

Les rencontres de Physique de la Vallée d'Aoste
La Thuile,
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Collider physics: the next steps

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The next steps in HEP build on

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

The important questions

- **Data driven:**

- DM
- Neutrino masses
- Matter vs antimatter asymmetry
- Dark energy
- ...

- **Theory driven:**

- The hierarchy problem and naturalness
- The flavour problem (origin of fermion families, mass/mixing pattern)
- Quantum gravity
- Origin of inflation
- ...

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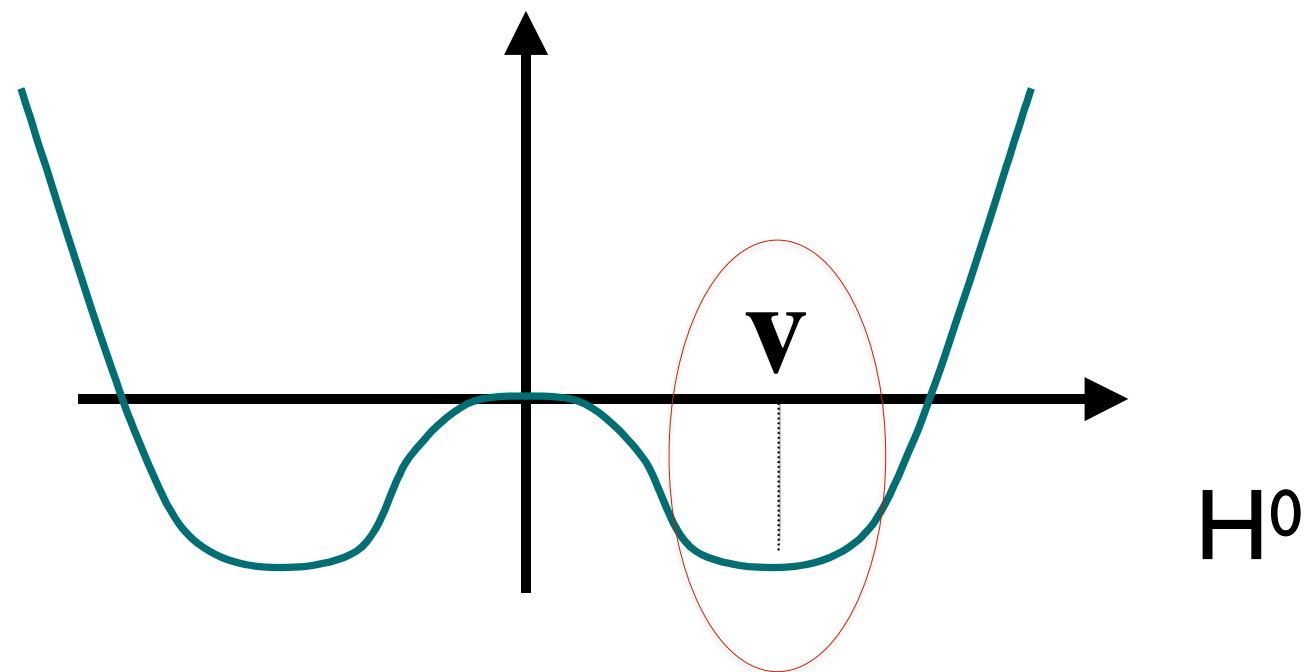
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- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are 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, ...)

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

Where does this come from?

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- 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.

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- 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
- ...

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- .. thus many theoretical ideas are emerging, postponing to much higher energies or to alternative scenarios the framework to understand the origin of the weak scale
- The detailed experimental investigation of Higgs properties remains nevertheless a sine qua non condition to make progress no matter what is our bias

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**Why don't we see the new physics we expected to
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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* \Rightarrow *higher statistics, better detectors and experimental conditions*
- *sensitivity (to elusive signatures)* \Rightarrow *ditto*
- ***extended energy/mass reach*** \Rightarrow ***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

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

The value of diversity and guaranteed deliverables in collider physics

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 SM measurements (jets, EW, top, b, Hs, ...)

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 \Rightarrow 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

- $m_W, m_{\text{top}}, \sin^2\theta_W$
- 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

Remarks

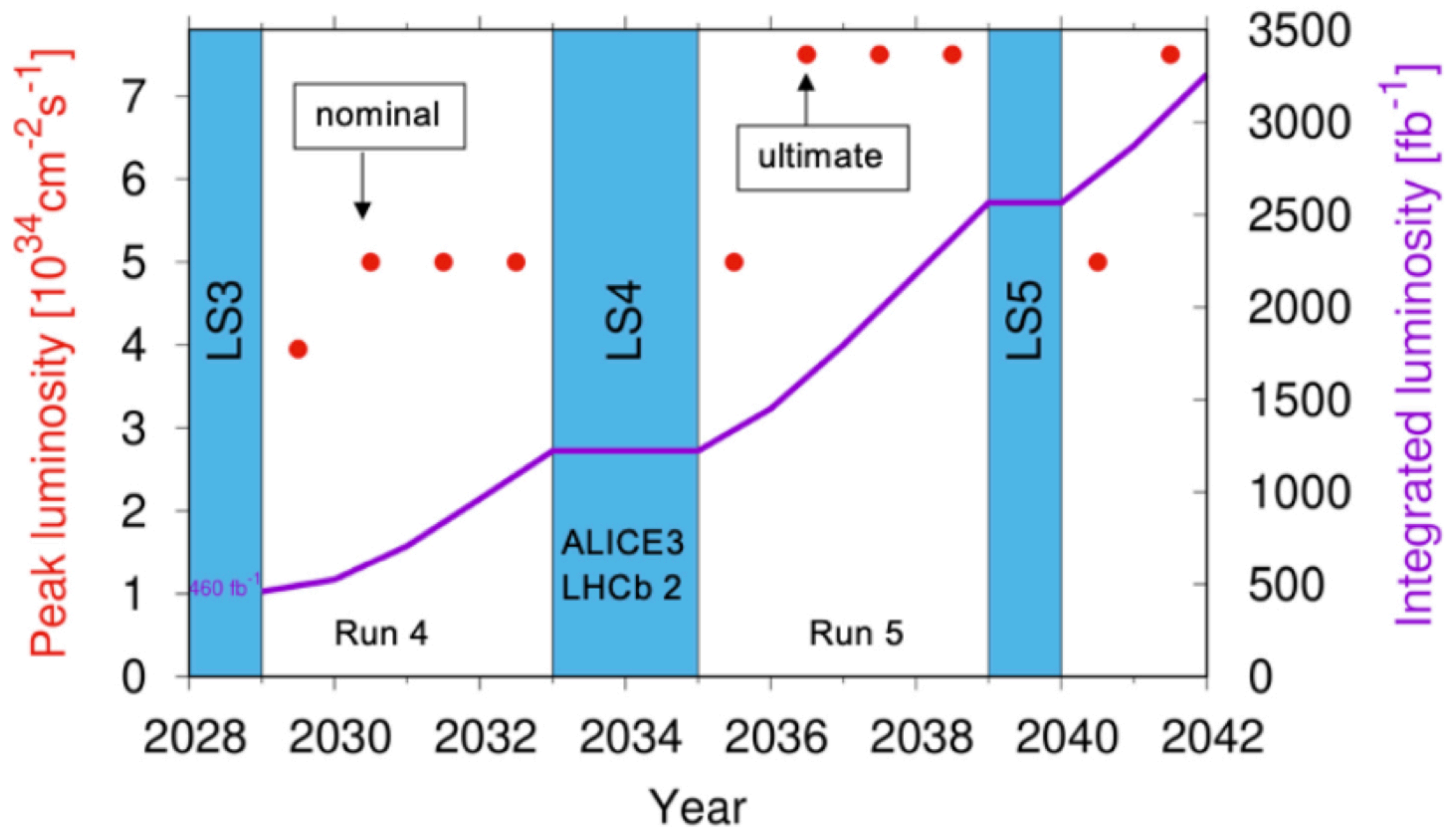
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I have a broad concept of “*new physics*”, which includes SM phenomena, emerging from the data, that are unexpected, surprising, or simply poorly understood.

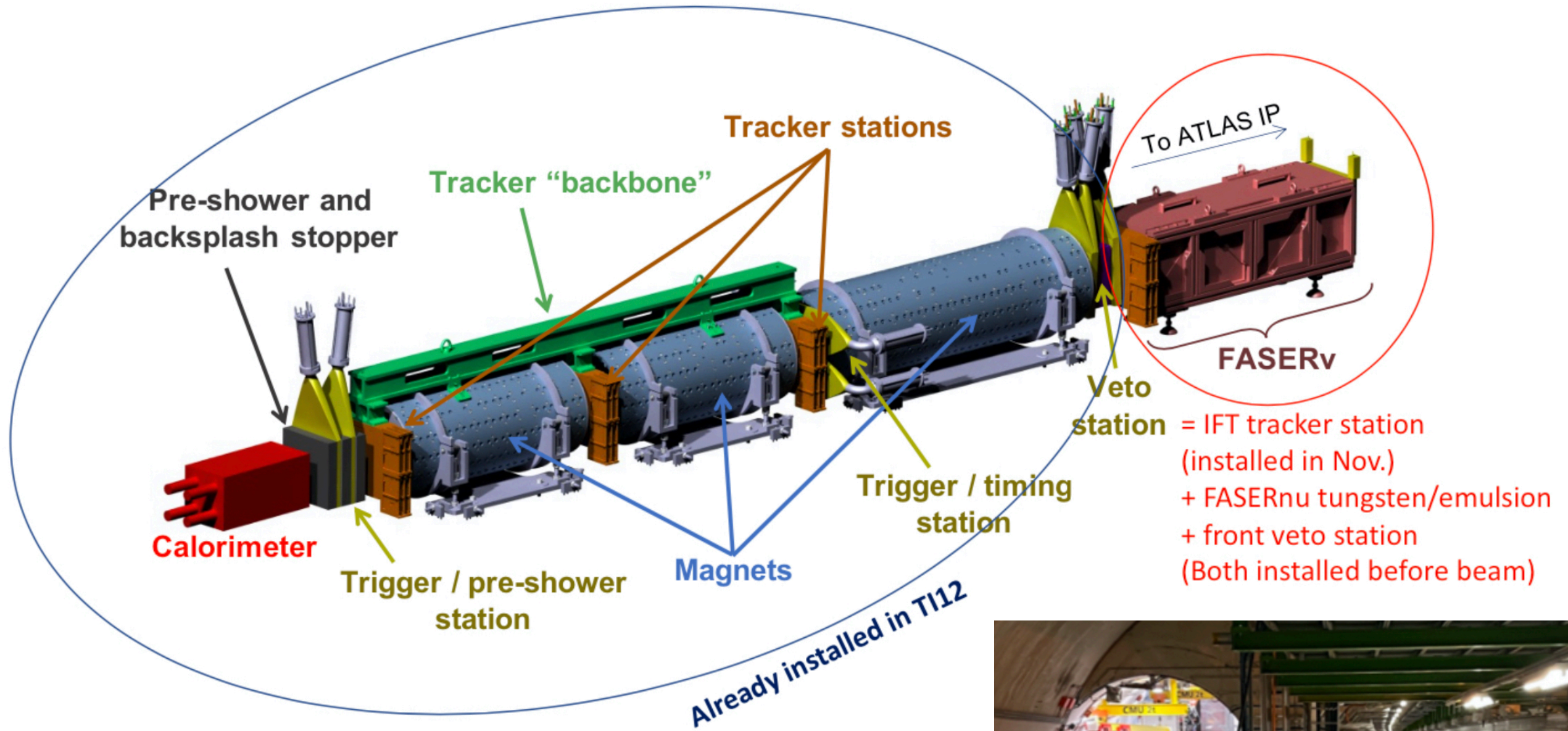
I consider as “new”, and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

“New physics” is emerging every day at the LHC!

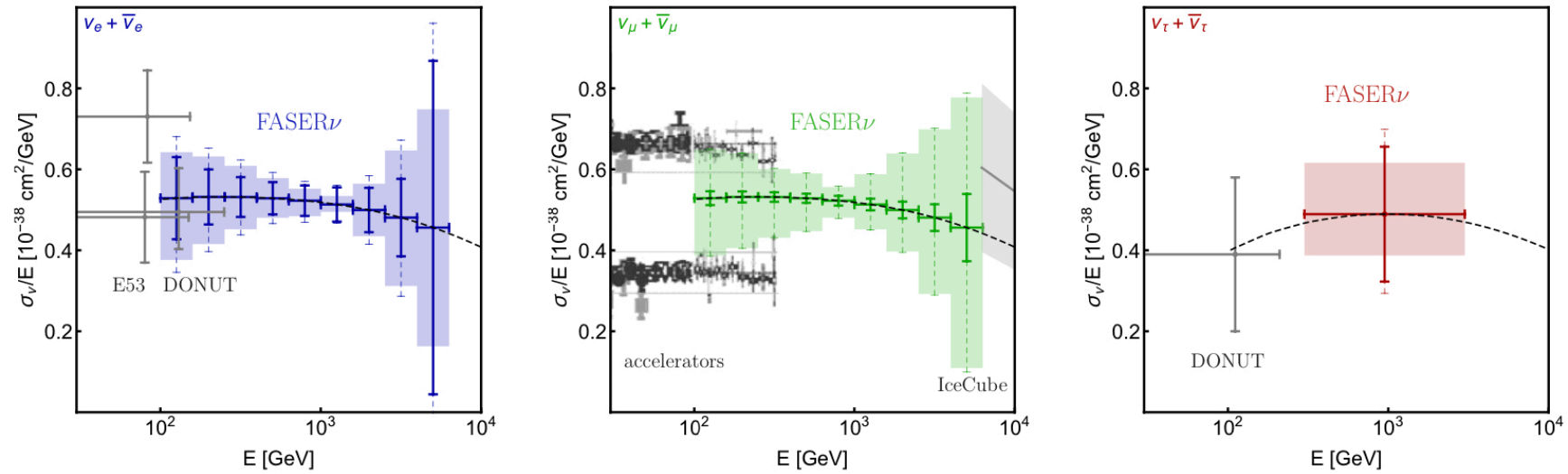
Preliminary (optimistic) schedule of HL-LHC



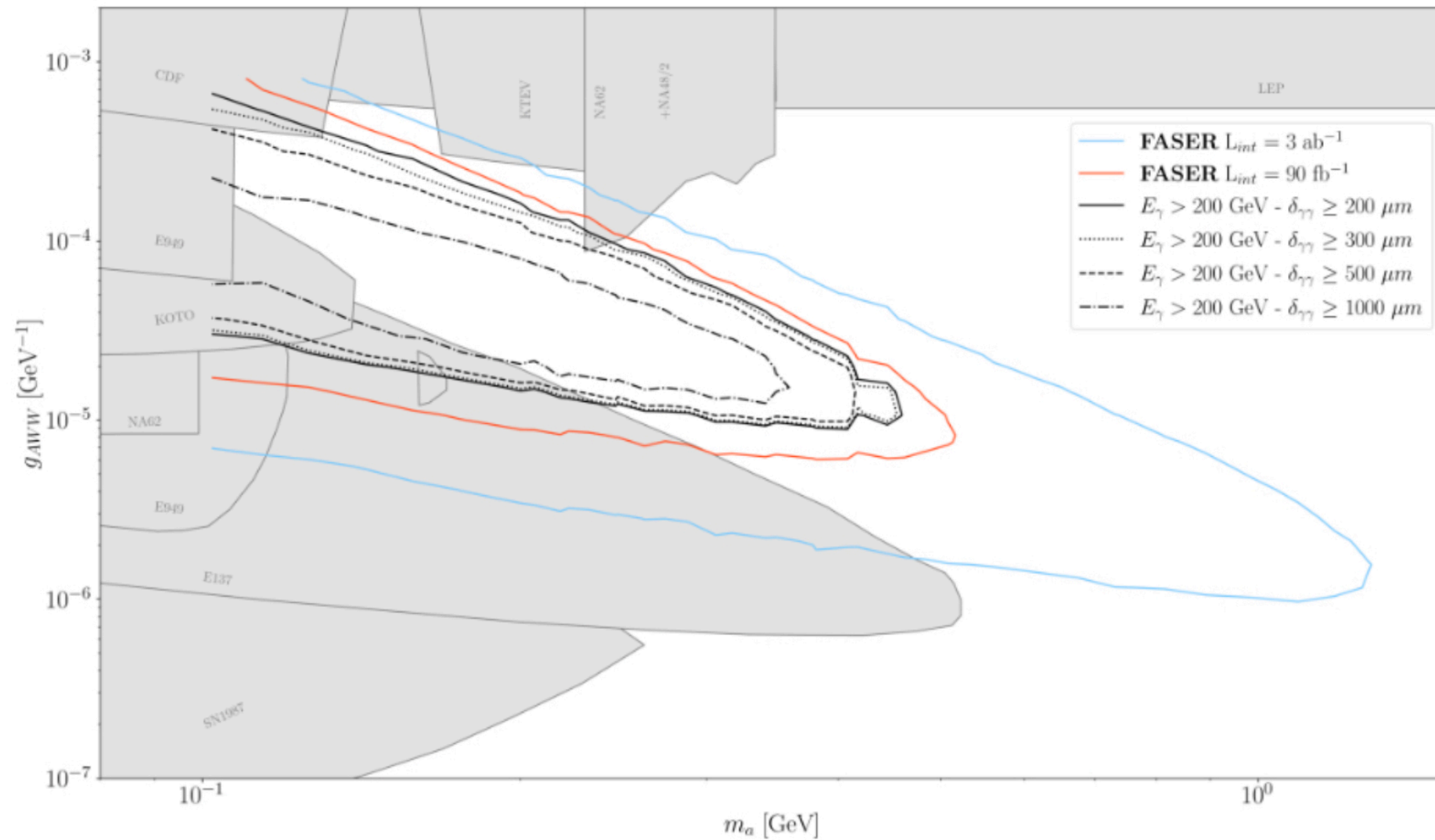
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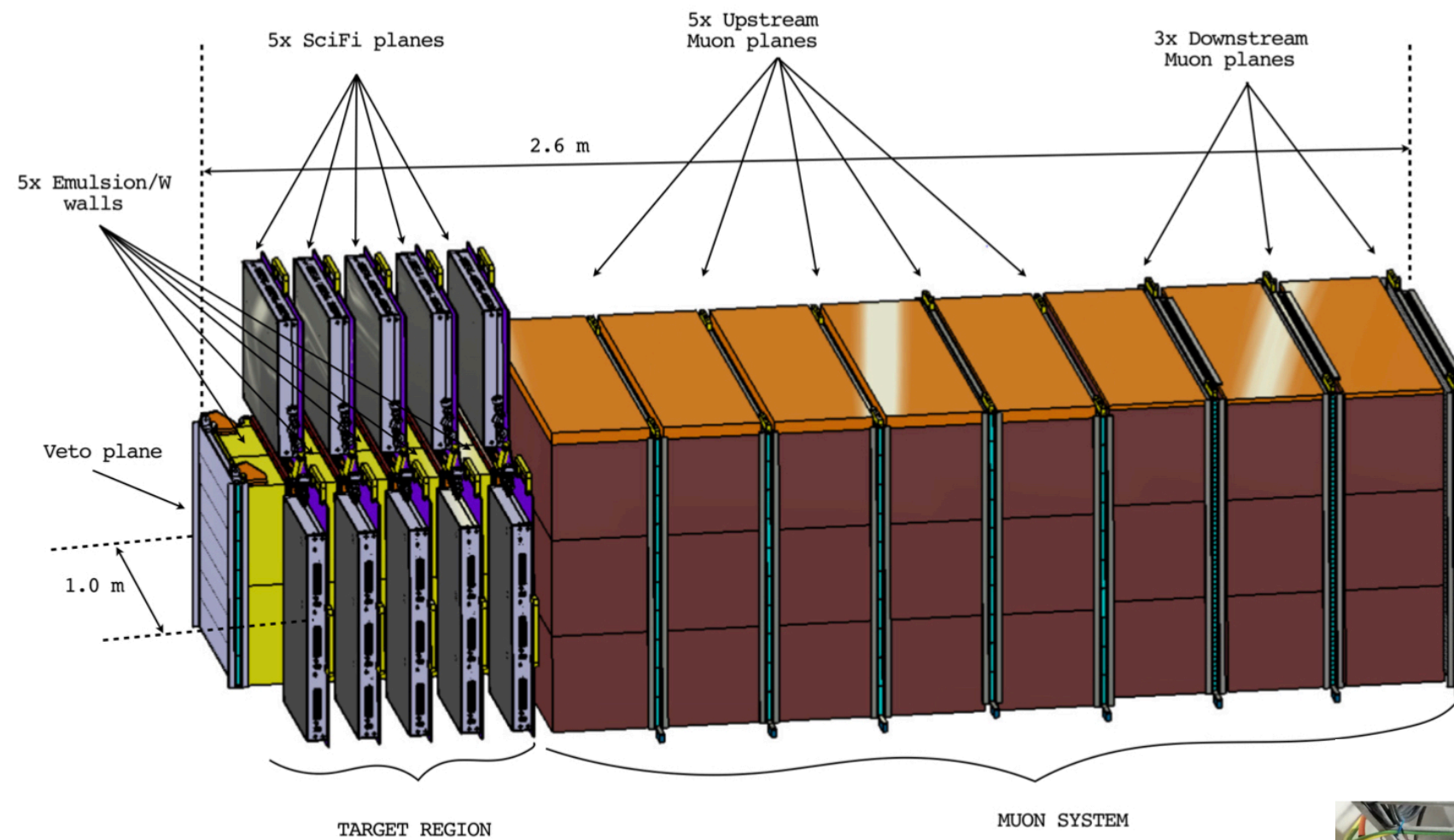


Guaranteed deliverables: neutrino cross sections



Exploration power: LLPs, ALPs $\rightarrow \gamma\gamma$, ...

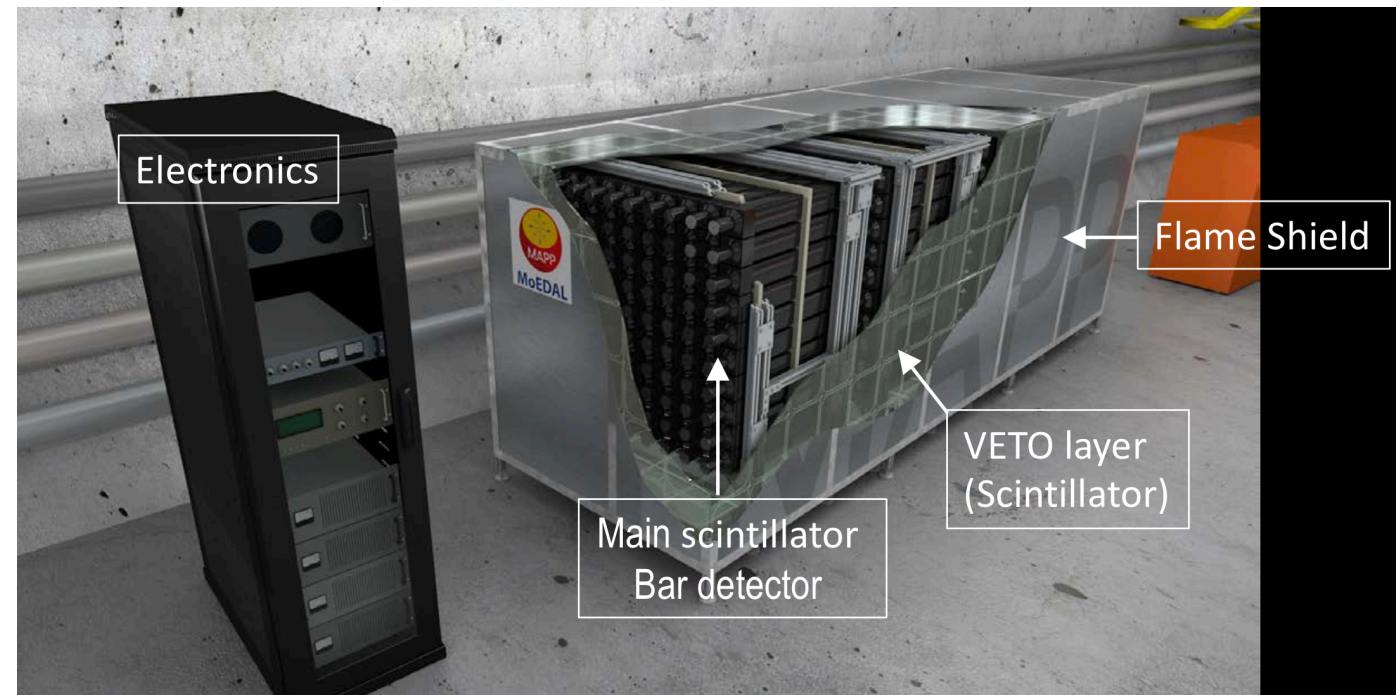
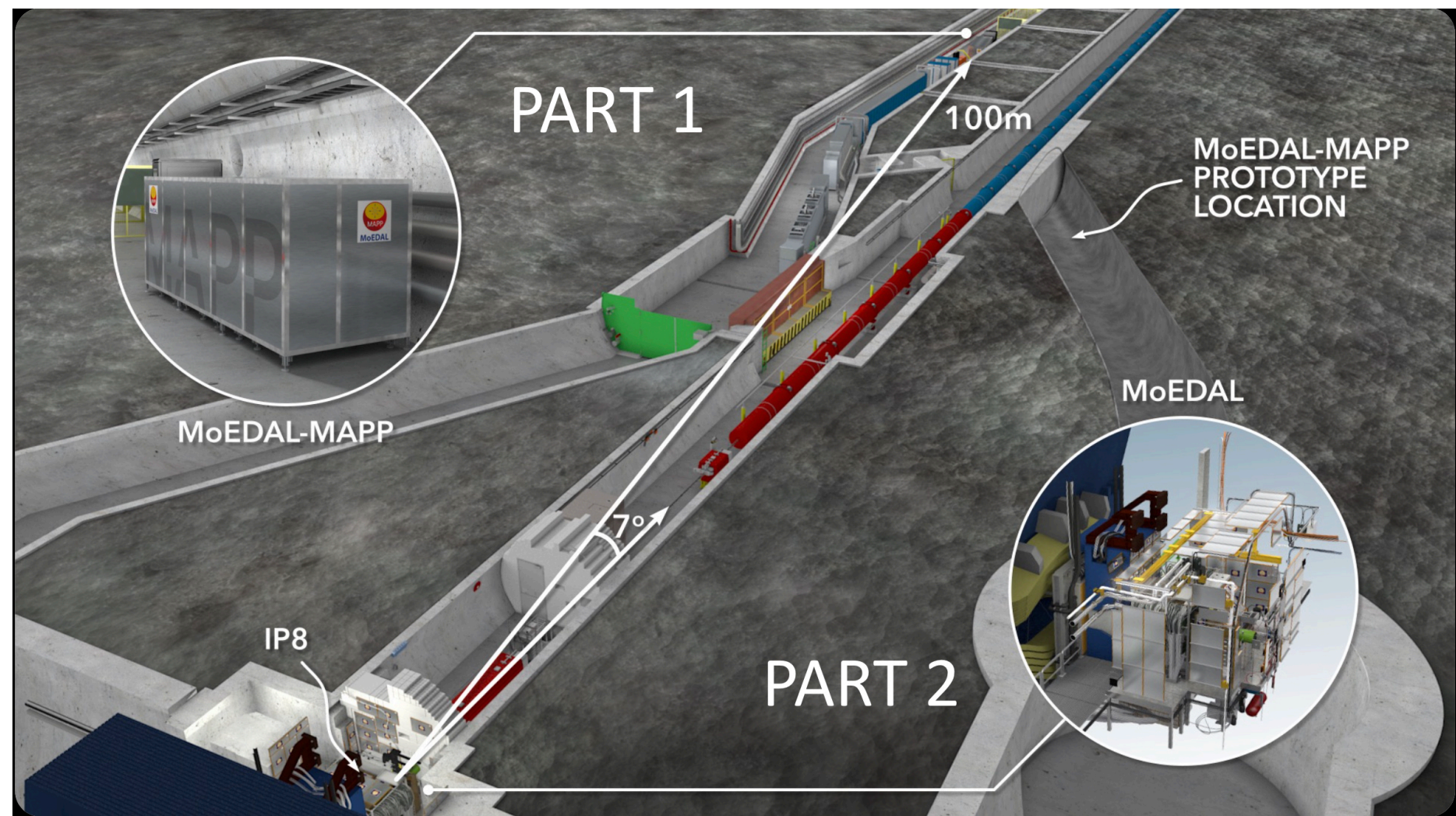




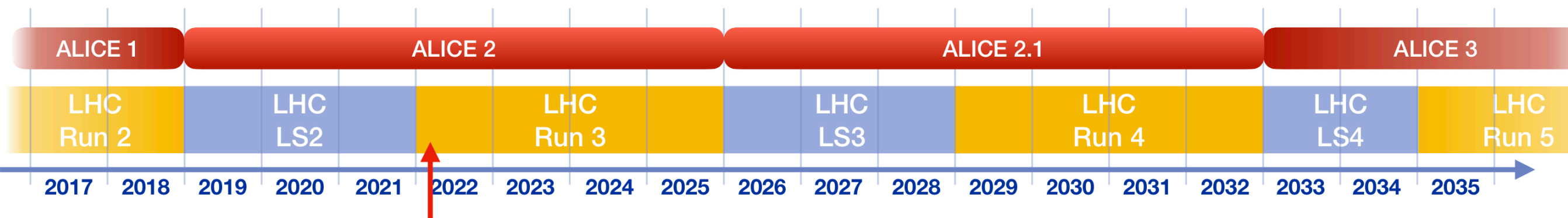
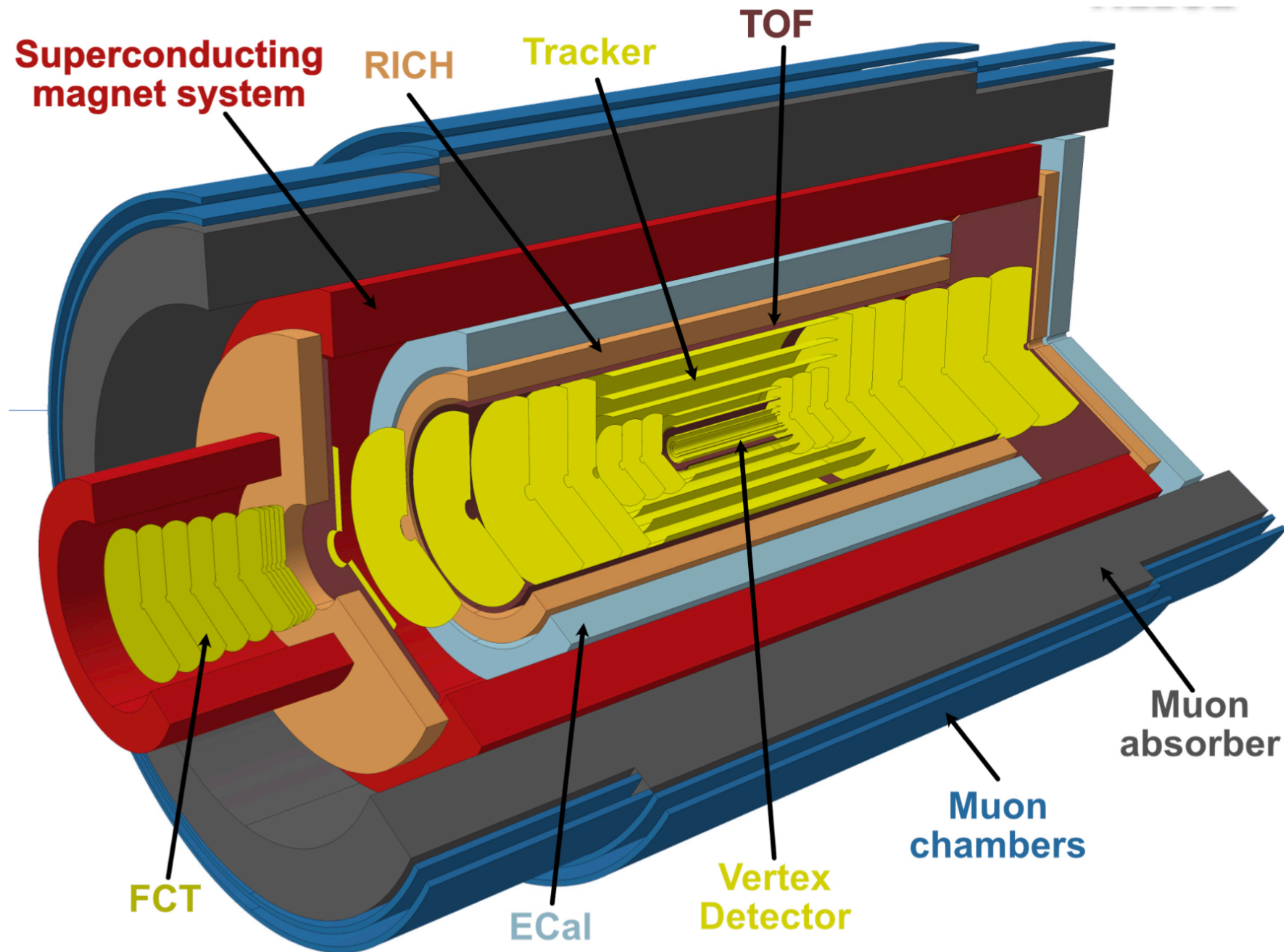
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MoEDAL MAPP: millicharged particles



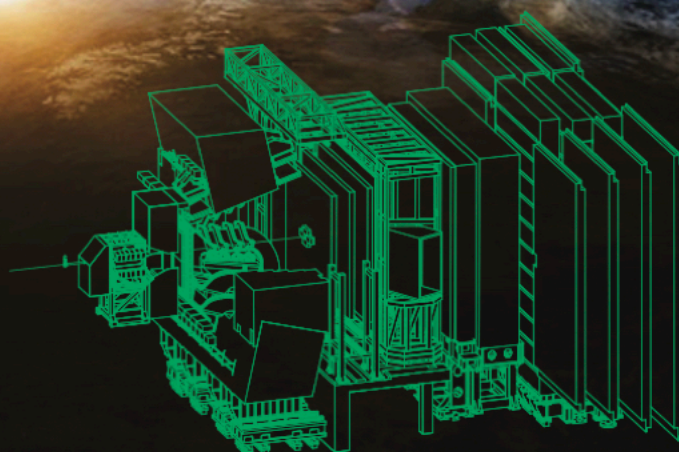
ALICE 3





CERN/LHCC 2021-012
LHCb TDR 23
24 February 2022

Framework LHCb UPGRADE II TDR



Technical Design Report



LHCb Upgrade II Framework TDR

CDS link <https://cds.cern.ch/record/2776420/>

165 pages, 10 chapters

1. *Executive summary*
2. *Introduction*
3. *Tracking detectors*
4. *Particle identification detectors*
5. *Data acquisition and online processing*
6. *Simulation and offline computing*
7. *Infrastructure*
8. *Environmental protection and safety*
9. *Project timeline*
10. *Detector scenarios and costs*

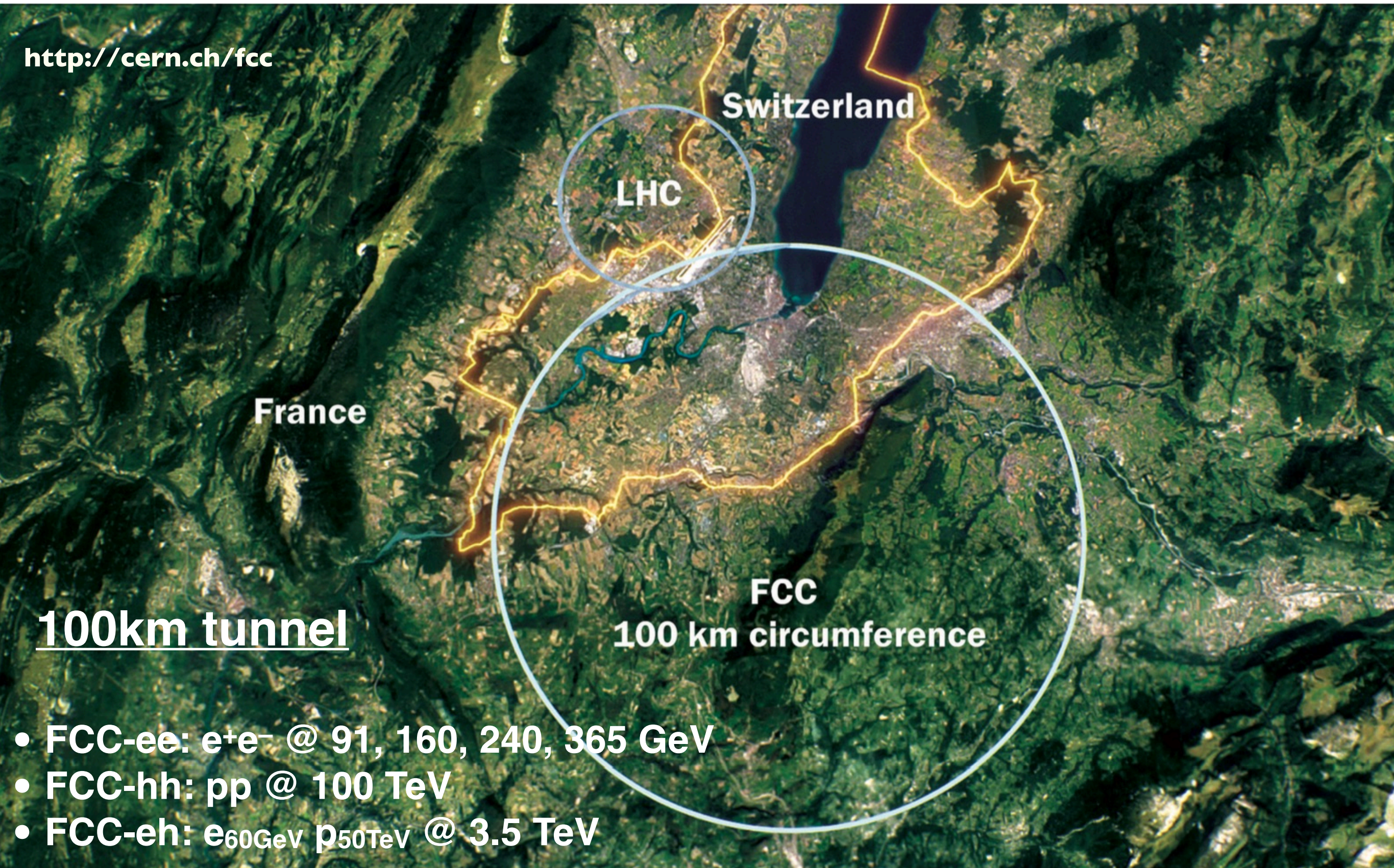
1113 authors from 91 institutes

LHCC review started September 2021

Beyond the LHC

Future Circular Collider

<http://cern.ch/fcc>



France

Switzerland

LHC

FCC

100 km circumference

100km tunnel

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

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- 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	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
	10^6	$5 \cdot 10^{12}$	10^8	10^6	$3 \cdot 10^{11}$	$1.5 \cdot 10^{12}$	10^{12}

FCC-hh	H	b	t	$W(\leftarrow t)$	$\tau(\leftarrow W \leftarrow t)$
	$2.5 \cdot 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5 \cdot 10^6$	$2 \cdot 10^7$

(1) guaranteed deliverables: Higgs properties

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 %



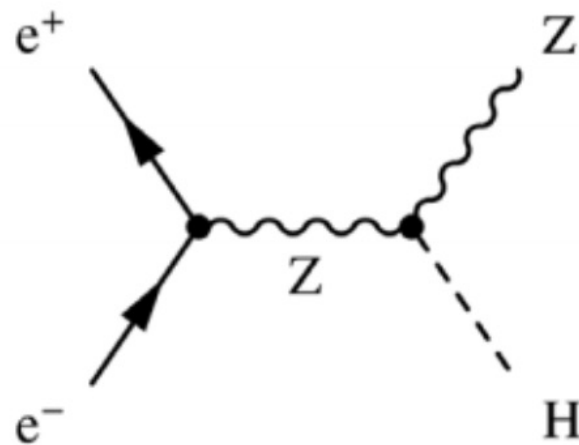
> 10%

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 3-5 σ evidence of deviations, and to cross-correlate coupling deviations across different channels

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

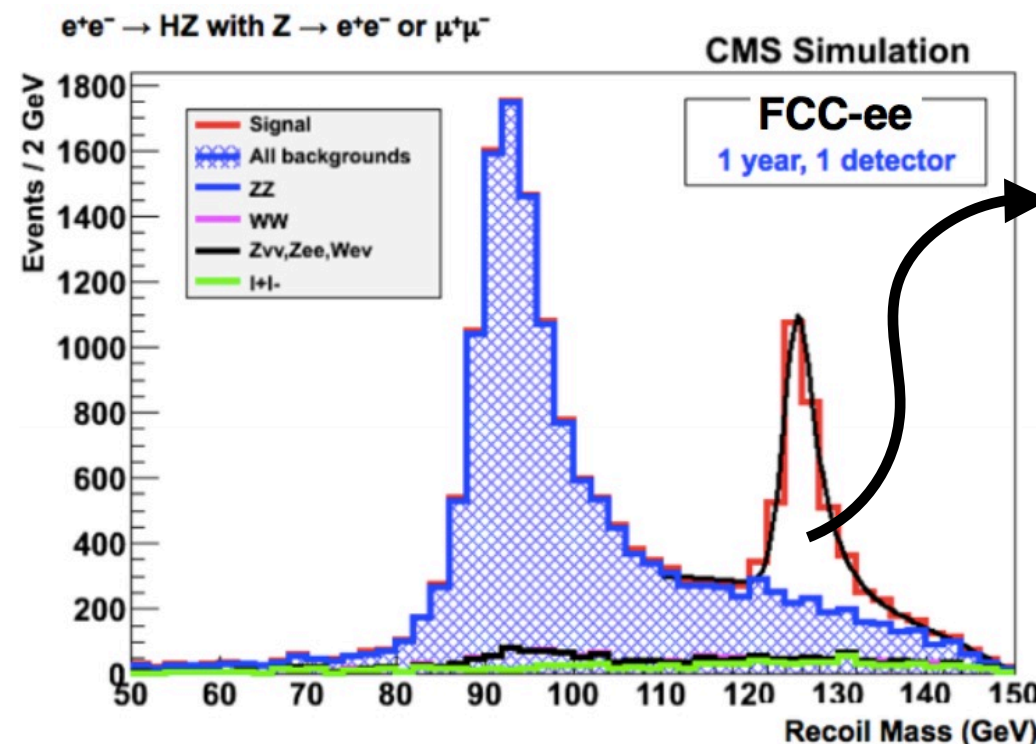
- the **model independent absolute** measurement of **HZZ** coupling, which allows the subsequent:
 - **sub-%** measurement of couplings to **W, Z, b, τ**
 - **%** measurement of couplings to **gluon and charm**



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

$$N(ZH[\rightarrow ZZ]) \propto$$

$$\sigma(ZH) \times \text{BR}(H \rightarrow ZZ) \propto$$

$$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$$

\Rightarrow absolute measurement of width and couplings

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

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 $\sim 5\%$ 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→Zγ,γγ) ~O(10⁻³) ⇒ O(10⁷) evts for Δ_{stat}~%

BR(H→μμ) ~O(10⁻⁴) ⇒ O(10⁸) evts for Δ_{stat}~%

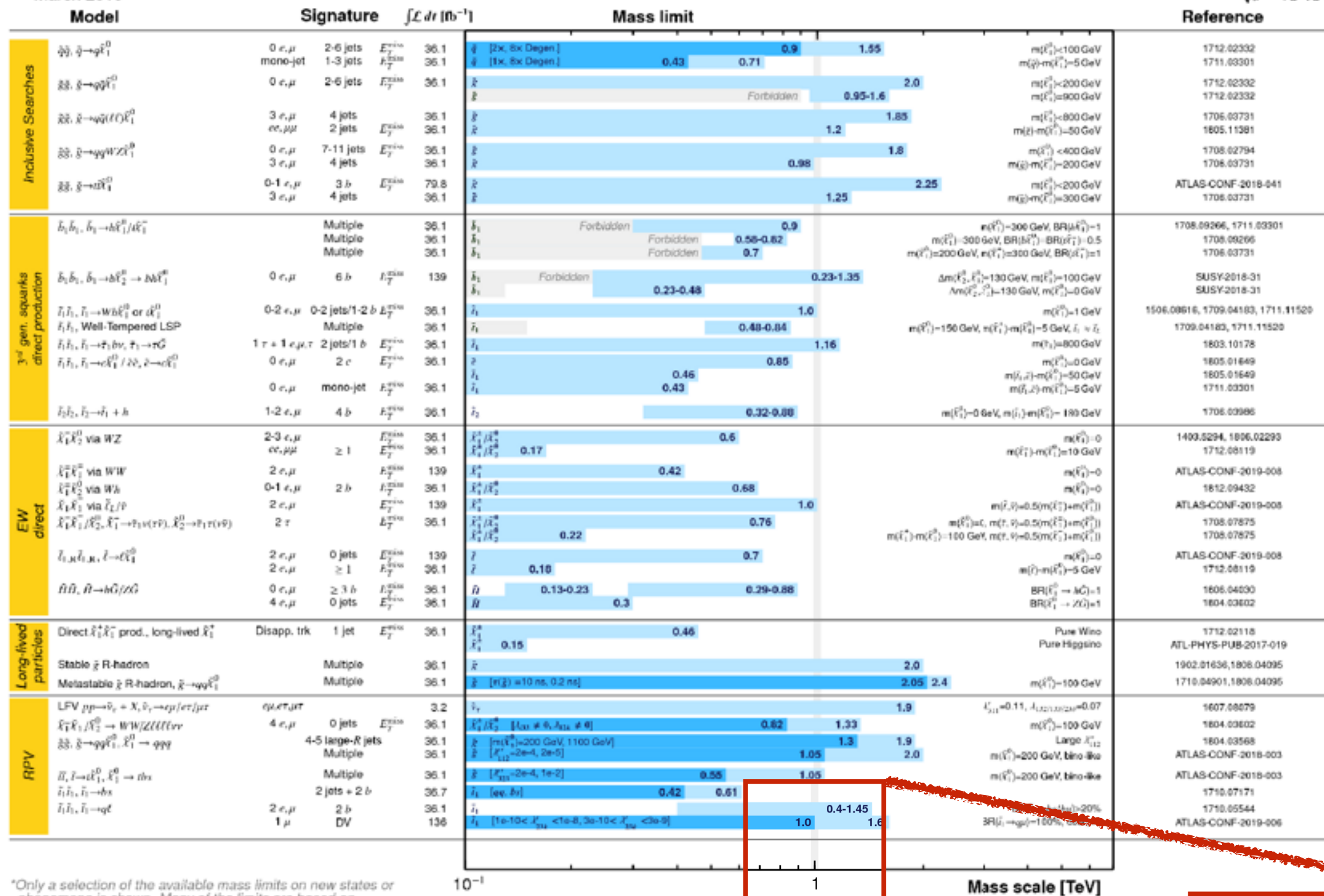


pp collider is essential to beat the % target, since no proposed ee collider can produce more than O(10⁶) H's

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

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

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

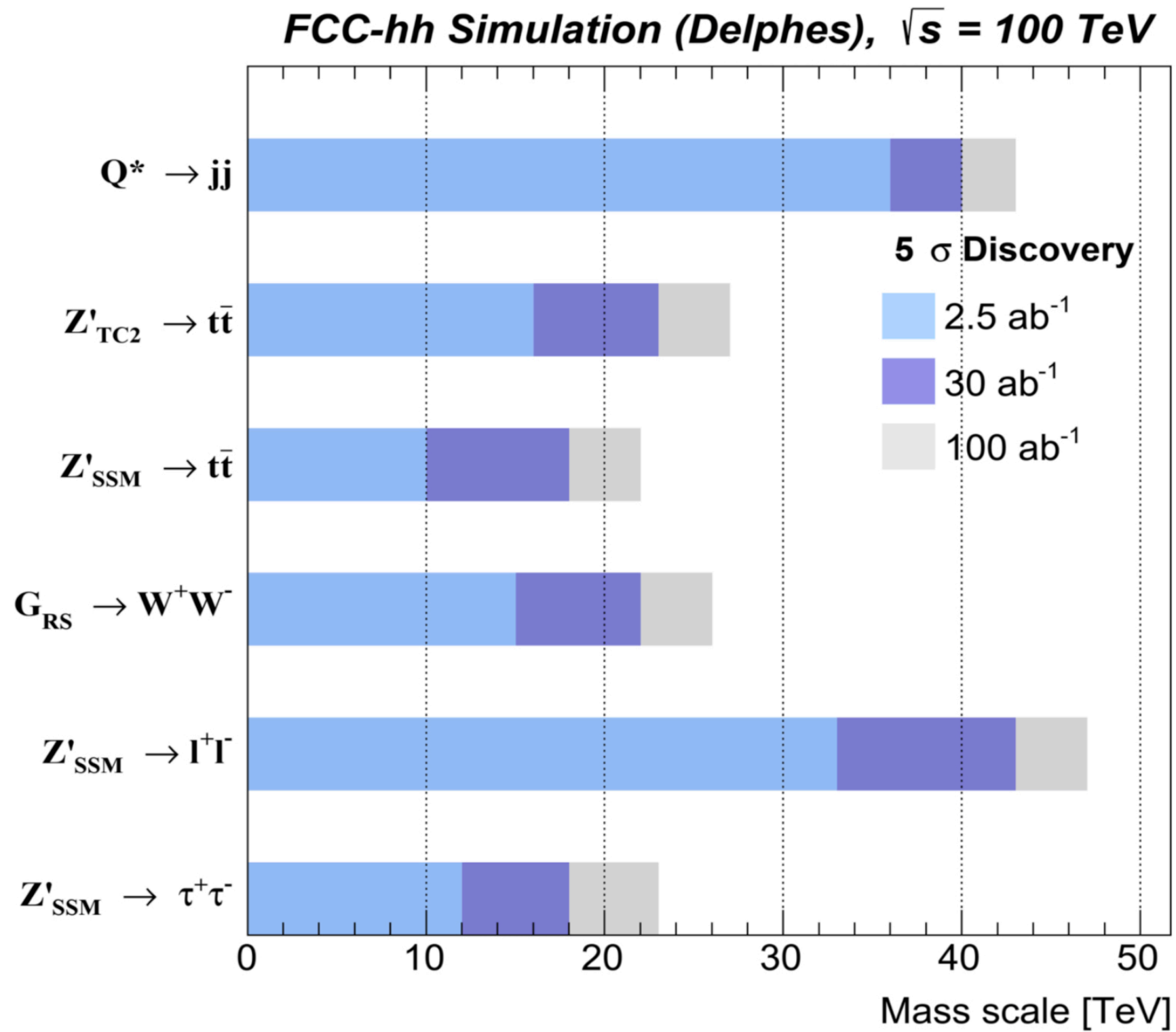


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

@14 TeV

@100 TeV

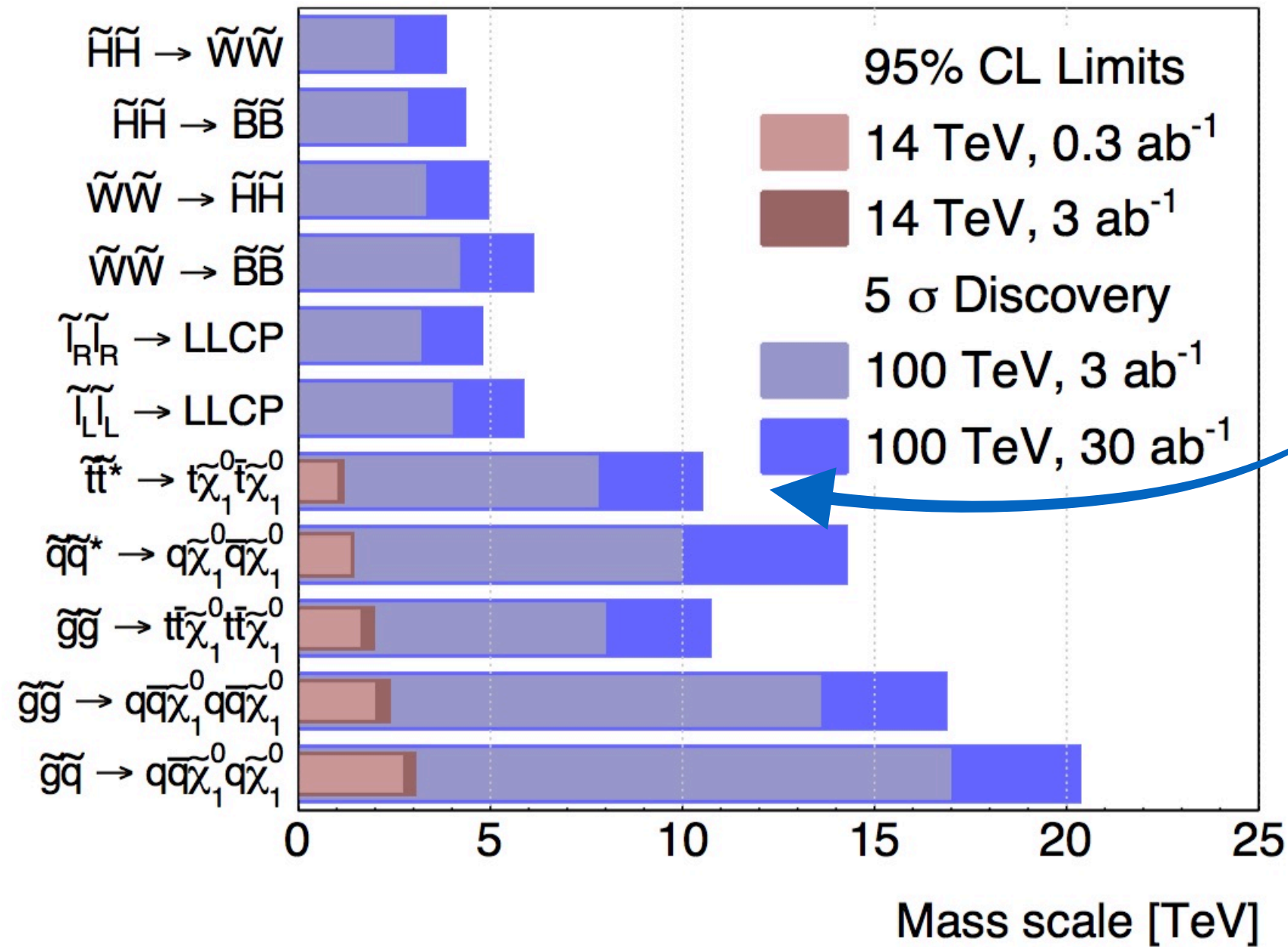
s-channel resonances



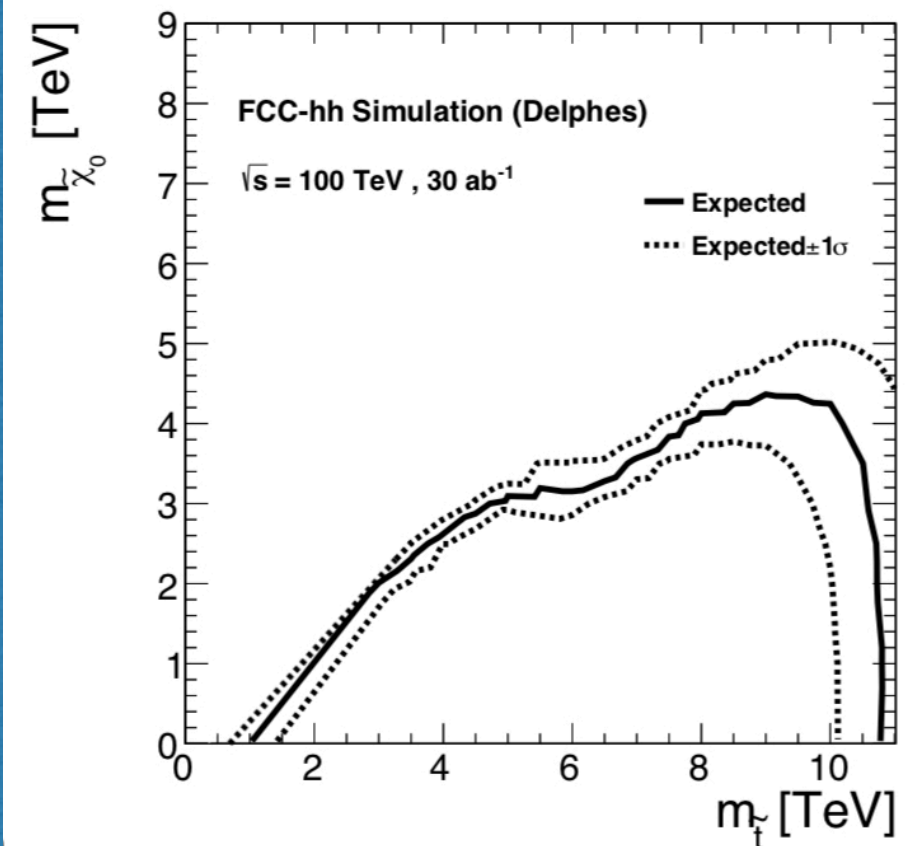
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

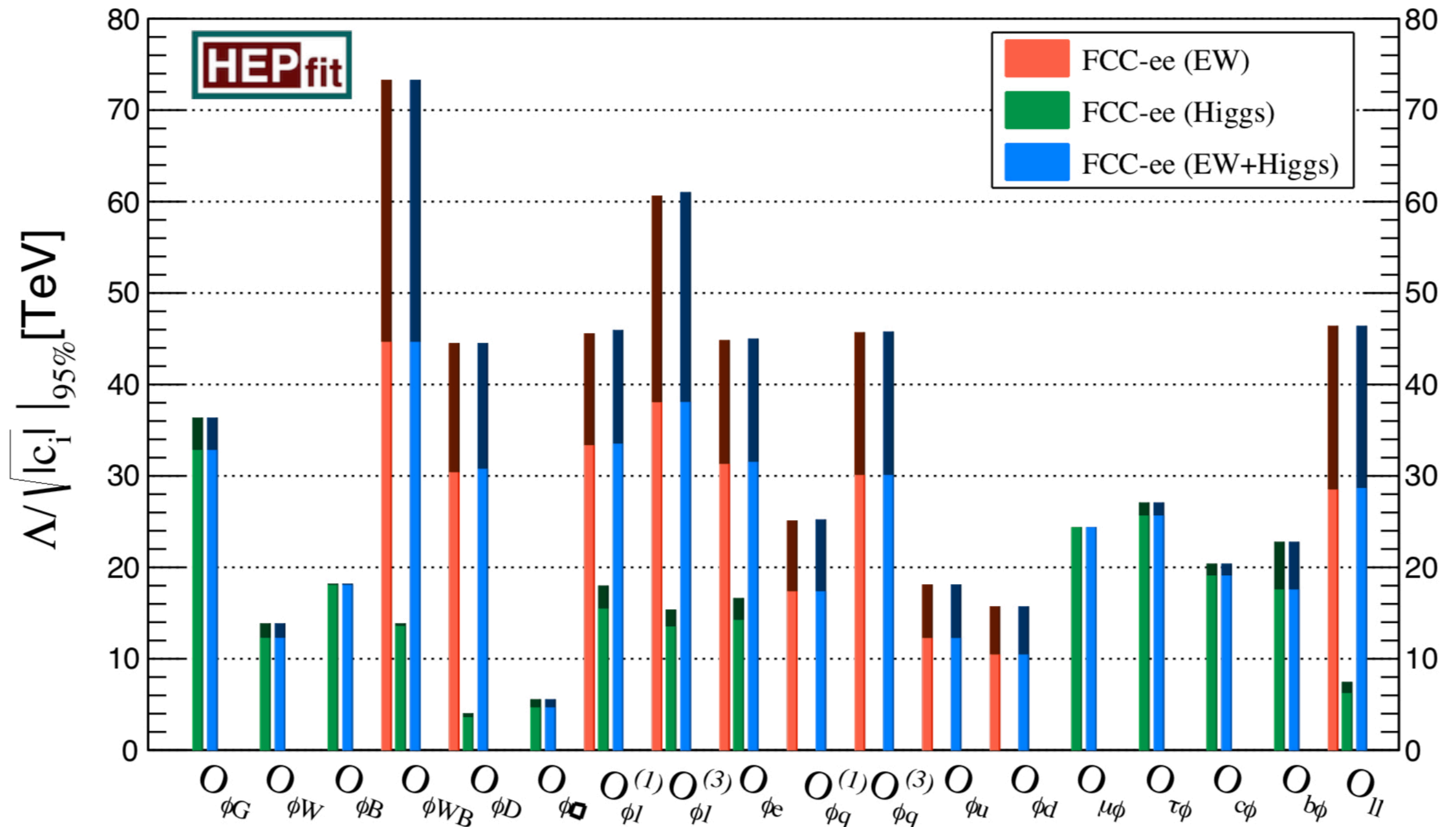
Early phenomenology studies



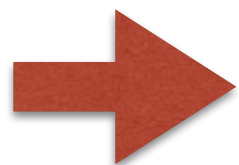
New detector performance studies



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, ($\chi \chi \leftrightarrow \text{SM}$)

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

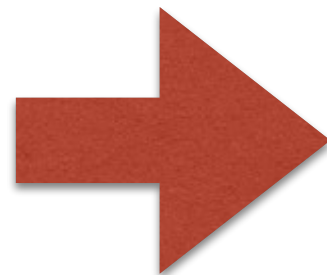
For a particle annihilating through processes which do not involve any larger mass scales:

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



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

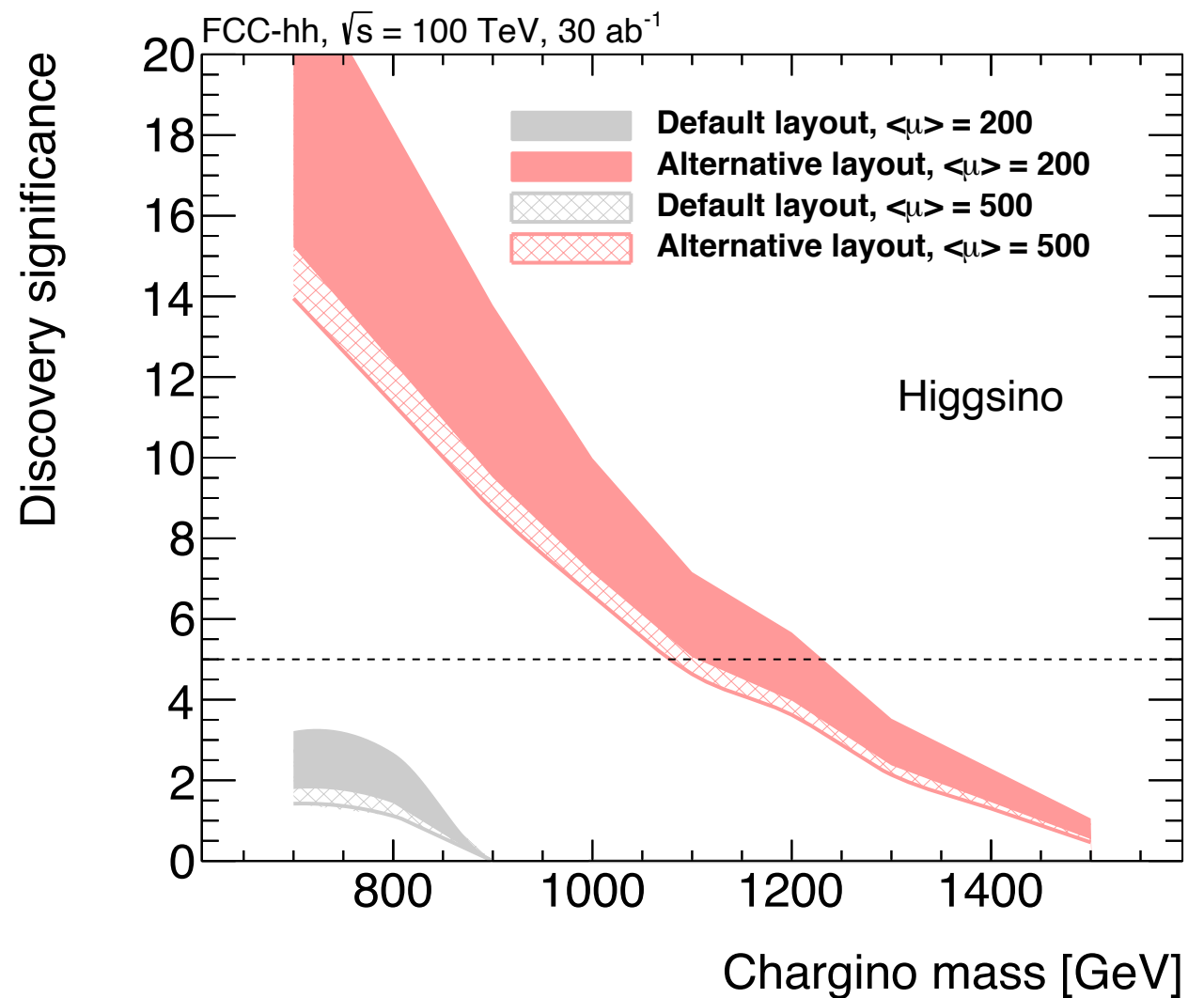
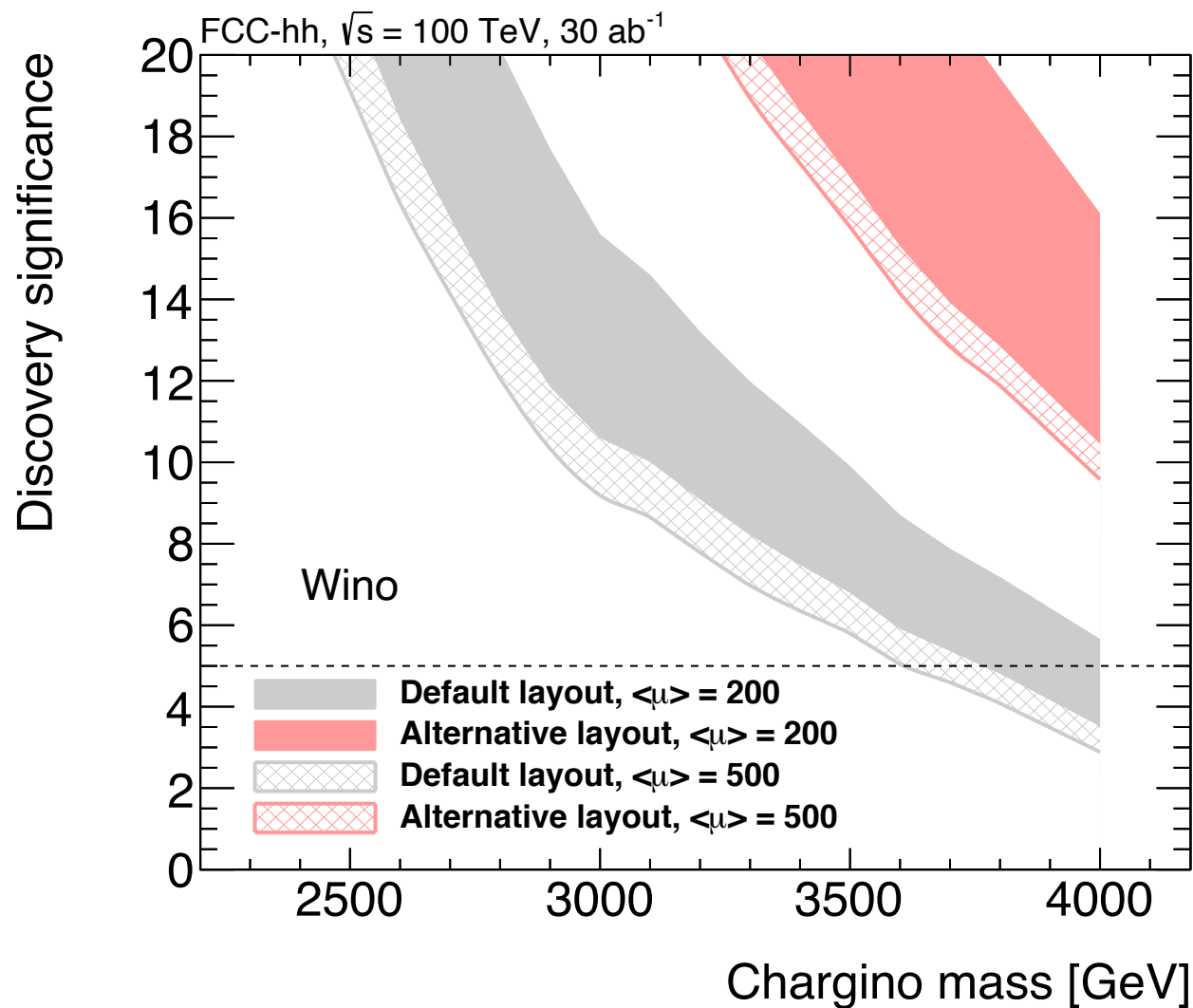
$$\Omega_{\text{wimp}} h^2 \lesssim 0.12$$



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

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 !!

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

... and much more ...

- 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 unmatched 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