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Oltre LHC: la fisica al Future Circular Collider (FCC)

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Why we need a future circular collider ?

… because there are many fundamental questions in our understanding of Nature, and thus of particle physics, which cannot be answered with the current accelerators and experiments

… in particular, once we understand **how** something works, it’s time to understand **why**

… and, in general, what we know and give for granted today may need revision once new evidence emerges, triggering new scientific revolutions

… therefore, we will always need a "**future**" experimental facility, to continue the endless exploration of nature at the most fundamental level

The discussion about, and study of, post-LHC colliders began well before the LHC even started

The open questions

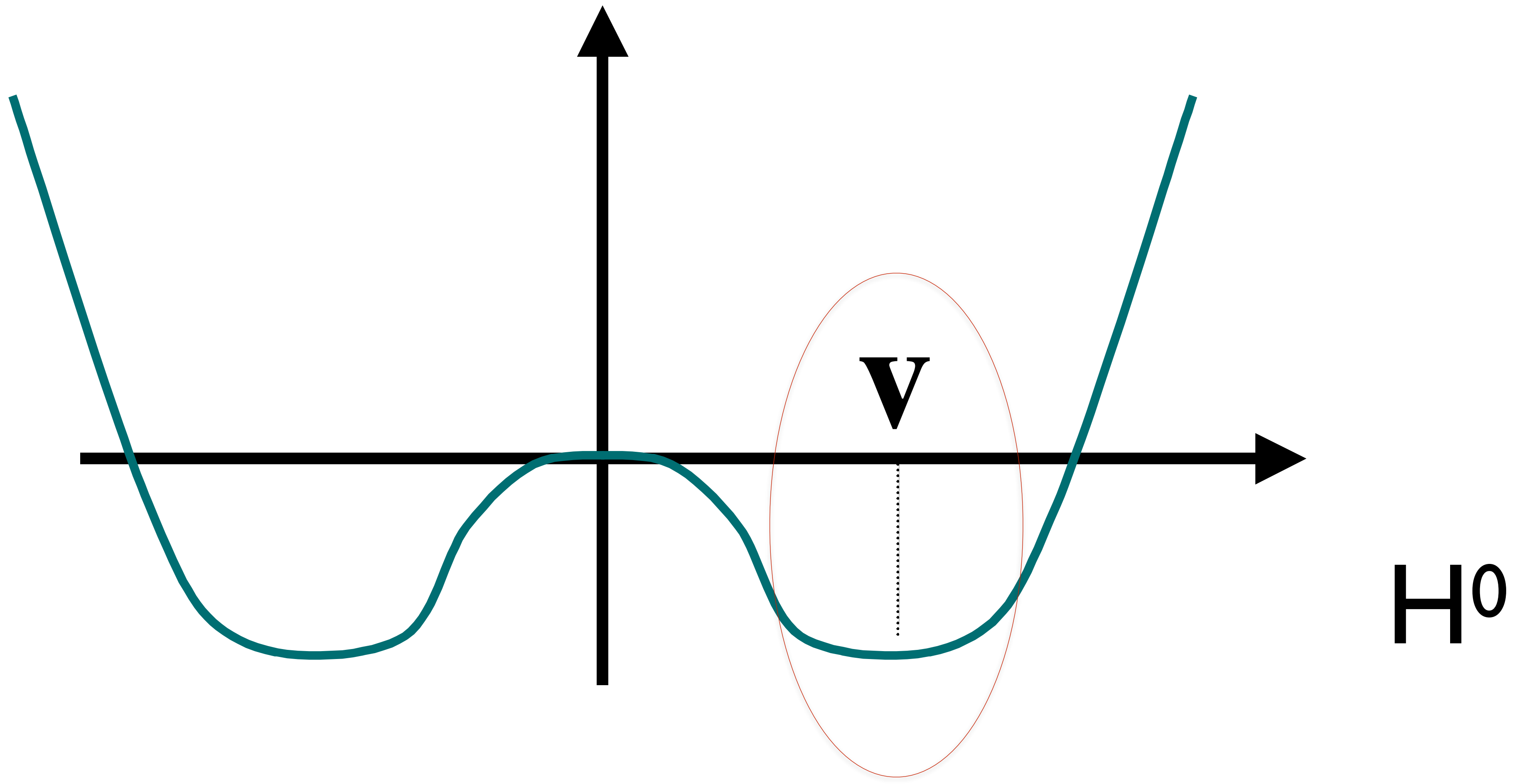
- *what's the origin of* ***dark matter*** *in the Universe ?*
- *what's the origin of the matter/antimatter* ***asymmetry*** *?*
- *what's the origin of* ***neutrino masses*** *?*
  - *are there additional* ***fundamental interactions****, too weak to have been observed so far?*
  - *are there* ***new families*** *of quarks and leptons ?*
  - *quarks & leptons: are they* ***elementary****, or composite of other more fundamental particles ?*
- ….

Answers to these questions imply the existence of new physics beyond the Standard Model

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*** to explore, to find the right clues
- 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, …)

But there is one central question to the progress of HEP, which can <u>only</u> be addressed by colliders



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

Where does this come from?

The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the Electroweak symmetry (EWSB).

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us …

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
- …

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 **same** Higgs field?
  - Do I_3=1/2 fermions (up-type quarks) get their mass from the **same** 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?

➡ the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, *which can only rely on the LHC and on a future generation of colliders*

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

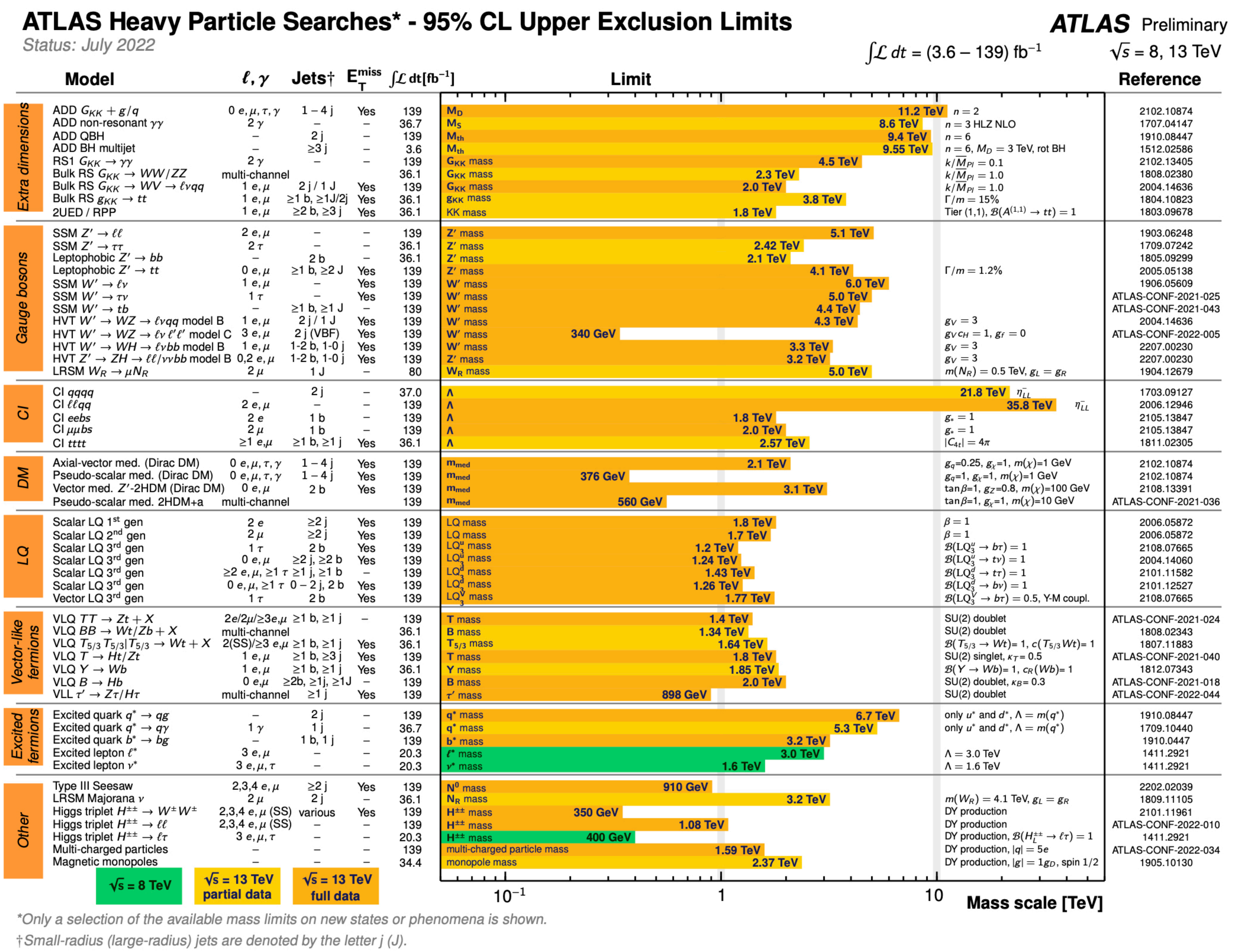
In search of the origin of known departures from the SM

- **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



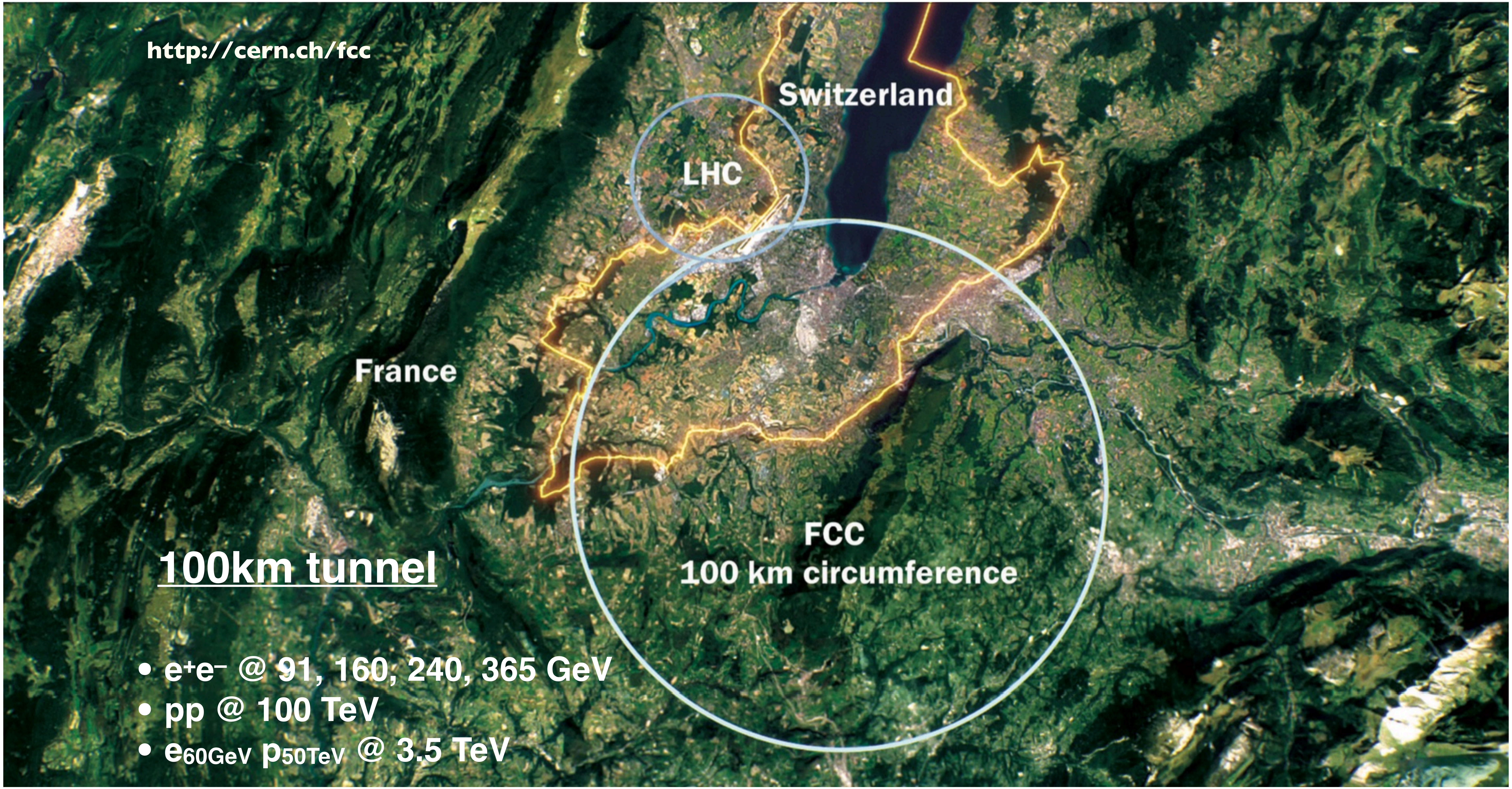
Why can't we find an answer to those "origin" questions with the LHC and other experiments?

- **Is the mass scale of new physics beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but the manifestations of new physics are elusive to the direct search ?**

To address both possibilities, we need a future circular collider to increase the:

- *precision* ⇒ *higher statistics, better detectors and experimental conditions*
- *sensitivity (to elusive signatures)* ⇒ *ditto*
- ***energy/mass reach*** ⇒ ***higher energy***

Future Circular Collider



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?
  - …

Direct vs indirect discovery

The serendipitous value of precision measurements: a few history lessons

- Tycho Brahe (1546-1601) spent his life measuring planets' positions more and more precisely
  - Johannes Kepler (1571-1630) used those data to extract a "phenomenological" interpretation, based on his 3 laws
  - Isaac Newton (1643-1727) discovered the underlying "theoretical" foundation of Kepler's laws … but it all started from Brahe's precision data!
- Newton's law became the new Standard Model for planetary motions. Precision measurements of the Uranus orbit, in the first half of the XIX century, showed deviations from this "SM": was it a break-down of the SM, or the signal of a new ~~particle~~ planet?
  - assuming the validity of the SM, interpreting the deviations as due to perturbations by a yet unknown planet, Neptun was discovered (1846), implicitly giving stronger support to Newton's SM
- Precision planetary measurements continued throughout the XIX century, revealing yet another SM deviation, in Mercury's motion. This time, it was indeed a beyond SM (BSM) signal: Einstein's theory of General Relativity!! Mercury's data did not motivate Einstein to formulate it, but once he had the equations, he used those precise data to confirm its validity!

Event rates at FCC: examples

e+e– collisions: very clean experimental environment, every single event is recorded and later analyzed, small backgrounds, high experimental precision and small systematic uncertainties

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}

pp collisions: very high energies, very large production rates, sensitivity to extremely rare processes and potential to directly observe new partiles of very large mass

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

How precise do we need Higgs measurements to be?

Coupling deviations for various BSM models, likely to remain unconstrained by direct searches at HL-LHC https://arxiv.org/pdf/1708.08912.pdf

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

5 – 10 %

> 10%

NB: when the b coupling is modified, BR deviations are smaller than the square of the coupling deviation. Eg in model 5, the BR to b, c, tau, mu are practically SM-like

(sub)-% precision must be the goal to ensure 3-5σ evidence of deviations, and to cross-correlate coupling deviations across different channels

Higgs coupling precision 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

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

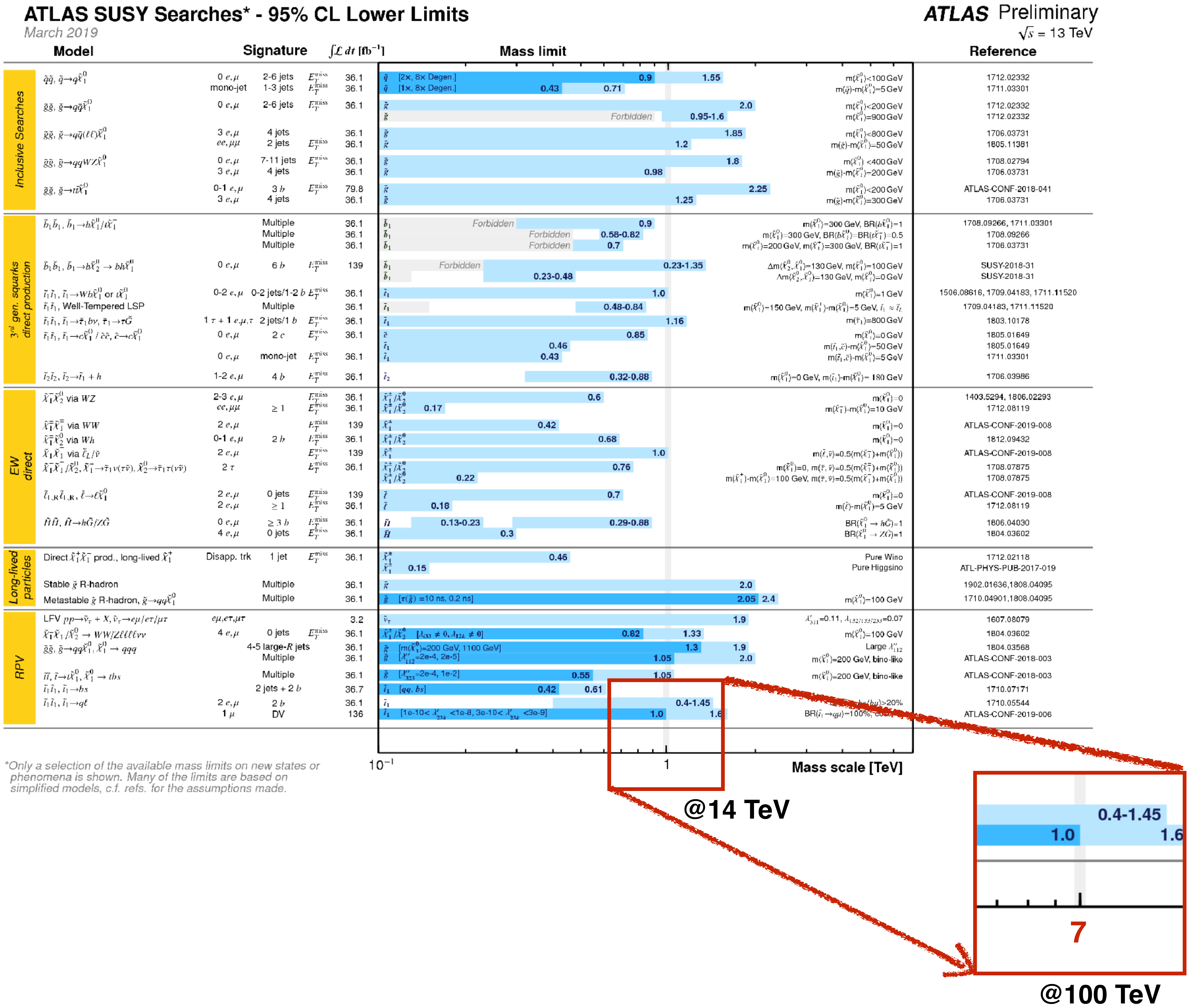
$BR(H \to \mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for Δ_{stat}~%**

→ **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 $B(H \to ZZ^*)$ @ FCC-ee

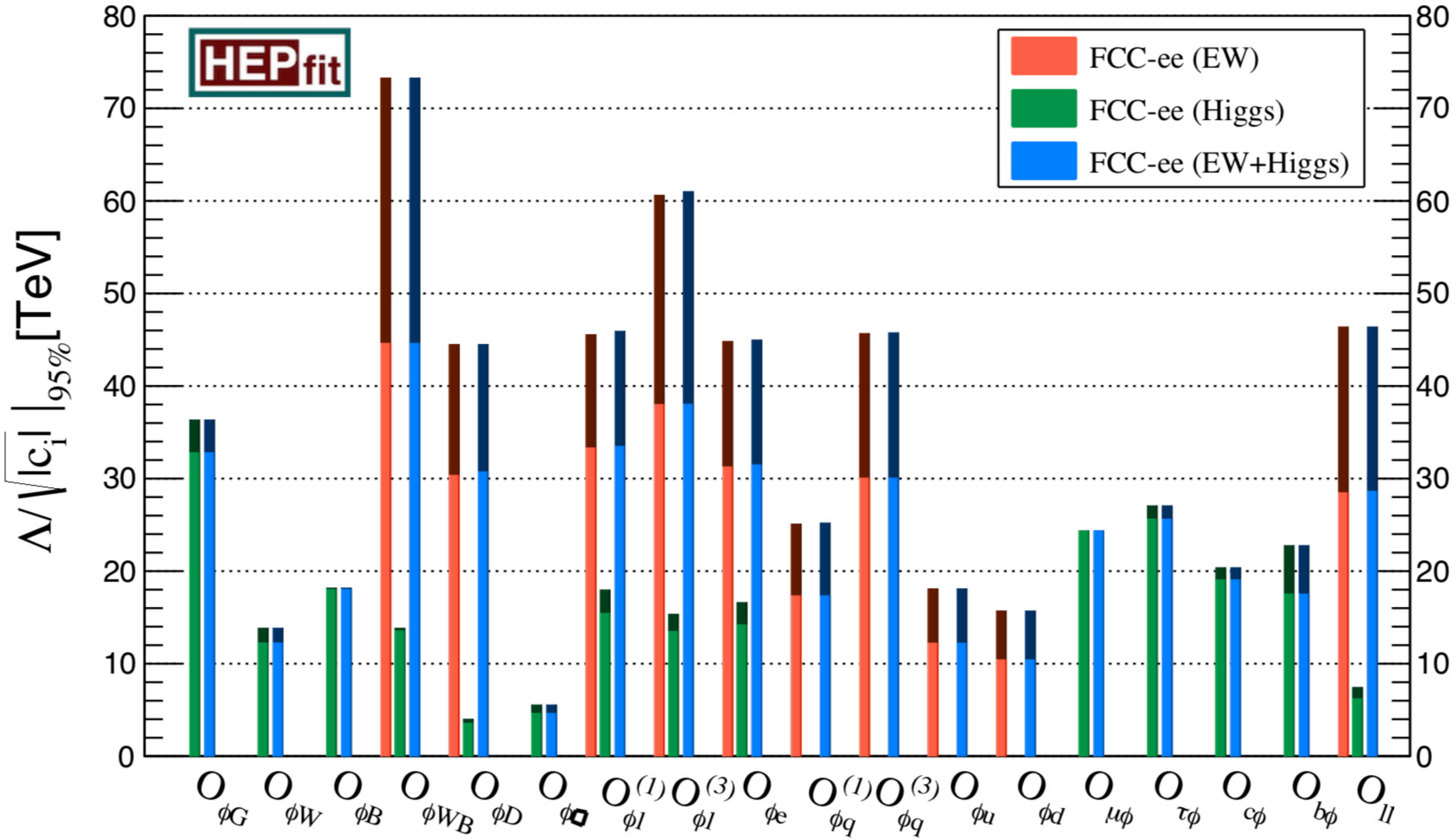
** From $pp \to ttH$ / $pp \to ttZ$, using $B(H \to bb)$ and ttZ EW coupling @ FCC-ee

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



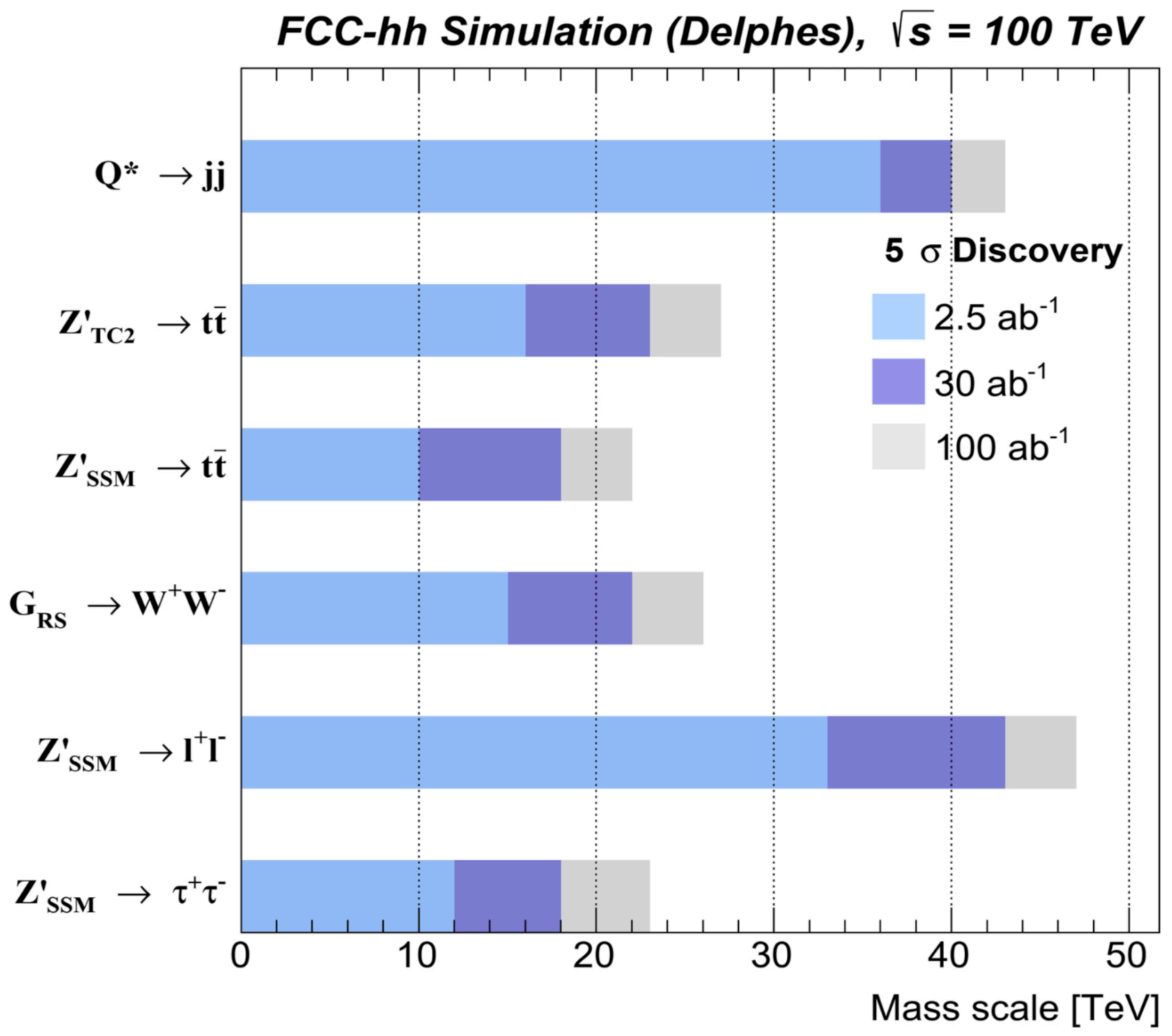
ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Forbidden
Stable g̃ R-hadron
Metastable g̃ R-hadron
Direct χ̃₁⁺χ̃₁⁻ prod., long-lived χ̃₁^±
Disapp. trk
Pure Wino
Pure Higgsino
*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.
10⁻¹
1
Mass scale [TeV]
@14 TeV
0.4-1.45
1.0
1.6
7
@100 TeV

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.

s-channel resonances



100 TeV allow to directly access the mass scales revealed indirectly by precision EW and H measurements at the future e+e– factory

What more will come from FCC? Some examples

- Reduce by 5-10 the scale at which the elementary nature of quarks and leptons are tested
- Increase by 5-10 in mass the search for new fundamental forces
- Cover the full range of parameters for possible weakly interacting massive particles (WIMPs) as sources of dark matter
- Explore new scenarios for dark matter candidates (dark photons, axion like particles, …)
- Countless studies of discovery potential for multiple BSM scenarios, from Supersymmetry to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, with plenty of opportunities for direct discovery even at FCC-ee and FCC-eh
- Sensitivity studies to SM deviations in the properties of top quarks, flavour physics in Z decays: huge event rates offer unique opportunities, that cannot be matched elsewhere
- Operations with heavy ions: new domains open up at 100 TeV in the study of high-T/high-density QCD. Broaden the targets, the deliverables, extend the base of potential users, and increase the support beyond the energy frontier community