Why FCC* ?

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* Future Circular Collider

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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

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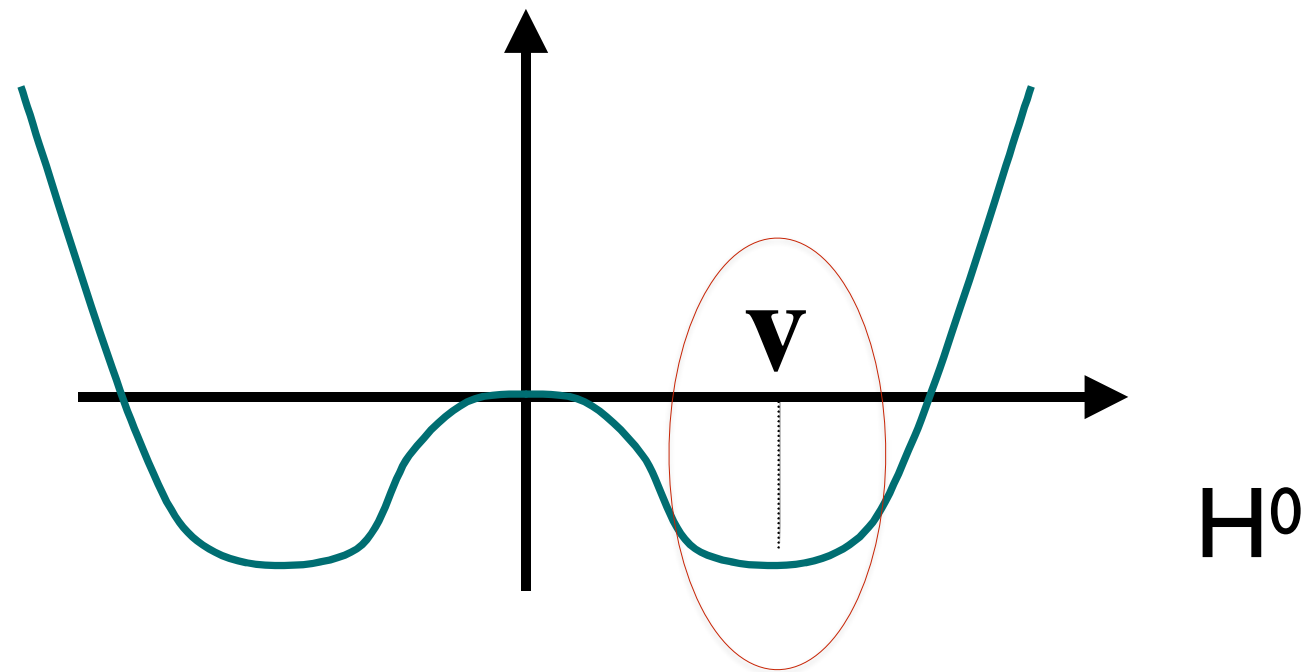
$$V(H) = - \mu^2 \, |H|^2 + \lambda \, |H|^4$$

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 **<u>same</u>** Higgs field?
  - Do $I_3 = 1/2$ fermions (up-type quarks) get their mass from the **<u>same</u>** Higgs field as $I_3 = -1/2$ fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H \to \mu\tau$? $H \to e\tau$? $t \to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

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

The importance of the in-depth exploration of the Higgs properties was acknowledged by the 2020 ESPP update, settling the question of "why a collider after the LHC":

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

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*

But the $100M question is:
Why don't we see as yet 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**

The program of detailed studies of the Higgs boson and EWSB must be coordinated with a parallel or successive program of **direct** exploration at the highest energy scale technologically achievable
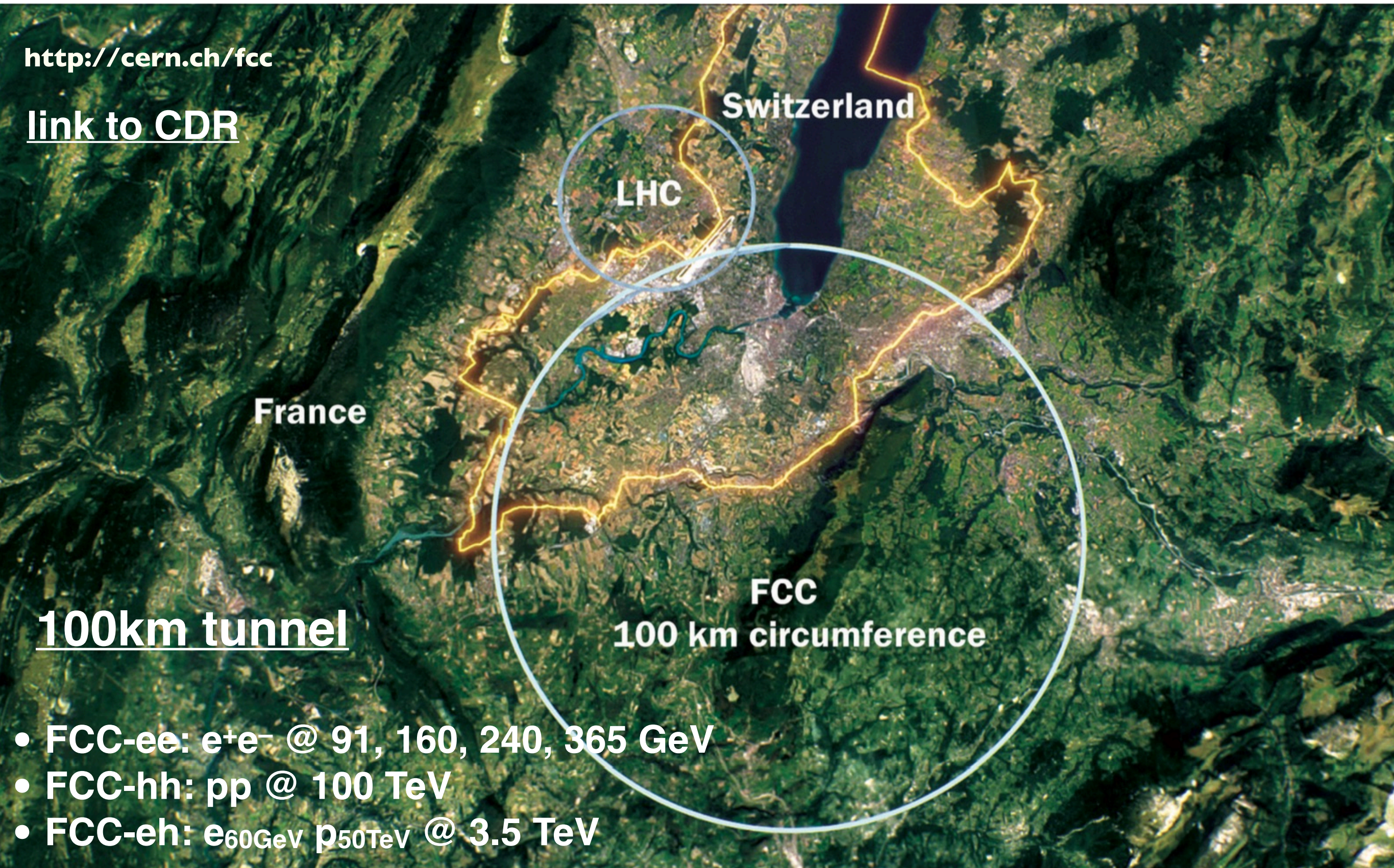
This would be certainly justified by the detection of SM deviations in precision measurements of Higgs properties, but remains justified in absence of such deviations

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 $\sqrt{s} \sim 240$ 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 $\sqrt{s} \sim 50$–100 TeV in the far future.
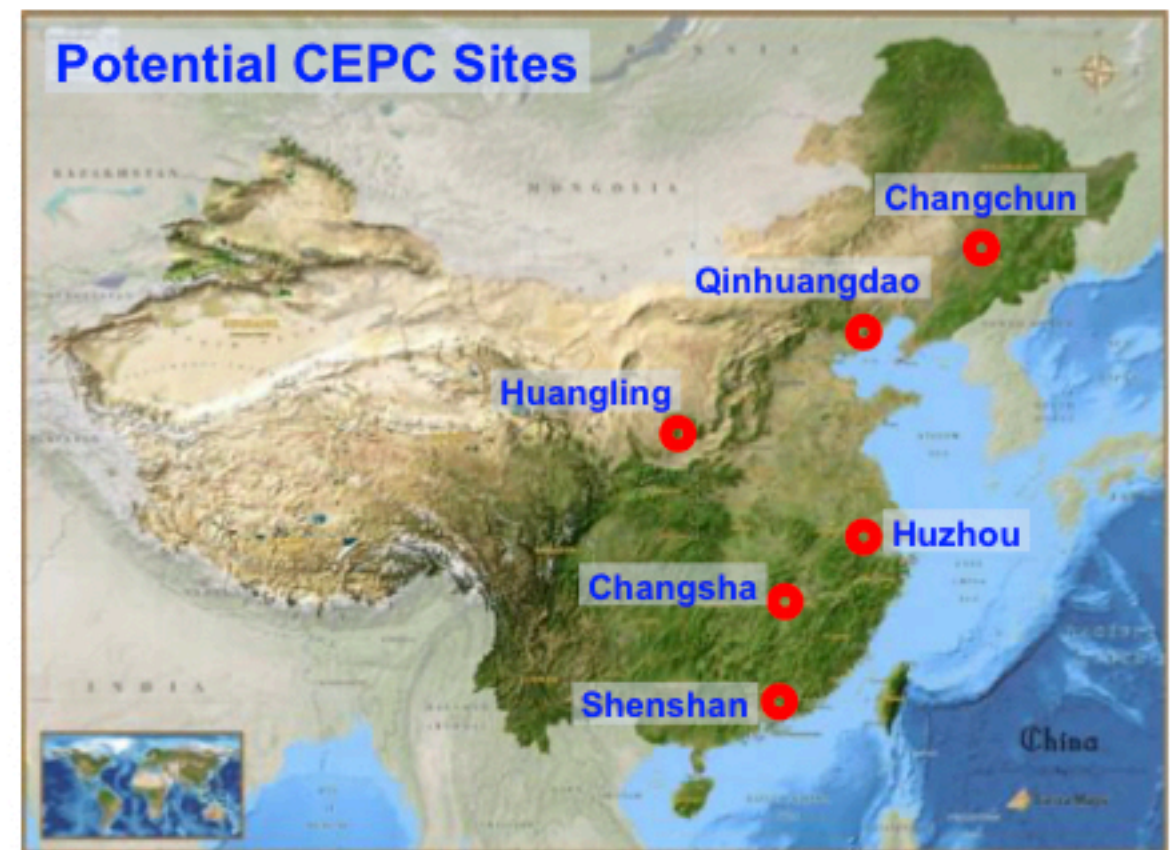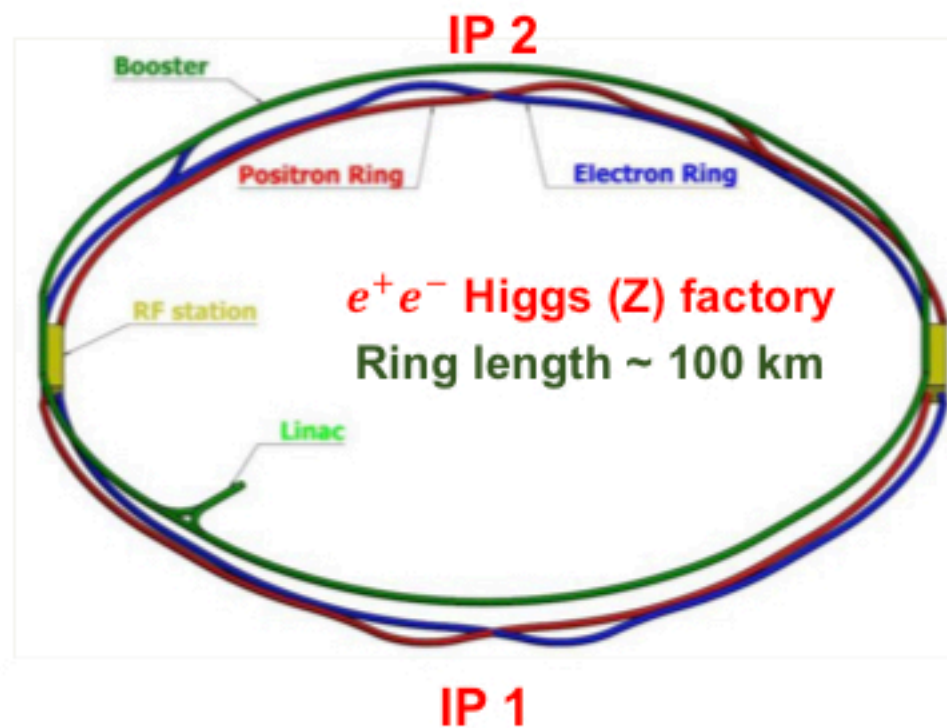
link to CDR

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.

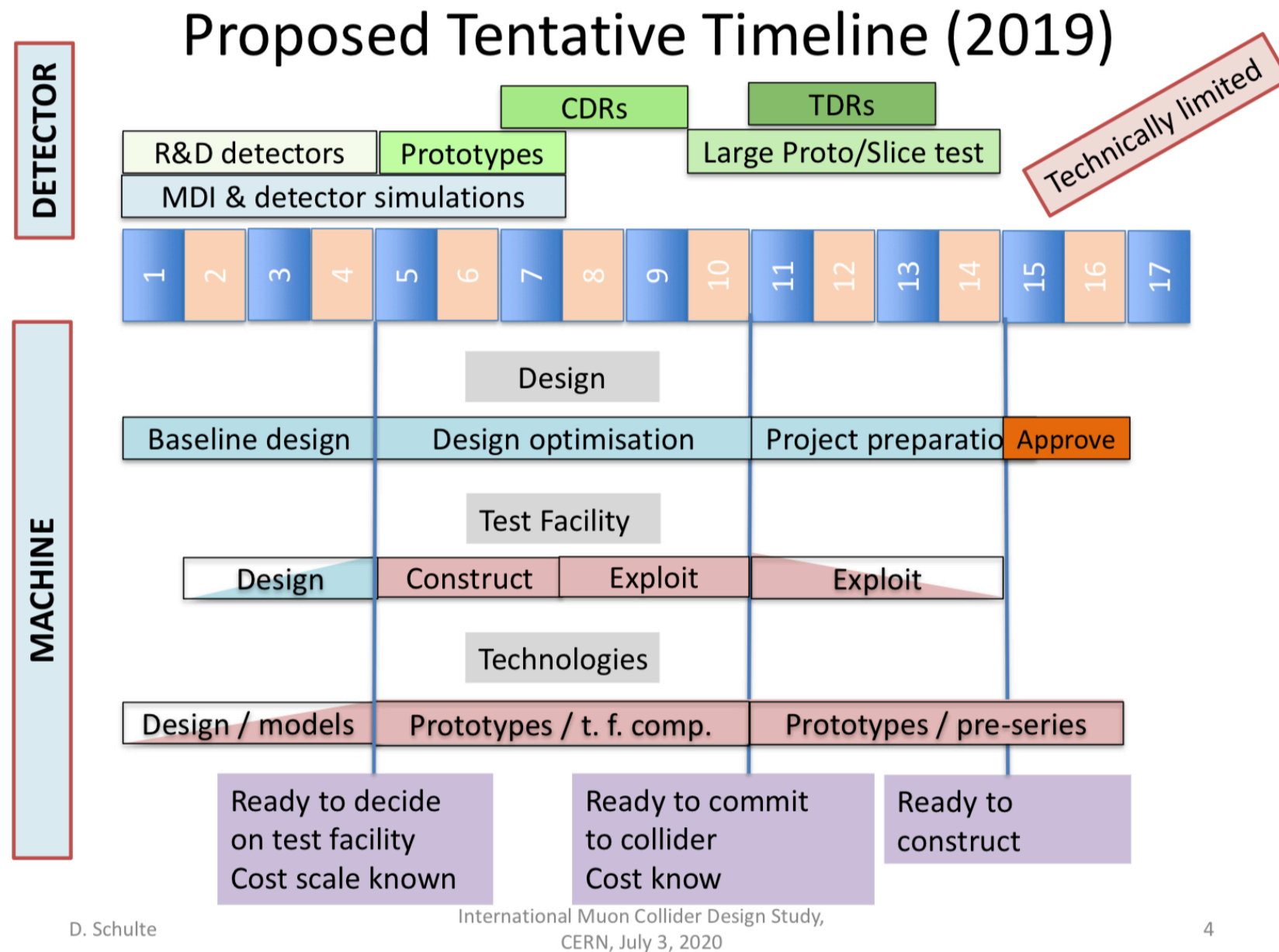|				
Energy, center-of-mass, U_{cm}[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}$[10^{34} s^{-1}cm^{-2}]	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert.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

Proposed Tentative Timeline (2019)

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

D. Schulte   International Muon Collider Design Study, CERN, July 3, 2020   4

* building on 2 decades of preliminary work, notably within the US Muon Accelerator Program (MAP) 18

One of the questions under debate is what timescale should "beyond" refer to.

It's generally agreed it's beyond the first, low-energy H factory.

Most "H factories" have upgrade paths (ILC from 250 GeV to 1 TeV, CLIC from 380 GeV to 3 TeV, FCC-ee to FCC-hh). Should the next generation technologies of the previous 2 slides compete in R&D and timescale with these "natural" upgrade paths?

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.

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 φs, …
- 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

This "leadership in diversity" was exhibited by LEP as well. The FCC integrated project FCC-ee+FCC-hh (plus a possible eh) provides the most natural evolution of the LEP/LHC strategy, optimally fulfilling the 3 criteria outlined above

What a future circular collider can offer

- <u>Guaranteed deliverables</u>:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

- <u>Exploration potential</u>:
  - 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*

- <u>Provide firm Yes/No answers</u> 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?
  - …

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

The absolutely unique power of e⁺e⁻ →ZH (circular or linear):
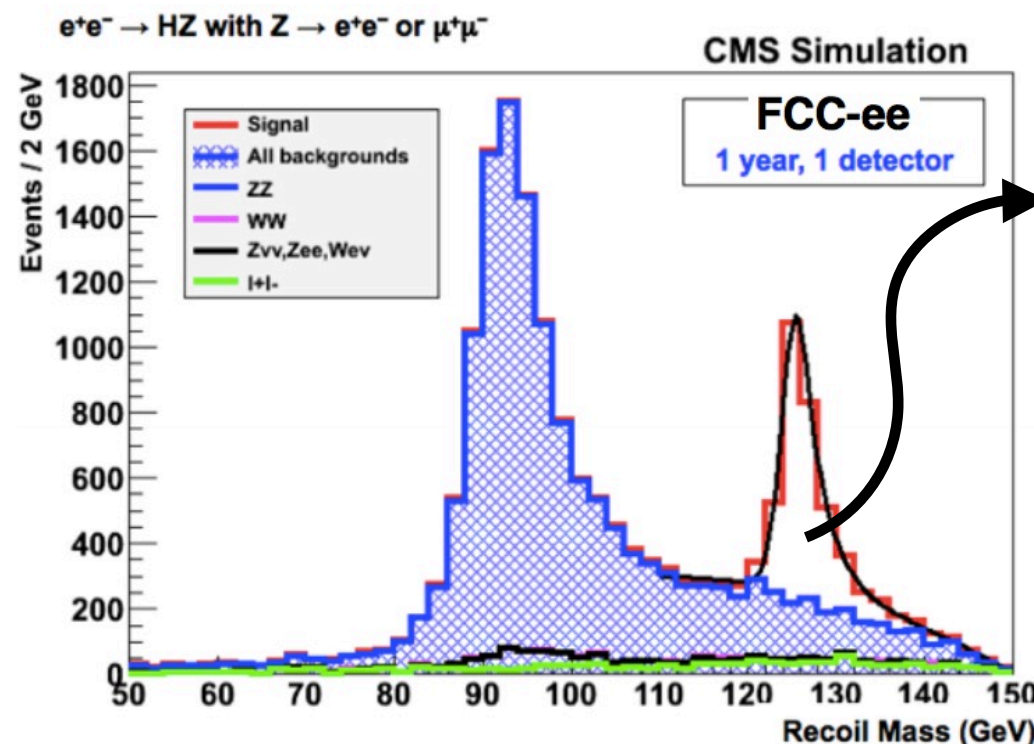
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm
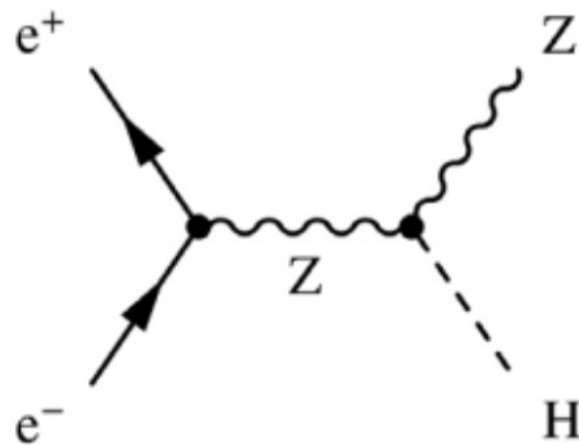
$p(H) = p(e^-e^+) - p(Z)$

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

reconstruct Higgs events independently of the Higgs decay mode!

$e^+e^- \to HZ$ with $Z \to e^+e^-$ or $\mu^+\mu^-$

CMS Simulation

FCC-ee
1 year, 1 detector

- Signal
- All backgrounds
- ZZ
- WW
- Zνν,Zee,Weν
- l+l-

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

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

=> absolute measurement of width and couplings

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

The absolutely unique power of pp →H+X:
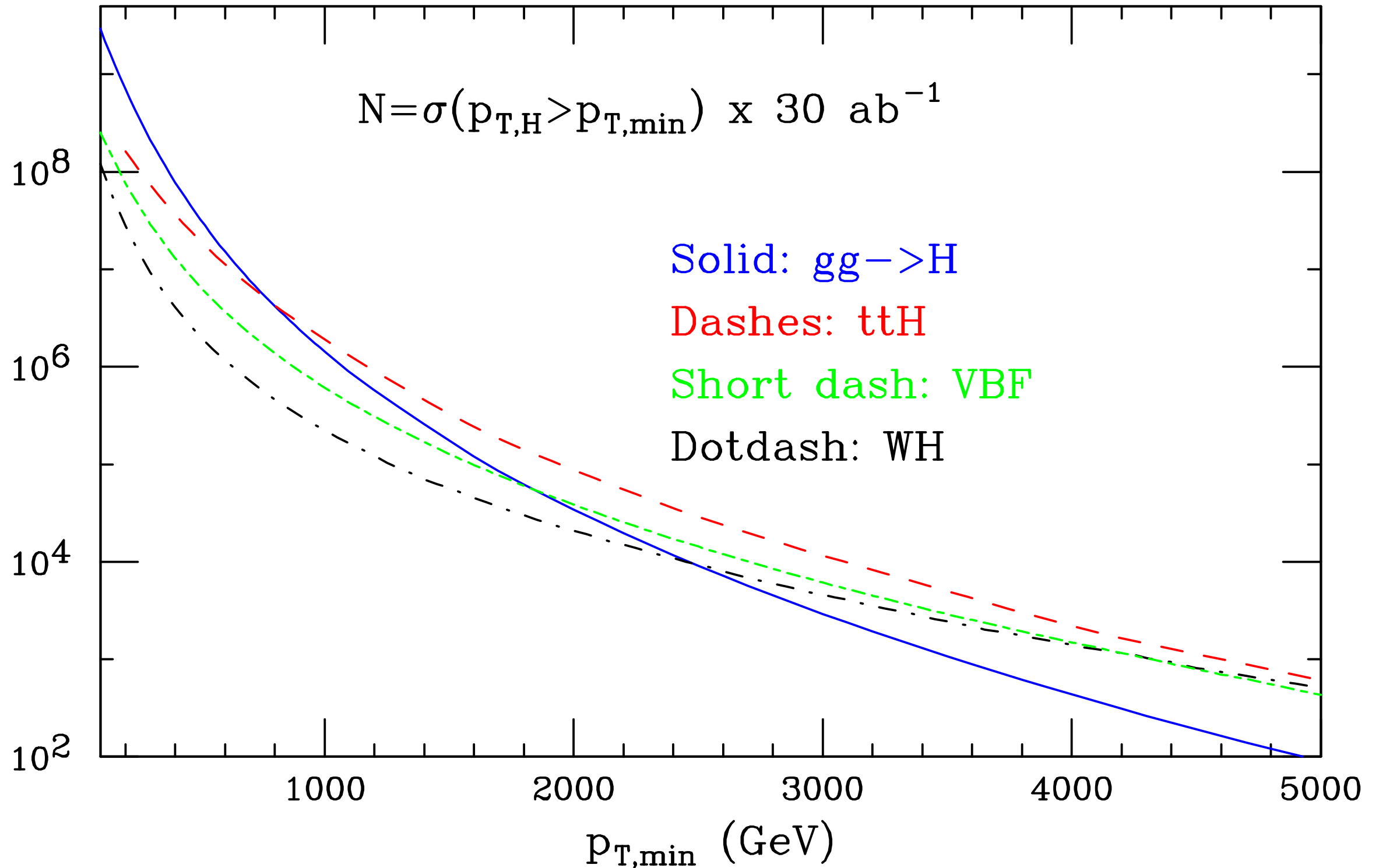
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling

- 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

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

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

H at large p_T

$$N = \sigma(p_{T,H} > p_{T,min}) \times 30 \text{ ab}^{-1}$$

Solid: gg−>H
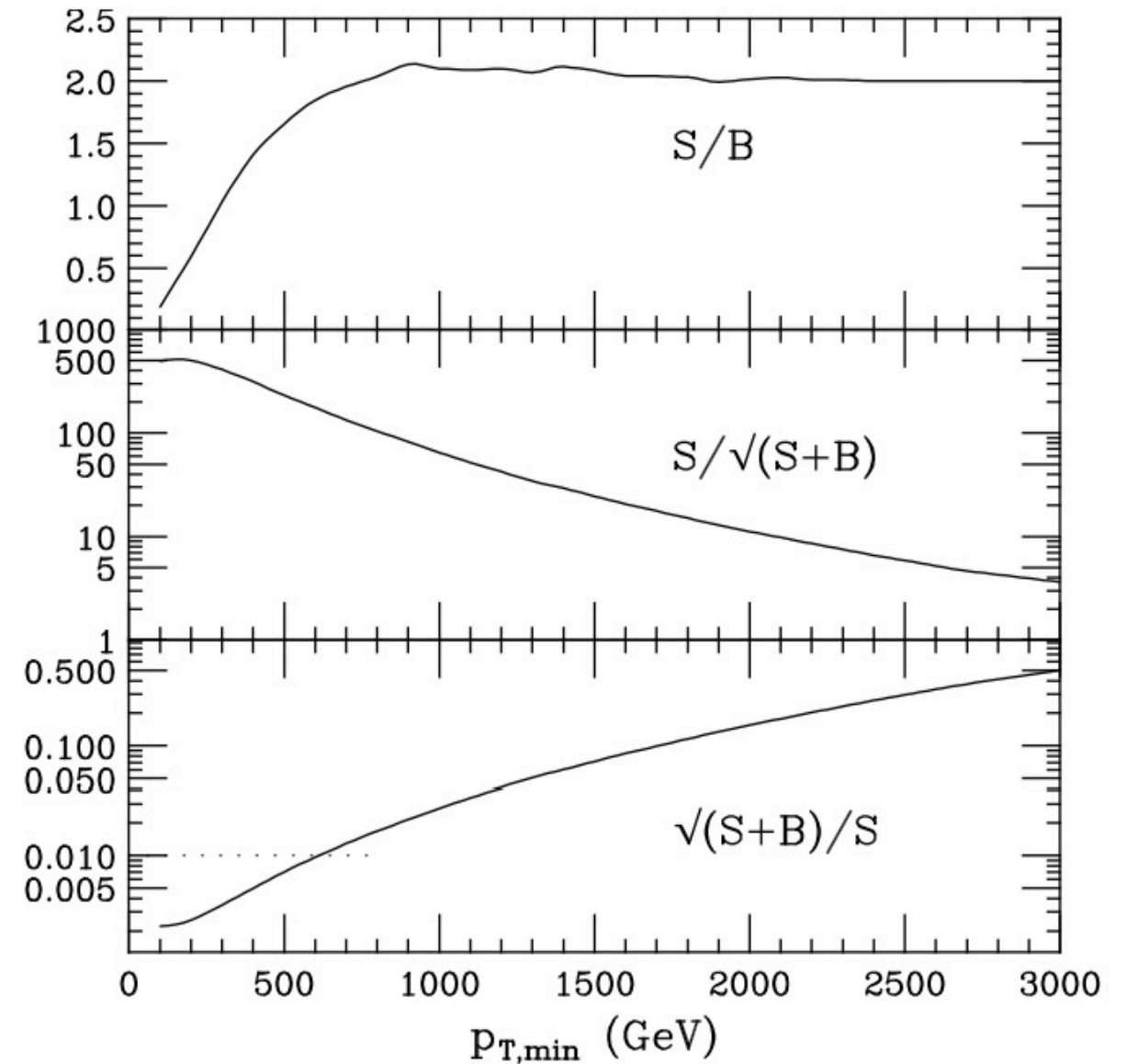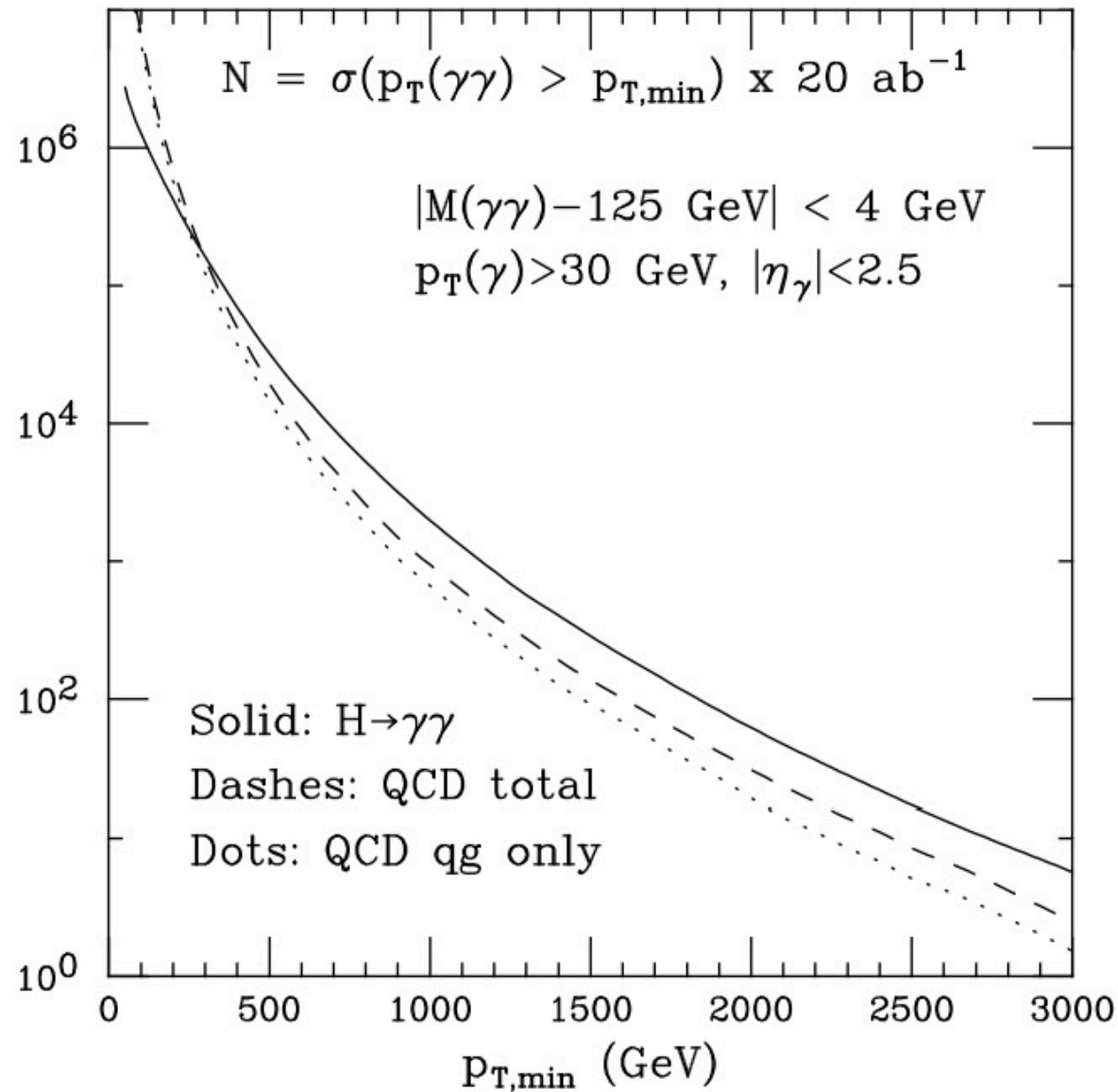
Dashes: ttH

Short dash: VBF

Dotdash: WH

$p_{T,min}$ (GeV)

- 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 $\Rightarrow$ low efficiency, large systematics

  ➡ det simulations challenging, likely unreliable $\Rightarrow$ regime not studied so far

- $p_T \gtrsim 100$ GeV :
  - stat uncertainty ~few $\times$ 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~m_H

gg→H→γγ at large p$_T$

$$N = \sigma(p_T(\gamma\gamma) > p_{T,min}) \times 20 \text{ ab}^{-1}$$

$$|M(\gamma\gamma) - 125 \text{ GeV}| < 4 \text{ GeV}$$

$$p_T(\gamma) > 30 \text{ GeV}, \quad |\eta_\gamma| < 2.5$$

Solid: H→γγ
Dashes: QCD total
Dots: QCD qg only

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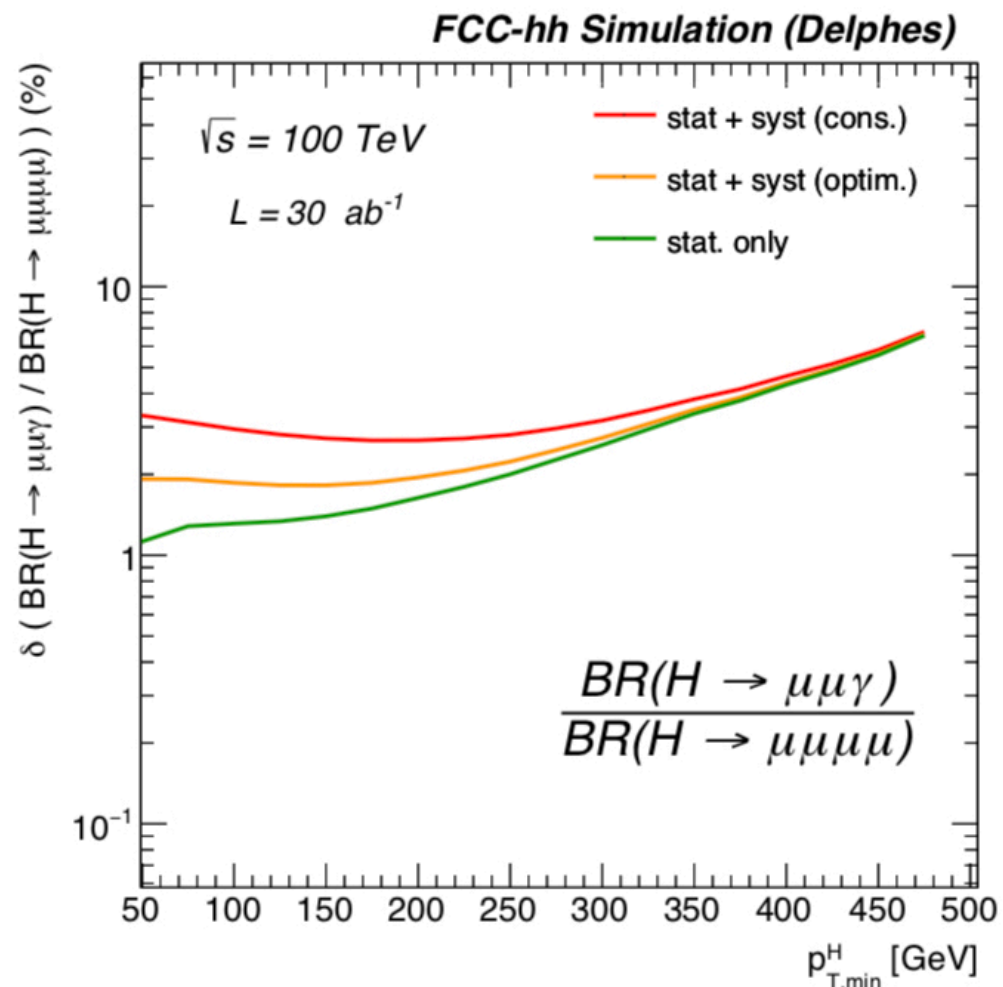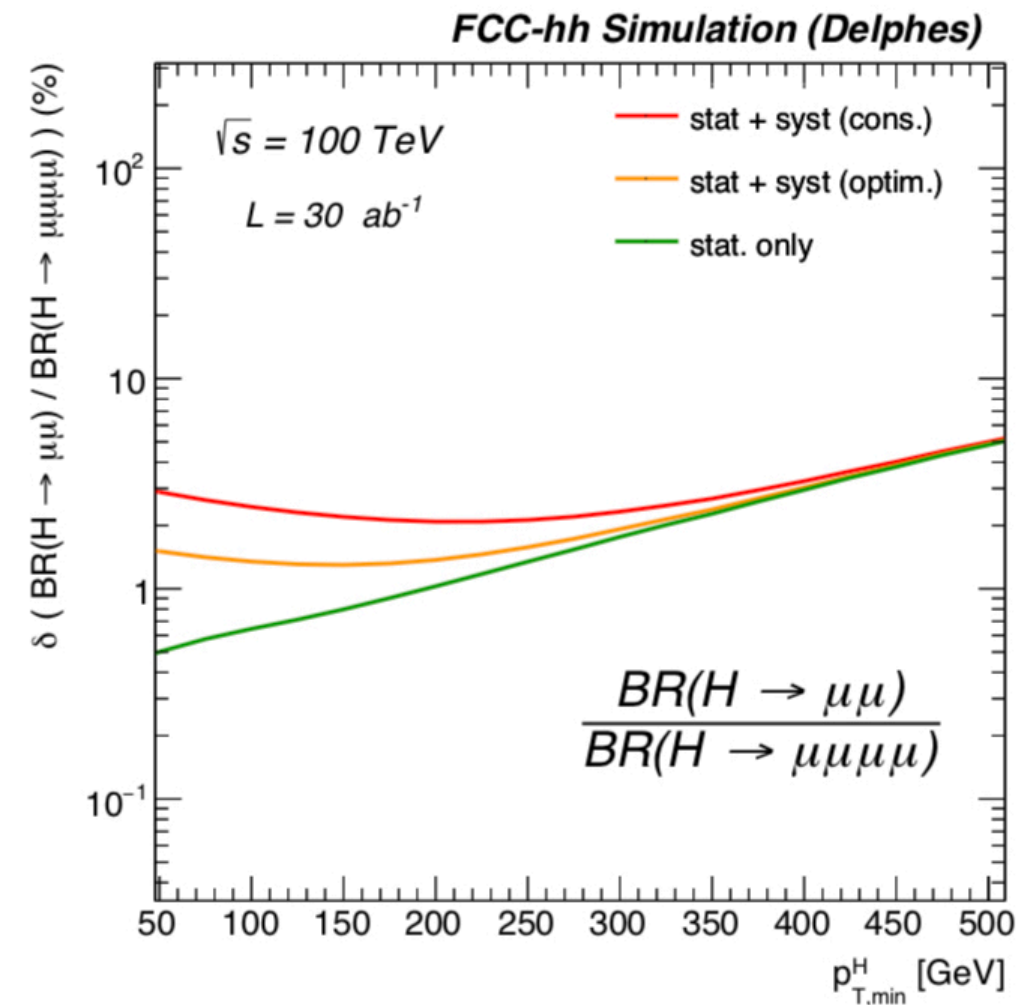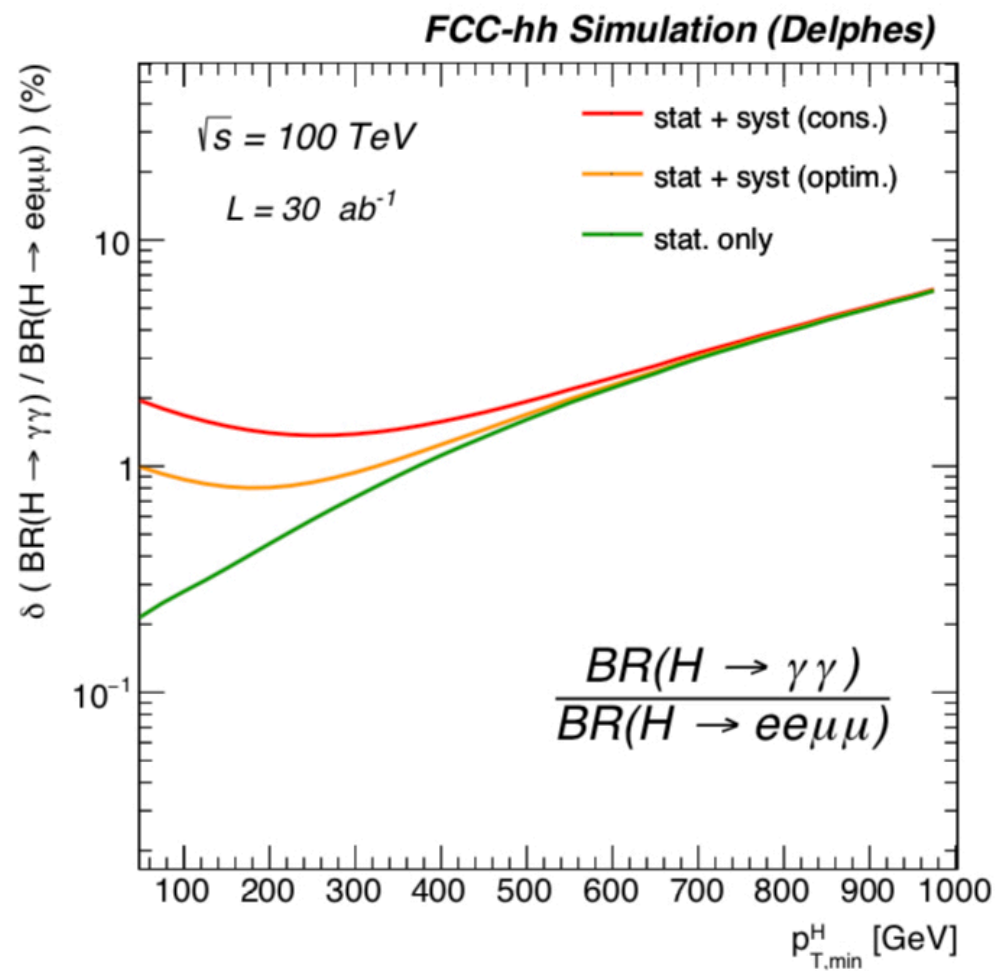
Normalize to BR(4l) from ee => sub-% precision for absolute couplings

Future work: explore in more depth data-based techniques, to <u>validate and then reduce</u> 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)	**3.5**
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 $\Delta_{stat}\sim\%$

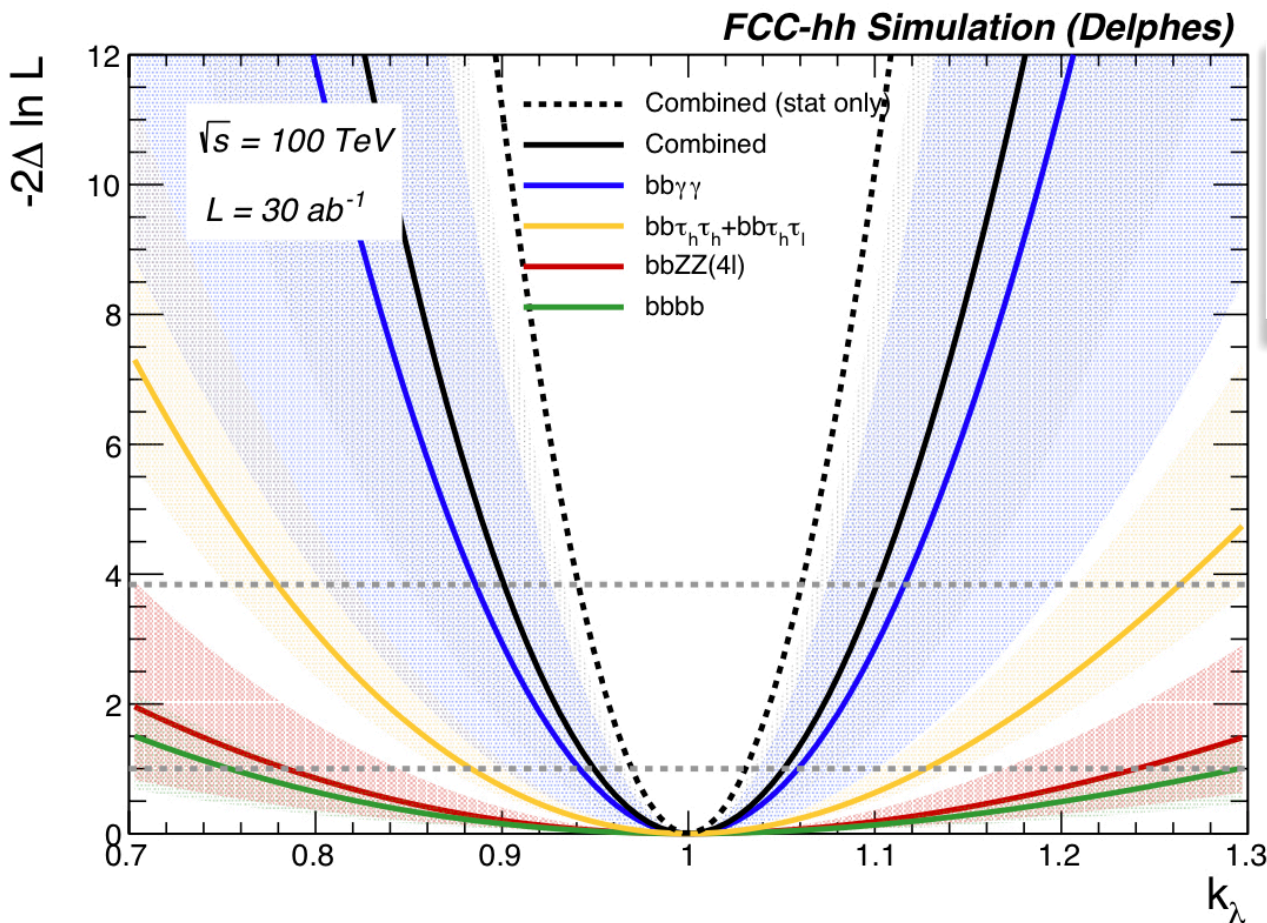$BR(H\to\mu\mu) \sim O(10^{-4}) \Rightarrow O(10^8)$ evts for $\Delta_{stat}\sim\%$

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

The Higgs self-coupling at FCC-hh   https://arxiv.org/abs/2004.03505

FCC-hh Simulation (Delphes)

$\sqrt{s} = 100$ TeV

$L = 30$ ab^{-1}

Legend:
- Combined (stat only)
- Combined
- bb$\gamma\gamma$
- bb$\tau_h\tau_h$+bb$\tau_h\tau_l$
- bbZZ(4l)
- bbbb

y-axis: -2Δ ln L
x-axis: k_λ

Figure 13. Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$ in all channels, and their combination. The solid line corresponds to the scenario II for systematic uncertainties. The band boundaries represent respectively scenario I and III. The dashed line represents the sensitivity obtained including statistical uncertainties only, under the assumptions of scenario I.

Syst scenarios

@68% CL		scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

Table 7. Combined expected precision at 68% CL on the di-Higgs production cross- and Higgs self coupling using all channels at the FCC-hh with $\mathcal{L}_{int} = 30$ ab^{-1}. The symmetrized value $\delta = (\delta^+ + \delta^-)/2$ is given in %.
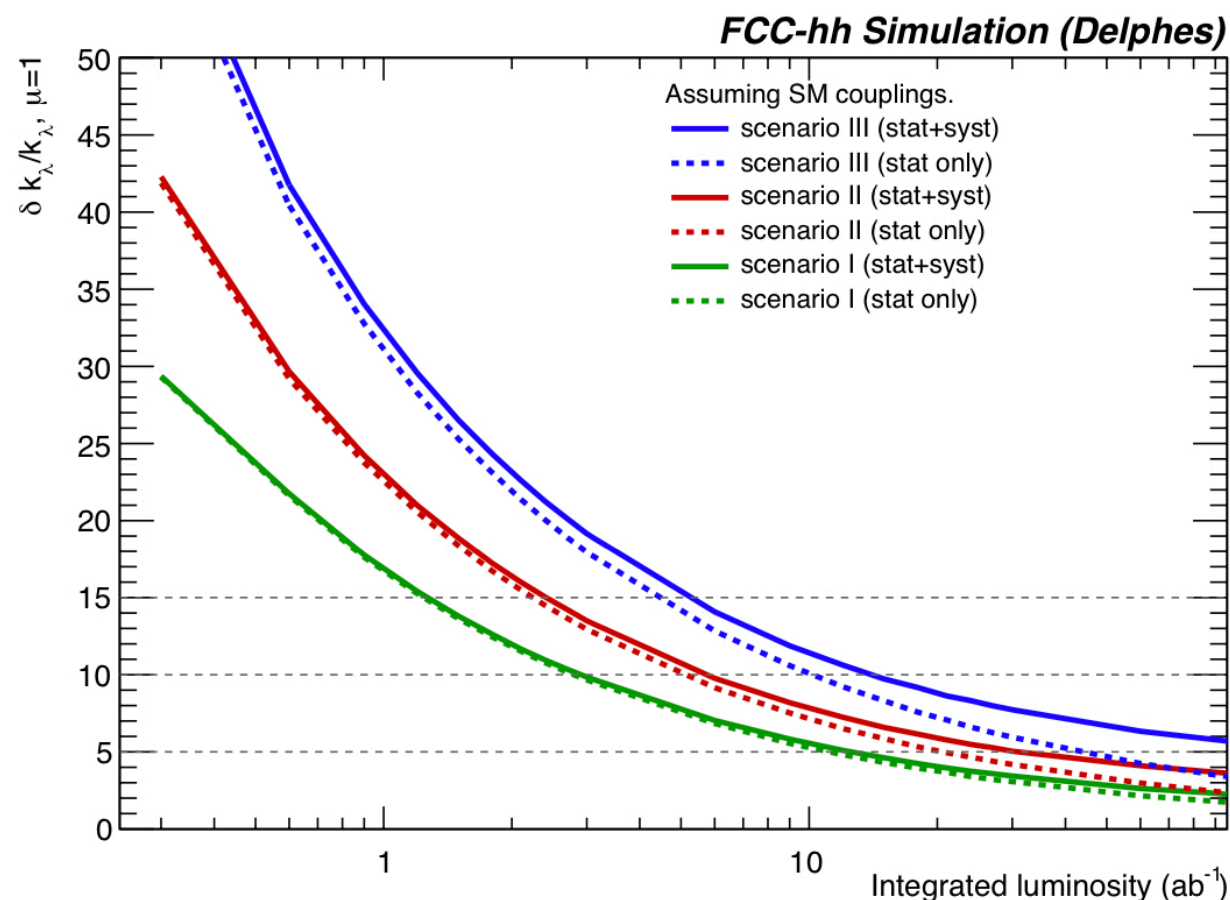
I. Target det performance: LHC Run 2 conditions
II. Intermediate performance
III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)

FCC-hh Simulation (Delphes)

Assuming SM couplings.
- scenario III (stat+syst)
- scenario III (stat only)
- scenario II (stat+syst)
- scenario II (stat only)
- scenario I (stat+syst)
- scenario I (stat only)

y-axis: $\delta k_\lambda/k_\lambda$, $\mu=1$
x-axis: Integrated luminosity (ab^{-1})

Expected precision on the Higgs self-coupling as a function of the integrated luminosity.

3-5 ab^{-1} are sufficient to get below the 10% level

=> within the reach of the first 5yrs of FCC-hh running, in the "low" luminosity / low pileup phase
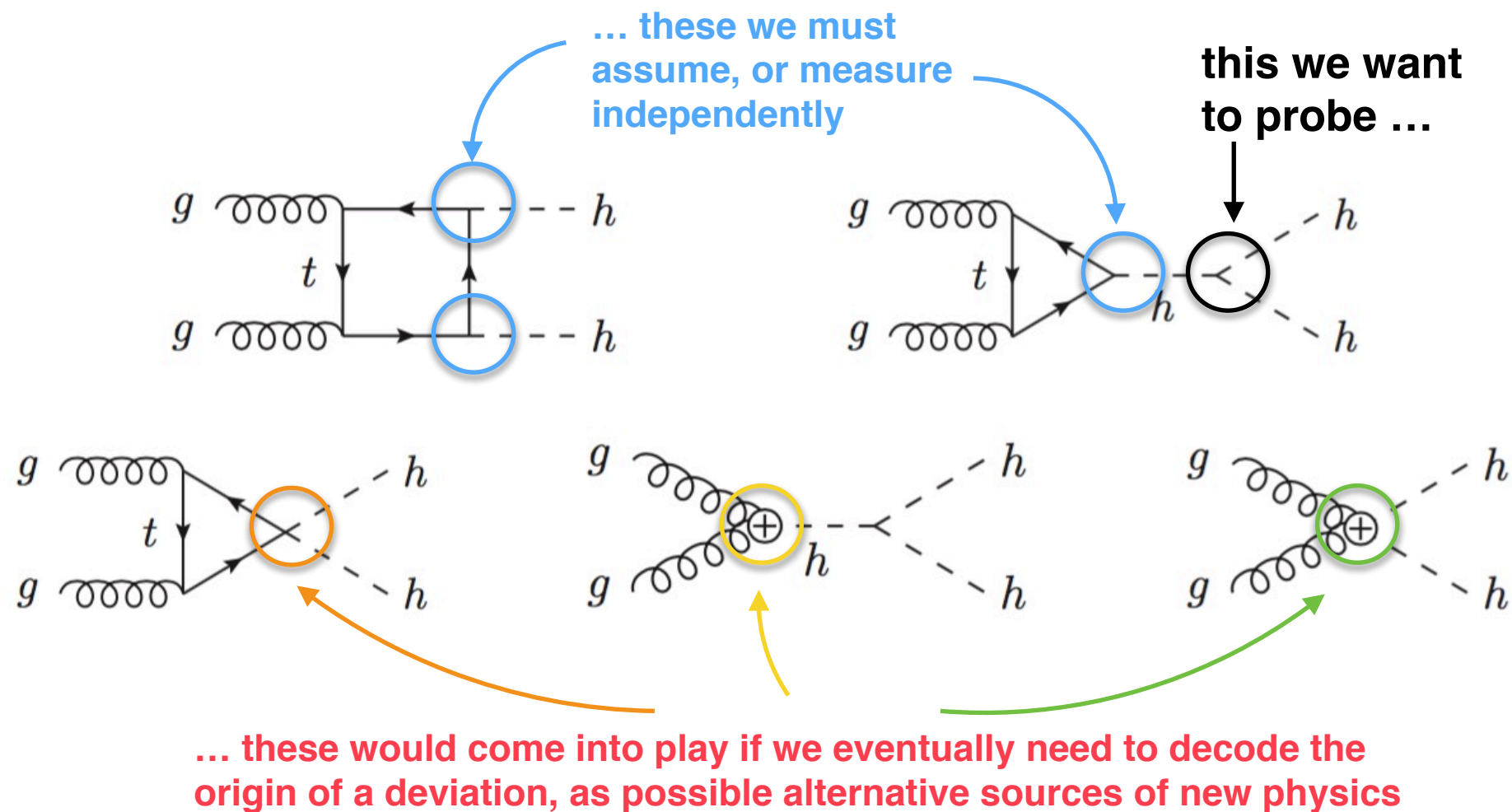
=> the 10% precision threshold can be reached within the timescale of a similar measurement by CLIC @ 3 TeV

# Extracting Higgs self-coupling from HH at FCC:

the power of ee/hh synergy & complementarity

**At FCC-hh we can precisely measure HH rate … but, to interpret this as H selfcoupling:**

… these we must assume, or measure independently

this we want to probe …

… these would come into play if we eventually need to decode the origin of a deviation, as possible alternative sources of new physics

Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

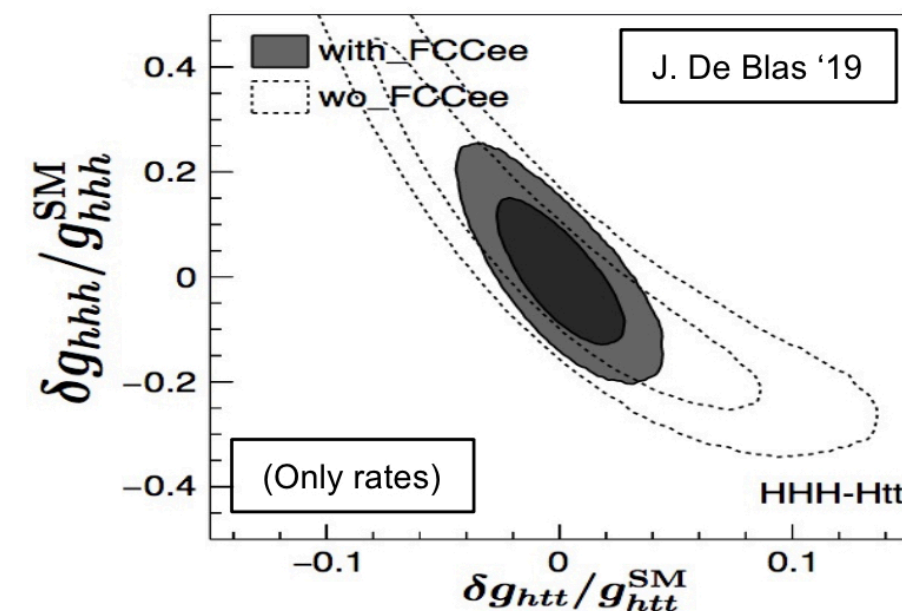**FCC-hh can measure R_t with $\Delta R_t/R_t < 2\%$ …. but:**
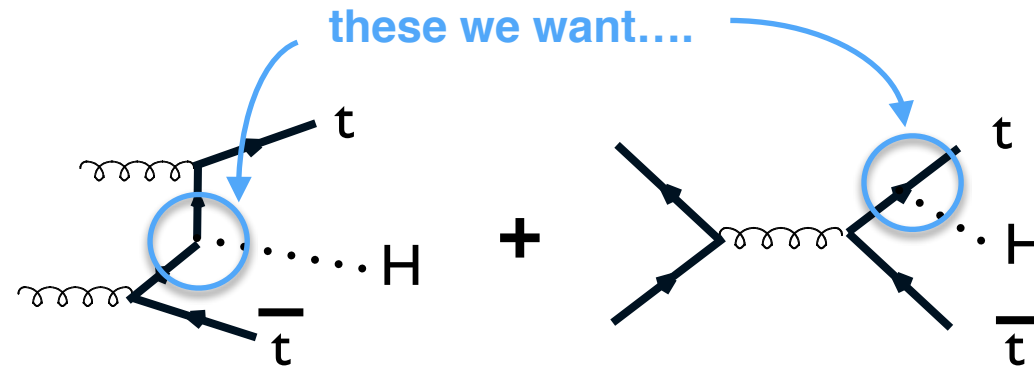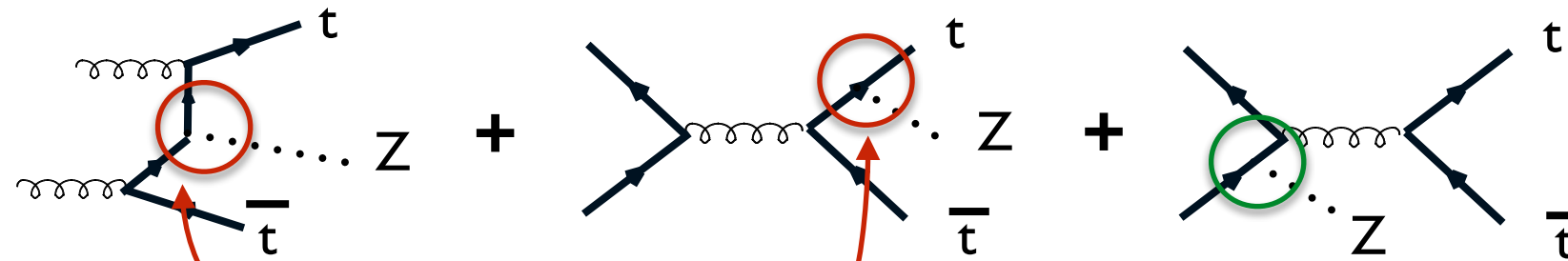
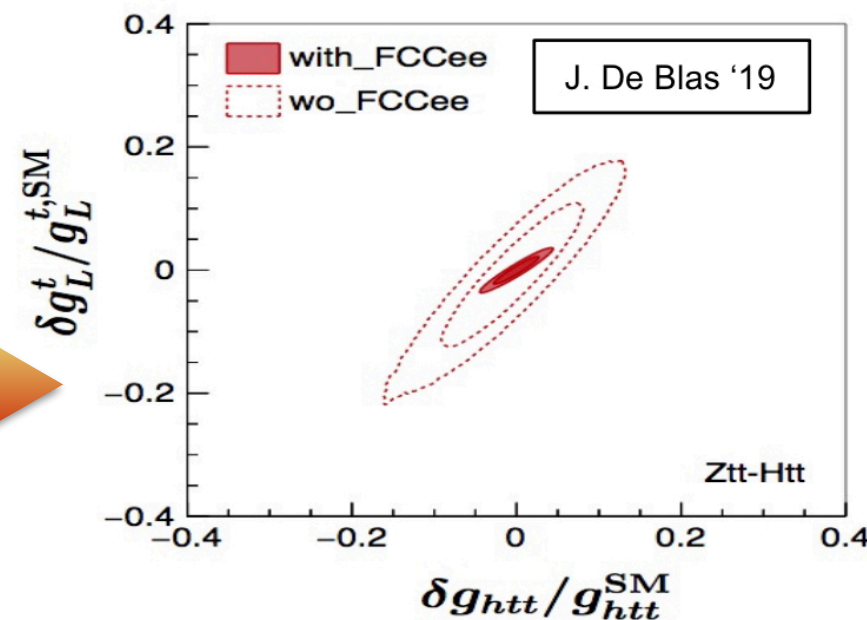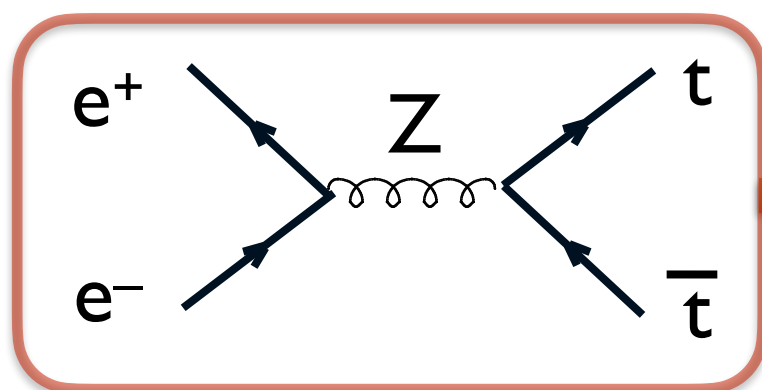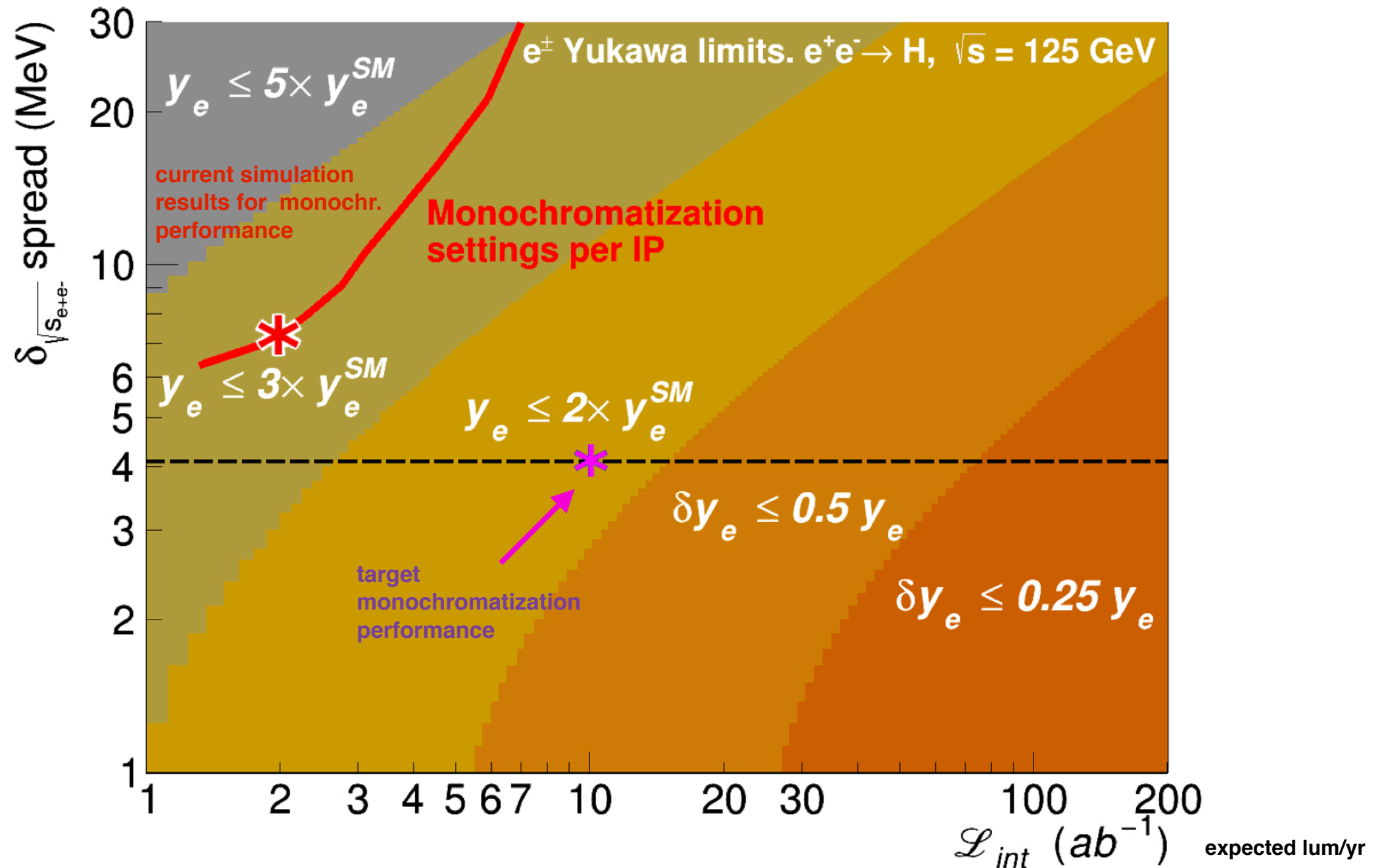# Unique at FCC-ee: $e^+e^- \to H$

D.D'Enterria et al, arXiv:2107.02686

Table 6. Individual significances (in std. deviations σ) expected per decay channel for s-channel Higgs boson production in e^+e^- collisions at FCC-ee for $\mathcal{L}_{\text{int}} = 10\,\text{ab}^{-1}$ and $\delta_{\sqrt{s}} = 4.1\,\text{MeV}$. The last column quotes the combined significance.

H → gg	H → WW* → $\ell\nu$ 2j; 2ℓ 2ν; 4j	H → ZZ* → 2j 2ν; 2ℓ 2j; 2ℓ 2ν	H → $b\bar{b}$	H → $\tau_{\text{had}}\tau_{\text{had}}$; $c\bar{c}$; $\gamma\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

(1) guaranteed deliverables: EW&flavour observables

The absolutely unique power of circular e⁺e⁻:

e⁺e⁻ → Z	e⁺e⁻ → WW	τ(←Z)	b(←Z)	c(←Z)	e⁺e⁻ → tt
$5 \cdot 10^{12}$	10^{8}	$3 \cdot 10^{11}$	$1.5 \cdot 10^{12}$	10^{12}	10^{6}

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

Flavour statistics from Z decays:

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	400	400	100	100	800	220

Additional bonus wrt B factory: (i) Lorentz boost (ii) B hadrons not accessible at the Y(4S,5S) thresholds

FCC-ee run plan

phase	Run duration (yrs)	$\sqrt{s}$ (GeV)	L_{int} (ab^{-1})	Event stats
ee→Z	4	88-95	150	3×10^{12} had Z decays
ee→WW	2	158-192	12	3×10^{8} WW
ee→ZH	3	240	5	10^{6} ZH
machine modification for RF installation and rearrangement: 1 year				
ee→tt	5	345-365	1.5	10^{6} tt + 4×10^{4} Hvv
ee→H	(3)	(125)	(21)	(H resonance)

Total programme duration: 14 years (including machine modifications) plus optional 3years @ H resonance

EW parameters @ FCC-ee

Improvement wrt current total uncertainties:

- stat precision ~ 10-1000 smaller
- with exptl syst ~ > 10-50 smaller

Currently limited by TH systematics =>
ee goals set during the ongoing Workshop

crucial for ttH and HHH couplings at FCC-hh

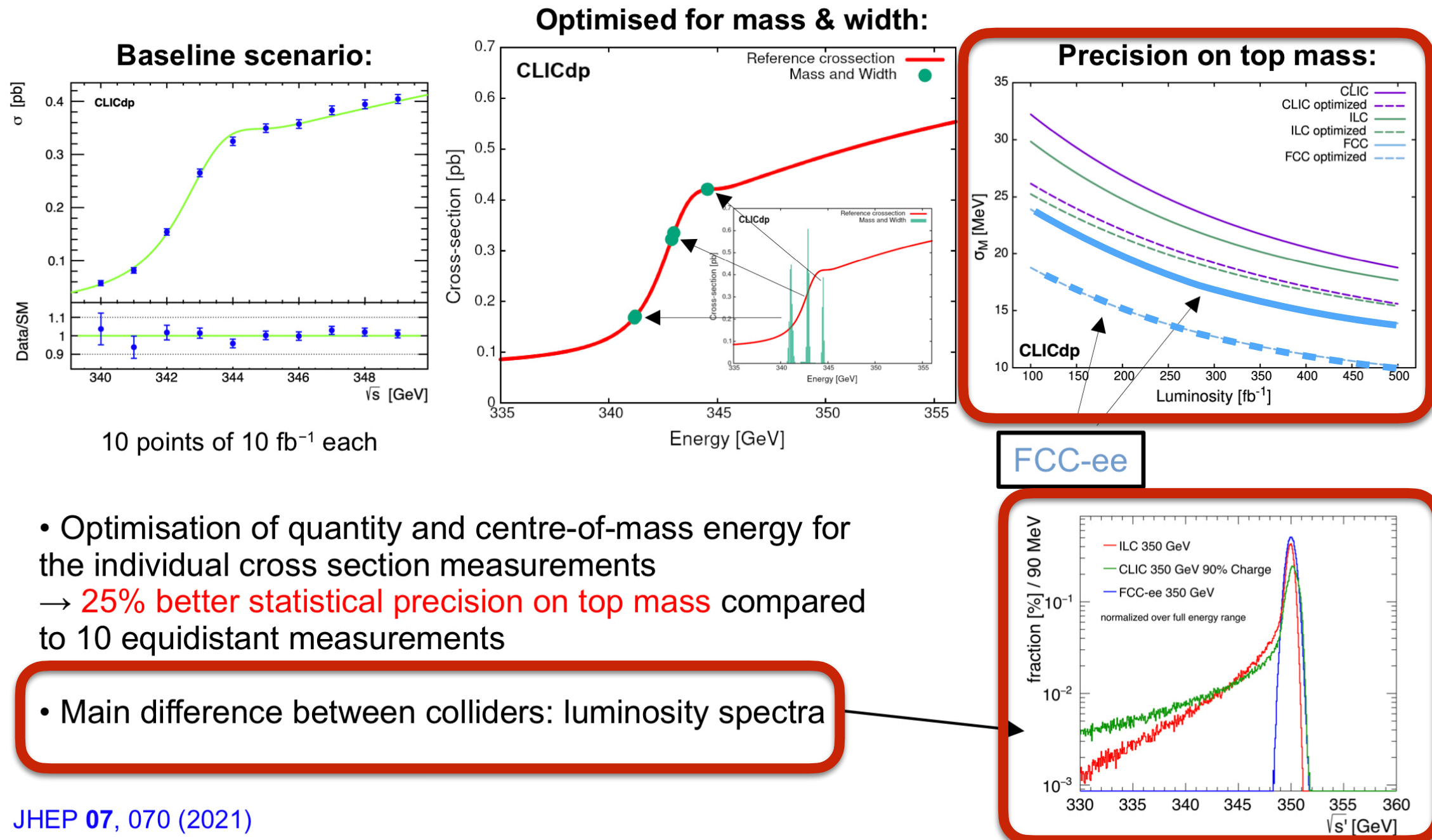| Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z ($\times 10^3$)	20767±25	0.06	0.2-1.0
α_s (m_Z) ($\times 10^4$)	1196±30	0.1	0.4-1.6
R_b ($\times 10^6$)	216290±660	0.3	<60
σ_{had}^0 ($\times 10^3$) (nb)	41541±37	0.1	4
N_ν ($\times 10^3$)	2991±7	0.005	1
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231480±160	3	2-5
$1/\alpha_{QED}$(m_Z) ($\times 10^3$)	128952±14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992±16	0.02	1-3
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498±49	0.15	<2
m_W (MeV)	80350±15	0.6	0.3
Γ_W (MeV)	2085±42	1.5	0.3
α_s (m_W) ($\times 10^4$)	1170±420	3	Small
N_ν($\times 10^3$)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{top}/\lambda_{top}^{SM}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 − 1.5%	Small

Flavour probes: eg lepton universality in tau decays
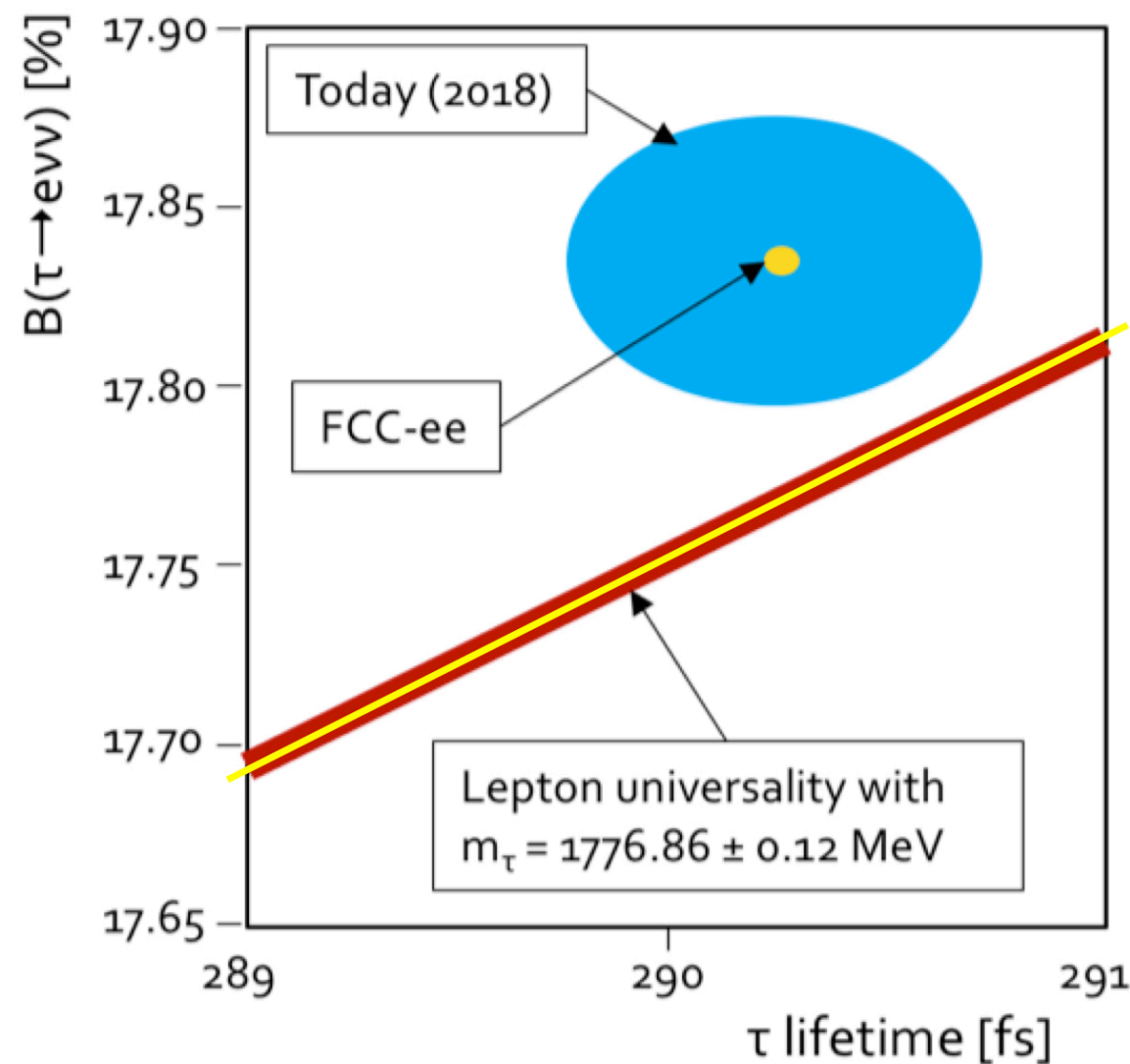
Lorentz boost crucial!

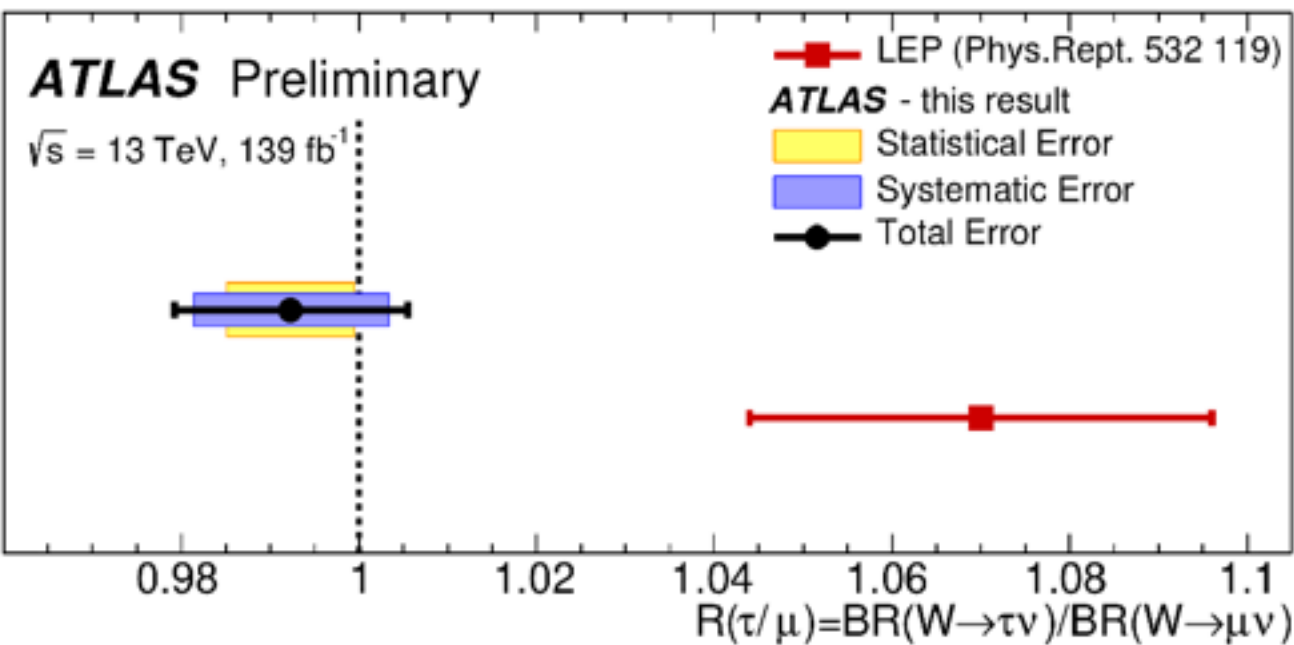| Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.04–0.1	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
$B(\tau \to e\nu\nu)$ [%]	Selection of $\tau^+\tau^-$, identification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

© M. Dam

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m$_{top}$: the advantage of circular

Optimisation of the threshold scan

Baseline scenario:

10 points of 10 fb^{-1} each

Optimised for mass & width:

Precision on top mass:

FCC-ee

• Optimisation of quantity and centre-of-mass energy for the individual cross section measurements
→ 25% better statistical precision on top mass compared to 10 equidistant measurements

• Main difference between colliders: luminosity spectra

JHEP **07**, 070 (2021)

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

LEP:
$BR(W{\to}\tau\nu)/BR(W{\to}\mu\nu) = 1.066 \pm 0.025$

ATLAS:
$BR(W{\to}\tau\nu)/BR(W{\to}\mu\nu) = 0.992 \pm 0.013$
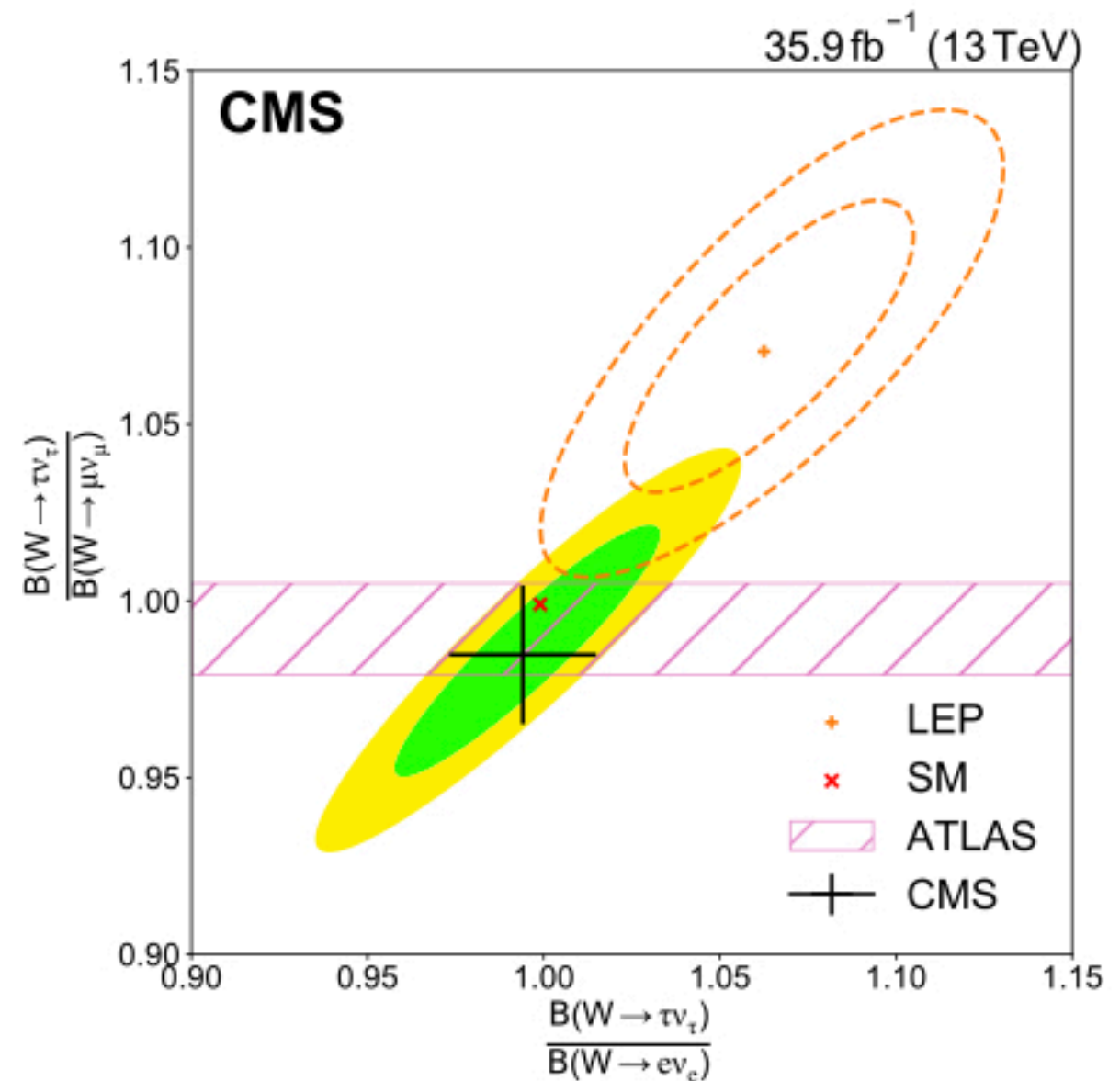
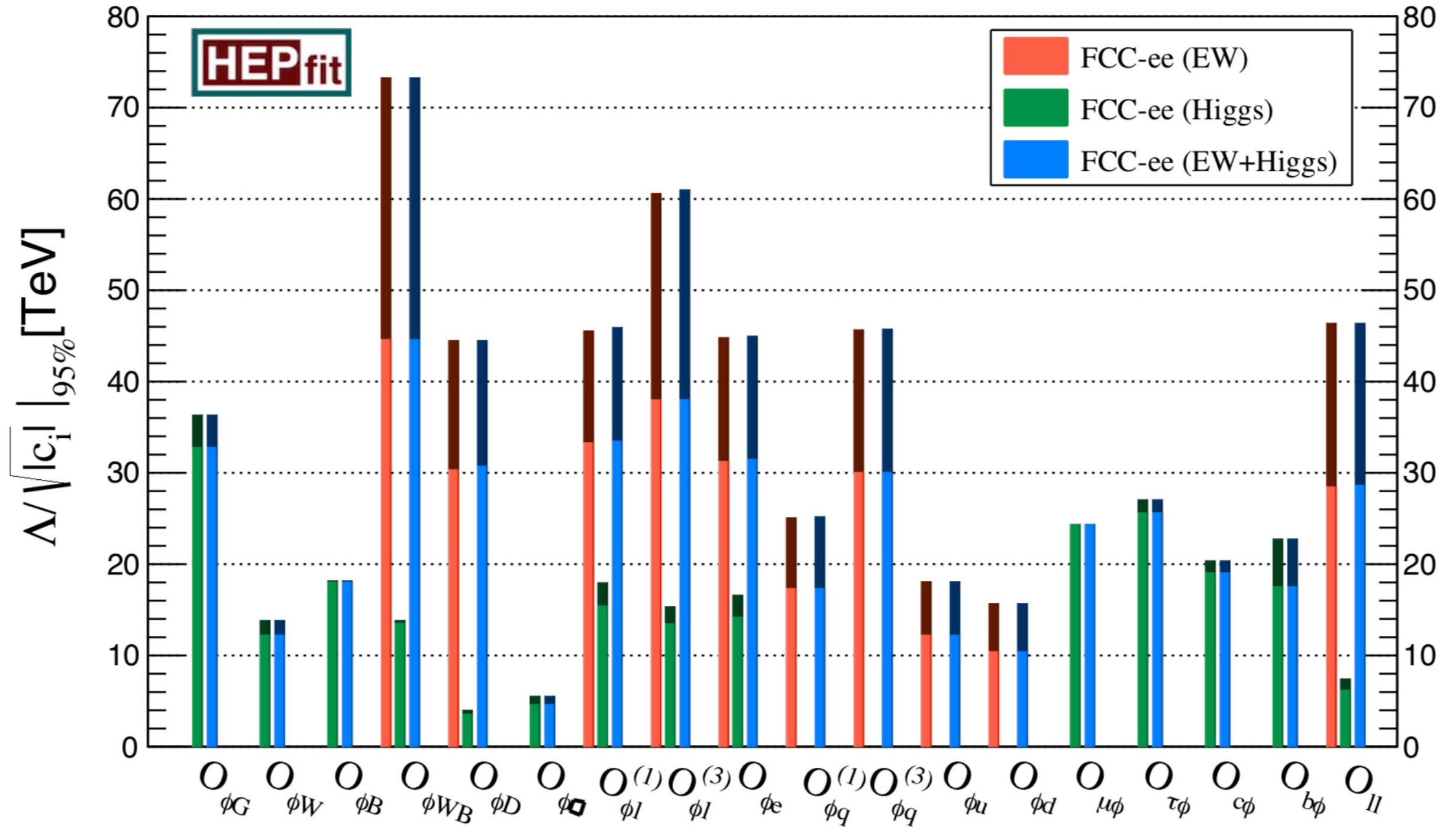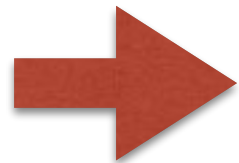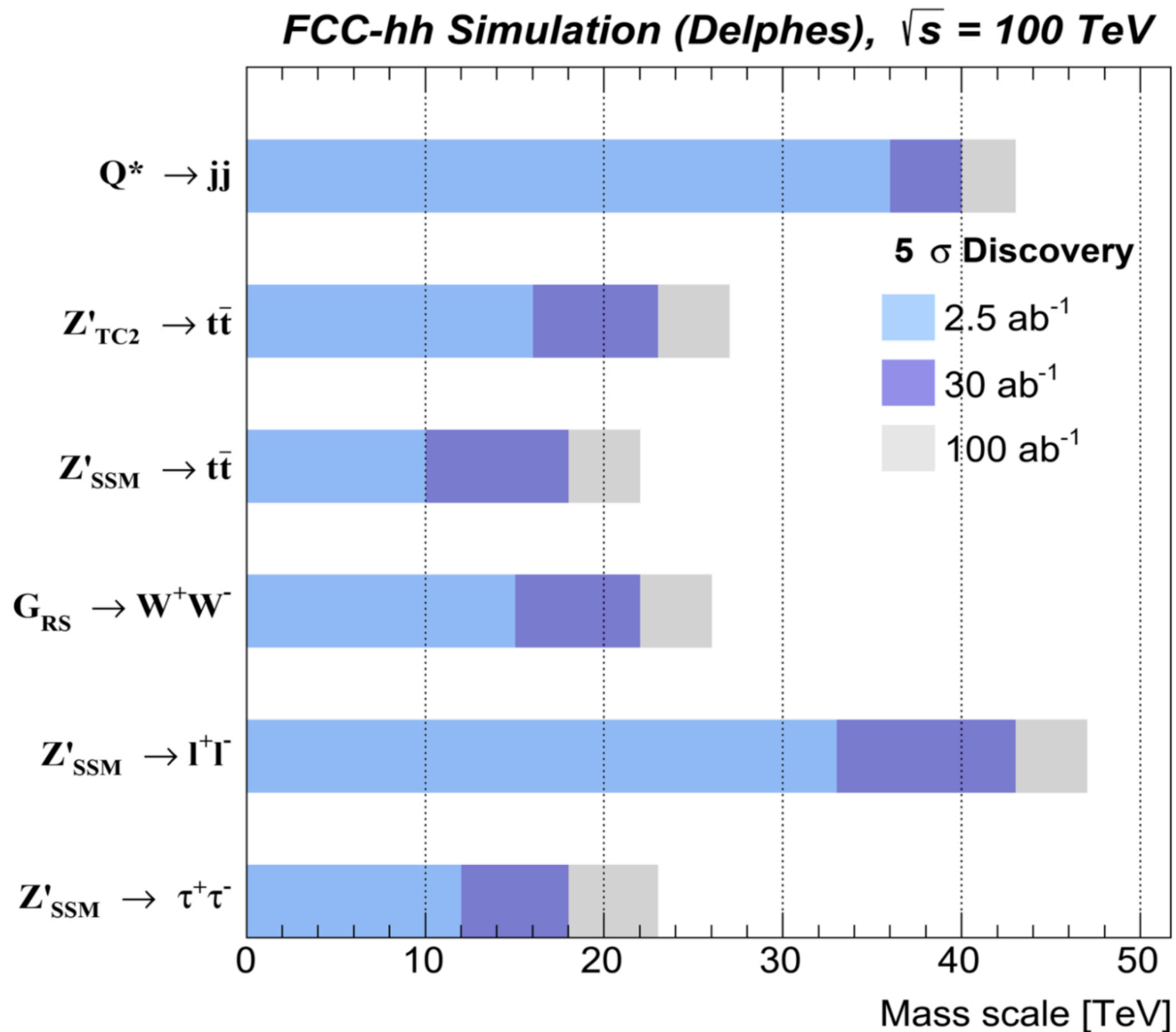| FCC-hh	t	W($\leftarrow$t)	τ($\leftarrow$W$\leftarrow$t)
	10^{12}	10^{12}	10^{11}

~ 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

FCC-hh Simulation (Delphes), $\sqrt{s}$ = 100 TeV

Mass scale [TeV]

5 σ Discovery
- 2.5 ab⁻¹
- 30 ab⁻¹
- 100 ab⁻¹

Channels: $Q^* \to jj$, $Z'_{TC2} \to t\bar{t}$, $Z'_{SSM} \to t\bar{t}$, $G_{RS} \to W^+W^-$, $Z'_{SSM} \to l^+l^-$, $Z'_{SSM} \to \tau^+\tau^-$

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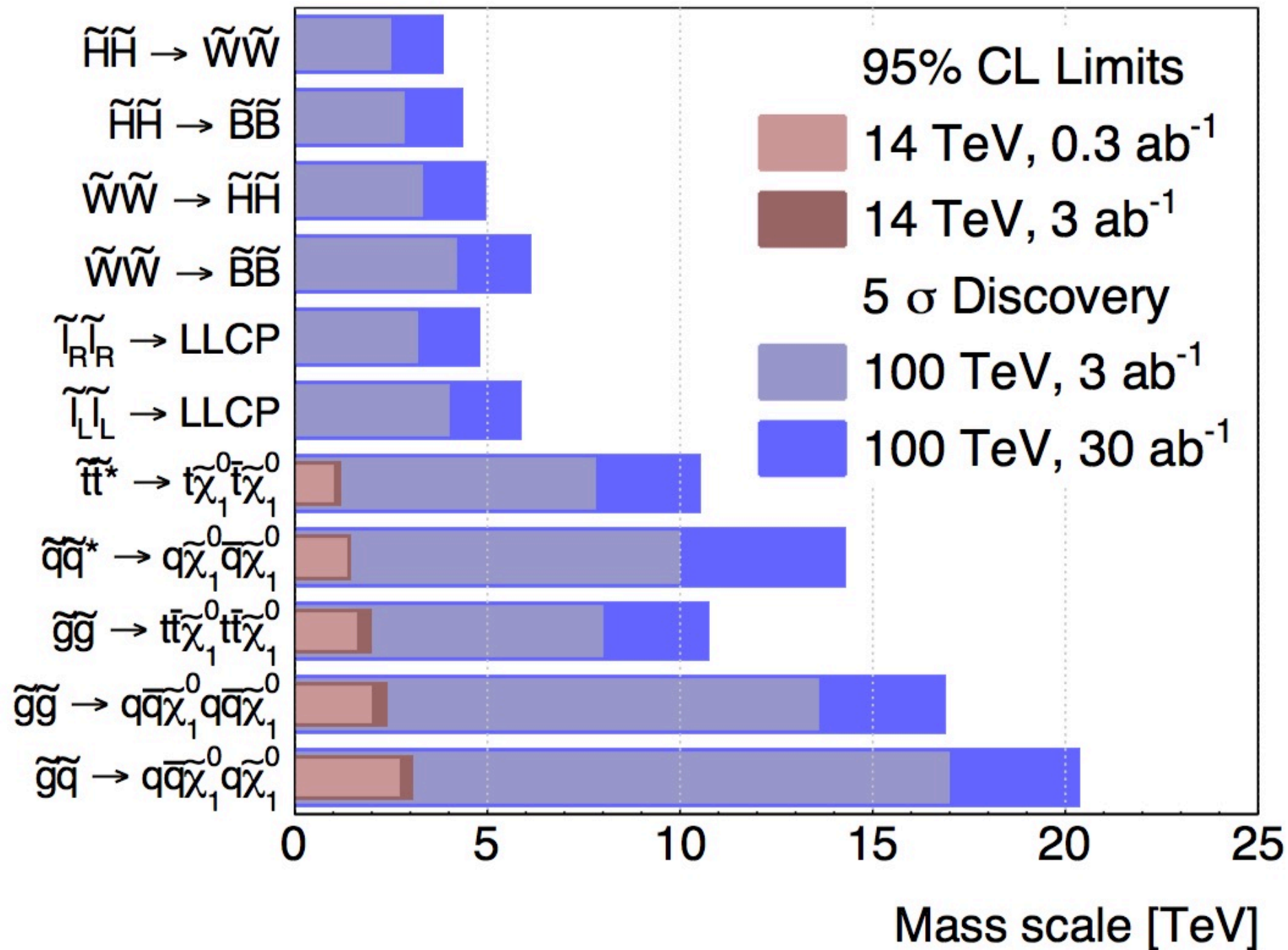
15-20 TeV squarks/gluinos would require a lepton collider in the ECM range of 30-50 TeV

(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 $\leftrightarrow$ SM)

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

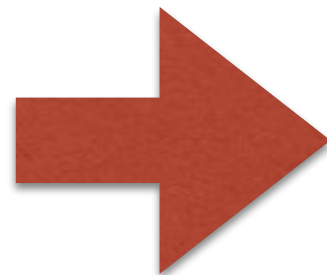**For a particle annihilating through processes which do not involve any larger mass scales:**

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

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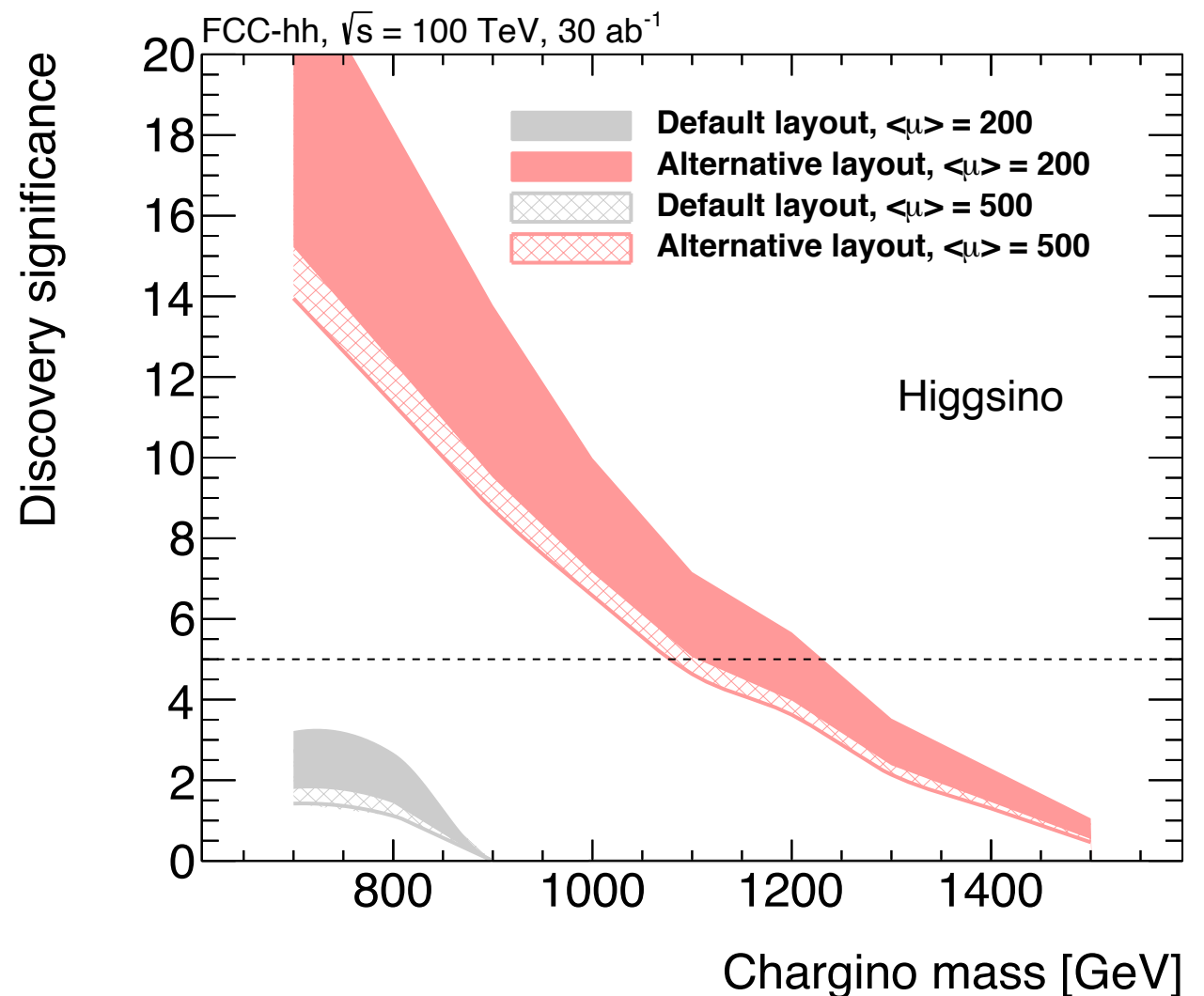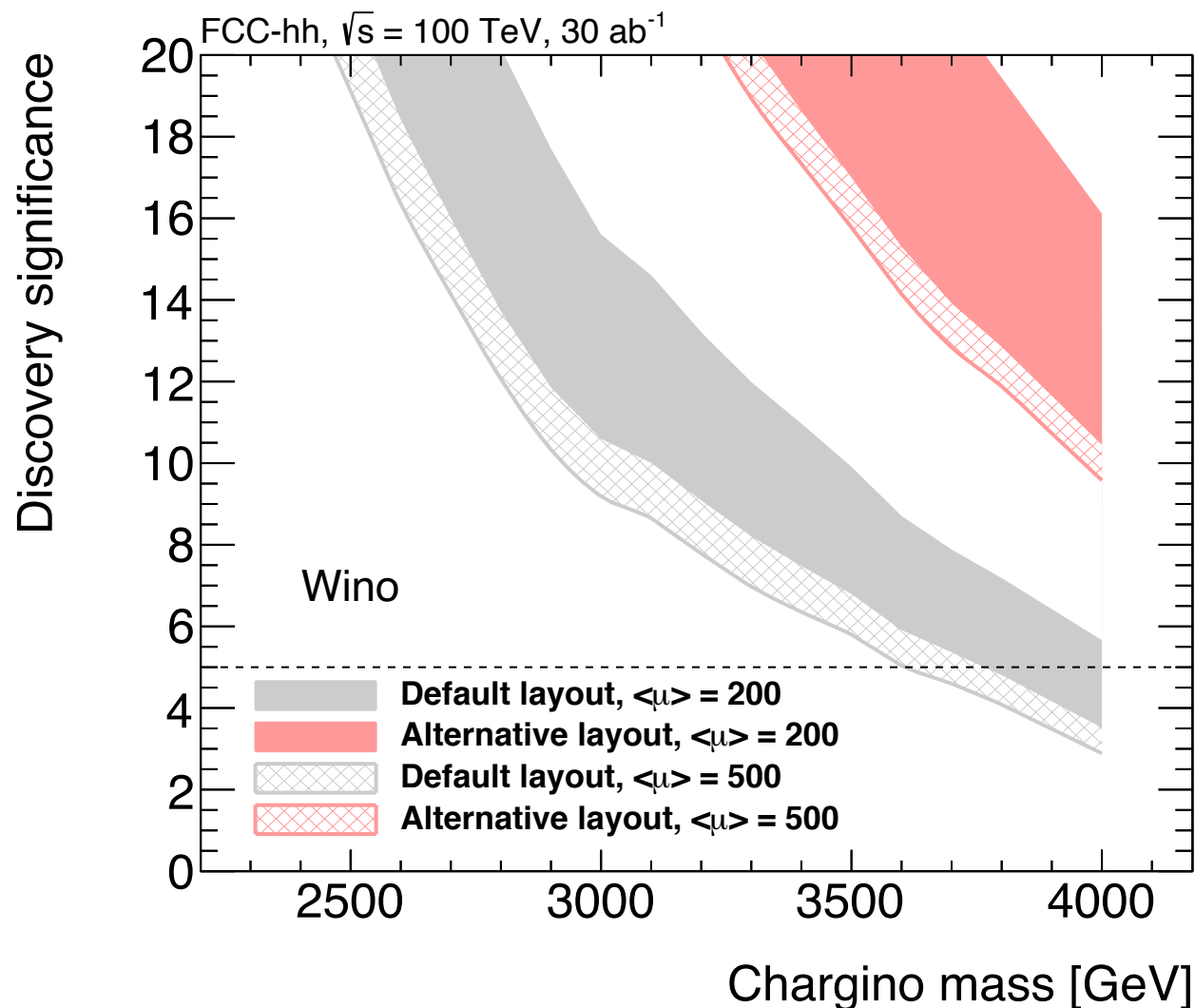
$$\Omega_{wimp} h^2 \lesssim 0.12$$

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

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 !!**

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

The nature of the EW phase transition
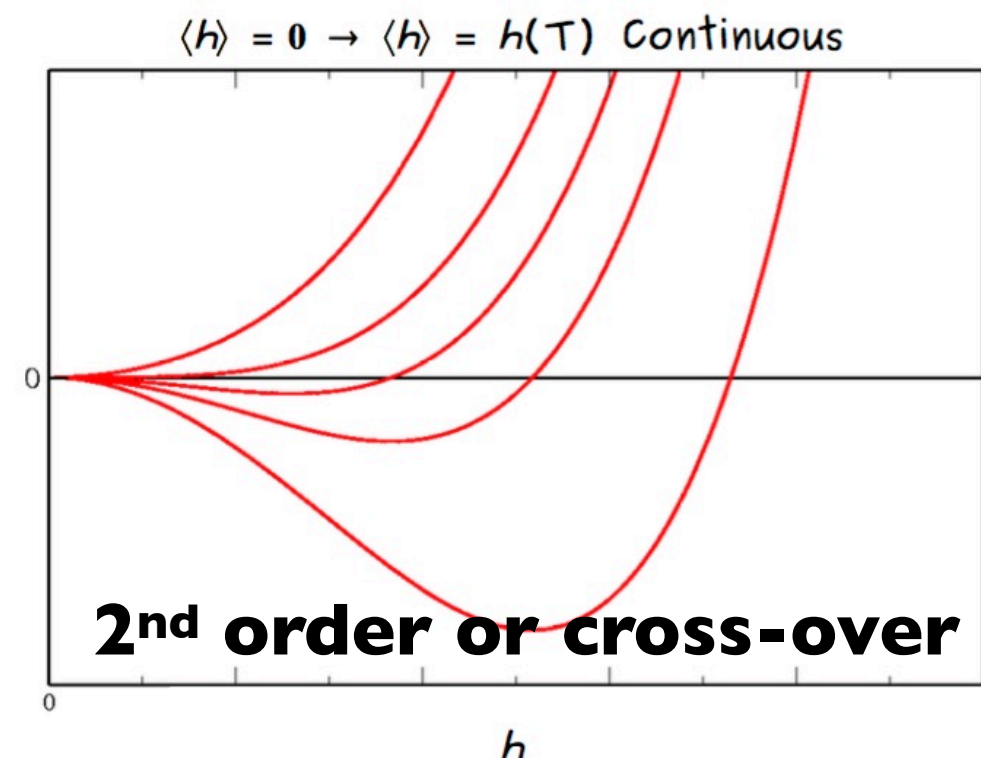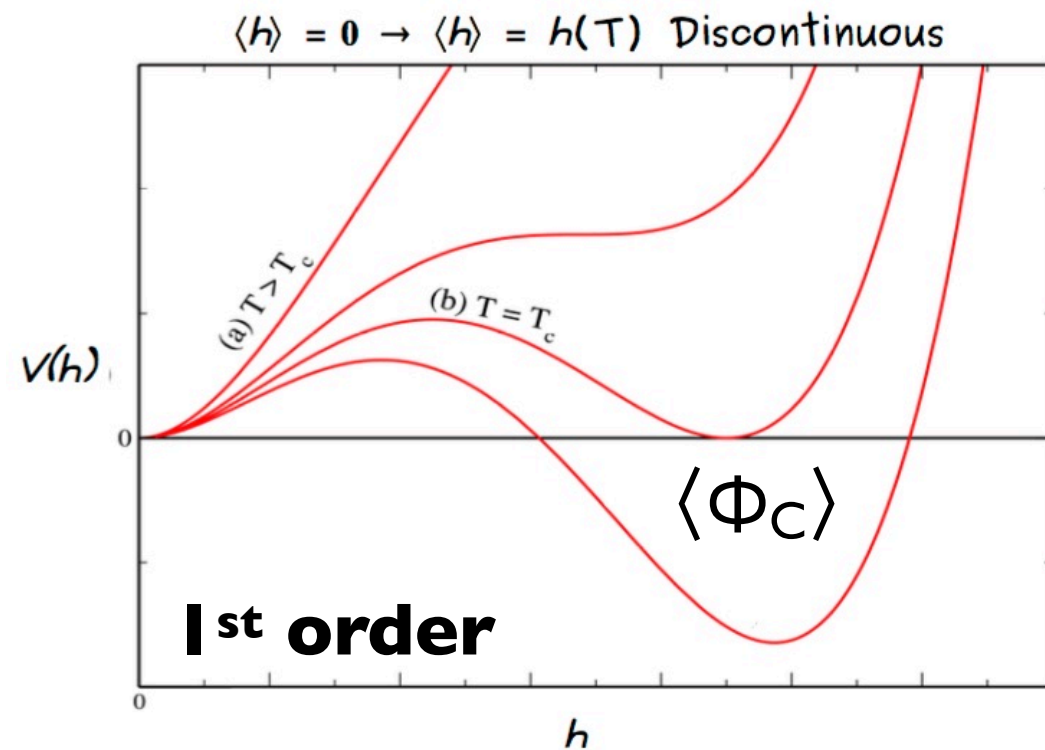
Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1st order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

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

Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible
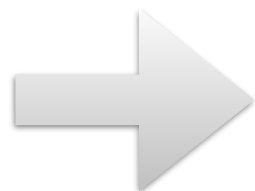
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

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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
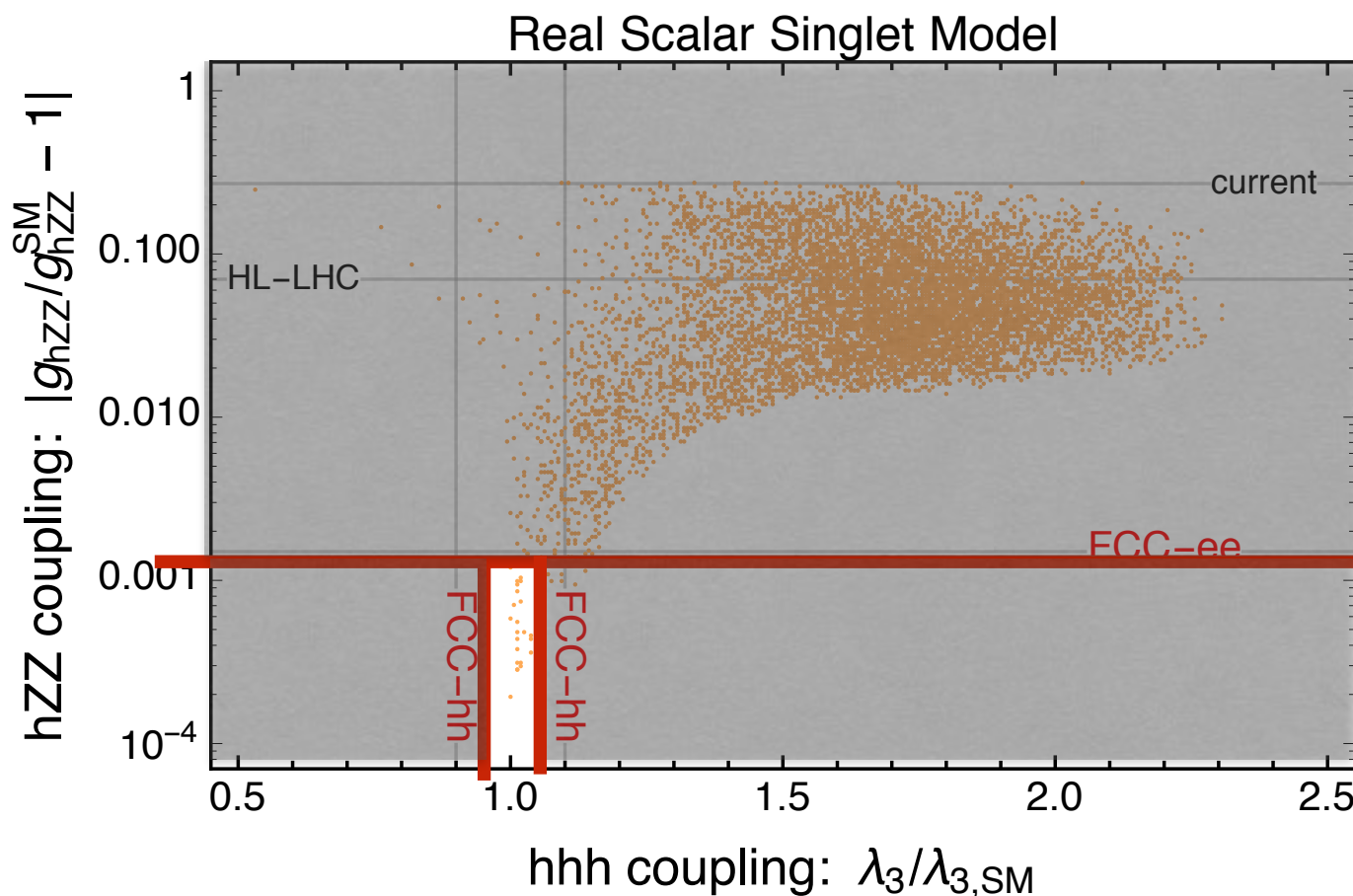
Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

Direct detection of extra Higgs states at FCC-hh

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

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

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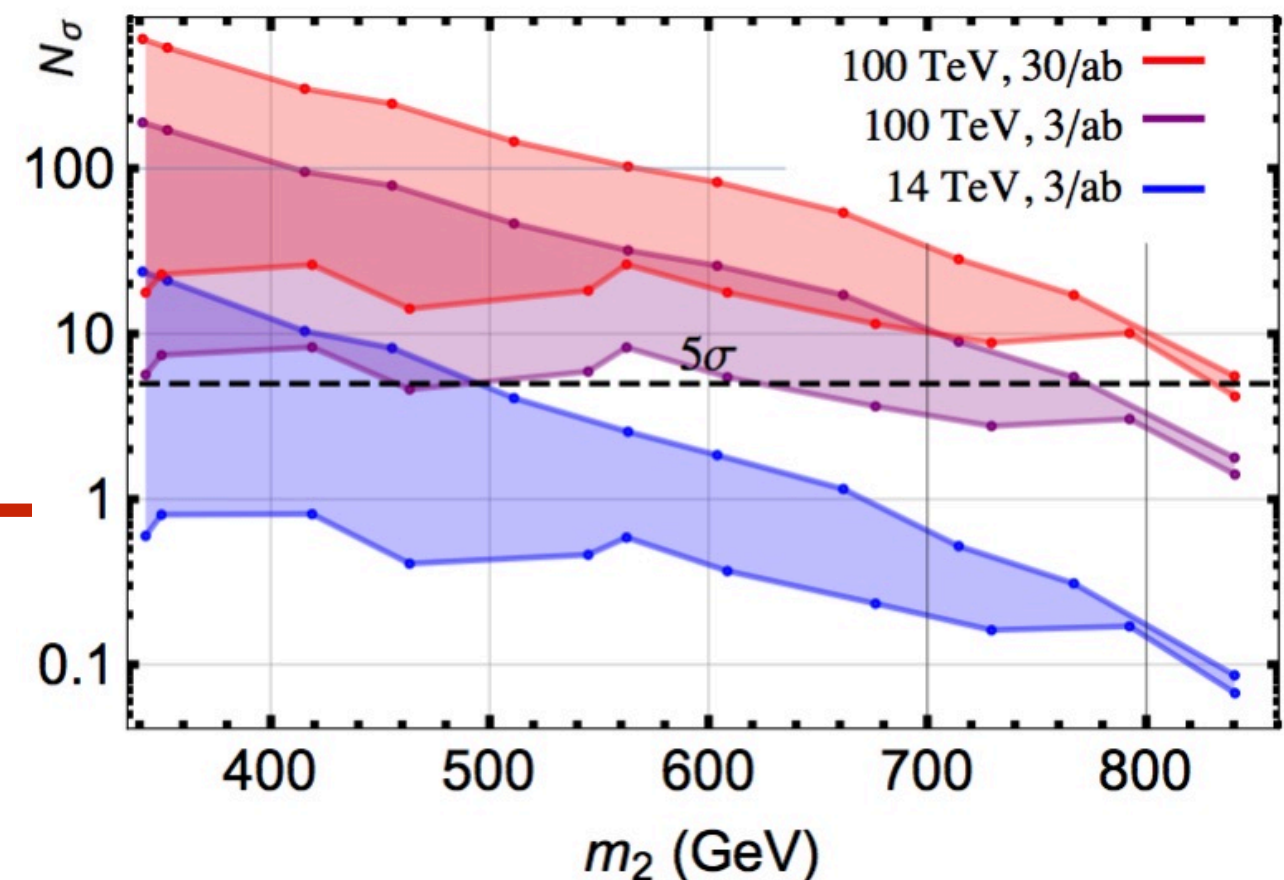
Remarks

- 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

Real Scalar Singlet Model
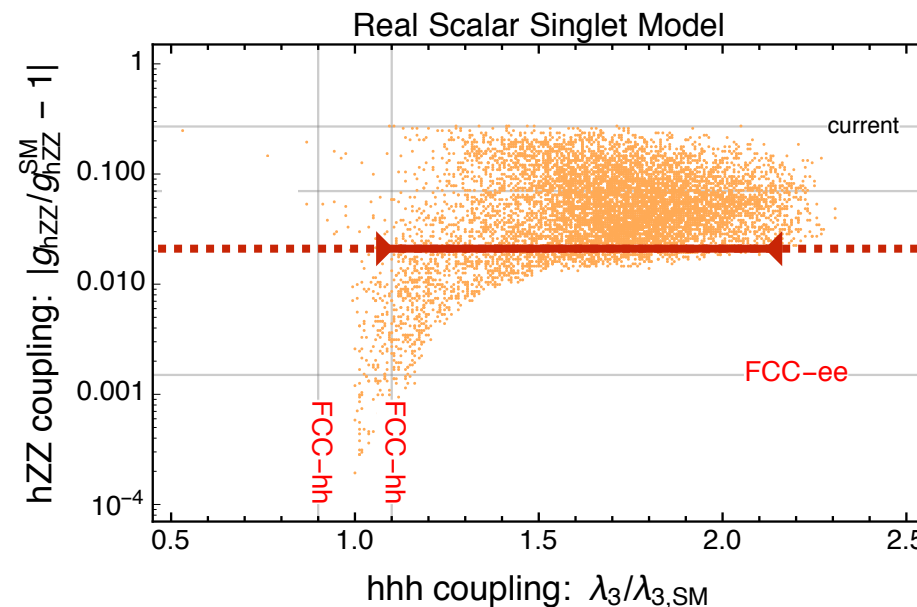
- The concept of *"which experiment sets a better constraint on a given parameter"* is a very limited comparison criterion, which looses value as we move from *"setting limits"* to *"diagnosing observed discrepancies"*

- 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

MSSM Higgs @ 100 TeV

Legend (left plot):
- bbH^0/A^0 →bbττ
- bbH^0/A^0 →bbtt
- t(t)H^0/A^0 →t(t)tt

Legend (right plot):
- tbH$^+$ →tbτν
- tbH$^+$ →tbtb
- LHC 3 ab^{-1}
- LHC 0.3 ab^{-1}

Left plot axes: $\tan\beta$ vs m_A [TeV], labeled **20 TeV**

Right plot axes: $\tan\beta$ vs m_{H^+} [TeV], labeled **20 TeV**, arrows pointing to **30 ab^{-1}** and **3 ab^{-1}**
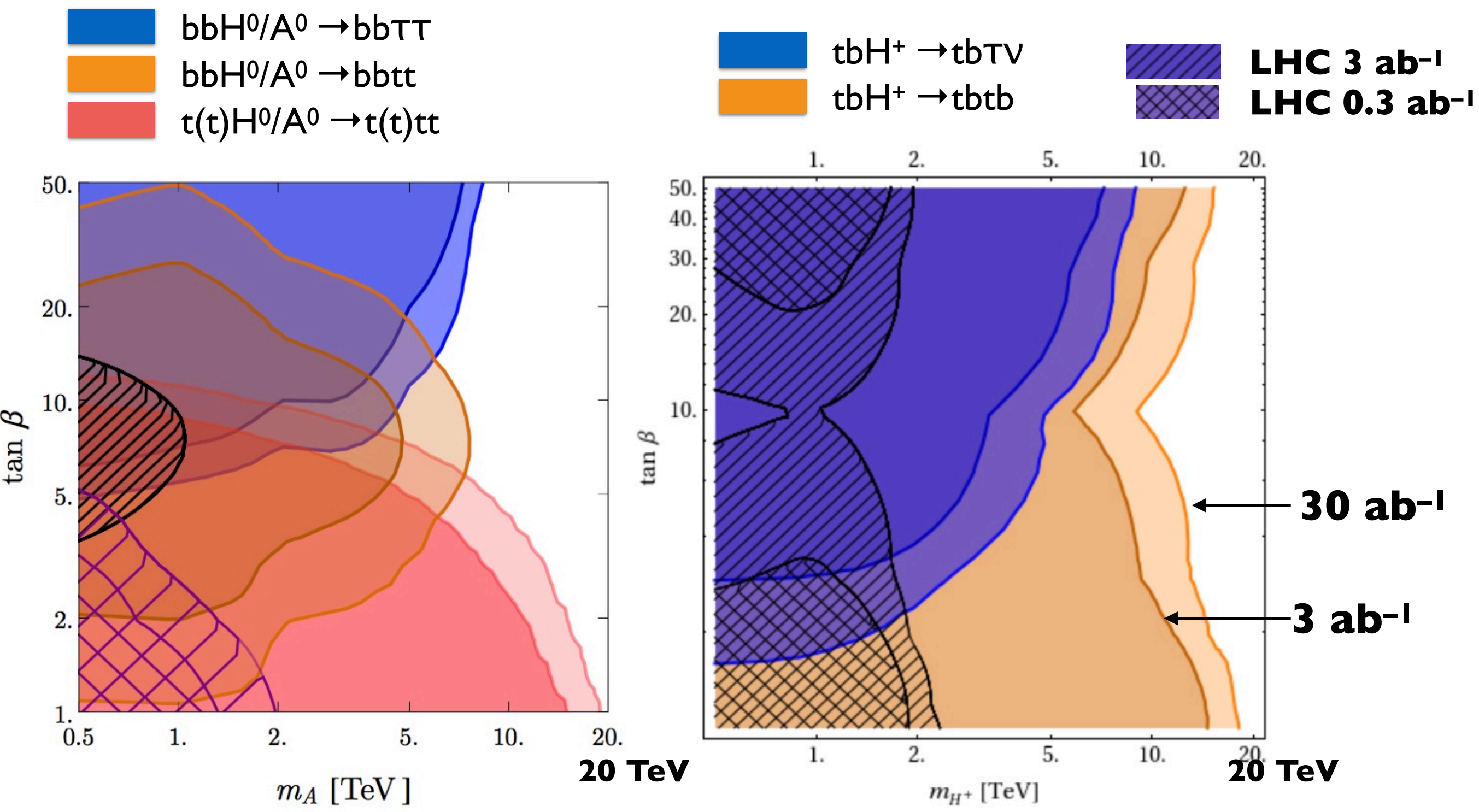
N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang,
arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu,
arXiv:1504.07617

… 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, with plenty of opportunities for direct discovery even at FCC-ee and FCC-eh

- Sensitivity studies to SM deviations in the properties of top quarks, flavour physics in Z decays: huge event rates offer unique opportunities, that cannot be matched elsewhere

- …

- Operations with heavy ions: new domains open up at 100 TeV in the study of high-T/high-density QCD. Broaden the targets, the deliverables, extend the base of potential users, and increase the support beyond the energy frontier community

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 circular 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

- I said nothing about the technological, financial and sociological challenges, that's a colloquium by itself. They are immense, and will test our 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

Highest priority goals:

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

>2030 start tunnel construction

>2038 machine installation

>2045 first ee collisions

~2028 approval

2026/7 ESPPU

>2030 - 37 element production

>2026 - 30 full technical design

2025/26 Feasibility proof

2025/26 Financing model Operation concept

2013 ESPPU

2014 FCC study kickoff

2018 FCC CDR

2020 ESPPU

2020 FCCIS kickoff

today

2012 Higgs discovery announced

2011 circular Higgs factory proposal

2020-25 FCC Feasibility Study FCCIS H2020 DS

FCC Feasibility Study Overview
Michael Benedikt
Paris, 30 May 2022

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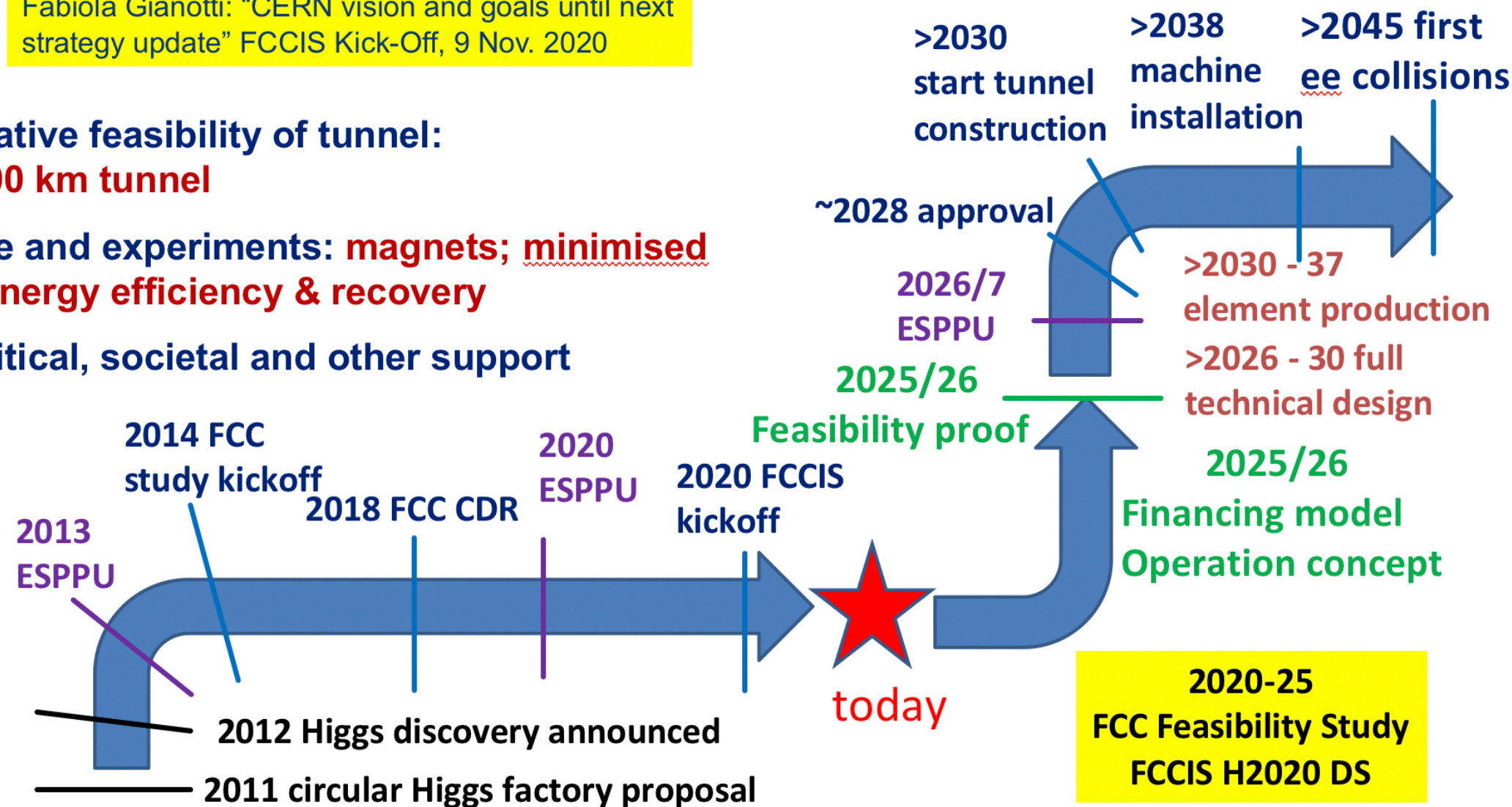
Timeline of the FCC integrated programme

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | .... | 19 | 20 | **FCC-ee** ~ 15 years operation | 10 years | **FCC-hh** ~ 25 years operation | 70 |

Feasibility Study — **ESPP**

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

- ❑ 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

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- **Feedback on** *in principle* **feasibility by directly engaging with local and regional stakeholders** in France and in Switzerland that are affected by the placement scenario.

- Launch of **common work with federal agencies in Switzerland and with national services in France on topics to be delt with at national level** (e.g. managemenet of exavated materials, access to water and electricity resources, road construction feasibility etc.).

- **Optimisation of the locations for geophysical and geotechnical investigations** with locally affected stakeholders (e.g. plot owners, residents).

- **Launch of initial field studies** to obtain a reference for environmental impact studies and estimation of the evolution of the territory without and FCC project.

- Feasibility **study of access to national railroad infrastructures** in France and in Switzerland via existing, to be refurbished or to be created terminals.

- Feasibility **study of access to French national highway system** at selected locations for handover of exavated materials.

- Interactions with local and regional development policy makers on **potentials and priorities for synergies between FCC and the hosting regions**.

Stage 1: updated parameters

K. Oide, D. Shatilov,

FUTURE CIRCULAR COLLIDER

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

Stage 2: FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36