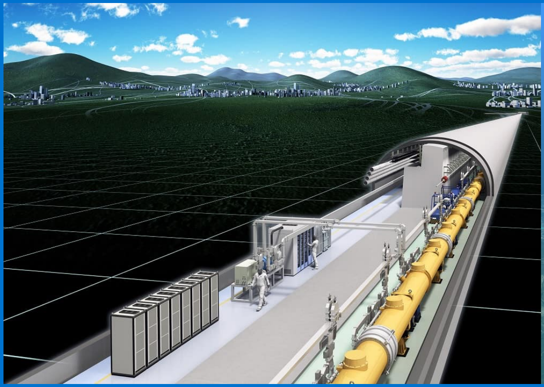
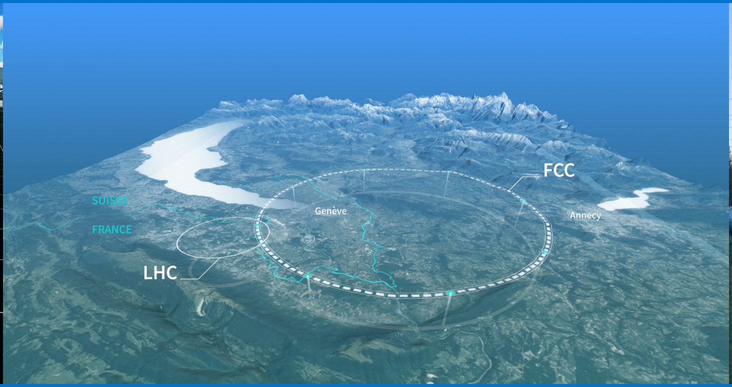
Prospects and challenges for future colliders





Dr Sarah Williams, University of Cambridge

Introduction to me

- Assistant Professor in High Energy Physics at Cambridge University and fellow in physics at Murray Edwards College.
- Member of the ATLAS collaboration at CERN since 2010, with focus on BSM searches, statistical methods and (more recently) precision SM tests.
- Significant focus on future colliders (specifically the Future Circular Collider or FCC) and UK representative on the European Committee for Future Accelerators (ECFA).

Overview of these lectures

Disclaimer: I am not an accelerator physicist- so please refer to experts on the challenges/prospects in accelerator R+D.

1: Introduction

- (selected) History of particle colliders.
- Where we are now
- Possible post-LHC colliders

2: e^+e^- colliders

- Circular vs linear colliders.
- Precision prospects
- BSM prospects
- Experimental and theoretical challenges

3: 10 TeV pCM colliders

- Energy frontier physics drivers and challenges
- 100 TeV Hadron colliders
- Muon colliders
- Conclusion + outlook

This will be an interactive course- please ask (and answer) questions!

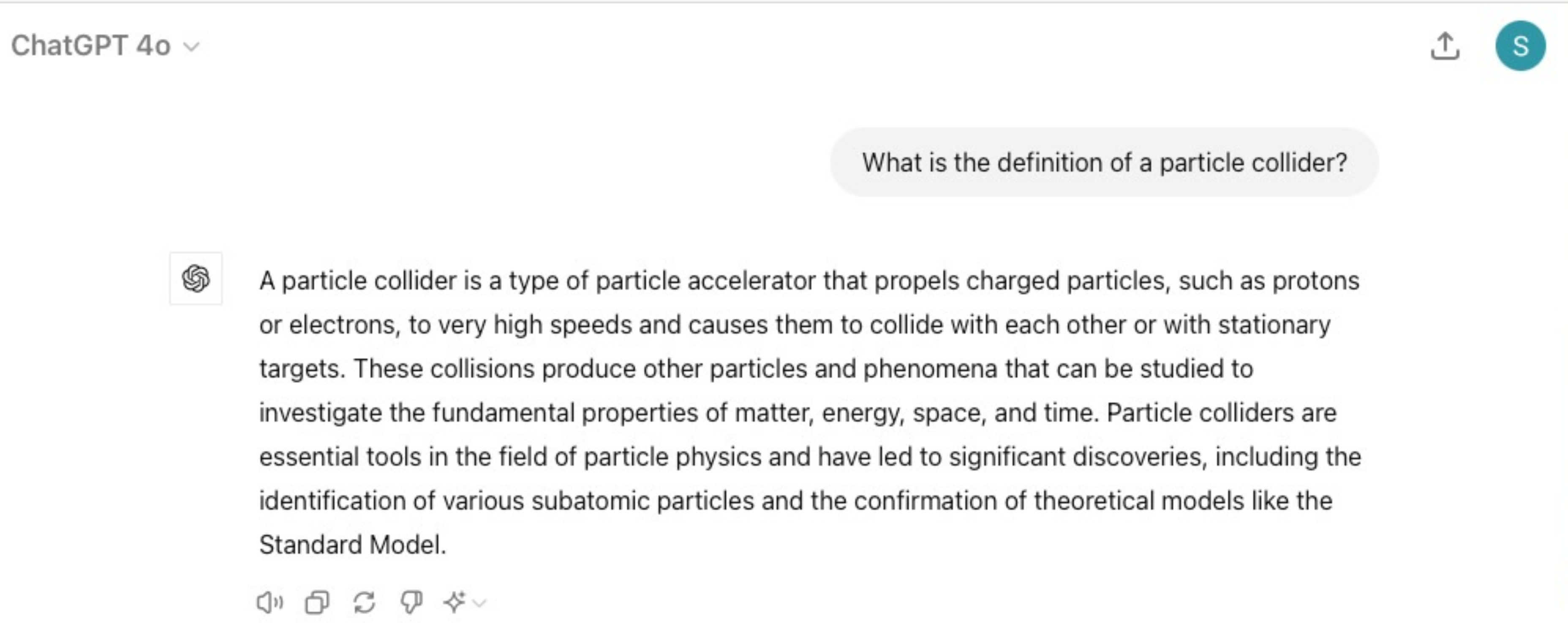
With that in mind…

- I have created a slido (this can also be accessed at www.slido.com with code #2195824) that will remain active until 6pm tomorrow.
- Please submit questions on the content (not answered in lectures) and/or requests for topics you'd like to learn a little more about.
- I'll try to devote some time in Lectures 2 and 3 to answer and/or address the most popular requests (within reason).
- Disclaimer: I will broadly avoid discussing the cost comparisons of future colliders… but a nice discussion can be found in the Snowmass '21 implementation taskforce report.

I will try to get through all of my slides by the end of the final lecture, but if I don't and we have great discussion along the way- that's ok ☺

1. Introduction

Particle colliders



What is the definition of a particle collider?

A particle collider is a type of particle accelerator that propels charged particles, such as protons or electrons, to very high speeds and causes them to collide with each other or with stationary targets. These collisions produce other particles and phenomena that can be studied to investigate the fundamental properties of matter, energy, space, and time. Particle colliders are essential tools in the field of particle physics and have led to significant discoveries, including the identification of various subatomic particles and the confirmation of theoretical models like the Standard Model.

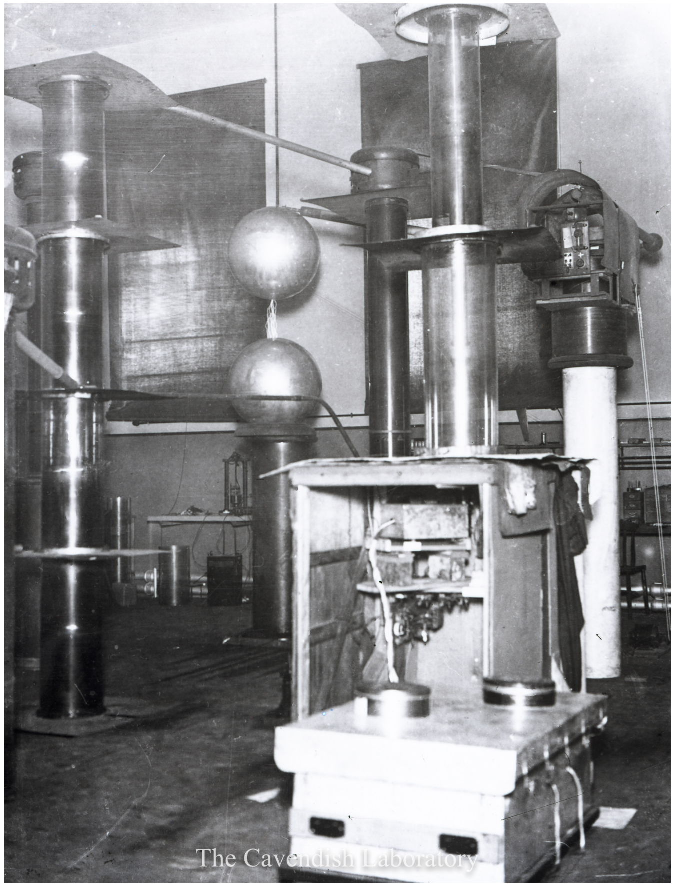
Warm-up discussion

What considerations might you have if designing/planning a collider?

Lets brainstorm…

Particle colliders over time…guess the name + year?

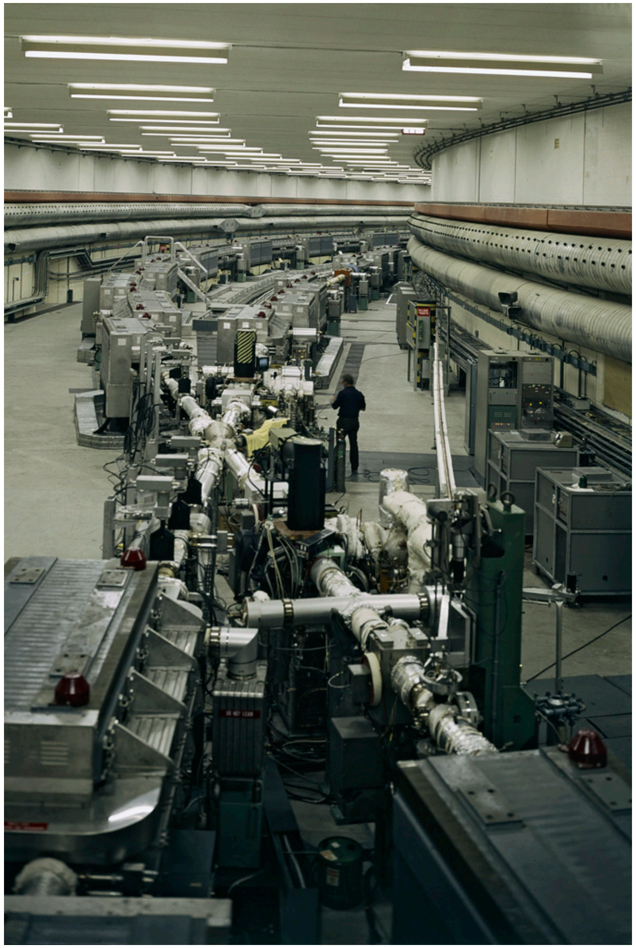
(1)



(2)

Particle colliders over time…guess the name + year?

(3)



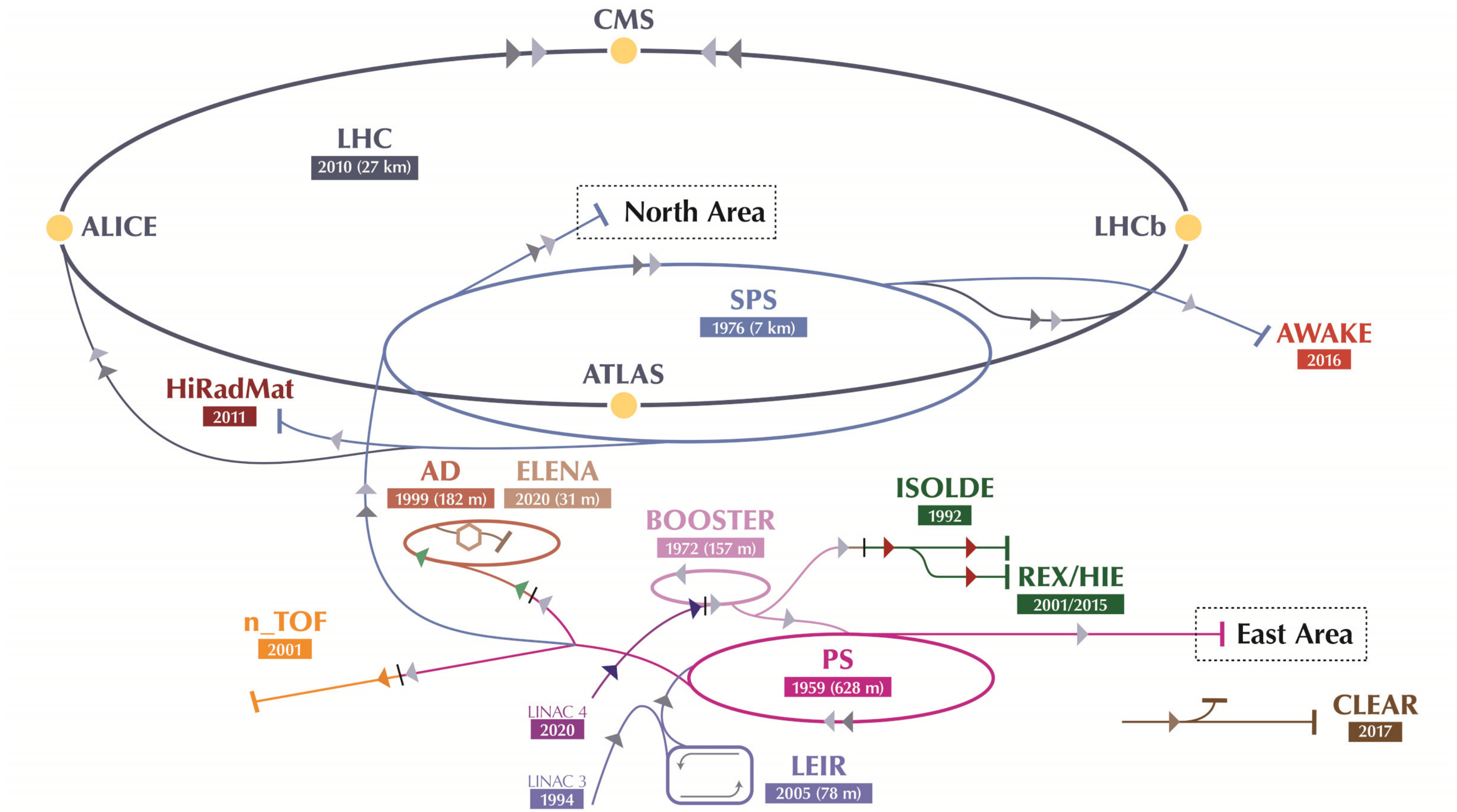
(4)

Particle colliders over time…guess the name + year?

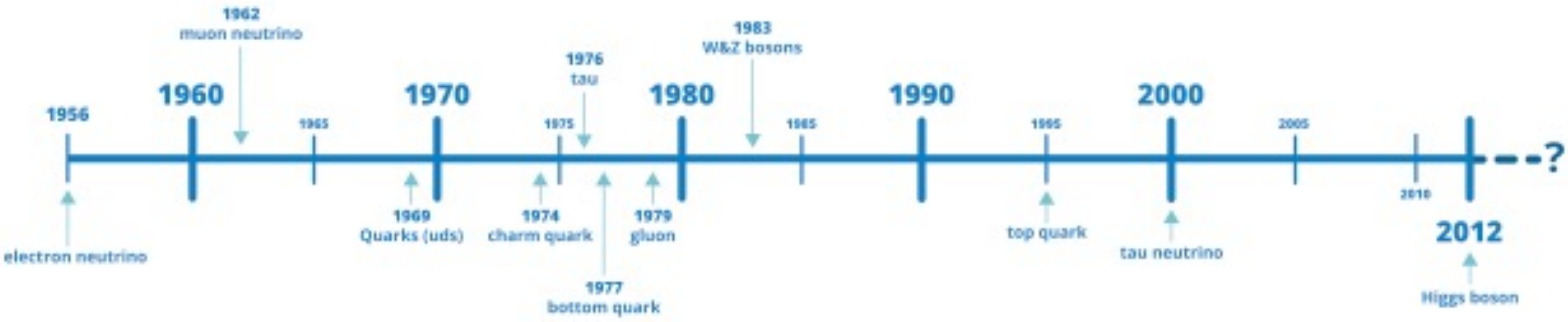
(No clues allowed here)

(5)

The CERN accelerator complex now



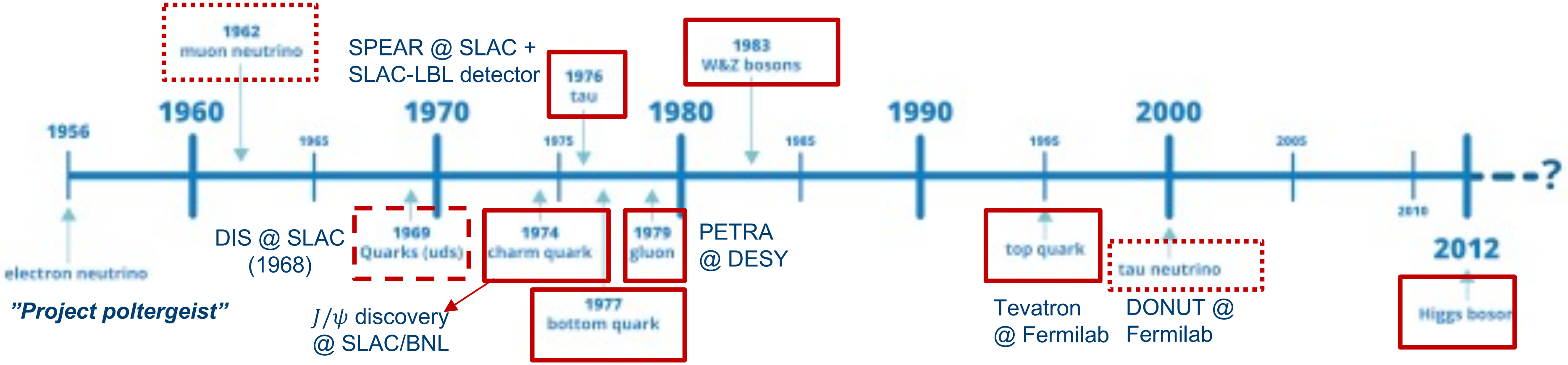
Discoveries of fundamental particles



How many of these new particle discoveries were associated with colliders?

Alternative question: which of them weren't…?

Discoveries of fundamental particles



ASG @ BNL

UA1+UA2 @ SPS, CERN

SPEAR @ SLAC +
SLAC-LBL detector

DIS @ SLAC
(1968)

PETRA
@ DESY

"Project poltergeist"

J/ψ discovery
@ SLAC/BNL

E288 experiment
@Fermilab

Tevatron
@ Fermilab

DONUT @
Fermilab

LHC @ CERN

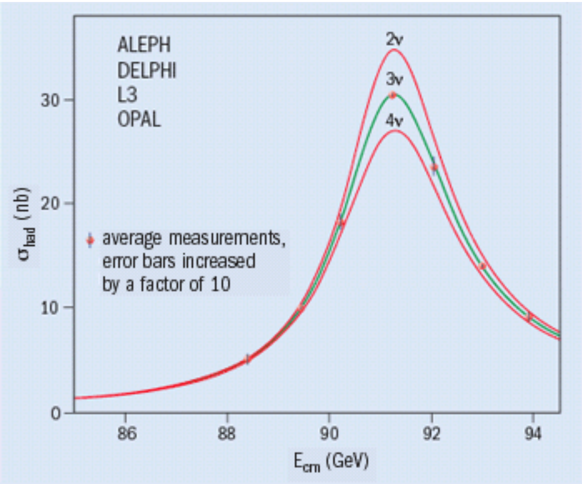
- Dotted : discovered through neutrino beam produced at colliders
- Dashed: model introduced and later verified at colliders
- Solid: direct discovery at particle collider

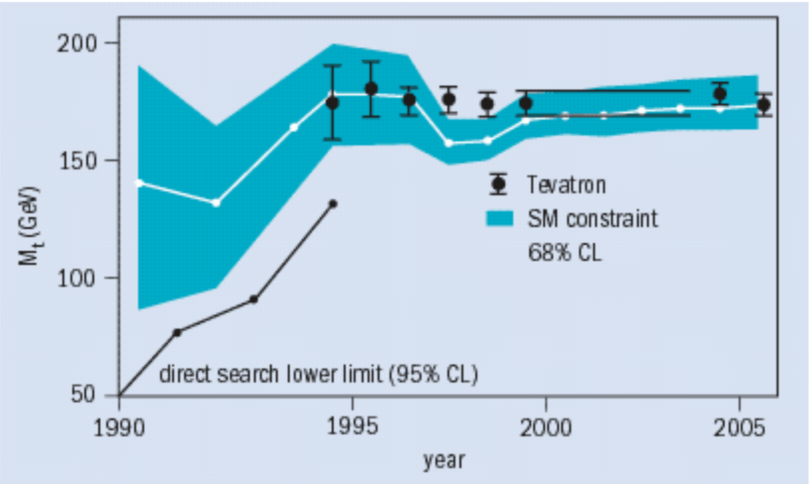
But…

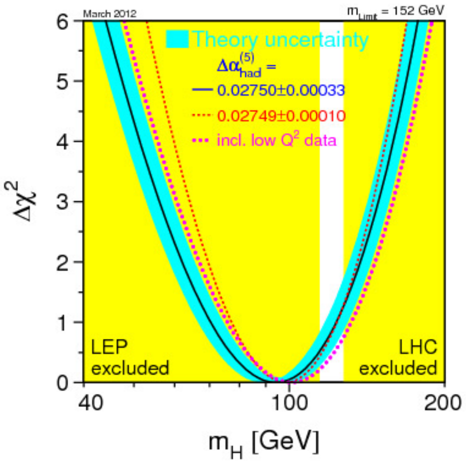
We shouldn't be so naïve as to judge the success of a collider on whether it achieves a 5σ discovery of new particles.

What collider am I referring to here?

Legacy of the Large Electron Positron Collider (LEP)







Z line-shape measurements

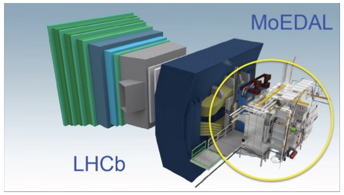
- strict bound on number of (light) neutrino species.

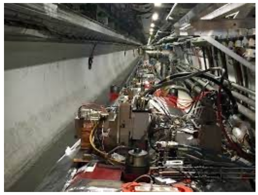
Precision electroweak measurements (O(10%)-> O(1%))

- Fits based on EW radiative corrections enabled predictions of the top-quark mass (discovered at Tevatron) and the Higgs' boson mass (discovered at LHC).

The Large Hadron Collider at CERN

+ MoEDAL-MAPP

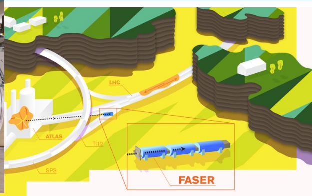




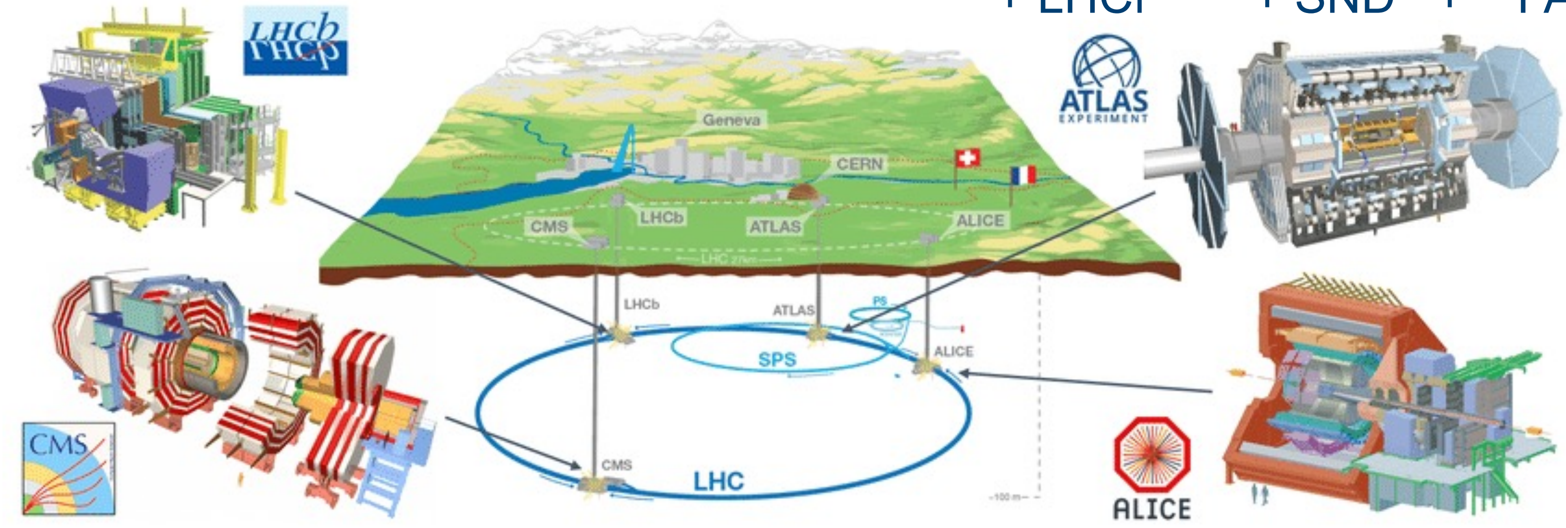
+ LHCf

+ SND

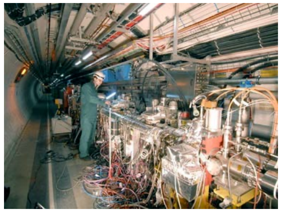
+



FASER



+ TOTEM



- **World's highest energy particle accelerator.**
- **High-Luminosity upgrade (HL-LHC) planned for later this decade to provide physics to the late 2030s…**

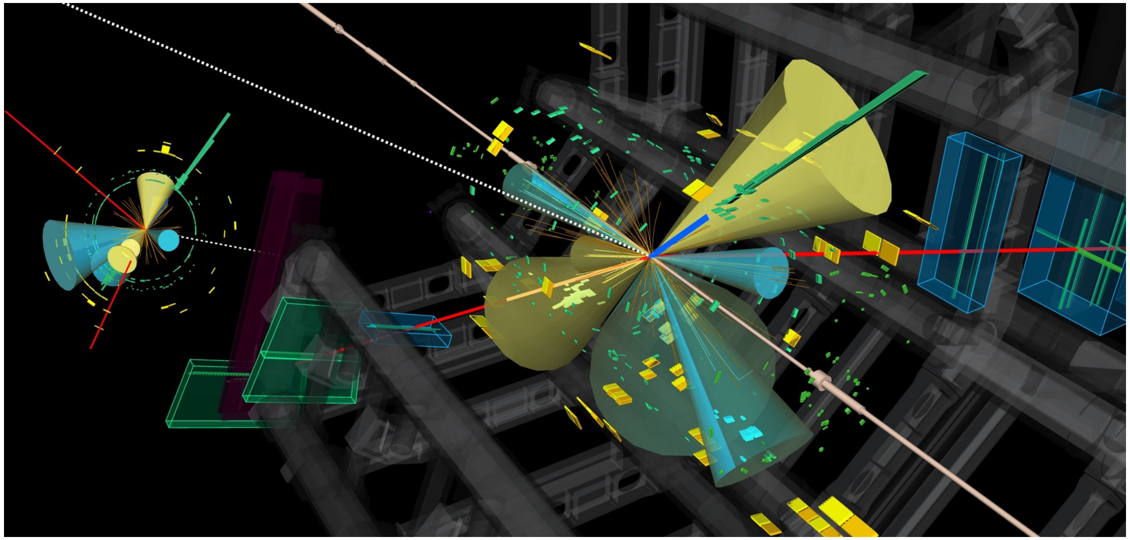
What should we consider a discovery?

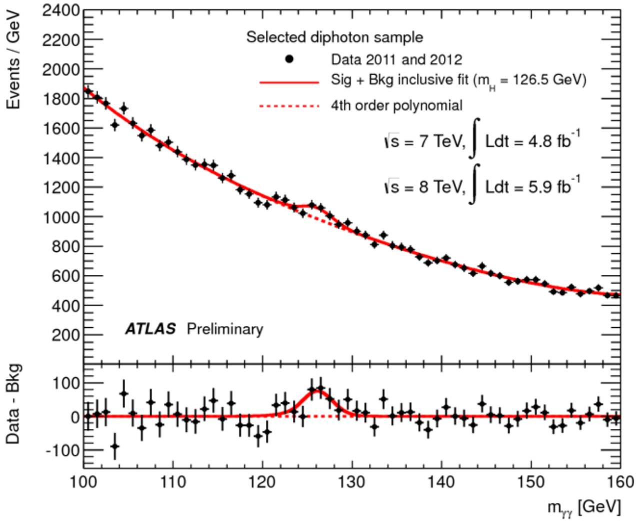
What’s a discovery in particle physics

- Detecting for the first time a new fundamental process
- Discovering new particles (indirectly or directly)

S. Gori

We have seen examples of both of these during LHC running…. But we often focus on the second one…



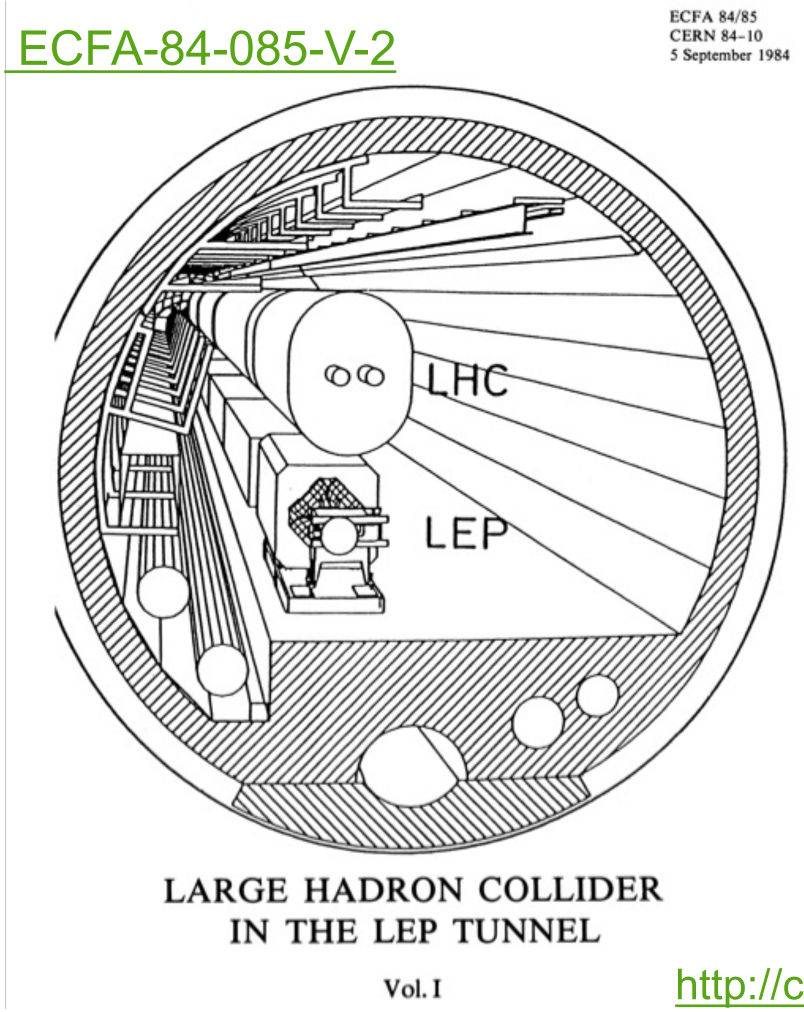


Timescales in particle physics

…are long…

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

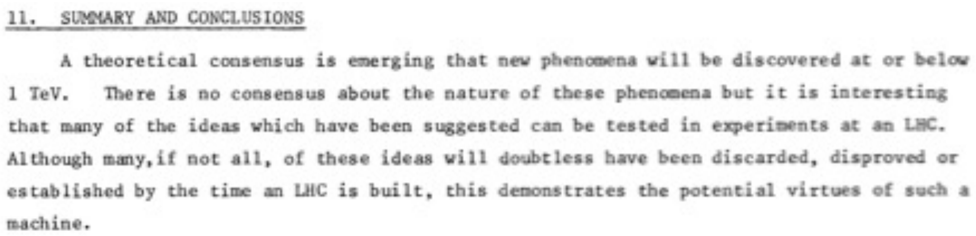
ECFA-84-085-V-2



ECFA 84/85
CERN 84–10
5 September 1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

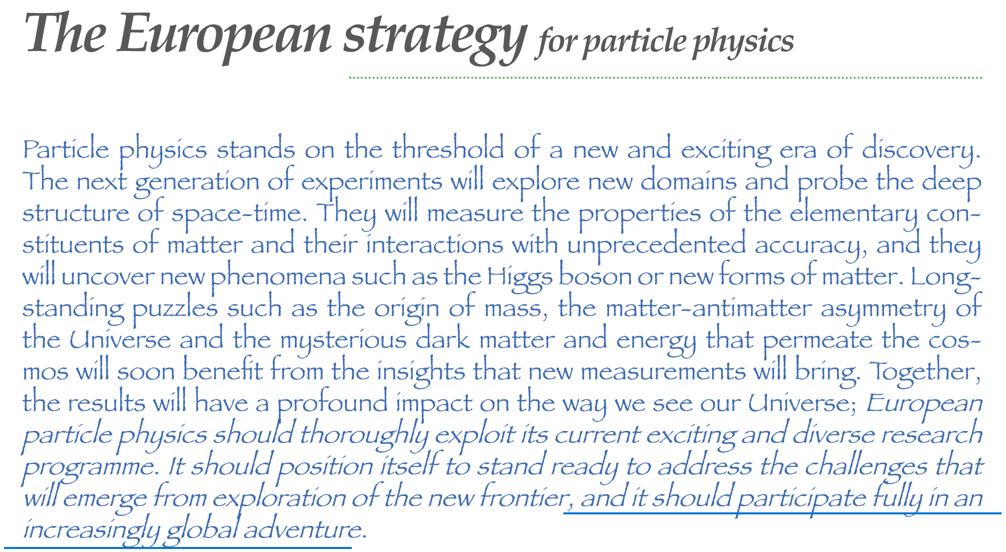
Vol. I



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

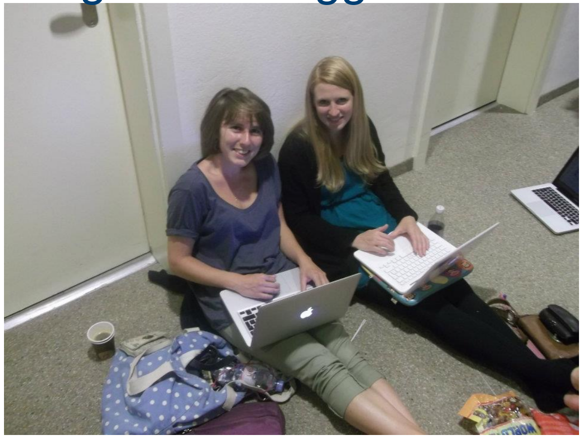
I have only been involved in a small part of the LHC journey…

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”

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

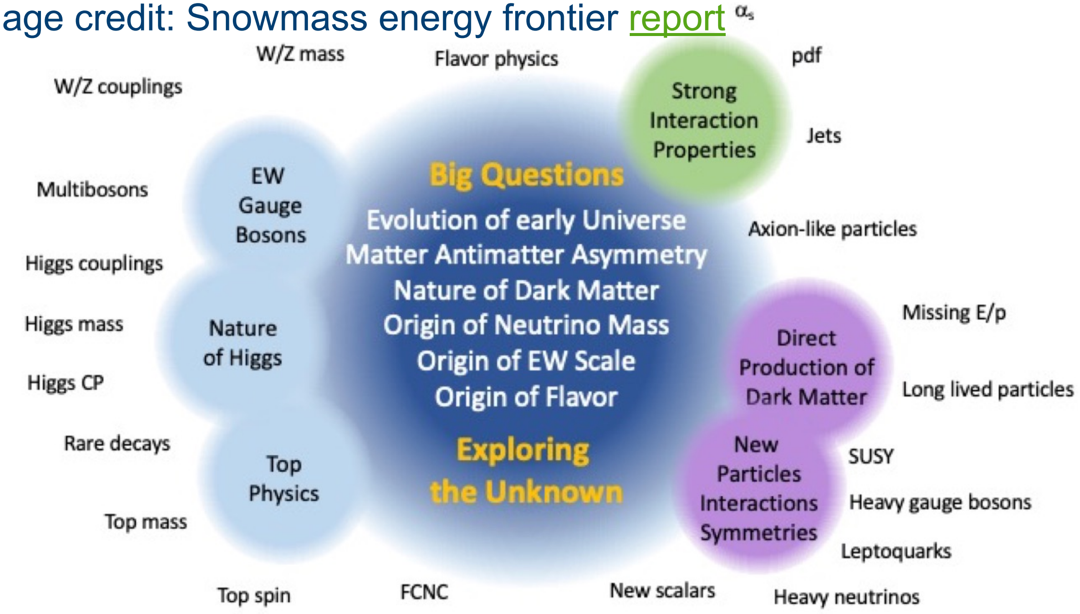
Snowmass 2021

“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)"

Big questions in particle physics today…

Motivations for BSM physics will be discussed in more detail in Tevong’s lectures…

Image credit: Snowmass energy frontier report



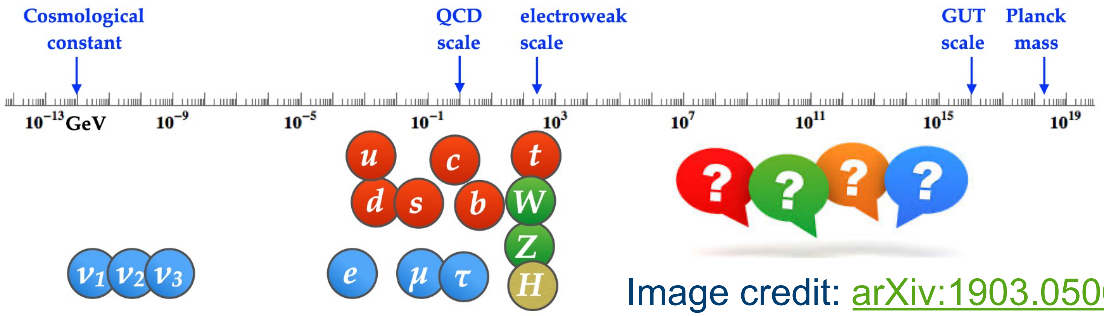
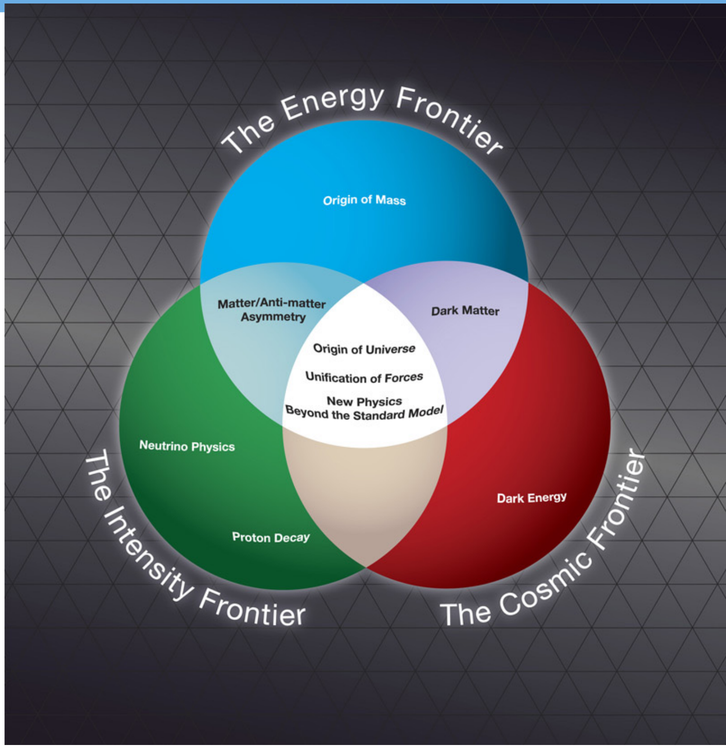


Image credit: arXiv:1903.05063

- 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…

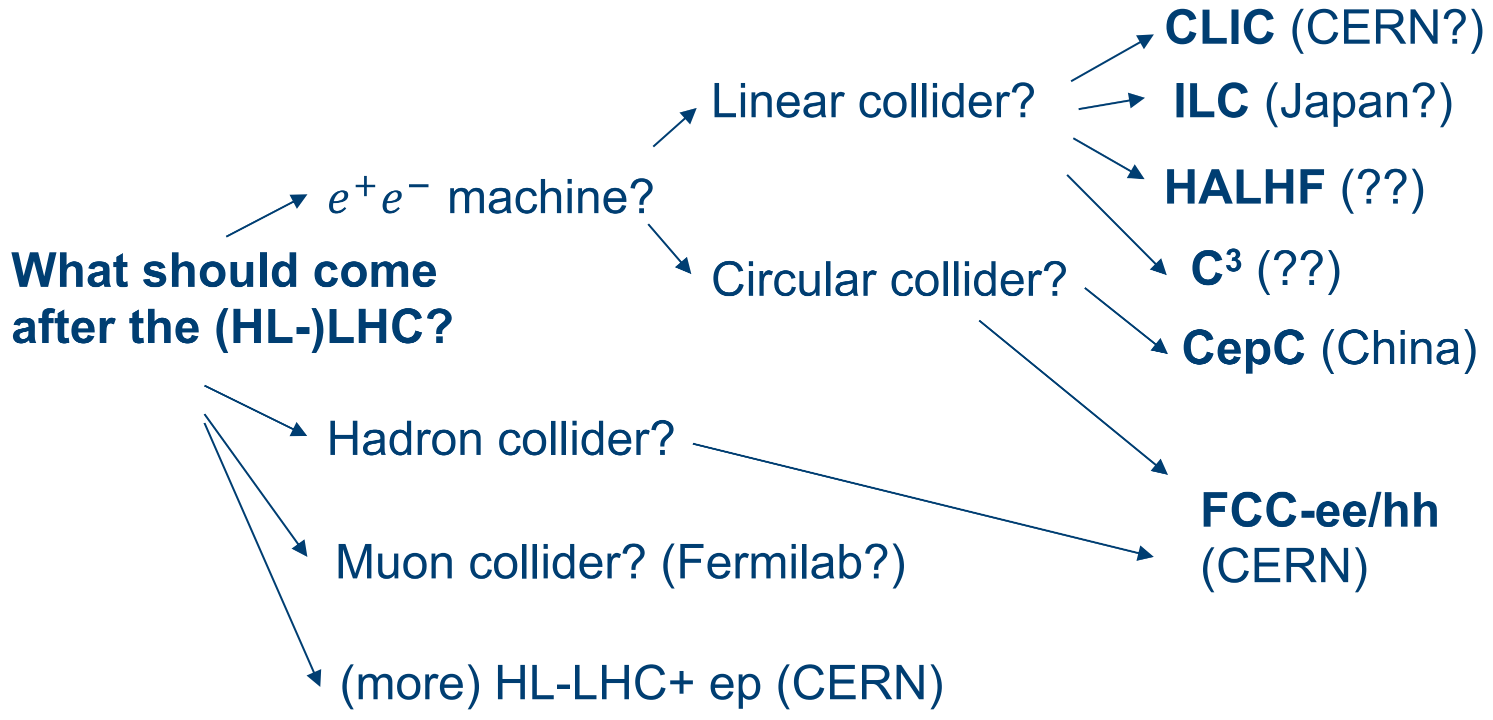
Frontiers in particle physics

- Pushing the intensity and energy frontiers represent two complementary routes for probing new physics. An oversimplified view:
    - Intensity frontier => precision measurements => indirect searches to new physics.
    - Energy frontier => access high-mass scales => direct searches for new physics.



They should not be seen as exclusive: the LHC has shown we can do precision measurements at hadron machines, and (as we'll see) intensity frontier e+e- machines can have unique sensitivity to some BSM scenarios.

What should come after the HL-LHC?



What should come after the (HL-)LHC?

e^+e^- machine?

Linear collider?

CLIC (CERN?)

ILC (Japan?)

HALHF (??)

C^3 (??)

Circular collider?

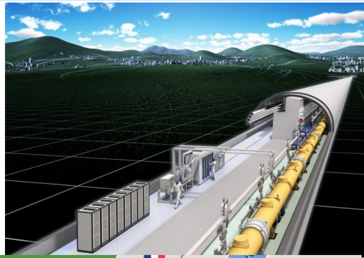
CepC (China)

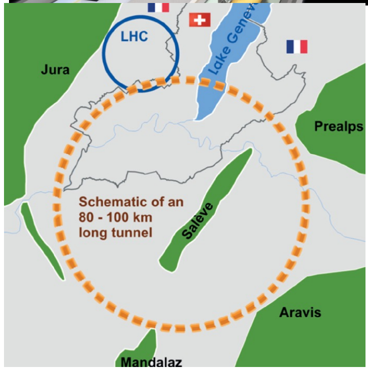
Hadron collider?

FCC-ee/hh (CERN)

Muon collider? (Fermilab?)

(more) HL-LHC+ ep (CERN)





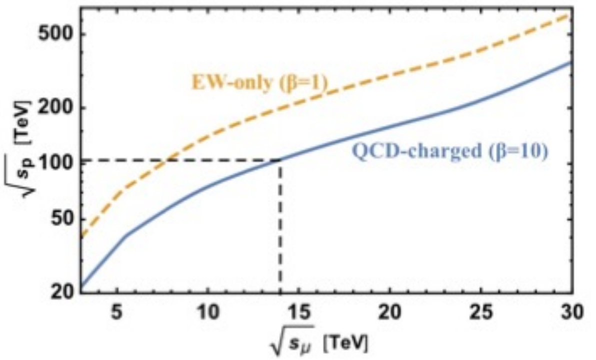
As mentioned earlier, broad agreement in most recent Update to the European Strategy for Particle Physics (ESPPU) and US Snowmass P5 processes for (1) an Intensity-Frontier ”Higgs factory” followed by (2) ambitions to push the Energy frontier into the 10 TeV pCM range…

Comparison of colliders

Apologies for potential over-simplifications here!

Hadron (pp)

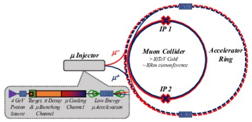
Composite $\sqrt{\hat{s}} \ll \sqrt{s}$
"Messy" collisions



100 TeV pp ≈ 10-15 TeV μμ

(more details in backup)

Muon collider (Fermilab siting) ~ 10 TeV (bigger version to come)



Lepton

Fundamental $\sqrt{\hat{s}} \sim \sqrt{s}$ => Clean(er) collisions

COM energy limited by synchrotron radiation

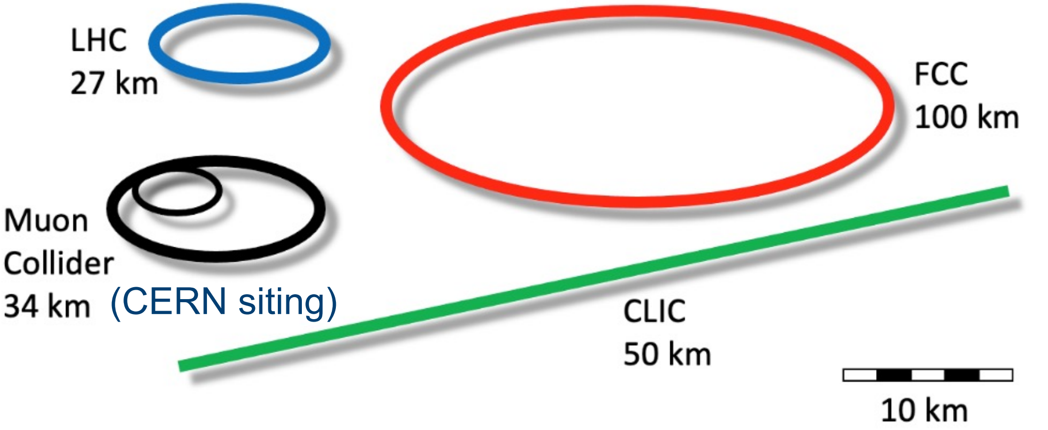
$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

$\boldsymbol{e^+e^-}$

~100 km ring for ~240 GeV

$\boldsymbol{\mu^+\mu^-}$

~10 km ring for ~10 TeV



(CERN siting)

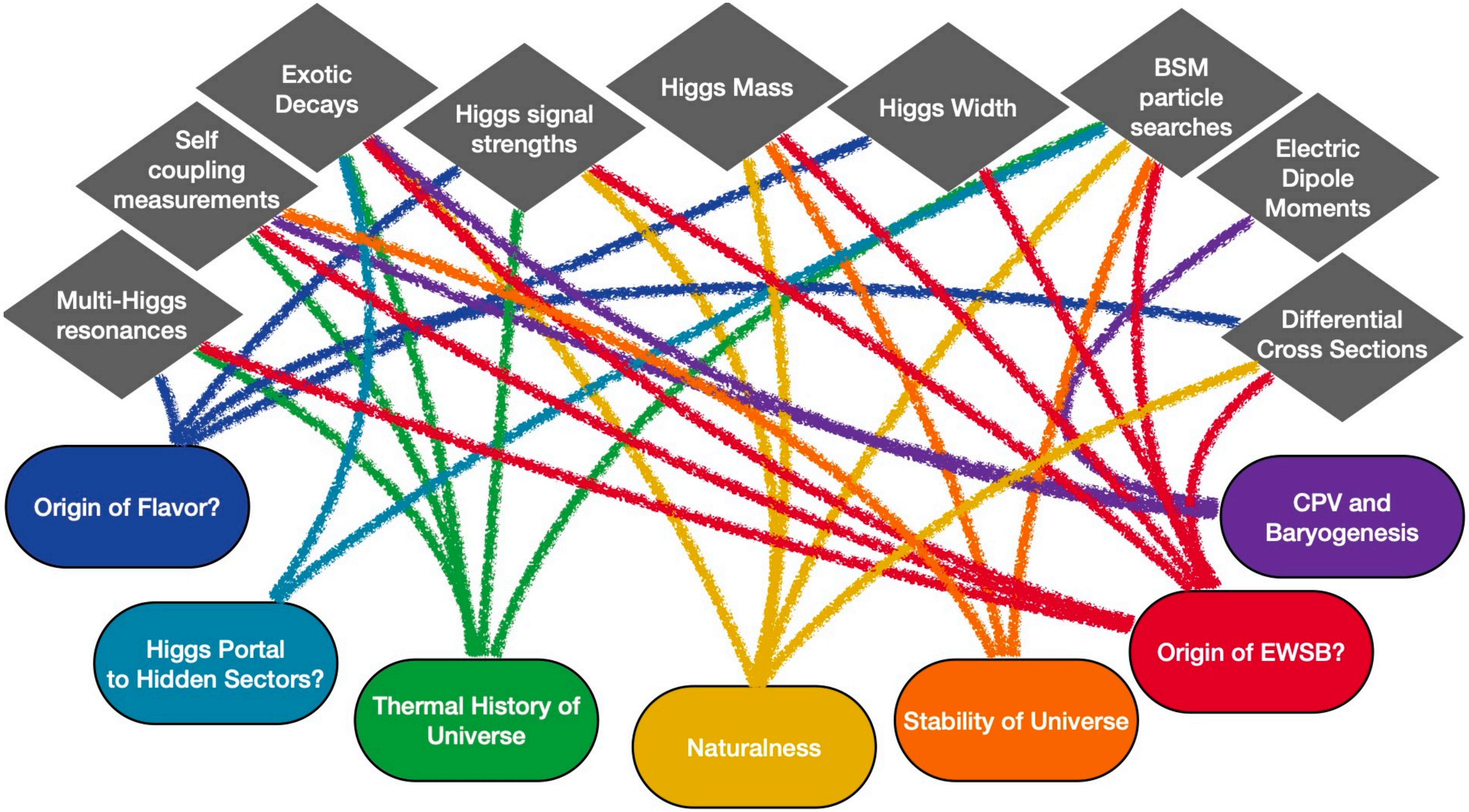
Before we go any further…

Any questions?

2. e^+e^- colliders

Why study the Higgs'?

Schematic taken from Snowmass topical group report on Higgs physics



“Higgs factory” physics drivers

Schematic from slides by M. Selvaggi at 2023 FCC week

Disclaimer: whilst a lot of my schematics/ examples are based on FCC-ee, physics prospects are similar for most Higgs-factory concepts and I’ll try to highlight key differences.

Higgs
factory

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

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/τ factory:

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

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

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Later on I’ll discuss some of the experimental/ theoretical challenges that must be overcome to meet these goals…

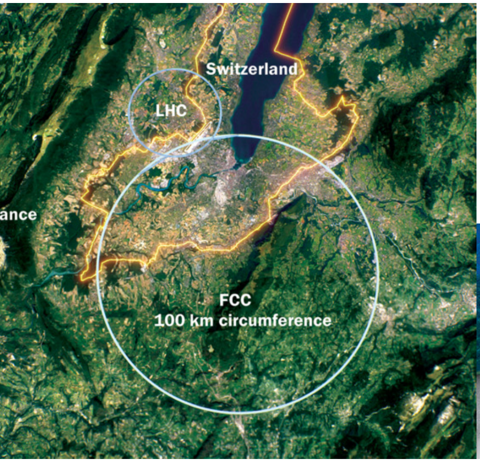
e^+e^- colliders: circular or linear?

Circular colliders

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

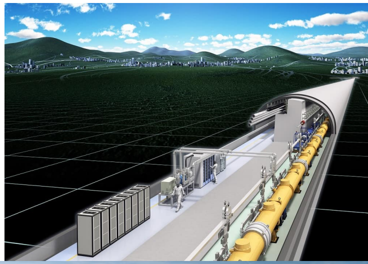
Linear colliders

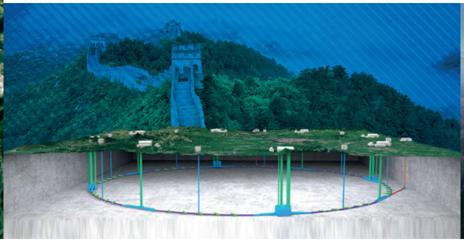
- Single pass at IP
- Maximum accelerating gradients
- No synchrotron radiation
- Can exploit (longitudinal) beam polarization
- Staged approach to higher energies (energy~length)



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

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





Question

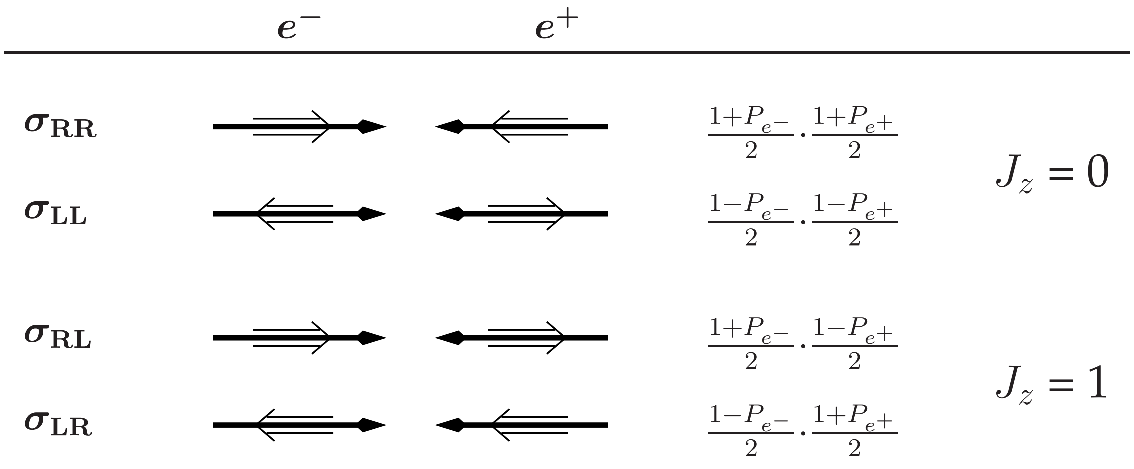
Why would longitudinal beam polarization be useful in e+e- colliders?

Beam polarisation

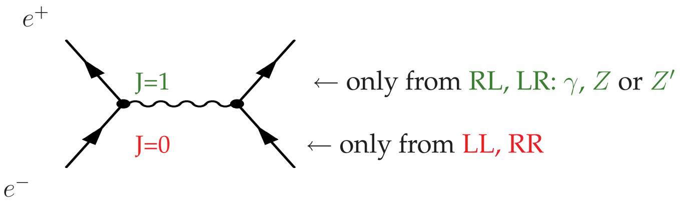
Phys.Rept. 460 (2008) 131-243

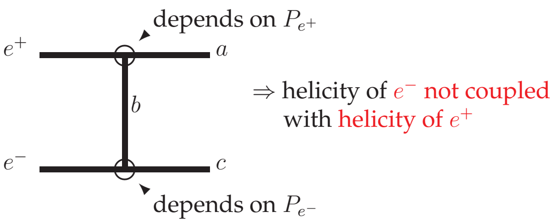
Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660003

One advantage of linear e^+e^- colliders is the opportunity to exploit beam polarization which can benefit precision SM measurements and BSM searches. Baseline design of ILC assumes 80% longitudinal polarization of electron beam and 30% polarization of positron beam.



- Enhance cross-section for SM vector-boson production OR suppress backgrounds in search for scalars.
- For t/u-channel exchanges, helicities of incoming beams directly coupled to helicities of outgoing particles.



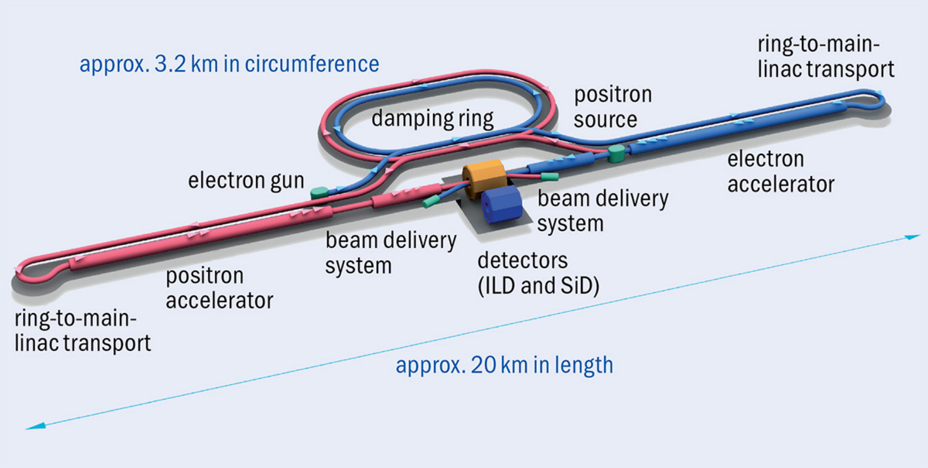


International Linear Collider (ILC)

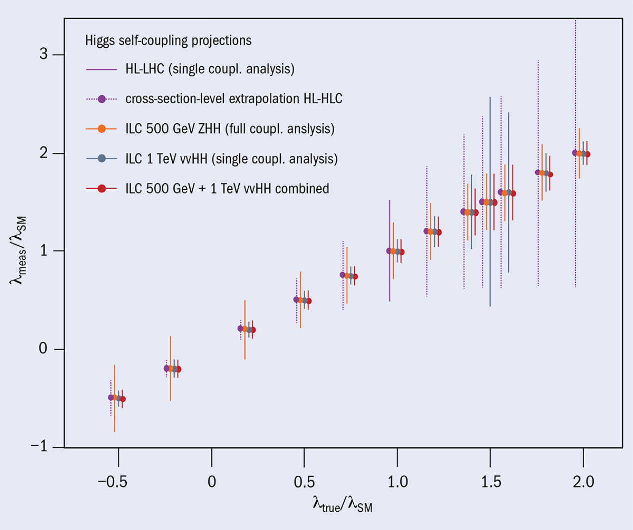
Image taken from CERN courier article on ILC (Jan 2021)

Long history based on established technology (global design effort launched in 2005), with design efforts focused on Japan since 2013.

TDR released in 2013 set initial program of e^+e^- collisions at 250 GeV (peak cross-section for $e^+e^- \to Zh$ for 125 GeV Higgs), with the possibility to upgrade to 500 GeV and 1 TeV, and perform dedicated runs at Z-pole ("giga-Z"-5×10^9 Z-bosons) and WW/tt production threshold.



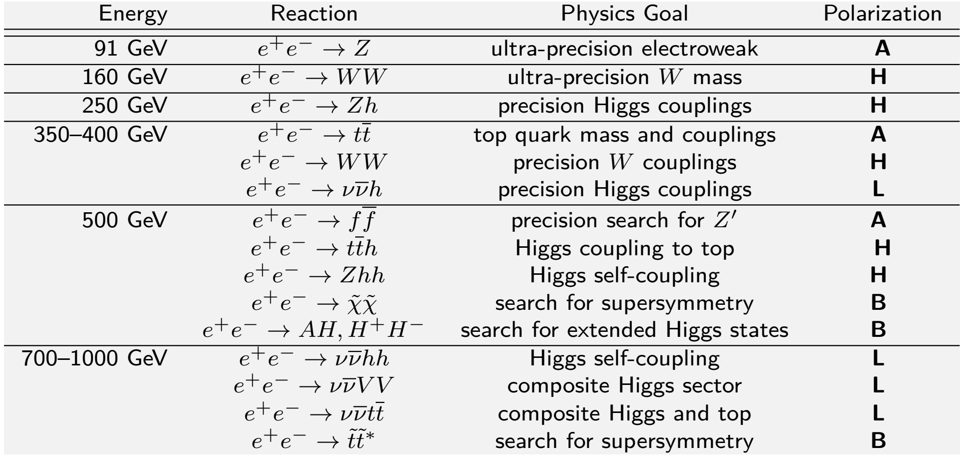
Initial 250 GeV stage would involve~ 20km length and two detectors in a push/pull configuration (SiD and ILD)



For 10-20% precision require combination of double Higgstrahlung and VBF

ILC physics prospects

Table taken from physics volume of ILC TDR
Figure from ILC Snowmass paper



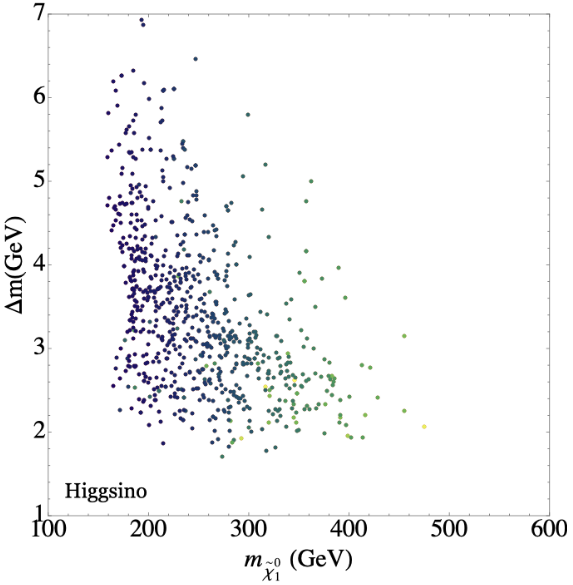
Energy	Reaction	Physics Goal	Polarization
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	A
160 GeV	$e^+e^- \to WW$	ultra-precision W mass	H
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	H
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	A
	$e^+e^- \to WW$	precision W couplings	H
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings	L
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'	A
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top	H
	$e^+e^- \to Zhh$	Higgs self-coupling	H
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry	B
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states	B
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling	L
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector	L
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top	L
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry	B

A= use information from beam polarization asymmetry measurements.

H= enhance luminosity for annihilation through colliding opposite e+ e- polarisations.

L= enhance rates of SM processes through $e_L^- e_R^+$

B= search for BSM by using $e_R^- e_L^+$ to suppress SM backgrounds



"As well as a Higgs' factory, it could also be a higgsino factory"

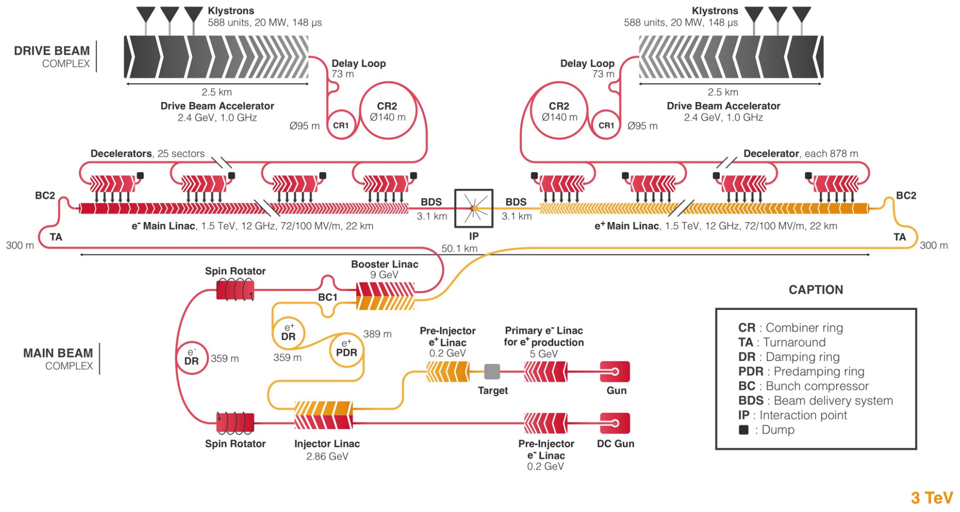
- ILC could identify/exclude new particles with EW interactions up to beam energy, and measure their masses/quantum numbers.

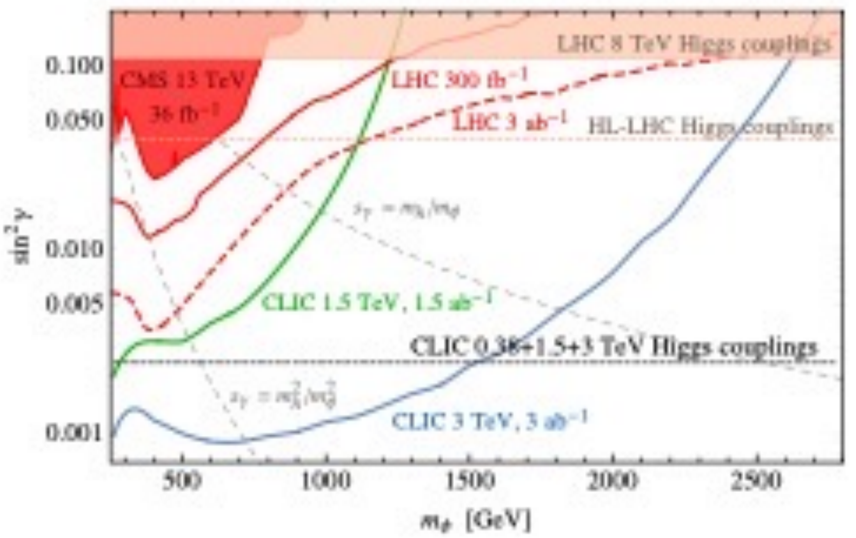
Plus exciting opportunities to probe hidden sectors/ LLPs and host additional beam dump experiments…

Compact Linear Collider (CLIC)

https://clic.cern/gallery

Staged approach to collision energies at 380 GeV, 1.5 TeV and 3 TeV for site lengths of 11-50 km. Ambitious goal of 100 MV/m accelerating gradient achieved by using novel transformer technology: couple high current low energy 'drive' beam to high energy, lower current 'main' beam





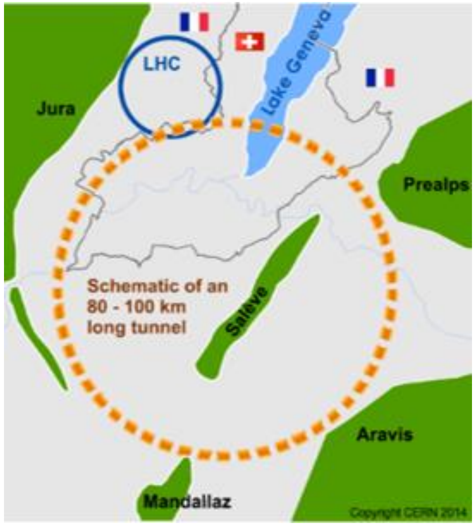
- Baseline proposal assumes 80% electron polarisation, no positron polarisation.
- Highest e^+e^- COM on the market → highest direct reach for BSM.

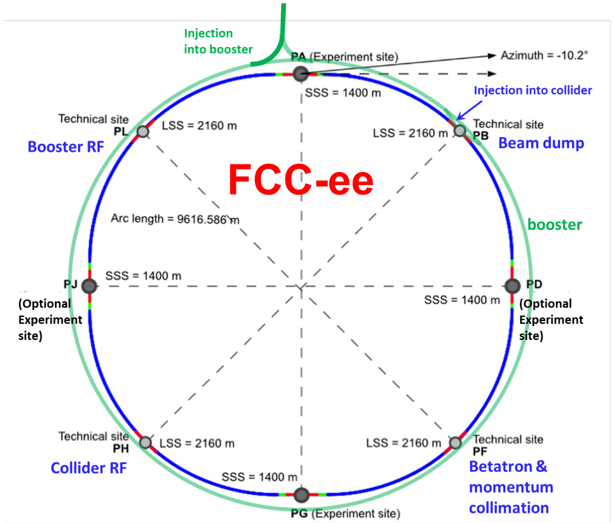
Integrated FCC programme

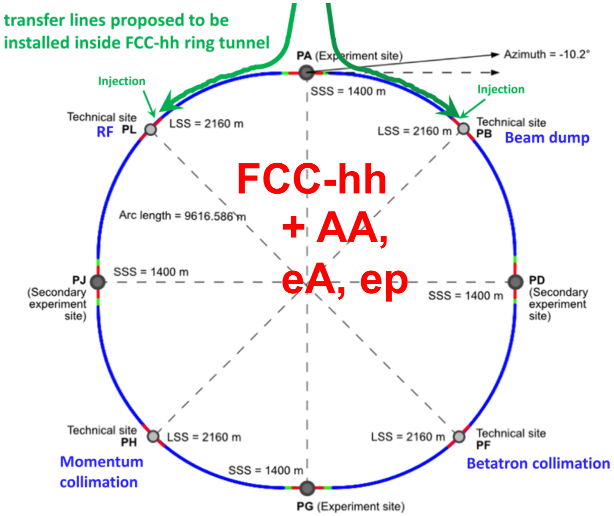
More on FCC-hh
later on..

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).



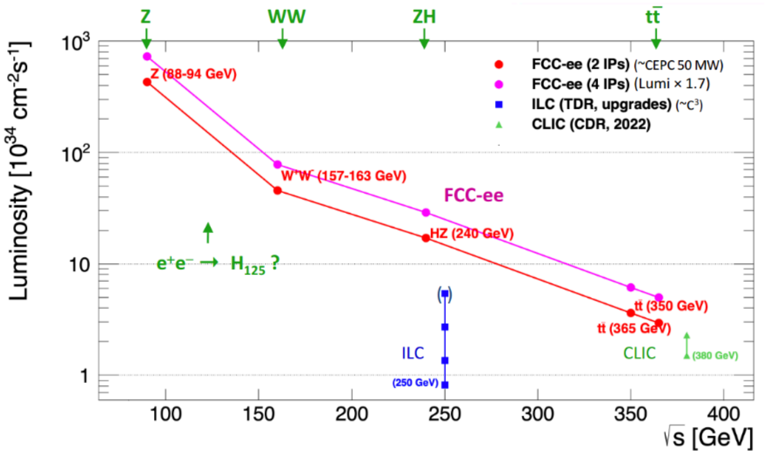




2020 - 2040 | 2045 - 2063 | 2070 - 2095

Ultimate precision @ FCC-ee

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



15 (20?) years of operations

	Z pole	**? H pole ?**	**WW**	**ZH**	**ttbar**
$\sqrt{s}$ [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 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

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)

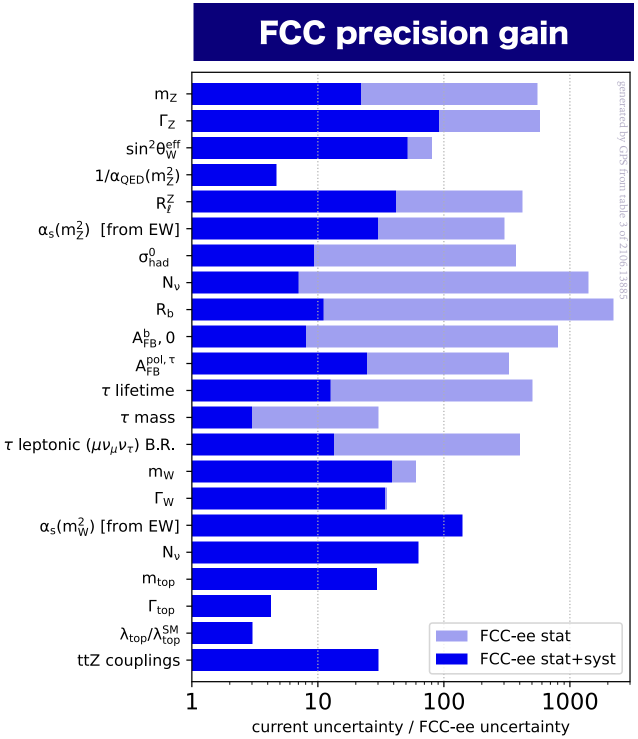
Luminosities and precision.

- The gains in precision at e+e- Higgs’ factories arise from high luminosities which give much higher statistics which drive down the (statistical) uncertainties.

- For linear colliders, polarization can provide an effective boost in statistics that can (partially) make up for lower luminosities (more later).

- Increased precision (sub-percent) gives indirect sensitivity to mass scales up to 50-70 TeV.

- Disclaimer: to fully reap the benefits of higher statistics the systematic uncertainties must be correspondingly brought down, and the theoretical precision must be comparable (more later)



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

Lets check the maths

1. Lets remind ourselves of the relationship between the cross-section for a process and the number of events expected at a collider

Relationship between cross-section and luminosity

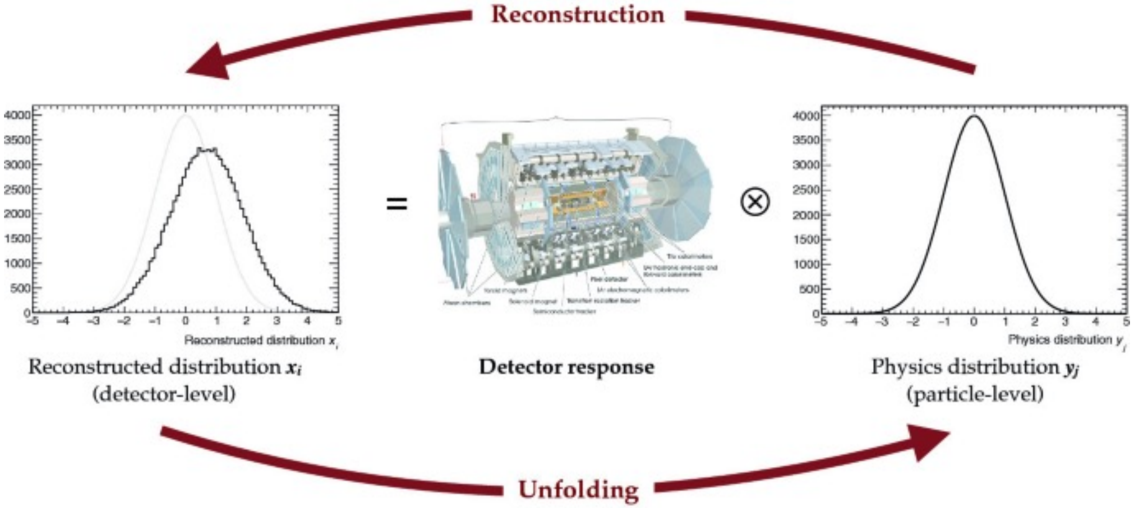
$$n_{events} = \sigma_{XX \rightarrow YY} \int \mathcal{L} dt$$

- $\mathcal{L}$ is the instantaneous luminosity.
- The cross-section relates to the quantum-mechanical probability of the event occurring (and has units of area).
- n_{events} is the total number predicted. The experimental observables we can use to measure σ are the number of (detector-level) events we reconstruct that satisfy a set of event-selection criteria,

Lets check the maths

2. How do we use colliders to measure cross-sections?

Measuring a (fiducial) cross-section



This would be its own lecture course!

$$\sigma^{fid}_{XX\rightarrow YY} = \frac{N_{data} - N_{bg}}{C \int \mathcal{L}\, dt}$$

- $N_{data} - N_{bg}$ is our best estimate of the number of reconstructed events that satisfy the selection (at detector-level) for that process.
- C is a correction factor that accounts for detector inefficiencies and mismeasurement effects (and can be estimated using Monte-Carlo).

Quick calculation

Assume $N_{bg} = 0$ (questionable assumption). Then undergraduate error propagation tell us:

$$\left(\frac{\Delta\sigma}{\sigma}\right)^2 = \left(\frac{\Delta N_{data}}{N_{data}}\right)^2 + \left(\frac{\Delta C}{C}\right)^2 + \left(\frac{\Delta(\int \mathcal{L}\, dt)}{(\int \mathcal{L}\, dt)}\right)^2$$

Now assume Poisson errors and that the second and third term on the RHS are negligible.

$$\left(\frac{\Delta\sigma}{\sigma}\right)^2 = \left(\frac{\sqrt{N_{data}}}{N_{data}}\right)^2 = \frac{1}{N_{data}} \rightarrow \left(\frac{\Delta\sigma}{\sigma}\right) = \frac{1}{\sqrt{N_{data}}}$$

Lets check the maths

3. Now compare expected statistical errors for Z-pole observables between LEP and (say) FCC-ee

Lets compare Z bosons at FCC-ee and LEP

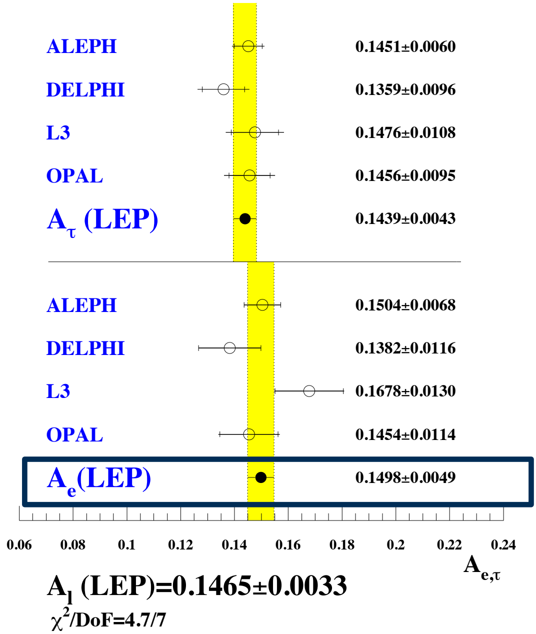
$$\frac{FCC}{LEP} = \frac{8\times10^{12}}{18\times10^{6}} = 4.44\ldots.\times10^{6} \Rightarrow \frac{\Delta\sigma_{FCC}}{\Delta\sigma_{LEP}} \sim \frac{1}{\sqrt{444444}} \sim \frac{1}{666.66}$$

i.e. reduction by a factor O(500)- consistent with statements like…

" The improvement in statistical uncertainties at the Z is typically a factor 500 "

Taken from FCC snowmass submission arXiv:2203.06520

Does this match up?



Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2 – 1.0	Ratio of hadrons to leptons; acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	0.4 – 1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

Choosing a measurement from LEP that has significant contributions from statistical uncertainties…

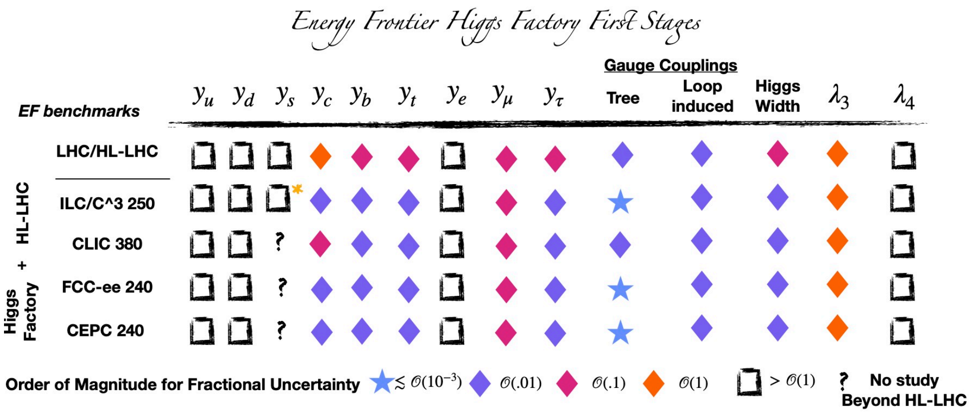
$$\frac{present\ error}{FCC-ee\ stat} = \frac{49}{0.07} = 700!$$

Discussion

4. Now let's discuss the (many) oversimplifications in this logic and other factors that must be considered…

Prospects at future e^+e^- machines- Higgs’

Key point: care should be taken when comparing prospects for future facilities due to differences in **staging options** (i.e. first phase vs integrated programme, upgrades in energy/luminosity), assumptions on systematic uncertainties, etc.



Energy Frontier Higgs Factory First Stages

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings		Higgs Width	λ_3	λ_4
											Tree	Loop induced			
	LHC/HL-LHC	☐	☐	☐	🟧	🟥	🟥	☐	🟥	🟥	🟪	🟪	🟥	🟧	☐
Higgs Factory + HL-LHC	ILC/C^3 250	☐	☐	☐*	🟪	🟪	🟪	☐	🟥	🟪	★	🟪	🟪	🟧	☐
	CLIC 380	☐	☐	?	🟥	🟪	🟪	☐	🟥	🟪	🟪	🟪	🟪	🟧	☐
	FCC-ee 240	☐	☐	?	🟪	🟪	🟪	☐	🟥	🟪	★	🟪	🟪	🟧	☐
	CEPC 240	☐	☐	?	🟪	🟪	🟪	☐	🟥	🟪	★	🟪	🟪	🟧	☐

Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ 🟪 $\mathcal{O}(.01)$ 🟥 $\mathcal{O}(.1)$ 🟧 $\mathcal{O}(1)$ ☐ $> \mathcal{O}(1)$ **? No study Beyond HL-LHC**

collider	Indirect-h	hh	combined
HL-LHC [40]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [31, 33]	49%	–	49%
ILC$_{500}$/C^3-550 [31, 33]	38%	20%	20%
ILC$_{1000}$/C^3-1000 [31, 33]	36%	10%	10%
CLIC$_{380}$ [35]	50%	–	50%
CLIC$_{1500}$ [35]	49%	36%	29%
CLIC$_{3000}$ [35]	49%	9%	9%
FCC-ee [36]	33%	–	33%
FCC-ee (4 IPs) [36]	24%	–	24%
FCC-hh [41]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [39]	-	15-30%	15-30%
μ(10 TeV) [39]	-	4%	4%

=> All Higgs’ factory scenarios operating around the Zh threshold (~240 GeV) can achieve sub-percent precision in many Higgs’ couplings but will not be able to directly access the Higgs’ self coupling.

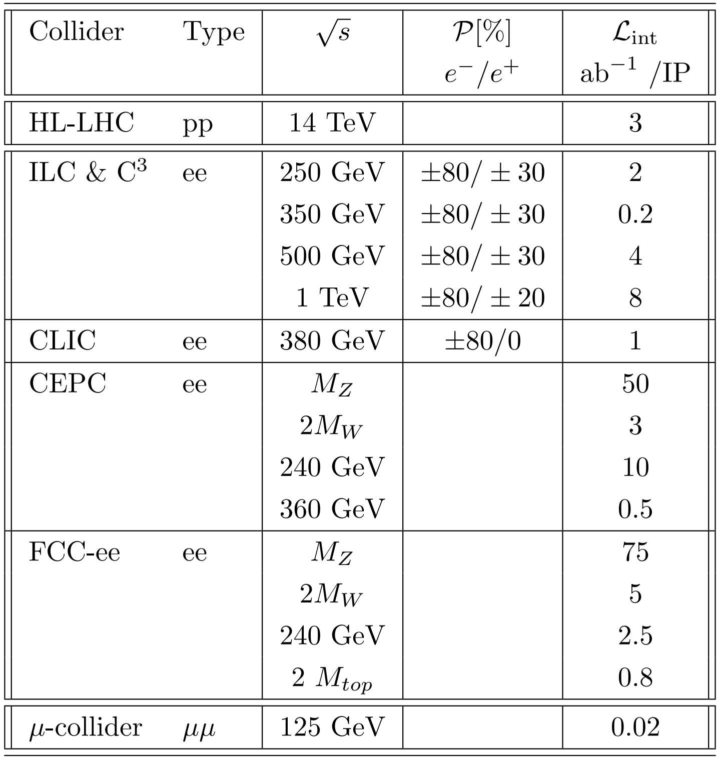
Prospects at future e^+e^- machines- EWPO

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8^*	17.8^*		3.8 (1.2)	17.8^*	
Δm_W (MeV)	12^*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1^*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1^*
Δm_H (MeV)	170^*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42^*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3^*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3^*
ΔA_e ($\times 10^5$)	190^*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500^*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400^*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000^*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700^*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\text{had}}$ (pb)	37^*			0.035 (4)	0.05 (2)	37^*
δR_e ($\times 10^3$)	2.4^*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6^*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2^*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1^*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c($\times 10^3$)	17^*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

- For the different options the first number is the statistical error, the second is the expected experimental systematic.
- For some EWPO linear colliders can reach comparable precision due to effective enhancement of statistics through exploiting polarization.

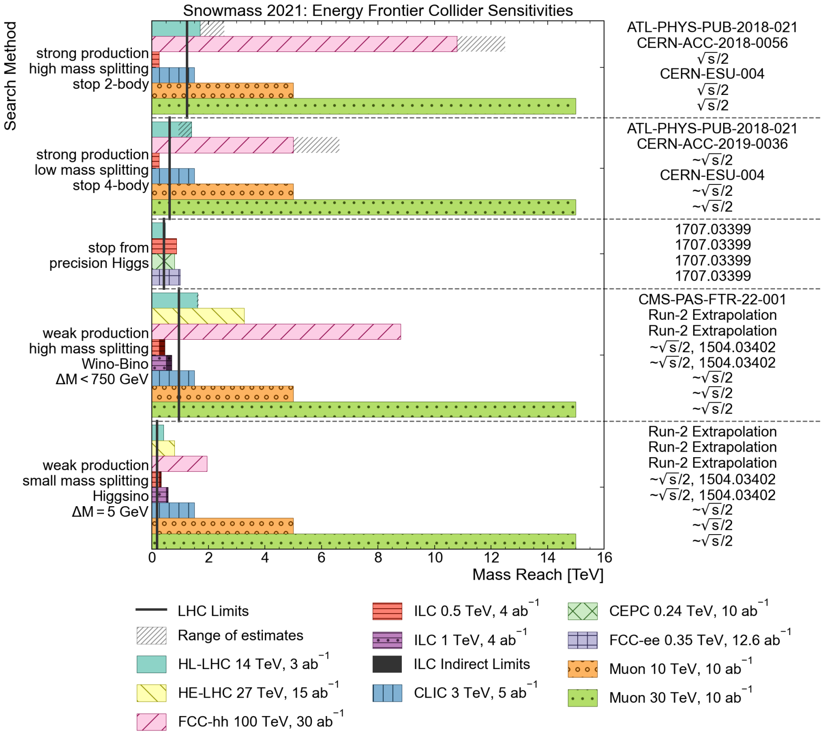
e^+e^- machines: benchmark scenarios

Benchmark Higgs factory scenarios considered in Snowmass ’21 studies



Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

Linear colliders reaching higher energy – sensitivity to BSM @ higher mass scales



Will now look in more detail at the prospects associated with running at the Z-pole, Zh WW and $t\bar{t}$ threshold that are the default for circular colliders…

CEPC vs FCC: similarities

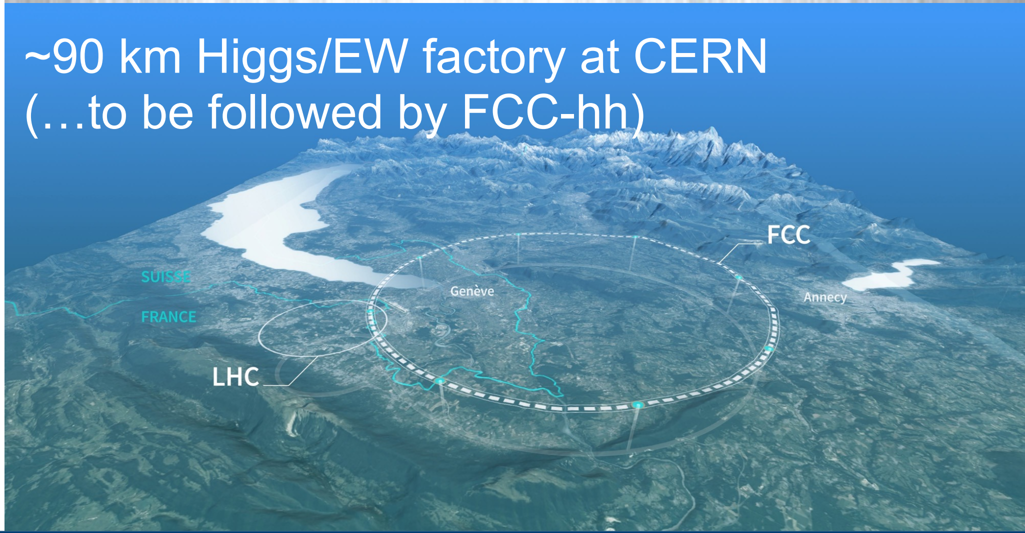
https://home.cern/science/accelerators/future-circular-collider

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. Exciting flavour opportunities associated with 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 **(next lecture)**.

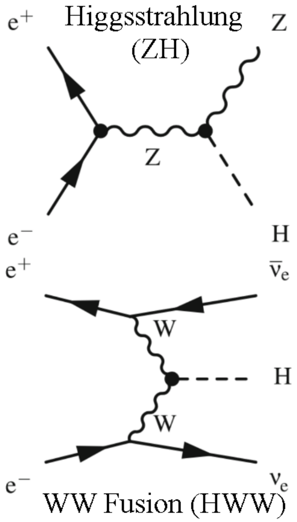
I will now expand on these points using FCC as a case study…

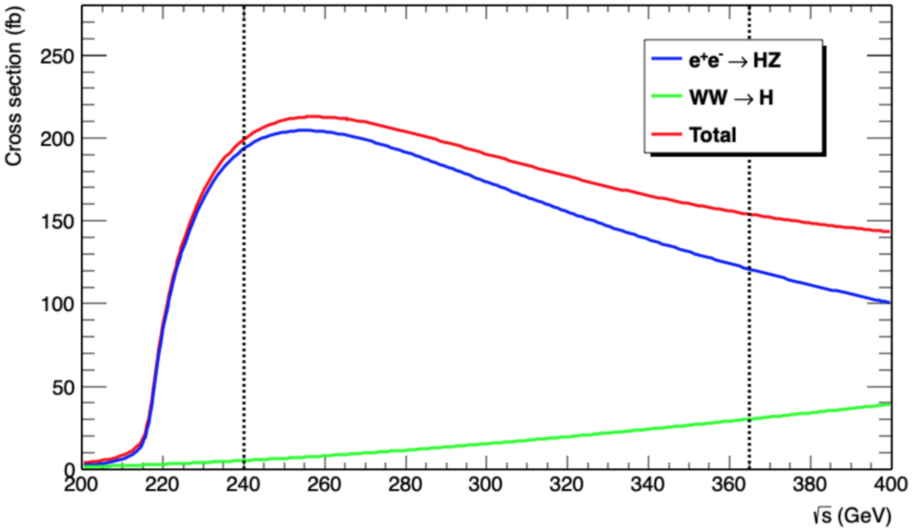
Case study- Higgs physics

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

> 1 million ZH events

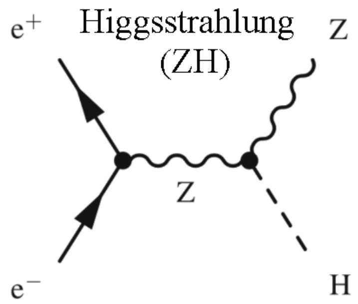
~ 100,000 WW fusion



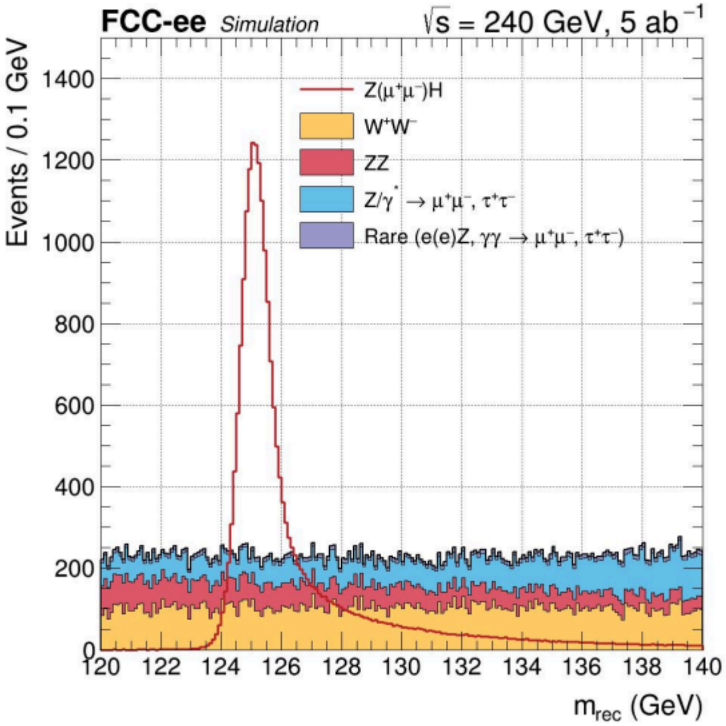


- Large rates, clean experimental environment (no UE, Pileup, triggerless) with no QCD background will open up a new era of Higgs precision physics.
- Opportunities to remove model-dependence from measurements and reach sub-percent level for post couplings.

Higgs recoil mass method



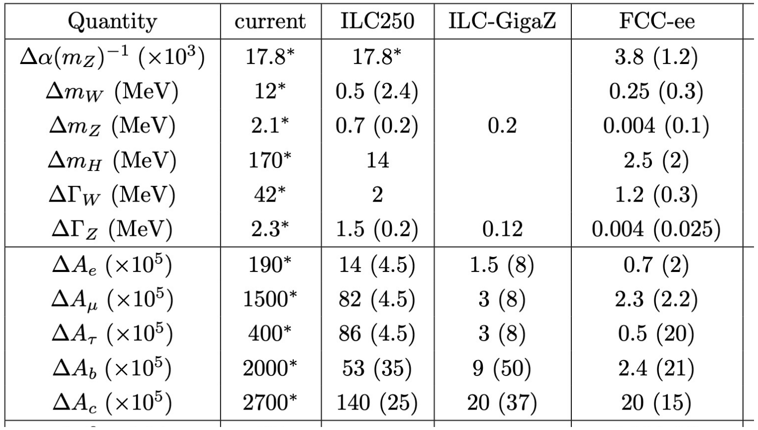
- **Precise C.O.M knowledge*** enables:
  - Z to be tagged (through leptons).
  - Construct recoil mass associated with Higgs $m_{\text{recoil}}^2 = s - 2\sqrt{s}E_{ll} + m_{ll}^2$
  - Event counting gives precise Zh production cross-section measurement.
    - Absolute + model independent measurement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



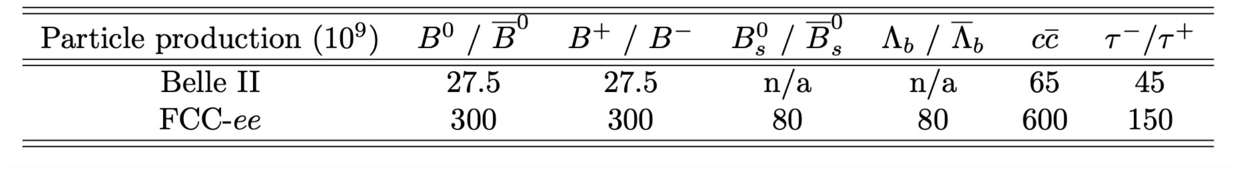
***Achieved through resonant depolarization (unique to circular l+l- colliders)**

Why do we need tera-Z?

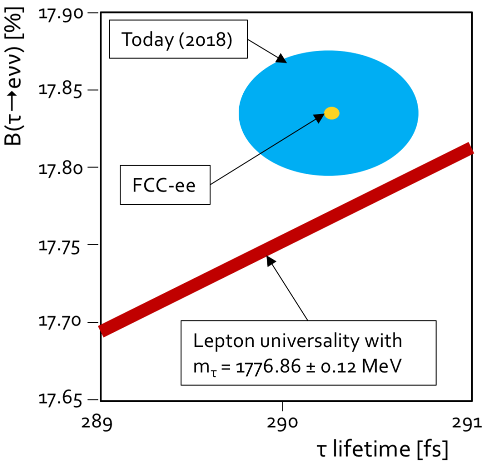
- Significantly higher statistics at Z-pole (~ $5{\times}10^{12}$ Z-bosons) generates ultimate precision for EWPO, and best sensitivity for BSM searches (i.e. HNLs).
- Unprecedented flavour opportunities- 10x more bb/cc pairs than final Belle-II statistics.



Quantity	current	ILC250	ILC-GigaZ	FCC-ee
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	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 ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)



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.

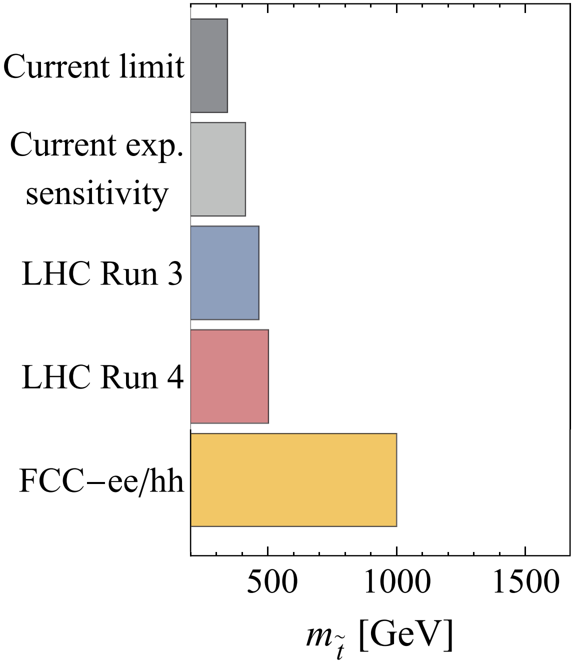
For flavour, see slides by Jernej. F. Kamenik at London FCC week

Direct and indirect BSM searches

Taken from FCC Snowmass submission

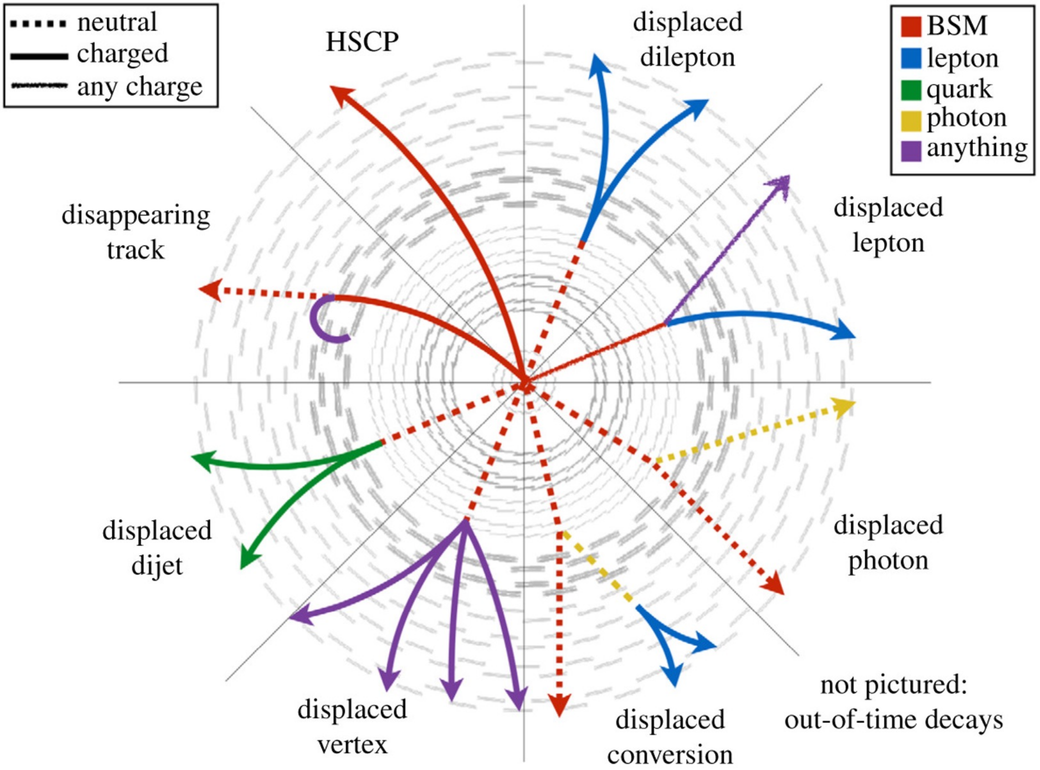
1. Indirectly discover new particles coupling to the Higgs or EW bosons up to scales of $\Lambda \approx 7$ and 50 TeV.
2. Perform tests of SUSY at the loop level in regions not accessible at the LHC.
3. Study heavy flavour/tau physics in rare decays inaccessible at the LHC.
4. Perform searches with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



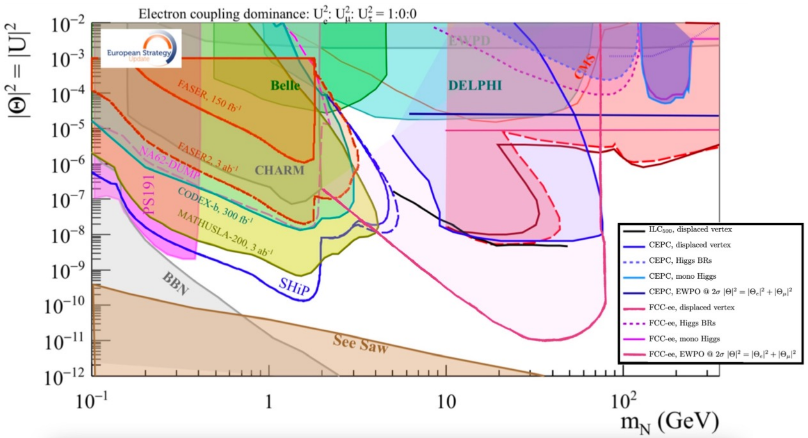
LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

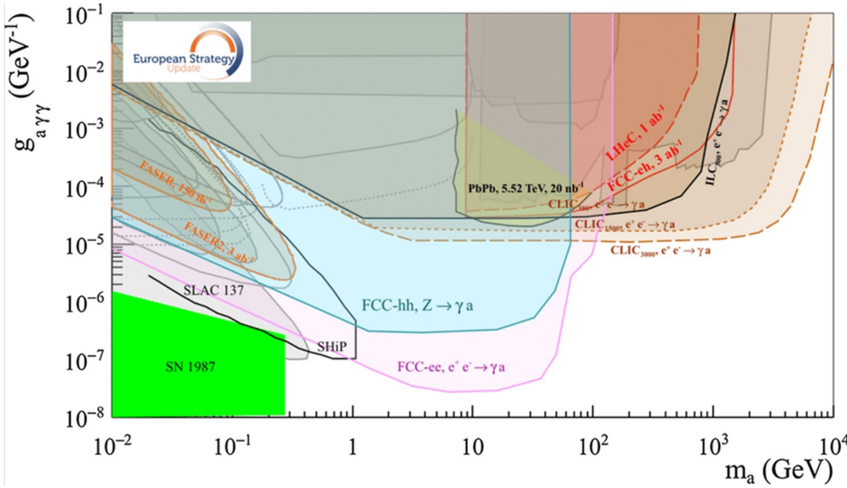
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

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

- 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).

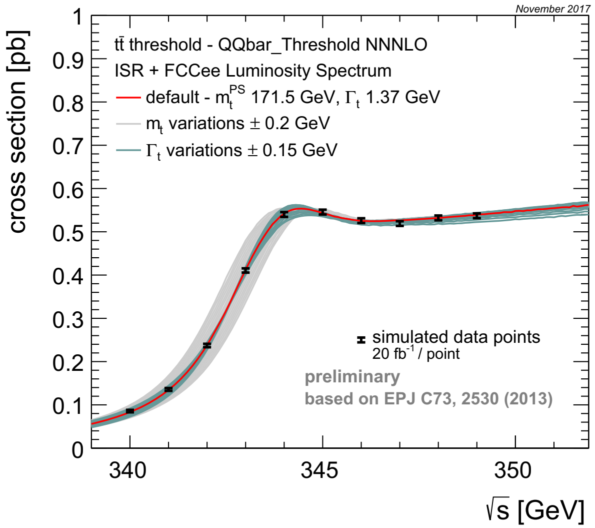




FCC-ee top opportunities

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.



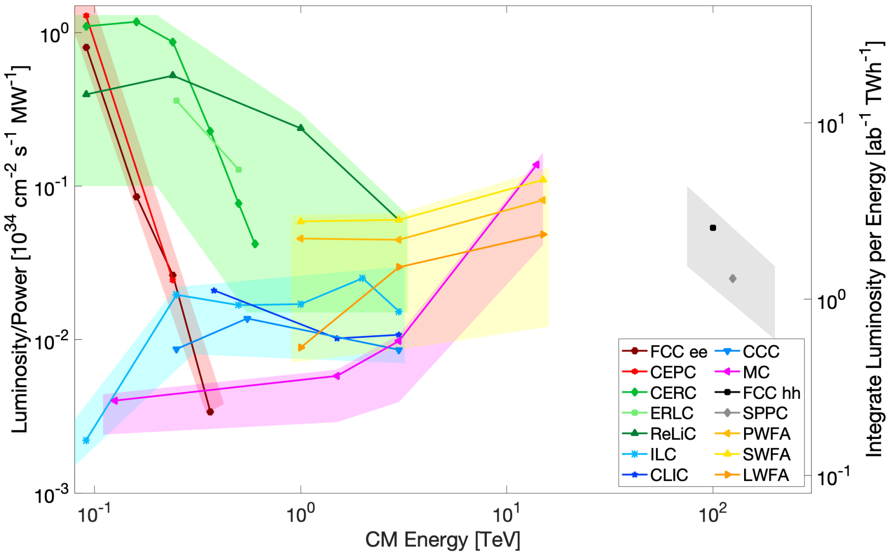
Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z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

Challenges for future e^+e^- colliders

Accelerator R+D:

- ILC and FCC-ee/CEPC accelerator technologies technologically advanced.
- CLIC accelerator technologies demonstrated; steps towards cavity industrialisation ongoing.
- Strong drive to improve energy efficiency of RF systems (particularly at higher-energy runs).
- Newer concepts (C^3, plasma-driven acceleration, ERLs) carry higher technological risks.



Continual disclaimer: I am not an accelerator expert, so apologies if I have missed/oversimplified here…

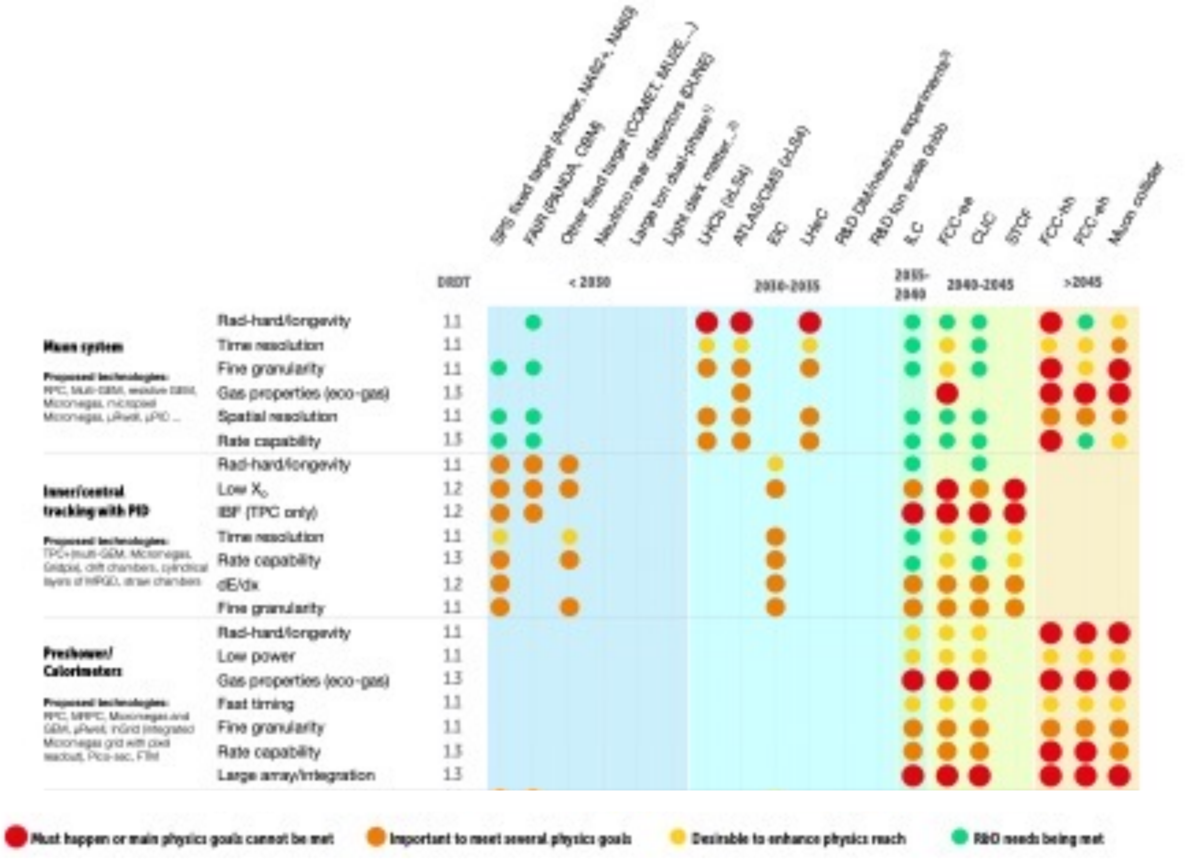
Challenges for future e^+e^- colliders

Detector R+D:

Schematic taken from 2 R+D roadmap

- There exist mature detector concepts for the established Higgs' factory concepts.

- The **red, orange** and **yellow** dots show there is still significant R+D required to reach the performance goals.



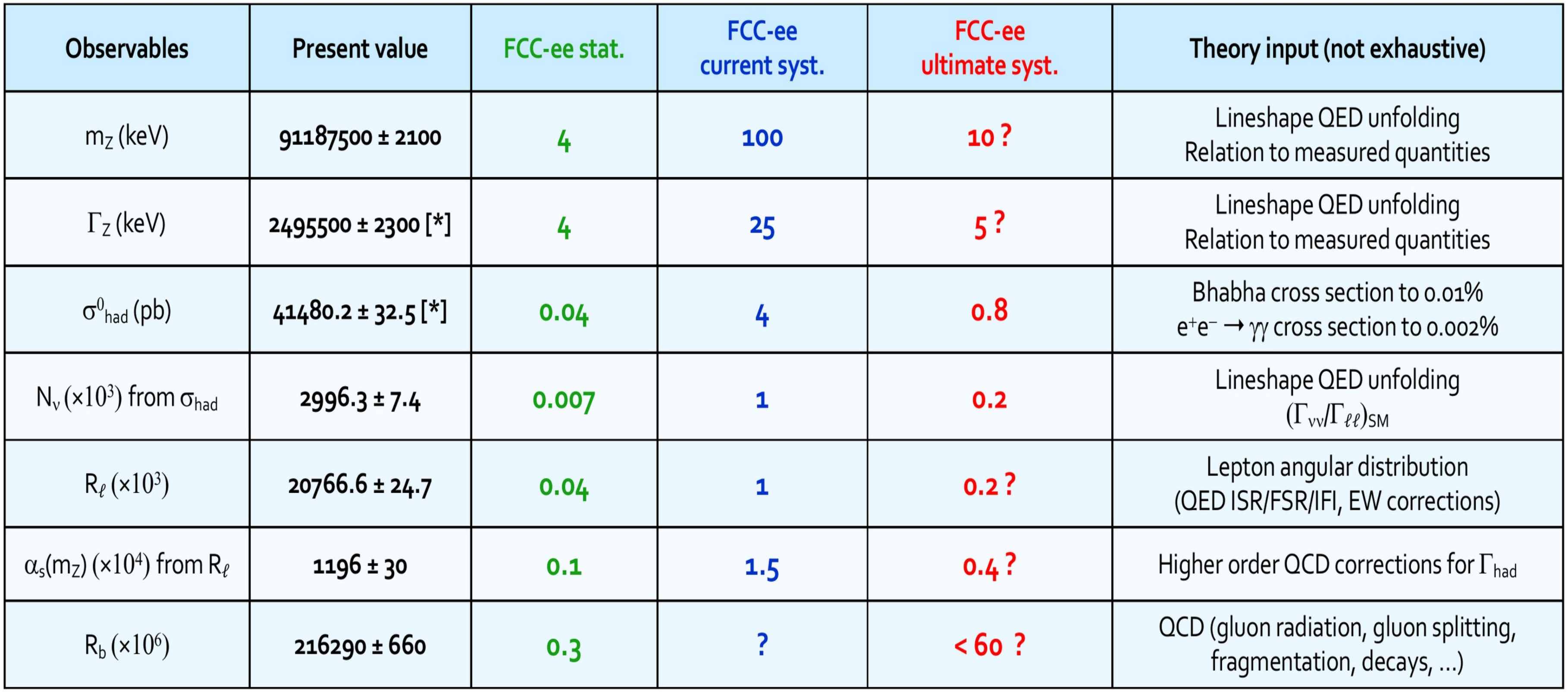
		DRDT	< 2030						2030-2035						2035-2040	2040-2045			>2045		
			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MUSE,...)	Neutrino near detectors (DUNE)	Large ton dual-phase?	Light dark matter,...?	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments?	R&D ton scale Grids	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, microspaced Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴

🔴 Must happen or main physics goals cannot be met
🟠 Important to meet several physics goals
🟡 Desirable to enhance physics reach
🟢 R&D needs being met

Challenges for future e^+e^- colliders

See slides by Christoph Paus at ZPW2024

Theory: substantial work on the theory side to reduce uncertainties and challenge the target experimental precision.



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

Challenges for future e^+e^- colliders

… and the list continues (though I don’t have time to discuss these in detail):

- **Software + computing:** need accurate simulations for future colliders (key interplay with theory), how to develop infrastructure whilst exploiting current machines. How can we use Machine Learning/AI?
- **”Sociological”:** how to reach a consensus on the route forwards?
- **”Political”:** if we do reach consensus, how to we get it funded/realized?

Quick plug- the 2026 European strategy update…

Save the date: 23-26 September ECFA-UK Workshop at IPPP, Durham

Interested to learn more? Check out the slides here: https://indico.stfc.ac.uk/event/1012/

Before we continue/finish…

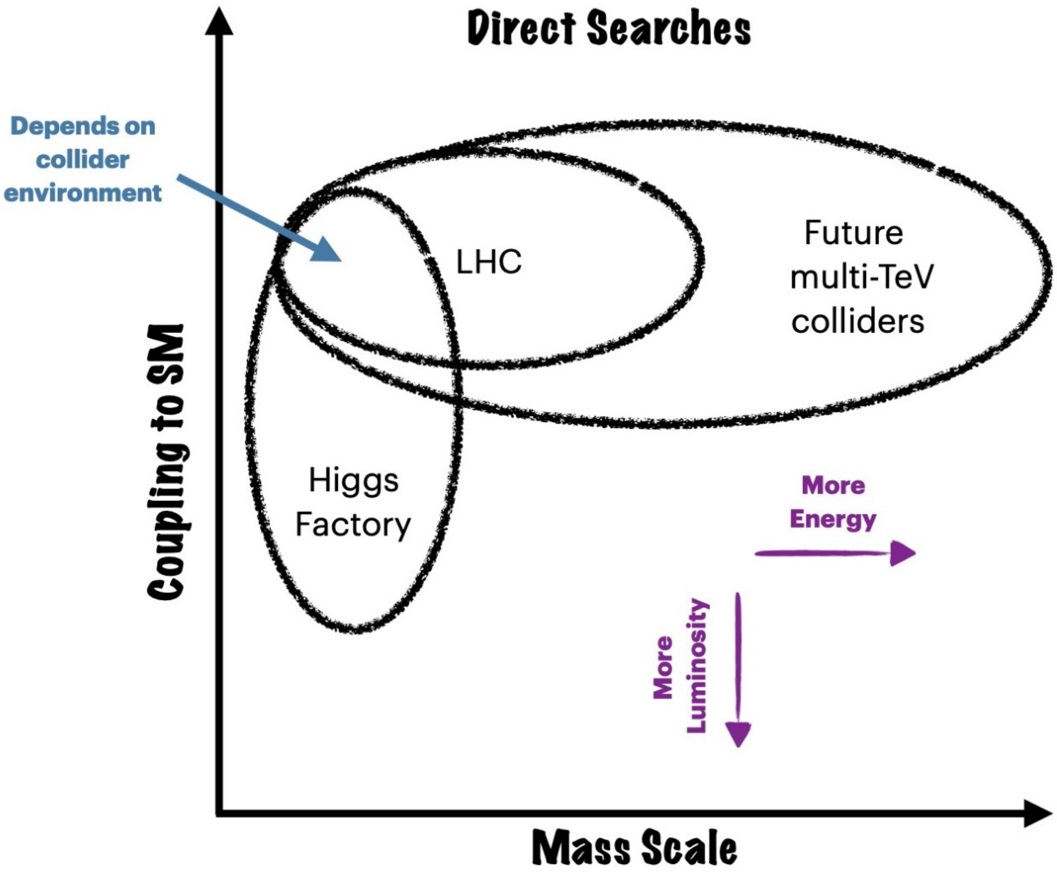
Any questions?

3. 10 TeV pCM colliders

Question

Why do you think we could/should explore the "tens of-TeV" energy range?

Why explore the “tens of-TeV” energy range?



- Whilst high-luminosity e^+e^- colliders could provide indirect access to new physics up to the 10s of TeV mass range, directly accessing these mass scales requires colliders with a parton centre of mass energy (pCM) in that range.
- Same arguments apply to higher mass SM processes (i.e. Higgs pair production).
- Ultra-high luminosities (=> statistics) can also enable rare processes to be studied.

Accessing ~ 10 TeV pCM collisions

What particles could/should we collide?

- e^+e^- machine?
- Hadron collider?
- Muon collider?

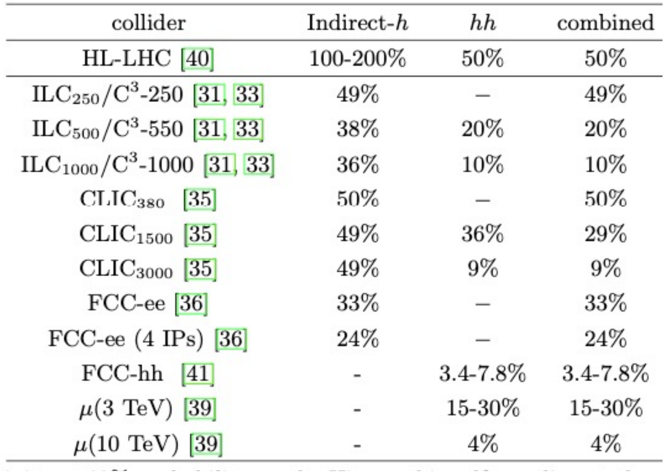
Which of these options could be feasible for that energy range?

Energy frontier physics drivers

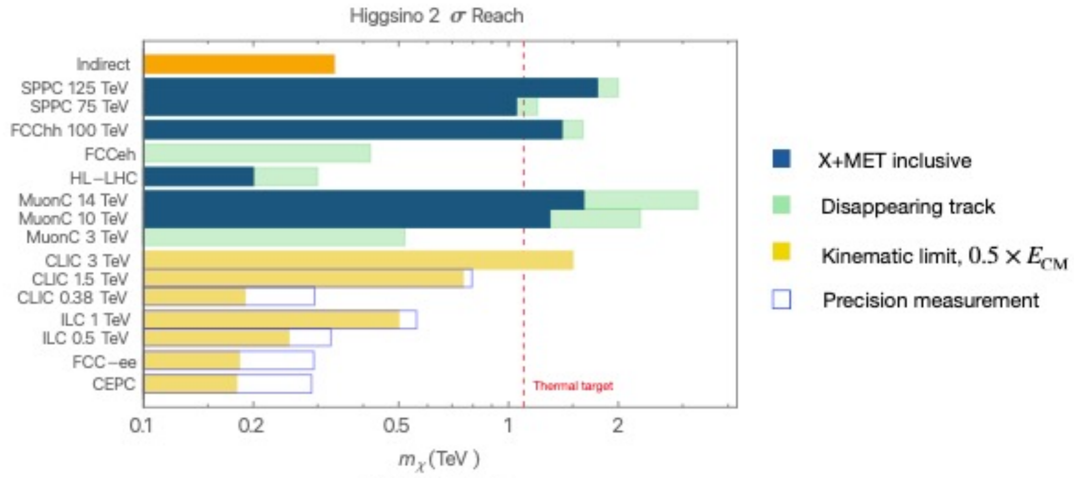
Details on Higgs-factory prospects of muon collider in backup!

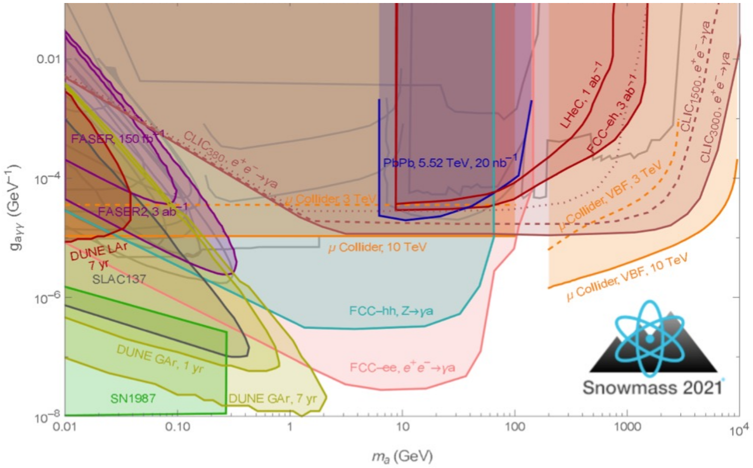
More info in the Snowmass energy frontier report: https://arxiv.org/pdf/2211.11084

- Higgs self-coupling (targeting ~ 5%).
- Rare Higgs decays (with high luminosities).
- Unprecedented BSM sensitivity.
- WIMP dark matter coverage.

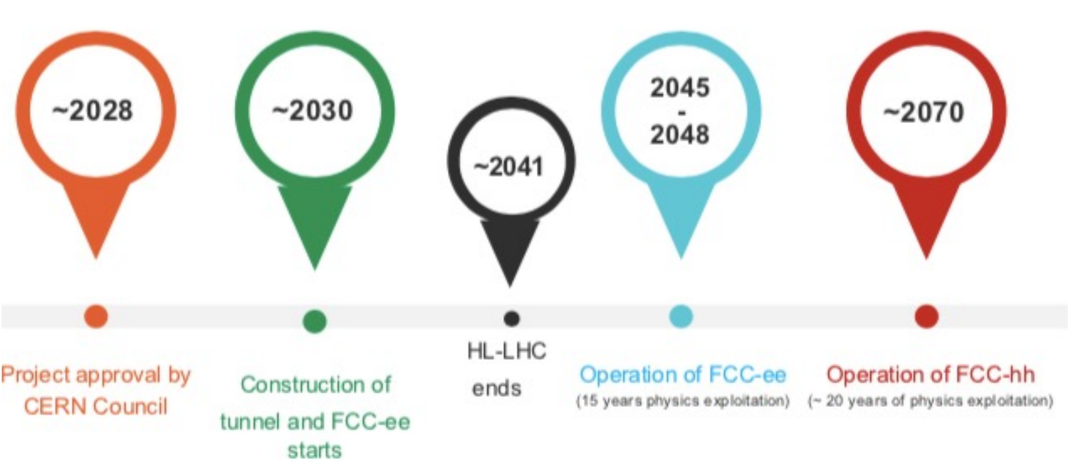


collider	Indirect-h	hh	combined
HL-LHC [40]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [31, 33]	49%	–	49%
ILC$_{500}$/C^3-550 [31, 33]	38%	20%	20%
ILC$_{1000}$/C^3-1000 [31, 33]	36%	10%	10%
CLIC$_{380}$ [35]	50%	–	50%
CLIC$_{1500}$ [35]	49%	36%	29%
CLIC$_{3000}$ [35]	49%	9%	9%
FCC-ee [36]	33%	–	33%
FCC-ee (4 IPs) [36]	24%	–	24%
FCC-hh [41]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [39]	-	15-30%	15-30%
μ(10 TeV) [39]	-	4%	4%





Timelines = long

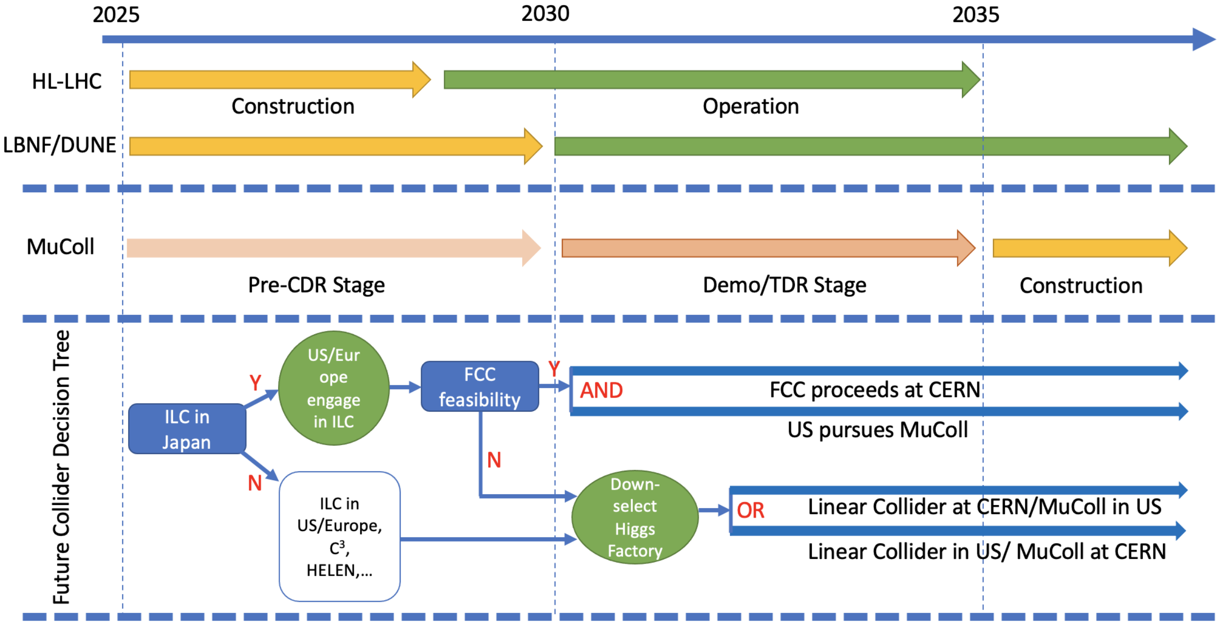

~2028
Project approval by CERN Council

~2030
Construction of tunnel and FCC-ee starts

~2041
HL-LHC ends

2045 - 2048
Operation of FCC-ee
(15 years physics exploitation)

~2070
Operation of FCC-hh
(~ 20 years of physics exploitation)


2025 2030 2035

HL-LHC
Construction
Operation

LBNF/DUNE

MuColl
Pre-CDR Stage
Demo/TDR Stage
Construction

Future Collider Decision Tree

ILC in Japan
Y
US/Eur ope engage in ILC
FCC feasibility
Y
AND
FCC proceeds at CERN
US pursues MuColl
N
ILC in US/Europe, C^3, HELEN,...
N
Down-select Higgs Factory
OR
Linear Collider at CERN/MuColl in US
Linear Collider in US/ MuColl at CERN

Above= "realistic" schedule for FCC

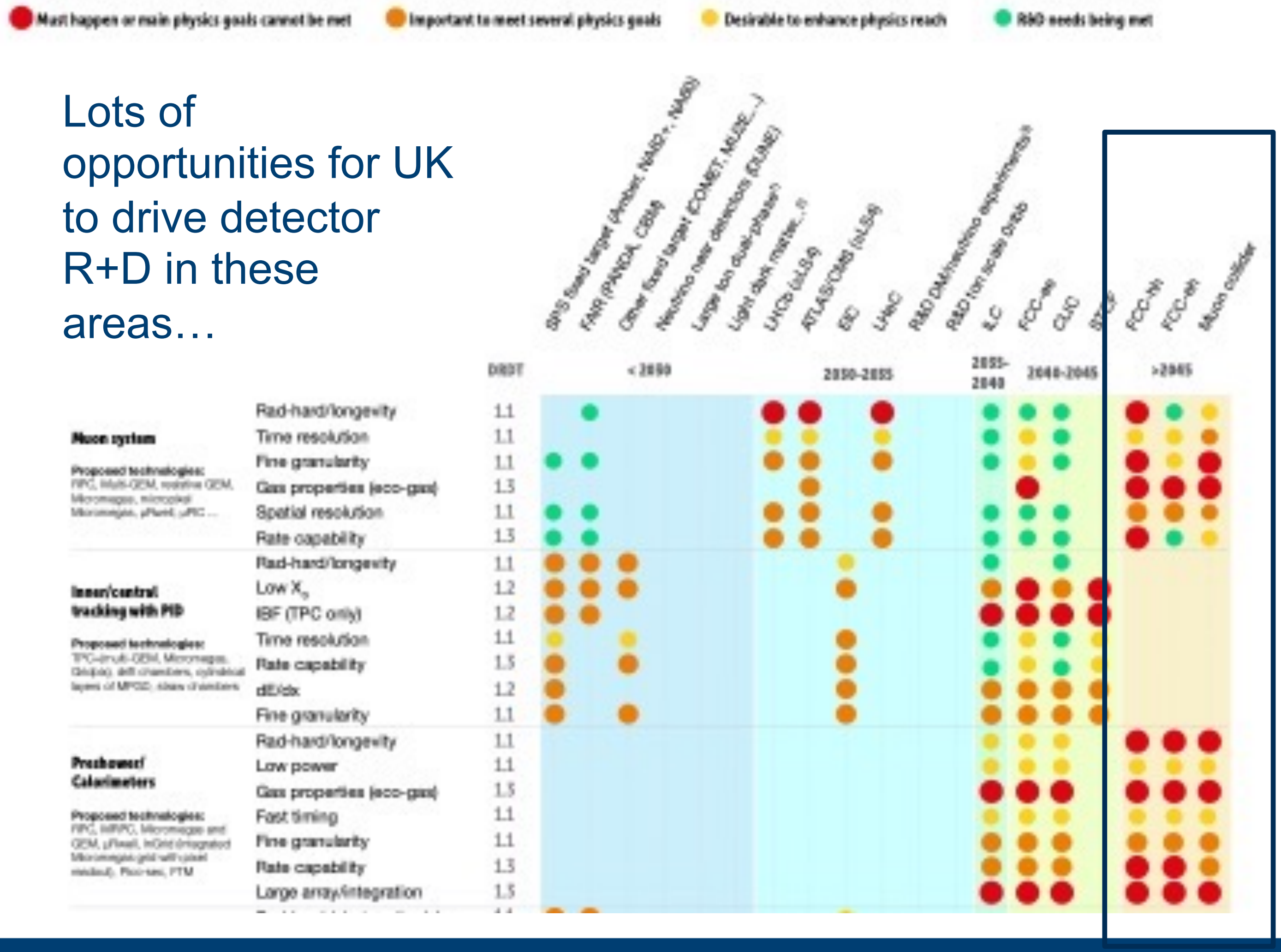
Left= "optimistic" technology-limited R+D timeline for muon collider from Snowmass.

Important to differentiate technical vs financial risk (and their error bars)

Detector R+D challenges

Taken from the ECFA R+D roadmap

Lots of opportunities for UK to drive detector R+D in these areas…



🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

		DRDT	SPS fixed target (Amber, NA62++, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MUSE,...)	Neutrino near detectors (DUNE)	Large ton dual-phase?	Light dark matter...?	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments?	R&D ton scale 0νββ	ILC	FCC-ee	CLIC	ST	FCC-hh	FCC-eh	Muon collider
			< 2030						2030-2035						2035-2040	2040-2045			>2045		
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, microplast Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴

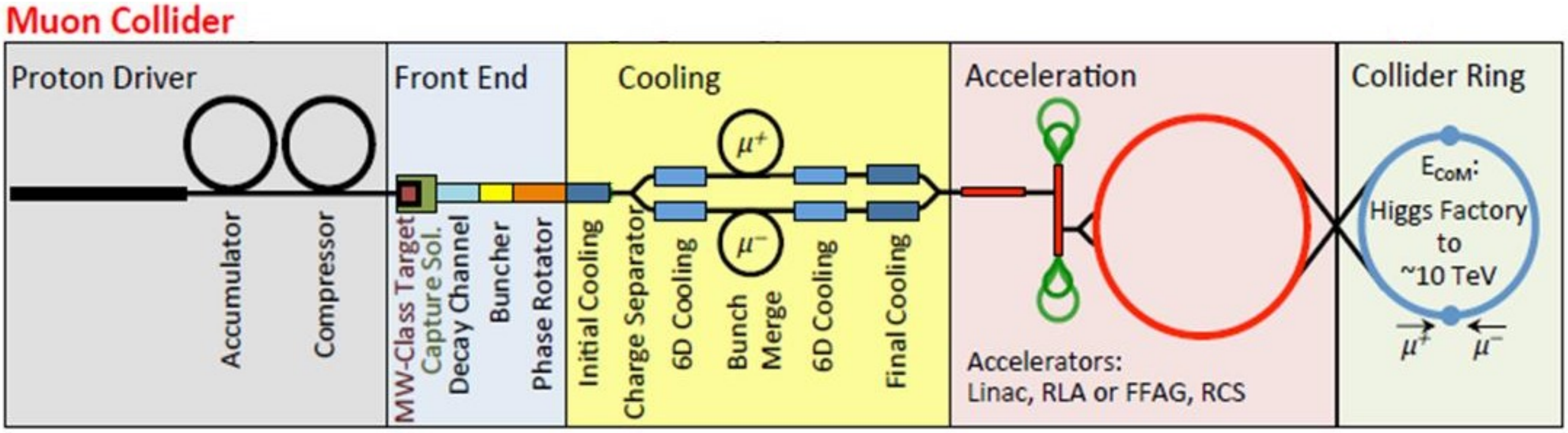
RED= Essential => We do not have the technology to build detectors to meet the physics needs of 10 TeV pCM EF exploration…

Question

What are the challenges associated with a muon collider?

Muon collider challenges => muon decay ($\tau_\mu \sim 2.2\times10^{-6}$s)!

For more information see ”Towards a muon collider” https://arxiv.org/abs/2303.08533

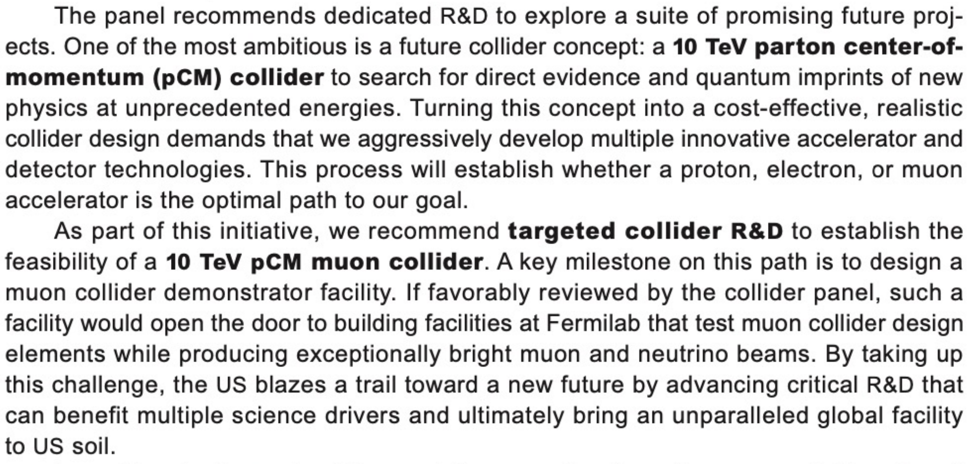


- After **production** (as tertiary beam) must be (6D) **cooled** into a single collimated bunch and (rapidly) **accelerated** (need fast ramp-up of magnets) before being **collided.**

- Additional challenges from **beam induced background** (BIB) and significant **neutrino radiation** (careful positioning and simulation studies).

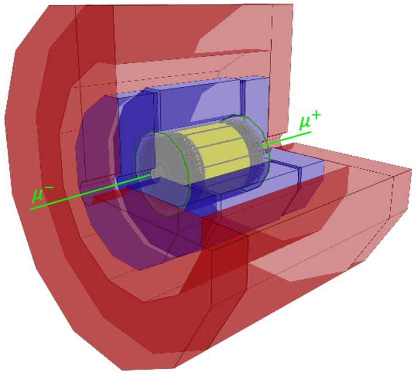
The road towards a muon collider…

See slides by Karol Krizka here



The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM) collider** to search for direct evidence and quantum imprints of new physics at unprecedented energies. Turning this concept into a cost-effective, realistic collider design demands that we aggressively develop multiple innovative accelerator and detector technologies. This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.



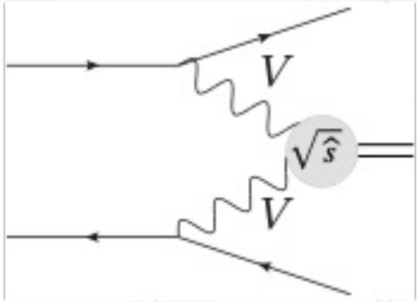
The next steps towards a muon collider would be a demonstrator of these technologies and further simulation studies on detector challenges and physics potential. Interesting synergies with other areas:

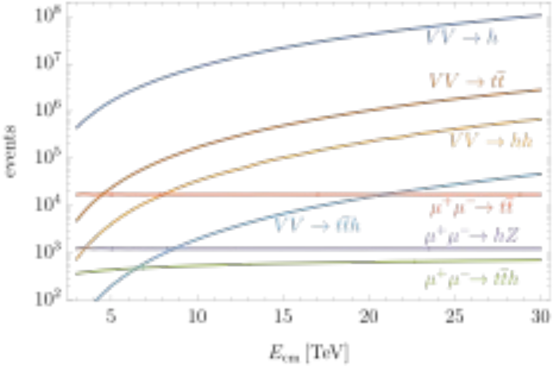
- NuSTORM (intense neutrino beam).
- Radiation tolerant and high-field Solenoids.
- High-field dipoles (would also benefit FCC-hh).

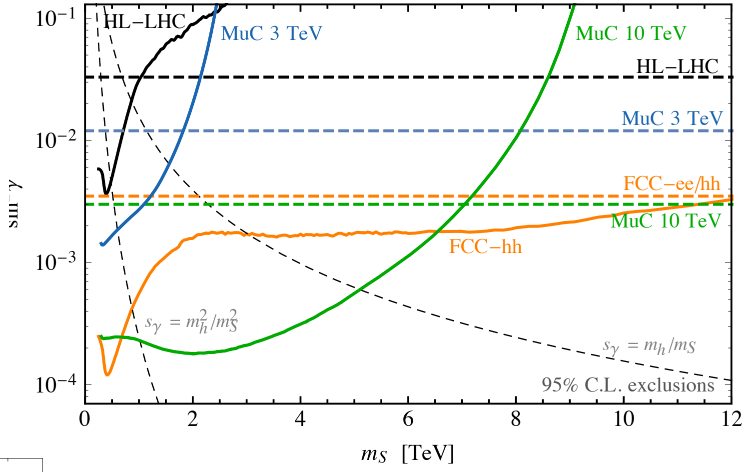
Direct BSM at muon colliders

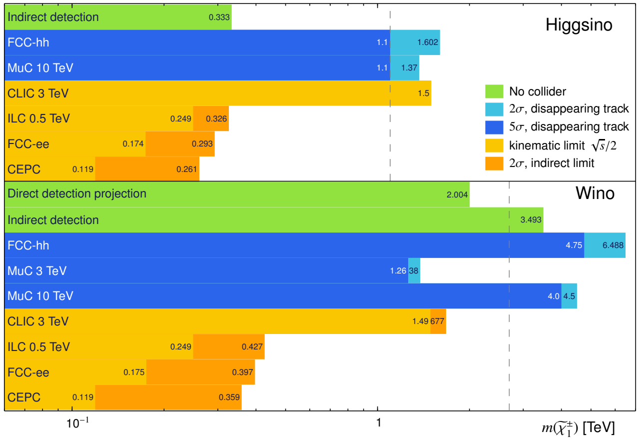
For more information see ”Towards a muon collider” https://arxiv.org/abs/2303.08533

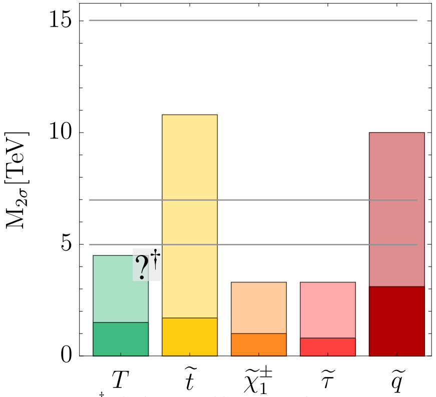
A high-energy muon collider would also be a vector-boson collider=> direct BSM and providing ”Higgs factory” (see next slide)











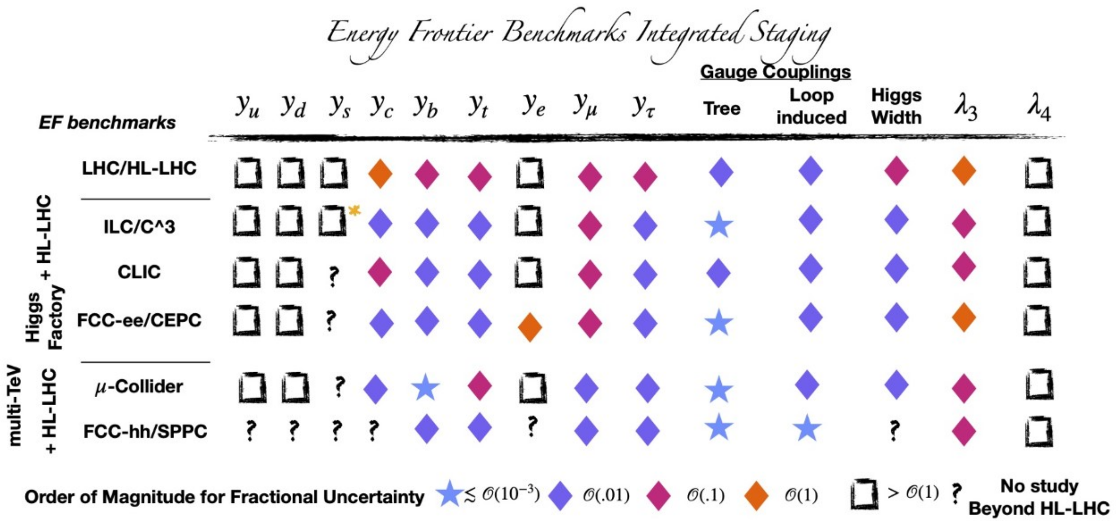
† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

Above: exclusion for scalar singlet mixing with Higgs

Left: comparison of HL-LHC (solid), FCC (shaded) and tentative muon collider reach at 10, 14, 30 TeV (lines)

Higgs precision at EF colliders

Snowmass energy frontier report

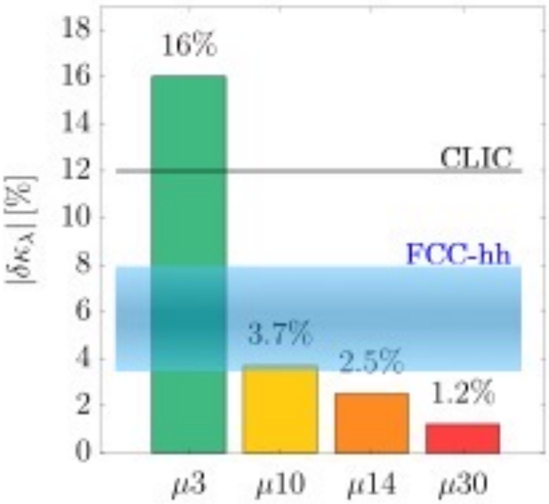


Energy Frontier Benchmarks Integrated Staging

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings		Higgs Width	λ_3	λ_4
											Tree	Loop induced			
	LHC/HL-LHC	□	□	□	🔶	◆	◆	□	◆	◆	🔷	🔷	◆	🔶	□
Higgs Factory + HL-LHC	ILC/C^3	□	□	□*	🔷	🔷	🔷	□	◆	🔷	★	🔷	🔷	◆	□
	CLIC	□	□	?	◆	🔷	🔷	□	◆	🔷	🔷	🔷	🔷	◆	□
	FCC-ee/CEPC	□	□	?	🔷	🔷	🔷	🔶	◆	🔷	★	🔷	🔷	🔶	□
multi-TeV + HL-LHC	μ-Collider	□	□	?	🔷	★	◆	□	🔷	🔷	★	🔷	🔷	◆	□
	FCC-hh/SPPC	?	?	?	?	🔷	🔷	?	🔷	🔷	★	★	?	◆	□

Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ 🔷 $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ 🔶 $\mathcal{O}(1)$ □ $> \mathcal{O}(1)$? No study Beyond HL-LHC

Figure 1-9. *A snapshot of future Higgs precision measurements of SM quantities based on the order of magnitude for the fractional uncertainties with the range defined through the geometric mean. In this figure the ultimate reach of the final stages of all Higgs factories and multi-TeV colliders are shown in combination with the HL-LHC results, as well as the HL-LHC separately. All benchmarks and stages are defined in Section 1.3 of the Energy Frontier Report. The specific precision associated to each coupling can be found in the Higgs-physics Topical Group report [14] and references therein. A * is put on the ILC measurements for the strange-quark Yukawa coupling to single it out as a new measurement proposed during Snowmass 2021, and shown in Fig 1-13. The ? symbol is used in the case where an official study has not yet been performed. It does not connotate that a given collider should be worse than similar ones, but simply that whether it is better or worse based on detector design has not been demonstrated.*



https://arxiv.org/abs/2303.08533

Question

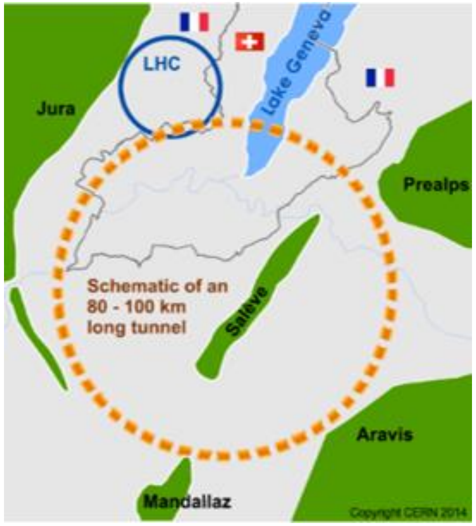
What are the challenges associated with a 100 TeV hadron collider?

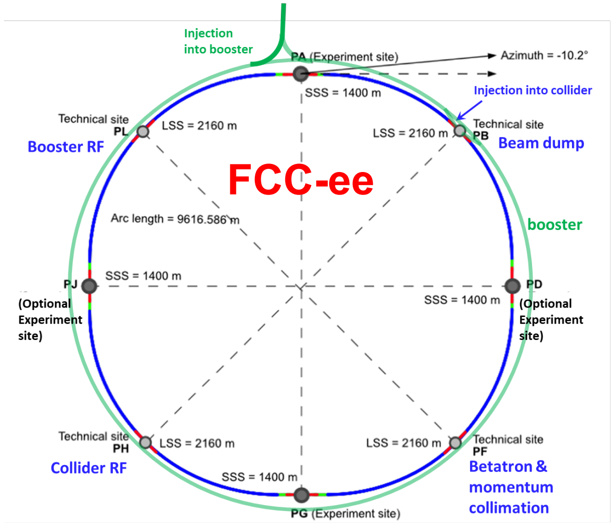
Note: in my subsequent discussion I'll use FCC-hh as an example, however similar arguments could be made about a 100 TeV pp collider following CEPC.

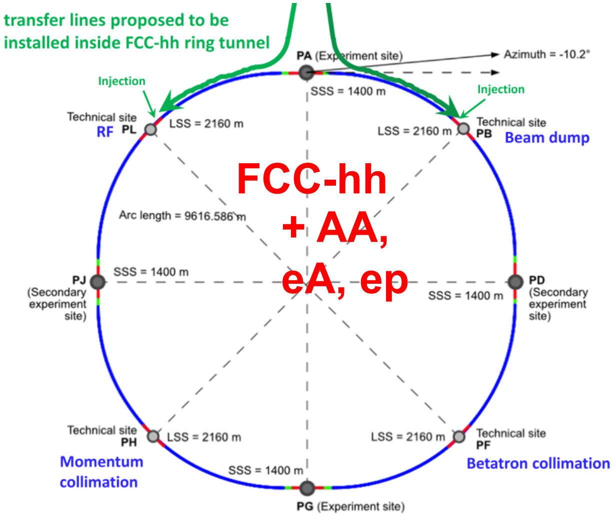
Reminder: Integrated FCC programme

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

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







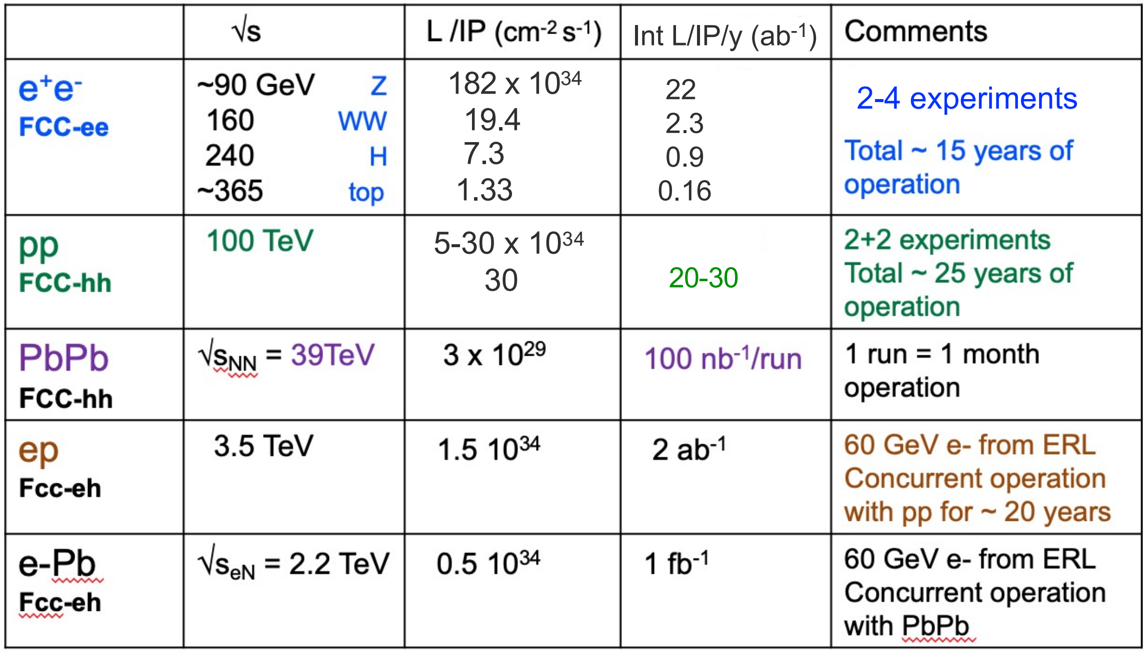
2020 - 2040

2045 - 2063

2070 - 2095

Integrated FCC programme

Taken from slides by F. Gianotti at FCC week.



	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182 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:

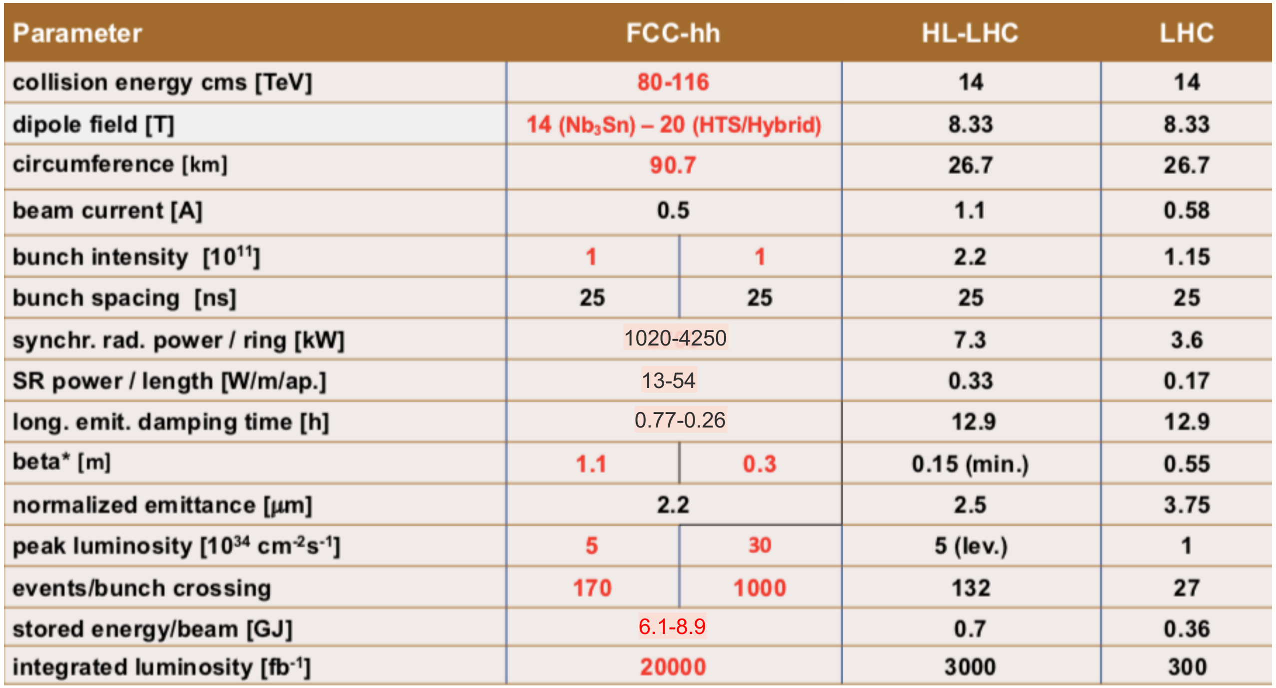
- Ultra-precise measurements of EW/ Higgs + top sectors of SM -> indirect sensitivity to BSM.
- Unique flavour opportunities
- Direct sensitivity to feebly interacting particles (LLPs)

FCC-hh:

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

FCC-hh parameters and challenges

Taken from slides by F. Gianotti at FCC week.



Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb$_3$Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	1020-4250		7.3	3.6
SR power / length [W/m/ap.]	13-54		0.33	0.17
long. emit. damping time [h]	0.77-0.26		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

If FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:
- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter

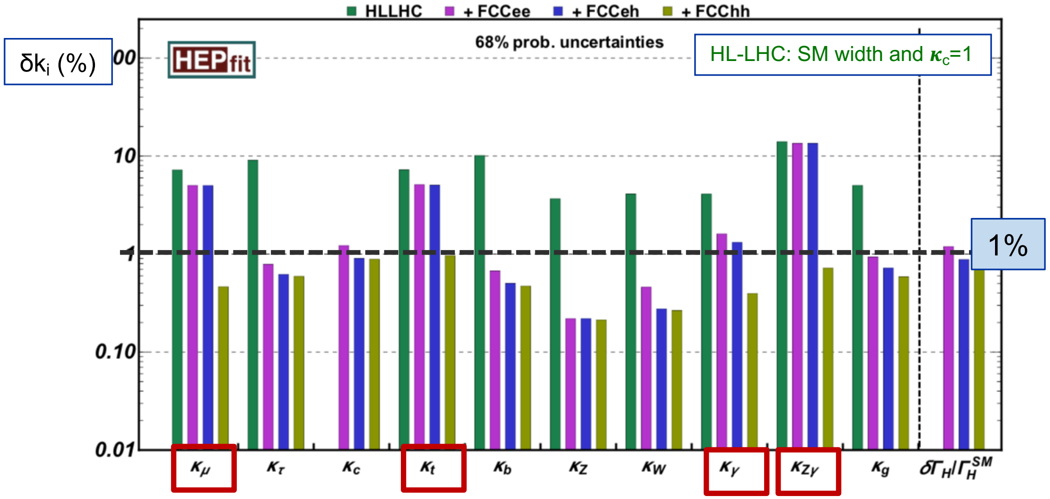
Challenges for future hadron colliders: magnets

- Large scale production of 16 T magnets for accelerator (CF ~ 8 T for HL-LHC) using Nb_3Sn technology.
- Possible alternative would be High-Temperature Superconductors (HTS) which could reach ~ 20 T.
- Recent milestone was attaining 14.6 T at 1.9 K using FRESCA2 (right), but still substantial roadmap ahead.

Note: when preparing the LHC, there was also R+D required to attain the required magnet strength. In the integrated programme, this R+D proceeds whilst FCC-ee is built and operated.

Synergies in FCC programme- Higgs physics

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



δk_i (%)

HL-LHC: SM width and κ_c=1

1%

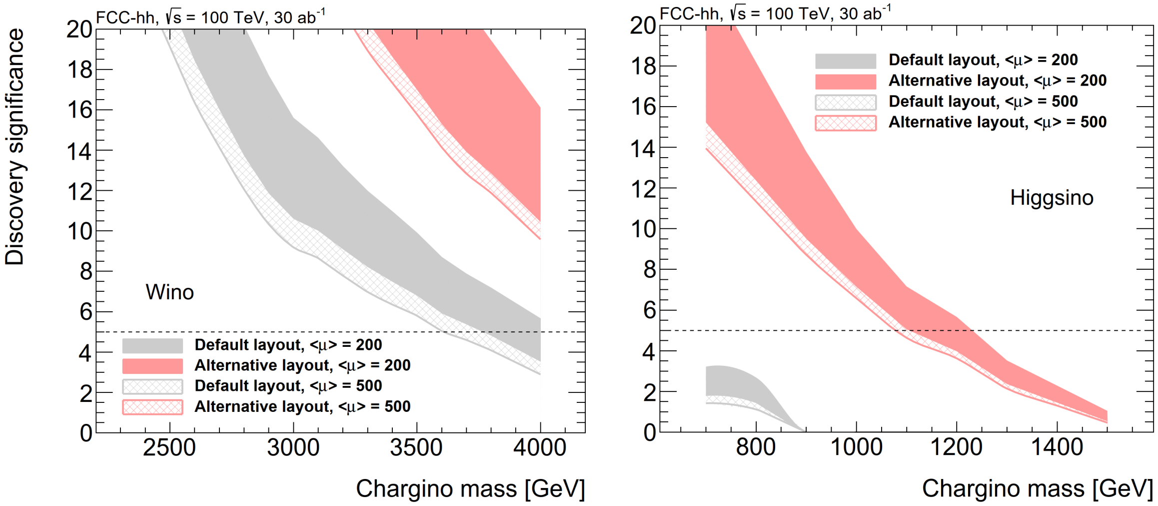
- Integrated FCC programme will provide order of magnitude improvement in Higgs couplings.
- e^+e^- colliders can provide a model independent measurement of g_{HZZ} => provides standard candle to normalize other Higgs couplings.

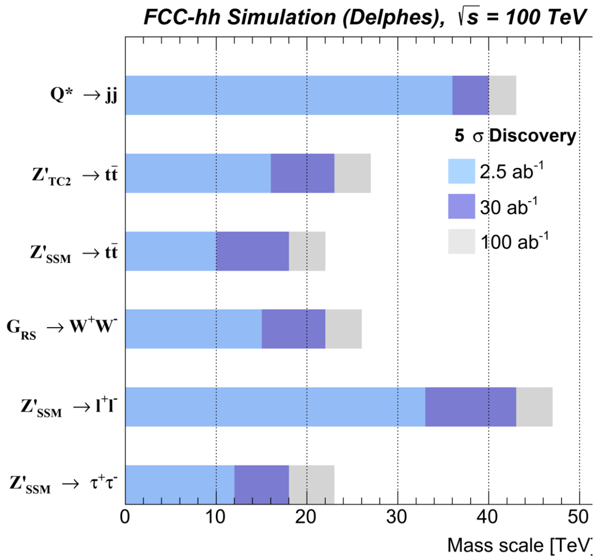
- Can also measure ttZ couplings through $ee \rightarrow t\bar{t}$. This gives a second standard candle used to extract g_{ttH} and g_{HHH} at subsequent hadron machines.
- High-energy pp collisions provide the statistics to access rarer Higgs decays ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$) and HH events to give precise ultimate tests of the EWPT (~ 20 million at FCC-hh).

Synergies between e+e- and pp collisions –BSM

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

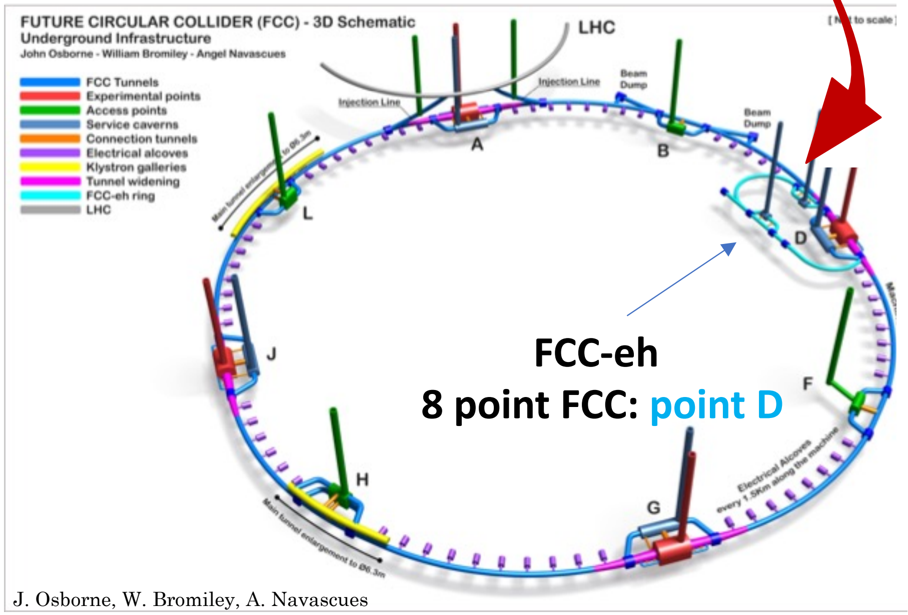
In summary- exciting possibilities to discover/characterize NP that could be indirectly predicted through precision measurements at FCC-ee

FCC-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 (see slides by M. Klein here)

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

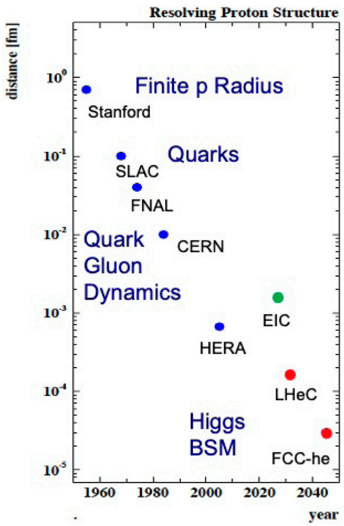


FCC-eh
8 point FCC: point D

J. Osborne, W. Bromiley, A. Navascues

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

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



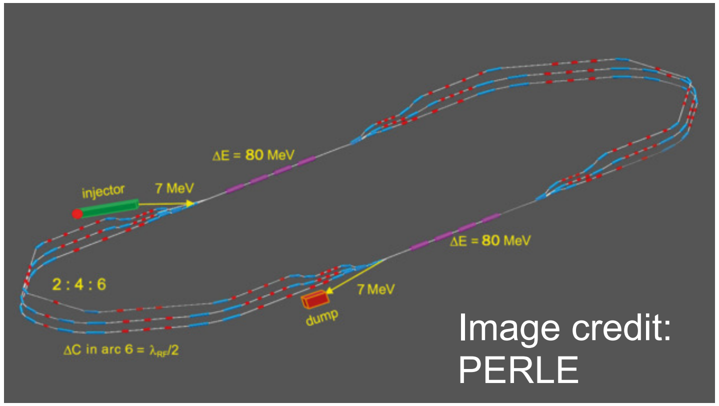


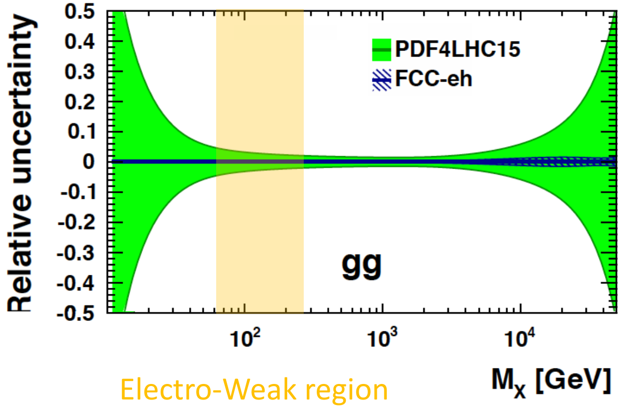
Image credit: PERLE

Synergies between ep and ee/pp collisions

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

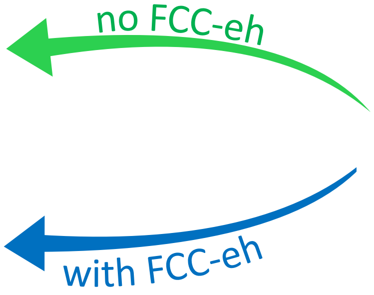
Taken from updated CDR

pp @ 100 TeV

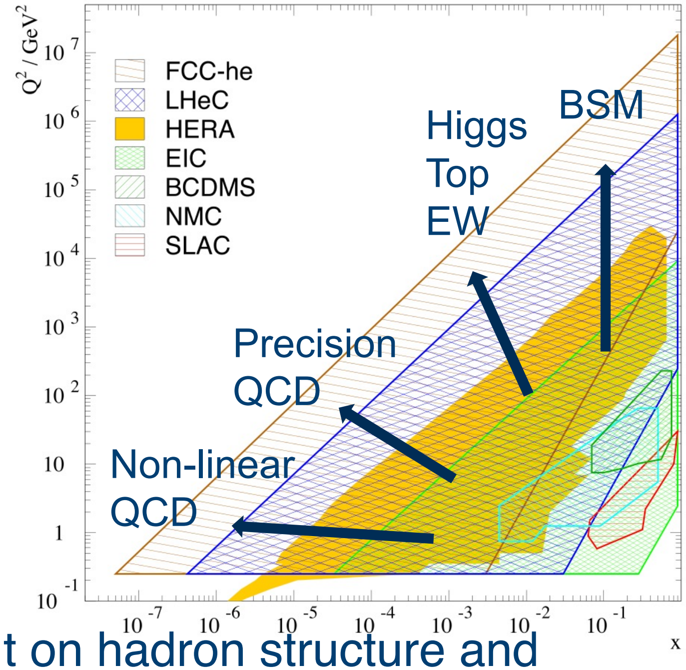


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)



~1% uncertainty on the σ(W,Z,H)

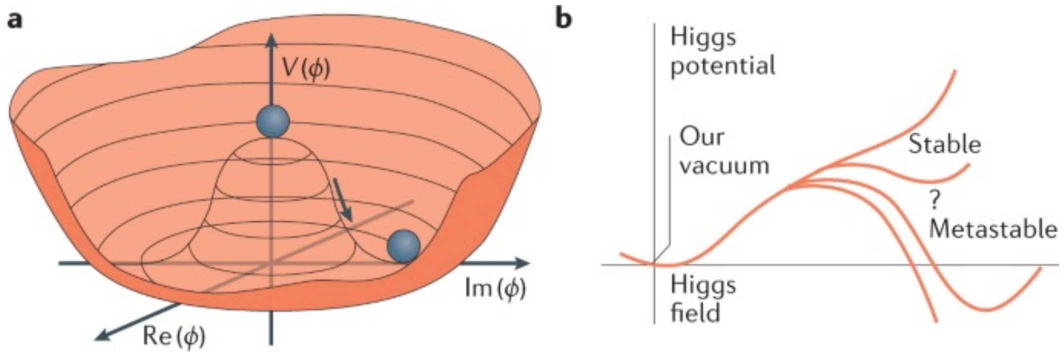


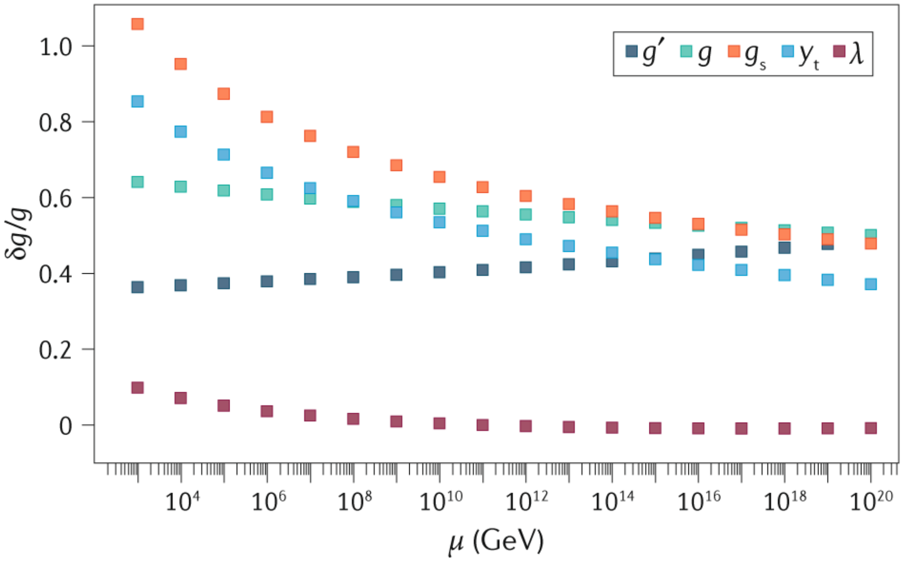
- Empower 100 TeV pp programme with precision input on hadron structure and strong coupling (to permille accuracy) during parallel running.
- Complementary measurements of Higgs couplings (CC+NC DIS x-sections, no pile-up, clean)
- Plus… complementary BSM prospects (LLPs, LFV, not-too-heavy scalars, GeV-scale bosons)

Significance of Higgs self coupling

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

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





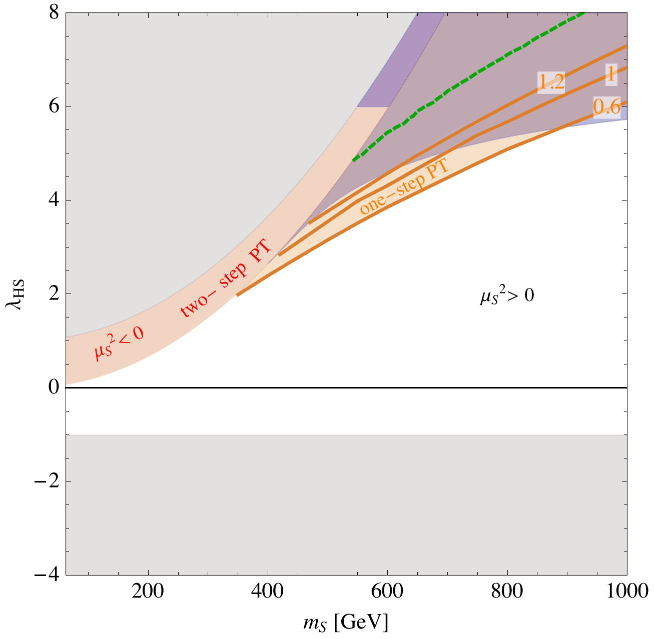
- On EWSB λ gives 3-higgs and 4-higgs (self-) interaction vertices - accessed through di-Higgs production at the LHC and future colliders.

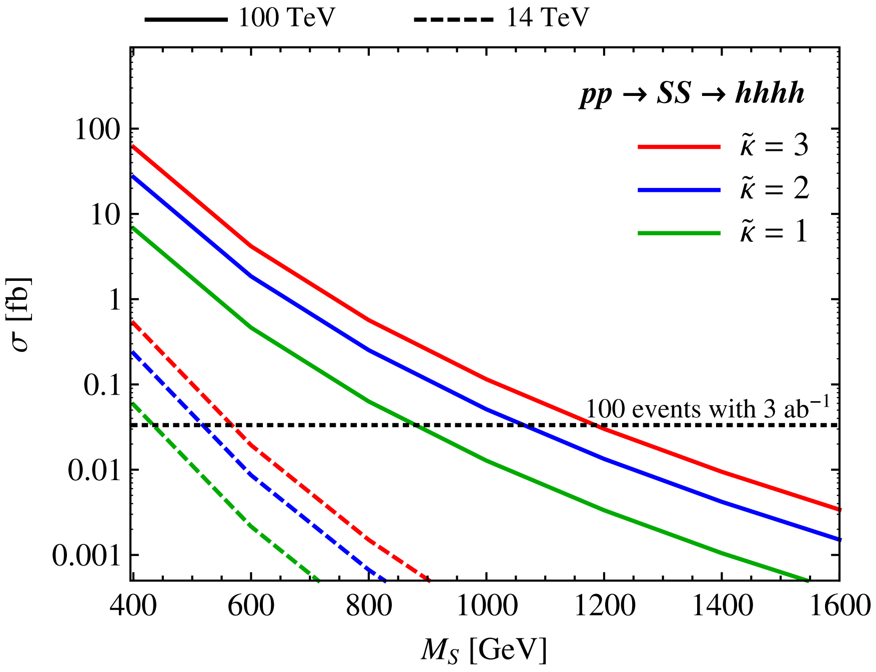
- Direct measurement could provide key understanding of EWPT and possible portal to new physics.

Probing EWPT at the FCC

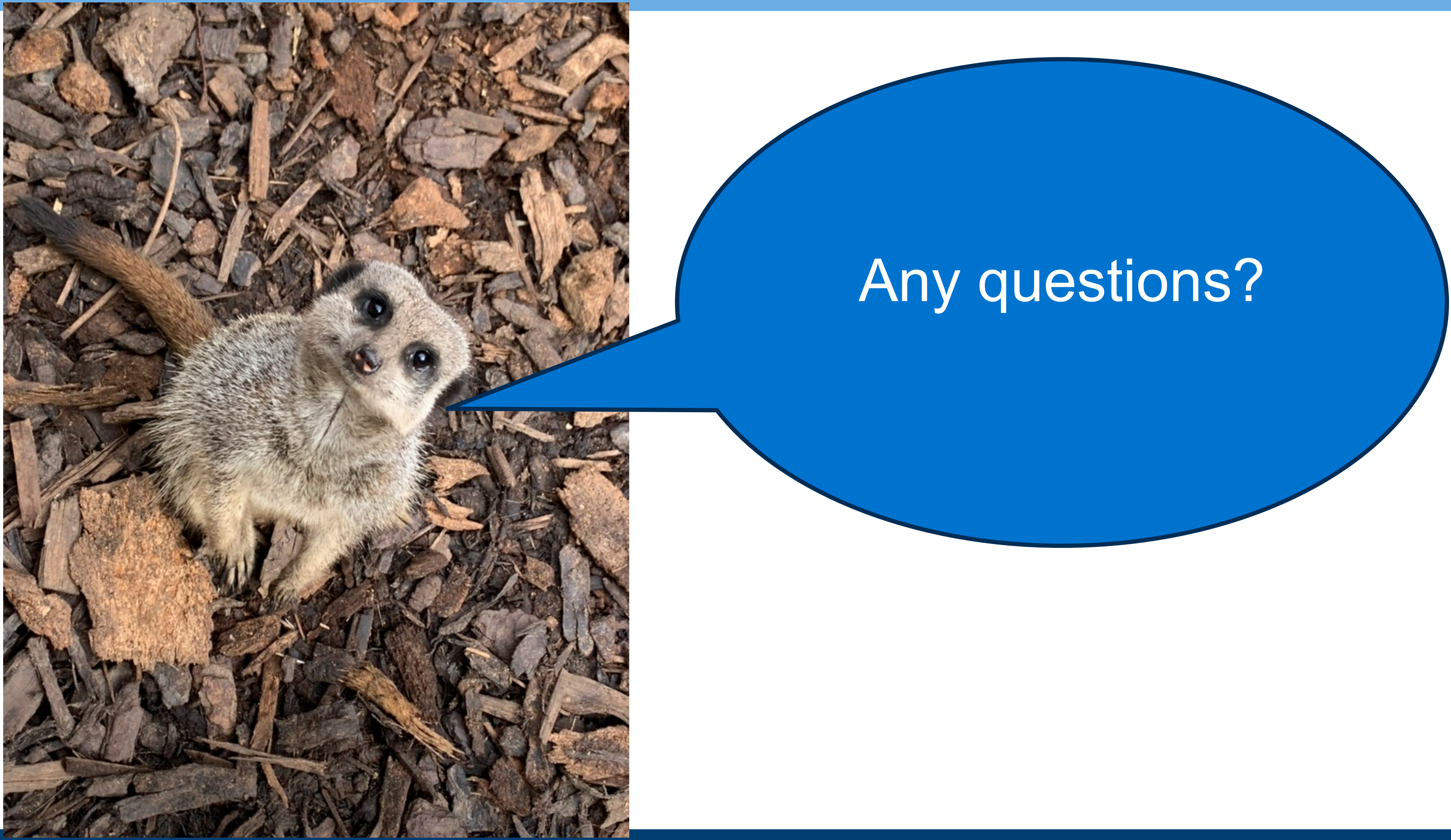
https://arxiv.org/abs/1511.06495

New physics required for a strong first order phase transition (needed for EWK baryogenesis) could be accessed 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%).





Before we finish…



Slido questions

- Could future colliders be built now in principle or does part of the planning process assume future innovations which do not currently exist?
- What impact does geopolitics have on the planning process?
- Have local governments become more reluctant to fund future colliders as a result of increased political pressure to consider environmental issues?

Conclusion + outlook

Conclusion

- I hope this course has provided you a very brief overview to the prospects and challenges associated with future colliders.
- This course is timely! Key decisions will be made in the coming years (please take part in the conversations) and your expertise (across the experimental and theoretical communities) will be essential to deliver these challenging programmes.
- I will leave the course slido open until 6pm today (and will circulate a document with responses questions I didn't answer today).
- Feel free to email me on sarah.louise.Williams@cern.ch !

Backup

CEPC vs FCC: timelines

Schematics taken from slides from 2023 FCC and CEPC weeks.

Conceptual Design Study (Conceptual Design Report end 2018)

Feasibility Study (geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

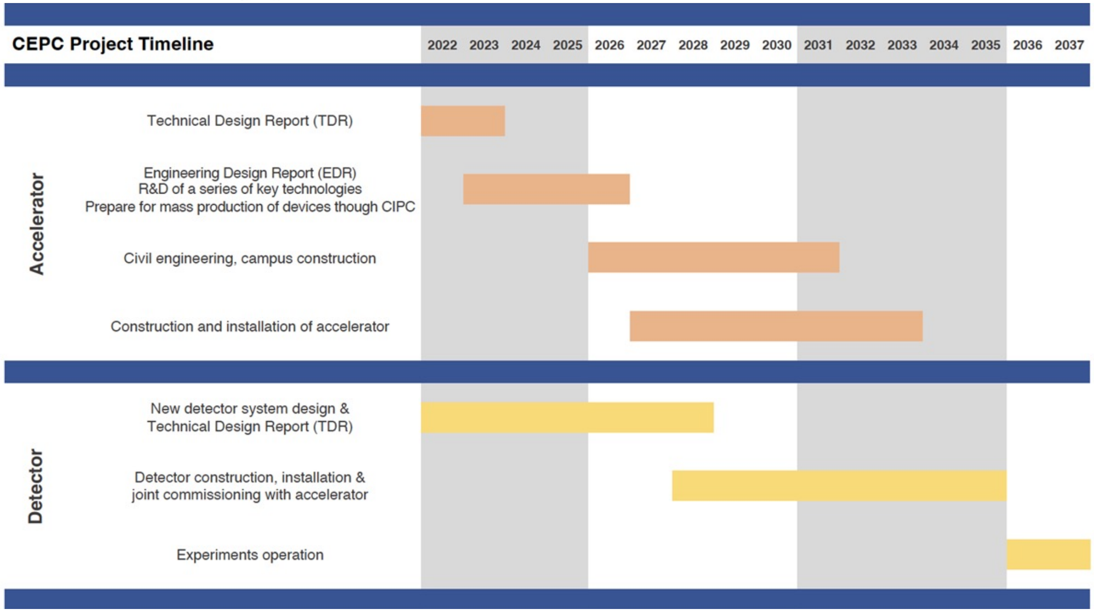
Project approval by CERN Council

Construction of tunnel and FCC-ee starts

HL-LHC ends

Operation of FCC-ee (15 years physics exploitation)

Operation of FCC-hh (~ 20 years of physics exploitation)



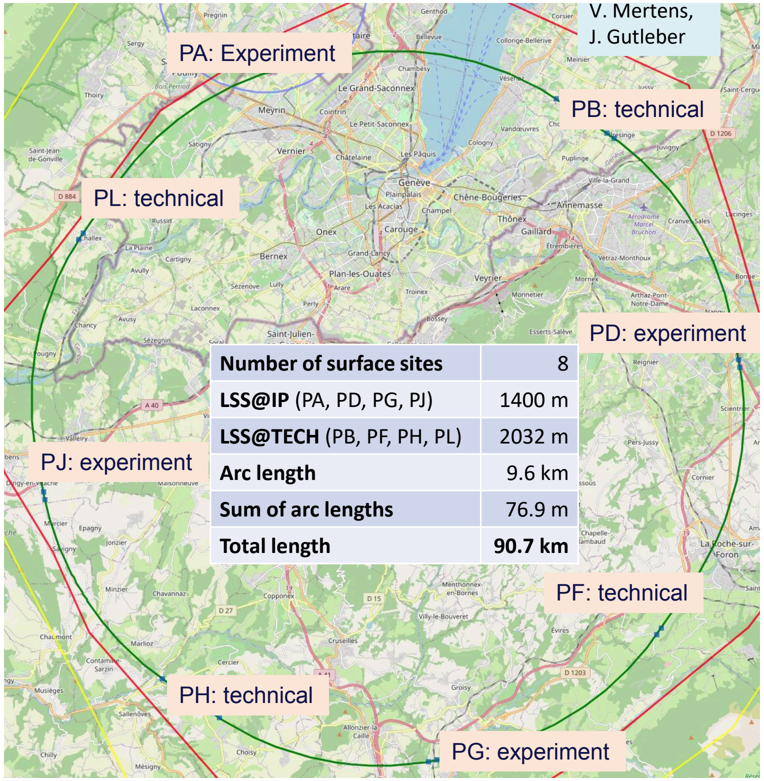
	CEPC Project Timeline	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
Accelerator	Technical Design Report (TDR)	▨	▨														
	Engineering Design Report (EDR) R&D of a series of key technologies Prepare for mass production of devices though CIPC		▨	▨	▨	▨											
	Civil engineering, campus construction					▨	▨	▨	▨	▨	▨						
	Construction and installation of accelerator						▨	▨	▨	▨	▨	▨	▨				
Detector	New detector system design & Technical Design Report (TDR)	▨	▨	▨	▨	▨	▨	▨									
	Detector construction, installation & joint commissioning with accelerator							▨	▨	▨	▨	▨	▨	▨	▨		
	Experiments operation															▨	▨

- 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.

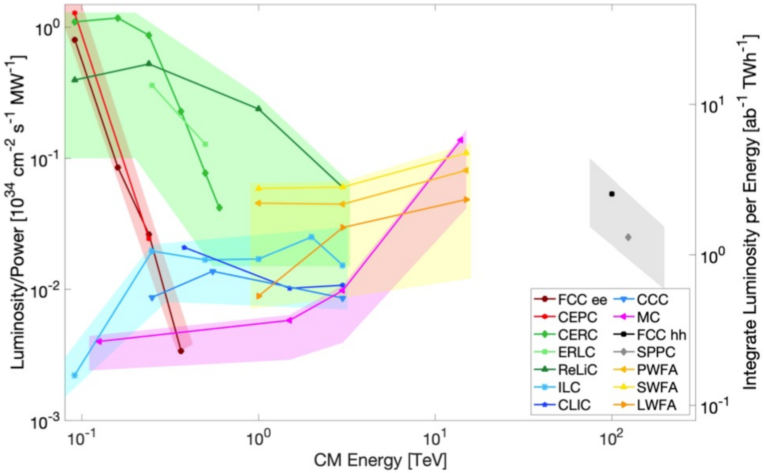


Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

- 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.



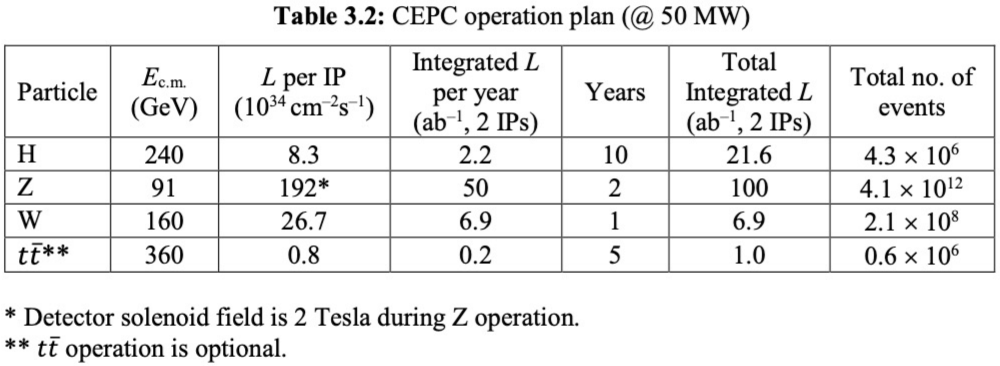
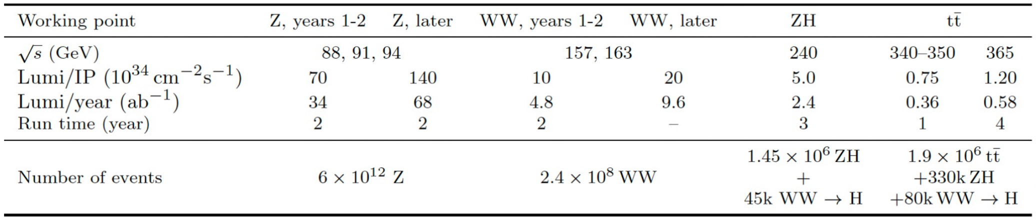


Table 3.2: CEPC operation plan (@ 50 MW)

Particle	$E_{\rm c.m.}$ (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)



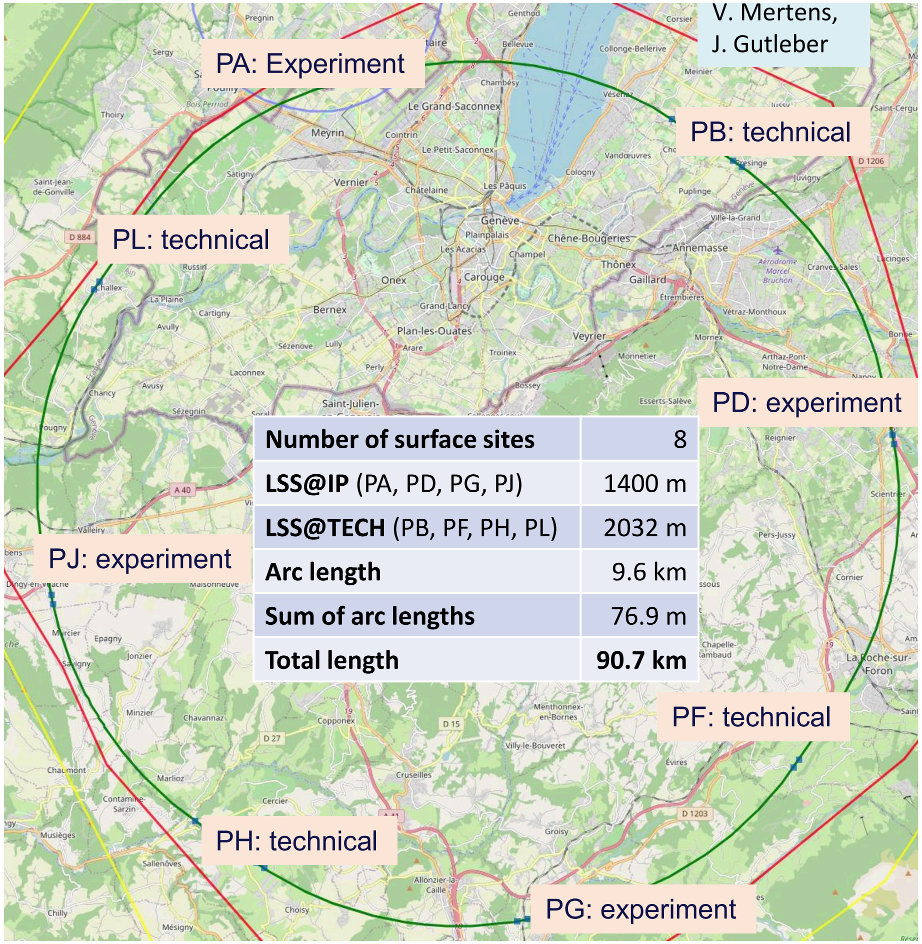
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8}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



V. Mertens, J. Gutleber

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