Status and plans for the Future Circular Collider (FCC)

Dr Sarah Williams, University of Cambridge

Introduction

- In the next ~ 45 minutes I'll aim to:

  1. Explain why we need to start planning for future colliders now.

  2. Provide an overview of **the Future Circular Collider** (FCC) integrated project.

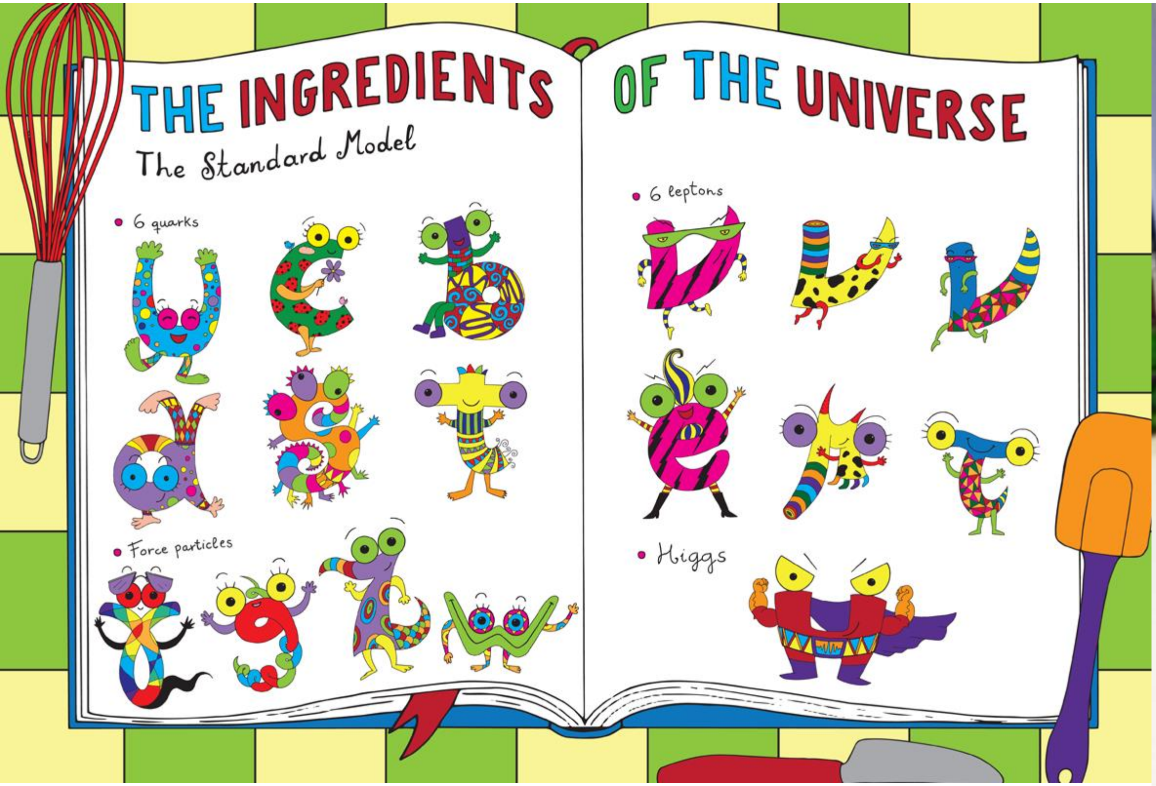
  3. Discuss the **opportunities** and **challenges** associated with this project.

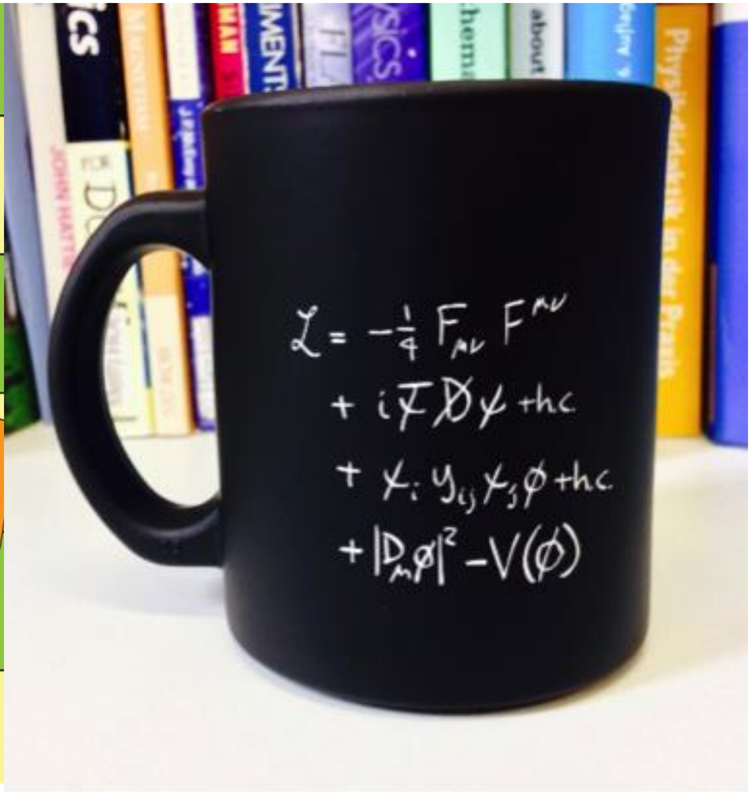
- I am happy to take questions as we go through, at the end or by email (sarah.louise.Williams@cern.ch)

Last time I was in Liverpool …

This trip…

The Standard Model

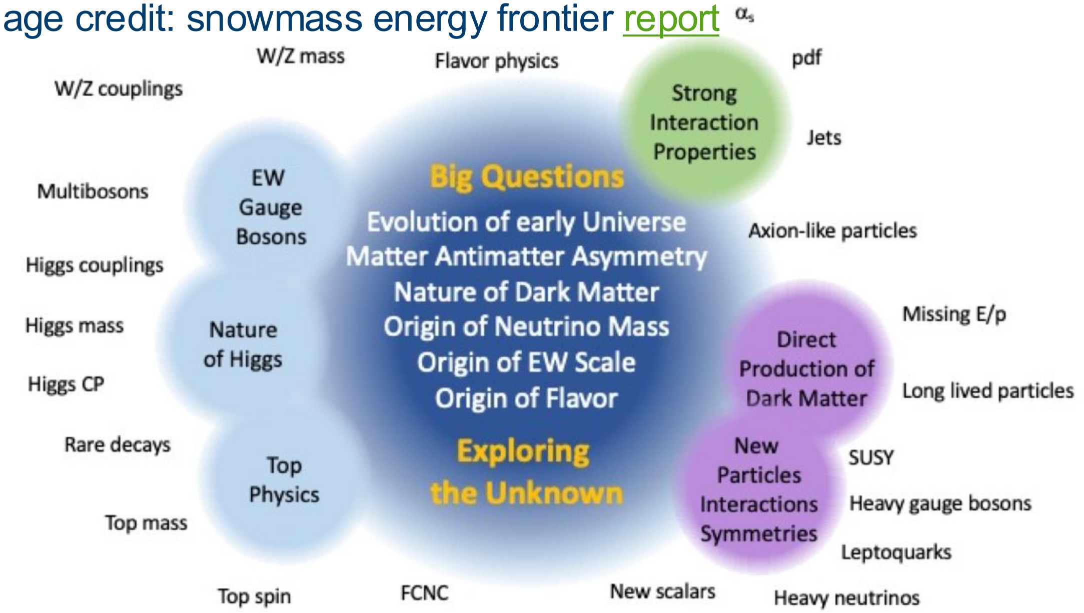




However you “view” the Standard Model, it is an immensely successful and well tested theory, but we know it has shortcomings…

Big questions in particle physics

Image credit: snowmass energy frontier report



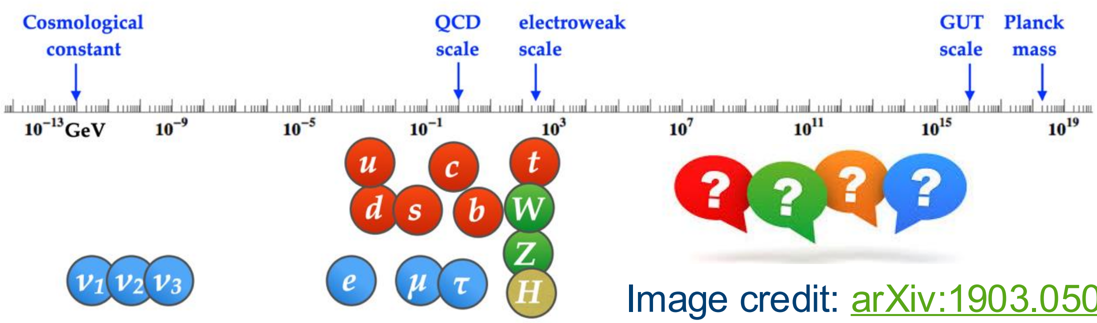


Image credit: arXiv:1903.05063

- Outstanding questions about nature/our universe could be solved through uncovering new physics at particle colliders.
- Unlike the Higgs discovery, we no longer have a clear idea of the (energy) scale at which it might appear.
- (Maximally) exploring the unknown is key…

Frontiers in particle physics

This diagram could do with an update (what about the quantum frontier?)

- Pushing the intensity and energy frontiers represent two complementary routes for probing new physics.

What's a discovery in particle physics
- Detecting for the first time a new fundamental process
- Discovering new particles (indirectly or directly)

S. Gori

- Whilst the 'focus' of e^+e^- machines is precision (intensity frontier) - a future Higgs factory could meet all definitions of discovery.
  - Possible evidence for electron/strange yukawa?
  - Direct discovery of ~ low-mass (very) weakly coupled BSM.
  - Indirect discoveries up to ~50-100 TeV.

- Pushing the energy frontier to its highest achievable scale will maximise (direct) sensitivity to NP…. (and deliver much more)

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?)

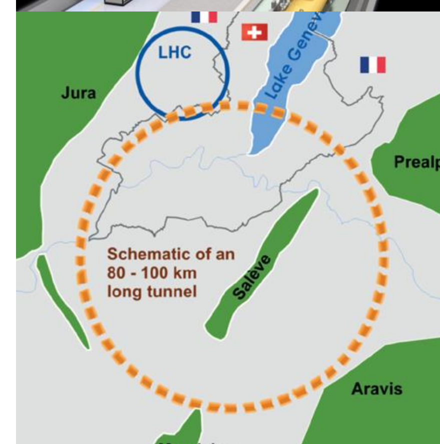
Circular collider?

CepC (China)

Hadron collider?

FCC-ee/hh (CERN)

Muon collider?



How might Europe fit into the global context?

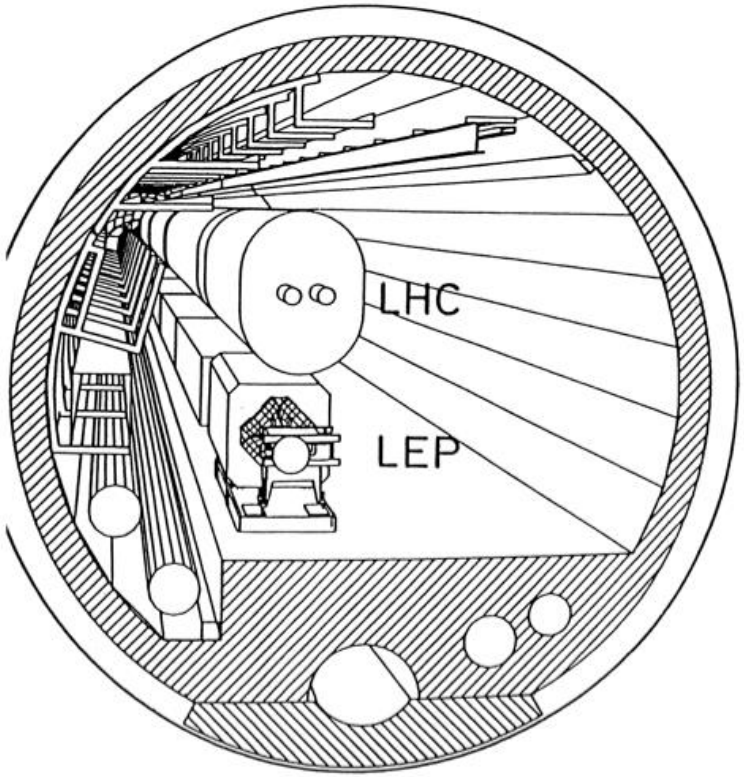
Timescales in particle physics

…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…

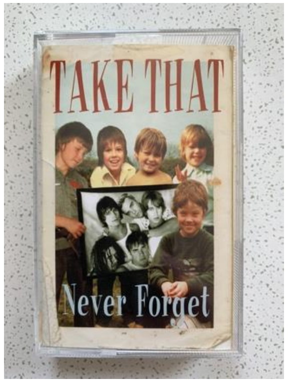
The European strategy for particle physics

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...?

Can you guess the films?

	1984	1995	2012
Music			
Film			

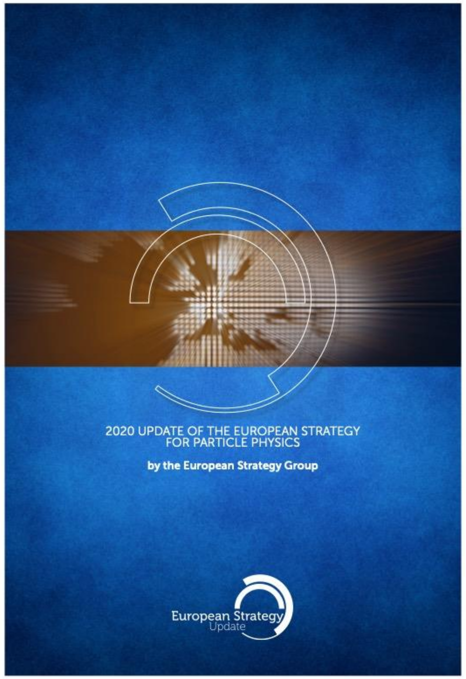
… many of us have only been involved in a small part of the LHC journey…

The 2020 European Strategy Update

Following ~ 2 years of consensus 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…

Timeline for the update of the European Strategy for Particle Physics

We are here now, just over a week away from the deadline for the final round of national inputs. Thanks to everyone who has participated in this (long but productive) process!

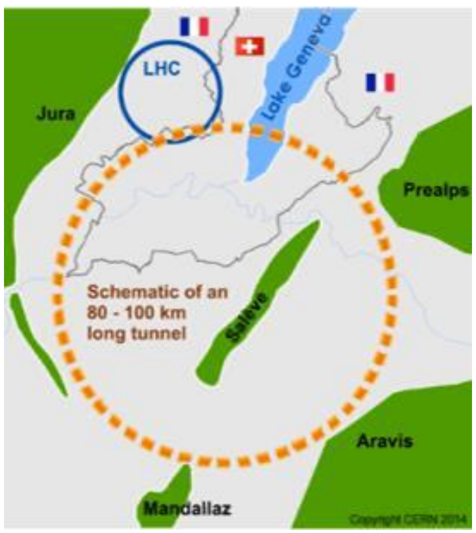
Headlines from the ESPPU so far

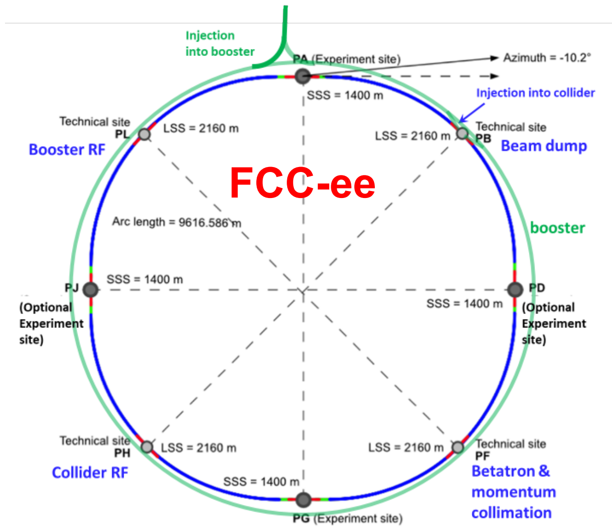
- Broad support for FCC as the next flagship collider for CERN (reflected in UK's national submission https://indico.cern.ch/event/1439855/contributions/6461578/).
- BUT the need to establish clear "plan B" alternatives highlighted.

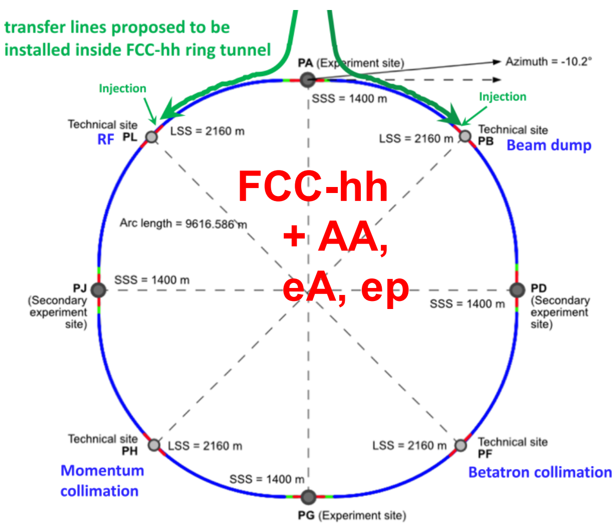
Integrated FCC programme

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 (~ 85 TeV) to maximise reach at the energy frontier, with pp, AA and e-h options (FCC-eh).



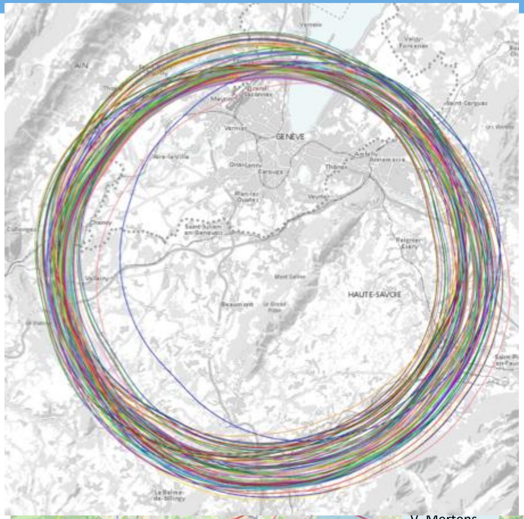


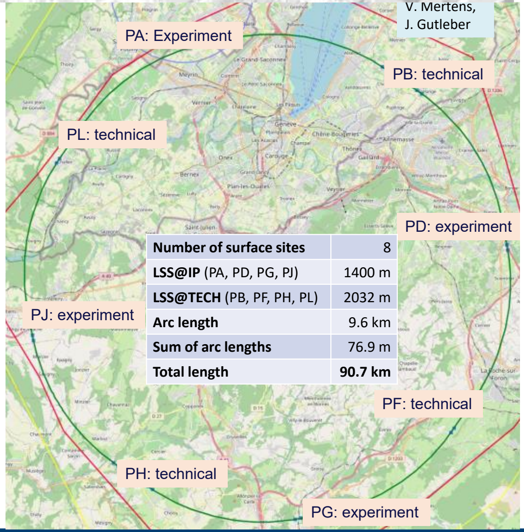


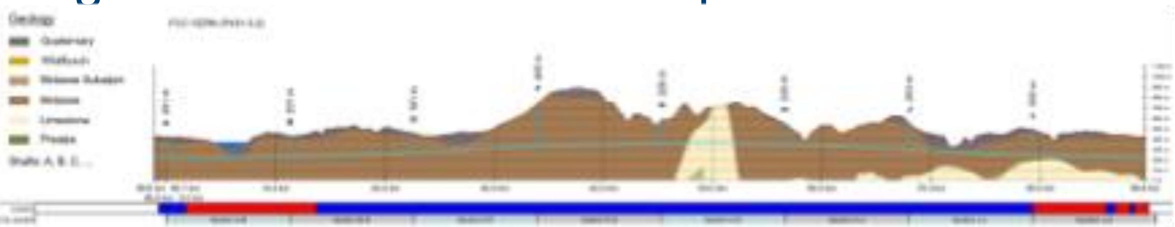
Status of the FCC project

https://cds.cern.ch/record/2928193

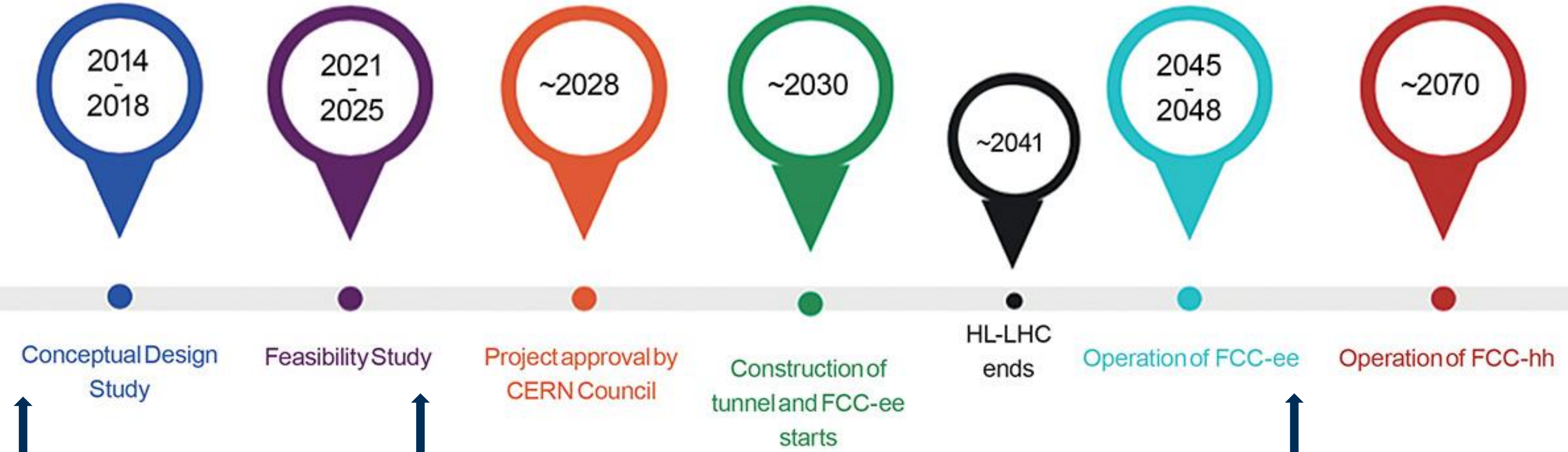
- Feasibility study report submitted as input to the ESPPU on 31st March this year.
- Key achievements: final choice of ring placement (PA31-4.0) and 4 interaction points.
- No showstoppers to feasibility – with ongoing/future R+D efforts for FCC-ee to focus on increasing energy and operational efficiency and reducing costs.
- For FCC-hh- significant challenge will be high-field magnets needed for ~ 14 T dipoles.

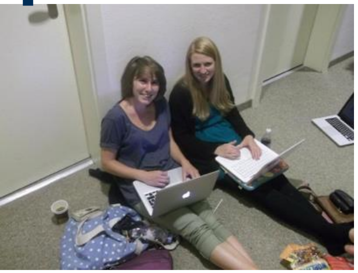






FCC timescales





2012- SW a PhD student at CERN

Olivia born 2025. Earliest date to start PhD~ 2047. (Retirement >2093)

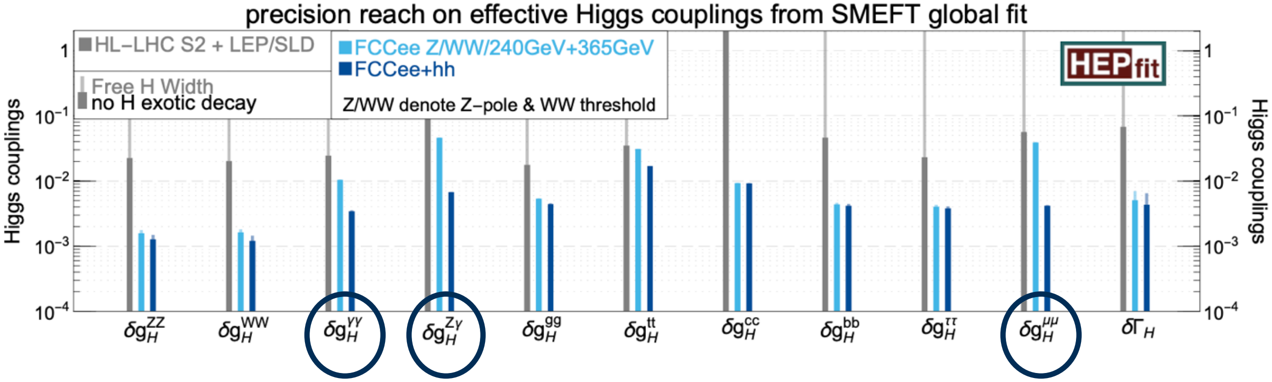
SW retirement around 2055

=> Realising FCC will be a multigenerational challenge!

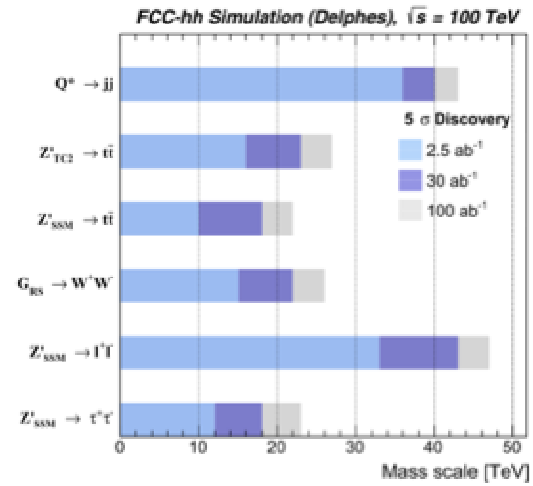
Synergies in FCC programme –BSM

https://cds.cern.ch/record/2928193

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



For rare decays- need FCC-hh to reach ultimate precision



- 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 Higgs self coupling).

=> FCC-hh could directly discover NP indirectly accessed at FCC-ee!

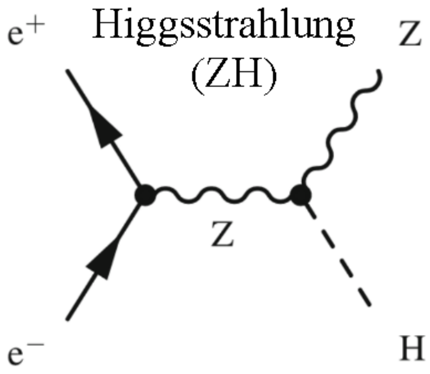
FCC-ee and -hh synergies - Higgs measurements

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-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

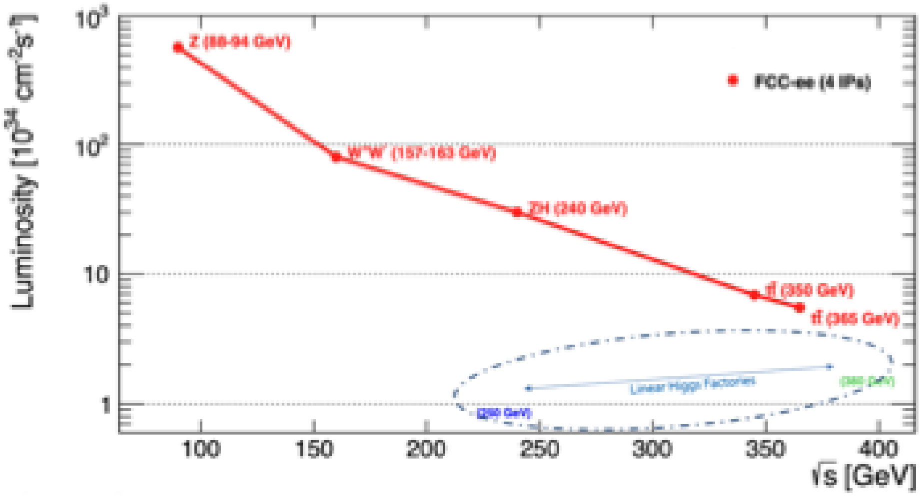
impact parameter resolution for large displacement

triggerless

$\Rightarrow$ Broad landscape of physics opportunities!

$\Rightarrow$ Significant effort to study impact of detector concepts across range of physics areas, with lots still to do in the coming years (opportunities for engagement)

Ultimate precision @ FCC-ee



- Unprecedented luminosity at multiple centre of mass energies will enable ultra-precise measurements of Higgs (and EW and top) sectors of the SM…
- New SRF plans enable flexibility of running order between Z/Zh/WW

- To. Illustrate this further… I thought we would play a game…

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

e^+e^- numbers game

Put these numbers in ascending order (and guess if you can?)

1. # Z bosons/hour at FCC-ee (Z-pole)
2. # Higgs bosons/day at FCC-ee (Zh pole)
3. # Z bosons produced at LEP
4. # Crème eggs produced by Birmingham Cadbury's factory per day
5. # Higgs bosons produced by the LHC in 2017.

In the interest of time- try guessing the highest and lowest…

e^+e^- numbers game

Disclaimer: these numbers have not been updated since the mid-term report- both for FCC and the Cadburys factory…

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

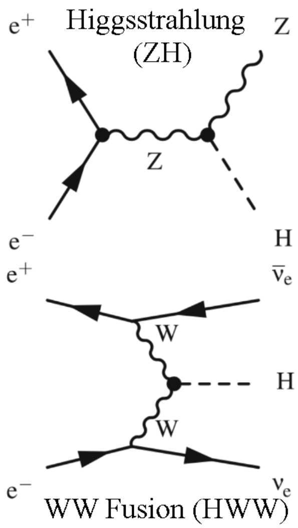
1. # Z bosons/hour at FCC-ee (Z-pole) => 360 million (5)
2. # Higgs bosons/day at FCC-ee (Zh pole) => 2000 (1)
3. # Z bosons produced at LEP => 18 million (4)
4. # Crème eggs produced by Birmingham Cadbury's factory per day => 1.5 million (2)
5. # Higgs bosons produced by the LHC in 2017 => 3 million (3)

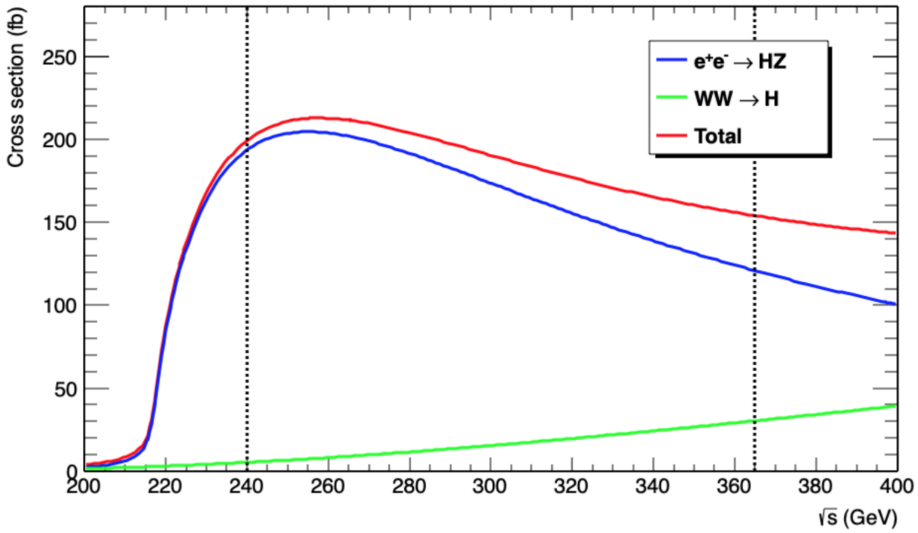
Case study- Higgs physics

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

> 1 million ZH events

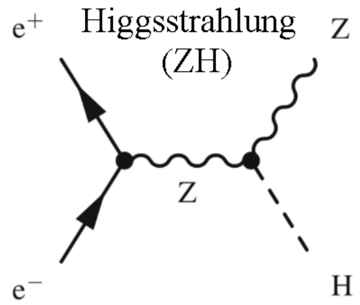
~ 100,000 WW fusion



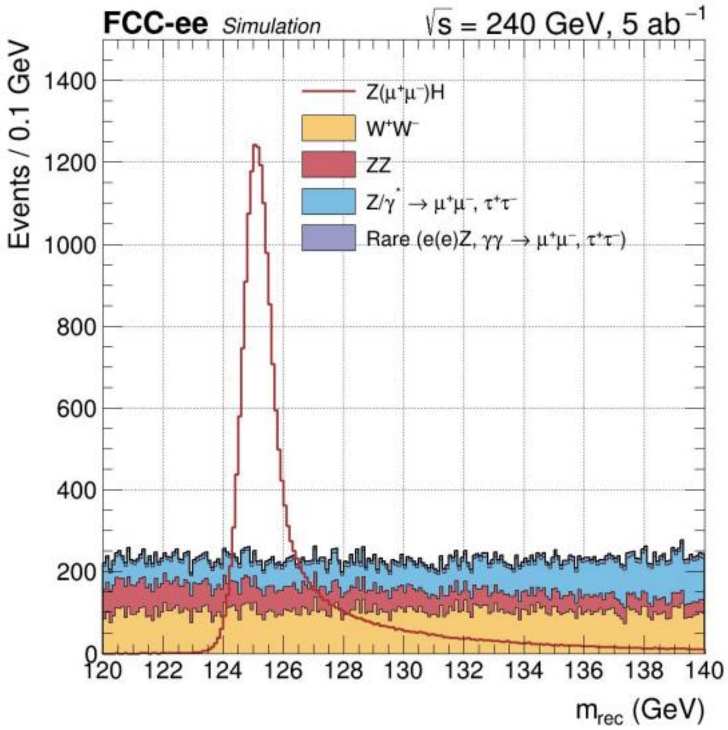


- Large rates, clean experimental environment (no UE, Pileup, triggerless) with no QCD background will open up a new era of Higgs precision physics.
- Opportunities to remove model-dependence from measurements and reach sub-percent level for post couplings.

Higgs recoil mass 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.



***Achieved through resonant depolarization (unique to circular l+l- colliders)**

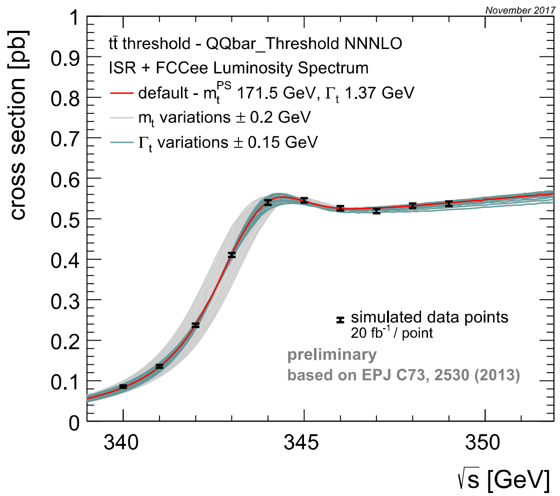
Top and flavour @ FCC-ee

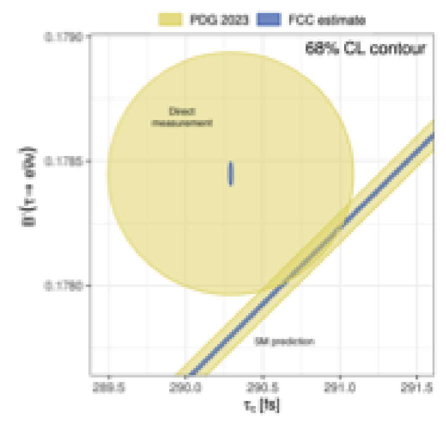
- $t\bar{t}$ threshold scan will enable most precise measurements of top-quark mass and width.

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

Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

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

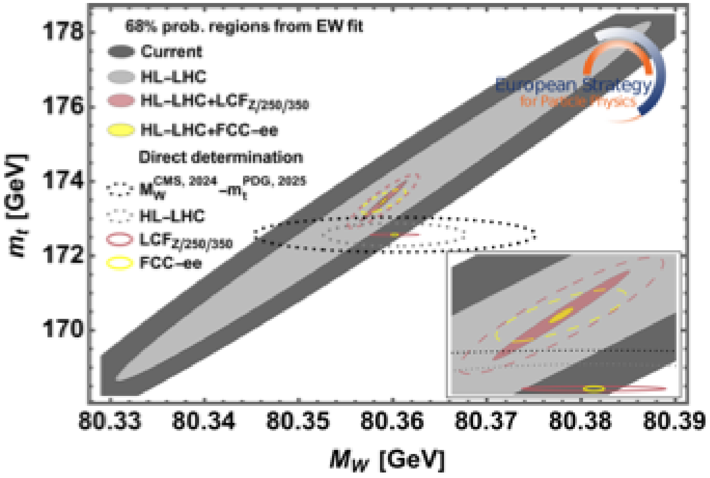




EWK precision @ FCC-ee

High-statistics at FCC-ee drives substantial improvements in EWK precision programme…

Observable	Current	FCC-ee	LCF	LEP3
Δm_Z (keV)	2000	4 (100)	200	7.5 (100)
$\Delta\Gamma_Z$ (keV)	2300	4 (12)	125	7.5 (23)
δR_μ $(\times 10^{-6})$ $R_\mu \equiv \frac{\Gamma_{had}}{\Gamma_\mu}$	1600	2.4 (2.3)	90 (90)	4.5 (2.3)
δR_b $(\times 10^{-6})$ $R_b \equiv \frac{\Gamma_b}{\Gamma_{had}}$	3300	1.2 (1.6)	70 (60)	2.2 (3.0)
$\Delta \sin^2\theta_W$ $(\times 10^6)$	130	0.4 (0.5)	2.7 (2.3)	0.75 (0.95)
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	14	0.8, 3.8	–	1.4, 7.3
Δm_W (keV)	9900	180 (160)	500 (1600)	430 (700)
$\Delta\Gamma_W$ (keV)	42000	270 (200)	2000	650 (500)



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

Theory input required for FCC programme

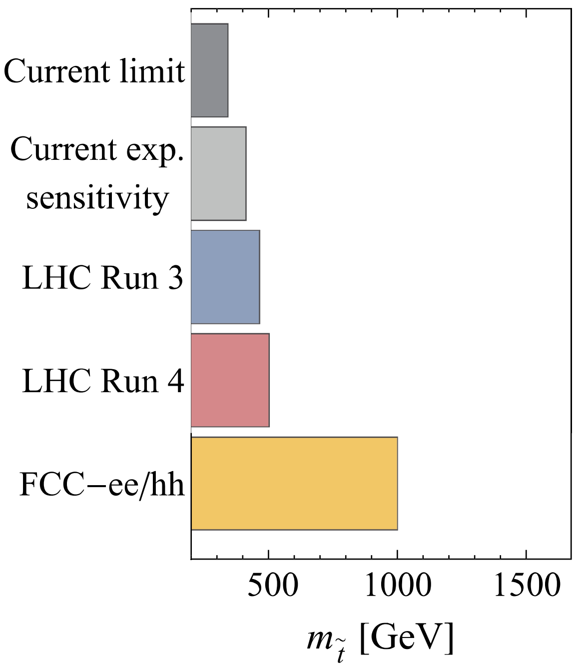
Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Theory status as of today	Needed theory improvement[†]
m_Z (MeV)	2.0	0.004 (0.1)	non-resonant $e^+e^- \to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6[th] order	NNLO for $e^+e^- \to f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2\theta^f_{\text{eff}}$	1.6×10^{-4}	$1.2\ (1.2) \times 10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \to WW$ near threshold	NLO ($e^+e^- \to 4f$ or EFT framework)	NNLO for $e^+e^- \to WW$, $W \to f\bar{f}'$ in EFT setup
HZZ coupling	–*	0.1%	cross section for $e^+e^- \to ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
m_{top} (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \to t\bar{t}$	N[3]LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}$(30 MeV) scale uncert.	Matching fixed orders with resummations, merging with MC, α_S (input)

BSM @ FCC-ee - a snapshot

Taken from FCC Snowmass submission

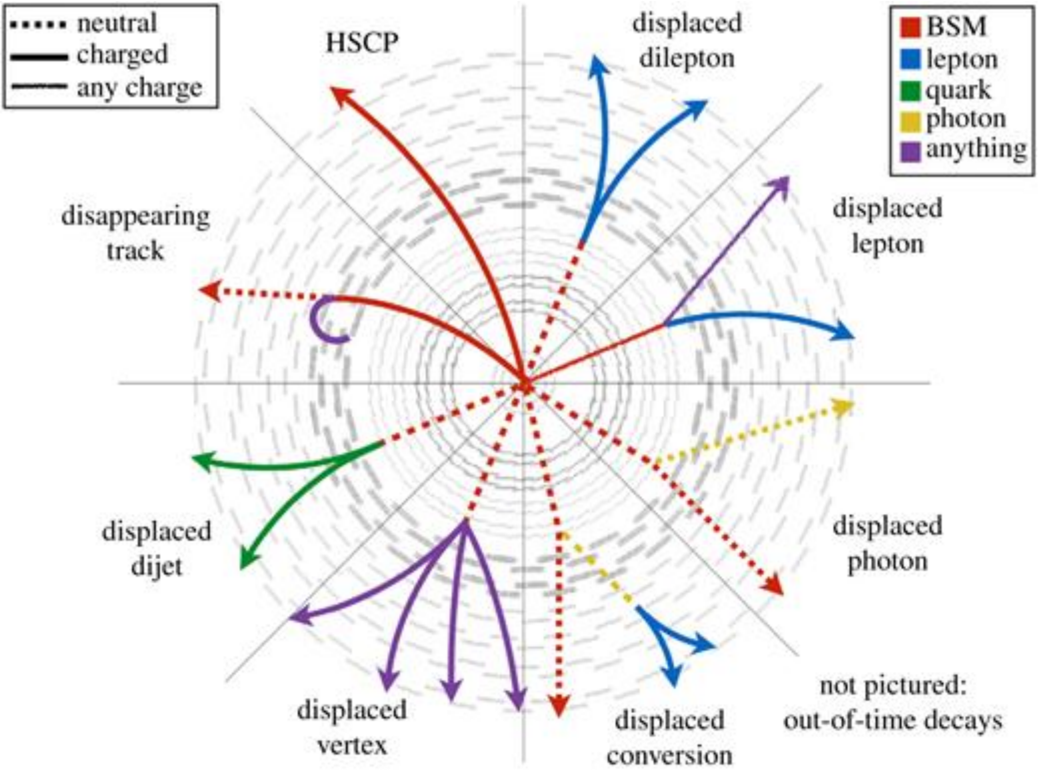
Image credit: FCC CDR

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 ≈ 90 GeV.



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:

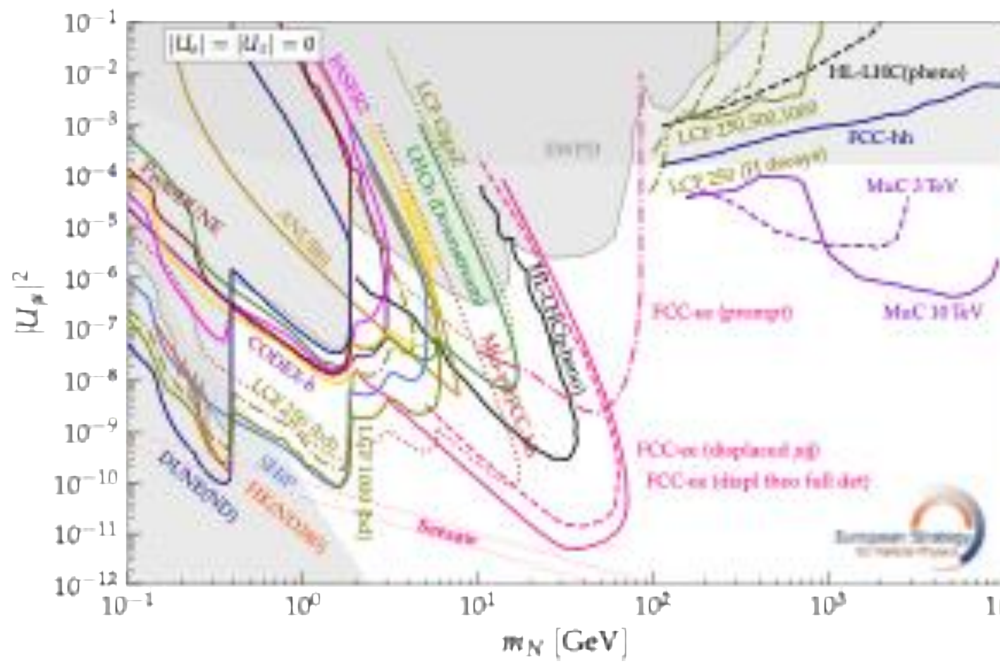
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

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

High luminosities at Z-pole and ZH threshold offer unique sensitivity to LLPs coupling to Z or Higgs.

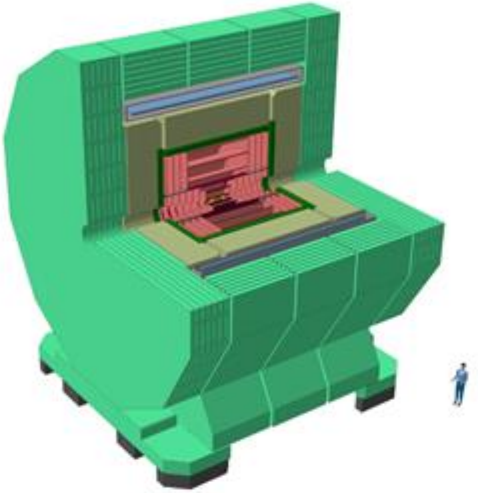
- No trigger requirements.
- Excellent vertex reconstruction and impact parameter resolution can target low LLP lifetimes (this can drive hardware choices).
- **Projections often assume background-free searches** (we should check these assumptions).



ESPPU briefing plot for HNLs mixing with muon neutrinos.

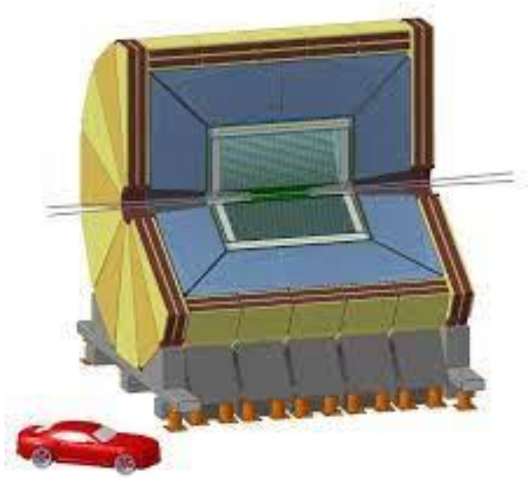
Detector concepts for FCC-ee

CLD ("CLIC-like Detector")



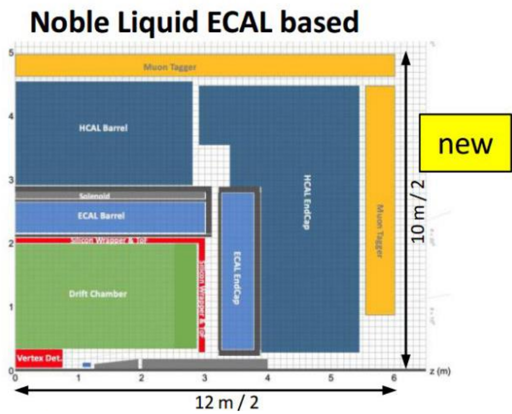
Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

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



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

"Allegra"

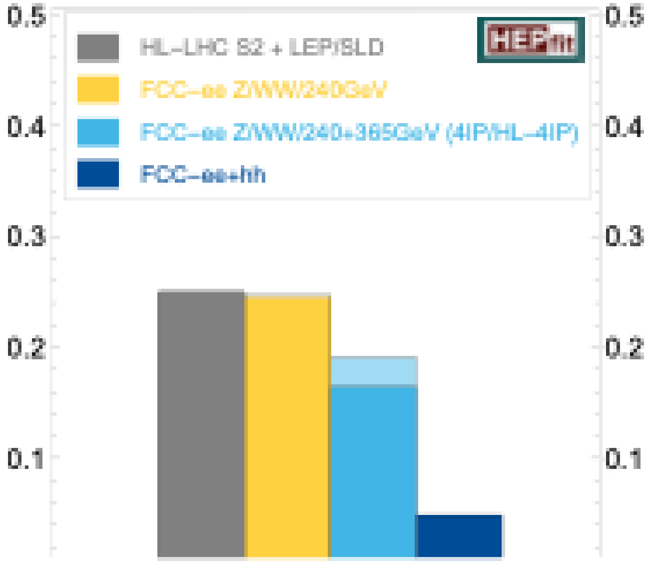


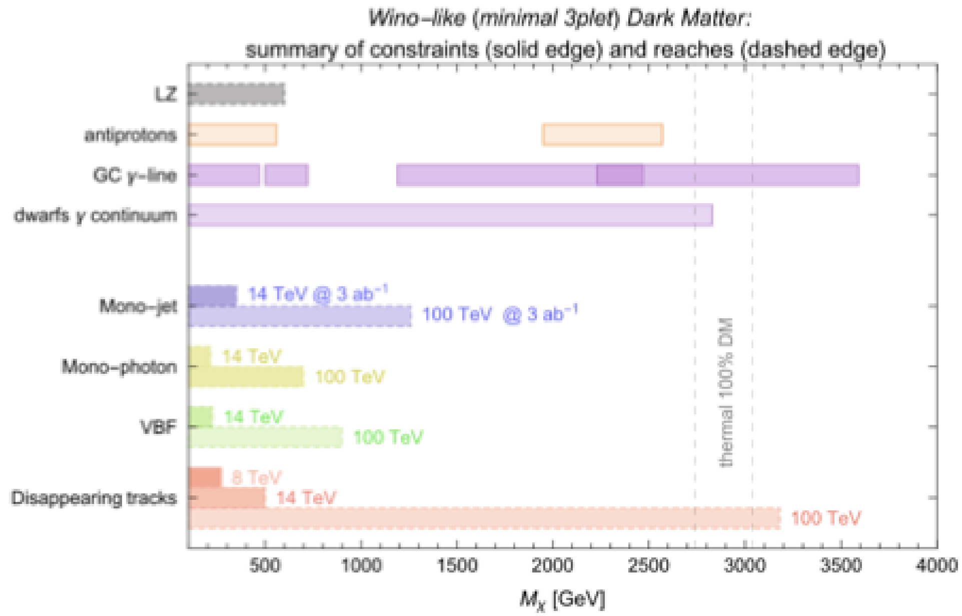
New proposal using liquid LAr calorimeter!

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

Physics opportunities at FCC-hh

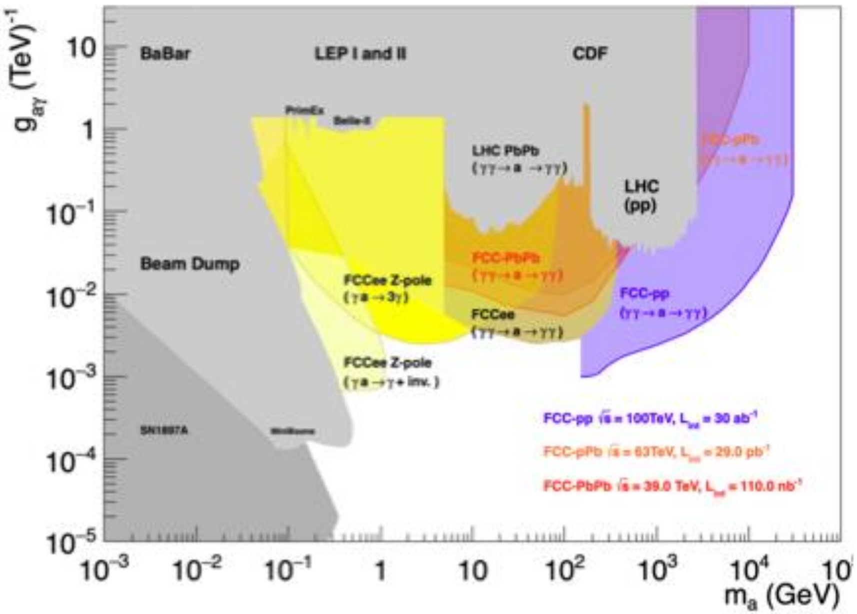
Key point: like the LHC- FCC-hh will also be a Higgs factory!





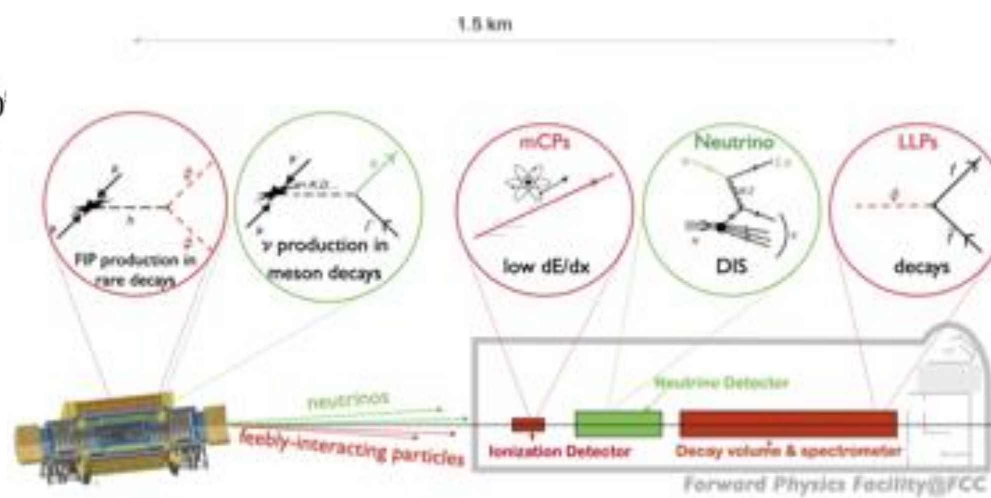
Despite the longer timescales, there was a dedicated effort to strengthen the physics case/ better understand detector considerations for FCC-hh and check the impact of different COM energies. This included more sophisticated simulations and applications of ML- see report!

Physics opportunities at FCC-hh



Complementary opportunity for LLPs compared to that at FCC-ee. i.e. opportunity to probe $\gamma\gamma \to a \to \gamma\gamma$ in pp/p-A/AA collisions

Exploit high-intensity beams of forward neutrinos and perform unique BSM searches through **FPF @ FCC-hh**



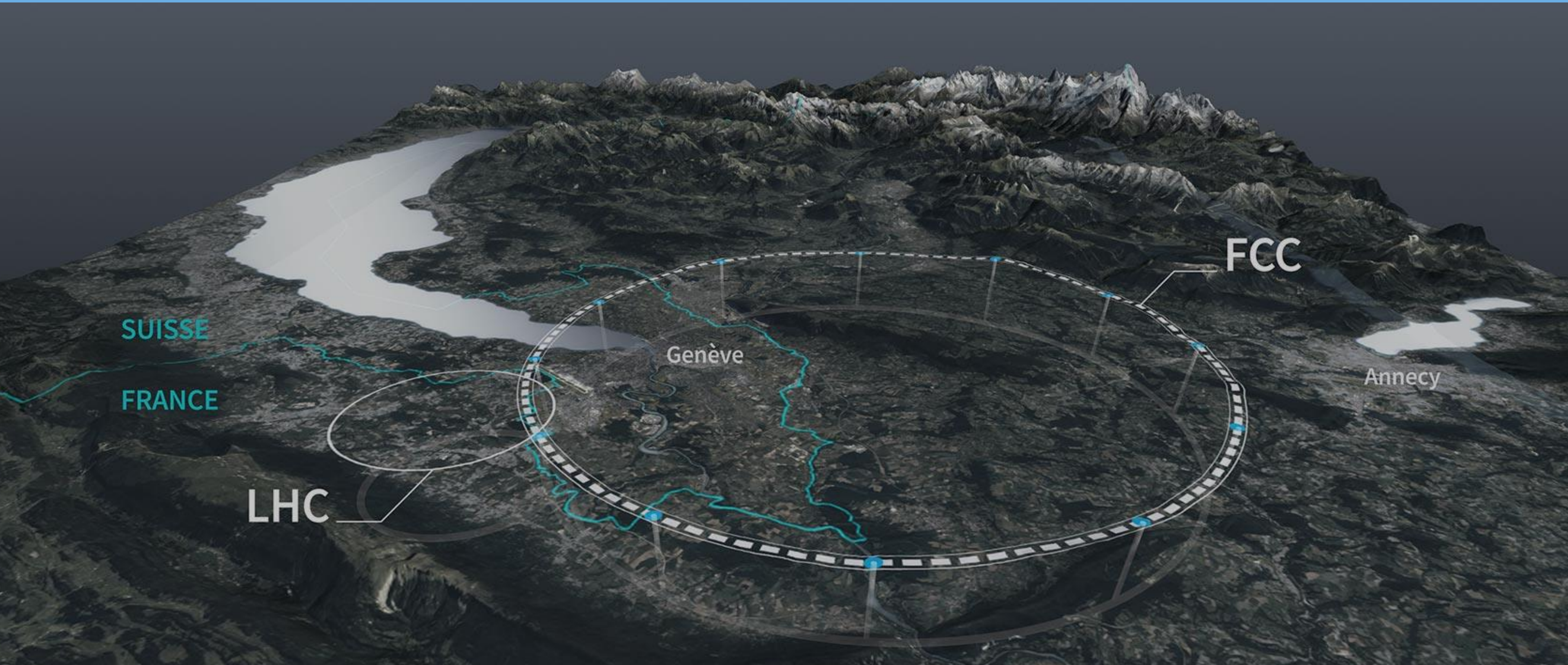
I’m excited by
FCC
are you?

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

- **Paradigm shift** in **precision** to EWK/ QCD/ Higgs physics.
- Exciting **flavour opportunities**.
- **Unprecedented sensitivity** to BSM.

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	Flocculant	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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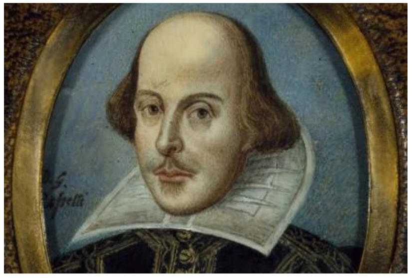
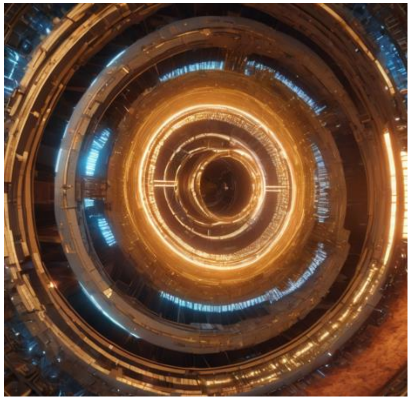
Safer starting point?





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

Next step

Hopefully

If only

Hopefully

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

Want to learn more about FCC/get involved?

- Further reading if you have:
  - ~ 1 day: browse the 10-page summaries submitted by FCC to the ESPPU https://indico.cern.ch/event/1439855/contributions/
  - ~ (we wish) 1-2 weeks: read the FCC Feasibility study report https://cds.cern.ch/record/2928193
- OR you could attend (virtually or in-person) the FCC-UK meeting on Wednesday 12th November at IPPP: https://conference.ippp.dur.ac.uk/event/1496/

Thanks for listening- I am happy to take questions ☺

Backup

Updated FCC costings

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, including four experiments	**15,320**

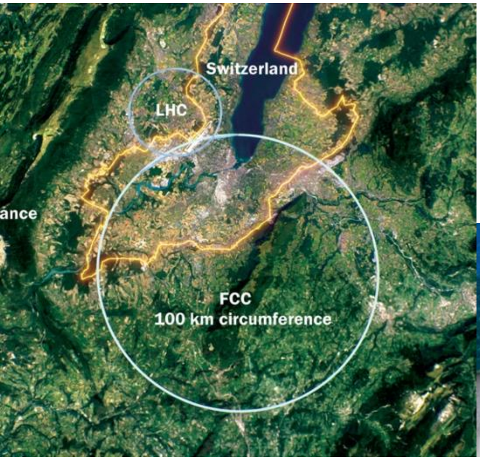
Domain	Cost (MCHF)
Civil engineering	520
Technical infrastructures	3,960
Injectors and transfer lines	1,000
Collider	13,400
FCC-hh total	**18,880**

(Assuming FCC-hh as part of integrated programme- after FCC-ee)

e^+e^- colliders: circular or linear?

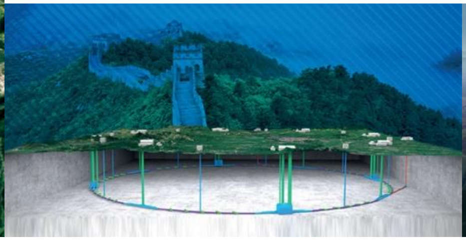
Circular colliders
- Multi-pass at IP
- Modest accelerating gradients
- Limited by synchrotron radiation
- No beam polarization
- Potential to re-use tunnel for hadron collisions.

Linear colliders
- Single pass at IP
- Maximum accelerating gradients
- No synchrotron radiation
- Can exploit (longitudinal) beam polarization
- Staged approach to higher energies (energy~length)



Left: FCC-ee (CERN)
Below: CEPC (China)

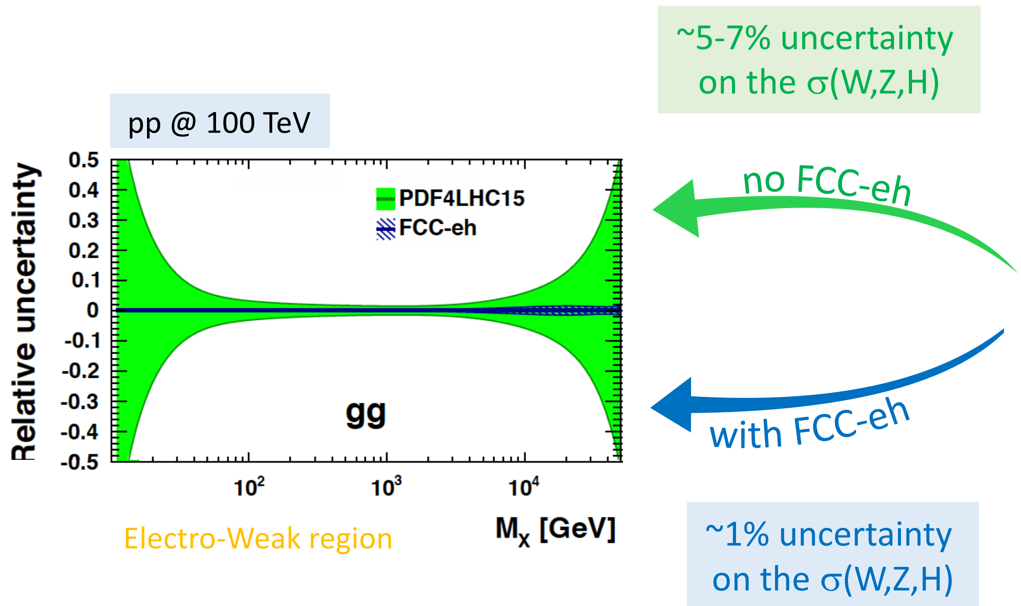
Right: ILC (Japan)
Below: CLIC (CERN)

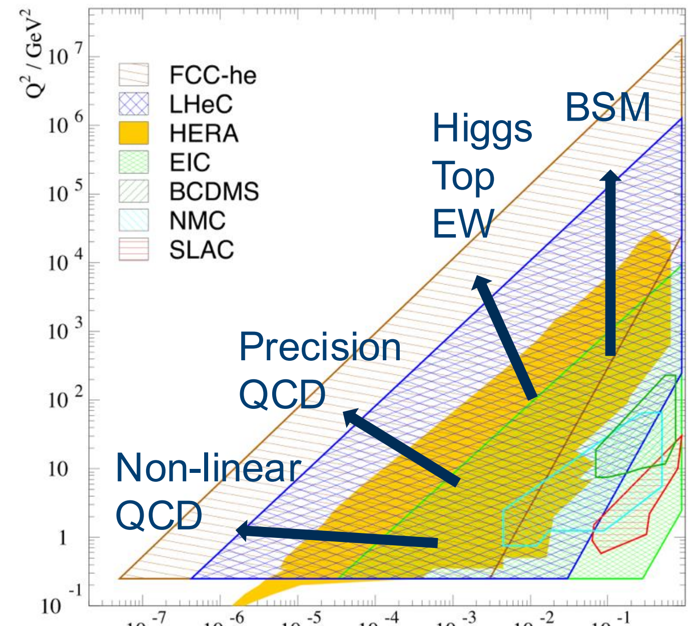


Synergies in FCC programme- FCC-eh

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

Taken from updated CDR





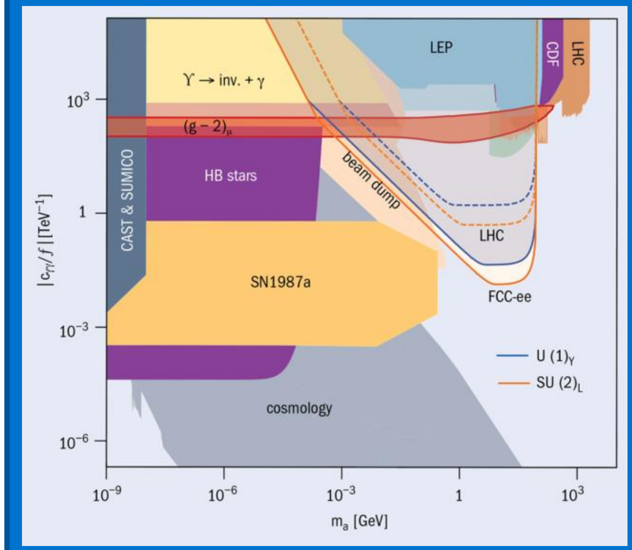
- Empower FCC-hh with precision input on hadron structure and strong coupling (to permille accuracy) during parallel running.
- Complementary measurements of Higgs couplings (CC+NC DIS x-sections, no pile-up, clean)- see slides by U. Klein here
- Plus… complementary BSM prospects (LLPs, LFV, not-too-heavy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

FCC-ee and -hh synergies - BSM

See slides by G. Salam at FCC week

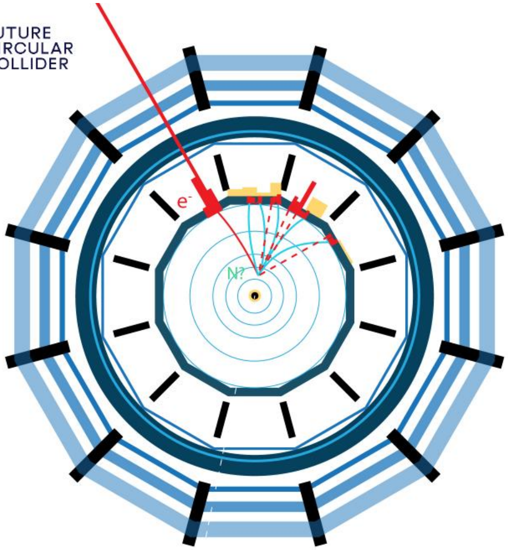
Direct FCC-ee sensitivity

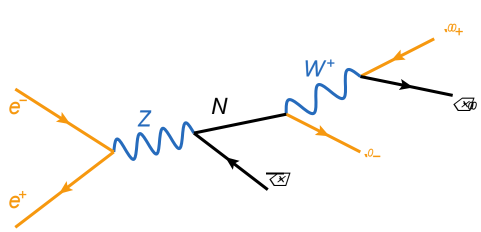
- HNLs
- Alps
- Exotic Higgs decays



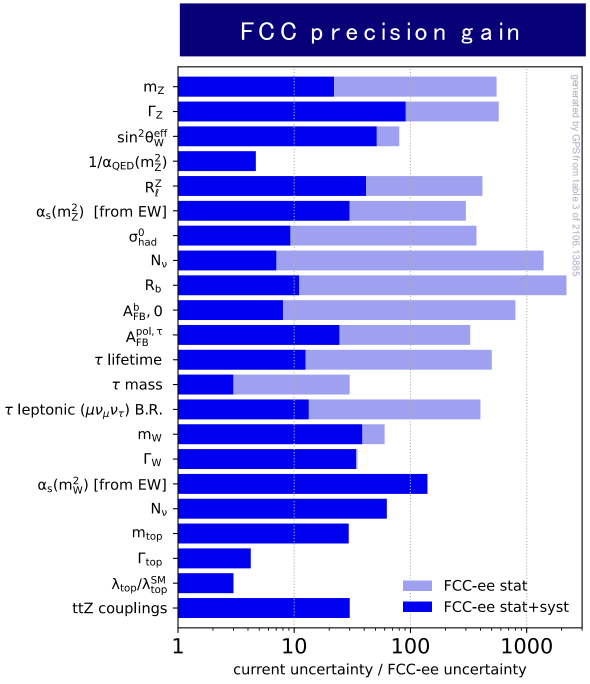
m_a: ALP mass, $c_{\gamma\gamma}$: ALP-photon coupling

FUTURE CIRCULAR COLLIDER





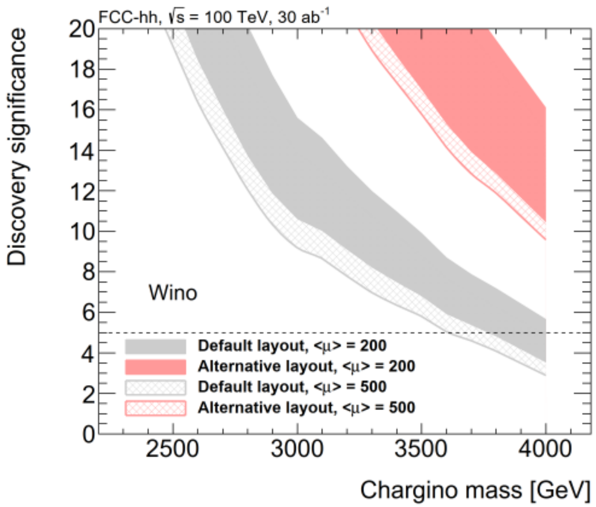
…plus **indirect access** to a range of BSM phenomena through ultra-precise measurements of SM parameters…

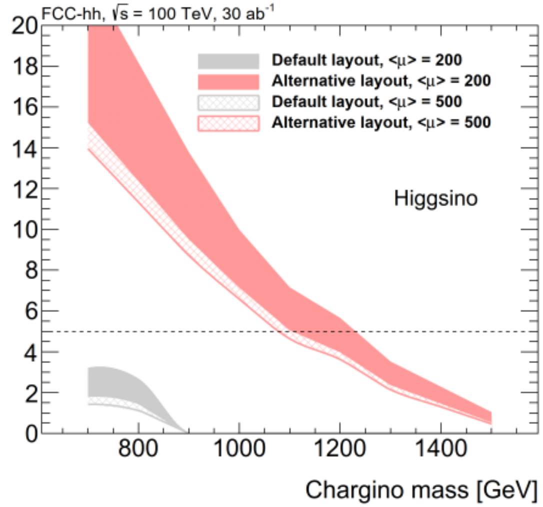


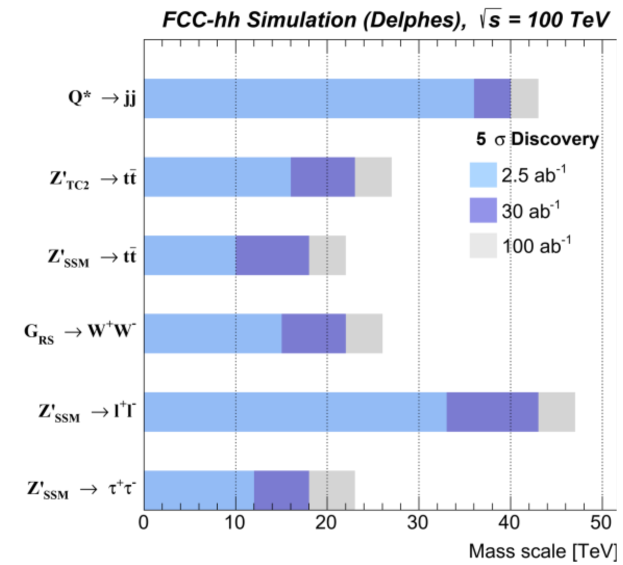
FCC-ee and -hh synergies - BSM searches

More details in FCC TDR and 2020 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

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)

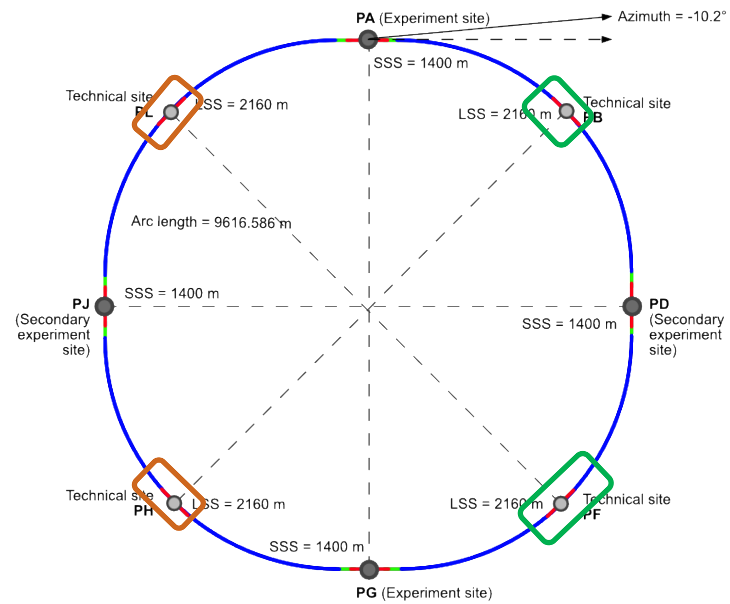
… is hard! Its important to define your comparison metrics carefully and consider the errors involved!

- 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.