EAIFR
ICTP—East African Institute for Fundamental Research

Hunting down minimally extended Higgs sectors

Shoaib Munir
East African Institute for Fundamental Research, Kigali

ICTP partner institute

National Centre for Nuclear Research, Warsaw

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United Nations Educational, Scientific and Cultural Organization

Contents

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- *Why additional Higgs bosons?*
- *Scenarios in minimal extensions of the SM:*
  1. *Enhanced EW production of multiple Higgs bosons*
  2. *Mass-degeneracies and propagator interference*
  3. *Explicit CP-violation in the Higgs sector*

The Standard Model Higgs field

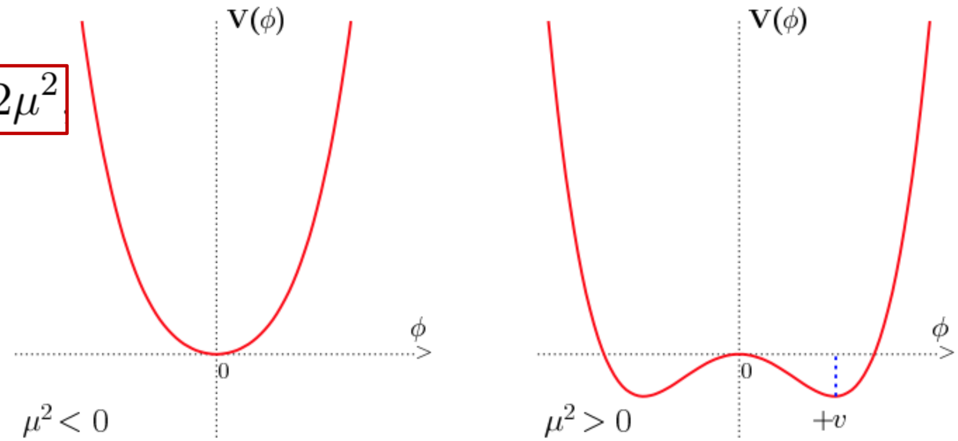
- ***Most recently discovered particle: a first of its kind - (elementary?) scalar - the Higgs boson, H_{125}***
- ***Lorentz invariance: only scalars acquire vacuum expectation values (VeVs)***
- ***VeV of the Higgs field in the SM: masses of the EW gauge bosons and charged leptons***

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

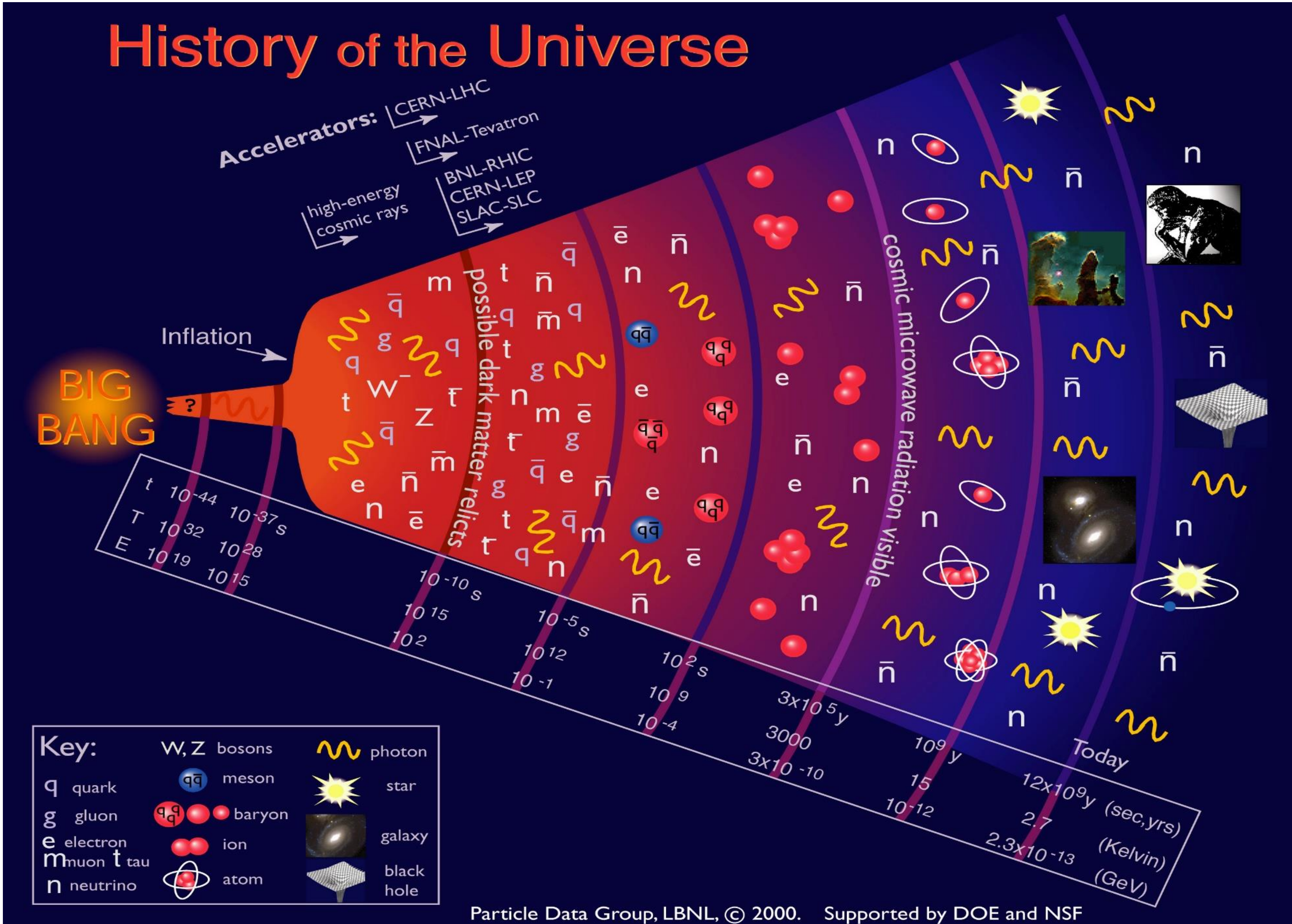
$$\langle \phi \rangle \equiv v = \left(\frac{\mu^2}{\lambda} \right)^{1/2} \Rightarrow \boxed{M_H^2 = \lambda v^2 = 2\mu^2}$$

$$m_W = \frac{1}{2} v g_2$$

$$\Phi(x) = \begin{pmatrix} \theta_2 + i\theta_1 \\ \frac{1}{\sqrt{2}}(v + H) - i\theta_3 \end{pmatrix}$$

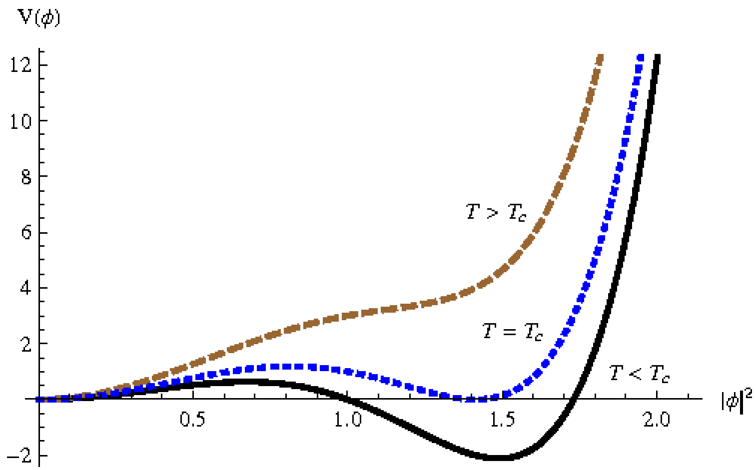


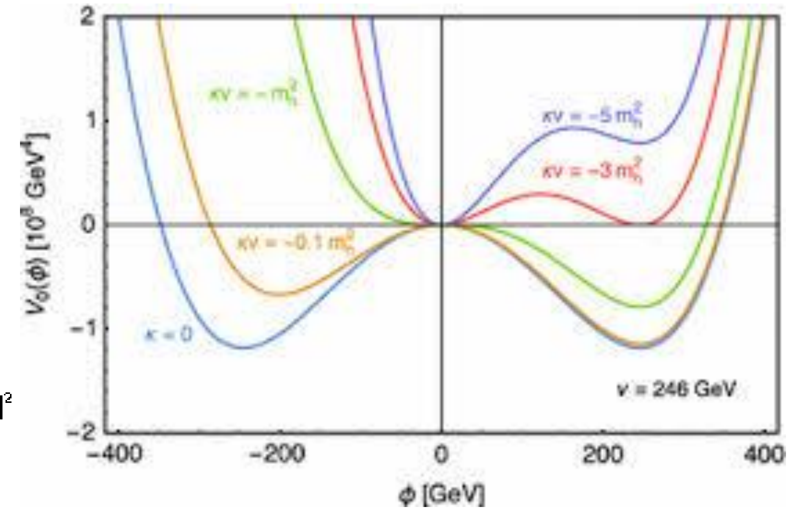
- ***Additional scalar fields could explain crucial primordial phenomena***


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

$\tilde{V}$

- ***Electroweak (EW) Baryogenesis: out of thermal equilibrium (strongly 1^{st}-order phase transition)***

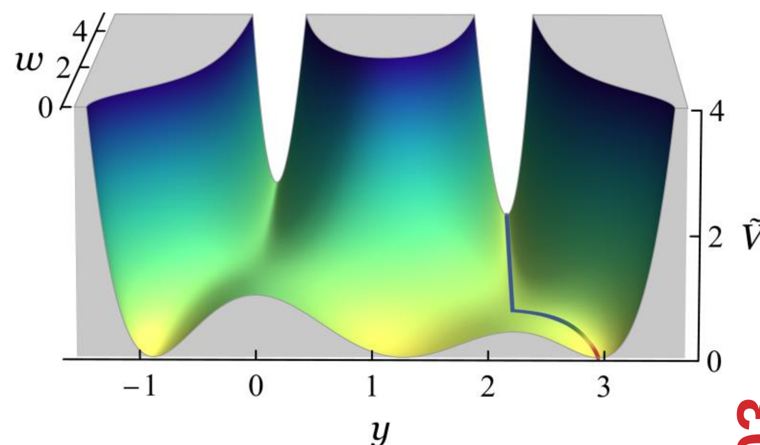




- ***Cosmic Inflation:***

$$\widetilde{V}(w,y) = \left(1 - y^2 + \alpha y^3\right)^2 + 2w^2y^2\left(1 - \frac{3\alpha y}{2}\right)^2$$

$$\text{with} \quad y = \frac{\phi_{24}/\mu}{\sqrt{2}} \quad \text{and} \quad w = \frac{S/\mu}{\sqrt{2}}$$



[W. Ahmed, M. Moosa, SM, U. Zubair, 2208.11888]

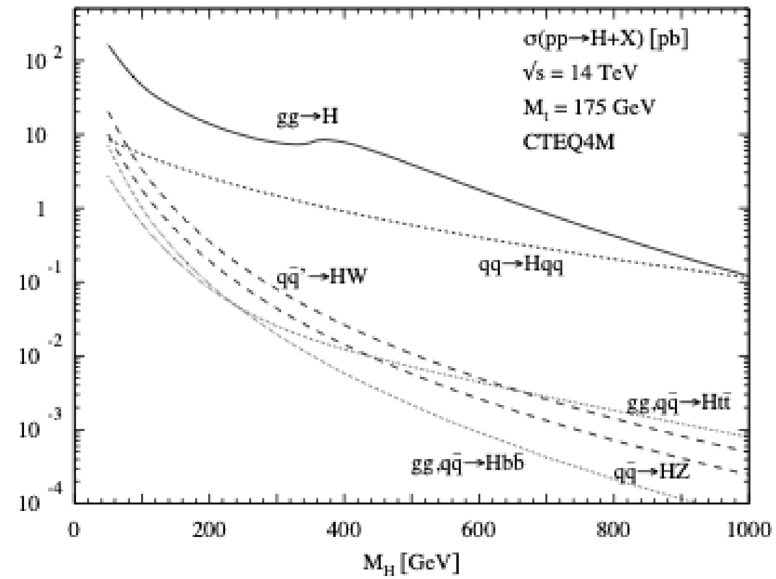
Additional Higgs Bosons

- *May provide the earliest signatures of most of the new physics frameworks*
- *But, couplings to the SM could be suppressed*

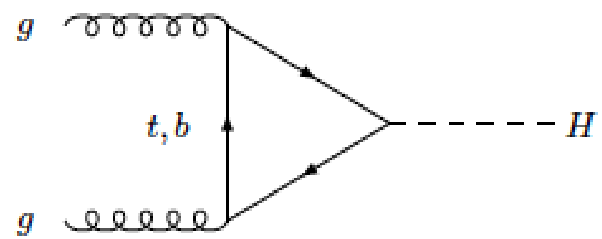
○ ***Mass O(10) GeV: SM background too large***

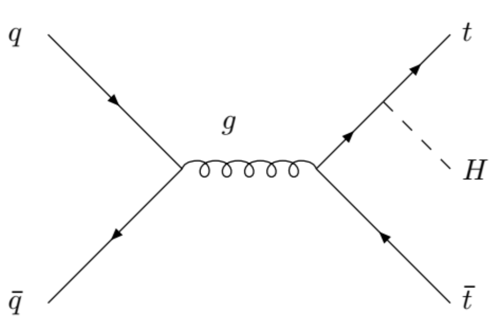
○ ***Mass ~125 GeV: hidden behind the observed H_{125}?***

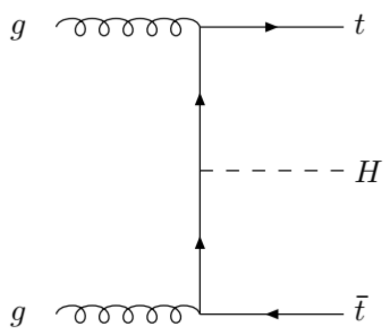
○ ***Mass O(100) GeV: small production rates***

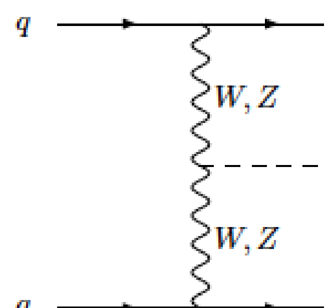


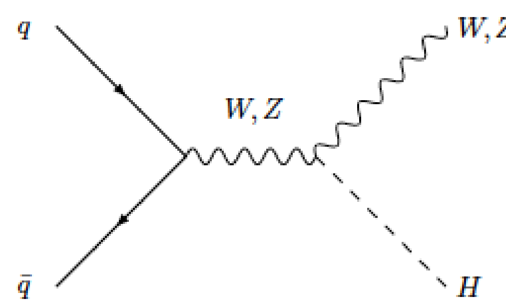
[A. Djouadi, hep-ph/0503173]











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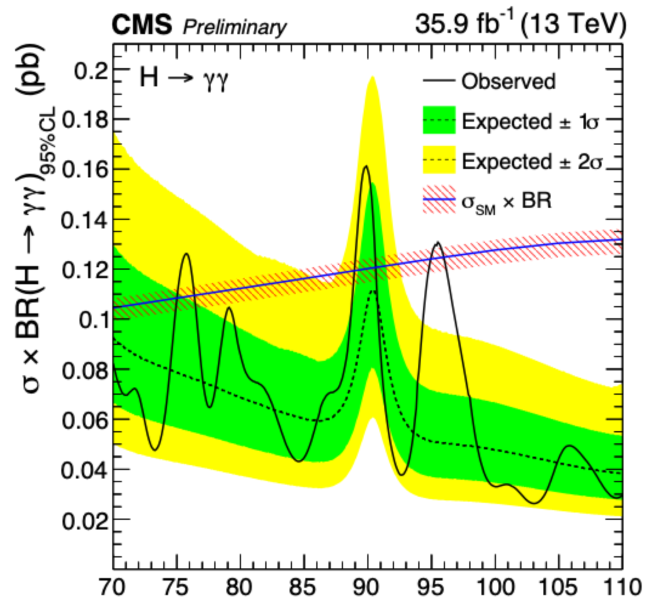

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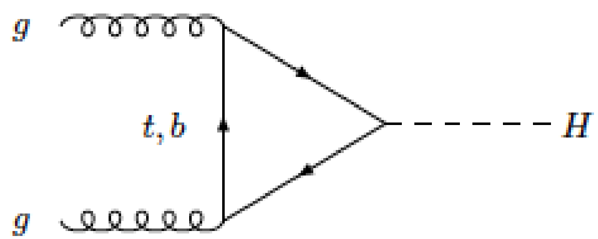

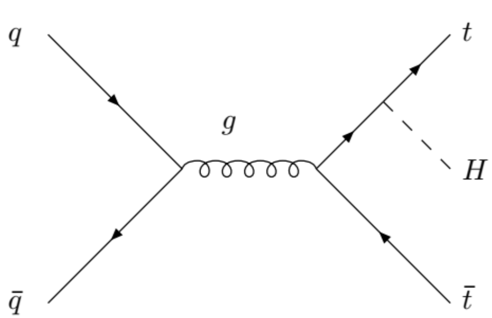

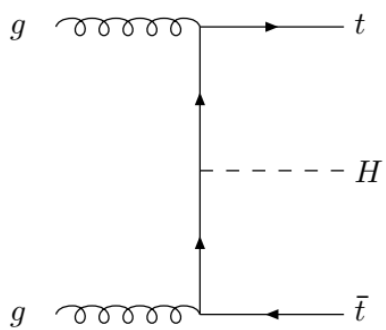

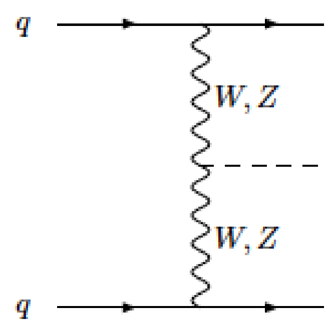

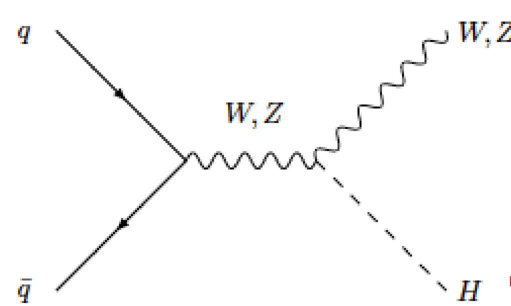

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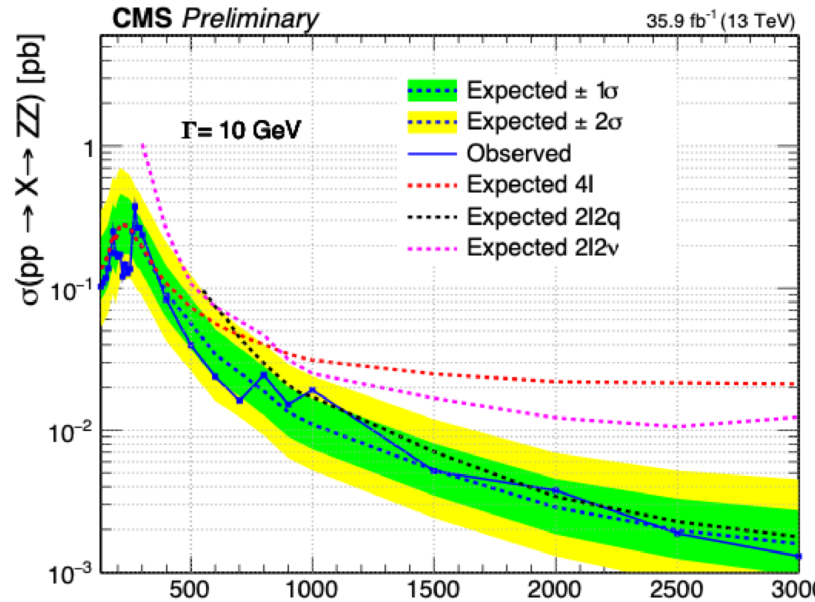

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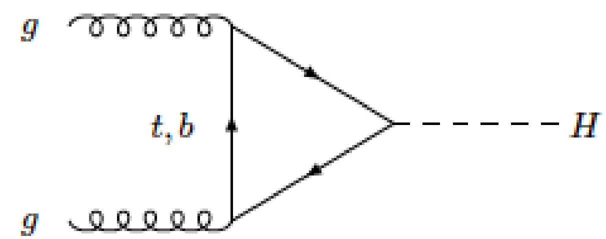
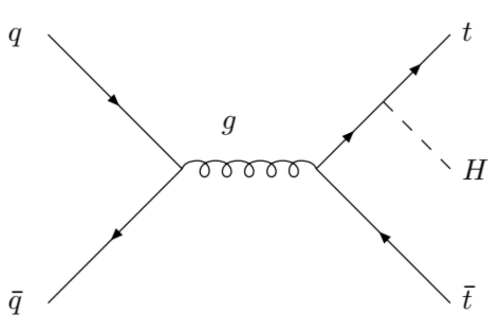
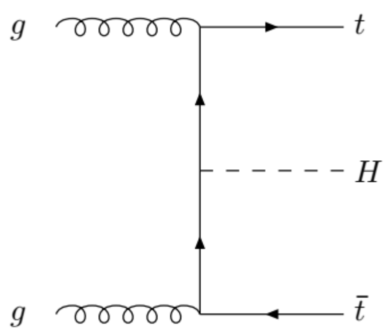
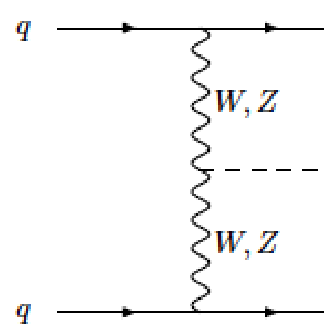
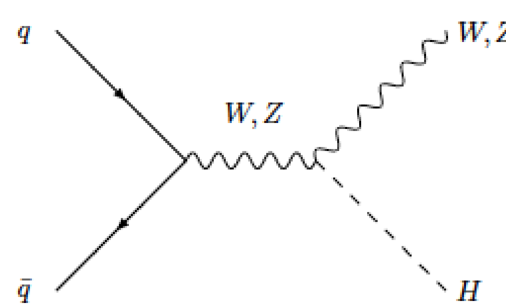








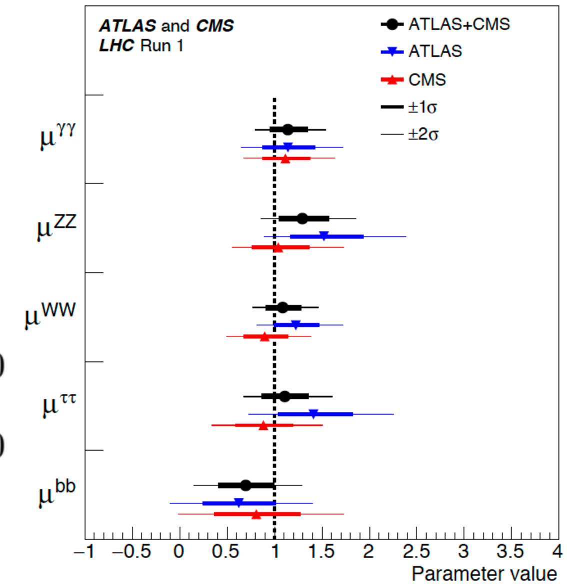


Potential Evidence

Deviations of the collider data from SM predictions

- ***Signal strengths of the observed Higgs boson***

$$R^X = \frac{\sigma(pp \to H_i)}{\sigma(pp \to H_{\rm SM})} \times \frac{BR(H_i \to X)}{BR(H_{\rm SM} \to X)}$$



- ***Anomolous magnetic moment of muon***

$$a_\mu^{\rm Exp-SM} = \begin{cases} (28.7 \pm 8.0) \times 10^{-10} \\ (26.1 \pm 8.0) \times 10^{-10} \end{cases}$$

- ***B/flavour physics***

Observable	Measurement	SM prediction
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$\mathrm{BR}(B_u \to \tau\nu)$	$(1.06 \pm 0.19) \times 10^{-4}$	$(0.82 \pm 0.29) \times 10^{-4}$
$R_D \equiv \frac{\mathrm{BR}(B\to D\tau\nu)}{\mathrm{BR}(B\to D\ell\nu)}$	$(0.403 \pm 0.040 \pm 0.024)$	0.300 ± 0.012
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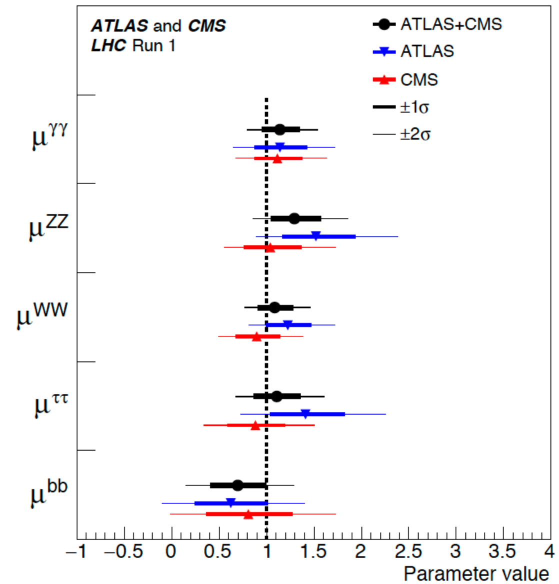
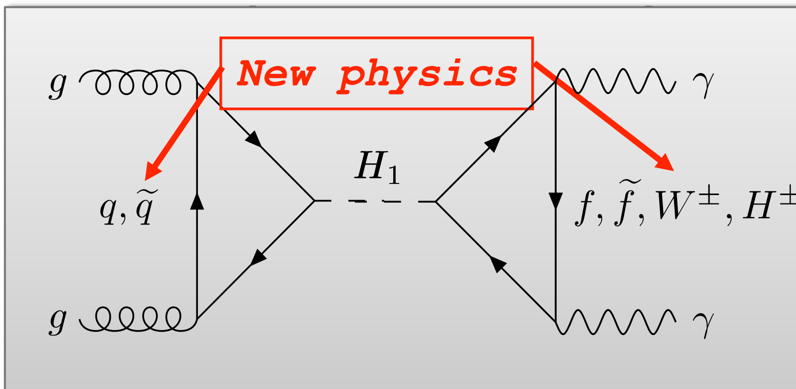


- ***Anomolous***



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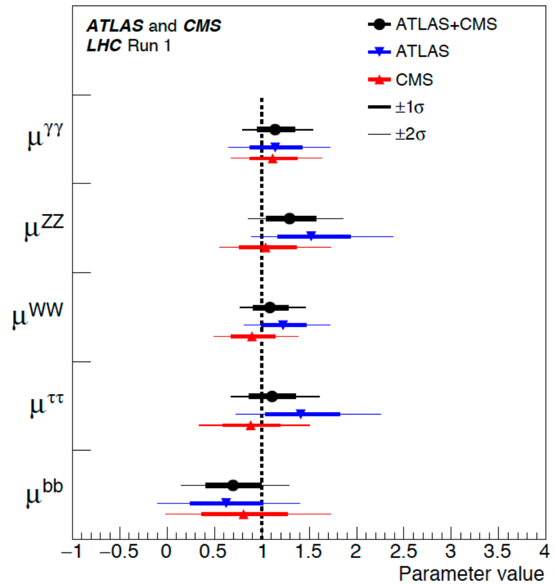

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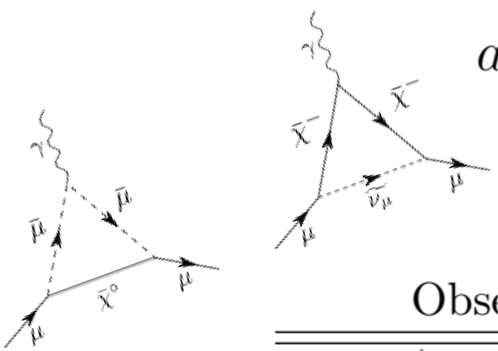

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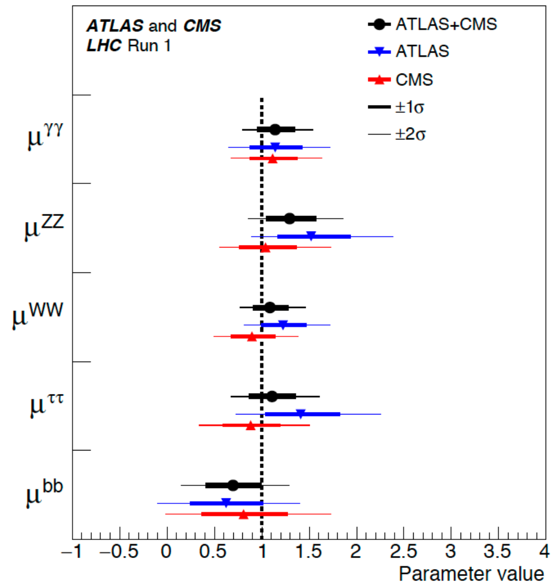

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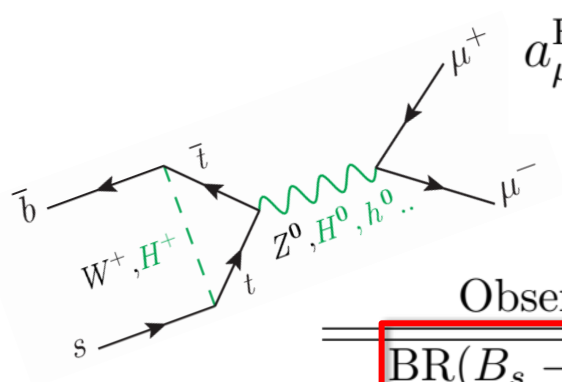

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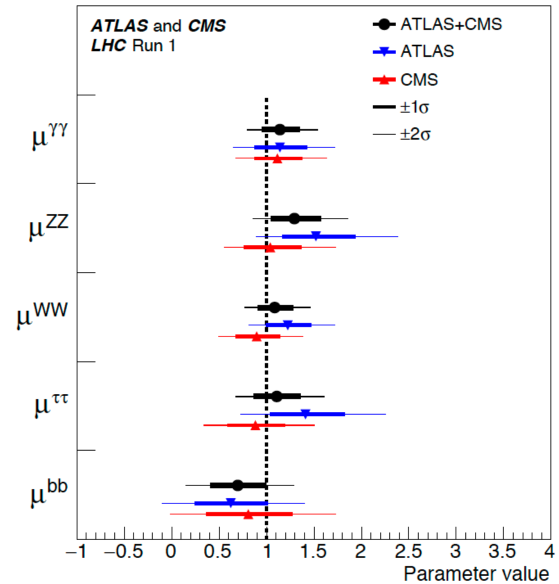

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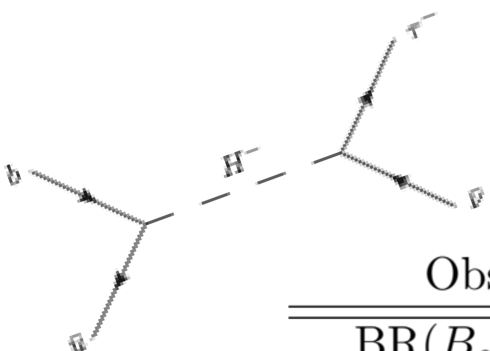

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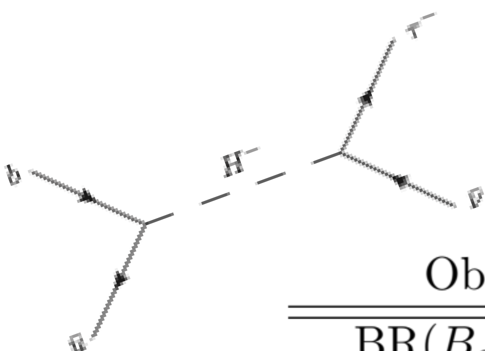

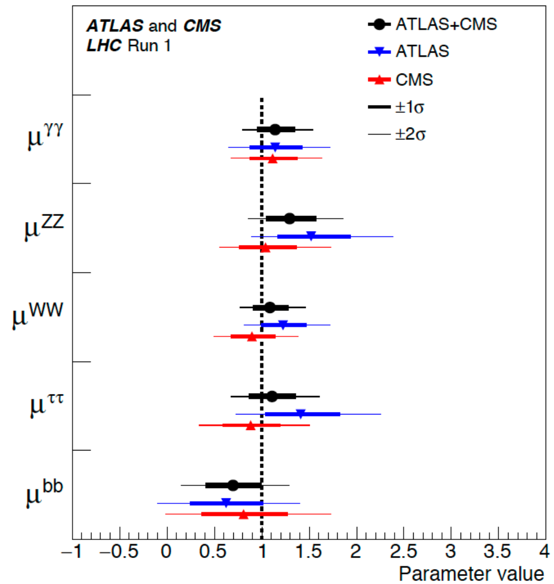

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Leptoquark, $H^\pm$, W' (R_D, R_{D^*})

LQ, Z' (R_K)

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e,μ	1 − 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e,μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	36.1	Λ 40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	≥ 1 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e,μ	1 − 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e,μ	1 − 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV_{\chi\chi}$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} \| T_{5/3} \to Wt + X$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e,μ	≥ 1 b, ≥ 1 j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb) = 1$, $c_R(Wb) = 1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1 j	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e,μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

Mass scale [TeV]: 10^{-1} 1 10

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Scenario 1: Enhanced EW production

The 2-Higgs-Doublet Model

$$
\begin{aligned}
V_{\rm 2HDM} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] \\
&\quad + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&\quad + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \cancel{[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]}\,\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}
\end{aligned}
$$

CP-conservation

After electroweak symmetry breaking:

$$
\Phi_1^0 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_1 + \Phi_{1R} + i\Phi_{1I}) \\ H_1^- \end{pmatrix}, \qquad \frac{\partial^2 V_{\rm 2HDM}}{\partial\Phi_{iX}\Phi_{jY}}
$$

$$
\Phi_2^0 = e^{i\theta_1}\begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v_2 + \Phi_{2R} + i\Phi_{2I}) \end{pmatrix} \qquad \mathcal{M}_0^2 = \left(\begin{array}{c|c} \mathcal{M}_S^2 & \cancel{\mathcal{M}_{SP}^2} \\ \hline \cancel{(\mathcal{M}_{SP}^2)^T} & \mathcal{M}_P^2 \end{array}\right)
$$

$$
O^T\mathcal{M}_S^2 O = \mathrm{diag}(m_h^2,\, m_H^2)
$$

- ***α mixes the scalar interaction eigenstates into two neutral Higgs bosons, h and H***
- ***We can identify either one of h and H with the H_{125}***
- ***There is also a pseudoscalar A and a $H^\pm$ pair***

Multi-Higgs production at the LHC

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A Z_2-symmetry is enforced on 2HDM to prevent FCNCs

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

B-physics constraints forbid $H^\pm$ masses less than ~600 GeV in the Type-II

Parameters in the model (besides the SM ones):

$$Y_h^u = g_u \frac{c_\alpha}{s_\beta}, \quad Y_h^{d/\ell} = g_{d/\ell} \frac{c_\alpha}{s_\beta},$$

$$Y_H^u = g_u \frac{s_\alpha}{s_\beta}, \quad Y_H^{d/\ell} = g_{d/\ell} \frac{s_\alpha}{s_\beta},$$

$$Y_A^u = \frac{g_u}{t_\beta}, \quad Y_A^{d/\ell} = -\frac{g_{d/\ell}}{t_\beta}$$

$$\left\langle \frac{\partial V_{\rm 2HDM}}{\partial \Phi_{iX}} \right\rangle = 0 \implies m_{11}^2,\, m_{22}^2 \to v_1^2,\, v_2^2$$

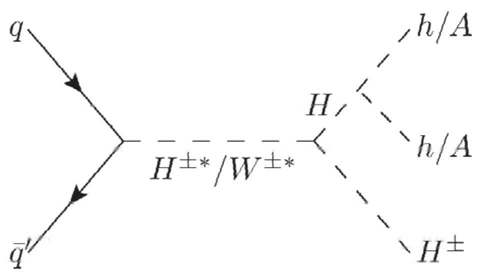
$$v_1,\, v_2 \to v = \sqrt{v_1^2 + v_2^2} \equiv 246\,\mathrm{GeV},\ \tan\beta \equiv v_1/v_2$$

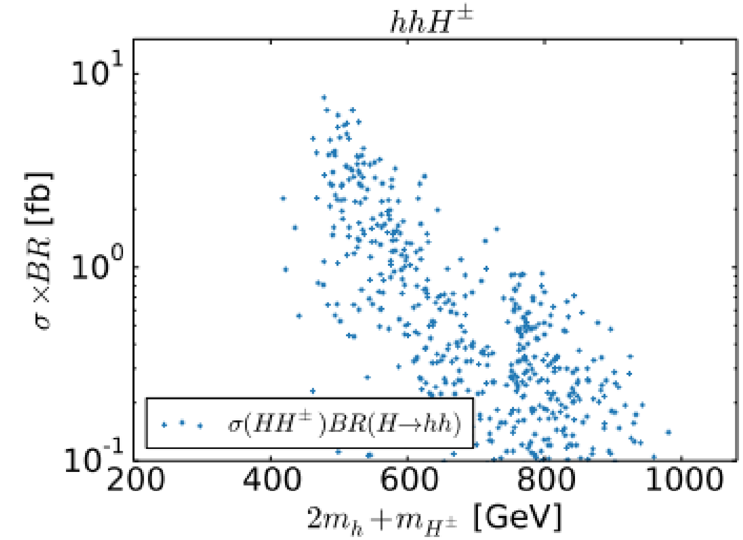
$$\lambda_1 \ldots \lambda_5 \to m_h,\, m_H,\, m_A,\, m_H^\pm,\, \sin(\beta-\alpha)$$

We always identify h with the H_{125}, implying that all the other Higgs bosons are heavier

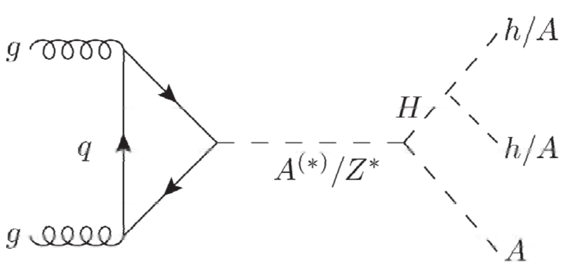
Multi-Higgs production at the LHC

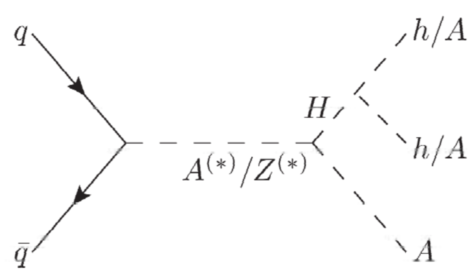
Only EW production of a charged final state possible

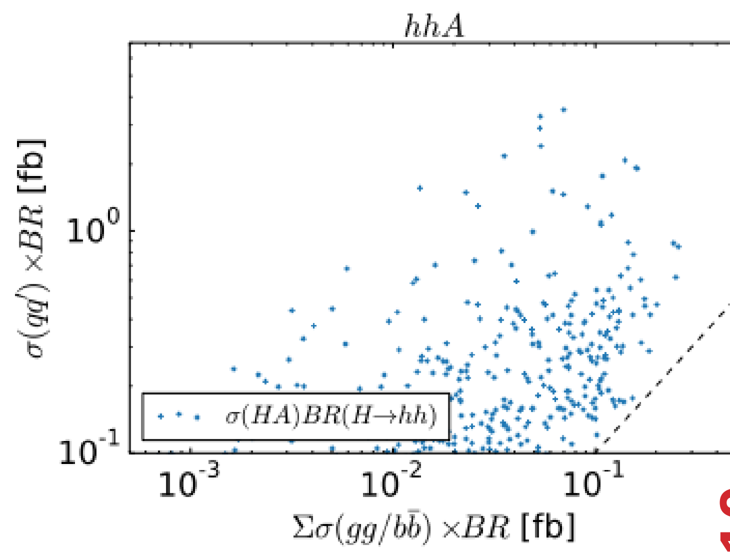




For neutral final state, EW production is generally dominated by QCD production, but can get sizeably enhanced in some parameter space regions







[R. Enberg, W. Klemm, S. Moretti, SM, 1812.08623]

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Higgs-Higgs couplings

Coupling	1. hh	2. HH	3. AA	4. $\boxed{H^+H^-}$	5. hH	6. $\boxed{hA}$	7. $\boldsymbol{hH^\pm}$	8. $\boxed{HA}$	9. $\boldsymbol{HH^\pm}$	10. $\boldsymbol{AH^\pm}$
a. λ_{hhh}	$(hhh)^*$				$(hhH)^*$	$(hhA)^*$	$(hhH^\pm)^*$			
b. λ_{hhH}		hhH			hhh			$\boxed{hhA}$	$\boxed{\boldsymbol{hhH^\pm}}$	
c. λ_{hHH}		$(hHH)^*$			$(hhH)^*$ hH^+H^-			$(hHA)^*$	$(hHH^\pm)^*$	
d. λ_{hAA}	(hAA)		$(hAA)^*$	$(hH^+H^-)^*$	HAA	$(hhA)^*$ AAA	$(AAH^\pm)^*$	$(hHA)^*$		
e. $\lambda_{hH^+H^-}$	hH^+H^-			$(hH^+H^-)^*$	HH^+H^-	AH^+H^-	$(hhH^\pm)^*$ $\boldsymbol{H^+H^-H^\pm}$		$(hHH^\pm)^*$	$(hAH^\pm)^*$
f. λ_{HHH}		$(HHH)^*$			$(hHH)^*$			$(HHA)^*$	$(HHH^\pm)^*$	
g. λ_{HAA}		HAA	$(HAA)^*$		hAA	$(hHA)^*$		$(HHA)^*$ $\boxed{AAA}$	$\boxed{\boldsymbol{AAH^\pm}}$	$\boldsymbol{HAH^\pm}$
h. $\lambda_{HH^+H^-}$		HH^+H^-		$(HH^+H^-)^*$			$(hHH^\pm)^*$	AH^+H^-	$(HHH^\pm)^*$ $\boldsymbol{H^+H^-H^\pm}$	$(HAH^\pm)^*$
i. λ_{hAZ}	hAZ		hAZ		HAZ	$\boxed{hhZ}$ AAZ	$\boldsymbol{AH^\pm Z}$	$\boxed{hHZ}$		$\boxed{\boldsymbol{hH^\pm Z}}$
j. λ_{HAZ}		HAZ	HAZ		hAZ	$\boxed{hHZ}$		$\boxed{HHZ}$ $\boxed{AAZ}$	$\boxed{\boldsymbol{AH^\pm Z}}$	$\boxed{\boldsymbol{HH^\pm Z}}$
k. $\lambda_{H^+H^-Z}$				H^+H^-Z						
l. $\lambda_{hH^+W^-}$	hH^+W^-			$\boxed{hH^+W^-}$	HH^+W^-	$\boxed{hH^+W^-}$ AH^+W^-	$\boxed{\boldsymbol{hhW^\pm}}$ $\boldsymbol{H^+H^-W^\pm}$		$\boxed{\boldsymbol{hHW^\pm}}$	$\boxed{\boldsymbol{hAW^\pm}}$
m. $\lambda_{HH^+W^-}$		HH^+W^-		$\boxed{HH^+W^-}$	hH^+W^-		$\boxed{\boldsymbol{hHW^\pm}}$	$\boxed{HH^+W^-}$ $\boxed{AH^+W^-}$	$\boxed{\boldsymbol{HHW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$	$\boxed{\boldsymbol{HAW^\pm}}$
n. $\lambda_{AH^+W^-}$			AH^+W^-	$\boxed{AH^+W^-}$			$\boxed{\boldsymbol{hAW^\pm}}$		$\boxed{\boldsymbol{HAW^\pm}}$	$\boxed{\boldsymbol{AAW^\pm}}$ $\boxed{\boldsymbol{H^+H^-W^\pm}}$

[R. Enberg, W. Klemm, S. Moretti, SM, 1812.01147]

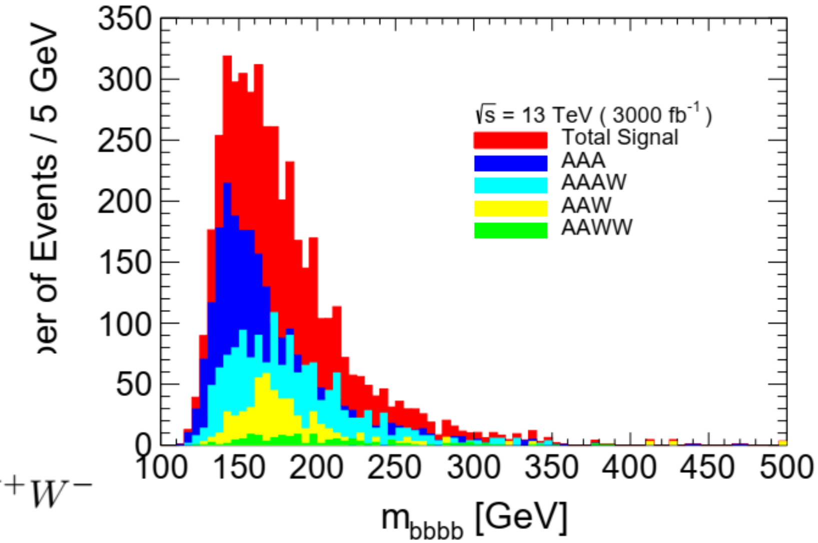
A Benchmark Configuration

[T. Mondal, S. Moretti, SM, P. Sanyal, 2211.xxxxx]

m_A	$m_{H^\pm}$	m_H	t_β	$s_{\beta-\alpha}$	m_{12}^2
70	169.7	144.7	7.47	0.988	2355.0

$$
\begin{aligned}
AAW^\pm &: \quad pp \to H^\pm(\to AW^\pm)A \to 4bW^\pm \\
AAAW^\pm &: \quad pp \to H^\pm(H^\pm \to AW^\pm)H(\to AA) \to 6bW^\pm \\
AAZW^\pm &: \quad pp \to H^\pm(H^\pm \to AW^\pm)H(\to AZ) \to 6bW^\pm
\end{aligned}
$$

$$
\begin{aligned}
AAA &: \quad pp \to H(\to AA)A \to 6b \\
AAZ &: \quad pp \to H(\to AZ)A \to 6b \\
AAW^+W^- &: \quad pp \to H^+(\to AW^+)H^-(\to AW^-) \to 4bW^+W^-
\end{aligned}
$$

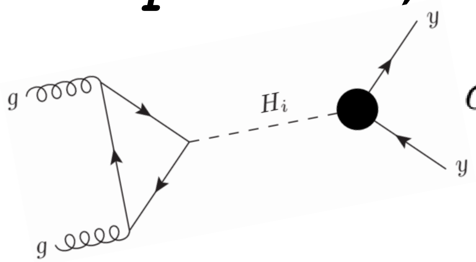


BP3: Selection Cuts	AAW $[fb]$	AAWW $[fb]$	AAA $[fb]$	AAAW $[fb]$	AAZ $[fb]$	AAZW fb
Basic Cuts: $P_T(\ell) > 10$ GeV; $\lvert\eta_\ell\rvert < 2.4$; $P_T(j) > 20$ GeV; $\lvert\eta_j\rvert < 5$; Jet size ≥ 4	131.387	28.660	111.265	62.514	0.678	0.346
MET cut $\not{E}_T > 10$ GeV	116.421	26.697	94.262	56.877	0.557	0.305
Leading b-jet: $P_T(b) > 50$ GeV	91.632	21.678	74.425	48.010	0.445	0.277
Atleast 4 b-jets with two pairs satisfying b-jet invariant mass condition $m_{bb} = 70 \pm 10$ GeV	1.730	0.305	3.140	1.457	0.018	0.014
$S/\sqrt{B}$ at 300 fb^{-1}	1.52	0.27	2.76	1.28	0.016	0.012
$S/\sqrt{B}$ at 3000 fb^{-1}	4.80	0.85	8.73	4.05	0.050	0.039

Scenario 2: Mass-degenerate Higgs bosons

The gluon-fusion process

Gluon-fusion is the leading production mechanism for the (SM) Higgs boson at the LHC. The amplitude for the process,



$$\sigma(pp \to yy) = \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{x_1} \frac{g(x_1)g(\tau/x_1)}{1024\pi\hat{s}^3} \left|\mathcal{A}_{gg\to H\to yy}\right|^2$$

$$\hat{s} = x_1 x_2 s \implies \tau \equiv \frac{s}{s} = x_1 x_2$$

with only one intermediate Higgs boson, is given as

$$\mathcal{A} = \mathcal{M}_P \frac{1}{\hat{s} - M_H^2 + i\Im\mathrm{m}\hat{\Pi}_H(\hat{s})} \mathcal{M}_{D^{yy}}$$

Using the narrow-width approximation,

$$\left|\frac{1}{\hat{s} - M_H^2 + iM_H\Gamma_H}\right|^2 \to \frac{\pi}{M_H\Gamma_H}\delta(\hat{s} - M_H^2)$$

the cross-section expression can be factorised as

$$\sigma(pp \to yy) \Longrightarrow \sigma(pp \to H) \times \mathrm{BR}(H \to yy)$$

Two (or more) Higgs bosons

If, instead, two Higgs bosons contribute to γγ-production, the complete propagator matrix

$$\mathcal{D}(\hat{s}) = \hat{s} \begin{pmatrix} \hat{s} - m_{H_1}^2 + i\Im\mathrm{m}\hat{\Pi}_{11}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{12}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{21}(\hat{s}) & \hat{s} - m_{H_2}^2 + i\Im\mathrm{m}\hat{\Pi}_{22}(\hat{s}) \end{pmatrix}^{-1}$$

with generalised self-energies given, e.g., as

$$\Im\mathrm{m}\hat{\Pi}_{ij}^{H_2}(s) = \frac{v^2}{16\pi}\frac{S_{ij}}{2} g_{H_i H_2 H_2} g_{H_j H_2 H_2} \sqrt{1 - 4\frac{m_{H_2}^2}{\hat{s}}}\ \Theta\left(s - 4m_{H_2}^2\right)$$

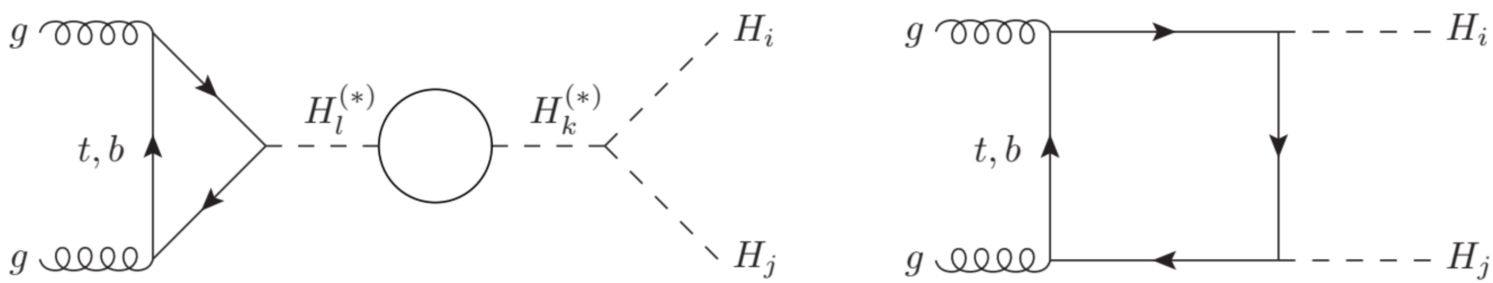
should appear in the amplitude, which becomes

$$\mathcal{A} = \sum_{i,j=1,2} \mathcal{M}_{P_i} \mathcal{D}_{ij}(\hat{s}) \mathcal{M}_{D_j^{\gamma\gamma}}$$

`Interference' between these can be sizeable if the magnitude of the off-diagonal terms is comparable to their mass-splitting (indicator: $\Gamma_{H_1} + \Gamma_{H_2} \sim \Delta m_H$)

Di-Higgs production

Two main contributions at the leading order,



with amplitude-squared of the process given as

$$\left|\mathcal{A}_{gg\to H_i H_j}\right|^2 = \left|C_\triangle F_\triangle + C_\Box F_\Box\right|^2 + \left|C_\Box G_\Box\right|^2 \qquad C_\Box = \sum_q g_{H_i\bar{q}q} g_{H_j\bar{q}q}$$

[T. Plehn, M. Spira, P. M. Zerwas, 9603205]

Define and compute:

$$\sigma_{\rm b} \sim C_\triangle^{\rm diag} \equiv \sum_{l=1}^{3} \mathcal{D}_{ll}(\hat{s})\lambda_{H_i H_j H_l} \qquad \sigma_{\rm c} \sim C_\triangle^{\rm full} \equiv \sum_{k,l=1}^{3} \mathcal{D}_{kl}(\hat{s})\lambda_{H_i H_j H_k}$$

Including NLO corrections (NNLO also available)

$$\Delta\sigma = \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{\bar{q}q}$$ [S. Dawson, S. Dittmaier, M. Spira, 9805244]

The Type-II Next-to-2HDM

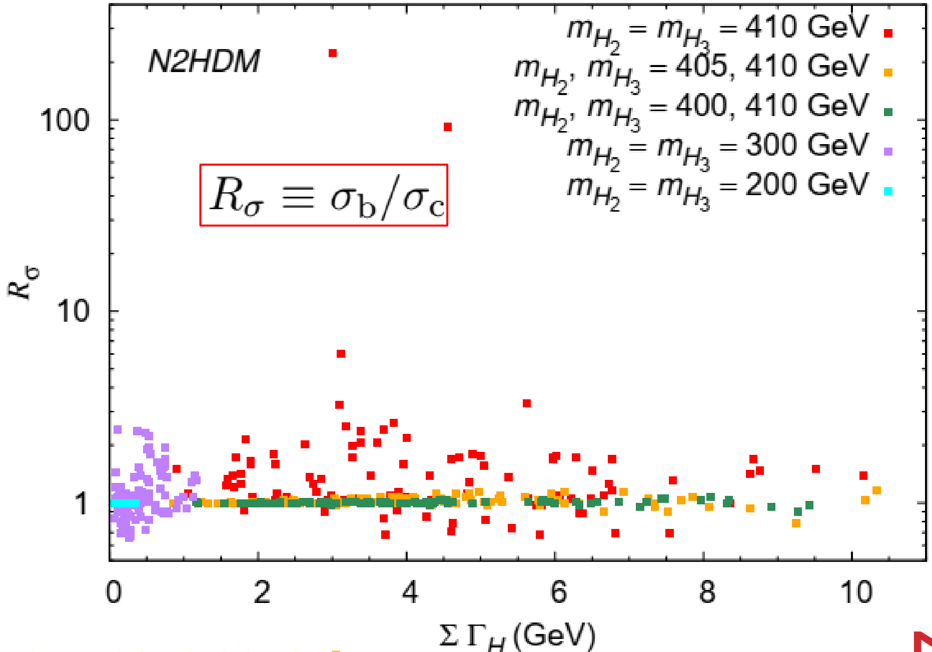
$\Phi_1 \to H_d, \quad \Phi_2 \to H_u \quad \lambda_6, \lambda_7 \to 0$ ***in the 2HDM, and introduce a real singlet field*** $\boxed{S = v_S + S_R}$

$$H_d^0 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + H_{dR} + iH_{dI}) \\ H_d^- \end{pmatrix}, \; H_u^0 = e^{i\phi_u} \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v_u + H_{uR} + iH_{uI}) \end{pmatrix}$$

$$V_{\text{N2HDM}} \;=\; V_{\text{2HDM}} + \frac{m_S^2}{2} S^2 + \frac{\lambda_6}{8} S^4 + \frac{\lambda_7}{2} \left(H_u^\dagger H_u\right) S^2 + \frac{\lambda_S}{2} \left(H_d^\dagger H_d\right) S^2$$

- 4 neutral Higgs bosons, h, h_s, H and A

Proof of principle: Interference effects increase as the splitting between m_H and m_{h_s} reduces



[B. Das, P. Poulose, S. Moretti, SM, 2012.09587]

Benchmark configurations

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Correspond to the $m_H = m_{h_s} = 410$ GeV case

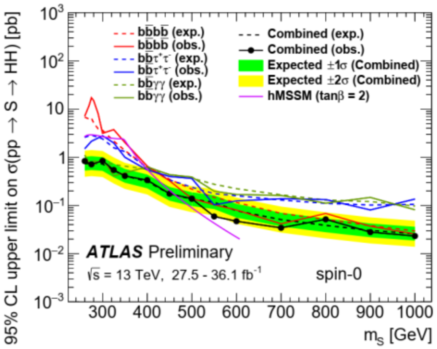
- *largest observed total widths, since H and h_s can decay into top-antitop pairs*

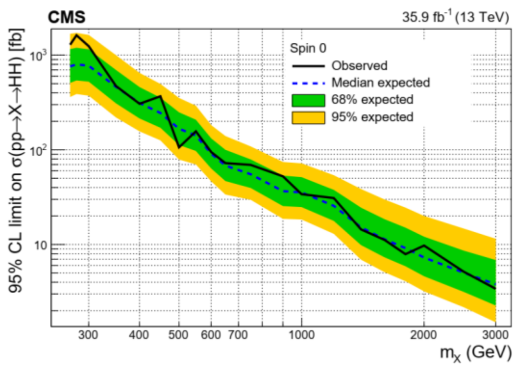
Parameter/Observable	BP1	BP2	BP3	BP4	BP5	BP6
m_A (GeV)	712.2	772.67	640.04	601.21	658.33	630.11
$m_{H^\pm}$ (GeV)	709.04	776.41	654.53	604.04	663.11	654.45
m_{12}^2 (GeV^2)	84725.4	71277.6	82115.1	61133.1	69580.1	65586.7
$\tan\beta$	1.3	1.0	1.3	2.0	1.8	1.2
$g_{H_1 t\bar{t}}$	1.024	1.038	0.955	0.981	0.989	0.986
$g_{H_1 VV}$	1.000	1.000	0.954	0.990	1.000	0.930
sign($\mathcal{R}_{13}$)	$-$	$+$	$-$	$+$	$-$	$+$
$\mathcal{R}_{23}$	-0.671	-0.569	-0.921	0.887	0.436	0.870
v_S (GeV)	1511.3	2357.5	1945.8	1667.5	2025.9	2459.4
σ_b (fb)	34536.1	13417.6	260.1	96.6	62.9	101.3
σ_c (fb)	154.3	146.7	153.1	96.2	63.6	102.6

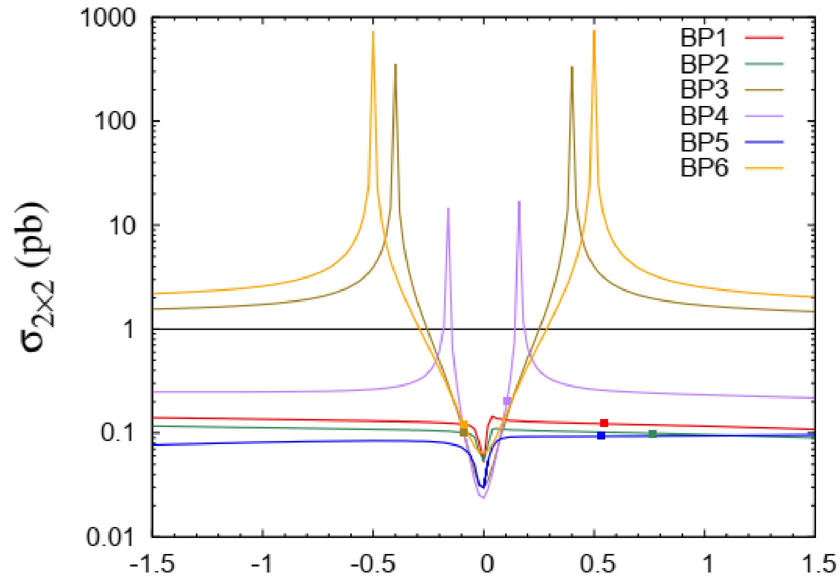
Negative interference reduces the total cross section by two orders of magnitude!

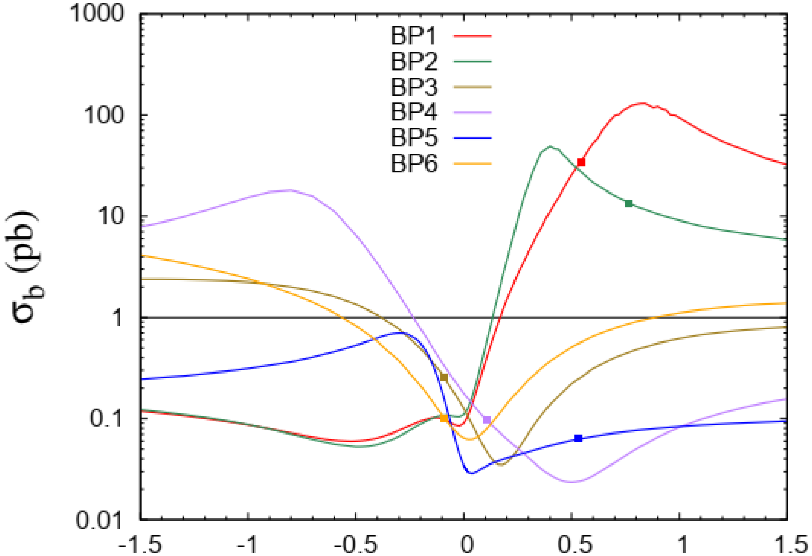
Dependence on couplings

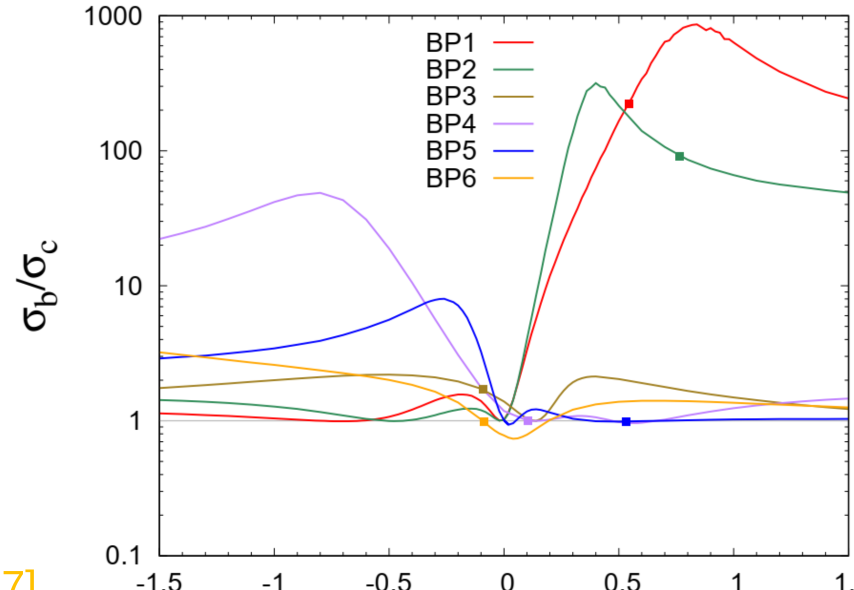
We varied $g_{H_2 t\bar{t}}$, with all other parameters fixed to their benchmark values











[B. Das, P. Poulose, S. Moretti, SM, 2012.09587]

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Scenario 3: Explicit CP-violation in the Higgs sector

Minimal supersymmetry

The Minimal Supersymmetric Standard Model (MSSM) has a Higgs sector mimicking the Type-II 2HDM

$$W_{\rm MSSM} = h_u\, \widehat{Q}\cdot \widehat{H}_u\, \widehat{U}^c_R + h_d\, \widehat{H}_d\cdot \widehat{Q}\, \widehat{D}^c_R + h_e\, \widehat{H}_d\cdot \widehat{L}\, \widehat{E}^c_R + \mu \widehat{H}_u\cdot \widehat{H}_d$$

Tree-level masses of the neutral Higgs bosons

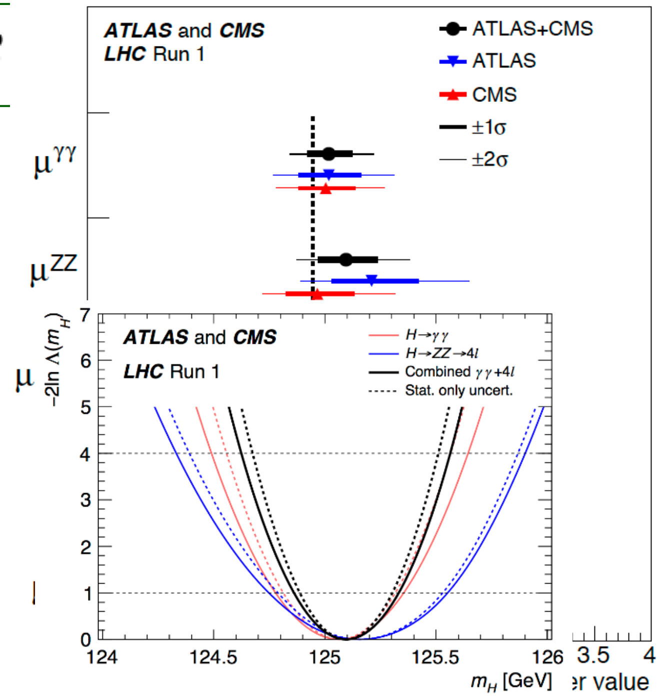
$$M^2_{h,H} = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2\cos^2 2\beta}\right]$$

$$\Rightarrow \boxed{M_h^2 \leq \min(M_Z^2,\, M_A^2)\cdot \cos^2 2\beta}$$

receive corrections from the scalar partner of the t-quark

$$\Delta M_h^2 \propto \ln\frac{M^2_{\rm SUSY}}{M_t^2} + \frac{X_t^2}{M^2_{\rm SUSY}}\left(1 - \frac{X_t^2}{12 M^2_{\rm SUSY}}\right)$$

Higgs measurements at the LHC strongly constrain $X_t = A_t - \mu\cot\beta$



Consistency with LHC data

To identify h with H_{125}

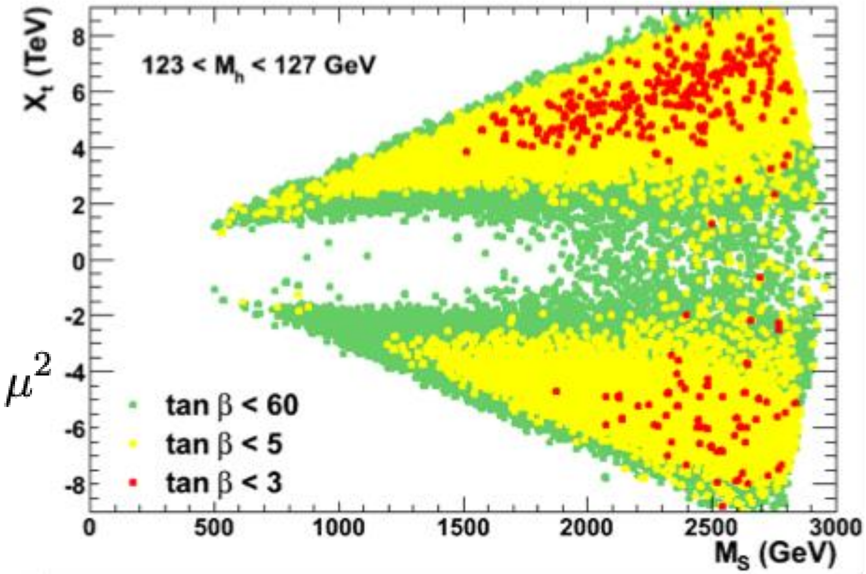
- *Maximise tree-level mass*
- *Enhance SUSY corrections*

But M_S and X_t too large

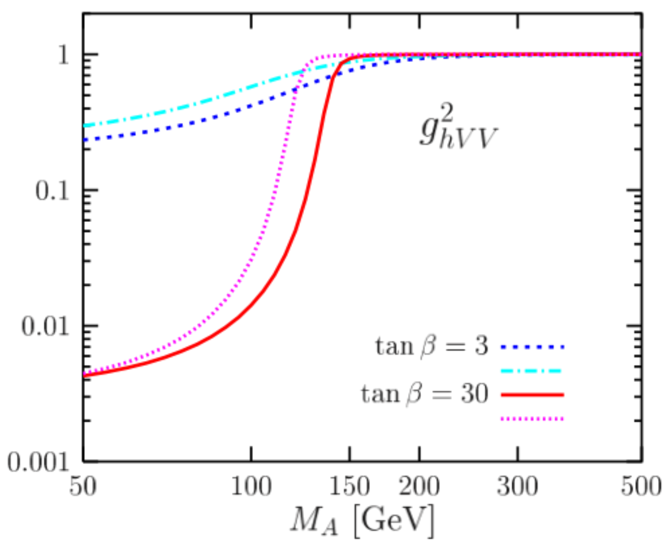
$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

fine-tuning problem redux!

[A. Arbey *et al.*, 1112.3028]



$\tan\beta \gg 1$ *Decoupling limit!*



$$M_{H^\pm} \xrightarrow{M_A \gg M_Z} M_A\left[1 + \frac{M_W^2}{2M_A^2}\right]$$

$$M_H \xrightarrow{M_A \gg M_Z} M_A\left[1 + \frac{M_Z^2\sin^2 2\beta + \epsilon\cos^2\beta}{2M_A^2}\right]$$

$$\boxed{M_H \simeq M_{H^\pm} \simeq M_A}$$

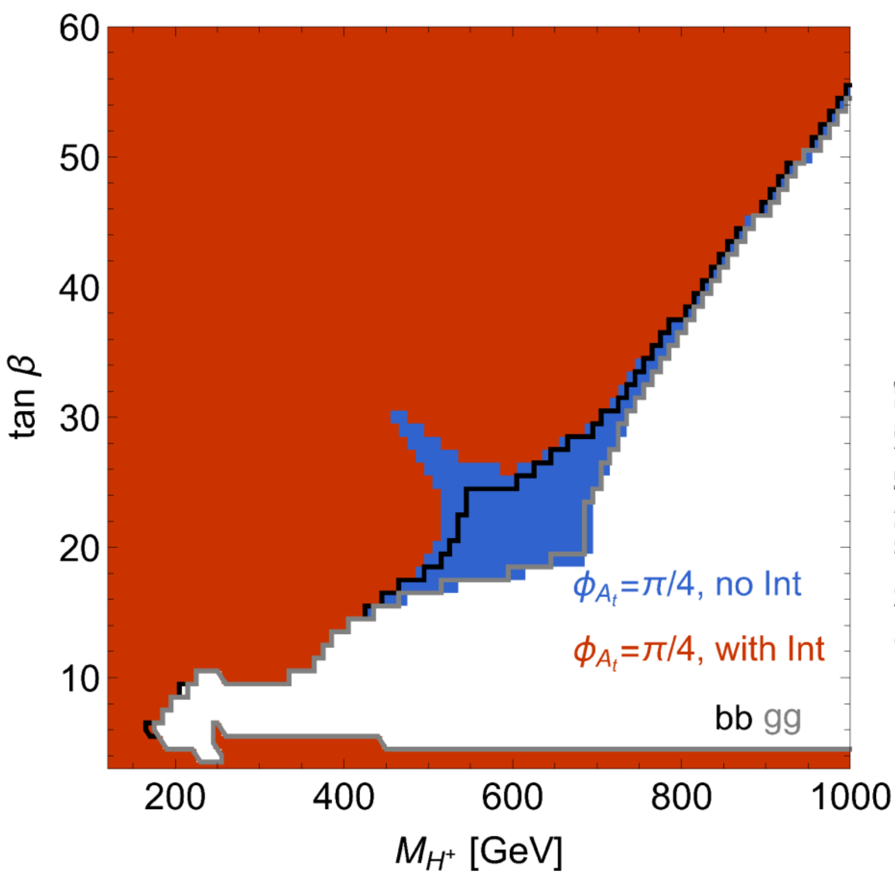
[A. Djouadi, hep-ph/0503173]

Interference effects in the MSSM

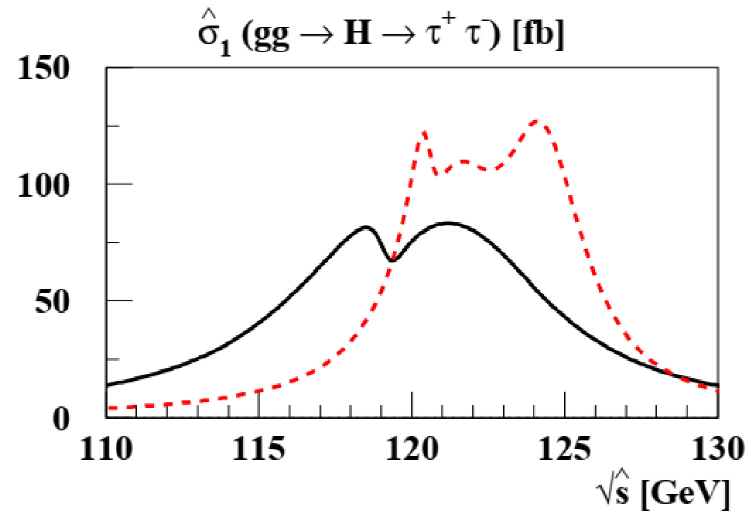
CP-violating Higgs sector:

h, H, A → ***H_1, H_2, H_3***

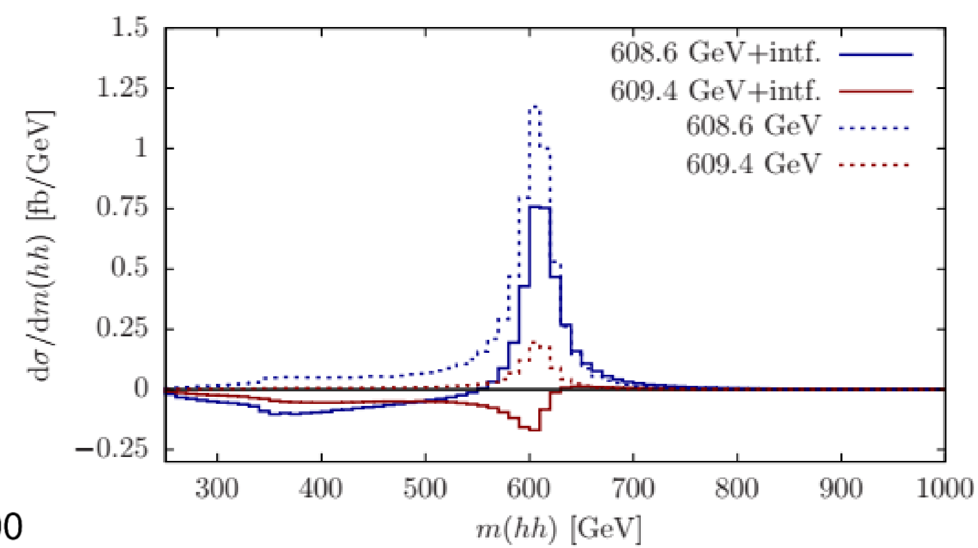
Decoupling limit: $M_{H_2} \approx M_{H_3}$



[E. Fuchs, G. Weiglein, 1705.05757]



[J. Ellis, J. S. Lee, A. Pilaftsis, 0404167]



[P. Basler, S. Dawson, C. Englert, M. Mühlleitner, 1909.09987]

The Next-to-MSSM

`μ-problem' of the MSSM: add a singlet superfield

$$W_{\rm NMSSM} = \widehat{U}^C \mathbf{h}_u \widehat{Q}\widehat{H}_u + \widehat{D}^C \mathbf{h}_d \widehat{H}_d \widehat{Q} + \widehat{E}^C \mathbf{h}_e \widehat{H}_d \widehat{L} + \cancel{\mu \widehat{H}_u} \widehat{H}_d + \lambda \widehat{S}\widehat{H}_u \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

Z_3-invaraint

$$S^0 = \frac{e^{i\phi_s}}{\sqrt{2}}(v_s + S_R + iS_I)$$

$$\boxed{\textbf{EWSB} \Rightarrow \mu_{\rm eff} \equiv \lambda\langle\widehat{S}\rangle = \lambda v_s}$$

$$\begin{aligned} V_0 = & \left|\lambda\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + \kappa S^2\right|^2 \\ & + \left(m_{H_u}^2 + |\mu + \lambda S|^2\right)\left(|H_u^0|^2 + |H_u^+|^2\right) + \left(m_{H_d}^2 + |\mu + \lambda S|^2\right)\left(|H_d^0|^2 + |H_d^-|^2\right) \\ & + \frac{g^2}{4}\left(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2\right)^2 + \frac{g_2^2}{2}\left|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}\right|^2 \\ & + m_S^2 |S|^2 + \left(\lambda A_\lambda \left(H_u^+ H_d^- - H_u^0 H_d^0\right) S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right), \end{aligned}$$

- 5 neutral Higgs bosons: h, h_s, H and a_s, A

- Possible enhancement in the tree-level mass of h

$$M_h^2 \le M_Z^2 \cos^2 2\beta \boxed{+ \frac{\lambda^2 v^2 \sin^2 2\beta}{2} - \frac{\lambda^2 v^2}{2\kappa^2}\left[\lambda - \sin 2\beta\left(\kappa + \frac{A_\lambda}{\sqrt{2} v_s}\right)\right]^2}$$

Higgs boson masses

For large-ish tanβ (H, A decoupled)

$$M^2_{h,h_s} \approx \frac{1}{2}\left\{M_Z^2 + 4(\kappa v_s)^2 + \kappa v_s A_\kappa \mp \sqrt{\left[M_Z^2 - 4(\kappa v_s)^2 - \kappa v_s A_\kappa\right]^2 + 4\lambda^2 v^2 \left[2\lambda v_s - (A_\lambda + \kappa v_s)\sin 2\beta\right]^2}\right\}$$

$$M^2_{a_s} \simeq \lambda(A_\lambda + 4\kappa v_s)\frac{v^2 \sin 2\beta}{2 v_s} - 3\kappa v_s A_\kappa$$

If the parameters are complex

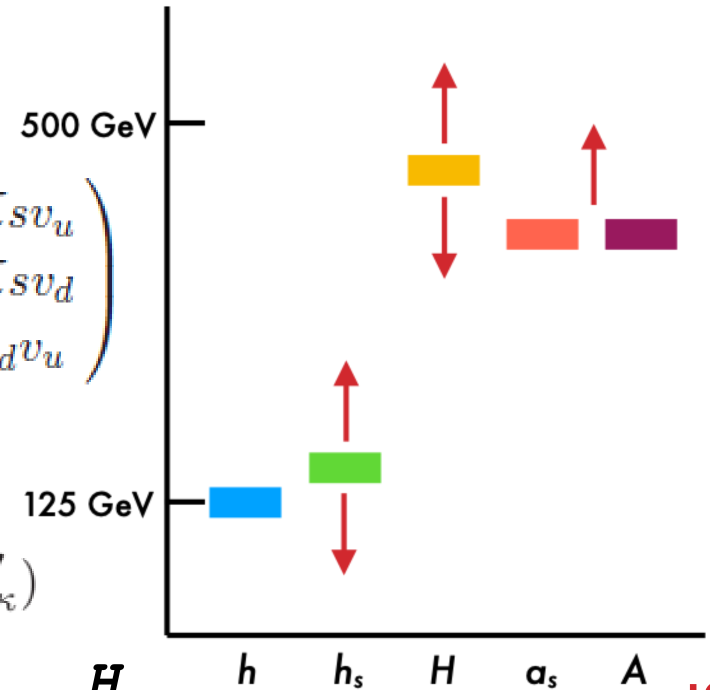
$$\lambda \equiv |\lambda| e^{i\phi_\lambda} \quad A_\lambda \equiv |A_\lambda| e^{i\phi_{A_\lambda}} \quad \kappa \equiv |\kappa| e^{i\phi_\kappa}$$

$$A_\kappa \equiv |A_\kappa| e^{i\phi_{A_\kappa}}$$

$$\mathcal{M}^2_{SP} = \begin{pmatrix} 0 & 0 & -\frac{3}{2}\mathcal{I} s v_u \\ 0 & 0 & -\frac{3}{2}\mathcal{I} s v_d \\ \frac{1}{2}\mathcal{I} s v_u & \frac{1}{2}\mathcal{I} s v_d & 2\mathcal{I} v_d v_u \end{pmatrix}$$

$$\mathcal{M}^2_0 = \left(\begin{array}{c|c} \mathcal{M}^2_S & \mathcal{M}^2_{SP} \\ \hline (\mathcal{M}^2_{SP})^T & \mathcal{M}^2_P \end{array}\right)$$

$$\mathcal{I} = |\lambda||\kappa| \sin(\phi'_\lambda - \phi'_\kappa)$$

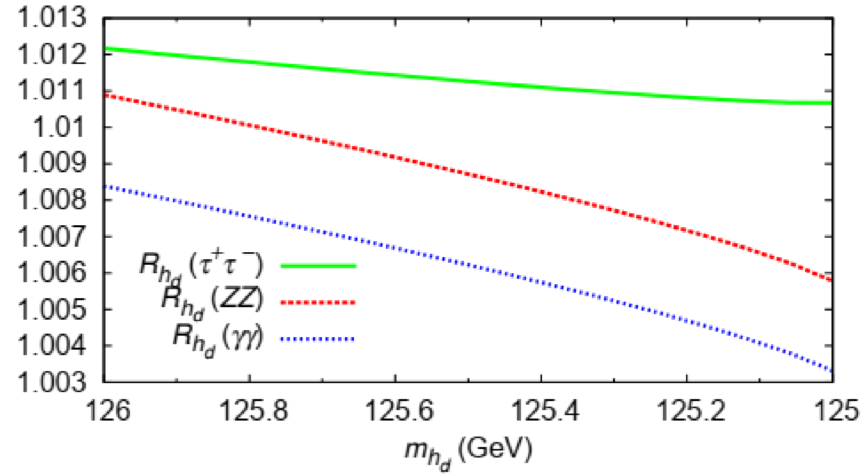


h, h_s, H, a_s, A $\Rightarrow$ h_d, h_s, h_p, H_s, H_p

A benchmark configuration

$$m_{h_s} < m_{h_d} < m_{h_p} \; ; \; m_{h_s} + m_{h_d} < m_{h_p}$$

[SM, 1310.8129]

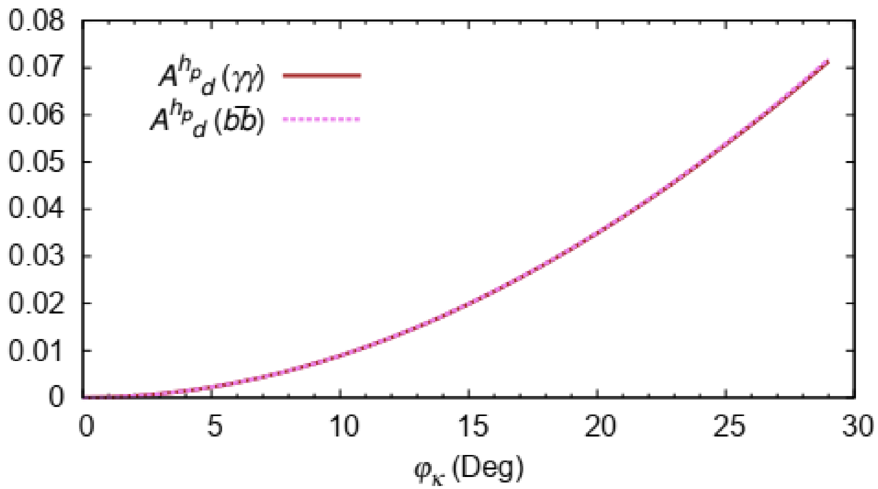


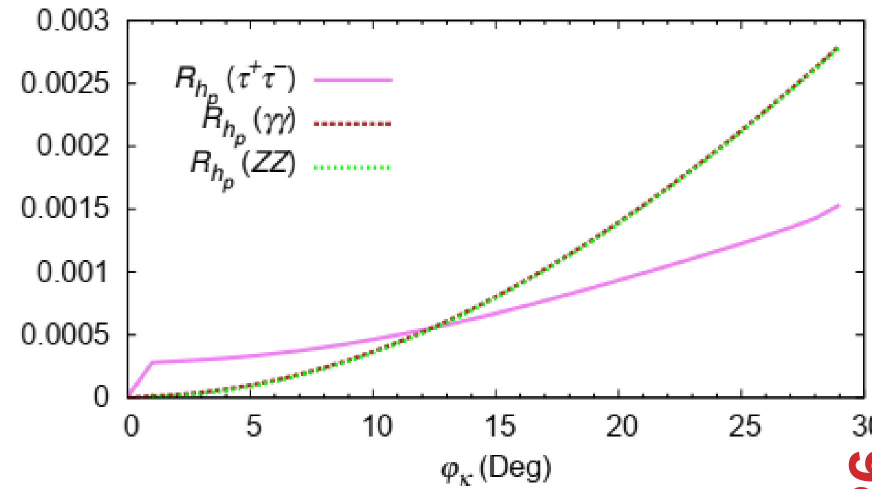
Define signal strengths

$$R_{h_i}(X) \equiv \frac{\Gamma(h_i \to gg)}{\Gamma(h_{\rm SM} \to gg)} \times \frac{{\rm BR}(h_i \to X)}{{\rm BR}(h_{\rm SM} \to X)}$$

and `auxiliary' rates

$$A_i^{h_p}(\gamma\gamma) \equiv \frac{\Gamma(h_p \to gg)}{\Gamma(h_{\rm SM} \to gg)} \times {\rm BR}(h_p \to h_d h_i) \times \frac{{\rm BR}(h_d \to \gamma\gamma)}{{\rm BR}(h_{\rm SM} \to \gamma\gamma)}$$





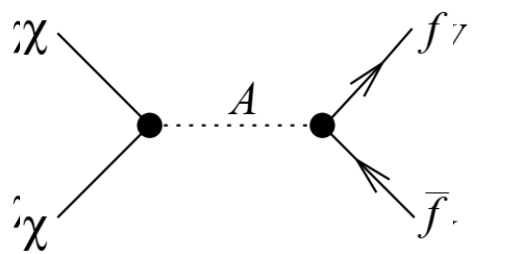
Light Dark Matter relic

[W. Ahmed, M. Goodsell, SM, 2201.10628]

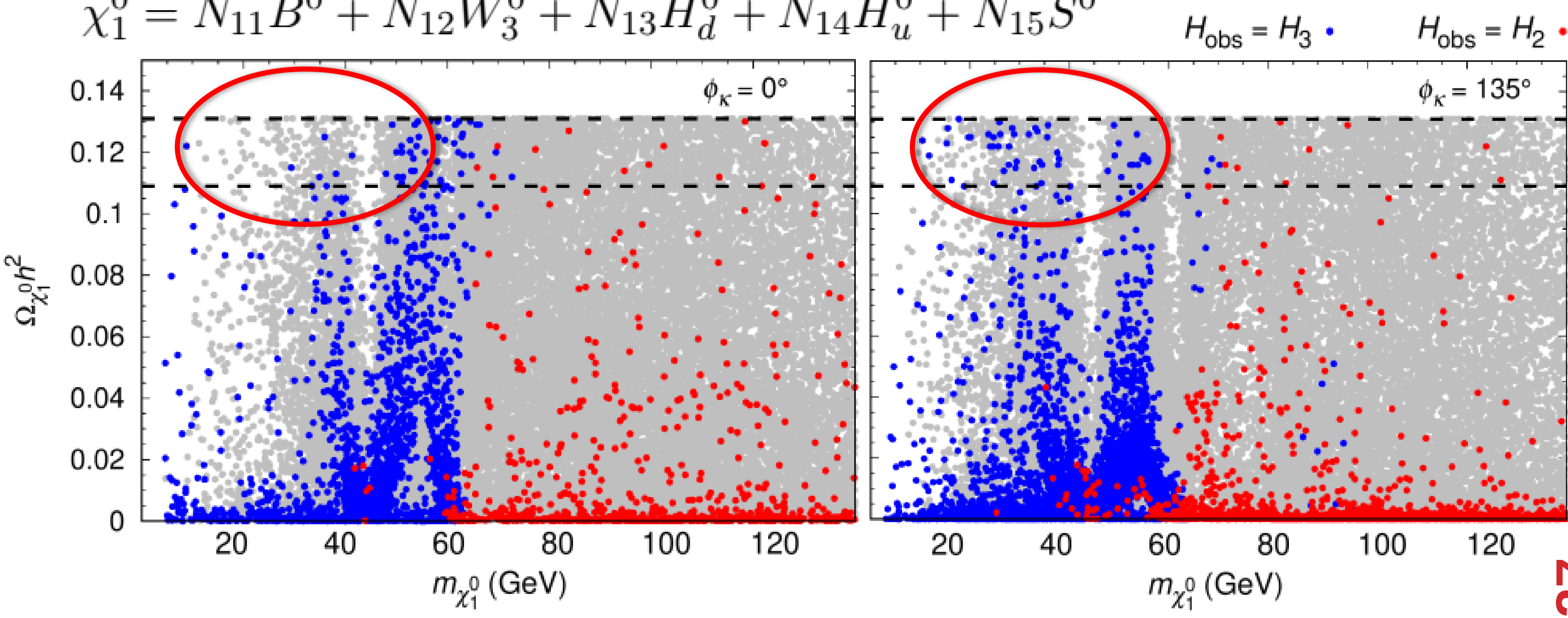
Complex phases appear in the neutralino sector also

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z \cos\beta s_W & m_Z \sin\beta s_W & 0 \\ & M_2 & m_Z \cos\beta c_W & -m_Z \sin\beta c_W & 0 \\ & & 0 & -\frac{|\lambda| v_S}{\sqrt{2}} e^{i\phi'_\lambda} & -\frac{|\lambda| v s_\beta}{\sqrt{2}} e^{i\phi'_\lambda} \\ & & & 0 & -\frac{|\lambda| v \cos\beta}{\sqrt{2}} e^{i\phi'_\lambda} \end{pmatrix}$$

$$\mathrm{diag}(m_{\tilde\chi^0_i}) = N^* \mathcal{M}_{\tilde\chi^0} N^\dagger$$



$$\tilde\chi^0_1 = N_{11}\widetilde{B}^0 + N_{12}\widetilde{W}^0_3 + N_{13}\widetilde{H}^0_d + N_{14}\widetilde{H}^0_u + N_{15}\widetilde{S}^0$$



Summary

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- *Minimal extensions of the SM (Higgs sector) have been around for decades and have been extensively studied theoretically and probed experimentally*
- *While their signatures remain elusive in the established search channels, there exist scenario in them that may require dedicated analyses*
- *One scenario is the enhanced EW multi-Higgs production compared to the QCD production*
- *Another is the possibility of Higgs bosons having nearly identical masses, and hence `interferening'*
- *CP-violating effects in the Higgs sectors – essential to explain EW baryogenesis – might have significant phenomenological implications*


THANK YOU!
MURAKOZE!