Higgs Trilinear Coupling as a Probe of Electroweak Phase Transition

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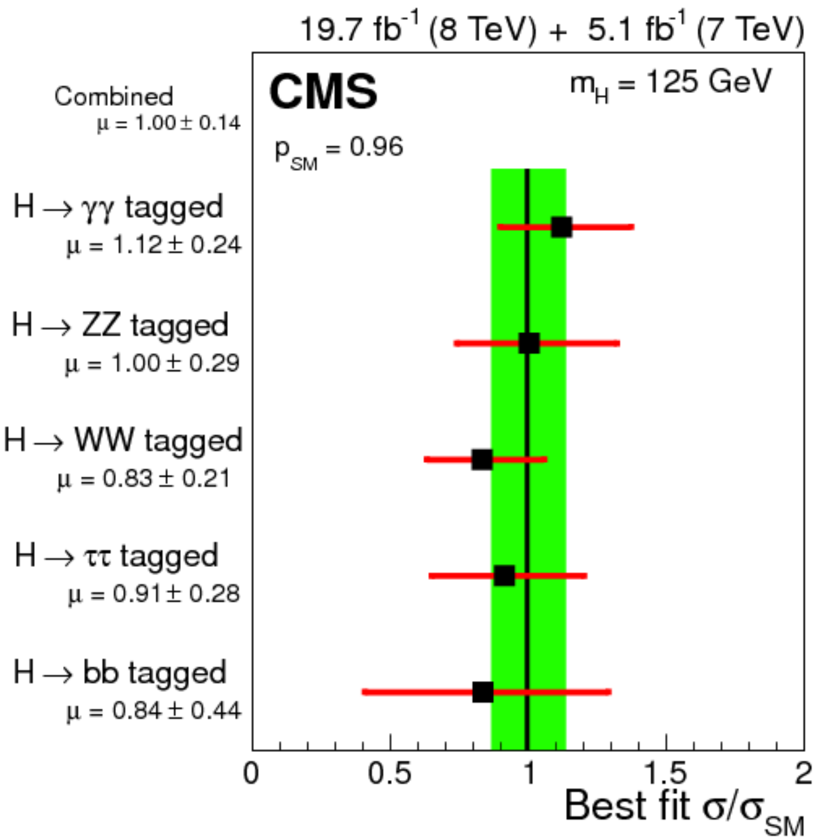
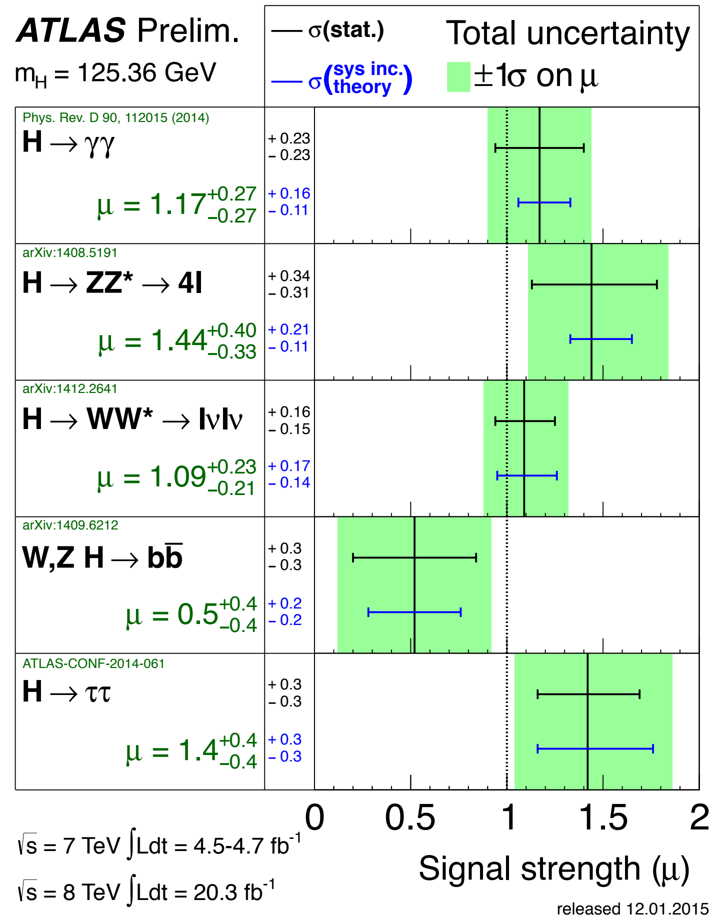
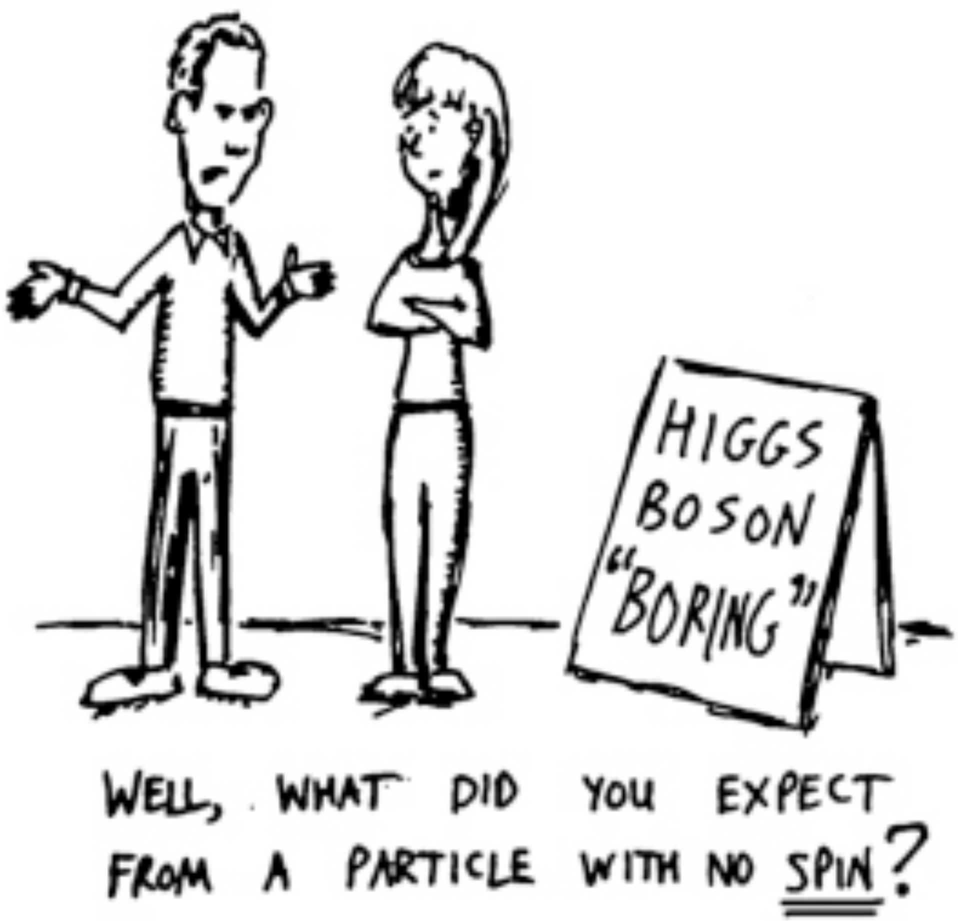
Here comes the Higgs boson!





Looks like a SM-like Higgs boson!

Hi there, can you tell us anything about new physics?



T. Whyntie

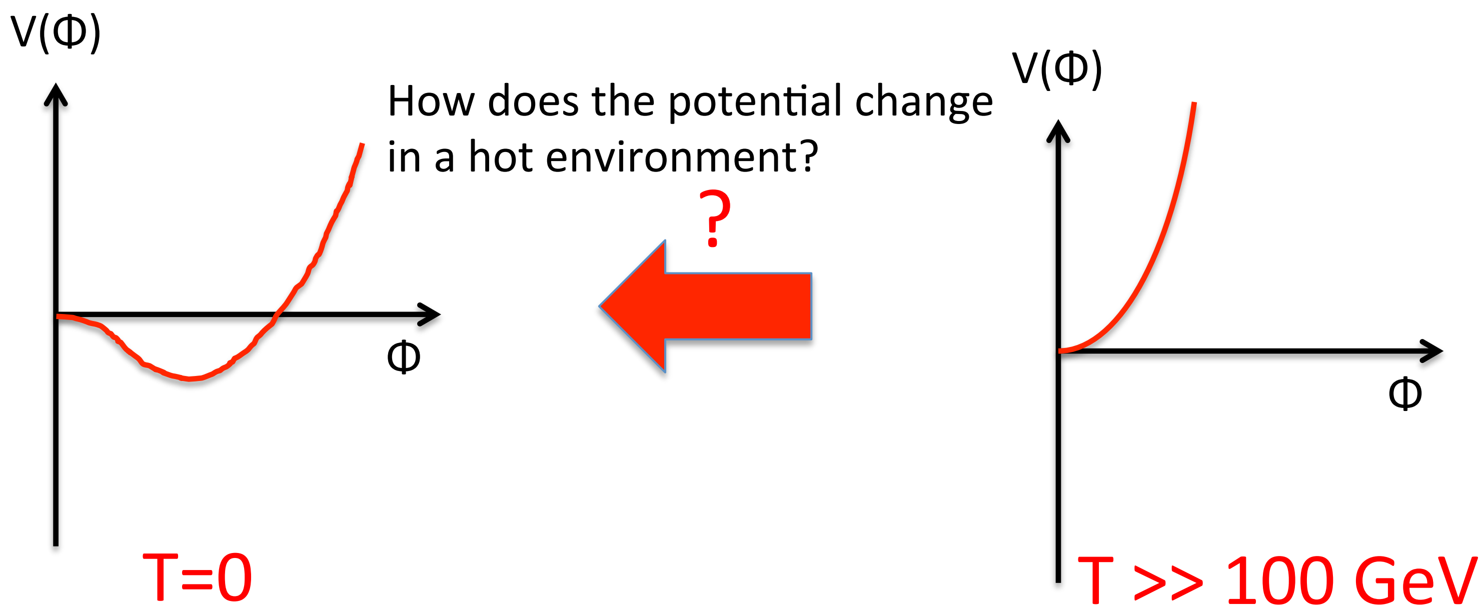
Outline

- Relate the Higgs trilinear coupling to Electroweak Phase transition

- Probe the Higgs trilinear coupling at the LHC

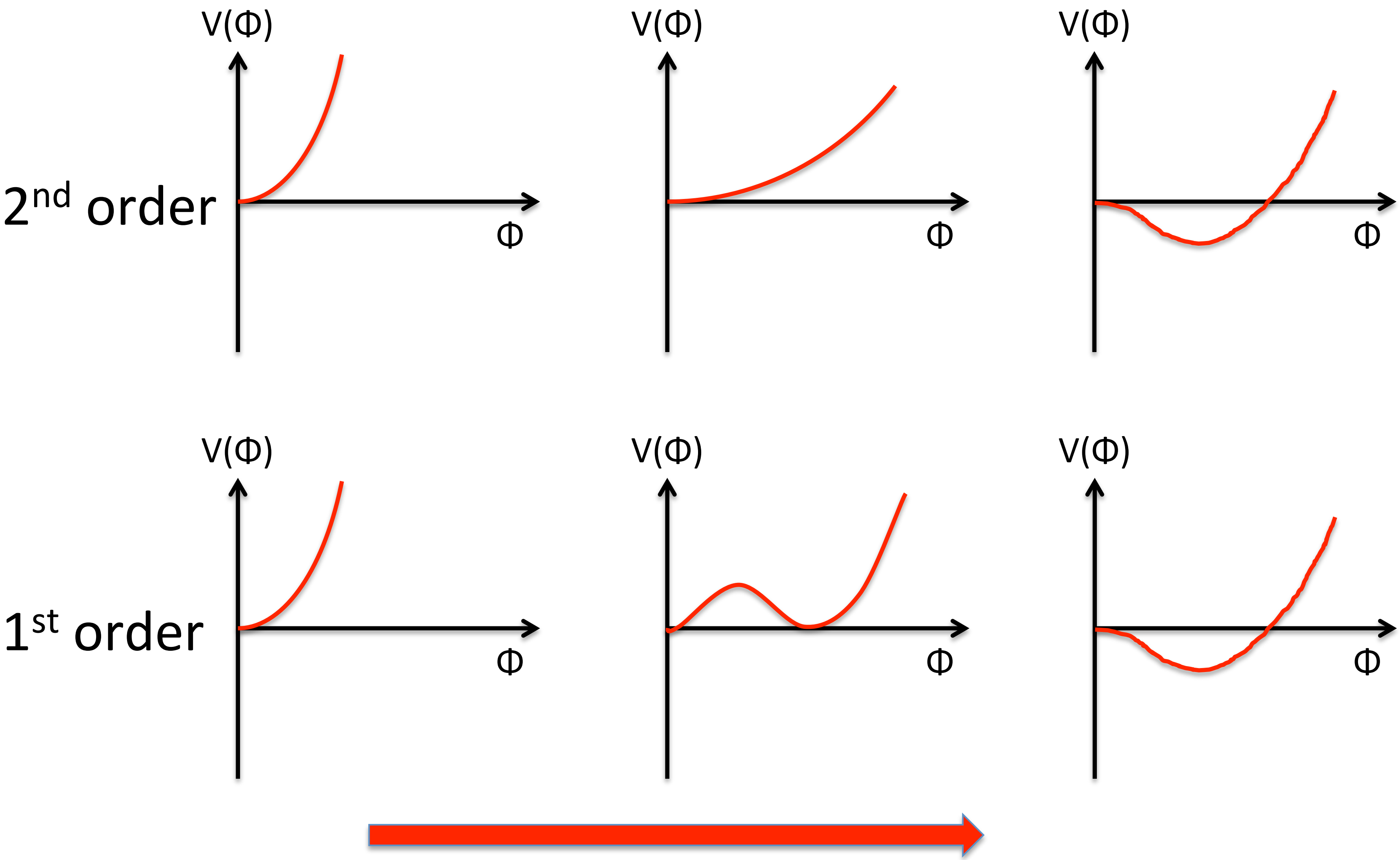
Higgs Potential at High Temperature

At high temperature, the Electroweak Symmetry is restored



As the Universe cools down, the symmetry is broken. The Higgs undergoes a Phase Transition from zero to non-zero VEV
What was the phase transition from unbroken phase to the broken phase look like?

Higgs Potential at Finite Temperature



Electroweak Phase Transition

- EWPT in the SM is 2nd order (unless the $m_h < 40$ GeV)
- New physics is required for a strongly first-order phase transition
- The new physics will alter the finite-temperature Higgs potential
- Higgs couples to SM particles differently, or couples to BSM particles
- Precision Higgs tests at the LHC and future colliders!

Example : Effective Potential Trilinear coupling

$$V(\phi, T) = \frac{m(T)^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{\kappa}{6}\phi^6$$

$$\lambda_3 = \frac{\partial^3 V}{\partial \phi^3} = 6\lambda v + 20\kappa v^3$$

$$\frac{\partial V}{\partial \phi}\,|_{\phi=v} = 0 \Rightarrow m^2 + \lambda v^2 + \kappa v^4 = 0$$

$$\frac{\partial^2 V}{\partial \phi^2}\,|_{\phi=v} = m_h^2 \Rightarrow 2\lambda v^2 + 4\kappa v^4 = m_h^2$$

$$\lambda_3 = \frac{3m_h^2}{v} + 8\kappa v^3 = \lambda_3^{SM}(1 + \frac{8}{3}\frac{\kappa v^4}{m_h^2})$$

Example : Effective Potential Electroweak phase transition

$$\frac{\partial V(\phi, T)}{\partial \phi}\Big|_{\phi=v_c} = 0 \Rightarrow m^2 + aT_c^2 + \lambda v_c^2 + \kappa v_c^4 = 0$$

$$V(v_c, T_c) = V(\phi = 0, T_c) \Rightarrow \frac{m^2 + aT_c^2}{2} + \frac{\lambda}{4} v_c^2 + \frac{\kappa}{6} v_c^4 = 0$$

$$\lambda = -\frac{4\kappa}{3} v_c^2$$

$$T_c^2 = \frac{\kappa}{a}(v_c^2 - v^2)(\frac{v_c^2}{3} - v^2)$$

$$T_c^2 > 0 \Rightarrow v_c > \sqrt{3}v \text{ or } v_c < v$$

Example : Effective Potential Trilinear coupling

$$m_h^2 = 2\lambda v^2 + 4\kappa v^4$$

$$\lambda = -\frac{4\kappa}{3} v_c^2$$

$$\kappa = \frac{m_h^2}{4v^4 - \frac{8}{3} v_c^2 v^2} > 0 \Rightarrow v_c < v$$

$$\kappa_{max} = \frac{3m_h^2}{4v^4}$$

$$\lambda_3^{max} = \lambda_3^{SM}\left(1 + \frac{8}{3}\frac{\kappa_{max} v^4}{m_h^2}\right) = 3\lambda_3^{SM}$$

for a ϕ^8 theory, $\lambda_3^{max} = 5\lambda_3^{SM}$, and for a ϕ^{10} theory, $\lambda_3^{max} \sim 7\lambda_3^{SM}$

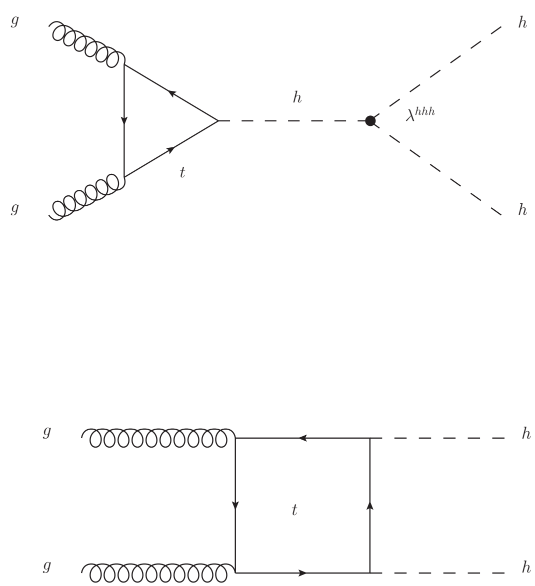
Other Examples

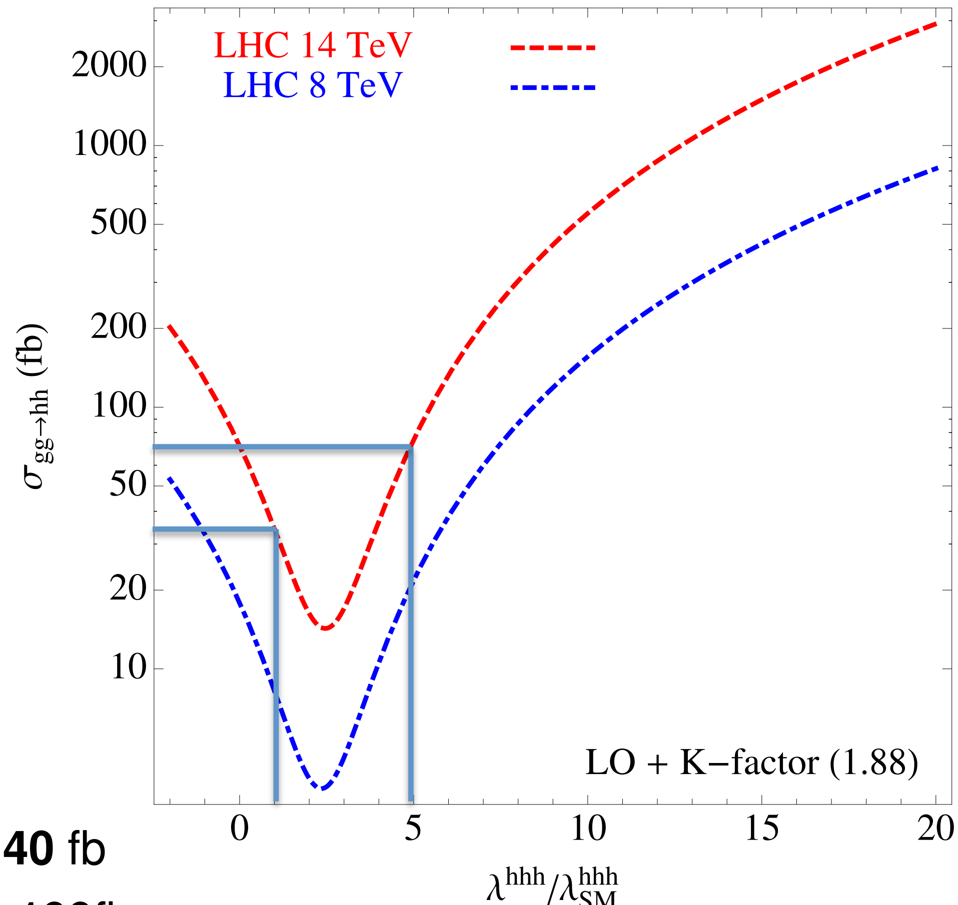
- In NMSSM, a $\lambda_3^{max} = 3\lambda_3^{SM}$ is expected with a a strong first-order EWPT. arxiv:1505:xxxxx PH, A. Joglekar, B. Li, and C. Wagner

- SM + a single BSM scalar, single BSM fermion, single BSM scalar + fermion, multiple BSM states – order 1 deviation is typical for models with a strong first-order EWPT. A. Nobel and M. Perelstein, 2008

- In the SM + singlet case, a $\lambda_3 = 4\lambda_3^{SM}$ can be achieved with a strong first-order EWPT. D. Curtin, P. Meade, and C. Yu

Probe the trilinear coupling at the LHC
Production cross section





At NNLO, 14 TeV,

- $\lambda_3 = \lambda_3^{SM}$, $\sigma(pp \to hh) = 40$ fb
- $\lambda_3 = 5\lambda_3^{SM}$, $\sigma(pp \to hh) = 100$fb

De Florian and Mazzitelli, Grigo, Melnikov, and Steinhauser

Spria, figure from Barger, Everett, Jackson, and Shaughnessy

Probe the trilinear coupling at the LHC hh -> bbγγ

- Main background : bbγγ (irreducible),tth(h>γγ), Zh - > bbγγ
- Subleading background : bbjj (jet faked photons), ccγγ (mis-tagged charms, 24% assuming b-tagging eff 70%, pile up = 50), jjγγ(mistaged jets, 2%), bbh.
- tth: veto extra leptons or jets
- Zh : require m_{bb} and $m_{\gamma\gamma}$ in the window of higgs mass

Probe the trilinear coupling at the LHC Snowmass study

- $\Delta R_{\gamma\gamma} < 2.5$ and $\Delta R_{b\bar{b}} < 2.0$
- $|\eta_{\gamma\gamma}| < 2.0$ and $|\eta_{b\bar{b}}| < 2.0$
- $Pt_{\gamma\gamma} > 100$ and $Pt_{b\bar{b}} > 100$ GeV
- $M_{b\bar{b}\gamma\gamma} > 300$ GeV/c^2

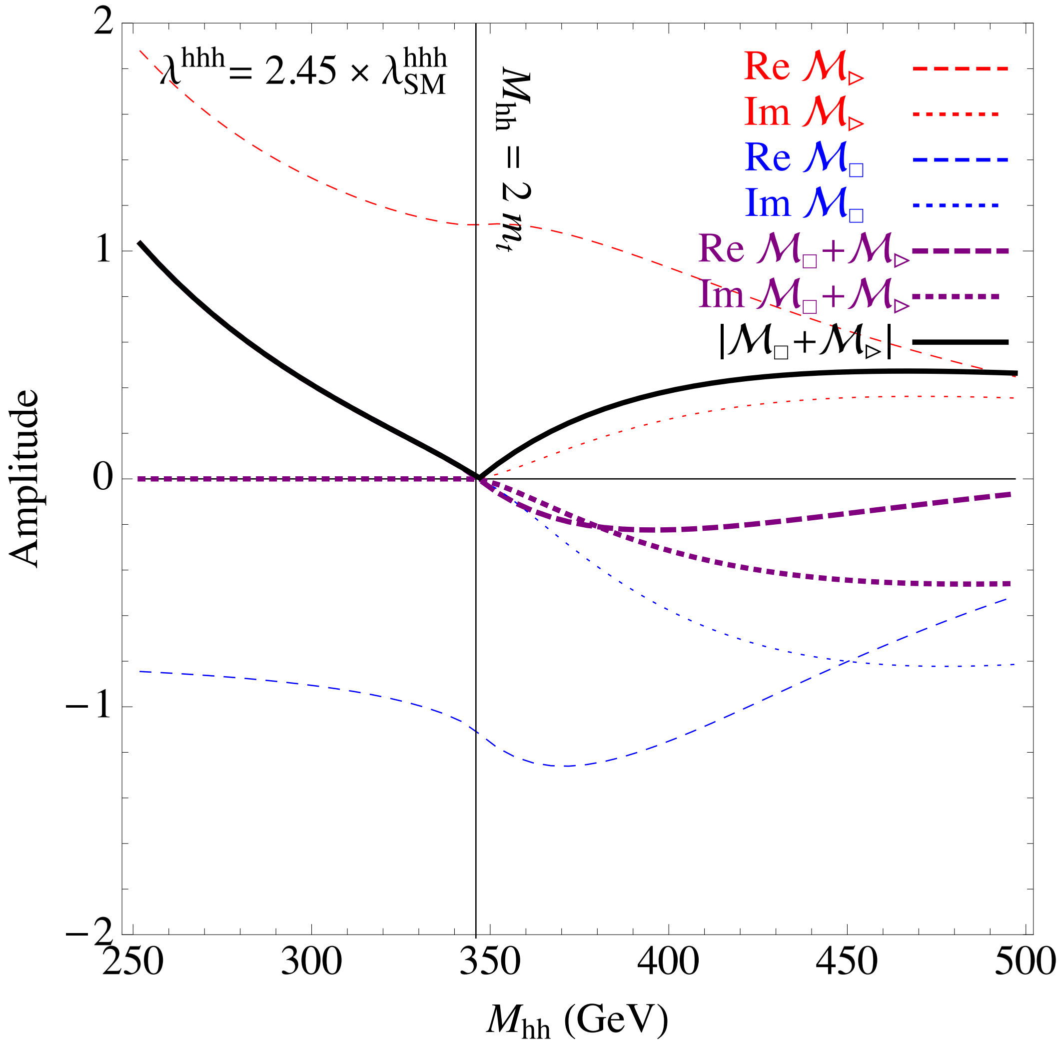
m_{bb} and $m_{\gamma\gamma}$ are within some window of m_h

- $\Sigma(njets + nphos + nleps + nmet) < 7$

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

Snowmass 1310.8361

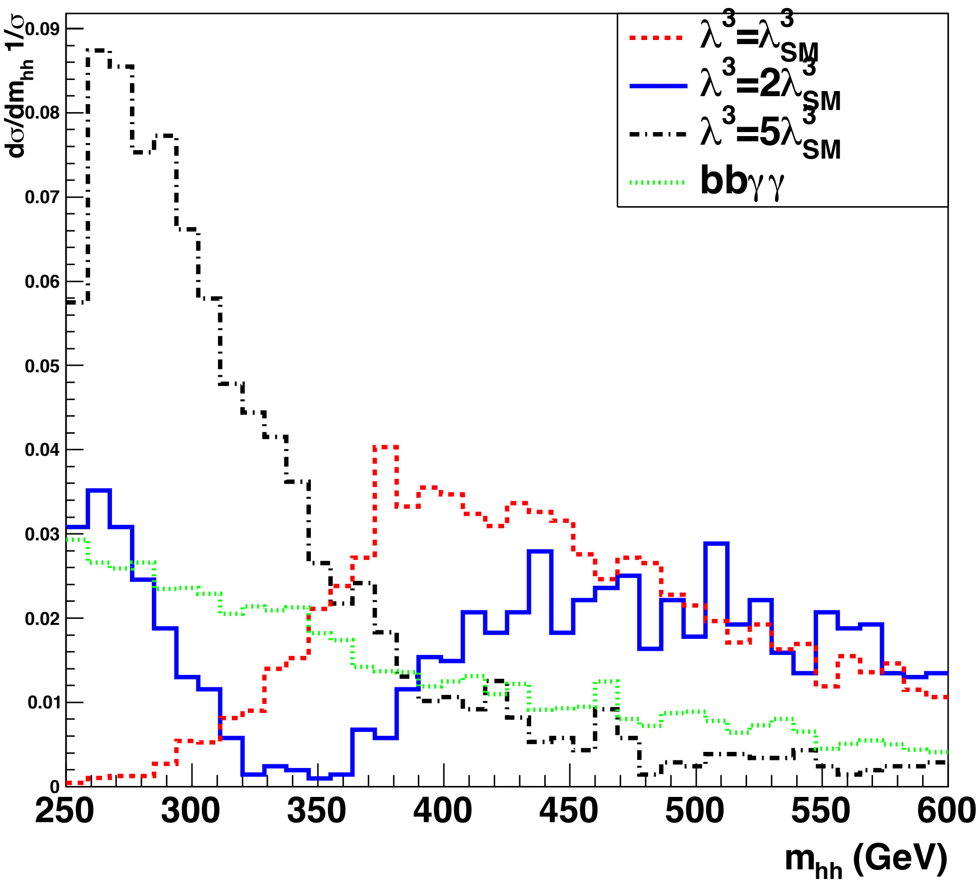
Probe the trilinear coupling at the LHC
Production cross section



Barger, Everett, Jackson, and Shaughnessy

- The destructive interference occurs between the real part of the triangle and the box diagrams
- Above the tt threshold, the amplitudes develop imaginary parts, the cancellation is not as strong as it is below the tt threshold.
- When λ_3 increases, the amplitude increases more below the tt threshold than above the threshold
- m_{hh} shifts to smaller value for large λ_3

Probe the trilinear coupling at the LHC
Acceptance goes down for large λ_3



Parton level, MCFM

- Re-design the cuts for large λ_3
- Studies in the literature tend to be too optimistic – assuming the acceptance stays the same

Probe the trilinear coupling at the LHC

- We have noticed some problems with the background calculations in the previous studies, so we redo the analysis in the hh -> bbγγ channel.
- Use different cuts for SM and new physics.
- Preliminary results
  - $\lambda_3 = \lambda_3^{SM}$, $S/\sqrt{B} = 2.6$
  - $\lambda_3 = 5\lambda_3^{SM}$, $S/\sqrt{B} = 2.3$

arxiv:1505:xxxxx PH, A. Joglekar, B. Li, and C. Wagner

Conclusion

- There is a tight correlation between the dynamics of the EWPT and the trilinear coupling of the Higgs boson
- A large deviation of the Higgs trilinear coupling from the SM prediction is expected for models exhibit a strong first-order EWPT
- Probe the trilinear coupling at the LHC is challenging. Should use different strategies for SM and new physics.