Physics at Future Colliders

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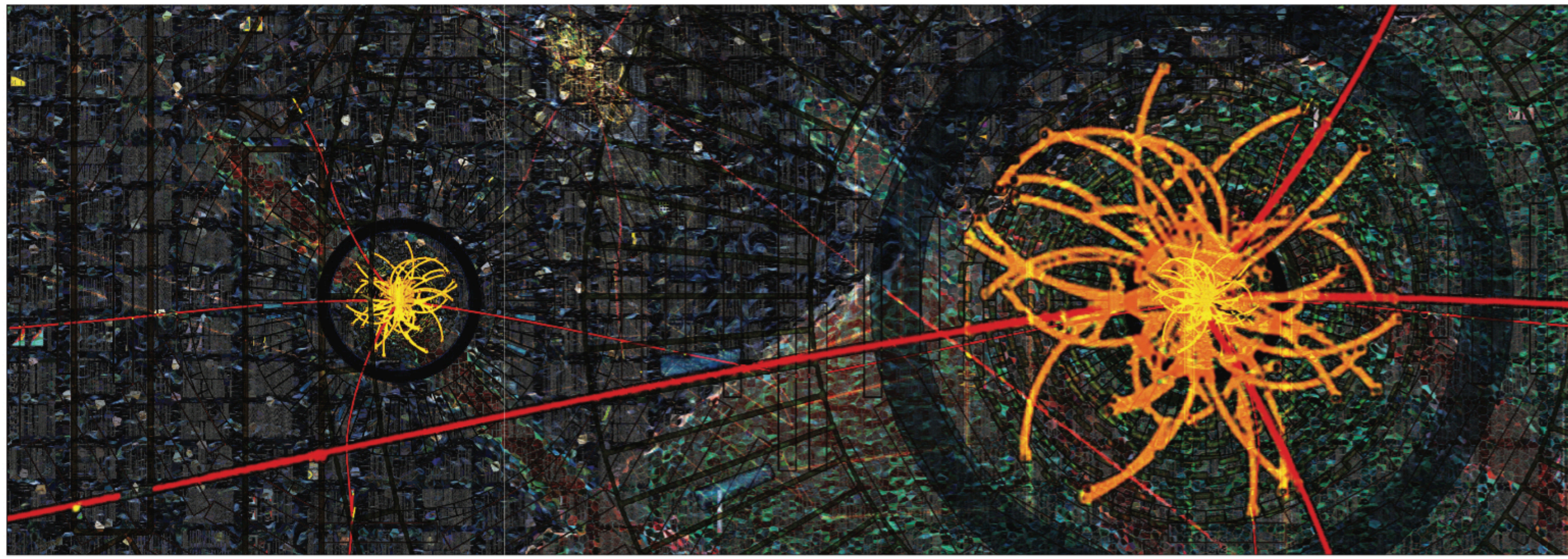
LHC AT 10: THE PHYSICS LEGACY

With just 5% of its ultimate dataset collected so far, the LHC's vast and unique physics programme has already transformed and enriched our understanding of elementary particles, writes Michelangelo Mangano.



Artful science *Detail from* In Search of the Higgs Boson, *a series of works produced by artist Xavier Cortada in collaboration with CMS.*

Ten years have passed since the first high-energy proton–proton collisions took place at the Large Hadron Collider (LHC). Almost 20 more are foreseen for the completion of the full LHC programme. The data collected so far, from approximately 150 fb^{-1} of integrated luminosity over two runs (Run 1 at a centre-of-mass energy of 7 and 8 TeV, and Run 2 at 13 TeV), represent a mere 5% of the anticipated 3000 fb^{-1} that will eventually be recorded. But already their impact has been monumental.

Three major conclusions can be drawn from these first 10 years. First and foremost, Run 1 has shown that the Higgs boson – the previously missing, last ingredient of the Standard Model (SM) – exists. Secondly, the exploration of energy scales as high as several TeV has further consolidated the robustness of the SM, providing no compelling evidence for phenomena beyond the SM (BSM). Nevertheless, several discoveries of new phenomena *within* the SM have emerged, underscoring the power of the LHC to extend and deepen our understanding of the SM dynamics, and showing the unparalleled diversity of phenomena that the LHC can probe with unprecedented precision.

Exceeding expectations

Last but not least, we note that 10 years of LHC operations, data taking and data interpretation, have overwhelmingly surpassed all of our most optimistic expectations. The accelerator has delivered a larger than expected luminosity, and the experiments have been able to operate at the top of their ideal performance and efficiency. Computing, in particular via the Worldwide LHC Computing Grid, has been another crucial driver of the LHC's success. Key ingredients of precision measurements, such as the determination of the LHC luminosity, or of detection efficiencies and of backgrounds using data-driven techniques beyond anyone's expectations, have been obtained thanks to novel and powerful techniques. The LHC has also successfully provided a variety of beam and optics configurations, matching the needs of different experiments and supporting a broad research programme. In addition to the core high-energy goals of the ATLAS and CMS experiments, this has enabled new studies of flavour physics and of hadron spectroscopy, of forward-particle production and total hadronic cross sections. The operations with beams of heavy nuclei have reached a degree of virtuosity that made it possible to collide not only the anticipated lead beams, but also beams of xenon, as well as combined proton–lead, photon–lead and photon–photon collisions, opening the way to a new generation of studies of matter at high density.

Theoretical calculations have evolved in parallel to the experimental progress. Calculations that were deemed of impossible complexity before the start of the LHC have matured and become reality. Next-to-leading-order (NLO) theoretical predictions are routinely used by the experiments, thanks to a new generation of automatic tools. The next frontier, next-to-next-to-leading order (NNLO), has been attained for many important processes, reaching, in a few cases, the next-to-next-to-next-to-leading order (N^3LO), and more is coming (*CERN Courier* April 2017 p18).

Aside from having made these first 10 years an unconditional success, all these ingredients are the premise for confident extrapolations of the physics reach of the LHC programme to come (*CERN Courier* March/April 2019 p9).

To date, more than 2700 peer-reviewed physics papers have been published by the seven running LHC experiments (ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM). Approximately 10% of these are related to the Higgs boson, and 30% to searches for BSM phenomena. The remaining 1600 or so report measurements of SM particles and interactions, enriching our knowledge of the proton structure and of the dynamics of strong interactions, of electroweak (EW) interactions, of flavour properties, and more. In most cases, the variety, depth and precision of these measurements surpass those obtained by previous experiments using dedicated facilities. The multi-purpose nature of the LHC complex is unique, and encompasses scores of independent research directions. Here it is only possible to highlight a fraction of the milestone results from the LHC's expedition so far.

Entering the Higgs world

The discovery by ATLAS and CMS of a new scalar boson in July 2012, just two years into LHC physics operations, was a crowning early success. Not only did it mark the end of a decades-long search, but it opened a new vista of exploration. At the time of the discovery, very little was known about the properties and interactions of the new boson. Eight years on, the picture has come into much sharper focus.

The structure of the Higgs-boson interactions revealed by the LHC experiments is still incomplete. Its couplings to the gauge bosons (W, Z, photon and gluons) and to the heavy third-generation fermions (bottom and top quarks, and tau leptons) have been detected, and the precision of these measurements is at best in the range of 5–10%. But the LHC findings so far have been key to establish that this new particle correctly embodies the main observational properties of the Higgs boson, as specified by the Brout–Englert–Guralnik–Hagen–Higgs–Kibble EW-symmetry breaking mechanism, referred hereafter as "BEH", a cornerstone of the SM. To start with, the measured couplings to the W and Z bosons reflect the Higgs' EW charges and are proportional to the W and Z masses, consistently with the properties of a scalar field breaking the SM EW symmetry. The mass dependence of the Higgs interactions with the SM fermions is confirmed by the recent ATLAS and CMS observations of the $H \to bb$ and $H \to \tau\tau$ decays, and of the associated production of a Higgs boson together with a $t\bar{t}$ quark pair (see figure 1).

These measurements, which during Run 2 of the LHC have surpassed the five-sigma confidence level, provide the second critical confirmation that the Higgs fulfills the role envisaged by the BEH mechanism. The Higgs couplings to the photon and the gluon (g), which the LHC experiments have probed via the $H \to \gamma\gamma$ decay and the $gg \to H$ production, provide a third, subtler test. These couplings arise from a combination of loop-level interactions with several SM particles, whose interplay could be modified by the presence of BSM particles, or interactions. The current agreement with data provides a strong validation of the SM scenario, while leaving open the possibility that small deviations

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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 two more, new, experiments: FASER & SND@LHC*

Not only Higgs and BSM !

Flavour physics

- B(s) $\rightarrow \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase φ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW param's and dynamics

- m_W, m_{top}, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

Remarks

- These 3000 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc
- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

The 10-yr LHC legacy of BSM searches: a small cultural revolution

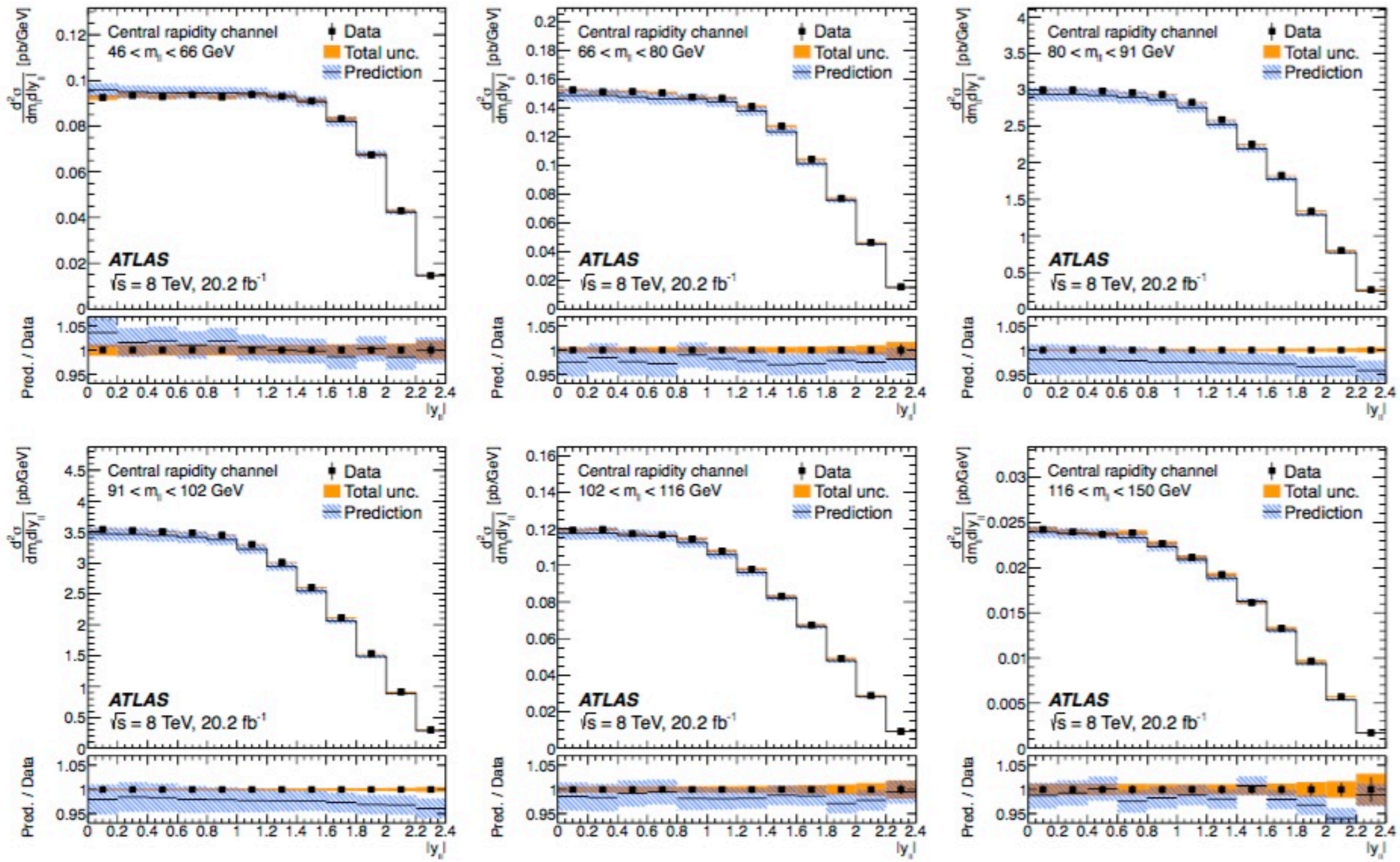
- pre-LHC benchmarks were models designed to solve all problems at once: hierarchy, DM, g–2, …
- gradual transition to searches in the context of simplified models
- BSM model building exploring less obvious scenarios, role of dark sectors, Higgs portals, often characterized by elusive signatures (little MET, LLP's, etc)
- Increased access to data, for reinterpretation and recasting: HEPdata, Rivet, Open Data, …
- Emergence of Effective Field Theory approaches to data interpretation…

Key targets for the next phase of LHC

- Continued study of the Higgs sector: higher precision, higher dynamical reach, rarer processes. Eg:
  - BR($H\to\gamma\gamma$) and BR($H\to ZZ^*$) to the few-% level
  - Higgs at high p_T, off-shell, high-mass associated production, …
  - Discovery of $H\to\mu\mu$, $H\to Z\gamma$ and $H\to cc$, probe H selfcoupling
- Pursue further and conclusively establish origin (stat, syst, or BSM?) of current anomalies in the data (eg LHCb lepton flavour non-univ)
- Expand BSM searches to cover new TH ideas, cover models or parameter regions where Run 1 & 2 had no sensitivity (challenging trigger, backgrounds, etc). Eg long-lived particles, light weakly-interacting resonances, compressed DM spectra, …
- Each bullet in the list 3 slides back is a target for future improved measurements/calculations/techniques ! In particular:
  - get ready to interpret/address possible TH/data discrepancies in distributions: BSM or systematics?

Measurement of the Drell–Yan triple-differential cross section in *pp* collisions at $\sqrt{s}$ = 8 TeV

arxiv:1710.05167



we must learn how to deal with the small - but significant - discrepancies that such %-level precision measurements expose … do they signal insufficient TH accuracy, the need to improve the proton PDFs, new physics ??

How do we avoid fitting away with PDFs / α_S possible mismodeling?

Colliders beyond the LHC:
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

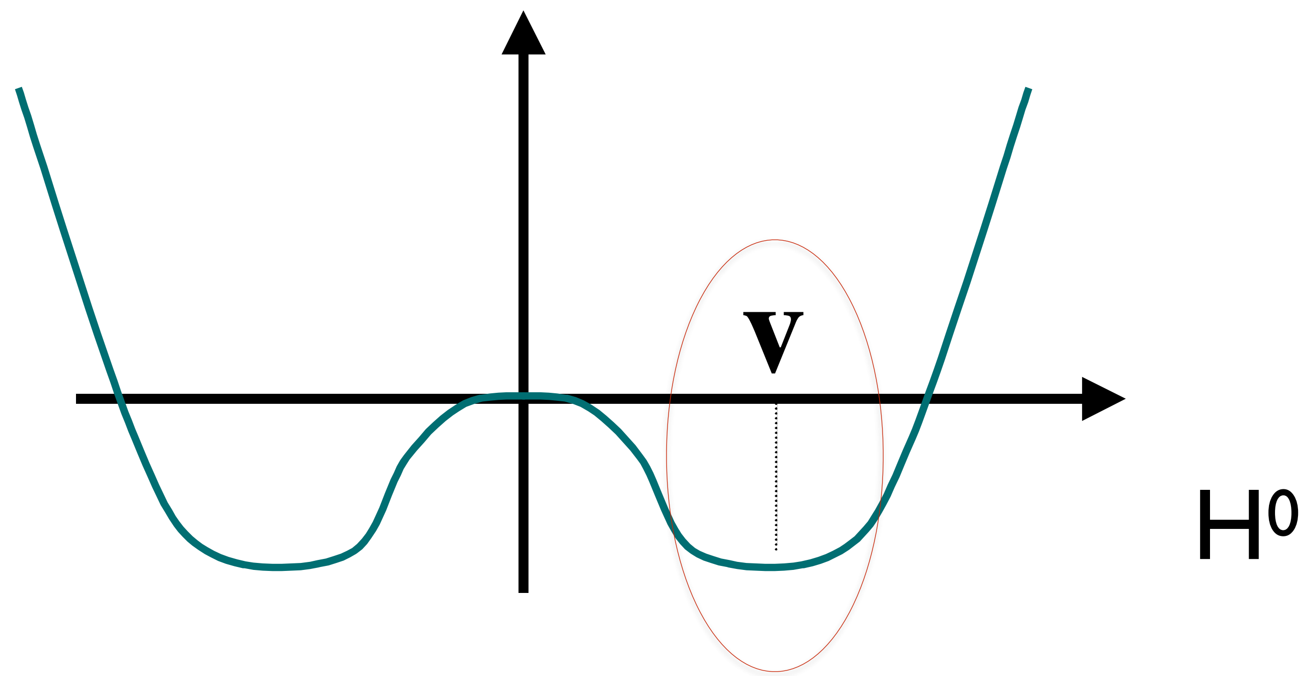
- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

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, …)

We have no guarantees as to where answers to these questions will come from, and what are the experiments that will eventually answer them.

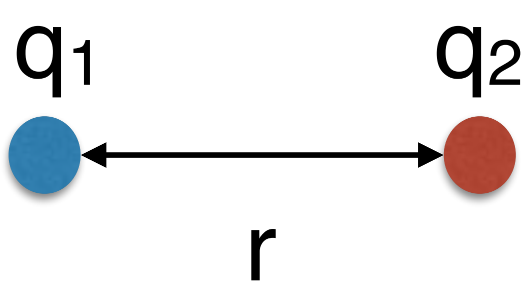
But there is one question that can only be addressed by colliders, and future collider efforts must focus on its thorough exploration



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

Where does this come from?

Electromagnetic vs Higgs dynamics

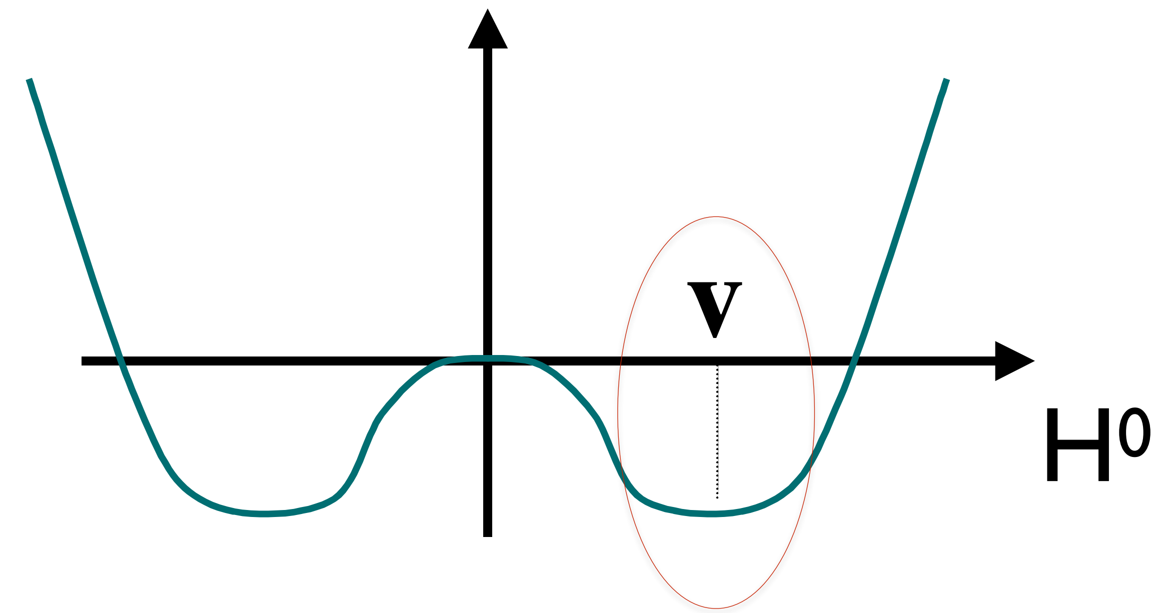


$$V(r) = +\frac{q_1 \times q_2}{r^1}$$

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
- …

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 a future generation of colliders***

The importance of the in-depth exploration of the Higgs properties was acknowledged by the 2020 update of the European Strategy for Particle Physics:

"An electron-positron Higgs factory is the highest-priority next collider"

What are we talking about when

we talk about future colliders?

Circular ...

HiLumi HL-LHC PROJECT

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

✓Approved 2027-38

FCC hh ee he

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

link to CDR

in a 100km tunnel around CERN

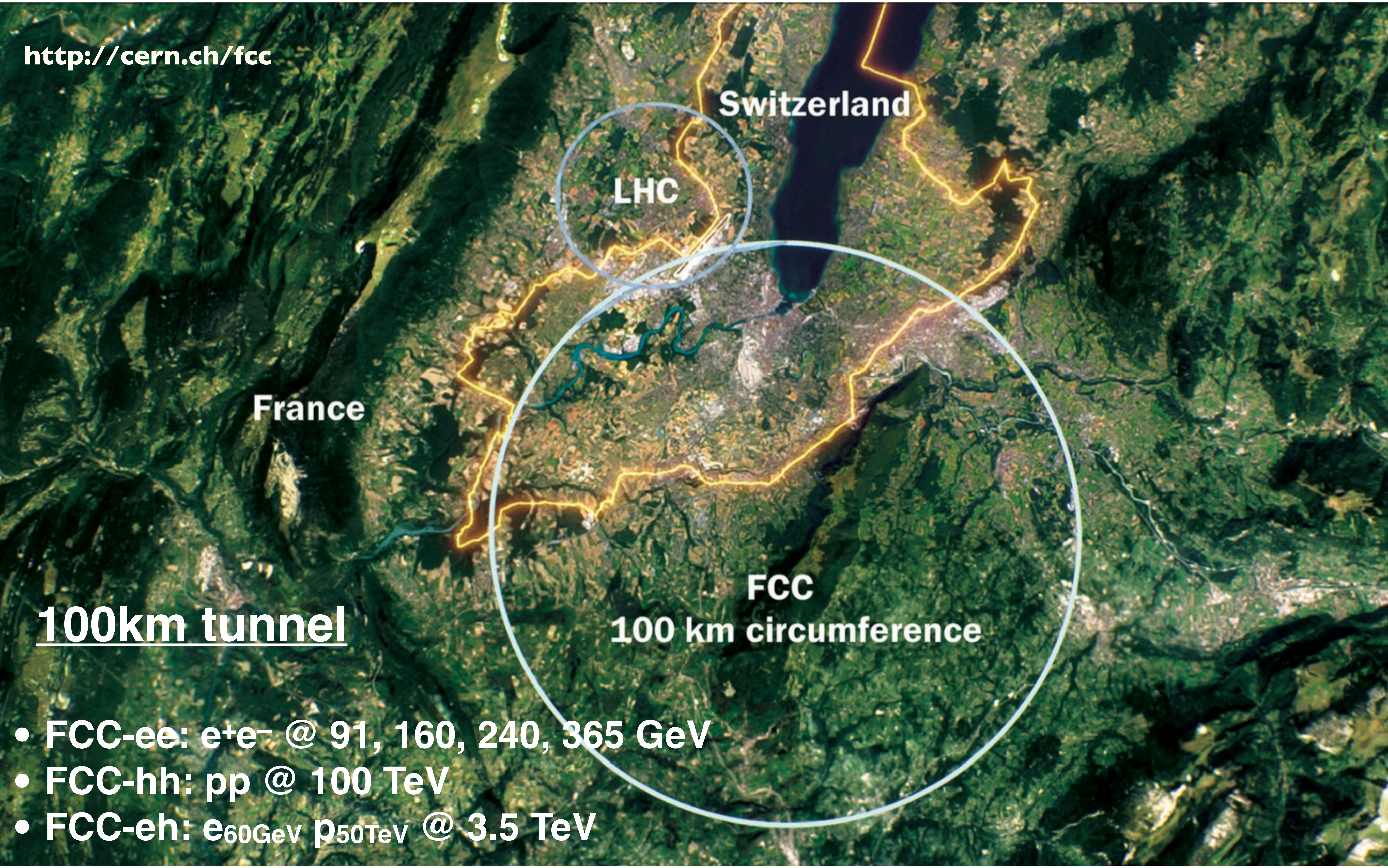
CEPC

- 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

Future Circular Collider



<u>100km tunnel</u>

- FCC-ee: e^+e^- @ 91, 160, 240, 365 GeV
- FCC-hh: pp @ 100 TeV
- FCC-eh: e_{60GeV} p_{50TeV} @ 3.5 TeV

... 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

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.

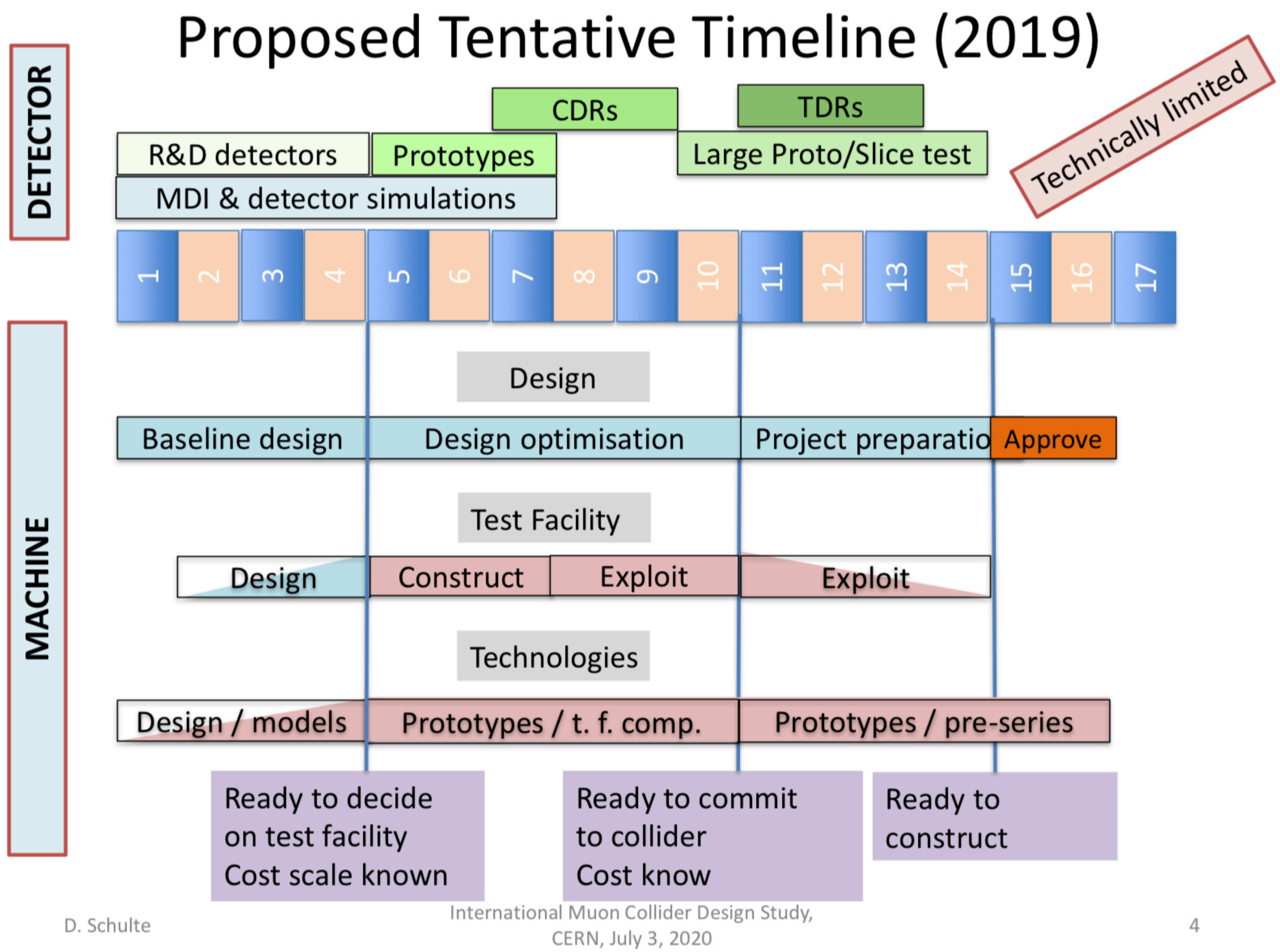
Energy, center-of-mass, U_{cm}[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}$[10^{34} s^{-1}cm^{-2}]	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size 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_{stage}	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), L_{total}[km]	0.07	0.3	0.9	9.0
Average laser power, P_{avg}[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), P_{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)*

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

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.

(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 examples of beyond-the-SM phenomena

.

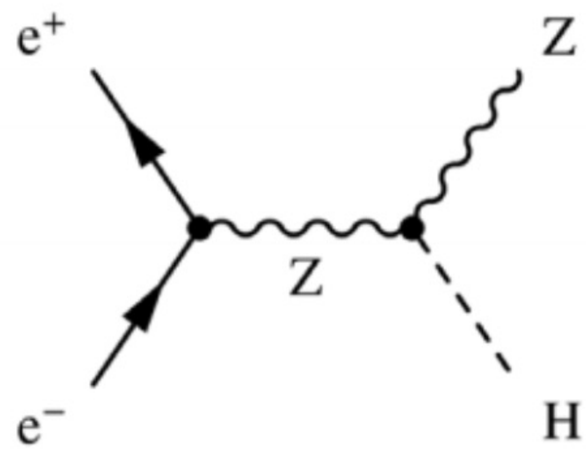
arXiv:1310.8361

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):

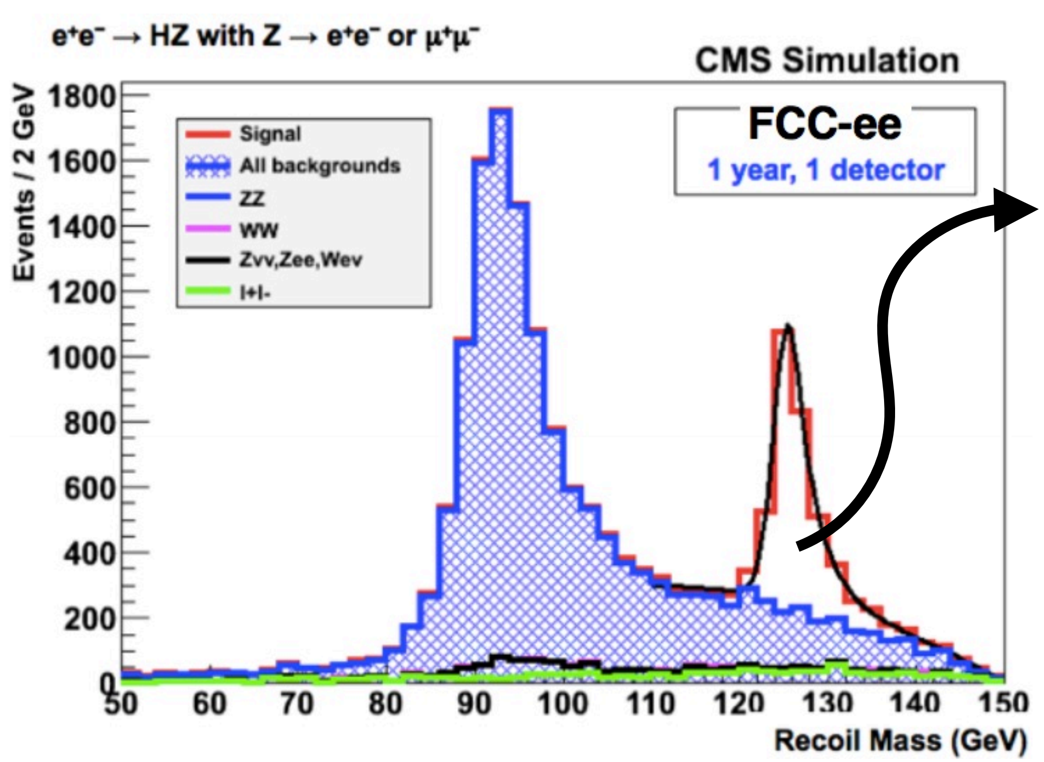
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

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

=> **absolute measurement of width and couplings**

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

- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR($H \to ZZ^*$), 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

	$gg \to H$	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

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

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

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

$BR(H\to Z\gamma,\gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ 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

(1) guaranteed deliverables: EW observables

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

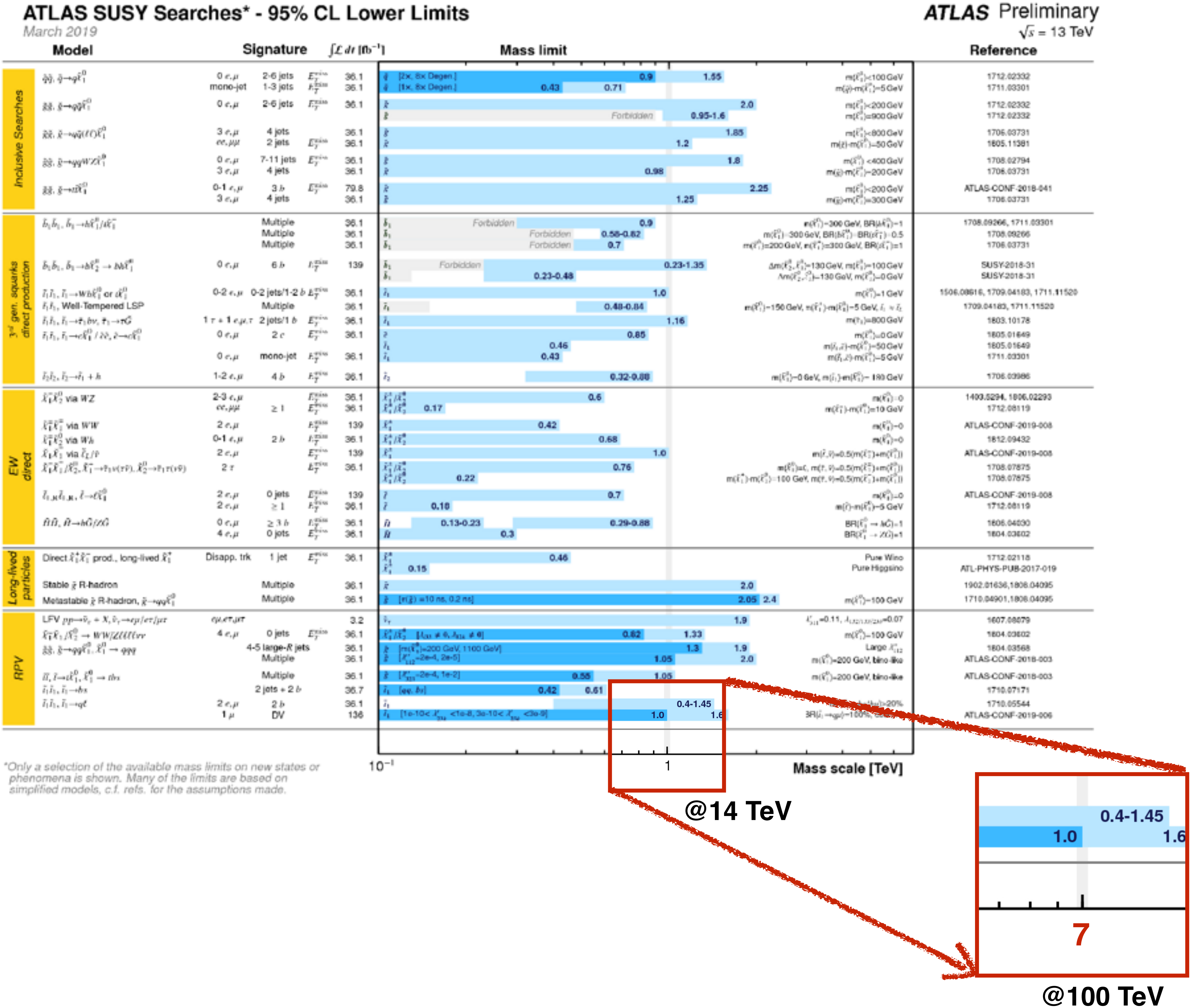
$e^+e^- \to Z$	$e^+e^- \to WW$	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
$5\ 10^{12}$	10^8	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

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

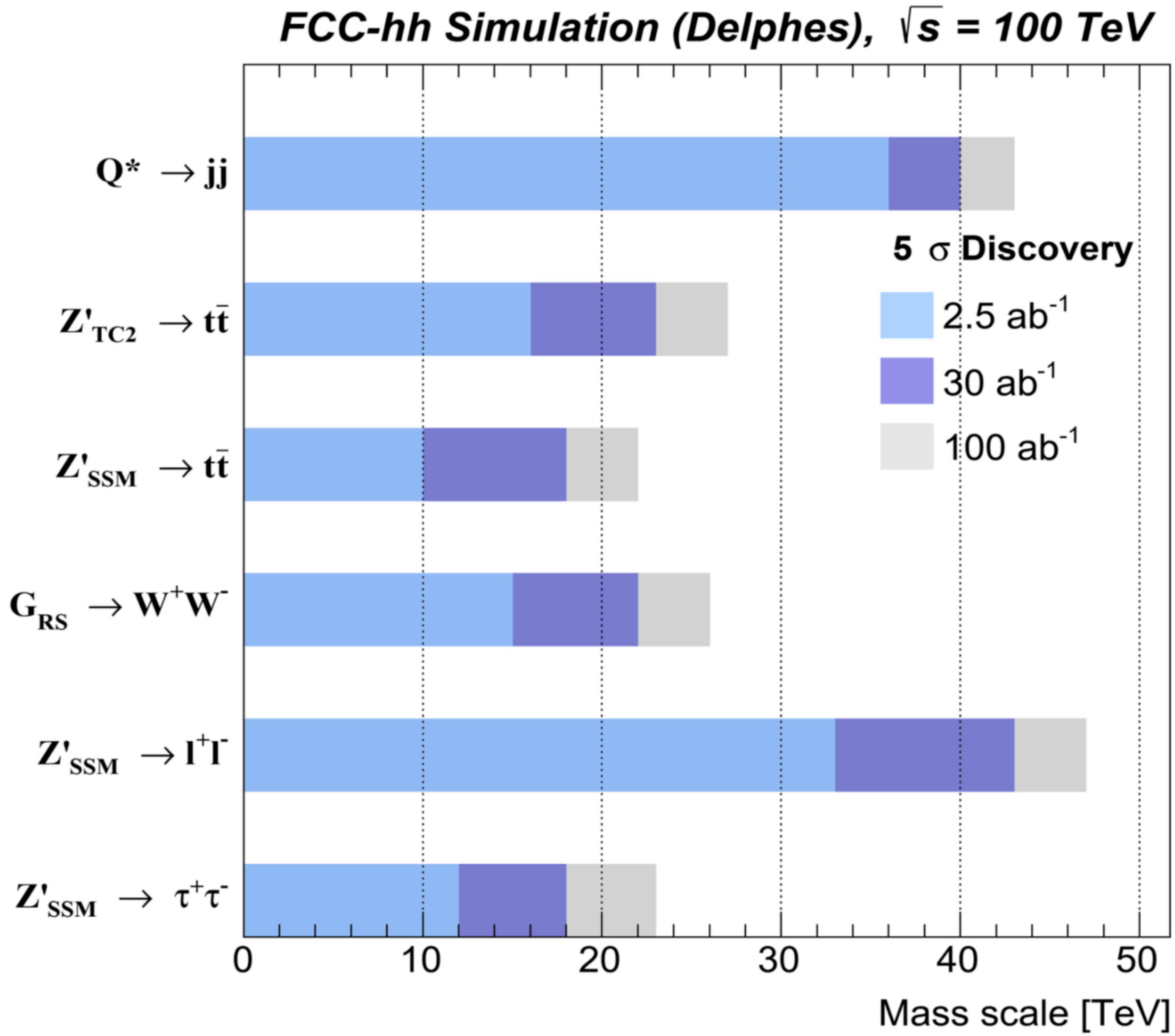
EW parameters @ FCC-ee

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 (×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
$\sin^2\theta_W^{eff}$ (×10⁶)	231480±160	3	2-5
$1/\alpha_{QED}(m_Z)$ (×10³)	128952±14	4	Small
$A_{FB}^{b,0}$ (×10⁴)	992±16	0.02	1-3
$A_{FB}^{pol,\tau}$ (×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
$\lambda_{top}/\lambda_{top}^{SM}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

(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
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

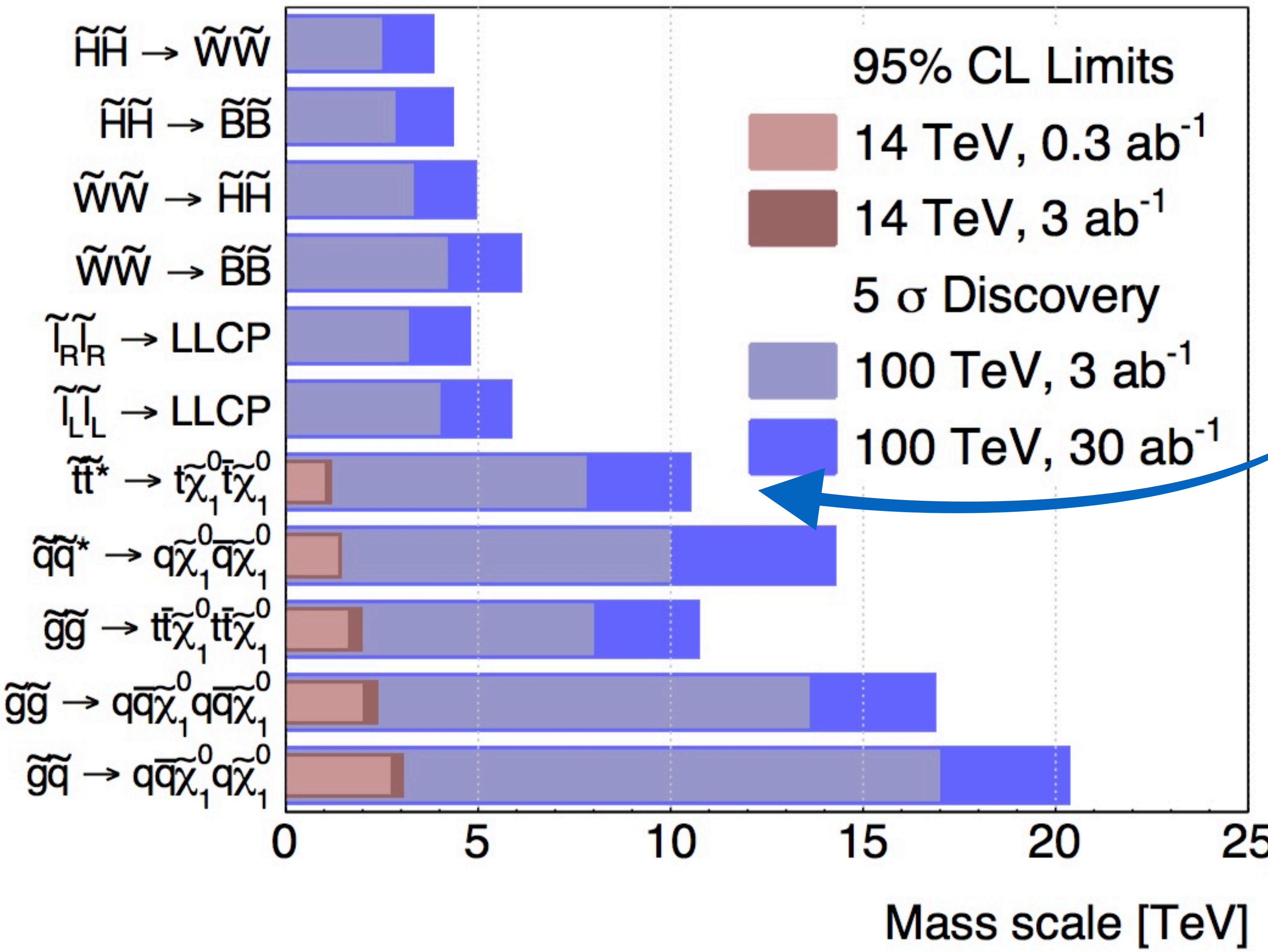
s-channel resonances

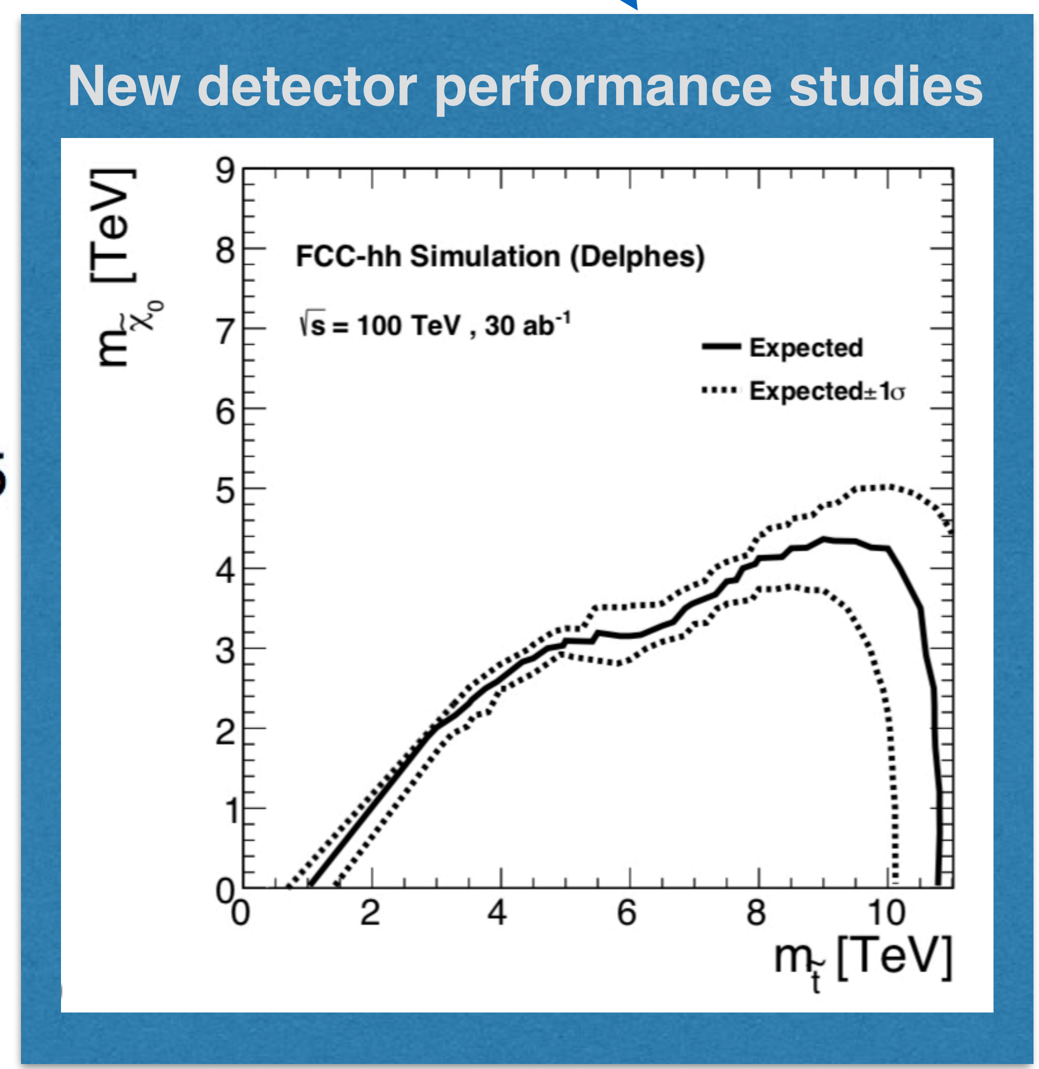


FCC-hh reach ~ 6 x HL-LHC reach

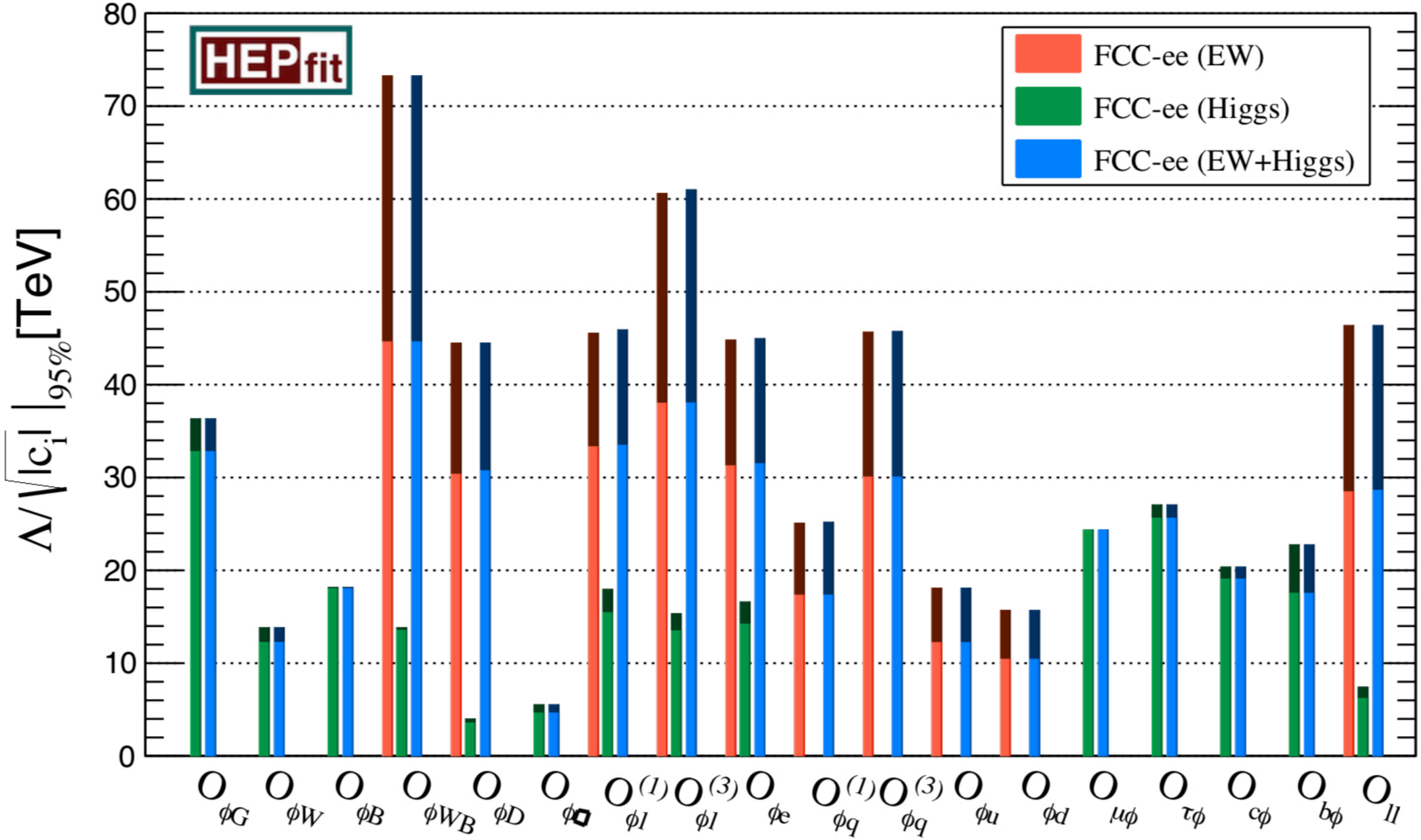
SUSY reach at 100 TeV

Early phenomenology studies





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:

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

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

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

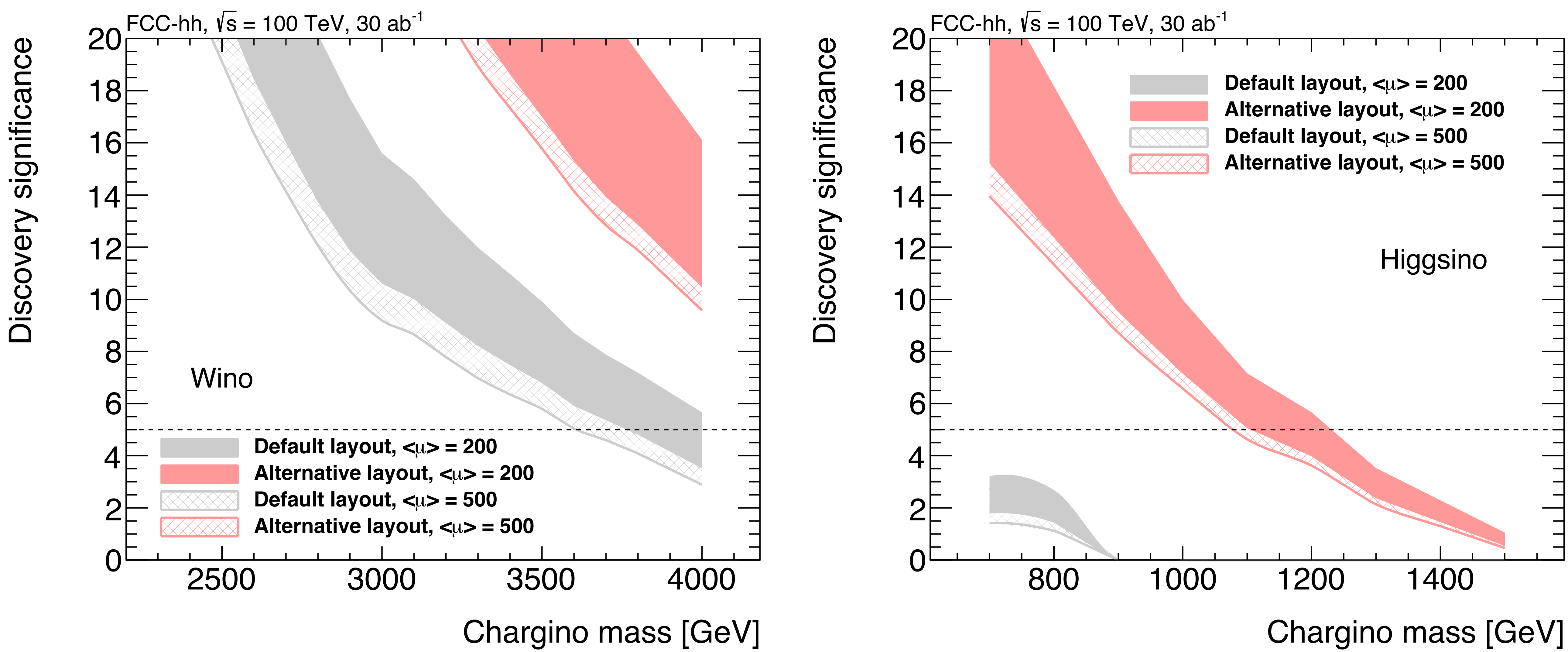
$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3}\right)^2$$

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

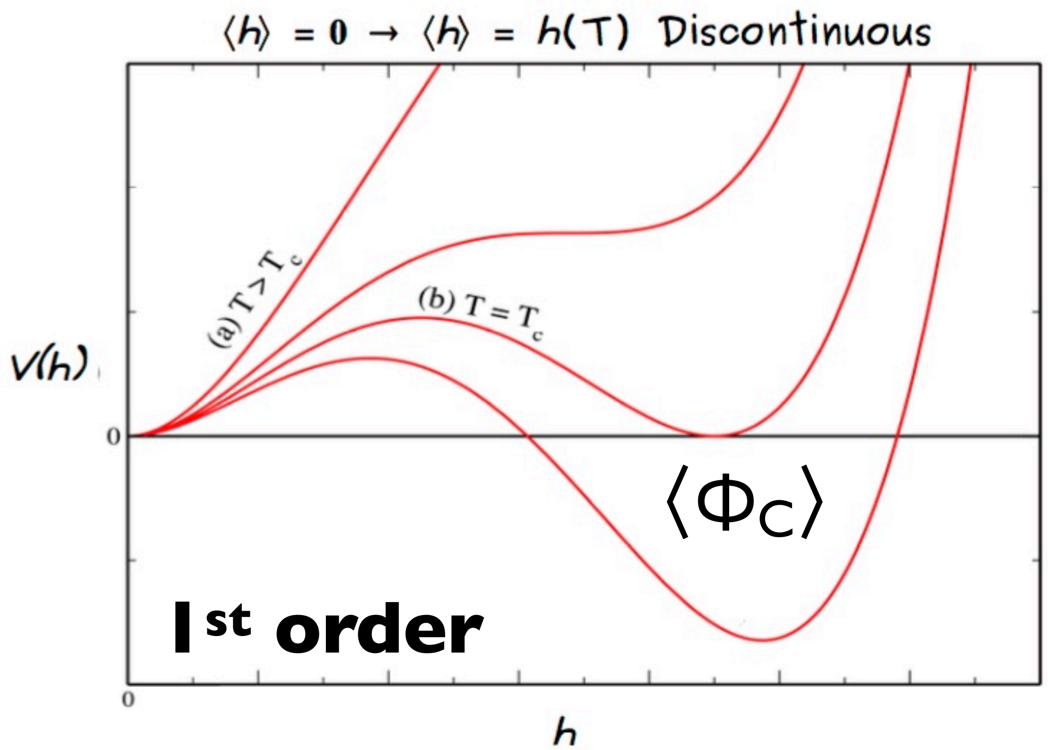
(at ~full pileup)

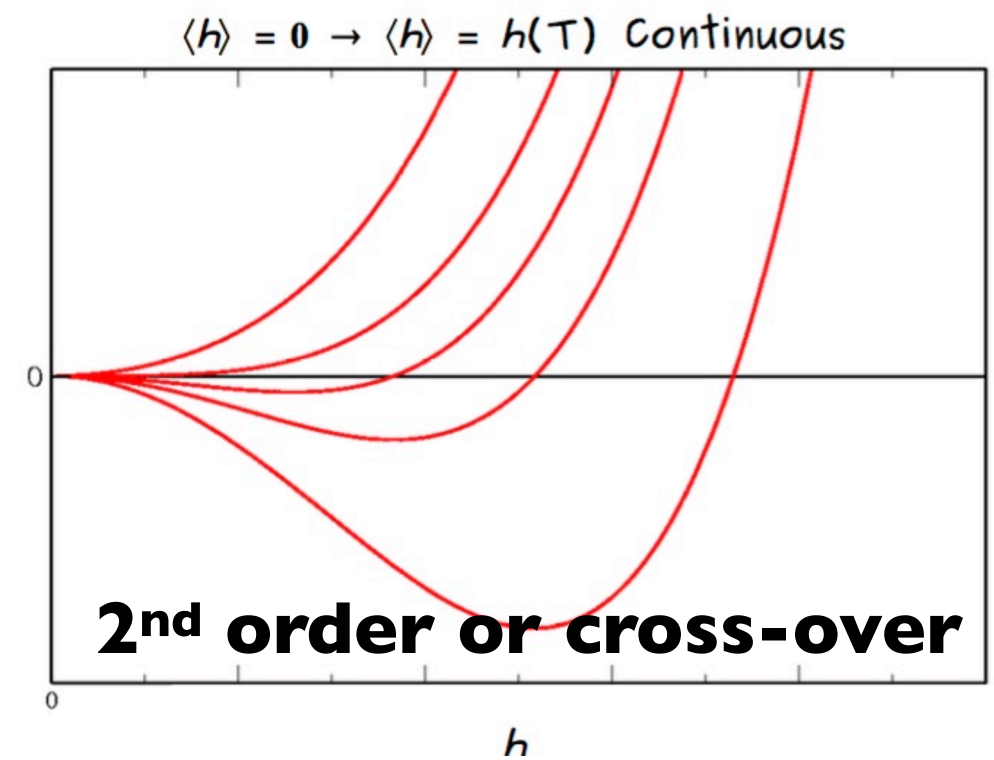


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

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 ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim$ 80 GeV, else transition is a smooth crossover.

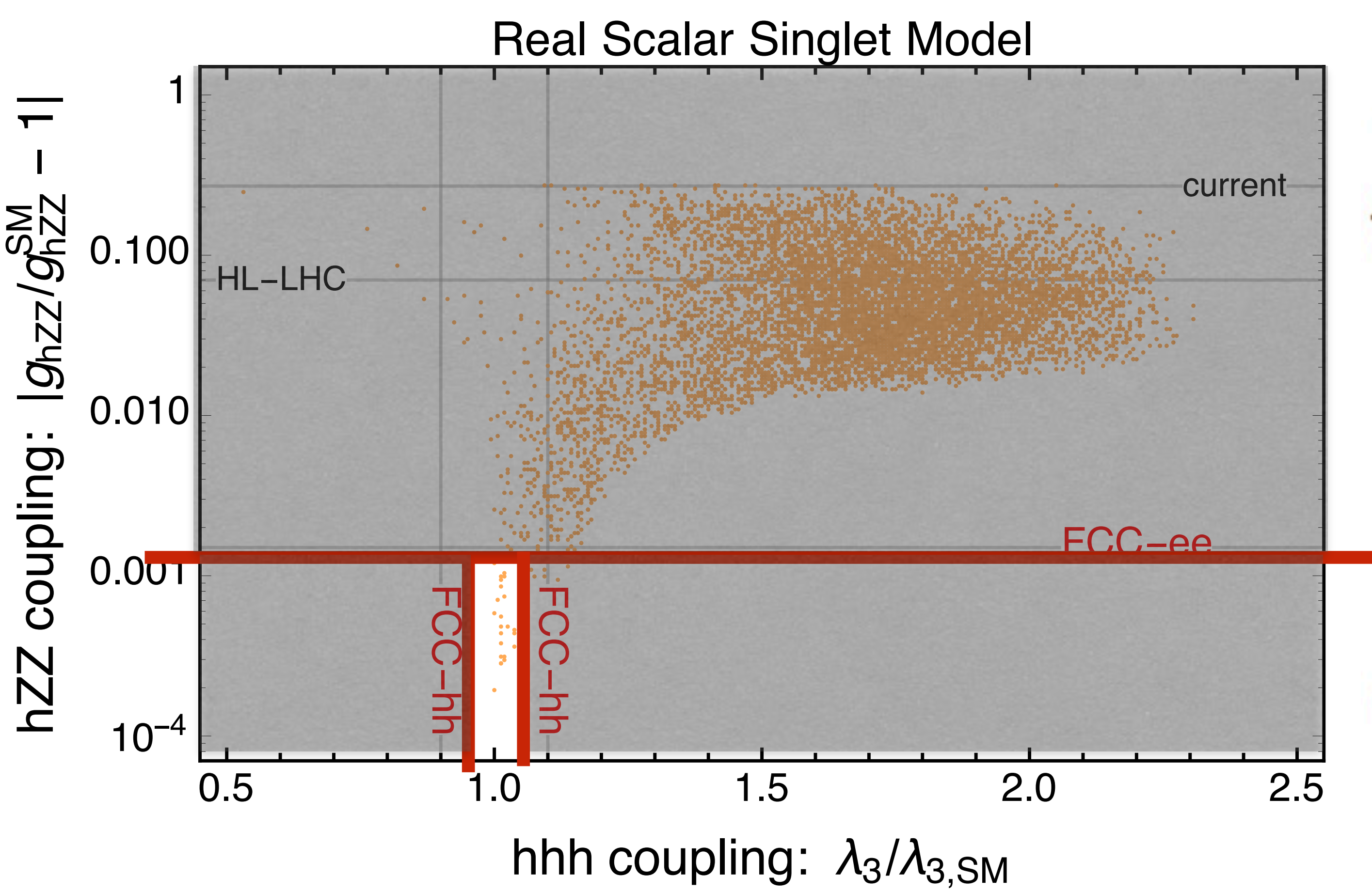
Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **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

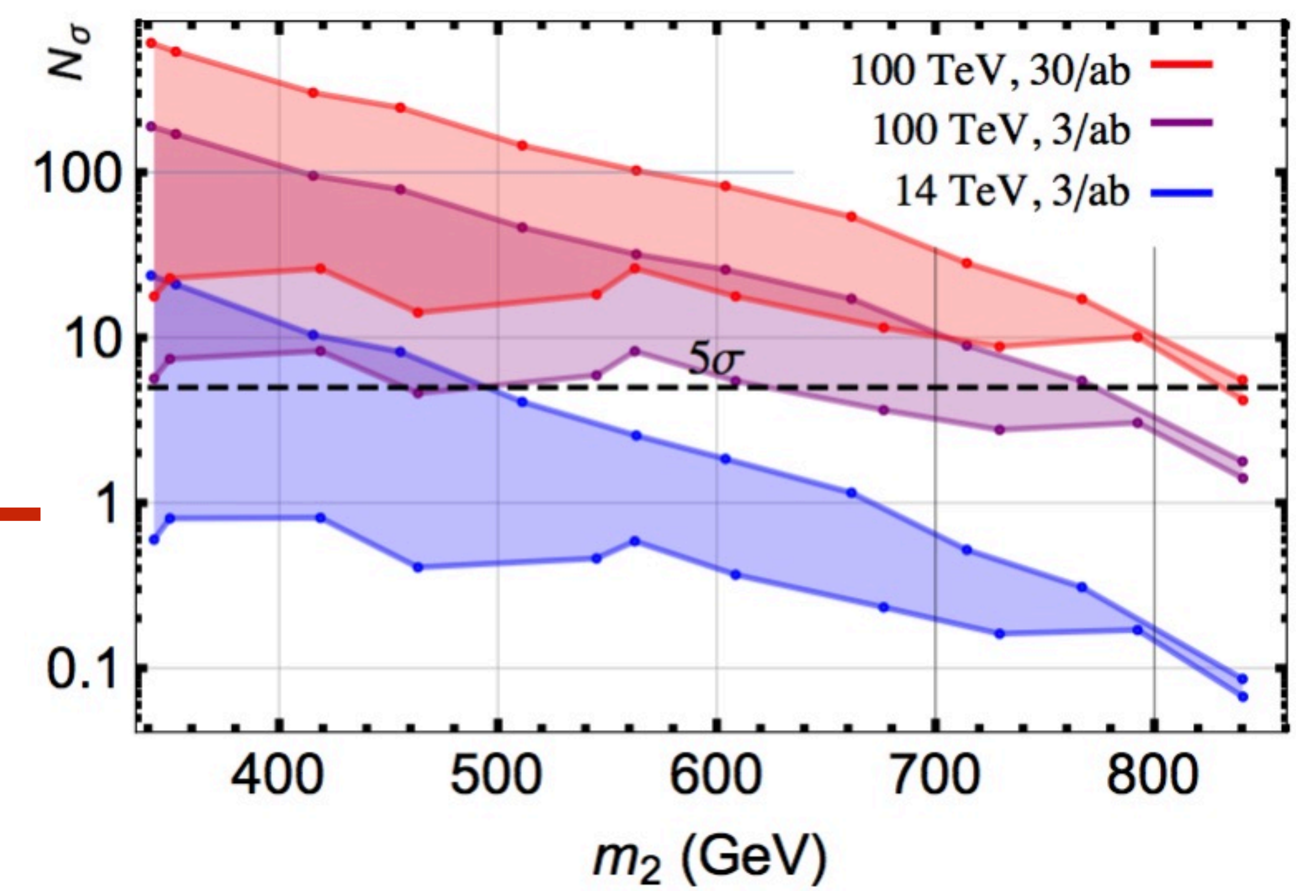
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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



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

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

Not covered

- Countless studies of discovery potential for multiple BSM scenarios, from SUSY to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, at FCC-ee, FCC-hh 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

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 exptl program possible at a future collider facility, combining a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, offers unmatchable breadth and diversity: concrete, compelling and indispensable Higgs & SM measurements enrich a unique direct & indirect discovery potential
- The technological, financial and sociological challenges are immense, and will test our community ability to build and improve on the experience of similar challenges in the past.
- The next 5-6 years, before the next review of the European Strategy for Particle Physics, will be critical to reach the scientific consensus and political support required to move forward