

Physics at the FCC (Future Circular Collider)



5th Summer School on Intelligent signal processing
for FrontIER Research and Industry

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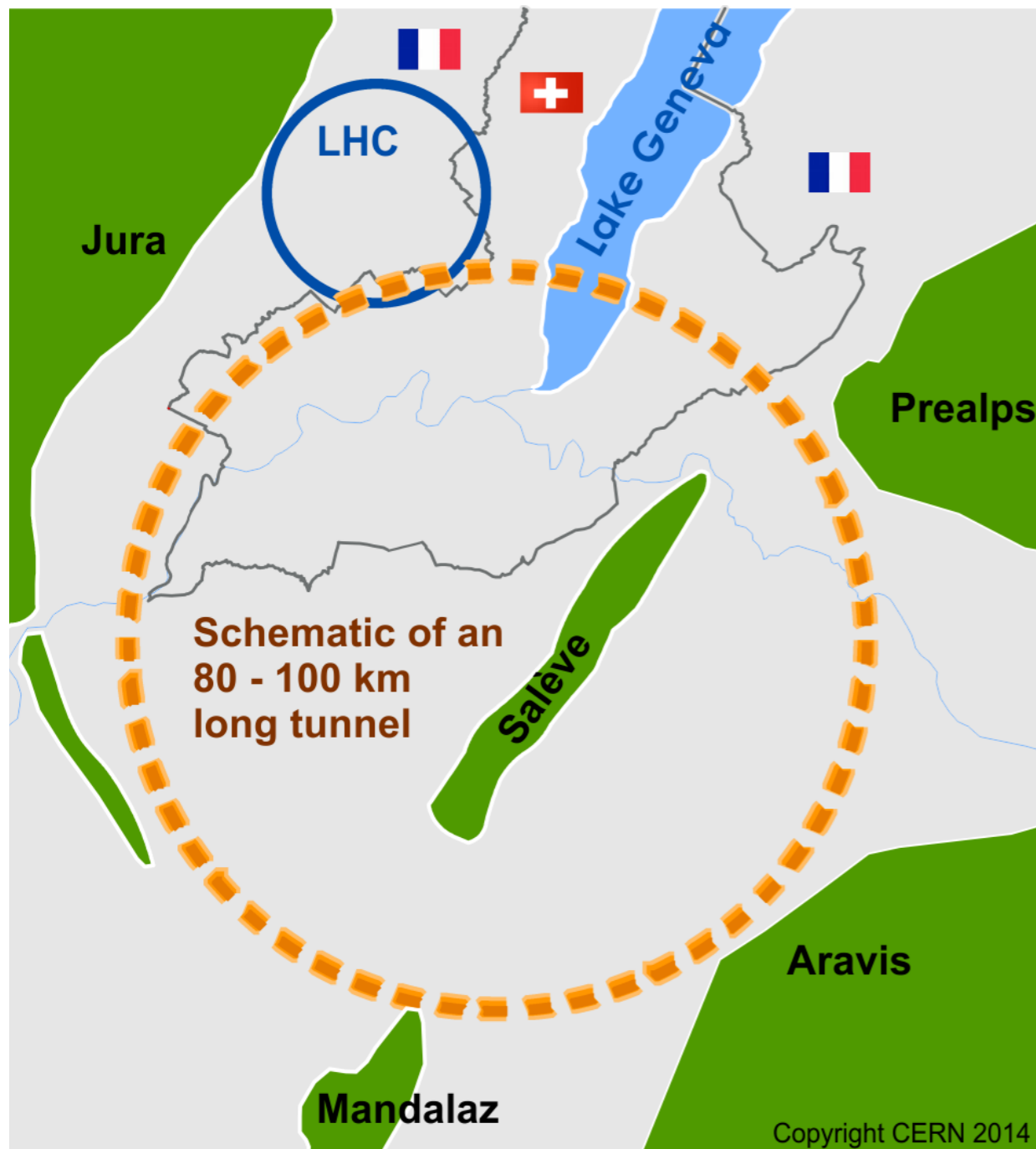
23 May 2019



FCC vs CEPC

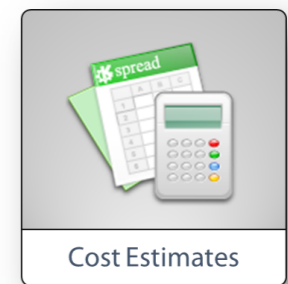
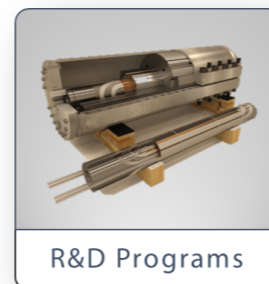
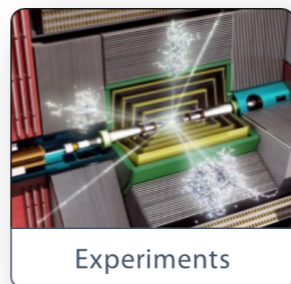
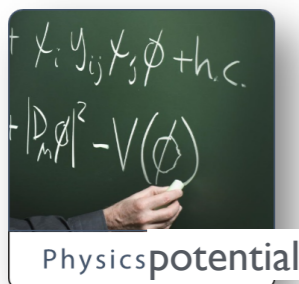
- Overall project similar to CEPC/SPPC, as just presented by Joao
- Main differences:
 - FCC key target is 100 TeV pp collider, of which the ee phase is meant as an intermediate step. The ee design must comply with the pp design priorities
 - ee operations must include physics at — and slightly above — the top-antitop production threshold

Future Circular Colliders (FCC)



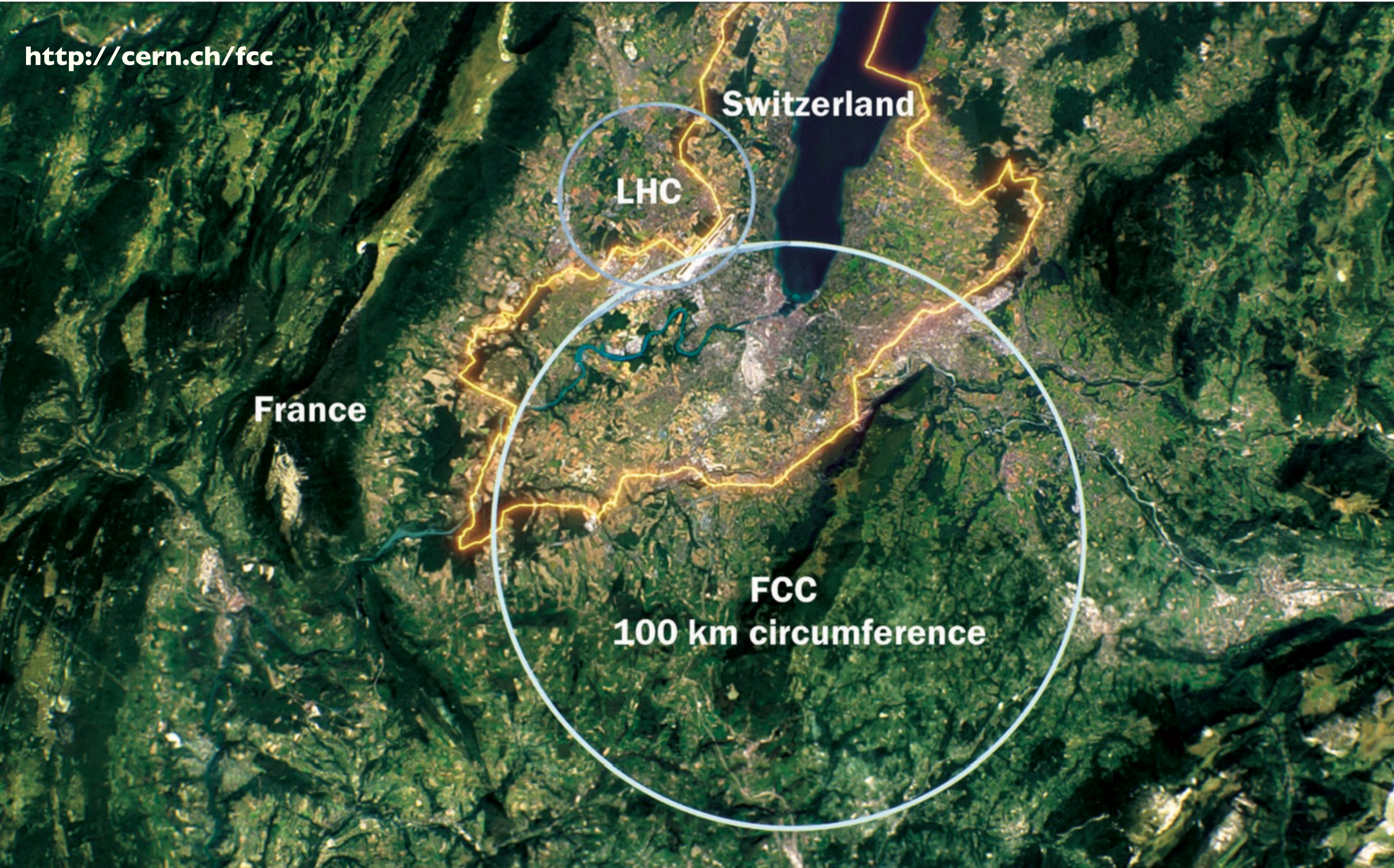
International FCC collaboration (CERN as host lab) to study:

- **pp -collider (*FCC-hh*)**
 → main emphasis, defining infrastructure requirements
~16 T \Rightarrow 100 TeV pp in 100 km
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*)**, as potential first step
- **HE-LHC** with *FCC-hh* technology
- **$p-e$ (*FCC-he*) option**, integration of one IP, e from ERL
- **CDR available at**
<https://fcc-cdr.web.cern.ch>



Future Circular Collider

<http://cern.ch/fcc>



Switzerland

LHC

France

FCC

100 km circumference

Plan of the lecture

- Review the physics motivations for future colliders
- Define the goals of a future collider
- Illustrate target performance, with emphasis on the role of the pp collider (for ee see Joao's talk)
- Brief overview of key technology challenges, and a possible timeline of the FCC project implementation plan

The next steps in HEP build on

- **having important questions to pursue**
- **creating opportunities to answer them**
- **being able to constantly add to our knowledge, while seeking those answers**

The important questions

- **Data driven:**

- What is Dark Matter?
- Origin of Neutrino masses?
- Origin of Matter vs antimatter asymmetry?
- What is Dark energy?
- ...

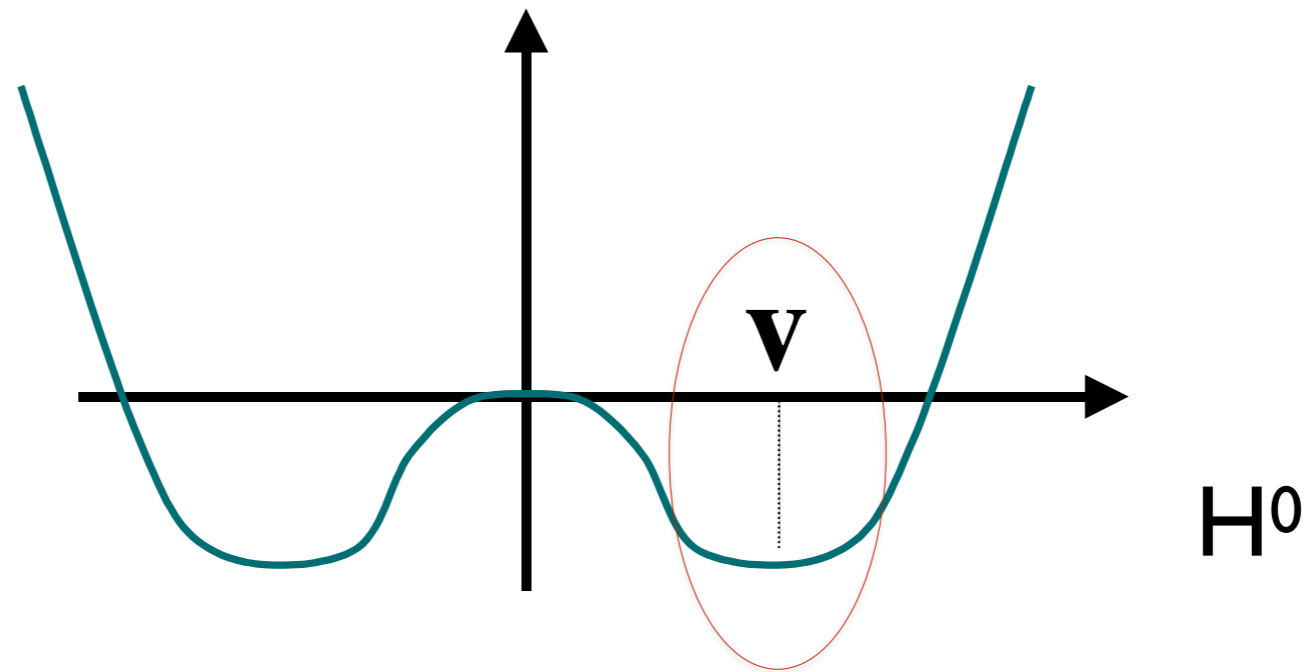
- **Theory driven:**

- The hierarchy problem and naturalness
- The flavour problem (origin of fermion families, mass/mixing pattern)
- Quantum gravity
- Origin of inflation
- ...

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
 - DM: could be anything from fuzzy 10^{-22} eV scalars, to $O(\text{TeV})$ WIMPs, to multi- M_{\odot} primordial BHs, passing through axions and sub-GeV DM
 - *a vast array of expts* is needed, even though most of them will end up empty-handed...
 - Neutrino masses: could originate anywhere between the EW and the GUT scale
 - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \rightarrow e\gamma$, $H \rightarrow \mu\tau$, ...): as for DM, *a broad range of options*
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, ...)

One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction....

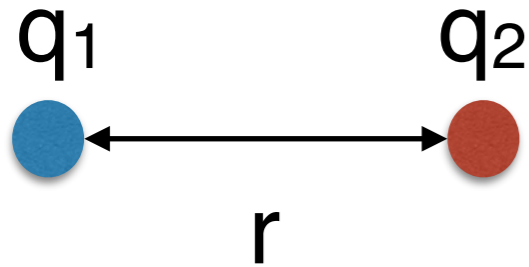


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics

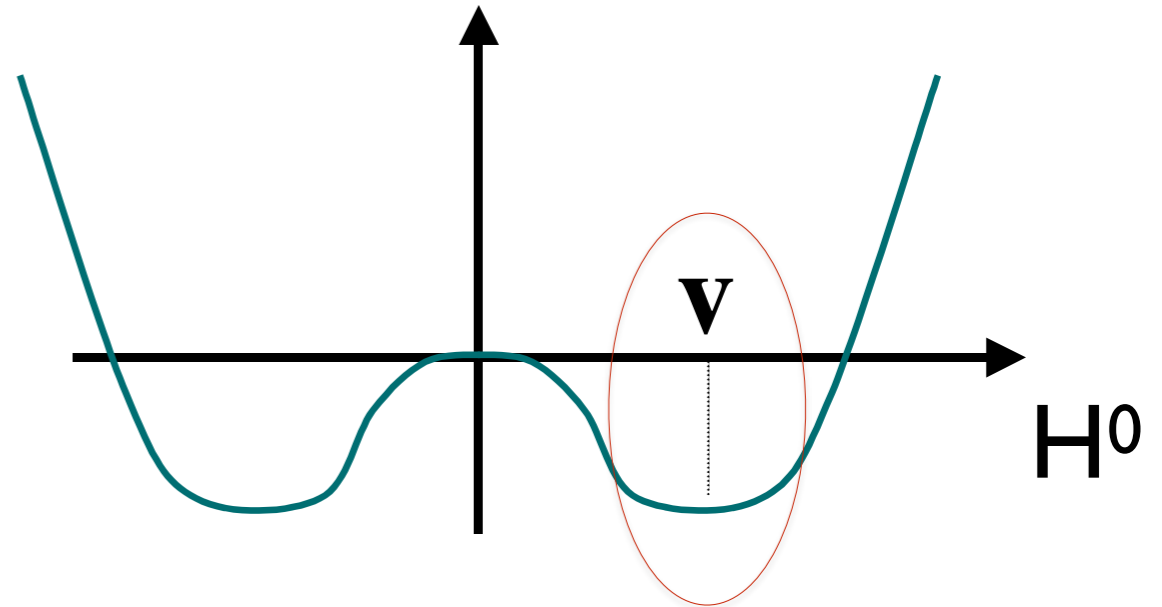


quantized,
in units of
fixed charge

$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem



any function of $|H|^2$ would be
ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign
and value
totally
arbitrary

>0 to ensure
stability, but
otherwise arbitrary

a historical example: superconductivity

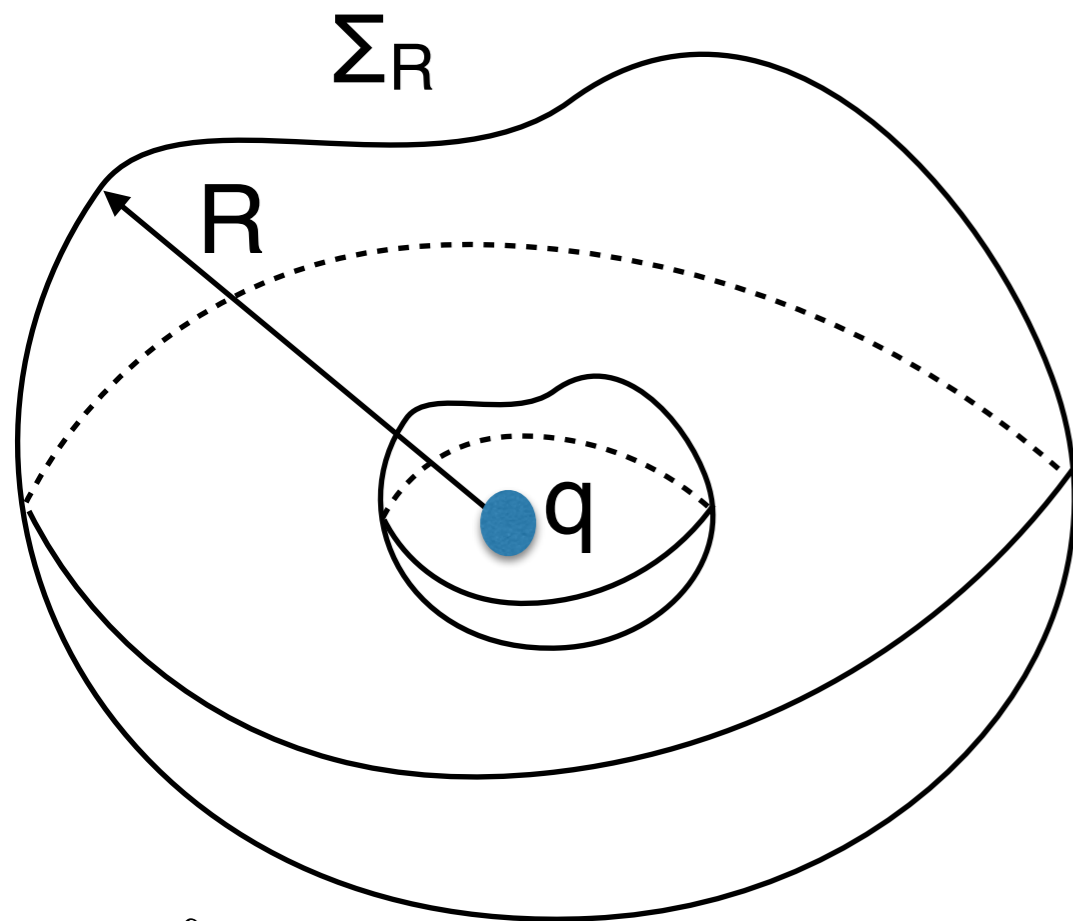
- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either case we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
 - $\lambda^2 \sim g^2 + g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
 - potential is fixed by susy & gauge symmetry
 - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- ...

Decoupling of high-frequency modes

E&M



$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter the charge seen at large scales

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

$$\mu^2_{\text{ren}} = \mu^2 + \text{loop}(W,H, g^2) + \text{loop}(t, -y_t^2)$$

$$\Delta\mu^2 \sim (c_B m_B^2 - c_F m_F^2) \times (\Lambda / v)^2$$

$$\lambda_{\text{ren}} = \lambda + \text{loop}(t, -y_t^4) + \text{loop}(h, \lambda^4)$$

$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \propto a m_H^4 - b m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ , dramatically altering the stability and dynamics \Rightarrow **hierarchy problem**

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
 - Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
 - again, “who ordered that?”
 - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted
 - what we’ve experimentally proven so far are basic properties, which, from the perspective of EFT and at the current level of precision of the measurements, could hold in a vast range of BSM EWSB scenarios
- ➡ *the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can only rely on a future generation of colliders*

**Key question for the future developments of HEP:
Why don't we see the new physics we expected to
be present around the TeV scale ?**

- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

What we want from a future collider

- Guaranteed deliverables:
 - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**
- Exploration potential:
 - exploit both direct (large Q^2) and indirect (precision) probes
 - **enhanced mass reach** for direct exploration
 - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
- Provide firm Yes/No answers to questions like:
 - is there a TeV-scale solution to the hierarchy problem?
 - is DM a thermal WIMP?
 - could the cosmological EW phase transition have been 1st order?
 - could baryogenesis have taken place during the EW phase transition?
 - could neutrino masses have their origin at the TeV scale?
 - ...

Event rates at FCC: examples

FCC-ee	H	Z	W	t	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
	10^6	$5 \cdot 10^{12}$	10^8	10^6	$3 \cdot 10^{11}$	$1.5 \cdot 10^{12}$	10^{12}

FCC-hh	H	b	t	$W(\leftarrow t)$	$\tau(\leftarrow W \leftarrow t)$
	$2.5 \cdot 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5 \cdot 10^6$	$2 \cdot 10^7$

Higgs couplings: beyond the HL-LHC

Collider	HL-LHC	HL-LHC update	ILC ₂₅₀	CLIC ₃₈₀	LEP3 ₂₄₀	CEPC ₂₅₀	FCC-ee ₂₄₀₊₃₆₅		
Lumi (ab ⁻¹)	3	3	2	0.5	3	5	5 ₂₄₀	+1.5 ₃₆₅	+ HL-LHC
Years	25	25	15	7	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	50	3.6	6.3	3.6	2.6	2.7	1.3	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	1.5	0.3	0.40	0.32	0.25	0.20	0.17	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	1.7	1.7	0.8	1.7	1.2	1.3	0.43	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	3.7	1.7	1.3	1.8	1.3	1.3	0.61	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	SM	2.3	4.1	2.3	1.8	1.7	1.21	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	2.5	2.2	2.1	2.1	1.4	1.6	1.01	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	1.9	1.9	2.7	1.9	1.4	1.4	0.74	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	4.3	14.1	n.a.	12	6.2	10.1	9.0	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	1.8	6.4	n.a.	6.1	4.7	4.8	3.9	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	3.4	–	–	–	–	–	–	3.1
BR _{EXO} (%)	SM	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with 5 ab⁻¹ at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional 1.5 ab⁻¹ at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $c\bar{c}$ and into exotic particles are set to their SM values.

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, <https://cds.cern.ch/record/2650162>.

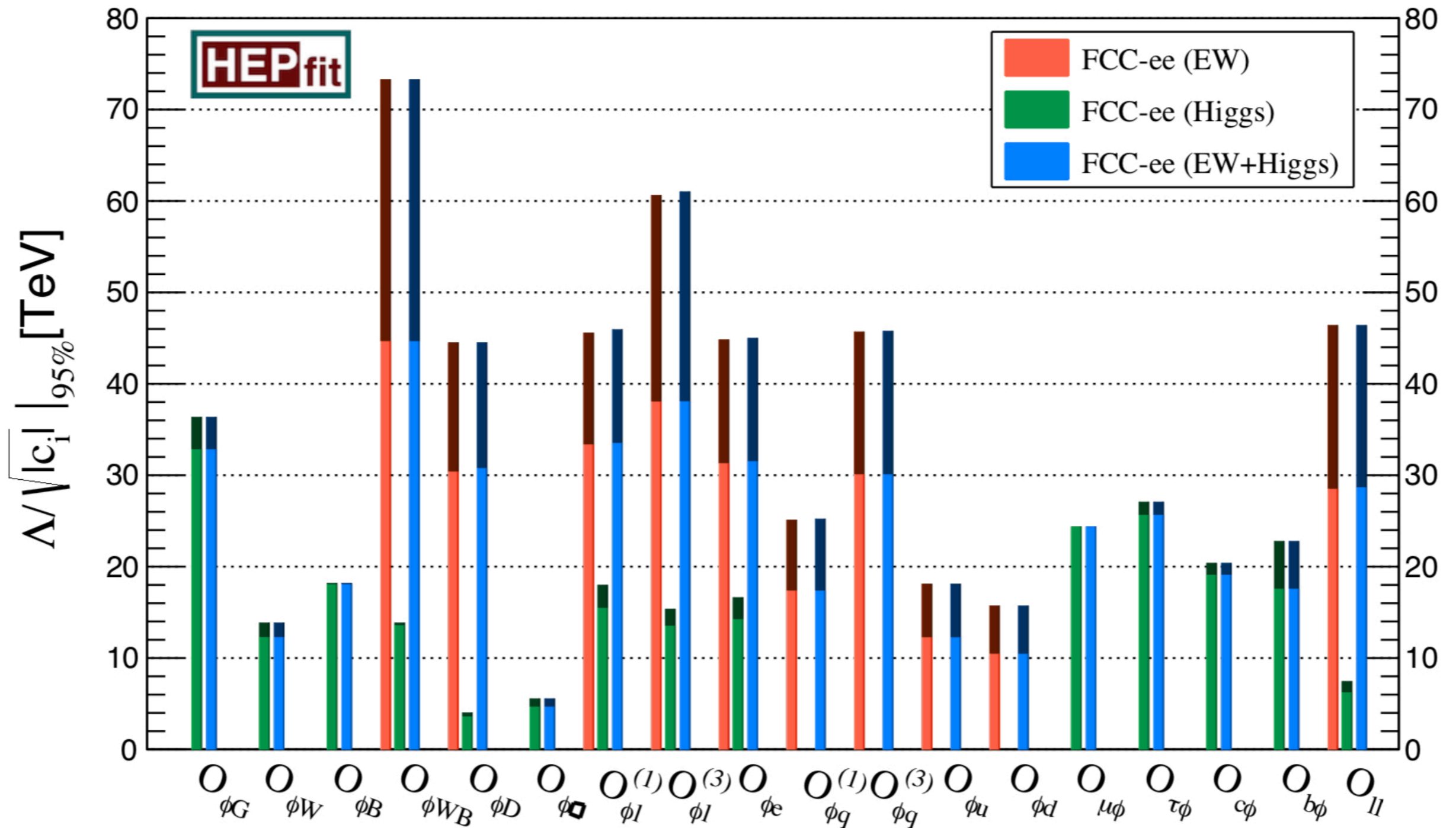
Remarks and **key messages**

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
 - Projections will improve as **new** analyses, allowed by higher statistics, will be considered
1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
 2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as $H\gamma\gamma$, $H\mu\mu$, $HZ\gamma$, Htt

EW parameters @ FCC-ee

Observable	present value \pm error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700 ± 2200	5	100
Γ_Z (keV)	2495200 ± 2300	8	100
R_l^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1.0
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6
R_b ($\times 10^6$)	216290 ± 660	0.3	<60
σ_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	0.1	4
N_ν ($\times 10^3$)	2991 ± 7	0.005	1
$\sin^2 \theta_W^{\text{eff}}$ ($\times 10^6$)	231480 ± 160	3	2-5
$1/\alpha_{\text{QED}}(m_Z)$ ($\times 10^3$)	128952 ± 14	4	Small
$A_{\text{FB}}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1-3
$A_{\text{FB}}^{\text{pol},\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2
m_W (MeV)	80350 ± 15	0.6	0.3
Γ_W (MeV)	2085 ± 42	1.5	0.3
$\alpha_s(m_W)$ ($\times 10^4$)	1170 ± 420	3	Small
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small
m_{top} (MeV)	172740 ± 500	20	Small
Γ_{top} (MeV)	1410 ± 190	40	Small
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2 ± 0.3	0.08	Small
ttZ couplings	$\pm 30\%$	0.5 – 1.5%	Small

Global EFT fits to EW and H observables at FCC-ee



Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

Remarks and **key messages**

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations
 1. An ee Higgs factory needs to operate at the Z pole and WW threshold to maximize the potential of precision measurements of the EW sector
- EW&Higgs precision measurements at future ee colliders could probe scales as large as several 10's of TeV ($c_i \sim 1 \div 4\pi$)
 2. To directly explore the origin of possible discrepancies, requires collisions in the several 10s of TeV region
 3. A 100-TeV pp collider is a natural, and likely required, extension of an ee facility

SM Higgs: event rates in pp@100 TeV

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

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

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

The unique contributions of a 100 TeV pp collider to Higgs physics

- Huge Higgs production rates:
 - access (very) rare decay modes
 - push to %-level Higgs self-coupling measurement
 - new opportunities to reduce syst uncertainties (TH & EXP) and push precision
- Large dynamic range for H production (in p_T^H , $m(H+X)$, ...):
 - new opportunities for reduction of syst 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 (eg *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
 - ...

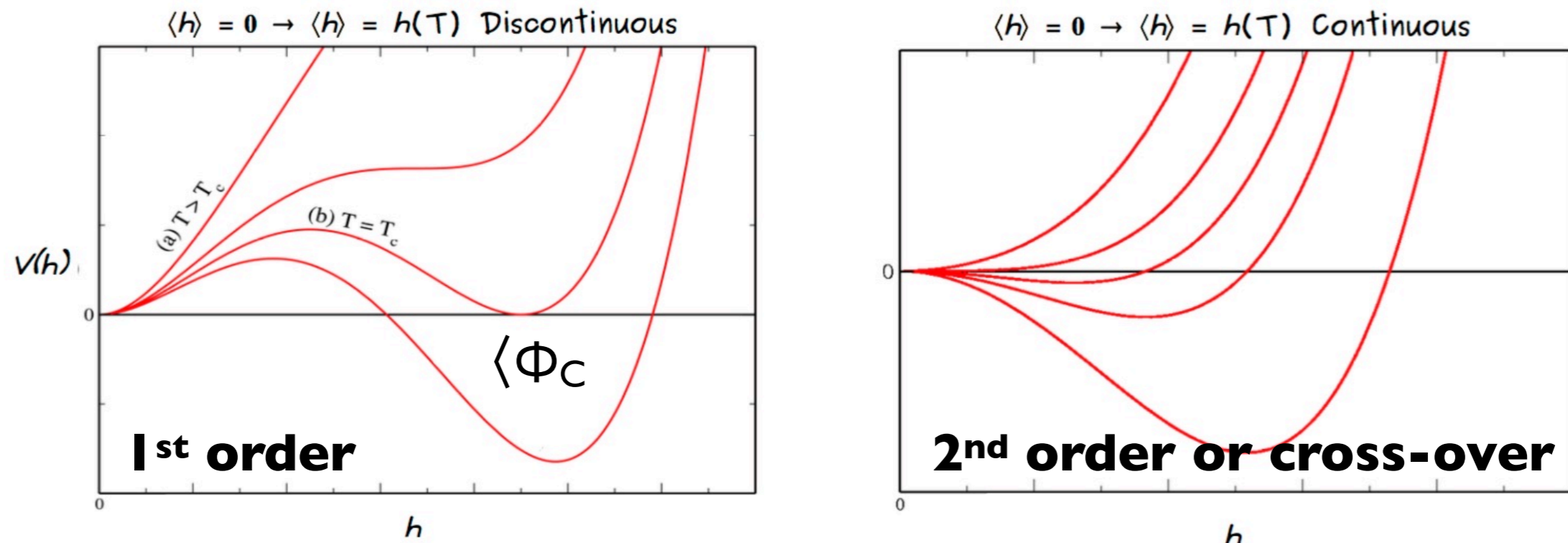
Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	1.3	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	0.65 (*)
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	0.4 (*)
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	0.95 (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	0.9 (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	6.5
BR_{exo} (95%CL)	$BR_{\text{inv}} < 2.5\%$	< 1%	$BR_{\text{inv}} < 0.025\%$

* From BR ratios wrt $B(H \rightarrow 4\text{lept})$ @ FCC-ee

** From $pp \rightarrow ttH$ / $pp \rightarrow ttZ$, using $B(H \rightarrow bb)$ and ttZ EW coupling @ FCC-ee

The nature of the EW phase transition



Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1st order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

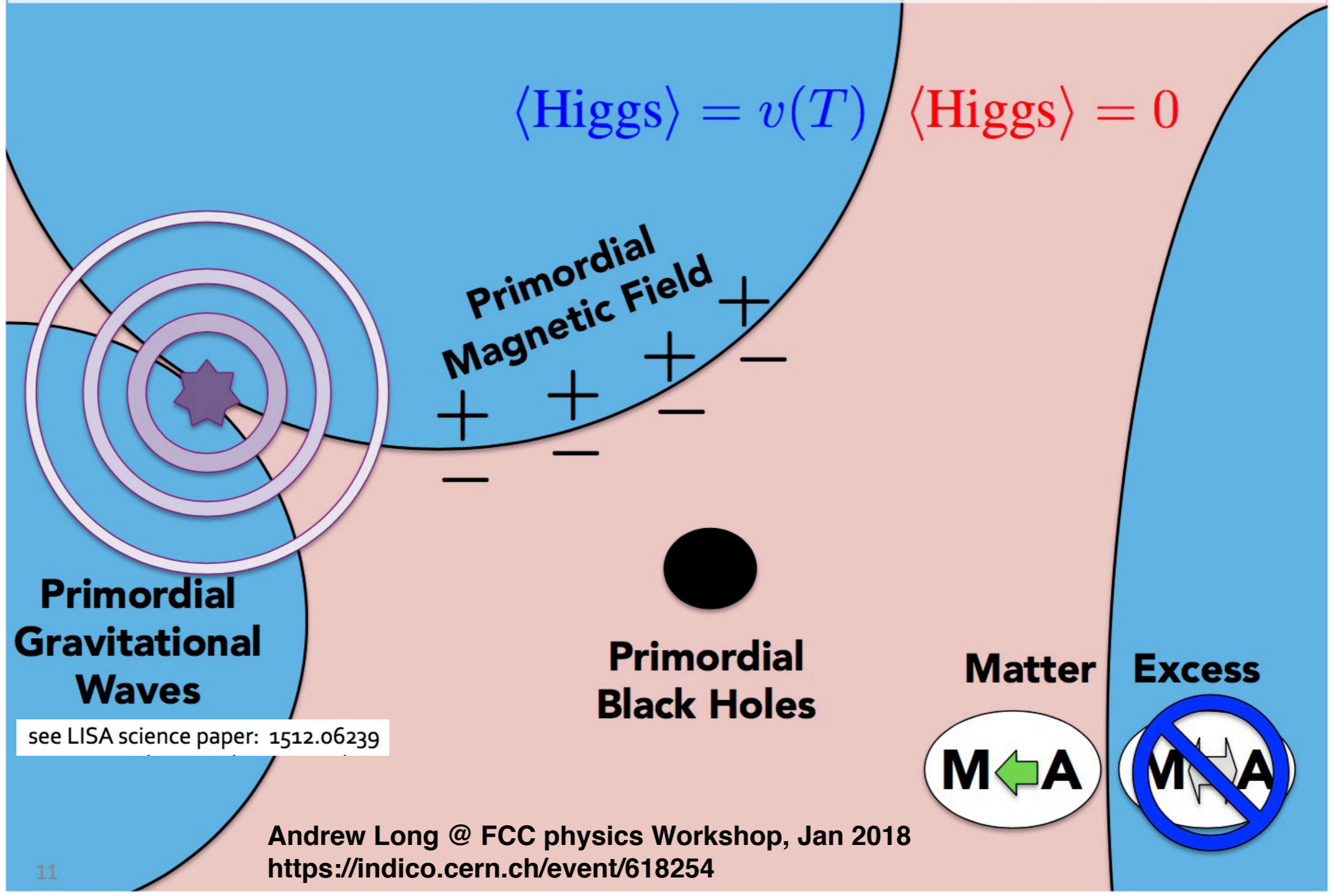
In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales $O(\text{TeV})$** , must modify the Higgs potential to make this possible



- Probe higher-order terms of the Higgs potential (selfcouplings)
- Probe the existence of other particles coupled to the Higgs

1st Order EWPT has profound implications for cosmology

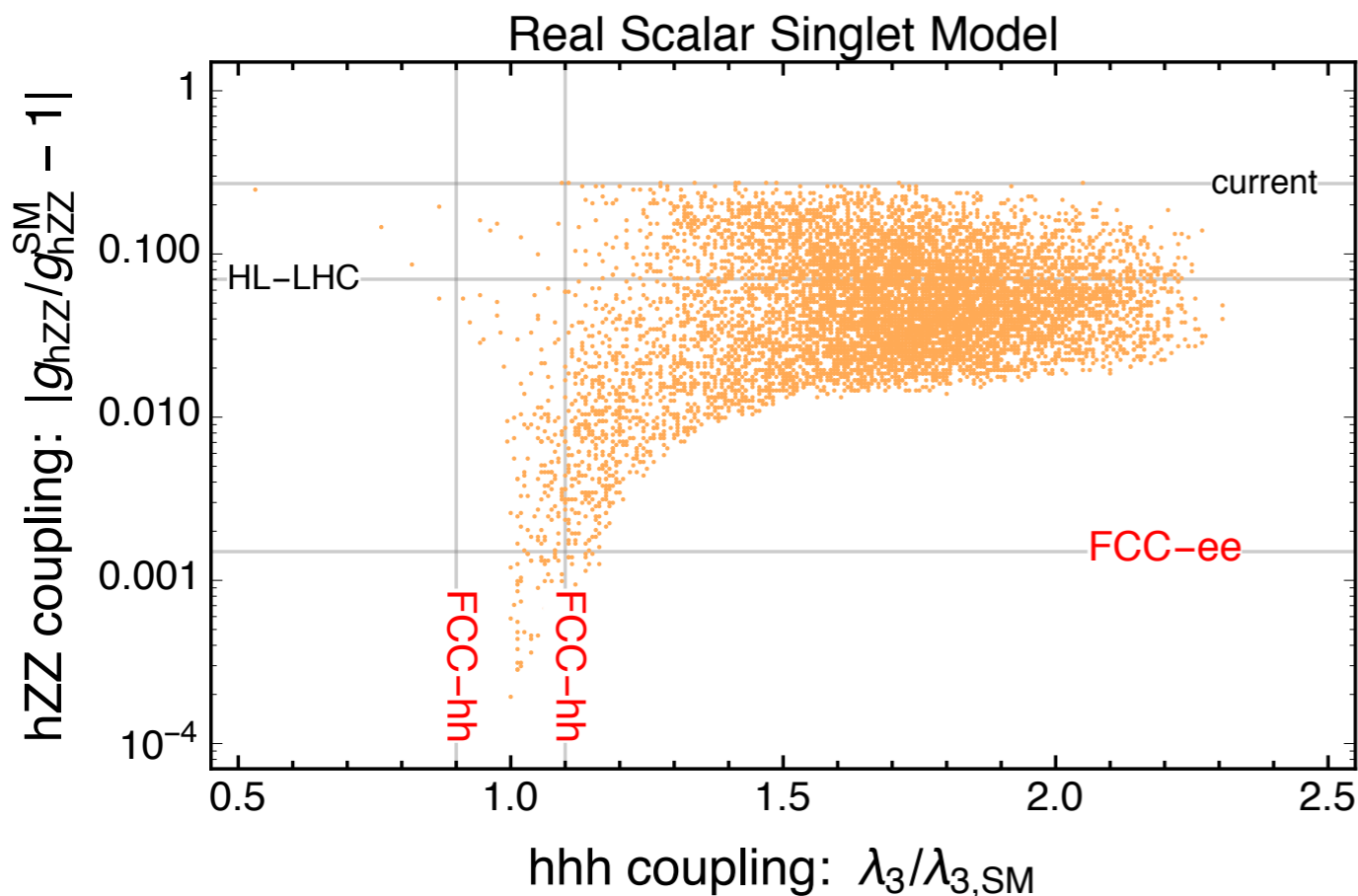


Andrew Long @ FCC physics Workshop, Jan 2018
<https://indico.cern.ch/event/618254>

Example of precision targets: constraints on models with 1st order phase transition

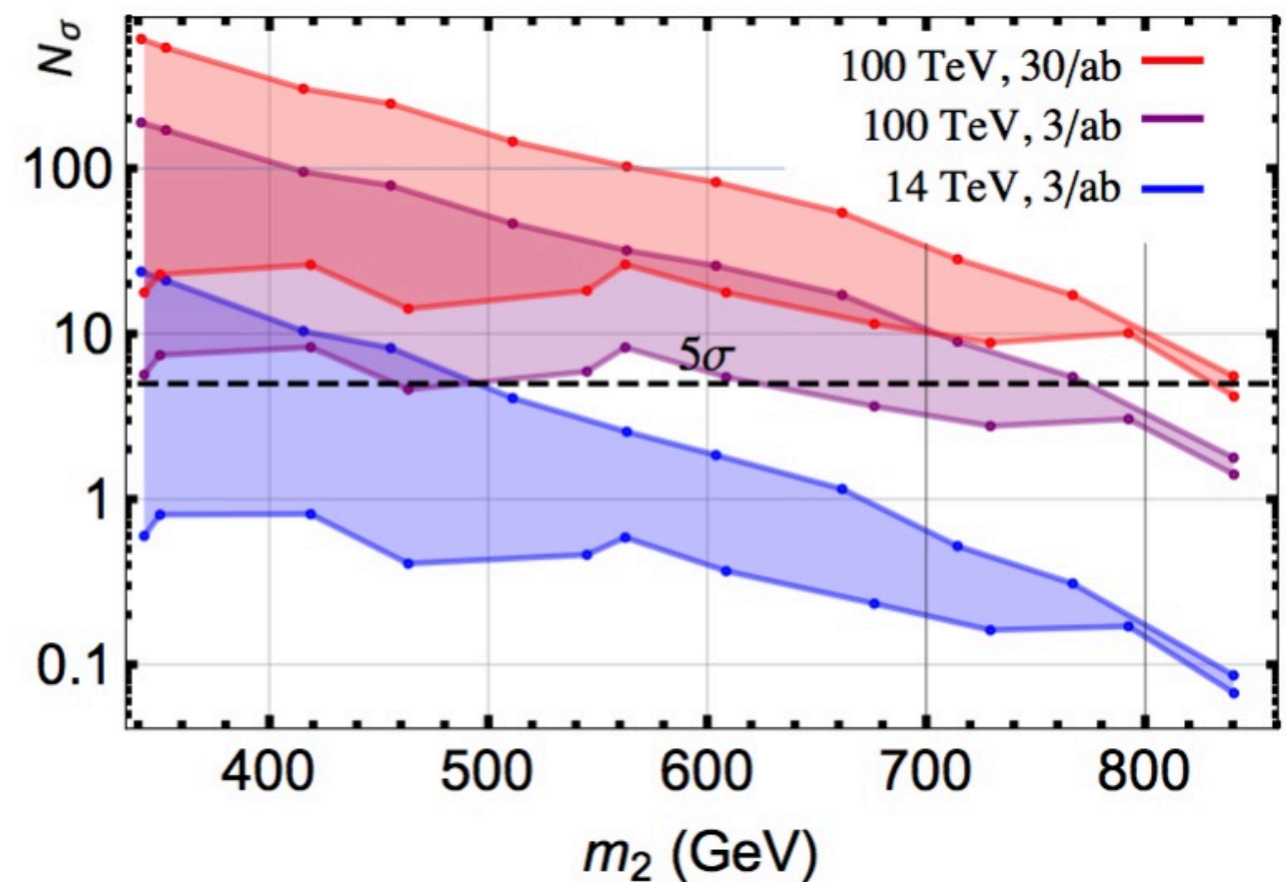
$$V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

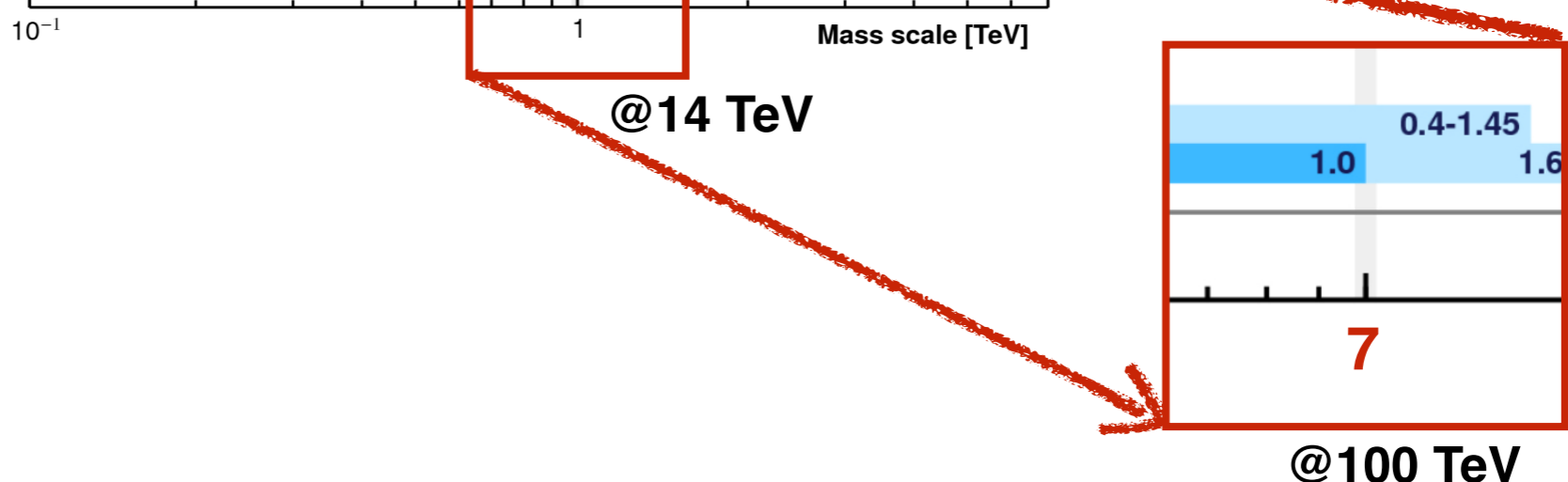
Direct detection of extra Higgs states at FCC-hh



$h_2 \rightarrow h_1 h_1$ ($b\bar{b}\gamma\gamma + 4\tau$)
($h_2 \sim S, h_1 \sim H$)

Direct discovery reach: the power of 100 TeV

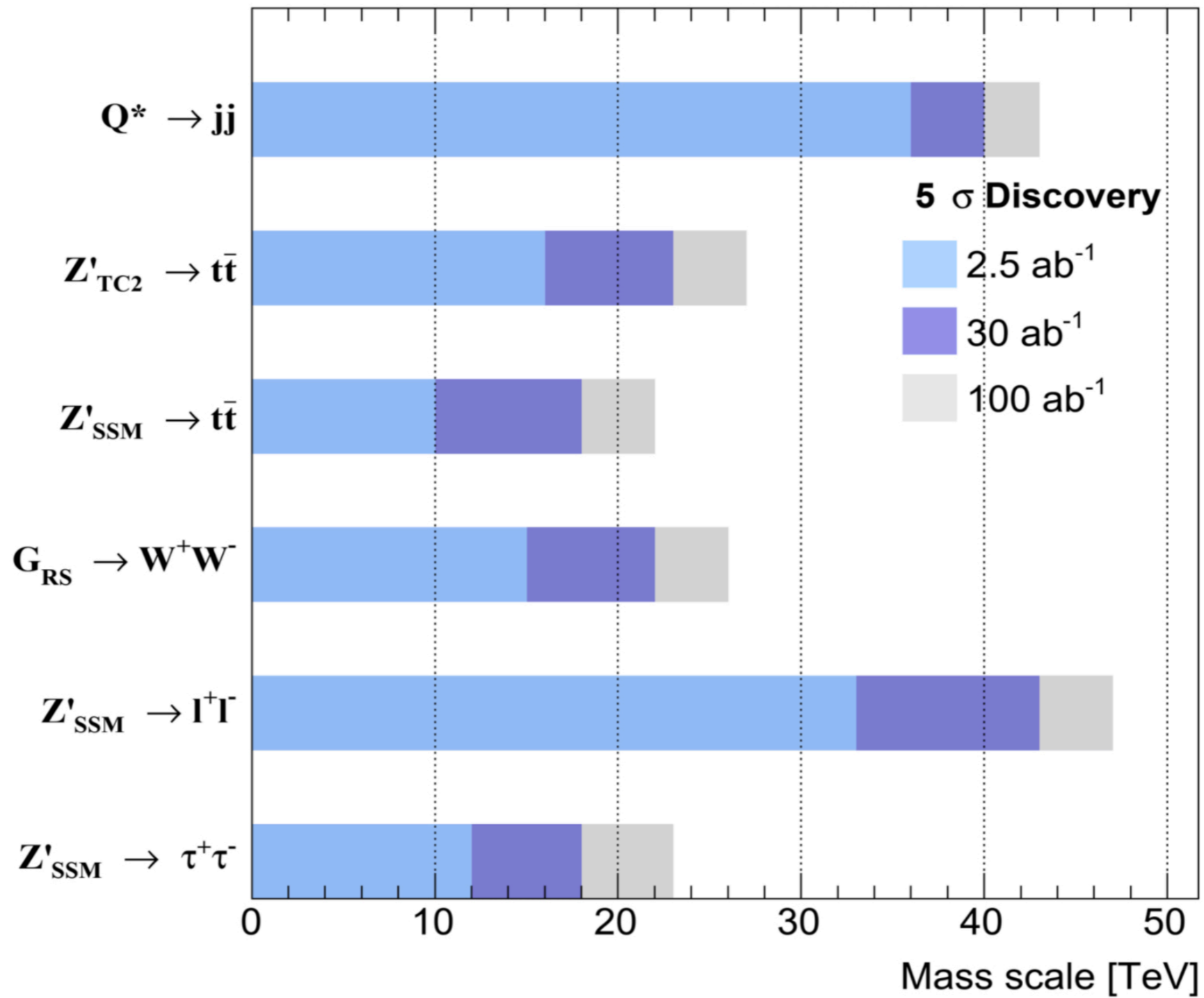
Model	Signature	$\int \mathcal{L} dt \text{ [fb}^{-1}\text{]}$	Mass limit	Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets E_T^{miss} 36.1	\tilde{q} [2x, 8x Degen.] \tilde{q} [1x, 8x Degen.] 0.43 0.71 0.9 1.55 $m(\tilde{\chi}_1^0) < 100 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets E_T^{miss} 36.1	\tilde{g} \tilde{g} Forbidden 0.95-1.6 2.0 $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 900 \text{ GeV}$	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ $ee, \mu\mu$	4 jets 2 jets E_T^{miss} 36.1	\tilde{g} \tilde{g} 1.2 1.85 $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e, μ 3 e, μ	7-11 jets 4 jets E_T^{miss} 36.1	\tilde{g} \tilde{g} 0.98 1.8 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ 3 e, μ	3 b 4 jets E_T^{miss} 79.8 36.1	\tilde{g} \tilde{g} 1.25 2.25 $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1706.03731
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$	Multiple Multiple Multiple	36.1 36.1 36.1	\tilde{b}_1 Forbidden 0.9 \tilde{b}_1 Forbidden 0.58-0.82 \tilde{b}_1 Forbidden 0.7 $m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(b\tilde{\chi}_1^0) = 1$ $m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(b\tilde{\chi}_1^0) = \text{BR}(t\tilde{\chi}_1^\pm) = 0.5$ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) = 300 \text{ GeV}, \text{BR}(t\tilde{\chi}_1^\pm) = 1$	1708.09266, 1711.03301 1708.09266 1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, μ	6 b E_T^{miss} 139	\tilde{b}_1 Forbidden 0.23-1.35 \tilde{b}_1 0.23-0.48 $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	SUSY-2018-31 SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b E_T^{miss} 36.1	\tilde{t}_1 1.0 $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP	Multiple	36.1	\tilde{t}_1 0.48-0.84 $m(\tilde{\chi}_1^0) = 150 \text{ GeV}, m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}, \tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1 $\tau + 1 e, \mu, \tau$	2 jets/1 b E_T^{miss} 36.1	\tilde{t}_1 1.16 $m(\tilde{\tau}_1) = 800 \text{ GeV}$	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ	2 c E_T^{miss} 36.1	\tilde{t}_1 0.85 \tilde{t}_1 0.46 $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1805.01649 1805.01649 1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	0 e, μ	mono-jet E_T^{miss} 36.1	\tilde{t}_1 0.43 \tilde{t}_2 0.32-0.88 $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180 \text{ GeV}$	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e, μ $ee, \mu\mu$	≥ 1 E_T^{miss} 36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17 $m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 10 \text{ GeV}$	1403.5294, 1806.02293 1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e, μ	E_T^{miss} 139	$\tilde{\chi}_1^\pm$ 0.42 $m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e, μ	2 b E_T^{miss} 36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.68 $m(\tilde{\chi}_1^0) = 0$	1812.09432
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	E_T^{miss} 139	$\tilde{\chi}_1^\pm$ 1.0 $m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ	E_T^{miss} 36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22 $m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 100 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	1708.07875 1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ 2 e, μ	0 jets ≥ 1 E_T^{miss} 139 36.1	$\tilde{\ell}$ 0.7 $\tilde{\ell}$ 0.18 $m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	ATLAS-CONF-2019-008 1712.08119
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	$\geq 3 b$ 0 jets E_T^{miss} 36.1 36.1	\tilde{H} 0.13-0.23 \tilde{H} 0.3 0.29-0.88 $\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 1804.03602	
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet E_T^{miss} 36.1	$\tilde{\chi}_1^\pm$ 0.46 $\tilde{\chi}_1^\pm$ 0.15 Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable \tilde{g} R-hadron	Multiple	36.1	\tilde{g} 2.0	1902.01636, 1808.04095
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$	Multiple	36.1	\tilde{g} [$\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}$] 2.05 2.4 $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1710.04901, 1808.04095
RPV	LFV $p\bar{p} \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\mu\tau$	$e\mu, e\tau, \mu\tau$	3.2	$\tilde{\nu}_\tau$ 1.9 $\lambda'_{311} = 0.11, \lambda'_{132/133/233} = 0.07$	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, μ	0 jets E_T^{miss} 36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda'_{333} \neq 0, \lambda'_{12k} \neq 0$] 0.82 1.33 $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	4-5 large-R jets	36.1	\tilde{g} [$m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}$] 1.3 1.9 \tilde{g} [$\lambda'_{112} = 2e-4, 2e-5$] 1.05 2.0 Large λ'_{112}	1804.03568
	$\tilde{u}\tilde{u}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	36.1	\tilde{g} [$\lambda'_{323} = 2e-4, 1e-2$] 0.55 1.05 $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003 ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	36.7	\tilde{t}_1 [qq, bs] 0.42 0.61 $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{bino-like}$	1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, μ 1 μ	2 b DV 36.1 136	\tilde{t}_1 0.4-1.45 \tilde{t}_1 [$1e-10 < \lambda'_{23k} < 1e-8, 3e-10 < \lambda'_{23k} < 3e-9$] 1.0 1.6 $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \text{cos}\theta > 0.5$	1710.05544 ATLAS-CONF-2019-006	



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

s-channel resonances

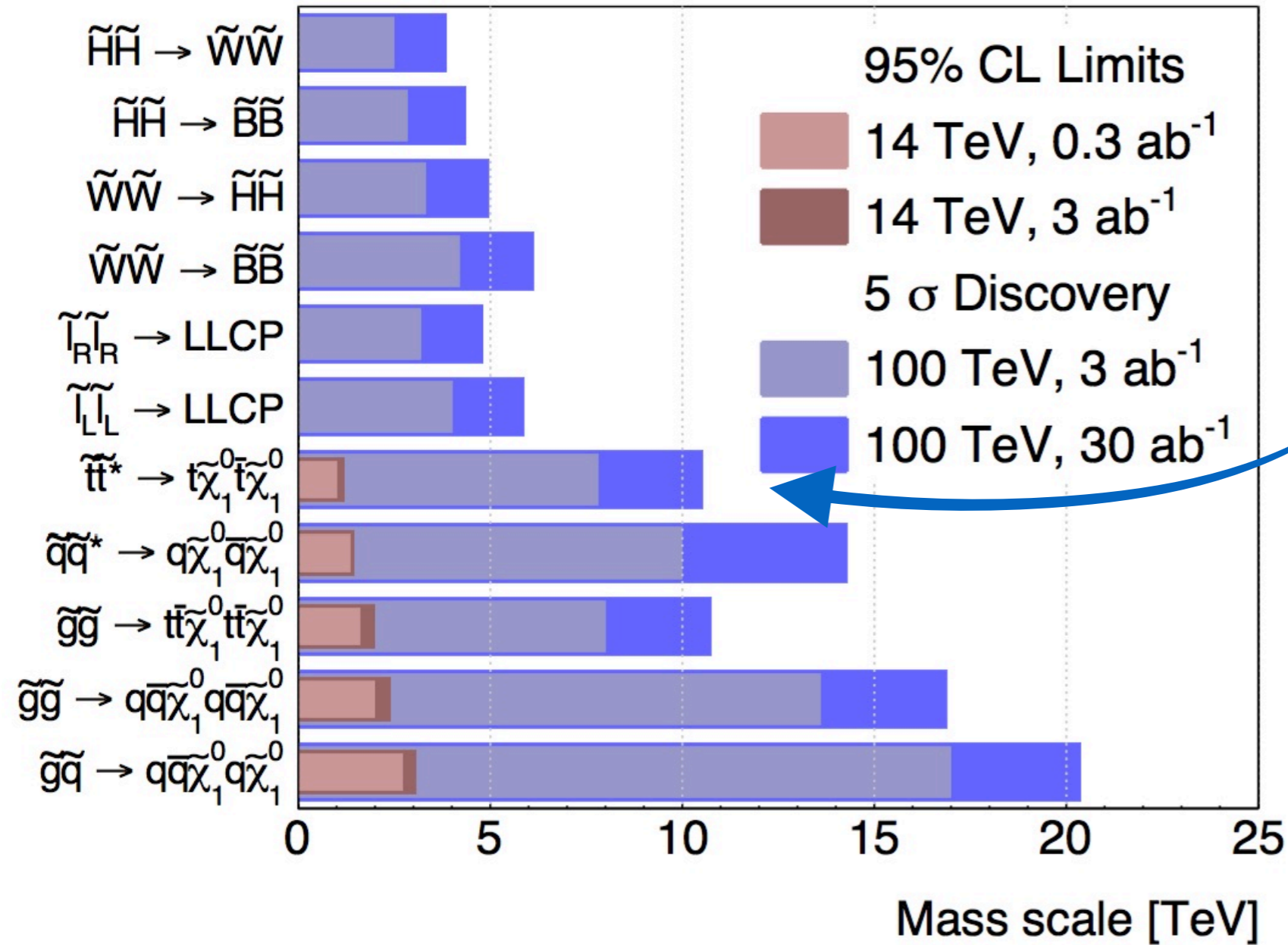
FCC-hh Simulation (Delphes), $\sqrt{s} = 100$ TeV



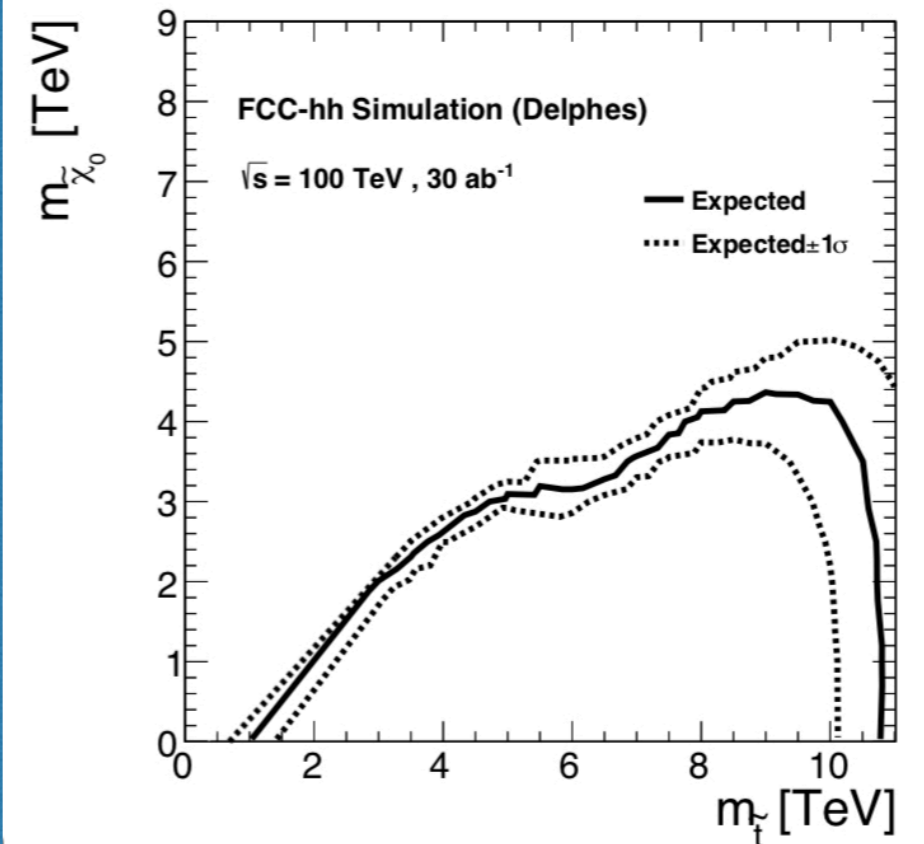
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies

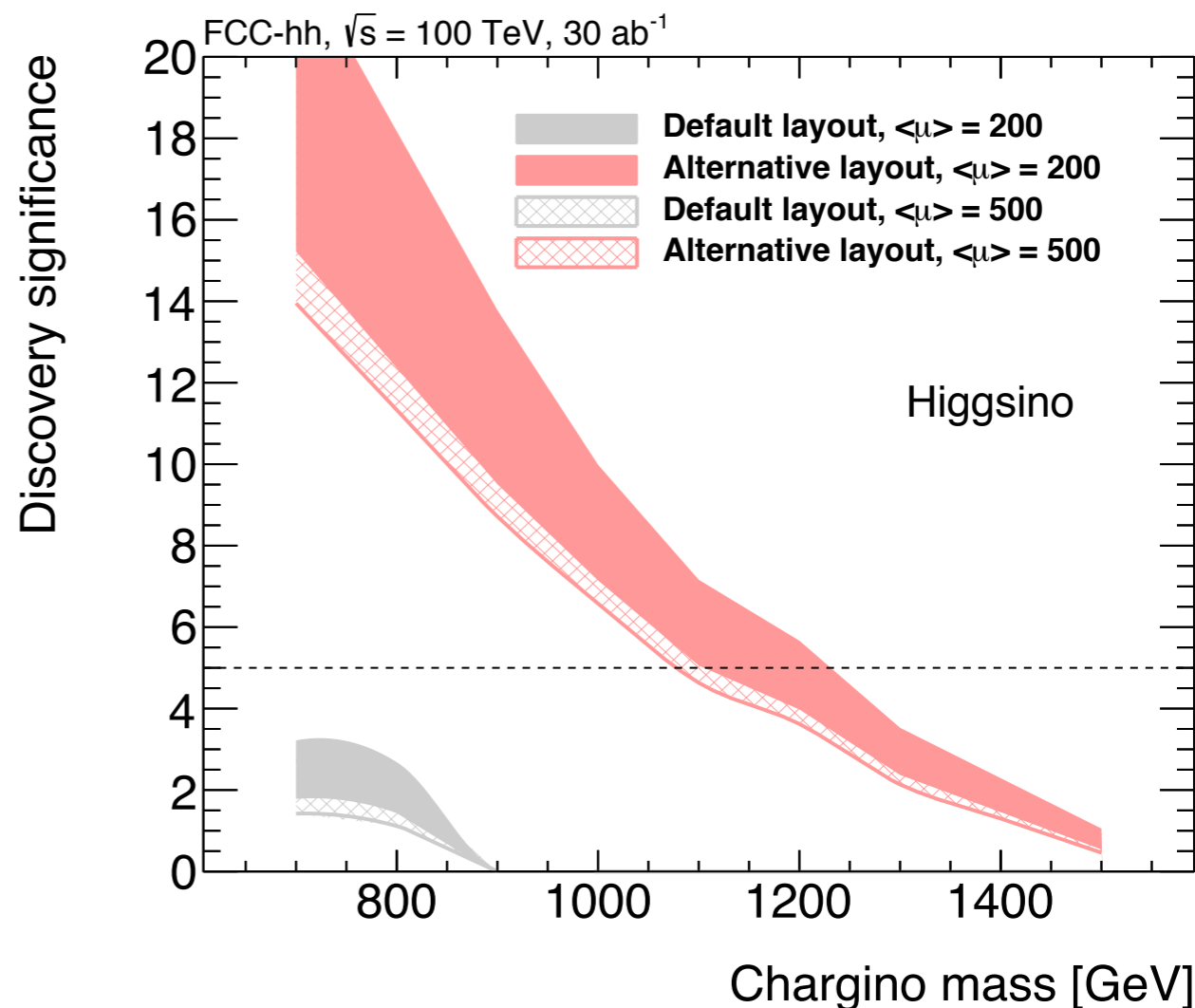
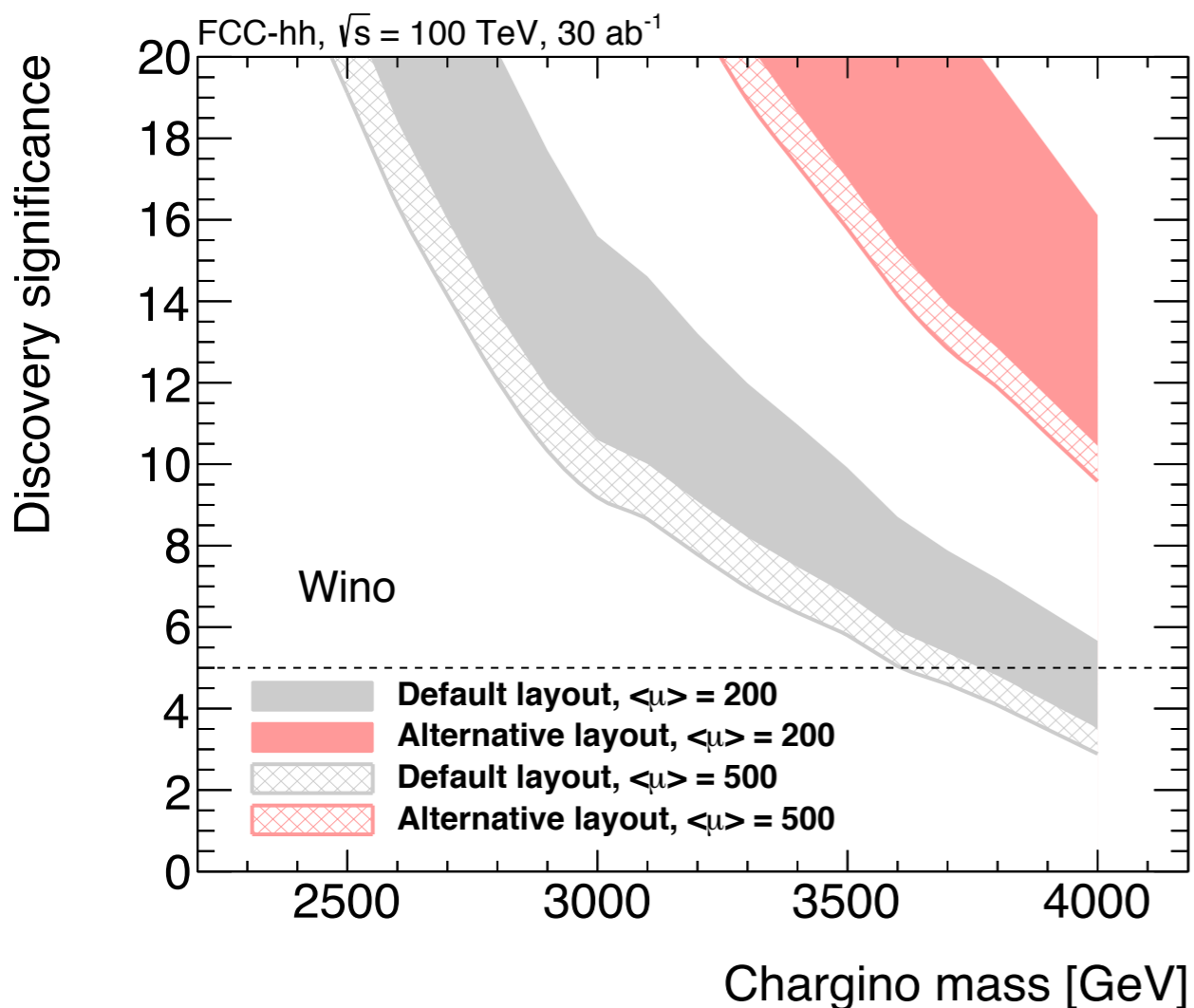


New detector performance studies



New detector performance studies

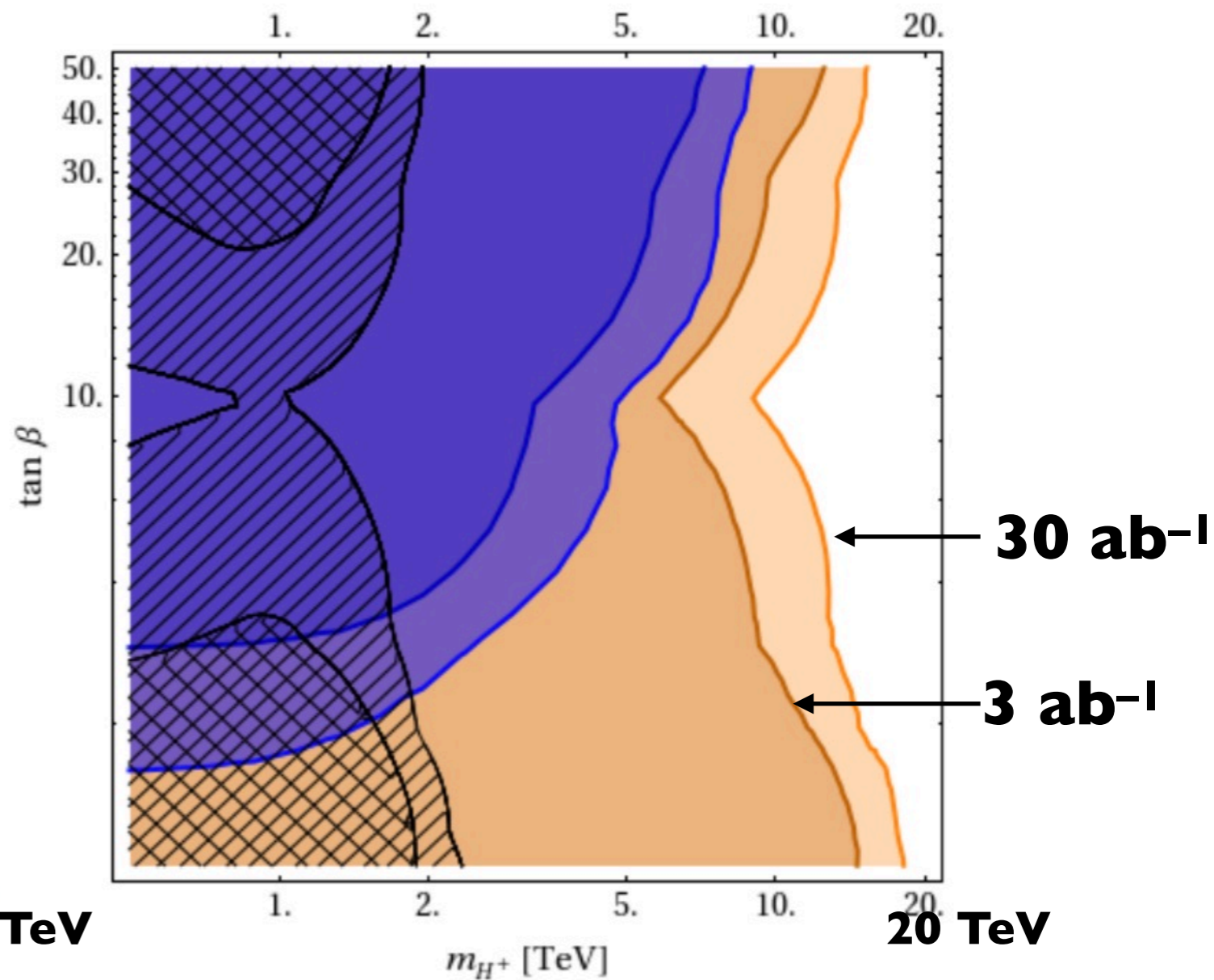
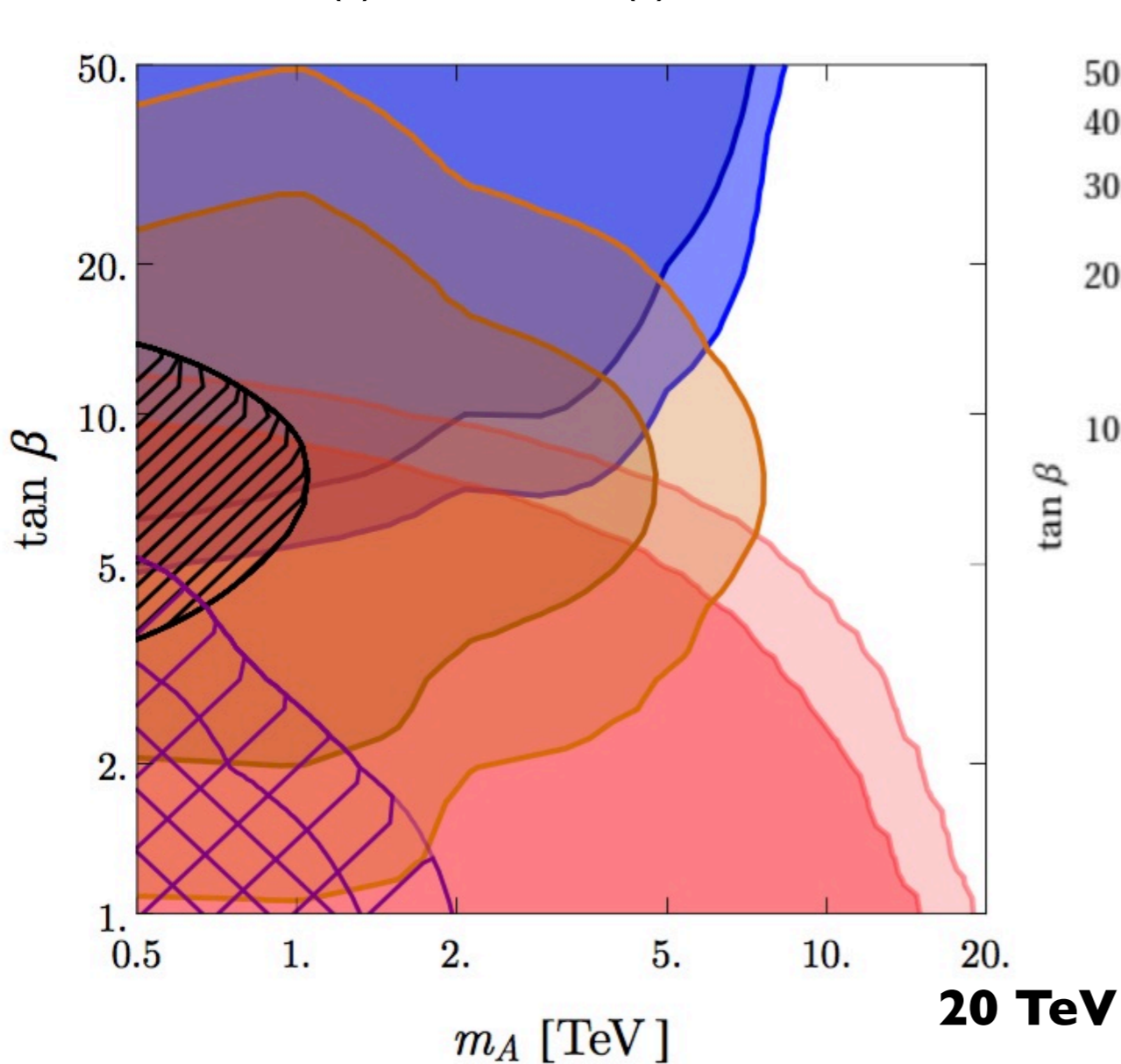
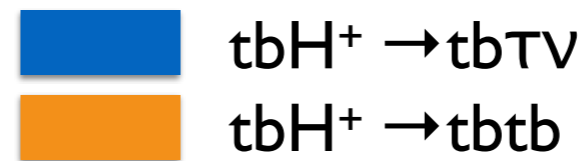
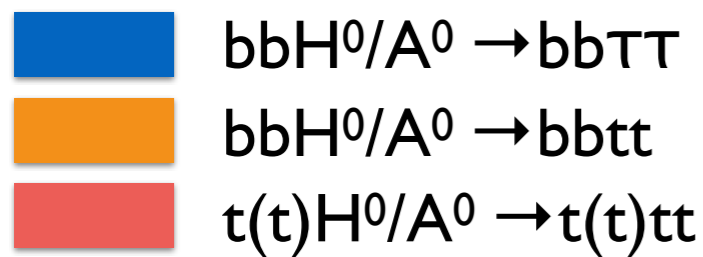
Disappearing charged track analyses (at ~full pileup)



=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{\text{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

MSSM Higgs @ 100 TeV



N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang,
arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu,
arXiv:1504.07617



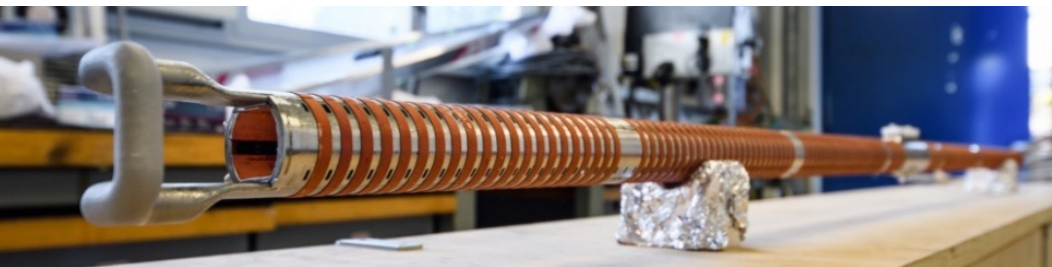
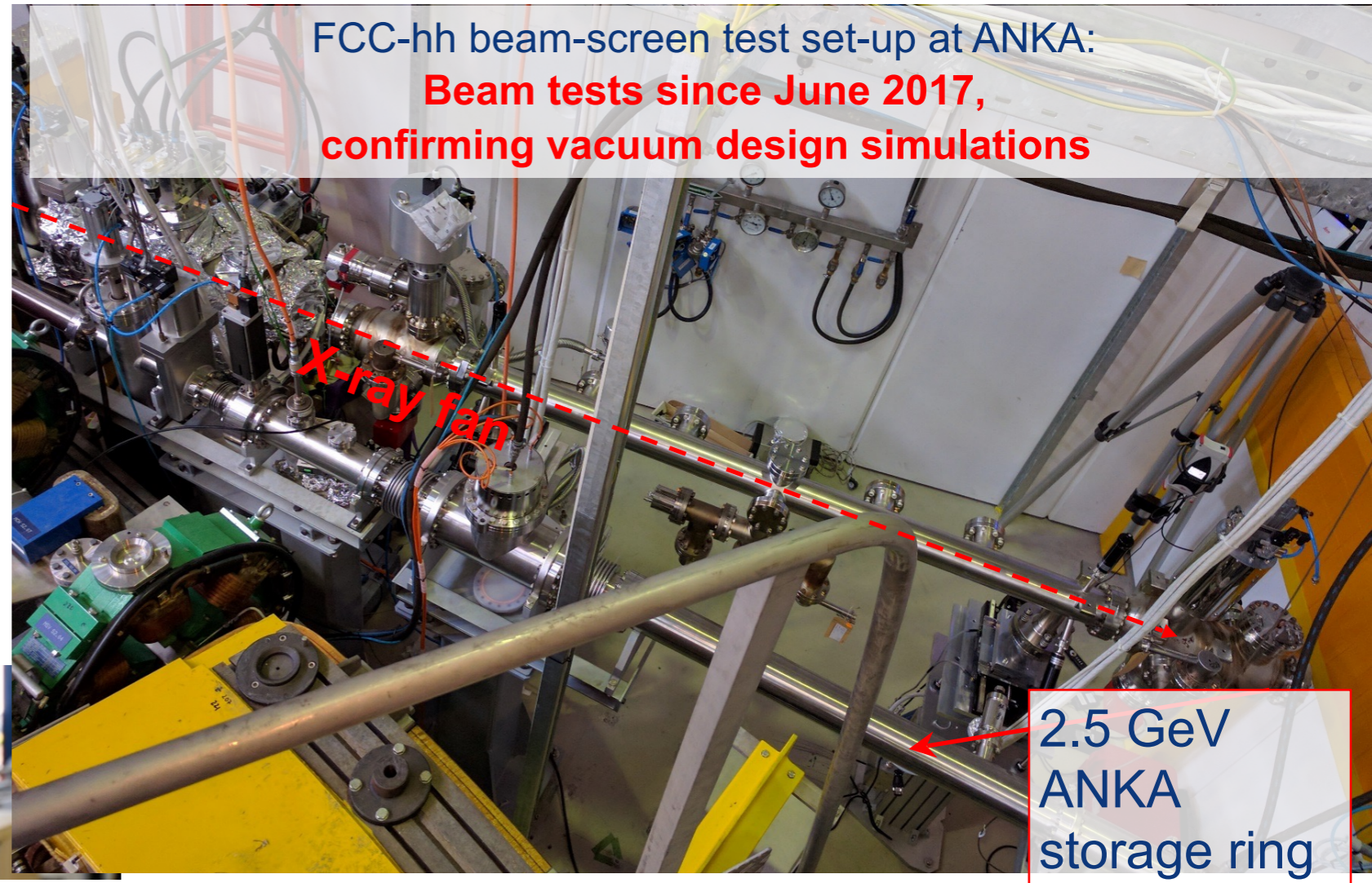
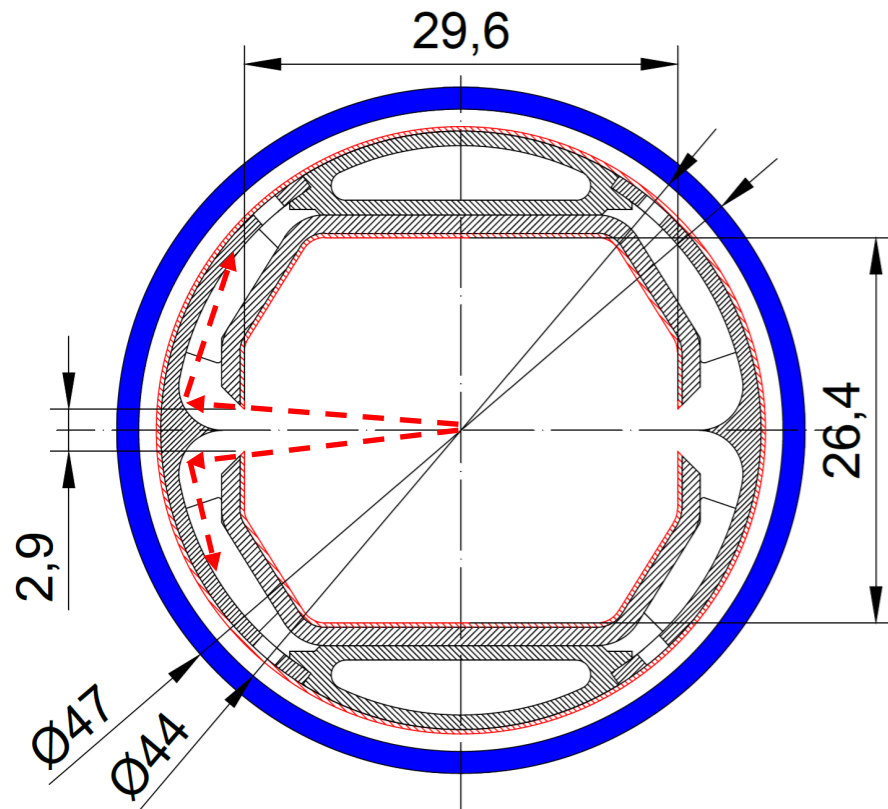
Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

Goal: 20-30 ab^{-1} during the collider lifetime

FCC-hh cryogenic beam vacuum system

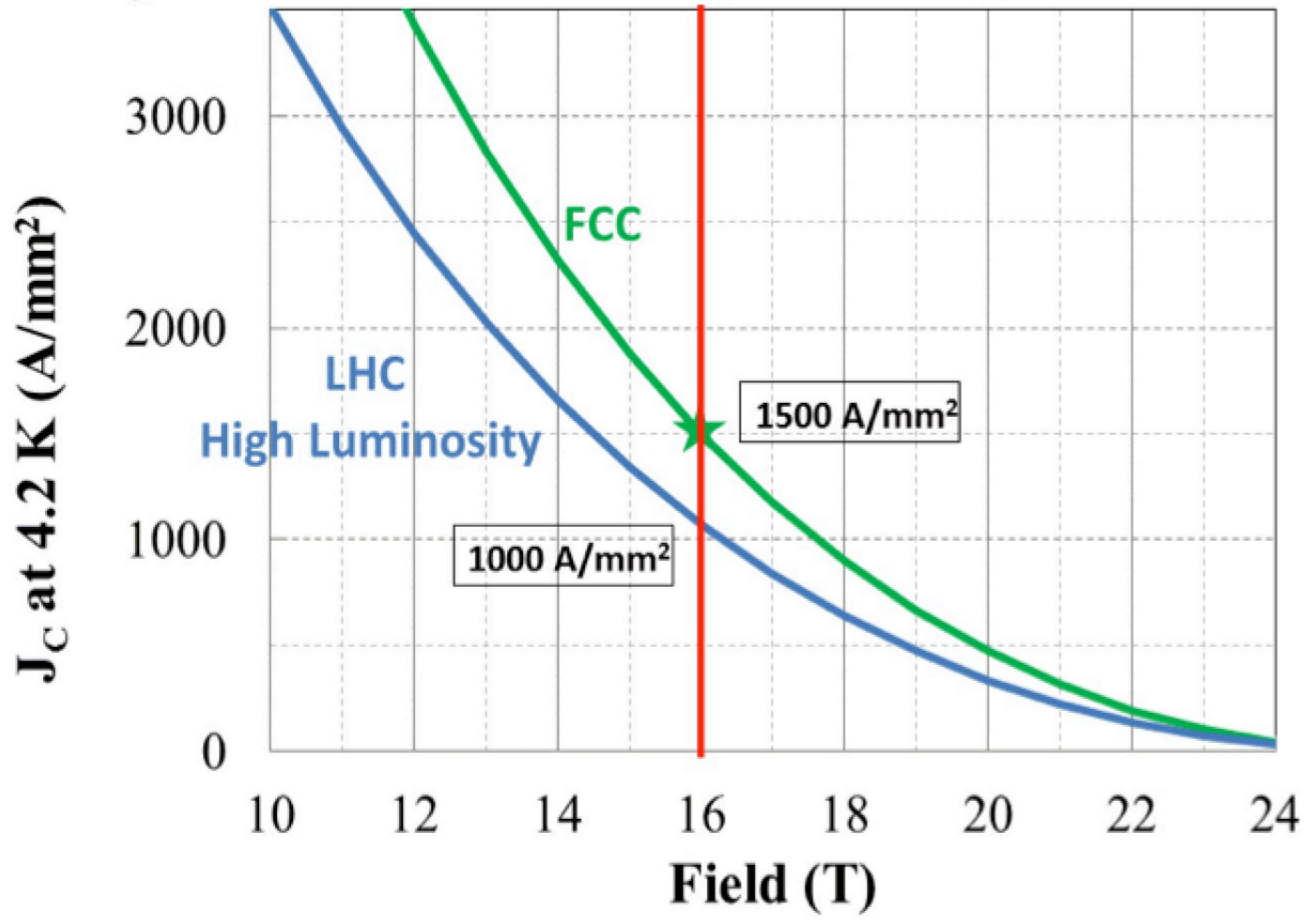
- Synchrotron radiation** ($\sim 30 \text{ W/m/beam}$ (@16 T field) (LHC $< 0.2 \text{ W/m}$) $\sim 5 \text{ MW}$ total load in arcs
- Absorption of synchrotron radiation at $\sim 50 \text{ K}$ for cryogenic efficiency (5 MW \rightarrow 100 MW cryoplant)**
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





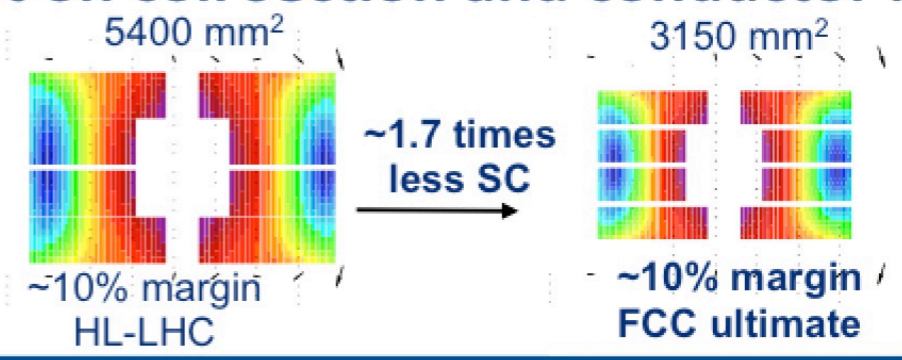
Nb₃Sn conductor development program

Nb₃Sn is one of the key cost & performance factors for FCC-hh / HE-LHC



- Main development goals:**
- J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
 - Reference wire diameter 1 mm
 - Potentials for large-scale production and cost reduction

Impact on coil section and conductor mass





Worldwide FCC Nb₃Sn program

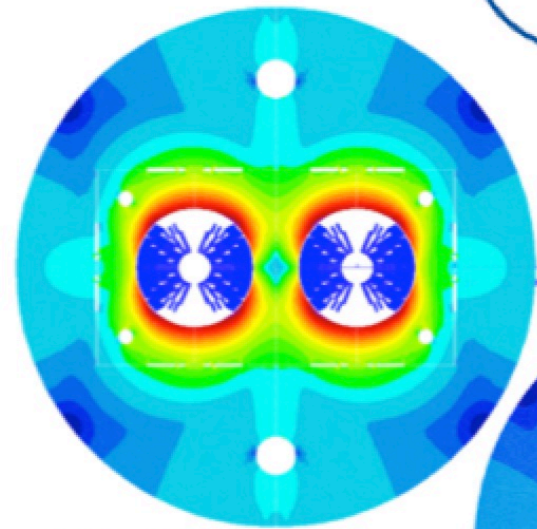
Established world activities from Nb₃Sn development

- **Procurement of state-of-the-art conductor:**
 - **Bruker-OST – European/US**
- **Conductor development with regional industry:**
 - **CERN/KEK – Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
 - **CERN/Bochvar High-technology Research Inst. – Russian** contribution. Russian **industry** (TVEL) and laboratories
 - **CERN/KAT – Korean** industrial contribution
- **Characterization of conductor & research with universities:**
 - **Technical Univ. Vienna, Geneva University, University of Twente**
 - **Applied Superconductivity Centre at Florida State University**



16 T dipole design activities and options

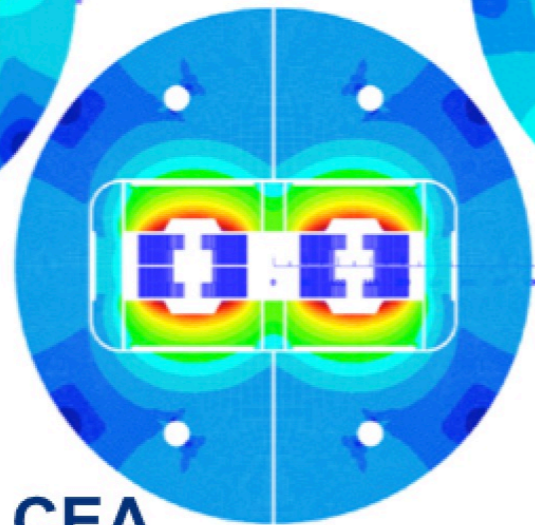
Cos-theta



INFN

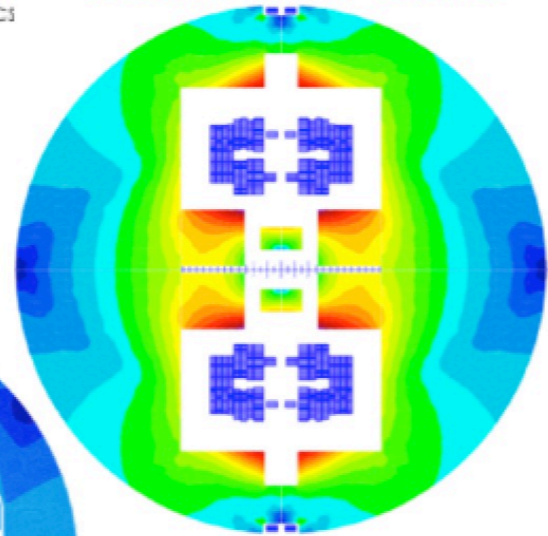


Blocks



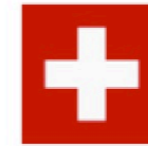
CEA

Common coils

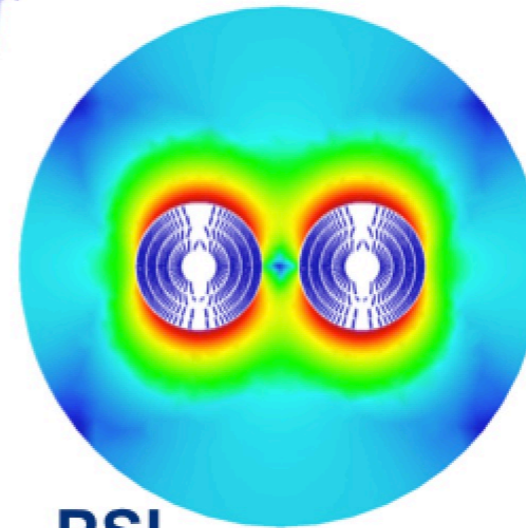


CIEMAT

Swiss contribution



Canted Cos-theta



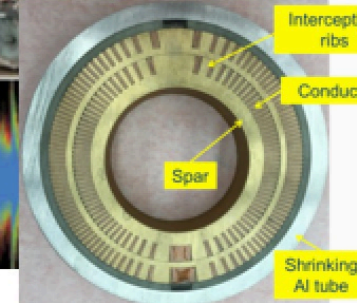
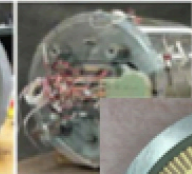
PSI



The U.S. Magnet Development Program Plan

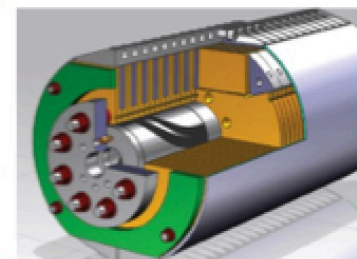


S. A. Gourlay, S. O. Probstemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
A. V. Zhlobin, L. Cooley
Fermi National Accelerator Laboratory



LBL

FNAL

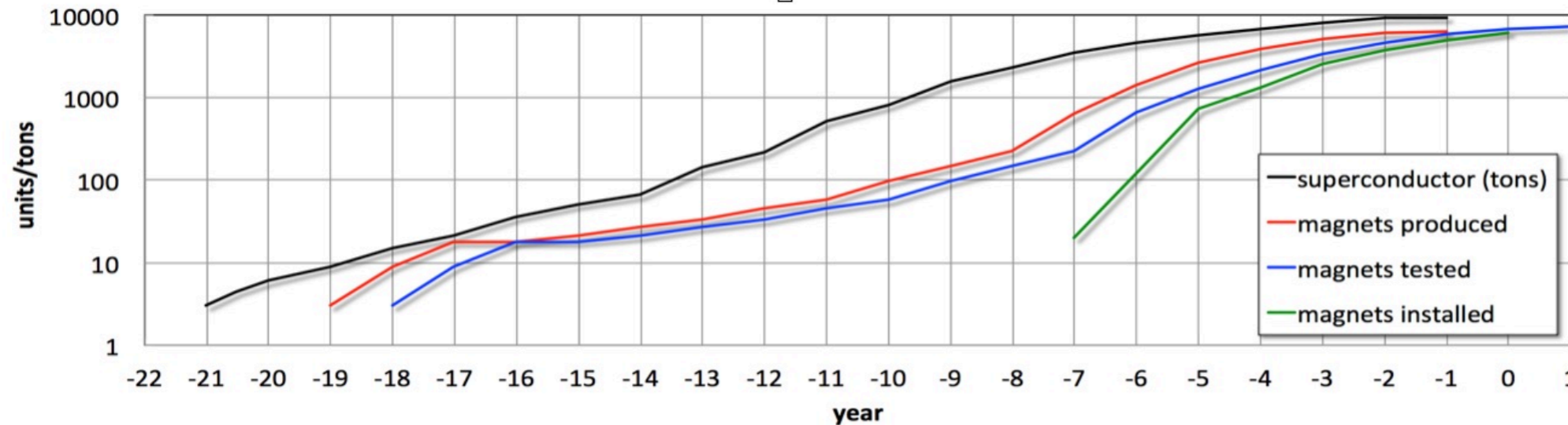


Short model magnets (1.5 m lengths) will be built from 2017 - 2021

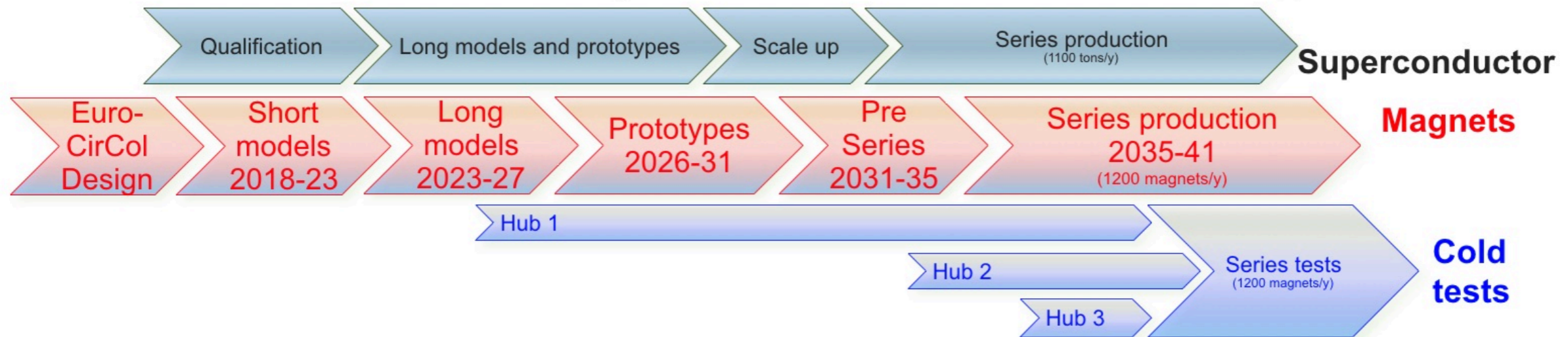


Future Circular Collider Study - Status
Michael Benedikt
SPC, CERN, 26. September 2017

16 T magnet R&D schedule

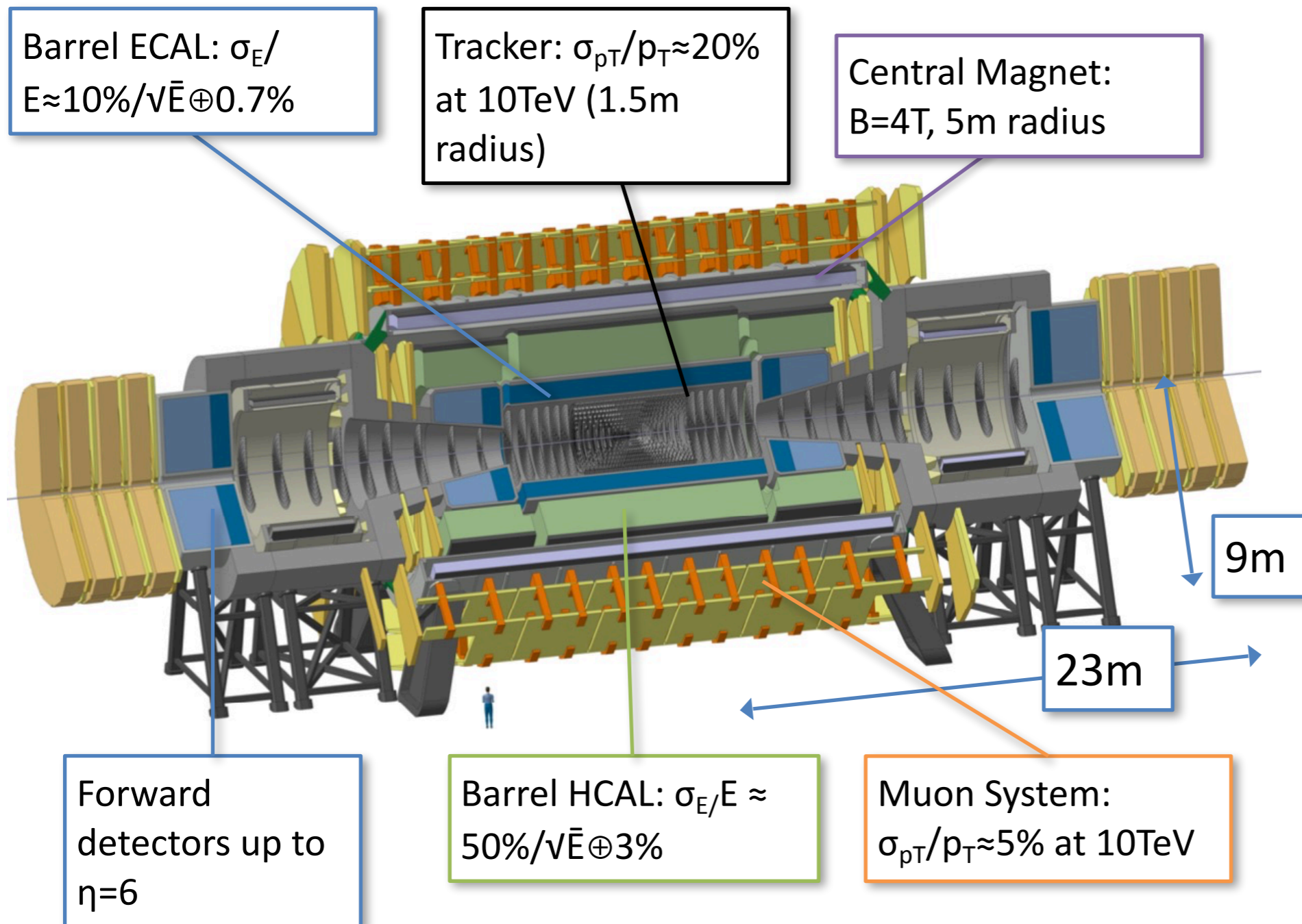


**total duration
of magnet
program:
~20 years**



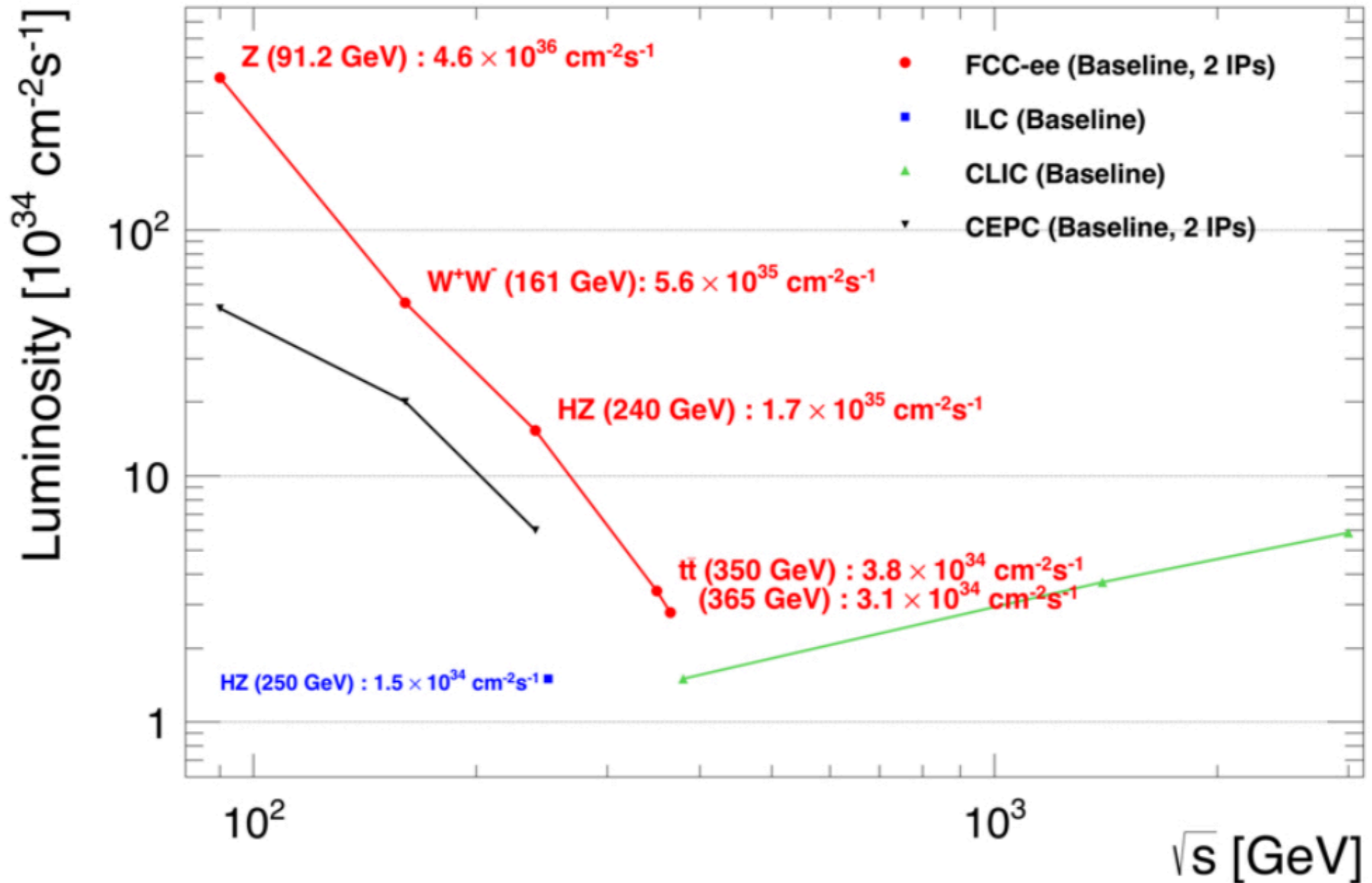
would follow HL-LHC Nb₃Sn program with long models at industry from 2023/24

FCC-hh Detector – Reference Design for CDR



- During last years converged on **reference design for an FCC-hh experiment**
- **Radiation simulations**
- Demonstrate in the CDR document, that an **experiment** exploiting the **full FCC-hh physics potential is technically feasible**
- → **Input for Delphes physics simulations**
- Room for other ideas, other concepts and different technologies

FCC-ee luminosity targets



FCC-ee run plan

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

Phase	Run duration (years)	Centre-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340-350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10^6 $t\bar{t}$ events

=> 14 years, including shutdowns for accelerator upgrades

FCC-ee + FCC-hh, project timeline

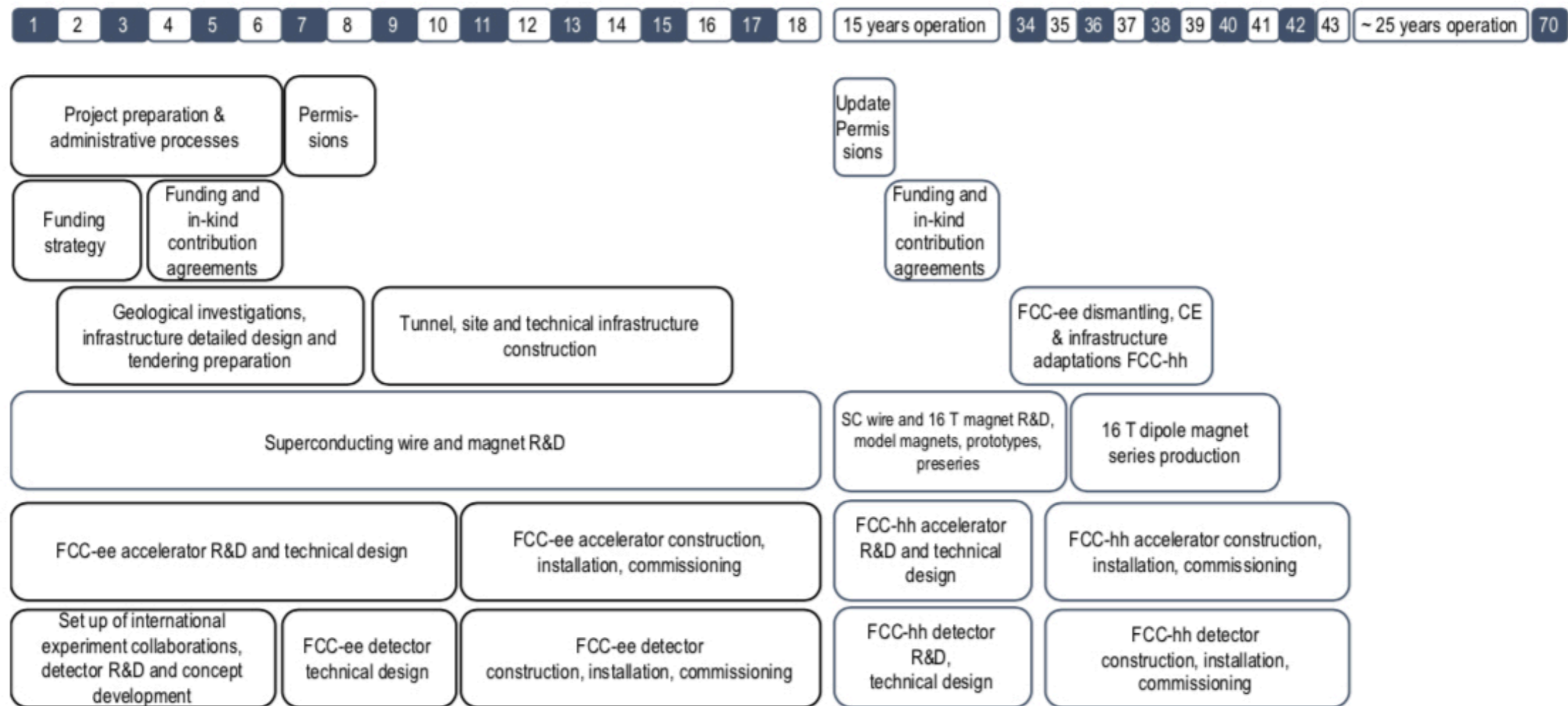
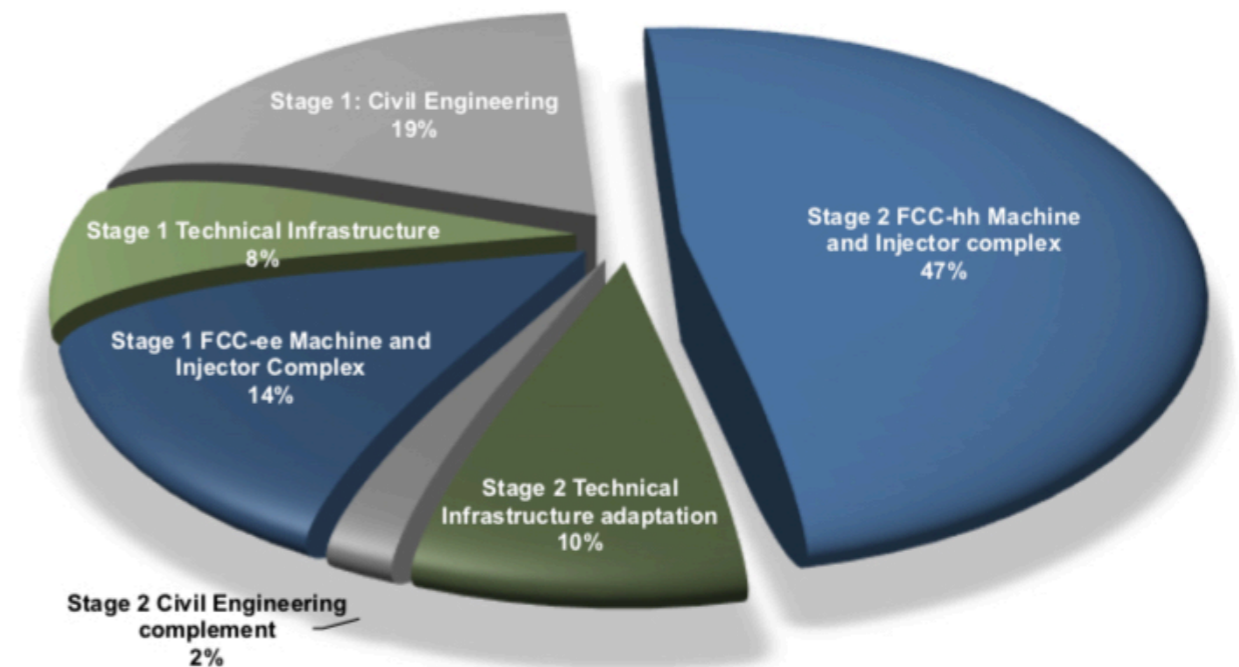
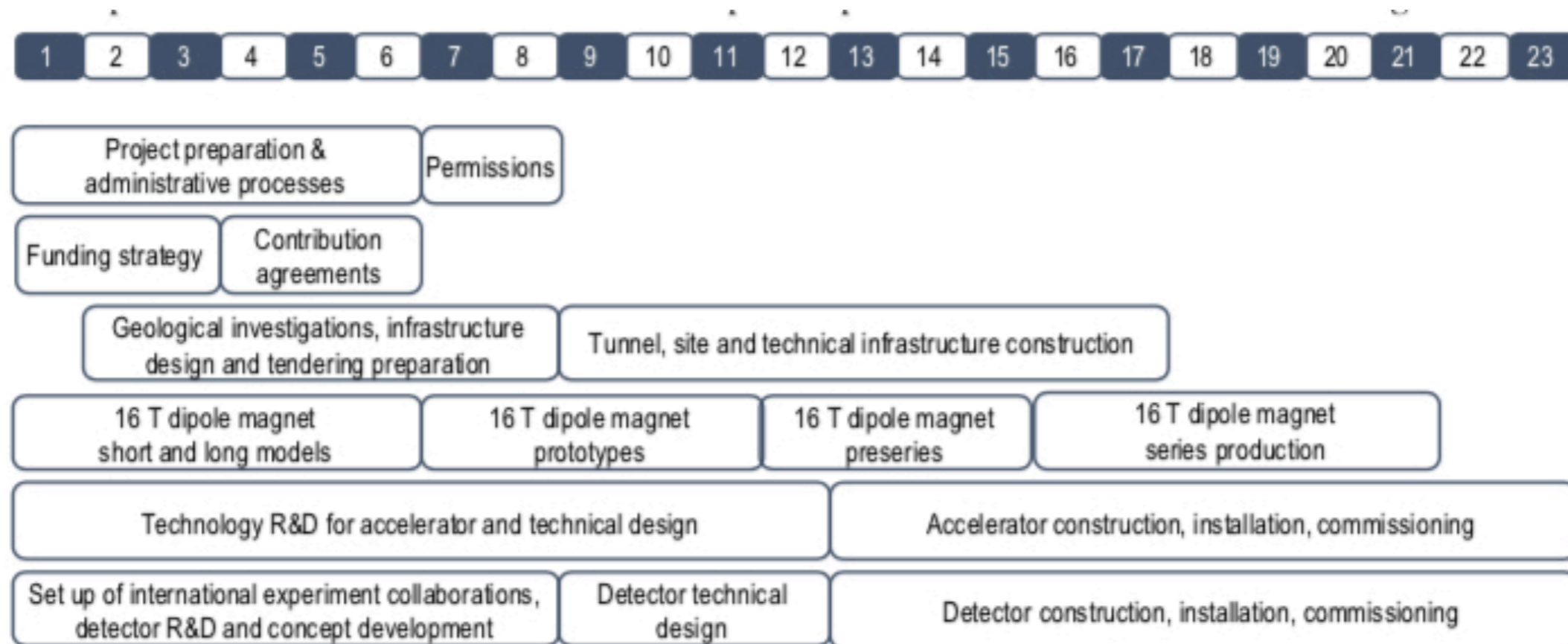


Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

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



FCC-hh stand-alone, project timeline&cost



Domain	Cost in MCHF
Collider and injector complex	13,600
Technical infrastructure	4,400
Civil Engineering	6,000
TOTAL construction cost	24,000

Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- The combination of a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, appears like the ideal facility for the post-LHC era
 - *complementary and synergetic precision studies of EW, Higgs and top properties*
 - *energy reach to allow direct discoveries at the mass scales possibly revealed by the precision measurements*
 - *flavor factory at the Z pole, heavy ions and ep collisions: extremely diversified program => broad community engagement*

Major events organized

FCC-ee

- 5th TLEP Workshop "TLEP physics and technology", Fermilab, 25-26 July 2013, <https://indico.cern.ch/event/246137/>
- 6th TLEP Workshop, CERN, 16-18 October 2013, <https://indico.cern.ch/event/257713/>
- FCC-ee/TLEP physics workshop (TLEP7), CERN, 19-21 June 2014, <https://indico.cern.ch/event/313708/>
- FCC-ee (TLEP) Physics Workshop (TLEP8), LPNHE Paris, 27-29 October 2014, <https://indico.cern.ch/event/337673/>
- FCC-ee (TLEP) Physics Workshop (TLEP9), SNS Pisa, 3-5 February 2015, <https://indico.cern.ch/event/357188/>
- 1st FCC-ee mini-workshop on Detector Requirements, CERN, 17-18 June 2015, <https://indico.cern.ch/event/393093/>
- FCC-ee mini-workshop on "Precision Observables and Radiative Corrections", CERN, 13-14 July 2015, <https://indico.cern.ch/event/387296/>
- First FCC-ee workshop on Higgs physics, CERN, 24-25 Sept. 2015, <https://indico.cern.ch/event/401590/>
- Workshop on high-precision α_s measurements: from LHC to FCC-ee, 12-13 October 2015, <https://indico.cern.ch/event/392530/>
- FCC-ee Mini-Workshop: "Physics Behind Precision", CERN, 2-3 February 2016, <https://indico.cern.ch/event/469561/>
- 10th FCC-ee Physics Workshop, CERN, CERN, 2-3 February 2016, <https://indico.cern.ch/event/469576/>
- Parton Radiation and Fragmentation from LHC to FCC-ee, CERN, 21-22 Nov 2016, <https://indico.cern.ch/event/557400/>
- 2nd mini-workshop on FCC-ee detector requirements CERN, 23-24 November 2016, <https://indico.cern.ch/event/570415/>
- Mini workshop: Precision EW and QCD calculations for the FCC studies, CERN 12-13 January 2018, <https://indico.cern.ch/event/669224/>
- FCC-ee mini-workshop on Flavours, CERN, 31 Jan.-1 Feb. 2018, <https://indico.cern.ch/event/687191/>
- 11th FCC-ee workshop: Theory and Experiments, CERN, 8 - 11 Jan 2019, <https://indico.cern.ch/event/766859/>

FCC-hh

- Ions at the Future Hadron Collider, Dec 16-17 2013, <https://indico.cern.ch/event/288576/>
- BSM physics opportunities at 100 TeV, Febr 10-11 2014, <https://indico.cern.ch/event/284800/>
- 1st Future Hadron Collider Workshop, May 26-28 2014, <https://indico.cern.ch/event/304759/>
- Ions at the Future Circular Collider, Sept 22-23 2014, <https://indico.cern.ch/event/331669/>
- Higgs & BSM at 100 TeV, March 11-13 2015, <https://indico.cern.ch/event/352868/>
- QCD, EW and tools at 100 TeV, Oct 7-9 2015, <https://indico.cern.ch/event/437912/>
- Dark Matter at a future hadron collider, Dec 4-6 2015, <https://indico.cern.ch/event/445743/>

FCC-eh

- LHeC and FCC-eh, CERN and Chavanne-de-Bogis, 24-26.6.2015, <https://indico.cern.ch/event/356714/>
- LHeC and FCC-eh, CERN, 11-13.9.2017, <https://indico.cern.ch/event/639067/>
- Electrons for the LHC - LHeC/FCC-eh and PERLE, Orsay, 27-29.6.2018, <https://indico.cern.ch/event/698368/>

Joint

- LHC, FCC-ee, FCC-hh Interplay, 25 November 2016, <https://indico.cern.ch/event/573689/>
- 1st FCC Physics Workshop, January 16-20 2017, <https://indico.cern.ch/event/550509/>
- 2nd FCC Physics Workshop, January 15-19 2018, <https://indico.cern.ch/event/618254/>

**... plus many events
worldwide dedicated
to physics at FCCs**

Reports produced

FCC-ee

- First Look at the Physics Case of TLEP, <https://arxiv.org/abs/1308.6176>
- High-Precision α_s Measurements from LHC to FCC-ee, Workshop report, <https://arxiv.org/abs/1512.05194>
- Physics Behind Precision, Workshop report, <https://arxiv.org/abs/1703.01626>
- Parton Radiation and Fragmentation from LHC to FCC-ee, Workshop report, <https://arxiv.org/abs/1702.01329>
- Standard Model Theory for the FCC-ee: The Tera-Z, Workshop report, <https://arxiv.org/abs/1809.01830>

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"Physics at 100 TeV", CERN Yellow Report:

- Standard Model processes <https://arxiv.org/abs/1607.01831>
- Higgs and EW symmetry breaking studies, <https://arxiv.org/abs/1606.09408>
- Beyond the Standard Model phenomena, <https://arxiv.org/abs/1606.00947>
- Heavy ions at the Future Circular Collider, <https://arxiv.org/abs/1605.01389>
- Physics Opportunities with the FCC-hh Injectors, <https://arxiv.org/abs/1706.07667>

... plus hundreds of articles inspired by the physics opportunities at FCCs

*Future Circular Collider Study
Conceptual Design Report
Volume 1: Physics Opportunities*
<https://fcc-cdr.web.cern.ch>

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