Status of the FCC Feasibility Study Towards a 100 TeV Hadron Collider

Martin Aleksa

Based on material from:

P. Azzi: Future Colliders PhD Course , YETI 2021 Lecture (https://conference.ippp.dur.ac.uk/event/1027/timetable/#20210706)
P. Janot and W. Riegler: Academic Training (https://indico.cern.ch/event/666889/)
FCC CDR Summary Volumes: https://fcc-cdr.web.cern.ch/, EPJ ST 228, 4 (2019) 755-1107
European Strategy Physics Briefing Book (https://arxiv.org/abs/1910.11775)

The FCC Feasibility Study

From ESPPU 2020 Document

Preamble:

"Given the unique nature of the Higgs boson, there are compelling scientific arguments for a new electron-positron collider operating as a Higgs factory"

Under "3. High-priority future initiatives":

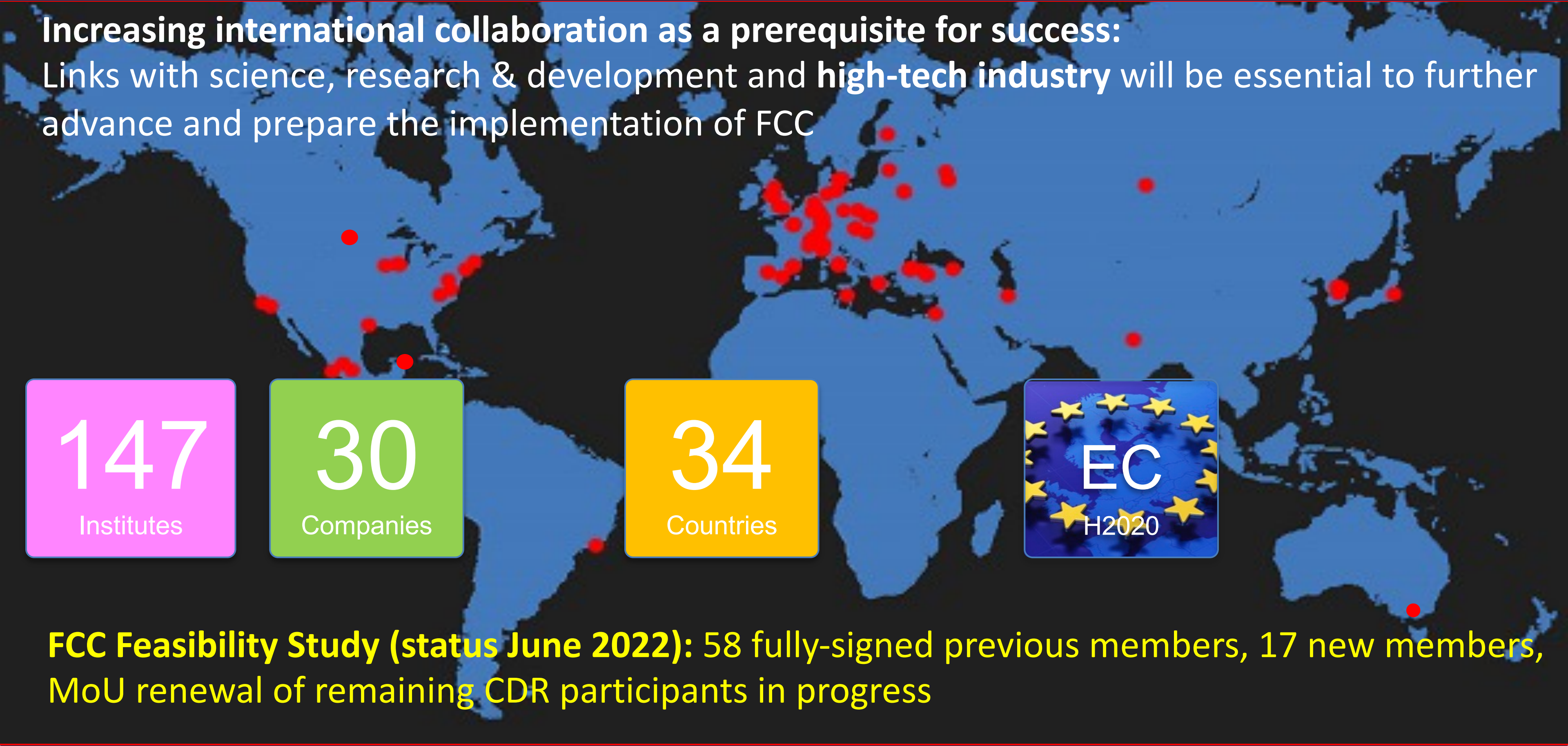
"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Under "4. Other essential scientific activities for particle physics":

"Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."

https://europeanstrategyupdate.web.cern.ch/resources

Global FCC Collaboration



Increasing international collaboration as a prerequisite for success:
Links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

147
Institutes

30
Companies

34
Countries

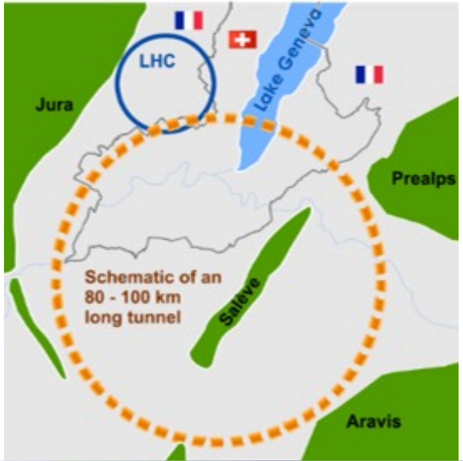
EC
H2020

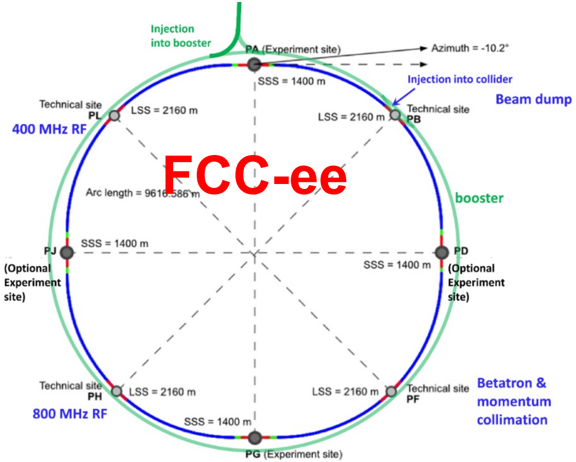
FCC Feasibility Study (status June 2022): 58 fully-signed previous members, 17 new members, MoU renewal of remaining CDR participants in progress

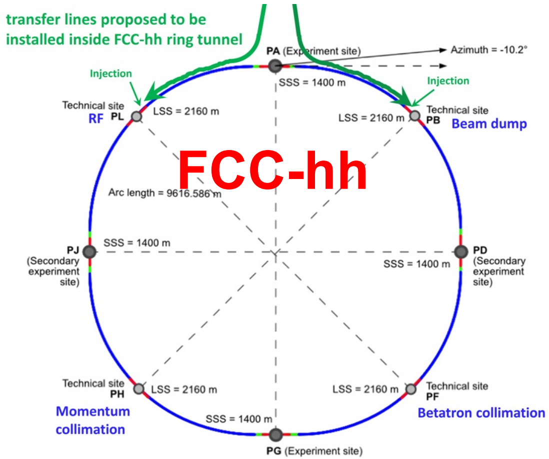
FCC Integrated Program

Inspired by successful LEP – LHC program

- Comprehensive long-term program maximizing physics opportunities
- Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- → complementary physics
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program

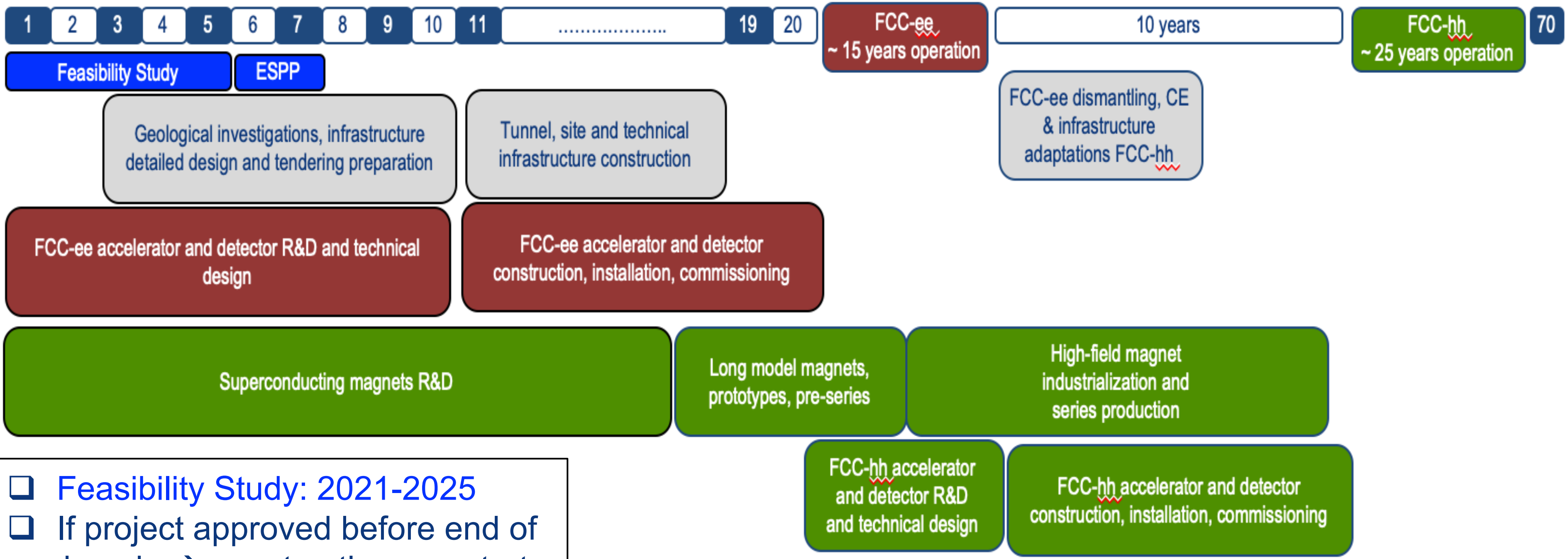






2020 - 2040 | **2045 - 2060** | **2070 - 2090++**

Timeline of the FCC Integrated Programme



1 2 3 4 5 6 7 8 9 10 11 ………………… 19 20

FCC-ee
~ 15 years operation

10 years

FCC-hh
~ 25 years operation

70

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

- ☐ Feasibility Study: 2021-2025
- ☐ If project approved before end of decade → construction can start beginning 2030s
- ☐ FCC-ee operation ~2045-2060
- ☐ FCC-hh operation 2070-2090++

F. Gianotti

Goals and Roadmap Towards e^+e^- Collisions

Fabiola Gianotti: “CERN vision and goals until next strategy update” FCCIS Kick-Off, 9 Nov. 2020

Highest priority goals:

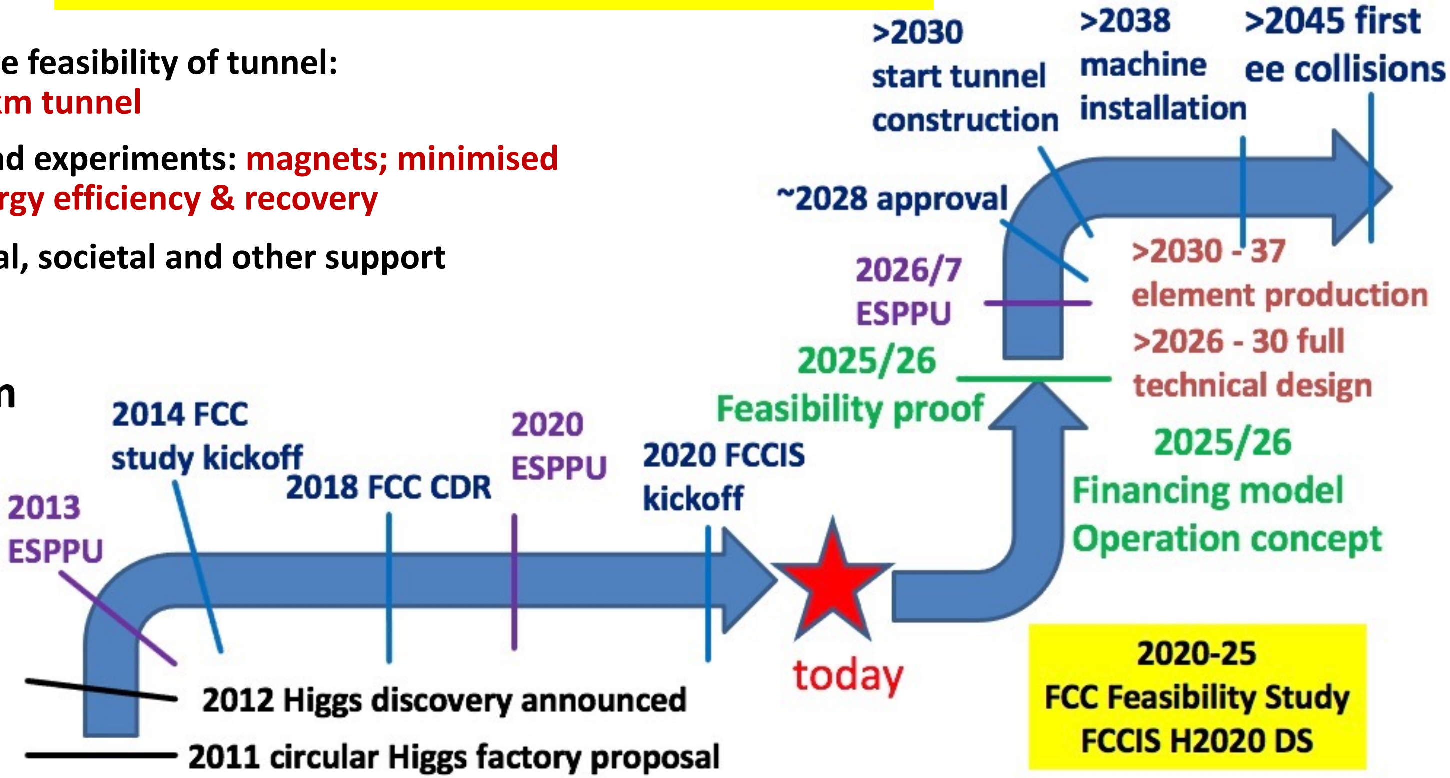
Financial feasibility

Technical and administrative feasibility of tunnel:
no show-stopper for ~100 km tunnel

Technologies of machine and experiments: magnets; minimised environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support

Planning for mid-term review & cost review in autumn 2023



2011 circular Higgs factory proposal

2012 Higgs discovery announced

2013 ESPPU

2014 FCC study kickoff

2018 FCC CDR

2020 ESPPU

2020 FCCIS kickoff

today

2025/26 Feasibility proof

2025/26 Financing model Operation concept

2026/7 ESPPU

~2028 approval

>2026 - 30 full technical design

>2030 - 37 element production

>2030 start tunnel construction

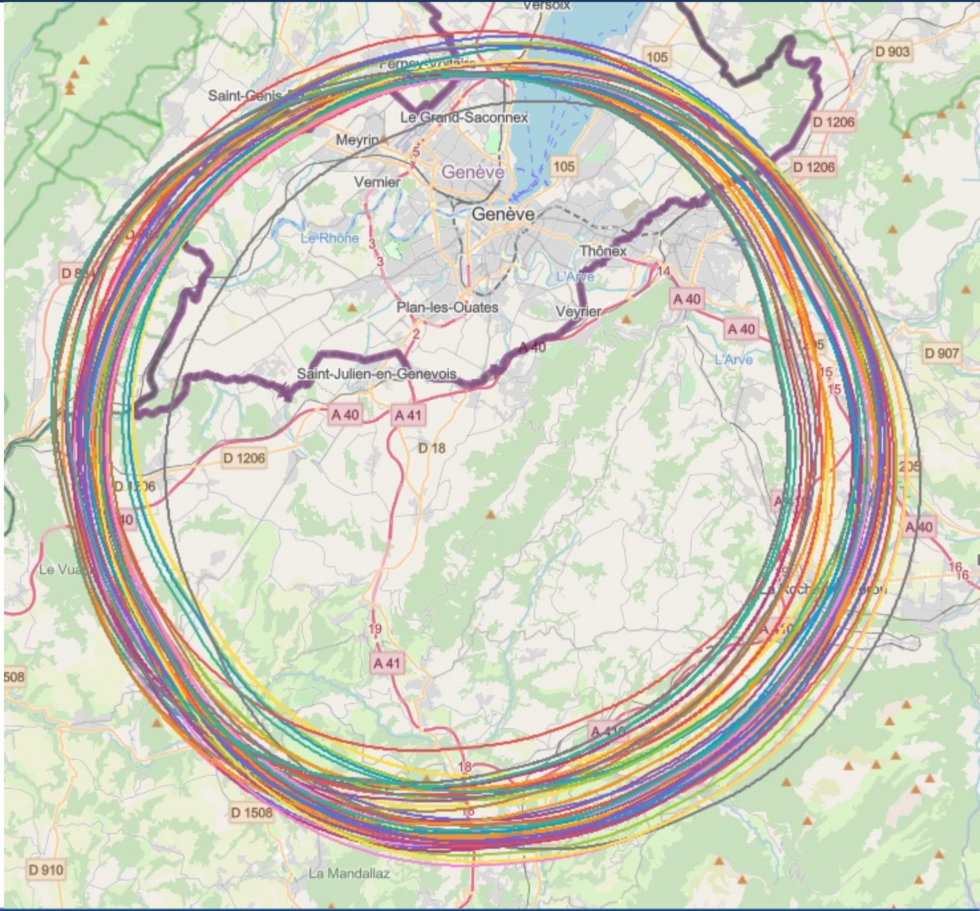
>2038 machine installation

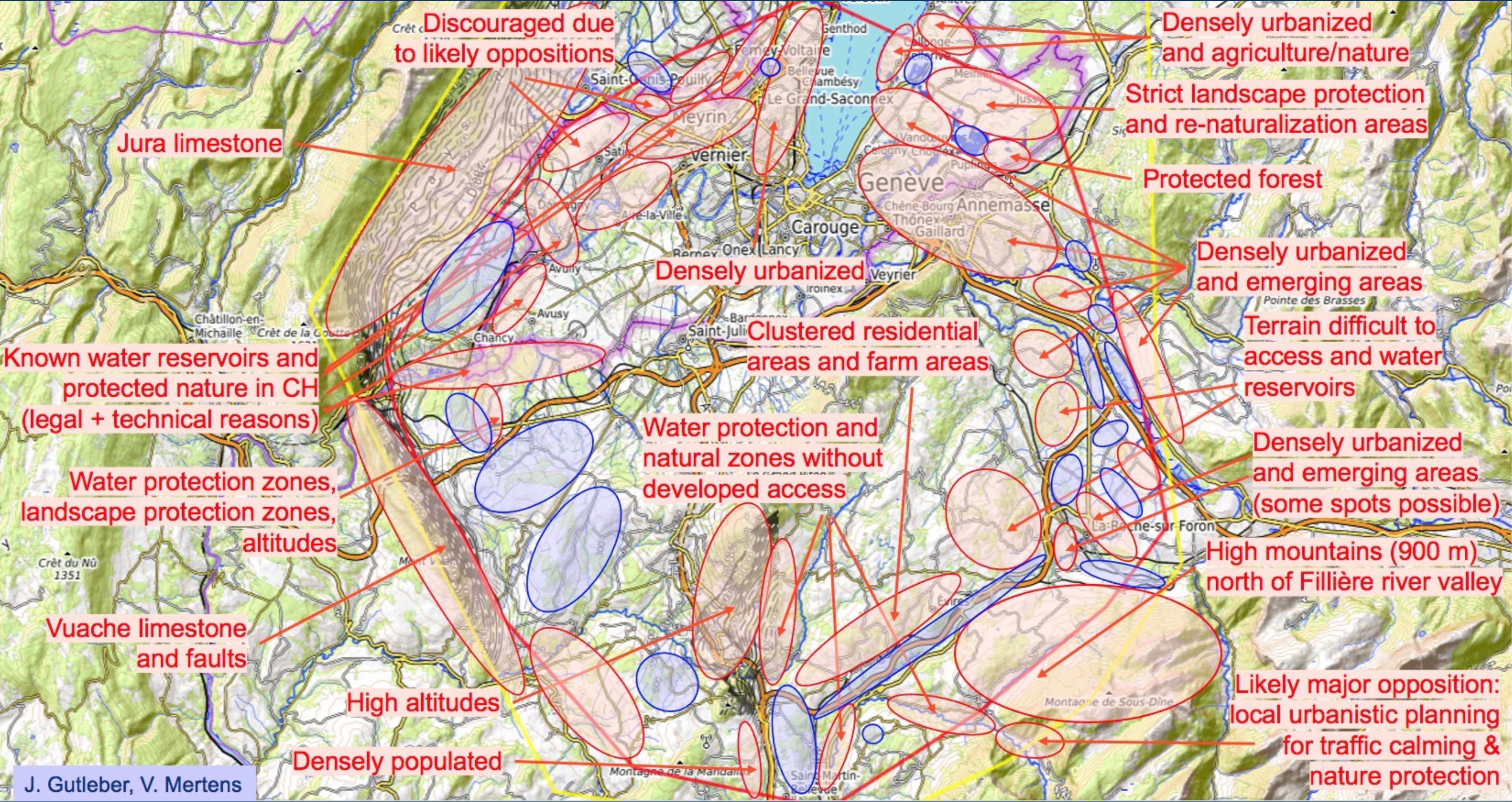
>2045 first ee collisions

2020-25
FCC Feasibility Study
FCCIS H2020 DS

Implementation Studies with Host States

- Layout & placement optimisation across both host states, Switzerland and France;
- Diverse requirements and constraints:
  - **technical feasibility of civil engineering** and subsurface geological constraints
  - **territorial constraints on surface** and subsurface
  - **nature, accessibility**, technical infrastructure, resource needs & constraints
  - **optimum machine performance and efficiency**
  - economic factors including benefits for, and synergies, with the **regional developments**
  - …
- **Collaborative effort:** FCC technical experts, consulting companies, government-notified bodies





Discouraged due to likely oppositions

Jura limestone

Known water reservoirs and protected nature in CH (legal + technical reasons)

Water protection zones, landscape protection zones, altitudes

Vuache limestone and faults

High altitudes

Densely populated

Densely urbanized

Clustered residential areas and farm areas

Water protection and natural zones without developed access

Densely urbanized and agriculture/nature

Strict landscape protection and re-naturalization areas

Protected forest

Densely urbanized and emerging areas

Terrain difficult to access and water reservoirs

Densely urbanized and emerging areas (some spots possible)

High mountains (900 m) north of Fillière river valley

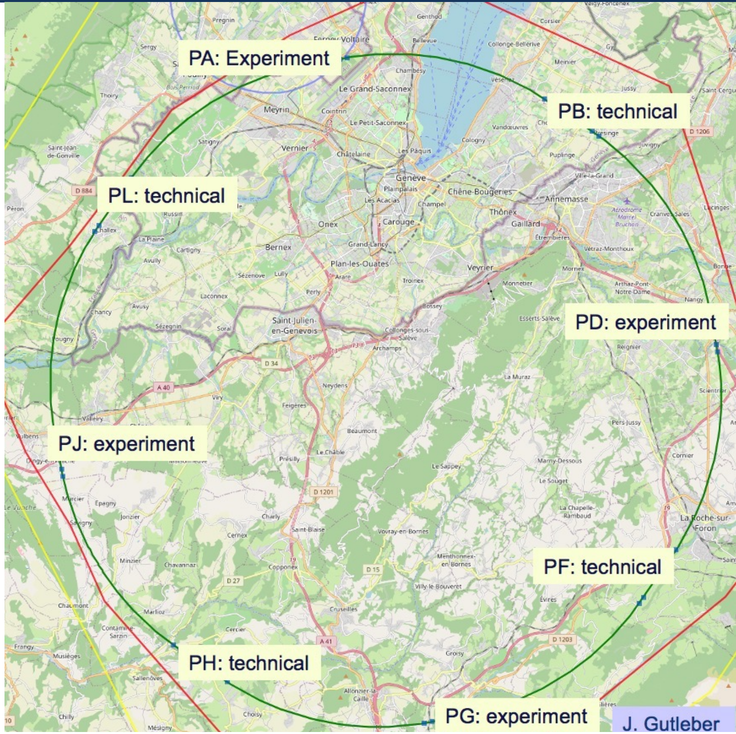
Likely major opposition: local urbanistic planning for traffic calming & nature protection

J. Gutleber, V. Mertens

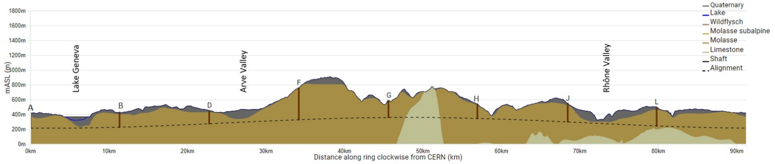
8-Site Baseline

Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- Shaft depth between 139m (PH) and 399m (PF)

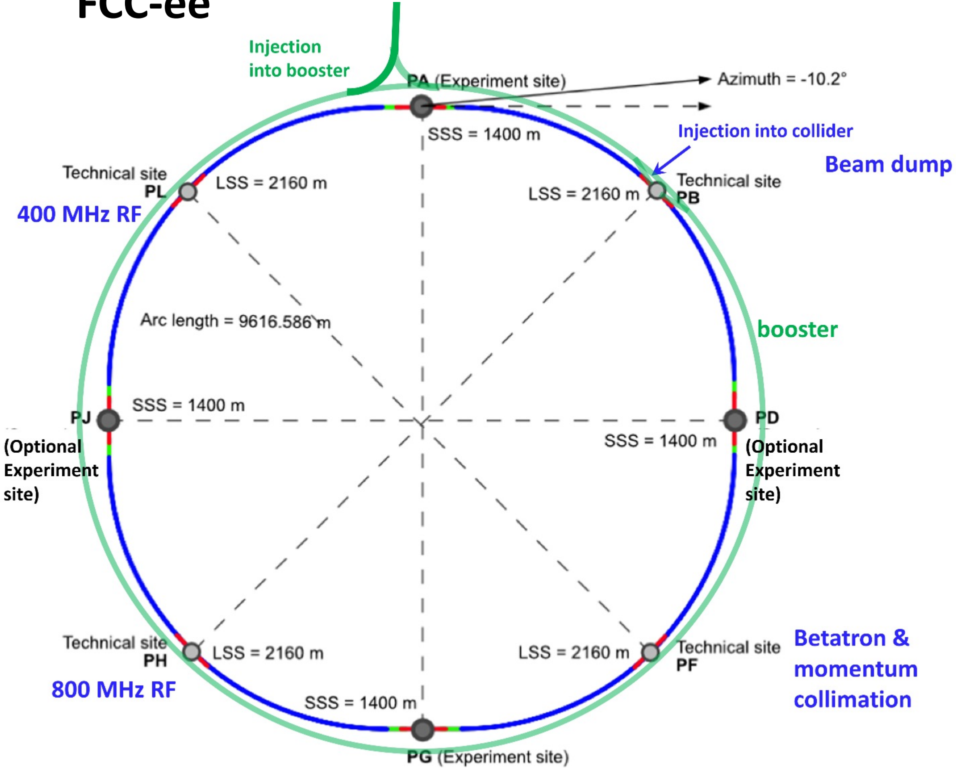


J. Gutleber

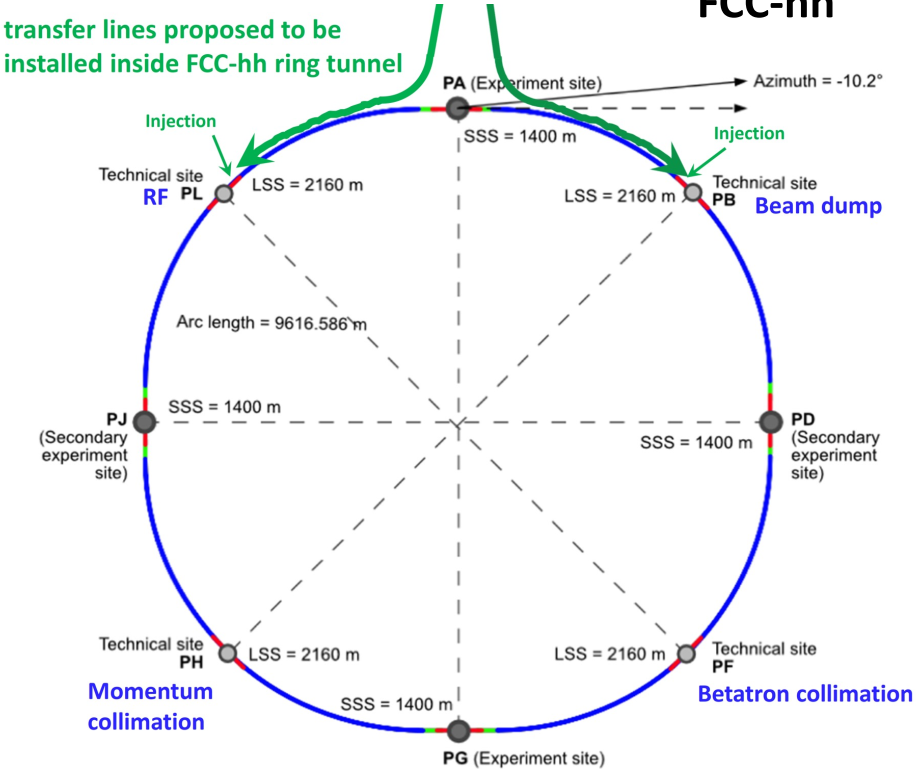


New Layout

FCC-ee



FCC-hh



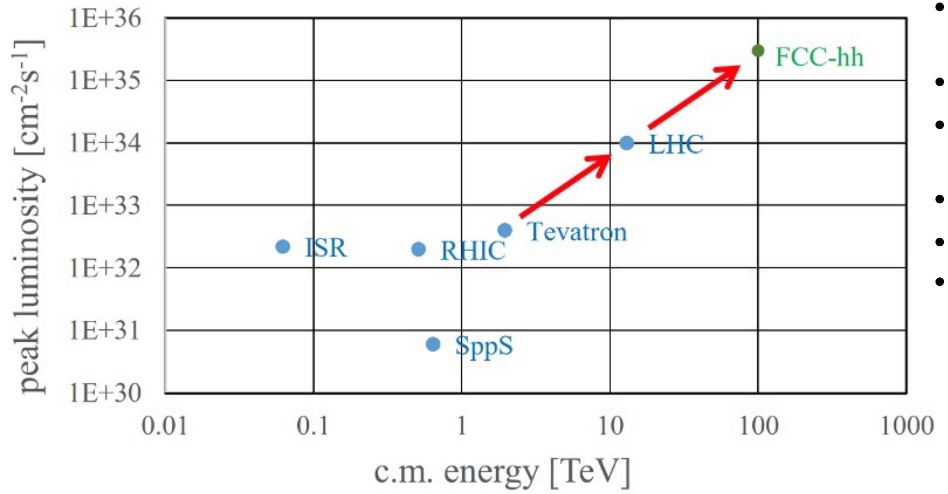
FCC-ee Parameter Table

Parameter [4 IPs, 91.2 km,T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

FCC-hh Parameter Table

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb. function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

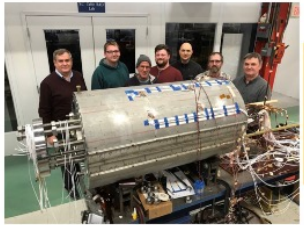
FCC-hh Main Challenge



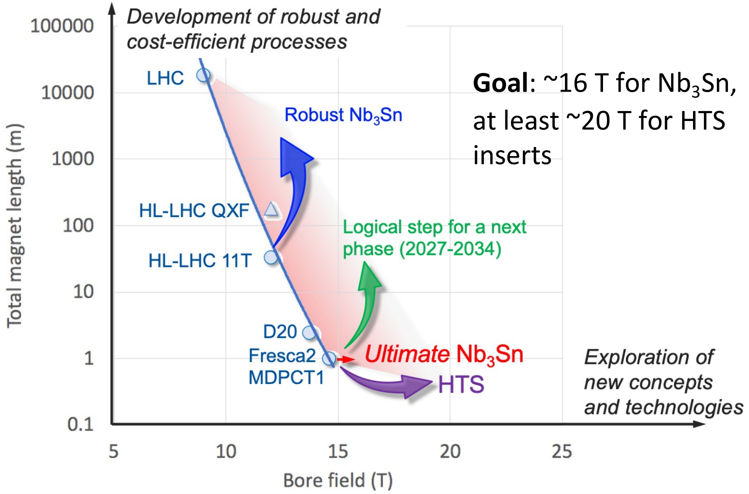
- **Order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV center of mass collision energy** (vs 14 TeV for LHC)
- 20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for HL-LHC)
- Similar performance increase as from Tevatron to LHC
- **Key technology**: high-field magnets (HFM)
- → In parallel to FCC Study, **HFM development program** as long-term separate R&D project (global collaboration already established during FCC CDR phase)

from
LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole demonstrator
4-layer cosϑ
14.5 T Nb_3Sn
in 2019



Goal: ~16 T for Nb_3Sn, at least ~20 T for HTS inserts

100 TeV Hadron Collider – FCC-hh

FCC-hh Parameter Table

CDR values

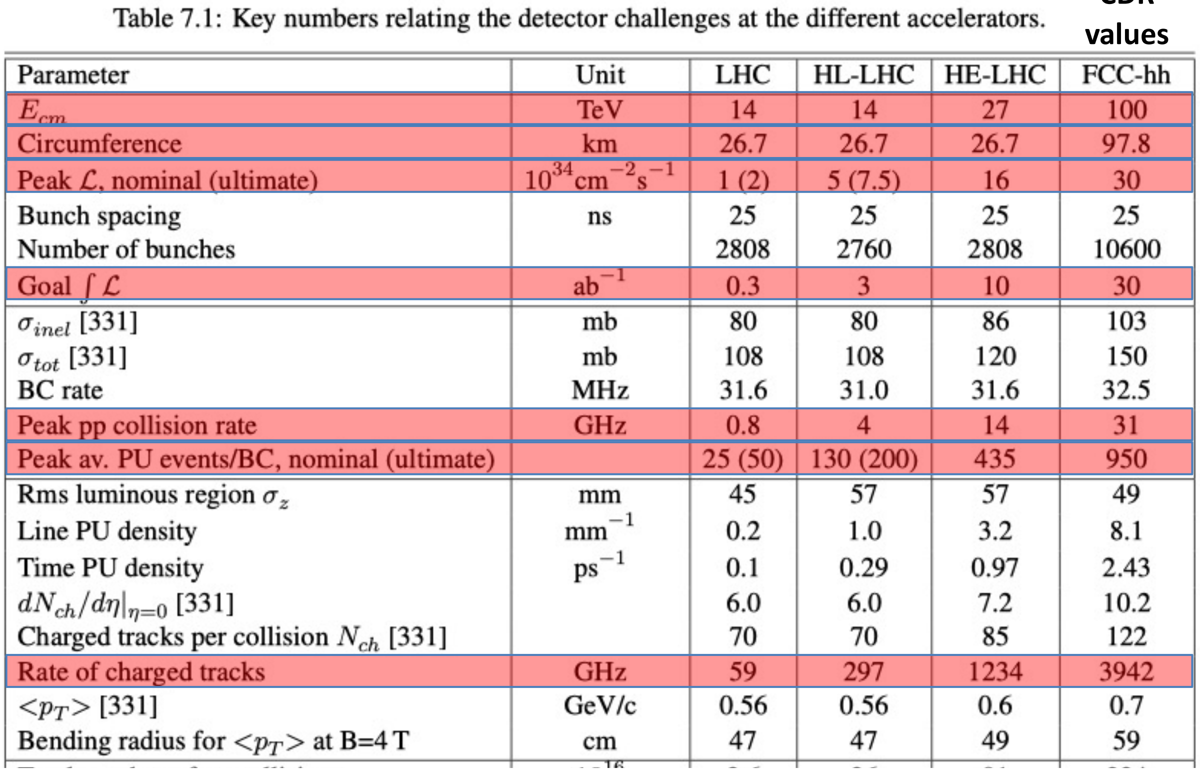


Table 7.1: Key numbers relating the detector challenges at the different accelerators.

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 $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int\mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rms luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\vert_{\eta=0}$ [331]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [331]		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $<p_T>$ at B=4 T	cm	47	47	49	59

- E_{cm} = 100 TeV
- O(100km) circumference
- $\mathcal{L} = 30 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int\mathcal{L} = 30\ \mathrm{ab}^{-1}$
- 31 GHz pp collisions
- Pile-up <μ> ≈ 1000
- 4 THz of charged tracks

FCC-hh Parameter Table

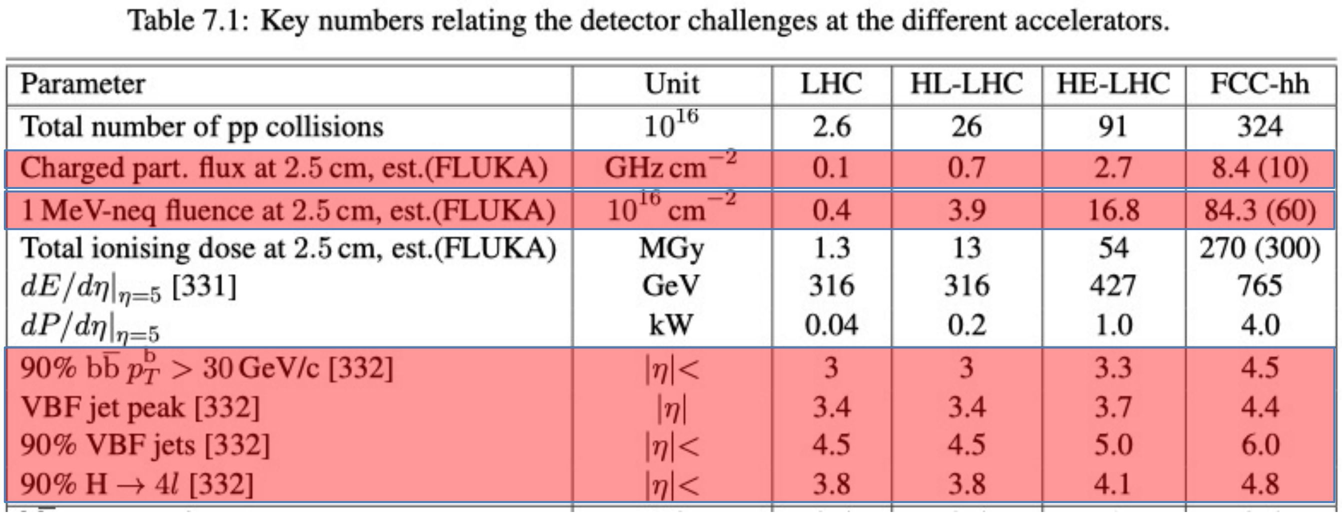
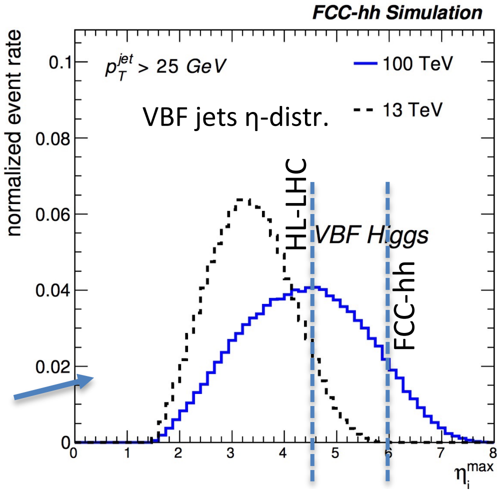
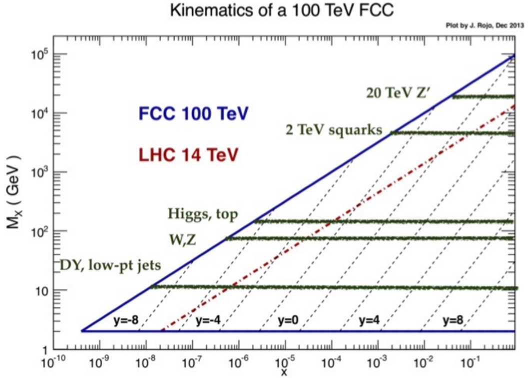


Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total 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 (10)
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 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8

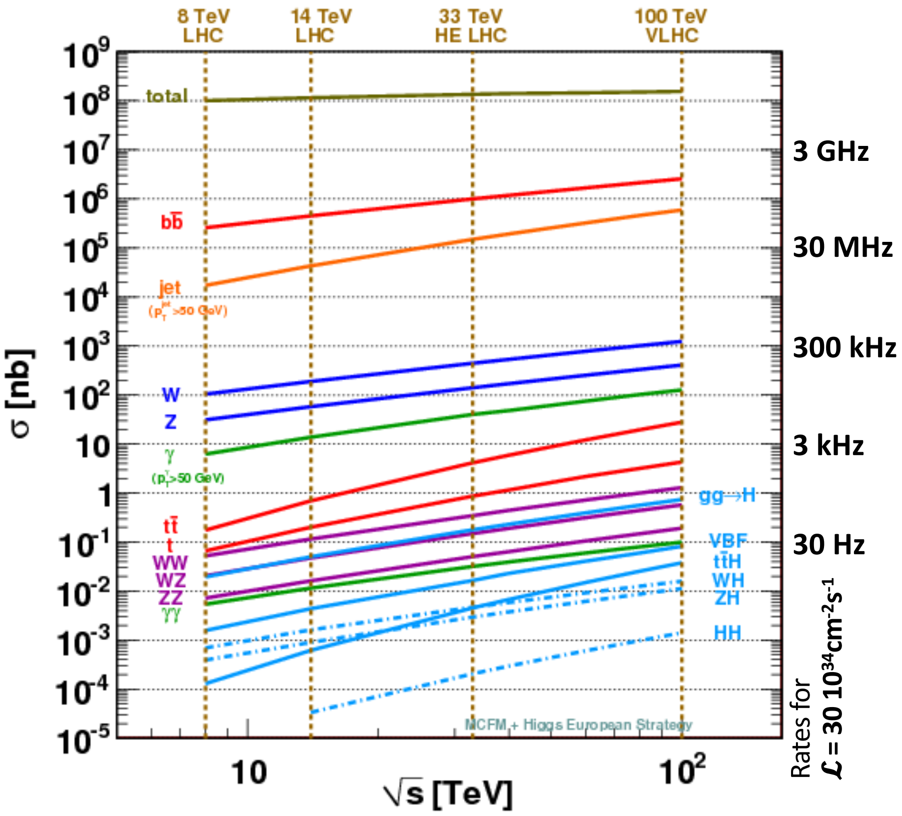




Unprecedented particle flux and radiation levels

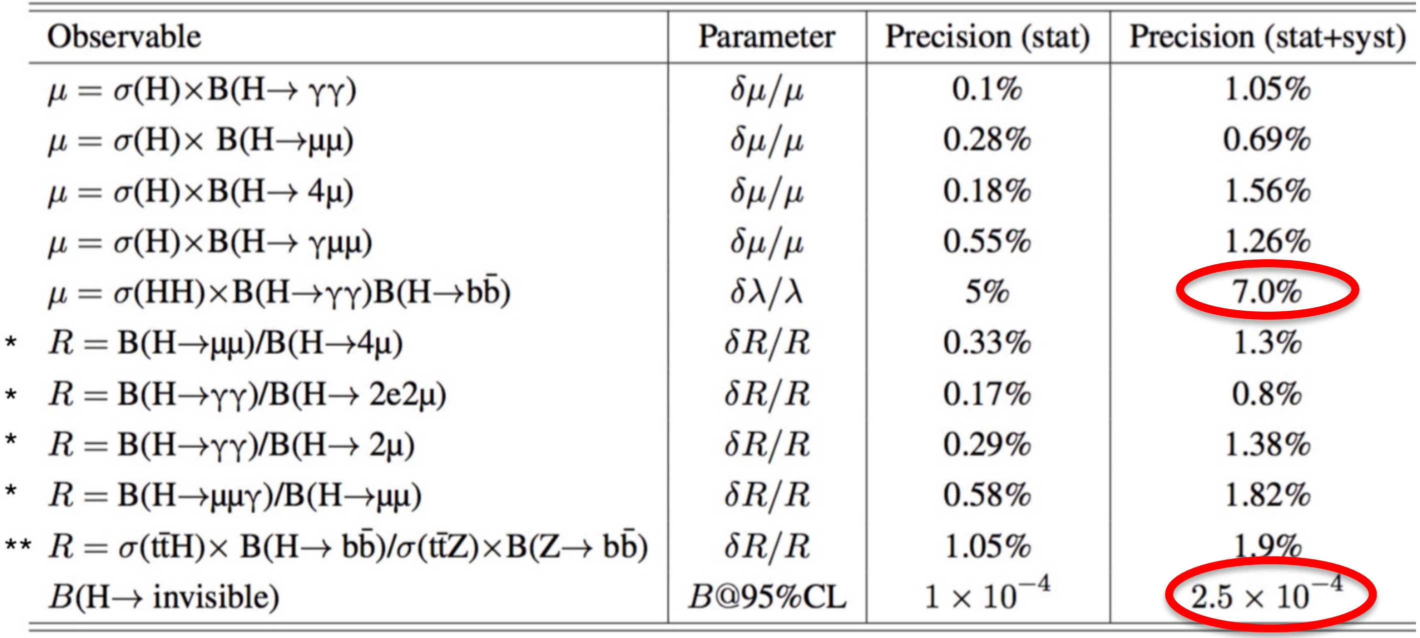
- **10 GHz/cm^2 charged particles**
- **≈ 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30ab^{-1} (first tracker layer, fwd calo)**
- **“Light” SM particles produced with increased forward boost**
  - **→ spreads out particles by 1-1.5 units of rapidity**

Cross-Sections for Key Processes



- **Total cross-section and Minimum Bias Multiplicity** show only a **modest increase** from LHC to FCC-hh.
- The **cross-sections for interesting processes, however, increase significantly** **(**e.g. HH x 50!**)**!
- Higher luminosity to increase statistics → pileup of 140 at HL-LHC to **pileup of 1000** at FCC-hh → **challenge for triggering and reconstruction**
- **$\mathcal{L}$ = 30x10^{34}cm^{-2}s^{-1}:**
  - 100MHz of jets p_T>50GeV,
  - 400kHz of Ws,
  - 120kHz of Zs,
  - 11kHz of ttbars
  - 200Hz of gg→H

Precision Higgs Measurements

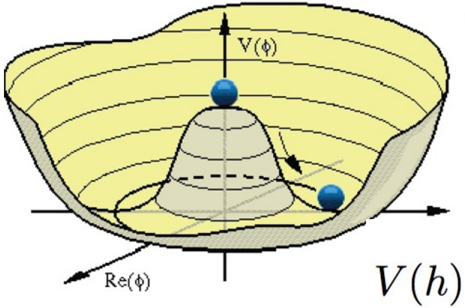


	Observable	Parameter	Precision (stat)	Precision (stat+syst)
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.05%
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\rightarrow\mu\mu)$	$\delta\mu/\mu$	0.28%	0.69%
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta\mu/\mu$	0.18%	1.56%
	$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\rightarrow\gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.26%
	$\mu = \sigma(\mathrm{HH})\times\mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)\mathrm{B}(\mathrm{H}\rightarrow b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
*	$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu)/\mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta R/R$	0.33%	1.3%
*	$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2e2\mu)$	$\delta R/R$	0.17%	0.8%
*	$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mu)$	$\delta R/R$	0.29%	1.38%
*	$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\rightarrow\mu\mu)$	$\delta R/R$	0.58%	1.82%
**	$R = \sigma(t\bar{t}\mathrm{H})\times\mathrm{B}(\mathrm{H}\rightarrow b\bar{b})/\sigma(t\bar{t}\mathrm{Z})\times\mathrm{B}(\mathrm{Z}\rightarrow b\bar{b})$	$\delta R/R$	1.05%	1.9%
	$B(\mathrm{H}\rightarrow \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

* Measurements of ratios of BRs, combined with the absolute measurement of the HZZ coupling at FCC-ee, will yield absolute coupling measurements in FCC-hh

** Will use results from FCC-ee: BR(H→bb), ttZ EW coupling

Higgs Self Coupling

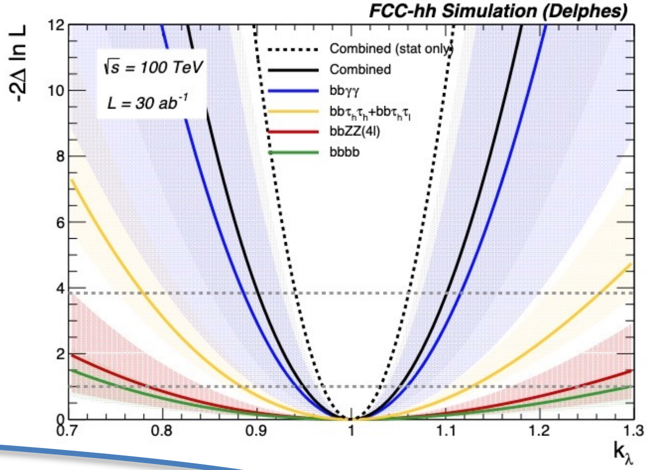


$$V(\mathcal{H}) = \underbrace{M_{\mathcal{H}}^2|\mathcal{H}|^2 + \frac{\lambda_{\mathcal{H}}}{2}|\mathcal{H}|^4}_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}|\mathcal{H}|^6}_{\text{BSM}}$$

$$V(h) = \overbrace{\frac{1}{2}M_H^2H^2 + \underbrace{\frac{1}{3!}\sqrt{3\lambda_H}M_HH^3} + \frac{1}{4!}\lambda_HH^4}^{\text{SM}}$$

$$\mathcal{H} = (0, \frac{H+v}{\sqrt{2}})$$

[arXiv:2004.03505v2](https://arxiv.org/abs/2004.03505v2)



Why is Higgs self coupling interesting?

- Study shape of Higgs potential
- Study EW phase transition → cosmological implications
- Impact on vacuum stability
- Self-coupling sensitive to new physics

HH→bбγγ is the golden channel for di-Higgs meas. in FCC-hh:

→ Important input for detector requirements

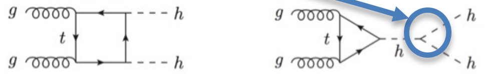
→ ECAL performance, b-tagging,…

Delphes parametrisation

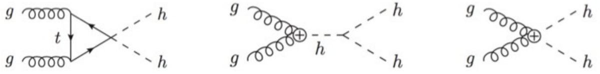
parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet → γ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

study di-Higgs decays

SM:

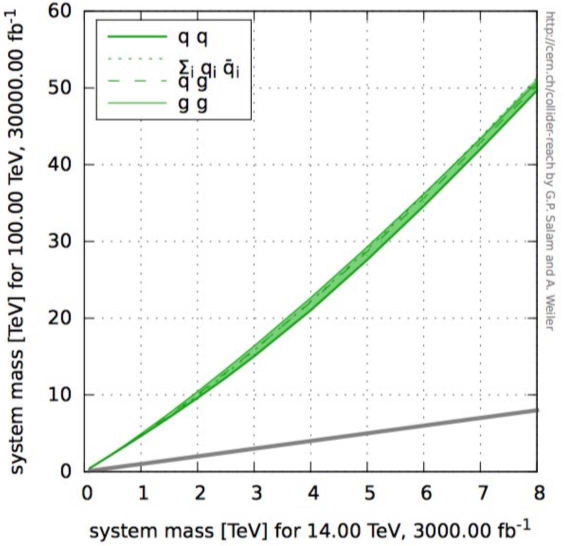


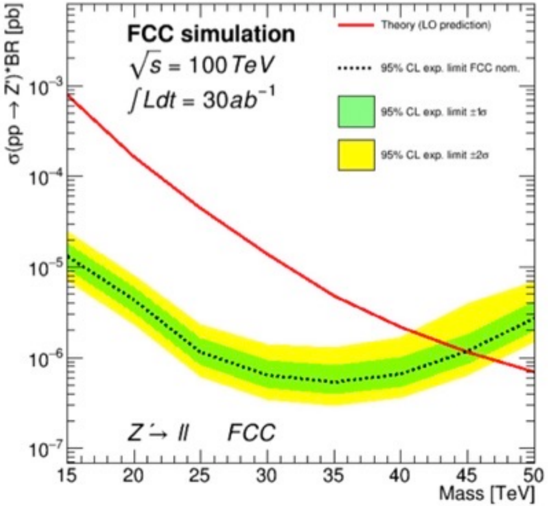
BSM:

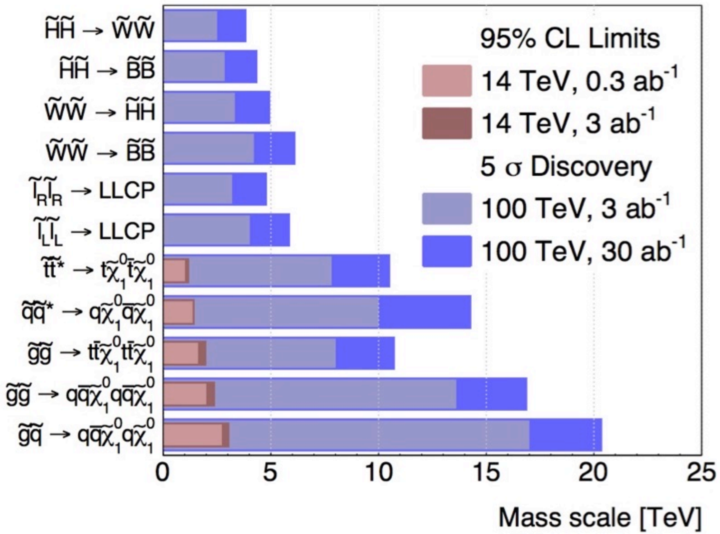


@68% CL		scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

Exploration Potential: Direct Mass Reach







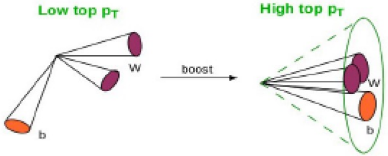
- **Mass reach of FCC-hh about 5-6 x HL-LHC**
- **Delphes simulation of realistic detector** including systematic uncertainties
  - → Demonstrate that we can fully exploit this potential

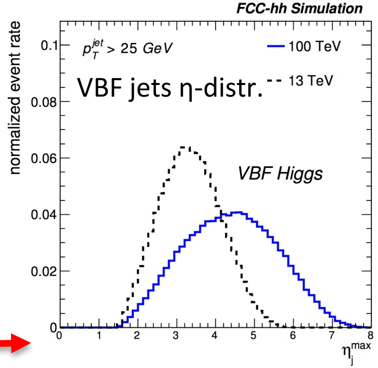
FCC-hh Detector

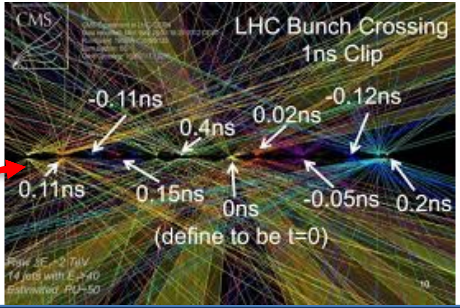
Requirements for FCC-hh Detector

Used in Delphes physics simulations

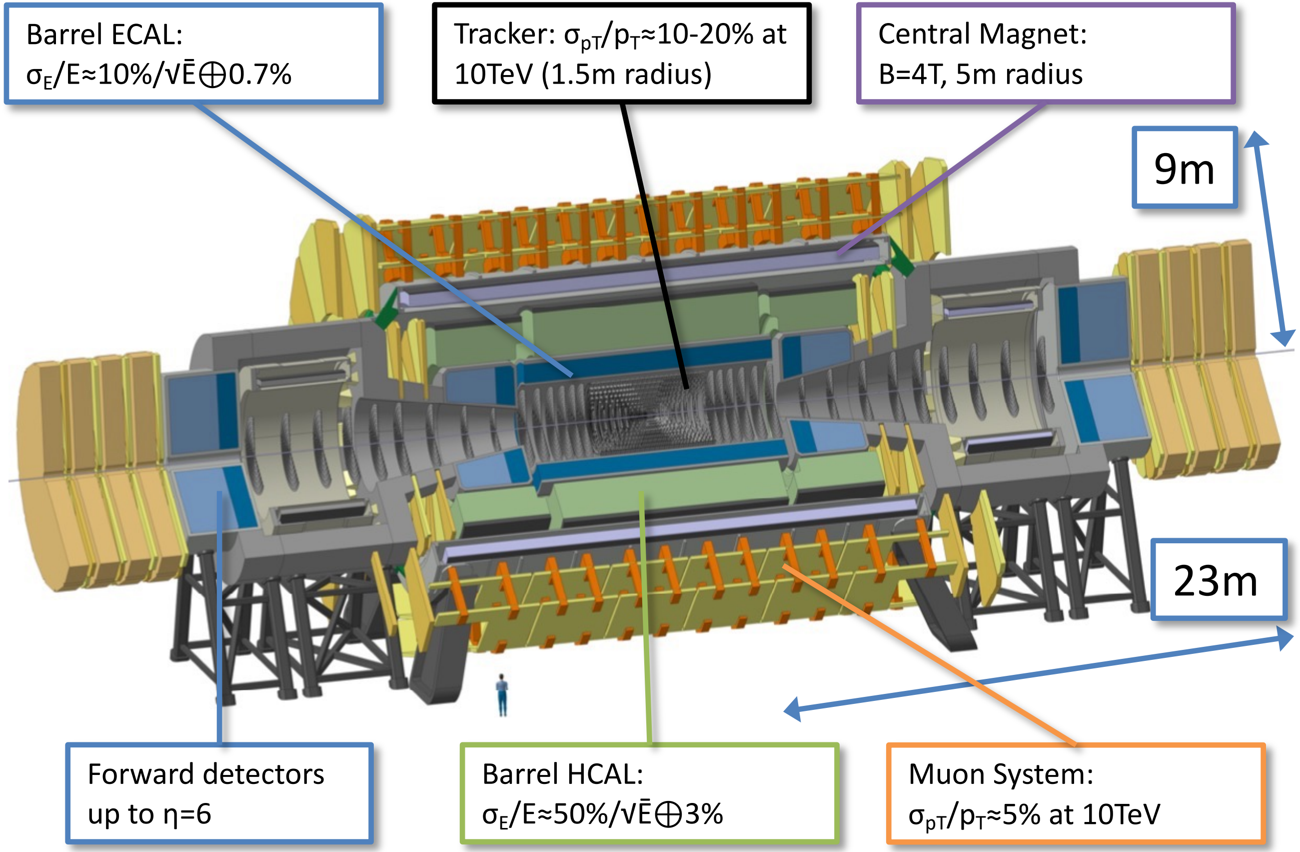
- **ID tracking target**: achieve σ_{pT} / p_T = 10-20% @ 10 TeV
- **Muon target**: σ_{pT} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ-tagging, particle ID**!
  - Pile-up of <μ>=1000 → 120μm mean vertex separation
- **High granularity** in tracker and calos (boosted obj.)
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6
- **→ Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**







A Possible FCC-hh Detector – Reference Design for CDR


Barrel ECAL:
$\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Tracker: $\sigma_{p_T}/p_T \approx$10-20% at 10TeV (1.5m radius)

Central Magnet:
B=4T, 5m radius

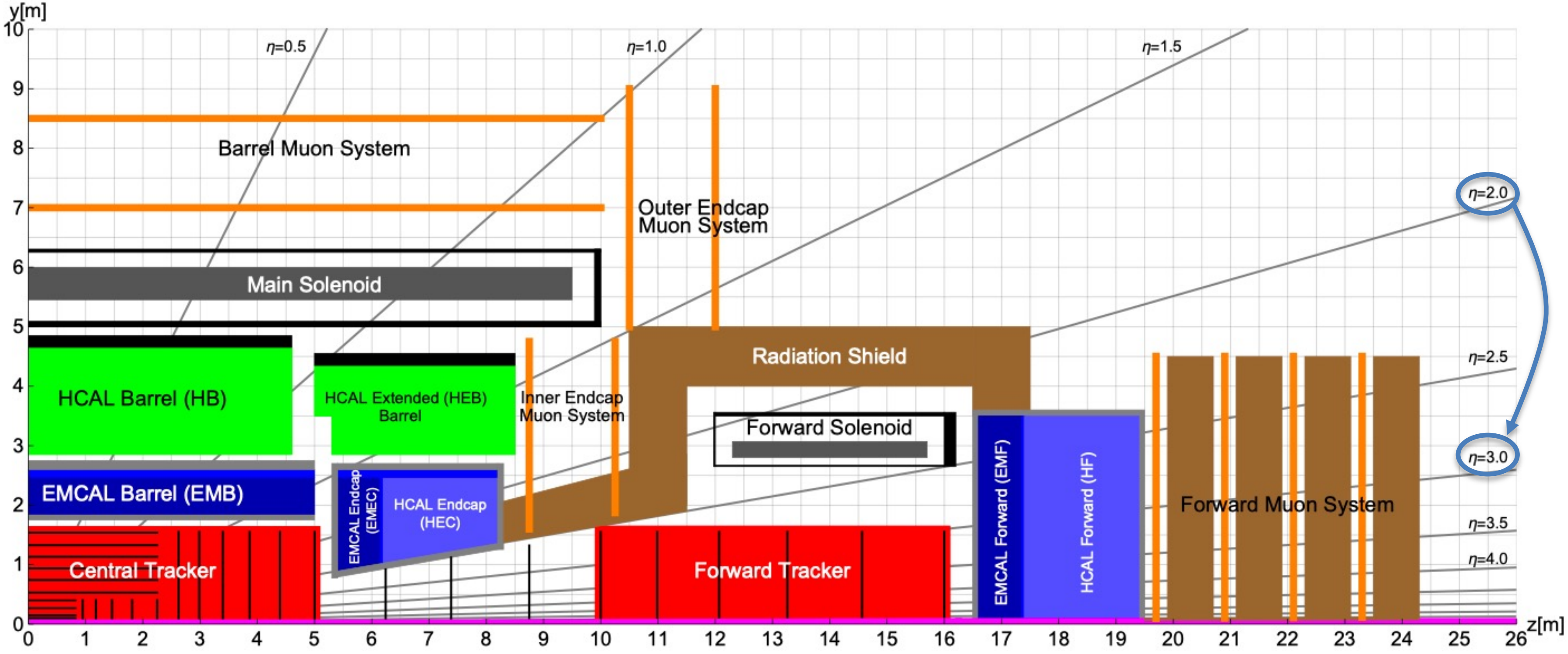
Forward detectors
up to η=6

Barrel HCAL:
$\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

Muon System:
$\sigma_{p_T}/p_T \approx 5\%$ at 10TeV

- Converged on **reference design for an FCC-hh experiment for FCC CDR**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**
- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

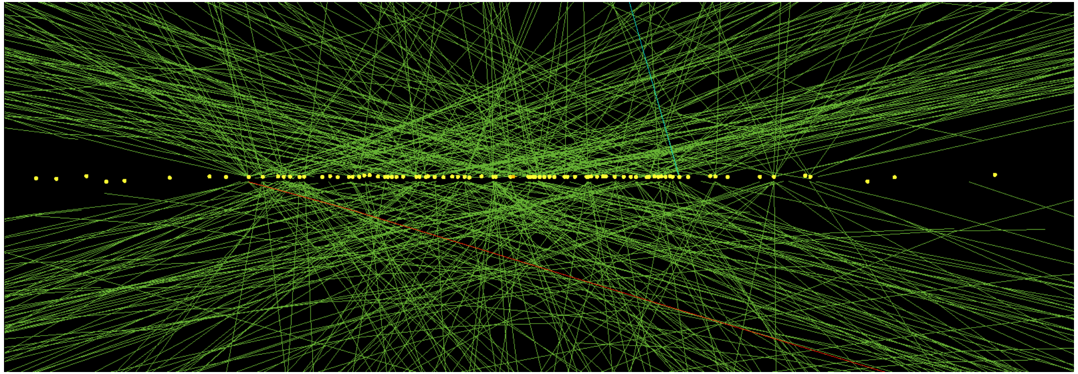
Reference Design for CDR



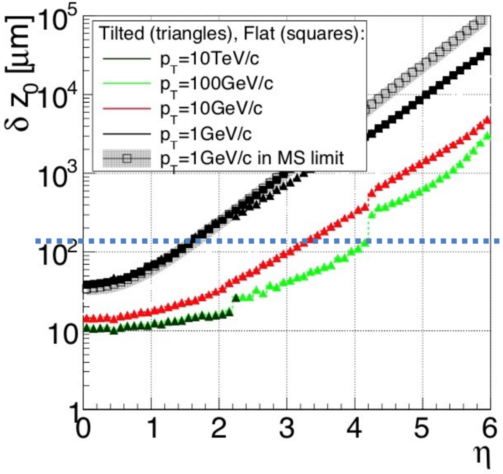
Forward solenoid adds about 1 unit of η with full lever-arm

Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

The Challenge of <μ> = 1000 Pile-Up



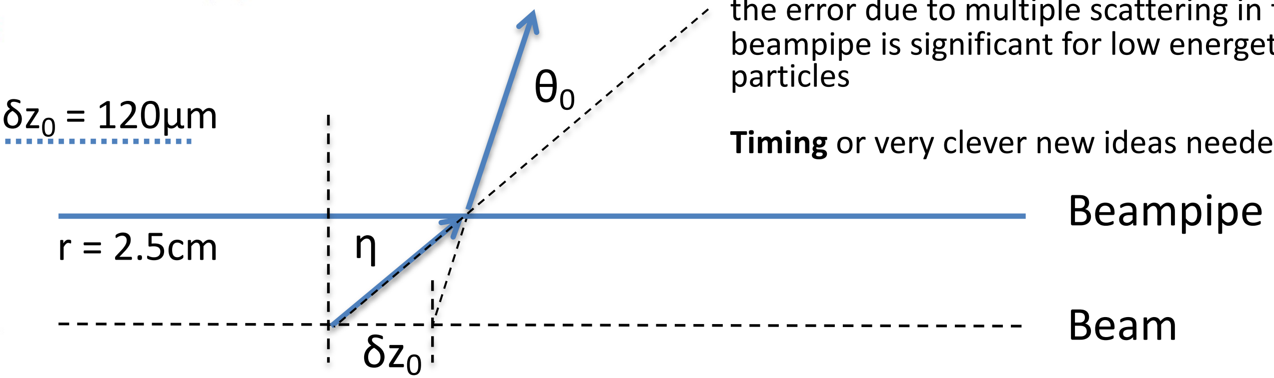
- HL-LHC average distance between vertices at z=0 is
  - **≈ 1mm in space and 3ps in time.**
- → For 6 times higher luminosity and higher c.m. energy at FCC-hh:
  - **≈ 120 μm in space and 0.4ps in time**
- **→ Future trackers will need to use both, position resolution and timing to identify the correct vertex!**



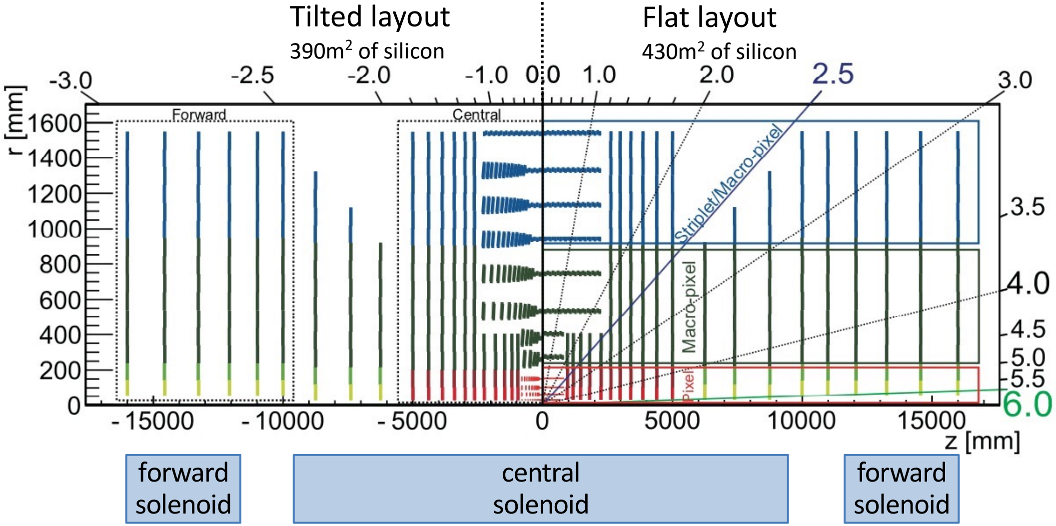
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

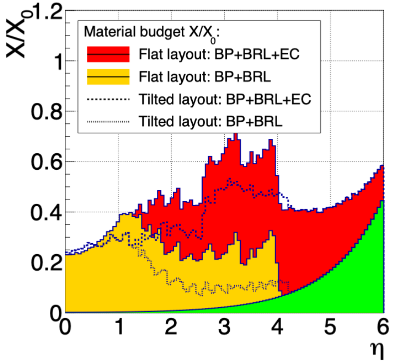
Multiple scattering in the beam pipe:
→ Even having a perfect tracking detector, the error due to multiple scattering in the beampipe is significant for low energetic particles

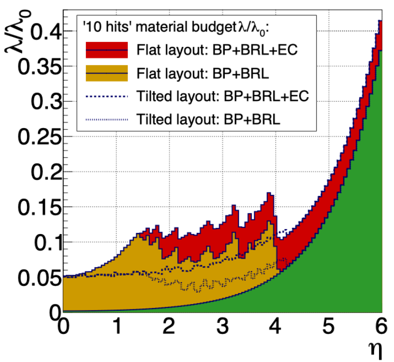
Timing or very clever new ideas needed …



FCC-hh Tracker







Tilted layout:		
$25 \times 50\,\mu m^2$ (1–4th BRL) $25 \times 50\,\mu m^2$ (1st EC ring) $33.3 \times 100\,\mu m^2$ (2nd EC ring) $33.3 \times 400\,\mu m^2$ (3–4th EC ring)	$33.3 \times 400\,\mu m^2$	$33.3\,\mu m \times 1.75\,mm$ (BRL) $33.3\,\mu m \times 1.75\,mm$ (EC) $33.3\,\mu m \times 50\,mm$ (12th BRL layer)

Assuming an r-phi resolution of 7.5-9.5µm per detector layer

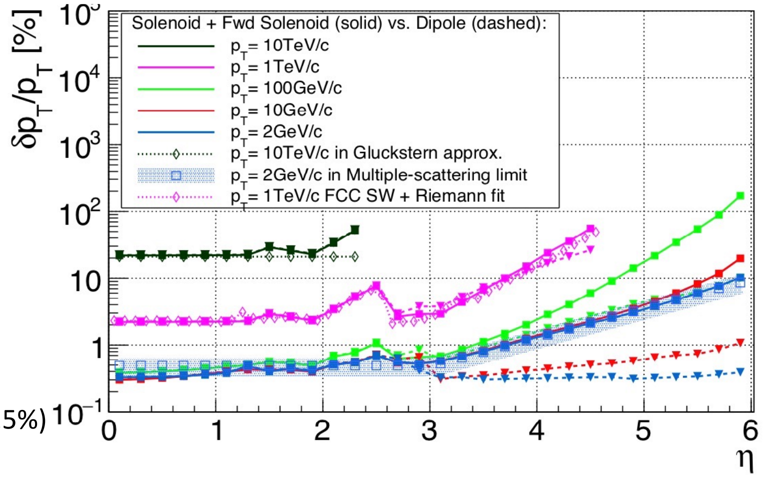
$\delta p_T/p_T$ ≤ 10% for

- ≤ 10 GeV/c and η ≤ 5.8
- ≤ 1 TeV/c and η ≤ 4.0

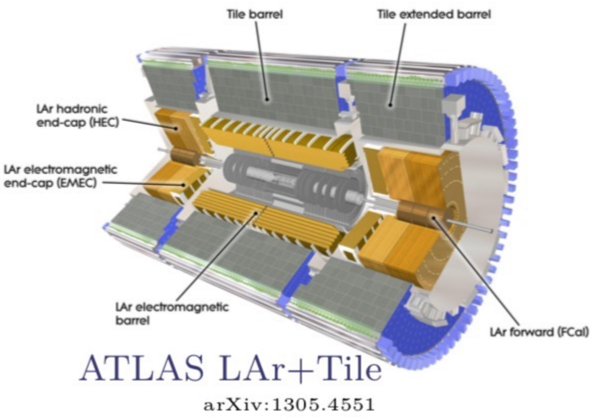
$\delta p_T/p_T$ = 20% for 10 TeV/c in the central region

Momentum resolution dominated by **multiple scattering** up to 250GeV (limit at $\delta p_T/p_T = 0.5\%$)

→ **low material tracker**!!



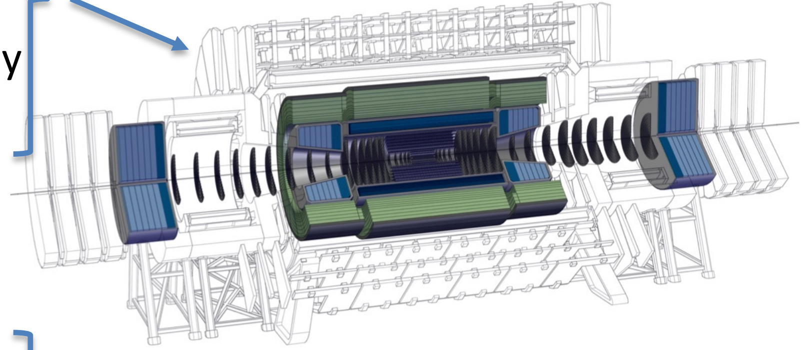
FCC-hh Calorimetry

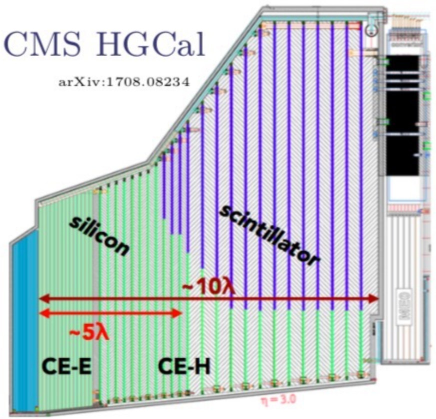


- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

FCC-hh Calorimetry

„conventional calorimetry“
optimized for particle flow
→ high granularity

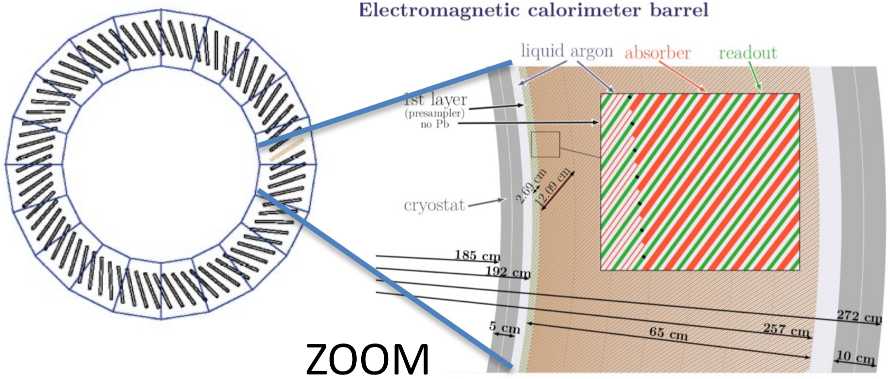


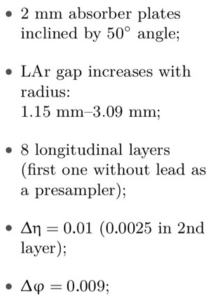


- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

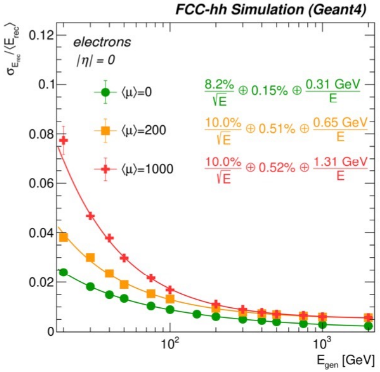
FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

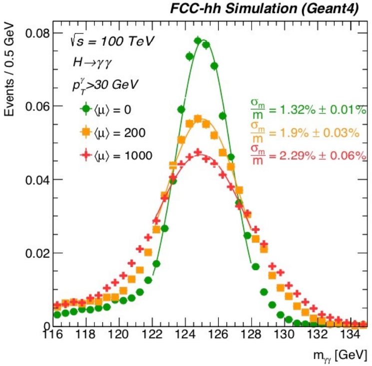
Electromagnetic Calorimeter (ECAL)



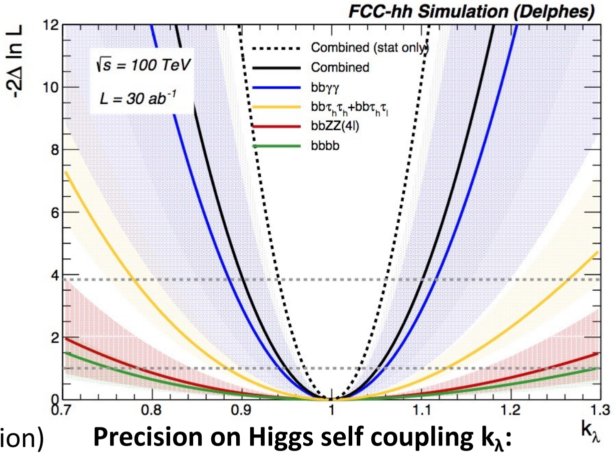


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity (Δη x Δϕ = 0.01 x 0.01, first layer Δη=0.0025),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√Ē, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (without in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Precision on Higgs self coupling k_λ:

$\delta k_\lambda/k_\lambda$ ≈5% (scenario II)

Conclusions

- **The European Strategy Update 2019/20 defined priorities for European Particle Physics and issued the request for a feasibility study of the FCC integrated programme to be delivered by end 2025.**
- **The FCC integrated program addresses the defined priorities for European Particle Physics in a unique way:**
  - **Higgs & EW factory followed by 100 TeV hadron collider**
- **The main activities of the FCC Feasibility Study are:**
  - concrete local/regional implementation scenario in collaboration with host state authorities,
  - accompanied by machine optimization, physics studies and technology R&D,
  - performed via global collaboration and supported by EC H2020 Design Study FCCIS,
  - in parallel High Field Magnet R&D program as separate line, to prepare for FCC-hh.
- **Next important milestone is the mid-term review planned for autumn 2023**
- **FCC-hh: Benchmark physics channels defined to determine requirements for experiments**
- **FCC-hh reference detector fulfilling these requirements has been developed and described in detail in the CDR and a CERN yellow report (to be published)**

Thank You for Your Attention!

Back-Up

FCC Stage 1: Infrastructure and FCC-ee Cost Estimate

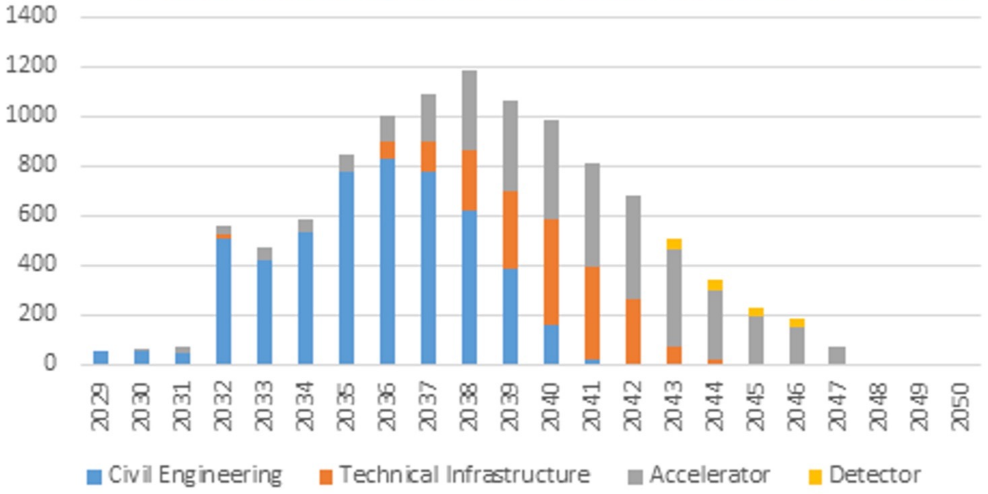
Construction cost estimate for FCC-ee

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

Spending profile for FCC-ee

- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.

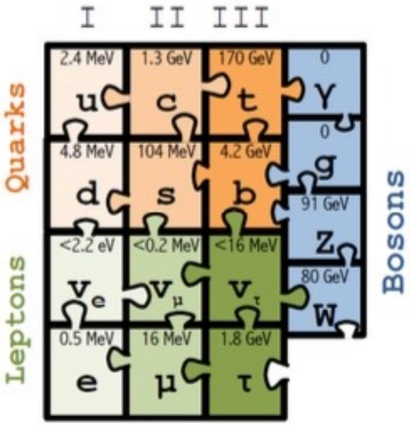


FCC Feasibility Study Overview
Michael Benedikt
Paris, 30 May 2022

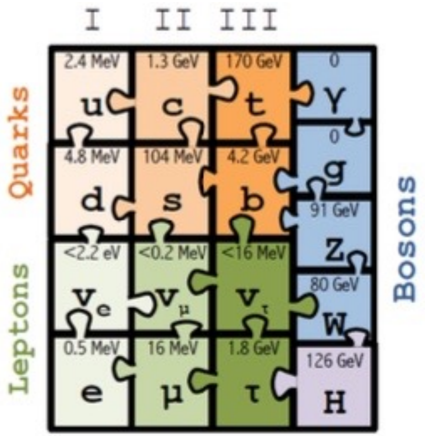
Why Future Colliders?

The Physics Landscape

1989–1999:
Top mass predicted
(LEP mZ and ΓZ)
Top quark observed
at the right mass
(Tevatron, 1995)
Nobel Prize 1999
(t'Hooft & Veltman)



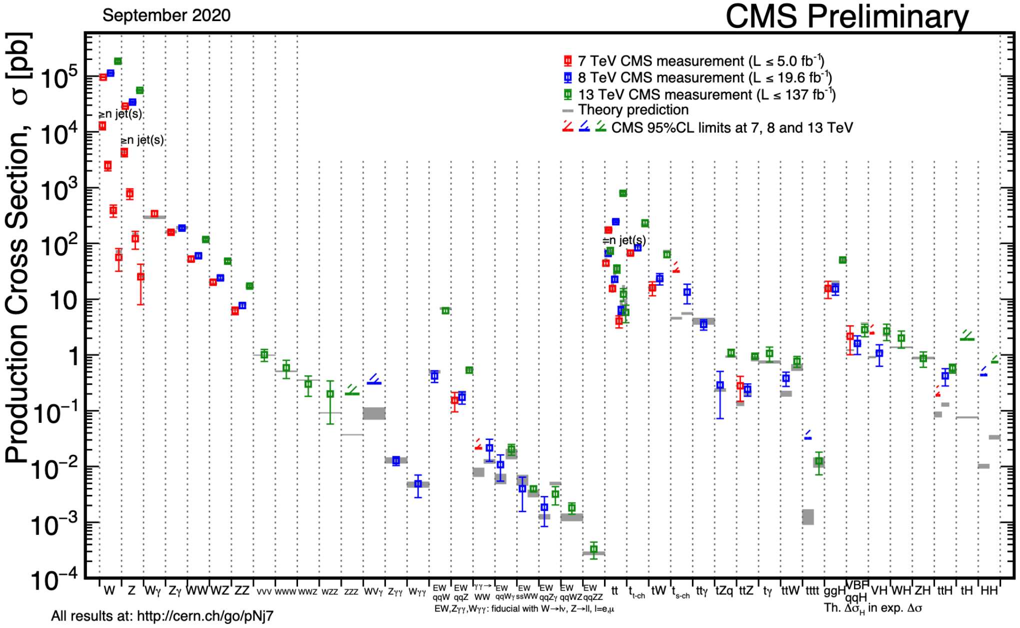
1997–2013:
Higgs mass cornered
(LEP EW + Tevatron mtop , mW)
Higgs boson observed
at the right mass
(LHC 2012)
Nobel Prize 2013
(Englert & Higgs)



It looks like the **Standard Model** (SM) is a **complete and consistent theory**

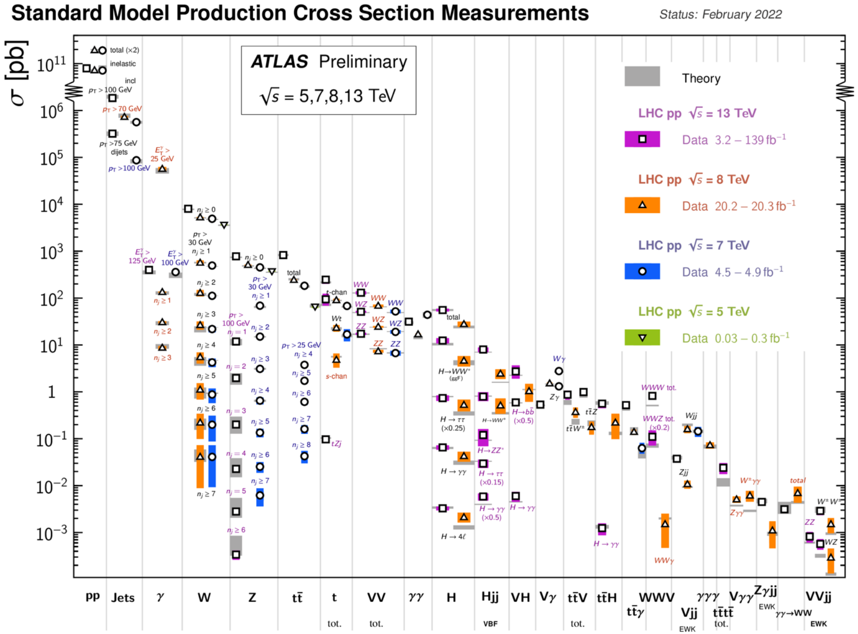
- It describes **all observed collider phenomena** – and actually **all particle physics** (except neutrino masses)
- Was beautifully **verified** in a complementary manner at LEP, SLC, Tevatron, and LHC
- **EWPO radiative corrections** predicted **top** and **Higgs** masses assuming **SM and nothing else**

The SM and … the LHC Data so Far


September 2020

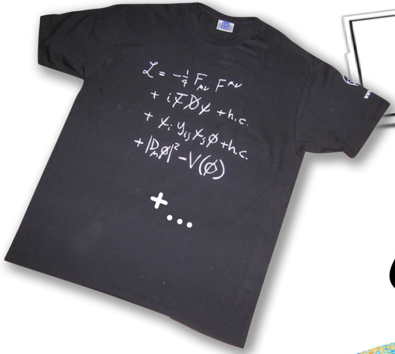
CMS Preliminary

All results at: http://cern.ch/go/pNj7


Standard Model Production Cross Section Measurements

Status: February 2022

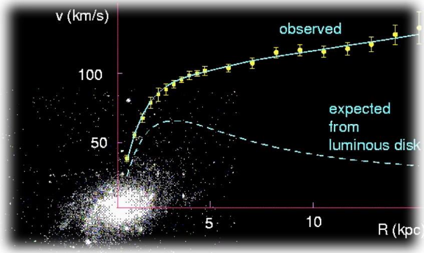
The SM and … the Rest of the Universe

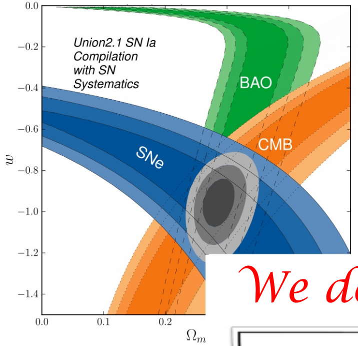


is not enough

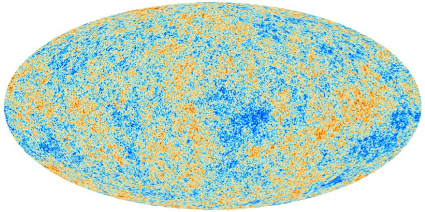
- Neutrino masses
- Dark Matter
- Dark Energy
- Quantum gravity

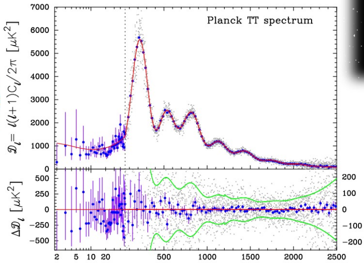
The observed rotation curve of the dwarf spiral galaxy M33 extends considerably beyond its optical image





Ωm-w with CMB, BAO, and SCP Union2.1 SN Constraints, including SN systematics

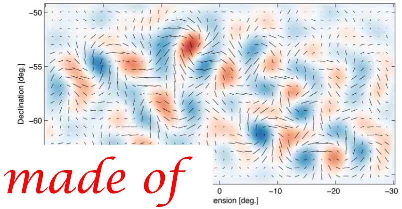




Angular power spectrum of CMB anisotropies measured from the latest Planck satellite data (© ESA and the Planck Collaboration). The wiggles seen in the spectrum are the feature of BAO, and the oscillation scale corresponds to the sound horizon at recombination. The best-fitting ΛCDM theoretical spectrum is plotted as the solid line in the upper panel.

COSMIC SWIRL Gravitational waves generated during a period of cosmic inflation twirl light from the cosmic microwave background, as seen in this sky map from the BICEP2 telescope. The lines trace the alignment, or polarization, of photons released after the Big Bang; the line lengths show the light's intensity. The colors indicate how strongly twisted the polarization is, both clockwise (red) and counterclockwise (blue).

BICEP2 COLLABORATION

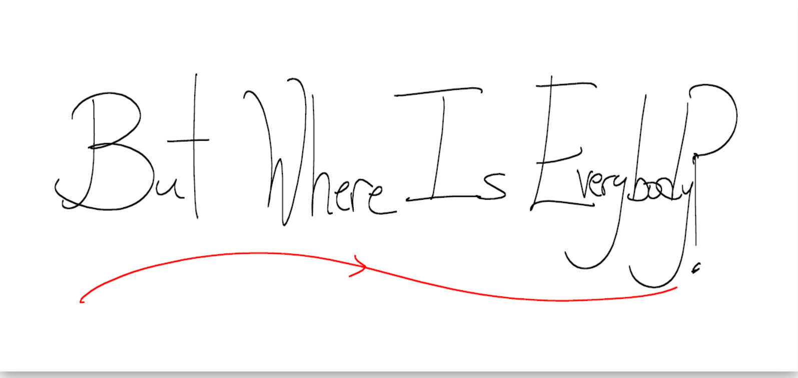


We do not understand the Matter the Universe is made of

Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?

LHC Sees No New Physics at the TeV Scale – Why?

- Is the mass scale beyond the LHC reach?
- Is the mass scale within the LHC's reach but final states are elusive to the direct search?
- A priori these scenarios are **equally likely**, but they impact in a different way the future of HEP and the assessment of the physics potential for possible future facilities.
- **To address both scenarios we need:**
  - Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles
    - → precision
  - Direct searches for new heavy particles
    - → extended energy and mass reach
  - Sensitivity to elusive signatures



But Where Is Everybody?

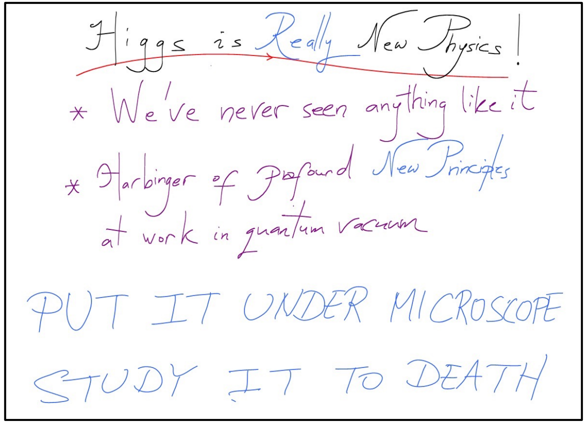
Nima Arkani-Hamed (FCC-Week 2019)

→ Precision frontier

→ Energy frontier

→ Luminosity & Detectors

A Concrete Target – The Higgs Boson

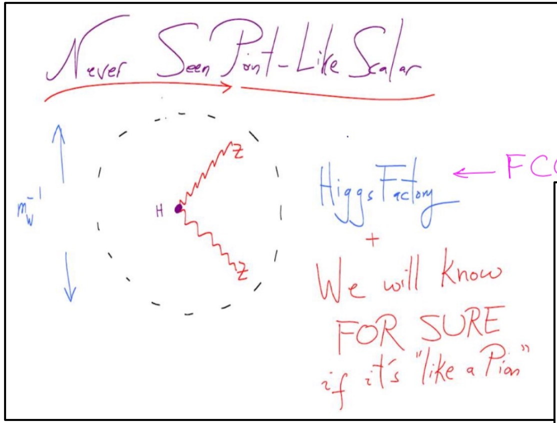


Higgs is Really New Physics!

- We've never seen anything like it
- Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH

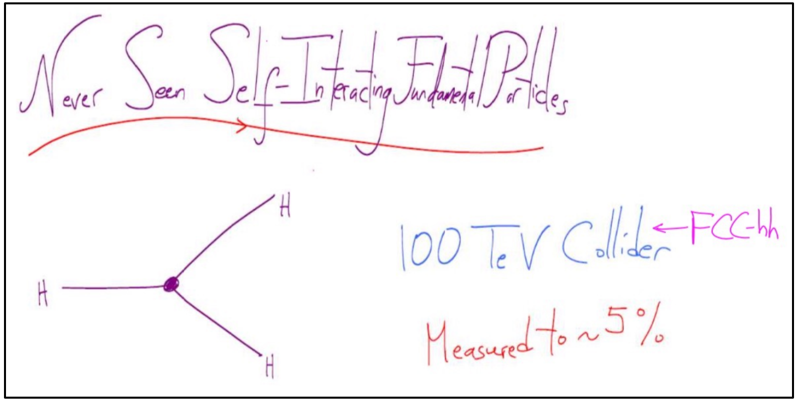


Never Seen Point-Like Scalar

Higgs Factory ← FCC-ee

+

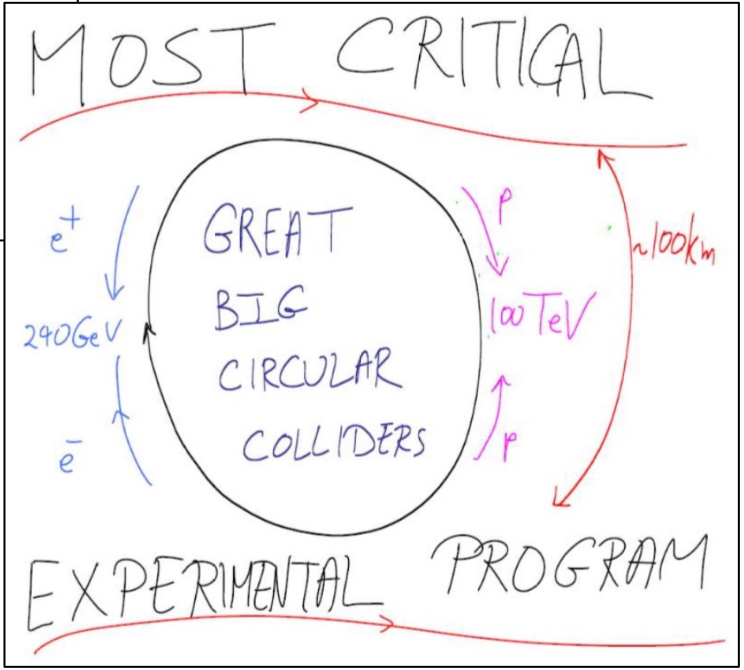
We will know FOR SURE if it's "like a Pion"



Never Seen Self-Interacting Fundamental Particles

100 TeV Collider ← FCC-hh

Measured to ~5%



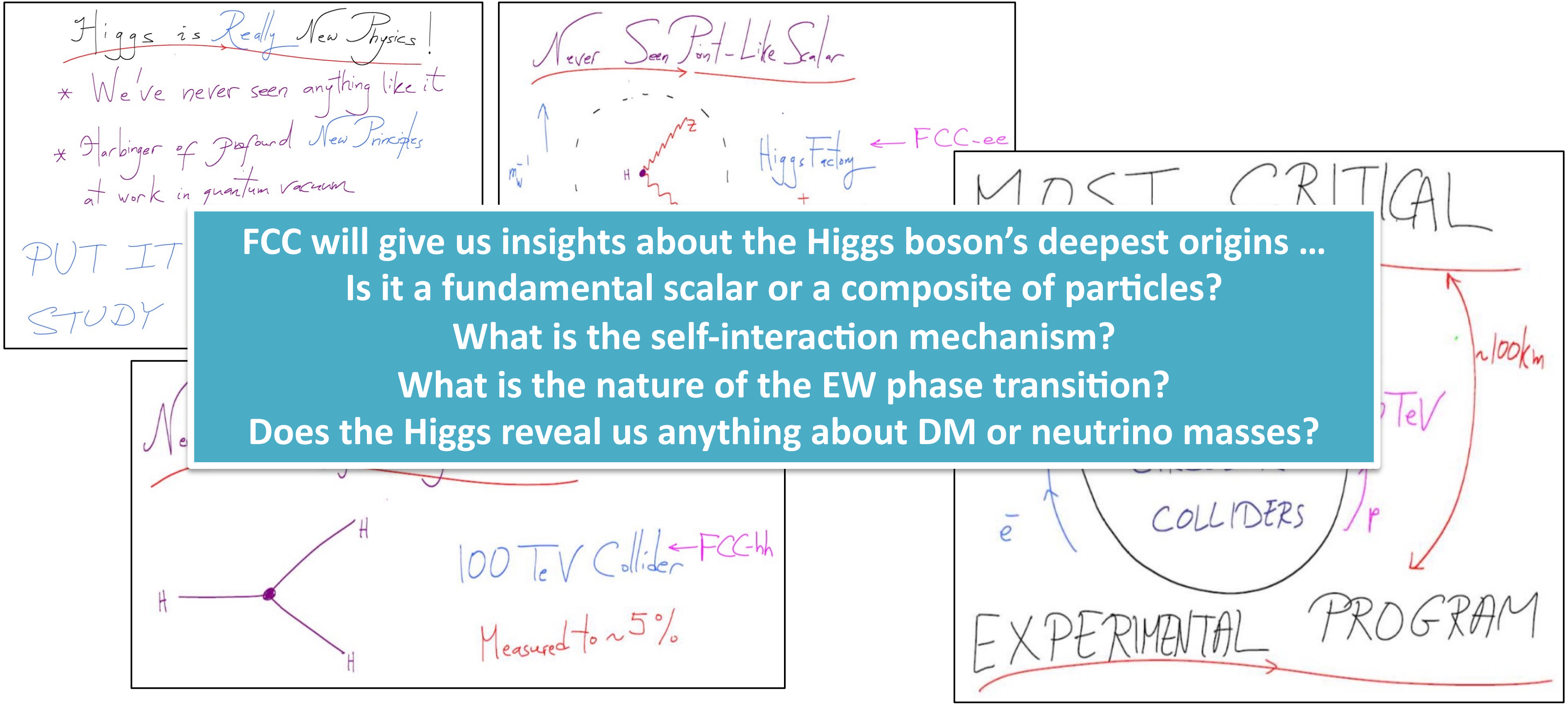
MOST CRITICAL

GREAT BIG CIRCULAR COLLIDERS

EXPERIMENTAL PROGRAM

Nima Arkani-Hamed (FCC-Week 2019, Higgs Symposium July 4, 2022)

A Concrete Target – The Higgs Boson



Higgs is Really New Physics!

* We've never seen anything like it

* Harbinger of Profound New Principles at work in quantum vacuum

PUT IT

STUDY

Never Seen Point-Like Scalar

Higgs Factory ← FCC-ee

100 TeV Collider ← FCC-hh

Measured to ~5%

MOST CRITICAL

COLLIDERS

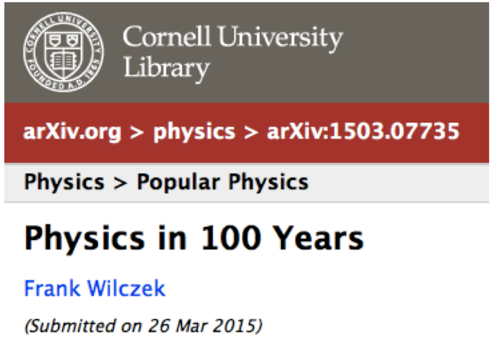
EXPERIMENTAL PROGRAM

FCC will give us insights about the Higgs boson's deepest origins …
Is it a fundamental scalar or a composite of particles?
What is the self-interaction mechanism?
What is the nature of the EW phase transition?
Does the Higgs reveal us anything about DM or neutrino masses?

Nima Arkani-Hamed (FCC-Week 2019, Higgs Symposium July 4, 2022)

A Unique Moment in the History of Physics

- The **Higgs** discovery is the triumph of 20th century physics – combination of **Quantum Mechanics and Special Relativiy**
- For the first time in the history of physics we have a **consistent** description of the **fundamental constitutents of matter** and their **interactions** and this description can be **extrapolated to very high energies** (up to M_{Planck}?)


Cornell University Library

arXiv.org > physics > arXiv:1503.07735

Physics > Popular Physics

Physics in 100 Years

Frank Wilczek

(Submitted on 26 Mar 2015)

The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

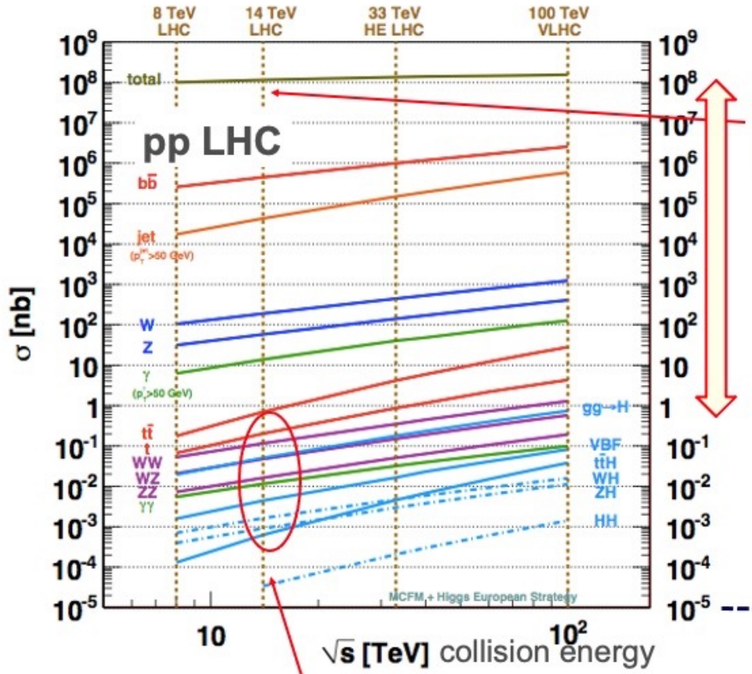
Historic Overview of Important Discoveries

Year	Discovery	Experiment	√s [GeV]	Observation
1974	**c quark** (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \rightarrow J/\Psi)$ $J/\Psi \rightarrow \mu^+\mu^-$
1975	**τ lepton** (m=1.777 GeV)	e^+e^- ring (SPEAR/SLAC)	8	$e^+e^- \rightarrow \tau^+\tau^-$ $e^+\mu^-$ events
1977	**b quark** (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \rightarrow \mu^+\mu^-$
1979	**gluon** (m = 0)	e^+e^- ring (PETRA/DESY)	30	$e^+e^- \rightarrow qqg$ Three-jet events
1983	**W, Z** (m ~ 80, 91 GeV)	pp ring (SPS/CERN)	900	$W \rightarrow \ell\nu$ $Z \rightarrow \ell^+\ell^-$
1989	**Three neutrino generations**	e^+e^- ring (LEP/CERN)	91	Z-boson lineshape *measurement*
1995	**t quark** (m=173 GeV)	pp ring (Tevatron/FNAL)	1960	Two semileptonic t-quark decays
2012	**Higgs boson** (m=125 GeV)	pp ring (LHC/CERN)	8000	$H \rightarrow \gamma\gamma$, $H \rightarrow Z^*Z \rightarrow 4\ell$

What do we see?

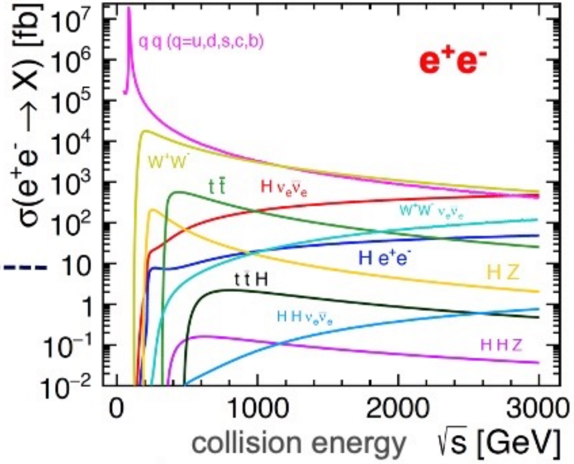
- Centre of mass energy increases
- Moving from fixed target to colliders
- Different types of particles colliding
- Alternance of e^+e^- and pp machines

e^+e^- vs. pp Collisions – Cross Section Comparison



LHC total cross section factor > 100 million !!

At LHC, much of the interesting physics needs to be found among a huge number of collisions

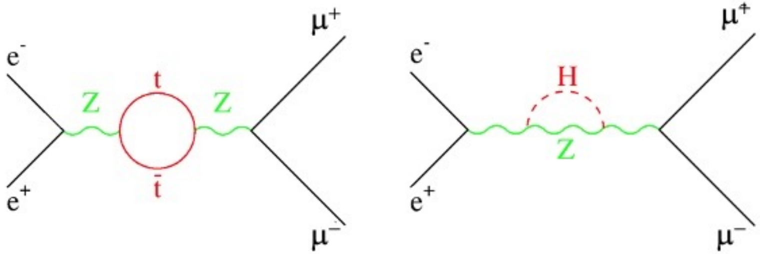


e^+e^- events are “clean”

Precision ↔ Discovery

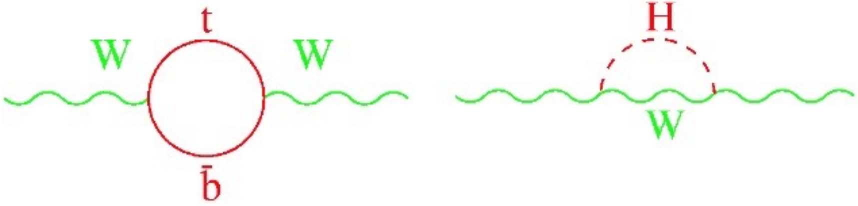
Electroweak observables are sensitive to heavy particles in “loops”

- For example, in the standard model: $\Gamma(Z\rightarrow\mu^+\mu^-)$ or m_W



$$\Gamma_{ll} = \frac{G_F}{\sqrt{2}} \frac{m_Z^3}{24\pi}\left(1+\left[\frac{1}{4}-\sin^2\theta_W^{eff}\right]^2\right)\times(1+\Delta\rho)$$

$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

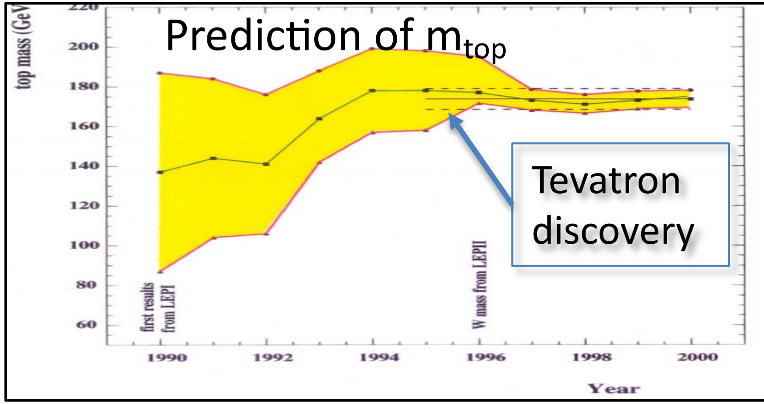


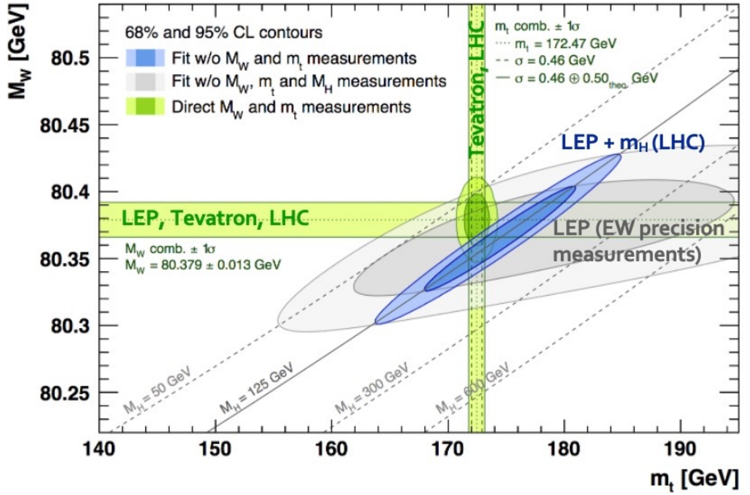
$$m_W^2 = \frac{\pi\alpha_{QED}\left(m_Z^2\right)}{\sqrt{2}G_F\sin^2\theta_W^{eff}} \times \frac{1}{1-\Delta r}$$

$$\Delta r = -\frac{\cos^2\vartheta_W}{\sin^2\vartheta_W}\Delta\rho + \frac{\alpha}{3\pi}\left[\frac{1}{2}-\frac{1}{3}\frac{\sin^2\vartheta_W}{1-\tan^2\vartheta_W}\right]\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots \approx 1\%$$

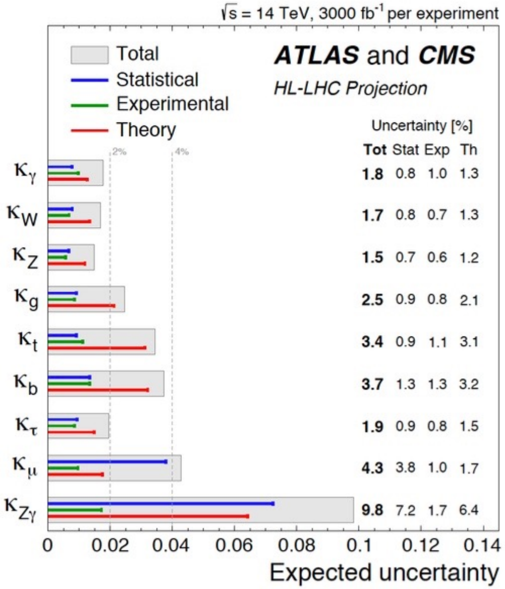
Precision ↔ Discovery

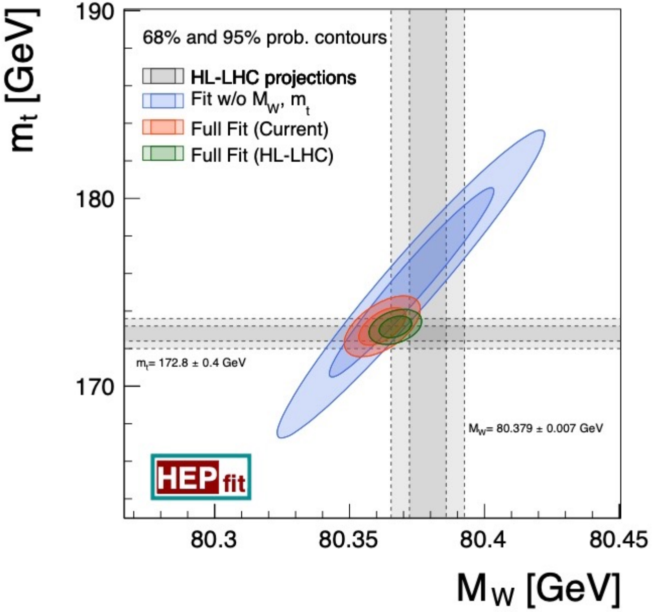
- **Top quark**
  - 1990-1994: Mass predicted from quantum loops
    - m_{top}(pred.) = 178.0 ± 10 GeV
  - 1995: Discovered at the Tevatron (DØ, CDF)
    - Today: m_{top}(obs.) = 173.23± 0.7 GeV
- **Higgs boson**
  - 1996-2011: Mass predicted from quantum loops
    - m_{Higgs}(pred.) = 98^{+25}_{-21} GeV
  - 2012: Discovery at the LHC (ATLAS, CMS)
    - Today: m_{Higgs}(obs.) = 125.09 ± 0.24 GeV
- → **Precision measurements** interpreted via quantum loop corrections can give very strong constraints on particles at higher masses than what can be directly probed!
- **Within current precision direct and indirect constraints are consistent**
  - → No evidence for the need for BSM physics
- **But what if measurements' precisions were improved ?**
  - Strong incentive to significantly improve the precision of all measurement





Where Will We Stand After HL-LHC





LHC is a Higgs factory (100 million H already produced)….
But:

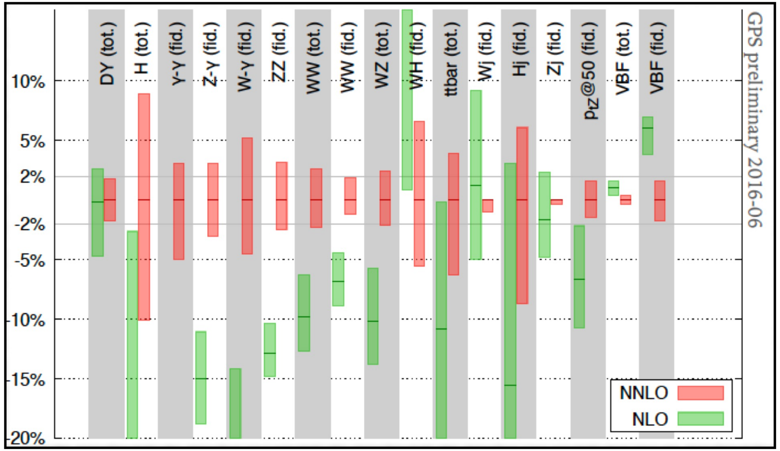
$$\sigma^{\text{observed}}_{\text{i}\to\text{f}} \propto \sigma_{\text{prod}} \frac{g^2_{\text{Hi}}\, g^2_{\text{Hf}}}{\Gamma_{\text{H}}}$$

σ_{prod} uncertain and $\boldsymbol{\Gamma}_{\text{H}}$ unknown until measured (SM value used) → difficult to extract couplings (must do ratios)!

- Careful studies and projections for the **physics at the HL-LHC** have shown:
  - We have designed amazing detectors (ATLAS, CMS and their Phase II Upgrades) that will be able to fully mitigate the conditions created by 200 pile-up events (collisions in the same bunch crossing)
  - Uncertainties on **Higgs couplings of the order of 2-4%** and top mass about ~200MeV
- **This precision might still not be sufficient to show the effect of new physics...**

FCC-ee: The SM Challenges

- **Statistical uncertainty will become less and less important → Systematic uncertainty will become dominant!**
- **We therefore require:**
  - Better control of parametric uncertainties, e.g. PDFs, α_s,m_t,m_H
  - Higher order theoretical computations, e.g. N…NLO
  - Access to phase-space limited regions
  - Understand correlations among bins in distributions
  - Detector systematics



Don't think future HEP is only EXP-business. Theorists have to work harder too!

FCC-hh: Criteria for Physics Potential of Future Colliders

- **Guaranteed Deliverables:**
  - Study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable precision and sensitivity
    - Sensitivity to the shape of the Higgs potential (Higgs self coupling, mainly FCC-hh)
  - Ultimate precision standalone and in combination with FCC-ee and FCC-eh
- **Exploration Potential:**
  - Mass reach enhanced by factor ~ E / 14 TeV
    - will be 5–7 at 100 TeV, depending on integrated luminosity
  - Sensitivity to rare processes enhanced by orders of magnitude
  - Benefit from indirect precision probes at low and high Q^2
- **Provide YES/NO Answers:**

  ...to questions like...
  - Is the SM dynamics all there is at the TeV scale?
  - Is there a TeV-scale solution to the hierarchy problem?
  - Is DM a thermal WIMP?
  - Was the cosmological EW phase transition 1st order?
  - Could baryogenesis take place during the EW phase transition?

M. Mangano, Sept. 2018

FCC-hh: SM Higgs: Event Rates at 100TeV

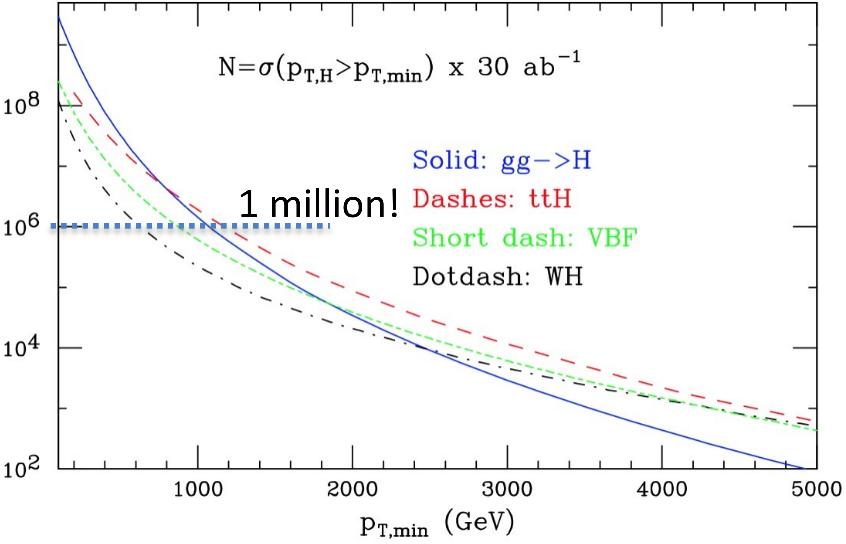
	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$$N_{100} = \sigma_{100\text{TeV}} \text{ x } 30\text{ab}^{-1}$$

$$N_{14} = \sigma_{14\text{TeV}} \text{ x } 3\text{ab}^{-1}$$

Large statistics!

FCC-hh – The ultimate Higgs Factory!

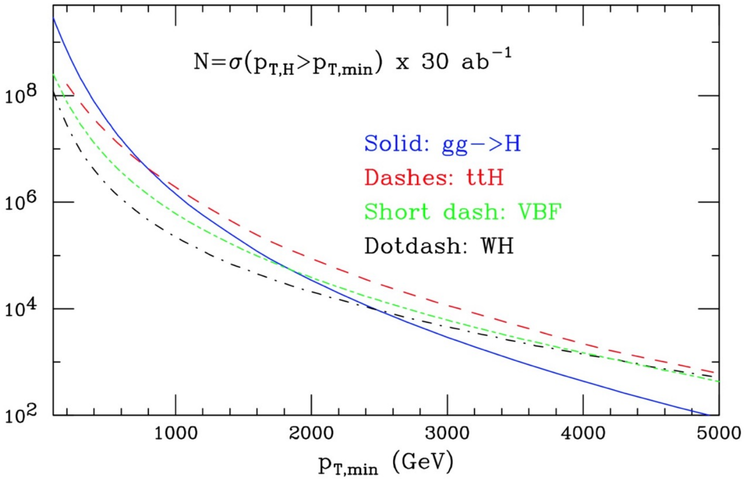


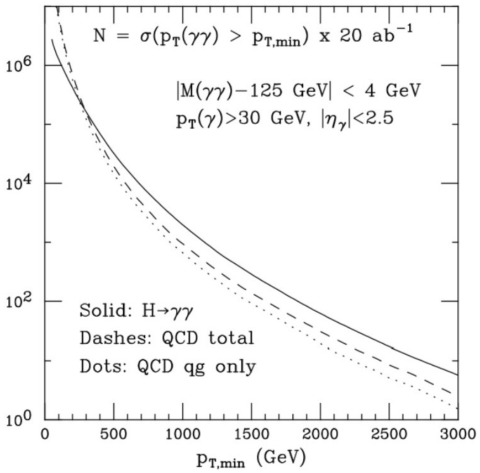
Large kinematic range of Higgs production

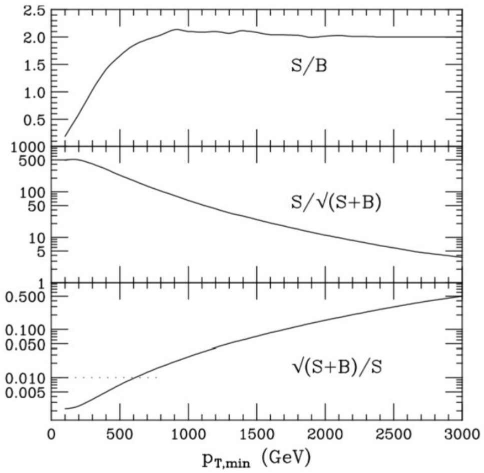
Hierarchy of production channels **changes at large p_T(H):**

- σ(ttH) > σ(gg→H) above 800 GeV
- σ(VBF) > σ(gg→H) above 1800 GeV

FCC-hh: Higgs at Large p_T

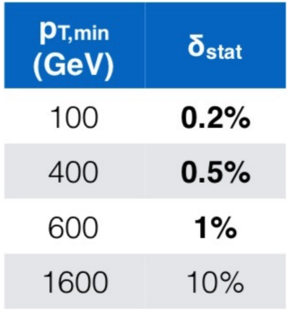






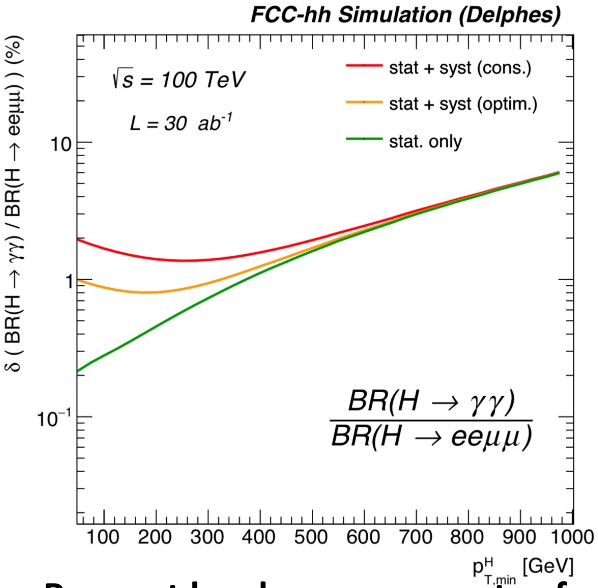
- Hierarchy of production channels changes at large $p_T(H)$:
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

- At LHC, S/B in the H→γγ channel is O(few %) ≈1/30
- At FCC, for $p_T(H)$>300 GeV, S/B≈1
- Potentially accurate probe of the H p_T spectrum up to large p_T

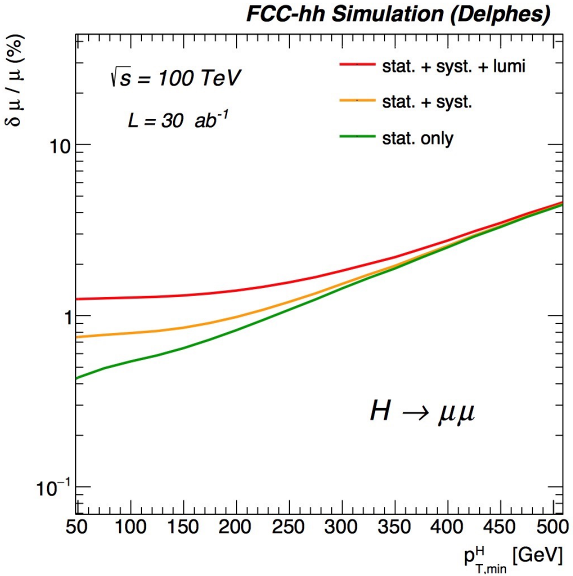


$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

FCC-hh: Example – Higgs Couplings

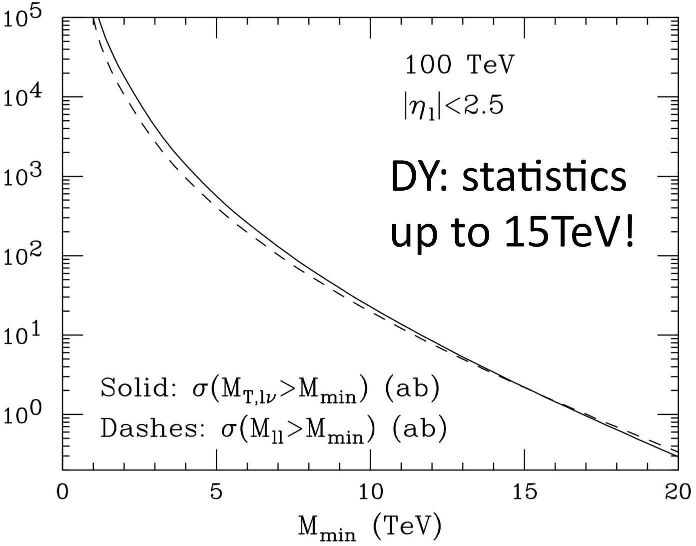


Delphes simulation of realistic detector including systematic uncertainties



- **Per-cent level measurements of ratios of branching ratios**
  - Model independent sensitivity to BSM
- Ratios of BR: Well defined fiducial region → **remove production and modeling systematics**
- **Normalise to BR (4 leptons) from FCC-ee** (known at the few per-mille, see before)
- **High p_T region:** Reduced systematics (e.g. from pile-up, from background)
- **→ Absolute sub-% measurements for rare decays → Precision on Higgs couplings in the sub-% range**

FCC-hh: Indirect Sensitivity to High-Energy Scales



DY: statistics up to 15TeV!

- Improve constraints on oblique parameters W and Y by two orders of magnitude!
- → **Sensitivity up to the 100TeV range!**

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
	luminosity	$2 \times 10^7\, Z$	$19.7\,\text{fb}^{-1}$	$20.3\,\text{fb}^{-1}$	$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$10^{12}\, Z$
NC	W $\times 10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	± 1.5	± 0.8	± 0.04	± 1.2
	Y $\times 10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	± 2.3	± 1.2	± 0.06	± 1.5
CC	W $\times 10^4$	—	± 3.9		± 0.7	± 0.45	± 0.02	—

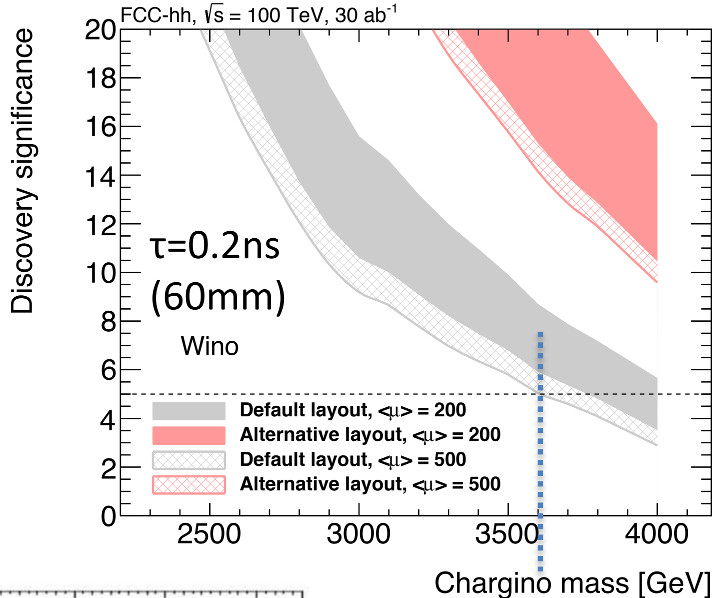
$g_*^2/\Lambda^2 = W/(4m_W^2) < 1/(100\ \text{TeV})^2$ → **Λ > 100 TeV**

FCC-hh: Yes/No Answers – WIMP DM

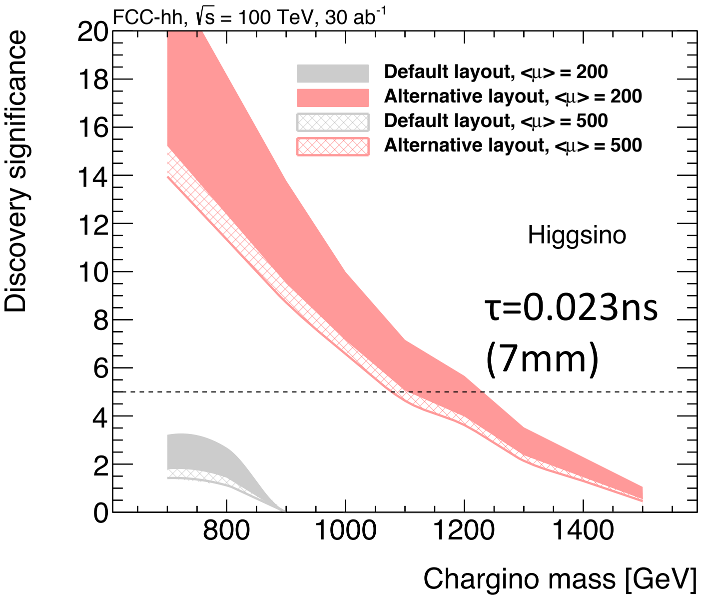
Disappearing tracks:

$$\chi^{\pm} \rightarrow \pi^{\pm}\chi^{0}$$

$\chi^{\pm}$ and χ^{0} degenerate → only 160MeV mass splitting (3 TeV Wino) → 0.2ns lifetime (60mm)

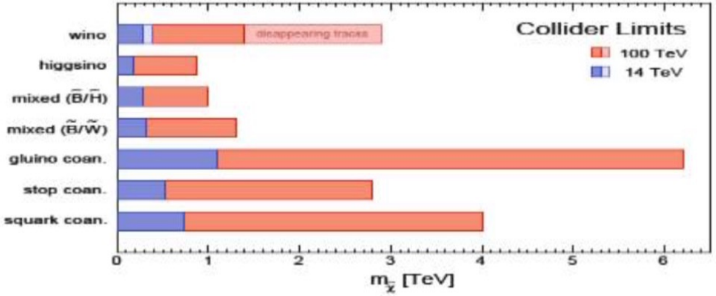


τ=0.2ns (60mm)



τ=0.023ns (7mm)

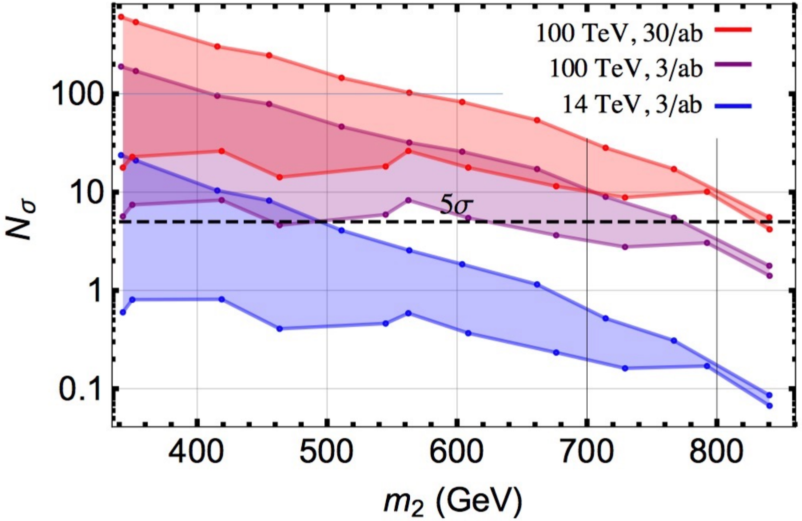
https://cds.cern.ch/record/2642474



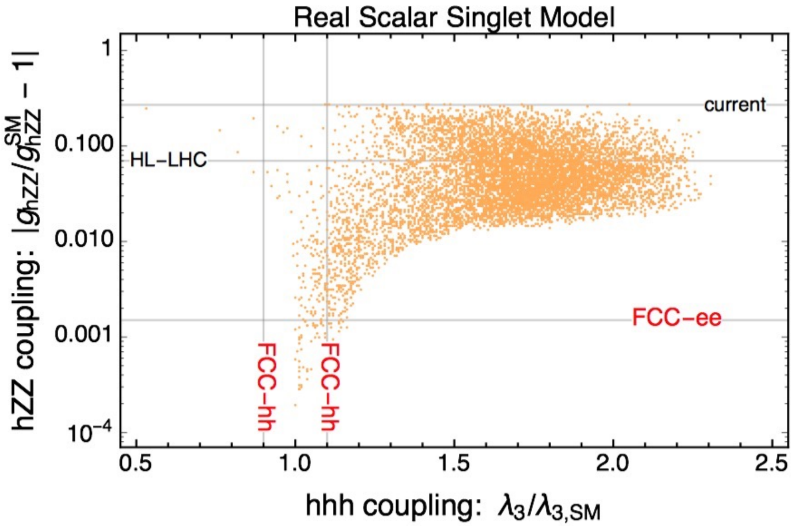
- If **DM is a WIMP**, then upper limit on M_{DM} of 110TeV (unitarity bound)
- Observed **relic abundance** of **DM → 1TeV (Higgsino-like), 3TeV (Wino-like)**
  - Disappearing tracks analysis shows discovery potential beyond upper limits of M_{DM}
- In a similar way FCC-hh can **explore conclusively EW charged WIMP models**

FCC-hh: Yes/No Answers – 1st Order EW Phase Transition

arXiv:1605.06123

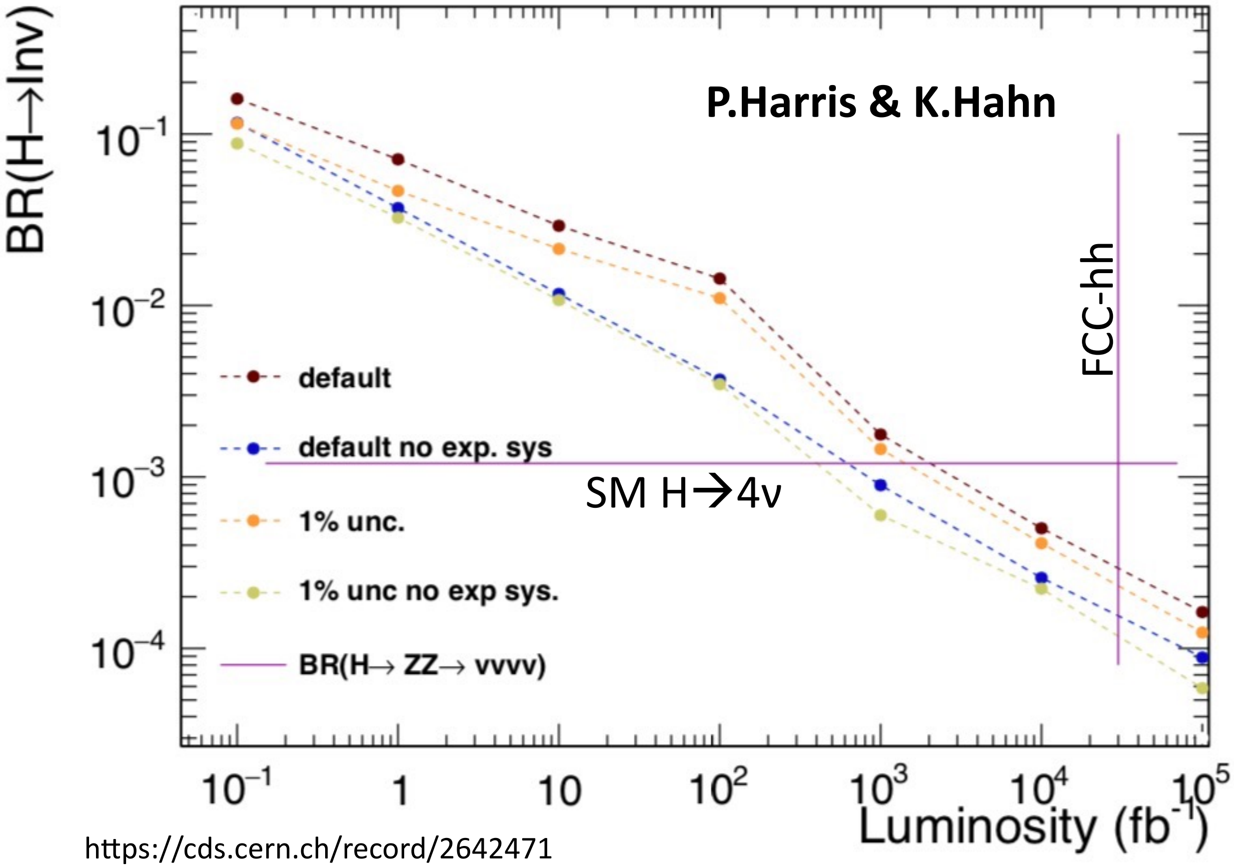


arXiv:1608.06619



- **Strong 1st order EWPT** required to induce **matter-antimatter asymmetry** at EW scale.
- **Example:** BSM scenarios with additional Higgs singlet m_2 decaying into SM Higgs pairs
- → **FCC-hh would enable direct discovery** over full possible mass range of m_2 (≤ 900GeV)
- → **Indirect: 7% precision on triple-Higgs coupling** will reduce number of possible BSM models → important redundancy

FCC-hh: Example – BR (H→inv) in H+X Prod. at Large p_T(H)



https://cds.cern.ch/record/2642471

Leading background from W/Z+jets

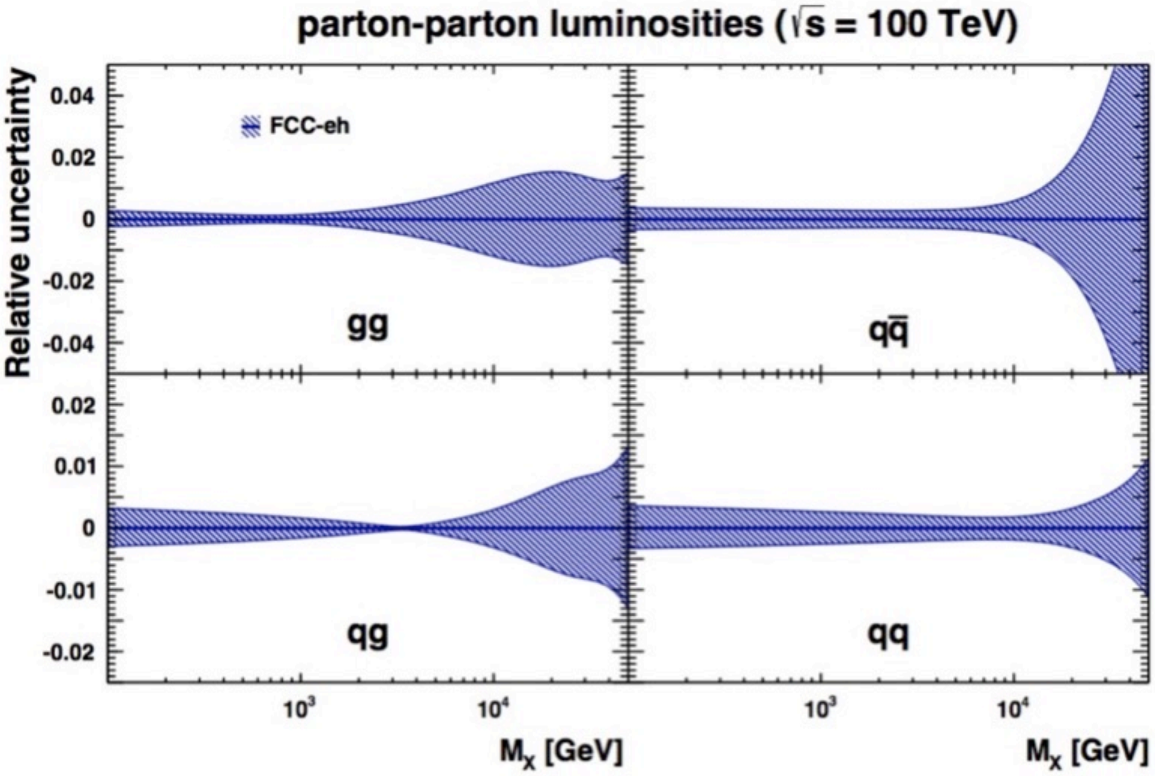
Constrain background p_T spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra

Sensitivity of $2x10^{-4}$!

→ Implications on dark matter searches!

FCC-eh: Ground Work for Precision at 100 TeV

PDF determination at FCC-eh



Uniqueness of FCC-hh Higgs Physics Potential

- **Huge Higgs Production Rates:**
  - Access (very) rare decay modes
  - Push to %-level Higgs self-coupling measurement
  - New opportunities to reduce systematic uncertainties (TH & EXP) and push precision
- **Large Dynamic Range for H Production (in p_T^H, m(H+X) , ...):**
  - New opportunities for reduction of systematic uncertainties (TH and EXP)
  - Different hierarchy of production processes
  - Develop indirect sensitivity to BSM effects at large Q^2, complementary to that emerging from precision studies (e.g. decay BRs) at $Q \sim m_H$
- **High Energy Reach:**
  - Direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
    - …

FCC-hh: Accelerator and Experiments

FCC-hh: Beam and Luminosity Evolution

During the beams are in collision the instantaneous value of the luminosity will change:

$$\mathcal{L}(t) = A\frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}}$$

The beam evolution with time is obtained by solving a system of four differential equations (dominant effects only shown here, more included in simulations):

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\sigma_{c,\mathrm{tot}}A\frac{N_b^2}{\sqrt{\epsilon_x\epsilon_y}}$$

Intensity

$$\frac{\mathrm{d}\epsilon_x}{\mathrm{d}t} = \epsilon_x(\alpha_{\mathrm{IBS},x} - \alpha_{\mathrm{rad},x})$$

Hor. Emittance

$$\frac{\mathrm{d}\epsilon_y}{\mathrm{d}t} = \epsilon_y(\alpha_{\mathrm{IBS},y} - \alpha_{\mathrm{rad},y})$$

Ver. Emittance

$$\frac{\mathrm{d}\sigma_s}{\mathrm{d}t} = \frac{1}{2}\sigma_s(\alpha_{\mathrm{IBS},s} - \alpha_{\mathrm{rad},s})$$

Bunch Length

with

$$A = f_{\mathrm{rev}}k_b/(4\pi\beta^*)$$

f_{rev} : revolution freq.
k_b : no. bunches/beam
β^* : β-function at IP
N_b : no. particles/bunch
ϵ : geom. emittances
σ_s : bunch length

$\sigma_{c,\mathrm{tot}}$: total cross-section
α_{IBS} : IBS growth rate
α_{rad} : rad. damping rate

J. Jowett, M. Schaumann,
FCC Week Washington 2015

FCC-hh Effects on the Emittance – A New Regime

Intra-Beam Scattering (IBS)

Multiple small-angle Coulomb scattering within a charged particle beam.

Emittance Growth

Growth rate dynamically changing with **beam properties**:

$$\alpha_{IBS} \propto \frac{r_0^2}{\gamma^4} \boxed{\frac{N_b}{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

IBS is weak for initial beam parameters, but increases with decreasing emittance .

(Synchrotron) Radiation Damping

A charged particle radiates energy, when it is accelerated, i.e. bend on its circular orbit.

Emittance Shrinkage

Damping rate is **constant** for a given energy:

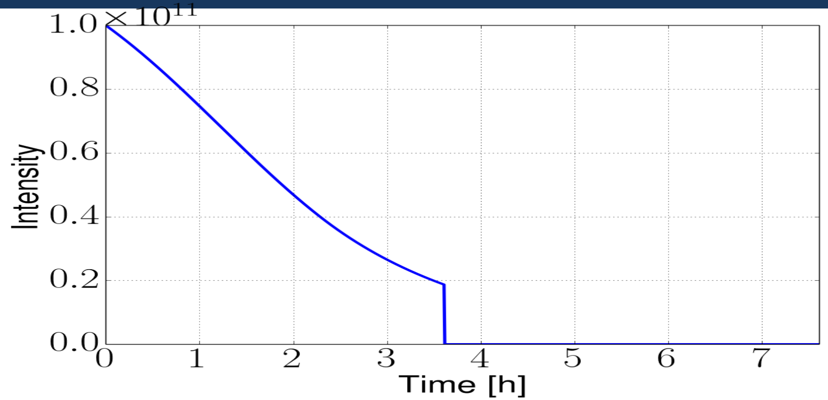
$$\alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}}$$

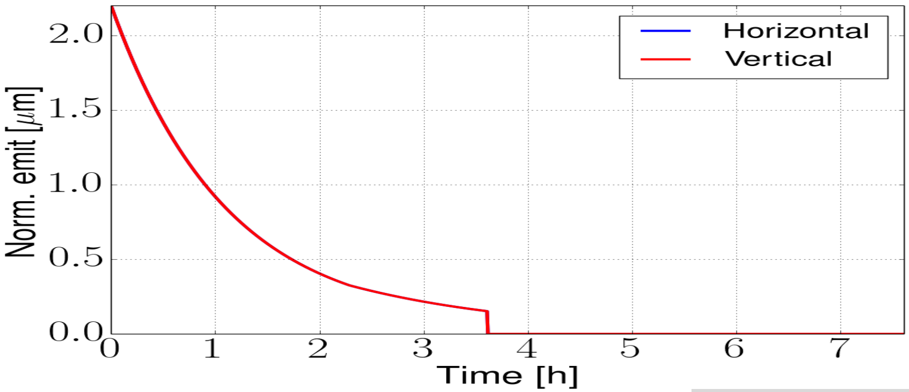
$$\frac{\alpha_{\mathrm{rad,FCC}}}{\alpha_{\mathrm{rad,LHC}}} \approx \frac{E^3_{\mathrm{FCC}}/C^2_{\mathrm{FCC}}}{E^3_{\mathrm{LHC}}/C^2_{\mathrm{LHC}}} \approx \frac{7^3}{4^2} \approx 22$$

J. Jowett, M. Schaumann, FCC Week Washington 2015

Fast emittance decrease at the beginning of the fill, until IBS becomes strong enough to counteract the radiation damping.

FCC-hh Beam and Luminosity Evolution





Developed model including most relevant effects

- Improvement with more detail planned

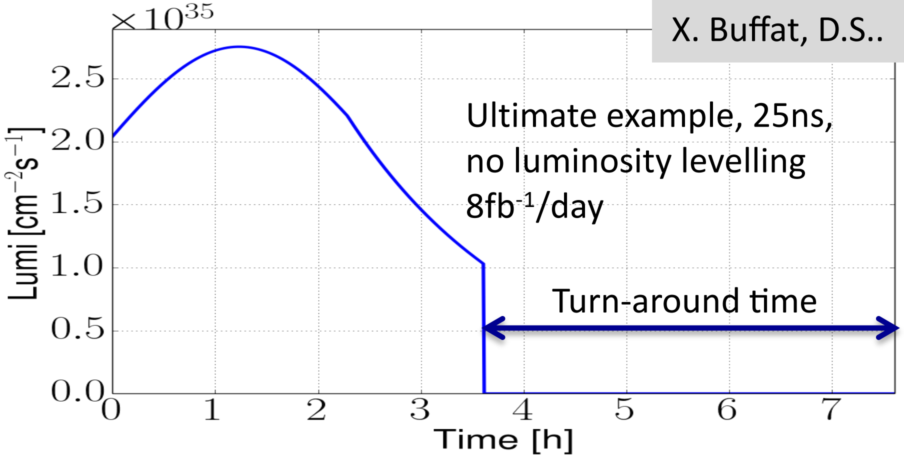
⇒ Reach 8fb^{-1}/day with ultimate for 25ns spacing

⇒ 5ab^{-1} per 5 year run

⇒ Beam is burned quickly

⇒ A reason to have enough charge stored

X. Buffat, D.S..



Ultimate example, 25ns, no luminosity levelling 8fb^{-1}/day

D. Schulte, FCC Week Berlin 2017

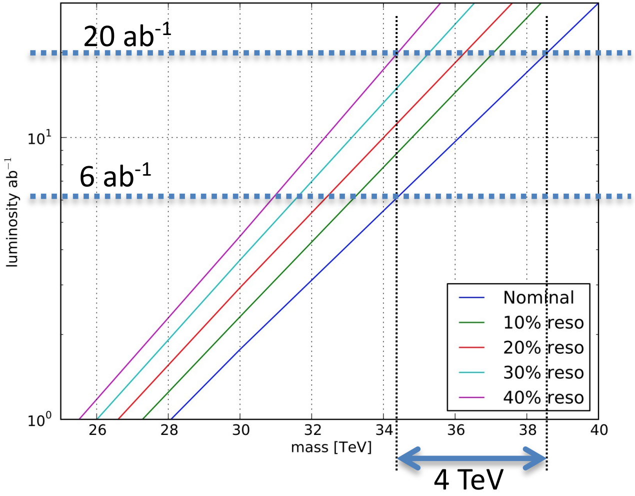
FCC-hh Physics Benchmarks – Detector Requirements

Physics at the $\mathcal{L}\sigma$-limit

Exploration potential through higher energy, increased statistics, increased precision

Example: Z'$_{SSM}$ discovery

luminosity versus mass for a 5σ discovery



Muon momentum resolution:

- **O(5%) at 10TeV.**
- **Compare to 10% at 1TeV spec. at LHC**

Tracking – Resolution degrading with higher momentum!

$$\frac{\Delta p}{p} \propto \frac{\sigma_{\text{pos}} \cdot p}{BL^2}$$

→ Have to improve on

- σ_{pos}: difficult
- Magnetic field B: go from 2T (ATLAS) to 4T (FCC-hh)
- Lever arm L: magnet cost scales with ≈ volume$^{2/3}$ → very quickly very expensive

FCC-hh Physics Benchmarks – Detector Requirements

Calorimetry – Improving resolution with higher energy!

Simple shower model: The detectable signal is proportional to the total number of produced signal quanta *N* (e.g. e⁻-ion pair, scintillation photon)

An estimation of the **energy resolution** is given by the **fluctuations of** the number ***N*** of produced signal quanta in the active medium (*N*: Poisson distributed). Need **average energy *W*** to produce 1 signal quantum.

$$N \approx \frac{E}{W}$$

Silicon detectors:	$W \approx 3.6$eV
Gas detectors:	$W \approx 30$eV
Plastic scintillators:	$W \approx 100$eV
Liquid Ar:	$W \approx 23.3$eV
Scint. crystal NaI:	$W \approx 25$eV
Scint. crystal PbWO$_4$:	$W \approx 10$keV

$$\frac{\sigma(E)}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{W}{E}}$$

Relative resolution improves with $1/E^{½}$

Paremetrization of resolution:

$$\frac{\sigma_E(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

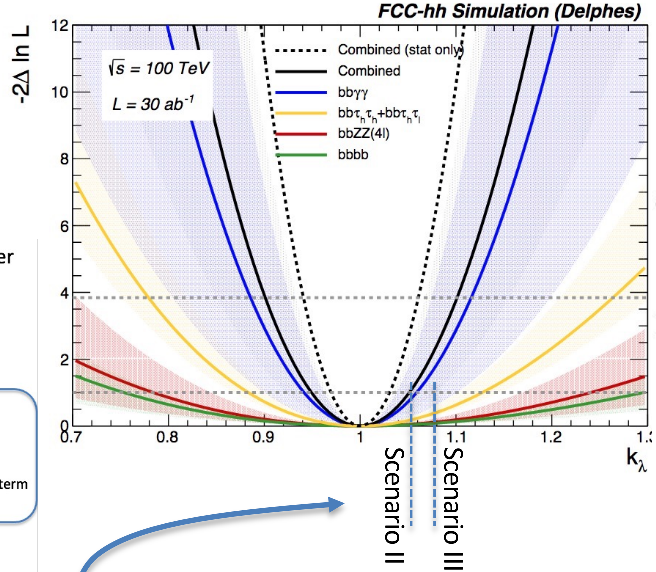
stochastic/sampling term

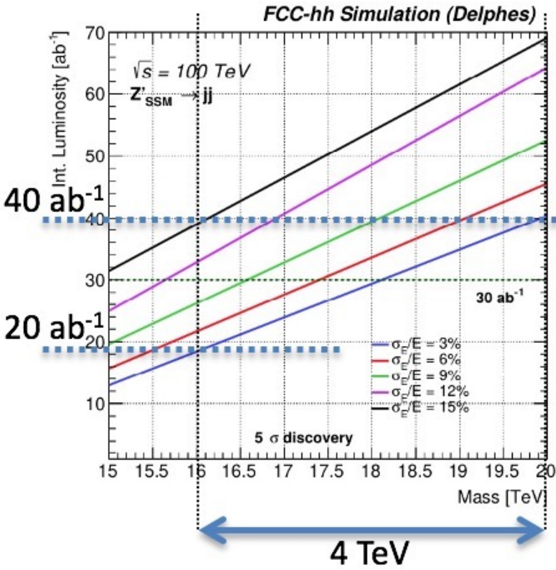
noise term

constant term

Delphes parametrisation:

parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20





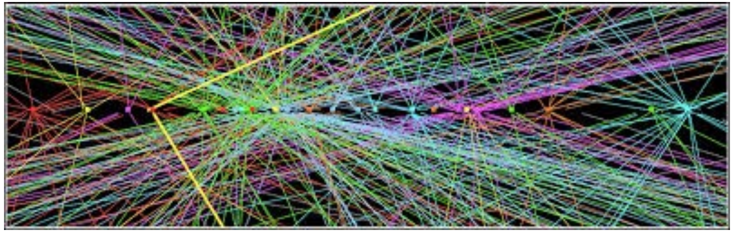
Higgs self-coupling $\delta\lambda/\lambda$ = 5% for $\Delta m_{\gamma\gamma} < 1.8$GeV (scenario II)

- → **EM-calorimeter resolution**
  sampl. term *a* ≈ *10%* and noise term *b* < *0.6GeV* (including pile-up)!

Di-jet resonances: HCAL constant term of *c* = 3% instead of 15%: extend discovery potential by 4TeV (or same disc. pot. for 50% lumi)

- → **full shower containment is mandatory !**
- → Large **HCAL depth (~ 12 λ_{int})!**

FCC-hh: Pile-Up, Number of pp Coll. per BunchCrossing

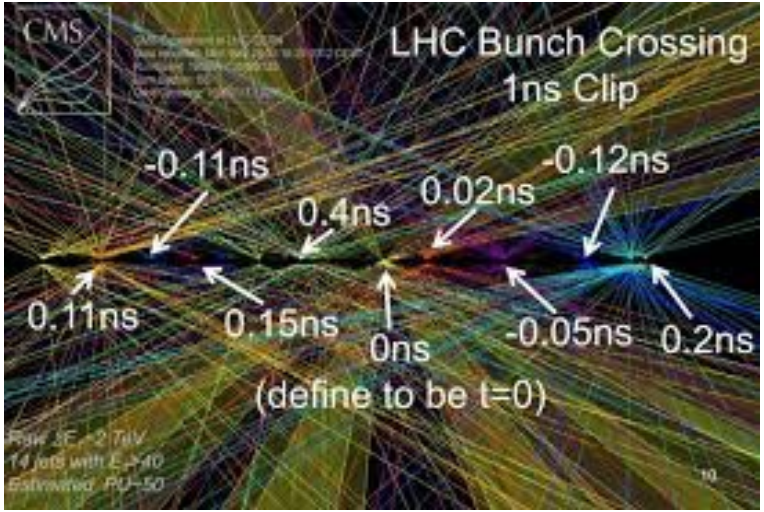


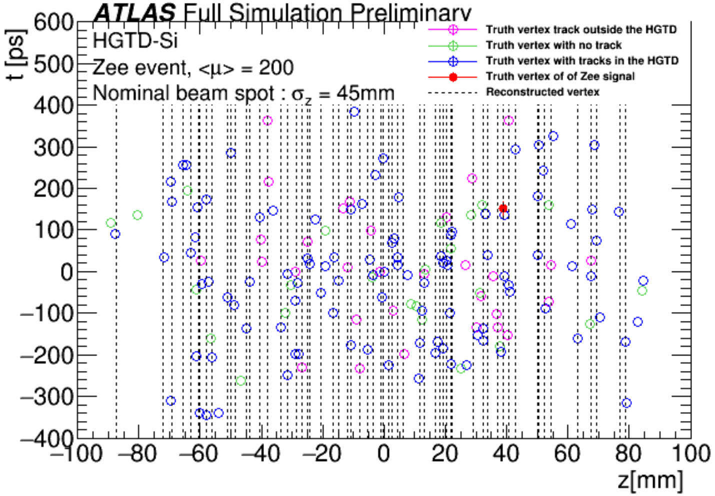
LHC ($2 \times 10^{34} cm^{-2}s^{-1}$)**: <μ> = 60**

HL-LHC: <μ> = 140

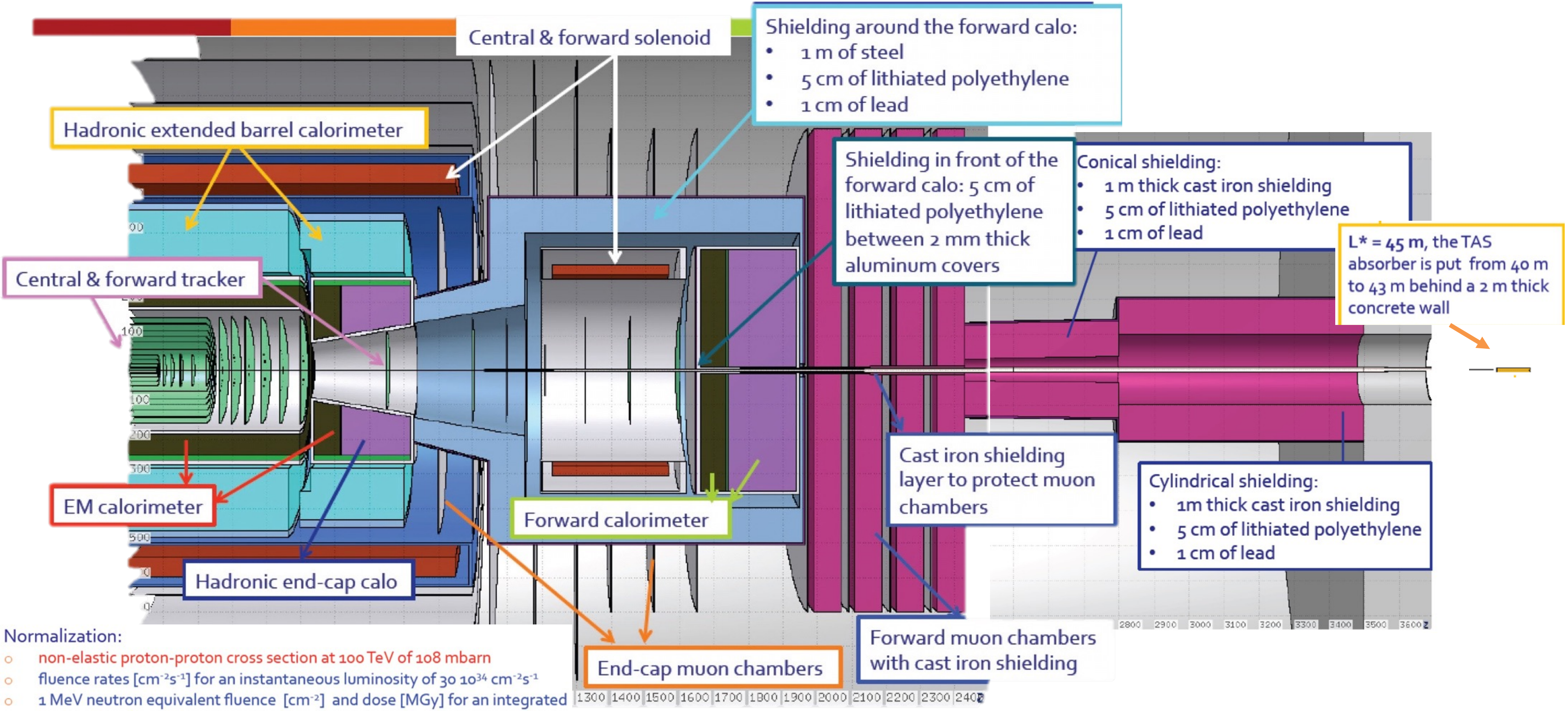
FCC-hh: <μ> = 1000

Small time differences between the individual collisions in one BC allow identification with detectors having order 10-20ps time resolution.





FCC-hh Radiation Levels Simulation



Central & forward solenoid

Shielding around the forward calo:
- 1 m of steel
- 5 cm of lithiated polyethylene
- 1 cm of lead

Hadronic extended barrel calorimeter

Shielding in front of the forward calo: 5 cm of lithiated polyethylene between 2 mm thick aluminum covers

Conical shielding:
- 1 m thick cast iron shielding
- 5 cm of lithiated polyethylene
- 1 cm of lead

L* = 45 m, the TAS absorber is put from 40 m to 43 m behind a 2 m thick concrete wall

Central & forward tracker

Cast iron shielding layer to protect muon chambers

Cylindrical shielding:
- 1m thick cast iron shielding
- 5 cm of lithiated polyethylene
- 1 cm of lead

EM calorimeter

Forward calorimeter

Hadronic end-cap calo

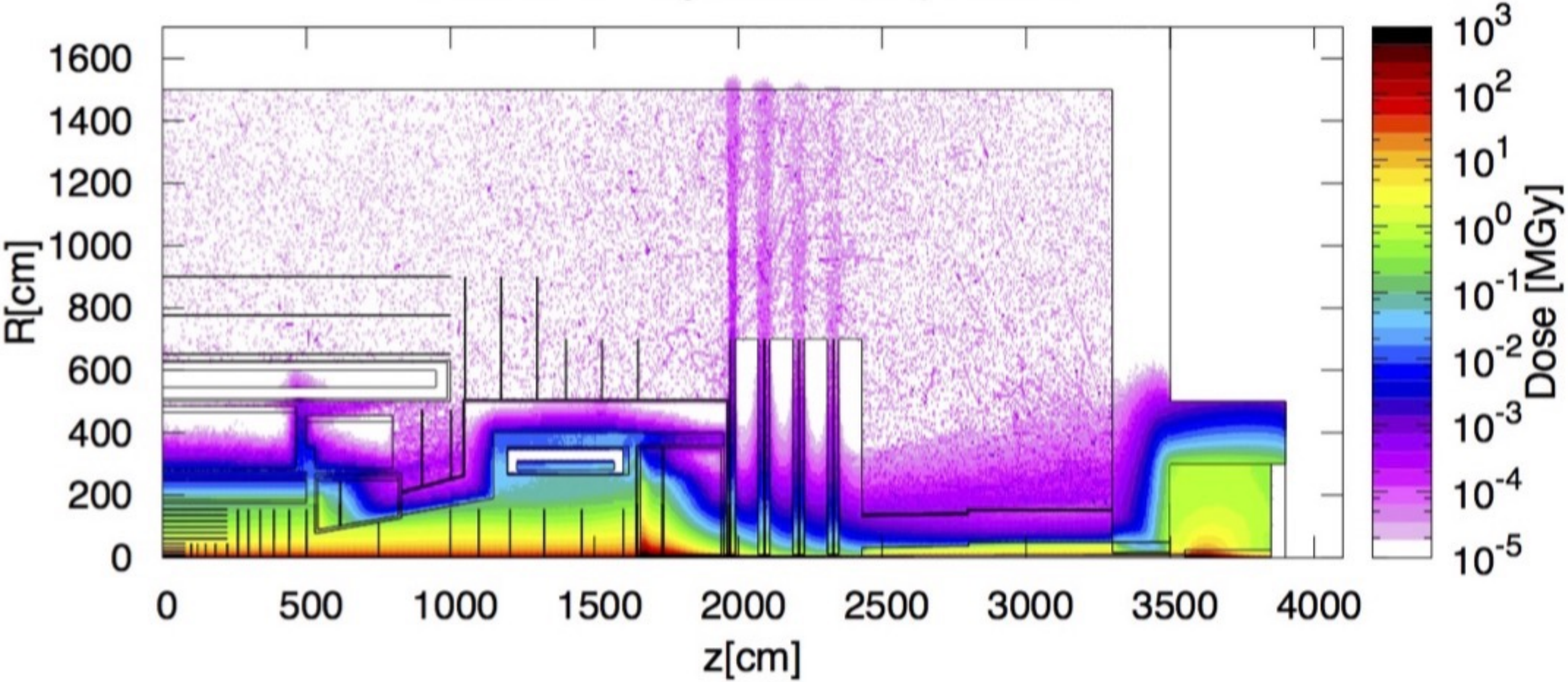
End-cap muon chambers

Forward muon chambers with cast iron shielding

Normalization:
- non-elastic proton-proton cross section at 100 TeV of 108 mbarn
- fluence rates [$cm^{-2}s^{-1}$] for an instantaneous luminosity of $30\ 10^{34}\ cm^{-2}s^{-1}$
- 1 MeV neutron equivalent fluence [cm^{-2}] and dose [MGy] for an integrated luminosity of 30 ab^{-1}

FCC-hh Total Ionizing Dose for $30ab^{-1}$

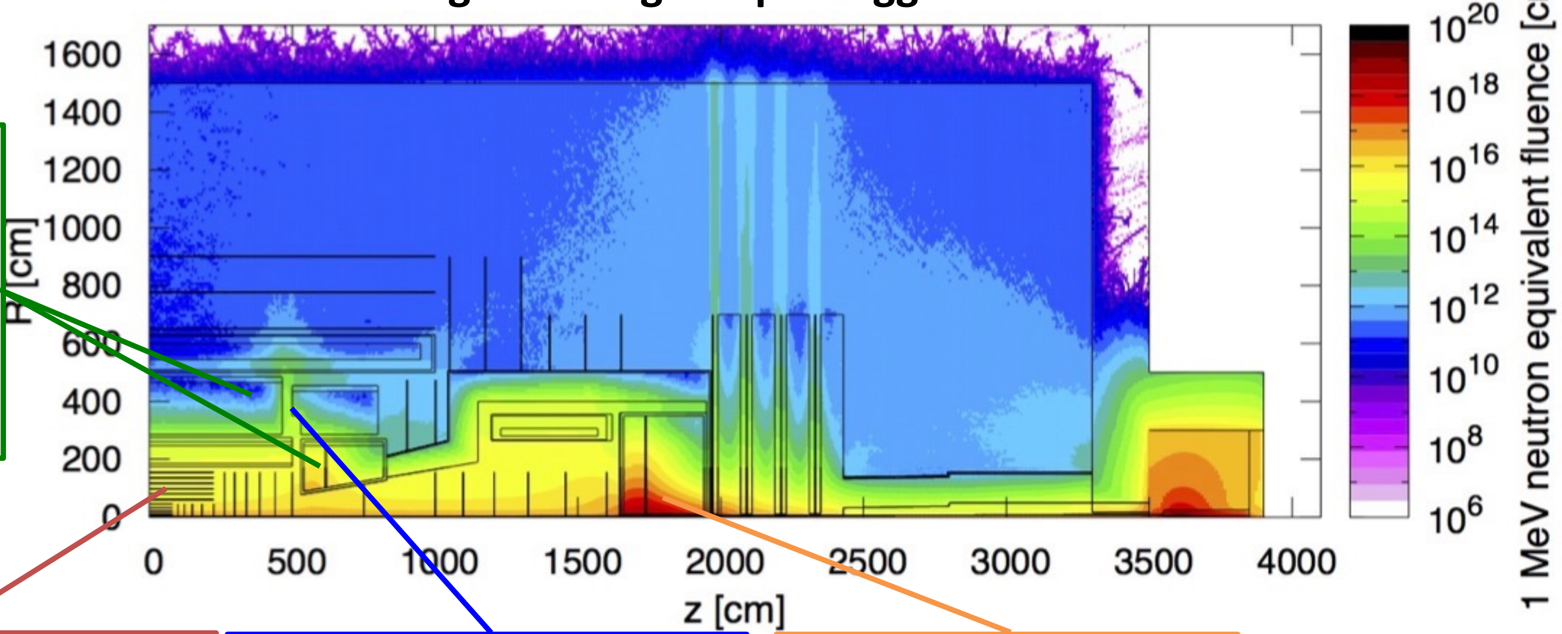
Dose of 300 MGy (30 Grad) in the first tracker layers.
< 10 kGy in HCAL barrel and extended barrel.



FCC-hh 1 MeV Neutron Equivalent Fluence for 30ab^{-1}

Generally ~10-30 times worse than HL-LHC

Exception: Forward calorimeter goes to higher η → bigger factor



Barrel calorimeter:

EM-calo: 4 10^{15} cm^{-2}

HAD-calo: 4 10^{14} cm^{-2}

End-cap calorimeter:

EM-calo: 2.5 10^{16} cm^{-2}

HAD-calo: 1.5 10^{16} cm^{-2}

Central tracker:

- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

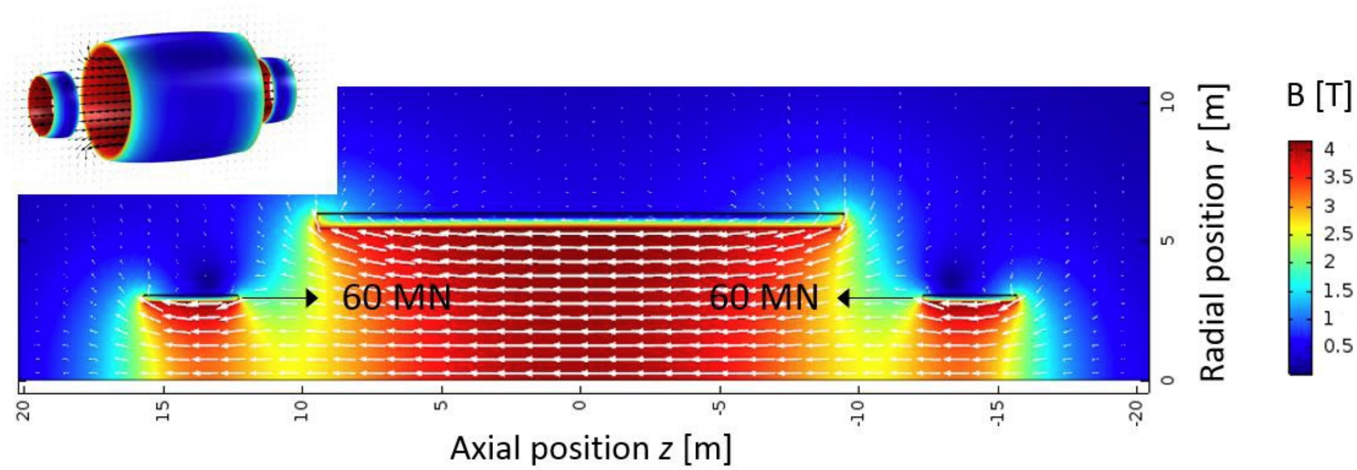
Calorimeter gap:

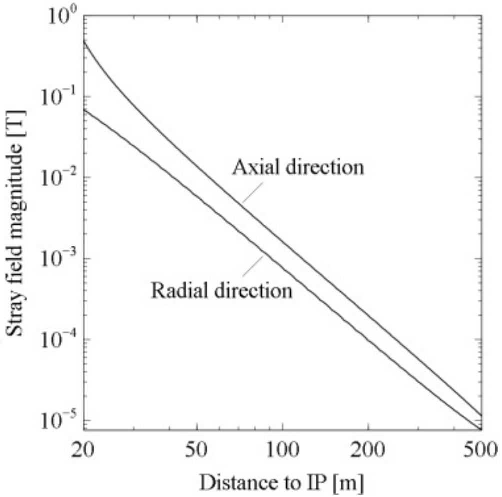
from 10^{16} cm^{-2} to 10^{14} cm^{-2}

Forward calorimeters:

~5 10^{18} cm^{-2} for both the EM and the HAD-calo

FCC-hh Detector Magnetic Field





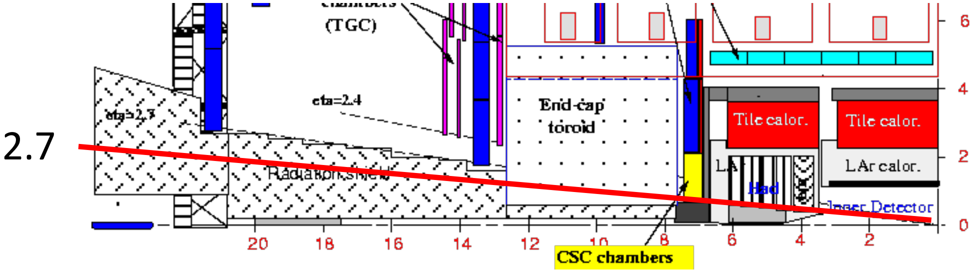
New reference design with three solenoids

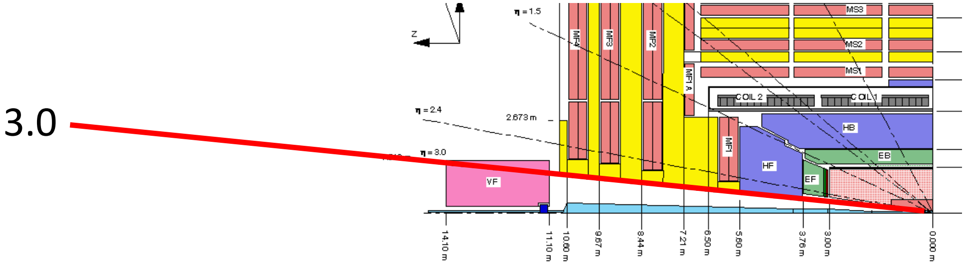
- 4 T in 10 m free bore
- 60 MN net force on forward solenoids handled by axial tie rods
- No shielding solenoid anymore (cost! smaller shaft!)
- Forward solenoids instead of forward dipoles → rotational symmetry important for performance physics
  - Solenoids extend high precision tracking by one unit of η

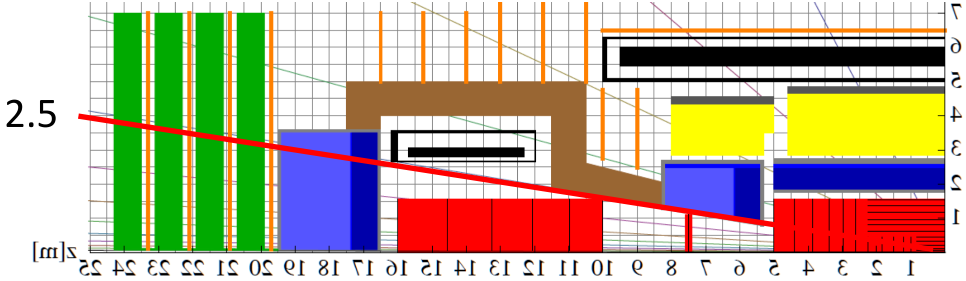
Result:

- Much simplified configuration
- Stored energy: 13.8 GJ
- Lowest degree of complexity from a cold-mass perspective
- But: with significant stray field

FCC-hh Radiation: Comparison to ATLAS & CMS



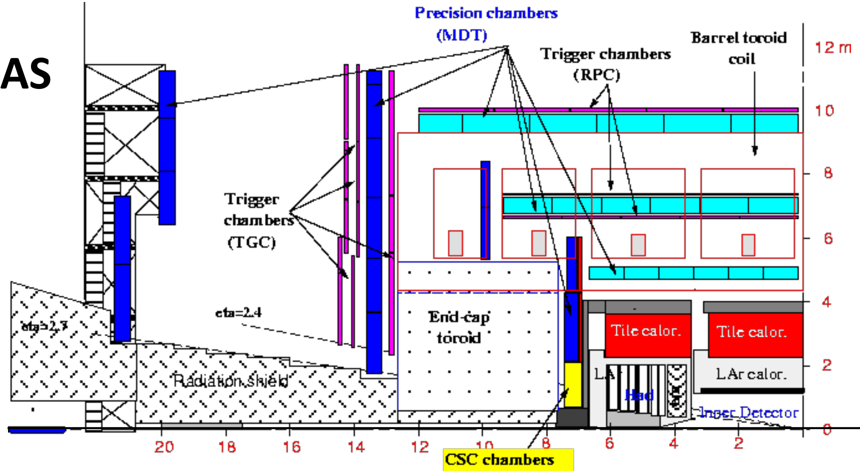




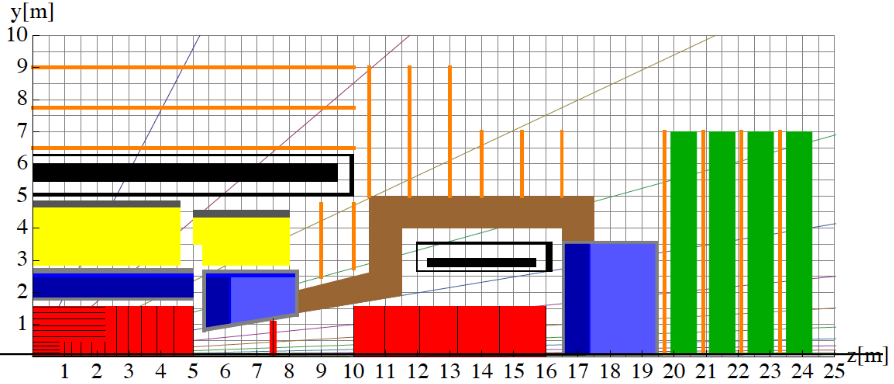
- The forward calorimeters are a very large source of radiation (diffuse neutron source).
- In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is enclosed by the return Yoke.
- For the FCC, the forward calorimeter is moved far out in order to reduce the radiation load and increase granularity.
- → A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.

FCC-hh Detector: Comparison to ATLAS & CMS

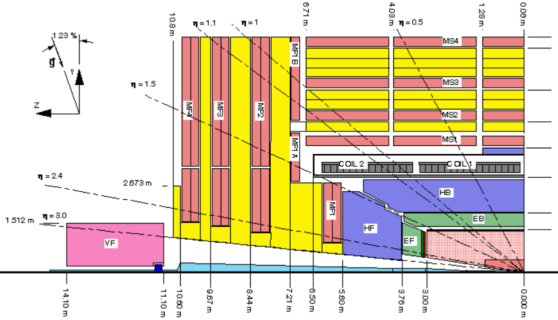
ATLAS

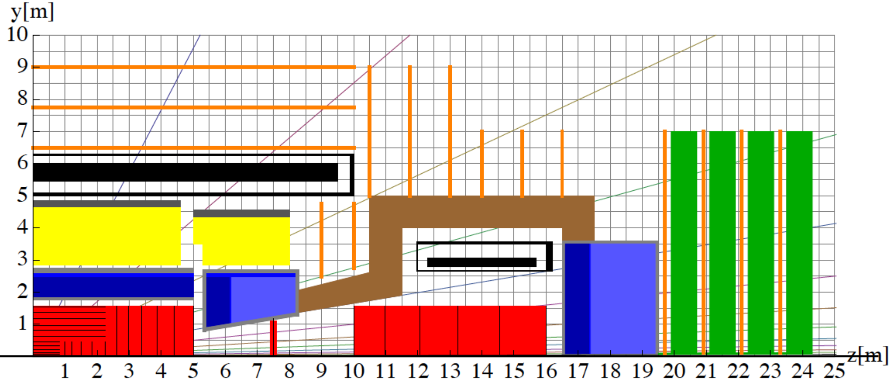


FCC-hh Reference Detector

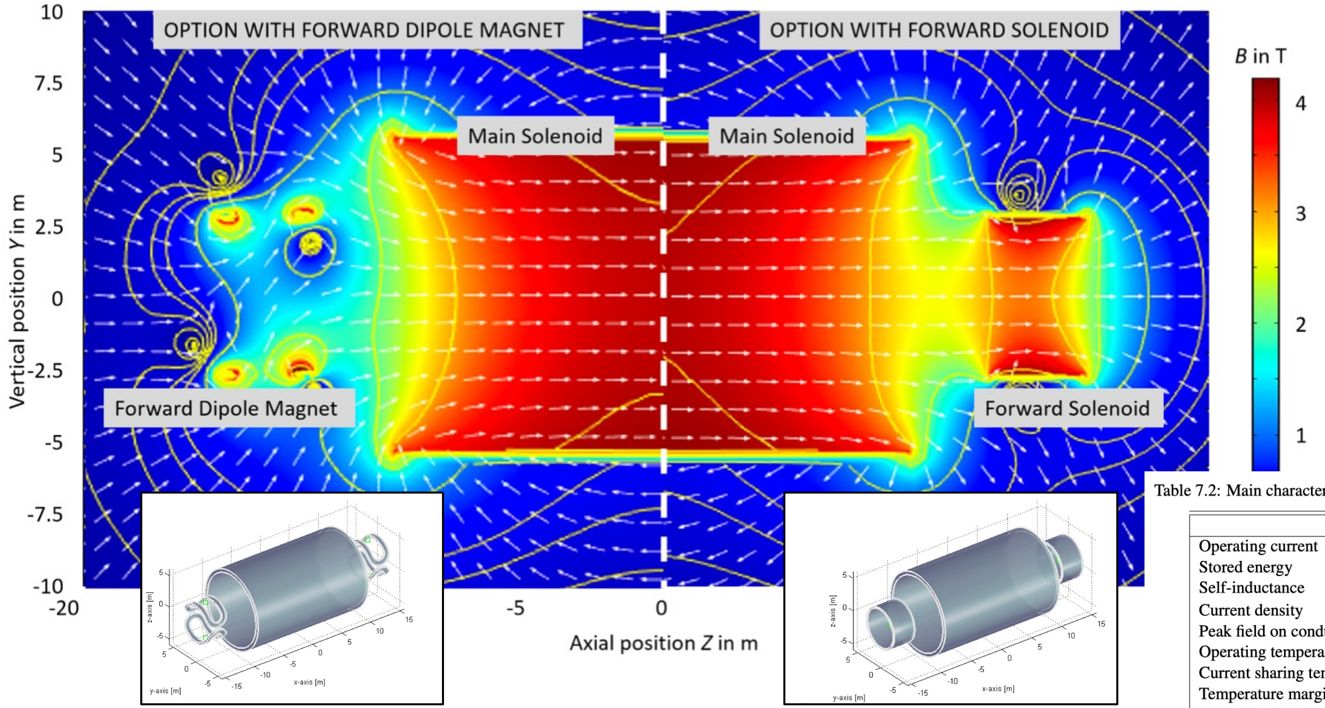


CMS





FCC-hh Magnet System



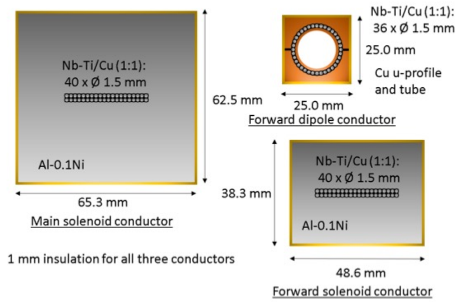


Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet.

	Unit	Main solenoid	Forward solenoid	Forward dipole
Operating current	kA	30	30	16
Stored energy	GJ	12.5	0.43	0.20
Self-inductance	H	27.9	0.96	1.54
Current density	A/mm^2	7.3	16.1	25.6
Peak field on conductor	T	4.5	4.5	5.9
Operating temperature	K	4.5	4.5	4.5
Current sharing temp.	K	6.5	6.5	6.2
Temperature margin	K	2.0	2.0	1.7
Heat load cold mass	W	286	37	50
Heat load thermal shield	W	5140	843	1500
Cold mass	t	1070	48	114
Vacuum vessel	t	875	32	48
Conductor length	km	84	16	23

ATLAS Magnet System 2.7 GJ

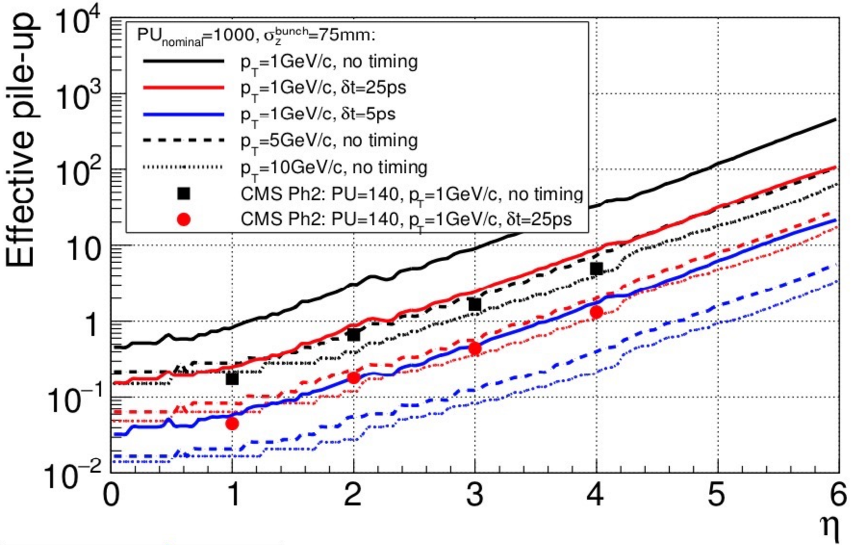
CMS Magnet System 1.6 GJ

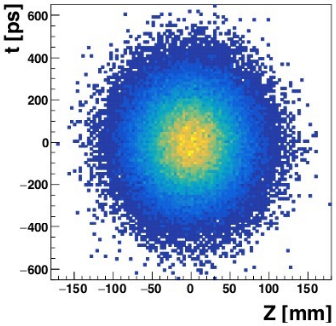
FCC-hh: ~13 GJ, cold mass + cryostat around 2000 tons.

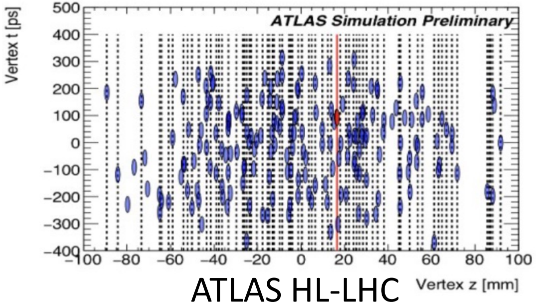
Possible alternative solutions: Ultra-thin solenoid positioned inside the calorimeter (difficulty: muon measurement!)

FCC-hh: Timing Information for Vertex Reco

- **Goal is to identify the primary vertex!**
- **Effective pile-up:** number of vertices compatible with reconstructed tracks (95%CL)
  - Eff. pile-up = 1: Indication for unambiguous primary vertex identification
- **Example:** eff. pile-up = 1 for $p_T = 5$GeV:
  - $\eta < |2|$ without timing (---)
  - $\eta < |3.5|$ with 25ps timing accuracy (---)
  - $\eta < |4.5|$ with 5ps timing accuracy (---)
- → **Very challenging!**







ATLAS HL-LHC

FCC-hh Experiment: Hadronic Calorimeter (HCAL)

Barrel HCAL:

- **ATLAS type TileCal optimized for particle flow**
  - Scintillator tiles – steel,
  - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
  - $\Delta\eta$ x $\Delta\phi$ = 0.025 x 0.025
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

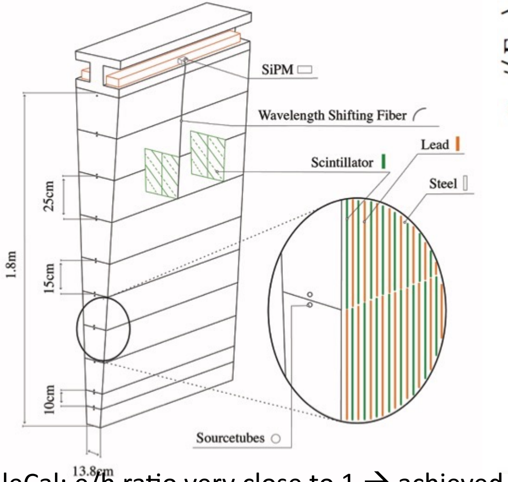
- Simple calibration: 44%/$\sqrt{\bar{E}}$ to 48%/$\sqrt{\bar{E}}$
- Calibration using neural network (calo only):
  - Sampling term of 37%/$\sqrt{\bar{E}}$

Jet resolution:

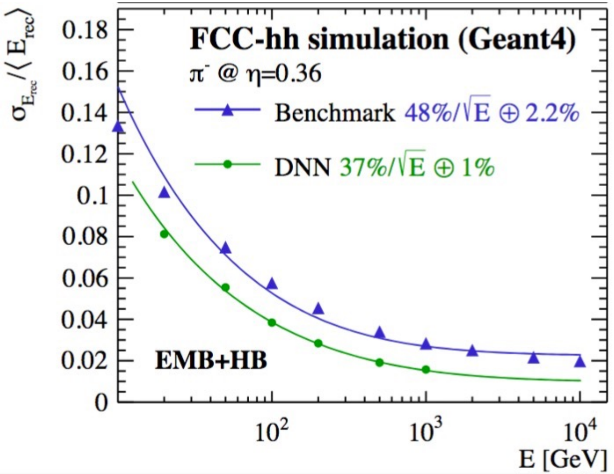
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

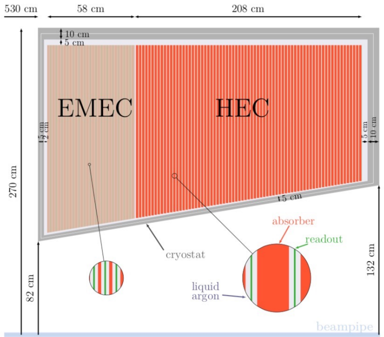
Endcap HCAL and forward calorimeter:

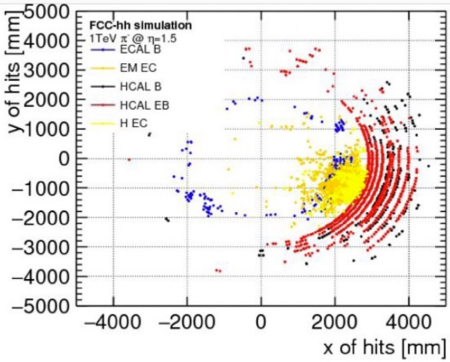
- Radiation hardness!
- LAr/Cu, LAr/W



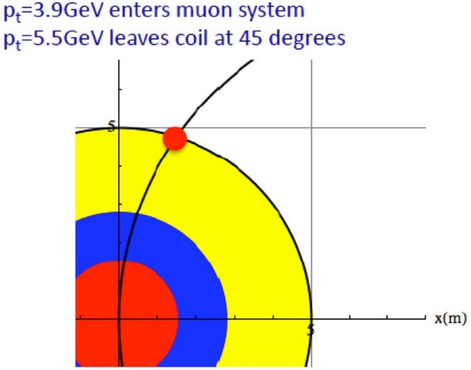
TileCal: e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)

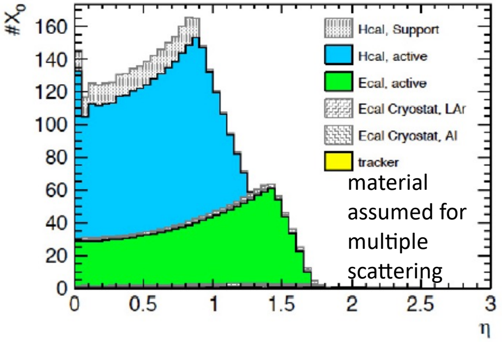


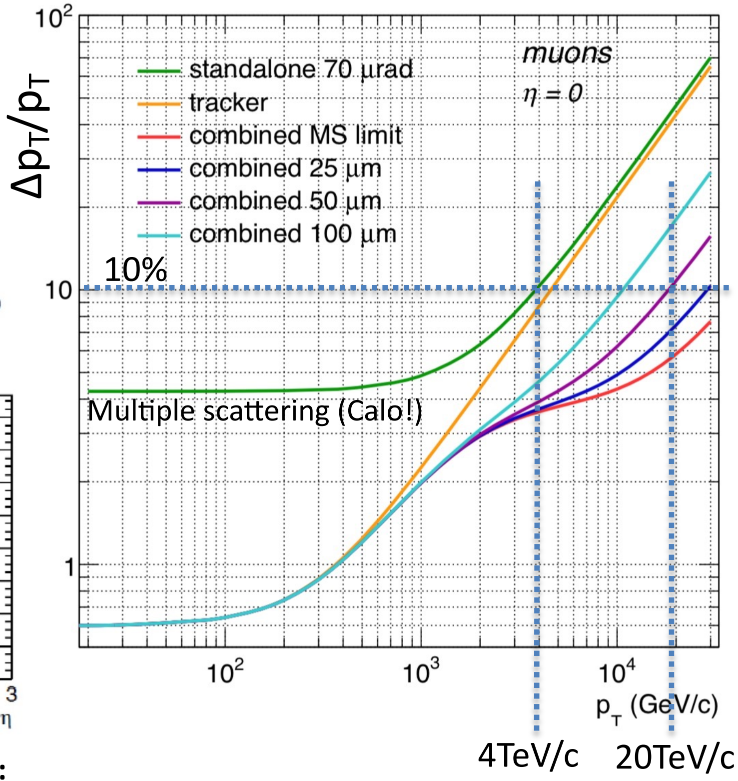




FCC-hh Experiment: Muon System





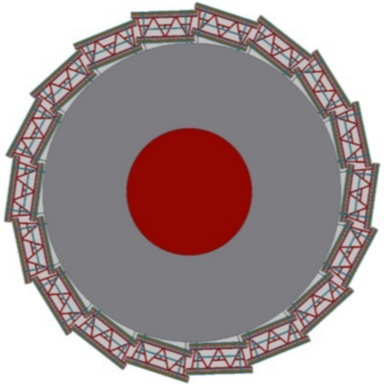


With 50µm position resolution and 70µrad angular resolution we find (η=0):

- ≤10% standalone momentum resolution up to 4TeV/c
- ≤10% combined momentum resolution up to 20TeV/c

Standalone muon performance not relevant, the task of muon system is **triggering and muon identification!**

Muon rate dominated by c and b decays → isolation is crucial for triggering W, Z, t!



Muon barrel: Rates of up to ~500Hz/cm^2 expected

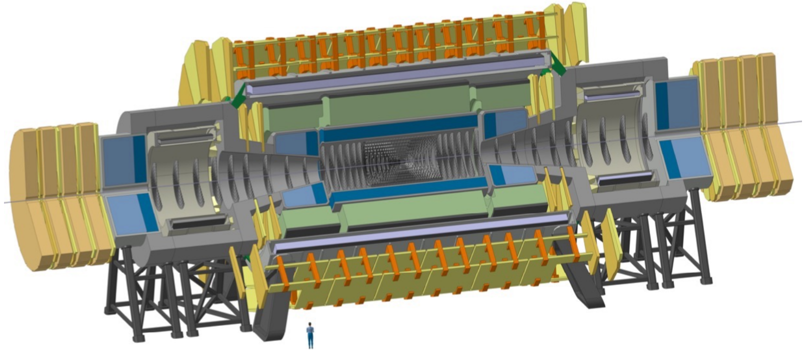
Muon detection in forward region:

Excpected rates up to 500kHz for r > 1m

→ **HL-LHC muon system gas detector technology will work for most of the FCC detector area**

FCC-hh: Reading Out Such a Detector → Trigger/DAQ

- **Example ATLAS**:
  - ATLAS Phase II calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.
  - Muon system will also be read out at 40MHz to produce a L1 Trigger.
- **FCC-hh detector**:
  - calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.
  - 40MHz readout of the tracker (using zero-suppression) would produce about 800TByte/s.



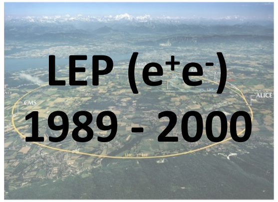
- **FCC-hh trigger strategy question:**
  - Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
    - Difficult: 400kHz of W's and 100MHz of jets (p_T > 50GeV)
  - Or: un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.

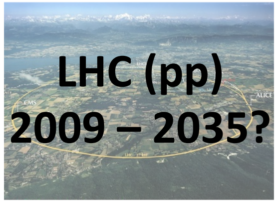
Conclusions

- FCC-ee and FCC-hh: Complementary, strong and diverse physics program – in-line with
- FCC-ee: EW-Higgs-Top factory as first step (ESPPU 2020 Document)
- FCC-hh: A 100TeV pp collider as continuation of the pp discovery programme

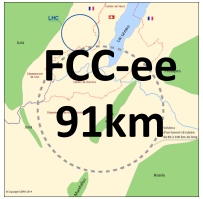
Tevatron 2TeV → x 7 → **LHC 14TeV** → x 7 → **FCC-hh 100TeV**

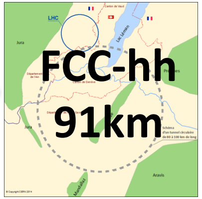
- 27km tunnel

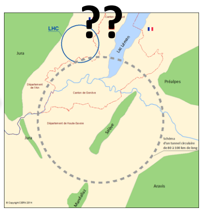

LEP (e^+e^-)
1989 - 2000


LHC (pp)
2009 – 2035?

- The next step: 91km tunnel


FCC-ee
91km


FCC-hh
91km


??

- Let's take the lessons from these successful projects!