CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

FERMILAB Joint Experimental-Theoretical Physics Seminar

The future of collider physics

(primarily tailored to the audience of the HCP Summer School)

14 August 2020

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Warning: I am biased !

- 1982. CERN summer student in UA1, preparing the run that led to the W and Z discovery
- 1988-1995. CDF member, top quark discovery
- 1995-2000. LEP2: coordinating workshops and LEPC member
- 2000-today. LHC: theoretical modeling, LHCC member and, since 2010, Coordinator of the LHC Physics Centre at CERN
- 2013-today. Future Circular Collider (FCC), coordinator of the FCC-hh physics studies

The 10-year legacy of the LHC*

CERN Courier March/April 2020
https://arxiv.org/abs/2003.05976

- The LHC works, and is more powerful than expected !
- The experiments work, and are more precise than expected !
- Theory works, and is more reliable than expected !
- The Higgs exists …
- … and nothing else beyond the Standard Model showed up …
- … but the spectrum of physics emerged from the LHC is far richer than expected !
- … in particular, the precision of the measurements and of their theoretical interpretations emerged as an outstanding feature and bonus of high-energy and high-luminosity hadron colliders

** building on the experience (accelerator & detector technology, experiments and analysis, theoretical understanding) of all colliders that preceded it*

LHC scientific production

Over 3000 papers published/submitted to refereed journals by the 7 experiments* (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on measurements of "the real world": jets, EW, top, b, HIs, … *(70% adding the Higgs …)*

** to be joined in Run3 by an 8th , new, experiment: FASER*

What are we talking about when

we talk about future colliders?

Circular …

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

✓Approved 2026-37

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

in a 100km tunnel around CERN

link to CDR

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

link to CDR

in a 100km tunnel in China

... linear

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

TDR 2012,
decision pending

TDR: Technical Design Report

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

CDR 2012+
update '16

CDR: Conceptual Design Report

All of this is consistent with the future landscape outlined in the top priority emerged from the 2020 update of the European Strategy for Particle Physics:

High-priority future initiatives, defined by the 2020 update of the European Strategy for Particle Physics

(1) ***An electron-positron Higgs factory is the highest-priority next collider.*** *For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology*

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

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

BEYOND…

From the deliberation document of the 2020 European Strategy Update:

[…] the accelerator R&D roadmap could contain:

- *the R&D for an effective breakthrough in plasma acceleration schemes (with laser and/or driving beams), as a fundamental step toward future linear colliders, possibly through intermediate achievements: e.g. building plasma-based free-electron lasers (FEL). Developments for compact facilities with a wide variety of applications, in medicine, photonics, etc., compatible with university capacities and small and medium-sized laboratories are promising;*

- *an international design study for a muon collider, as it represents a unique opportunity to achieve a multi- TeV energy domain beyond the reach of e+e– colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;*

beyond, with electrons (linear)

Multi-TeV e^+e^- colliders, from plasma wakefield acceleration

The ALEGRO collaboration https://www.lpgp.u-psud.fr/icfaana/alegro

Reference documents:

https://arxiv.org/pdf/1901.08436.pdf https://arxiv.org/pdf/1901.08436.pdf

Table 2.4: LWFA single stage parameters operating at a plasma density of $n_0 = 10^{17}$ cm^{-3}.

Plasma density (wall), n_0[cm^{-3}]	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, r_c[μm]	25
Laser wavelength, λ[μm]	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), L_b[μm]	36
Efficiency (wake-to-beam), η_b	75%
e^-/e^+ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

Example parameter sets for 0.25, 1, 3, 30 TeV center-of-mass LWFA-based colliders.

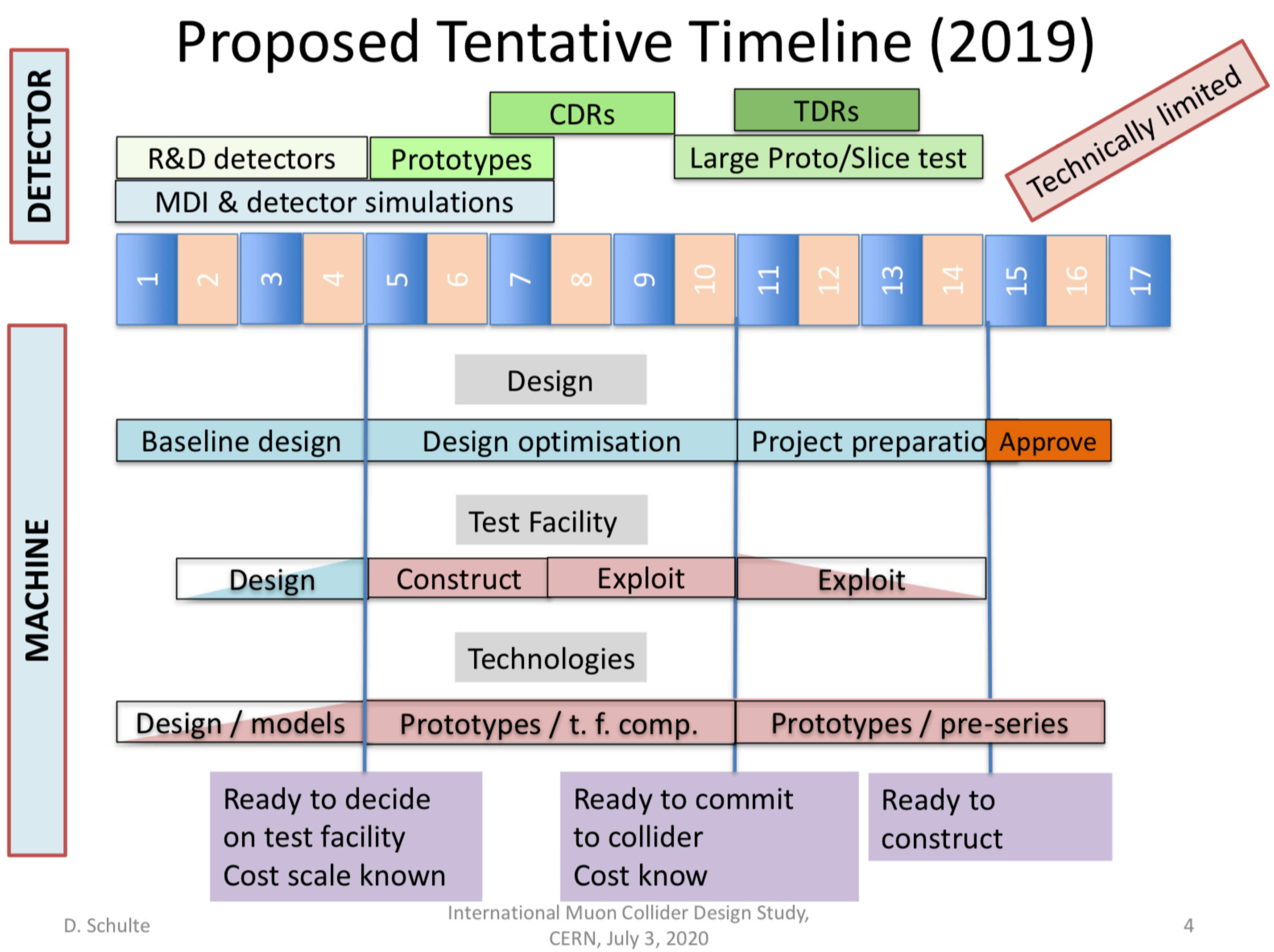
Energy, center-of-mass, $U_{\rm cm}$[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}[10^{34}\ \mathrm{s^{-1}cm^{-2}}]$	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size at IP, σ_y^*[nm]	1	1	0.5	0.5
Beamstrahlung parameter, Υ	0.5	2	16	2890
Beamstrahlung photons, n_γ	0.6	0.5	0.8	2.8
Beamstrahlung energy spread, δ_γ	0.06	0.08	0.2	0.8
Disruption paramter, D_x	0.07	0.02	0.05	3.0
Number of stages (1 linac), $N_{\rm stage}$	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), $L_{\rm total}$[km]	0.07	0.3	0.9	9.0
Average laser power, $P_{\rm avg}$[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), $P_{\rm wall}$[MW]	30	120	450	1250

peak accelerating field: 4.2 GeV/meter

beyond, with muons (circular)

=> International Muon Collider Design Study* recently set up

Kick-off meeting: https://indico.cern.ch/event/930508/



** building on 2 decades of preliminary work, notably within the US Muon Accelerator Program (MAP)*

the perspective of the skeptical

- **the technology skeptical** (“*too ambitious, too $$*”)
- **the timescale skeptical** (“*call me when you’re ready*”)
- **the discovery skeptical** (“*no guarantee*”)
- **the precision skeptical** (“*how boring, who cares*”)
- …

so, why do we reeeeally need future colliders ??

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

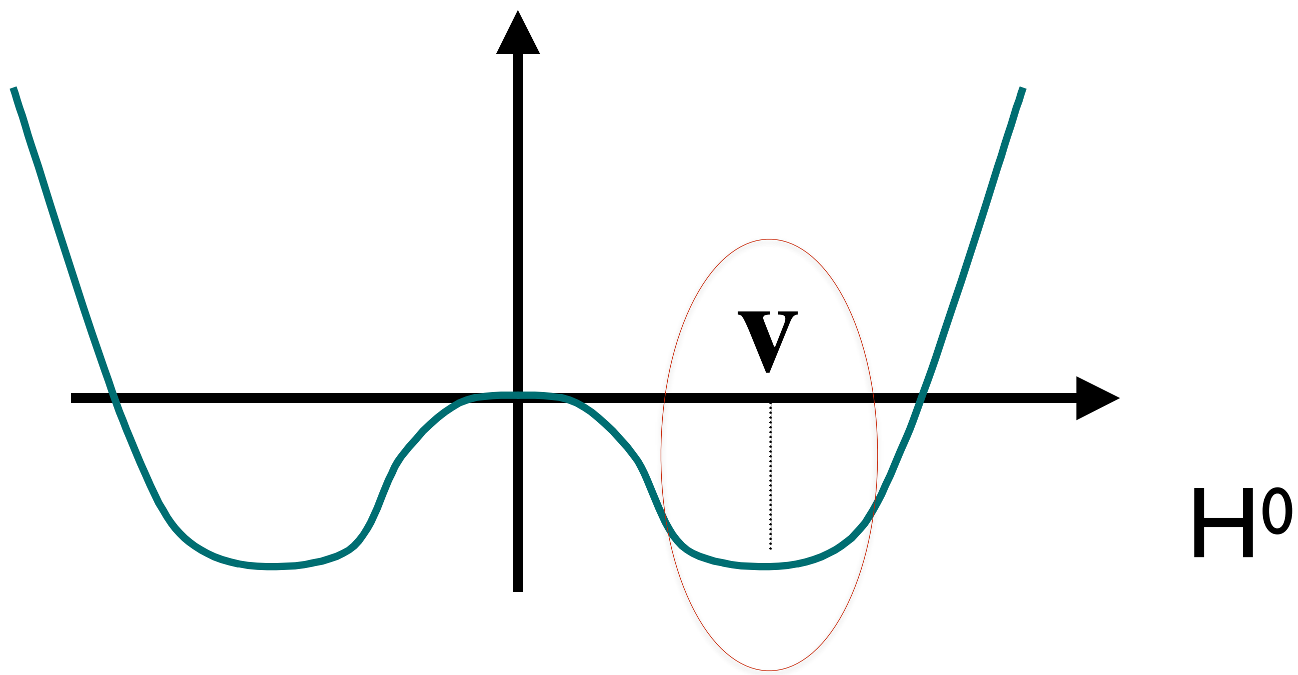
The important questions

- **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….

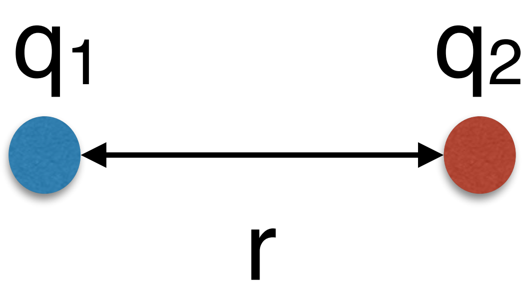


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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

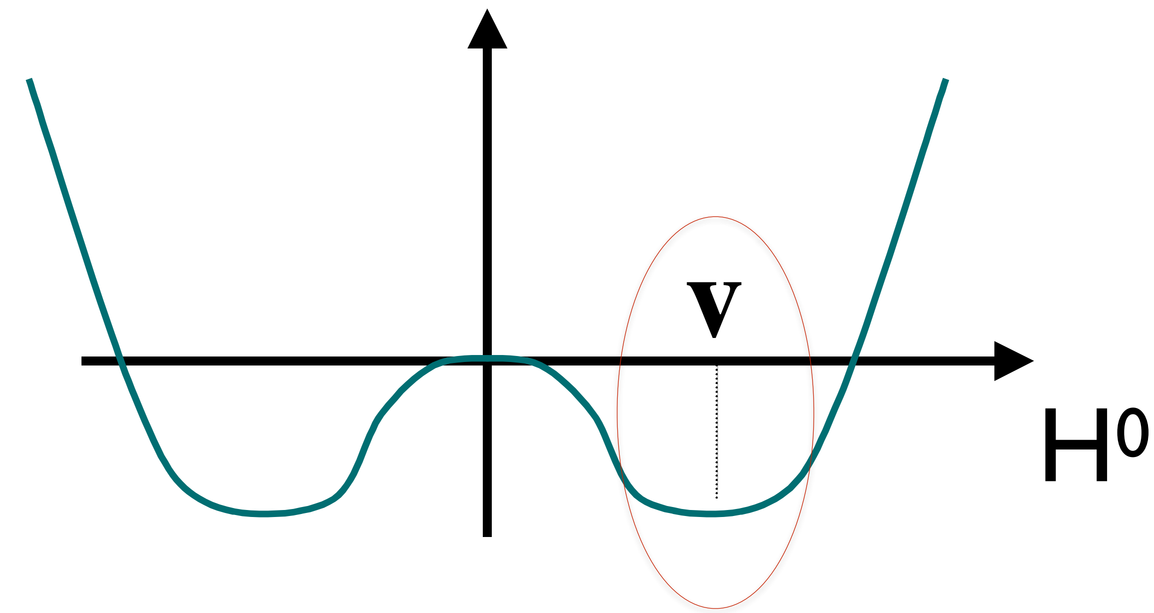


$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

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.

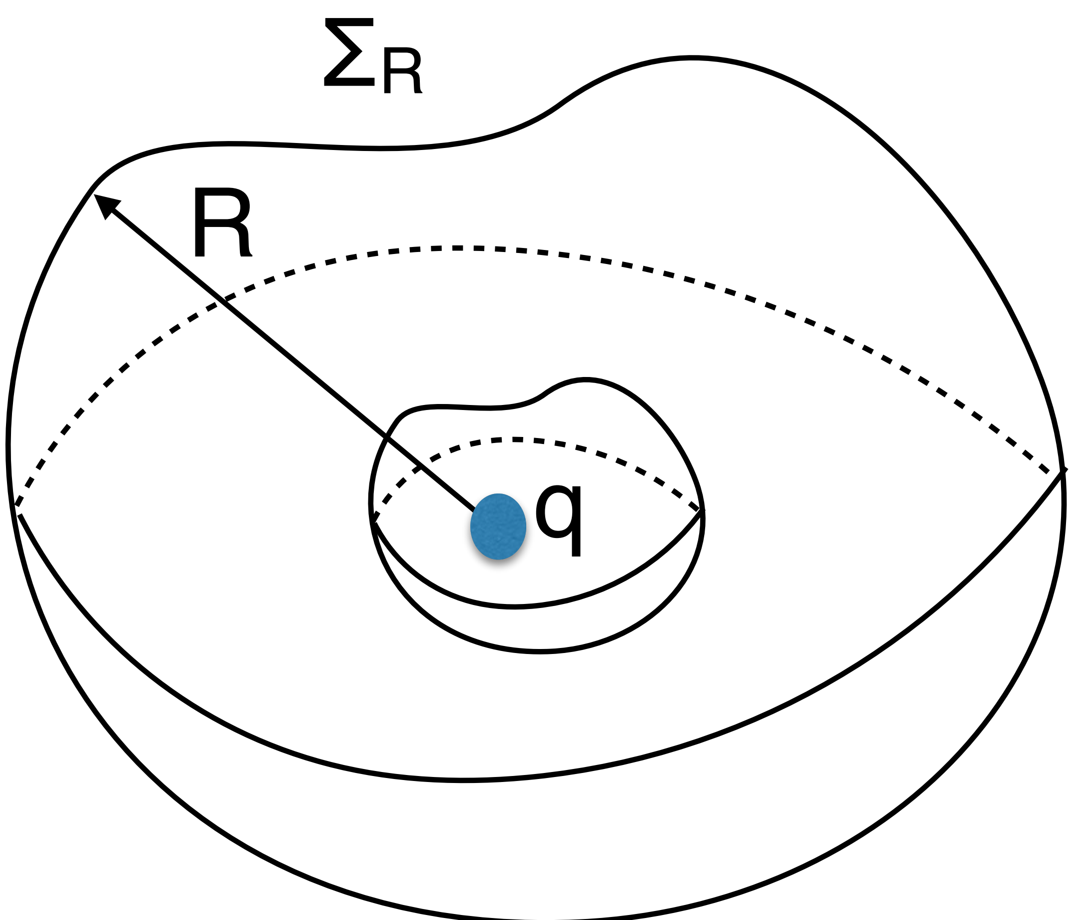
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases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

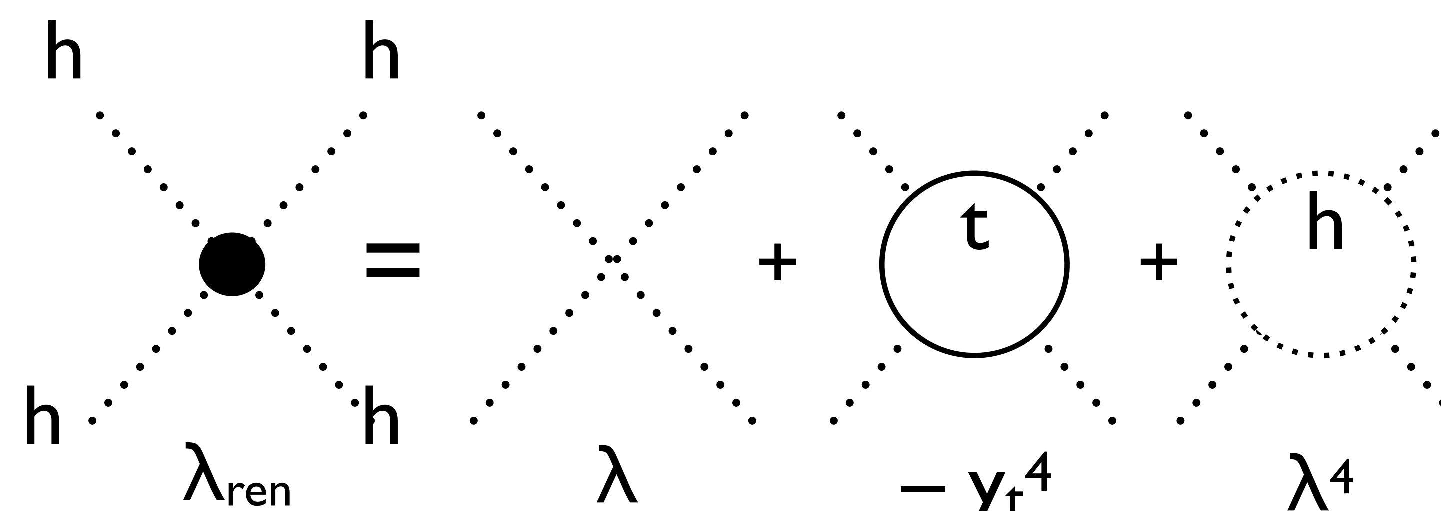


$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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**

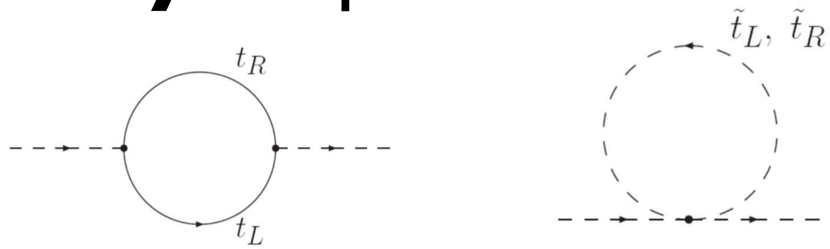
bottom line

- 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

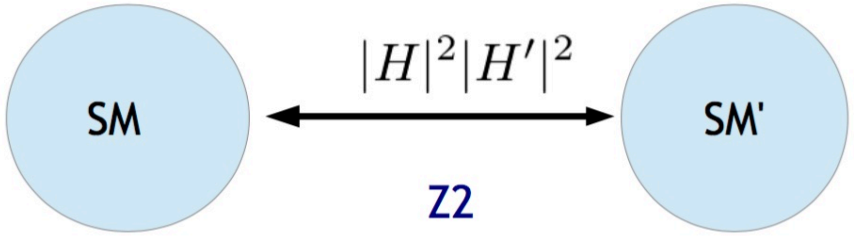
$\Rightarrow$ **naturalness**

Examples

- **Supersymmetry**: stop vs top (colored naturalness)



- **Extra-dimensions**: Planck scale closer than in 4-D, or Higgs as 4-D scalar component of a higher-dim gauge vector (KK modes, etc)
- **Little Higgs**: Higgs as a pseudo-Nambu-Goldstone boson of a larger symmetry, mass protected by global symmetries (top partners)
- **Neutral naturalness**: top contributions canceled by triplets of new particles neutral under SM gauge groups, but sharing the Higgs couplings with SM fermions (Higgs portals). Typically comes with doubling of (part of) SM gauge group (eg $SU(3)_A \times SU(3)_B$).
  - twin Higgs



  - folded SUSY ($SU(3)_B$ stops cancel Higgs couplings to $SU(3)_A$ tops)

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

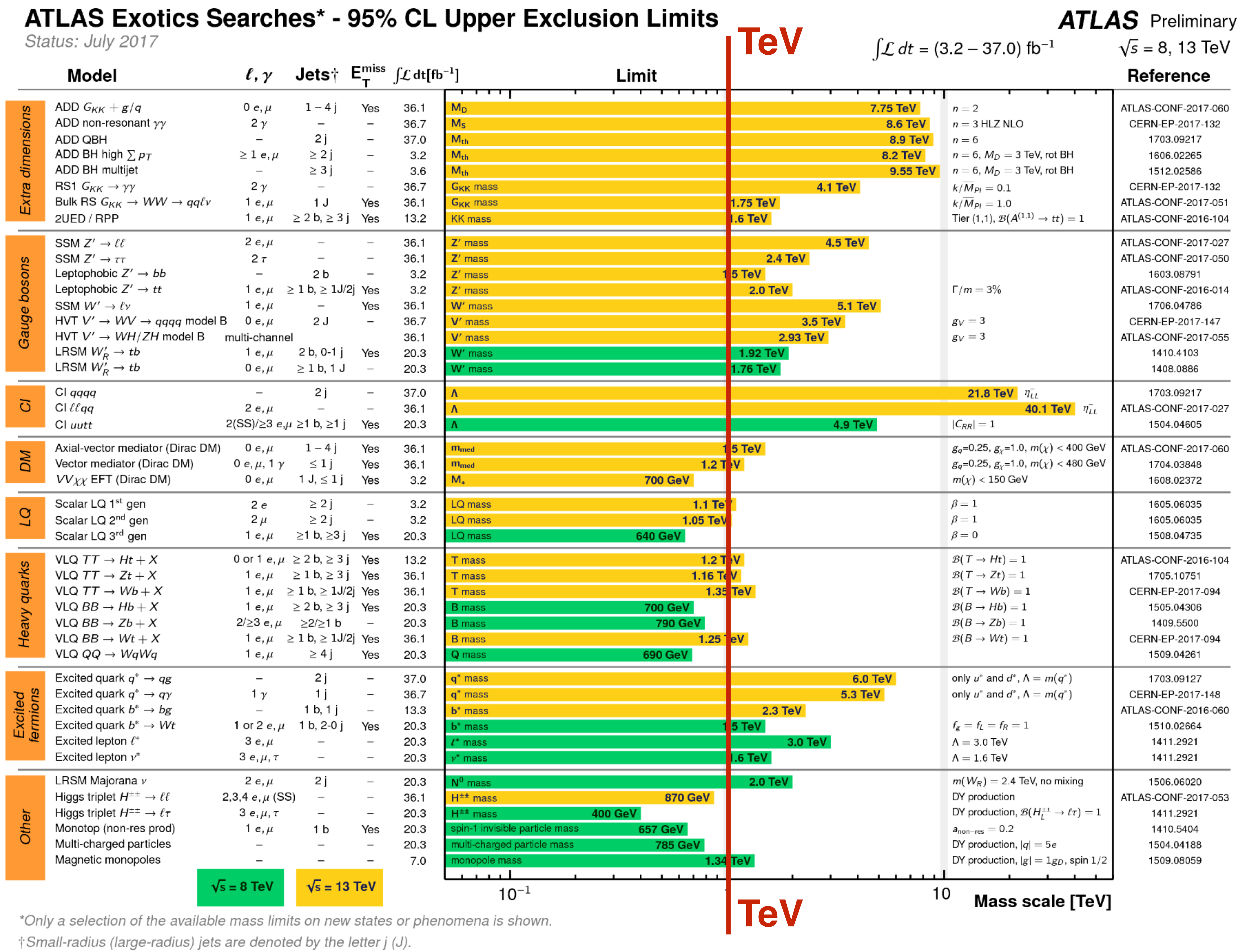
In search of the origin of known departures from the SM

- **Dark matter, long lived particles**
- **Neutrino masses**
- **Matter/antimatter asymmetry of the universe**

To explore alternative extensions of the SM

- **New gauge interactions (Z', W') or extra Higgs bosons**
- **Additional fermionic partners of quarks and leptons, leptoquarks, ...**
- **Composite nature of quarks and leptons**
- **Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, ...)**
- **Extra dimensions**
- **New flavour phenomena**
- **unanticipated surprises ...**

So far, no *conclusive* signal of physics beyond the SM



The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is 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, hold true 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>*

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **<u>same</u>** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **<u>same</u>** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H \to \mu\tau$? $H \to e\tau$? $t \to Hc$?

- Is there a deep reason for the apparent metastability of the Higgs vacuum?

- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

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*

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

On the role of measurement & precision

- 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?
  - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

(1) the **guaranteed deliverables**

(2) the **exploration potential**

(3) conclusive **yes/no answers** to relevant, broad questions.

In the rest of this talk, I'll give examples of these 3 points from the perspective of the Future Circular Collider facility (ee, pp, ep)

For more examples and details, look up the FCC CDR volumes cited in a previous slide

The purpose is not to prove superior performance relative to other proposals … the judgement is left to the world community, through the ongoing Snowmass process and future European Strategy reviews….

if you feel your preferred collider project is the best, fight for it!!

What a future circular collider can offer

- 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 at 100 TeV
    - *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: 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
	$2.5\ 10^{6}$	$2\ 10^{7}$

(1) guaranteed deliverables: Higgs properties

Sensitivity of various Higgs couplings to <u>examples</u> of beyond-the-SM phenomena

.

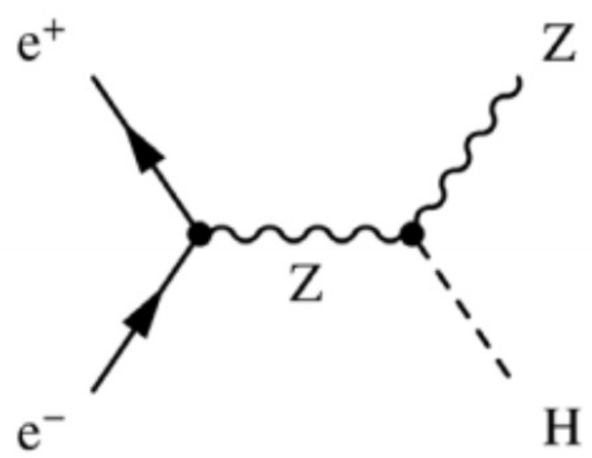
arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

=> for evidence of 3σ deviations from SM, the precision goal should be (sub)percent!

The absolutely unique power of $e^+e^- \to ZH$ (circular or linear):

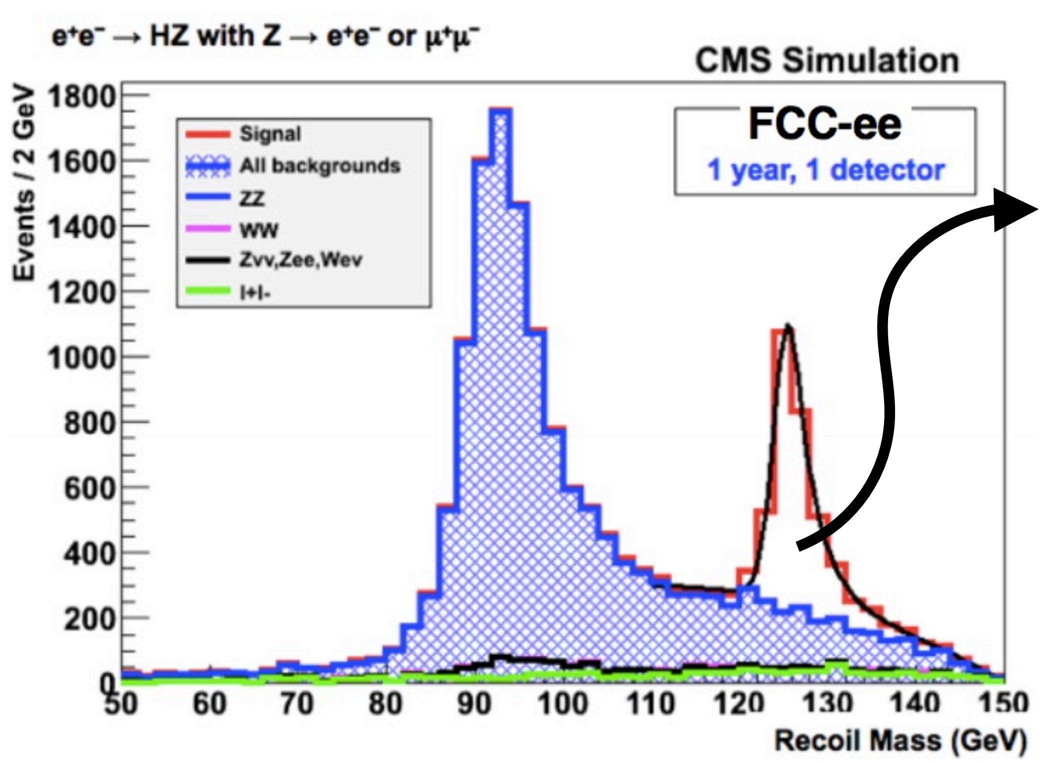
- the model independent % measurement of $\Gamma(H)$, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\ p(e^-e^+) - p(Z)\ ]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!



$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\to ZZ]) \propto$
$\sigma(ZH) \times BR(H \to ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

=> absolute measurement of width and couplings

$m_{recoil} = \sqrt{[\ p(e^-e^+) - p(Z)\ ]^2}$

The absolutely unique power of pp $\rightarrow$H+X:

- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR($H\rightarrow ZZ^*$), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	$gg\rightarrow H$	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

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

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

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)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

$BR(H\rightarrow Z\gamma,\gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for Δ_{stat}~%**

$BR(H\rightarrow\mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for Δ_{stat}~%**

pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt $B(H\rightarrow ZZ^*)$ @ FCC-ee

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

(I) guaranteed deliverables: EW observables

The absolutely unique power of **circular** e^+e^-:

$e^+e^- \to Z$	$e^+e^- \to WW$	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
$5\ 10^{12}$	10^{8}	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

=> $O(10^5)$ larger statistics than LEP at the Z peak and WW threshold

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
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480±160	3	2-5
$1/\alpha_{\mathrm{QED}}(m_Z)$ ($\times 10^3$)	128952±14	4	Small
$A_{\mathrm{FB}}^{b,0}$ ($\times 10^4$)	992±16	0.02	1-3
$A_{\mathrm{FB}}^{\mathrm{pol},\tau}$ ($\times 10^4$)	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
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

Precision W physics with pp→tt[→Wb]

MLM @ SEARCH2016

A concrete application:
testing lepton universality in W decays

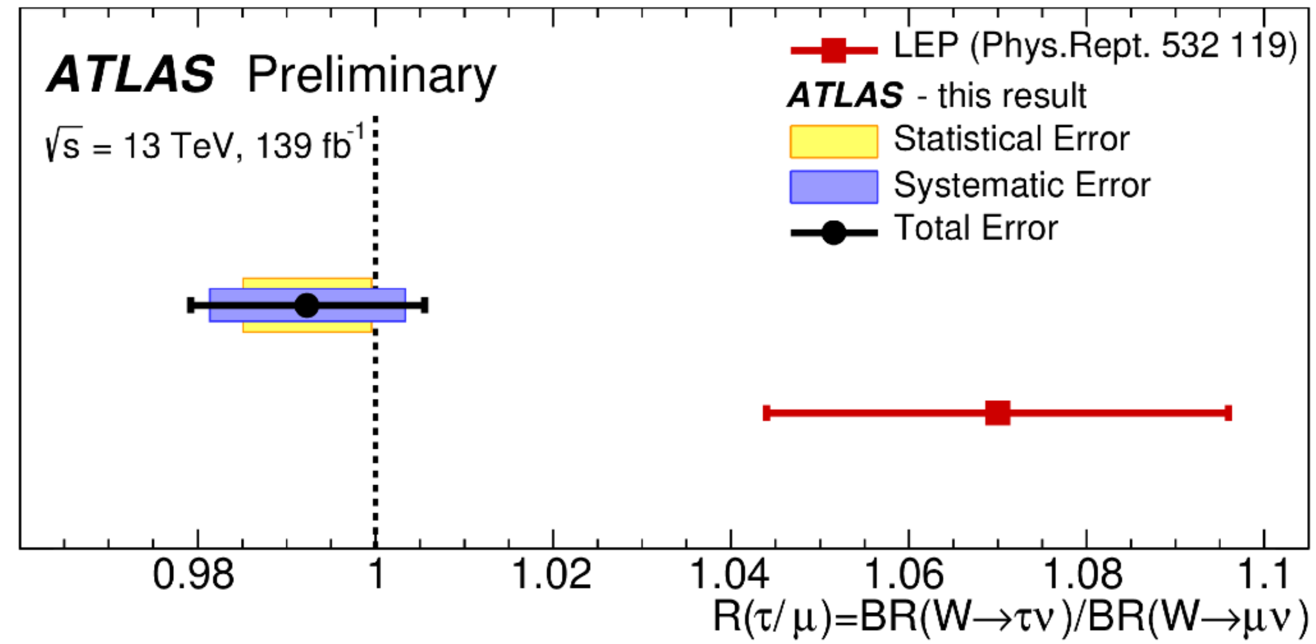
PDG entries dominated by LEP2 data

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40192
$\mu^+\nu$		(10.63 ± 0.15) %		40192
$\tau^+\nu$		(11.38 ± 0.21) %		40173

BR(τ) / BR(e/μ) ~ 1.066 ± 0.025 => ~ 2.5 σ

can the LHC clarify this issue with its eventual 10^7 leptonic W decays from the top?

ATLAS 2020:

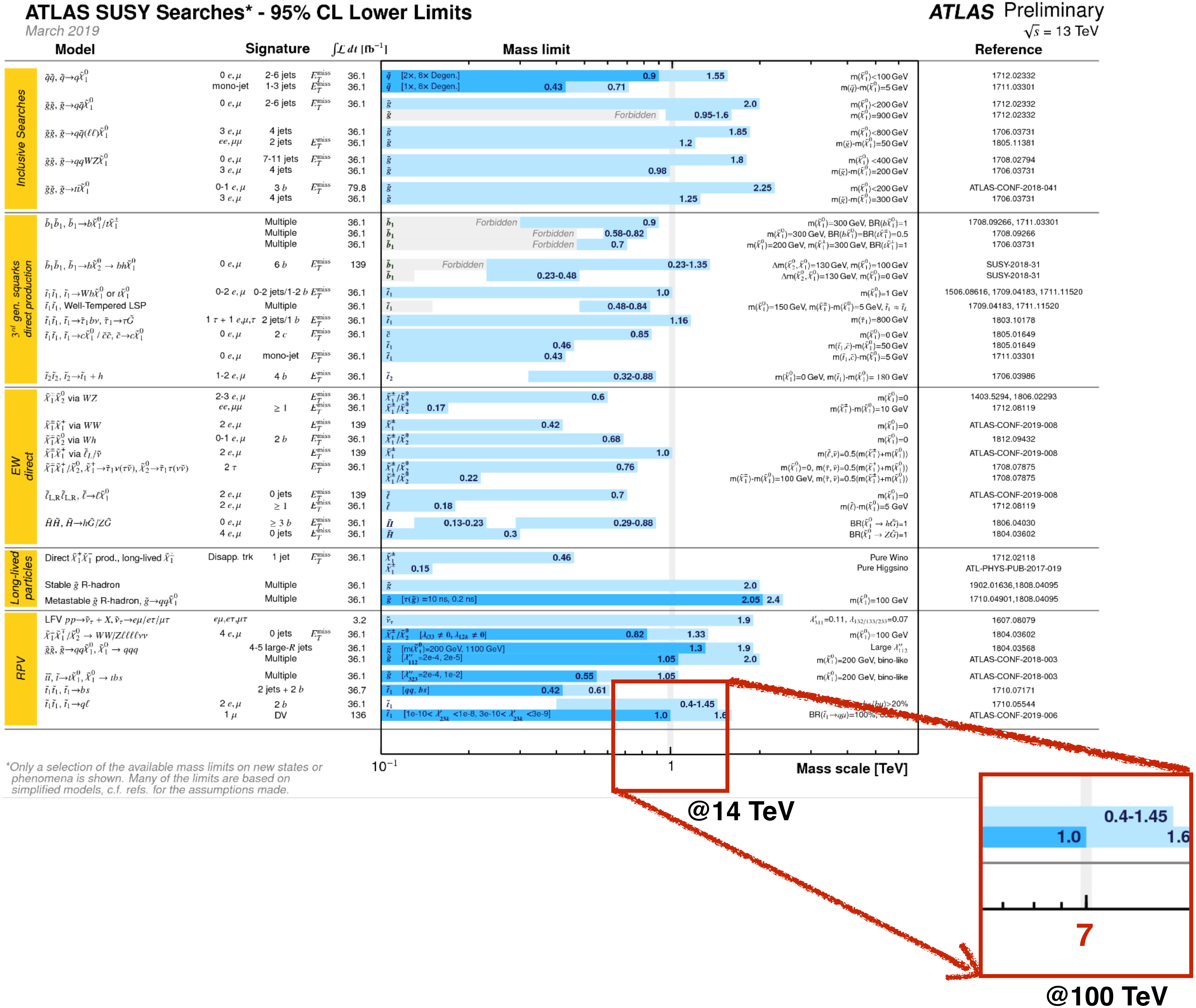


LEP:
***BR*(W→τν)/*BR*(W→μν) = 1.066 ± 0.025**

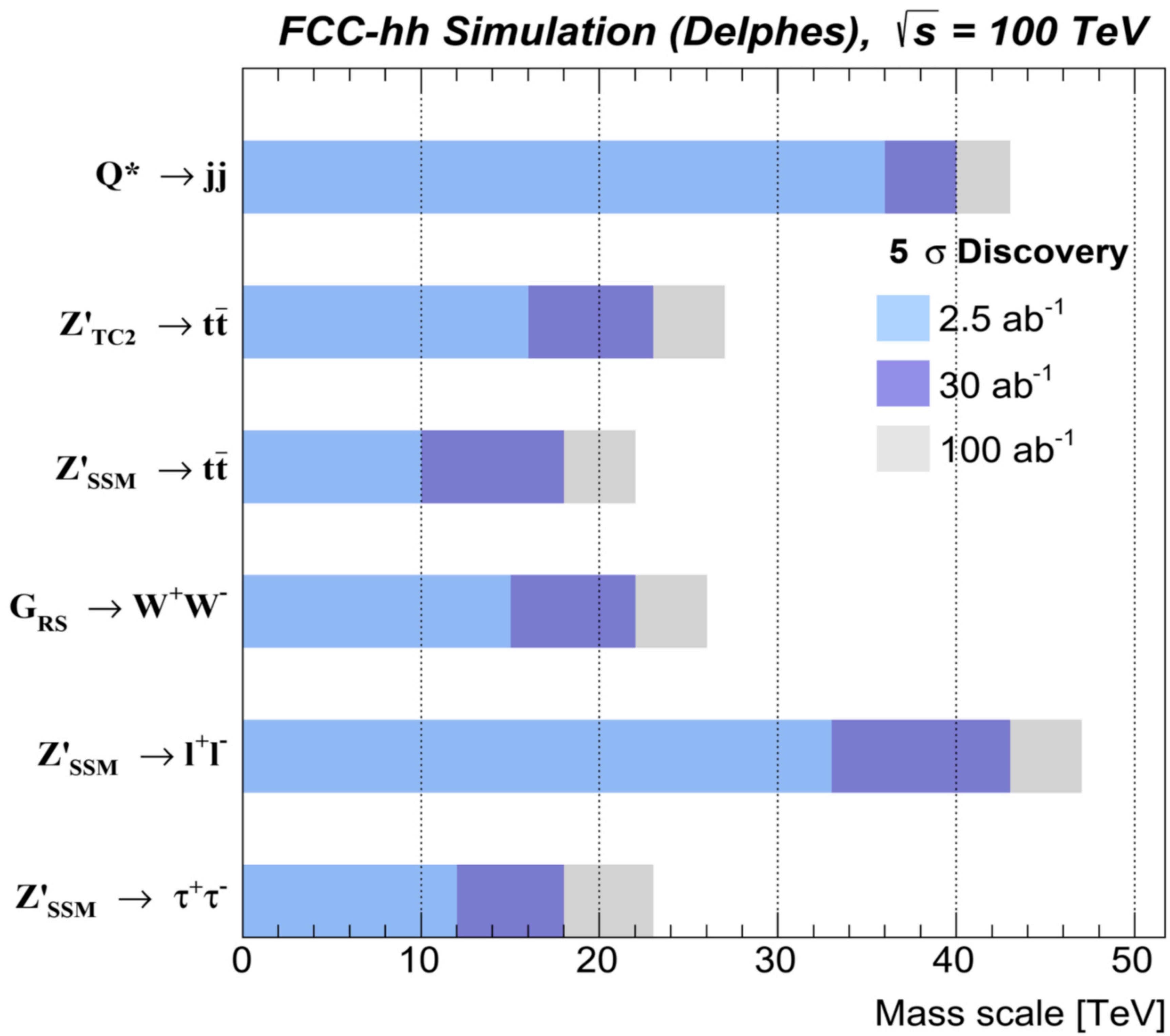
ATLAS:
***BR*(W→τν)/*BR*(W→μν) = 0.992 ± 0.013**

FCC-hh	t	W(←t)	τ(←W←t)
	10^{12}	10^{12}	10^{11}

(2) Direct discovery reach at high mass: the power of 100 TeV


ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\, dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
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

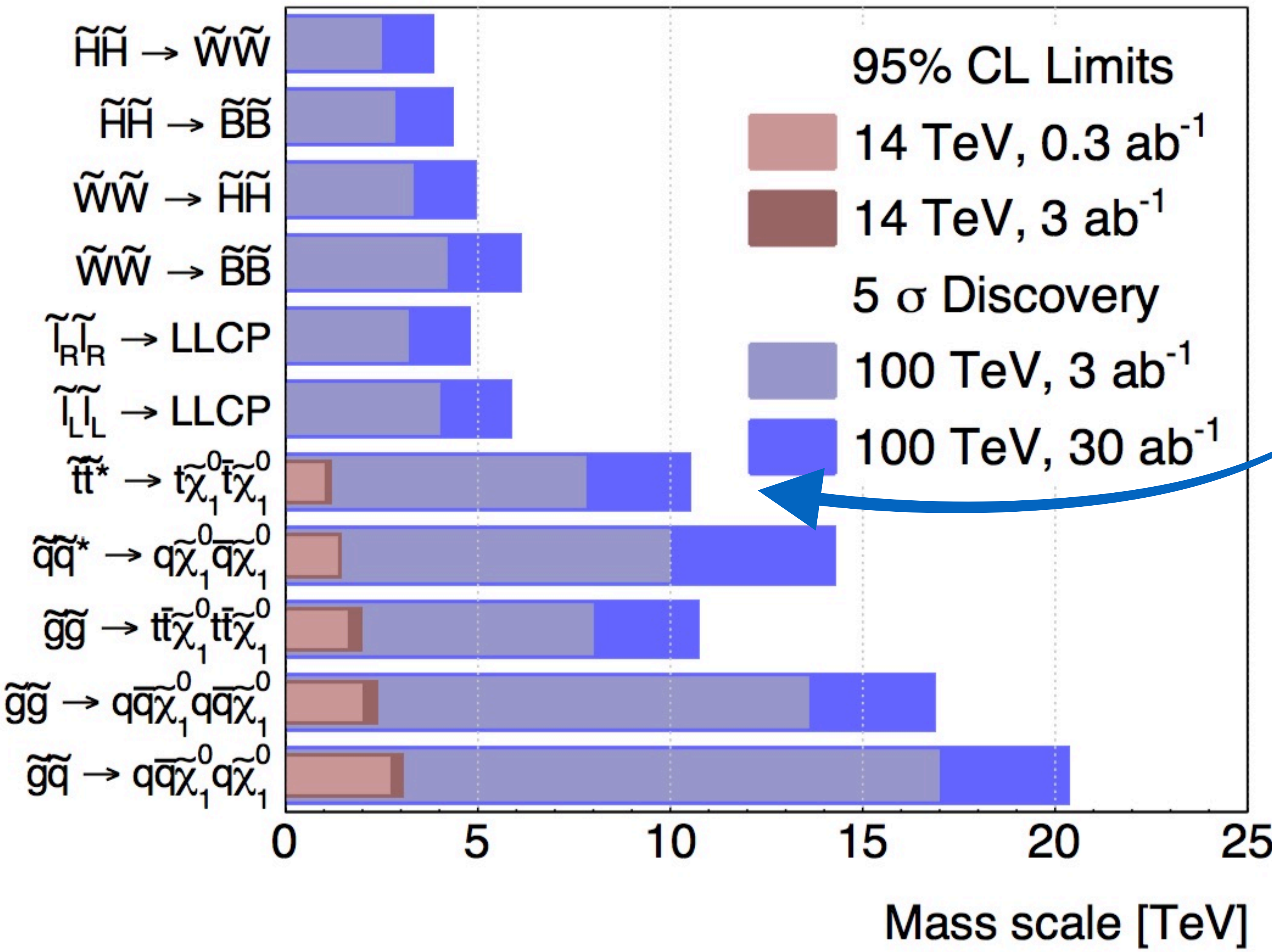
s-channel resonances



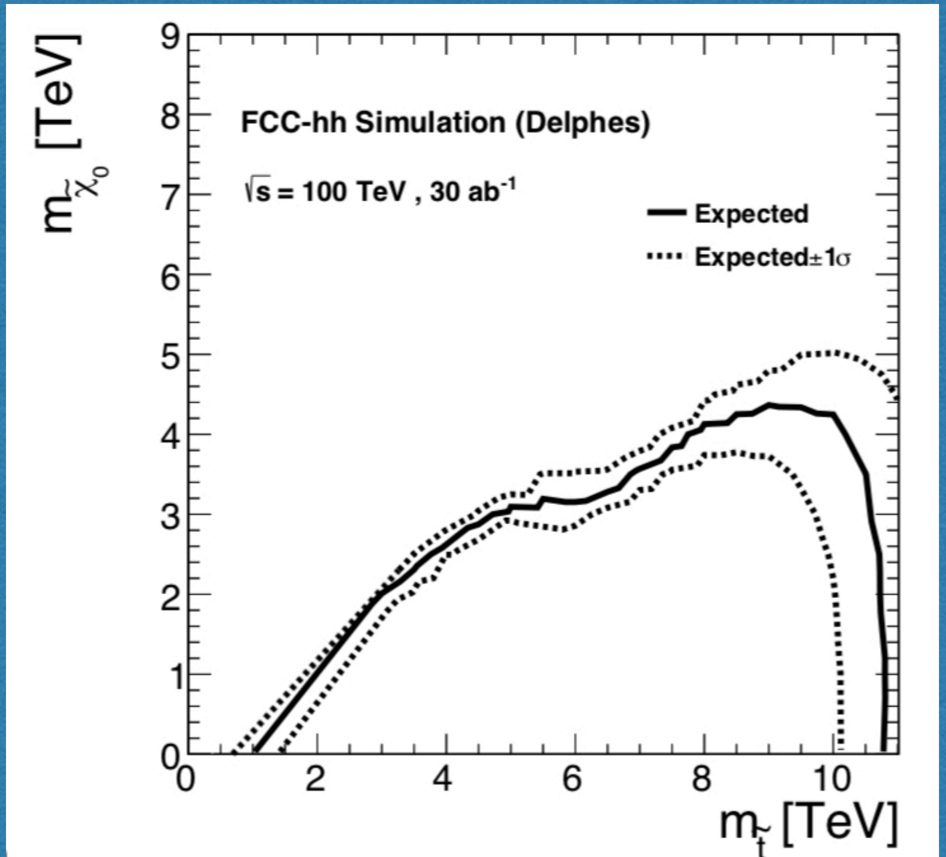
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

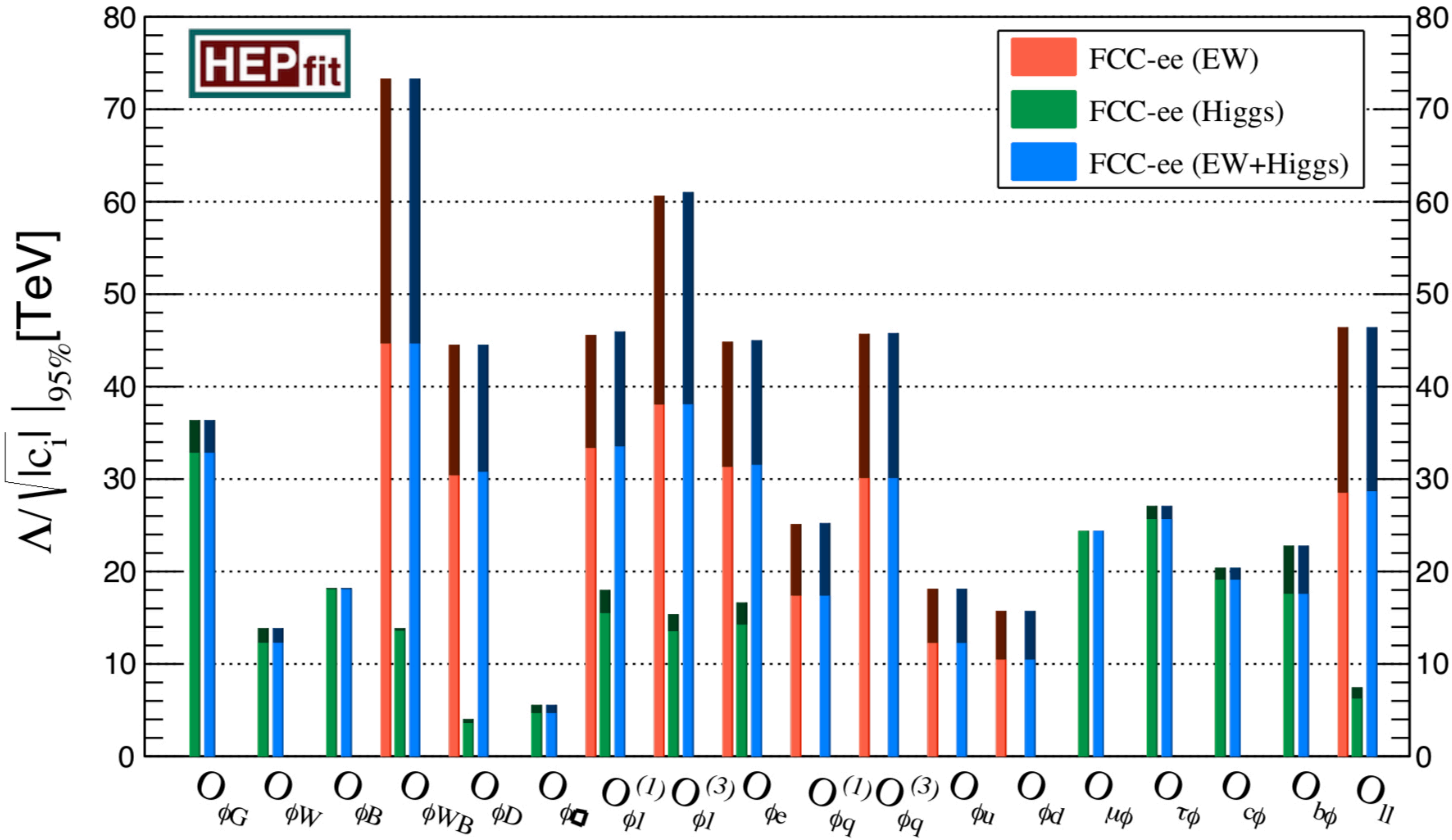
Early phenomenology studies



New detector performance studies



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.

100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision EW and H measurements at the future ee collider

(3) **The potential for yes/no answers to important questions**

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\rm DM} h^2 \sim \frac{10^9 {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

$$\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

$$\Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}} \right)^2 \left(\frac{0.3}{g_{\rm eff}} \right)^4$$

$$\Omega_{wimp}\, h^2 \lesssim 0.12$$

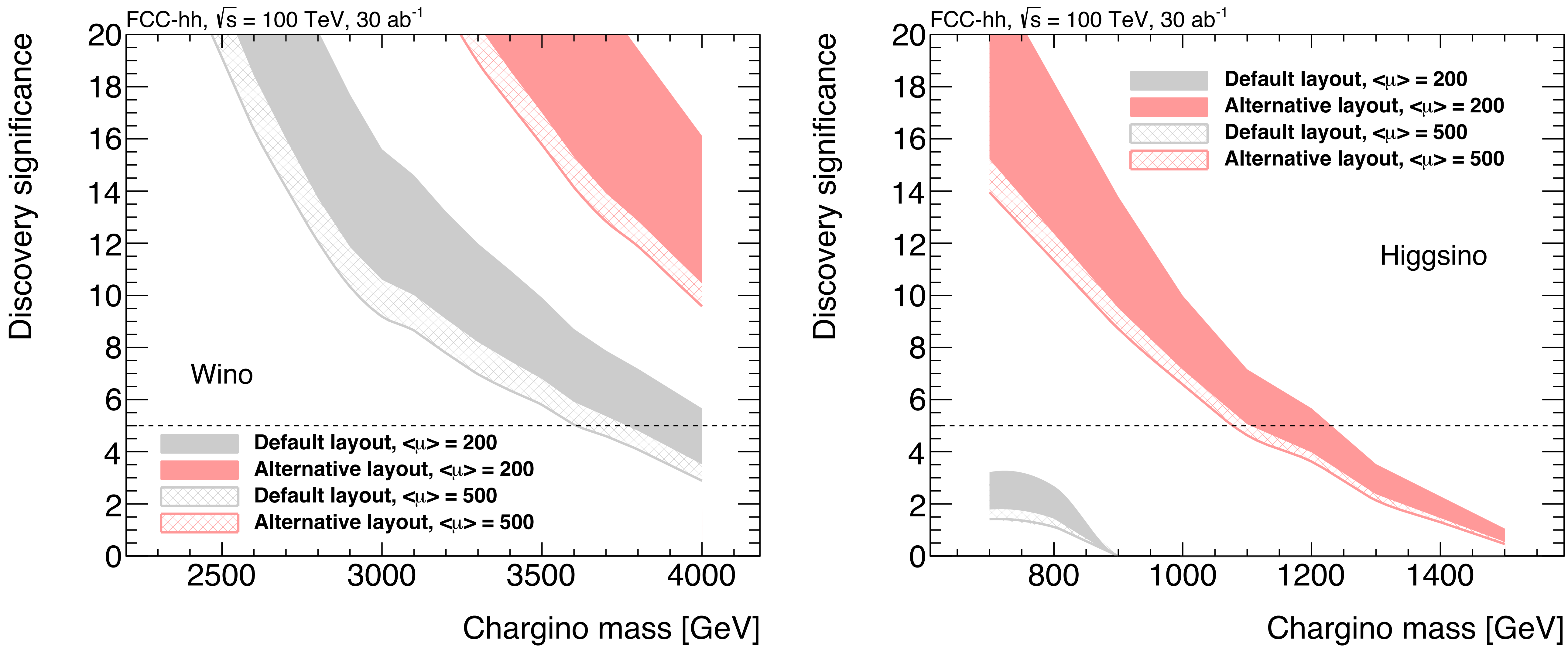
$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3} \right)^2$$

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

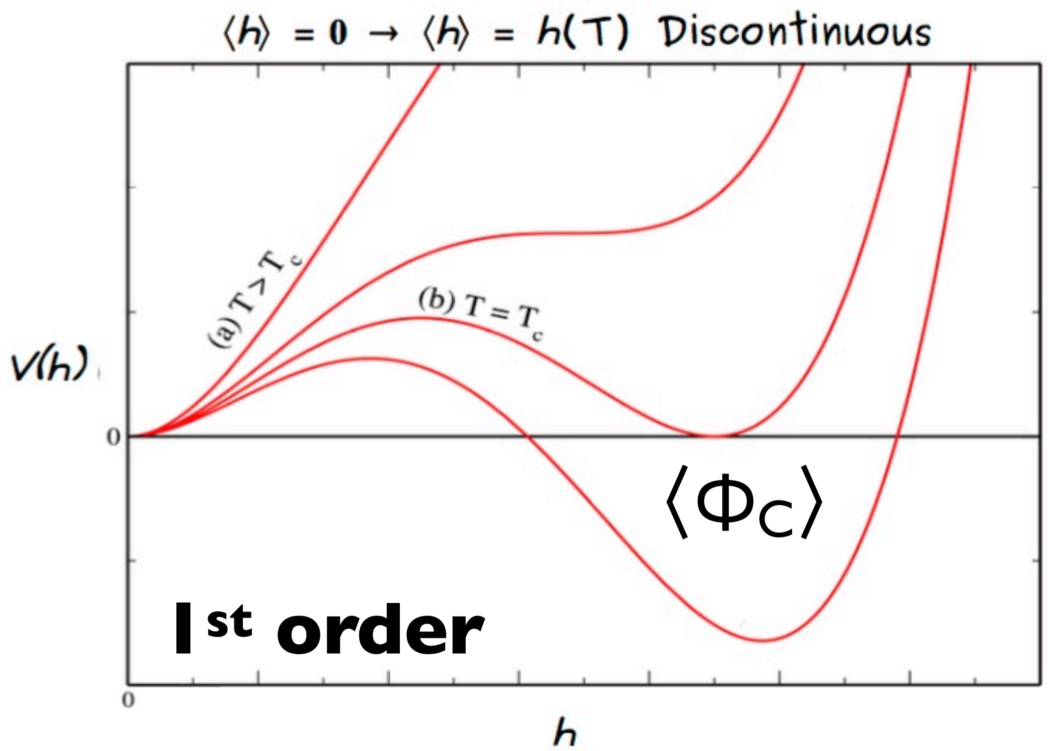
(at ~full pileup)

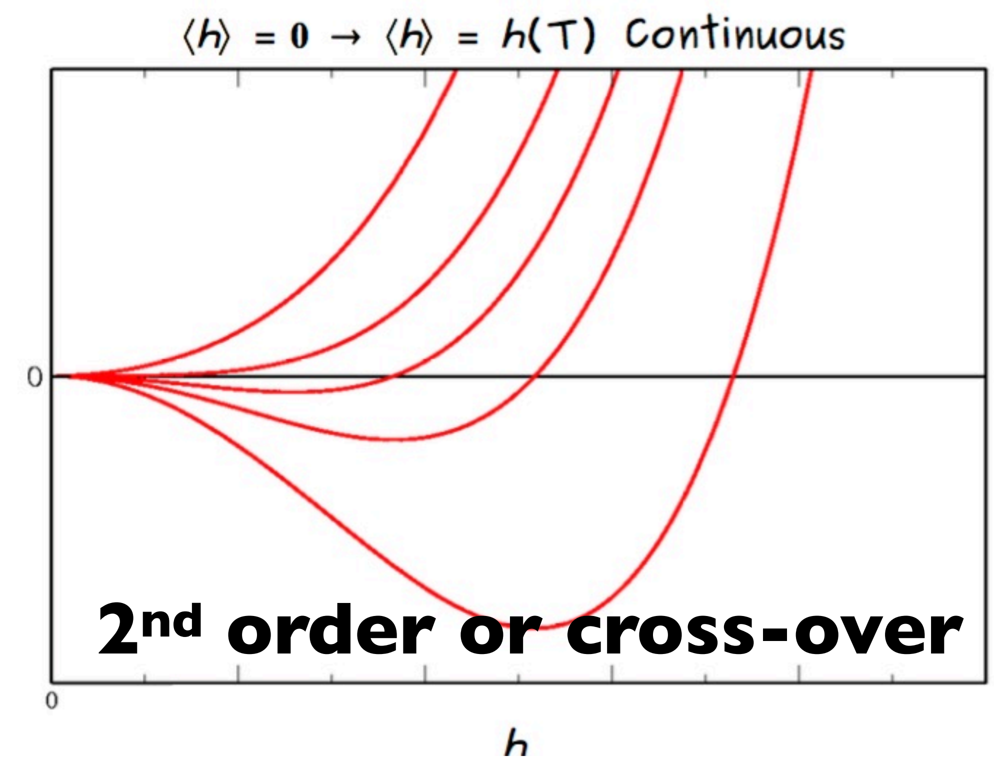


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3}\right)^2$$

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.

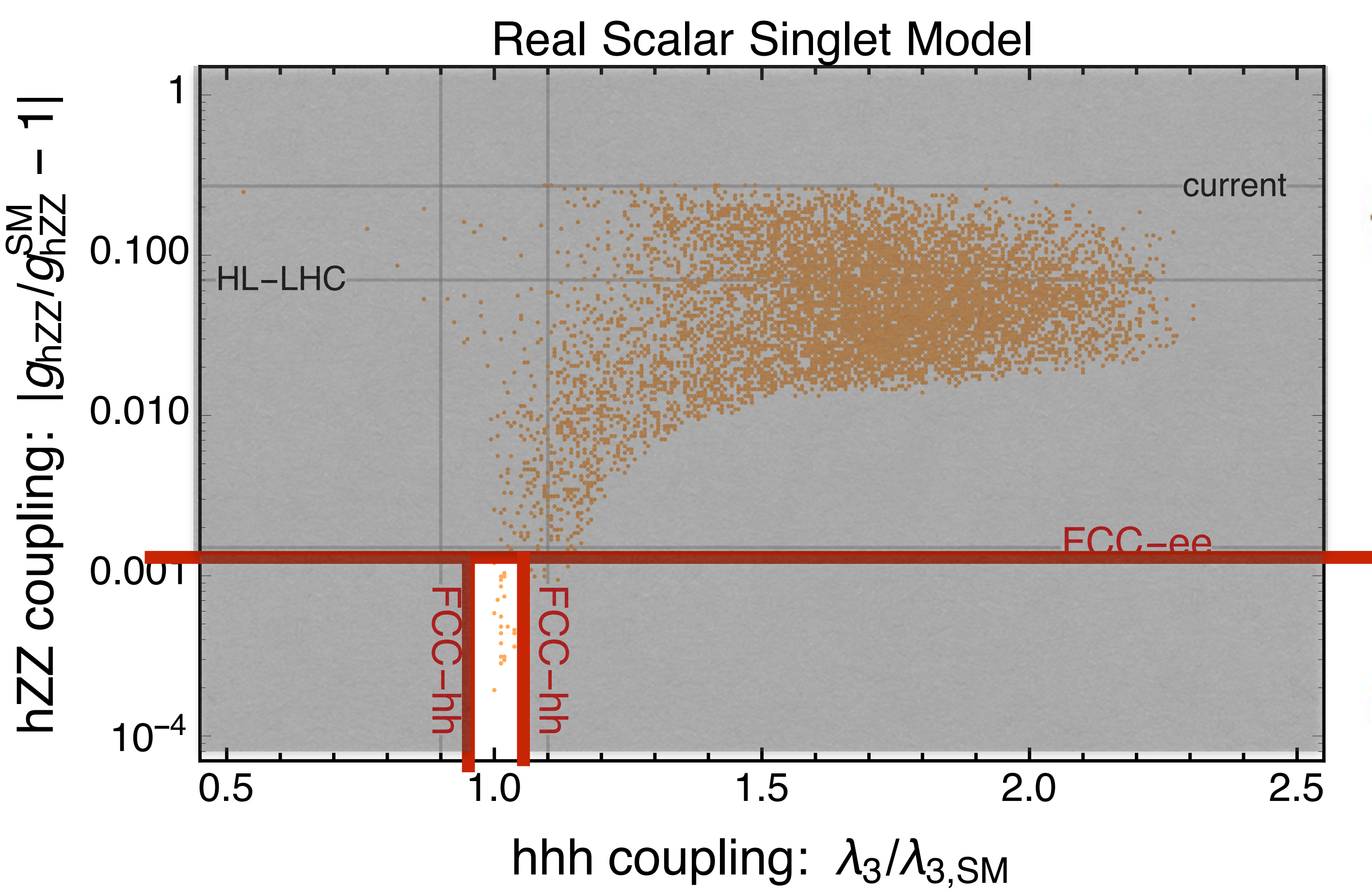
Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

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

Constraints on models with 1st order phase transition at the FCC

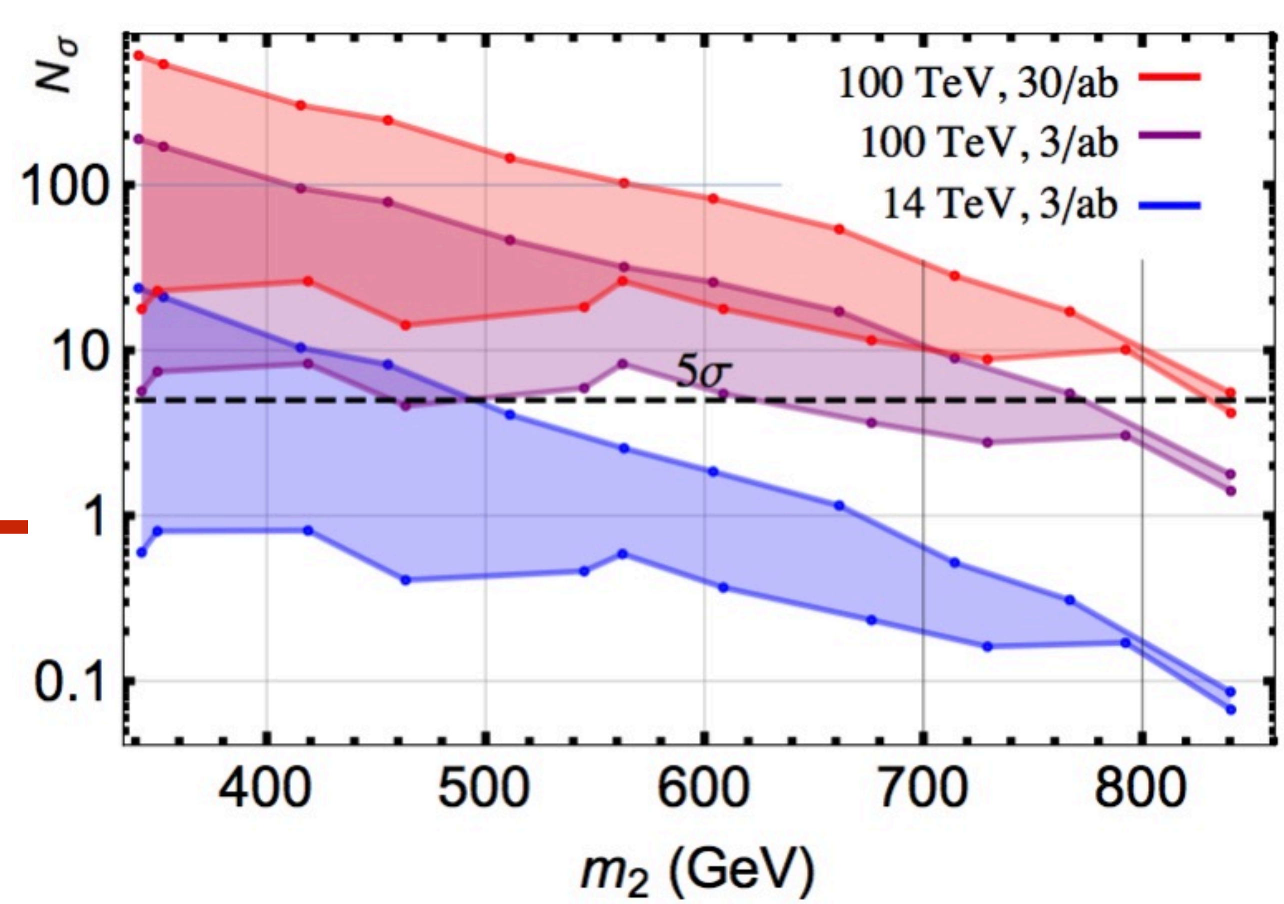
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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

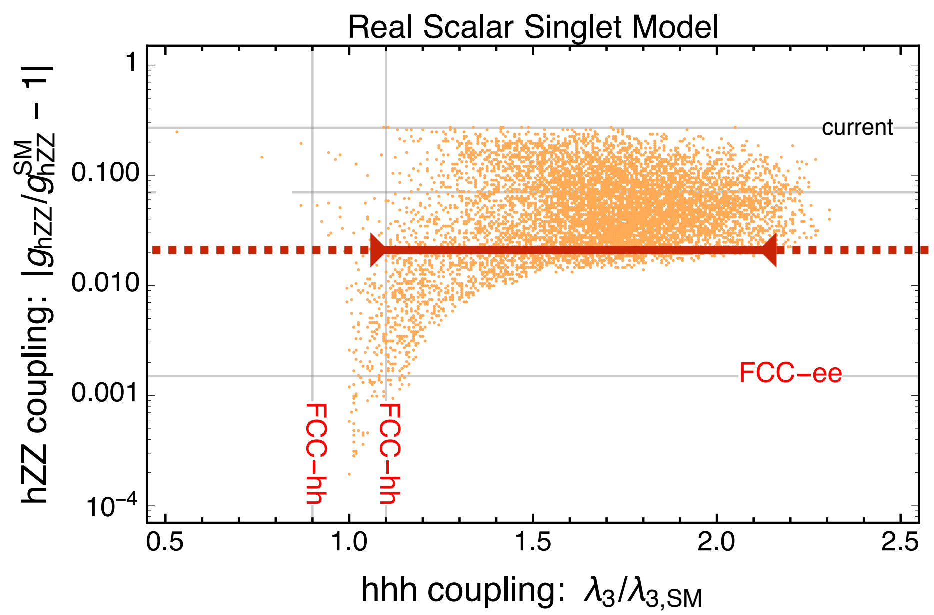


$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

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

Remarks

- Apparently, adding the self-coupling constraint does not add much in terms of exclusion power, wrt the HZZ coupling measurement …
- … BUT, should HZZ deviate from the SM, λ_{HHH} is necessary to break the degeneracy among all parameter sets leading to the same HZZ prediction



- The concept of *"which experiment sets a better constraint on a given parameter"* is a very limited comparison criterion, which looses value as we move from *"setting limits"* to *"diagnosing observed discrepancies"*
- Likewise, it's often said that some observable sets better limits than others: "all known model predict deviations in X larger than deviations in Y, so we better focus on X". But once X is observed to deviate, knowing the value of Y could be absolutely crucial ….
- Redundancy and complementarity of observables is of paramount importance

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 breadth and diversity of the non-collider exptl program (see eg satellite, cosmological, underground and table-top probes of DM or the multitude of neutrino probes, from astrophysics to CR to accelerator to $\nu 0 2\beta$ decays etc) find a match in the huge variety of the exptl program possible at a future collider facility, where concrete, compelling and indispensable Higgs & SM measurements enrich a unique direct & indirect discovery potential
- The *personal* perspective: 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*