The theory vision

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The vision for HEP builds on

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

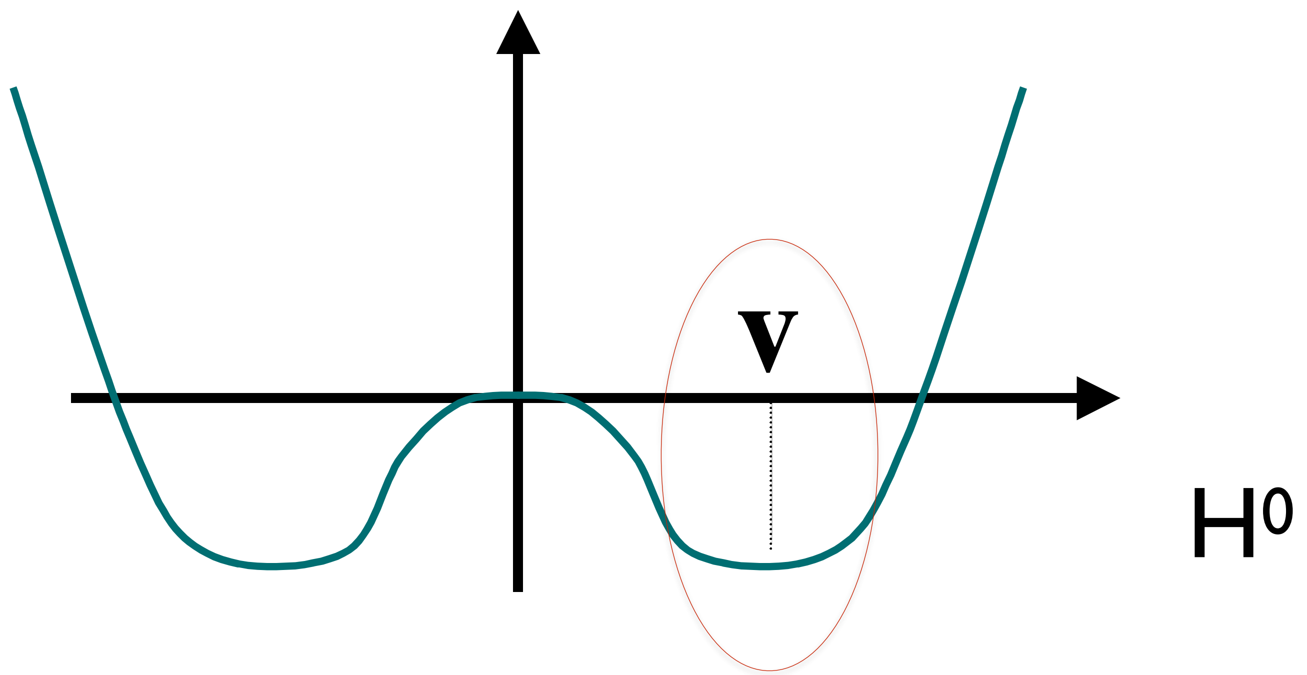
The important questions

- **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….

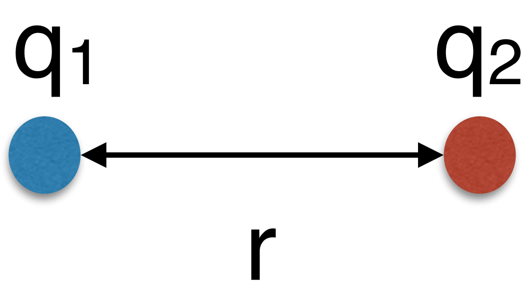


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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

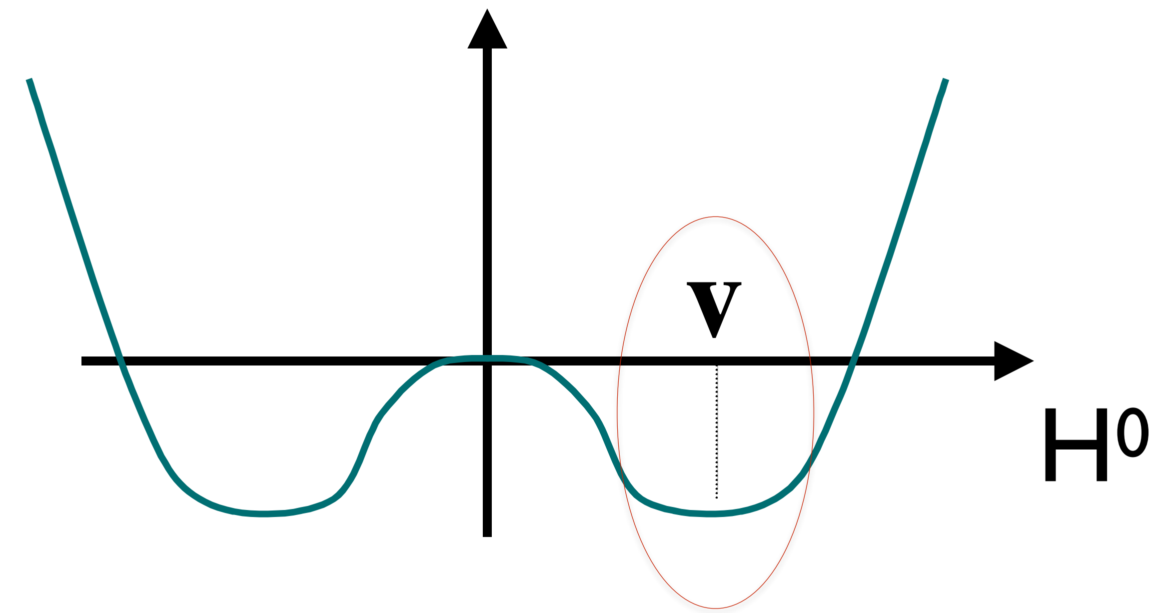


quantized,
in units of
fixed charge

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

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.

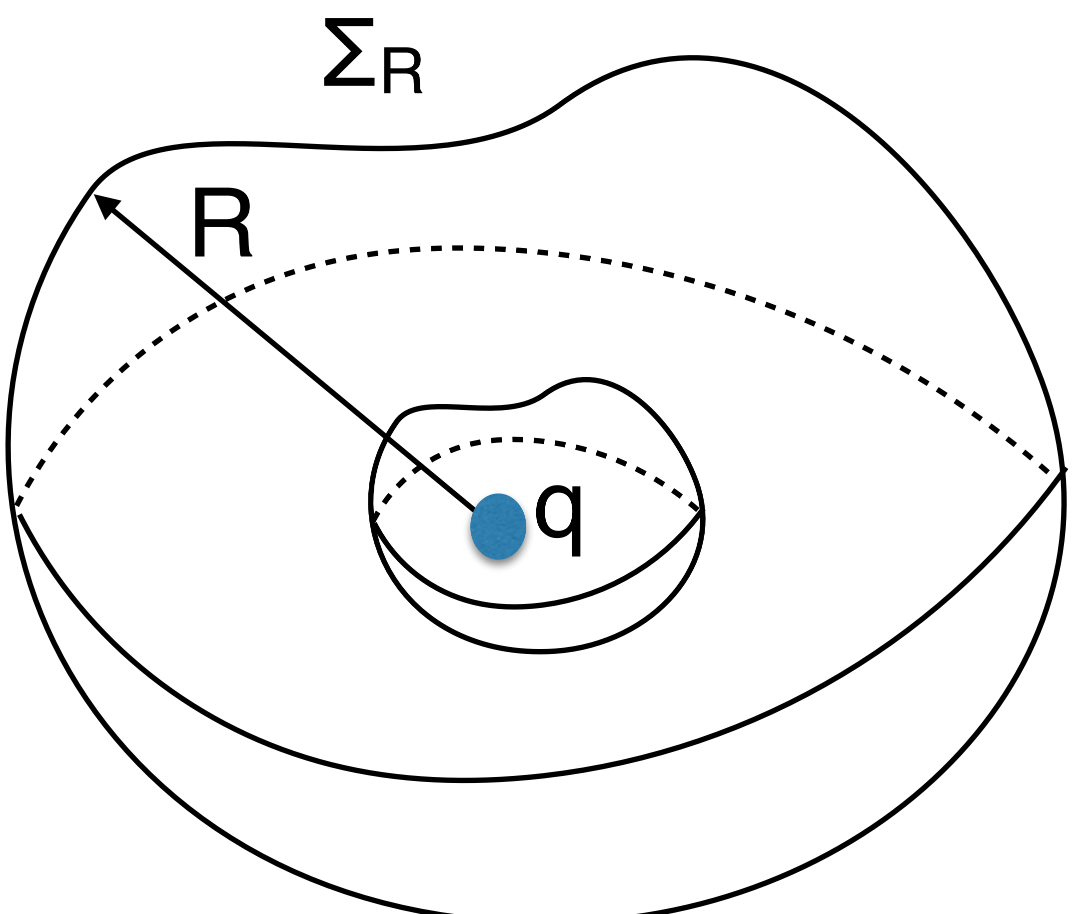
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either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

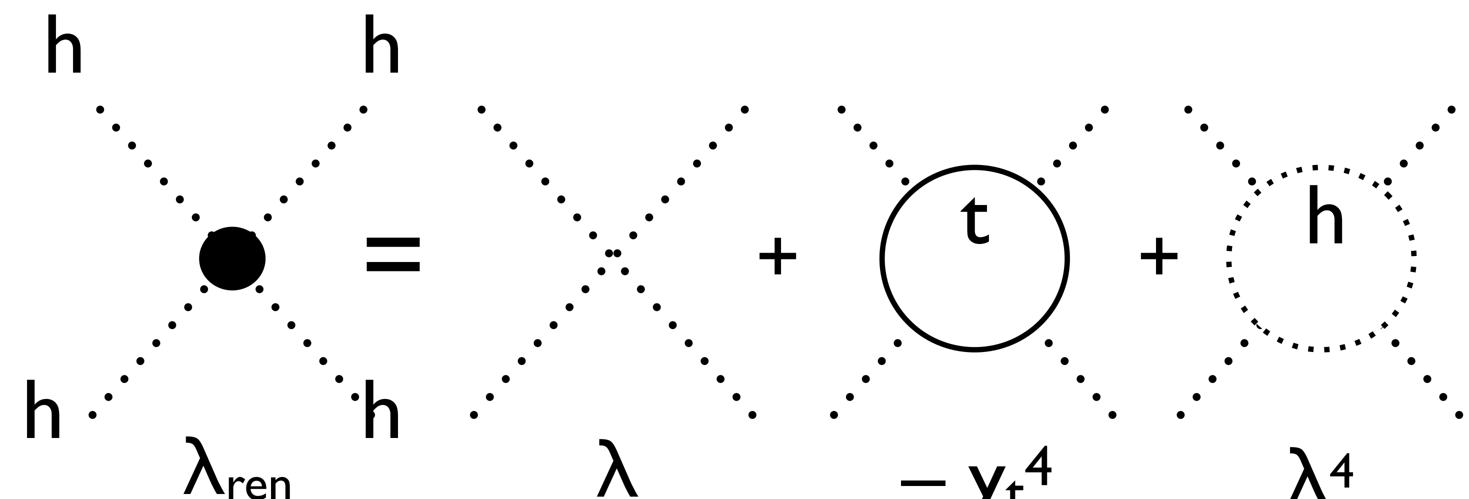


$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

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

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



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

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

bottom line

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the "natural" scale defined by the measured parameters v and m_H

$\Rightarrow$ **naturalness**

message

- Naturalness and the origin of the Higgs go hand in hand, and are unavoidably tied to BSM physics. They have 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, and relying on a future generation of colliders***

On the role of measurement

- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, it's about finding out how things work
- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … but who knows how important a given measurement can become, to assess the validity of a future theory?
  - Tycho Brahe (data) => Kepler (phenomenology) => Newton (theory)
  - Mercury's perihelion precession measurements vs GR: Einstein did not develop GR to explain Mercury's orbit. But those data were crucial to validate his theory!
  - the day some BSM signal is found somewhere, the available precision measurements, whether they agree or deviate from the SM, will be useful to establish the nature of the signal

Criteria to judge a future facility

- Guaranteed deliverables
- Extensive exploration potential
- Firm Yes/No answers to relevant questions

Example: the case of a future circular collider facility (FCC, CEPC/SPPC)

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**
- Exploration potential:
  - **enhanced mass reach** for direct exploration (pp@100TeV)
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
  - exploit both direct (large Q^2) and indirect (precision) probes
- 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?
  - …

Some examples

=> See also afternoon talks by Michele and Joao

Higgs couplings (κ fit): HL-LHC → 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**	–	**0.95** (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–	**0.9** (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**6.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

§ M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, Higgs Physics at the HL-LHC and HE-LHC, arXiv:1902.00134

§§ SM width assumed in the global fit. Will be measured to ~20% (68%CL) via off-shell H->4l, to ~5% (95%CL) from global fit of Higgs production cross sections.

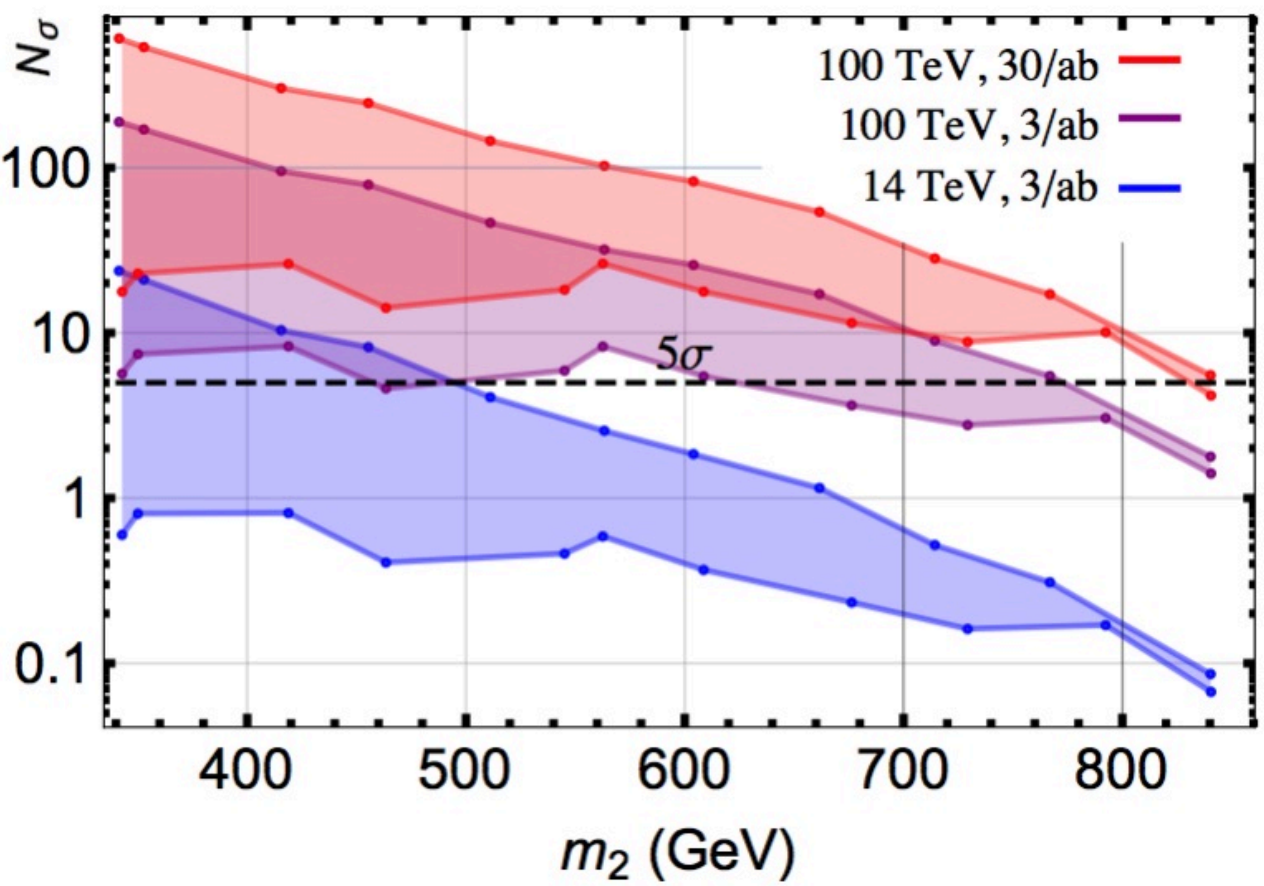
* From BR ratios wrt B(H→4lept) @ FCC-ee

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

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

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

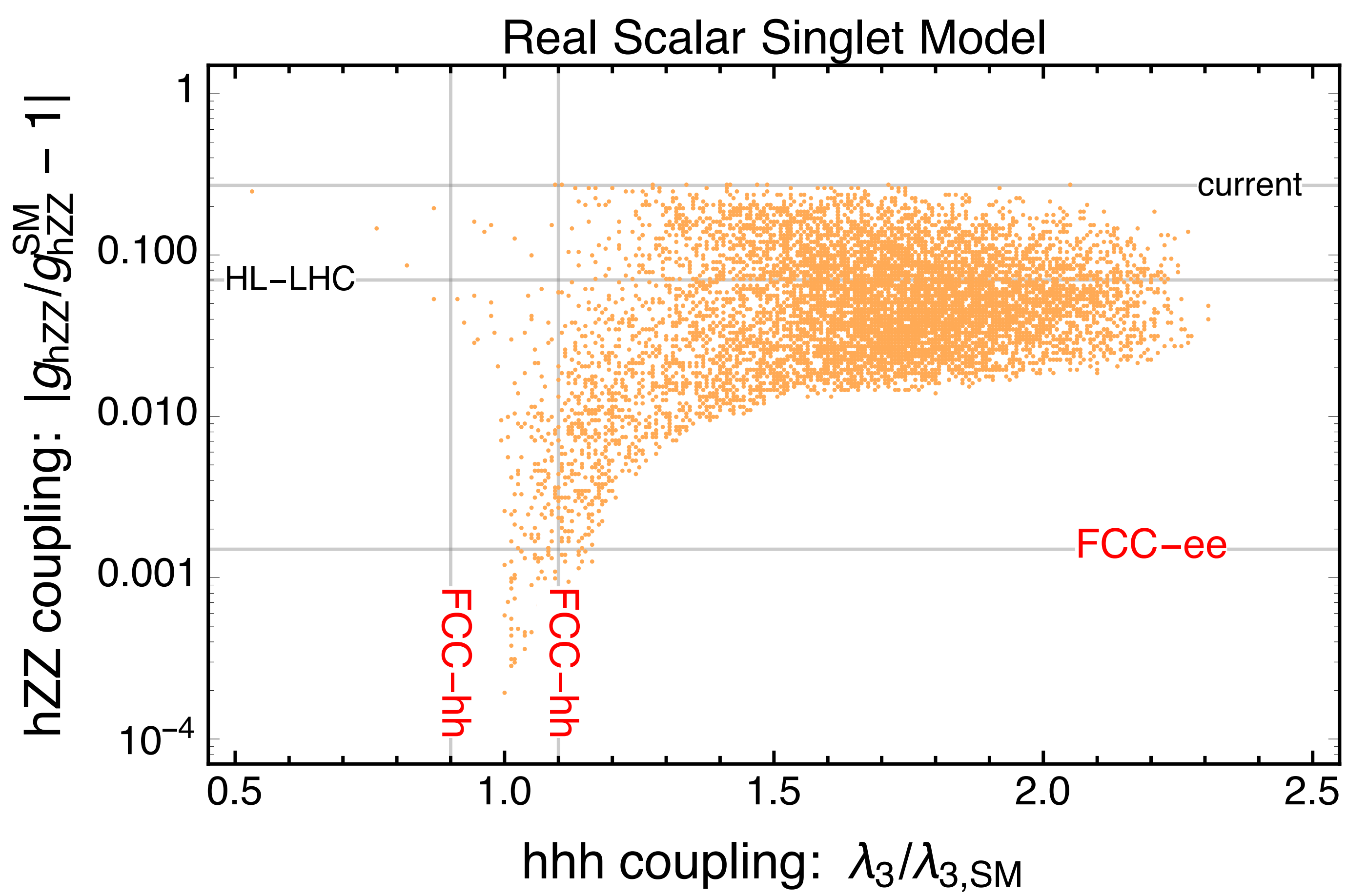
Direct detection of extra Higgs states at FCC-hh



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

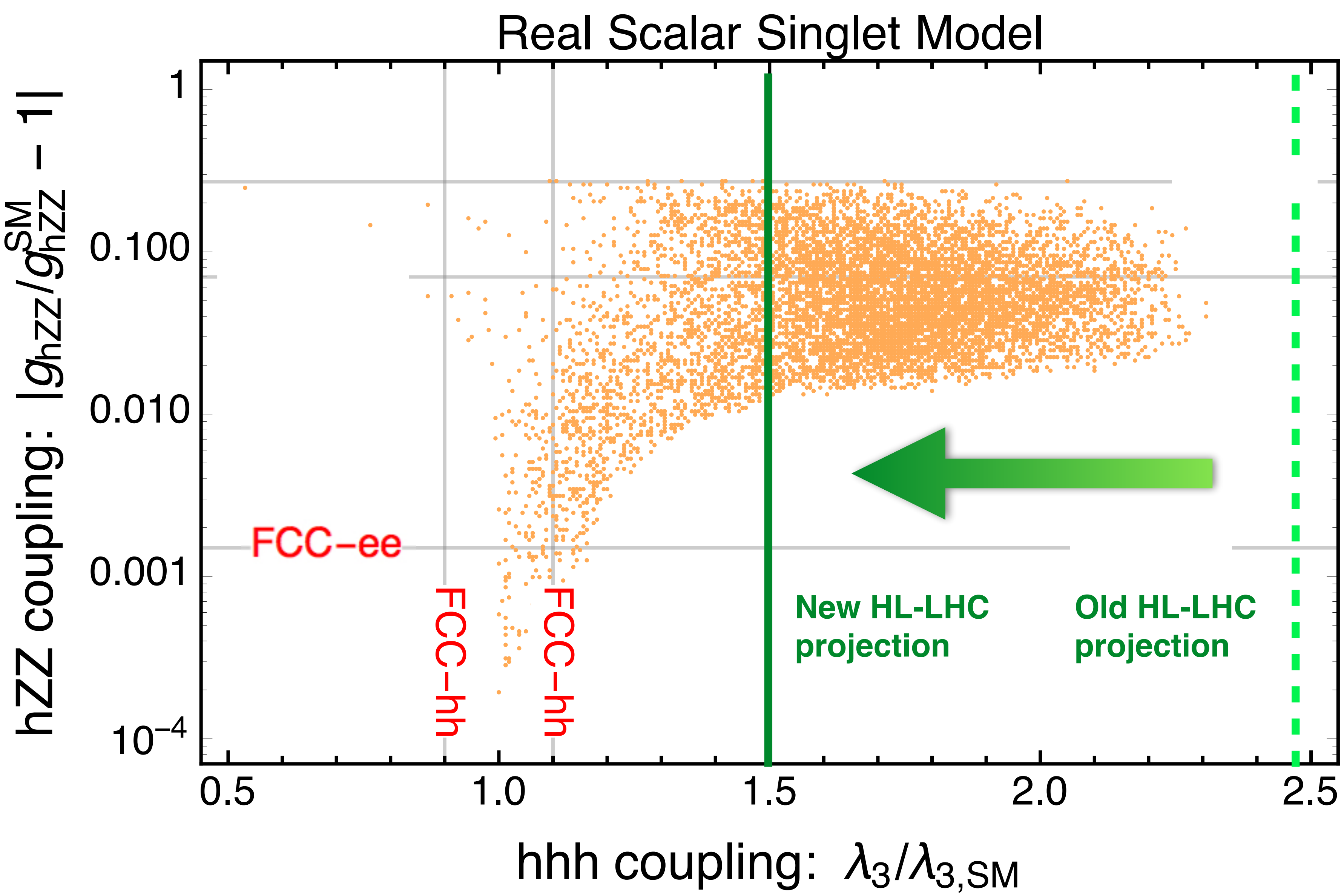
$(h_2 \sim S, \quad h_1 \sim H)$

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.

HL-LHC parenthetical remark



Bringing the HL-LHC sensitivity to the ±50% level, makes a big dent in this class of BSM models!

On the interplay of precision and kinematic reach in probing new physics indirectly

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\, \langle f | L | i \rangle \,|^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots \right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

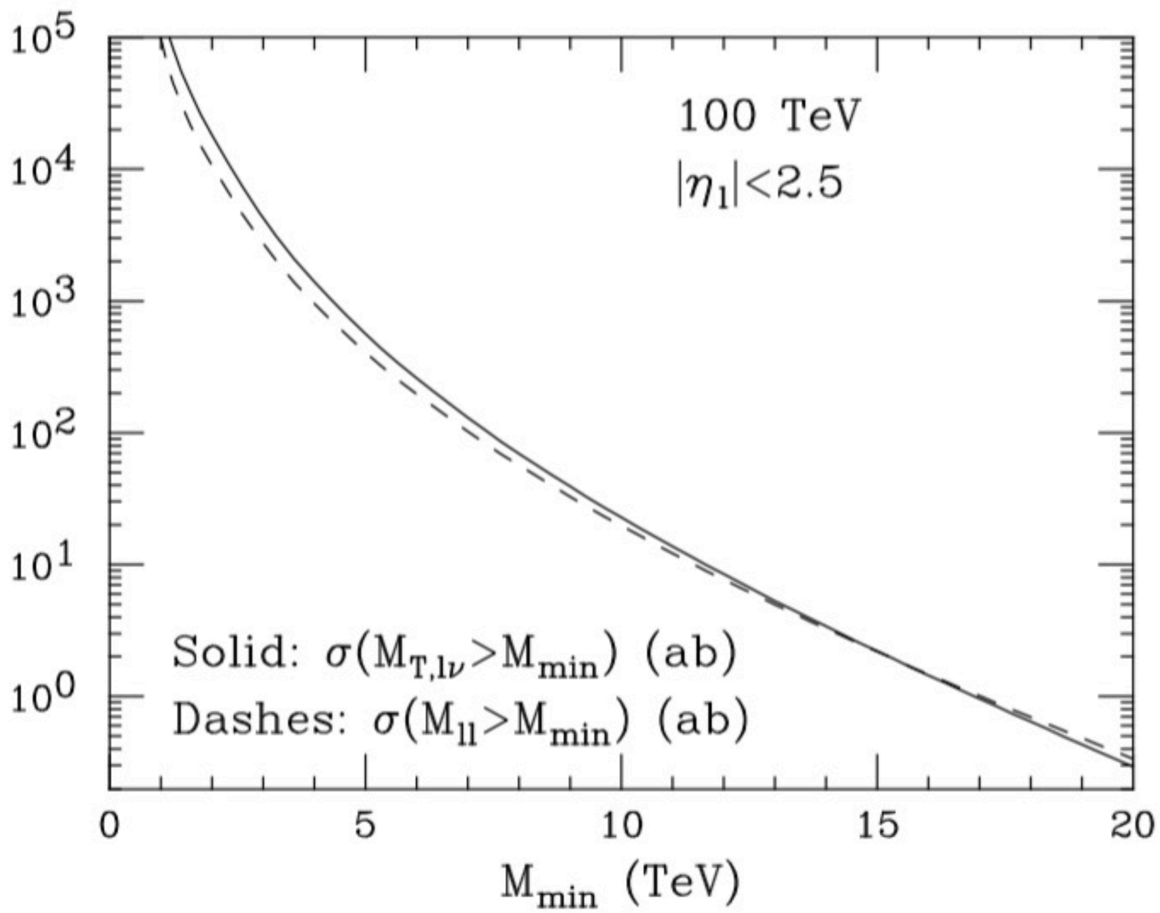
⇒ **kinematic reach** probes large Λ even if precision is "low"

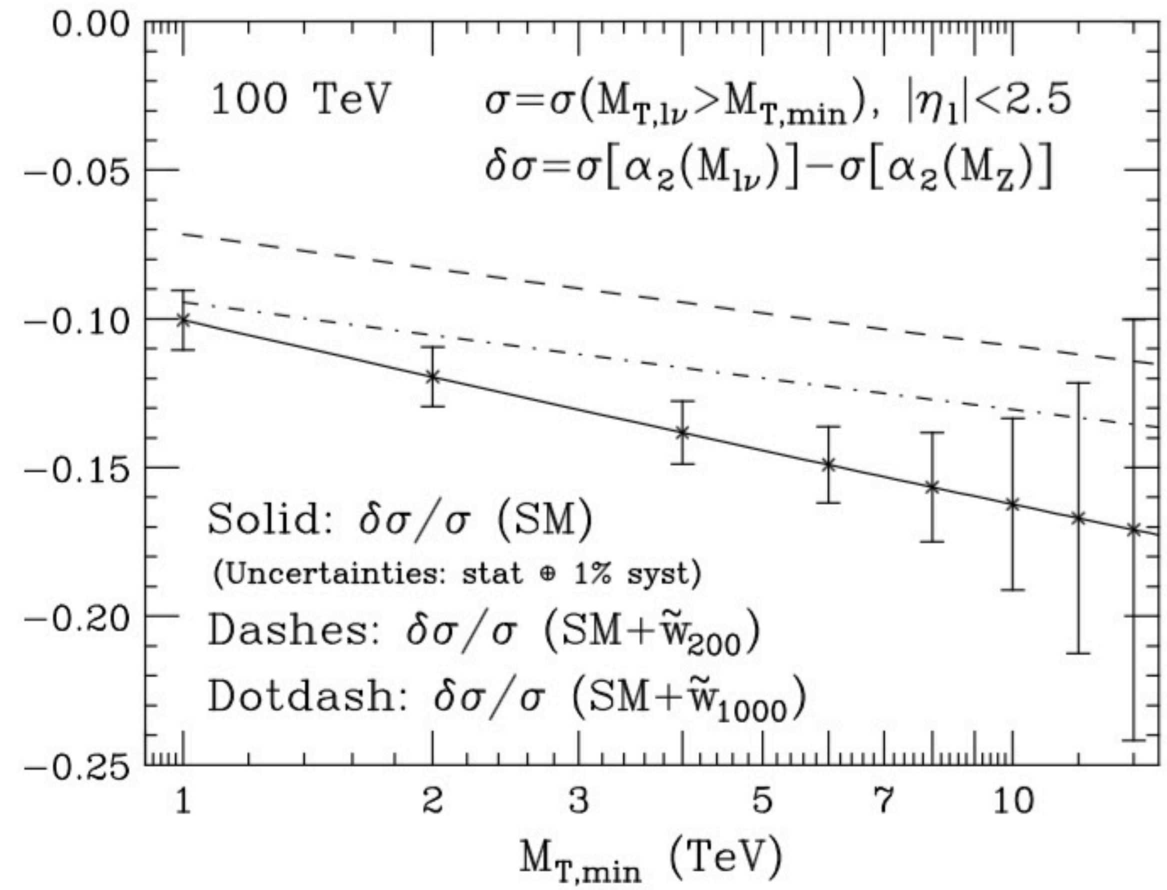
e.g. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV

Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

Example: high mass DY

α_W running and sensitivity to new EW particles





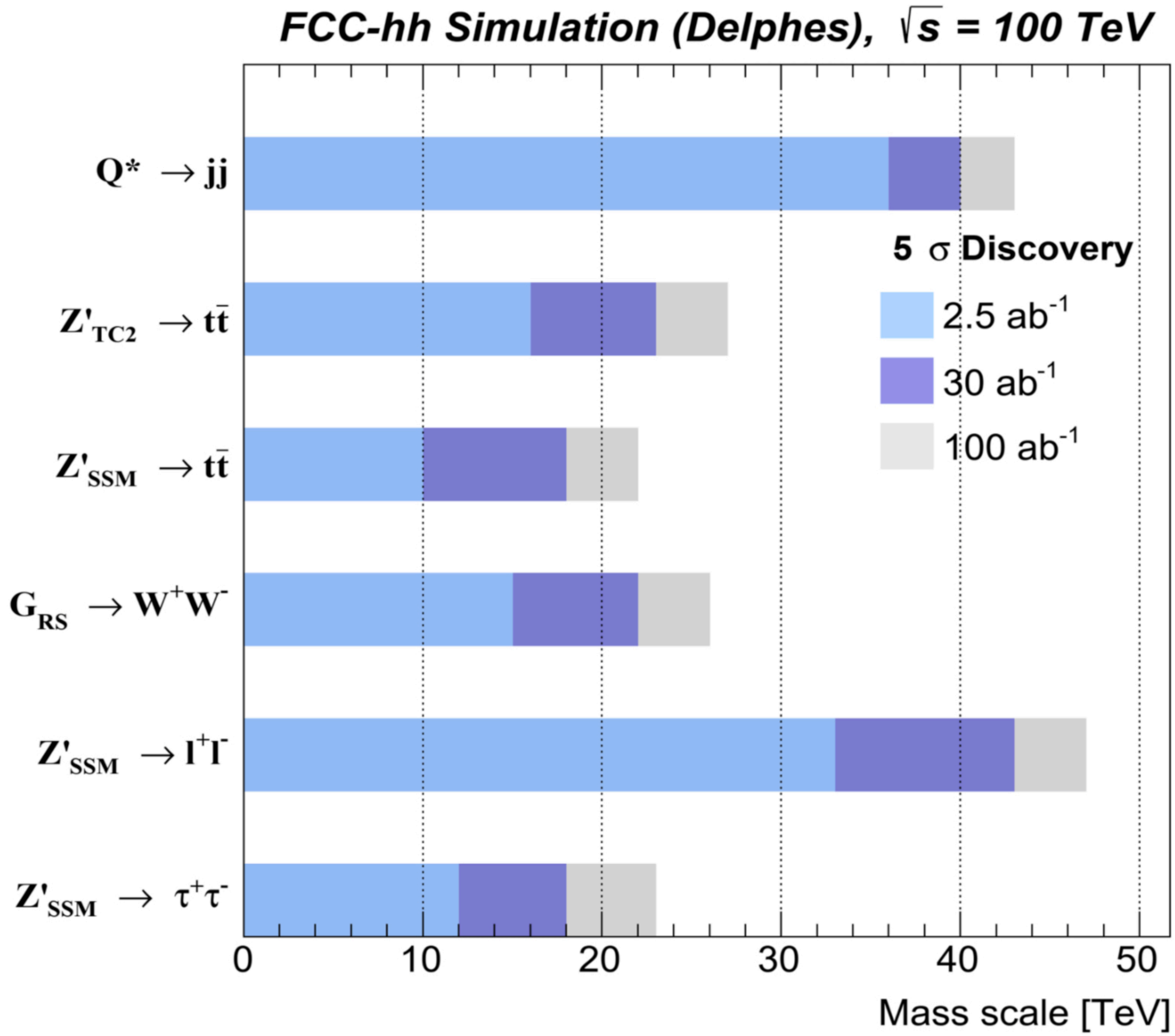
Constraints on Higher-dim op's

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

		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
	luminosity	$2\times10^7\,Z$	19.7 fb^{-1}	20.3 fb^{-1}	0.3 ab^{-1}	3 ab^{-1}	10 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	—

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

Direct discovery reach: s-channel resonances

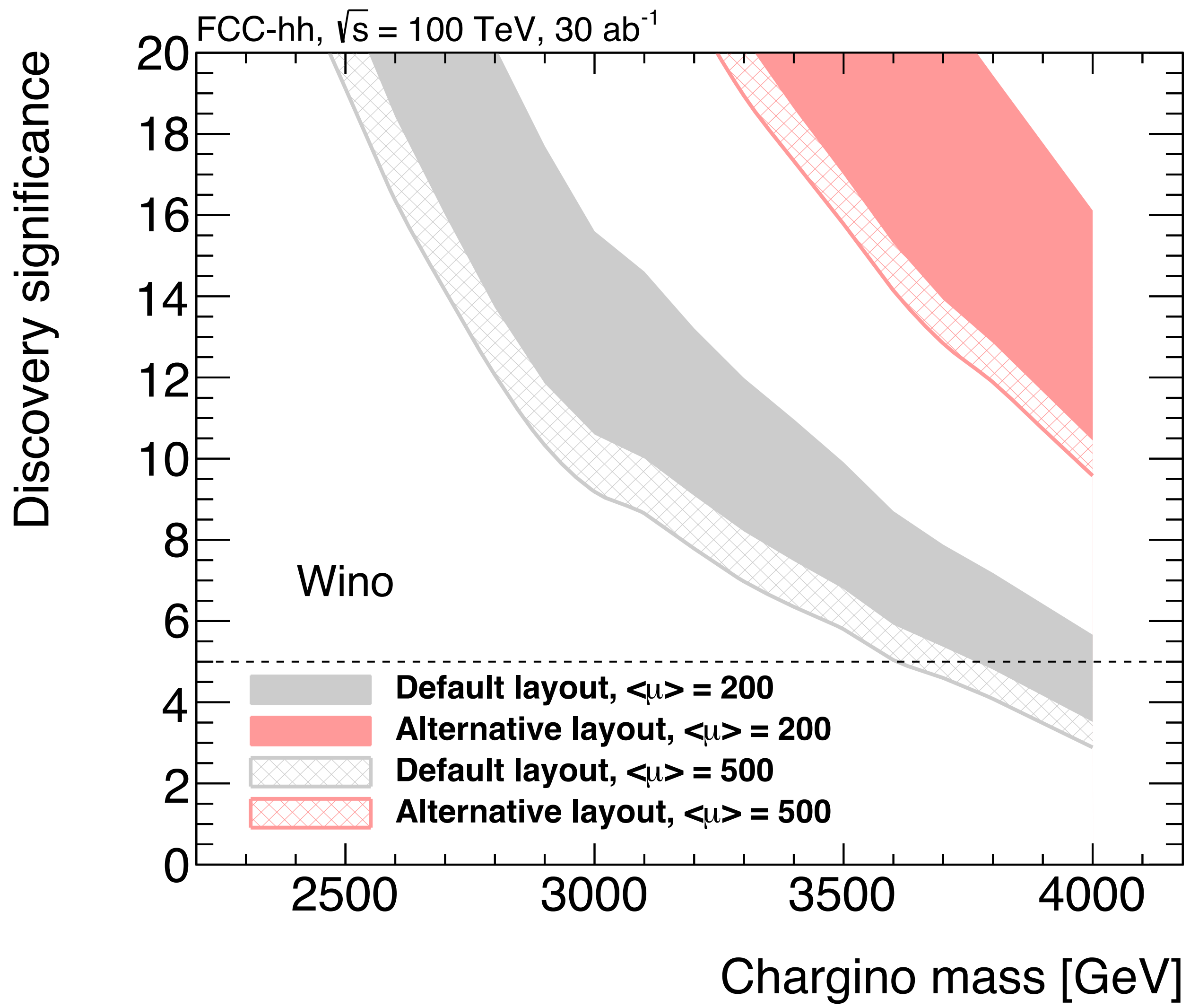


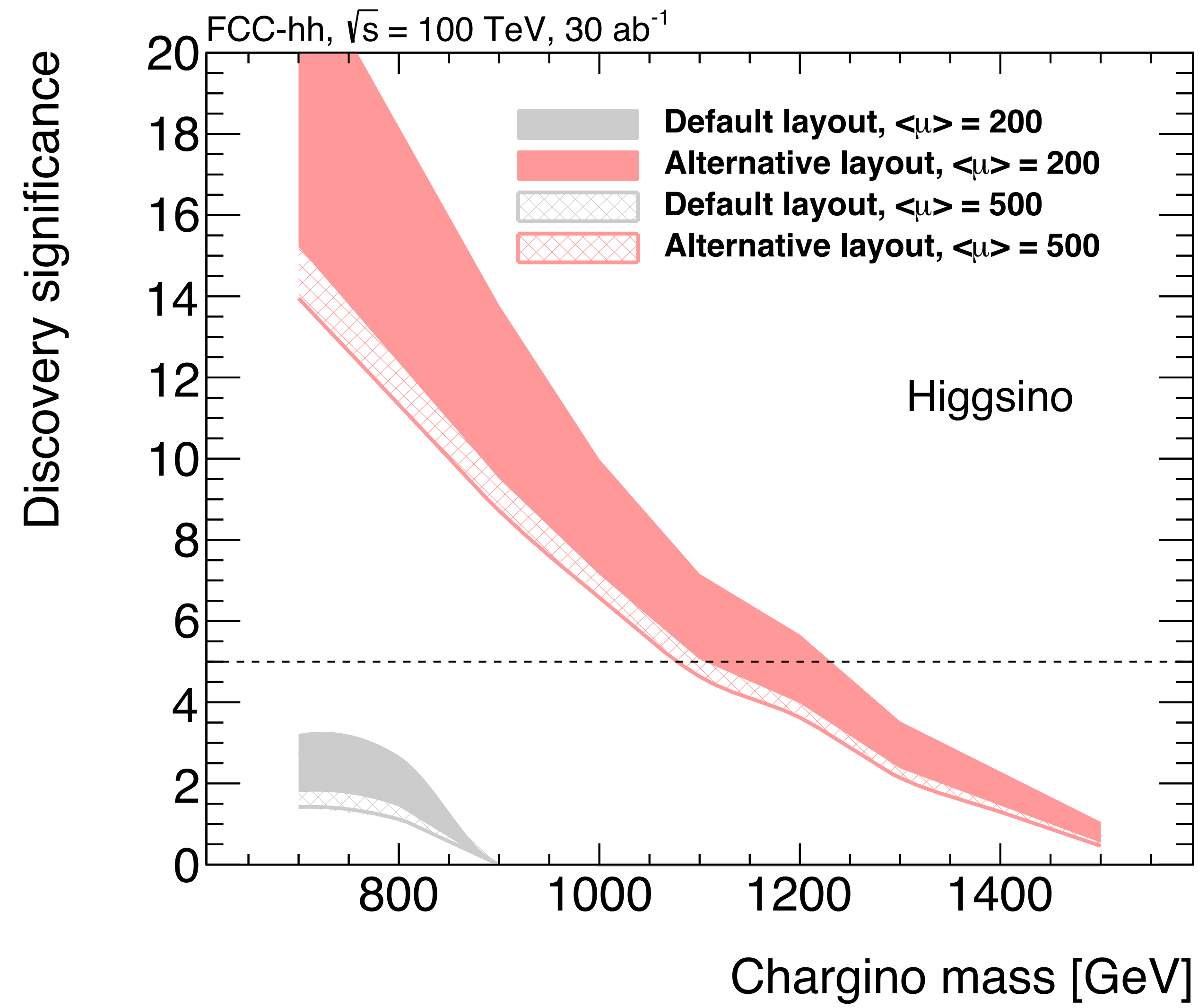
FCC-hh reach ~ 6 x HL-LHC reach

Prospects to discover/exclude WIMP DM:
coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

Disappearing charged track analyses

(at ~full pileup)





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.

To learn more about future circular colliders:

FCC hh ee he

CERN

CERN
4-5 March 2019
500-1-001 - Main Auditorium

Starts 4 Mar 2019, 13:30

Ends 5 Mar 2019, 18:30

PHYSICS AT FCC

OVERVIEW OF THE
FCC CONCEPTUAL
DESIGN REPORT

https://indico.cern.ch/event/789349/

In preparation for the discussions at the European Strategy meeting in Granada, this Conference will review the main findings of the physics studies carried out in the context of the FCC CDR. The physics discussion will be accompanied by a status report of the overall project, reviewing the technological challenges for both accelerator and detectors, the ongoing actions to address them, the project implementation strategy, and the cost estimates.

This Conference is open to colleagues, interested in the future of high energy physics in Europe, to learn more about the extraordinary progress made in the past 5 years in defining a realistic plan to meet the ambitious physics targets of the FCC.

https://indico.cern.ch/event/789349/

The International Workshop on the Circular Electron Positron Collider EU EDITION 2019

Oxford, April 15-17, 2019

http://www.physics.ox.ac.uk/confs/CEPC2019/

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