Higgs Trilinear Coupling as a Probe of Electroweak Phase Transition

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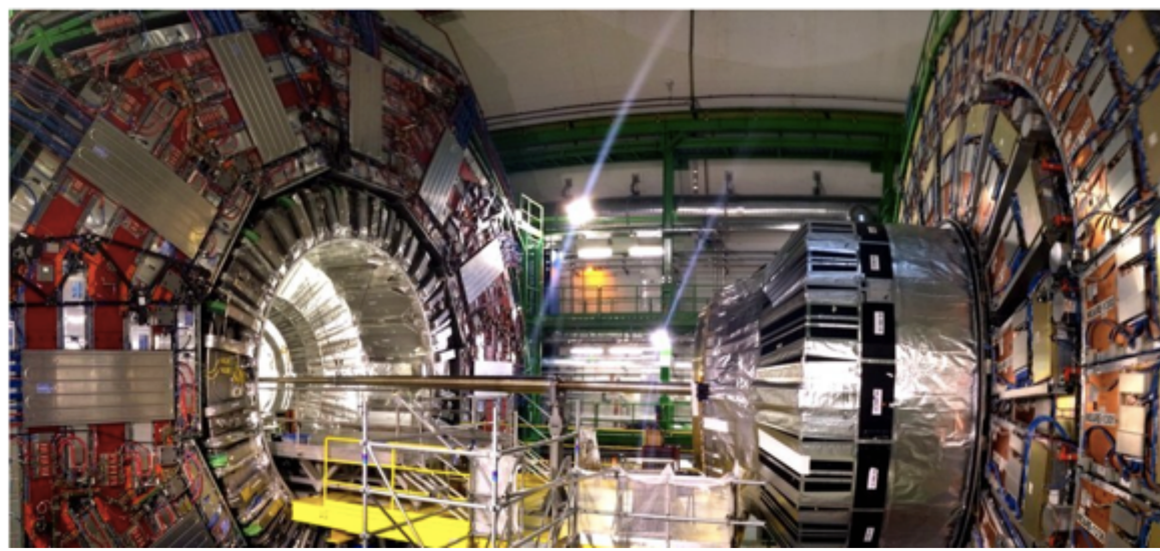
Following

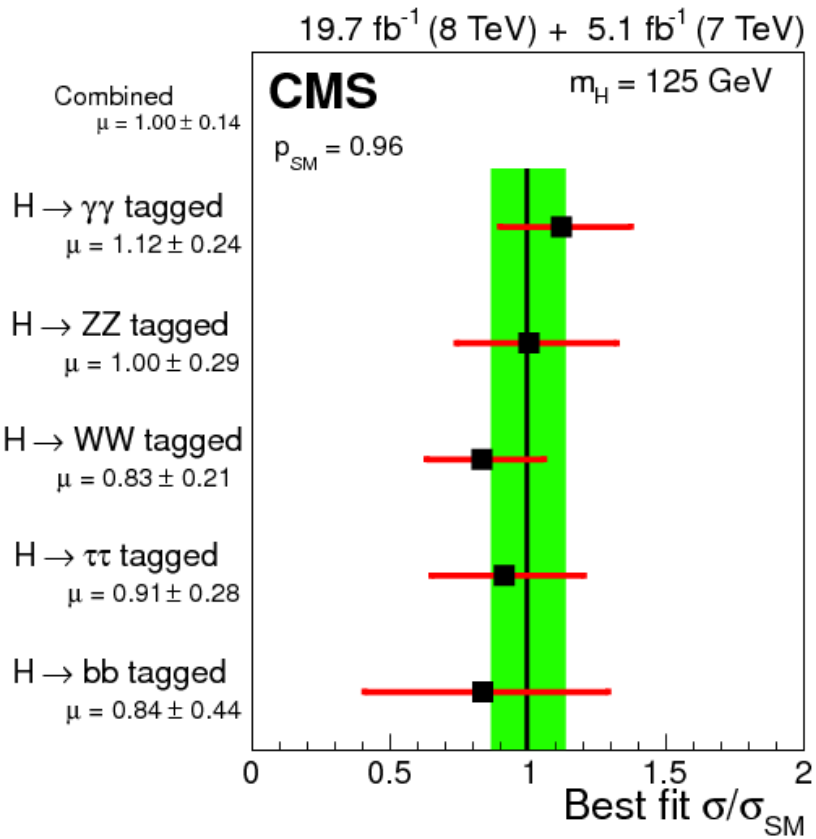
Upgraded Large Hadron Collider Brings Atom Smashin' Back in Fashion - nbcnews.to/1F8dAom

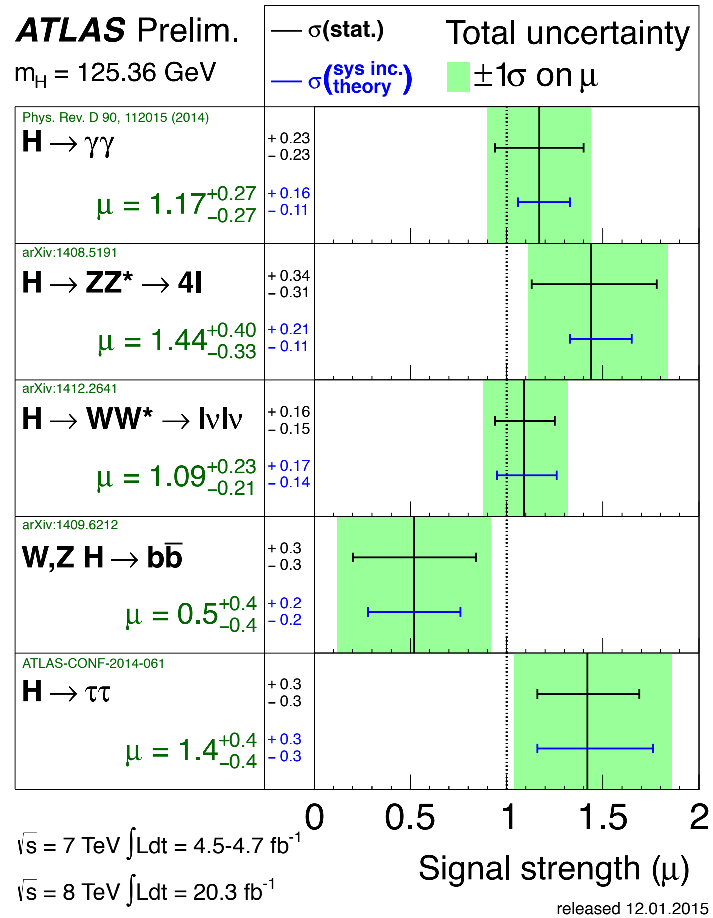
LHC restart: 'We want to break physics'

By Jonathan Webb
Science reporter, BBC News



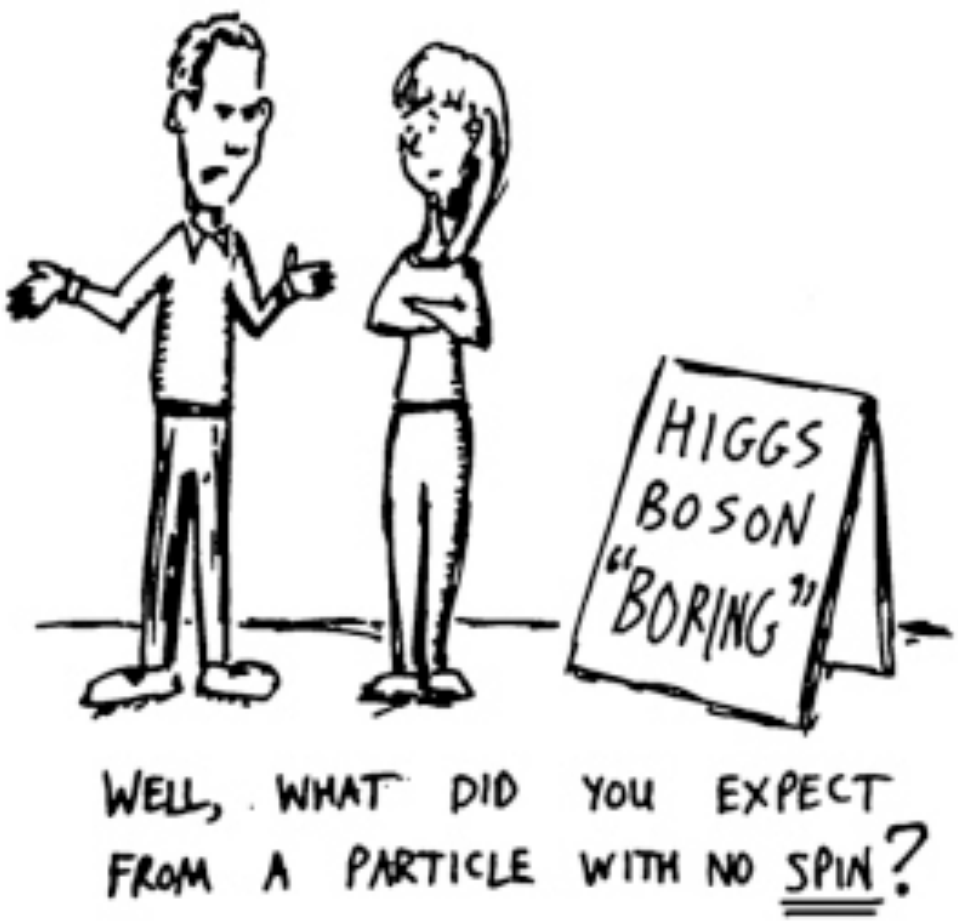
Here comes the Higgs boson!





Looks like a SM-like Higgs boson!

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



T. Whyntie

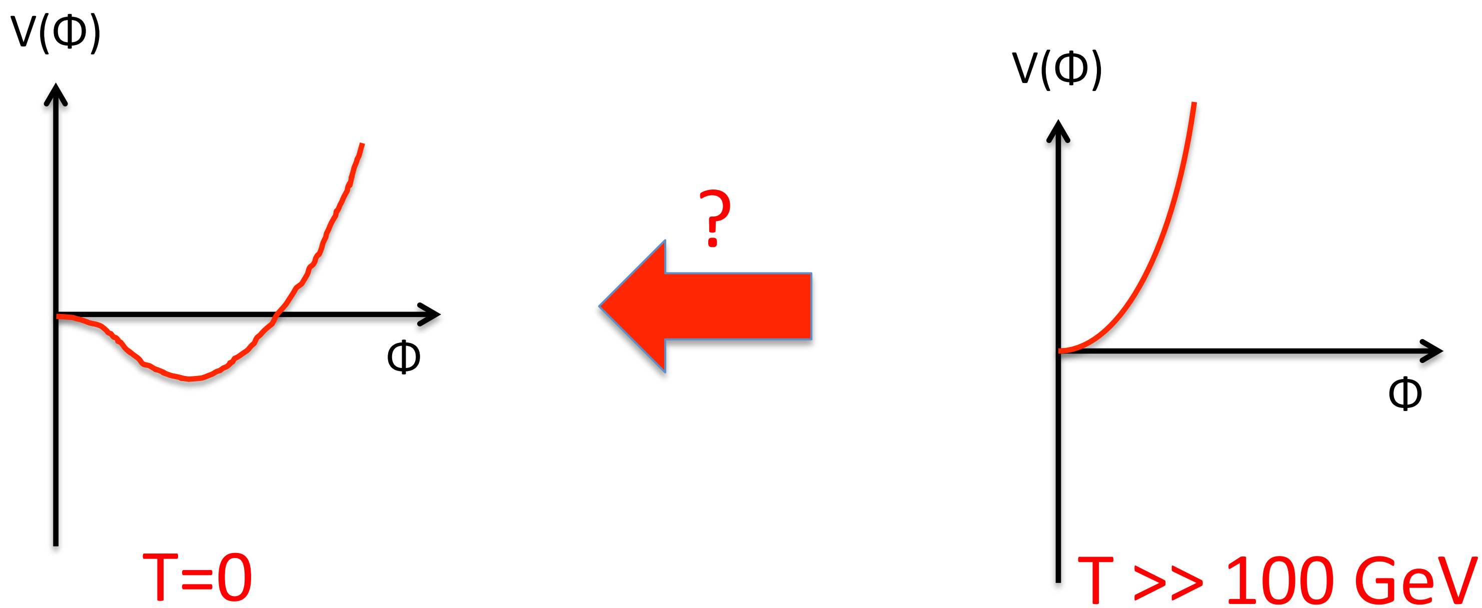
Outline

- Relate the Higgs trilinear coupling to Electroweak Phase transition
  - SM + higher dim operators
  - NMSSM

- Probe the Higgs trilinear coupling at the LHC

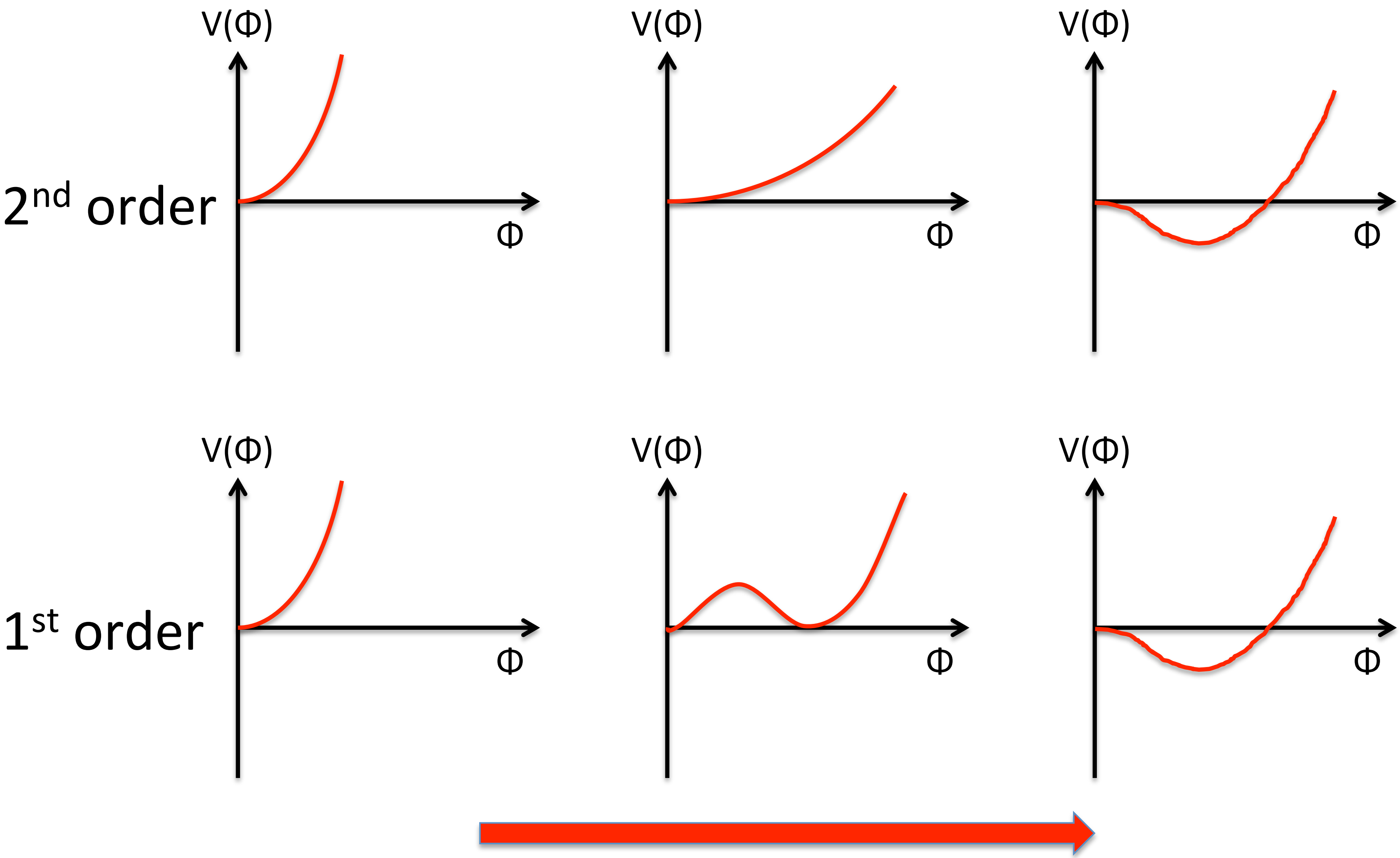
Higgs Potential at High Temperature

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 2^{nd} order
- 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 1 : Effective Potential Trilinear coupling

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

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

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

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

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

Example 1 : Effective Potential Electroweak phase transition

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

The critical temperature T_c and the VEV at $T_{C,}$ v_c, are defined by the two conditions

$$V(v_c, T_c) = V(\phi = 0, Tc)$$

$$\frac{\partial V(\phi, T)}{\partial \phi}\,\Big|_{\phi = v_c} = 0$$

Example 1 : Effective Potential Electroweak phase transition

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

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

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

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

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

Example 1 : Effective Potential Trilinear coupling

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

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

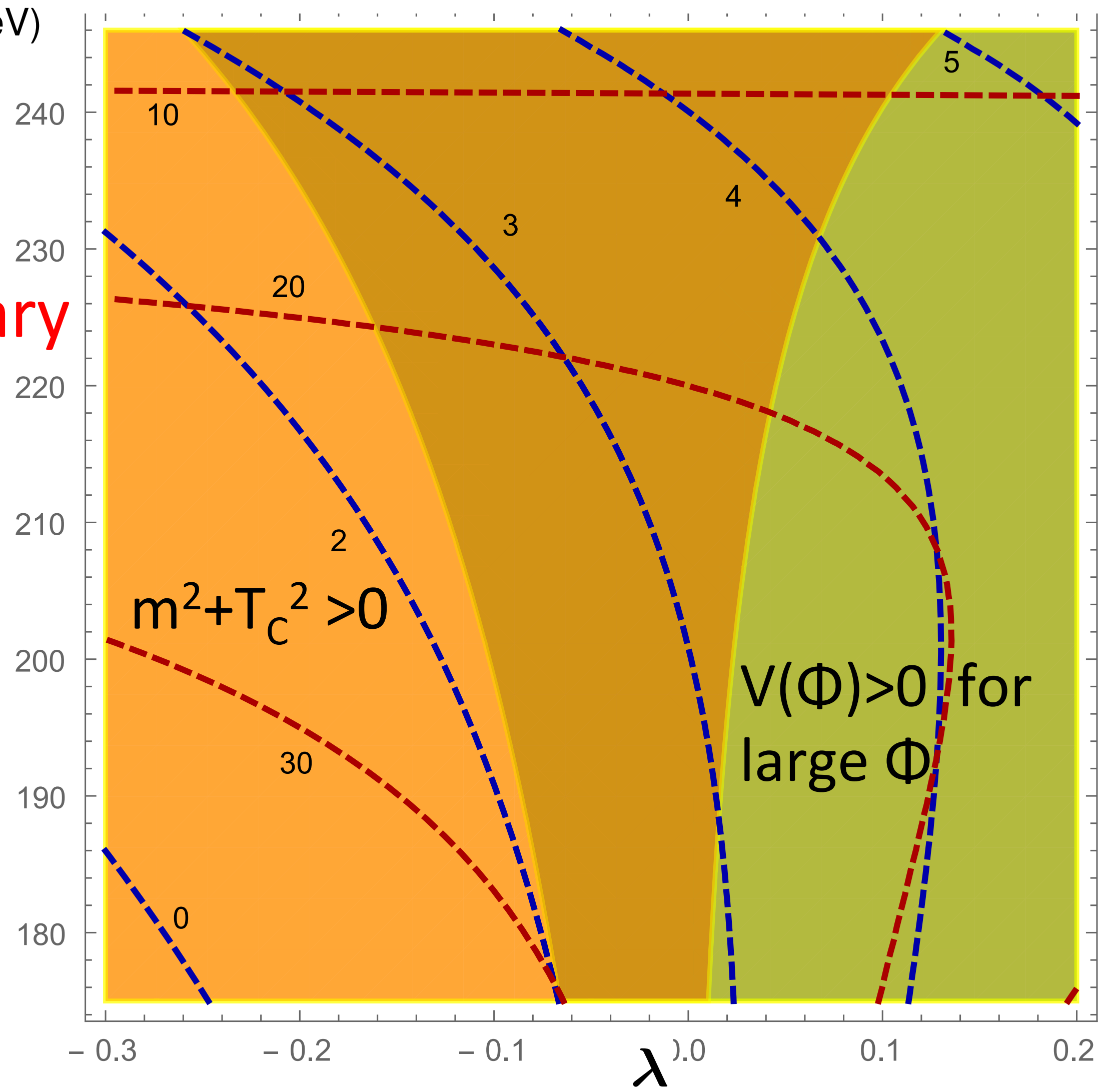
$$\kappa = \frac{m_h^2}{4v^4 - \frac{8}{3} v_c^2 v^2} > 0 \Rightarrow v_c < v$$

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

$$\lambda^3_{max} = \lambda^3_{SM}(1 + \frac{8}{3}\frac{\kappa_{max} v^4}{m_h^2}) = 3\lambda_{SM}$$

Example 1 : Effective Potential Trilinear coupling, Φ^8

Preliminary



$$\lambda^3_{max} = 5\lambda^3_{SM}$$

T_c $\frac{\lambda^3}{\lambda^3_{SM}}$

For a Φ^{10} theory,

$$\lambda^3_{max} \sim 7\lambda^3_{SM}$$

Example 2: NMSSM

MSSM is lovely, but

- The μ problem

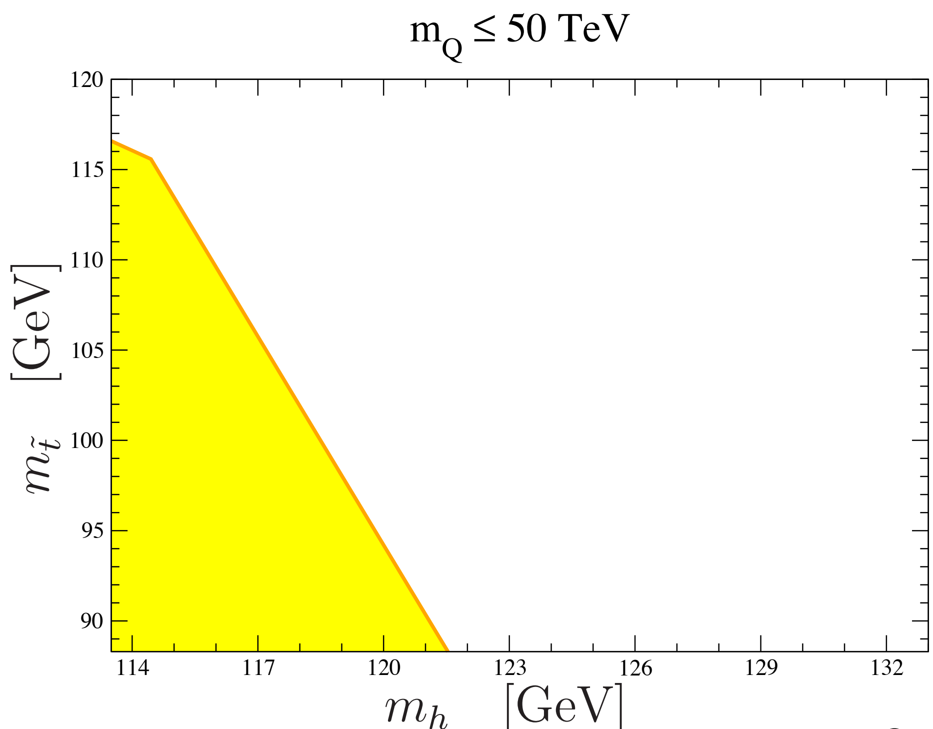
$$W \supset \mu H1 \cdot H2$$

  - $\mu \sim m_{weak}$ is needed to break the electroweak symmetry
  - why not $\mu \sim m_P$ or m_{GUT}?
- Higgs mass
  - At tree level, $m_h^2 < m_Z^2 \cos^2 2\beta$.
  - from the LHC, $m_h = 125.19$ GeV
- Electroweak Baryogengesis
  - It is difficult to obtain strong first order phase transition as required in electroweak baryogengesis.

Example 2: NMSSM
EWPT in MSSM

$$V(\phi, T) \sim \frac{1}{2}(m^2 + aT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3$$

In MSSM(and also SM), E is related to the bosonic loop.



Carena, Nardini ,Quiros, Wagner, 2012

Example 2: NMSSM

Adding a singlet S:
replace the μ term with a singlet S that gets a VEV

$$W \supset \lambda S H_1 \cdot H_2$$

- The μ problem

$$\mu_{eff} = \lambda < S >$$

- Higgs mass

$$m_h^2 < m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

- Electroweak Phase Transition: The $SH_1 \cdot H_2$ term can make the electroweak phase transition more strongly first order.

Example 2: NMSSM

NMSSM Superpotential

Panagiotakopoulos, Pilaftsis

$$W = \lambda S H_1 \cdot H_2 + \frac{m_{12}^2}{\lambda} S + W_{MSSM}.$$

The singlet self-couplings are forbidden by a Z_5^R or Z_7^R symmetry.
Has neither problems with the stability of the hierachy nor with the domain walls

Example 2 : NMSSM
Electroweak phase transition

Consider the effective tree-level potential, including the leading thermal corrections:

$$V(\phi, T) = (m^2 + aT^2)\phi^2 + \tilde{\lambda}^2\phi^4 + m_s^2\phi_s^2 + 2t_s\phi_s + 2\tilde{a}\phi^2\phi_s + \lambda^2\phi^2\phi_s^2$$

Along the trajectory $\frac{\partial V}{\partial \varphi_S} = 0$

$$V(\phi, T) = (m^2 + aT^2)\phi^2 + \tilde{\lambda}^2\phi^4 - \frac{(t_s + \tilde{a}\phi^2)^2}{m_s^2 + \lambda^2\phi^2}$$

Example 2 : NMSSM
Electroweak phase transition

Solve for T_c and v_c

$$v_c^2 = \frac{1}{\lambda^2}(-m_s^2 + \frac{1}{\tilde{\lambda}}|m_s \tilde{a} - \frac{\lambda^2 t_s}{m_s}|)$$

$$T_c^2 = (F(v_c^2) - F(v^2))/a$$

$$F(\phi^2) = 2\tilde{a}(\frac{t_s + \tilde{a}\phi^2}{m_s^2 + \lambda^2\phi^2}) - \lambda^2(\frac{t_s + \tilde{a}\phi^2}{m_s^2 + \lambda^2\phi^2})^2 - 2\tilde{\lambda}^2\phi^2$$

Condition for first-order phase transition:

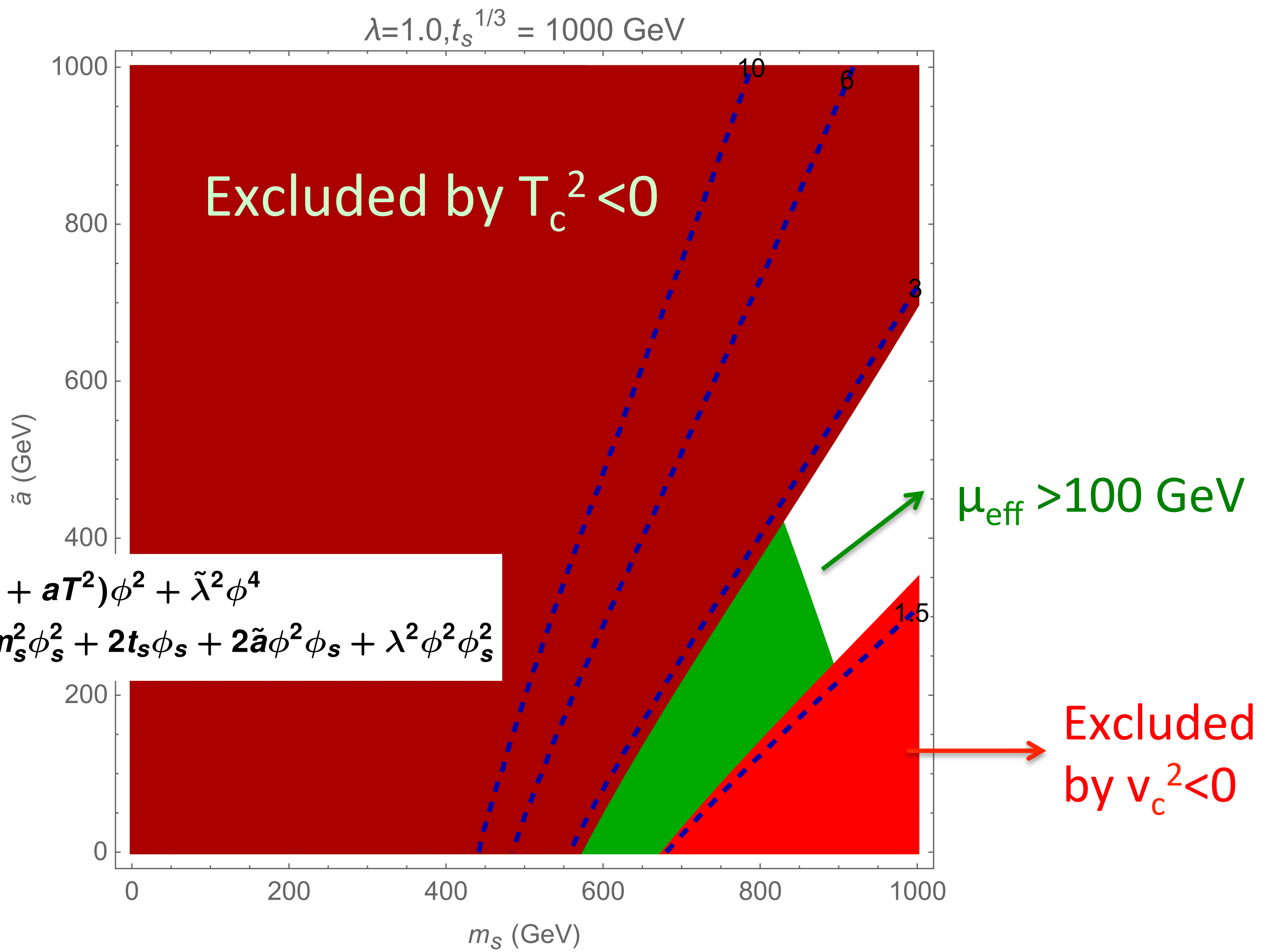
$$m_s^3 < \frac{1}{\tilde{\lambda}}|m_s^2 - a_\lambda \sin\beta\cos\beta\lambda^2 t_s|$$

Example 2 : NMSSM
Trilinear coupling

$$\lambda^3 = \lambda^3_{SM}\left(1 + \frac{16\lambda^2 v^4 (a_\lambda \sin\beta\cos\beta m_s^2 - t_s\lambda^2)^2}{m_h^2 (m_s^2 + v^2\lambda^2)^4}\right)$$

- require first-order phase transition,
  - $T_c \to 0$, $\lambda^3 \sim 3\lambda^3_{SM}$
  - $v_c \to 0$, $\lambda^3 \sim 1.3\lambda^3_{SM}$

Example 2 : NMSSM, Preliminary



$$V(\phi, T) = (m^2 + aT^2)\phi^2 + \tilde{\lambda}^2\phi^4 + m_s^2\phi_s^2 + 2t_s\phi_s + 2\tilde{a}\phi^2\phi_s + \lambda^2\phi^2\phi_s^2$$

Other Examples

- 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

Trilinear coupling and Electroweak phase transition

- For a simplified theory

$$V(\phi, T) = \frac{m(T)^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{\kappa}{6}\phi^6 + \frac{\eta}{8}\phi^8 + \frac{\zeta}{10}\phi^{10}$$

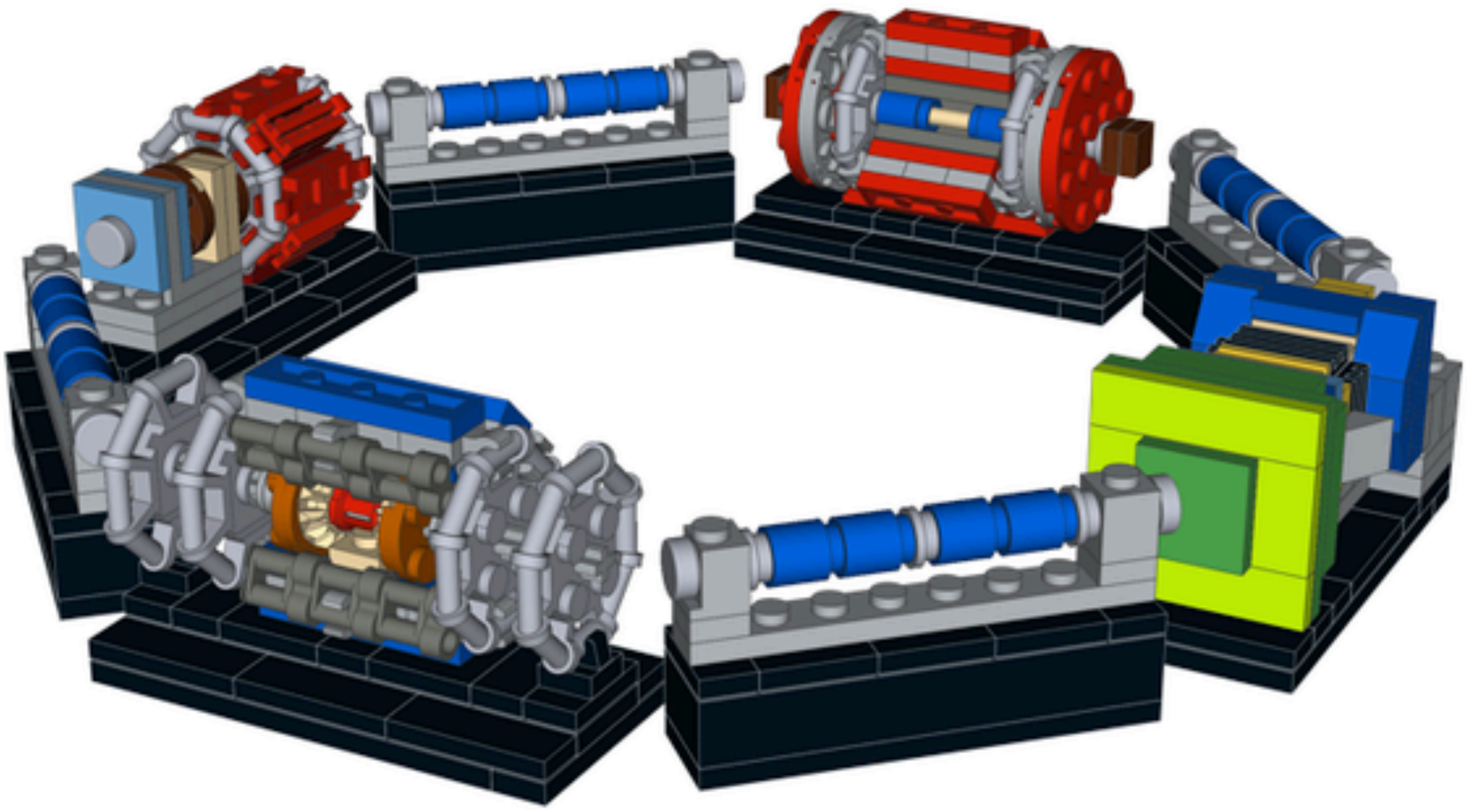
$$\lambda^3_{max} \sim 7\lambda^3_{SM}$$

- For NMSSM,

$$V(\phi, T) = (m^2 + aT^2)\phi^2 + \tilde{\lambda}^2\phi^4 + m_s^2\phi_s^2 + 2t_s\phi_s + 2\tilde{a}\phi^2\phi_s + \lambda^2\phi^2\phi_s^2$$

$$\lambda^3_{max} \sim 3\lambda^3_{SM}$$

Probe the trilinear coupling at the LHC



Probe the trilinear coupling at the LHC 50% precision on λ^3?

One sometimes encounters the claim that a ~ 50% precision on λ^3 can be achieved from the HH->bbγγ channel alone

Table 1-22. *Signal significance for $pp \to HH \to bb\gamma\gamma$ and percentage uncertainty on the Higgs self-coupling at future hadron colliders, from [102].*

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

Higgs working group report, 1310.8361

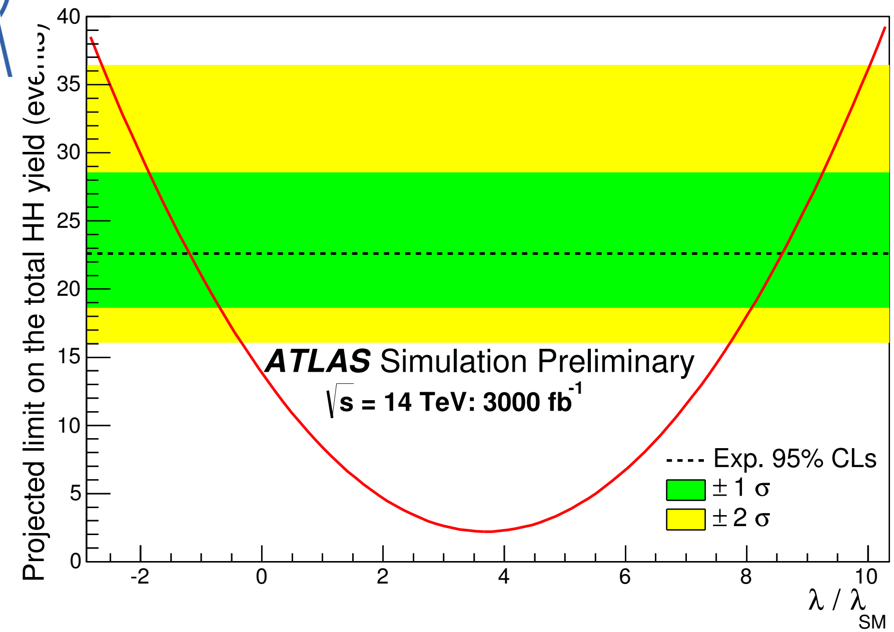
Probe the trilinear coupling at the LHC
Not that optimistic according to ATLAS

ATLAS NOTE

ATL-PHYS-PUB-2014-019

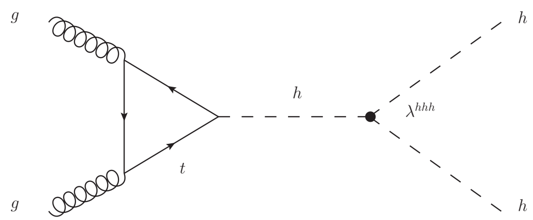
21st October 2014

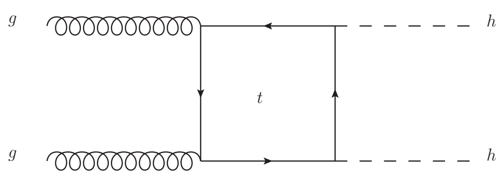
Prospects for measuring Higgs pair production in the channel $H(\to \gamma\gamma)H(\to b\bar{b})$ using the ATLAS detector at the HL-LHC

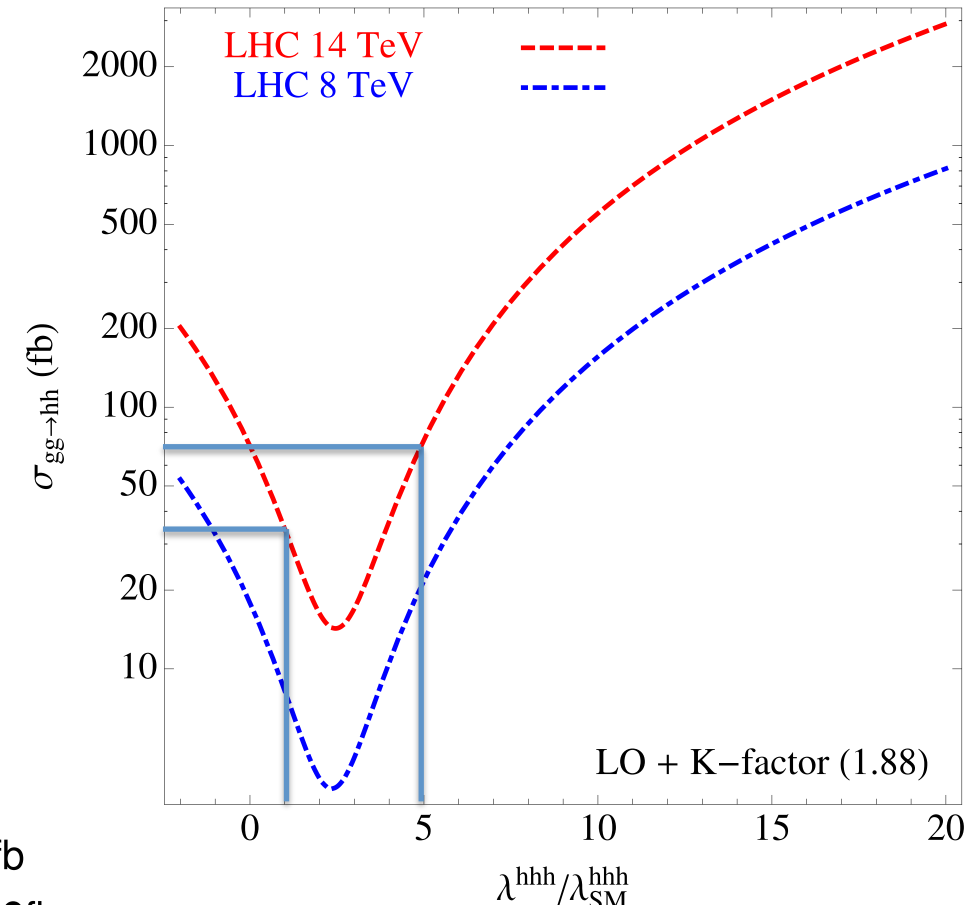


The projections of the analysis described in the note foresee an exclusion at 95% C.L. of BSM models with $\lambda/\lambda_{SM} \lesssim -1.3$ and $\lambda/\lambda_{SM} \gtrsim 8.7$.

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

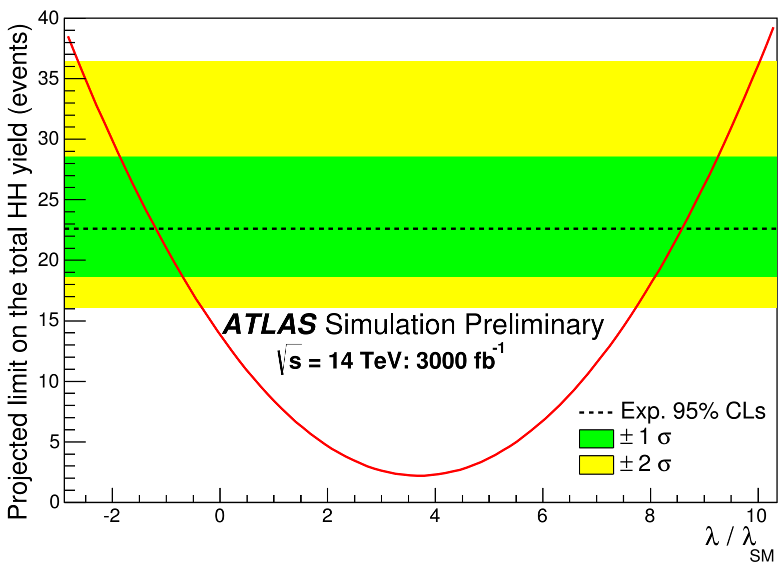
De Florian and Mazzitelli, Grigo, Melnikov, and Steinhauser

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

Probe the trilinear coupling at the LHC
Acceptance goes down for large λ^3

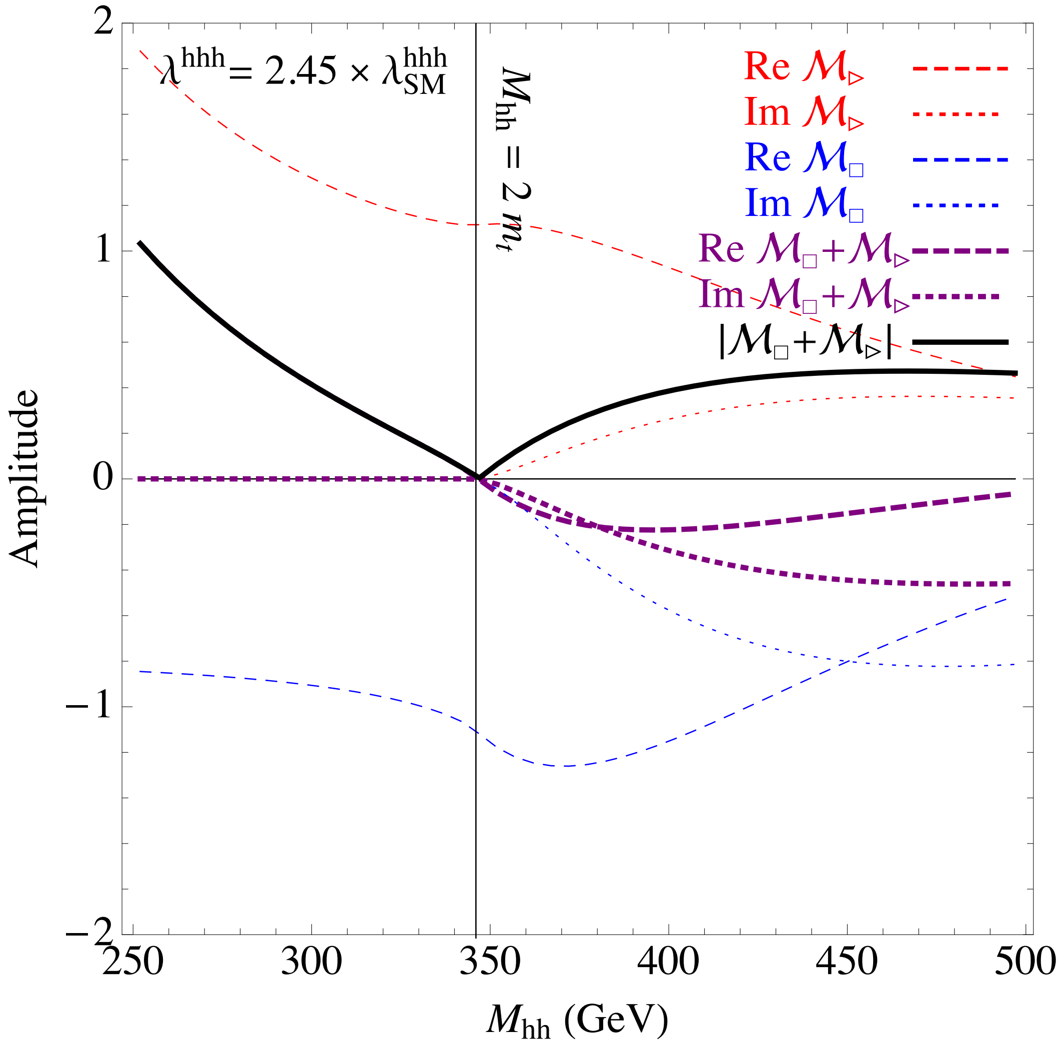
Event Selection Criteria ATL-PHYS-PUB-2014-019
≥ 2 isolated photons, with $p_T > 30$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$
≥ 2 jets identified as b-jets with leading/subleading $p_T > 40/25$ GeV, $\|\eta\| < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\|\eta\| < 2.5$
< 6 jets with $p_T > 25$ GeV, $\|\eta\| < 2.5$
$0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}$, $p_T^{b\bar{b}} > 110$ GeV

Cut on m_{hh}



$m_{hh} > 350$ GeV is required in the Snowmass study

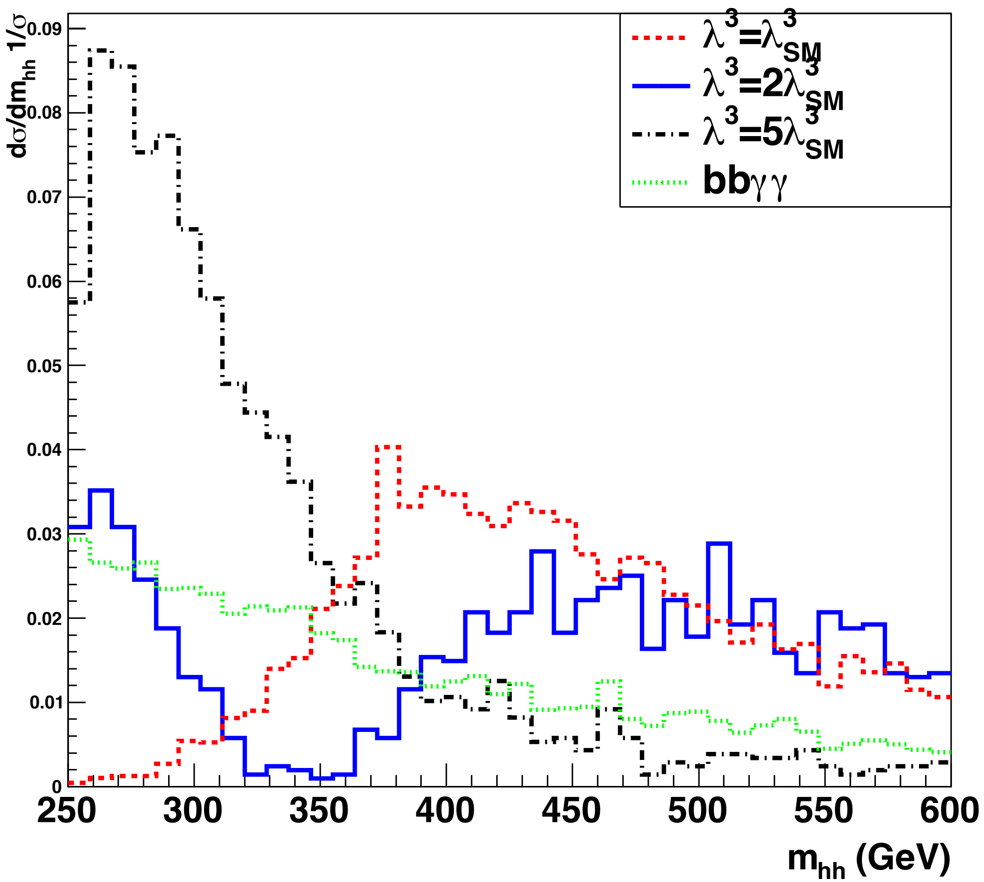
Probe the trilinear coupling at the LHC
Production cross section



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 does not occur
- When λ^3 increases, the amplitudes 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



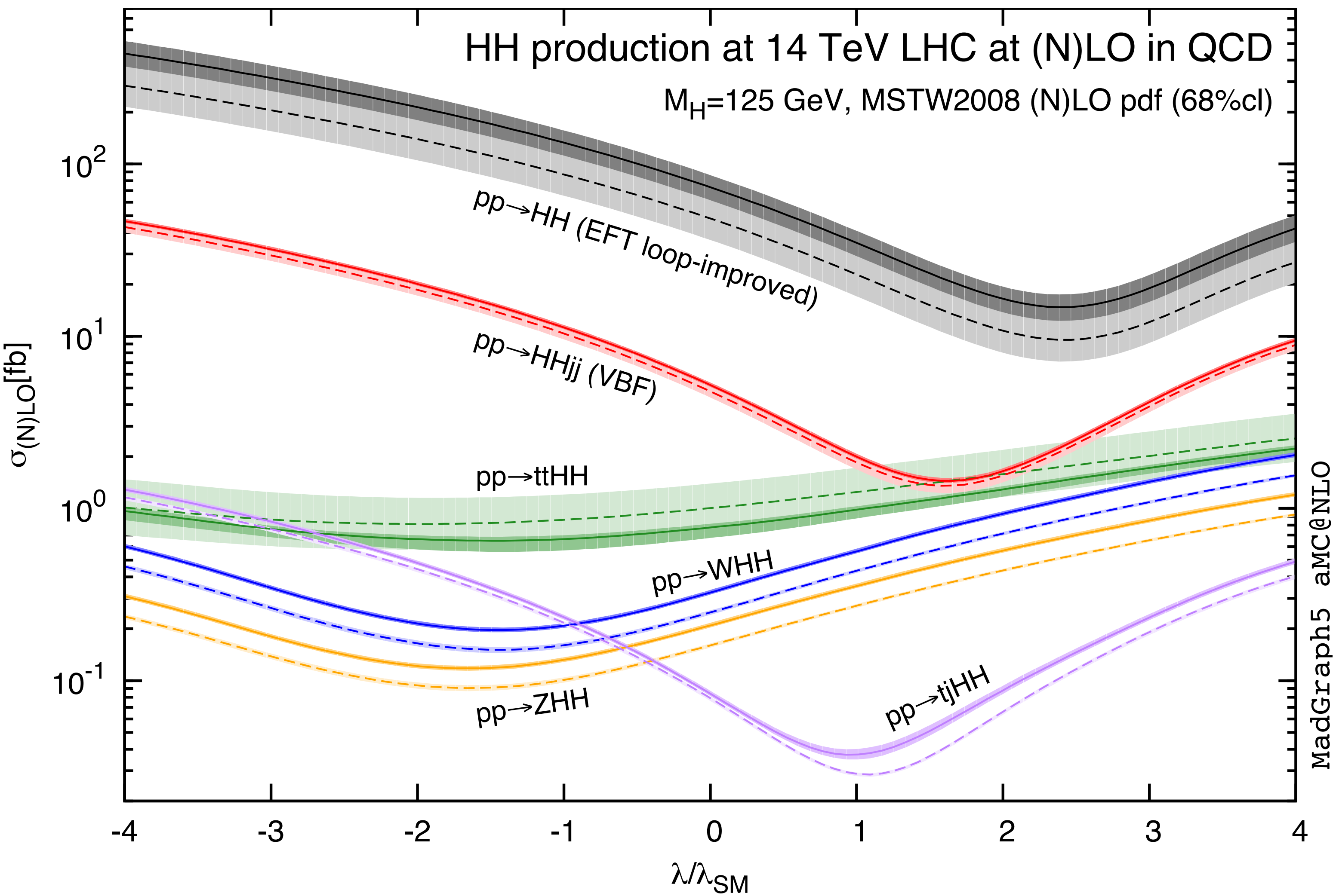
Parton level, MCFM

- Re-design the cuts for large λ^3
- The Snowmass study is too optimistic – assuming the acceptance stays the same

Probe the trilinear coupling at the LHC Preliminary results

- Remove the cuts related to m_{hh} in the ATLAS study
- m_{hh} is weakly related to other cuts
- Apply a cut of 250 GeV < m_{hh} < 350 GeV
- Expect 14 events (3 in the ATLAS projection) for $\lambda^3 = 5\lambda^3_{SM}$
- Background (bbγγ) goes up by a little more than a factor of 2
- Get a similar significance for $\lambda^3 = 5\lambda^3_{SM}$ to SM with the ATLAS cuts

Probe the trilinear coupling at the LHC
Other channels?



Probe the trilinear coupling at the LHC Future colliders?

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

	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

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. Detailed study is needed