The Higgs Potential at future colliders

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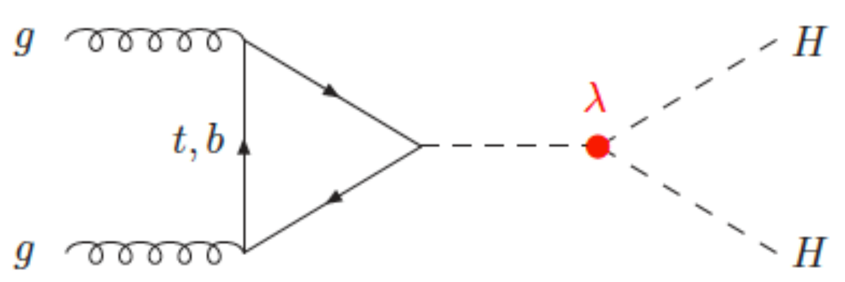
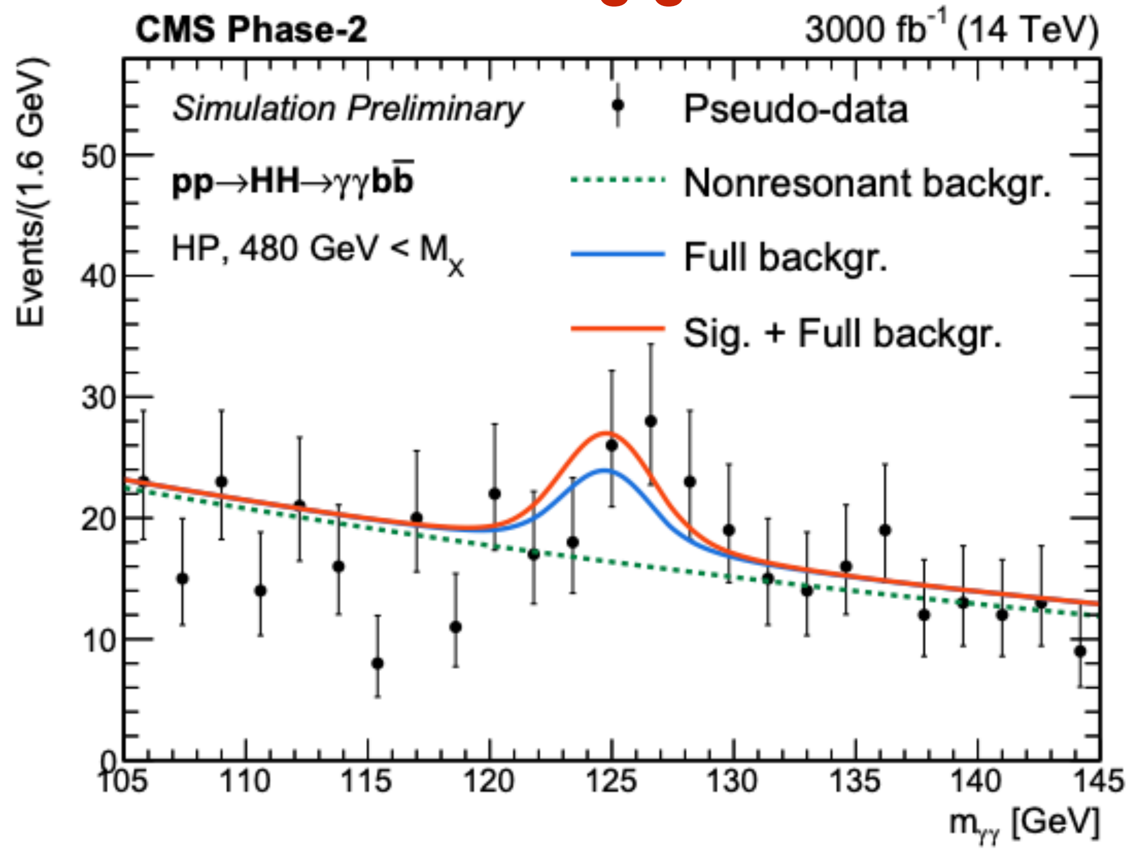
Snowmass `20 - 06/10/2020

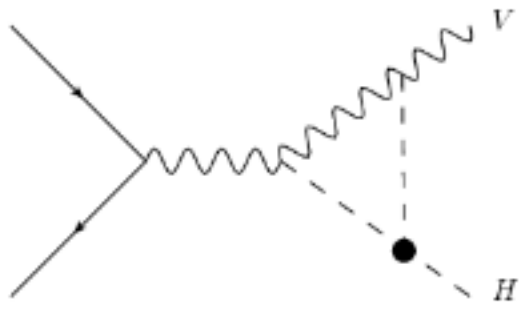
Self coupling @ HL-LHC measurements



[1902.00134](https://arxiv.org/abs/1902.00134) [hep-ph]

bbγγ





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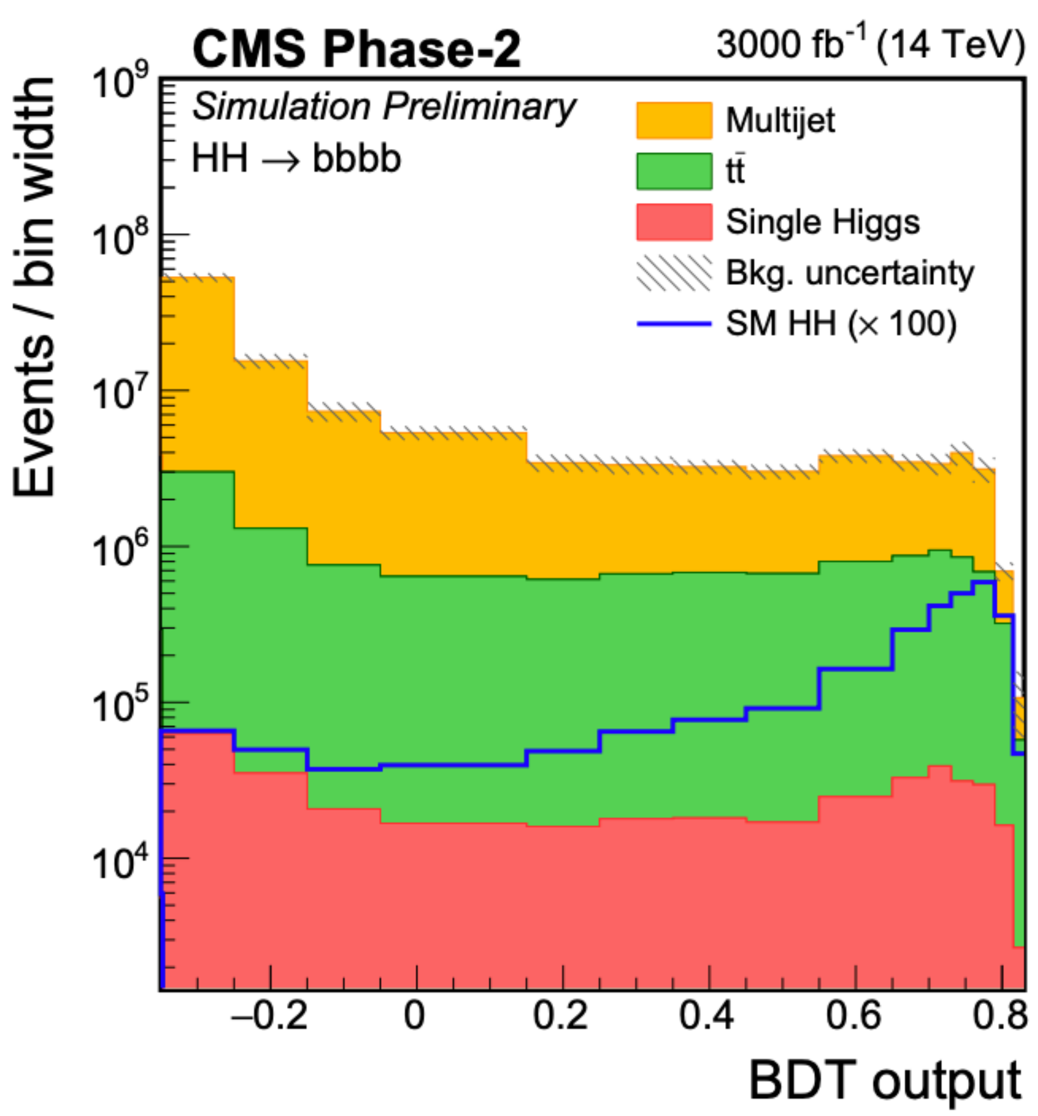
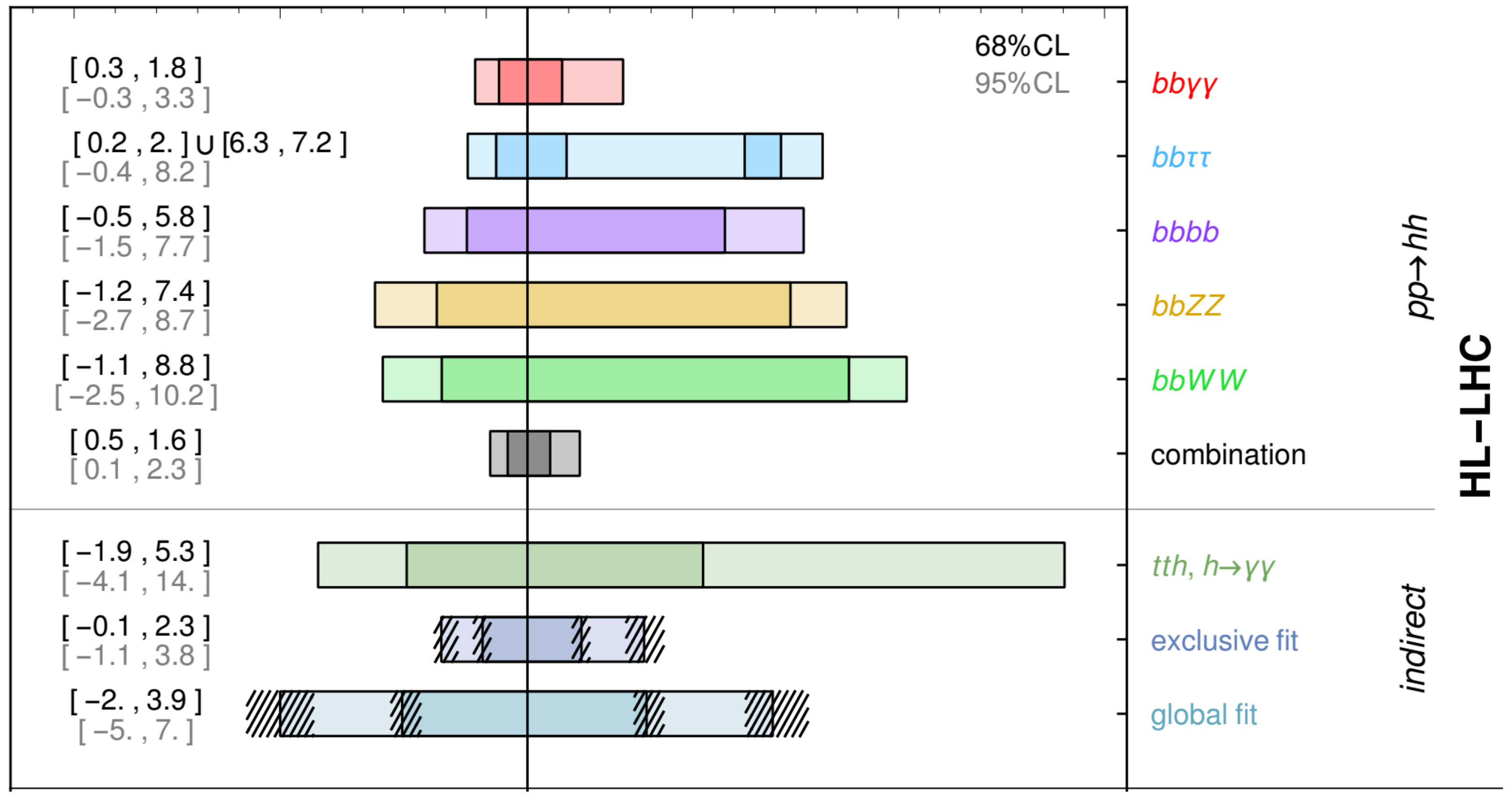


- At the (HL-)LHC the self-coupling can be measured via both:
  - **Higgs pair production**
  - **single Higgs production**

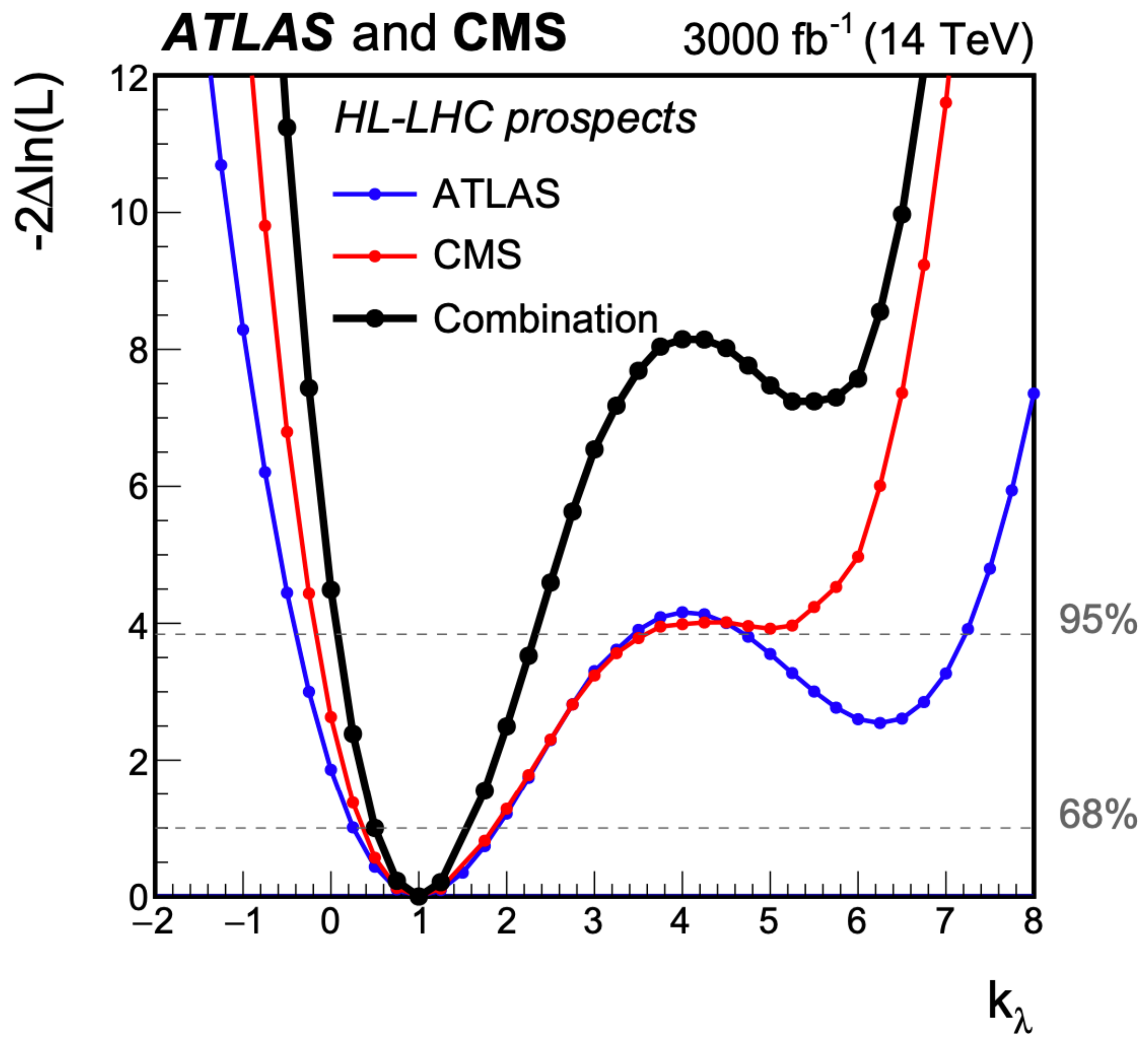
- Indirect constraint from ggH and ttH:
  - $\delta\kappa_\lambda \approx 100\%$ (exclusive)
  - $\delta\kappa_\lambda \approx 200\%$ (global)

- Direct measurement:
  - $\delta\kappa_\lambda \approx 50\%$

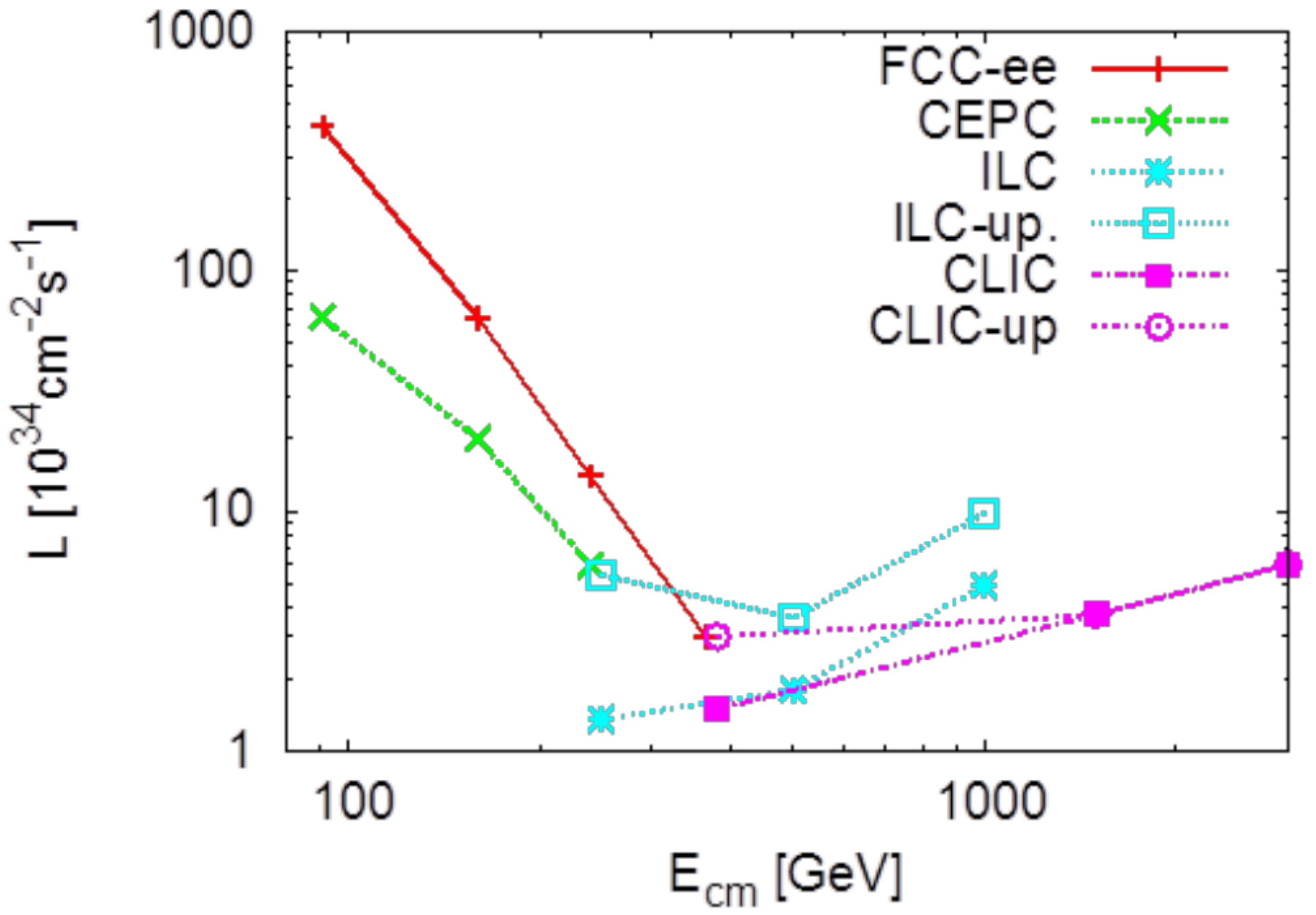
combination HL-LHC



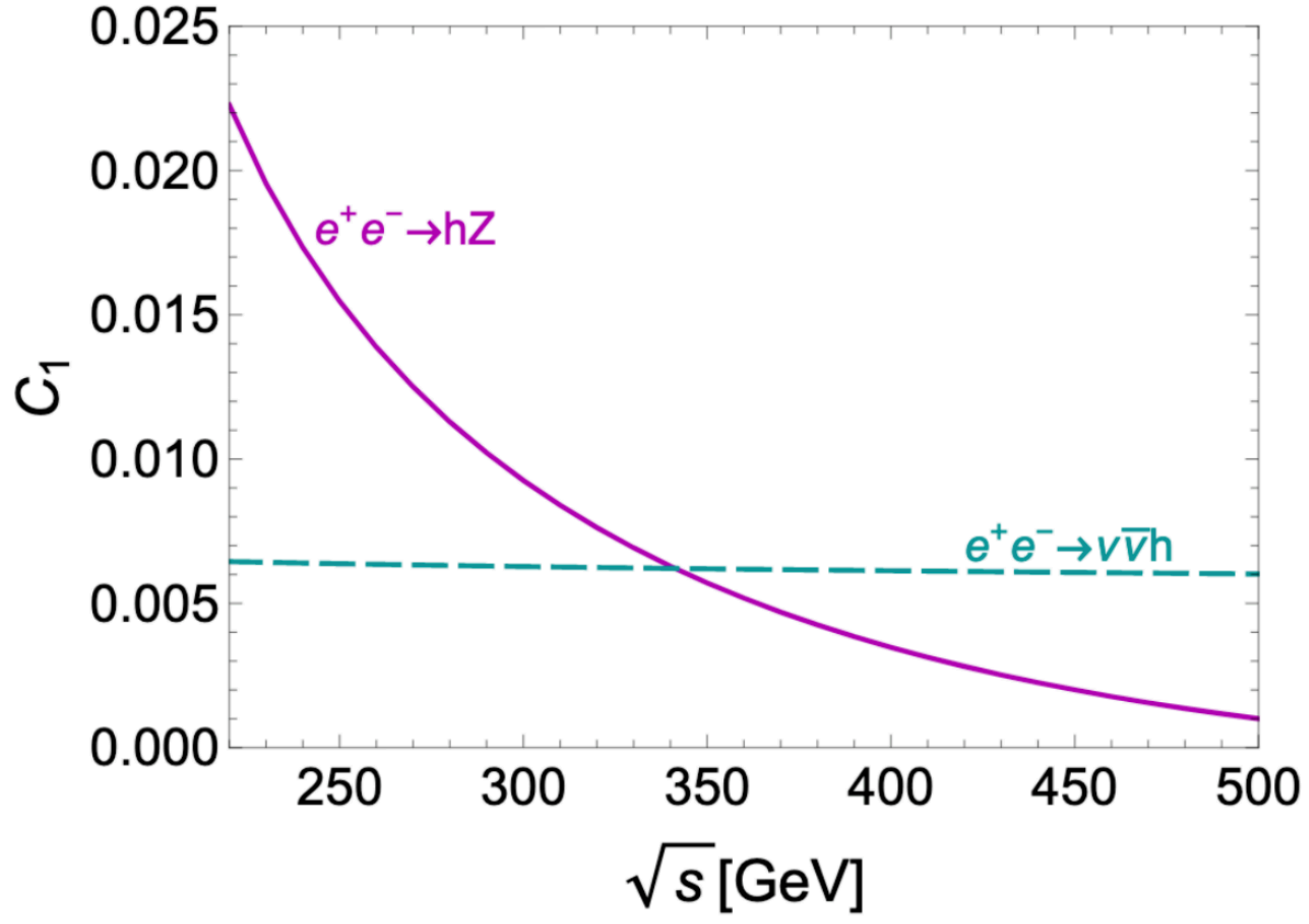
combination HL-LHC

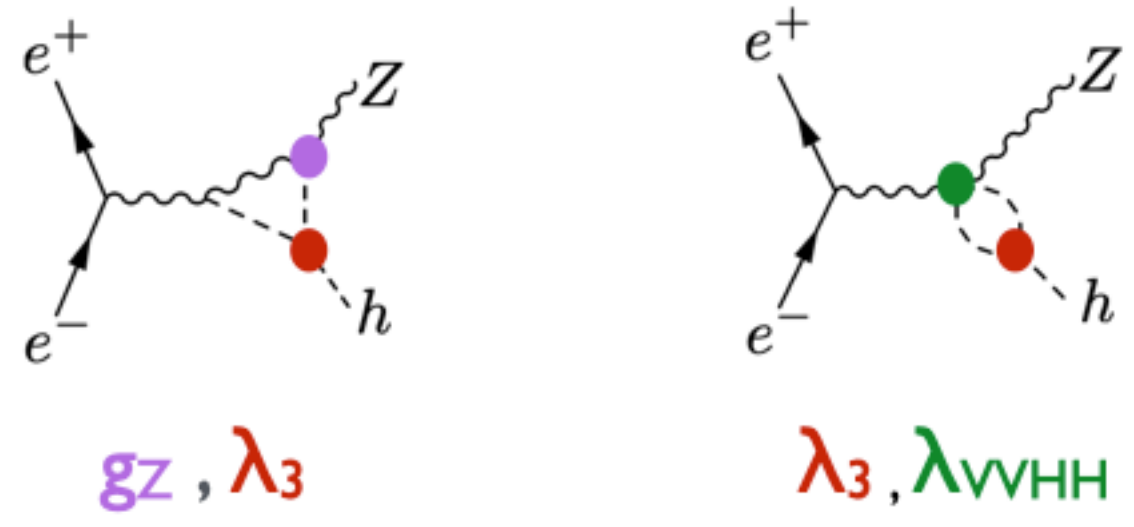


Self-coupling at circular e^+e^- colliders

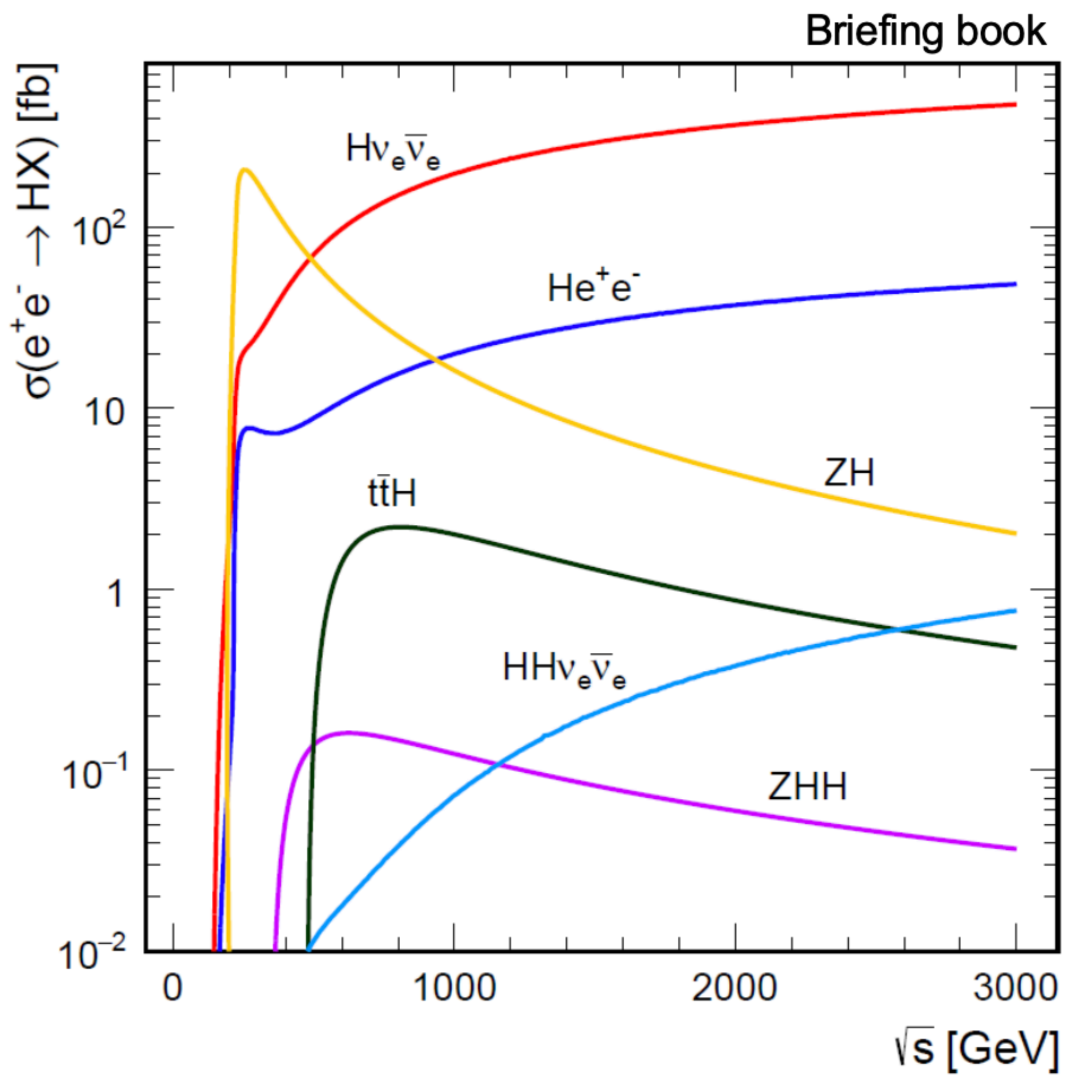


[1312.3322](https://arxiv.org/abs/1312.3322) [hep-ph]





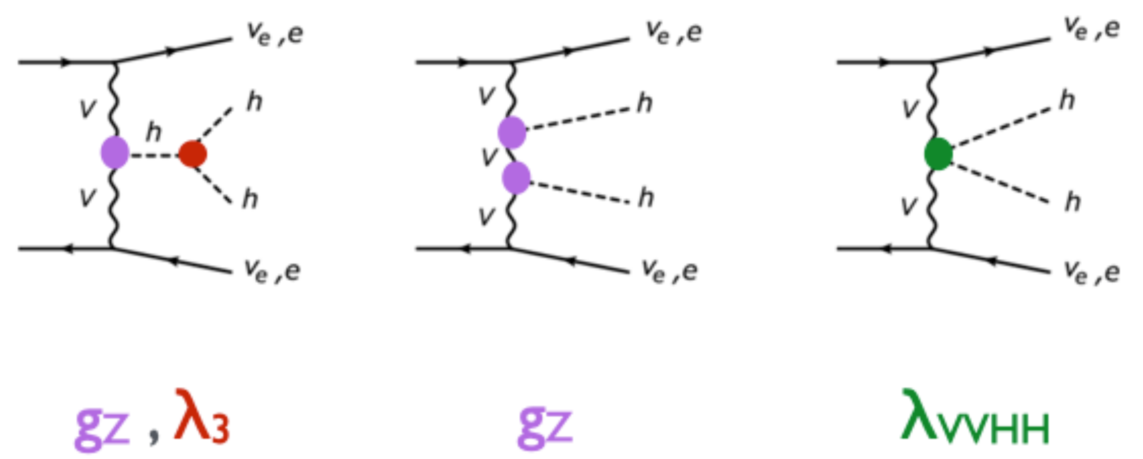
- At **low energy $\sqrt{s}$ < 500 GeV** the self-coupling is measured via **single Higgs production** (FCC-ee)
- Precise ZH cross-section measurement at various energies can resolve λ_3 , λ_{VVHH}
- **FCC-ee gives the best indirect measurement:**
  - $\delta\kappa_\lambda$ = 33% (2 IPs)
  - $\delta\kappa_\lambda$ = 24% (4 IPs)

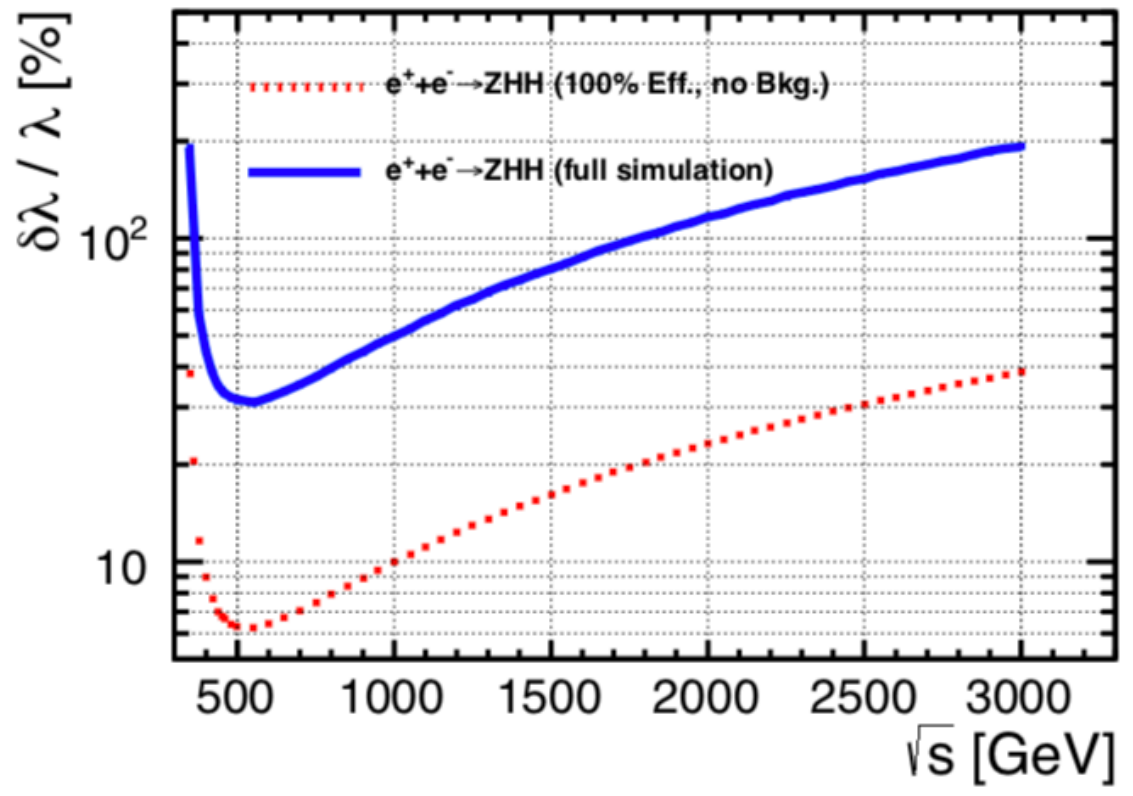


Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 2IP 27./24. 4IP

global fit, with/without HL-LHC input

Self-coupling at linear e+e- colliders

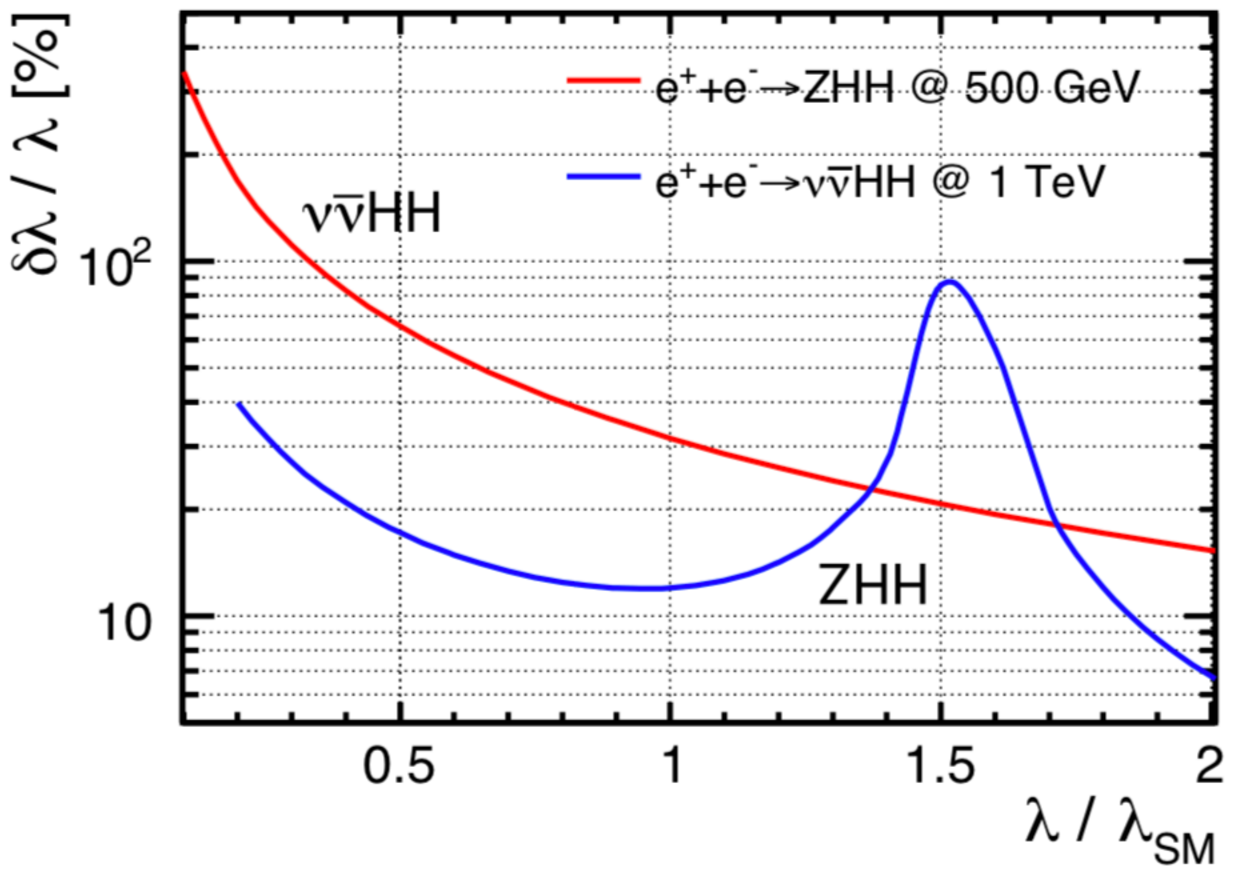




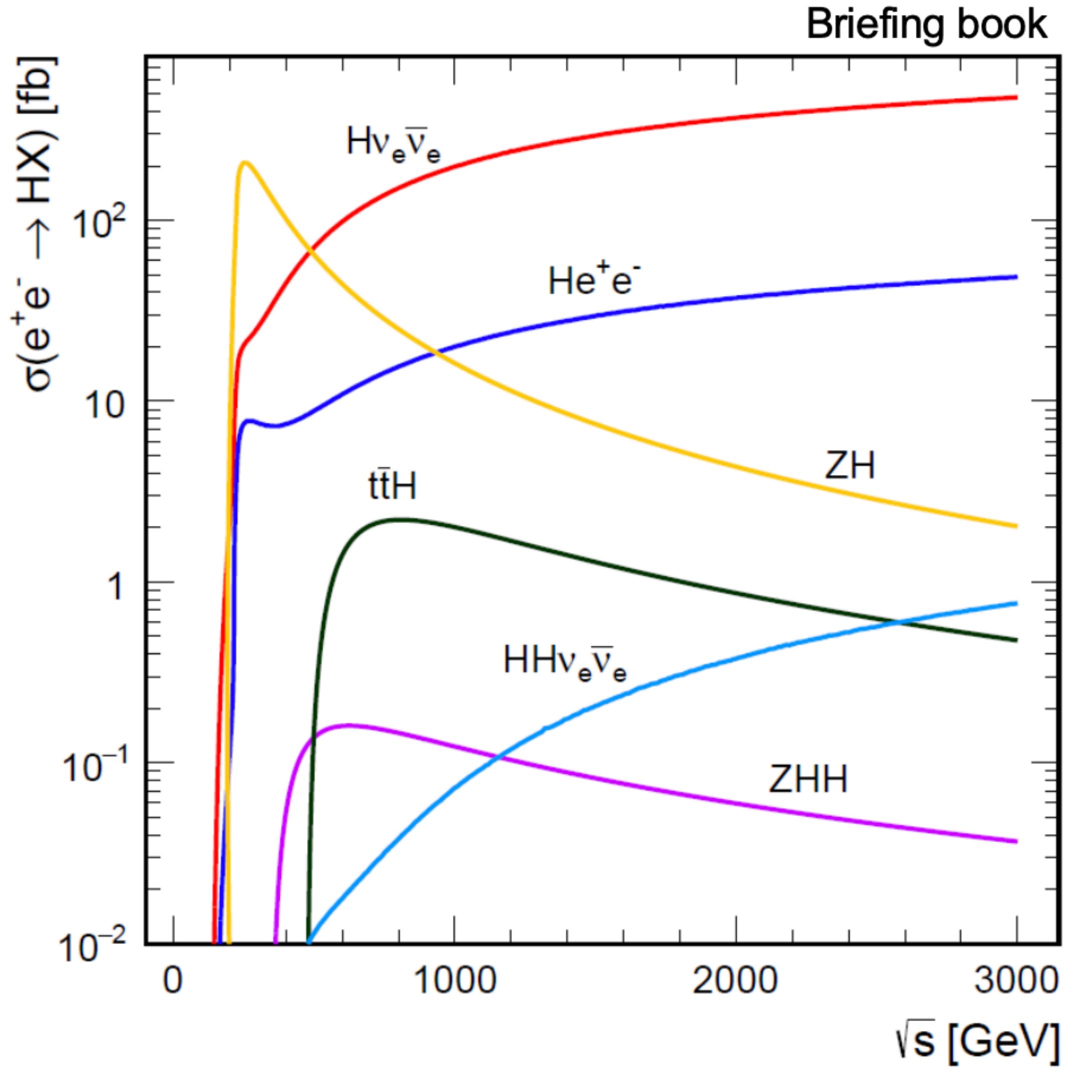
ILC - 1 TeV

- At high **energies √s > 500 GeV** self-coupling is measured via double Higgs production (ZHH and vvHH)
- Cross-section at various energies depends on λ_3
- Measured in *ll*bbbb (ZHH) and vvbbbb, vvbbWW (vvHH)
- **ILC and CLIC best direct measurement at e+e-:**
  - $\delta\kappa_\lambda$ = 10% (ILC_{1000})
  - $\delta\kappa_\lambda$ = 9% ($CLIC_{3000}$)

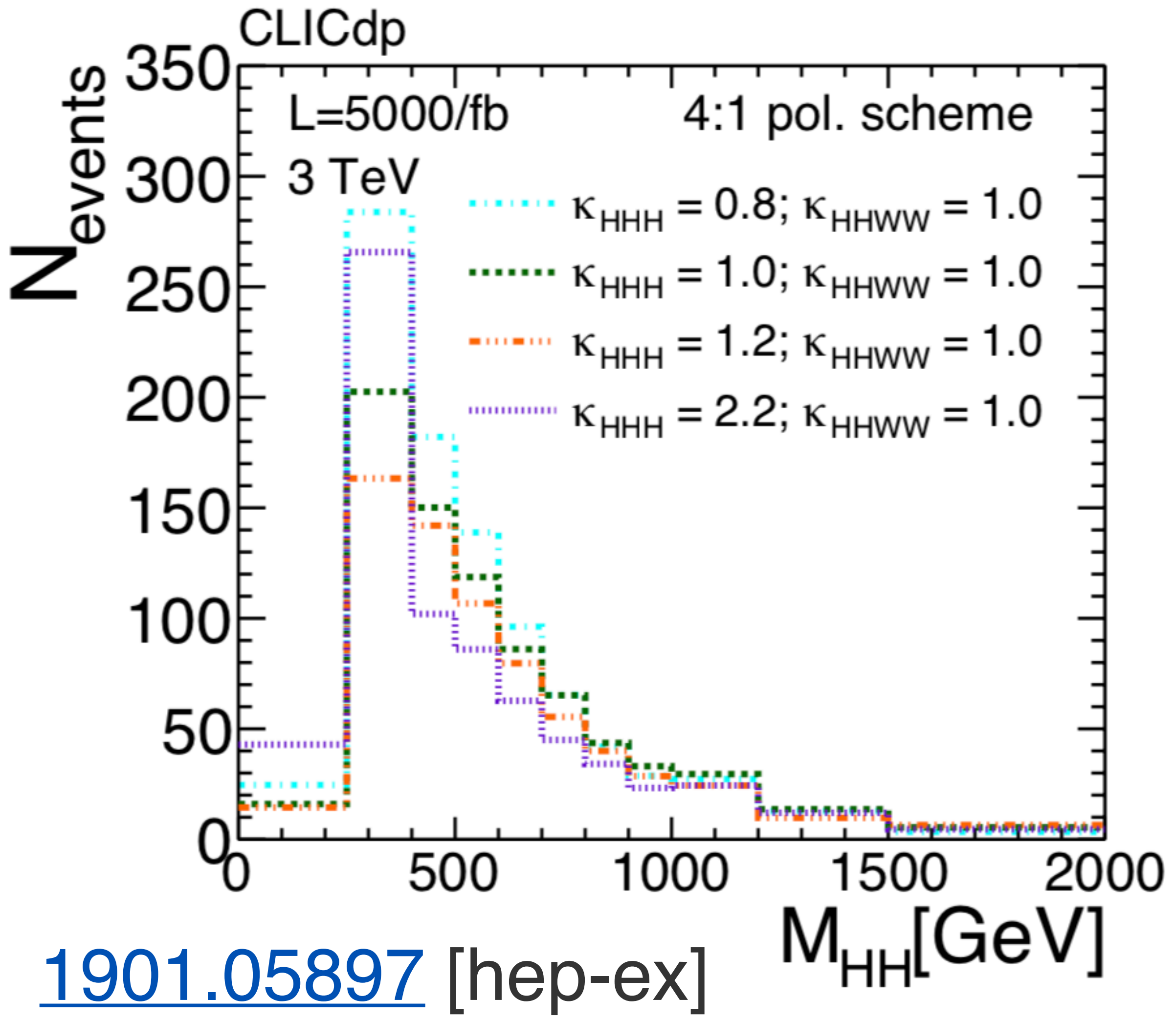
1910.00012 [hep-ph]



Collider	ILC_{500}	ILC_{1000}	CLIC
g_{HHH} (%)	27.	10.	9.

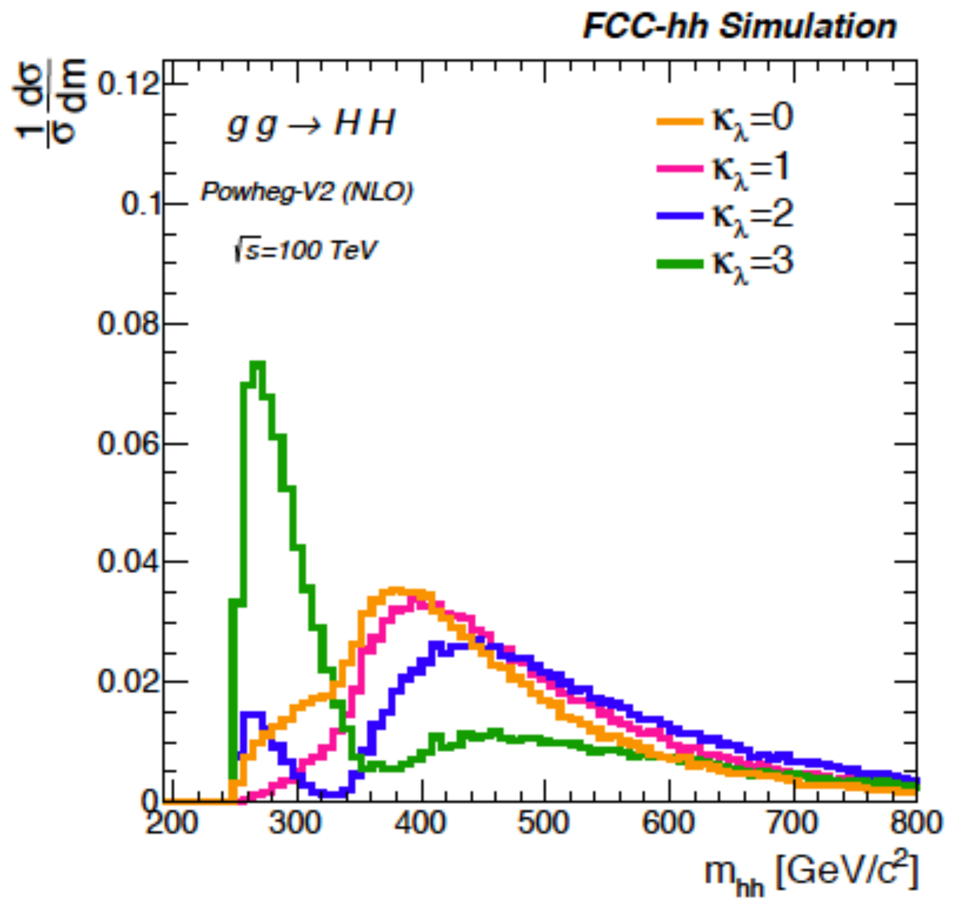


CLIC - 3TeV



1901.05897 [hep-ex]

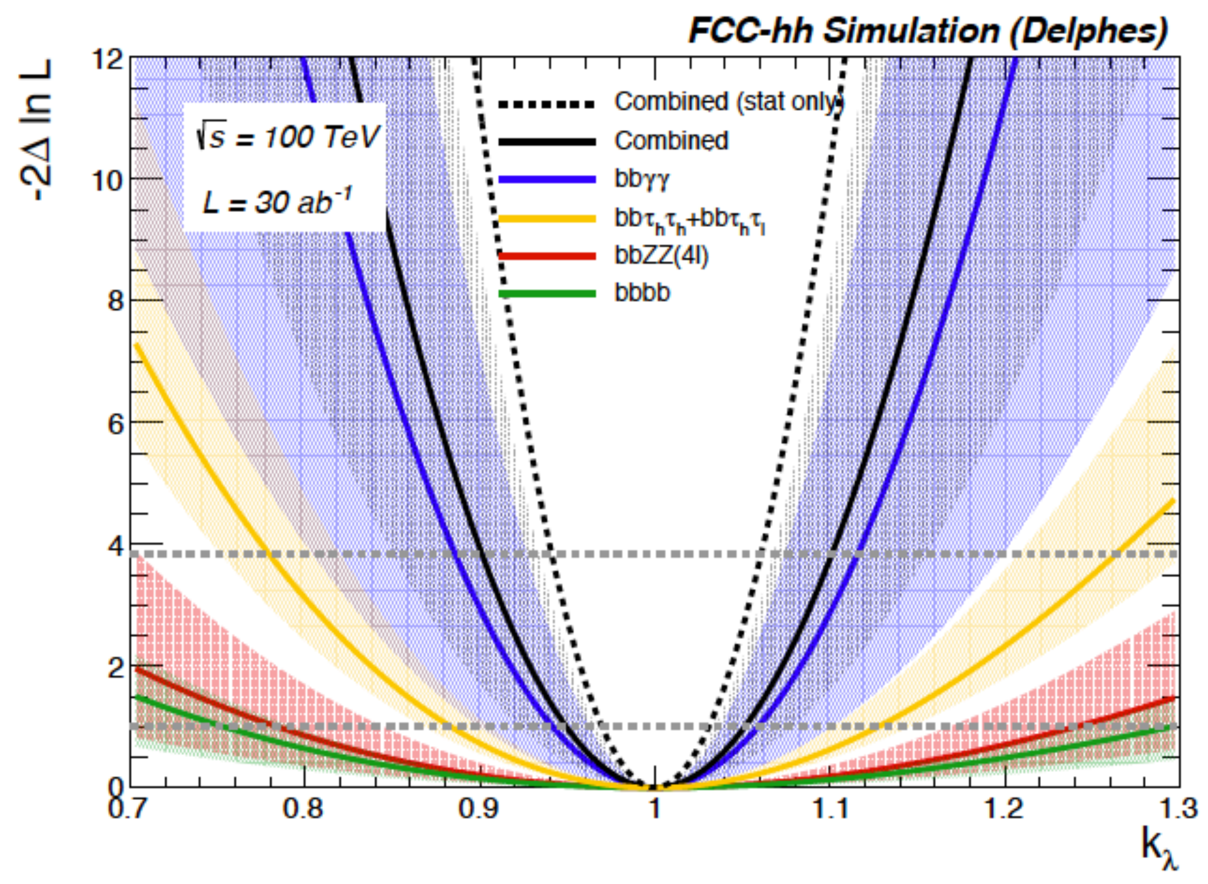
Self-coupling at the FCC-hh

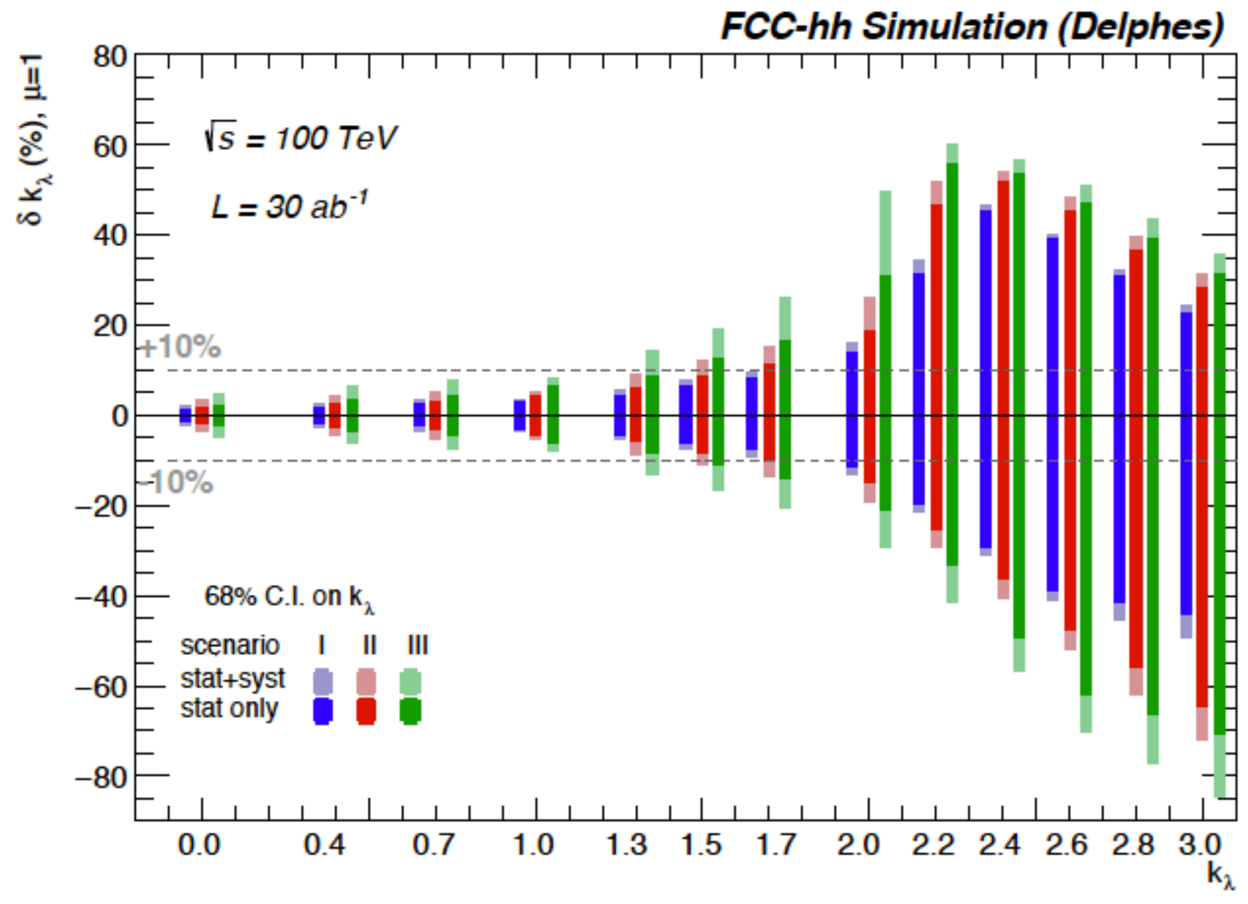


2004.03505 [hep-ph]

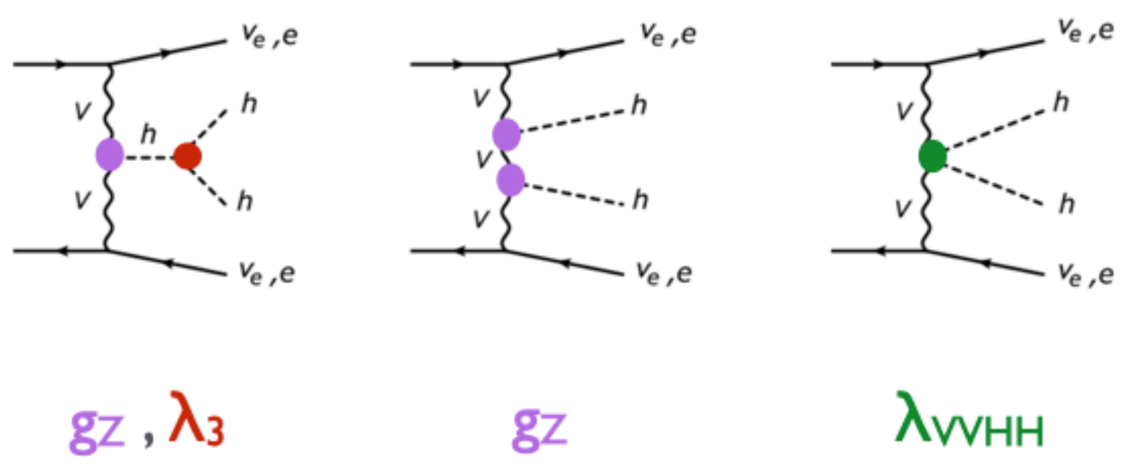
parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

- At 100 TeV pp, Higgs pair production gives best precision on λ_3
- Measured in:
  - bbγγ (golden channel), bbττ, bbbb, bbZZ(4l)
- Combined precision:
  - 3.5-7% for SM (3% stat. only)
  - 10-20% for $\lambda_3 = 1.5^* \lambda_3^{SM}$

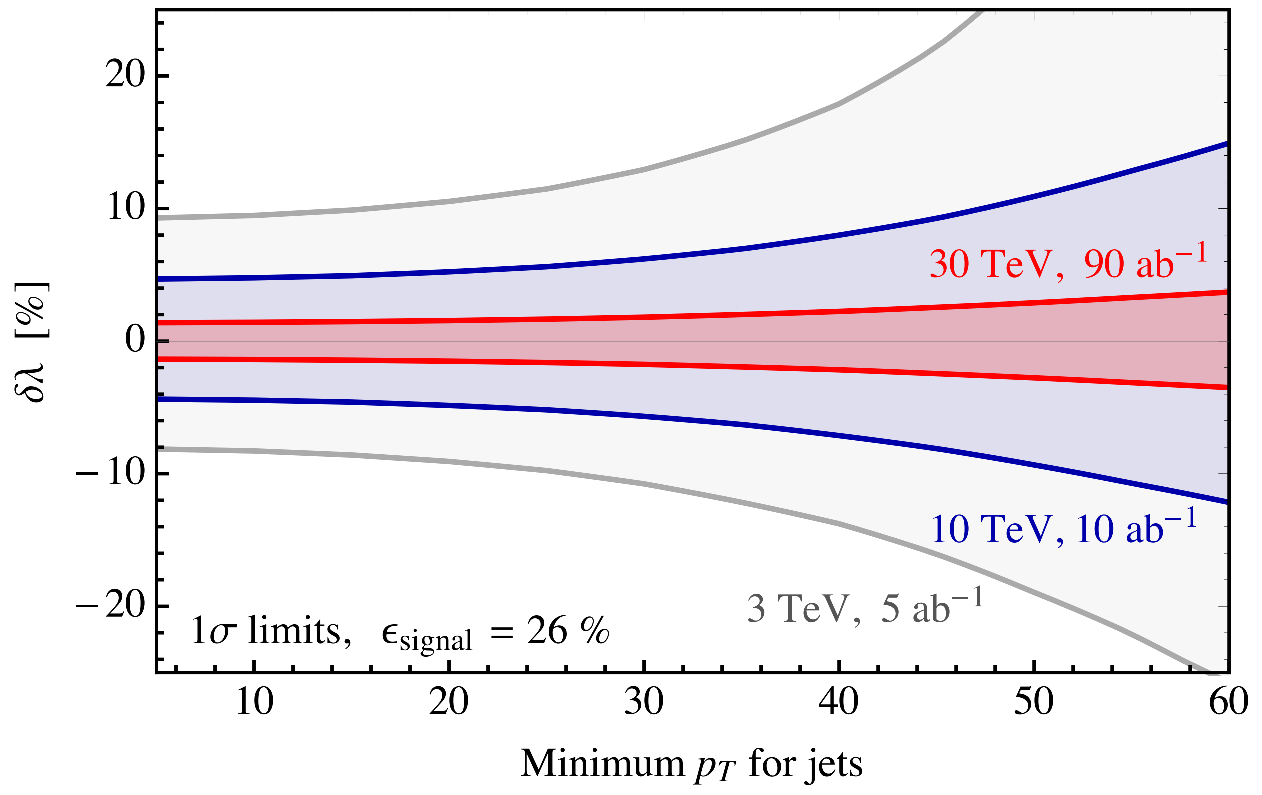




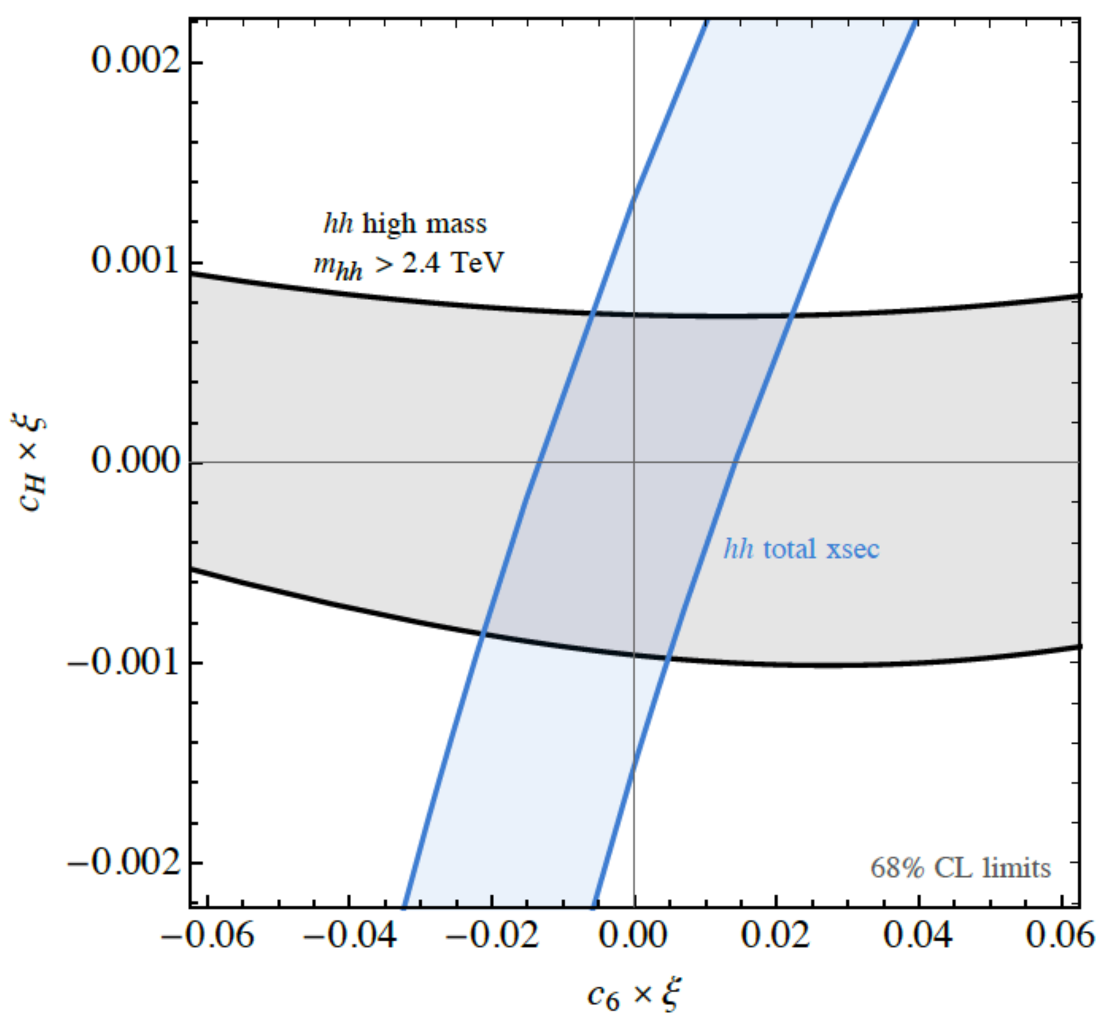
Self-coupling at the Muon Collider



Buttazzo, Franceschini, Wulzer

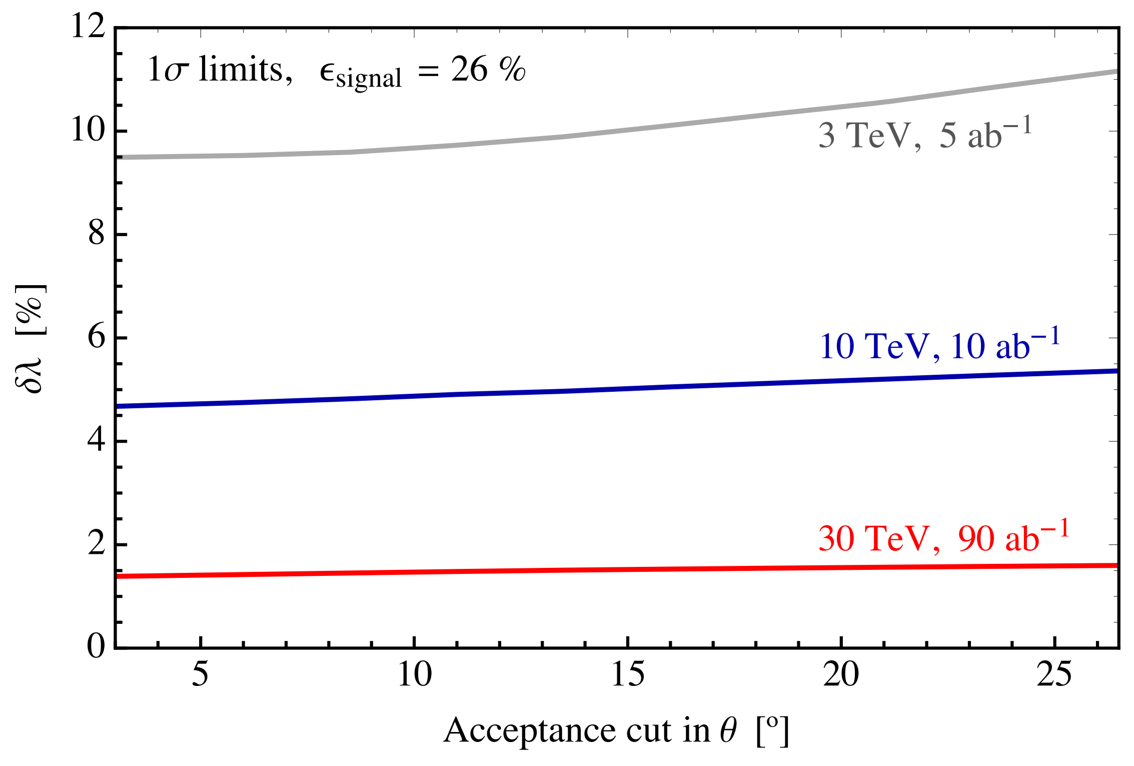


- At 10-30 TeV muon collider, the VBF pair production dominates (~ CLIC)

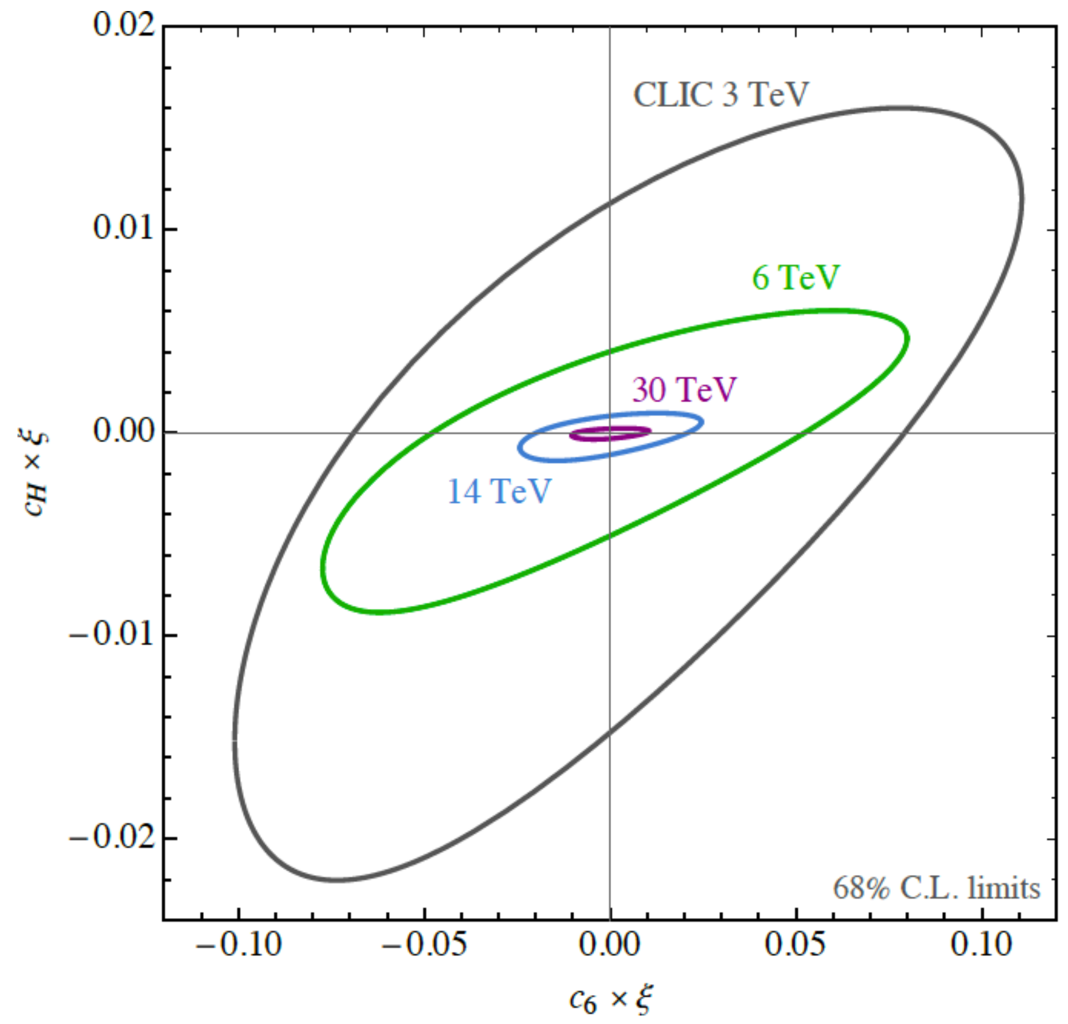


- vvbbbb final state (4jets + ME)

- Muon collider could potentially provide the best precision ~2% (stat only) ?



- More studies needed, **parton level** only for now



Open questions:

- For simplicity, most of the **benchmarking on future colliders capabilities** in made assuming λ_3^{SM} (allows for easy comparison), or varying λ_3 alone.
    - desirable to investigate use of global — (SM)EFT fit from exp. community, or this exercise can be left to theorists?
    - how about indirect measurements? (e.g single Higgs production or W/Z mass)
    - how approach global fits as a community (pheno/exp)

- Various proposed future colliders present different **levels of maturity**
    - How do we deal with detector effects (Pile-up , Beam Induced Background) ?
        - Can be indirectly **parameterised** if full-sim is not available (very different environment) ?
    - Treatment of dominant systematic uncertainties (theory vs. exp)
    - How do we estimate **uncertainties** (performance/systematics) on future colliders?

Open questions:

- What is the **interplay between auxiliary measurements** at various colliders to allow for best self- coupling precision? e.g
    - at proton collider precise measurement of $\boldsymbol{\lambda_3}$ requires $\mathbf{y_t}$ (itself requiring g_{ttZ})?
    - at lepton (and proton) colliders need both measurements of $\boldsymbol{\lambda_{VVHH}}$ and λ_3

- How about $\boldsymbol{\lambda_{VVHH}}$ and $\boldsymbol{\lambda_4}$?
    - missing exp. efforts so far (see backup for pheno. work)

Open questions

- A **strongly first-order EWPT** requires new physics coupling to the Higgs.
  - What does this imply generically for **di-Higgs rates**?
  - Does it imply a **minimum deviation** pattern in Higgs couplings?
  - How does the reach of **Higgs coupling measurements** compare to other **direct** and **indirect probes**?

- What can we learn about the **history of the universe** from **collider measurements ?**

BACKUP

The Standard Model Higgs Potential

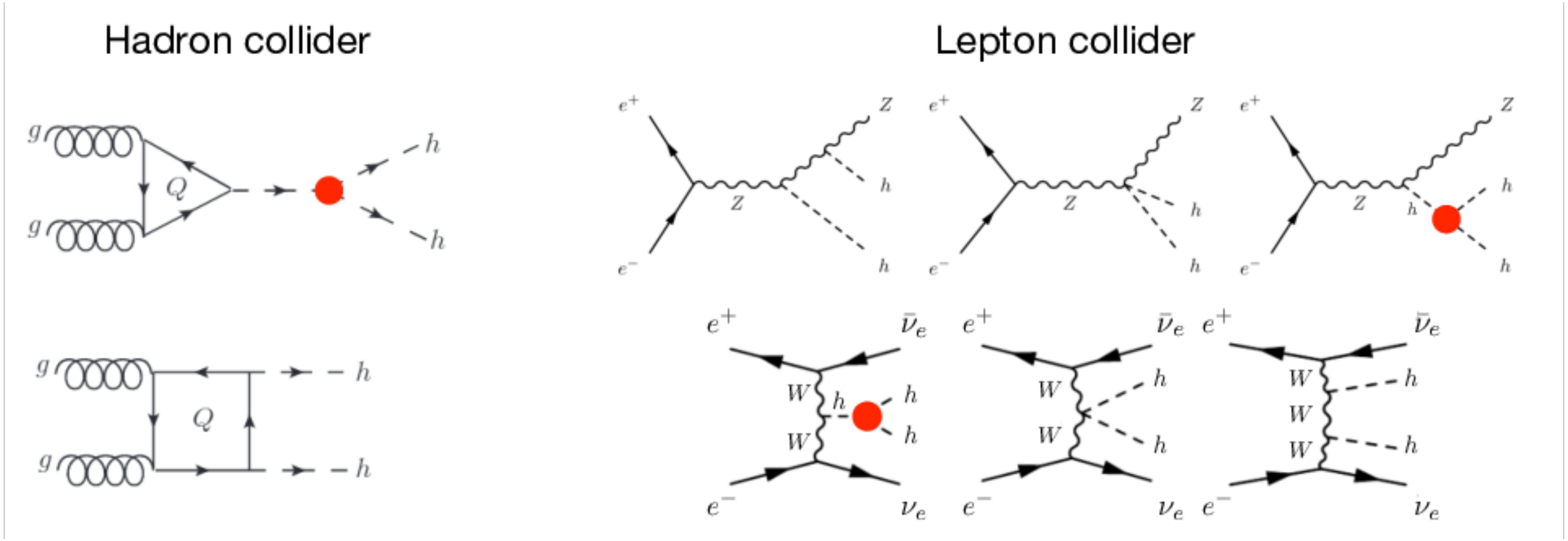
$$\begin{aligned} V &= -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 \\ &\to -\frac{\lambda}{4} v^4 + \frac{1}{2}(2\lambda v^2)\, h^2 + \lambda\, v\, h^3 + \frac{\lambda}{4}\, h^4 \\ &= V_0 + \frac{1}{2} m_h^2 h^2 + \lambda_3 v\, h^3 + \frac{\lambda_4}{4} h^4 \end{aligned}$$

- Fix the two parameters $(\mu^2,\, \lambda)$ with two observables $(v,\, m_h)$.
- Predictions:

$$\lambda_3 = \lambda_4 = \frac{m_h^2}{2v^2}$$

Testing the SM Higgs Potential

- Measure di-Higgs (tri-Higgs?) production to probe λ_3 (λ_4): **[talk by M. Selvaggi]**



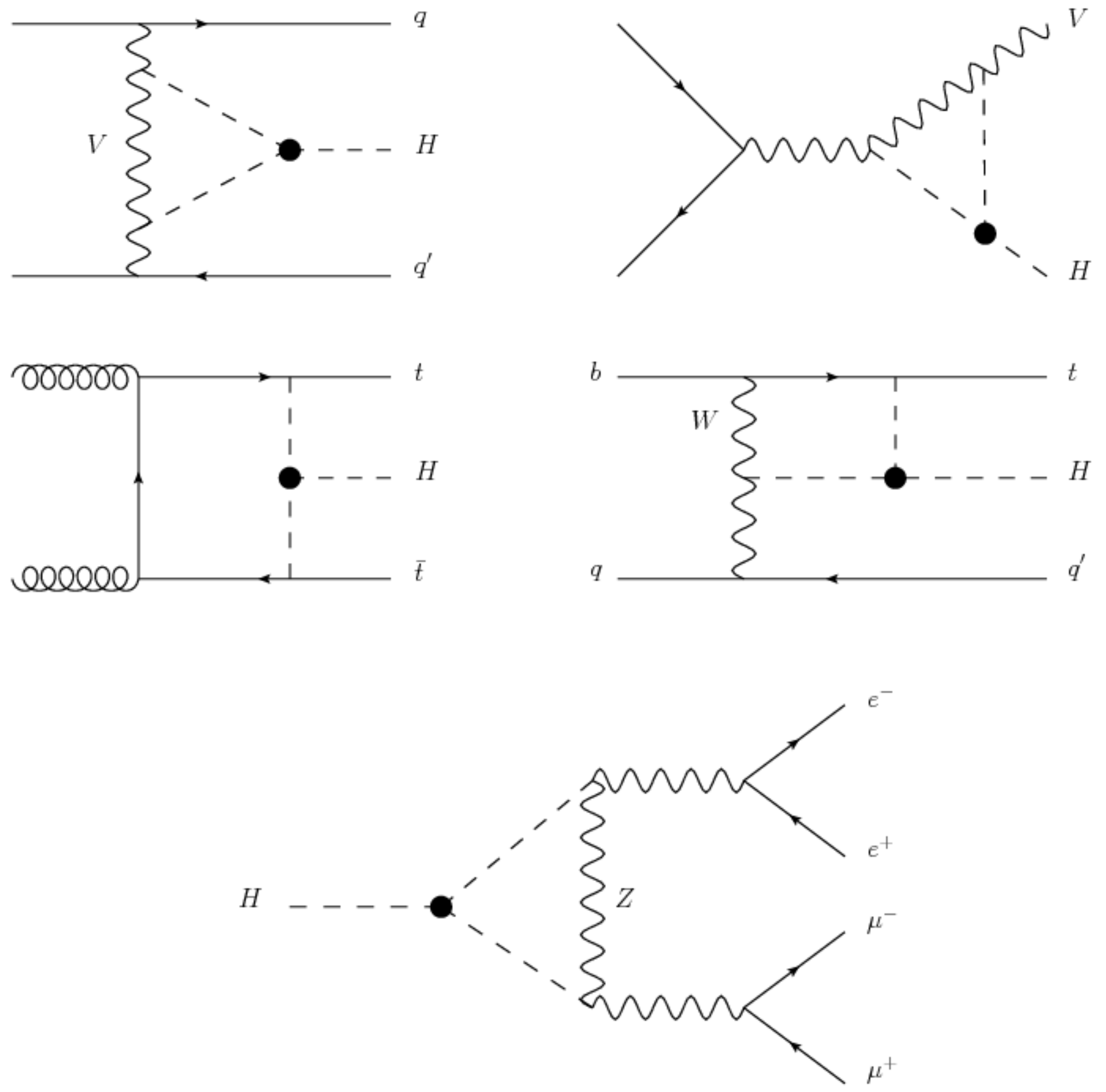
[de Blas *et al*. 1905.03764]

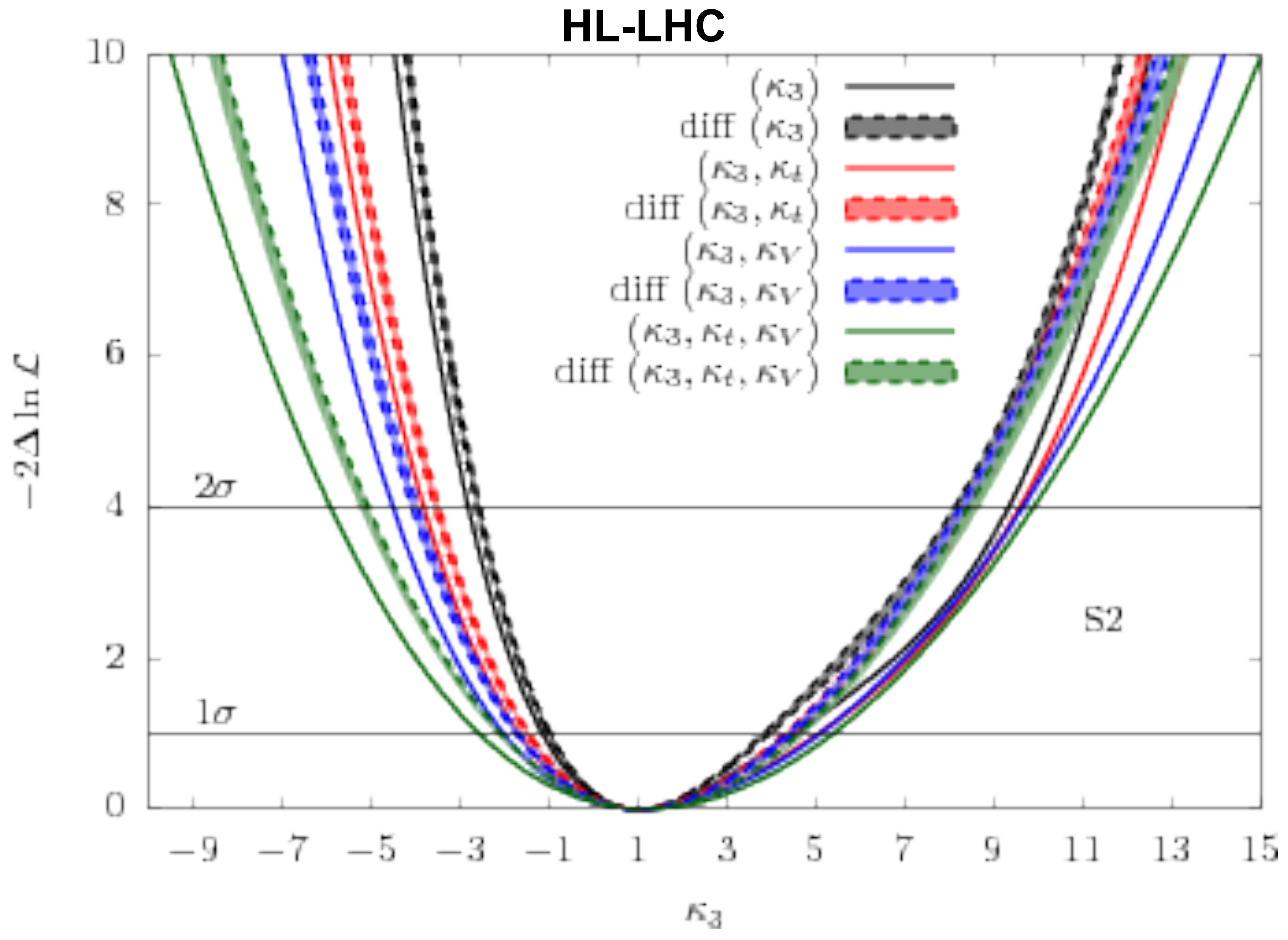
- Must be part of a global fit to Higgs couplings, requires high SM precision!

[*e.g.* Di Vita, Grojean, Riembau, Vantalon 1704.01953]

Testing the SM Higgs Potential

- Look for NLO effects of λ_3 in single Higgs production:

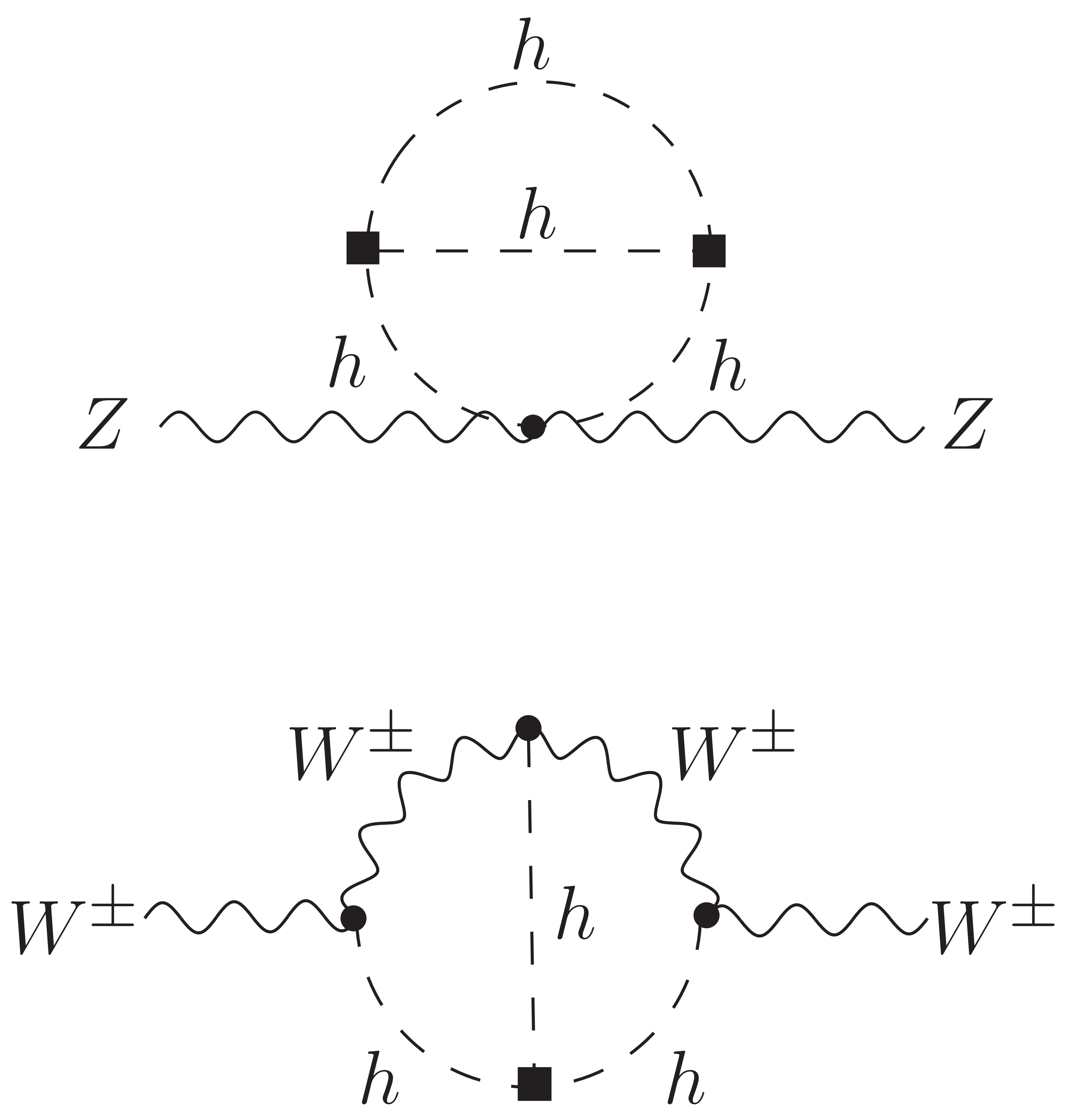


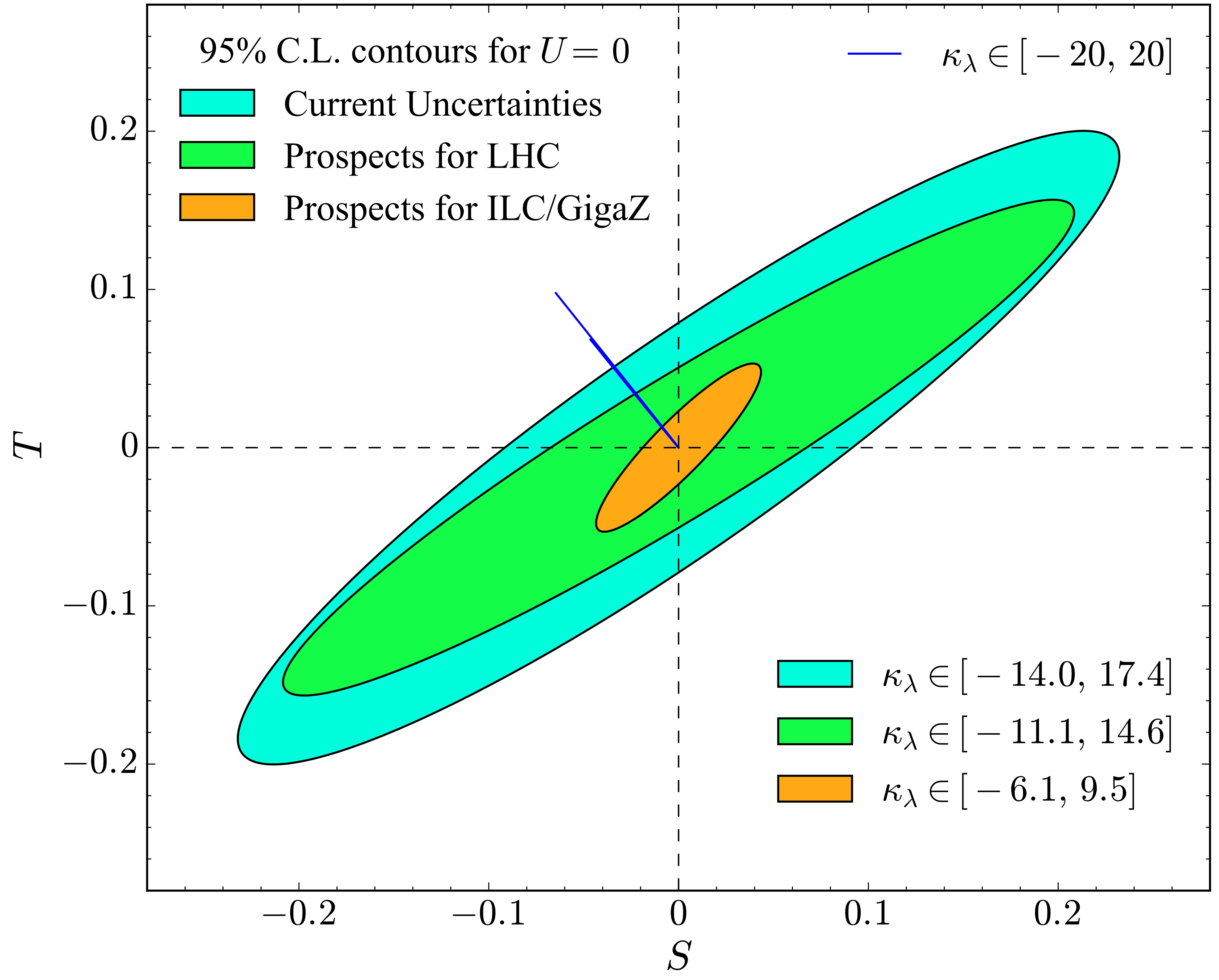


[McCullough 1312.3322; Maltoni, Pagani, Shivaji, Zhao 1709.08649]

Testing the SM Higgs Potential

- Look for effects of λ_3 in precision electroweak observables:





[Degrassi, Fedele, Giardino 1702.01737; Kribs, Maier, Rzehak, Spannowsky, Waite 1702.07678]

Higgs Potential Beyond the SM

- Heavy new physics can yield effective operators that modify the potential.

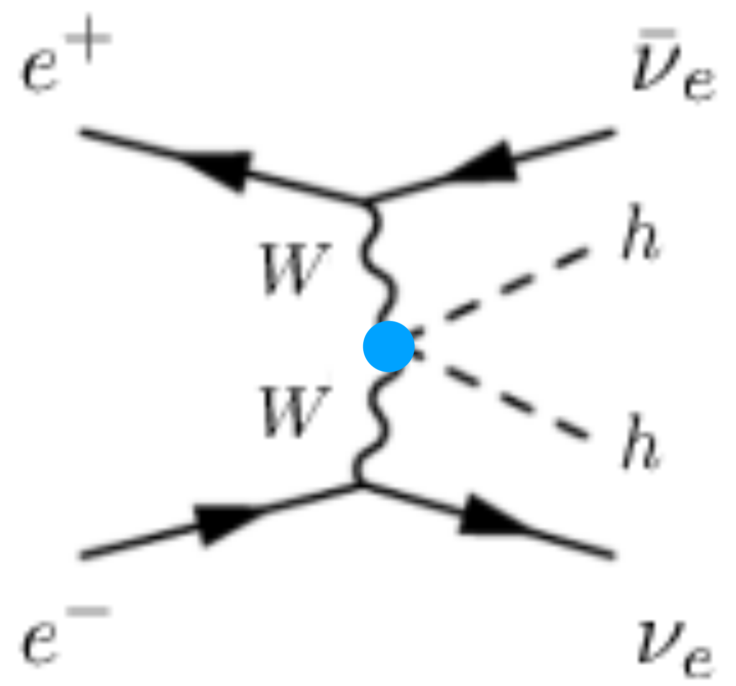
[*e.g.* Giudice, Grojean, Pomarol, Rattazzi hep-ph/0703164; Brivio, Trott 1706.08945]

$$\mathcal{L} \supset \frac{c_H}{2\Lambda^2}[\partial_\mu (H^\dagger H)]^2 - \frac{c_6\,\lambda}{\Lambda^2}(H^\dagger H)^3$$

$$\frac{\lambda_3}{\lambda_3^{SM}} = 1 + c_6 \frac{v^2}{\Lambda^2} - \frac{3}{2} c_H \frac{v^2}{\Lambda^2}$$

$$\frac{\lambda_4}{\lambda_4^{SM}} = 1 + \left(6c_6 - \frac{25}{3} c_H\right) \frac{v^2}{\Lambda^2}$$

- Note: c_H also modifies hhVV couplings!

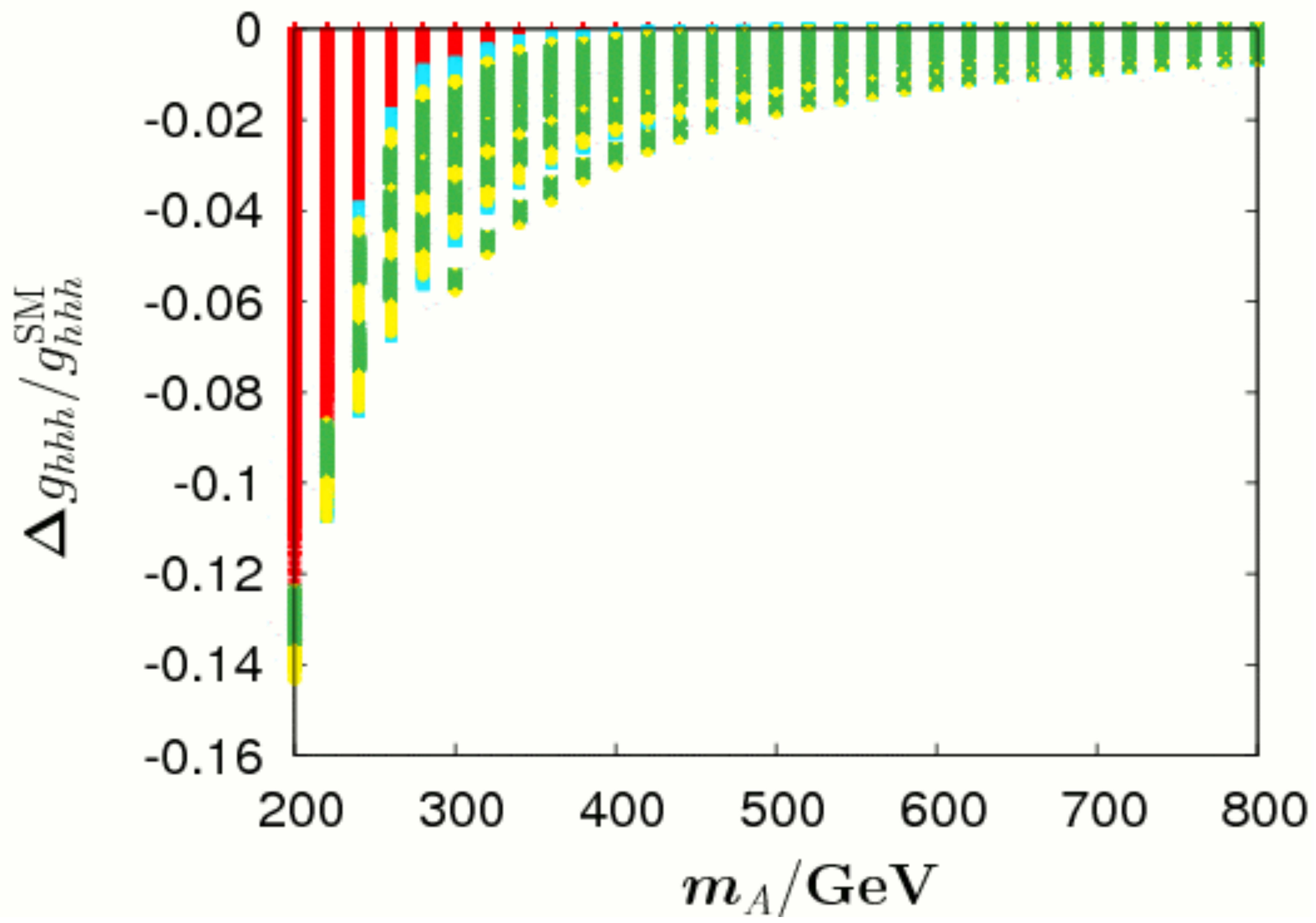


Higgs Potential Beyond the SM

- Higgs mixing with other fields or new sources of EWSB can too.

e.g.

Model	$\max\{\frac{\lambda_3}{\lambda_3^{SM}} - 1\}$
Mixed-in Singlet	-18%
Composite Higgs	$\mathcal{O}(10\%)$
MSSM	-15%
NMSSM	-25

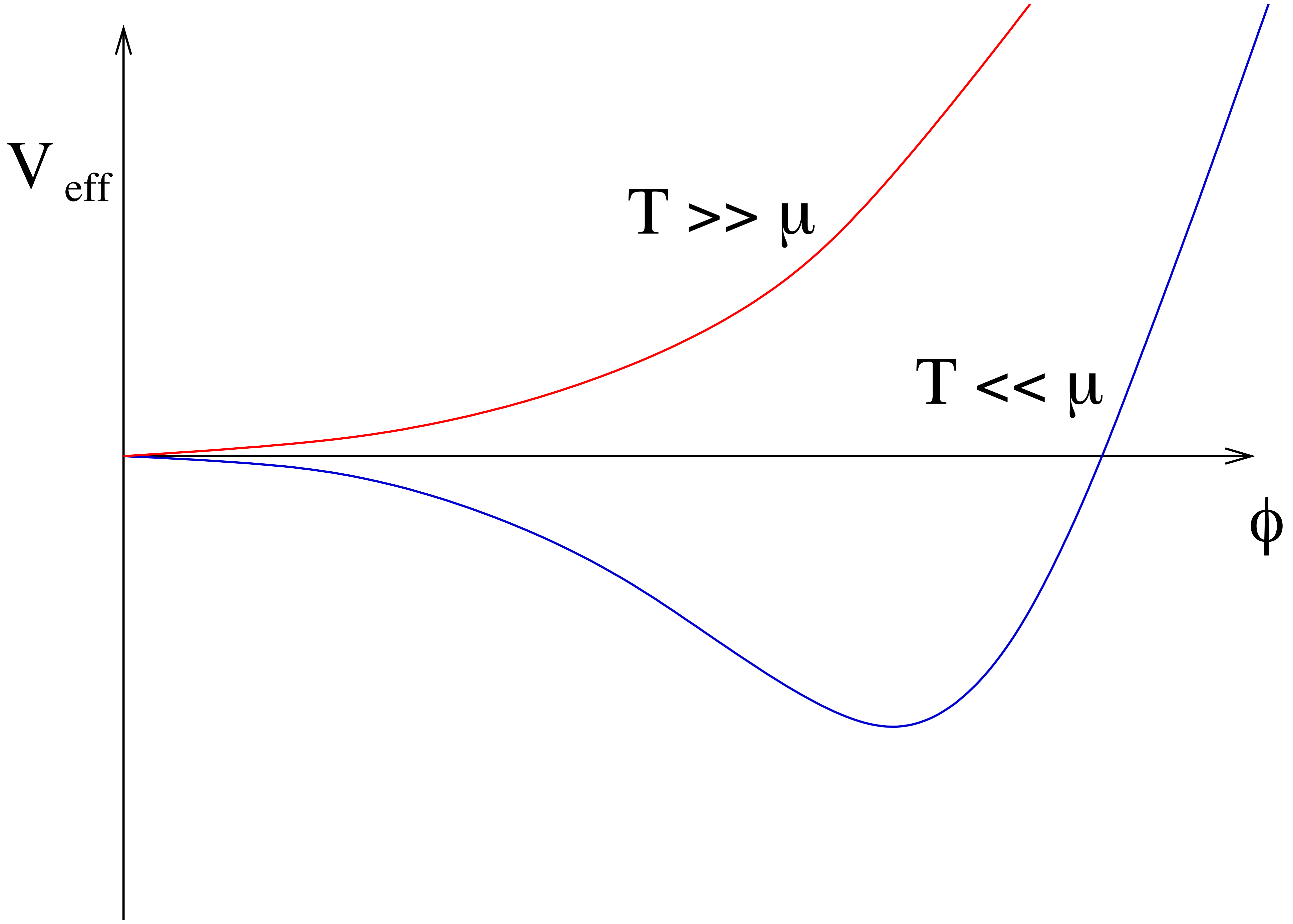


[Gupta, Rzehak, Wells 1305.6397]

Higgs Potential in the Early Universe

- Thermal effective potential:

$$V(\phi, T) \simeq (\xi T^2 - \mu^2)\phi^2 - AT(\phi^2 + B)^{3/2} + \lambda\phi^4$$

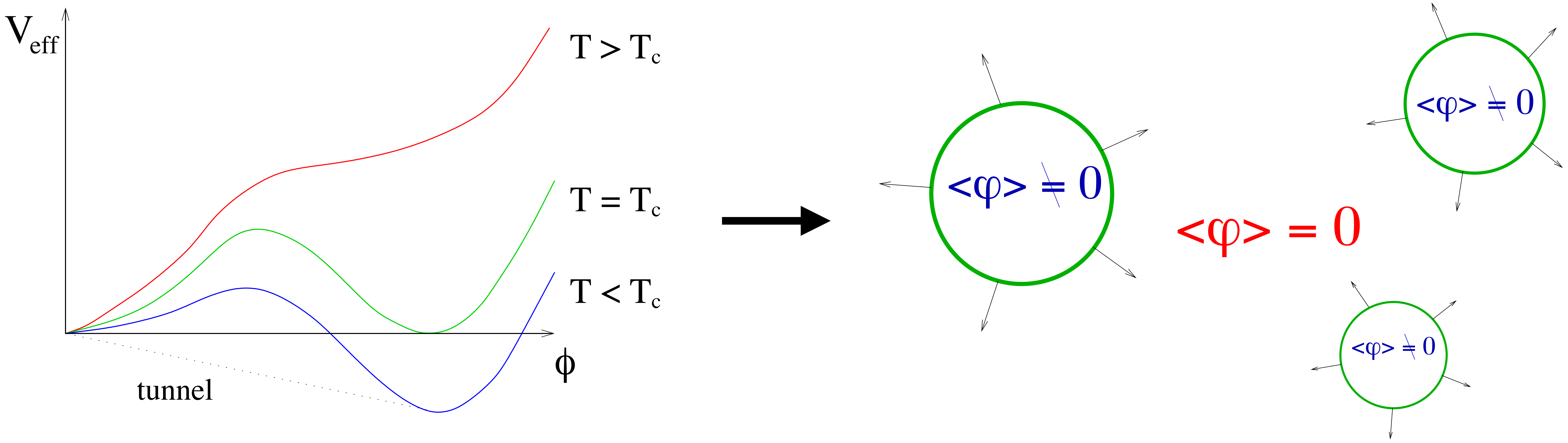


→ electroweak phase transition (EWPT)

Electroweak Phase Transition

- SM: the electroweak phase transition is a smooth crossover. **[Kajantie *et al.* hep-lat/9510020]**

- BSM: the EWPT can be strongly first order if new physics couples to the Higgs.



- A strong first-order EWPT can allow baryogenesis or make gravitational waves!

[*e.g.* Shaposhnikov NPB287, 575; Kamionkowski, Kosowsky, Turner astro-ph/9310044; Cohen, Kaplan, Nelson hep-ph/9302210; Grojean, Servant hep-ph/0607107, LOIs by Carena *et al.*]

A First Order EWPT

- Requires new physics that couples to the Higgs.

- SM-charged new physics ⇒ modified Higgs production and decay rates.

  e.g. gluon fusion rates rule out a SFO EWPT from light stops in the MSSM

  [Cohen, DM, Pierce 1203.2924; Curtin, Jaiswal, Meade 1203.2932]

- SM-singlet new physics - main effect can be to alter the self-coupling λ_3.

  - Higgs-singlet portal: $\lambda_{HS}\, S^2 H^\dagger H$

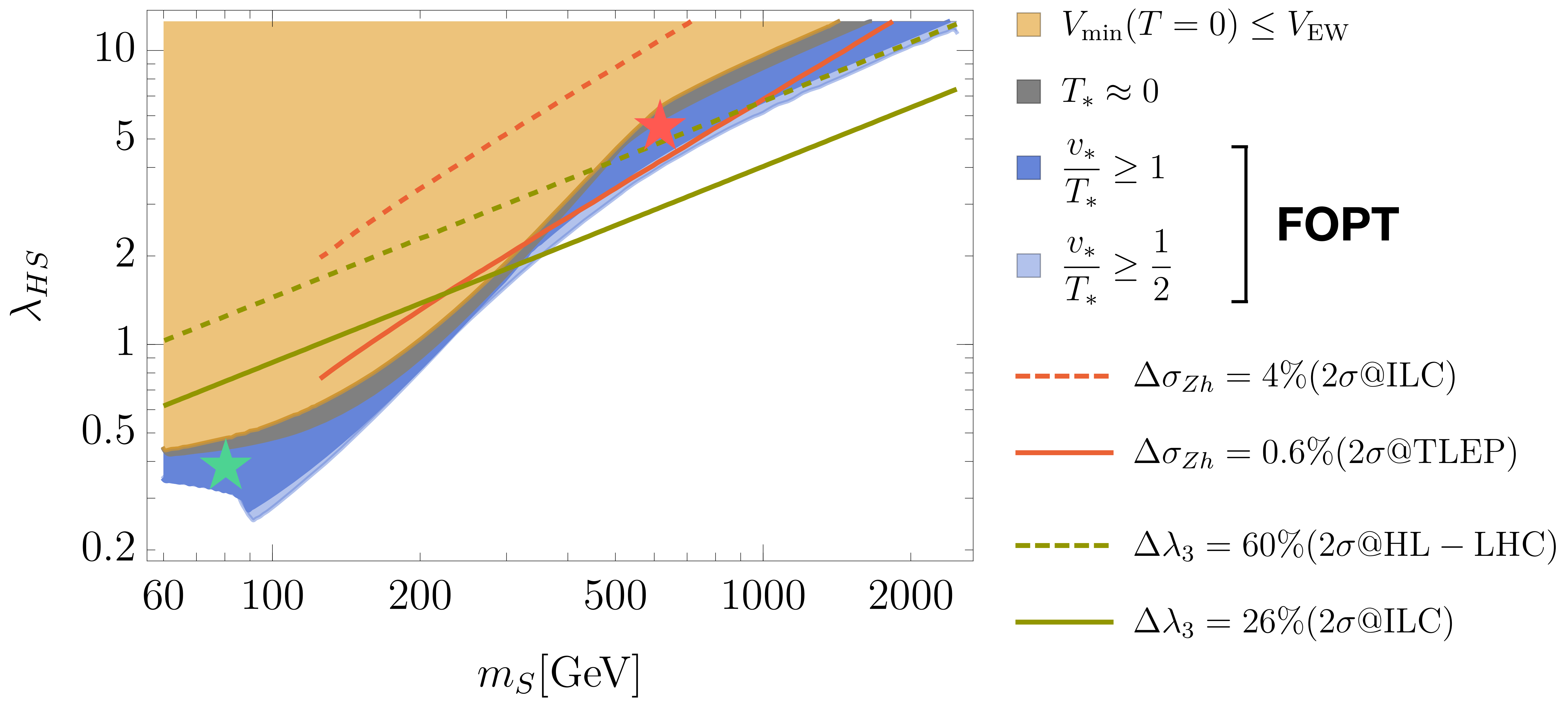
    [Noble, Perelstein 0711.3018; Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342; Curtin, Meade, Yu 1409.0005]

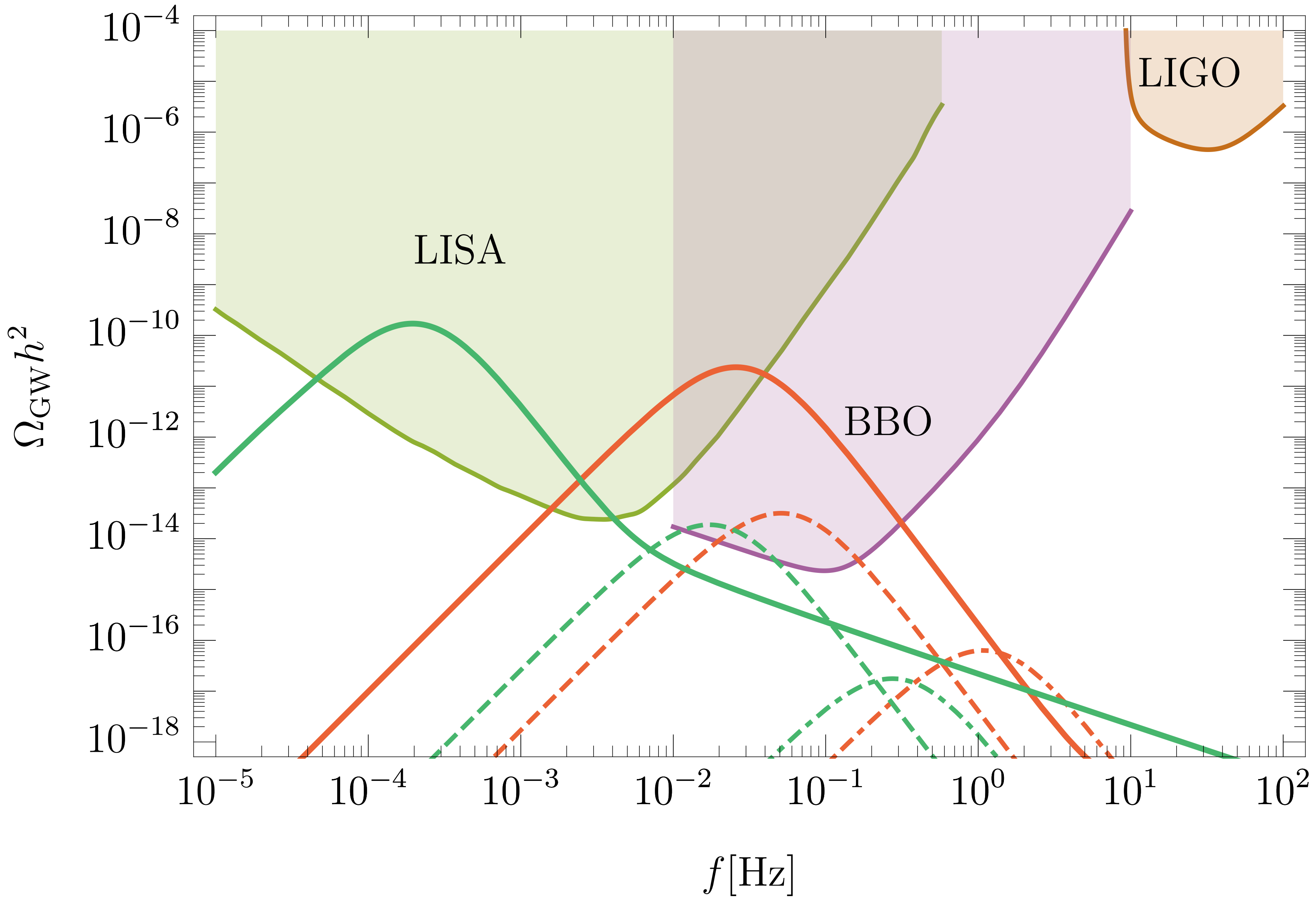
  - SMEFT operator: $\frac{c_6}{\Lambda^2}(H^\dagger H)^3$

    [Grojean, Servant, Wells hep-ph/0407019; Noble, Perelstein 0711.3018]

A First Order EWPT with Singlet

- For the Higgs-singlet portal: $\lambda_{HS}\, S^2 H^\dagger H$





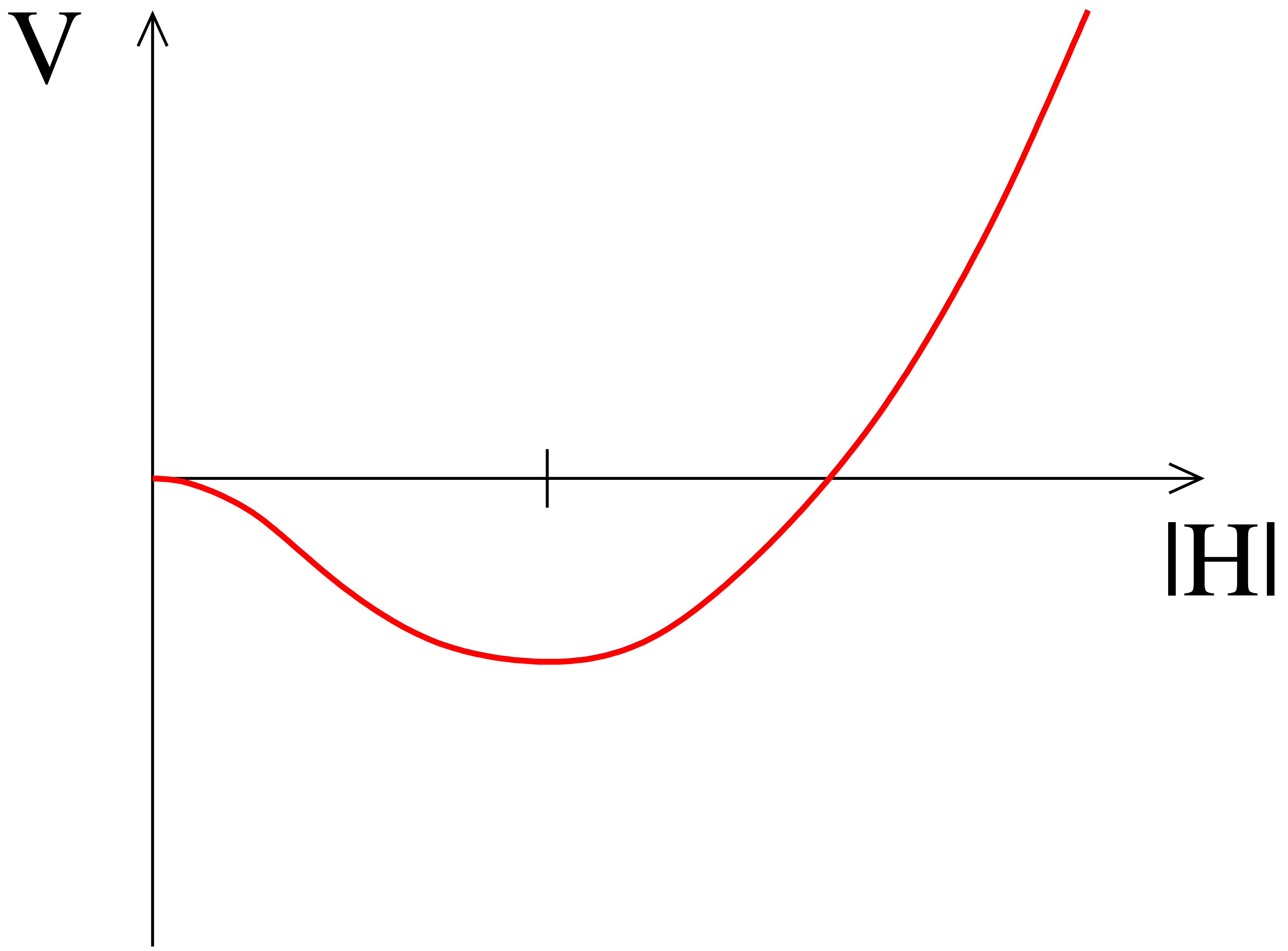
[Curtin, Meade, Yu 1409.0005; Kotwal, Ramsey-Musolf, No, Winslow 1605.06123; Huang, Long, Wang 1608.06619; <u>Beniwal, Lewicki, Wells, White, Williams 1702.06124</u>]

The Standard Model Higgs Potential

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

hierarchy problem

Higgs metastability



[KC Green, gunshowcomic.com]

(Higgs) Potential Questions

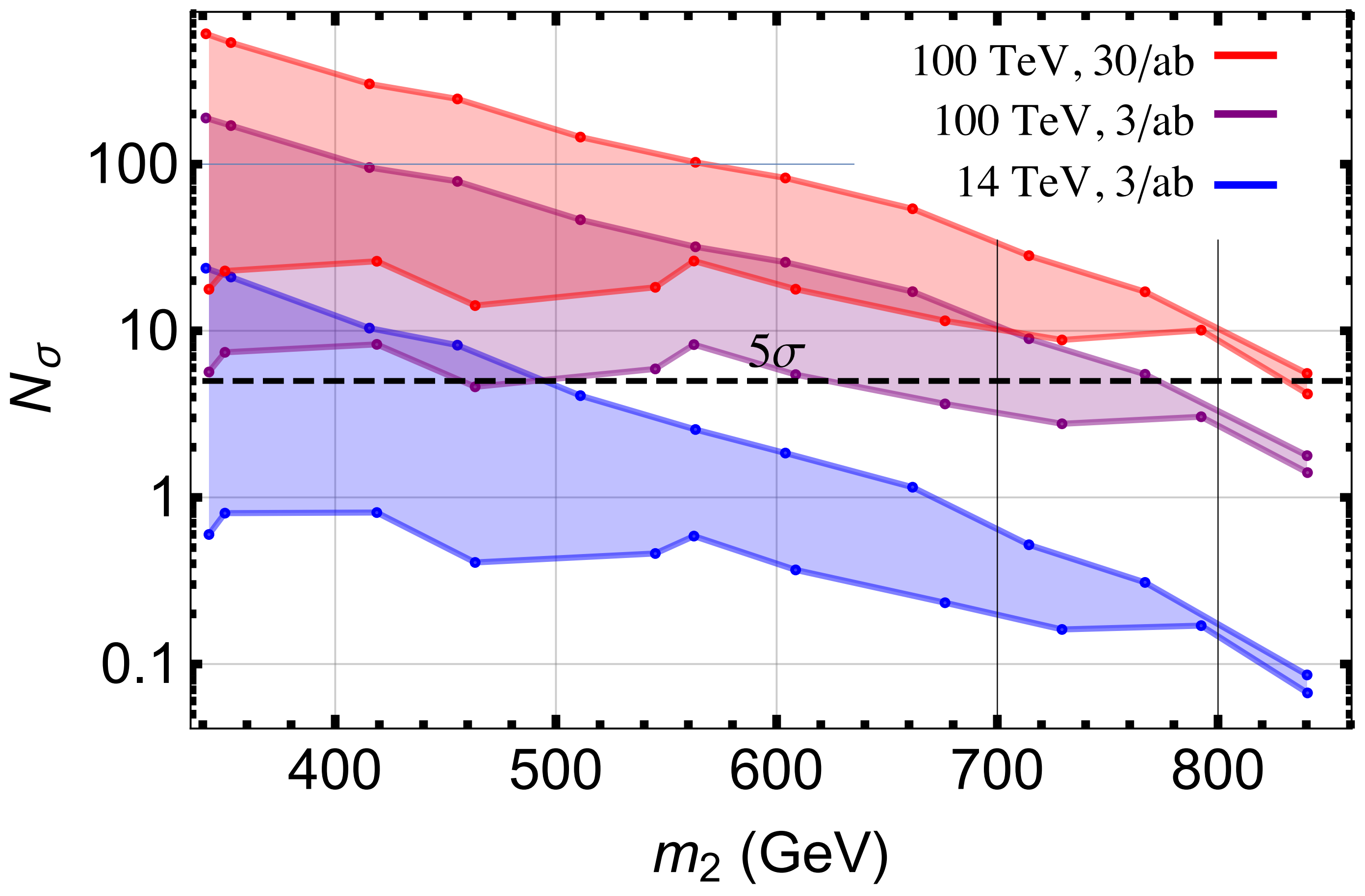
- What can we learn about new physics from Higgs couplings?
- A strongly first-order EWPT requires new physics coupling to the Higgs:
  - What does this imply generically for di-Higgs rates?
  - Does it imply a minimum deviation pattern in Higgs couplings?
  - How does the reach of Higgs coupling measurements compare to other direct and indirect probes?

Higgs Potential Beyond the SM

- **Note 1**: extractions of λ_3 are sensitive to other deviations in Higgs couplings as well as uncertainties in SM parameters.

- **Note 2**: some BSM scenarios can even interfere with the full realization of electroweak symmetry at high temperature. **[*e.g.* Meade, Ramani 1807.07578; Baldes, Servant 1807.08770]**

- **Note 3**: in Higgs-singlet scenarios with a first-order EWPT, finding the new (mostly) singlet scalar might be easier than measuring Higgs rates.



$$pp \to h_2^{(*)} \to hh$$

[Kotwal, Ramsey-Musolf, No, Winslow 1605.06123; Papaefstathiou, White 2010.00597]

Summary future λ_3 measurements

1) LHC
   - O(10)-O(2)
   - Could detect large anomalous coupling

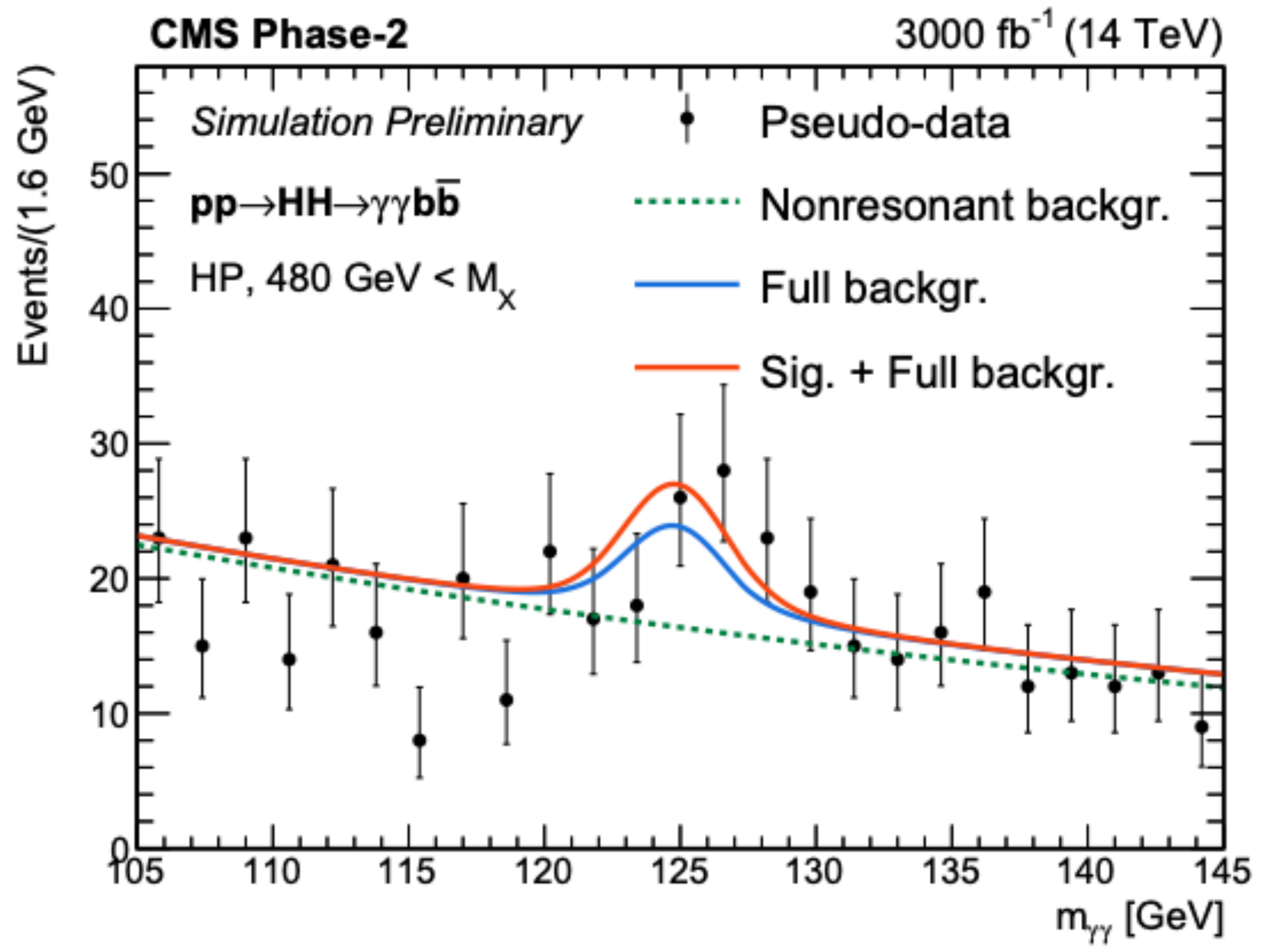
2) HL-LHC
   - O(1)
   - Potential for evidence (3σ precision)

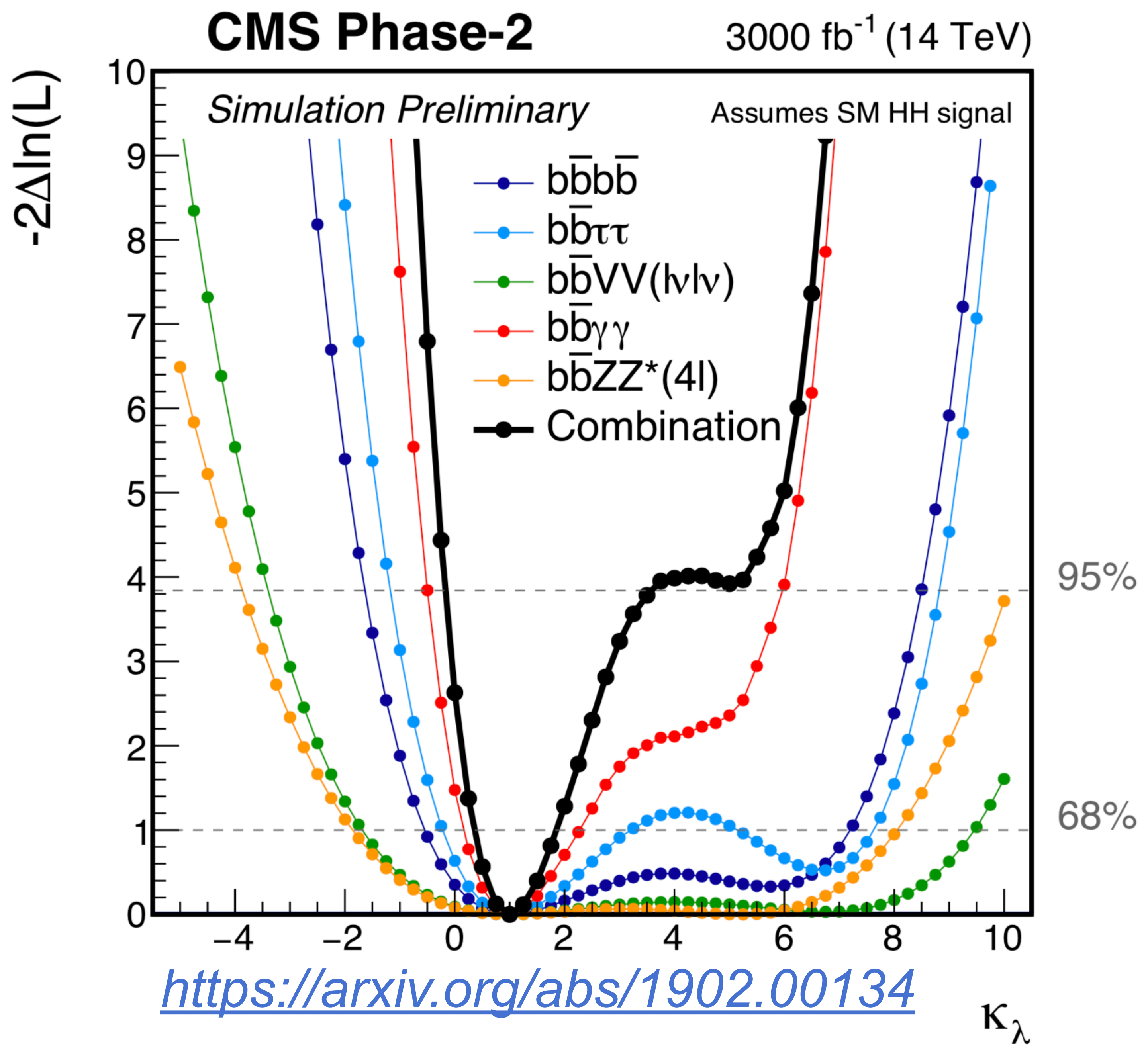
3) CEPC/FCC-ee : single H couplings + indirect measurement
   - Potential for observation (5σ precision)
   - δg_{ttZ} ~ 1%, allows for δy_t ~ 1% @FCC-hh

4) ILC/CLIC : ~ 10 % precision

5) FCC-hh : precision measurement: 3.5-7.8%

6) Muon Collider: precision 2-3% (stat only) ?





https://arxiv.org/abs/1902.00134

Global fit in indirect ee measurements

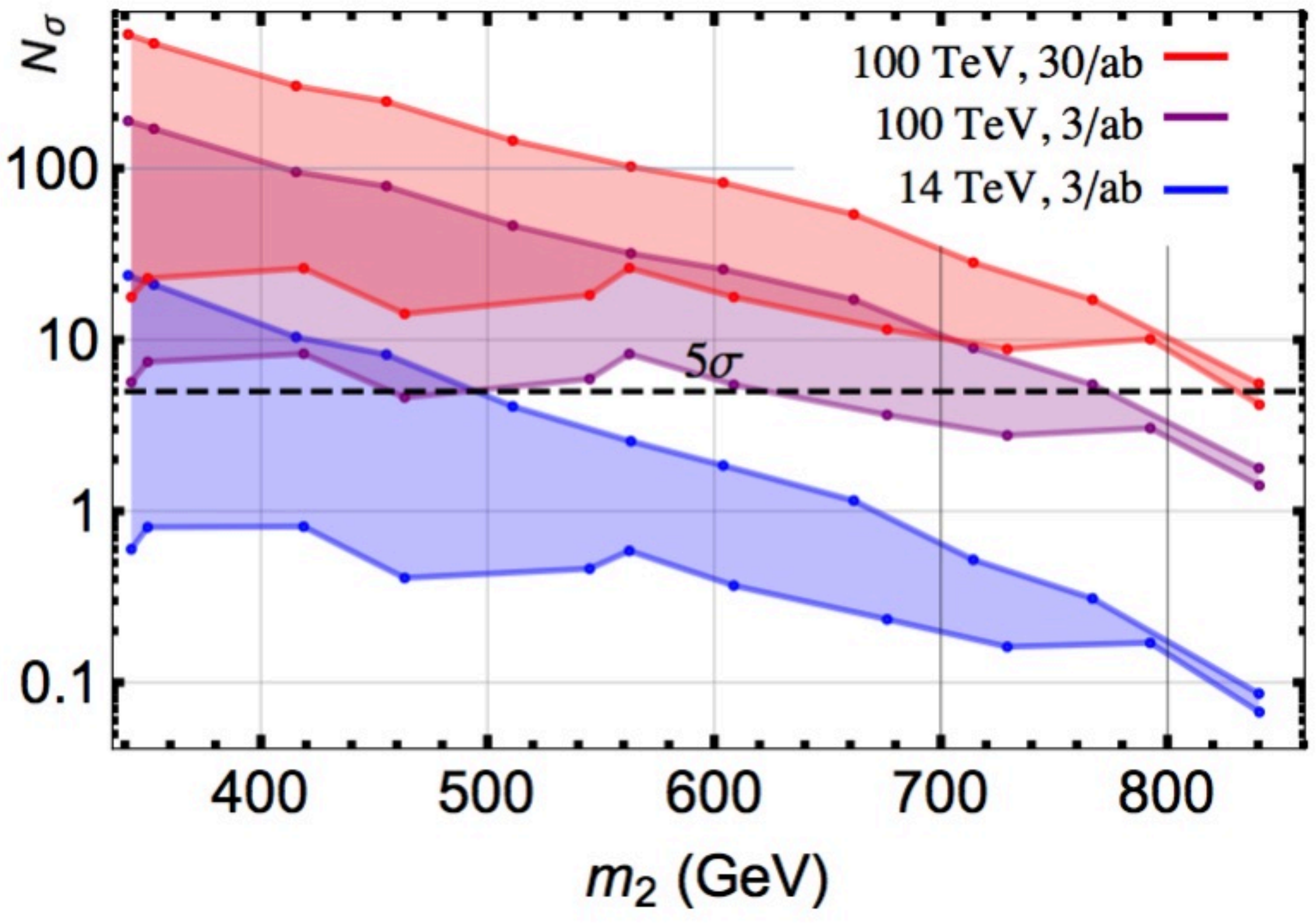
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

1910.00012 [hep-ph]

Higgs Self-coupling and constraints on models with 1st order EWPT

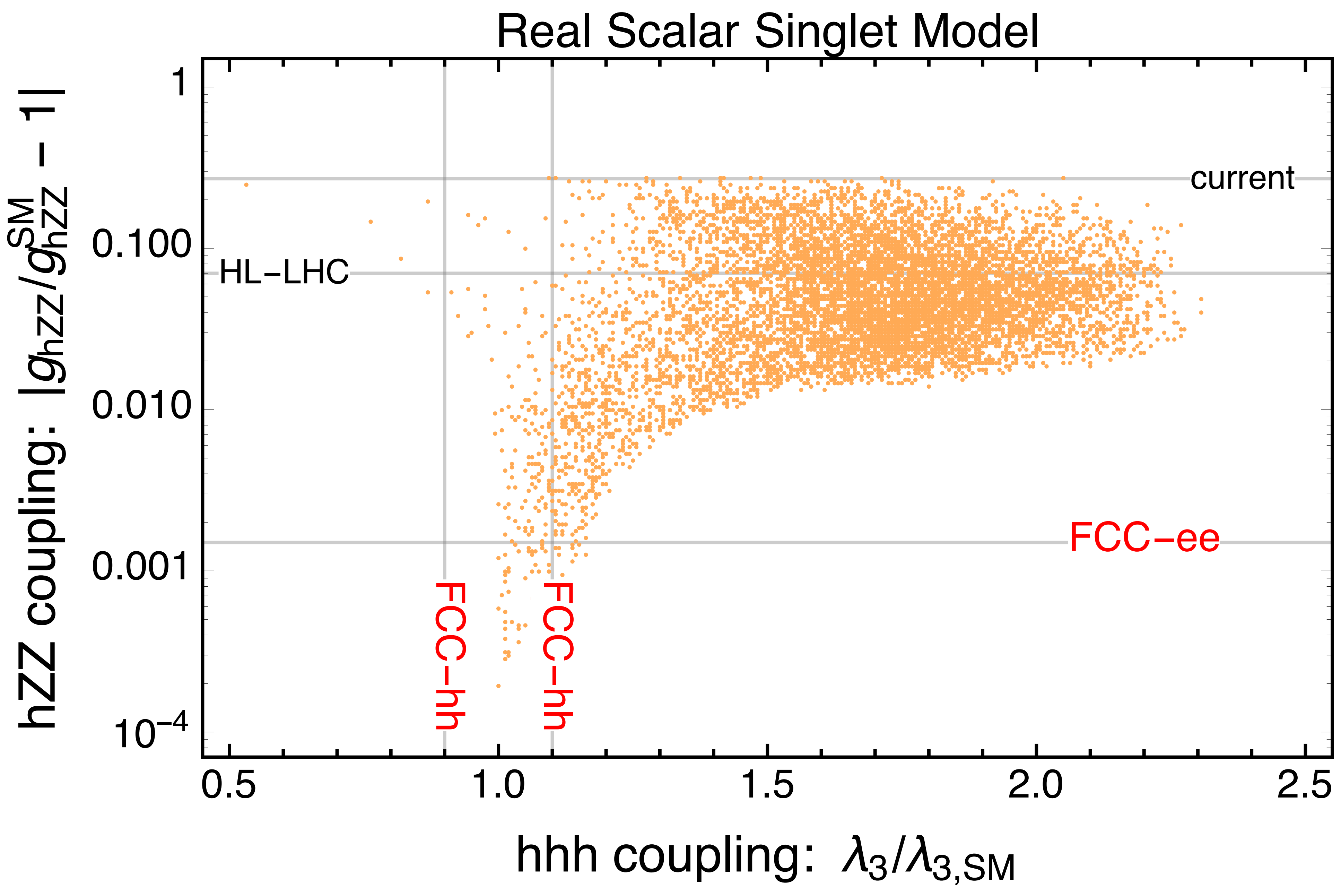
- **Strong 1st order EWPT** needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



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

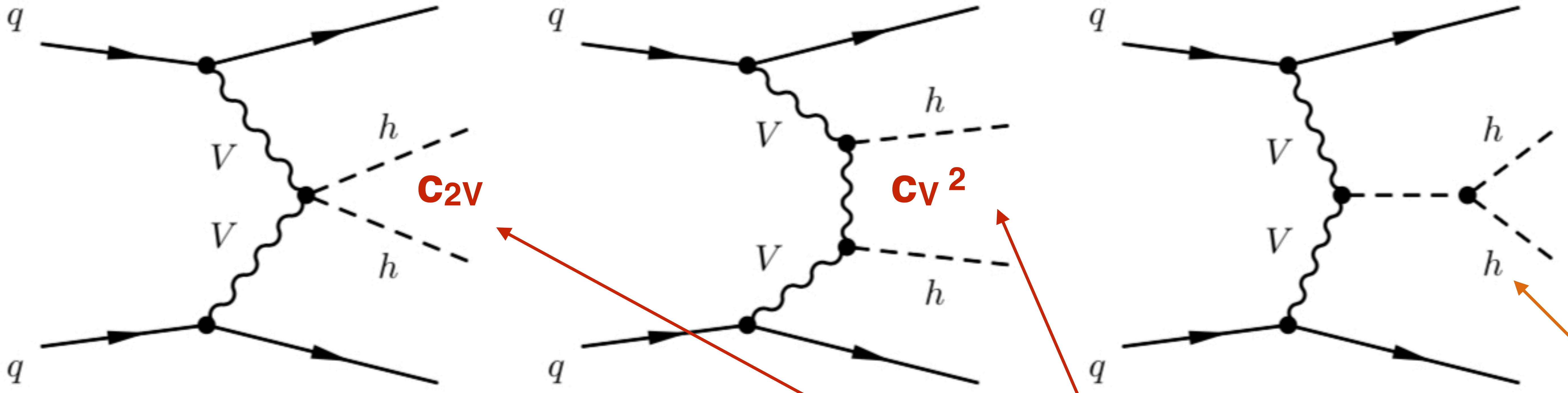
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



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

$V_L V_L \to HH$

[1611.03860]

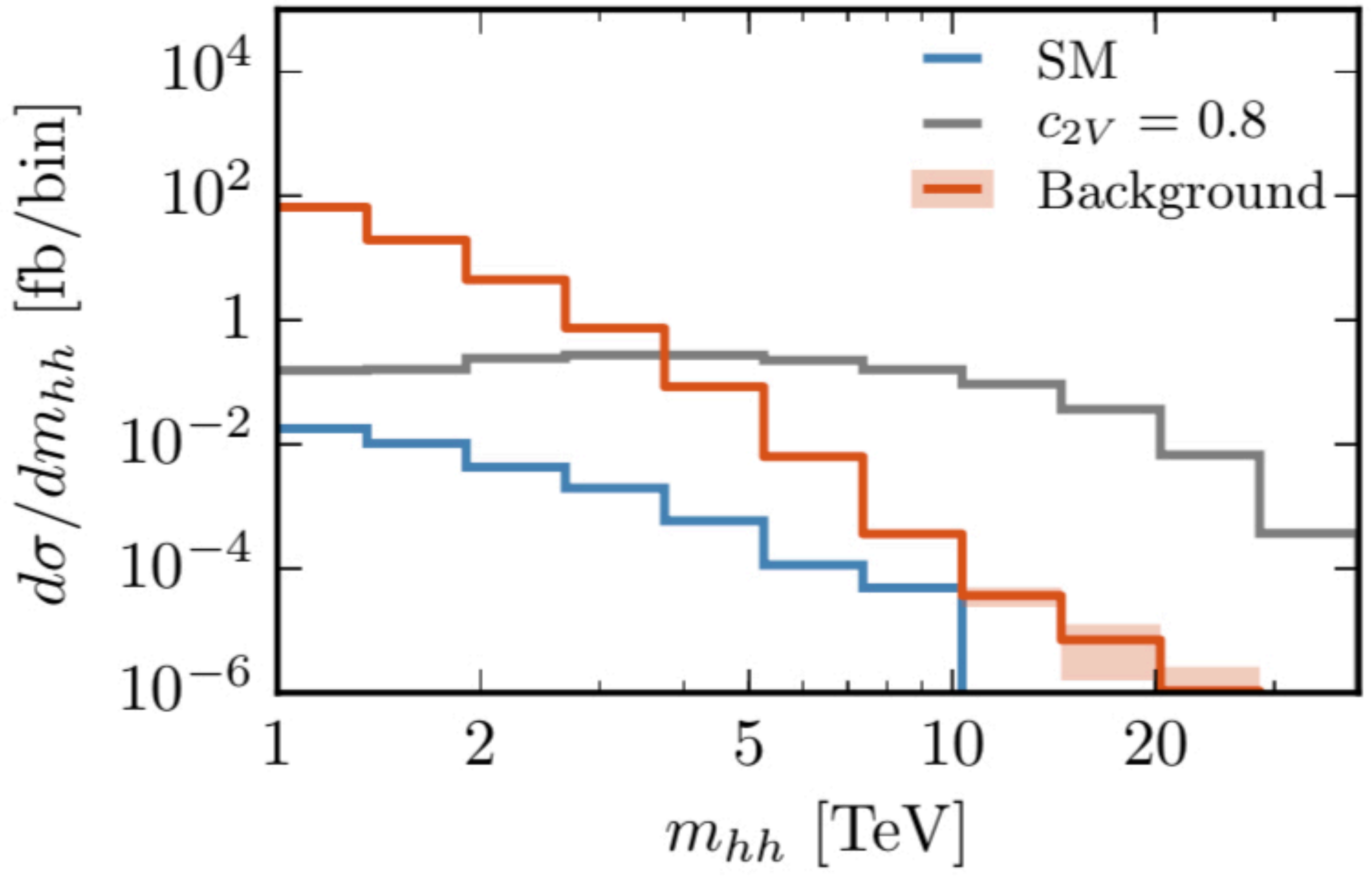


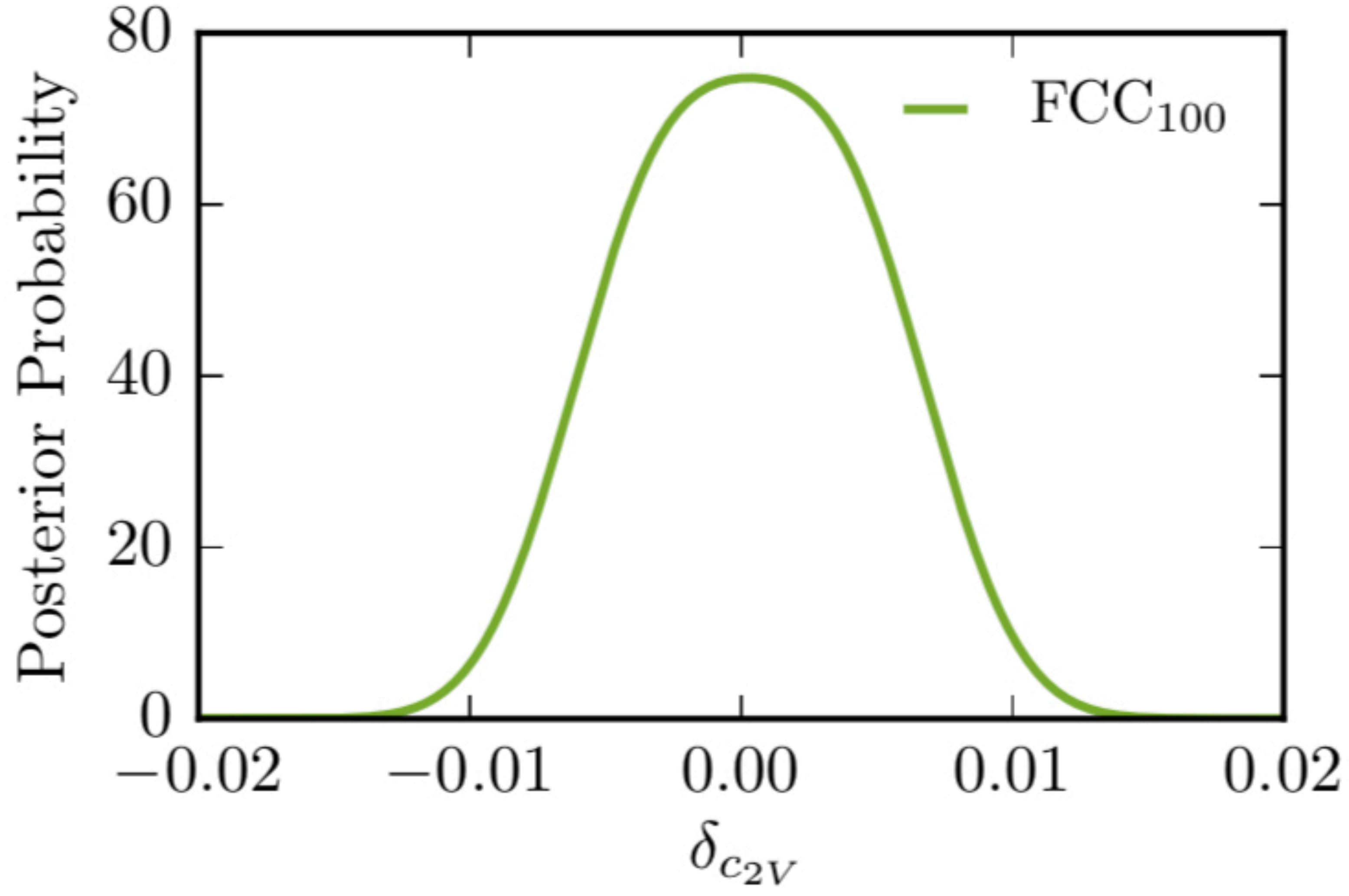
negligible at large m_{HH}

$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$

0 in the SM

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E

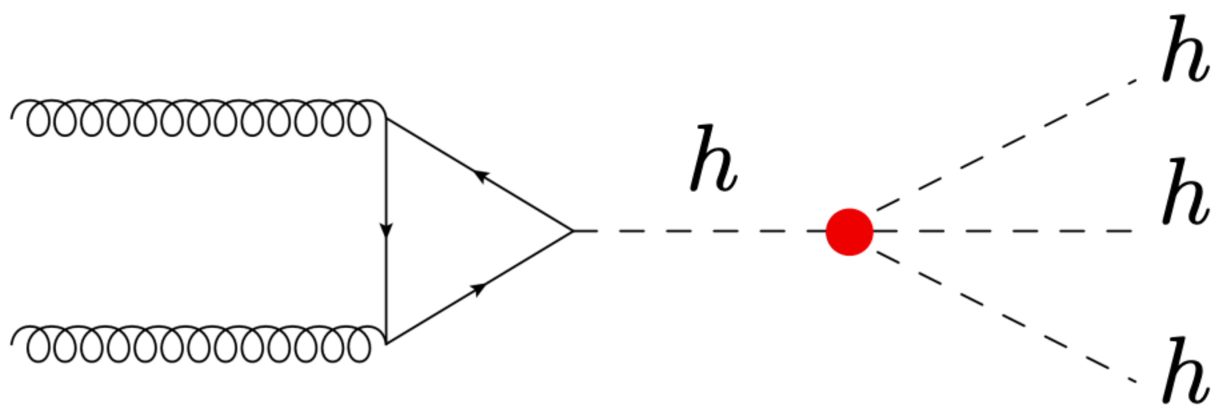




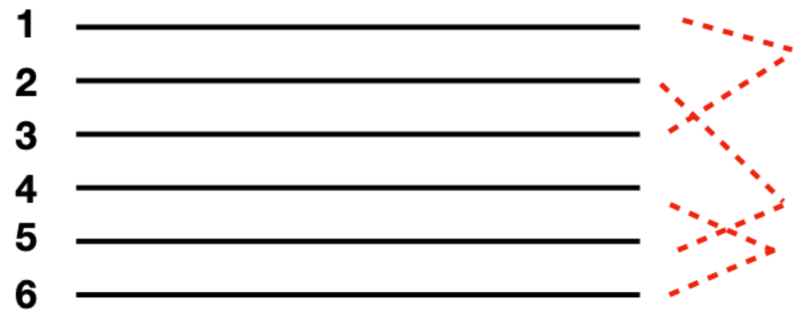
With c_V from FCC-ee, $\delta c_{2V} < 1\%$

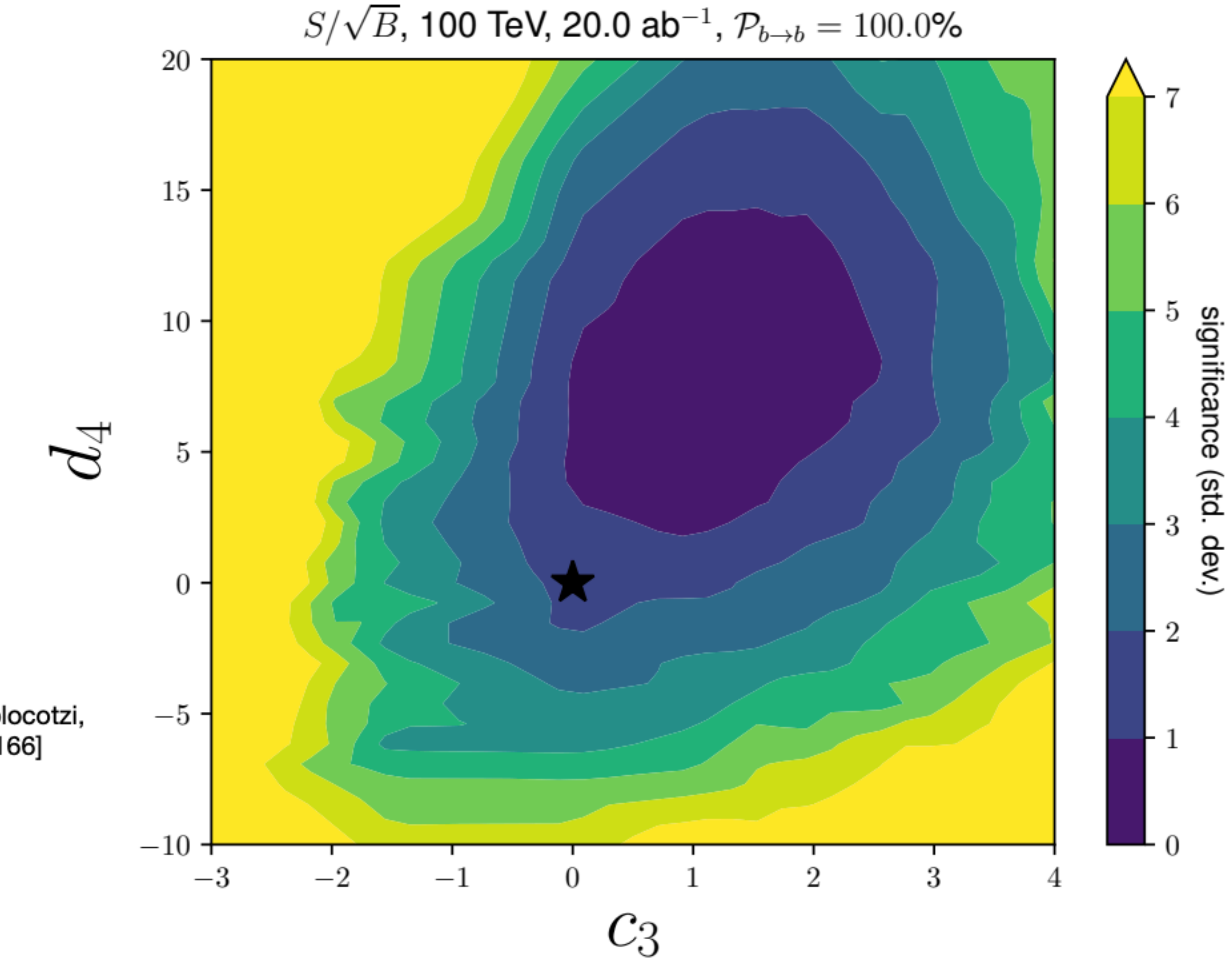
HHH→bbbbbb

[1909.09166](1909.09166) [hep-ph]



$$\chi^2 = \sum_{qr \in \text{pairings } I} (M_{qr} - m_h^2)^2$$





[AP, Tetlalmatzi-Xolocotzi, Zaro, 1909.09166]

SM significance ~ 1.7σ

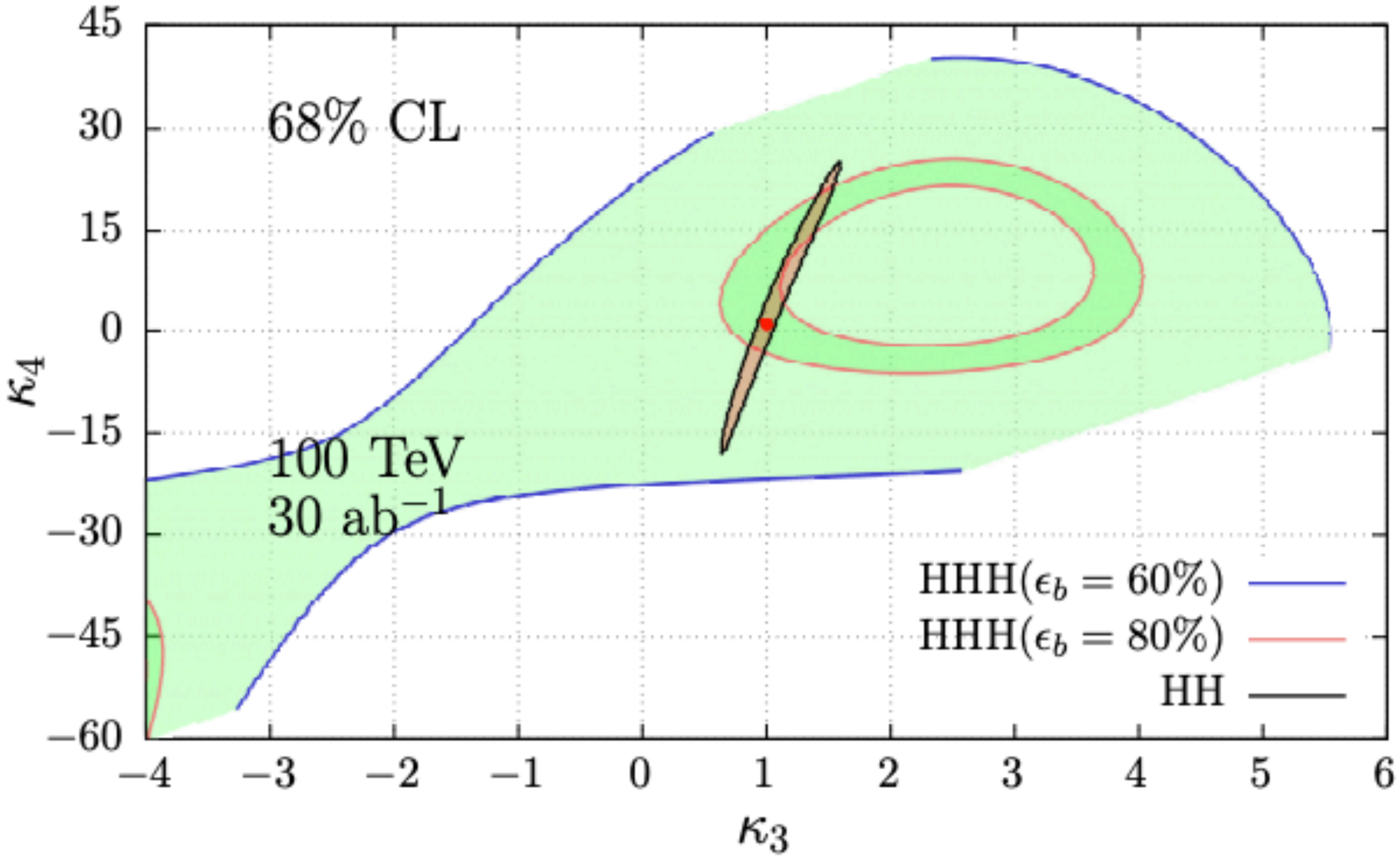
$d_4 \in$ [-1.7, 13.3]

[Maltoni, Vryonidou

$hhh \to$ final state	BR (%)	$N_{20\text{ab}^{-1}}$	
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	22207	
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.20	8328	
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.31	7297	→ Fuks, Kim, Lee, 1510.07697, Fuks, Kim, Lee, 1704.04298.
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.58	1824	
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.98	1128	
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.90	1041	→Kilian, Sun, Yan, Zhao, Zhao, 1702.03554.
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.69	799	
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.23	263	→ AP, Sakurai, 1508.06524,

Quartic bounds from di-Higgs

1811.12366 [hep-ph]



$$\kappa_4 \in [-2.3, 4.3] \text{ at } 68\%\text{CL}$$