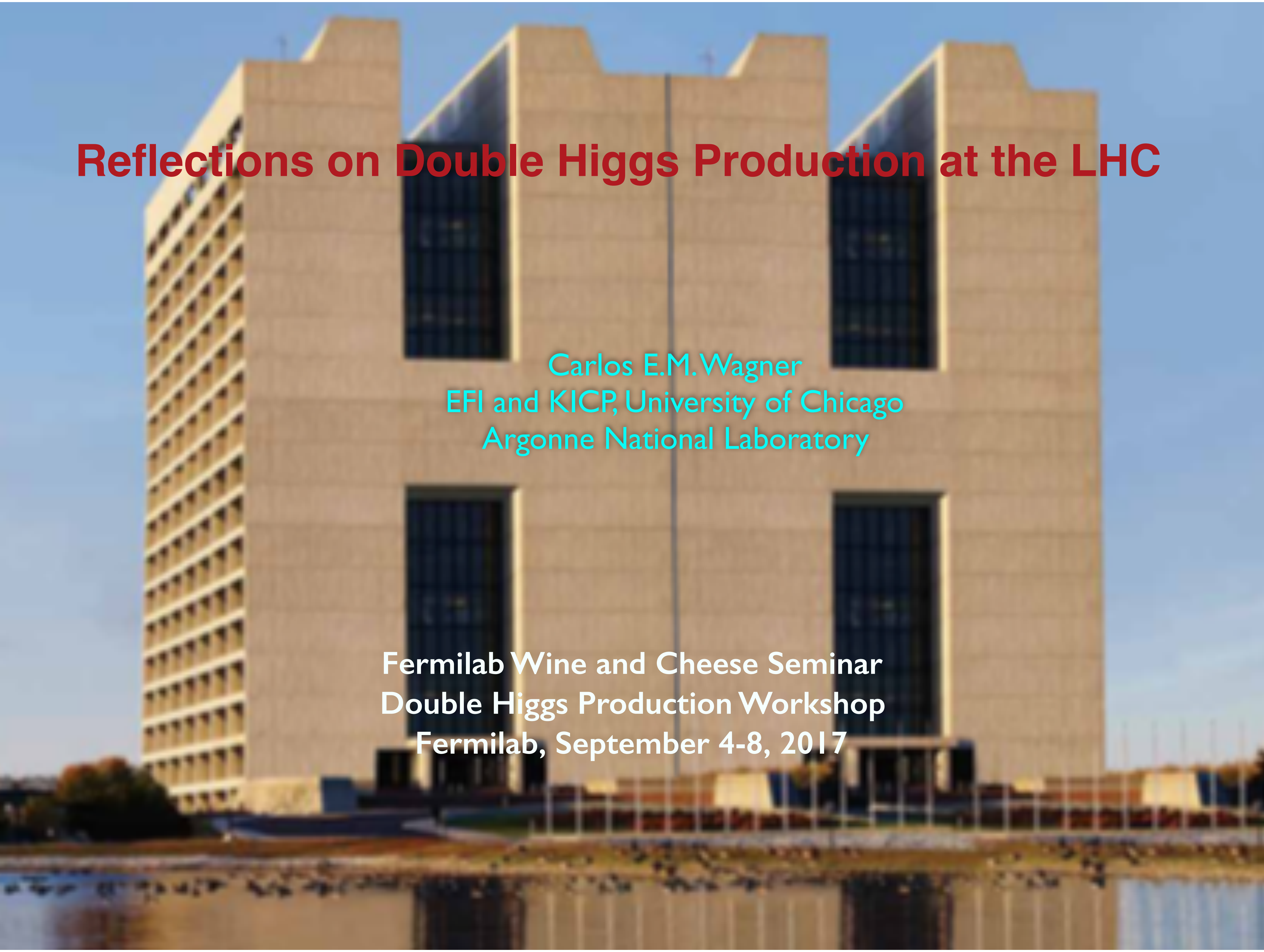
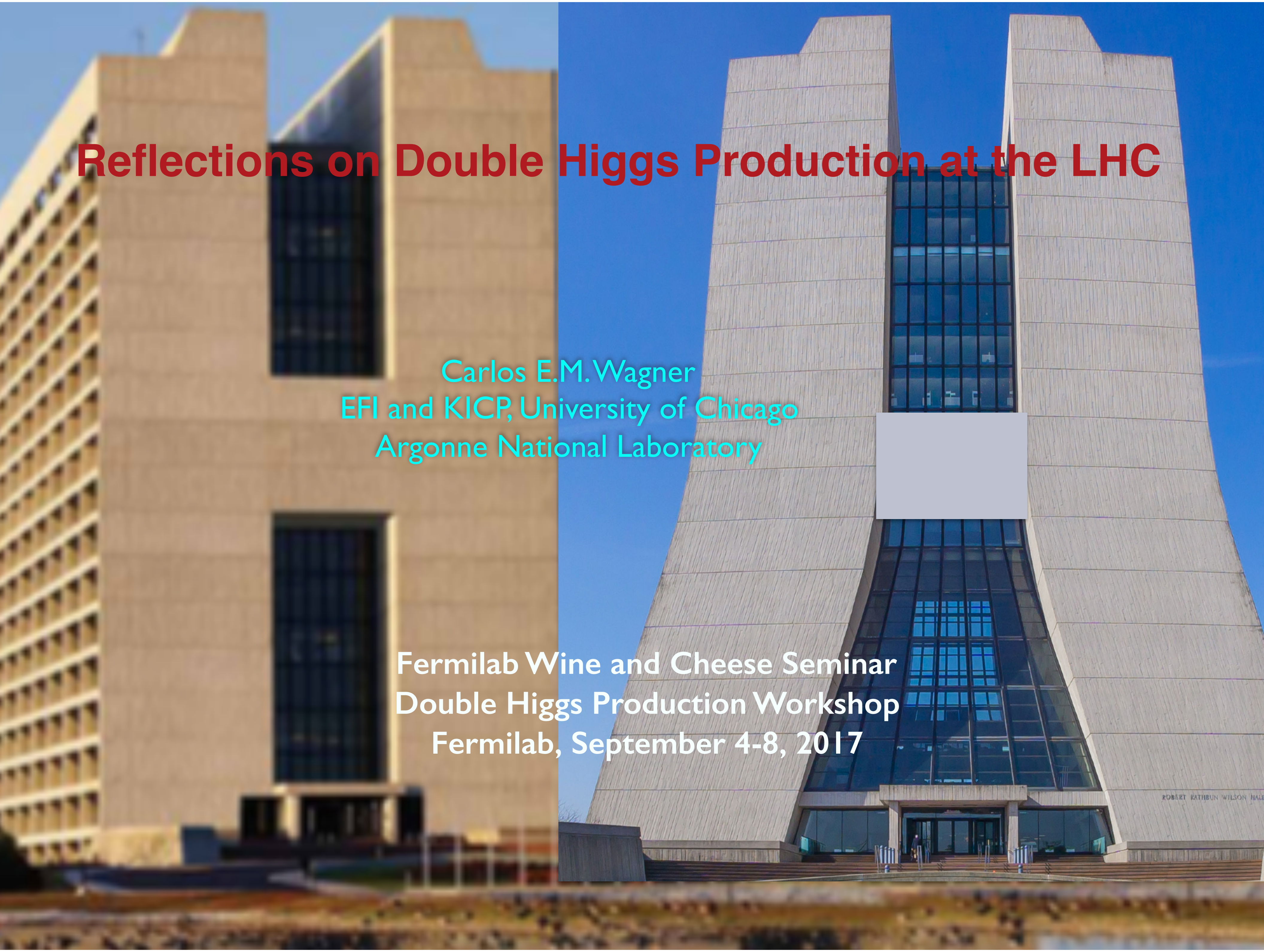


Reflections on Double Higgs Production at the LHC

Carlos E.M. Wagner
EFI and KICP, University of Chicago
Argonne National Laboratory

Fermilab Wine and Cheese Seminar
Double Higgs Production Workshop
Fermilab, September 4-8, 2017



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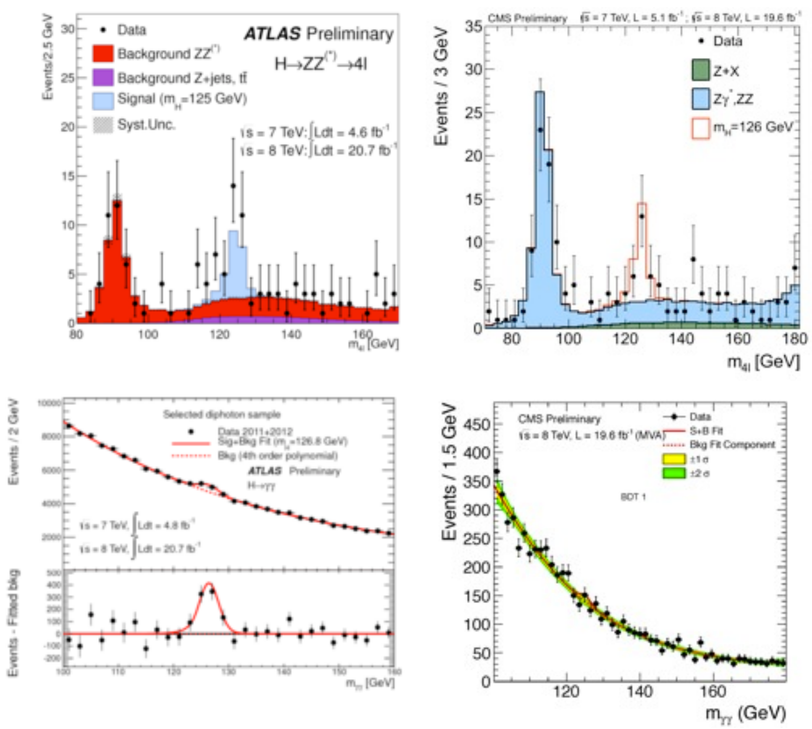
A Standard Model-like Higgs particle has been discovered by the ATLAS and CMS experiments at CERN

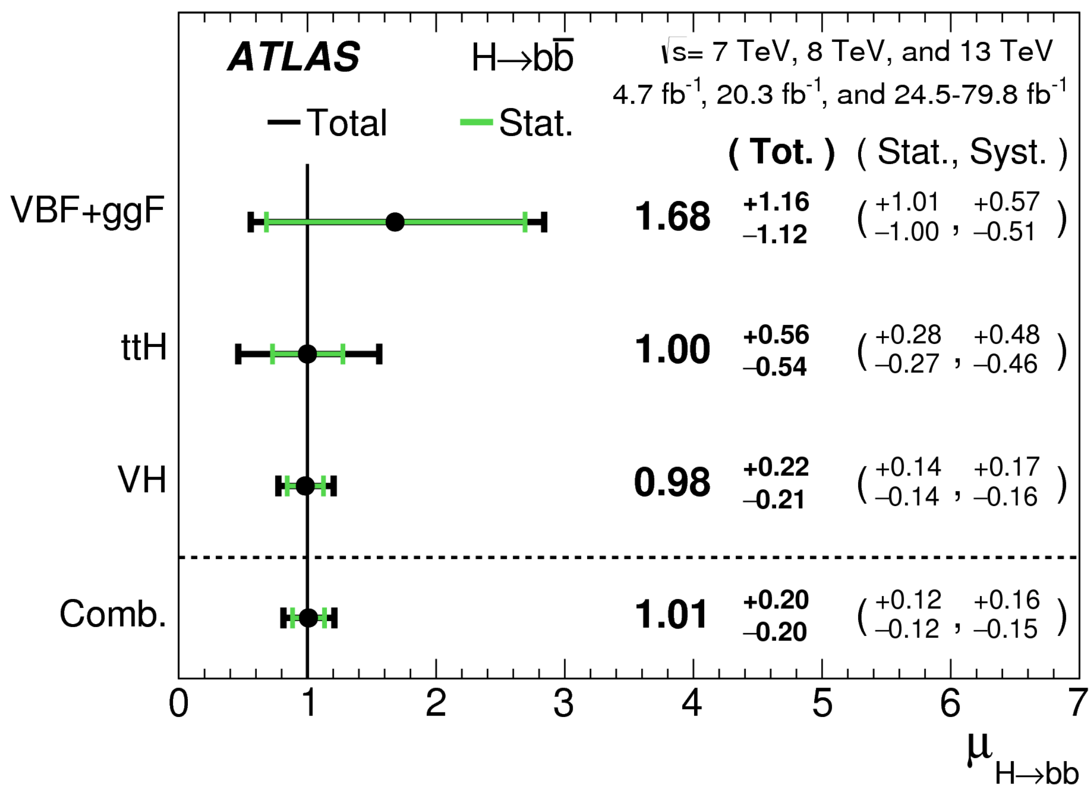


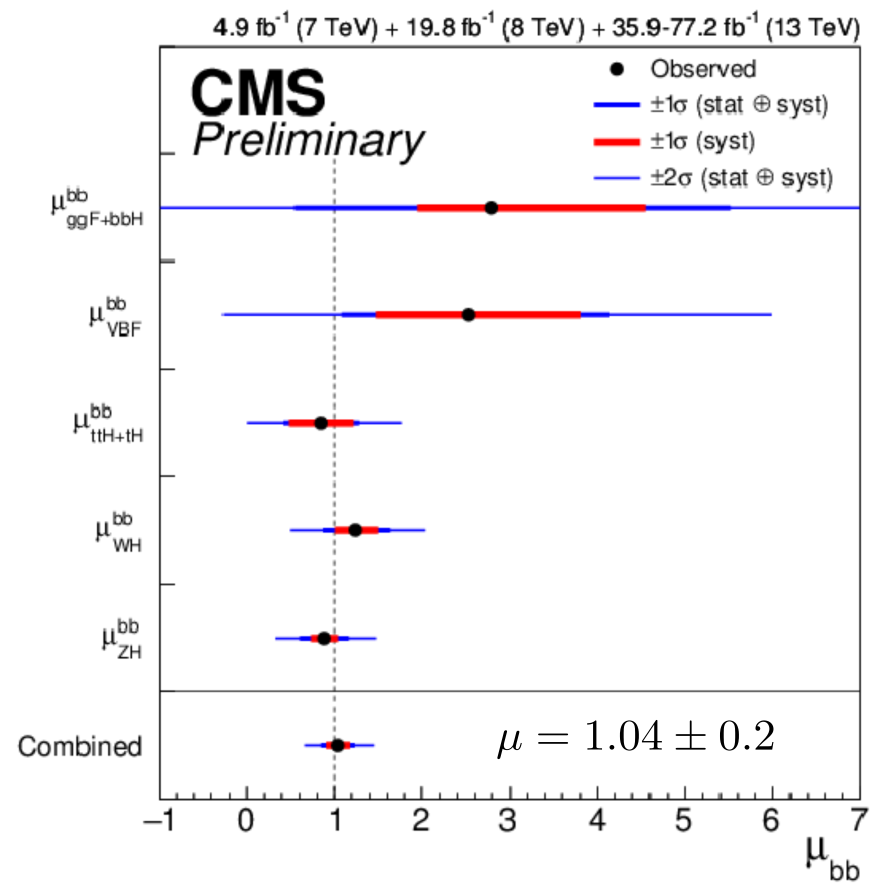
We see evidence of this particle in multiple channels.

We can reconstruct its mass and we know that is about 125 GeV.

The rates are consistent with those expected in the Standard Model.

We have observed the Higgs decaying to bottom quarks



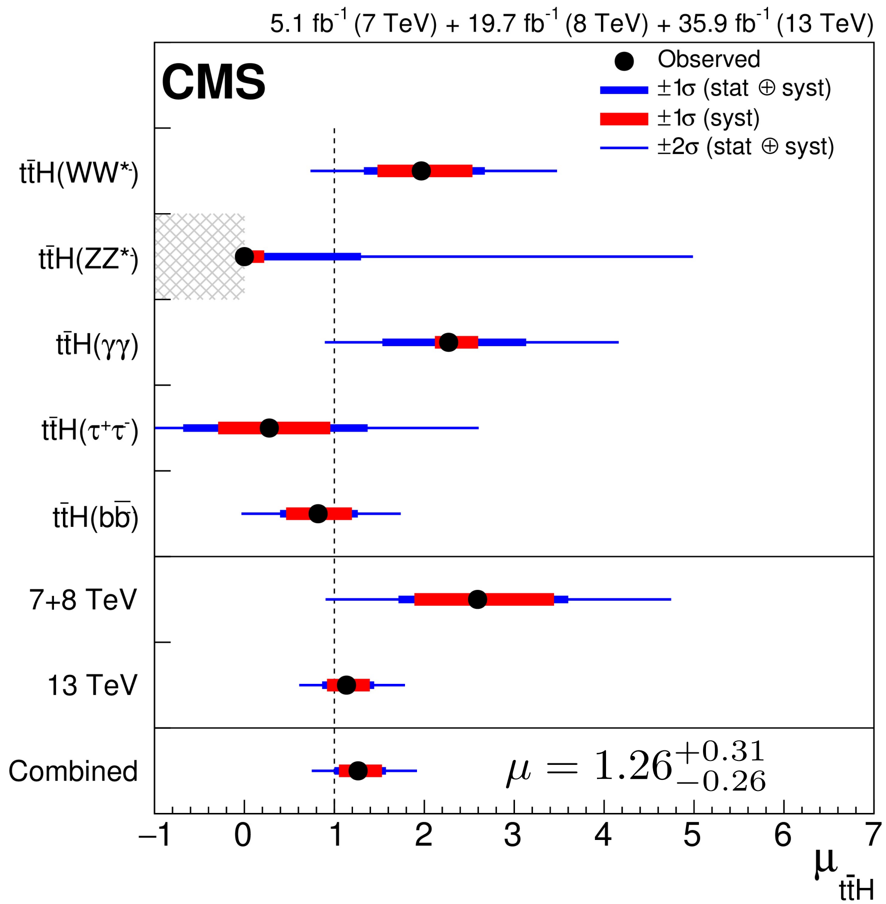


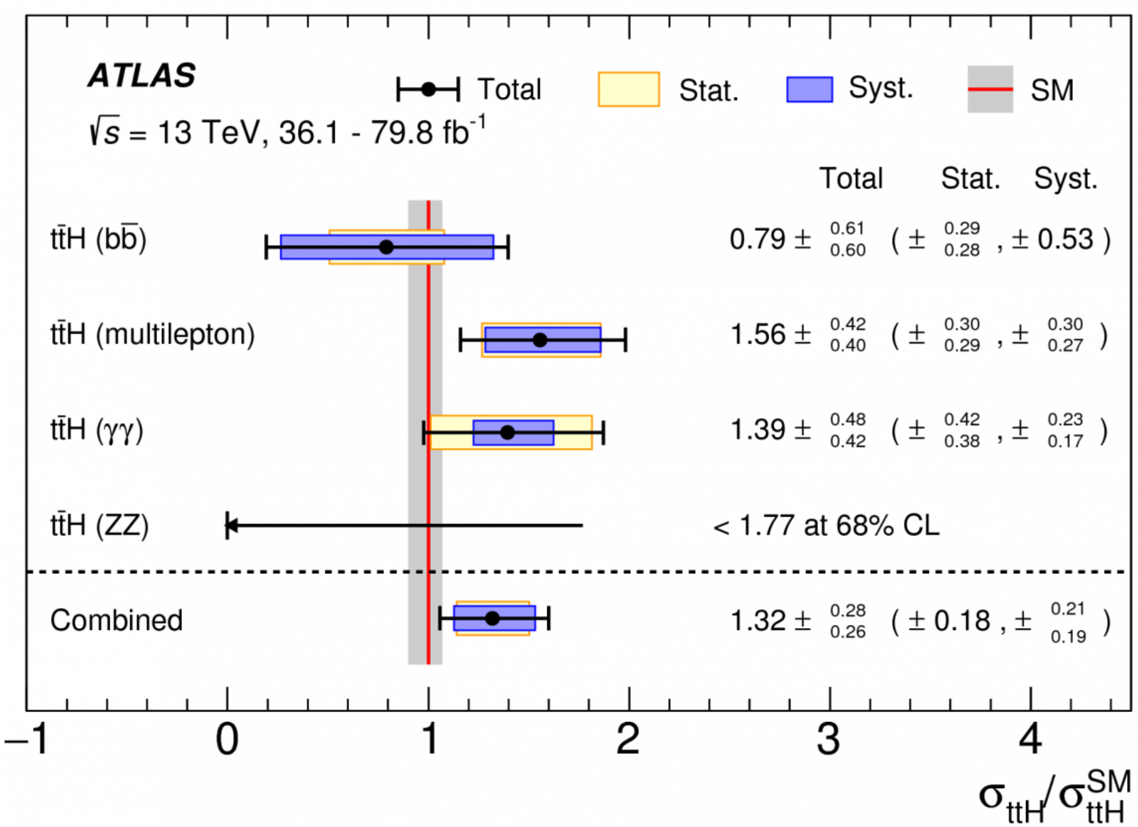
Consistency with SM results

Errors are still large an admit deviations of a few tens of percent from the SM results

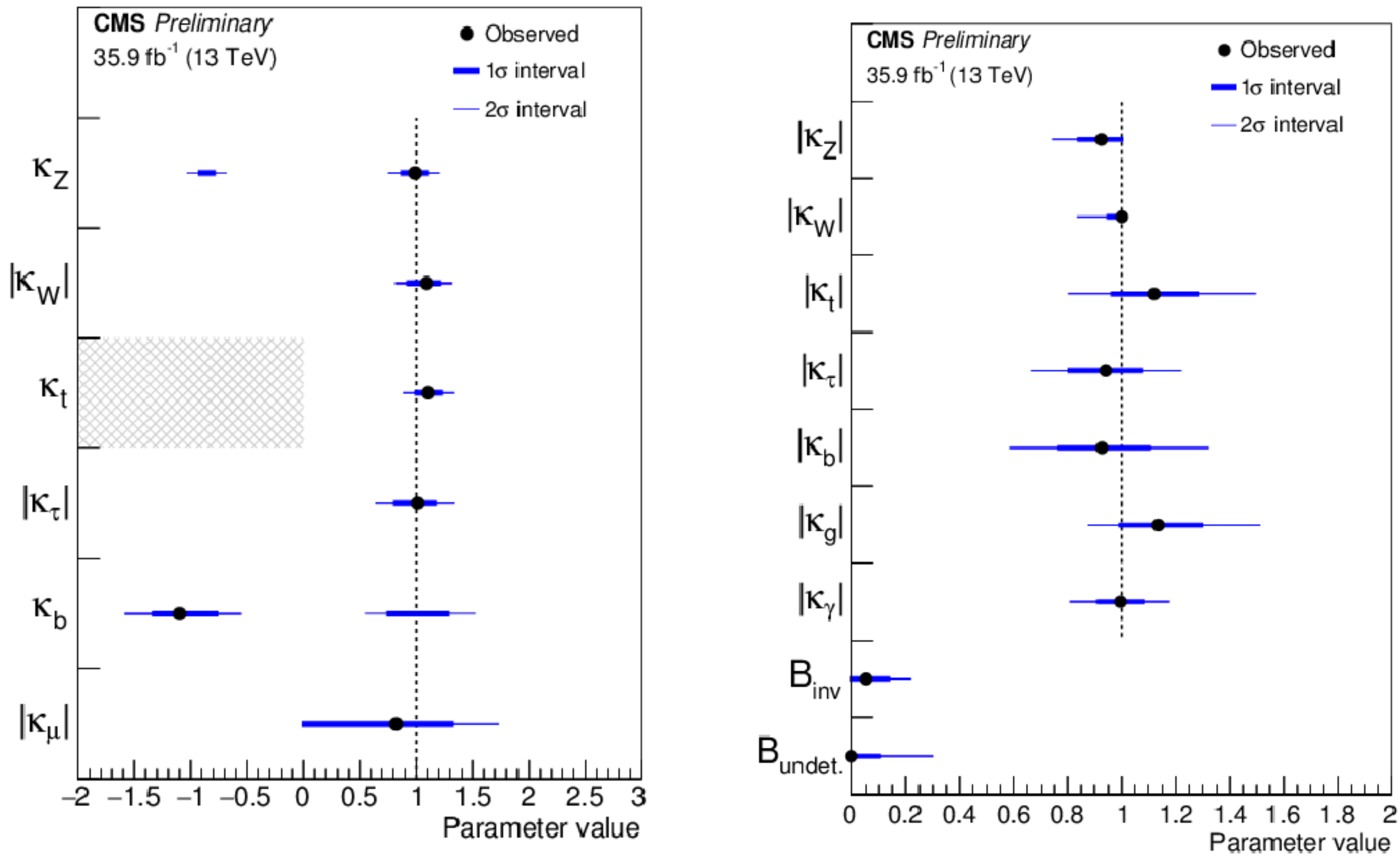
New tth results

Values overall consistent with the SM, but a few interesting small discrepancies are present at both experiments.



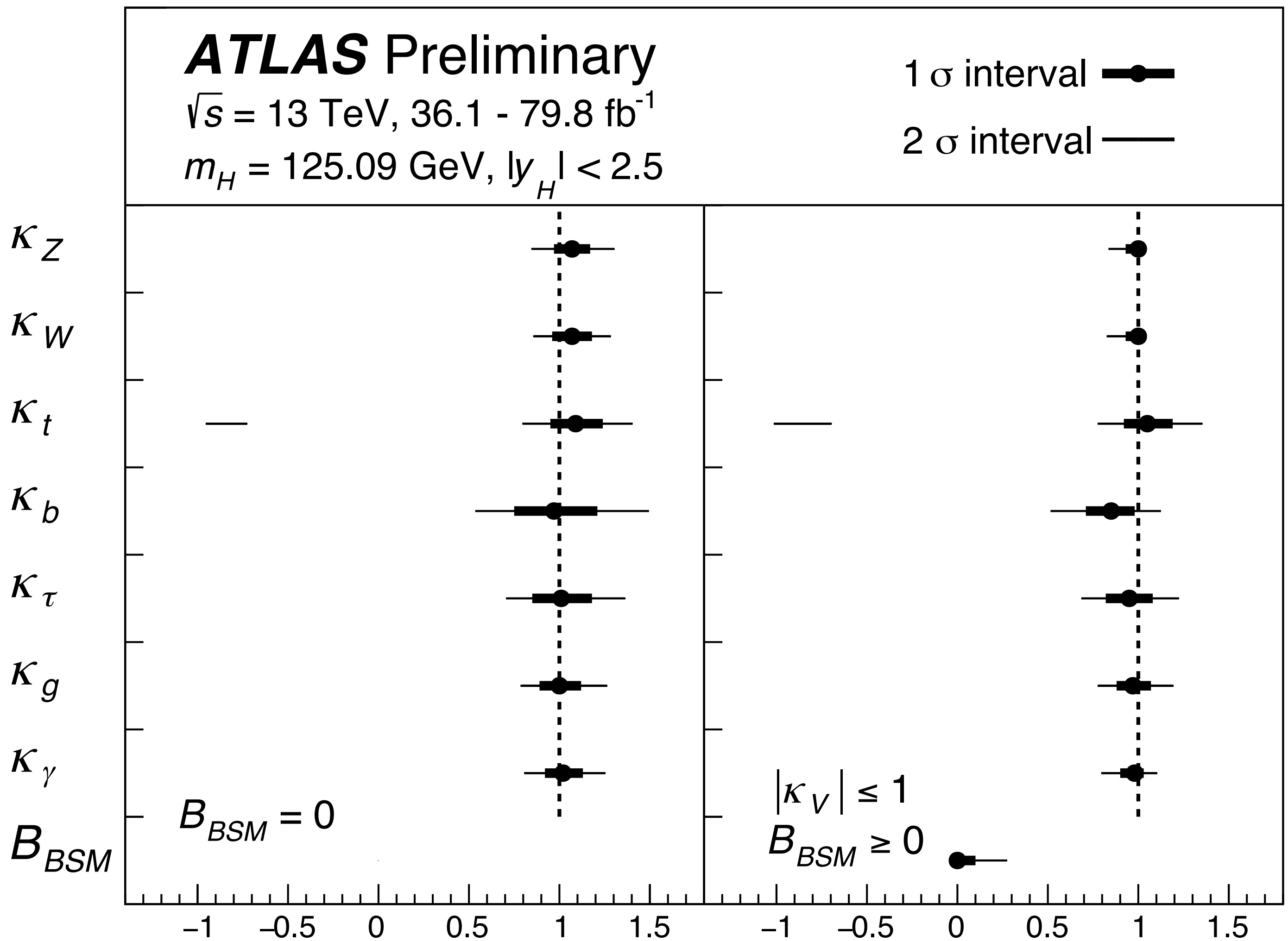


CMS Fit to Higgs Couplings
Remarkable agreement with SM values



ATLAS Fit to Higgs Couplings

Departure from SM predictions of the order of few tens of percent allowed at this point



Still Unexplored : Self-Couplings of the Higgs Boson

- In the Standard Model, the self couplings are completely determined by the Higgs mass and the vacuum expectation value

$$V_{SM}(h) = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h}{8v^2} h^4$$

- In particular, the trilinear coupling is given by

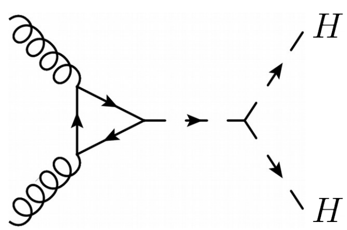
$$g_{hhh} = \frac{3m_h^2}{v}$$

- The Higgs potential can be quite different from the SM potential. So far, we have checked only the Higgs vev and the mass, related to the second derivative of the Higgs at the minimum.
- Therefore, it is important to measure the trilinear and quartic coupling to check its consistency with the SM predictions.
- Double Higgs production allows to probe the trilinear Higgs Coupling.

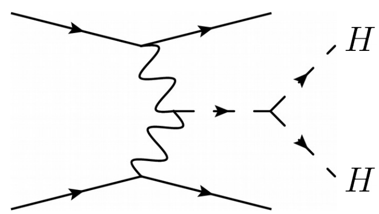
J. Mazzitelli, this workshop

HH production modes

Gluon fusion

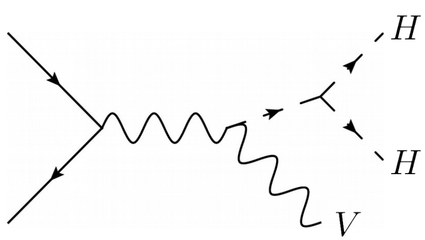


Vector boson fusion



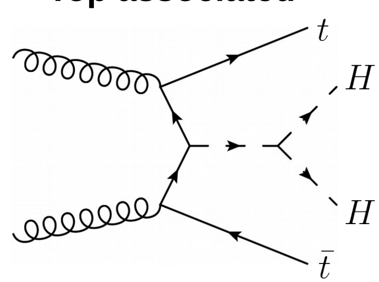
NLO [1,2] NNLO [3],
LO ggF contamination [6]

Higgs–strahlung

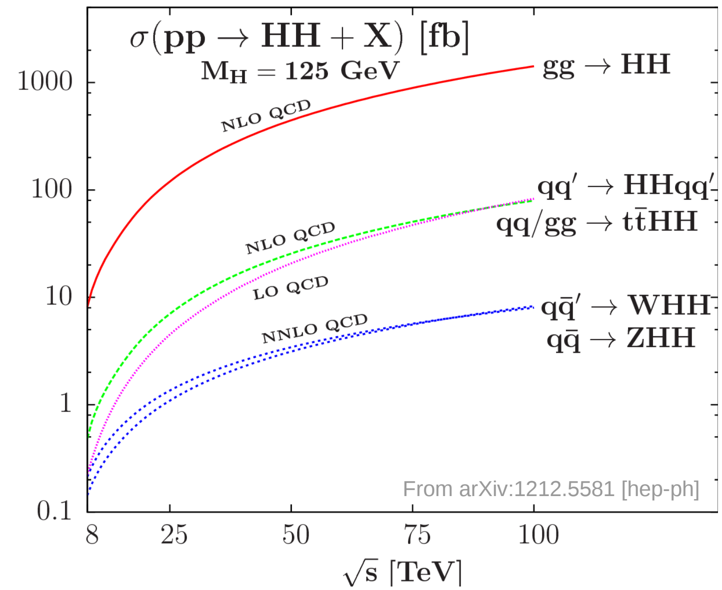


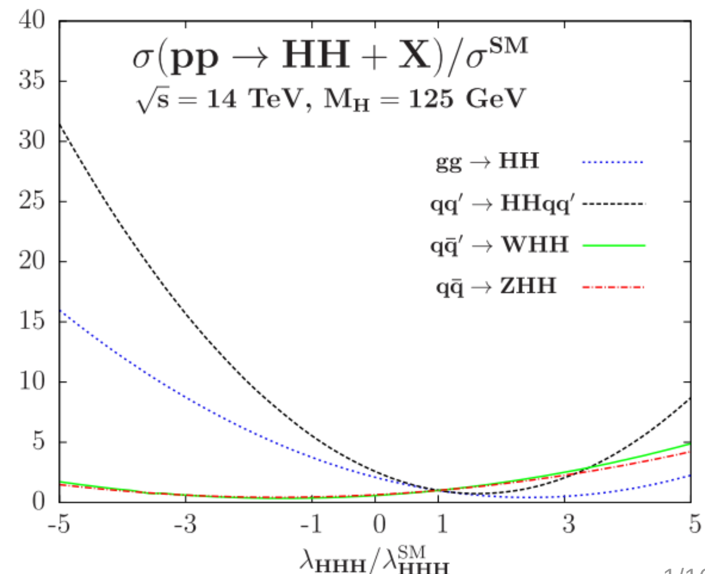
NLO [1,2] NNLO [1,4,5]

Top associated



NLO [2]

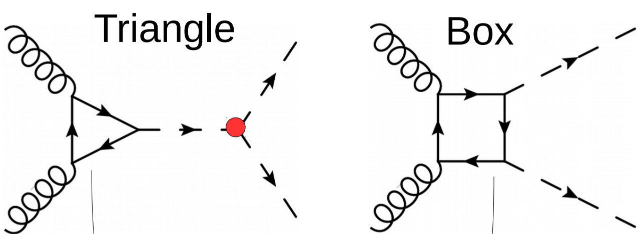




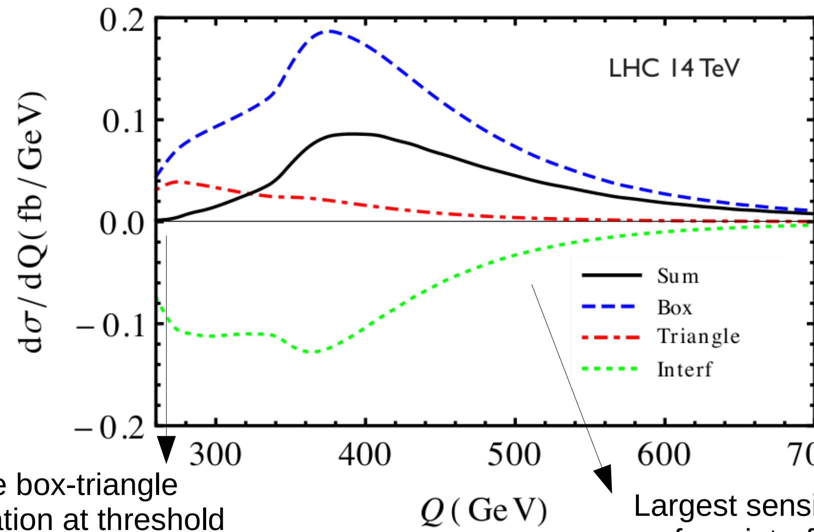
[1] Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira 12;
[2] Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro 14;
[3] Ling, Zhang, Ma, Guo, Li, Li 14; [4] Li, Wang 16; [5] Li, Li, Wang 17;
[6] Dolan, Englert, Greiner, Nordstrom, Spannowsky 15;

Gluon fusion status

- **Leading Order: loop-induced**
  Glover, van der Bij 88



Mostly top contribution
(bottom effects <1%)

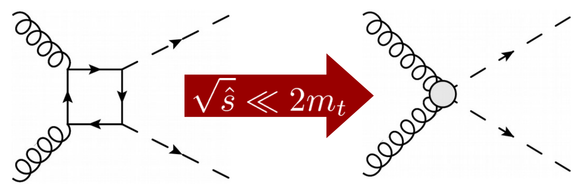


Large box-triangle cancellation at threshold

Largest sensitivity to λ from interference

- **Next-to-Leading Order approximations**
  - NLO in the Born-improved heavy m_t limit (HTL) **+90%**
    Dawson, Dittmaier, Spira 98
  - FTapprox: full m_t dependence in real radiation **-10%**
    Maltoni, Vryonidou, Zaro 14
  - $1/m_t$ expansion in virtual corrections **±10%**
    Grigo, Hoff, Melnikov, Steinhauser 13; Grigo, Hoff, Steinhauser 15

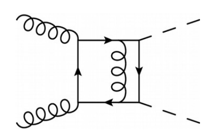
Heavy top limit / HEFT



Born improved:

$$d\sigma^{\text{B-i}}_{\text{N}^i\text{LO}} = d\sigma^{\text{HTL}}_{\text{N}^i\text{LO}} \times \frac{d\sigma_{\text{LO}}}{d\sigma^{\text{HTL}}_{\text{LO}}}$$

- **Full NLO corrections** **-15% w.r.t. B-i NLO**
  Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16;
  Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16
  - Two-loop corrections computed numerically using sector decomposition
  - Grid+interpolation for fast numerical evaluation



New independent calculation, see Julien Baglio's talk

J. Mazzitelli, this workshop

NNLO total cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO_{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO_{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO_{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO_{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO_{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\mathrm{NNLO_{FTapprox}/NLO}$	1.118	1.116	1.096	1.067

$$\mu_0 = m_{hh}/2$$
$$m_h = 125 \text{ GeV}$$
$$m_t = 173 \text{ GeV}$$

Recall, in YR4:

$$\sigma_{\mathrm{YR4}} = \sigma^{\mathrm{HTL}}_{\mathrm{NNLL}} + \left(\sigma^{\mathrm{full}}_{\mathrm{NLO}} - \sigma^{\mathrm{HTL}}_{\mathrm{NLO}}\right)$$

$$\sigma(13 \text{ TeV}) = 33.53 \text{ fb}$$

and arbitrary ±5% m_t uncertainties

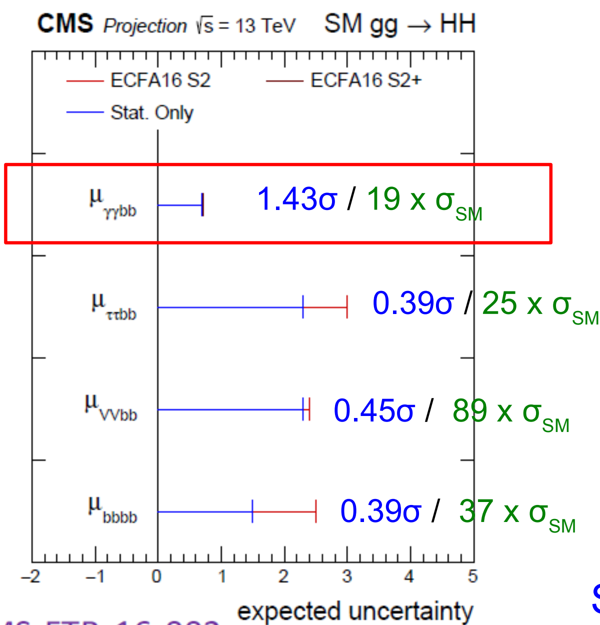
- **Increase** w.r.t. previous order of about **12% for LHC** (~20% for $\mu=m_{hh}$), size decreasing with the energy
- Smaller cross sections compared to previous approximations (larger difference for higher energies)
- Strong **reduction** of the **scale uncertainties**
- Size of **missing m_t effects** estimated at the **few percent level**
  Based on performance at previous order and on comparison between different approximations
- PDF+α_s uncertainties: ±3.0% at the LHC

Small cross sections, together with relevant background limit the sensitivity of the Standard Model trilinear couplings at the LHC

D. Delgove, this workshop

Projection for yybb

- Systematic uncertainty in jet energy scale is expected to reach 1%
- 1 (2) % uncertainty in the selection efficiency of b (c) quark
- 2-10% of uncertainty in misidentifying a light jet
- No degradation of the resolution and vertex finding



CMS-FTR-16-002

- The following cuts are applied :

Photon selection :
- Leading $p_T > m_{yy}/3$
- Sub-Leading $p_T > m_{yy}/4$
- $|\eta| < 2.5$
- $100 < m_{yy} < 180$ GeV

Jet Selection :
- $p_T > 25$ GeV
- $\Delta Ryj > 0.4$
- $|\eta| < 2.4$
- $80 < m_{jj} < 200$ GeV

- The events are classified depending on the b-tagging score of the jets and m_{hh}

Significance for 3000fb^{-1} projected from 2.3-2.7 fb^{-1} / Expected limit – Run 2 analyses (36fb^{-1})

Efforts to increase the significance of the bbWW channel by using “topness” and “Higgsness” variables (talk by J. Kim, this workshop)

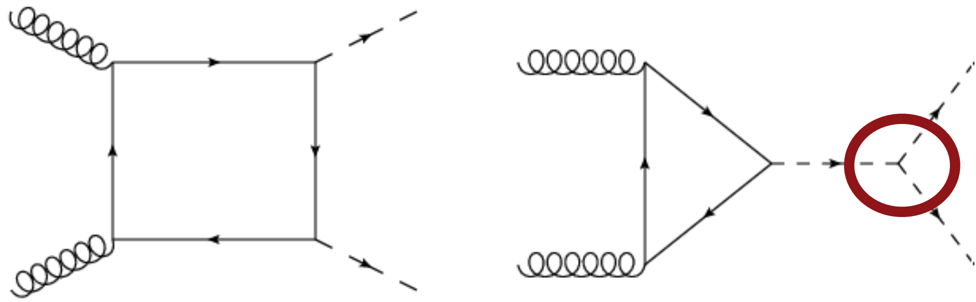
Beyond the Standard Model

- The Higgs mass parameter is sensitive to new physics effects that could modify its value to values of the order of the new physics scale.
- For this reason, one expects new physics not far above the TeV scale.
- Such new physics could lead to a modification of the Higgs couplings to SM particles, and also of the Higgs self couplings.
- In particular, modifications of the top Yukawa coupling or the trilinear Higgs coupling would lead to a modification of the loop induced rate.

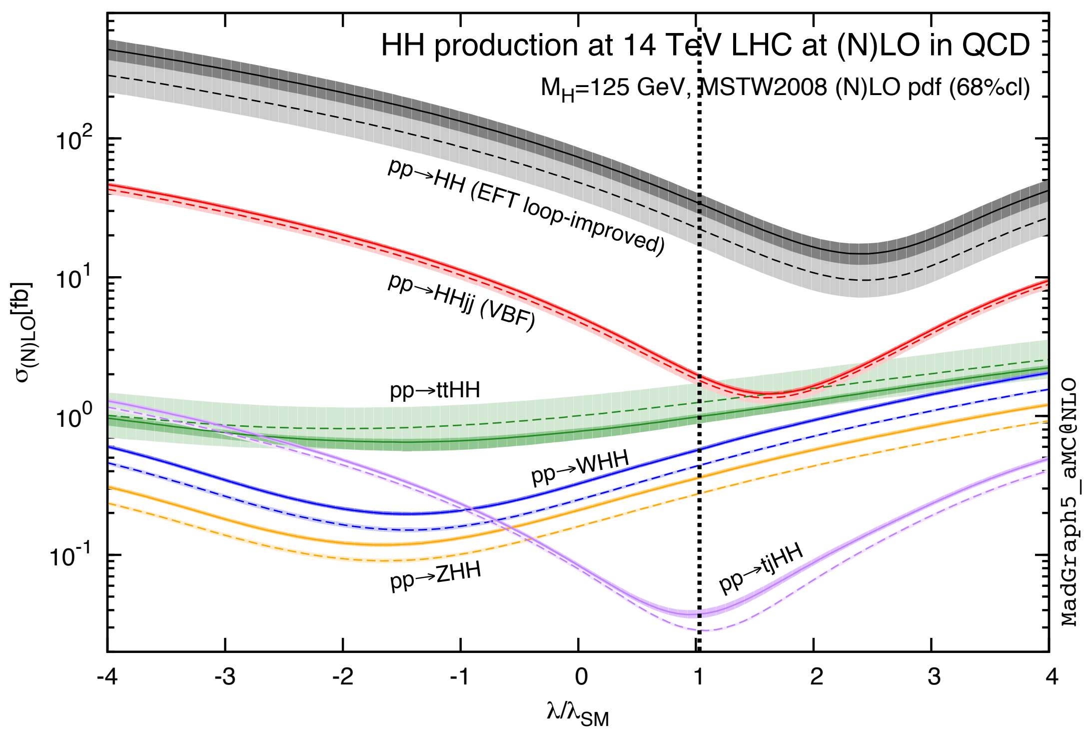
Other things may happen :

- New particles can appear in the loop, dealing to modified Double Higgs production cross section.
- New resonances can appear, decaying to Higgs pairs.

Di-Higgs Production dependence on the Higgs self coupling



Top Coupling Fixed to the SM value.



Frederix et al'14

Box Diagram is dominant, and hence interference in the gluon fusion channel tends to be enhanced for larger values of the coupling. At sufficiently large values of the coupling, or negative values, the production cross section is enhanced.

S. Di Vita's talk, this workshop

Large λ_3 in tuned Higgs Portal

1 dimensionless parameter — 1 coupling — 1 scale — singlet — potential — dimensionless argument

$$\mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_*\varphi/m_*)$$

Linear EFT valid if
(expansion in h/v)

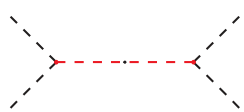
$$\varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2} \ll 1$$

Otherwise only derivative expansion
is allowed, many more couplings!!

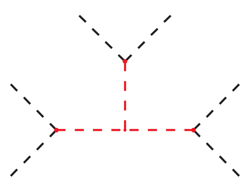
parametrically large λ_3
(paying some tuning)

$$\theta \simeq 1\,,\ g_* \simeq 3\,,\ m_* \simeq 2.5\ \mathrm{TeV}$$

$$\varepsilon \simeq 0.1\,,\ 1/\Delta \simeq 1.5\%\,,\ \delta c_z \simeq 0.1\,,\ \boldsymbol{\delta\kappa_\lambda \simeq}$$



$$\begin{cases} (H^\dagger H)^2 & \Rightarrow \text{tuning of quartic } \Delta \sim \dfrac{\theta^2 g_*^2}{\lambda_3^{\rm SM}} \\ \partial_\mu (H^\dagger H)\partial^\mu (H^\dagger H) & \Rightarrow \delta c_z \sim \theta^2 g_*^2 \dfrac{v^2}{m_*^2} = \theta\varepsilon \end{cases}$$



$$(H^\dagger H)^3 \quad \Rightarrow \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2} = \varepsilon\Delta$$

DV, Grojean, Panico, Riembau, Vantalon [1704.01953]

P. Bokan, this workshop

Limits on the cross-section as a function of κ_λ

$4b$

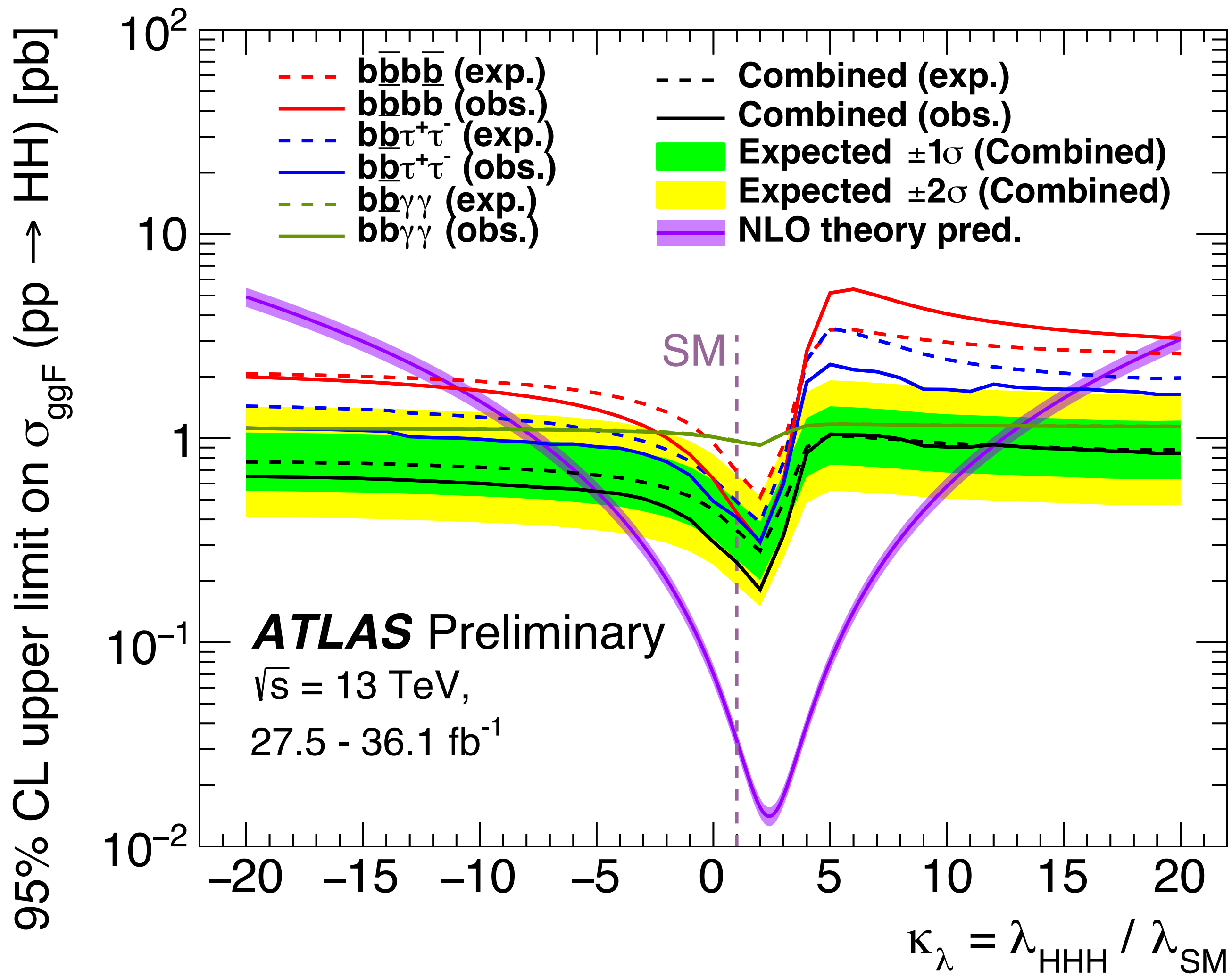
$bb\tau\tau$

$bb\gamma\gamma$

combination

dashed: expected

solid: observed



The scale factor κ_λ is observed (expected) to be constrained in the range:

$$-5.0 < \kappa_\lambda < 12.1 \; (-5.8 < \kappa_\lambda < 12.0)$$

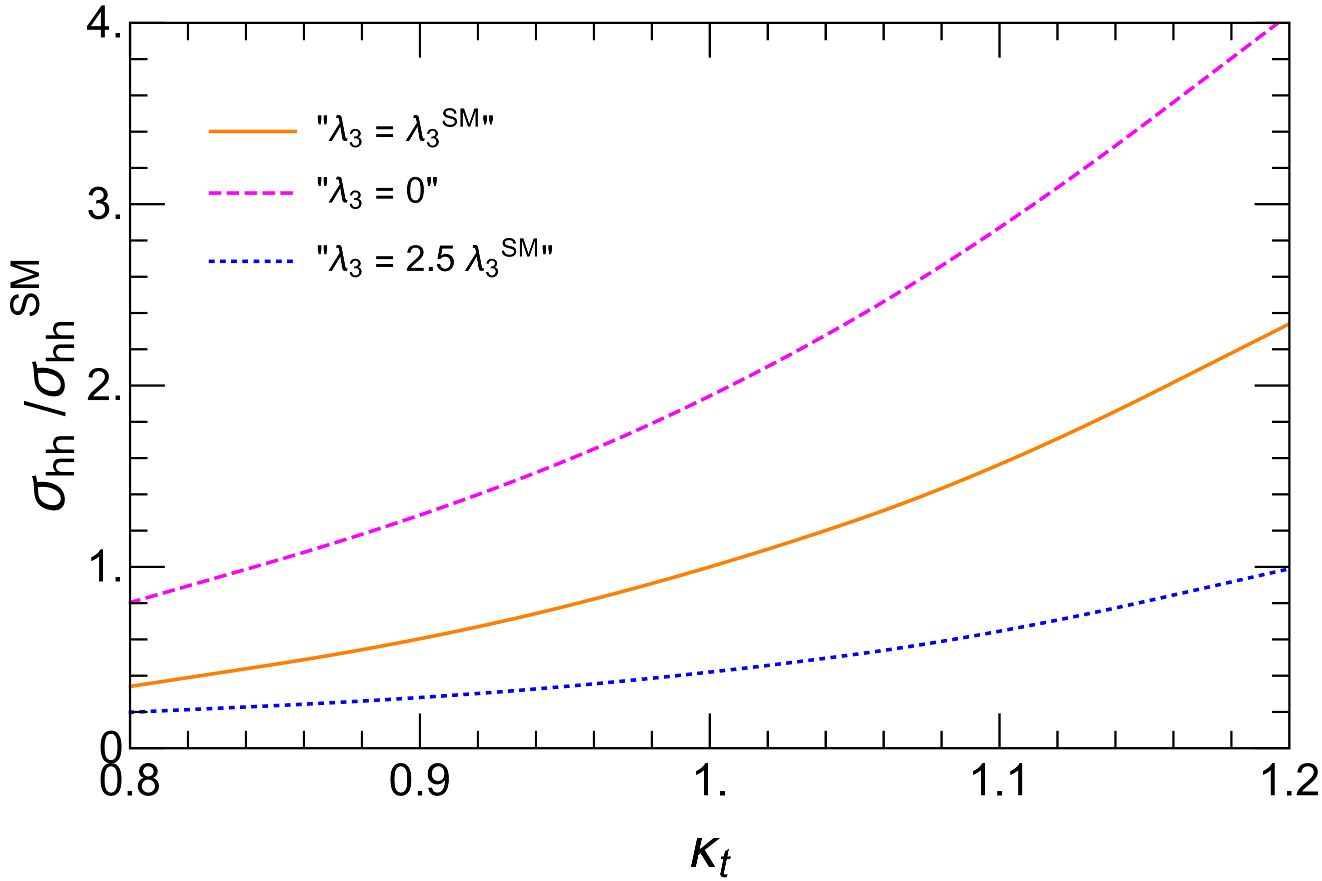
High Lumi LHC : limit on κ_λ (for ATLAS with only yybb channel) :

$0.2 < \kappa_\lambda < 6.9$

D. Delgove, this workshop

Variation of the Di-Higgs Cross Section with the Top Quark and Self Higgs Couplings

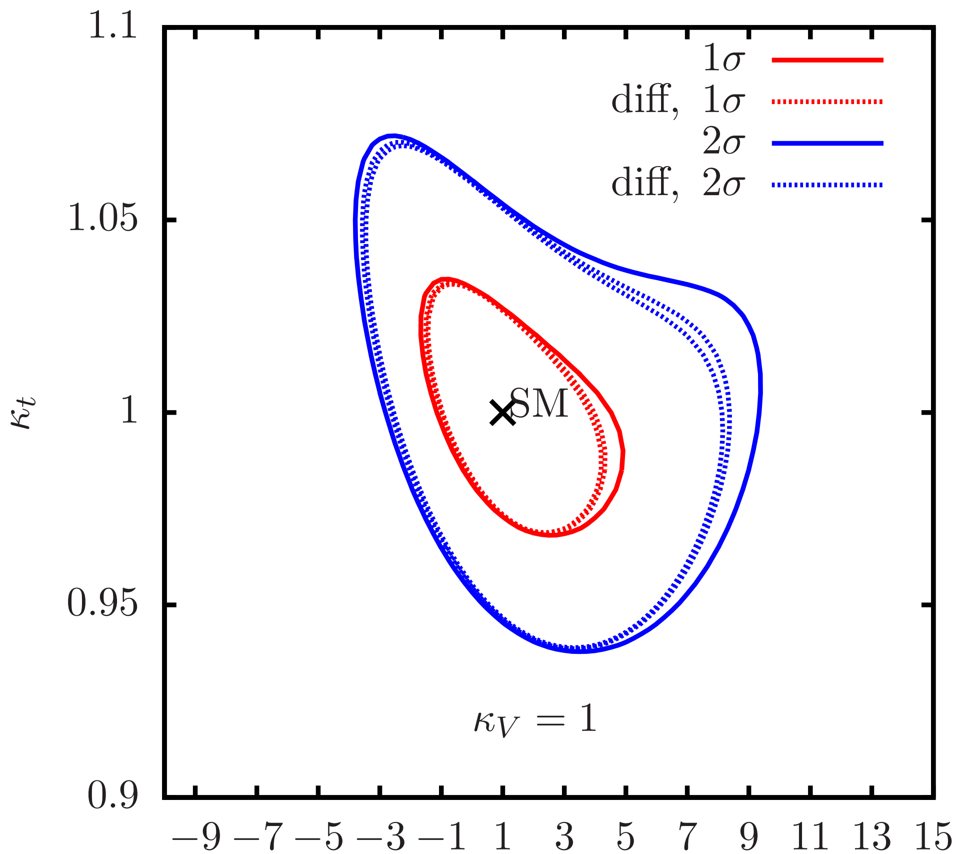
Huang, Joglekar, Li, C.W.'17

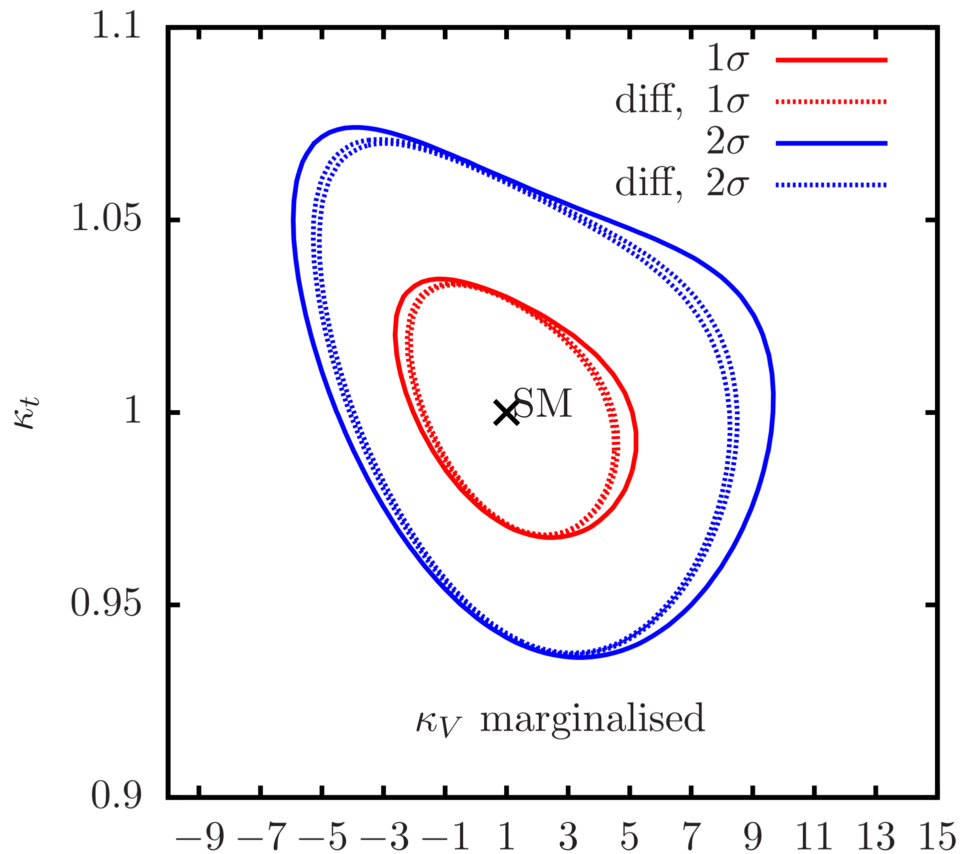


Strong dependence on the value of kt and λ3
Even small variations of kt can lead to 50 percent variations of the di-Higgs cross section

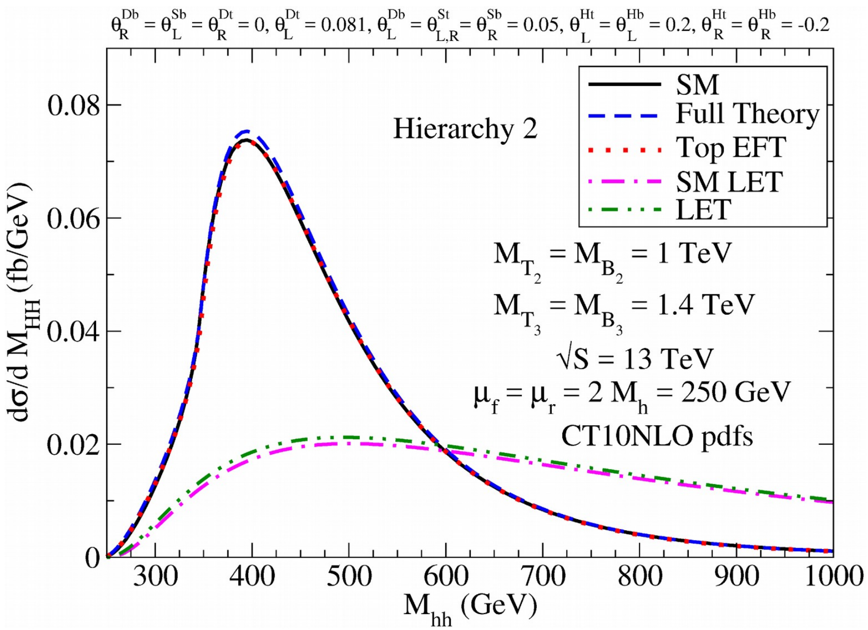
Putting everything together : Sensitivity at the high luminosity LHC

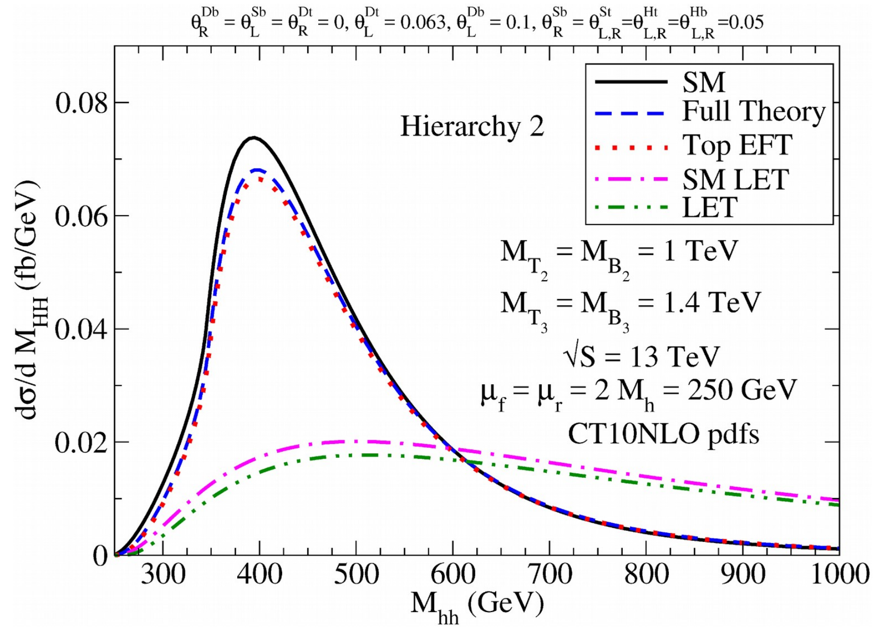
A. Shivaji's talk





New Fermions in the Loop



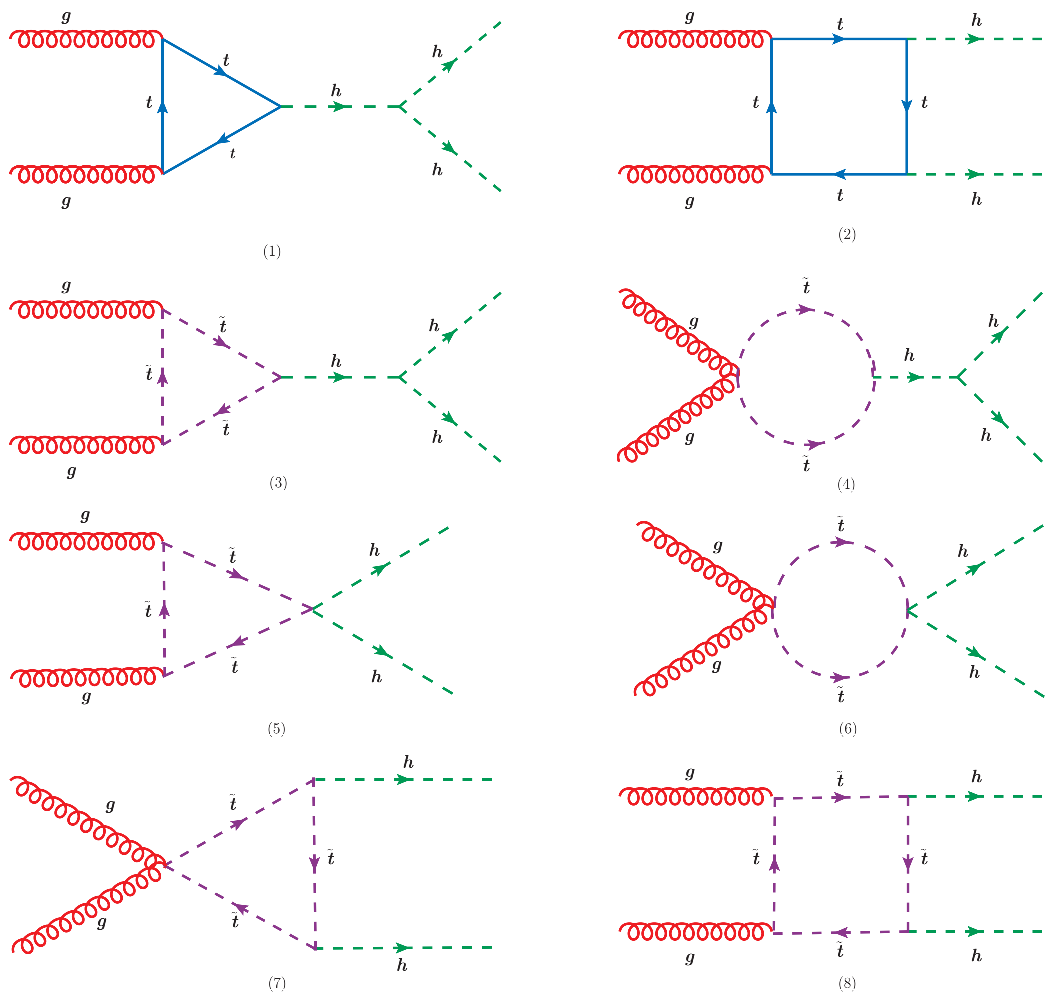


Dawson, Furlan, **IL** PRD87 (2013) 014007; Chen, Dawson, **IL** PRD90 (2014) 035016

- Assume full vector-like quark generation:
  - SU(2) Doublet: $Q = (T, B)^t$
  - Two SU(2) Singlets: $U,\ D$
- Two up-type and two down-type heavy quarks: $T_2,\ T_3,\ B_2,\ B_3$

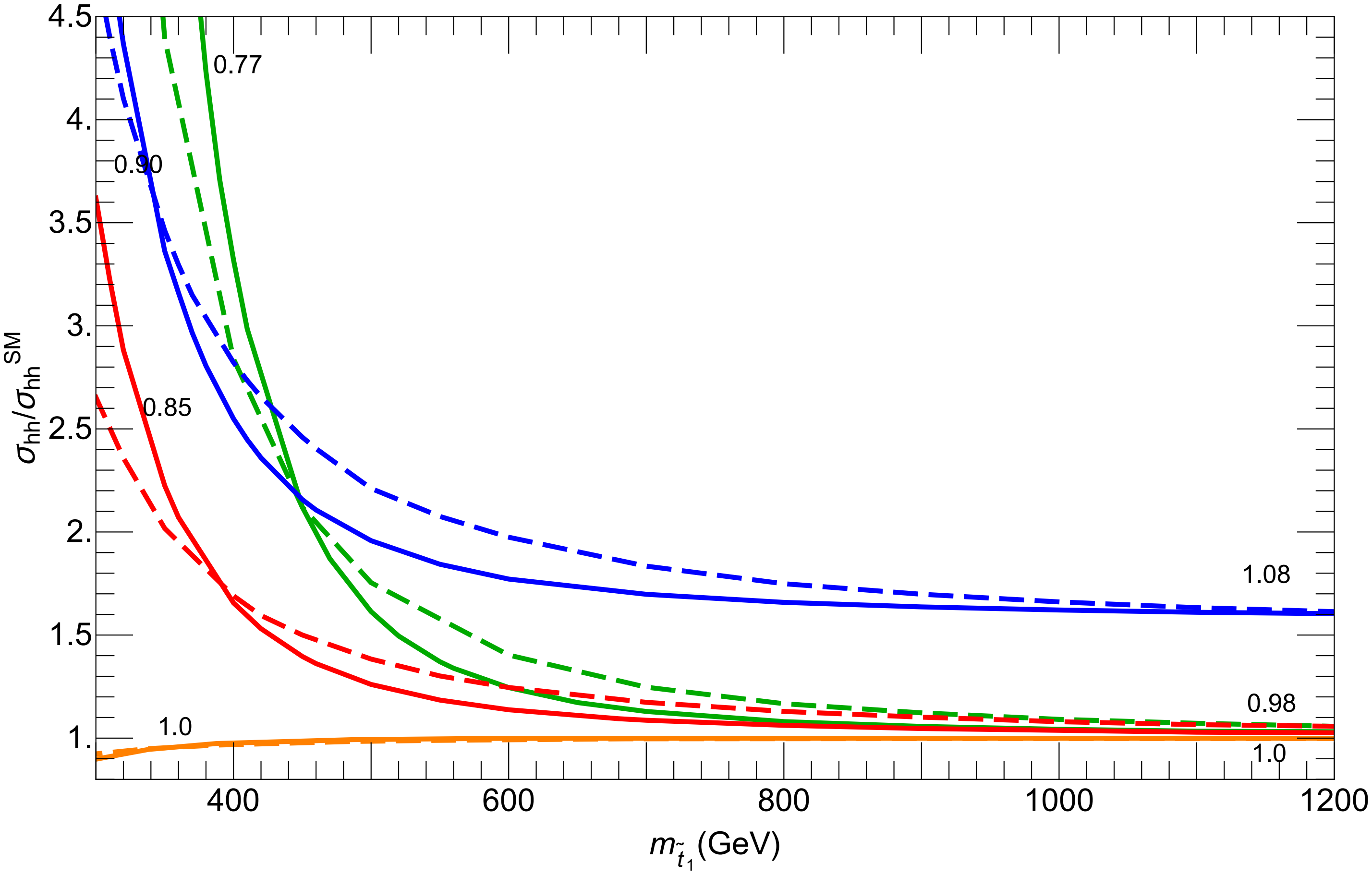
Huang, Joglekar, Li, C.W.'17

Stop Contributions



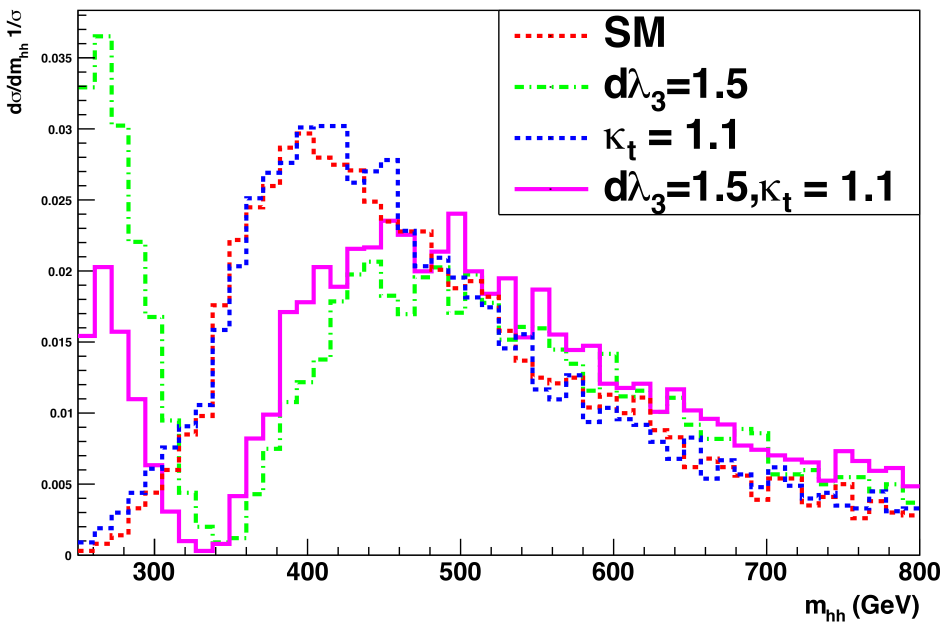
Stop Effects on Di-Higgs Production Cross Section

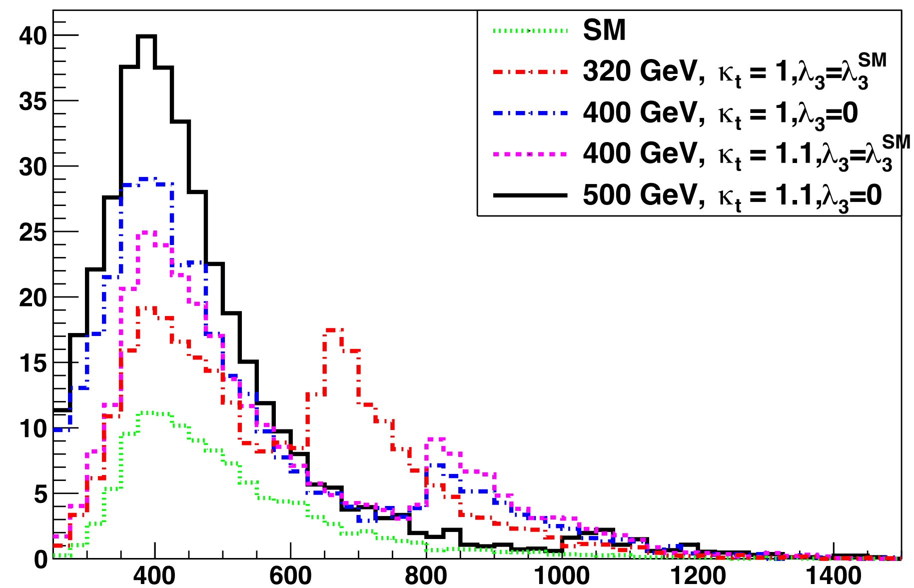
Huang, Joglekar, Li, C.W.'17



Orange : Stop corrections to kappa_g decoupled
Red : X_t fixed at color breaking vacuum boundary value, for light mA
Green : X_t fixed at color breaking boundary value, for mA = 1.5 TeV
Blue : Same as Red, but considering \kappa_t = 1.1

Invariant Mass Distributions





Provided lambda3 is not shifted to large values, acceptances similar as in the Standard Model

Why do we care about the potential ?

- First of all, it is a fundamental part of the Standard Model. If new physics is at very high scales, one expects a renormalizable potential, like in the SM

$$V(\phi, 0) = \frac{m^2}{2}(\phi^\dagger\phi) + \frac{\lambda}{4}(\phi^\dagger\phi)^4 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}} \left(\phi^\dagger\phi\right)^{n+2}$$

- All terms beyond the first two would cancel.
- If, however, there is new physics coupled to the Higgs close to the weak scale, one would expect non-trivial modifications to the potential, that should be measurable.
- The trilinear coupling may be obtained, in general,

P. Huang, A. Joglekar, B. Li, C.W.'15

$$\lambda_3 = \frac{3m_h^2}{v}\left(1 + \frac{8v^2}{3m_h^2}\sum_{n=1}^{\infty}\frac{n(n+1)(n+2)c_{2n+4}v^{2n}}{2^{n+2}\Lambda^{2n}}\right).$$

- Hence, the departures from the SM prediction are a probe of the potential modifications.

$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1 = \frac{8v^2}{3m_h^2}\sum_{n=1}^{\infty}\frac{n(n+1)(n+2)c_{2n+4}v^{2n}}{2^{n+2}\Lambda^{2n}}$$

Theory vs. Observation

- Baryons annihilate with antibaryons via strong interactions mediated by mesons. Assuming you start from equal number of batons and antibaryons, this is a very efficient annihilation channel and one can show that the density will freeze at

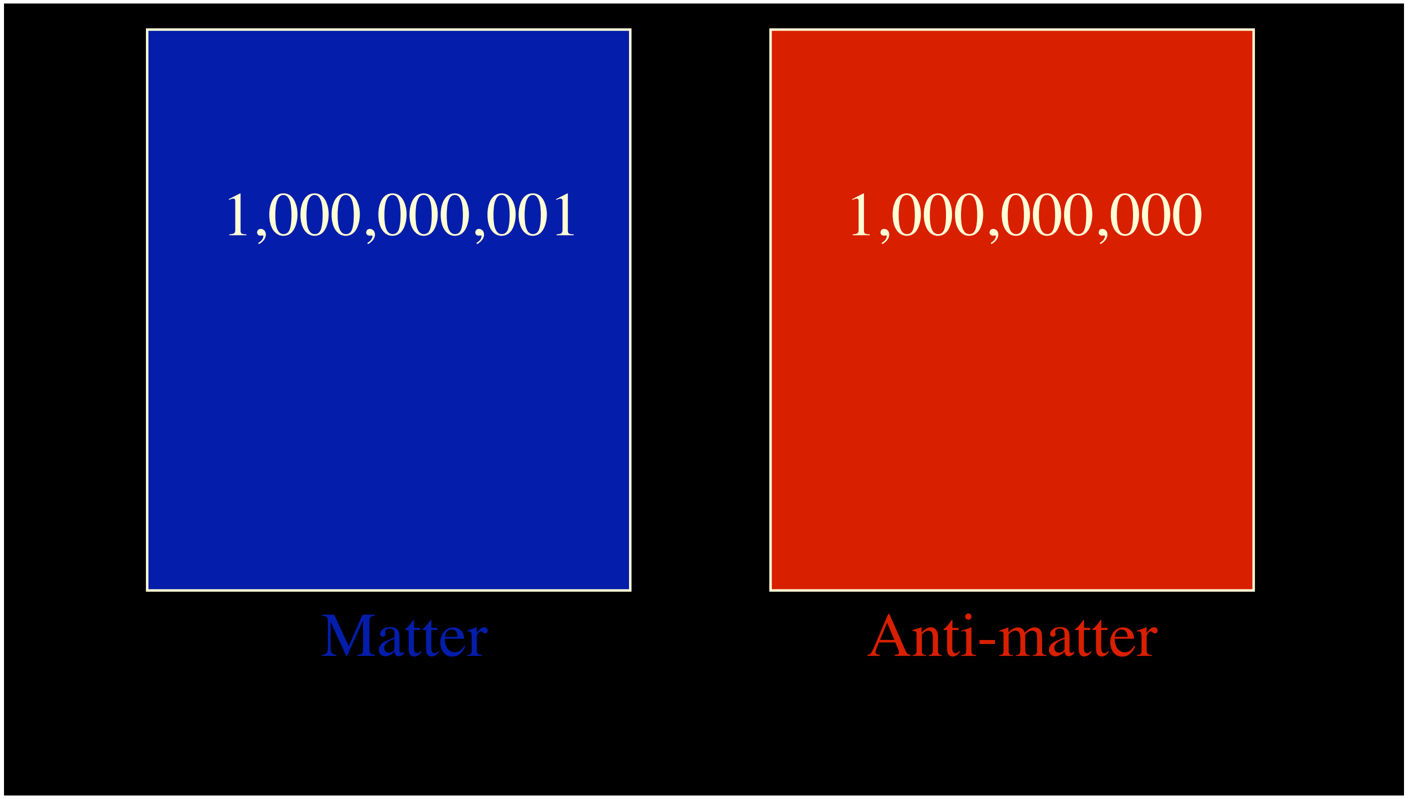
$$\frac{n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \simeq 10^{-20}$$

- How does this compare to experiment ? First of all, we have the problem of the unobserved antimatter. Secondly, from the analysis of BBN and CMBR, one obtains, consistently

$$\frac{n_B}{n_\gamma} \approx 6\ 10^{-10}$$

- How to explain the absence of antimatter and the appearence of such a small asymmetry ?

Small Asymmetry may be generated primordially : Baryogenesis



Murayama

Assuming the existence of a small primordial asymmetry solves the puzzle. Indeed, matter-antimatter annihilation can now occur efficiently and finally the small asymmetry will lead to observable matter in the Universe

Baryogenesis at the weak scale

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :

- Baryon number violation: Anomalous Processes

- C and CP violation: Quark CKM mixing

- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s}\,\exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}}\exp\left(-\frac{\mathrm{E_{sph}}(\mathrm{T_c})}{\mathrm{T_c}}\right)\right)$$

$$\mathbf{E_{sph}} \propto \frac{8\pi\,\mathbf{v}}{\mathbf{g}}$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

Klinkhamer and Manton '85, Arnold and Mc Lerran '88

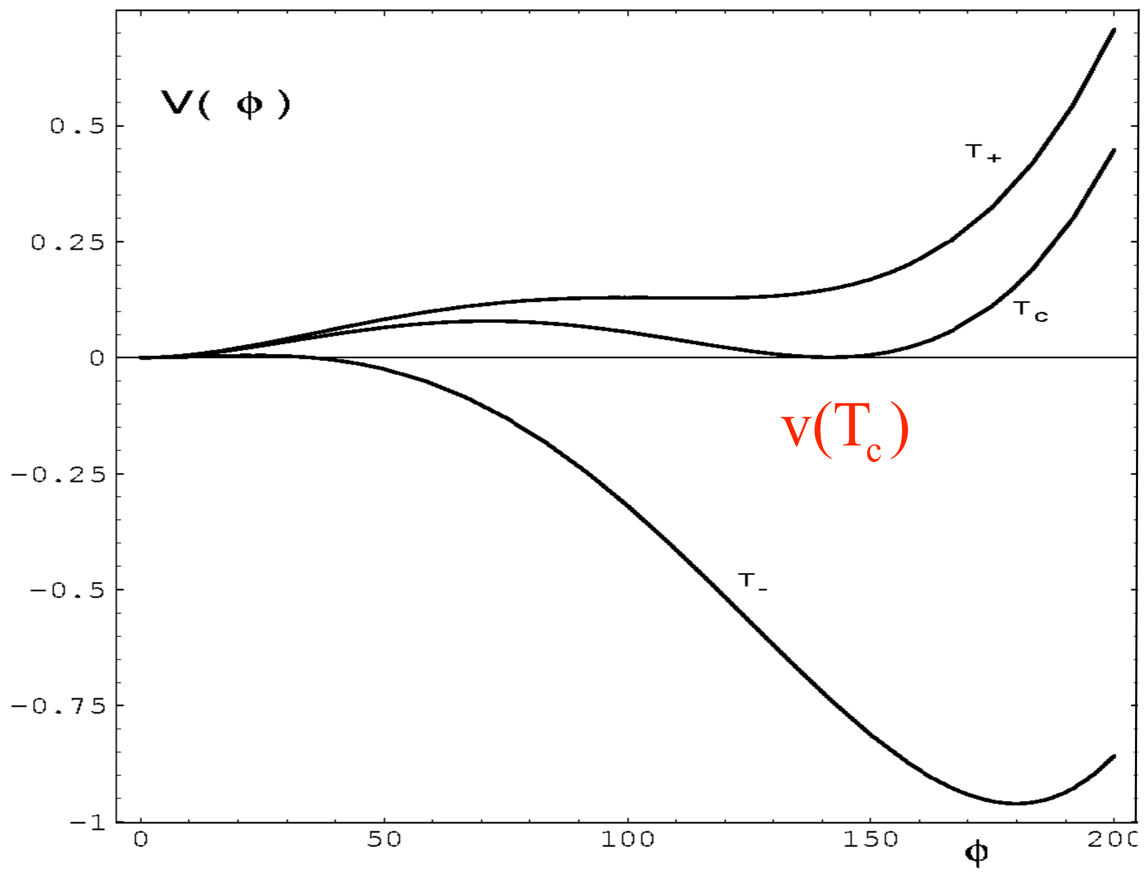
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

$$\frac{\mathrm{v}(T_c)}{T_c} > 1$$

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Gravitational Waves may be produced at the Phase Transition

Ghosh, this workshop

First Order Phase Transition

Grojean, Servant, Wells'06
Joglekar, Huang, Li, C.W.'15

- Simpler case

$$V(\phi, T) = \frac{m^2 + a_0 T^2}{2}\left(\phi^\dagger \phi\right) + \frac{\lambda}{4}\left(\phi^\dagger \phi\right)^2 + \frac{c_6}{8\Lambda^2}\left(\phi^\dagger \phi\right)^3$$

$$\lambda_3 = \frac{3m_h^2}{v}\left(1 + \frac{2c_6 v^4}{m_h^2 \Lambda^2}\right)$$

- Demanding the minimum at the critical temperature to be degenerate with the trivial one, we obtain

$$\left(\phi_c^\dagger \phi_c\right) = v_c^2 = -\frac{\lambda \Lambda^2}{c_6}. \qquad \lambda + \frac{3c_6}{2\Lambda^2} v^2 = \frac{m_h^2}{2v^2}$$

- Negative values of the quartic coupling, together with positive corrections to the mass coming from non-renormalizable operators demanded.

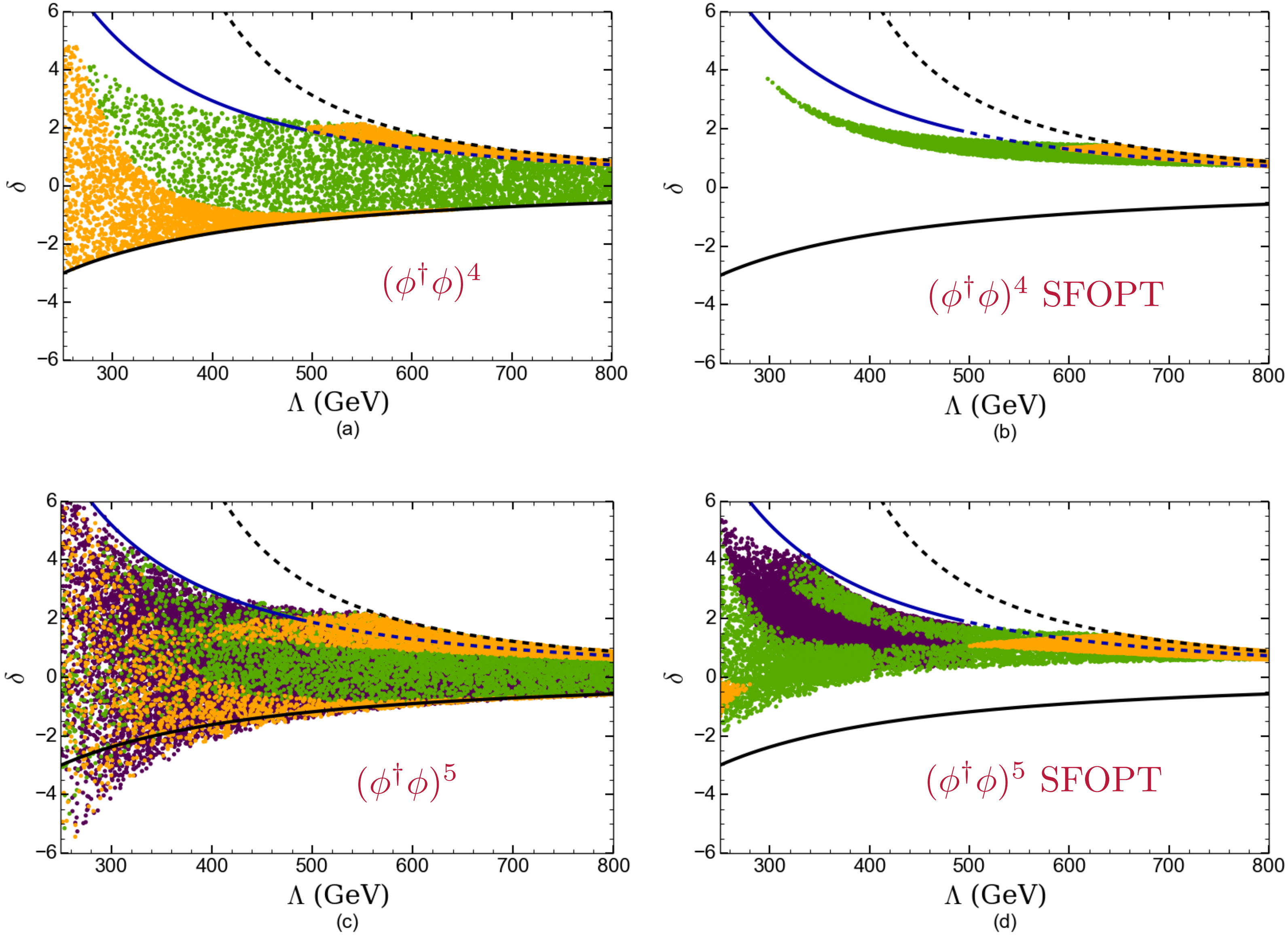
- It is simple algebra to demonstrate that, $T_c^2 = \frac{3c_6}{4\Lambda^2 a_0}\left(v^2 - v_c^2\right)\left(v^2 - \frac{v_c^2}{3}\right).$

$$\frac{2}{3} \leq \delta \leq 2. \qquad \frac{v^2}{m_h} < \Lambda < \frac{\sqrt{3} v^2}{m_h}$$

- Now, in the two extremes, either vc or Tc go to zero, so in order to fulfill the baryogengesis conditions one would like to be somewhat in between.

More General Modifications of the Potential

In general, it is difficult to obtain negative values of δ and at the same time a strongly first order phase transition (SFOPT)



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Realizing the Effective Theory

- It turns out that one can realize the effective theory by integrating out a singlet.
- In this case, there is a relation between the modifications of the potential and the trilinear coupling with the mixing of the singlet with the SM Higgs

$$V(\phi_h, \phi_s, T) = \frac{m_0^2 + a_0 T^2}{2}\phi_h^2 + \frac{\lambda_h}{4}\phi_h^4 + a_{hs}\phi_s\phi_h^2 + \frac{\lambda_{hs}}{2}\phi_s^2\phi_h^2 + t_s\phi_s + \frac{m_s^2}{2}\phi_s^2 + \frac{a_s}{3}\phi_s^3 + \frac{\lambda_s}{4}\phi_s^4$$

- Integrating out the singlet, for as and lambdas small, one obtains a modification of the effective quartic and c6 couplings

Menon, Morrissey, C.W.'04
Carena, Shah, C.W.'12

$$V(h, T) = \frac{m^2(T)}{2}\phi_h^2 + \frac{\lambda_h}{4}\phi_h^4 - \frac{\left(t_s + a_{hs}\phi_h^2\right)^2}{2\left(m_s^2 + \lambda_{hs}\phi_h^2\right)}.$$

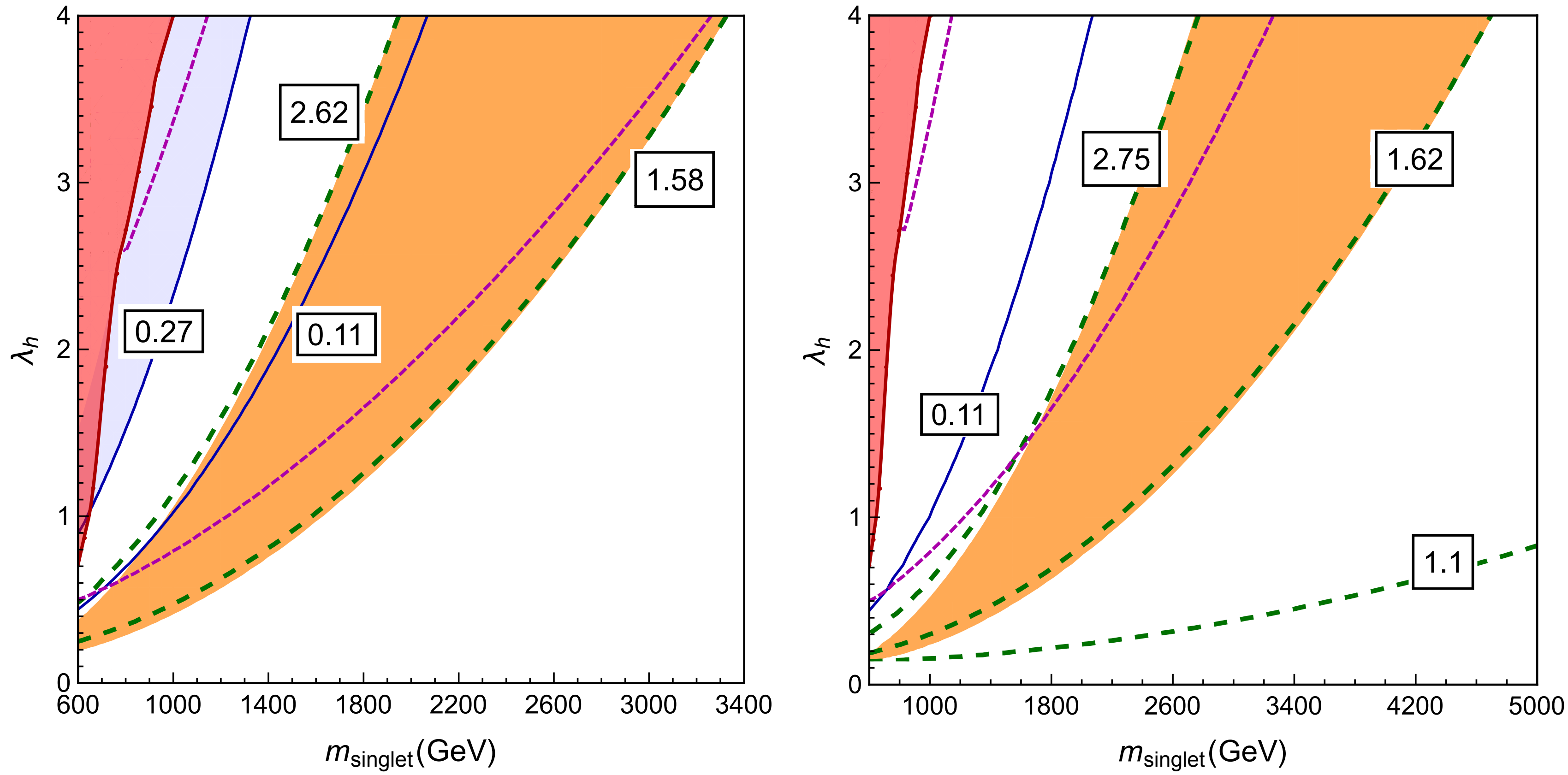
- Moreover, the trilinear coupling can be rewritten in terms of the mixing with the singlet

$$\lambda_3 = 6\lambda_h v_h \cos^3\theta \left[1 + \left(\frac{\lambda_{hs}v_s + a_{hs}}{\lambda_h v_h}\right)\tan\theta + \frac{\lambda_{hs}}{\lambda_h}\tan^2\theta\right].$$

Modified λ_3, mixing angle and SFOPT

Orange :SFOPT
Solid lines : Higgs mixing angle
Dashed lines : 1 + δ

Joglekar, Huang, Li, C.W.'15



Positive corrections to λ_3
Mixing angle suppresses Higgs coupling to the top
Difficult to test experimentally

Modified couplings and resonant contributions in 2HDMs and beyond

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs Hd would couple to down-quarks and charge leptons, while the Higgs Hu couples to up quarks and neutrinos. Therefore,

$$g_{hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{(-\sin\alpha)}{\cos\beta}, \qquad g_{Hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{\cos\alpha}{\cos\beta}$$

$$g_{hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{(\cos\alpha)}{\sin\beta}, \qquad g_{Hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{\sin\alpha}{\sin\beta}$$

- If the mixing is such that $\cos(\beta - \alpha) = 0$

$$h = -\sin\alpha H_d^0 + \cos\alpha H_u^0 \qquad \sin\alpha = -\cos\beta, \qquad \tan\beta = \frac{v_u}{v_d}$$

$$H = \cos\alpha H_d^0 + \sin\alpha H_u^0 \qquad \cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like.
We shall call this situation ALIGNMENT

Haber and Gunion'03, Delgado, Nardini, Quiros'13,
N. Craig, J. Galloway &Thomas'13, Dev and Pilaftsis'14
M. Carena, H. Haber, I. Low, N. Shah and C.W.'15 and '15

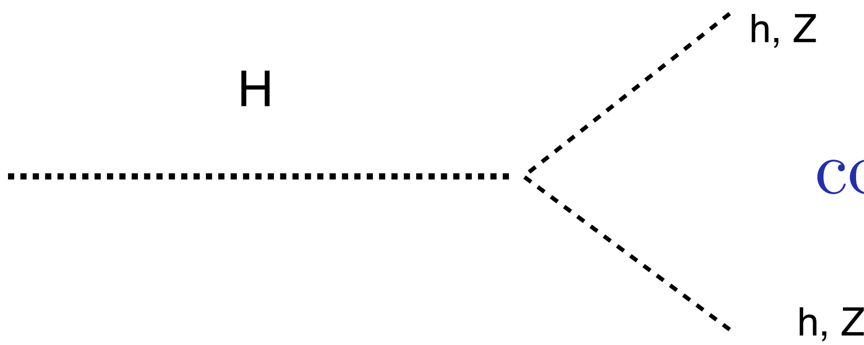
- Observe that close to the alignment limit, the heavy Higgs couplings to down quarks and up quarks are enhanced (suppressed) by a $\tan\beta$ factor.

- It is important to stress that the couplings of the CP-odd Higgs boson are

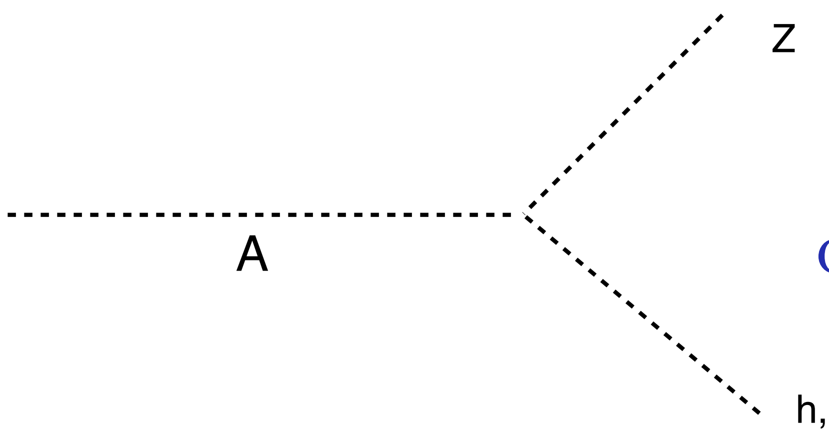
$$g_{Aff}^{dd,ll} = \frac{\mathcal{M}_{\rm diag}^{\rm dd}}{v} \tan\beta, \qquad g_{Aff}^{uu} = \frac{\mathcal{M}_{\rm diag}^{\rm uu}}{v\tan\beta}$$

H and A Decay to Higgs and Gauge Boson Pairs

Suppressed at Alignment



$$\cos(\beta - \alpha)$$



$$\cos(\beta - \alpha)$$

Carena, Low, Shah, C.W.'13

Deviations from Alignment

$$c_{\beta-\alpha} = t_\beta^{-1}\eta \ , \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

The couplings of down fermions are not only the ones that dominate the Higgs width but also tend to be the ones which differ at most from the SM ones

$$g_{hVV} \approx \left(1 - \frac{1}{2} t_\beta^{-2}\eta^2\right) g_V \ , \qquad g_{HVV} \approx t_\beta^{-1}\eta \ g_V \ ,$$

$$g_{hdd} \approx (1-\eta)\, g_f \ , \qquad g_{Hdd} \approx t_\beta(1 + t_\beta^{-2}\eta) g_f$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \ , \qquad g_{Huu} \approx -t_\beta^{-1}(1-\eta) g_f$$

Impact of Modified Couplings

- In general, assuming modified couplings, and no new light particle the Higgs can decay into, the new decay branching ratios are given by

$$BR(h \to XX) = \frac{\kappa_X^2 \; BR(h \to XX)^{\rm SM}}{\sum_i \kappa_i^2 \; BR(h \to ii)^{\rm SM}}$$

- For small variations of (only) the bottom coupling, and $X \neq b$

$$BR(h \to b\bar{b}) \simeq BR(h \to b\bar{b})^{\rm SM}(1 + 0.4(\kappa_b^2 - 1))$$

$$BR(h \to XX) \simeq BR(h \to XX)^{\rm SM}(1 - 0.6(\kappa_b^2 - 1))$$

$$\frac{BR(h \to b\bar{b})}{BR(h \to XX)} = \frac{BR(h \to b\bar{b})^{\rm SM}}{BR(h \to XX)^{\rm SM}}(1 + (\kappa_b^2 - 1))$$

- So, due to the its large contribution to the Higgs decay width, a modification of a bottom coupling leads to a large modification of all other decay branching ratios (larger than the one into bottoms !)
- Observe that the coefficients are just given by the SM bottom decay branching ratio and its departure from one.

Carena, Haber, Low, Shah, C.W.'14

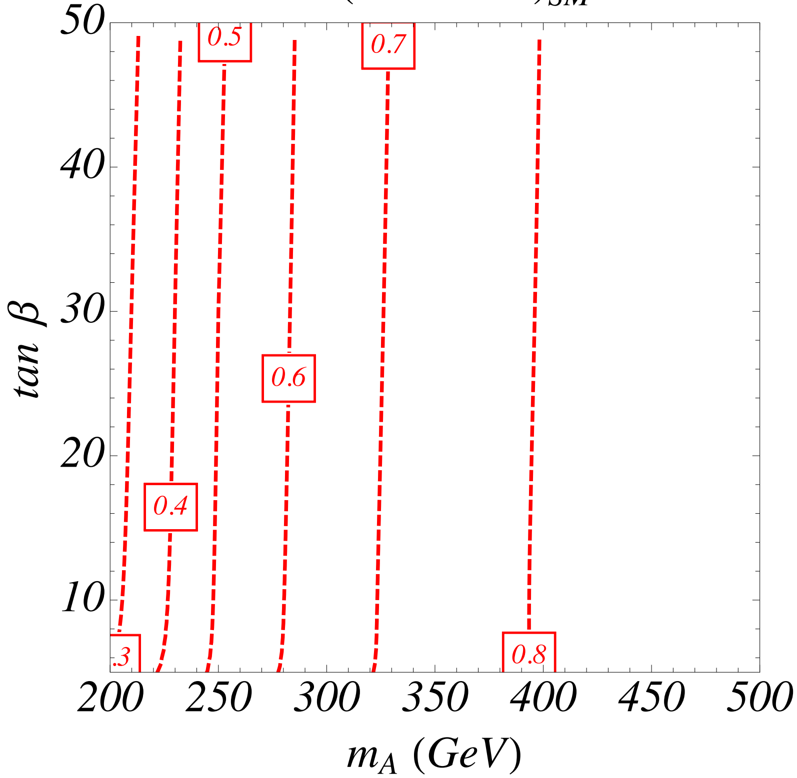
M. Carena, I. Low, N. Shah, C.W.'13

Higgs Decay into Gauge Bosons

Mostly determined by the change of width

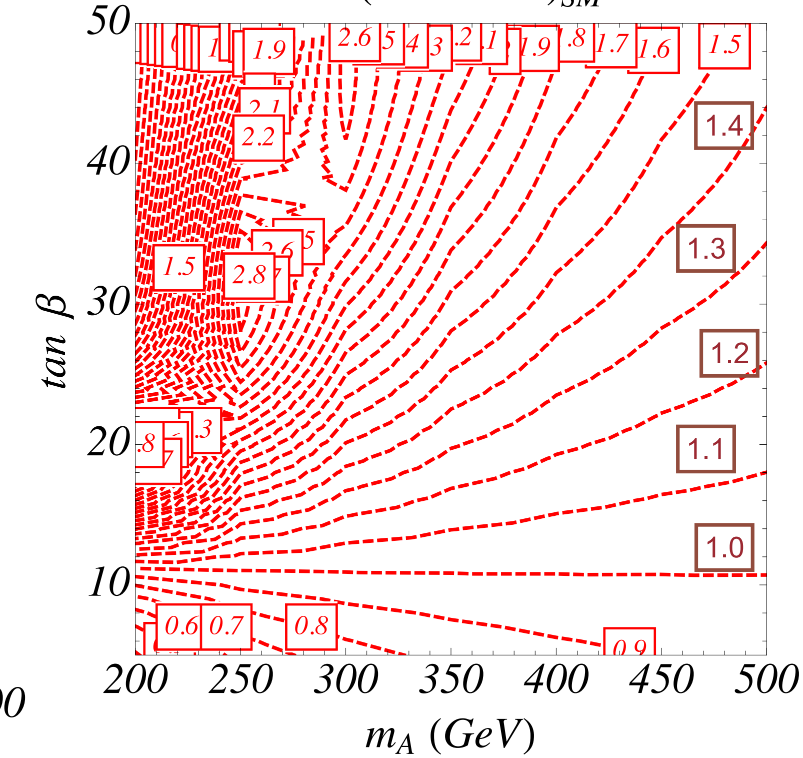
Small μ

$$\frac{BR\,(h \to WW)}{BR\,(h \to WW)_{SM}}$$



$\mu/M_{\rm SUSY} = 2, \quad A_t/M_{\rm SUSY} \simeq 3$

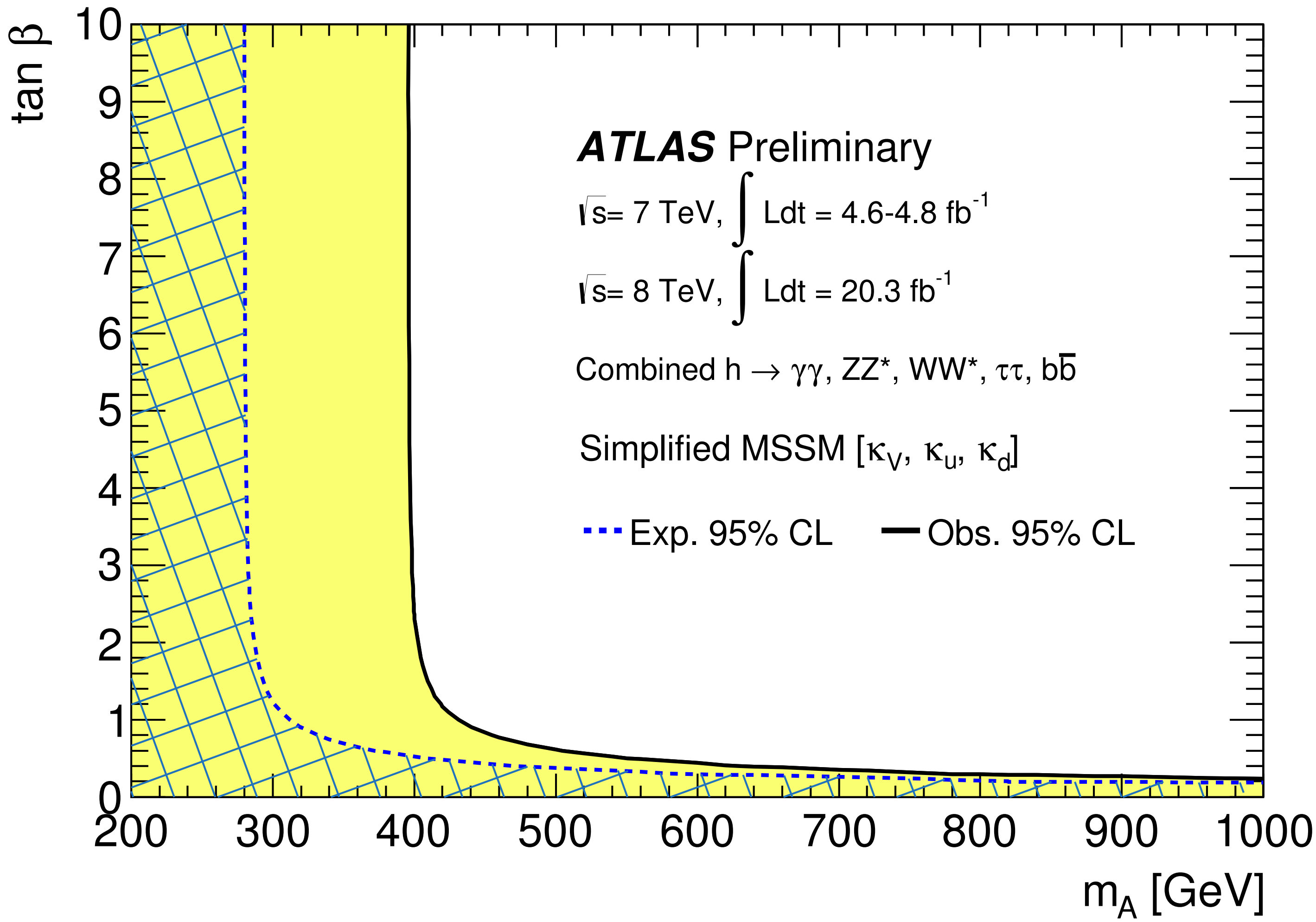
$$\frac{BR\,(h \to WW)}{BR\,(h \to WW)_{SM}}$$



CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Low values of μ similar to the ones analyzed by ATLAS

ATLAS-CONF-2014-010



Bounds coming from precision h measurements

Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

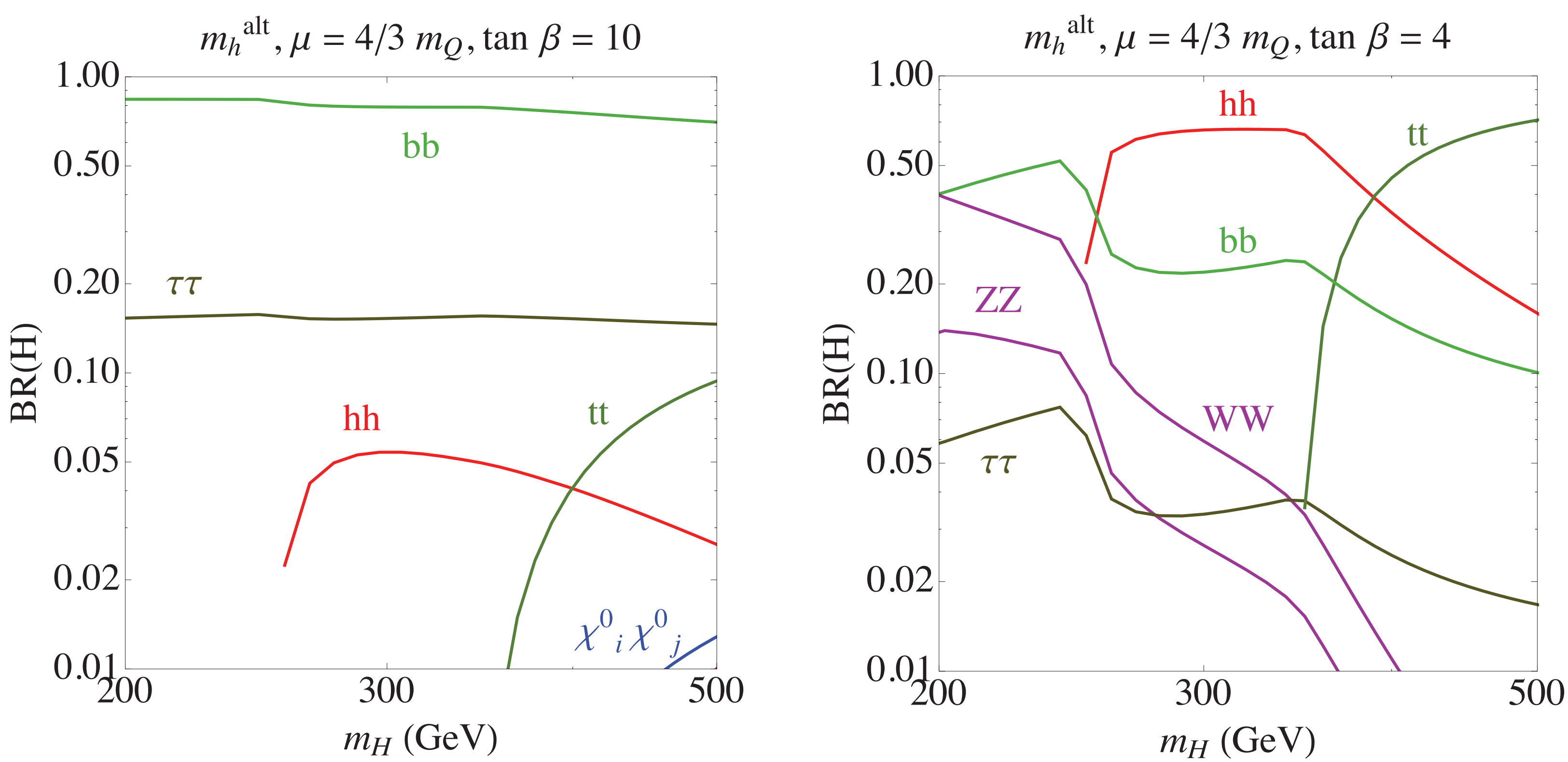
Precision measurement constraining M_H
to be above 500 GeV away from alignment

$\sigma(gg \to H) = 1100,\ 330,\ 70$ fb
$\sigma(bbH) = 9, 39, 239$ fb
at $M_H = 500$ GeV and $\tan\beta = 2, 4, 10$.

Carena, Haber, Low, Shah, C.W.'14

$m_h^{\rm alt}$: Large μ. Alignment at values of $\tan\beta \simeq 12$

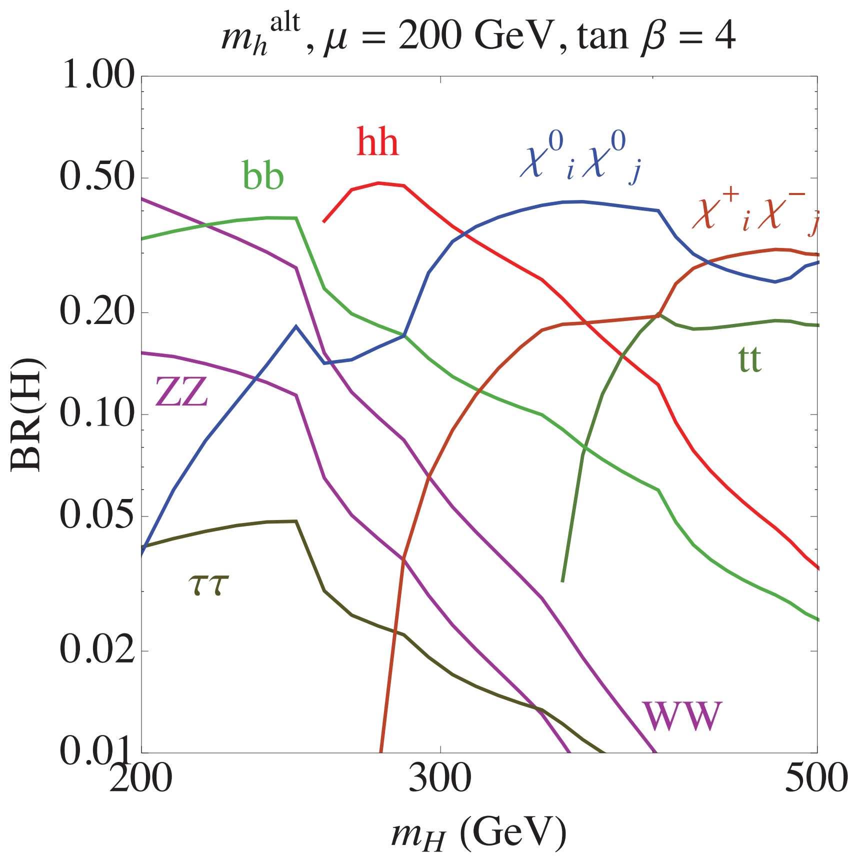
Depending on the values of μ and tanβ different search strategies must be applied.

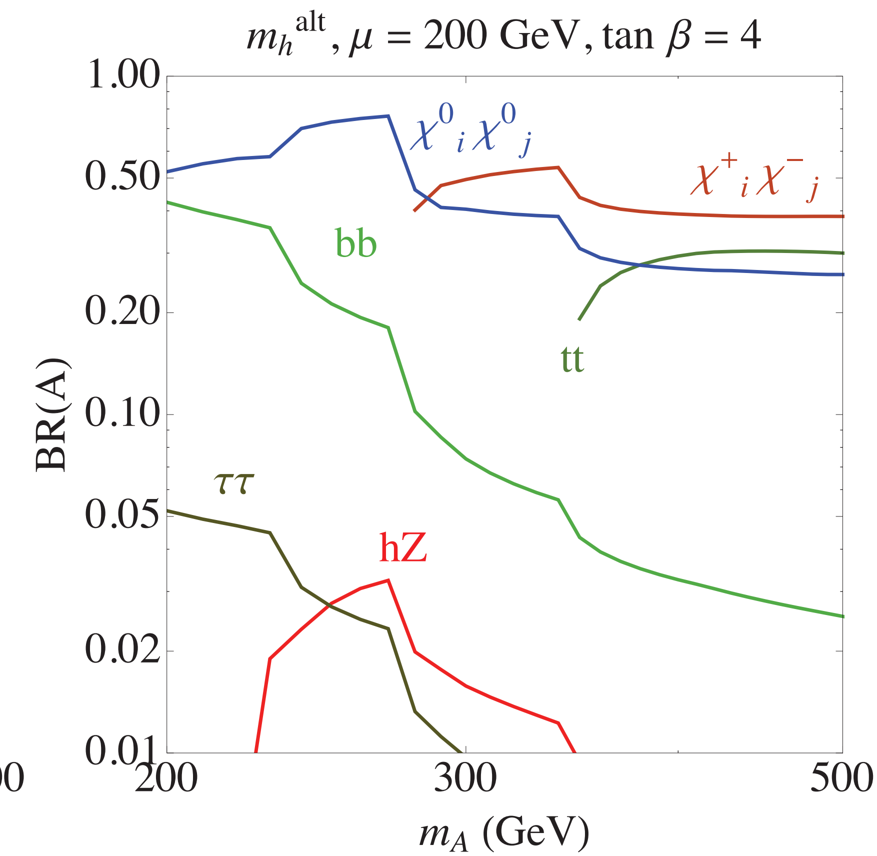


At large tanβ, bottom and tau decay modes dominant.
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

Carena, Haber, Low, Shah, C.W.'14



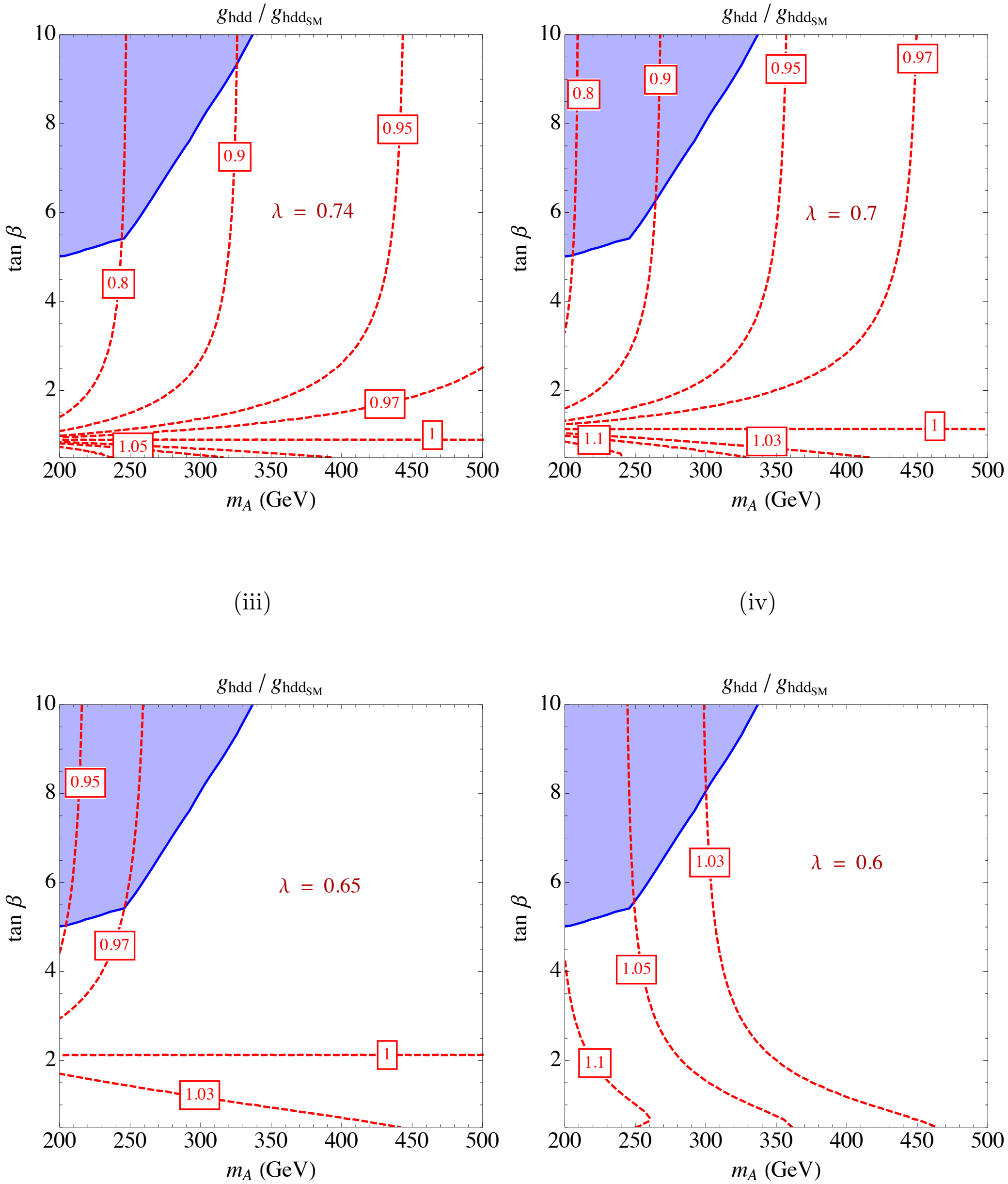


At small values of μ ($M_2 \simeq 200$ GeV here), chargino and neutralino decays prominent. Possibility constrained by direct searches.

Extensions of the Higgs sector containing two Higgs doublets and Singlets

(well known example : NMSSM)

Alignment in the NMSSM (heavy or Aligned singlets)



Carena, Low, Shah, C.W.'13

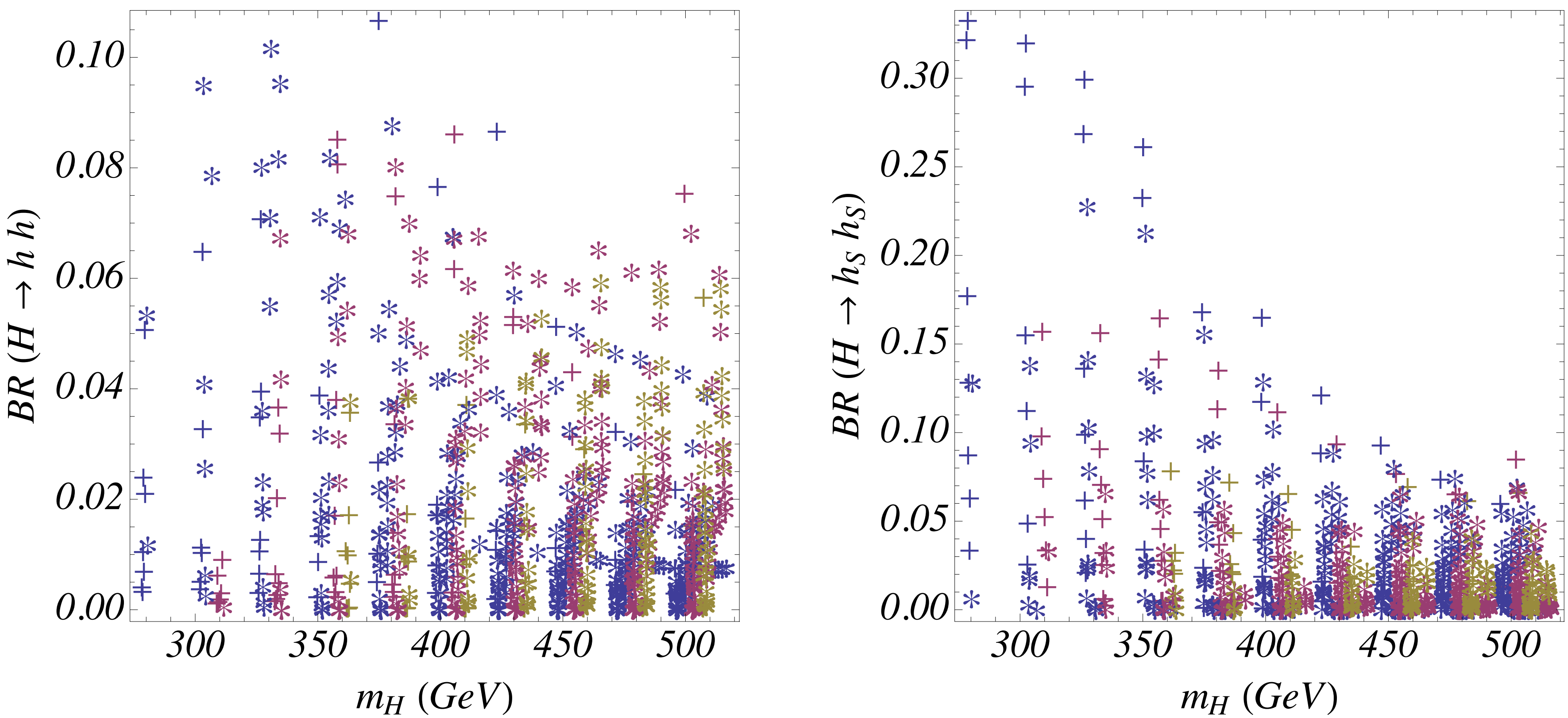
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided λ is about 0.65

Decays into pairs of SM-like Higgs bosons suppressed by alignment

Carena, Haber, Low, Shah, C.W.'15

Crosses : H1 singlet like
Asterix : H2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$



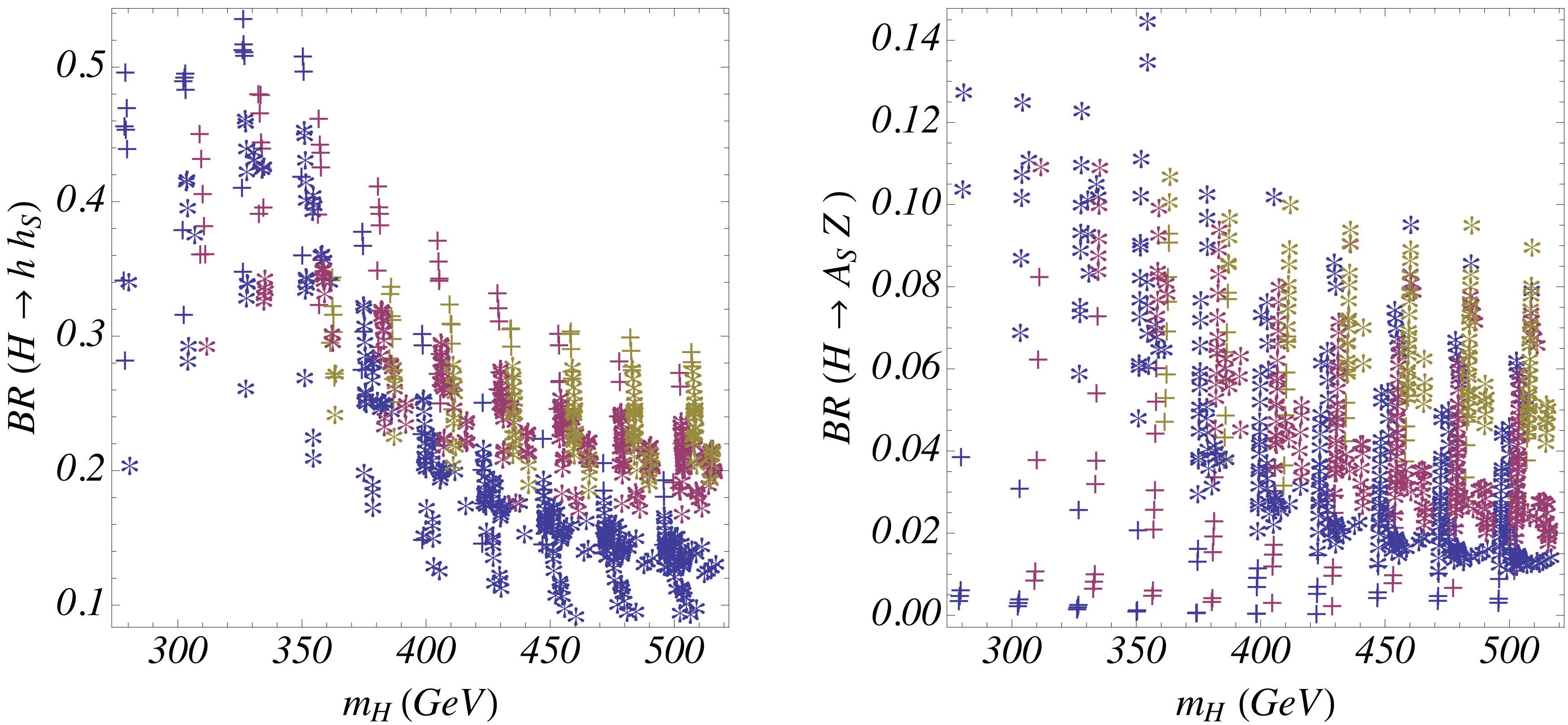
Significant decays of heavier Higgs Bosons into lighter ones and Z's

Relevant for searches for Higgs bosons

Crosses : H1 singlet like
Asterix : H2 singlet like

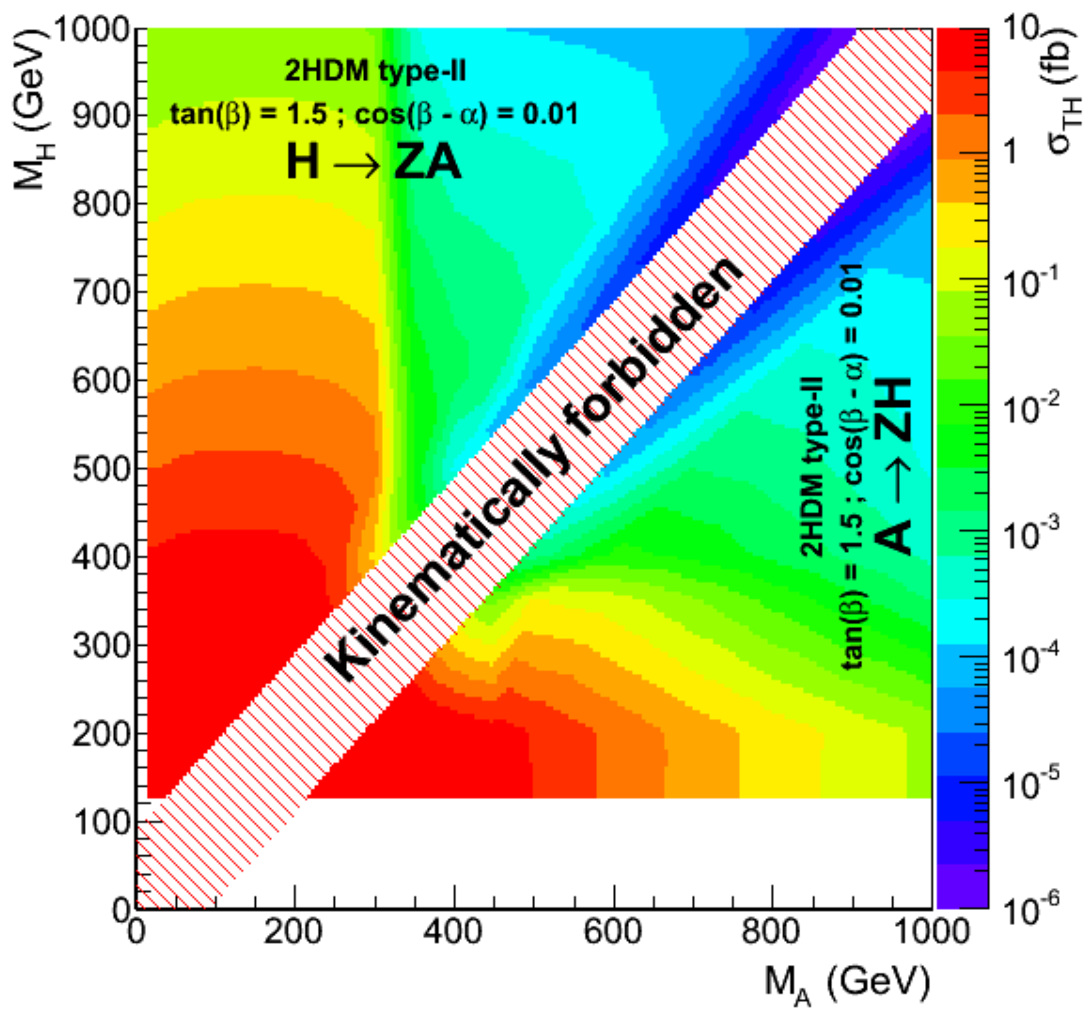
Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$

Carena, Haber, Low, Shah, C.W.'15



Search for (psudo-)scalars decaying into lighter ones

CMS-PAS-HIG-15-001



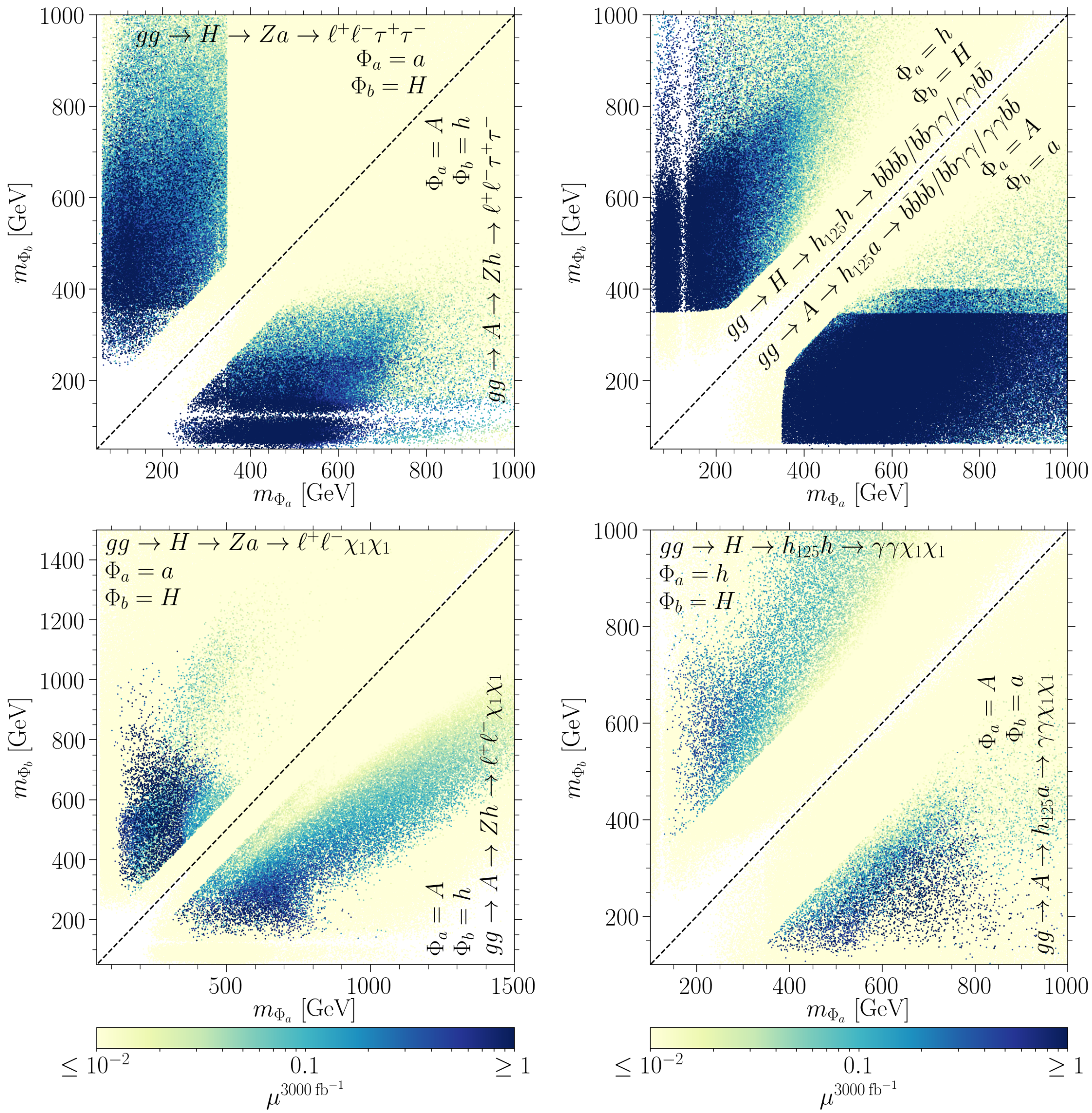
It is relevant to perform similar analyses replacing
the Z by a SM Higgs (and changing the CP property of the Higgs)

Reach at the high luminosity LHC
Depends on decay of singlet modes

N. Shah, this workshop

S.Baum, N. Shah'18

Baum, Freese, Shah'18

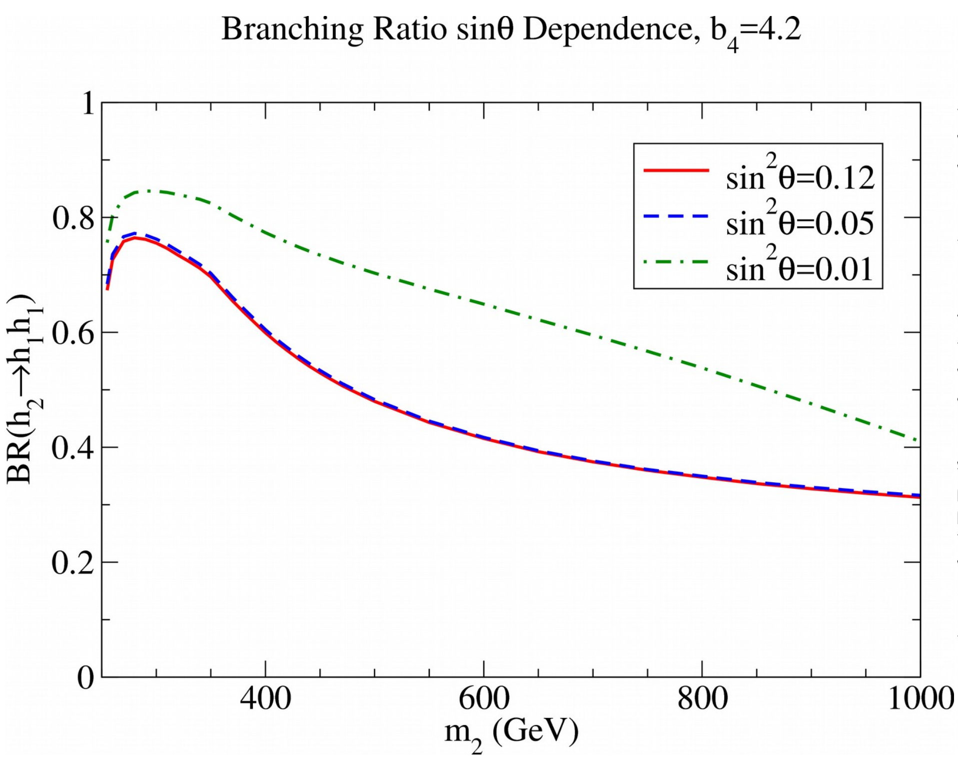


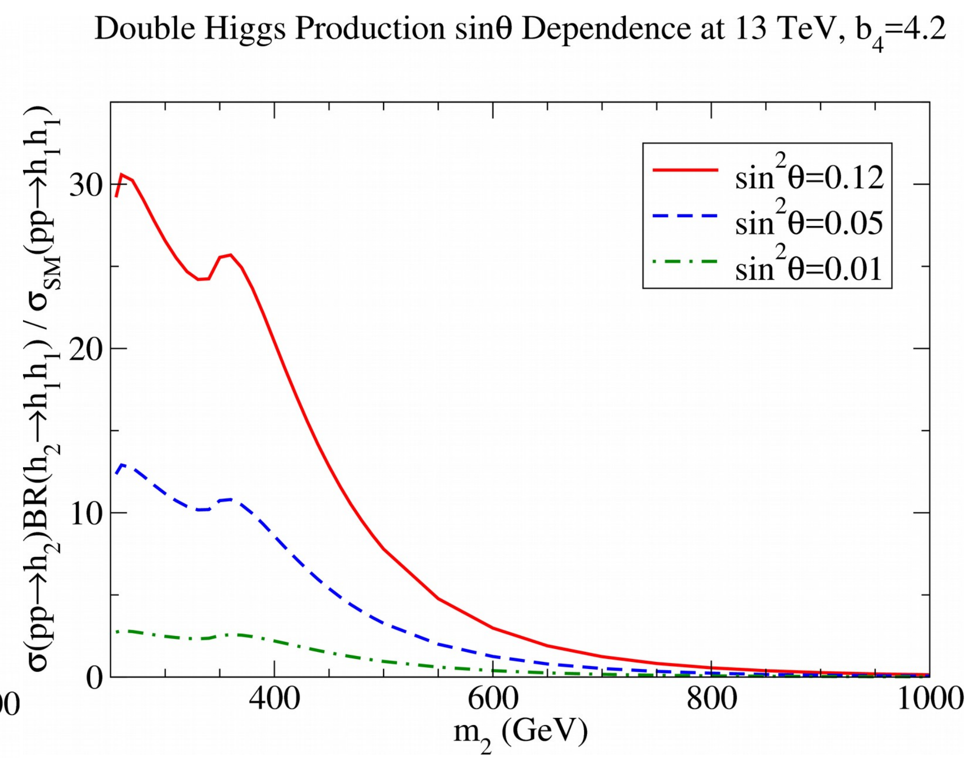
Can we do better for double Higgs production and test a SFOPT ? Back to the singlet extension

- Branching ratios into 2 SM Higgs bosons may be enhanced if other couplings are suppressed
- This happens in the singlet extension of the SM, since all singlet couplings are proportional to its mixing with the SM (not only the trilinear)
- Unfortunately, the production of the singlet is also proportional to the mixing angle square and hence, double Higgs production can only be sizable for small values of the singlet mass and some departure from alignment
- For not very large values of the singlet mass, interference between the resonant and non-resonant production may become relevant

Constraints on $pp \to h_2 \to h_1 h_1$ rates

- Cannot arbitrarily increase Higgs branching ratios.
  - More complicated scalar potential, more minima: 6 extrema in total
  - Singlet cannot contribute to fermion and vector boson masses.
  - Have to guarantee that global minimum has Higgs doublet vev is 246 GeV.





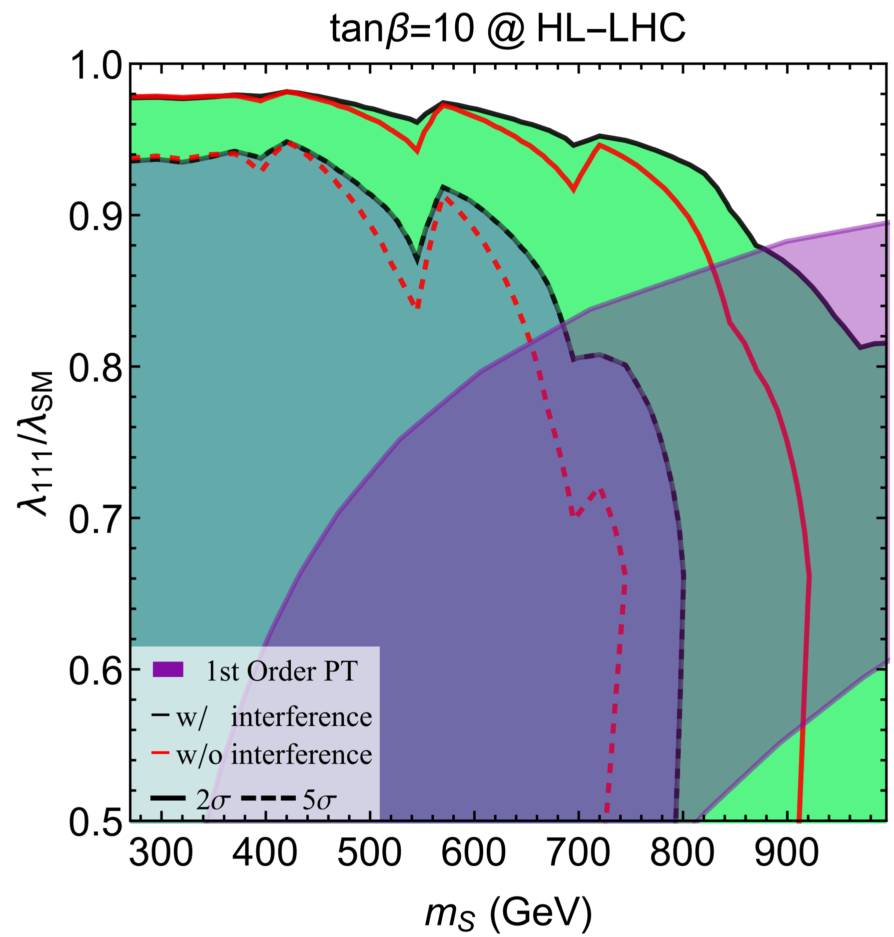
IL, M. Sullivan PRD96 (2017) 035037

M. Carena, S. Liebler, this workshop

Interference effects and SFOPT

There are interesting interference effects between the SM production rate and the resonance production rate that modifies your reach

Dependence on mixing angle implicit in the definition of the trilinear coupling (not the effective field theory one)



Di-Higgs Production as a signal of Enhanced Yukawa couplings

Bauer, MC, Carmona (1801.00363)

Correlation between enhanced Higgs-fermion couplings and di-Higgs production in 2HDM w/ flavour symmetry

Visible in resonant & non-resonant, dedicated LHC searches

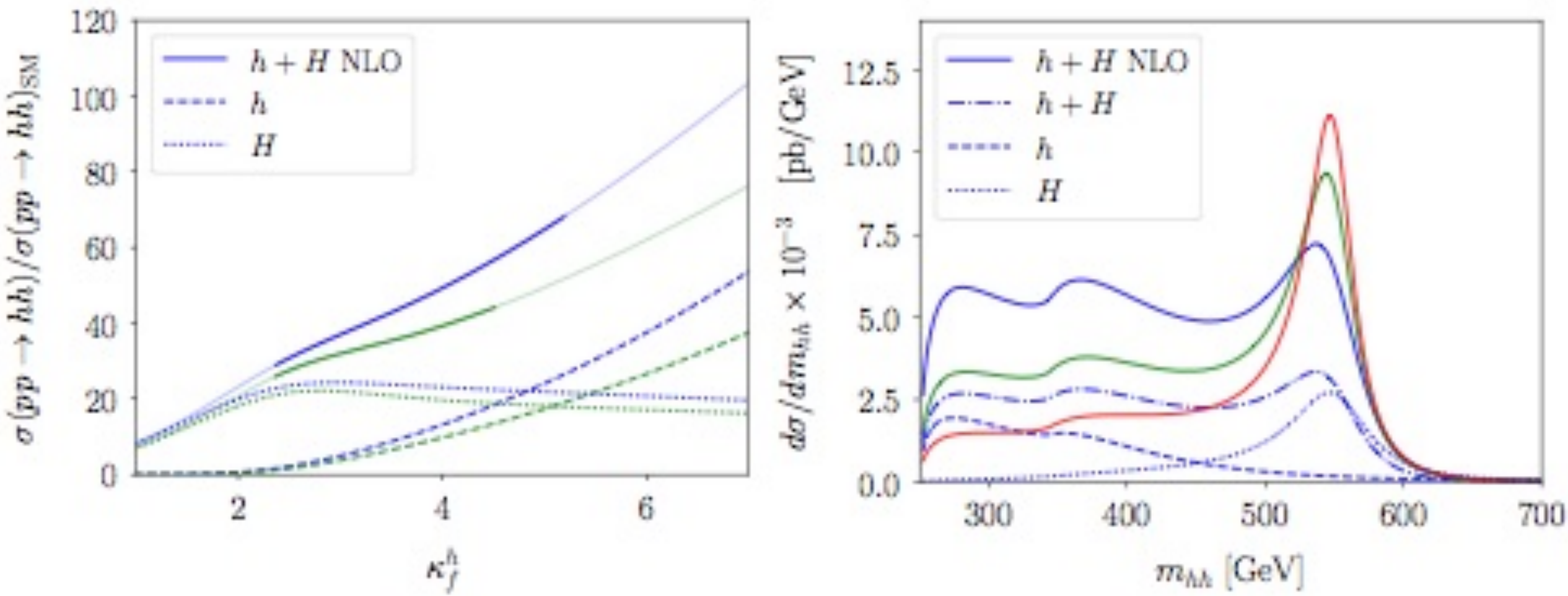


FIG. 2: Left: Cross section for Higgs pair production in units of the SM prediction as a function of κ_f^h for $c_{\beta-\alpha} = -0.45$ (-0.4) and $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV in blue (green) at $\sqrt{s} = 13$ TeV. Right: Invariant mass distribution for the different contributions to the signal with $c_{\beta-\alpha} = -0.45$ and $\kappa_f^h = 5$ (blue), $\kappa_f^h = 4$ (green) and $\kappa_f^h = 3$ (red) at $\sqrt{s} = 13$ TeV, respectively. Solid (dot-dashed) lines correspond to the NLO (LO) calculation for the sum of the resonant and non-resonant production, while dotted (dashed) lines correspond to the pure resonant (non-resonant) contributions.

Conclusions

- The structure of the Higgs potential is still unknown and can differ significantly from the SM one. Only known is the location of the minimum and the second derivative of the potential, given by v and the square of mh.

- The trilinear coupling provides a way of going beyond this knowledge, and can be probed at best by double Higgs production.

- Rate of double Higgs production rate in the SM very well known, of order 30 fb.

- Small rates and large backgrounds make the determination of the trilinear coupling difficult.

- Current projections show that the high luminosity LHC may be sensitives to trilinear couplings from values close to zero up to about 5 times the SM values can be probed.

- Rates may also be increased by modifications of the top coupling, or extra particles in the loop. These effects may be tested in single Higgs production, demanding a global fit to all couplings to determine the trilinear one.

- Resonant production of di-Higgs final states can be significant, but suppressed by Higgs mixing.

- Production of non-standard states, together with the SM one, may be relevant.