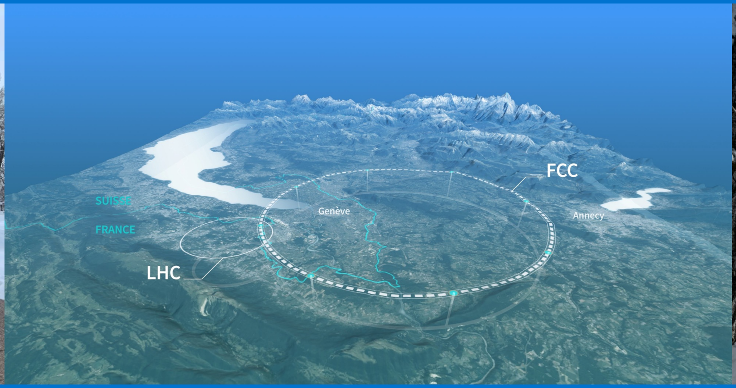
Physics opportunities at (future) e+e- machines

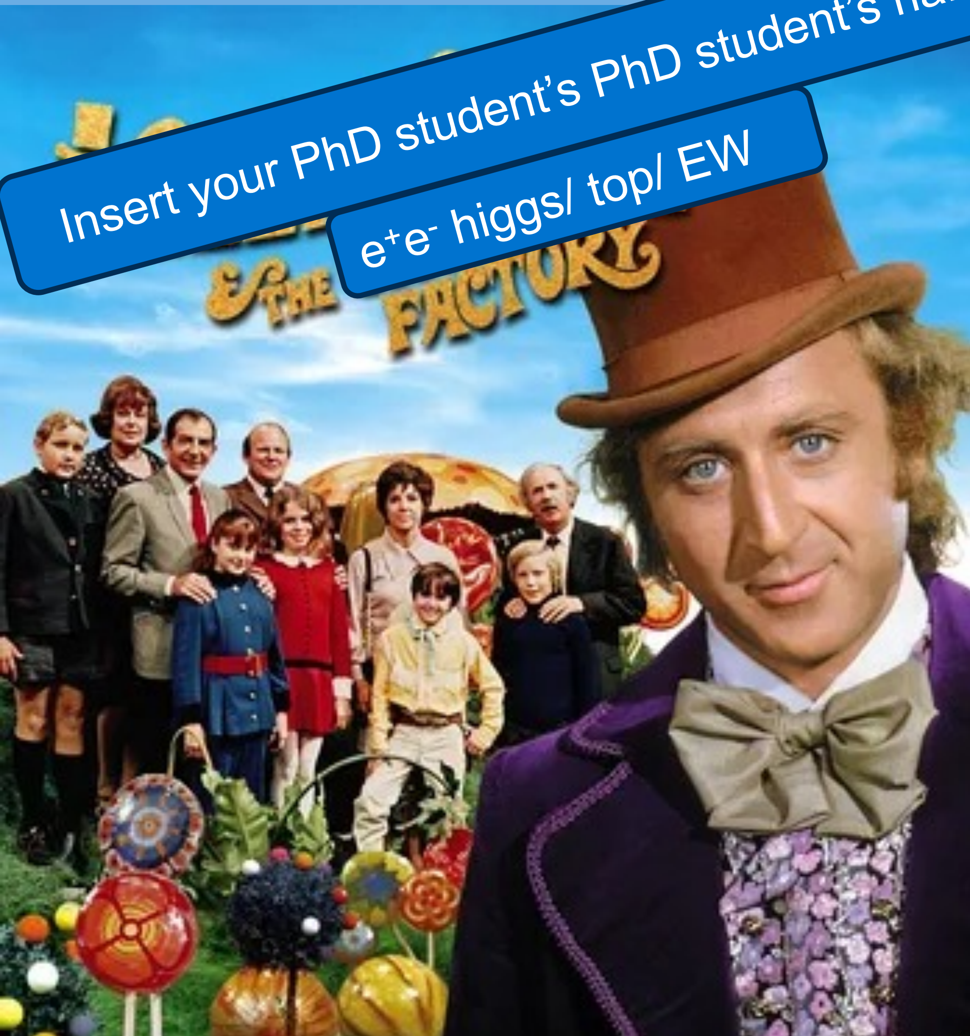


Dr Sarah Williams, University of Cambridge

An alternative title

Insert your PhD student's PhD student's name

e^+e^- higgs/ top/ EW



"A golden ticket for future discoveries…?"

- Not starring: Gene Wilder or Timothee Chalamet
- Potentially starring: some of us?

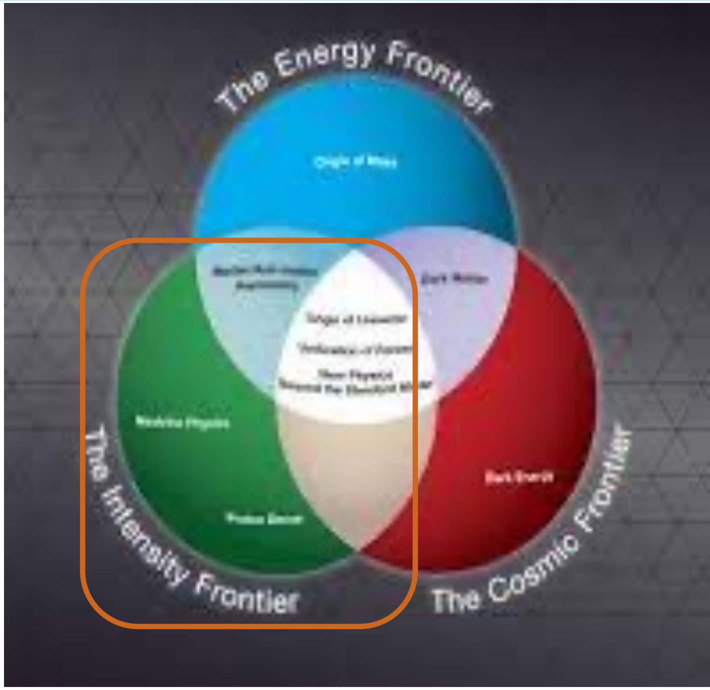
Introduction

Disclaimer: I am NOT going to go through all of the physics opportunities in detail have altered this talk significantly based on discussions from this week

- 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***

- In the next ~ 20 minutes I hope to convince you that a circular e^+e^- machine could do both of these. As a snapshot…
  - Possible evidence for electron/strange yukawa? **(lets challenge ourselves further here…?)**
  - Direct discovery of ~ low-mass (very) weakly coupled BSM.
  - Indirect discoveries up to ~50-100 TeV.



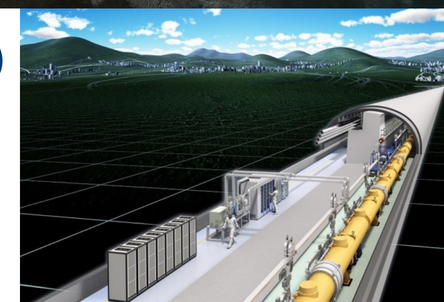
Please ask lots of questions, either after the talk, during coffee, or via email (sarah.louise.williams@cern.ch)

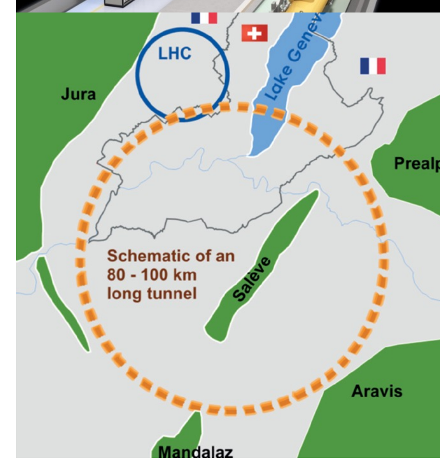
What should come after the HL-LHC?

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?)
    - **HALHF** (??)
    - **C³** (??)
  - Circular collider?
    - **CepC** (China)
    - **FCC-ee/hh** (CERN)
- Hadron collider?
  - **FCC-ee/hh** (CERN)
- Muon collider?





We can't do everything - a coherent global strategy is key!

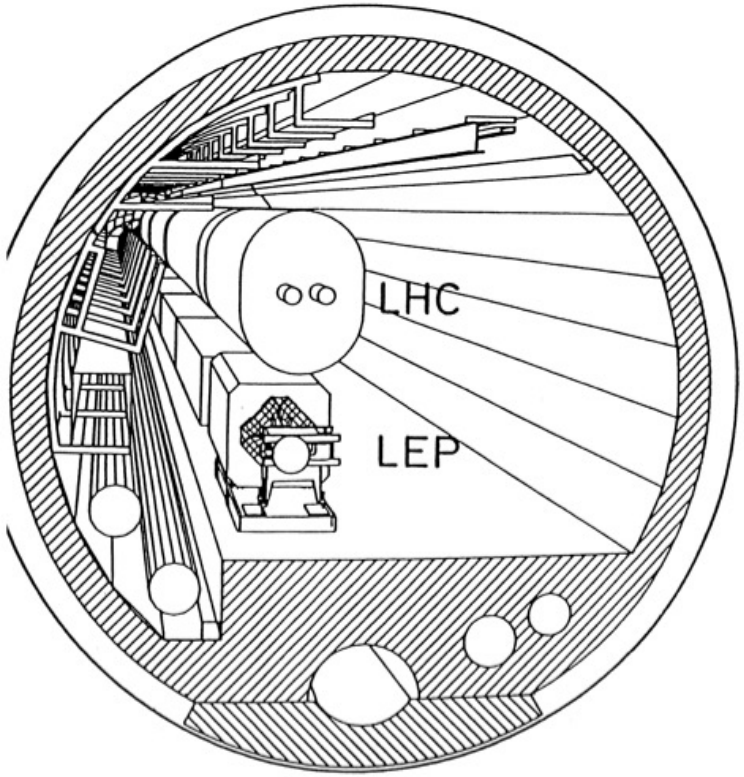
Timescales in particle physics

…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

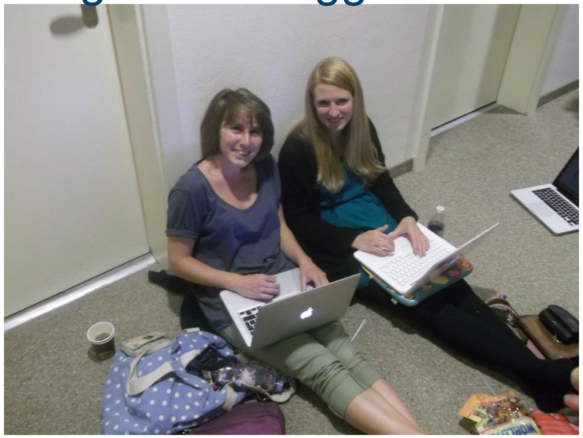
I have only been involved in a small part of the LHC journey…

1995

SW- aged 7

2012

Queuing for the Higgs seminar



What this means for us…?

If we want to avoid a (long) gap in data-taking- decisions on the next collider must happen soon…

2020 European strategy update

"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"

Snowmass 2021

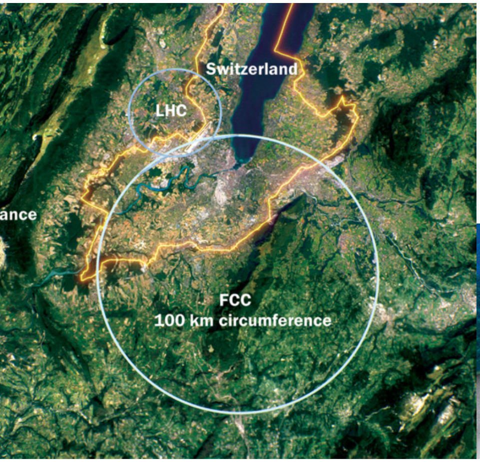
"The EF supports a fast start for the construction of an e+e Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron/muon)"

This talk will focus on one of the options for a future e+e- Higgs (+ EW/top) factory

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

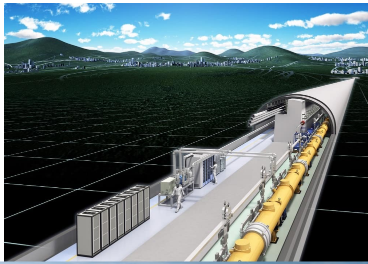
Circular colliders
- Multi-pass at IP
- Modest accelerating gradients
- Limited by synchrotron radiation
- No beam polarization
- Potential to re-use tunnel for hadron collisions.

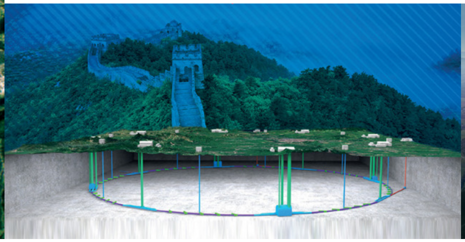
Linear colliders
- Single pass at IP
- Maximum accelerating gradients
- No synchrotron radiation
- Can exploit (longitudinal) beam polarization
- Staged approach to higher energies (energy~length)

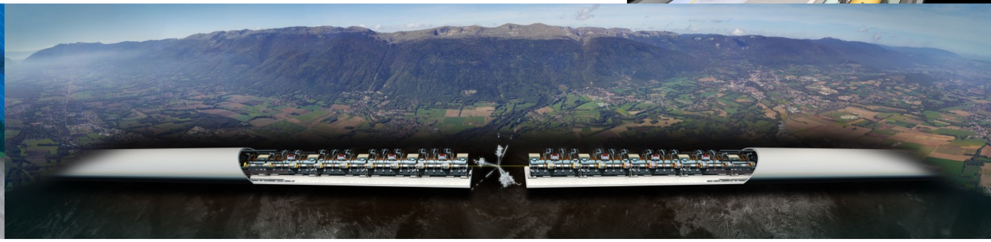


Left: FCC-ee (CERN)
Below: CEPC (China)

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







CEPC vs FCC: similarities

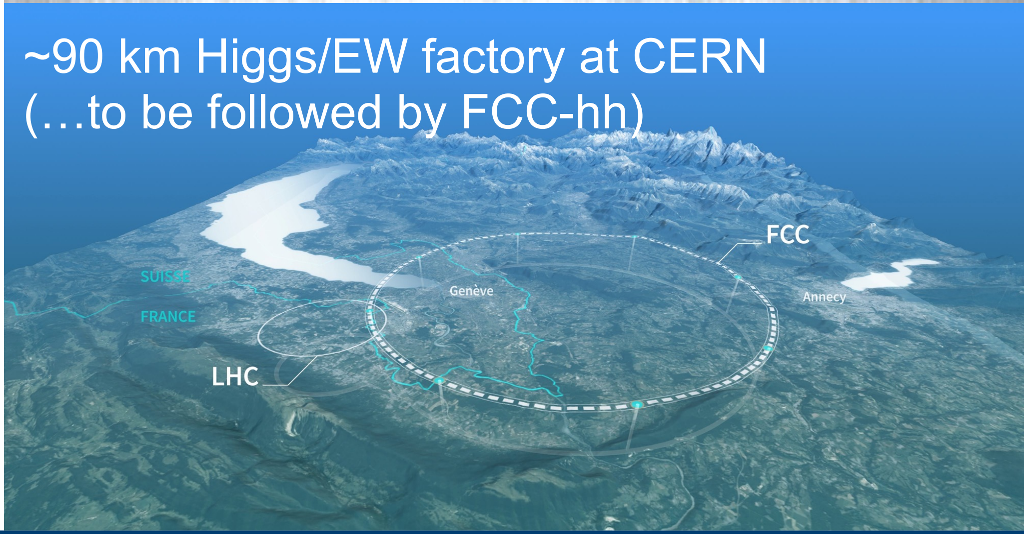
https://home.cern/science/accelerators/future-circular-collider

Lots of similarities between CEPC and FCC-ee:

1. Similar circumference.
2. Separate beams for e+ and e-
3. Superconducting RF technology for particle acceleration, with energy booster and top-up injection.
4. Similar luminosity and energy for Higgs/ Z-pole/ WW and top* threshold runs…

*$t\bar{t}$ run currently optional for CEPC based on TDR.

CEPC: 100km Higgs/EW factory in China (could be followed by SppC pp collider)



~90 km Higgs/EW factory at CERN (…to be followed by FCC-hh)

Physics opportunities at circular e+e- colliders

Whilst I have tried to document some of the differences between CEPC and FCC in the backup for reference, the physics cases and opportunities are VERY similar…

1. Push the intensity frontier at multiple energies enabling ultra-precise measurements of EW/Higgs/top parameters of SM.
2. Unique BSM sensitivity to low-mass feebly interacting particles.
3. Unique flavour opportunities due to tera-Z datasets.
4. Opportunity to reuse tunnel to push energy frontier through ~100 TeV pp collisions and benefit from **synergies** between ee/ep and pp collisions **(I won't be able to discuss- ask me about after)**.

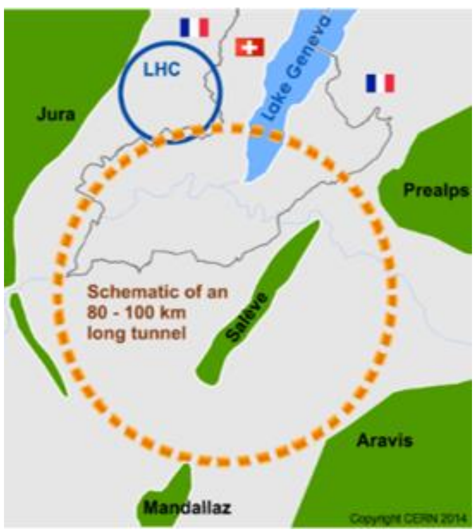
I will now expand on these points using FCC as a case study…

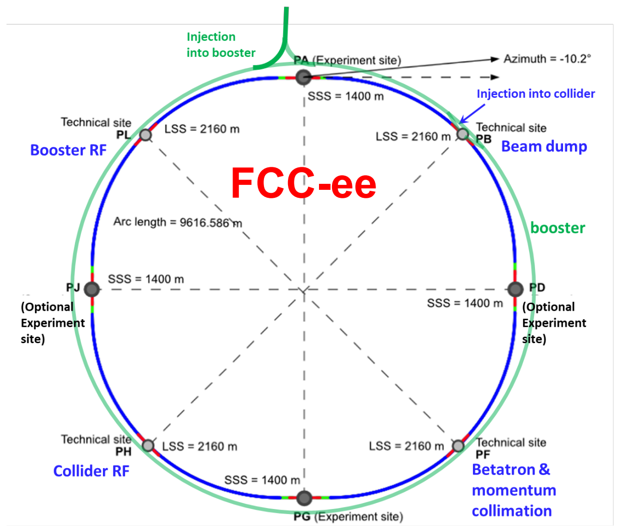
Case study: integrated FCC programme

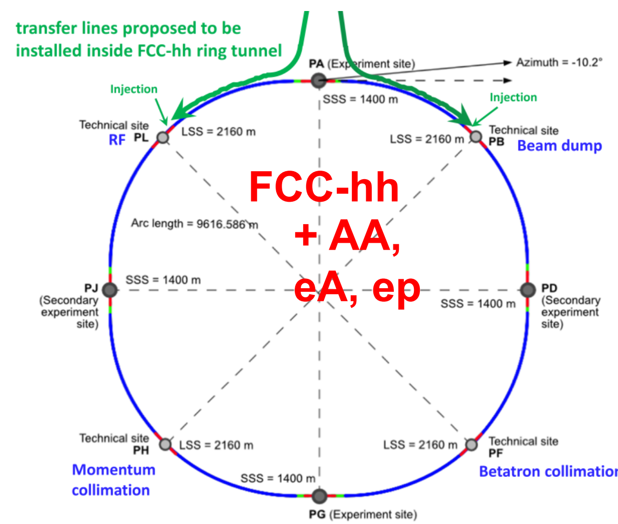
Comprehensive long-term programme maximises physics opportunities at the intensity and energy frontier:

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.

	√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.

Physics landscape for circular e+e- machines

Schematics from slides by M. Selvaggi at FCC week

Physics landscape

Higgs factory	**Flavor** "boosted" B/D/τ factory:	**QCD - EWK** most precise SM test	**BSM** feebly interacting particles
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	CKM matrix CPV measurements Charged LFV Lepton Universality τ properties (lifetime, BRs..) $B_c \to \tau\nu$ $B_s \to D_s K/\pi$ $B_s \to K^*\tau\tau$ $B \to K^*\nu\nu$ $B_s \to \varphi\nu\nu$ …	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	Heavy Neutral Leptons (HNL) Dark Photons Z_D Axion Like Particles (ALPs) Exotic Higgs decays

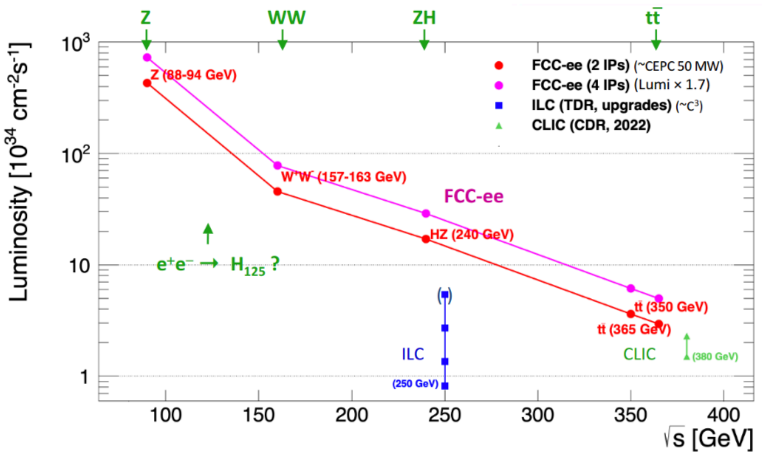
Detector requirements

Higgs factory	**Flavor** "boosted" B/D/τ factory:	**QCD - EWK** most precise SM test	**BSM** feebly interacting particles
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	track momentum resolution (low X_0) IP/vertex resolution PID capabilities Photon resolution, pi0 reconstruction	acceptance/alignment knowledge to 10 µm luminosity	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).

Targeting ultimate precision

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…

e^+e^- numbers game

In the spirit of Roger Freedman’s talk- lets do some active learning!

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

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

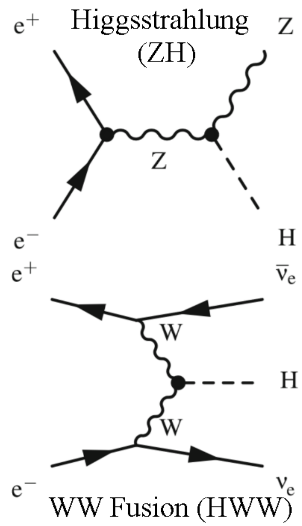
1. # Z bosons/hour at FCC-ee (Z-pole) => 360 million (5)
2. # Higgs bosons/day at FCC-ee (Zh pole) => 2000 (1)
3. # Z bosons produced at LEP => 18 million (4)
4. # Crème eggs produced by Birmingham Cadbury's factory per day => 1.5 million (2)
5. # Higgs bosons produced by the LHC in 2017 => 3 million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

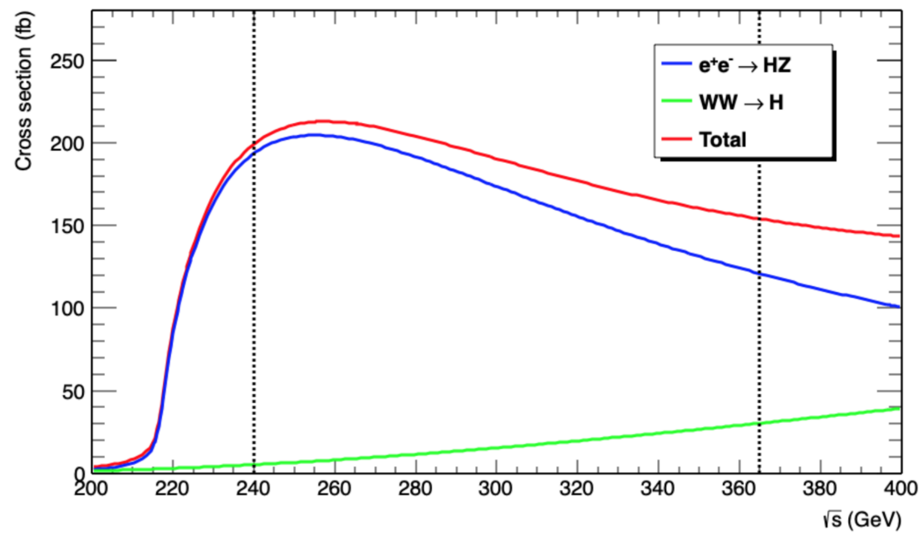
Case study- Higgs physics

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

> 1 million ZH events

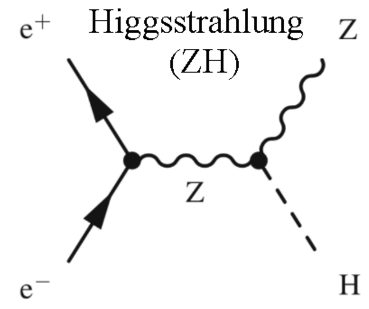
~ 100,000 WW fusion



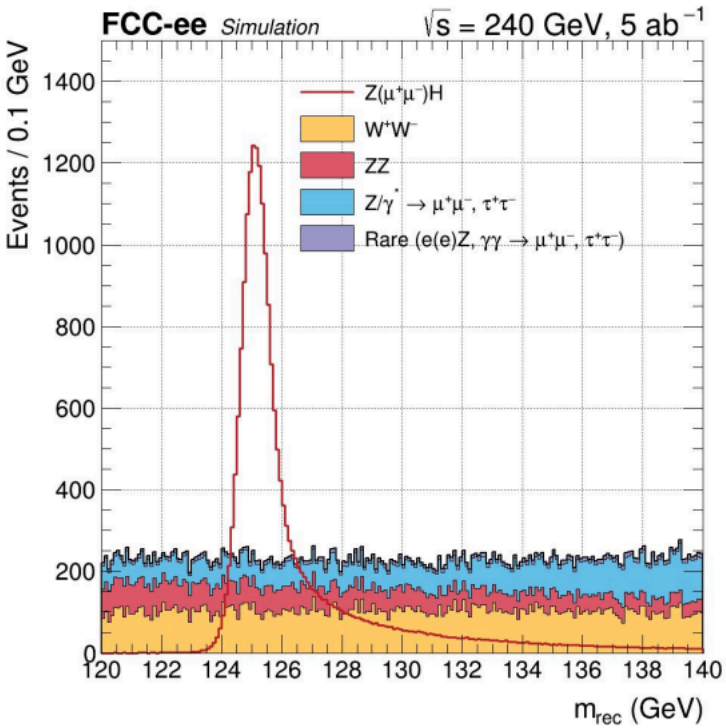


- Large rates, clean experimental environment (no UE, Pileup, triggerless) with no QCD background will open up a new era of Higgs precision physics.
- Opportunities to remove model-dependence from measurements and reach sub-percent level for post couplings.

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)**

Why do we need tera-Z?

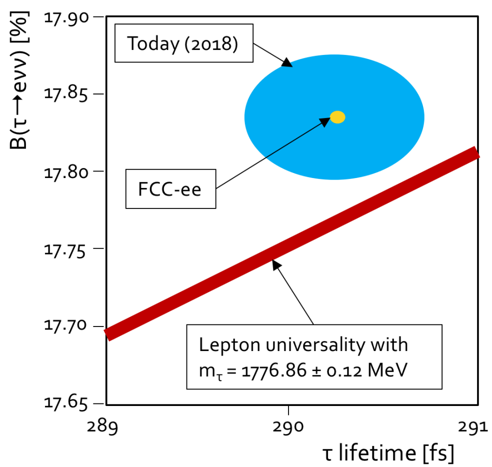
- Significantly higher statistics at Z-pole (~ 5×10^{12} Z-bosons) generates ultimate precision for EWPO, and best sensitivity for BSM searches (i.e. HNLs).

Quantity	current	ILC250	ILC-GigaZ	FCC-ee
$\Delta\alpha(m_Z)^{-1}$ ($\times10^3$)	17.8*	17.8*		3.8 (1.2)
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)
Δm_H (MeV)	170*	14		2.5 (2)
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)
ΔA_e ($\times10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)
ΔA_μ ($\times10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)
ΔA_τ ($\times10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)
ΔA_b ($\times10^5$)	2000*	53 (35)	9 (50)	2.4 (21)
ΔA_c ($\times10^5$)	2700*	140 (25)	20 (37)	20 (15)

- 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 / $\overline{\Lambda}_b$	$c\overline{c}$	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.



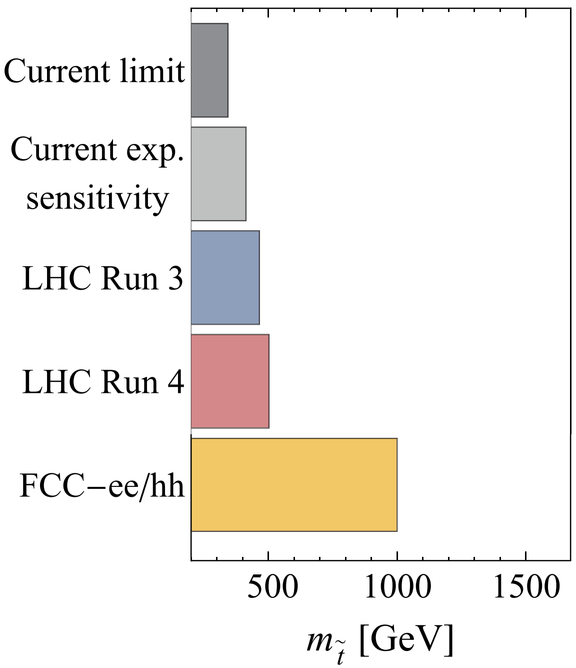
For flavour, see slides by Jernej. F. Kamenik at London FCC week

Direct and indirect BSM searches

Taken from FCC Snowmass submission

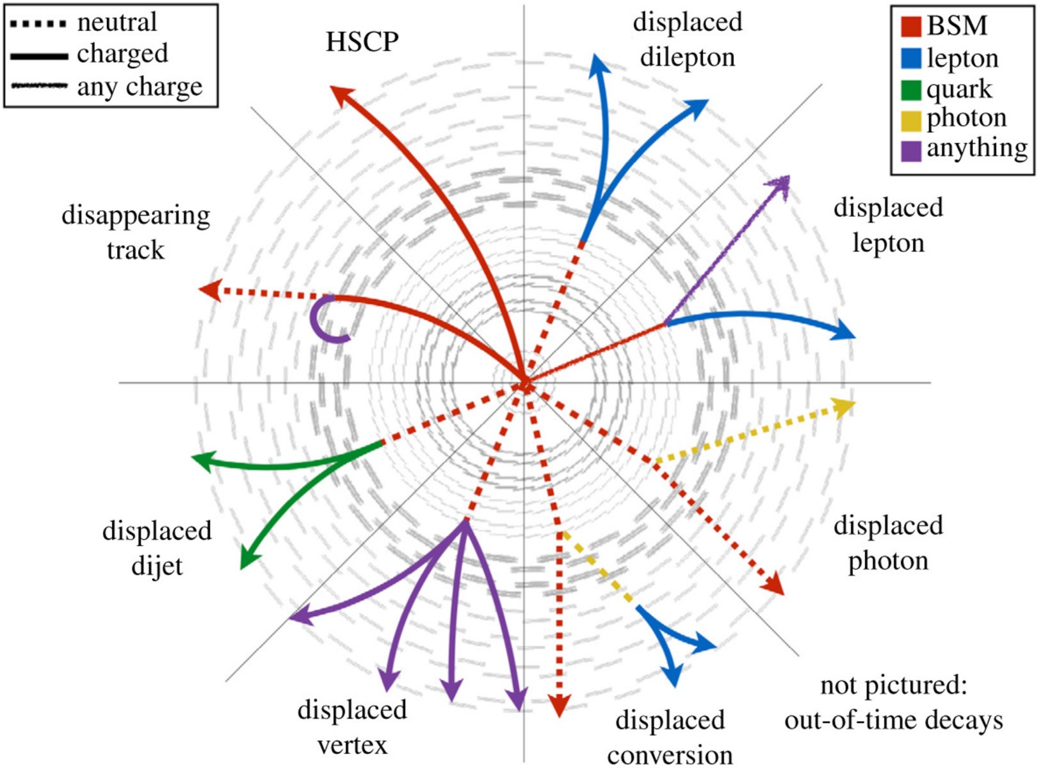
1. Indirectly discover new particles coupling to the Higgs or EW bosons up to scales of $\Lambda \approx 7$ and 50 TeV.
2. Perform tests of SUSY at the loop level in regions not accessible at the LHC.
3. Study heavy flavour/tau physics in rare decays inaccessible at the LHC.
4. Perform searches with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

Image credit: FCC CDR



Projected 2σ indirect reach from Higgs couplings on stops.

Long-lived particles



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

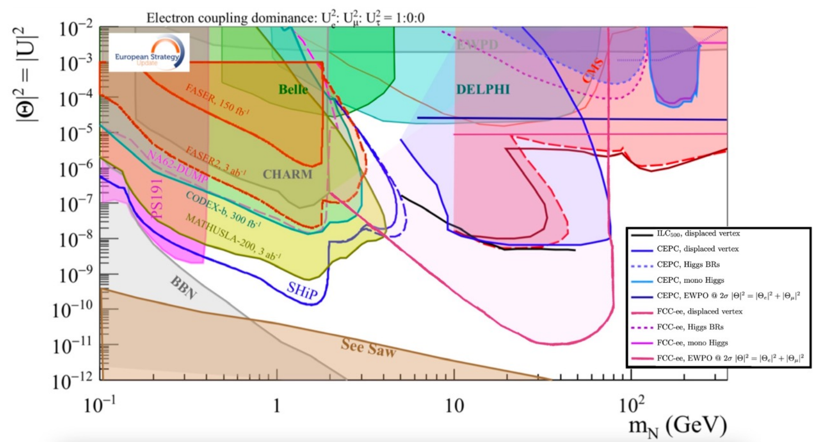
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

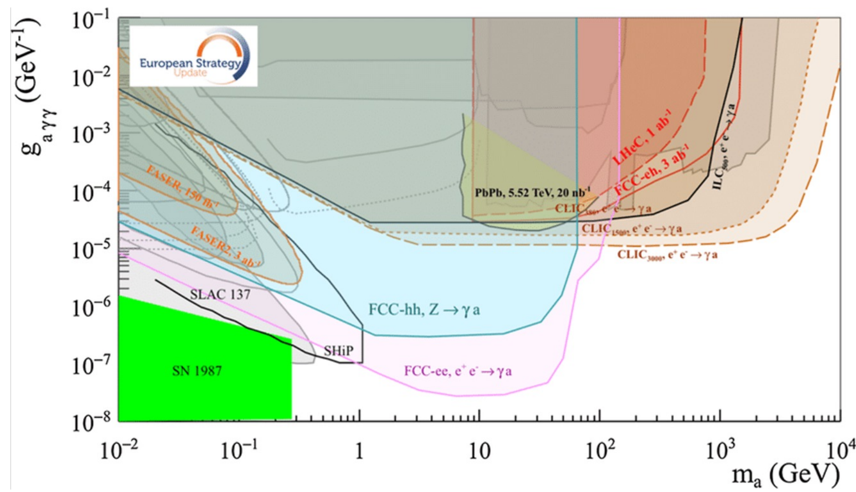
The range of unconventional signatures and rich phenomenology means that understanding the impact of detector design/performance on the sensitivity of future experiments is key!

LLPs in e+e- colliders

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).





Conclusion: Opportunities and challenges associated with circular e^+e^- machines

Paradigm shift in precision/sensitivity to

- EWK+ QCD
- Higgs
- Flavour
- BSM

(… in combination with energy frontier pp/ep collisions)

Subject to overcoming…

Suite of challenges we need to overcome to get there:

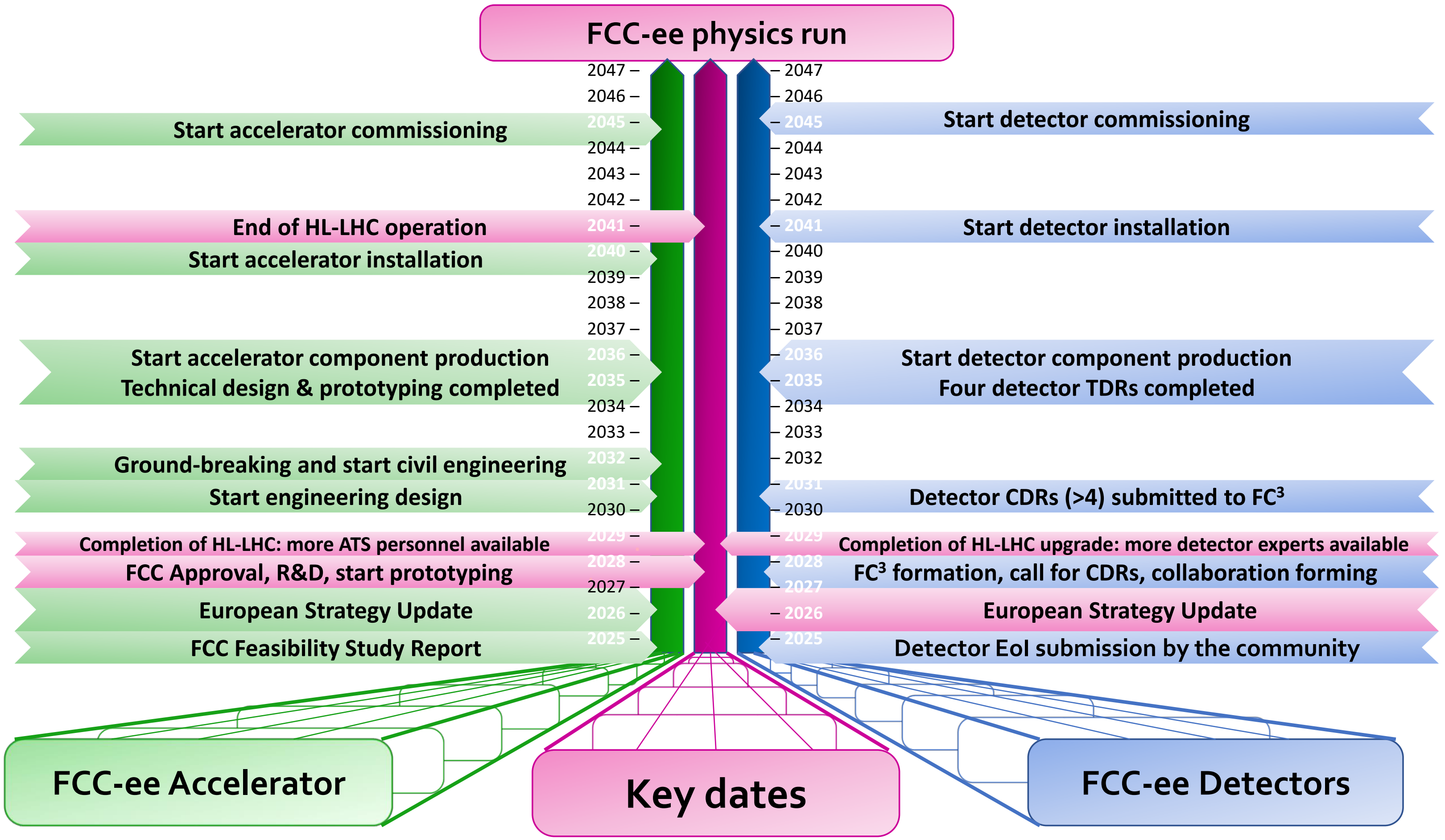
- Theory
- Technological (detector development+ design, accelerators, computing).
- Sociological.
- Political.

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

Thanks for a fruitful week of discussions!

Circular e+e- colliders are cool! What do you think?

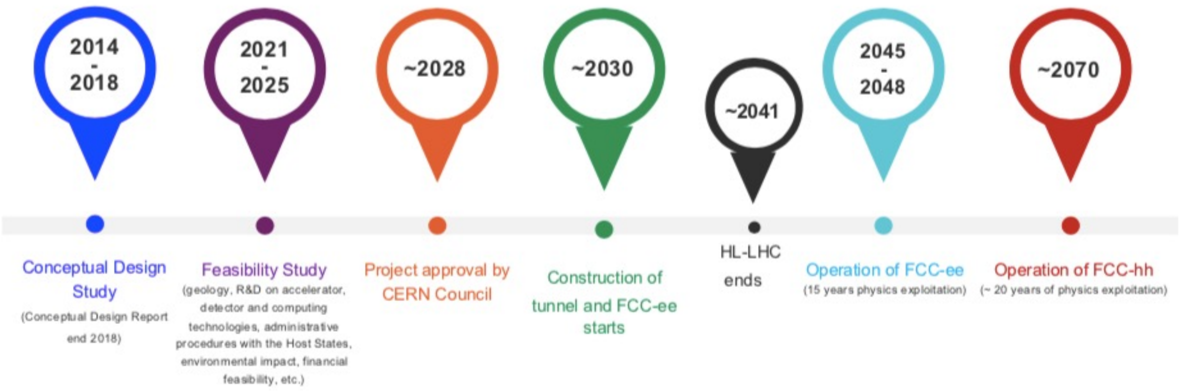
A possible look to the future

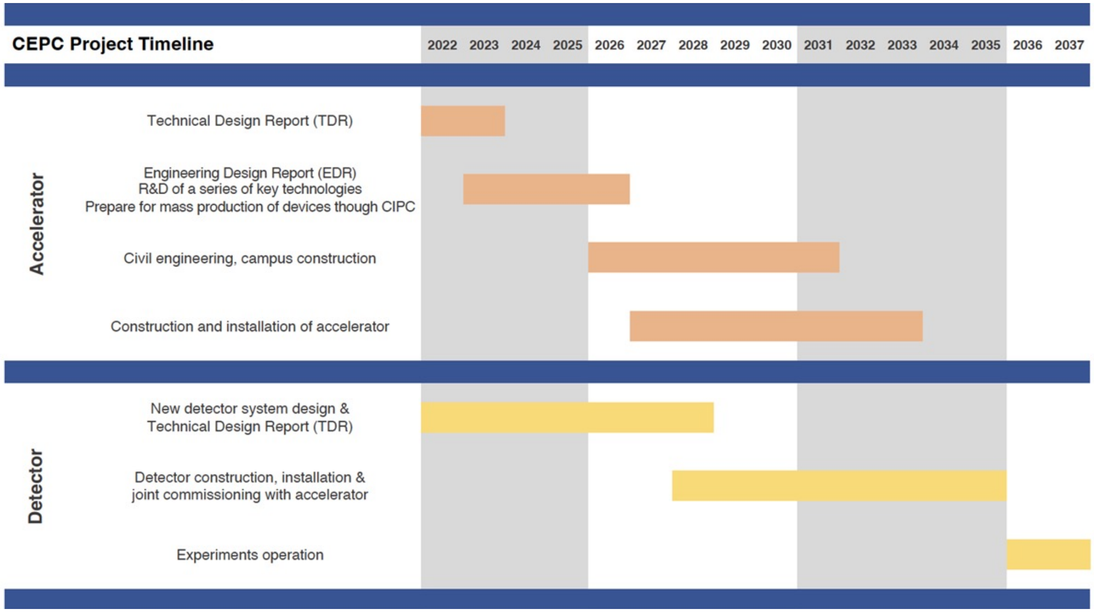


Backup

CEPC vs FCC: timelines

Schematics taken from slides from 2023 FCC and CEPC weeks.



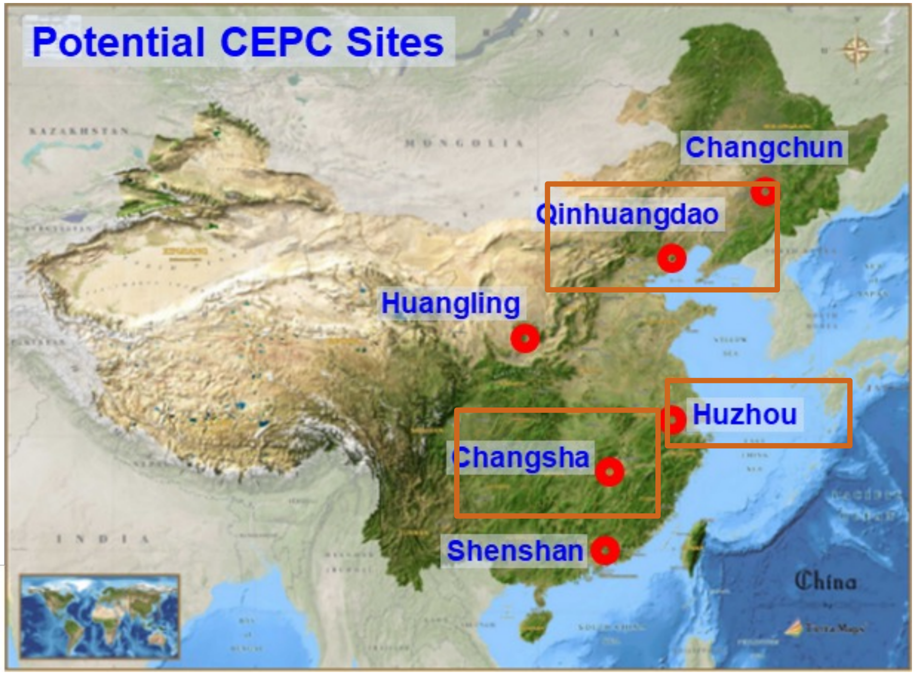


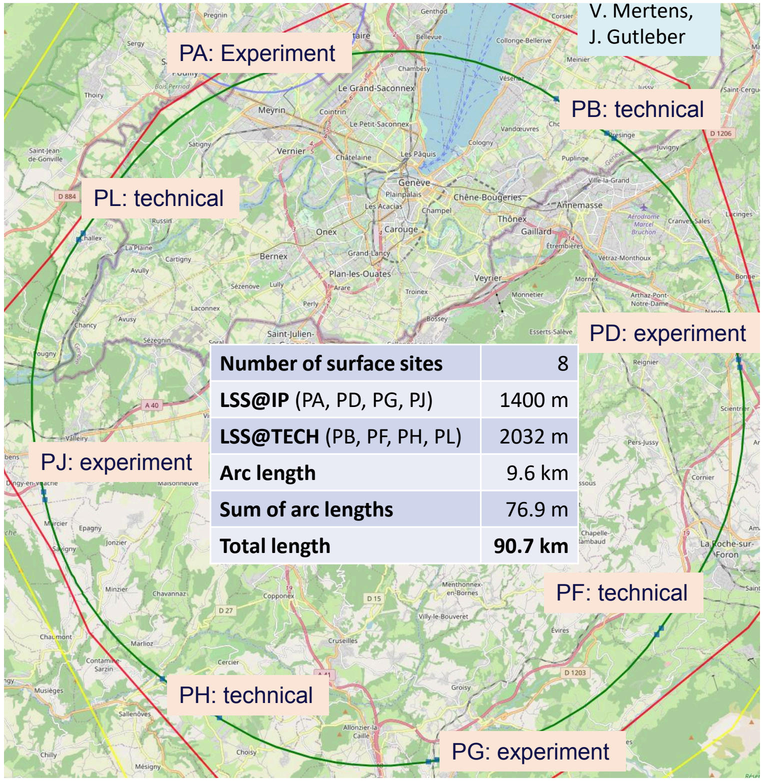
- Based on current hopes/plans- FCCee would commence operation in mid/late 2040s compared to mid 2030s for CEPC.
- This is mainly driven by constraints on FCC from LHC operations => the times from construction to operation are similar.

CEPC vs FCC: location and costs

(…which are linked on some level…)

- FCC location is (exactly) fixed (one highlight of the feasibility study) whilst of 6 considered sites for CEPC, 3 have been selected for further study.





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**

- Quoted expected construction cost of CEPC ~ half that of FCC (variations in purchasing/labour costs)

CEPC vs FCC: other differences

- #IPs: CEPC has 2, whilst FCC (as of the mid-term review of the feasibility study) has 4.
- Different baseline operating plan.

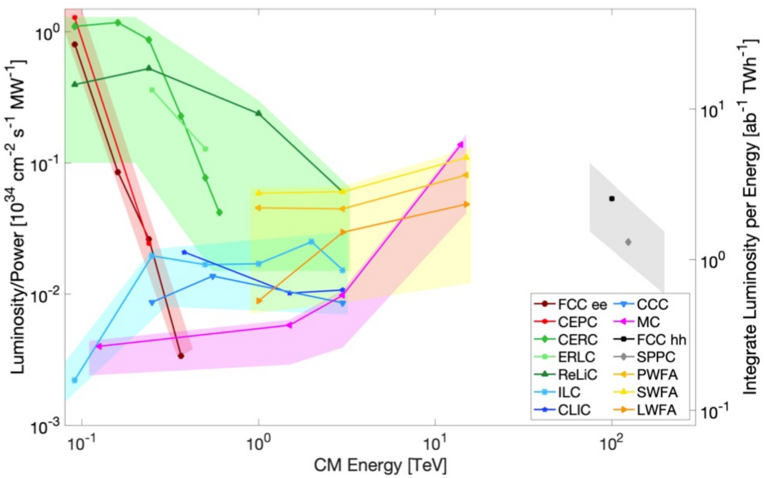


Table 3.2: CEPC operation plan (@ 50 MW)

Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	8.3	2.2	10	21.6	4.3×10^6
Z	91	192*	50	2	100	4.1×10^{12}
W	160	26.7	6.9	1	6.9	2.1×10^8
$t\bar{t}$**	360	0.8	0.2	5	1.0	0.6×10^6

* Detector solenoid field is 2 Tesla during Z operation.
** $t\bar{t}$ operation is optional.

FCC with 4 IPs (not fixed, additional opportunities e.g. 125 GeV)

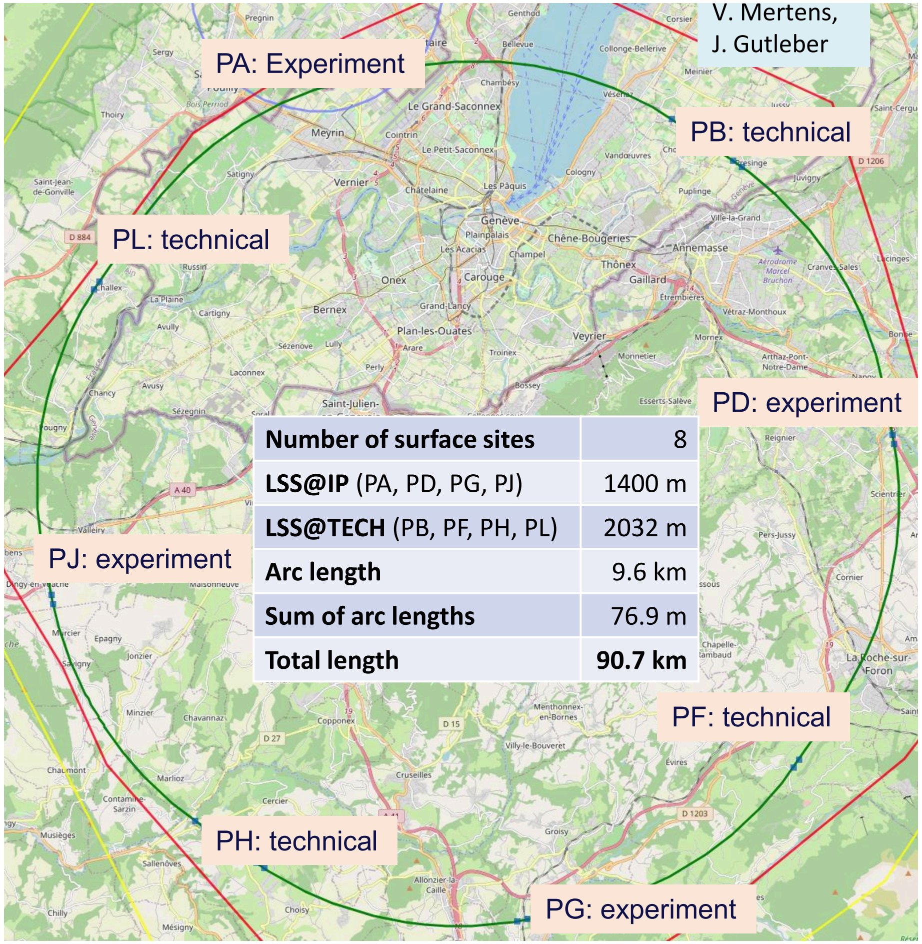
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^8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

- Power consumption ~ similar but carbon footprint currently higher for CEPC due to China's (current) prevalent use of coal as an energy source.

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).

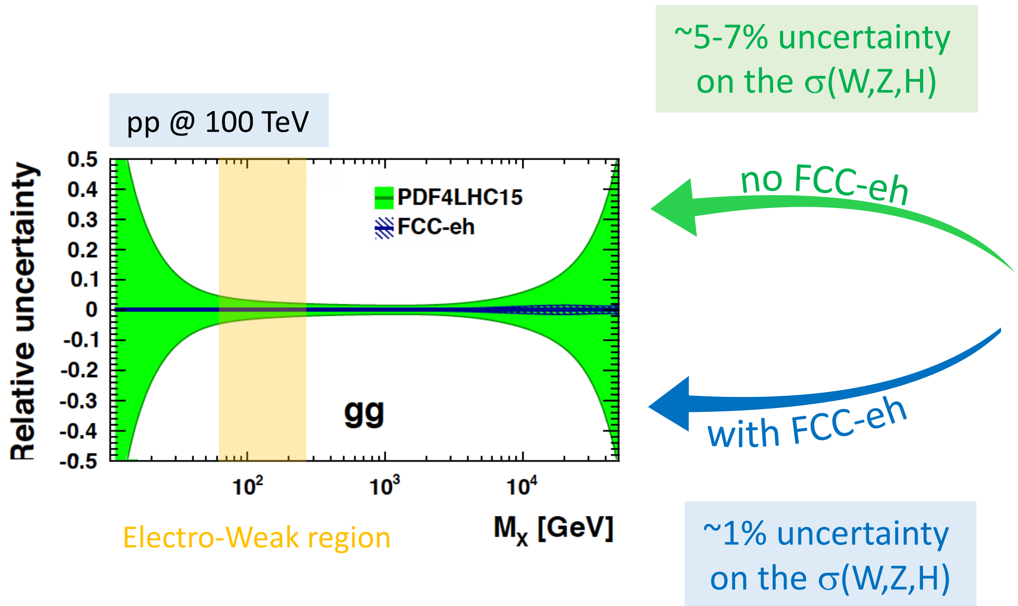


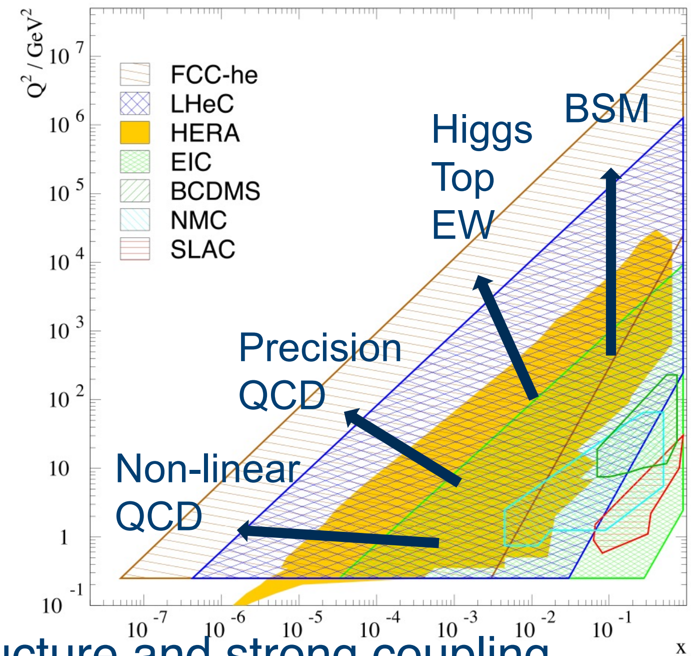
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Synergies in FCC programme- FCC-eh

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

Taken from updated CDR

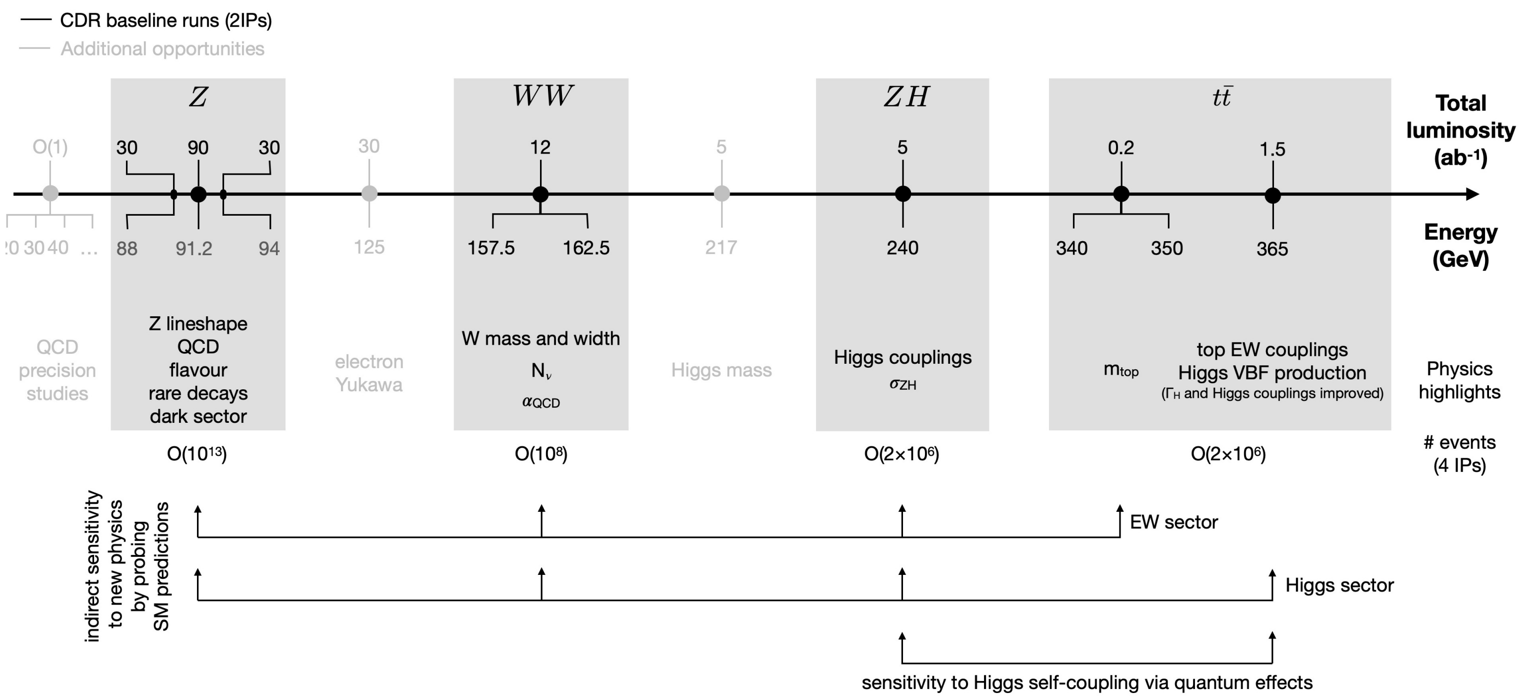




- Empower FCC-hh with precision input on hadron structure and strong coupling (to permille accuracy) during parallel running.
- Complementary measurements of Higgs couplings (CC+NC DIS x-sections, no pile-up, clean)- see slides by U. Klein here
- Plus… complementary BSM prospects (LLPs, LFV, not-too-heavy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

FCC-ee physics runs ordered by energy

Image credit: Christophe Grojean



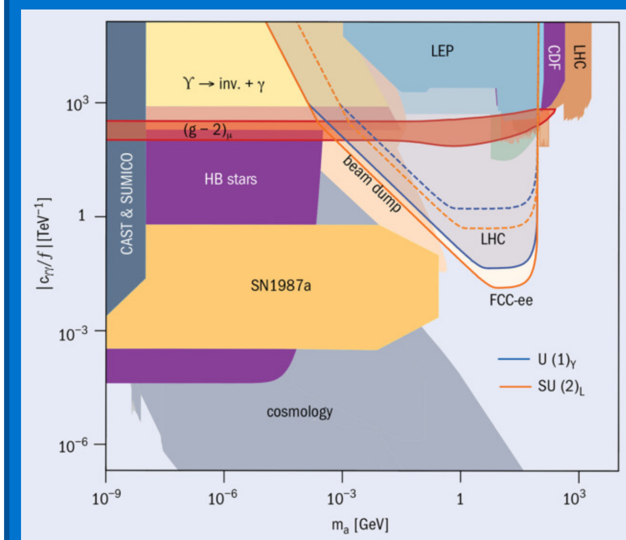
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events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

FCC-ee and -hh synergies - BSM

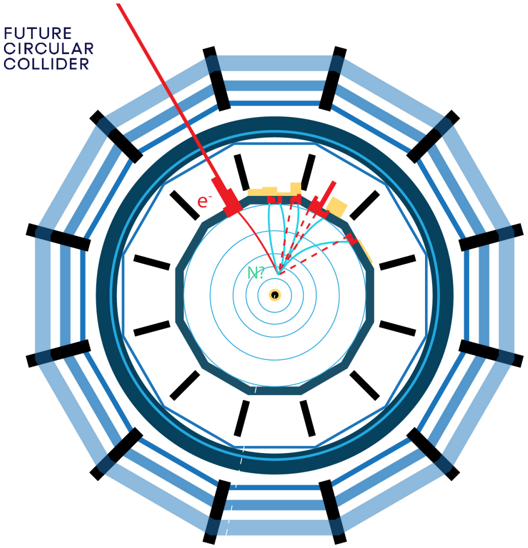
See slides by G. Salam at FCC week

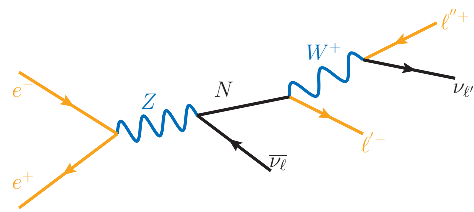
Direct FCC-ee sensitivity

- HNLs
- Alps
- Exotic Higgs decays

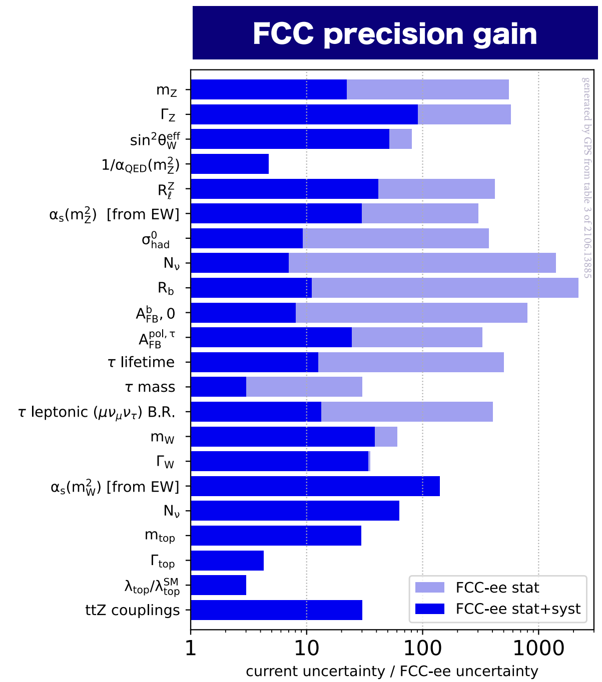


m_a: ALP mass, $c_{\gamma\gamma}$: ALP-photon coupling





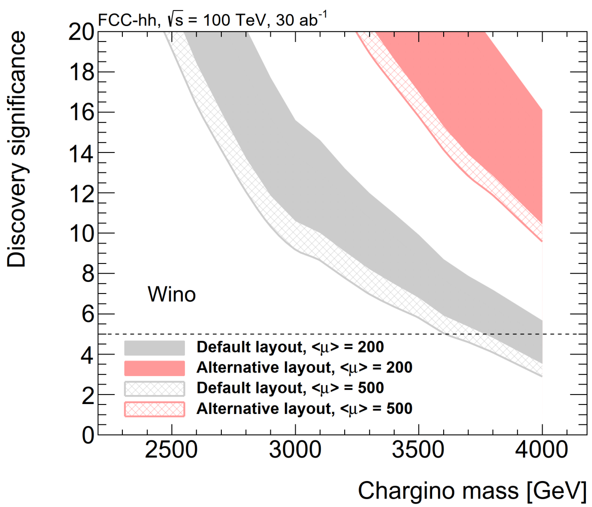
…plus **indirect access** to a range of BSM phenomena through ultra-precise measurements of SM parameters…

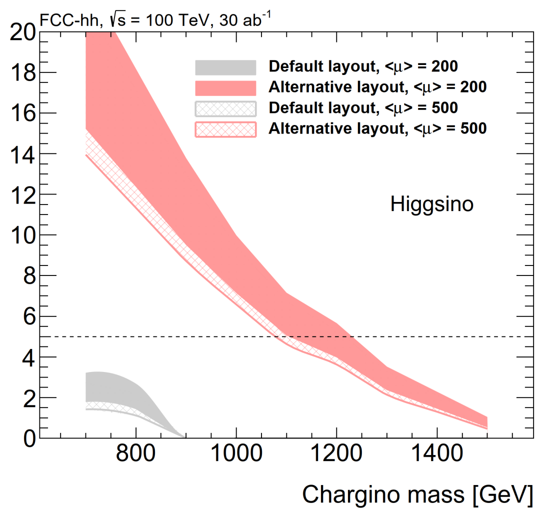


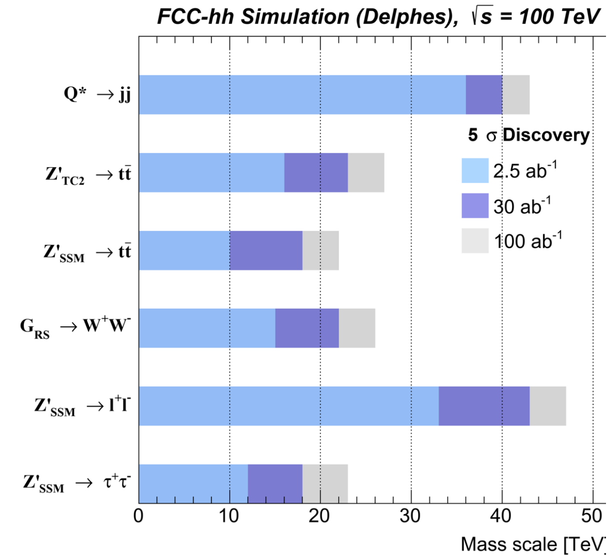
FCC-ee and -hh synergies - BSM searches

More details in FCC TDR and ESU submissions here

FCC-hh sensitivity to direct NP







Cover full mass range for discovery of WIMP dark matter candidates

Substantial discovery reach for heavy resonances

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

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

FCCee EWK precision – targets and challenges

See slides by Christoph Paus at ZPW2024

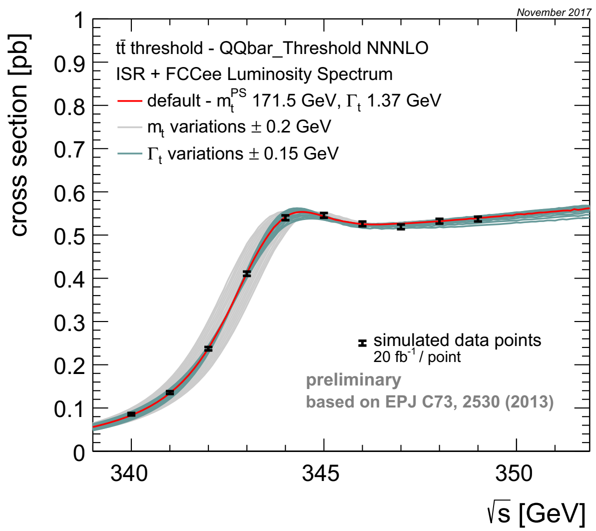
Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ 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…

FCC-ee top opportunities

See snowmass energy frontier report

- $t\bar{t}$ threshold scan will enable most precise measurements of top-quark mass and width.
- Precise measurements of top quark EW couplings provide essential input to precise extraction of top yukawa at FCC-hh.

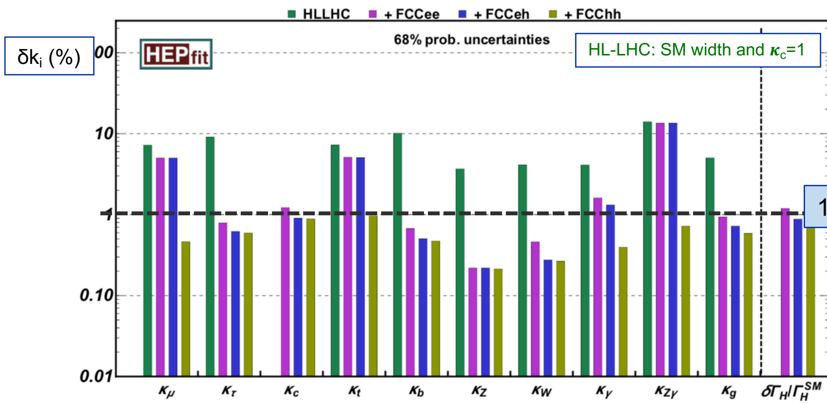


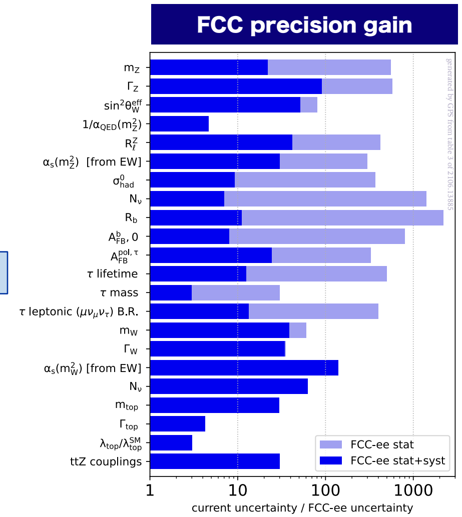
Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024

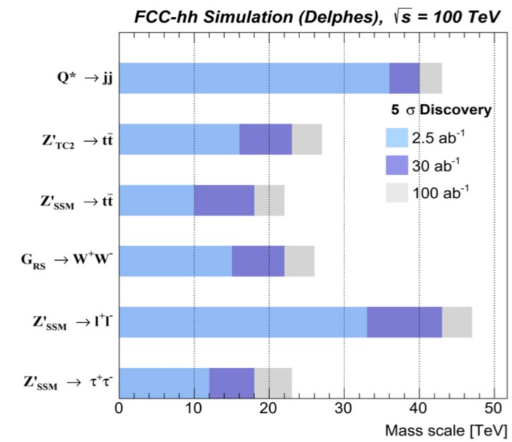
- Searches for FCNC interactions above threshold can also provide strong probe of BSM.

Synergies between e+e- and pp collisions –BSM

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







- Order of magnitude improvement in Higgs couplings.
- Factor of 10-50 improvement in EW precision observables (indirect sensitivity up to ~ 70 TeV)

- Direct sensitivity up to ~ 50 TeV in 100 TeV pp collisions (and access to Higg self coupling).

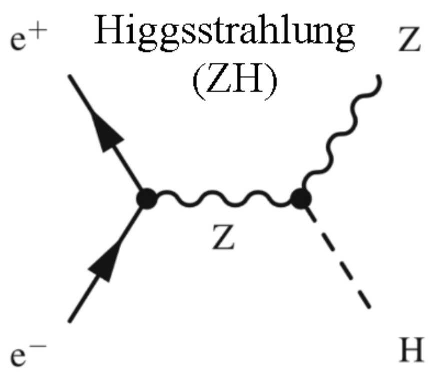
Synergies between e^+e^- and pp collisions - Higgs measurements

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

- High intensity e^+e^- colliders 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.

- Can also measure ttZ couplings through $ee \rightarrow t\bar{t}$. This gives a second standard candle used to extract g_{ttH} and g_{HHH} at subsequent hadron machines.

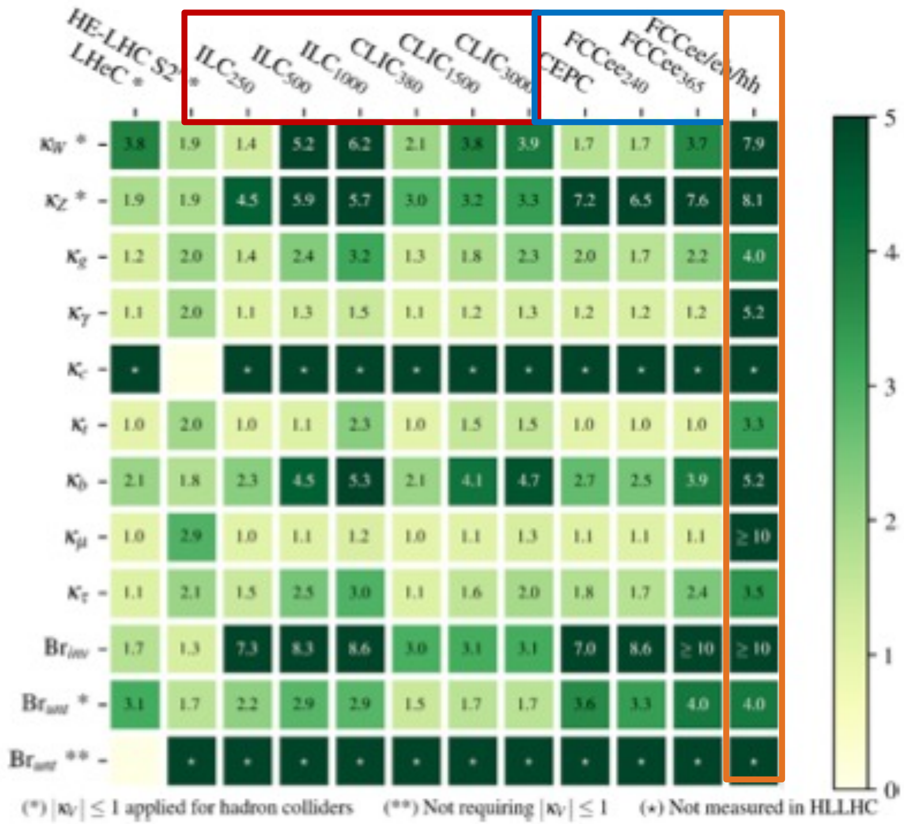
- High-energy pp collisions provide the statistics to access rarer Higgs decays ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$) and HH events to give precise ultimate tests of the EWPT (~ 20 million at FCC-hh).



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
	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)
	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
	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.

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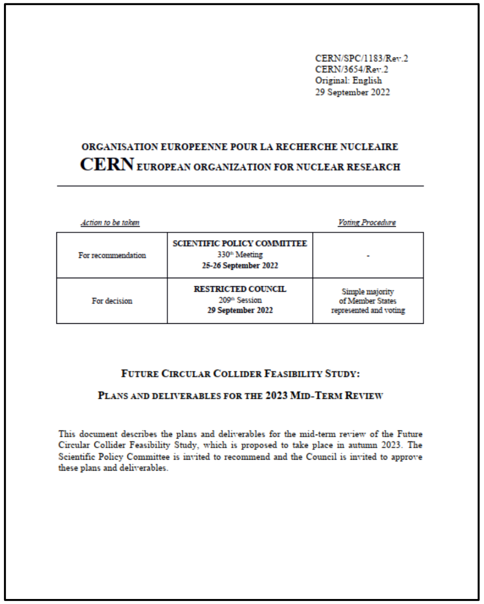
FCC costings- planned updates

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.

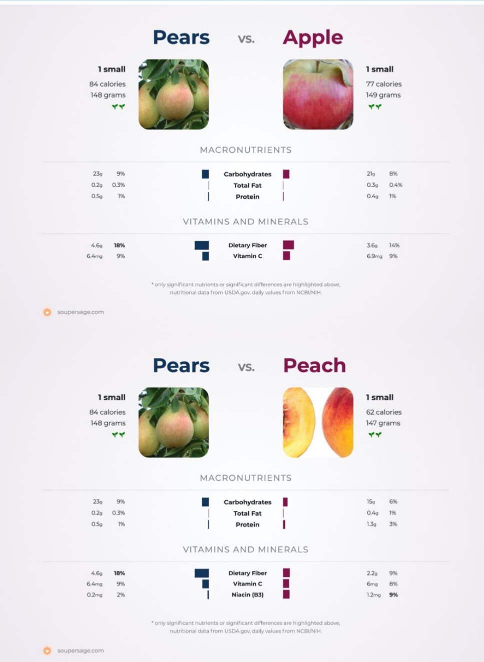
Members: The CRP consists of around 10 international experts, not directly involved in the Feasibility Study, with renowned expertise in costing and project management aspects related to the scientific and technical domains relevant to the Study (accelerators, technical infrastructure, civil engineering,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

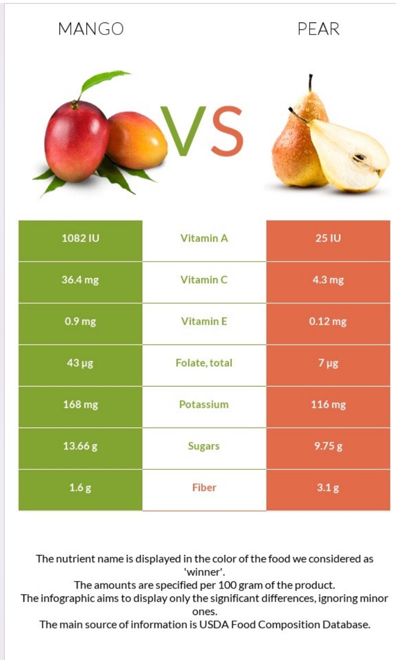
CRP members:

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)

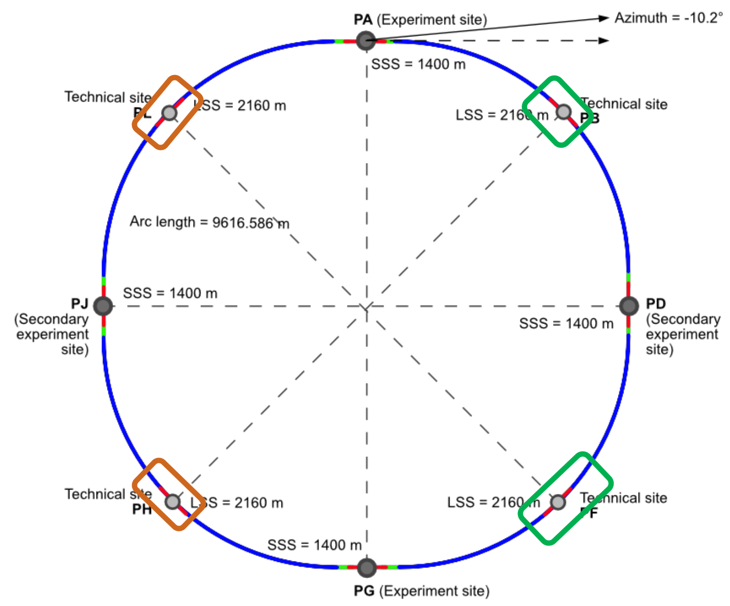
… is hard! Its important to define your comparison metrics carefully and consider the errors involved!

- 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

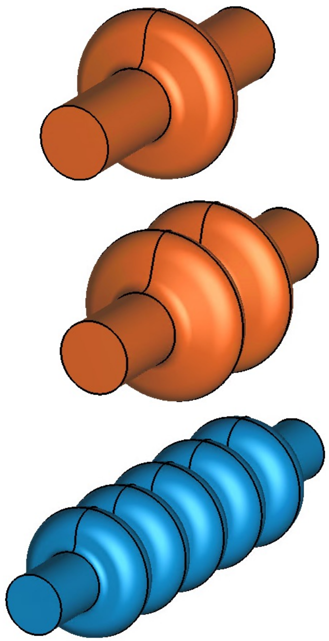
1-cell 400 MHz, Nb/Cu

W, H

2-cell 400 MHz, Nb/Cu

ttbar, booster

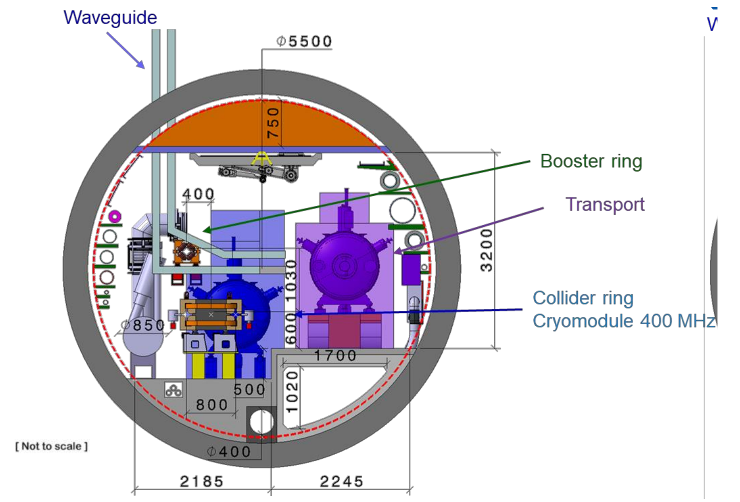
5-cell 800 MHz, bulk Nb



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

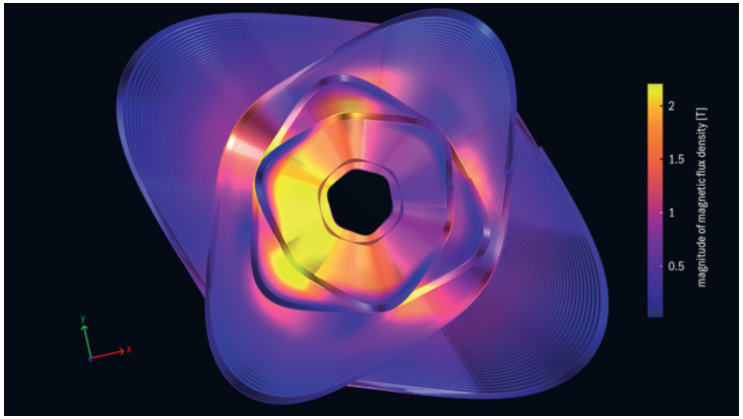


RF for collider and booster in separate sections (collider in PH- 400 & 800 MHz, booster in ML- 800 MHz only) with fully separated technical infrastructure (cryogenics)

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

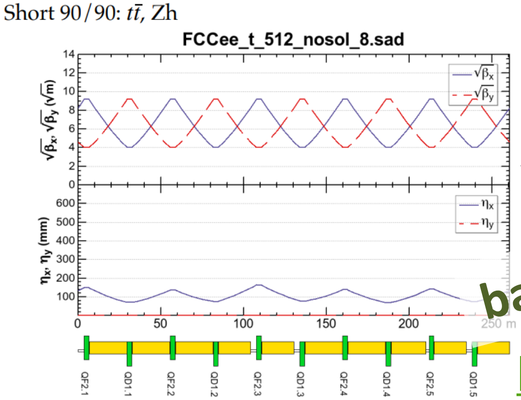
Maximising energy efficiency is a major factor!



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

arc

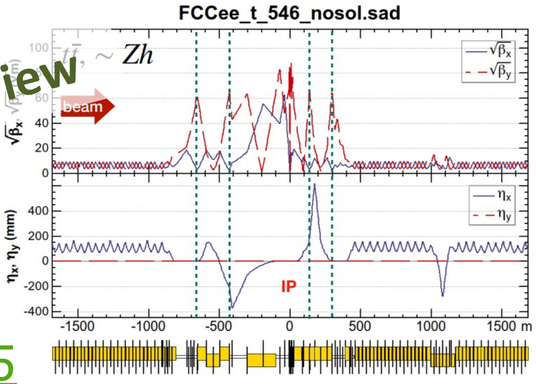
interaction region



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

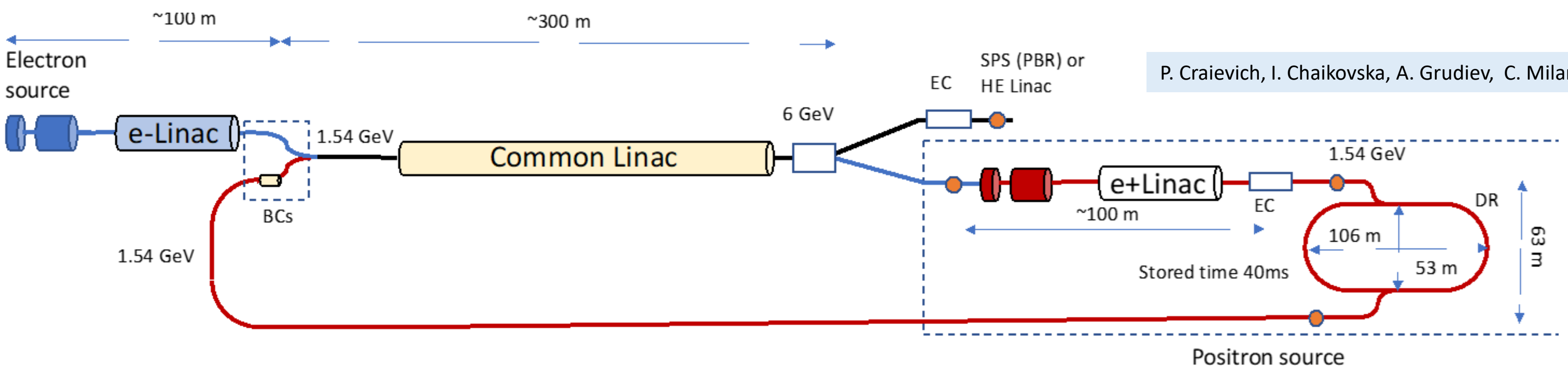
baseline for 2023 FCC "mid-term" review

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



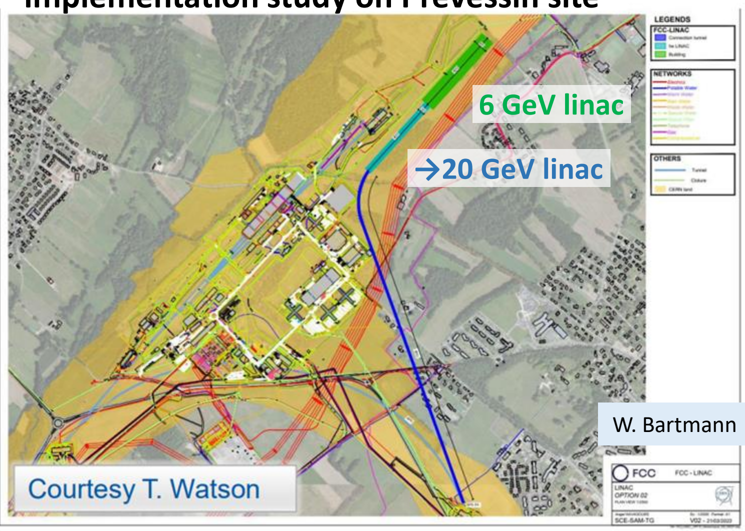
New FCC-ee injector layout

Taken from slides by M. Benedikt at FCC week

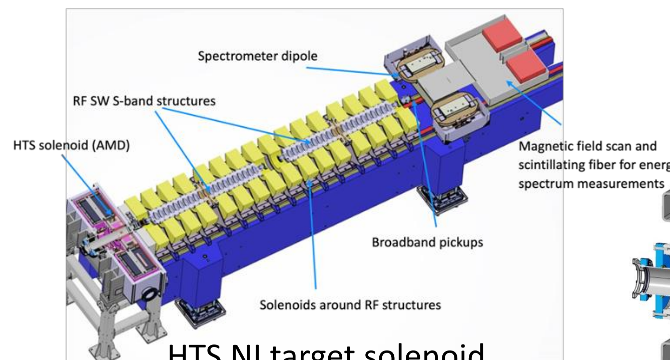


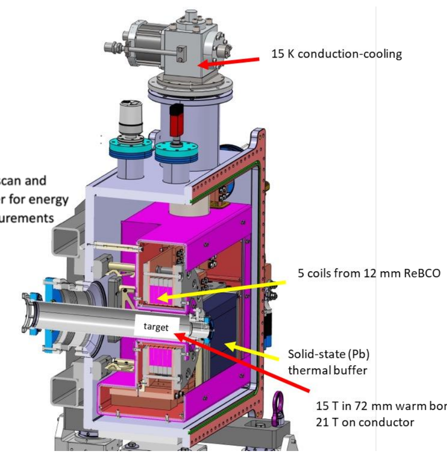
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

implementation study on Prevessin site



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





HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

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.

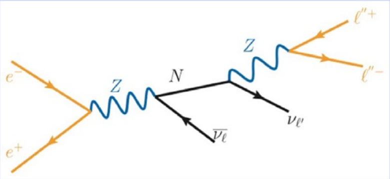
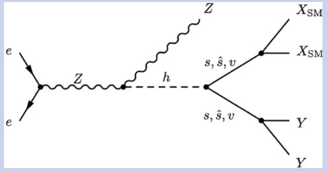
Searches for long-lived particles at the future FCC-ee

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!

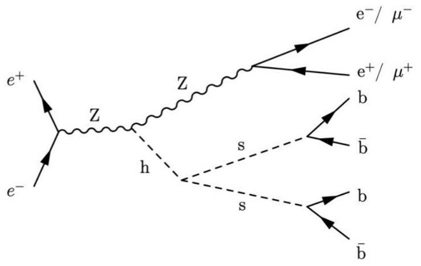
Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and detector-level selection studies for ee$\nu\nu$. First look at ee$\nu\nu$. First look at Dirac vs Majorana	• Update ee$\nu\nu$ studies for winter23 samples. •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

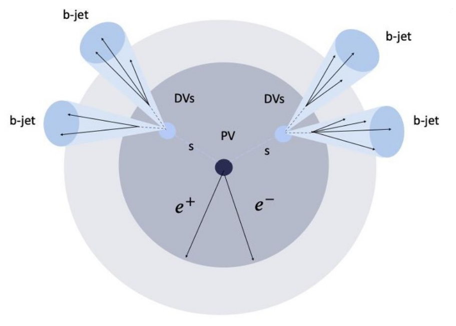
FCC-ee LLP studies: recent highlights

Magdalena Vande Voorde, Giulia Ripellino

Nice overview by Juliette Alimena at EPS 2023

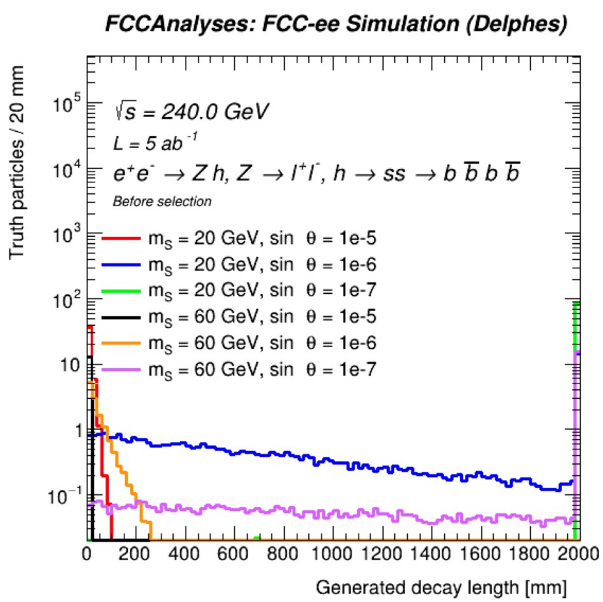
First simulation and sensitivity studies for Higgs decays to long-lived scalars





- 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

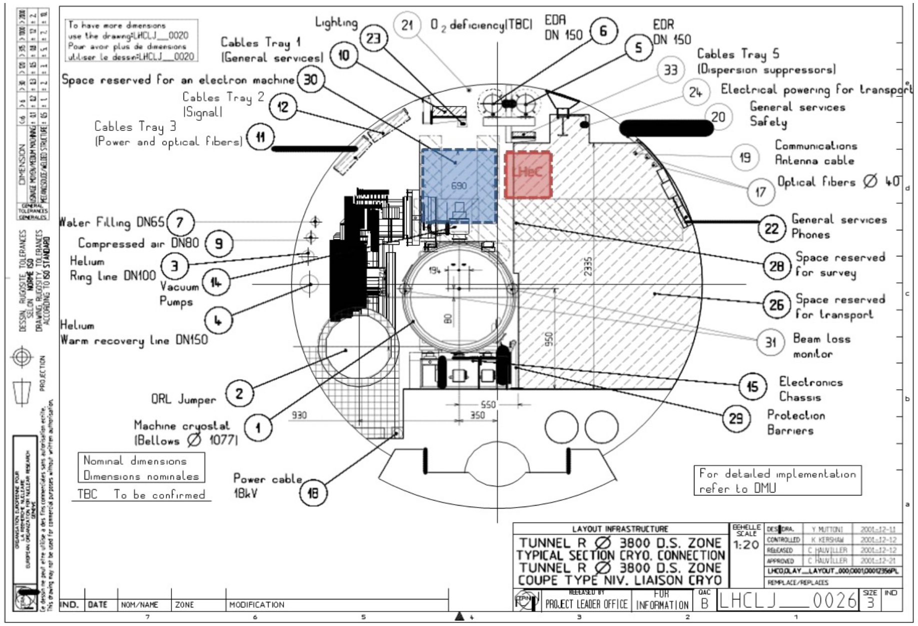
What about LEP3/TLEP?

For more information see: https://cds.cern.ch/record/1470982/files/ATS_Note-2012_062%20(2).pdf

Proposal from ~ 2012 to put a Higgs factory inside the LHC tunnel, that could also be combined with proposals for LHeC

Some (fairly old) projections:

	ILC	LEP3 (2)	LEP3 (4)	TLEP (2)	LHC (300)	HL-LHC
σ_{HZ}	3%	1.9%	1.3%	0.7%	–	–
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	0.8%	0.5%	0.2%	–	–
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.0%	2.2%	1.3%	–	–
$\sigma_{HZ} \times BR(H \to W^+W^-)$	8%	3.6%	2.5%	1.6%	–	–
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	?	9.5%	6.6%	4.2%	–	–
$\sigma_{HZ} \times BR(H \to \mu^+\mu^-)$	–	–	28%	17%	–	–
$\sigma_{HZ} \times BR(H \to \text{invisible})$	?	1%	0.7%	0.4%	–	–
g_{HZZ}	1.5%	0.9%	0.6%	0.3%	13%/5.7%	4.5%
g_{Hbb}	1.6%	1.0%	0.7%	0.4%	21%/14.5%	11%
$g_{H\tau\tau}$	3%	2.0%	1.5%	0.6%	13%/8.5%	5.4%
g_{Hcc}	4%	?	?	0.9%	?/?	?
g_{HWW}	4%	2.2%	1.5%	0.9%	11%/5.7%	4.5%
$g_{H\gamma\gamma}$	?	4.9%	3.4%	2.2%	?/6.5%	5.4%
$g_{H\mu\mu}$	–	–	14%	9%	?	?
g_{Htt}	–	–	–	–	14%	8%
m_H (MeV/c^2)	50	37	26	11	100	100



https://arxiv.org/pdf/1208.1662.pdf