The future, and challenges, of HEP

from the colliders' perspective

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Question on the table:

What should follow the LHC?

The question is hotly debated since a while, for the coexistence of different prospects and perspectives on some key issues:

- **science**
  - ***why insist with colliders?***
  - ***what's the best way to achieve our goals?***
  - ***what's the best compromise between timescales/costs and deliverables?***
- **technology**
  - ***if ready => not attractive/ambitious, if challenging => risky***
- **politics**
  - ***regional scientific leadership ambitions vs financial environment***

The debate, formally started for the 2020 update of the European Strategy for Particle Physics, is now moving to the US, in the context of their own Snowmass/P5 strategy process

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

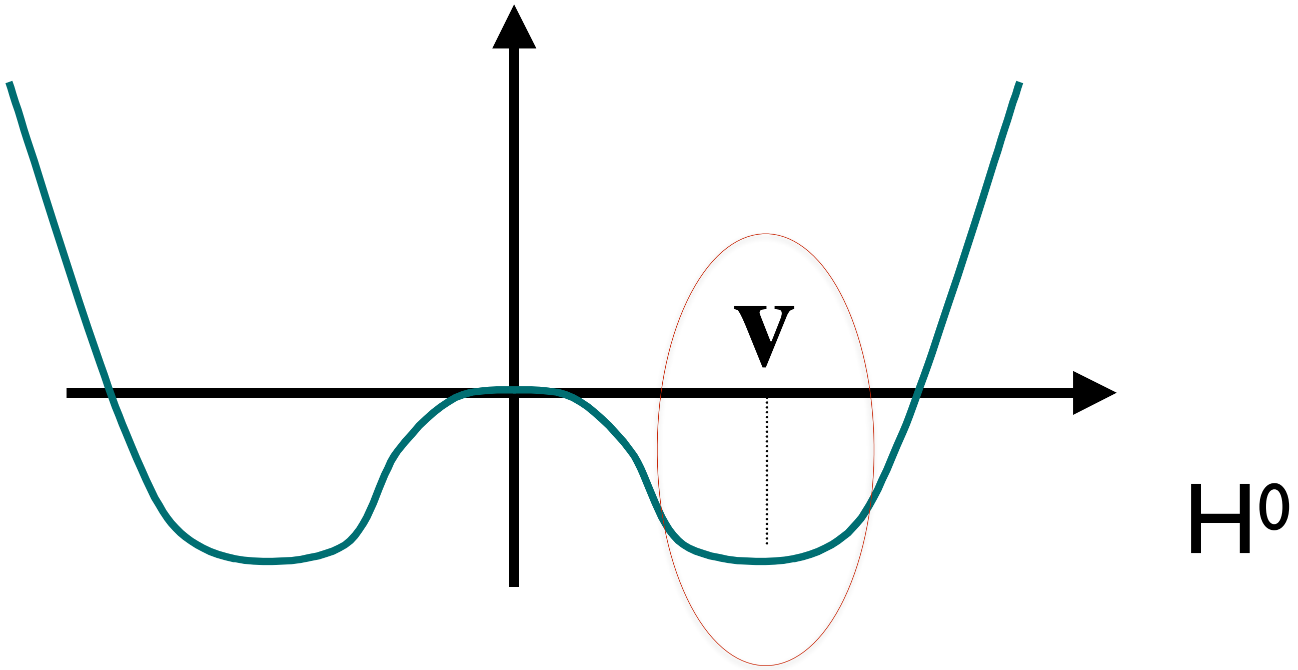
The important questions

- **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, …)

But there is one question that can only be addressed by colliders



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

Where does this come from?

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”

From ESPP 2020:

“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. “

What do we expect out of a Higgs factory?

- The precision measurement of Higgs properties must be a guaranteed deliverable of all future colliders: whether they will challenge or confirm the SM properties, these measurements are a key ingredient in exploration of physics beyond the SM.

- Should they show deviations from the SM, the hint to BSM will be explicit, and the correlations among the various deviations will guide the interpretation of their origin

- Should they agree with the SM, the more accurate the measurements, the more constraining their power in identifying the microscopic origin of possible BSM effects observed in other parts of the programme or elsewhere

  - *The LEP precision measurements are still today an essential constraint in evaluating BSM models proposed whenever some anomaly is detected in the data*

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, HIs, …)

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

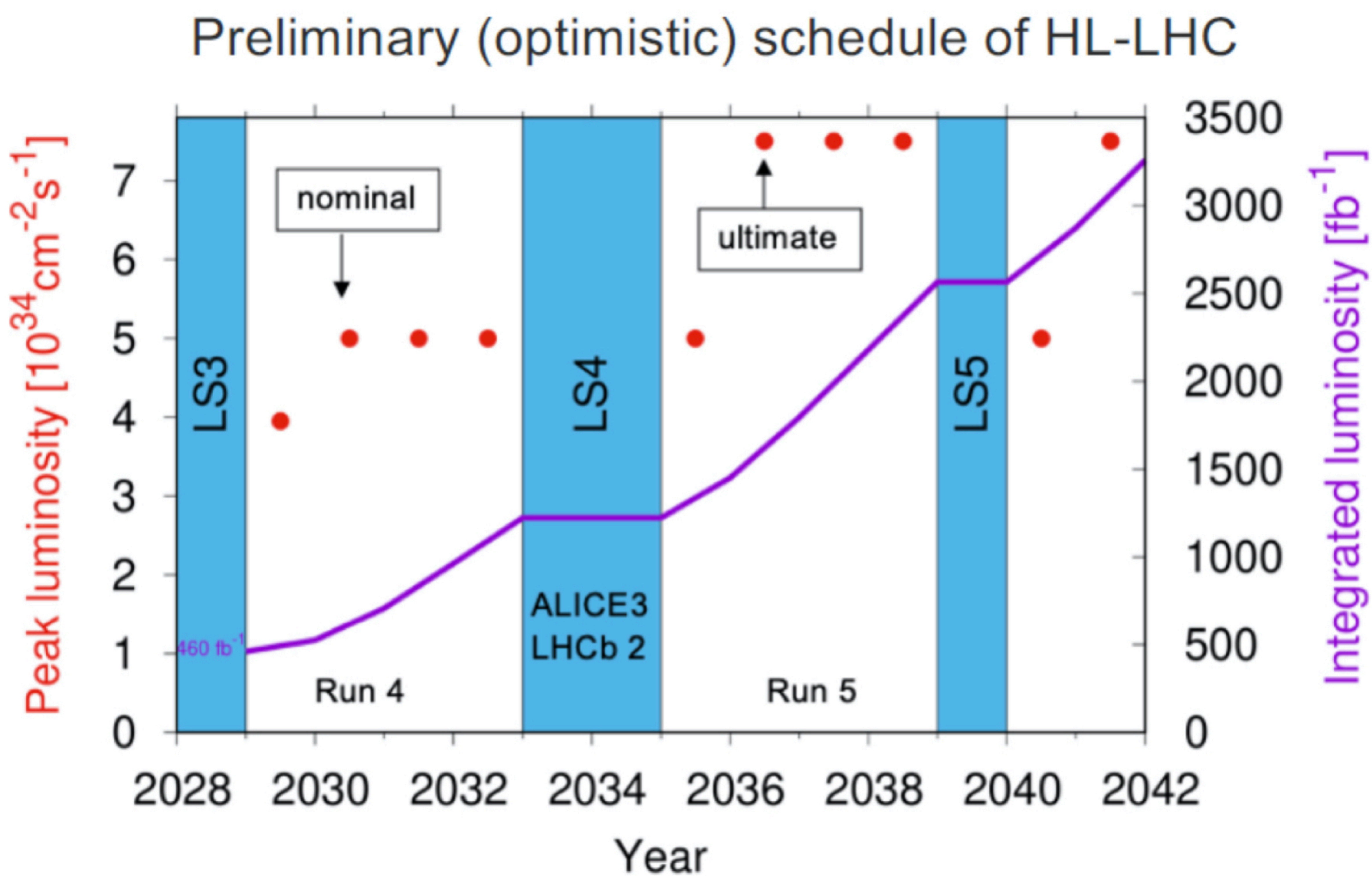
- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

What are we talking about when

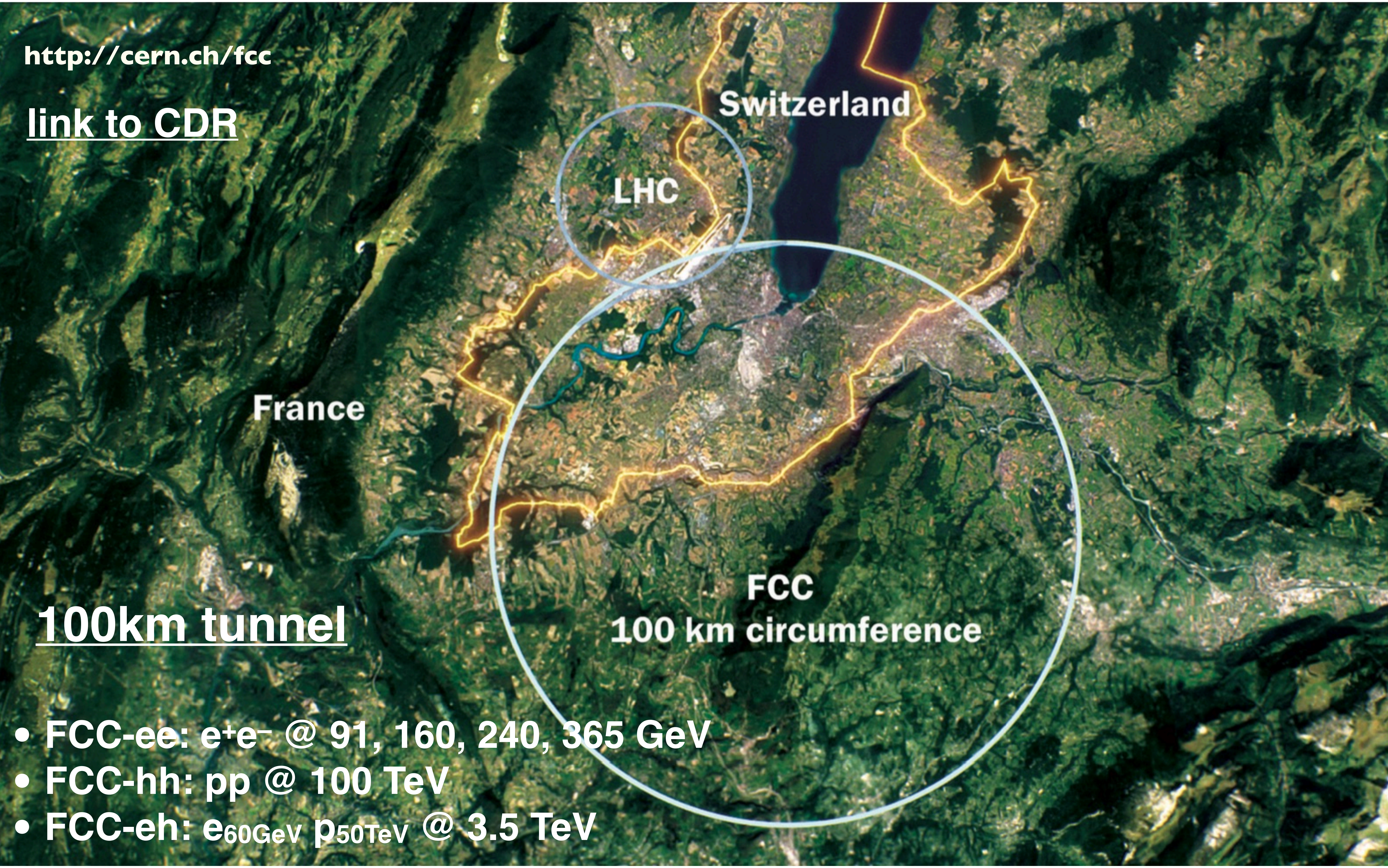
we talk about future colliders?

Circular ...

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



Future Circular Collider



http://cern.ch/fcc

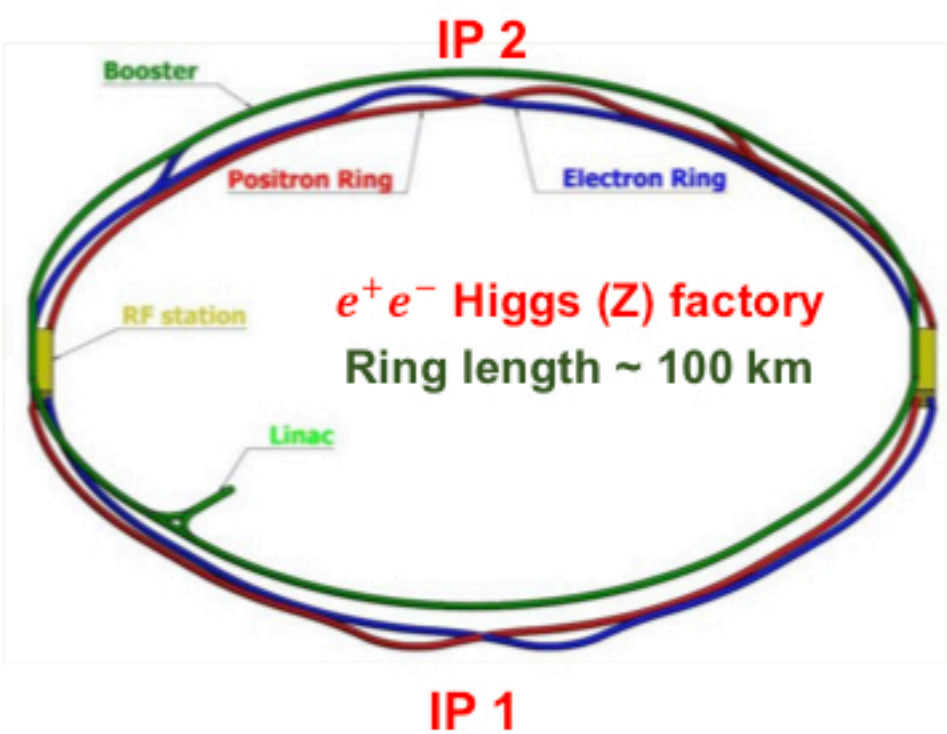
link to CDR

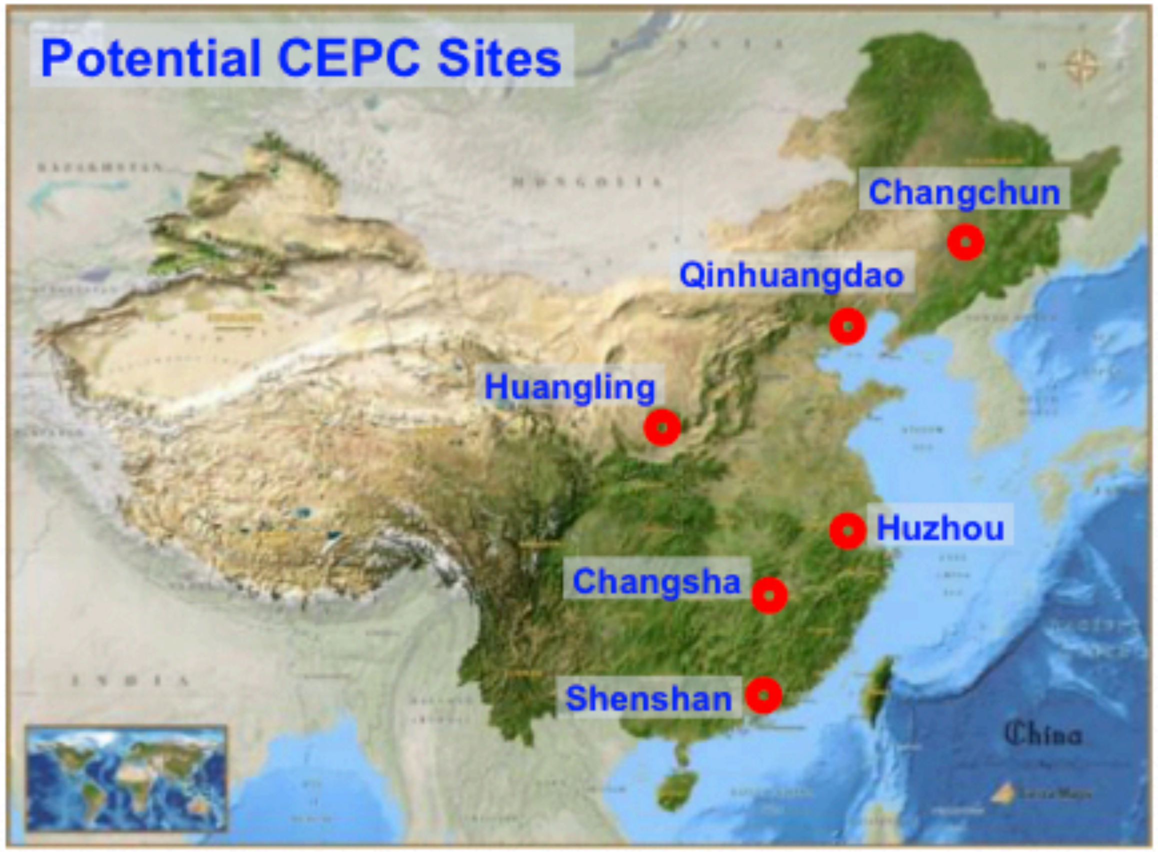
100km tunnel

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

Circular electron-positron Collider

- The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.
- To run at $\sqrt{s}$ ~ 240 GeV, above the **ZH** production threshold for ≥1 M Higgs; at the **Z** pole for ~Tera Z; at the **W^+W^-** pair and possible $t\bar{t}$ pair production thresholds.
- Higgs, EW, flavor physics & QCD, probes of physics BSM.
- Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the far future.





link to CDR

… 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

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.

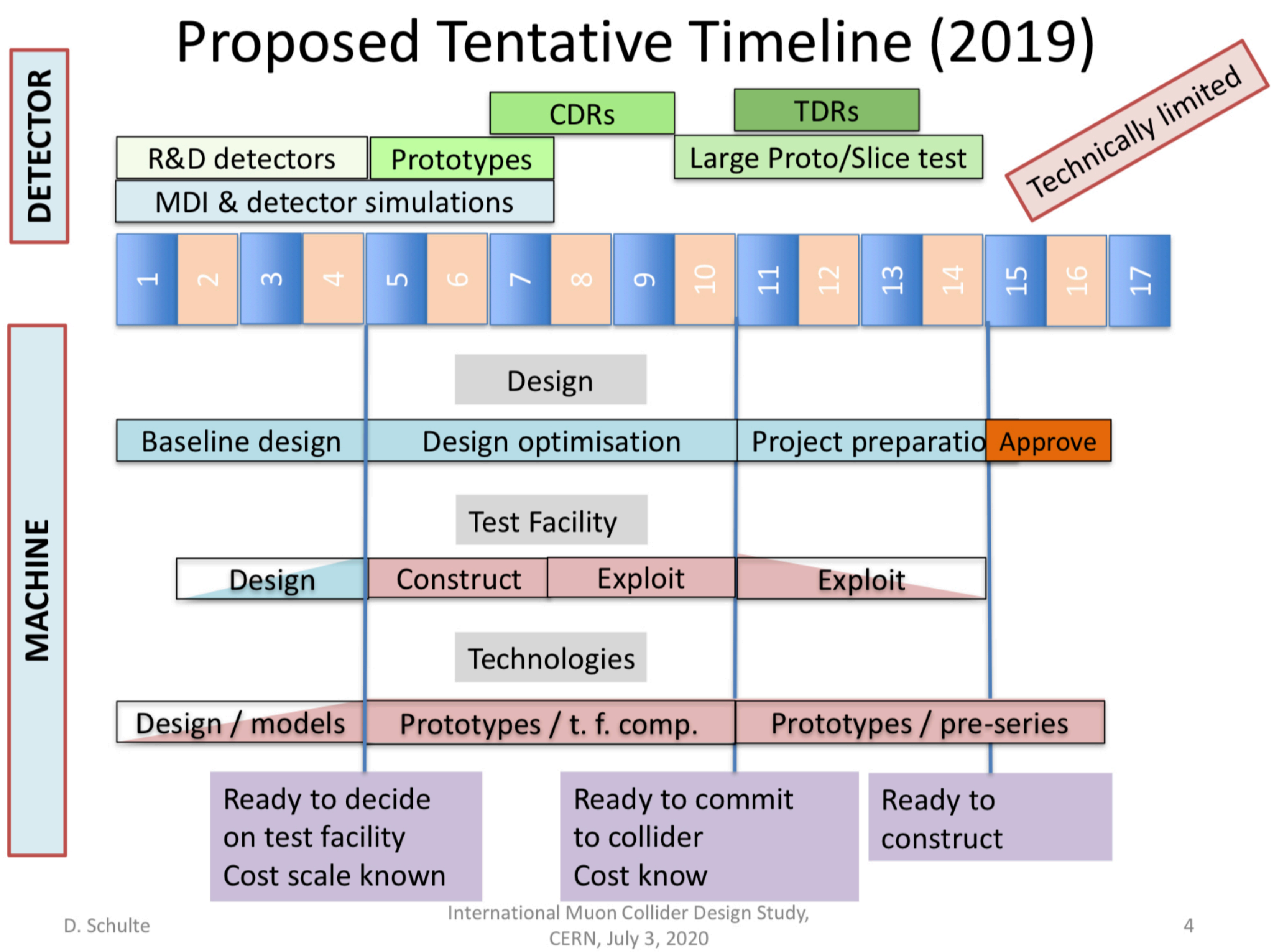
Energy, center-of-mass, $U_{\rm cm}$[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}$[10^{34} s^{-1}cm^{-2}]	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. 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)*

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
- **Muon Collider** Collaboration, J. de Blas et al., “The physics case of a 3 TeV muon collider stage,” arXiv:2203.07261
- **Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020,** arXiv:1910.11775

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

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

[blue box] 5 – 10 %

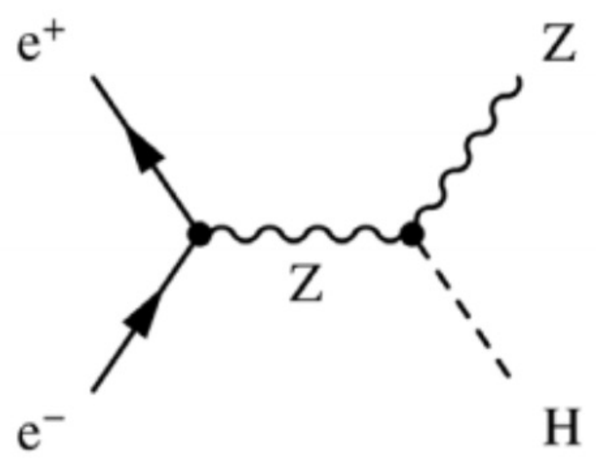
[red box] > 10%

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

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

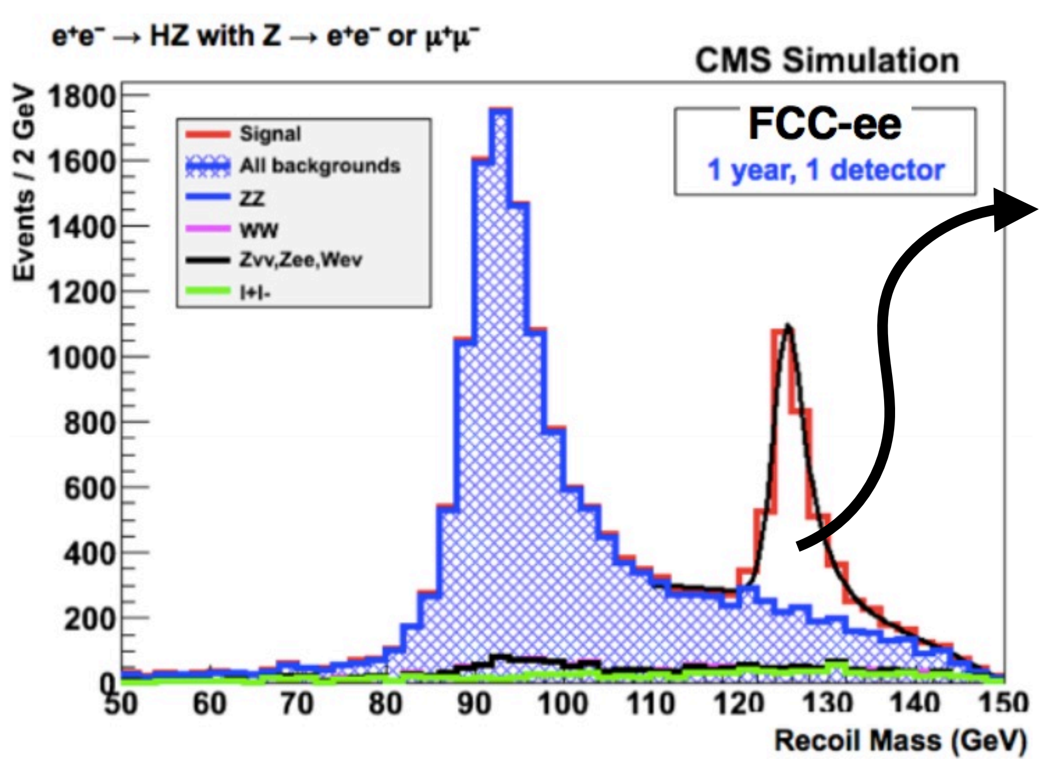
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

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

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

The absolutely unique power of pp →H+X:

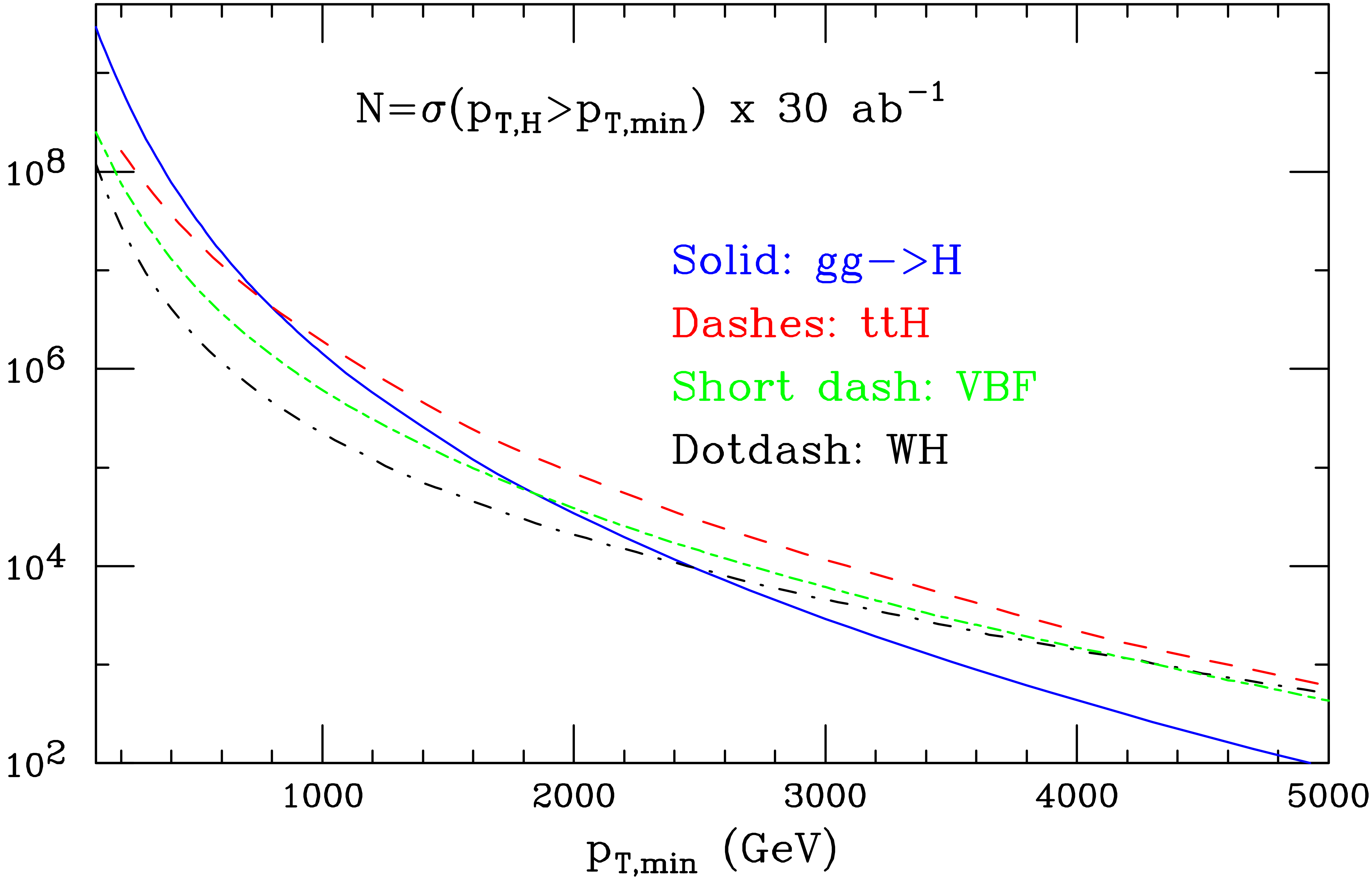
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4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

	gg→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

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

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

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

Three kinematic regimes

- Inclusive production, $p_T > 0$:
  - largest overall rates
  - most challenging experimentally:
    - triggers, backgrounds, pile-up ⇒ low efficiency, large systematics

  ➡ det simulations challenging, likely unreliable ⇒ regime not studied so far

- $p_T \gtrsim 100$ GeV :
  - stat uncertainty ~few × 10^{-3} for H→4l, γγ, …
  - improved S/B, realistic trigger thresholds, reduced pile-up effects ?

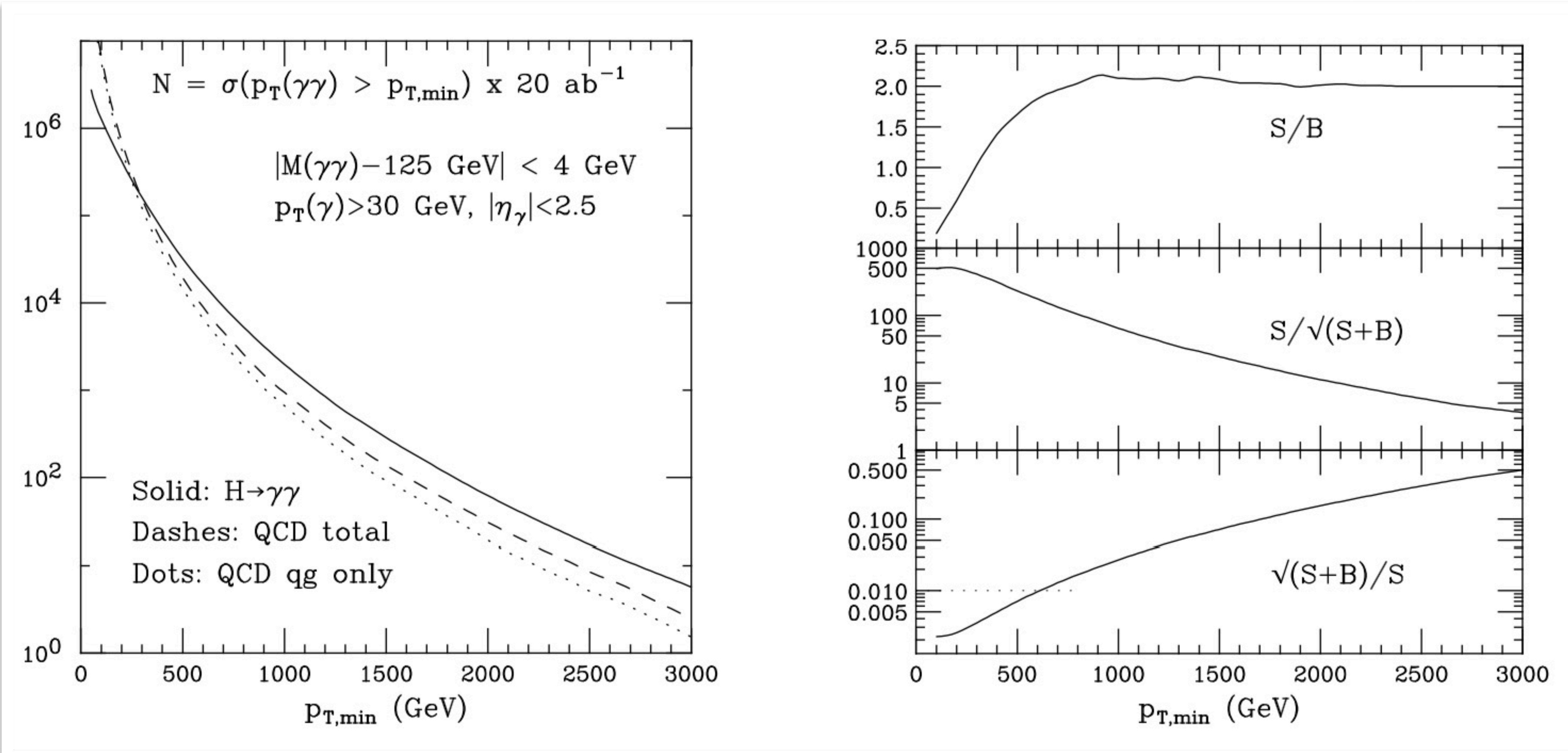
  ➡ current det sim and HL-LHC extrapolations more robust

  ➡ focus of FCC CDR Higgs studies so far

  ➡ sweet-spot for precision measurements at the sub-% level

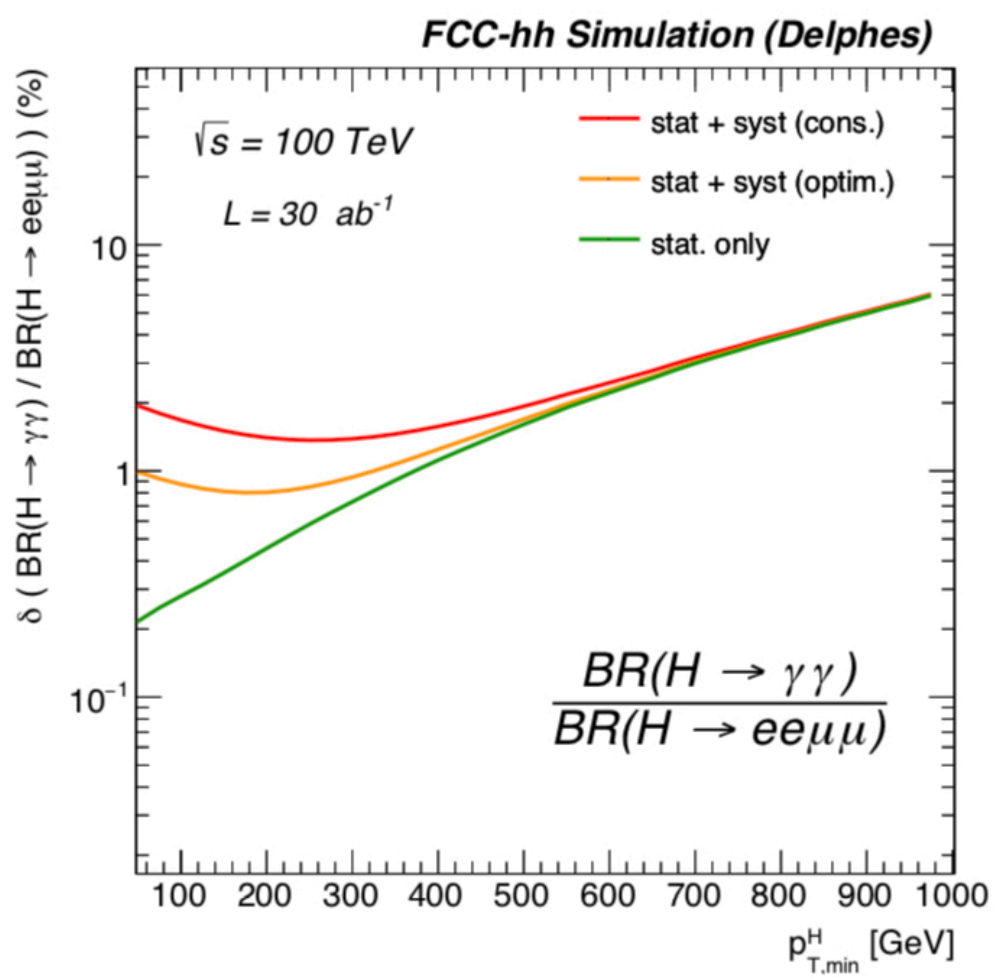
- $p_T \gtrsim$ TeV :
  - stat uncertainty O(10%) up to 1.5 TeV (3 TeV) for H→4l, γγ (H→bb)
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

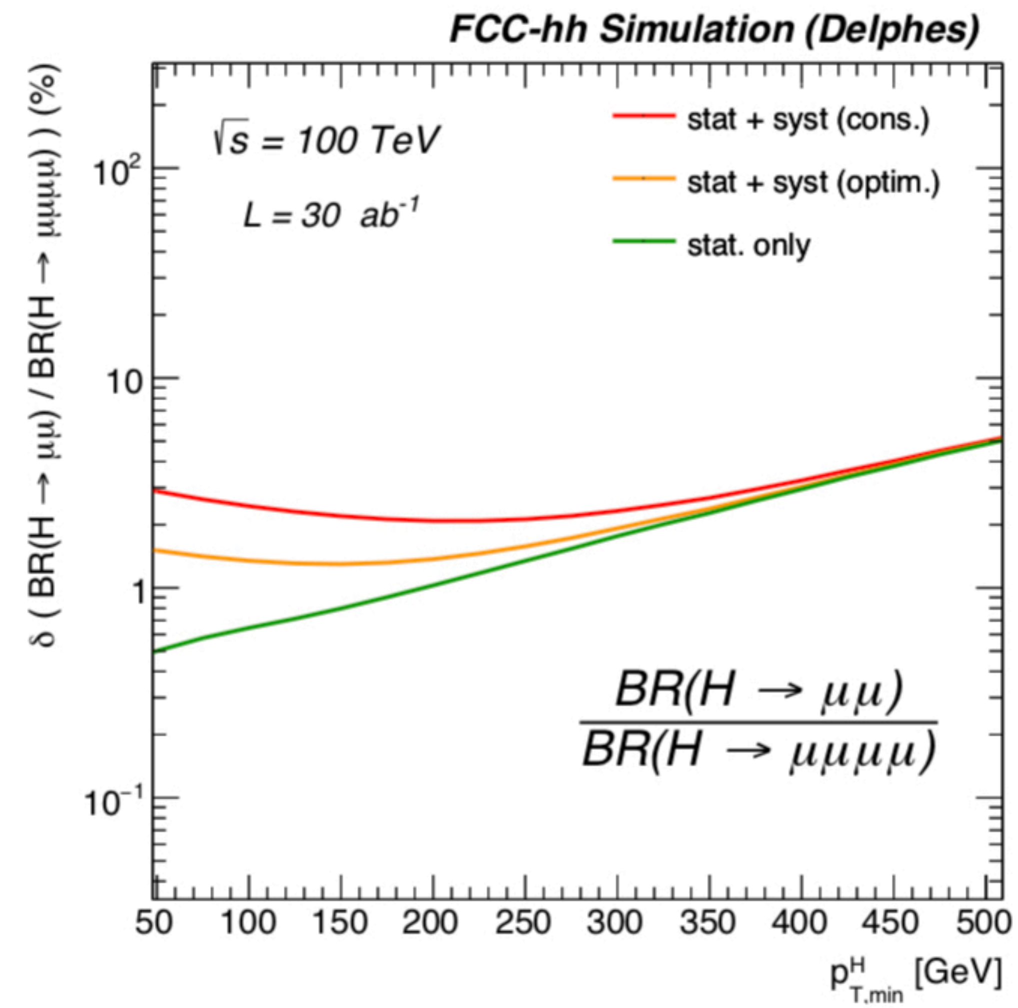
gg→H→γγ at large p_T

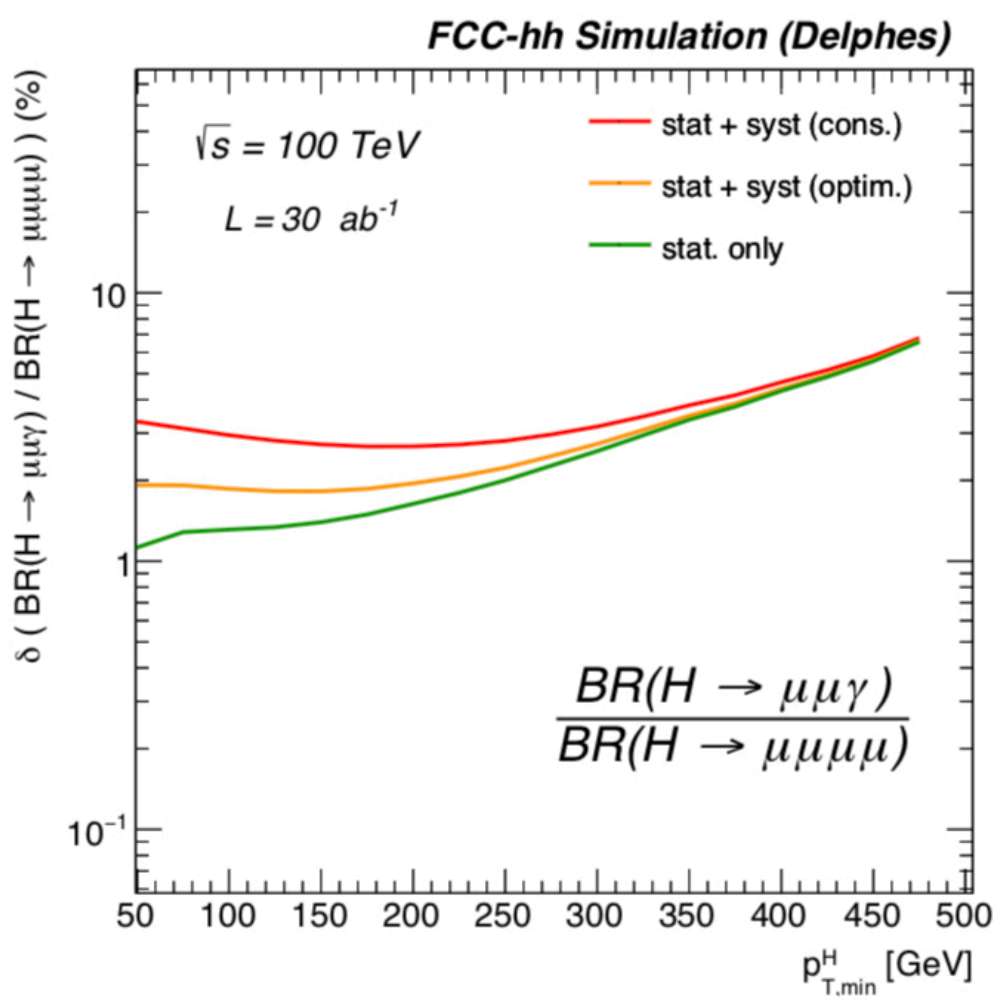


- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%







Normalize to BR(4l) from ee => sub-% precision for absolute couplings

Future work: explore in more depth data-based techniques, to validate and then reduce the systematics in these ratio measurements, possibly moving to lower pt's and higher stat

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^-:

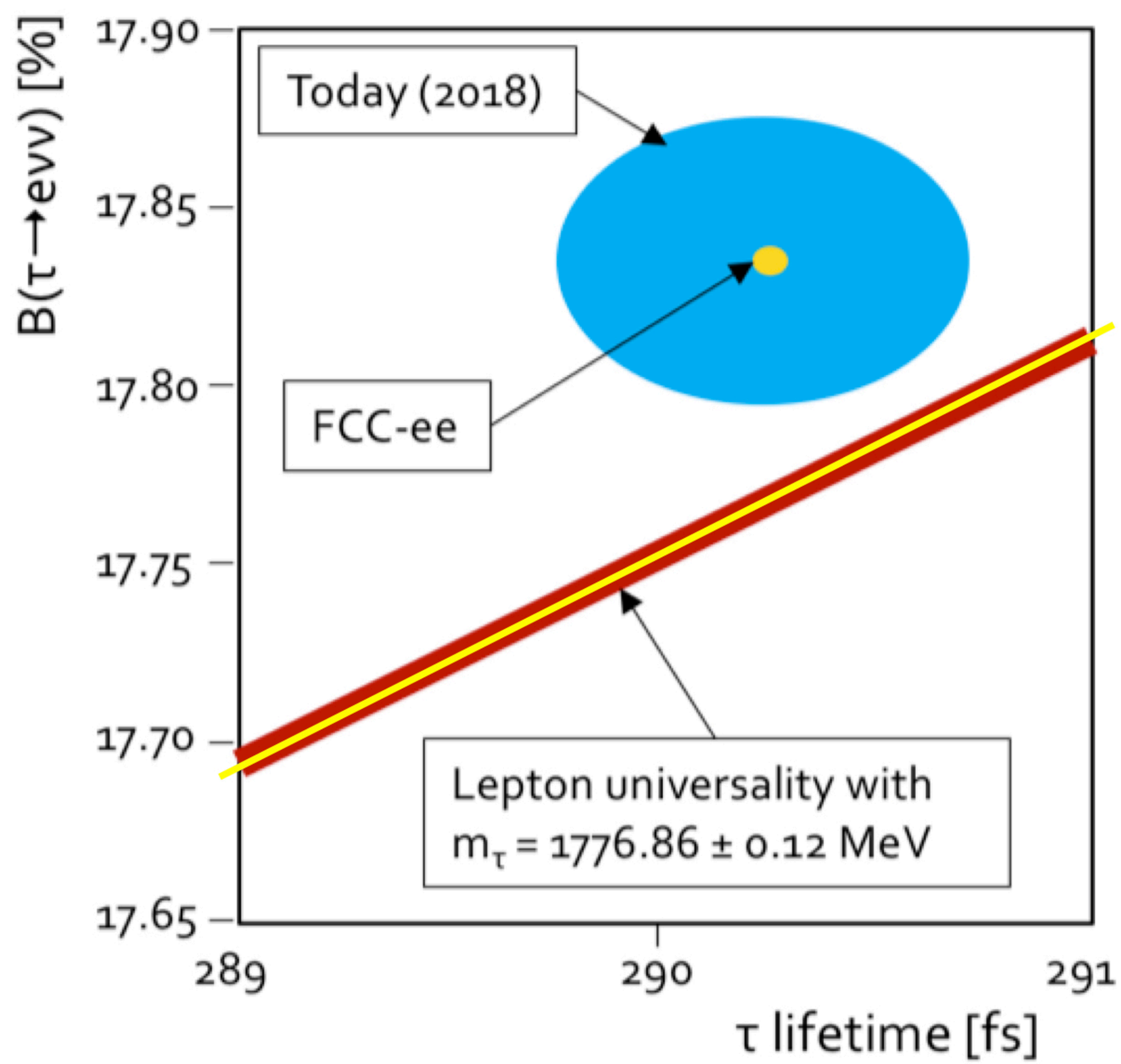
$e^+e^- \rightarrow Z$	$e^+e^- \rightarrow WW$	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
$5\ 10^{12}$	10^8	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

=> $O(10^5)$ 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

Flavour probes: eg lepton universality in tau decays

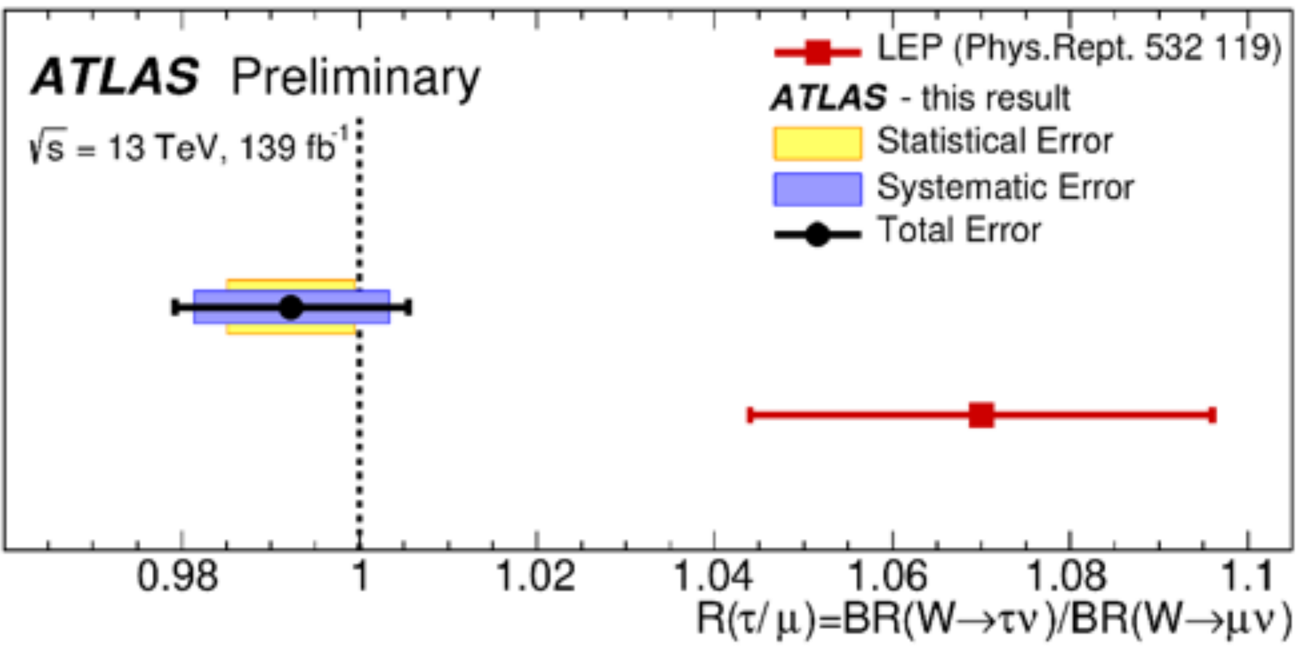


Lorentz boost crucial!

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.04–0.1	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
B(τ→eνν) [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
B(τ→μνν) [%]		17.39 ± 0.05			

Precision W physics at FCC-hh: *LHC docet*

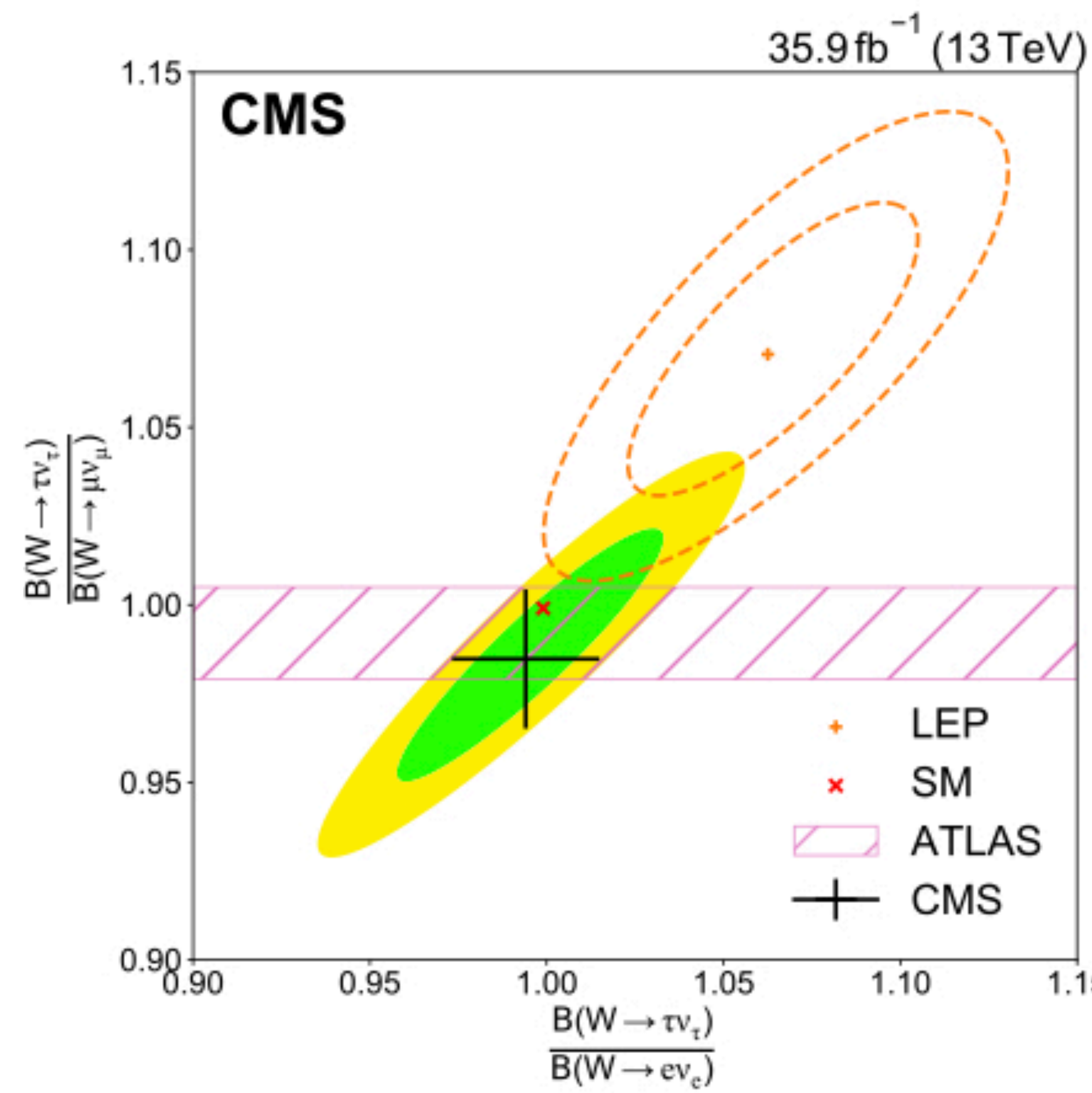
ATLAS 2020: arXiv:2007.14040



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

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

CMS 2022: arXiv:2201.07861

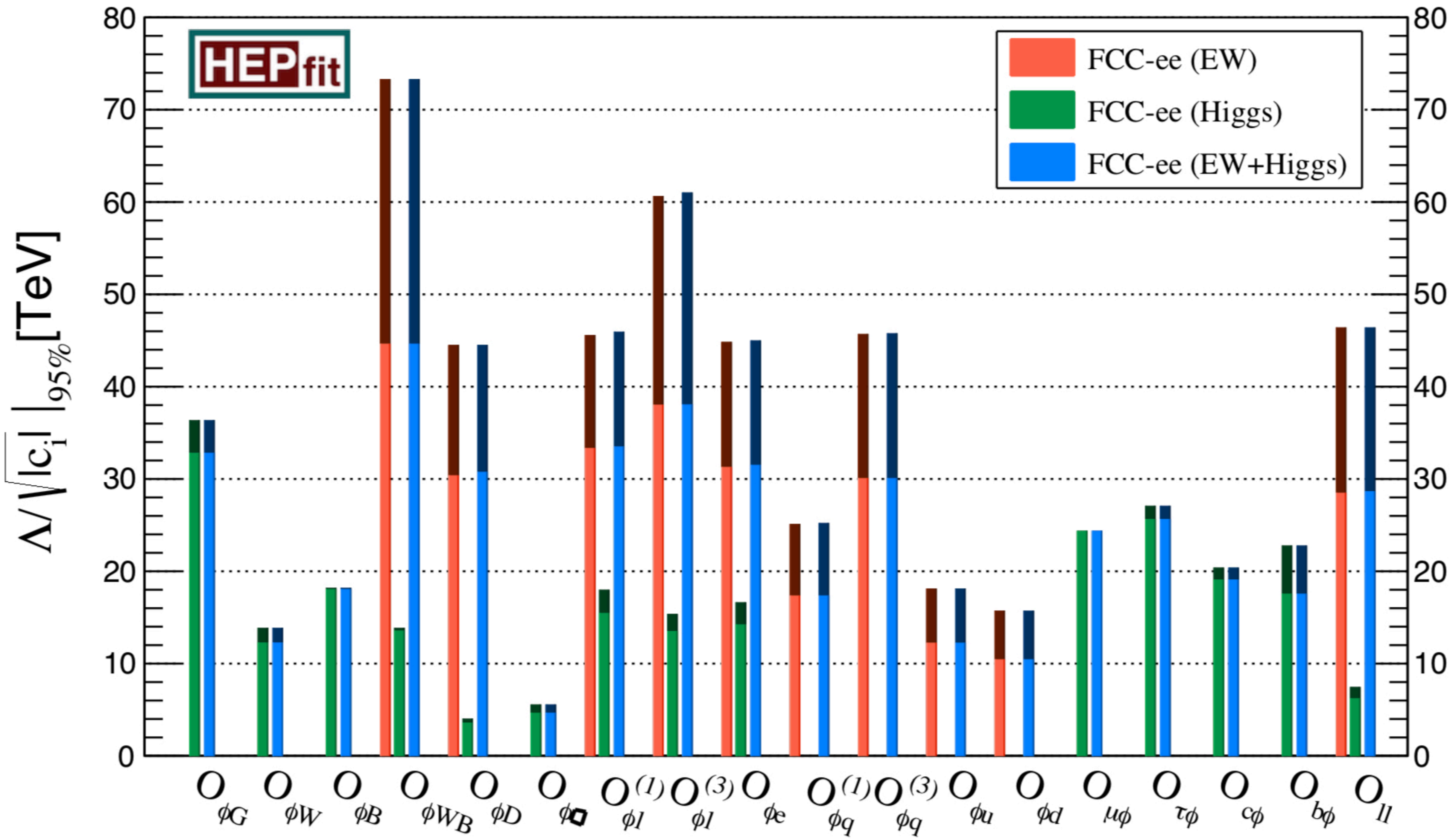


FCC-hh	t	W(←t)	τ(←W←t)
	10^{12}	10^{12}	10^{11}

~ 300 x HL-LHC statistics

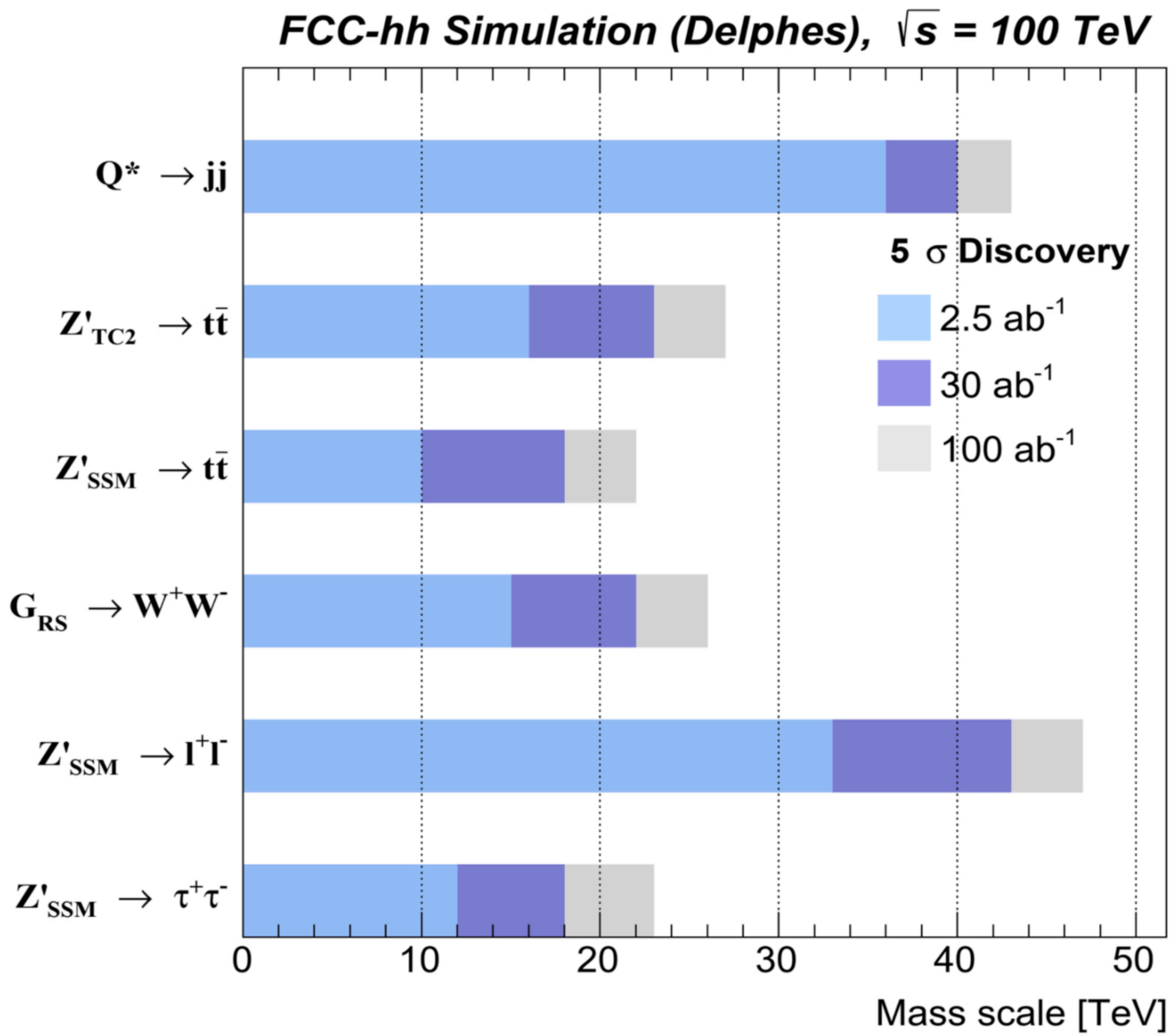
(2) **Direct discovery reach at high mass: the power of 100 TeV**

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.

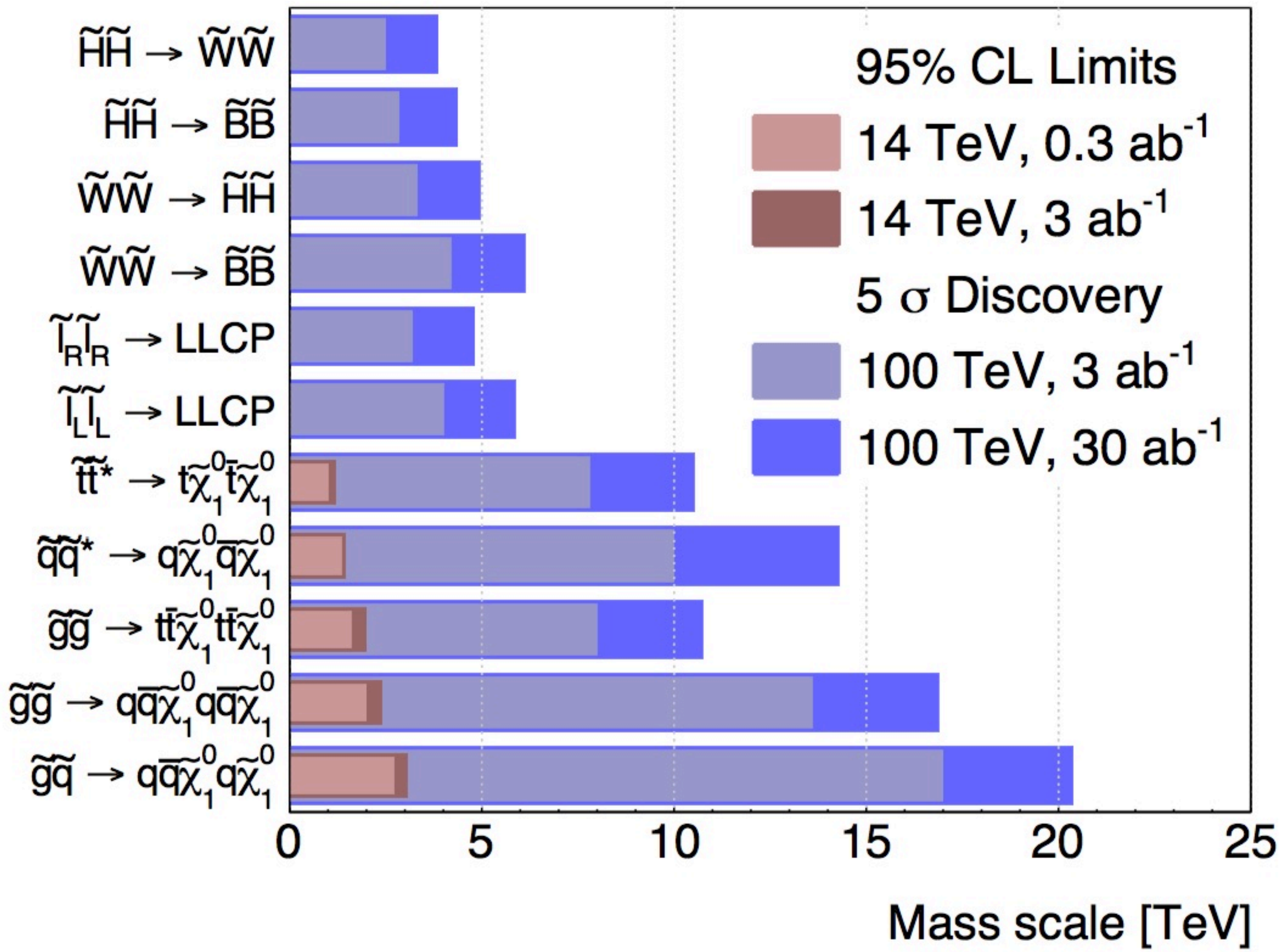
s-channel resonances



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

Matching this discovery reach with a lepton collider would require a multi-tens TeV facility (beyond-the-beyond?).

SUSY reach at 100 TeV



15-20 TeV squarks/gluinos would require a lepton collider in the ECM range of 30-50 TeV

Sequential Z' reach: comparison across colliders, direct vs indirect reach

Indirect observation through EW precision observables (blue box)

Direct observation (red box)

Machine	Type	$\sqrt{s}$ (TeV)	$\int Ldt$ (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)	
HL-LHC	pp	14	3	RH [395]	$Z'_{SSM} \to$ dijet	4.2	**5.2**	
				ATLAS [396]	$Z'_{SSM} \to l^+l^-$	6.4	**6.5**	
				CMS [397]	$Z'_{SSM} \to l^+l^-$	–	**6.8**	
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**6**	
ILC250, CLIC380 or FCC-ee	e^+e^-	0.25	2	ILC [398]	$Z'_{SSM} \to f^+f^-$	4.9	**7.7**	
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**7**	
HE-LHC	pp	27	15	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**11**	
				ATLAS [396]	$Z'_{SSM} \to e^+e^-$	12.8	**12.8**	
ILC	e^+e^-	0.5	4	ILC [398]	$Z'_{SSM} \to f^+f^-$	8.3	**13**	
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**13**	(1)
CLIC	e^+e^-	1.5	2.5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**19**	
Muon Collider	$\mu^+\mu^-$	3	1	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	10	**20**	
ILC	e^+e^-	1	8	ILC [398]	$Z'_{SSM} \to f^+f^-$	14	**22**	
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**21**	
CLIC	e^+e^-	3	5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**24**	
FCC-hh	pp	100	30	RH [395]	$Z'_{SSM} \to$ dijet	25	**32**	
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**35**	(2)
				EPPSU [399]	$Z'_{SSM} \to l^+l^-$	43	**43**	
Muon Collider	$\mu^+\mu^-$	10	10	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	42	**70**	

Table 2-14. *For each collider we list the operating point and mass reach, for 5σ discovery and 95% CL exclusion, of the SSM Z' model taken from Refs. [395, 399, 396, 397, 398], and the mass reach of the universal Z' model with a coupling $g_{Z'} = 0.2$ from Refs. [392, 384] that we determined from Fig. 2-32.*

1. ***A TeV-scale ee collider already sets (indirect) limits well above the direct discovery potential from a 10-TeV scale lepton collider***

2. ***A 100 TeV pp collider extends the direct search well beyond the sensitivity of indirect evidence from ILC, CLIC and a 3 TeV muon collider. With a discovery reach at over 40 TeV, and sensitivity to lepton and quark decays above 25 TeV, this collider would allow a direct exploration of the coupling properties of the object responsible for the SM deviations to EW observables induced in a 10-TeV scale lepton collider***

3. ***For direct observation of a charged resonance (eg W') the HL-LHC is as powerful as a 13 TeV lepton collider (pair production)***

Compressed higgsinos: comparison across colliders for direct reach

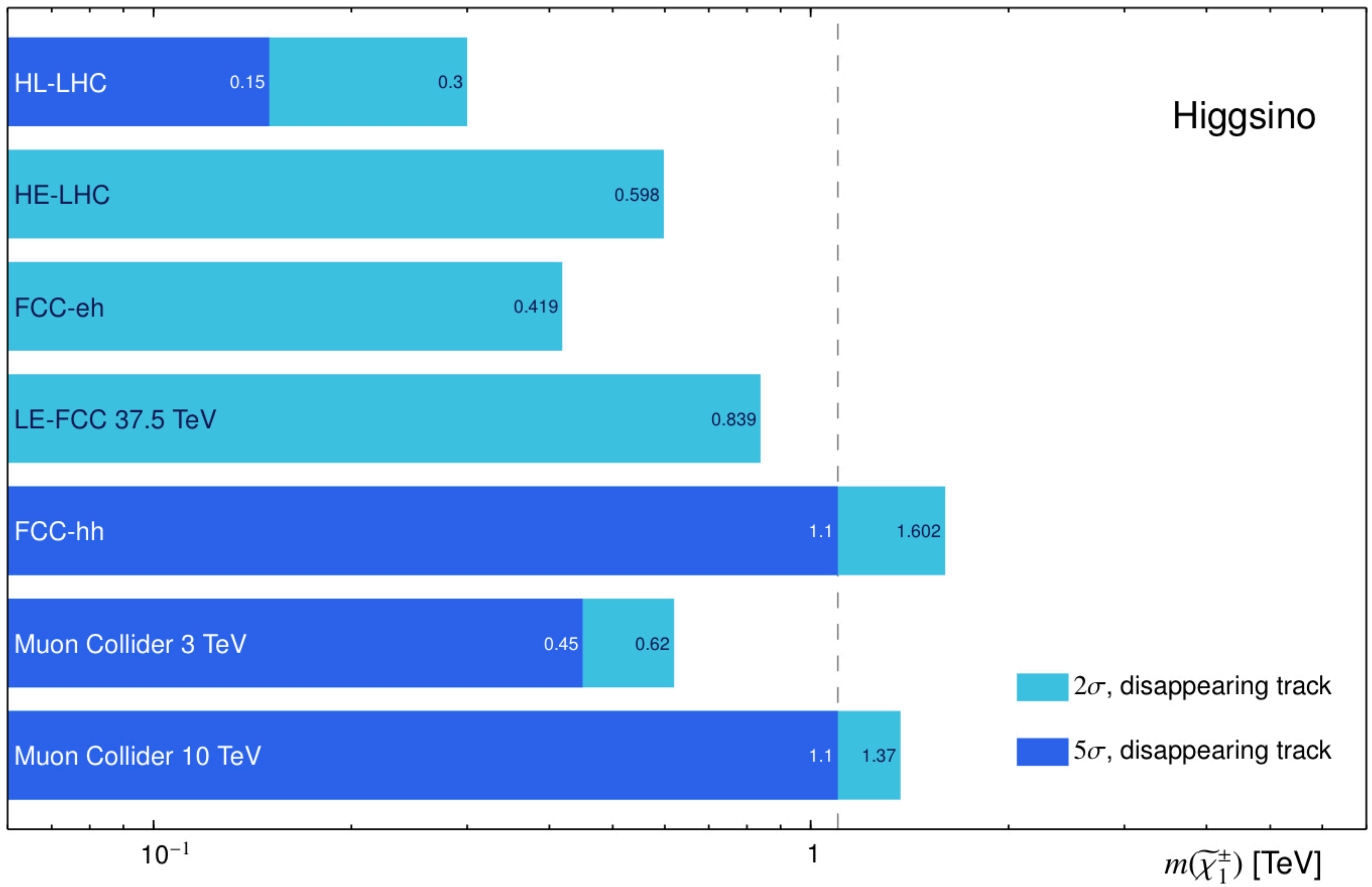


Figure 2-34. *Overview plot for the sensitivity to the pure Higgsino, assuming its natural mass splitting, for various future colliders. Figure adapted from [410].*

The direct discovery reach for an elusive weakly interacting particle at a lepton collider with CM energy E compete with that of a pp collider at ~ 10xE CM energy

(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:

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

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

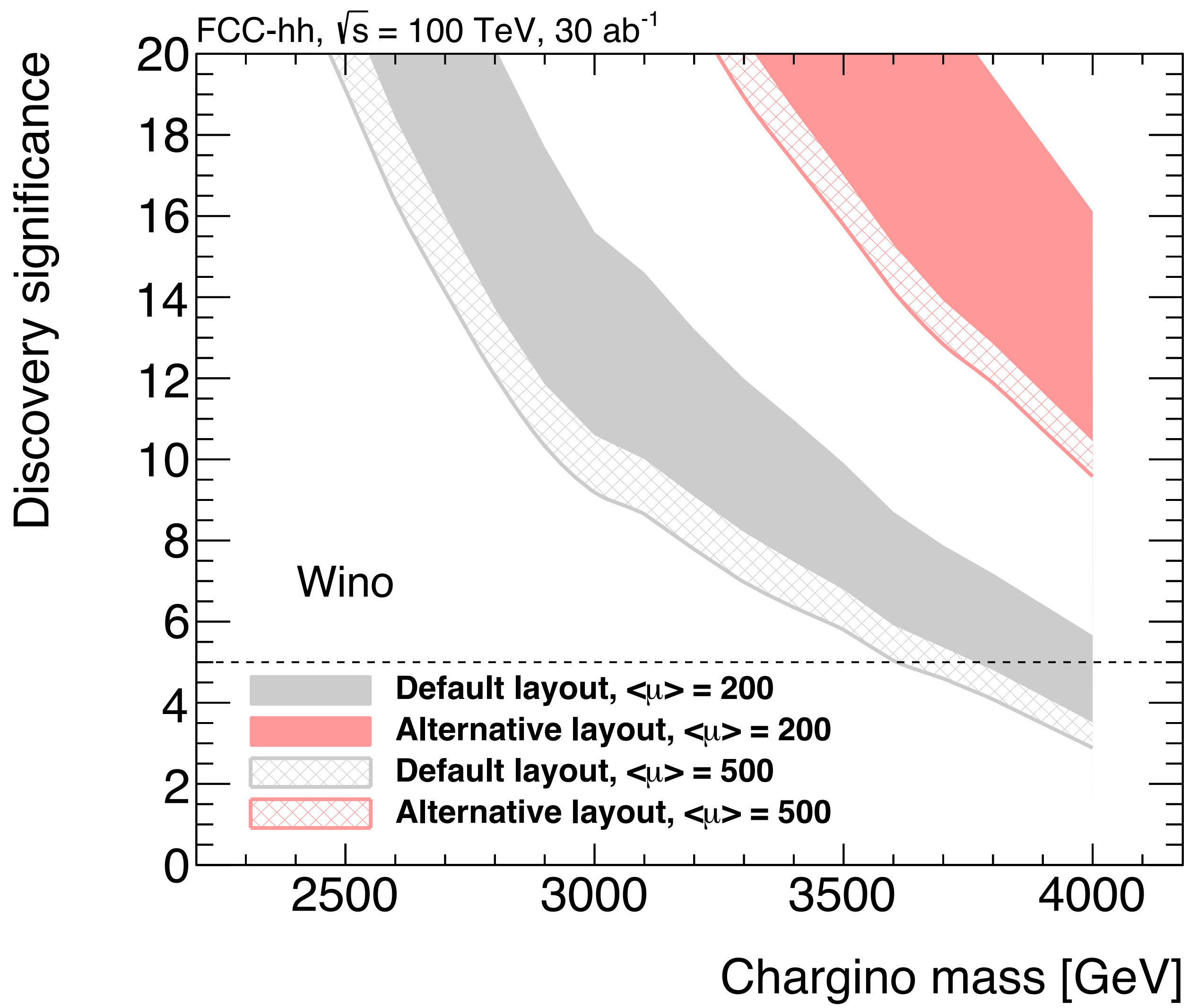
$$\Omega_{wimp}\, h^2 \lesssim 0.12$$

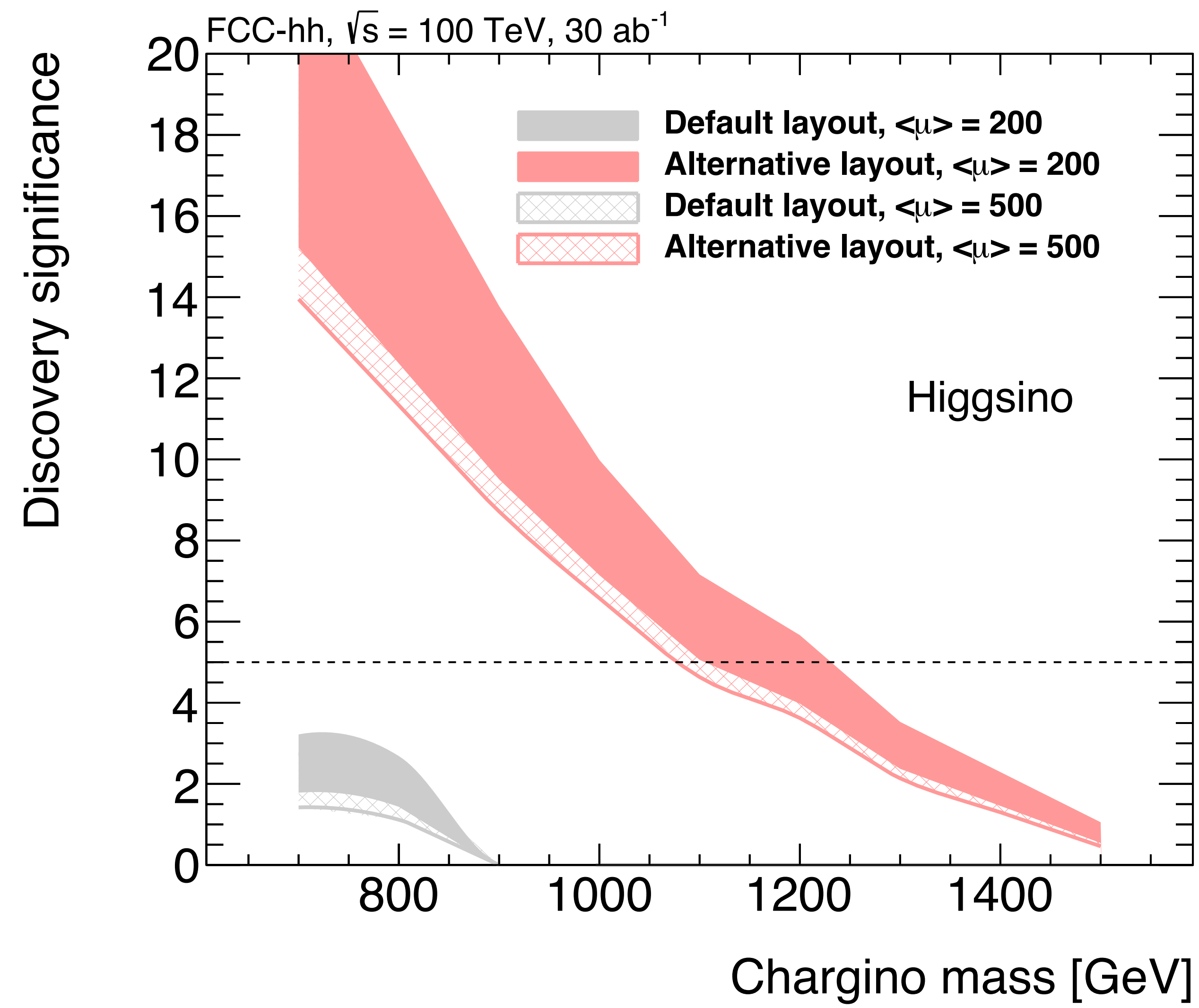
$$M_{wimp} \lesssim 2 \text{ TeV} \left(\frac{g}{0.3} \right)^2$$

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)

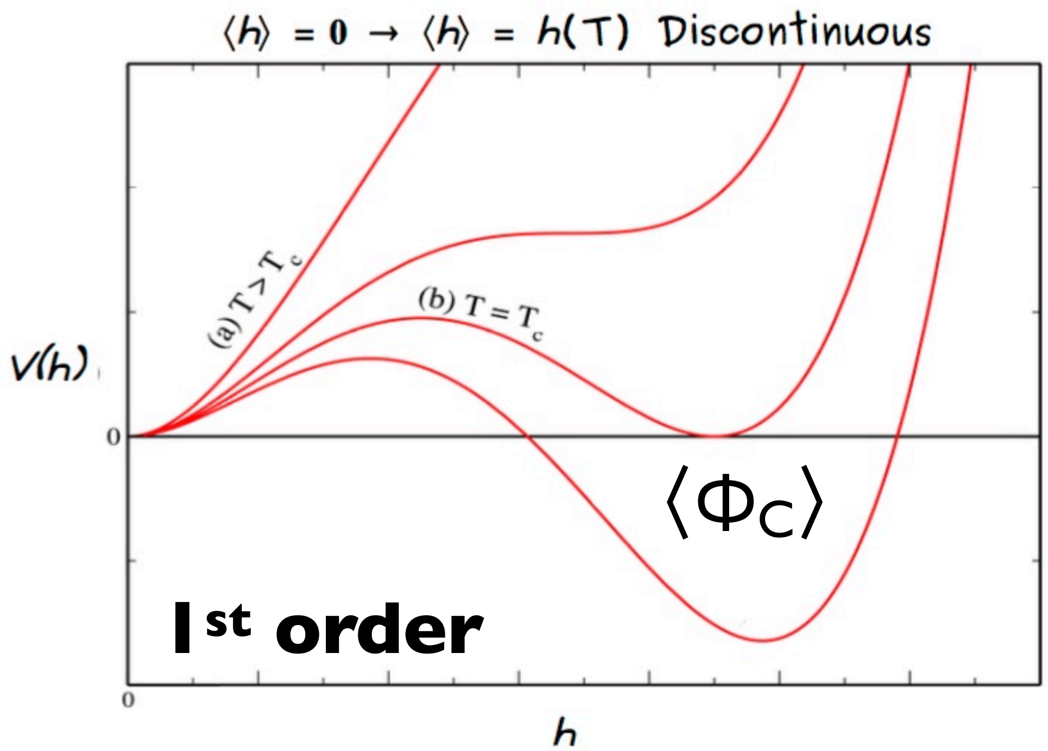


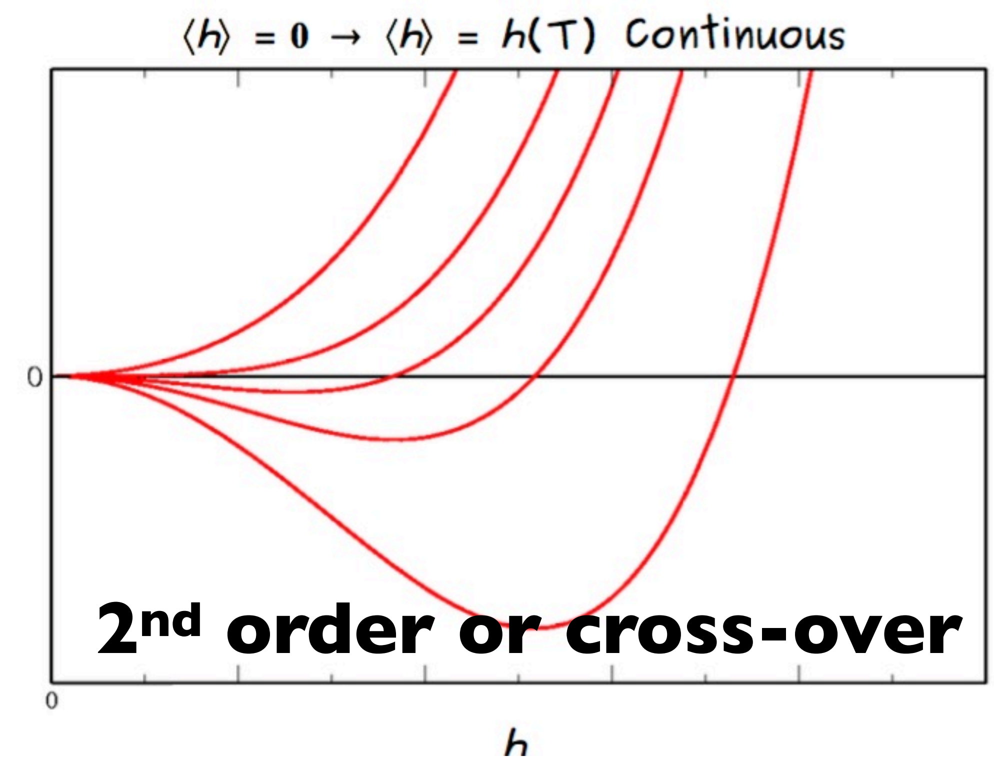


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

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.

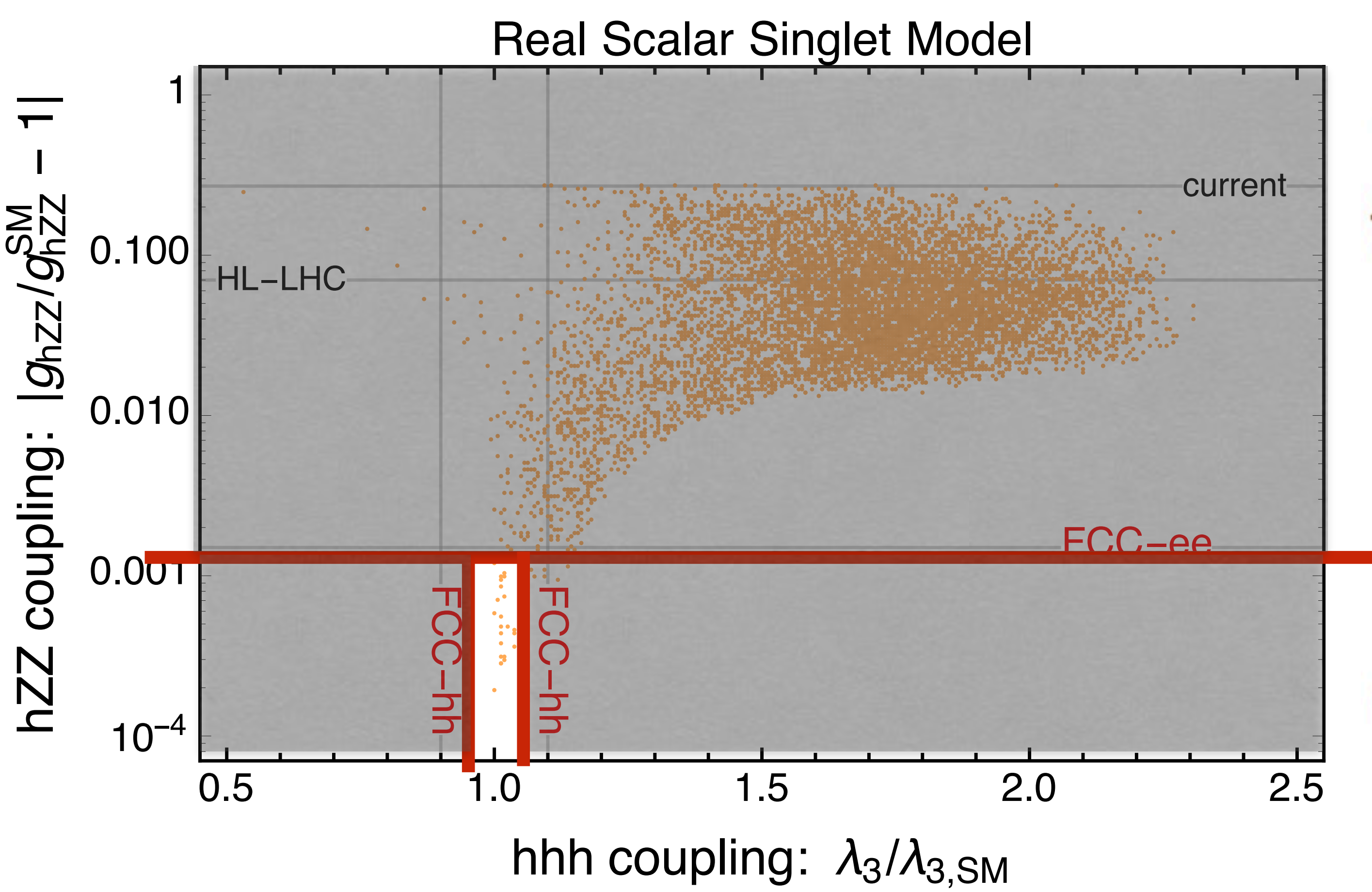
Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **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

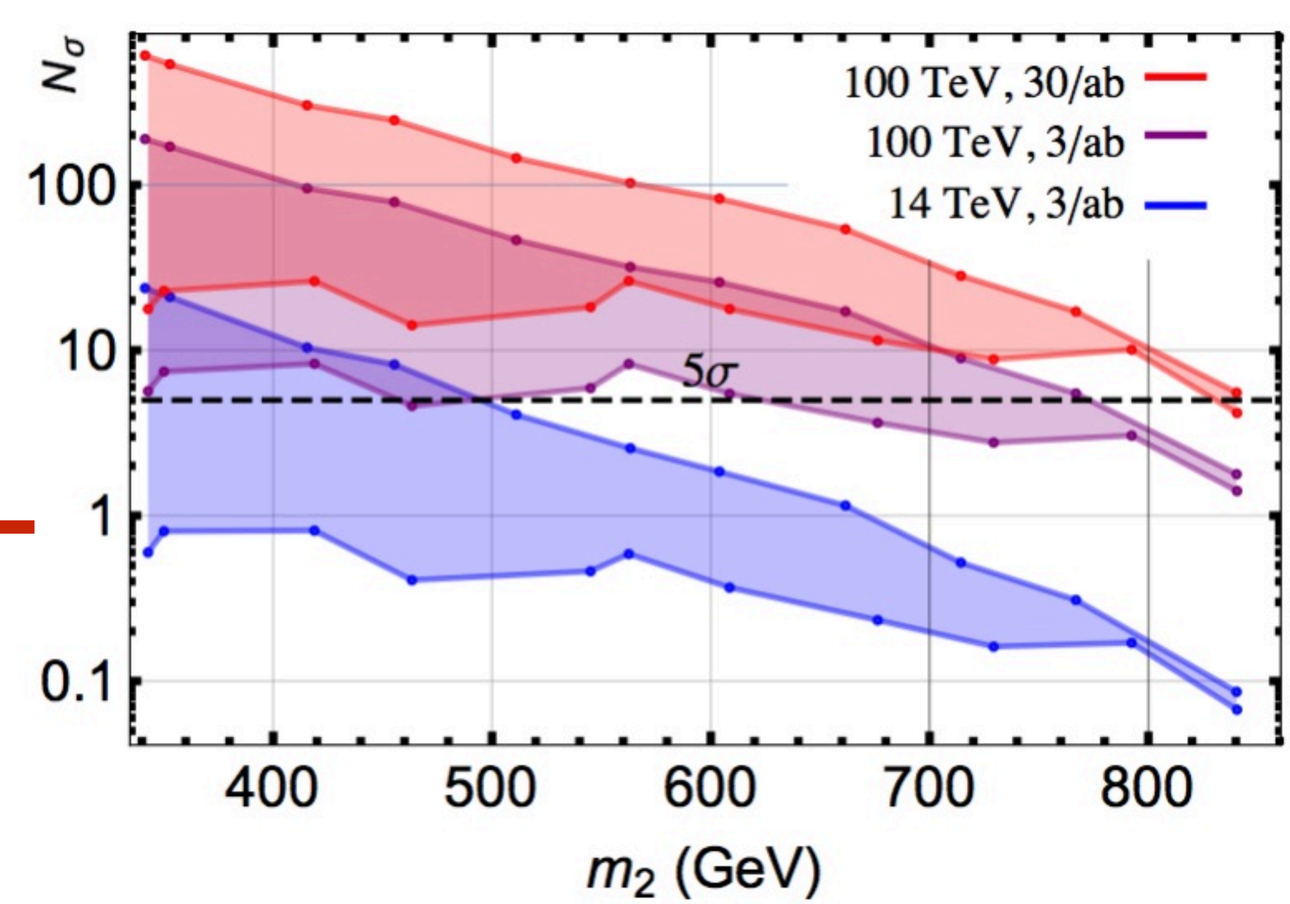
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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

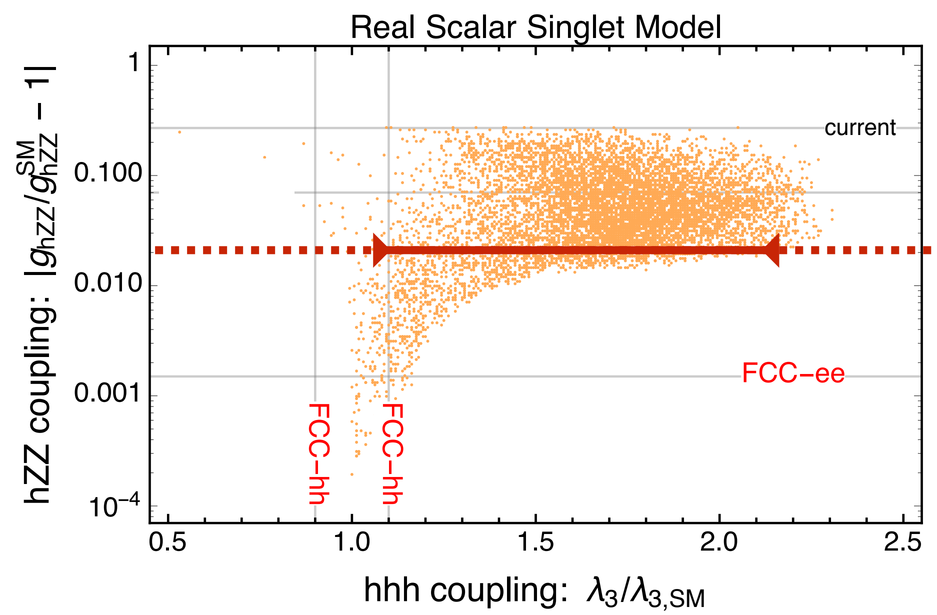


$h_2 \to h_1 h_1$ ($b\bar{b}\gamma\gamma$ + 4τ)

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

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

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

Feasiblity study goals and roadmap towards first e^+e^- collisions

FUTURE CIRCULAR COLLIDER

Highest priority goals:

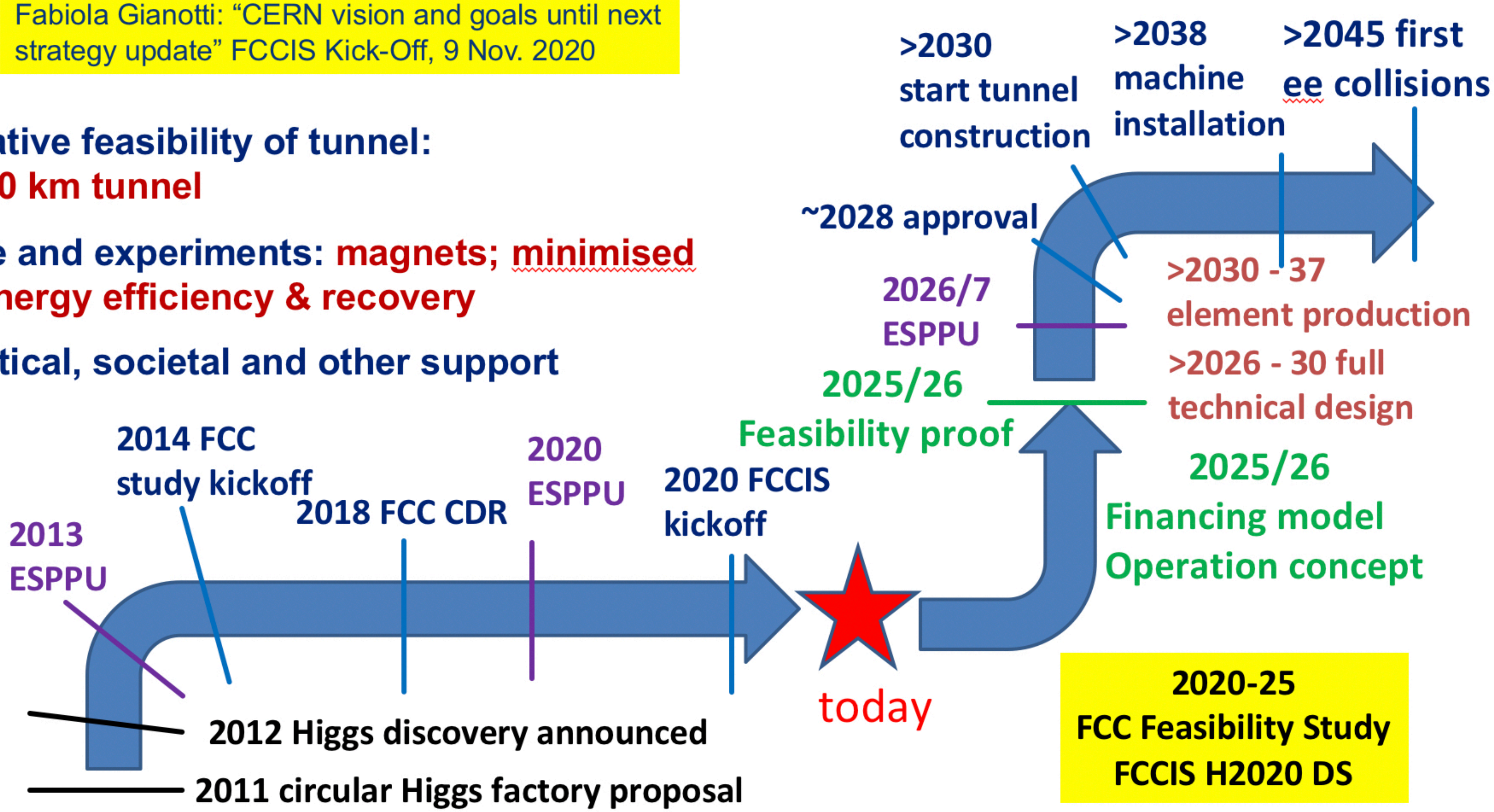
Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

Financial feasibility

Technical and administrative feasibility of tunnel:
no show-stopper for ~100 km tunnel

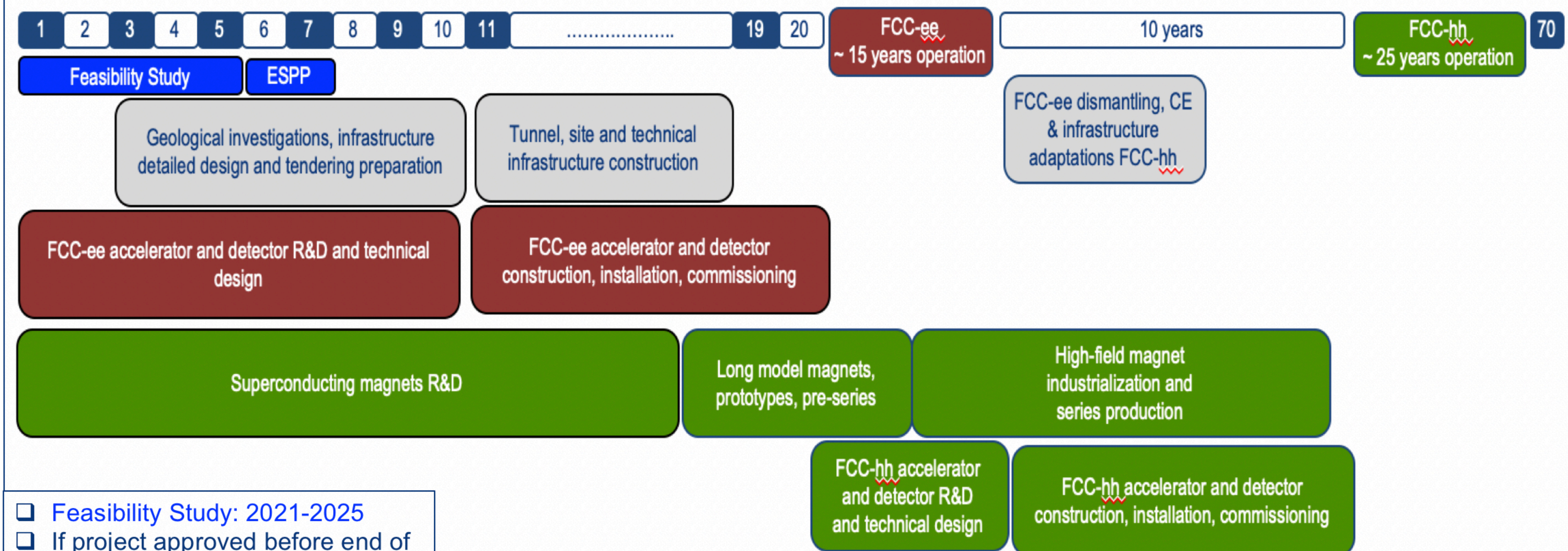
Technologies of machine and experiments: magnets; minimised environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support



FUTURE CIRCULAR COLLIDER

Timeline of the FCC integrated programme



- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

FCC Feasibility Study Overview
Michael Benedikt
Paris, 30 May 2022