Physics at the FCC
(Future Circular Collider)

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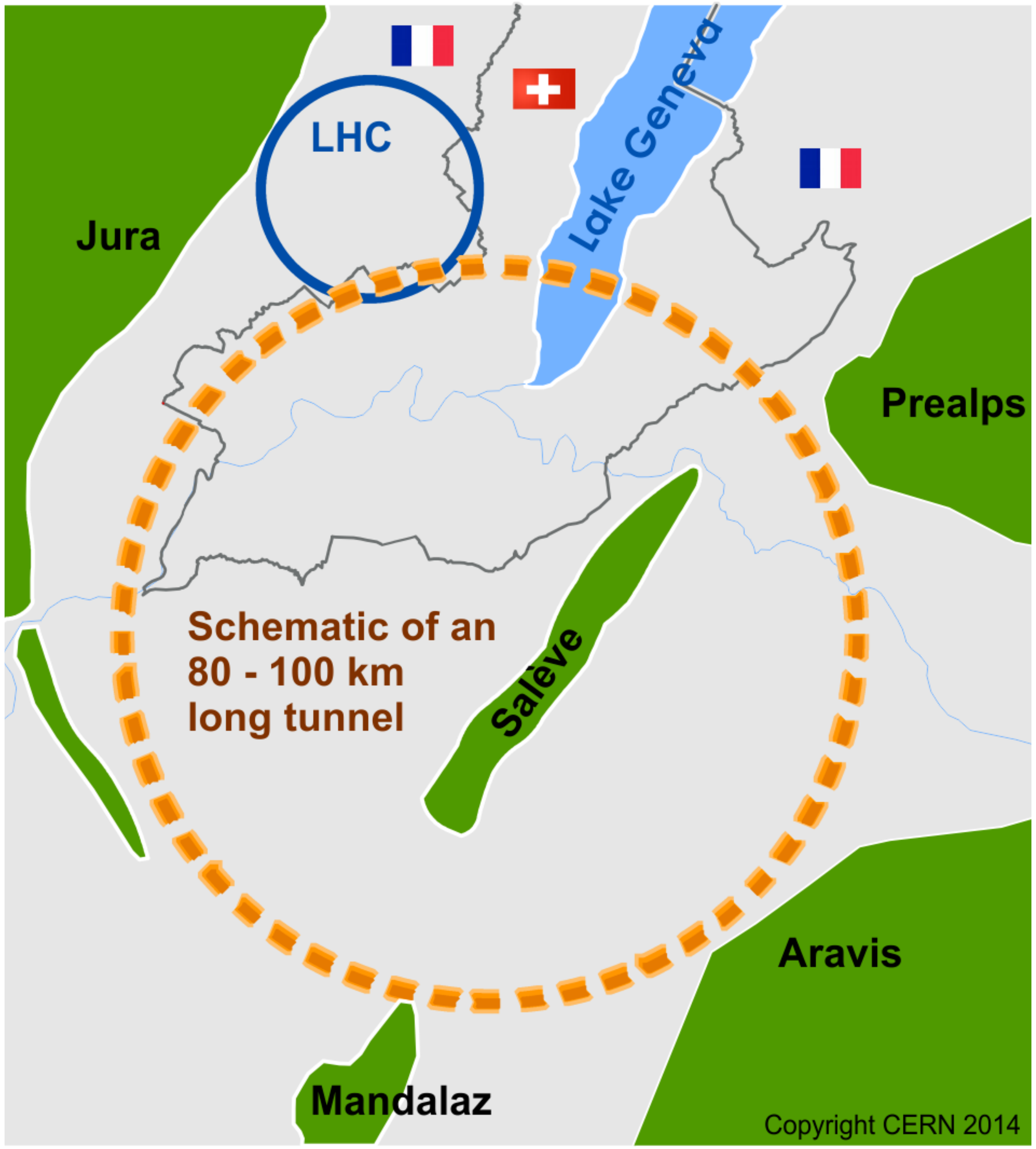
FCC vs CEPC

- 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

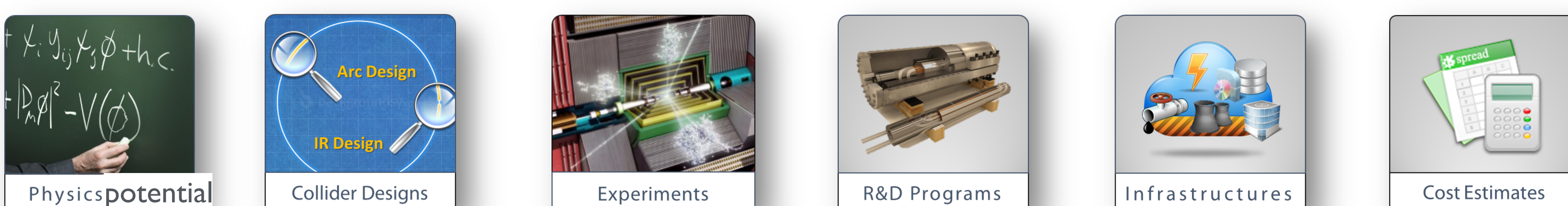
Future Circular Colliders (FCC)



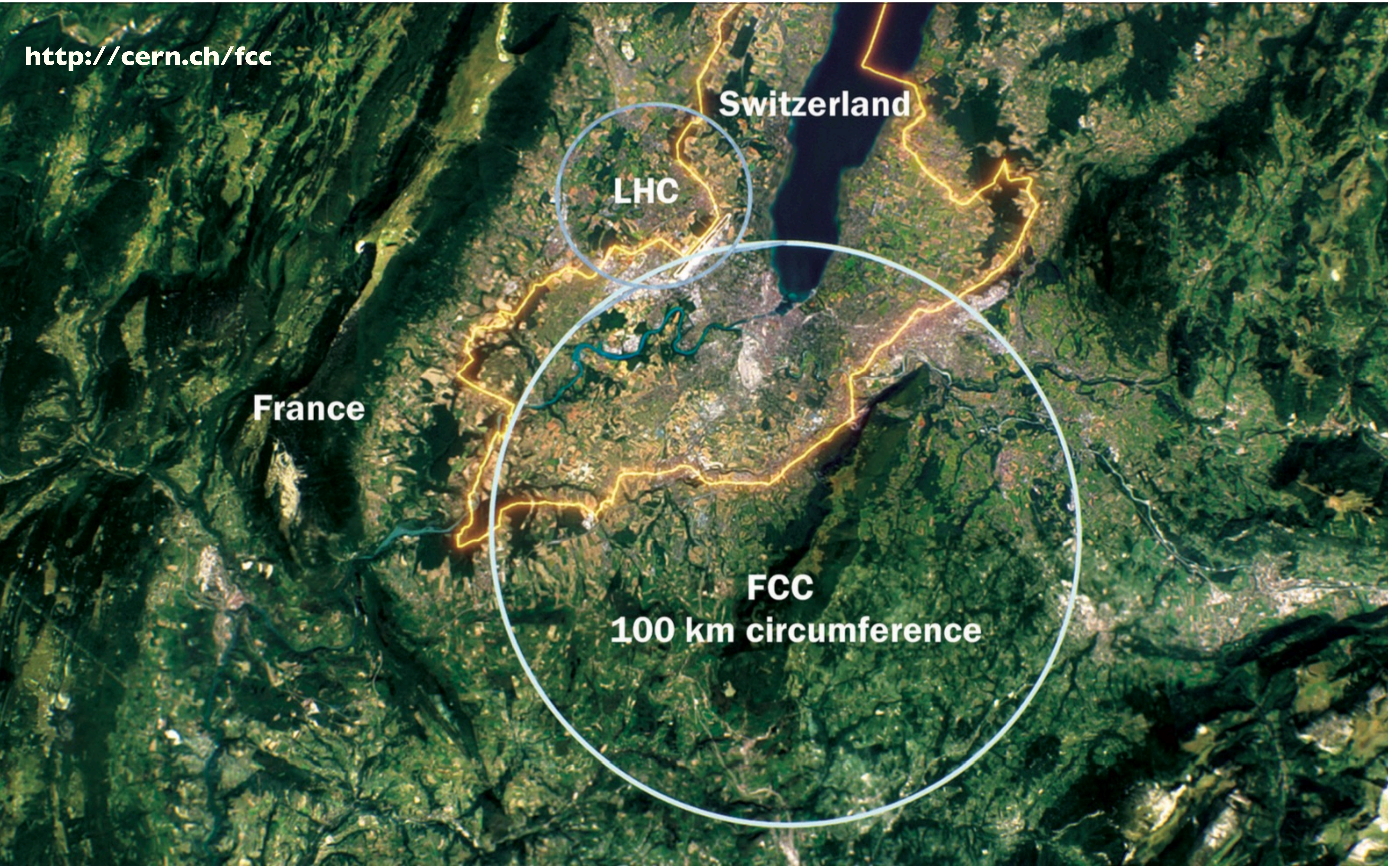
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 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



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

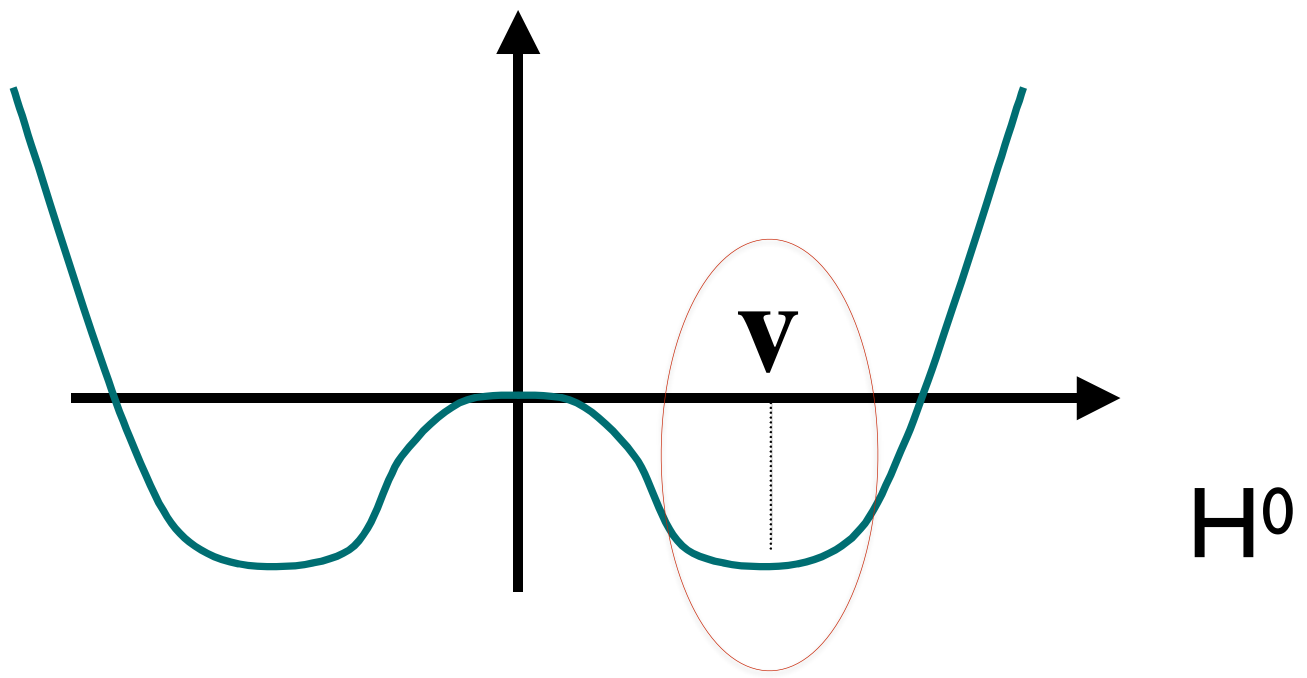
The important questions

- **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(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 ($\mu \to e\gamma$, $H \to \mu\tau$, …): 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….

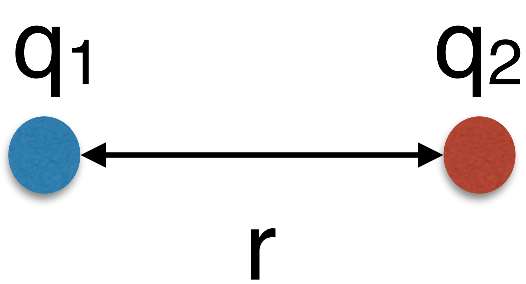


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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

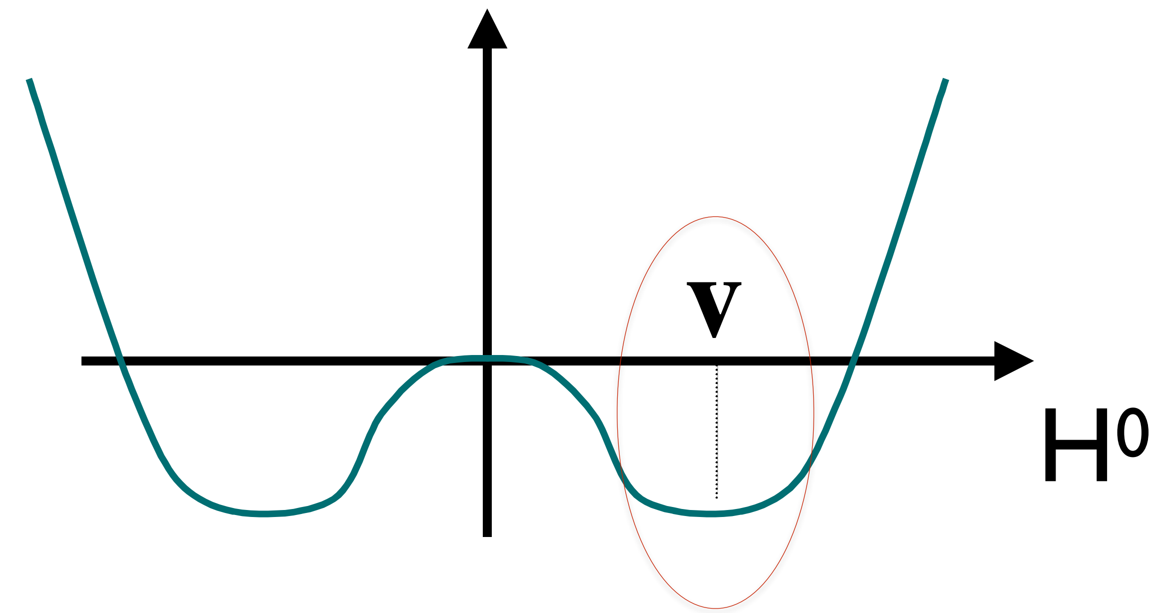


$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

quantized, in units of fixed charge

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.

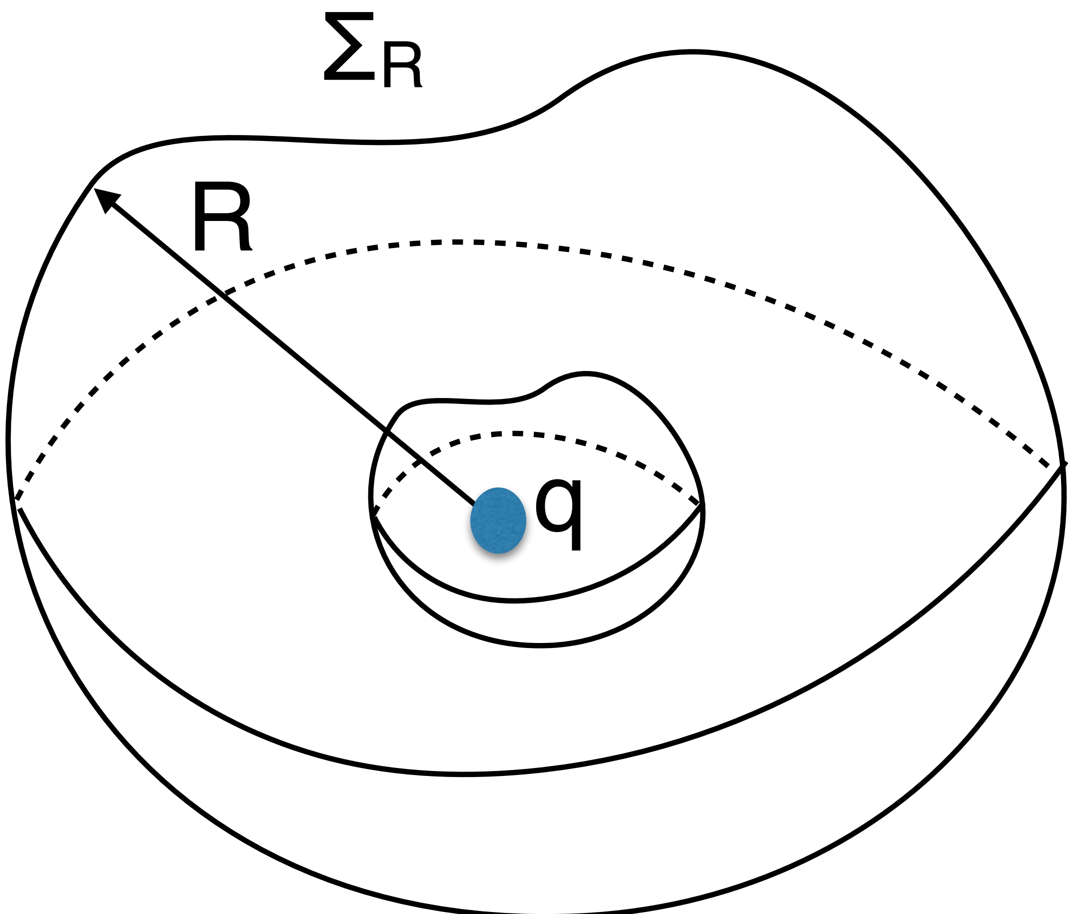
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either 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

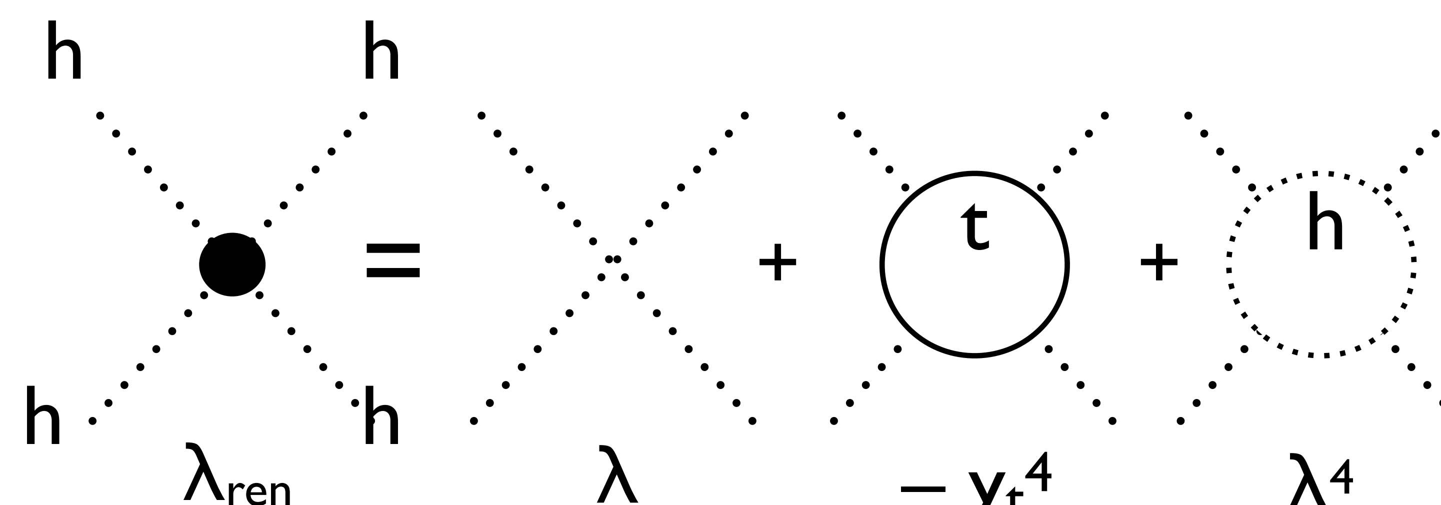


$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

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

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



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

high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics => **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, <u>which can only rely on a future generation of colliders</u>*

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	$5\ 10^{12}$	10^8	10^6	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

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

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

Higgs couplings: beyond the HL-LHC

Collider	HL-LHC	**HL-LHC update**	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\mathrm{FCC\text{-}ee}_{240+365}$		
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	
$\delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}$ (%)	SM	50	3.6	6.3	3.6	2.6	2.7	**1.3**	1.1
$\delta g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}$ (%)	3.5	**1.5**	0.3	0.40	0.32	0.25	0.20	**0.17**	**0.16**
$\delta g_{\mathrm{HWW}}/g_{\mathrm{HWW}}$ (%)	3.5	**1.7**	1.7	0.8	1.7	1.2	1.3	**0.43**	**0.40**
$\delta g_{\mathrm{Hbb}}/g_{\mathrm{Hbb}}$ (%)	8.2	**3.7**	1.7	1.3	1.8	1.3	1.3	**0.61**	**0.56**
$\delta g_{\mathrm{Hcc}}/g_{\mathrm{Hcc}}$ (%)	SM	**SM**	2.3	4.1	2.3	1.8	1.7	**1.21**	**1.18**
$\delta g_{\mathrm{Hgg}}/g_{\mathrm{Hgg}}$ (%)	3.9	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{\mathrm{H\tau\tau}}/g_{\mathrm{H\tau\tau}}$ (%)	6.5	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{\mathrm{H\mu\mu}}/g_{\mathrm{H\mu\mu}}$ (%)	5.0	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{\mathrm{H\gamma\gamma}}/g_{\mathrm{H\gamma\gamma}}$ (%)	3.6	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{\mathrm{Htt}}/g_{\mathrm{Htt}}$ (%)	4.2	**3.4**	–	–	–	–	–	–	**3.1**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	$< \mathbf{1.0}$	$< \mathbf{1.0}$

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 $5\ \mathrm{ab}^{-1}$ at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional $1.5\ \mathrm{ab}^{-1}$ 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

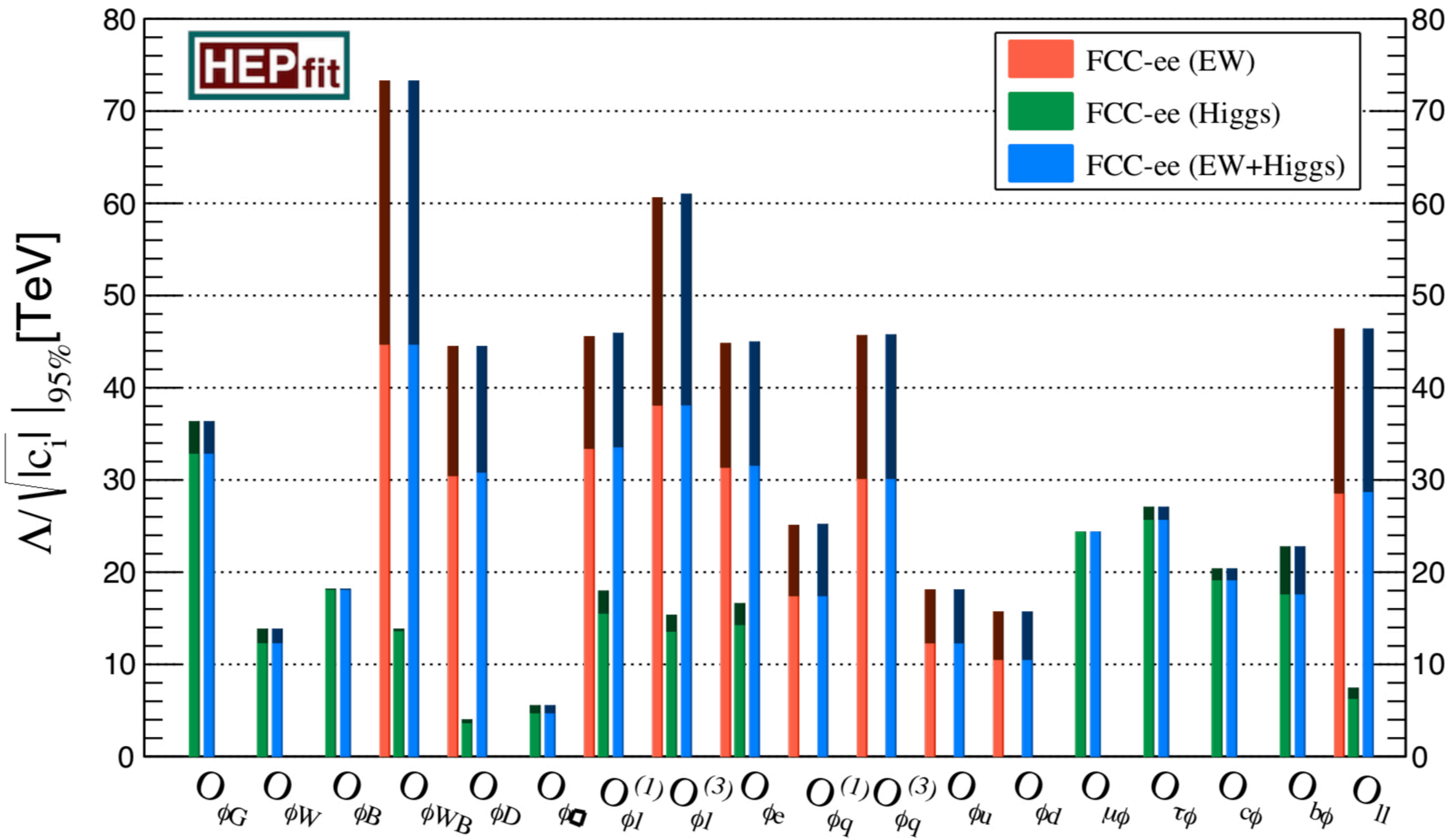
- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - 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 ± 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
α_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^0_{had} ($\times 10^3$) (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
$A_{FB}^{b,0}$ ($\times 10^4$)	992±16	0.02	1-3
$A_{FB}^{\text{pol},\tau}$ ($\times 10^4$)	1498±49	0.15	<2
m_W (MeV)	80350±15	0.6	0.3
Γ_W (MeV)	2085±42	1.5	0.3
α_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
$\lambda_{top}/\lambda_{top}^{SM}$	1.2±0.3	0.08	Small
ttZ couplings	±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

	$gg \to H$	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

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

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

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
    - …

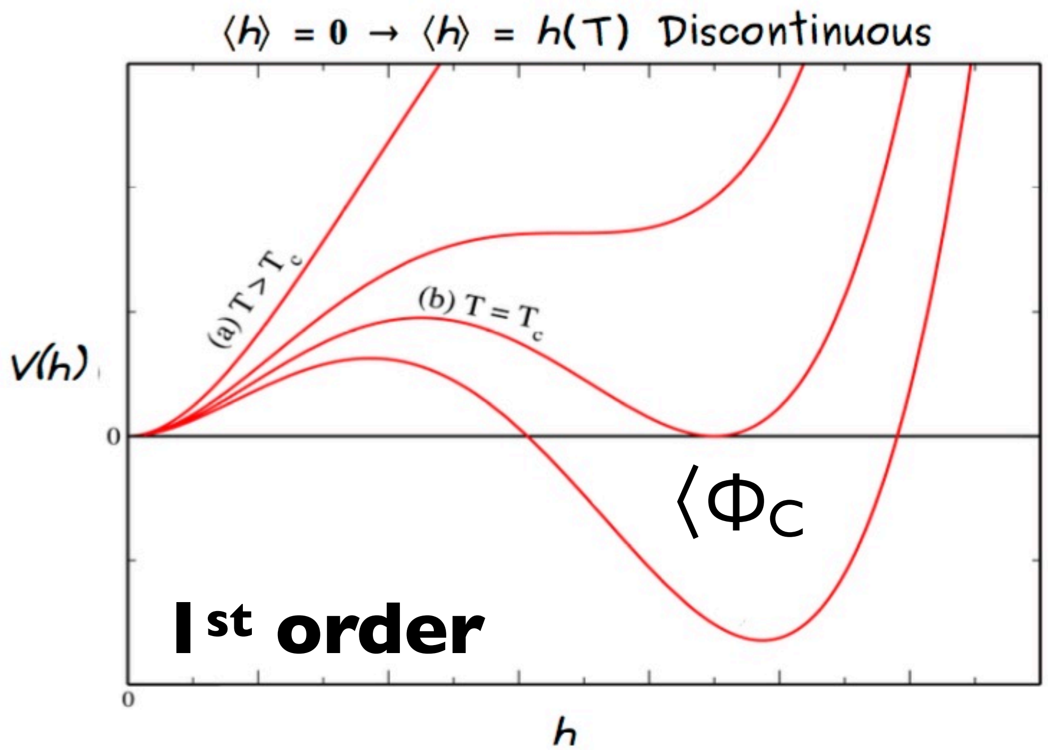
Higgs couplings after FCC-ee / hh

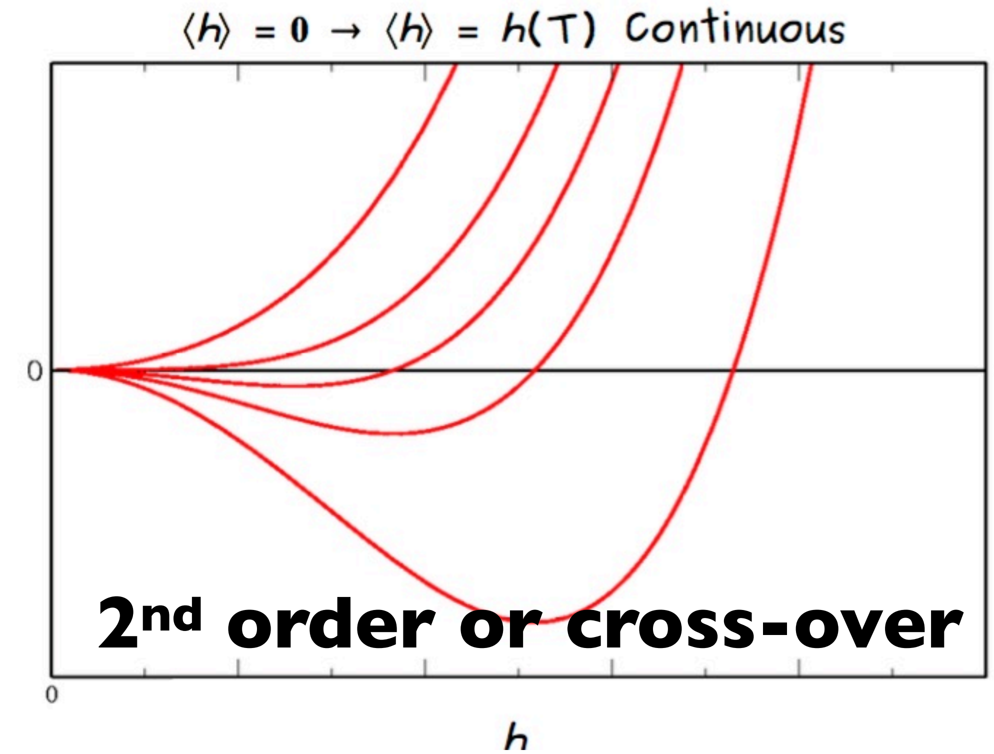
	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**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_{inv} < 2.5%	**< 1%**	**BR_{inv} < 0.025%**

* From BR ratios wrt B(H→4lept) @ FCC-ee

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

The nature of the EW phase transition





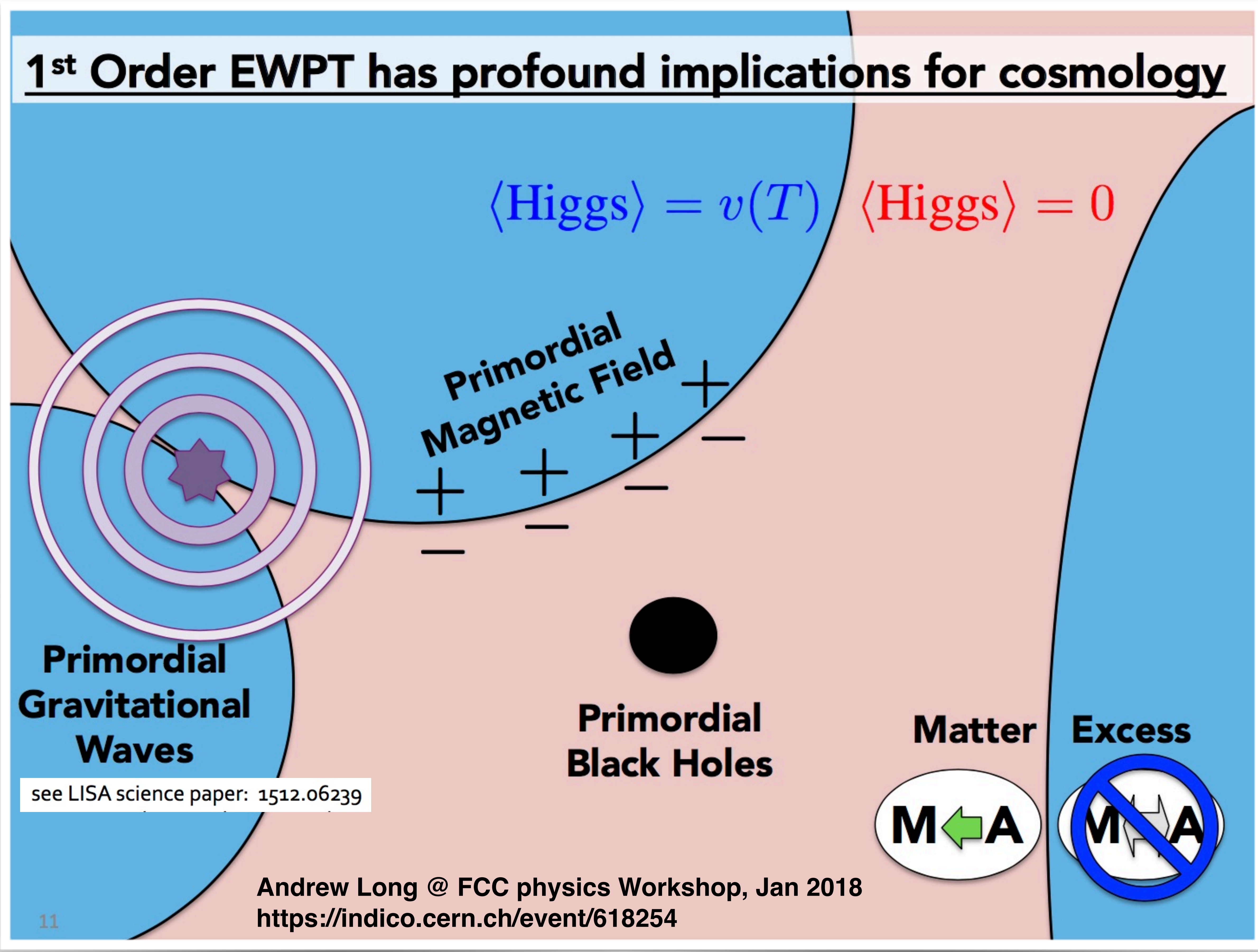
Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

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(TeV)**, must modify the Higgs potential to make this possible

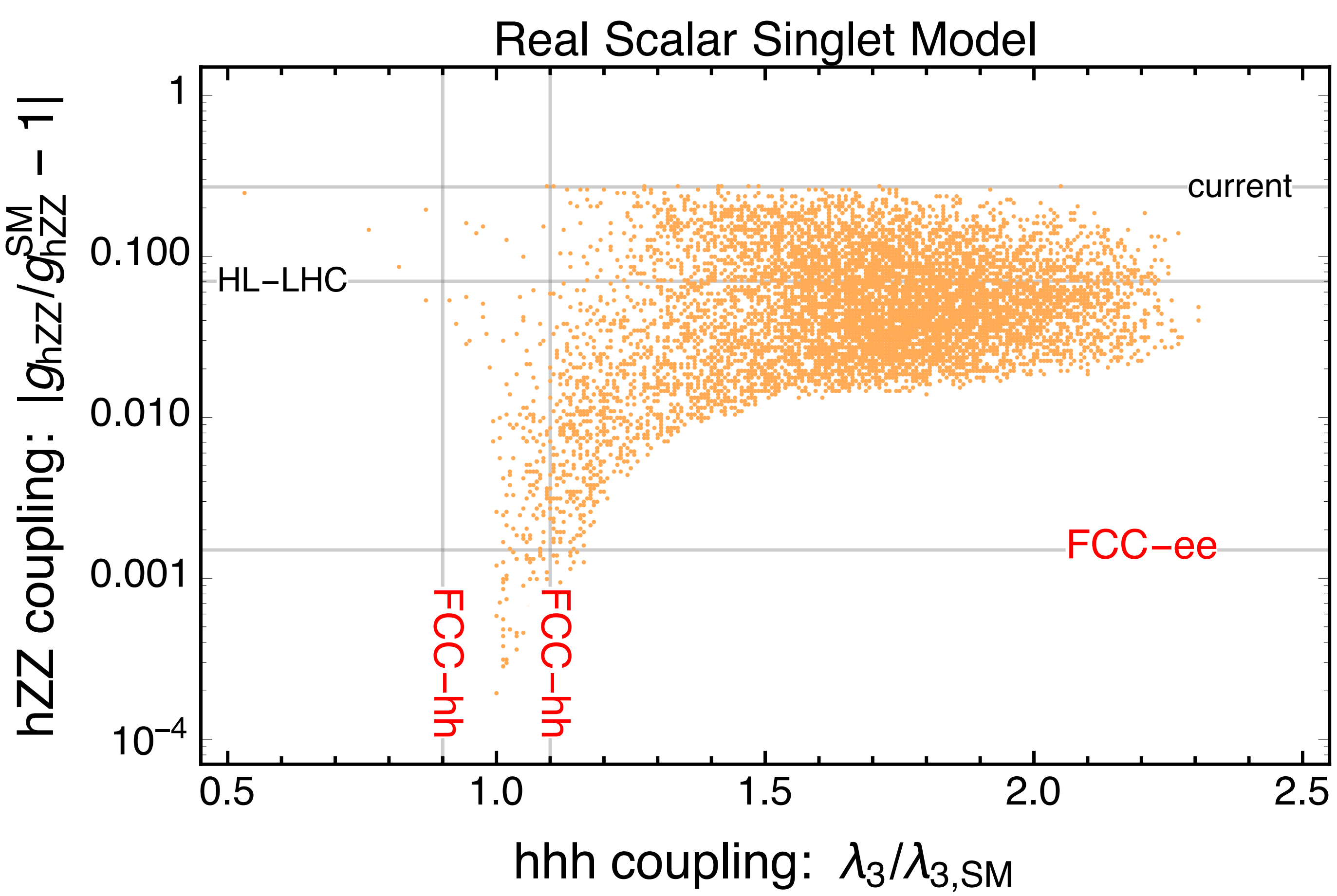
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**


1st Order EWPT has profound implications for cosmology
⟨Higgs⟩ = v(T)
⟨Higgs⟩ = 0
Primordial Magnetic Field
Primordial Gravitational Waves
see LISA science paper: 1512.06239
Primordial Black Holes
Matter
Excess
M A
M A
Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254
11

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

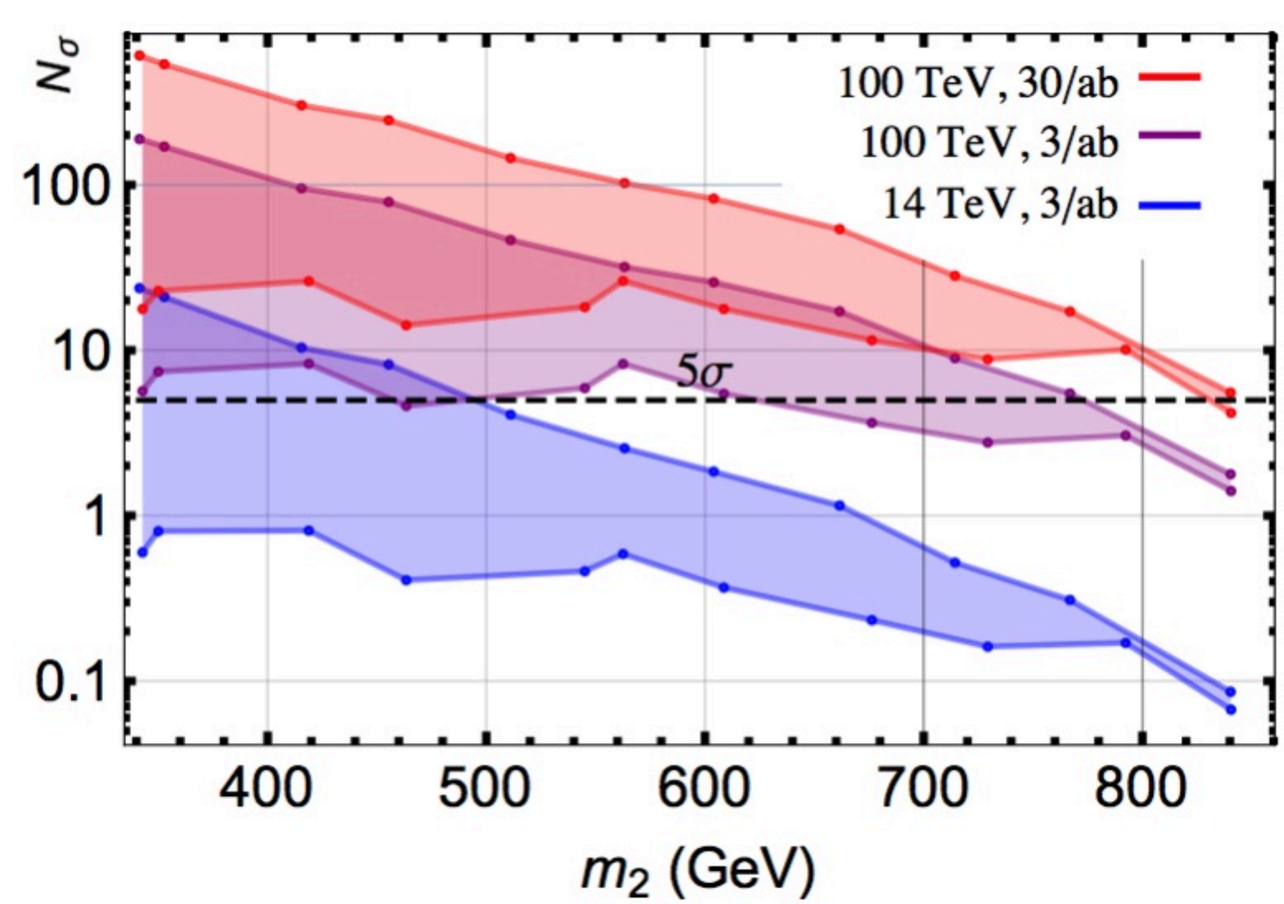
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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.

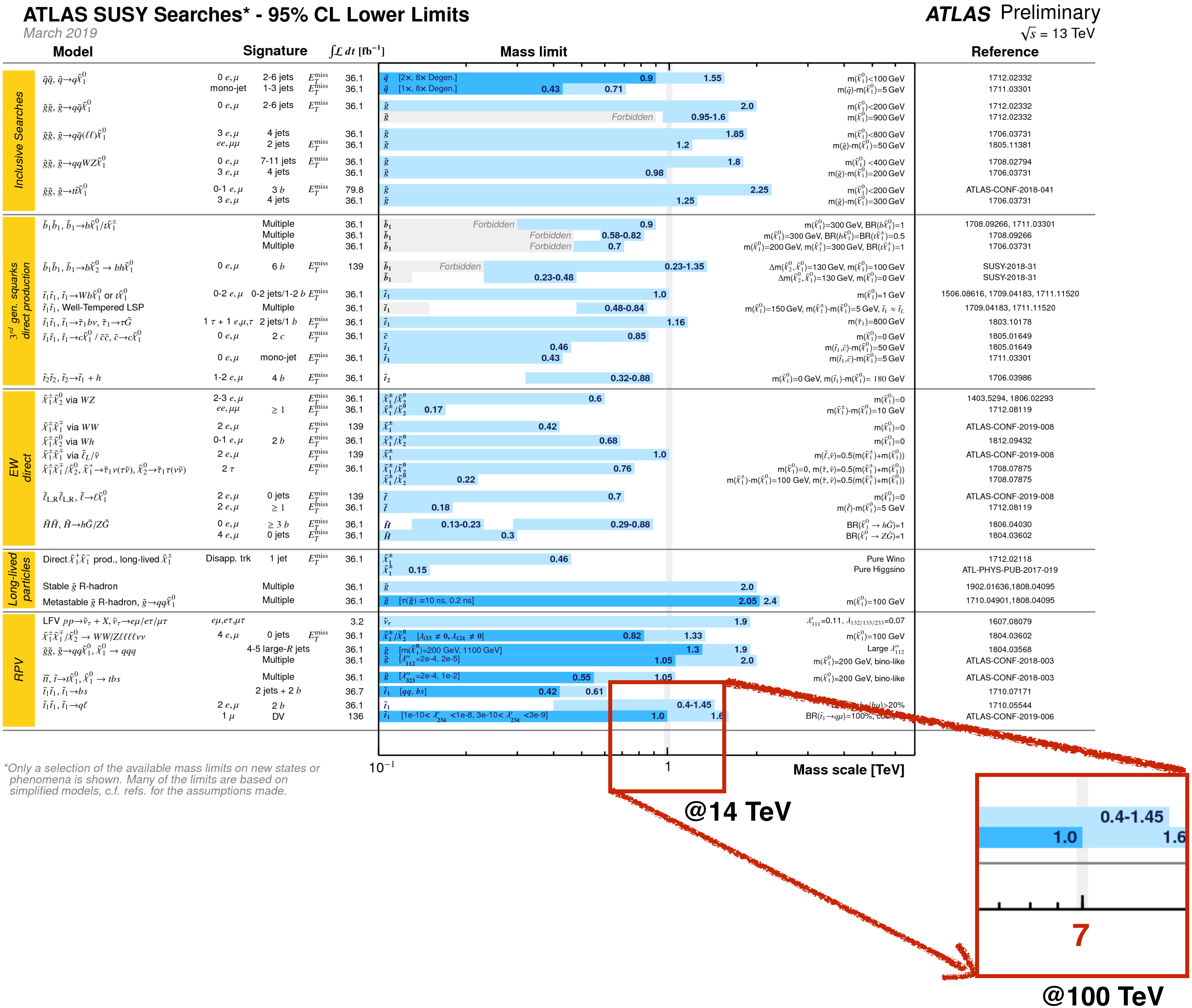
Direct detection of extra Higgs states at FCC-hh



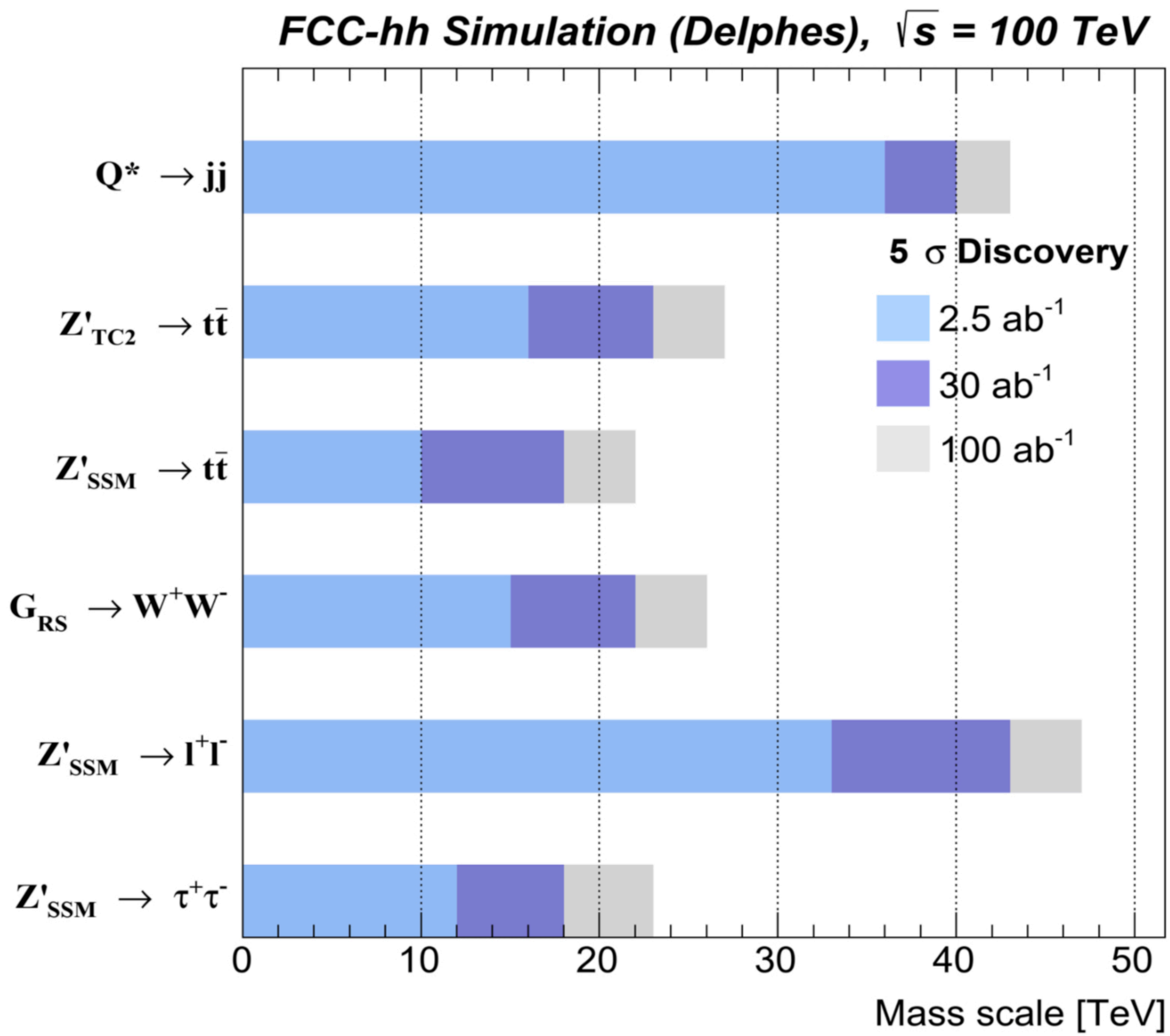
$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

$(h_2 \sim S, \quad h_1 \sim H)$

Direct discovery reach: the power of 100 TeV


ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
[2x, 8x Degen.] 0.9 1.55 m(χ̃⁰₁)<100 GeV 1712.02332
[1x, 8x Degen.] 0.43 0.71 m(q̃)-m(χ̃⁰₁)=5 GeV 1711.03301
2.0 m(χ̃⁰₁)<200 GeV 1712.02332
Forbidden 0.95-1.6 m(χ̃⁰₁)=900 GeV 1712.02332
1.85 m(χ̃⁰₁)<800 GeV 1706.03731
1.2 m(g̃)-m(χ̃⁰₁)=50 GeV 1805.11381
1.8 m(χ̃⁰₁) <400 GeV 1708.02794
0.98 m(g̃)-m(χ̃⁰₁)=200 GeV 1706.03731
2.25 m(χ̃⁰₁)<200 GeV ATLAS-CONF-2018-041
1.25 m(g̃)-m(χ̃⁰₁)=300 GeV 1706.03731
Forbidden 0.9
Forbidden 0.58-0.82
Forbidden 0.7
Forbidden 0.23-1.35 SUSY-2018-31
0.23-0.48 SUSY-2018-31
1.0 m(χ̃⁰₁)=1 GeV 1506.08616, 1709.04183, 1711.11520
Well-Tempered LSP 0.48-0.84 1709.04183, 1711.11520
1.16 m(τ̃₁)=800 GeV 1803.10178
0.85 m(χ̃⁰₁)=0 GeV 1805.01649
0.46 1805.01649
0.43 1711.03301
0.32-0.88 1706.03986
0.6 1403.5294, 1806.02293
0.17 1712.08119
0.42 ATLAS-CONF-2019-008
0.68 1812.09432
1.0 ATLAS-CONF-2019-008
0.76 1708.07875
0.22 1708.07875
0.7 ATLAS-CONF-2019-008
0.18 1712.08119
0.13-0.23 0.29-0.88 1806.04030
0.3 1804.03602
Disapp. trk 0.46 Pure Wino 1712.02118
0.15 Pure Higgsino ATL-PHYS-PUB-2017-019
Stable g̃ R-hadron 2.0 1902.01636,1808.04095
Metastable g̃ R-hadron [τ(g̃) =10 ns, 0.2 ns] 2.05 2.4 m(χ̃⁰₁)=100 GeV 1710.04901,1808.04095
LFV 1.9 1607.08079
0.82 1.33 m(χ̃⁰₁)=100 GeV 1804.03602
[m(χ̃⁰₁)=200 GeV, 1100 GeV] 1.3 1.9 Large λ''₁₁₂ 1804.03568
1.05 2.0 m(χ̃⁰₁)=200 GeV, bino-like ATLAS-CONF-2018-003
0.55 1.05 m(χ̃⁰₁)=200 GeV, bino-like ATLAS-CONF-2018-003
[qq, bs] 0.42 0.61 1710.07171
0.4-1.45 1710.05544
1.0 1.6 ATLAS-CONF-2019-006
10⁻¹
1
Mass scale [TeV]
*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.
@14 TeV
0.4-1.45
1.0
1.6
7
@100 TeV

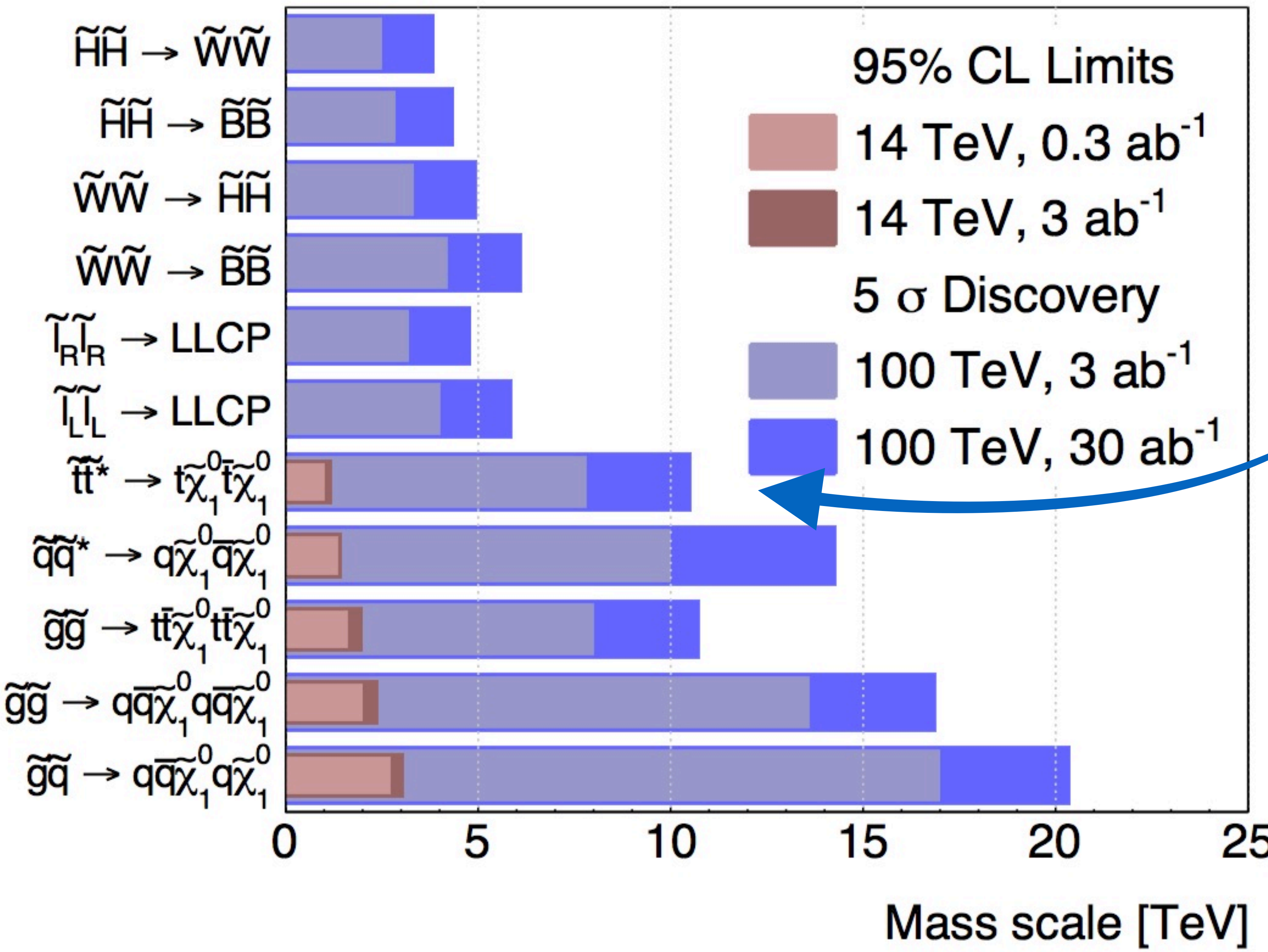
s-channel resonances



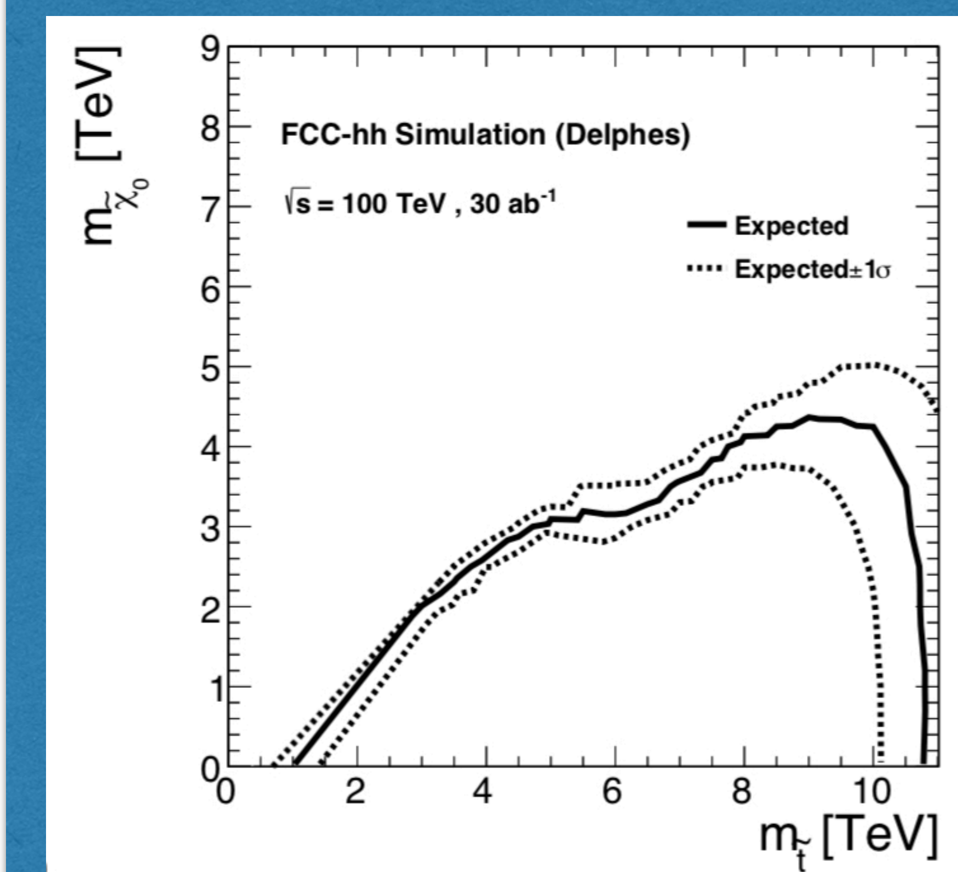
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies



New detector performance studies

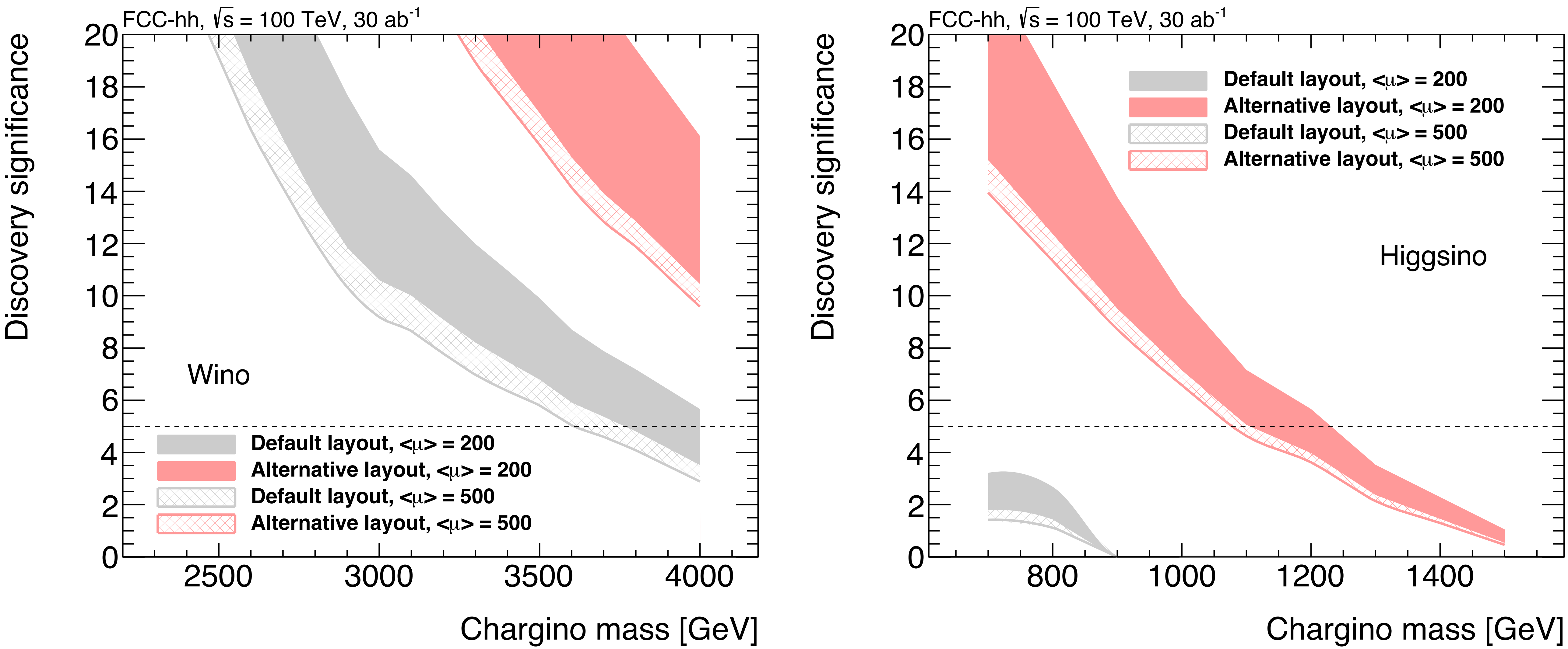


K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

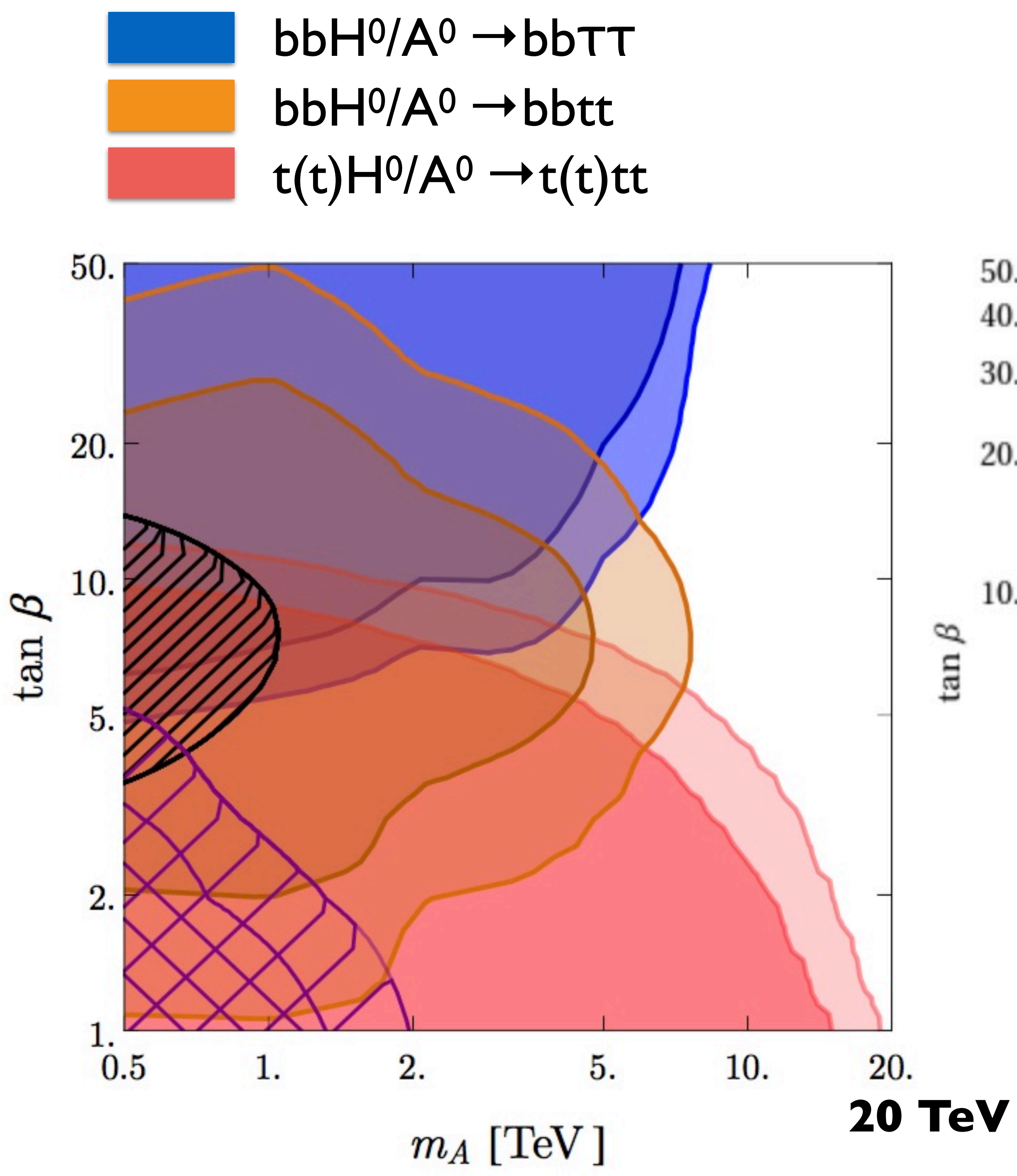
(at ~full pileup)

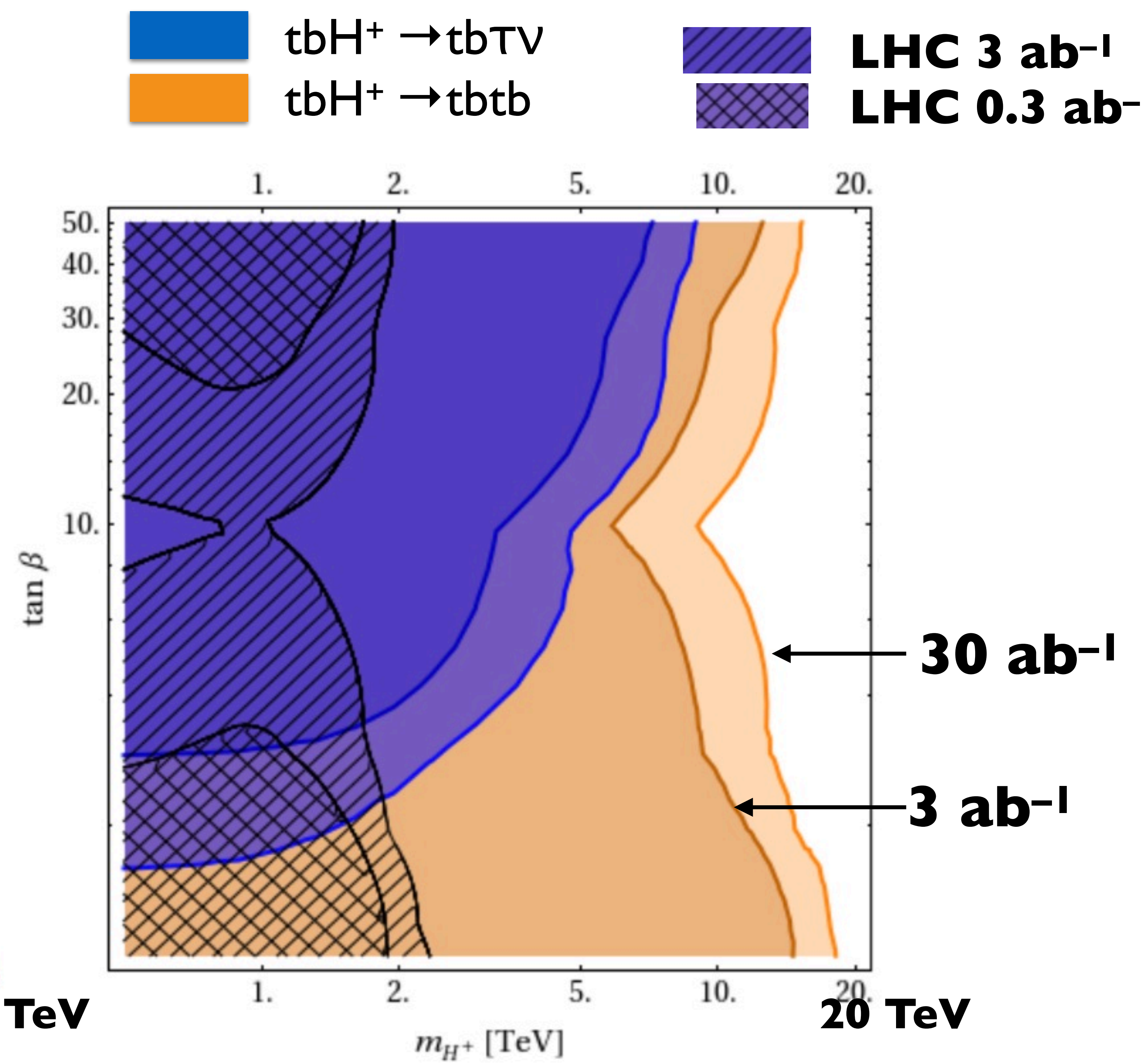


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

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*)

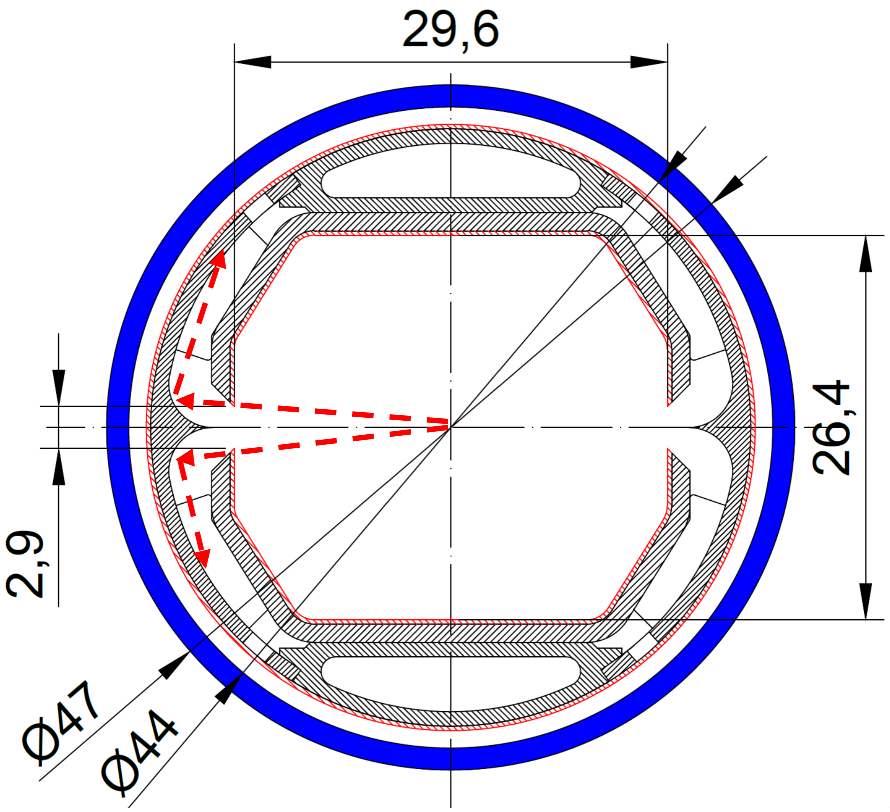
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [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} cm^{-2}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

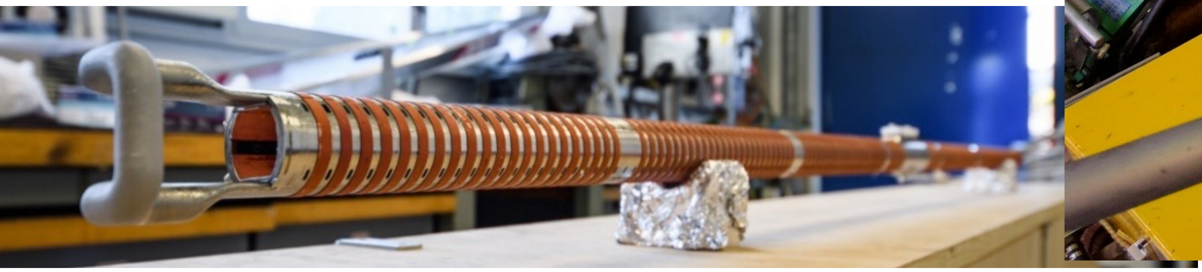
Goal: 20-30 ab^{-1} during the collider lifetime

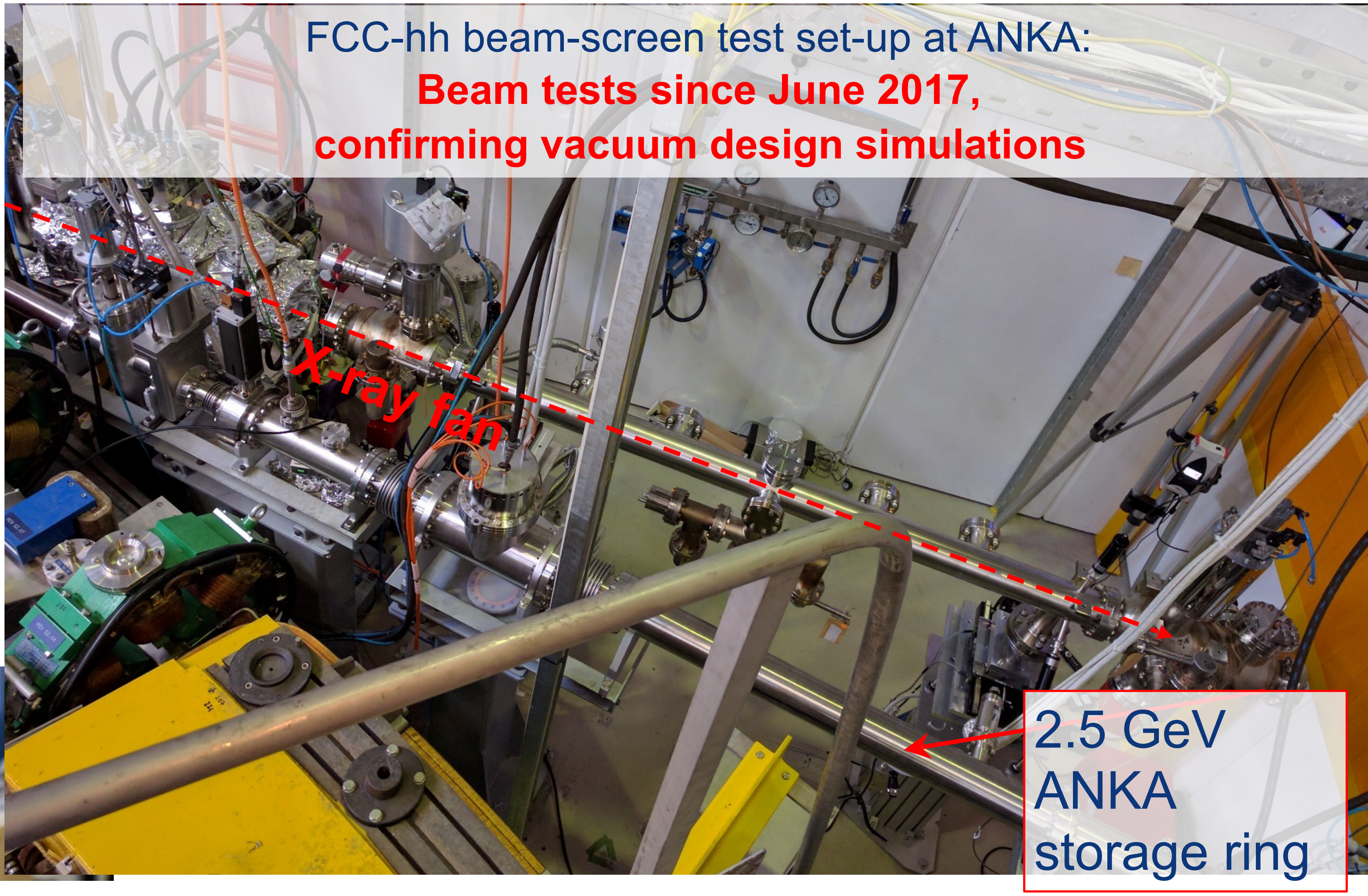
FCC-hh cryogenic beam vacuum system

Synchrotron radiation **(~ 30 W/m/beam (@16 T field)** (LHC <0.2W/m) **~ 5 MW total load in arcs**

- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (**5 MW →100 MW cryoplant**)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.

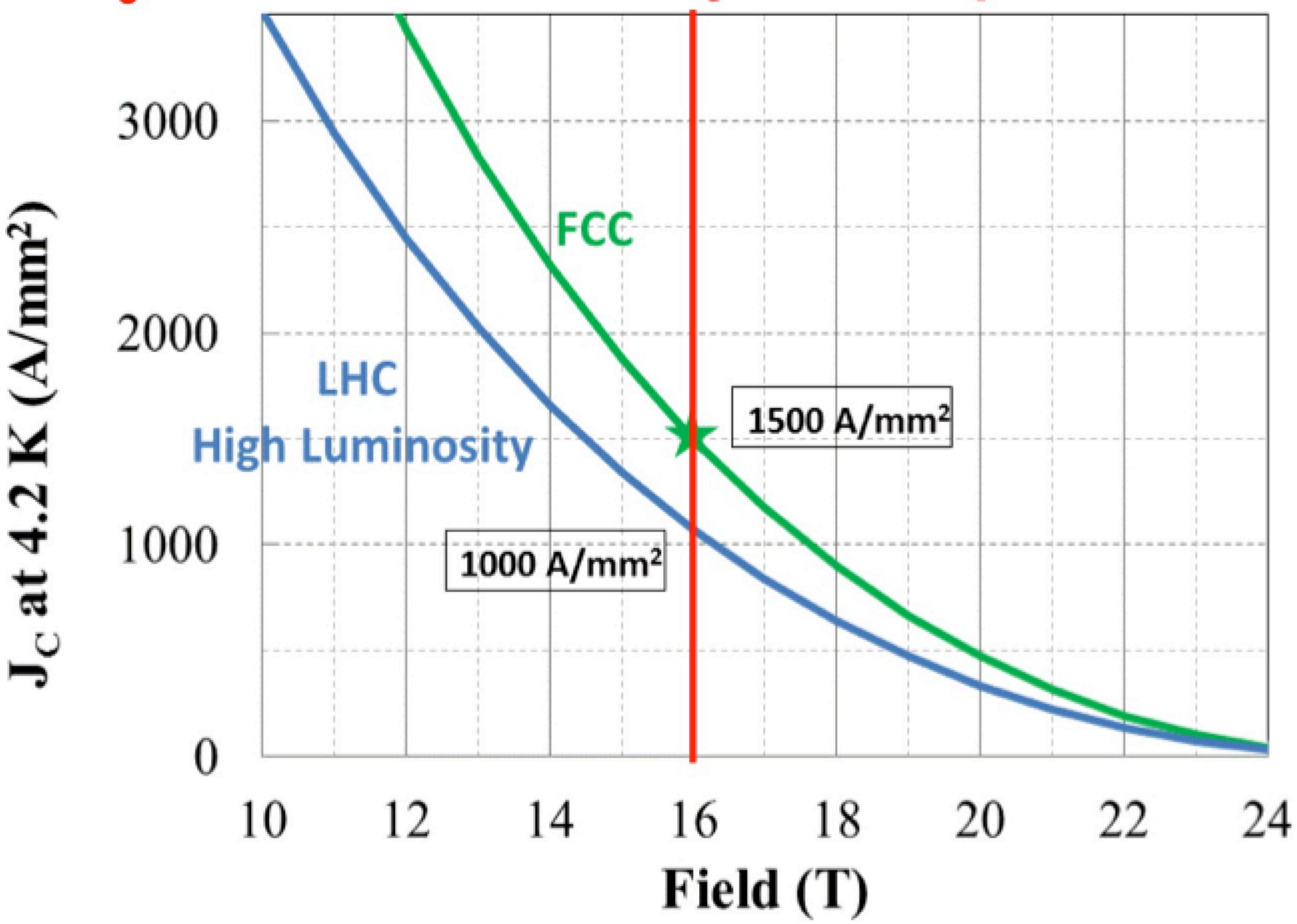






Nb_3Sn conductor development program

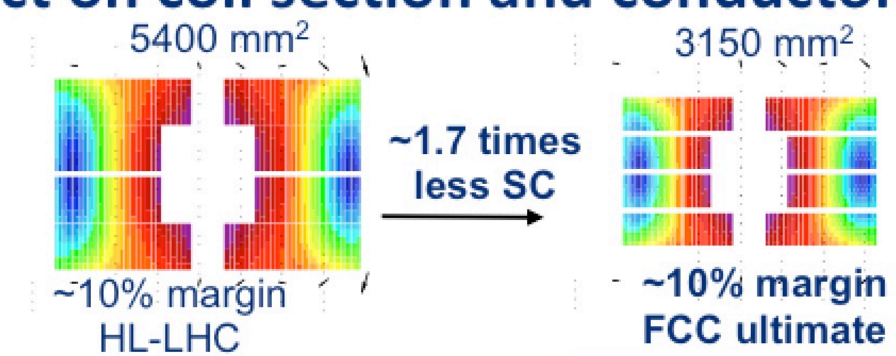
Nb_3Sn is one of the key cost & performance factors for FCC-hh / HE-LHC



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 Nb_3Sn program

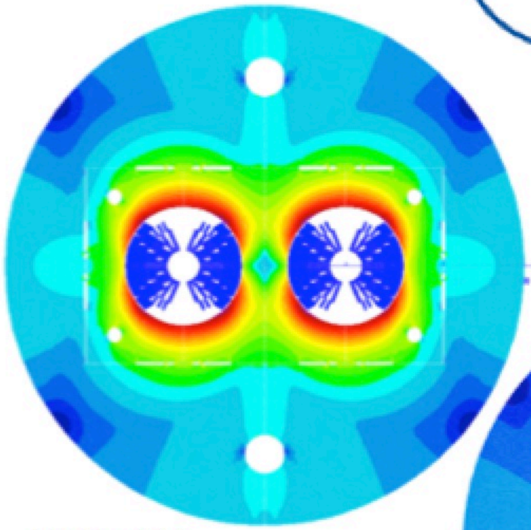
Established world activities from Nb_3Sn development

- **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

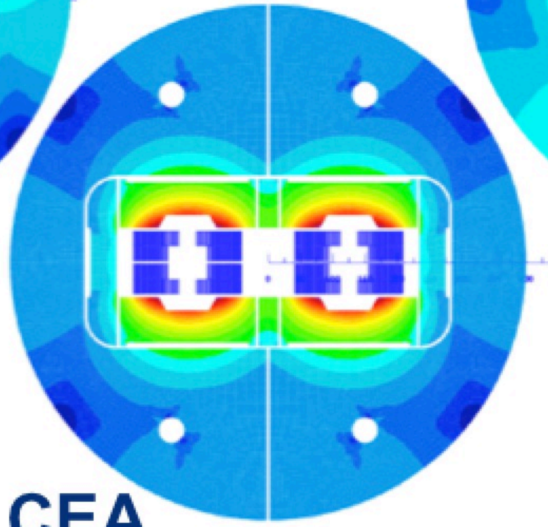
H2020 EuroCirCol
A key to New Physics

Cos-theta



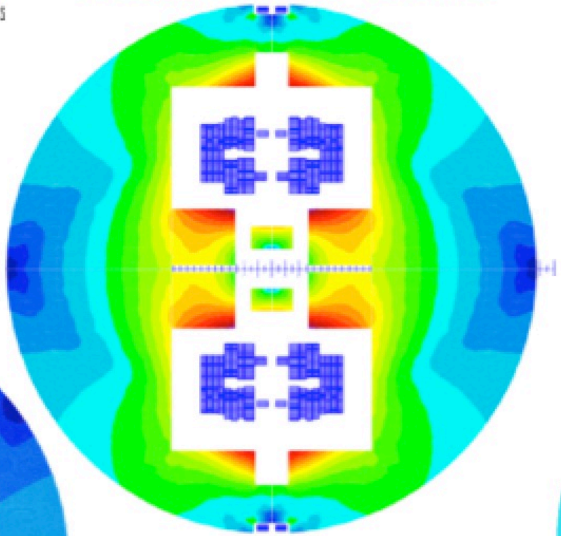
INFN

Blocks



CEA

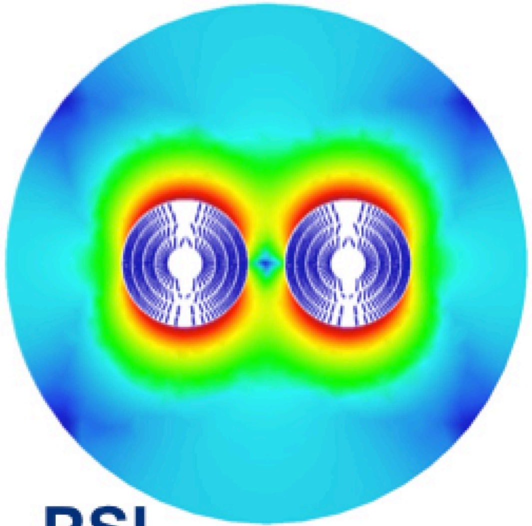
Common coils



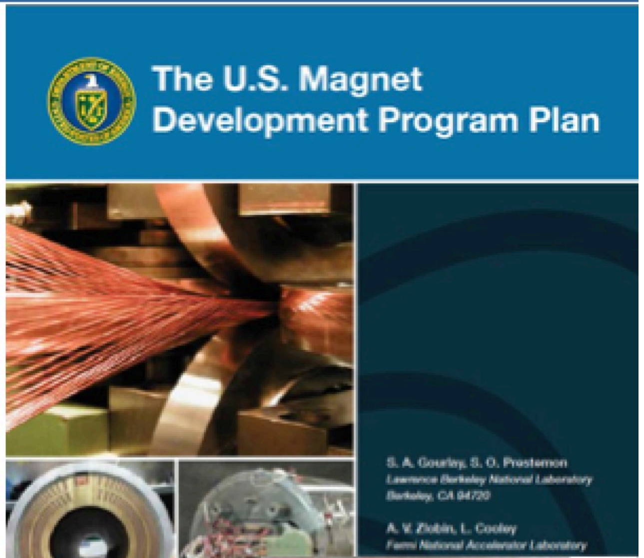
CIEMAT

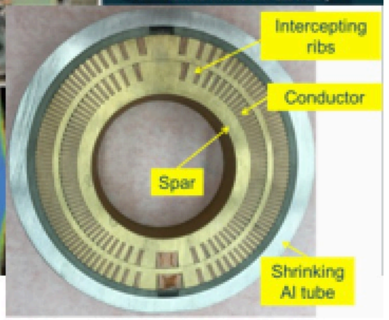
Swiss contribution

Canted Cos-theta

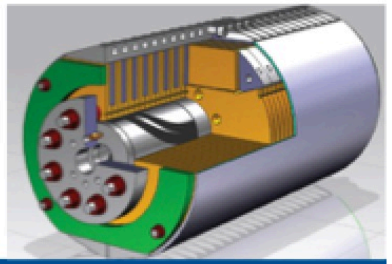


PSI





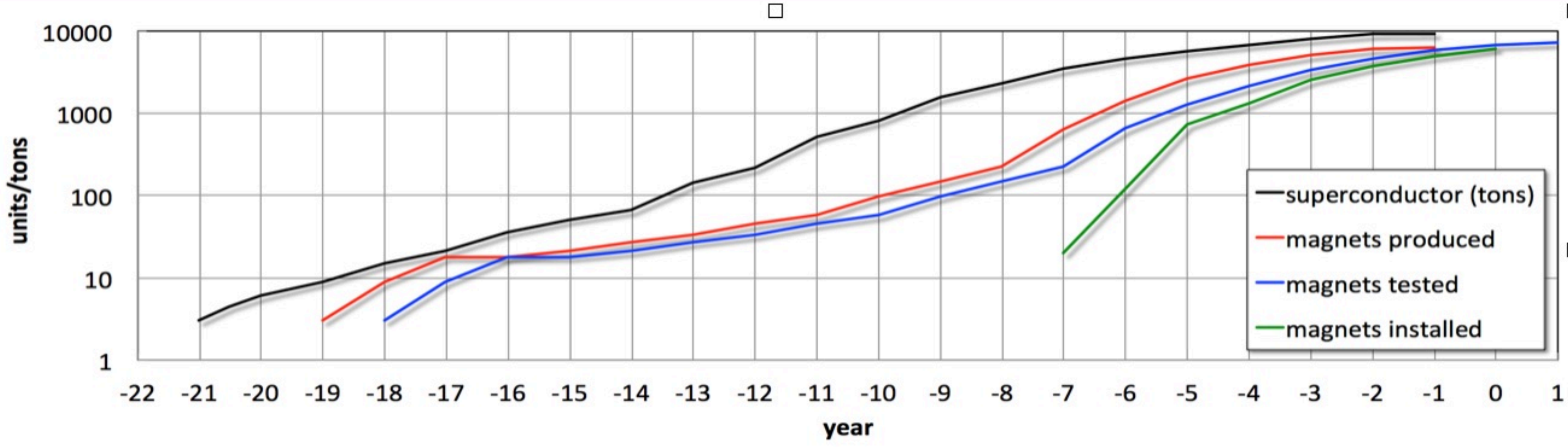
LBNL



FNAL

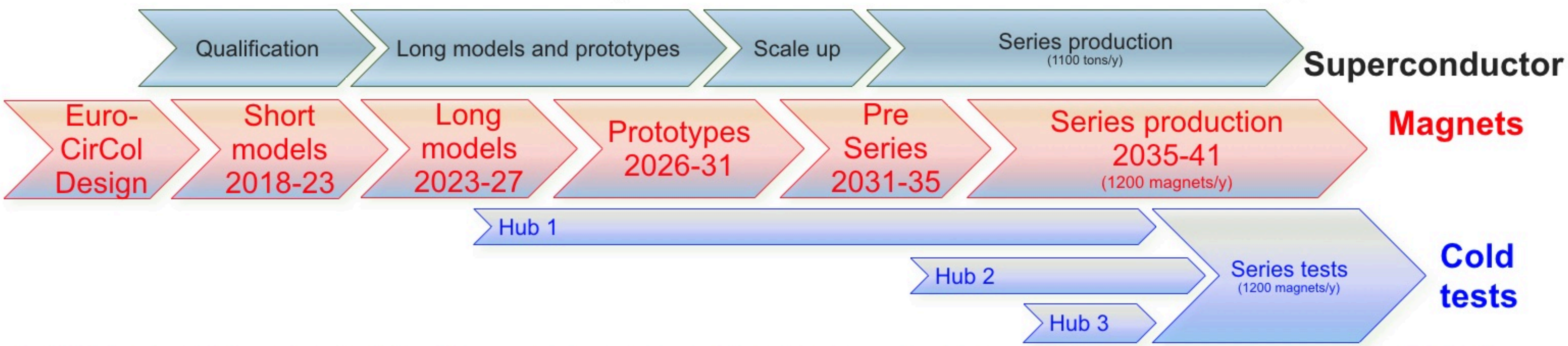
Short model magnets (1.5 m lengths) will be built from 2017 - 2021

16 T magnet R&D schedule



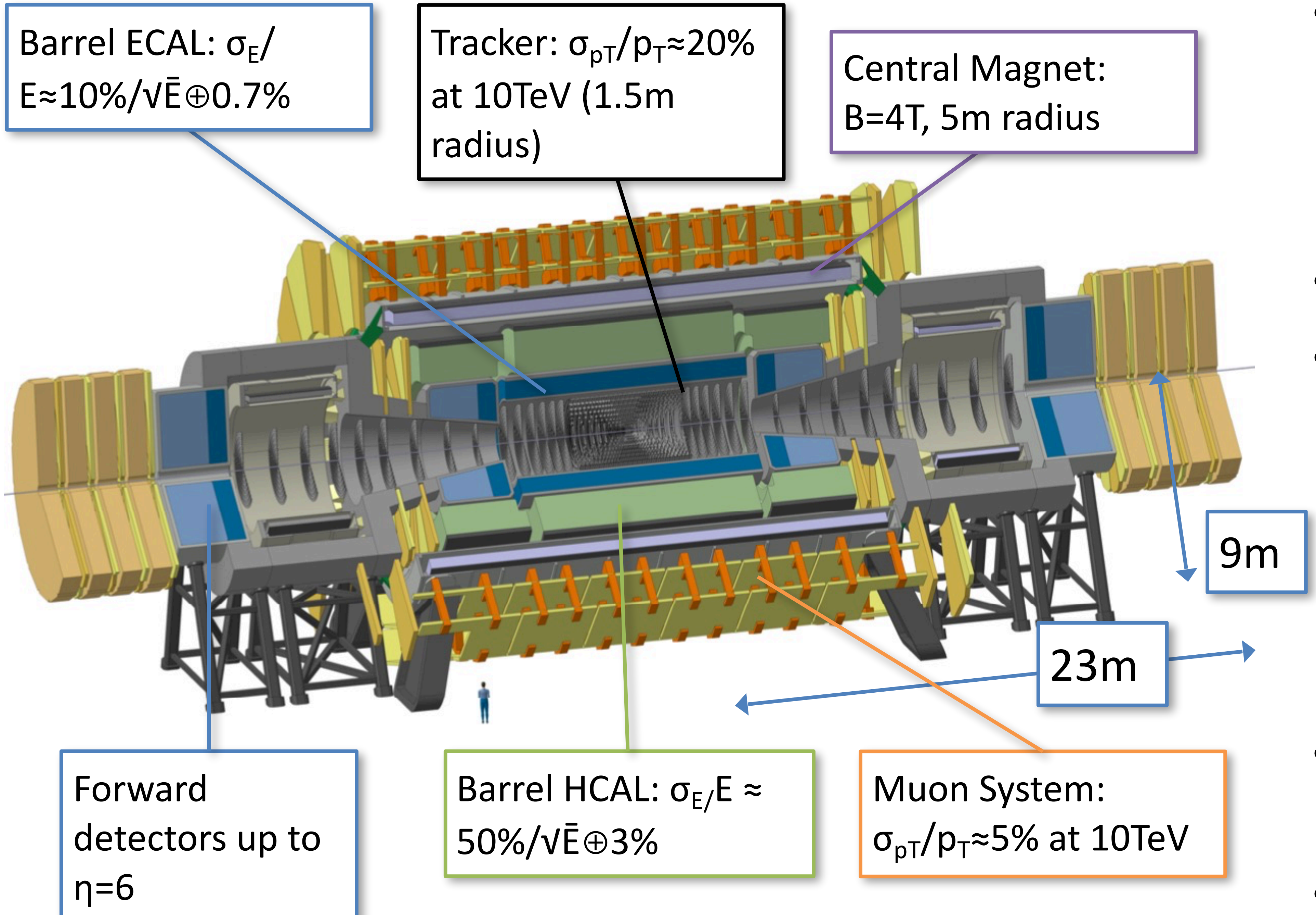
total duration of magnet program:

~20 years



would follow HL-LHC Nb_3Sn program with long models at industry from 2023/24

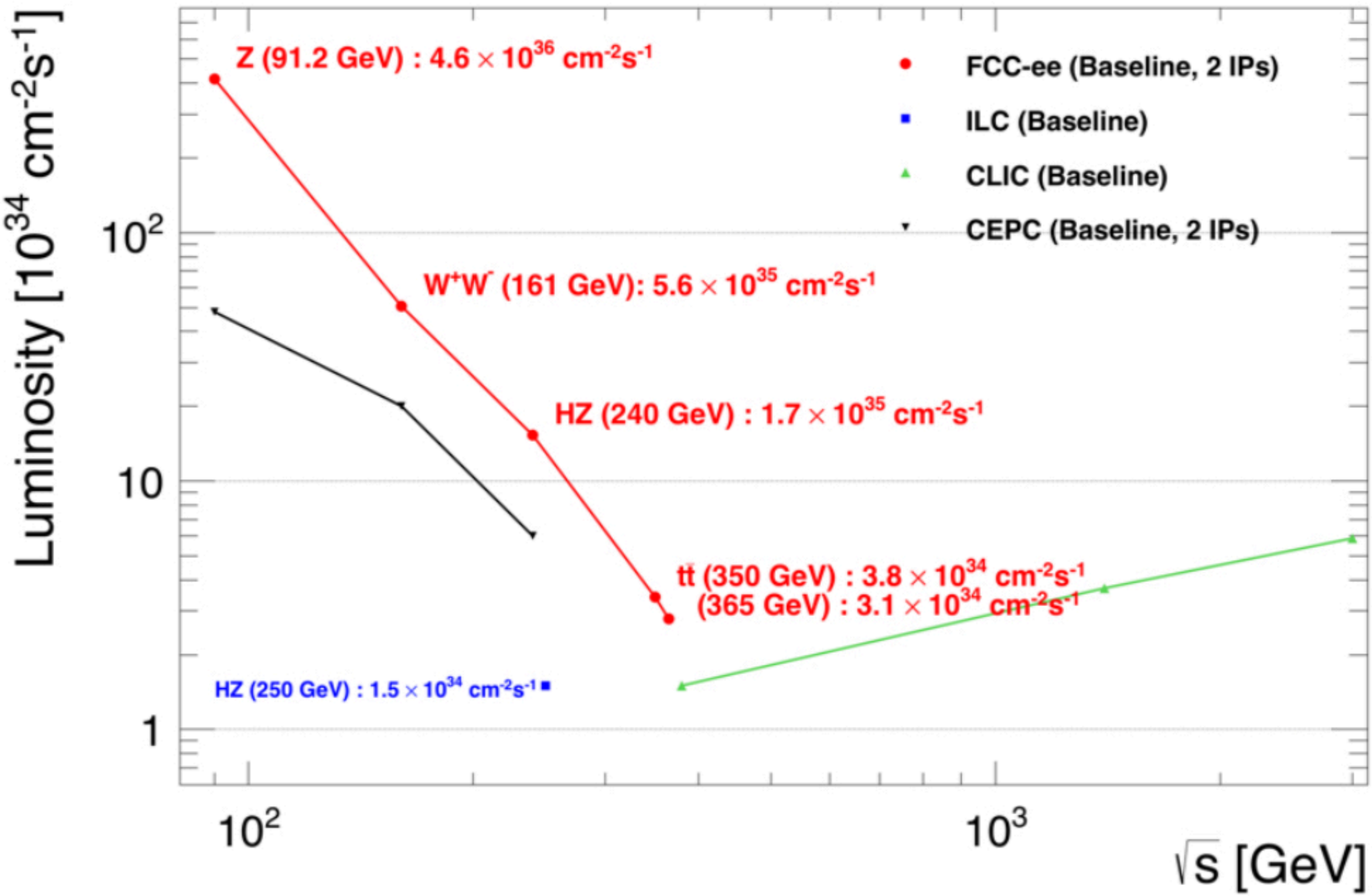
FCC-hh Detector – Reference Design for CDR



- 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

See FCC CDR Volume 3, Chapter 7

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

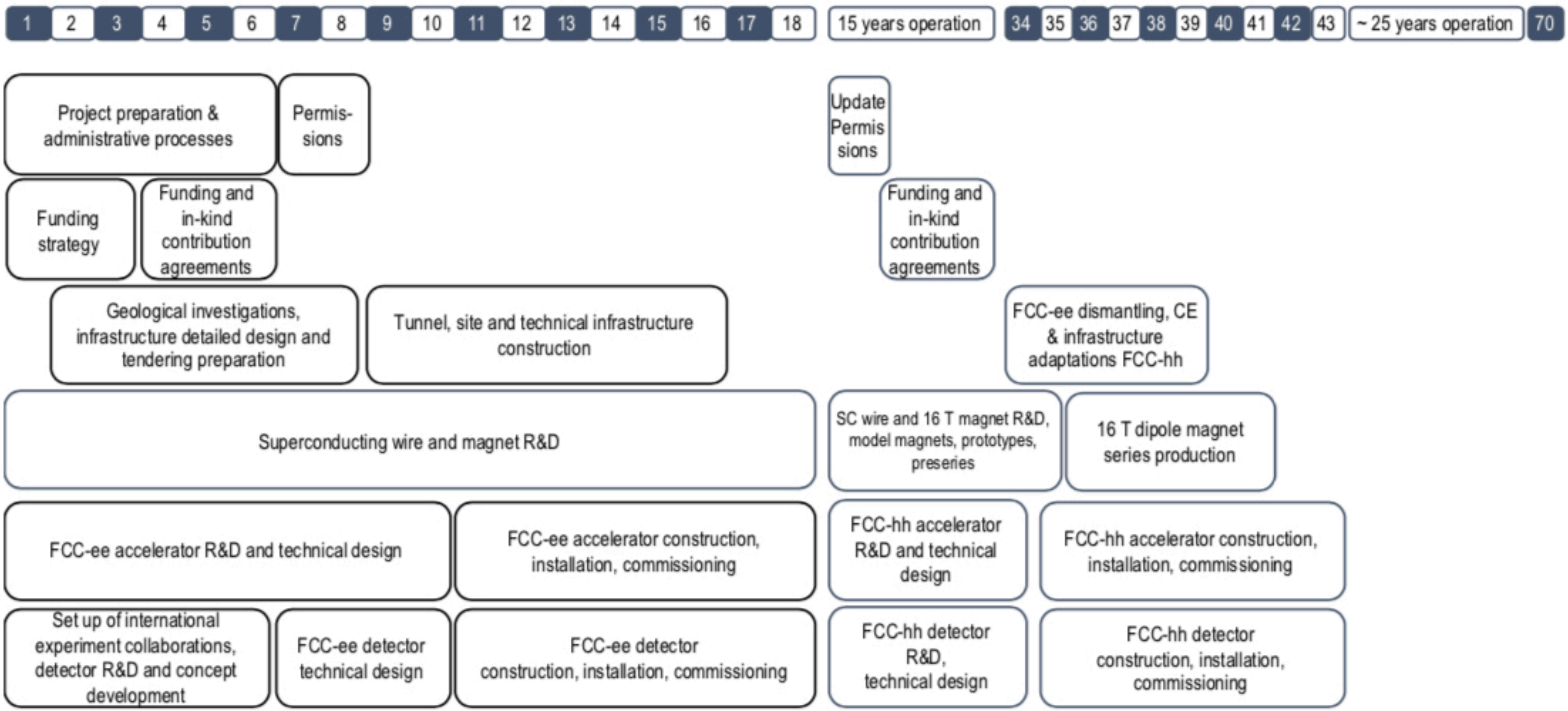
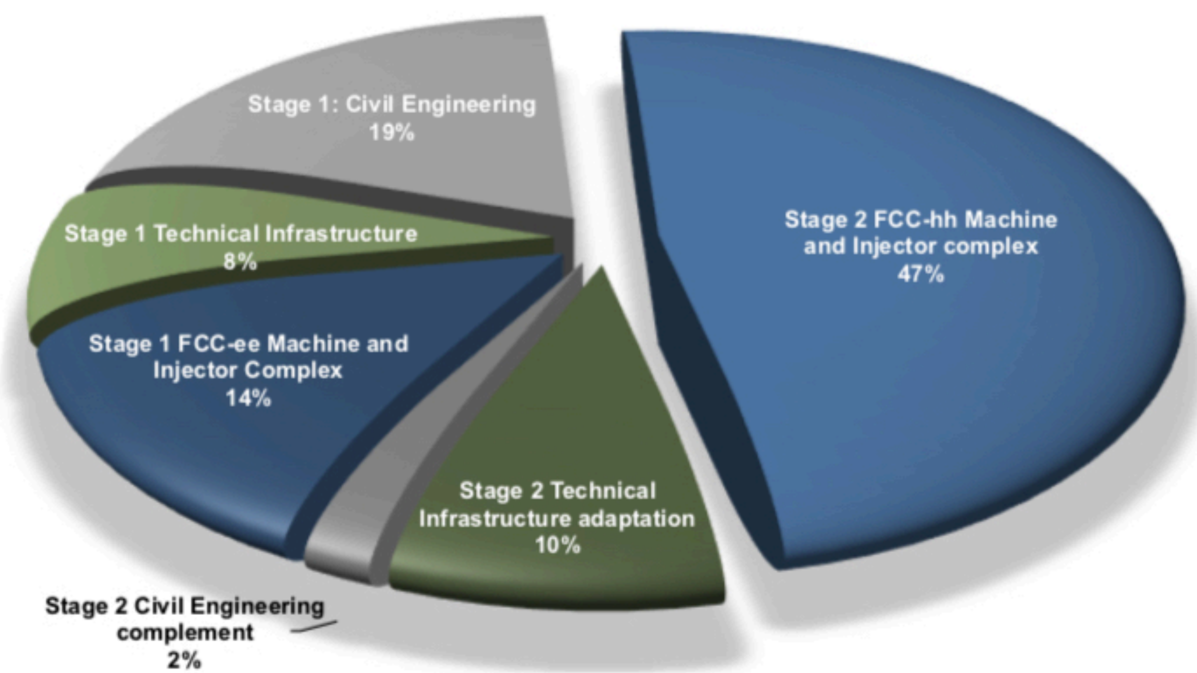
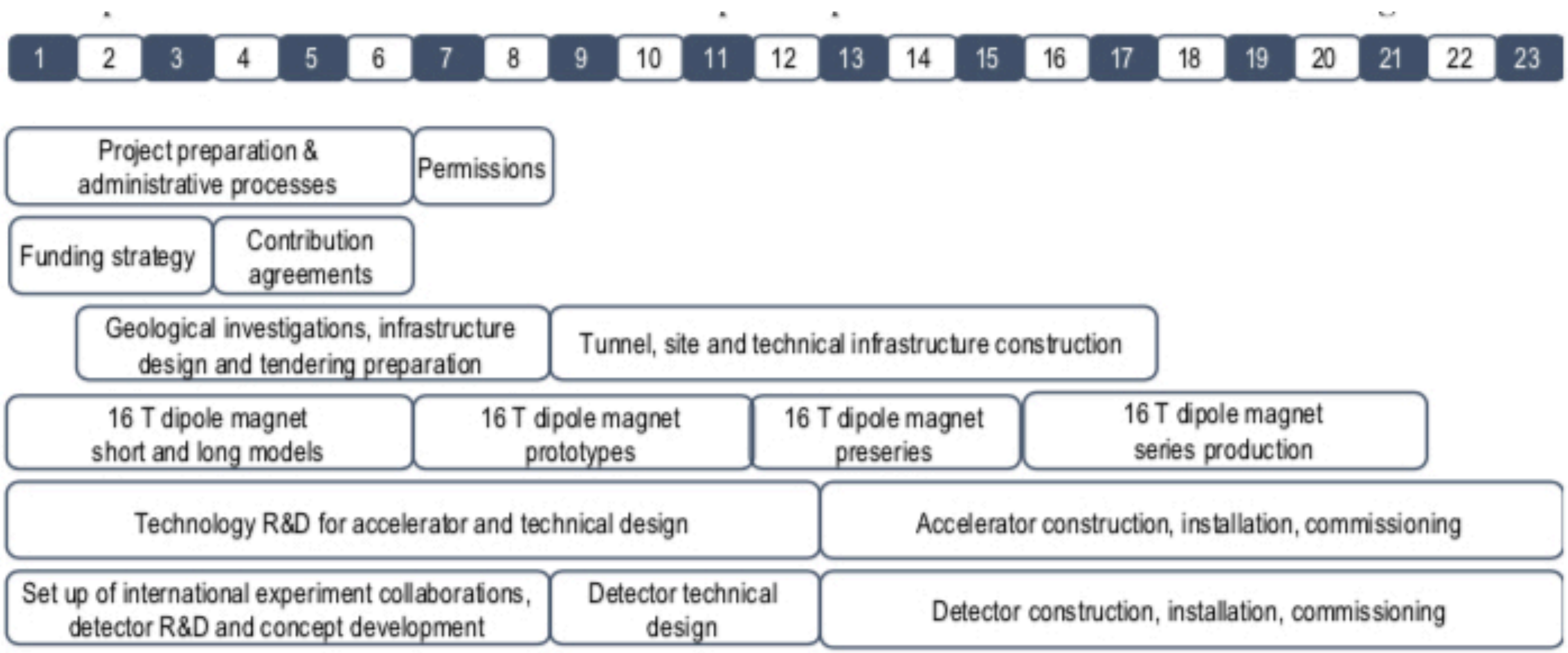


Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

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, 13-14July 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, Dec16-17 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 αs 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

FCC-hh

"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