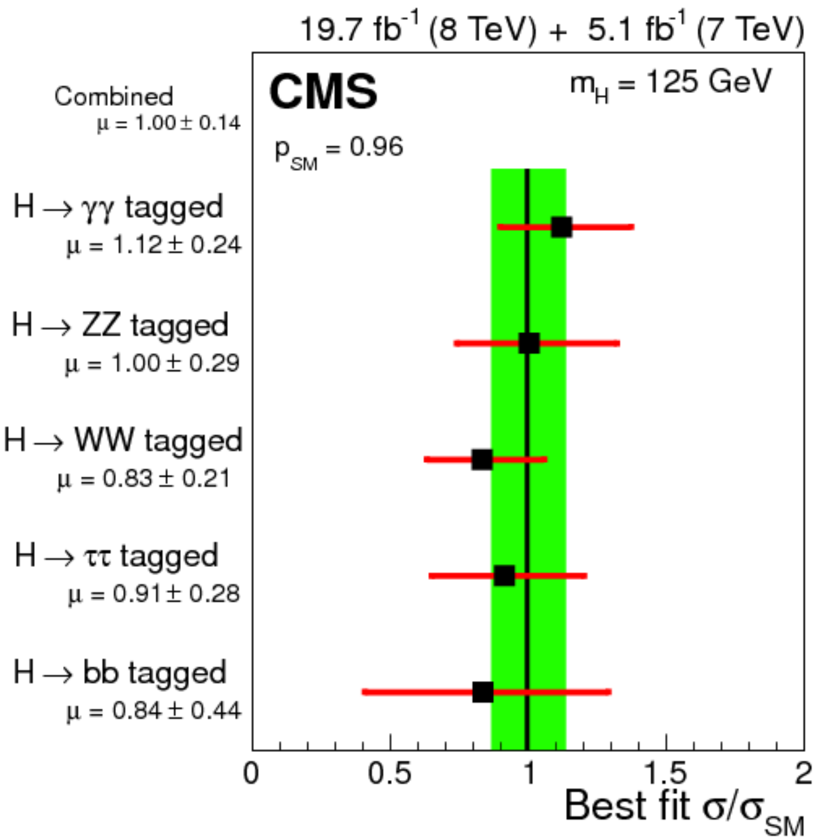
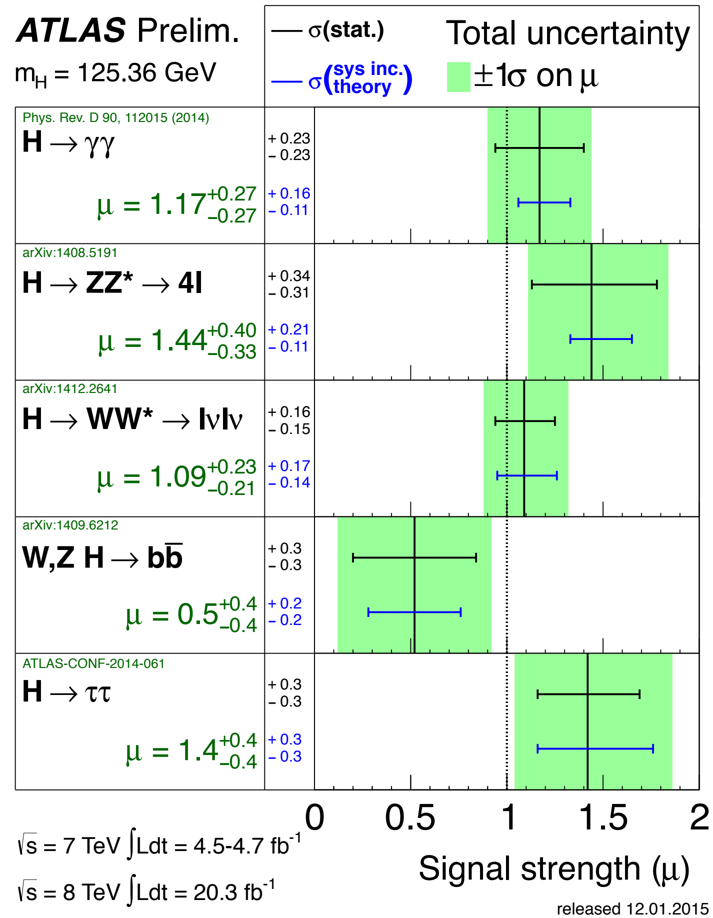
Probe the Higgs Trilinear Coupling at the LHC

Peisi Huang
University of Chicago/Argonne
SUSY 2015, Lake Tahoe

Work with A. Joglekar, B. Li, and C. Wagner

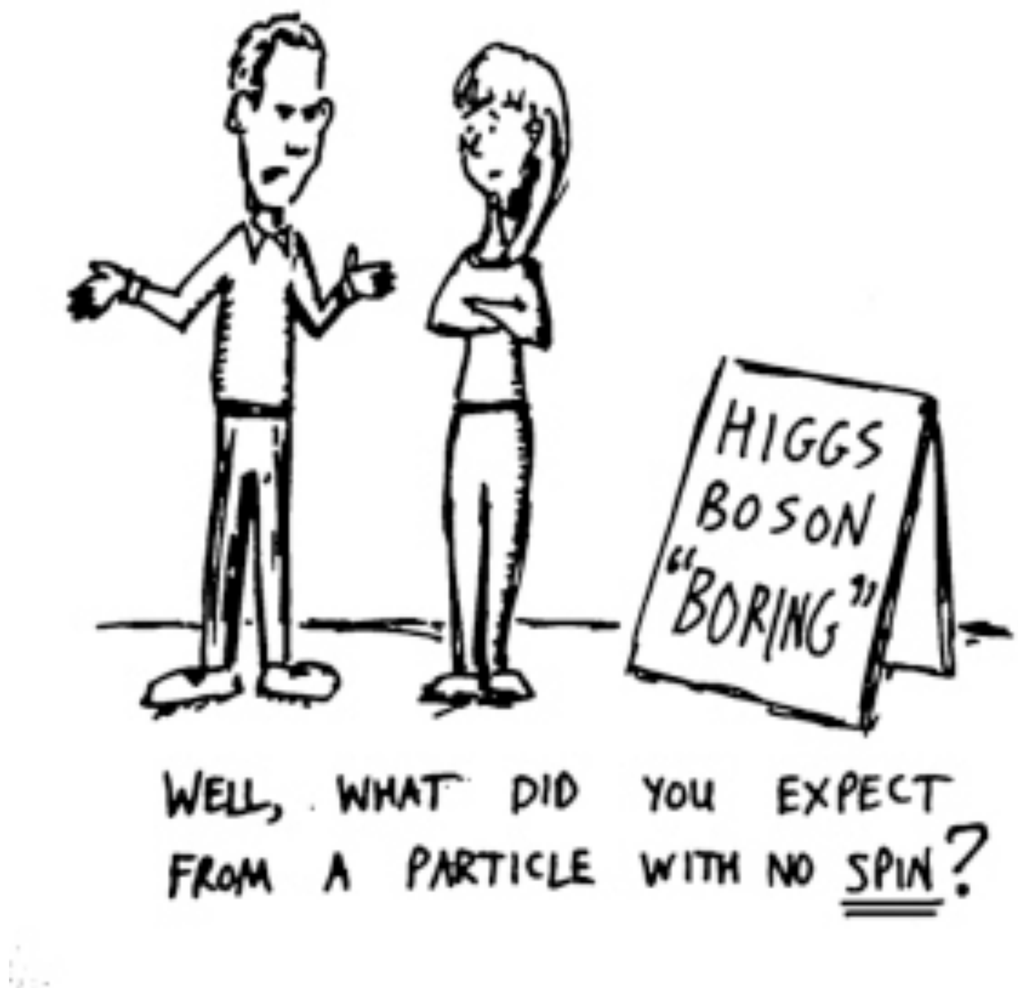
Here comes the Higgs boson!





Looks like a SM-like Higgs boson!

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



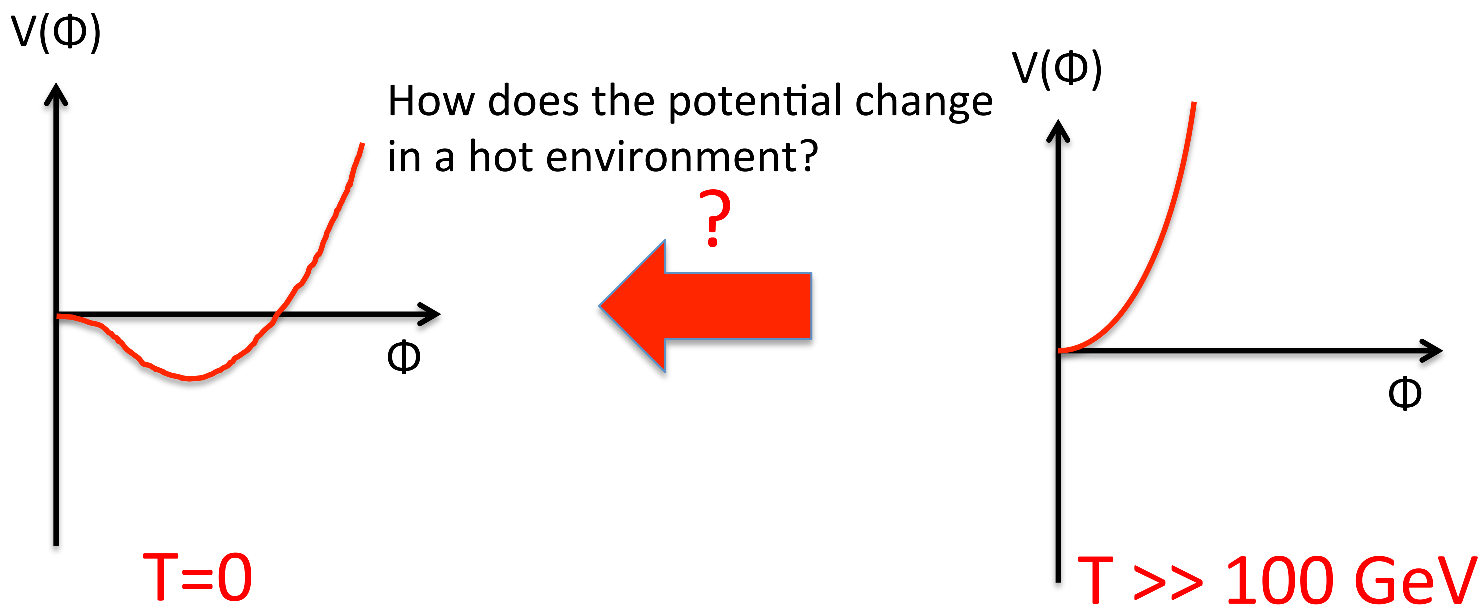
T. Whyntie

Outline

- Relate the Higgs trilinear coupling to Electroweak Phase transition
- Probe the Higgs trilinear coupling at the LHC and a 100 TeV collider.

Higgs Potential at High Temperature

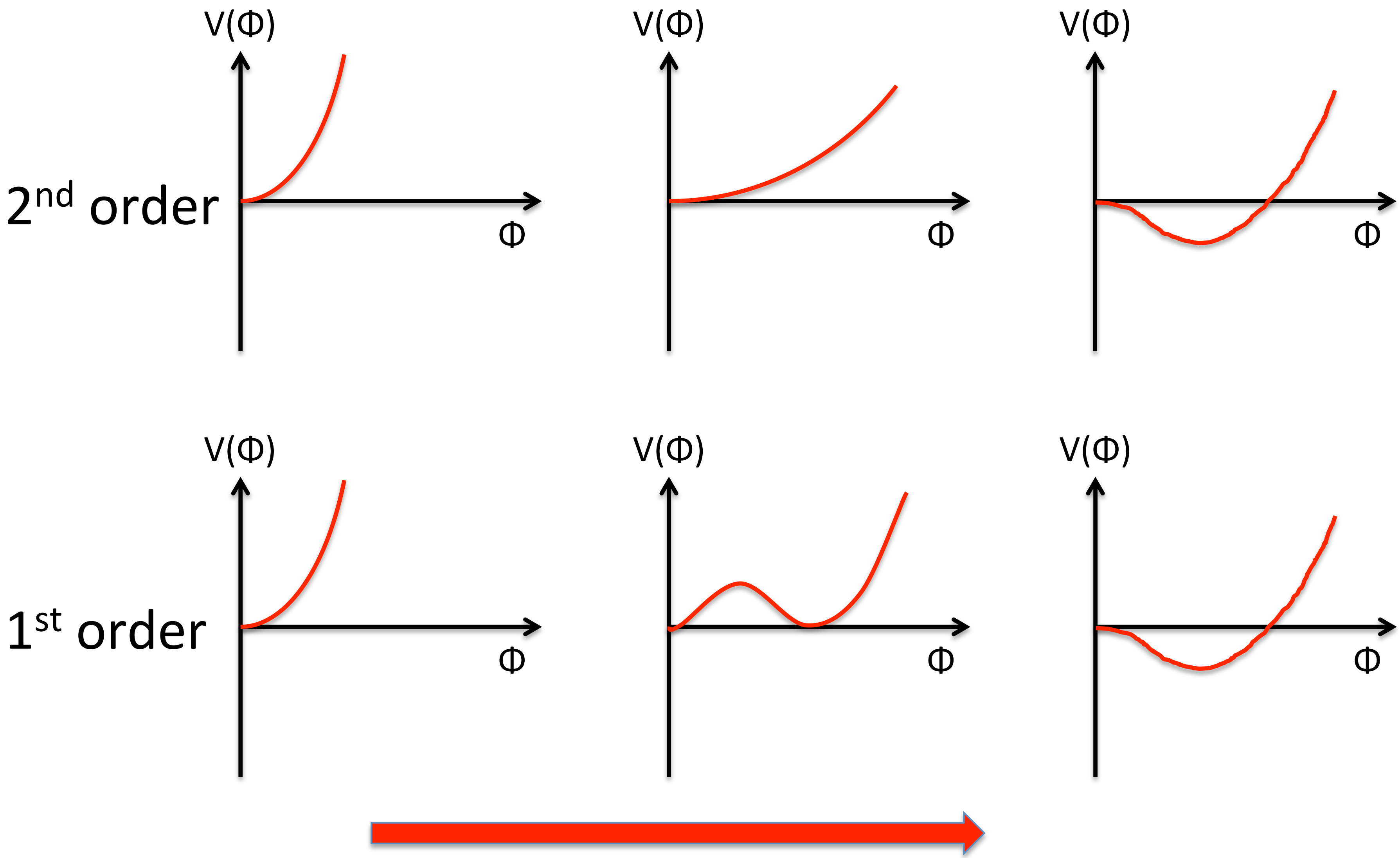
At high temperature, the Electroweak Symmetry is restored



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 2^{nd} 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

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

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

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

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

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

Example : Effective Potential Trilinear coupling

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

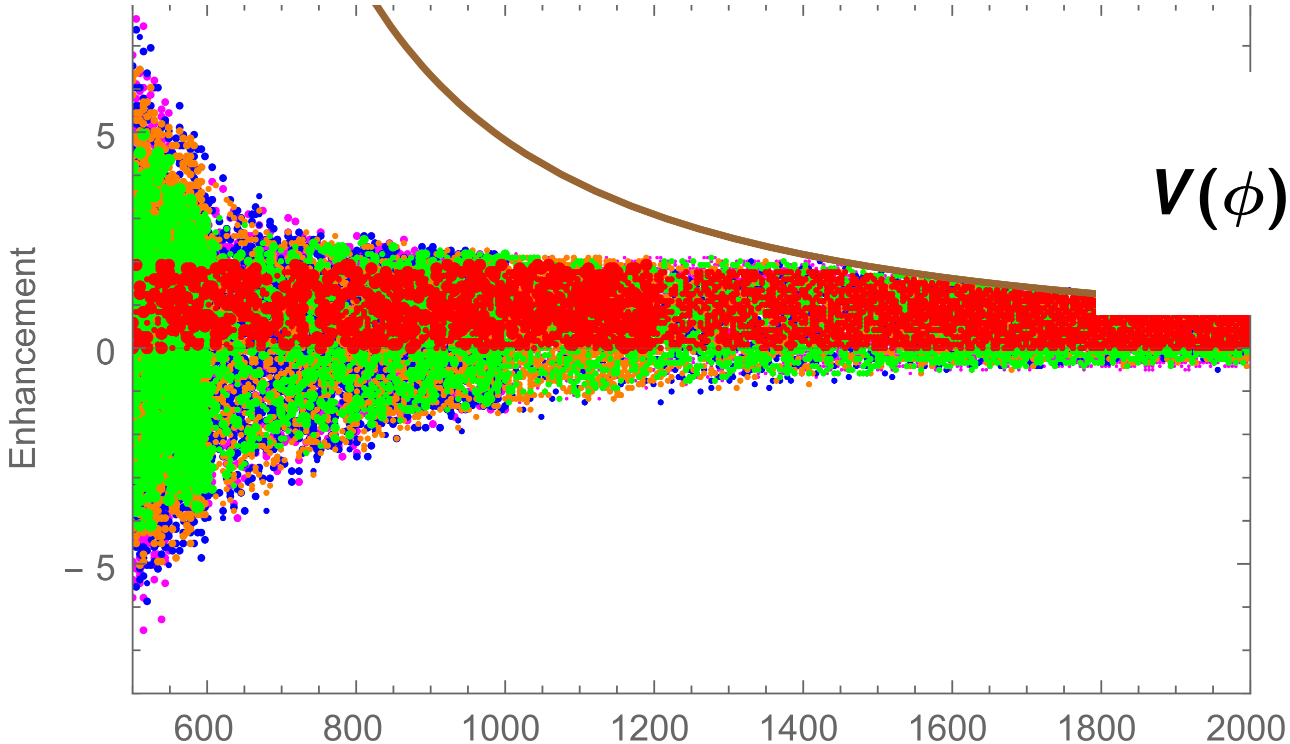
$$\lambda = -\frac{4\kappa}{3} v_c^2$$

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

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

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

Example: Effective Potential Including higher orders



$$V(\phi) = \sum_{n=1}^{\infty} \kappa_{2n}\phi^{2n}$$

ϕ^8 , ϕ^{10} , ϕ^{12} ϕ^{14}

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

First order PT tends to associate with positive enhancement, while negative enhancement tends to associate with second order PT.

arxiv:1509:xxxxx PH, A. Joglekar, B. Li, and C. Wagner

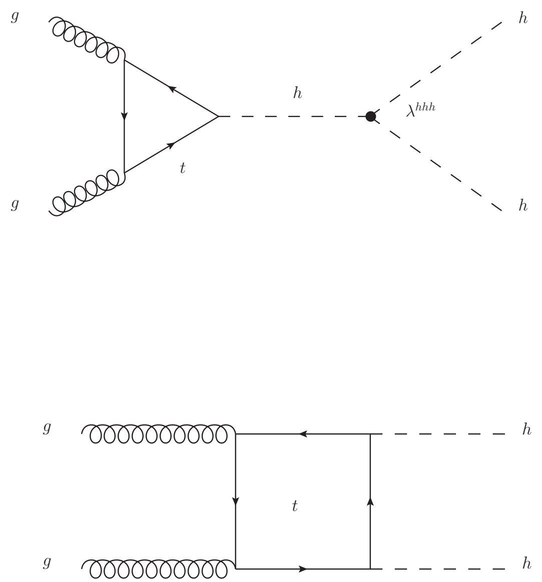
Other Examples

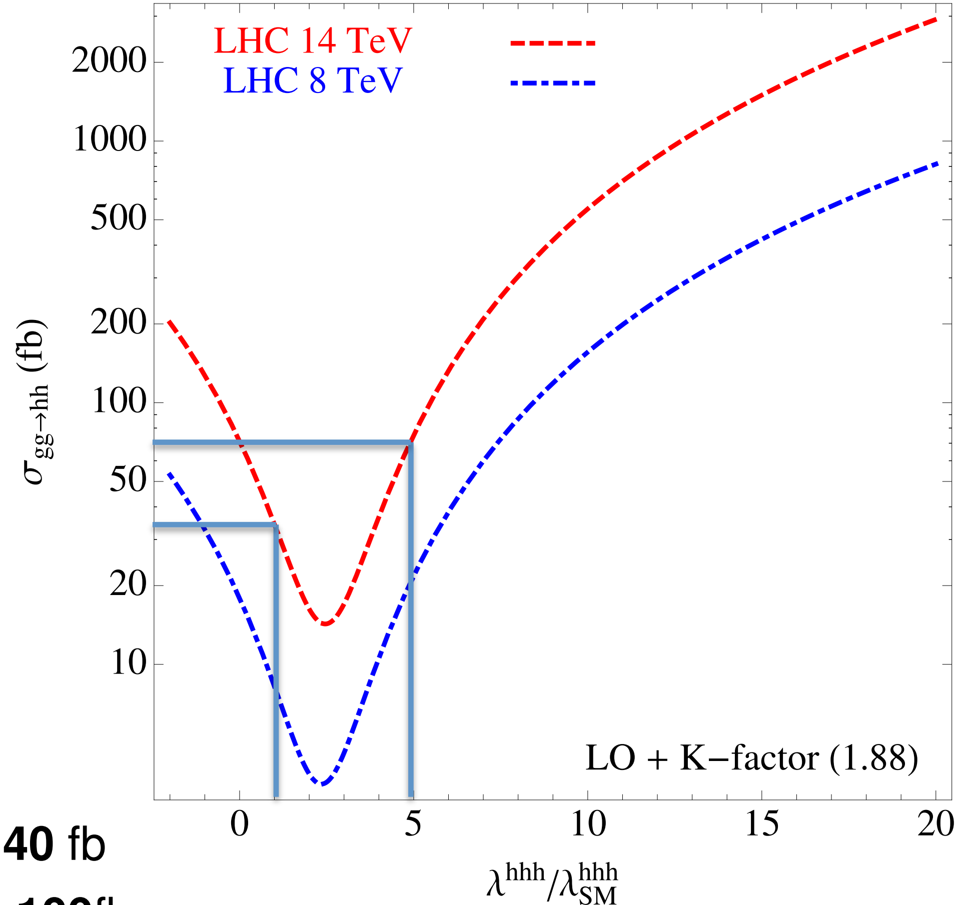
- In NMSSM, a $\lambda_3^{max} = 3\lambda_3^{SM}$ is expected with a strong first-order EWPT. arxiv:1509:xxxxx PH, A. Joglekar, B. Li, and C. Wagner

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

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

	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

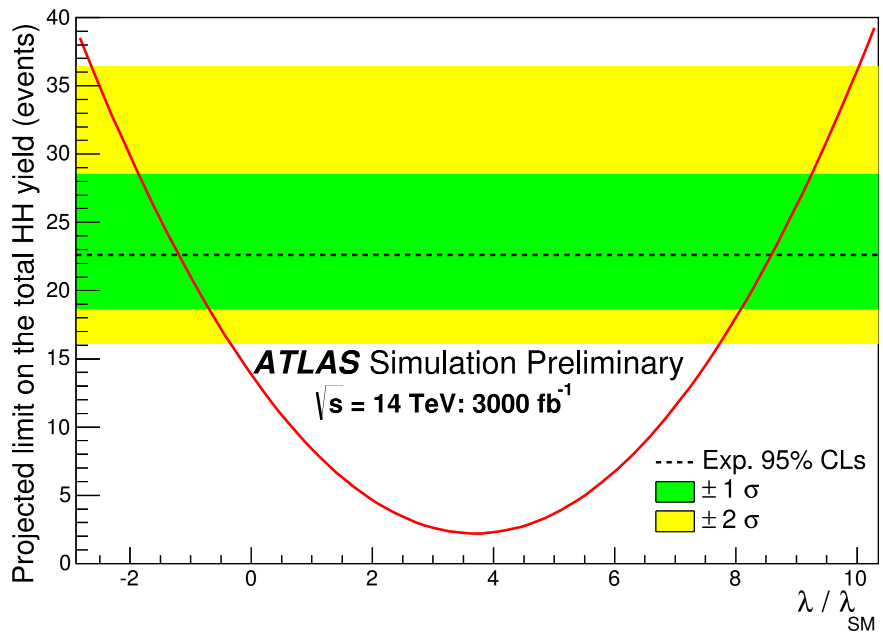
Probe the trilinear coupling at the LHC

ATLAS NOTE

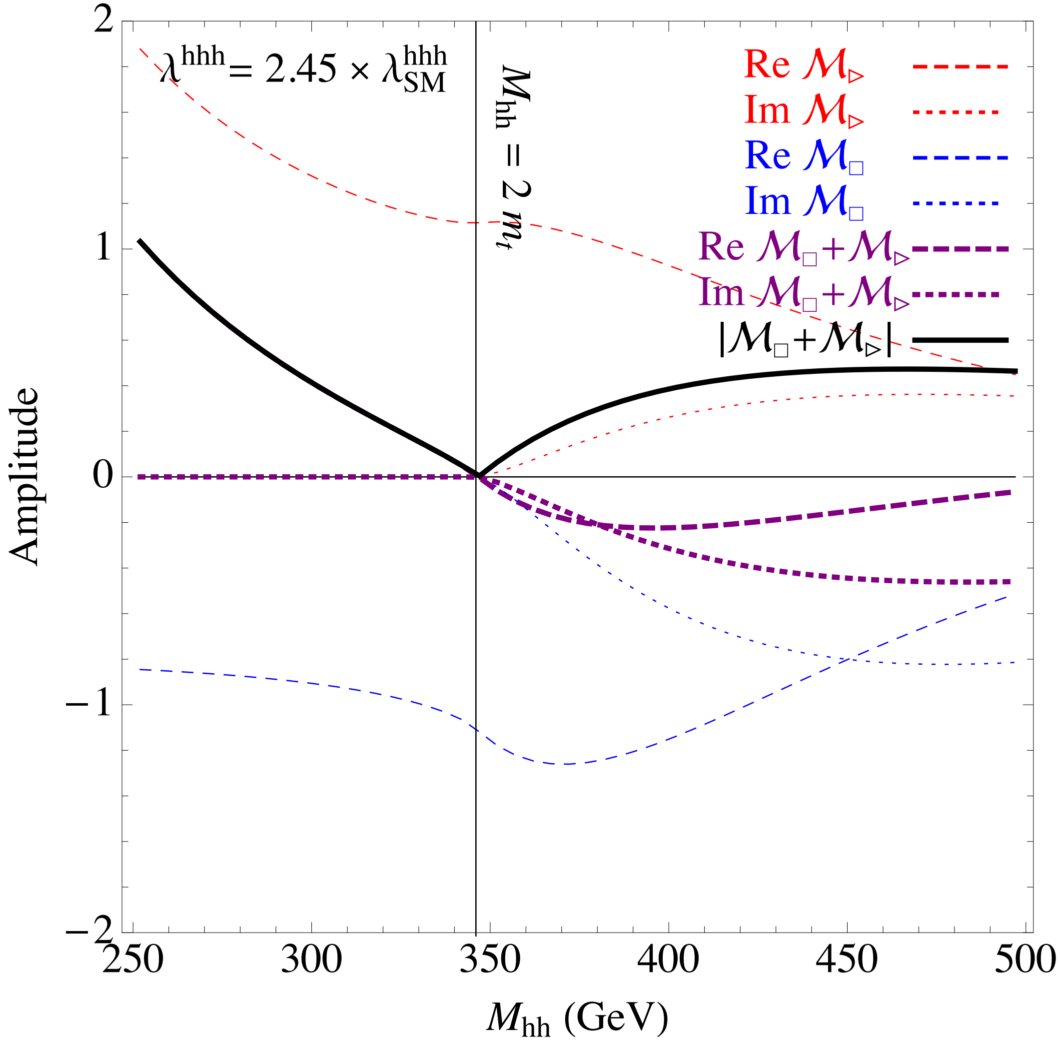
ATL-PHYS-PUB-2014-019

21st October 2014

Prospects for measuring Higgs pair production in the channel $H(\rightarrow \gamma\gamma)H(\rightarrow b\bar{b})$ using the ATLAS detector at the HL-LHC



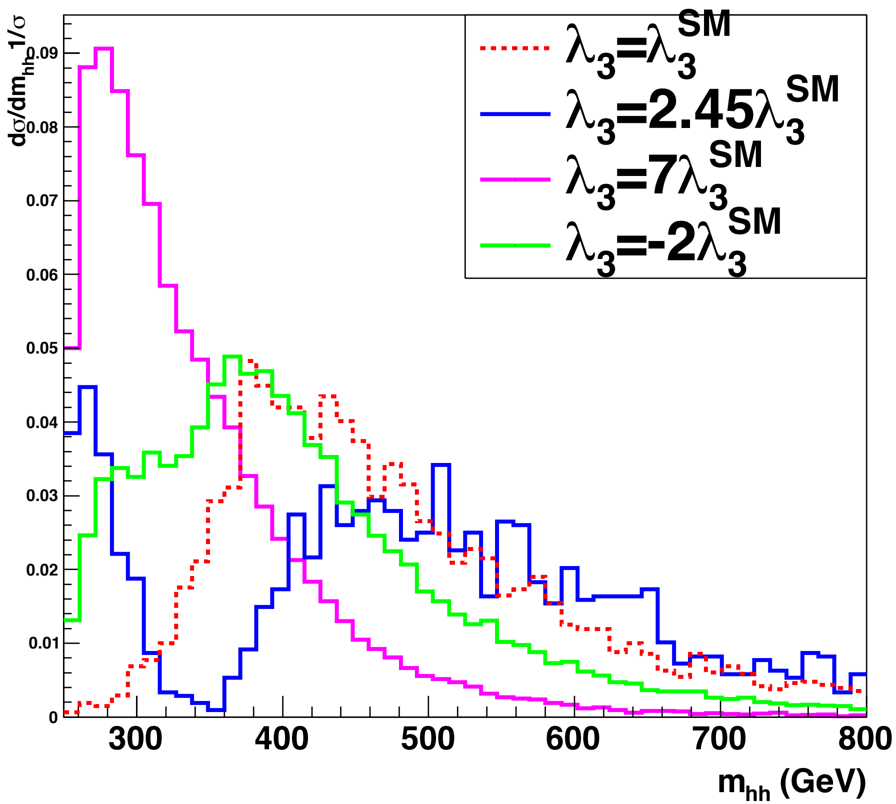
Probe the trilinear coupling at the LHC
Production cross section



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 receives extra contributions .
- 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



Re-design the cuts for large λ_3

Studies in the literature tend to be too optimistic – assuming the acceptance stays the same with new particles in the loop, see talk by A. Ismail(Friday)

Parton level, MCFM

arxiv:1509:xxxxx PH, A. Joglekar, B. Li, and C. Wagner

Probe the trilinear coupling at the LHC and 100 TeV collider

- 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.
- LHC 14 $3ab^{-1}$
  - $\lambda_3 = \lambda_3^{SM}$, $S/\sqrt{B} = 2.6$
  - $\lambda_3 = 5\lambda_3^{SM}$, $S/\sqrt{B} = 2.3$
- 100 TeV collider, $3ab^{-1}$
  - $\lambda_3 = \lambda_3^{SM}$, $S/\sqrt{B} = 11$
  - $\lambda_3 = 3\lambda_3^{SM}$, $S/\sqrt{B} = 4.5$
  - $\lambda_3 = 5\lambda_3^{SM}$, $S/\sqrt{B} = 5$

arxiv:1509: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.