

Aspects of the Physics Potential of FCC-hh

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On behalf of the FCC Collaboration

Lepton-Photon 2025

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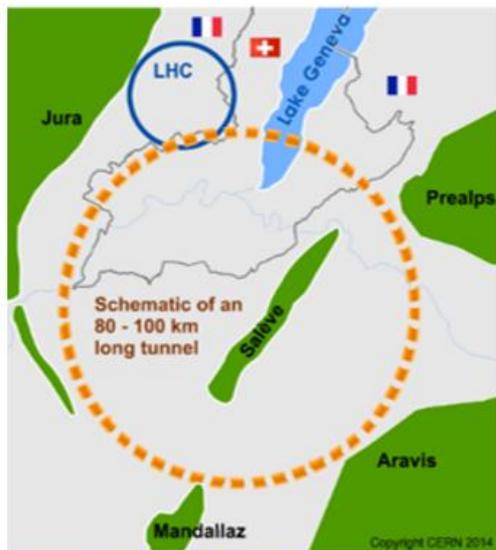
The FCC feasibility study is now complete. Technical feasibility OK !
The FCC program goes well beyond the successful LEP – LHC (1976-2041) program

Comprehensive cost-effective program maximizing physics opportunities and Complementary physics

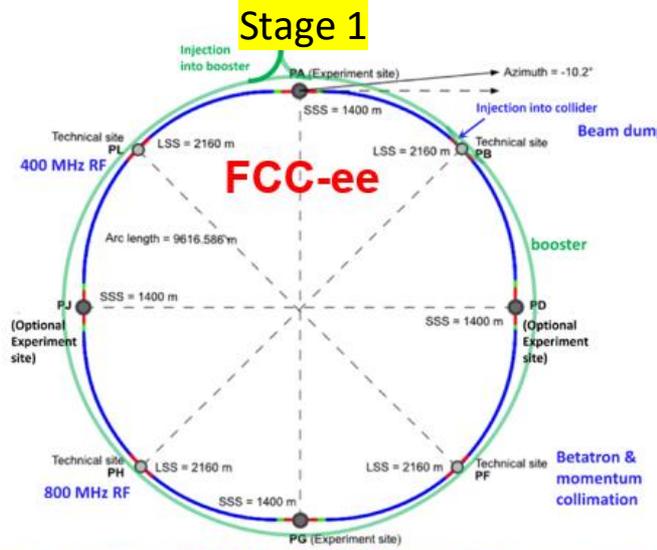
- Stage 1: FCC-ee (Z, WW, H, tt, m_H?) as best Higgs, EW, Heavy Flavour and top factory at the highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with heavy ions and eh options

- The FCC-INT project is fully integrated with the HL-LHC exploitation
- It provides a natural transition for higher precision, energy & scope

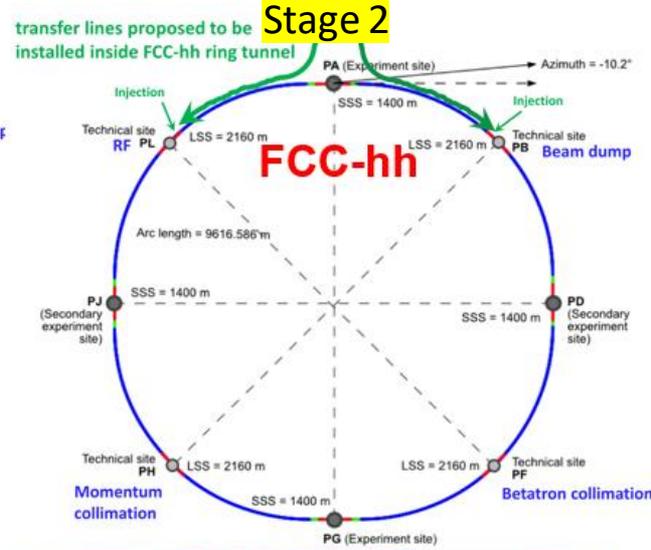
- Common civil engineering and technical infrastructures
- Building on and reusing CERN’s existing infrastructure.



2020 - 2040

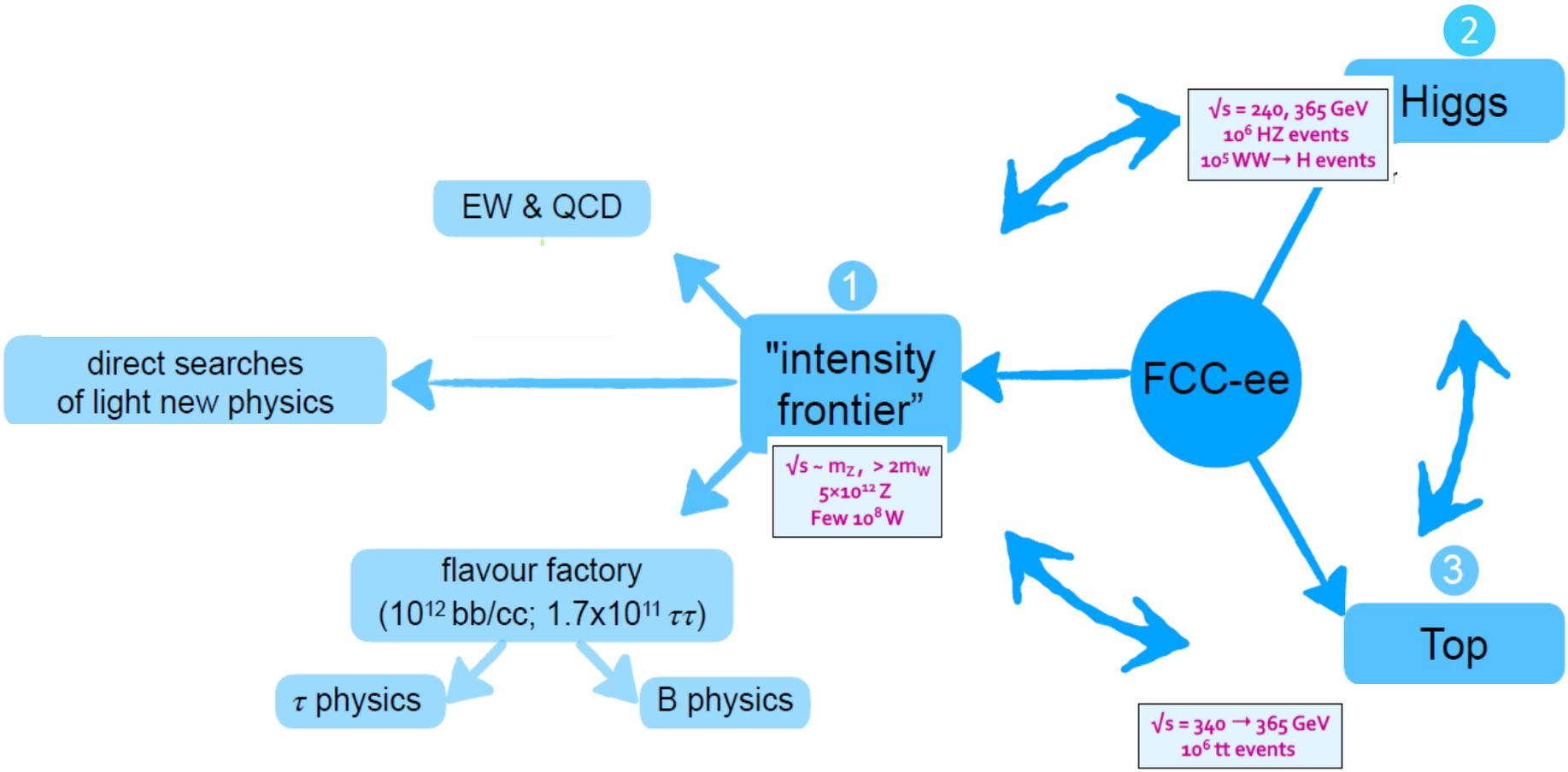


2045 - 2065



2074 - 2095

at Circular Colliders → Rich e^+e^- Physics Program ...



The potential of an hh machine at the energy frontier in the same circular tunnel is also excellent:

- Measurement of Higgs Self-coupling at the $\sim 3-4\%$ level
- Highest reach in sensitivity for di-higgs studies, dark matter searches and more
- New heavy particles could be directly discovered for masses up to 20-40 TeV
- Large potential also from indirect searches

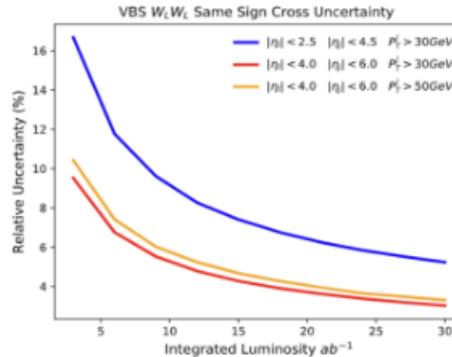
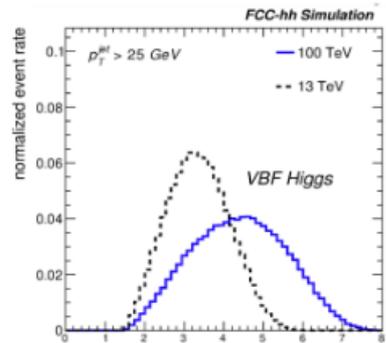
But we are not yet ready to build the hh machine, more R&D on the magnets is needed.

We may however build an ~ 80 TeV machine by 2055 if we go directly for such machine.

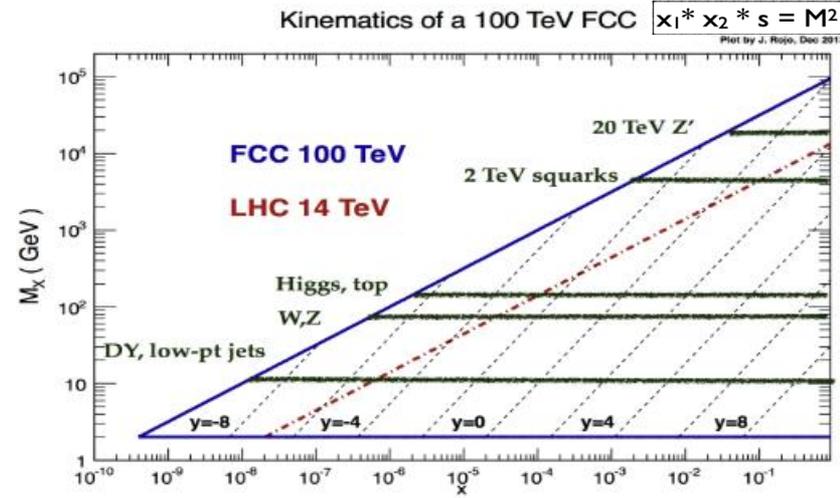
SM Physics is more forward @ 100TeV

- If we want to maintain high efficiency in states produced at threshold need large rapidity (with tracking) and low p_T coverage

→ highly challenging levels of radiation at large rapidities



Tracking and calorimetry needed up to $|\eta| < 6$ for \sim VBF signatures



→ measure leptons, jets, photons, muons originating \sim 40-50 TeV resonances

Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \oplus B$

- Tracking target : $\sigma / p = 20\%$ @ 10 TeV
- Muons target: $\sigma / p = 10\%$ @ 20 TeV
- Calorimeters target: containment of $p_T = 20$ TeV jets

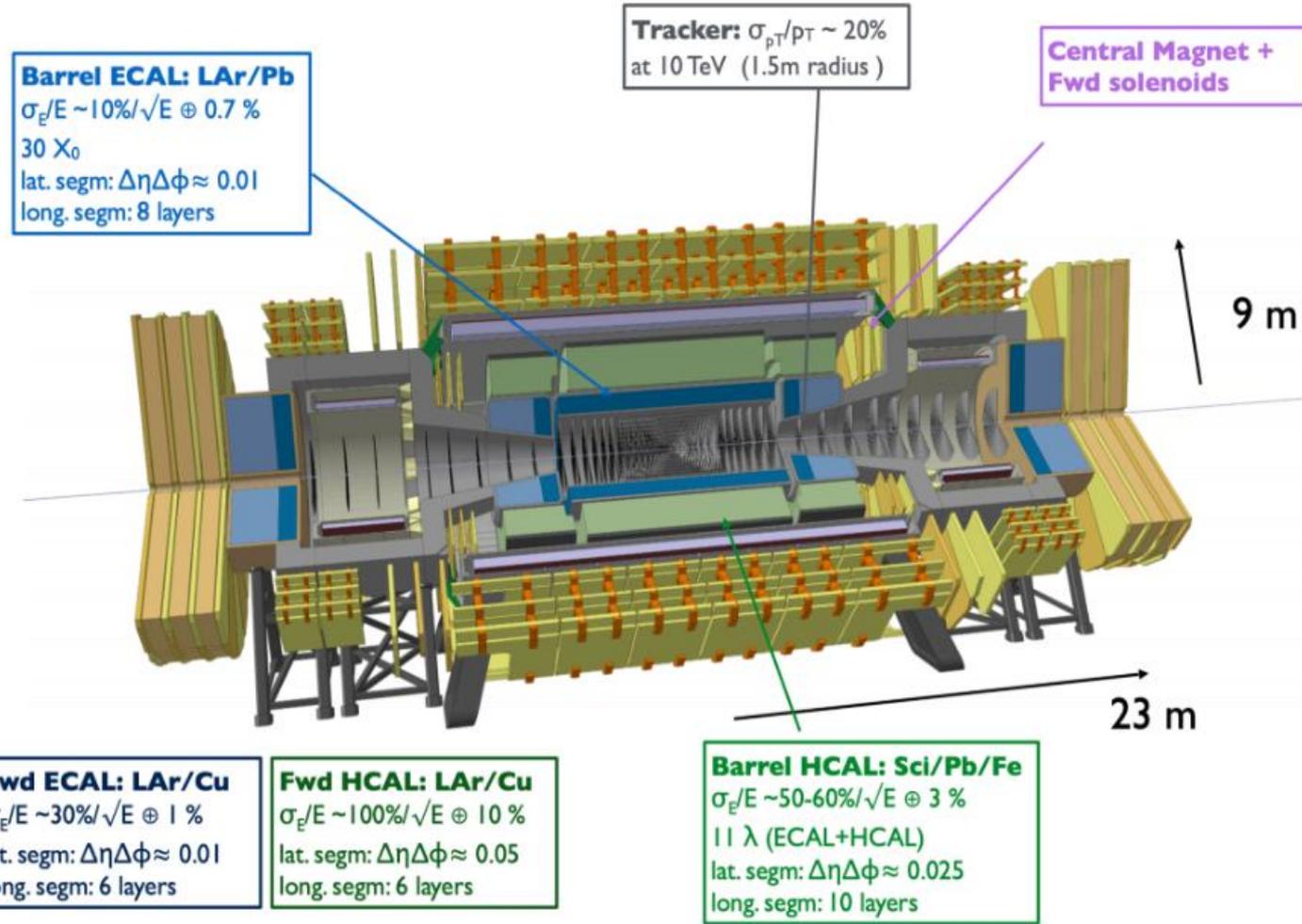
Machine and Detector requirements / radiation levels

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\text{cm}^{-2}\text{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta _{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$\langle p_T \rangle$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta _{\eta=5}$	GeV	316	316	427	765
$dP/d\eta _{\eta=5}$	kW	0.04	0.2	1.0	4.0

→ x50 HL-LHC

$10^{18} \text{ cm}^{-2} \text{ MeV-neq}$
@ 2.5 cm !!

Detector concept



Challenges

- Large dynamic range
- High occupancy (1000 PU)
 - Timing (3 ps resolution)
- High data rates
 - 10x data vs HL-LHC
- High radiation
 - 3×10^{18} 1MeV neq/cm²

Higgs complementarity with lepton machines

At pp colliders we can only measure:

$$\sigma_{\text{prod}} \text{BR}(i) = \sigma_{\text{prod}} \Gamma_i / \Gamma_H$$

→ we do not know the total width.

In order to perform global fits, we have to make **model-dependent assumptions**

Instead, by performing measurements of ratios of BRs at hadron colliders:

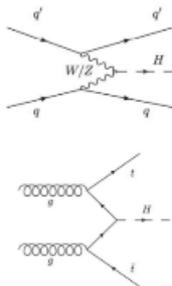
$$\text{BR}(H \rightarrow XX) / \text{BR}(H \rightarrow ZZ) \approx g_X^2 / g_Z^2$$

← from e⁺e⁻

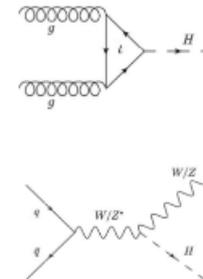
We can “convert” relative measurements into absolute via g_Z thanks to e⁺e⁻ measurement

→ synergy between lepton and hadron colliders

Higgs production in hadron machines



	$\sigma(13 \text{ TeV})$	$\sigma(100 \text{ TeV})$	$\sigma(100)/\sigma(13)$
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55
HH (NNLO)	40 fb	1.2 pb	30



Expected improvement at FCC-hh:

- **20 billion Higgses** produced at FCC-hh
- **factor 10-50** in cross sections (and $L \times 10$)
- reduction of a factor **10-20** in statistical uncertainties

Large statistics will allow:

- **sub %- level precision** in statistically limited rare channels ($\mu\mu, Z\gamma$)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
 - higher S/B
 - smaller (relative) impact of systematic uncertainties

> 10M Higgs boson with $p_T(H) > 500 \text{ GeV}$

Improvements on Higgs couplings with FCC-hh

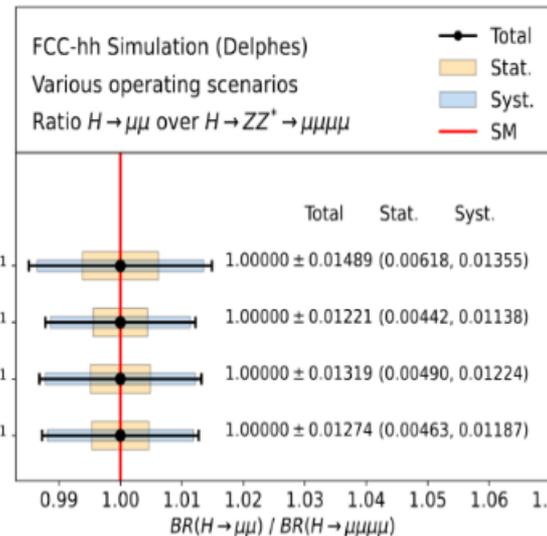
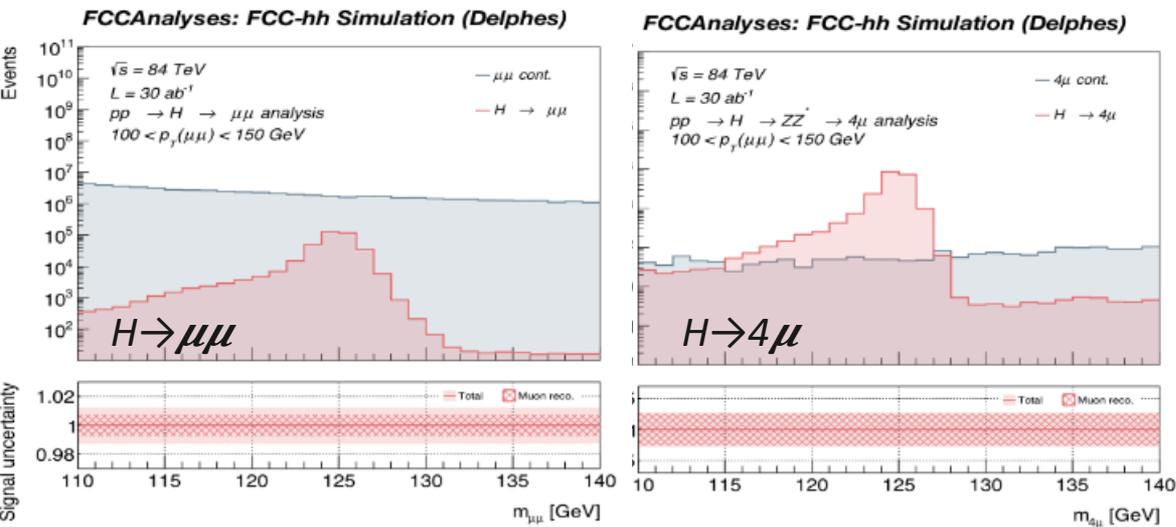
- **Higgs self-coupling**
- **top Yukawa**
- **Higgs \rightarrow invisible**
- **rare decays** ($BR(\mu\mu)$, $BR(Z\gamma)$, ratios, ..) measurements will be statistically limited at FCC-ee

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_s $ (%)	–	+29 –67	+29 –67
Γ_H (%)	–	0.78	0.69
\mathcal{B}_{inv} (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
\mathcal{B}_{unt} (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

Single Higgs couplings: Ratio $H(\mu\mu)/H(4\mu)$

CDS note

[10.17181/sxreb-8h751](https://cds.cern.ch/record/10.17181/sxreb-8h751)



Benefit from large statistics at high $p_T(H)$, where experimental efficiency systematics are smaller.

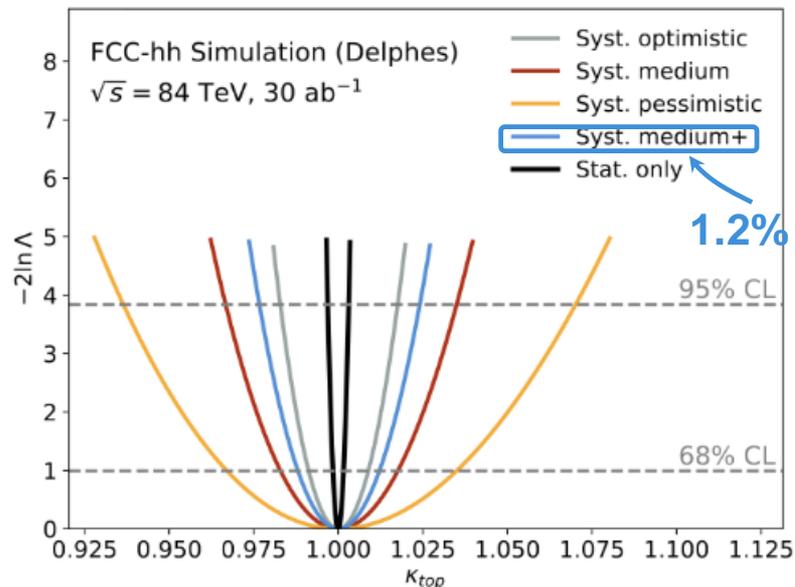
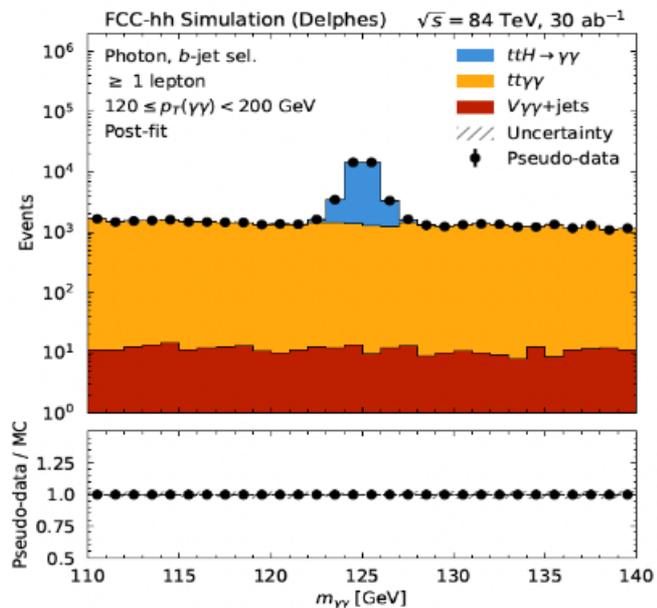
Furthermore focus on ratios of signal strengths to cancel (theory) systematic uncertainties

Updated results from differential fit in $p_T(H)$ bins, for the different operating scenarios

Single Higgs couplings: $t\bar{t}H(\gamma\gamma)$ analysis

CDS note

[10.17181/tr6k7-bm770](https://cds.cern.ch/record/10.17181/tr6k7-bm770)



New channel for precision measurement of top Yukawa coupling κ_{top}

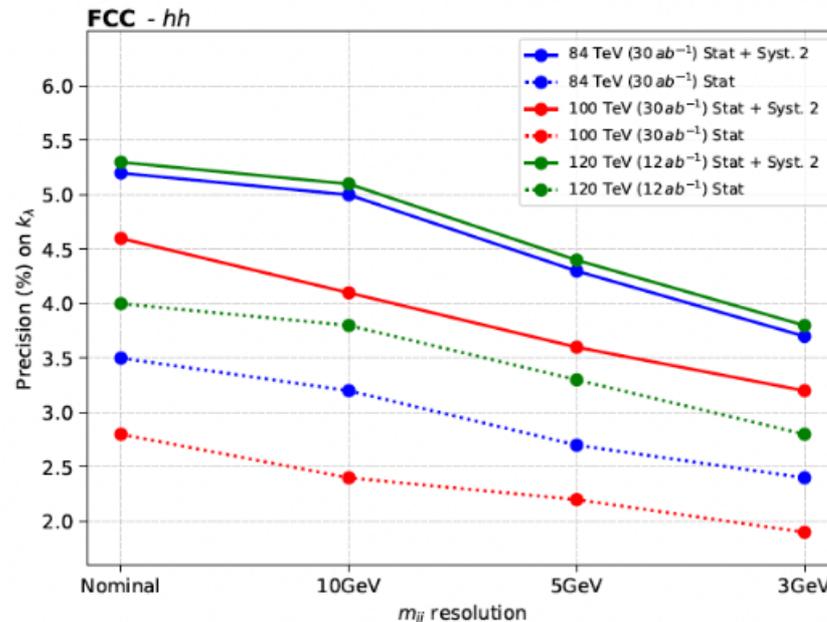
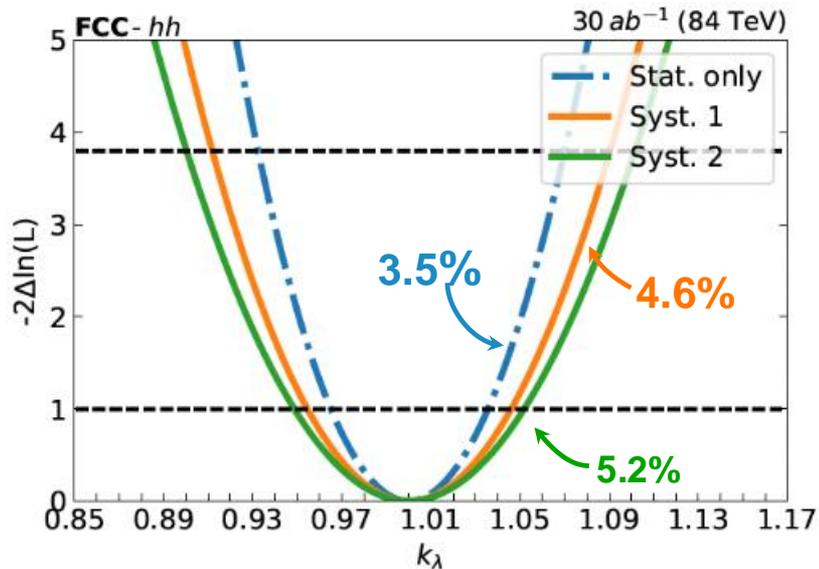
Extract from fits to invariant di-photon mass in $p_T(H)$ bins

Expected precision for 84 TeV and different assumptions on systematics

Higgs self-coupling: $bb\gamma\gamma$ analysis

CDS note

[10.17181/w6928-gr929](https://cds.cern.ch/record/10.17181/w6928-gr929)



Re-optimized strategy: Event selection with Deep Neural Network

Fit invariant di-photon mass in bins of invariant di-jet mass, with different assumptions

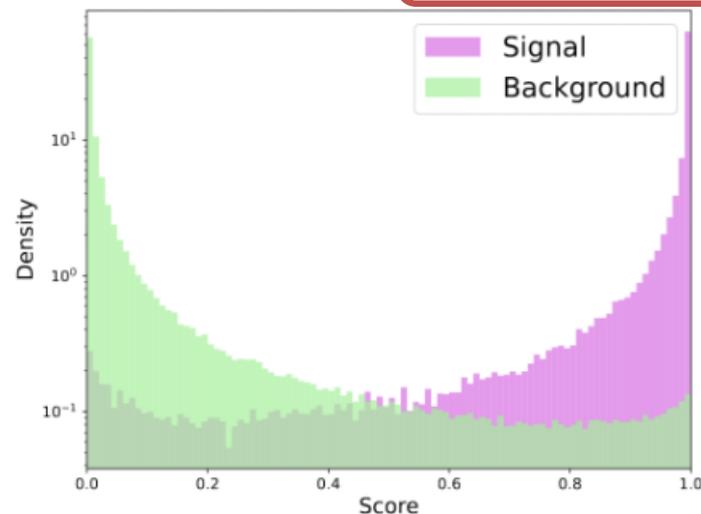
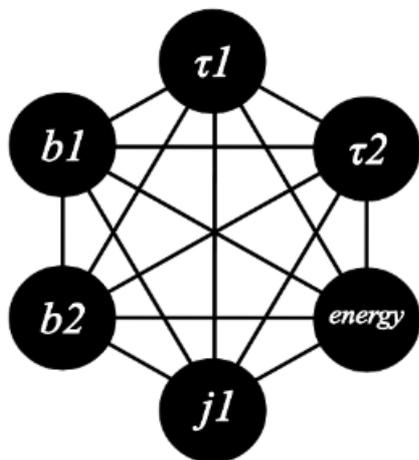
Consider different energies & resolutions of invariant d-jet mass

➔ Impact of di-jet resolution is critical

Higgs self-coupling: $b\bar{b}\tau\tau$ analysis

CDS note

[10.17181/8cdq9-dj340](https://cds.cern.ch/record/10.17181/8cdq9-dj340)



Focus on channels with hadronic τ decay

Re-optimized strategy:

Event selection with Graph Neural Network
(events modelled as fully connected graph)

Working on extraction of κ_λ precision at 84 TeV
from fits to GNN score in bins of invariant di-Higgs mass

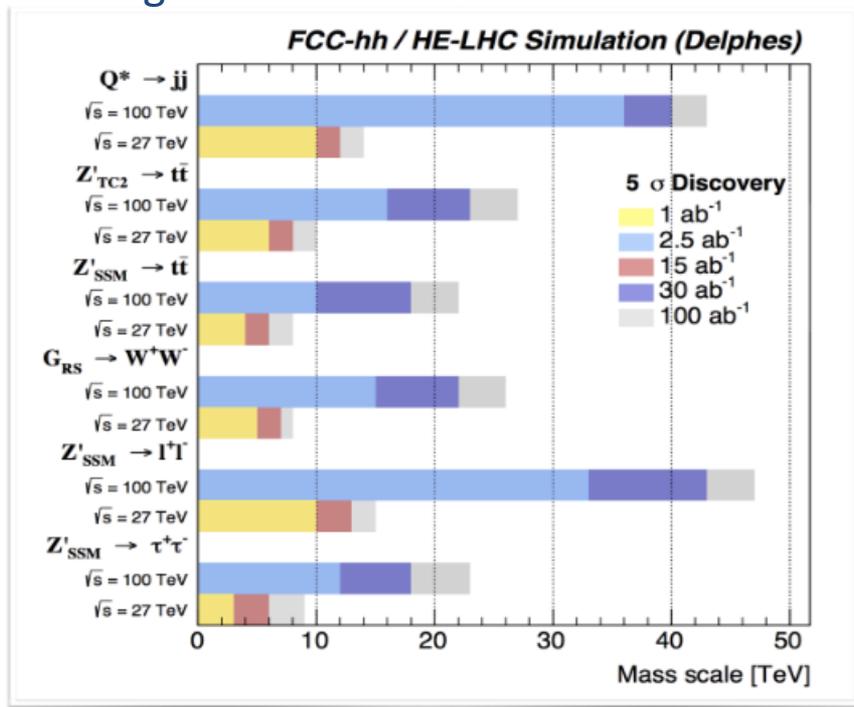
Competitive with $b\bar{b}\gamma\gamma$

→ A combination is planned

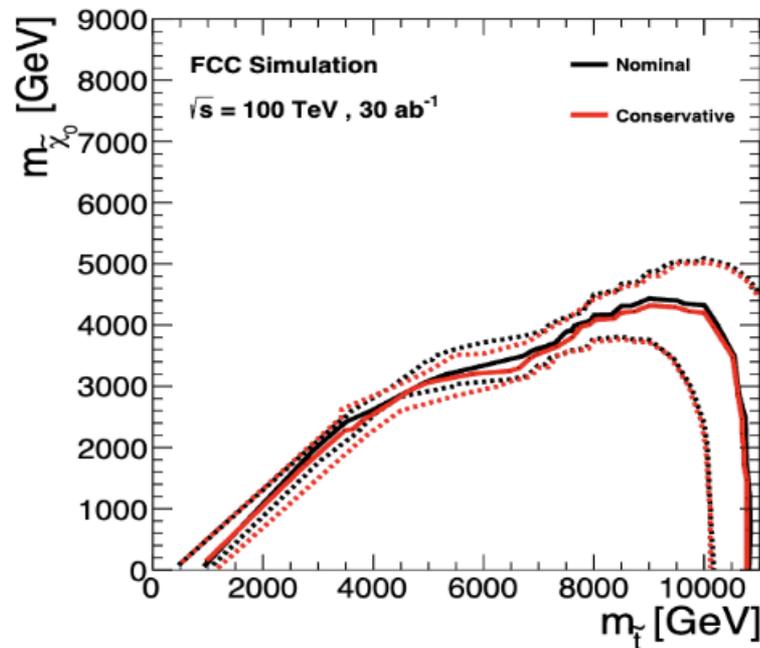
3%(stat) + 3%(syst) on $HH(bb\tau\tau)$ cross-section

BSM Searches at the Energy Frontier

High mass resonances



stop



Challenges: multi-TeV collimated top, W, τ highly collimated.

Tracking is the key and highly segmented calorimetry

Energy/Luminosity Scenarios

name	F12LL	F12HL	F12PU	F14	F17	F20
Dipole Field (T)	12	12	12	14	17	20
\sqrt{s} (TeV)	72	72	72	84	102	120
current (A)	0.5	1.12	1.12	0.5	0.5	0.2
PU (# Pile-Up)	600	3000	1000	600	700	150
SR power (MW) 2 beams	1.3	2.9	2.9	2.4	5.2	4.0
Lumi/yr (ab-1)	1	2	1.3	0.9	0.9	0.35

Limiting factor: 5 MW synchrotron power $\sim \sqrt{s}^4$

Sensitivity with the different scenarios

Higgs SM precision

Higgs couplings

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} (\%)$	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu} (\%)$	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma} (\%)$	0.9	1.0	0.8

Higgs self-coupling precision at 80 TeV $\rightarrow \sim 3\text{-}4\%$
assuming same detector performances

BSM reach

WIMP DM still in reach at 80 TeV

Scenario name	Energy	Lumi/year	DM/ Compress EWK 3.0 \rightarrow	Change in stop mass limit [TeV] 12.5 \rightarrow	Change in Z' limit [TeV] 40 \rightarrow
F12LL	72 TeV	950 fb ⁻¹	~ 2.6	~ 9.6	~ 30
F12HL	72 TeV	2000 fb ⁻¹	~ 3.2	~ 10.4	~ 32
F12PU	72 TeV	1300 fb ⁻¹	~ 2.8	~ 10.0	~ 31
F14	84 TeV	950 fb ⁻¹	~ 2.8	~ 10.8	~ 34
F20	120 TeV	370 fb ⁻¹	~ 2.5	~ 12.6	~ 42

Preliminary conclusions:

For Higgs physics and lower mass new resonances,
a higher luminosity can make up for a lower energy.
For higher masses searches, it is as expected harder

But going for 84 TeV is now the default choice

FCC-hh timelines

Milestone	Date
Conceptual design study	2014-18
Definition of placement scenario	2022
Feasibility Report ready	2025
Main technologies R&D completion	2054
Technical Design Report ready	2054
Latest Project Approval	2054
Environmental evaluation & project authorization processes	2054-2058
Industrialisation & magnet production	2054-2069
Civil engineering – collider	2060-2068
FCC-ee dismantling	2063-2064
TI installation – collider	2065-2069
Accelerator installation – collider	2068-2072
HW commissioning – collider	2071-2073
Beam commissioning – collider	2073
Physics operation start	2074

FCC-hh timeline as a second phase after FCC-ee.

Milestone	Date
Conceptual design study	2014-18
Definition of placement scenario	2022
Feasibility Report ready	2025
Latest Project Approval	2033
Environmental evaluation & project authorization processes	2026-35
Main technologies R&D completion	2037
Technical Design Report ready	2037
Industrialisation & magnet production	2038-2053
Civil engineering – collider	2037-2046
TI installation – collider	2043-2050
Accelerator installation – collider	2046-2052
HW commissioning – collider	2049-2053
Beam commissioning – collider	2054
Physics operation start	2055

Fastest possible FCC-hh timeline as a stand-alone project.

Conclusions

- FCC-hh, supported by the results of an e+e- Higgs Factory has an outstanding physics program even if running at 84 TeV, both on the Higgs and on the searches for new resonances which can reach masses of ~ 34 TeV.
- FCC-hh as FCC's 2nd stage, possibly based on HTS magnets, could start operation in ~ 2074
- If another Higgs Factory (e.g. CEPC) would be built and ready well before 2045, FCC may go directly to FCC-hh based on 14T Nb₃Sn magnets and could start operation in ~ 2055 , with a centre-of-mass energy ~ 85 TeV, as a standalone project.
- The cost of FCC-hh is estimated to 19B CHF (after the ~ 16 B CHF of FCC-ee). If going directly to FCC-hh the cost will be about 27B CHF, but on a timeline 10 years longer
- The ESG will propose by \sim December what will be its plan B, since by now it is widely assumed that FCC-ee will be plan A, but plan B is still wide open.

**Thanks
for your
attention**



Building a viable financial path

Updated project cost for FCC-ee up to and including operation at ZH and 4 experiments
t-tbar upgrade requires additional 1.3 BCHF

Domain	Cost [MCHF]
Civil engineering	6160
Technical infrastructures	2840
Injectors and transfer lines	590
Booster and collider	4140
CERN contribution to four experiments	290
FCC-ee total	14 020
+ Four experiments (non-CERN part)	1300
FCC-ee total, including four experiments	15 320

Funding of FCC (or any other major future collider project) expected to come from two main sources:

- CERN Budget (i.e. revenues from Member and Associate Member States): would cover more than 50% of FCC investment
 - External contributions:
 - additional voluntary contributions (in-cash or in-kind) from Member and Associate Member States
 - contributions from non-Member States
 - exploring possible contributions from the European Union in the next Multiannual Financial Framework (MFF 2028-2034)
 - exploring possible contributions of private donors (→ in Dec 2024, Council approved “Policy for fundraising from private donors for scientific activities at CERN”)
- good progress over the past months

Several funding scenarios developed, based on different assumptions (e.g. constant or slightly increased CERN Budget)
→ ongoing discussions in Council

resource requirements – capital cost and operation

Cost summary table in 2024 MCHF for the construction of FCC-hh.

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	19080

The annual cost of operation has not been determined.

The cost of electricity is of order 150–200 MCHF p.a.

The human resources required for FCC-hh have not been estimated.

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

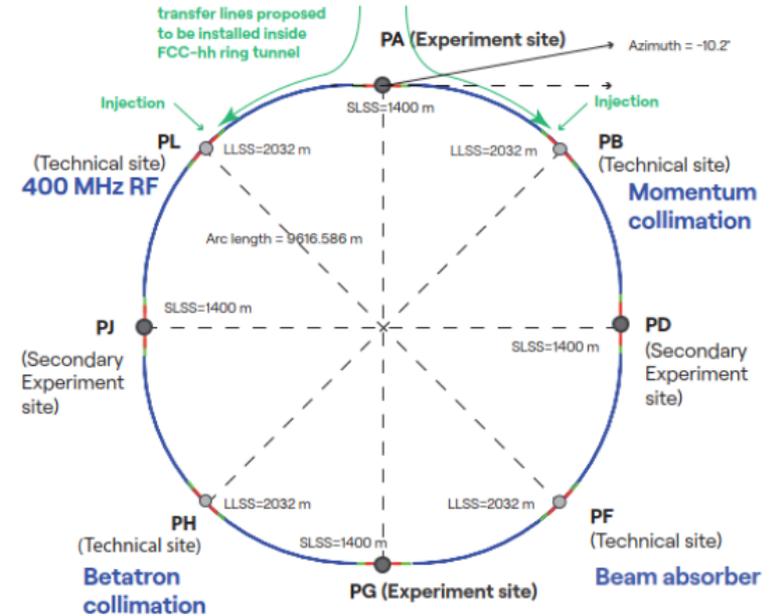
future circular hadron collider FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb_3Sn , ~14T, 1.9 K)

Main parameters FSR 2025

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

FCC-hh functional layout



FCC-hh injector options

- 1) superconducting machine in the SPS tunnel (scSPS)
- 2) modified faster-ramping LHC
- 3) new 4 T machine in the LHC tunnel
- 4) **2 T superferric machine in the LHC tunnel (1.75 TeV**, not shown in the table), resulting **energy swing x14**, similar to LHC (~15)

	unit	scSPS	modif. LHC	4 T LHC
circumference	km	6.8	26.7	26.7
#apertures		1	2	1
injection energy	GeV	26	450	450
extraction energy	TeV	1.3	3.3	3.3
injection field	T	0.12	0.6	0.6
maximum field	T	6	6	6
energy/field swing		50	7	7
#dipoles		372	1232	1232
#bunches		640	2600	2600
stored energy	MJ	15	167	167
collider filling time	min	37	46	39

technical readiness and R&D requirements for FCC-hh

Component /Subsystem	TRL	Main parameter to be improved	Improvement factor	R&D effort (CERN contributions)		
				Personnel [FTEy]	Material [MCHF]	Timescale [years]
Nb ₃ Sn conductor ^a	7	Cost & industrialisation (more manufacturers)	3	10	30	7
Nb ₃ Sn magnet short model	6	max. field ^b	20%	100	20	5
Nb ₃ Sn scaling to 5 m	5	length	3	100	40	10
Nb ₃ Sn scaling to 15 m	4	length	3	100	100	15
HTS magnet short model 20 T	3	field ^c & all accelerator magnet features	5-10	100	50	10
HTS long magnet 20 T	1	length	15	100	150	25

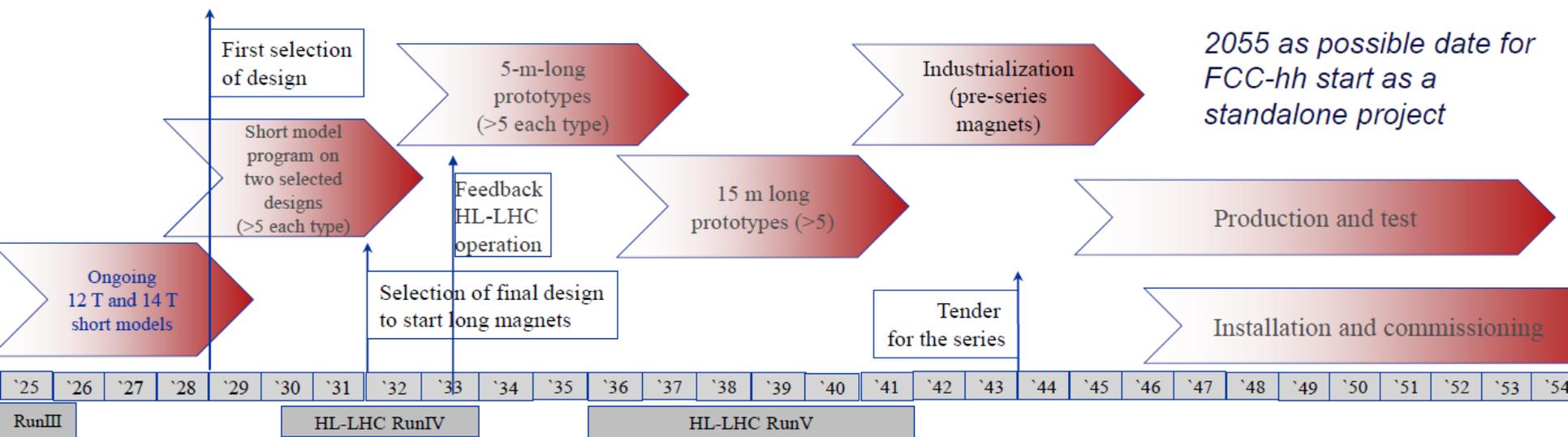
^aThis includes only contracts to lower the price and to have more manufacturers.

^bTarget of 15 T, for operation at 14 T.

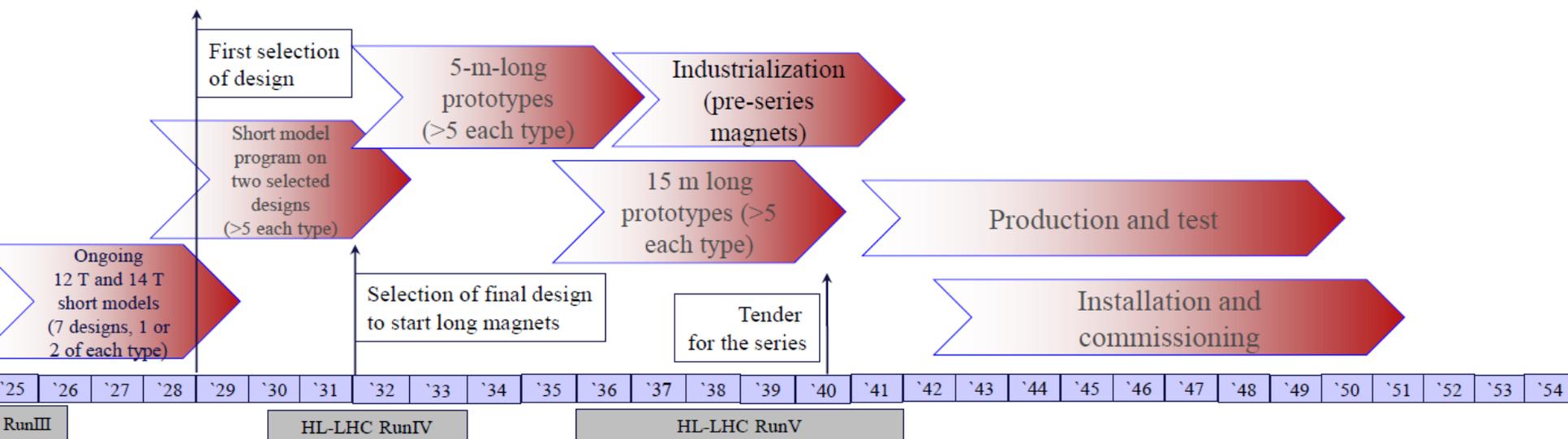
^c2 to 4 T already achieved, but not with all requirements.

14 T Nb₃Sn “accelerated” roadmap: short models & scaling in length

- Select the design by 2028/29 (first indications from HFM tests in 2026-2027)
- Short model program to verify reproducibility and optimize manufacturing processes: in 2029-2031
- Scaling in length in two steps: TRL 7 achieved between 2032 and 2040
- Industrialization for final magnets, with pre-series
- 9 years of production, installation and commissioning in parallel



14 T Nb₃Sn further “accelerated” roadmap w. early industry involvement & parallelisation



this roadmap indicates 2051 as possible date for FCC-hh start as a standalone project

Environmental impact (peak & integrated energy consumption)

FCC-hh power demand by technical systems at 85 TeV beam centre-of-mass energy

system	power [MW]
radiofrequency	17
cryogenics	207
cooling & ventilation	40
magnet powering	33
experiments	24
data centre	8
general services	26
total	355

FCC-hh power demand during different operational periods for operation at collision energy of 85 TeV, with cryo eco-mode

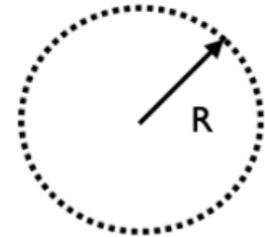
period	days / year	power [MW]
shutdown	120	122
technical stop	10	122
downtime	37 (=185*0.2)	122
commissioning	30	324
machine development	20	324
beam operation	148 (=185x0.8)	355

High energy hadron machines

$$p \text{ [TeV/c]} = 0.3 B \text{ [T]} R \text{ [km]}$$

Pros:

- relatively democratic initial states, strong and electro-weak force
- high center of mass, thanks to \sim small synchrotron power loss $(m_e/m_p)^4$
 - caveat: at 100 TeV it becomes significant!
- high luminosity up to high energy



Cons:

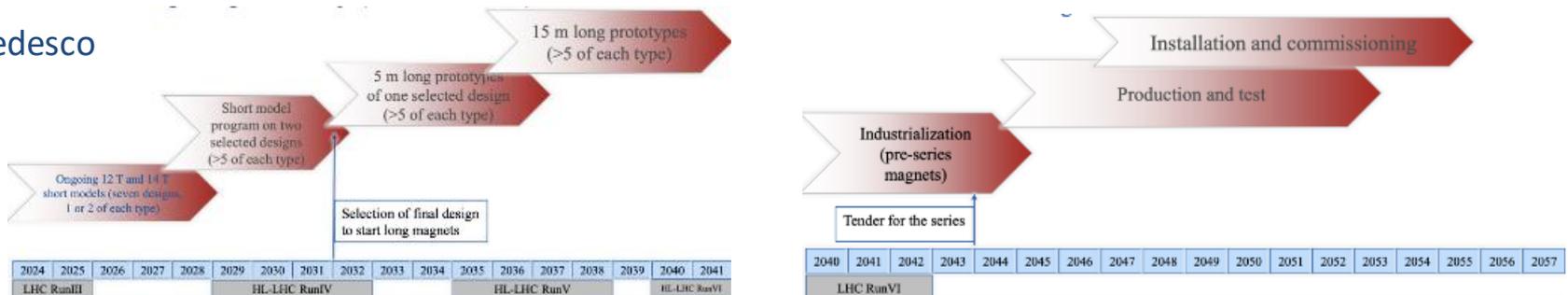
- large backgrounds compared to lepton machines ($\alpha_s > \alpha_{EM,W}$), from
 - high Q2 physics (di-jet, ttbar ...)
 - “simultaneous” p-p collision (pile-up)

- Discovery machines for heavy new states
- Also suited for precision (thanks to high rates)

Magnet challenge

- Baseline FCC-hh design: $B = 14 \text{ T}$ ($\sqrt{s} = 84 \text{ TeV}$)
- New conductor Nb_3Sn supports higher fields due to its larger critical current density and critical field
 - HTS ? far from required specs still ... \rightarrow needed for higher energy (120 TeV)
- Wider coils (50–55 mm vs. 30 mm in LHC dipoles) are needed to maintain a conservative 400 A/mm² overall current density.
- This design demands 2–2.5 times more conductor material than in LHC dipoles.
 - 4.7k magnets (cost will be addressed in the ESPPU $\sim 10 \text{ BCHF}$)
- Still intense R&D required to reach 15-16 T (including safety margin)

Ezio tedesco



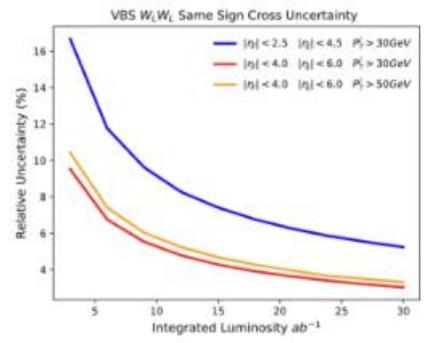
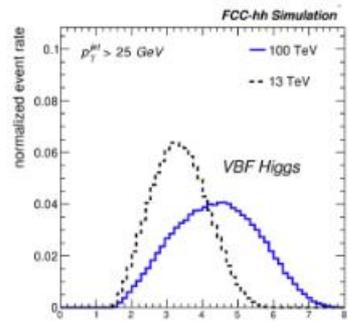
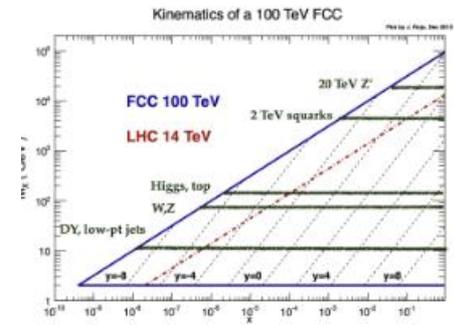
Physics at threshold

SM Physics is more forward @100TeV

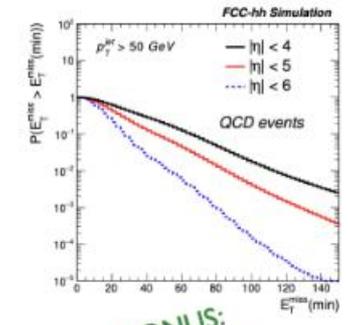
- If we want to maintain high efficiency in states produced at threshold need large rapidity (with tracking) and low p_T coverage

→ highly challenging levels of radiation at large rapidities

$$x_1 * x_2 * s = M^2$$



Tracking and calorimetry needed up to $|\eta| < 6$ for \sim VBF signatures



BONUS:
Hermeticity
 $E_{T,miss}$ resolution

Boosted topologies at multi-TeV energies

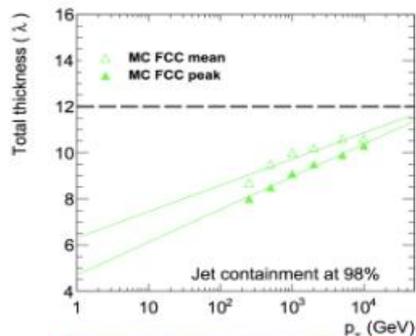
The boosted regime:

→ measure leptons, jets, photons, muons originating ~ 40-50 TeV resonances

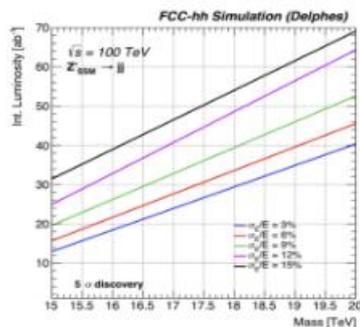
Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \oplus B$

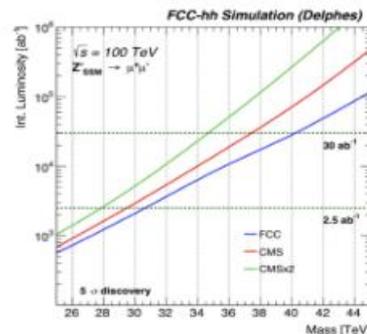
- Tracking target : $\sigma / p = 20\% @ 10 \text{ TeV}$
- Muons target: $\sigma / p = 10\% @ 20 \text{ TeV}$
- Calorimeters target: containment of $p_T = 20 \text{ TeV}$ jets



$\geq 11 \lambda_l$ for EM + Had



high p_T jets



high p_T muons

High p_T flavor tagging

- The boosted regime:
 - measure b-jets, taus from multi-TeV resonances

- Long-lived particles live longer:

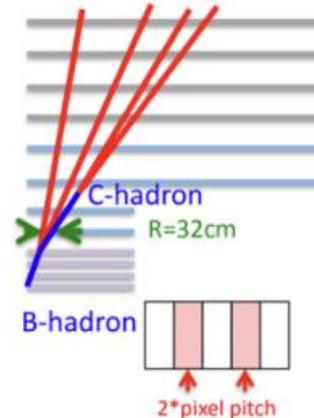
ex: 5 TeV b-Hadron travels 50 cm before decaying
 5 TeV tau lepton travels 10 cm before decaying

- extend pixel detector further?

- useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)
- number of channels over large area can get too high

- re-think reconstruction algorithms:

- hard to reconstruct displaced vertices
- exploit hit multiplicity discontinuity

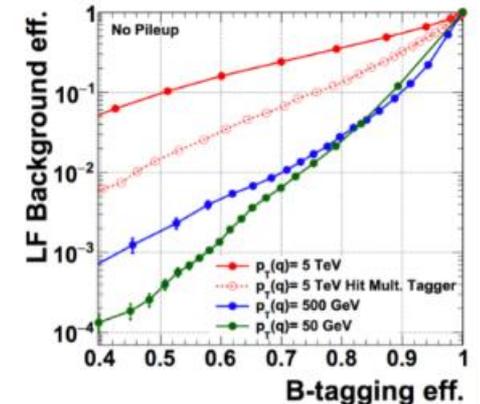


Only 71% 5 TeV b-hadrons decay $<$ 5th layer.

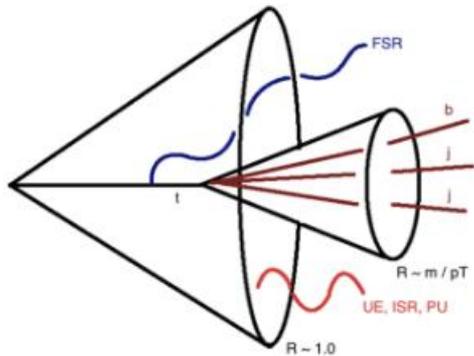
- displaced vertices

Perez Codina, Roloff [CERN-ACC-2018-0023]

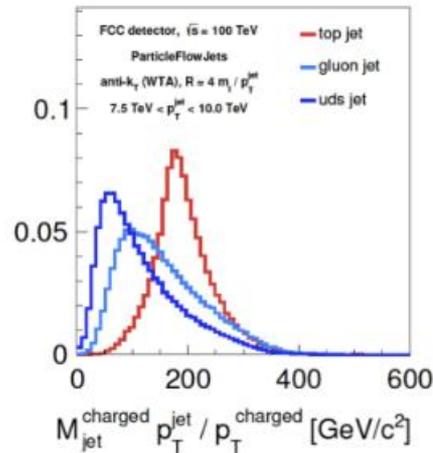
Traditional tagger vs hit multiplicity tagger



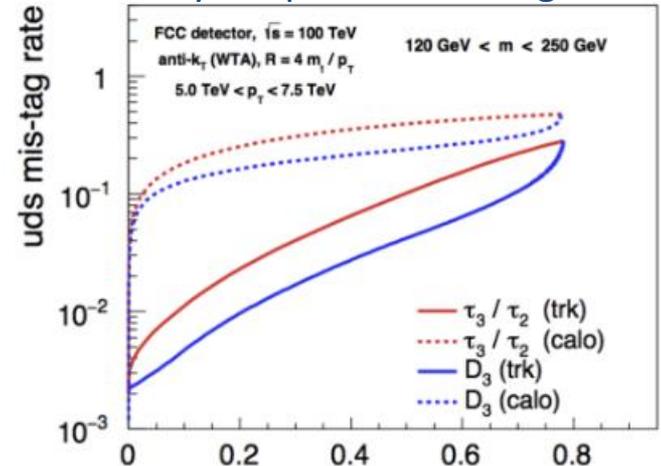
Boosted Colored Resonances



Track-based jet Mass

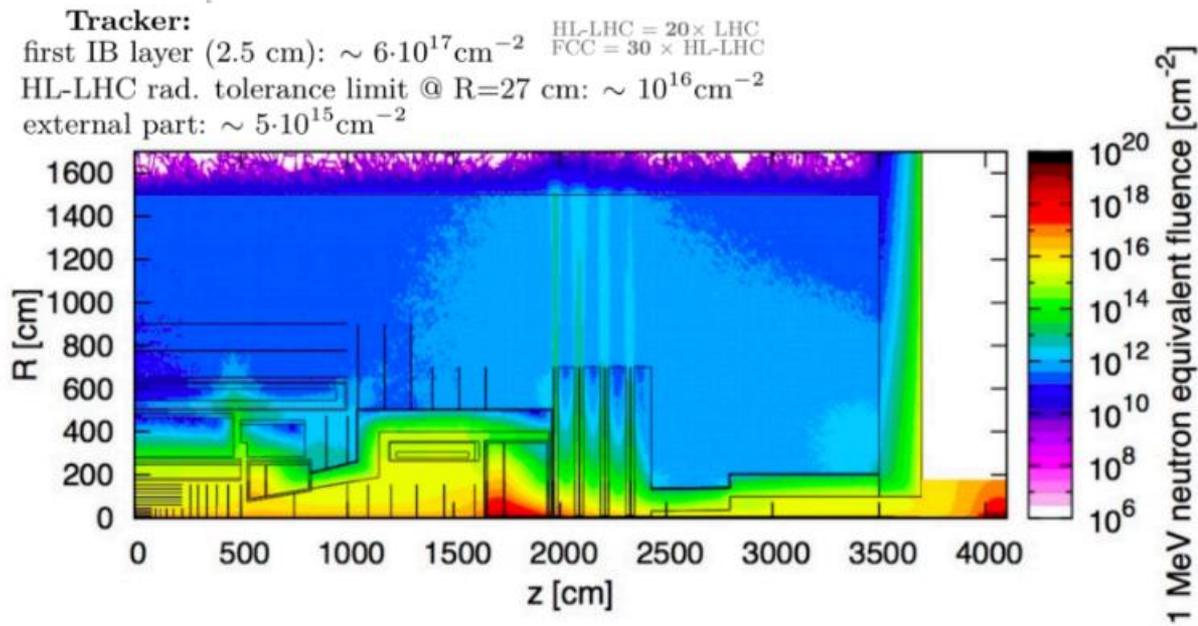


Very simple heuristic algo



- Multi TeV top radiates FSR at a typical scale angular scale $\sim m / p_T$ (deadcone)
- Large cone FSR can spoil mass by adding $\Delta m \sim m_{top}$ even for 1 GeV emission
 - \rightarrow use shrinking cone algo by reclustering with $R \sim 4m/p_T$
 - use tracking for substructure

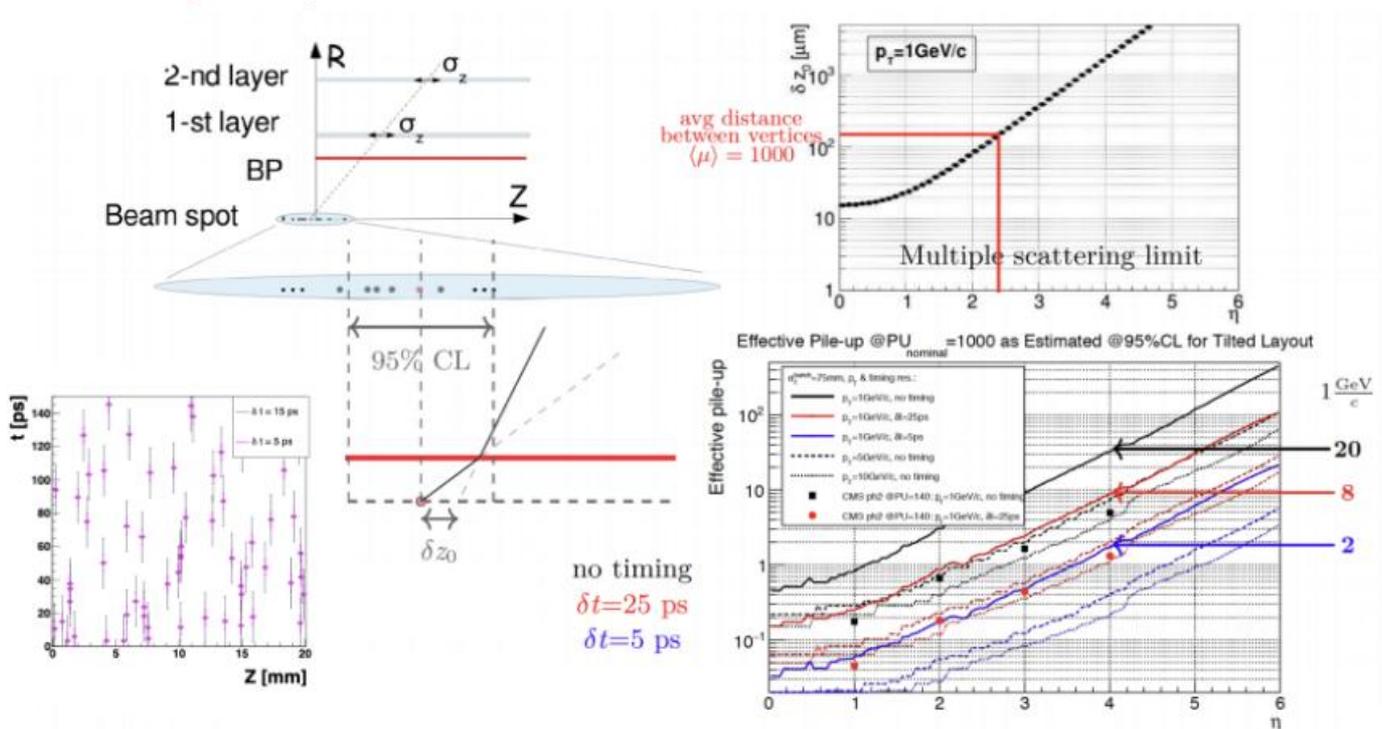
Radiation tolerance



Forward calorimetry:
 maximum at $\sim 10^{18} \text{ cm}^{-2}$

- A hadron fluence $> 10^{16} \text{ cm}^{-2}$ is very challenging for silicon sensors
- This limit is reached already @ 27 cm from the beam pipe
- Dedicated R&D needed to push the limit of radiation hardness (LHCb Upgrade II)

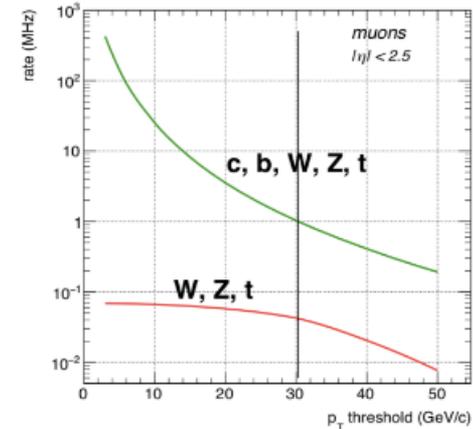
Pile-up and timing information



With PU density = 8 mm⁻¹ need $\delta z_0 \sim 100 \mu\text{m}$ resolution in track longitudinal impact parameter
 → at large angles this corresponds to beam-pipe contribution alone !!!

High resolution (~ 5-10 ps) timing information needed !!

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b} p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b} p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{\text{jet}} > 50$ GeV/c cross-section [341]	μb	21	21	56	300
Jets $p_T^{\text{jet}} > 50$ GeV/c rate	MHz	0.2	1.1	14	90

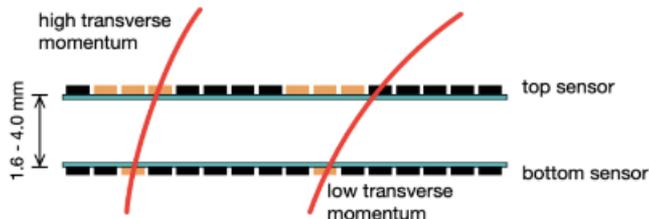


Phase II:

- ATLAS/CMS readout calorimeters/muons @40MHz and send via optical fibres to Level I trigger outside the cavern to create LI trigger decisions
- CMS reads out (part of) the tracker at LI 50 Tb/s
- Full detector readout @1MHz (5Mb/event)
 - @40MHz it would correspond to 200 Tb/s

FCC-hh:

- At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
- However full detector would correspond to 1-2 Pb/s
 - Seems hardly feasible (30 yrs from now)
- How much data can be transferred out, without spoiling the performance?



Road to 1% precision on the self-coupling

Photons

- energy/momentum resolution
 - Homogenous LXe calorimeter ?
 - $M_R \sim 5 \text{ cm}, X_0 \sim 2.5 \text{ cm}$
 - $3\%/\sqrt{E}$
- Eff - low misID
 - Pile-up rejection ($\sim 10 \text{ ps}$ timing)

(B-)jet energy momentum resolution

- Intrinsic HCAL resolution,
- Calorimeter segmentation for optimal particle-flow
- Timing for pile-up rejection

Flavor Tagging

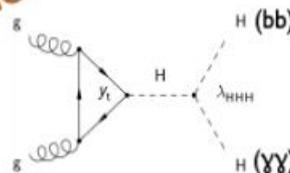
- Close to IP (radiation damage !!!) (1/d)
 - $\sim @1 \text{ cm} \rightarrow 1e19 \text{ 1 MeV neq/cm}^2$
- Light vertex detector ($\sqrt{X_0}$)
 - but power/cooling needed to extract data
- target single point resolution $\sim 10 \mu\text{m} \times 10 \mu\text{m}$

$\delta\kappa_\lambda \text{ (stat)} \sim 2\text{-}3\%$

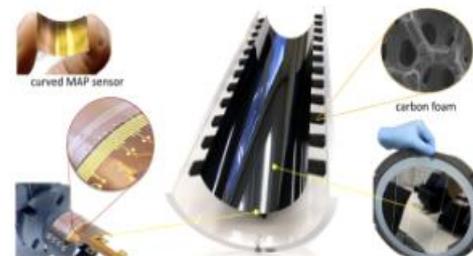
[MLM, Ortona, MS]

[Taliervo et al.]

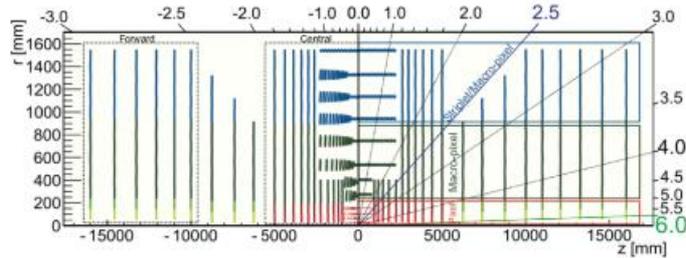
**DISCLAIMER:
HIGHLY SPECULATIVE**



XENONnT:

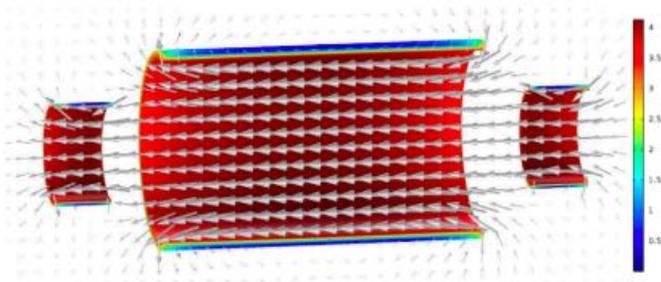


maps $\sim 1e15 \text{ 1 MeV neq/cm}^2$



Calorimeters

- ECAL: LArg, 30X₀, 1.6 λ, r = 1.7-2.7 m (barrel)
- HCAL: Fe/Sci, 9 λ, r = 2.8 - 4.8 m (barrel)

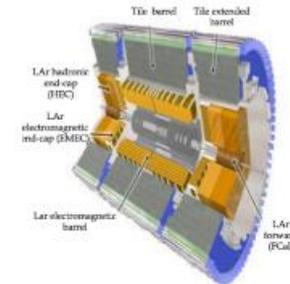


Muon spectrometer

- Two stations separated by 1-2 m
- 50 μm pos., 70 μrad angular

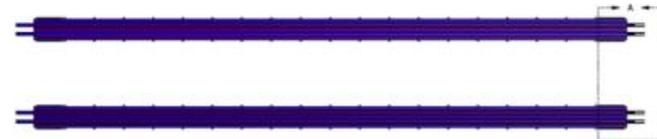
Tracker

- -6 < η < 6 coverage, 20-40% total X/X₀
- pixel : σ_{rφ} ~ 10 μm, σ_z ~ 15-30 μm, X/X₀(layer) ~ 0.5-1.5%
- outer : σ_{rφ} ~ 10 μm, σ_z ~ 30-100 μm, X/X₀(layer) ~ 1.5-3%



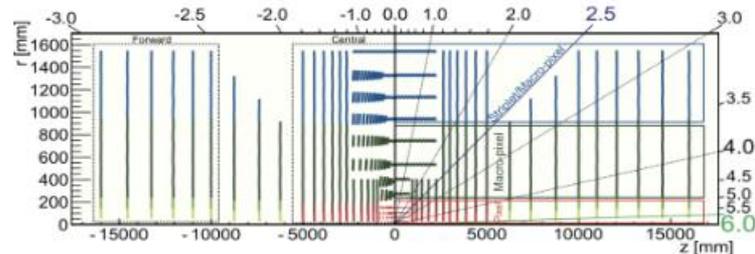
Magnet

- central R = 5, L = 10 m, B = 4T
- forward R = 3m , L = 3m , B = 3.5T

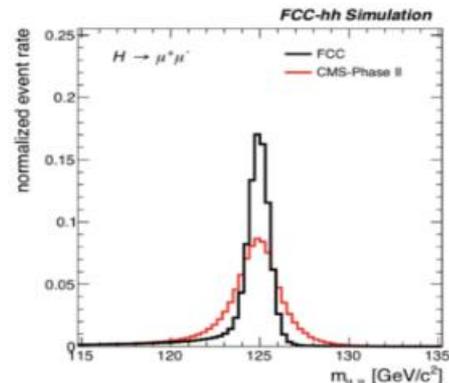
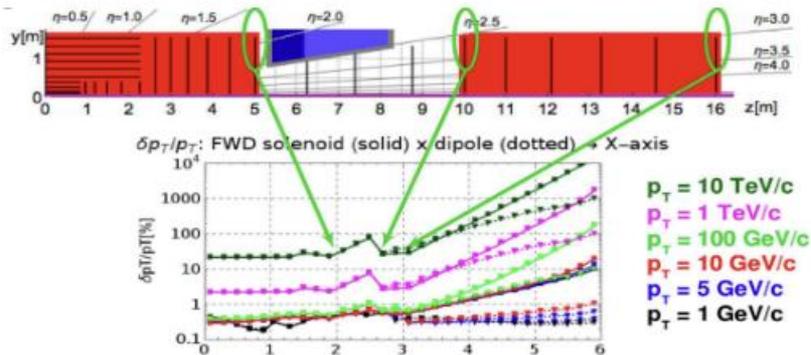


Tracker

- Binary readout
- 16 billions readout channels, x(3-10) phase II detectors)
- Radiation hardness is an issue for innermost layers

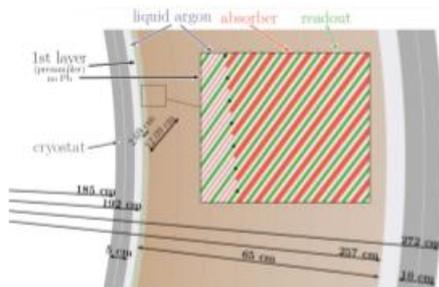


- Tilted geometry with inclined modules:
 - minimize effect of Multiple scattering (low material)
 - helps with pattern recognition

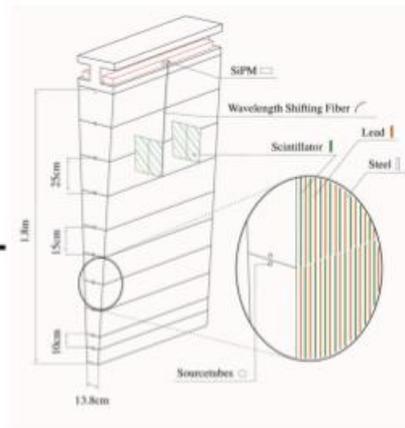


low p_T muons \rightarrow resolution dominated by MS

Calorimeters



ECAL

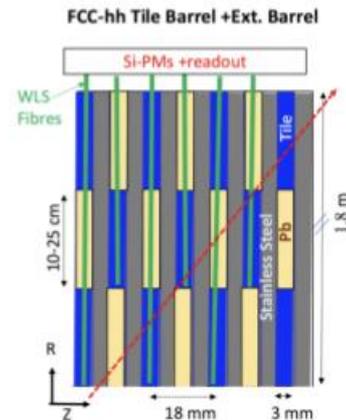


HCAL

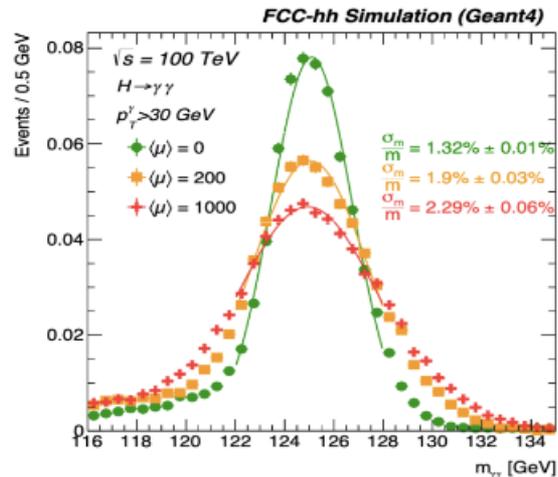
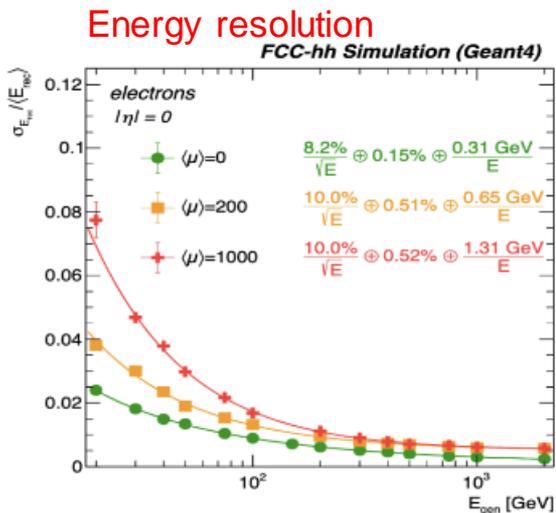
- ECAL: LAr + Pb technology driven by radiation hardness
- HCAL:
 - Organic scintillator + Steel, R/O with WLS fiber + SiPM
 - LAr in the forward (Dose > 10 MGy)

• Design goals:

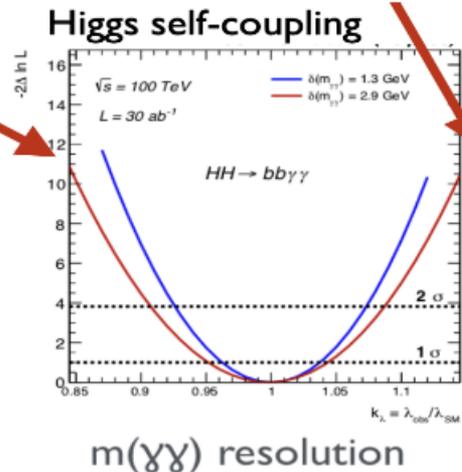
- High longitudinal (7+10 layers) + transverse segmentation (x4 CMS and ATLAS)
- Particle-flow compliant
- standalone PU rejection



Photon performance



- **Target:** σ/m as small as possible for $HH \rightarrow b\bar{b}\gamma\gamma$
- Large impact of in time PU on the noise term (out of the box with no improvements)!!
- severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)
- impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
- some thought needed (tracking, timing information can help?)



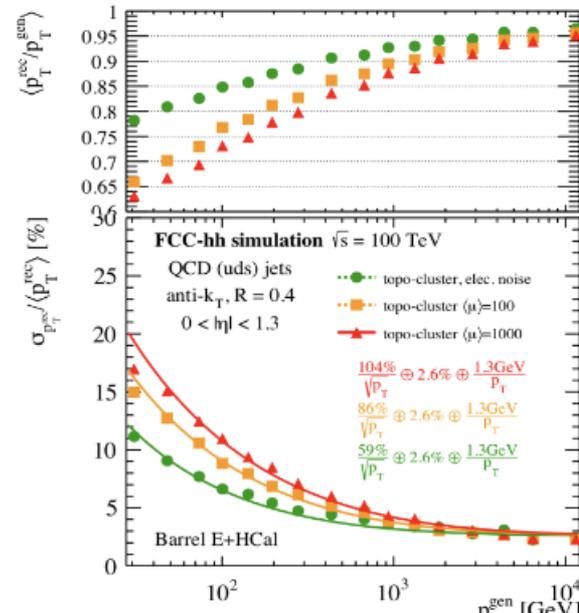
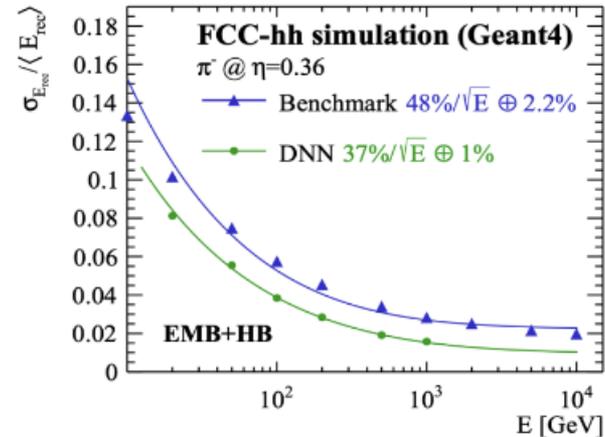
Jet performance

- Excellent resolution up to $p_T = 10 \text{ TeV}$!!
- Large impact of PU at low p_T (as expected)

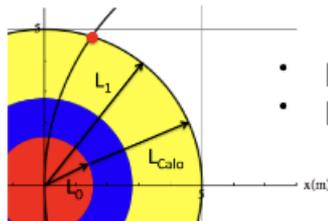
- crucial for low mass di-jet resonances (again, such as $HH \rightarrow b\bar{b}\gamma\gamma$)

- Further motivation for Particle-flow

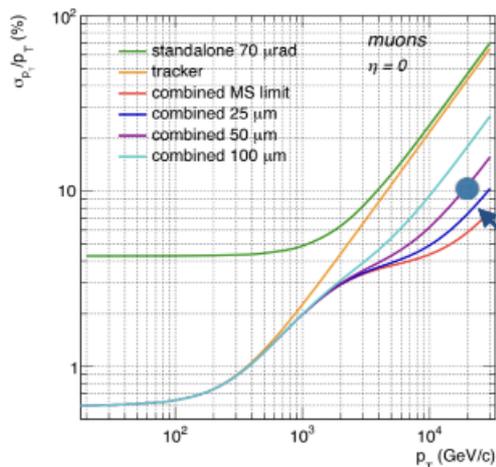
→ since charged PU contribution can be easily subtracted (Charged Hadron Subtraction)



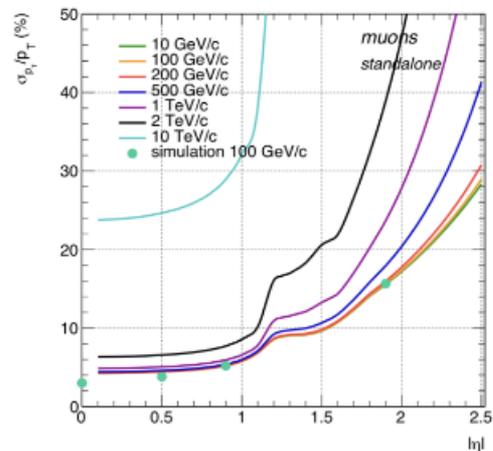
Muons



- $p_T = 4$ GeV muons enter the muon system
- $p_T = 5.5$ GeV leave coil at 45 degrees



$\sigma_p/p = 10\%$
@20 TeV



Calo + Coil = 180-280 X_0

- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 μm position resolution (combining with tracker)
- Good standalone resolution below $|\eta| < 2.5$
- Rates manageable with HL-LHC technology (sMDT)



Horizon Europe (2028-2034) will build on the achievements of its predecessors, scaling what works, simplifying what is possible, and focusing investment where Europe needs it most. It will be tightly connected to the European Competitiveness Fund.

Moonshots (in the MFF=Multi-annual Financial Framework)

Objective: ambitious technology driven projects that boost the EU's strategic autonomy through research, development and deployment.

▶ the future circular collider ▶ clean aviation ▶ quantum computing ▶ next-generation AI ▶ data sovereignty ▶ automated transport and mobility ▶ regenerative therapies ▶ fusion energy ▶ space economy ▶ zero water pollution ▶ ocean observation

Based on orientation of the steering mechanism for the next MFF including the Competitiveness Coordination Tool, the Horizon Europe programme and the European Competitiveness Fund could finance a coherent sequence between research and innovation, demonstration, development and deployment, focusing efforts and funding, from the EU and national, public and private sector of ‘moonshots’ projects with a strong scientific component, boosting EU-wide value creation and strategic autonomy (see examples below) .

Possible ‘moonshots’:

- Investing in the European Organization for Nuclear Research's (CERN) Future Circular Collider, alongside other CERN's participating countries. The objective is to maintain Europe's leadership in particle physics research. The funding (up to 20% of the overall cost) could come from Horizon Europe.