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NEW PHYSICS WITH EXTRA HIGGS

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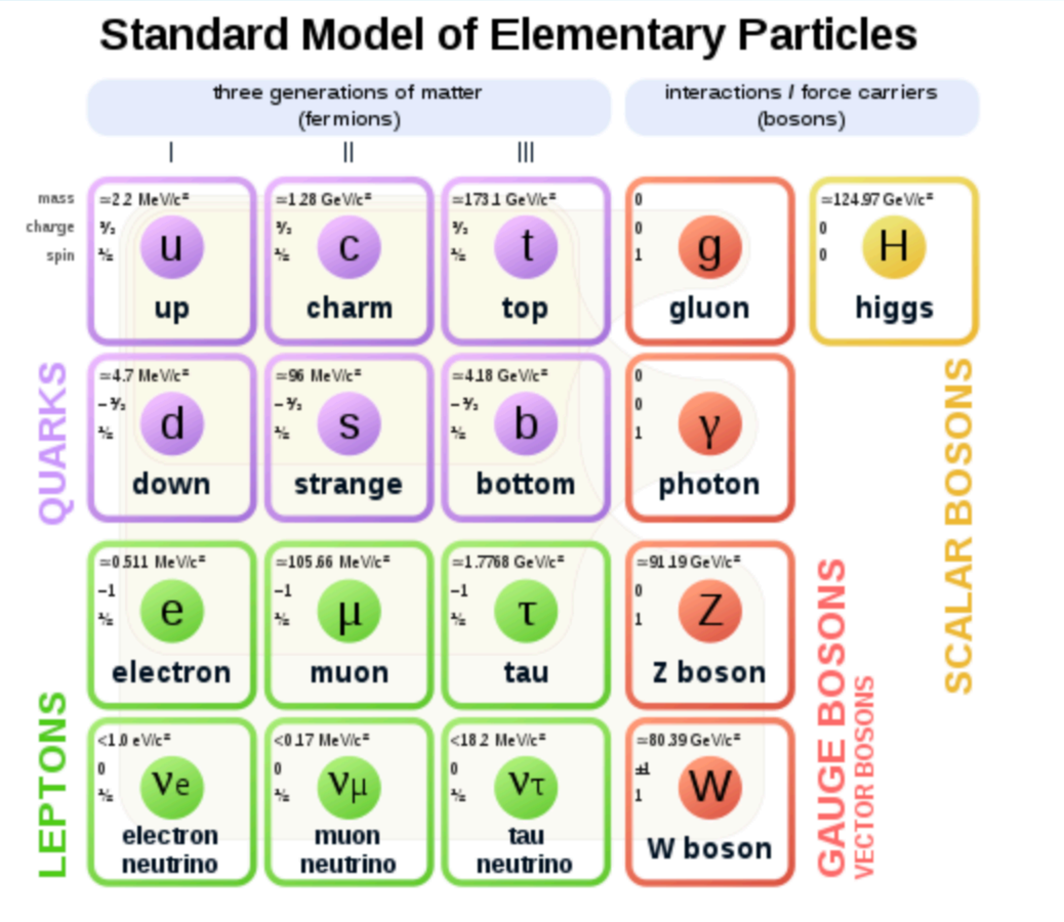
JHEP 04 (2020) 197

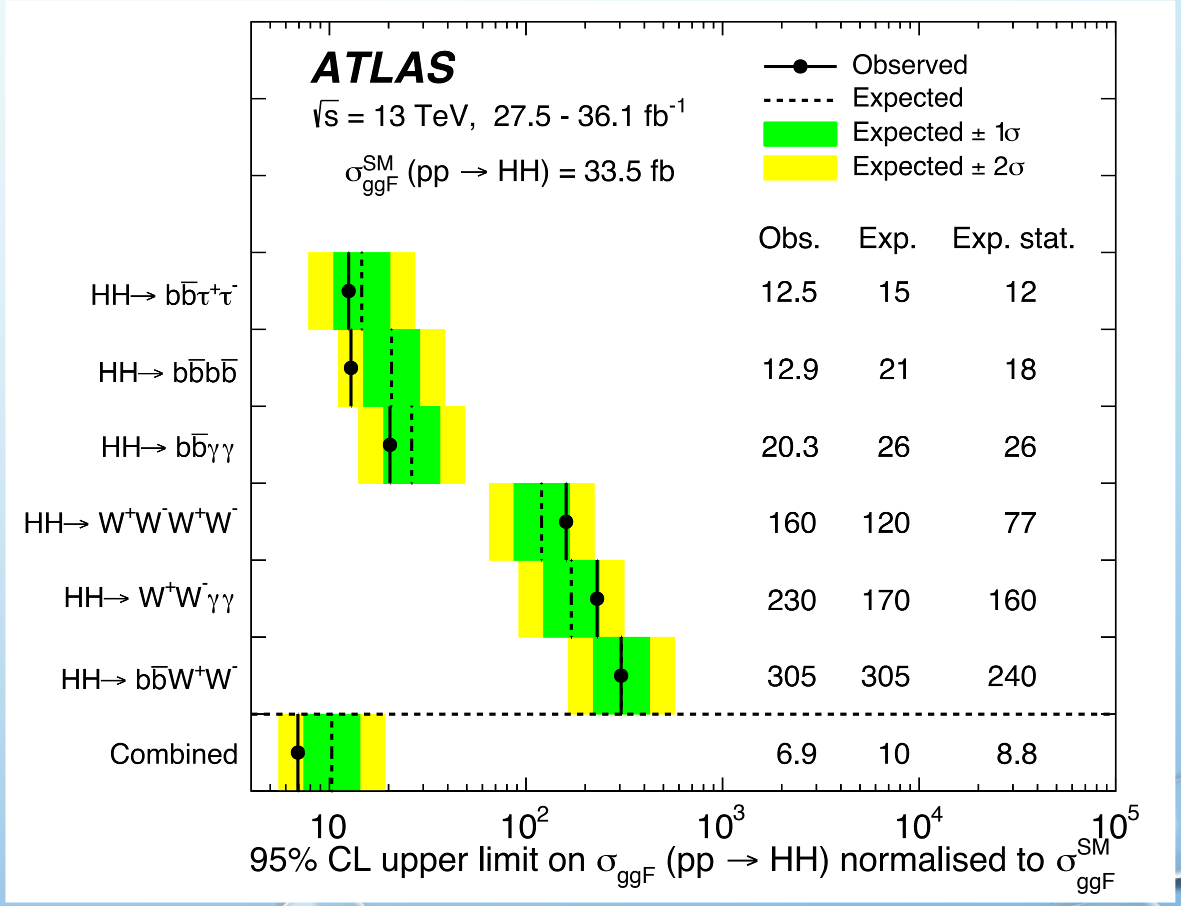
JHEP11 (2020) 066

JHEP 03 (2019) 008

JHEP 06 (2018) 150

SM MASS ORIGIN

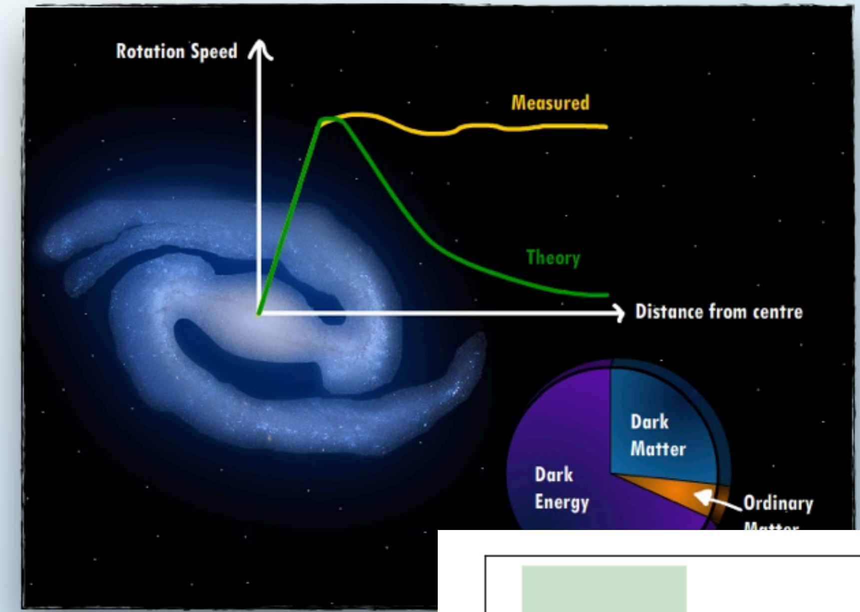


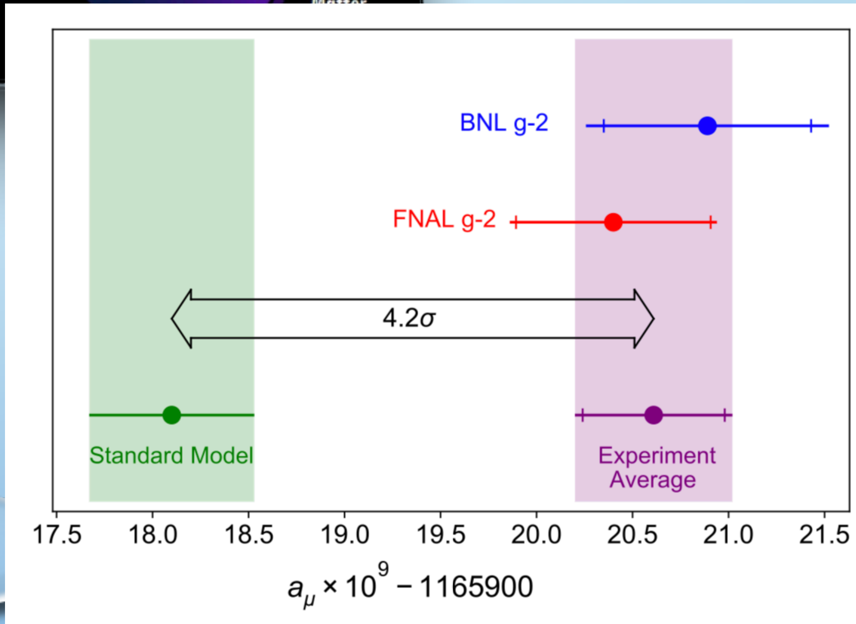


ATLAS, Phys. Lett. B 800 (2020) 135103

NEW PHYSICS BEYOND SM

- Dark Matter Candidates?
- Dark Energy?
- Gravity?
- Fermion Generation?
- Strong CP problem?
- Neutrino mass?
- Muon g-2?
- Hierarchy?
- ……





EXTRA HIGGS CAN BE ONE ANSWER FOR NEW PHYSICS

Extra Higgs how to answer New Physics

- **One complex scalar for $\Delta a_{e/\mu}$**
- **A Light Scalar Explanation of $g-2_{\mu}$and the KOTO Anomaly**
- **A Light Higgs at the LHC and the B-Anomalies**

How to looking for extra Higgs

- **Long Lived particle search at HGCAL**
- **Triple Higgs search at LHC**

ONE COMPLEX SCALAR FOR $\Delta a_{e/\mu}$

JHEP 03 (2019) 008

$$\Delta a_e \equiv a_e^{\rm exp} - a_e^{\rm SM} = (-88 \pm 36) \times 10^{-14}$$

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.74 \pm 0.73) \times 10^{-9}$$

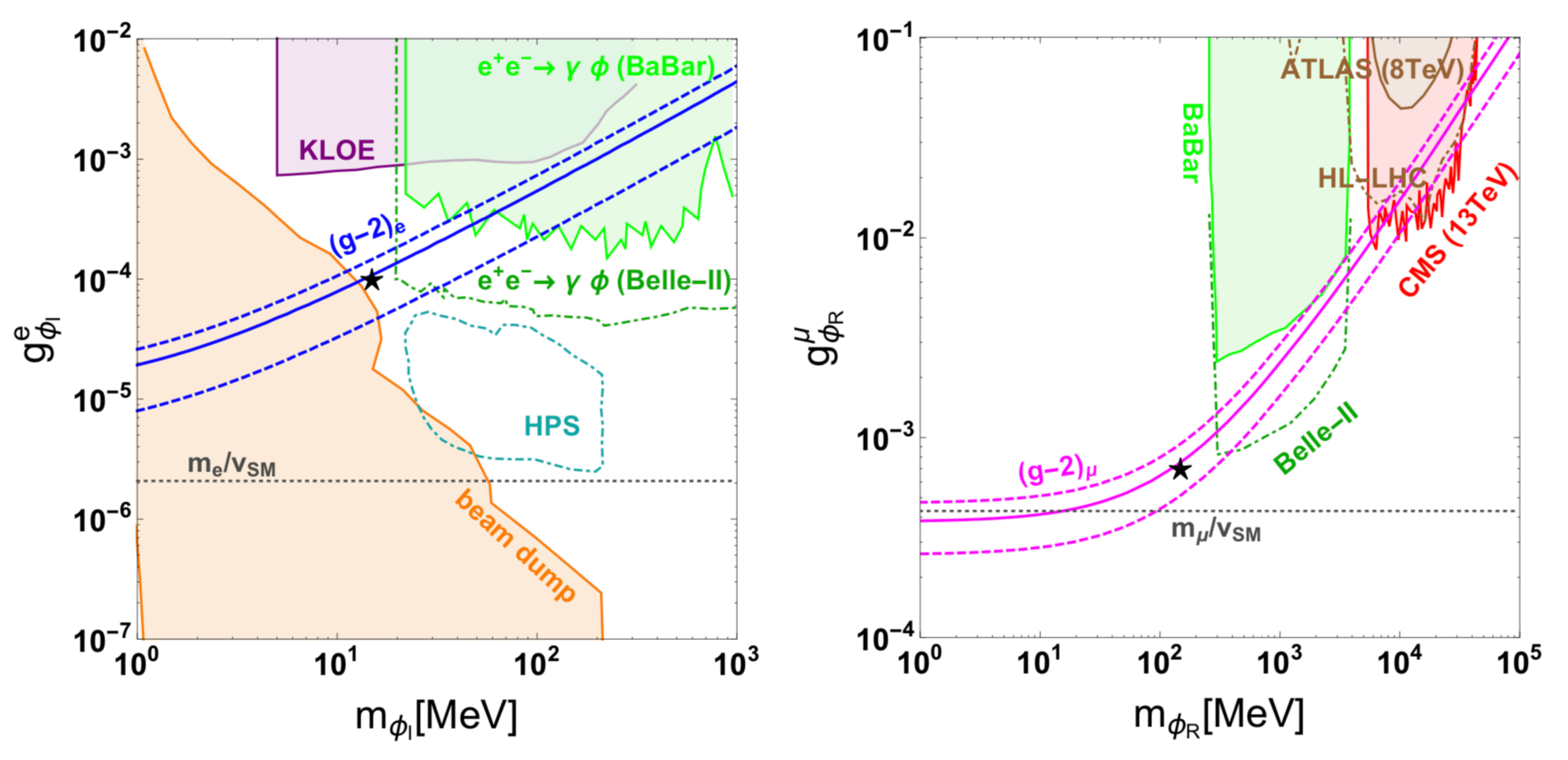
- Scalar contribution to $\Delta a_{e/\mu}$

$$\Delta a_\ell = \frac{1}{8\pi^2} \int_0^1 dx \frac{(1-x)^2 \left((1+x) g_R^2 - (1-x) g_I^2\right)}{(1-x)^2 + x\left(m_S/m_\ell\right)^2}$$

- CP conservation

$$\mathcal{L}_{\rm int} = i g^e_{\phi_I} \phi_I \bar{e} \gamma_5 e + g^\mu_{\phi_R} \phi_R \bar{\mu} \mu$$

ONE COMPLEX SCALAR FOR $\Delta a_{e/\mu}$



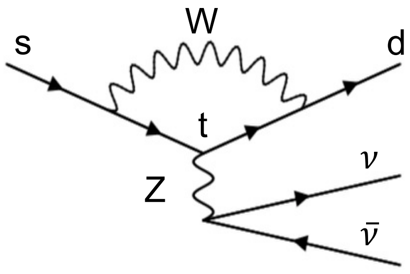
A LIGHT SCALAR FOR $g-2_\mu$ AND KOTO ANOMALY

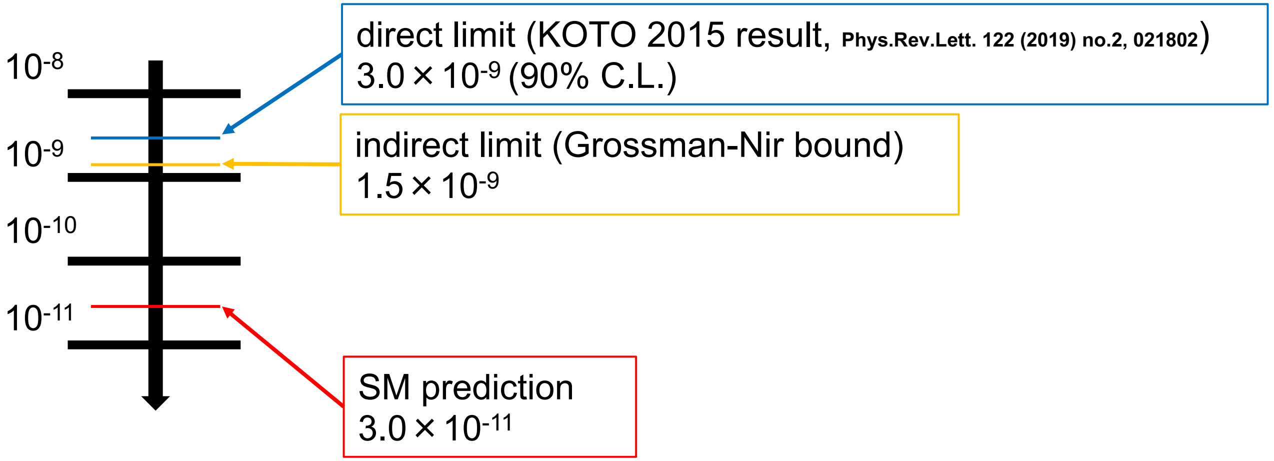
JHEP 04 (2020) 197

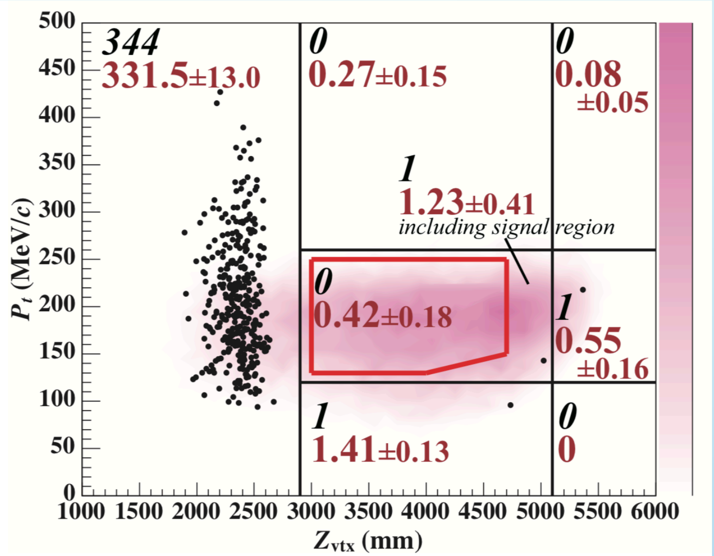
$K_L \to \pi^0 \nu\bar{\nu}$ decay

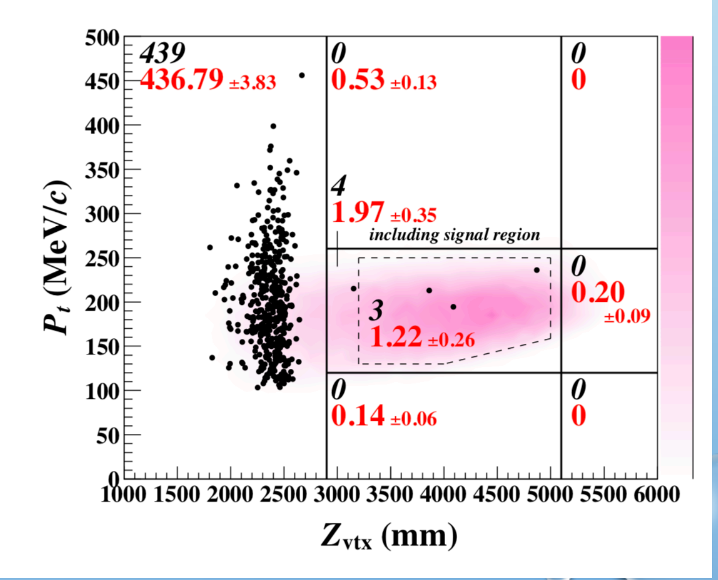
- Direct CPV
- FCNC : highly suppressed decay
  - BR (SM) : 3×10^{-11}
- Small theoretical uncertainty（~2%）

  → Good probe for new physics search



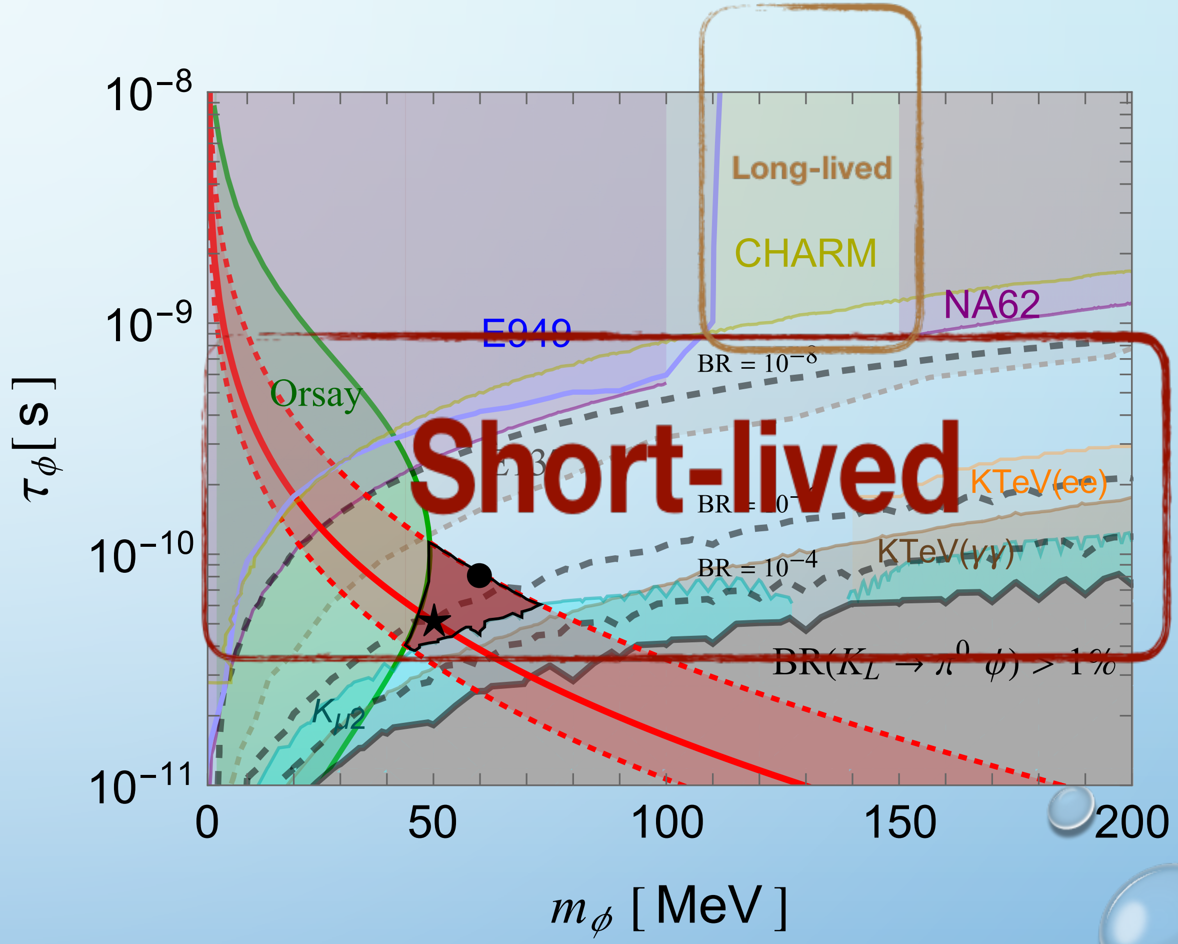






A LIGHT SCALAR FOR $g-2_\mu$ AND KOTO ANOMALY

- PROBLEM:
- KOTO signal
  - Bkg = 0.34(0.08), obs= 3 → BR($K_L \to \pi^0 \nu\nu$)~ 2x10^{-9}
- NA62/E949 constraints
  - BR($K^+ \to \pi^+ \nu\nu$) < 1.85x10^{-10}
- Nir-Grossman bound
  - isospin symmetry
  - Using lifetime of charged and neutral Kaons, BR($K^0 \to \pi^0 \nu\nu$) < 4.3 BR($K^+ \to \pi^+ \nu\nu$)



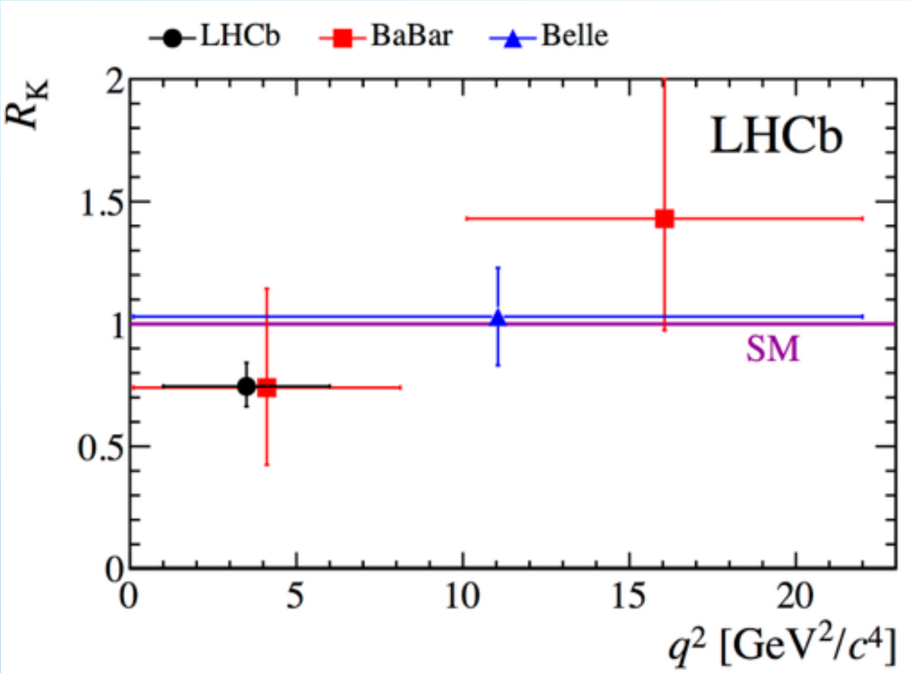
SOLUTION:

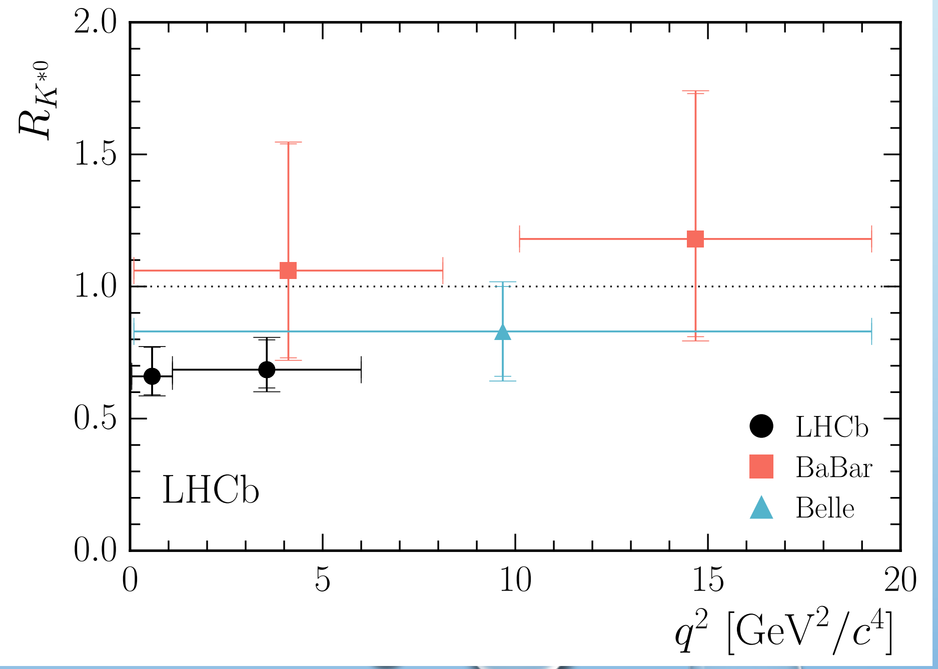
- Long-lived particle with mass around 140 MeV, due to the bkg $K^+ \to \pi^+ \pi^0$
- Short-lived particle with life time around 0.1ns ~3 cm. It decays inside the charged Kaon experiment, thus vetoed in measurement of $K^+ \to \pi^+ \bar{\nu}\nu$ (KOTO ~ 3m, NA62 ~ 150 m)

A LIGHT HIGGS AT THE LHC AND THE B-ANOMALIES

JHEP 06 (2018) 150

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)} \qquad R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}$$

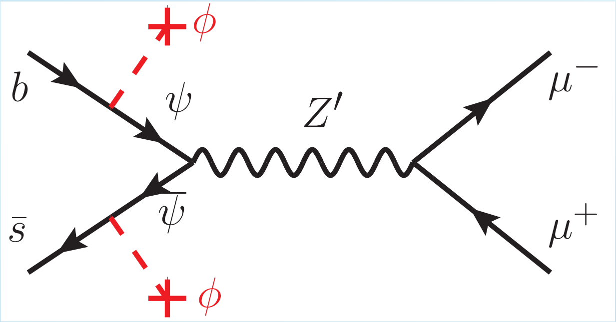




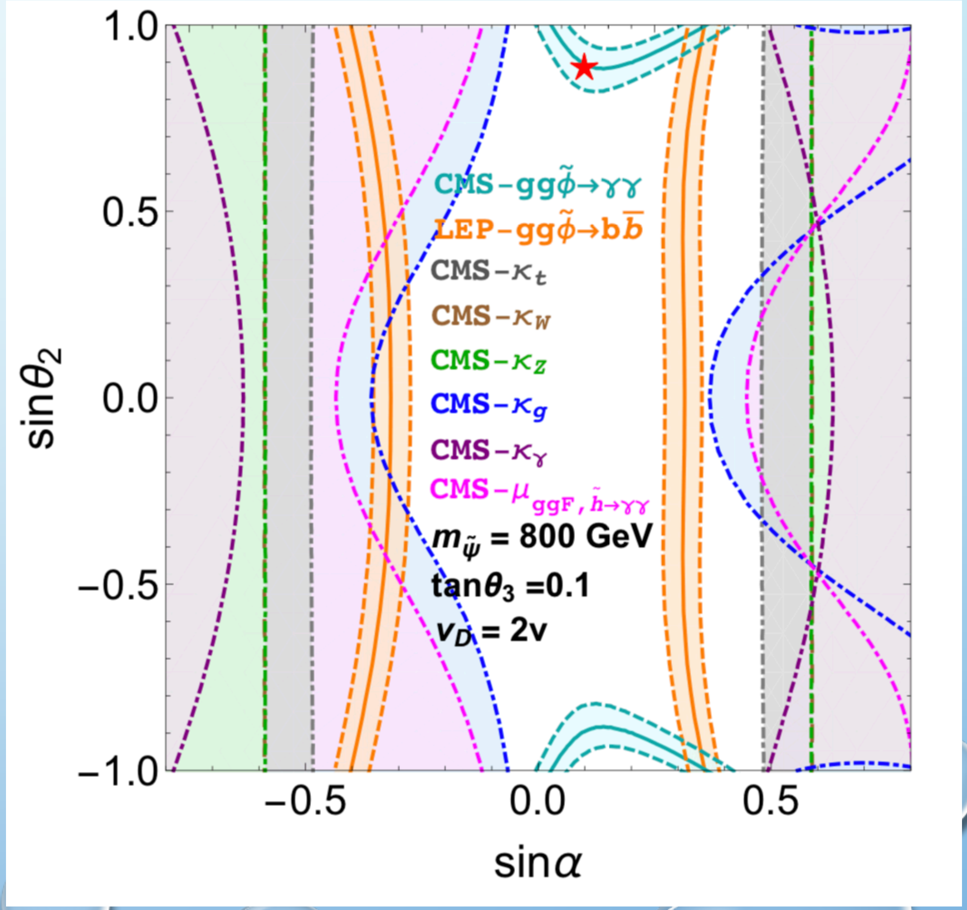
A LIGHT HIGGS AT THE LHC AND THE B-ANOMALIES

$$\mathcal{H}_{eff}^{NP} = -\mathcal{L}_{eff}^{NP} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_{em}}{4\pi}(V_{tb}V_{ts}^*)C_9^{NP}\bar{\tilde{b}}_L\gamma_\mu\tilde{s}_L\,\bar{\mu}\gamma^\mu\mu + H.c.$$

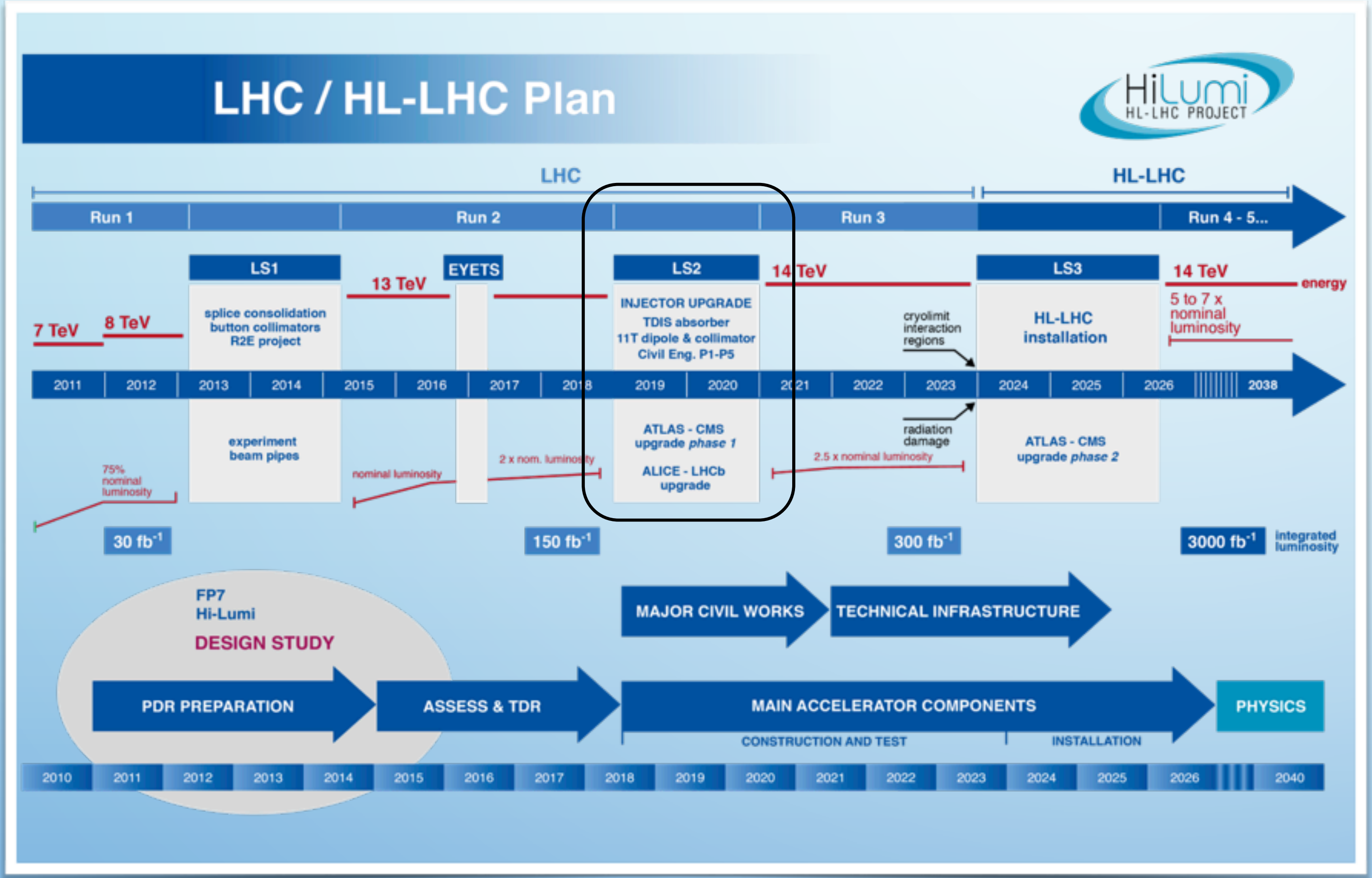
-1.56

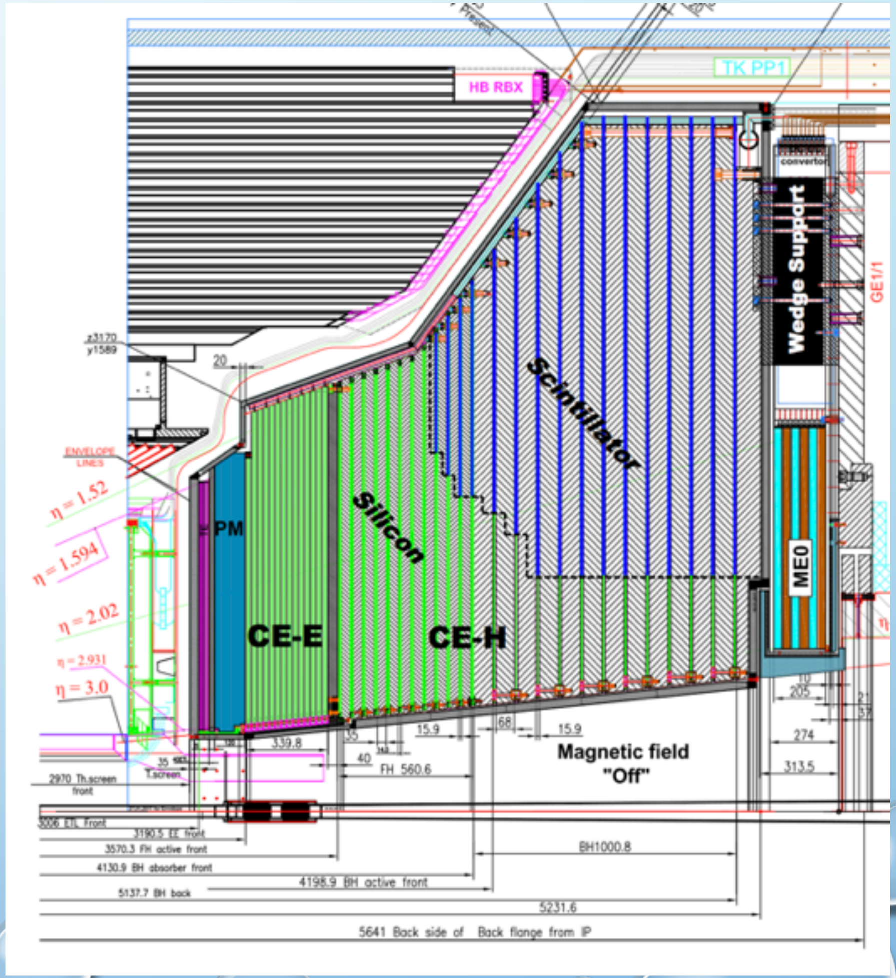


$b\bar{b}$	$\tau\bar{\tau}$	$c\bar{c}$	gg	$\gamma\gamma$	WW^*	ZZ^*	total
15.9%	1.66%	18.23%	63.9%	1.8×10^{-3}	8.3×10^{-4}	1.41×10^{-4}	1
0.019	0.022	0.002	0.077	2.18×10^{-4}	1×10^{-4}	1.7×10^{-5}	0.12



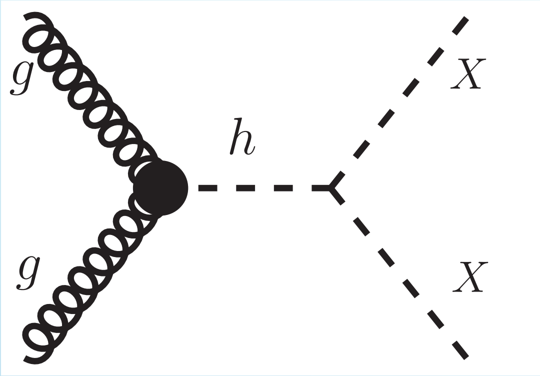
LONG LIVED PARTICLE SEARCH AT HGCAL

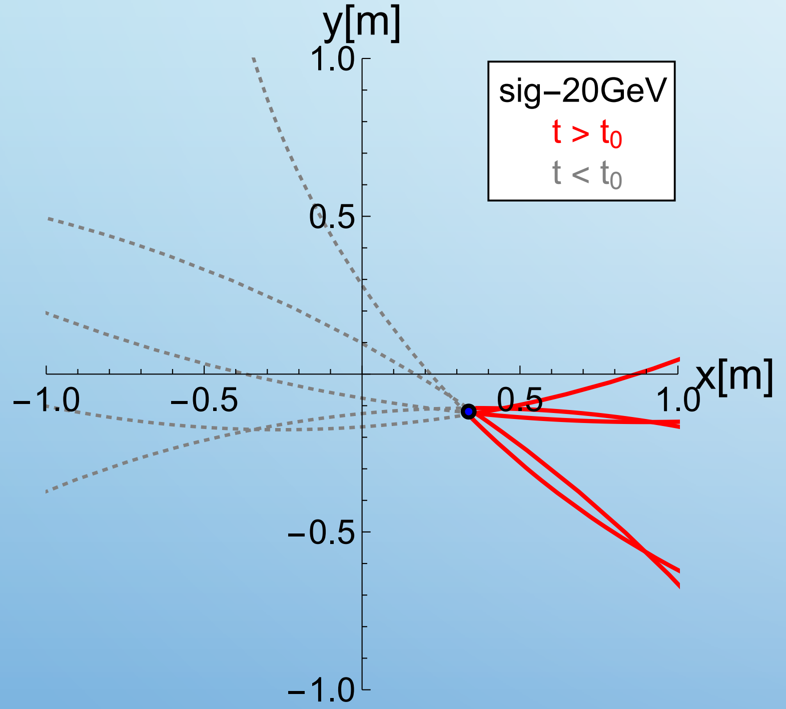




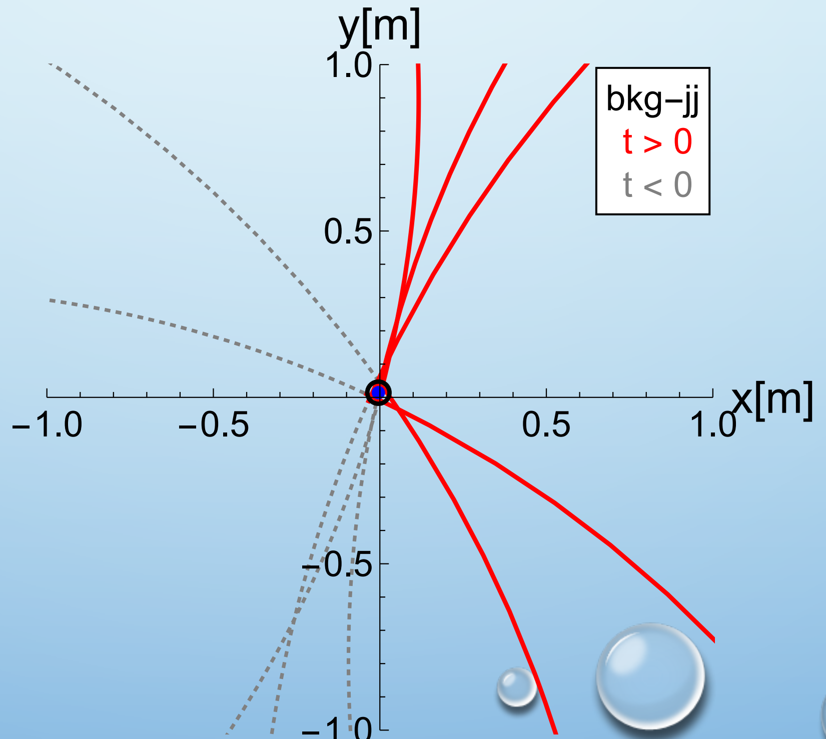
LONG LIVED PARTICLE SEARCH AT HGCAL

JHEP 07 (2019) 159

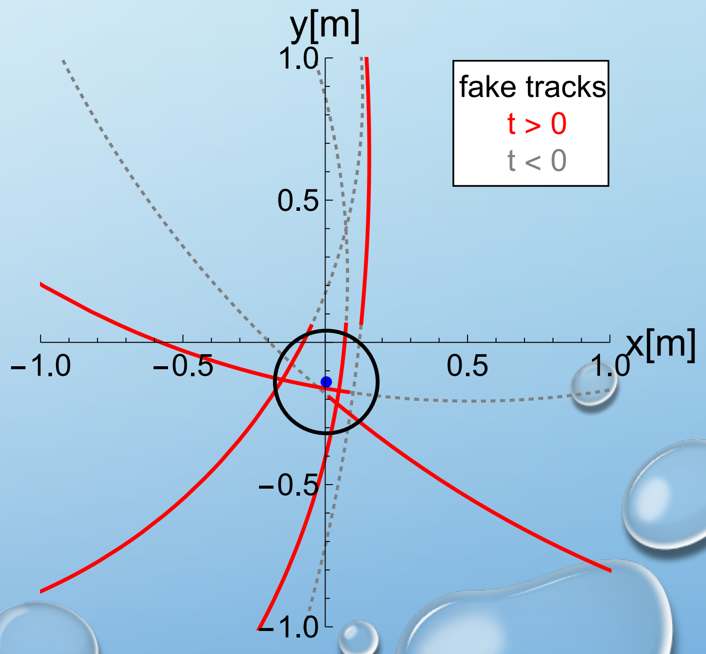




QCD backgrounds

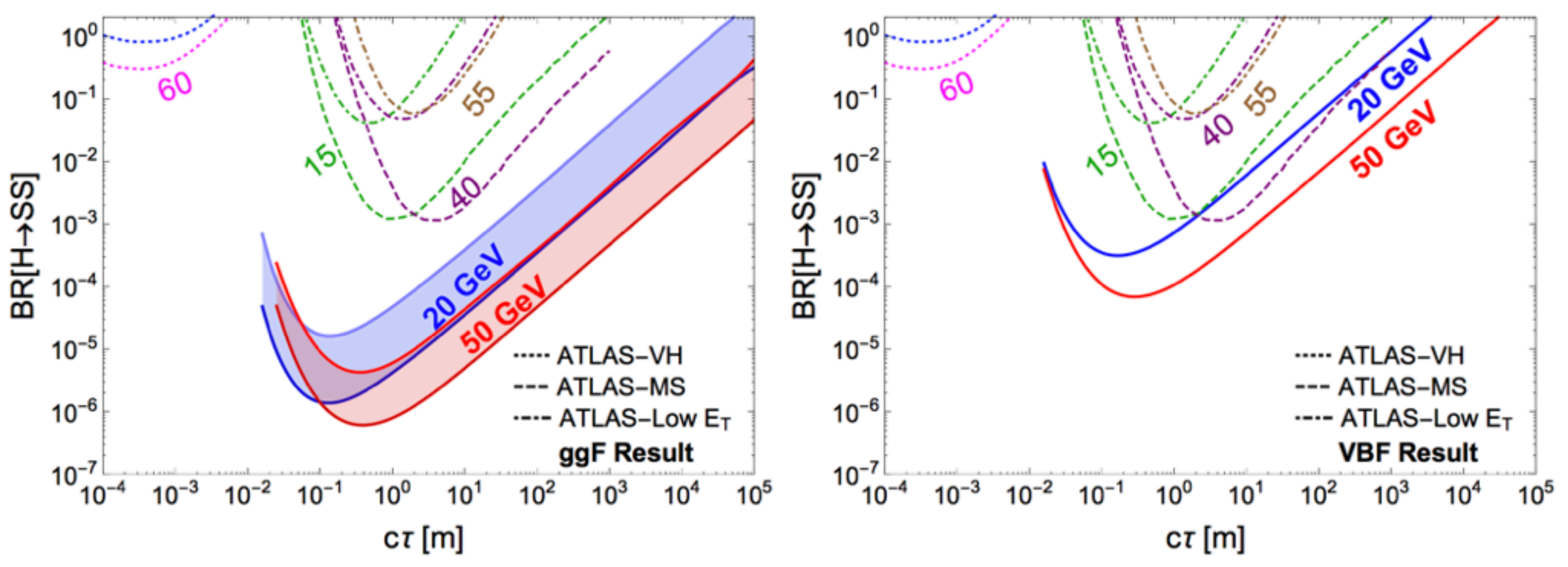


Fake track backgrounds



LONG LIVED PARTICLE SEARCH AT HGCAL

cut conditions	jj dijet	$b\bar{b}$ dijet	fake-track	ggF $m_s = 20$ GeV	ggF $m_s = 50$ GeV
$N_{\rm ini}$	5.1×10^{14}	1.1×10^{13}	1×10^{12}	$1.3 \times 10^{8} \times$ BR	$1.3 \times 10^{8} \times$ BR
$\epsilon_{\rm vtc}$	2.1×10^{-1}	2.1×10^{-1}	4.0×10^{-13}	3.4×10^{-1}	2.4×10^{-1}
$(d_0 > 0.03\ {\rm m})^5$	$(5.7 \times 10^{-4})^5$	$(6.8 \times 10^{-4})^5$	3.4×10^{-1}	2.6×10^{-1}	8.1×10^{-1}
$N_{\rm fin}$	5.7×10^{-3}	2.9×10^{-4}	1.4×10^{-1}	$9.7 \times 10^{5} \times$ BR	$5.3 \times 10^{6} \times$ BR



TRIPLE HIGGS SEARCH AT LHC

arXiv:2012.00773

- Counting the number of d.o.f. in CPX 2HDM

$$\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left[Y_3 e^{-i\eta} H_1^\dagger H_2 + h.c.\right]$$
$$+ \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left[\frac{Z_5}{2} e^{-2i\eta}(H_1^\dagger H_2)^2 + Z_6 e^{-i\eta}(H_1^\dagger H_1)(H_1^\dagger H_2) + Z_7 e^{-i\eta}(H_2^\dagger H_2)(H_1^\dagger H_2) + h.c.\right]$$

- Minimization condition in the Higgs basis:

$$Y_1 = -\frac{1}{2} Z_1 v^2 \qquad\qquad Y_3 = -\frac{1}{2} Z_6 v^2$$

- Z_2 Symmetry:

Haber+collaborators: 2001.01430

$$(Z_1 - Z_2)\left[Z_{34} Z_{67}^* - Z_1 Z_7^* - Z_2 Z_6^* + Z_5^* Z_{67})\right] - 2 Z_{67}^* \left(|Z_6|^2 - |Z_7|^2\right) = 0\,.$$

- Free parameters:

$$\{Y_2, Z_1, Z_2, Z_3, Z_4\} \Rightarrow \{Y_2, Z_1, Z_3, Z_4\}$$
$$\{Z_5, Z_6, Z_7\} \Rightarrow \{Z_5, Z_6, \mathrm{Re}[Z_7]\}$$

- 9 real free parameters!

TRIPLE HIGGS SEARCH AT LHC

- Free parameters:

$\{Y_2, Z_3, Z_1, Z_5, Z_6, Re[Z_7], Z_4\}$ $\Rightarrow$ $\{m_{h_1}, m_{h_2}, m_{h_3}, \theta_{12}, \epsilon, Z_3, m_{H^\pm}, \mathrm{Re}[\tilde{Z}_7], v\}$

- Alignment Limit:

$$\widetilde{R} = R_{12}R_{13} = \begin{pmatrix} c_{12}c_{13} & -s_{12} & -c_{12}s_{13} \\ s_{12}c_{13} & c_{12} & -s_{12}s_{13} \\ s_{13} & 0 & c_{13} \end{pmatrix} = \begin{pmatrix} -\epsilon\, c_{12} & -s_{12} & -c_{12}(1-\epsilon^2/2) \\ -\epsilon\, s_{12} & c_{12} & -s_{12}(1-\epsilon^2/2) \\ 1-\epsilon^2/2 & 0 & -\epsilon \end{pmatrix}$$

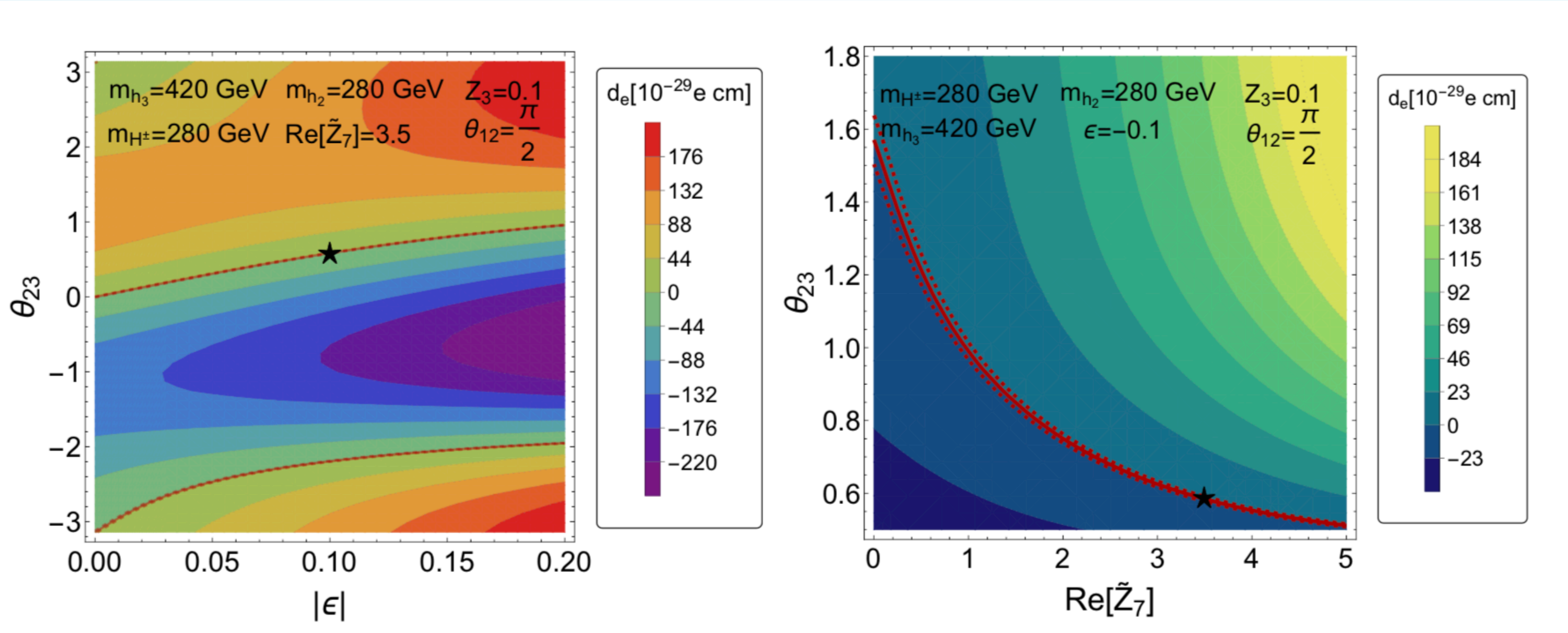
- CP conservative Limit
  - Case I: $\theta_{13} = \frac{\pi}{2}, \theta_{23} = 0, \theta_{12} = \left\{0, \frac{\pi}{2}\right\}, \mathrm{Im}\,[Z_7] = 0$
  - Case 2: $\theta_{23} = \pi/2\ ,\ \theta_{12} = \{0, \pi/2\}\ ,\ \mathrm{Im}[Z_7] = 0$

- CP conservative and Alignment Limit CTHDM

  - $\epsilon \neq 0, \mathrm{Im}[Z_7] \sim 0, \mathrm{Re}[Z_7] \sim 0, \theta_{23} \neq 0, \frac{\pi}{2}$

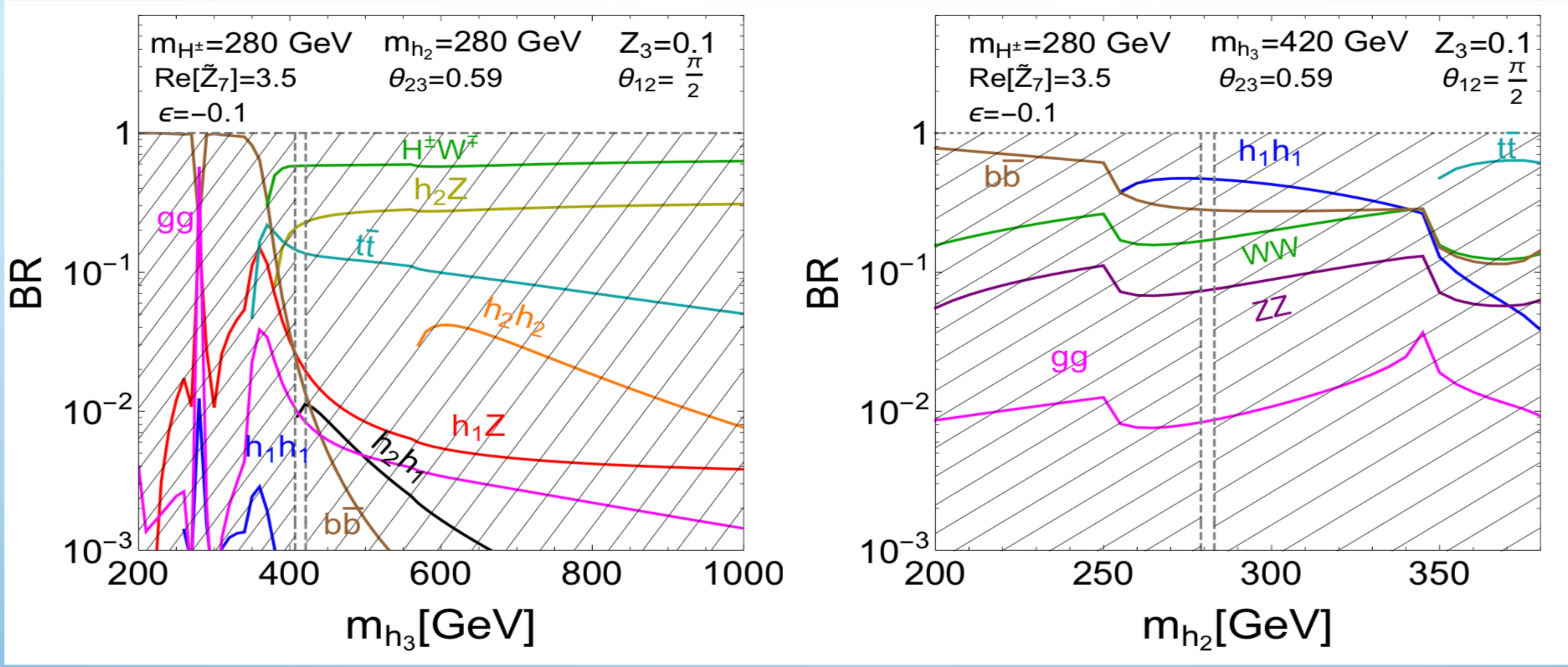
TRIPLE HIGGS SEARCH AT LHC

$\{m_{h_3}, \theta_{12} = \frac{\pi}{2}, \epsilon, Z_3, \mathrm{Re}[\tilde{Z}_7], m_{h_2} = m_{H^\pm}\} + \theta_{23}$



TRIPLE HIGGS SEARCH AT LHC

- Branching ratios for benchmark points: $g_{h_1 h_2 h_3} = \epsilon\, v\, \mathrm{Re}[\tilde{Z}_7 e^{-2i\theta_{12}}]$



$$\sigma(gg \to h_2) \simeq 3.2 \text{ pb} \,, \qquad \sigma(gg \to h_3) \simeq 1.7 \text{ pb}$$

SUMMARY

- EXTRA HIGGS IS AN IMPORTANT MESSAGE FOR NEW PHYSICS.
- EXTRA HIGGS CAN BE SEARCH AT LOW ENERGY EXPERIMENTS.
- EXTRA HIGGS CAN BE SEARCHED AT LHC VIA
  - $h_3 \to h_2 h_1 \to h_1 h_1 h_1$
  - LONG LIVED PARTICLE SEARCH

Thank you