https://indico.cern.ch/event/1439509

Sth FCCPHYSICSPHYSICSPHYSICSPHYSICSPHYSICSJanuary 13-16, 2025+ Satellite workshop on Jan. 17PCERN

FUTURE CIRCULAR COLLIDER

earch and innovation Action proje om the European Union's H2020

FCC-hh physics potential: status and next steps

Michelangelo Mangano, CERN TH

The work so far:

Physics at the FCC-hh

https://e-publishing.cern.ch/index.php/CYRM/issue/view/35 Chapter 1: Standard Model Processes Chapter 2: Higgs and EW Symmetry Breaking Studies Chapter 3: Beyond the Standard Model Phenomena Chapter 4: Heavy lons at the Future Circular Collider Chapter 5: Physics Opportunities with the FCC-hh Injectors



FCC Conceptual Design Report:

Volume 1: Physics Opportuniities, Eur.Phys.J.C 79 (2019) 6, 474 Volume 3: The FCC-hh, Eur.Phys.J.ST 228 (2019) 4, 755

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THE EUROPEAN **PHYSICAL JOURNAL SPECIAL TOPICS**

Regular Article

FCC-hh: The Hadron Collider

Future Circular Collider Conceptual Design Report Volume 3

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Recent developments motivated by

- Continued progress in the exploration of the general physics potential
 - synergy/complementarity between FCC-ee and FCC-hh
 - experimental opportunities beyond general-purpose detectors -> Rojo
- Changes in baseline accelerator configuration (layout and dipole field targets -> Todesco)
- Contributions to the ESPP

FCC-hh physics and performance WG (https://indico.cern.ch/category/18813/) =>
Birgit's talk

Presentations at the 4 general mtgs:

- Energy/luminosity/operation scenarios Frank Zimmermann
- 100TeV -> 80/120 TeV CDR projections: results so far Michelangelo Mangano
- FCC-hh simulation studies: the work ahead Michele Selvaggi
- Update on longitudinal same-sign WW scattering studies Marc-Andre Pleier
- Heavy Neutral Leptons at the FCC-hh: Where do we stand? Stefan Antusch
- DM in mono-X and VBF Giulio Marino
- Heavy vector singlets at future colliders Timothy Martonhelyi
- Higgs without Higgs Francesco Riva
- Exploring the Flavour Symmetry Landscape Riccardo Rattazzi
- ALPs and massive gravitons in yy David d'Enterria
- FASER-like experiments for FCC-hh Juan Rojo
- 4D tracking algorithms to improve pile-up robustness Valentina Cairo
- Update on HH->bbyy studies Angela Taliercio
- Status/plans for updated HH->bbττ studies Monica D'Onofrio
- Single Higgs studies, DESY team Daina Leyva Pernia
- Search for ttHZ Shankha Banerjee
- Towards updated Higgs coupling projections at the FCC-hh Juan Rojo
- High-level comparisons of energy and luminosity scenarios Elliot Lipeles
- UHE atmospheric neutrinos and FCC-hh, Maria Vittoria Garzelli

• Improving the sensitivity of the Higgs self-coupling by exploiting the kinematical properties - Bastien Voirin



Assumptions & possible parameter range

		2	
With present layout of the FCC, and after	Dipole field [T]	c.m. energy	Comment
diligent optimization (by Massimo, Gustavo, and Thys), the following energies can be	12	72	not far above peak field of HL- LHC Nb ₃ Sn quadrupoles
reached according to the dipole field:	14	84	Nb ₃ Sn or HTS
	17	102	HTS
	20	120	HTS

Increasing the c.m. energy beyond ~100 TeV, we will assume that the synchrotron-radiation power could not increase, beyond a total of about 4 MW (which must be removed from inside the cold magnets) **

On the other hand, when decreasing the beam energy, one can hold either the synchrotron-radiation power (increasing current up to HL-LHC values) or the beam current constant. Also, the pile-up might need to be limited, e.g. to ~1000 events/crossing. We thus consider three scenarios for 12 T (0.5 A and 1.12 A beam current, the latter without or with pile-up levelling).

Finally, further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.

** 30 W/m/beam => 5 MW total, released inside magnets operating at 1.9K !! Absorption by beam screen at 50K to room T => 100MW cryo plant ...



Assumptions & possible parameter range **Dipole field [T]** Comment c.m. energy 12 72 not far above peak field of HL-LHC Nb₃Sn quadrupoles new baseline reached according to the dipole field: Nb₃Sn pr HTS 14 84 (see Todesco) 17 102 HTS 20 120 HTS Increasing the c.m. energy beyond ~100 TeV, we will assume that the synchrotron-radiation power could **not increase, beyond a total of about 4 MW** (which must be removed from inside the cold magnets) +On the other hand, when decreasing the beam energy, one can hold either the synchrotron-radiation power (increasing current up to HL-LHC values) or the beam current constant. Also, the pile-up might need to be limited, e.g. to ~1000 events/crossing. We thus consider three scenarios for 12 T (0.5 A and 1.12 A Finally, further overall lowering the synchrotron radiation power, by reducing the number of bunches, in 29,6 order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated ** 30 W/m/beam => 5 MW total, released inside magnets operating at 1.9K !! 2,9

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beam current, the latter without or with pile-up levelling).

luminosity by the same factor.

Absorption by beam screen at 50K to room T => 100MW cryo plant ...





Six scenarios

- A machine based on 12 T dipoles, with a 16 T FCC-hh machine (F12LL).
- 2) A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
- 3) The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
- 4) A machine based on 14 T dipoles, and 0.5 A current (F14).
- 5) A machine based on High Temperature Superconductor (HTS) dipole magnets with a field of 17 T, just exceeding 100 TeV c.m., still with 0.5 A (F17).
- 6) A machine also based on High Temperature Superconductor (HTS) dipole magnets with a field of 20 T, and a beam current of 0.2 A, so that the synchrotron-radiation power is limited to about 2 MW / beam (F20).

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- 6) A machine also based on High Temperature S with a field of 20 T, and a beam current of 0.2 power is limited to about 2 MW / beam (F20).

Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
nb ⁻¹ s ⁻¹	175	845	286	172	209	39	(50, lev'd) 10
	580	2820	955	590	732	141	(135) 27
h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10
Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
fb⁻¹	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
fb⁻¹	950	2000	1300	920	920	370	240 (55)
	Unit nb ⁻¹ s ⁻¹ h Unit fb ⁻¹	UnitF12LLnb-1s-1175580580h3.8UnitF12LLfb-17.9fb-1950	UnitF12LLF12HLnb-1s-11758451755802820h3.83.3UnitF12LLF12HLfb-17.917.1fb-19502000	UnitF12LLF12HLF12PUnb ⁻¹ s ⁻¹ 1758452865802820955h3.83.36.3UnitF12LLF12HLF12PUfb ⁻¹ 7.917.110.8fb ⁻¹ 95020001300	UnitF12LLF12HLF12PUF14nb-1s-11758452861725802820955590h3.83.36.33.8The second seco	UnitF12LLF12HLF12PUF14F17nb-1s-11758452861722095802820955590732h3.83.36.33.83.4UnitF12LLF12HLF12PUF14F17fb-17.917.110.87.77.7fb-195020001300920920	UnitF12LLF12HLF12PUF14F17F20nb-1s-1175845286172209395802820955590732141h3.83.36.33.83.44.2UnitF12LLF12HLF12PUF14F17F20fb-17.917.110.87.77.73,1fb-195020001300920920370

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initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10
Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal ∫ <i>L</i> d <i>t</i> /day	fb⁻¹	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
∫ <i>L</i> d <i>t</i> / year	fb⁻¹	950	2000	1300	920	920	370	240 (55)

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Early assessment of new energy scenarios for benchmark projections: Higgs (assuming equal luminosity)

Minor impact on key observables, notably precision measurements of rare couplings and self-coupling — within range of systematics



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Early assessment of new energy scenarios for benchmark projections: Higgs (assuming equal luminosity)

Minor impact on key observables, notably precision measurements of rare couplings and self-coupling — within range of systematics

Higgs couplings beyond precision reach of H factory

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
δg _{Hγγ} / g _{Hγγ} (%)	0.4	0.4	0.4
δg _{Hµµ} / g _{Hµµ} (%)	0.65	0.7	0.6
δg _{HZγ} / g _{HZγ} (%)	0.9	1.0	0.8

Higgs self-coupling

 $\delta \kappa_{HHH}(\%)$

Det performance/systematics sc

https://arxiv.org/abs/2004.03505

- I. Target det performance: LHC Run 2 cor
- II. Intermediate performance
- III.Conservative: extrapolated HL-LHC per with today's algo's (eg no timing, etc)

100 TeV	S	s	s III	80 TeV	s I	s	s	I 20 TeV	s	s	
stat	3.0	4.1	5.6	stat	3.5	4.7	6.4	stat	2.6	3.6	
syst	1.6	3.0	5.4	syst	I.6	3.0	5.4	syst	1.6	3.0	
tot	3.4	5.1	7.8	tot	3.8	5.6	8.4	tot	3.1	4.7	

enarios	$rac{\sigma_{HH}(80 { m TeV})}{\sigma_{HH}(100 { m TeV})} \sim 0.72 => { m reduce} \delta_{ m stat} { m by} { m l}$
IUILIONS	$\sigma_{HH}(120 \text{TeV})$
rformance,	$\frac{111}{\sigma_{HH}(100 \text{TeV})} \sim 1.3 => \text{ increase } \delta_{\text{stat}} \text{ by}$









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stat	3.0	4. I	5.6	stat	3.5	4.7	6.4	stat	2.6	3.6	
syst	1.6	3.0	5.4	syst	1.6	3.0	5.4	syst	1.6	3.0	
tot	3.4	5.1	7.8	tot	3.8	5.6	8.4	tot	3. I	4.7	

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Final assessment, including updated analyses: ongoing work by Performance WG, Birgit's talk









Disappearing charged track analyses (at ~full pileup)

$$M_{wimp} \lesssim 2 \text{ TeV} \left(\frac{g}{0.3}\right)^2$$

Excluded region for thermal WIMP DM

80 TeV study, vs 100 TeV:

- signal rates @ 80 TeV
- kinematic selection reoptimised
- bgd rates unchanged
 - discovery reach

<u>conservative</u>

 5σ higgsino reach drops from 1150 GeV to 1000 GeV



Saito, Sawada, Terashi, Asai, https://arxiv.org/abs/1901.02987 w. 80 TeV study by Saito

100 TeV

80 TeV





Significant impact of potential luminosity loss at the highest energy

Comparing 102 TeV (F17) to 120 TeV to (F20)

"Collider-Reach" tool from Salam and Weiler: http://collider-reach.web.cern.ch/





Luminosity Matters

102 TeV with 920 fb⁻¹/year beats 120 TeV with 370 fb-1/year for everything except really high masses objects

This is the best comparison for searches, for precision measurements parton luminosity would be better

My conclusion is that unless the synchrotron radiation (SR) cooling issue can be improved 120 TeV is not that interesting.

Elliot @ https://indico.cern.ch/event/1461211/



Significant impact of potential luminosity loss at the highest energy

change of discovery reach w.r.t. canonical 100 TeV CDR scenario, in different mass regions:

Scenario name	Energy	Lumi/year	Cross- over	DM/ Compress EWK 3.0 →	Change in stop mass limit [TeV] 12.5 →	Change in Z' limit [TeV] 40→
FI2LL	72 TeV	950 fb-≀	~always worse	~2.6	~9.6	~30
FI2HL	72 TeV	2000 fb-1	~3 TeV	~3.2	~10.4	~32
FI2PU	72 TeV	I 300 fb-1	~125 GeV	~2.8	~10.0	~31
FI4	84 TeV	950 fb-1	~always worse	~2.8	~10.8	~34
F20	120 TeV	370 fb-I	~25 TeV	~2.5	~12.6	~42

Collider-reach extrapolations, Elliot @ https://indico.cern.ch/event/1461211/

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Preliminary conclusions of the studies of new baseline and variations

Preliminary conclusions of the studies of new baseline and variations

- 100 -> O(80) TeV
 - the reduced rates for physics in the O(TeV) mass region (eg Higgs, EW, EWinos) can be compensated by higher luminosity or improved detector performance
 - energy reduction well below 80 TeV might compromise ability to fully cover DM WIMP scenarios with EW doublets (higgsino-like), and reduce precision for H selfcoupling
 - mass reach at the highest masses ($\sqrt{\hat{s}} \sim 0.5 \sqrt{S}$) is reduced by 15-20%, depending on luminosity

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 - mass reach at the highest masses ($\sqrt{\hat{s}} \sim 0.5 \sqrt{S}$) is reduced by 15-20%, depending on luminosity
- 100 -> 120 TeV
 - if drop in luminosity wrt baseline remains significant, O(2-3):
 - potential loss for precision measurement in the TeV region (to be evaluated however in the context of reduced pileup, which might improve systematics limitations)
 - marginal gain in mass reach only at the highest possible masses



Next steps: short-term (< 31 March 2025)

- Document latest studies for the ESPP submission
 - impact of various energy scenarios

• updated Higgs studies (Birgit talk), including updated impact on global EW/H fits (Tentori, de Blas talks) • mature studies resulting from the work shown in the recent WG mtgs (mail form conveners will follow)

Next steps: short-term (< 31 March 2025)

- Document latest studies for the ESPP submission
 - impact of various energy scenarios

Next steps: medium-term (< 23 June 2025)

Complete ongoing studies for contributions to the ESPP Symposium in Venice

• updated Higgs studies (Birgit talk), including updated impact on global EW/H fits (Tentori, de Blas talks) • mature studies resulting from the work shown in the recent WG mtgs (mail form conveners will follow)

1. Expand scope of ee-hh synergy

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- 2. Review and keep uptodate detector performance potential, in view of
 - accelerator operating scenarios (eg higher pileup scenarios at lower energies),
 - technology evolution,
 - analysis progress (match to progress of LHC experiments),
 - etc.etc.

- 1. Expand scope of ee-hh synergy
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 - accelerator operating scenarios (eg higher pileup scenarios at lower energies),
 - technology evolution,
 - analysis progress (match to progress of LHC experiments),
 - etc.etc.
- 3. Expand landscape of complementary experiments/detectors (Forward, HI, Flavour)

Expanding the scope of ee-hh synergy studies

Key question to address:

given a discovery at FCC-ee (whether direct, eg ALPs, HNL, BSM H decays, ..., or indirect, eg deviations in EWPO or in Higgs properties), how will FCC-hh contribute to the interpretation of this discovery?

- How will it uncover the microscopic origin of SM deviations see at FCC-ee?

• What information will it add to the study of the properties of new particles observed at FCC-ee?

- Higgs
 - detailed studies for the complete spectrum of SM Higgs decays (eg only basic studies available for $H \rightarrow WW^*$, $\tau\tau$, cc) and production modes (VH, VBF, large pt, ...)
 - reach for rare/forbidden/exotic Higgs decays possibly accessible to FCC-ee, and beyond (Gallen's talk)

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FCC-hh will have a Higgs sample larger than the full FCC-ee statistics produced at p_T larger than 1 TeV: are there opportunities to probe exotic Higgs decays?



• EWPO: heavy vector resonances (see Torre's talk)



Plots like this should not be read in terms of "which facility promises the best constraint", but in terms of "should FCC-ee find a 3σ deviation in S/T/U, which handles will the FCC-hh have to fully decode the source of this deviation"

Single-particle SM extensions, the Granada dictionary (Allwicher, Vuong talks)

Linear extensions of the Standard Model

- De Blas et al. 1711.10391
- > Finite number of new states can couple linearly to the SM fields: Granada dictionary
- > Matching to SMEFT at d = 6 well known

Scalar	S	\mathcal{S}_1	\mathcal{S}_2	arphi	Ξ	Ξ_1	Θ_1	Θ_3
	$(1,1)_0$	$\left(1,1 ight) _{1}$	$(1,1)_2$	$(1,2)_{rac{1}{2}}$	$(1,3)_0$	$\left(1,3 ight) _{1}$	$(1,4)_{rac{1}{2}}$	$(1,4)_{rac{3}{2}}$
	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{rac{2}{3}}$	$(3,1)_{-rac{4}{3}}$	$(3,2)_{rac{1}{6}}$	$(3,2)_{rac{7}{6}}$	$(3,3)_{-rac{1}{3}}$		
	Ω_1	Ω_2	Ω_4	Υ	Φ			
	$(6,1)_{rac{1}{3}}$	$(6,1)_{-rac{2}{3}}$	$(6,1)_{rac{4}{3}}$	$(6,3)_{rac{1}{3}}$	$(8,2)_{rac{1}{2}}$			
Fermion	N	E	Δ_1	Δ_3	Σ	Σ_1		
	$(1,1)_{0}$	$(1,1)_{-1}$	$(1,2)_{-rac{1}{2}}$	$(1,2)_{-rac{3}{2}}$	$(1,3)_0$	$\left(1,3 ight) _{-1}$		
	U	D	Q_1	Q_5	Q_7	T_1	T_2	
	$(3,1)_{rac{2}{3}}$	$(3,1)_{-rac{1}{3}}$	$(3,2)_{rac{1}{6}}$	$(3,2)_{-rac{5}{6}}$	$(3,2)_{rac{7}{6}}$	$(3,3)_{-rac{1}{3}}$	$(3,3)_{rac{2}{3}}$	
Vector	B	\mathcal{B}_1	\mathcal{W}	\mathcal{W}_1	${\cal G}$	\mathcal{G}_1	${\cal H}$	\mathcal{L}_1
	$(1,1)_0$	$\left(1,1 ight) _{1}$	$\left(1,3 ight) _{0}$	$\left(1,3 ight) _{1}$	$(8,1)_{0}$	$\left(8,1 ight)_{1}$	$(8,3)_0$	$(1,2)_{rac{1}{2}}$
	\mathcal{L}_3	\mathcal{U}_2	\mathcal{U}_5	\mathcal{Q}_1	\mathcal{Q}_5	\mathcal{X}	\mathcal{Y}_1	\mathcal{Y}_5
	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{rac{2}{3}}$	$(3,1)_{rac{5}{3}}$	$(3,2)_{rac{1}{6}}$	$(3,2)_{-rac{5}{6}}$	$(3,3)_{rac{2}{3}}$	$(ar{6},2)_{rac{1}{6}}$	$(ar{6},2)_{-rac{5}{6}}$

All (except very few) new states are probed by EWPOs at one-loop

What are the actual prospects to detect these particles at FCC-hh, in the relevant mass ranges?





• ALPs and HNLs (Polesello, Kontaxakis talks)



- Include FCC-hh reach
- **Explore implications at FCC-hh of concrete models for ALPs and HNLs,** considering potential signals of other manifestations of such models

