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Testing the Higgs Potential

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Snowmass Community Planning
"Fermilab"
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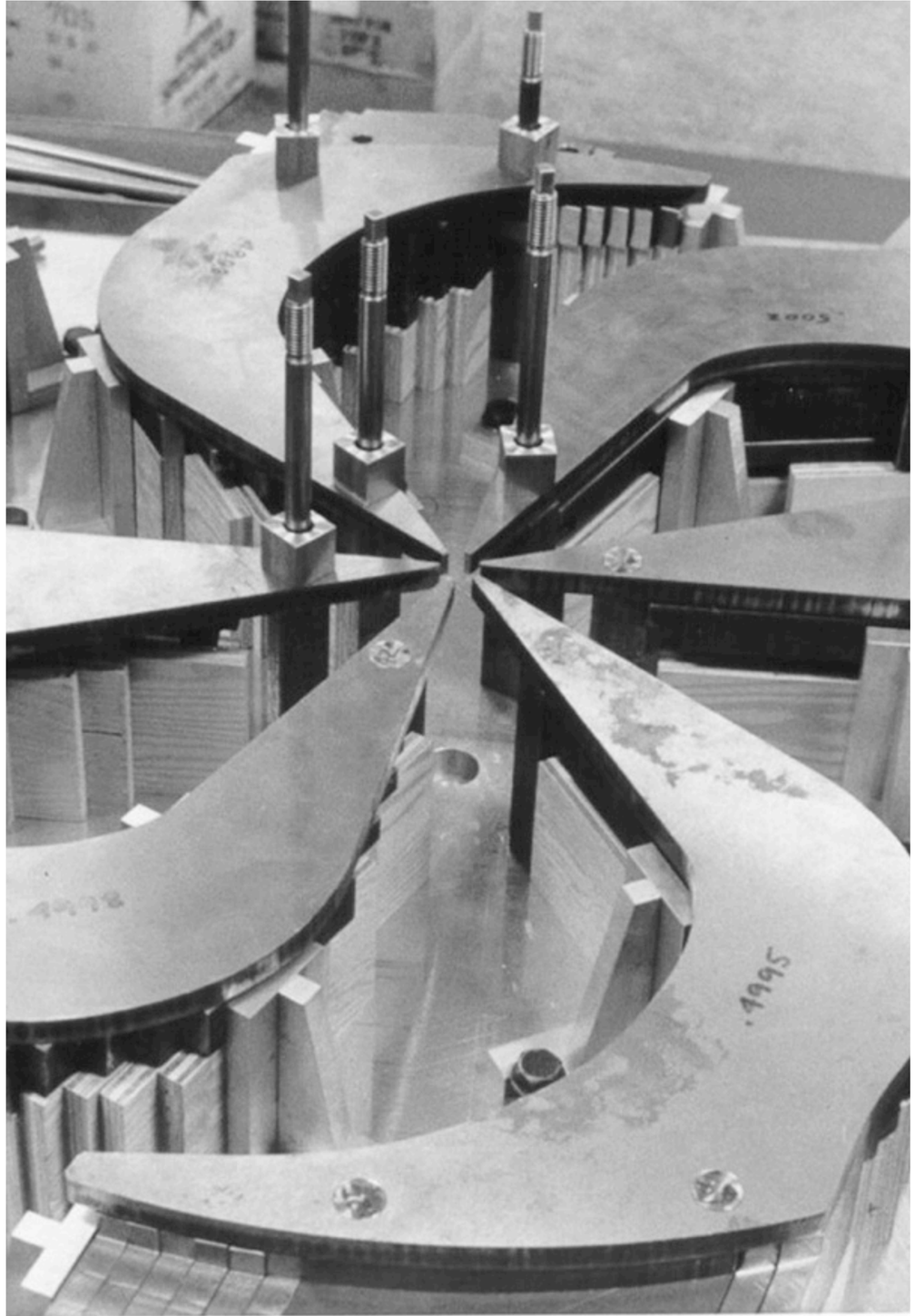


Discovery, accelerated

The Standard Model Higgs Potential

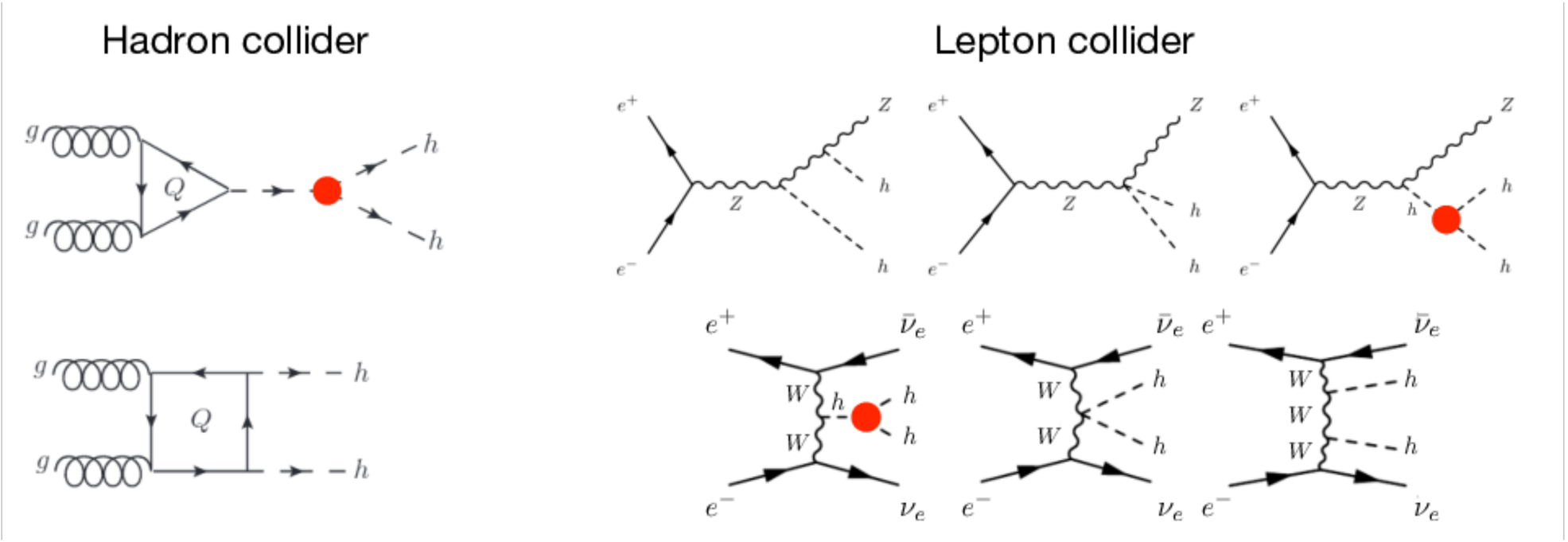
$$
\begin{aligned}
V &= -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 \\
&\to -\frac{\lambda}{4} v^4 + \frac{1}{2}(2\lambda v^2)\, h^2 + \lambda\, v\, h^3 + \frac{\lambda}{4}\, h^4 \\
&= V_0 + \frac{1}{2} m_h^2 h^2 + \lambda_3 v\, h^3 + \frac{\lambda_4}{4} h^4
\end{aligned}
$$

- 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]**



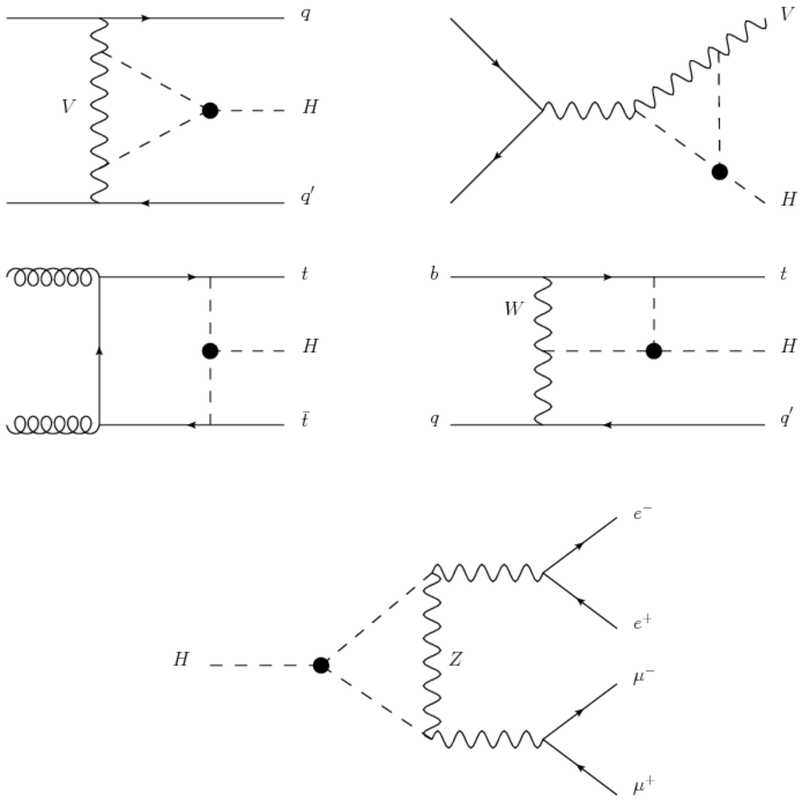
[de Blas *et al*. 1905.03764]

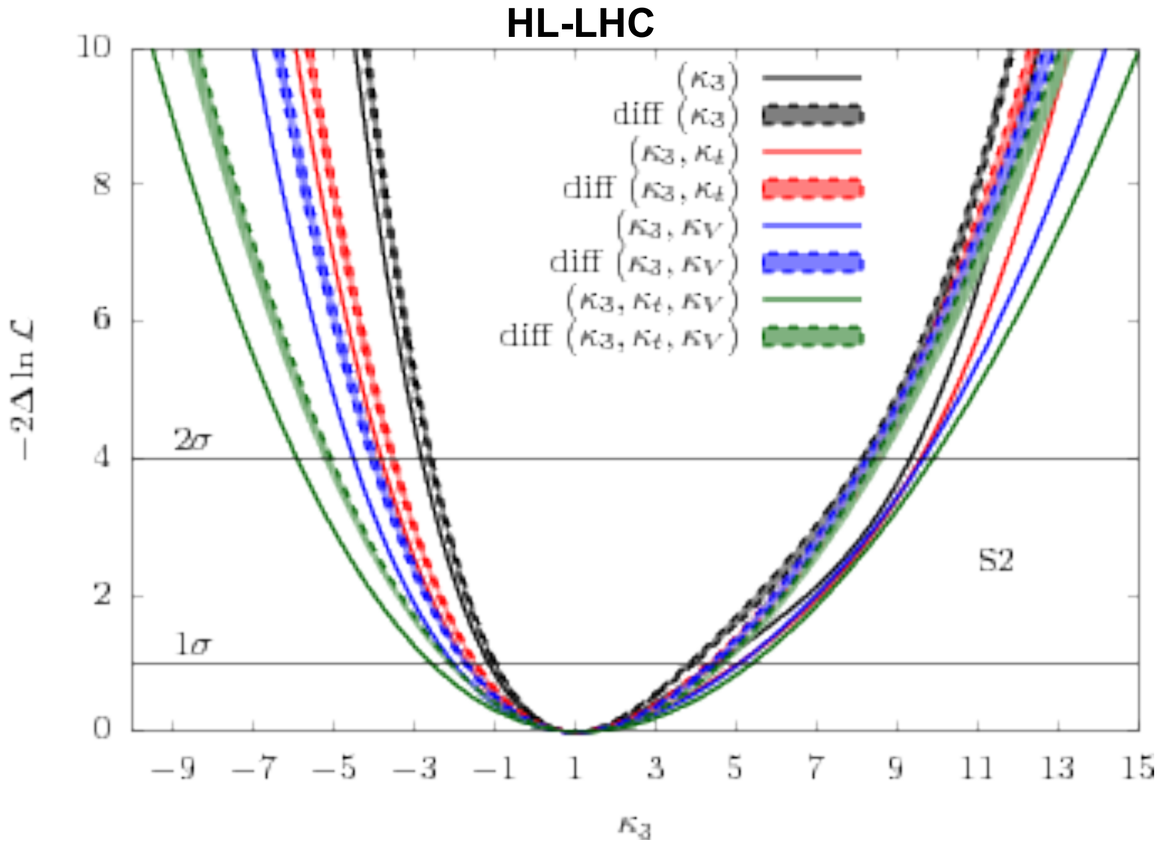
- Must be part of a global fit to Higgs couplings, requires high SM precision!

[*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:

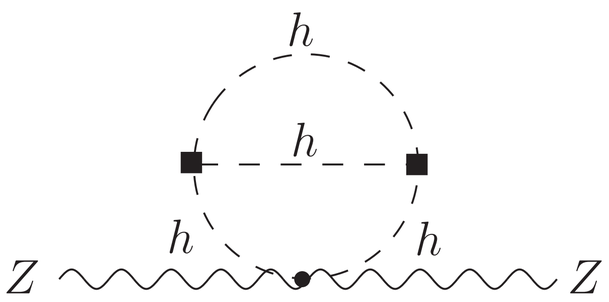


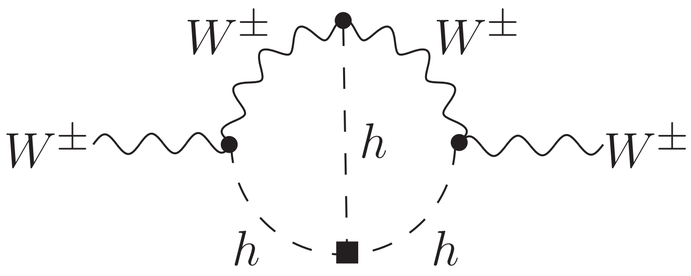


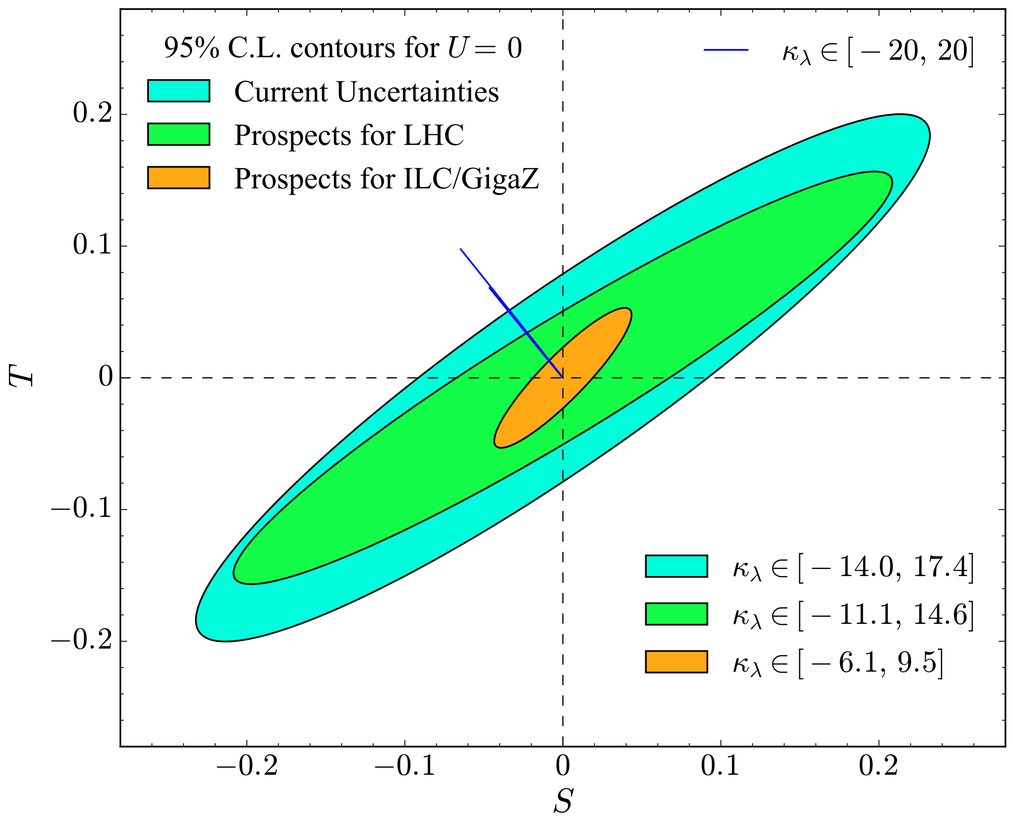
[McCullough 1312.3322; Maltoni, Pagani, Shivaji, Zhao 1709.08649]

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

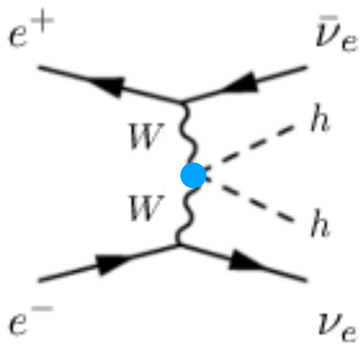
- Heavy new physics can yield effective operators that modify the potential.

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

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

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

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



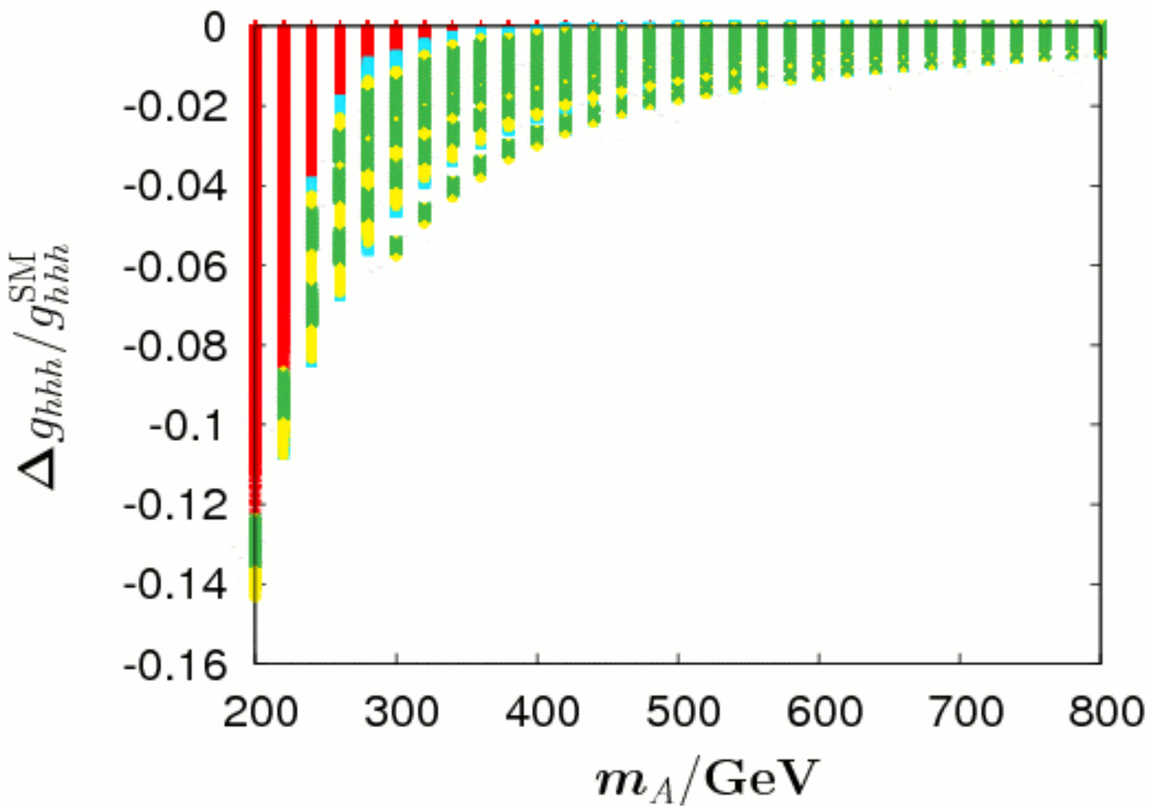
- Note: c_H also modifies hhVV couplings!

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

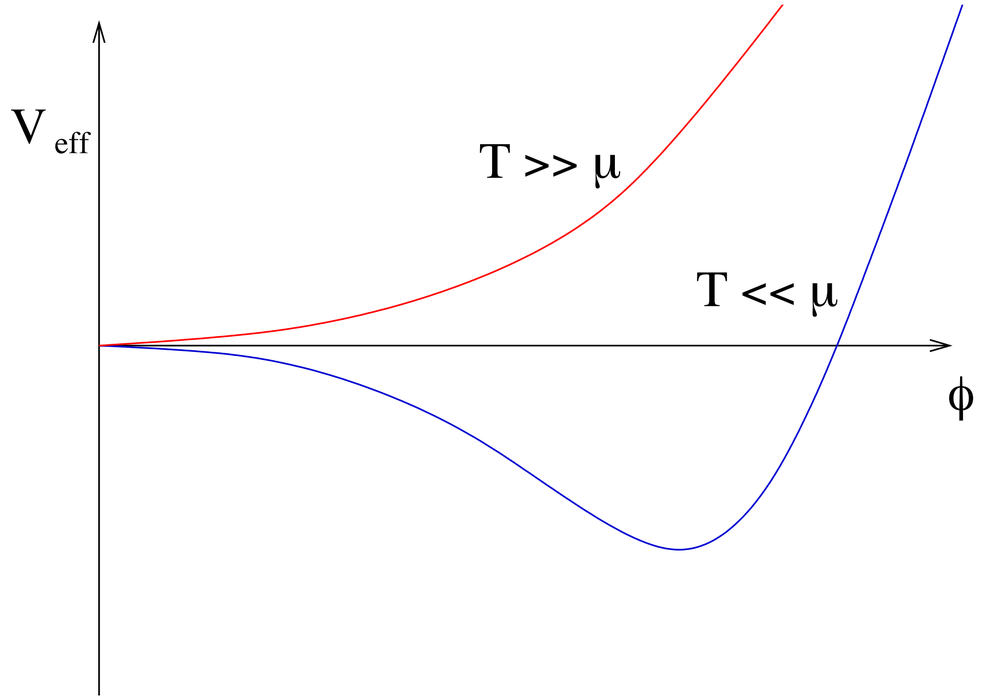


[Gupta, Rzehak, Wells 1305.6397]

Higgs Potential in the Early Universe

- Thermal effective potential:

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

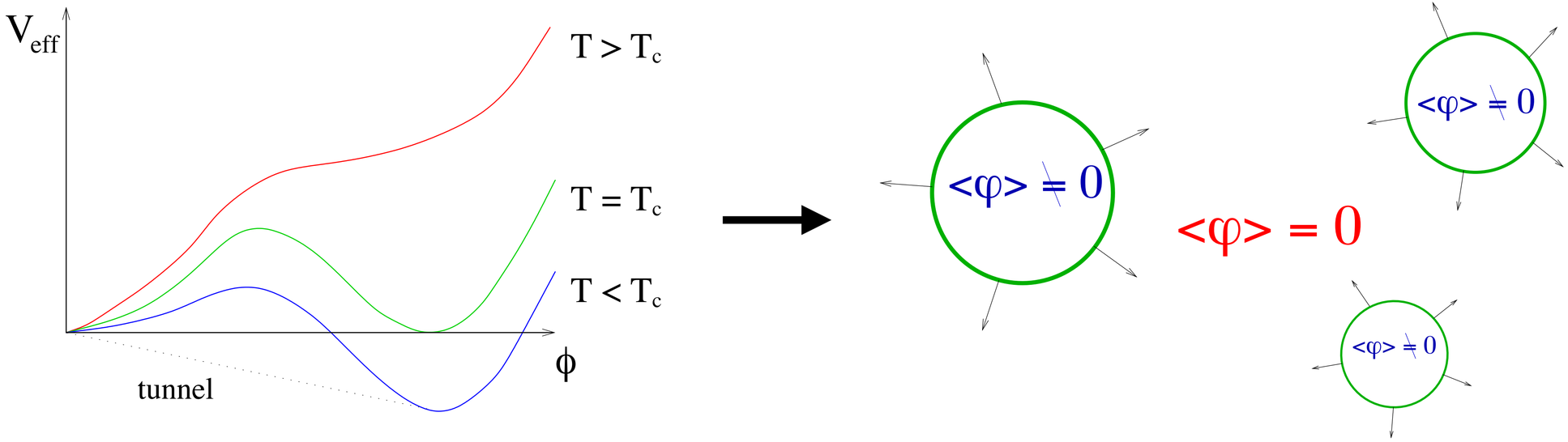


→ electroweak phase transition (EWPT)

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: $\lambda_{HS}\, S^2 H^\dagger H$

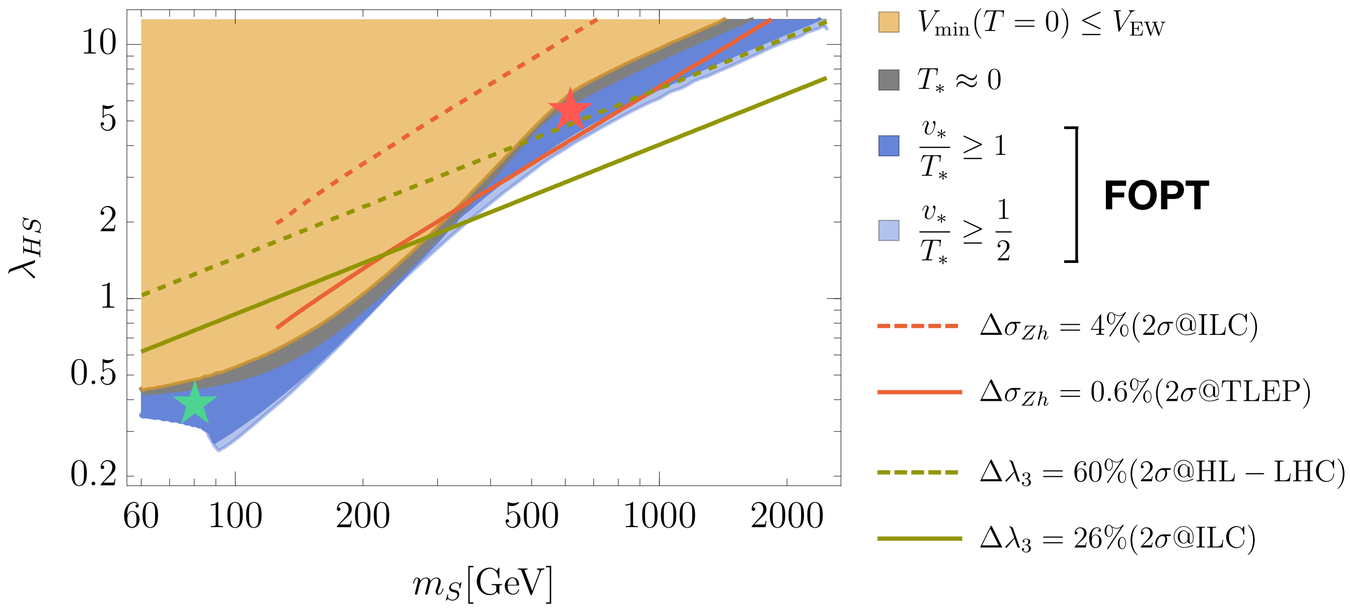
    [Noble, Perelstein 0711.3018; Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342; Curtin, Meade, Yu 1409.0005]

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

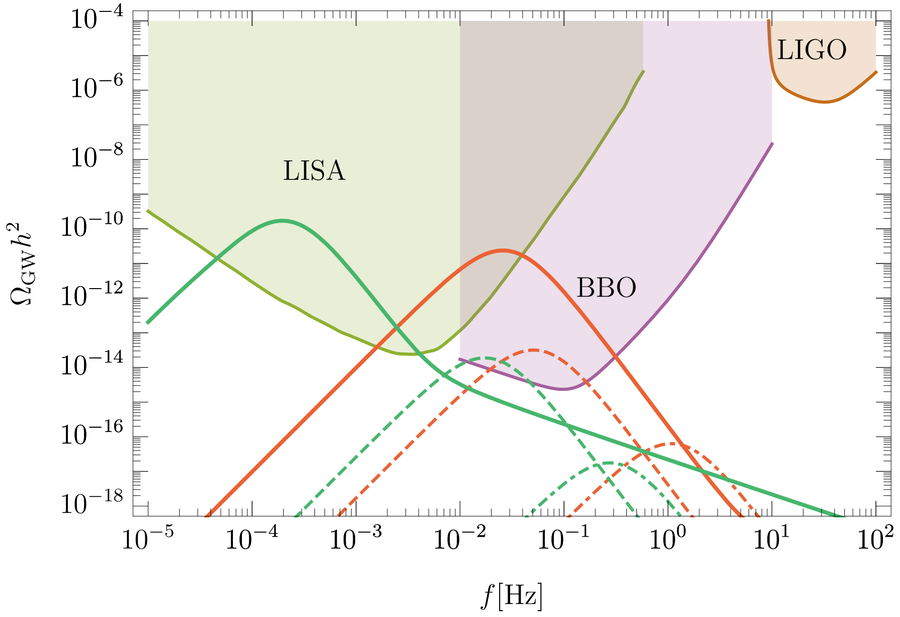
    [Grojean, Servant, Wells hep-ph/0407019; Noble, Perelstein 0711.3018]

A First Order EWPT with Singlet

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



Gravitational Wave Signals



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

(Higgs) Potential Questions

- Lots, but wait for the talk by Michele Selvaggi!

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Thank you
Merci

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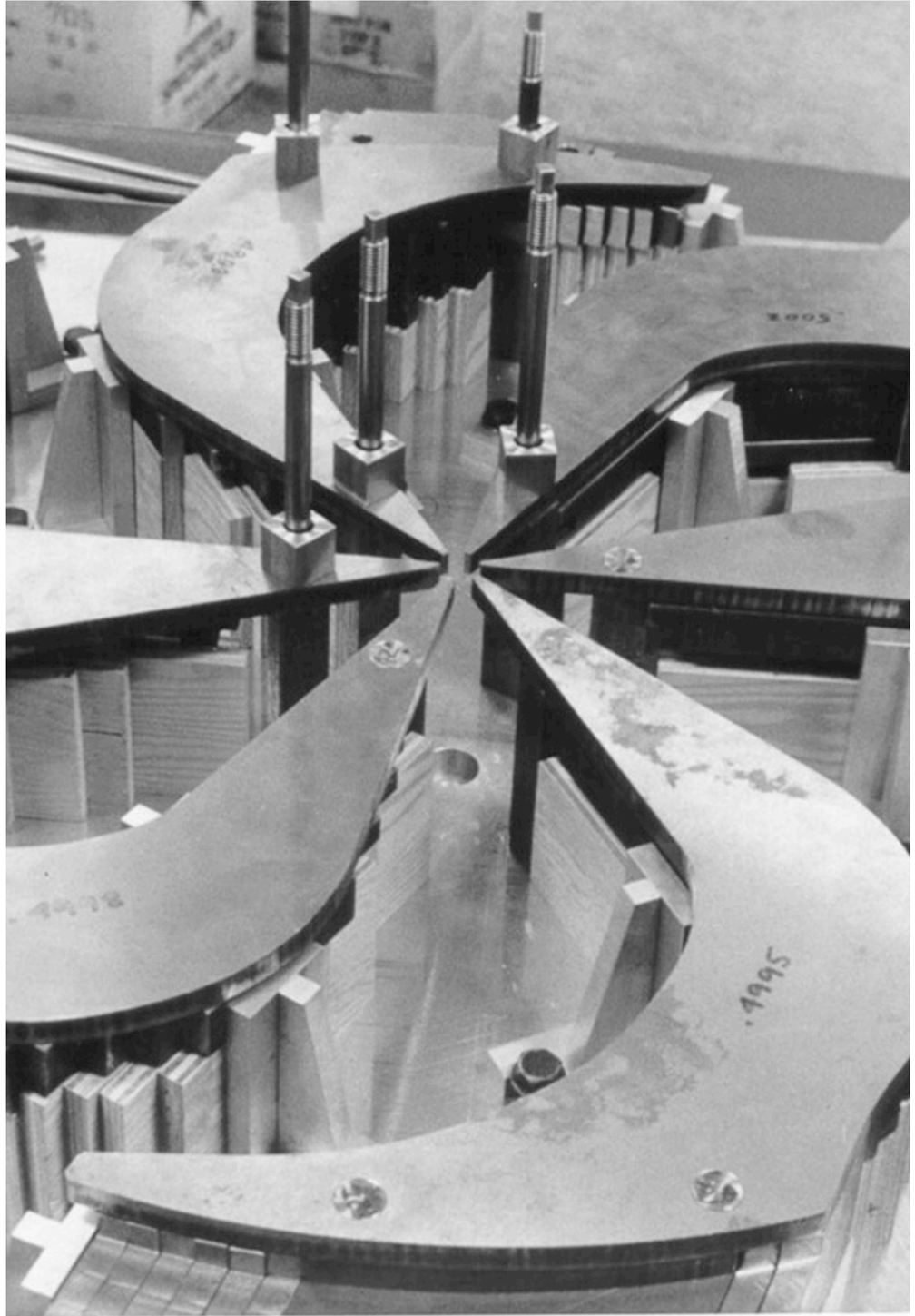


Discovery, accelerated

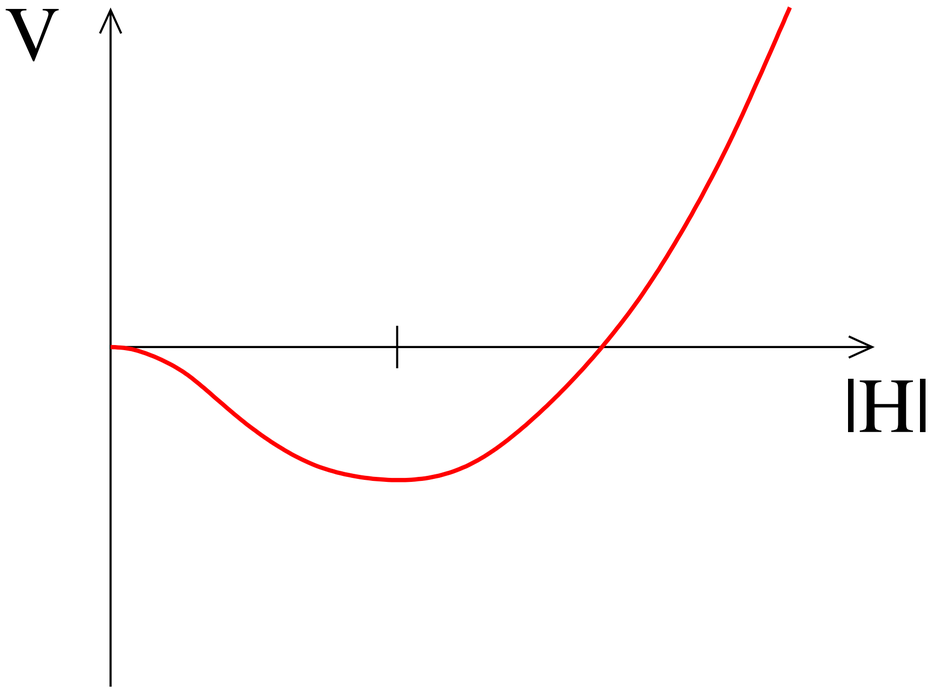
Extra Slides

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

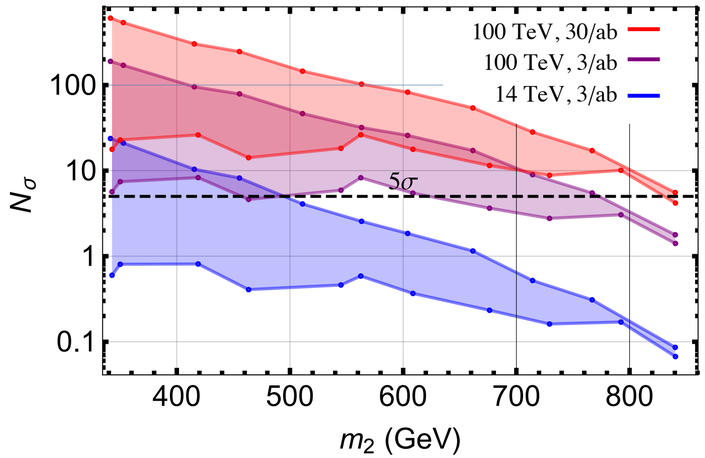
- What can we learn about new physics from Higgs couplings?
- A strongly first-order EWPT requires new physics coupling to the Higgs:
  - What does this imply generically for di-Higgs rates?
  - Does it imply a minimum deviation pattern in Higgs couplings?
  - How does the reach of Higgs coupling measurements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

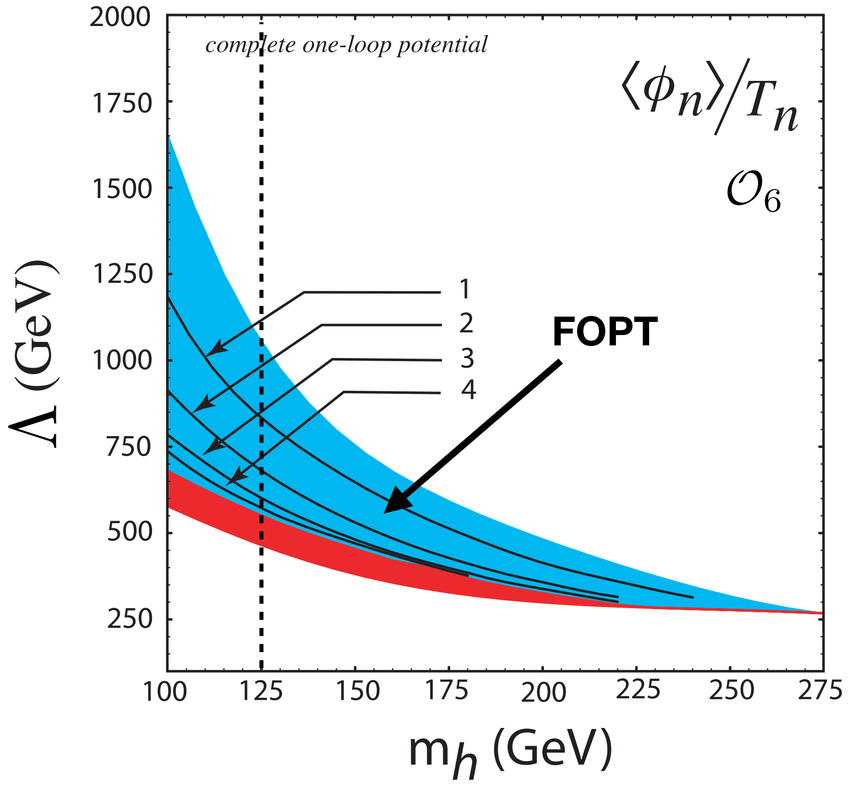


$$pp \to h_2^{(*)} \to hh$$

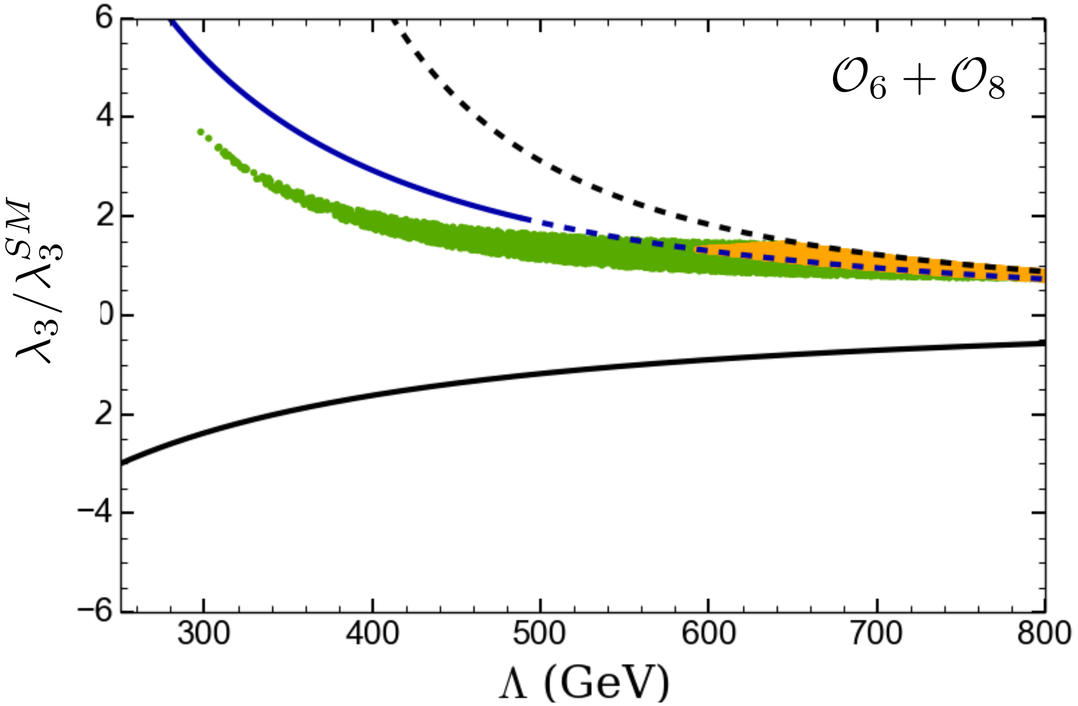
[Kotwal, Ramsey-Musolf, No, Winslow 1605.06123; Papaefstathiou, White 2010.00597]

A First-Order EWPT with $\mathcal{O}_6$ and More

- With d = 6, 8… Higgs operators: $$\frac{c_6}{\Lambda^2}(H^\dagger H)^3 + \frac{c_8}{\Lambda^2}(H^\dagger H)^8 + \ldots$$



[Grojean, Servant, Wells hep-ph/0407019; Delaunay, Grojean, Wells 0711.2511]



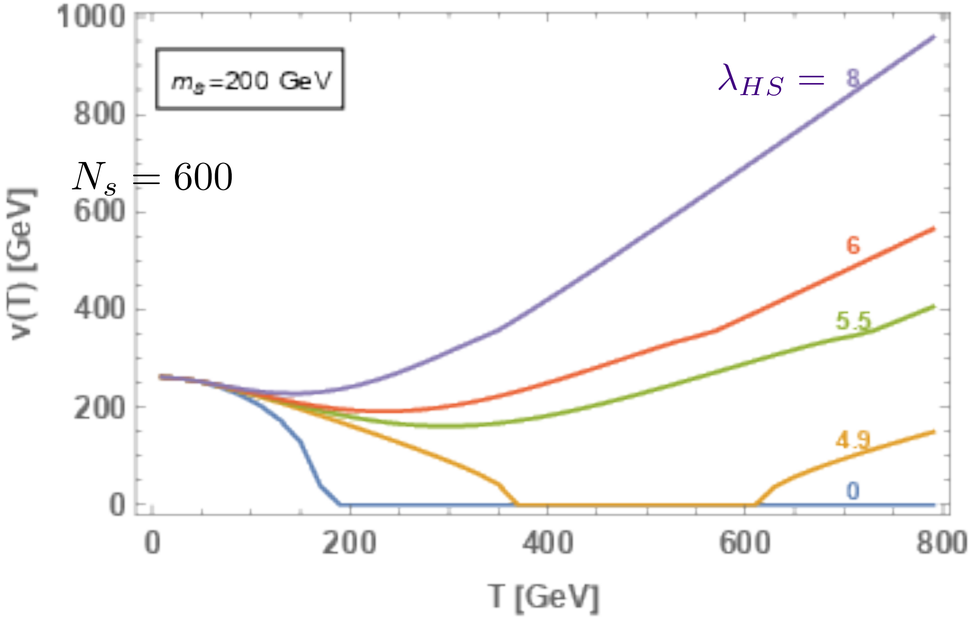
[Huang, Joglekar, Li, Wagner 1512.00068]

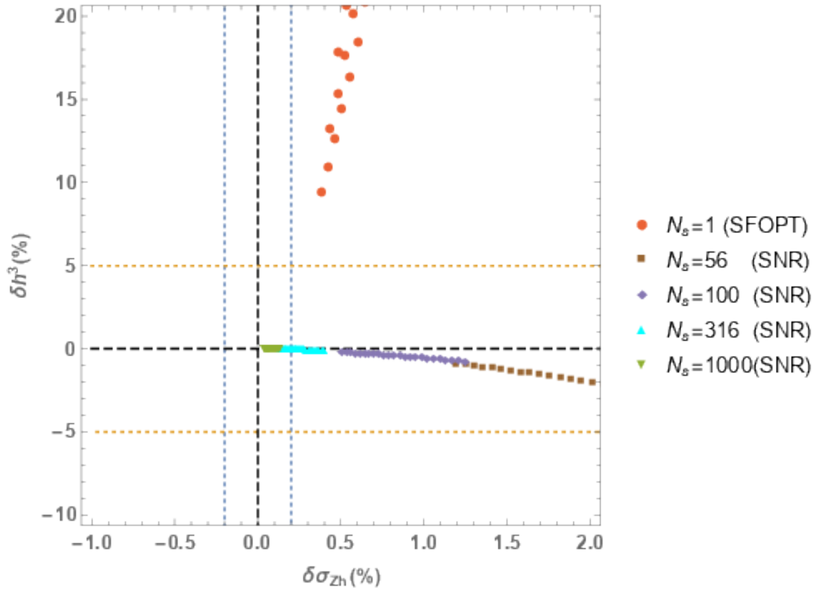
EW Symmetry Non-Restoration

- New physics can even impede EW symmetry restoration at high T!

[Meade, Ramani 1807.07578; Baldes, Servant 1807.08770; Glioti, Rattazzi, Vecchi 1811.11740; LOI by Carena *et al.*]

- For N_s copies of singlets: $V \supset -\lambda_{HS} S^2 H^\dagger H$





[Meade, Ramani 1807.07578]