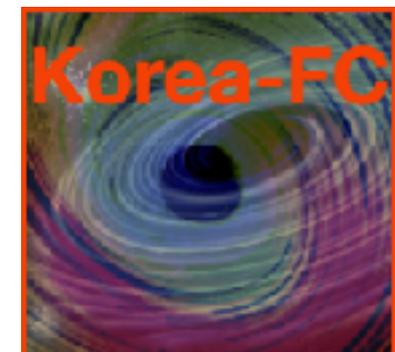


# General overview of (physics at) Future Circular Colliders

Kick off meeting of the Korea FC consortium

25 February 2021

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CERN, Geneva



# Contents

- Collider physics goals beyond the LHC
- Why circular colliders?
- Overview of the physics potential of the future 100 TeV hadron collider (*for ee see Christophe talk*)
- Conclusions

# The important questions

- **Data driven:**

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

- **Theory driven:**

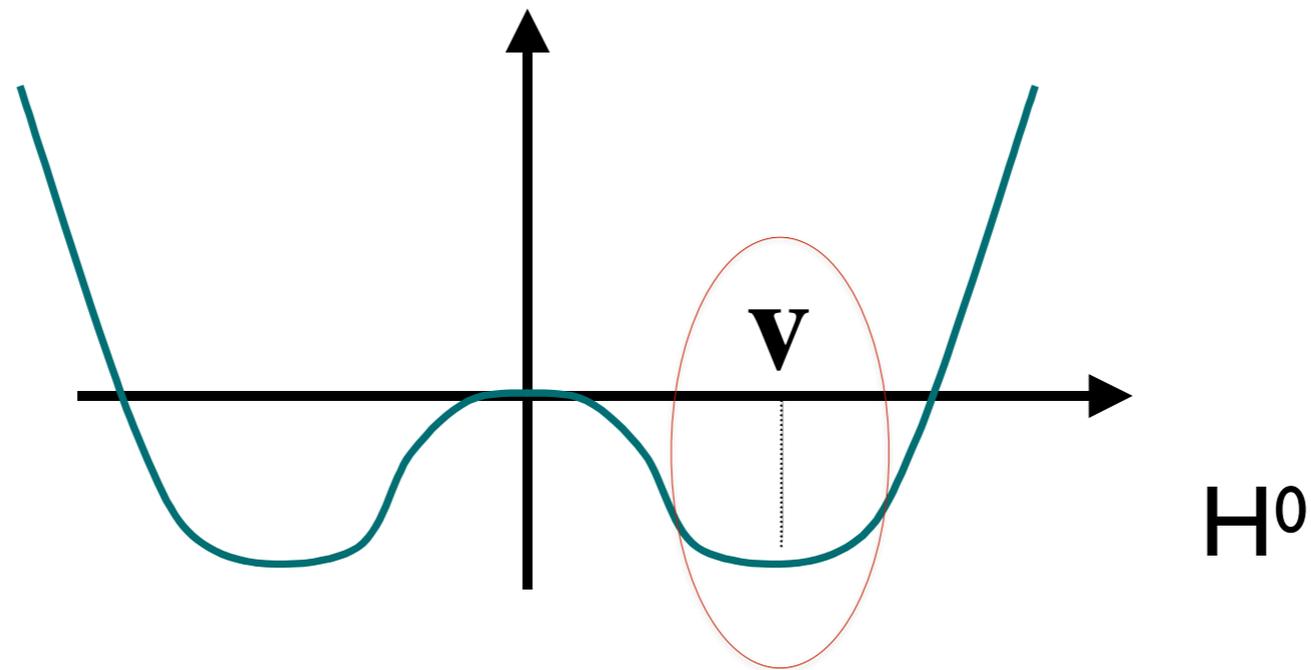
- The hierarchy problem and naturalness
- The flavour problem (origin of fermion families, mass/mixing pattern)
- Quantum gravity
- Origin of inflation
- ...

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

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

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

**Where does this come from?**

# 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.  $H^\pm, A^0, H^{\pm\pm}, \dots$ , 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?**  $H \rightarrow \mu\tau$ ?  $H \rightarrow e\tau$ ?  $t \rightarrow Hc$ ?
- 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?

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➡ *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”**

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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*

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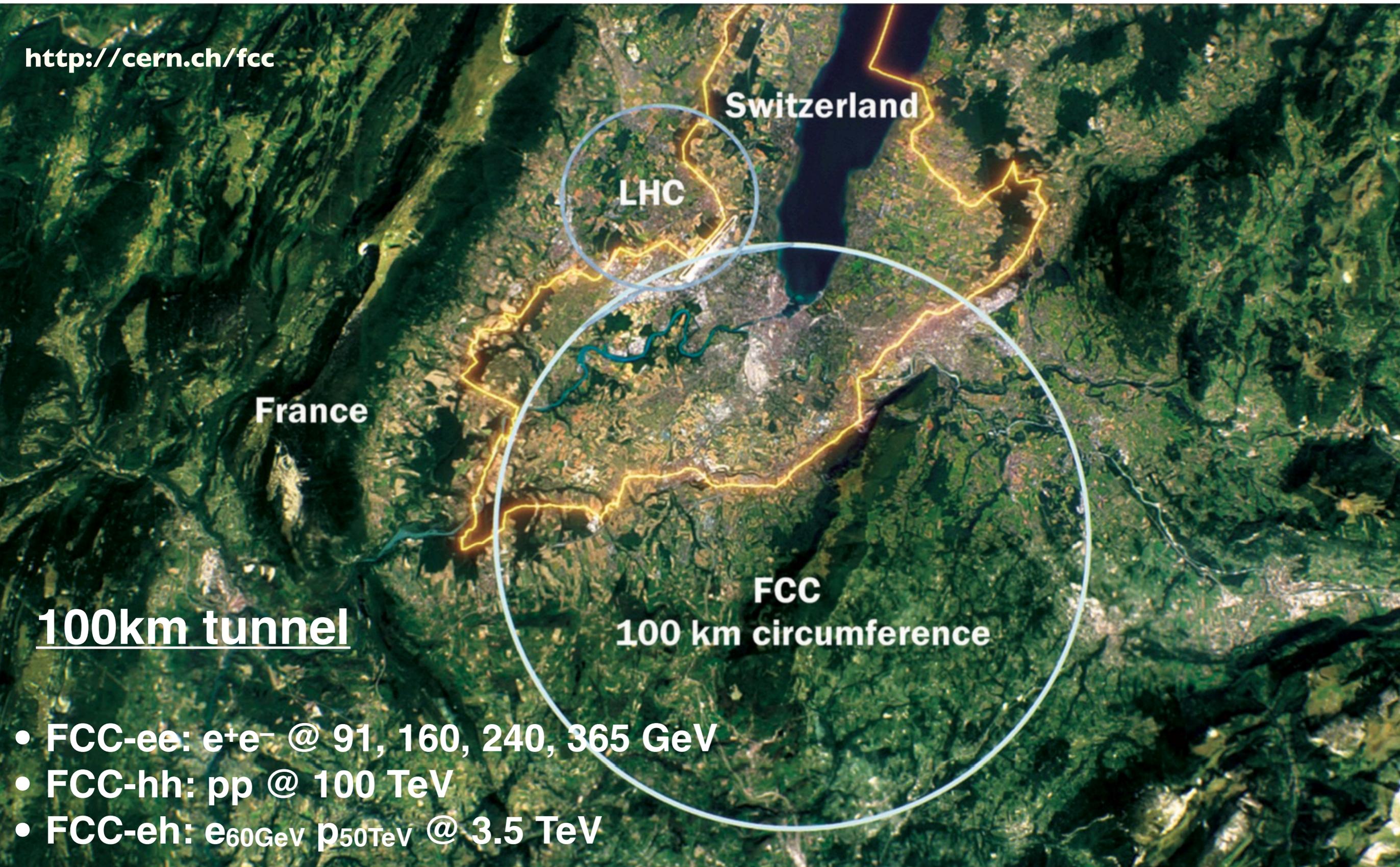
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- Exploration potential:
  - exploit both direct (large  $Q^2$ ) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration at 100 TeV
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

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    - *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?
  - ...

# Future Circular Collider

<http://cern.ch/fcc>



# 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**

# Sensitivity of various Higgs couplings to examples of beyond-the-SM phenomena

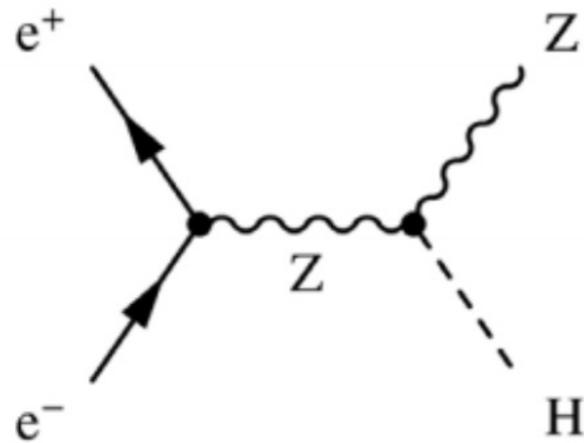
*arXiv:1310.8361*

Model	$\kappa_V$	$\kappa_b$	$\kappa_\gamma$
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -0.4\%$
Composite	$\sim -3\%$	$\sim -(3 - 9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

- **for evidence of  $3\sigma$  deviations from SM, the precision goal should be (sub)percent!**
- **even where direct search is more powerful for the BSM observation, deviations in H couplings are important to help pin down the BSM model**

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

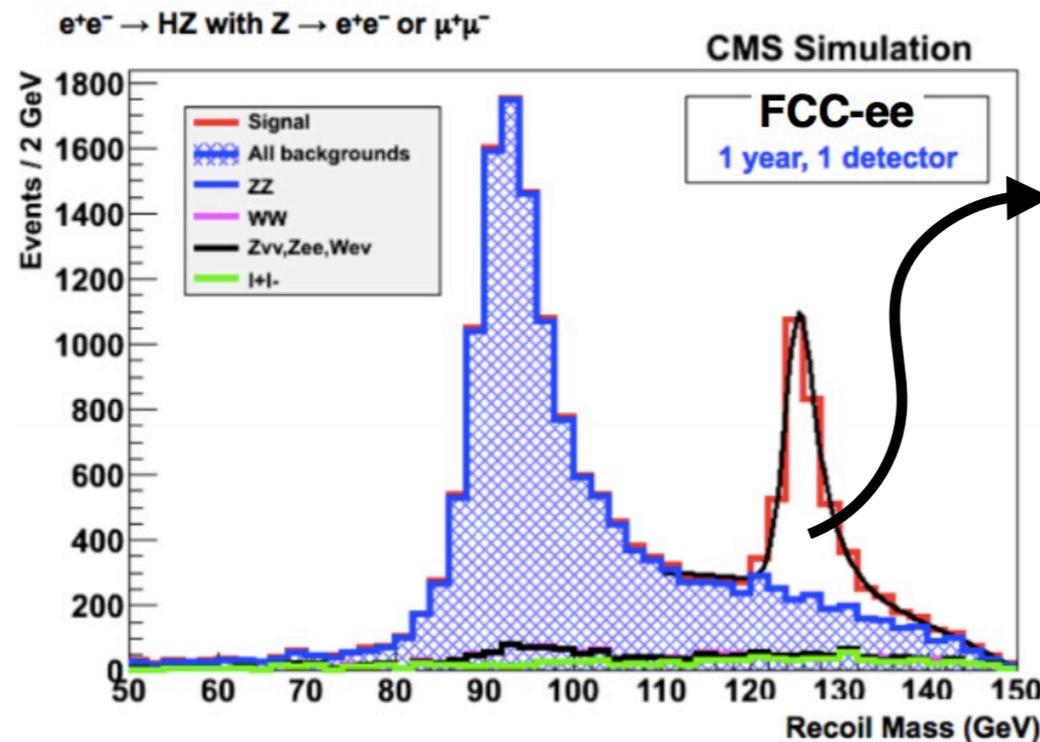
- the **model independent** absolute measurement of **HZZ** coupling, which allows the subsequent:
  - **sub-%** measurement of couplings to **W, Z, b,  $\tau$**
  - **%** measurement of couplings to **gluon and charm**



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

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

$\Rightarrow$  absolute measurement of width and couplings

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

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

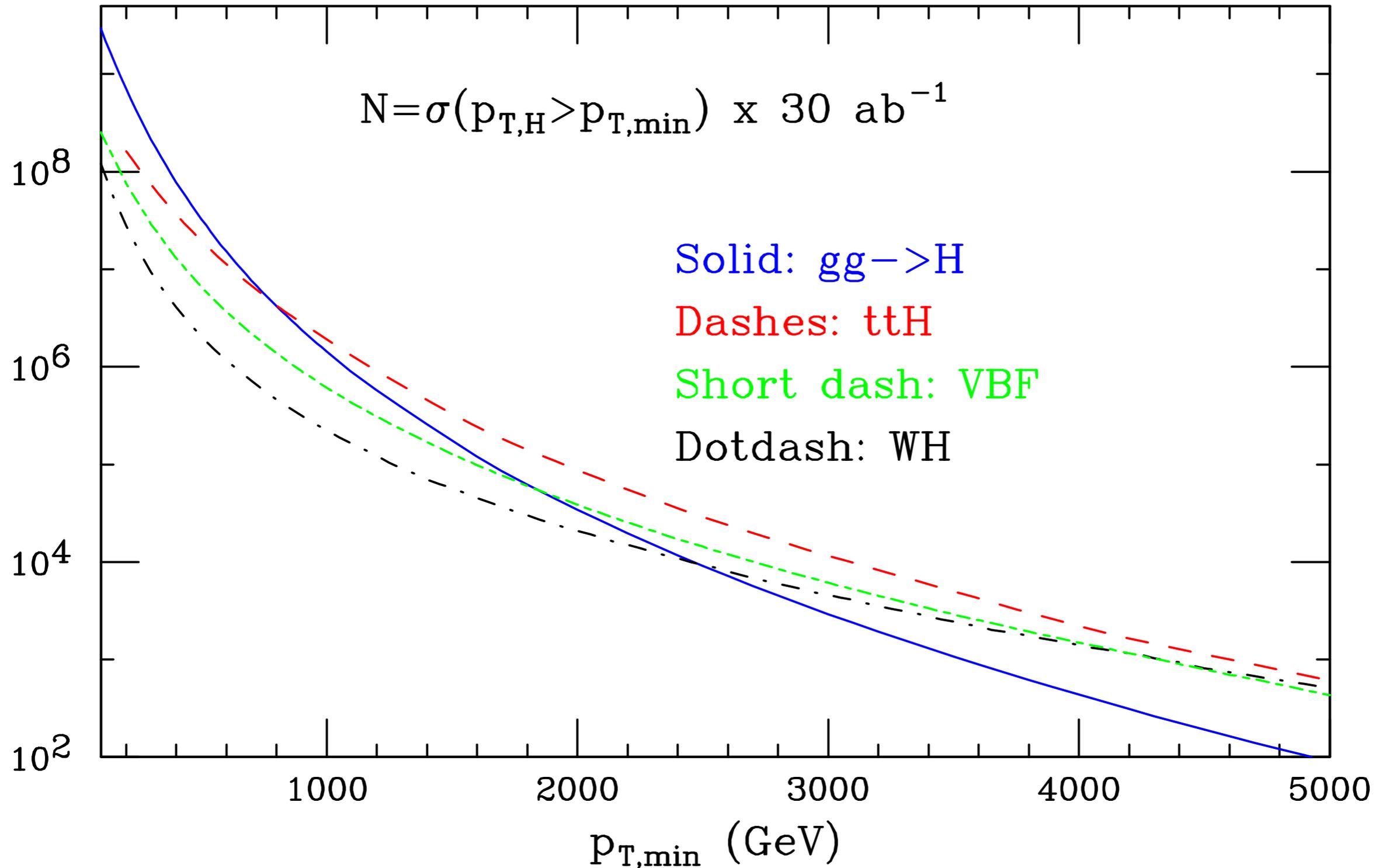
- the extraordinary statistics that, complemented by the per-mille  $e^+e^-$  measurement of eg  $BR(H \rightarrow ZZ^*)$ , allows
  - the sub-% measurement of rarer decay modes
  - the  $\approx 5\%$  measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg  $pt(H)$  up to several 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
$N_{100}$	$24 \times 10^9$	$2.1 \times 10^9$	$4.6 \times 10^8$	$3.3 \times 10^8$	$9.6 \times 10^8$	$3.6 \times 10^7$
$N_{100}/N_{14}$	180	170	100	110	530	390

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

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

# H at large $p_T$



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

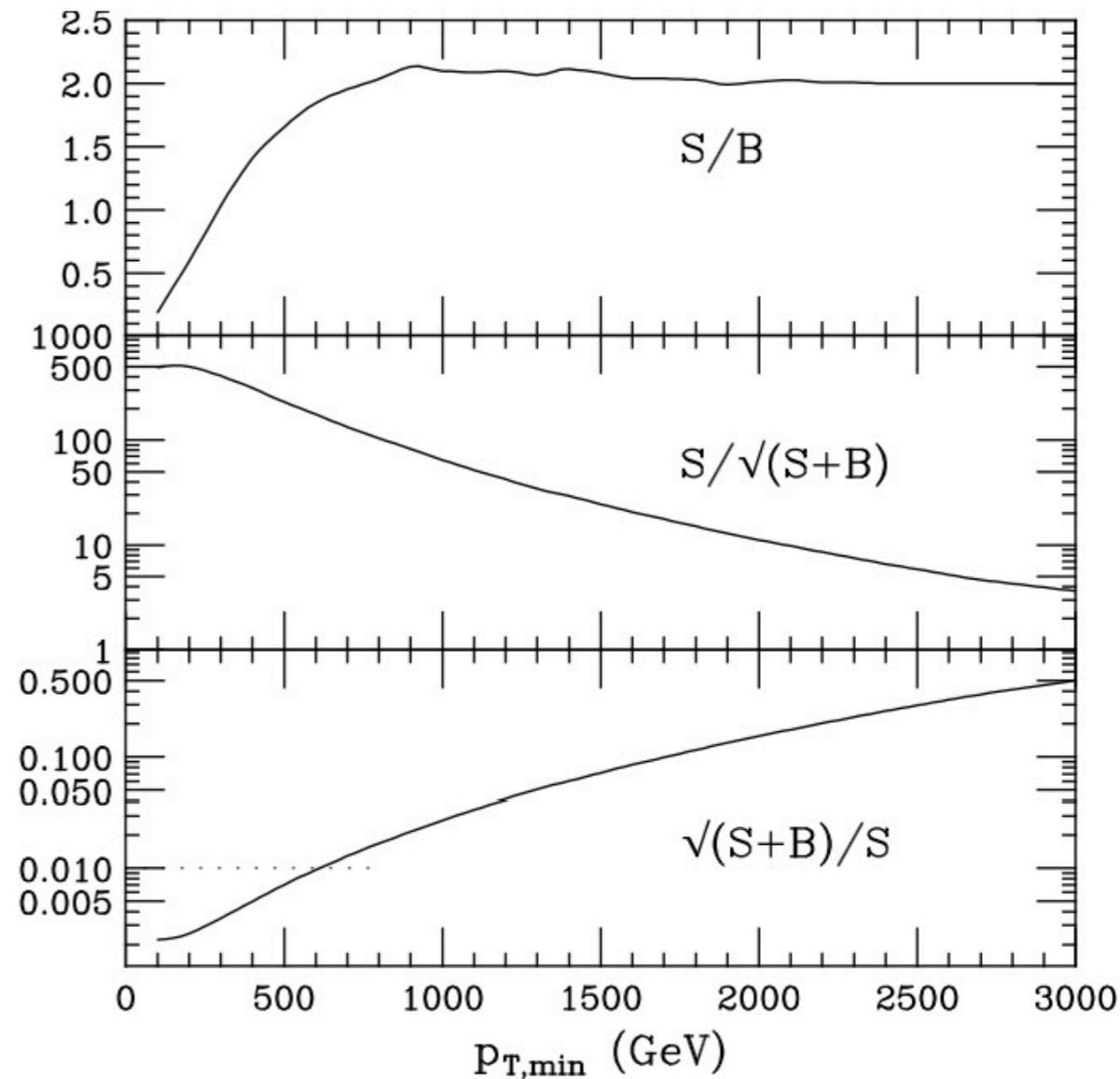
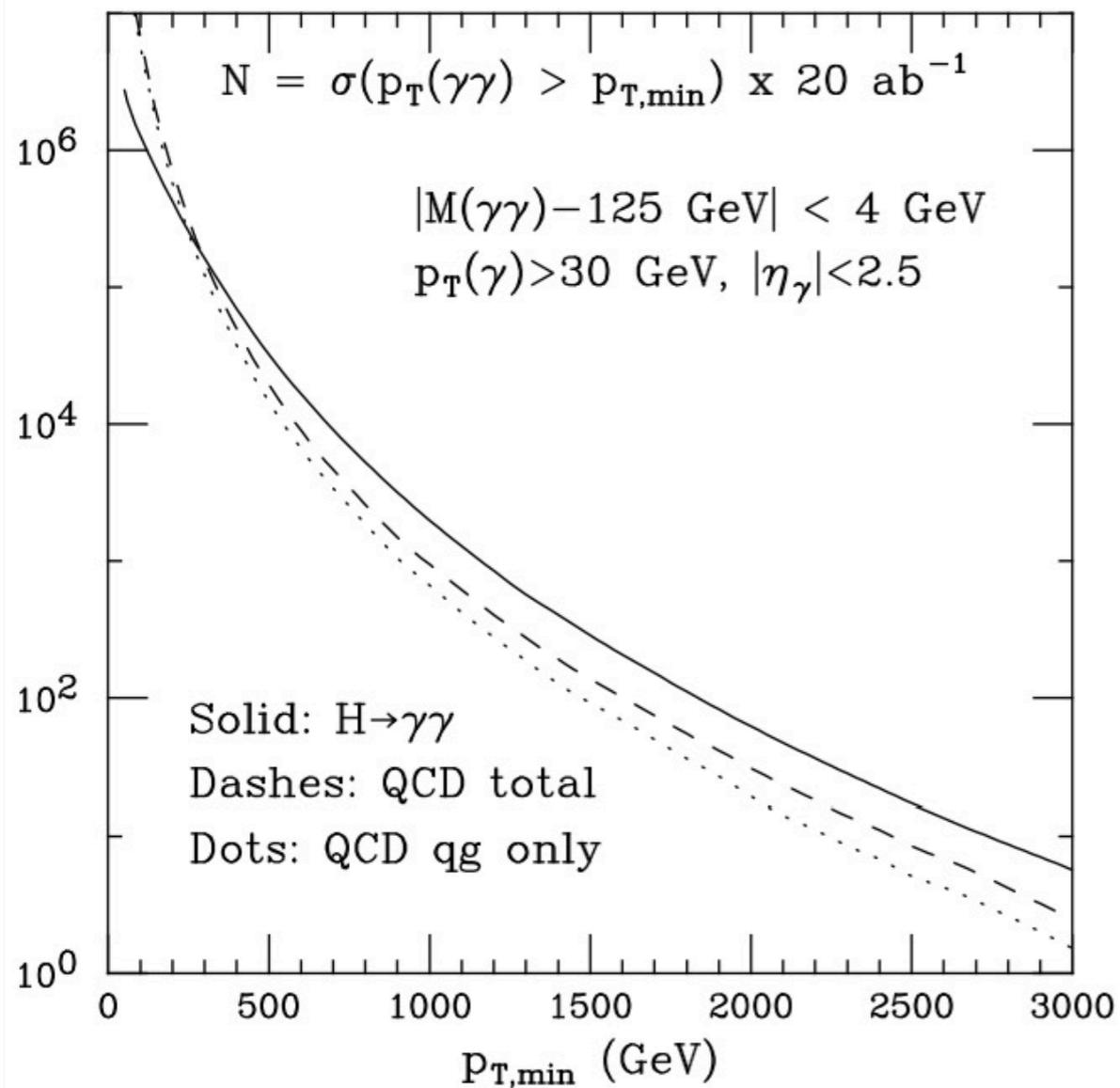
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  - stat uncertainty  $\sim$  few  $\times 10^{-3}$  for  $H \rightarrow 4l, \gamma\gamma, \dots$
  - improved S/B, realistic trigger thresholds, reduced pile-up effects ?
  - ➡ current det sim and HL-LHC extrapolations more robust
  - ➡ focus of FCC CDR Higgs studies so far
  - ➡ sweet-spot for precision measurements at the sub-% level

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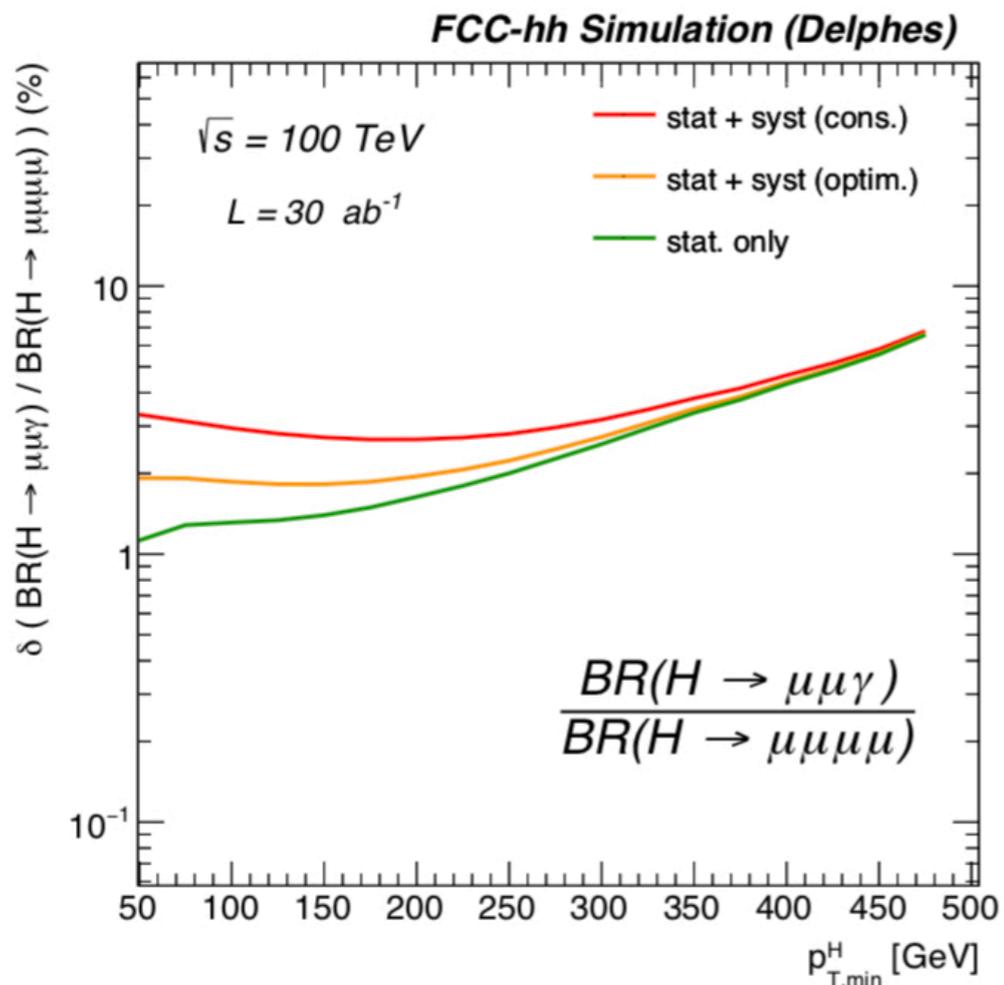
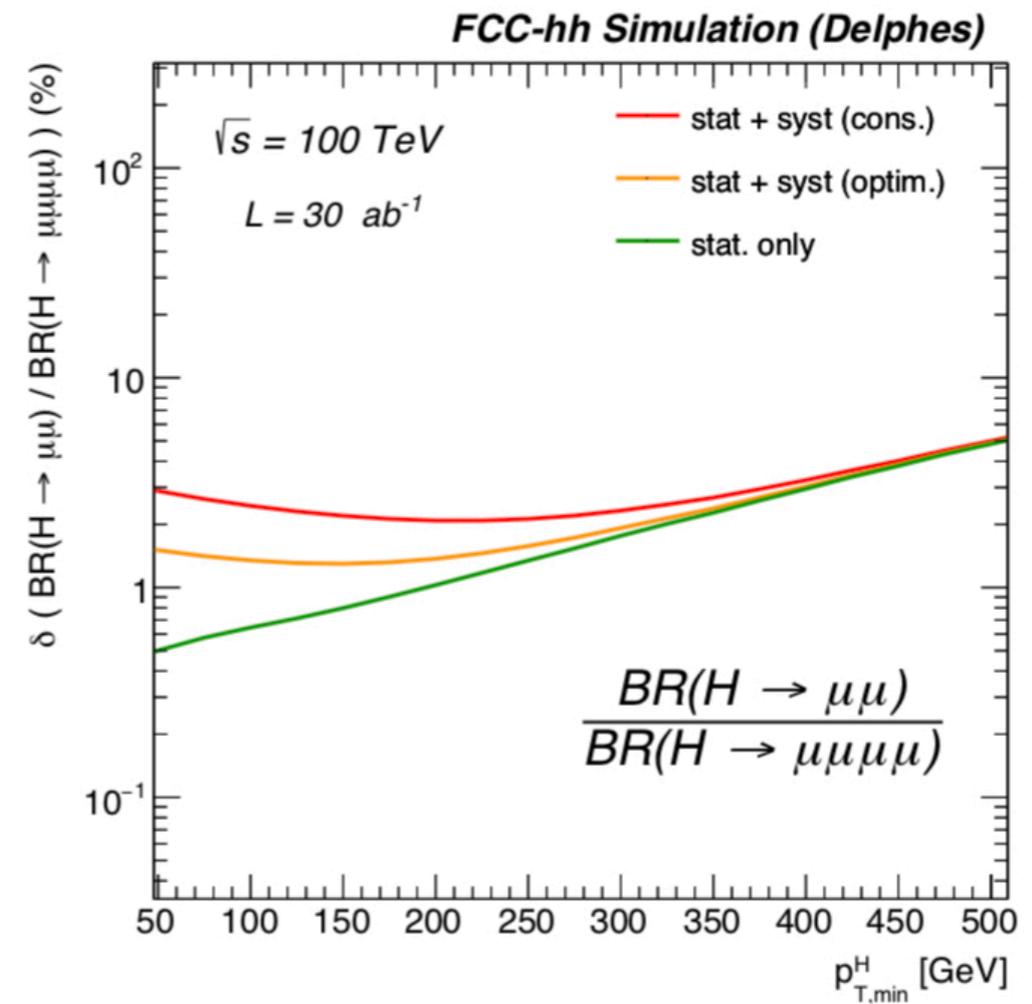
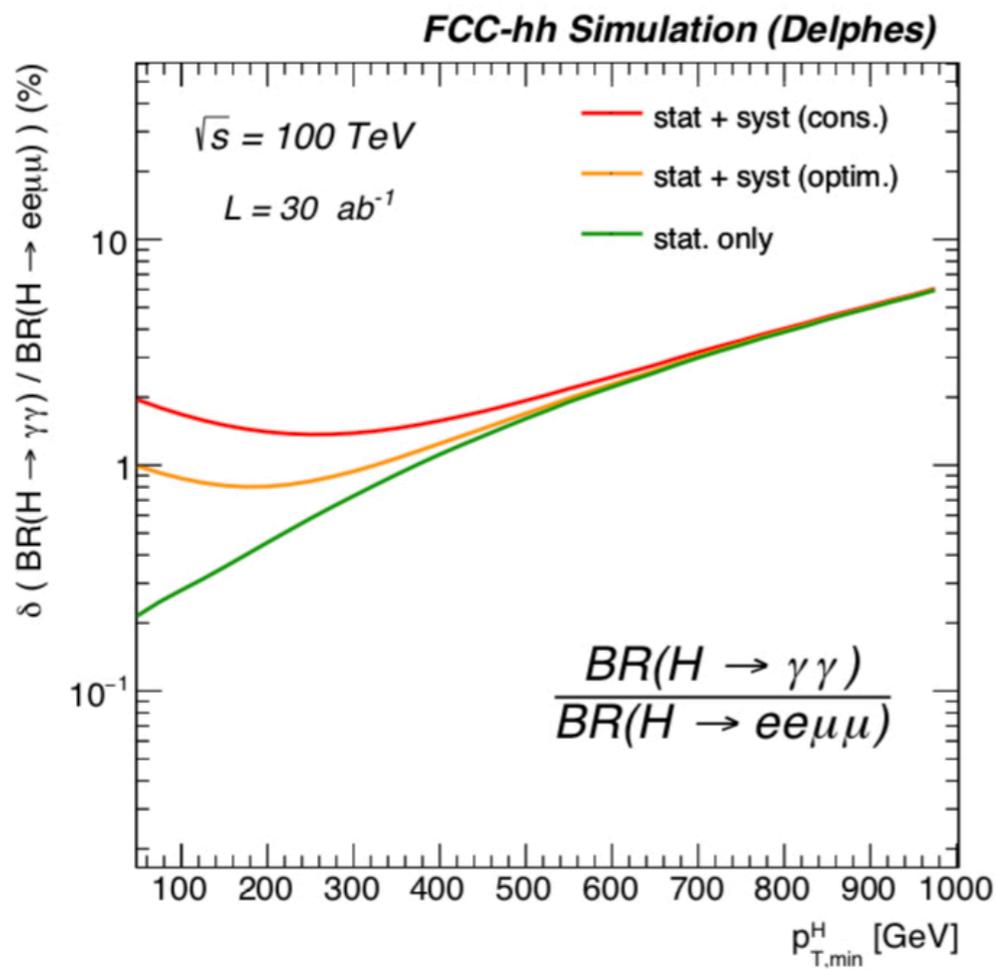
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- $p_T \gtrsim \text{TeV}$  :
  - stat uncertainty  $O(10\%)$  up to 1.5 TeV (3 TeV) for  $H \rightarrow 4l, \gamma\gamma$  ( $H \rightarrow bb$ )
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production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

# $gg \rightarrow H \rightarrow \gamma\gamma$ at large $p_T$



- At LHC,  $S/B$  in the  $H \rightarrow \gamma\gamma$  channel is  $O(\text{few } \%)$
- At FCC, for  $p_T(H) > 300 \text{ GeV}$ ,  $S/B \sim 1$
- Potentially accurate probe of the  $H$   $p_T$  spectrum up to large  $p_T$

$p_{T,\min}$ (GeV)	$\delta_{\text{stat}}$
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

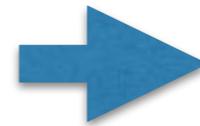
# Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	<b>1.3</b>	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	<b>0.17</b>	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	<b>0.43</b>	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	<b>0.61</b>	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	<b>1.21</b>	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	<b>1.01</b>	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	<b>0.74</b>	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	<b>0.65 (*)</b>
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	<b>0.4 (*)</b>
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	<b>0.95 (**)</b>
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	<b>0.9 (*)</b>
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	<b>5</b>
$BR_{\text{exo}} (95\%CL)$	$BR_{\text{inv}} < 2.5\%$	<b>&lt; 1%</b>	<b><math>BR_{\text{inv}} &lt; 0.025\%</math></b>

**NB**

$BR(H \rightarrow Z\gamma, \gamma\gamma) \sim O(10^{-3}) \Rightarrow O(10^7)$  evts for  $\Delta_{\text{stat}} \sim \%$

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



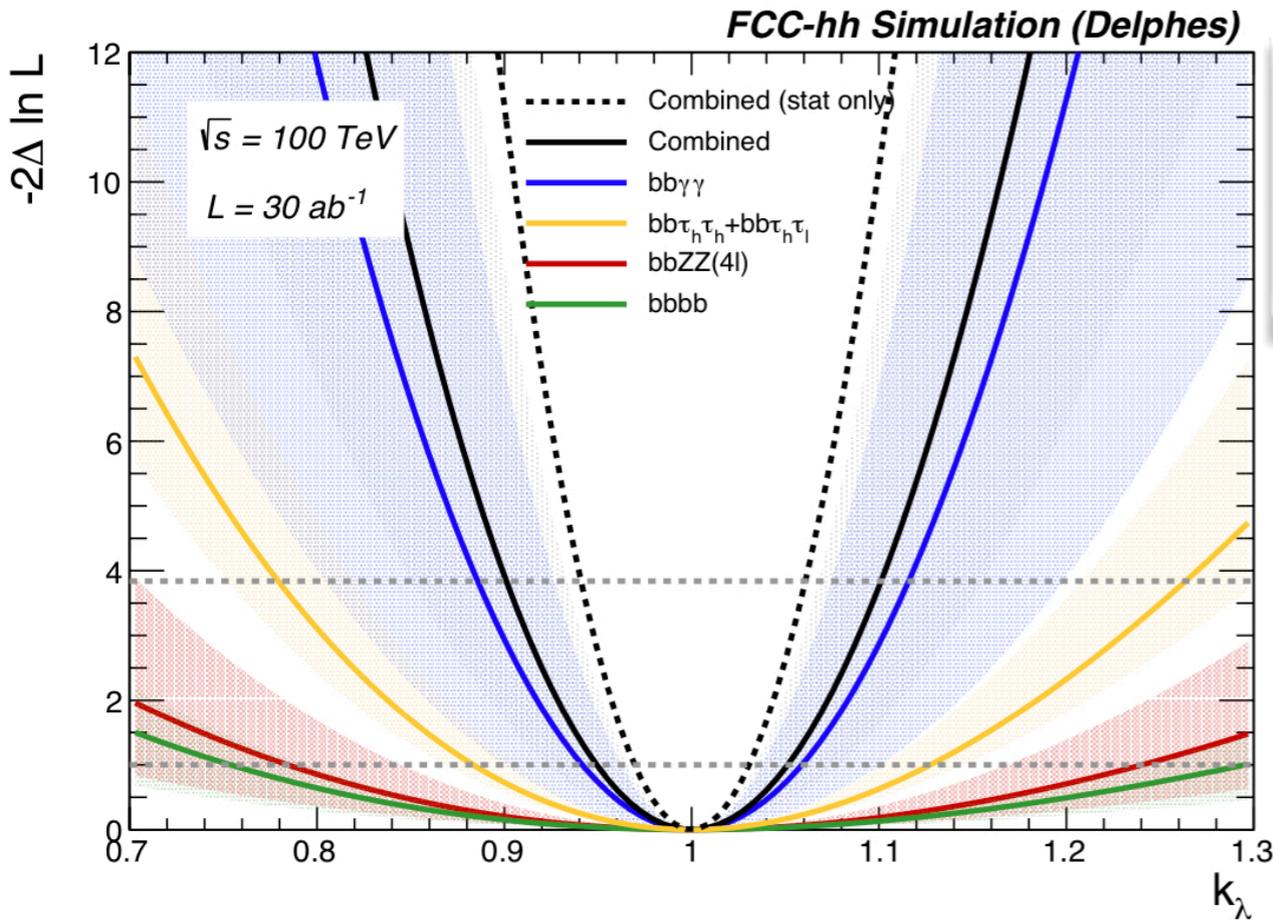
pp collider is essential to beat the % target, since no proposed ee collider can produce more than  $O(10^6)$  H's

\* From BR ratios wrt  $B(H \rightarrow ZZ^*)$  @ FCC-ee

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

## **Further work to do on decay-properties measurements:**

- Apply to FCC-hh the various techniques proposed for the measurement of the total H width at the LHC: what is the precision reach?
- Consider decays to other large-BR channels,  $bb$ ,  $WW$ ,  $\tau\tau$ :
  - unlikely to improve FCC-ee measurements, but ...
  - ... can use to extend use of H as a tool (eg to reach larger  $p_{T^H}$  regions)
- Probes of  $Hcc$ :  $H \rightarrow cc$  in boosted jets, exclusive  $H \rightarrow J/\psi \gamma$  decays, ...
- Couplings to lighter quarks (exclusive decays)
- Rare/forbidden decays ( $e\mu$ ,  $\mu\tau$ ,  $e\tau$ , ..., multibodies, ...)



**Figure 13.** Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier  $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$  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

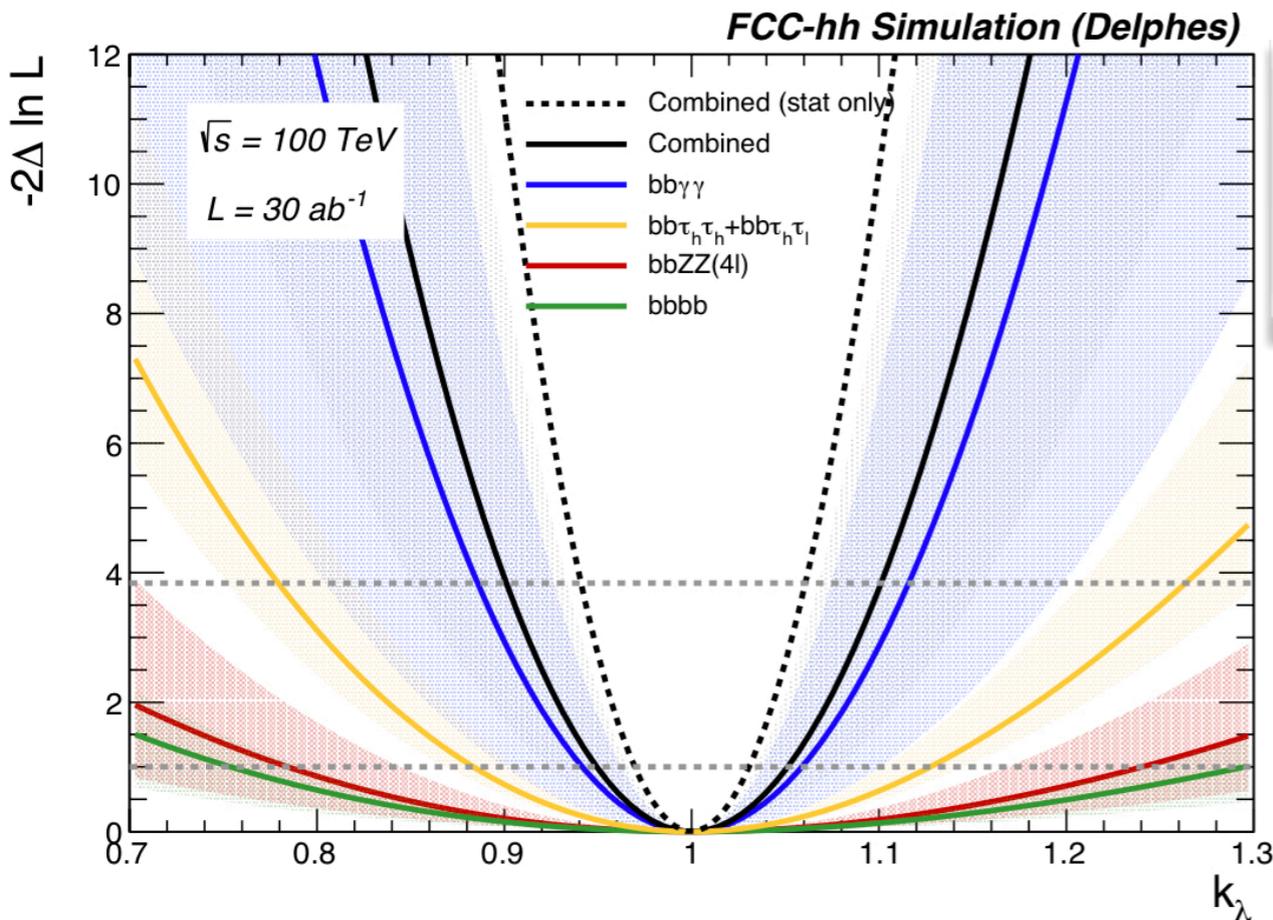
		@68% CL	scenario I	scenario II	scenario III
$\delta_\mu$	stat only		2.2	2.8	3.7
	stat + syst		2.4	3.5	5.1
$\delta_{\kappa_\lambda}$	stat only		3.0	4.1	5.6
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**Table 7.** Combined expected precision at 68% CL on the di-Higgs production cross- and Higgs self coupling using all channels at the FCC-hh with  $\mathcal{L}_{int} = 30 \text{ ab}^{-1}$ . 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)

# The Higgs self-coupling at FCC-hh

<https://arxiv.org/abs/2004.03505>

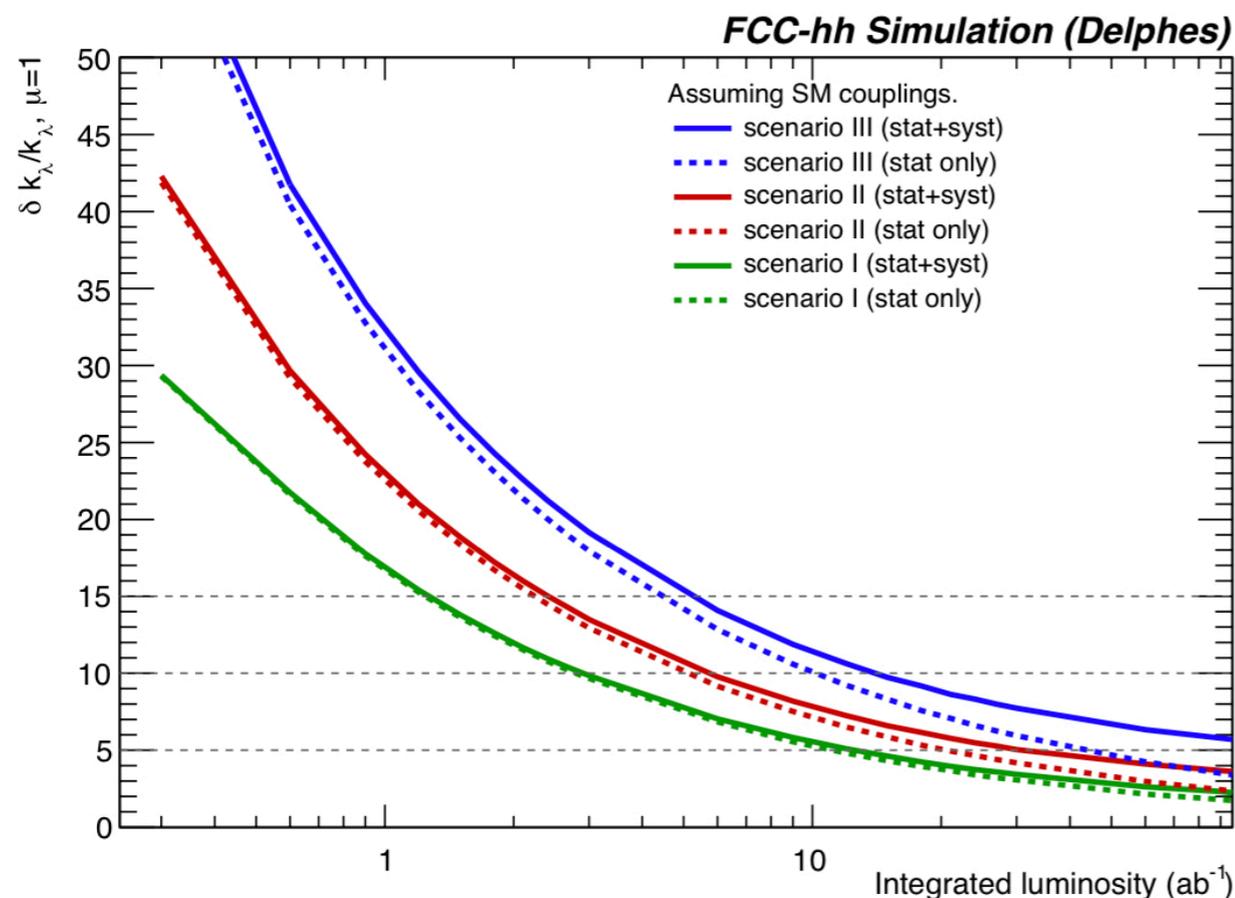


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Expected precision on the Higgs self-coupling as a function of the integrated luminosity.

**3-5  $\text{ab}^{-1}$  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**

**=> compatible with the timescale for a similar precision measurement by CLIC @ 3 TeV**

- Large literature on Higgs probes of the nature of the EW phase transition, and impact of self-coupling measurement
- **TO DO:** *more systematic studies needed to explore sensitivity to BSM deviations. Eg*
  - *$m_{HH}$  shape fits in presence of multiple EFT ops (see eg <https://arxiv.org/abs/1502.00539>, <https://arxiv.org/abs/1908.08923> )*
  - *global EFT fits including single-H and EW observables*

# Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \dots$$

$$O = | \langle f | L | i \rangle |^2 = O_{SM} [1 + O(\mu^2 / \Lambda^2) + \dots]$$

For H decays, or inclusive production,  $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2 \Rightarrow \text{precision probes large } \Lambda$$

$$\text{e.g. } \delta O = 1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV}$$

For H production off-shell or with large momentum transfer  $Q$ ,  $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2 \Rightarrow \text{kinematic reach probes}$$

large  $\Lambda$  even if precision is low

$$\text{e.g. } \delta O = 15\% \text{ at } Q = 1 \text{ TeV} \Rightarrow \Lambda \sim 2.5 \text{ TeV}$$

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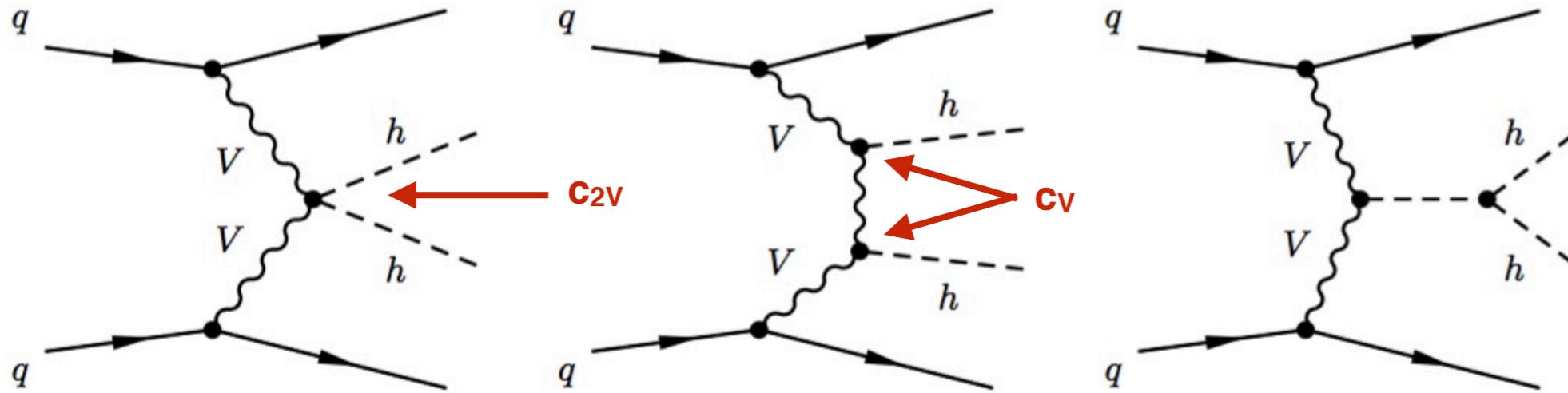
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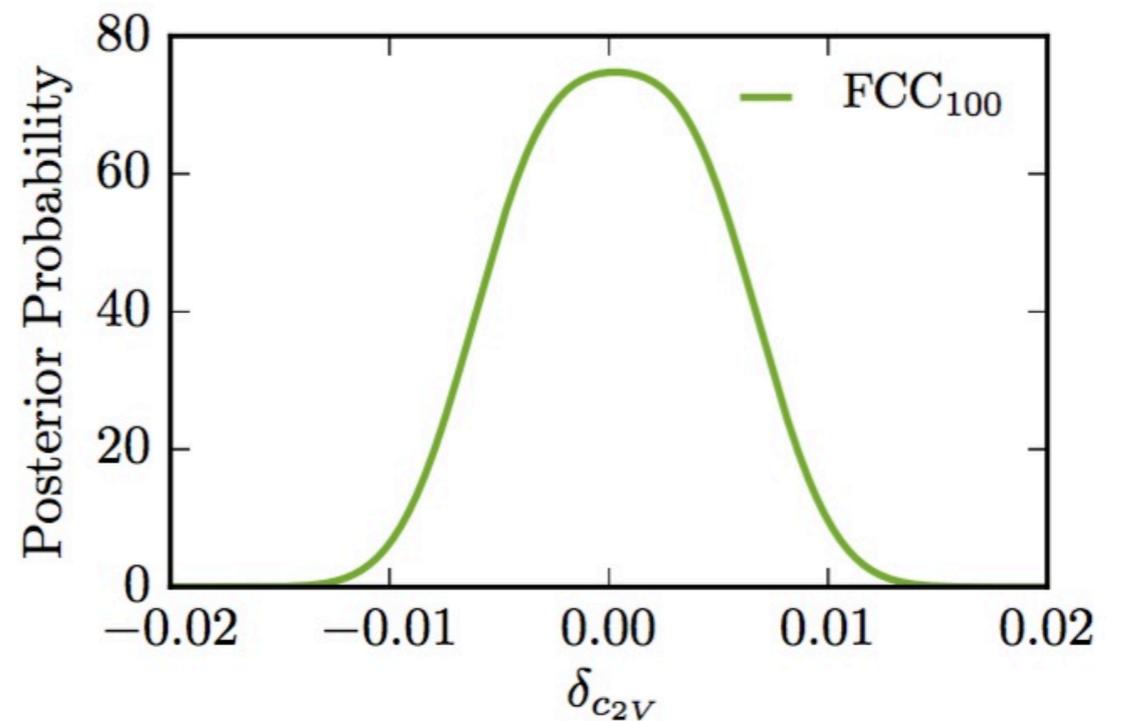
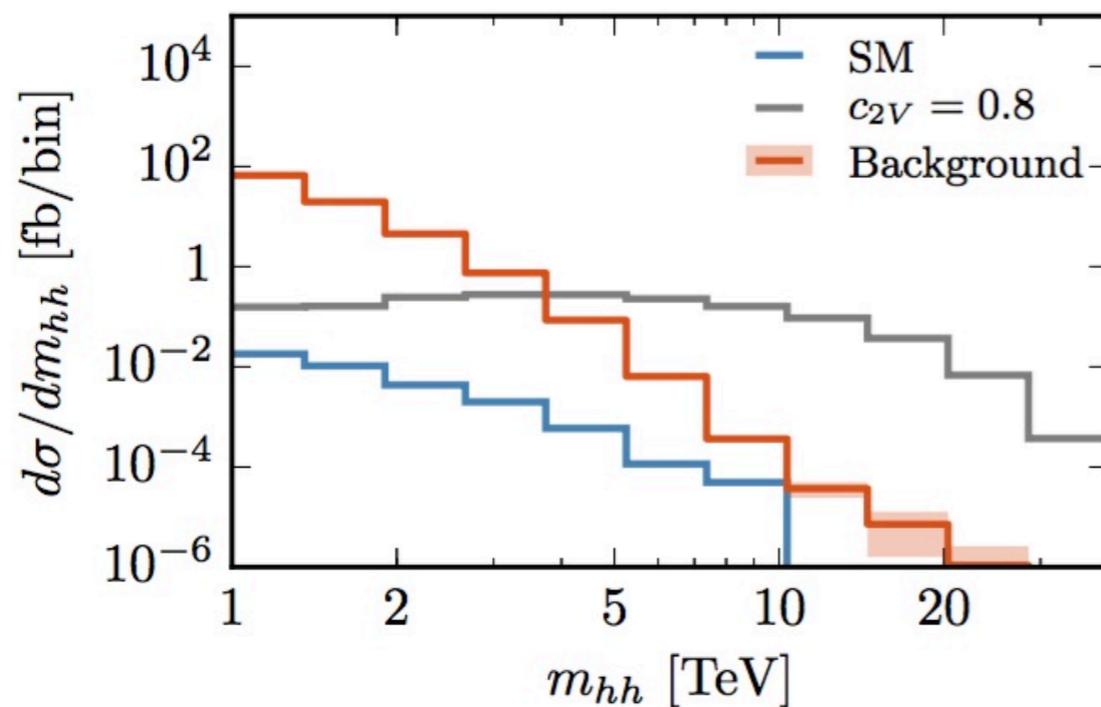
**Precision and extensive kinematic reach provide unique complementarity and redundancy, crucial to interpret possible SM deviations manifest in either of these observables**

# Example: high mass $VV \rightarrow HH$

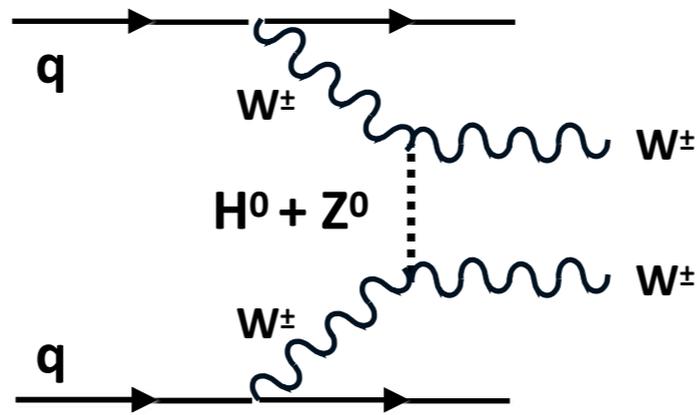


$$A(V_L V_L \rightarrow HH) \sim \frac{\hat{s}}{v^2} (c_{2V} - c_V^2) \cdot \text{where} \quad \begin{cases} c_V = g_{HVV} / g_{HVV}^{SM} \\ c_{2V} = g_{HHVV} / g_{HHVV}^{SM} \end{cases} \Rightarrow (c_{2V} - c_V^2)_{SM} = 0$$

$c_{2V} \neq c_V^2$  probes custodial symmetry breaking, extended Higgs sectors, ...

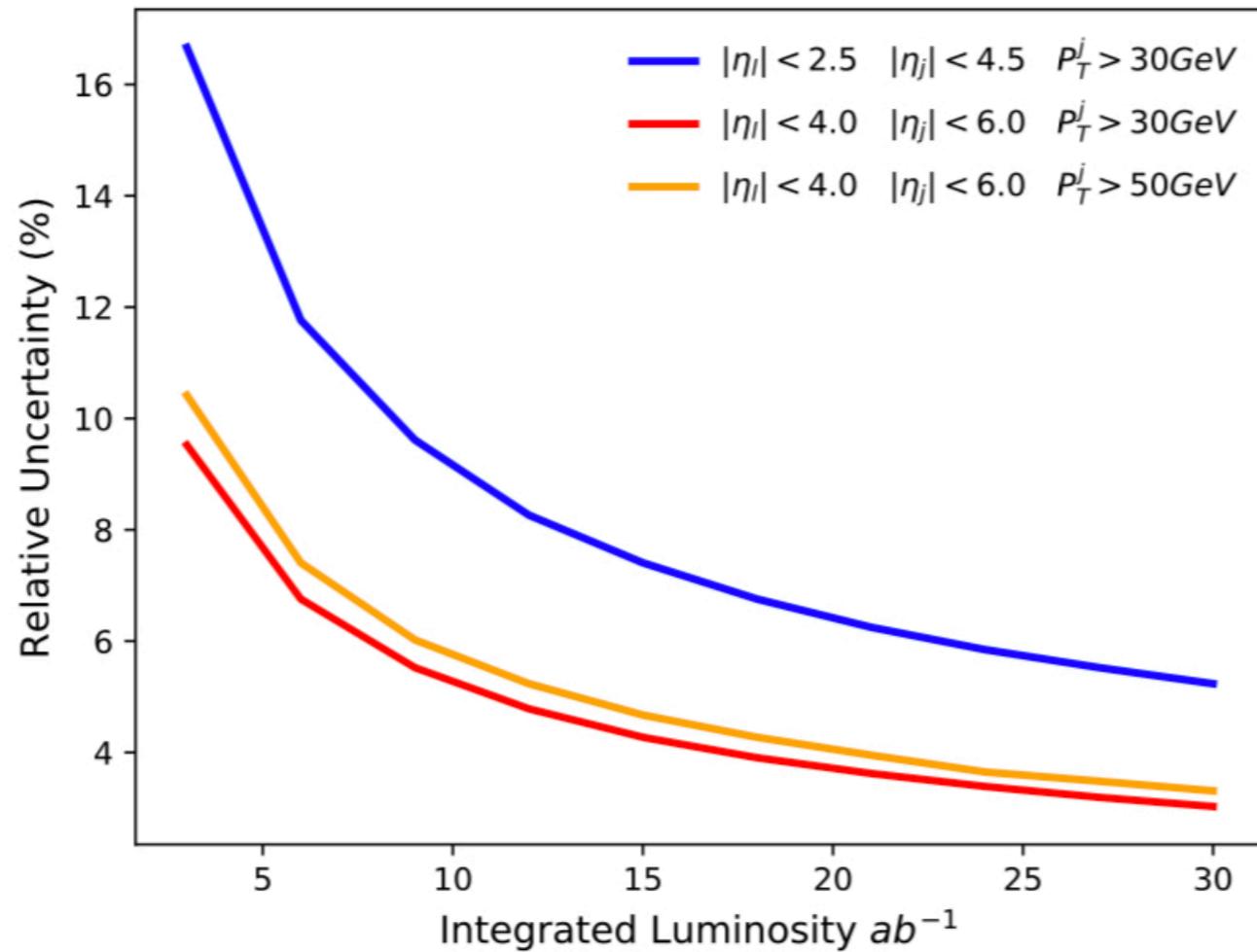


# $W_L W_L$ scattering



large  $m_{W}$

VBS  $W_L W_L$  Same Sign Cross Uncertainty



FCC-hh Simulation (Delphes)

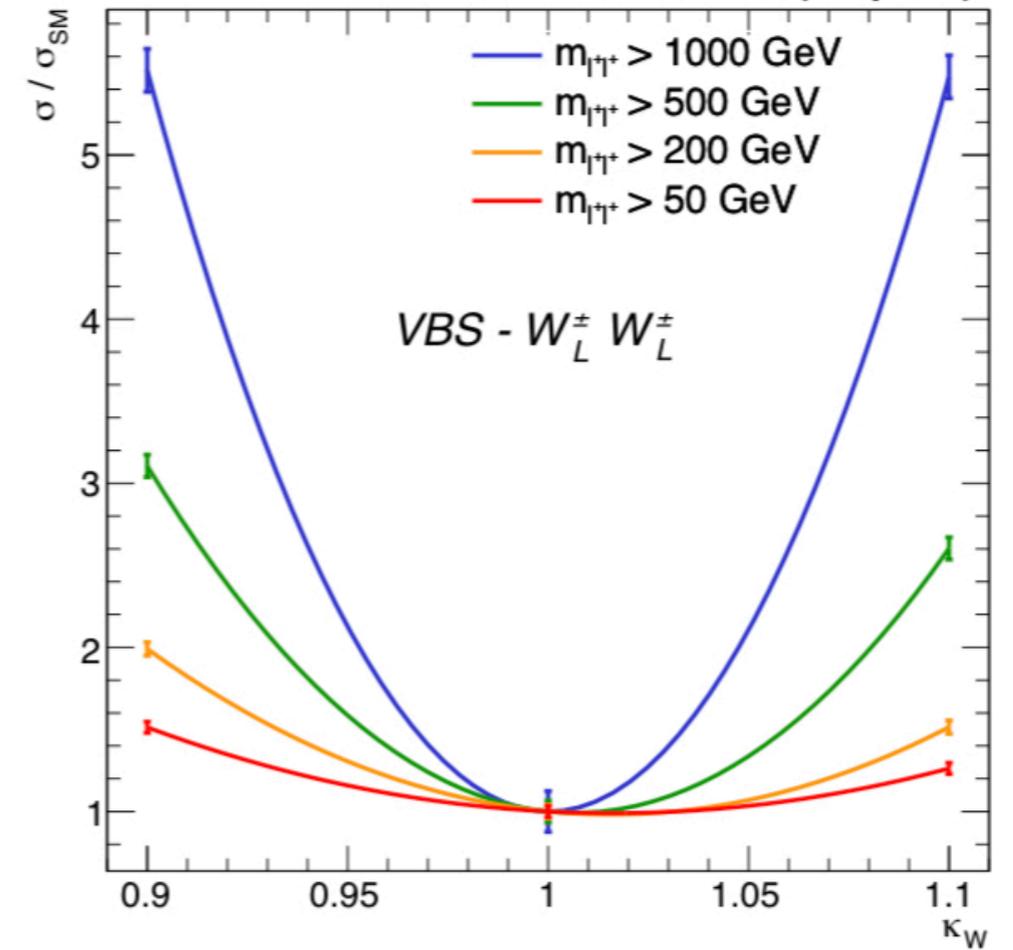


Table 4.5: Constraints on the HWW coupling modifier  $\kappa_W$  at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the  $W_L W_L \rightarrow HH$  process.

$m_{l+l^+}$ cut	$> 50$ GeV	$> 200$ GeV	$> 500$ GeV	$> 1000$ GeV
$\kappa_W \in$	[0.98, 1.05]	[0.99, 1.04]	[0.99, 1.03]	[0.98, 1.02]

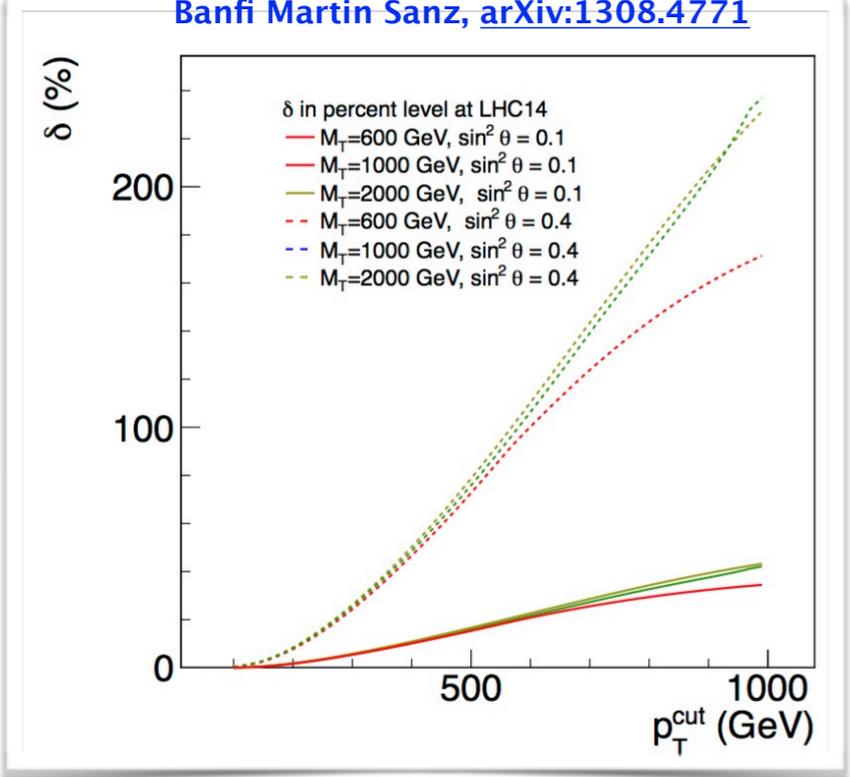
$$\kappa_W = \frac{g_{HWW}}{g_{HWW}^{SM}}$$

# to do's

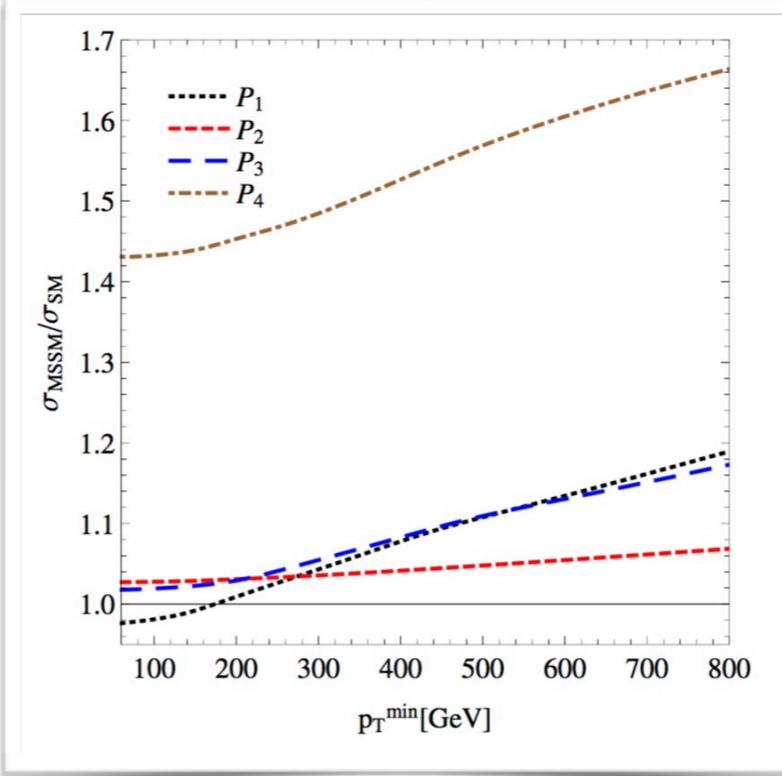
=> Re-iterate at 100 TeV the many studies done for LHC about BSM constraints from high-pT Higgs production. Eg

## gg → Hg

Banfi Martin Sanz, arXiv:1308.4771



top partners T in the loop

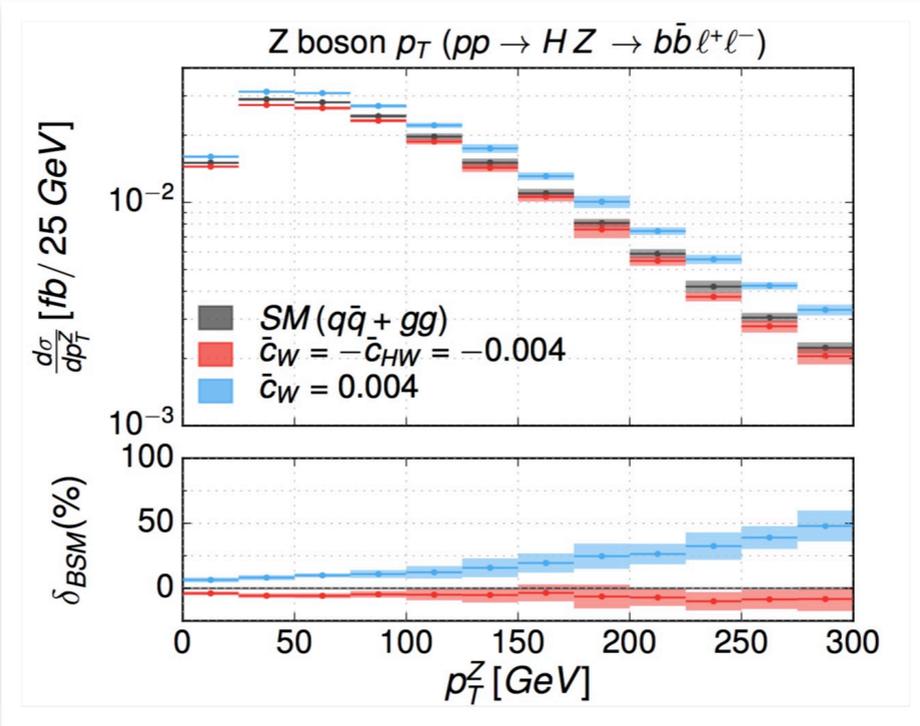
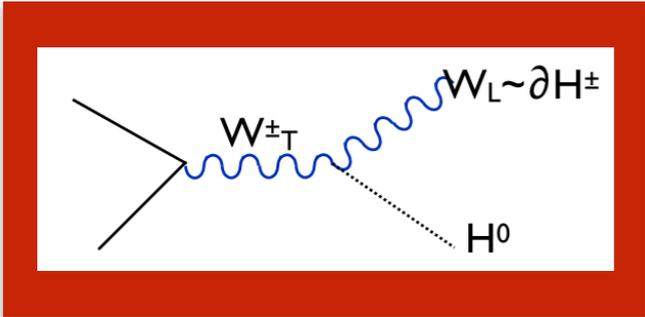


Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	$A_t$ [GeV]	$\Delta_t$
$P_1$	171	440	490	0.0026
$P_2$	192	1224	1220	0.013
$P_3$	226	484	532	0.015
$P_4$	226	484	0	0.18

### top squarks in the loop

Grojean, Salvioni, Schlafer, Weiler  
arXiv:1312.3317

(See also  
Azatov and Paul arXiv:1309.5273v3)



Mimasu, Sanz, Williams,  
arXiv:1512.02572v

See also  
Biekötter, Knochel, Krämer, Liu, Riva,  
arXiv:1406.7320

# more to do's

## **Quantify complementarity and synergy** among

- precision measurements from FCC-ee (H and EW properties)
- Higgs/EW measurements at high- $Q^2$  at 100 TeV
- HH production
- direct BSM searches

In particular, consider concrete BSM scenarios, play the “inverse problem” game using all available inputs, etc...

# (I) guaranteed deliverables: EW observables

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

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

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

# EW parameters @ FCC-ee

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

# Precision W physics with $pp \rightarrow tt[\rightarrow Wb]$

## MLM @ SEARCH2016

A concrete application:  
testing lepton universality in W decays

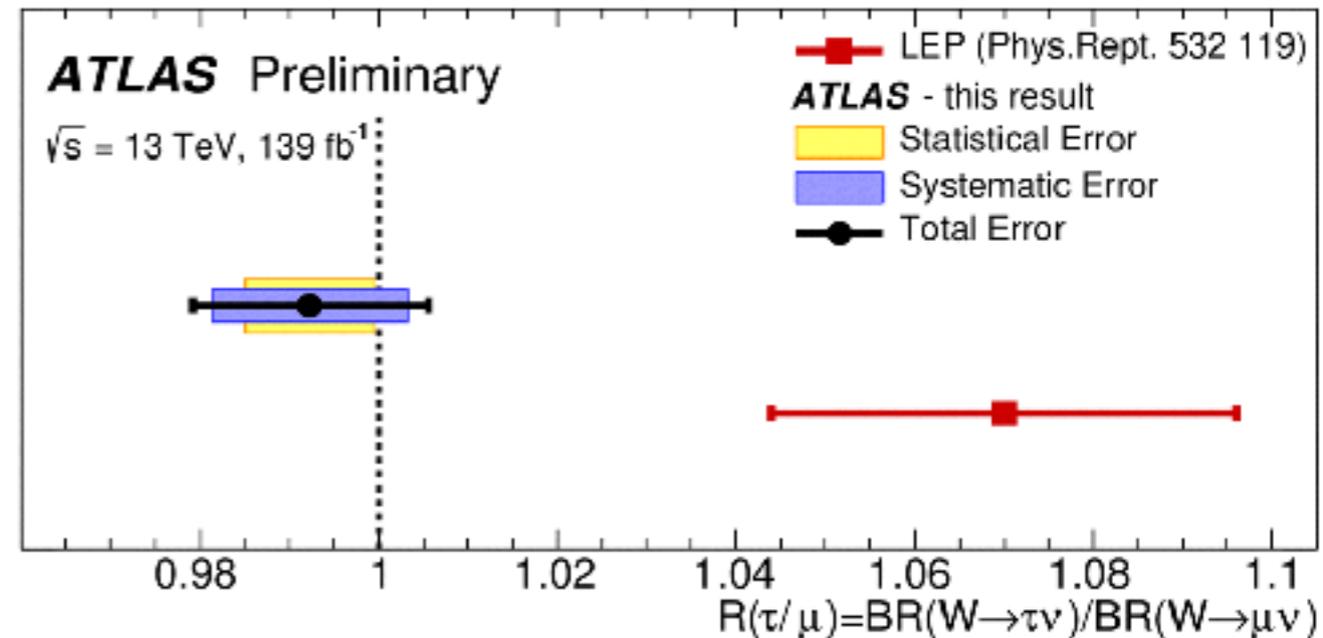
PDG entries dominated by LEP2 data

$W^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$P$ (MeV/c)
$\ell^+\nu$	[b] $(10.86 \pm 0.09) \%$		-
$e^+\nu$	$(10.71 \pm 0.16) \%$		40192
$\mu^+\nu$	$(10.63 \pm 0.15) \%$		40192
$\tau^+\nu$	$(11.38 \pm 0.21) \%$		40173

$$BR(\tau) / BR(e/\mu) \sim 1.066 \pm 0.025 \Rightarrow \sim 2.5 \sigma$$

can the LHC clarify this issue with its eventual  
 $10^7$  leptonic W decays from the top?

## ATLAS 2020:



LEP:

$$BR(W \rightarrow \tau\nu) / BR(W \rightarrow \mu\nu) = 1.066 \pm 0.025$$

ATLAS:

$$BR(W \rightarrow \tau\nu) / BR(W \rightarrow \mu\nu) = 0.992 \pm 0.013$$

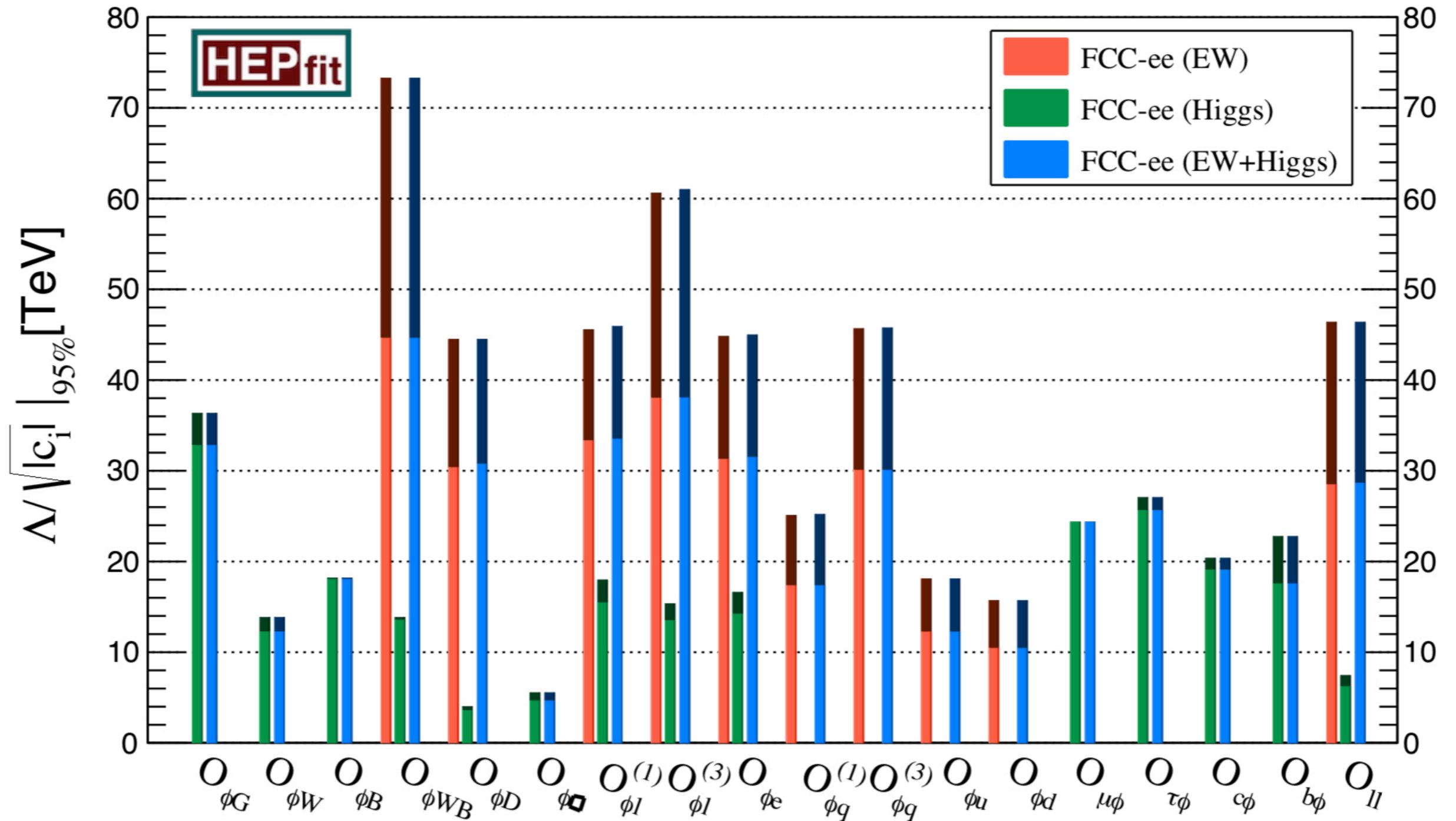
FCC-hh	t	$W(\leftarrow t)$	$\tau(\leftarrow W \leftarrow t)$
	$10^{12}$	$10^{12}$	$10^{11}$

*For the interpretation and impact of the combined EW and higgs precision measurements, in the context of EFT, see Christophe's talk*

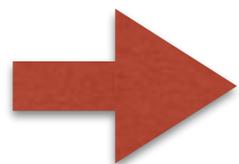
## **(2) Direct discovery reach at high mass: the power of 100 TeV**

*for the direct discovery reach at FCC-ee (eg light dark sectors, ...) see Christophe's talk*

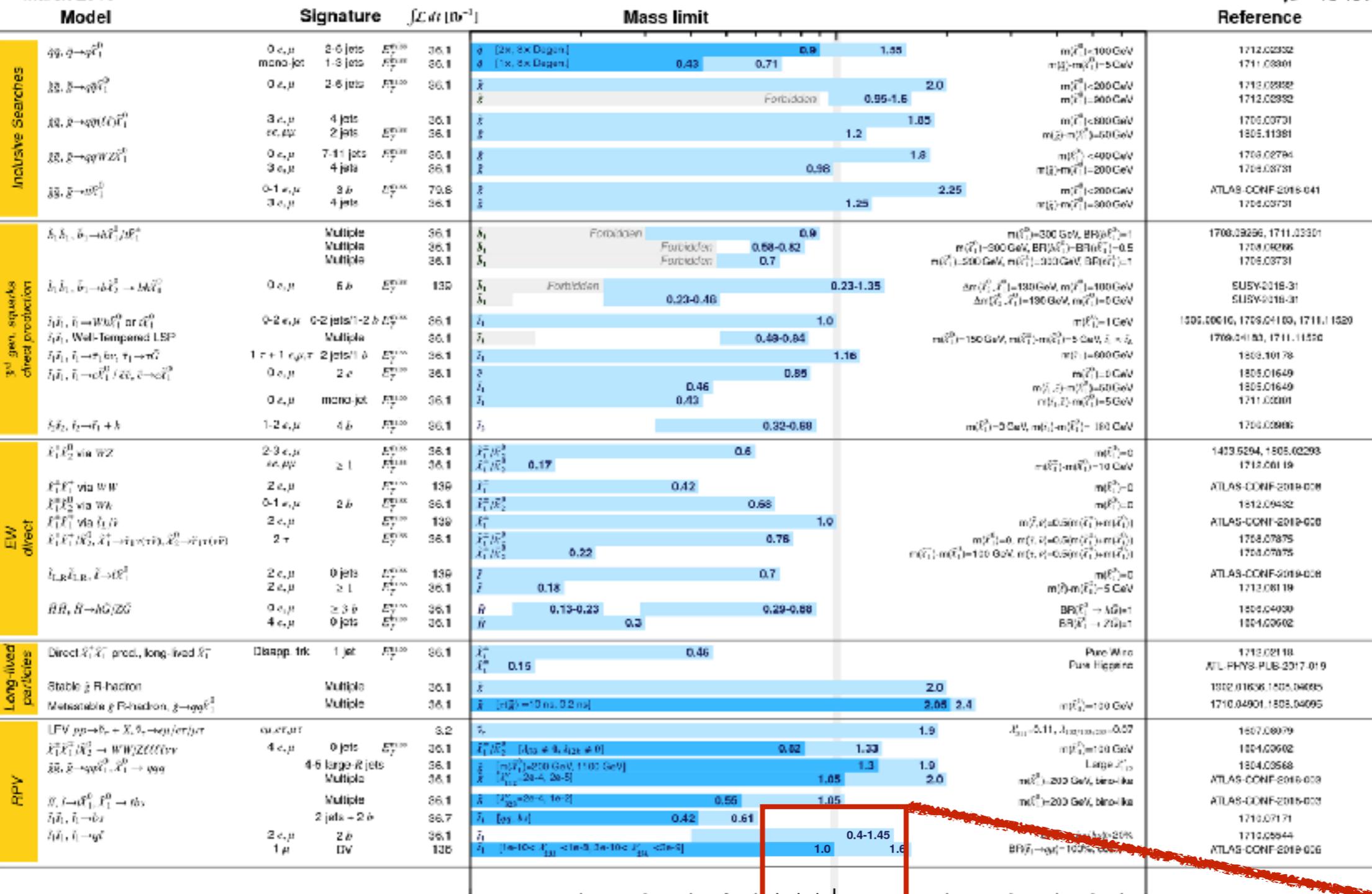
# Global EFT fits to EW and H observables at FCC-ee



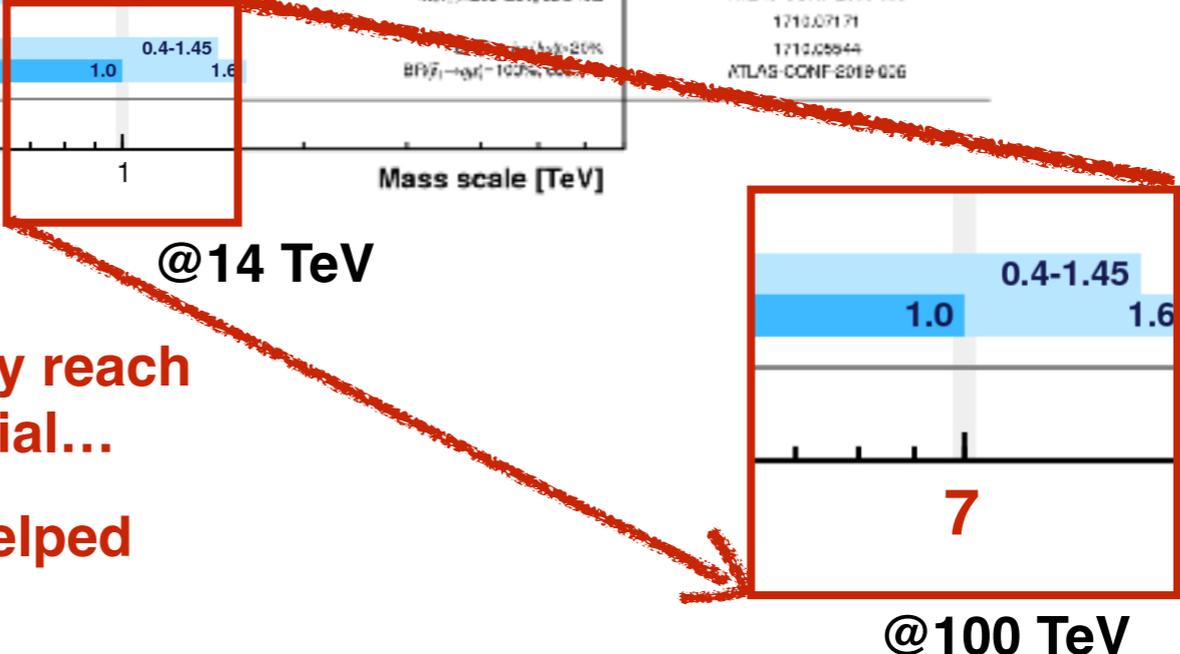
Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.



**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**



\*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.

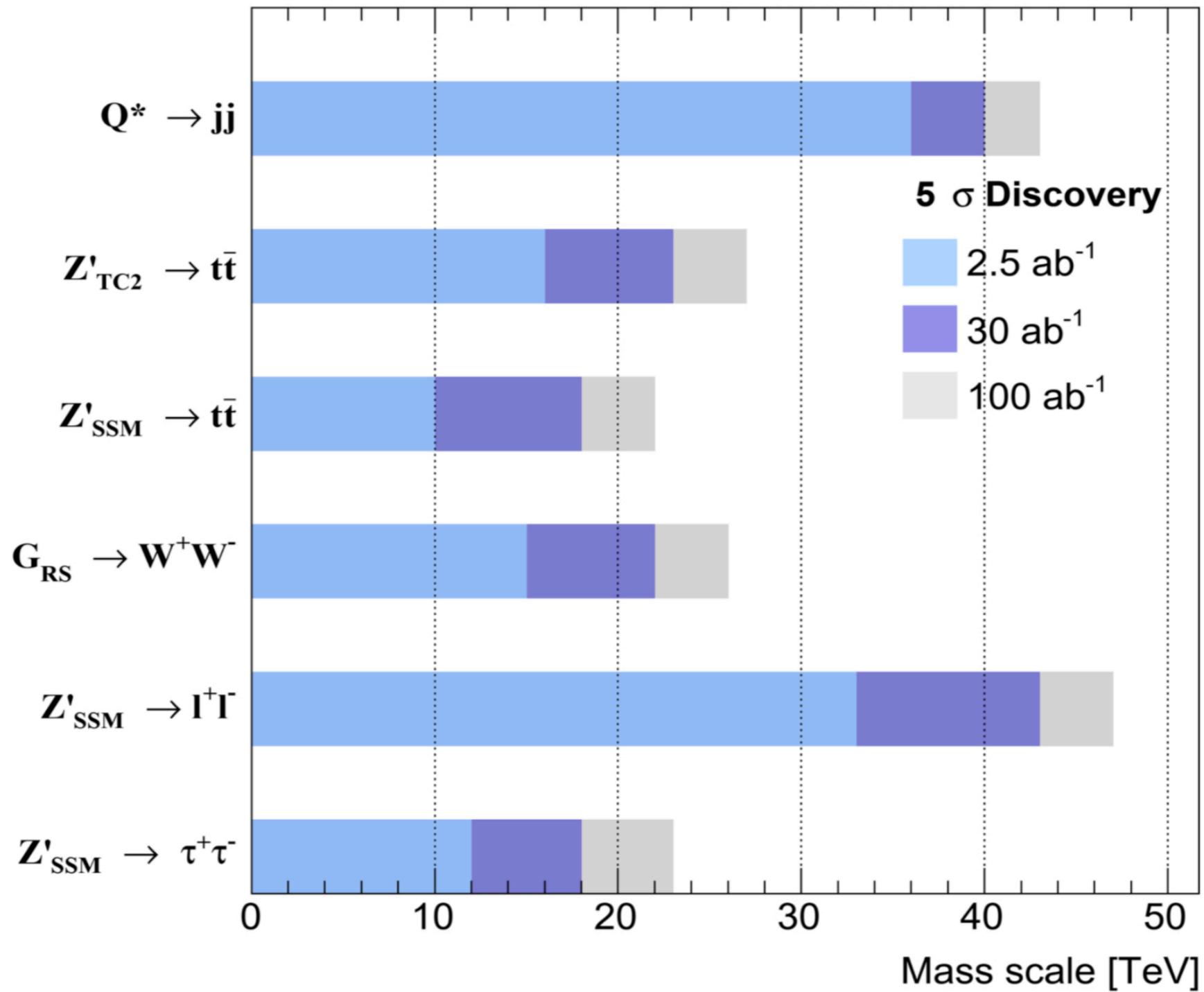


Good rule of thumb to estimate FCC discovery reach at high mass: scale up by ~6x the LHC potential...

Explicitly verified in many examples, which helped setting detector performance targets

# s-channel resonances

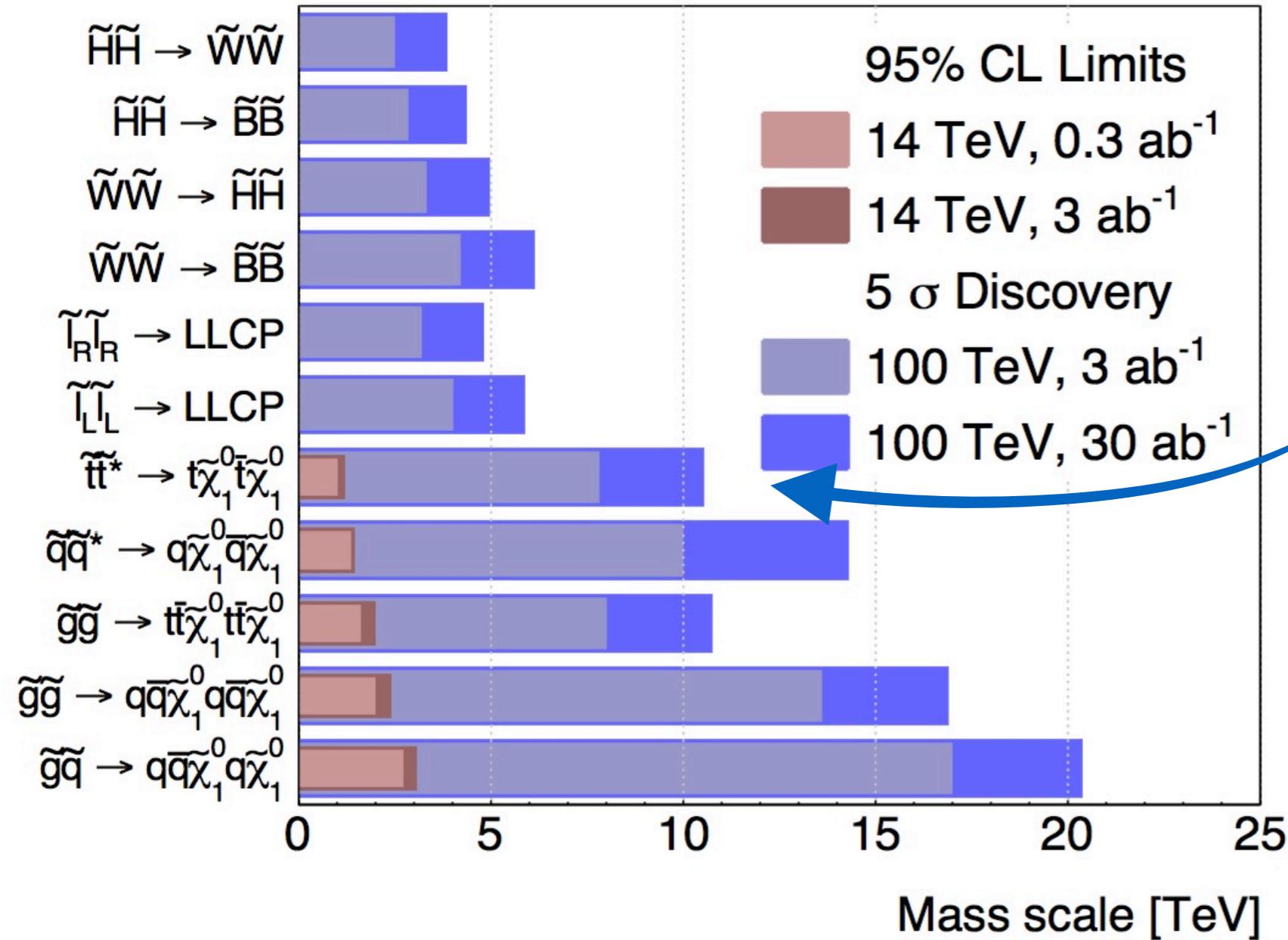
*FCC-hh Simulation (Delphes),  $\sqrt{s} = 100$  TeV*



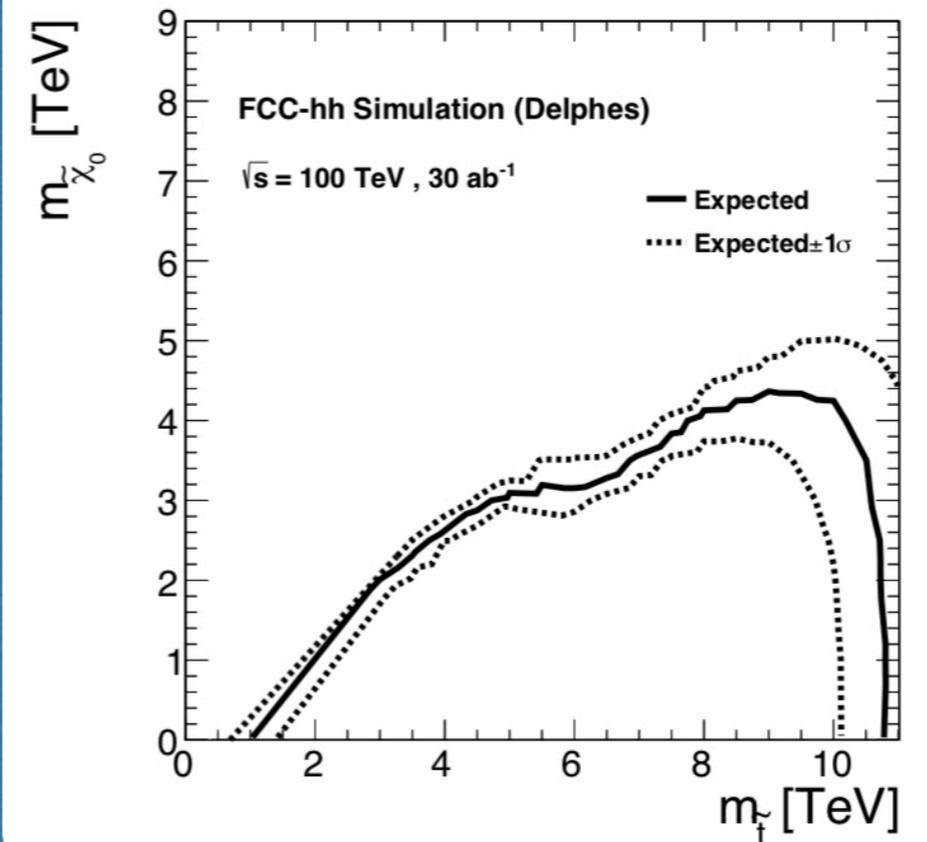
**FCC-hh reach  $\sim 6$  x HL-LHC reach**

# SUSY reach at 100 TeV

## Early phenomenology studies



## New detector performance studies



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

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

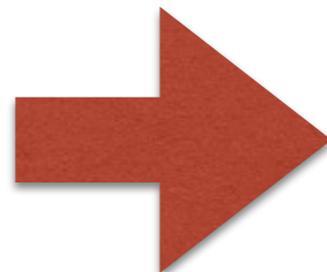
For a particle annihilating through processes which do not involve any larger mass scales:

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



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

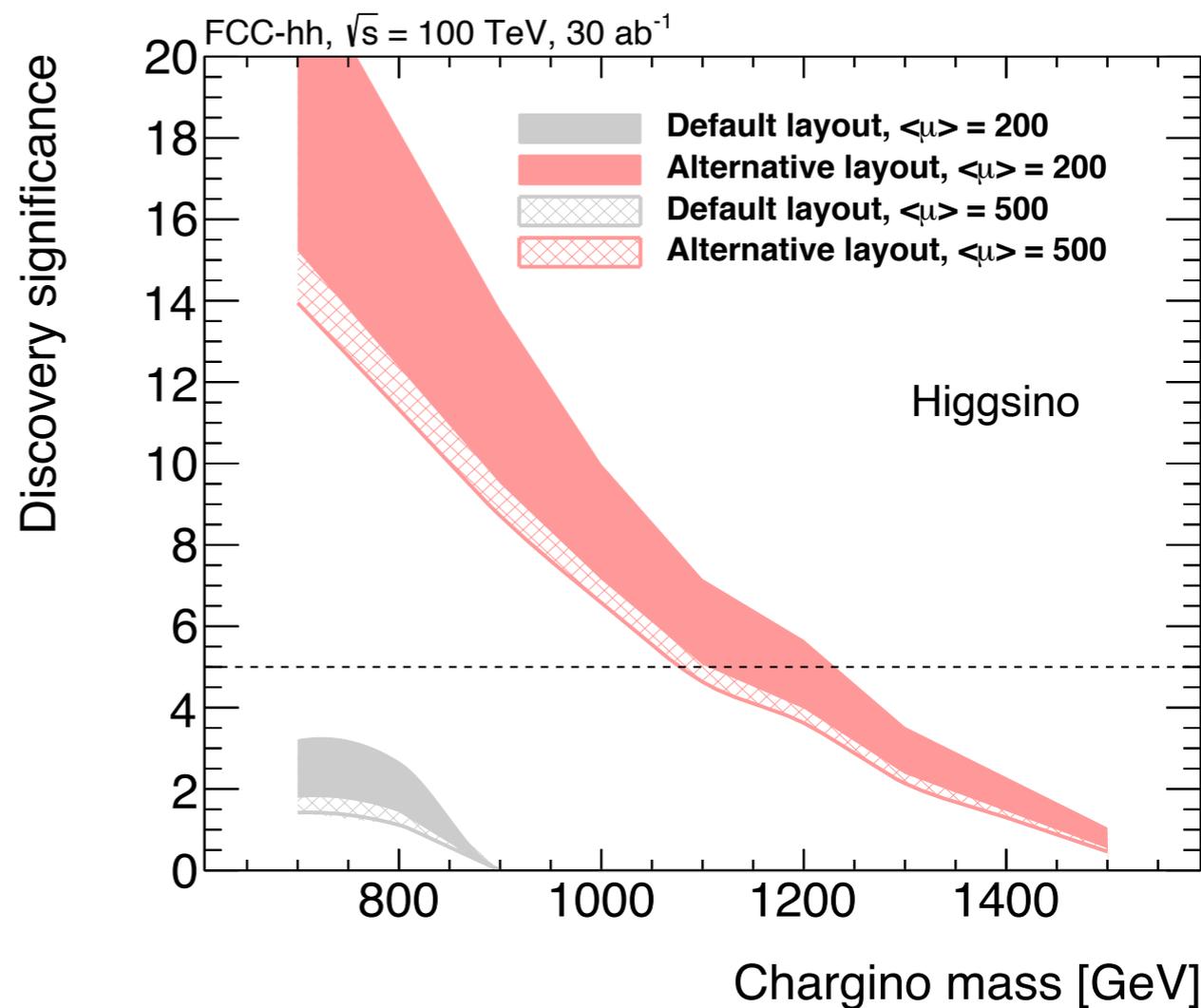
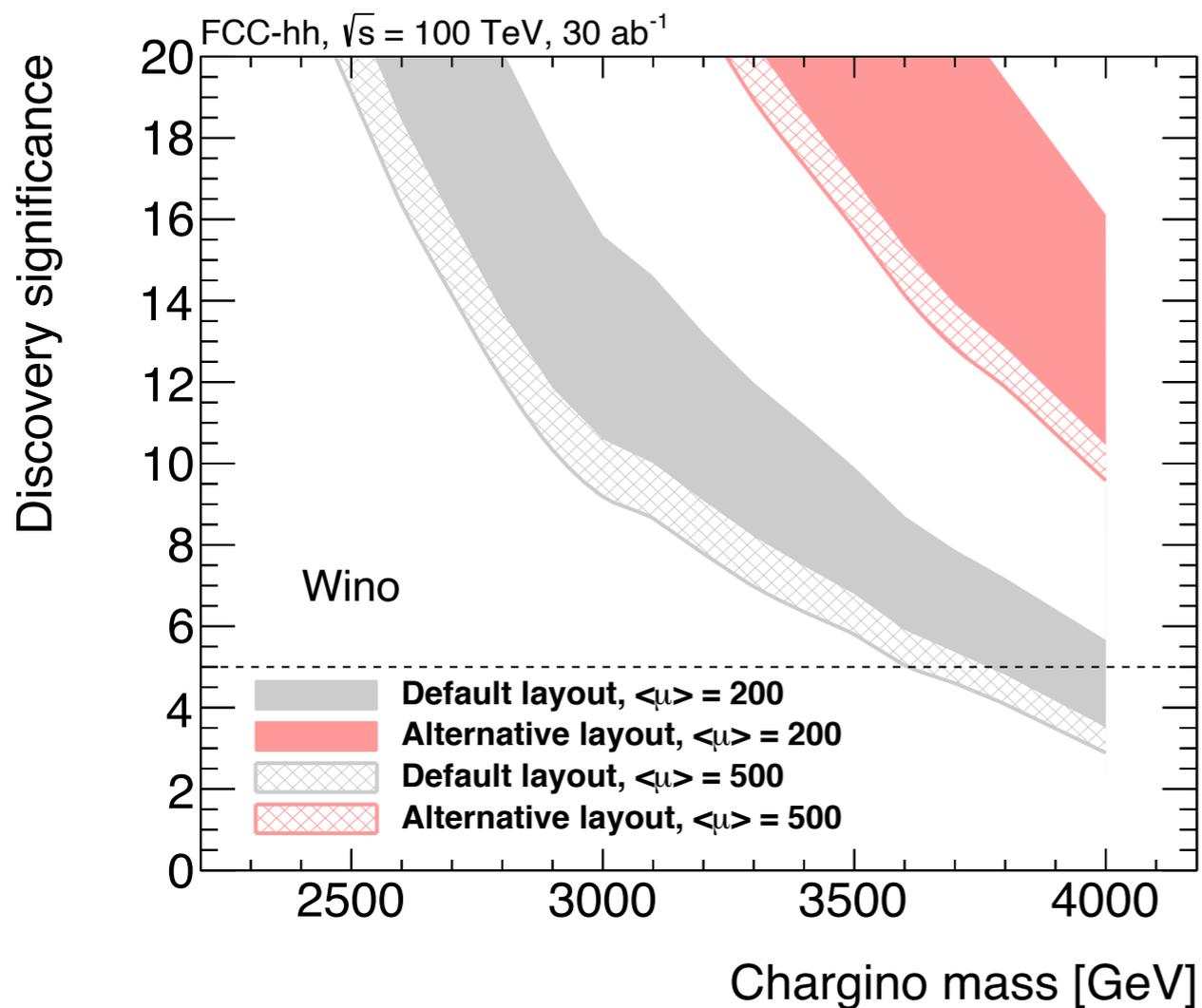
$$\Omega_{\text{wimp}} h^2 \lesssim 0.12$$



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

## DM WIMP searches in the most elusive, compressed scenarios:

### Disappearing charged track analyses (at ~full pileup)



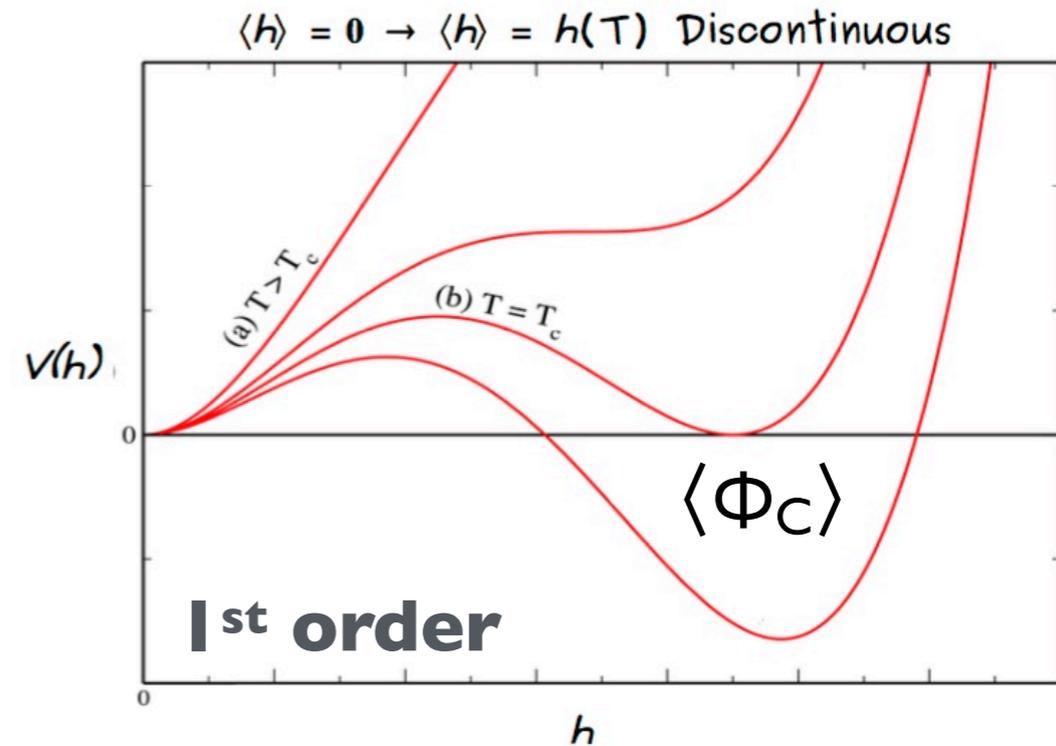
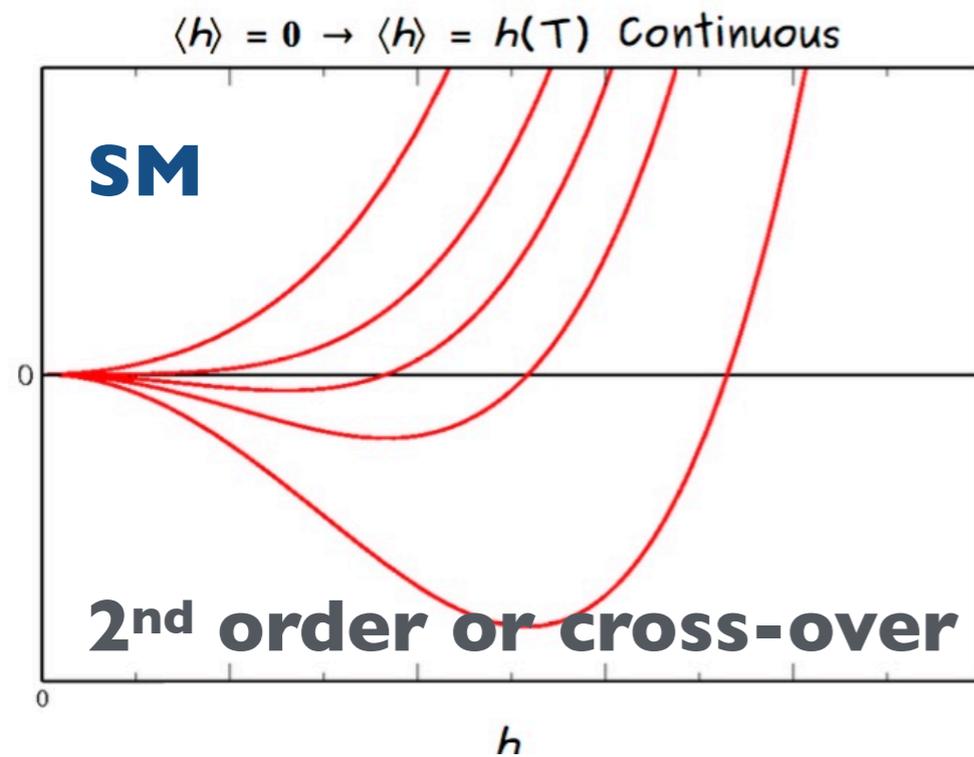
**=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!**

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

## To do:

- Study more systematically the prospects to discover challenging stealthy final states, leaving no gaps in the parameter space of interesting models
- Consider opportunities for detectors dedicated and optimized to difficult BSM final states (eg Long Lived Particles)

# The nature of the EW phase transition



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

**Strong** 1<sup>st</sup> 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  $O(\text{TeV})$** , 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**

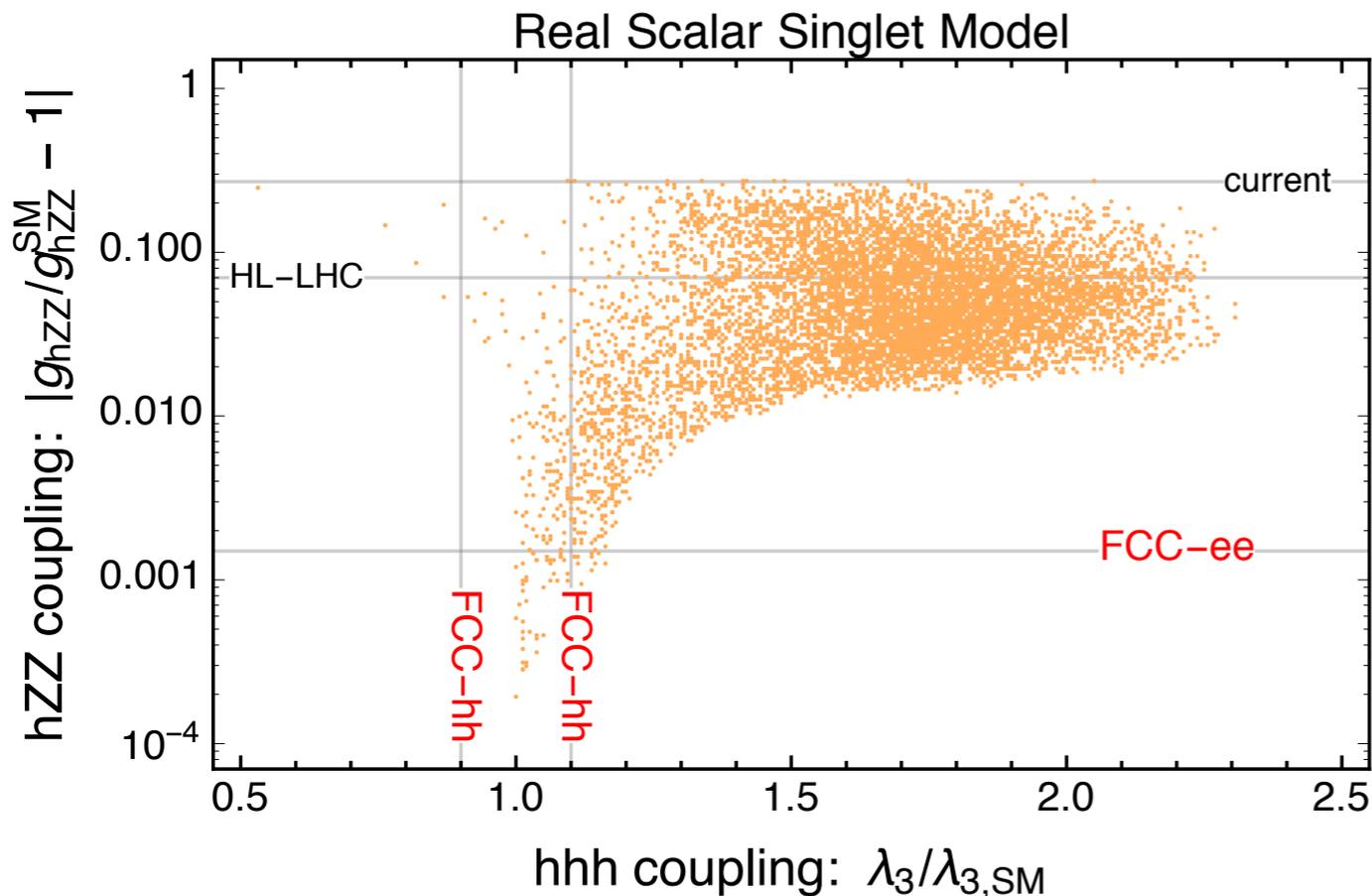
## Constraints on models with 1<sup>st</sup> order phase transition at the FCC

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

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Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

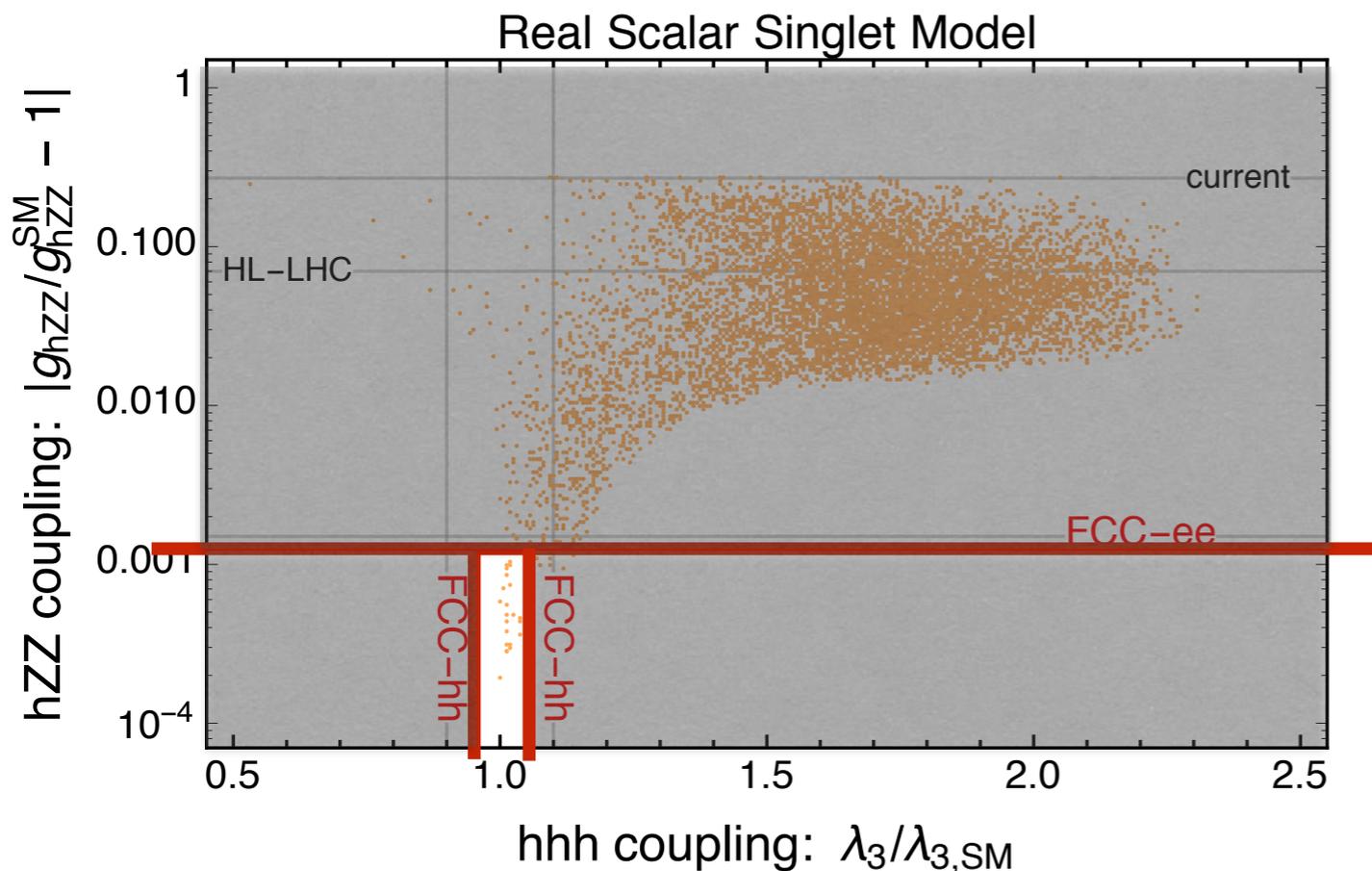


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

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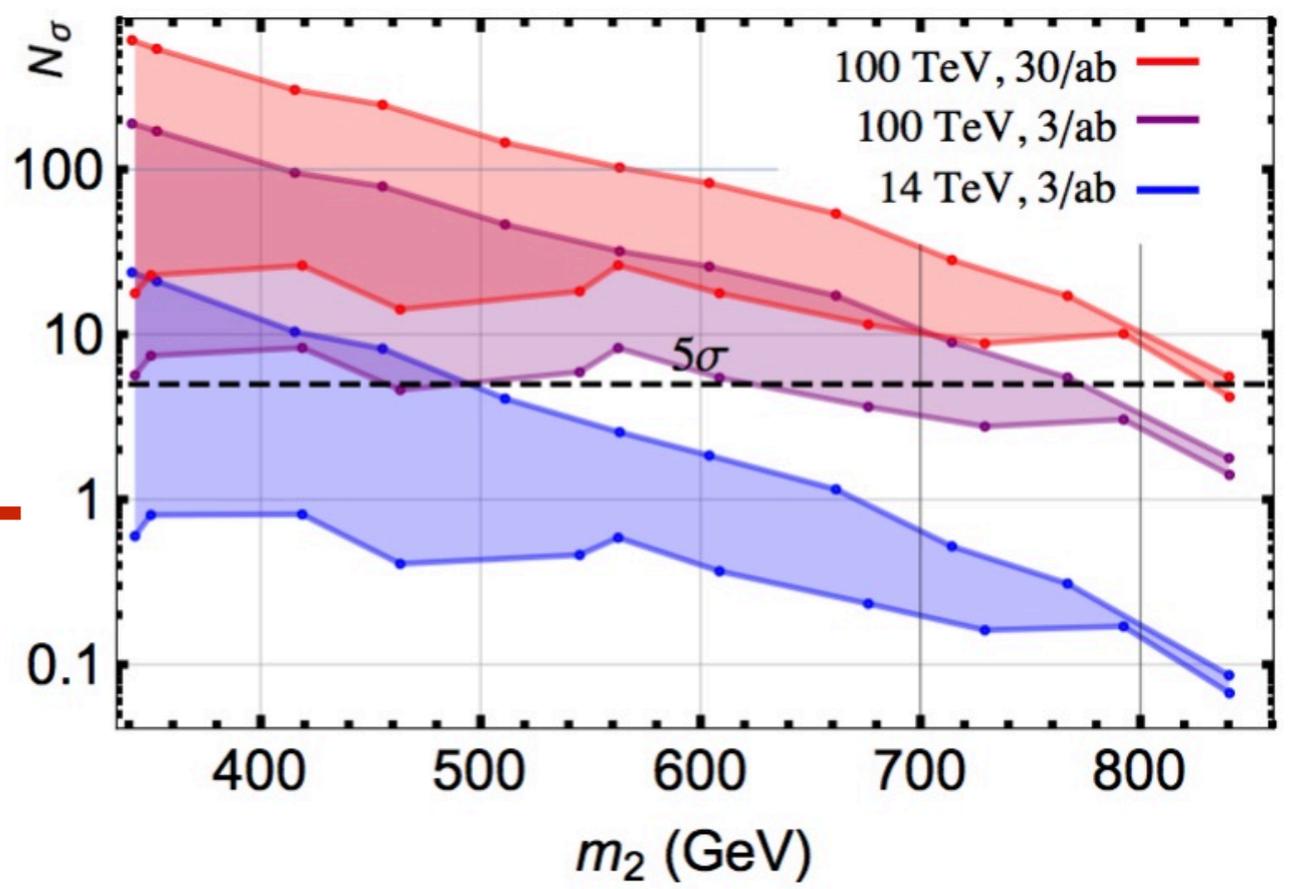
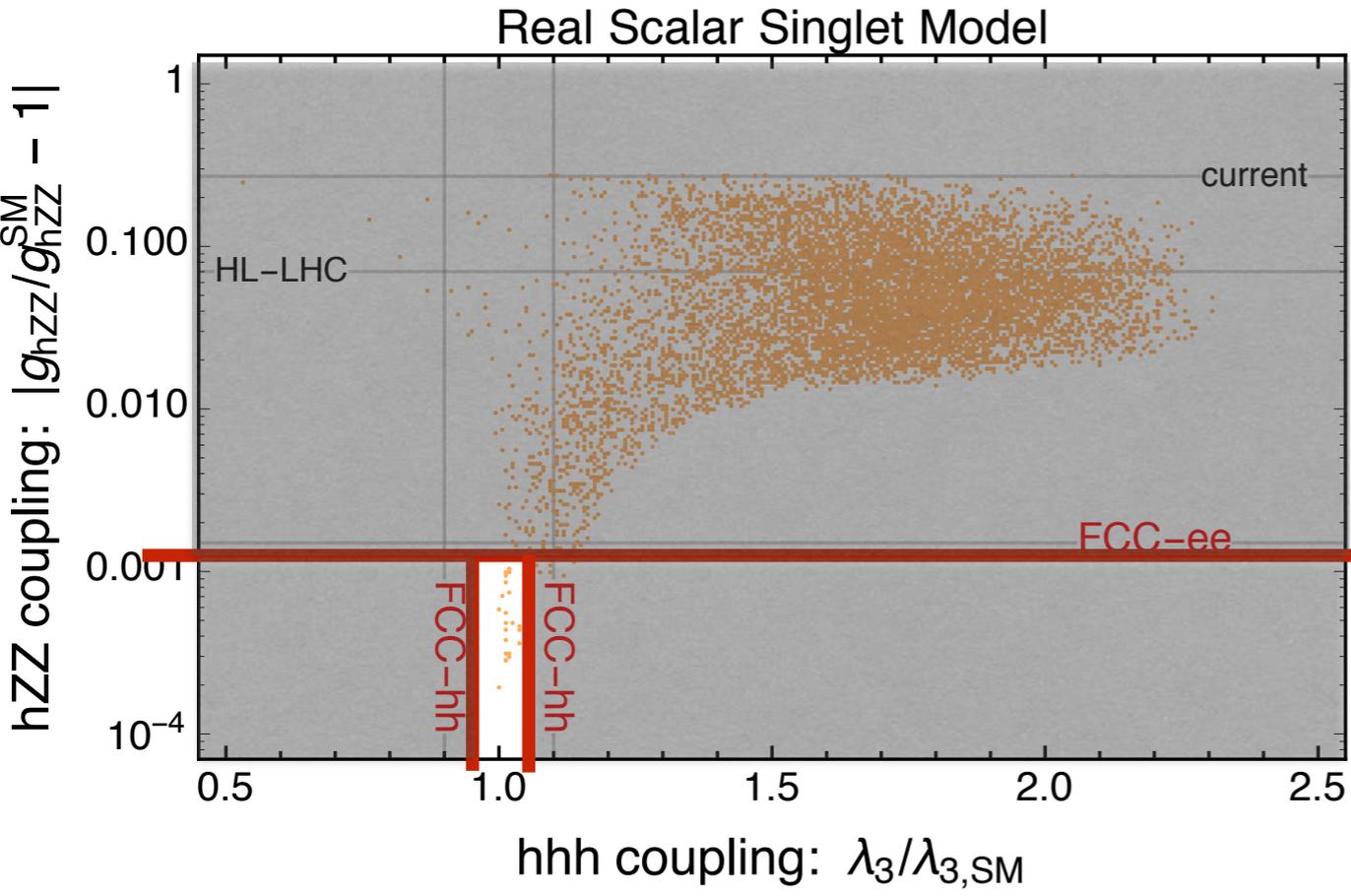
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Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

Direct detection of extra Higgs states at FCC-hh



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

$h_2 \rightarrow h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$   
 $(h_2 \sim S, \quad h_1 \sim H)$

# Remarks

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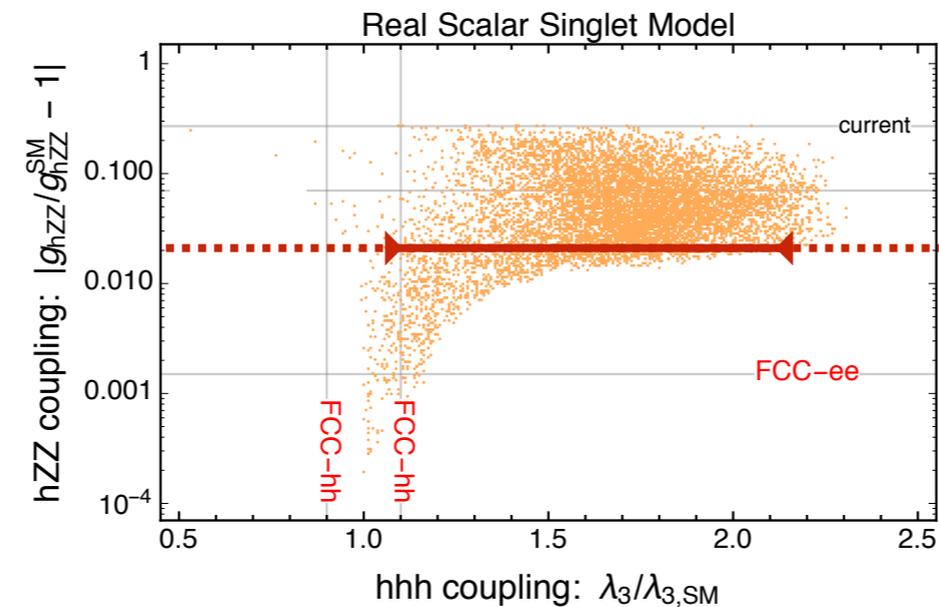
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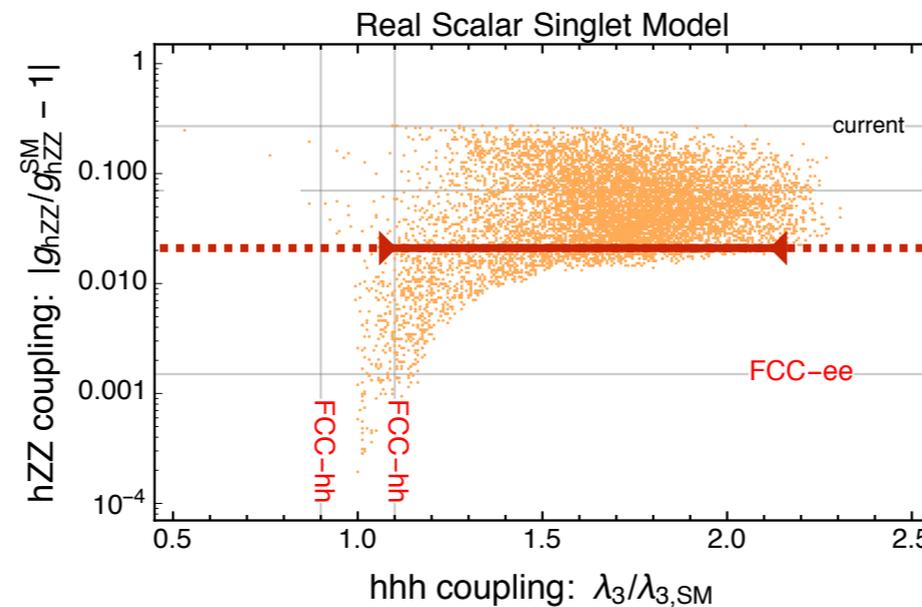
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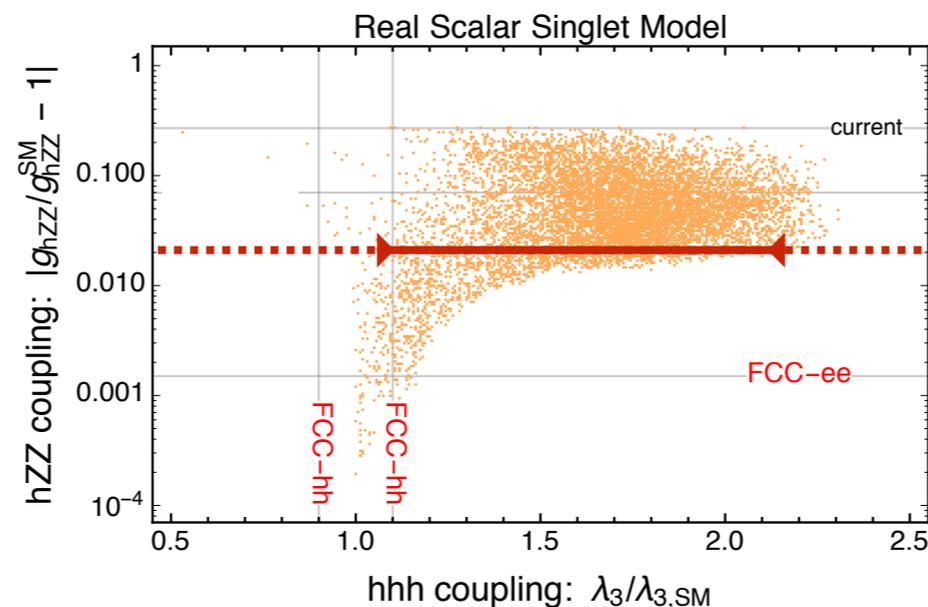
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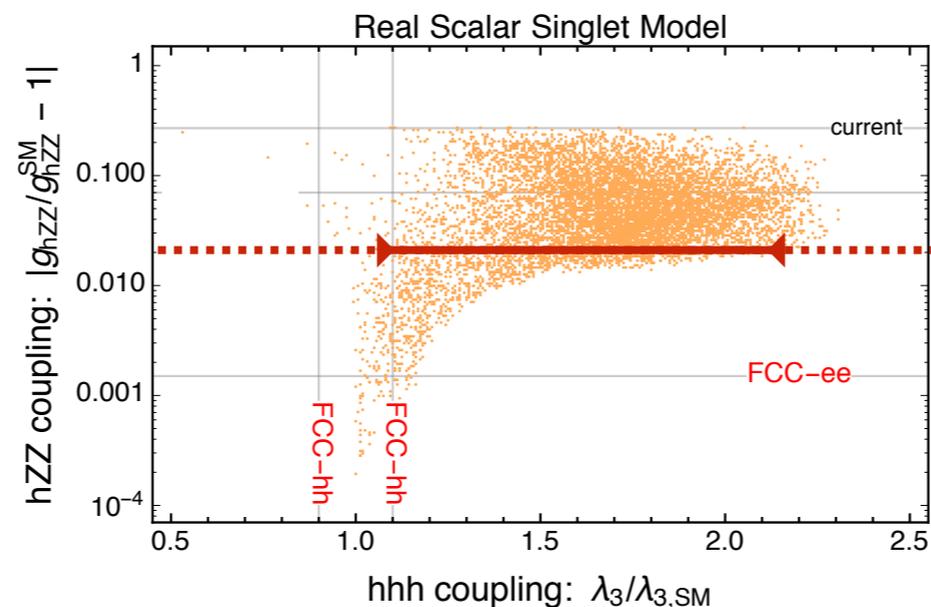
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- Likewise, it’s often said that some observable sets better limits than others: “all known model predict deviations in X larger than deviations in Y, so we better focus on X”. But once X is observed to deviate, knowing the value of Y could be absolutely crucial ....

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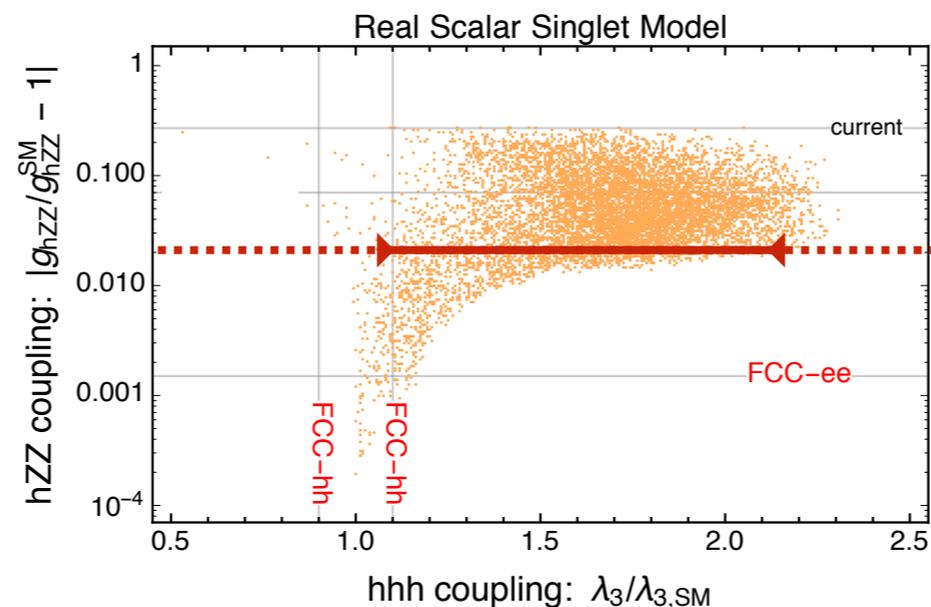
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- Redundancy and complementarity of observables is of paramount importance

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- 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
- The full, integrated, FCC programme, is the only proposed facility capable of providing such a complementarity

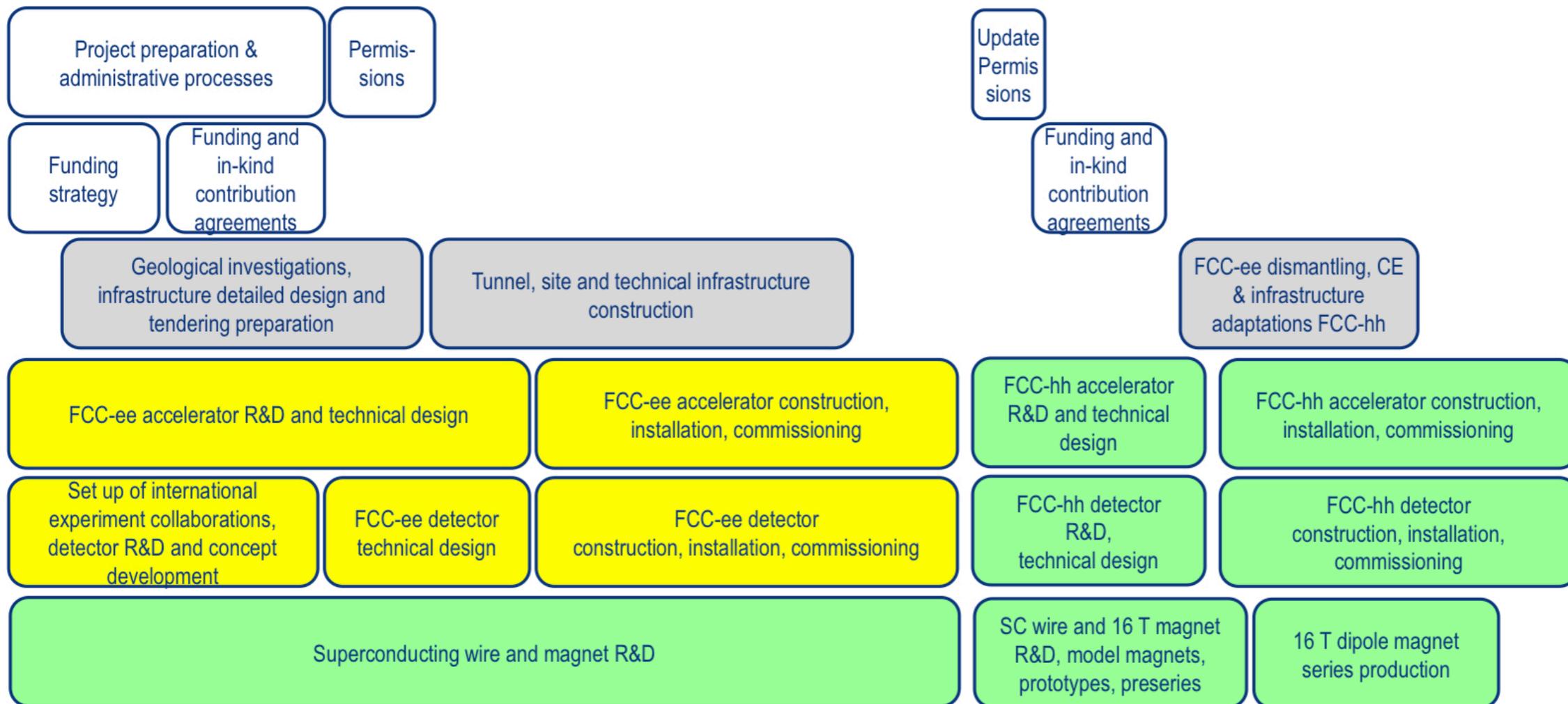
# Not covered

- 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

# FCC-ee + FCC-hh, project timeline



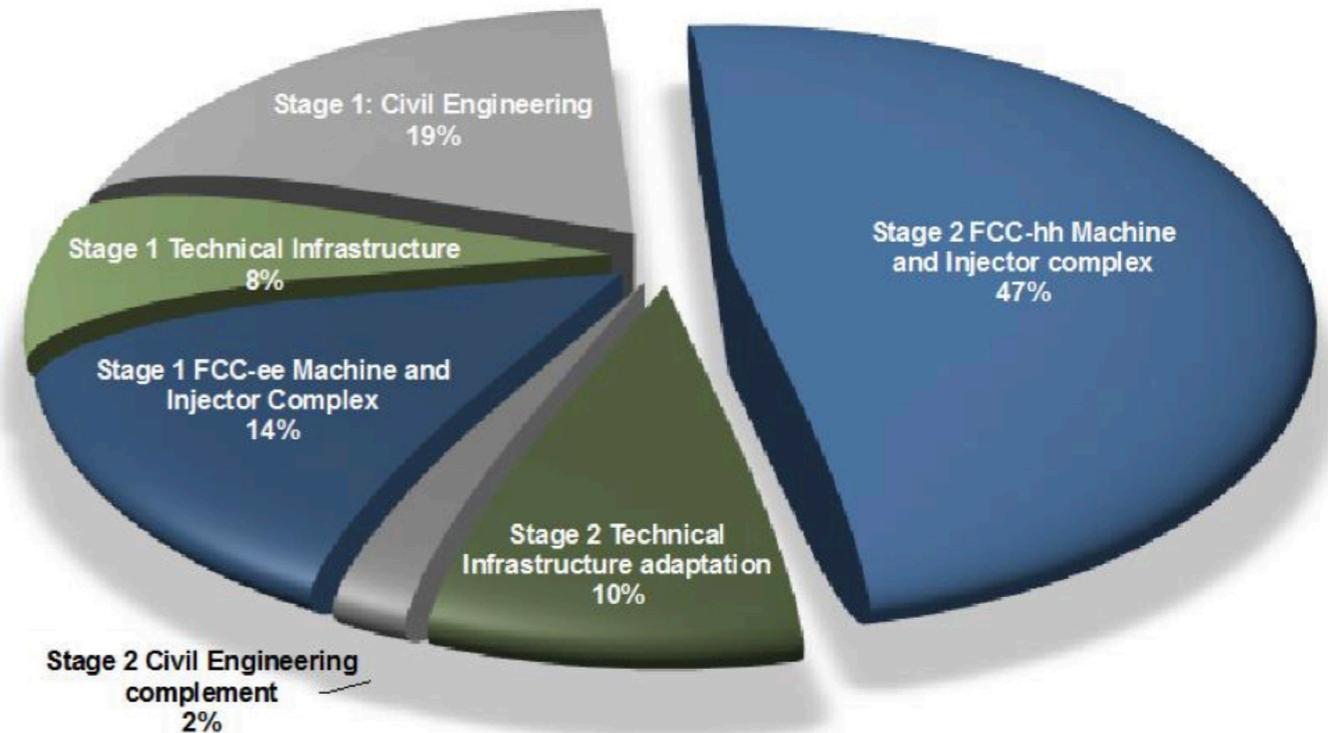
## FCC integral project technical schedule





# FCC-integrated cost estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
<b>TOTAL construction cost for integral FCC project</b>	<b>28,600</b>



**Total construction cost FCC-ee (Z, W, H) amounts to 10,500 MCHF & 1,100 MCHF (tt).**

- Associated to a total project duration of ~20 years (2025 – 2045)

**Total construction cost for subsequent FCC-hh amounts to 17,000 MCHF.**

- Associated to a total project duration of ~25 years (2035 – 2060) (FCC-hh stand alone 25 BCHF)



# 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

# Additional material: recent reports on Future Circular Colliders

- **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](#)