Title: Exploring new physics through double Higgs production

Date: Feb 20, 2015 03:30 PM

URL: http://pirsa.org/15020131

Abstract: <p>The Higgs boson was discovered at the LHC more than two years ago.
So far, the LHC data is consistent with the Standard Model (SM)
predictions. Given its increased rate in the next run of the LHC
with a center-of-mass energy of 14 TeV, double Higgs production will
become an important channel in the search for deviations from the SM
due to new heavy particles. The study of double Higgs production is
also important for understanding the structure of the scalar potential.
In this talk, I will review the production mechanism of double Higgs
production in the SM and consider a model with an additional singlet scalar.
I'll discuss the size of the corrections to single and double Higgs production
in this model and the search for regions of parameter space where double
Higgs production is enhanced relative to the SM prediction.</p>

Exploring new physics through double Higgs production

Chien-Yi Chen

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C.-Y.C., S. Dawson, I. Lewis. [arXiv:hep-ph:1410.5488]

PERIMETER INSTITUTE
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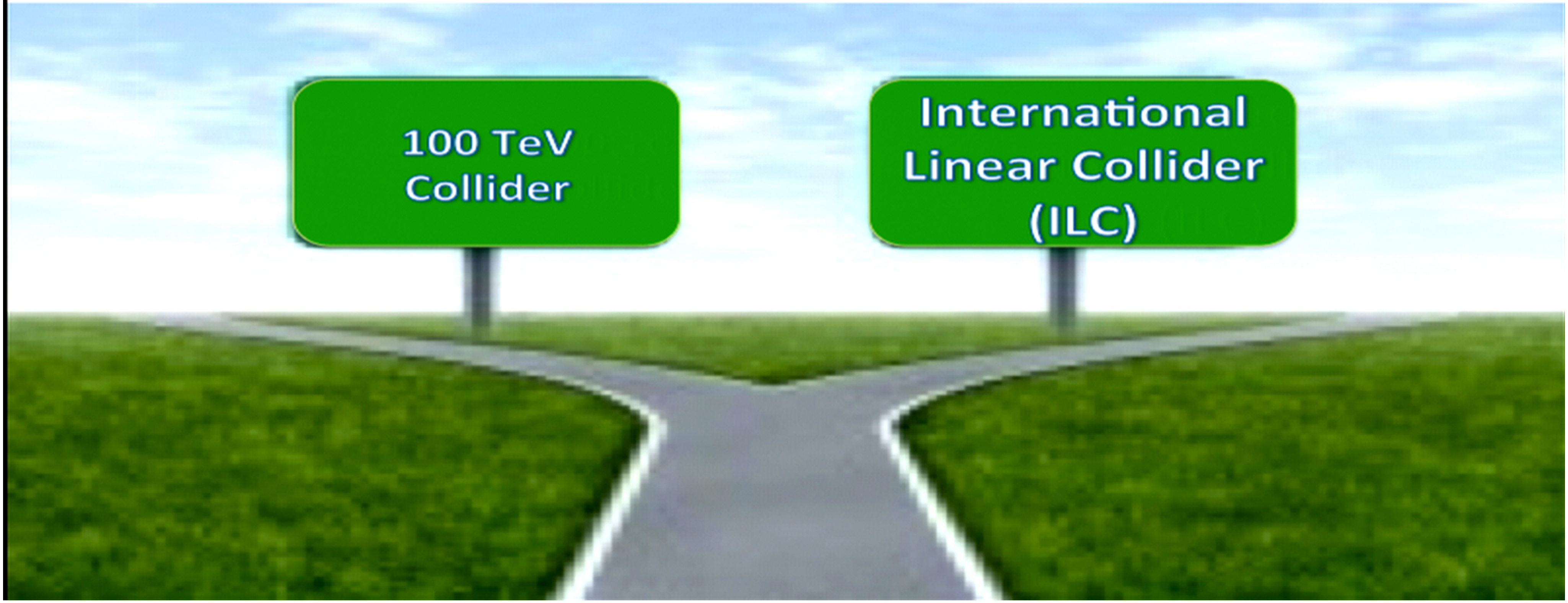
February 20, 2015

Major scientific Breakthrough: Higgs discovery!!

- **Where:** CERN, Large Hadron Collider (LHC)
- **When:** July 4, 2012
- **Scientific impact:** explain the origin of mass

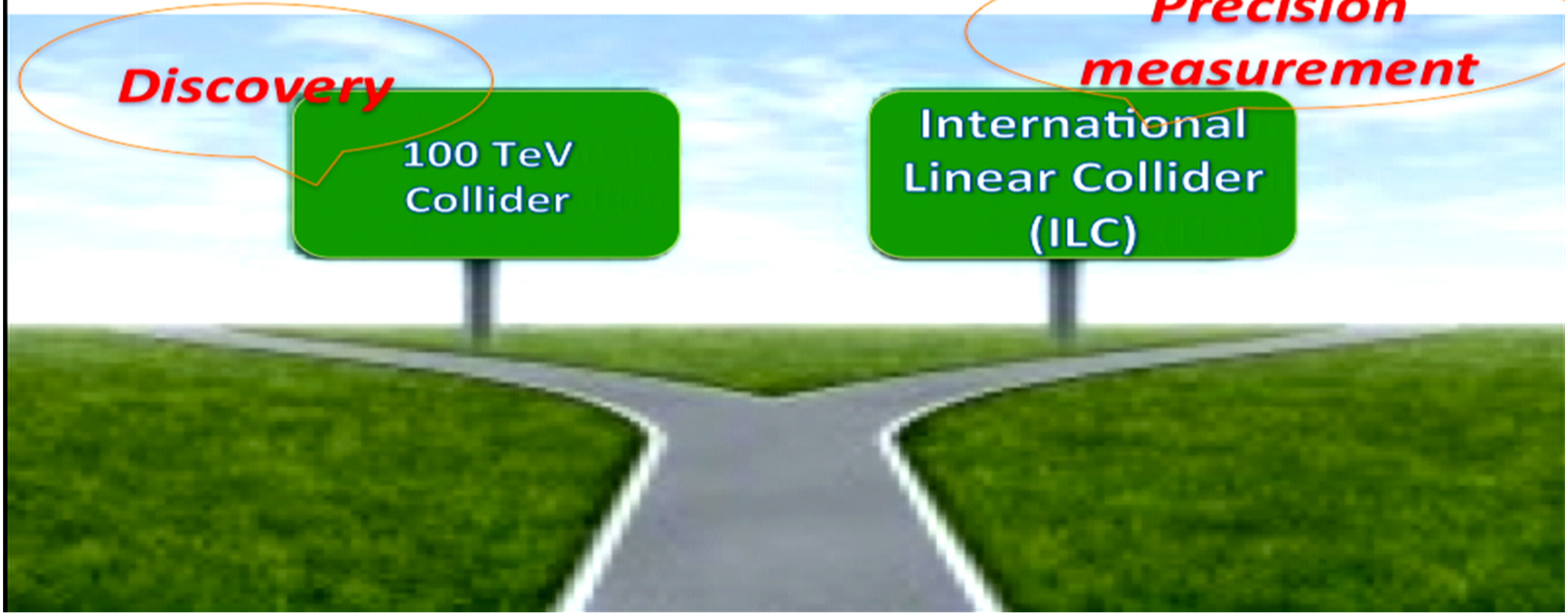
Next Step

- We have found the Higgs boson, what's next?



Next Step

- Discovery: to find new heavy particles, such as top partners or heavy Higgs bosons …



Motivations

- At high energy pp colliders, we can do both
  - Discovery
  - Precision measurement of Higgs self couplings
- Address one of the most fundamental issues, the origin of the electroweak symmetry breaking.
- Connection to electroweak baryogenesis
- Enhancement of total cross section in new physics models

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Outline

- Higgs potential in SM
  - Coupling measurement
- Double Higgs production in
  - Standard Model
    - Self-coupling measurement
  - Singlet model (main focus) [CC, Dawson and Lewis, 1410.5488]
    - Constraints on parameters
    - Enhancement of total cross section
  - Two Higgs doublet model (type II)
    - Enhancement of total cross section

[Baglio et. al., 1403.1264]

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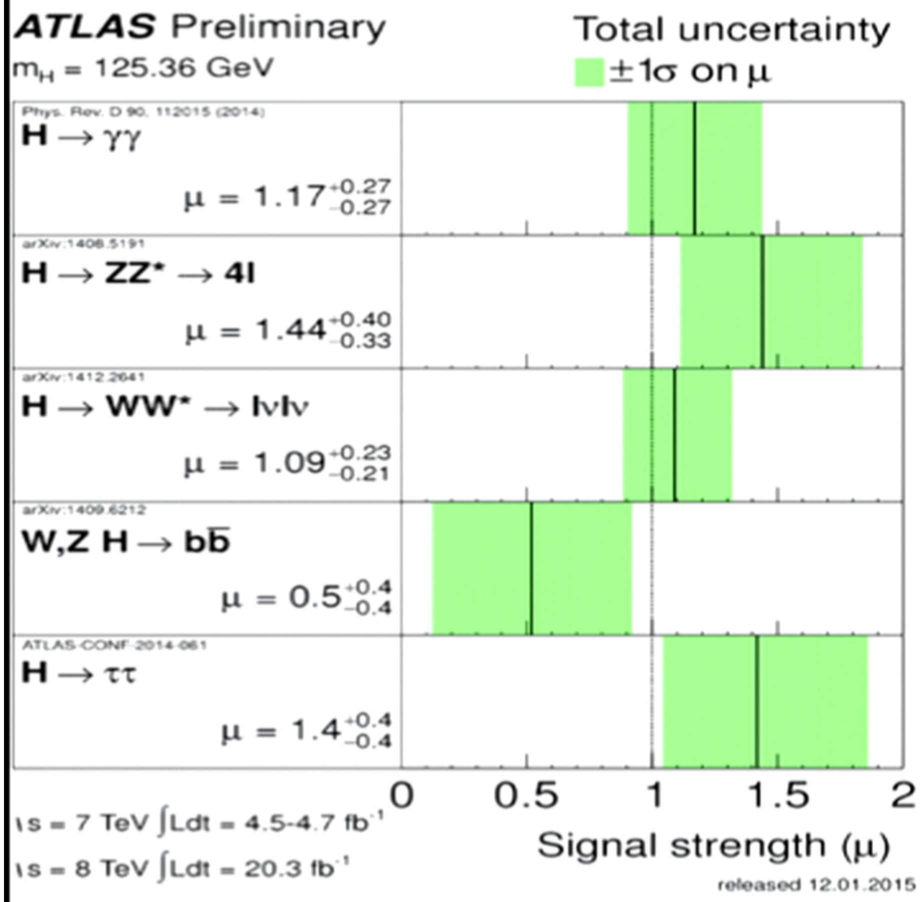
[Baglio et. al., 1403.1264]

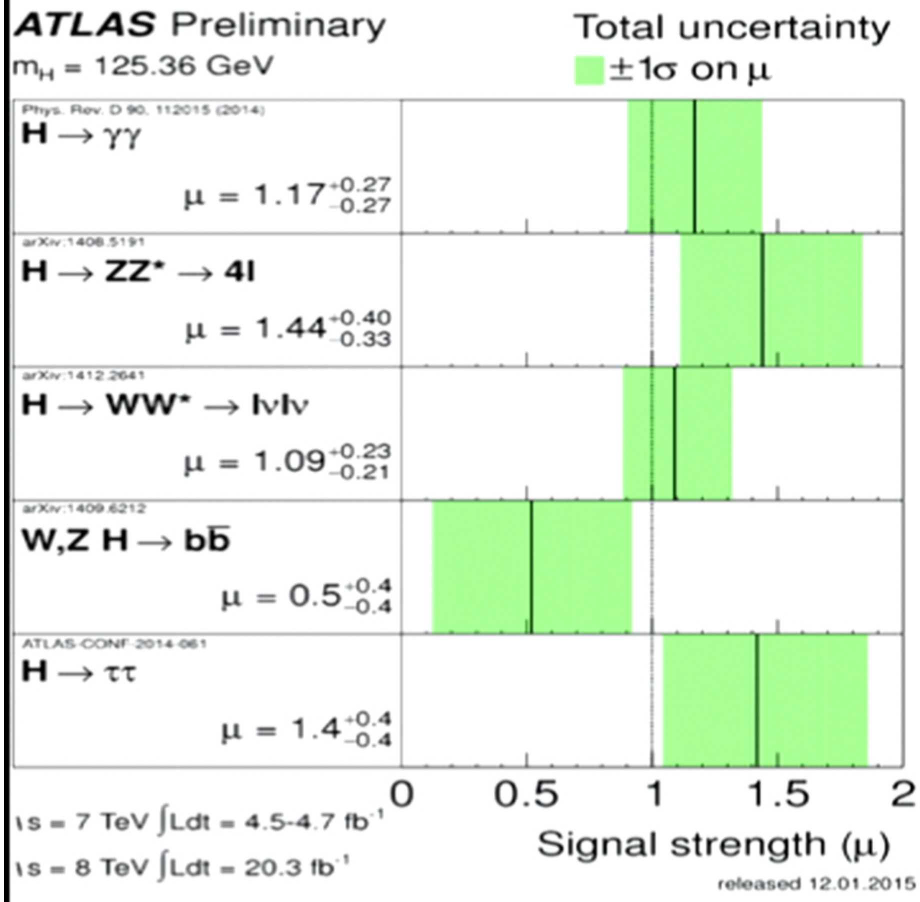
Higgs Data: signal strength

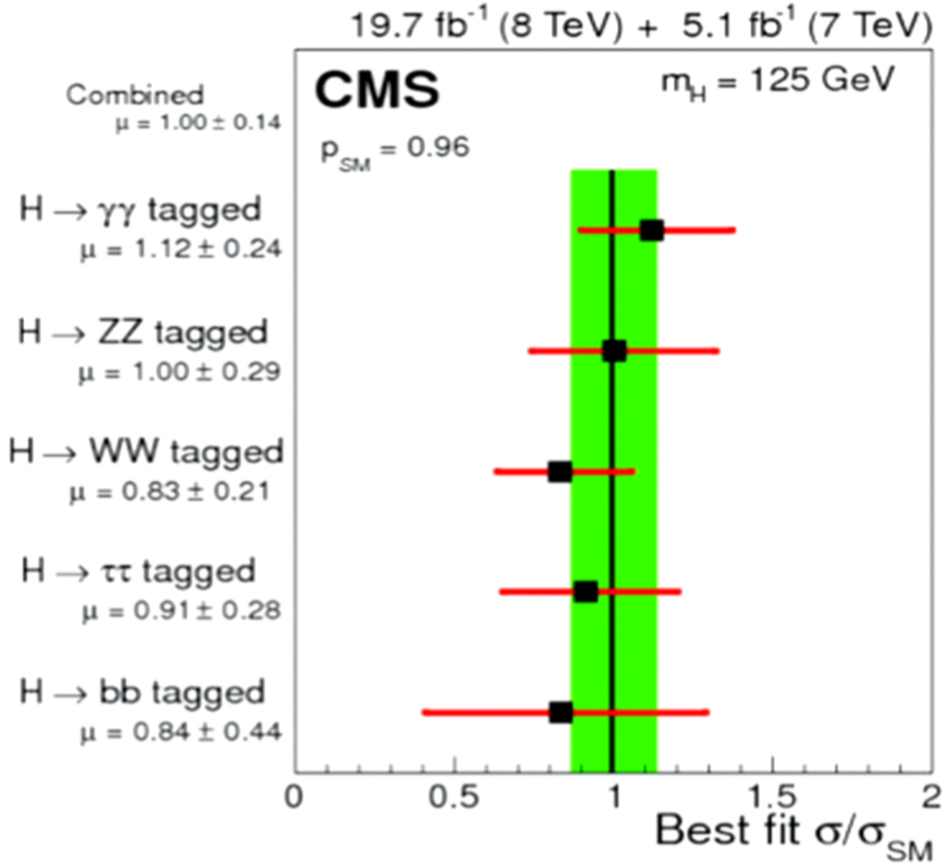


$$\mu \equiv \frac{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \mathsf{decay})|_{\mathrm{observed}}}{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \mathsf{decay})|_{\mathrm{SM}}}$$

- $\mu = 1$: Standard Model Higgs
- Measuring deviations of the couplings from the SM

Higgs Data: signal strength





[arXiv:1412.8662]

Theory overview

- Scalar potential in SM

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

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ H + v \end{pmatrix},$$ in unitary gauge

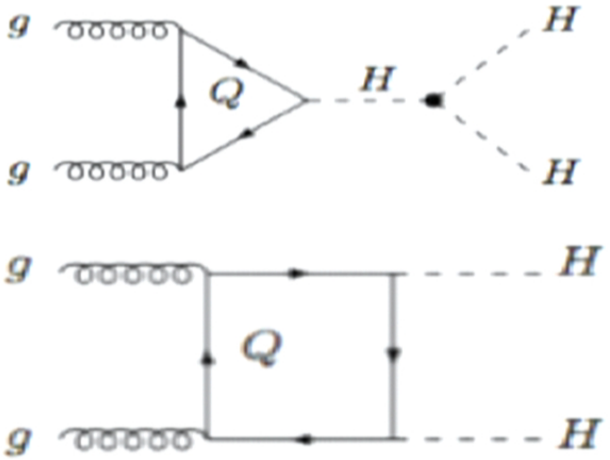
$$V \supset \tfrac{1}{2}m_H^2 H^2 + \tfrac{1}{3!}\lambda_{HHH}H^3 + \tfrac{1}{4!}\lambda_{HHHH}H^4$$

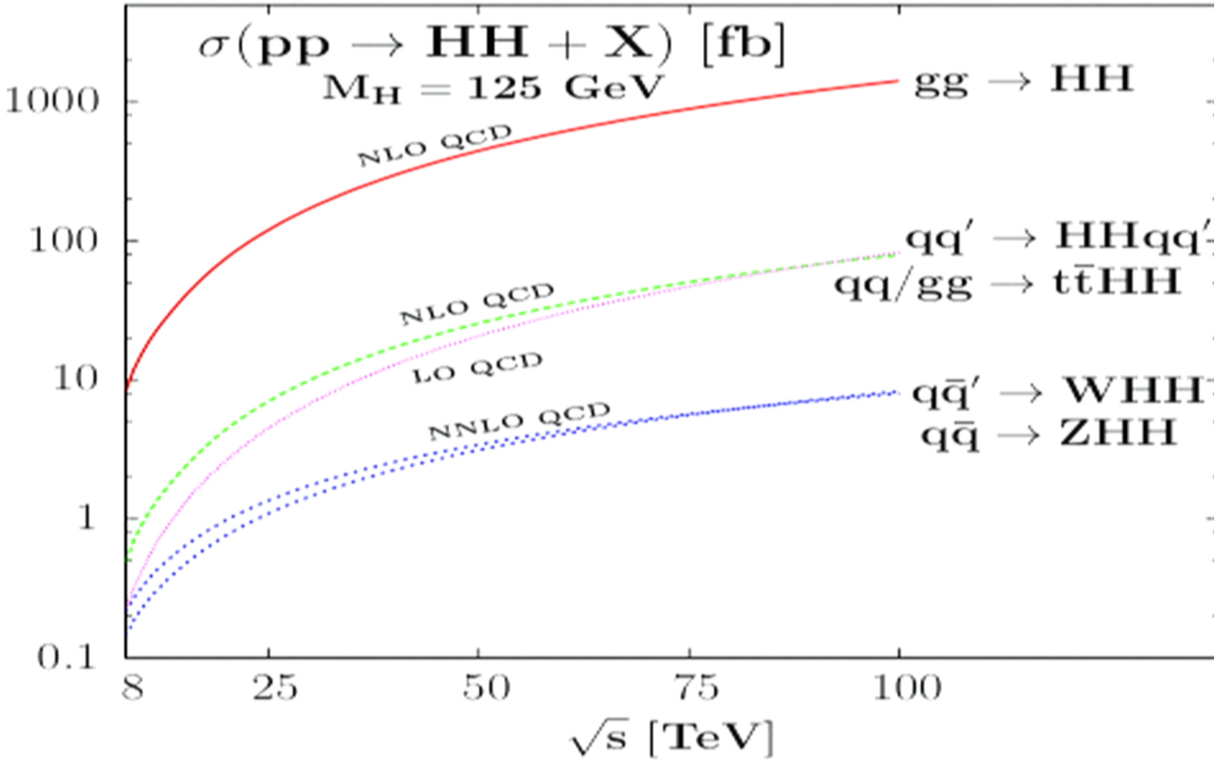
- SM predictions

$$\lambda_{HHH} = \frac{3m_H^2}{v} \sim 190.5\ \mathrm{GeV} \qquad \lambda_{HHHH} = \frac{3m_H^2}{v^2} \sim 0.77$$

Di-Higgs production in SM

- Gluon fusion dominant:

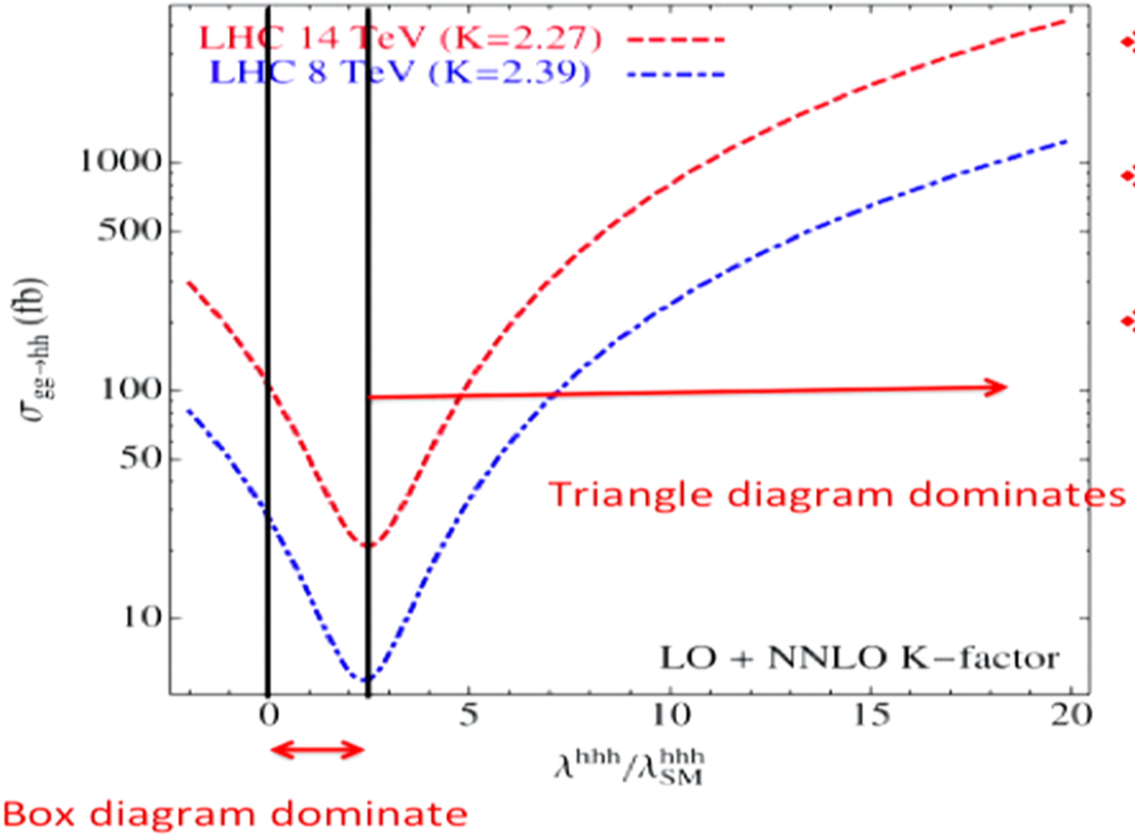




[Baglio et al, 1212.5581]

Di-Higgs production: variation of triple coupling

- Competition between the triangle and box diagrams.



- Destructive interference between two diagrams
- Minimum occurs at $\lambda_{hhh} = 2.45 \times \lambda^{hhh}_{SM}$
- SM corresponds to $\lambda^{hhh}/\lambda^{hhh}_{SM} = 1$, box diagram dominates

[Barger et al., Phys. Lett. B728,433]

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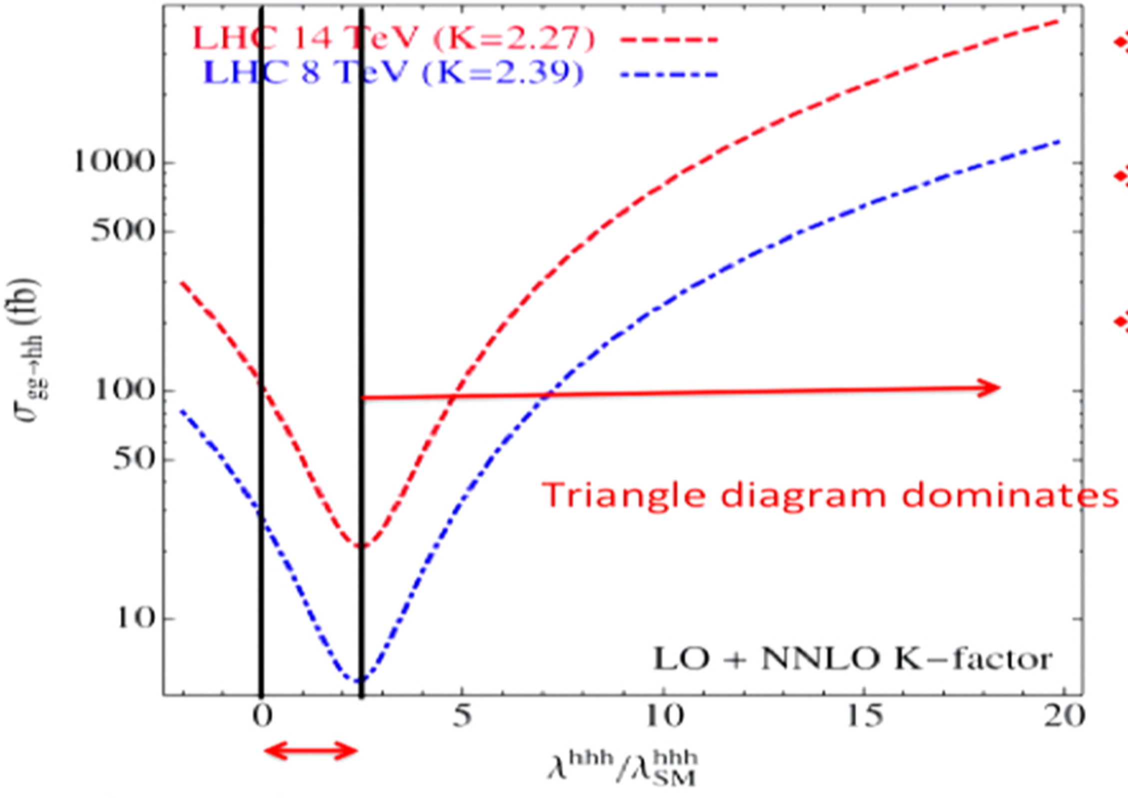

Triangle diagram dominates

Box diagram dominate

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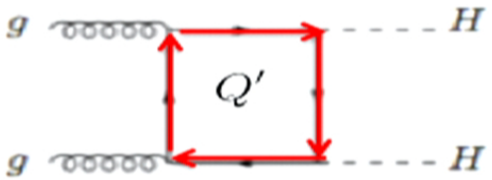
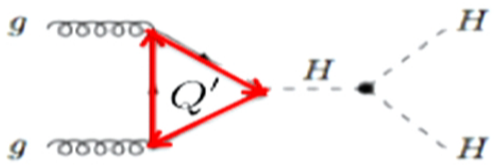
How new physics comes into di-Higgs production?

- **Example: 1)** Through new fermions (Q') loop

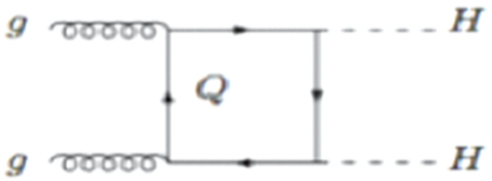


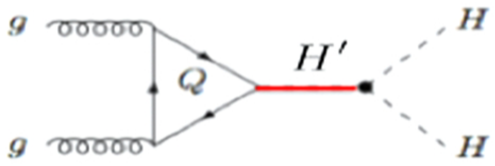


[Dawson et. al., 1210.6663]

[CC, Dawson and Lewis, 1406.3349]

- **Example: 2)** Through new scalars (H')





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[Dolan, et. al. 1210.8166]

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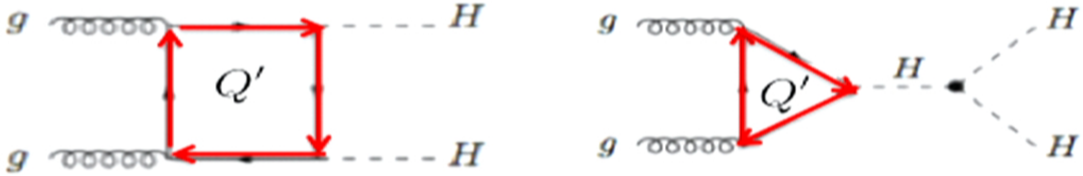

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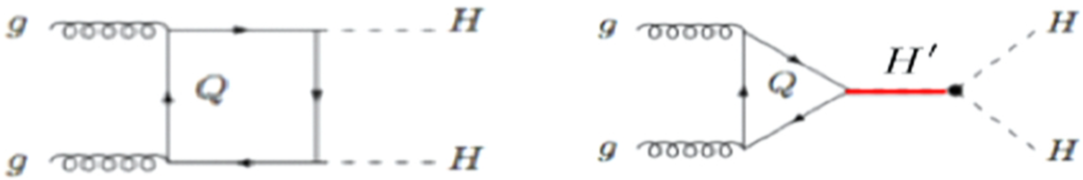

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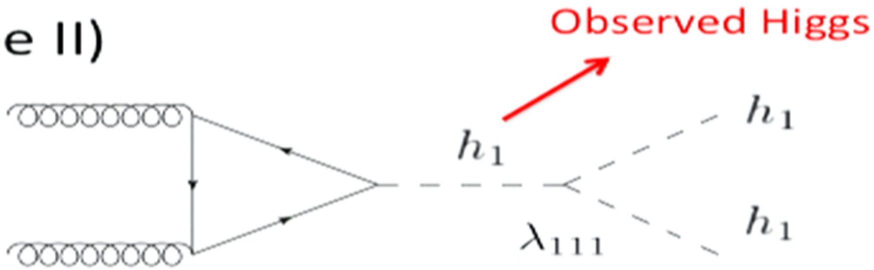
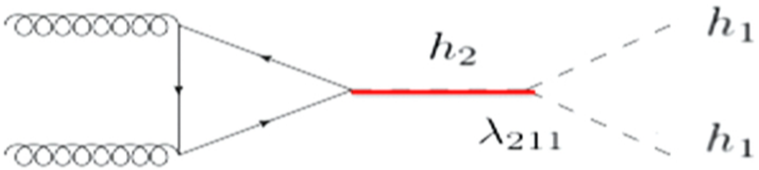
New physics models

- **New physics models**
  1. SM + Singlet
  2. Two Higgs doublet models (type II)





- Production cross section of di-Higgs can be enhanced due to the decay of heavy resonances

SM + Singlet

- SM Higgs doublet H mixed with an additional singlet S. The singlet doesn't couple to SM fermions and gauge bosons.

$$V = V_H + V_{HS} + V_S,$$

Keep it general.
No Z_2 symmetry!

SM + Singlet

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$$V = V_H + V_{HS} + V_S,$$

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

$$V_{HS}(H,S) = \frac{a_1}{2} \cancel{H^\dagger H} S + \frac{a_2}{2} H^\dagger H S^2$$

$$V_S(S) = \cancel{b_1} S + \frac{b_2}{2} S^2 + \cancel{\frac{b_3}{3} S^3} + \frac{b_4}{4} S^4$$

Z_2 symmetry:
S-> -S

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$$V = V_H + V_{HS} + V_S,$$

$$\begin{aligned} V_H(H) &= -\mu^2\, H^\dagger H + \lambda (H^\dagger H)^2 \\ V_{HS}(H,S) &= \cancel{\frac{a_1}{2}\, H^\dagger H\, S} + \frac{a_2}{2}\, H^\dagger H\, S^2 \\ V_S(S) &= \cancel{b_1 S} + \frac{b_2}{2} S^2 + \cancel{\frac{b_3}{3} S^3} + \frac{b_4}{4} S^4 \end{aligned}$$

Z_2 symmetry:
S-> -S

- After spontaneous symmetry breaking:

$$H \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h + v \end{pmatrix},$$ in unitary gauge

$$S \to S + x$$

SM + Singlet

- The scalar mass matrix can be written as

$$V_{\rm mass} = \frac{1}{2} U M^2 U^T, \text{ where } U = \begin{pmatrix} h & S \end{pmatrix}$$

$$\begin{aligned} M^2 &\equiv \begin{pmatrix} M^2_{11} & M^2_{12} \\ M^2_{12} & M^2_{22} \end{pmatrix} \\ &= \begin{pmatrix} 3\lambda v^2 - \mu^2 + x(a_1 + a_2 x)/2 & a_1 v/2 + a_2 v x \\ a_1 v/2 + a_2 v x & b_2 + a_2 v^2/2 + x(2b_3 + 3b_4 x) \end{pmatrix} \end{aligned}$$

$$\tan 2\theta = \frac{2M^2_{12}}{M^2_{11} - M^2_{22}}$$

- Off diagonal terms cannot be too big due to strong experimental constraints on the mixing angle

SM + Singlet

- Mass eigenstates and mixing angle:

$$h_1 = h\cos\theta + S\sin\theta$$
$$h_2 = -h\sin\theta + S\cos\theta$$

  - h_1 : the Higgs we observed; its couplings to fermions and gauge bosons are **universally suppressed by a factor of** $\cos\theta$.
  - h_2 : Heavy Higgs; its couplings to fermions and gauge bosons are **universally suppressed by a factor of** $\sin\theta$.

- Diagonalize the mass matrix to obtain the mass eigenvalues m_1 and m_2
- Using $m_1, m_2,$ and θ as input parameters instead of $\lambda, a_1,$ and b_2

Minimizing potential

- The minimum of the potential is obtained by requiring

$$\partial V(v,x)/\partial v = 0 \text{ and } \partial V(v,x)/\partial x = 0$$

➡

$$\frac{v}{\sqrt{2}}(-2\mu^2 + 2\lambda v^2 + a_1 x + a_2 x^2) = 0,$$

$$x(b_2 + b_3 x + b_4 x^2 + \frac{v^2}{2} a_2 x) + b_1 + \frac{v^2}{4} a_1 = 0.$$

- A shift of the singlet field by $S \rightarrow S + \Delta_S$ is just a redefinition of the parameters and does not change the physics.
- It is always possible to choose a solution $(v,x) = (\sqrt{\frac{\mu^2}{\lambda}}, 0)$ provided $b_1 = -\frac{v^2}{4} a_1$.

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Counting parameters

- Model parameters:

$$\mu, \lambda, a_1, a_2, b_1, b_2, b_3, \text{ and } b_4$$

- Phenomenological parameters:

$$m_1 = 126 \text{ GeV}, \; m_2, \; \theta, \; v_{EW} = 246 \text{ GeV}, \; x = 0, \; a_2, \; b_3, \; b_4$$

Experimental and theoretical constraints

- Constraints on mixing angle:
  - Collider
  - Electroweak precision measurements (STU)
- Unitarity (b_4)
- Vacuum stability (a_2)
- Require that global minimum is EW minimum (v,x)=(246,0) GeV. (a_2 and b_3)
- Direct collider searches of double Higgs production: production cross section

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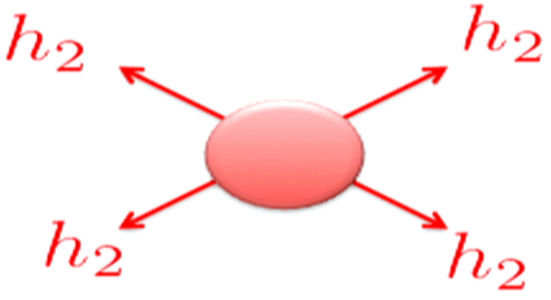
Unitarity

- Unitarity bound on b_4:
  - relevant coupling:

$$\lambda_{2222} = 6(s^2c^2a_2 + c^4b_4 + \lambda s^4)$$



High energy scattering of $h_2h_2 \to h_2h_2$.
The $J = 0$ partial wave is

$$|\mathrm{Re}\ \ a_0(h_2h_2 \to h_2h_2)| < \frac{1}{2}$$

$$|\mathrm{Re}\ \ a_0(h_2h_2 \to h_2h_2)| \xrightarrow[s>>m_2^2]{} \frac{3b_4}{8\pi}$$

$$\boxed{b_4 < 4.2}$$

Vacuum stability

- Vacuum stability requires the scalar potential to be positive definite as h and S become large.

λ and b_4 are positive definite

- For $a_2 > 0$

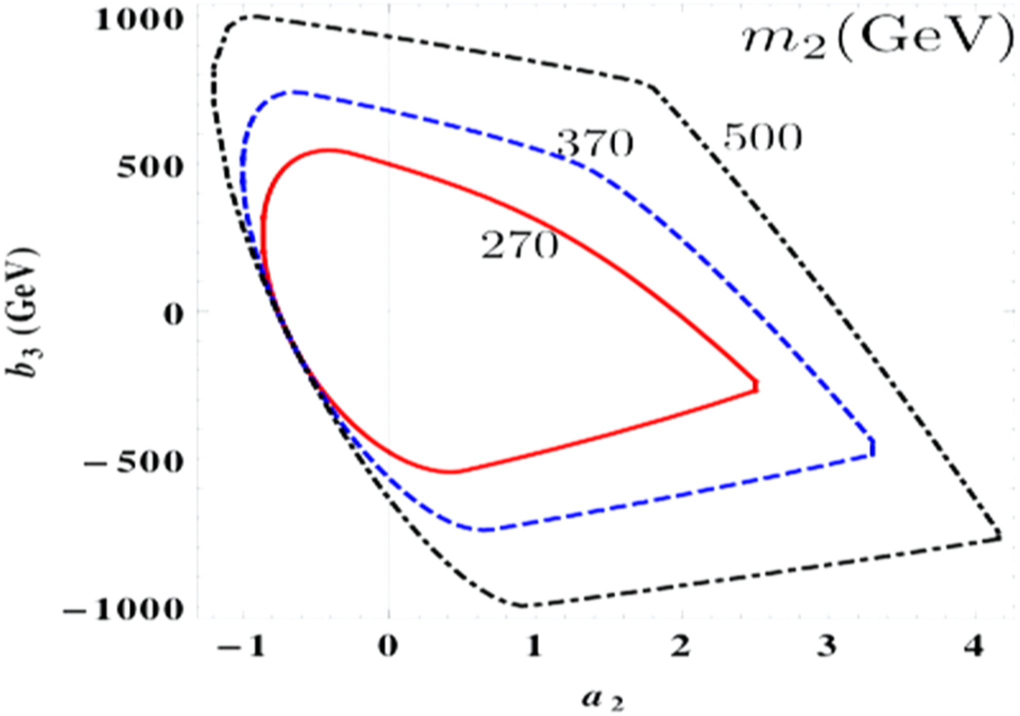
$$\lambda h^4 + a_2 h^2 S^2 + b_4 S^4 > 0 \quad \Rightarrow \quad a_2 < \infty$$

- For $a_2 < 0$

$$\boxed{(\sqrt{\lambda} h^2 + \frac{a_2}{2\sqrt{\lambda}} S^2)^2} + (b_4 - \frac{a_2^2}{4\lambda}) S^4 > 0 \quad \Rightarrow \quad -4\lambda b_4 < a_2$$

Positive definite

Constraints



- Requiring that the global minimum is at (v,x)=(246,0)GeV, for $m_2 = 270, 370,$ and 500 GeV
- Provides upper limits for a_2 for a given value of b_3

$$b_4 = 1$$
$$\cos\theta = 0.94$$
$$m_1 = 126 \text{ GeV}$$

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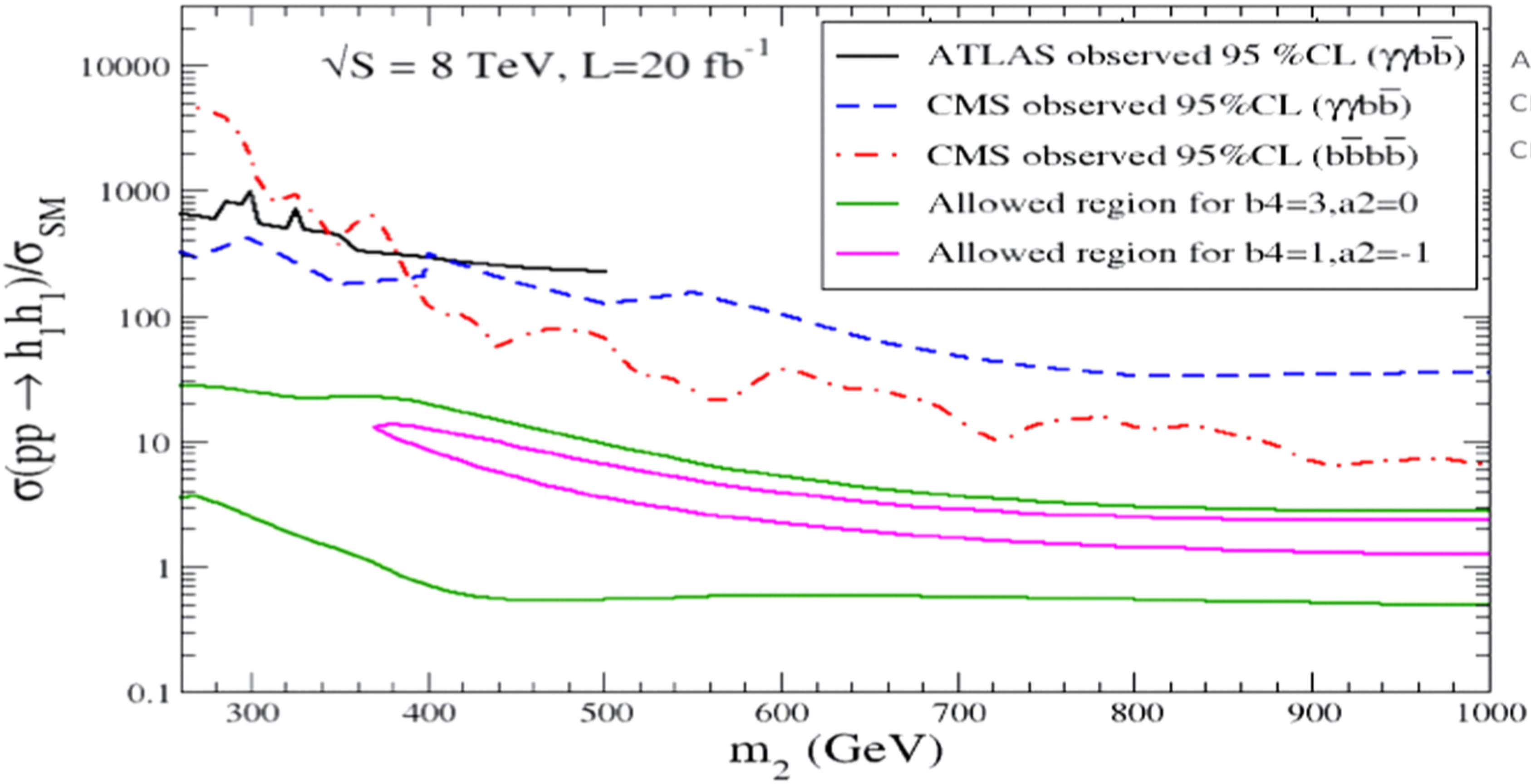
Positive definite

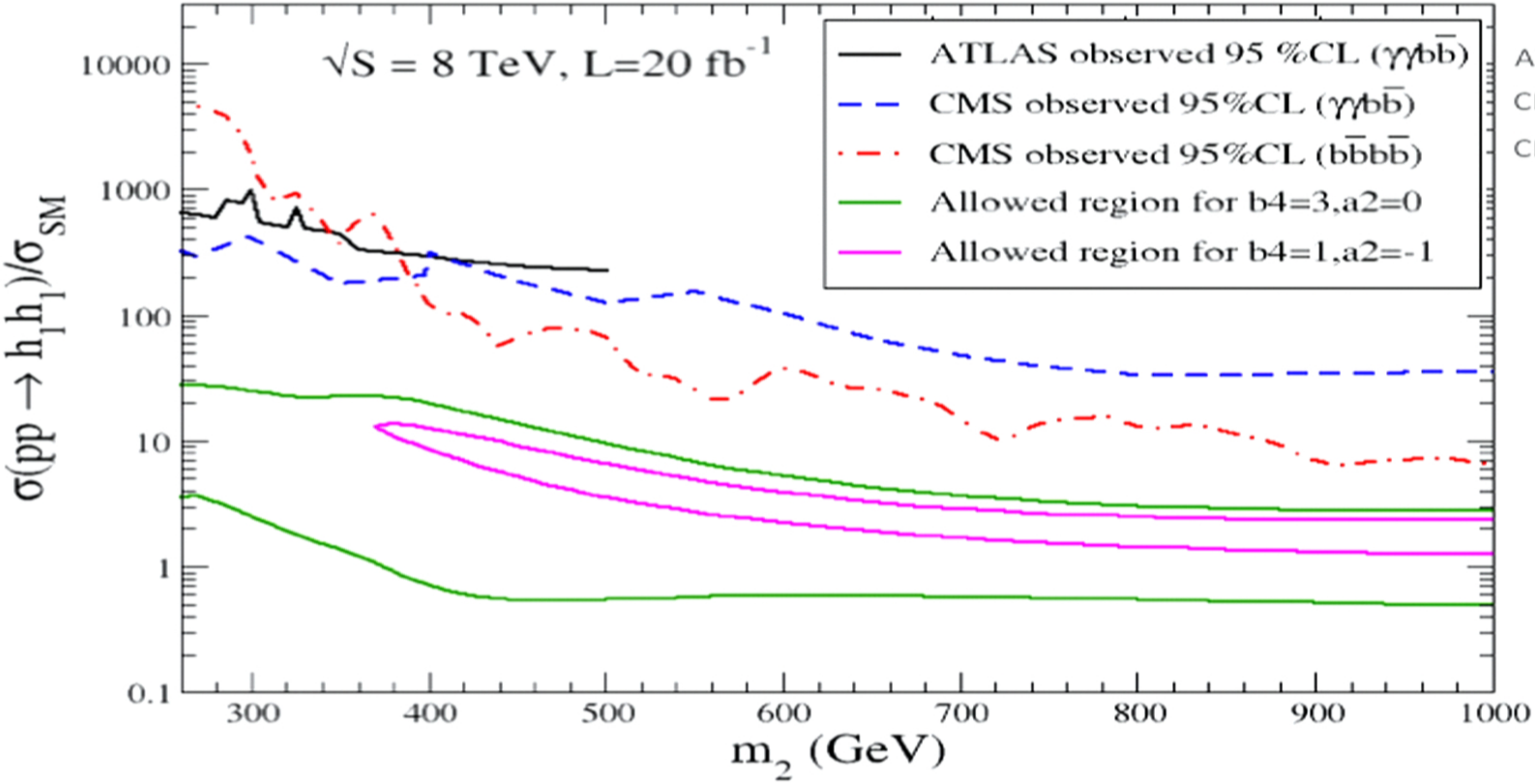
Collider constraints on cross section at 8 TeV



ATLAS, 1406.5053
CMS PAS HIG-13-032
CMS PAS HIG-13-013

- Production cross section of di-Higgs in the singlet model relative to the SM prediction at leading order

Collider constraints on cross section at 8 TeV



ATLAS, 1406.5053

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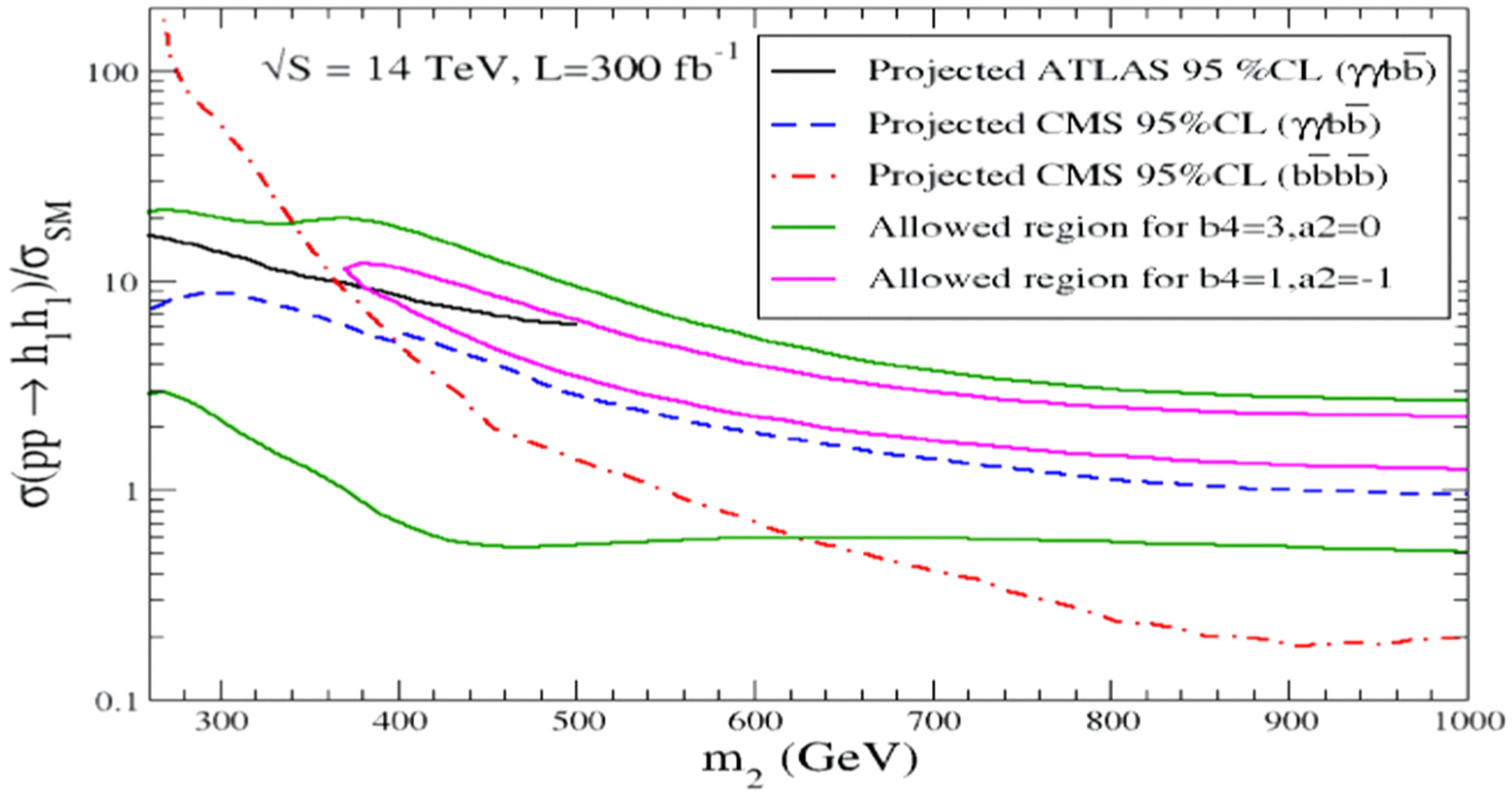
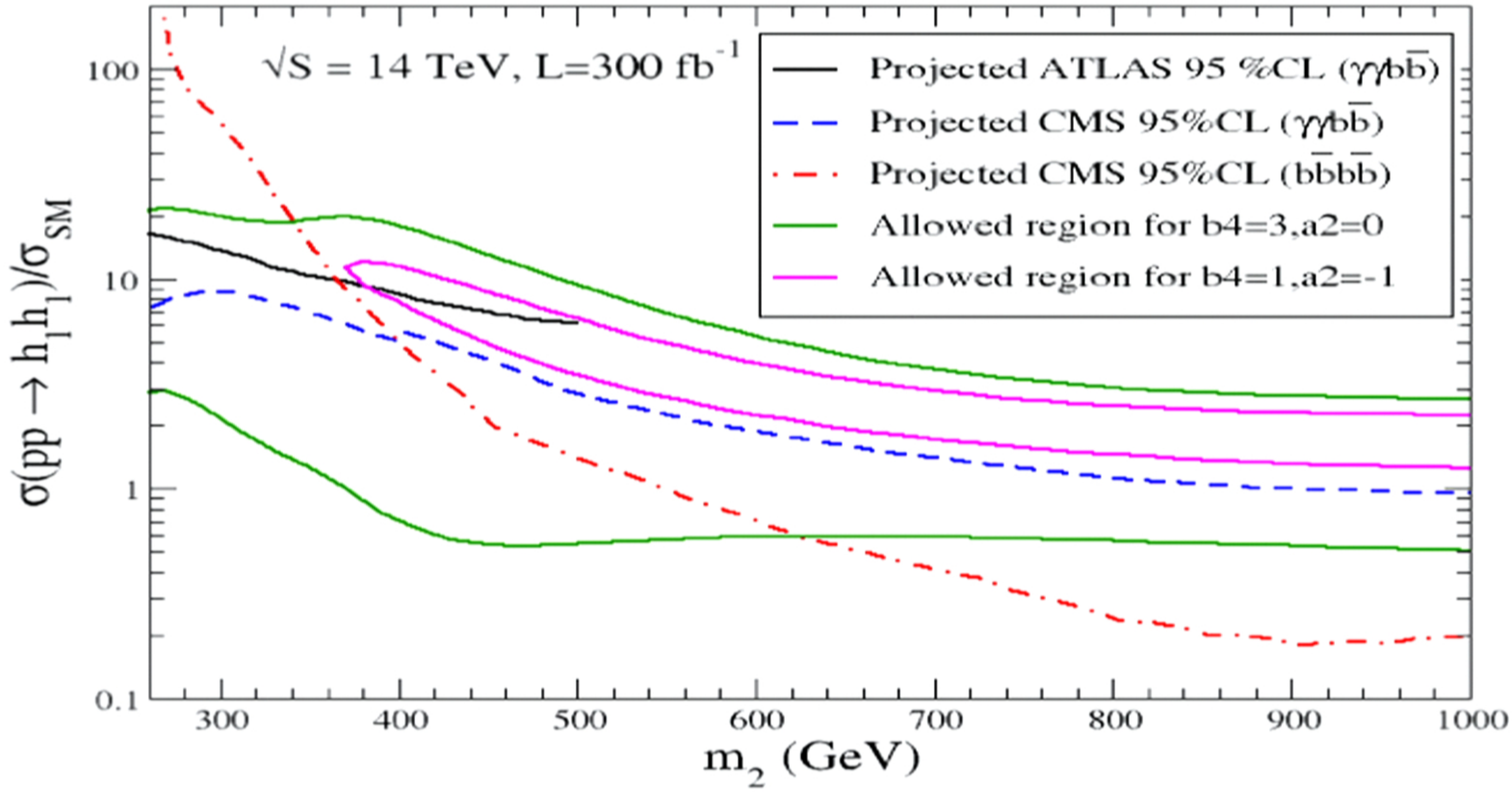
Collider constraints on cross section at 14 TeV



- Projected bounds based on expected 95%CL limits from ATLAS and CMS.
- Rule out the allowed region for b_4=1 and a_2= -1 (magenta) using CMS results.

Collider constraints on cross section at 14 TeV



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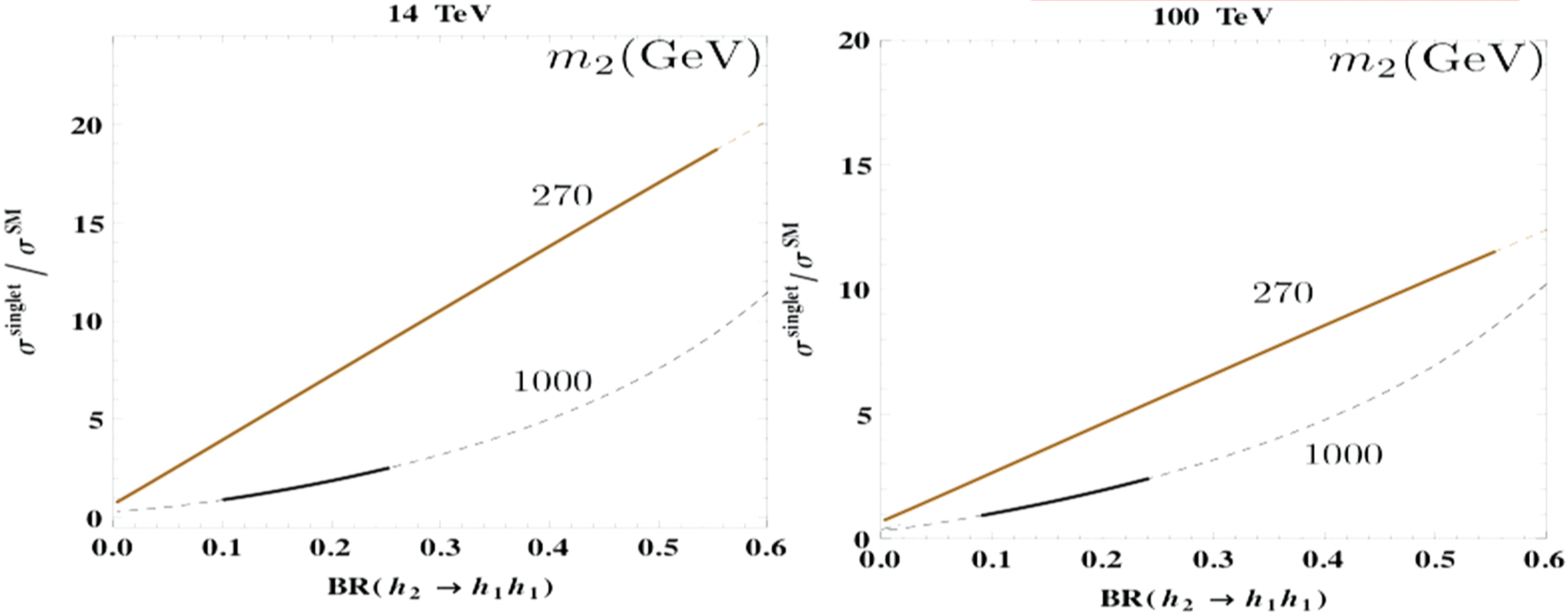
Looking for big enhancement

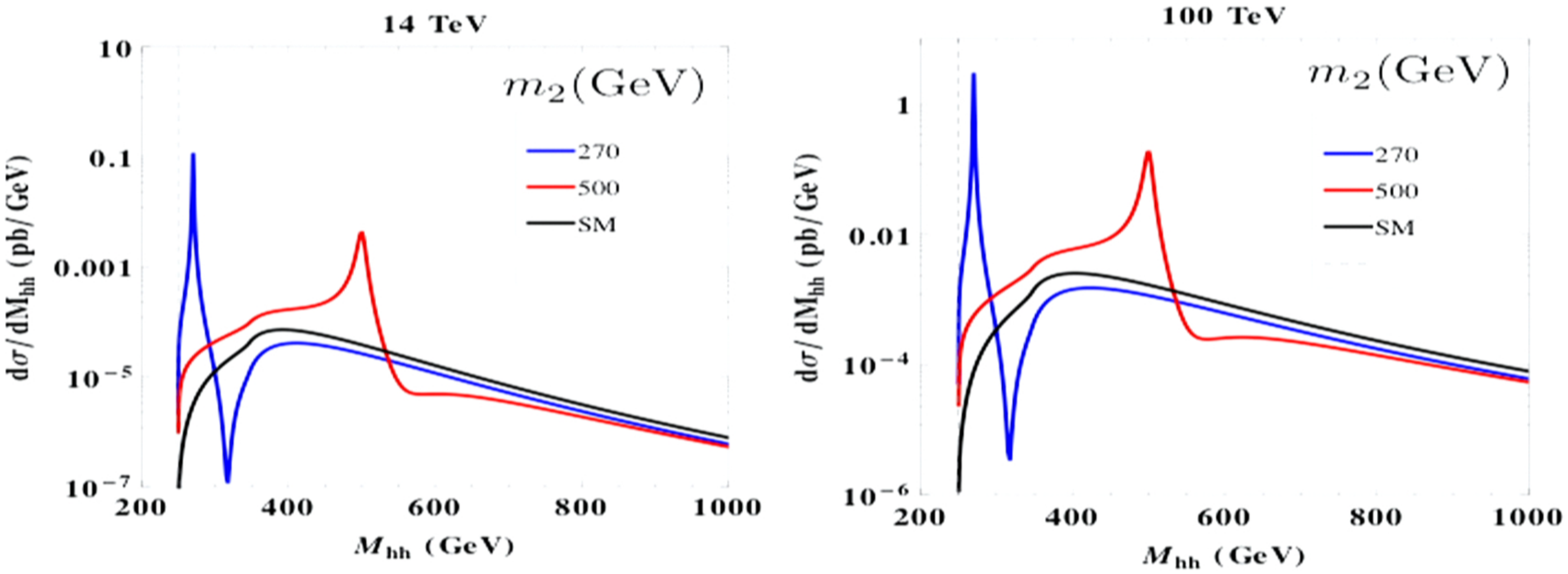
$b_4 = 1, \quad a_2 = 0,$
$\cos\theta = 0.94$
$m_1 = 126 \text{ GeV}$



Dashed line: Excluded by the EW minimum is the global minimum.
Solid line: Allowed range.

Differential cross section distributions

- Kinematic threshold $\sqrt{s} > 2m_h$
- Peak at m_2 due to resonance decay
- Cancellations occur near $2m_t$
- Pronounced peaks are useful for discovery of the heavy resonances.



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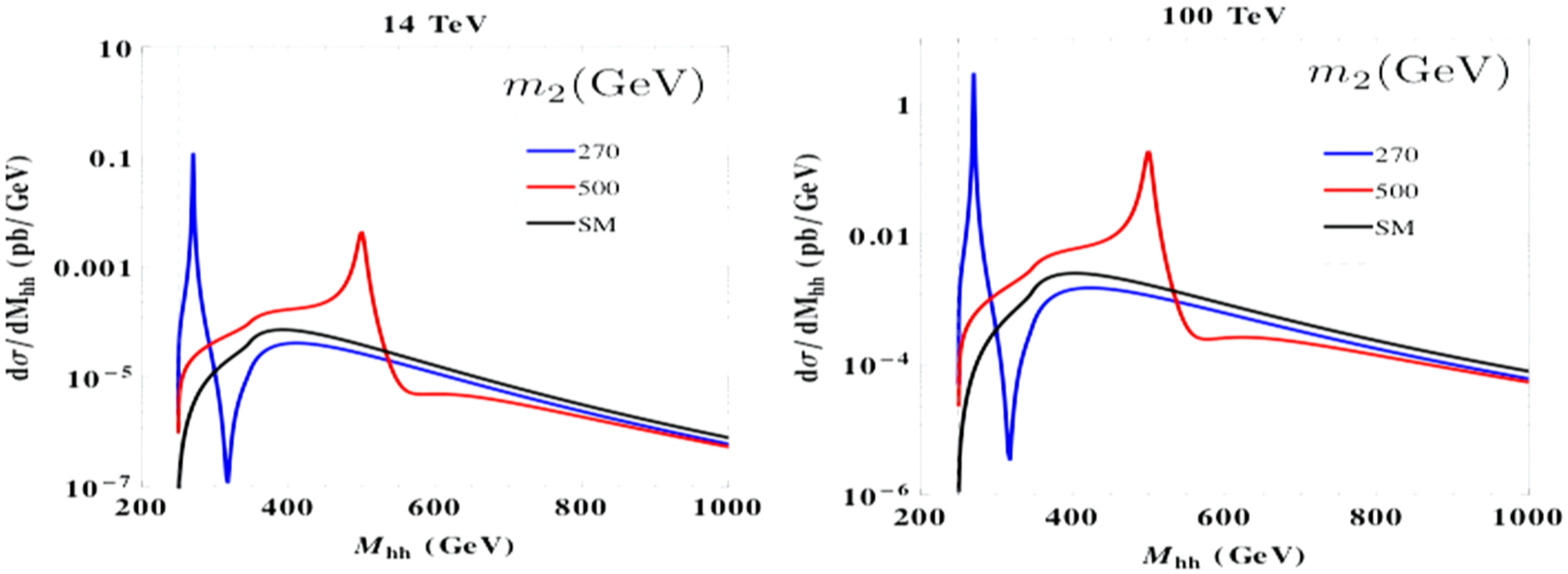


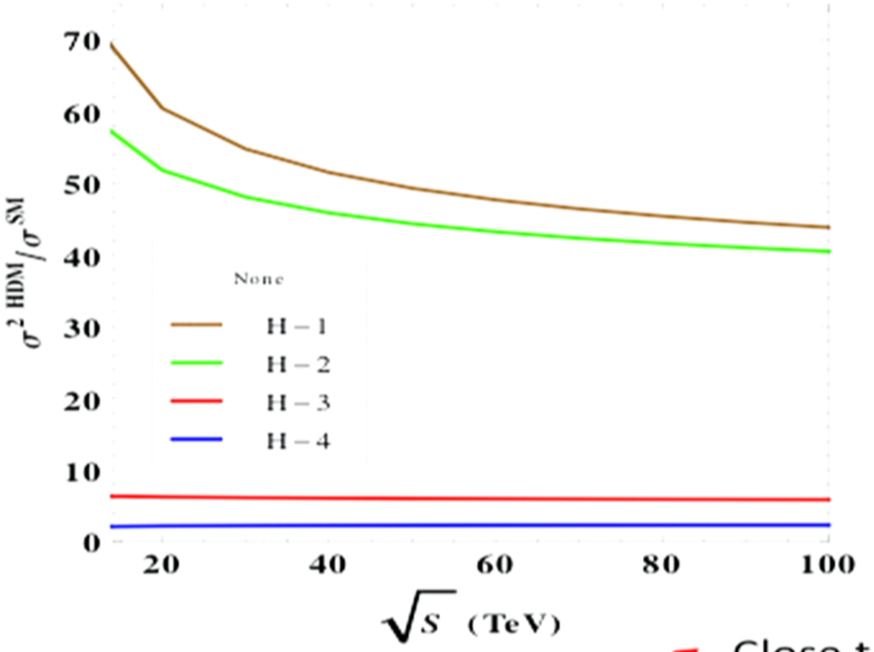
Two Higgs doublet models

- Introduce another Higgs doublet in addition to the SM one, ϕ_1 and ϕ_2
- Focus on type II: One Higgs doublet couples to up type quarks and the other to down-type quarks and leptons.
- Characterized by seven parameters

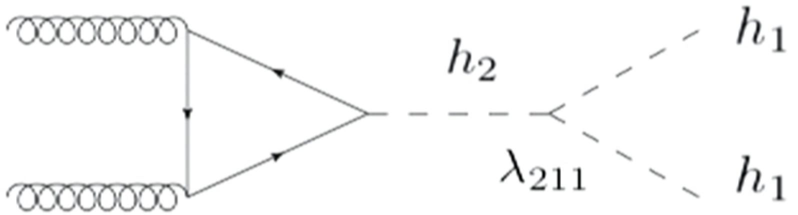
$$M_h\,, M_H\,, M_{H\pm}\,, M_A, \alpha, \tan\beta,\ \text{and}\ m_{12}$$

[Branco Phys. Rept. 516 (2012) 1-102]

Two Higgs doublet models: branching fractions



Dominant contribution:



[Baglio et. al., 1403.1264]

Close to alignment limit $\beta - \alpha = \pi/2$

	$\tan\beta$	$(\beta-\alpha)/\pi$	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	m_{12}^2 [GeV^2]	$BR(h_2 \to h_1 h_1)$
H-1	1.75	0.522	300	441	442	38300	59.0
H-2	2.00	0.525	340	470	471	44400	63.7
H-3	4.26	0.519	450	546	548	43200	29.0
H-4	4.28	0.513	600	658	591	76900	21.1

Take home messages

- **Singlet:** the double Higgs rate can increase up to ~20 times of the SM prediction.
- **Type II 2HDM:** the double Higgs rate can increase by 60-70 times of the SM prediction.
- LHC Run 2 can rule out large part of parameter space that is allowed by theoretical constraints.
- The Higgs self couplings in new physics models can potentially be measured at the LHC Run 2 or a 100 TeV collider due to the large enhancement.