FCC - plans for a giant collider at CERN

Jana Faltová

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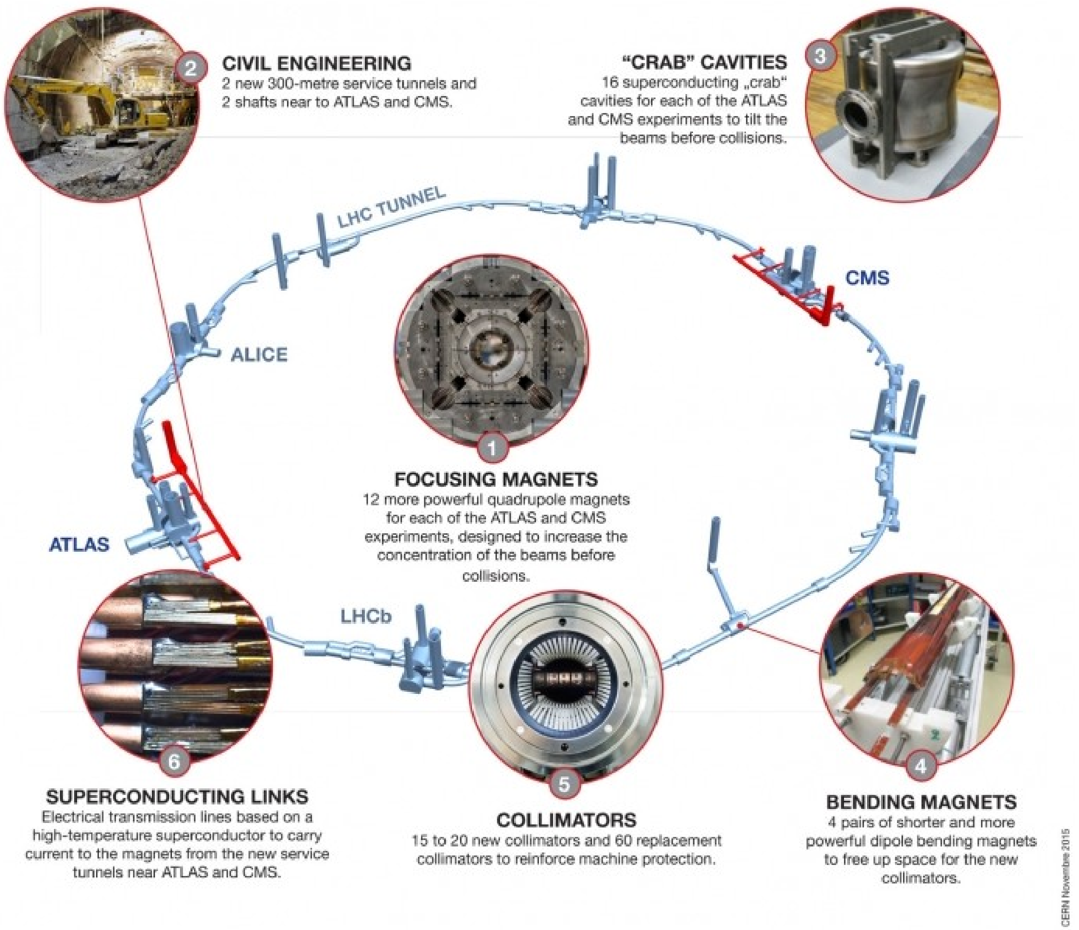
CERN accelerators

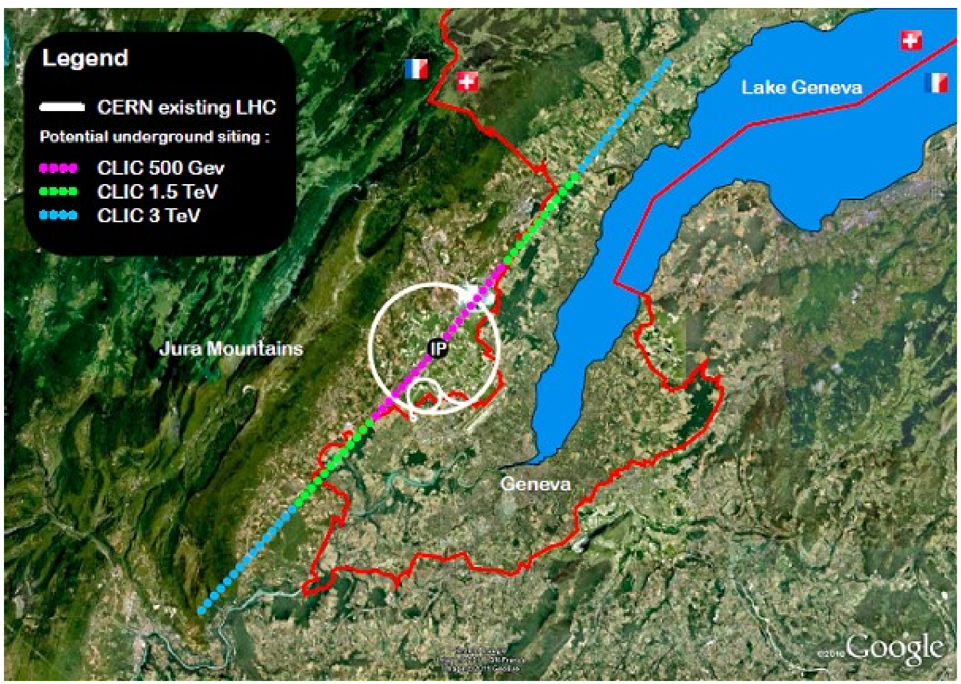
- **LHC**
  - $\sqrt{s}$ = 13 TeV
  - L_{int} <500 fb^{-1}
  - 2011 – 2023
- **HL-LHC**
  - High luminosity upgrade of LHC
  - $\sqrt{s}$ = 13 TeV, L_{int} = 4000 fb^{-1}
  - 2026 – 2038



Future accelerators at CERN

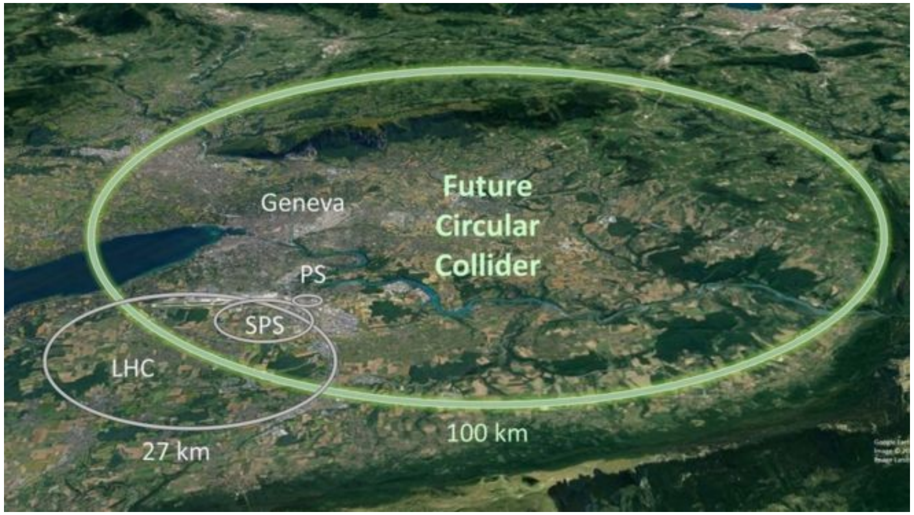
CLIC

- Linear e+e- accelerator
- 50 km long
- Energies up to $\sqrt{s}$ = 3 TeV



FCC

- Circular e+e- / pp collider
- 100 km long
- **IPNP team: T. Davidek, JF + 2 bachelor students**

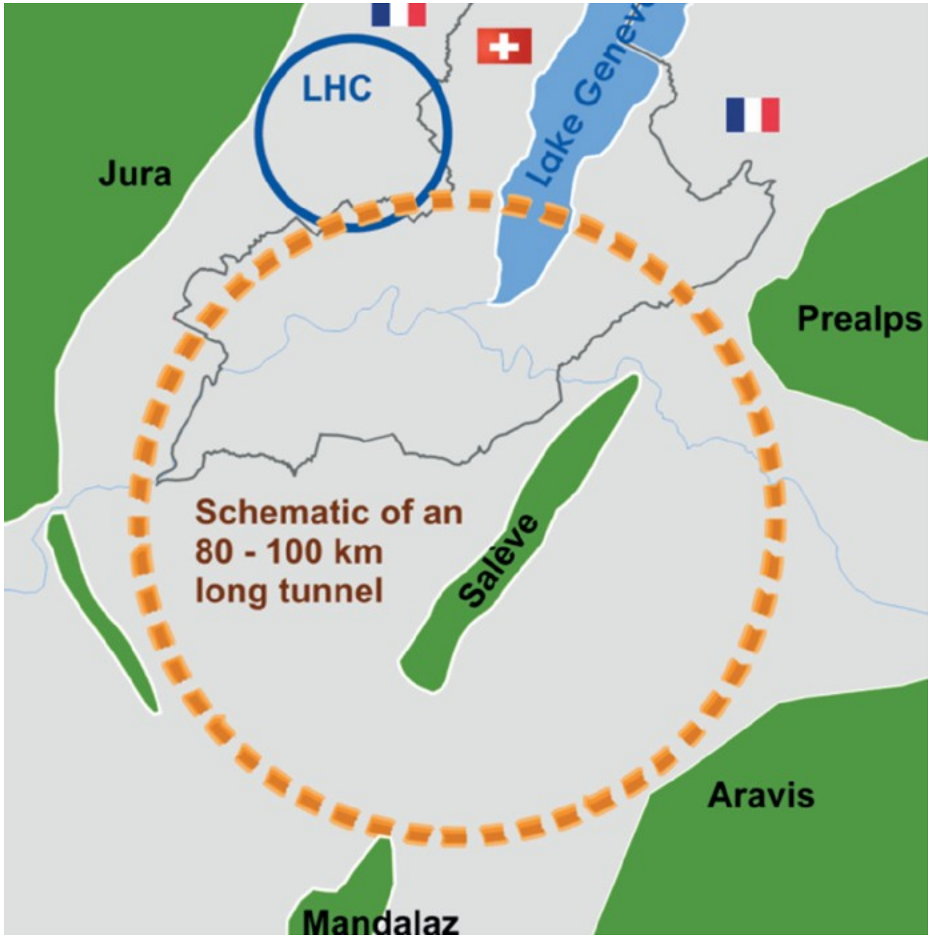


Future Circular Collider (FCC)

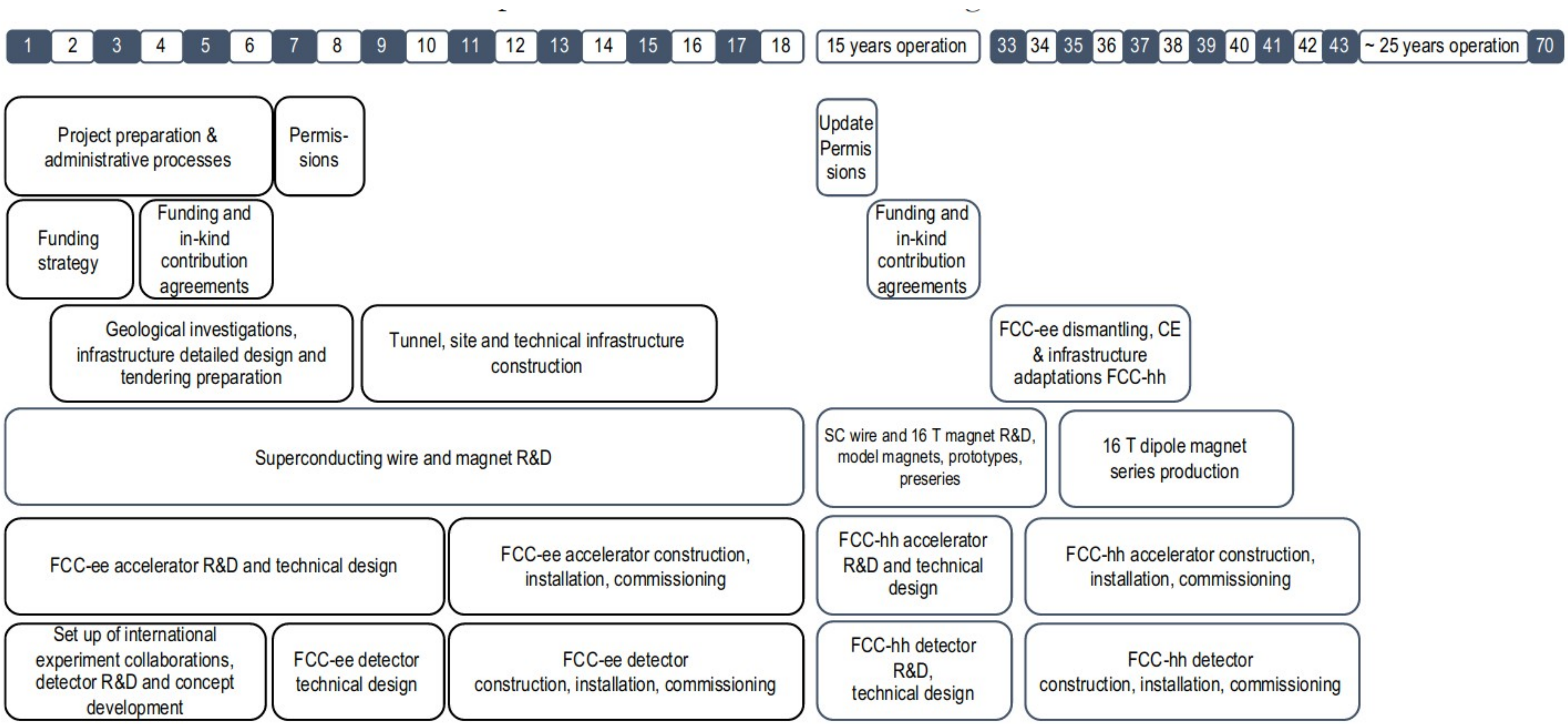
International collaboration (136 institutes, 34 countries)

- ***e^+e^-* collider (FCC-ee)**
  - $\sqrt{s}$ = 90 – 365 GeV
- ***pp* collider (FCC-hh)**
  - $\sqrt{s}$ = 100 TeV
  - Ongoing R&D on Nb_3Sn **16 T magnets**
- ***pe* (FCC-he)**
  - Possible option

→ Summarized in Conceptional Design Report for European Strategy Update 2019/20

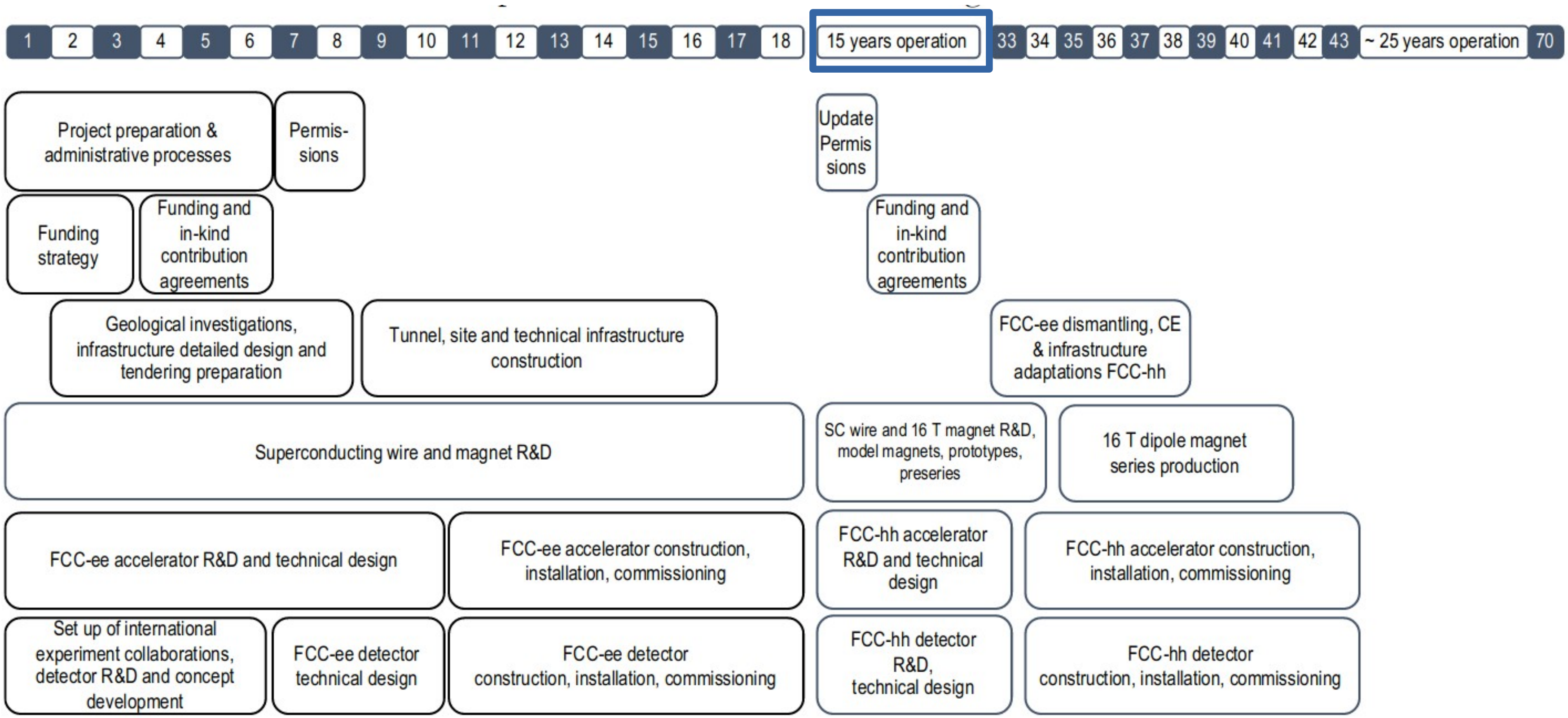


Timeline


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
15 years operation
33 34 35 36 37 38 39 40 41 42 43
~ 25 years operation
70
Project preparation & administrative processes
Permis-sions
Update Permis sions
Funding strategy
Funding and in-kind contribution agreements
Funding and in-kind contribution agreements
Geological investigations, infrastructure detailed design and tendering preparation
Tunnel, site and technical infrastructure construction
FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
Superconducting wire and magnet R&D
SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
16 T dipole magnet series production
FCC-ee accelerator R&D and technical design
FCC-ee accelerator construction, installation, commissioning
FCC-hh accelerator R&D and technical design
FCC-hh accelerator construction, installation, commissioning
Set up of international experiment collaborations, detector R&D and concept development
FCC-ee detector technical design
FCC-ee detector construction, installation, commissioning
FCC-hh detector R&D, technical design
FCC-hh detector construction, installation, commissioning

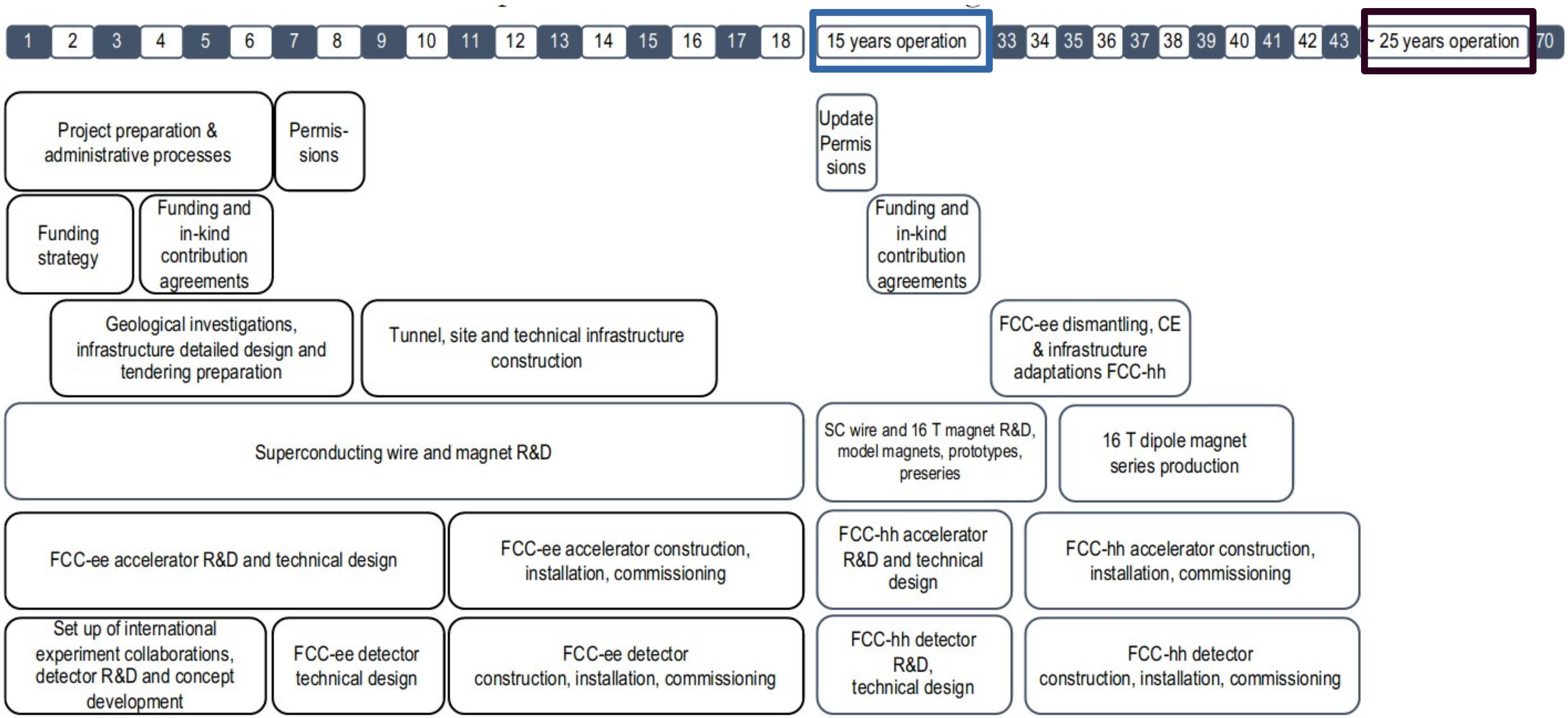
Timeline

- **FCC-ee** – 15 years of operation from end-2030s



Timeline

- **FCC-ee** – 15 years of operation from end-2030s
- **FCC-hh** – 25 years of operation from mid-2060s

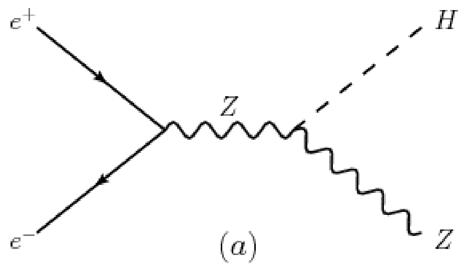


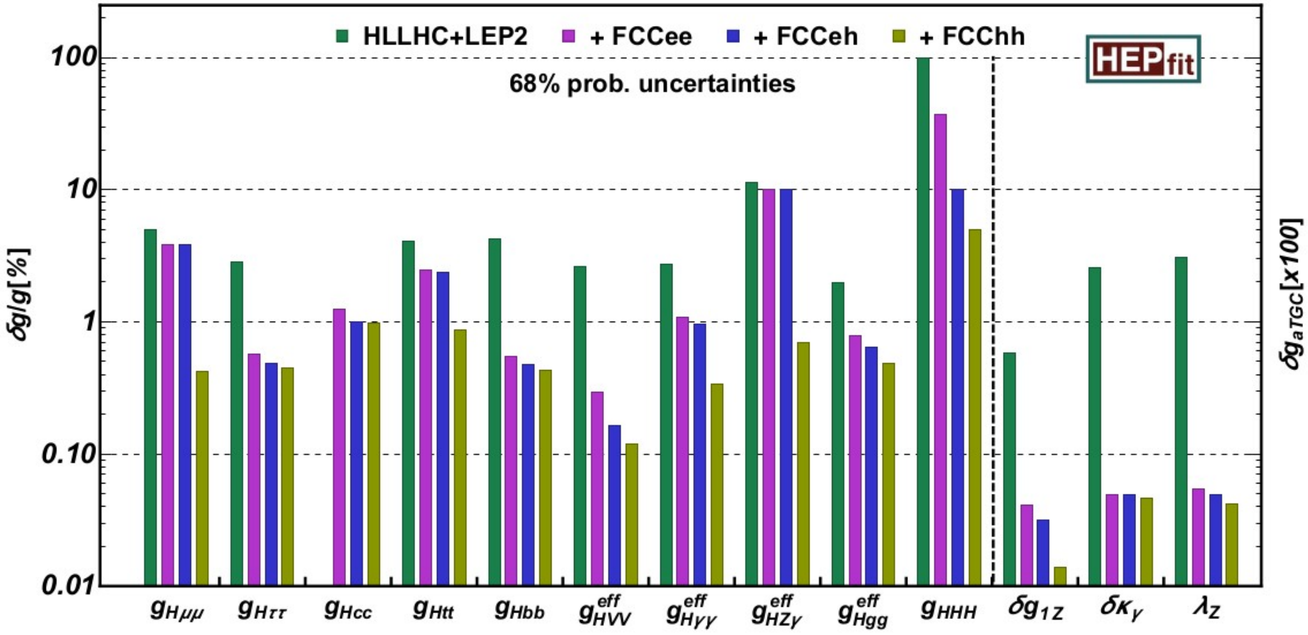
FCC goals

- Measurement of properties of the **Higgs and EW gauge bosons**
- Direct searches for new particles at high masses
  - e.g. search for **dark matter**
- Indirect searches – probe energy scales beyond the direct kinematic reach

Higgs studies

- FCC-ee: *ee* → *ZH*
  - Absolute measurement of the *H* coupling to *Z*
- FCC-ee + FCC-hh
  - Rare decays (*H* → *cc*, *H* → *gg*, *H* → *μμ*, *H* → *Zγ*)
  - Most of the Higgs couplings to a precision from few per mil to ~1%
  - Higgs self-coupling with a precision of 5-7%

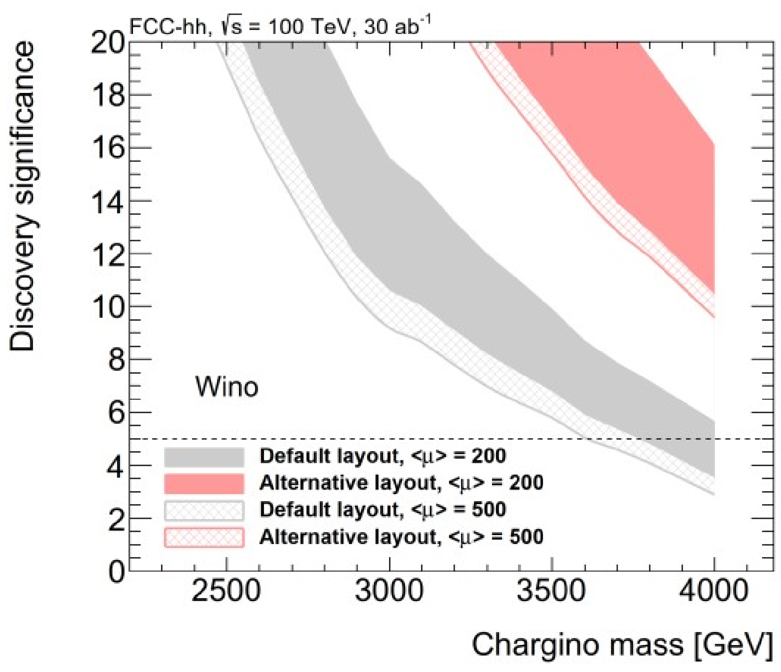


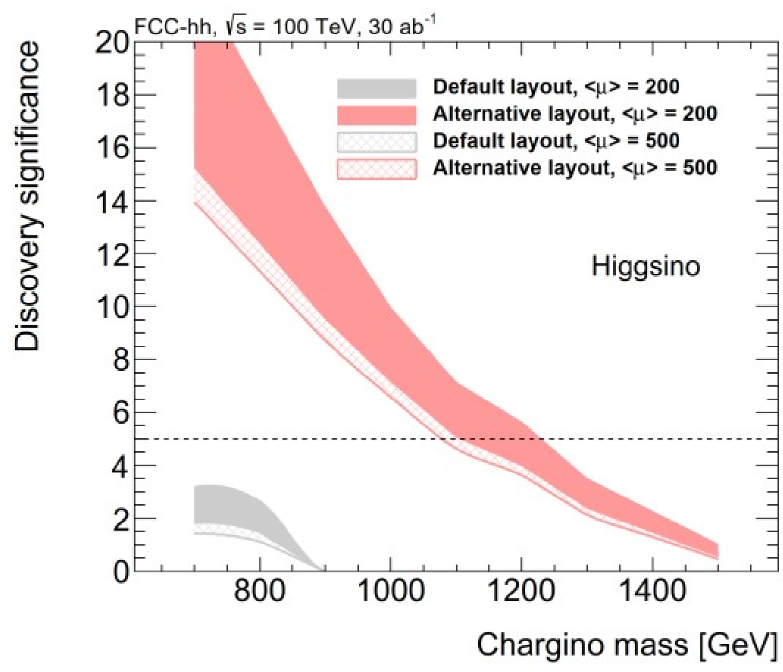


Dark matter searches

- Broad class of models with particles of masses from GeV – 10's TeV
- Example: Weakly interacting massive particles (WIMPs)

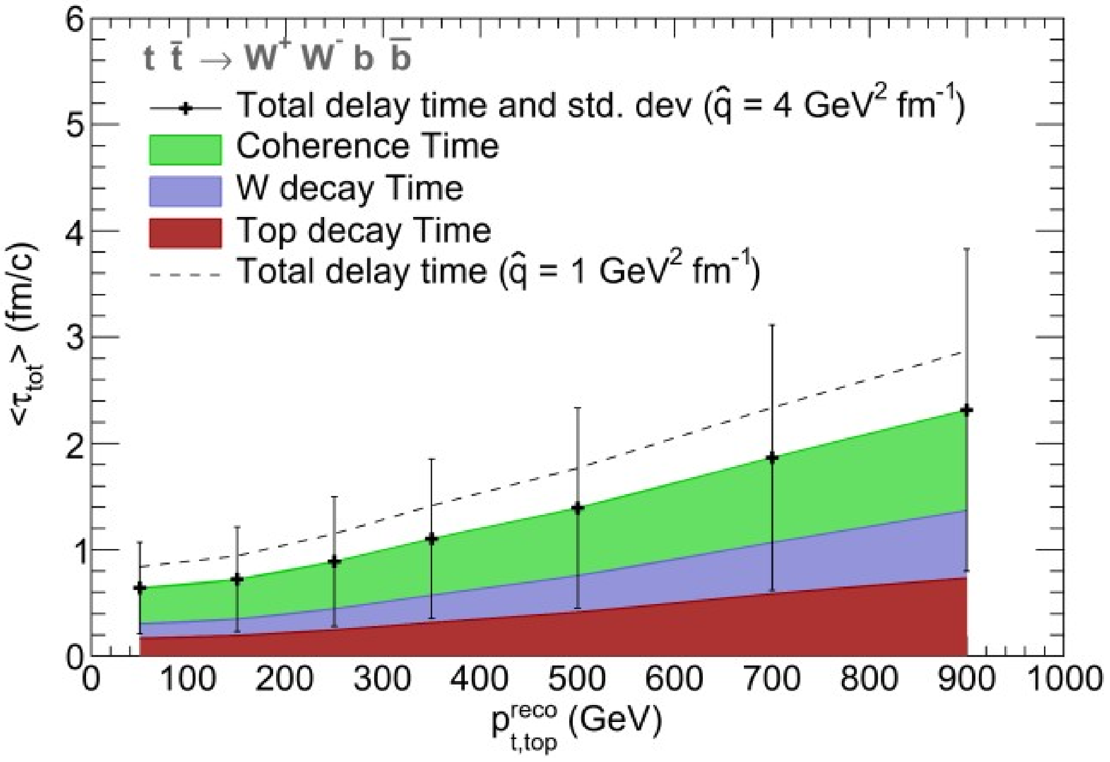
The FCC covers the full mass range for the discovery of these WIMP Dark Matter candidates.

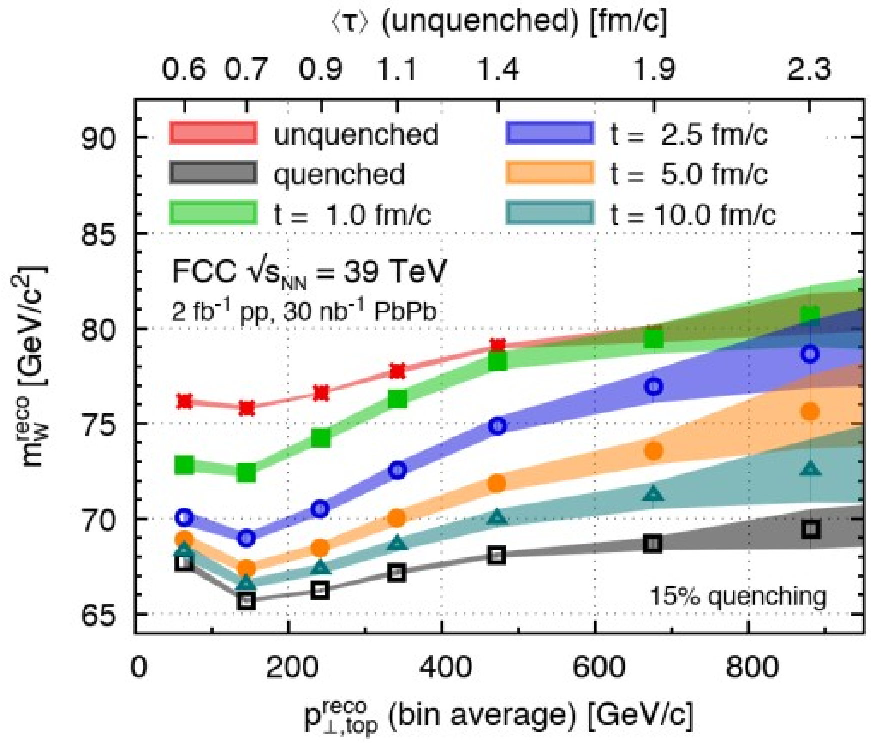




Heavy ions

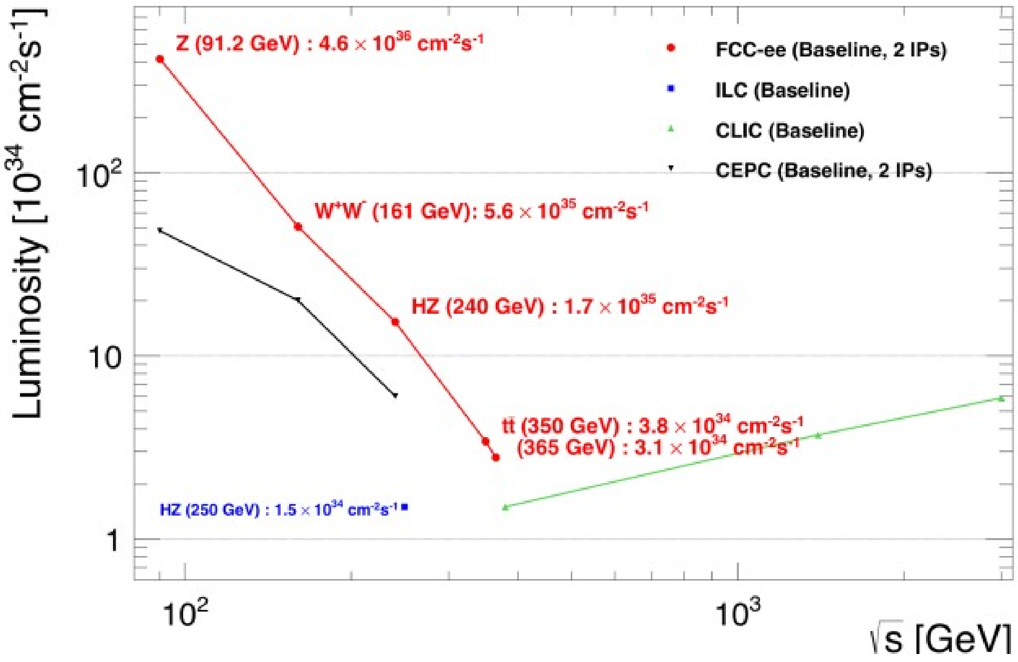
- Operation with heavy ions at FCC-hh
  - PbPb collisions at $\sqrt{s_{NN}}$ ~ 39 TeV

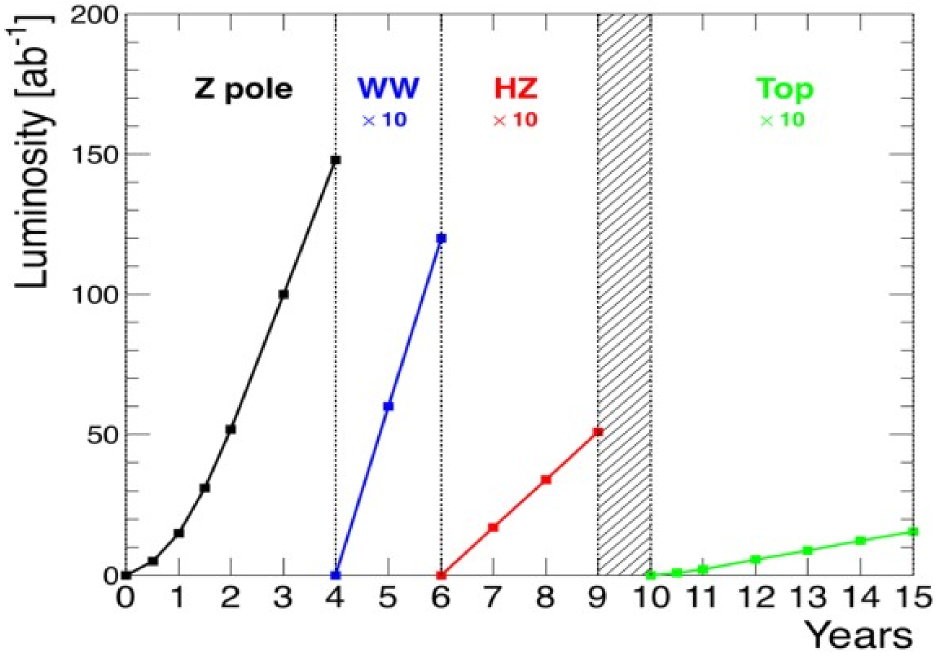




FCC-ee operation

- Highest-luminosity electron-positron collider
- Energies from 88 to 365 GeV
- Samples of 5.10[12] *Z* bosons, 10[8] *WW*, 10[6] *H*, 10[6] top quark pairs





FCC-hh operation

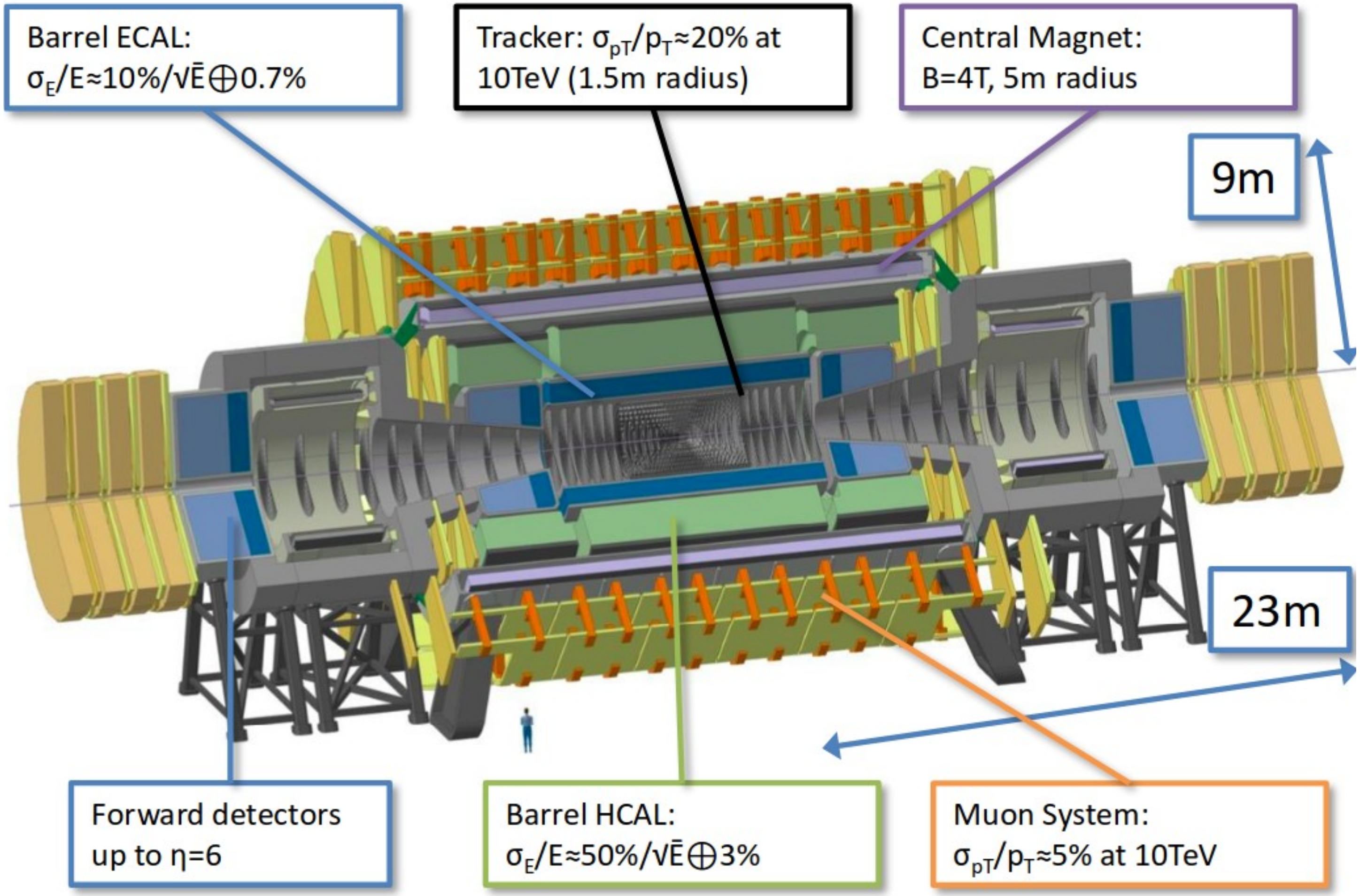
- **Operation scenario**
  - 10 years with ~250 fb^{-1} / year
  - 15 years with ~1000 fb^{-1} / year

  → In total O(20) ab^{-1} over 25 years of operation

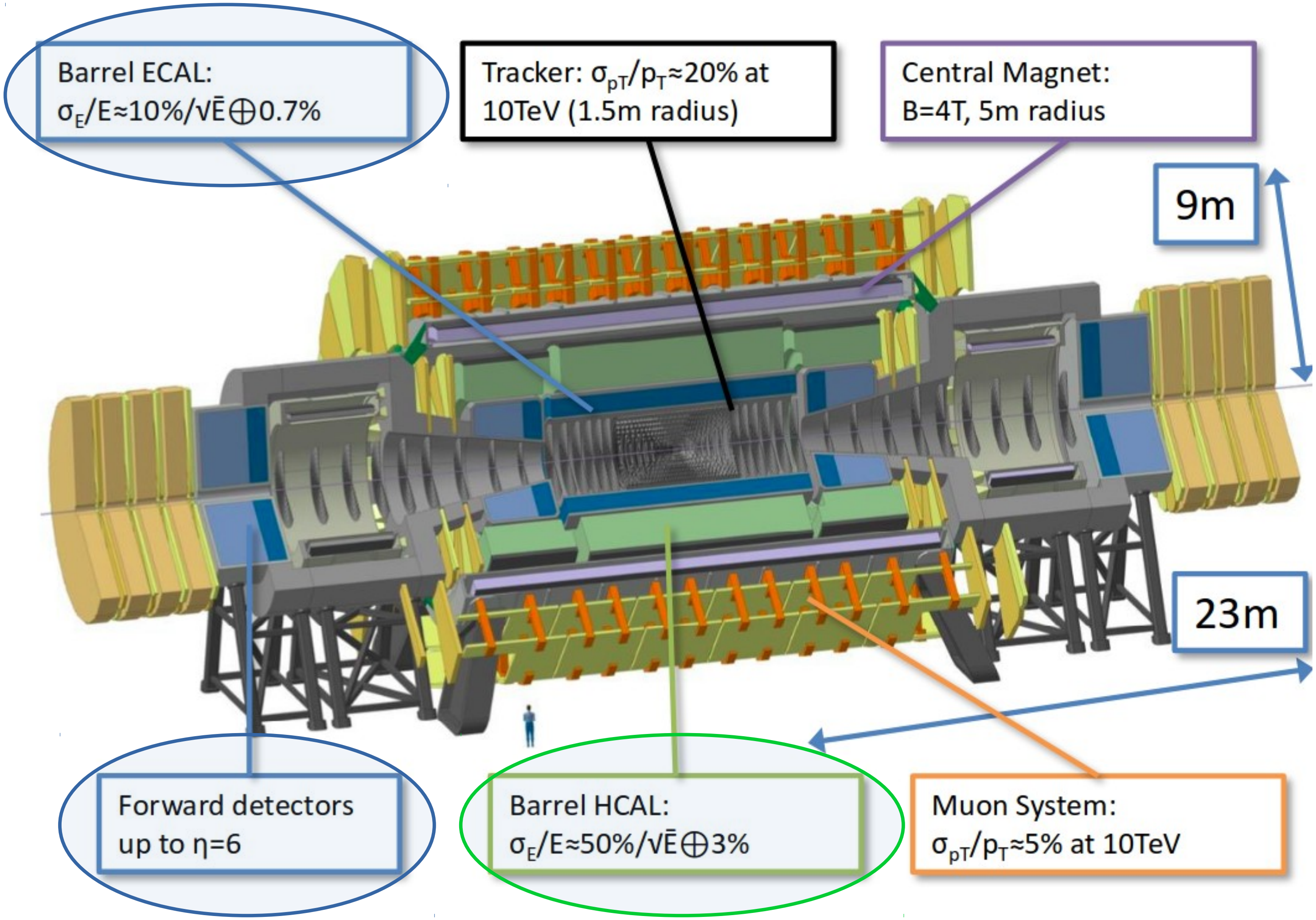
- **Pile-up of 1000 in the ultimate scenario**
  - 5 x more than on HL-LHC!

parameter	FCC-hh		HE-LHC	HL-LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	1.1
bunch intensity [10^{11}]	1	1	2.2	2.2
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3
SR power / length [W/m/ap.]	28.4		4.6	0.33
long. emit. damping time [h]	0.54		1.8	12.9
beta* [m]	1.1	0.3	0.45	0.15 (min.)
normalized emittance [μm]	2.2		2.5	2.5
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	16	5 (lev.)
events/bunch crossing	170	1000	460	132
stored energy/beam [GJ]	8.4		1.3	0.7

FCC-hh reference detector



FCC-hh calorimetry

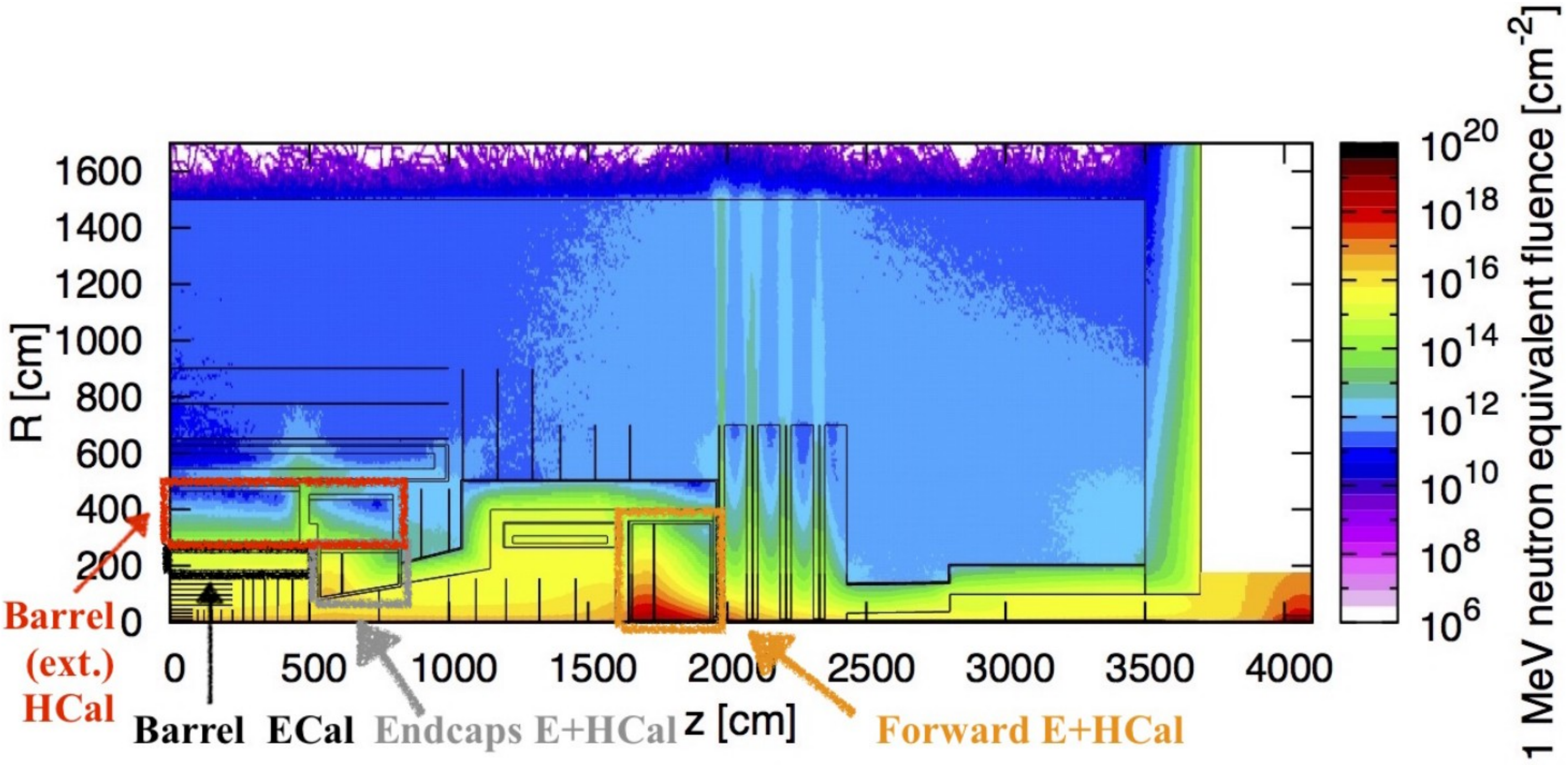


ECAL Forward and Endcaps
LAr / Pb (Cu)

Central HCAL
Scintillating tiles / Fe + Pb
SiPM

- Inspired by ATLAS calorimetry, but with higher granularity

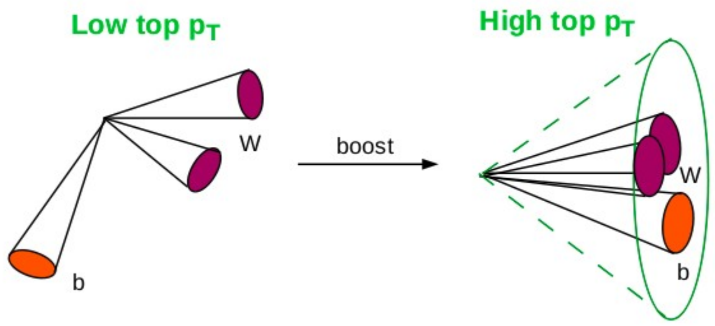
Radiation hardness

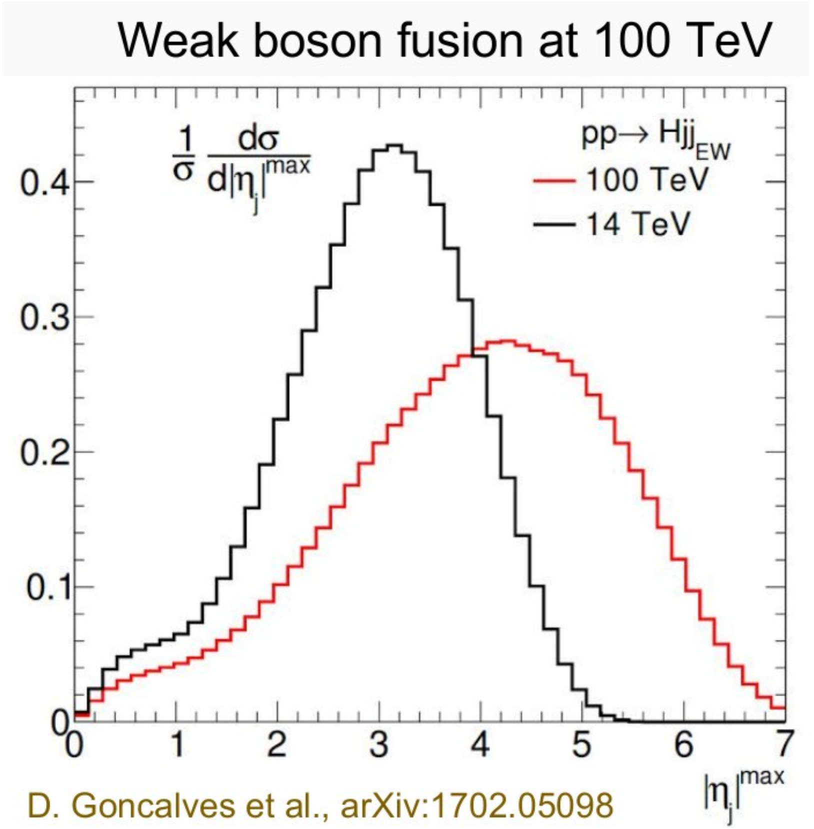


	1 MeV neq [cm^{-2}]	dose
ECal Barrel	$\leq 5 \times 10^{15}$	$\leq$ 100 kGy
HCal Barrel	$\leq 3 \times 10^{14}$	$\leq$ 8 kGy
Endcap	$\leq 3 \times 10^{16}$	$\leq$ 1 MGy
Forward	$\leq 5 \times 10^{18}$	$\leq$ 5 GGy

Requirements for calorimetry

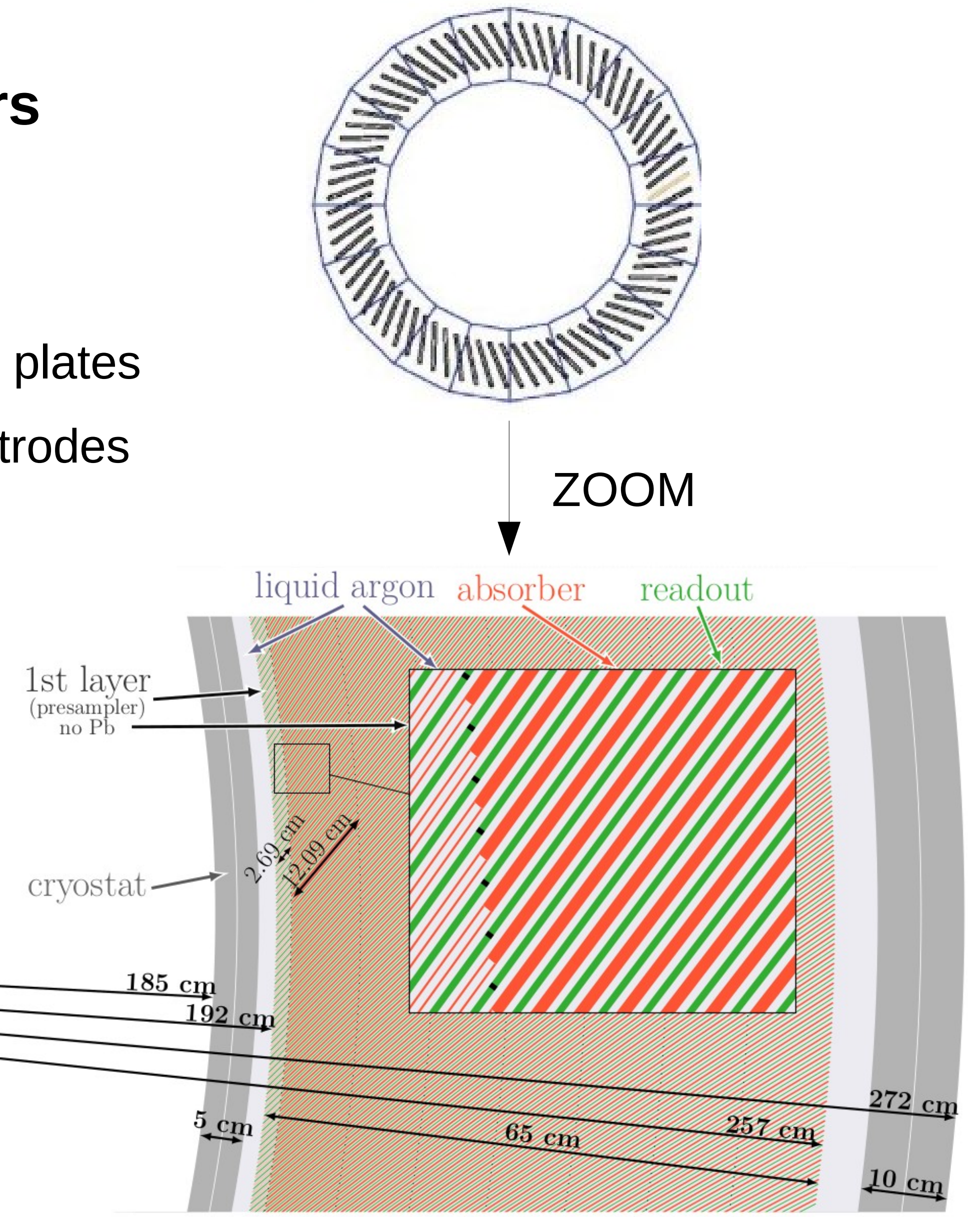
- Energy resolution $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$
- Radiation hardness
- Precise measurements up to $|\eta| = 4$, coverage up to $|\eta| = 6$
- Fine granularity
- Timing





Central electromagnetic calorimeter

- **LAr technology with Pb absorbers**
  - Novel design
  - Higher segmentation wrt ATLAS
  - Easy construction with straight inclined plates
  - Using straight multi-layer read-out electrodes

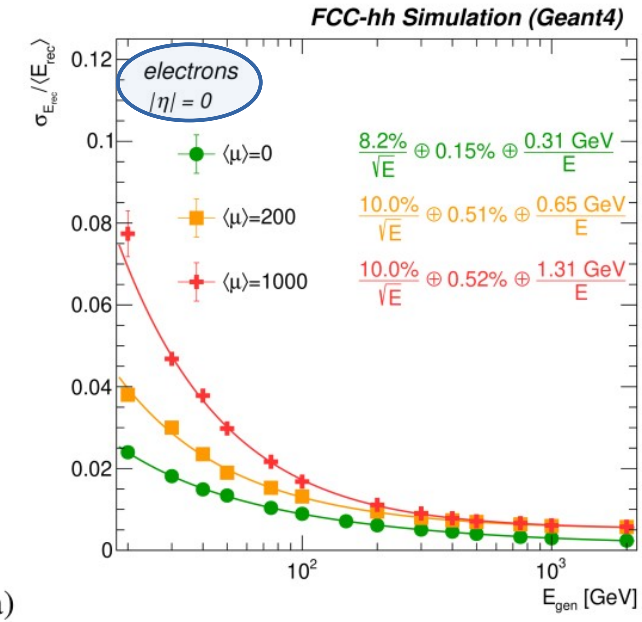


2 mm Pb/steel plates inclined by 50°
LAr gap increases with radius:
1.15 mm-3.09 mm
8 longitudinal layers
$\Delta\eta = 0.01 \ \Delta\phi = 0.009$

Electron / photon reconstruction

- Sampling term ≤ 10%/√*E*
- Constant term well bellow 0.7%
- Noise term
  - Electronic noise of ~300 MeV
  - In-time pile-up of <μ> = 1000 leads to a noise term of 1.3 GeV

  → Efficient in-time suppression is crucial



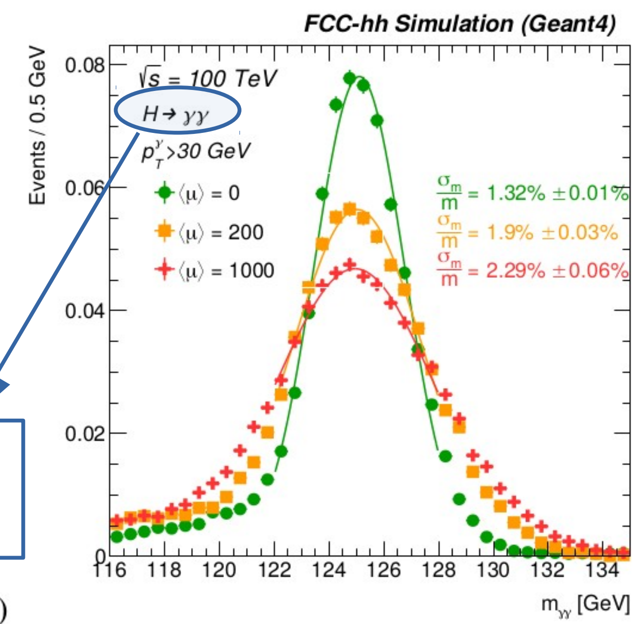
a)

→ Required energy resolution achieved

→ Noise rejection strategies needed

Measurement of Higgs self-coupling with *HH* → bbγγ

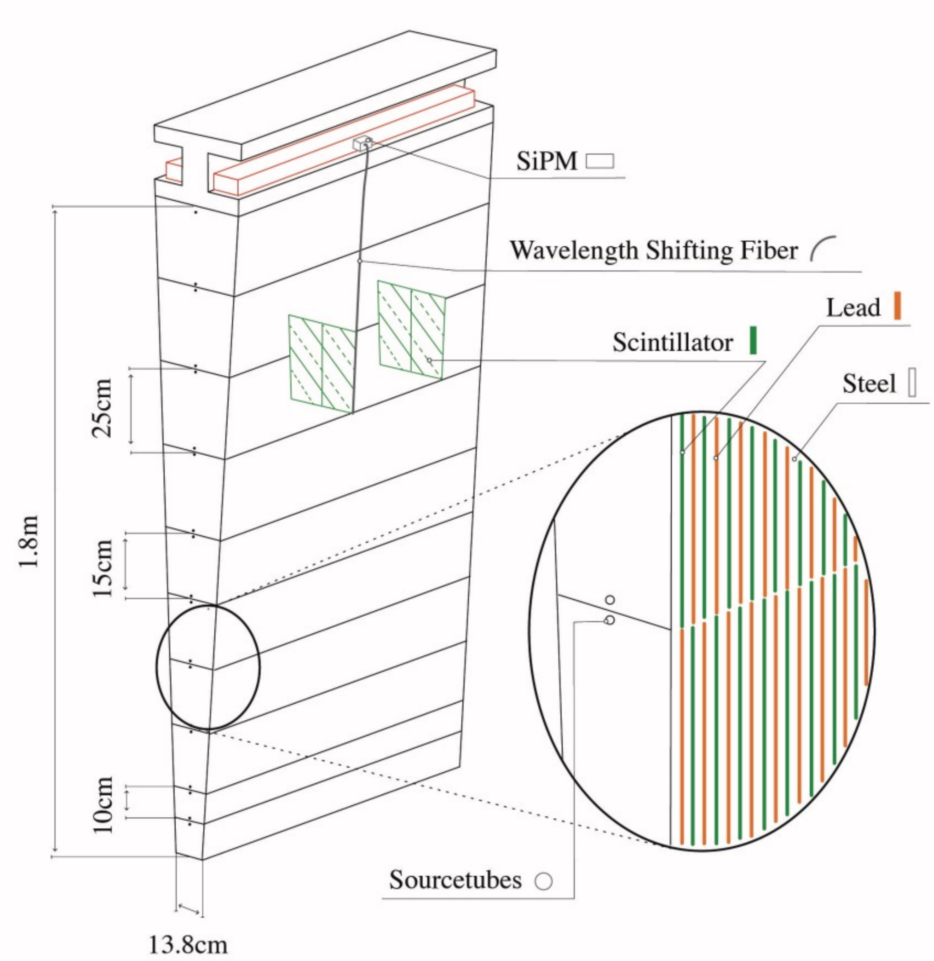
- $\Delta m_{\gamma\gamma}$ = 1.3 GeV → precision of 7%



b)

Central hadronic calorimeter

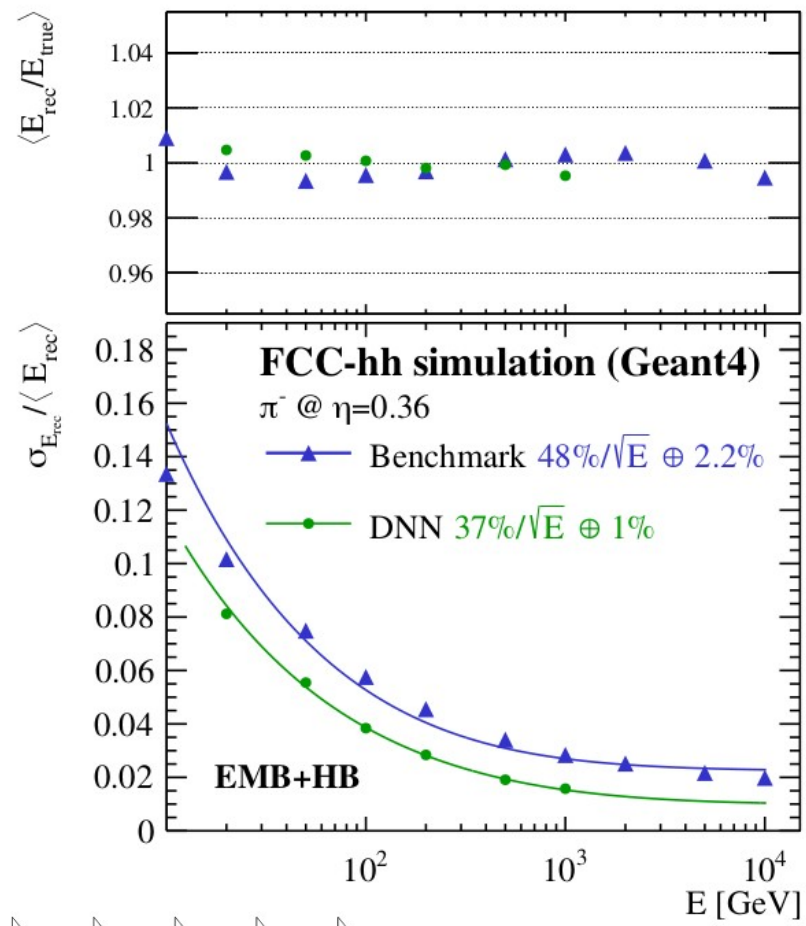
- **Scintillator tile calorimeter**
  - Scintillator / Lead / Steel
  - High granularity
  - Read-out by SiPM at the outer radius
- **Tests with tiles and SiPMs being performed in the laboratory**

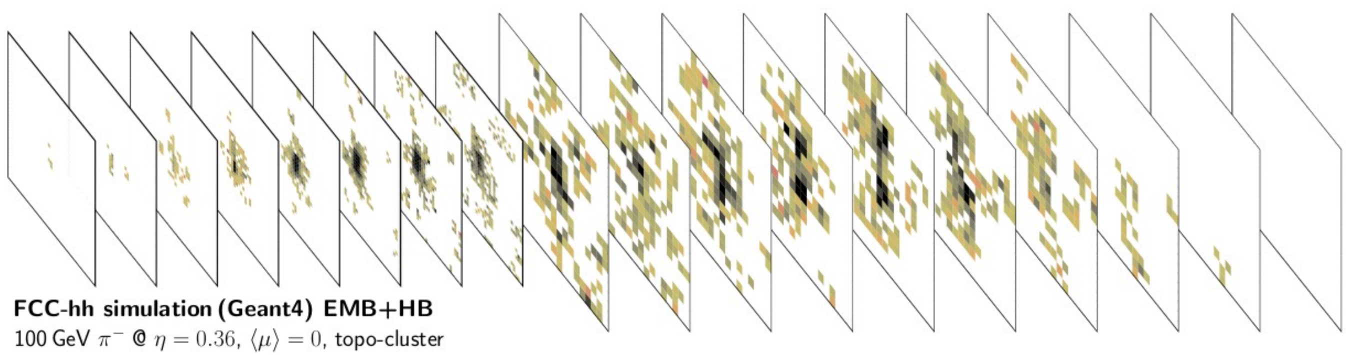


5 mm steel absorber plates,
alternate w/ 3 mm Si and 4 mm Pb tiles
10 longitudinal layers
$\Delta\eta(> 0.006) = 0.025$ $\Delta\phi = 0.025$

Combined reconstruction of pions

- **Simple calibration**
  - Sampling term of ***48%/√E***
  - Constant term **~2%**
- **First results using a convolutional neutral network (DNN)**
  - No tracker information, only high-segmented cells in calorimeters
  - Training with 8M events (no electronic noise at the moment)
  - Sampling term of ***37%/√E*** achieved!





LAr-based calorimeter for FCC-ee (I)

- **High-segmented LAr ECAL shown to be suitable for FCC-hh**
  - R&D projects concerning cryostat material optimisation, readout through PCBs and timing defined
- **Could such a detector be used for FCC-ee?**
  - Until now two concepts for ECAL considered: Si/W (CLIC concept), Dual read-out calorimeter (IDEA)
  - LAr technology: reliable and proofed concept (lot of experience from ATLAS), very cheap

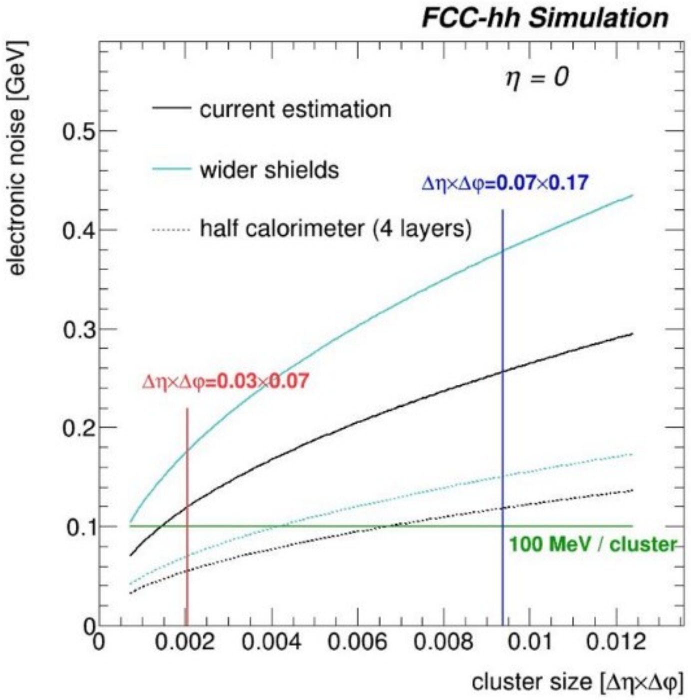
Requirements for FCC-ee calos (I)

- Radiation tolerance similar to LHC
- Particle flow technique
- Excellent particle identification
- Good timing
  - ATLAS LAr: <200 ps
- Position resolution
- Excellent jet resolution (~30%/$\sqrt{E}$) to separate W and Z decays
  - LAr+HCAL, no tracker: 37%/$\sqrt{E}$ using DNN

Requirements for FCC-ee calos (II)

- **Measure particles down to 300 MeV**
  - This is the size of the noise term at the moment
- **How to decrease the noise**
  - Minimize material in front of the calorimeter (cryostat)
  - Optimization of the cluster sizes for low energy deposits
  - Slower shaping time

→ **100 MeV noise seems feasible**



Conclusions

- Conceptional Design Report (CDR) released in January 2019
  - Detailed documents planned for 2019
- Calorimeter studies
  - R&D projects defined
  - Optimisation of LAr-based ECAL for FCC-ee
- **More people more fun**

Backup

Cost

Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

Domain	**Cost in MCHF**
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**

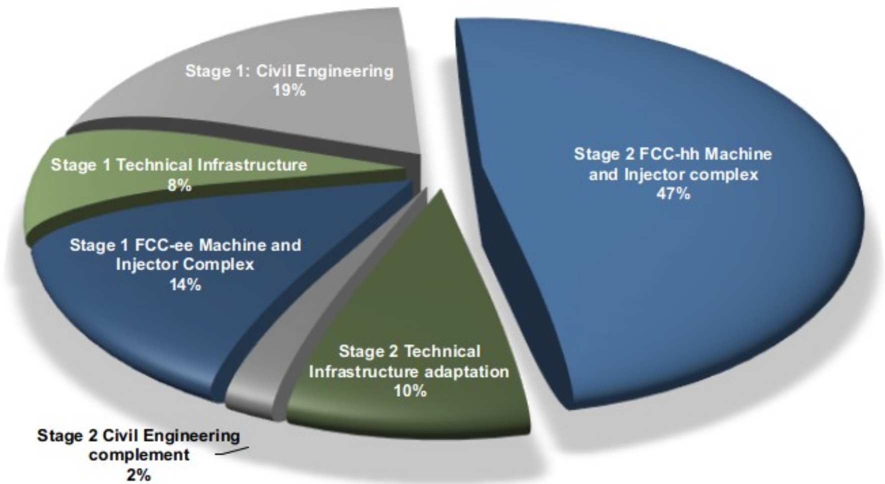


Figure 10: FCC-hh capital cost per domain for the integral FCC project.

Higgs studies – precision

- FCC-ee
- FCC-hh

Collider	HL-LHC	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC	2
Years	25	3	**+4**	-	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4	1.7
BR_{EXO} (%)	SM (0.0)	<1.2	**<1.0**	<1.0	n.a.

Observable	Parameter	Precision (stat.)	Precision (stat.+syst.+lumi.)
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)\, B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

FCC-hh: Searches for new particles

- Mass reach extended by a factor of 5 to 7 compared to LHC

	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

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

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

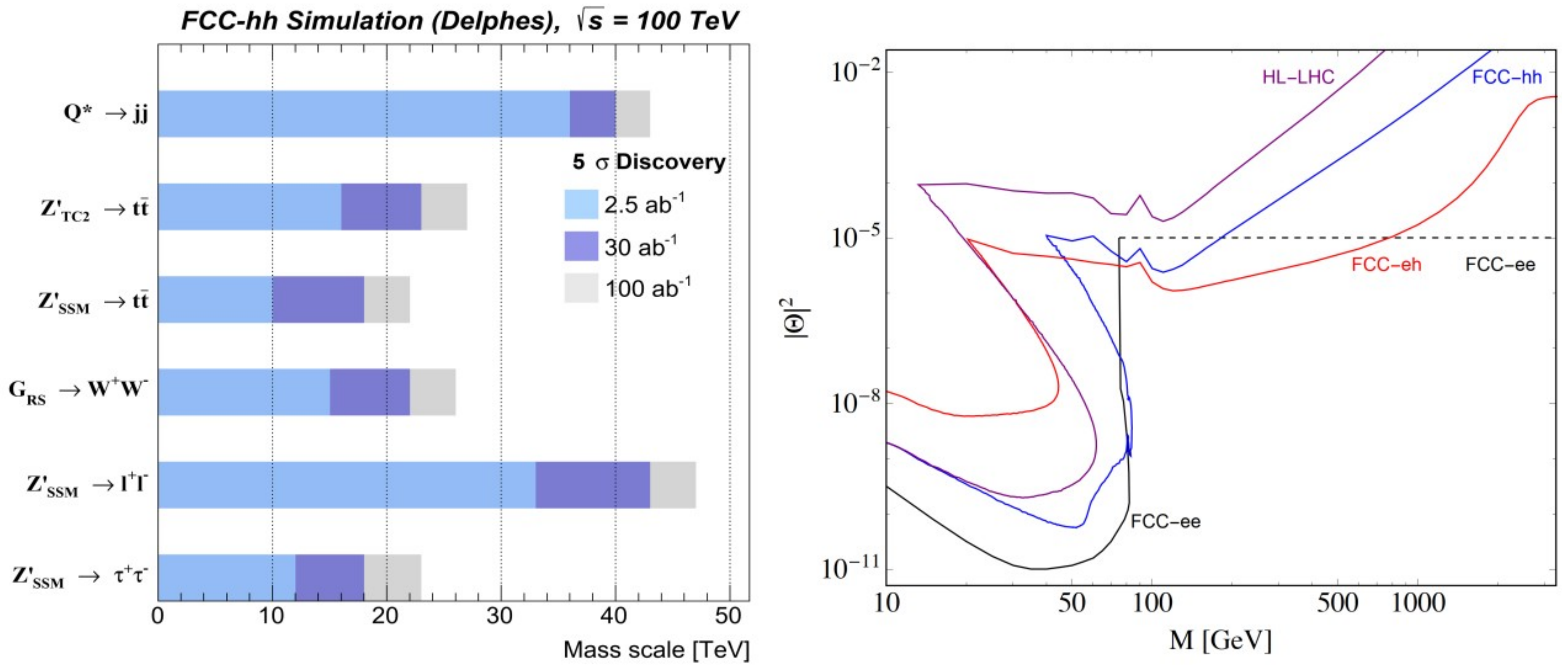


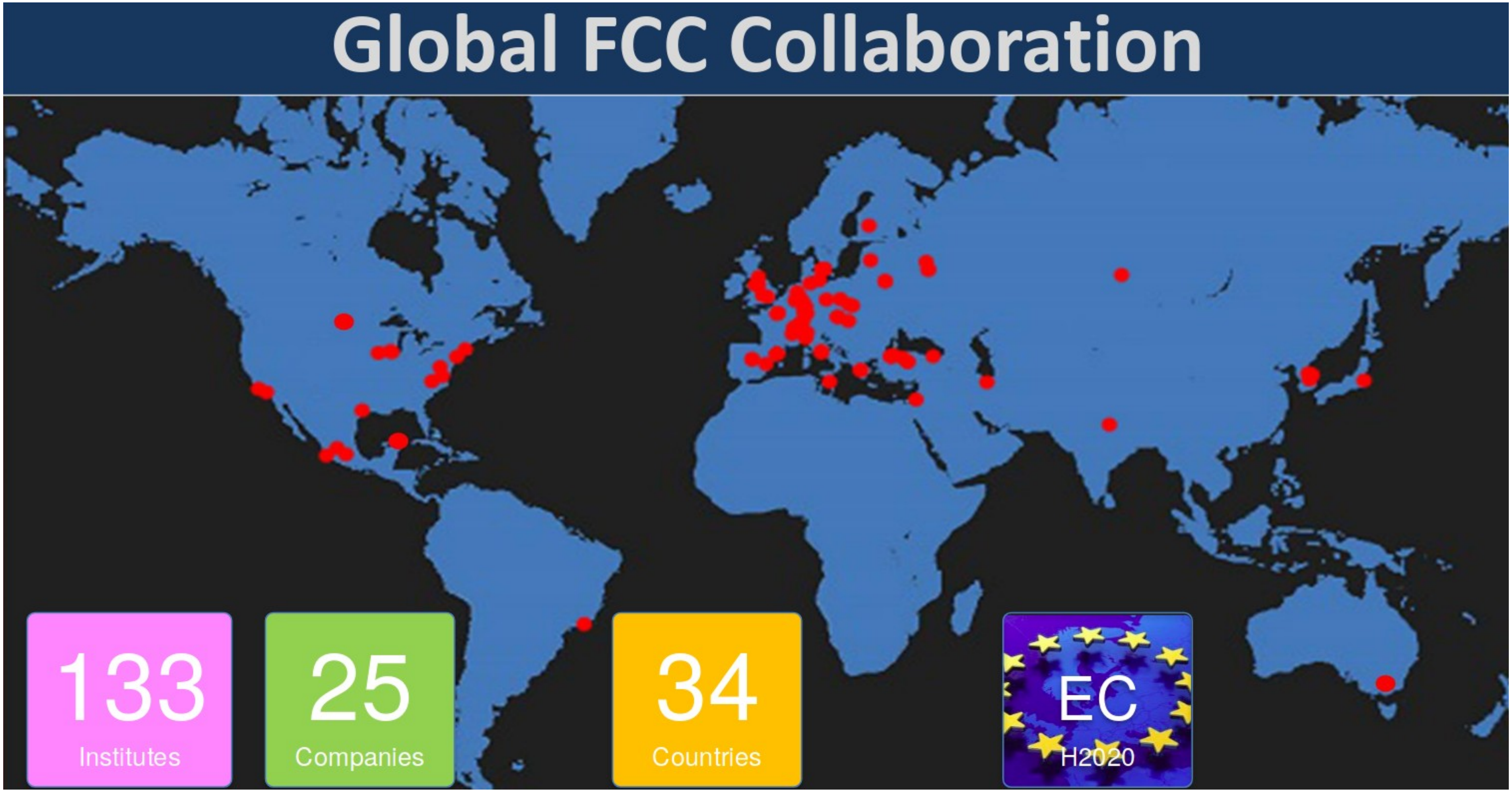
Figure 5: Left: FCC-hh mass reach for different s-channel resonances. Right: Summary of heavy sterile neutrino discovery prospects at all FCC facilities. Solid lines show direct searches at FCC-ee (black, in Z decays), FCC-hh (blue in W decays) and FCC-eh (in production from the incoming electron). The dashed line denotes the impact on precision measurements at the FCC-ee, it extends up to more than 60 TeV.

FCC-ee: EW sector

Table 3: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precision. The systematic uncertainties are present estimates and might improve with further examination. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in some specific new physics models.

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV)	91186700±2200	5	100	Z line shape scan; beam energy calibration
Γ_Z (keV)	2495200±2300	8	100	Z line shape scan; beam energy calibration
R_l^Z (×10³)	20767±25	0.06	0.2-1.0	ratio hadrons / leptons, lepton acceptance
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6	from R_l^Z above
R_b (×10⁶)	216290±660	0.3	<60	ratio $b\bar{b}$/hadrons, stat. extrapol. from SLD
σ^0_{had} (×10³) (nb)	41541±37	0.1	4	peak hadronic cross section, luminosity meas.
N_ν (×10³)	2991±7	0.005	1	Z peak cross sections, luminosity measurement
$\sin^2\theta_W^{eff}$ (×10⁶)	231480±160	3	2-5	from $A_{FB}^{\mu\mu}$ at Z peak, beam energy calibration
$1/\alpha_{QED}(m_Z)$ (×10³)	128952±14	4	Small	from $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ (×10⁴)	992±16	0.02	1-3	b-quark asymmetry at Z pole, from jet charge
$A_{FB}^{pol,\tau}$ (×10⁴)	1498±49	0.15	<2	τ polarisation, charge asymmetry, τ decay physics
m_W (MeV)	80350±15	0.6	0.3	WW threshold scan; beam energy calibration
Γ_W (MeV)	2085±42	1.5	0.3	WW threshold scan; beam energy calibration
α_s (m_W) (×10⁴)	1170±420	3	Small	from R_l^W
N_ν(×10³)	2920±50	0.8	Small	ratio invisible to leptonic in radiative Z returns
m_{top} (MeV)	172740±500	20	Small	$t\bar{t}$ threshold scan; QCD errors dominate
Γ_{top} (MeV)	1410±190	40	Small	$t\bar{t}$ threshold scan; QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2±0.3	0.08	Small	$t\bar{t}$ threshold scan; QCD errors dominate
ttZ couplings	±30%	0.5 – 1.5%	Small	from E_{CM} = 365 GeV run

FCC Collaboration

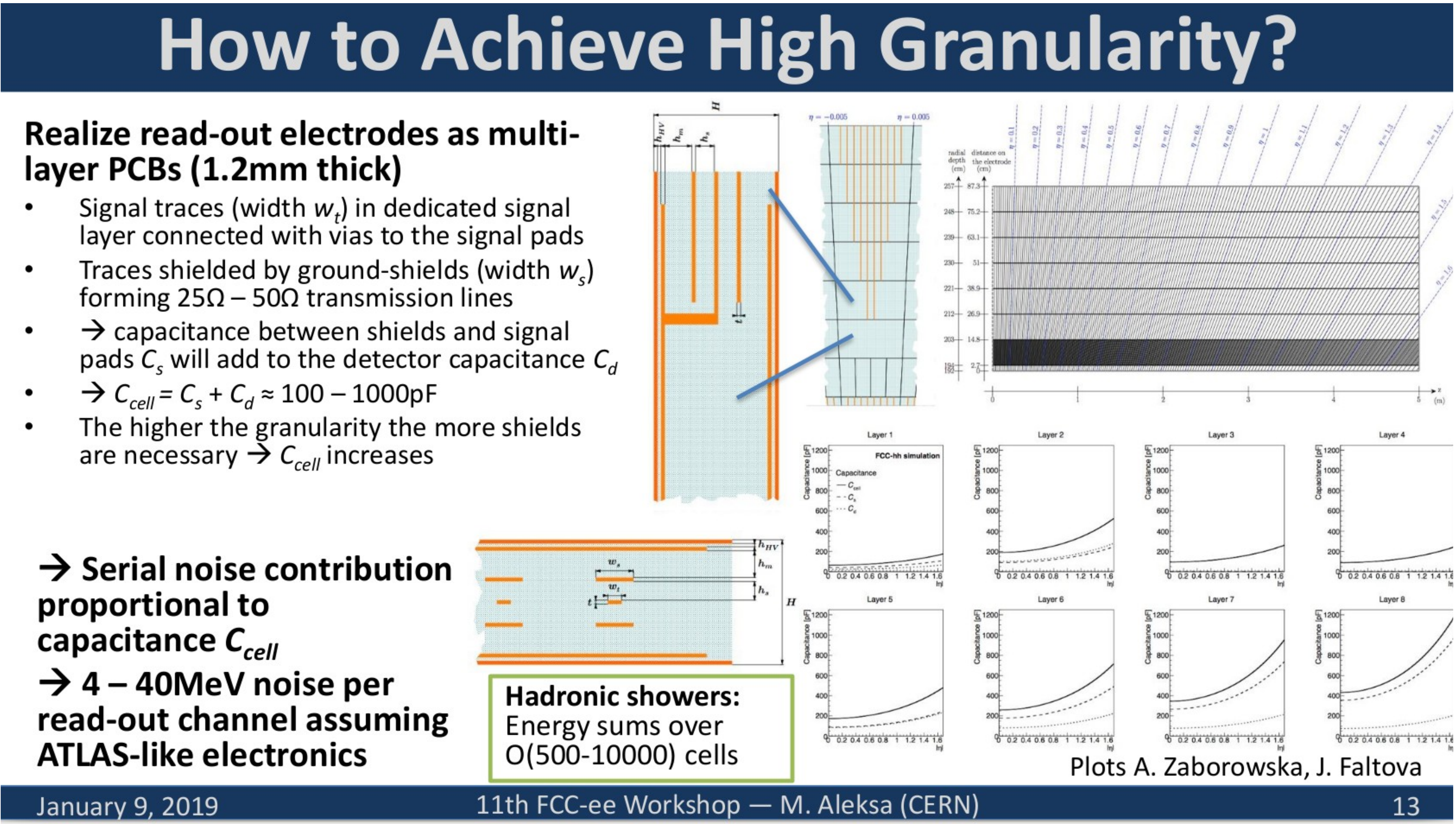


FCC-ee: Power consumption

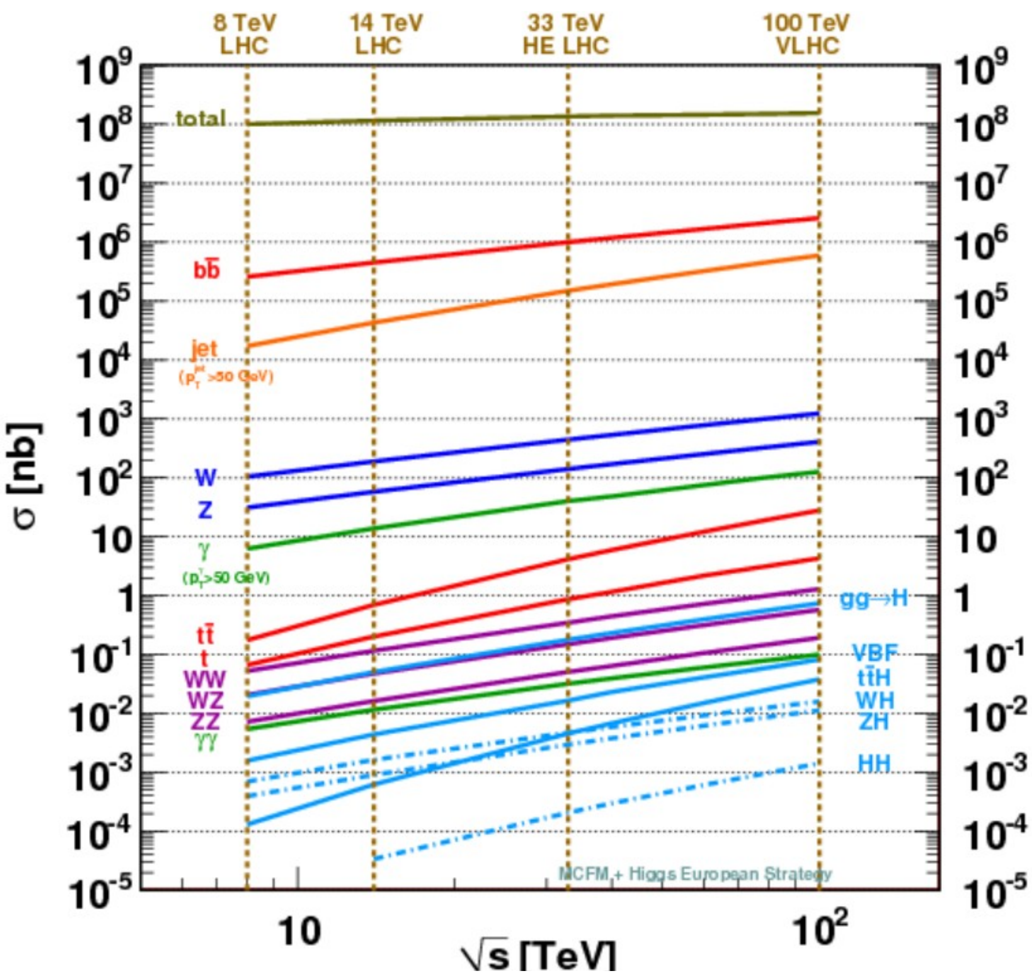
- Electric power consumption is one of the operating costs, but not the cost-driver
- Average electricity consumption

CERN today	1.2 TWh/year
HL-LHC	1.4 TWh/year
FCC-ee	1.9 TWh/year
FCC-hh	4.0 TWh/year

LAr granularity



Cross sections



M. Mangano,
arXiv:1710.06353
CERN-2017-003-M

Total cross-section similar to LHC

Small increase pro low energy collisions (Min. bias events)

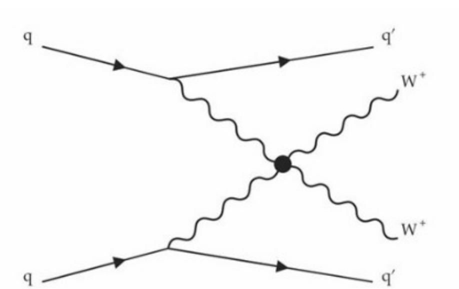
- Cross-section for inelastic collisions of 80 → 108 mb
- <p_T> of charged particles 0.6 GeV → 0.8 GeV

Significantly higher cross-sections for “interesting processes”

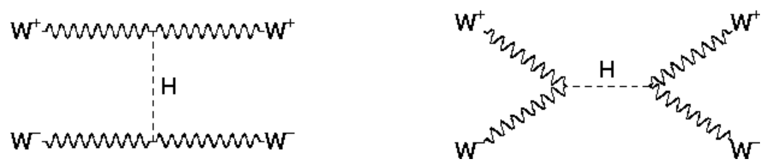
- Another difference: p_T up to 7x larger compared to LHC

Rozptyl *WW*, VBF mechanismus

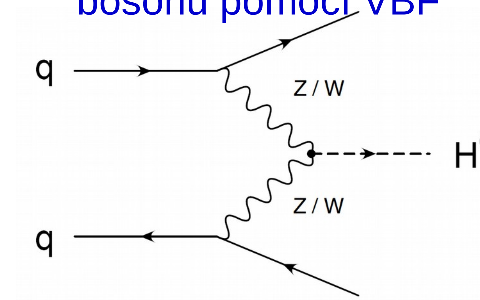
- Důkladné měření procesu *WW* → *WW* jako důležitý test zkoumání narušení elektroslabé symetrie
- Nová fyzika by se mohla nepřímo prokázat v tomto procesu. Hledání těžkých bosonů rozpadajících se na *WW*, *ZZ*, *HH*, ….



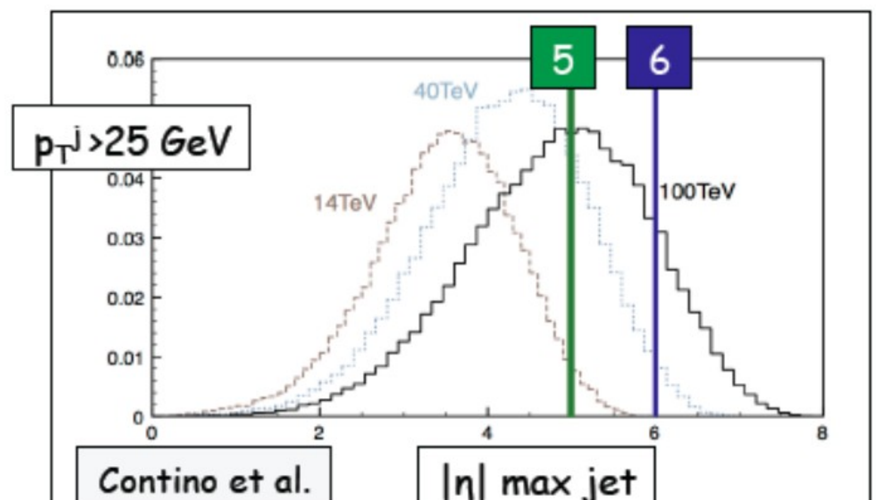
Rozptyl *WW*



Produkce Higgsova bosonu pomocí VBF

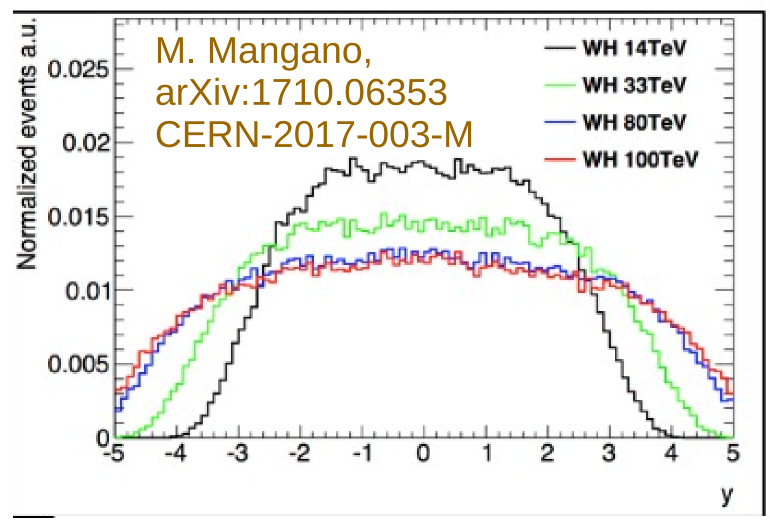


- Vector Boson Fusion (VBF) při produkci Higgsova bosonu
  - Potřebujeme zachytit jety v dopředné oblasti
  - 100 TeV: jety mezi |*η*| = 2 – 6 musíme být schopni naměřit a odlišit od pile-up jetů

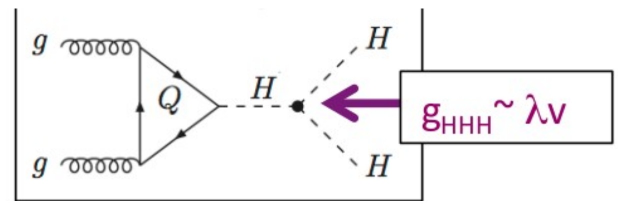


Přesné měření Higgsova bosona

- ***H* → 4 leptony**
  - 30-50% ztráta v akceptanci na 100 TeV v porovnání se 14 TeV, pokud máme drahový detektor a přesné měření z EM kalorimetru do |*η*|<2,5 (ATLAS, CMS)
  - Pokud rozšíříme oblast přesného měření do |*η*|<4,0, můžeme se dostat na úroveň experimentů na LHC



- **Higgs self-coupling**
  - produkce *HH* (42 x častější než na LHC)



FCC

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L} dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

W', Z' at FCC-hh

Rate of possible new DY resonances (fb)