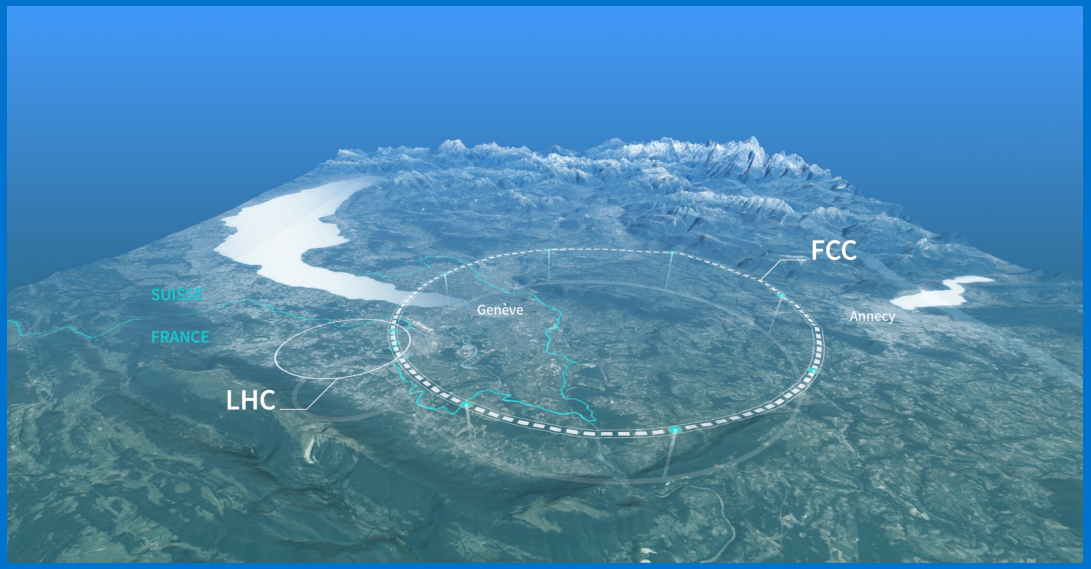
UNIVERSITY OF CAMBRIDGE

Murray Edwards College
University of Cambridge

FUTURE CIRCULAR COLLIDER

Searches for BSM Physics at FCC



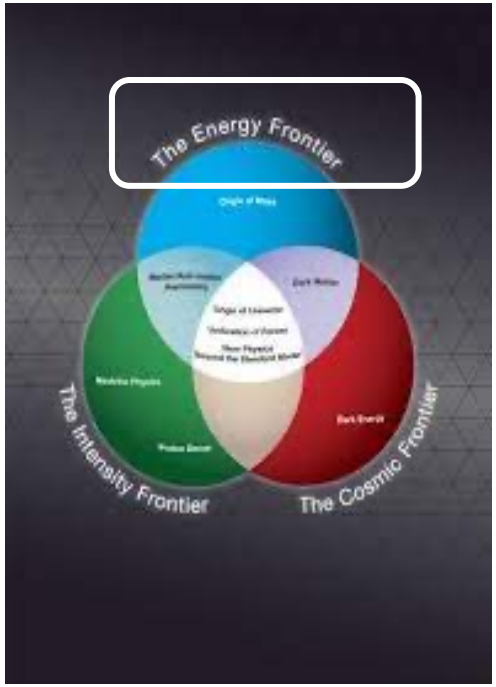
Dr Sarah Williams, on behalf of the FCC collaboration

Introduction

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

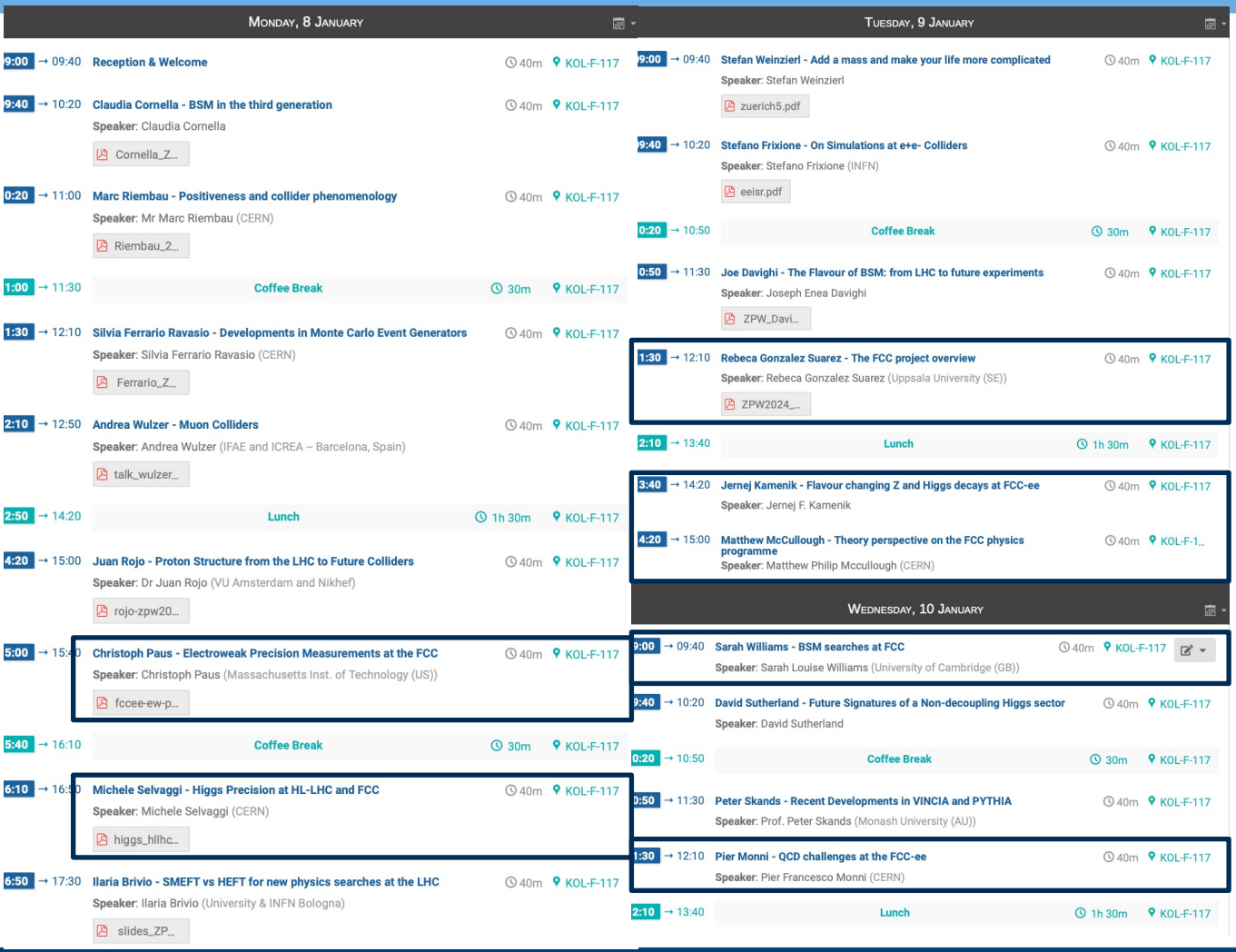
- I am going to attempt to summarise prospects for BSM searches at FCC.
- This includes:
  - Direct searches for new particles.
  - Indirect searches through precision SM tests.
- For more detailed overviews of the status of various FCC physics studies (and their detector implications) see the slides at the London FCC week.

FCC= ultimate energy frontier machine



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

Disclaimer



Monday, 8 January

9:00 → 09:40 Reception & Welcome — 40m — KOL-F-117

9:40 → 10:20 Claudia Cornella - BSM in the third generation — 40m — KOL-F-117
Speaker: Claudia Cornella
Cornella_Z...

10:20 → 11:00 Marc Riembau - Positiveness and collider phenomenology — 40m — KOL-F-117
Speaker: Mr Marc Riembau (CERN)
Riembau_2...

11:00 → 11:30 Coffee Break — 30m — KOL-F-117

11:30 → 12:10 Silvia Ferrario Ravasio - Developments in Monte Carlo Event Generators — 40m — KOL-F-117
Speaker: Silvia Ferrario Ravasio (CERN)
Ferrario_Z...

12:10 → 12:50 Andrea Wulzer - Muon Colliders — 40m — KOL-F-117
Speaker: Andrea Wulzer (IFAE and ICREA -- Barcelona, Spain)
talk_wulzer...

12:50 → 14:20 Lunch — 1h 30m — KOL-F-117

14:20 → 15:00 Juan Rojo - Proton Structure from the LHC to Future Colliders — 40m — KOL-F-117
Speaker: Dr Juan Rojo (VU Amsterdam and Nikhef)
rojo-zpw20...

15:00 → 15:40 Christoph Paus - Electroweak Precision Measurements at the FCC — 40m — KOL-F-117
Speaker: Christoph Paus (Massachusetts Inst. of Technology (US))
fccee-ew-p...

15:40 → 16:10 Coffee Break — 30m — KOL-F-117

16:10 → 16:50 Michele Selvaggi - Higgs Precision at HL-LHC and FCC — 40m — KOL-F-117
Speaker: Michele Selvaggi (CERN)
higgs_hllhc...

16:50 → 17:30 Ilaria Brivio - SMEFT vs HEFT for new physics searches at the LHC — 40m — KOL-F-117
Speaker: Ilaria Brivio (University & INFN Bologna)
slides_ZP...

Tuesday, 9 January

9:00 → 09:40 Stefan Weinzierl - Add a mass and make your life more complicated — 40m — KOL-F-117
Speaker: Stefan Weinzierl
zuerich5.pdf

9:40 → 10:20 Stefano Frixione - On Simulations at e+e- Colliders — 40m — KOL-F-117
Speaker: Stefano Frixione (INFN)
eeisr.pdf

10:20 → 10:50 Coffee Break — 30m — KOL-F-117

10:50 → 11:30 Joe Davighi - The Flavour of BSM: from LHC to future experiments — 40m — KOL-F-117
Speaker: Joseph Enea Davighi
ZPW_Davi...

11:30 → 12:10 Rebeca Gonzalez Suarez - The FCC project overview — 40m — KOL-F-117
Speaker: Rebeca Gonzalez Suarez (Uppsala University (SE))
ZPW2024_...

12:10 → 13:40 Lunch — 1h 30m — KOL-F-117

13:40 → 14:20 Jernej Kamenik - Flavour changing Z and Higgs decays at FCC-ee — 40m — KOL-F-117
Speaker: Jernej F. Kamenik

14:20 → 15:00 Matthew McCullough - Theory perspective on the FCC physics programme — 40m — KOL-F-1...
Speaker: Matthew Philip Mccullough (CERN)

Wednesday, 10 January

9:00 → 09:40 Sarah Williams - BSM searches at FCC — 40m — KOL-F-117
Speaker: Sarah Louise Williams (University of Cambridge (GB))

9:40 → 10:20 David Sutherland - Future Signatures of a Non-decoupling Higgs sector — 40m — KOL-F-117
Speaker: David Sutherland

10:20 → 10:50 Coffee Break — 30m — KOL-F-117

10:50 → 11:30 Peter Skands - Recent Developments in VINCIA and PYTHIA — 40m — KOL-F-117
Speaker: Prof. Peter Skands (Monash University (AU))

11:30 → 12:10 Pier Monni - QCD challenges at the FCC-ee — 40m — KOL-F-117
Speaker: Pier Francesco Monni (CERN)

12:10 → 13:40 Lunch — 1h 30m — KOL-F-117

There are a lot of FCC talks at this workshop (this is a good thing)!

I apologies that there will be some overlap/interplay with other talks (I have tried to minimize).

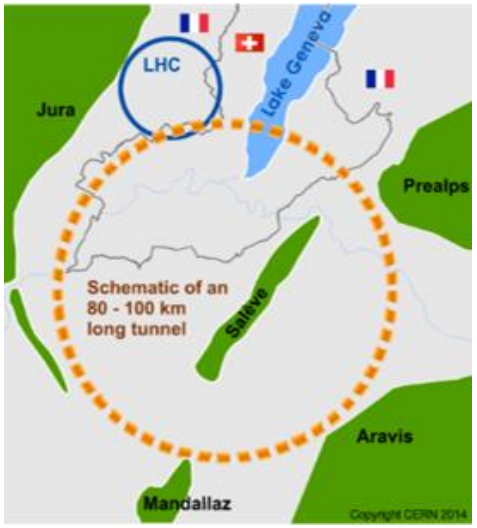
=> on some level: the entire FCC physics programme constitutes the most comprehensive BSM search we can perform!

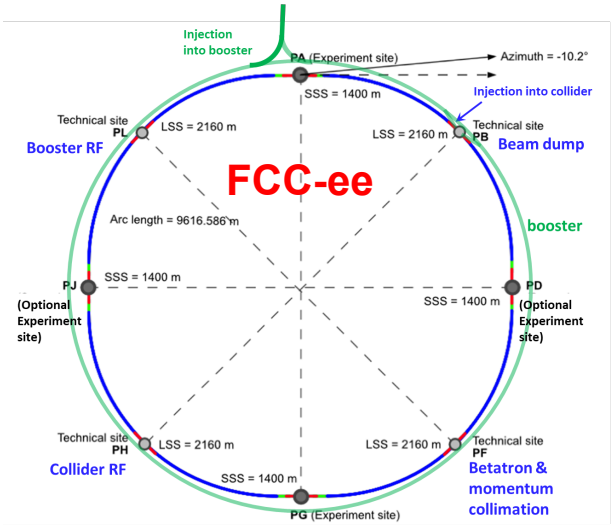
Reminder: Integrated FCC programme

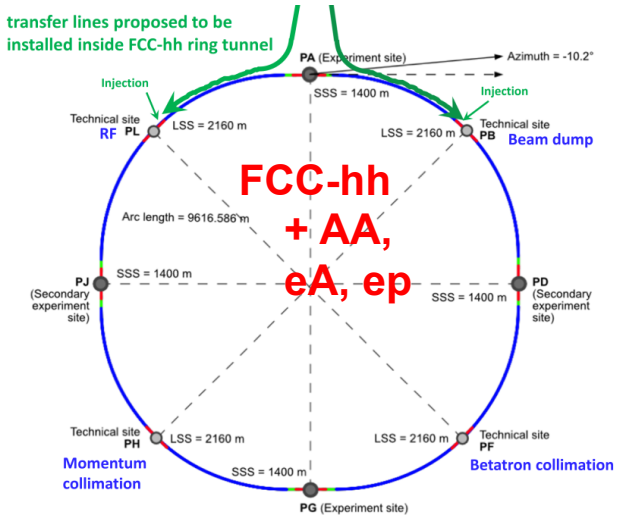
Taken from slides by M. Benedikt at FCC week.

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 (FCC-eh).







2020 - 2040 | 2045 - 2063 | 2070 - 2095

Integrated FCC programme

Taken from slides by F. Gianotti at FCC week.

	√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 x 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	5-30 x 10^{34} 30	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

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.

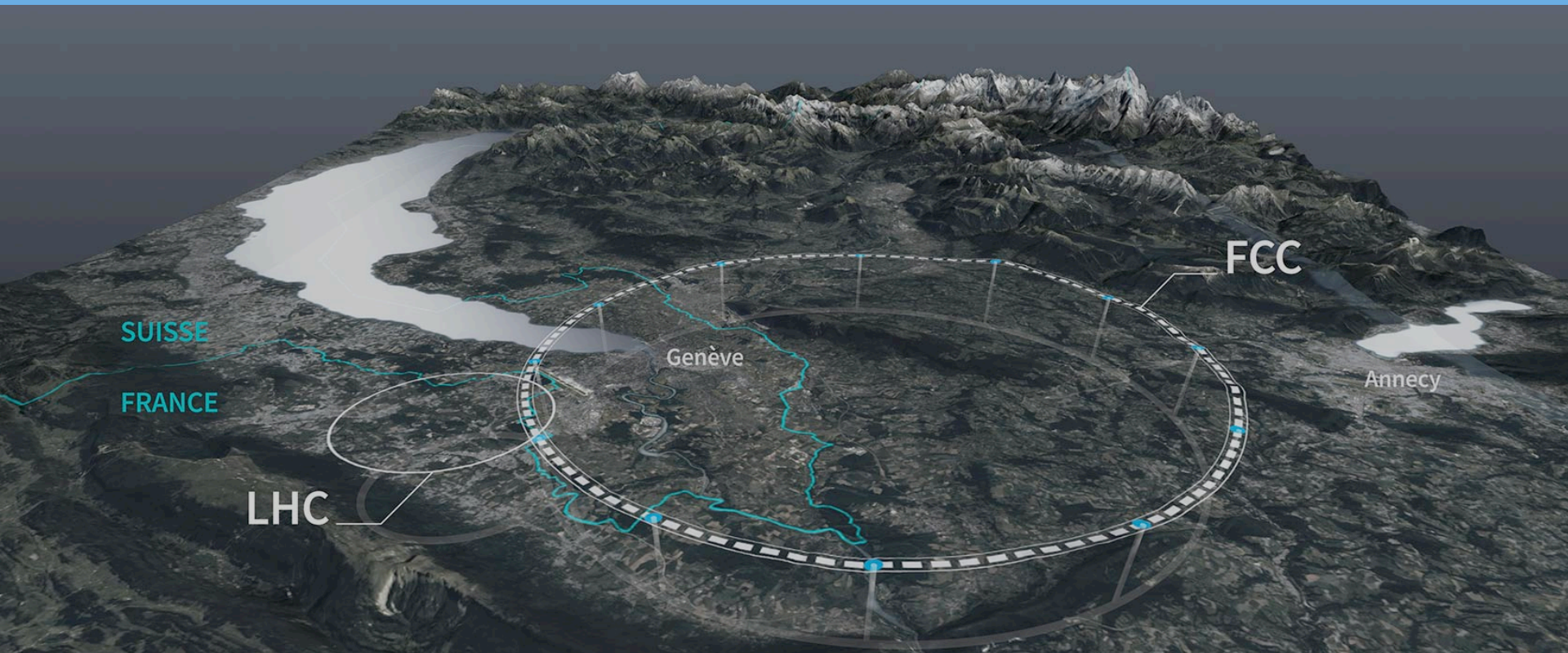
FCC-ee:

- 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 the FCC programme



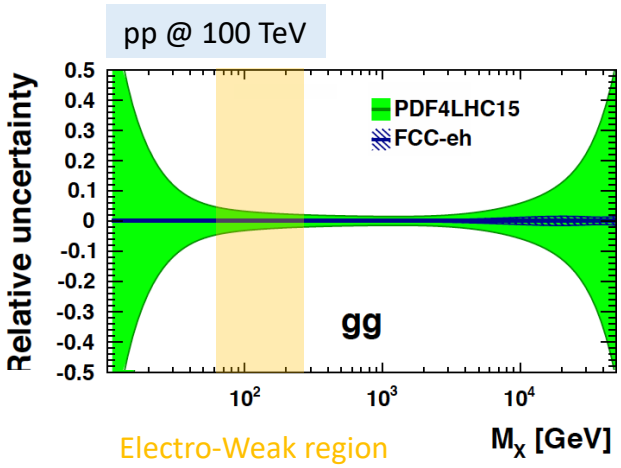
Integrated programme combines precision at the intensity frontier (FCC-ee) giving indirect sensitivity to a multitude of NP as well as unique direct sensitivity to low-mass and weakly interacting BSM physics, with discovery potential at the energy frontier (FCC-hh) that will furtger extend the precision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

Synergies in FCC programme

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

Taken from updated HE-LHC CDR

Opportunities for FCC-eh…

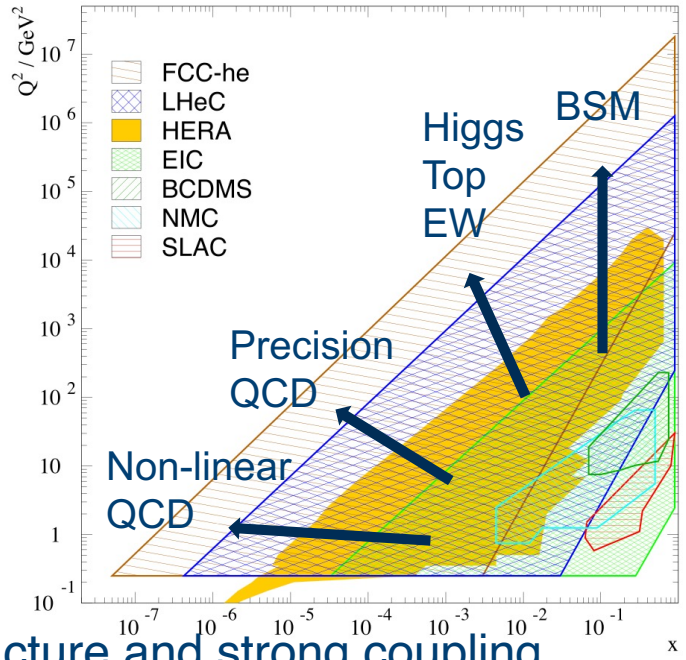


~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)



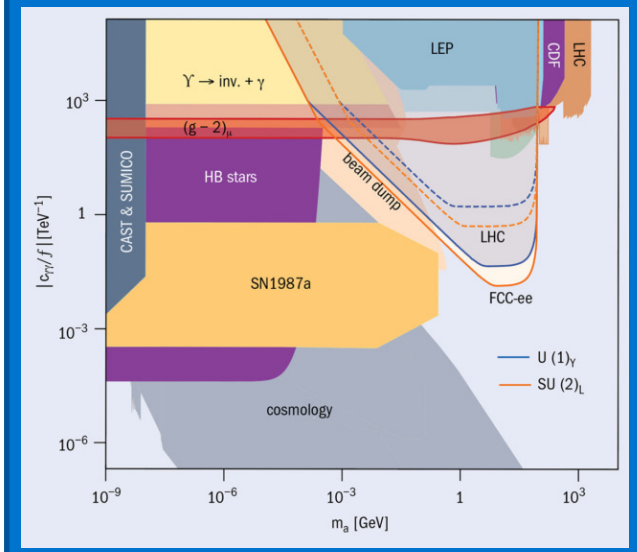
- Empower FCC-hh with precision input on hadron structure and strong coupling (to permille accuracy) during parallel running.
- Complementary measurements of Higgs couplings (CC+NC DIS x-sections, no pile-up, clean).
- Plus… complementary BSM prospects (LLPs, LFV, not-too-heavy scalars, GeV-scale bosons)-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

FCC-ee and -hh synergies – BSM searches

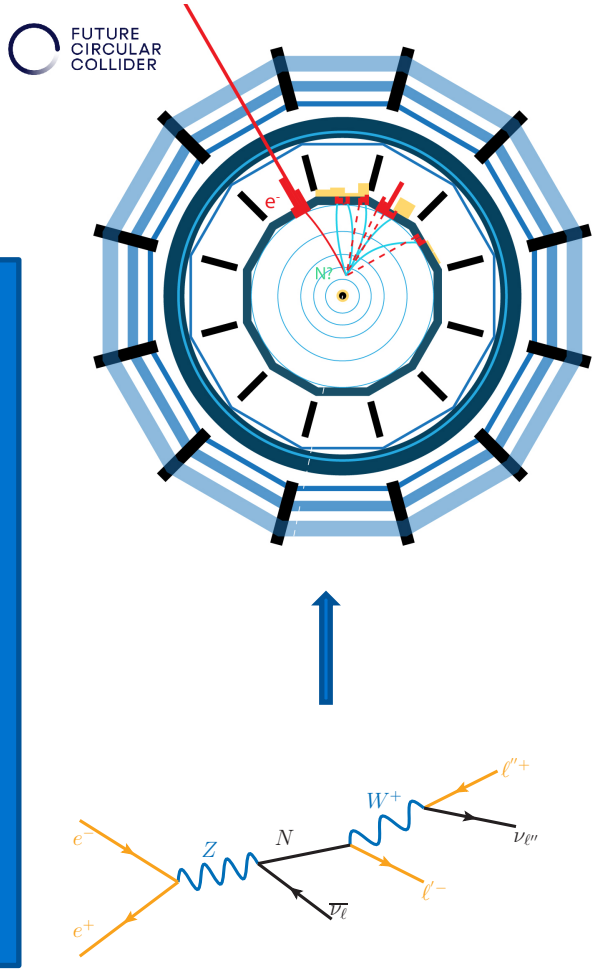
See slides by G. Salam at FCC week

Direct FCC-ee sensitivity

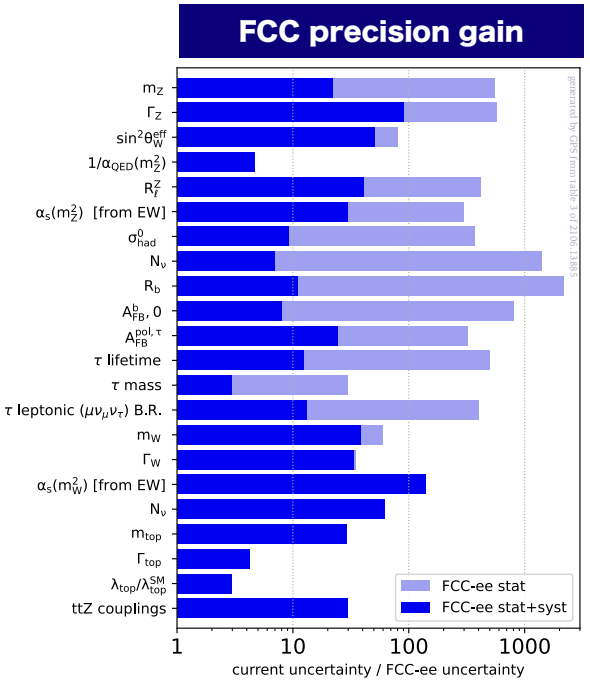
- HNLs
- Alps
- Exotic Higgs decays



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



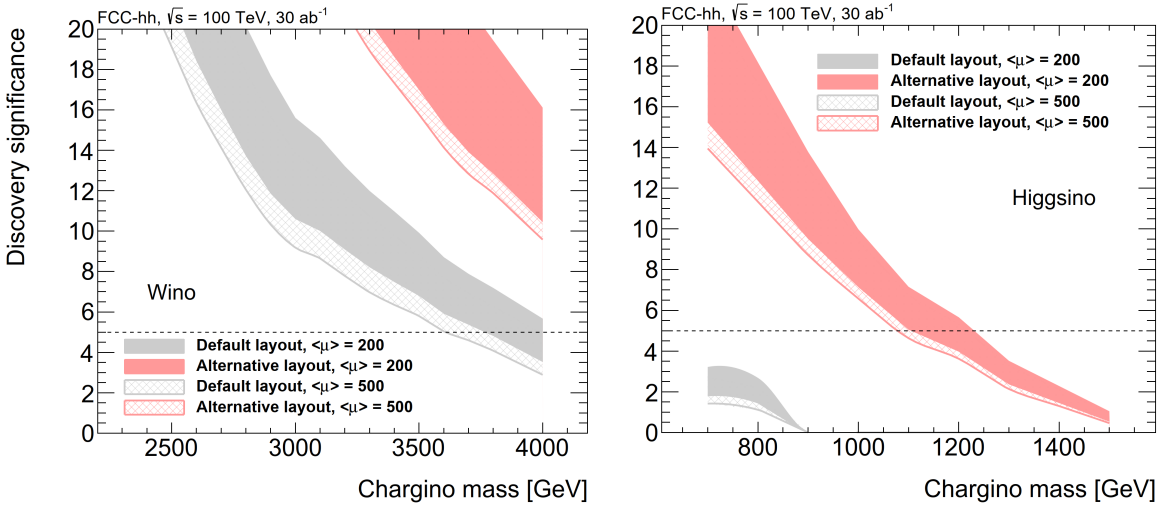
…plus **indirect access** to a range of BSM phenomena through ultra-precise measurements of SM parameters…

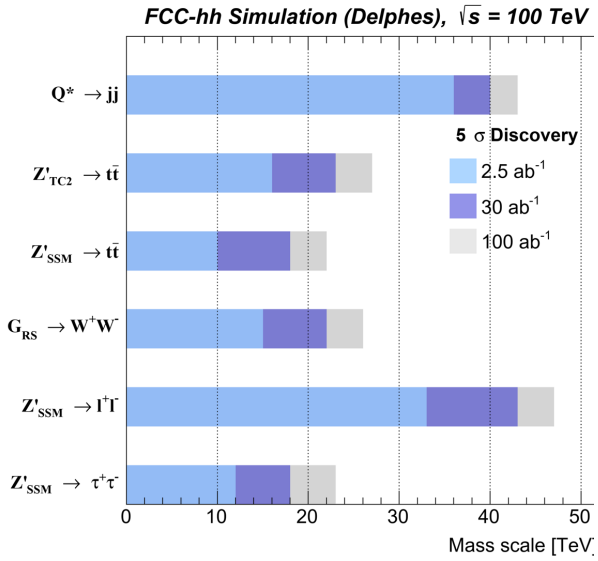


FCC-ee and -hh synergies - BSM searches

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

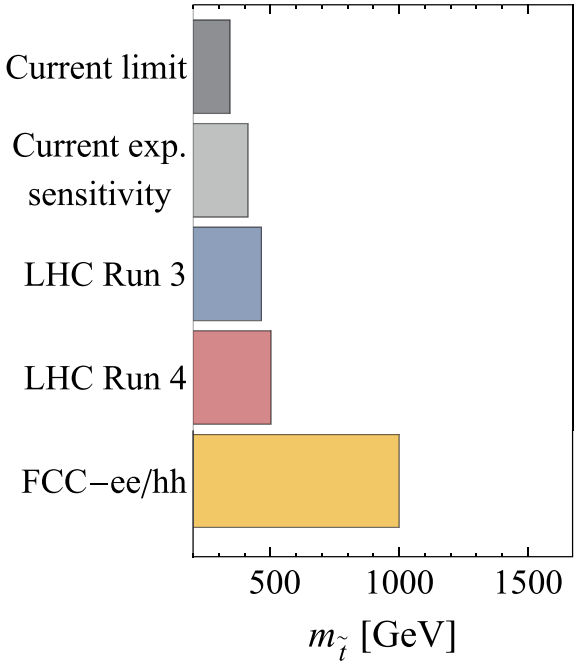
In summary- exciting possibilities to discover/characterize NP that could be indirectly predicted through precision measurements at FCC-ee

FCC-ee BSM snapshot

Taken from FCC Snowmass submission

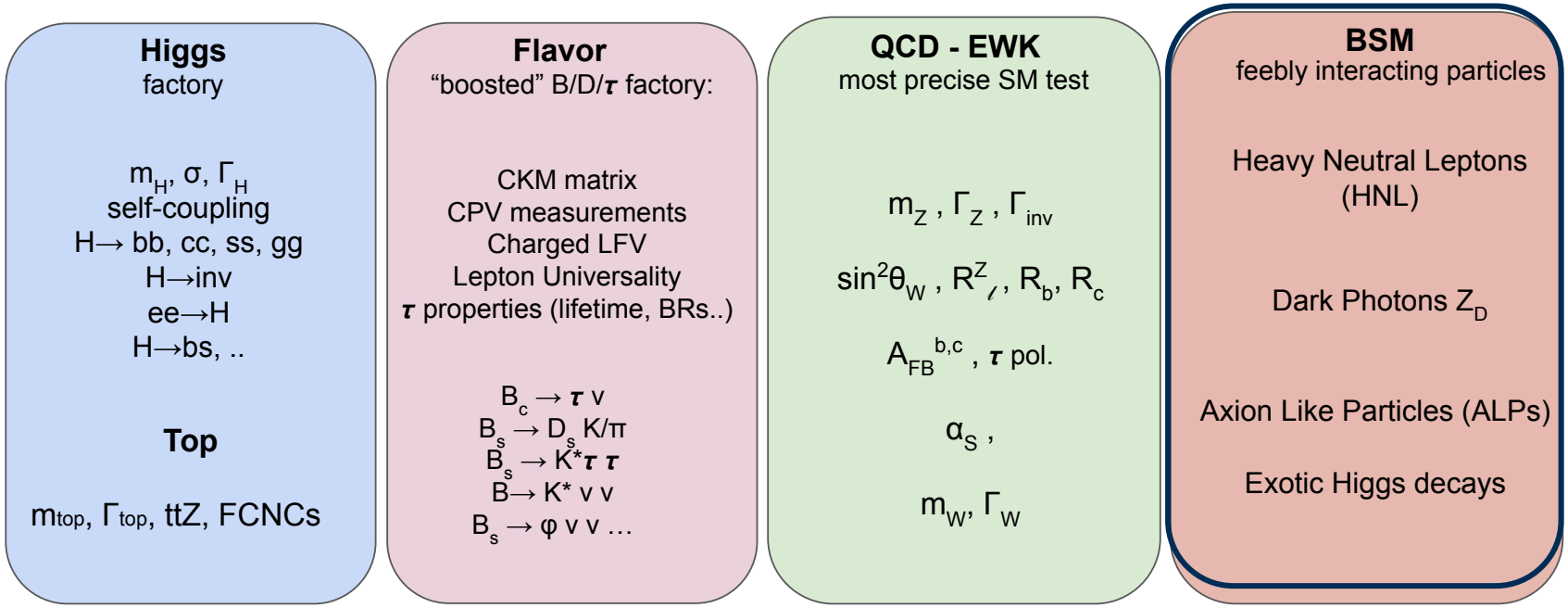
1. Indirectly discover new particles coupling to the Higgs or EW bosons up to scales of $\Lambda \approx 7$ and 50 TeV.
2. Perform tests of SUSY at the loop level in regions not accessible at the LHC.
3. Study heavy flavour/tau physics in rare decays inaccessible at the LHC.
4. Perform searches with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

Image credit: FCC CDR



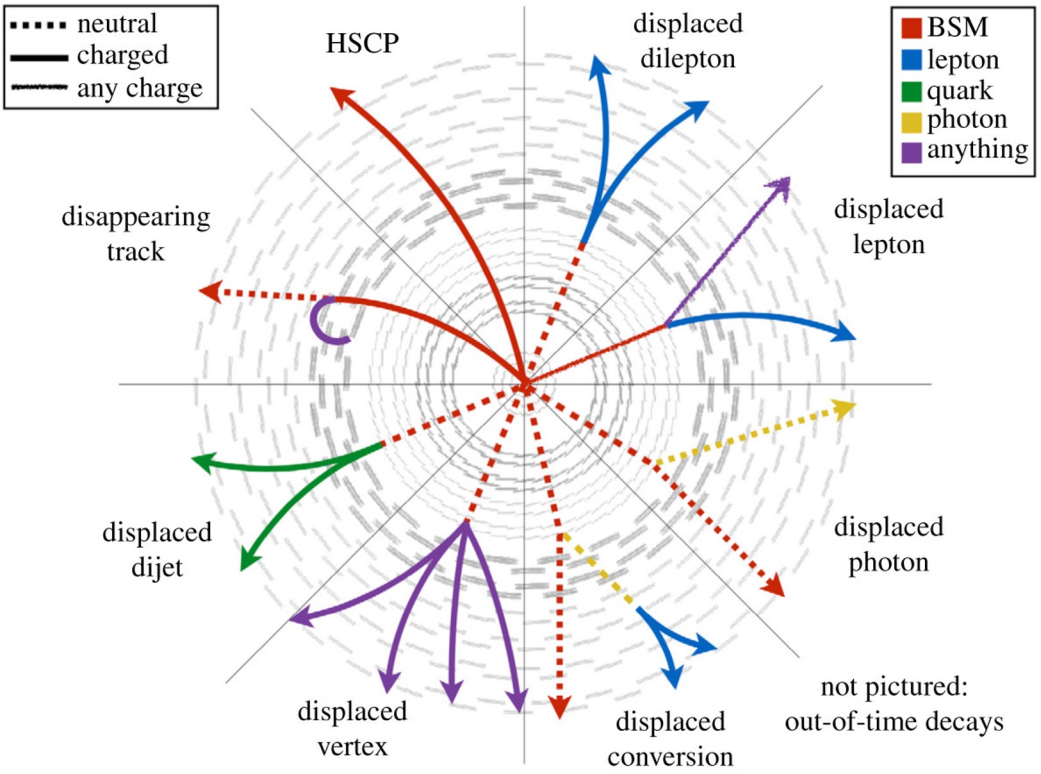
Projected 2σ indirect reach from Higgs couplings on stops.

Physics landscape at FCC-ee



- Broad landscape of physics opportunities which include direct and indirect sensitivity to new physics.
- Unique sensitivity to feebly interacting particles and LLPs means we are in an exciting position to design detectors with these scenarios in mind.

FCC-ee case study: LLPs



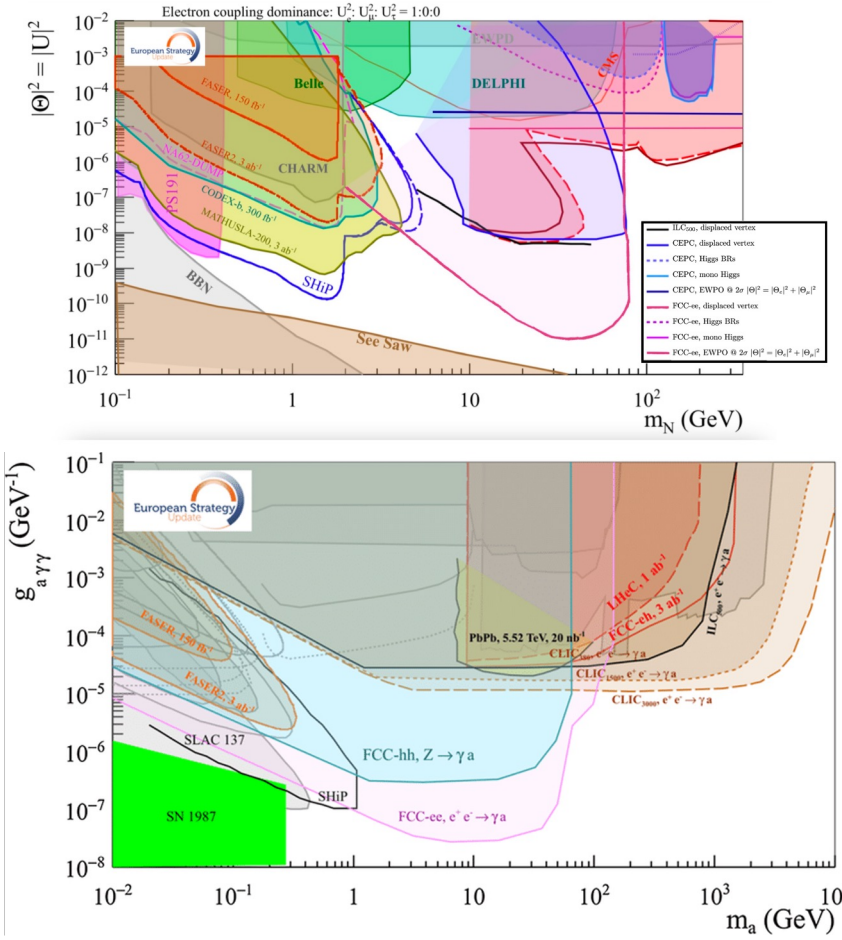
LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

- 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

- 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).



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.

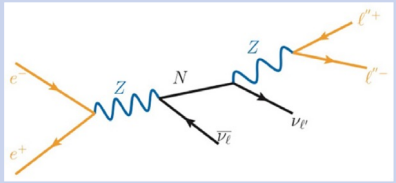
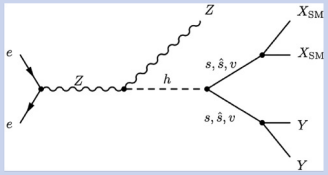
Searches for long-lived particles at the future FCC-ee

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!

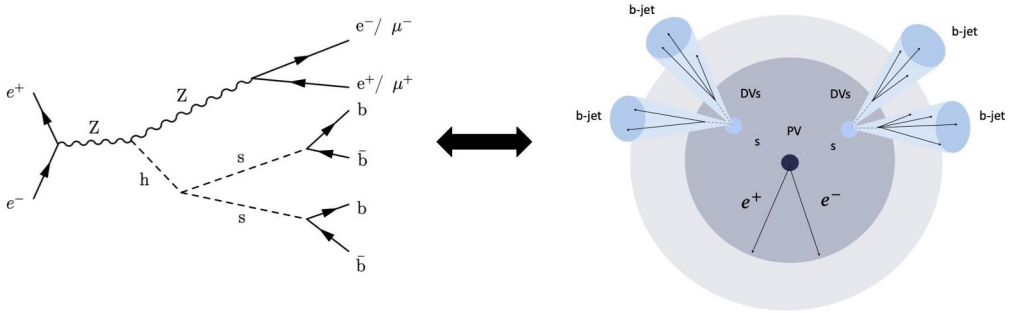
Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and detector-level selection studies for ee$\nu\nu$. First look at Dirac vs Majorana	• Update ee$\nu\nu$ studies for winter23 samples. • First look at $\mu\mu\nu\nu$ 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

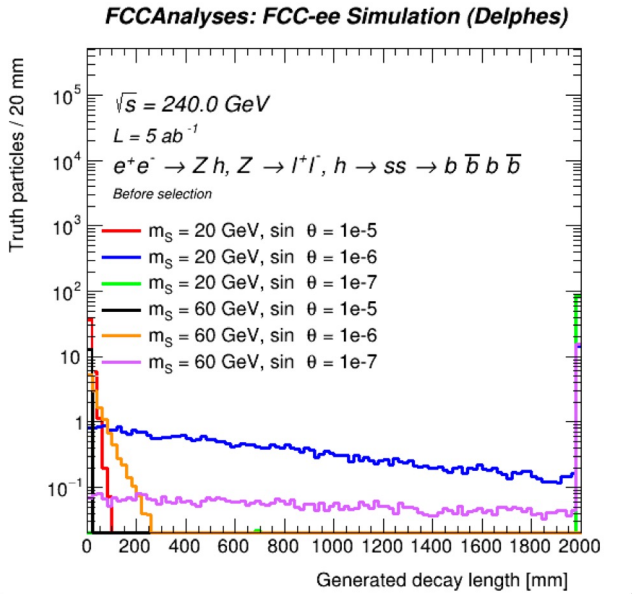
Nice overview by Juliette Alimena at EPS 2023

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.



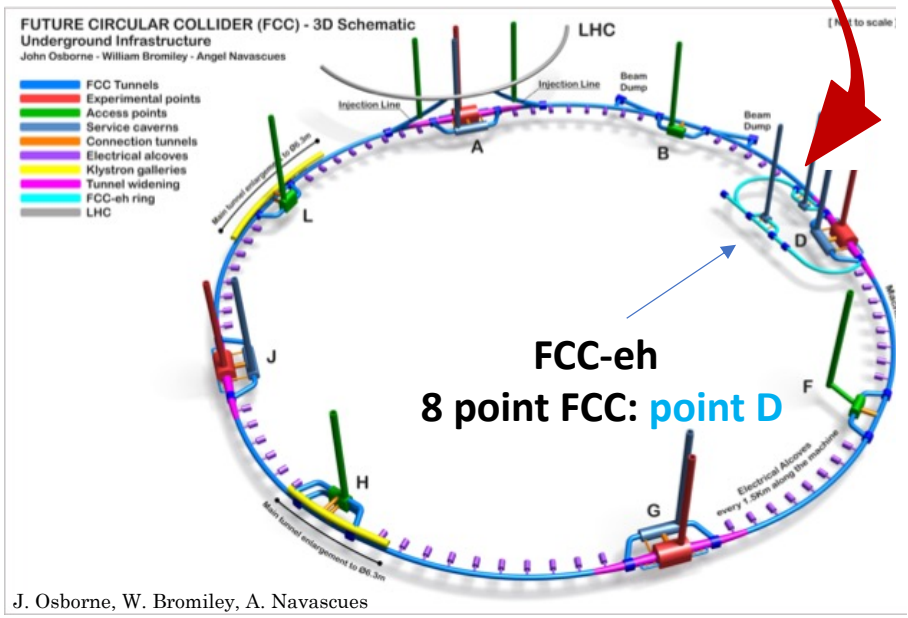
For further details see presentation by Magda at topical ECFA WG1-SRCH meeting

FCC-eh

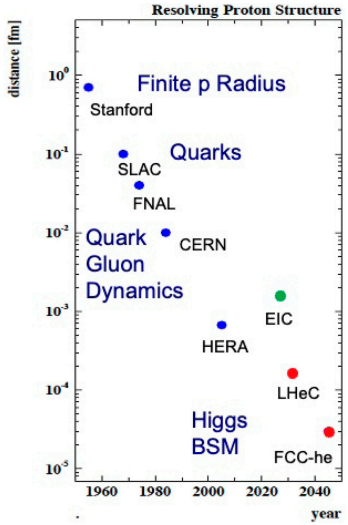
For a nice review of electron-hadron colliders (including EIC) see https://cds.cern.ch/record/2811194

Novel use of Energy Recovery Linac (ERL) technology that will be demonstrated with the PERLE ERL demonstrator

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



Use of ERL technologies a key step towards improving sustainability whilst maintaining high luminosities.

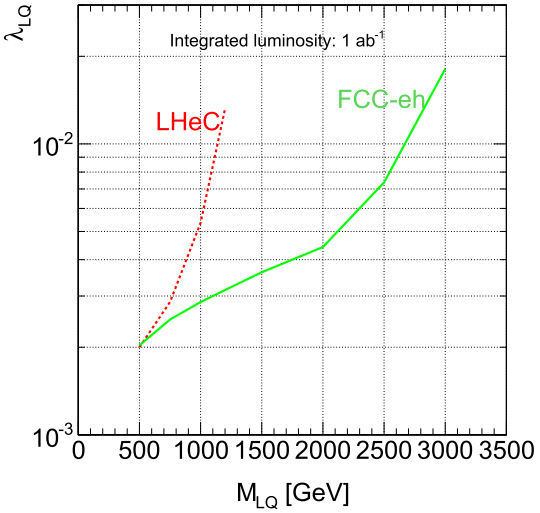


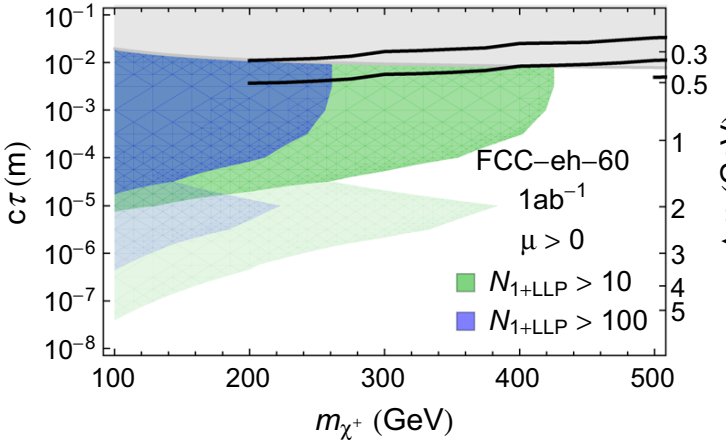
Relatively keen environment associated with e-p collisions provides a new window to discover new physics…

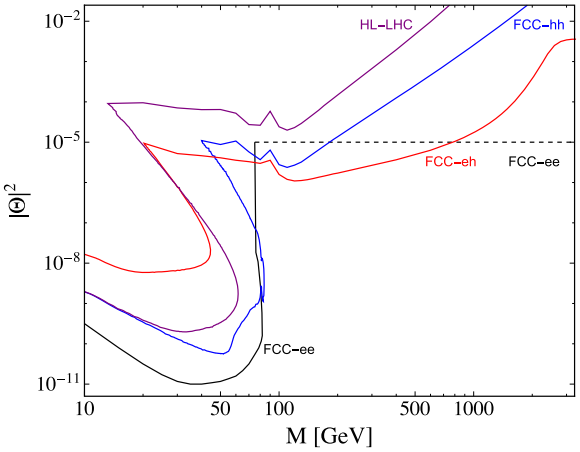
Taken from slides by J. D"Hondt at FCC week

FCC-eh BSM snapshot

1. Unique opportunities for leptoquark searches up to 3 TeV.
2. Sensitivity to compressed supersymmetric scenarios that would elude discovery at FCC-hh.
3. Novel charged current interactions for Heavy Neutral Lepton (HNL) discovery







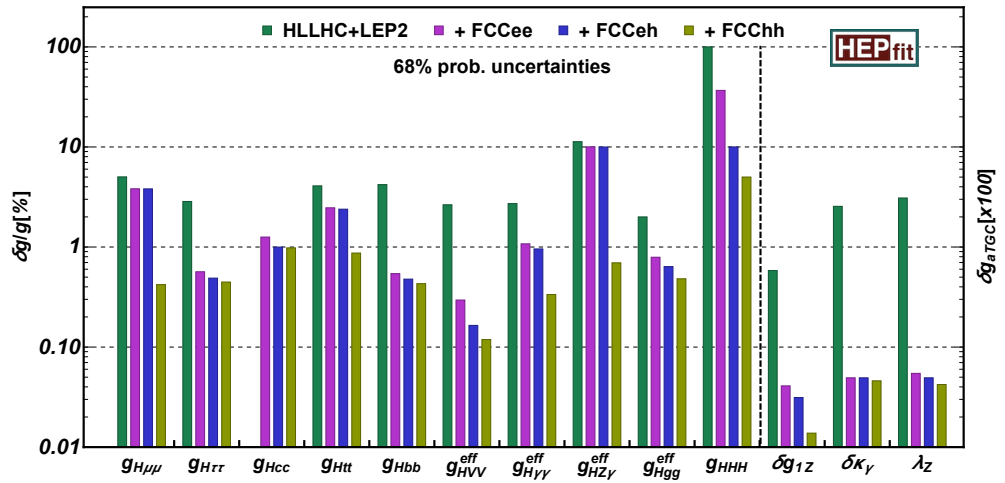
Plots taken from vol. 1 of FCC CDR: https://fcc-cdr.web.cern.ch/

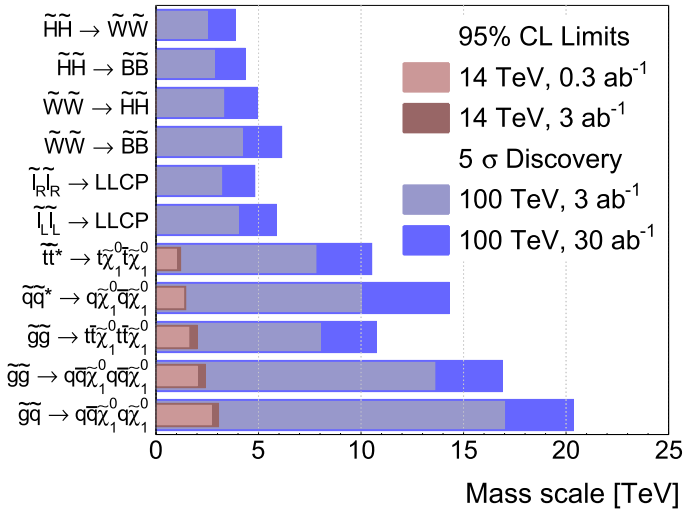
FCC-hh BSM snapshot

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

1. Direct discovery potential up to ~50 TeV.
2. Precision measurement of Higgs self coupling.
3. Conclusively test the WIMP dark matter paradigm.

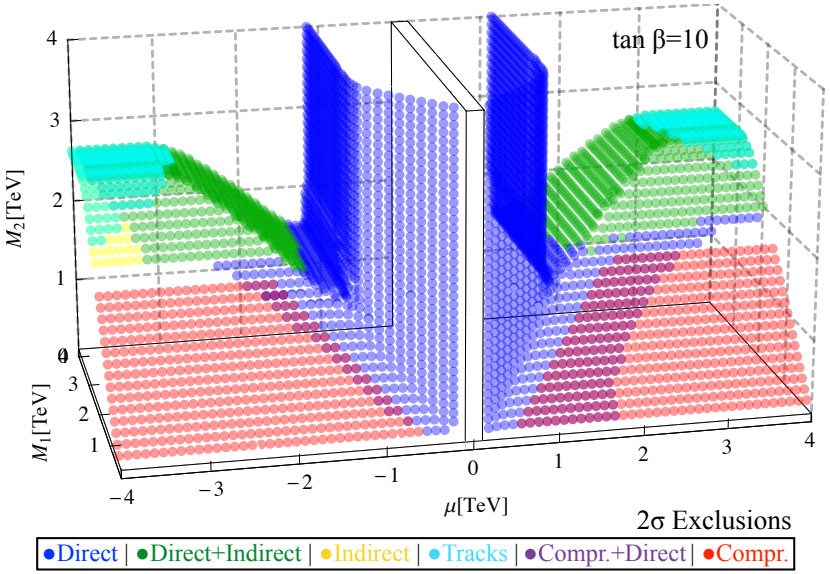
Plus: further indirect probes through rarer/higher mass Higgs processes.





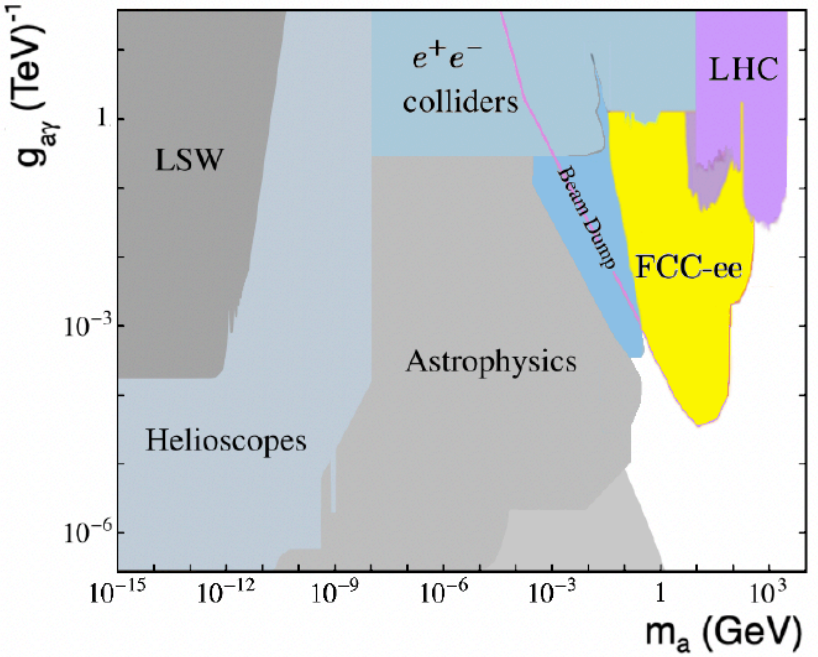
Dark matter complementarity…

… between direct/indirect detection and collider searches…



Full coverage of thermal surface in MSSM (image credit: arXiv:1606.00947)

… between collider, non-collider searches + astrophysical constraints…



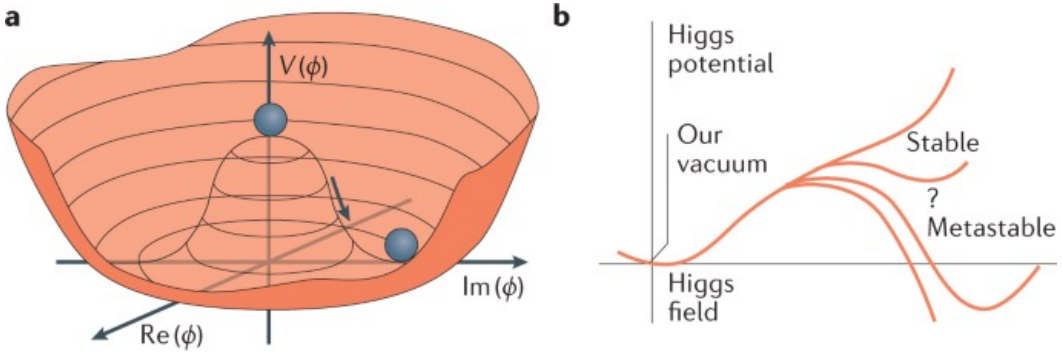
ALP sensitivity (FCC-ee focussed) shown in Rebeca's slides yesterday.

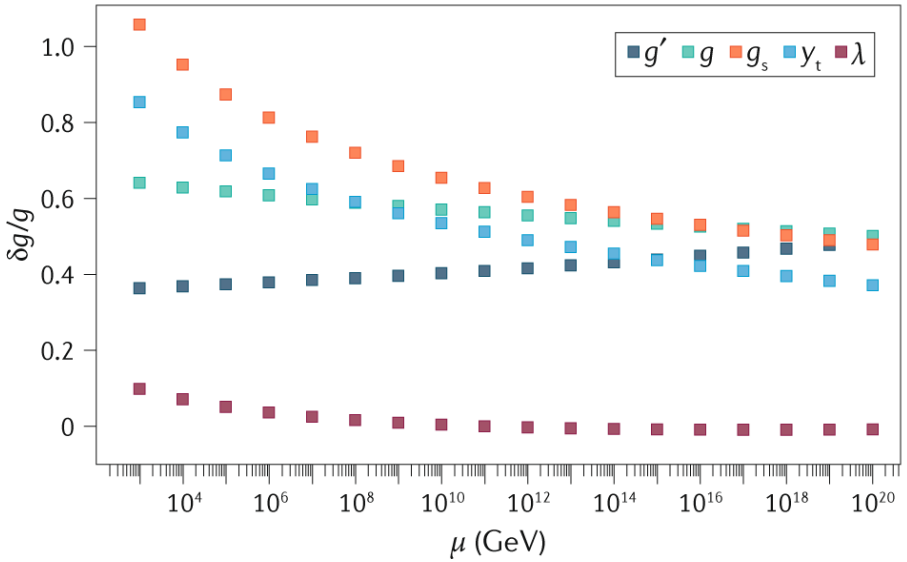
Back to slide 26

Significance of Higgs self coupling

https://www.nature.com/articles/s42254-021-00341-2

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$



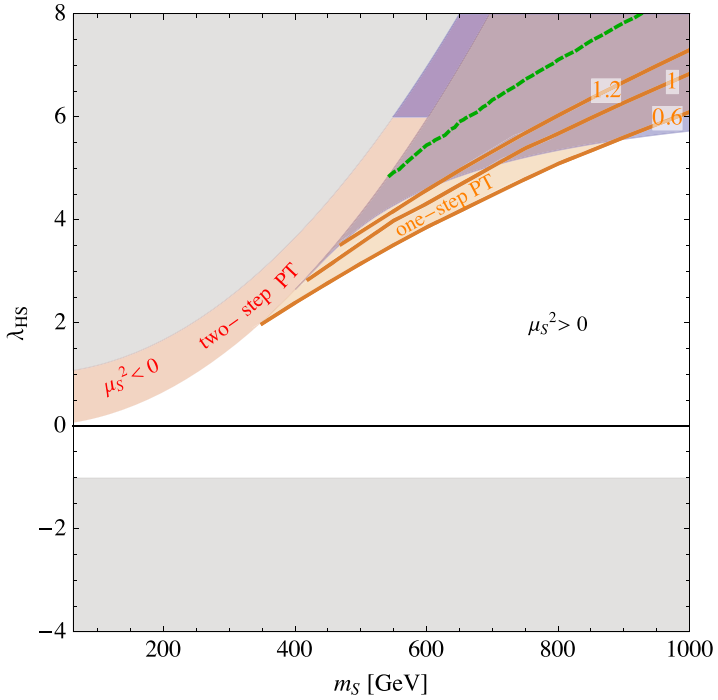


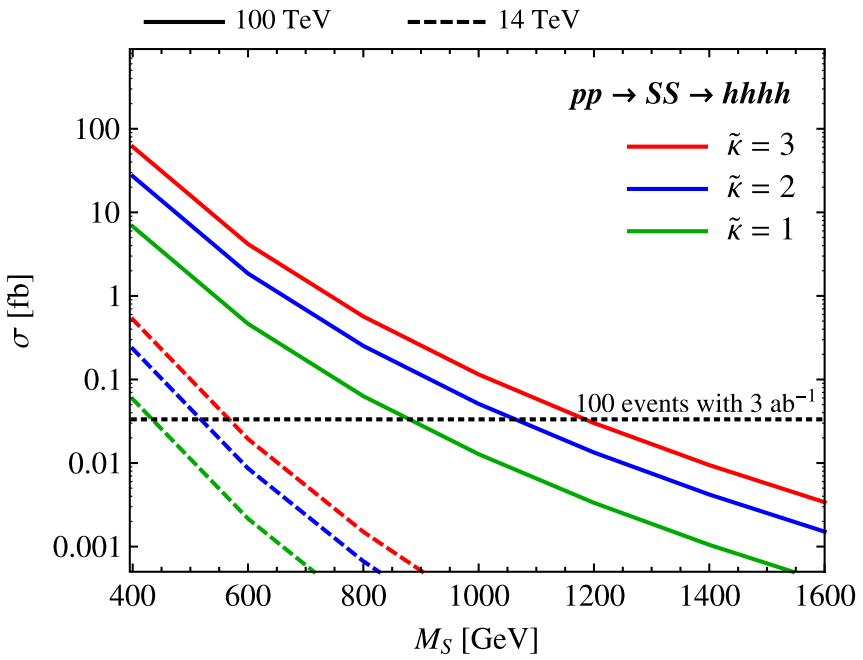
- On EWSB λ gives 3-higgs and 4-higgs (self-) interaction vertices - accessed through di-Higgs production at the LHC and future colliders.
- Direct measurement could provide key understanding of EWPT and possible portal to new physics.

Probing EWPT at the FCC

https://arxiv.org/abs/1511.06495

New physics required for a strong first order phase transition (needed for EWK baryogenesis) either by directly discovering new states (which can't be too much heavier than the Higgs) or through O(1) deviations in the Higgs self-coupling (which will be measured to ~ 10%).





Thoughts for the future

We are In the middle of an exciting journey with significant opportunities and challenges.

- How can we better work together to:
  - Build/gather consensus?
  - Overcome challenges (technical, financial, sociological)
  - Balancing current and future projects?

Some ideas from this workshop

- MC generators and theory predictions.
- Model building - are we missing topologies?
- Refining benchmarks

+ some you might have?

What's in a name?

FUTURE CIRCULAR COLLIDER

ADJECTIVES STARTING WITH F

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

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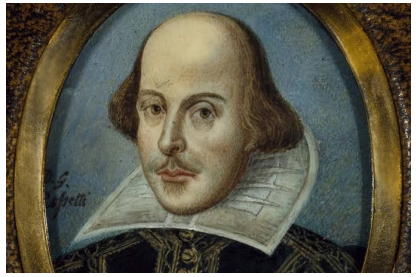
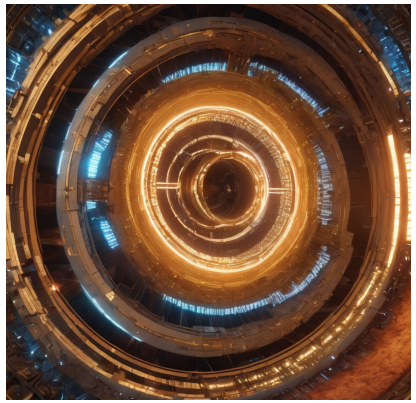
Safer starting point?





POSITIVE ADJECTIVES THAT START WITH F

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

Next step

If only...

Hopefully

Hopefully

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

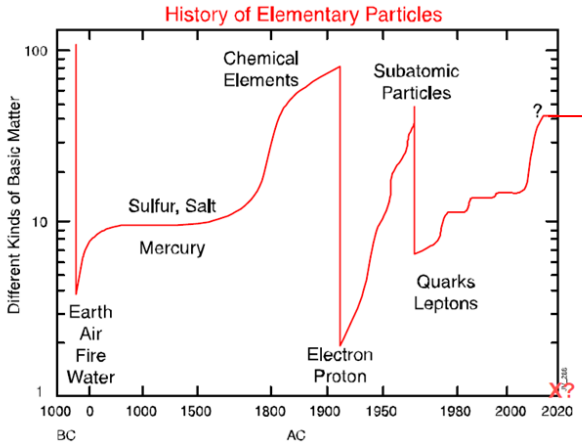
Conclusion and outlook

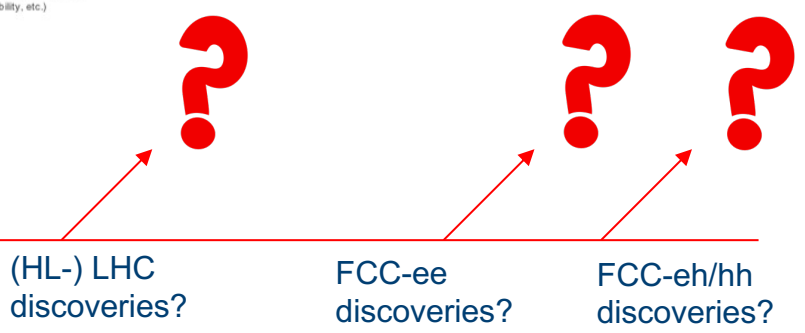
Integrated FCC programme exploits complementarities and synergies between ee/ep/pp collisions to maximise BSM sensitivity through:

1. Ultra-precise measurements of EW/top/higgs parameters in SM.

2. Conclusively probing new states required by a strong 1st order EWPT.

3. Unique reach for less-than weakly coupled particles.





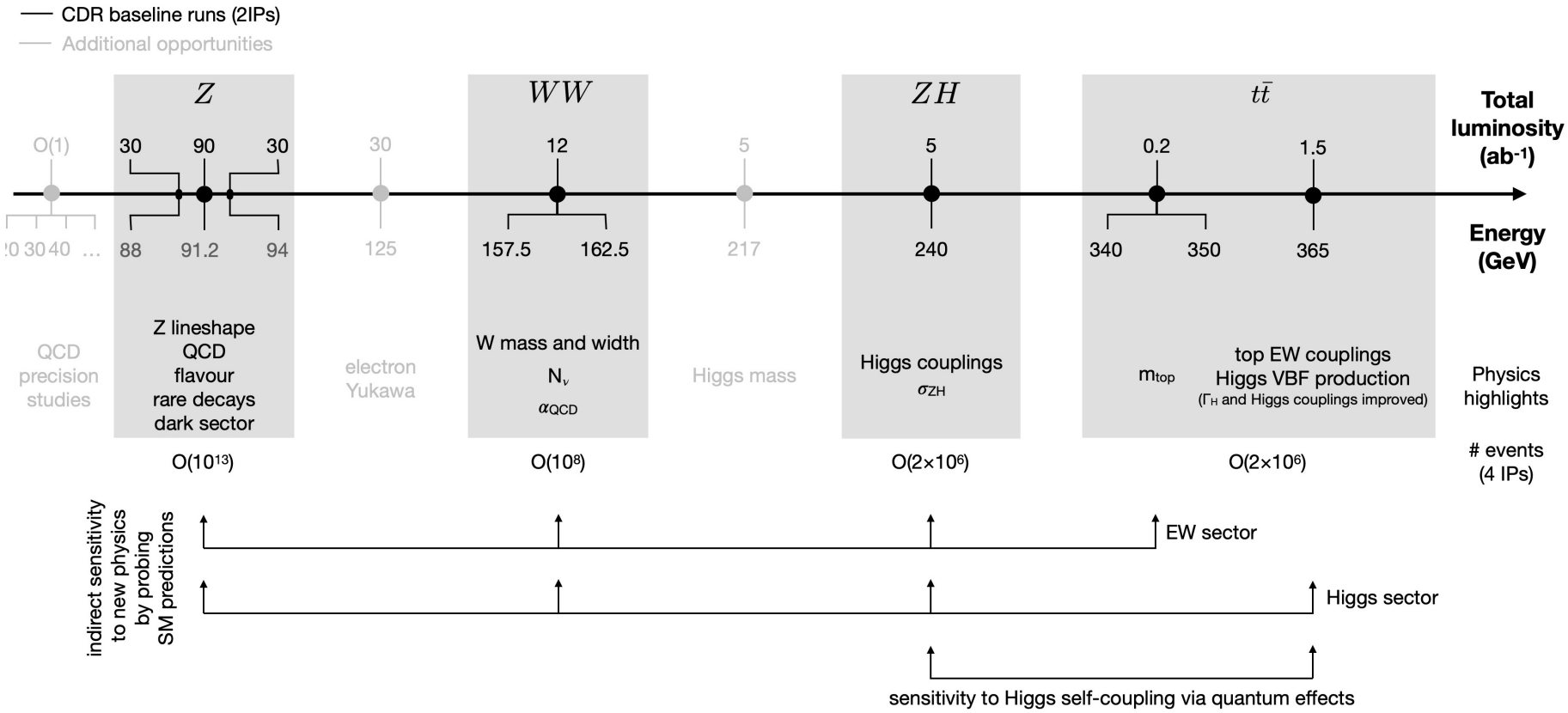
4. Thorough **exploration** of energy frontier.

Thank you for listening- any 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 ($10^{34}\,cm^{-2}s^{-1}$)	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 → H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW → H	

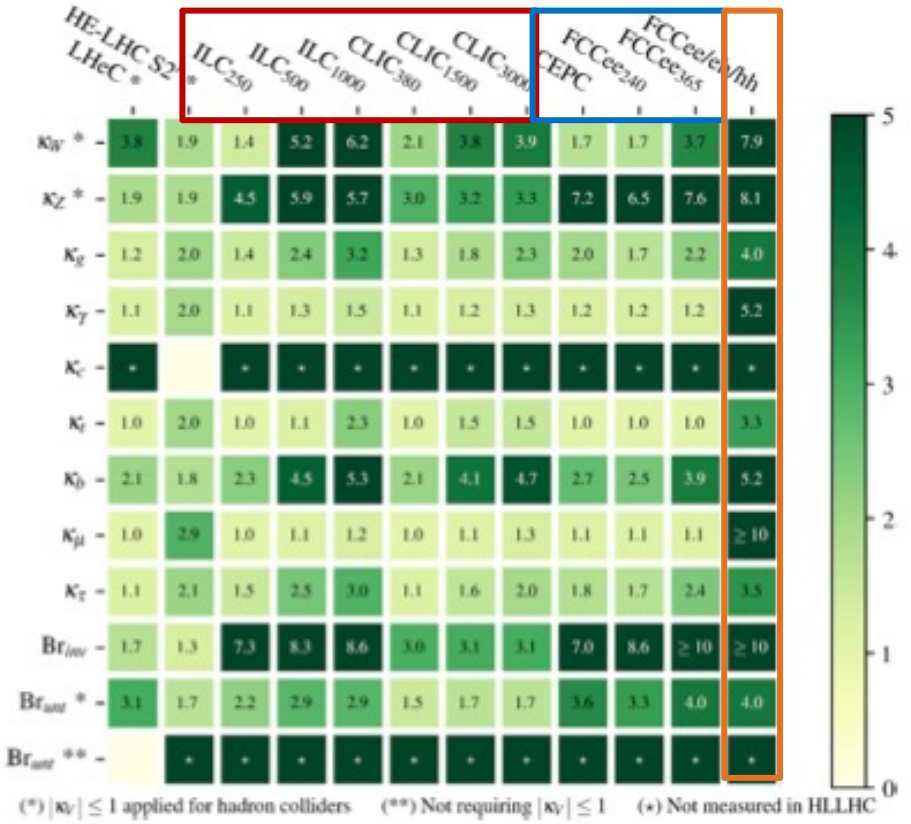
CEPC Operation mode		ZH	Z	W^+W^-	ttbar
		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	*L* / IP [$\times10^{34}$ $cm^{-2}s^{-1}$]	3	32	10	-
	[ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	1×10^{6}	7×10^{11}	2×10^{7}	-
Run time [years]		10	2	1	5
Latest (50MW)	*L* / IP [$\times10^{34}$ $cm^{-2}s^{-1}$]	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).

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.



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FCC and the Higgs potential

Expand Higgs potential about minimum:

$$V(h) = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\sqrt{3\lambda_h}m_h h^3 + \frac{1}{4!}\lambda_h h^4$$

Where

$$m_h^2 = \frac{d^2V(h)}{dh^2}\Big|_{h=0},\ \sqrt{3\lambda_h}m_h = \frac{d^2V(h)}{dh^2}\Big|_{h=0},\ \lambda_h = \frac{d^2V(h)}{dh^2}\Big|_{h=0}$$

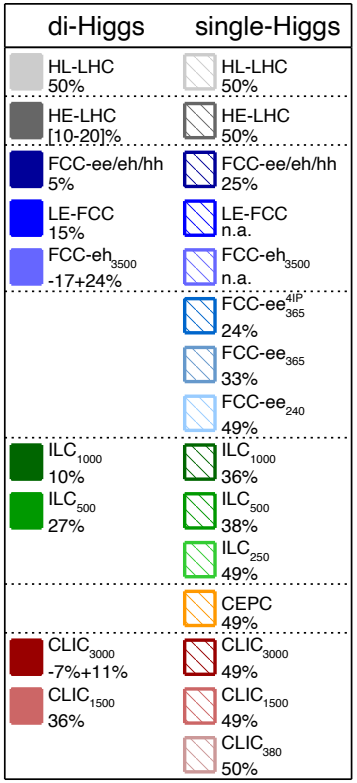
Higgs cubic self-interaction can be directly accessed through di-Higgs production!

Extend SM using EFT where EW symmetry linearly realised

$$\mathcal{L} = \mathcal{L}^{SM} + \frac{c_\phi}{2\Lambda^2}\partial_\mu|\phi|^2\partial^\mu|\phi|^2 - \frac{c_6\lambda_h^{SM}}{\Lambda^2}|\phi|^6$$

$$\rightarrow \kappa_\lambda = \frac{\lambda_h}{\lambda_h^{SM}} = 1 + \left(c_6 - \frac{3}{2}c_\phi\right)\cdot\frac{v^2}{\Lambda^2}$$

Higgs@FC WG *September 2019*



All future colliders combined with HL-LHC

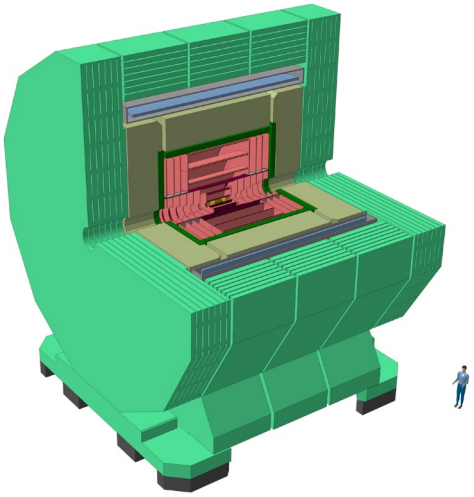
FCC can also provide 2σ sensitivity to Higgs quartic coupling

Sensitivity at 68% CL to "κ_3"(κ_λ)

Detector concepts for FCC-ee

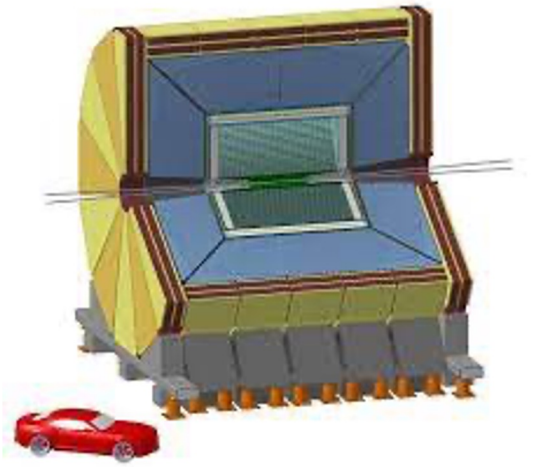
See HECATE article for discussion on gains in sensitivity with additional instrumentation on the cavern

CLD ("CLIC-like Detector")



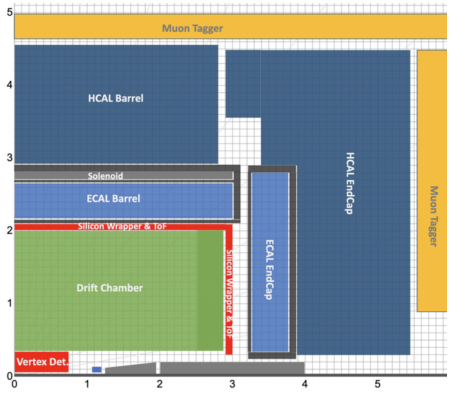
Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

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



Silicon vertex detector
Short-drift chamber tracker.
Dual-readout calorimeter (solenoid inside)

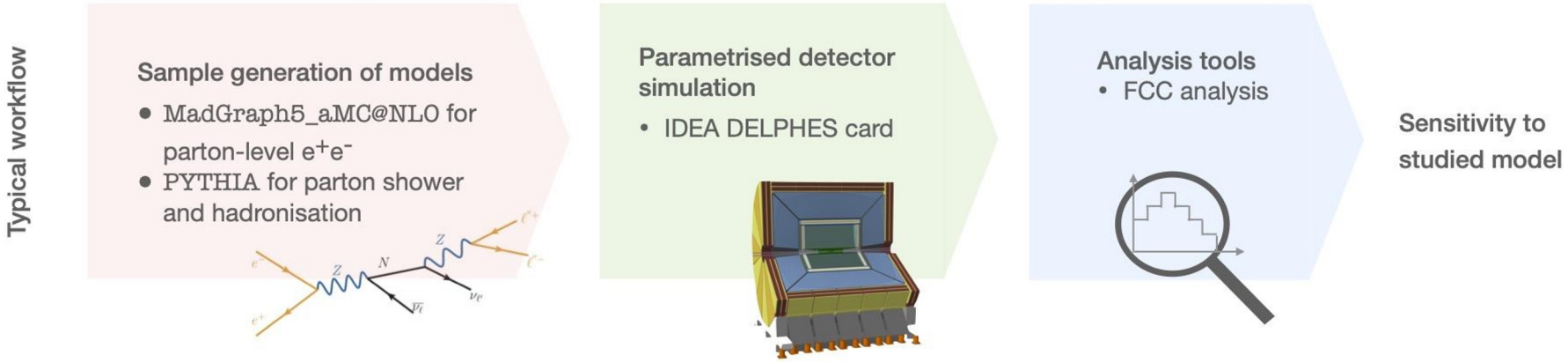
Noble-liquid ECAL (newest proposal)



HG noble liquid ECAL.
LAr or LAr+lead absorber

We have exciting prospects to optimize detector design with LLP searches in mind!

Current workflow in FCC-ee LLP studies



- Use FCCAnalysis software to analyse centrally generated EDM4HEP files, though some signal files produced privately.
- Dedicated LLP tutorial prepared by Juliette Alimena enables full workflow.
- Current limitations include scalability of code and limited MC statistics (more on that later).