matter and energy that permeate the cosmos will soon benefit from the insights that new measurements will bring. Together, the results will have a profound impact on the way we see our Universe; *European particle physics should thoroughly exploit its current exciting and diverse research programme. It should position itself to stand ready to address the challenges that will emerge from exploration of the new frontier, and it should participate fully in an increasingly global adventure.*

http://council-strategygroup.web.cern.ch/council-strategygroup/

To put this in context...?

1984

My parents

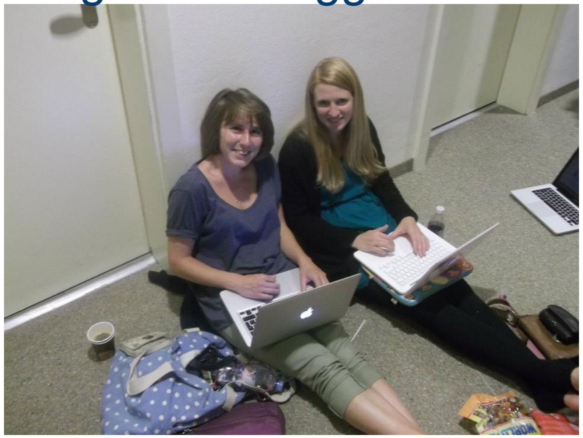
I have only been involved in a small part of the LHC journey…

1995

SW- aged 7

2012

Queuing for the Higgs seminar



The 2020 European Strategy Update

Following ~ 2 years of conensus 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

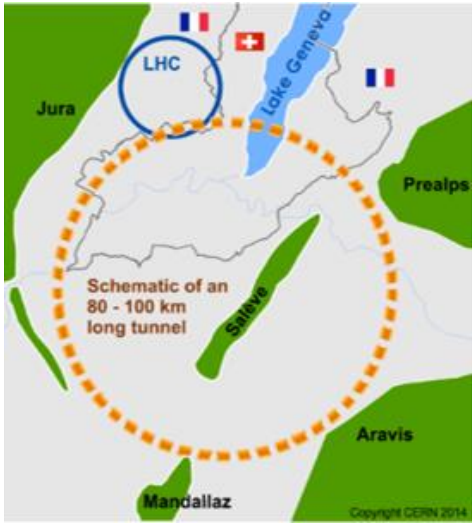
2. Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage

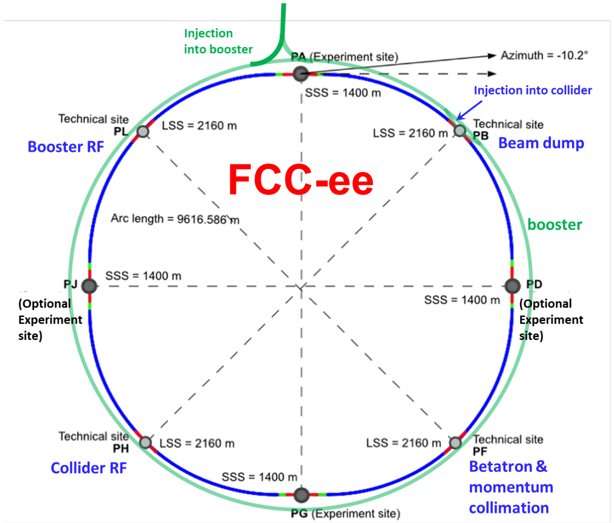
Following the 2020 ESU, the FCC feasibility study was launched in 2021, aiming to provide input by 2025 to feed into the next ESU…

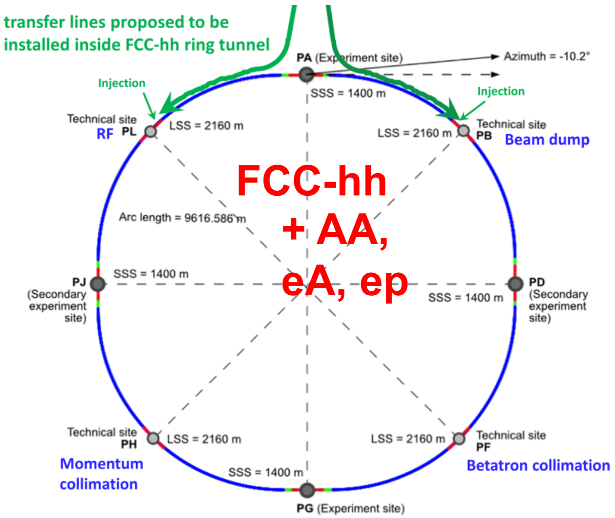
Integrated FCC programme

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 (FCC-eh).







2020 - 2040 | 2045 - 2063 | 2070 - 2095

Integrated FCC programme

Taken from slides by F. Gianotti at FCC week.

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182×10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	$5\text{-}30 \times 10^{34}$ 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3×10^{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

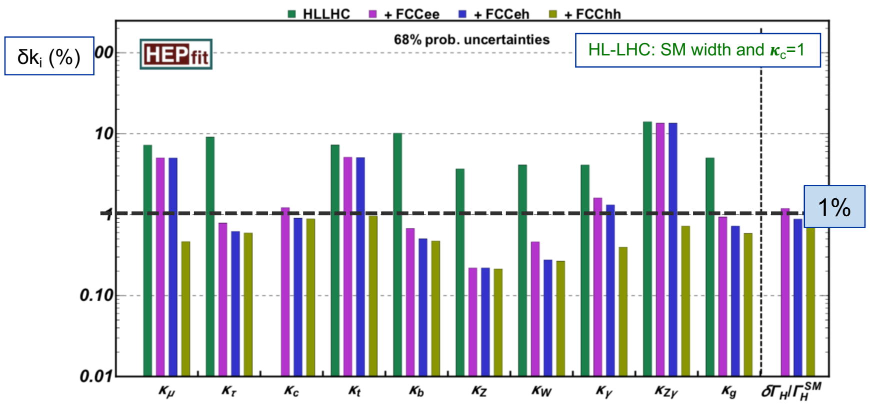
FCC-eh:
- Energy-frontier ep collisions provide ultimate super-microscope to fully resolve hadron structure and empower physics potential of hadron colliders.
- Very precise measurements of Higgs/top and EW parameters in synergy with ee and hh

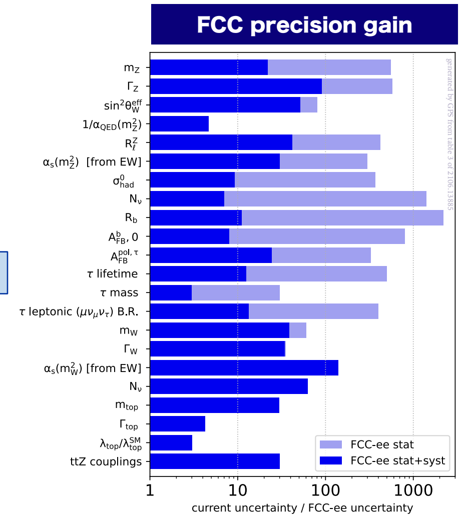
FCC-ee:
- Ultra-precise measurements of EW/ Higgs + top sectors of SM -> indirect sensitivity to BSM.
- Unique flavour opportunities
- Direct sensitivity to feebly interacting particles (LLPs)

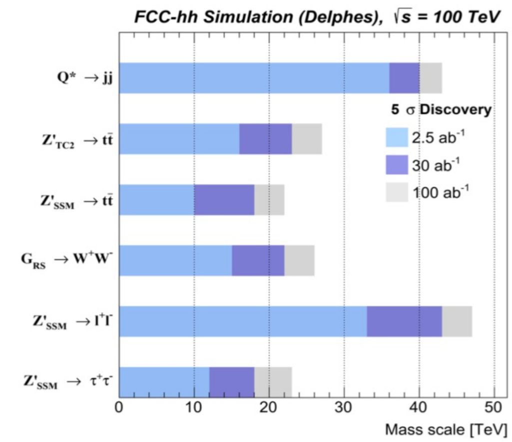
FCC-hh:
- High-statistics for rare Higgs decays and 5% measurement of Higgs self interaction.
- Unprecedented direct sensitivity to BSM.

Synergies in FCC programme –BSM

https://fcc-cdr.web.cern.ch/





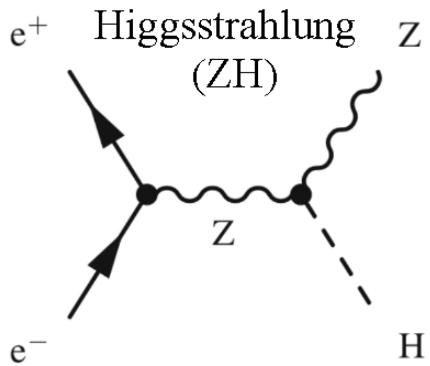


- Order of magnitude improvement in Higgs couplings.
- Factor of 10-50 improvement in EW precision observables at FCC-ee (indirect sensitivity up to ~ 70 TeV)
- Direct sensitivity up to ~ 50 TeV at FCC-hh (and access to Higg self coupling).

FCC-ee and -hh synergies - Higgs measurements

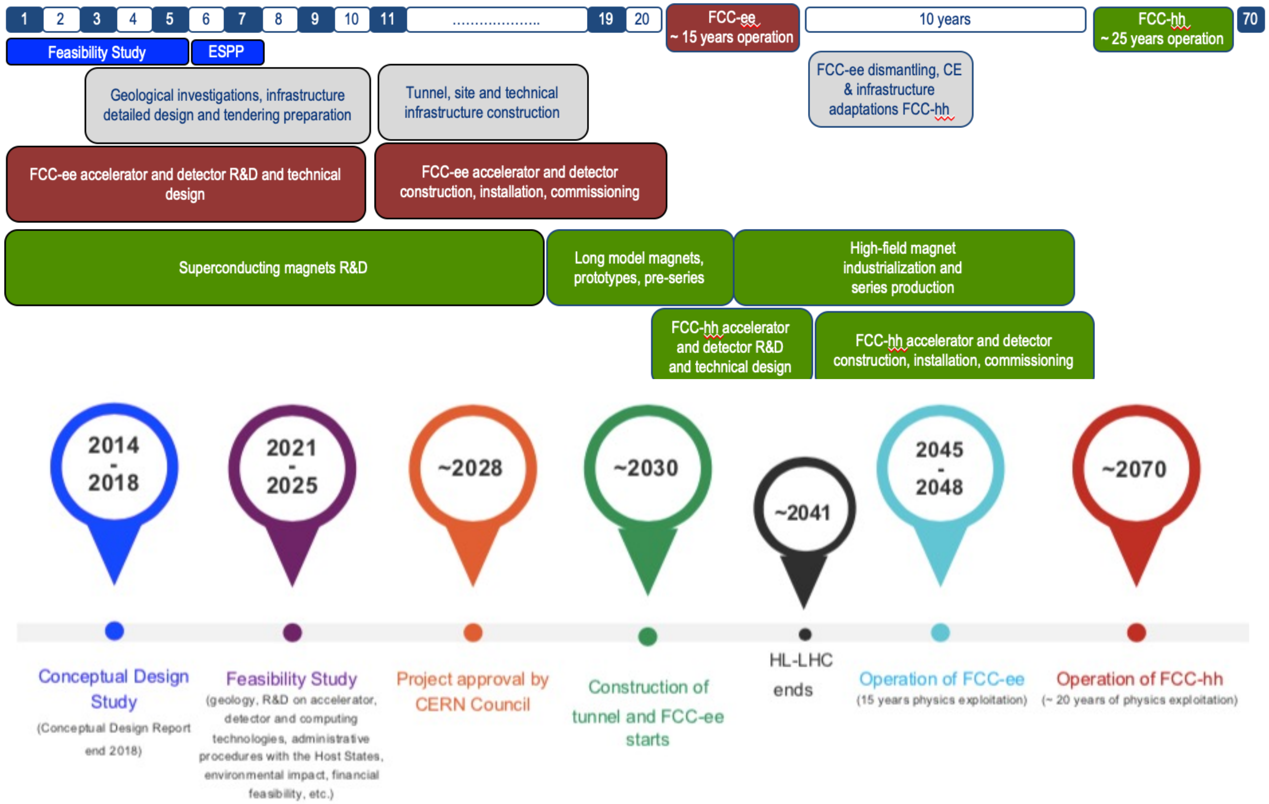
https://fcc-cdr.web.cern.ch/

- 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 timelines

Taken from slides by F. Gianotti at FCC week.



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

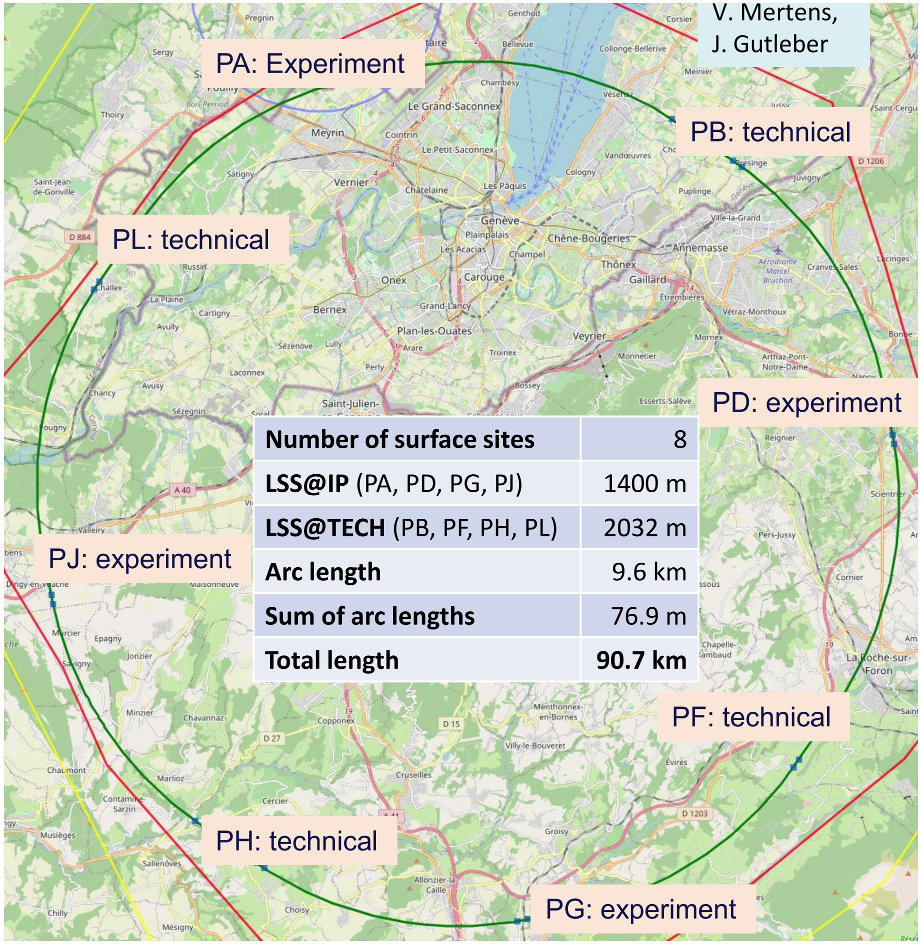
More **realistic schedule**, accounting for past experience of building colliders, approval timelines, HL-LHC operation…

Obvious comment: long timescales mean that ECR engagement is key- thanks to those who attended the ECR-organized town-hall meeting in Birmingham earlier this year!..

Status of FCC feasibility study: mid-term review

For more details see slides by S. Williams at CEPC workshop.

- Mid-term review just completed (approval by council soon).
- Key updates:
  - Choice of ring placement and 4 IPs (higher statistics).
  - Adaptation of accelerator RF/ optics for new placement (details in backup).
- Significant R+D ongoing to improve energy efficiency (including HTS).



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**

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 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

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→ bb, cc, ss, gg
H→inv
ee→H
H→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..)

$B_c \to \tau\nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau\tau$
$B \to K^* \nu\nu$
$B_s \to \varphi \nu\nu$ …

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

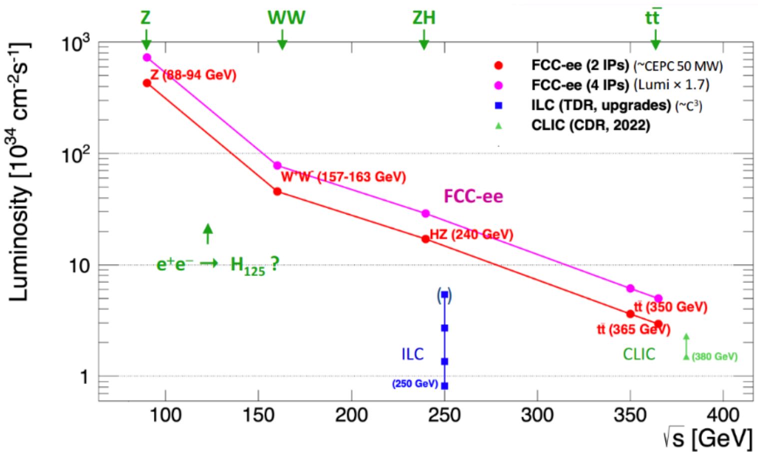
impact parameter resolution for large displacement

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).

Ultimate precision @ FCC-ee

Plot + table taken from slides
by M. Selvaggi at ZPW2024



15 (20?) years of operations

	Z pole	? H pole ?	WW	ZH	ttbar
√s [GeV]	88 - 91 - 94	125	157 - 161	240	350 - 365
Lumi / IP [10^{34} cm^2 s^{-1}]	182	80	19.4	7.3	1.33
Int. lumi / 4IP [ab^{-1} / yr]	87	38	9.3	3.5	0.65
N_{years}	**4**	**5**	**2**	**3**	**5**
N_{events}	8 Tera	8 K	300 M	2 M	2 M

- Unprecedented luminosity at multiple centre of mass energies will enable ultra-precise measurements of Higgs (and EW and top) sectors of the SM…
- Rather than listing them… I thought we would play a game…

FCC-ee numbers game

Put these numbers in ascending order (and guess if you can/ want to…?)

1. # Z bosons/hour at FCC-ee (Z-pole)
2. # Higgs bosons/day at FCC-ee (Zh pole)
3. # W bosons/hour at FCC-ee (WW threshold)
4. # Z bosons produced at LEP
5. # Crème eggs produced by Birmingham Cadbury's factory per day
6. # W mass candidates in 2023 7 TeV ATLAS W-mass re-analysis.
7. # Higgs bosons produced by the LHC in 2017.

Can you guess what the prize is?

FCC-ee numbers game

Put these numbers in ascending order (and guess if you can/ want to…?)

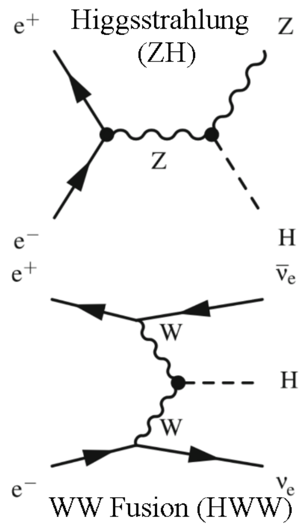
1. # Z bosons/hour at FCC-ee (Z-pole) => 360 million (7)
2. # Higgs bosons/day at FCC-ee (Zh pole) => 2000 (1)
3. # W bosons/hour at FCC-ee (WW threshold) => ~ 10,000 (2)
4. # Z bosons produced at LEP => 18 million (6)
5. # Crème eggs produced by Birmingham Cadbury's factory per day => 1.5 million (3)
6. # W mass candidates in 2023 7 TeV ATLAS W-mass re-analysis => 14 million (5)
7. # Higgs bosons produced by the LHC in 2017 => 3 million (4)

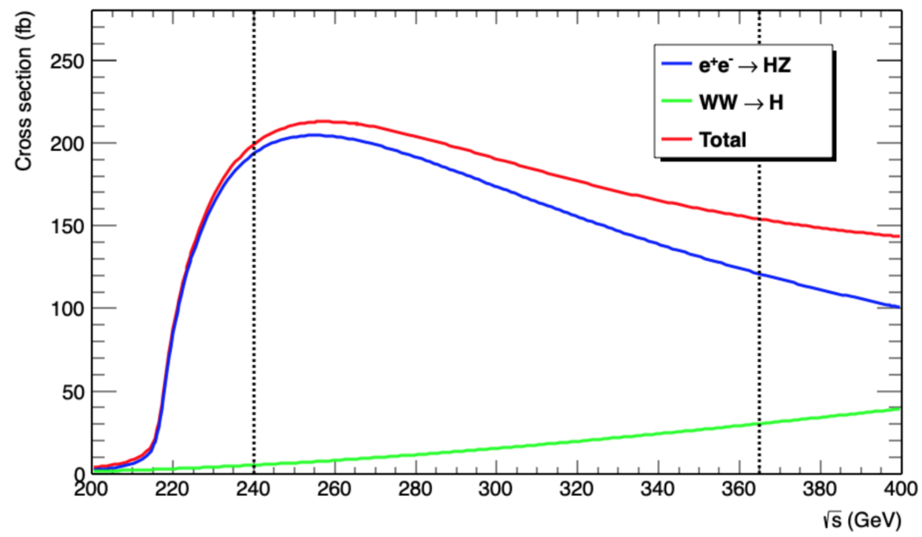
Higgs physics @ FCC-ee

Plots taken from vol. 1 of FCC CDR: https://fcc-cdr.web.cern.ch/

> 1 million ZH events

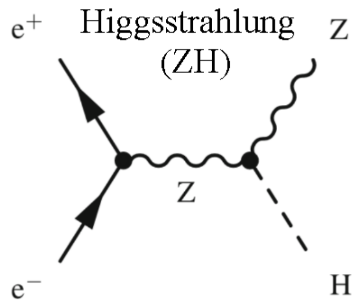
~ 100,000 WW fusion



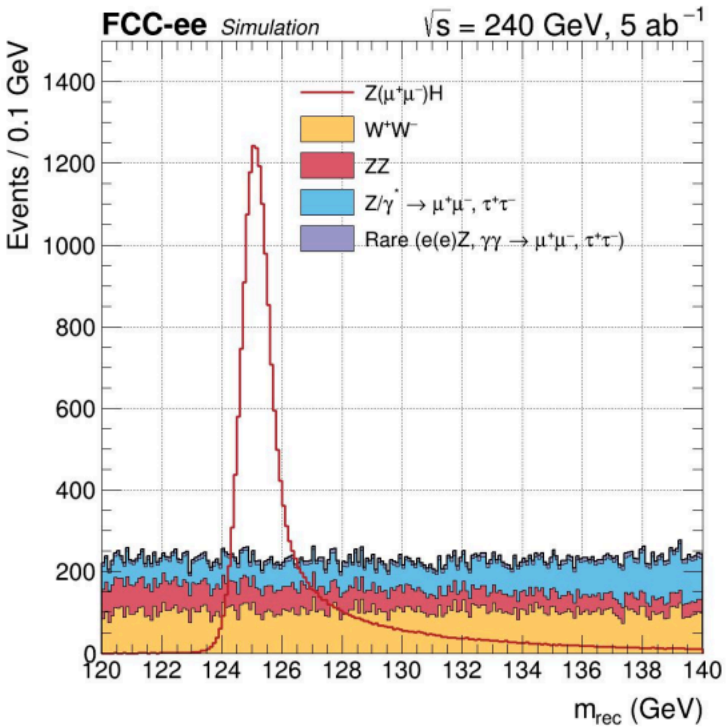


- Large rates, clean experimental environment (no UE, Pileup, triggerless) with no QCD background will open up a new era of Higgs precision physics.
- Opportunities to remove model-dependence from measurements and reach sub-percent level for post couplings.

FCC-ee recoil method



- Precise C.O.M knowledge enables:
  - Z to be tagged (through leptons).
  - Construct recoil mass associated with Higgs $m^2_{\text{recoil}} = s - 2\sqrt{s}E_{ll} + m^2_{ll}$
  - Event counting gives precise Zh production cross-section measurement.
    - Absolute + model independent measurement of g_Z coupling.



EWK precision @ FCC-ee

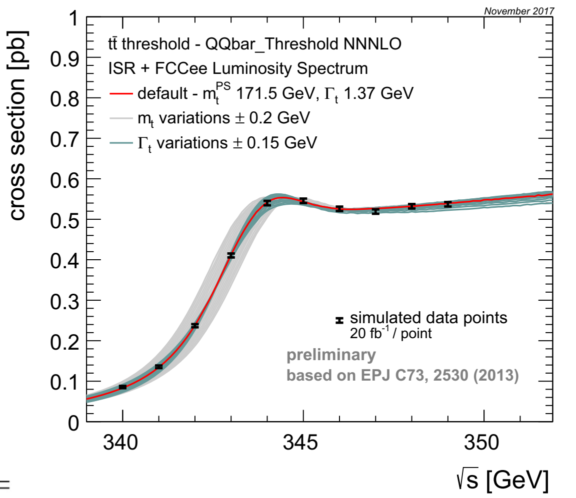
See slides by Christoph Paus at ZPW2024

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \rightarrow \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, …)

Challenges (and opportunities) in theory and on the experimental side (energy calibration/luminosity measurement) to reach ultimate precision…

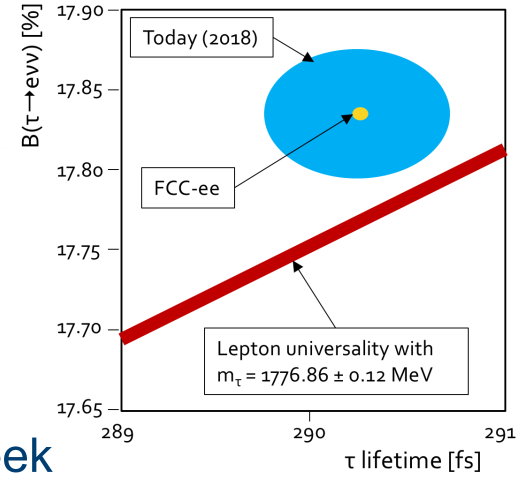
Top and flavour @ FCC-ee

- $t\bar{t}$ threshold scan will enable most precise measurements of top-quark mass and width.



- Tera-Z run offers unprecedented flavour opportunities- 10x more bb/cc pairs than final Belle-II statistics.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150



- Exciting physics potential with boosted b/τ, and opportunities to probe LFV/LFU in τ decays.

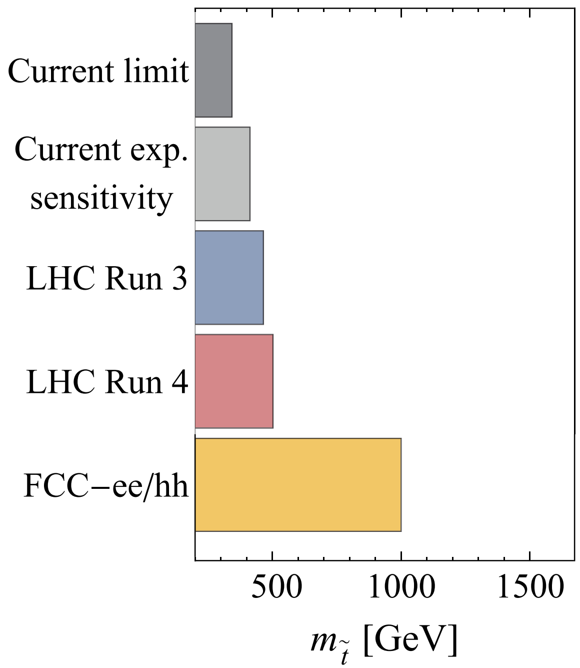
For flavour, see slides by Jernej. F. Kamenik at London FCC week

BSM @ FCC-ee - a snapshot

Taken from FCC Snowmass submission

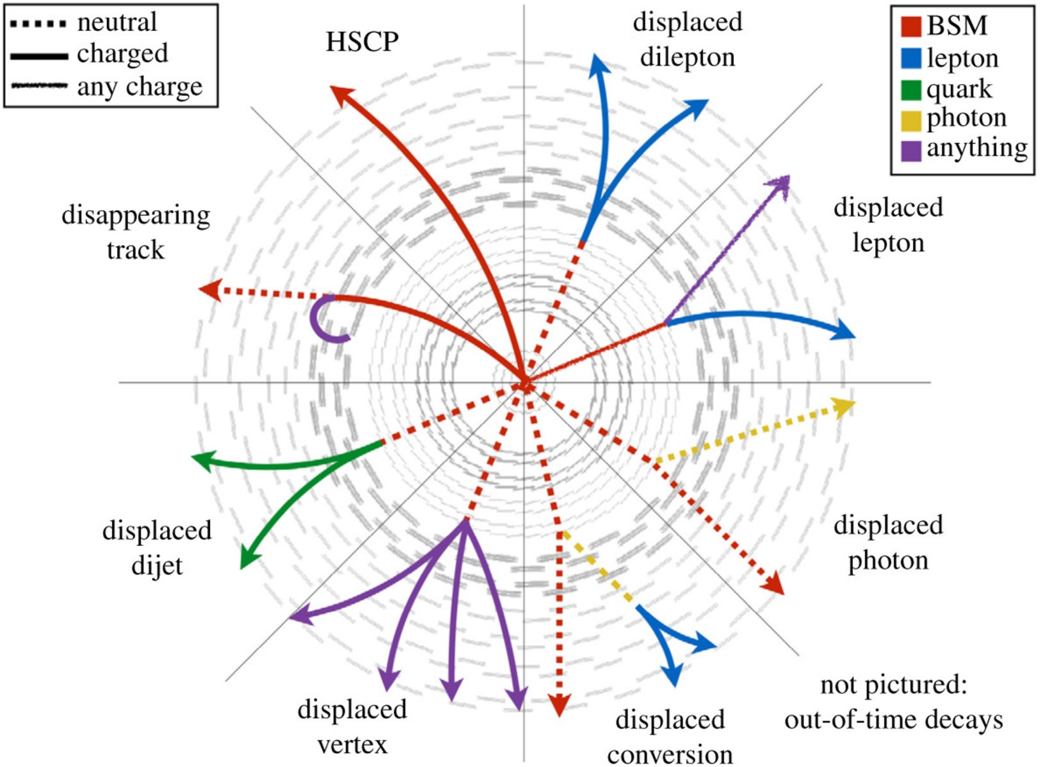
1. Indirectly discover new particles coupling to the Higgs or EW bosons up to scales of $\Lambda \approx 7$ and 50 TeV.
2. Perform tests of SUSY at the loop level in regions not accessible at the LHC.
3. Study heavy flavour/tau physics in rare decays inaccessible at the LHC.
4. Perform searches with best collider sensitivity to dark matter, sterile neutrinos and ALPs up to masses $\approx$ 90 GeV.

Image credit: FCC CDR



Projected 2σ indirect reach from Higgs couplings on stops.

FCC-ee case study: LLPs



LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

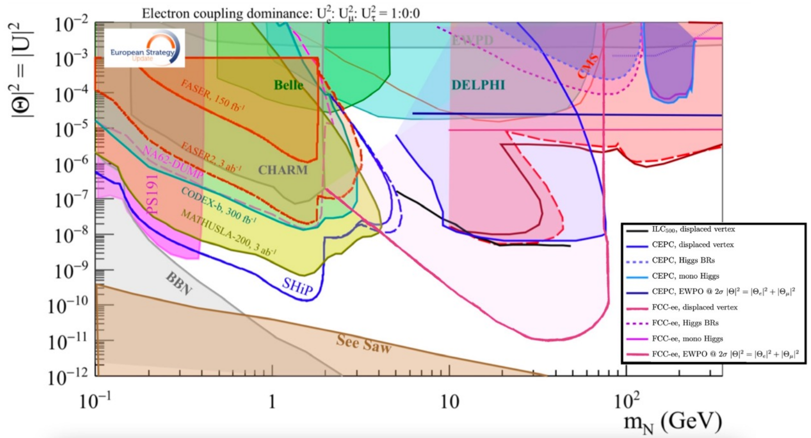
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

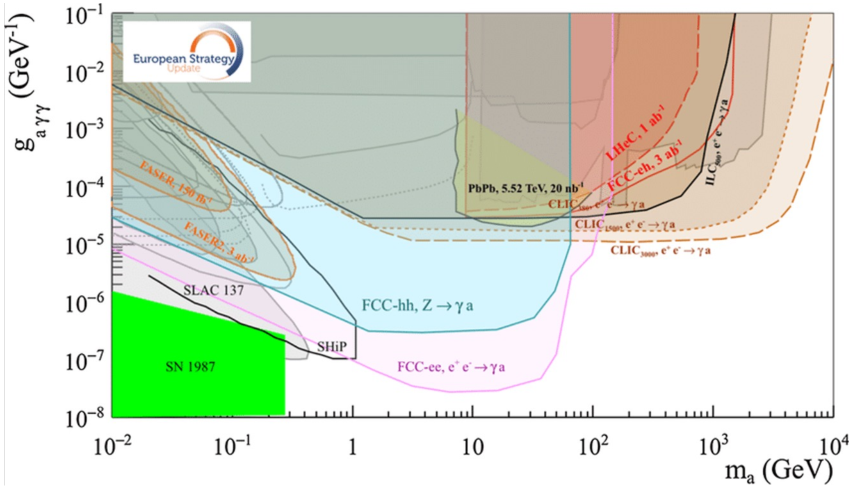
The range of unconventional signatures and rich phenomenology means that understanding the impact of detector design/performance on the sensitivity of future experiments is key!

LLPs @ FCC-ee

Interested? There are more details in the backup …

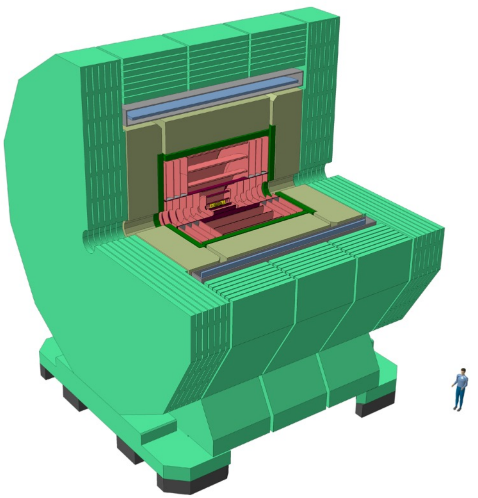
- Targeting precision measurements of EWK/Higgs/top sector of SM.
- Unique sensitivity to LLPs coupling to Z or Higgs.
  - No trigger requirements.
  - Excellent vertex reconstruction and impact parameter resolution can target low LLP lifetimes (this can drive hardware choices).
  - **Projections often assume background-free searches** (should check these assumptions).





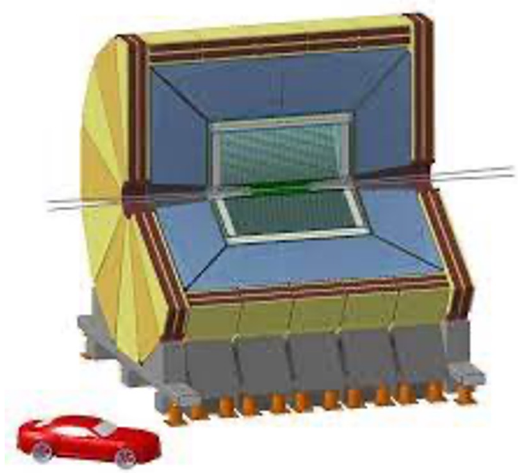
Detector concepts for FCC-ee

CLD ("CLIC-like Detector")



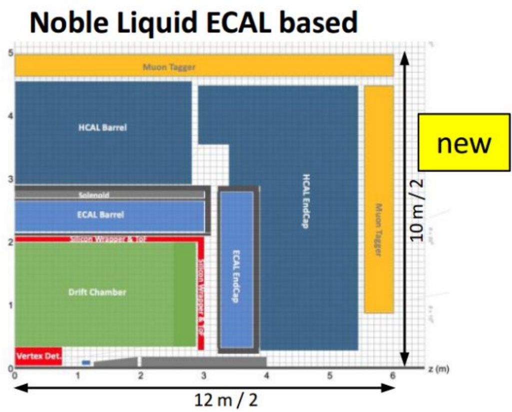
Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

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



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

…Plus new proposals …



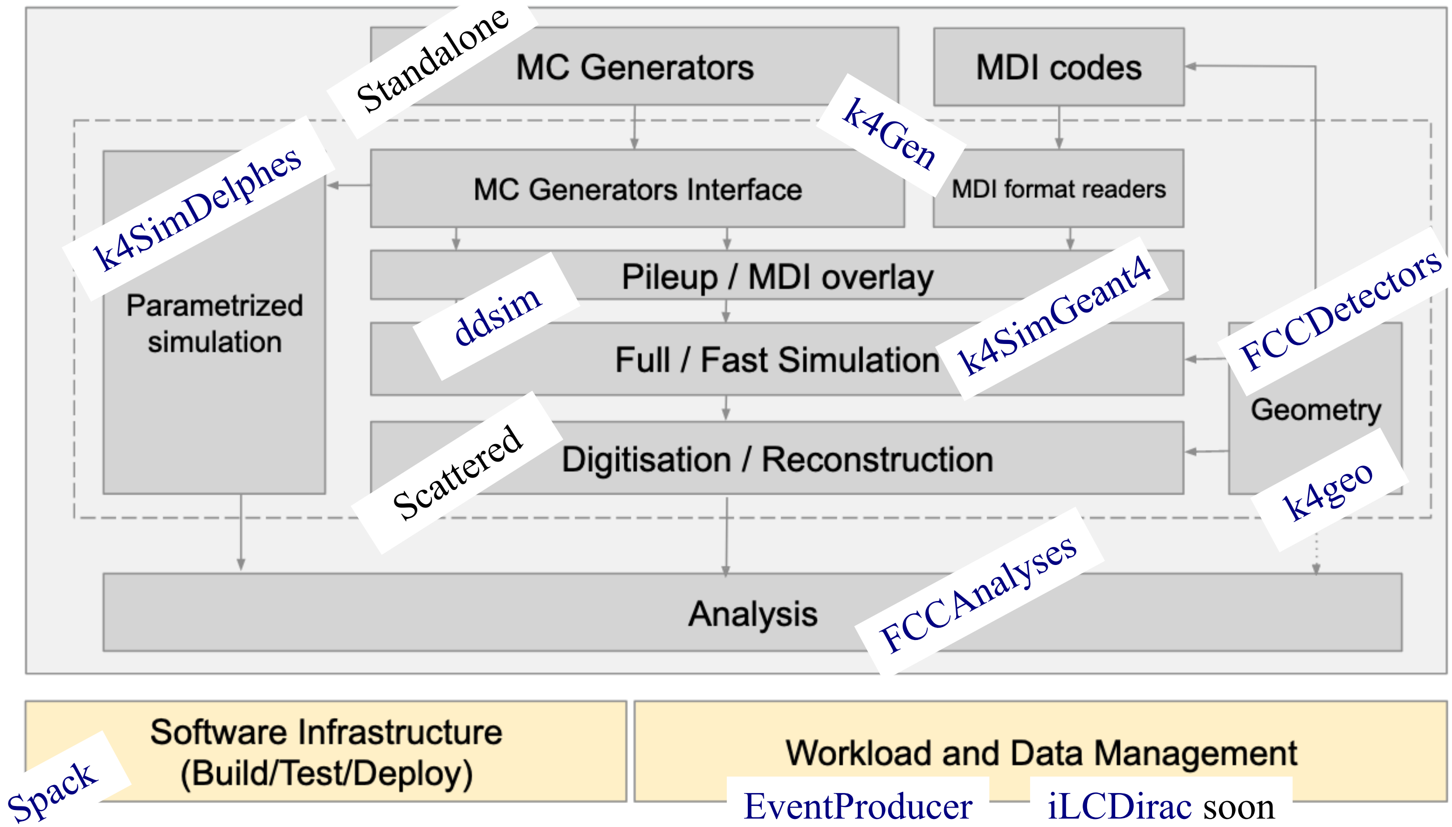
New proposal using liquid LAr calorimeter!

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

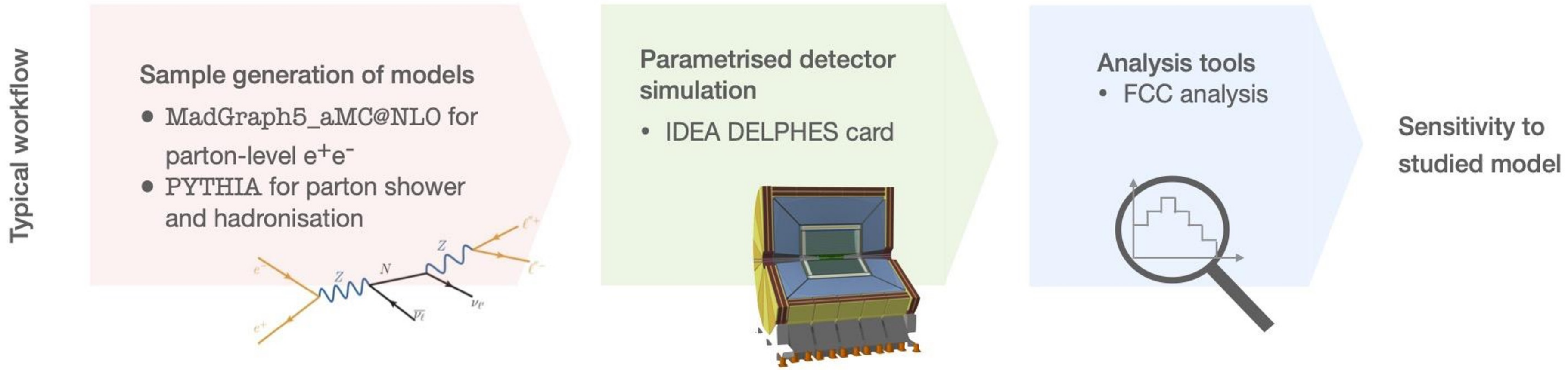
Sophisticated software ecosystem in place to perform simulations and physics/detector studies…



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.

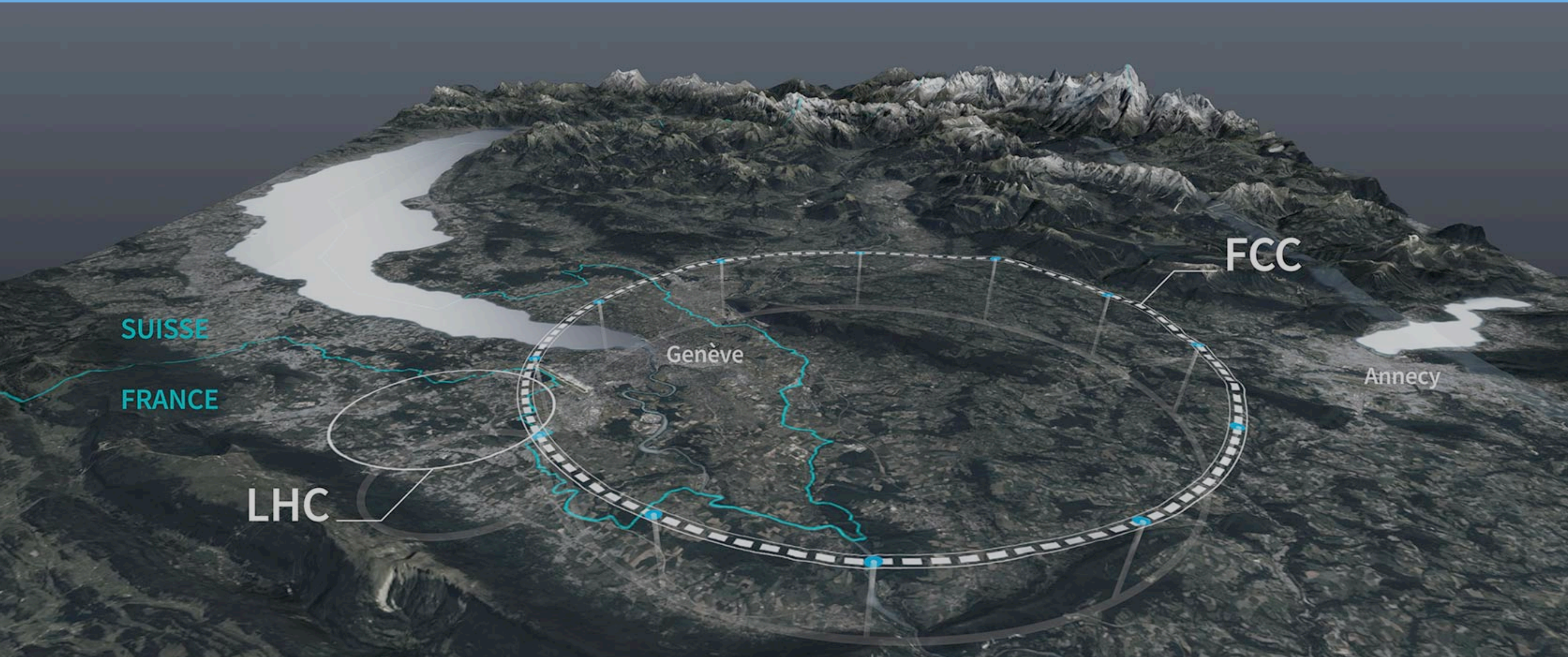


Conclusion + outlook

1. Why think about future colliders now?

- To avoid a significant gap in data-taking after the High-Luminosity LHC key decisions need to be taken in the coming years.
- Knowledge transfer to those that will deliver the project (i.e. ECRs) cannot wait.
- We are resource limited (including person power)- making the HL-LHC must be our top priority, so making a future collider reality in parallel will require…
  - Consensus in the community.
  - Strategic planning and collaboration

2. The integrated FCC project…



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!

3. Opportunities and challenges associated with FCC-ee

Paradigm shift in precision/sensitivity to

- EWK+ QCD
- Higgs
- Flavour
- BSM

(… in combination with FCC-eh/hh)

Subject to overcoming…

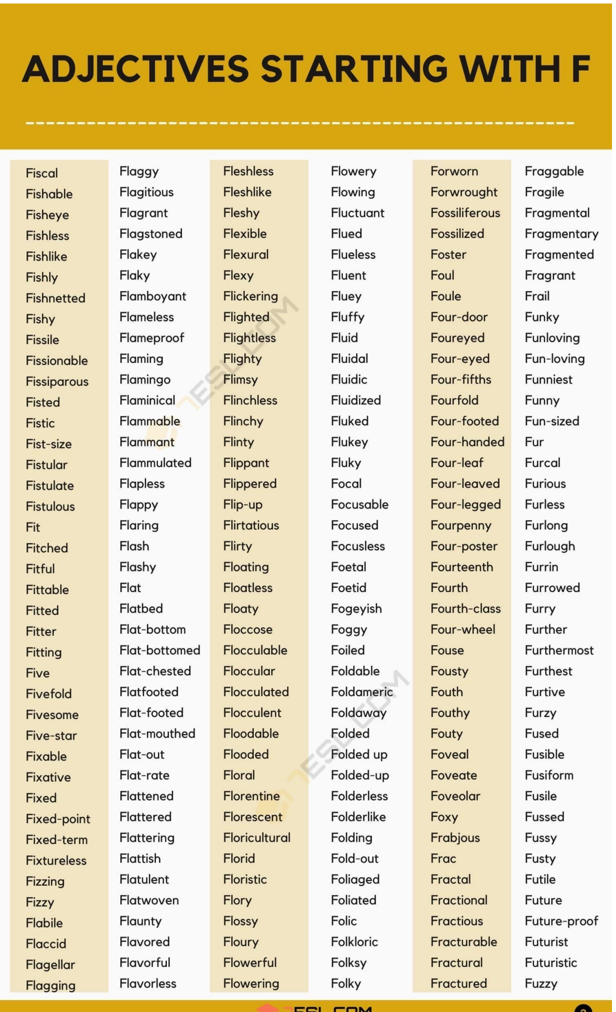
Suite of challenges we need to overcome to get there:

- Theory
- Technological (detector development+ design, accelerators, computing).
- Sociological.
- Political.

In my opinion- this is achievable and definitely worth it…

What’s in a name?

FUTURE CIRCULAR COLLIDER



ADJECTIVES STARTING WITH F

Fiscal	Flaggy	Fleshless	Flowery	Forworn	Fraggable
Fishable	Flagitious	Fleshlike	Flowing	Forwrought	Fragile
Fisheye	Flagrant	Fleshy	Fluctuant	Fossiliferous	Fragmental
Fishless	Flagstoned	Flexible	Flued	Fossilized	Fragmentary
Fishlike	Flakey	Flexural	Flueless	Foster	Fragmented
Fishly	Flaky	Flexy	Fluent	Foul	Fragrant
Fishnetted	Flamboyant	Flickering	Fluey	Foule	Frail
Fishy	Flameless	Flighted	Fluffy	Four-door	Funky
Fissile	Flameproof	Flightless	Fluid	Foureyed	Funloving
Fissionable	Flaming	Flighty	Fluidal	Four-eyed	Fun-loving
Fissiparous	Flamingo	Flimsy	Fluidic	Four-fifths	Funniest
Fisted	Flaminical	Flinchless	Fluidized	Fourfold	Funny
Fistic	Flammable	Flinchy	Fluked	Four-footed	Fun-sized
Fist-size	Flammant	Flinty	Flukey	Four-handed	Fur
Fistular	Flammulated	Flippant	Fluky	Four-leaf	Furcal
Fistulate	Flapless	Flippered	Focal	Four-leaved	Furious
Fistulous	Flappy	Flip-up	Focusable	Four-legged	Furless
Fit	Flaring	Flirtatious	Focused	Fourpenny	Furlong
Fitched	Flash	Flirty	Focusless	Four-poster	Furlough
Fitful	Flashy	Floating	Foetal	Fourteenth	Furrin
Fittable	Flat	Floatless	Foetid	Fourth	Furrowed
Fitted	Flatbed	Floaty	Fogeyish	Fourth-class	Furry
Fitter	Flat-bottom	Floccose	Foggy	Four-wheel	Further
Fitting	Flat-bottomed	Flocculable	Foiled	Fouse	Furthermost
Five	Flat-chested	Floccular	Foldable	Fousty	Furthest
Fivefold	Flatfooted	Flocculated	Foldameric	Fouth	Furtive
Fivesome	Flat-footed	Flocculent	Foldaway	Fouthy	Furzy
Five-star	Flat-mouthed	Floodable	Folded	Fouty	Fused
Fixable	Flat-out	Flooded	Folded up	Foveal	Fusible
Fixative	Flat-rate	Floral	Folded-up	Foveate	Fusiform
Fixed	Flattened	Florentine	Folderless	Foveolar	Fusile
Fixed-point	Flattered	Florescent	Folderlike	Foxy	Fussed
Fixed-term	Flattering	Floricultural	Folding	Frabjous	Fussy
Fixtureless	Flattish	Florid	Fold-out	Frac	Fusty
Fizzing	Flatulent	Floristic	Foliaged	Fractal	Futile
Fizzy	Flatwoven	Flory	Foliated	Fractional	Future
Flabile	Flaunty	Flossy	Folic	Fractious	Future-proof
Flaccid	Flavored	Floury	Folkloric	Fracturable	Futurist
Flagellar	Flavorful	Flowerful	Folksy	Fractural	Futuristic
Flagging	Flavorless	Flowering	Folky	Fractured	Fuzzy

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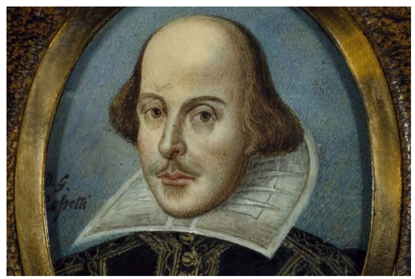
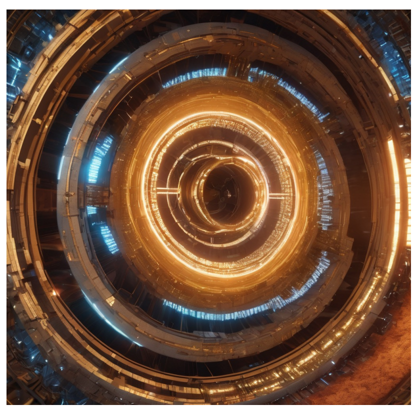
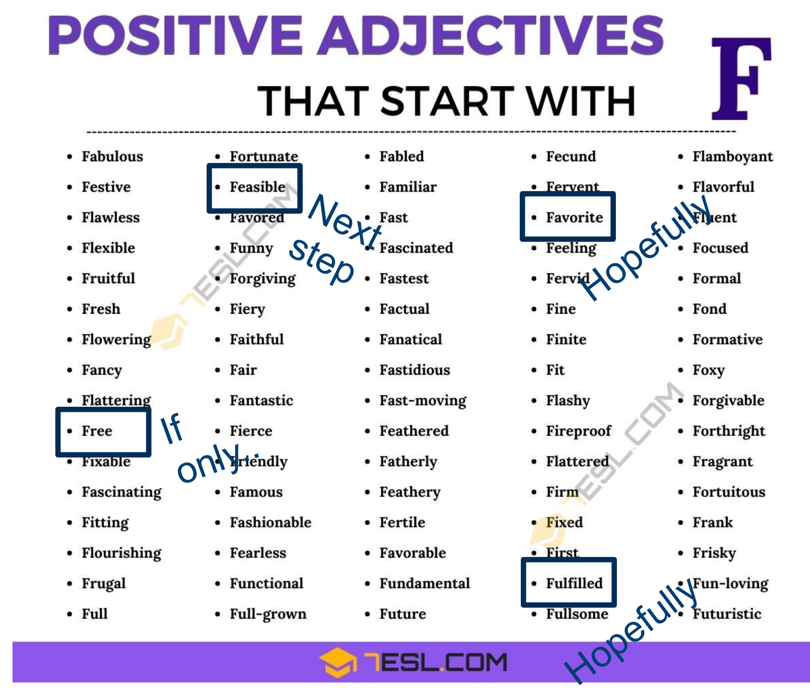
Safer starting point?







POSITIVE ADJECTIVES THAT START WITH F

Fabulous	Fortunate	Fabled	Fecund	Flamboyant
Festive	Feasible	Familiar	Fervent	Flavorful
Flawless	Favored	Fast	Favorite	Fluent
Flexible	Funny	Fascinated	Feeling	Focused
Fruitful	Forgiving	Fastest	Fervid	Formal
Fresh	Fiery	Factual	Fine	Fond
Flowering	Faithful	Fanatical	Finite	Formative
Fancy	Fair	Fastidious	Fit	Foxy
Flattering	Fantastic	Fast-moving	Flashy	Forgivable
Free	Fierce	Feathered	Fireproof	Forthright
Fixable	Friendly	Fatherly	Flattered	Fragrant
Fascinating	Famous	Feathery	Firm	Fortuitous
Fitting	Fashionable	Fertile	Fixed	Frank
Flourishing	Fearless	Favorable	First	Frisky
Frugal	Functional	Fundamental	Fulfilled	Fun-loving
Full	Full-grown	Future	Fullsome	Futuristic

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Next step

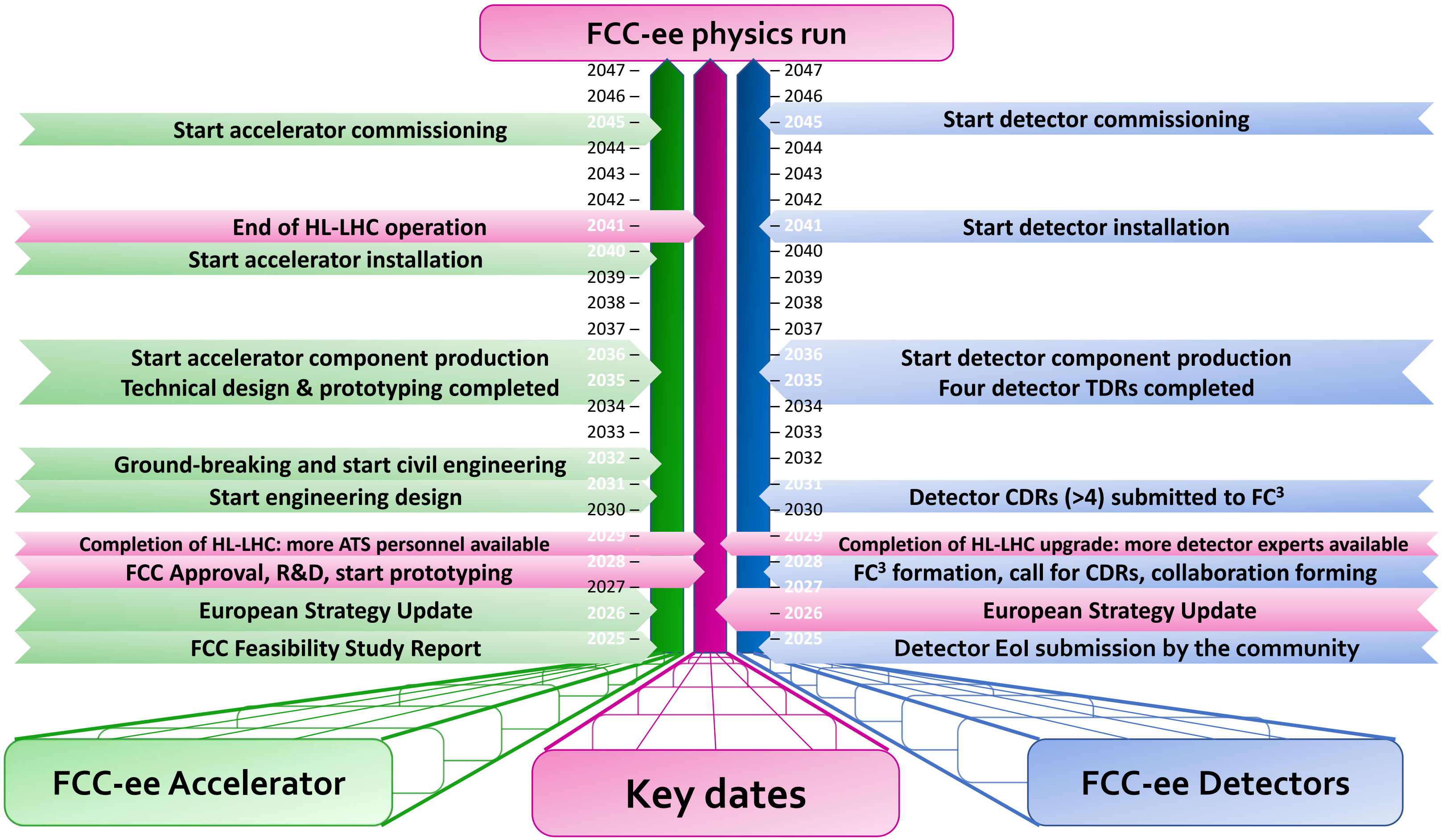
Hopefully

If only

Hopefully

Left: AI generated image of “fuzzy circular collider” (from https://gencraft.com/generate)

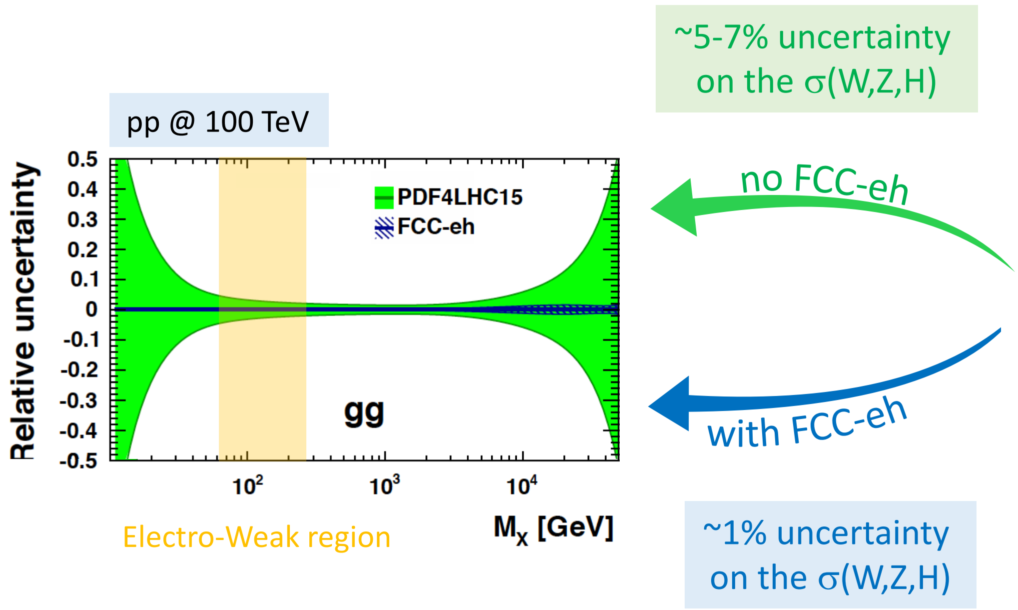
A possible look to the future- thanks for listening!

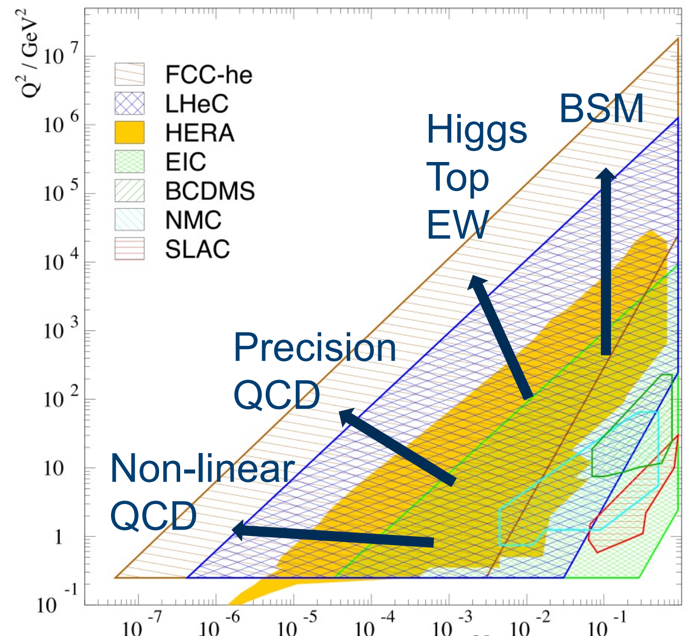


Backup

Synergies in FCC programme- FCC-eh

Taken from slides by J. D"Hondt at FCC week Taken from updated CDR

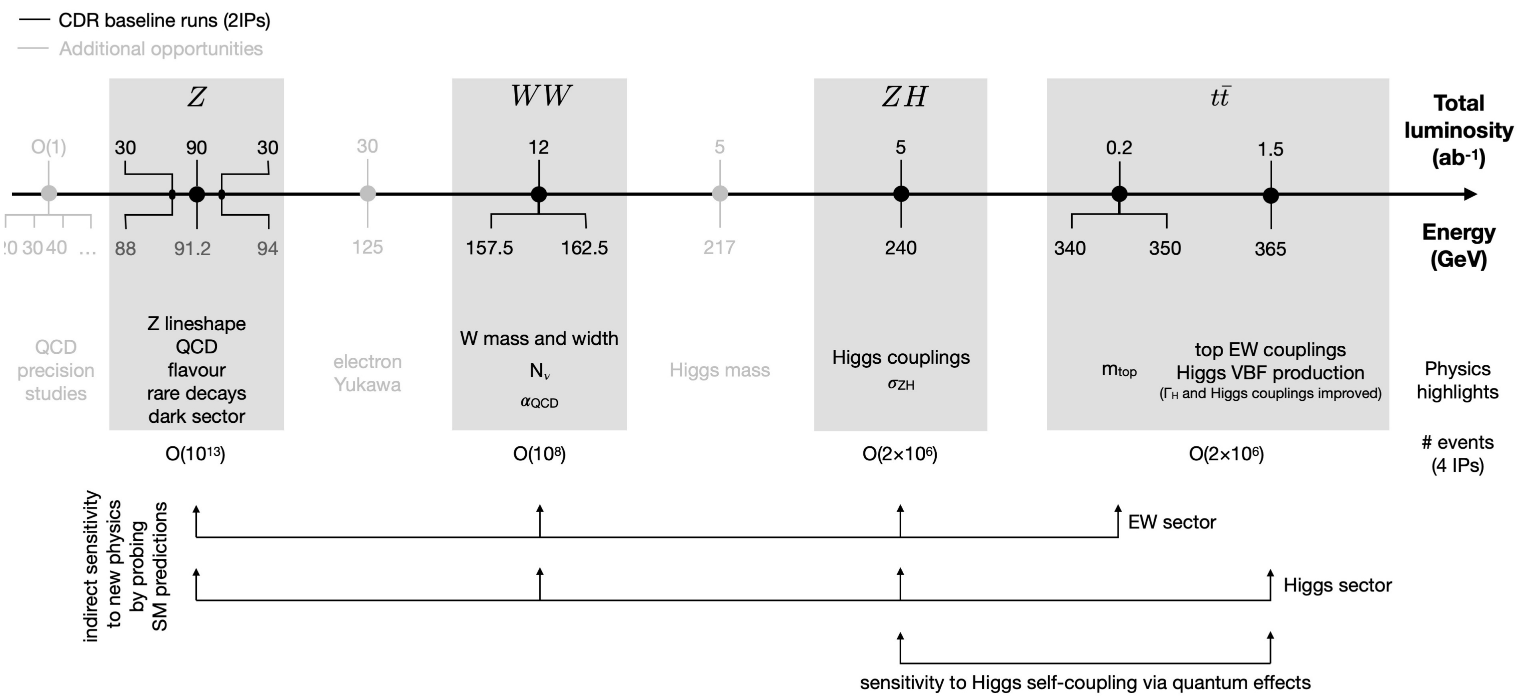




- Empower FCC-hh with precision input on hadron structure and strong coupling (to permille accuracy) during parallel running.
- Complementary measurements of Higgs couplings (CC+NC DIS x-sections, no pile-up, clean)- see slides by U. Klein here
- Plus… complementary BSM prospects (LLPs, LFV, not-too-heavy scalars, GeV-scale bosons)

FCC-ee physics runs ordered by energy

Image credit: Christophe Grojean



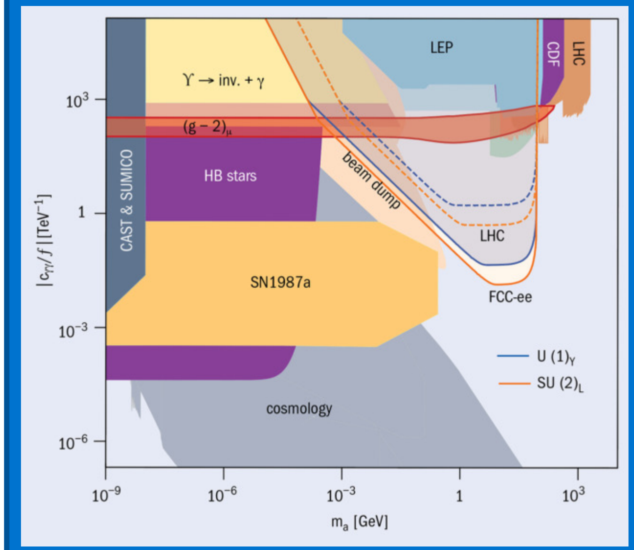
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z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

FCC-ee and -hh synergies - BSM

See slides by G. Salam at FCC week

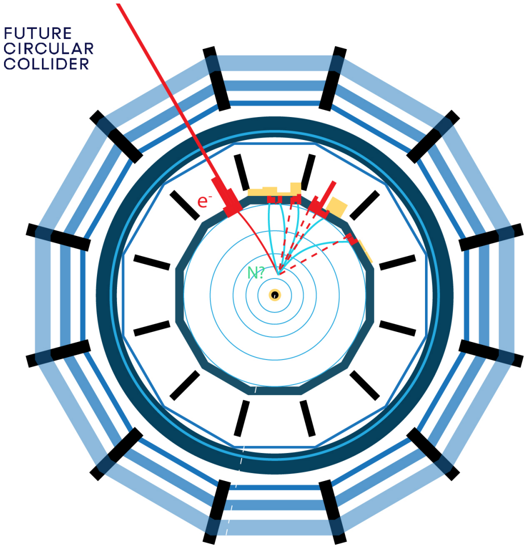
Direct FCC-ee sensitivity

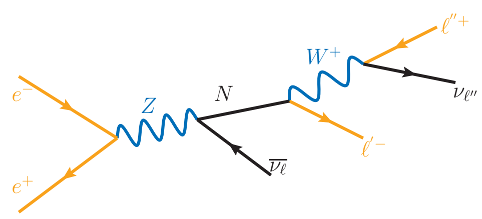
- HNLs
- Alps
- Exotic Higgs decays



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

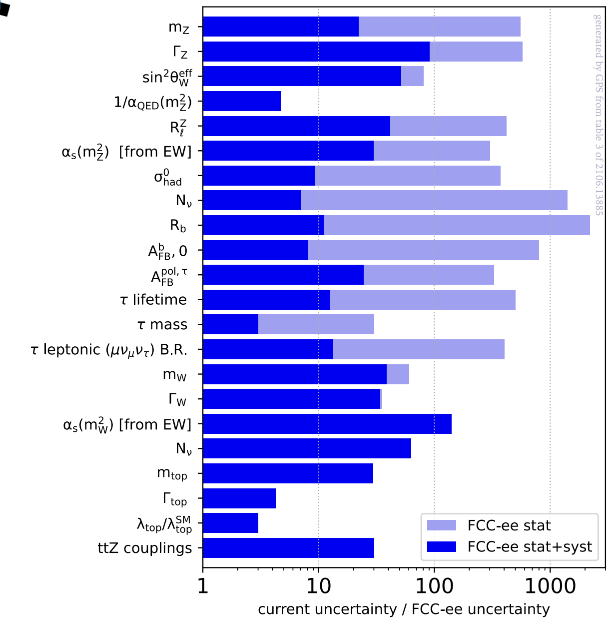
FUTURE CIRCULAR COLLIDER





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

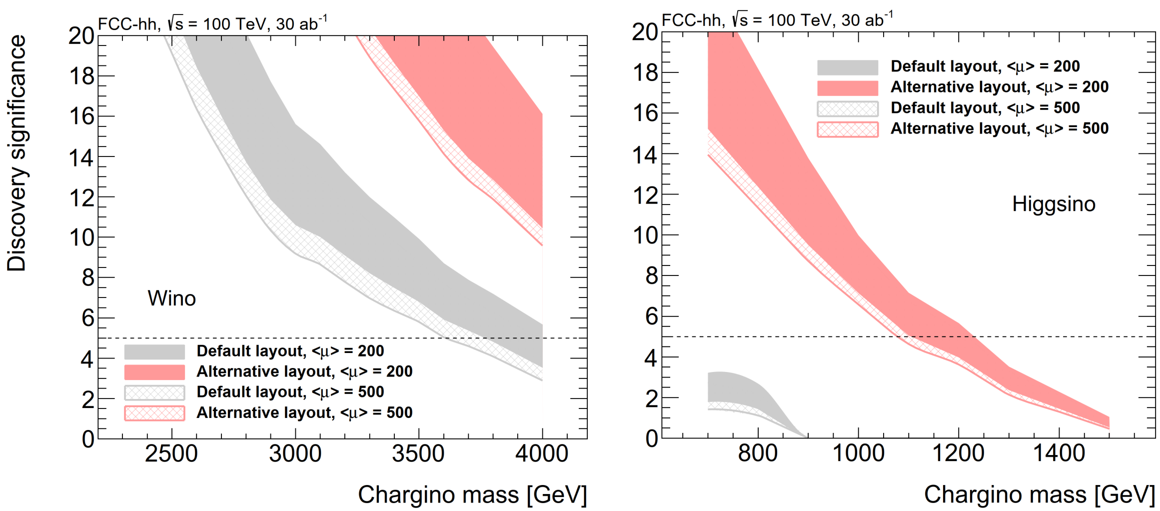
FCC precision gain

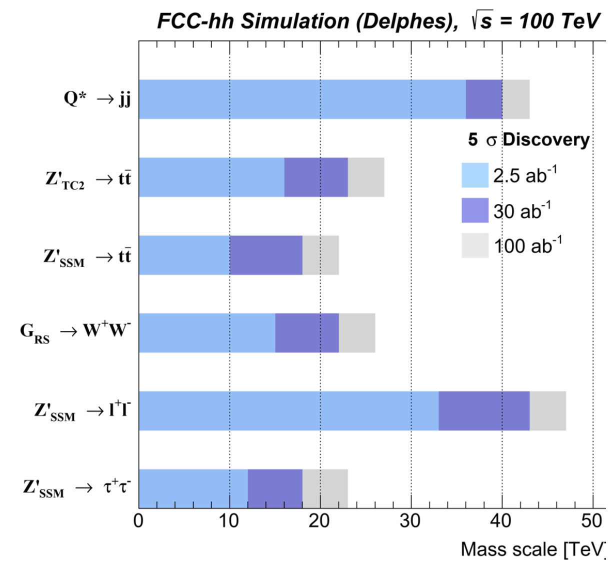


FCC-ee and -hh synergies - BSM searches

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

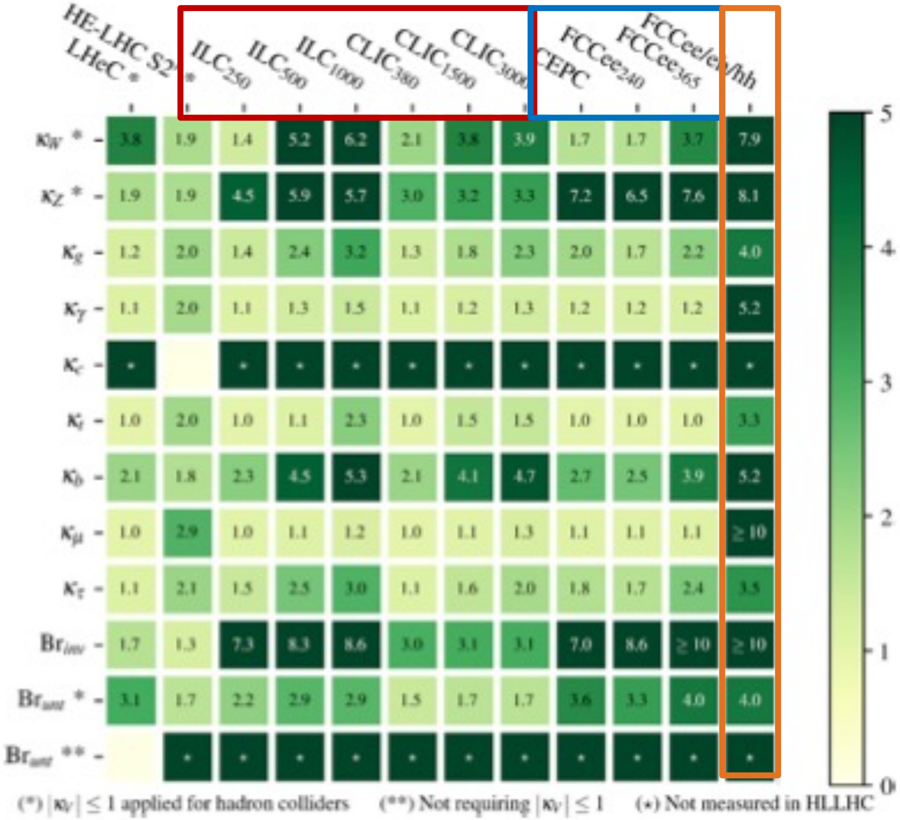
Substantial discovery reach for heavy resonances

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

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.



Costs of future projects

Taken from slides by H. Abramowicz at EPS open symposium 2019

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
CC hh	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
CC ee	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
LC ee	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

A. Yamamoto, 190513b

*Cost estimates are commonly for "Value" (material) only.

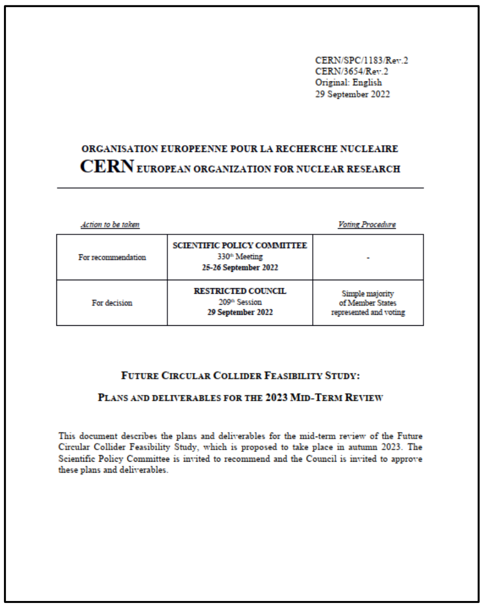
26

FCC costings- planned updates

Taken from slides by M. Benedikt at FCC week

FUTURE CIRCULAR COLLIDER

mid-term cost review – Cost Review Panel (CRP)



CERN/SPC/1183/Rev.2
CERN/3654/Rev.2
Original: English
29 September 2022

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		*Voting Procedure*
For recommendation	**SCIENTIFIC POLICY COMMITTEE** 330th Meeting **25-26 September 2022**	-
For decision	**RESTRICTED COUNCIL** 209th Session **29 September 2022**	Simple majority of Member States represented and voting

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:

PLANS AND DELIVERABLES FOR THE 2023 MID-TERM REVIEW

This document describes the plans and deliverables for the mid-term review of the Future Circular Collider Feasibility Study, which is proposed to take place in autumn 2023. The Scientific Policy Committee is invited to recommend and the Council is invited to approve these plans and deliverables.

The CRP will

- review the methodology and assumptions used in producing the cost estimates,
- identify inaccurate or missing cost information,
- check the consistency of the cost estimates with respect to applicable reference work, e.g., recent large-scale infrastructure and accelerator projects,
- review the uncertainty estimates,
- identify potential areas of savings and cost mitigation for future work, and
- advise the FCC study team on matters of cost estimation in view of preparation of the final Feasibility Study Report for end 2025.

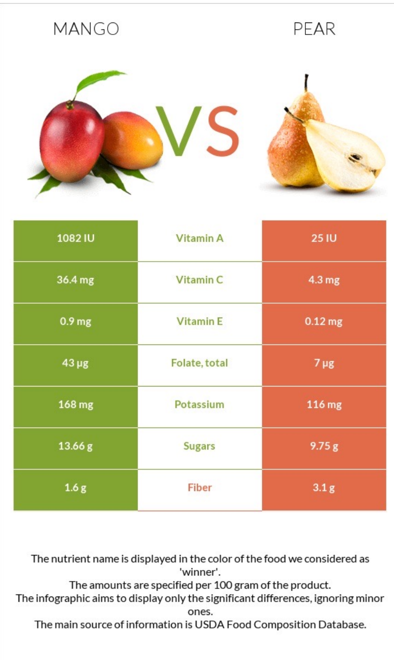
Members: The CRP consists of around 10 international experts, not directly involved in the Feasibility Study, with renowned expertise in costing and project management aspects related to the scientific and technical domains relevant to the Study (accelerators, technical infrastructure, civil engineering, detectors, etc.). Members and Chair appointed by SC.

CRP members:

Carlos Alejaldre (F4E), Austin Ball (CERN, ret.), Umberto Dosselli (INFN), Vincent Gorgues (CEA), Norbert Holtkamp, chair (Stanford U.), Christa Laurila (VTV), Ursula Weyrich (DKFZ), Jim Yeck (BNL), Thomas Zurbuchen (ETH Zürich)

Comparing future colliders

See report from the Snowmass '21 Implementation task force



(Also consider whether the people making the comparison might prefer apples or pears)

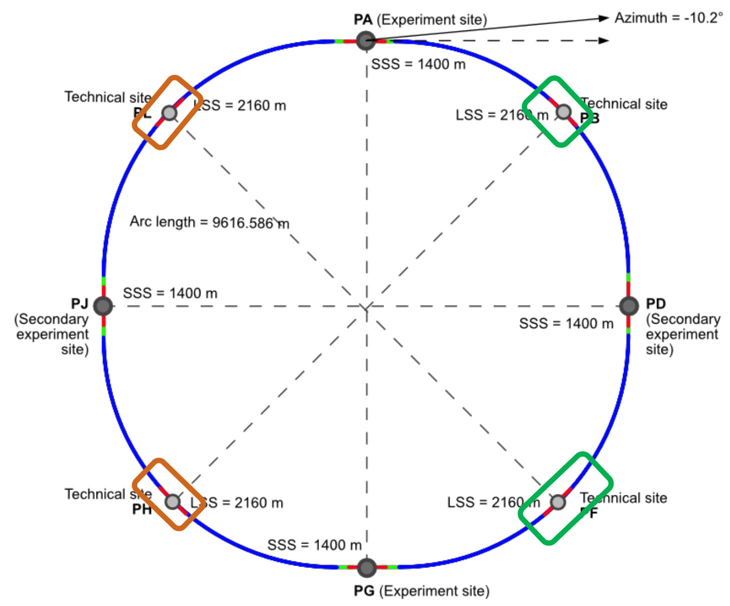
… is hard! Its important to define your comparison metrics carefully and consider the errors involved!

- See slides by L. Nevay at IOP-HEPP 2023
- Some claim that *"FCC-ee is, by very large factors, the least disruptive in terms of environmental impact"* (arXiv:2208.10466).
- For discussion of the potential of HTS to make FCC-ee more sustainable see these slides.

Personal recommendation: go through the numbers, look at the whole picture (physics goals, upgrades, operation time etc) and critique the numbers for yourselves!

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

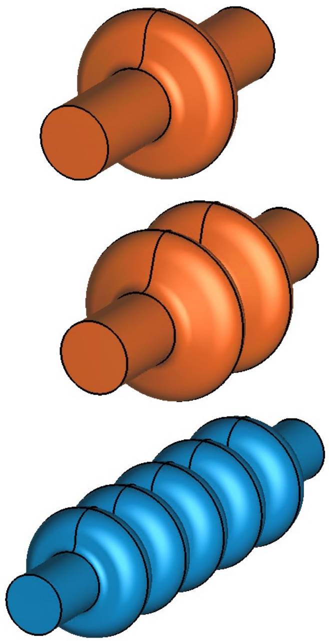
1-cell 400 MHz, Nb/Cu

W, H

2-cell 400 MHz, Nb/Cu

ttbar, booster

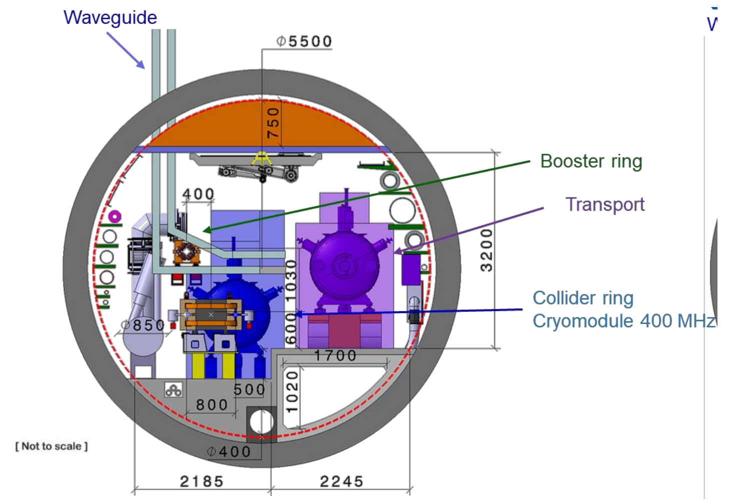
5-cell 800 MHz, bulk Nb



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

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

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

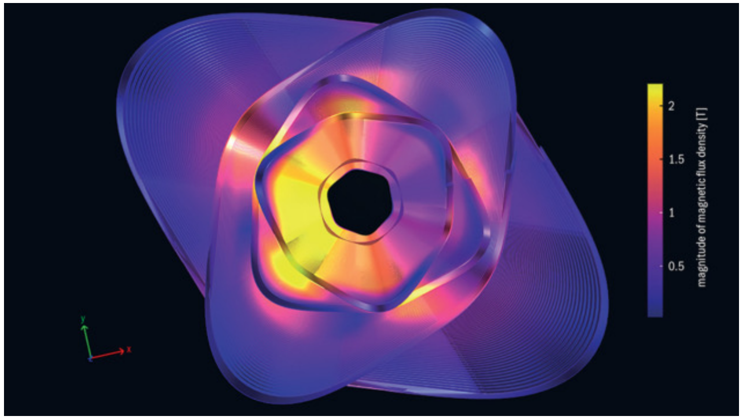


RF for collider and booster in separate sections (collider in PH- 400 & 800 MHz, booster in ML- 800 MHz only) with fully separated technical infrastructure (cryogenics)

FCC-ee beam optics

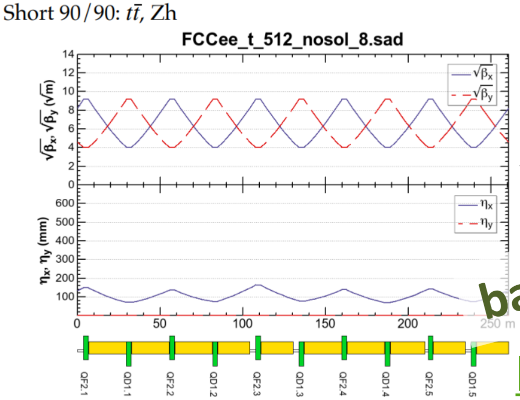
Two new projects backed by CHART aim to explore use of HTS to improve energy efficiency. See CERN courier article here

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).

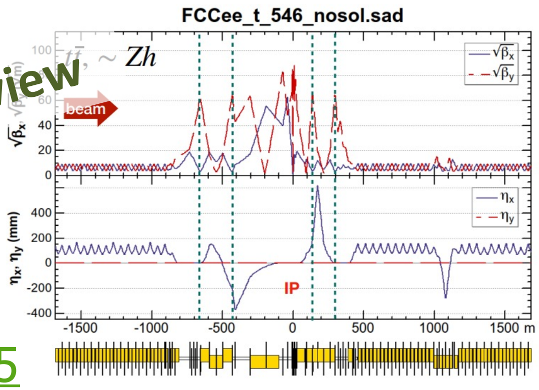
arc



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

baseline for 2023 FCC "mid-term" review

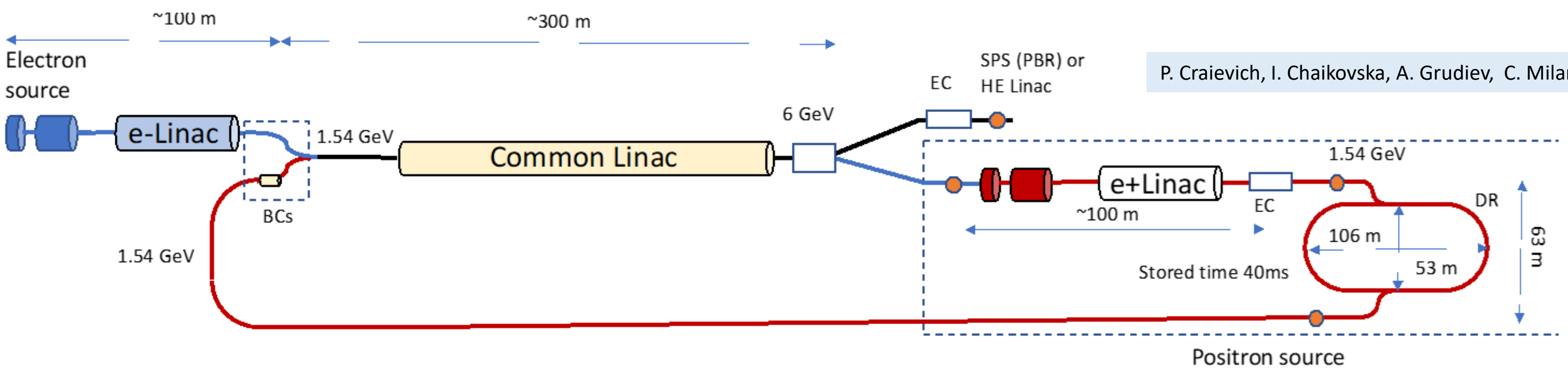
interaction region



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

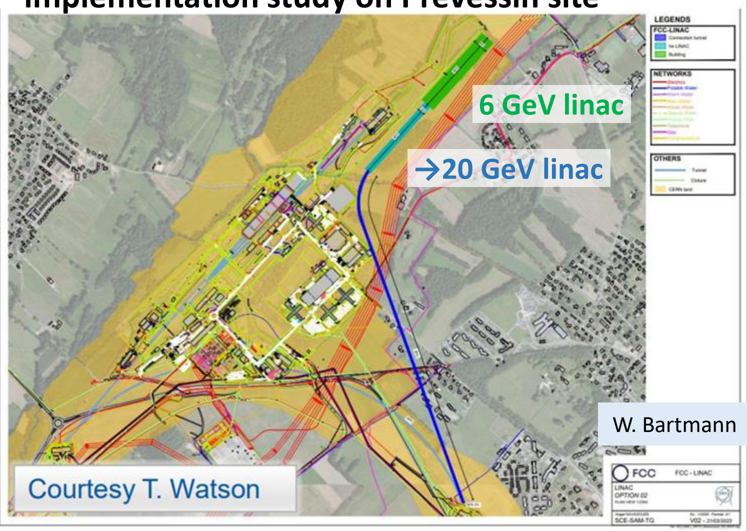
New FCC-ee injector layout

Taken from slides by M. Benedikt at FCC week



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

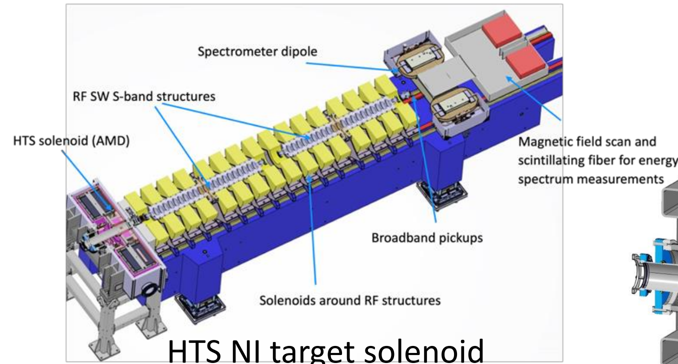
implementation study on Prevessin site



W. Bartmann

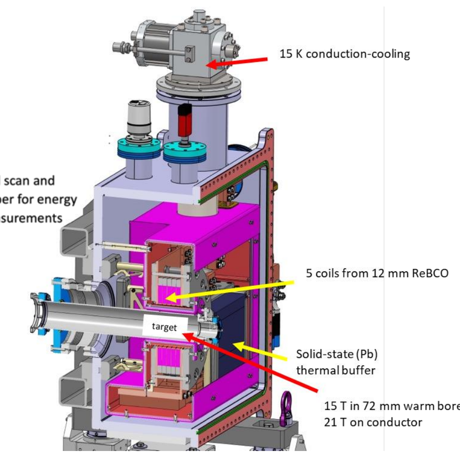
Courtesy T. Watson

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



HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues



FCC-ee LLP group: past and present

- Following a Snowmass LOI, an LLP white paper was recently published in Front. Phys. 10:967881 (2022) which included case studies with the official FCC analysis tools.
- These initial studies motivate further optimization of experimental conditions and analysis techniques for LLP signatures.
- Currently a very active community, with meetings on Thursdays 13:00 CERN time.

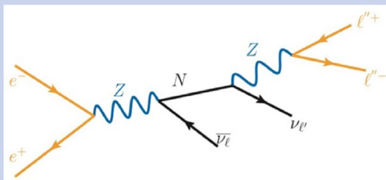
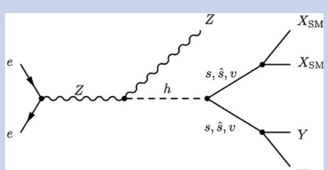
Searches for long-lived particles at the future FCC-ee

C. B. Verhaaren[1], J. Alimena[2]*, M. Bauer[3], P. Azzi[4], R. Ruiz[5], M. Neubert[6,7], O. Mikulenko[8], M. Ovchynnikov[8], M. Drewes[9], J. Klaric[9], A. Blondel[10], C. Rizzi[10], A. Sfyrla[10], T. Sharma[10], S. Kulkarni[11], A. Thamm[12], A. Blondel[13], R. Gonzalez Suarez[14] and L. Rygaard[14]

[1]Department of Physics and Astronomy, Brigham Young University, Provo, UT, United States, [2]Experimental Physics Department, CERN, Geneva, Switzerland, [3]Department of Physics, Durham University, Durham, United Kingdom, [4]INFN, Section of Padova, Padova, Italy, [5]Institute of Nuclear Physics, Polish Academy of Sciences, Kracow, Poland, [6]Johannes Gutenberg University, Mainz, Germany, [7]Cornell University, Ithaca, NY, United States, [8]Leiden University, Leiden, Netherlands, [9]Université Catholique de Louvain, Louvain-la-Neuve, Belgium, [10]University of Geneva, Geneva, Switzerland, [11]University of Graz, Graz, Austria, [12]The University of Melbourne, Parkville, VIC, Australia, [13]LPNHE, Université Paris-Sorbonne, Paris, France, [14]Uppsala University, Uppsala, Sweden

Ongoing FCC-ee LLP studies

Note: this table will soon be updated following the mid-term review!

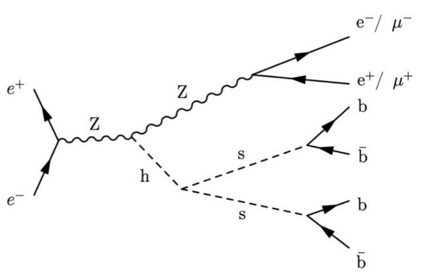
Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and detector-level selection studies for ee$\nu\nu$. First look at Dirac vs Majorana	• Update ee$\nu\nu$ studies for winter23 samples. • First look at $\mu\mu\nu\nu$ channel (prompt +LLP) • First look at $\mu\nu$jj (prompt+LLP) • First look at eνjj including Dirac vs majorana (prompt)
Axion-like particles (ALPs)	Displaced photon/lepton pair	Generator-level validation for a→γγ at Z-pole run.	*No studies ongoing* ***-> Opportunities to get involved :)***
Exotic Higgs decays	e.g. 	Theoretical discussion and motivation for studies at ZH-pole	• Reco-level studies (inc. vertexing) for h→ss→bbbb

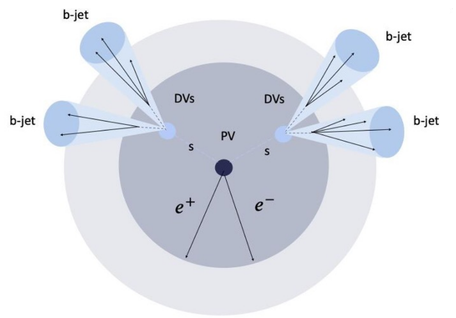
FCC-ee LLP studies: recent highlights

Magdalena Vande Voorde, Giulia Ripellino

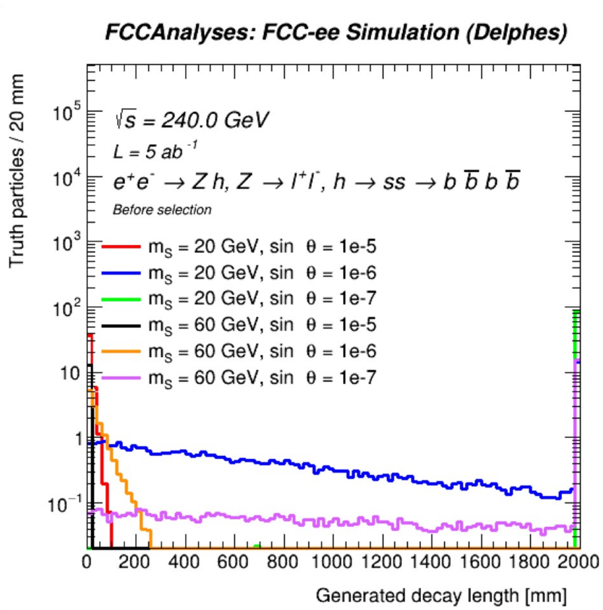
Nice overview by Juliette Alimena at EPS 2023

First simulation and sensitivity studies for Higgs decays to long-lived scalars





- Extend SM with additional scalar.
- Probe h→ss→bbbb in events with 2 displaced vertices, tagged by Z



- Look at events with at least one scalar within acceptance region 4mm<r<2000mm- all except longest and shortest on RHS.
- Aim to develop event selection and perform early sensitivity study.

For further details see presentation by Magda at topical ECFA WG1-SRCH meeting