李政道研究所
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Probing Electroweak Phase Transition in the Singlet Standard Model at the LHC

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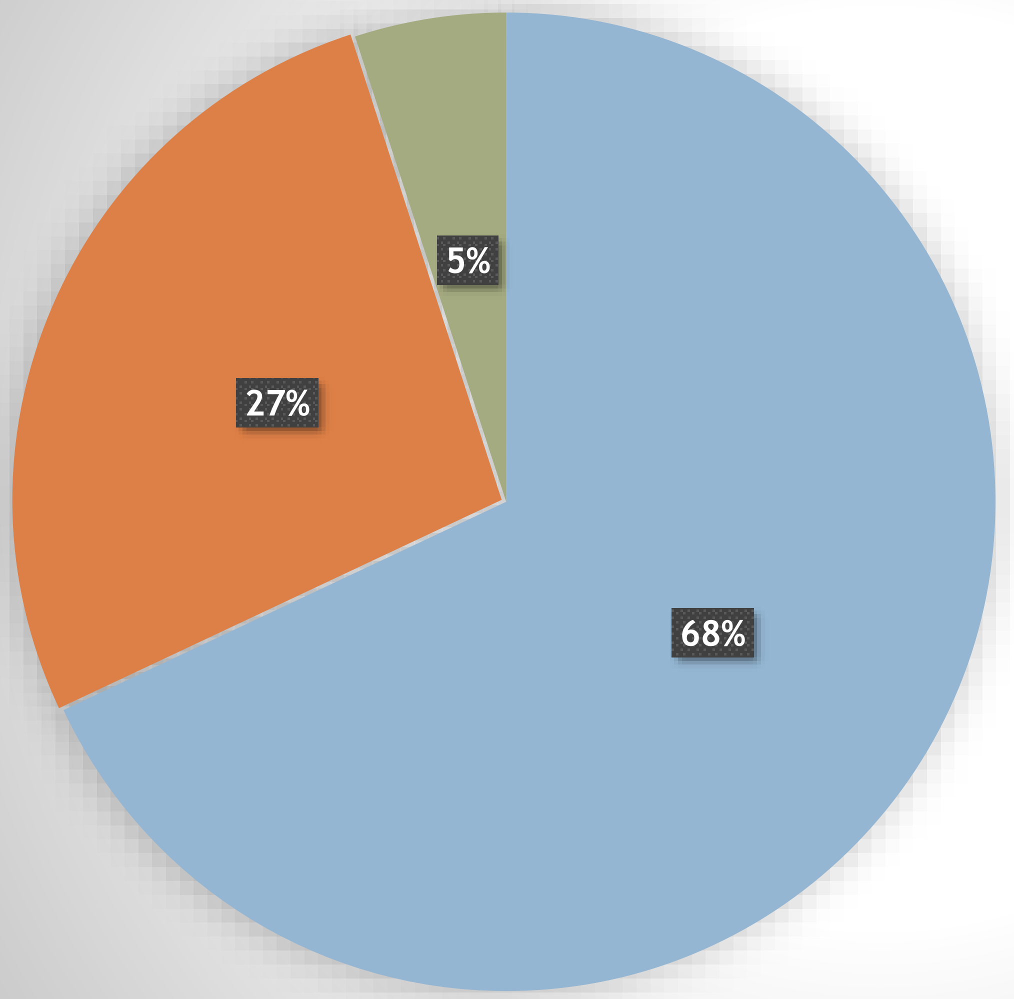
Hao-Lin Li, Kun Liu, Michael Ramsey-Musolf, Yonghao Zeng

1

arXiv: 2303.03612

Cosmic Energy Budget



$$\eta^{CMB} = \frac{n_b - n_{\bar{b}}}{s}$$
$$= (8.7 \pm 0.3) \times 10^{-11}$$

Bayon asymmetry of the Universe

44 different ways to creat baryons in the Universe

1. GUT baryogenesis
2. GUT baryogenesis after preheating
3. Baryogenesis from primordial black holes
4. String scale baryogenesis
5. Affleck-Dine (AD) baryogenesis
6. Hybridized AD baryogenesis
7. No-scale AD baryogenesis
8. Single field baryogenesis
9. Electroweak (EW) baryogenesis
10. Local EW baryogenesis
11. Non-local EW baryogenesis
12. EW baryogenesis at preheating
13. SUSY EW baryogenesis
14. String mediated EW baryogenesis
15. Baryogenesis via leptogenesis
16. Inflationary baryogenesis
17. Resonant leptogenesis
18. Spontaneous baryogenesis
19. Coherent baryogenesis
20. Gravitational baryogenesis
21. Defect mediated baryogenesis
22. Baryogenesis from long cosmic strings
23. Baryogenesis from short cosmic strings
24. Baryogenesis from collapsing loops
25. Baryogenesis through collapse of vortons
26. Baryogenesis through axion domain walls
27. Baryogenesis through QCD domain walls
28. Baryogenesis through unstable domain walls
29. Baryogenesis from classical force
30. Baryogenesis from electrogenesis
31. B-ball baryogenesis
32. Baryogenesis from CPT breaking
33. Baryogenesis through quantum gravity
34. Baryogenesis via neutrino oscillations
35. Monopole baryogenesis
36. Axino induced baryogenesis
37. Gravitino induced baryogenesis
38. Radion induced baryogenesis
39. Baryogenesis in large extra dimensions
40. Baryogenesis by brane collision
41. Baryogenesis via density fluctuations
42. Baryogenesis from hadronic jets
43. Thermal leptogenesis
44. Nonthermal leptogenesis

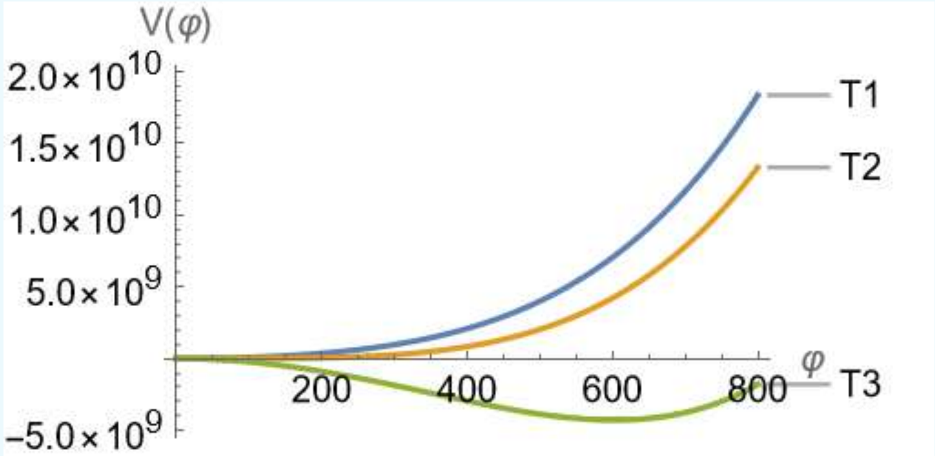
Shaposhnikov, DISCRETE 08, 11, Dec

Sakharov conditions:

- Baryon number violating interactions. ☑
- C and CP violation. ☒
- Departure from thermal equilibrium. ☒ → Sphaleron washout? Strong First Order Electroweak Phase Transition **BSM**

A.Sakharov JETP 5, 24 (1967)

Electroweak Phase Transition in the SM



$$V_{eff}(h,s,T) = V_0(h,s) + V_{CW}^{T=0}(h,s) + V_{\mathrm{T}\neq 0}(h,s,T).$$

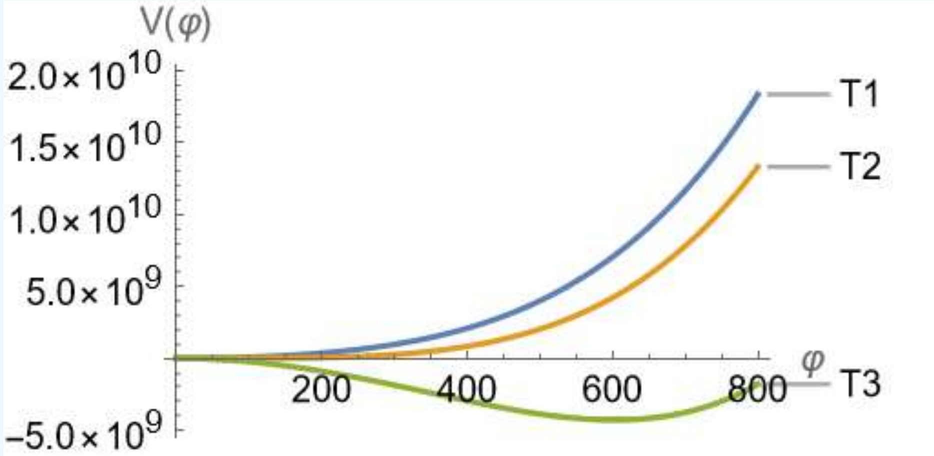
$$V_{CW}^{T=0} = \sum_k \frac{(-1)^{2s_k}}{64\pi^2} g_k \, [M_k^2]^2 \left(\log\frac{M_k^2}{\mu^2} + c_k\right),$$

$$\begin{aligned} &V^{High-T}(h,s,T) \\ &= V_0(h,s) + \frac{T^2}{48}\left(12m_t^2\right) + \frac{T^2}{24}\left(3m_G^2 + m_h^2 + m_s^2 + m_A^2 + 6M_W^2 + 3M_Z^2\right) \\ &= V_0(h,s) + \frac{1}{2}\left(\frac{\lambda}{8} + \frac{\delta_2}{24} + \frac{3g_2^2 + g_1^2}{16} + \frac{y_t^2}{4}\right) h^2T^2 + \frac{\delta_2 + d_2}{48} s^2T^2. \end{aligned}$$

$$V_{eff}(\phi,T) \simeq D\left(T^2 - T_0^2\right)\phi^2 - ET\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$

→ **Negative for $T < T_0$, non-zero minimum.**

Electroweak Phase Transition in the SM



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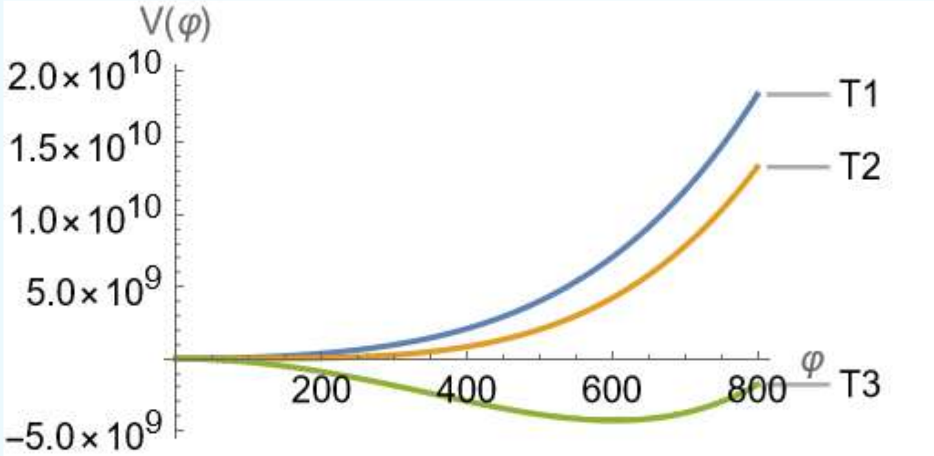
Generate barriers

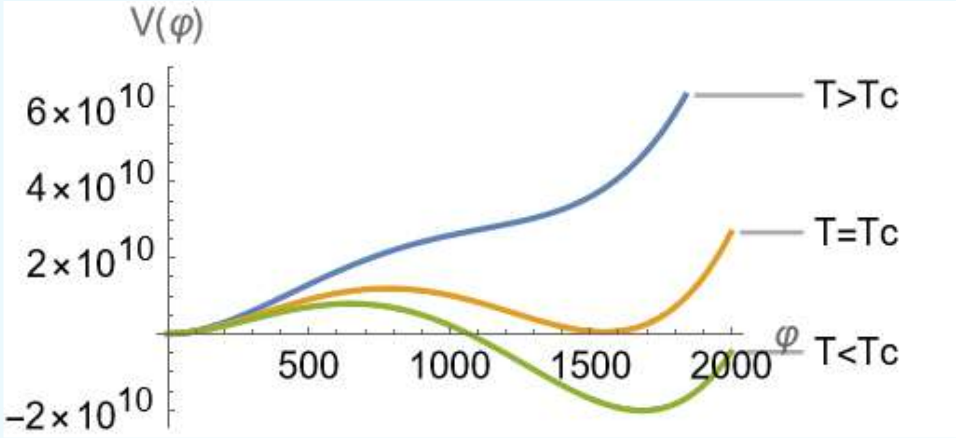
$$V_{eff}(\phi,T) \simeq D\left(T^2 - T_0^2\right)\phi^2 - ET\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$

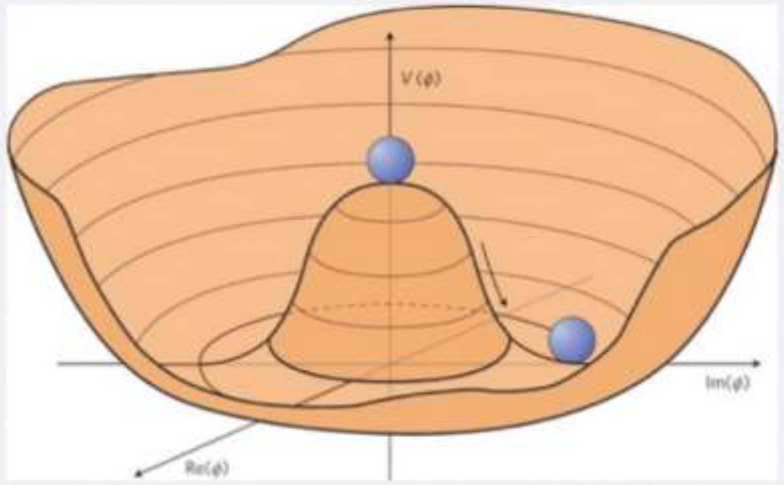
Negative for $T < T_0$, non-zero minimum.

Electroweak Phase Transition in the SM



First-order EWPT





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$$V_{eff}(\phi, T) \simeq D\left(T^2 - T_0^2\right)\phi^2 - ET\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$

Negative for $T < T_0$

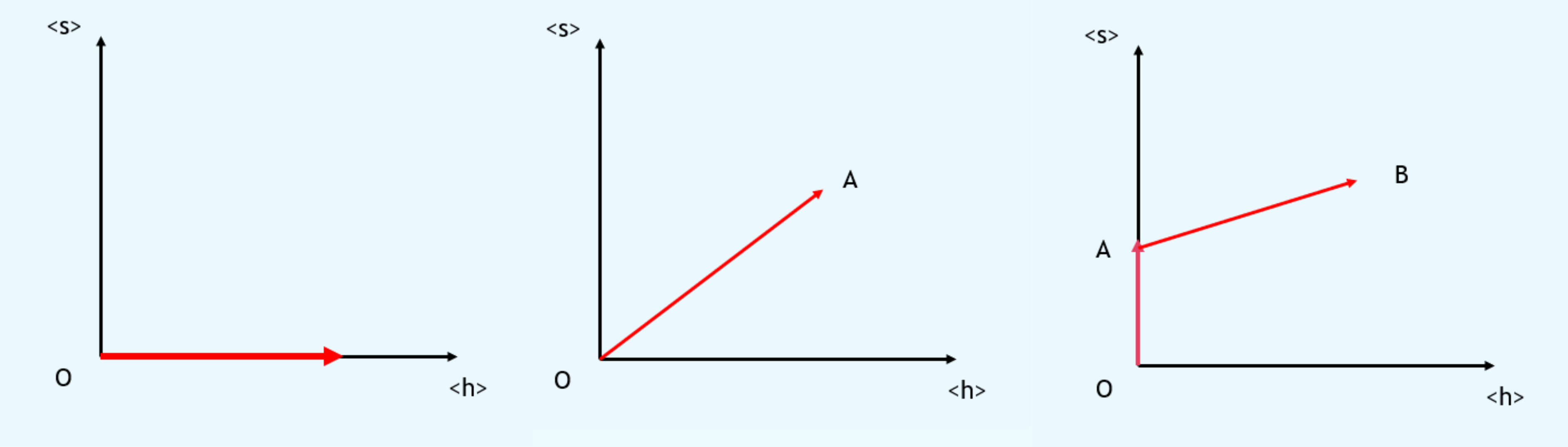
SM: Crossover!

SFOEWPT in BSM: Multi-step EWPT

The simplest model in extended SM that generate multiple-step EWPT: the xSM.

a. The xSM can be a simplified model for many UV complete model that realise multiple-step SFOEWPT.

b. The pheno of xSM is typical and representative to models that realise SFOEWPT.

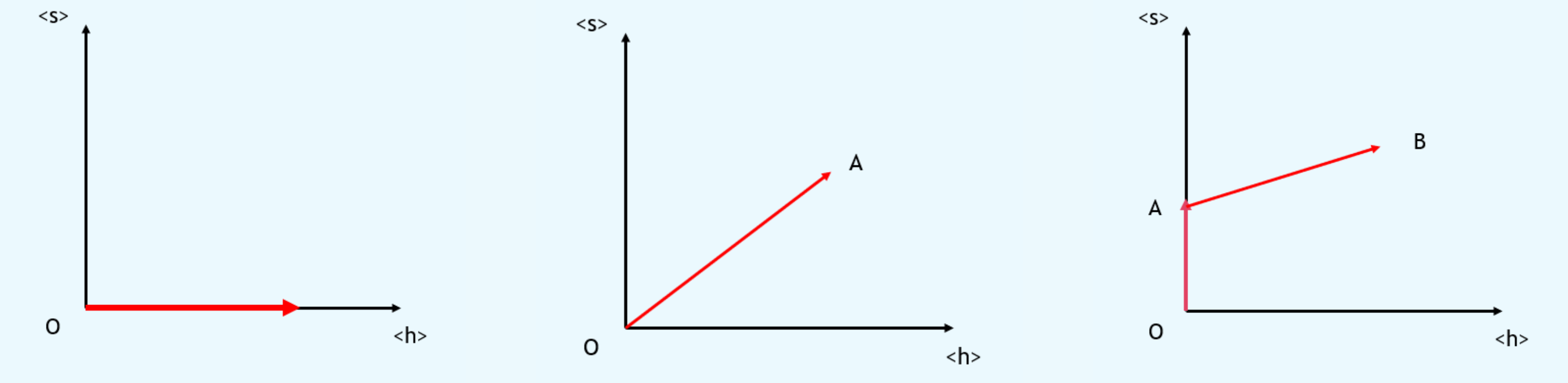


a. b. c.

The xSM

$$V_0(H,S) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{a_1}{2}(H^\dagger H)S + \frac{a_2}{2}(H^\dagger H)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4,$$

$S = x_0 + s$



Key-item to generate a barrier in FOEWPT: a_2, a_1, b_3

The xSM

$$V_0(H,S) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{a_1}{2}(H^\dagger H)S + \frac{a_2}{2}(H^\dagger H)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4,$$

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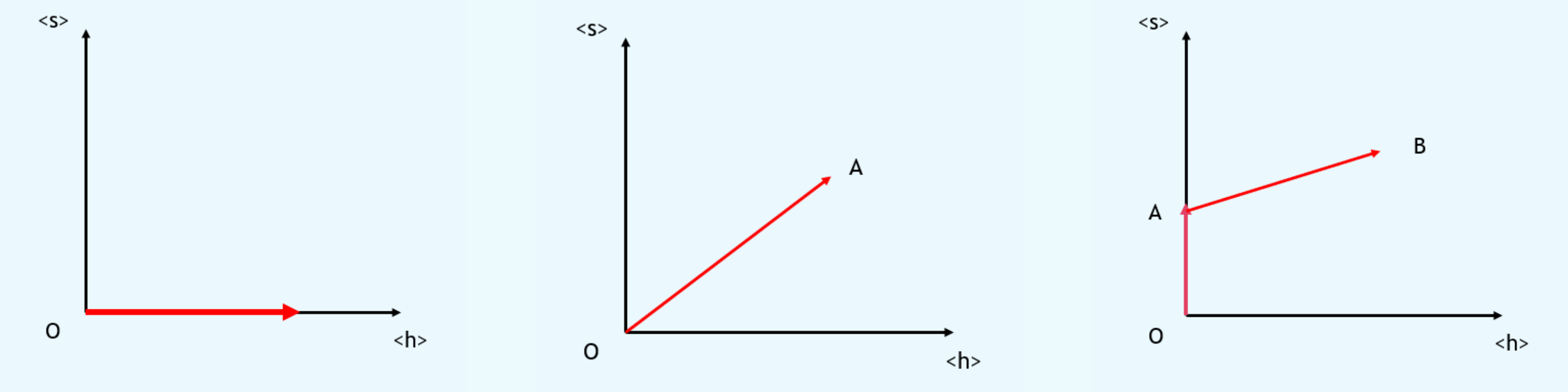

Key-item to generate a barrier in FOEWPT: a_2, a_1, b_3

The question is:

Can these terms be as large as we want?
What's the consequence of adding these terms?
How to probe them?

The xSM

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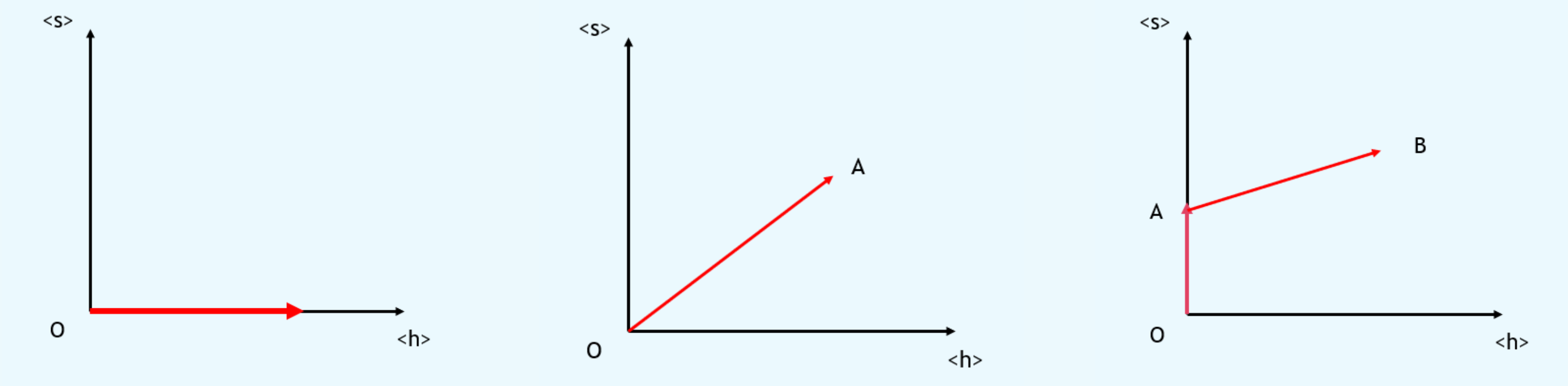


Key-item to generate a barrier in FOEWPT: a_2, a_1, b_3

The question is:

Can these terms be as large as we want?
What's the consequence of adding these terms?
How to probe them?

One consequence: Scalar sector mixing:

$$\mathcal{M}^2 = \begin{pmatrix} -\frac{a_1 v_0^2}{4x_0} + x_0\left(b_3 + 2b_4 x_0\right) & \frac{v_0}{2}\left(a_1 + 2a_2 x_0\right) \\ \frac{v_0}{2}\left(a_1 + 2a_2 x_0\right) & 2\lambda v_0^2 \end{pmatrix}.$$

xSM Constraints: Vaccum Stability

$$V_0(H,S) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{a_1}{2}(H^\dagger H)S + \frac{a_2}{2}(H^\dagger H)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4,$$

- **Vaccum (v_0, x_0) is a stable minimum.**

$$\begin{vmatrix} \frac{\partial^2 V}{\partial v_0^2} & \frac{\partial^2 V}{\partial v_0 \partial x_0} \\ \frac{\partial^2 V}{\partial v_0 \partial x_0} & \frac{\partial^2 V}{\partial x_0^2} \end{vmatrix} > 0$$

- **The minimum (v_0, x_0) is global minimum.**
- **The potential is *bounded from below*.**

$$\begin{vmatrix} \lambda & \frac{a_2}{4} \\ \frac{a_2}{4} & \frac{b_4}{4} \end{vmatrix} > 0$$

xSM Constraints: Perturbation

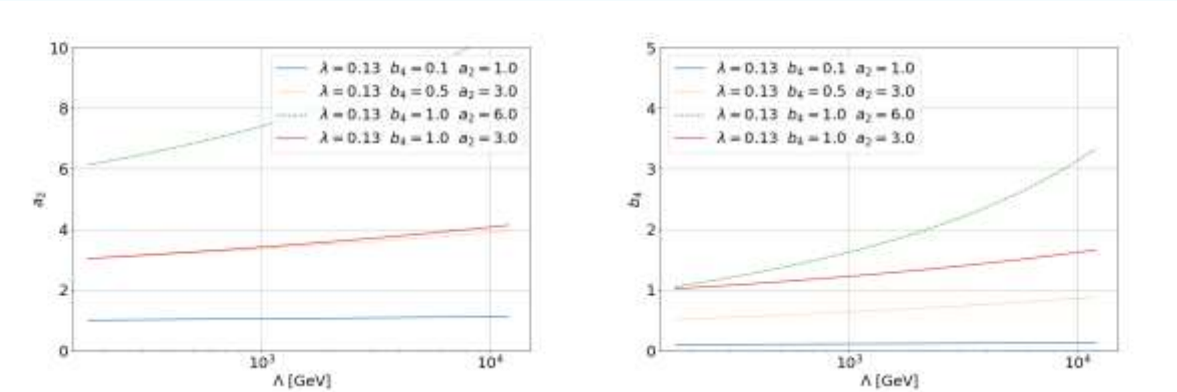
$$V_0(H,S) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{a_1}{2}(H^\dagger H)S + \frac{a_2}{2}(H^\dagger H)S^2$$
$$+ \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4,$$

Input parameters: Dim-1 and Dim-0 $a_1, b_3, b_4, \lambda, x_0$

EW effective theory: Normalisation Scale–10 TeV.

$$\mathrm{d}X/\mathrm{d}\log\mu = \frac{1}{(4\pi)^2}\beta^{(1)}(X), \quad 0 < 6\lambda, 6b_2, |a_2| < 4\pi$$

$$\beta^{(1)}(b_4) = 2a_2^2 + 18b_4^2$$
$$\beta^{(1)}(a_2) = 12a_2\lambda + 4a_2^2 + 6a_2b_4 - \frac{3}{2}a_2g_1^2 - \frac{9}{2}a_2g_2^2 + 6a_2|y_t|^2$$
$$\beta^{(1)}(a_1) = -\frac{3}{2}a_1g_1^2 - \frac{9}{2}a_1g_2^2 + 12a_1\lambda + 4a_1a_2 + 4a_2b_3$$
$$\beta^{(1)}(b_3) = +3a_1a_2 + 18b_3b_4$$
$$\beta^{(1)}(b_2) = a_1^2 + 4b_3^2 - 4a_2\mu + 6b_2b_4$$



xSM Constraints: EWPO

$$\Delta\mathcal{O} = (\cos^2\theta - 1)\mathcal{O}^{\rm SM}(m_{h_1}) + \sin^2\theta\mathcal{O}^{\rm SM}(m_{h_2}) = \sin^2\theta\left[\mathcal{O}^{\rm SM}(m_{h_2}) - \mathcal{O}^{\rm SM}(m_{h_1})\right]$$

$$\begin{aligned} S - S_{SM} &= 0.04 \pm 0.11 \\ T - T_{SM} &= 0.09 \pm 0.14 \\ U - U_{SM} &= -0.02 \pm 0.11 \end{aligned}$$

$$\rho_{ij} = \begin{pmatrix} 1 & 0.92 & -0.68 \\ 0.92 & 1 & -0.87 \\ -0.68 & -0.87 & 1 \end{pmatrix}.$$

$$\chi^2 = (X - \hat{X})_i (\sigma^2)^{-1}_{ij} (X - \hat{X})_j < 5.99$$

$\rightarrow$ **For 2 DoF, 95% C.L.**

Eur.Phys.J.C 78 (2018) 8

xSM Constraints: EW Presion Observables

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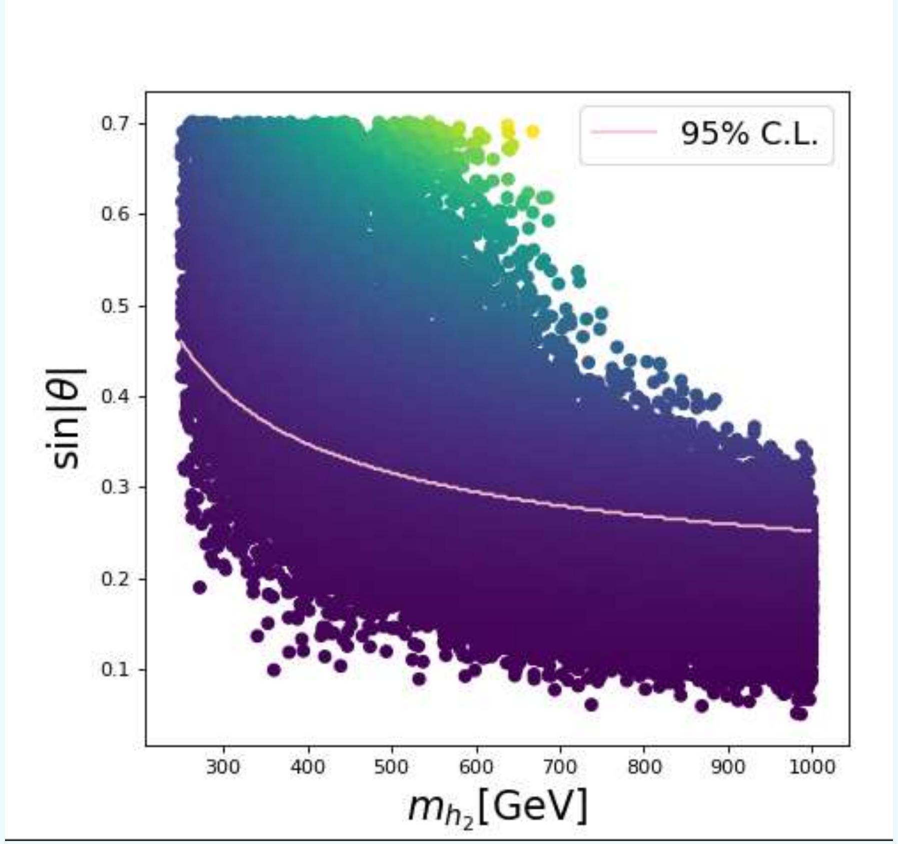

YC, MJRM, LZ, WZ,
arXiv:2307.07615

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Eur.Phys.J.C 78 (2018) 8

xSM Constraints: Higgs Measurement

$$\Delta\mathcal{O} = (\cos^2\theta - 1)\mathcal{O}^{\rm SM}(m_{h_1}) + \sin^2\theta\mathcal{O}^{\rm SM}(m_{h_2}) = \sin^2\theta\left[\mathcal{O}^{\rm SM}(m_{h_2}) - \mathcal{O}^{\rm SM}(m_{h_1})\right]$$

.

$$\Delta S = 0.086 \pm 0.077,$$
$$\Delta T = 0.177 \pm 0.070$$

$$\rho_{ij} = \begin{pmatrix} 1 & 0.89 \\ 0.89 & 1 \end{pmatrix}.$$

$$\chi^2 = (X - \hat{X})_i(\sigma^2)^{-1}_{ij}(X - \hat{X})_j < 5.99$$

CDF, Science 376, 170 (2022).

xSM Constraints: Higgs Measurement

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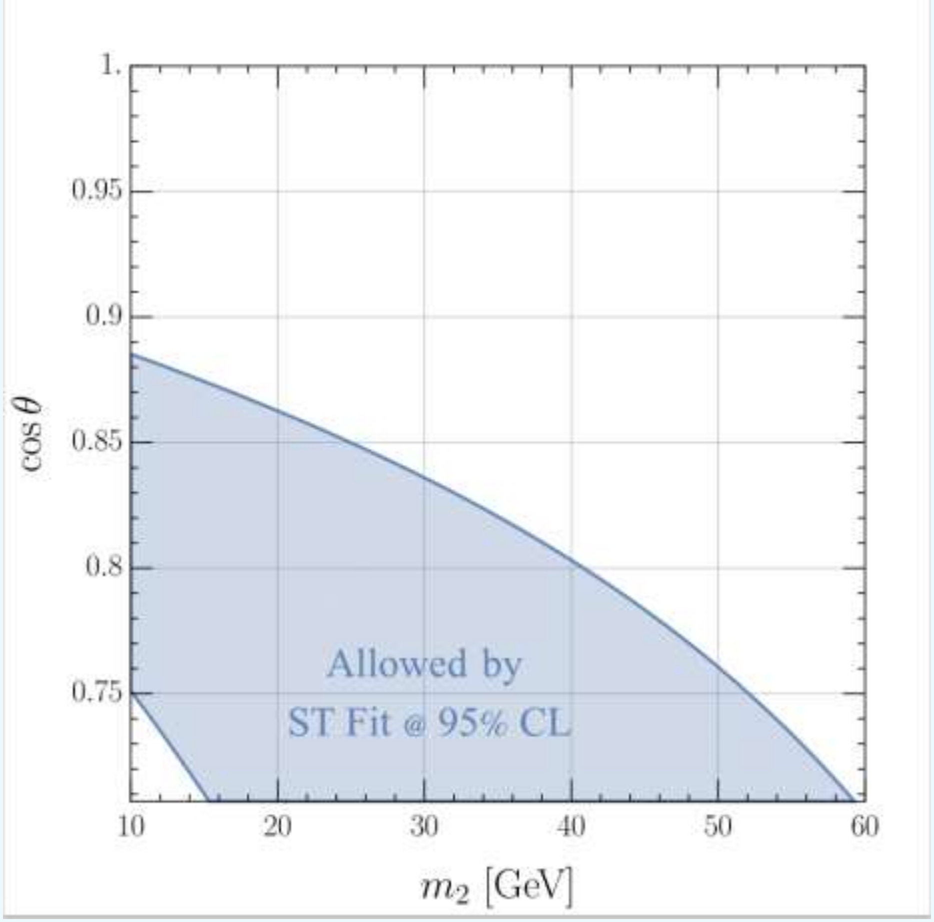

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CDF, Science 376, 170 (2022).

xSM Constraints: Higgs Measurement

New physics may induce deviation in Higgs couplings. Therefore it modifies the Higgs signal strength in Higgs measurement.

Production mode	ggF+$b\bar{b}H$	VBF	WH	ZH	$t\bar{t}$H	tH
$\sum_f \mu_{i\to h_1\to ff}$	$1.03^{+0.07}_{-0.07}$	$1.10^{+0.13}_{-0.12}$	$1.16^{+0.23}_{-0.22}$	$0.96^{+0.22}_{-0.21}$	$0.74^{+0.24}_{-0.24}$	$6.61^{+4.24}_{-3.76}$

Nature 607, 52–59 (2022)

$$\mu_{pp\to h_1\to XX} = \frac{\sigma_{pp\to h_1}\ BR(h_1 \to XX)}{\sigma^{SM}_{pp\to h}\ BR(h\to XX)_{SM}} \simeq \cos^4\theta,$$

$$\chi^2 = \sum_{i,f} \frac{(\mu^{xSM}_{i\to h_1\to f} - \mu^{obs}_{i\to h_1\to f})^2}{\sigma^2_{\mu_{i\to h\to f}}},\quad \Delta\chi^2 = \chi^2 - \chi^2_{min} < 3.841.$$ → **For 1 DoF, 95% C.L.**

This set $||\sin\theta|| < 0.193$.

Probe SFOEWPT at the LHC: Heavy Scalar Resonance

$$\mathcal{M}^2 = \begin{pmatrix} -\frac{a_1 v_0^2}{4x_0} + x_0 (b_3 + 2b_4 x_0) & \frac{v_0}{2}(a_1 + 2a_2 x_0) \\ \frac{v_0}{2}(a_1 + 2a_2 x_0) & 2\lambda v_0^2 \end{pmatrix}.$$

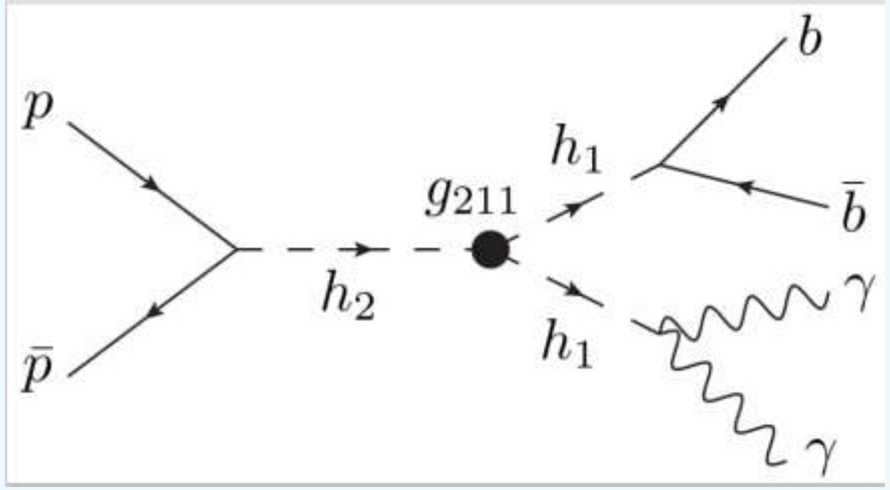
Di-Higgs	Ref.
$4b$	JHEP 01 (2019) 030, JHEP 08 (2018) 152
$bb\nu\bar{\nu}$	JHEP 04 (2019) 092, JHEP 01 (2018) 054
$bbl\nu l\bar{\nu}$	JHEP 01 (2018) 054
WW^*WW^*	JHEP 05 (2019) 124
$bb\tau\tau$	Phys.Rev.Lett. 122 (2019) 8, 089901, Phys.Lett.B 778 (2018) 101-127
$bb\gamma\gamma$	JHEP 11 (2018) 040, JHEP 11 (2018) 040
...	...

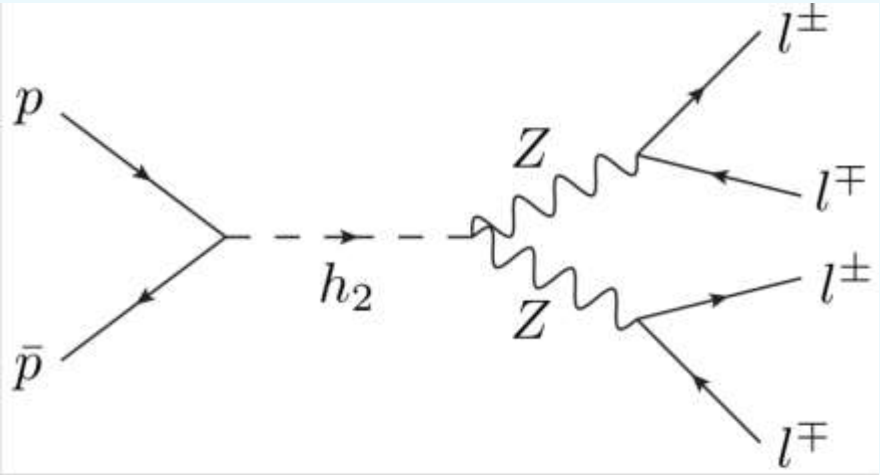
Di-Boson	Ref.
Semileptonic	Eur.Phys.J.C 80 (2020) 12, JHEP 03 (2018) 042
Hadronic	Phys.Lett.B 777 (2018) 91-113, JHEP 09 (2016) 173
Leptonic	Eur.Phys.J.C 78 (2018) 4, 293, Phys.Rev.D 98 (2018) 5 Eur.Phys.J.C 78 (2018) 1, 24
...	...

Di-Fermion	Ref.
$\tau\bar{\tau}$	Phys.Rev.Lett. 125 (2020) 5, JHEP 01 (2018) 055
$b\bar{b}$	Phys.Rev.D 102 (2020) 3
$t\bar{t}$	JHEP 07 (2023) 203
...	...

All channels are effective in probing the xSM !

The first step: $b\bar{b}\gamma\gamma$ and $ZZ \to 4l$





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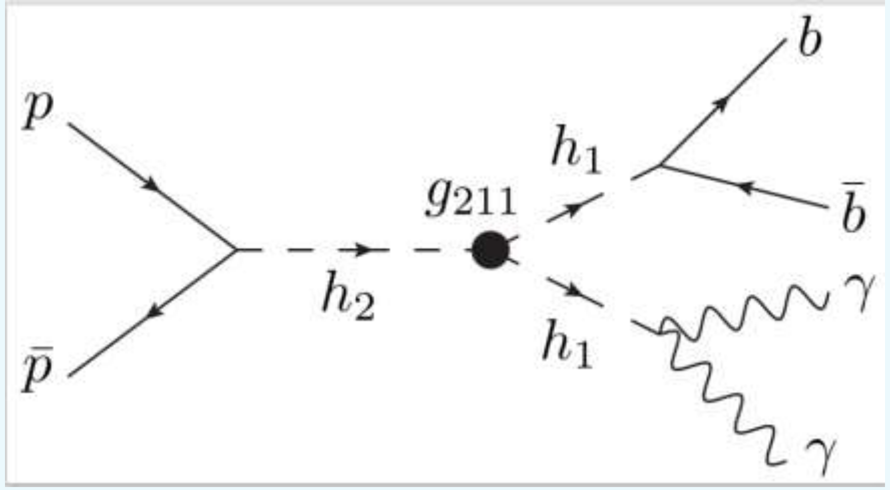
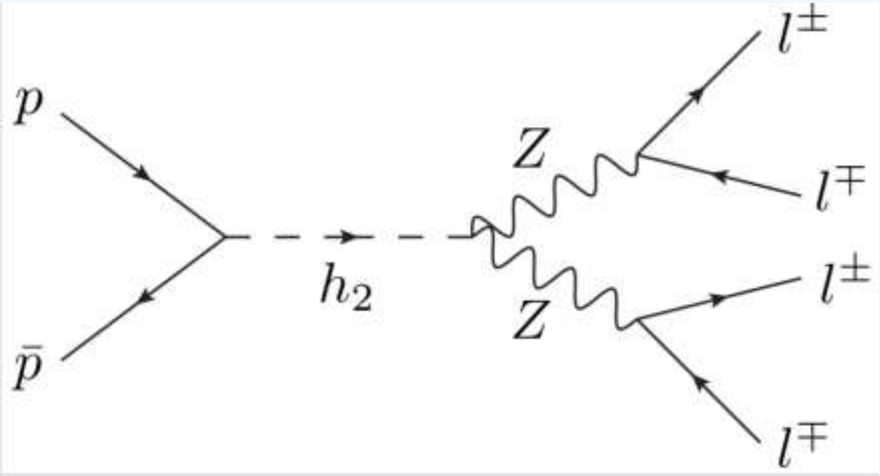
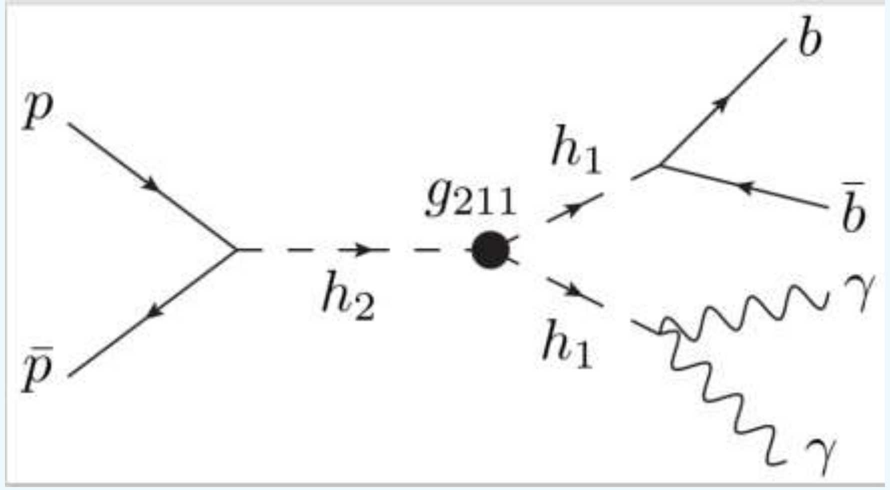
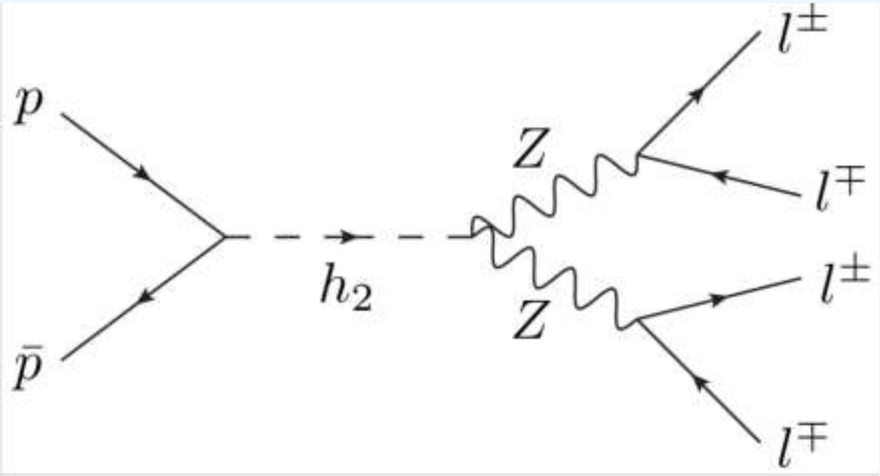




$$g_{211} = \frac{1}{4}[(a_1 + 2a_2x_0)\cos^3\theta + 4v_0\,(a_2 - 3\lambda)\cos^2\theta\sin\theta - 2\,(a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)\cos\theta\sin^2\theta - 2a_2v_0\sin^3\theta].$$

The first step: $b\bar{b}\gamma\gamma$ and $ZZ \to 4l$





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$$- 2\,(a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)\cos\theta\sin^2\theta - 2a_2v_0\sin^3\theta].$$

$$\sigma_{bb\gamma\gamma} = \sigma_{pp\to h_2} \times BR(h_2 \to h_1h_1) \times BR(h_1 \to b\bar{b}) \times BR(h_1 \to \gamma\gamma),$$
$$\sigma_{4\ell} = \sigma_{pp\to h_2} \times BR(h_2 \to ZZ) \times BR(ZZ \to 4\ell)$$

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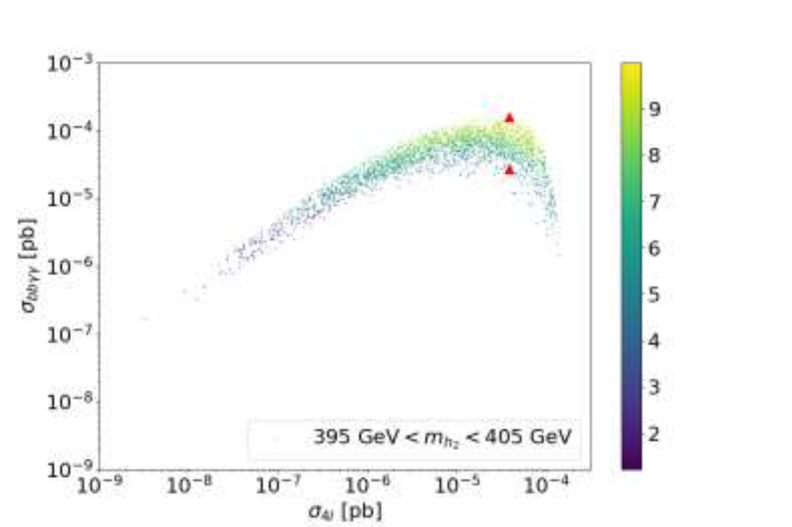
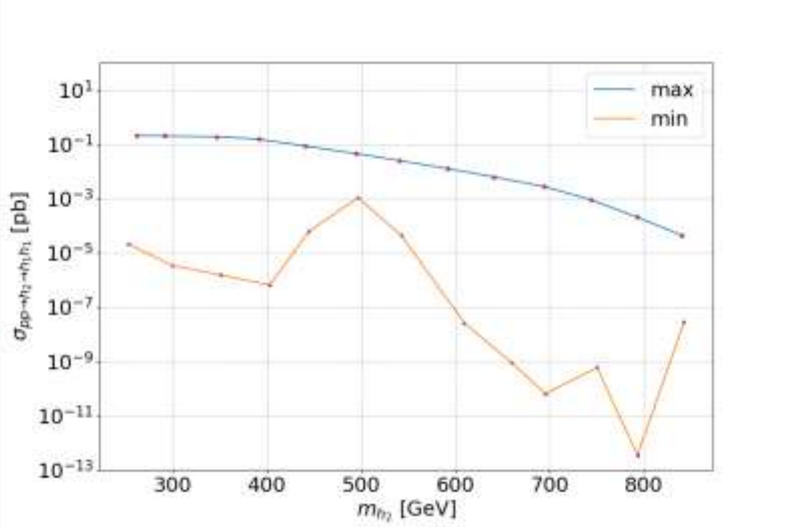
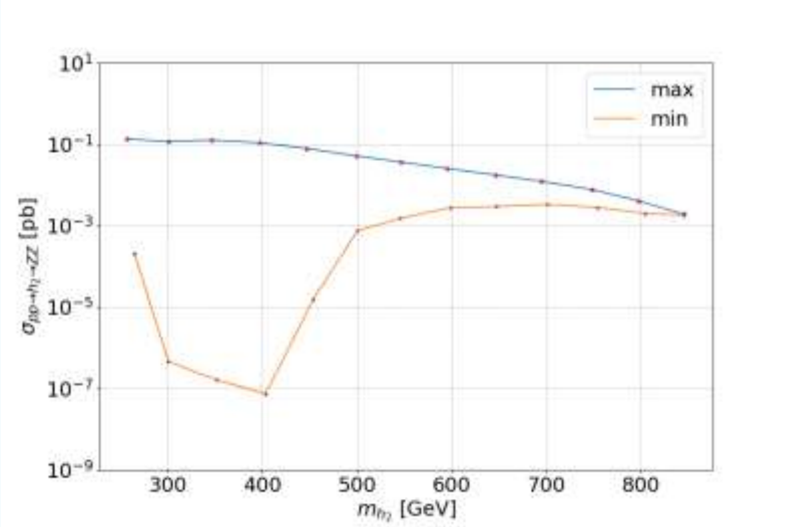






$$\sigma_{bb\gamma\gamma} = \sigma_{pp\to h_2} \times BR(h_2 \to h_1h_1) \times BR(h_1 \to b\bar{b}) \times BR(h_1 \to \gamma\gamma),$$

$$\sigma_{4\ell} = \sigma_{pp\to h_2} \times BR(h_2 \to ZZ) \times BR(ZZ \to 4\ell)$$

The problem is: How to combine them together? Will the combined bound be stronger?

Standard of combination of multiple channels

JHEP 11 (2018) 040
DOI: 10.1007/JHEP11(2018)040

CERN-EP-2018-130
13 Jul 2018

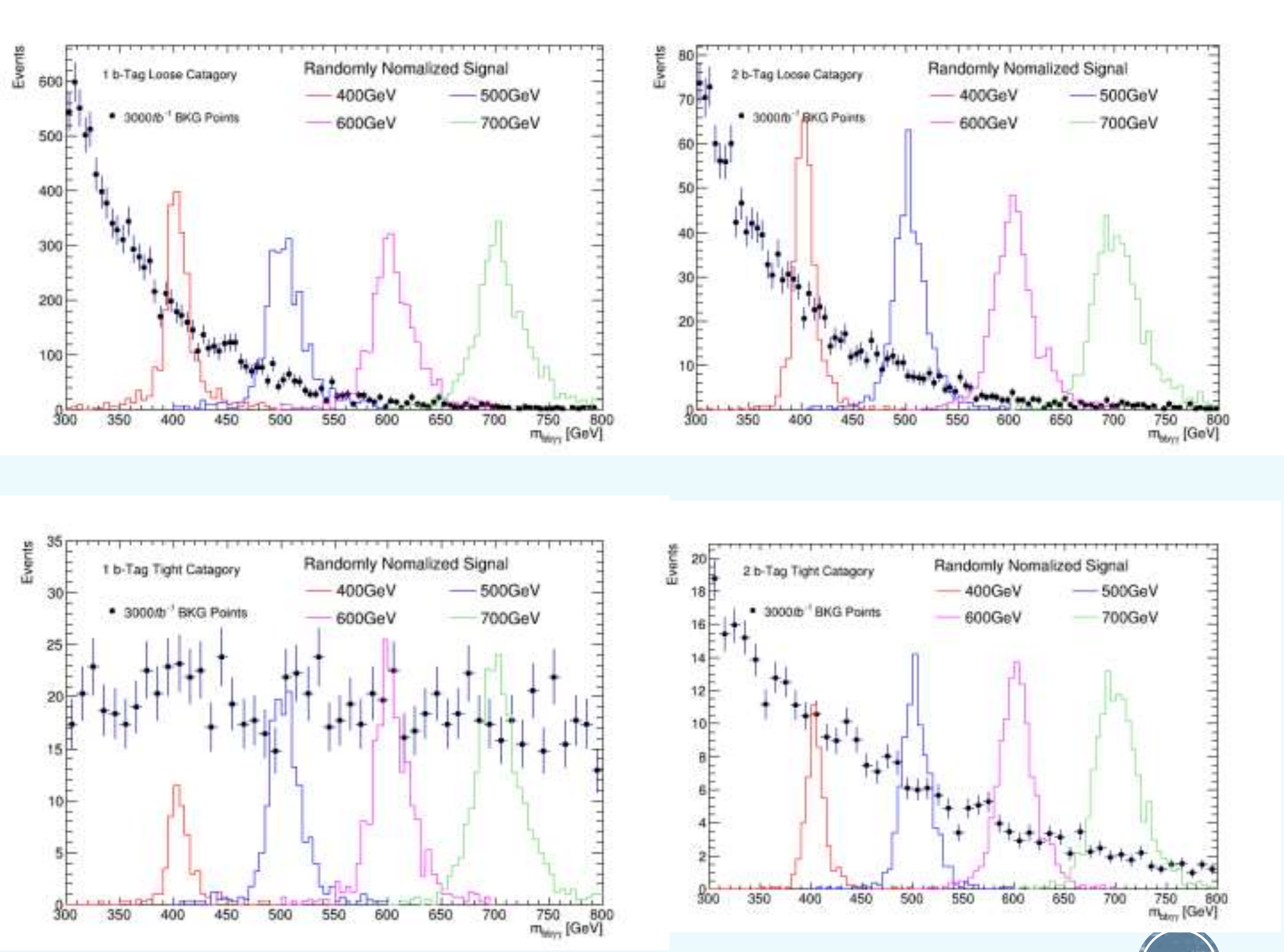
Search for Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final state with 13 TeV pp collision data collected by the ATLAS experiment

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Eur. Phys. J. C 78 (2018) 293
DOI: DOI:10.1140/epjc/s10052-018-5686-3

CERN-EP-2017-251
4th May 2018

Search for heavy ZZ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



Standard of combination of multiple channels

JHEP 11 (2018) 040
DOI: 10.1007/JHEP11(2018)040

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13 Jul 2018

Search for Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final state with 13 TeV pp collision data collected by the ATLAS experiment

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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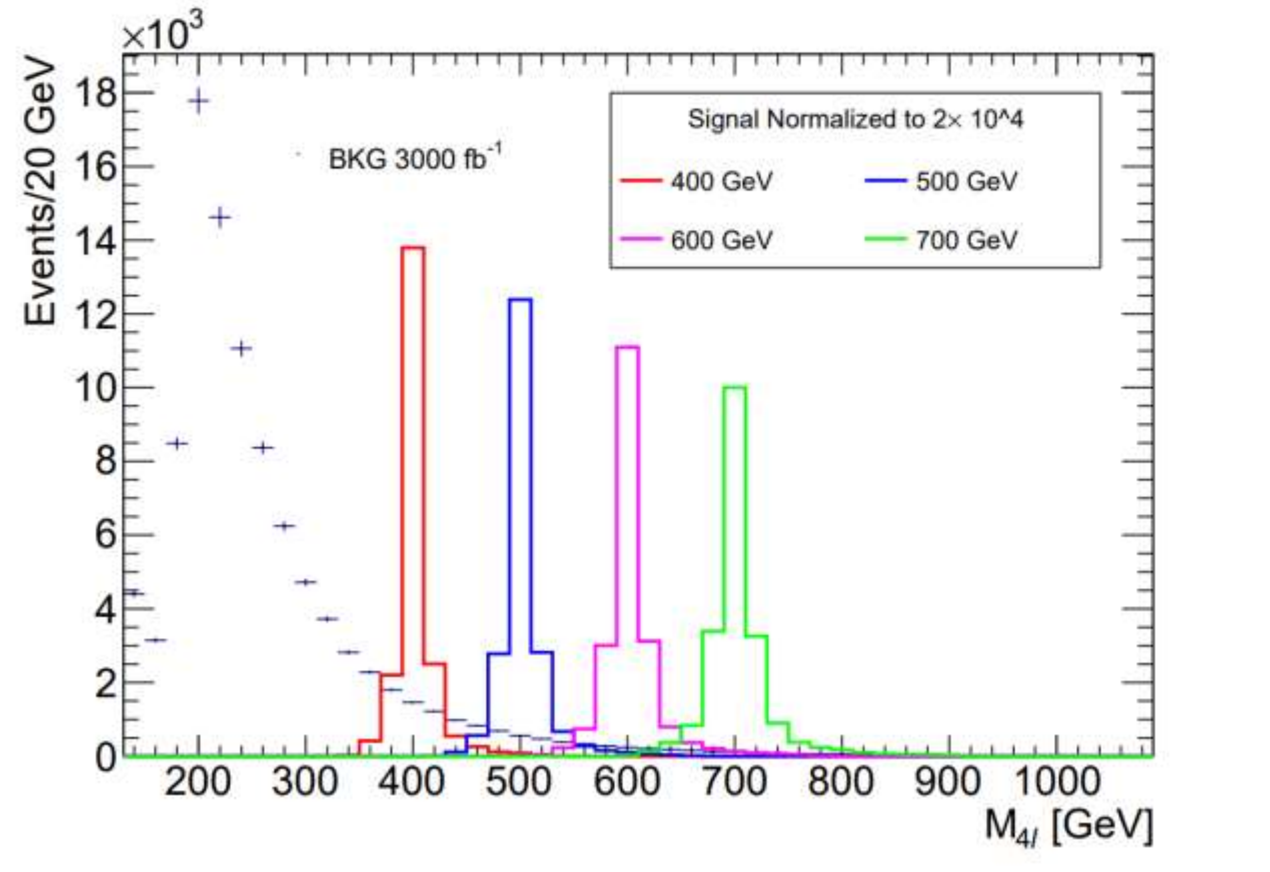
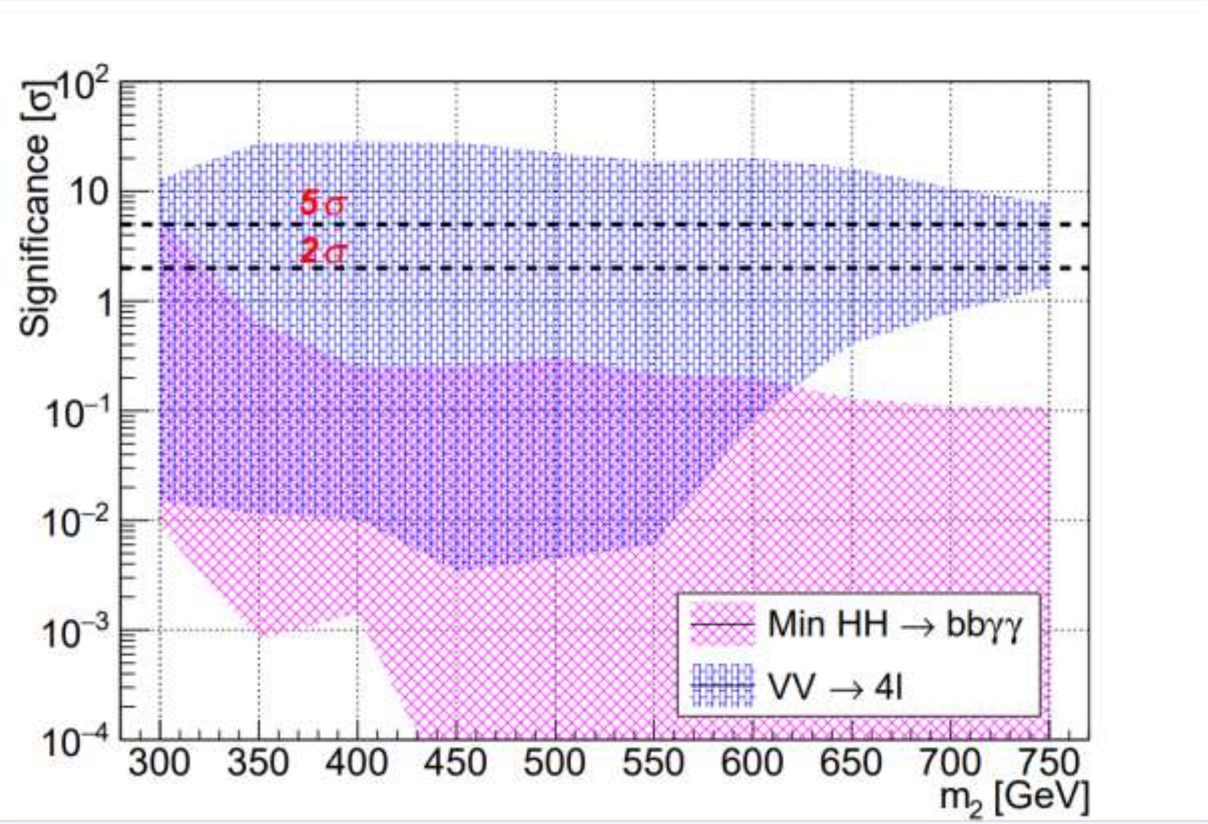
4th May 2018

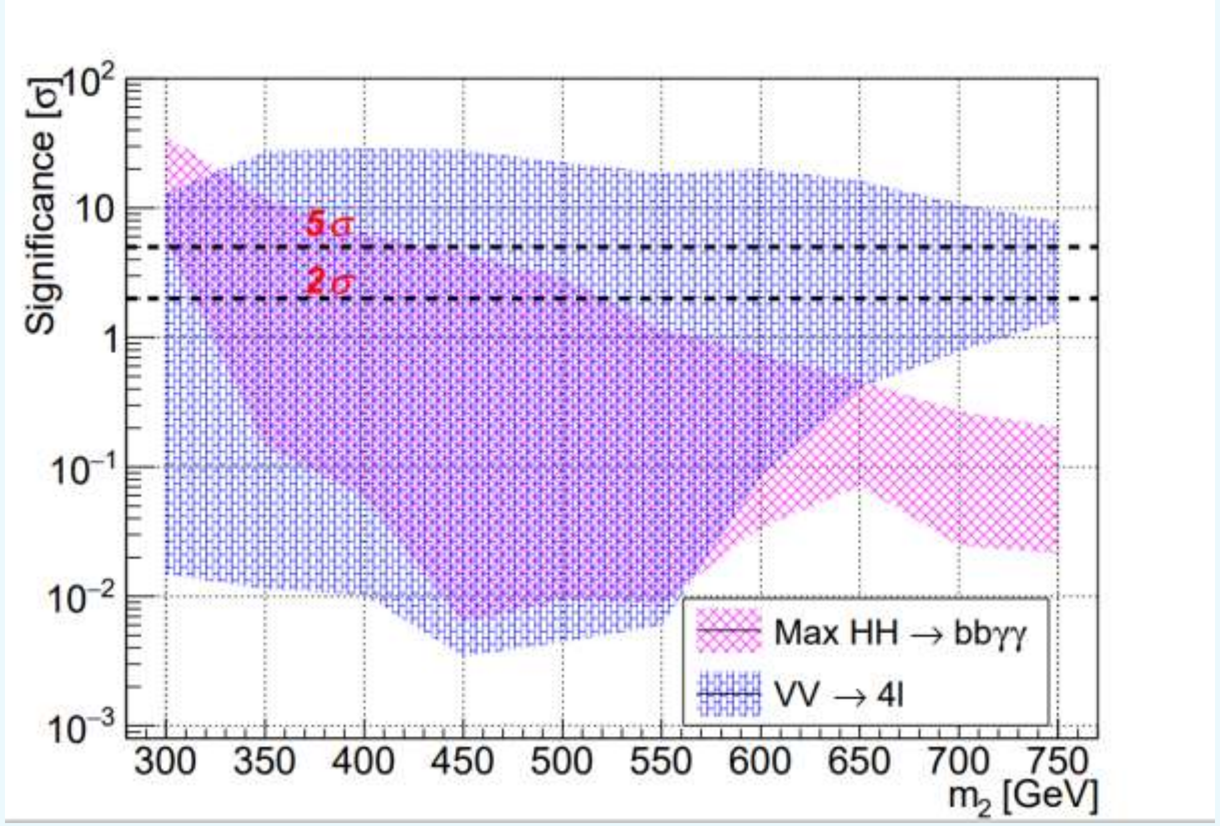
Search for heavy ZZ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector



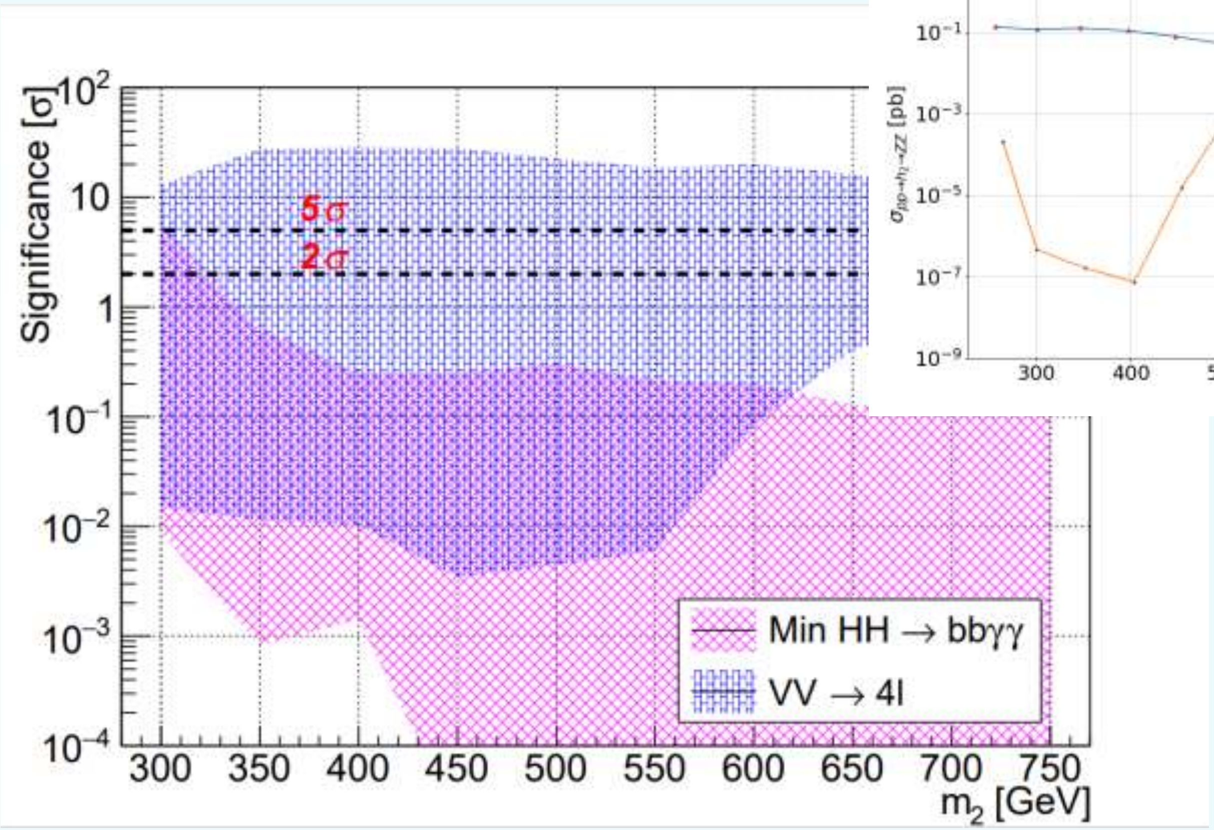
Experiment: Distributions and Efficiency
Simulation: Upper limit cross sections.

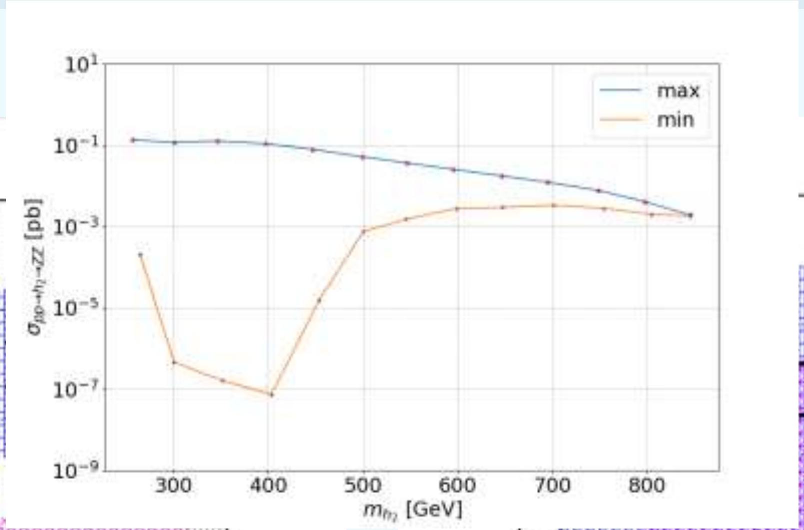
Results: The combined exclusion bound

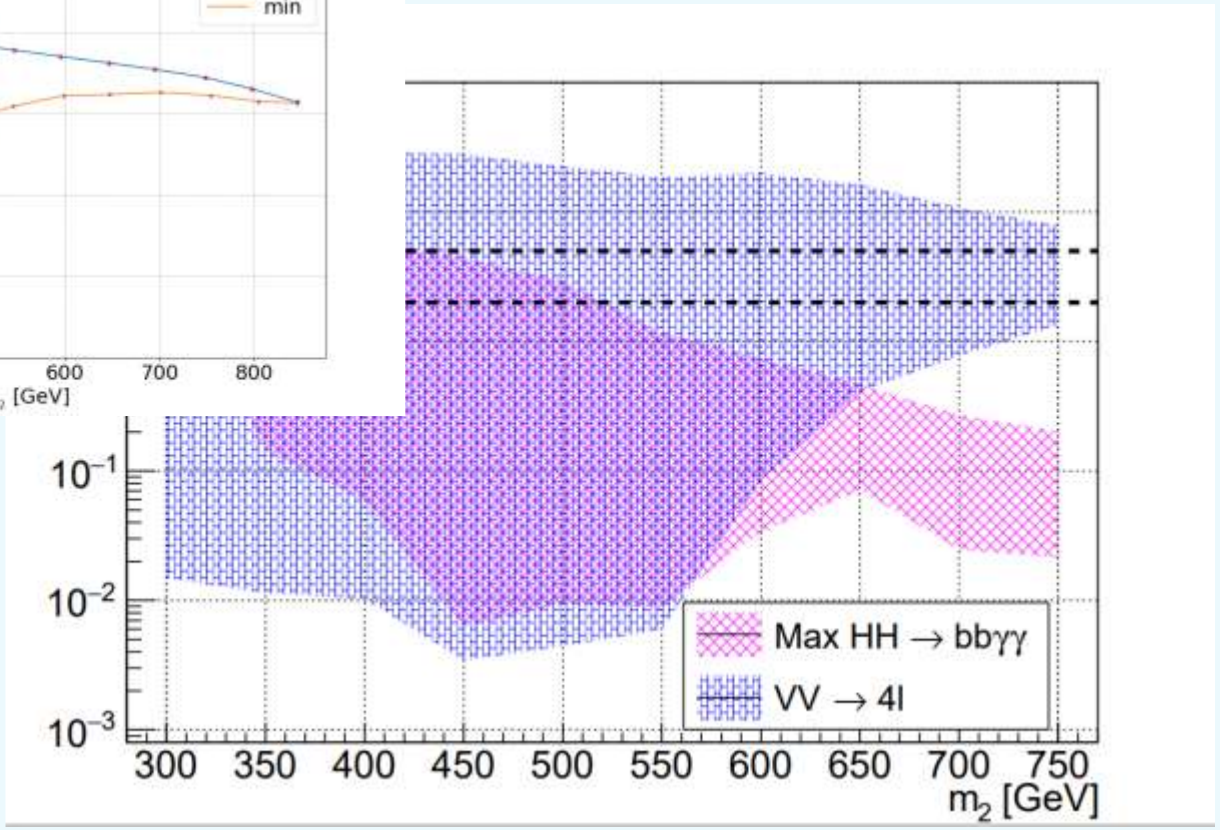




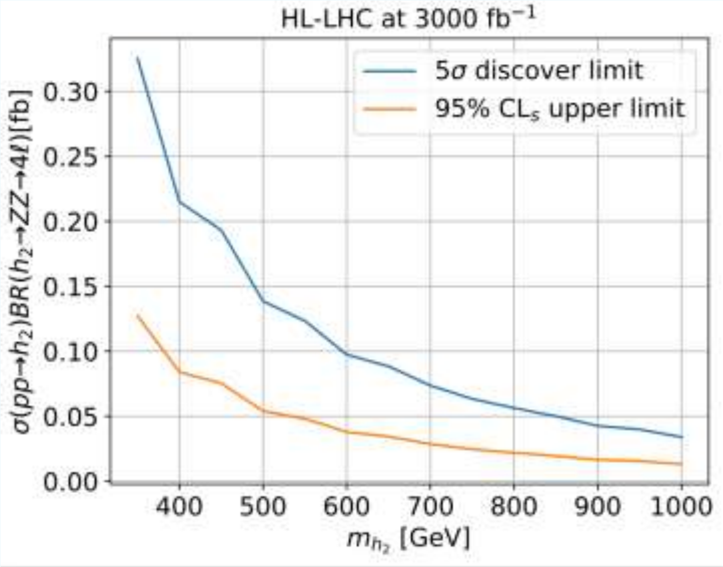
Results: The combined exclusion bound

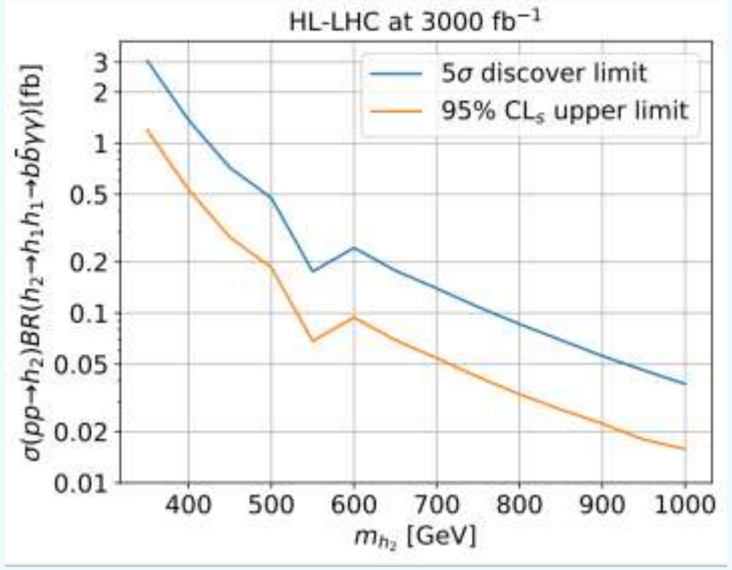


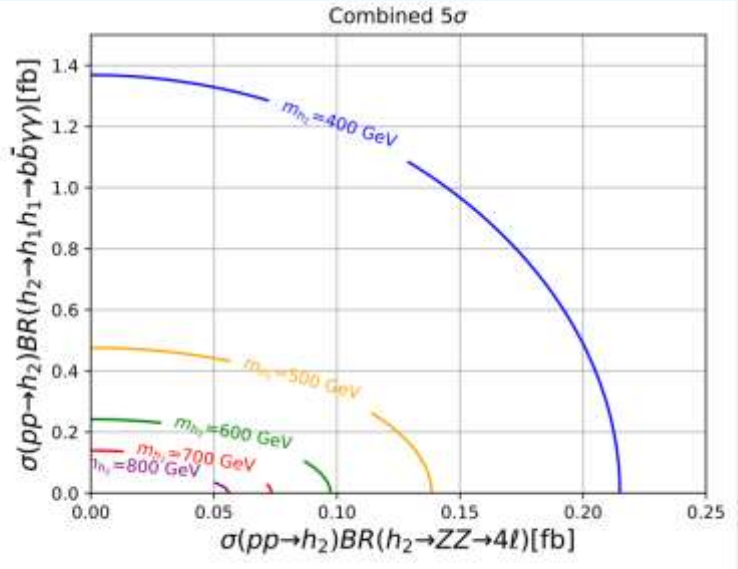


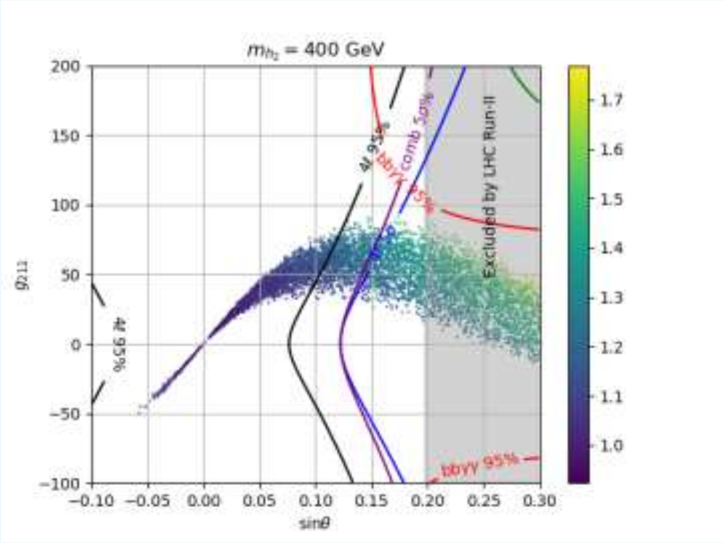


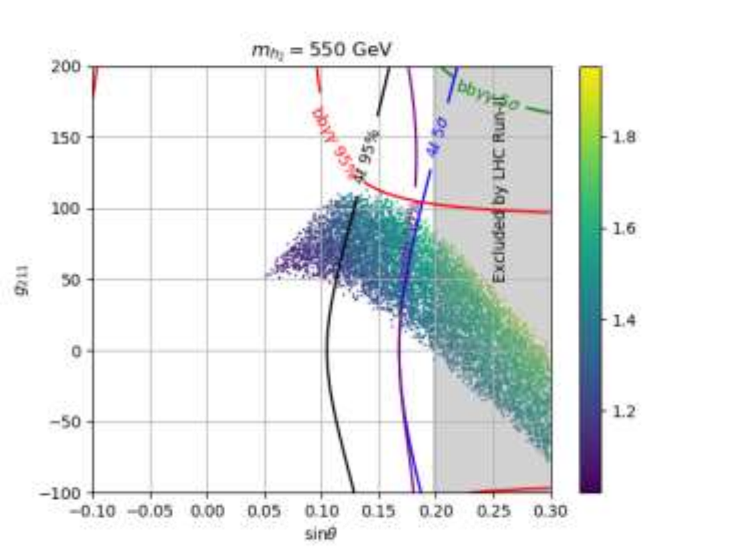
Combination of channels : $b\bar{b}\gamma\gamma$ and $ZZ \to 4l$

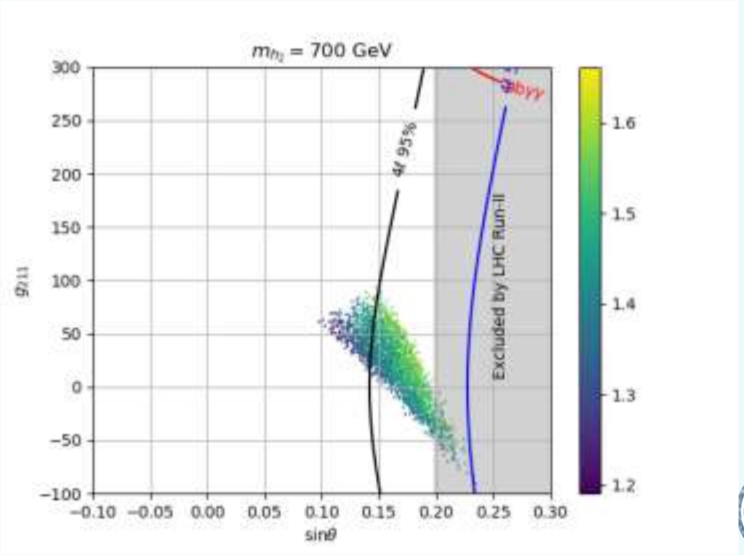




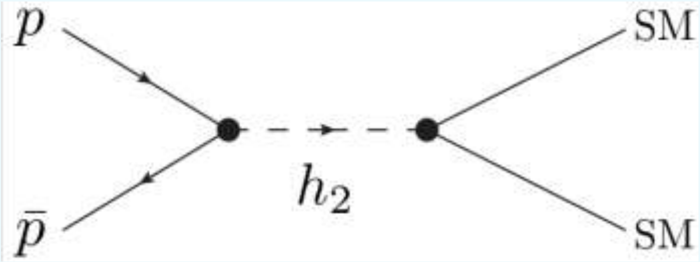








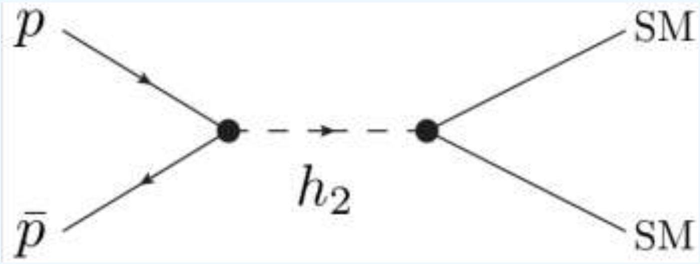
Open Questions: Test the sign of the mixing angle ?



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

Higgs measurement only constrain $\cos^2\theta$, but not the sign of θ.

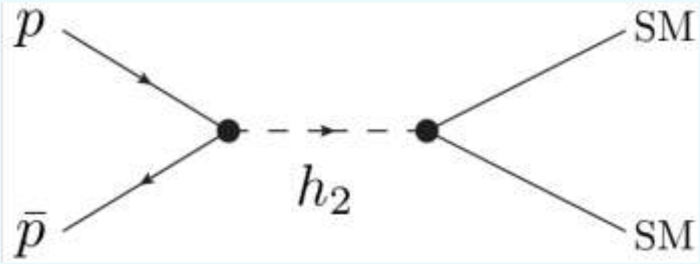
Open Questions: Test the sign of the mixing angle ?



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

What happened in the xSM ?

Open Questions: Test the sign of the mixing angle ?



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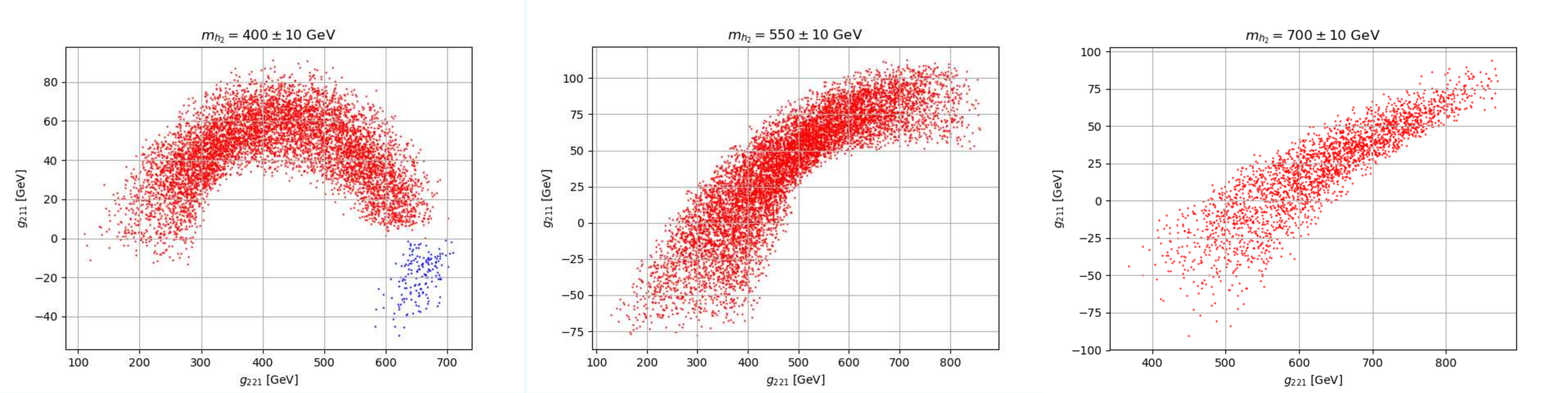

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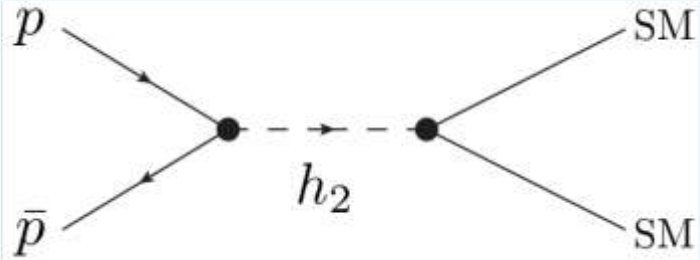
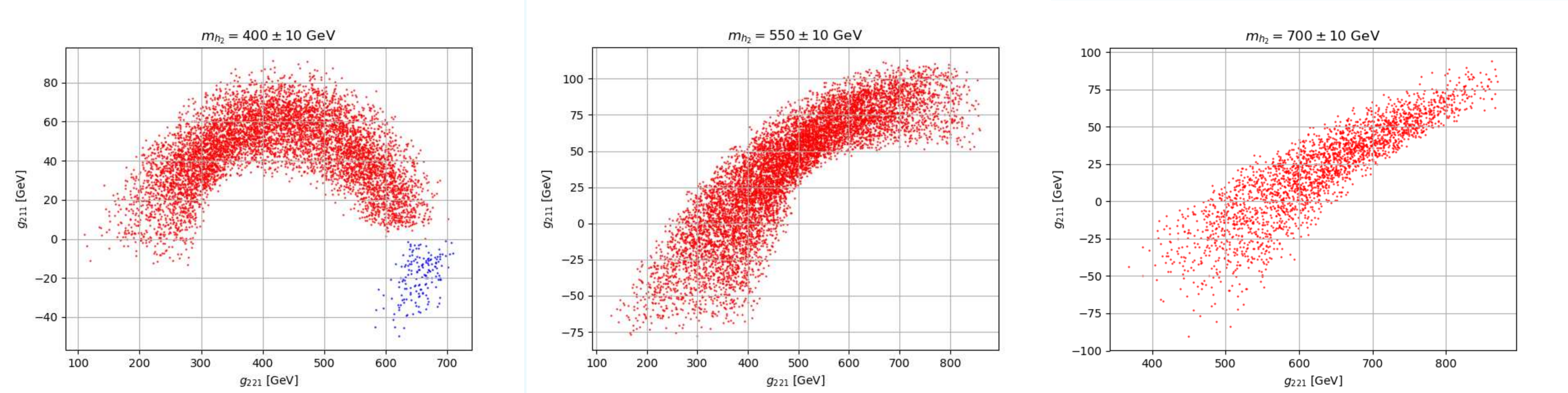
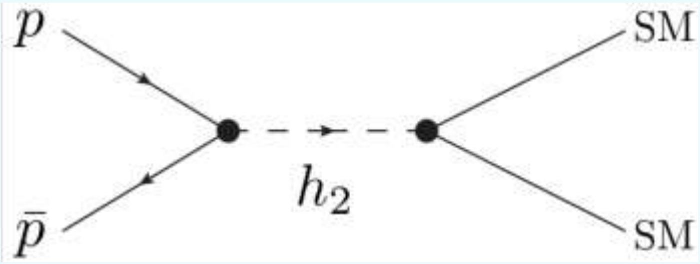


$$h_1 = h\cos\theta + s\sin\theta$$
$$h_2 = s\cos\theta - h\sin\theta$$

$$\sin 2\theta = \frac{(a_1 + 2a_2 x_0)v_0}{m_1^2 - m_2^2}$$

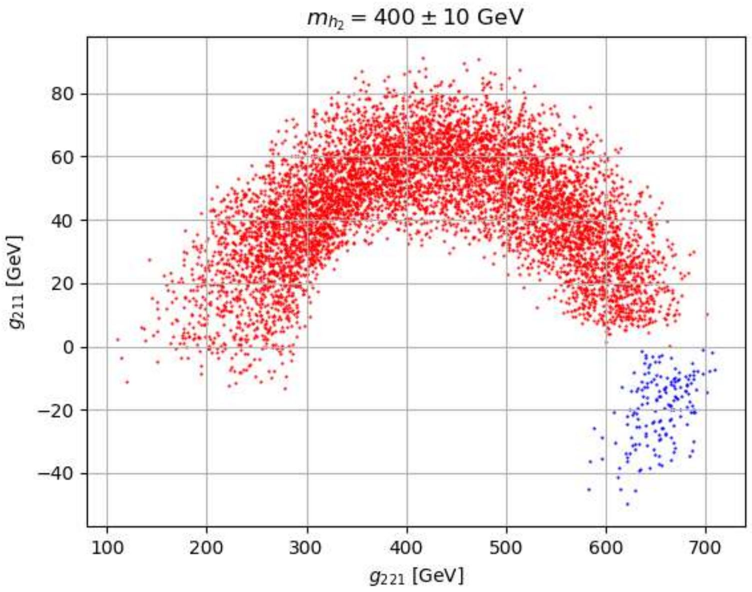


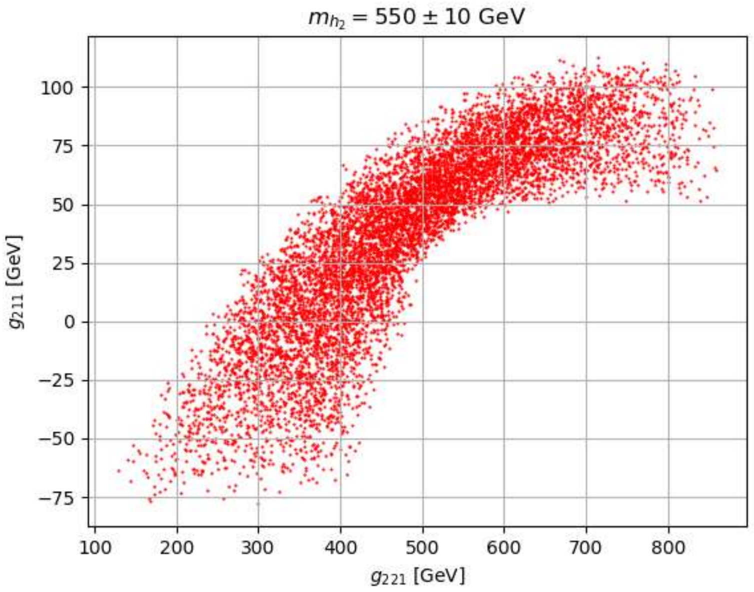
Open Questions: Test the sign of the mixing angle ?

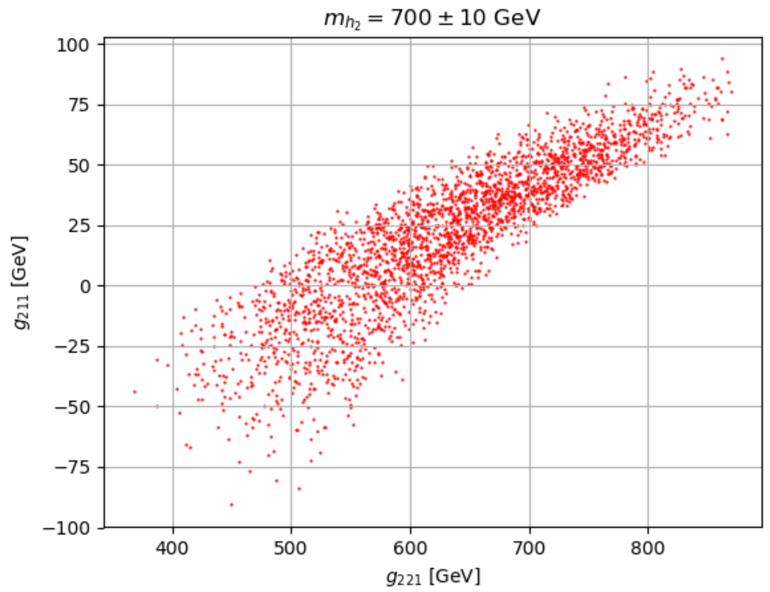


$$h_1 = h\cos\theta + s\sin\theta$$
$$h_2 = s\cos\theta - h\sin\theta$$

$$g_{211} = \frac{1}{4}[(a_1 + 2a_2x_0)\cos^3\theta + 4v_0(a_2 - 3\lambda)\cos^2\theta\sin\theta - 2(a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)\cos\theta\sin^2\theta - 2a_2v_0\sin^3\theta].$$





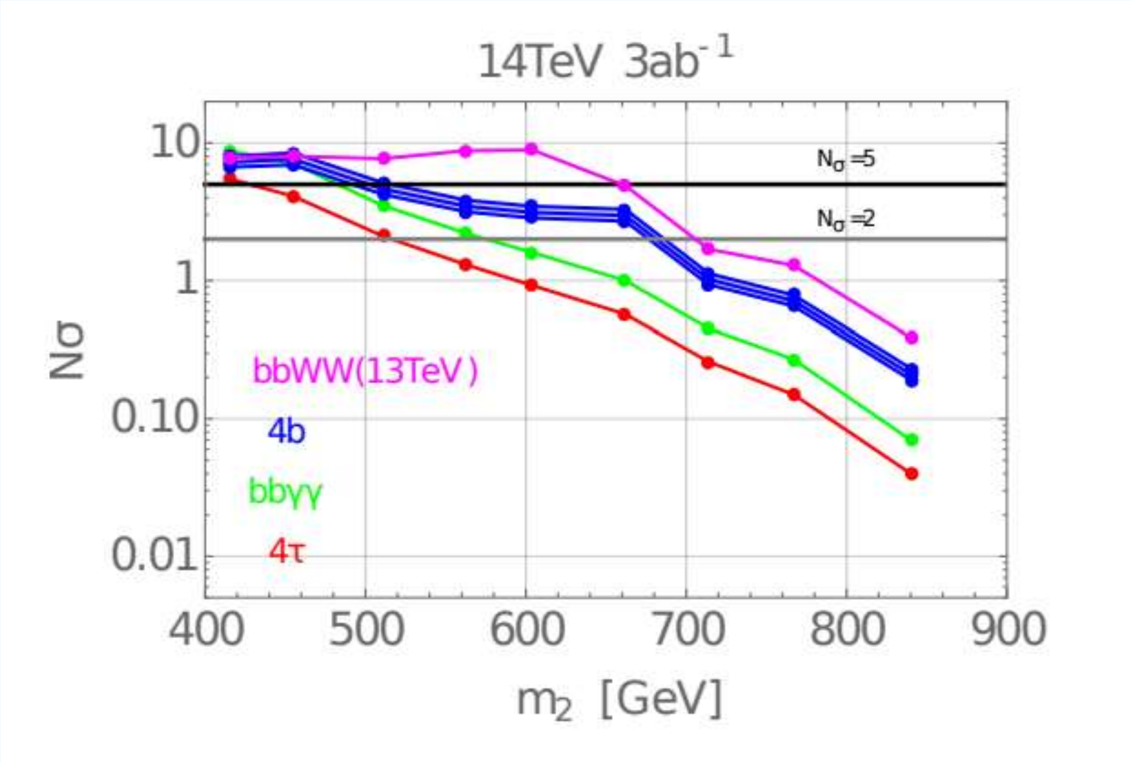


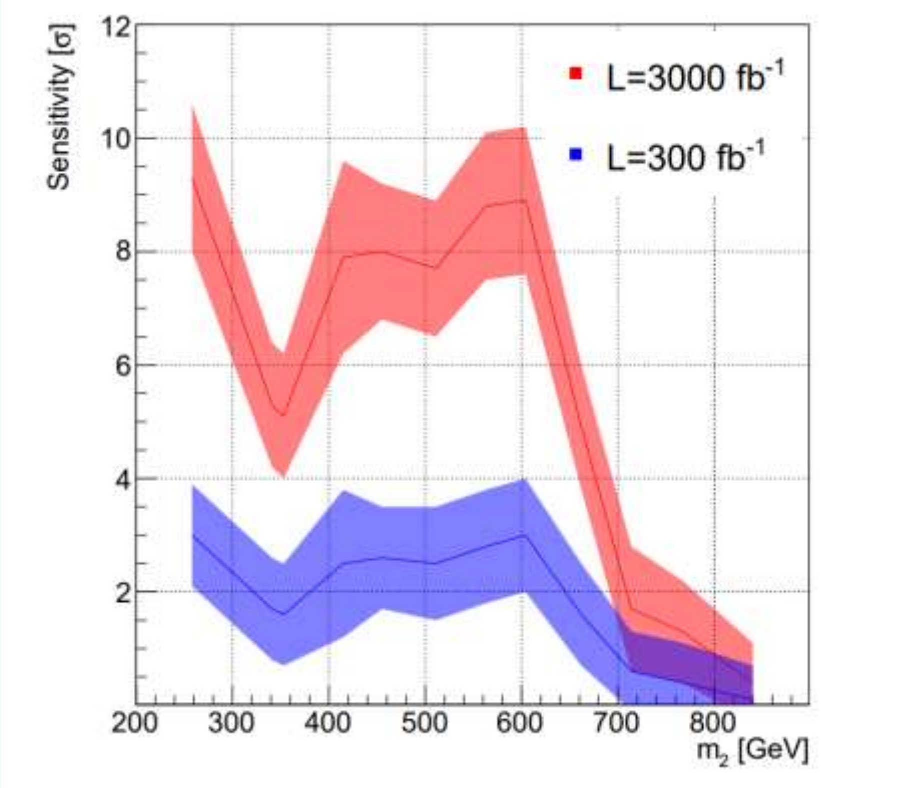
Who breaks the plus-minus symmetry ?

Summary

- We study the SFOEWPT in xSM and searches for heavy resonant di-Higgs production.
- We introduce the current constraints on this model from EWPO, Higgs measurement, vaccum stability...
- We introduce a new scheme to combine the current LHC di-Higgs channels and di-boson channels and show $bb\gamma\gamma$ and $4l$ detection ability.
- SFOEWPT is hard to be probed up to 5σ for $m_{h_2} > 700$ GeV.
- Combination of $bb\gamma\gamma$ and $4l$ can be powerful in low mass region.
- An interesting open question: SFOEWPT prefer positive mixing angle. How to check the sign of the mixing angle in the future?

Review: Single Channel Searches





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HL, MJRM, SW

Phys.Rev.D 96 (2017) 3, 035007
TH, JMN, LP, MJRM, AS