Conclusions and PED vision

Guy Wilkinson
University of Oxford and CERN
16/1/25

Conclusions and PED vision

not my choice of word, but
what was assigned to me

Guy Wilkinson
University of Oxford and CERN
16/1/25

Visions of the divine

[Pointe d'Andey, Haute Savoie]

Visions of the future – for some

Worldwide physics community reaches unanimous and harmonious decision

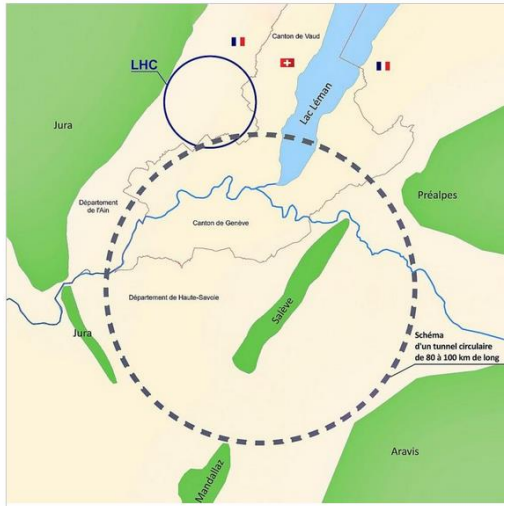
Physicists from Europe and beyond met last week in Venice to decide on what should be the next atom smasher' to be built at CERN. The discussion was good natured throughout and there was no difference in opinion whatsoever. It concluded with those in attendance voting unanimously in favour of the Future Circular Collider. Professor Karl Jakobs, Chair of the event said "The FCC offers the best science prospects for particle physics, and everyone was in perfect agreement.' Professor Michael Peskin of the SLAC National Accelerator Laboratory was not available for comment.

Reuters

Physicists vote YES for the Future Circular Collider

By MATTHEW CHALMERS

BBC NEWS WORLD NEWS POLITICS BUSINESS



New atom smasher given thumbs-up in Venice

Wed, 15 Jan 2025

CERN council expected to rubber stamp decision in coming weeks

Read more...

(Caution: beware 'fake news')

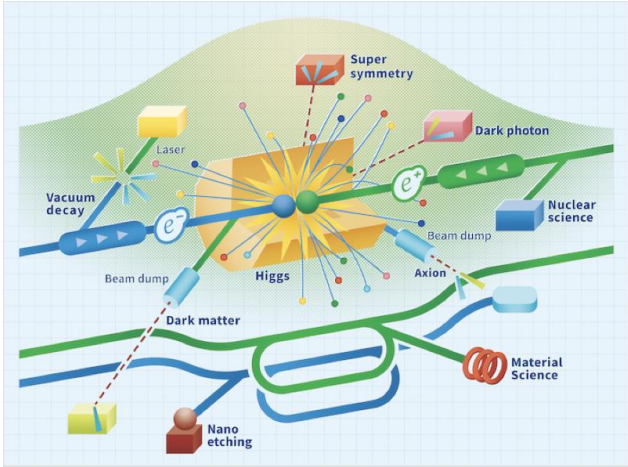
Visions of the future – for others

Linear Collider Vision Community Event 2025

8–10 Jan 2025
CERN
Europe/Zurich timezone

Born at LCWS2024, Linear Collider Vision (LC Vision) brings together proponents and supporters of all kinds of Linear Collider projects, in order to discuss common topics, to develop a united perspective on the long-term evolution of a Linear Collider Facility, and to propose such a facility for CERN.

At this meeting, the LC Vision plans for the EPPSU will presented to the interested community.



Outline

- Recent achievements
- Things to keep in mind for the EPPSU
- Towards the pre-TDR phase

Achievements and important developments since the Midterm Report

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning." W.S. Churchill

The Final Report of the Feasibility Study is almost ready !

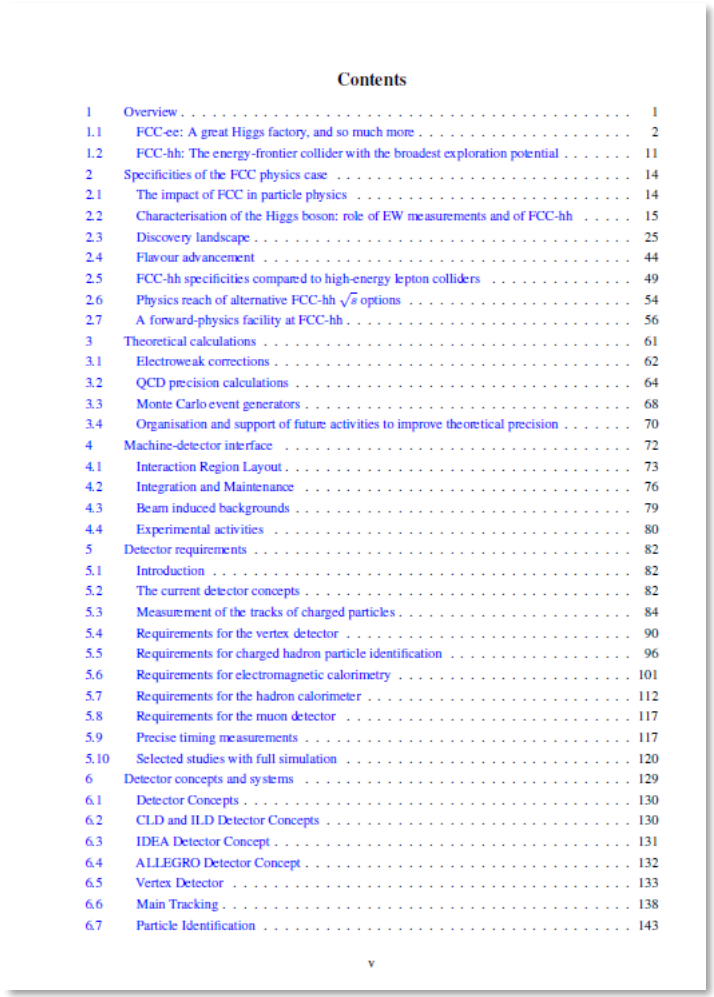
Structure:Three Volumes

- ***Vol. 1:*** *Physics, Experiments and Detectors (~200 pages)*
- ***Vol. 2:*** *Accelerators, Technical Infrastructures, Safety Concepts (~400 pages)*
- ***Vol. 3:*** *Civil Engineering, Implementation & Sustainability (~200 pages)*
- **Executive Summary of the FCC Feasibility Study: ~40 pages**

Many thanks to all who worked directly, or indirectly, on the PED Volume.

In addition to this Report, it may be prudent to make focused submissions to the EPPSU in certain key areas. See satellite discussion meeting tomorrow.

Volume 1 (PED: table of contents



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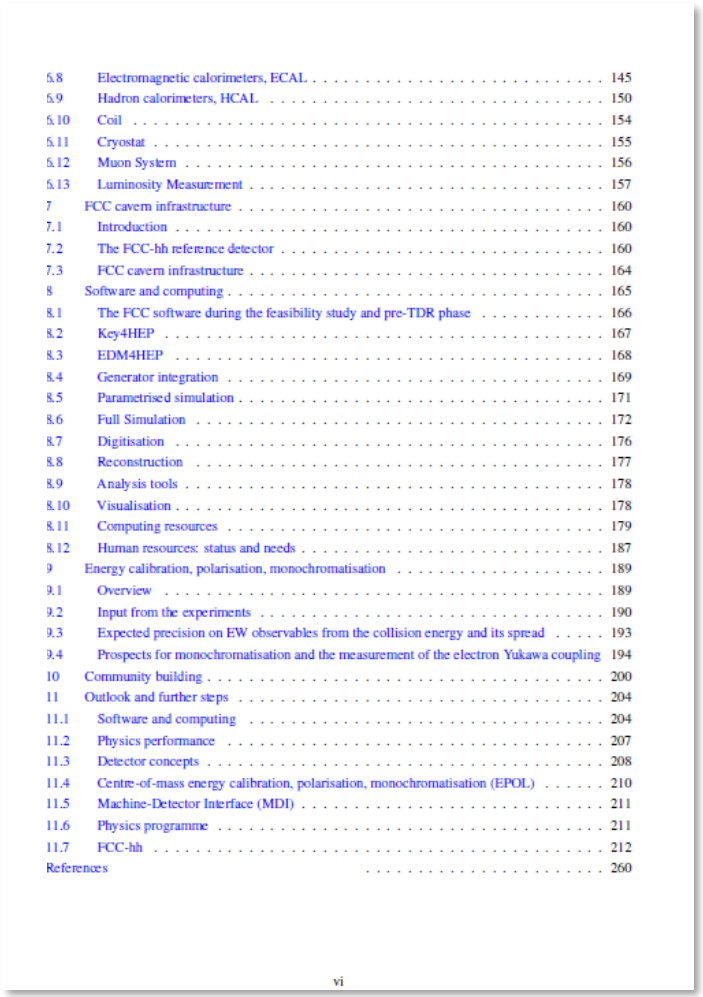

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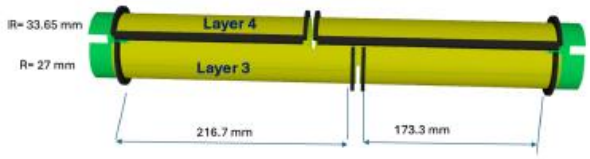
Huge work on detector, computing and physics studies

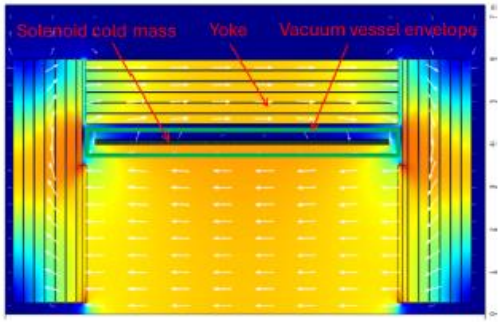
Detector Concepts in the FSR

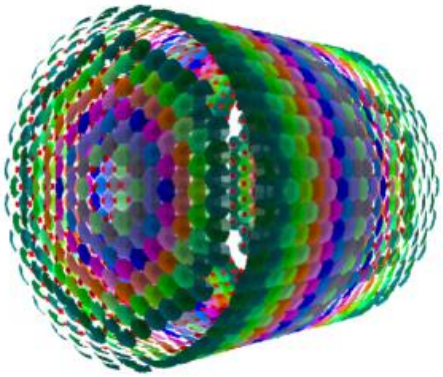
Content

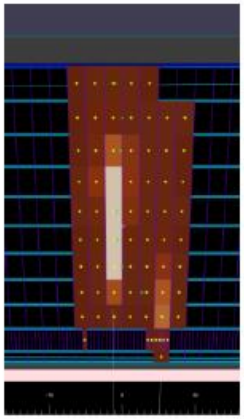
Detector Systems

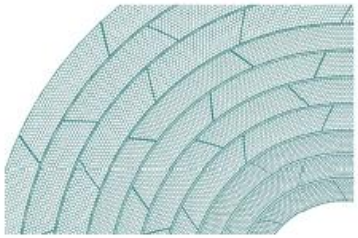
- Technology, rationale
- Sub-system lay-out
- R&D status and challenges

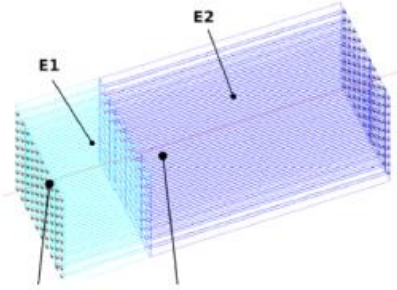


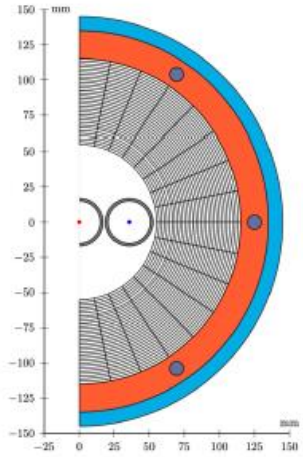








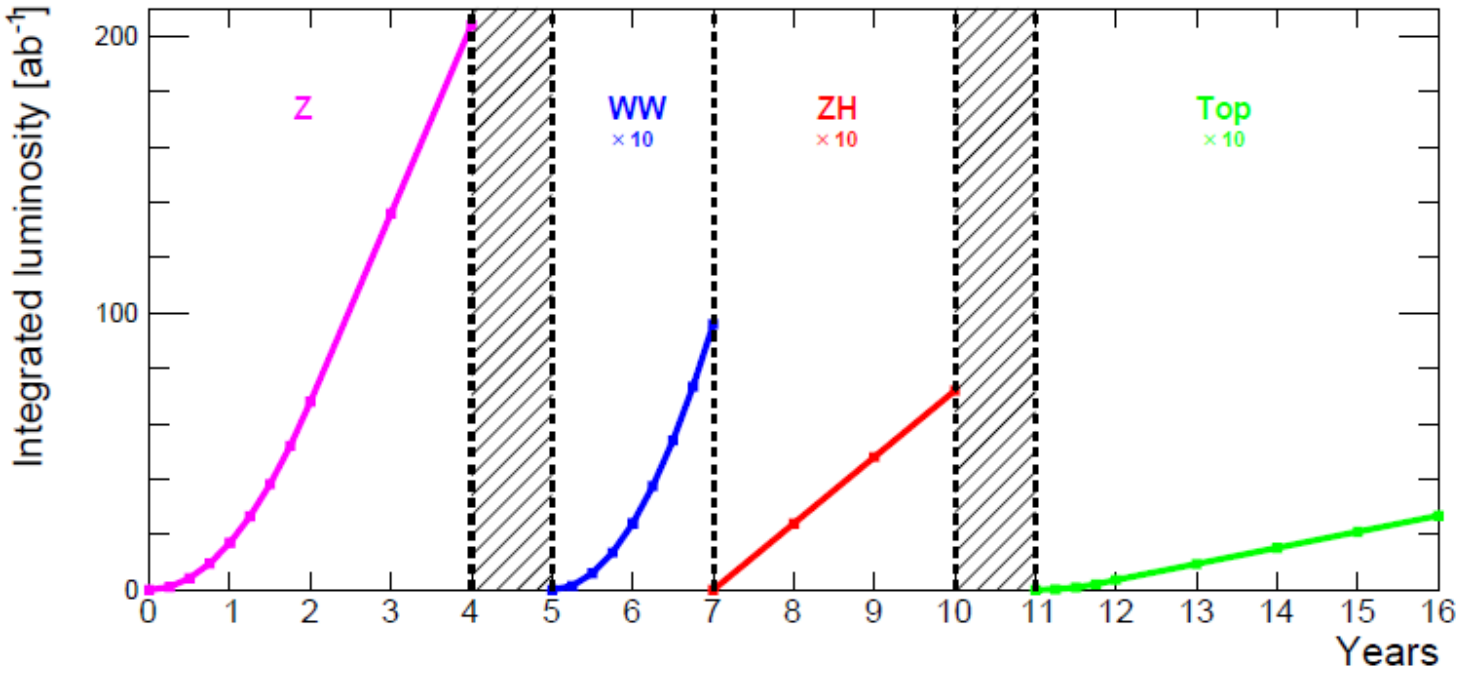




[Felix Sefkow]

Developments since MTR: flexibility in running order

Status at time of MTR: different RF configuration required for Z and (WW+ZH) meaning that hard choices needed to be made about which runs came first.

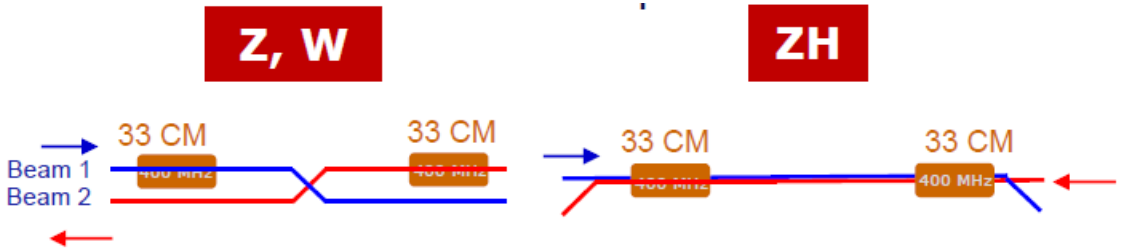


Also. a year's shutdown required to switch from one to the other. Ugh !

Developments since MTR: flexibility in running order

New RF strategy for Z, WW and ZH:

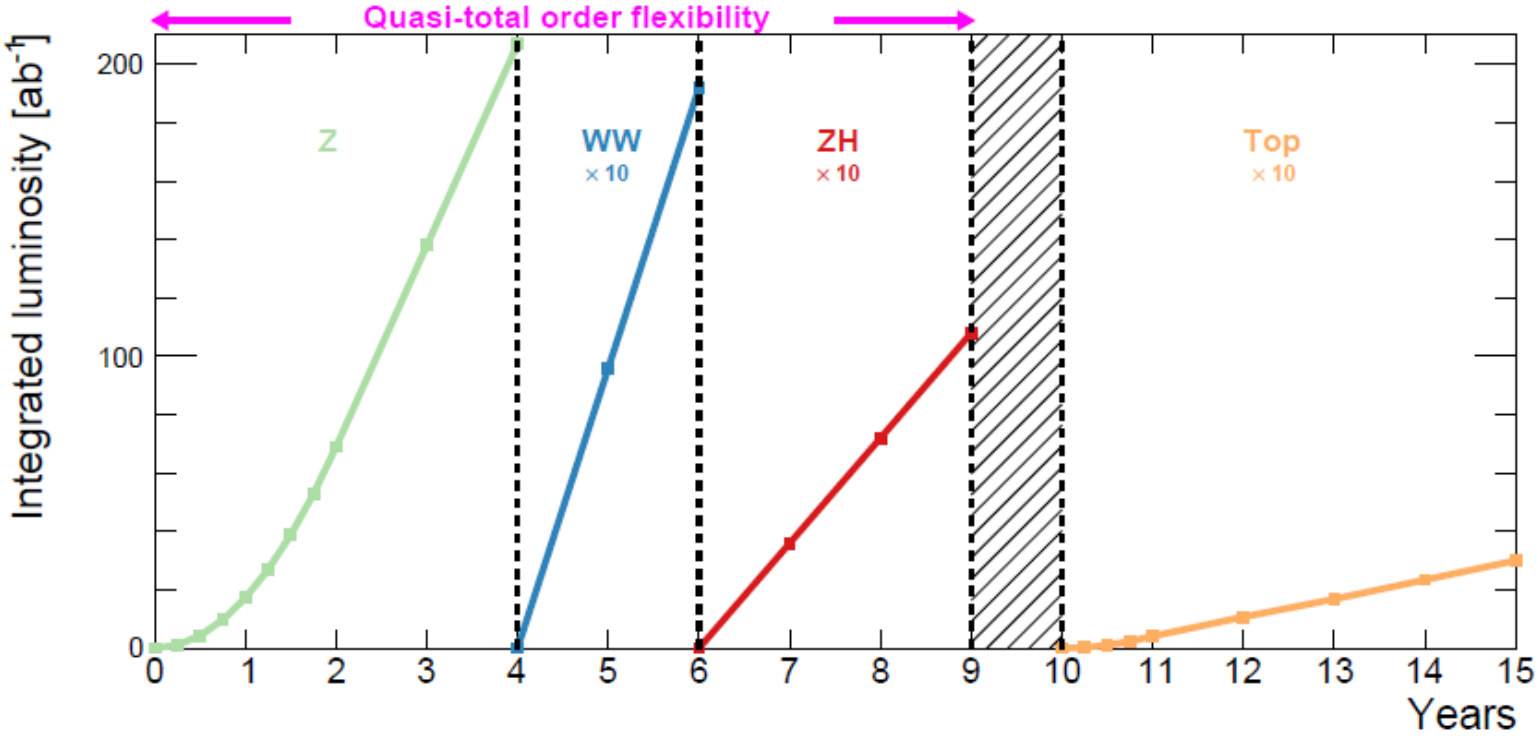
- Two-cell 400 MHz cavities for all three working points;
- Reverse phase operation;
- Separators for switching beams in and out of cavities.



Allows for high flexibility in switching between operation energies.

Developments since MTR: flexibility in running order

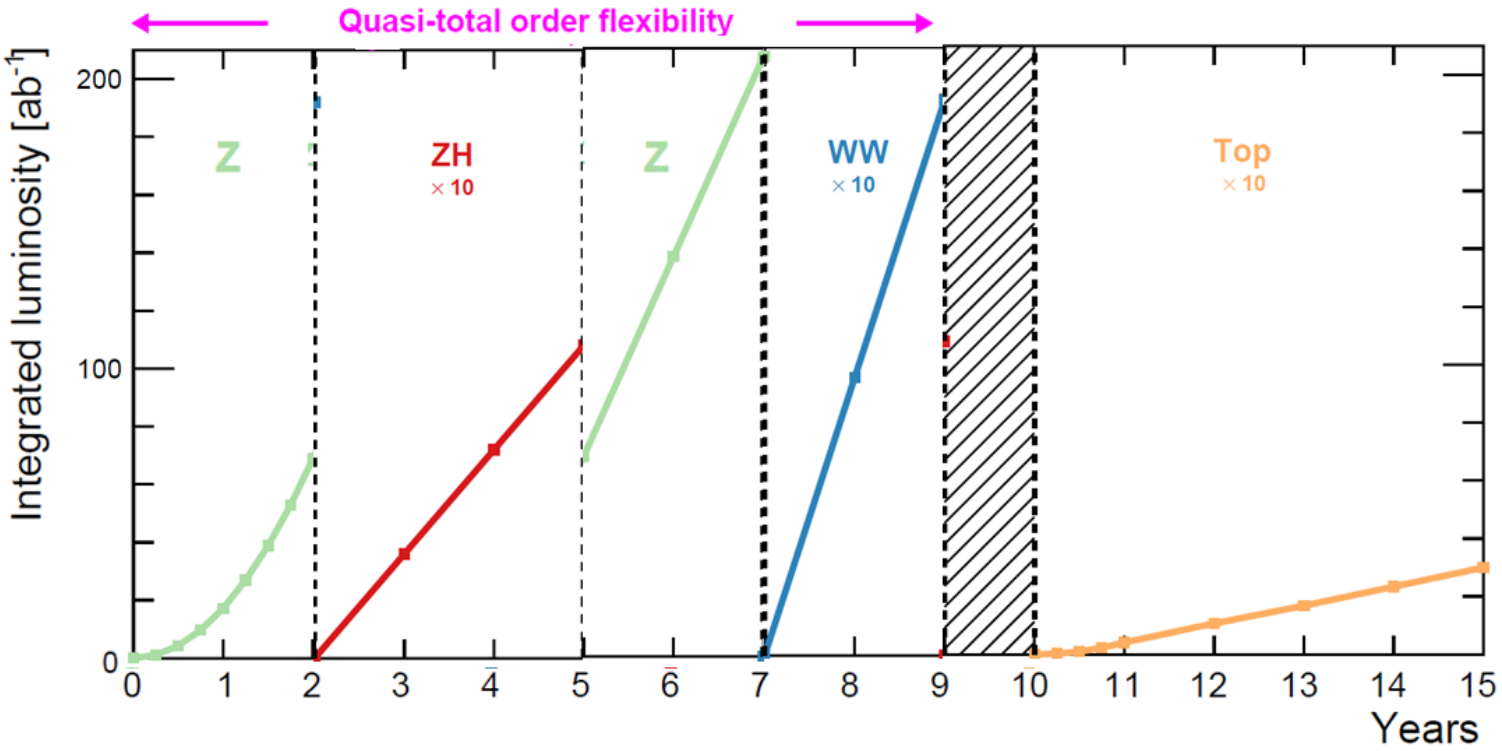
This is the figure in the Final Report.



But scheduling all the Z running in the first four years would be most unwise, as this encompasses the most demanding measurements, which require the best possible understanding of both the detectors and the accelerator.

Developments since MTR: flexibility in running order

Something like this might be more optimal.



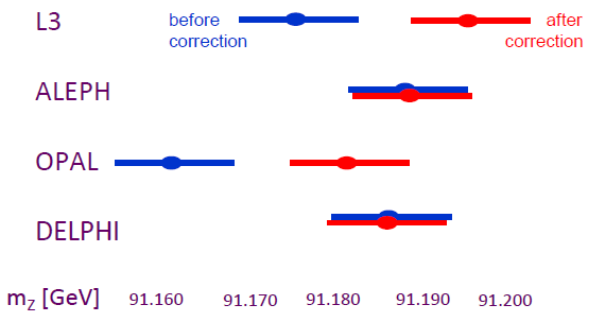
This also has the advantage of not postponing the excitement of the Higgs running until late in the schedule. With hew RF scheme most things are possible !

Developments since MTR: four interaction points

Decision to go from 2 to 4 interaction points is an important step forward:

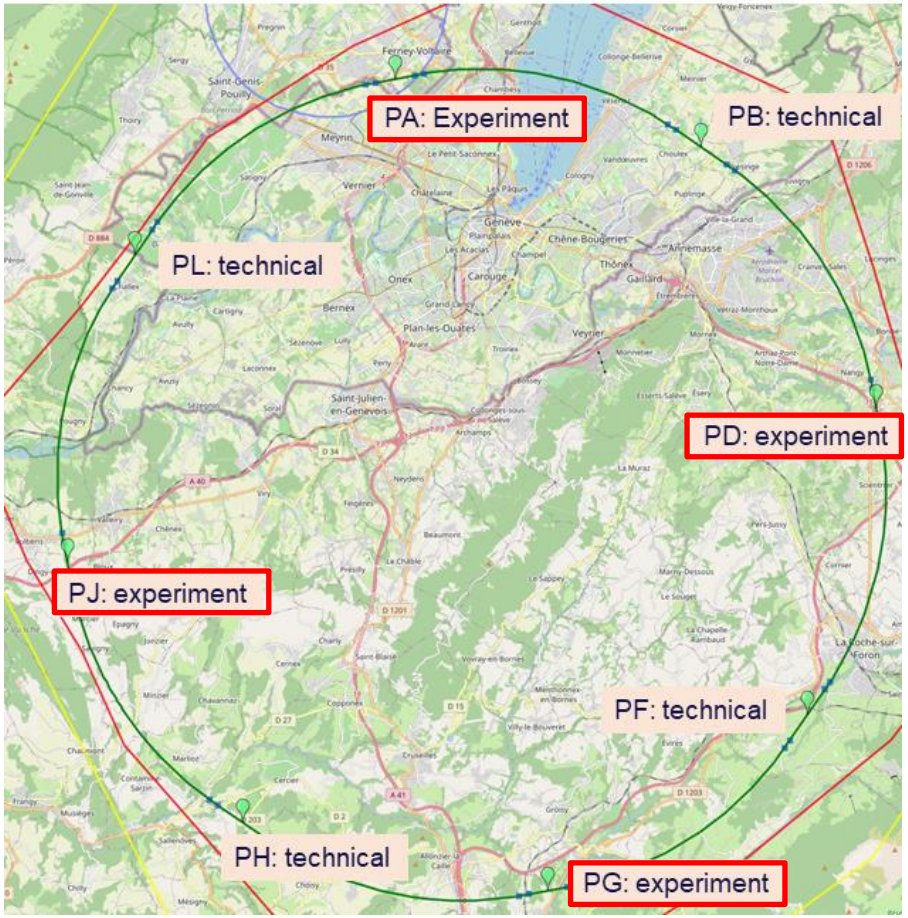
- Increases integrated luminosity by (almost) same factor;
- Provides systematic robustness;

Lessons from LEP – discovery of impact of `RF sawtooth' on Z mass



[PLB 307 (1993) 187]

- Allows for different detector solutions, which will ensure full coverage of the physics goals.



Things to keep in mind for the EPPSU (that you know already)

Higgs-physics corridor chat (or things you hear at national EPPSU meetings)

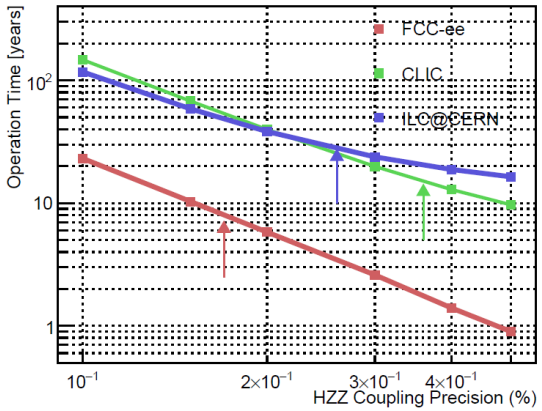
1) “All future e^+e^- Higgs factories have ~ equal physics reach”

Higgs-physics corridor chat (or things you hear at national EPPSU meetings)

1) "All future e^+e^- Higgs factories have ~ equal physics reach"

Some are more equal than others.

Precision on HZZ coupling

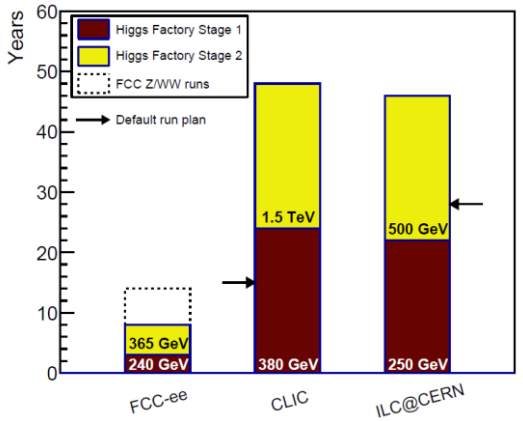


[A. Blondel, C. Grojean, P. Janot & G.W, arXiv:2412.13130]

Operation time to reach FCC-ee sensitivity

Duration (years)	FCC-ee$_{240+365}$	CLIC$_{380+1500}$	ILC$_{250+500}$
b	8	26	43
c	8	50	41
τ	8	54	47
Z	8	54	49
W	8	56	49
Average duration (years)	8	48	46
Electricity consumption (TWh)	13	55	41

(arrows indicate default running time)



Higgs-physics corridor chat (or things you hear at national EPPSU meetings)

1) “All future e^+e^- Higgs factories have ~ equal physics reach”

2) “Improved analysis techniques mean that the HL-LHC may do better than initially thought. So do we really need an e^+e^- machine ? ”

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Fantastic if the HL-LHC exceeds expectations ! Nonetheless:

- FCC-ee offers an order of magnitude improvement in precision for many quantities, and accesses regime where quantum effects are important;
- Certain quantities only accessible at e^+e^- (*e.g.* κ_c, Higgs width…), or close-to-accessible (*e.g.* κ_s, κ_e).

Coupling	HL-LHC	FCC-ee (240–365 GeV)
κ_W [%]	1.5*	0.29
κ_Z [%]	1.3*	0.11
κ_g [%]	2*	0.68
κ_γ [%]	1.6*	0.18
$\kappa_{Z\gamma}$ [%]	10*	10.2
κ_c [%]	–	0.96
κ_t [%]	3.2*	3.1
κ_b [%]	2.5*	0.50
κ_μ [%]	4.4*	3.50
κ_τ [%]	1.6*	0.47
BR_{inv} (<%, 95% CL)	1.9*	0.12
BR_{unt} (<%, 95% CL)	4*	0.72

[table from Final Report]

Higgs-physics corridor chat (or things you hear at national EPPSU meetings)

1) “All future e^+e^- Higgs factories have ~ equal physics reach”

2) “Improved analysis techniques mean that the HL-LHC may do better than initially thought. So do we really need an e^+e^- machine ? ”

3) “We need a 500 GeV e^+e^- machine to learn about Higgs potential and κ_λ.”

Higgs-physics corridor chat (or things you hear at national EPPSU meetings)

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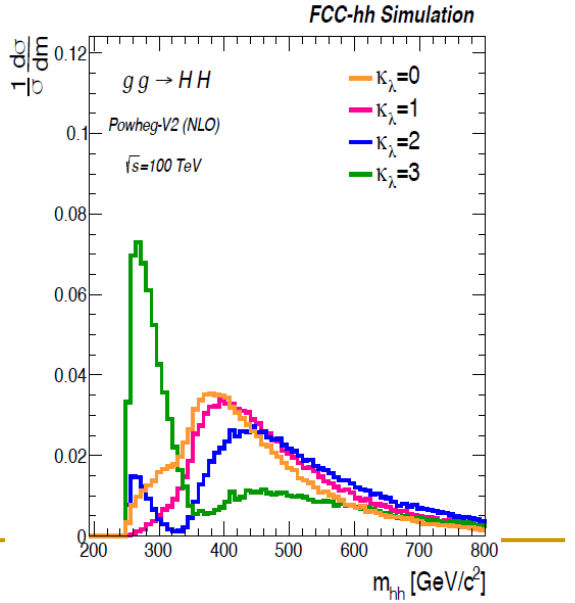
3) "We need a 500 GeV e^+e^- machine to learn about Higgs potential and κ_λ."

Expected κ_λ precision at ILC from di-Higgs production ~25%. May improve.

But reason to hope HL-LHC will not be so much worse than this (see 2). Furthermore, information available from single-Higgs x-section at FCC-ee, which, together with HL-LHC input, could give sub-20% precision.

But given the importance of this parameter, we have a duty to measure it much, much better. And this can be done at FCC-hh !



A false dichotomy

Sometimes we mislead ourselves (and the public), by making a misleading distinction between the categories of experimental programmes we pursue.

Direct discovery vs. Precise measurement

A false dichotomy

Sometimes we mislead ourselves (and the public), by making a misleading distinction between the categories of experimental programmes we pursue.

Direct discovery vs. Precise measurement

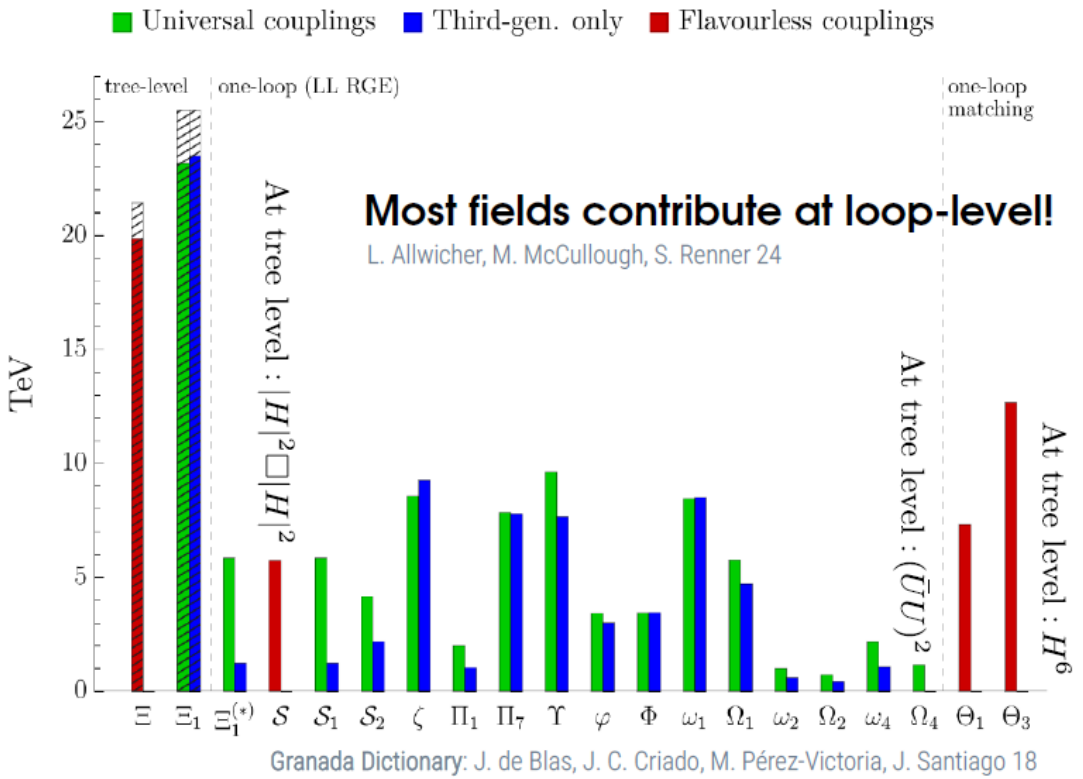
Of course precise measurement *is* a powerful method of discovery !

By forgetting this, we downplay the real excitement of the FCC-ee physics programme (which of course, also has avenues of direct discovery, *e.g.* LLPs).

The power of precision

Exquisite precision of Higgs studies, EWPO measurements at Tera-Z and higher energies, and heavy-flavour programme, will have ferocious search potential !

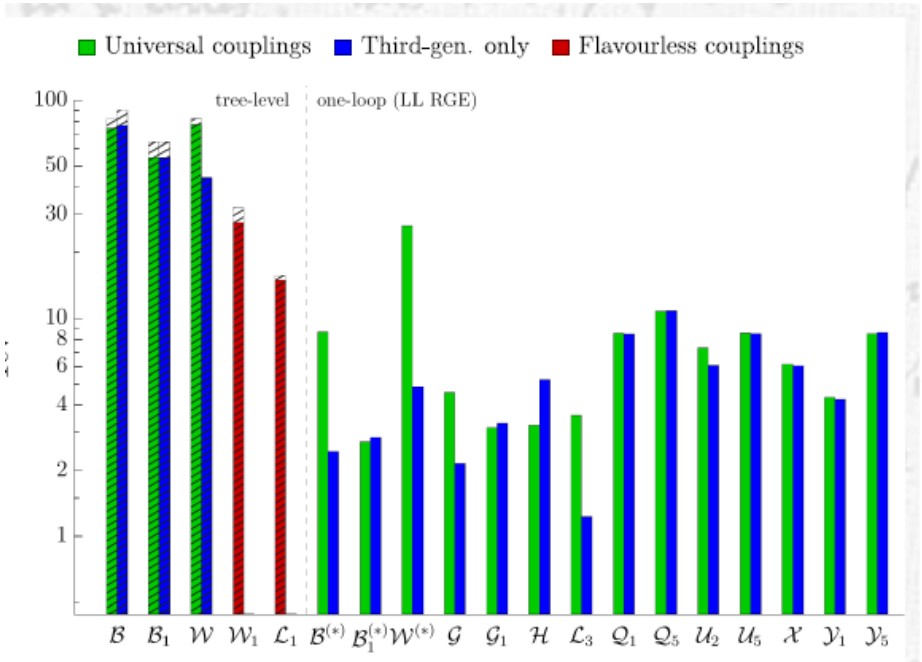
Tera-Z: where *nothing* can hide

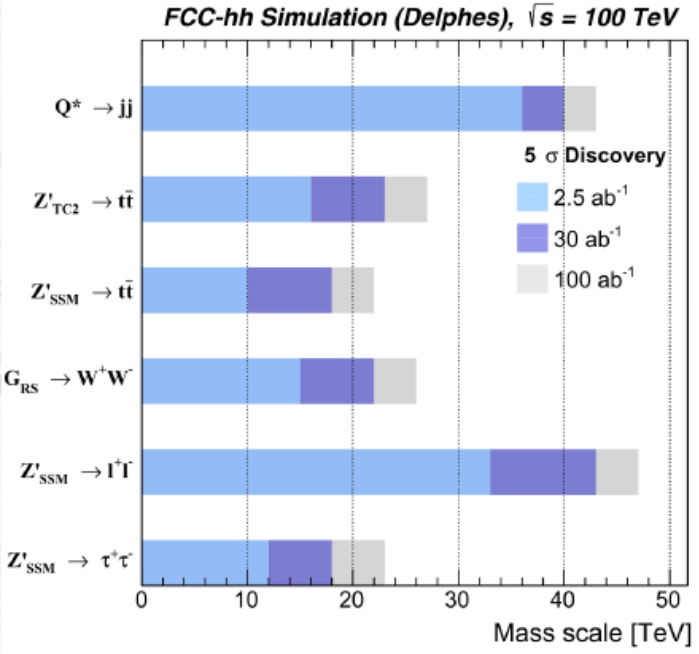


[Maria Ramos, ECR session, Monday]

Precision, and the road beyond

Any pattern of deviations found in the precision measurements must then be understood in what on-shell particles are discovered at higher energy.



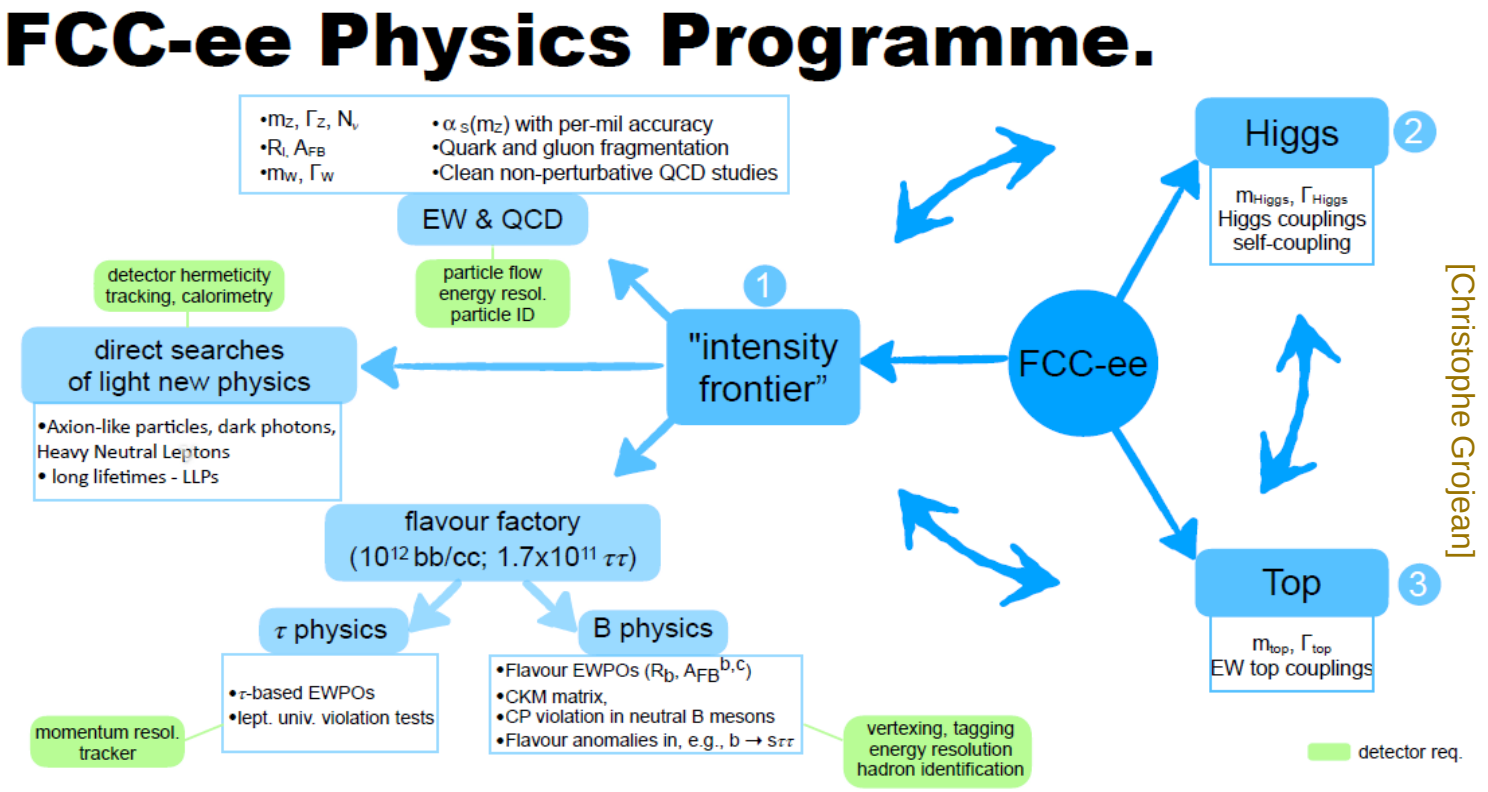


[Matthew McCullough]

FCC-ee is also a natural staging post on the road towards FCC-hh, which will complete our understanding of the Higgs, and have remarkable direct search potential, telling us more about any anomalies exposed by FCC-ee.

“I am large, I contain multitudes.” Walt Whitman

FCC physics programme is immensely broad…



…many areas to explore, many places with New Physics could manifest itself. (And the programme is still wider than in above cartoon: *e.g.* spectroscopy, non-collider opportunities with injector &/or booster [workshop].)

“I am large, I contain multitudes.” Walt Whitman

FCC physics programme is immensely broad…

Higgs… electroweak precision…
top… QCD… heavy flavours…
long-lived particles…photon science…

Such a wide programme can present challenges when seeking to formulate an ‘elevator pitch’ to those outside particle physics. But in talking to our colleagues it is a key argument.

…many areas to explore, many places with New Physics could manifest itself. (And the programme is still wider than in above cartoon: *e.g.* spectroscopy, non-collider opportunities with injector &/or booster [workshop].)

Towards the pre-TDR phase

The pre-TDR phase (*i.e.* the next ~3 years)

The pre-TDR phase begins in March, and last until project approval is sought from Council, in late 2027 or sometime in 2028.

During this period we will need to answer questions and achieve goals that will allow us to write the TDR with confidence.

This will be a major responsibility for the civil engineering, machine *etc*.

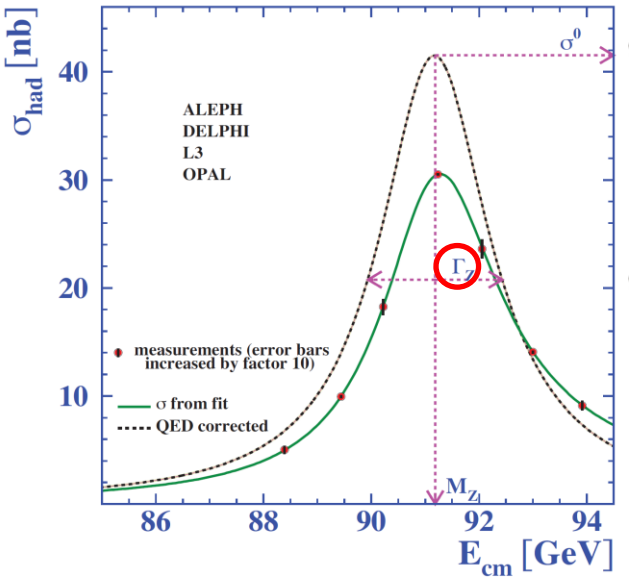
But PED must play its part, with first step to define list of milestones.

(→ all are encouraged to help with this. And indeed, if anyone has the time or inclination to play a more central role in the coordination of PED activities, then please contact Patrick, Christophe and myself.)

No attempt to do this today. Rather, I will provide some general thoughts about the tasks and challenges that lie ahead (some not concerning PED alone).

Refining the physics case: whack-a-mole

None of our important physics measurements will be easy to do well, particularly given the very large statistics at the Z pole. Progress in one area, may then mandate progress in another. Example from this week: the Z-width measurement.



Uncertainty	m_Z [keV]	Γ_Z [keV]	$\sin^2\theta_W^{eff}$ [$\times 10^{-6}$]	$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)}$ [$\times 10^{-5}$]	m_W [keV]
	Observable				
Absolute	100	2.5	/	0.1	150
Point-to-point	14	11	1.2	0.5	50
Sample size	1	1	0.1	/	3
Energy spread	/	5	/	0.1	/
Total $\sqrt{s}$ related	101	12	1.2	0.5	158
FCC-ee statistical	4	4	2	3	180

The hope is now that the E_{CM} – related systematic is approaching the statistical uncertainty….

Whack-a-mole of FCC systematics

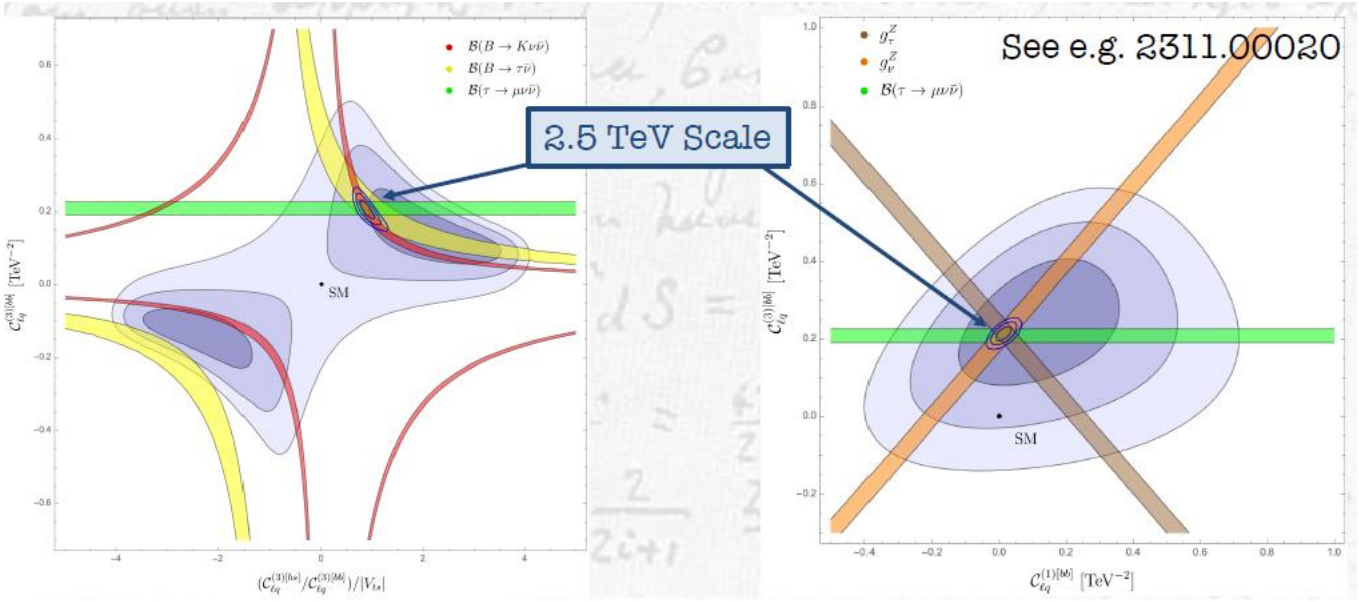
…in this case, however, it is likely that the point-to-point lumi uncertainty becomes dominant [Mogens Dam]. Can we hope to control the relative luminosity uncertainty to 10^{-5}, or better ?

And we need progress on theoretical understanding for all these measurements !

Refining the physics case: flavour

Still work to be done to understand the opportunities in flavour physics at FCC-ee (lazy to say 'huge statistics', as environment is equally important), as well as the interplay between flavour and electroweak observables.

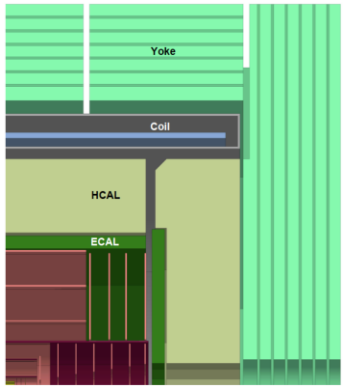
Nice example below [shown by Matthew M] – these observables *ideal* for FCC-ee.

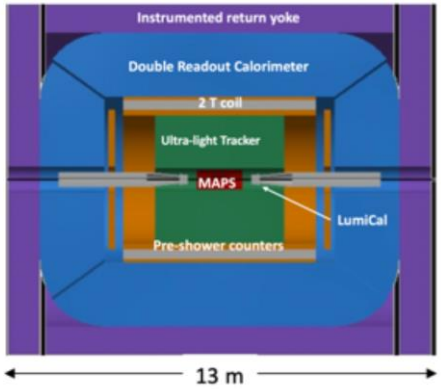


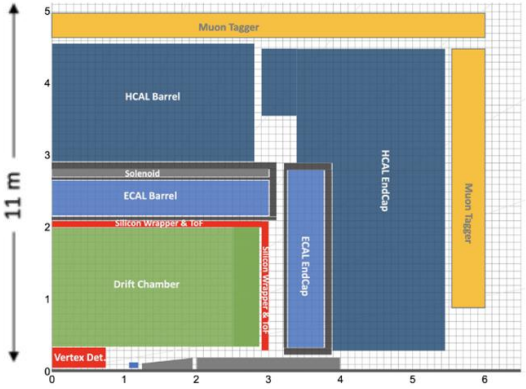
Charm prospects largely unexplored. But see study of $D^0 \to \pi\pi\nu\nu$ [Weds, T. Hacheney].

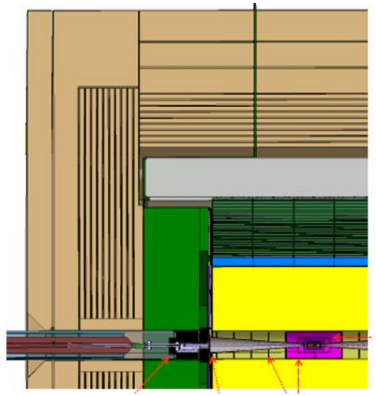
Detector concepts

Intensify studies on detector concepts to arrive at technologies and designs that are well suited (as far as is possible) to ALL goals of the FCC-ee physics programme.









EoI initiative, which will be the focus of a satellite meeting tomorrow, is an important step in catalysing work at sub-detector level for this purpose.

Related to this is need to ensure coherent activity with DRD collaborations.

Continued engagement with the HEP community

The EPPSU process is a scientific discussion, not a competition, still less a war ! We should not perceive its conclusion in terms of 'winners' and 'losers', even if we consider the FCC to be the best outcome for particle physics.

Important that we continue to extend a warm welcome to all, now, and as EPPSU process is concluding, such that our currently linearly inclined colleagues can find opportunities to contribute to pre-TDR phase of FCC-ee.

We need widespread enthusiasm, not grudging acceptance, for our project, and we need the talents and insights of the entire community !

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We need widespread enthusiasm, not grudging acceptance, for our project, and we need the talents and insights of the entire community !

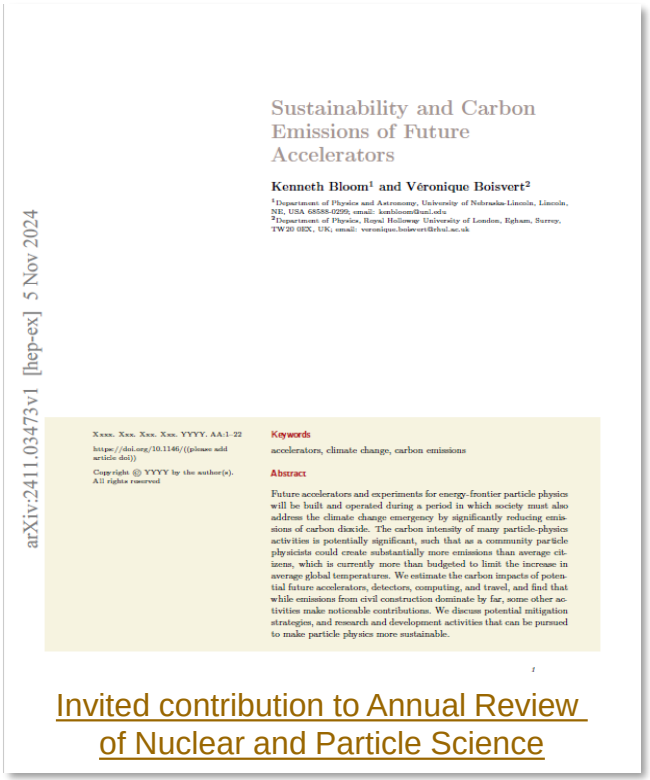
I repeat we are engaged in a scientific discussion, not a war. Nonetheless, a military analogue may still serve a purpose.

Hiroo Onoda, a Japanese soldier in WWII, finally laid down his arms in 1974.

Not good for particle physics for there to be too many 'next-collider Hiroo Onodas'.

Engaging with the public, and the sustainability question

The primary arguments that we must present to the public for the FCC must be scientific. After this, we can talk of other societal benefits. Beyond this, sustainability arguments are likely to become and increasingly important topic.



Sustainability and Carbon Emissions of Future Accelerators

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Xxxx. Xxx. Xxx. Xxx. YYYY. AA:1–22
https://doi.org/10.1146/((please add article doi))

Keywords
accelerators, climate change, carbon emissions

Abstract

Future accelerators and experiments for energy-frontier particle physics will be built and operated during a period in which society must also address the climate change emergency by significantly reducing emissions of carbon dioxide. The carbon intensity of many particle-physics activities is potentially significant, such that as a community particle physicists could create substantially more emissions than average citizens, which is currently more than budgeted to limit the increase in average global temperatures. We estimate the carbon impacts of potential future accelerators, detectors, computing, and travel, and find that while emissions from civil construction dominate by far, some other activities make noticeable contributions. We discuss potential mitigation strategies, and research and development activities that can be pursued to make particle physics more sustainable.

Invited contribution to Annual Review of Nuclear and Particle Science

Higgs factory options for CERN

A comparative study

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Abstract

"All future e^+e^- Higgs factories have similar reach for the precise measurement of the Higgs boson properties.": this popular statement has often led to the impression that all e^+e^- options are scientifically equivalent when it comes to choosing the future post-LHC collider at CERN. More recently, the concept of sustainability has been added in attempts to rank Higgs factories. A comparative analysis of the data currently available is performed in this note to clarify these issues for three different options: the future circular colliders (FCC), and two linear collider alternatives (CLIC and ILC@CERN).

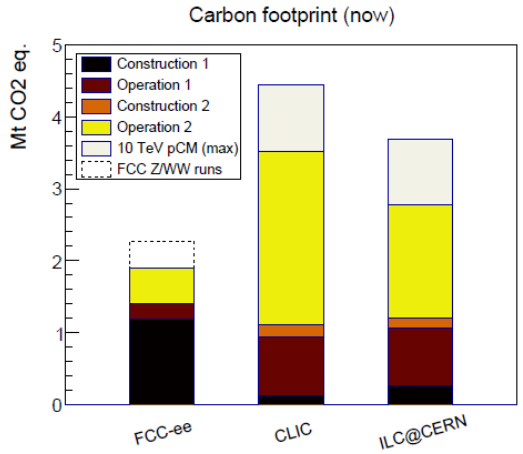
The main observation is as follows. For the precise measurement of already demonstrated Higgs decays ($b\bar{b}$, $\tau^+\tau^-$, gg, ZZ, WW) and for $H \to c\bar{c}$, it would take half a century to CLIC and ILC@CERN to reach the precisions that FCC-ee can achieve in 8 years thanks to its large luminosity and its four interactions points. The corresponding electricity consumption, cost and carbon footprint would also be very significantly larger with linear colliders than with FCC-ee.

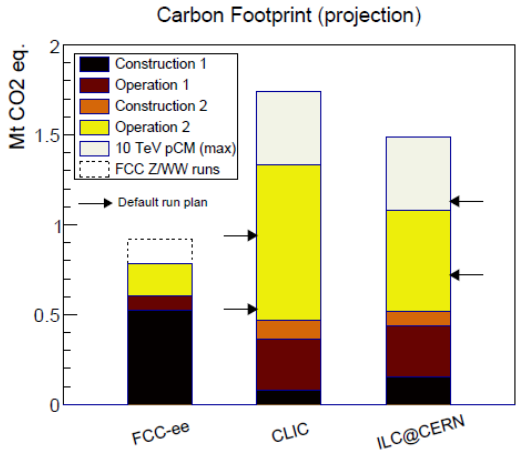
Considering in addition that *(i)* FCC-ee is the only place to attempt the measurement of the electron Yukawa coupling, thanks to the ability to produce the Higgs boson directly at $\sqrt{s} \sim m_H$ with reduced centre-of-mass energy spread; *(ii)* for the precise measurement of the many Higgs boson couplings that require the production of billions of Higgs bosons (such as $H\gamma\gamma$, $HZ\gamma$, $H\mu\mu$, or HHH), the combination of FCC-ee and FCC-hh is order of magnitude better than what linear colliders can ever do; *(iii)* FCC-ee is much more than a Higgs factory and, in an entirely new context where neither the mass scale of new physics nor the intensity of its couplings to the Standard Model are known, only the large luminosities of FCC-ee at the electroweak scale and the parton-parton collision energies at FCC-hh can provide the necessary exploration breadth with a real chance of discovery; and *(iv)* the vast experimental programme achievable with both FCC-ee and FCC-hh is out of reach of linear colliders; it is found that FCC-ee is a vastly superior option for CERN, and the only first step en route to the 100 TeV hadron collider.

arXiv:2412.13130

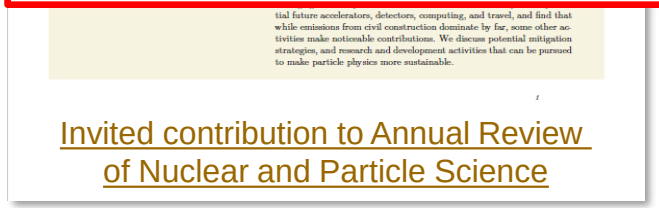
Engaging with the public, and the sustainability question

The primary arguments that we must present to the public for the FCC must be scientific. After this, we can talk of other societal benefits. Beyond this, sus ic.





Of course, here public are more likely to be concerned with absolute numbers, rather than comparison between facilities.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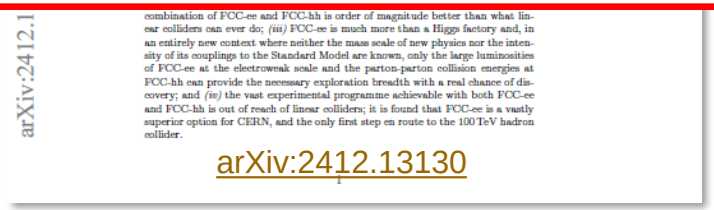
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Listening to the ECR community

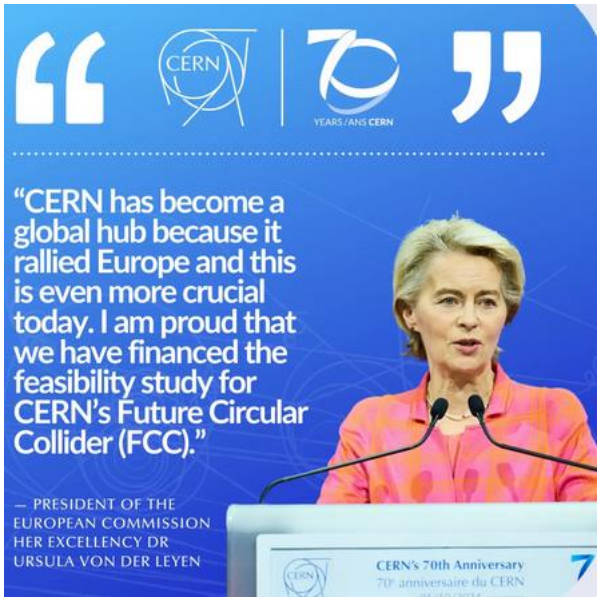
Already impressive engagement from the early career community,
e.g. Monday morning event: ~55 in person, ~90 on Zoom.

[photo: Armin Ilg]

see backups for
more information
& how to subscribe
to ECR group

These are the people who will operate and exploit the FCC, and so their opinions and input will be increasingly important throughout the pre-TDR phase.

Ongoing engagement with politicians and potential influencers



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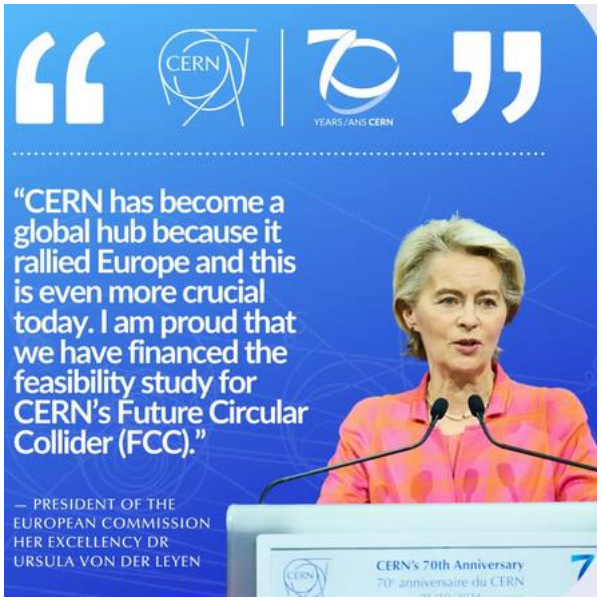

Although the times ahead are without doubt uncertain…

Final words

Thank you again for your contribution to PED activities throughout the Feasibility Study, and for your participation at this Physics Workshop.

Safe travels home, either tonight, or after the satellite meetings tomorrow morning.

Keep focused throughout the EPPSU and be ready to make the pre-TDR phase a success.

We will meet again in Vienna !

Backups

FCC Early Career Forum

- For everyone that identifies as **early career** and is **working on or interested in FCC**
  - Experimentalists, theorists, accelerator physicists, engineers, economists, …
  - Meet, discuss, learn, exchange and network
- First event this Monday morning: More than 50 people in person, up to 90 on Zoom
- **Monthly events** planned:
  - Next event in mid-February, at CERN and on Zoom
  - **Bookmark the indico page** where our events will be listed
  - **Join our *fcc-early-career-forum* e-group** to get informed about our events
- Want to contribute or have ideas?
  - ➢ Contact the organisers: fcc-early-career-forum-organisers@cern.ch