“Higgs precision” a window to new physics

Kentarou Mawatari

大阪大学
OSAKA UNIVERSITY

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H-boson observation, evidence, Nobel prize!

- 2012 July
  - Observation of a new particle in the search for the Standard Model (SM) Higgs boson with the ATLAS detector at the LHC
  - Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
- 2013 July
  - Evidence for the spin-0 nature of the Higgs boson
- 2013 October
  - Physics Nobel Prize [F. Englert (Brussels) and P. Higgs (Edinburgh)]

The SM has been established, and we are seeking for new physics.

However, neither supersymmetry…

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

Legend: $\sqrt{s}$ = 7, 8 TeV (green) · $\sqrt{s}$ = 13 TeV (blue)

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$		Mass limit	$\sqrt{s}$		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	13 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	1712.02332
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	710 GeV	13 TeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1711.03301
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	13 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	1712.02332
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	13 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1712.02332
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	1.7 TeV	13 TeV	$m(\tilde{\chi}_1^0)$<300 GeV,	1611.05791
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$	1.87 TeV	13 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1706.03731
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8 TeV	13 TeV	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
Inclusive Searches	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV	13 TeV		1607.05979
Inclusive Searches	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$	2.15 TeV	13 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
Inclusive Searches	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$	2.05 TeV	13 TeV	$m(\tilde{\chi}_1^0)$=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
Inclusive Searches	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	7, 8 TeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	1.92 TeV	13 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	1711.01901
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$	1.97 TeV	13 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	1711.01901
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	950 GeV	13 TeV	$m(\tilde{\chi}_1^0)$<420 GeV	1708.09266
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	275-700 GeV	13 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})= m(\tilde{\chi}_1^0)$+100 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV; 200-720 GeV	7, 8 TeV; 13 TeV	$m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
3^{rd} gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	90-198 GeV; 0.195-1.0 TeV	7, 8 TeV; 13 TeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
3^{rd} gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	90-430 GeV	13 TeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
3^{rd} gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-600 GeV	7, 8 TeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
3^{rd} gen. squarks direct production	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	290-790 GeV	13 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1706.03986
3^{rd} gen. squarks direct production	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$	320-880 GeV	13 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$	90-500 GeV	13 TeV	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2017-039
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$	750 GeV	13 TeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$	760 GeV	13 TeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1708.07875
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	1.13 TeV	13 TeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	580 GeV	13 TeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	270 GeV	7, 8 TeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
EW direct	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	635 GeV	7, 8 TeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
EW direct	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	7, 8 TeV	$c\tau$<1 mm	1507.05493
EW direct	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$	1.06 TeV	13 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$	460 GeV	13 TeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1712.02118
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	495 GeV	7, 8 TeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
Long-lived particles	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	7, 8 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
Long-lived particles	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	1.58 TeV	13 TeV		1606.05129
Long-lived particles	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	13 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
Long-lived particles	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$	2.37 TeV	13 TeV	$\tau(\tilde{g})$=0.17 ns, $m(\tilde{\chi}_1^0)$ = 100 GeV	1710.04901
Long-lived particles	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	7, 8 TeV	10<tanβ<50	1411.6795
Long-lived particles	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	7, 8 TeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
Long-lived particles	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7, 8 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	13 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
RPV	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	7, 8 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$	1.14 TeV	13 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow\tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	7, 8 TeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
RPV	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$	1.875 TeV	13 TeV	$m(\tilde{\chi}_1^0)$=1075 GeV	SUSY-2016-22
RPV	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	2.1 TeV	13 TeV	$m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$	1704.08493
RPV	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow\tilde{t}_1t, \tilde{t}_1\rightarrow bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	1.65 TeV	13 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$	1704.08493
RPV	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	100-470 GeV; 480-610 GeV	13 TeV		1710.07171
RPV	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$	0.4-1.45 TeV	13 TeV	BR($\tilde{t}_1\rightarrow be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	510 GeV	7, 8 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

Mass scale [TeV] (axis from 10^{-1} to beyond 1)

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

nor non-SUSY exotics so far…

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ 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 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 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	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η^-_{LL}		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV η^-_{LL}		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ 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 $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥ 3 e, μ	≥ 2/≥ 1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	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^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	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	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	ATLAS-CONF-2017-053
	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, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

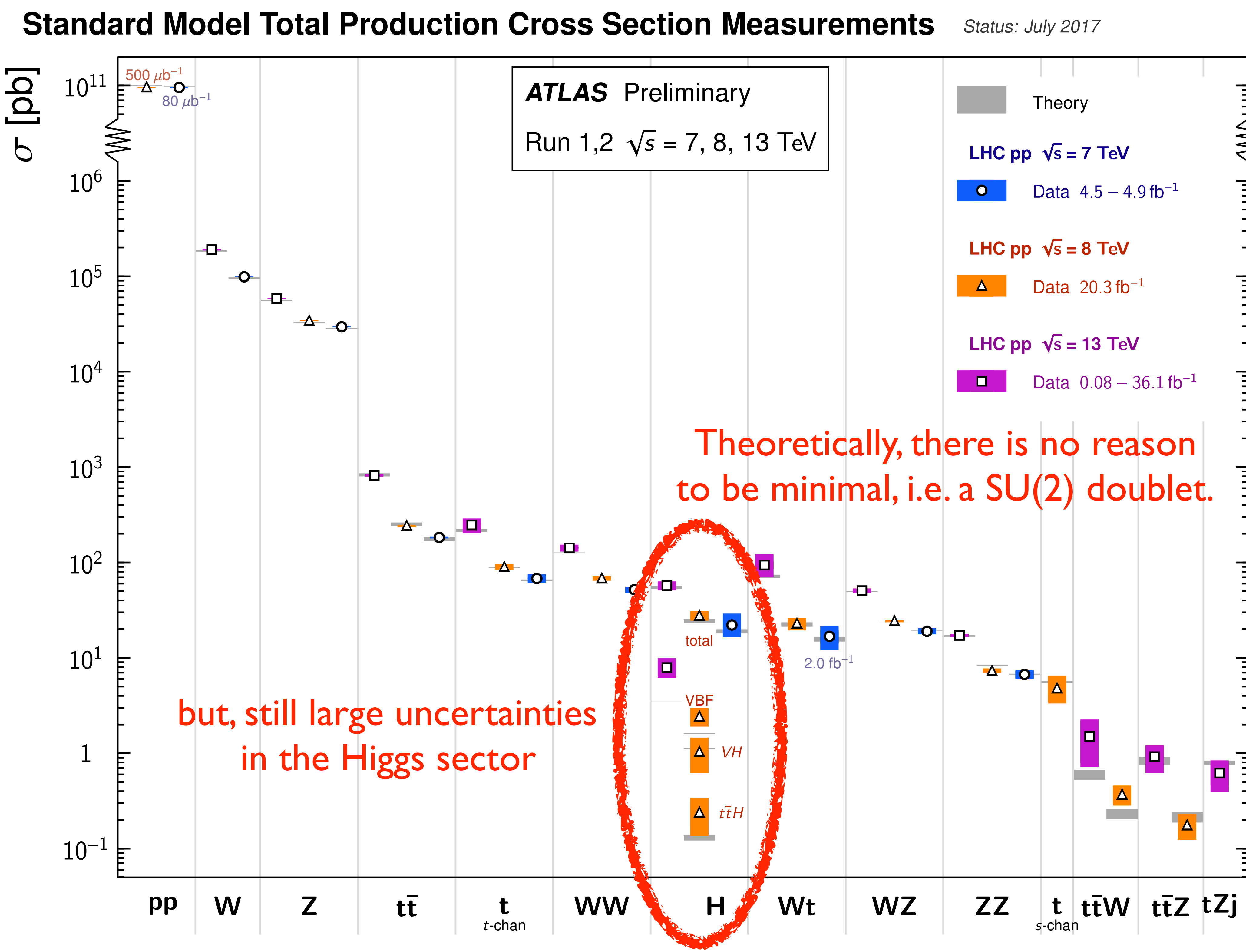
$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

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

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

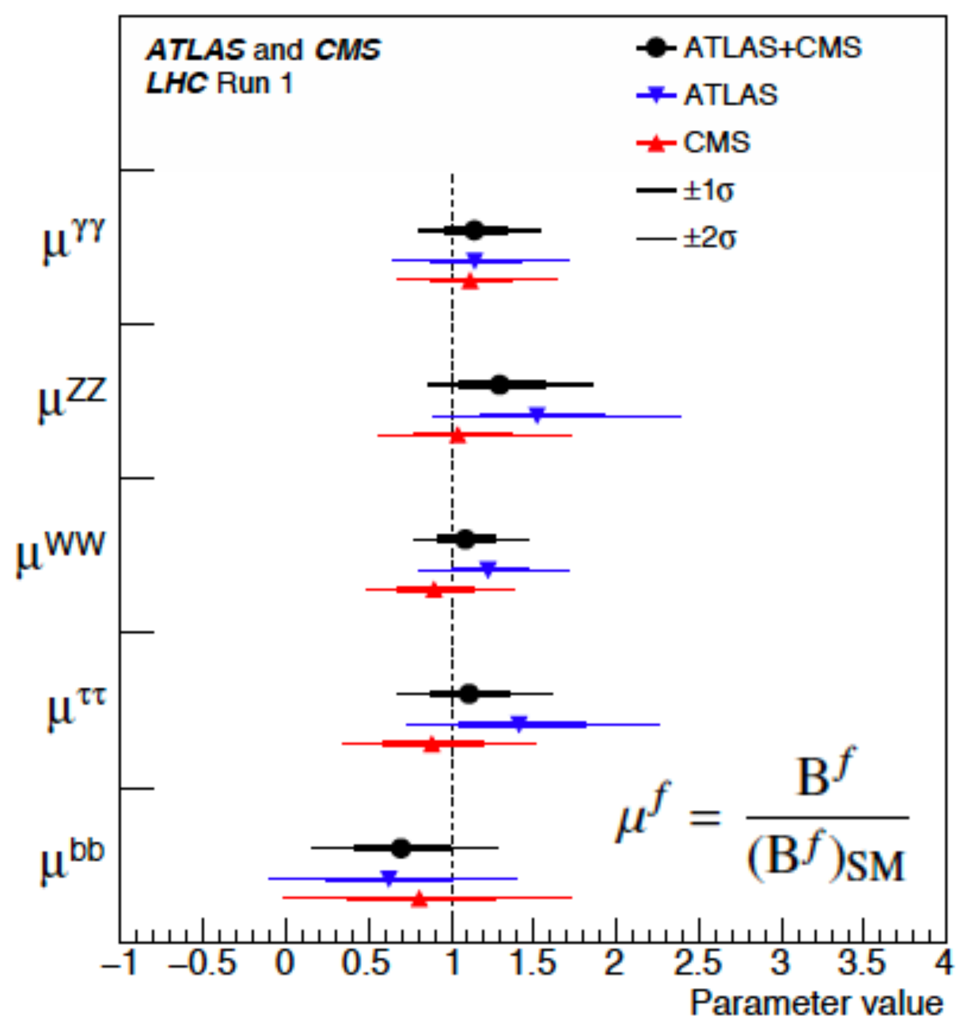
†Small-radius (large-radius) jets are denoted by the letter j (J).

On the other hand, the SM looks so good…

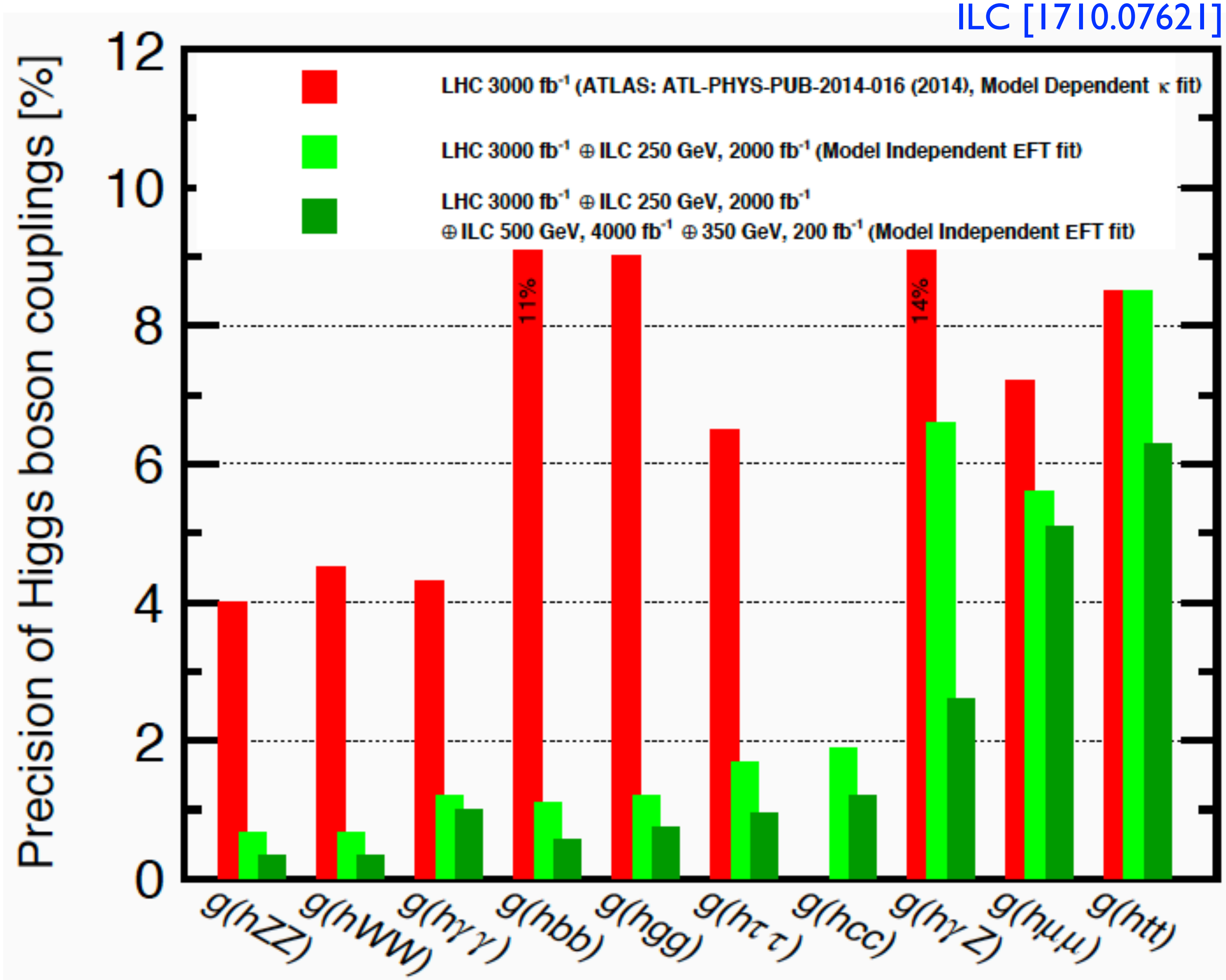


Higgs precision @HL-LHC, ILC, …

ATLAS+CMS [1606.02266]



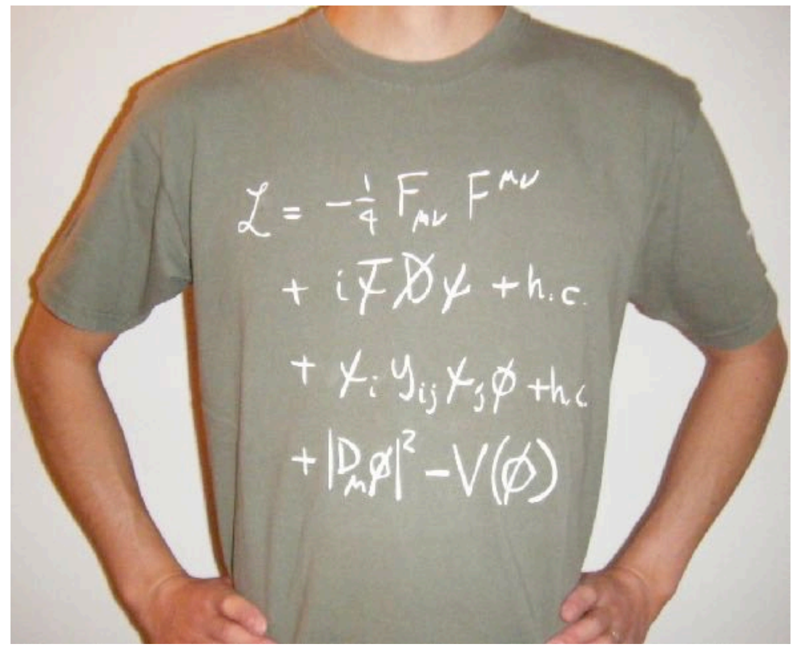
ILC [1710.07621]



Precision measurements = indirect search for new physics

→ Precision calculations

How do we extend the Higgs sector?



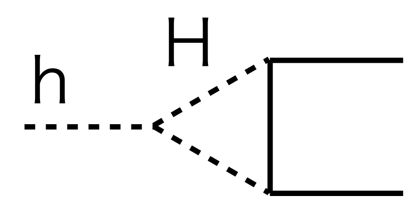
Top-down approach

deviation from SM

Bottom-up approach

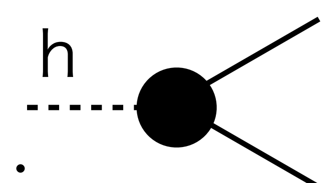
UV model : SUSY, ExtraDim, Compositeness, $\cdots$

$$\{\mathcal{L}; m_1, m_2, \cdots, g_1, g_2, \cdots\}$$



EFT : SM gauge group, particles

$$\{\mathcal{L}; \Lambda, c_1, c_2, \cdots\} \quad \mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i O_i^{\rm D6} + \cdots$$



Looking for deviations systematically and model-independently.

YR1: Inclusive Observables [1101.0593]
YR2: Differential Distributions [1201.3084]
YR3: Higgs properties [1307.1347]

YR4: Deciphering the nature of the Higgs sector

HXSWG [1610.07922] (about 400 authors, 869 pages, 295 figures, 248 tables and 1645 references)

Abstract

… The main goal of the working group was to present the state-of-the-art of Higgs physics at the LHC, integrating all new results that have appeared in the last few years. …

Contents

I. Standard Model Predictions (I.6 ttH and tH)
II. Effective Field Theory Predictions (II.3 EFT application)
III. Measurements and Observables
IV. Beyond the Standard Model Predictions

Higgs Characterisation (HC)
based on the effective field theory (EFT)

- HC provides a framework, based on the EFT, that allows for the study of the Higgs properties in a consistent, systematic and accurate (NLO-QCD+PS) way.
- HC has been implemented in a complete simulation chain from Lagrangian to hadron-level events, especially in the FeynRules/MadGraph5_aMC@NLO framework.
- The model file is publicly available at the FeynRules repository: https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

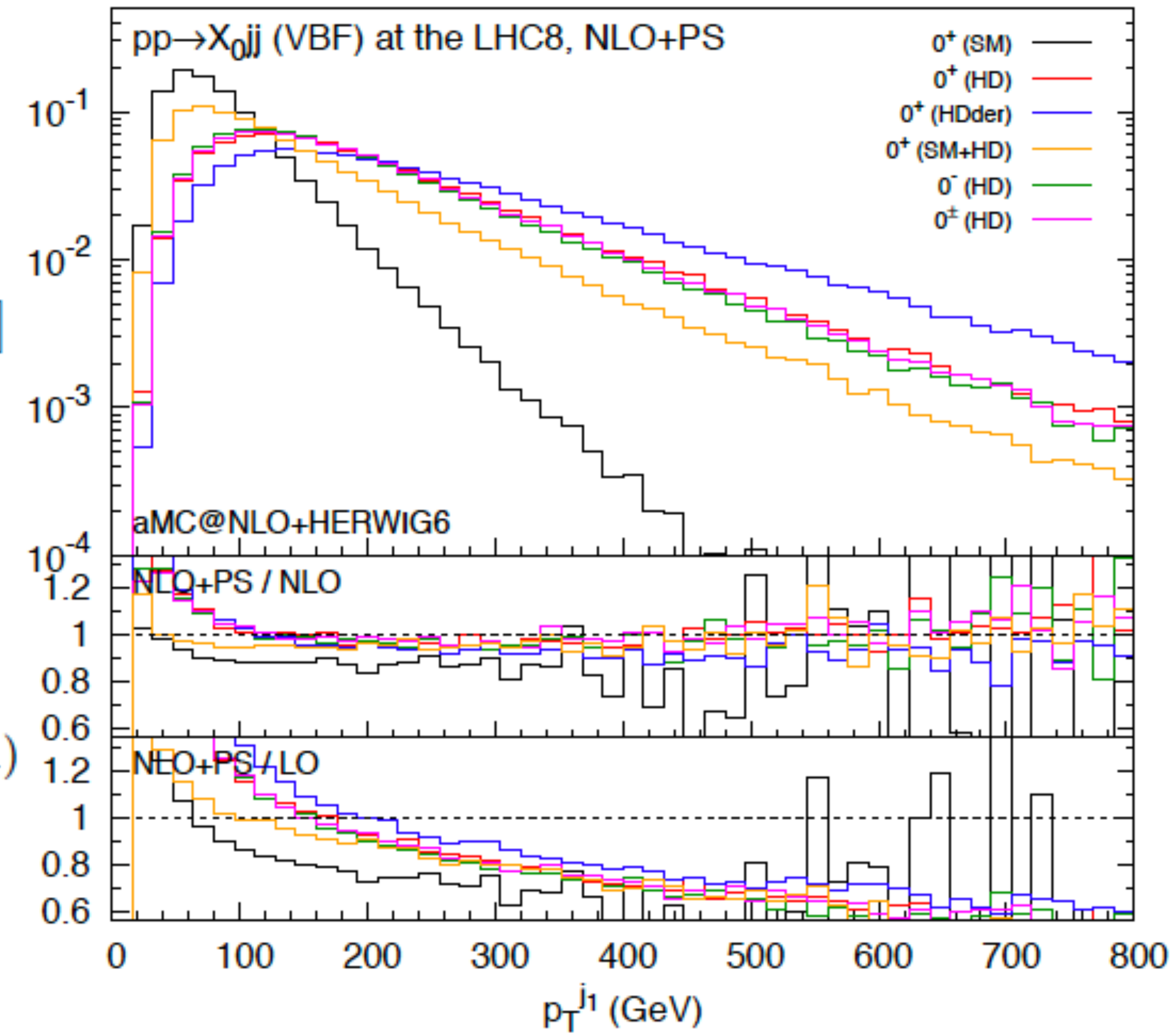
- HC1 (spin-0,1,2): "A framework for Higgs characterisation" [1306.6464, JHEP]
  Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro
- HC2 (VBF/VH): "Higgs characterisation via VBF/VH: NLO and parton-shower effects" [1311.1829, EPJC]
  Maltoni, Mawatari, Zaro
- HC3 (GF(H+jets)/ttH): "Higgs characterisation at NLO: CP properties of the top Yukawa" [1407.5089, EPJC]
  Demartin, Maltoni, Mawatari, Page, Zaro
- HC4 (tH): "Higgs production in association with a single top quark at the LHC" [1504.00611, EPJC]
  Demartin, Maltoni, Mawatari, Zaro
- HC5 (tWH): "tWH associated production at the LHC" [1607.05862, EPJC]
  Demartin, Maier, Maltoni, Mawatari, Zaro

Higgs characterisation in VBF

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\
& \qquad + \left(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\right)\big] \Big\} X_0 \,, \qquad (1)
\end{aligned}
$$

parameter	description
Λ [GeV]	cutoff scale
c_α ($\equiv \cos\alpha$)	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter

HC2: Maltoni, KM, Zaro [1311.1829, EPJC]



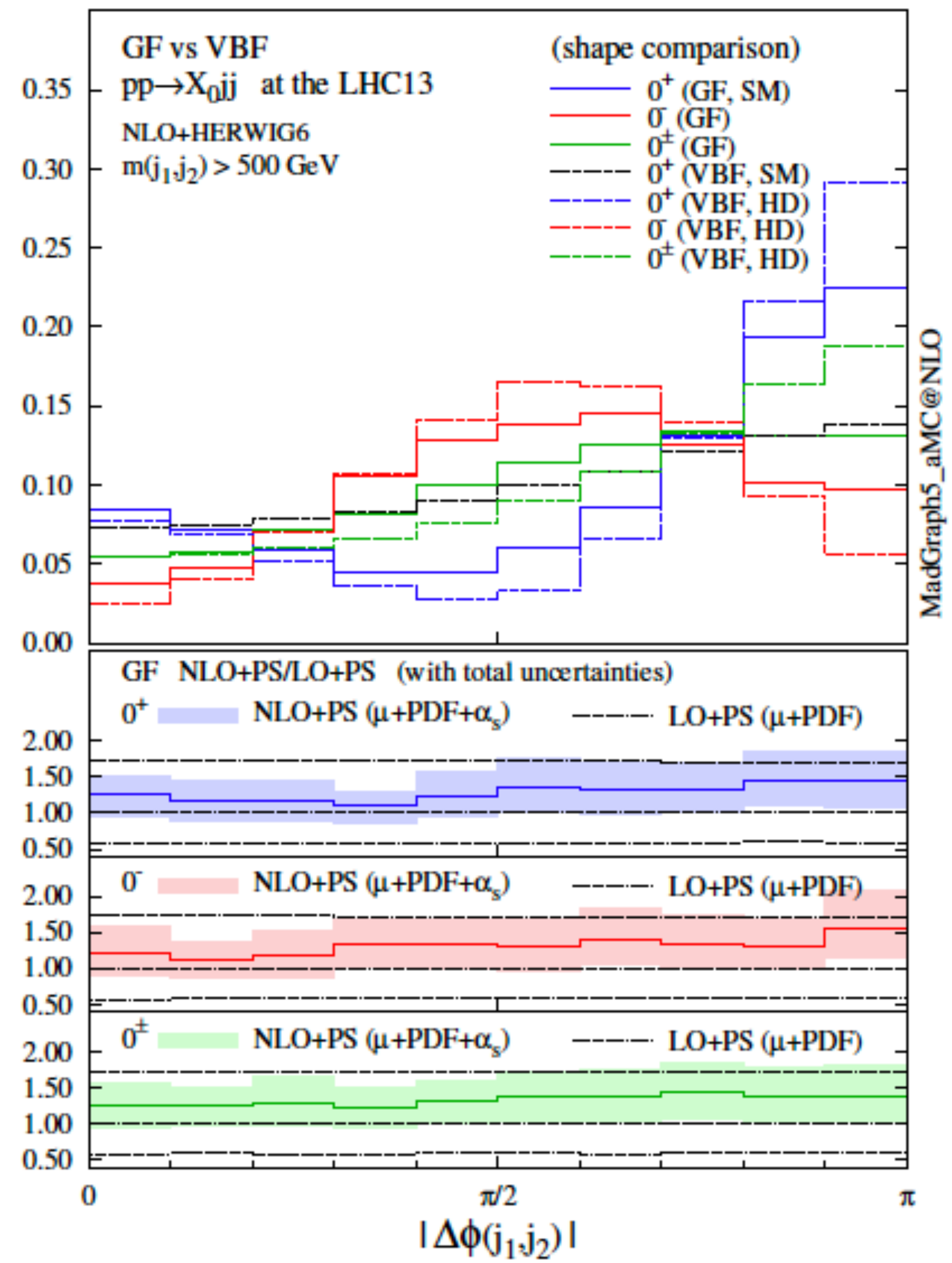
Simple rescaling of the coupling is not enough → beyond the κ framework

Higgs characterisation in VBF/GF

HC3: Demartin, Maltoni, KM, Page, Zaro [1407.5089, EPJC]

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda}c_\alpha\big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\
& \qquad + \big(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0 \,, \qquad (1)
\end{aligned}
$$

parameter	description
Λ [GeV]	cutoff scale
c_α ($\equiv \cos\alpha$)	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter

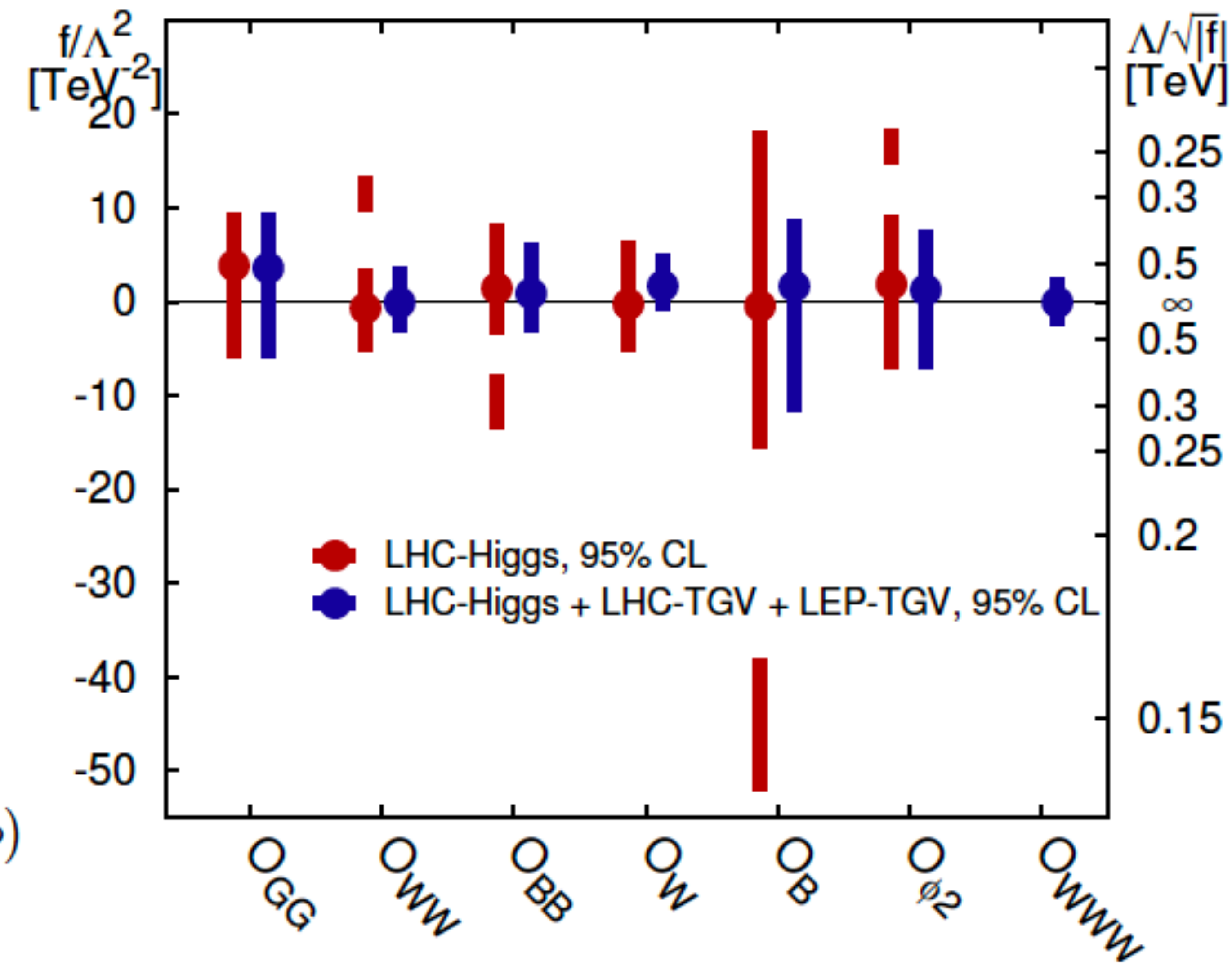


SMEFT global fit

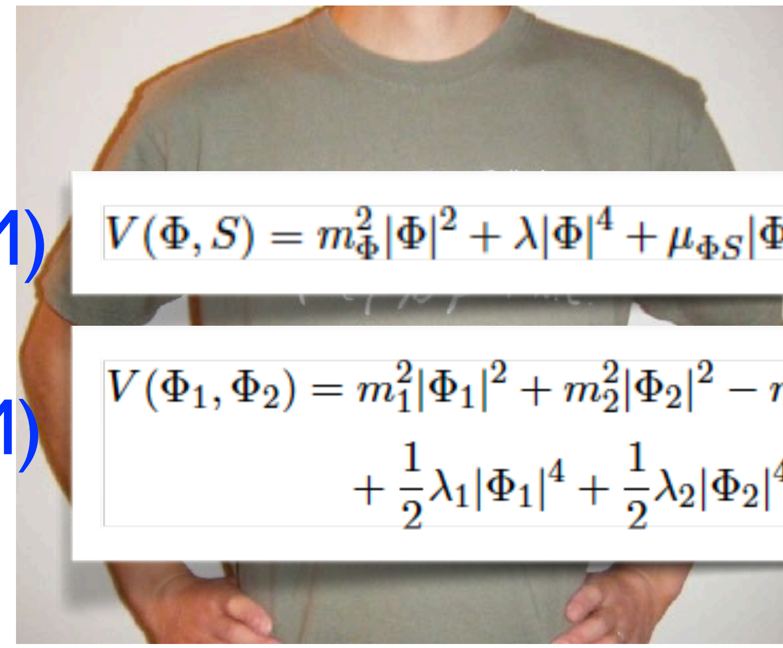
e.g. Butter et al. [1604.03105, JHEP]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{\alpha_s}{8\pi}\frac{f_{GG}}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_{\phi,2}}{\Lambda^2}\mathcal{O}_{\phi,2} + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW}$$
$$+ \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_\tau m_\tau}{v\Lambda^2}\mathcal{O}_{e\phi,33} + \frac{f_b m_b}{v\Lambda^2}\mathcal{O}_{d\phi,33} + \frac{f_t m_t}{v\Lambda^2}\mathcal{O}_{u\phi,33} .$$

$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu}$$
$$\mathcal{O}_W = (D_\mu\phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\phi)$$
$$\mathcal{O}_{e\phi,33} = (\phi^\dagger\phi)(\bar{L}_3\phi e_{R,3})$$
$$\mathcal{O}_{WWW} = \text{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho\right)$$
$$\mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi$$
$$\mathcal{O}_B = (D_\mu\phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\phi)$$
$$\mathcal{O}_{u\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\tilde{\phi}u_{R,3})$$
$$\mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$
$$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu\left(\phi^\dagger\phi\right)\partial_\mu\left(\phi^\dagger\phi\right)$$
$$\mathcal{O}_{d\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\phi d_{R,3})$$



How do we extend the Higgs sector?



singlet extension (HSM)

$$V(\Phi,S)=m_\Phi^2|\Phi|^2+\lambda|\Phi|^4+\mu_{\Phi S}|\Phi|^2S+\lambda_{\Phi S}|\Phi|^2S^2+t_SS+m_S^2S^2+\mu_SS^3+\lambda_SS^4$$

doublet extension (THDM)

$$V(\Phi_1,\Phi_2)=m_1^2|\Phi_1|^2+m_2^2|\Phi_2|^2-m_3^2(\Phi_1^\dagger\Phi_2+\text{h.c.})+\frac{1}{2}\lambda_1|\Phi_1|^4+\frac{1}{2}\lambda_2|\Phi_2|^4+\lambda_3|\Phi_1|^2|\Phi_2|^2+\lambda_4|\Phi_1^\dagger\Phi_2|^2+\frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2+\text{h.c.}]$$

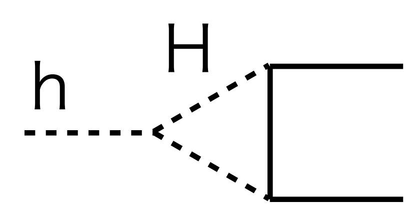
Top-down approach

deviation from SM

Bottom-up approach

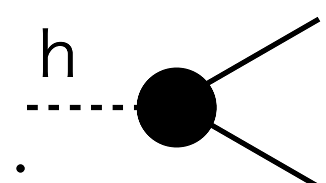
UV model : SUSY, ExtraDim, Compositeness, $\cdots$

$$\{\mathcal{L};m_1,m_2,\cdots,g_1,g_2,\cdots\}$$

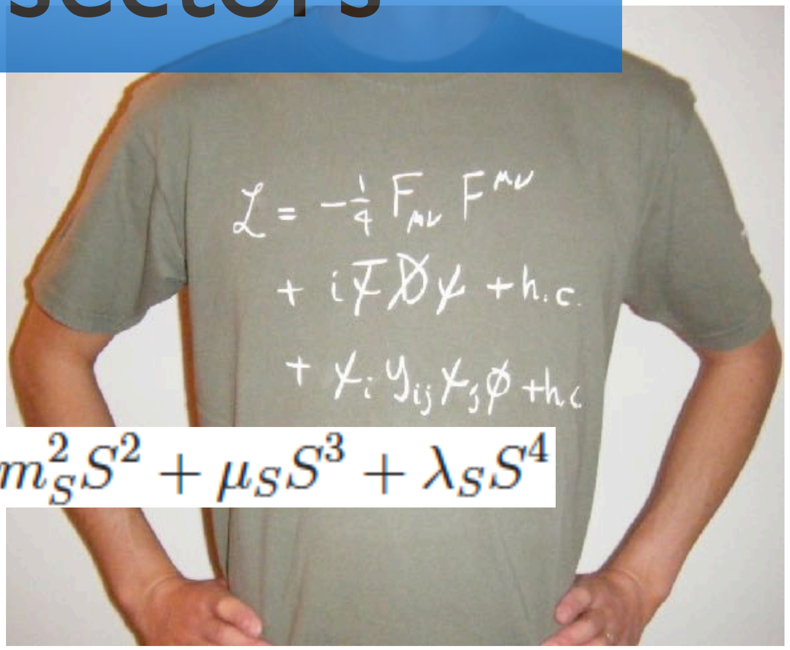


EFT : SM gauge group, particles

$$\{\mathcal{L};\Lambda,c_1,c_2,\cdots\}\quad\mathcal{L}=\mathcal{L}_{\rm SM}+\frac{1}{\Lambda^2}\sum_i c_iO_i^{\rm D6}+\cdots$$



Effects of extended Higgs sectors



- HSM: Higgs singlet model (NMSSM, …)

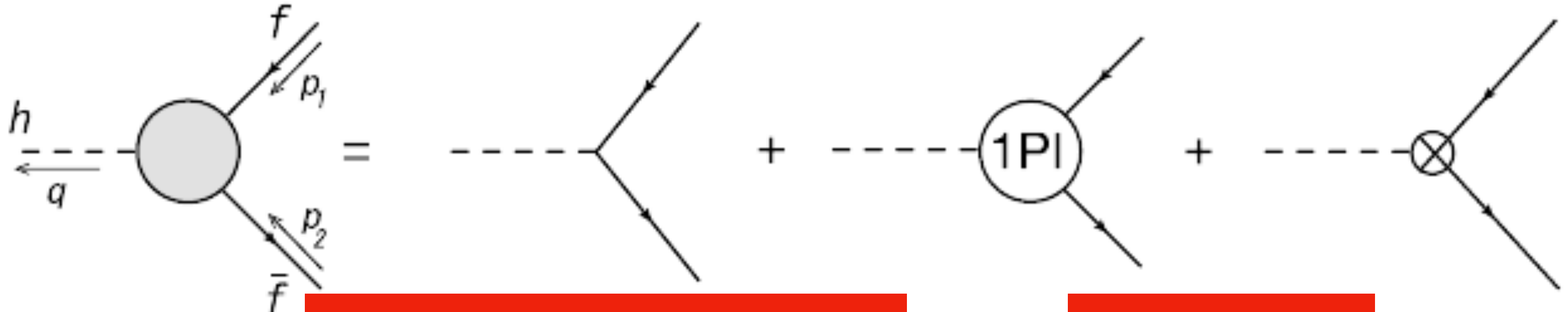
$$V(\Phi, S) = m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \lambda_{\Phi S} |\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4$$

$$m_H, \quad \alpha, \quad \lambda_S, \quad \lambda_{\Phi S}, \quad \mu_S$$

- THDM: Two Higgs doublet model (MSSM, …)

$$V(\Phi_1, \Phi_2) = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.})$$
$$+ \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

$$m_H, \ m_A, \ m_{H^\pm}, \ s_{\beta-\alpha}, \ \tan\beta, \ M^2, \ \text{Sign}(c_{\beta-\alpha})$$

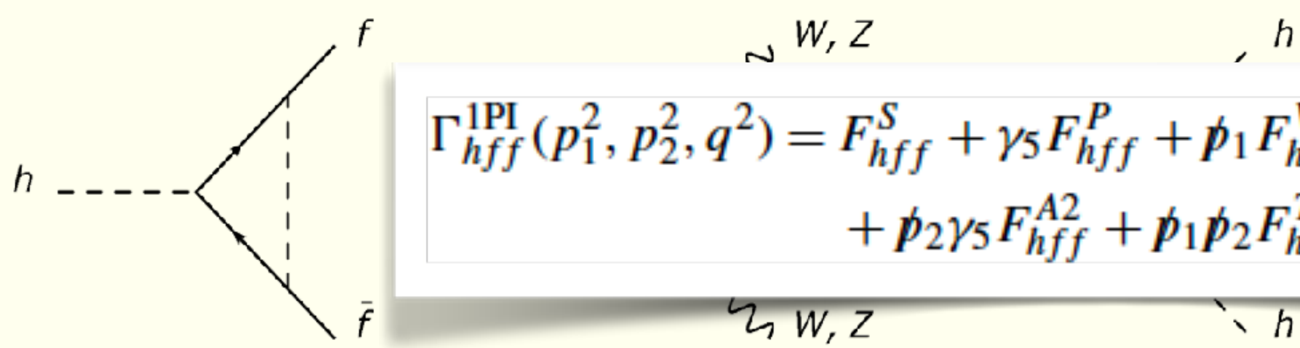


tree-level mixing effects

loop effects

www-het.phys.sci.osaka-u.ac.jp

H-COUP



$$\Gamma^{1PI}_{hff}(p_1^2, p_2^2, q^2) = F^S_{hff} + \gamma_5 F^P_{hff} + \not{p}_1 F^{V1}_{hff} + \not{p}_2 F^{V2}_{hff} + \not{p}_1\gamma_5 F^{A1}_{hff} + \not{p}_2\gamma_5 F^{A2}_{hff} + \not{p}_1\not{p}_2 F^{T}_{hff} + \not{p}_1\not{p}_2\gamma_5 F^{PT}_{hff}.$$

H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The impolved on-shell renormalization scheme is adopted, where the gauge depdence is eliminated.

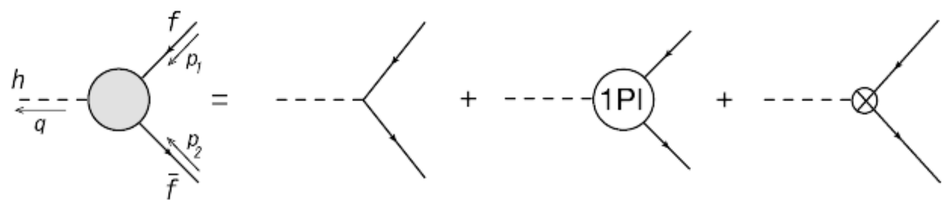
Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 1.0 can be taken on arXiv:1710.04603 [hep-ph].

See Kodai Sakurai's talk tomorrow afternoon for more details.

Downloads

- H-COUP version 1.0 : [HCOUP-1.0.zip]   [The manual is here]



$$\Gamma^{1\mathrm{PI}}_{hff}(p_1^2,p_2^2,q^2) = F^S_{hff} + \gamma_5 F^P_{hff} + \not{p}_1 F^{V1}_{hff} + \not{p}_2 F^{V2}_{hff} + \not{p}_1\gamma_5 F^{A1}_{hff} + \not{p}_2\gamma_5 F^{A2}_{hff} + \not{p}_1\not{p}_2 F^{T}_{hff} + \not{p}_1\not{p}_2\gamma_5 F^{PT}_{hff}.$$

Kanemura, Kikuchi, Yagyu [1511.06211, NPB]

Kanemura, Kikuchi, Yagyu [1502.07716, NPB]

Singlet extension

$$\Gamma^{S,\mathrm{tree}}_{hf\bar{f},\mathrm{HSM}} = -\frac{m_f}{v} c_\alpha$$

$$\begin{aligned}
(16\pi^2)F^{1\mathrm{PI}}_{hff,S}[p_1^2,p_2^2,q^2] &= -4c_\alpha \frac{m_f}{v}\left\{\frac{m_Z^2}{v^2}(v_f^2-a_f^2)C^{hff,S}_{FVF}[f,Z,f] + (Q_f e)^2 C^{hff,S}_{FVF}[f,Z,f]\right\} \\
&+ \frac{m_f^3}{v^3}c_\alpha\left\{c_\alpha^2 C^{hff,S}_{FSF}[f,h,f] + s_\alpha^2 C^{hff,S}_{FSF}[f,H,f] - c_\alpha C^{hff,S}_{FSF}[f,G^0,f]\right\} \\
&- 2c_\alpha \frac{m_f m_{f'}^2}{v^3} C^{hff,S}_{FSF}[f',G^\pm,f'] - 8c_\alpha \frac{m_Z^4}{v^3} m_f (v_f^2-a_f^2) C_0[Z,f,Z] \\
&- 2\frac{m_f^2}{v^2}\left\{3c_\alpha^2 \lambda_{hhh} C_0[h,f,h] + s_\alpha^2 \lambda_{hHH} C_0[H,f,H] + c_\alpha s_\alpha \lambda_{hhH}(C_0[h,f,H] + C_0[H,f,h])\right\} \\
&+ 2\frac{m_f^2}{v^2}\left\{\lambda_{hG^0G^0}\frac{m_f}{v}C_0[G^0,f,G^0] + \lambda_{hG^+G^-}\frac{m_{f'}}{v}C_0[G^\pm,f',G^\pm]\right\} \\
&- c_\alpha \frac{m_W^2 m_f}{v^3}(C^{hff,S}_{SFV}[G^\pm,f',W] + C^{hff,S}_{VFS}[W,f',G^\pm]) \\
&- c_\alpha \frac{m_Z^2 m_f}{2v^3}(C^{hff,S}_{SFV}[G^0,f,Z] + C^{hff,S}_{VFS}[Z,f,G^0]),
\end{aligned} \tag{D41}$$

Z_2 charge assignment

	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

2HDM

$$\Gamma^{S,\mathrm{tree}}_{hf\bar{f},\mathrm{THDM}} = -\frac{m_f}{v}(s_{\beta-\alpha} + \zeta_f c_{\beta-\alpha})$$

$$\begin{aligned}
\left(\frac{m_f}{v}\right)^{-1} F^S_{hff} &= -2g_Z^4 v^2 (v_f^2 - a_f^2) s_{\beta-\alpha} C_0(Z,f,Z) \\
&- 4\xi_h^f\Big\{e^2 Q_f^2[m_f^2 C_0 + p_1^2(C_{11}+C_{21}) + p_2^2(C_{12}+C_{22}) + p_1\cdot p_2(2C_{23}-C_0) + 4C_{24} - 1](f,\gamma,f) \\
&+ g_Z^2(v_f^2-a_f^2)[m_f^2 C_0 + p_1^2(C_{11}+C_{21}) + p_2^2(C_{12}+C_{22}) + p_1\cdot p_2(2C_{23}-C_0) + 4C_{24} - 1](f,Z,f)\Big\} \\
&+ \xi_h^f \frac{m_f^2}{v^2}\Big[(\xi_h^f)^2 C^{FSF}_{hff}(f,h,f) + (\xi_H^f)^2 C^{FSF}_{hff}(f,H,f) - C^{FSF}_{hff}(f,G^0,f) - \xi_f^2 C^{FSF}_{hff}(f,A,f)\Big] \\
&- \xi_h^{f'} \frac{2m_{f'}^2}{v^2}\Big[C^{FSF}_{hff}(f',G^\pm,f') + \xi_f \xi_{f'} C^{FSF}_{hff}(f',H^\pm,f')\Big] \\
&- \frac{m_f^2}{v}\Big\{6(\xi_h^f)^2 \lambda_{hhh} C_0(h,f,h) + 2(\xi_H^f)^2 \lambda_{HHh} C_0(H,f,H) + 2\xi_h^f \xi_H^f \lambda_{Hhh}[C_0(h,f,H) + C_0(H,f,h)] \\
&\qquad - 2\lambda_{G^0G^0h} C_0(G^0,f,G^0) - 2\xi_f^2 \lambda_{AAh} C_0(A,f,A) - \xi_f \lambda_{AG^0h}[C_0(A,f,G^0) + C_0(G^0,f,A)]\Big\} \\
&+ \frac{2m_{f'}^2}{v}\Big\{\lambda_{G^+G^-h} C_0(G^\pm,f',G^\pm) + \xi_f \xi_{f'} \lambda_{H^+H^-h} C_0(H^\pm,f',H^\pm) \\
&\qquad + \frac{1}{2}\lambda_{H^+G^-h}(\xi_f + \xi_{f'})[C_0(G^\pm,f',H^\pm) + C_0(H^\pm,f',G^\pm)]\Big\} \\
&- \frac{g^2}{4} s_{\beta-\alpha}\Big[C^{VFS}_{hff}(W,f',G^\pm) + C^{SFV}_{hff}(G^\pm,f',W)\Big] \\
&- \frac{g^2}{4} \xi_f c_{\beta-\alpha}\Big[C^{VFS}_{hff}(W,f',H^\pm) + C^{SFV}_{hff}(H^\pm,f',W)\Big] \\
&- \frac{g_Z^2}{8} s_{\beta-\alpha}\Big[C^{VFS}_{hff}(Z,f,G^0) + C^{SFV}_{hff}(G^0,f,Z)\Big] \\
&- \frac{g_Z^2}{8} \xi_f c_{\beta-\alpha}\Big[C^{VFS}_{hff}(Z,f,A) + C^{SFV}_{hff}(A,f,Z)\Big],
\end{aligned} \tag{C36}$$

Higgs decay rates in extended Higgs models at tree level

$$\Delta R(h \to XX) = \frac{\Gamma_{\rm NP}(h \to XX)}{\Gamma_{\rm SM}(h \to XX)} - 1$$

$$\Gamma^{S,\rm tree}_{hff} = -\frac{m_f}{v}\kappa_f, \quad \Gamma^{1,\rm tree}_{hVV} = \frac{2m_V^2}{v}\kappa_V$$

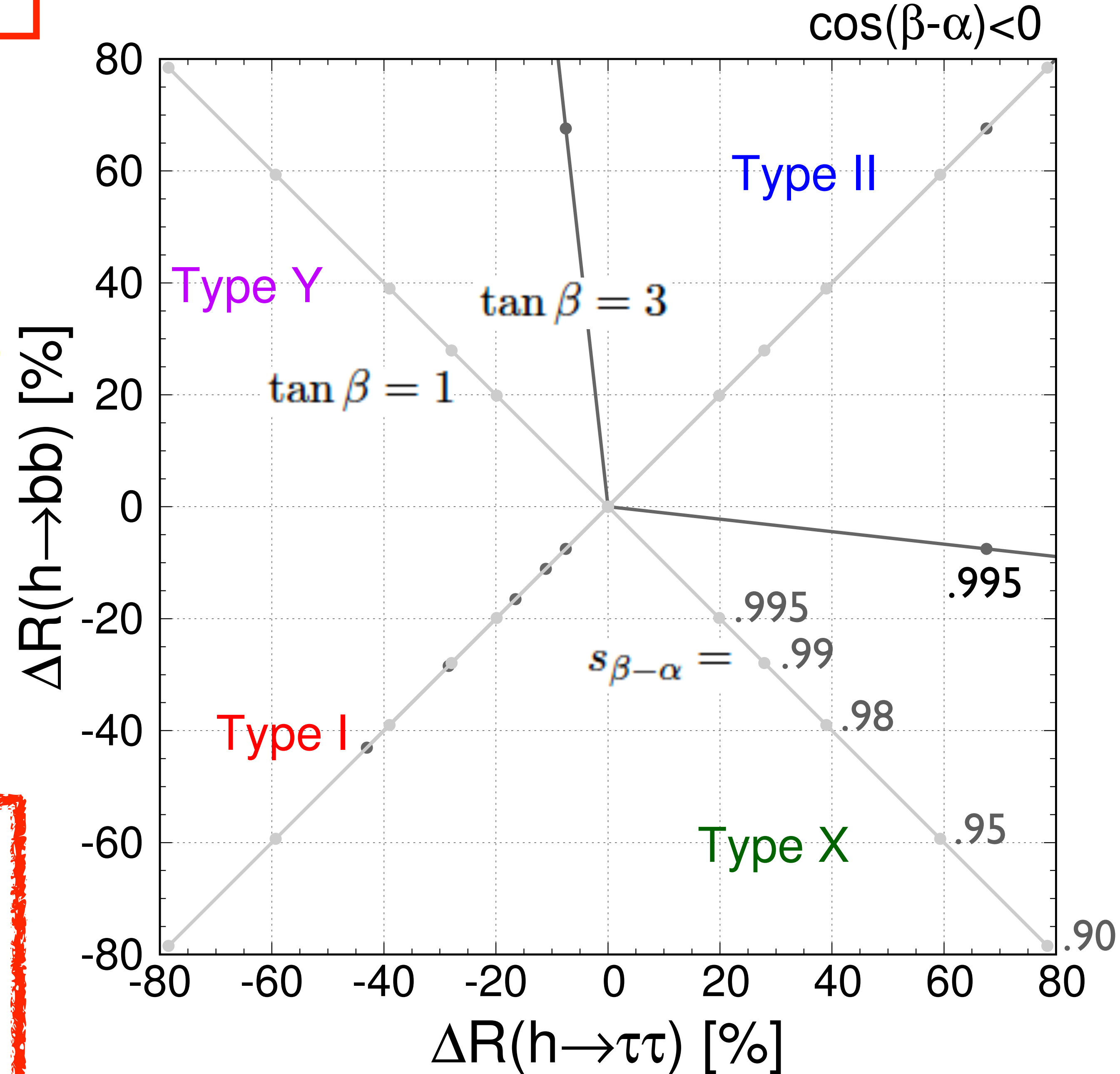
$\kappa_f = \kappa_V = c_\alpha$ for HSM,

$\kappa_f = s_{\beta-\alpha} + \zeta_f c_{\beta-\alpha}, \quad \kappa_V = s_{\beta-\alpha}$ for THDM

	ζ_u	ζ_d	ζ_e
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Tree-level mixing effects
→ pattern of deviations
→ fingerprints of NP models

e.g. Kanemura, Tsumura, Yagyu, Yokoya [1406.3294, PRD]



Higgs decay rates in extended Higgs models at one loop

$$\Delta R(h \to XX) = \frac{\Gamma_{\rm NP}(h \to XX)}{\Gamma_{\rm SM}(h \to XX)} - 1$$

Parameter scans:

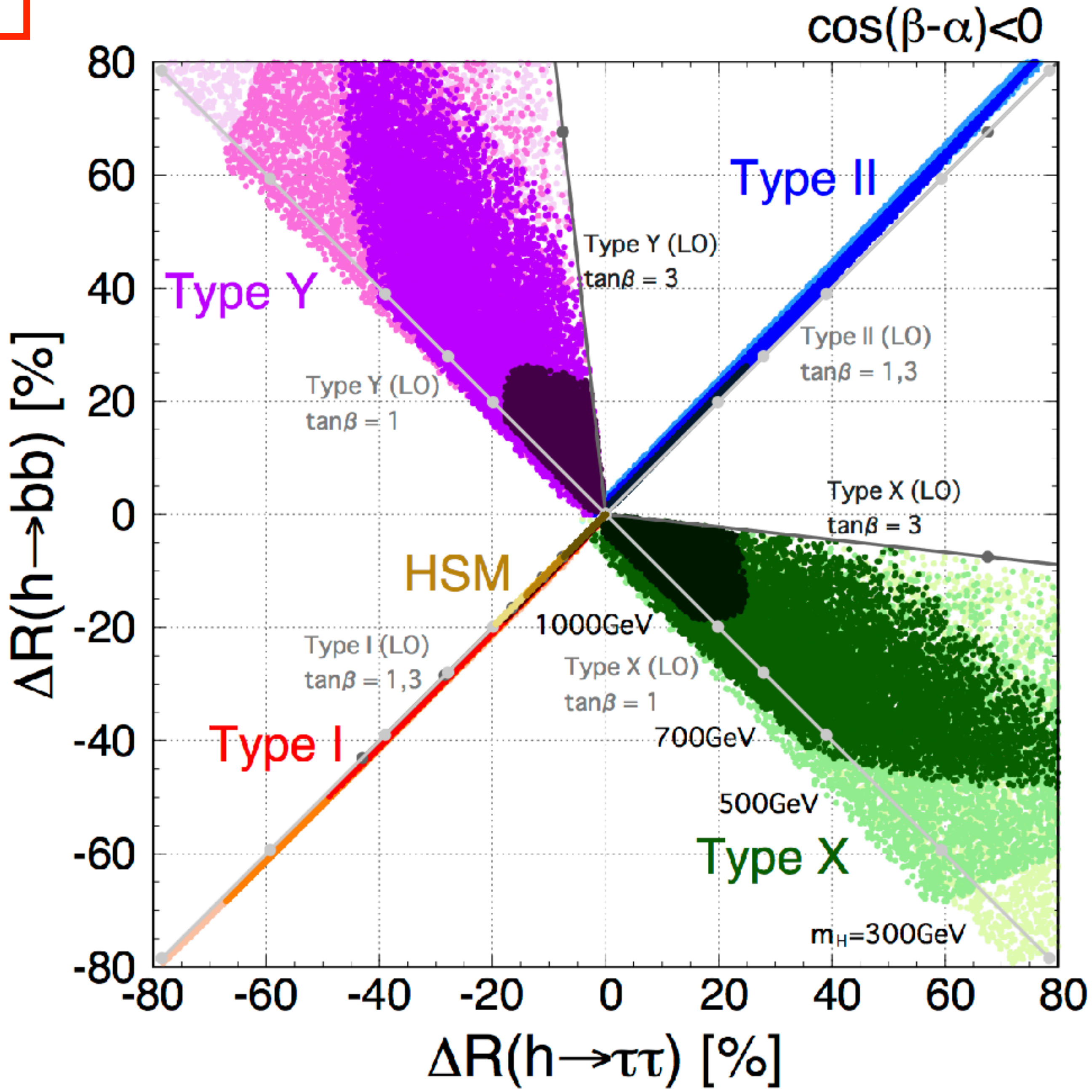
- HSM
  $0.9 < c_\alpha < 1,\ 0 < M^2 < m_H^2$
- THDM
  $0.9 < s_{\beta-\alpha} < 1,\ 1 < \tan\beta < 3,$
  $0 < M^2 < m_H^2\ (m_H = m_A = m_{H^\pm})$

Theoretical constraints:

- perturbative unitarity
- vacuum stability
- EW S,T parameters

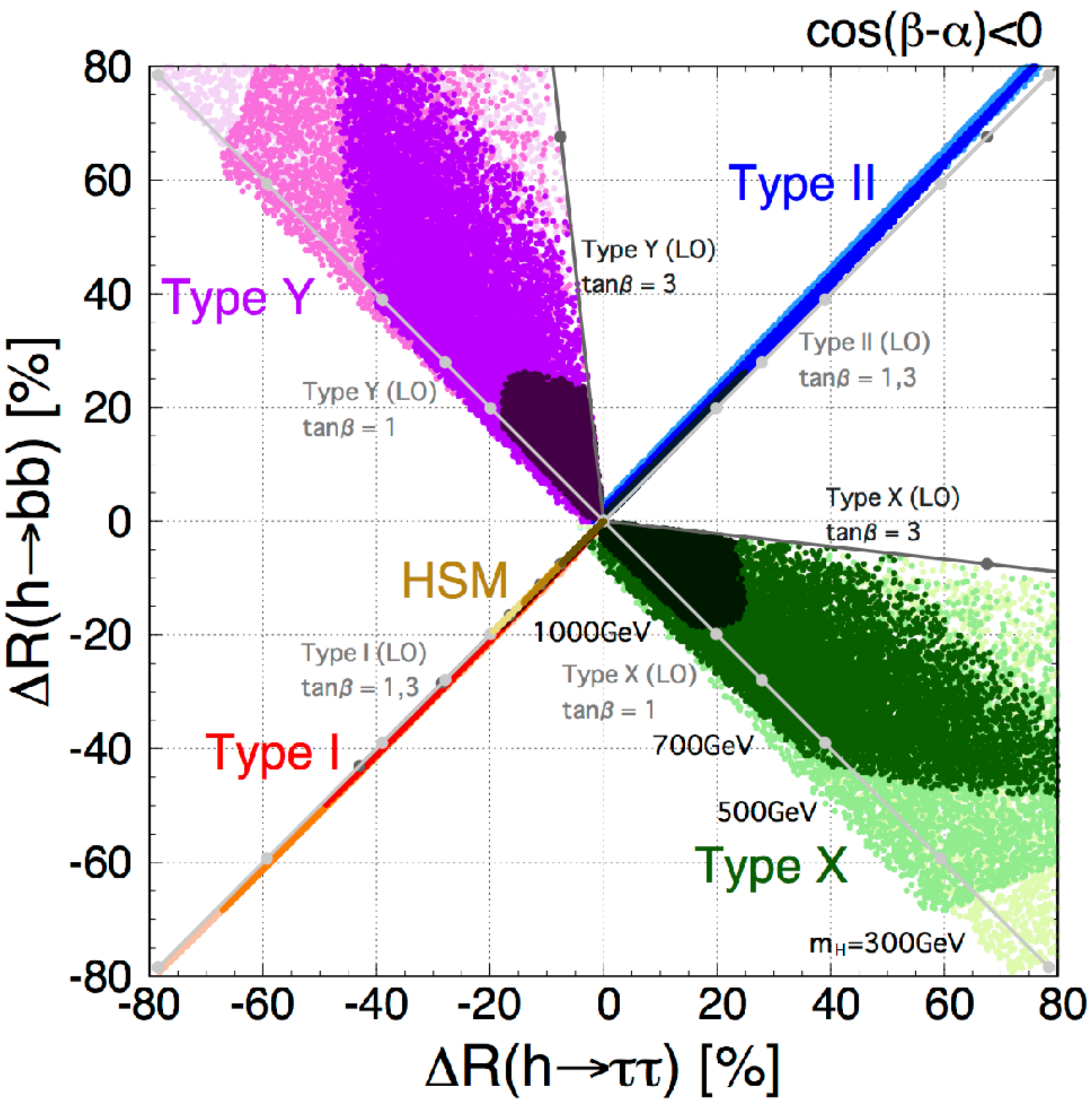
Loop effects
→ magnitude of deviations
→ NP scales

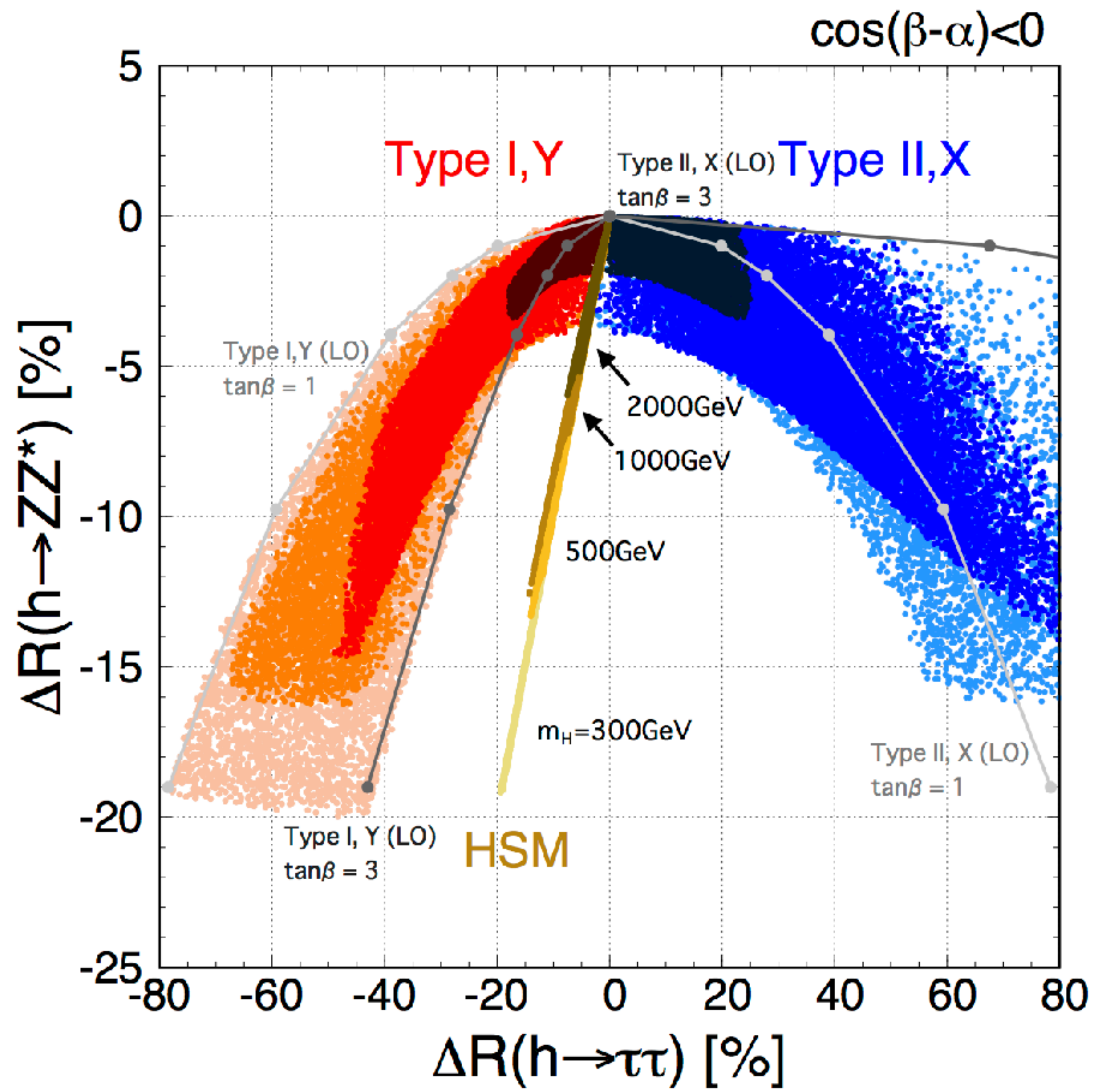
Kanemura, Kikuchi, KM, Sakurai, Yagyu [in progress]



Various correlations of the Higgs decay rates

Kanemura, Kikuchi, KM, Sakurai, Yagyu [in progress]

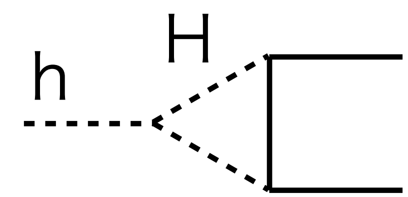


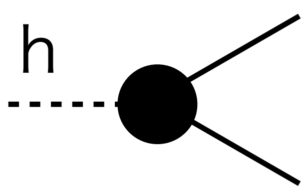


See Kodai Sakurai's talk tomorrow afternoon for more details.

Summary: Higgs precision era

The Higgs sector is a key to explore new physics.





looking for deviations based on the EFT systematically and model-independently (beyond the κ framework)

→ deviation from SM

at the LHC, HL-HLC, ILC, …

Yes!

- pattern of the deviations
  → selection of NP models
- magnitude of the deviations
  → NP scales

➡ build a 100TeV collider?

No…

- constraints NP models
  → more accurate calculations…