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# Closing Words: 5<sup>th</sup> FCC Physics Workshop

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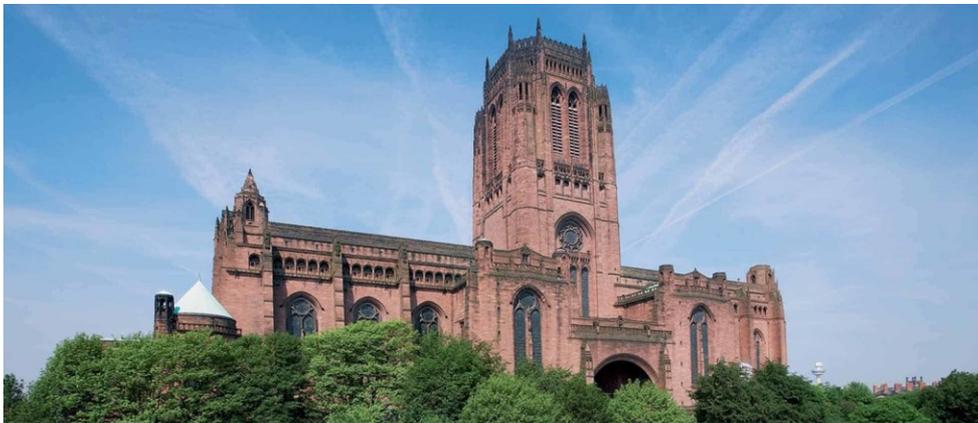
Guy Wilkinson  
University of Oxford  
11 February 2022

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# Outline

- What we missed out on
- The FCC physics case (this you should know)
- Convincing the community and the world
- Feasibility study and thoughts on timescales
- PED contributions to the feasibility study

# What we missed out on



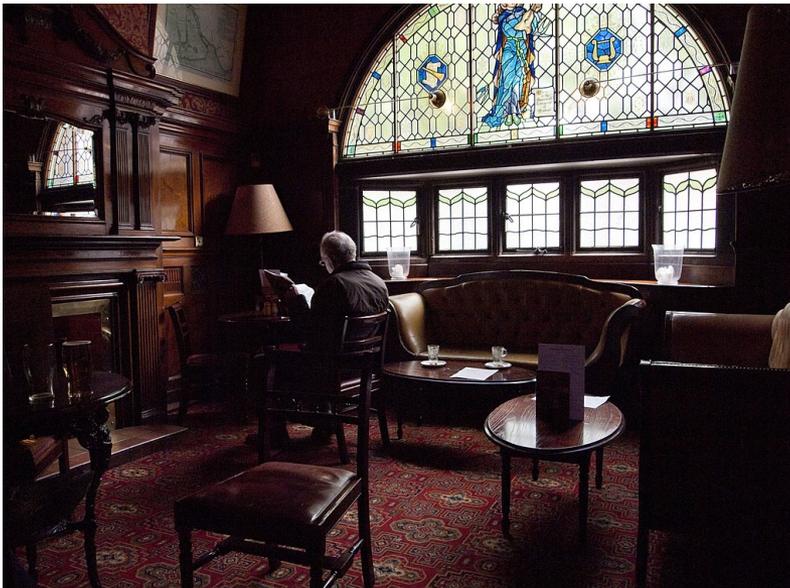
# What we missed out on – most importantly



‘Philharmonic Dining Rooms’:

Magnificent Art Deco pub  
(Grade-1 listed building).

The urinals are a particular highlight.



# Tuesday evening: Liverpool Cathedral

Discussions on Science and Faith (and outreach for FCC...). > 100 attended.

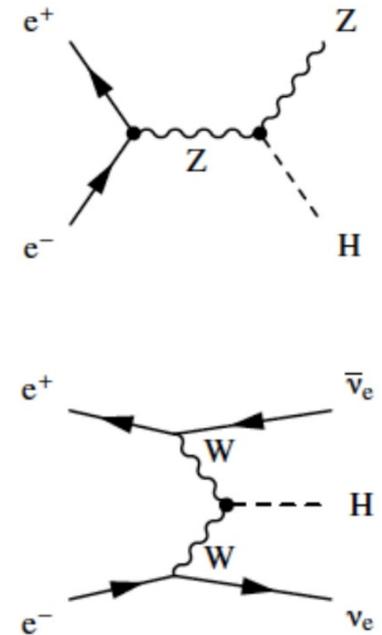
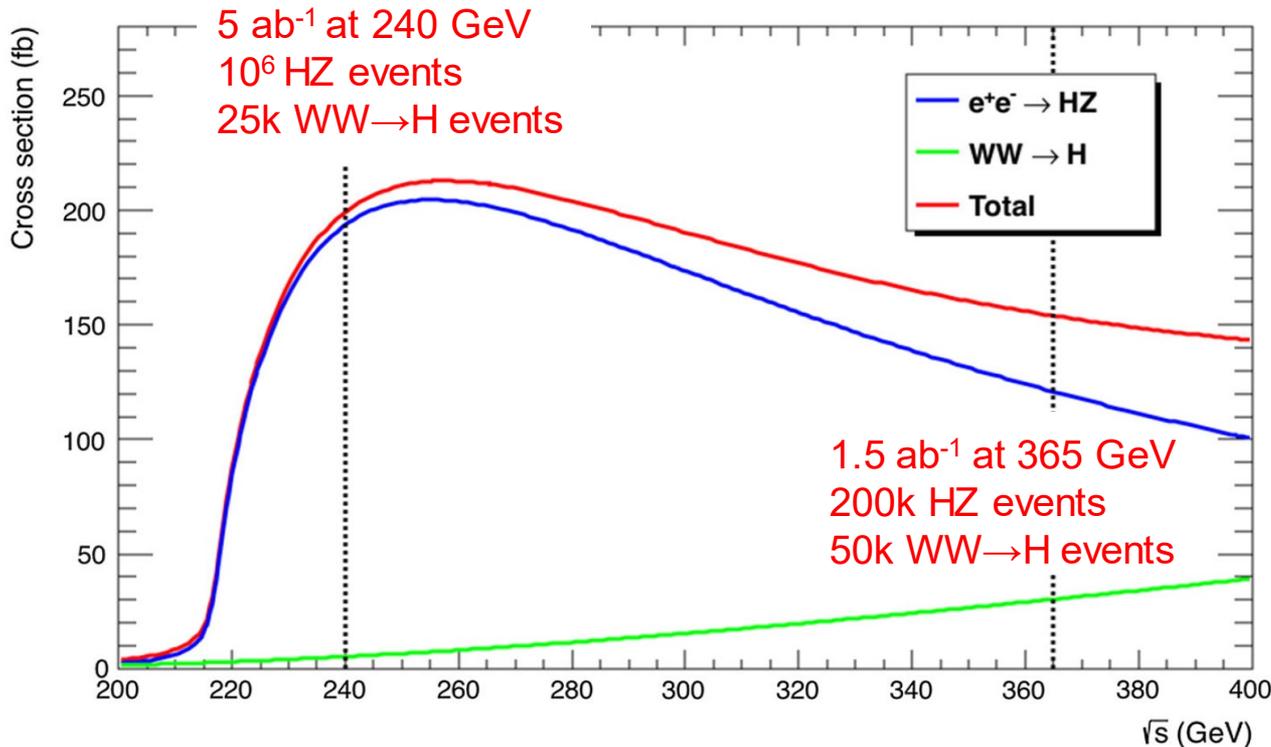


Carsten hopes to make recording available.



# FCC-ee: the ultimate $e^+e^-$ Higgs laboratory

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with ( $<$ )% precision. Achieved through operation at two energy points.



Sensitivity to both processes very helpful in improving precision on couplings.

# FCC-ee: the ultimate $e^+e^-$ Higgs laboratory

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.

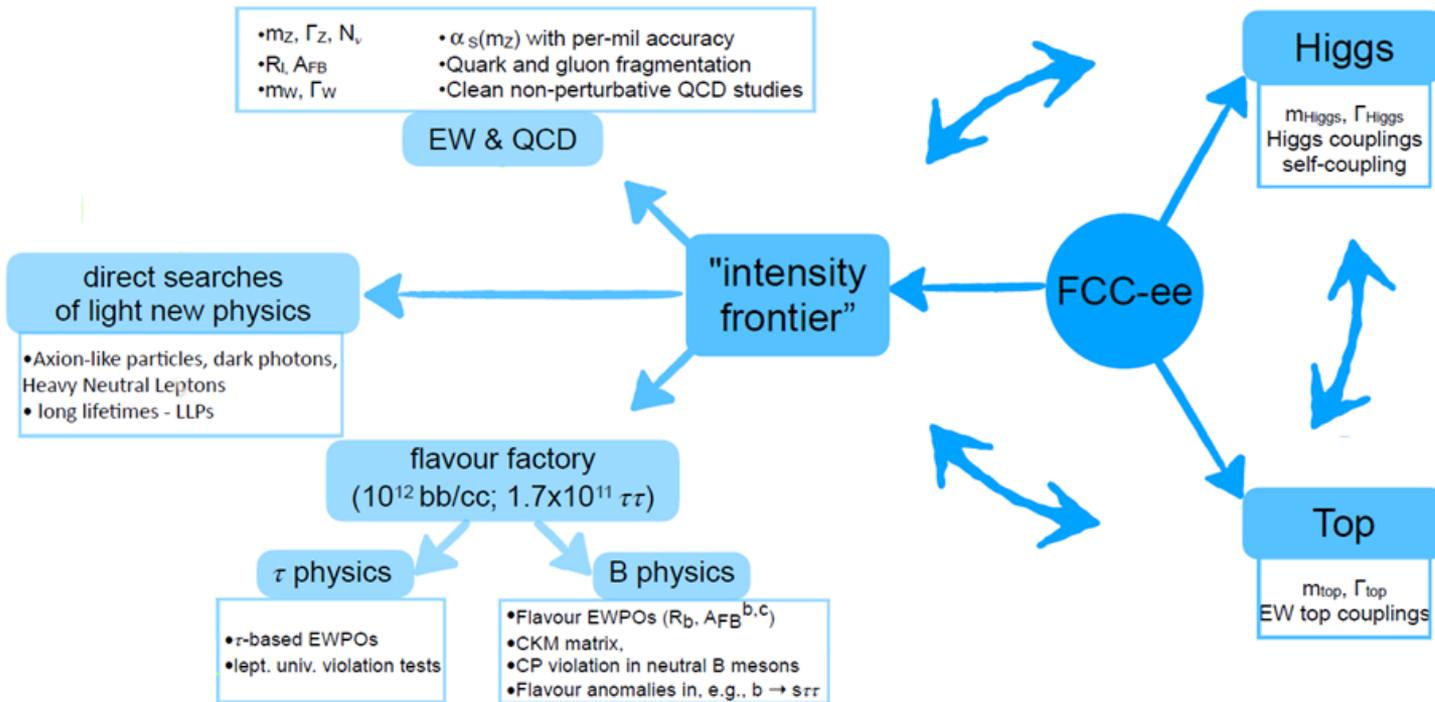
Excellent precision achievable for all couplings; good complementarity to HL-LHC

Collider	HL-LHC	ILC <sub>250</sub>	CLIC <sub>380</sub>	LEP <sub>3240</sub>	CEPC <sub>250</sub>	FCC-ee <sub>240+365</sub>		
Lumi (ab <sup>-1</sup> )	3	2	1	3	5	5 <sub>240</sub>	+ 1.5 <sub>365</sub>	+ HL-LHC
Years	25	15	8	6	7	3	+ 4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	<b>1.3</b>	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	<b>0.17</b>	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	<b>0.43</b>	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	<b>0.61</b>	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	<b>1.21</b>	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	<b>1.01</b>	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	<b>0.74</b>	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	<b>9.0</b>	3.8
$\delta g_{HY\gamma}/g_{HY\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	<b>3.9</b>	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR <sub>EXO</sub> (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< <b>1.0</b>	< <b>1.0</b>

Sensitivity to both processes very helpful in improving precision on couplings.

# FCC-ee: much more than a Higgs factory

But Higgs is only one of three aspects of FCC-ee programme: there is also top & the 'intensity frontier'; the latter, in particular, offers an amazingly rich field of studies.

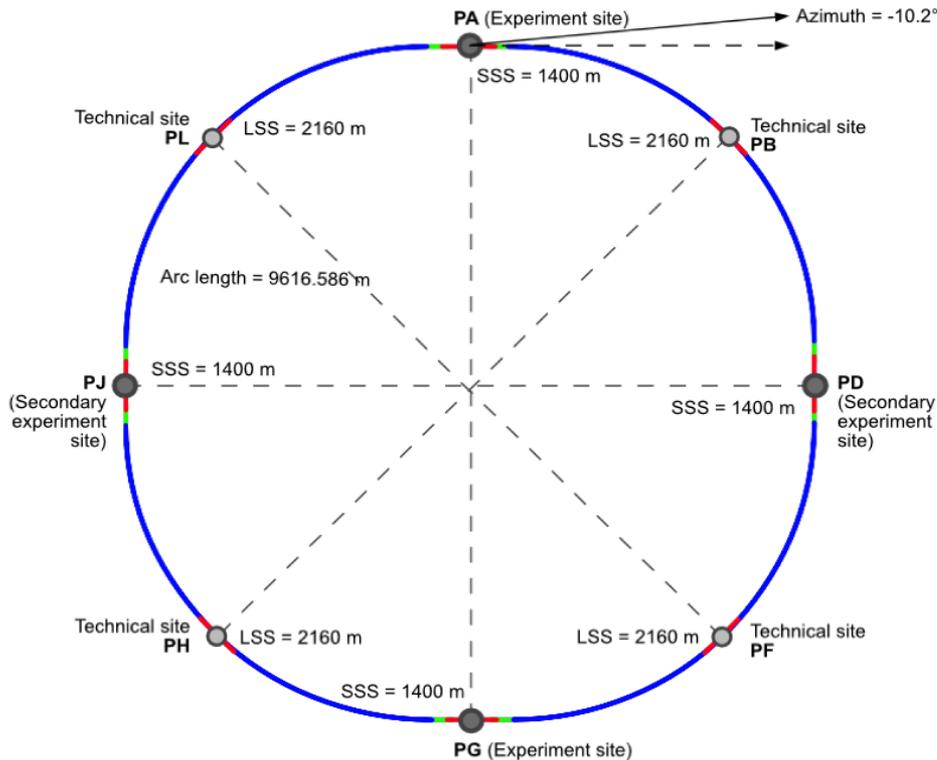


C. Grojean, Monday

These opportunities are unique to FCC-ee (+CEPC). Be in no doubt that all aspects of the programme are aimed at *discovery*, including the precision measurements !

# Important developments

“New ‘lowest risk’ placement / optics allows four experiments” Michael Benedikt



4-fold symmetry and  
4-fold superperiodicity

FCC-ee 2 or 4 IPs

FCC-hh 4 IPs

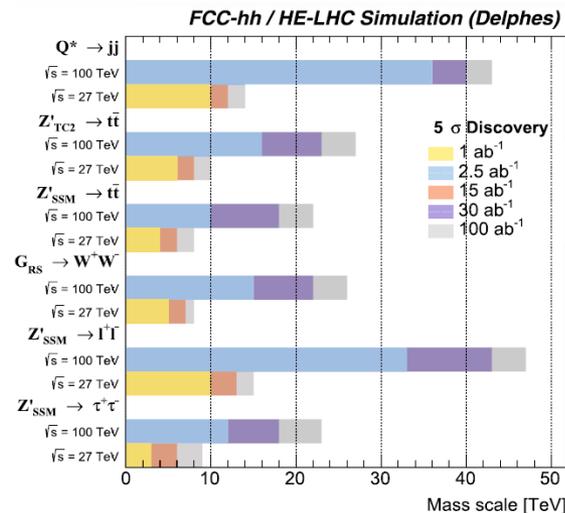
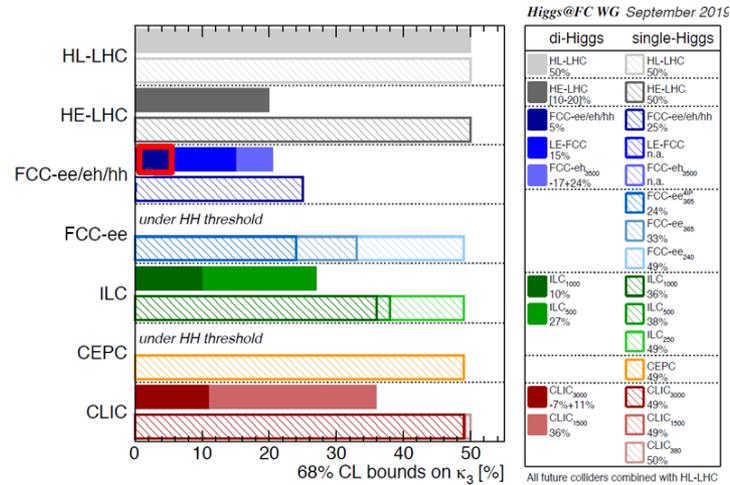
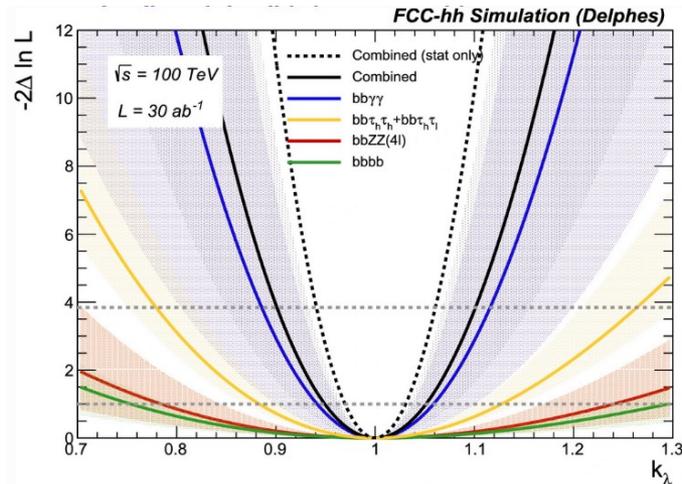
FCC-ee programme greatly benefits from having four interaction points:

- More data, sooner;
- Systematic robustness with redundancy;
- Better physics coverage.

# FCC-hh: the infinity machine

~30 ab<sup>-1</sup> at 100 TeV provides astounding physics reach. Jewel in the crown: precision study of the Higgs potential, with self-coupling measured to 3.4 – 7.8%.

Eur. Phys. J. C 80 (2020) 1030



Impressive direct-search potential  
e.g. certain heavy resonances  
accessible up to beyond 30 TeV

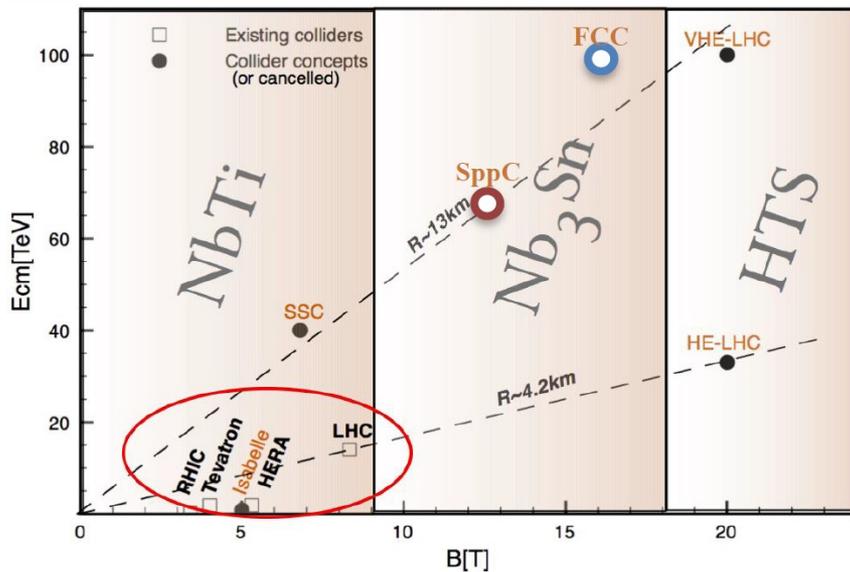
M. DiOnofrio, Monday

# FCC-hh: the challenges

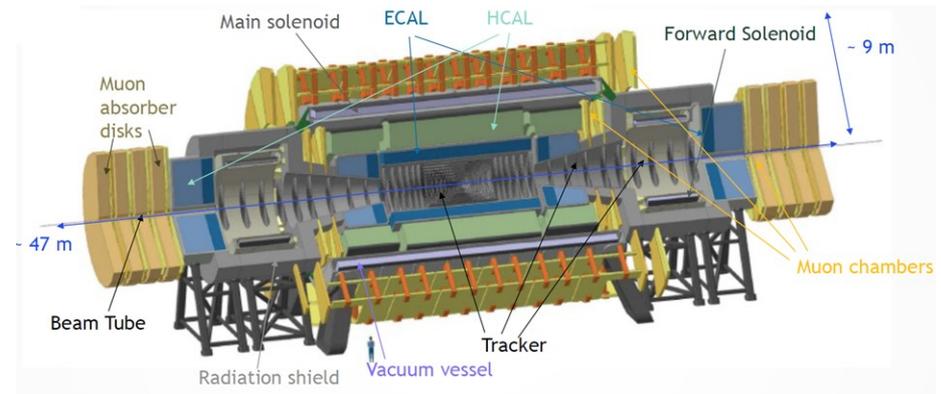
Formidable challenges to be overcome before FCC-hh becomes realisable project.

Reliable high-field magnets at affordable cost.

Radiation environment for experiments will be very severe (M. D'Onifrio, Monday)

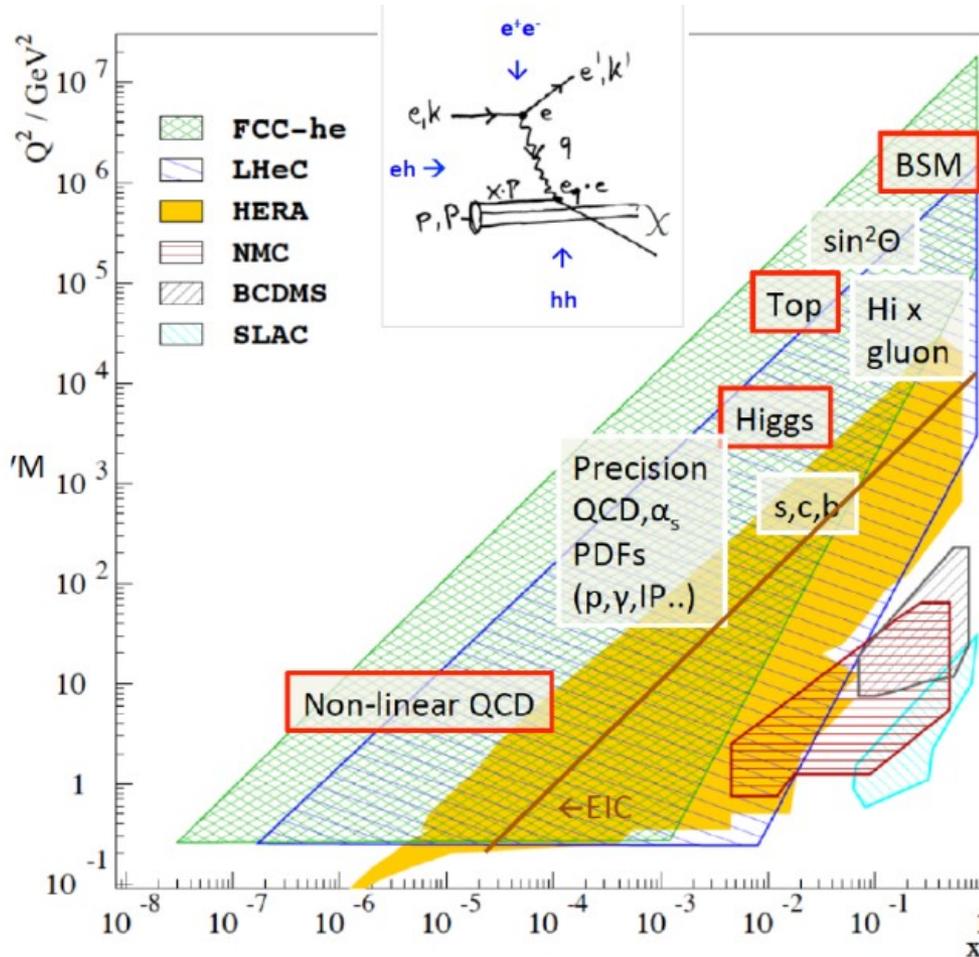


See S. Prestemon summary (Monday).  
Ongoing efforts in Europe, US, Japan & China.



Radiation levels generally 10-30 x worse than HL-LHC, but much bigger for forward calorimeter and innermost tracking layers – beyond capabilities of current technologies.

# Completing the picture: FCC-eh



## deliveries of ep/eA at the energy frontier

- cleanest high resolution microscope: QCD discovery
- empowering the LHC/FCC search program
- precision Higgs facility together with LHC/FCC-hh
- precision and discovery facility (top, EWK, BSM)
- unique nuclear physics facility

→ **diversity**

# Convincing the community, convincing the wider world

The physics prospects of the FCC integrated programme appear to me both vast and to be addressing some of the most important questions in nature. But this view is not shared by all. On Monday the CERN Research Director told us:

“ I strongly believe that we have to strengthen and sharpen our physics arguments

- Just higher precision is not enough !
- What are the connections to the really big fundamental questions and miracles of the Universe? ”

Indeed we cannot ignore ‘the matrix of confidence’ (here focusing on FCC-ee & hh).

	FCC community	HEP community	Wider world
The next lepton collider should be FCC-ee	✓	?	?
FCC-hh is critical for our scientific progress	✓	✓	?

Note that arguments that work for column 2 may not be sufficient for column 3.

# Making the case: some thoughts

Can we do more to convince our colleagues of the importance of the intensity frontier, both of the possibilities of direct discovery and the power of precision measurements? The power of EWPO is maybe seen more clearly in the context of specific models, than in effective field theories.

LHC had a no-lose theorem (the Higgs discovery). Harder to find at future facilities. Still, is it possible to find 'killer apps'? What about the Higgs self-coupling?

- FCC-hh: the prospects here are tremendous;
- FCC-ee: good 'indirect' (?) sensitivity through precise x-section measurements.

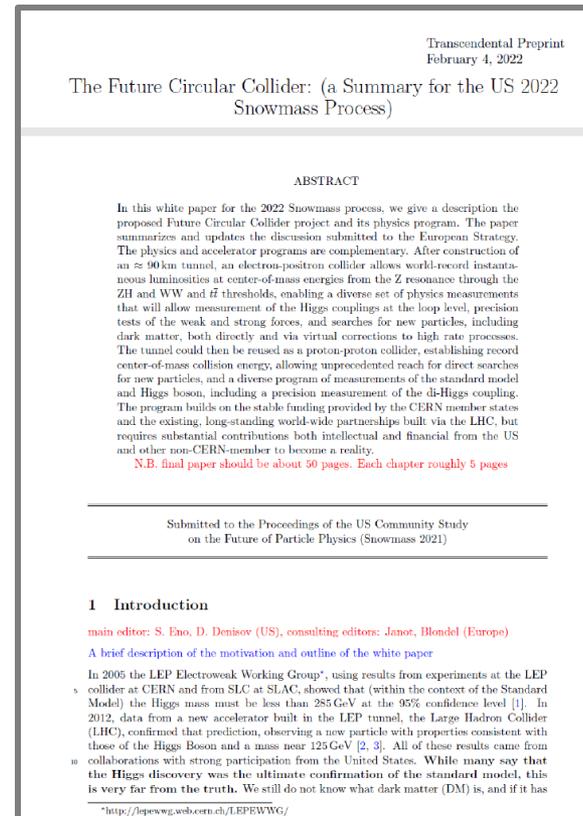
However, we should not be shy of emphasising the immense breadth and richness of the programme. Likely  $O(10^4)$  different publications, conducted by  $O(10)$  of separate experiments over many decades addressing the  $\sim$  full range of HEP.

Certainly, we should put more efforts into spreading the word, within the community and outside. (Again, it's a great shame we could not be in Liverpool in person).

# Indeed, FCC is becoming a truly global endeavour

At the Informal Forum of National Contacts (Thurs evening) ~20 nations reported FCC-related activity. In certain places important discussions are occurring.

e.g. substantial whitepaper on FCC being prepared for US Snowmass Process

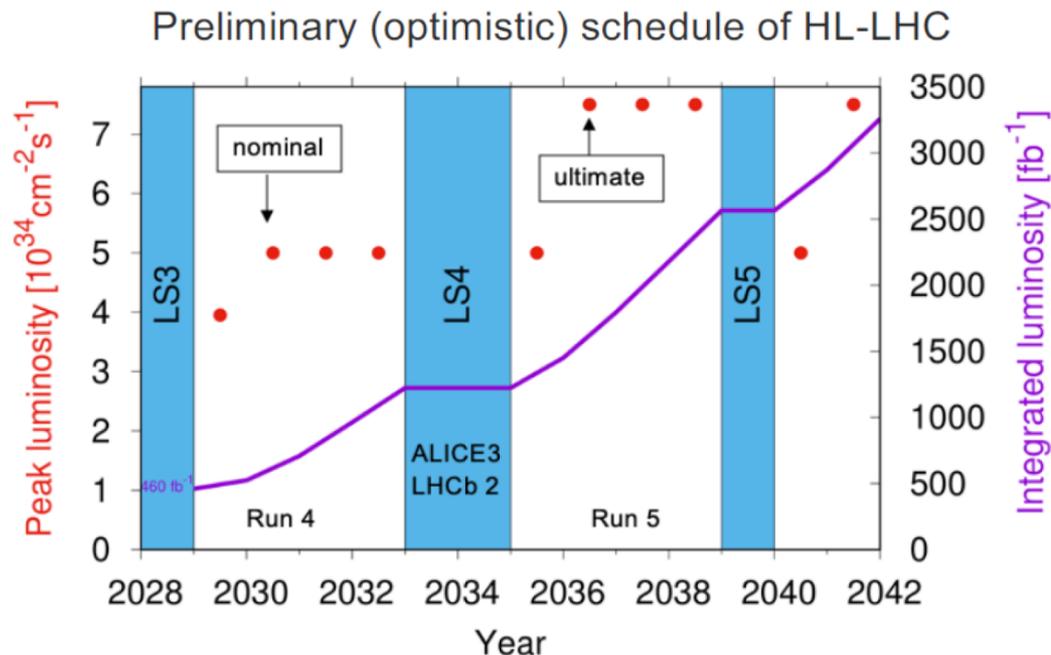


Sarah Eno, Monday



# A balancing act

There is a delicate balancing act between full exploitation of HL-LHC and delivering next facility. What is the necessary time interval between end of HL-LHC and start of FCC ? For LEP  $\rightarrow$  LHC it was 10 years (same tunnel), but for  $Spp\bar{S} \rightarrow$  LEP it was -2 years. Clear dependence on financial and human resources.



Joachim Mnich, Monday

Above schedule and (say) 7 years puts FCC-ee start 27 years from now.

# The timescale: a 'local' perspective

Thirty years was the time Liverpool spent in the wilderness before reclaiming the English Premier League title (& I would have been happier if it had been longer...)



1990 (as you can tell from the shorts)



2020

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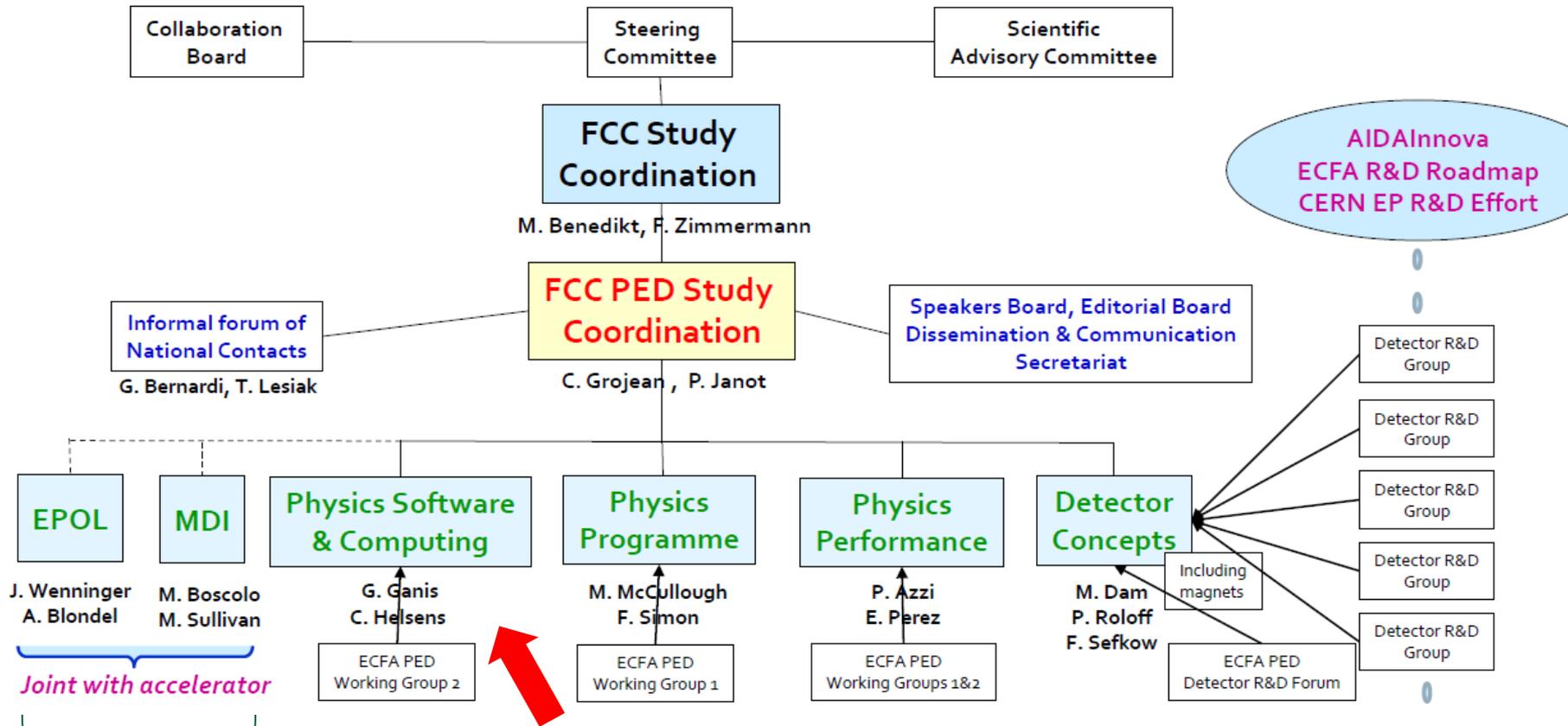
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2020

This was a long time to wait, but of course did not diminish the joy of the locals.

Physicists are less patient. Let us continue constructive discussions with CERN to ensure that FCC begins as soon as possible, compatible with LHC exploitation.

# PED contributions to the Feasibility Study



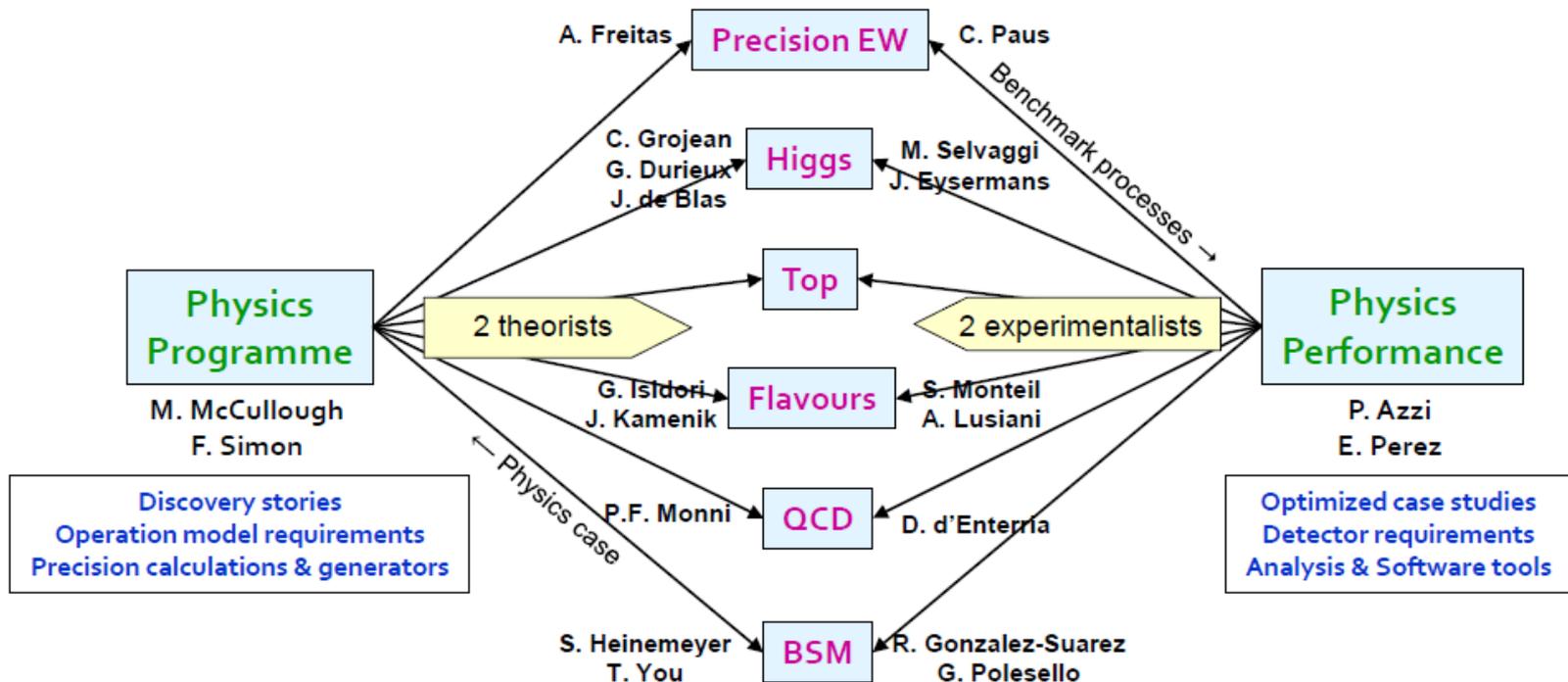
Joint with accelerator

No time to comment on these today

Heroic work to date, and success of this work package is clearly essential, but progress is hampered by lack of core group at CERN. Any injection of effort from outside most welcome! Also hope that some benefit can come here (and for other activities) from the ECFA PED WGs (K. Jakob, Monday).

# The Physics Work Packages

Physics groups with conveners defined common both to Physics Programme and Physics Performance Work Packages. Critical that work on benchmark processes and case studies intensifies, to provide input for Detector Concepts.

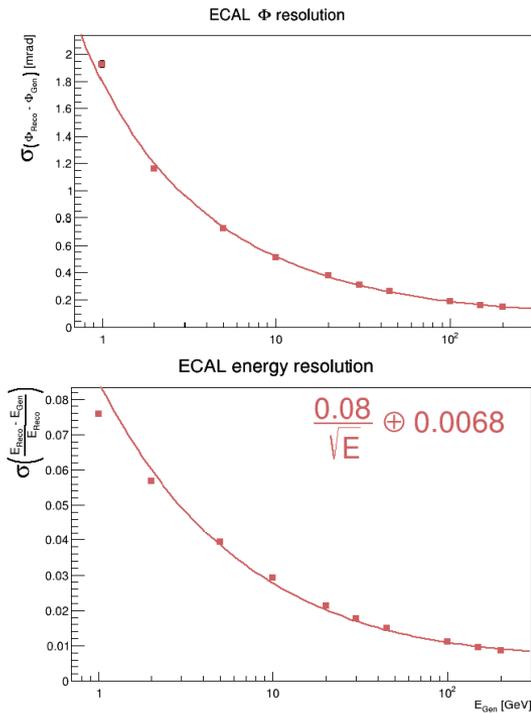


# Required progress in Detector Concepts

For Detector Concepts WP it is essential that simulation & reconstruction s/w for proposed sub-detectors is developed, & made available in a plug'n'play format.

Promising example from this week: implementation of Noble Liquid Calorimeter in FCCSW & intention to develop an entire detector concept around this key element.

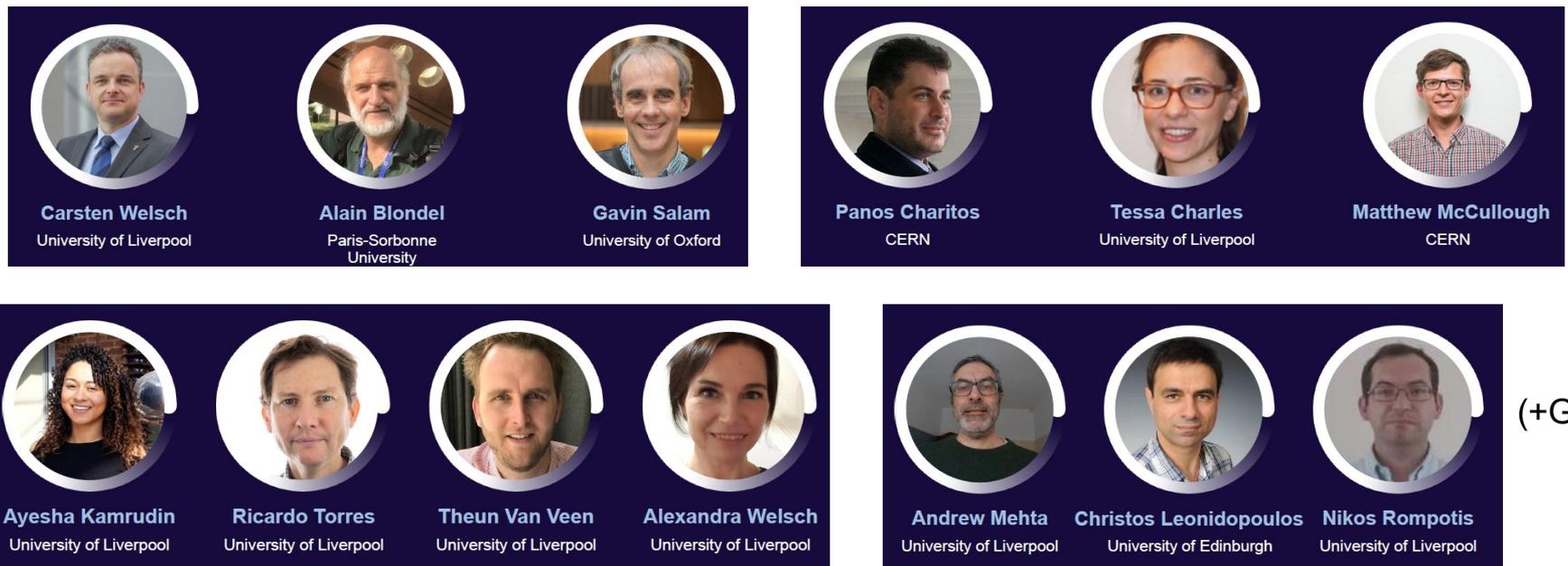
Briec François, Weds + Fri



Remember: Detector Concepts must pay attention to *full range* of FCC-ee physics !

# Many thanks to the Carsten and the LOC

Even though we did not make it to Liverpool in the end, an enormous amount of work was done in preparation, which helped make for a very successful event.



And of course thanks to the Scientific Programme Committee.

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**Ta Ra for now !** (scouse for good bye)



Liverpool – a unique destination

We hope to be there (in person) soon !

**Ta Ra for now !** (scouse for good bye)

