CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Physics prospects of future hadron colliders

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Theory Department,
CERN, Geneva

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

✓Approved
2026-37

HiLumi
HL-LHC PROJECT

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

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FCC
hh ee he

link to CDR

100km tunnel

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

LHC tunnel: HE-LHC

- pp @ 27 TeV, 15ab^{-1}

Lecture 2 by B. Ferrando

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Lecture 2 by B. Ferrando

CEPC

[link to CDR]

100km tunnel

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

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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

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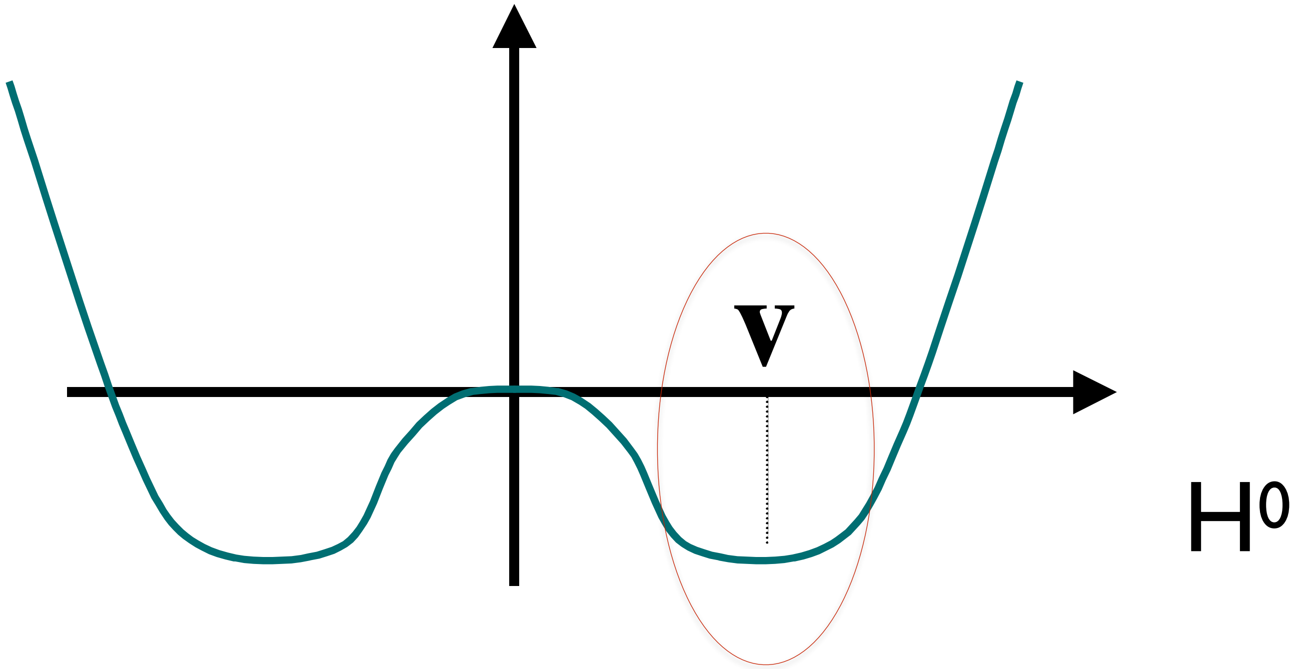
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase 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?
  - …

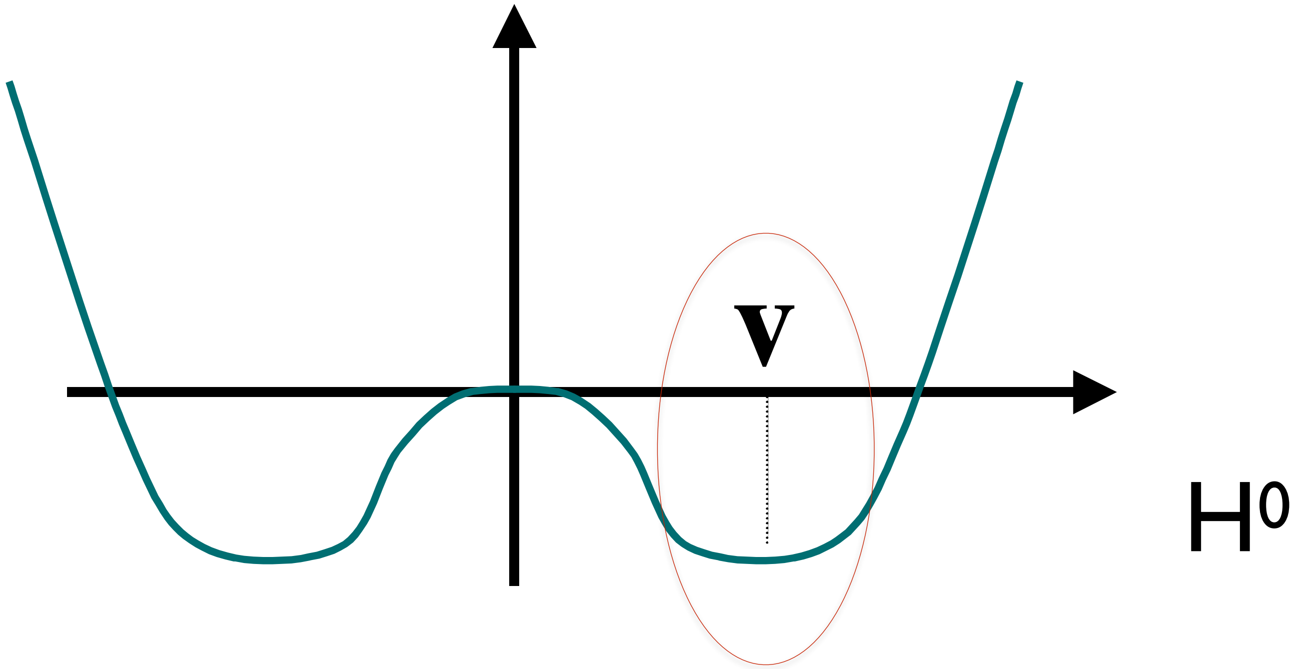
Guaranteed deliverables:

what more will we need to know about the Higgs after the HL-LHC? will it not get “boring” to keep studying the Higgs and the top?



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

Who ordered that ?



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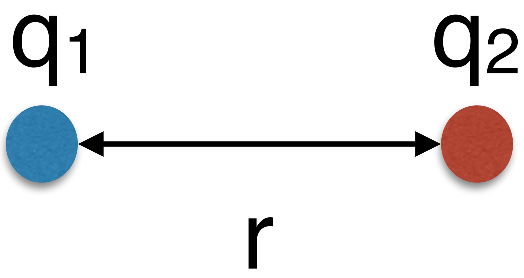
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics



$$V(r) = + \frac{q_1 \mathrm{x}\, q_2}{r^{1}}$$

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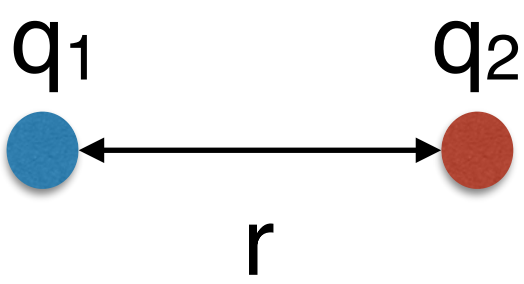

quantized,
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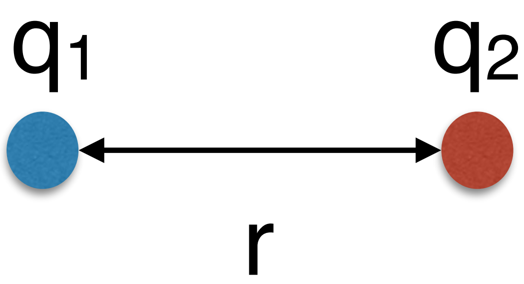

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power determined by gauge
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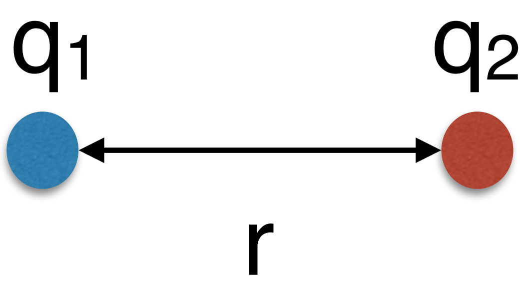

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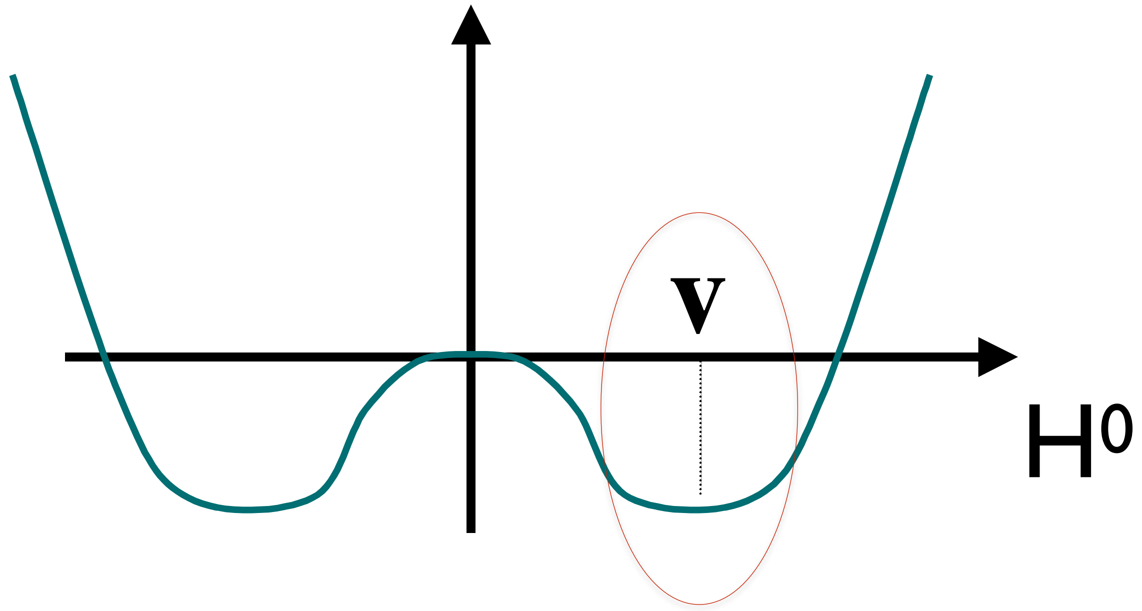

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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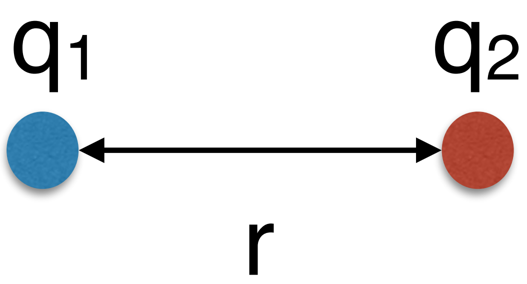

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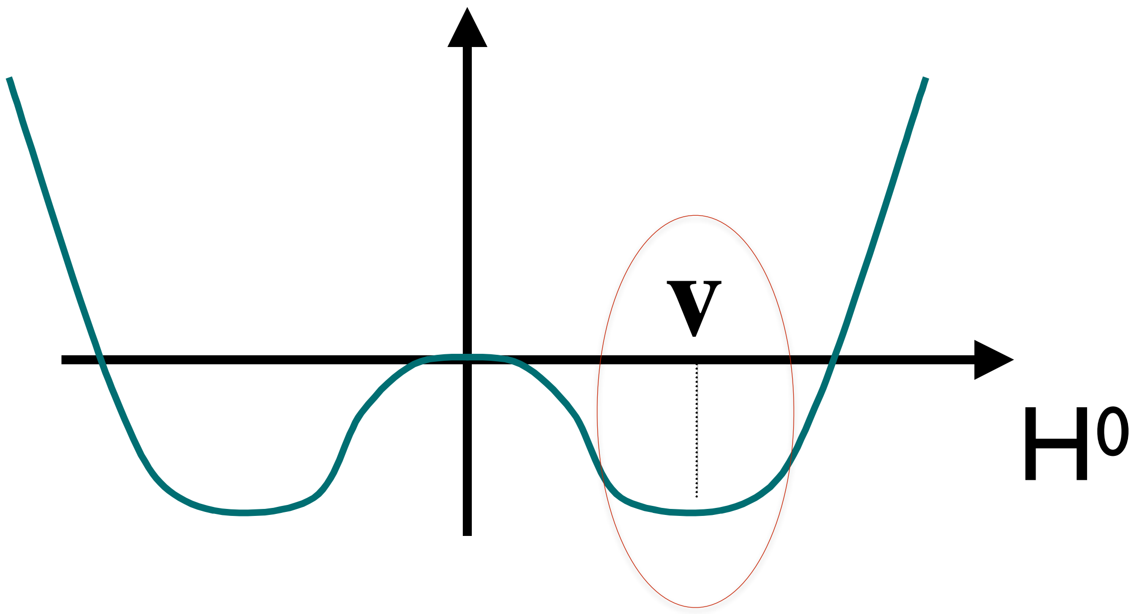

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both sign
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>0 to ensure
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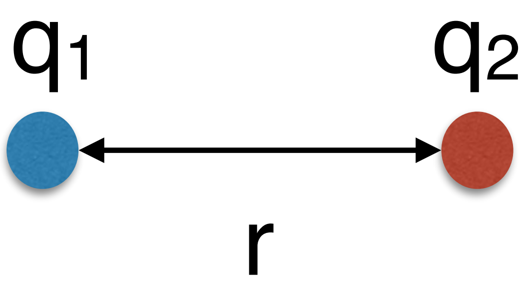
Electromagnetic vs Higgs dynamics



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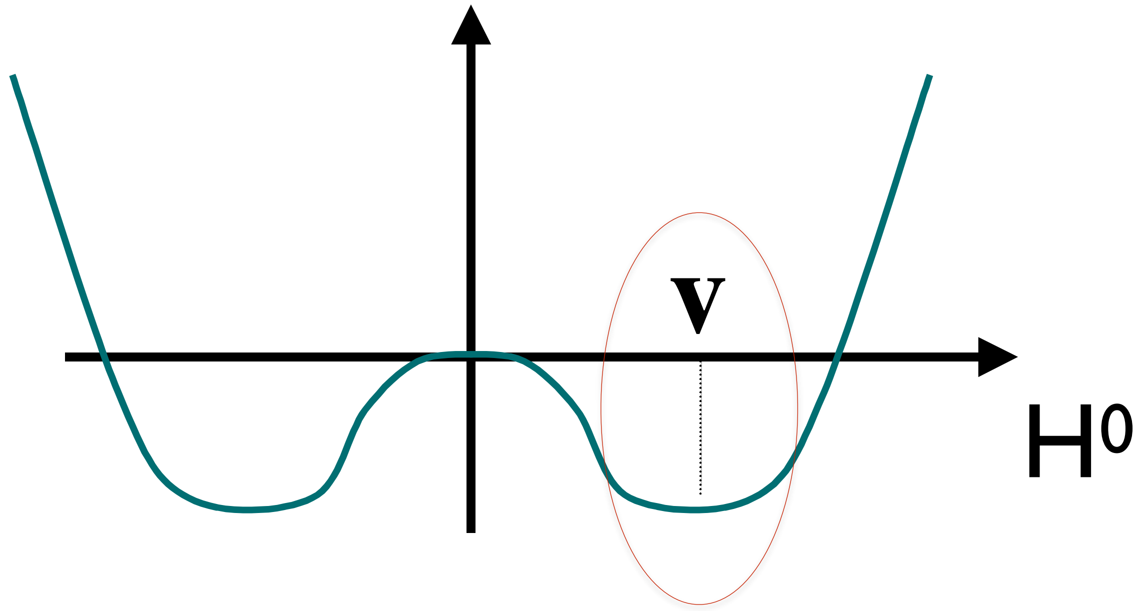

any function of $|H|^2$ would be ok wrt known symmetries

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both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

a historical example: superconductivity

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

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

examples of possible scenarios

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

furthermore …

Hierarchy problem and naturalness !!

Lecture 2 by M. Mc Cullough

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=> colliders are the only facilities that make this possible

Other important open issues on the Higgs sector

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- 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)?
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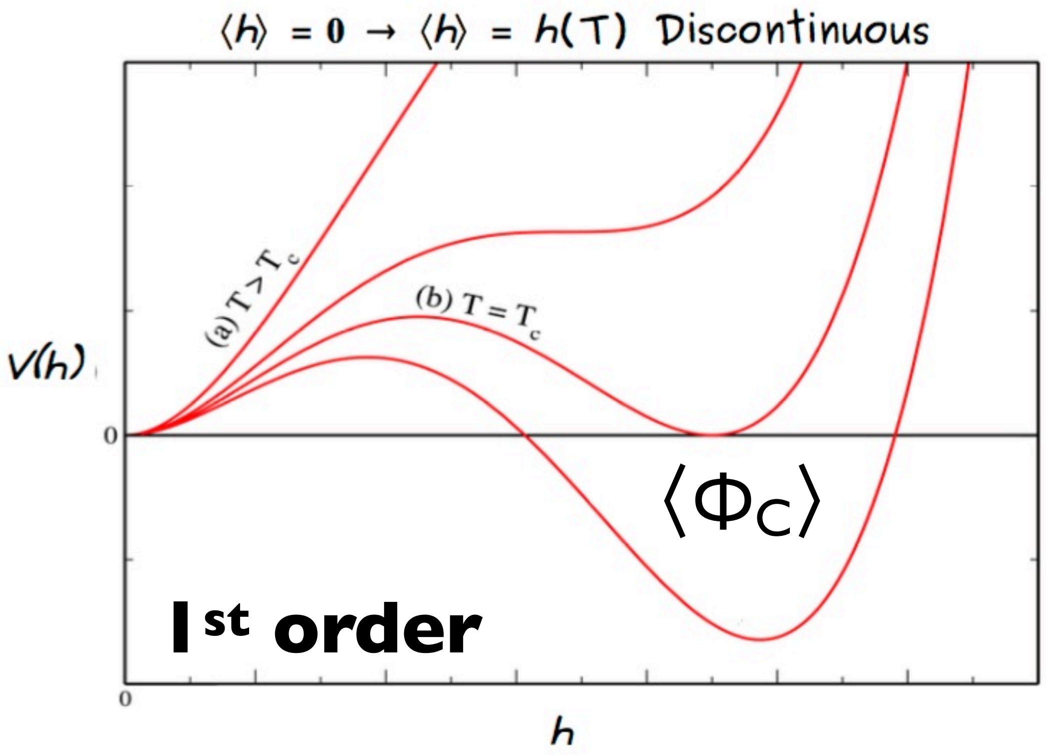
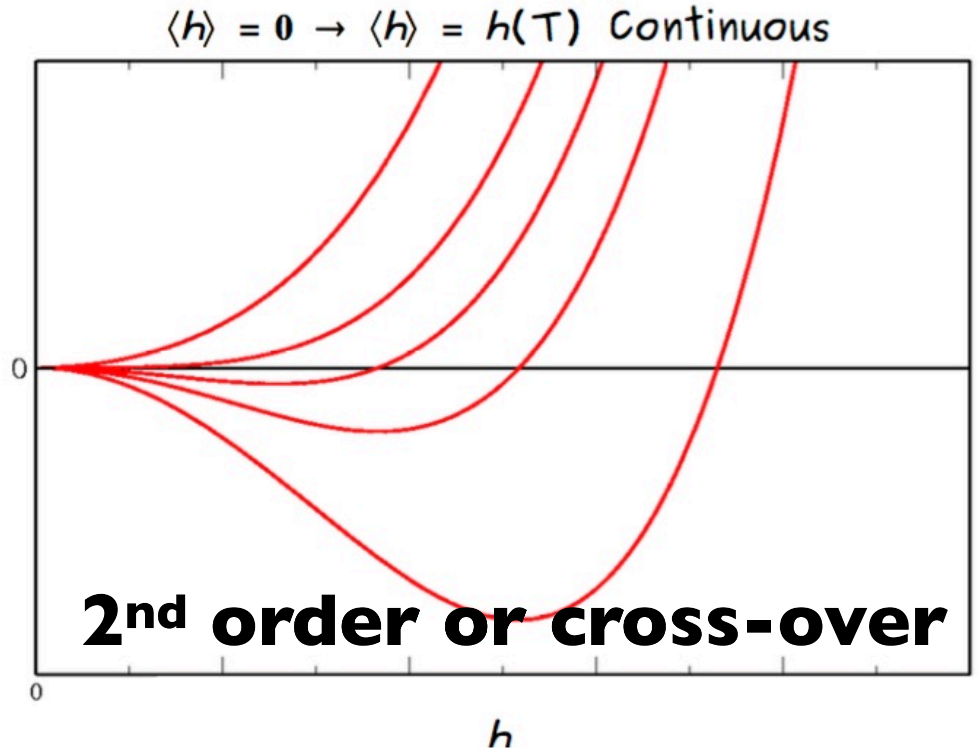
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

The nature of the EW phase transition





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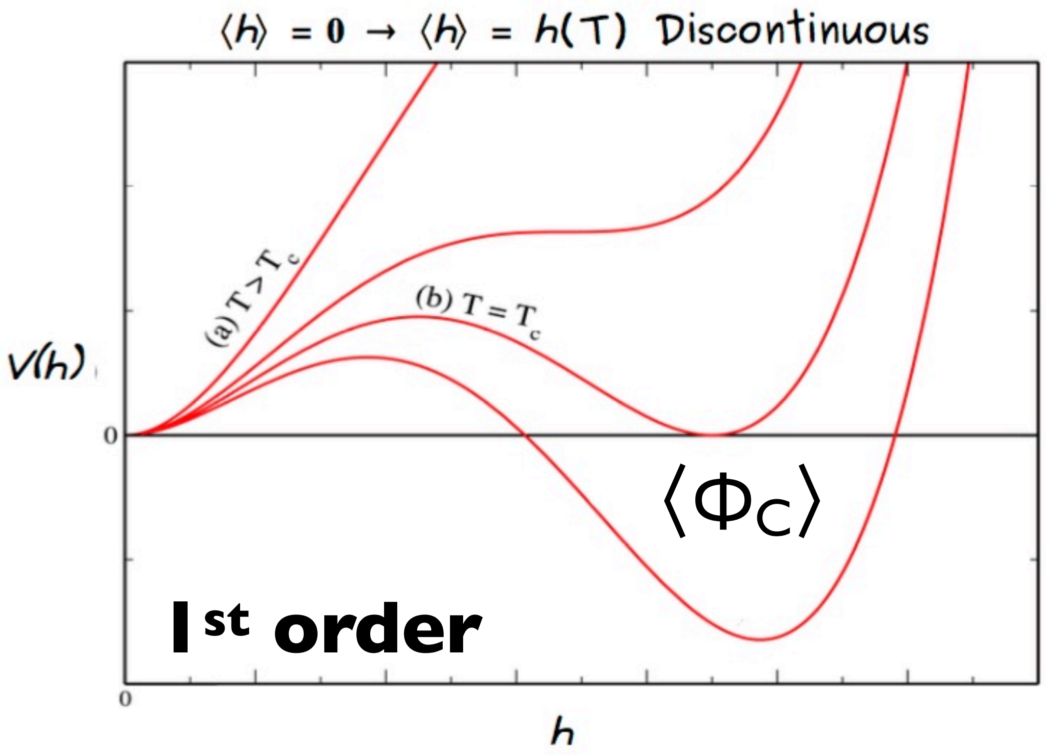

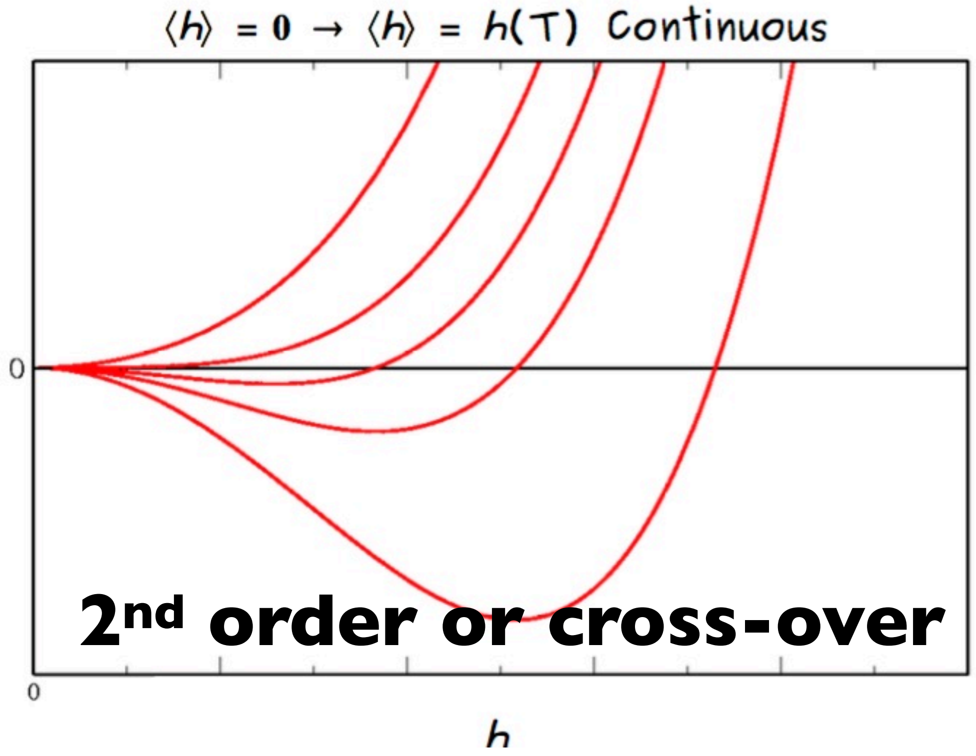

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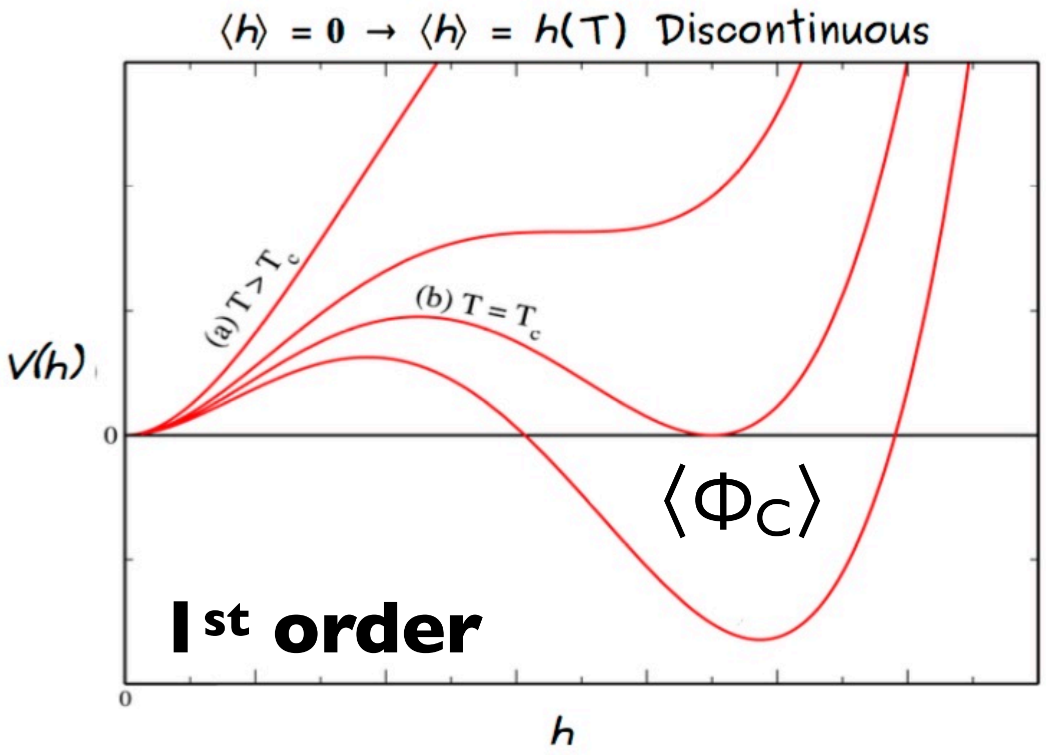

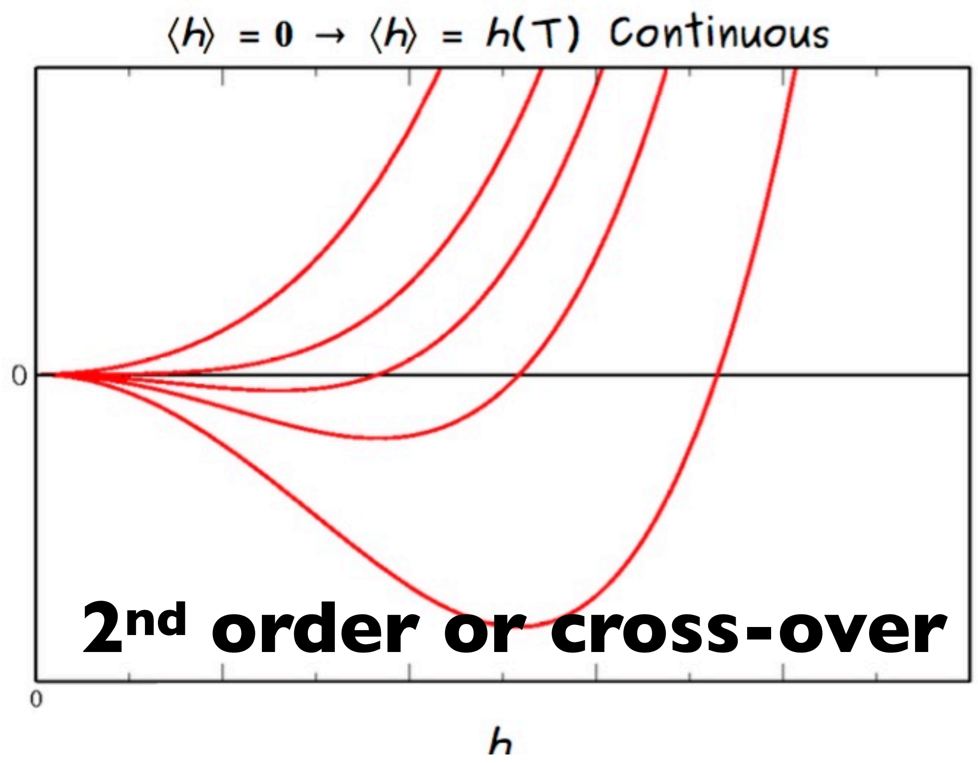

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Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

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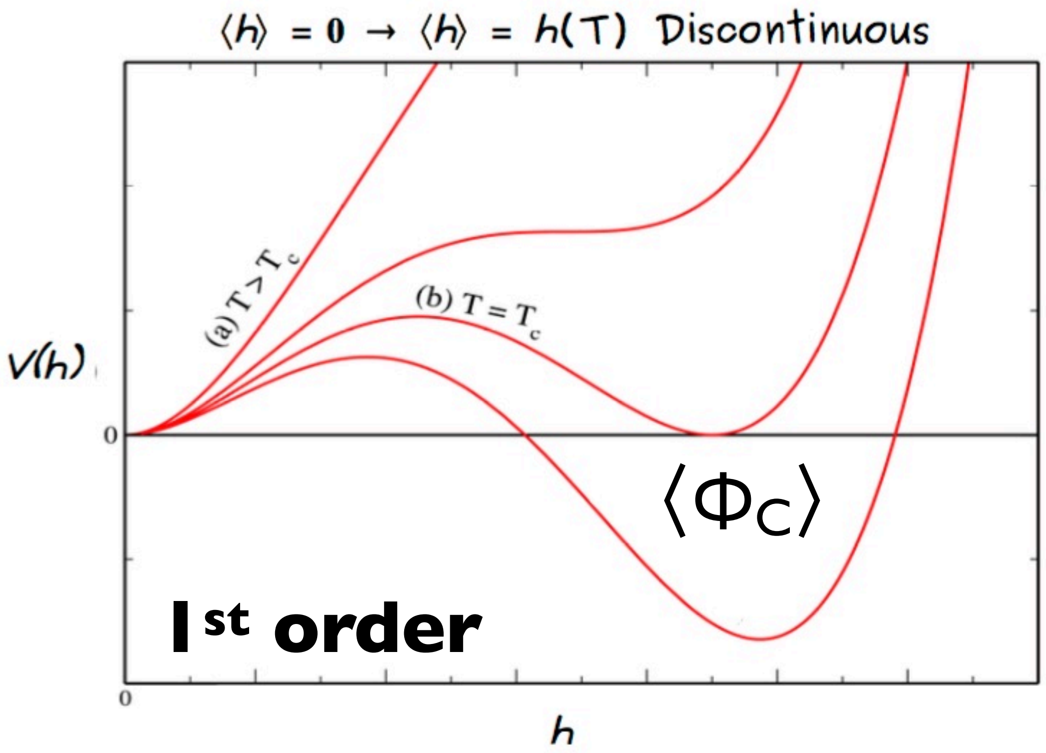

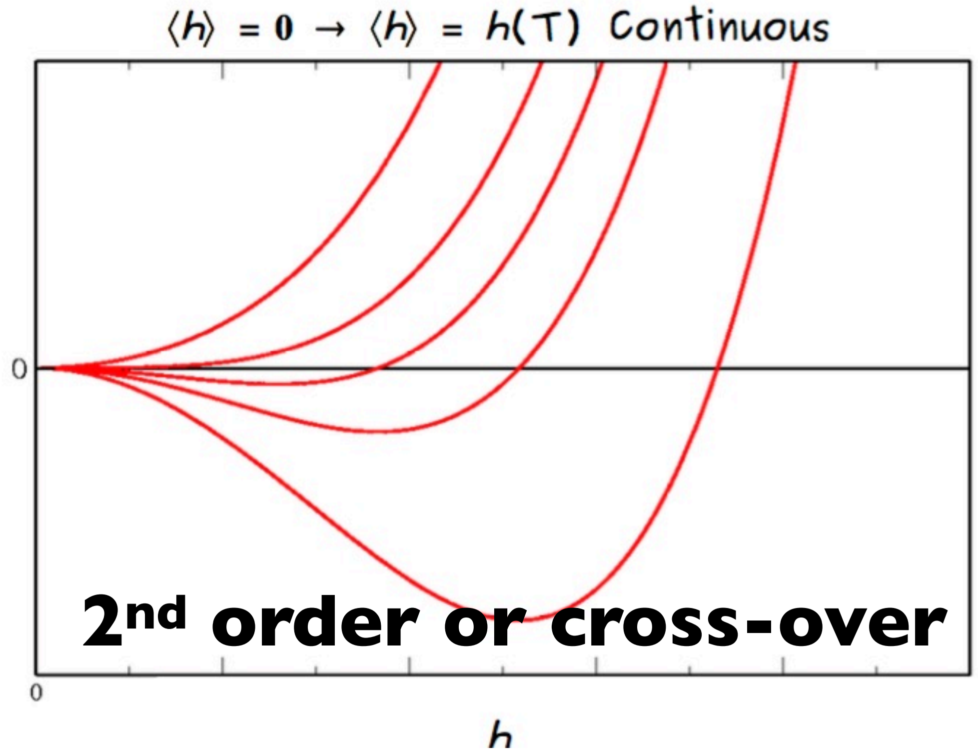

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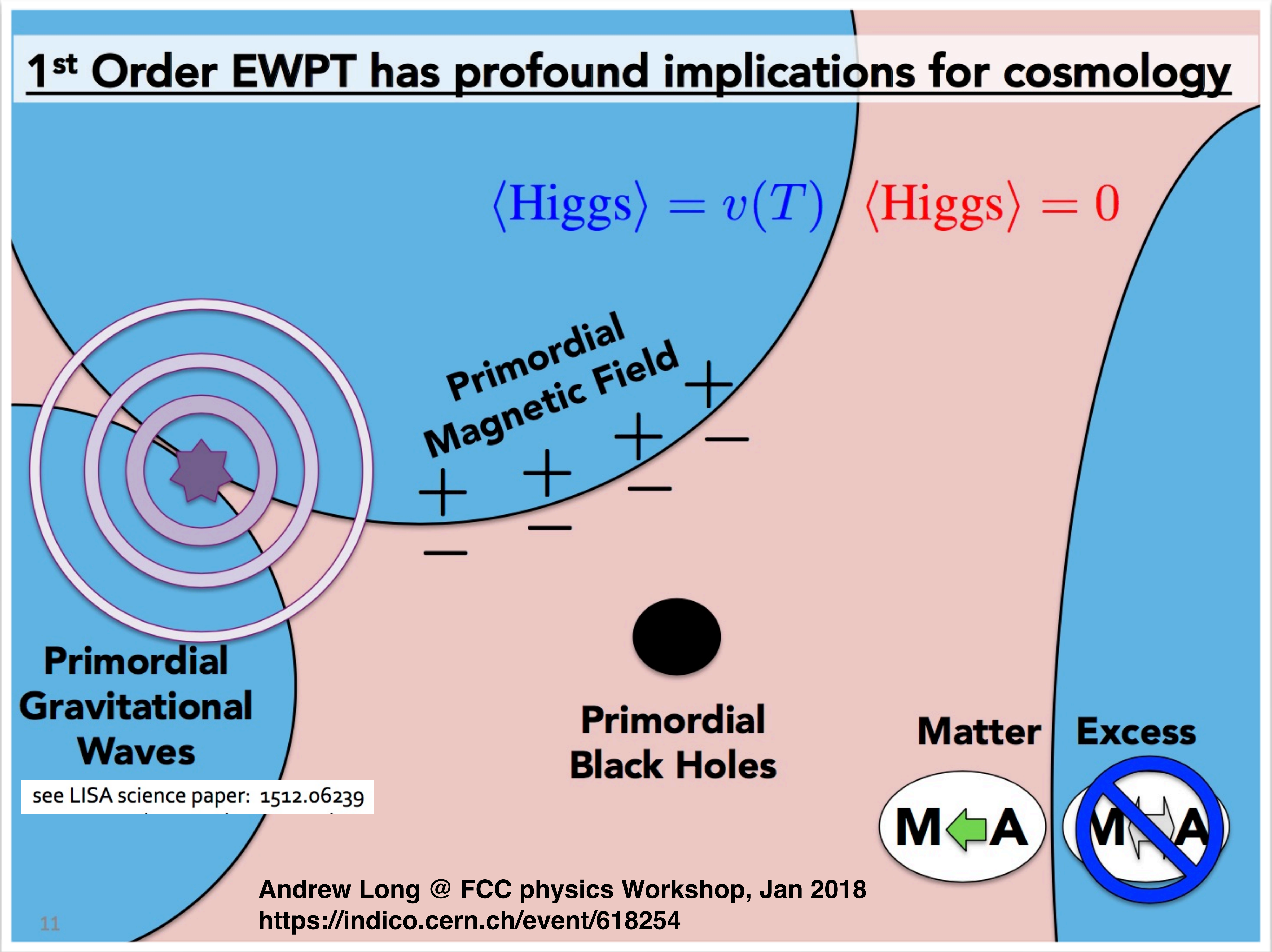
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**



1st Order EWPT has profound implications for cosmology

$\langle \text{Higgs} \rangle = v(T)$ $\langle \text{Higgs} \rangle = 0$

Primordial Magnetic Field

Primordial Gravitational Waves

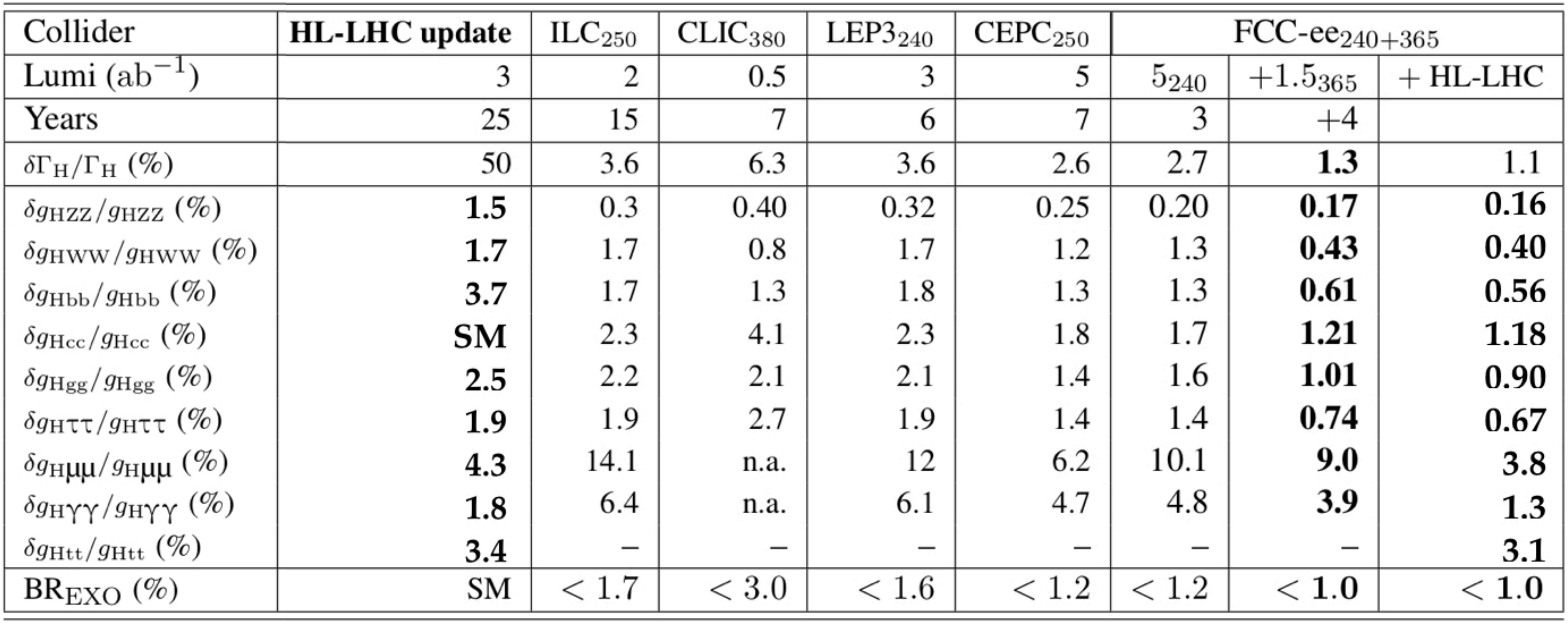
see LISA science paper: 1512.06239

Primordial Black Holes

Matter Excess

Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

Higgs couplings, beyond the HL-LHC: the e^+e^- phase



Collider	**HL-LHC update**	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\mathrm{FCC\text{-}ee}_{240+365}$		
Lumi (ab^{-1})	3	2	0.5	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	7	6	7	3	+4	
$\delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}$ (%)	50	3.6	6.3	3.6	2.6	2.7	**1.3**	1.1
$\delta g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}$ (%)	**1.5**	0.3	0.40	0.32	0.25	0.20	**0.17**	**0.16**
$\delta g_{\mathrm{HWW}}/g_{\mathrm{HWW}}$ (%)	**1.7**	1.7	0.8	1.7	1.2	1.3	**0.43**	**0.40**
$\delta g_{\mathrm{Hbb}}/g_{\mathrm{Hbb}}$ (%)	**3.7**	1.7	1.3	1.8	1.3	1.3	**0.61**	**0.56**
$\delta g_{\mathrm{Hcc}}/g_{\mathrm{Hcc}}$ (%)	**SM**	2.3	4.1	2.3	1.8	1.7	**1.21**	**1.18**
$\delta g_{\mathrm{Hgg}}/g_{\mathrm{Hgg}}$ (%)	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{\mathrm{H\tau\tau}}/g_{\mathrm{H\tau\tau}}$ (%)	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{\mathrm{H\mu\mu}}/g_{\mathrm{H\mu\mu}}$ (%)	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{\mathrm{H\gamma\gamma}}/g_{\mathrm{H\gamma\gamma}}$ (%)	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{\mathrm{Htt}}/g_{\mathrm{Htt}}$ (%)	**3.4**	–	–	–	–	–	–	**3.1**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	$< \mathbf{1.0}$	$< \mathbf{1.0}$

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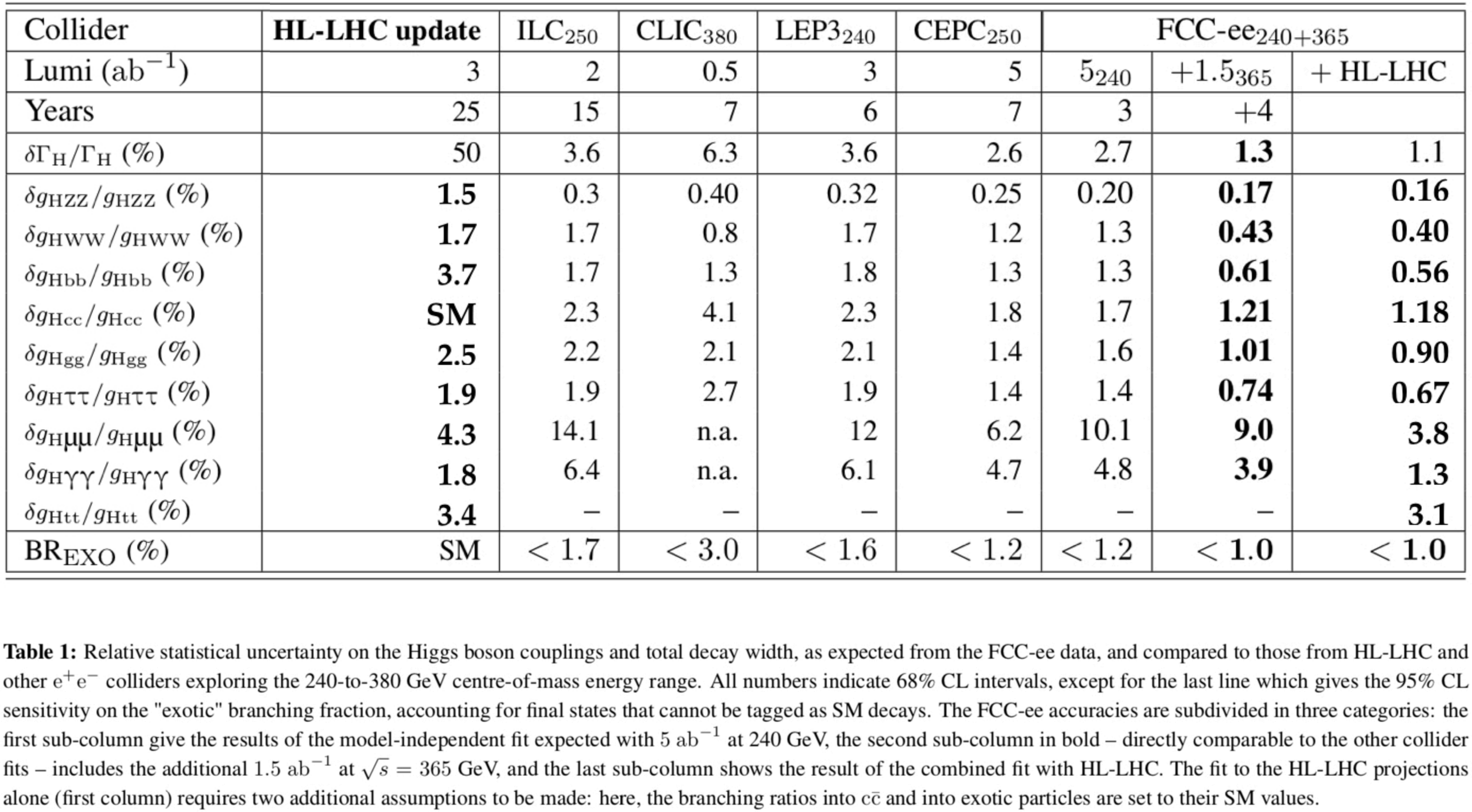

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$\delta g_{Hgg}/g_{Hgg}$ (%)	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{Htt}/g_{Htt}$ (%)	**3.4**	–	–	–	–	–	–	**3.1**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	$\mathbf{< 1.0}$	$\mathbf{< 1.0}$

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with 5 ab^{-1} at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $c\bar{c}$ and into exotic particles are set to their SM values.

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as $H\gamma\gamma$, $H\mu\mu$, $HZ\gamma$, Htt

The unique contributions of a *100 TeV pp collider to Higgs physics*

- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition
    - …

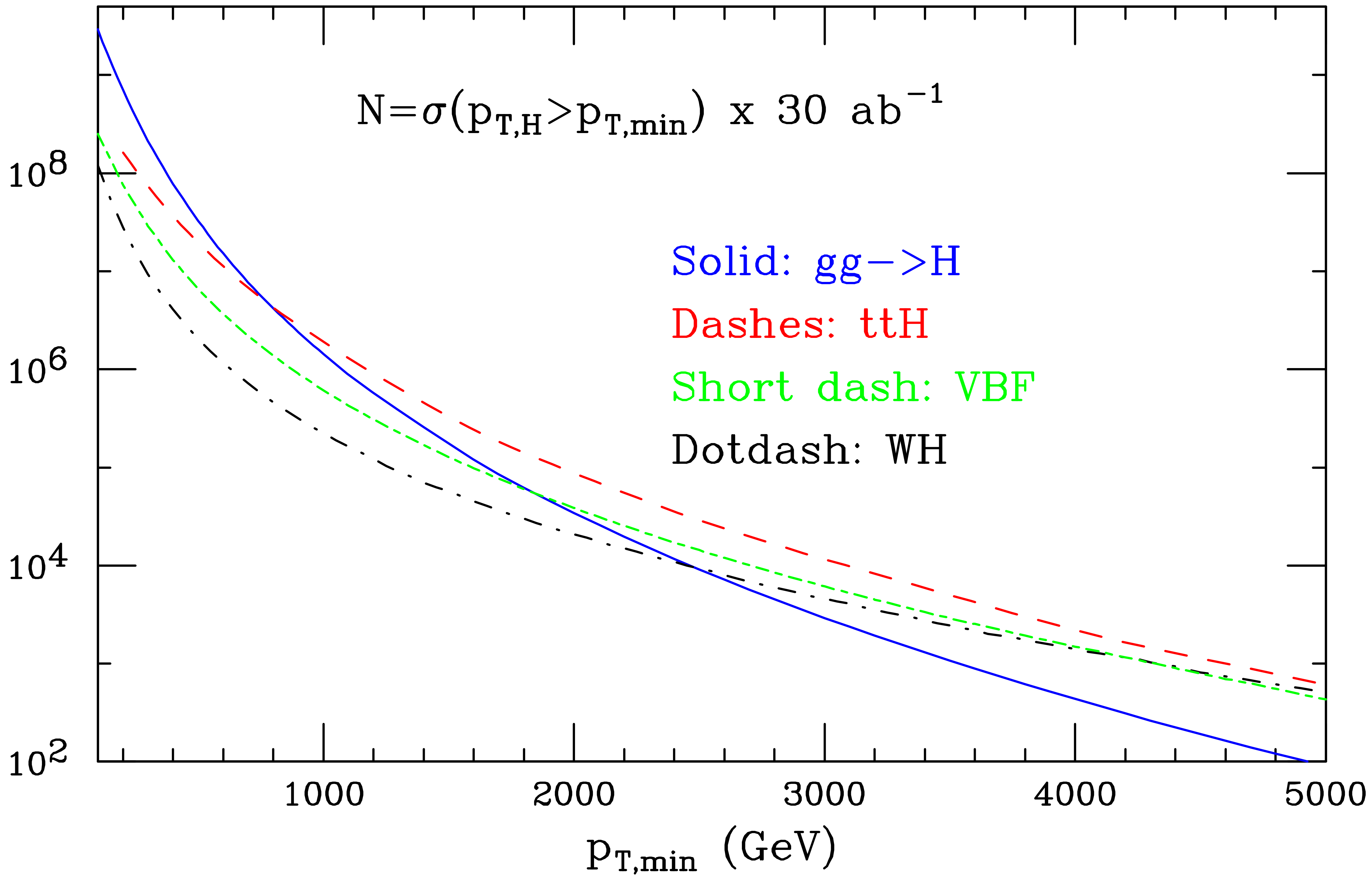
SM Higgs: event rates in pp@100 TeV

	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

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

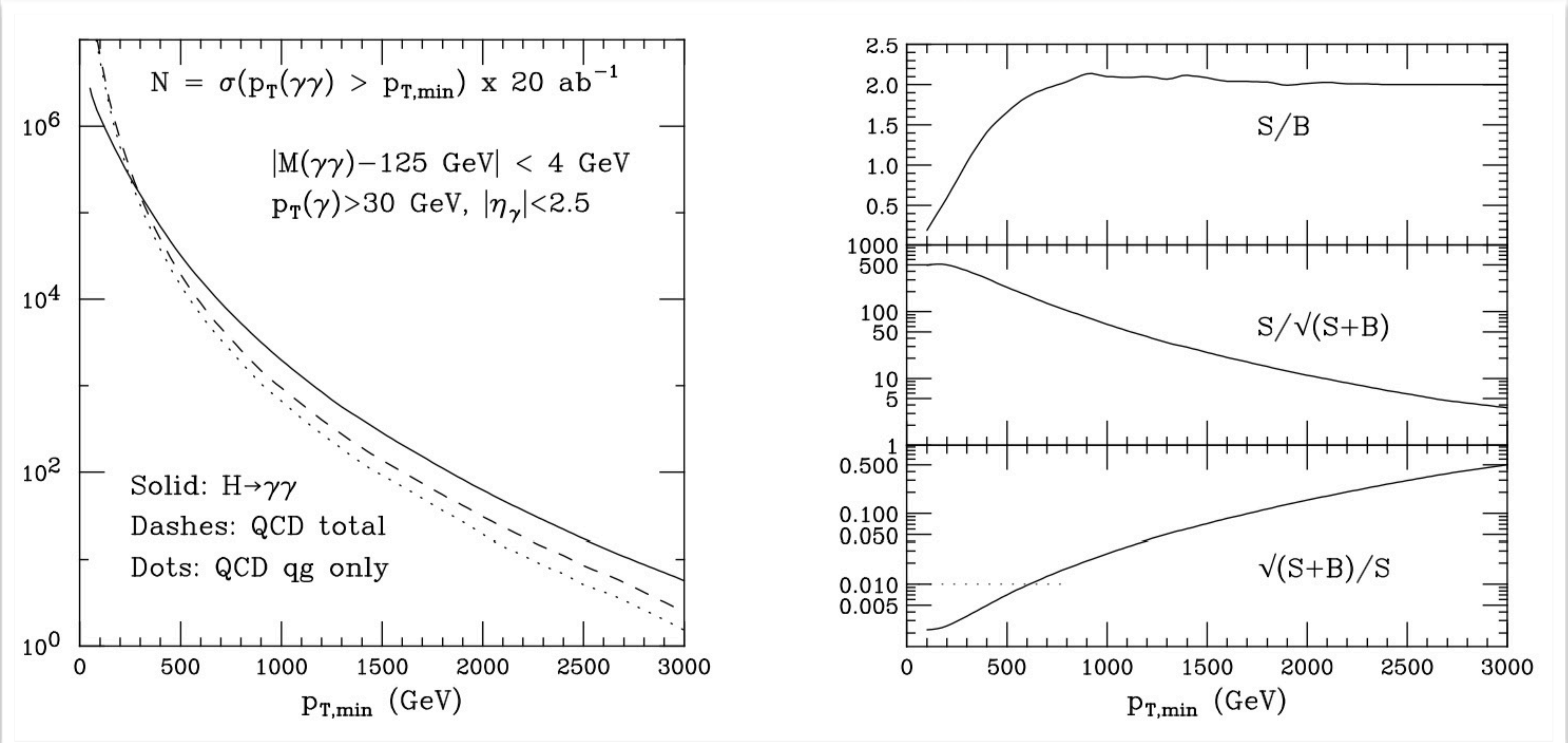
$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

H at large p_T



- Hierarchy of production channels changes at large p_T(H):
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

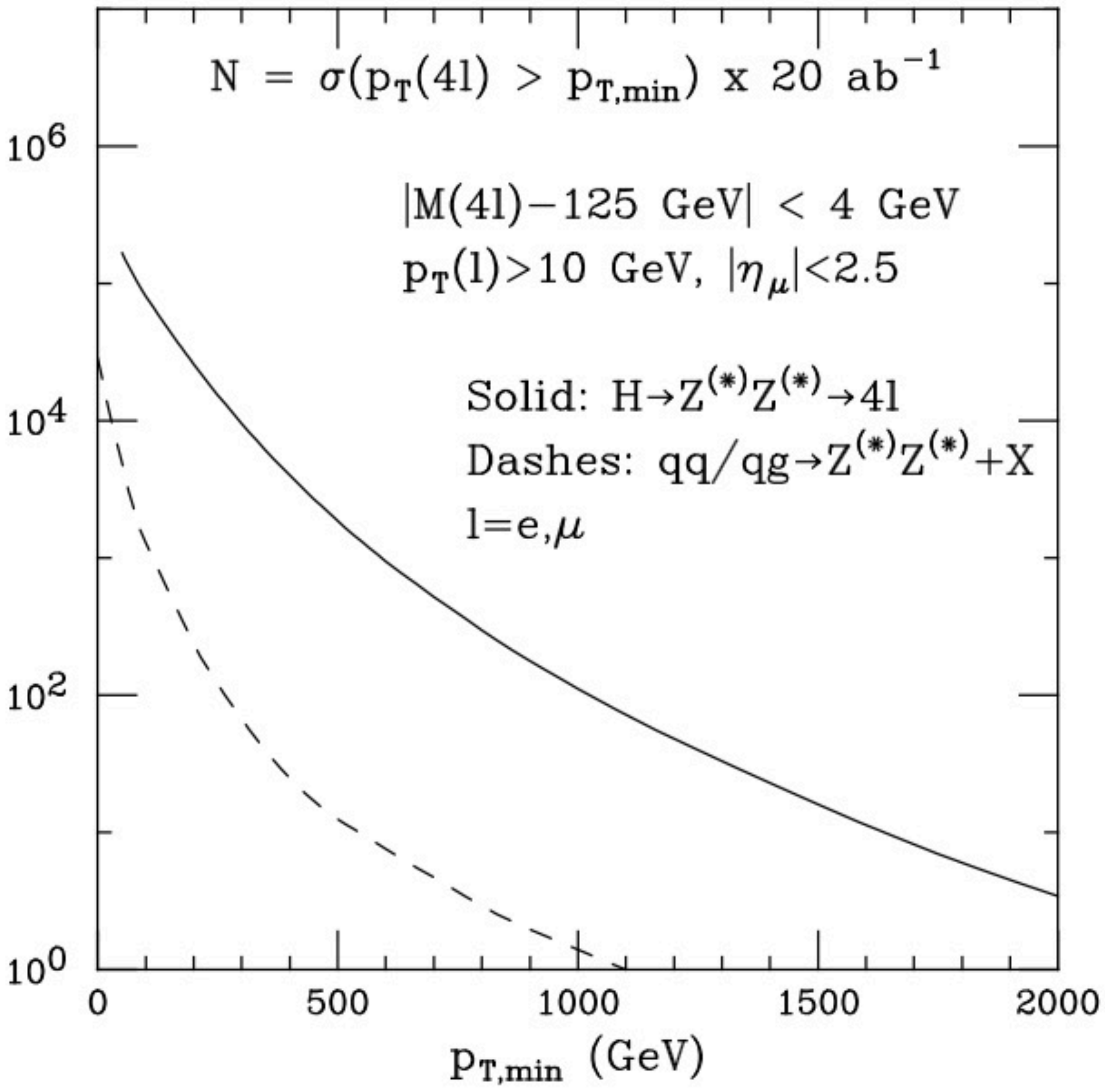
gg→H→γγ at large p_T

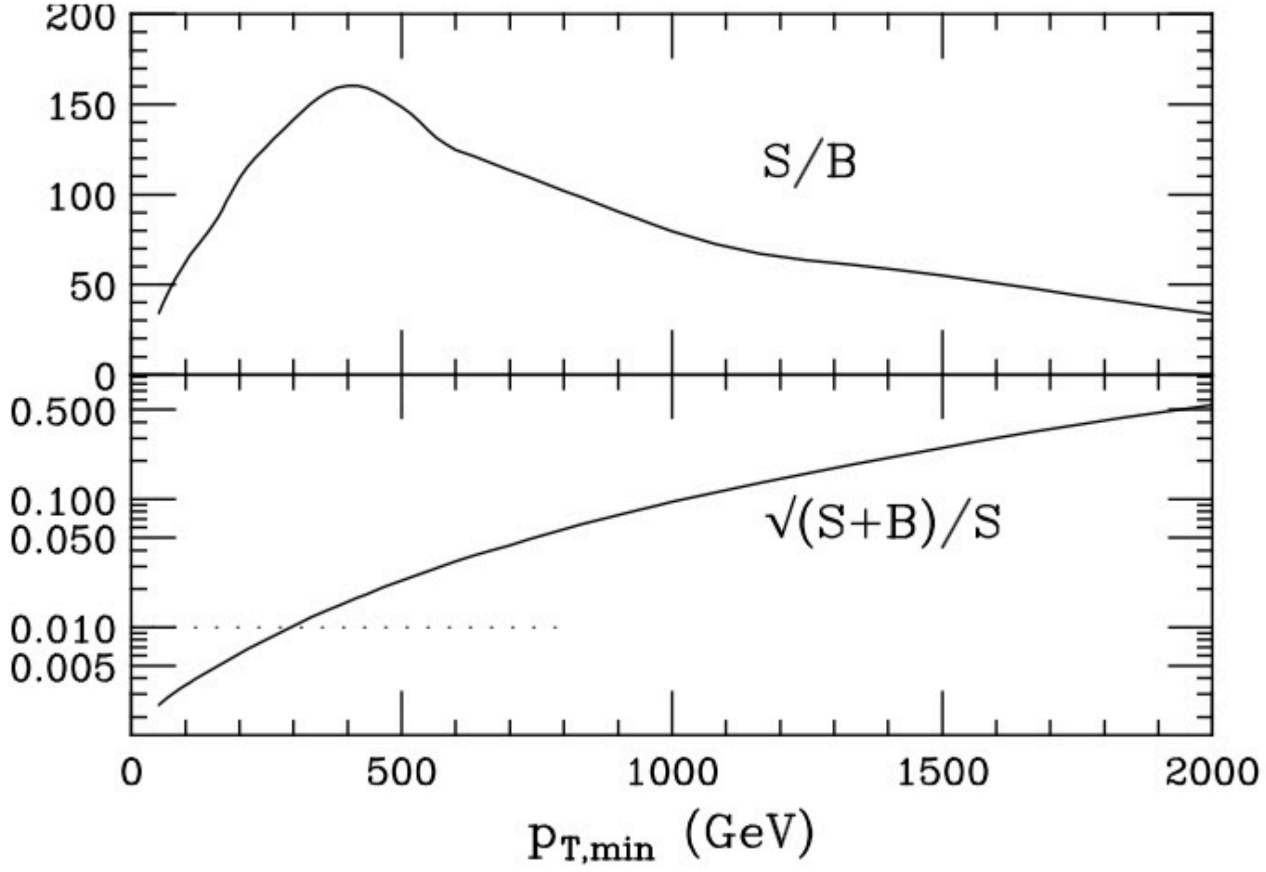


- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

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

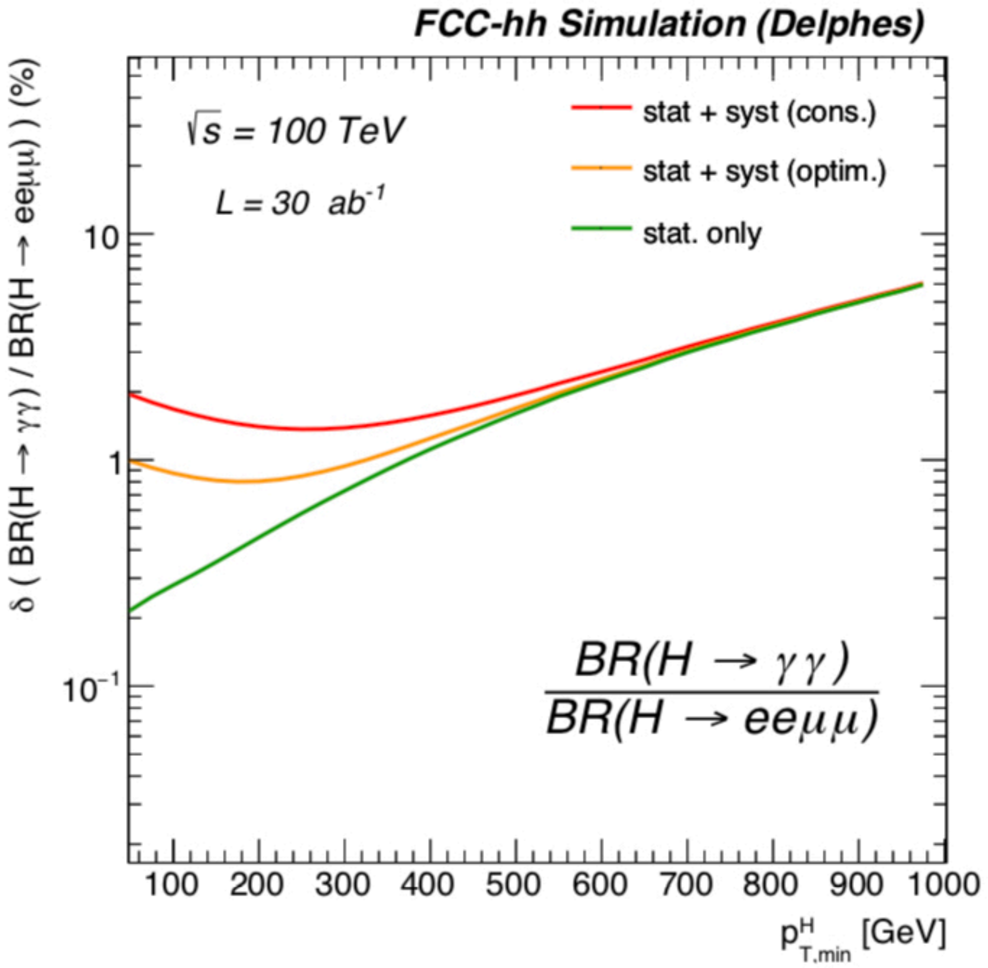
$gg \to H \to ZZ^* \to 4l$ at large p_T

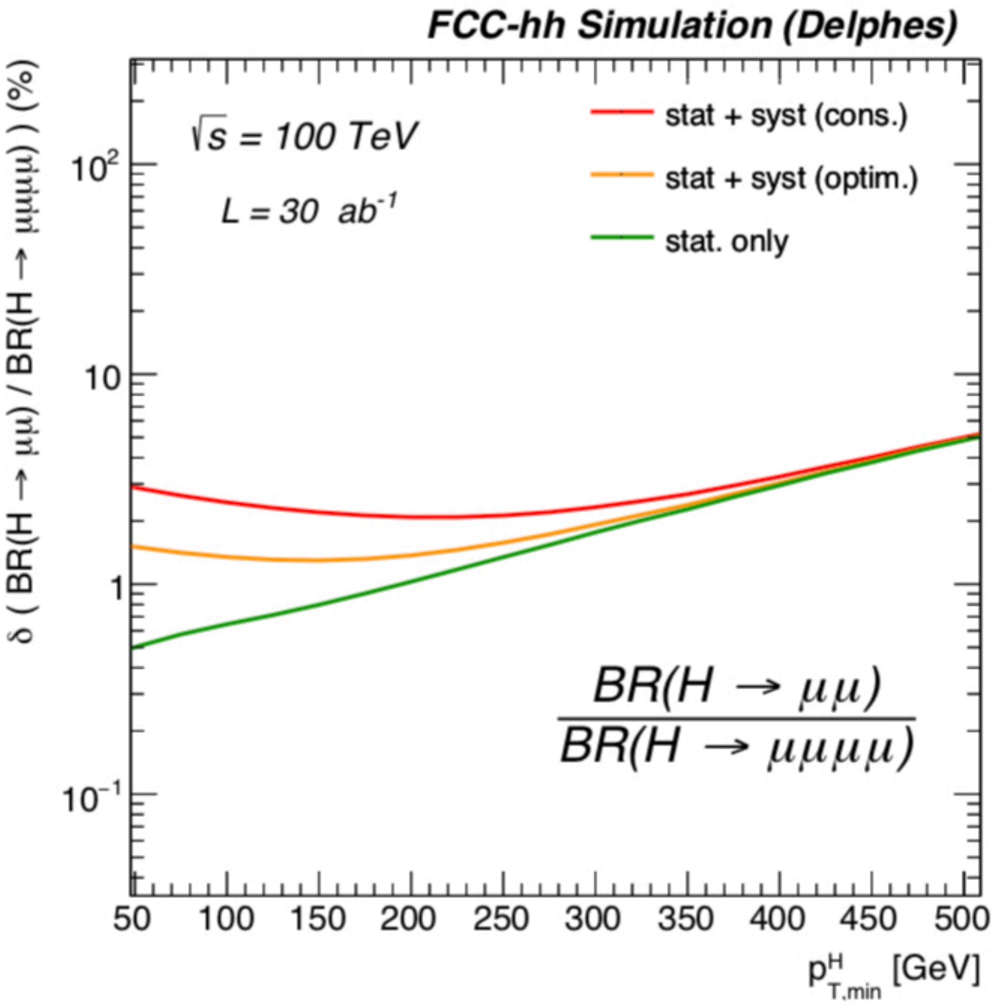


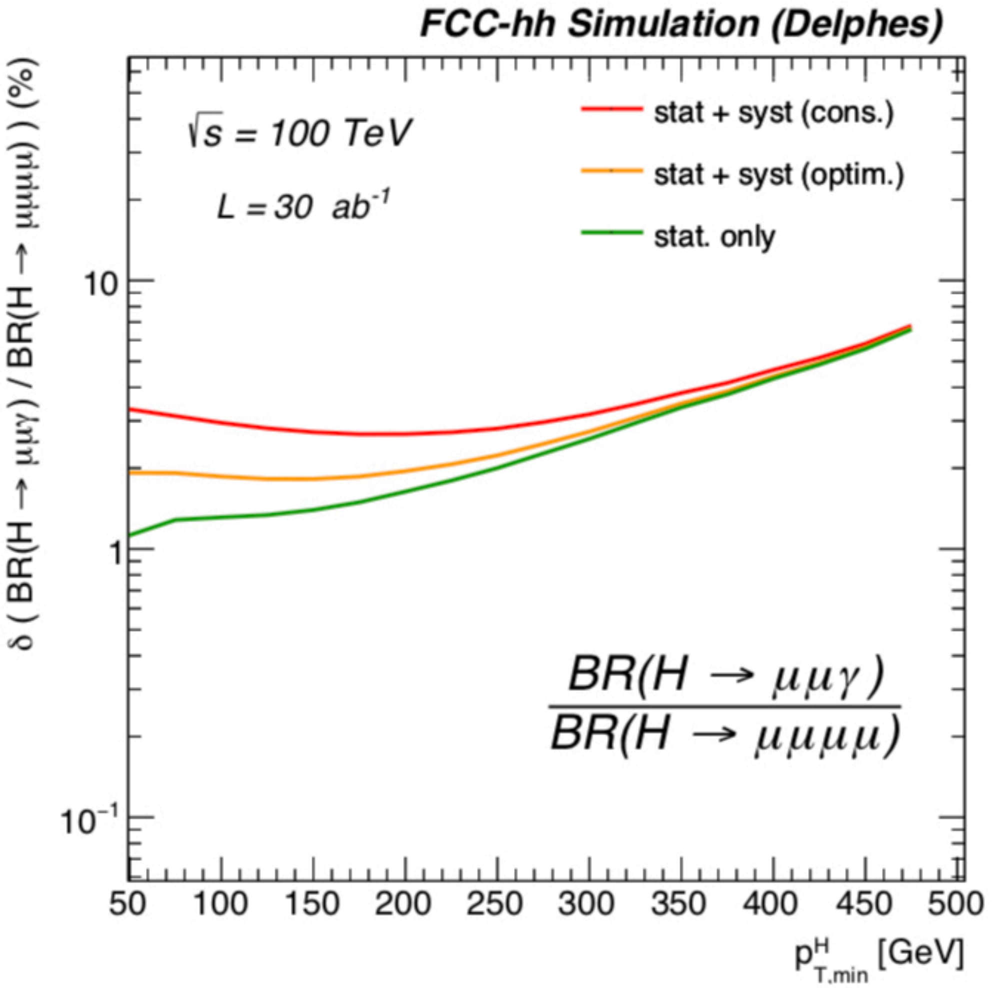


- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \gamma\gamma)}{BR(H \rightarrow ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
10
1
10^{-1}
100 200 300 400 500 600 700 800 900 1000
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \mu\mu)}{BR(H \rightarrow \mu\mu\mu\mu)}$
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
10^{2}
10
1
10^{-1}
50 100 150 200 250 300 350 400 450 500
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \rightarrow \mu\mu\gamma)}{BR(H \rightarrow \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
10
1
10^{-1}
50 100 150 200 250 300 350 400 450 500
$p_{T,min}^{H}$ [GeV]

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

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)	**6.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4lept) @ FCC-ee

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

Higgs self-coupling, gg→HH

From the detector performance studies:

Pheno-level studies:

	bbγγ	bbZZ[→4l]	bbWW[→2jlν]	4b+j	2b2τ+j
δκλ (%)	6.5	14	40	30	8

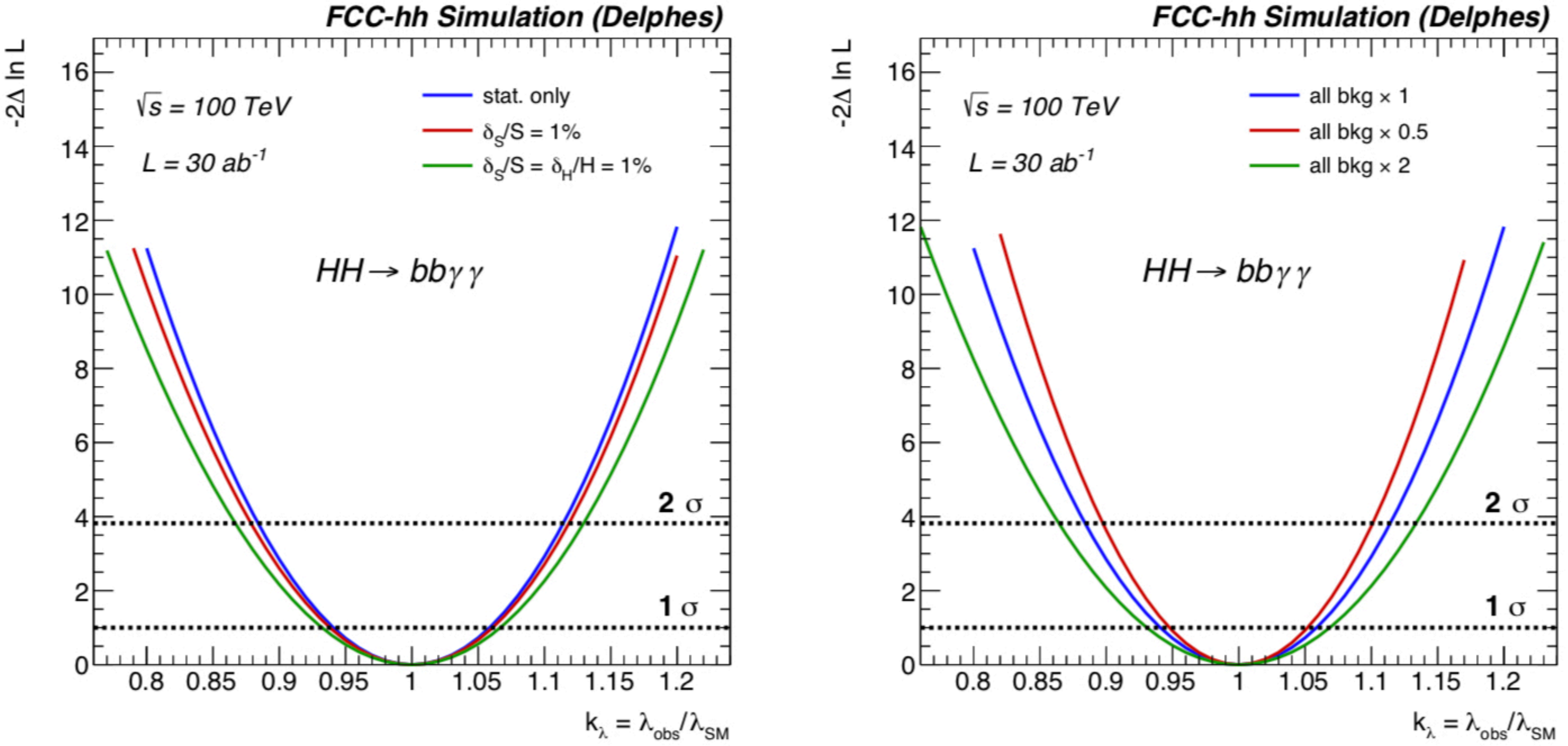


Figure 10.4: Expected precision on the Higgs self-coupling modifier κ_λ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively ×1, ×2, ×0.5 background yields (right).)

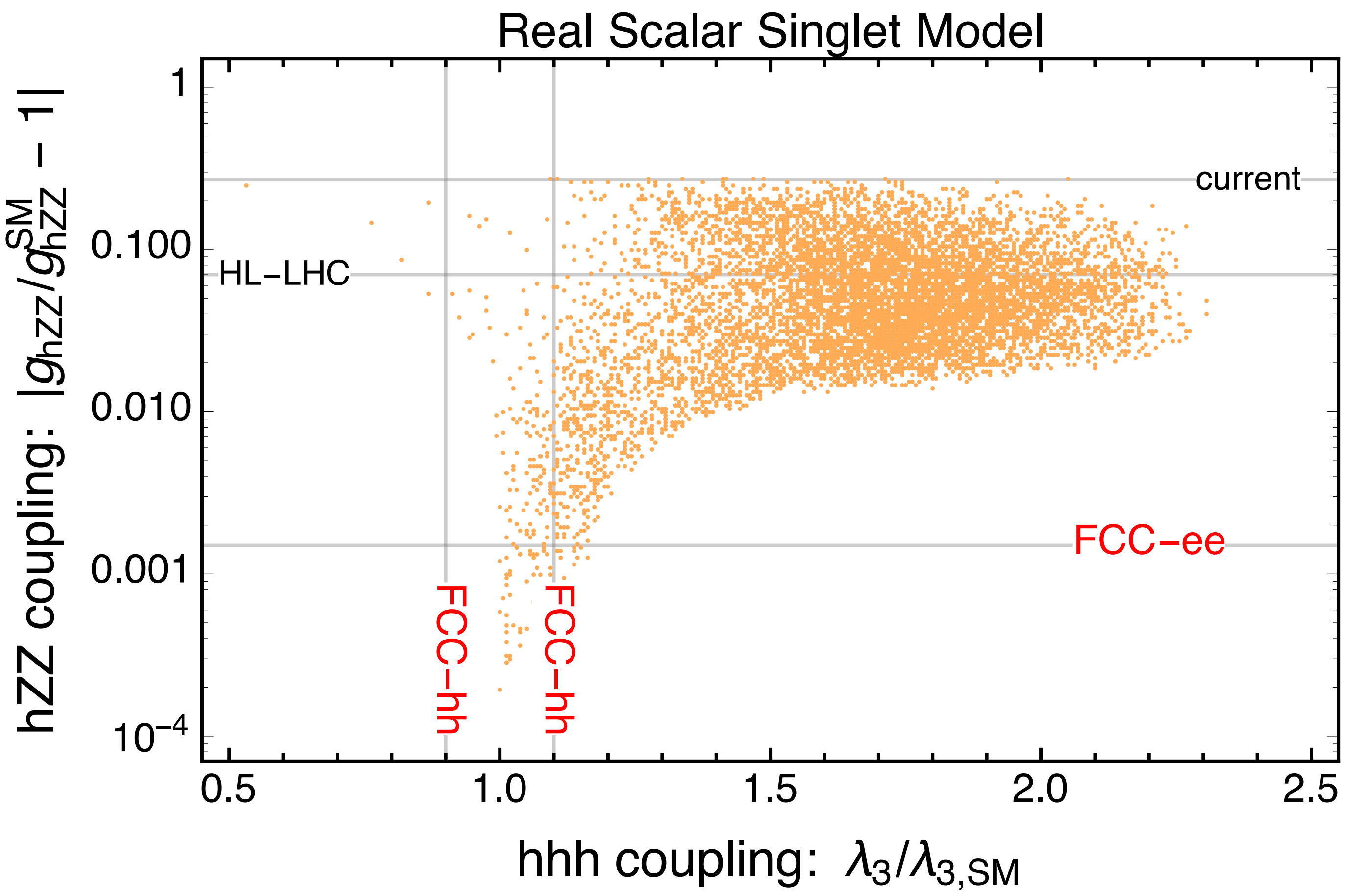
Example of precision targets: constraints on models with 1st order phase transition

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

Example of precision targets: constraints on models with 1st order phase transition

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

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

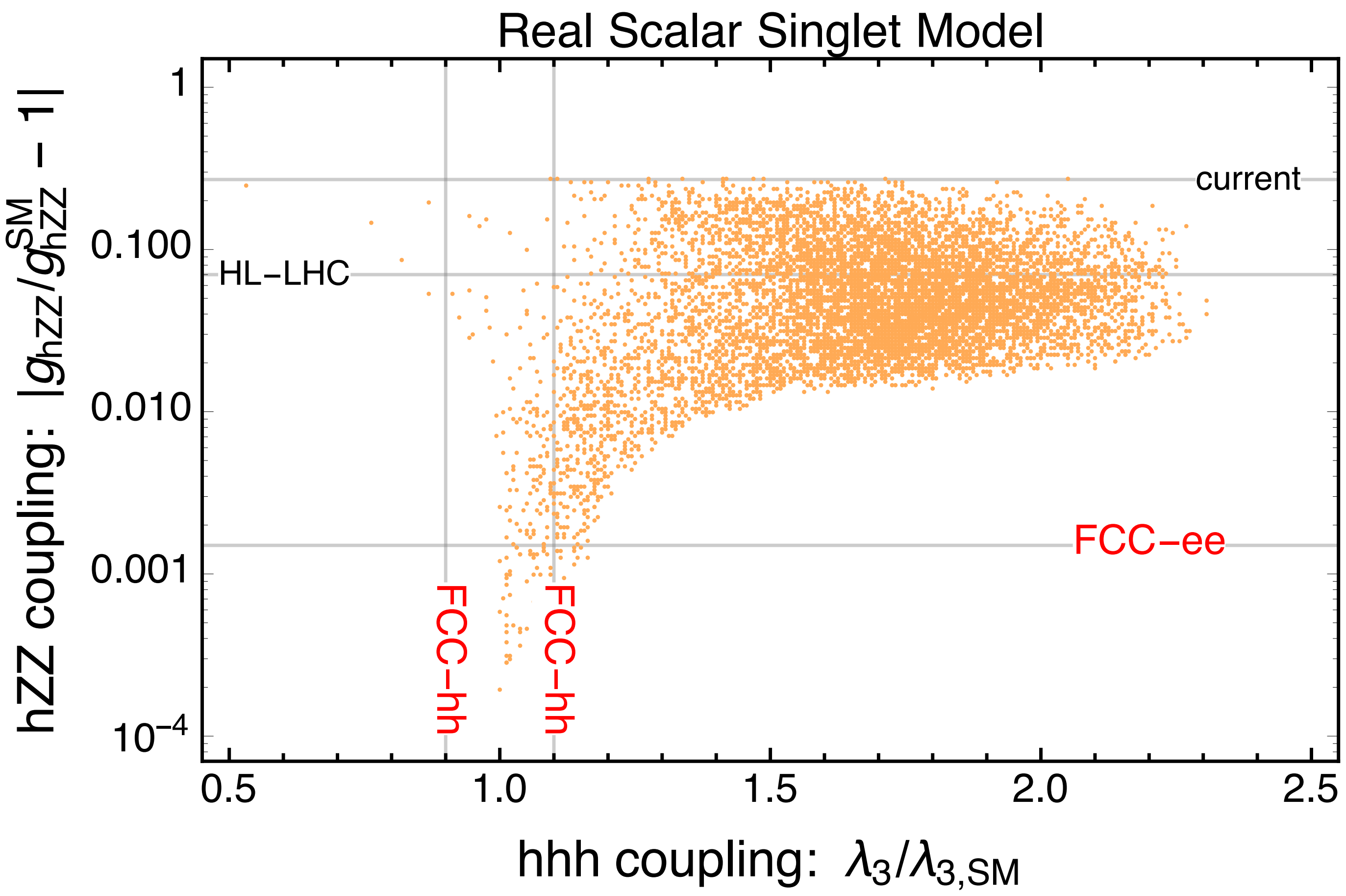


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

Example of precision targets: constraints on models with 1st order phase transition

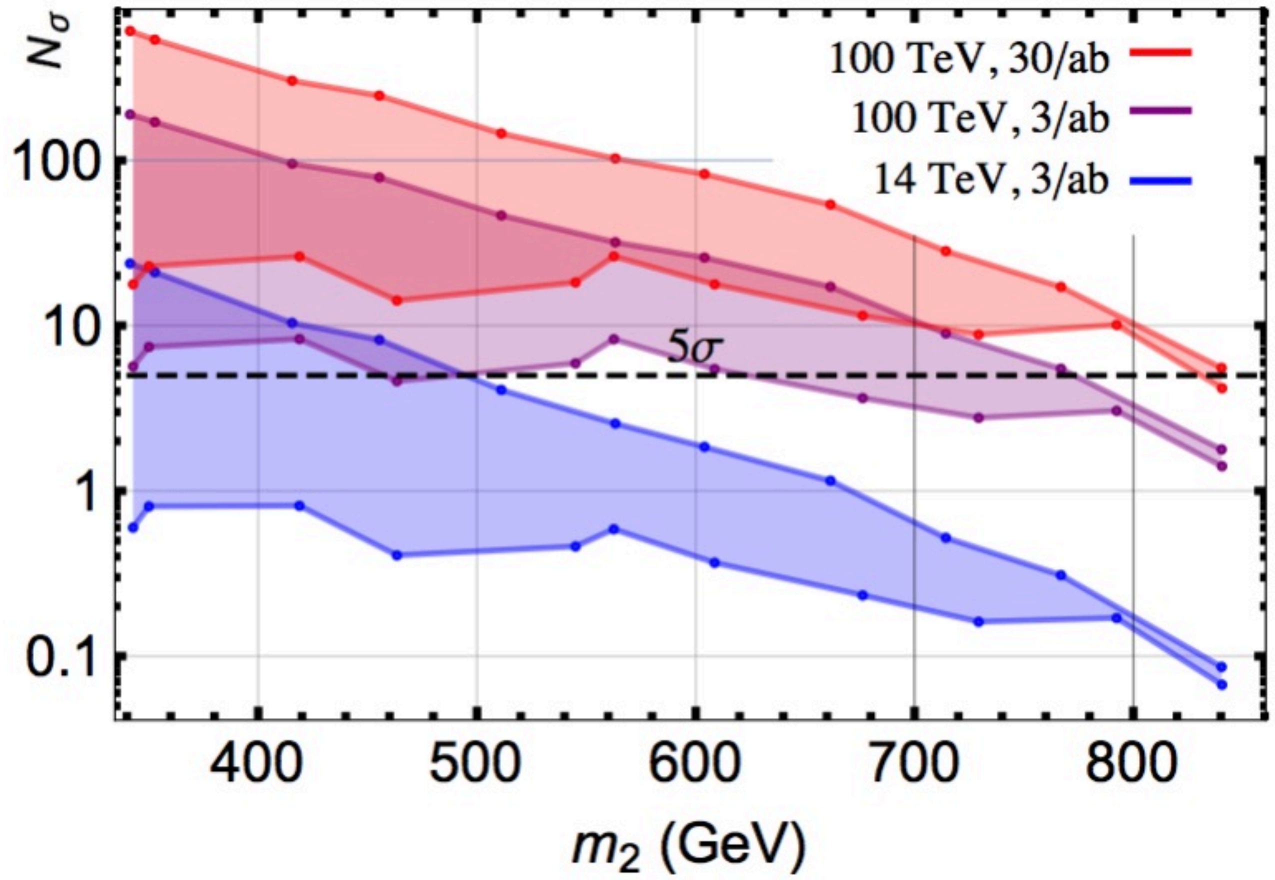
$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$

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



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

Direct detection of extra Higgs states at FCC-hh



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

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

Precision vs sensitivity

Precision vs sensitivity

- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.

Precision vs sensitivity

- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- ***Sensitivity*** may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

High-Q^2 observables : precision vs dynamic reach

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

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

High-Q² observables : precision vs dynamic reach

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

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

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

High-Q^2 observables : precision vs dynamic reach

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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. $\delta O = 10\%$ at Q=1.5 TeV ⇒ $\Lambda \sim 5$ TeV

High-Q^2 observables : 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, μ~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. δO=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, μ~O(Q)

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

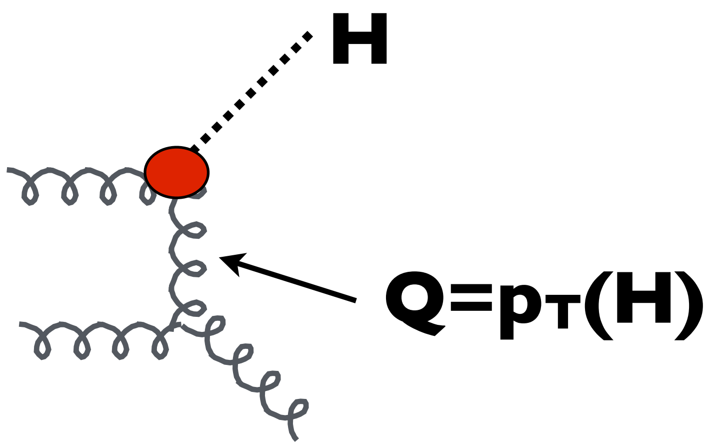
⇒ **kinematic reach** probes large Λ even if precision is "low"

e.g. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV

Complementarity between precise measurements at ee collider and large-Q studies at 100 TeV

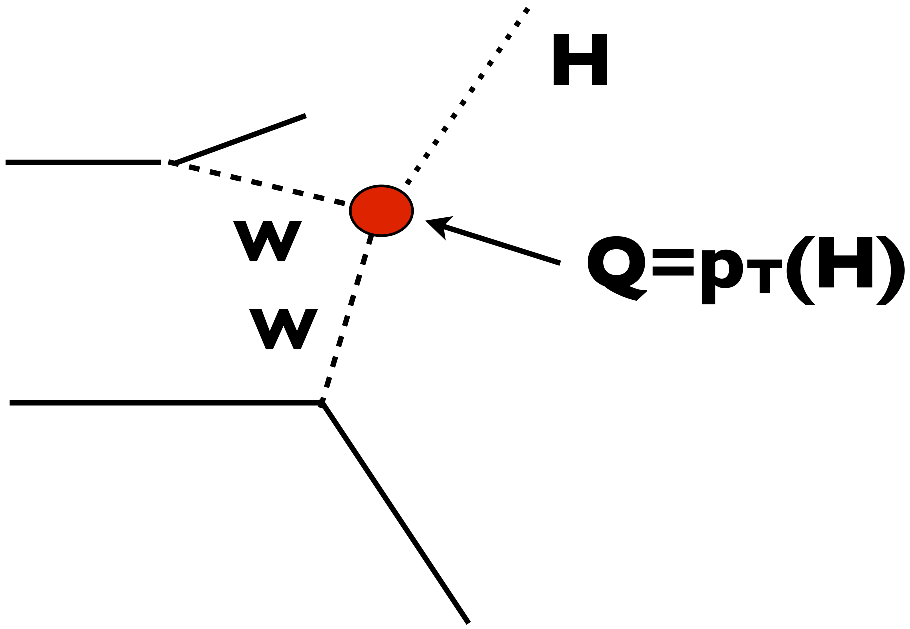
Examples

δBR(H→gg)

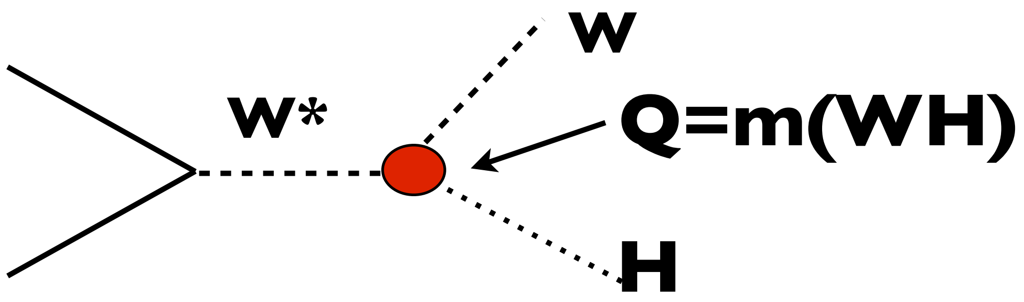


δBR(H→WW*)

(a)



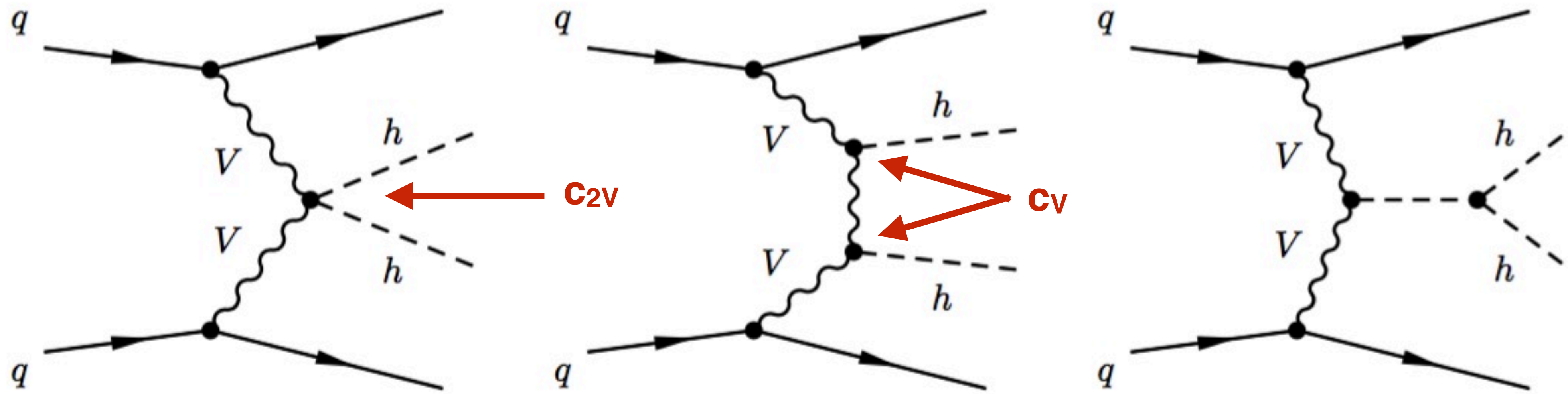
(b)



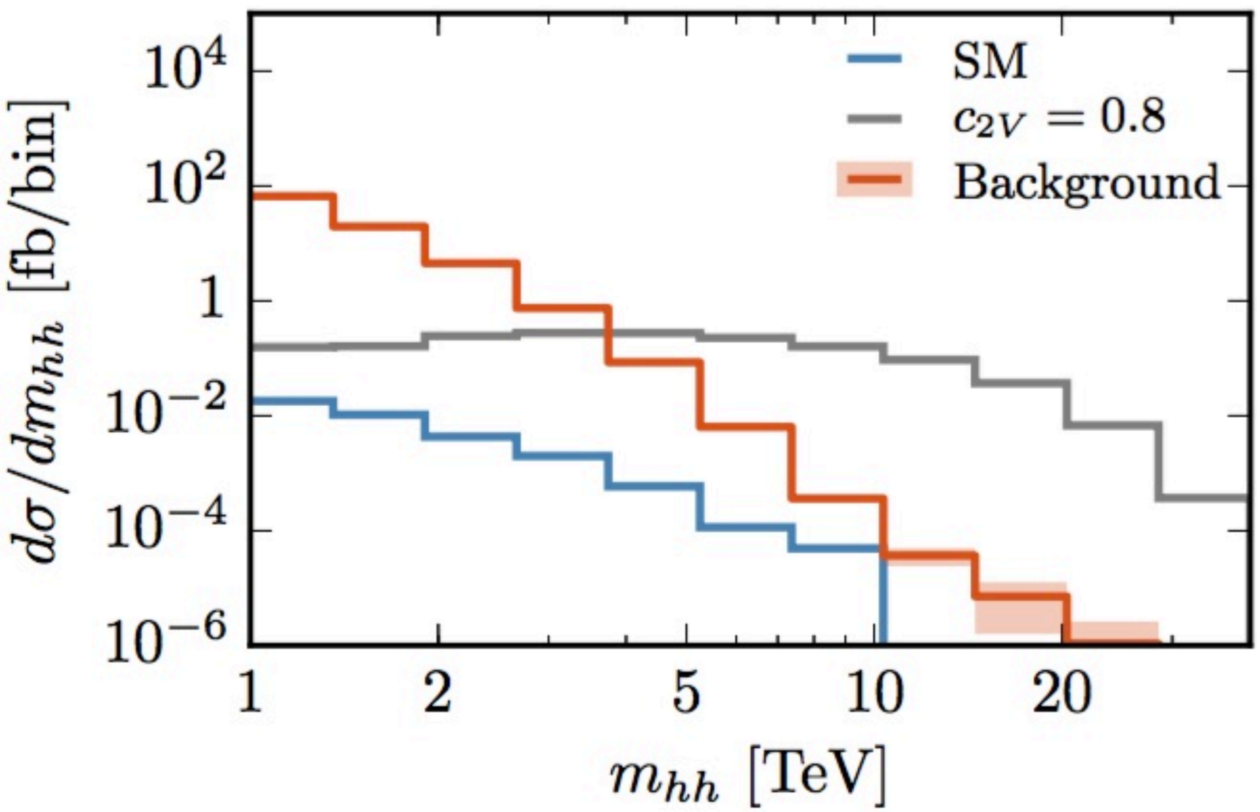
$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

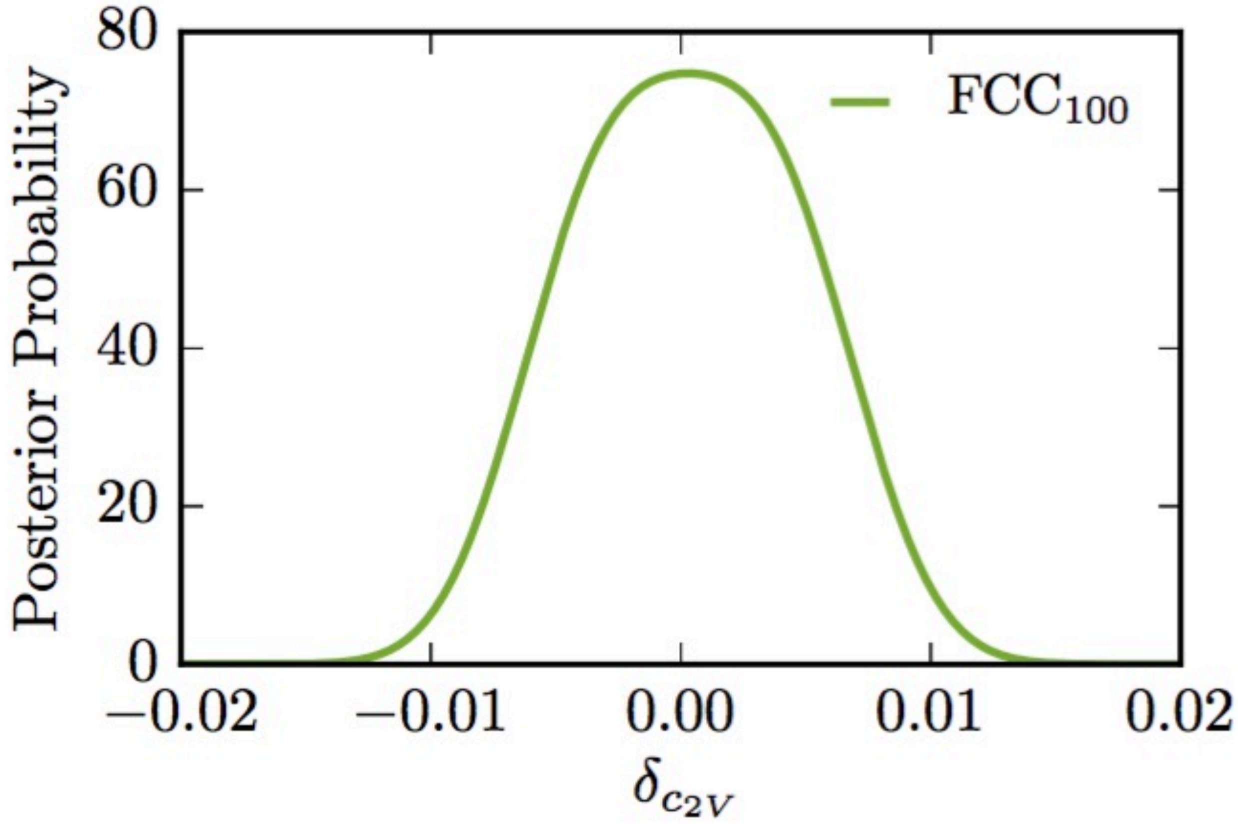
$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

Example: high mass VV → HH

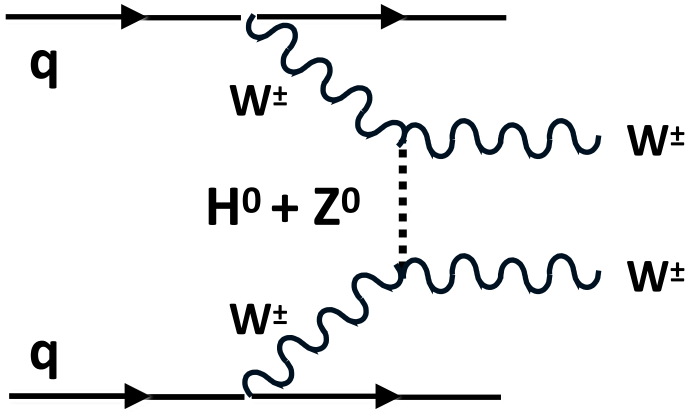


$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) \cdot \text{ where } \begin{cases} c_V = g_{HVV}/g_{HVV}^{SM} \\ c_{2V} = g_{HHVV}/g_{HHVV}^{SM} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$$

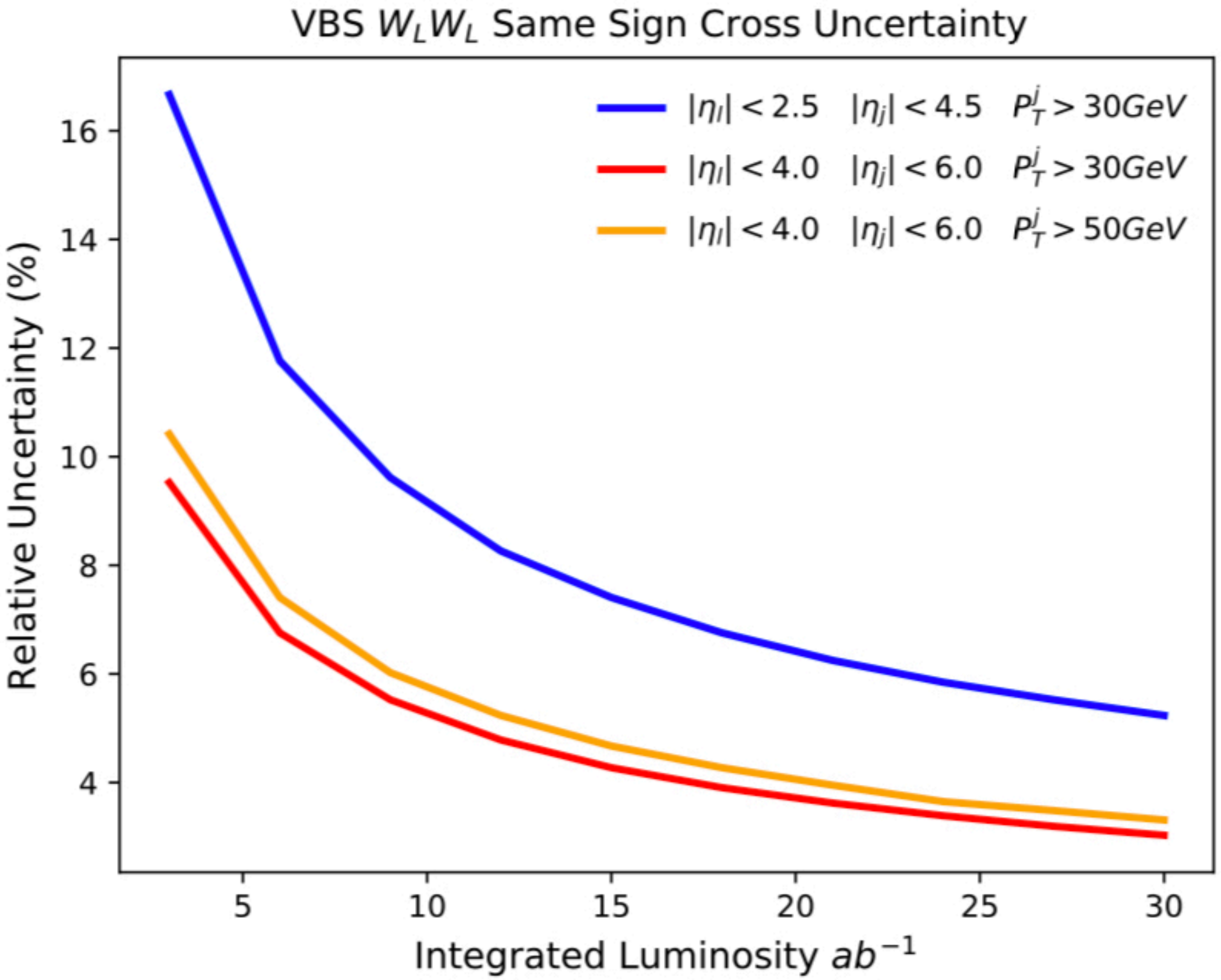




$W_L W_L$ scattering



large m_{WW}



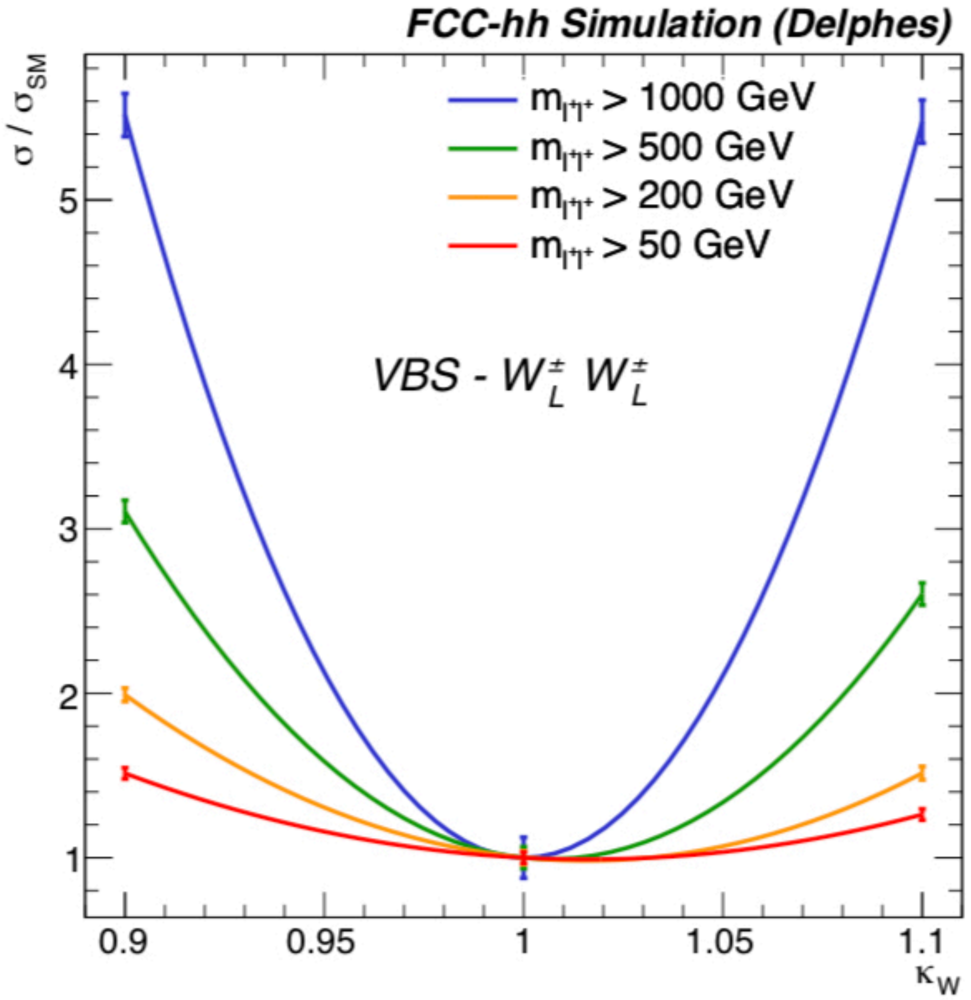
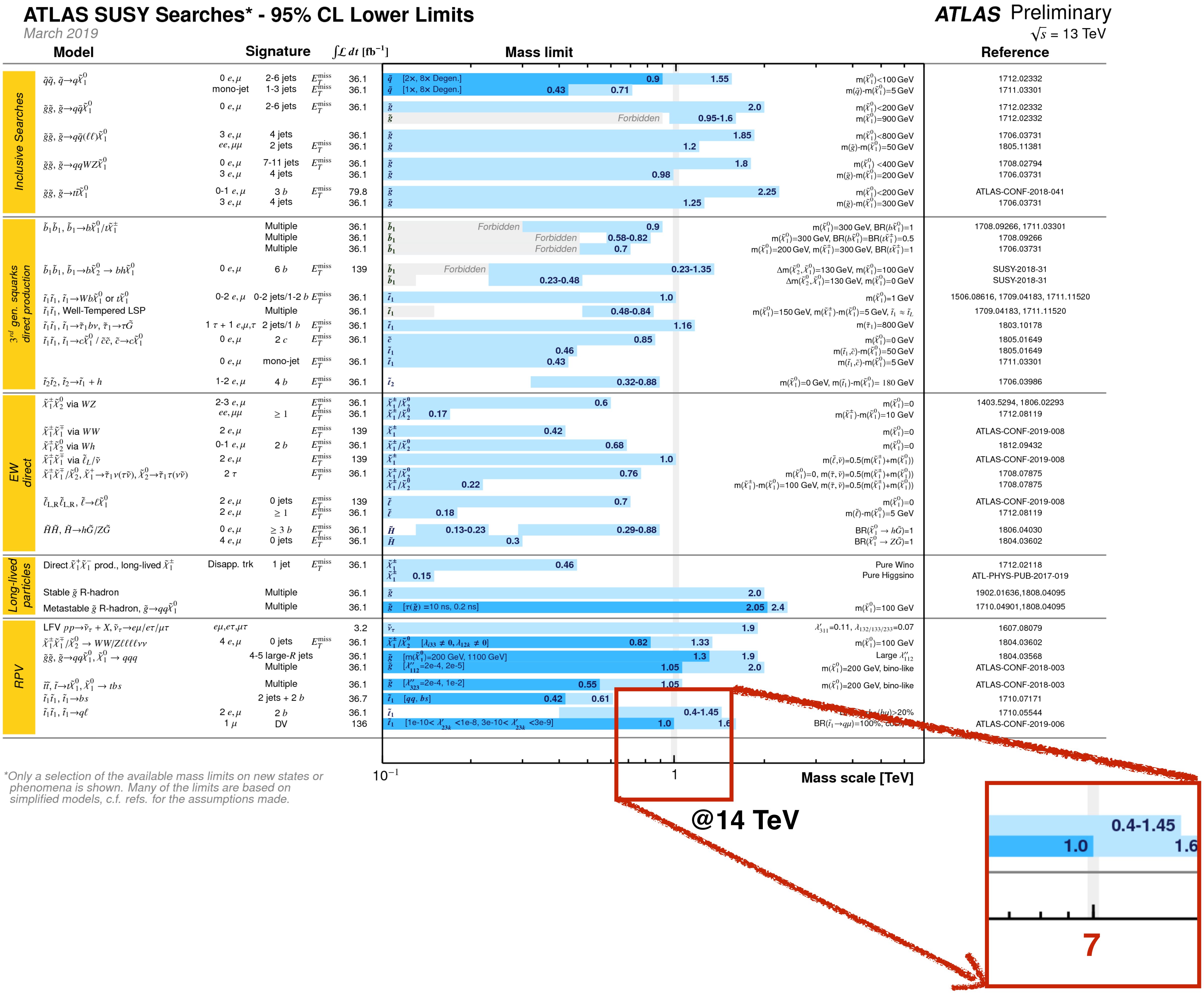


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \rightarrow HH$ process.

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

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

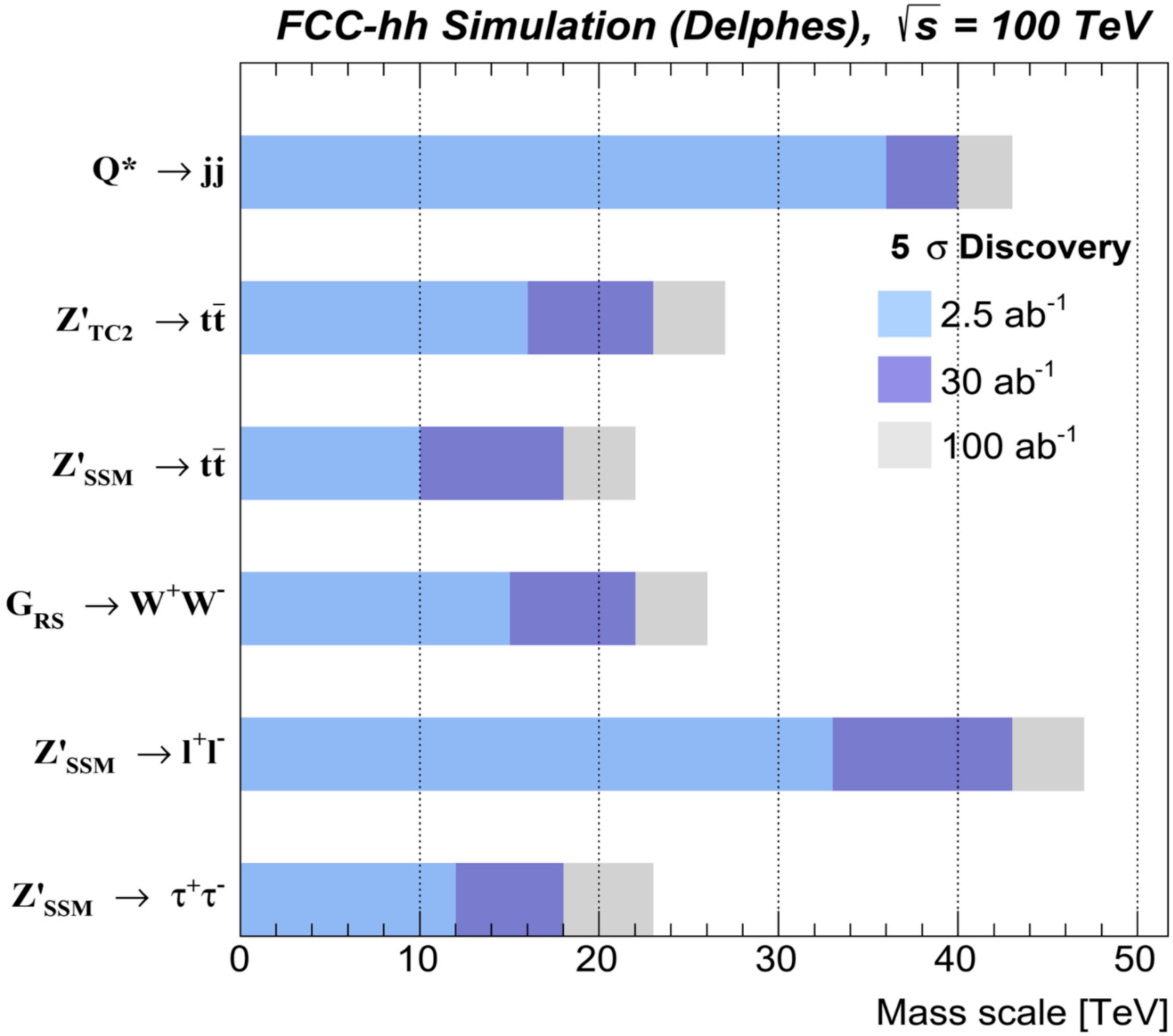
Direct discovery reach: the power of 100 TeV



@14 TeV

@100 TeV

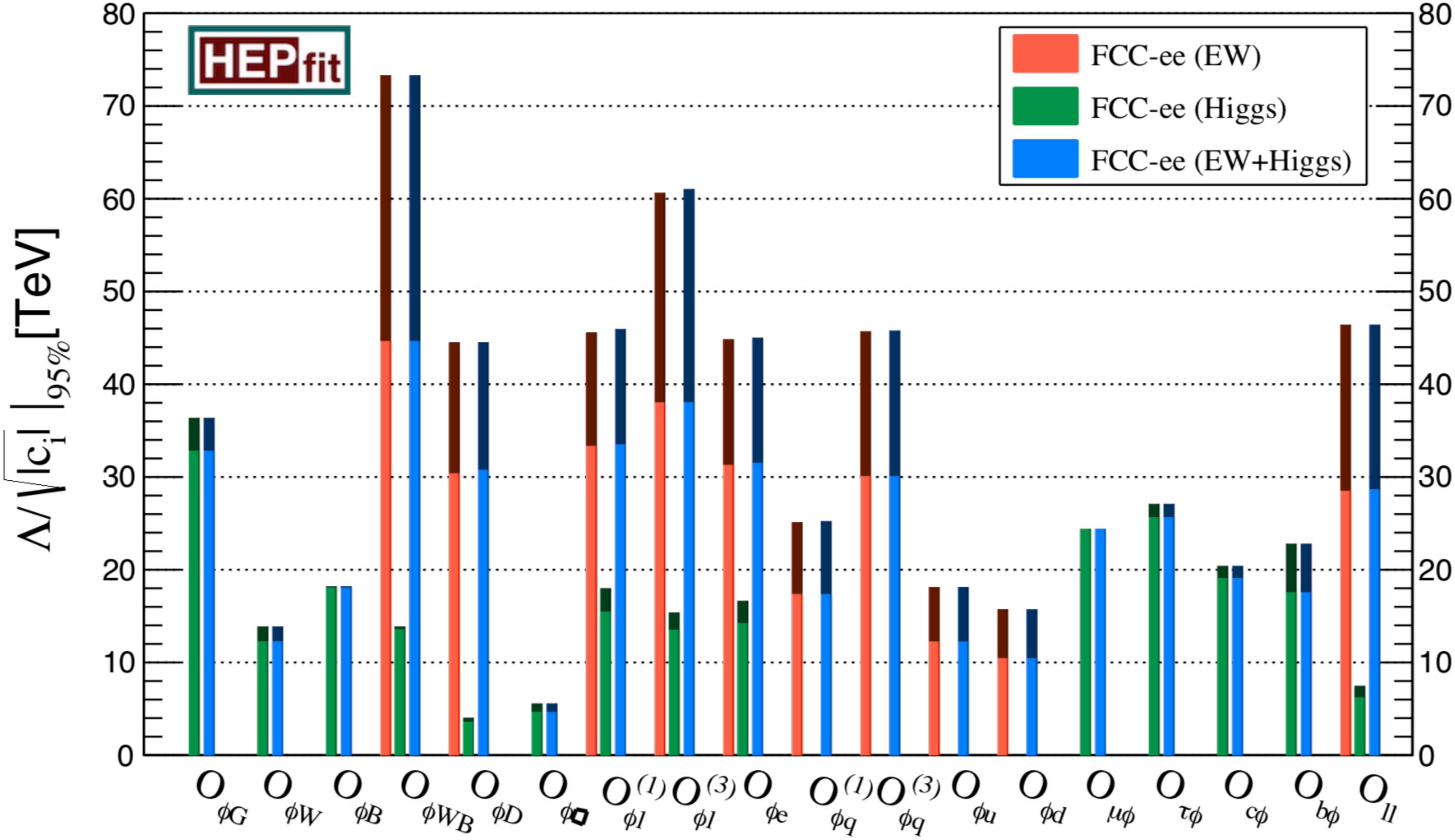
s-channel resonances



FCC-hh reach ~ 6 x HL-LHC reach

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

=> see L. Reina lecture 3

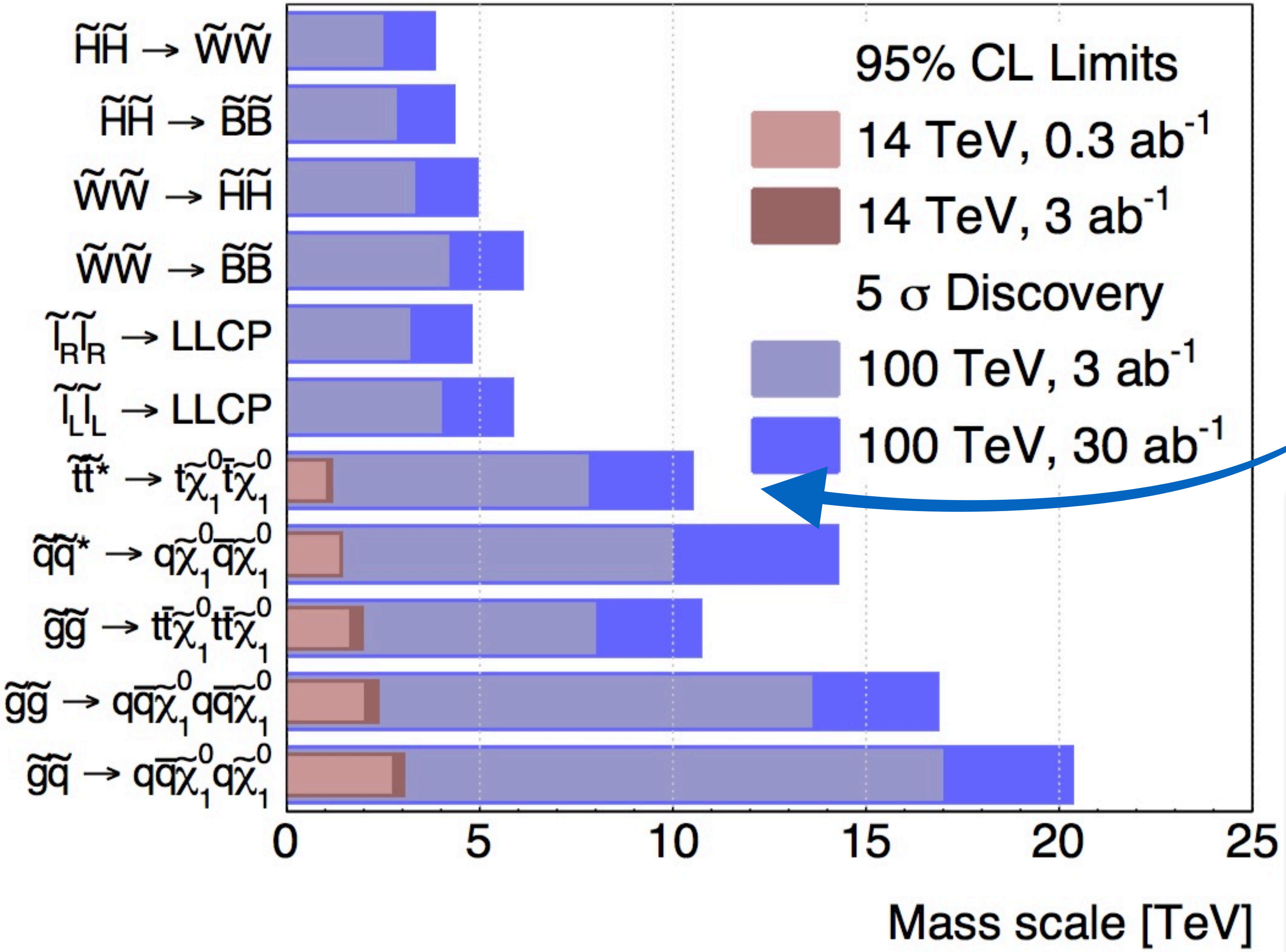


Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

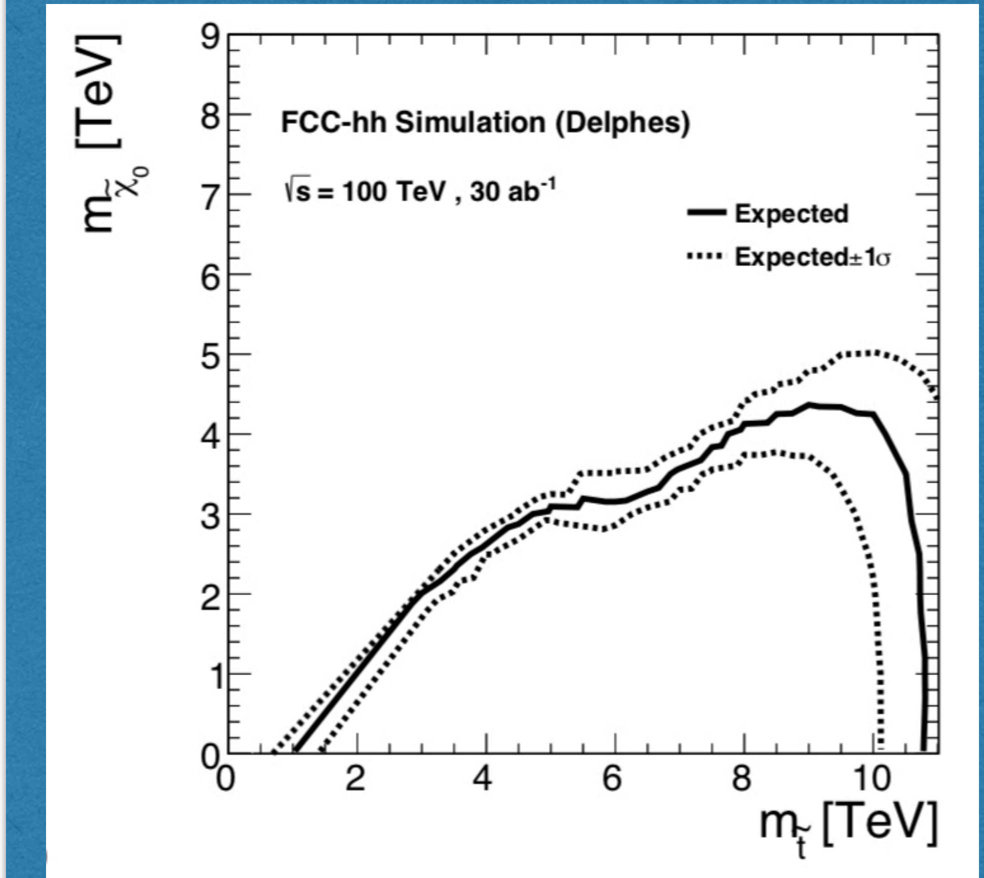
100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision EW and H measurements at the future ee collider

SUSY reach at 100 TeV

Early phenomenology studies



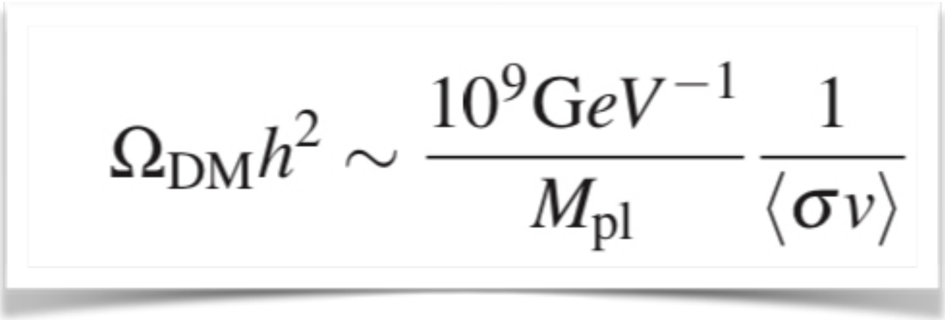
New detector performance studies



WIMP DM theoretical constraints

See lecture 1 by M. Mc Cullough

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



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

WIMP DM theoretical constraints

See lecture 1 by M. Mc Cullough

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

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

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

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

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

WIMP DM theoretical constraints

See lecture 1 by M. Mc Cullough

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

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

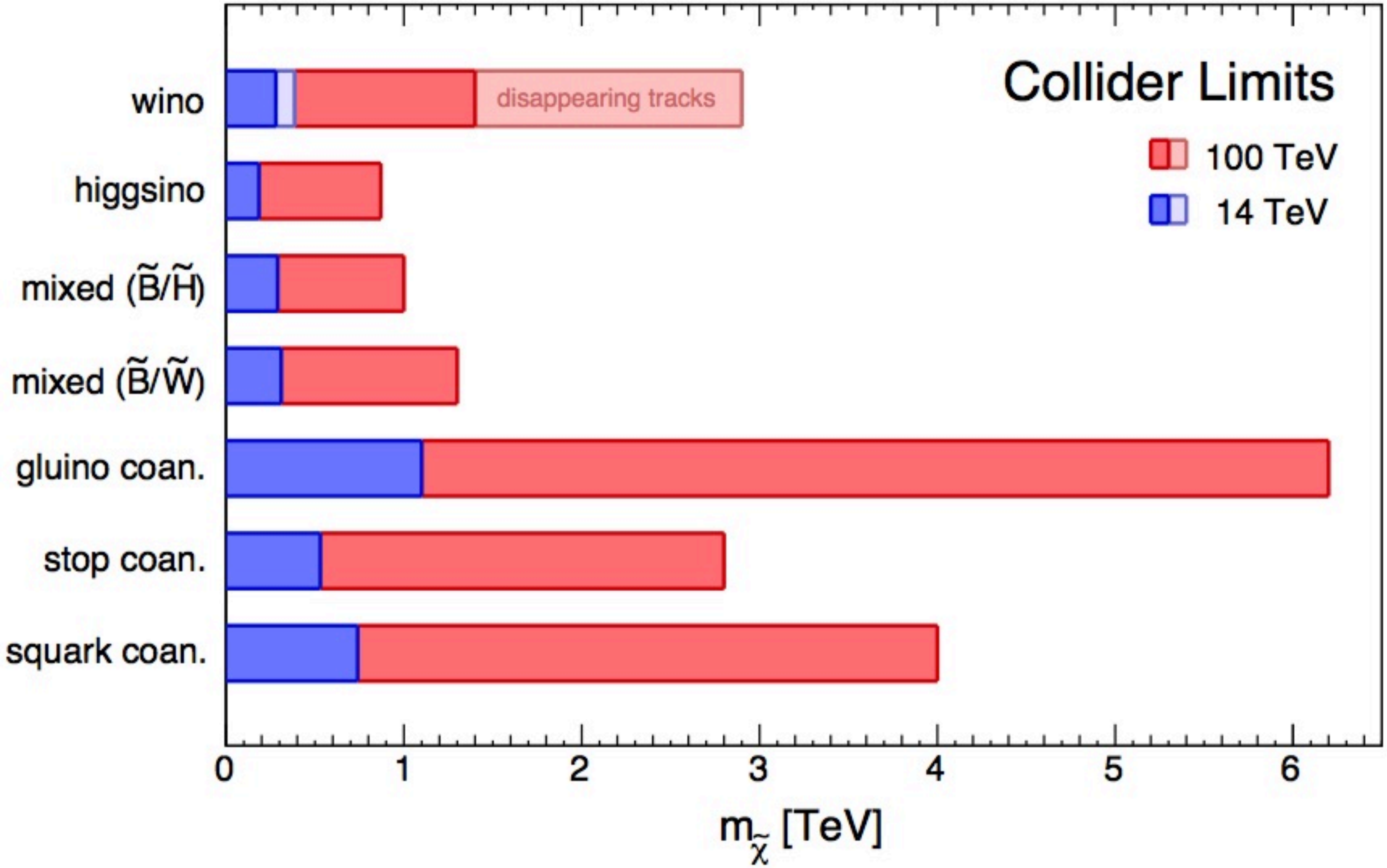
$$\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

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

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

DM reach at 100 TeV

Early phenomenology studies

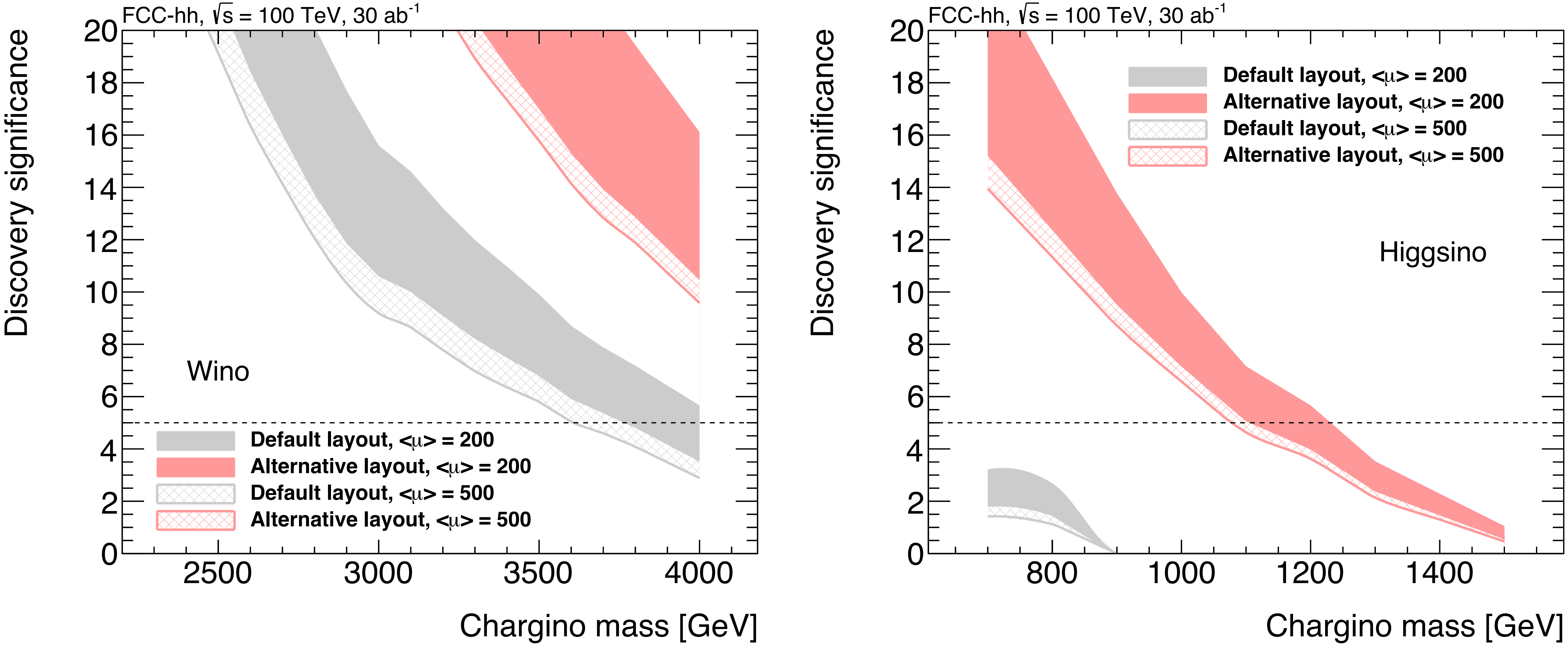


K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

(at ~full pileup)

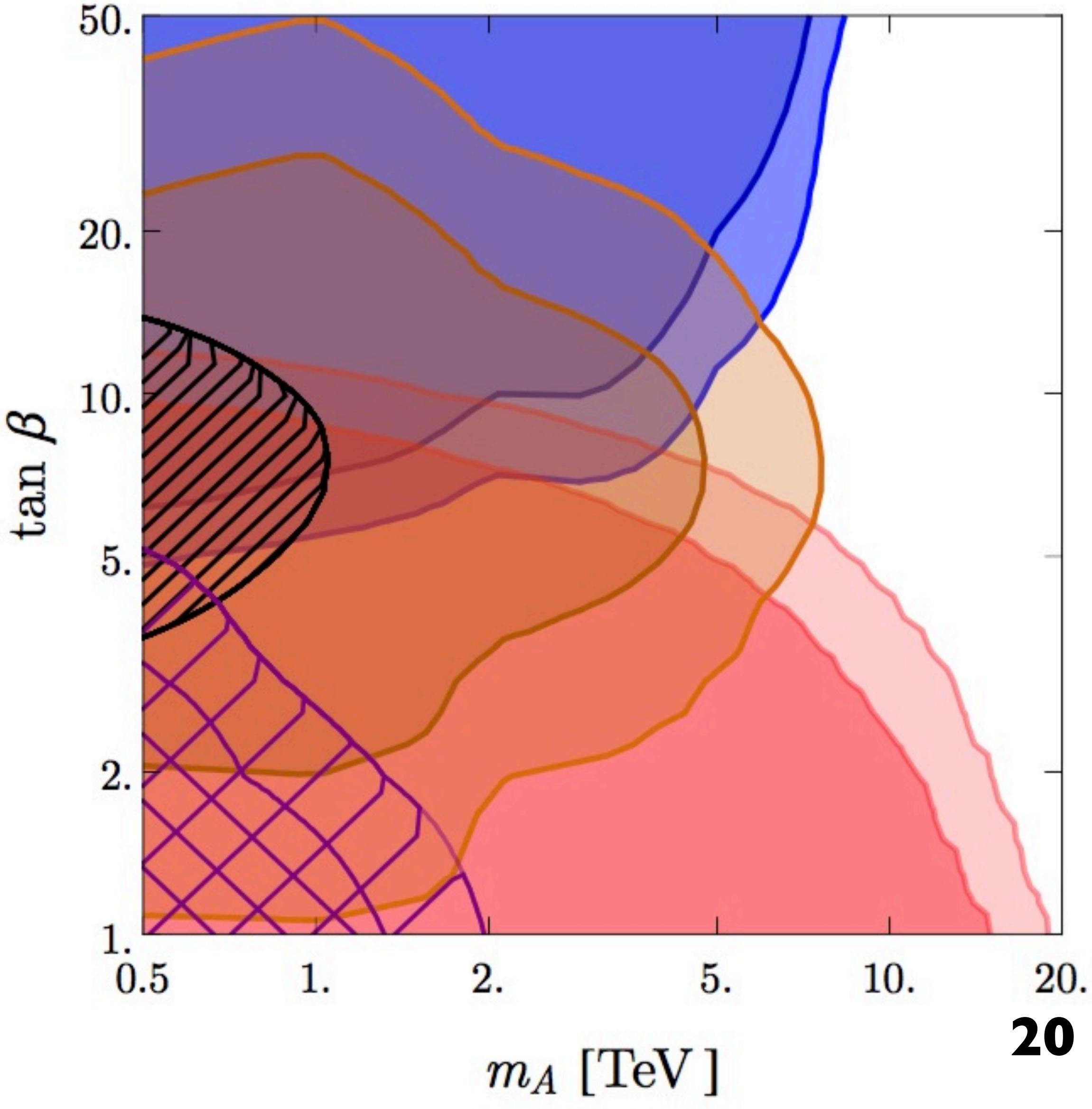


=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

MSSM Higgs @ 100 TeV

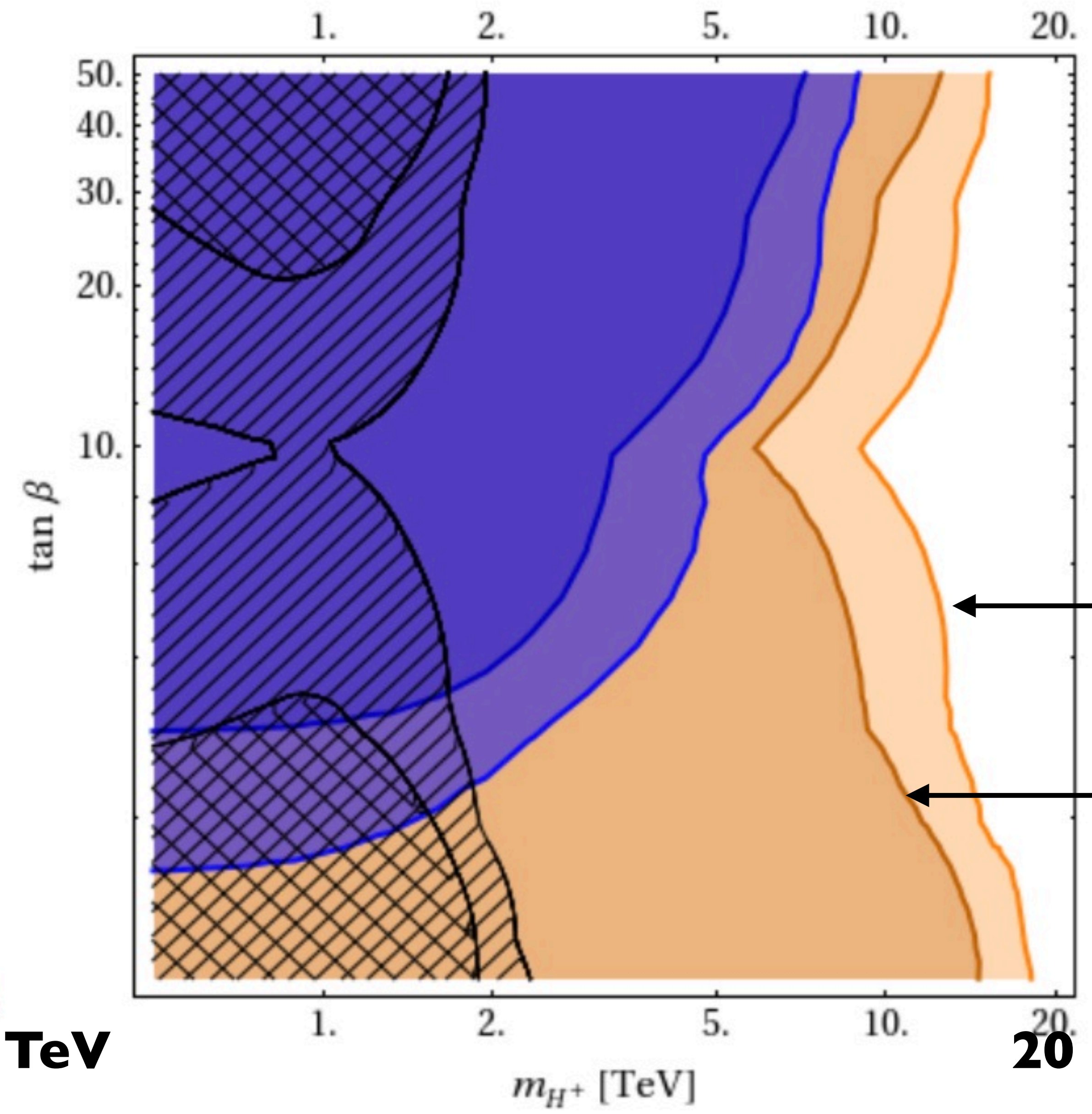
🟦 $bbH^0/A^0 \to bb\tau\tau$
🟧 $bbH^0/A^0 \to bbtt$
🟥 $t(t)H^0/A^0 \to t(t)tt$



20 TeV

🟦 $tbH^+ \to tb\tau\nu$
🟧 $tbH^+ \to tbtb$

▨ **LHC 3 ab^{-1}**
▦ **LHC 0.3 ab^{-1}**



30 ab^{-1}

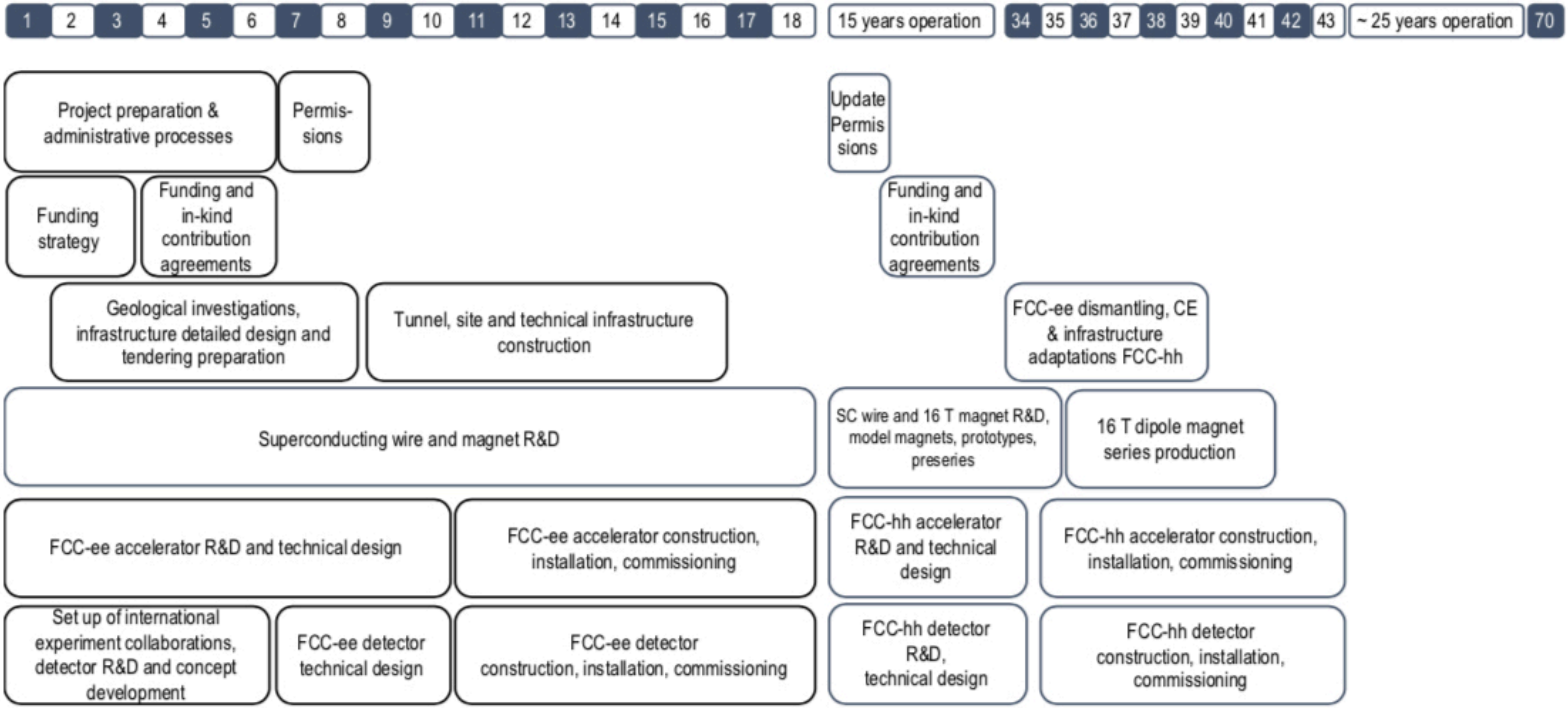
3 ab^{-1}

20 TeV

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

FCC-ee + FCC-hh, project timeline



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Funding strategy

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

Superconducting wire and magnet R&D

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

Update Permis sions

Funding and in-kind contribution agreements

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

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC-hh accelerator R&D and technical design

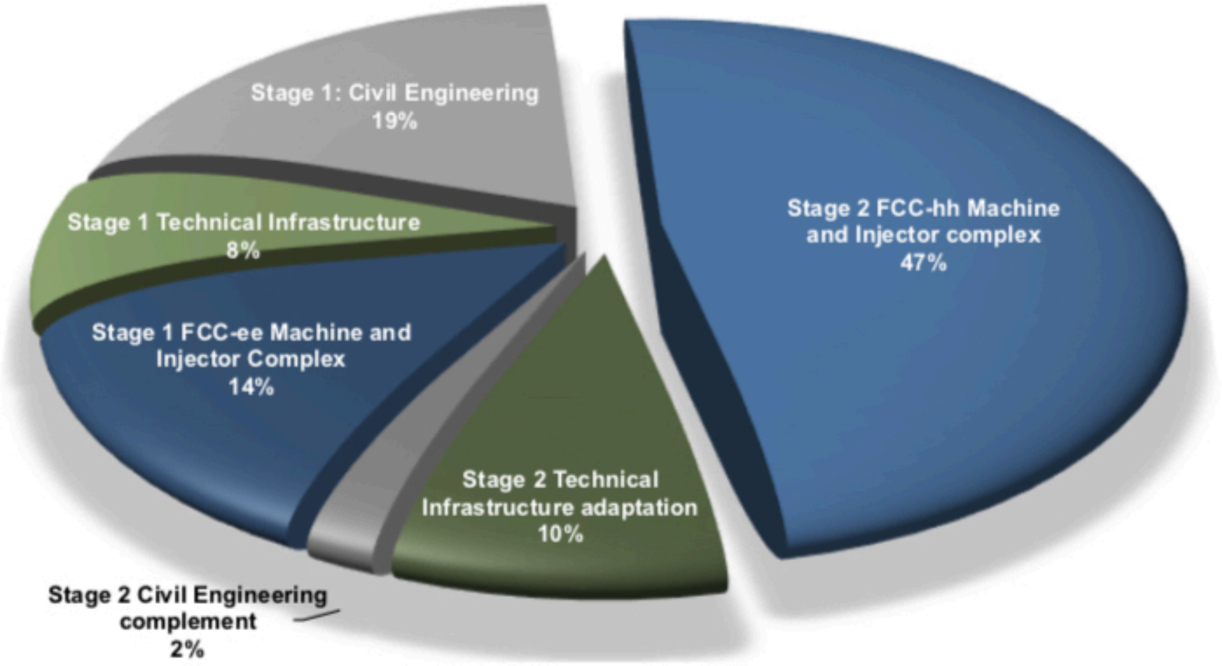
FCC-hh accelerator construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

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
TOTAL construction cost for integral FCC project	**28,600**



Final remarks

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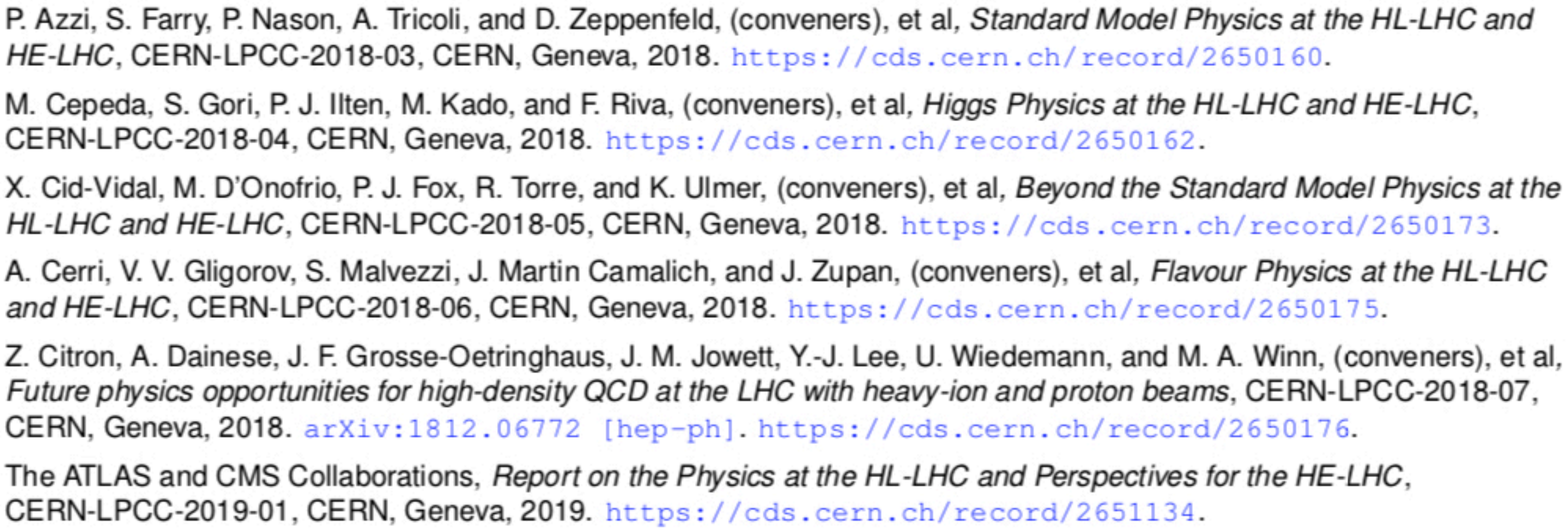
  - *complementary and synergetic precision studies of EW, Higgs and top properties*
  - *energy reach to allow direct discoveries at the mass scales possibly revealed by the precision measurements*

Additional material
on physics at HE-LHC

For details see



P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld, (conveners), et al, *Standard Model Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-03, CERN, Geneva, 2018. https://cds.cern.ch/record/2650160.

M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.

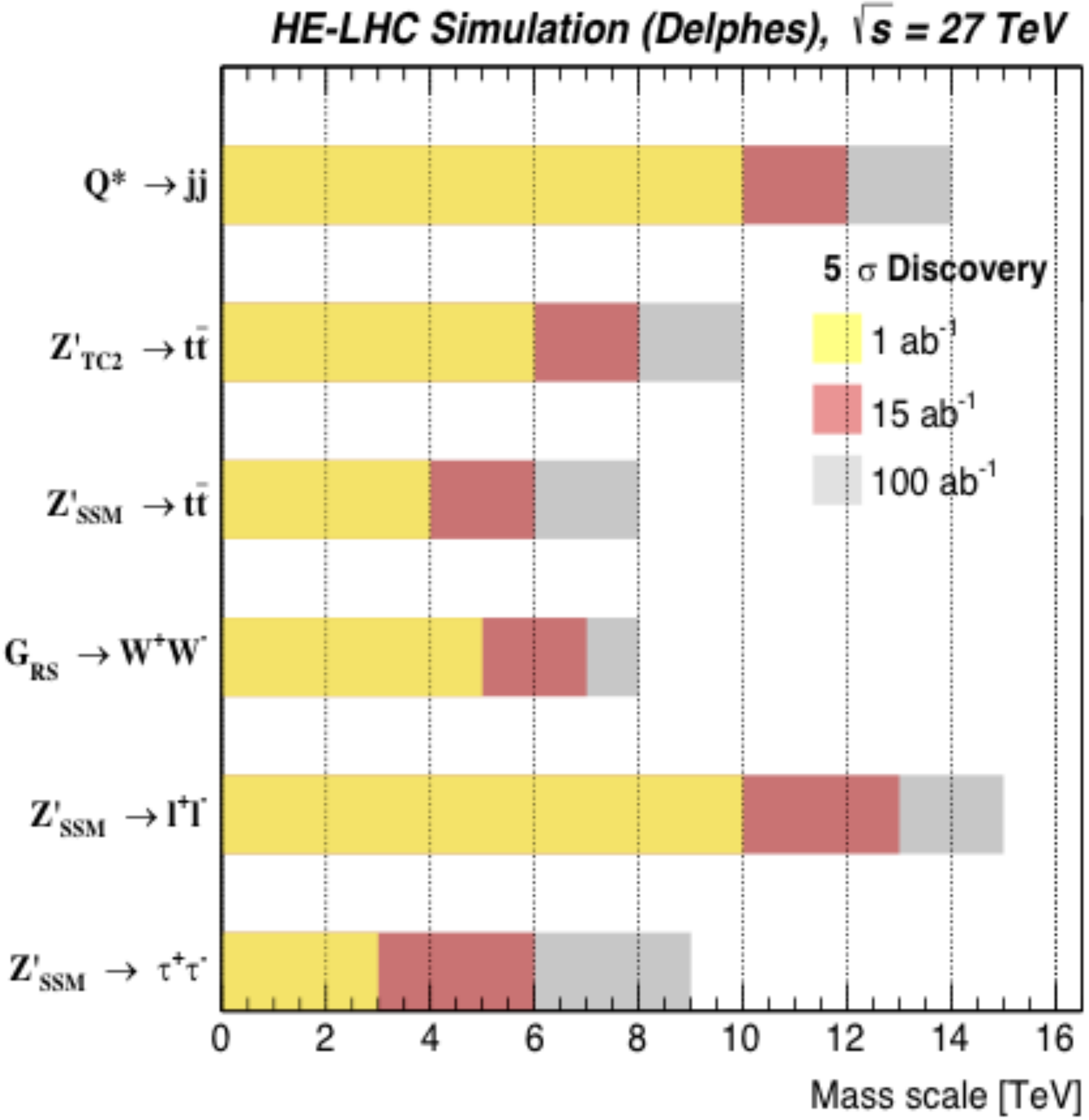
X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer, (conveners), et al, *Beyond the Standard Model Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-05, CERN, Geneva, 2018. https://cds.cern.ch/record/2650173.

A. Cerri, V. V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan, (conveners), et al, *Flavour Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-06, CERN, Geneva, 2018. https://cds.cern.ch/record/2650175.

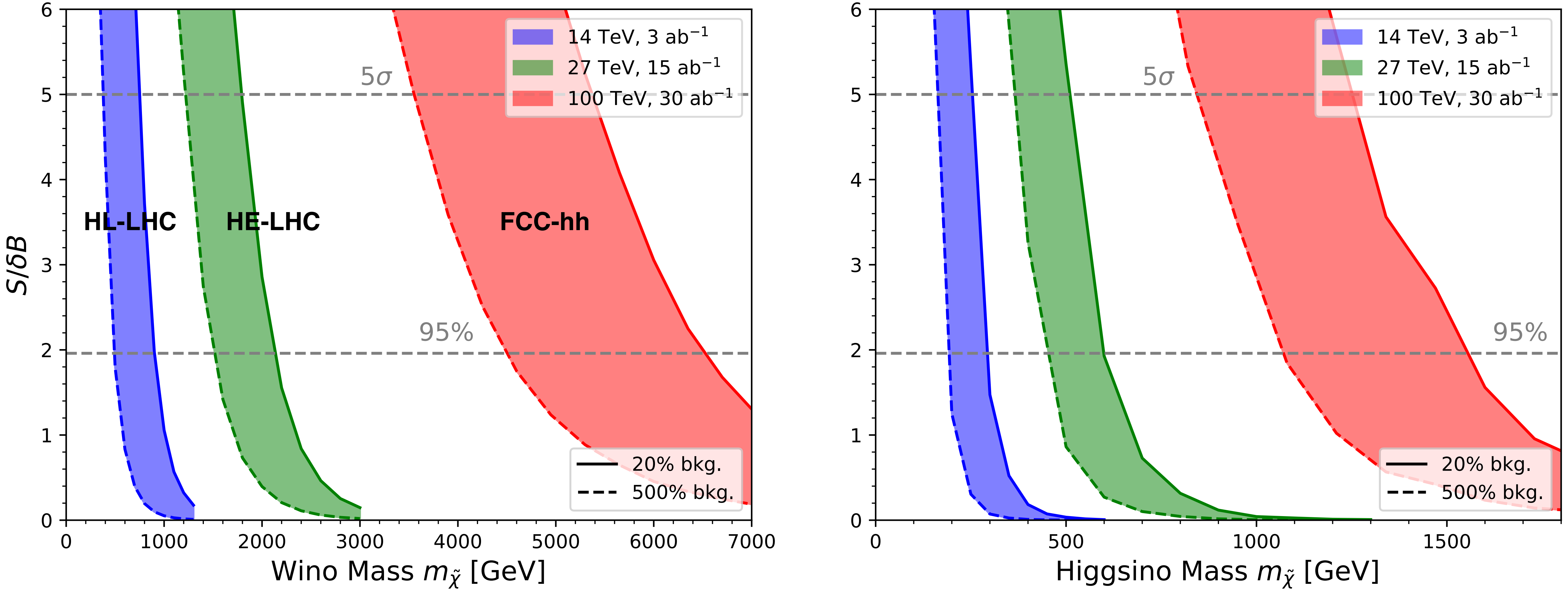
Z. Citron, A. Dainese, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, and M. A. Winn, (conveners), et al, *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*, CERN-LPCC-2018-07, CERN, Geneva, 2018. arXiv:1812.06772 [hep-ph]. https://cds.cern.ch/record/2650176.

The ATLAS and CMS Collaborations, *Report on the Physics at the HL-LHC and Perspectives for the HE-LHC*, CERN-LPCC-2019-01, CERN, Geneva, 2019. https://cds.cern.ch/record/2651134.

(1) extension of mass reach for discovery: s-channel resonances



(I) EW-ino DM searches



T. Han, S. Mukhopadhyay, and X. Wang, *Electroweak Dark Matter at Future Hadron Colliders*, `arXiv:1805.00015 [hep-ph]`.

(II+III) precision measurements and EWSB probes: Higgs observables

Examples of goals in the Higgs sector:

(a) improve the sensitivity to the Higgs self-coupling

(b) reduce to the few percent level all major Higgs couplings

(c) improve the sensitivity to possible invisible Higgs decays

(d) measure the charm Yukawa coupling

	gg→H	WH	ZH	ttH	HH
N_{27}	2.2×10^9	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

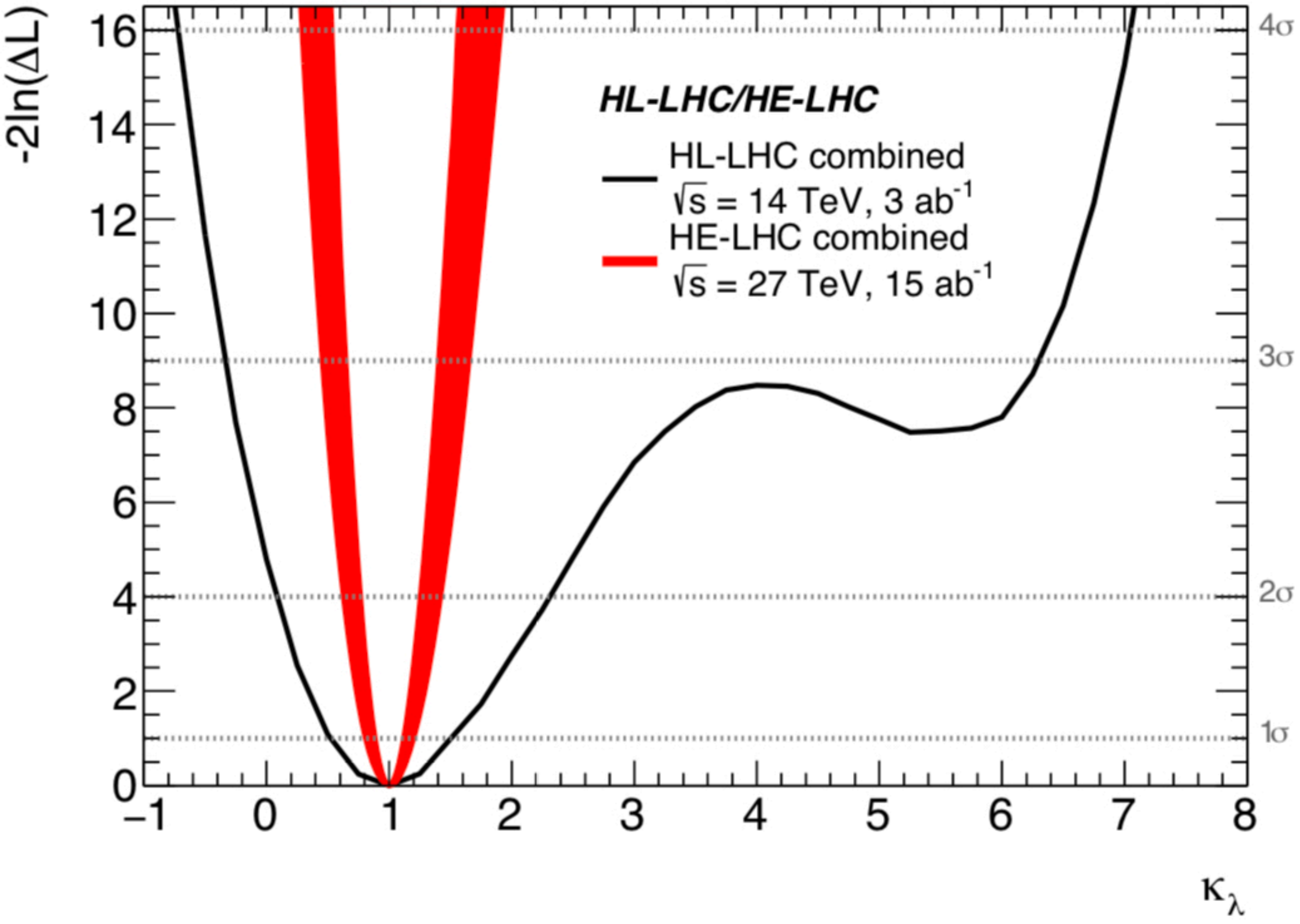
$N_{27}=\sigma(27\text{ TeV}) * 15\text{ ab}^{-1}$

$N_{14}=\sigma(14\text{ TeV}) * 3\text{ ab}^{-1}$

Higgs self-coupling at HE-LHC vs HL-LHC

HL-LHC: λ/λ_{SM} ~1±0.5 (68%CL)

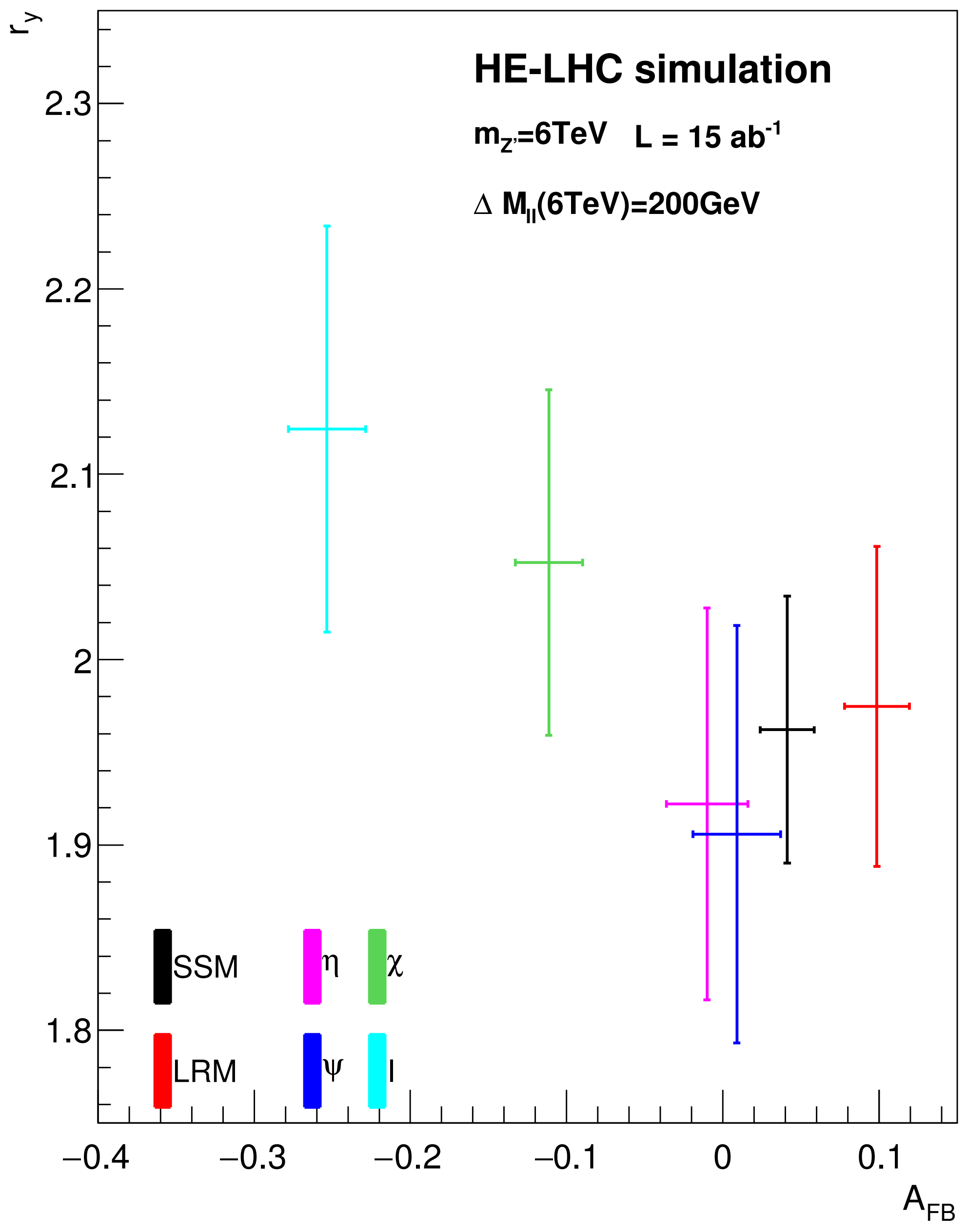
HE-LHC: λ/λ_{SM} ~1±0.15 (68%CL)

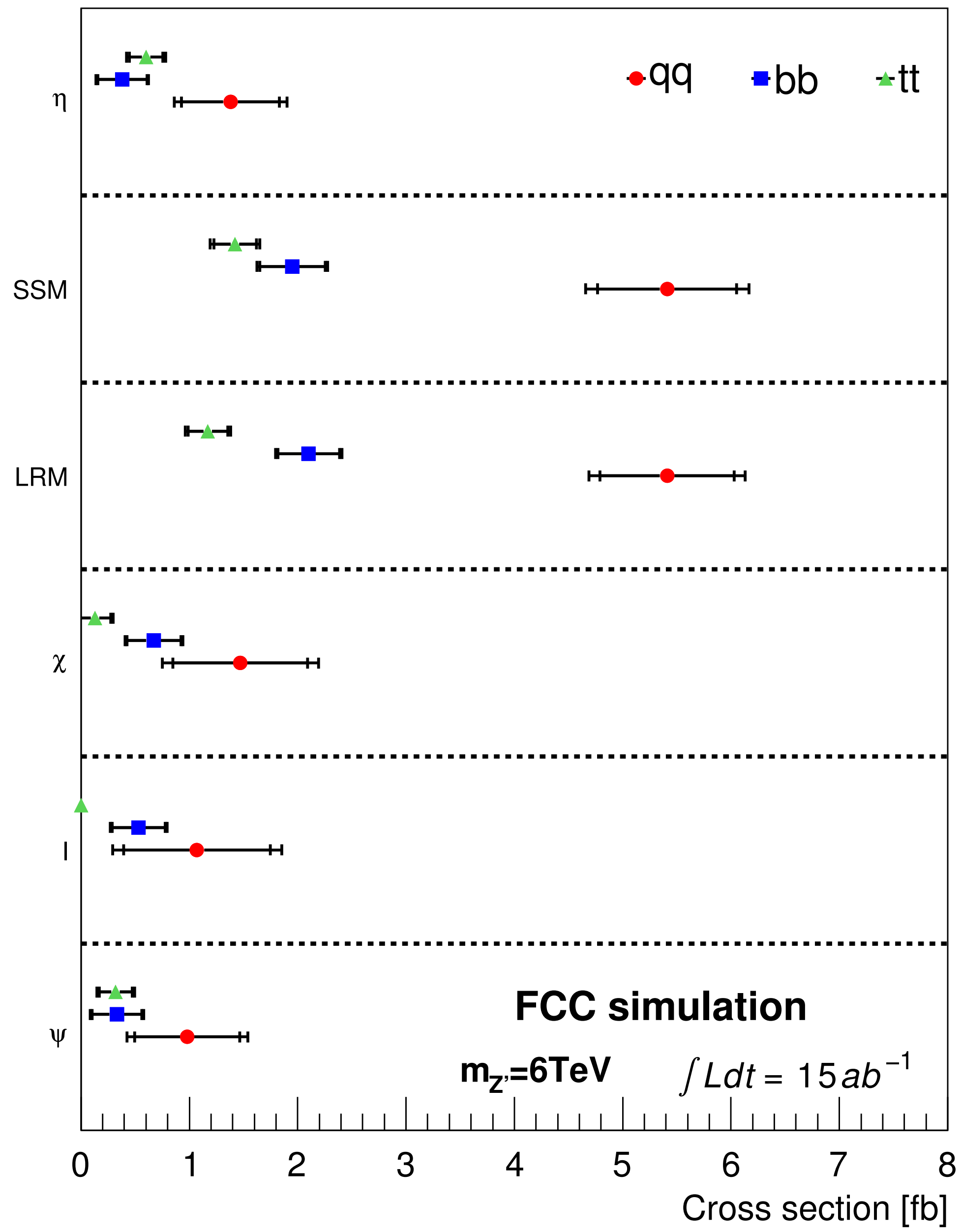


See also: D. Gonçalves, T. Han, F. Kling, T. Plehn, and M. Takeuchi, *Higgs Pair Production at Future Hadron Colliders: From Kinematics to Dynamics*, `arXiv:1802.04319 [hep-ph]`.

(IV) Exploration at 27 TeV of LHC discoveries: characterization of Z' models within reach of LHC observation

NB: uncertainty bars reflect very conservative syst assumptions



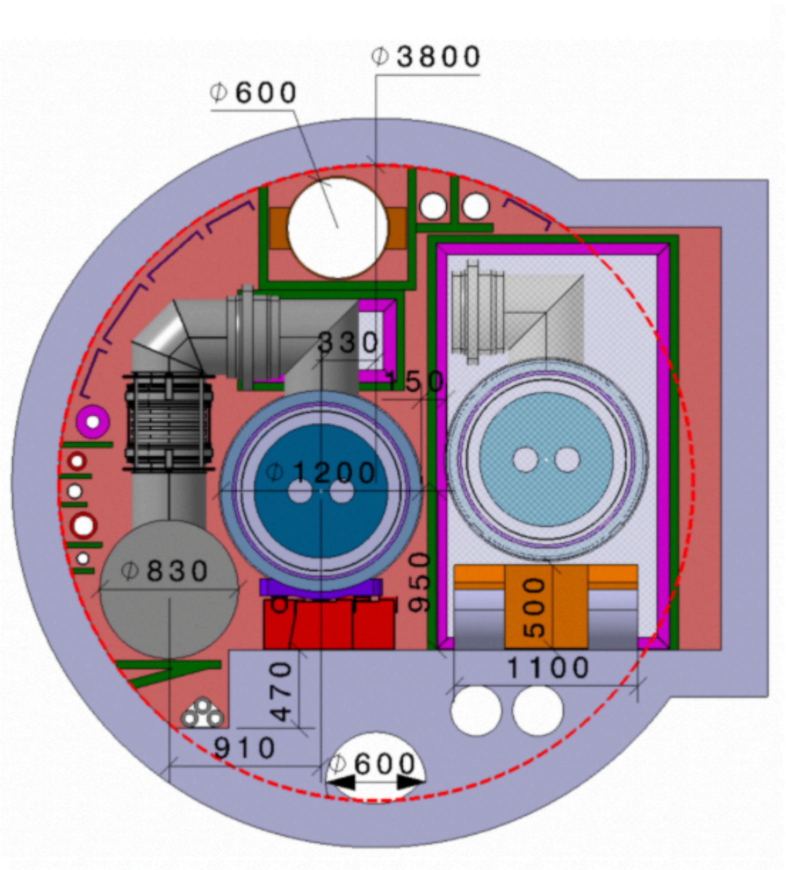


Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

T. G. Rizzo, *Exploring new gauge bosons at a 100 TeV collider*, Phys. Rev. **D89** (2014) no. 9, 095022, `arXiv:1403.5465 [hep-ph]`.

HE-LHC: the challenges

- 16T Nb_3Sn magnets: more challenging than for FCC-hh, due to reduced space in the tunnel (requires dedicated R&D)



- SPS upgrade, to SC technology, to allow injection at 0.9-1.3 TeV
- Full replacement and strengthening of all infrastructure on the surface and underground cryogenics
- Significant civil engineering work both on the surface and in the tunnel (new SPS transfer lines, new caverns for cryogenics, 2 new shafts, …)
- Overhaul/full replacement of detectors (radiation damage after HL-LHC, limited lifetime of key systems like magnets, use of new technologies, …)
- …

HE-LHC, project timeline/cost

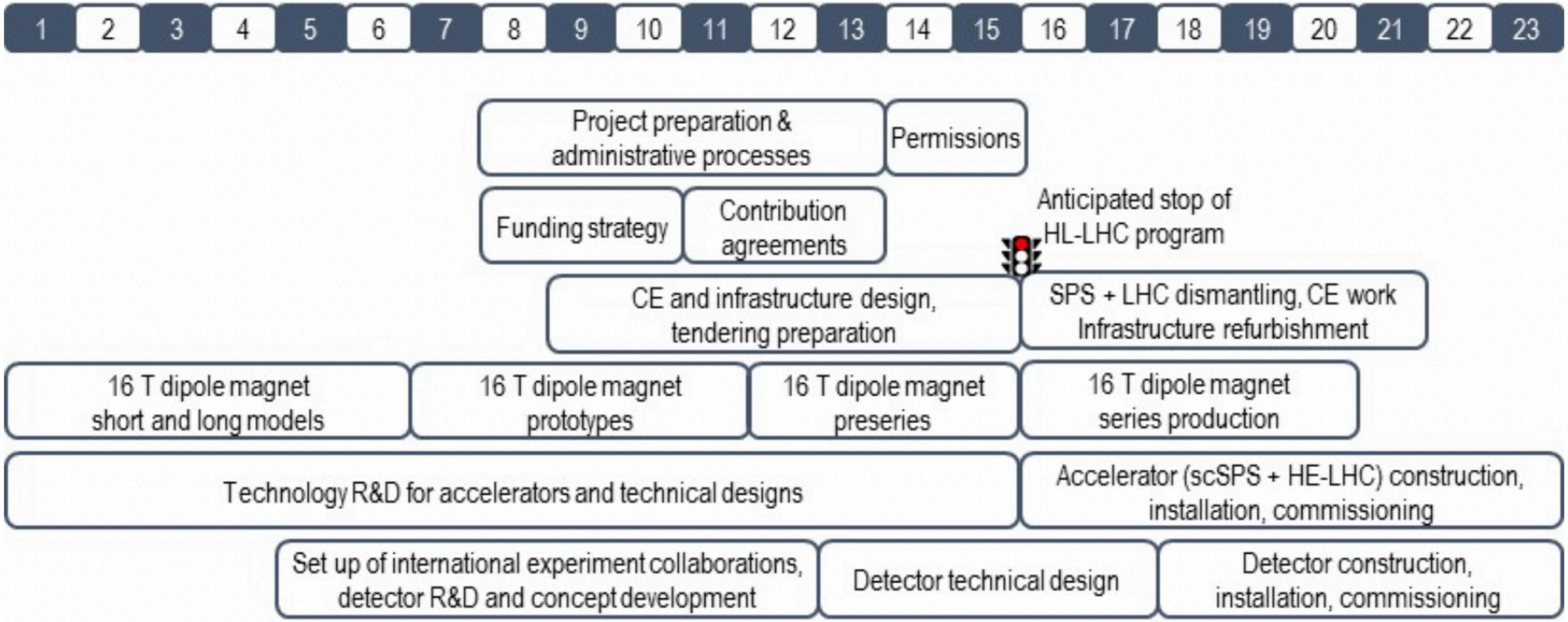
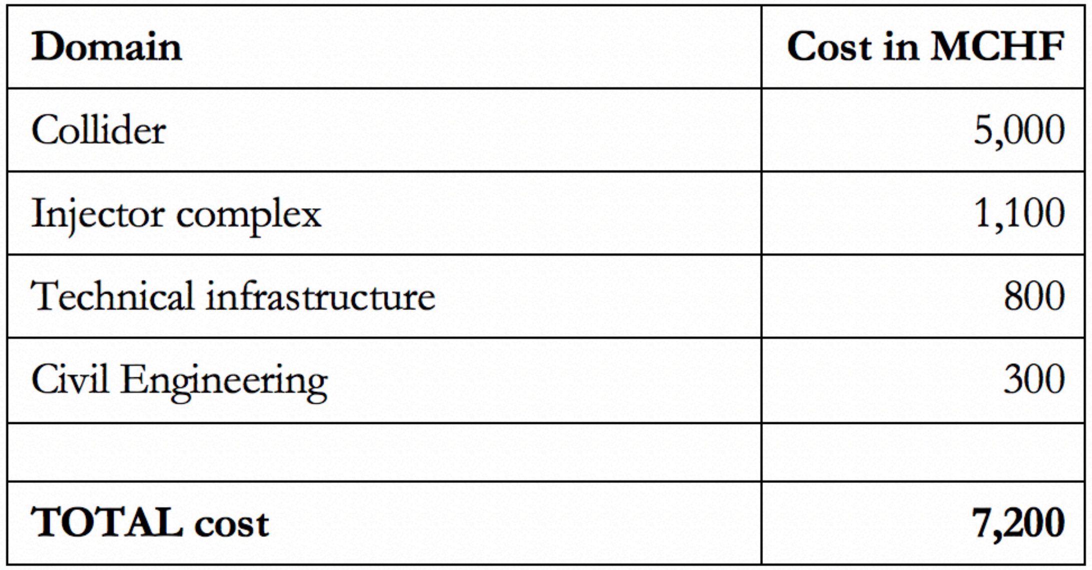


Figure 7: Overview of implementation timeline for the HE-LHC project starting in 2020. Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.



Domain	**Cost in MCHF**
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

Table 2: Summary of capital cost for implementation of the HE-LHC project.