Physics at a Future Circular Collider

Free Meson Seminar

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Future Circular Colliders

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

link to CDR

in a 100km tunnel around CERN

⇒ see Mike Koratzinos FMS on August 13

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and $e_{60GeV}\ p_{35TeV}$

link to CDR

in a 100km tunnel in China

⇒ see Jie Gao FMS next week

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

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

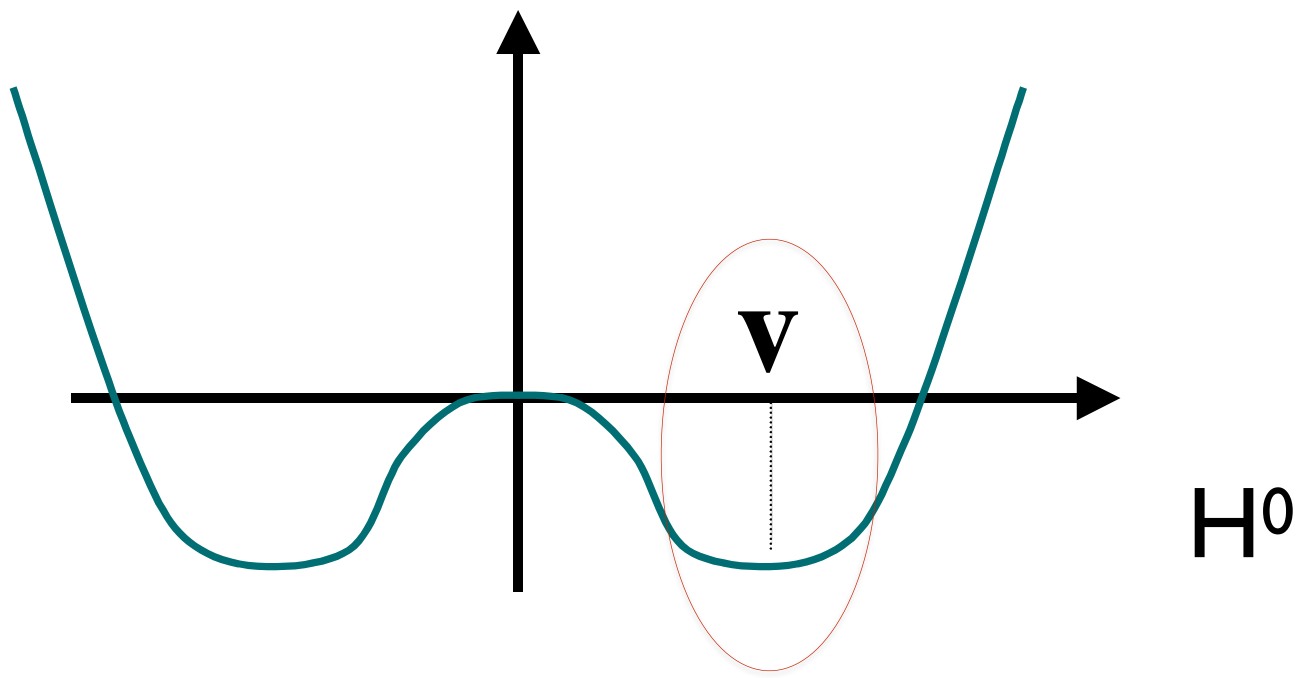
The important questions

- **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, …)

One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction….

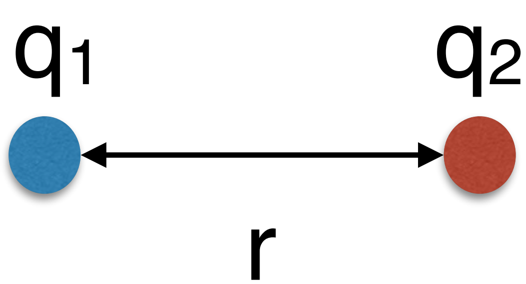


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics

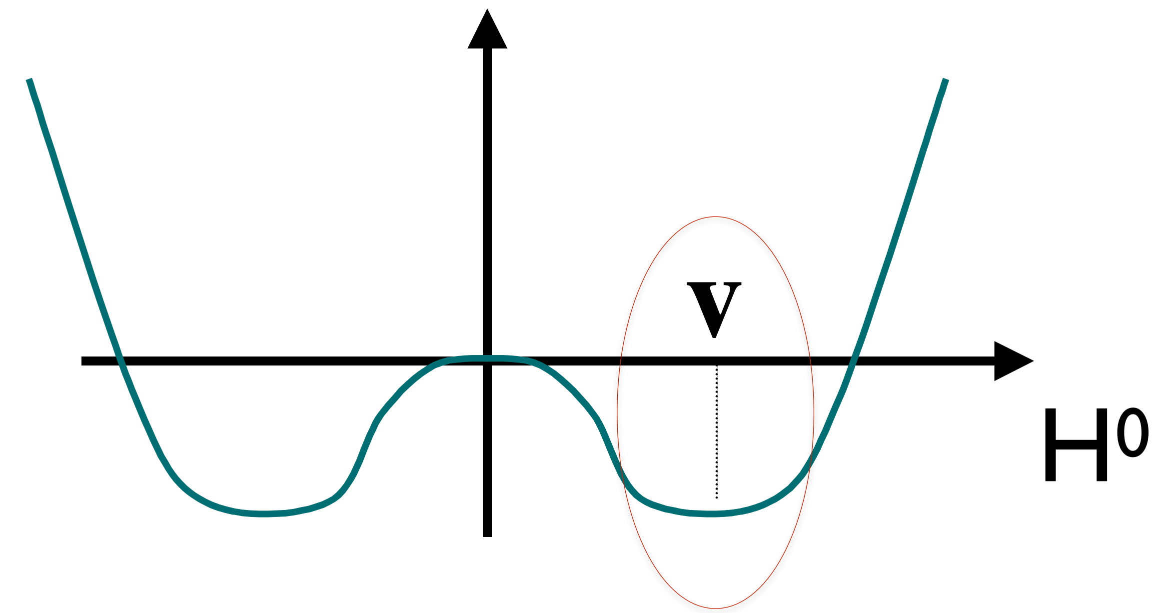


quantized, in units of fixed charge

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

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem



any function of $|H|^2$ would be ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

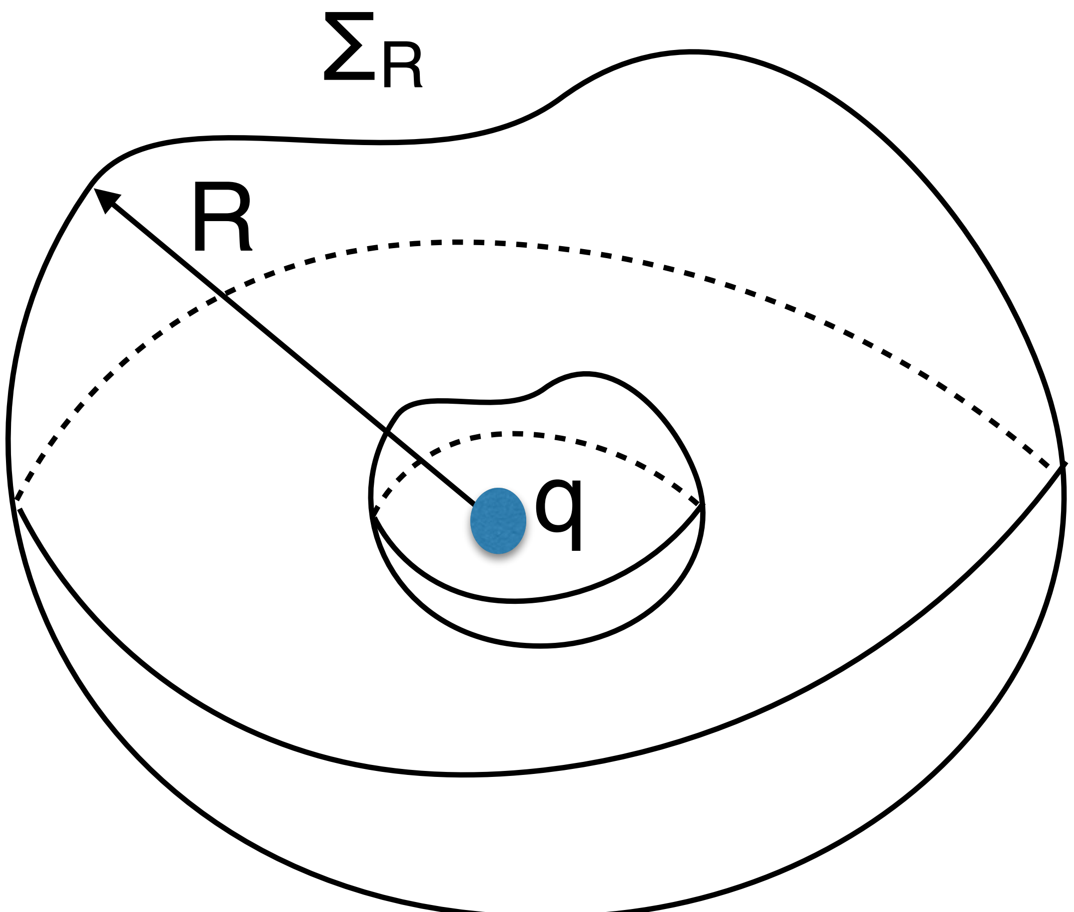
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Decoupling of high-frequency modes

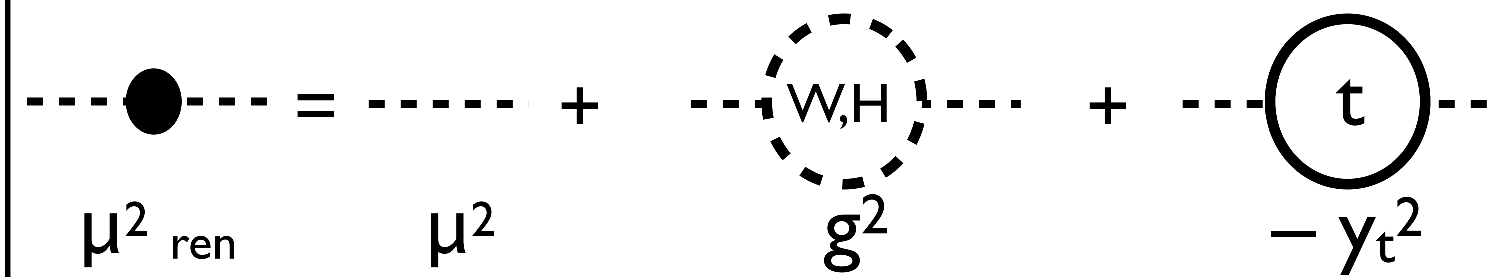
E&M



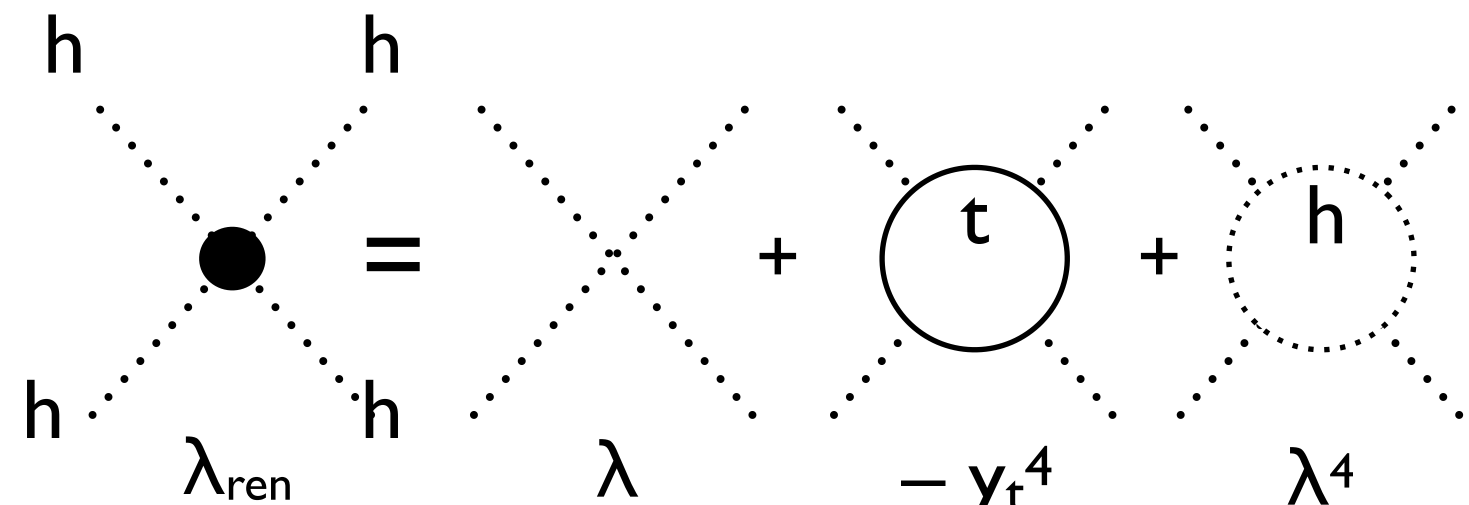
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter the charge seen at large scales

$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$



$$\Delta\mu^2 \sim (c_B \, m_B^2 - c_F \, m_F^2) \times (\Lambda / v)^2$$



$$\Longrightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a \, m_H^4 - b \, m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics => **hierarchy problem**

bottom line

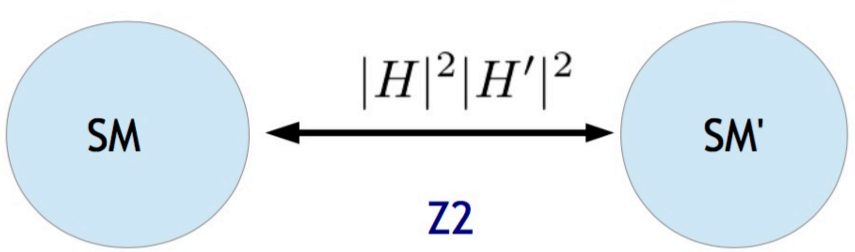
- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the "natural" scale defined by the measured parameters v and m_H

$\Rightarrow$ **naturalness**

Examples

- **Supersymmetry**: stop vs top (colored naturalness)

- **Extra-dimensions**: Planck scale closer than in 4-D, or Higgs as 4-D scalar component of a higher-dim gauge vector (KK modes, etc)
- **Little Higgs**: Higgs as a pseudo-Nambu-Goldstone boson of a larger symmetry, mass protected by global symmetries (top partners)
- **Neutral naturalness**: top contributions canceled by triplets of new particles neutral under SM gauge groups, but sharing the Higgs couplings with SM fermions (Higgs portals). Typically comes with doubling of (part of) SM gauge group (eg $SU(3)_A \times SU(3)_B$).
  - twin Higgs



  - folded SUSY ($SU(3)_B$ stops cancel Higgs couplings to $SU(3)_A$ tops)

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
  - again, "who ordered that?"
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted
  - what we've experimentally proven so far are basic properties, which, from the perspective of EFT and at the current level of precision of the measurements, hold true in a vast range of BSM EWSB scenarios

➡ *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>*

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?

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*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

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.

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?
  - …

Next I'll give few examples of the physics potential, focusing on the hh case

(for ee, see Koratzinos' talk)

Event rates: examples

FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←Z)
	10^6	$5\ 10^{12}$	10^8	10^6	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

FCC-hh	H	b	t	W(←t)	τ(←W←t)
	$2.5\ 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

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

(1) guaranteed deliverables: Higgs properties

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

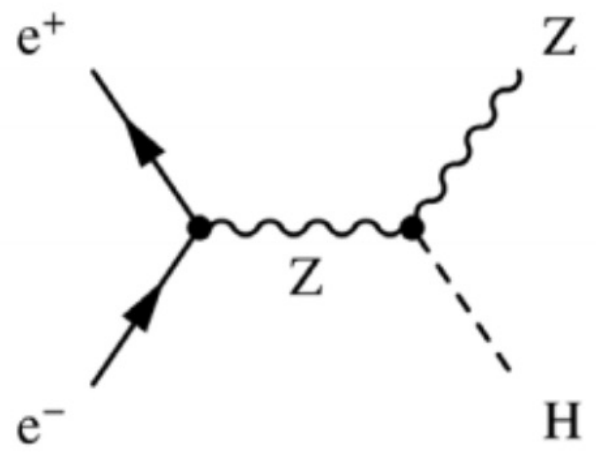
arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

=> for evidence of 3σ deviations from SM, the precision goal should be (sub)percent!

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

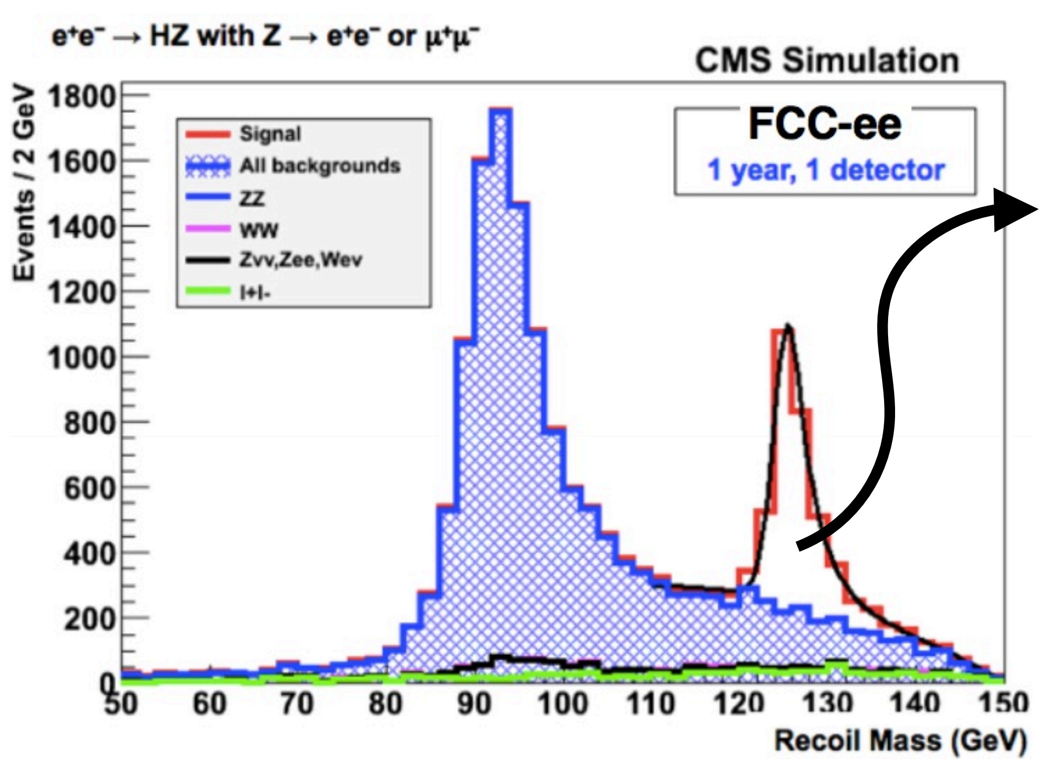
- the model independent % measurement of **Γ(H)**, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

=> absolute measurement of width and couplings

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

The absolutely unique power of pp →H+X:

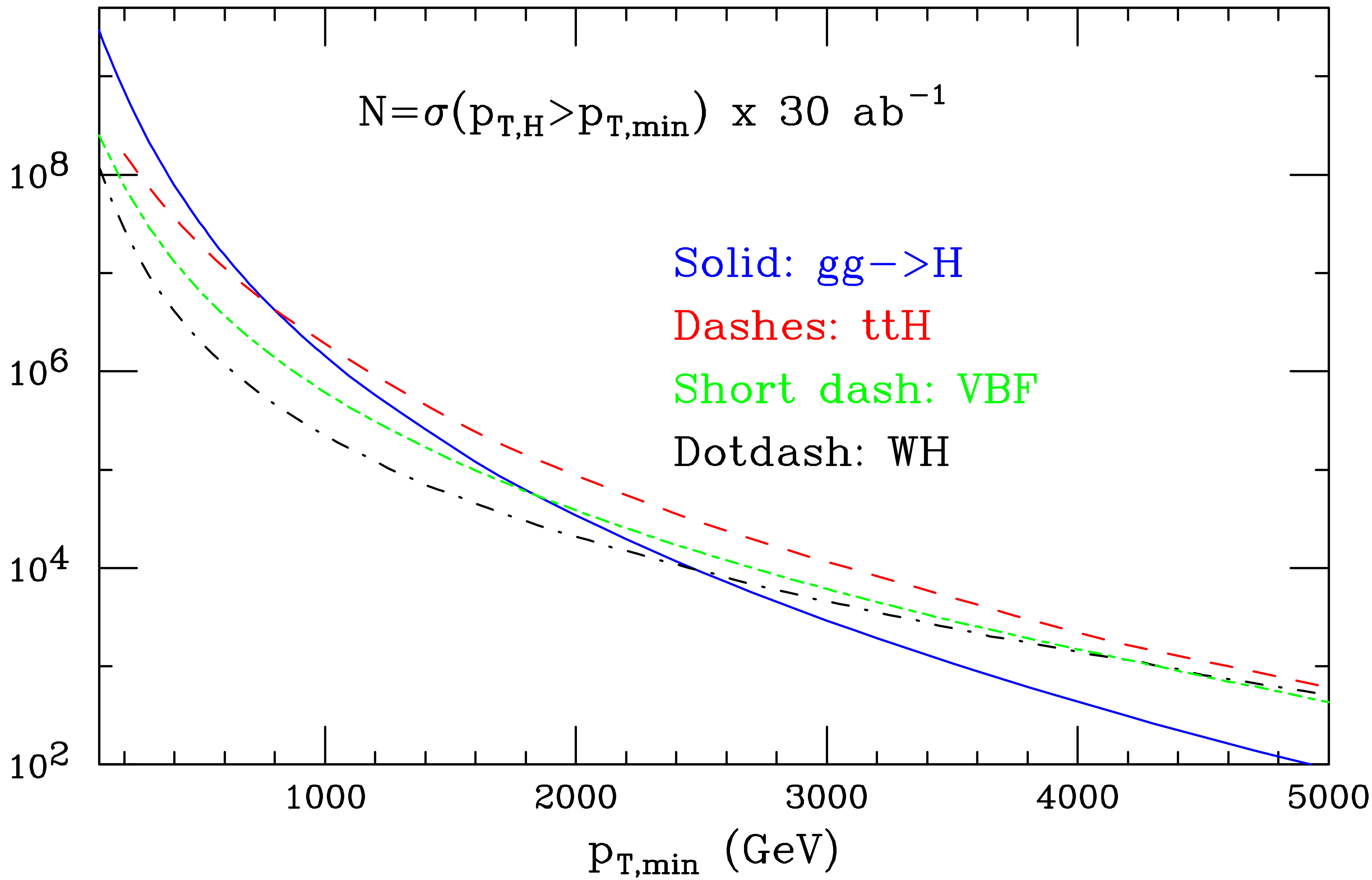
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4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



- 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 $H \to 4l, \gamma\gamma, \ldots$
  - improved S/B, realistic trigger thresholds, reduced pile-up effects ?

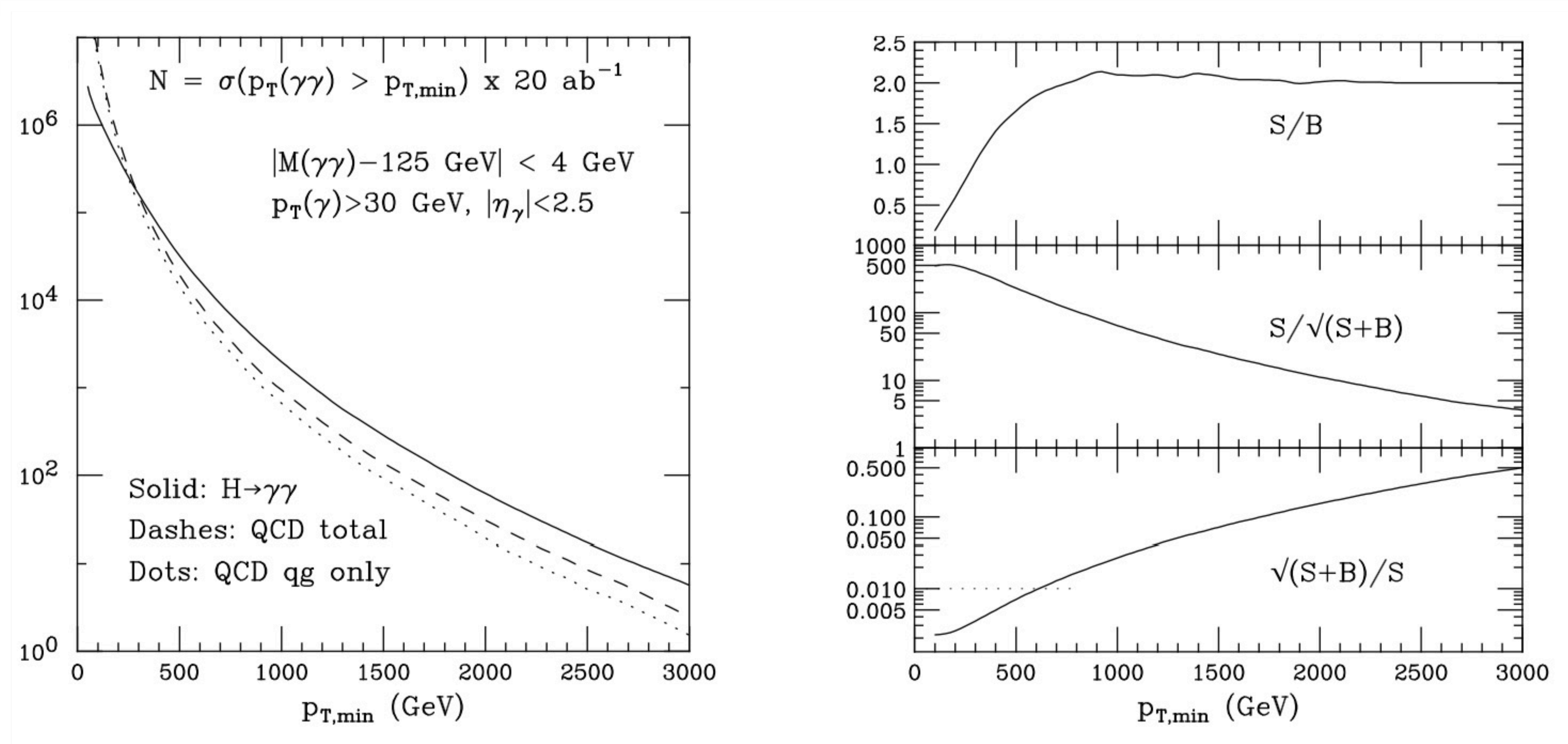
  ➡ current det sim and HL-LHC extrapolations more robust

  ➡ focus of FCC CDR Higgs studies so far

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

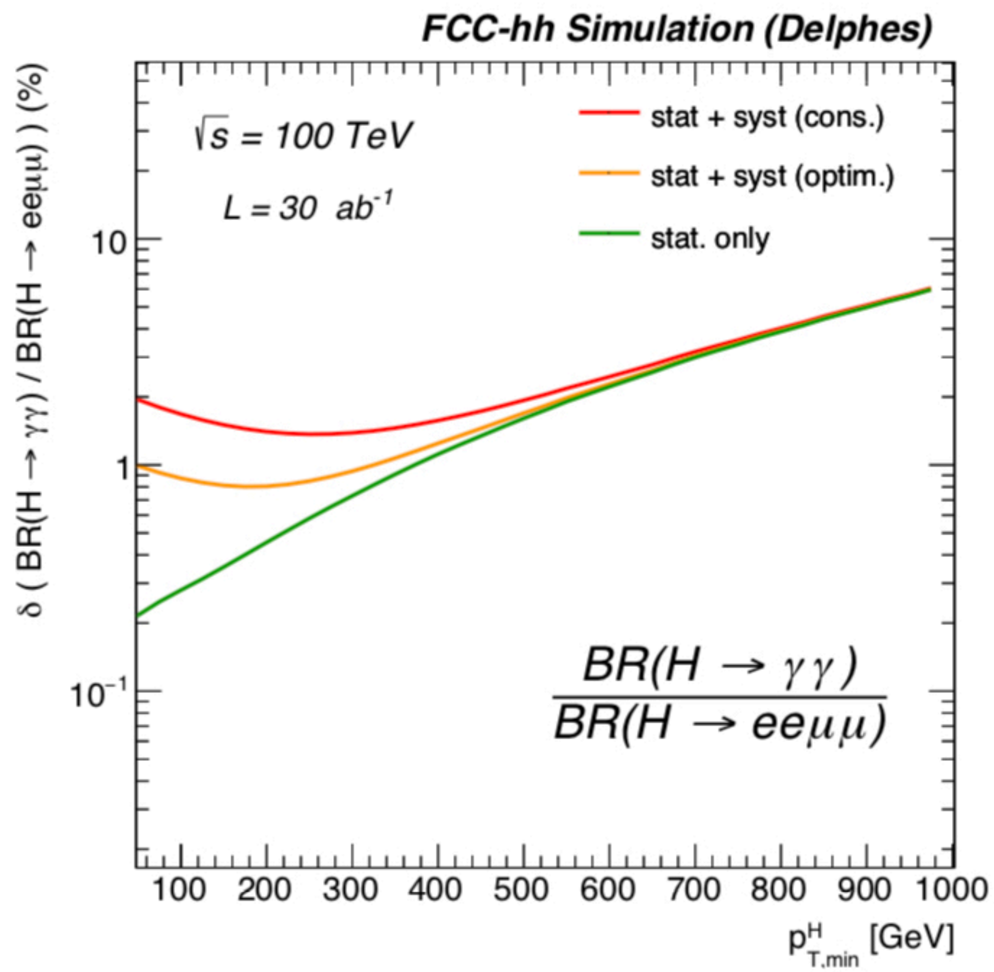
- $p_T \gtrsim$ TeV :
  - stat uncertainty O(10%) up to 1.5 TeV (3 TeV) for $H \to 4l, \gamma\gamma$ ($H \to bb$)
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - indirect sensitivity to BSM effects at large Q^2 , complementary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

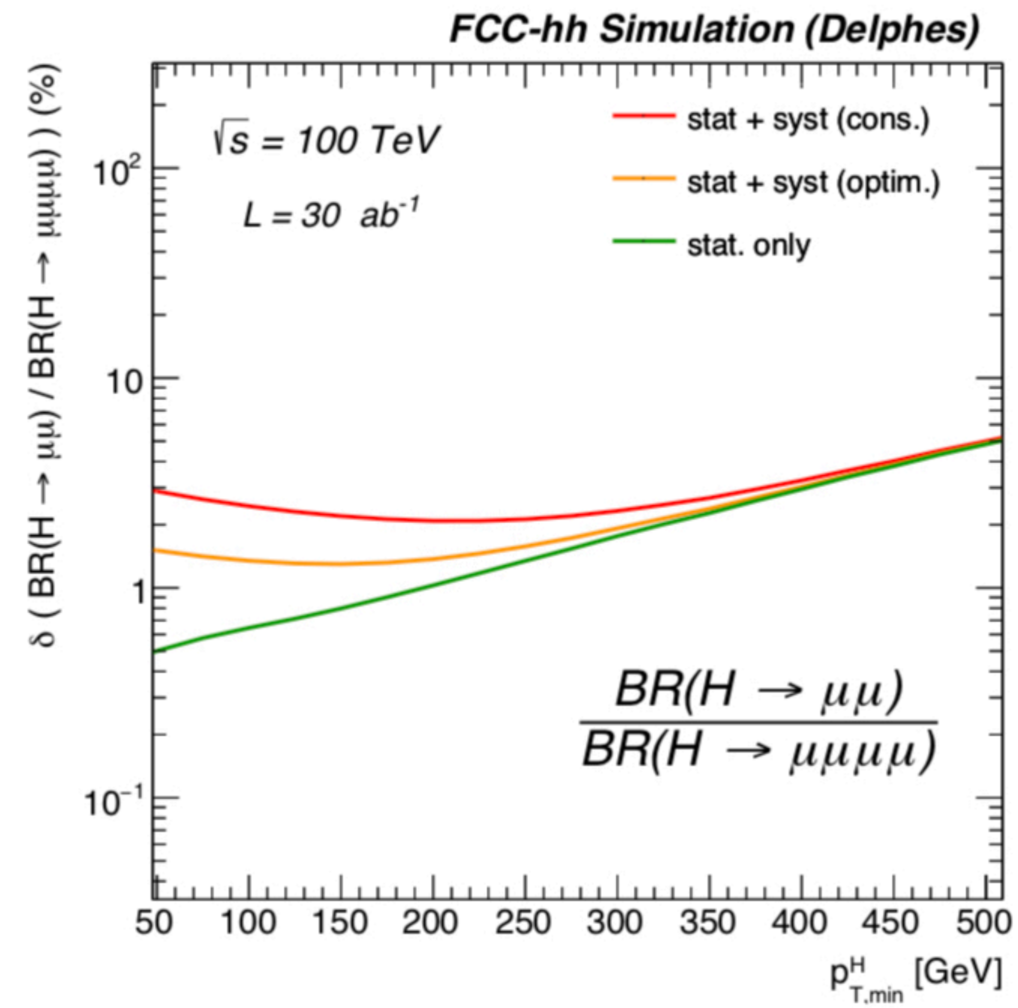
$gg \to H \to \gamma\gamma$ at large p_T

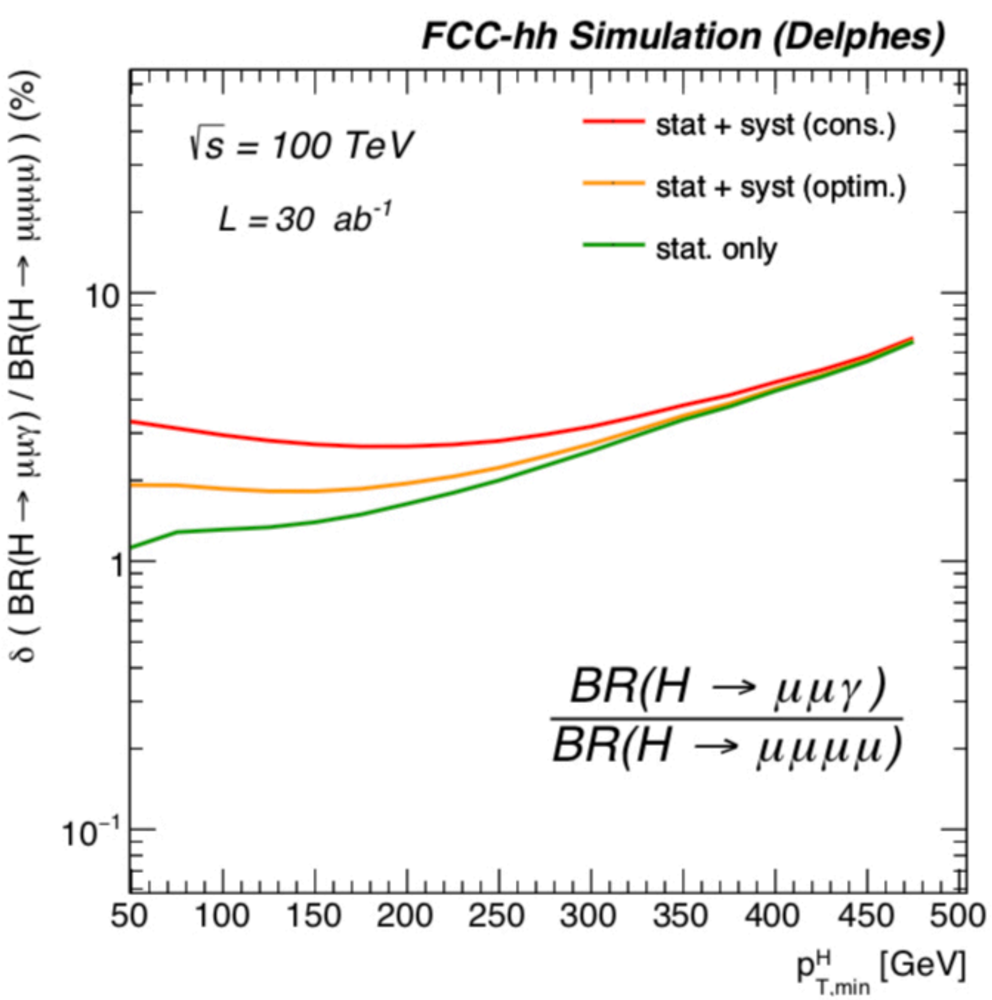


- At LHC, S/B in the $H \to \gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

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







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

Possible 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

Importance of standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

2nd gen’n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

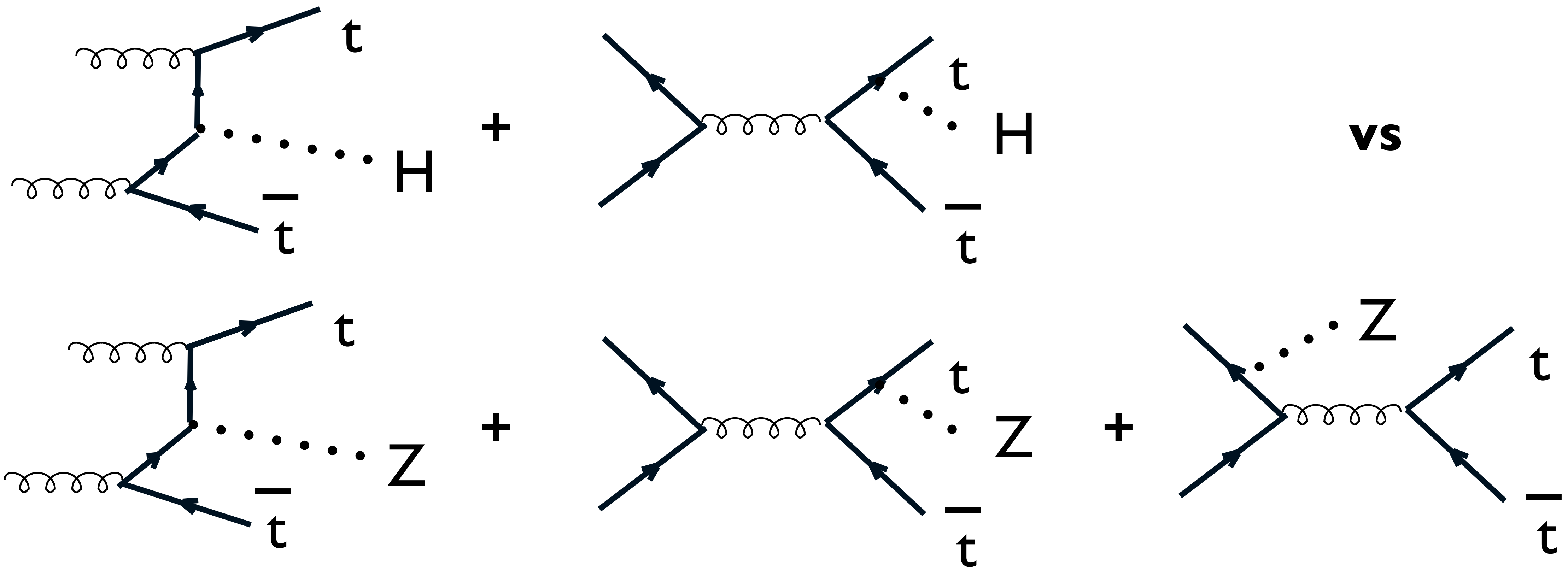
BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

Possible work: study impact of precise ratio measurements in the context of specific BSM models, set targets. Any special opportunities?

Top Yukawa coupling from σ(ttH)/σ(ttZ)

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- **$m_Z \sim m_H$ ⇒ almost identical kinematic boundaries:**

  o correlated PDF systematics
  o correlated m_{top} systematics

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

Analysis in arXiv:1507.08169 used boosted H/Z→bb decays (large stat, reduced combinatoric bg, correlated b-tagging efficiencies, …)
Reloaded with FCC-hh det sim in https://cds.cern.ch/record/2642471

- ttjj and ttbb bgs "measured" with data at mjj>200 with negligible δ_{stat}. Syst to be assessed for shape modeling under mH peak systematics
- ttZ kinematics validated with Z→leptons
- N(ttH)/N(ttZ) = 1.64 ± 0.01 (stat.) after perfect bg subtraction

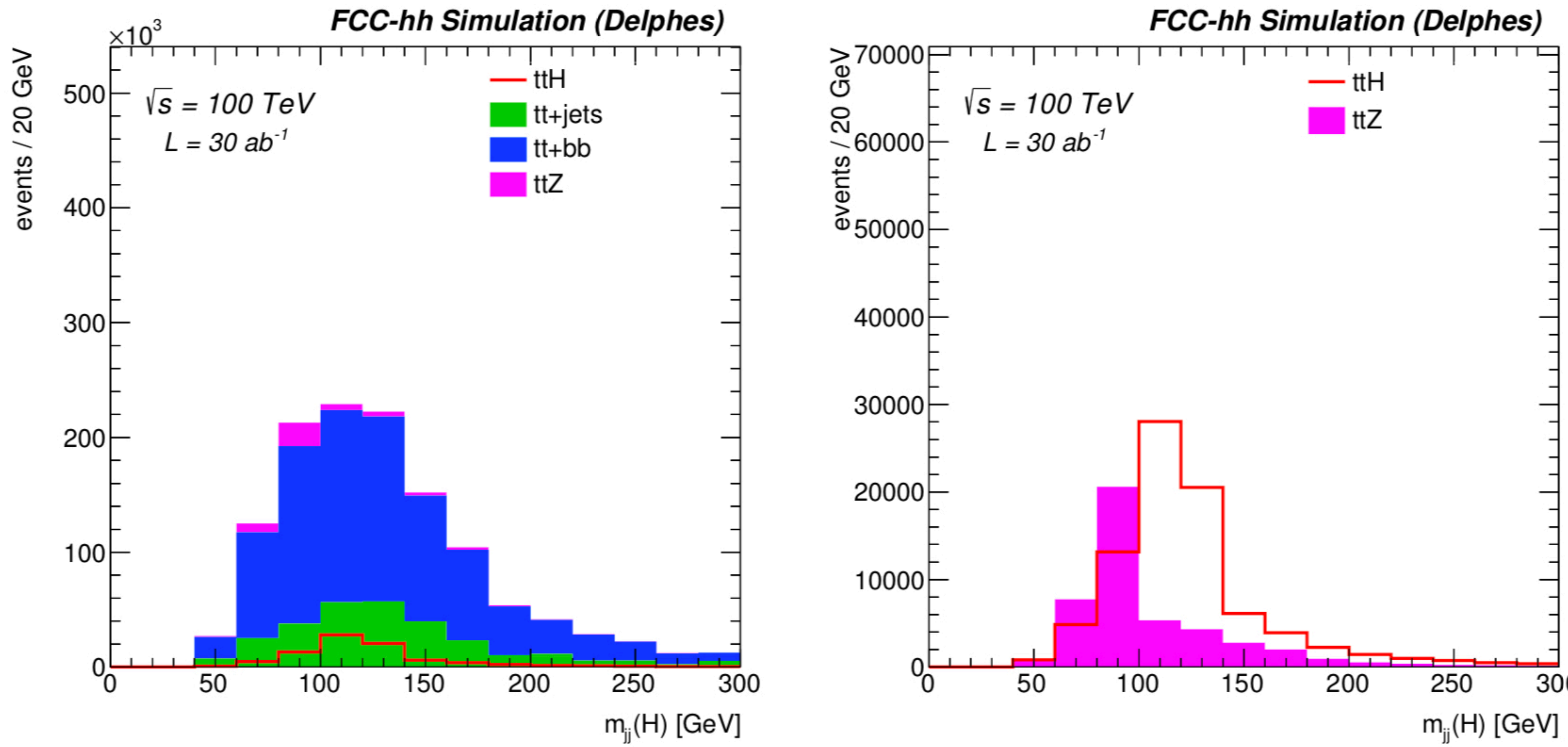


Figure 7: Invariant mass the di-jet pair forming the Higgs candidate including all backgrounds (left) and after (perfect) background subtraction as input for measuring the ttH/ttZ fraction (right).

Remarks

- This measurement requires knowledge of ttZ EW coupling to % level => FCC-ee
- **Further work to be done:**
  - consolidate determination of bg shapes and impact on overall fit of ttH and ttZ components ($H/Z \rightarrow bb$)
  - explore different final states…
  - Eg ttH($\rightarrow\gamma\gamma$) / ttZ($\rightarrow$ee): doesn't require large boost, much reduced bgs, correlated E scales and ID eff (e vs γ), …

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

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

$BR(H \rightarrow \mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ 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 $B(H \rightarrow ZZ^*)$ @ 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, ττ:
  - 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→cc in boosted jets, exclusive H→J/ψ γ decays, …
- Couplings to lighter quarks (exclusive decays)
- Rare/forbidden decays (eμ, μτ, eτ, …, multibodies, …)

Higgs as a BSM probe: precision vs dynamic reach

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

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

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

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

⇒ **precision** probes large Λ

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

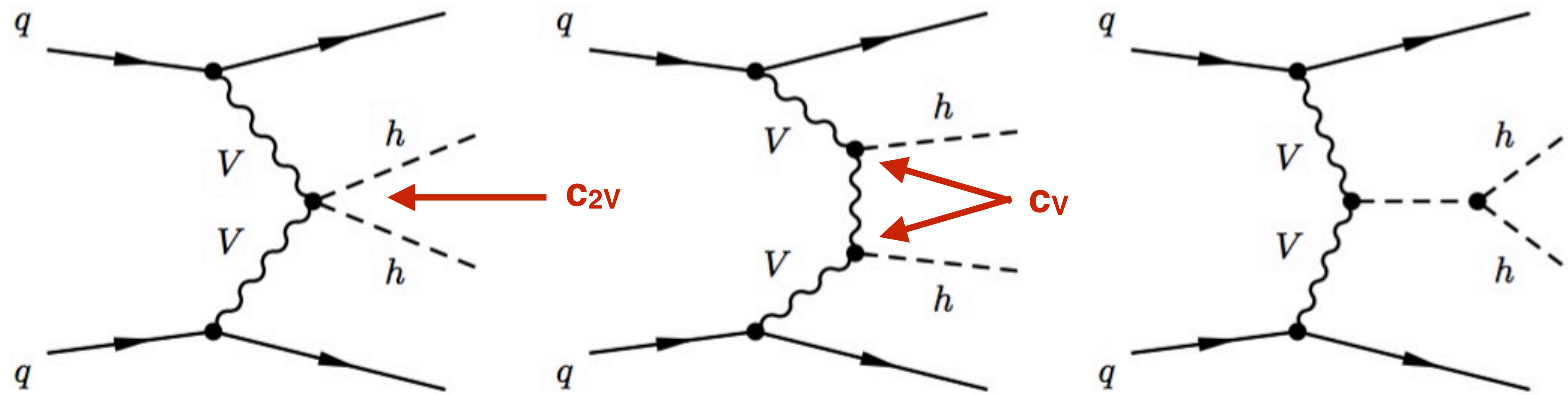
For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

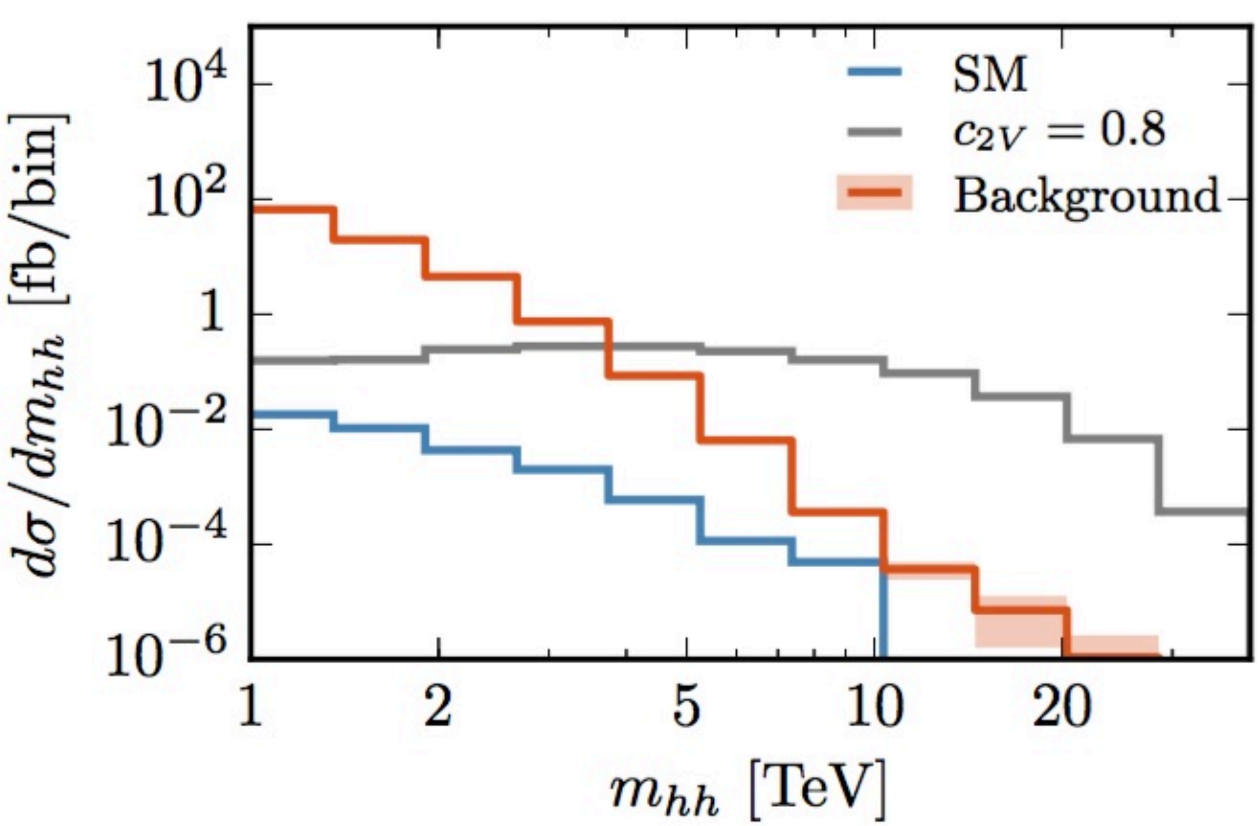
⇒ **kinematic reach** probes large Λ even if precision is low

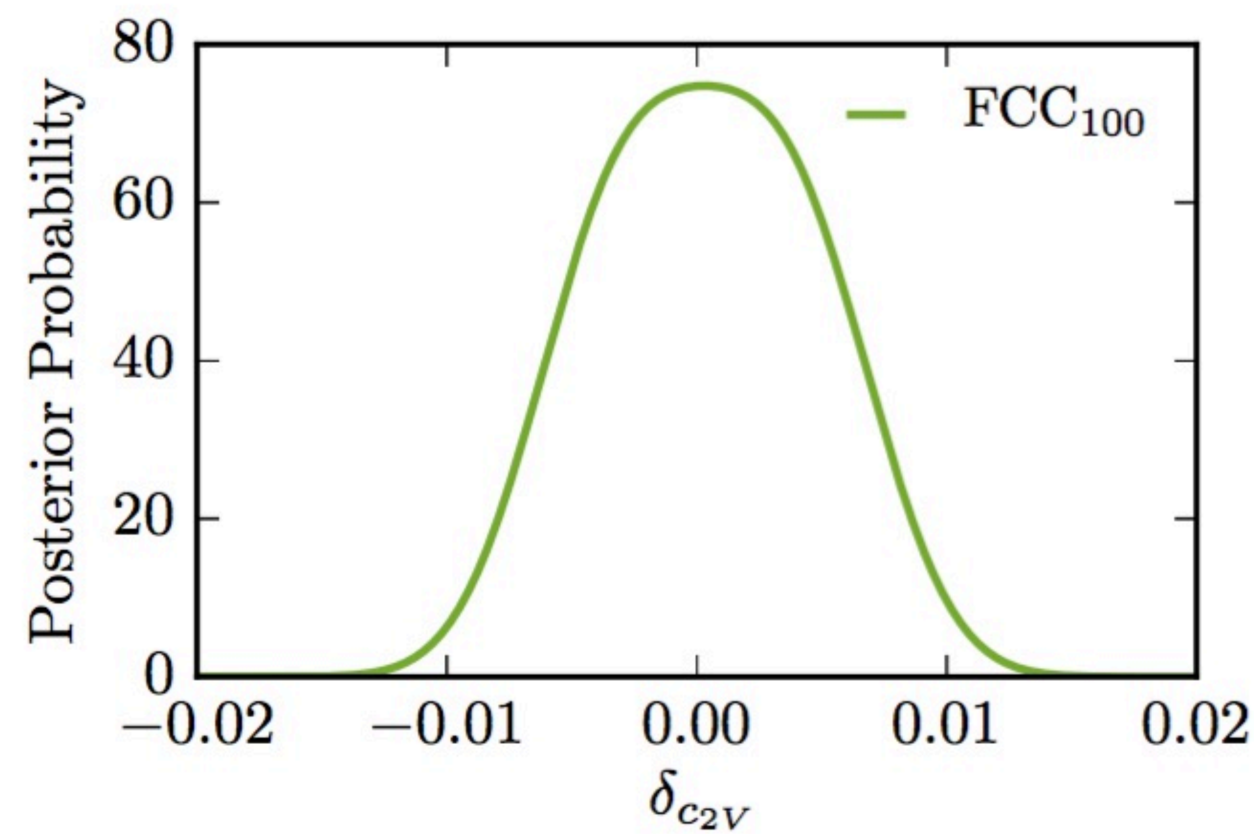
e.g. $\delta O = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV

Example: high mass VV → HH

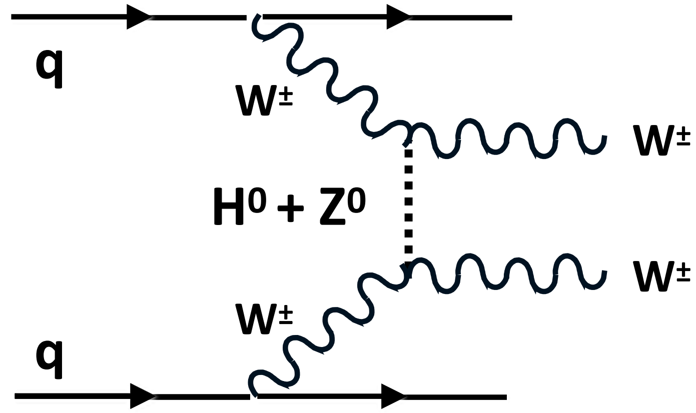


$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) \cdot$$ **where** $$\begin{cases} c_V = g_{HVV}/g_{HVV}^{SM} \\ c_{2V} = g_{HHVV}/g_{HHVV}^{SM} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$$

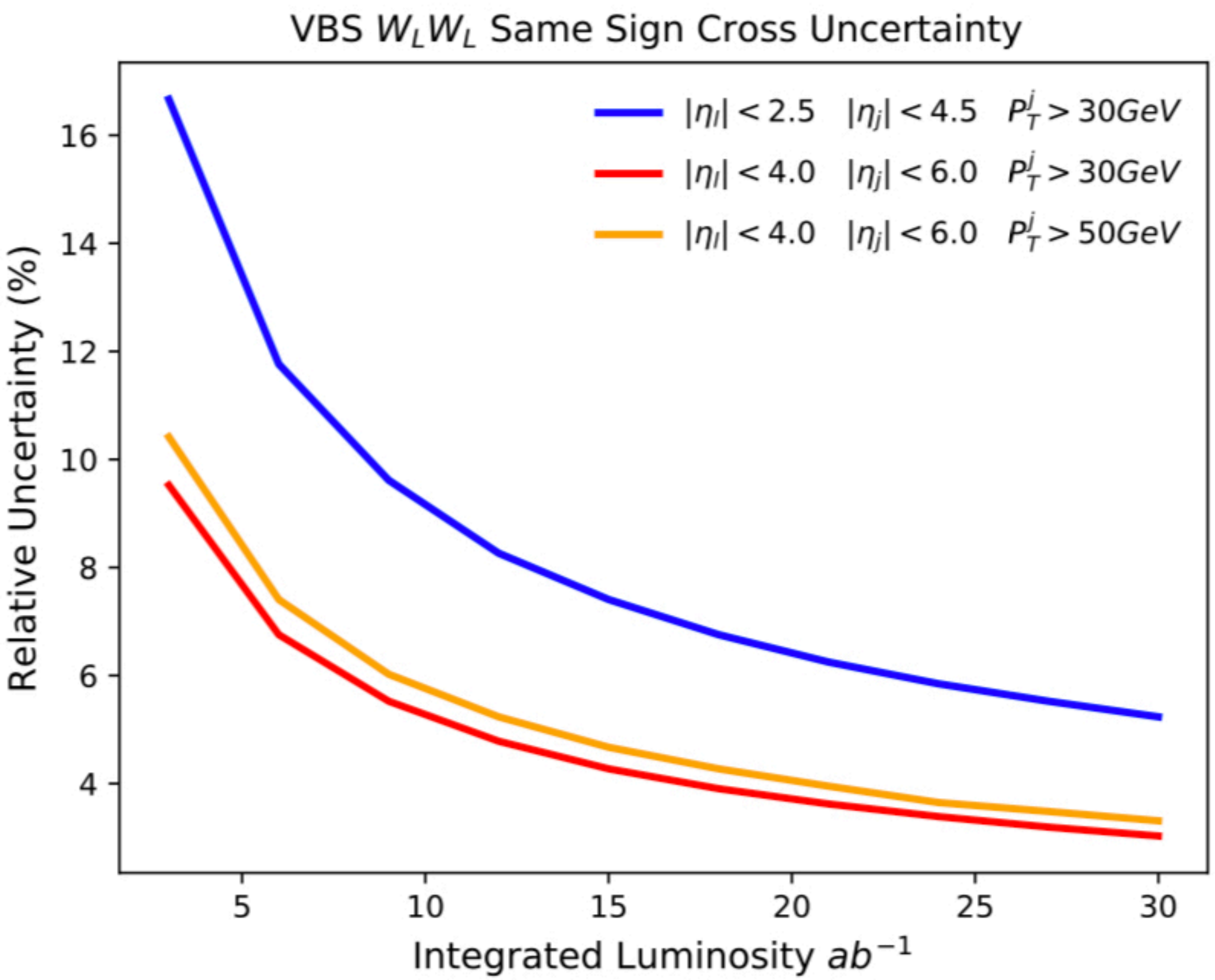




W_LW_L scattering



large m_{WW}



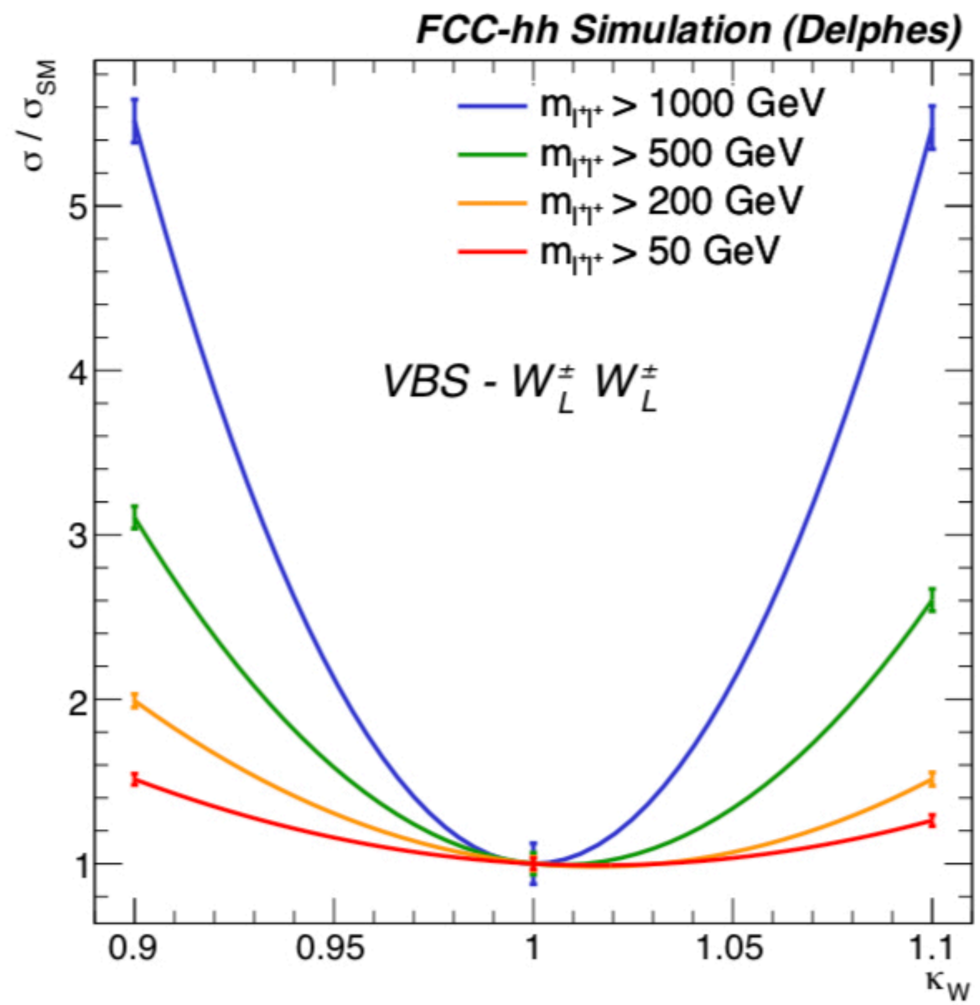


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \to HH$ process.

$m_{l^+l^+}$ 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]

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

(1) guaranteed deliverables: EW observables

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

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

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

EW parameters @ FCC-ee

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z ($\times10^3$)	20767±25	0.06	0.2-1.0
α_s (m_Z) ($\times10^4$)	1196±30	0.1	0.4-1.6
R_b ($\times10^6$)	216290±660	0.3	<60
σ^0_{had} ($\times10^3$) (nb)	41541±37	0.1	4
N_ν ($\times10^3$)	2991±7	0.005	1
$\sin^2\theta_W^{\text{eff}}$ ($\times10^6$)	231480±160	3	2-5
$1/\alpha_{\text{QED}}(m_Z)$ ($\times10^3$)	128952±14	4	Small
$A_{\text{FB}}^{b,0}$ ($\times10^4$)	992±16	0.02	1-3
$A_{\text{FB}}^{\text{pol},\tau}$ ($\times10^4$)	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) ($\times10^4$)	1170±420	3	Small
N_ν($\times10^3$)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

Precision W physics with pp→tt[→Wb]

MLM @ SEARCH2016

A concrete application:
testing lepton universality in W decays

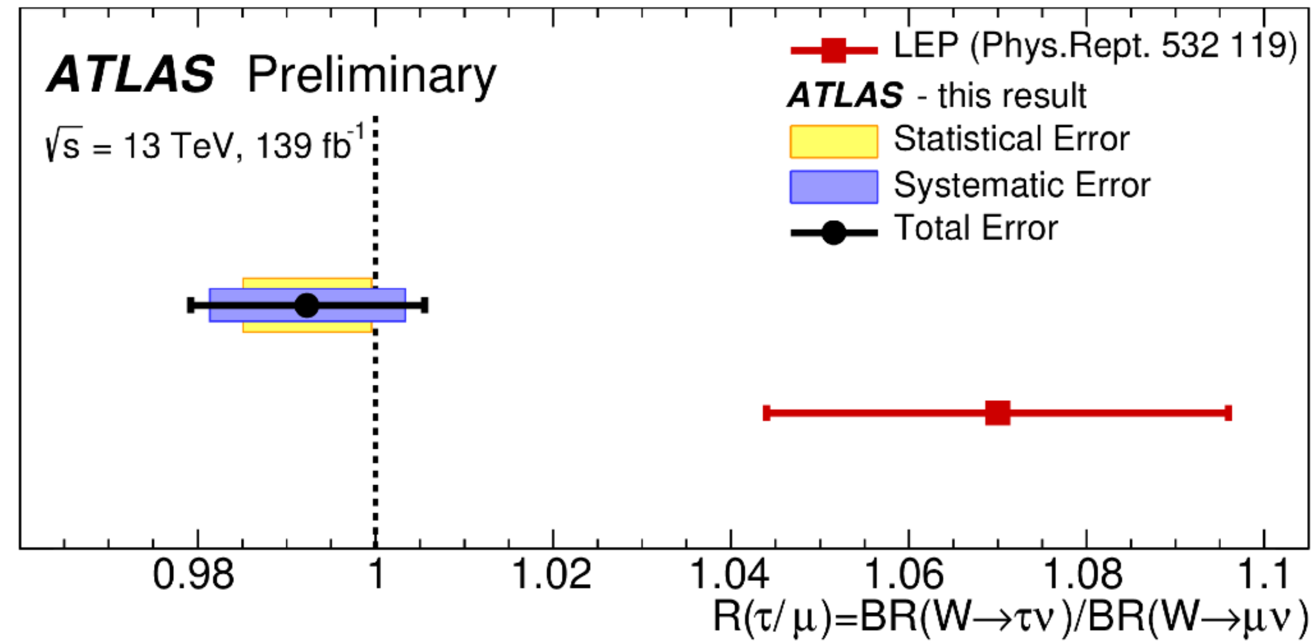
PDG entries dominated by LEP2 data

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40192
$\mu^+\nu$		(10.63 ± 0.15) %		40192
$\tau^+\nu$		(11.38 ± 0.21) %		40173

BR(τ) / BR(e/μ) ~ 1.066 ± 0.025 => ~ 2.5 σ

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

ATLAS 2020:

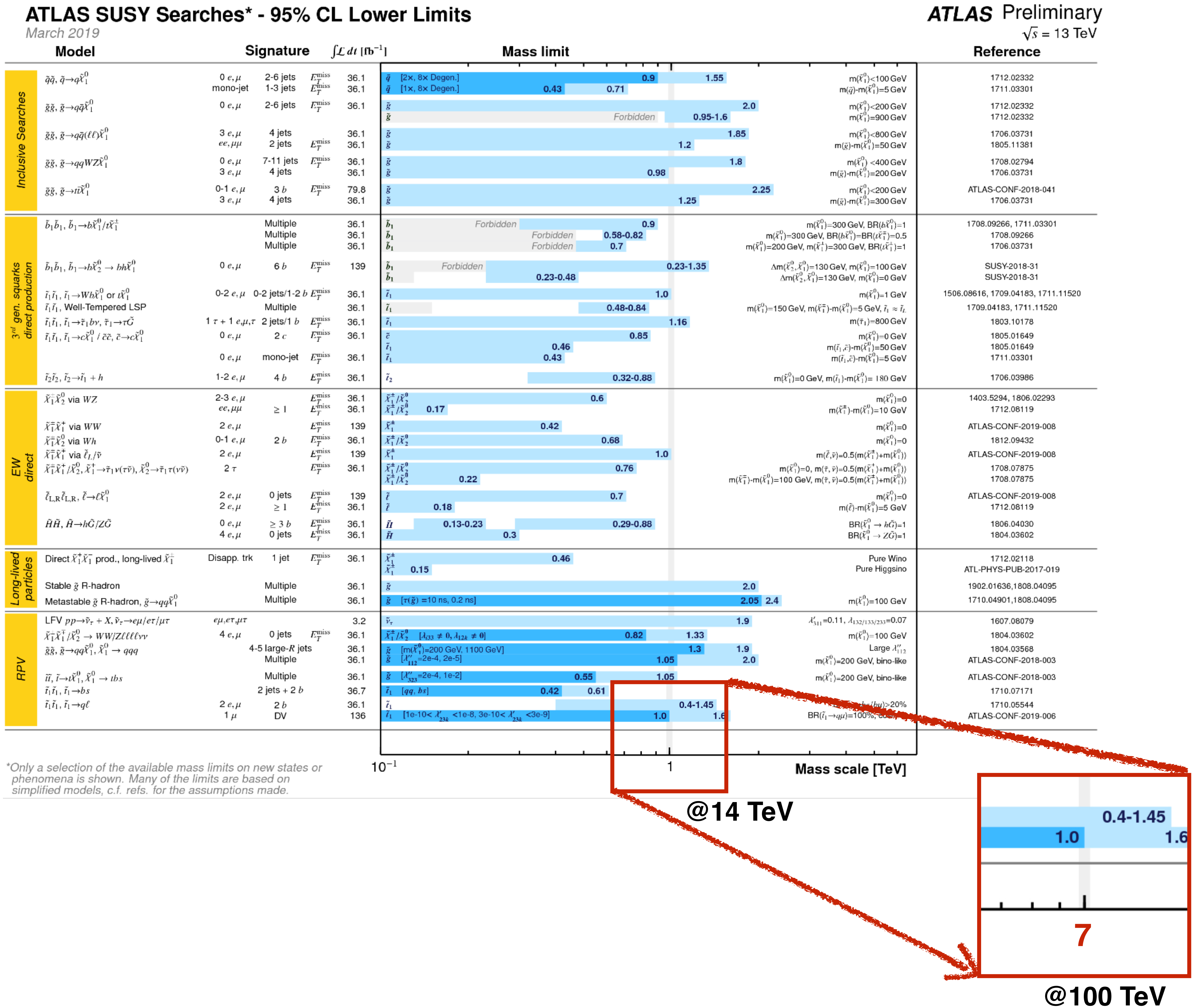


LEP:
***BR*(W→τν)/*BR*(W→μν) = 1.066 ± 0.025**

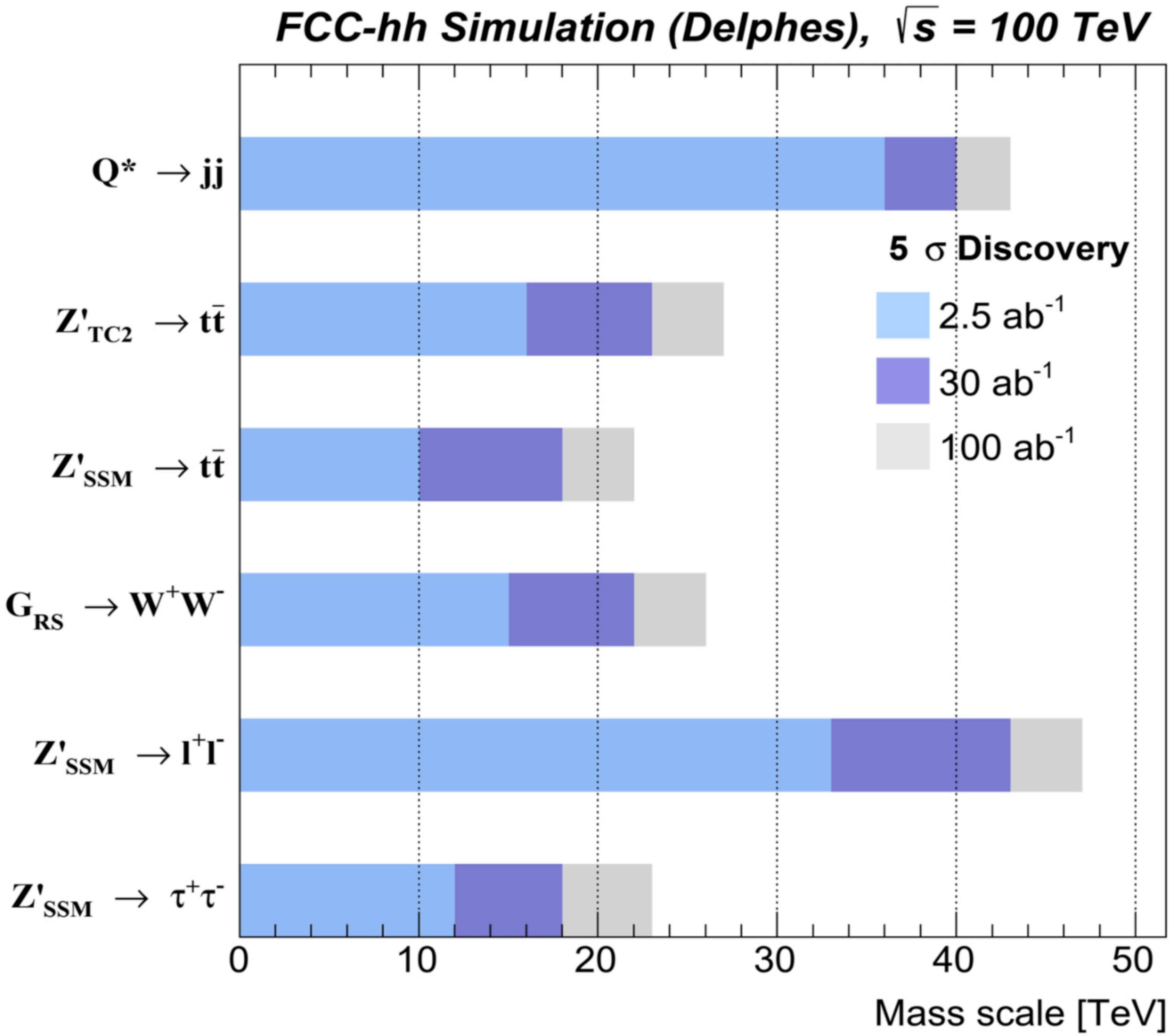
ATLAS:
***BR*(W→τν)/*BR*(W→μν) = 0.992 ± 0.013**

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

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


ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Forbidden
Direct χ̃₁⁺χ̃₁⁻ prod., long-lived χ̃₁±
Disapp. trk
Stable g̃ R-hadron
Metastable g̃ R-hadron, g̃→qqχ̃₁⁰
Pure Wino
Pure Higgsino
Multiple
mono-jet
10⁻¹
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
@14 TeV
0.4-1.45
1.0
1.6
7
@100 TeV

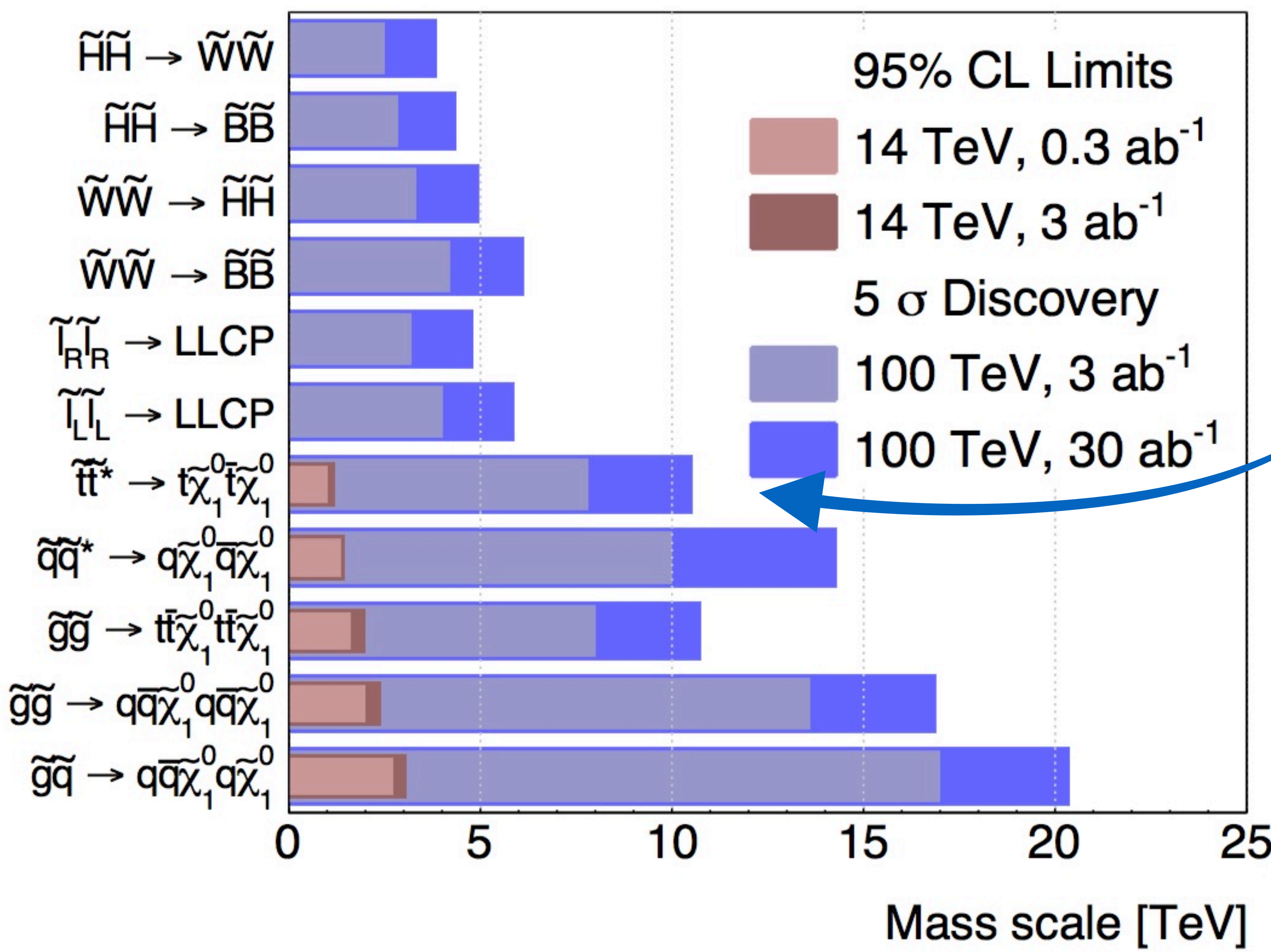
s-channel resonances



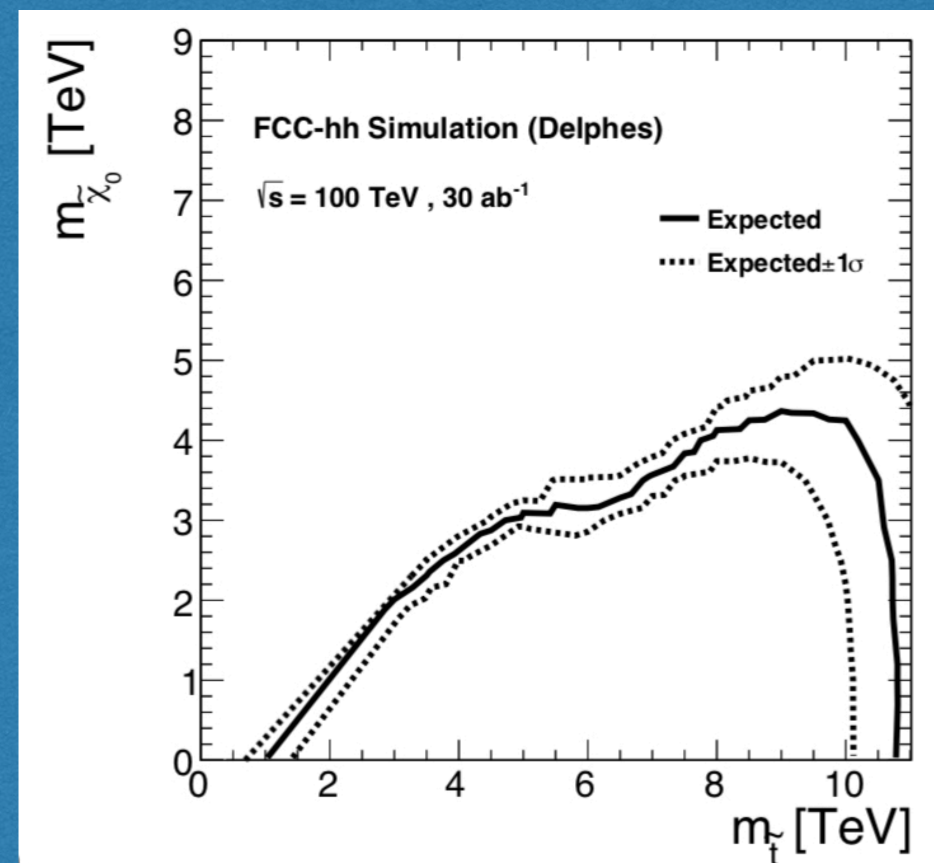
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

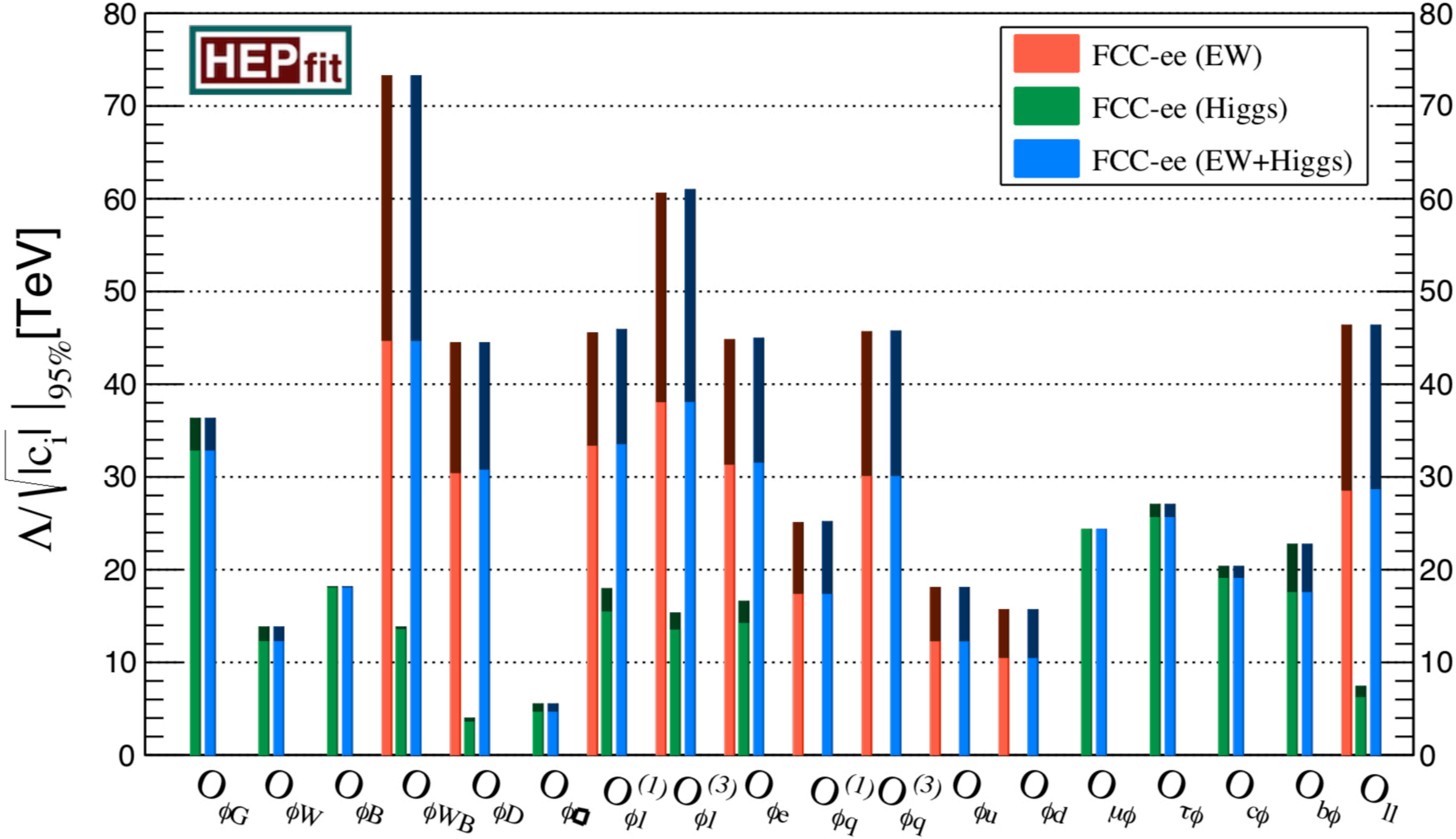
Early phenomenology studies



New detector performance studies



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



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

100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision EW and H measurements at the future ee collider

(3) The potential for yes/no answers to important questions

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

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

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

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

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

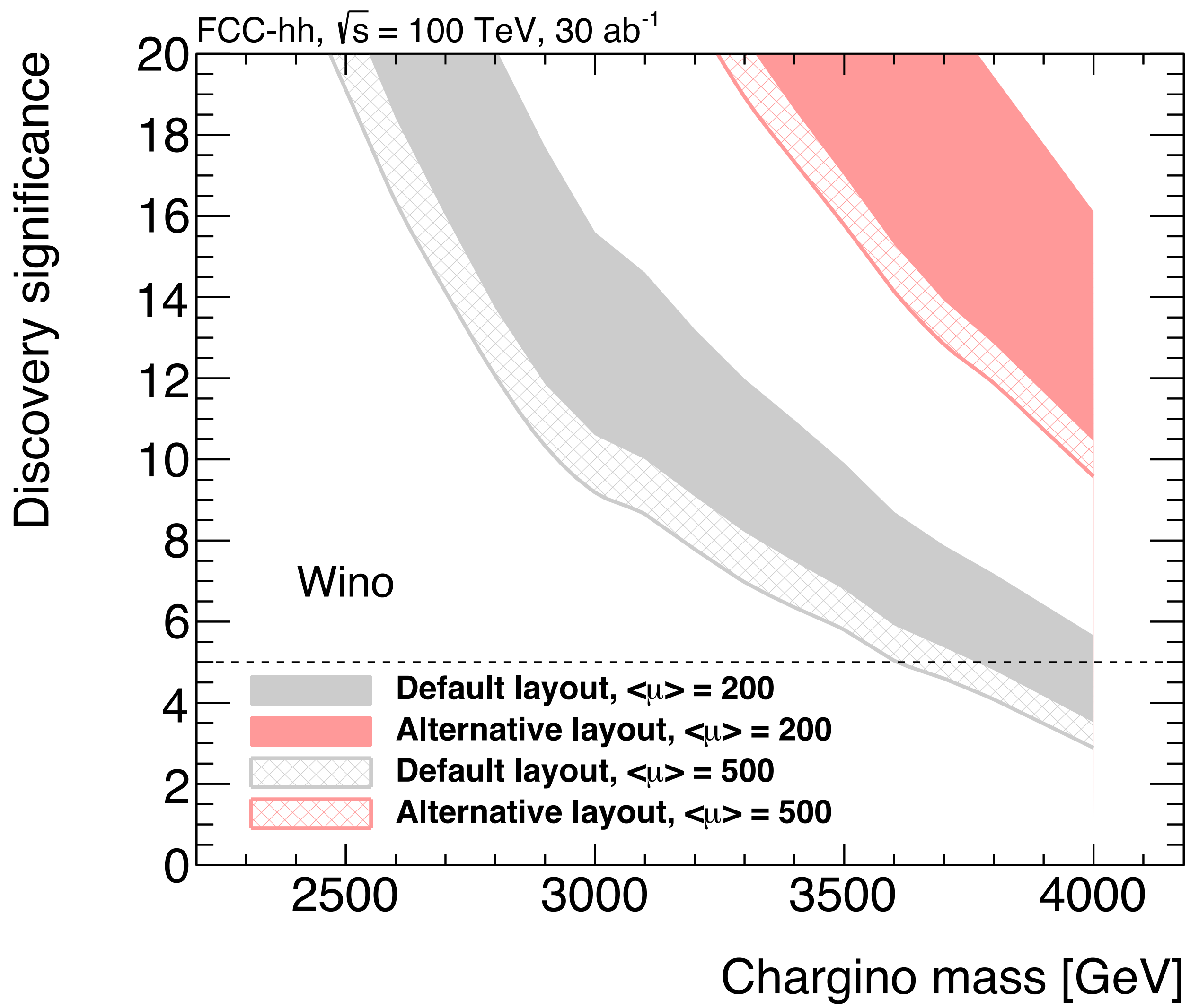
$$\Omega_{wimp}\, h^2 \lesssim 0.12 \quad \Rightarrow \quad M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3} \right)^2$$

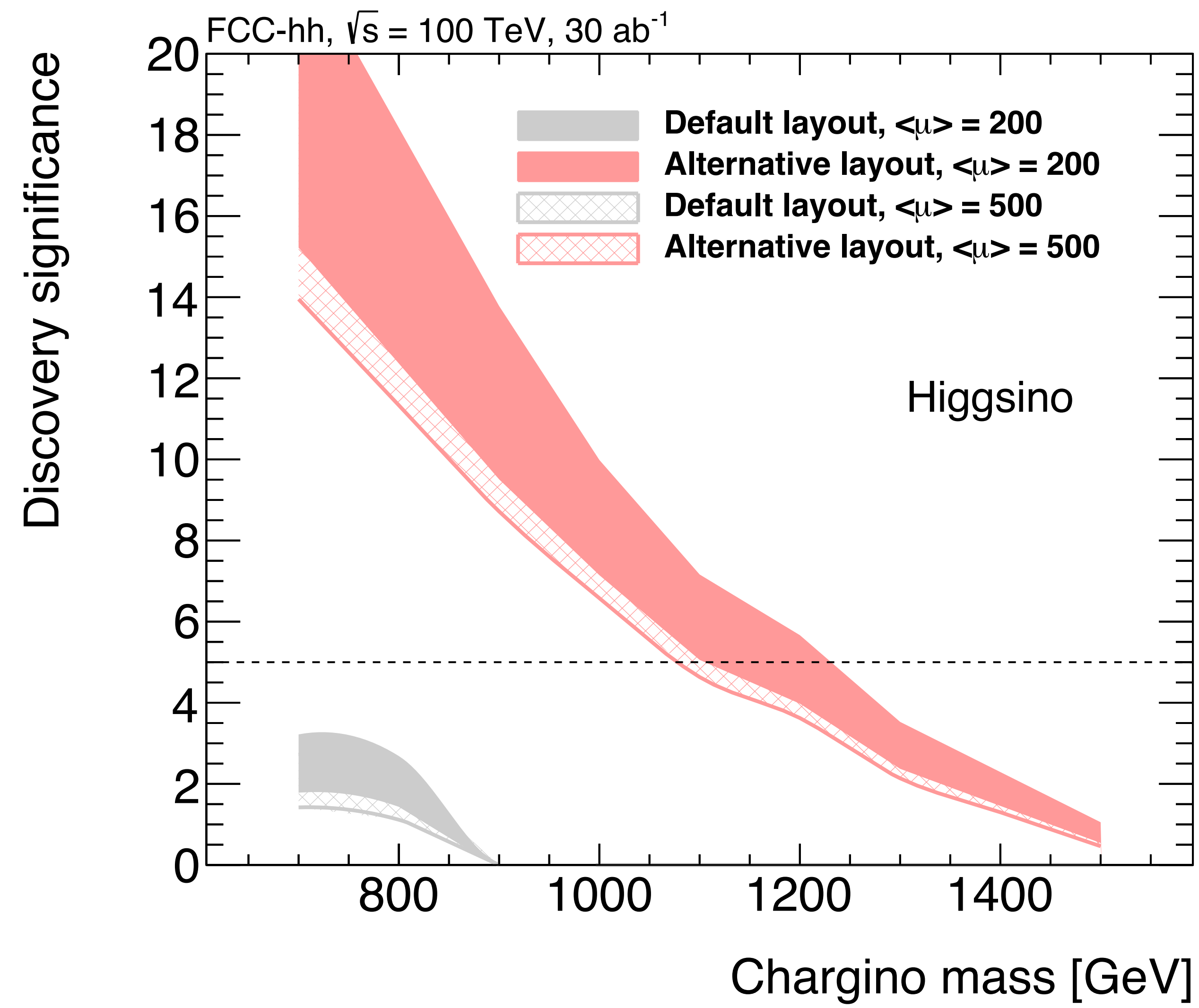
K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

(at ~full pileup)

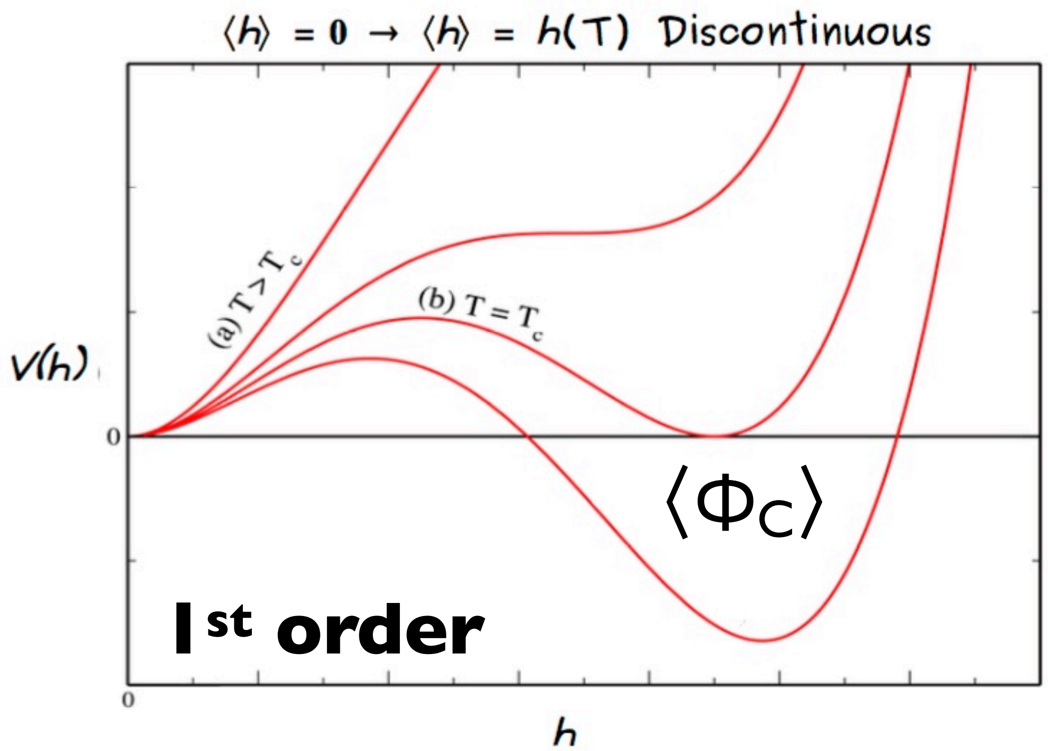


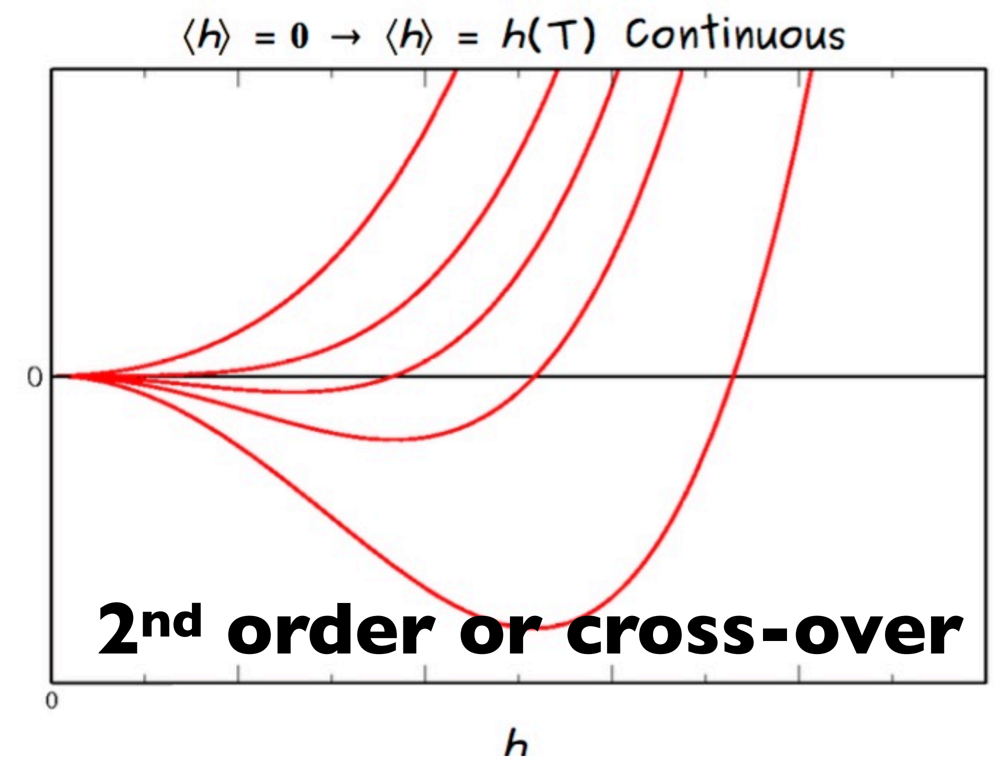


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

The nature of the EW phase transition





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

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

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

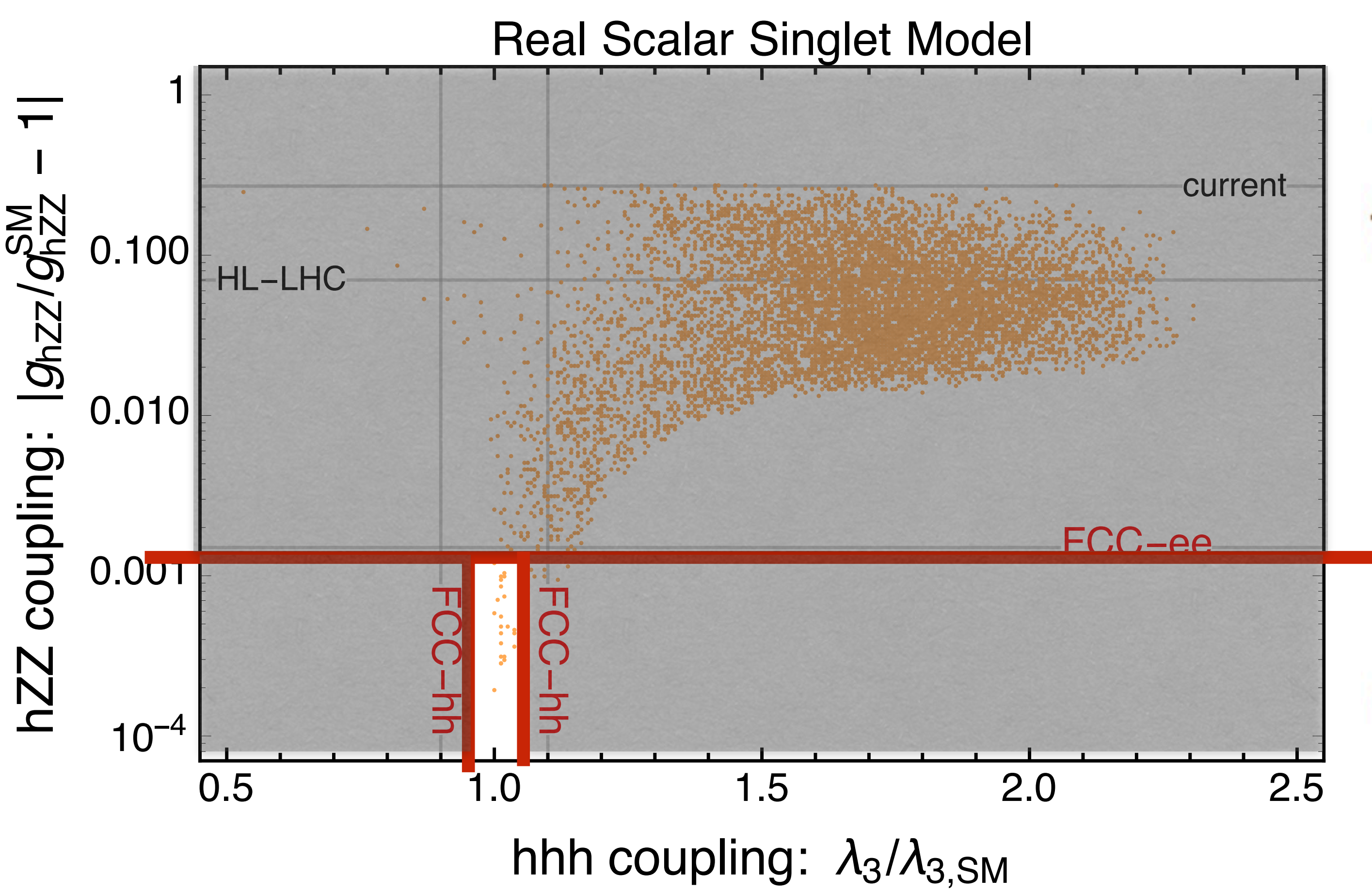
Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

Constraints on models with 1st order phase transition at the FCC

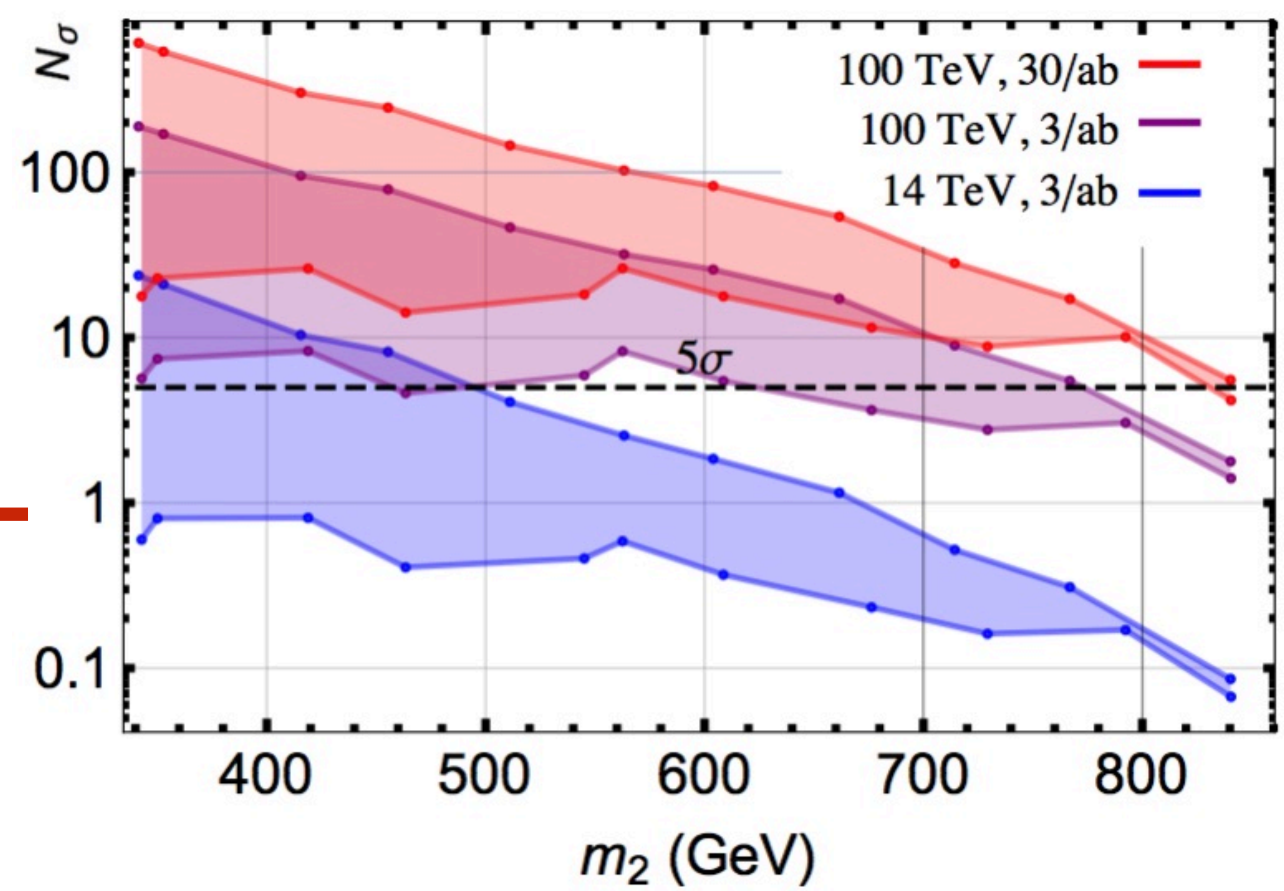
$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

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



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

Direct detection of extra Higgs states at FCC-hh

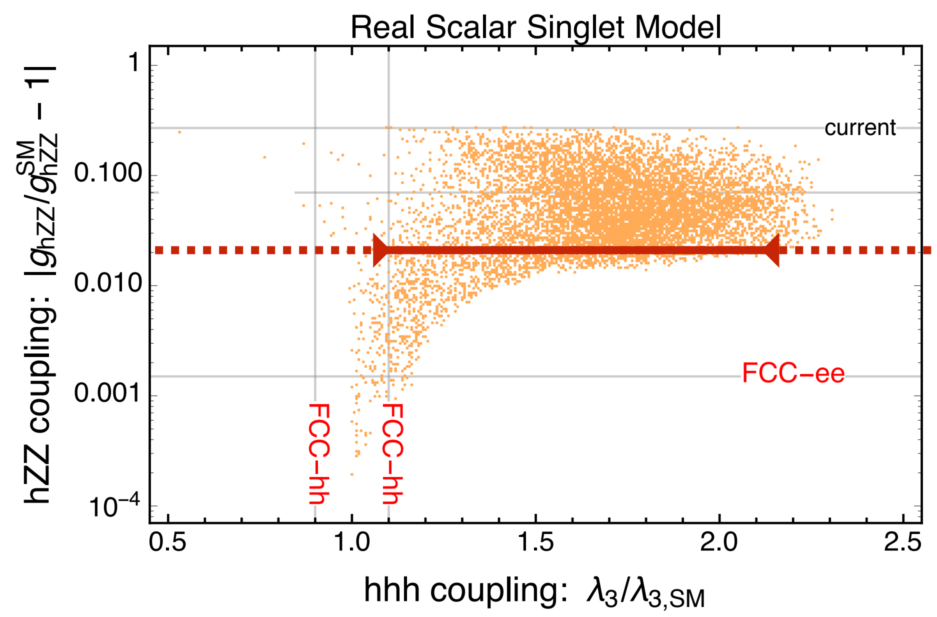


$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

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

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

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 combination of a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, appears like the ideal facility for the post-LHC era
  - *complementary and synergetic precision studies of EW, Higgs and top properties*
  - *energy reach to allow direct discoveries at the mass scales possibly revealed by the precision measurements*