Singlet Extension III: Resonant di-Higgs production

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

ACFI Workshop
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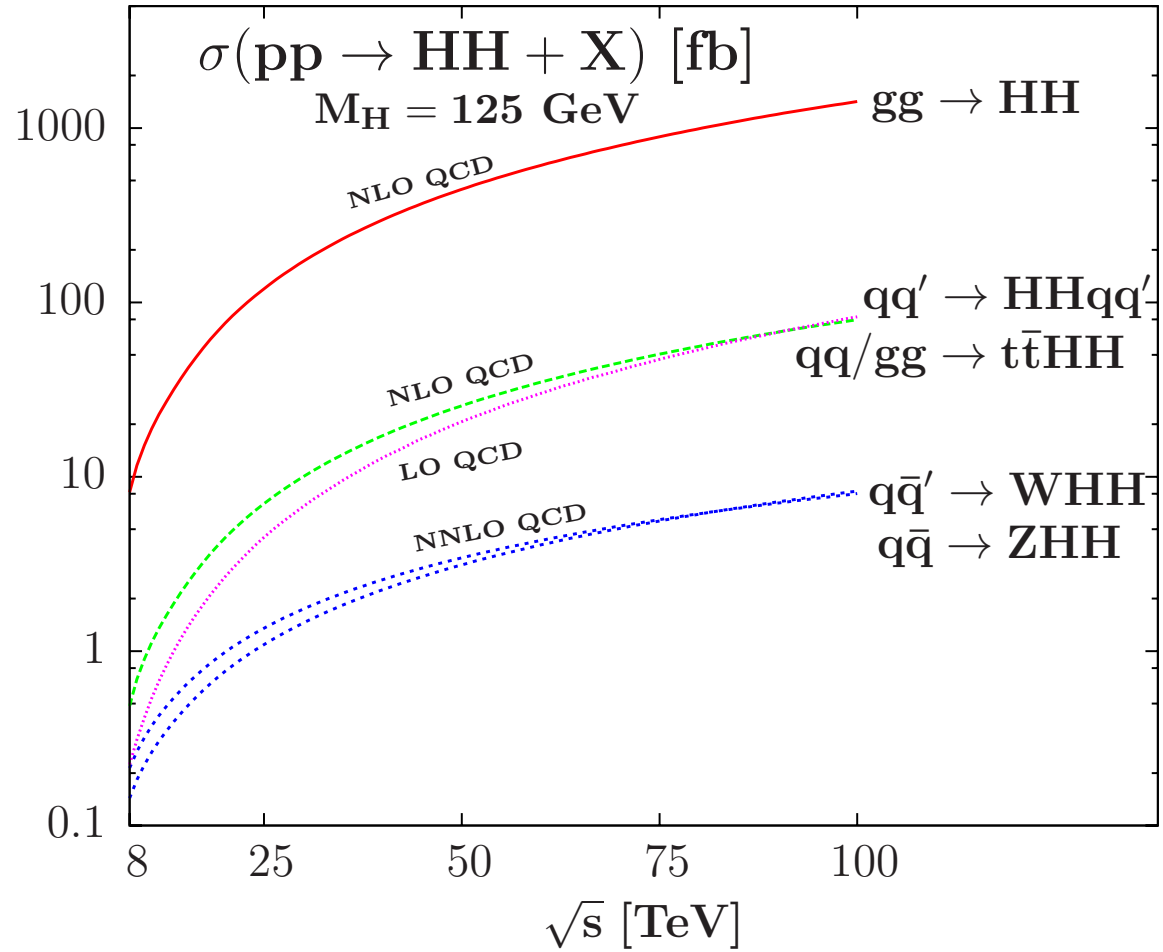
Why go big?

- At high energy pp colliders, we can
  - Discover new particles
  - Precision measurement of Higgs self couplings (using double Higgs production)
- Address one of most fundamental issues, origin of electroweak symmetry breaking.
- Better understanding of the structure of the scalar potential
- Connection to electroweak baryogenesis

Goals

- Focus on collider study in a model with an additional singlet scalar
- In which part of parameter space can we have big enhancement of di-Higgs rate?
- Current constraints (both experimental and theoretical) on model parameters

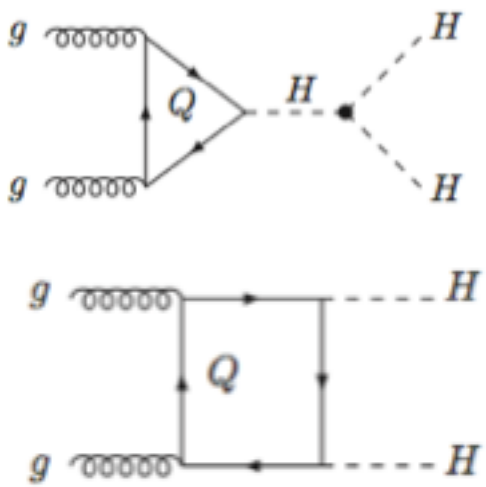
Di-Higgs production in SM

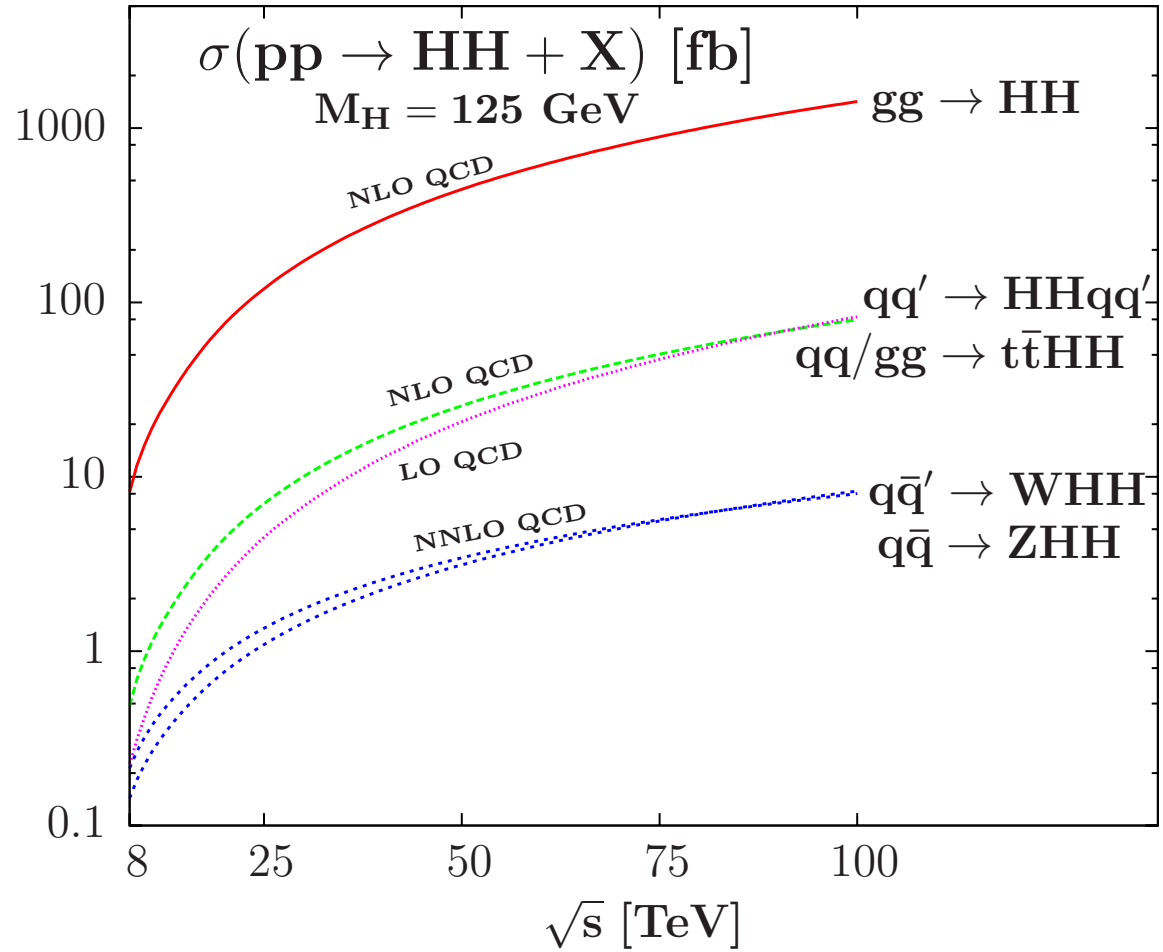


[Baglio et al, 1212.5581]

Di-Higgs production in SM

- Dominant channel: Gluon fusion





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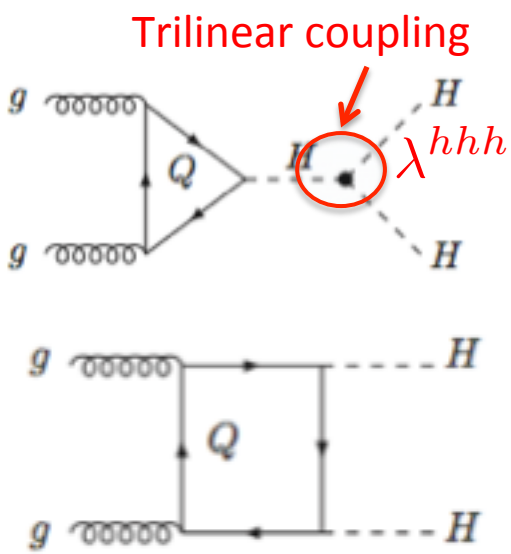

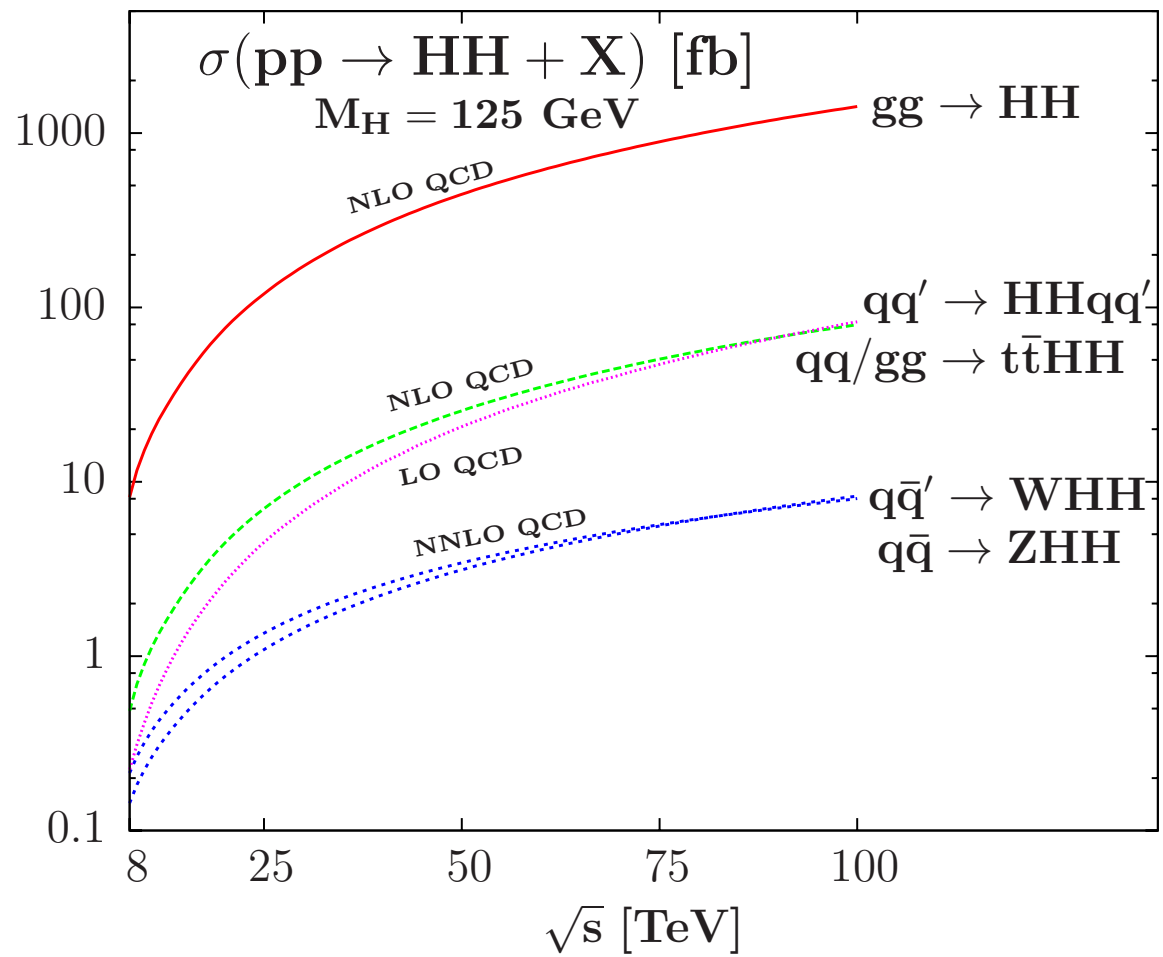

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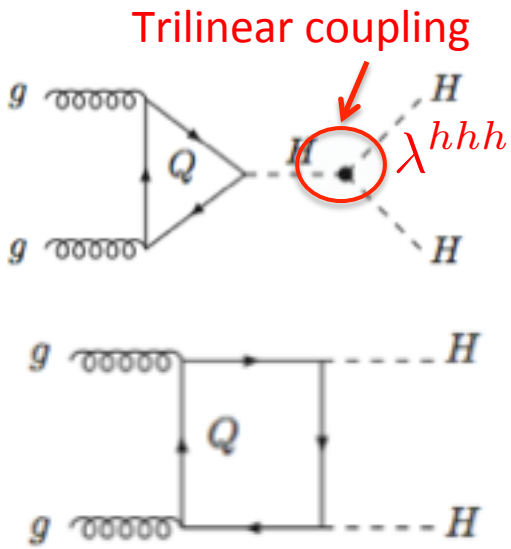

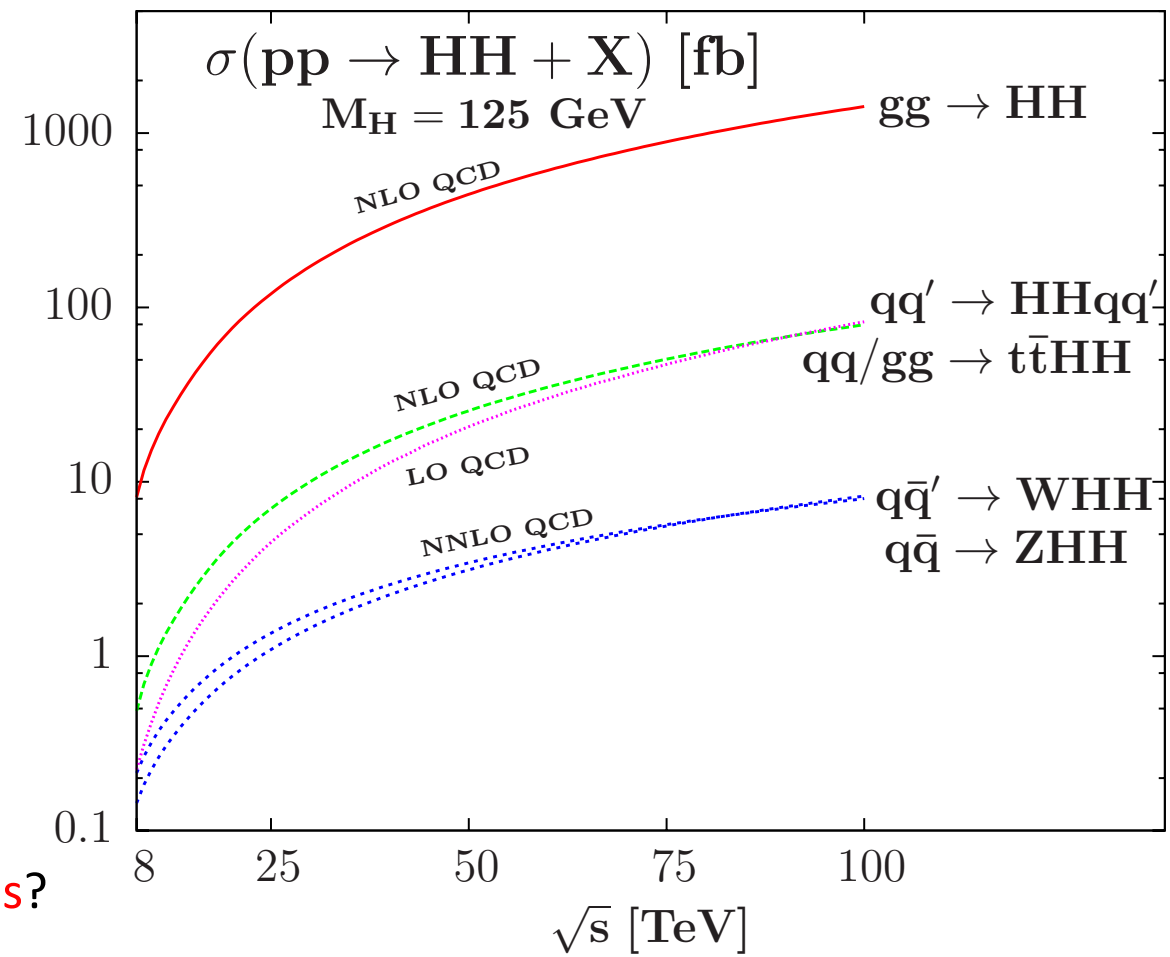

1. How do they interfere?

2. Which diagram dominates?

[Baglio et al, 1212.5581]

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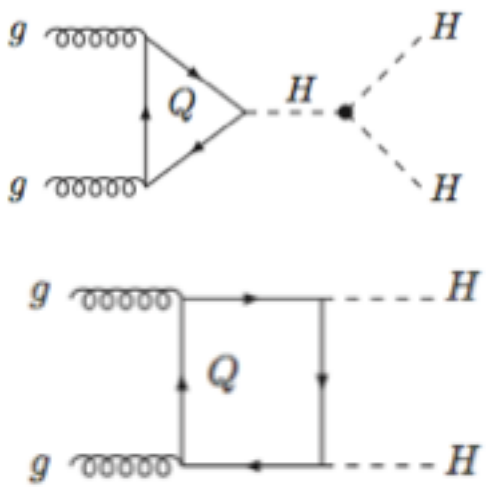

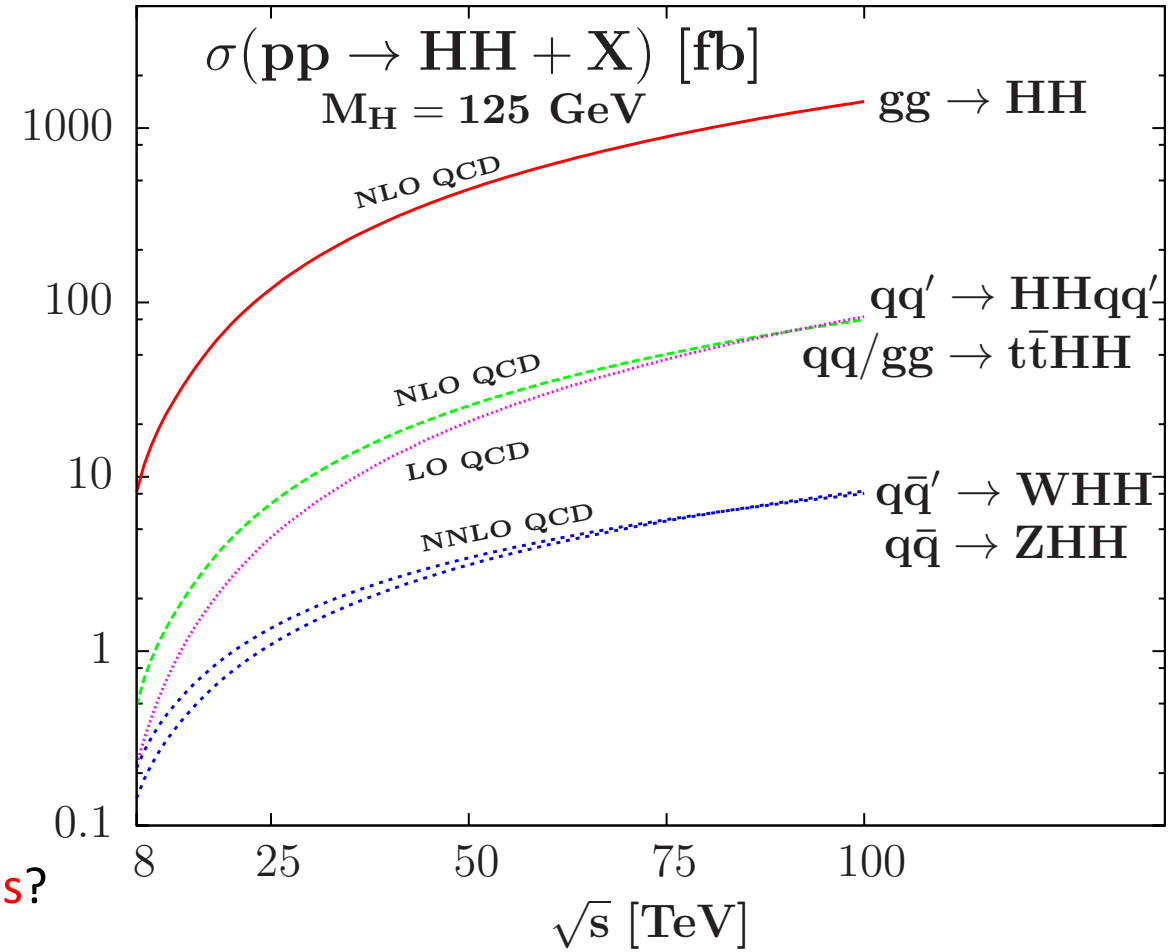

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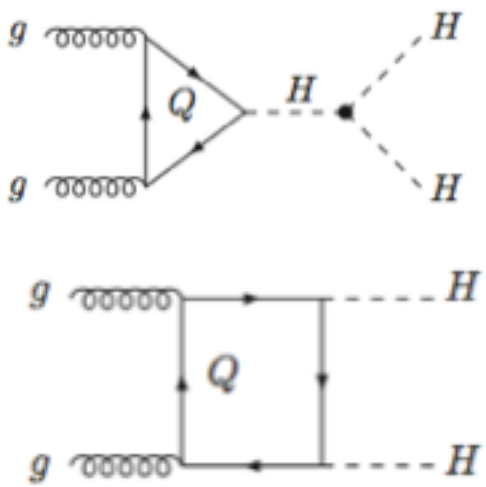

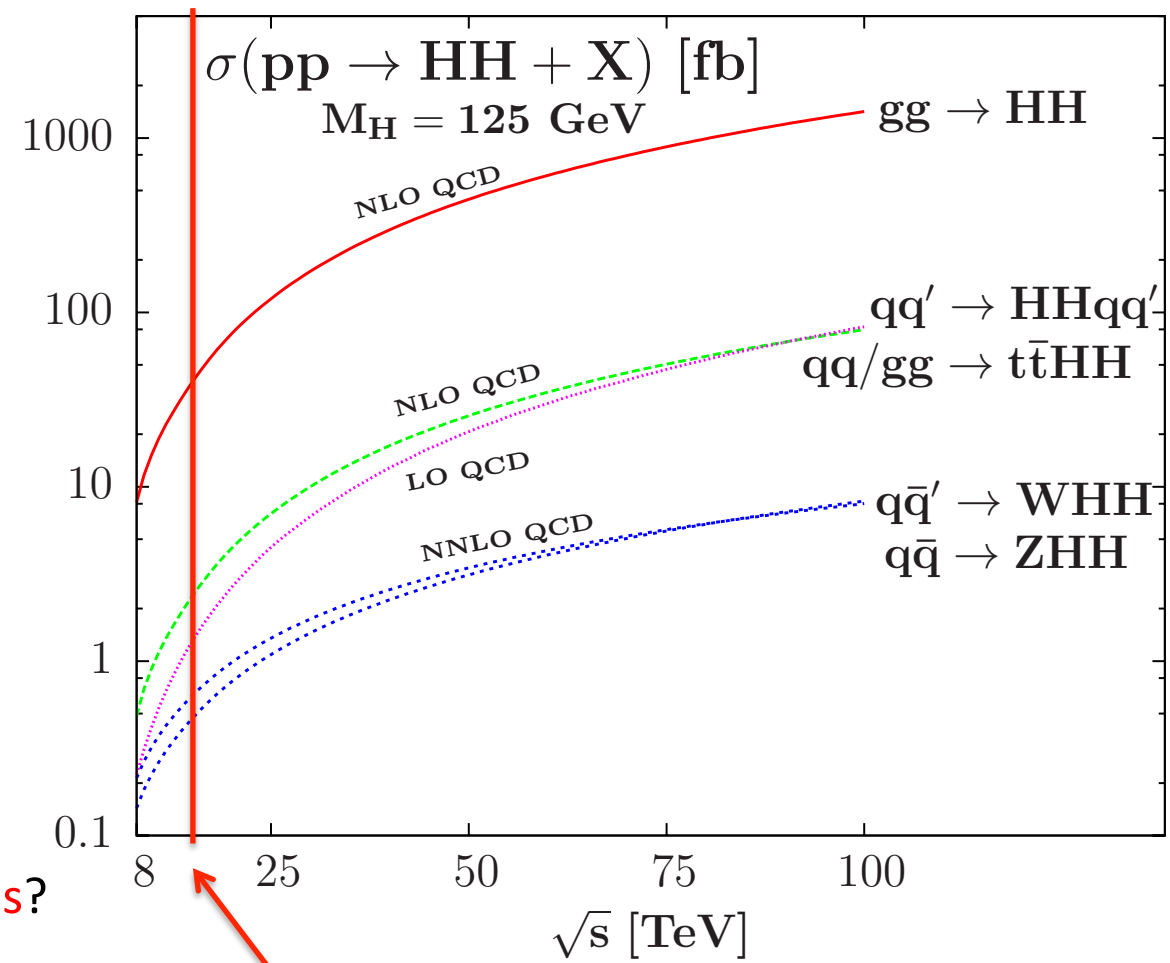

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14 TeV, cross section 40 fb

[Baglio et al, 1212.5581]

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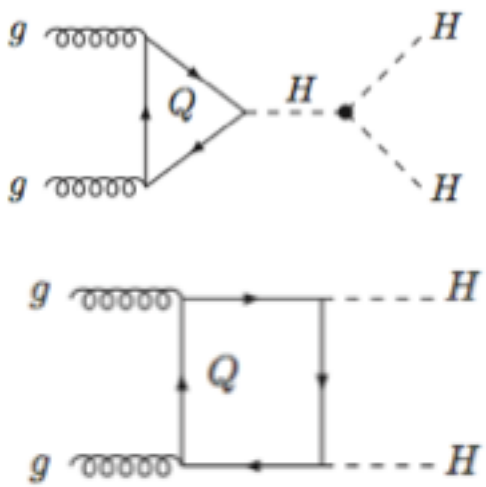

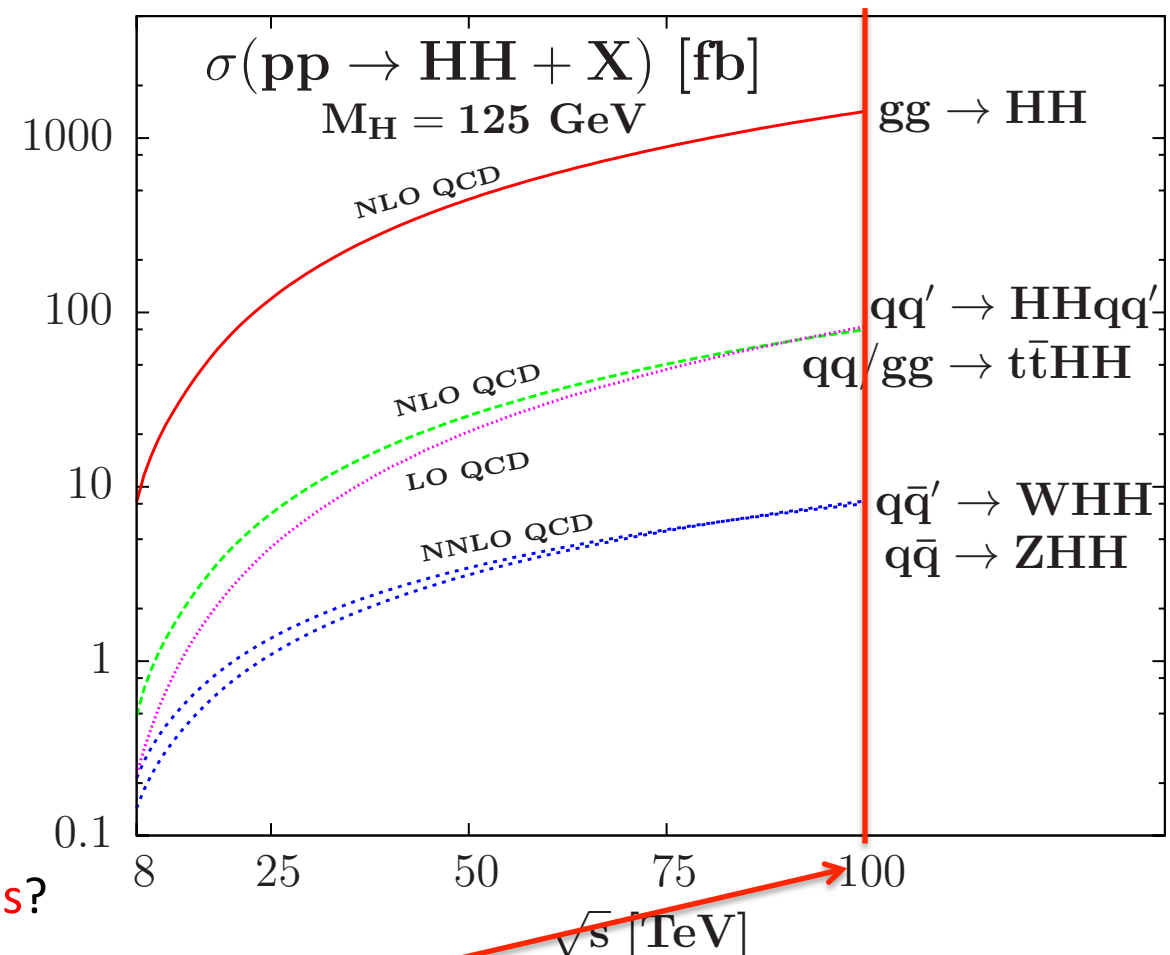

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100 TeV, cross section ~ 1 pb

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Collider study: di-Higgs production

- Using $\gamma\gamma b\bar{b}$ channel.
- Statistical significance: 1.3 sigma (ATLAS) with 3/ab at 14 TeV. 15 sigma (snowmass) with 3/ab at 100 TeV.

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[conference talk at HKUST by Yao, 2015]

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- Depending on efficiencies, background estimates, and approximations, etc.

Resonant di-Higgs production

- Production cross section of di-Higgs can be enhanced due to the decay of heavy resonances in many new physics scenarios
- BSM Models
  - SM + Singlet

[Liu, Wang and Zhu, 1310.3634]

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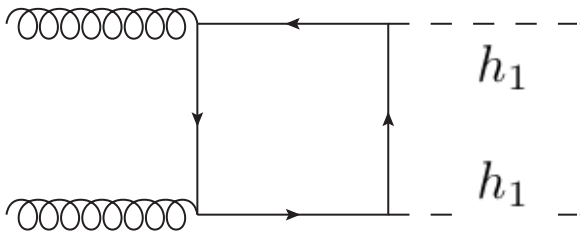

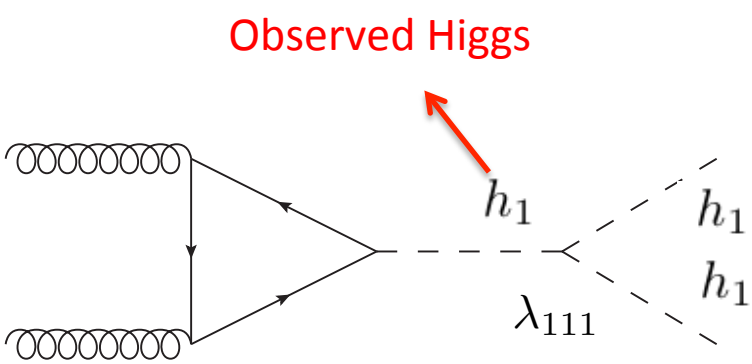

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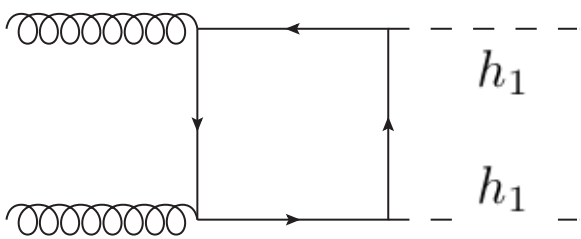
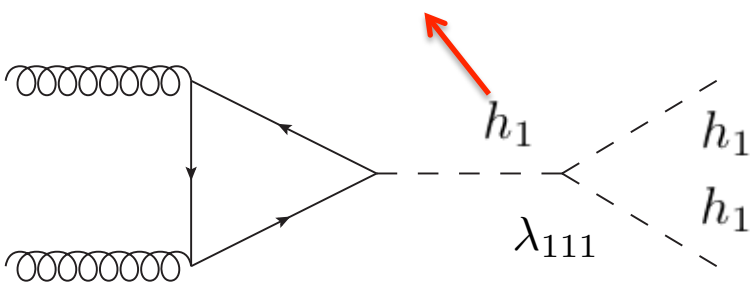


Study $b\bar{b}\tau^+\tau^-$ final state, discovery of the h_2 at the LHC may be achieved with ~< 100 fb−1 at LHC14 for parameter points relevant to cosmology

Observed Higgs



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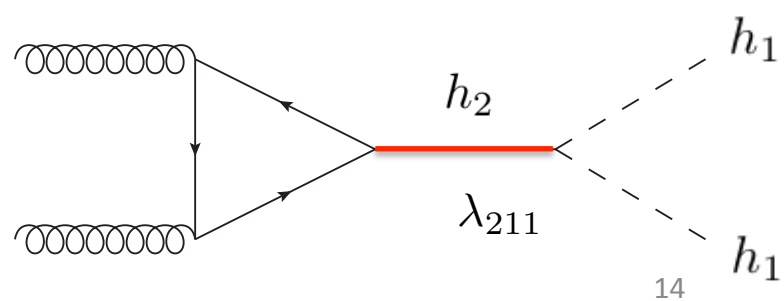

SM + Singlet

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

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Keep it general.
No Z_2 symmetry!

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

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Z_2 symmetry:
S-> -S

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- 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 $\sin\theta$.

Shift invariance

- A shift of the singlet field by $S \to S + \Delta_S$ is just a redefinition of the parameters and does not change the physics.

- The minimum of the potential is obtained by requiring

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

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

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

  - It is always possible to choose a solution $(v,x) = (\sqrt{\frac{\mu^2}{\lambda}}, 0)$ provided $b_1 = -\frac{v^2}{4} a_1$.

Couplings

- Higgs self potential in terms of mass eigenstates:

$$\sin\theta \equiv s$$
$$\cos\theta \equiv c$$

$$V_{\text{self}} \supset \frac{\lambda_{111}}{3!}h_1^3 + \frac{\lambda_{211}}{2!}h_2h_1^2 + \frac{\lambda_{221}}{2!}h_2^2h_1 + \frac{\lambda_{222}}{3!}h_2^3 + \frac{\lambda_{1111}}{4!}h_1^4 + \frac{\lambda_{2111}}{3!}h_2h_1^3 + \frac{\lambda_{2211}}{4}h_2^2h_1^2 + \frac{\lambda_{2221}}{3!}h_2^3h_1 + \frac{\lambda_{2222}}{4!}h_2^4$$

$$\lambda_{111} = 2s^3b_3 + \frac{3a_1}{2}sc^2 + 3a_2s^2cv + 6c^3\ \lambda v,$$

$$\boxed{\lambda_{211} = 2s^2cb_3 + \frac{a_1}{2}c(c^2-2s^2) + (2c^2-s^2)sva_2 - 6\lambda sc^2v}$$

Relevant for di-Higgs resonant production

$$\lambda_{221} = 2c^2sb_3 + \frac{a_1}{2}s(s^2-2c^2) - (2s^2-c^2)cva_2 + 6\lambda cs^2v$$

$$\lambda_{222} = 2c^3b_3 + \frac{3a_1}{2}cs^2 - 3a_2c^2sv - 6s^3\ \lambda v,$$

- One can increase the cross section of the di-Higgs production by tuning the value of b_3 .
- Quartic couplings are not sensitive to EWPT, too small

Trilinear couplings

- Higgs self potential in terms of mass eigenstates:

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$$(a1 = \frac{m_1^2 - m_2^2}{v_{EW}} \sin 2\theta)$$

Small angle approximation

$\sin\theta \to 0$

$$\lambda_{111} \to 6\lambda v + \frac{3}{2} a_1 s + 3vs^2(a_2 - 3\lambda) \longrightarrow 6\lambda v$$
$$\lambda_{211} \to \frac{a_1}{2} + sv(-6\lambda + 2a_2) + \frac{s^2}{4}(8b_3 - 7a_1) \longrightarrow 0$$
$$\lambda_{221} \to 2sb_3 - a_1 s + (1 - \frac{7}{2} s^2) va_2 + 6\lambda s^2 v \longrightarrow a_2 v$$
$$\lambda_{222} \to (2 - 3s^2) b_3 + \frac{3a_1}{2} s^2 - 3a_2 sv, \longrightarrow 2b_3$$

- Trilinear couplings can potentially be sensitive to EWPT

Counting parameters

- Model parameters:

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

- Phenomenological parameters:

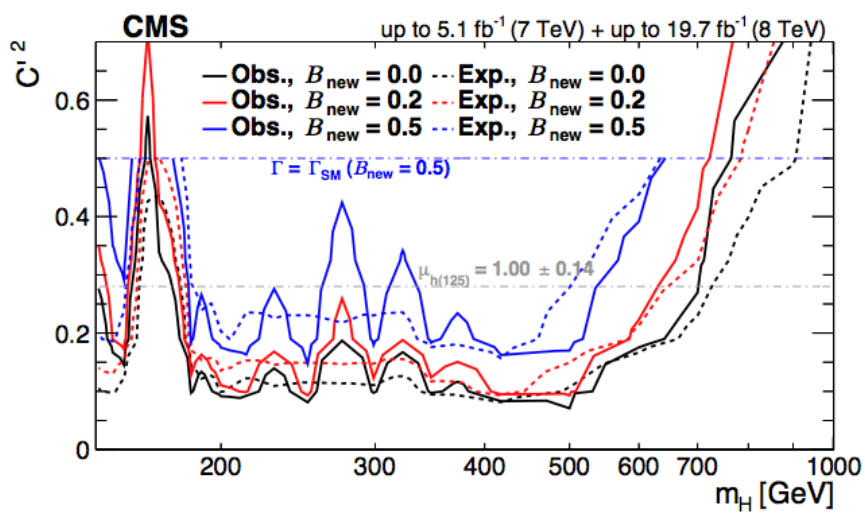
$$m_1 = 126 \text{ GeV}, \; m_2, \; \theta, \; v_{EW} = 246 \text{ GeV}, \; x = 0, \; a_2, \; b_3, \; b_4$$

Constraints on mixing angle

- Light Higgs coupling measurements: $\sin^2\theta < 0.12$
  - Combined $h \to \gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}$
  - Independent of branching ratios of new decay channels

ATLAS-CONF-2014-010

- Heavy Higgs searches:
  - Depend on branching ratios of new decay channels
  - Choose B_{new} =0, $\sin^2\theta < 0.2$ for $200 < m_{h_2} < 600$ GeV

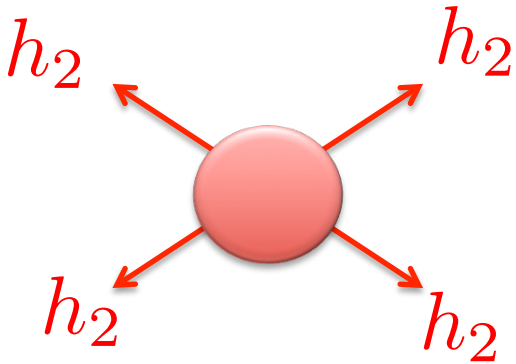


arXiv: 1504.00936, CMS

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 $a_2 > 0$

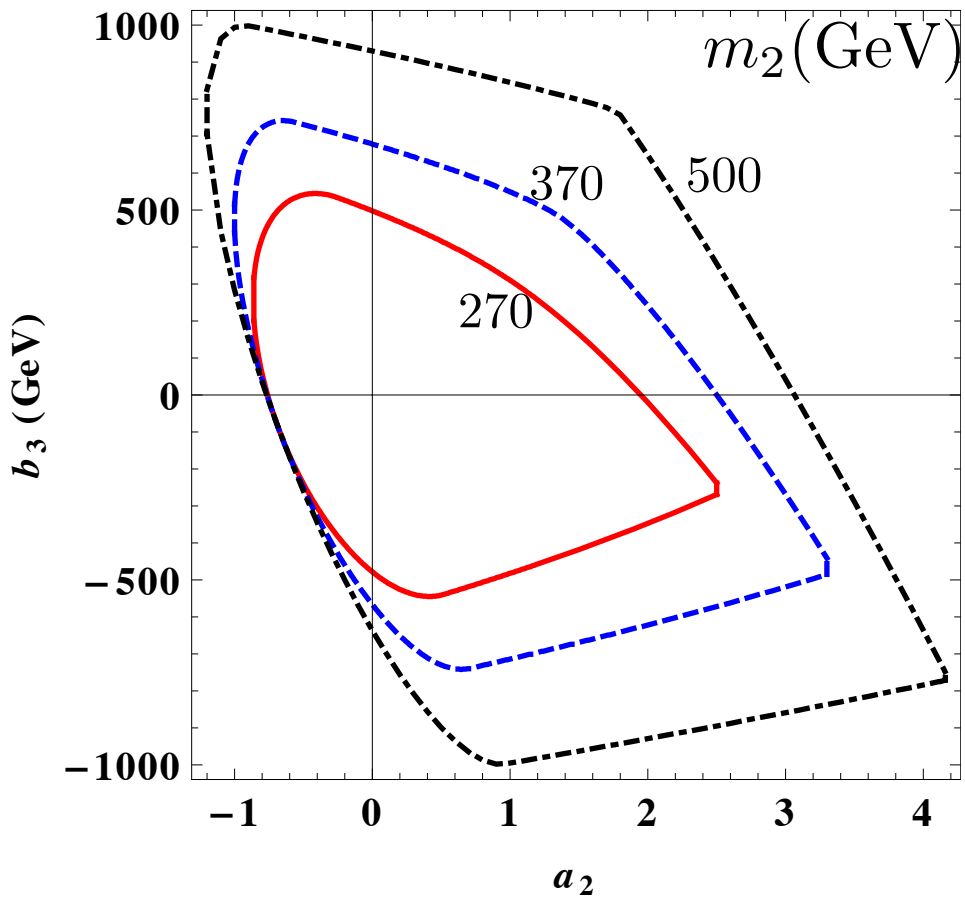
$$\lambda h^4 + a_2 h^2 S^2 + b_4 S^4 > 0 \quad \Rightarrow \quad a_2 < \infty$$

- 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

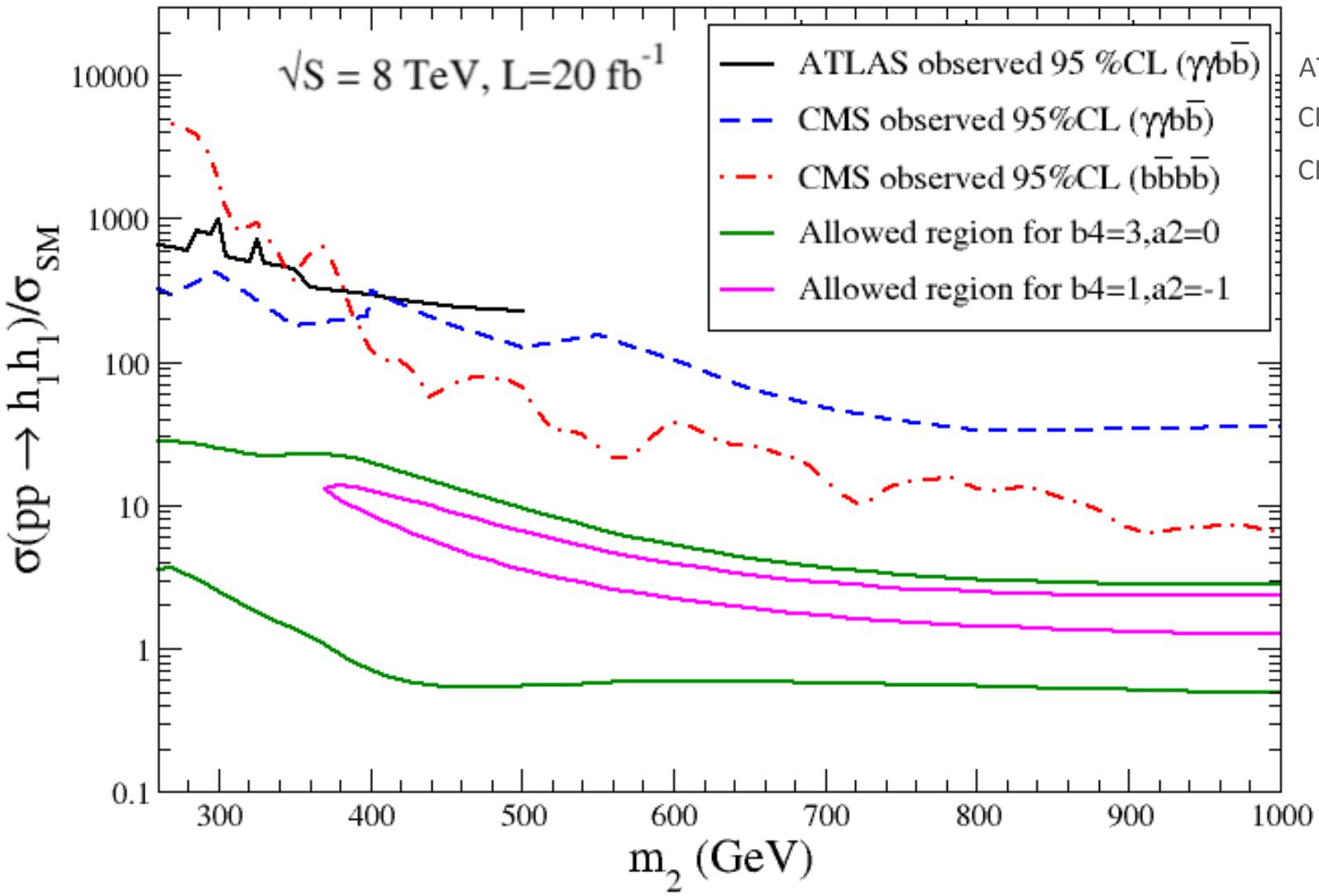
Constraints



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

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

Collider constraints on cross section at 8 TeV



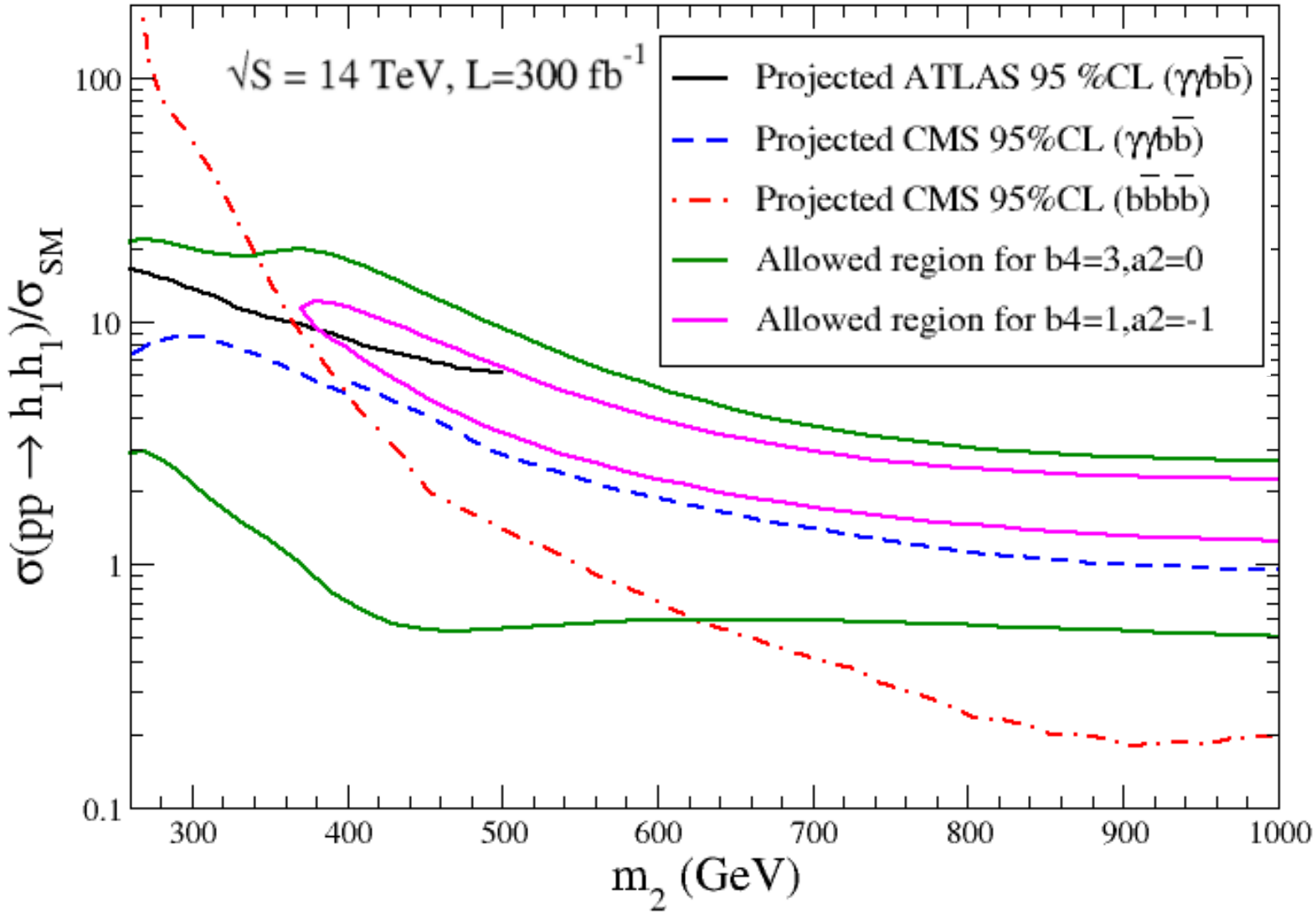
ATLAS, 1406.5053

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

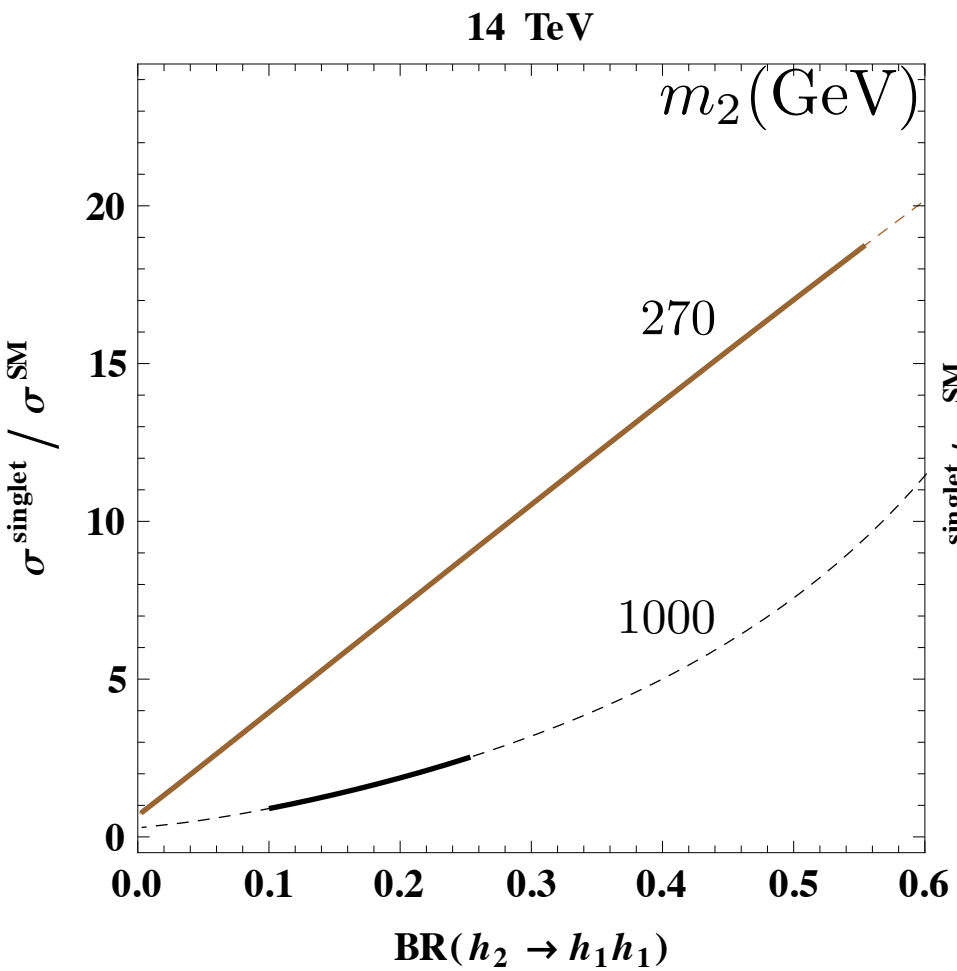
Collider constraints on cross section at 14 TeV

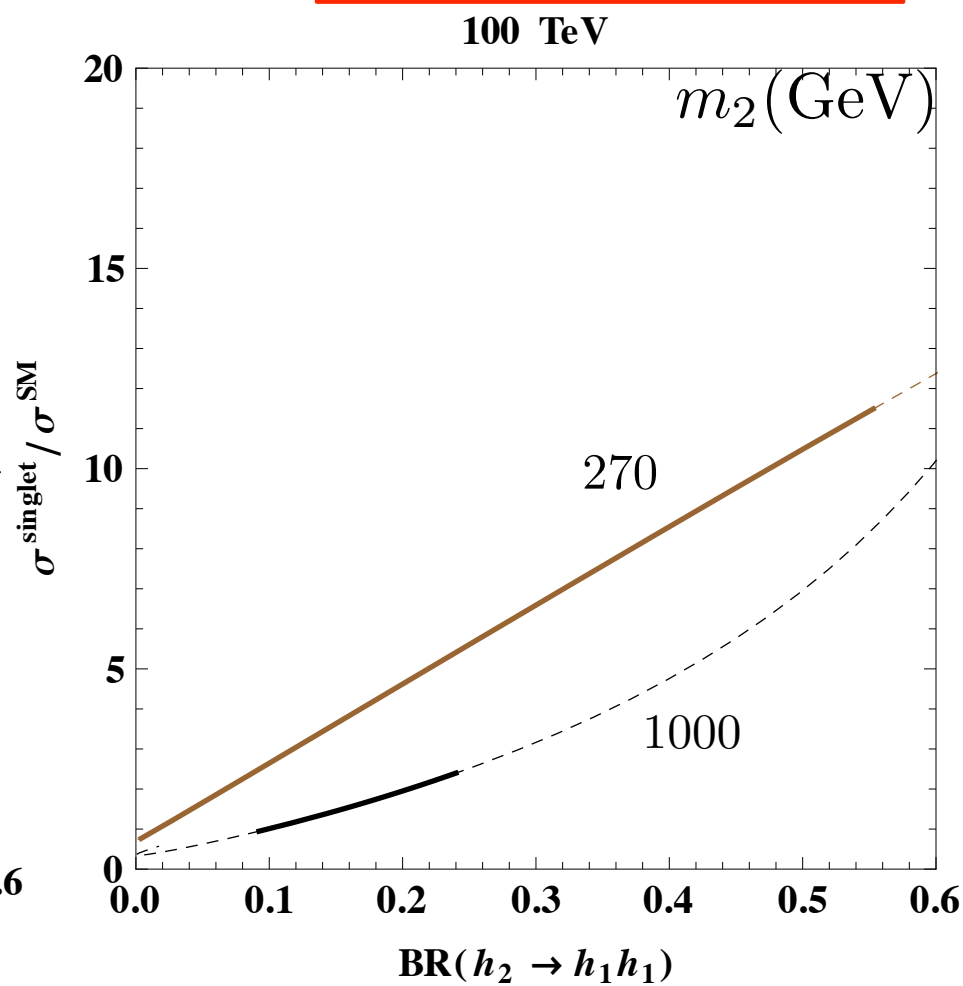


- Projected bounds based on expected 95%CL limits from ATLAS and CMS.
- Rule out the allowed region for b_4=1 and a_2= -1 (magenta) using CMS results.

Looking for big enhancement

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

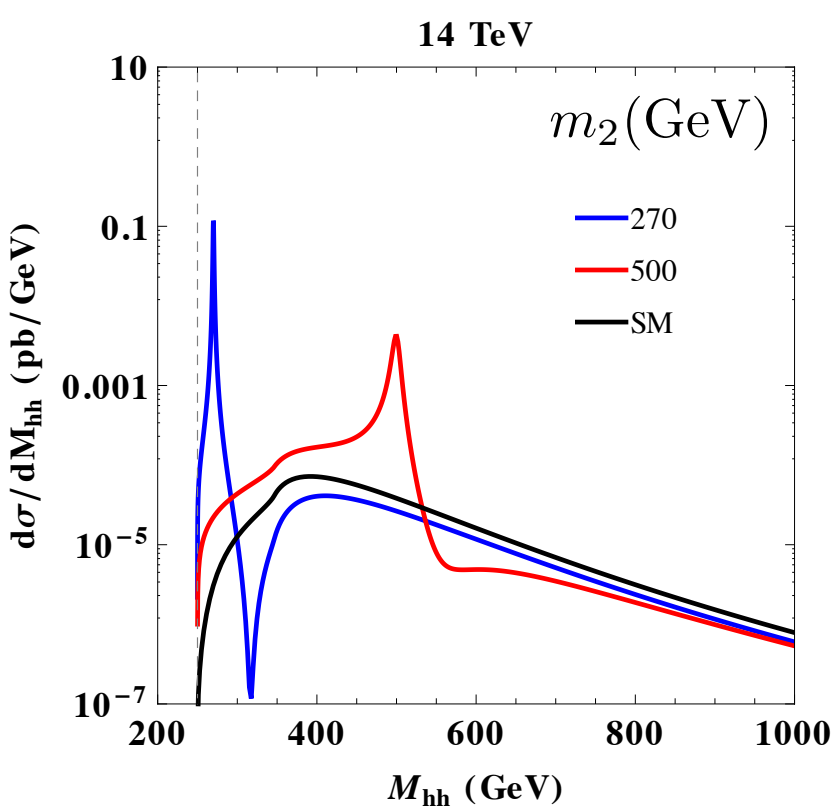


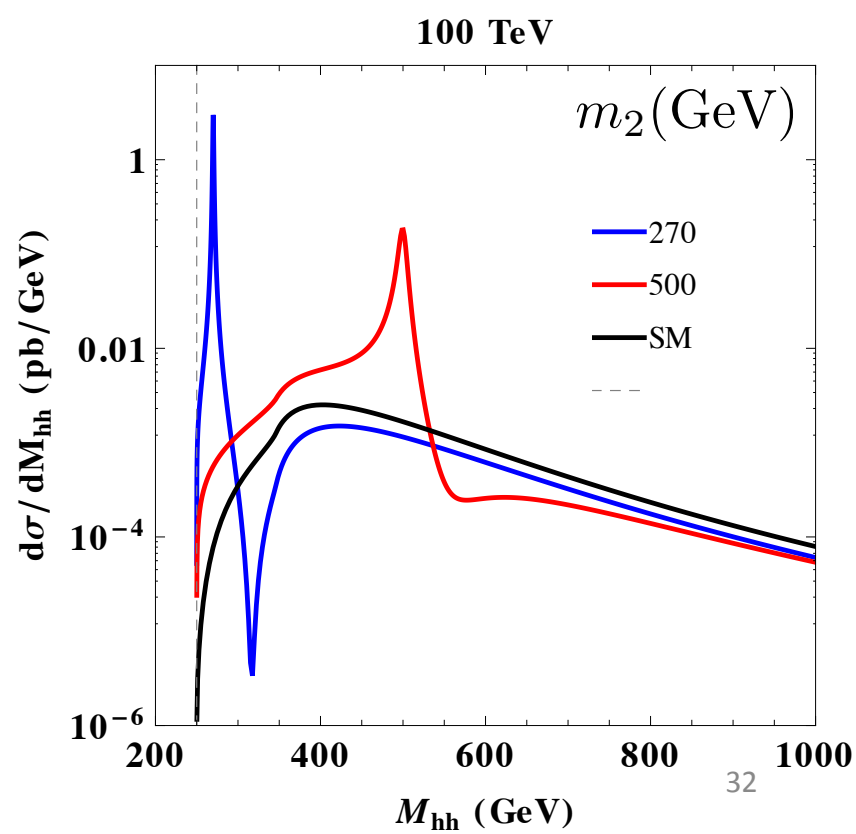


Dashed line: Excluded by the EW minimum is the global minimum.
Solid line: Allowed range.

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.





Take home messages

- In the model with an additional singlet, the double Higgs rate could increase up to ~20 times of the SM prediction.
- LHC Run 2 can rule out large part of parameter space that is allowed by theoretical constraints.
- The coupling b_3 plays an important role in the enhancement of di-Higgs rate
- The Higgs self couplings in the singlet model can potentially be measured due to the large enhancement.

THANK YOU!

BACKUP SLIDES

SM + Singlet

- The scalar mass matrix can be written as

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

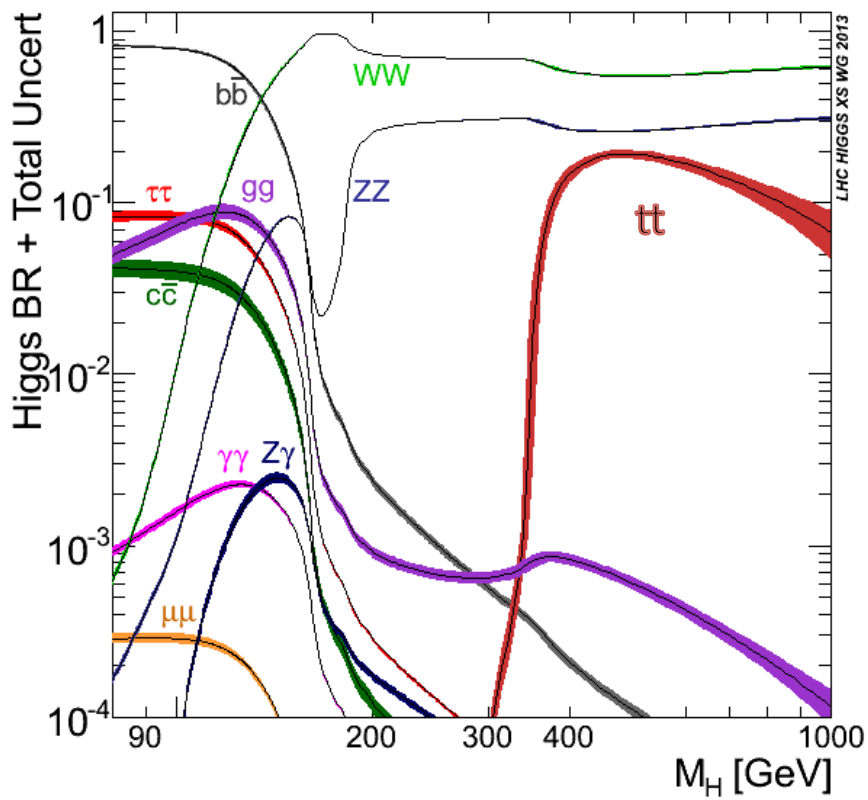
$$M^2 \equiv \begin{pmatrix} M_{11}^2 & M_{12}^2 \\ M_{12}^2 & M_{22}^2 \end{pmatrix} = \begin{pmatrix} 3\lambda v^2 - \mu^2 + x(a_1 + a_2 x)/2 & a_1 v/2 + a_2 v x \\ a_1 v/2 + a_2 v x & b_2 + a_2 v^2/2 + x(2b_3 + 3b_4 x) \end{pmatrix}$$

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

- Diagonalize the mass matrix to obtain the mass eigenstates m_1 and m_2, and mixing angle θ
- Using m_1, m_2, and θ as input parameters instead of λ, a_1, and b_2

Branching ratios

- Assuming SM couplings: dominant decay channels of heavy Higgs are WW, ZZ and $t\bar{t}$ (if $m_H > 350$ GeV)

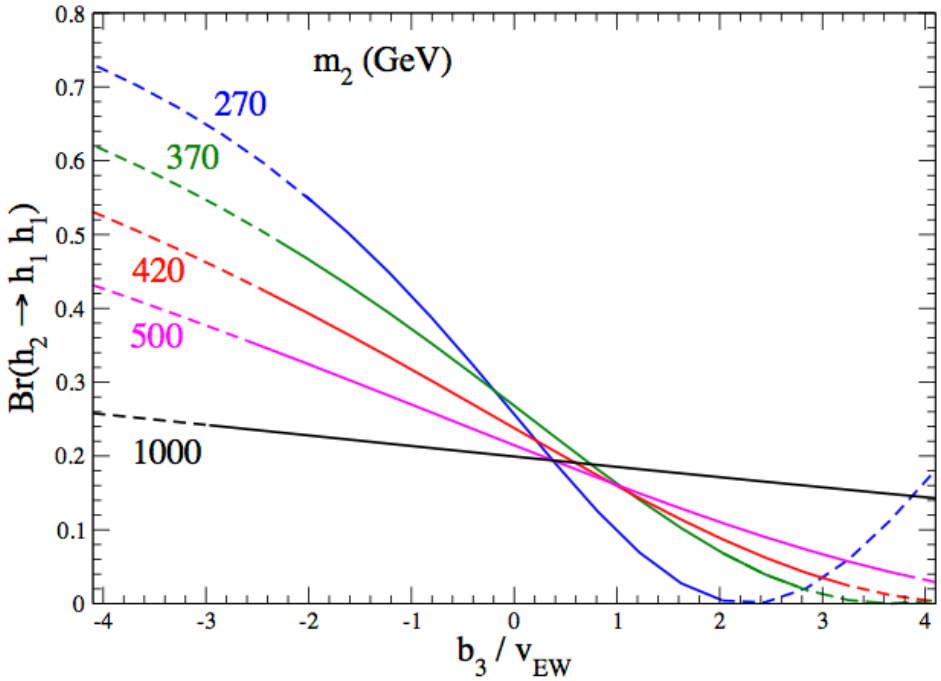


$$\Gamma(H \to VV) \sim m_H^3$$
$$\Gamma(H \to f\bar{f}) \sim m_f^2$$

- If Hhh coupling is large enough, BR(H-> hh) can also be significant.

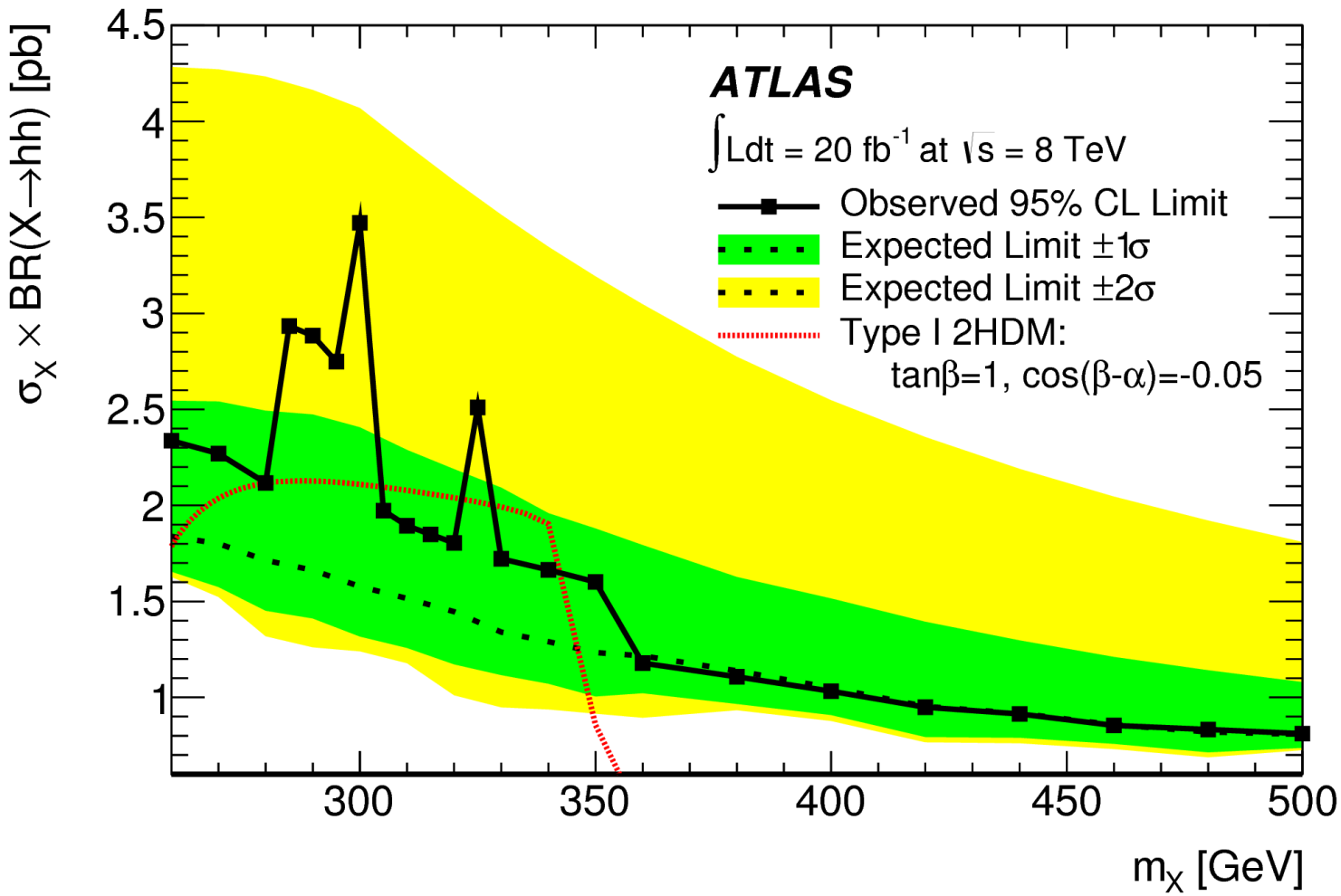
$\mathrm{BR}(h_2 \to h_1 h_1)$ v.s. b_3

$$\lambda_{211} = \sin\theta \left[-\frac{2m_1^2 + m_2^2}{v_{EW}} \cos^2\theta - a_2 v_{EW} \left(1 - 3\cos^2\theta\right) + b_3 \sin(2\theta) \right]$$



Collider constraints at 8 TeV

ATLAS, 1406.5053

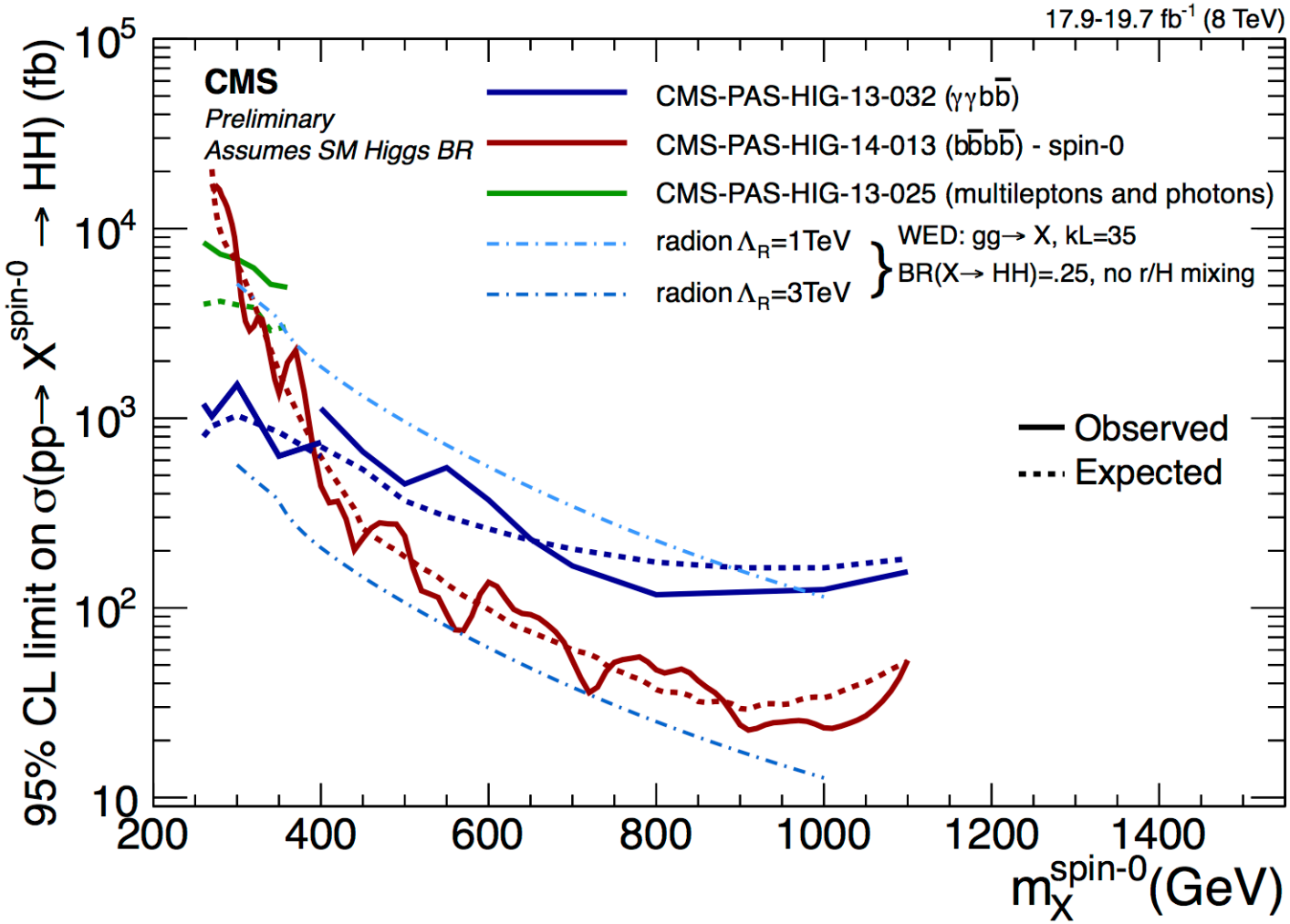


- ATLAS $\gamma\gamma b\bar{b}$ channel.

Collider constraints at 8 TeV

CMS PAS HIG-13-032

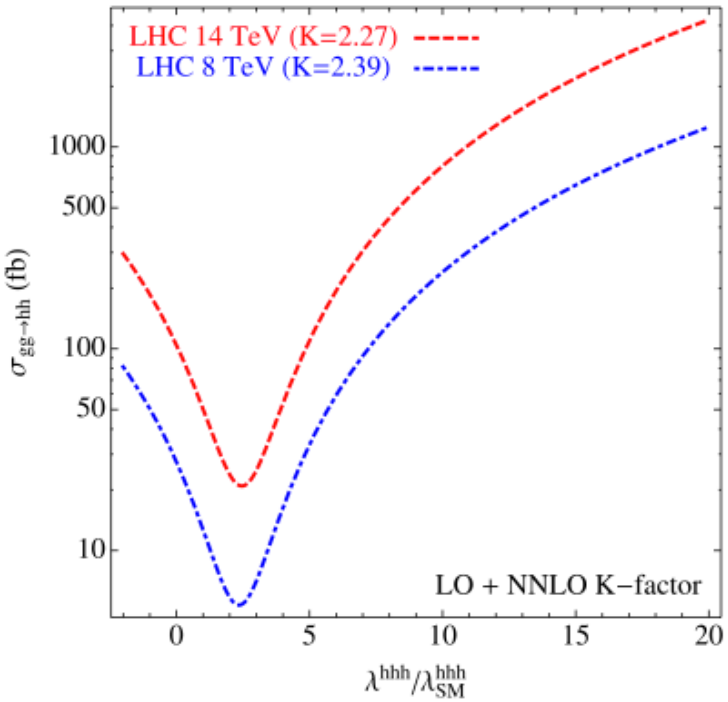
CMS PAS HIG-13-013

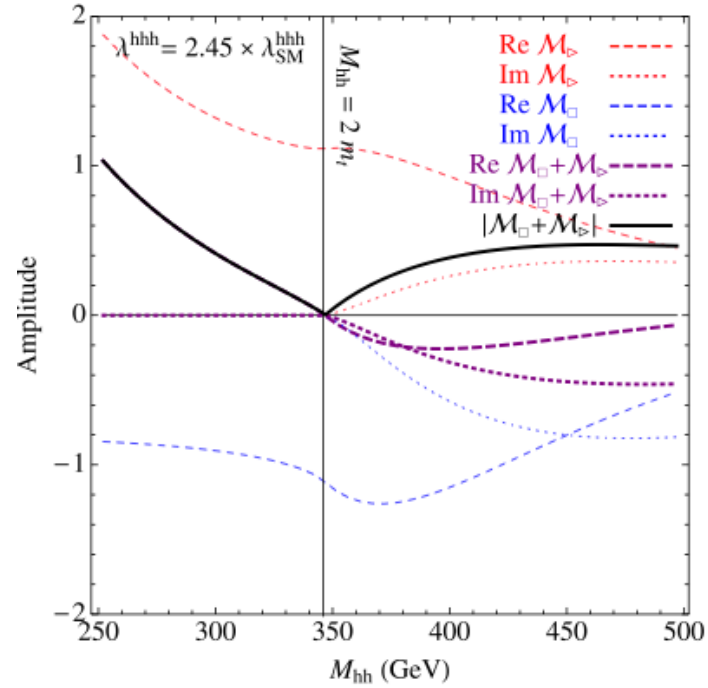


- 4 b channel gives a better constraint for m_2 above 400 GeV.

Di-Higgs production: variation of triple coupling

- Competition between the triangle and box diagrams.

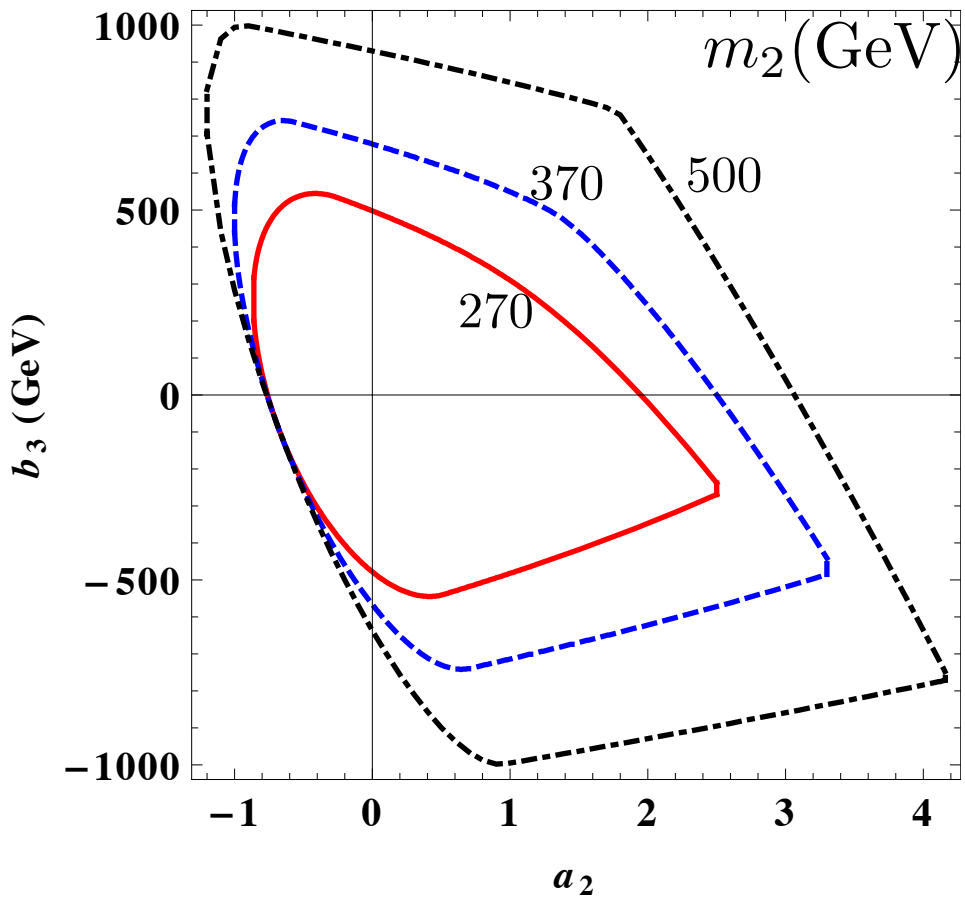


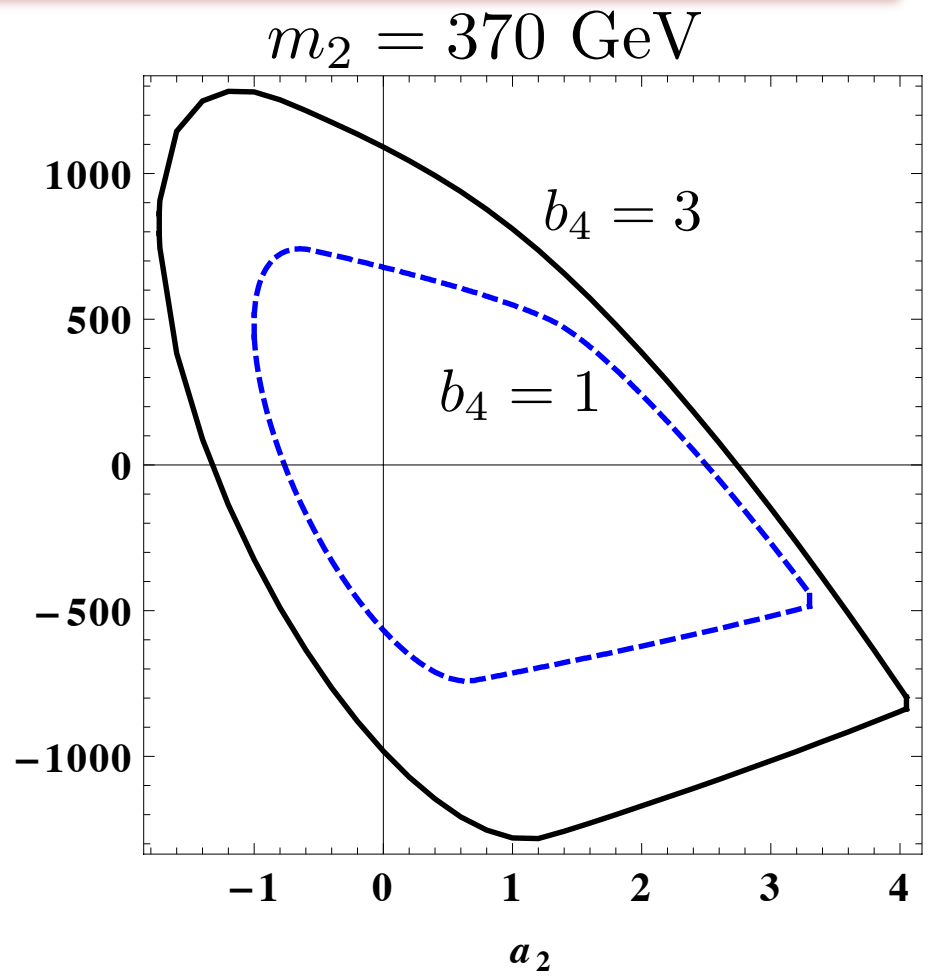


[Barger et al., Phys. Lett. B728,433]

- Box diagram dominant
- Destructive interference between two diagrams
- Minimum occurs at $\lambda_{\rm hhh} = 2.45 \times \lambda^{\rm hhh}_{\rm SM}$

Constraints





$b_4 = 1$
$\cos\theta = 0.94$
$m_1 = 126$ GeV

- Constraint becomes weaker when increasing b_4.

SENSITIVITY

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%