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Physics at Future Colliders

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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

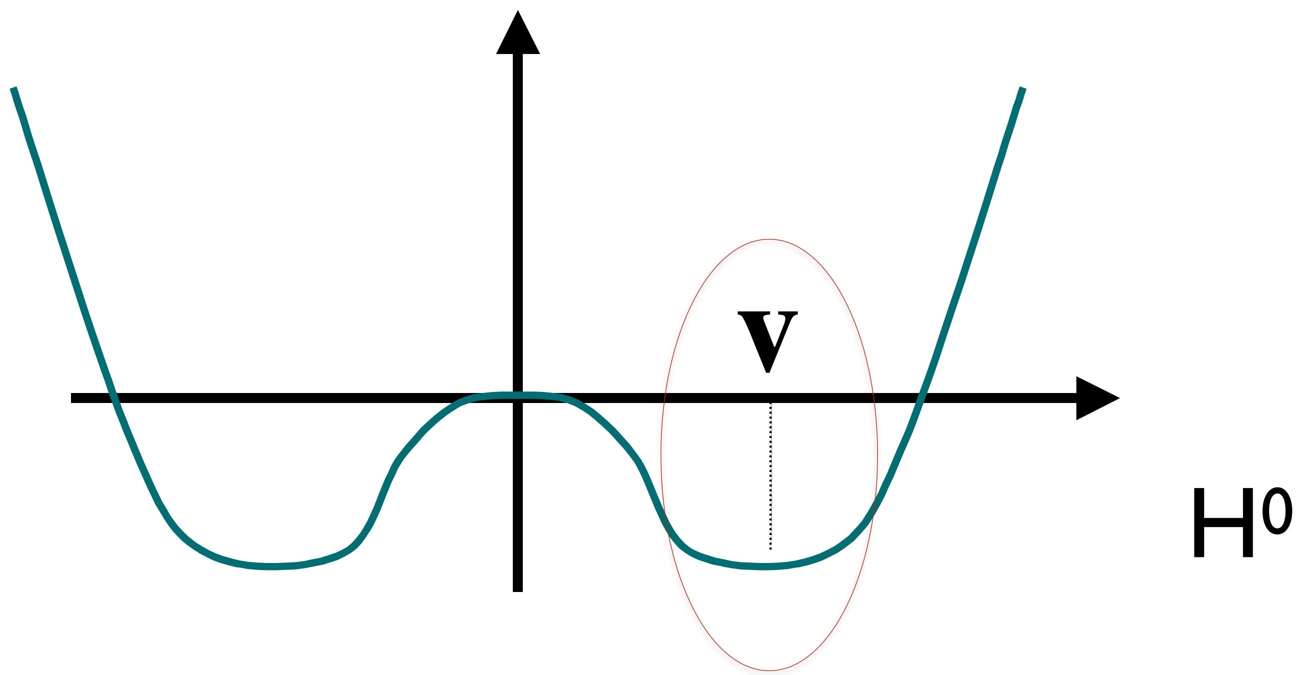
The important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - 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….

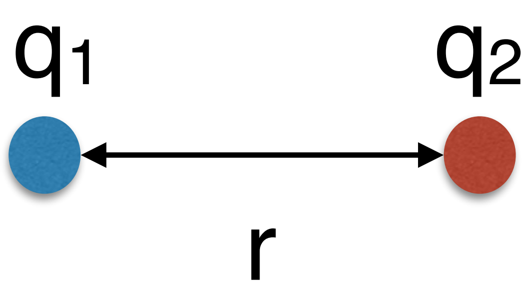


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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

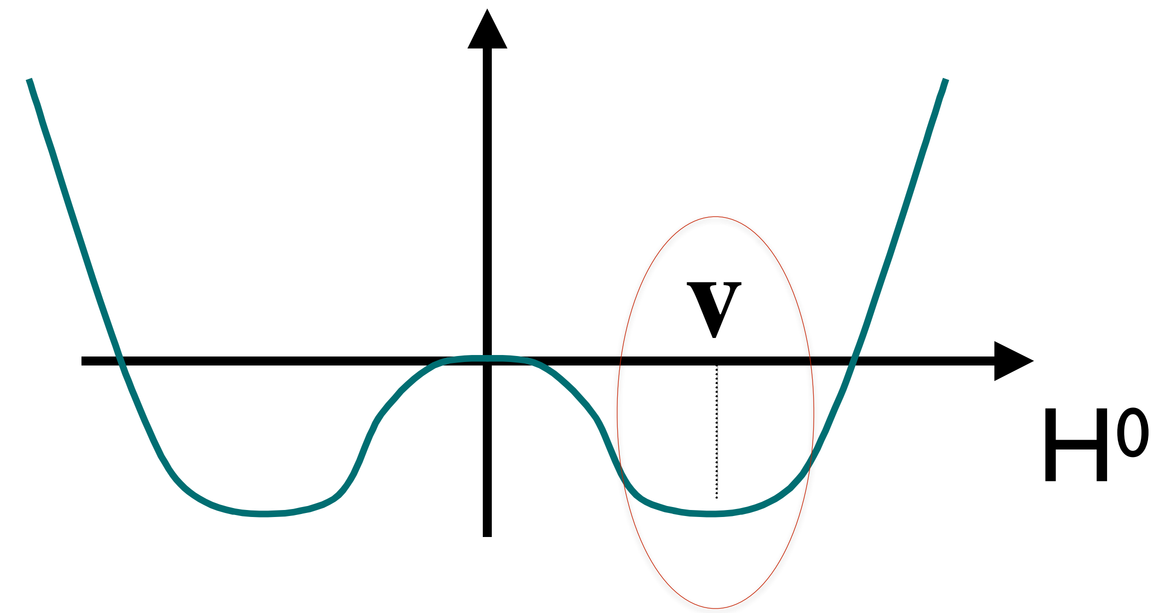


quantized, in units of fixed charge

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

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.

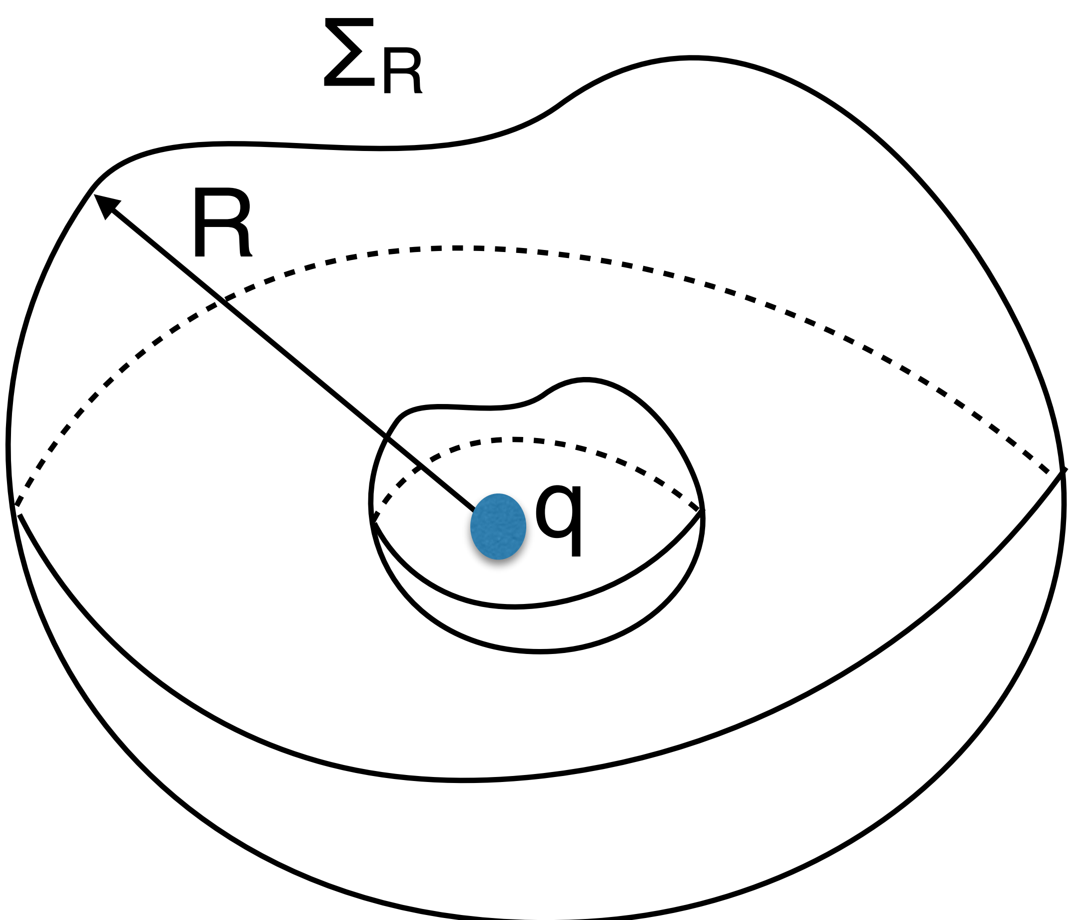
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either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

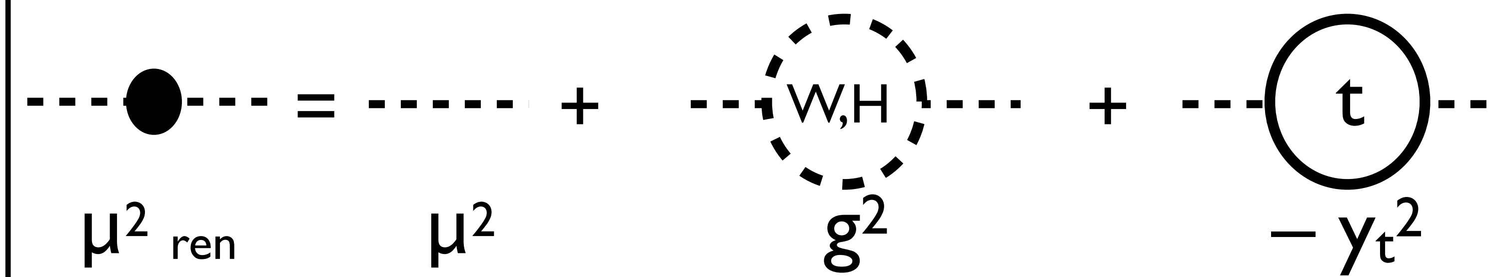
E&M



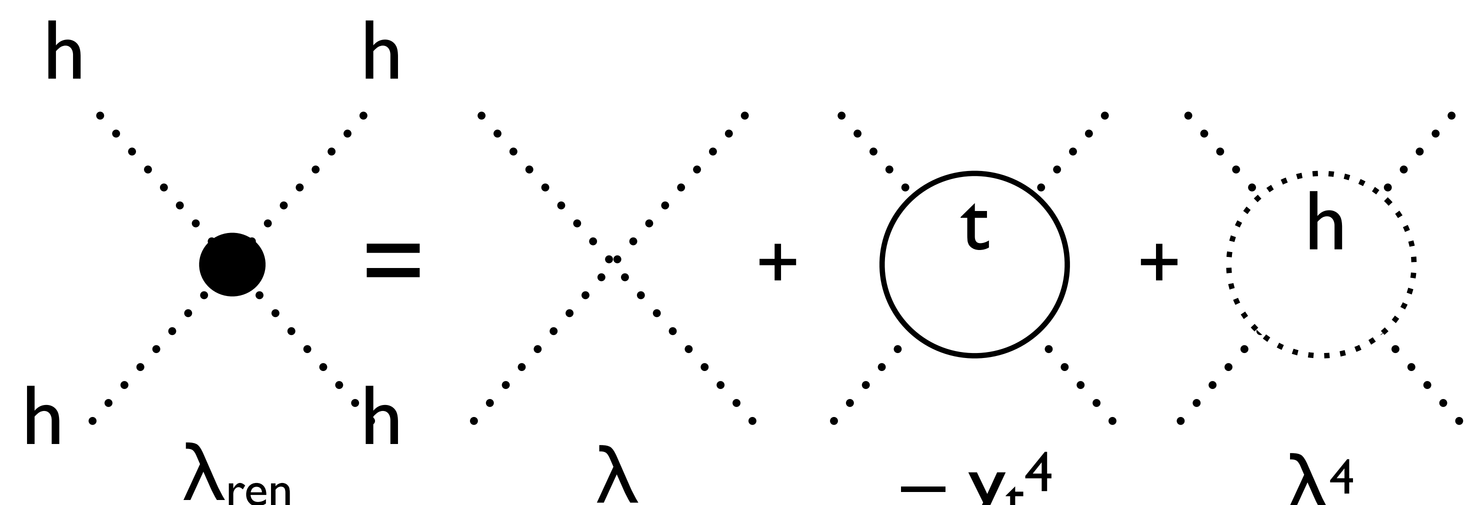
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

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



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



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

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>*

What are we talking about when we're talking future colliders: at CERN…

HiLumi HL-LHC PROJECT

pp @ 14 TeV, 3ab^{-1}

✓Approved 2026-37

CLIC

e^+e^- @ 380 GeV, 1.5 & ~3 TeV

CDR 2012+
update '16

CDR: Conceptual Design Report

FCC hh ee he

CDR (end '18)

100km tunnel

- pp @ 100 TeV
- e^+e^- @ 91, 160, 240, 365 GeV
- $e_{60GeV}\ p_{50TeV}$ @ 3.5 TeV

LHC tunnel: HE-LHC

- pp @ 27 TeV, 15ab^{-1}

… and in the rest of the world:

e^+e^- @ 250, 350, 500 GeV

TDR 2012,
decision postponed to end 2020

TDR: Technical Design Report

CDR (Fall ’18)
decision by 2020?

<u>100km tunnel</u>

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and e_{60GeV} p_{35TeV}

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?
  - …

I will illustrate these points using few examples, taken from the studies of the FCC physics potential

Event rates: examples

FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←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(←t)	τ(←W←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
Lumi (ab^{-1})	3
Years	25
$\delta\Gamma_H/\Gamma_H$ (%)	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5
$\delta g_{HWW}/g_{HWW}$ (%)	3.5
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6
$\delta g_{Htt}/g_{Htt}$ (%)	4.2
BR_{EXO} (%)	SM

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.

=> See also Marumi's talk !

Remarks and key messages

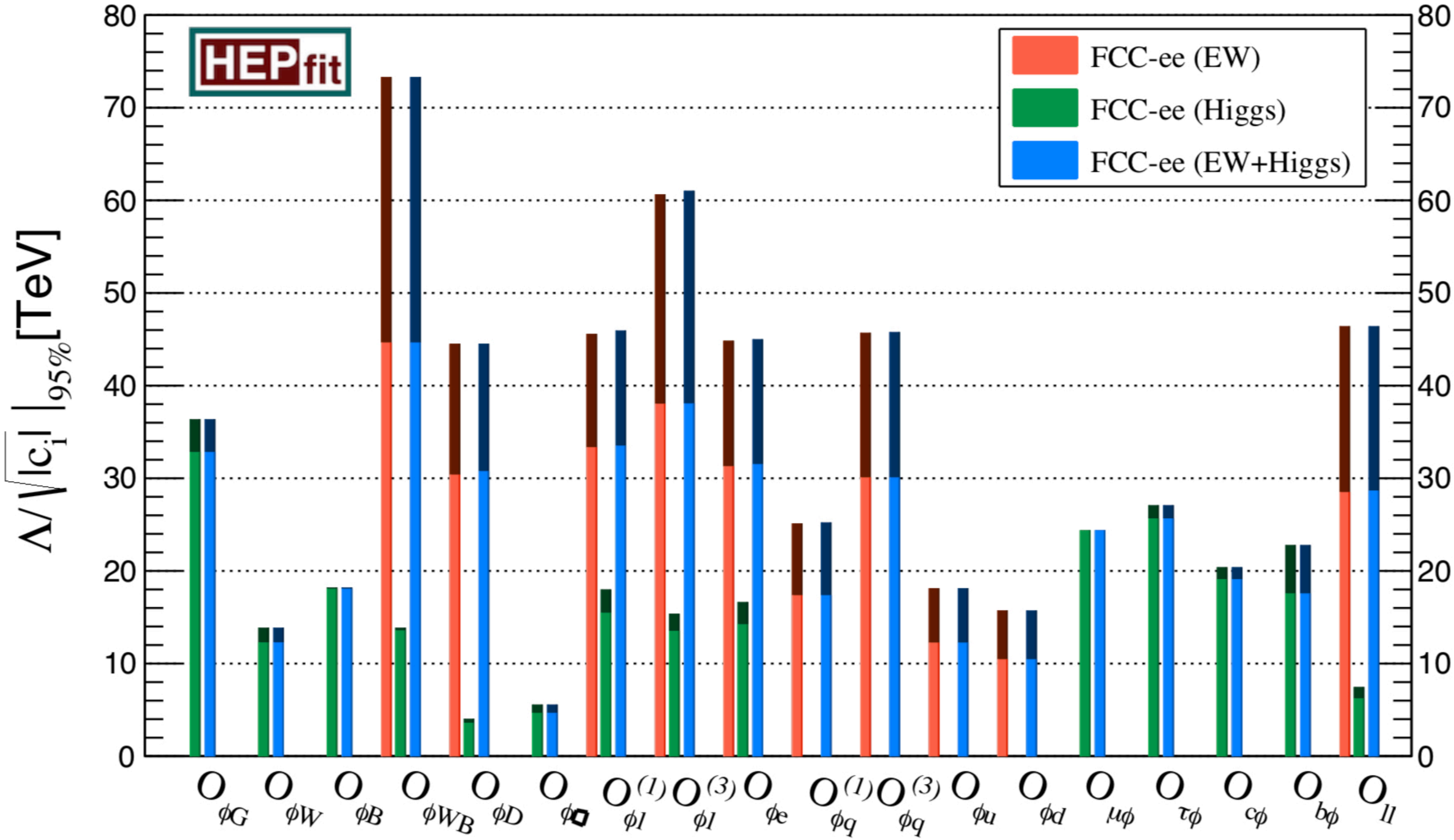
- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - 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 (×10³)	20767±25	0.06	0.2-1.0
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6
R_b (×10⁶)	216290±660	0.3	<60
σ^0_{had} (×10³) (nb)	41541±37	0.1	4
N_ν (×10³)	2991±7	0.005	1
$\sin^2\theta_W^{\mathrm{eff}}$ (×10⁶)	231480±160	3	2-5
$1/\alpha_{\mathrm{QED}}(m_Z)$ (×10³)	128952±14	4	Small
$A_{\mathrm{FB}}^{b,0}$ (×10⁴)	992±16	0.02	1-3
$A_{\mathrm{FB}}^{\mathrm{pol},\tau}$ (×10⁴)	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) (×10⁴)	1170±420	3	Small
N_ν(×10³)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	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

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

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

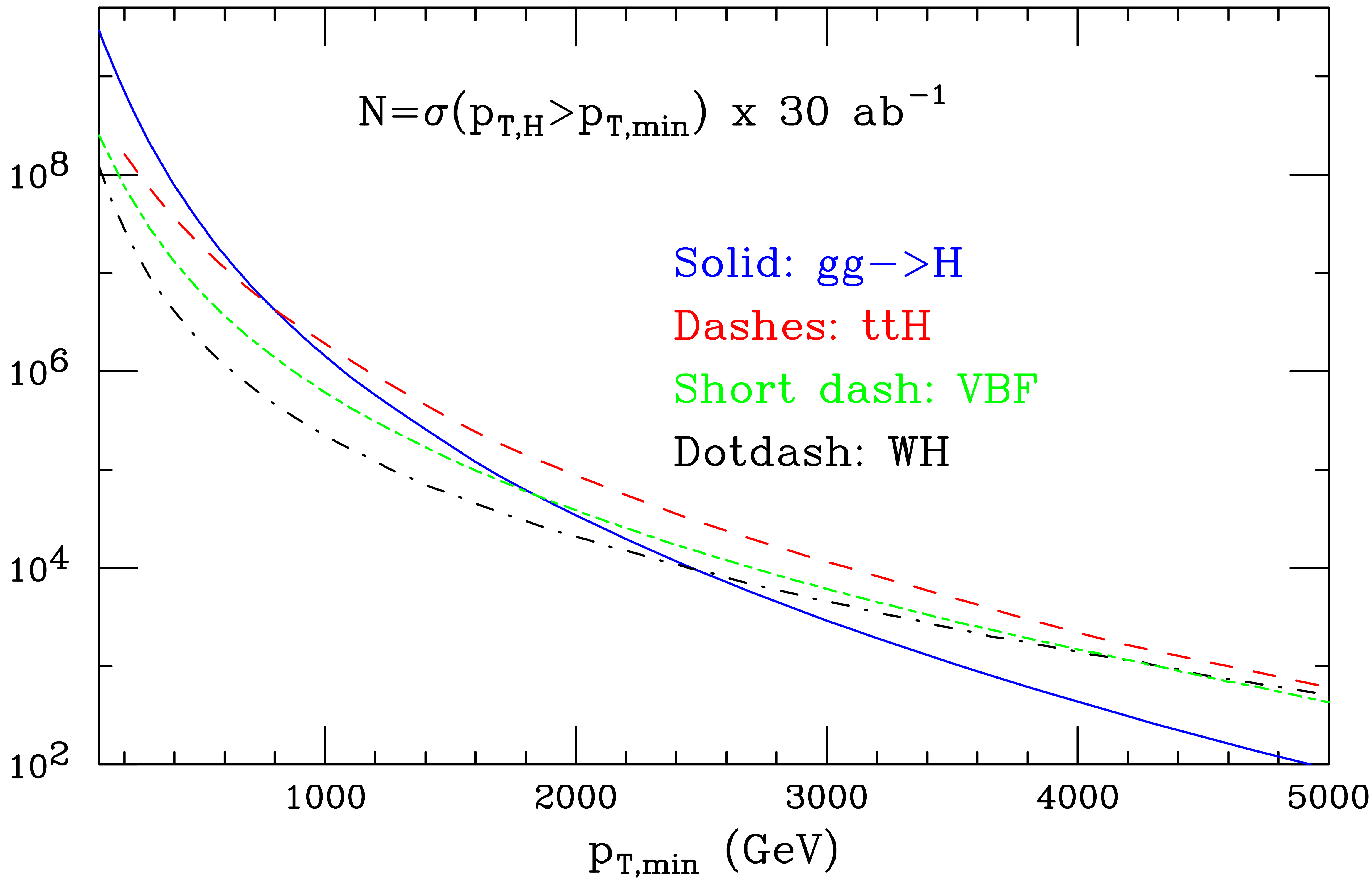
The unique contributions of a *100 TeV pp collider to Higgs physics*

- 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 $Q \sim m_H$

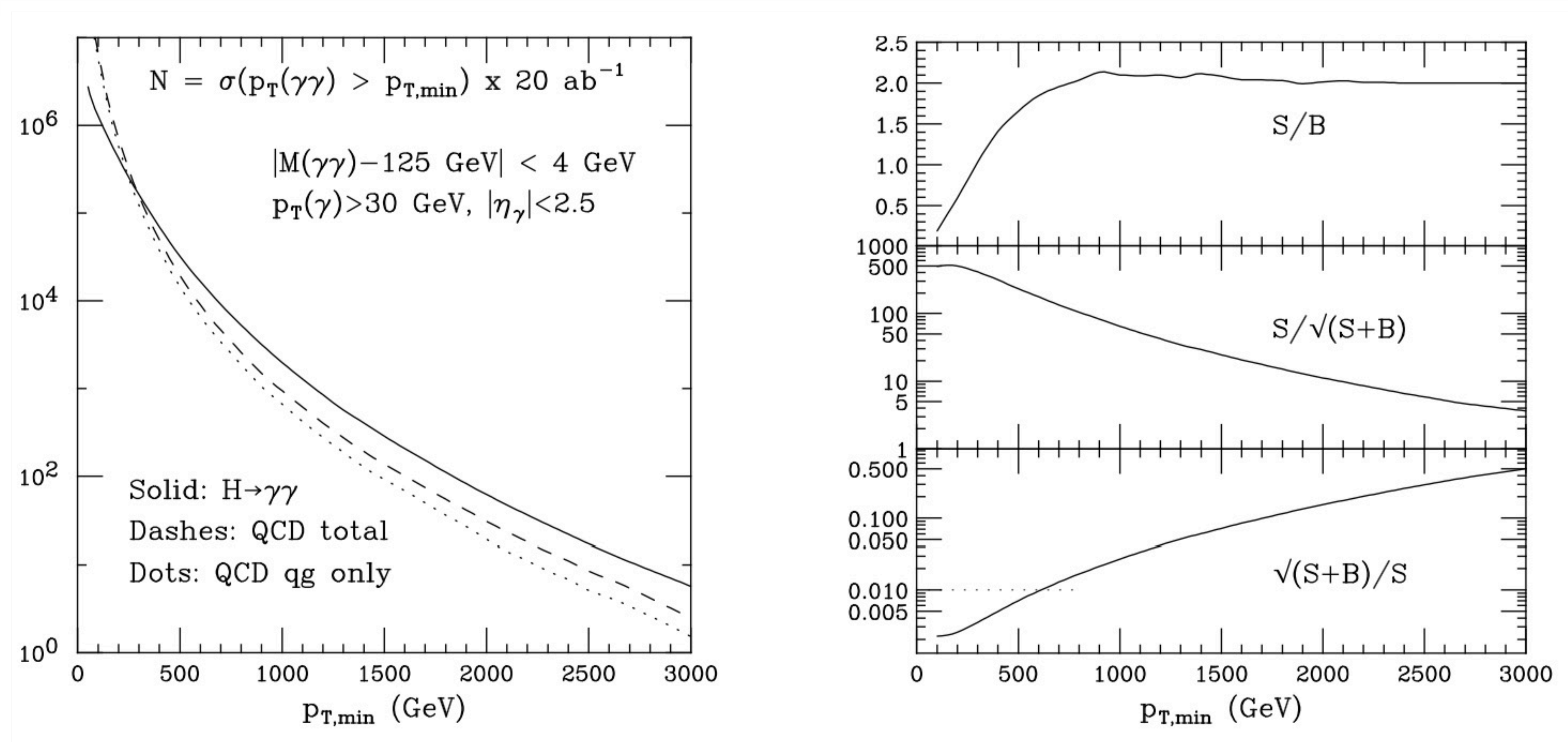
- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition
    - …

H at large p_T



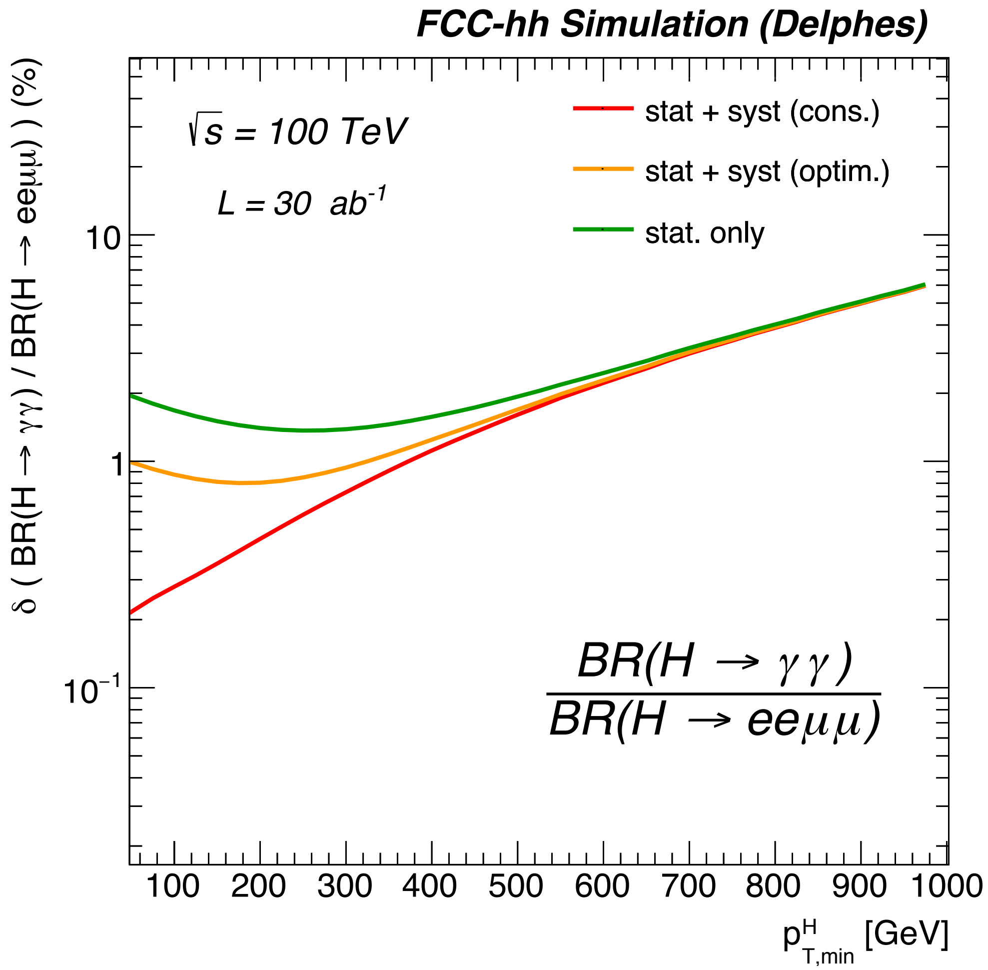
- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

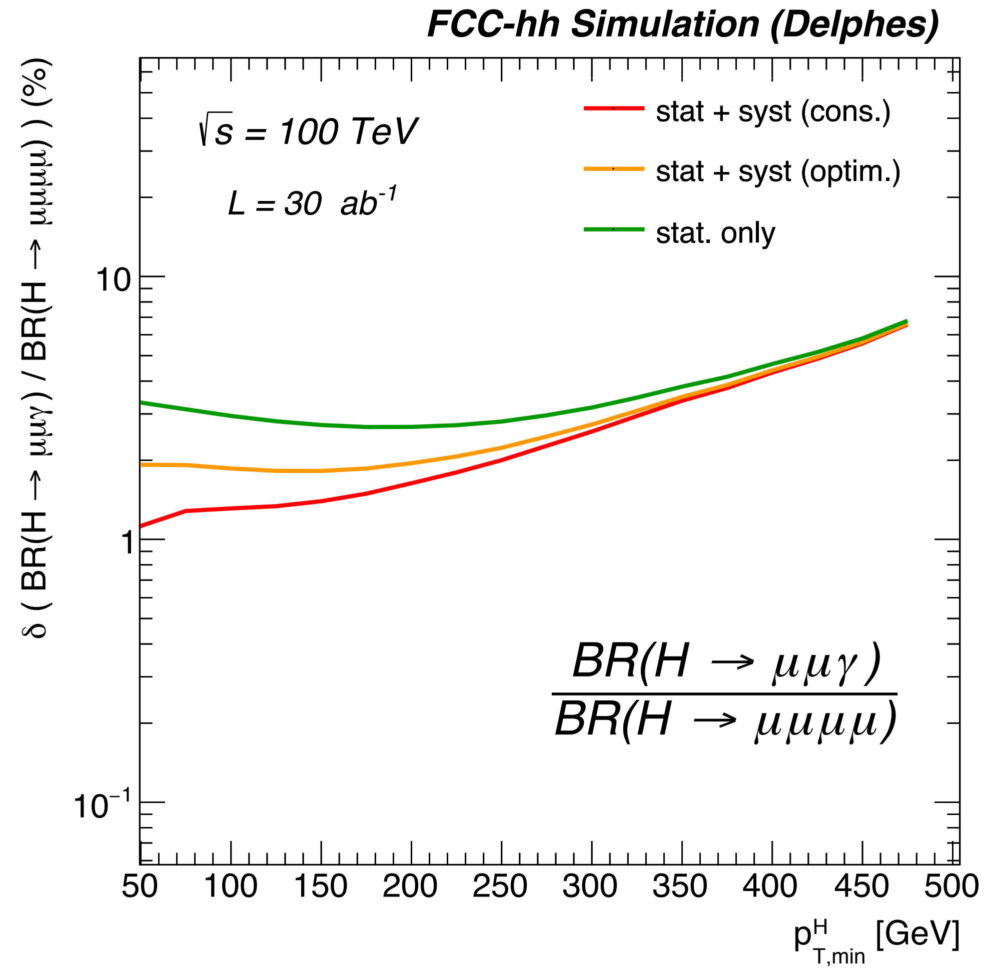
gg→H→γγ at large p_T

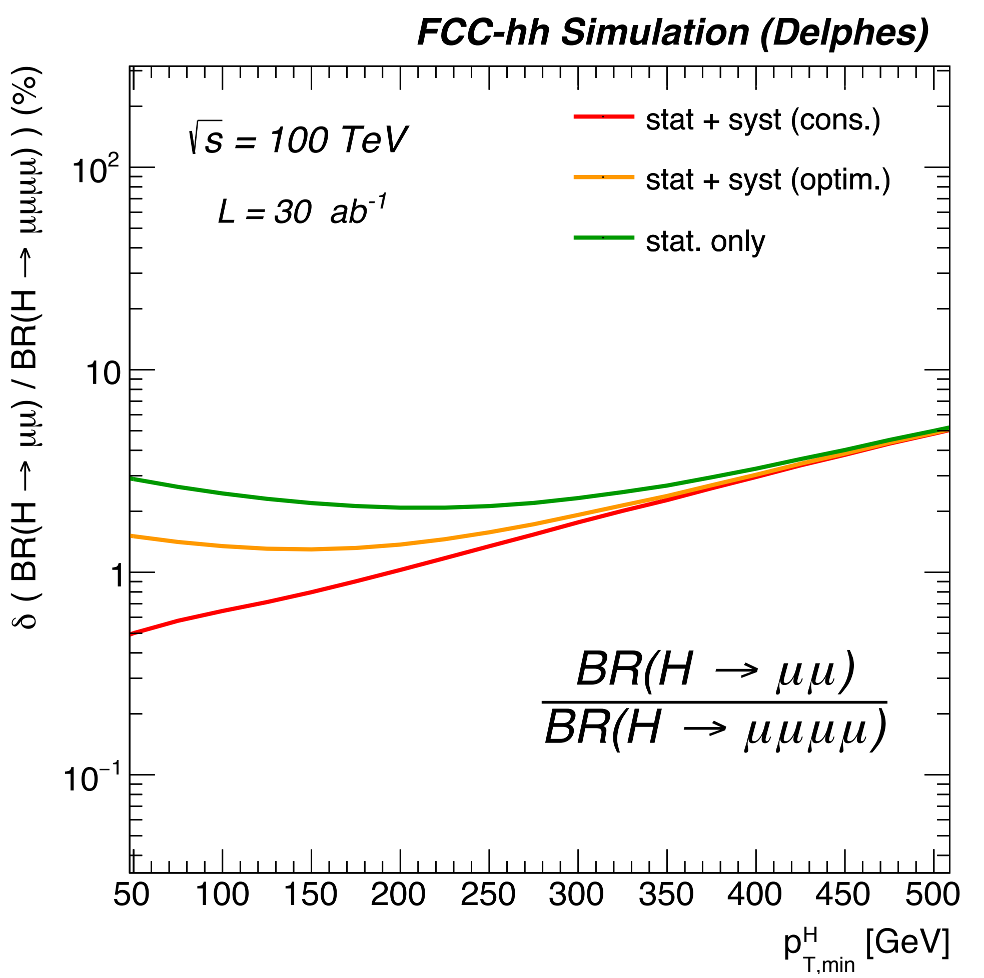


- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

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







Normalize to BR(4l) from FCC-ee
=>
absolute sub-% for couplings

M.Selvaggi

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

Higgs self-coupling, gg→HH

	From the detector performance studies:				Pheno-level studies:
	bbγγ	bbZZ[→4l]	bbWW[→2jlv]	4b+j	2b2τ+j
$\delta\kappa_\lambda$ (%)	6.5	14	40	30	8

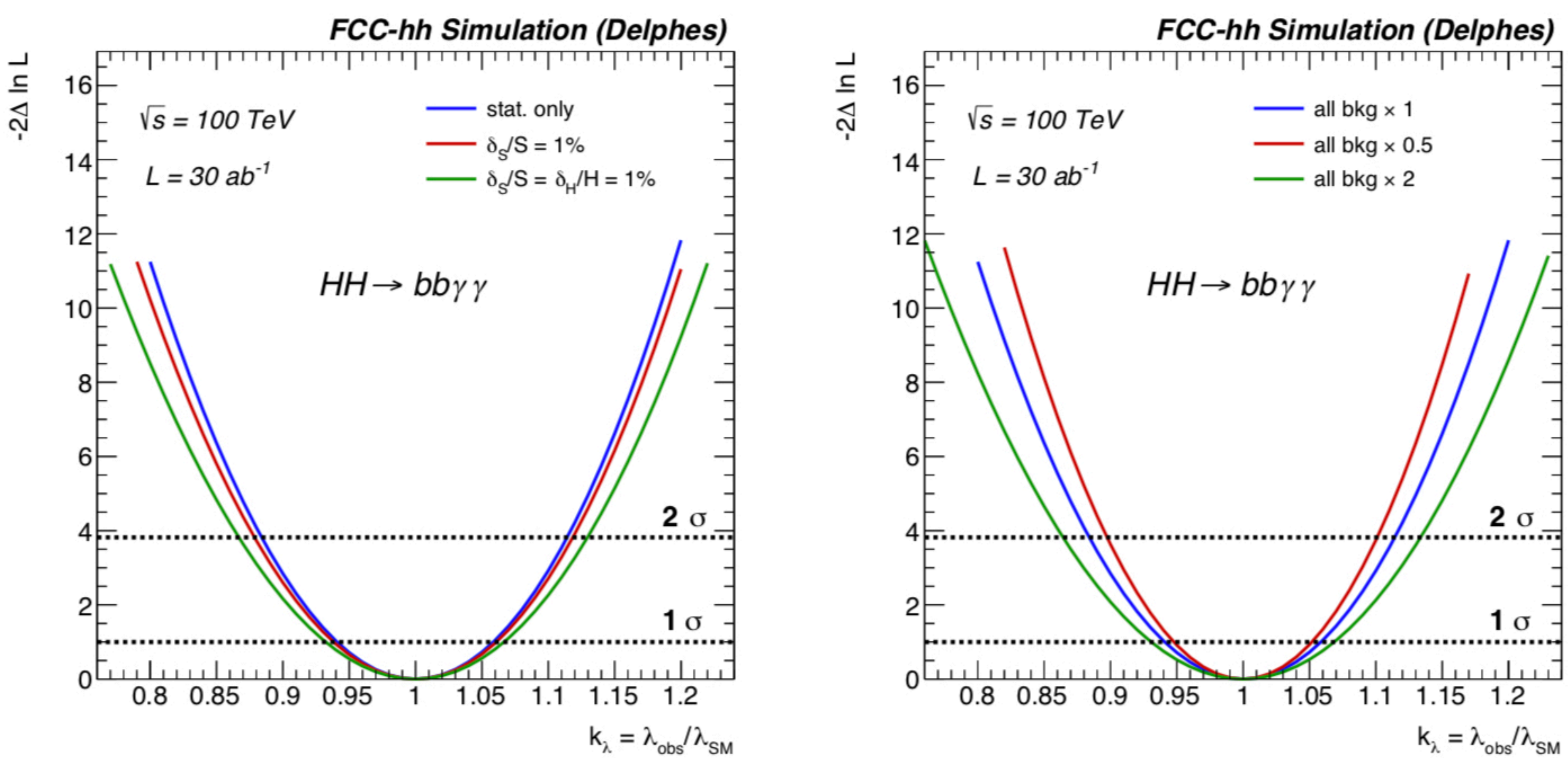
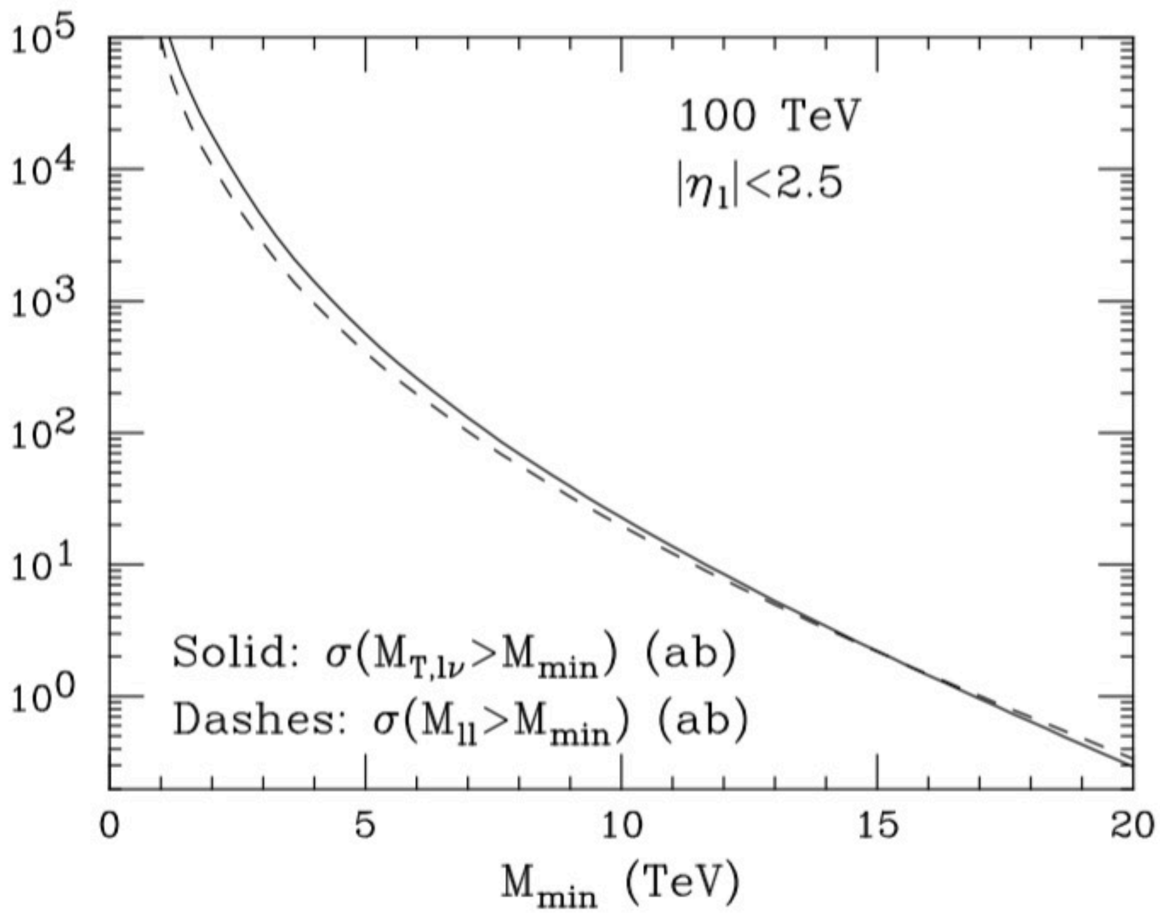


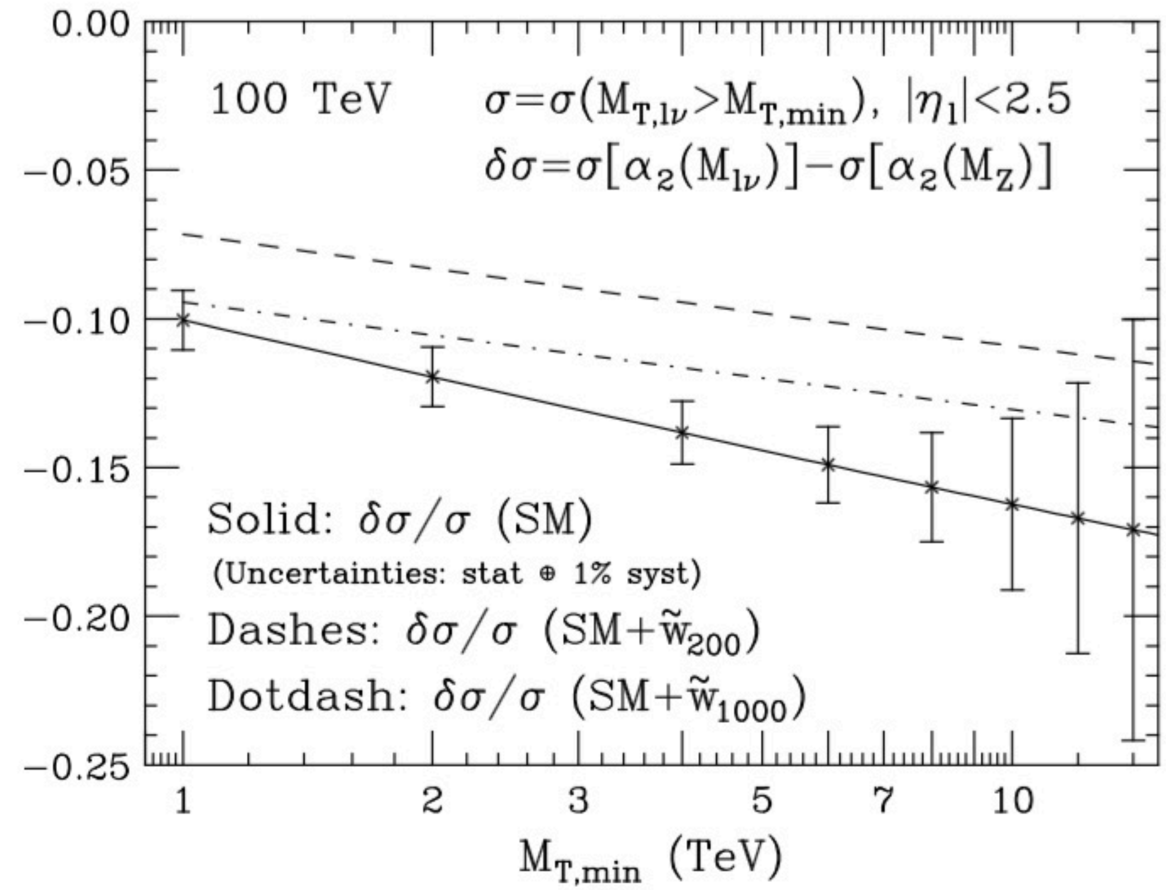
Figure 10.4: Expected precision on the Higgs self-coupling modifier κ_λ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively $\times 1$, $\times 2$, $\times 0.5$ background yields (right).)

High-Q^2 probes of EW dynamics & EWSB

Example: high mass DY

α_W running and sensitivity to new EW particles





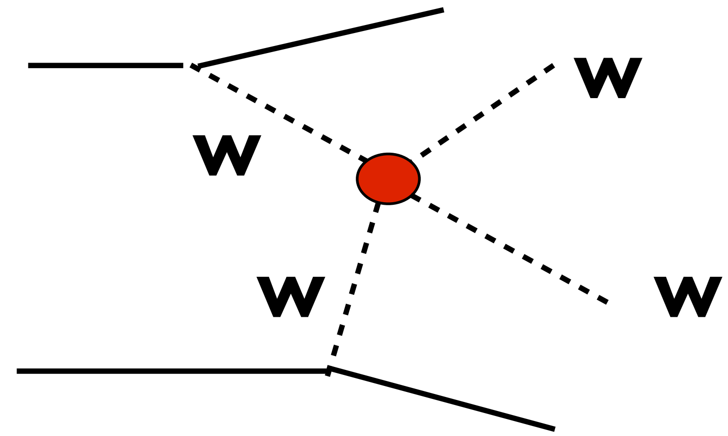
Constraints on Higher-dim op's

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

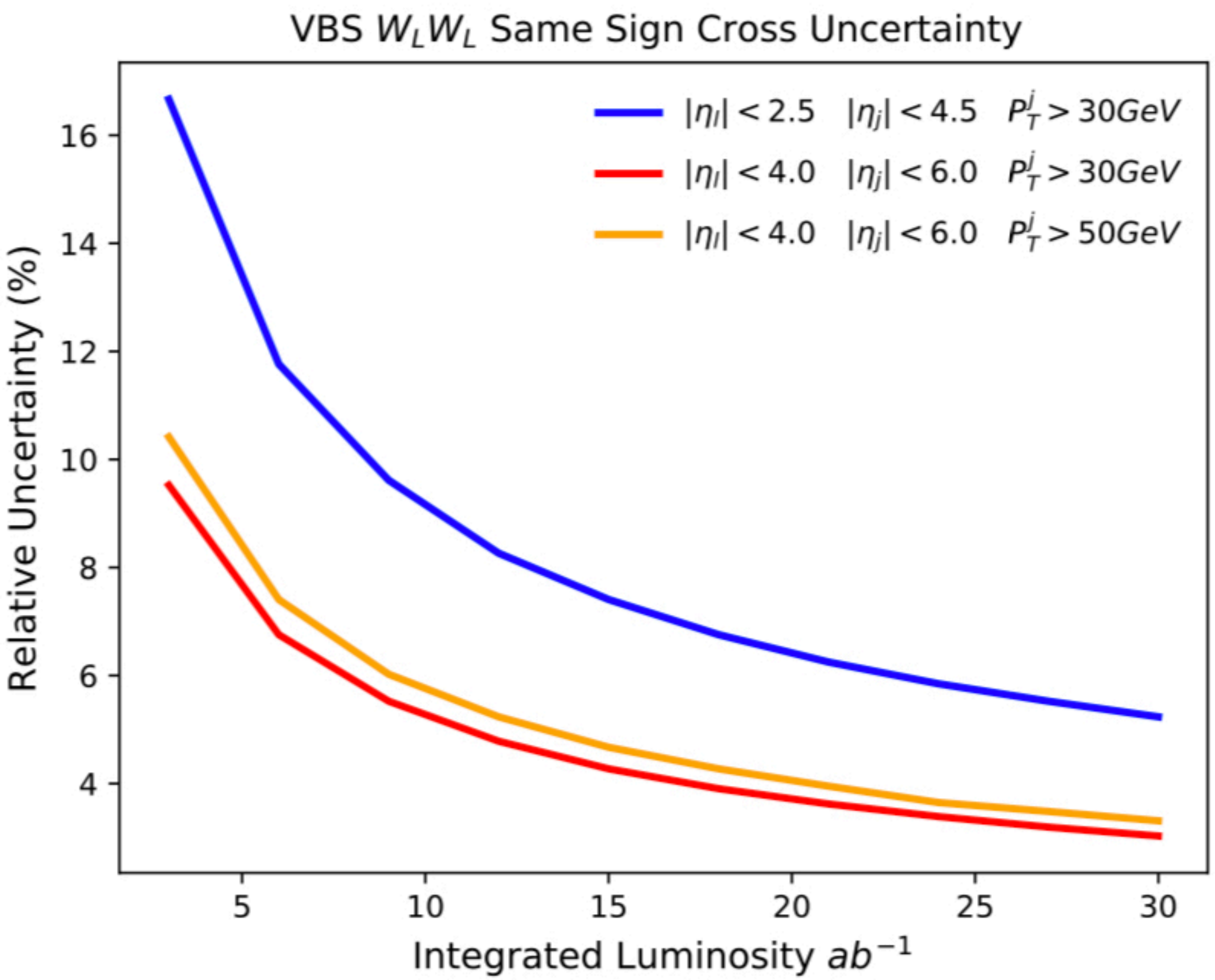
		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
	luminosity	$2\times10^7\,Z$	$19.7\,\text{fb}^{-1}$	$20.3\,\text{fb}^{-1}$	$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$10^{12}\,Z$
NC	W $\times10^4$	$[-19,3]$	$[-3,15]$	$[-5,22]$	±1.5	±0.8	±0.04	±1.2
	Y $\times10^4$	$[-17,4]$	$[-4,24]$	$[-7,41]$	±2.3	±1.2	±0.06	±1.5
CC	W $\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—

$W / 4m_W^2 \;<\; 1 / (100\text{ TeV})^2$

$W_L W_L$ scattering



large m_{WW}



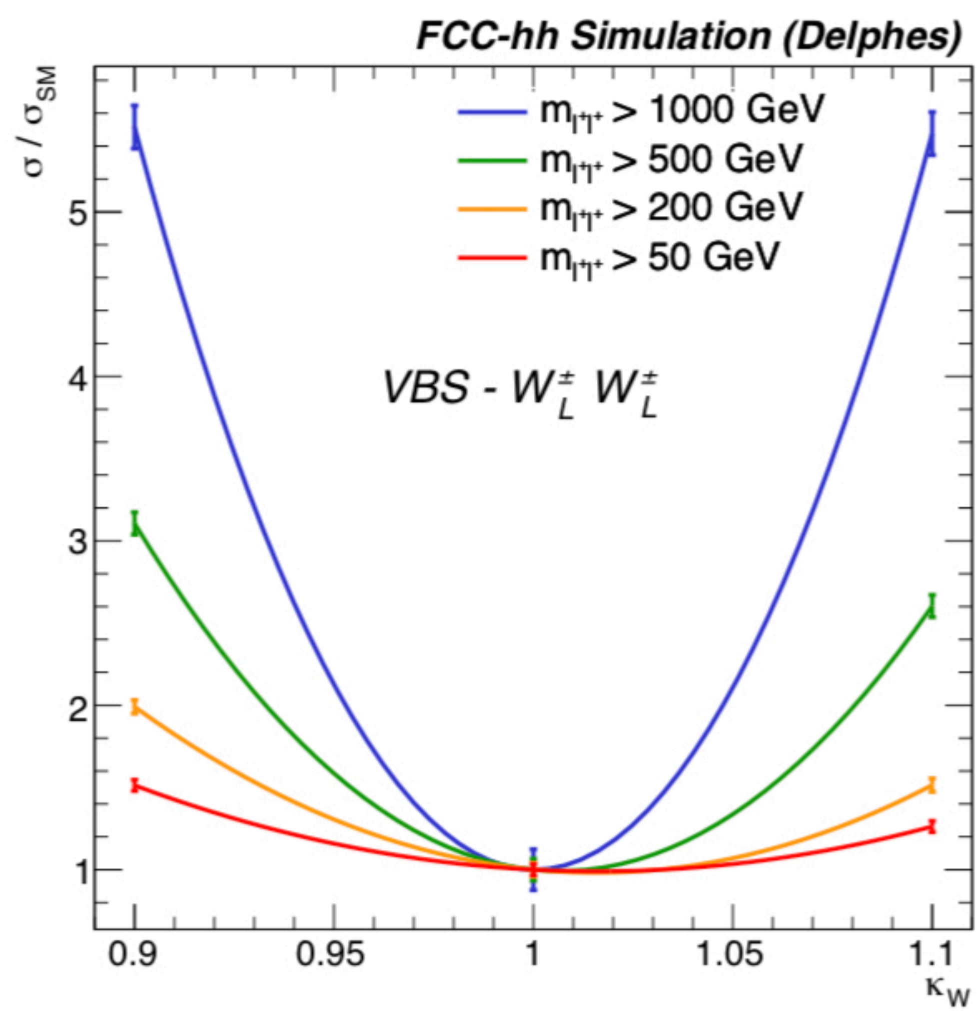
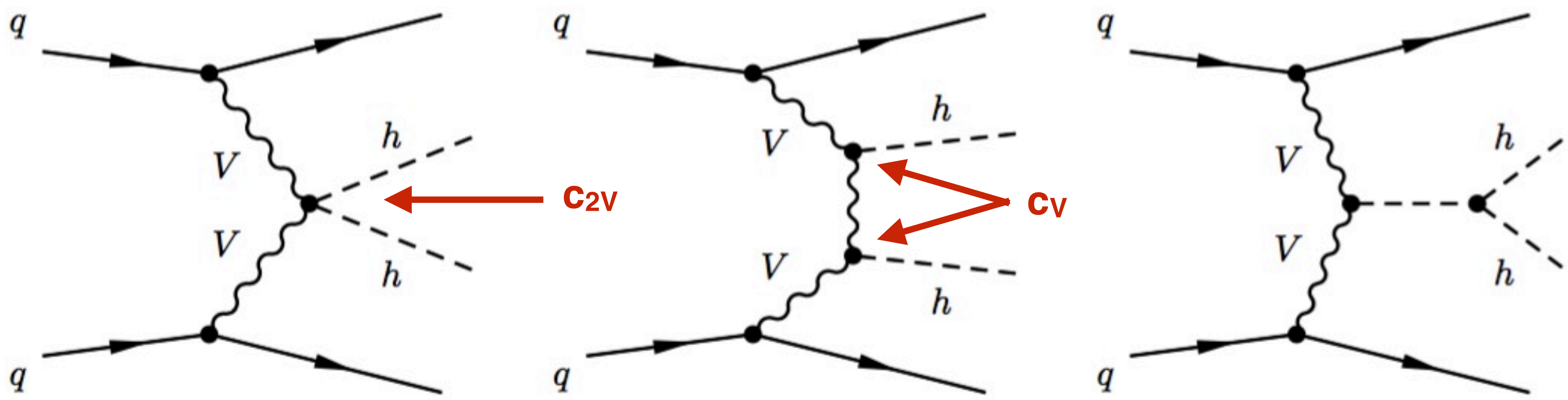


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

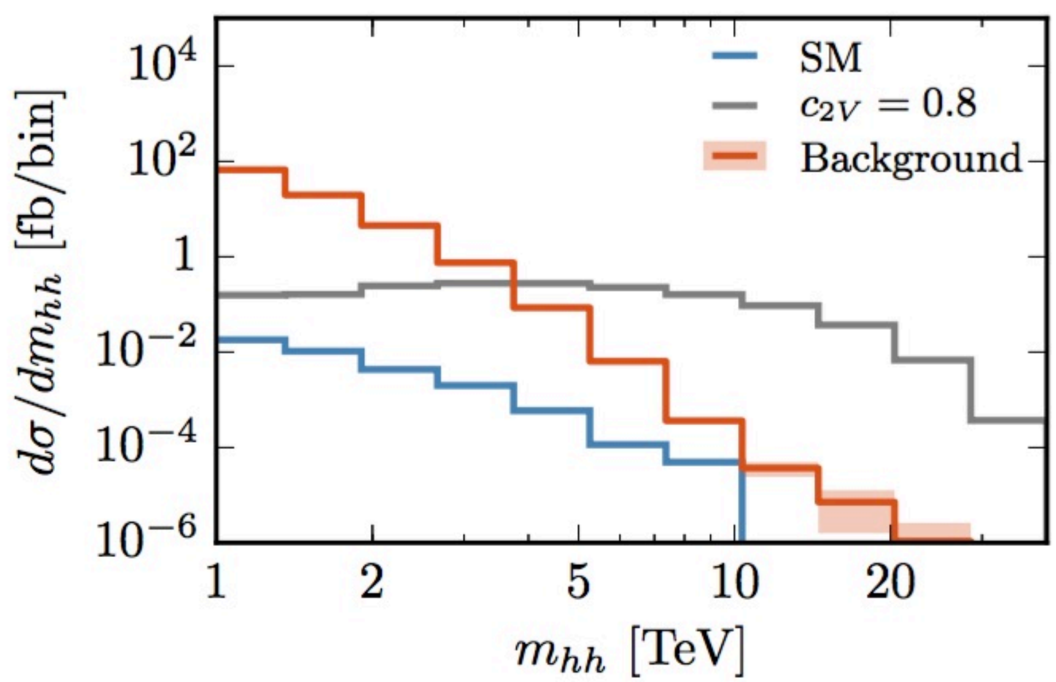
$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

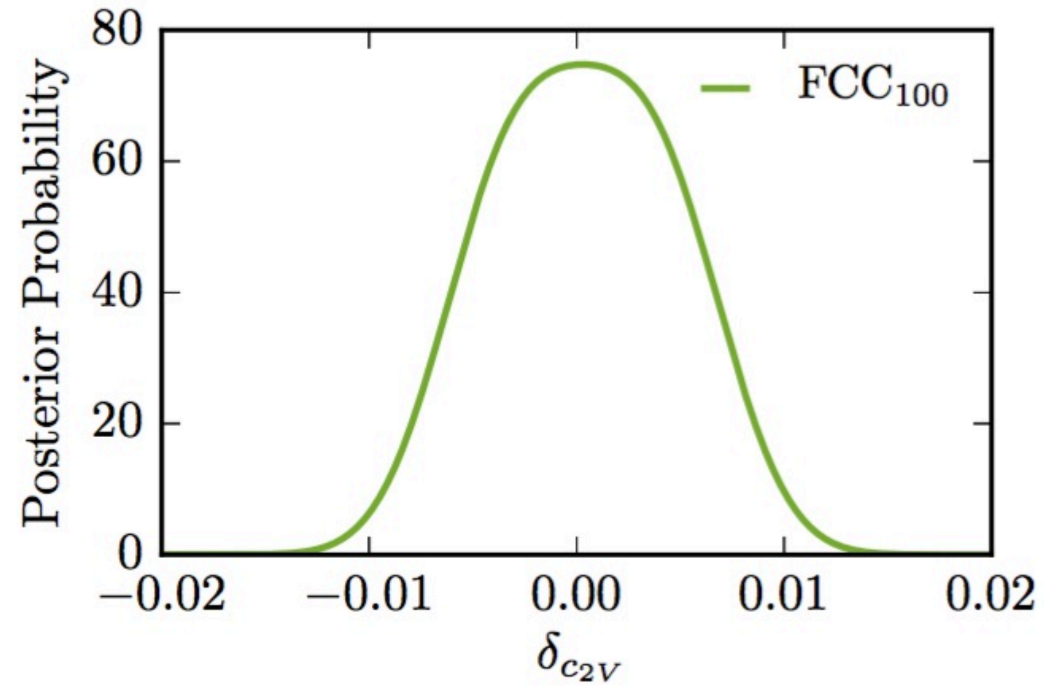
Example: high mass VV → HH

$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)\,.$$



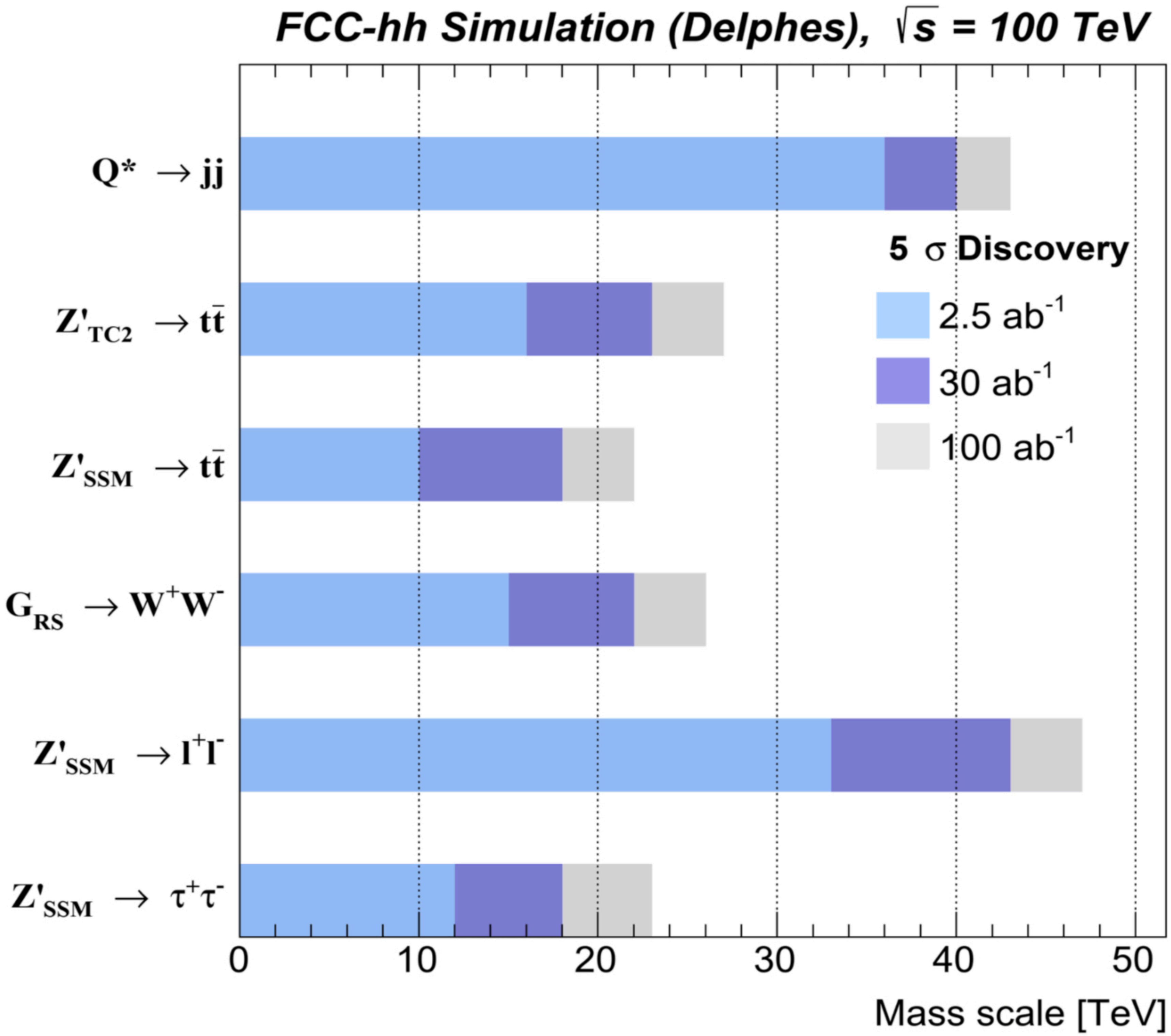
$c_{2V} = c_V^2$ in the SM





Direct discovery reach:
the power of 100 TeV

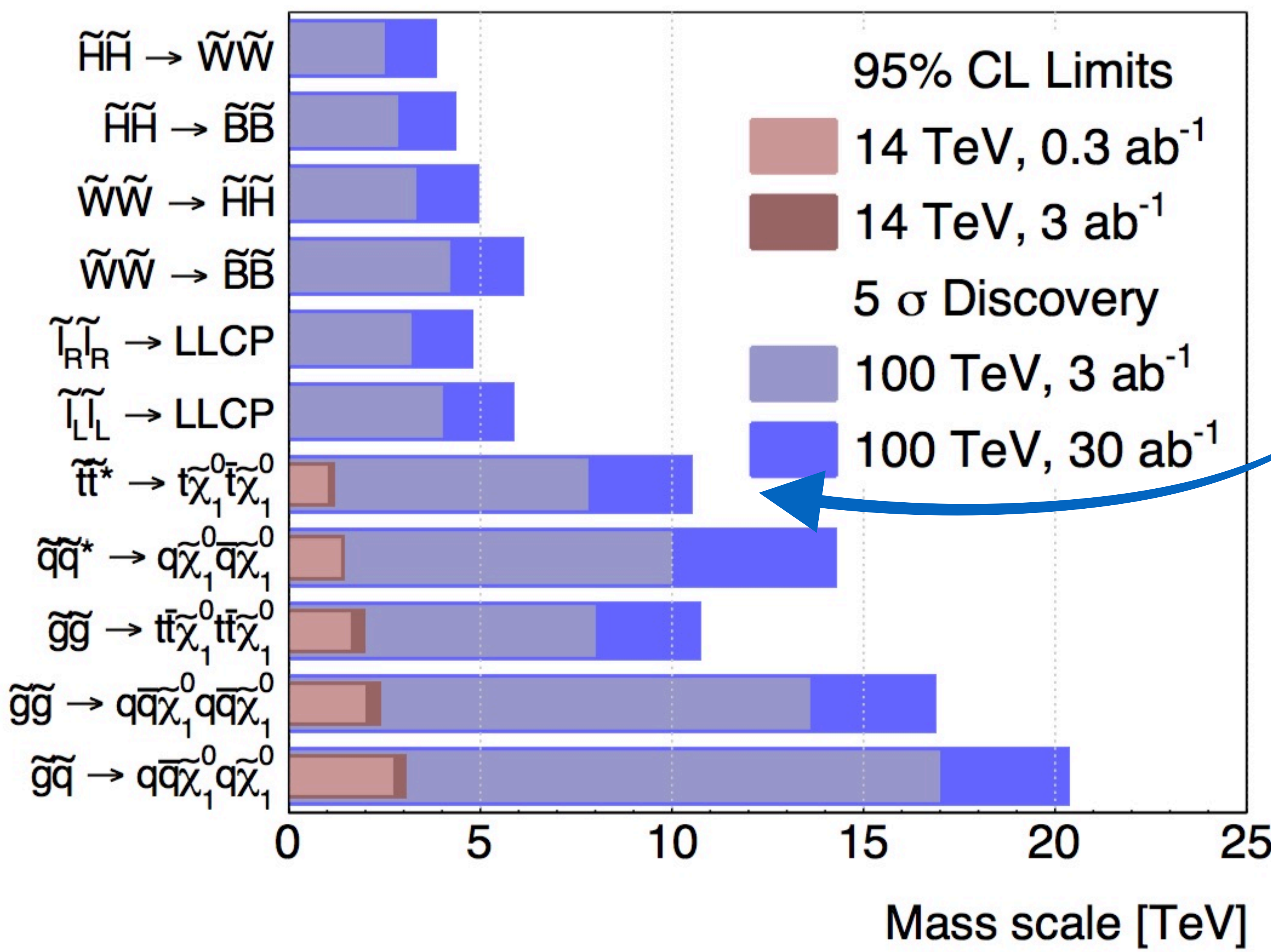
s-channel resonances



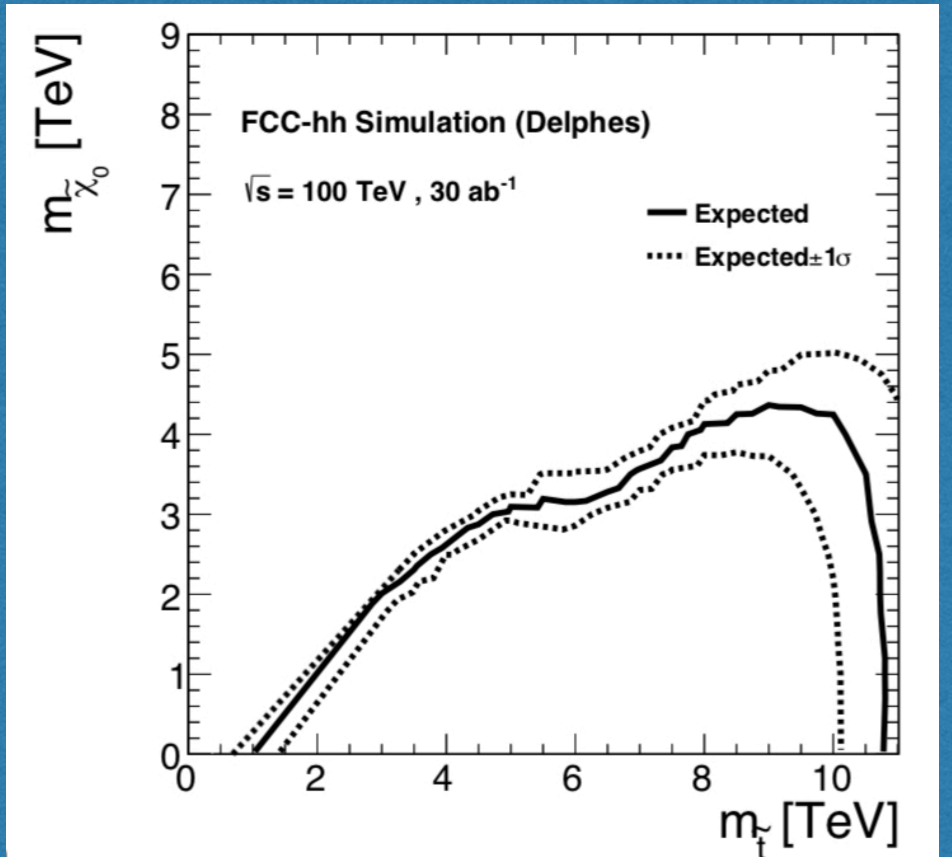
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies

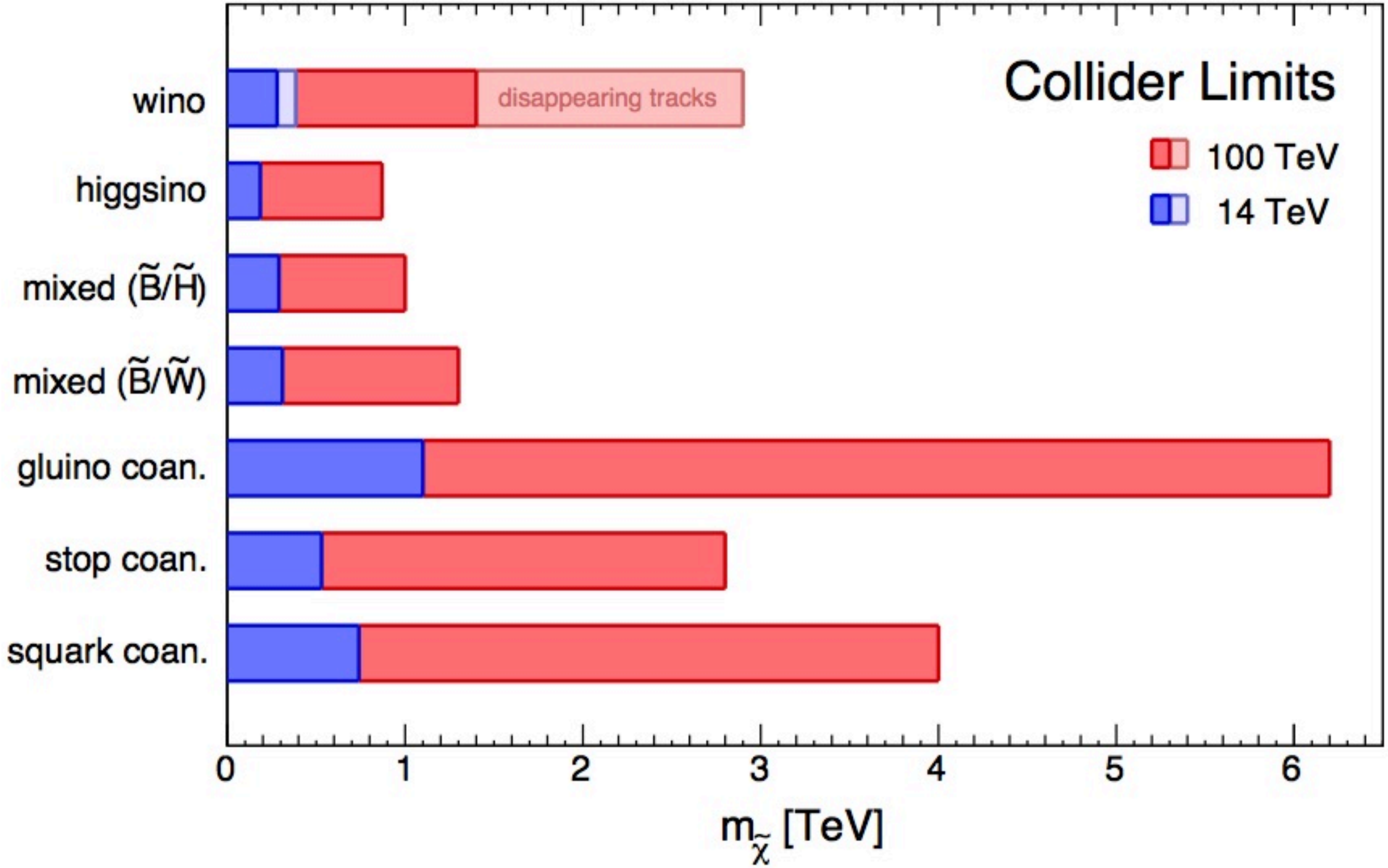


New detector performance studies



DM reach at 100 TeV

Early phenomenology studies

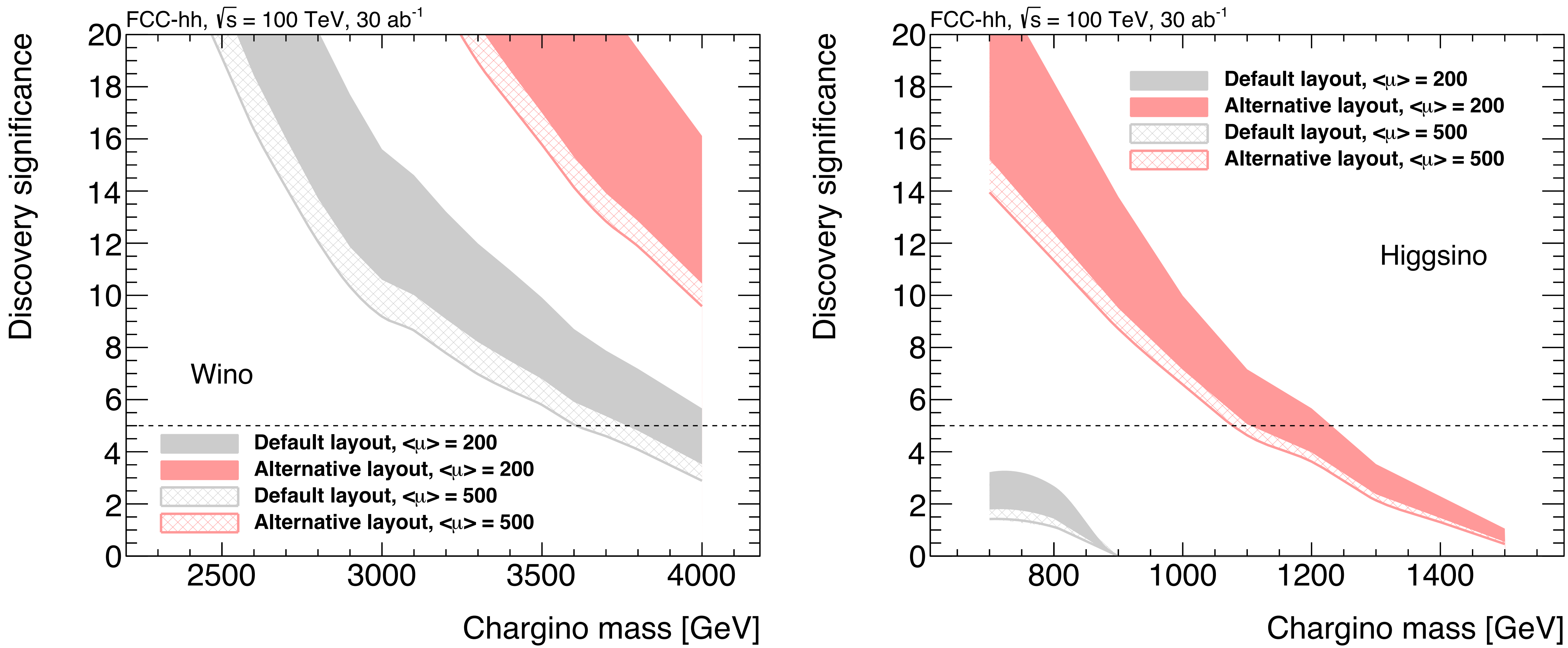


K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

(at ~full pileup)



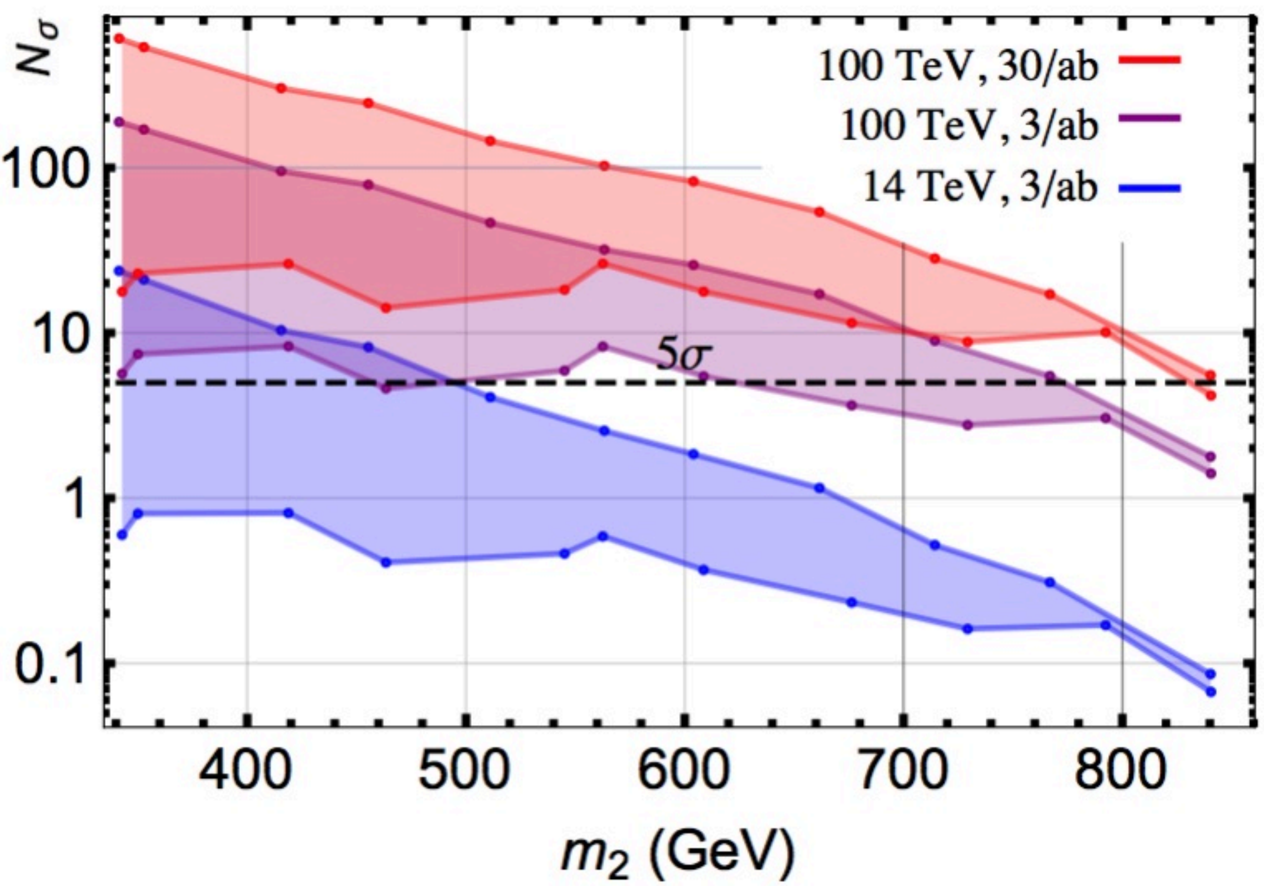
=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

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

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

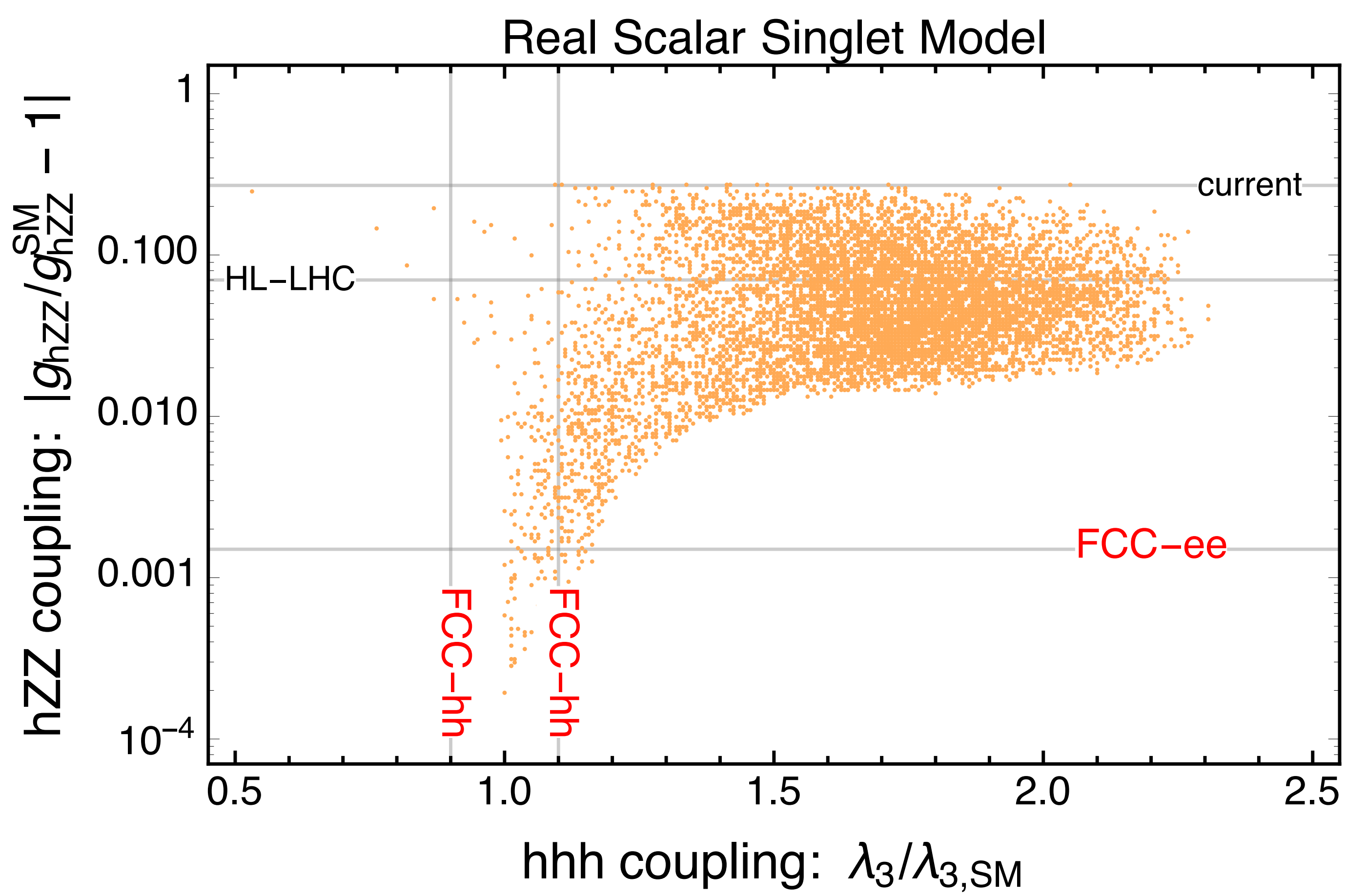
Direct detection of extra Higgs states at FCC-hh



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

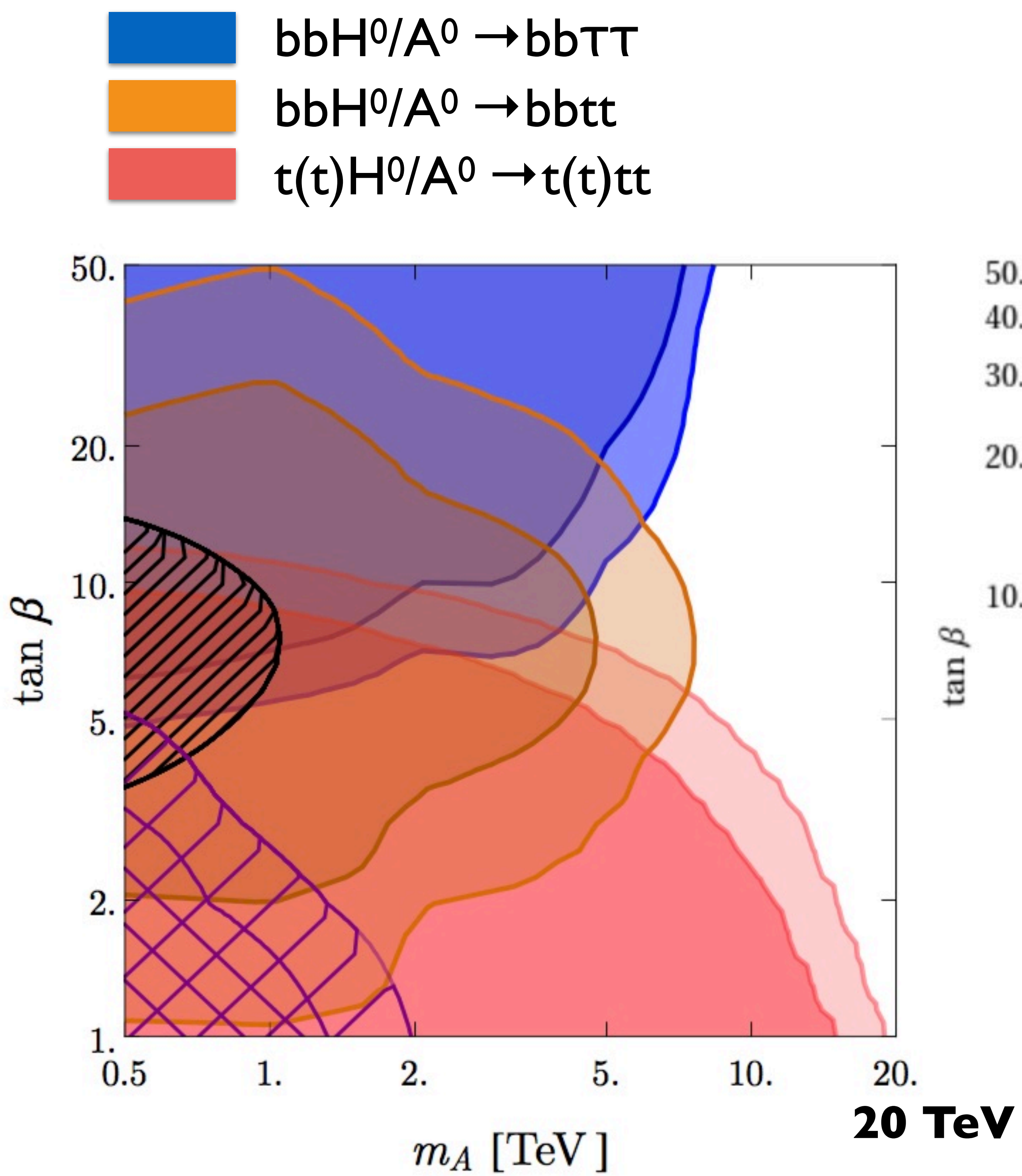
$(h_2 \sim S, \quad h_1 \sim H)$

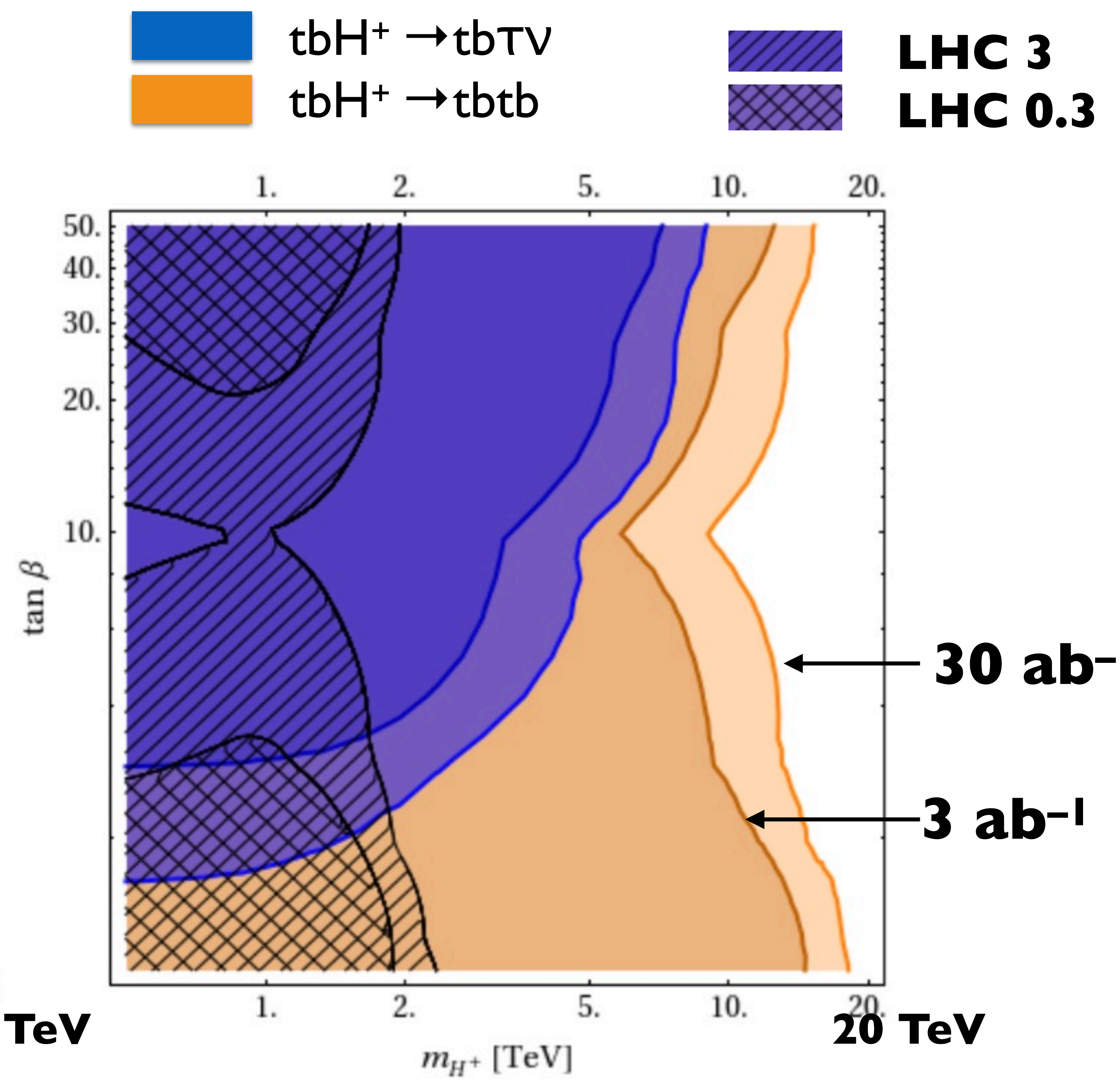
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



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

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

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

backup material

Additional material: recent reports on future projects

- **ILC:** Physics Case for the 250 GeV Stage, K. Fujii et al, arxiv:1710.07621
- **CLIC:** Potential for New Physics, J. de Blas et al,, arxiv:1812.02093
- **HL/HE-LHC** Physics Workshop reports
  - P. Azzi, et al, Standard Model Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-03, CERN, Geneva, 2018. https://cds.cern.ch/record/2650160.
  - M. Cepeda, et al, Higgs Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.
  - X. Cid-Vidal, et al, Beyond the Standard Model Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-05, CERN, Geneva, 2018. https://cds.cern.ch/record/2650173.
  - A. Cerri, et al, Flavour Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-06, CERN, Geneva, 2018. https://cds.cern.ch/record/2650175.
  - Z. Citron,et al, Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams, CERN-LPCC-2018-07, CERN, Geneva, 2018. arXiv:1812.06772 [hep-ph]. https://cds.cern.ch/record/2650176.
- **FCC CDR**:
  - Vol.1: Physics Opportunities (CERN-ACC-2018-0056) http://cern.ch/go/Nqx7
  - Vol.2: The Lepton Machine (CERN-ACC-2018-0057) http://cern.ch/go/7DH9
  - Vol.3: The Hadron Machine (CERN-ACC-2018-0058), http://cern.ch/go/Xrg6
  - Vol.4: High-Energy LHC (CERN-ACC-2018-0059) http://cern.ch/go/S9Gq
- **"Physics at 100 TeV"**, CERN Yellow Report: https://arxiv.org/abs/1710.06353
- **CEPC CDR**: Physics and Detectors

Additional material:

FCC timeline and cost

FCC-ee + FCC-hh, project timeline

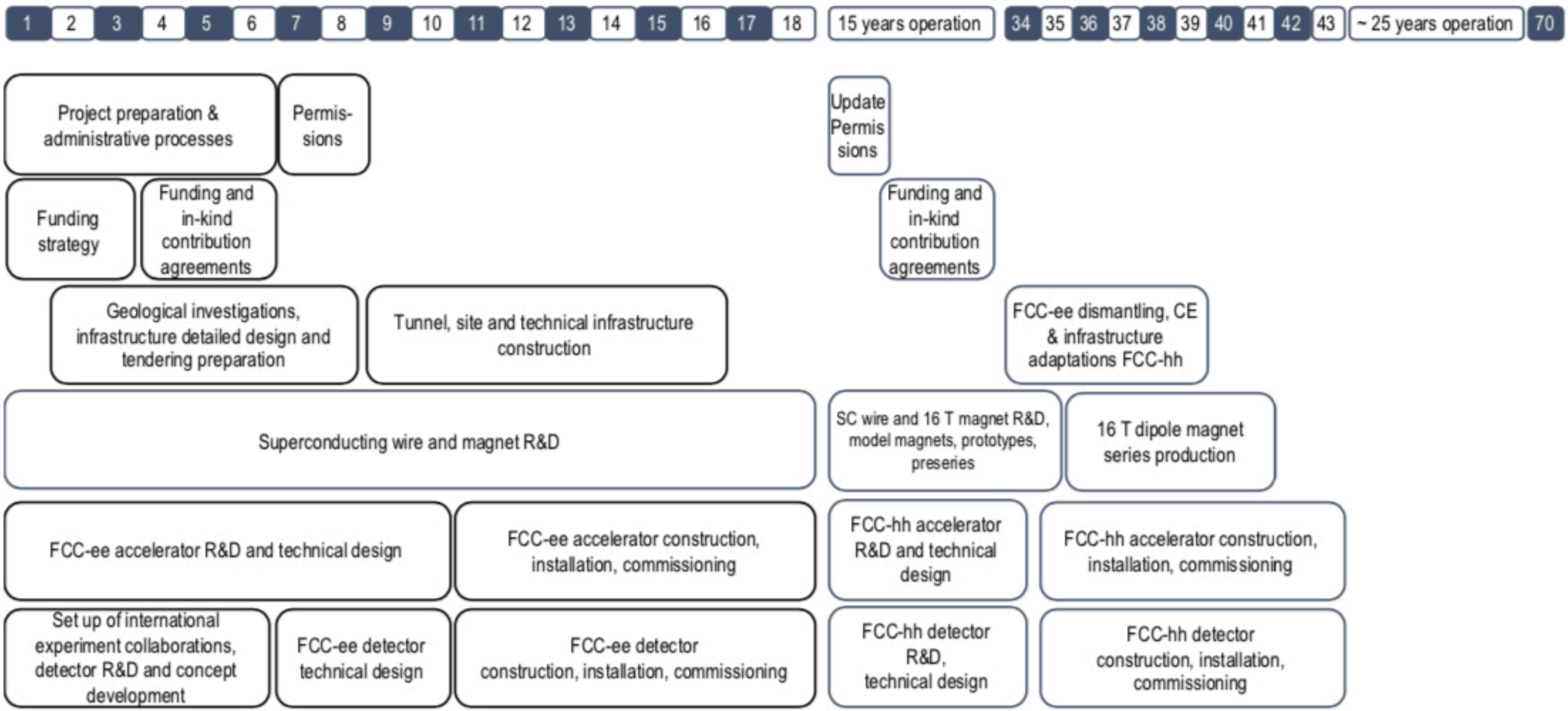
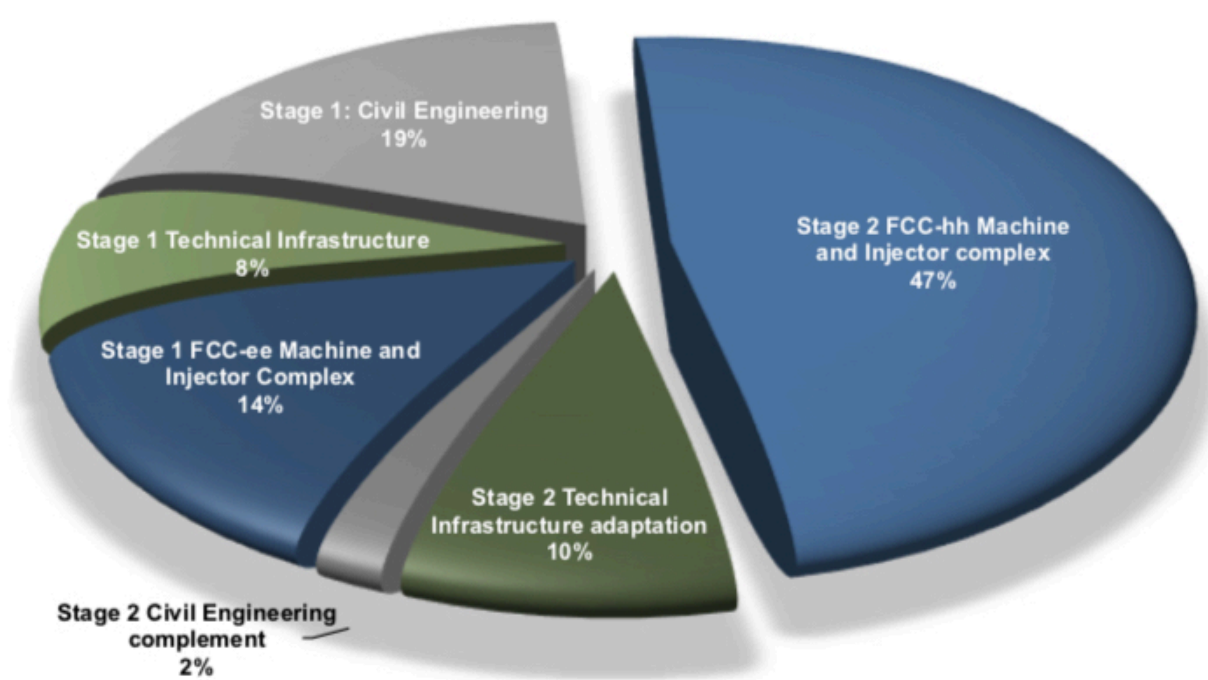
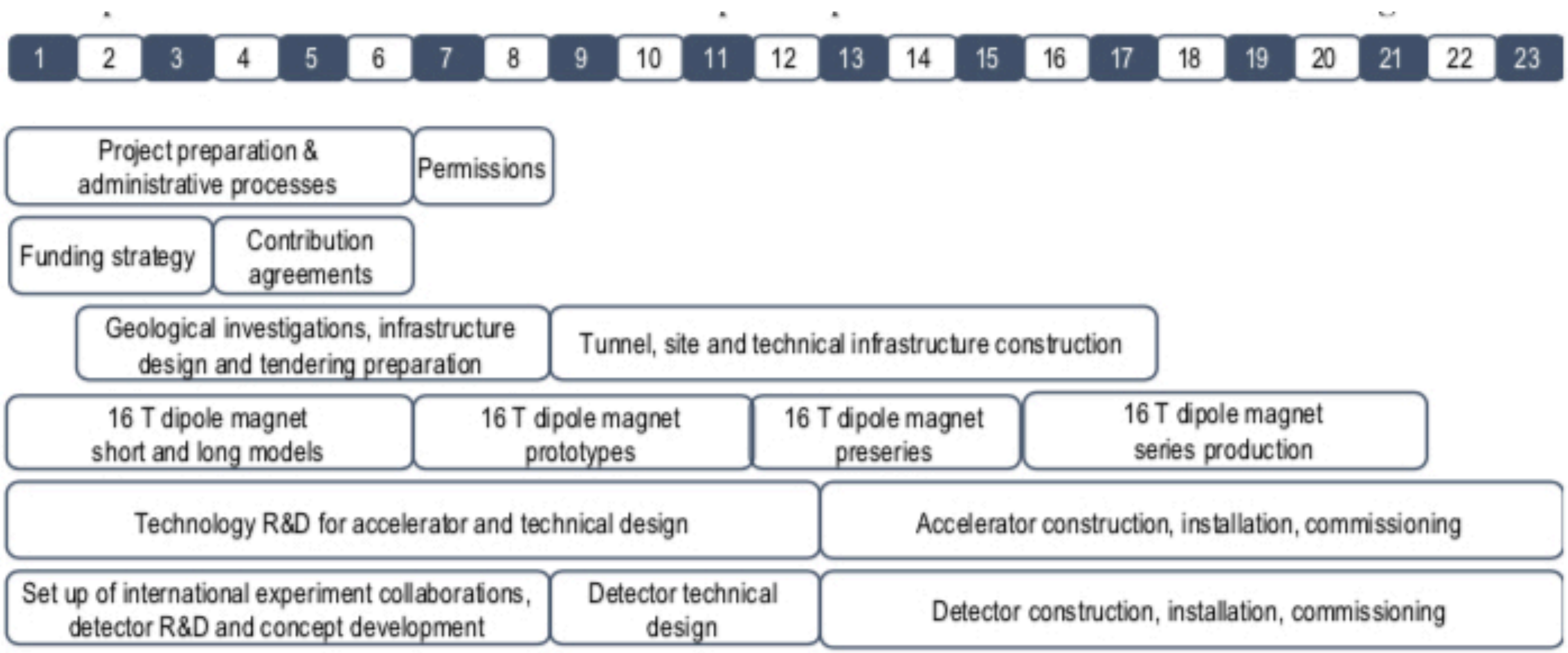


Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

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**

Additional material:

HE-LHC, pp@27 TeV
in the LHC tunnel

HE-LHC physics potential: domains to be evaluated

(1) extension of the LHC direct search for new particles (approximately doubling its mass reach);

(2) the Higgs self-coupling: establishing firm evidence for the structure of the symmetry-breaking Higgs potential;

(3) increased precision in the measurements made by the LHC, and the consequent increased sensitivity to new physics (indirectly to high mass scales, and, directly, to elusive final states such as dark matter);

(4) exploration of future LHC discoveries, confirmation of preliminary signs of discovery from the LHC, or the search for the underlying origin of new phenomena revealed indirectly **(e.g. the flavour anomalies under discussion nowadays)** or in experiments other than the LHC ones (e.g. dark matter or neutrino experiments).

(I) extension of mass reach for discovery: "natural" supersymmetry examples

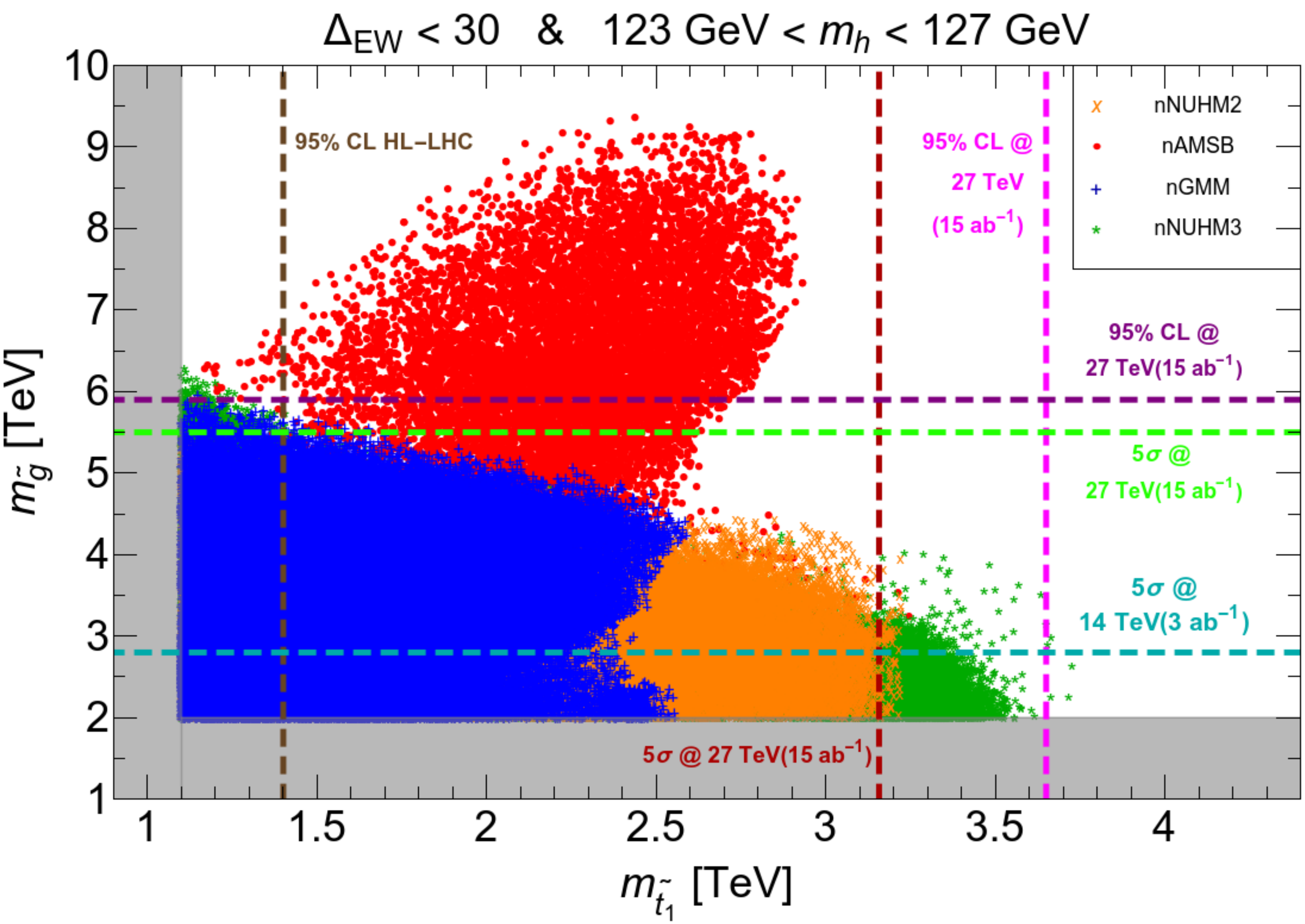
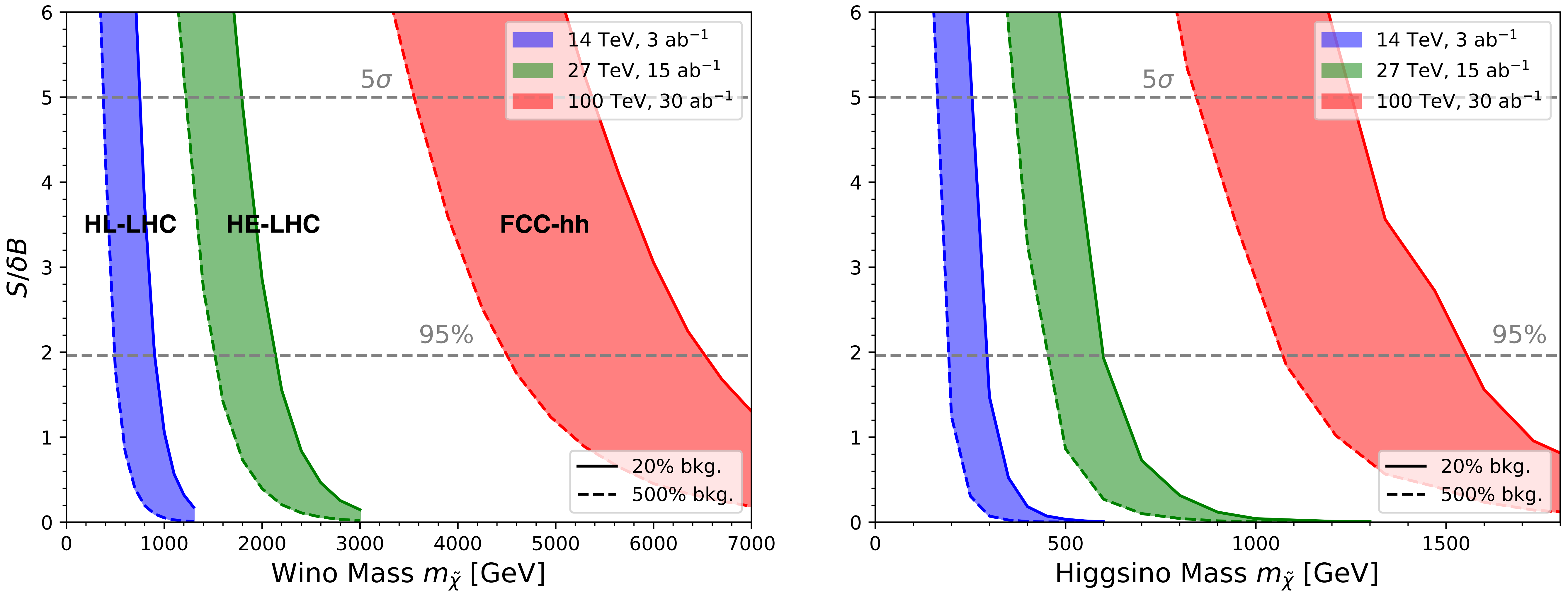


Figure 1.2: Discovery reach at the HE-LHC for gluinos and stops in various, compared to the HL-LHC reach and to the expectations of a several classes of natural supersymmetric models.

H. Baer, *talk at the Fermilab Workshop on HL-HE/LHC Physics, April 2-4 2018*, `https://indico.fnal.gov/event/16151/session/4/contribution/46/`.

(I) EW-ino DM searches



T. Han, S. Mukhopadhyay, and X. Wang, *Electroweak Dark Matter at Future Hadron Colliders*, `arXiv:1805.00015 [hep-ph]`.

(II+III) precision measurements and EWSB probes: Higgs observables

Examples of goals in the Higgs sector:

(a) improve the sensitivity to the Higgs self-coupling

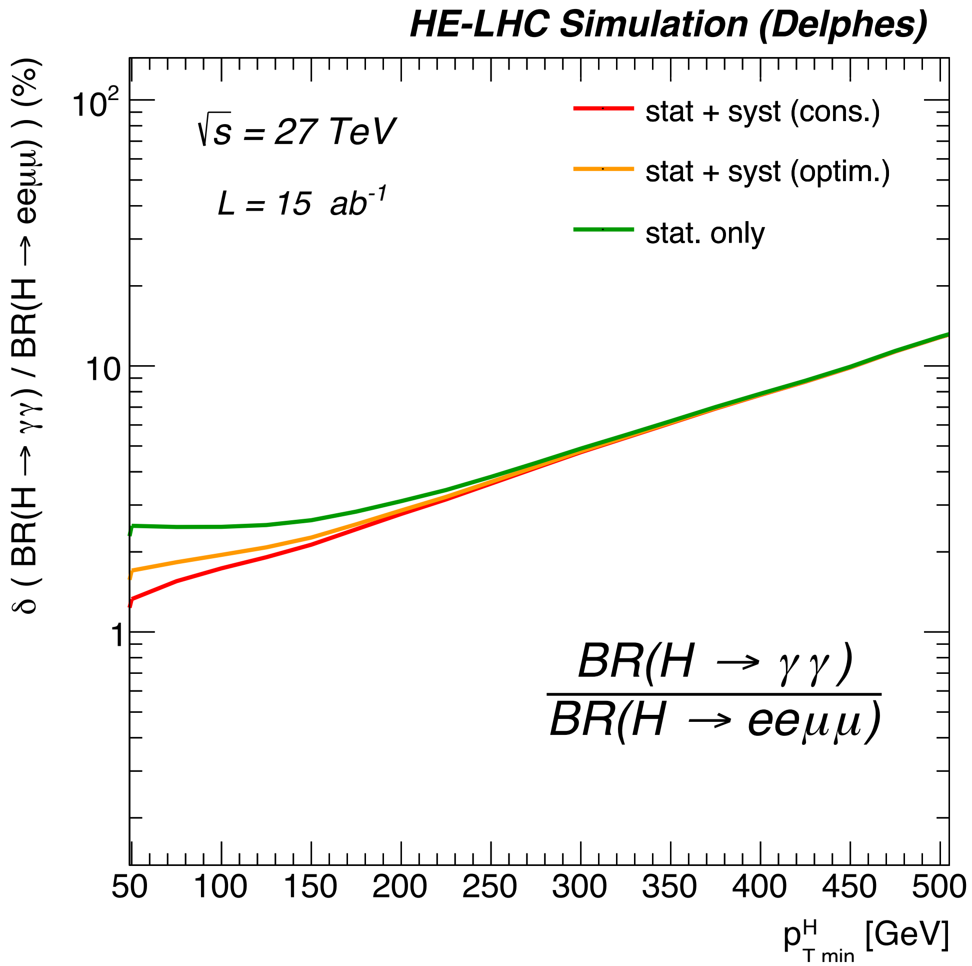
(b) reduce to the few percent level all major Higgs couplings

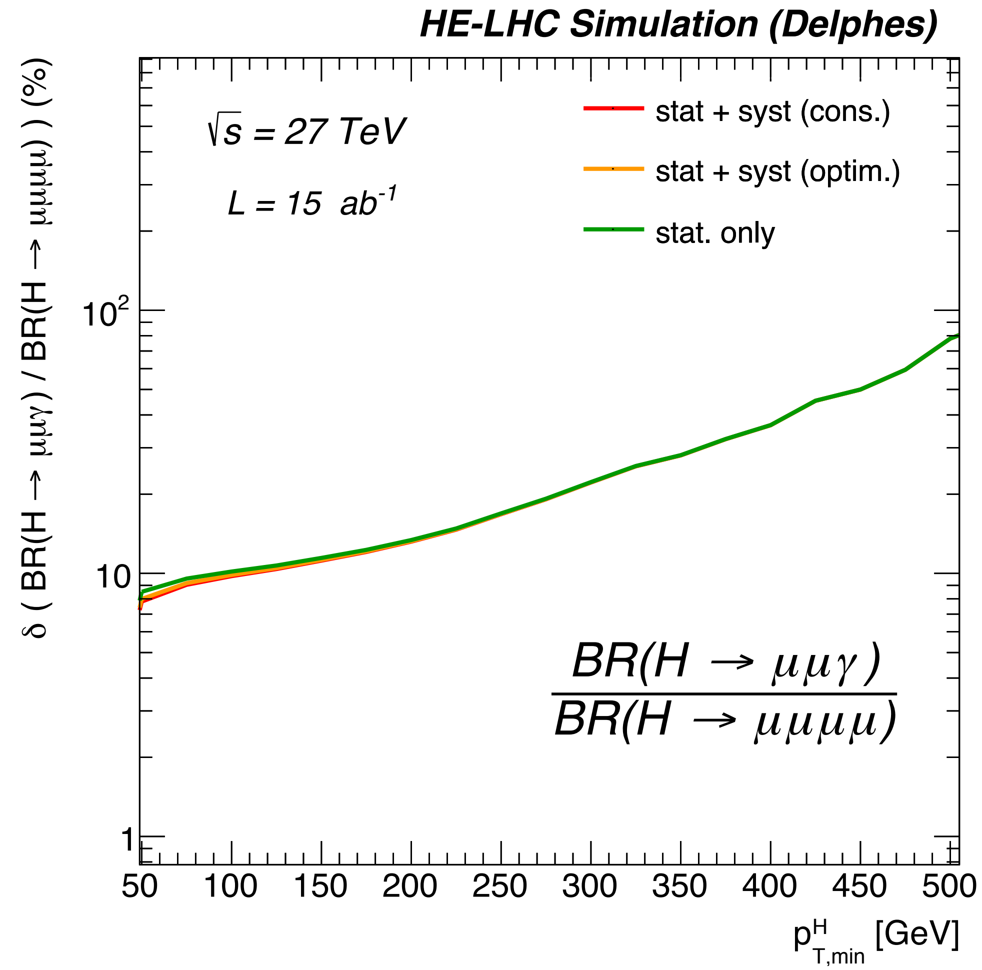
(c) improve the sensitivity to possible invisible Higgs decays

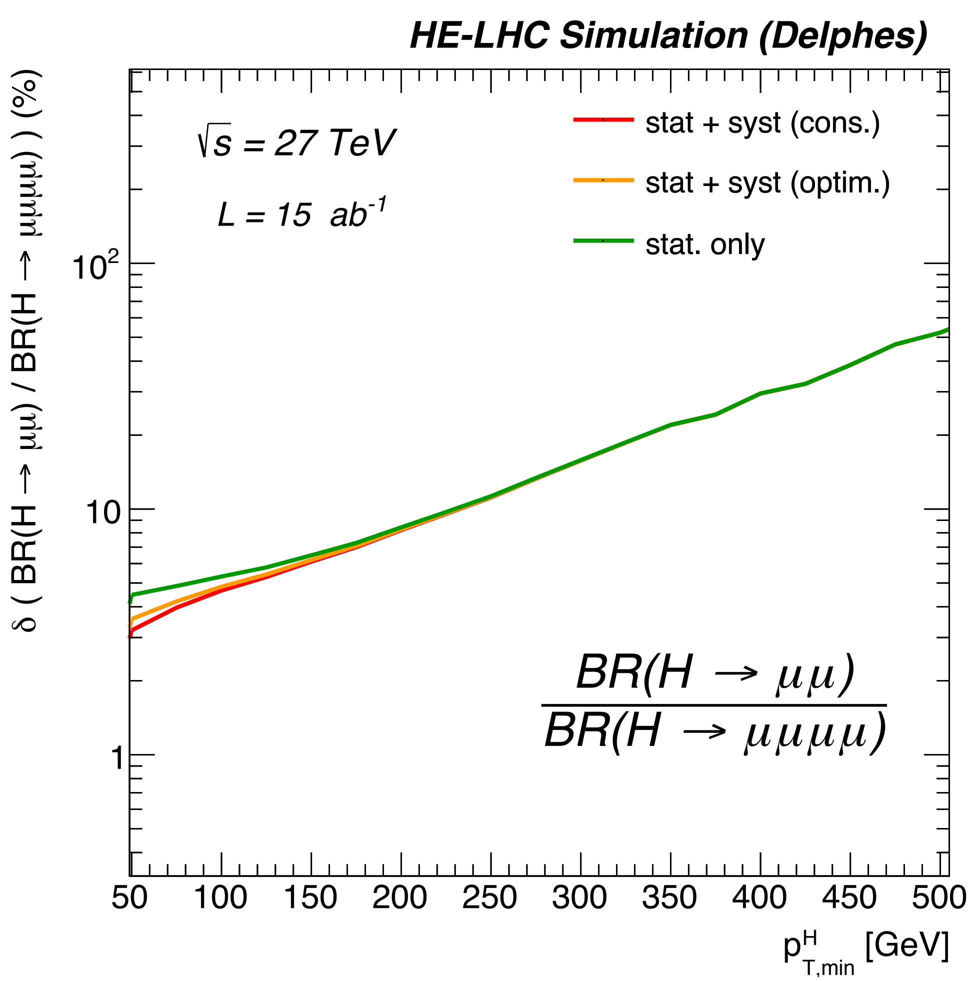
(d) measure the charm Yukawa coupling

	$gg \to H$	WH	ZH	ttH	HH
N_{27}	2.2×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

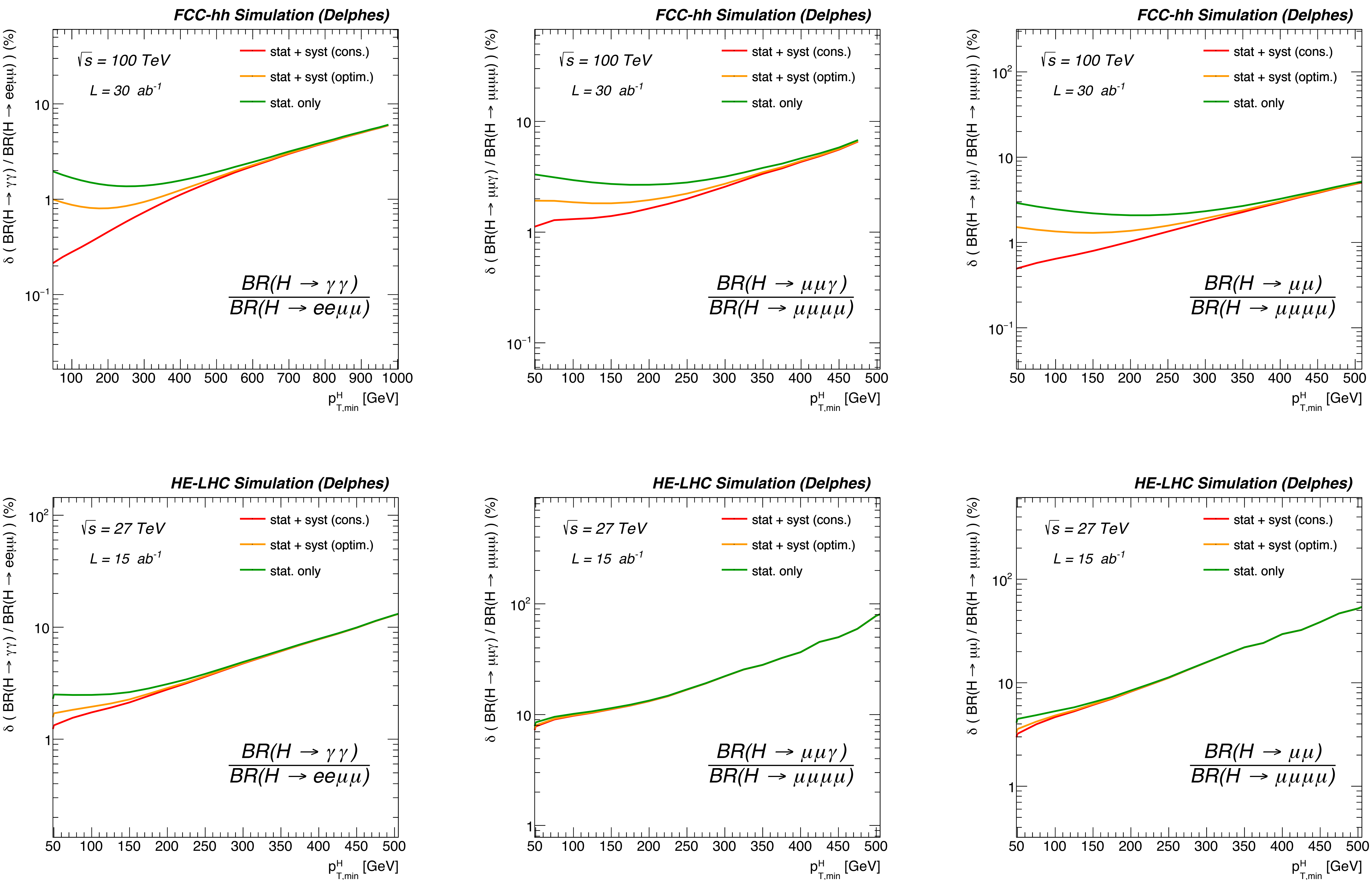
$N_{27} = \sigma(27\ \text{TeV}) * 15\ \text{ab}^{-1}$ $N_{14} = \sigma(14\ \text{TeV}) * 3\ \text{ab}^{-1}$


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \gamma\gamma)}{BR(H \to ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
$p^H_{T\,min}$ [GeV]


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu\gamma)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
$p^H_{T,min}$ [GeV]


HE-LHC Simulation (Delphes)
$\sqrt{s}$ = 27 TeV
L = 15 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
$p^H_{T,min}$ [GeV]

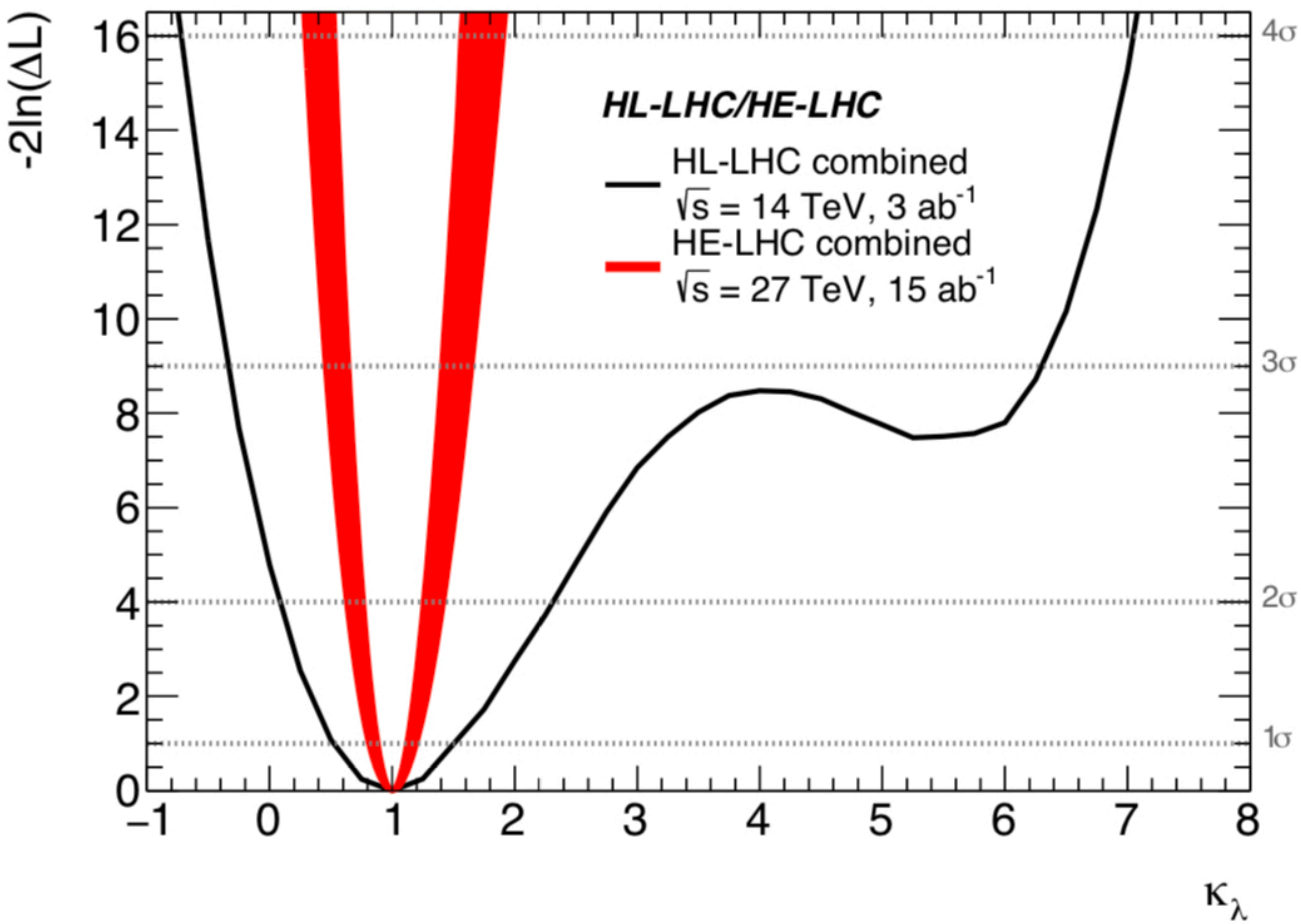
100 vs 27 TeV


FCC-hh Simulation (Delphes)
√s = 100 TeV
L = 30 ab-1
stat + syst (cons.)
stat + syst (optim.)
stat. only
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
BR(H → γγ) / BR(H → eeμμ)
p^H_T,min [GeV]
FCC-hh Simulation (Delphes)
√s = 100 TeV
L = 30 ab-1
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
BR(H → μμγ) / BR(H → μμμμ)
p^H_T,min [GeV]
FCC-hh Simulation (Delphes)
√s = 100 TeV
L = 30 ab-1
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
BR(H → μμ) / BR(H → μμμμ)
p^H_T,min [GeV]
HE-LHC Simulation (Delphes)
√s = 27 TeV
L = 15 ab-1
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
BR(H → γγ) / BR(H → eeμμ)
p^H_T,min [GeV]
HE-LHC Simulation (Delphes)
√s = 27 TeV
L = 15 ab-1
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
BR(H → μμγ) / BR(H → μμμμ)
p^H_T,min [GeV]
HE-LHC Simulation (Delphes)
√s = 27 TeV
L = 15 ab-1
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
BR(H → μμ) / BR(H → μμμμ)
p^H_T,min [GeV]

Higgs self-coupling at HE-LHC vs HL-LHC

HL-LHC: λ/λ_{SM} ~1±0.5 (68%CL)

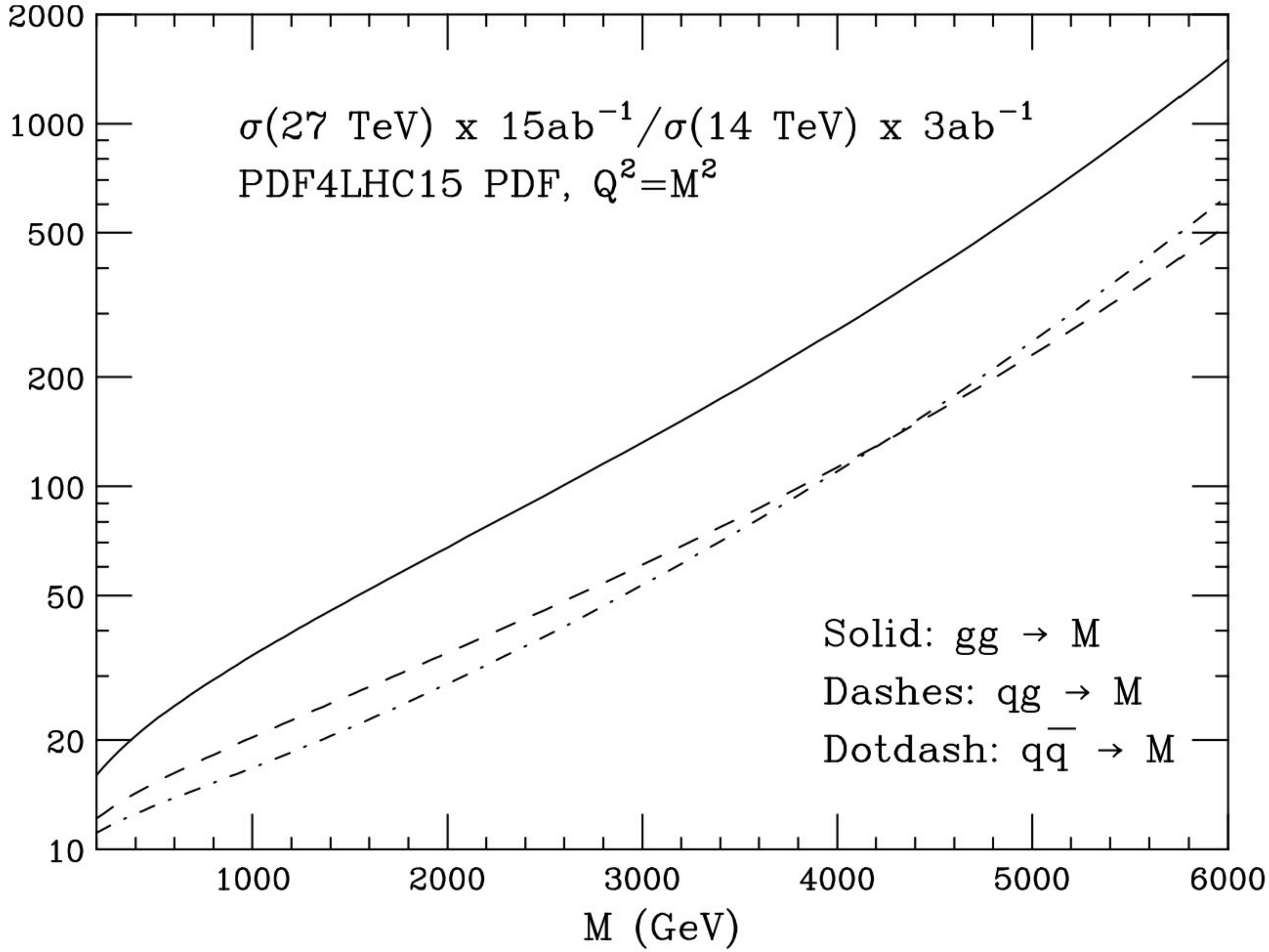
HE-LHC: λ/λ_{SM} ~1±0.15 (68%CL)



See also:

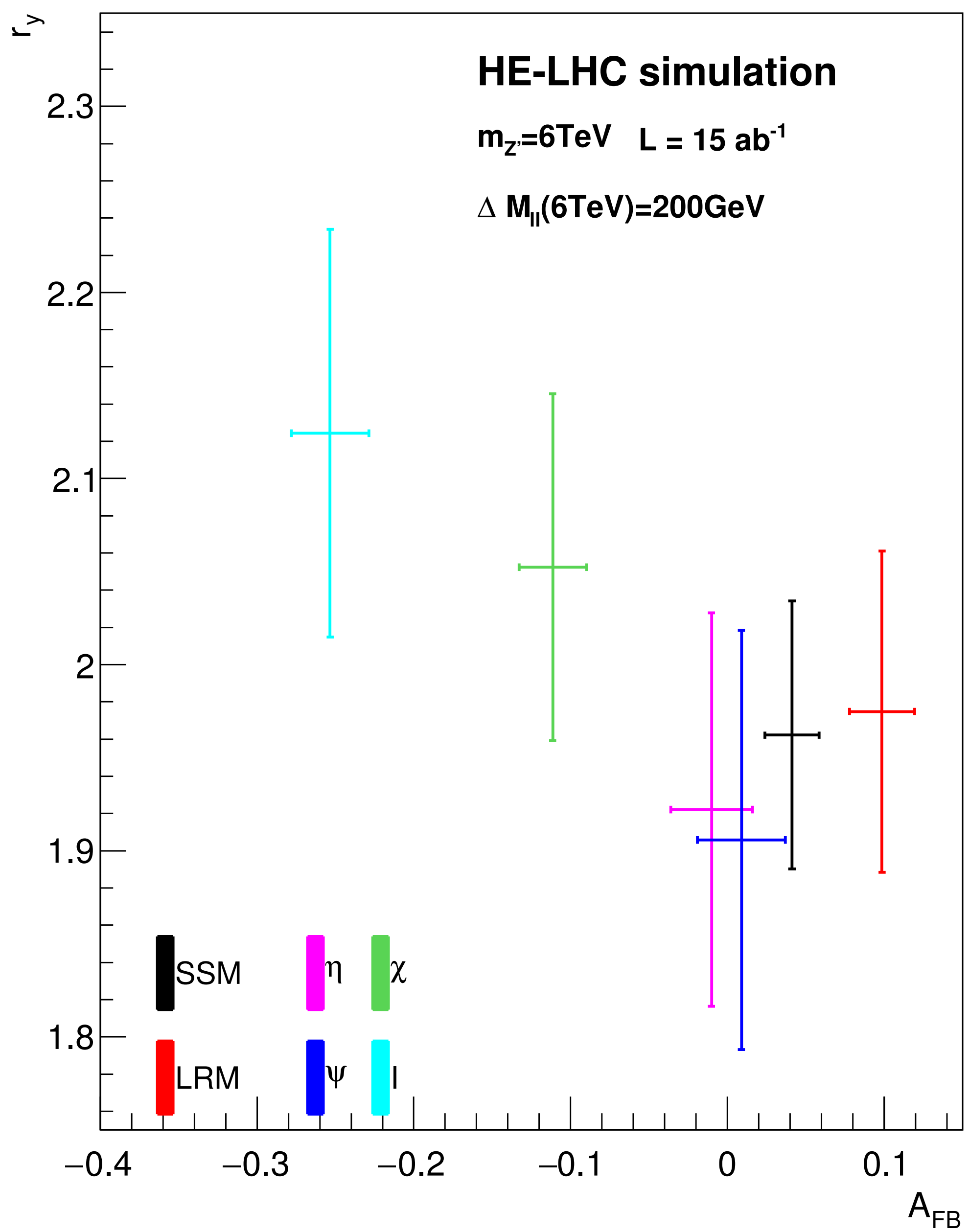
D. Gonçalves, T. Han, F. Kling, T. Plehn, and M. Takeuchi, *Higgs Pair Production at Future Hadron Colliders: From Kinematics to Dynamics*, arXiv:1802.04319 [hep-ph].

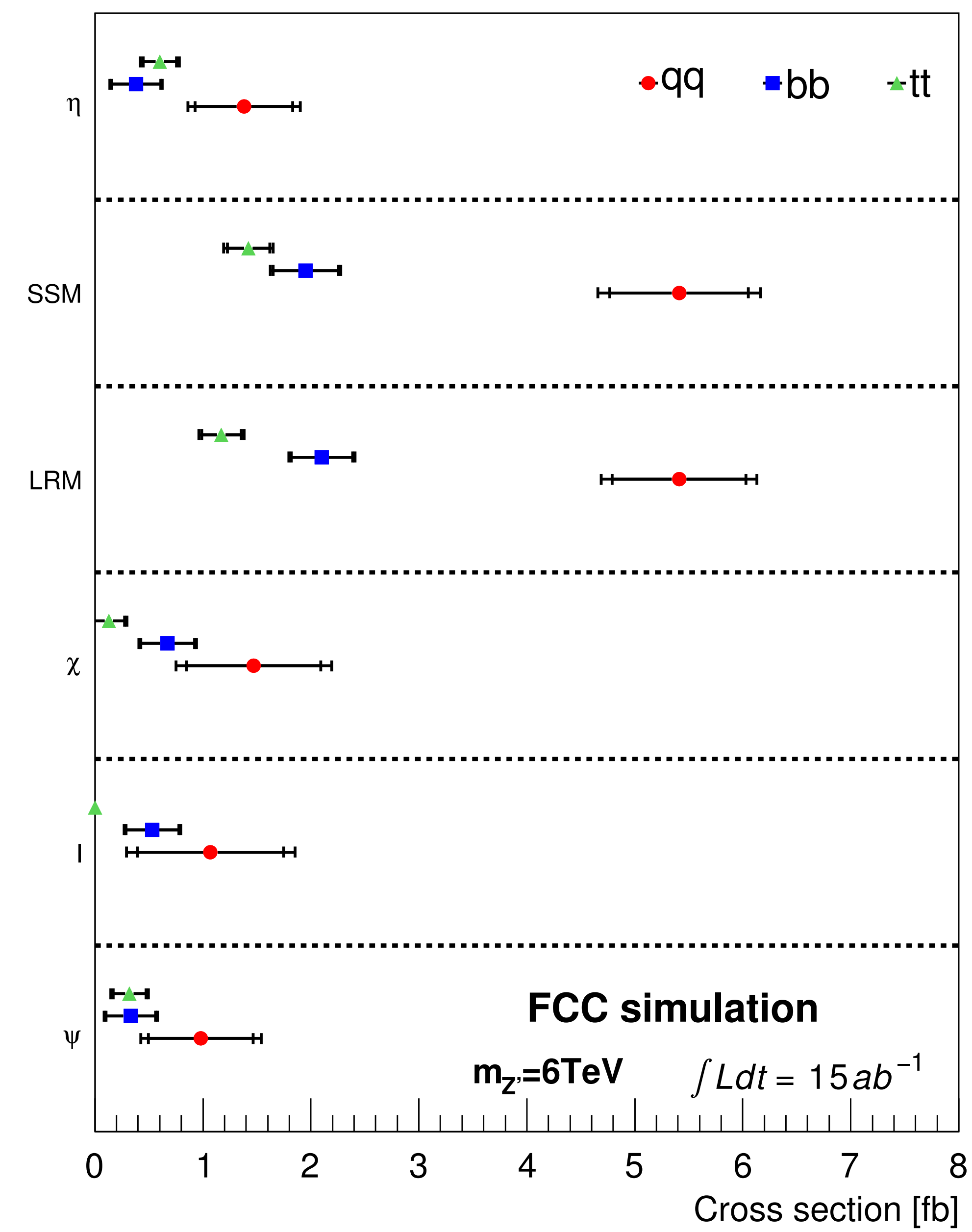
(IV) Exploration at 27 TeV of LHC discoveries: generic results



(IV) Exploration at 27 TeV of LHC discoveries: characterization of Z' models within reach of LHC observation

NB: uncertainty bars reflect very conservative syst assumptions

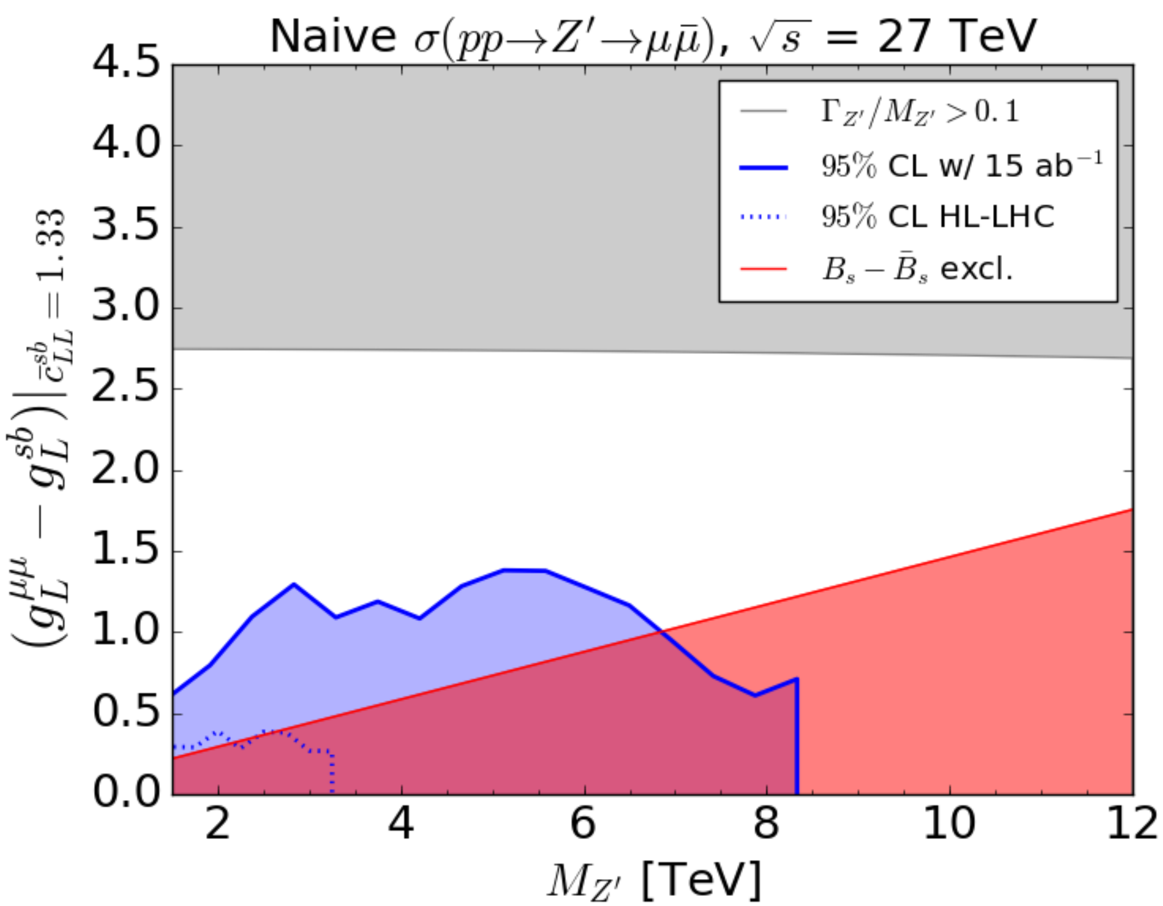


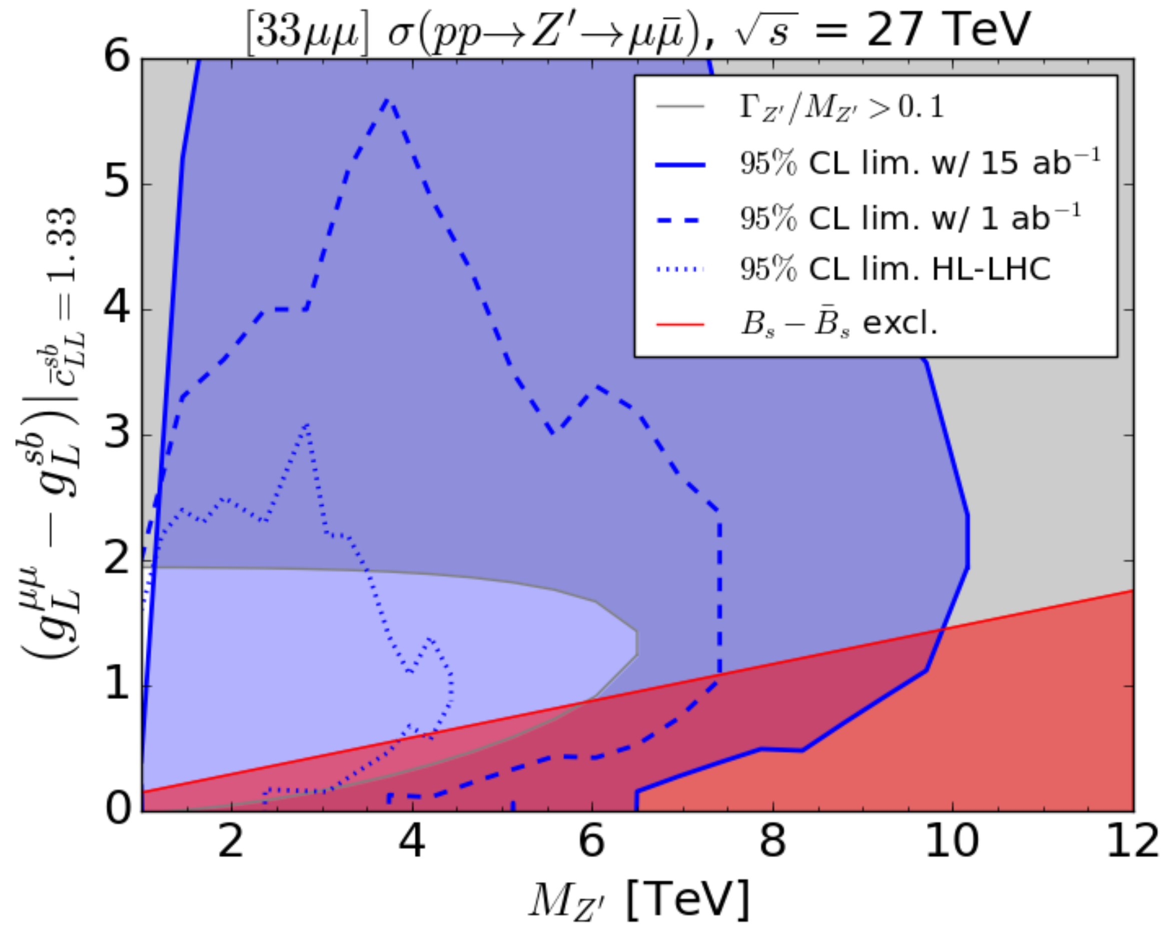


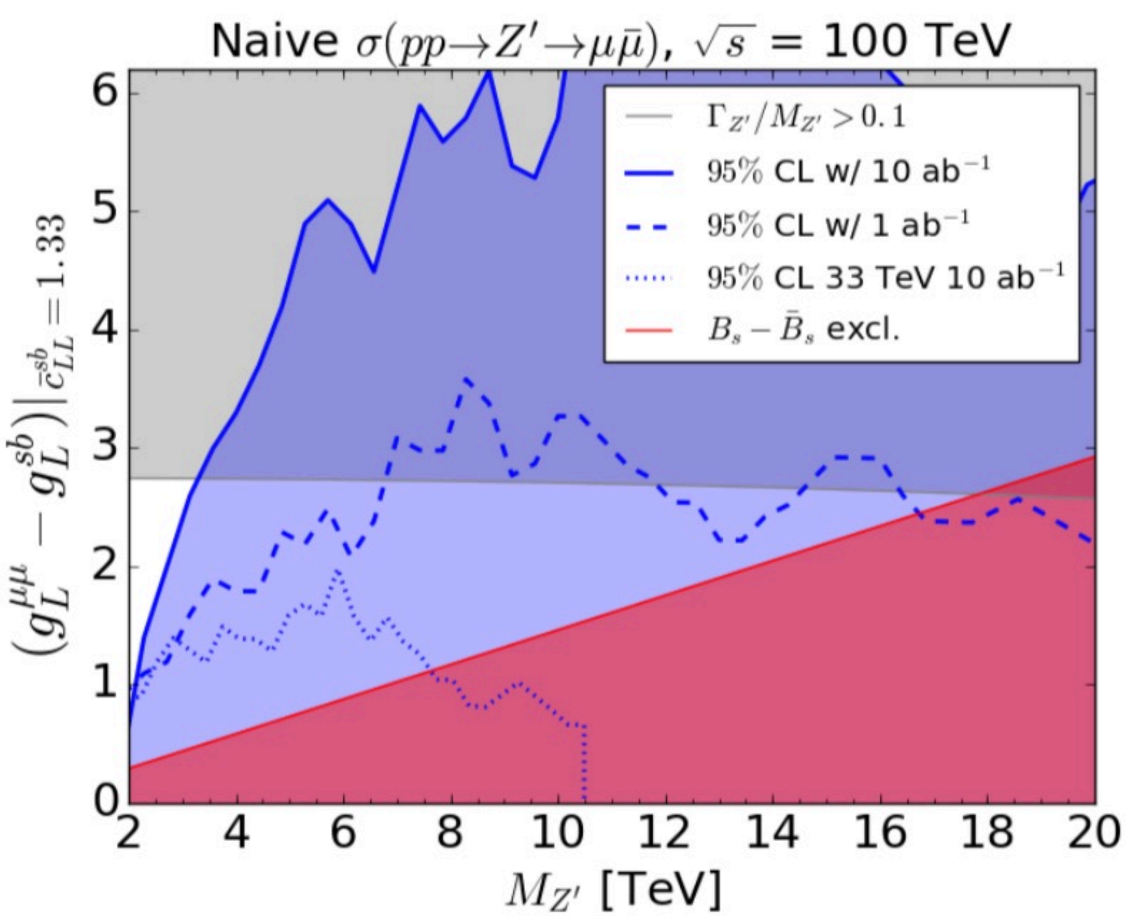
Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

T. G. Rizzo, *Exploring new gauge bosons at a 100 TeV collider*, Phys. Rev. **D89** (2014) no. 9, 095022, arXiv:1403.5465 [hep-ph].

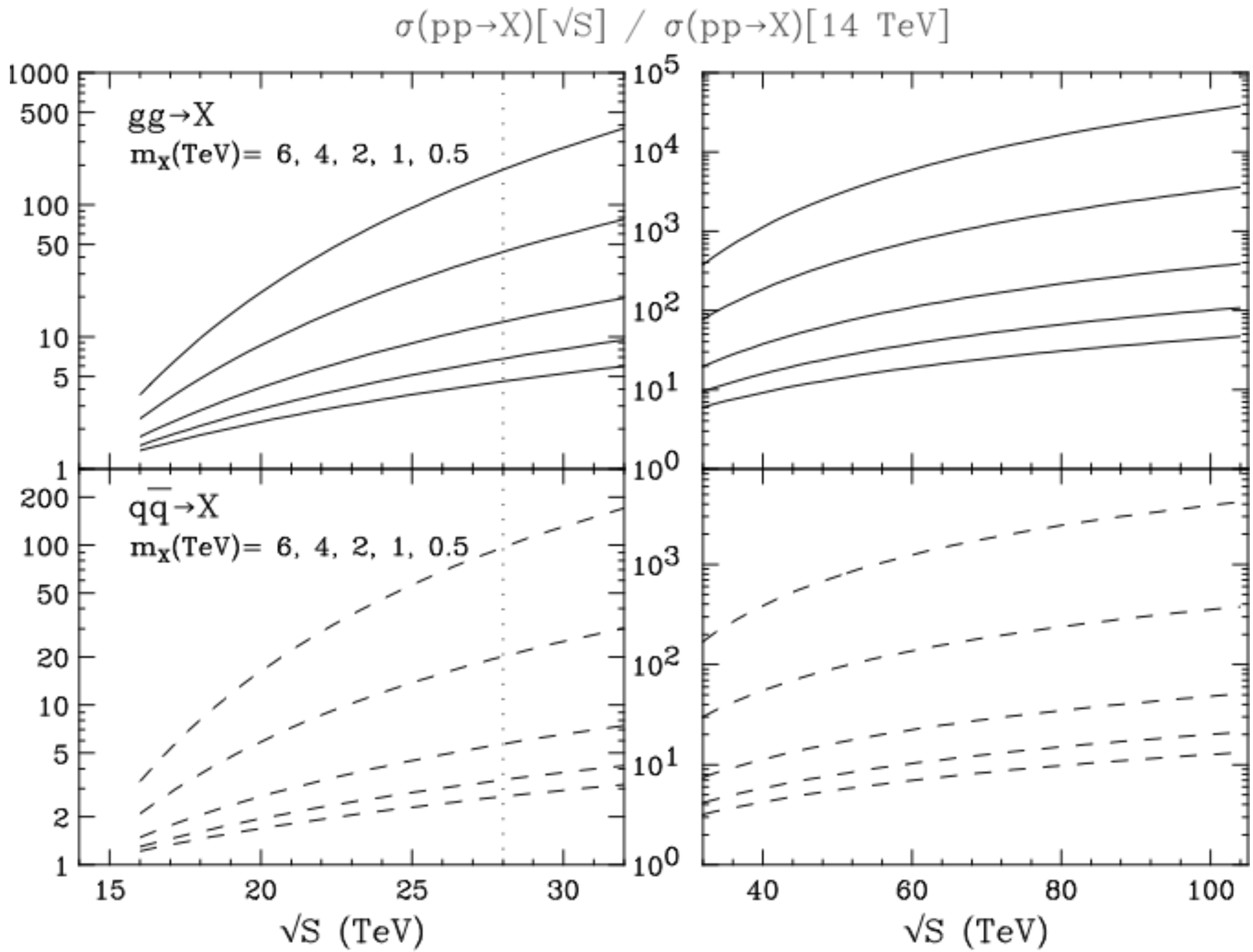
(IV) Exploration at 27 TeV of LHC discoveries: Z' from $R_{K(*)}$





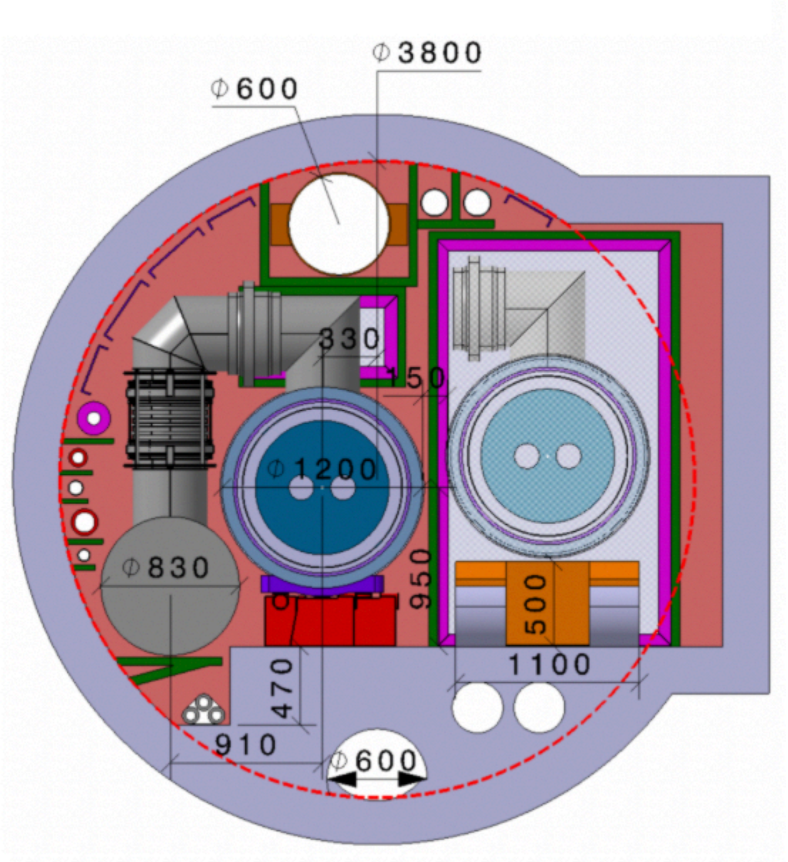


27 or 100? √S evolution of LHC discovery scenarios



HE-LHC: the challenges

- 16T Nb_3Sn magnets: more challenging than for FCC-hh, due to reduced space in the tunnel (requires dedicated R&D)



- SPS upgrade, to SC technology, to allow injection at 0.9-1.3 TeV
- Full replacement and strengthening of all infrastructure on the surface and underground cryogenics
- Significant civil engineering work both on the surface and in the tunnel (new SPS transfer lines, new caverns for cryogenics, 2 new shafts, …)
- Overhaul/full replacement of detectors (radiation damage after HL-LHC, limited lifetime of key systems like magnets, use of new technologies, …)
- …

HE-LHC, project timeline/cost

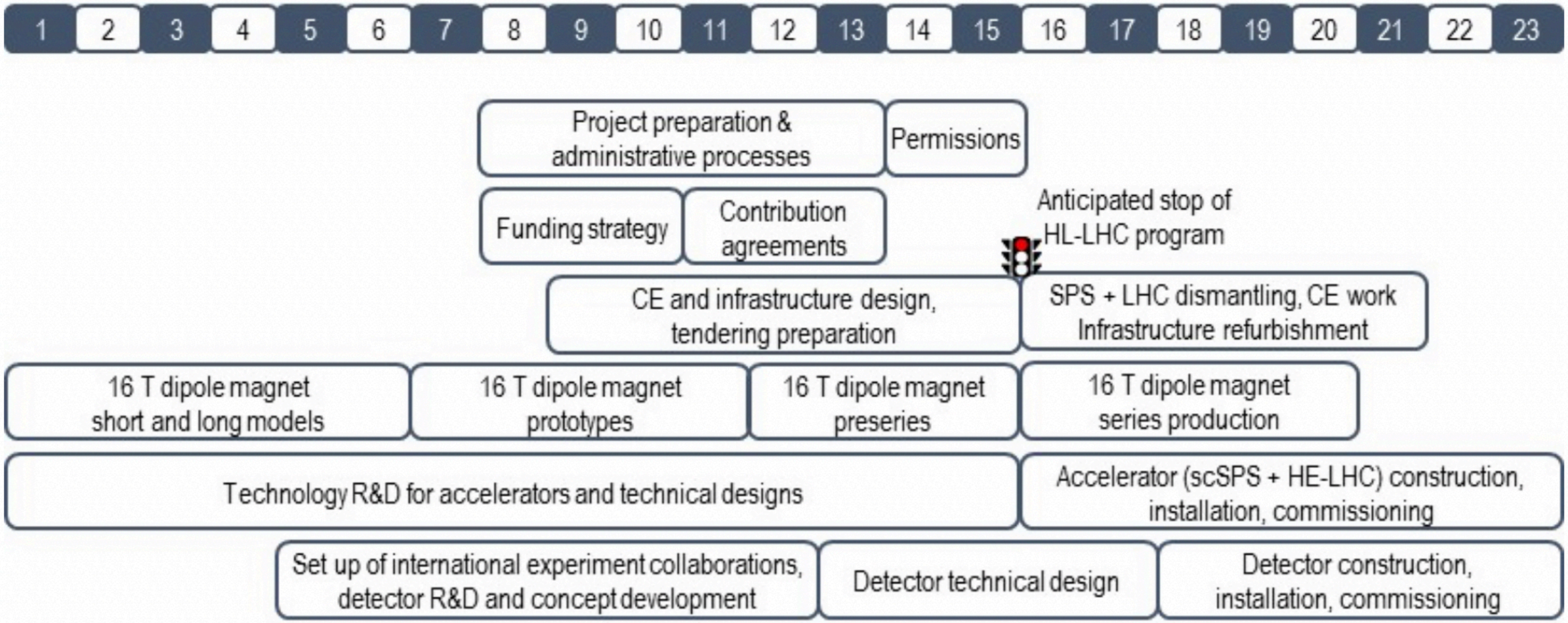


Figure 7: Overview of implementation timeline for the HE-LHC project starting in 2020. Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.

Domain	**Cost in MCHF**
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

Table 2: Summary of capital cost for implementation of the HE-LHC project.