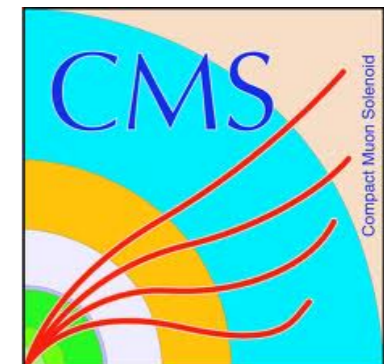


HIGGS SEARCHES BEYOND THE STANDARD MODEL AT THE LARGE HADRON COLLIDER

P. Meridiani

INFN Roma

Universita` "La Sapienza" - 10/06/2015



- Run I at the LHC: the birth of the Higgs physics
- Precision Higgs physics as a way to probe BSM
- BSM Higgs decays
- Searches for additional Higgs bosons
- Perspectives for Run2 & beyond

Disclaimer: my personal selection of the most significant results from Run 1

Discovery of the Higgs boson

$$M_H = (125.09 \pm 0.21 \pm 0.11) \text{ GeV}$$

8th October 2013

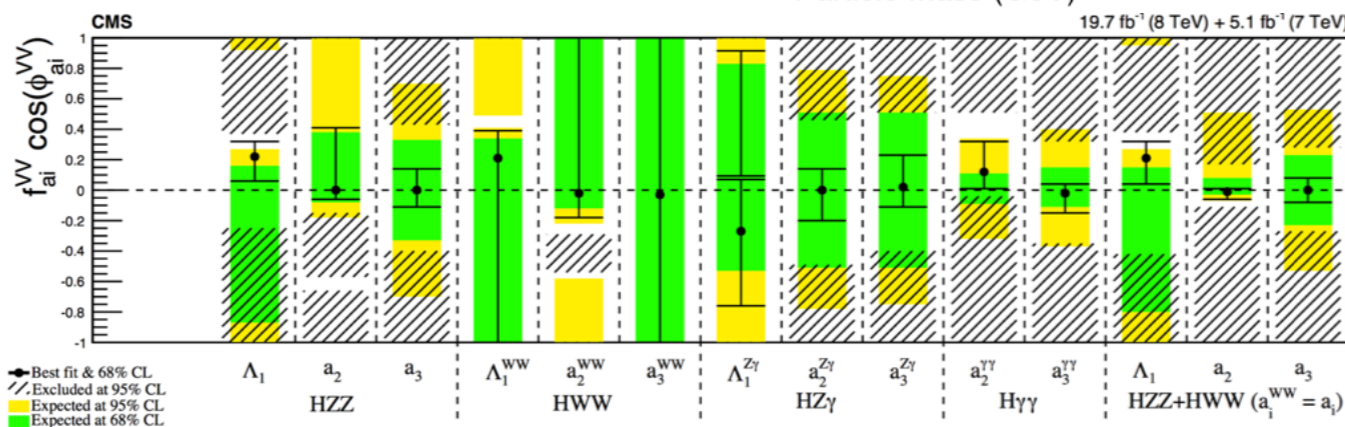
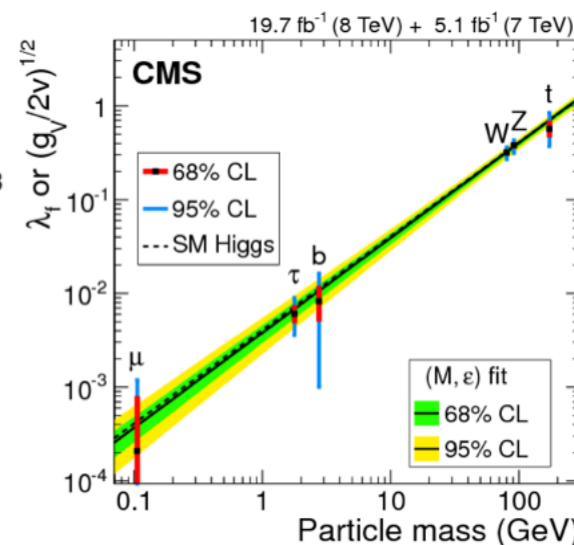
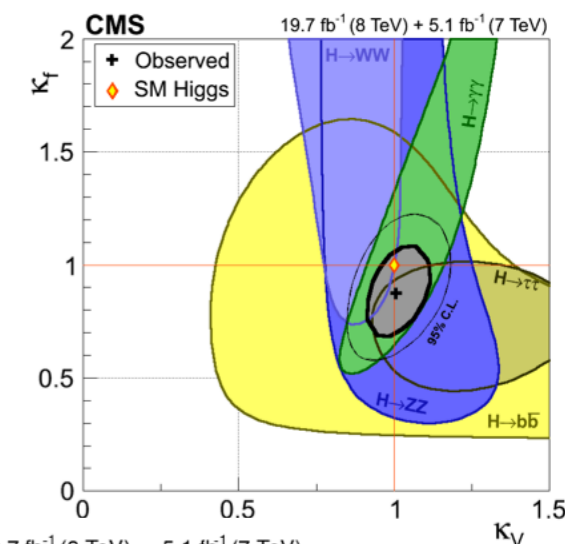
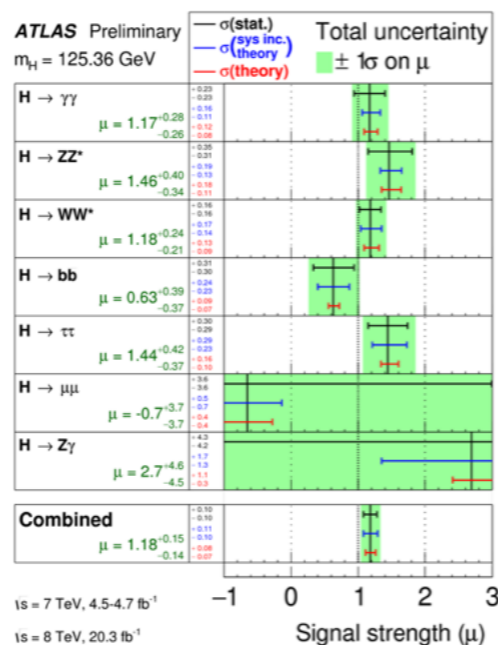
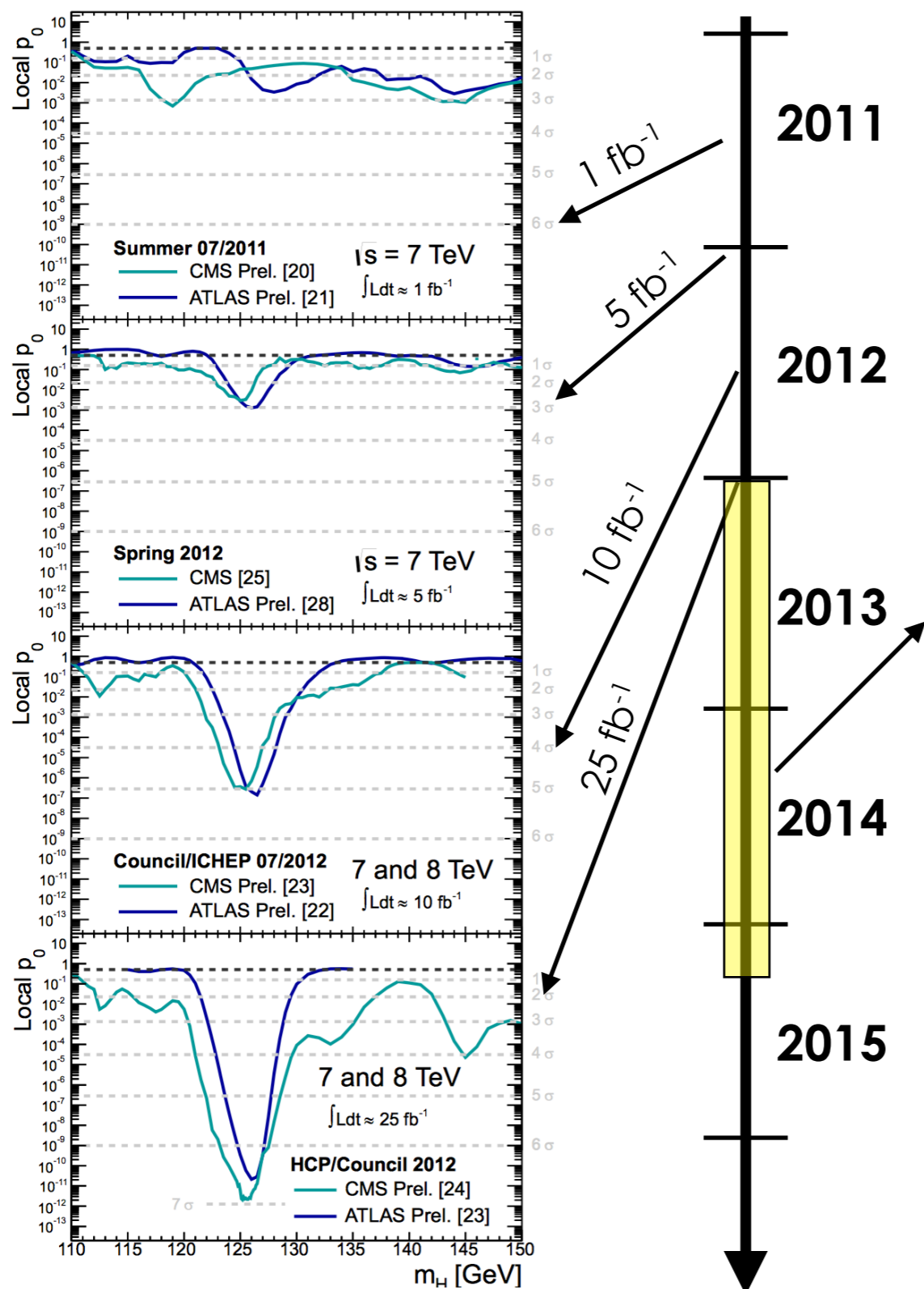


THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

No direct sign of new physics... yet

RUN I: THE BIRTH OF THE HIGGS PHYSICS

From a text-book discovery to the start of the precision Higgs physics with full Run I statistics:



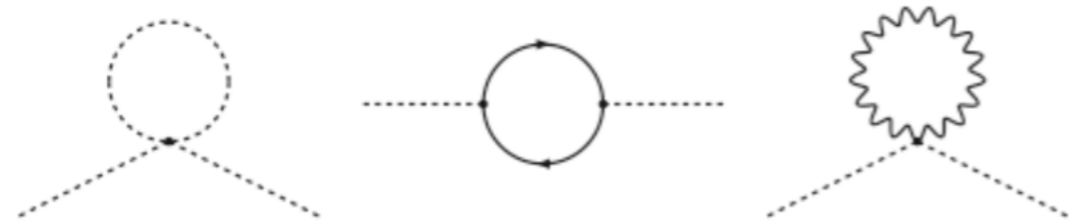
THE “STANDARD THEORY”

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^- - \frac{1}{2}\alpha_h [H^4 + (\phi^0)^4 - 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}\frac{M}{g} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+)) - igs_w A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 \frac{s_w^2}{c_w} (W_\mu^+ W_\mu^- + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu (\phi^+ \phi^- + W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{1}{2}g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{d}_j^\lambda (\gamma^\partial + \eta_e^\lambda) A_\mu^\lambda \bar{d}_j^\lambda (\gamma^\partial + \eta_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\partial + m_d^\lambda) d_j^\lambda + \\
 & igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \frac{1}{3}Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 + \gamma^5) u_j^\lambda)]] + \frac{ig}{2\sqrt{2}} M [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + \\
 & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Self consistent up to large scales [JHEP 1208 (2012) 098]

EWSB: THE NATURALNESS PUZZLE

Higgs potential is renormalizable, however loop corrections to the Higgs boson mass quadratically divergent



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

Not an issue if cut-off Λ not far from TeV, instead if SM \rightarrow Planck scale fine-tuning

Elegant Solutions (some including dark matter candidates):

- **Additional symmetries:** supersymmetry
- **Composite Higgs,** Higgs as a “ π^0 ” of a new strong interaction
- **Extra-dimensions,** “move the Planck scale”
- **New ideas:** arXiv:1504.07551

Or:

- **Deal with it,** anthropic principle/multiverse

SUPERSYMMETRY SEARCHES

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

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

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	\tilde{q}, \tilde{g} 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	\tilde{q} 850 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1405.7875
	$\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	\tilde{q} 250 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$	1411.1559
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	\tilde{g} 1.33 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20	\tilde{g} 1.2 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20	\tilde{g} 1.32 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	\tilde{g} 1.6 TeV	$\tan\beta > 20$	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g} 1.28 TeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	\tilde{g} 619 GeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	\tilde{g} 900 GeV	$m(\tilde{\chi}_1^0) > 220 \text{ GeV}$	1211.1167
GGM (higgsino NLSP)	2 $e, \mu (Z)$	0-3 jets	Yes	5.8	\tilde{g} 690 GeV	$m(\text{NLSP}) > 200 \text{ GeV}$	ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	20.3	\tilde{g} 865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$	1502.01518	
3 rd gen. \tilde{g} med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	\tilde{g} 1.25 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1407.0600
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	\tilde{g} 1.1 TeV	$m(\tilde{\chi}_1^0) < 350 \text{ GeV}$	1308.1841
	$\tilde{g} \rightarrow t\tilde{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.34 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1407.0600
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.3 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1407.0600
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	20.1	\tilde{b}_1 100-620 GeV	$m(\tilde{\chi}_1^0) < 90 \text{ GeV}$	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{b}_1 275-440 GeV	$m(\tilde{\chi}_1^\pm)=2 m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	\tilde{t}_1 110-167 GeV 230-460 GeV	$m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1 90-191 GeV 215-530 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	1-2 b	Yes	20	\tilde{t}_1 210-640 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	1407.0583, 1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	\tilde{t}_1 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0) < 85 \text{ GeV}$	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu (Z)$	1 b	Yes	20.3	\tilde{t}_1 150-580 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu (Z)$	1 b	Yes	20.3	\tilde{t}_2 290-600 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1403.5222
EW direct	$\tilde{\ell}_{LR}\tilde{\ell}_{LR}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\ell}\nu(\ell\bar{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^-))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\tau}\nu(\tau\bar{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^-))$	1407.0350
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\ell\bar{\nu}), \ell\tilde{\nu}\tilde{\ell}_L(\ell\bar{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^-))$	1402.7029
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$	1403.5294, 1402.7029
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_2^0, \tilde{\chi}_3^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^+)-m(\tilde{\chi}_1^-)=160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)=0.2 \text{ ns}$
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g} 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
Stable \tilde{g} R-hadron		trk	-	-	19.1	\tilde{g} 1.27 TeV	-	1411.6795
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	$10 < \tan\beta < 50$	1411.6795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	$2 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{ SPS8 model}$	1409.5542
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\mu$ (RPV)		1 μ , displ. vtx	-	-	20.3	\tilde{q} 1.0 TeV	$1.5 < c\tau < 156 \text{ mm}, \text{ BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$	ATLAS-CONF-2013-092
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda'_{311}=0.10, \lambda_{132}=0.05$	1212.1272
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda'_{311}=0.10, \lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g} 1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LS} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{121} \neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g} \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	\tilde{g} 916 GeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{b})=\text{BR}(\tilde{c})=0\%$	ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g} 850 GeV	-	1404.2500	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c} 490 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1501.01325

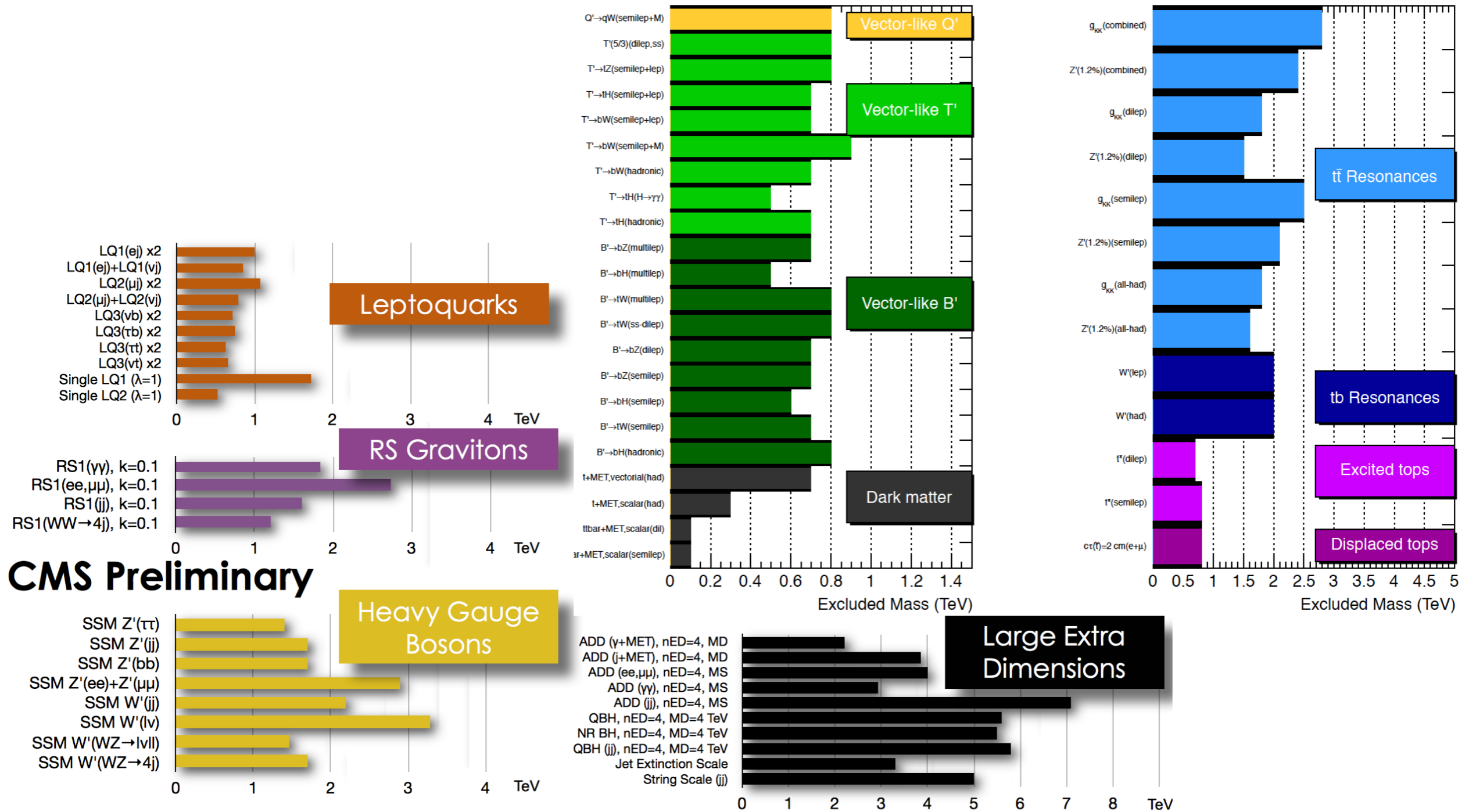
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



EXOTICS SEARCHES

CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)



CMS Preliminary

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

Complementary directions to look for BSM physics in Higgs sector

Precision

mass
scalar couplings
spin/CP
differential cross sections
off shell couplings/width

Rare/new H decays

$Z\gamma, \gamma\gamma^*$
 $\mu\mu$
 $J/\Psi\gamma$
lepton flavour violation

H



Extended Higgs sector

2HDM
MSSM, NMSSM
double charged Higgs

H as a tool for discovery

portal to DM: invisible Higgs decays
portal to hidden sectors
portal to BSM physics: decays to HH, WH,
ZH, tH, ...
FCNC: $t \rightarrow cH$

Complementary directions to look for BSM physics in Higgs sector

Precision

mass
scalar couplings
spin/CP
differential cross sections
off shell couplings/width

Rare/new H decays

$Z\gamma, \gamma\gamma^*$
 $\mu\mu$
 $J/\Psi\gamma$
lepton flavour violation

H

Extended Higgs sector

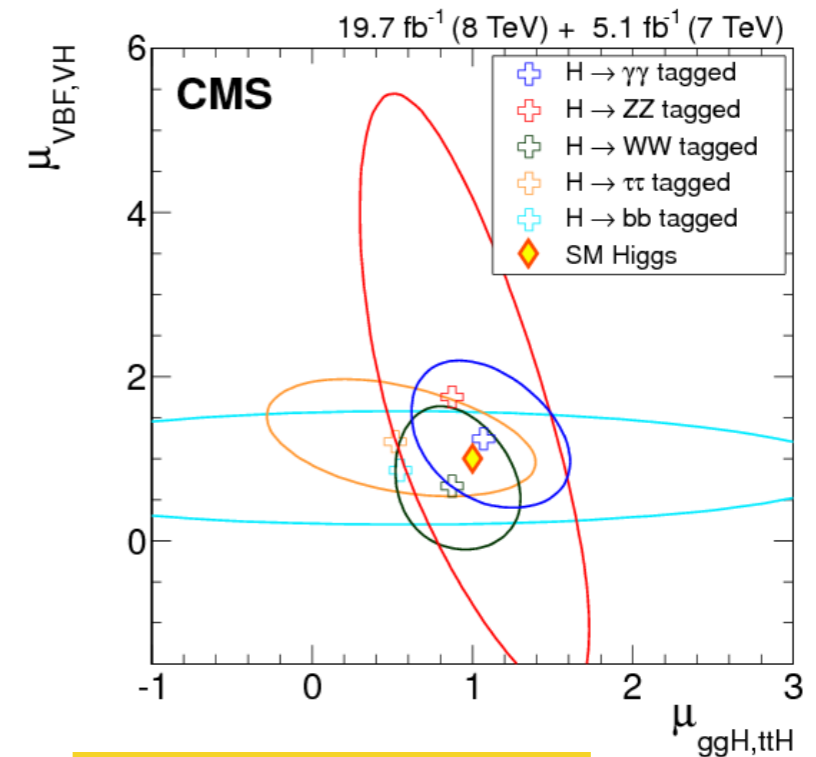
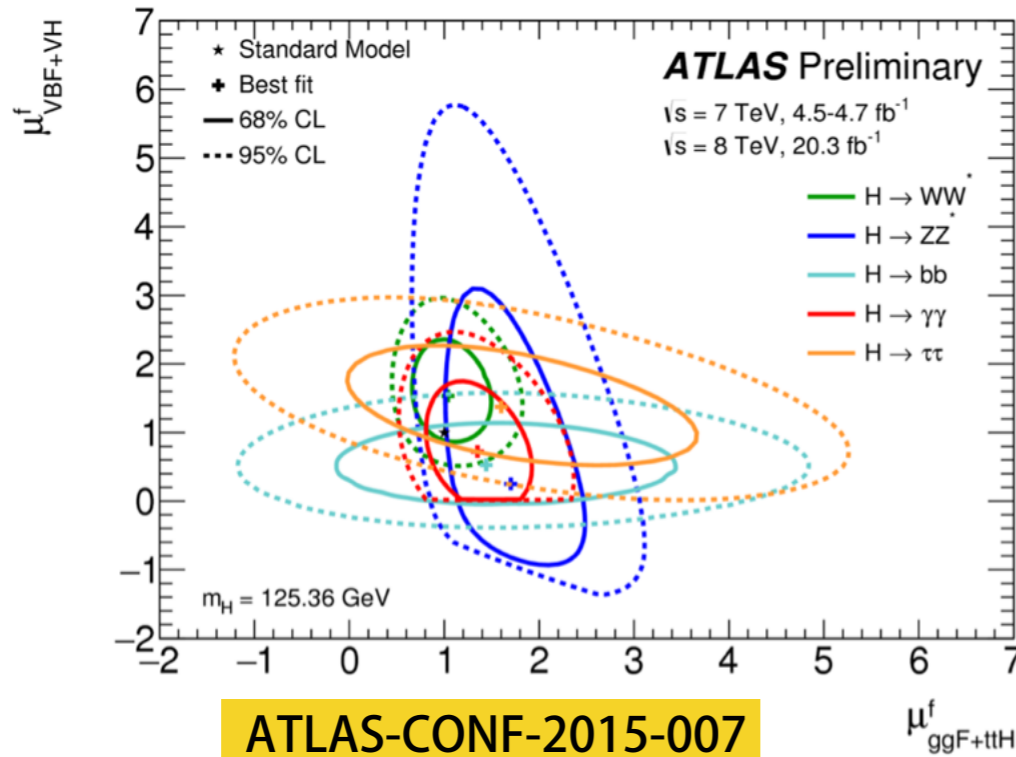
2HDM
MSSM, NMSSM
double charged Higgs

H as a tool for discovery

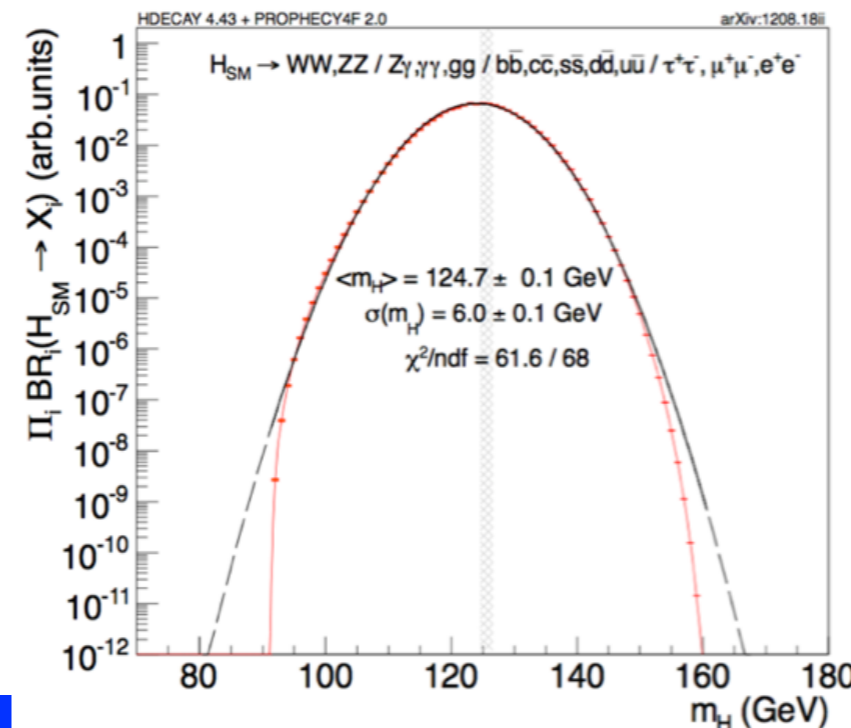
portal to DM: invisible Higgs decays
portal to hidden sectors
portal to BSM physics: decays to HH, WH,
ZH, tH, ...
FCNC: $t \rightarrow cH$

THE HIGGS PICTURE FROM RUN I

$$\mu \equiv \sigma \cdot \text{Br} / (\sigma \cdot \text{Br})_{\text{SM}}$$



Nature was very kind with us
 product of BR \sim max @ 125 GeV



PRECISION: COUPLINGS DEVIATIONS

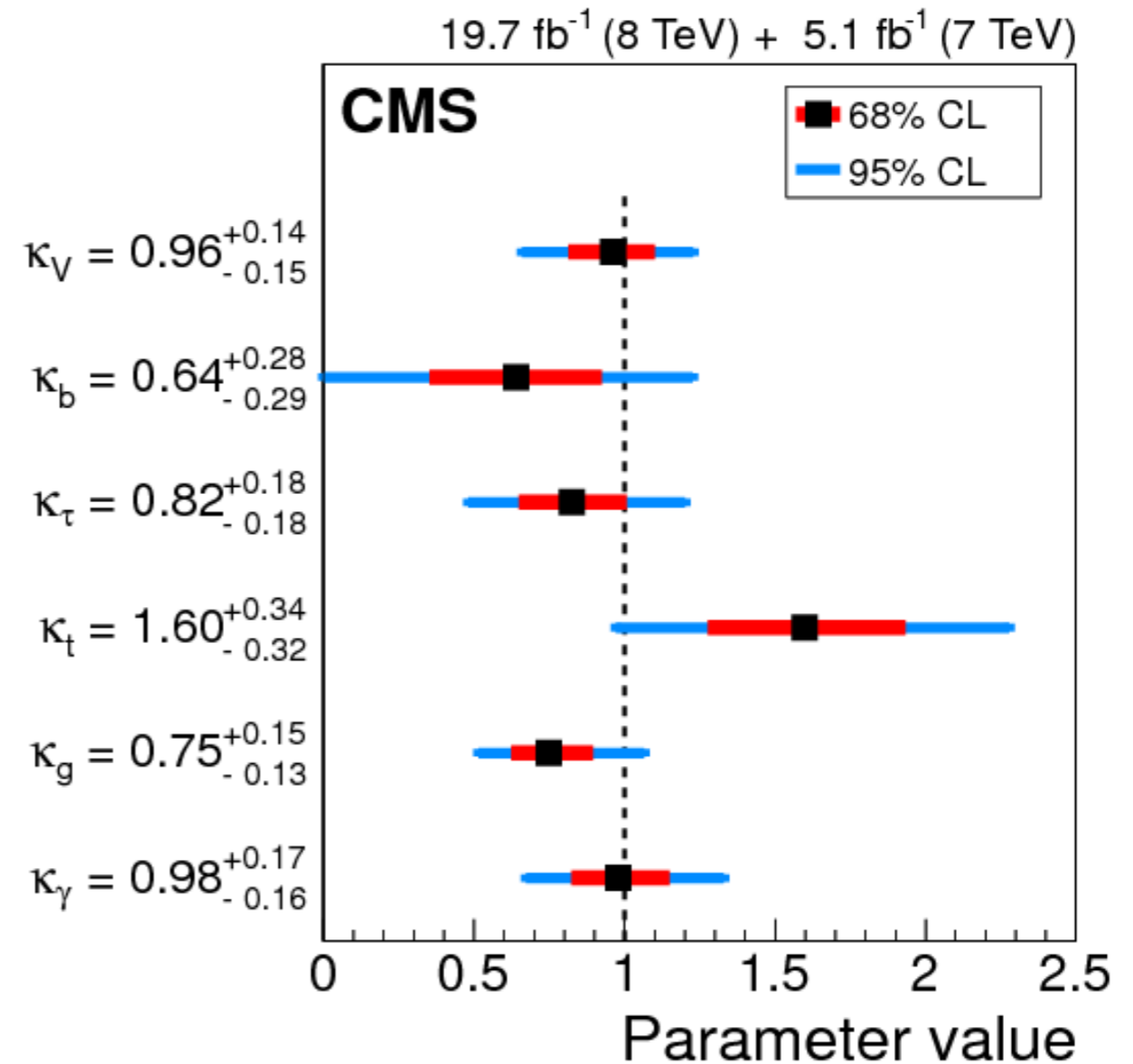
Looking for Higgs couplings deviations:
use an “effective approach”

- parametrize deviation from SM with coupling modifiers, “kappa”, $k_x^{SM}=1$
 - ▶ tensor structure kept as SM
 - ▶ ok for Run1 precision

e.g. signal strength in $H \rightarrow \gamma\gamma$:

	$H \rightarrow \gamma\gamma$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
$t\bar{t}H$	$\frac{\kappa_t^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
VBF	$\frac{\kappa_{VBF}^2 (\kappa_Z, \kappa_W) \cdot \kappa_\gamma^2}{\kappa_H^2}$
WH	$\frac{\kappa_W^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
ZH	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

LHC Run I probe Higgs couplings
@ 15-30% level



Still large room for BSM

“CLASSIC” HIGGS BSM SCENARIOS

Extended Higgs sector: E.g. 2HDM/MSSM, EWSB via 2 Higgs doublets.

Direct searches: look for additional scalars (neutral or charged), if SUSY direct searches for SUSY partners

Indirect searches: b-physics ($B \rightarrow \tau \nu$, $B \rightarrow D^{(*)} \tau \nu$, $b \rightarrow s \gamma$, $B_s \rightarrow \mu \mu$), H(125) couplings

Composite Higgs: Higgs as pseudo Goldstone boson of a new strong interaction

Direct searches: new vector resonances, new “light” fermion partner states

Indirect searches: stringent constraints from EWPT, H(125) couplings (controlled by $\xi = (v/f)^2$ compositeness parameter)

INTERPRETATION EXAMPLE: 2HDM

Effective theory with 2 complex scalar doublets

▶ 5 physical scalar fields after EWSB

- ➔ neutral: h, H CP even, A CP odd
- ➔ charged: H^\pm

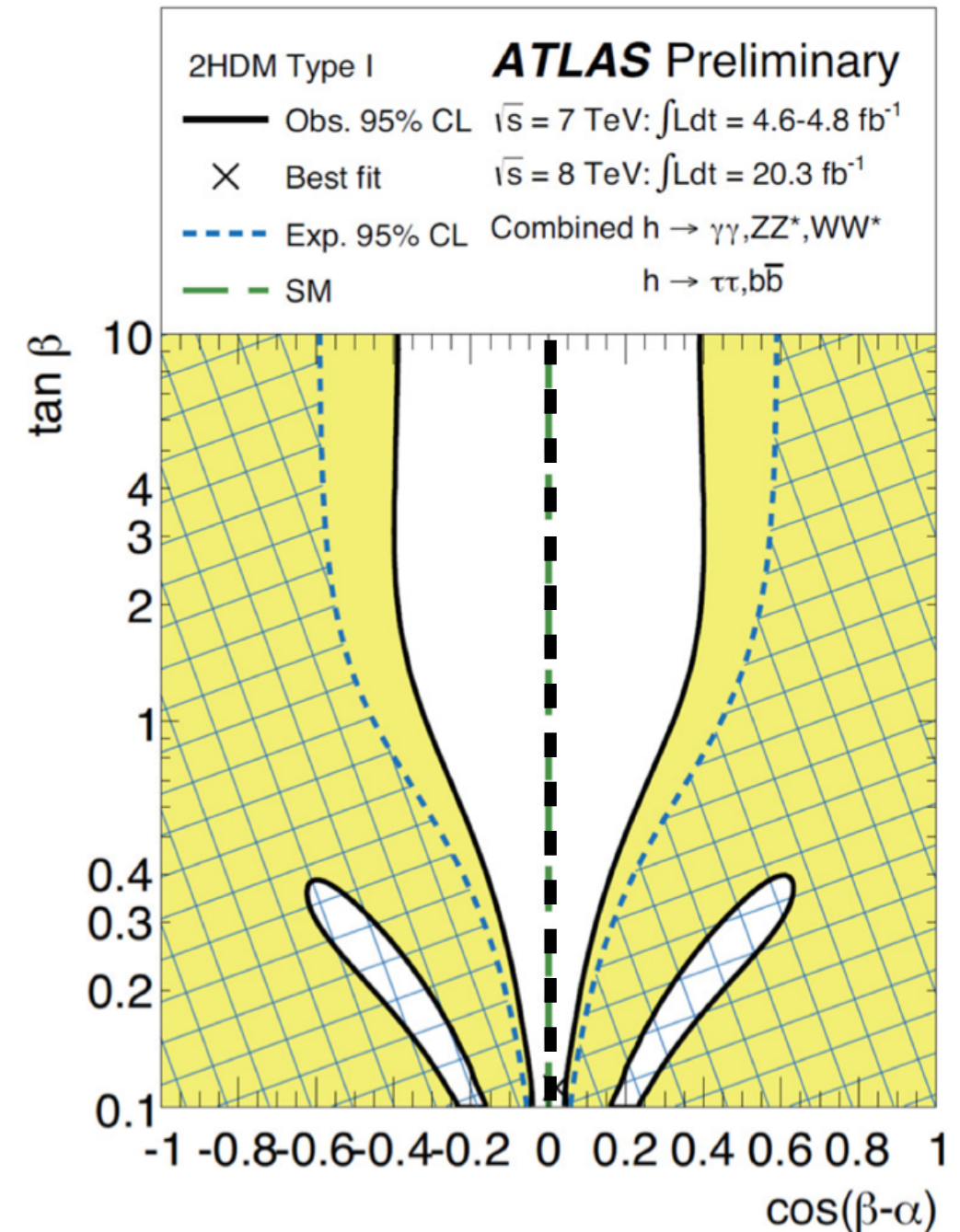
Couplings described by 2 mixing angles

- ▶ $\tan\beta = v_1/v_2$, α mixing angle h/H

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = (g_{hVV}^{\text{SM}})^2$$

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$
κ_d	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$
κ_l	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$

ATLAS-CONF-2014-010



Decoupling region: Higgs very close to SM or $m_{A,H} \gg m_h$ not probed given current precision

INTERPRETATION EXAMPLE: MSSM

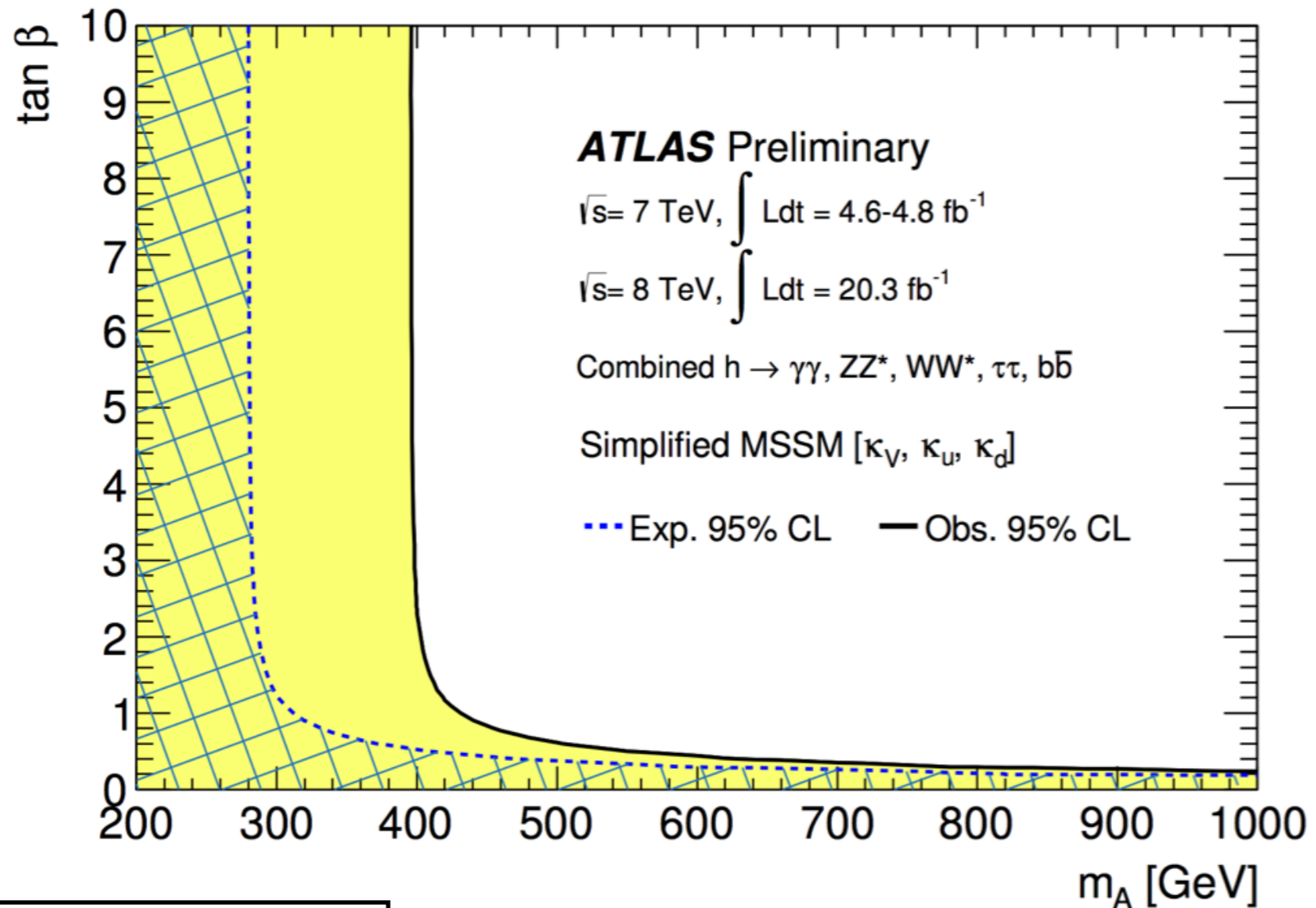
MSSM: a particular 2HDM Type II model

Simplified MSSM: m_h used to parametrise radiative corrections

Djouadi et al. [arXiv:1305.2172](https://arxiv.org/abs/1305.2172)

At low $\tan\beta$ implies a very large M_s SUSY scale

ATLAS-CONF-2014-010



$$\kappa_V = \frac{s_d(m_A, \tan\beta) + \tan\beta s_u(m_A, \tan\beta)}{\sqrt{1 + \tan^2\beta}}$$

$$\kappa_U = s_u(m_A, \tan\beta) \frac{\sqrt{1 + \tan^2\beta}}{\tan\beta}$$

$$\kappa_D = s_d(m_A, \tan\beta) \sqrt{1 + \tan^2\beta},$$

$$s_u = \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2\beta}{(m_Z^2 + m_A^2 \tan^2\beta - m_h^2(1 + \tan^2\beta))^2}}}$$

$$s_d = \frac{(m_A^2 + m_Z^2) \tan\beta}{m_Z^2 + m_A^2 \tan^2\beta - m_h^2(1 + \tan^2\beta)} s_u.$$

$m_A > \sim 400$ GeV

INTERPRETATION EXAMPLE: COMPOSITE HIGGS

MCHM: $SO(5)/SO(4)$ symmetry breaking

Coupling k_V “universally” modified, proportional to $\xi = v^2/f^2$

Coupling k_F depends on the actual model implementation

[arXiv:hep-ph/0412089](https://arxiv.org/abs/hep-ph/0412089)

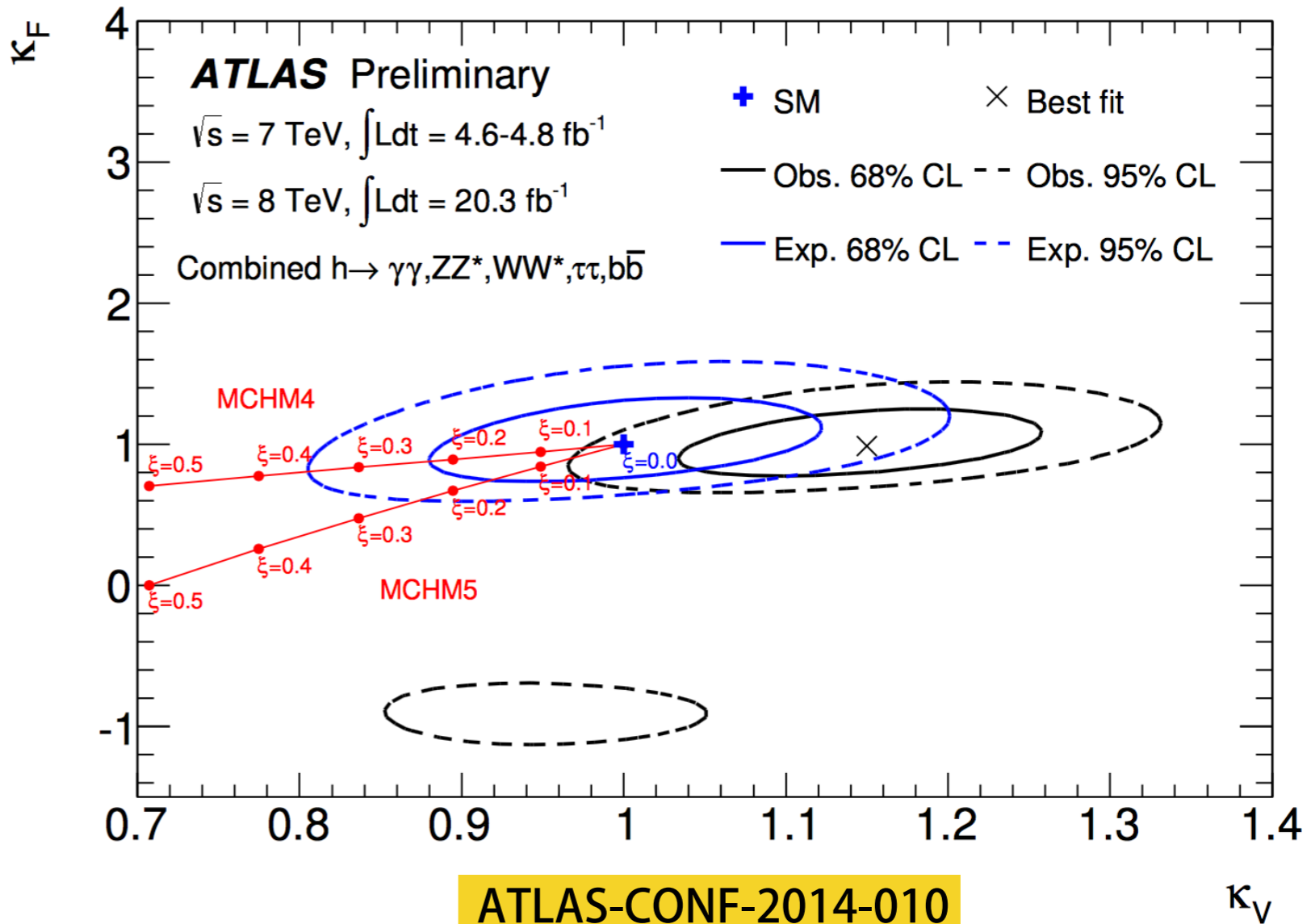
MCHM4

$$K = K_V = K_F = \sqrt{1 - \xi}$$

MCHM5

$$K_V = \sqrt{1 - \xi}$$

$$K_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$



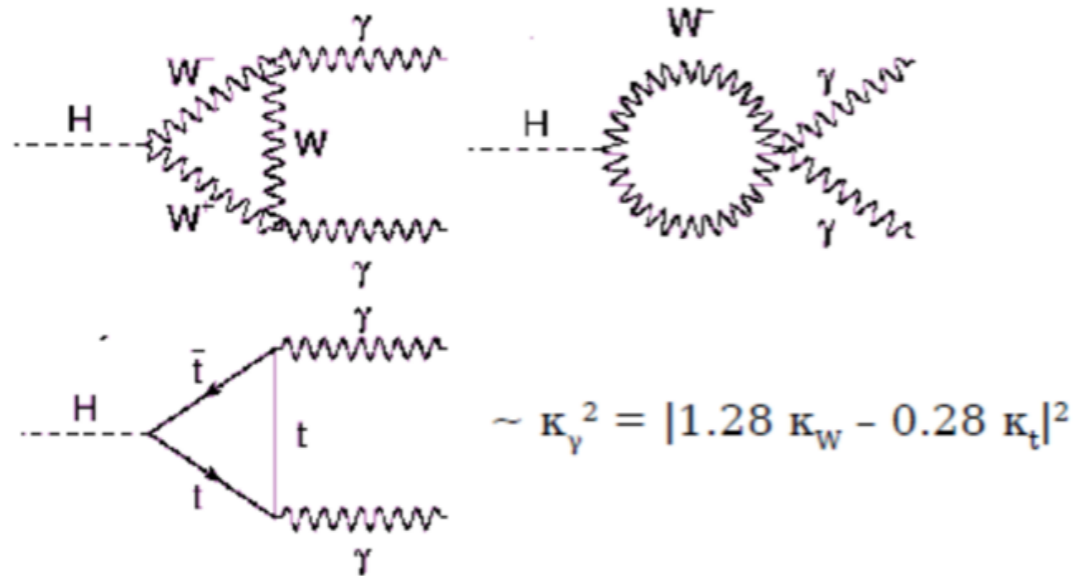
$f > \sim 1 \text{ TeV}$

PROBING k_V/k_F RELATIVE PHASE

Reversed phase for fermion coupling
 $K_f = -1$ disfavoured by k_V/k_F couplings fit

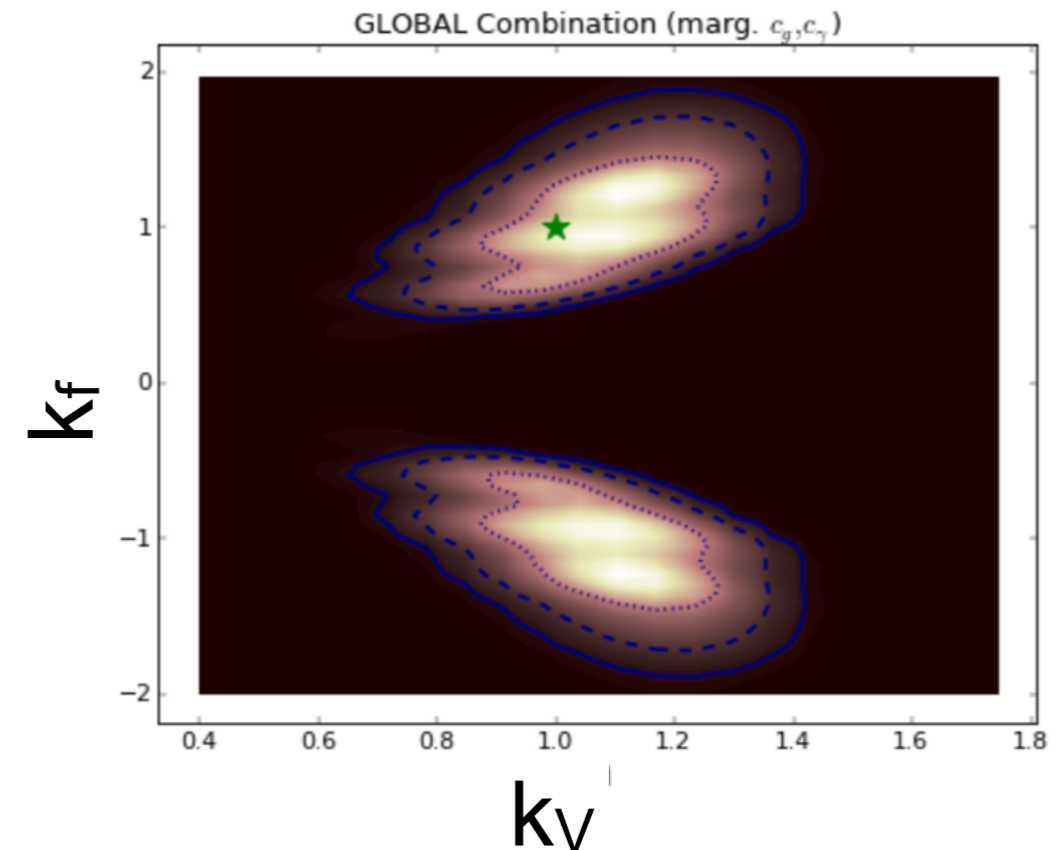
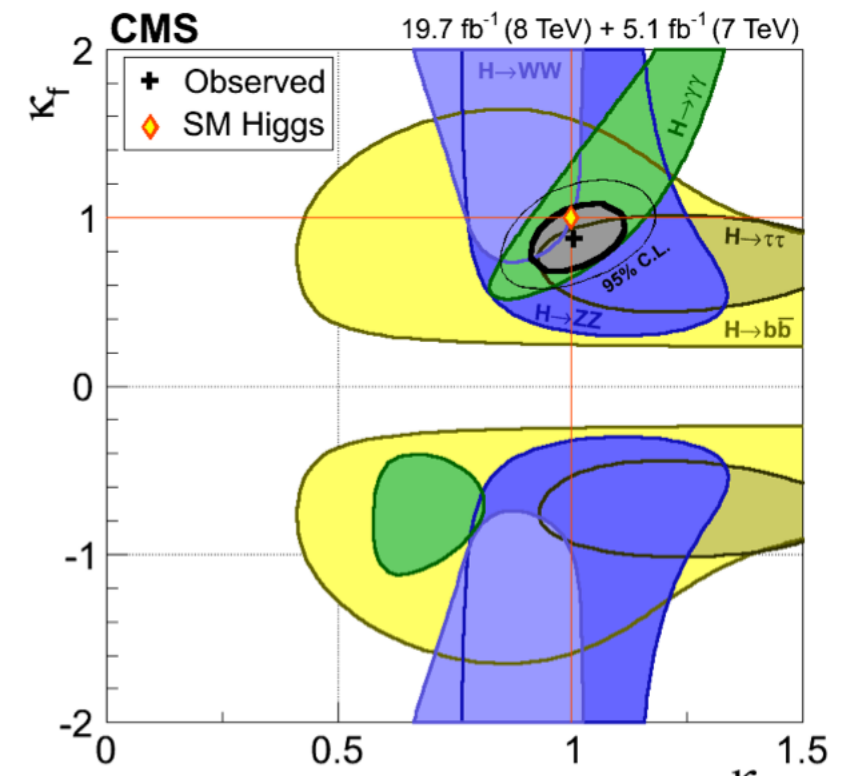
Most channels constraints independent from relative phase

Degeneracy broken by $H \rightarrow \gamma\gamma$: BR enhanced if phase is reversed



However, when assuming BSM contributions in k_g & $k_{\gamma\gamma}$, still degeneracy in k_V/k_f plane

[J.Ellis, T.You, JHEP 06 (2013) 103]



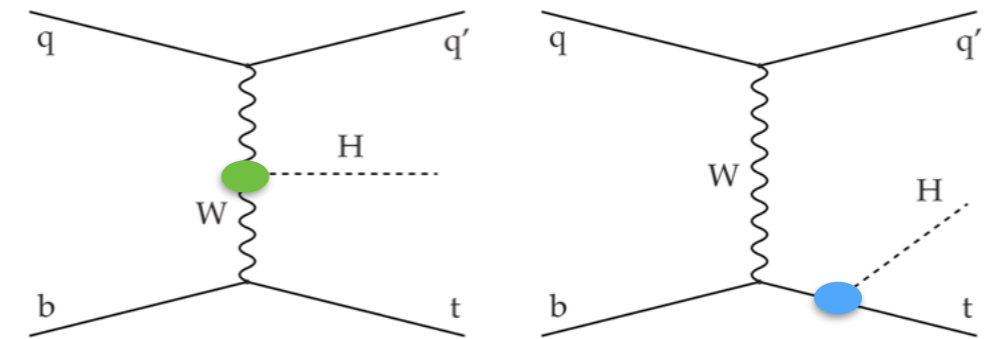
A BETTER INTERFEROMETER: T+H

t+H: SM tree level cancellation

$\sigma(t+H) = 18 \text{ fb}$ @ 8 TeV ($\sigma \sim 1/10$ of ttH)

x15 σ if Y_t relative sign reversed wrt SM

t+H: first proposed by Biwas, Mele, Gabrielli as a probe for Htt sign [JHEP 01 (2013) 088]



Strong involvement of CMS Rome group

Analysis testing $k_t = -1$ hypothesis, assuming rest of SM still valid

not realistic, but allows easy interpretation
test also other BSM models where t+H enhanced

Combination to be published soon: sensitivity to exclude $\sim x 2 \sigma(k_t = -1)$

Potential to exclude $k_t = -1$ with $< 20 \text{ fb}^{-1}$ @ 13 TeV

95% CL exclusion limits on $\sigma/\sigma(k_t = -1)$

CMS HIG-14-001 t+H($\rightarrow \gamma\gamma$)	Obs 4.1 (Exp 4.1)
CMS HIG-14-015 t+H($\rightarrow bb$)	Obs 7.6 (Exp 5.2)
CMS HIG-14-026 t+H(WW, $\tau\tau$)	Obs 6.7 (Exp 5.0)

H $\rightarrow \gamma\gamma$ final state most sensitive thanks to BR enhancement

Complementary directions to look for BSM physics in Higgs sector

Precision

mass
scalar couplings
spin/CP
differential cross sections
off shell couplings/width

Extended Higgs sector

2HDM
MSSM, NMSSM
double charged Higgs

H

Rare/new H decays

$Z\gamma, \gamma\gamma^*$
 $\mu\mu$
 $J/\Psi\gamma$
lepton flavour violation

H as a tool for discovery

portal to DM: invisible Higgs decays
portal to hidden sectors
portal to BSM physics: decays to HH, WH,
ZH, tH, ...
FCNC: $t \rightarrow cH$

$$\Gamma_H = \sum_i \kappa_i^2 \Gamma_i^{\text{SM}}$$

Undetected/invisible Higgs decays indirect constraint at $\sim <30\%$ at 95% CL.

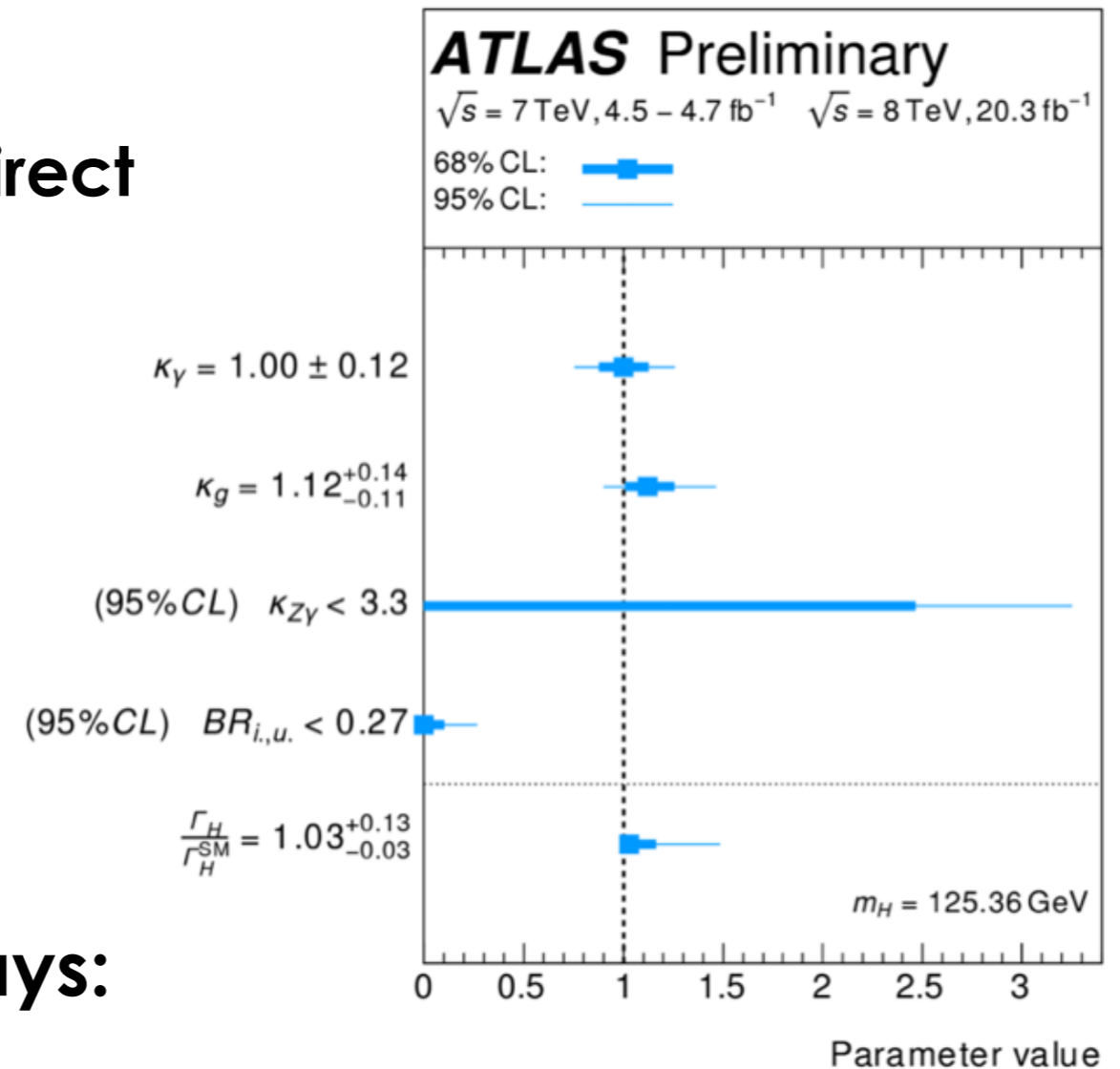
$$\Gamma_H^{\text{SM}} = 4.2 \text{ MeV}$$

total width very small. Even small couplings implies sizeable BRs!

Direct searches for BSM Higgs decays:

- $h \rightarrow \text{Invisible (MET)}, h \rightarrow \gamma + \text{MET}$
- $h \rightarrow \mu\tau$ (lepton flavour violation)
- $h \rightarrow \phi\phi \rightarrow xx yy$
- $h \rightarrow \text{long lived particles}$
- $h \rightarrow \dots$

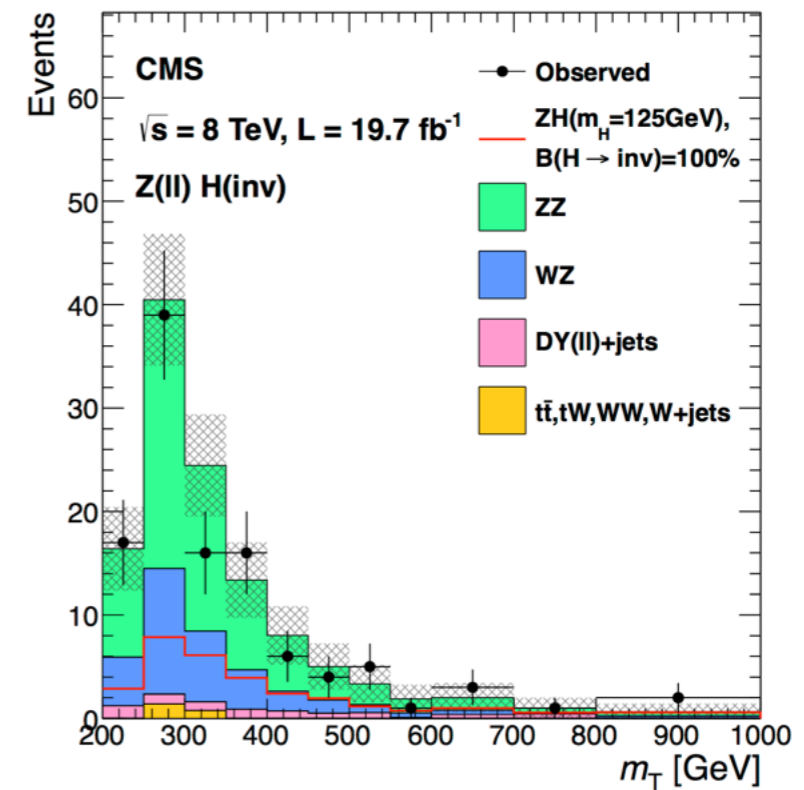
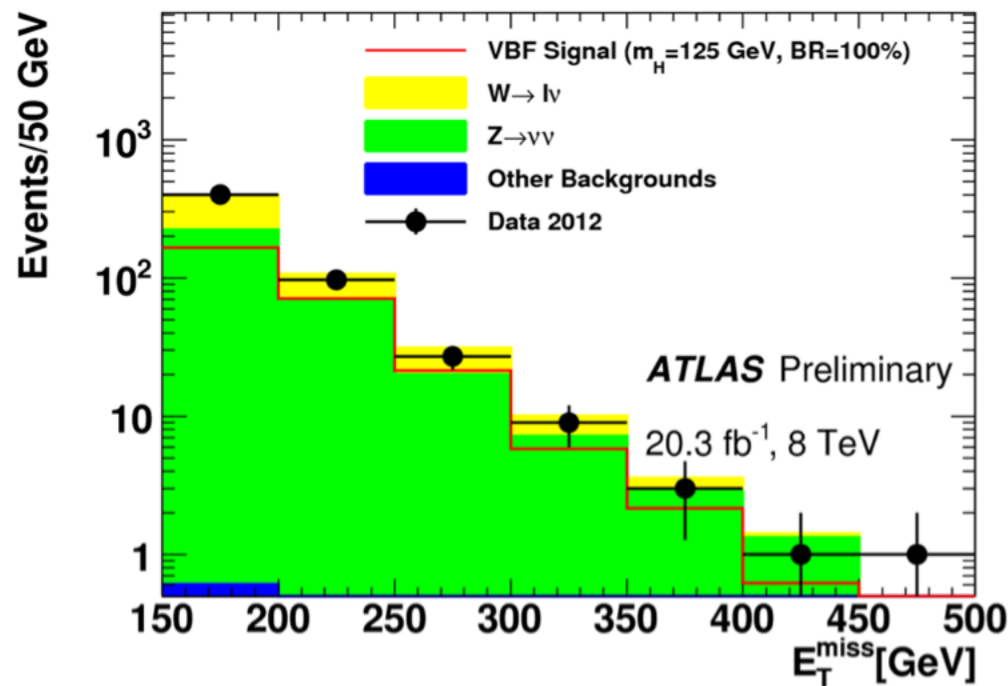
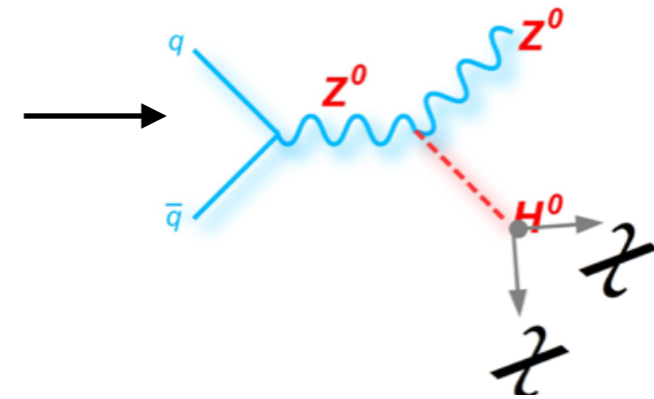
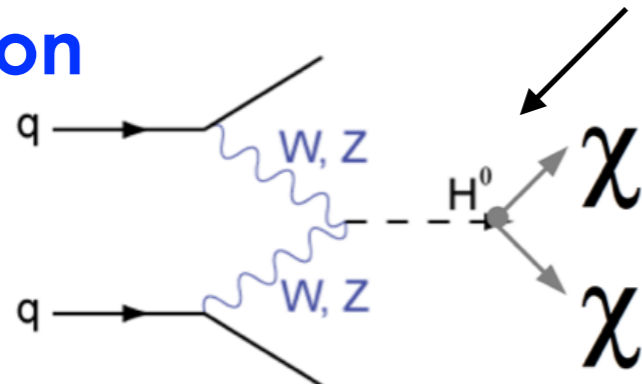
ATLAS-CONF-2015-007



H → INVISIBLE

Direct search for invisible Higgs: interesting in the context of Dark Matter

Exploit associated Vector Boson Fusion and VH production



Most sensitive channel. H(125) BR upper limits:

ATLAS: 29% (exp 35%), CMS: 57% (exp 40%)

H(125) BR upper limits

ATLAS: Z(→ll)+H 75% (exp 62%)

ATLAS: Z(→jj)+H 78% (exp 86%)

CMS: Z(→ll, →bb)+H 81% (exp 83%)

H → INVISIBLE

Complementary search wrt direct dark matter experiments for low mass DM: $m_\chi < m_H/2$

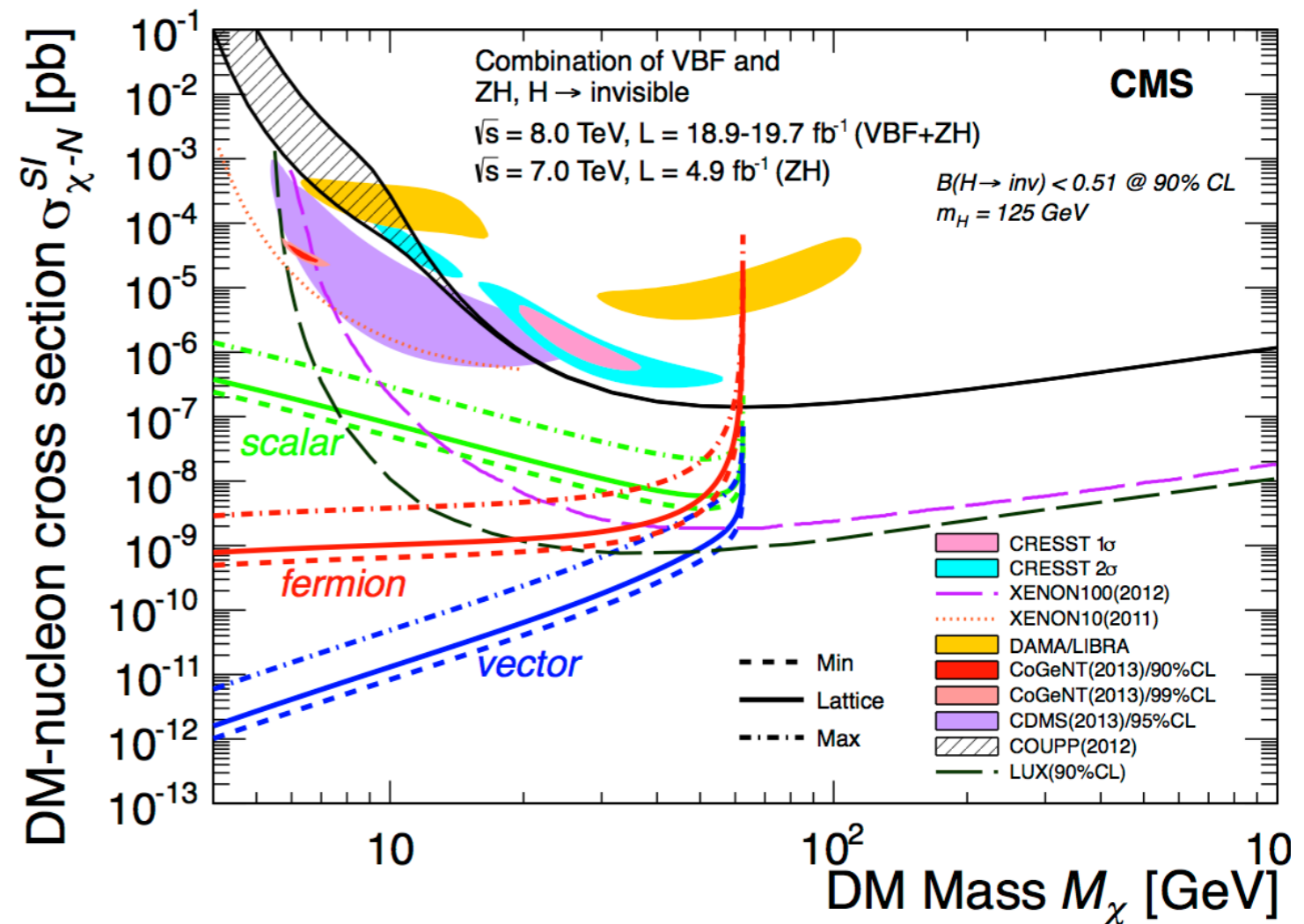
Higgs portal models: direct interactions of Higgs with DM candidate

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

E.g. spin independent nucleon-scalar DM cross section

$$\sigma_{S-N}^{\text{SI}} = \frac{4\Gamma_{\text{inv}}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

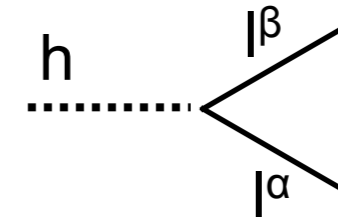
f_N : Higgs-nucleon form factor from lattice QCD



H → μτ: LEPTON FLAVOUR VIOLATION

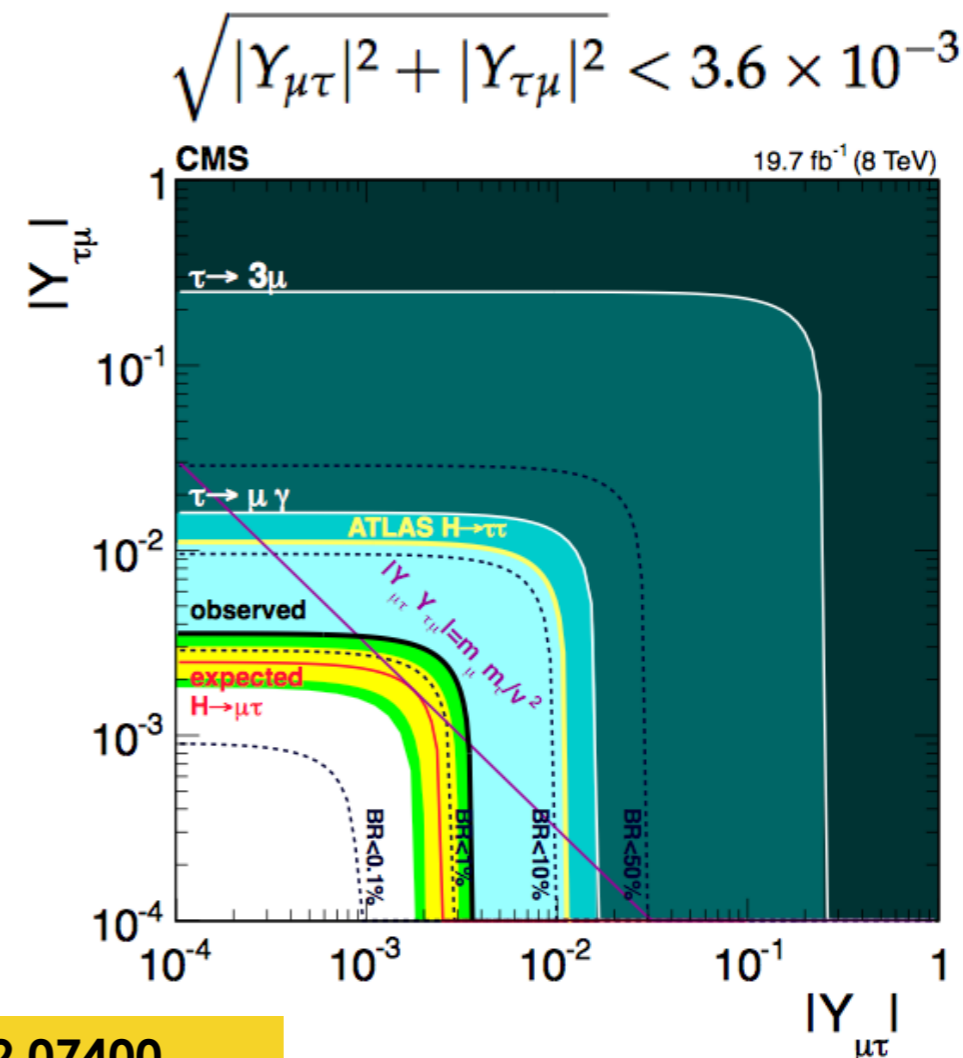
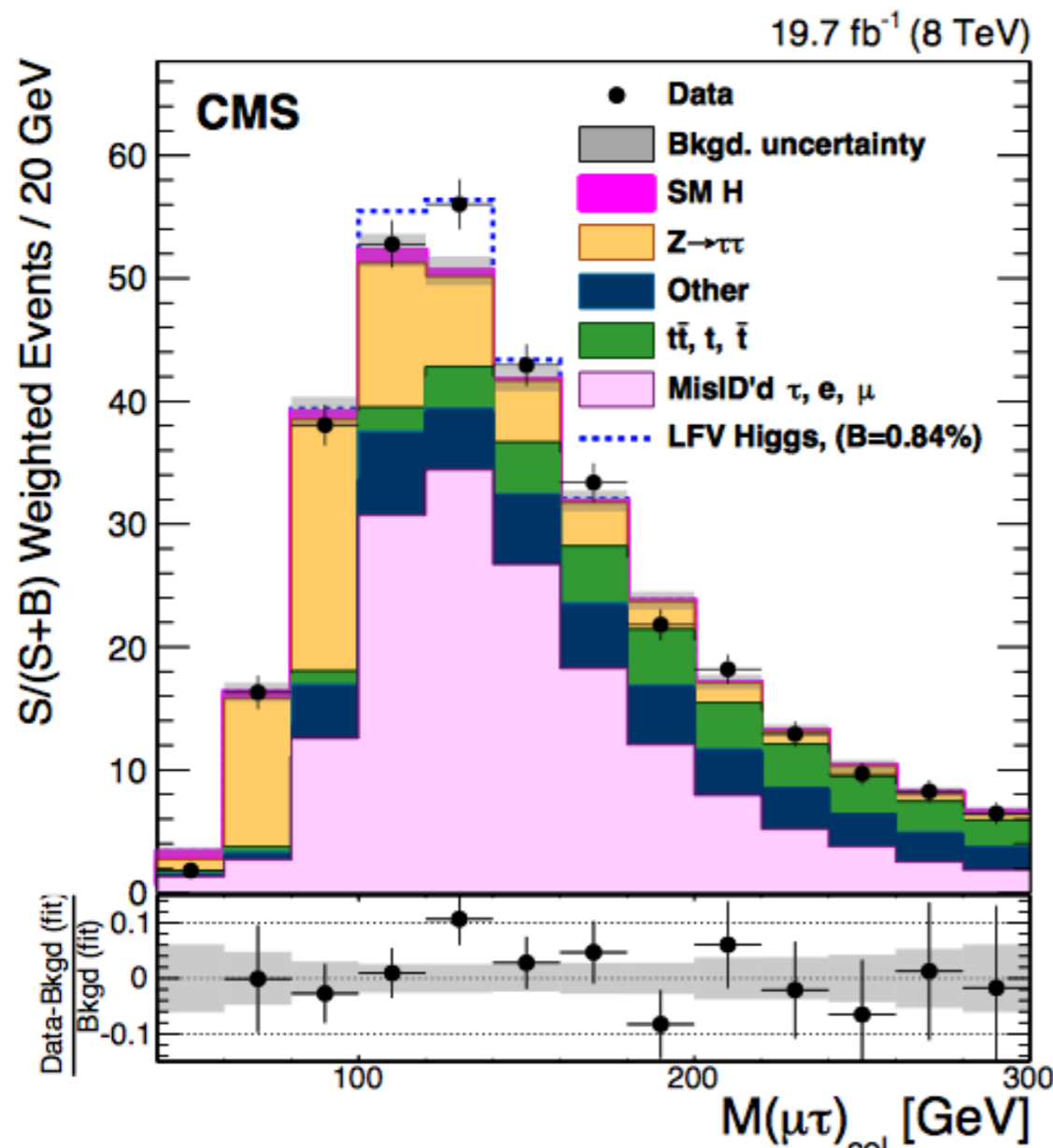
FCNC heavily constrained in the quark sector, but lepton sector less constrained

Indirect limits on BR(H → μτ) from τ rare decays search (τ → 3μ, τ → μγ): ~10%



$$\Gamma(H \rightarrow \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi} (|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2)$$

Direct limit on BR(H → μτ) < 1.57% (2.4σ excess...)



$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$

CMS: arXiv:1502.07400

LIGHT SCALARS: $H \rightarrow \phi\phi$

Search for light scalars mostly motivated in the NMSSM (Next-to Minimal SSM) context

MSSM: μ -problem, higgsino mass parameter μ imposed at EWSB scale

NMSSM: generate μ dynamically, adding a singlet super field S

$$\mu = \lambda \langle S \rangle \quad \text{from: } \lambda \hat{S} \hat{H}_u \hat{H}_d$$

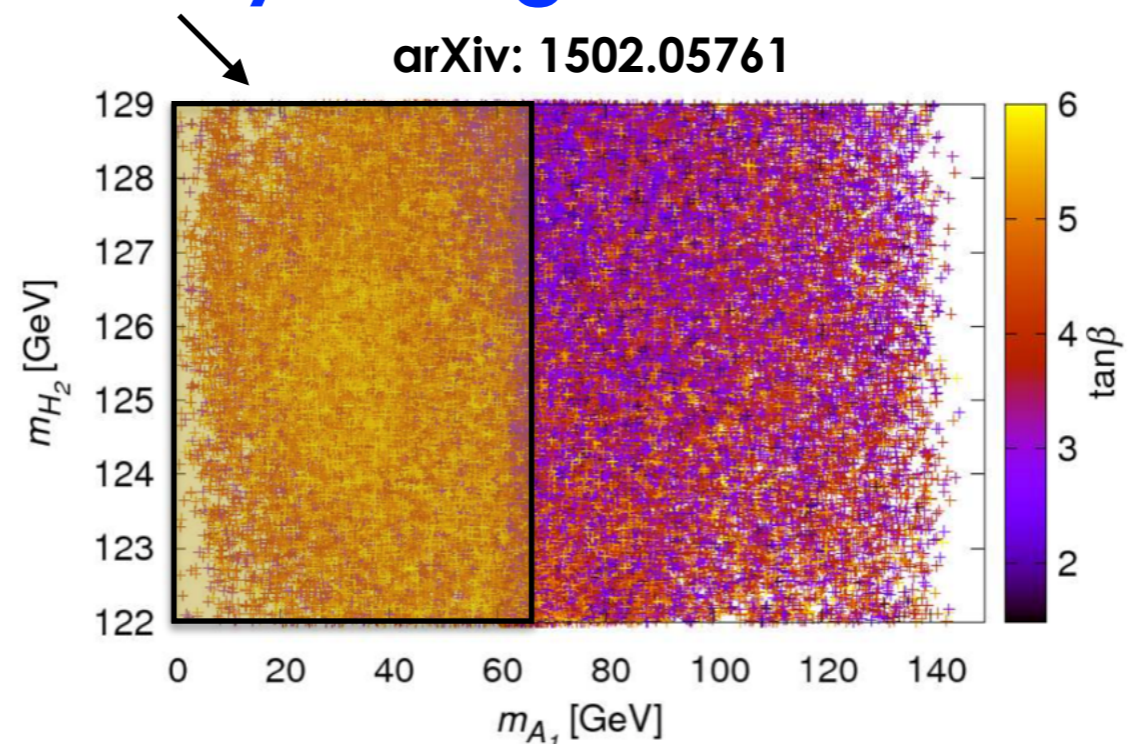
Less fine-tuning than in MSSM

$$\text{MSSM: } m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

$$\text{NMSSM: } m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$$

NMSSM: larger Higgs sector: 3 CP-even H, 2 CP-odd A, 2 charged H^\pm . H(125) not necessarily the lightest scalar

Include constraints from
b-physics, dark matter
relic density, LEP & LHC
Higgs searches



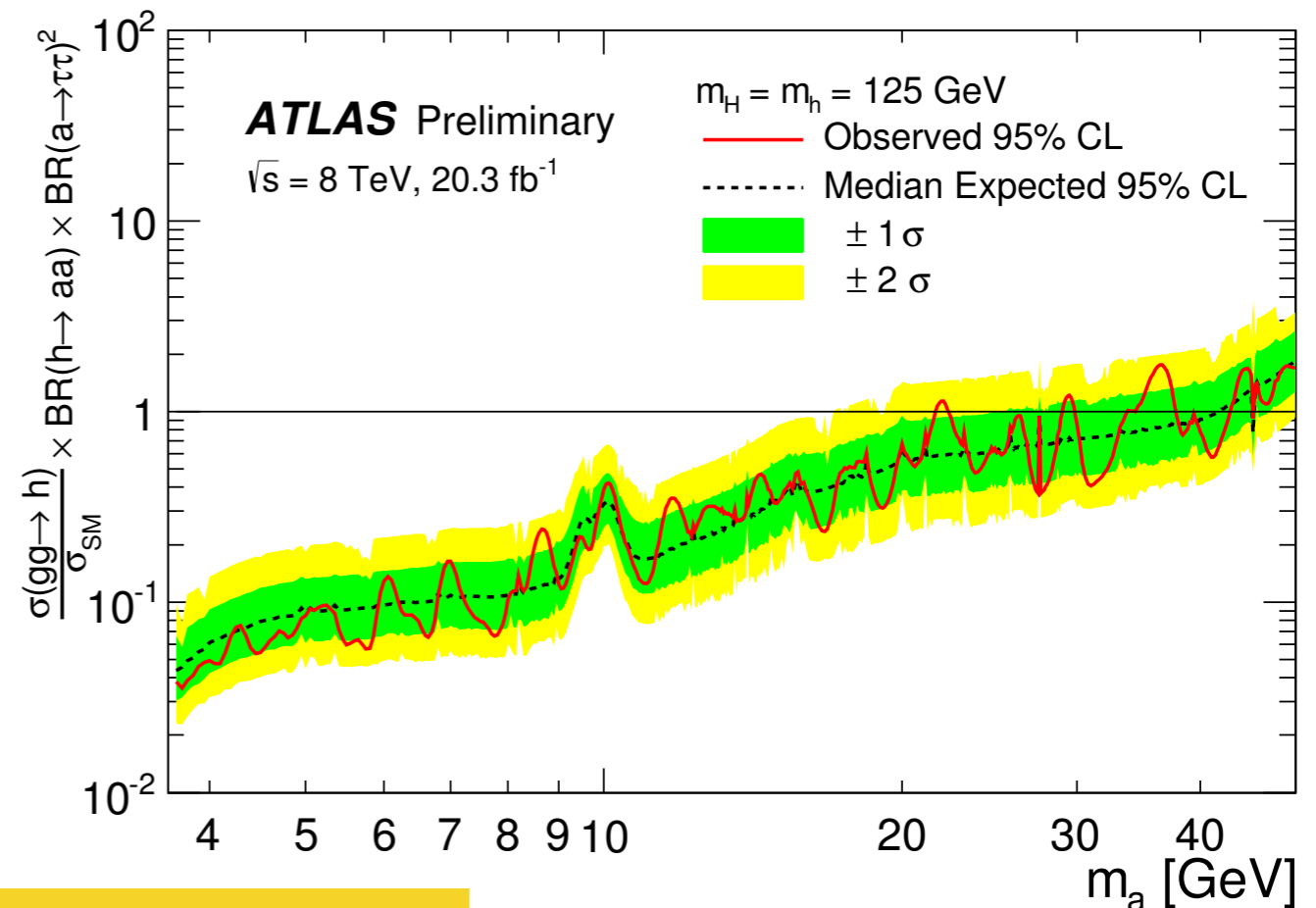
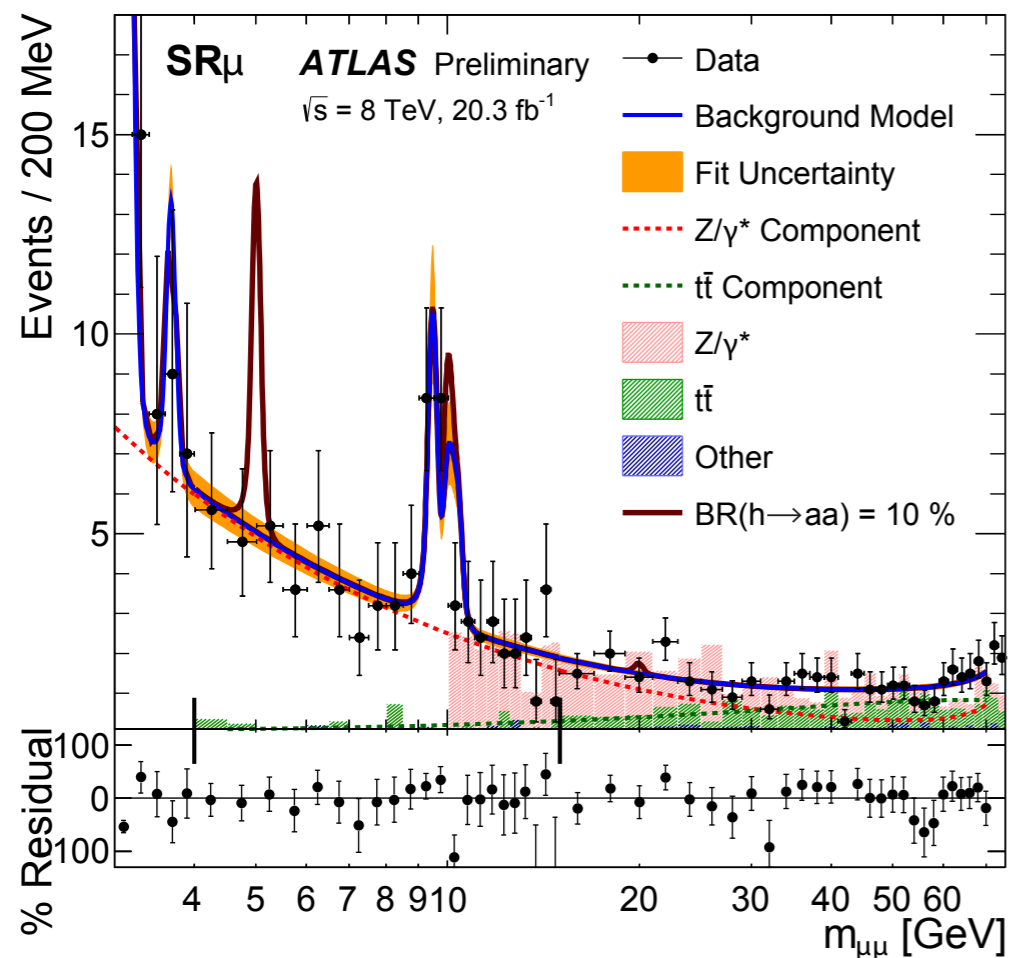
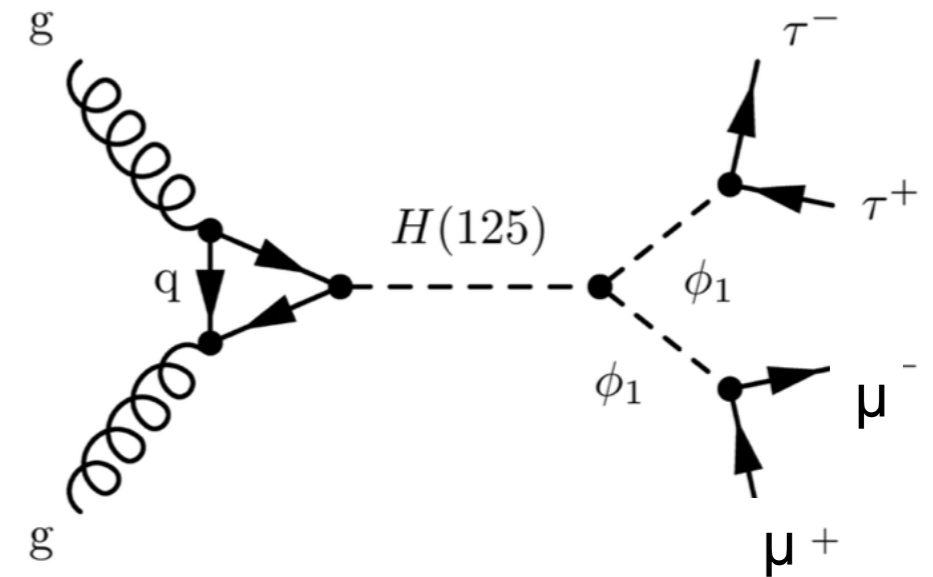
LIGHT SCALARS: $H \rightarrow \phi\phi \rightarrow 2\mu 2\tau$

Searches performed so far:

$H \rightarrow \phi\phi \rightarrow 4\mu, 4\tau, 2\mu 2\tau$

$BR(\phi \rightarrow XX)$ expected to be proportional to m_X^2

$2\mu 2\tau$ good compromise: use clean $m_{\mu\mu}$ as final observable



Complementary directions to look for BSM physics in Higgs sector

Precision

mass
scalar couplings
spin/CP
differential cross sections
off shell couplings/width

Rare/new H decays

$Z\gamma, \gamma\gamma^*$
 $\mu\mu$
 $J/\Psi\gamma$
lepton flavour violation

H



Extended Higgs sector

2HDM
MSSM, NMSSM
double charged Higgs

H as a tool for discovery

portal to DM: invisible Higgs decays
portal to hidden sectors
portal to BSM physics: decays to HH, WH,
ZH, tH, ...
FCNC: $t \rightarrow cH$

HEAVY SCALAR SEARCHES

$$\phi(A/H) \rightarrow \tau\tau$$

$$A \rightarrow Zh$$

$$H^\pm \rightarrow \tau\nu, H^\pm \rightarrow cs, H^\pm \rightarrow tb$$

← MSSM inspired

$$H \rightarrow hh$$

$$H \rightarrow WW, ZZ$$

$$\phi \rightarrow \gamma\gamma, Z\gamma$$

← Mostly performed as
model independent
searches for new scalars

$$H^\pm \rightarrow WZ$$

$$\phi^{++}$$

↙

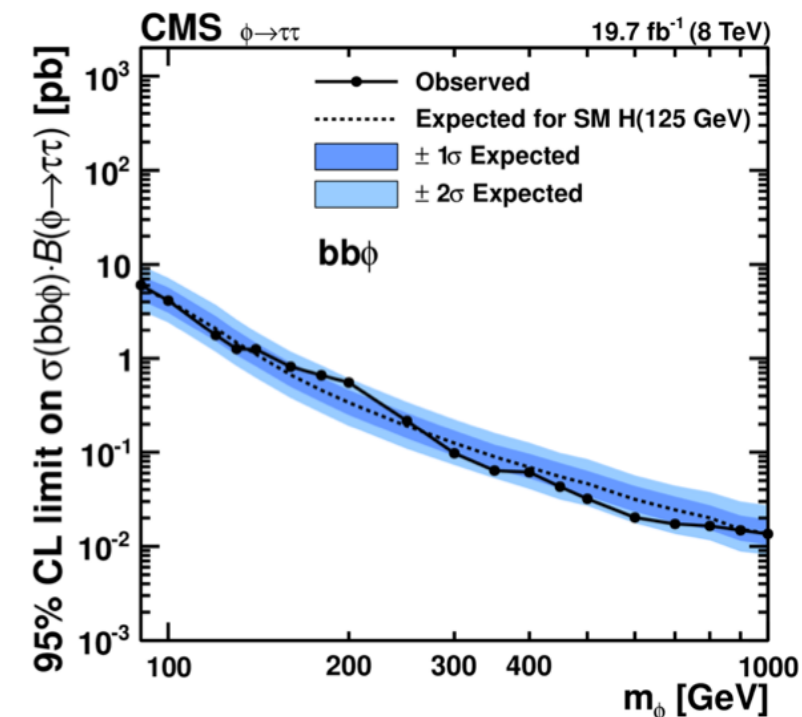
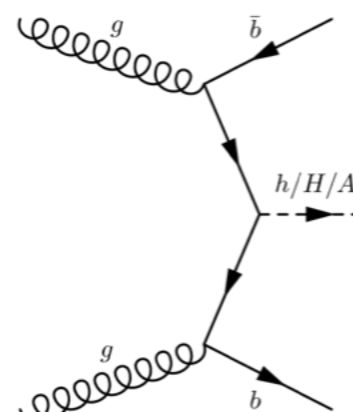
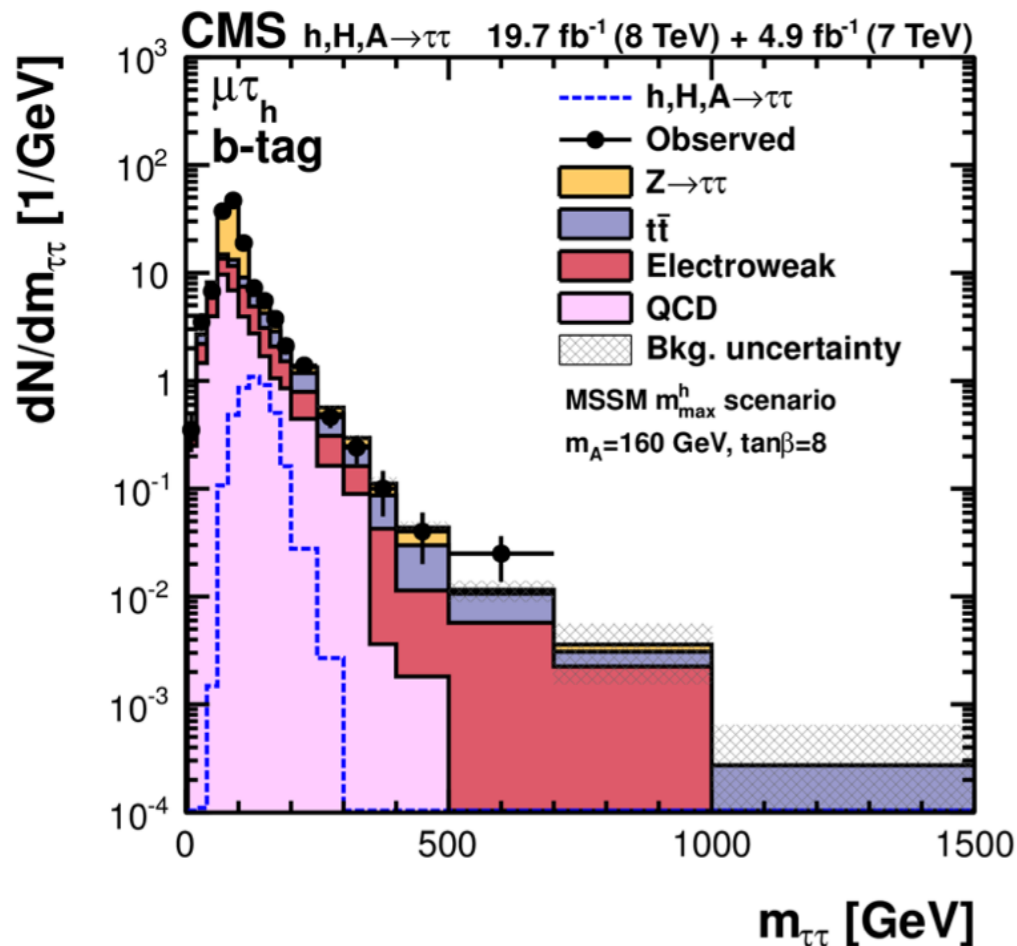
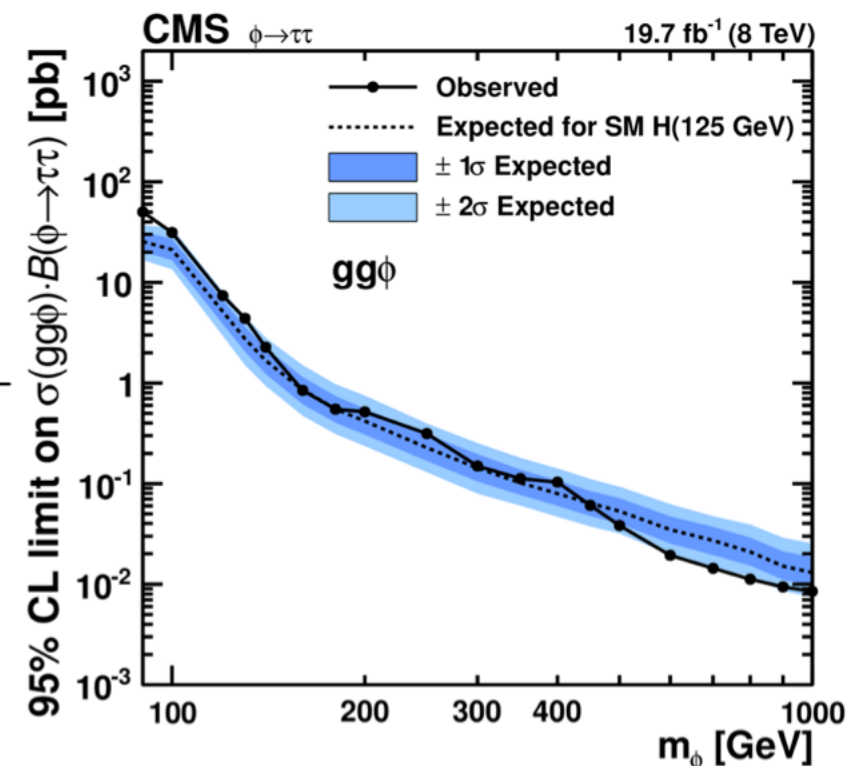
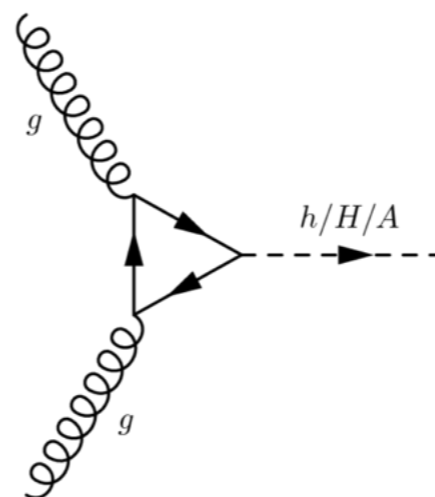
$\phi \rightarrow \tau\tau$

MSSM: large $BR(\phi \rightarrow \tau\tau)$ for $\tan\beta > 5$

Analysis builds up on SM $h \rightarrow \tau\tau$. Bump search in reconstructed $m_{\tau\tau}$

Several final states considered for the τ decay: $\tau_e, \tau_\mu, \tau_{had}$

b-tag categories for $bb\phi$ production

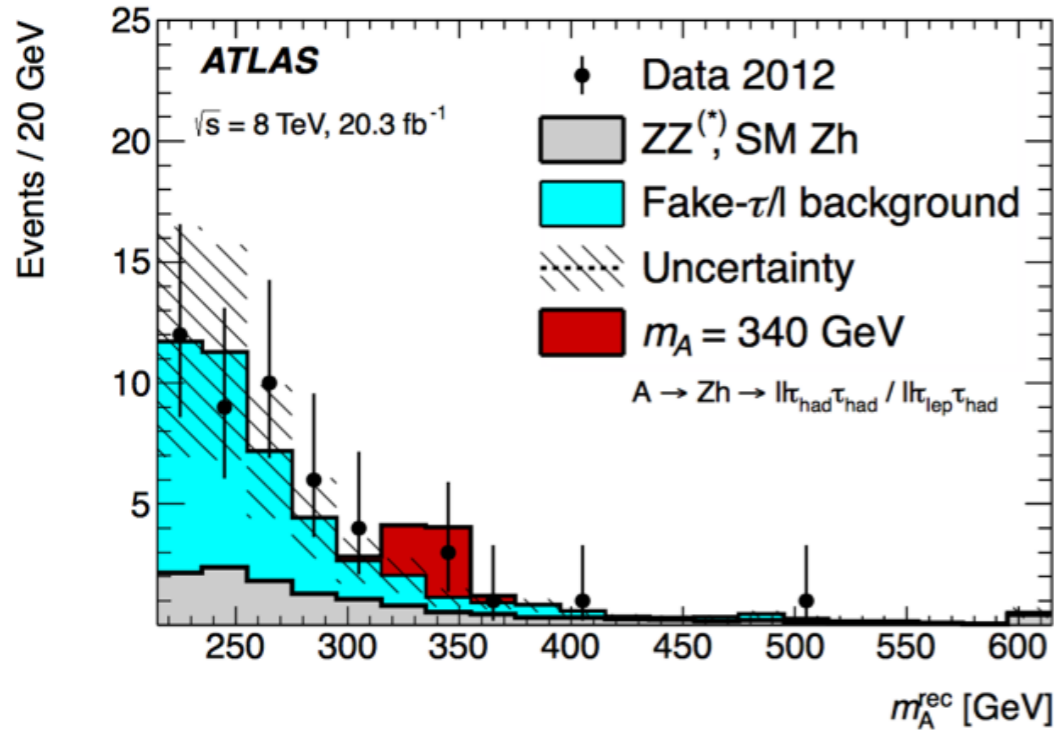


ATLAS: JHEP 11 (2014) 056

CMS: JHEP 10 (2014) 160

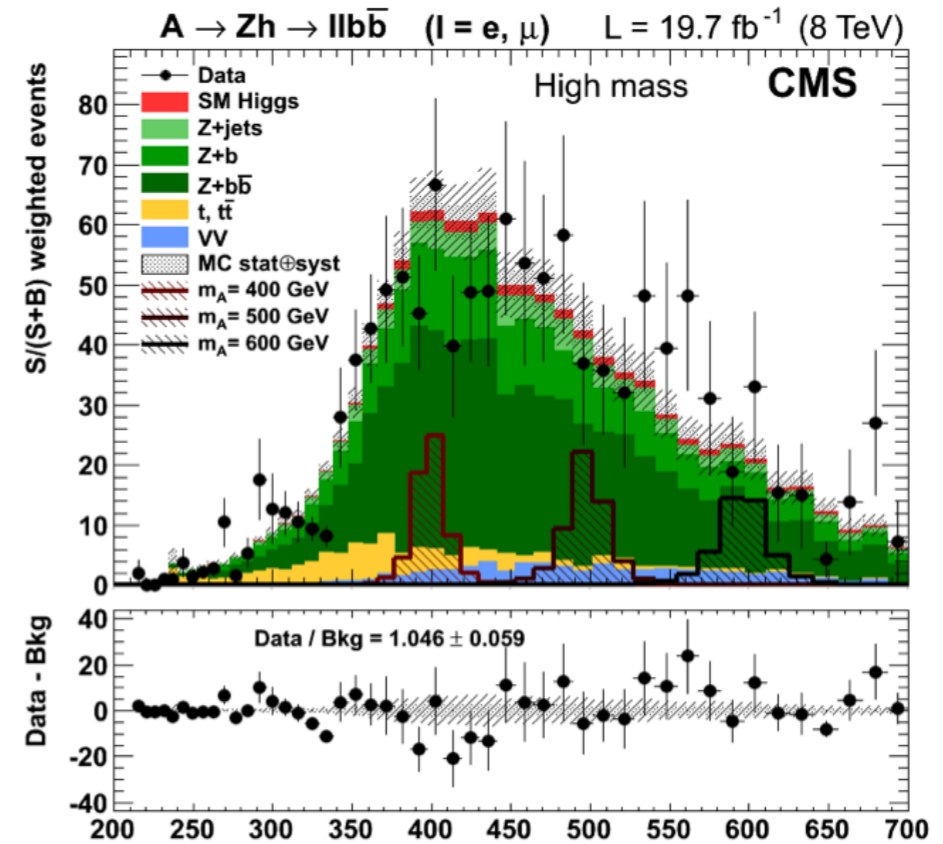
A → ZH

A → Z(→ll)h(→ττ)

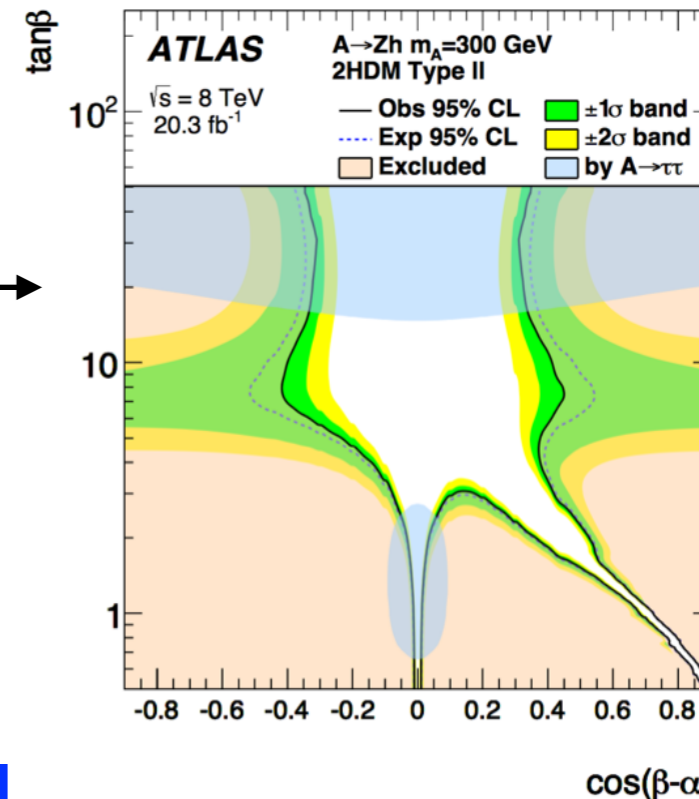


Strong involvement of ATLAS Rome group

A → Z(→ll)h(→bb)



Extend sensitivity in low $\tan\beta$ for 2HDM/MSSM models not covered by the $\phi \rightarrow \tau\tau$ search



ATLAS: PLB 744 (2015) 163-183

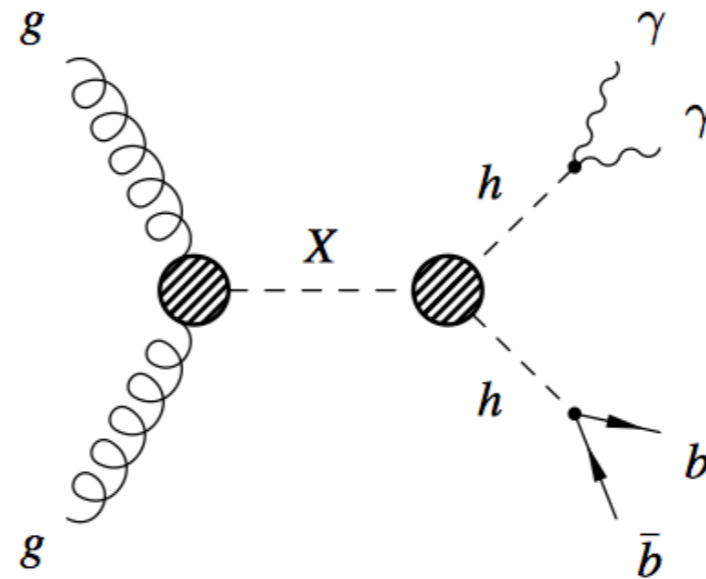
CMS: arXiv:1504.04710

$X \rightarrow HH$

Interesting in the context of 2HDM for low $\tan\beta$ region $m_H < 350$

Strong involvement of ATLAS & CMS Rome group

ATLAS: Phys. Rev. Lett. 114, 081802 (2015)

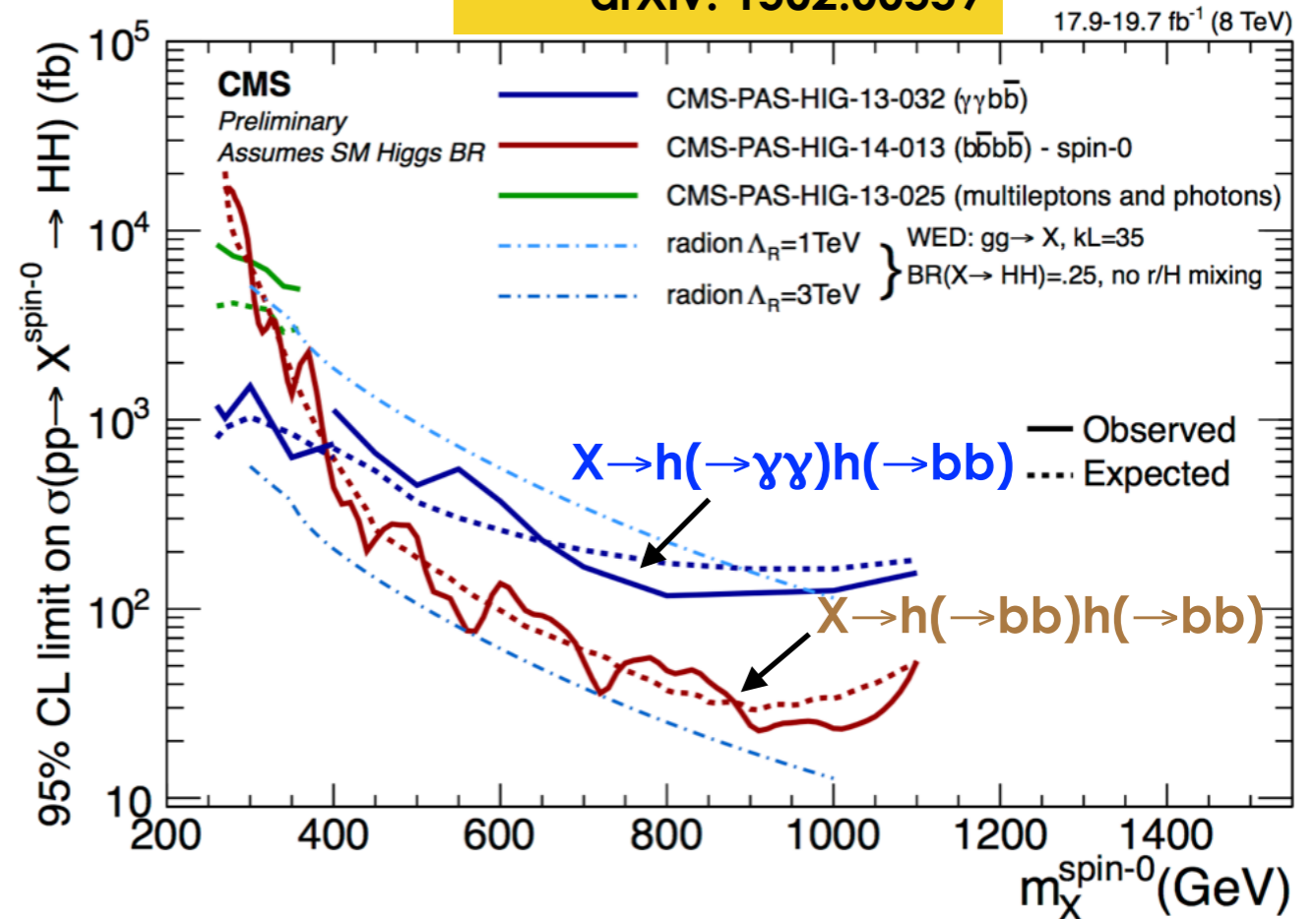
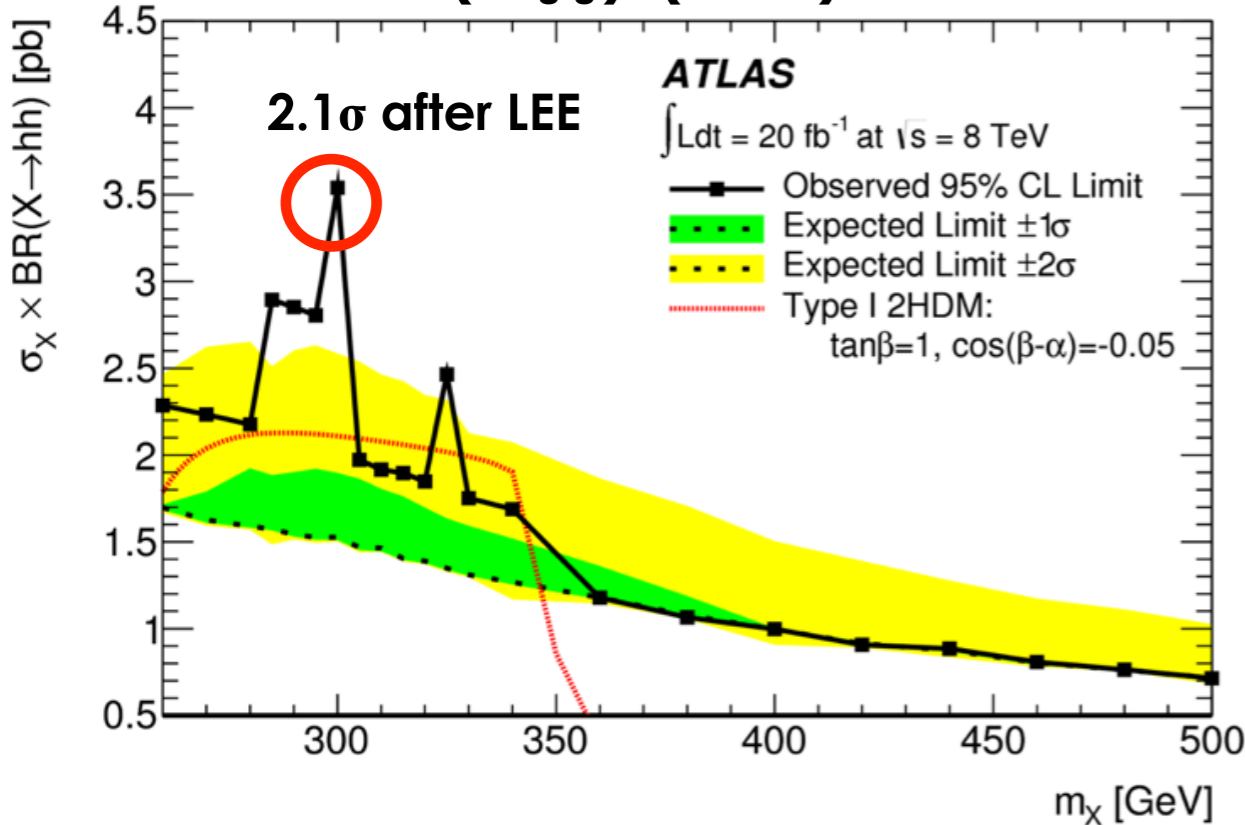


CMS: PRD 90, 112013

HIG-13-032

arXiv: 1502.00559

$X \rightarrow h(\rightarrow \gamma\gamma)h(\rightarrow bb)$



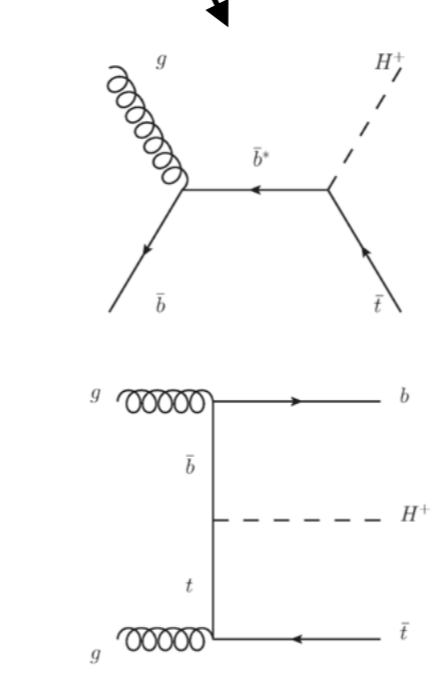
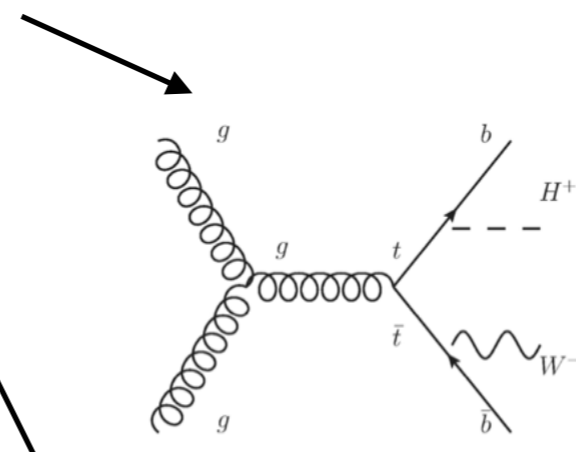
CHARGED HIGGS: $H^\pm \rightarrow \tau^\pm \nu$

$M_{H^\pm} < m_{\text{top}}$: production in $t\bar{t}$ decay
[$t\bar{t} \rightarrow HbWb$]

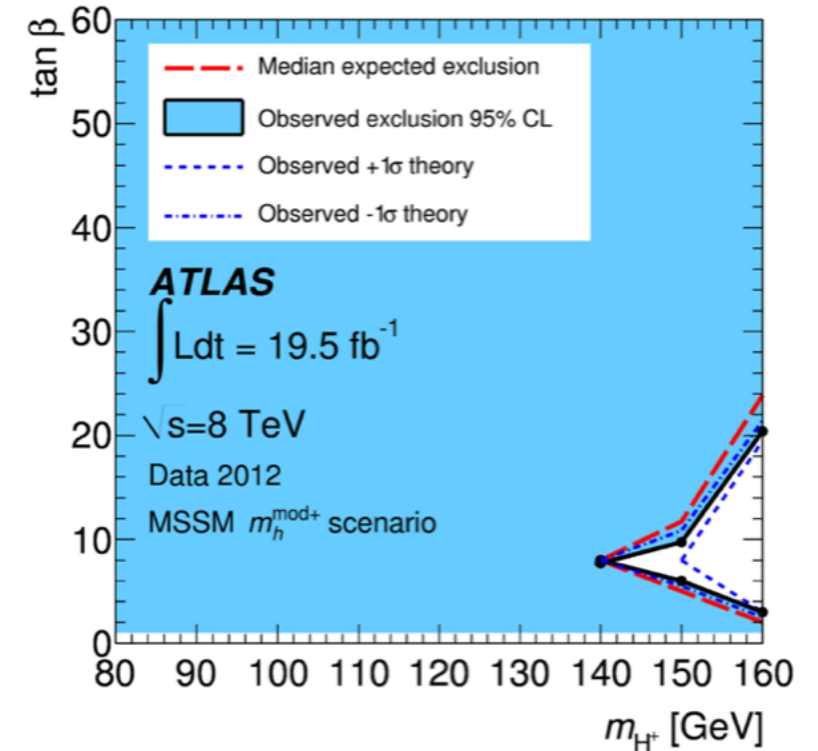
$M_{H^\pm} > m_{\text{top}}$: associated production
with top [$tH(b)$]

$\tau_{\text{had}} + \text{MET} + b\text{-jets}$ final state

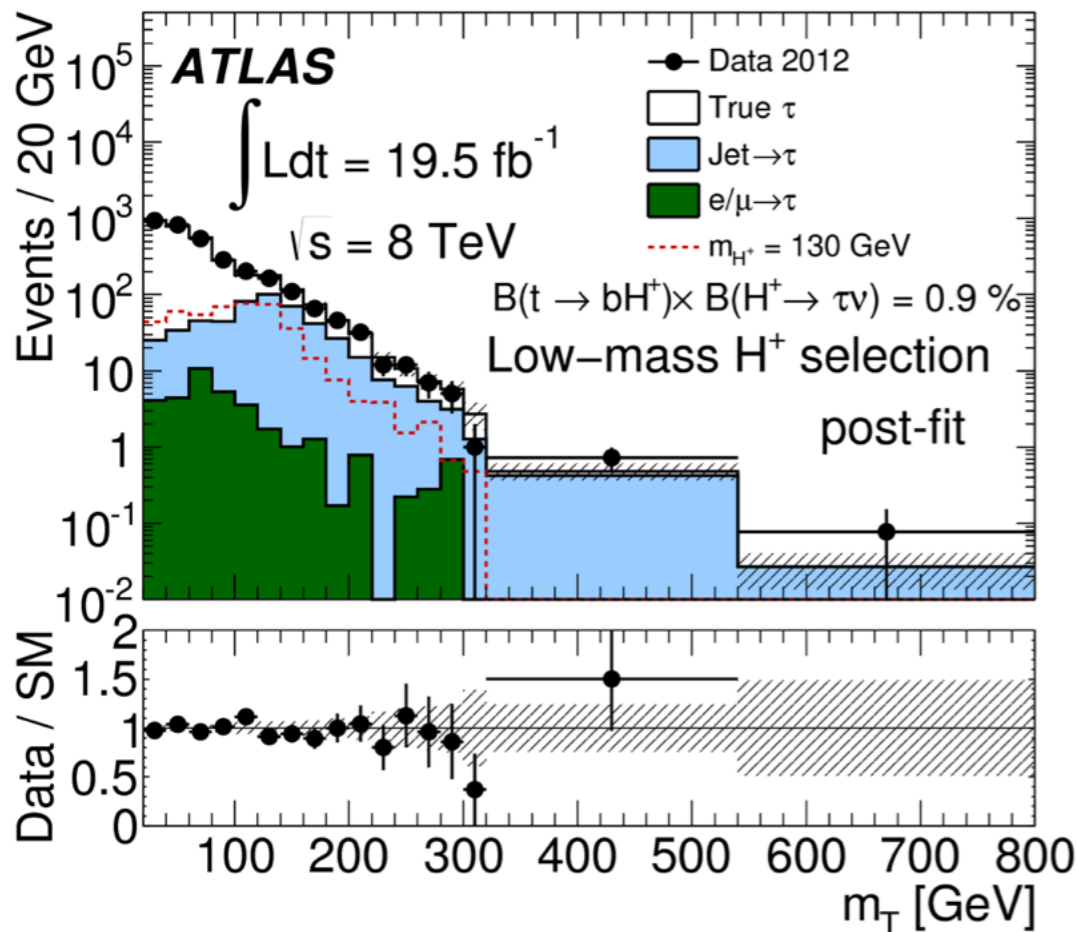
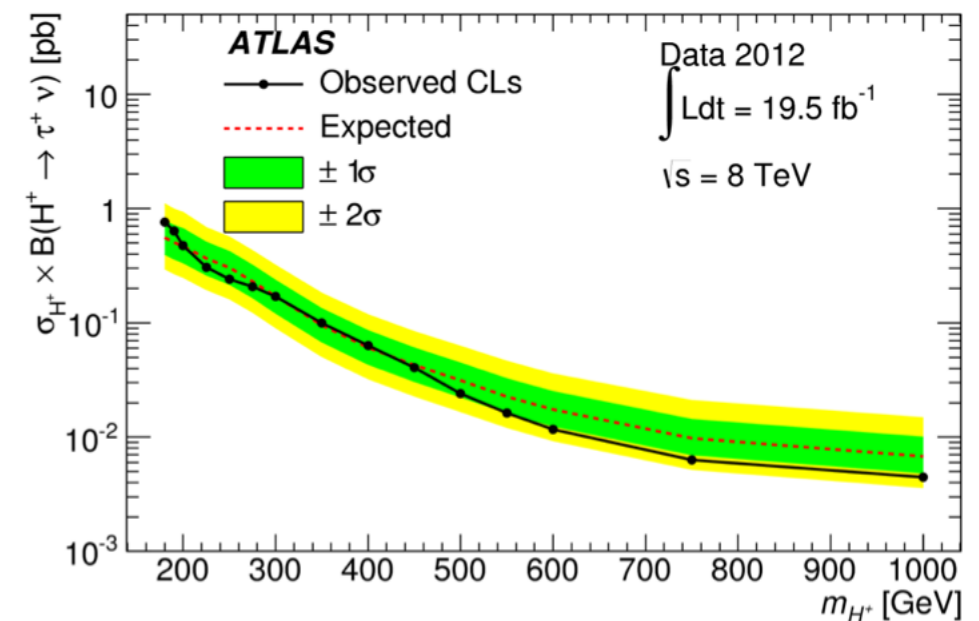
able to exclude full MSSM phase space for $m_{H^\pm} < 160$ GeV



low m_{H^\pm}



high m_{H^\pm}

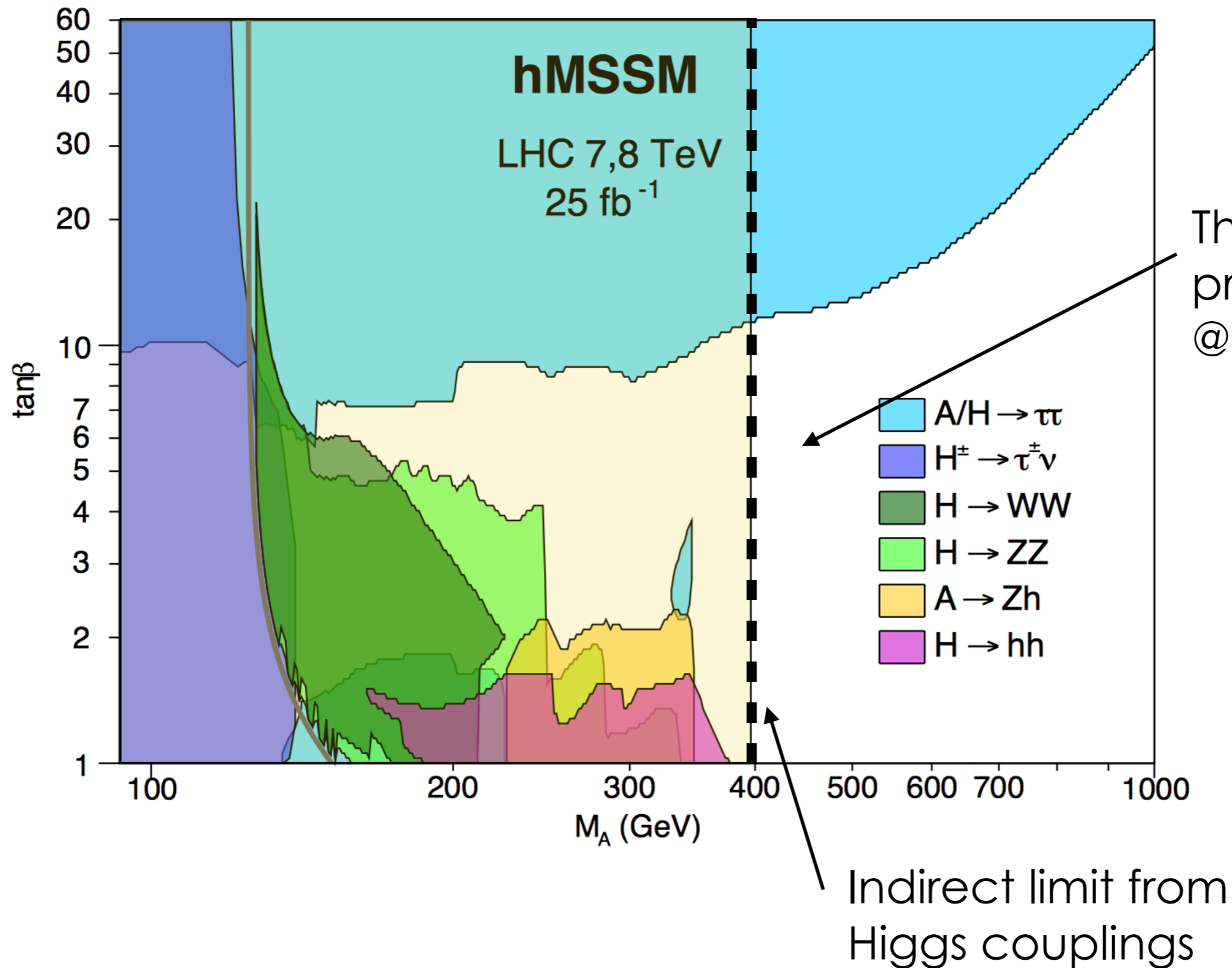


ATLAS: JHEP 03 (2015) 88

CMS-HIG-14-020

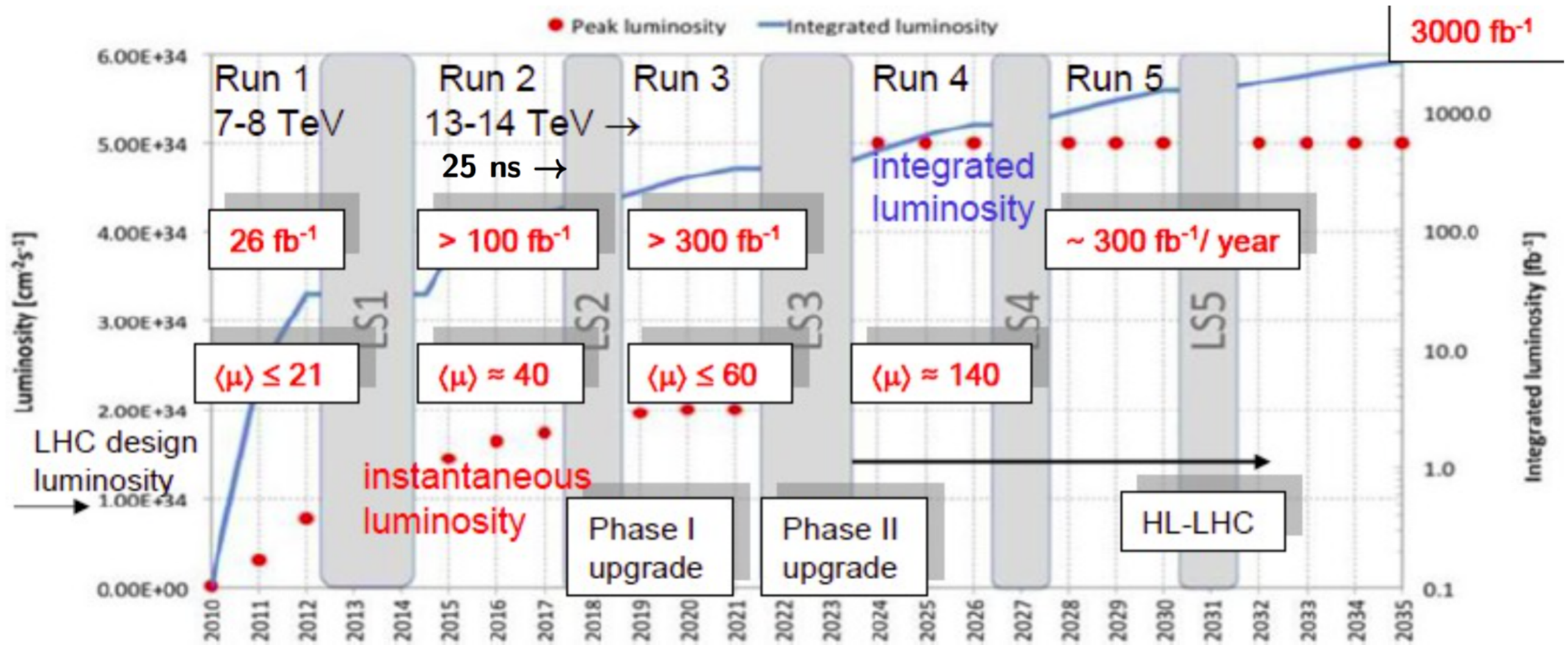
hMSSM: RUN I SUMMARY

A. Djouadi et al: arXiv:1502.05653



This region can be probed also looking @ $\phi \rightarrow t\bar{t}$

BEYOND RUN 1



Target for 2015: 5-10 fb⁻¹ First stable collisions: 03.06.2015

>100 fb⁻¹ by 2018, >300 fb⁻¹ by 2023

HL-LHC: ~3000 fb⁻¹, 5 x 10³⁴ cm⁻²s⁻¹ requires detector+DAQ+trigger upgrades

13 TeV: H cross section ~ x 2, ttH ~ x4

Run I sensitivity/precision will be reached for H analyses ~10 fb⁻¹ @ 13 TeV

Full Run2+3 statistics (~300 fb⁻¹):

~10M H produced

~400k H useful for precision measurements

Rare processes: **H**→μμ @ & 3σ, **H**→Zγ @ > 2σ

Direct ttH coupling could be established @ ~ 5σ

Higgs couplings can be tested at levels better than 10%

Differential cross-sections for H→γγ, H→ZZ, H→WW improving sensitivity for new physics looking also at kinematic deviations

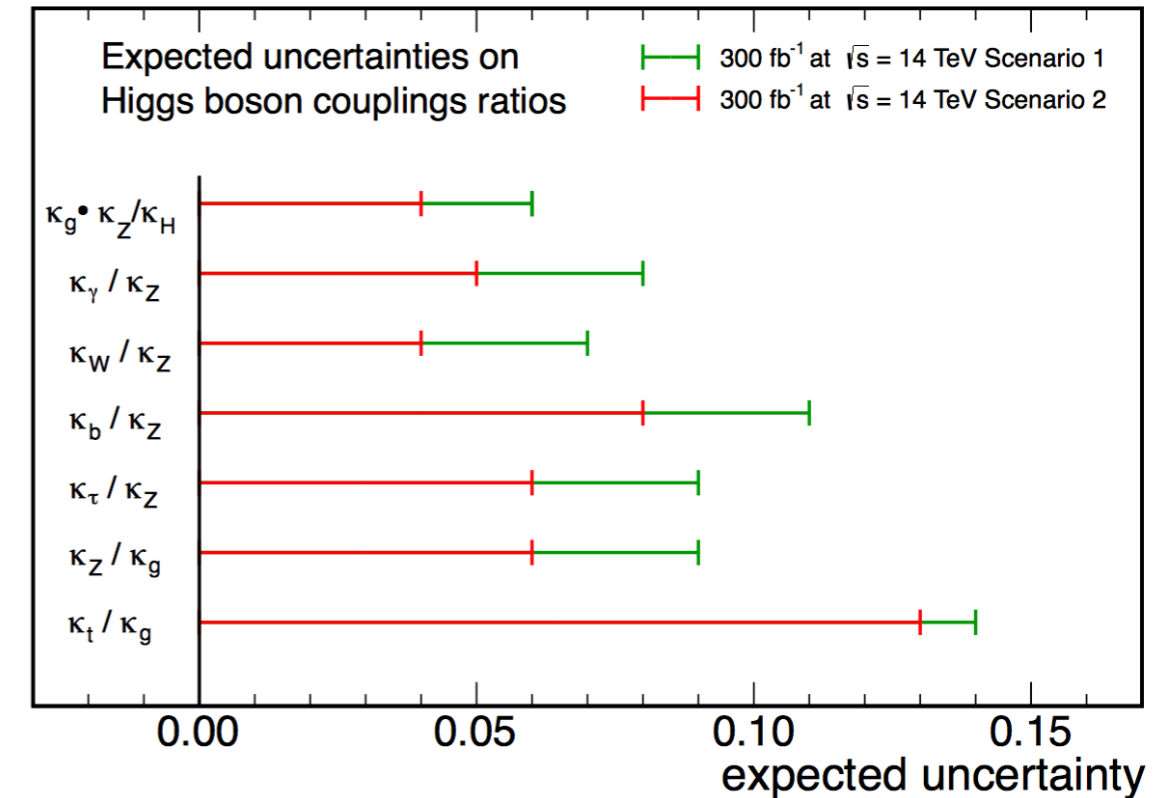
	$\sigma(8 \text{ TeV})$	$\sigma(13 \text{ TeV})$	ratio
gg→H	19.3	43.9	2.3
VBF	1.58	3.75	2.4
WH	0.70	1.38	2.0
ZH	0.42	0.87	2.1
ttH	0.13	0.51	3.9

Transition from statistically limited to systematically limited in the Higgs precision physics

Reaching the ultimate precision will require new tools and new ideas, paving the grounds for HL-LHC.

Theory and experiment working together
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG>

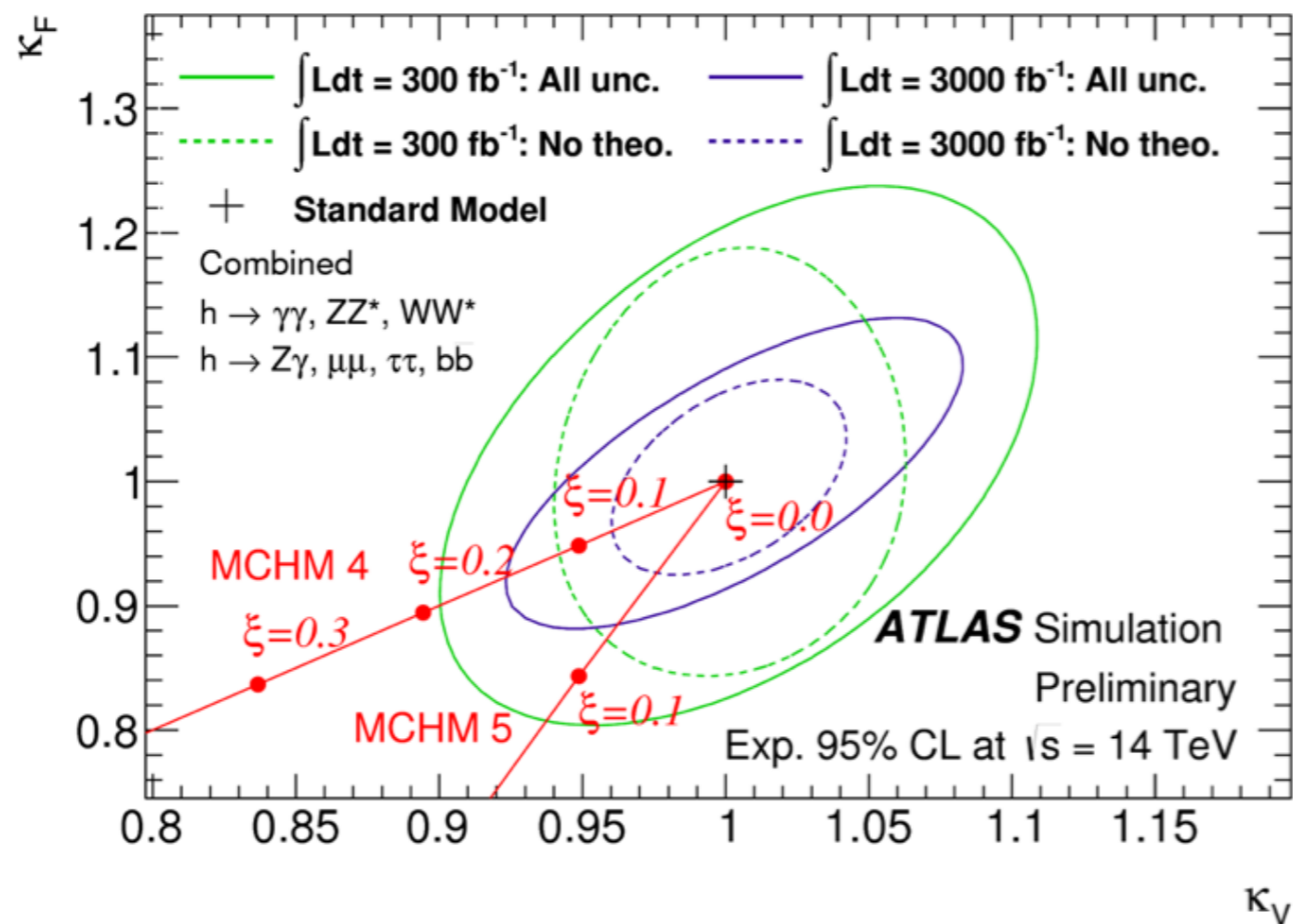
CMS Projection



- We are organized in 3 working groups.

Group TWiki	Mail to conveners	ATLAS	CMS	THEORY	
Higgs XS&BR	Mail	Bruce Mellado (Witwatersrand)	Pasquale Musella (CERN)	Massimiliano Grazzini (Zürich)	Robert Harlander (Wuppertal)
Higgs Properties	Mail	Michael Dührssen (CERN)	Andre David (CERN)	Adam Falkowski (Orsay-LPT)	Gino Isidori (Zürich)
BSM Higgs	Mail	Nikolaos Rompotis (Washington)	Mario Pelliccioni (Torino)	Ian Low (Argonne and Northwestern)	Margarete Mühlleitner (Karlsruhe)

ATLAS-PHYS-PUB-2014-017



HL-LHC (3000 fb⁻¹): ultimate precision for the Higgs coupling measurements

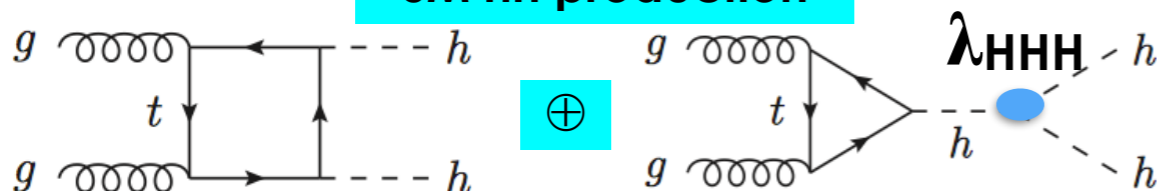
If no direct sign of BSM found, Higgs precision physics will be the most important tool to look for new physics

HL-LHC: PROBING HIGGS SELF COUPLING

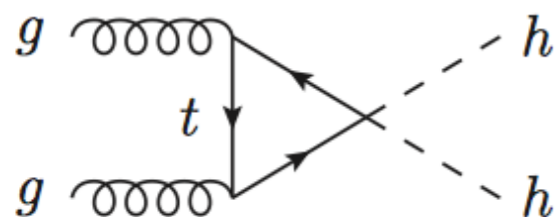
hh non-resonant production: small cross-section in the SM $\sim 40\text{fb}$ @ **14 TeV**

- potential to measure the Higgs self coupling
- can reveal anomalous hh couplings

SM hh production

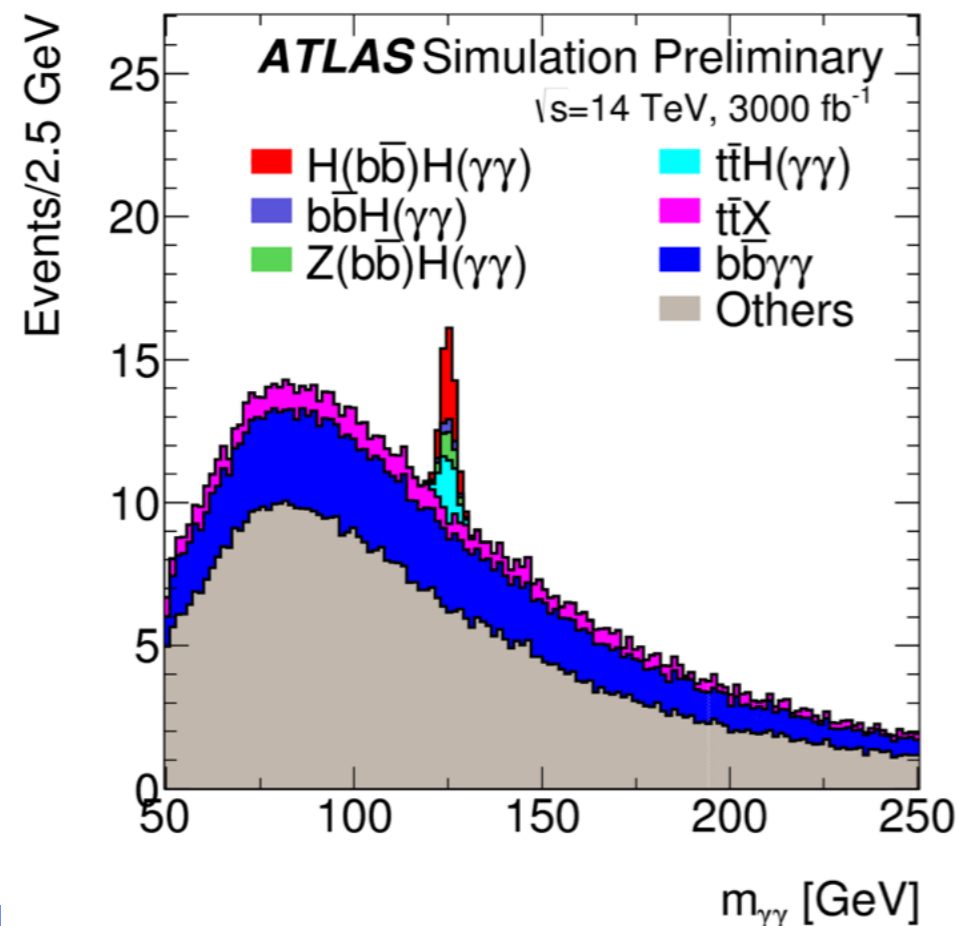
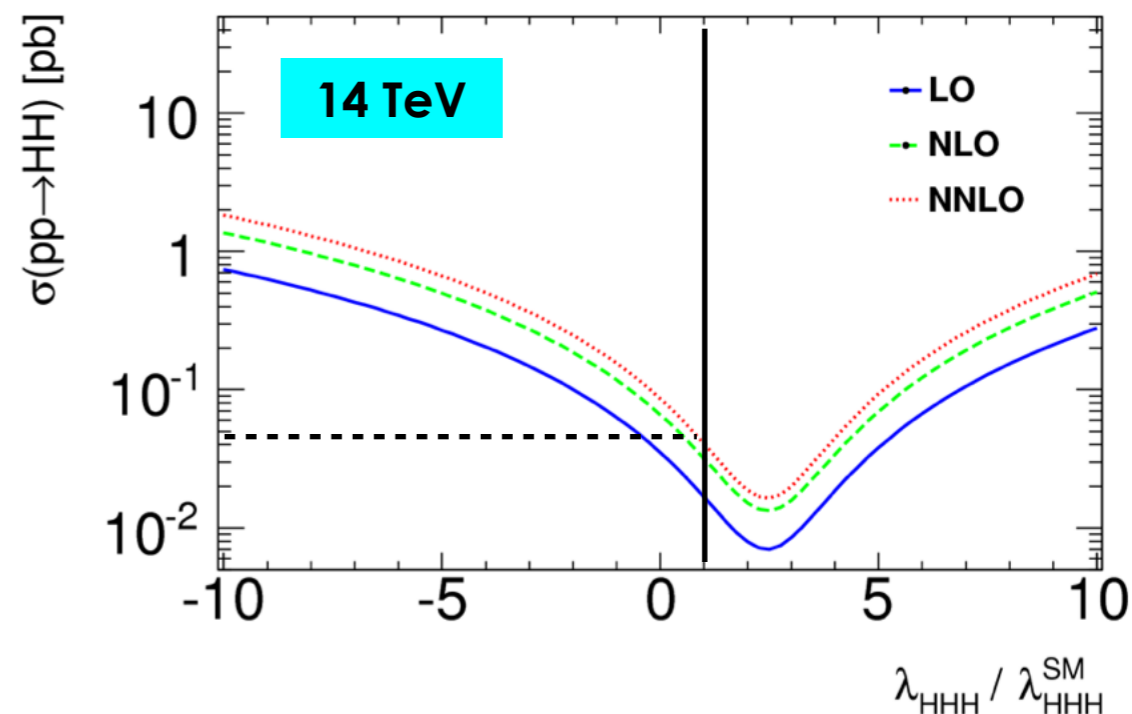


Anomalous BSM hh production



$h(\rightarrow\gamma\gamma)h(\rightarrow bb)$ the most promising channel @ HL-LHC: $\sim 2\sigma$ per experiment according to current projections

$h(\rightarrow\tau\tau)h(\rightarrow bb)$ also being studied



Run 1: from Higgs discovery, to the start of the Higgs physics

we have a new toy to play

Run 2: pushing the Higgs physics into the precision era

$\sim 10 \text{ fb}^{-1}$ @ 13 TeV needed to achieve Run I sensitivity

<10% precision on Higgs couplings at the end of Run 2

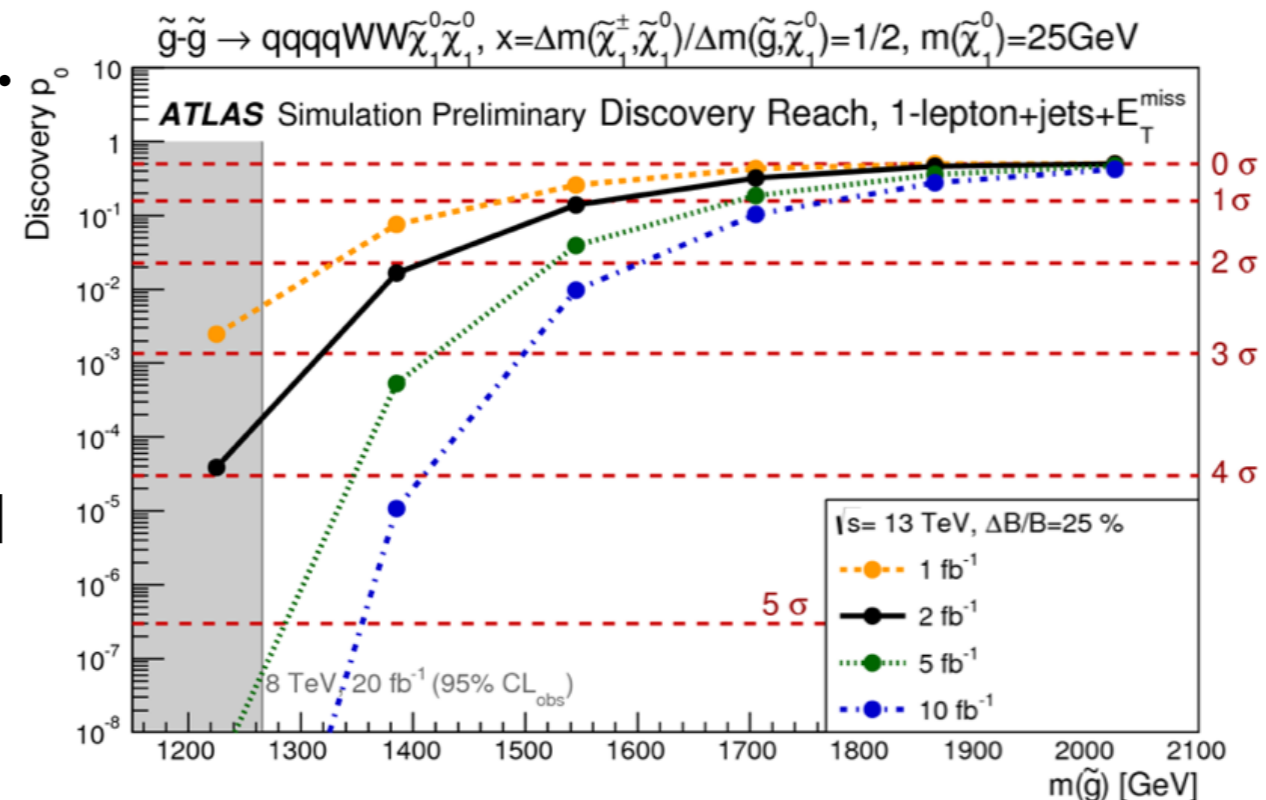
prepare grounds for HL-LHC where ultimate precision will be reached

General feeling of “Higgs and no BSM”.

However:

Wait for Run2! Direct searches reach increase very rapidly thanks to increase in \sqrt{s}

Smaller BSM cross-sections can be probed later-on thanks to the Run 2 statistics



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG>

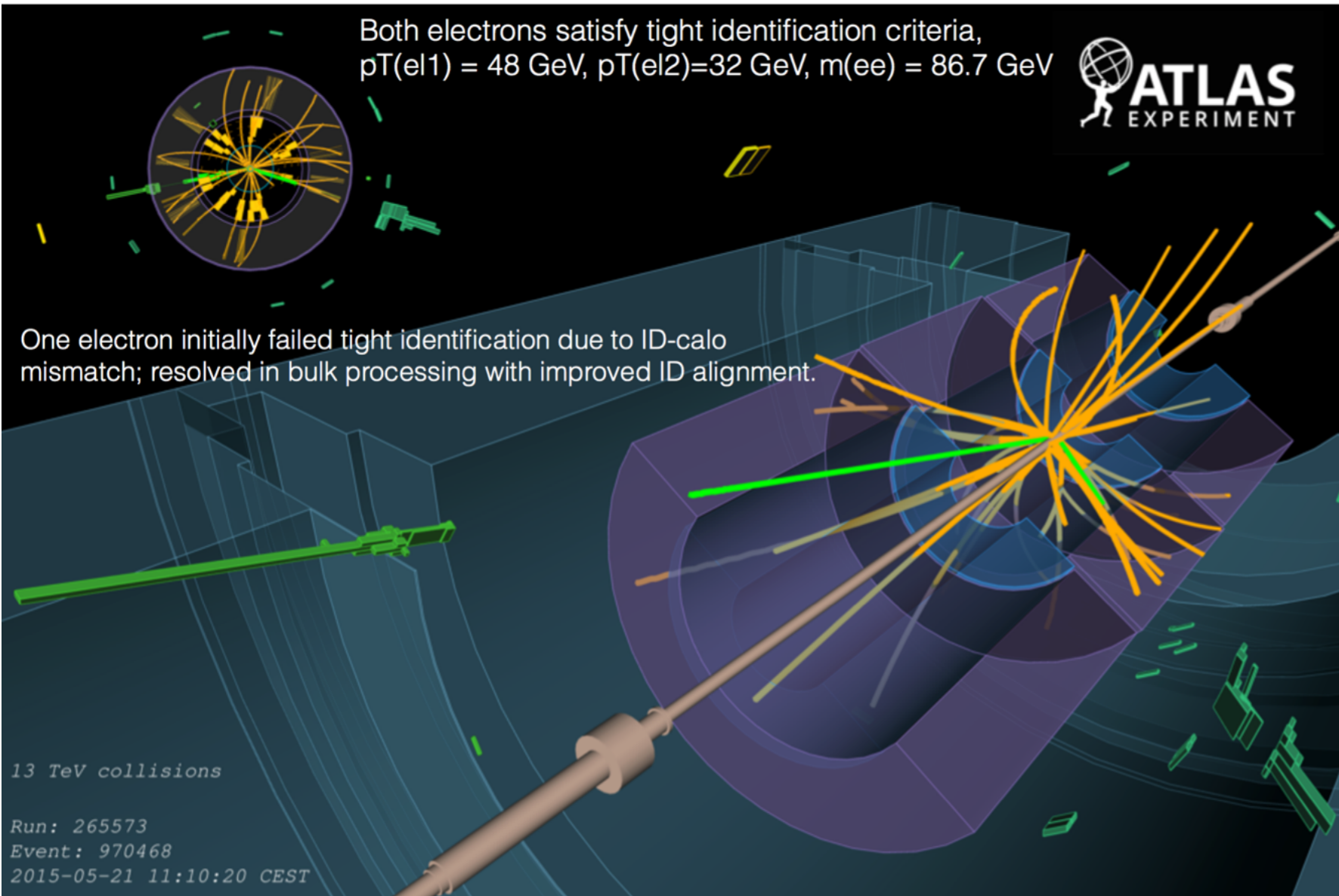
RUN2 HAS STARTED!

$Z \rightarrow e^+e^-$ candidate

Both electrons satisfy tight identification criteria,
 $p_T(e1) = 48 \text{ GeV}$, $p_T(e2) = 32 \text{ GeV}$, $m(ee) = 86.7 \text{ GeV}$



One electron initially failed tight identification due to ID-calorimeter mismatch; resolved in bulk processing with improved ID alignment.

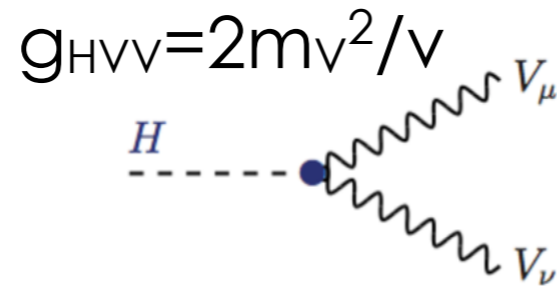




BACKUP

THE HIGGS IN THE SM

$$|D_\mu \phi|^2$$

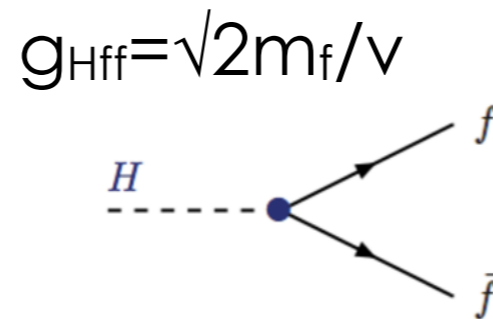


$$\frac{M_W}{M_Z} = \rho \frac{g^2}{g^2 + g'^2} = \rho \cos^2 \theta_W$$

$$\rho = 1$$

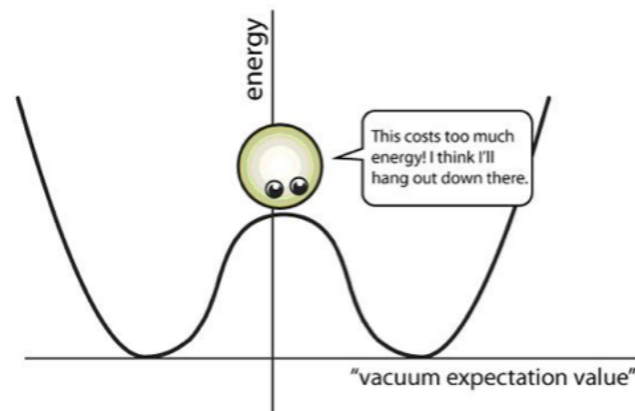
Discovery not really a surprise:
LEP legacy

$$\chi_i y_{ij} \chi_j \phi + h.c.$$

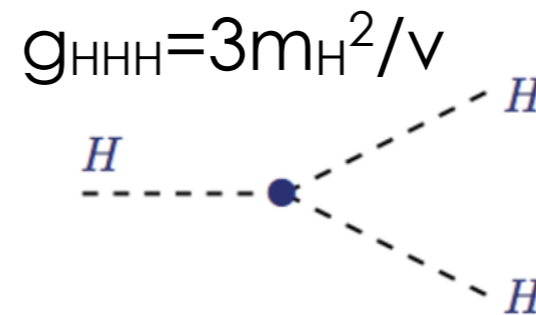


**Flavour hierarchy
unexplained**

$$V(\phi)$$

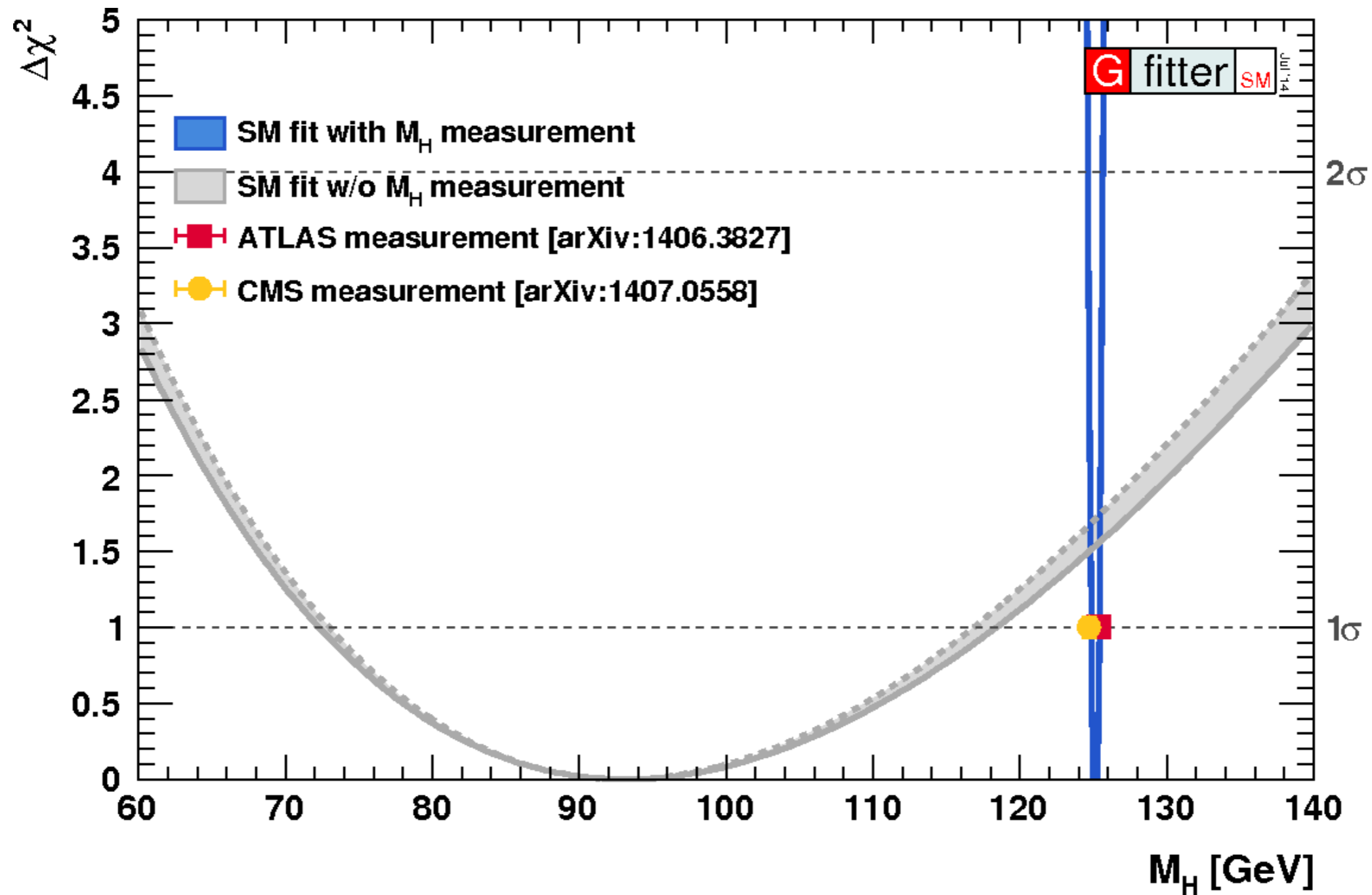


$$V = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



**The most challenging
coupling to be tested
at the LHC**

LOOKING FOR SM DEVIATION: MASS



Consistent with SM EWK precision tests

$H \rightarrow \mu\mu$ & $H \rightarrow ee$

$BR(H \rightarrow \mu\mu) = 2.2 \times 10^{-4} \sim 1/10 \times BR(H \rightarrow \gamma\gamma)$

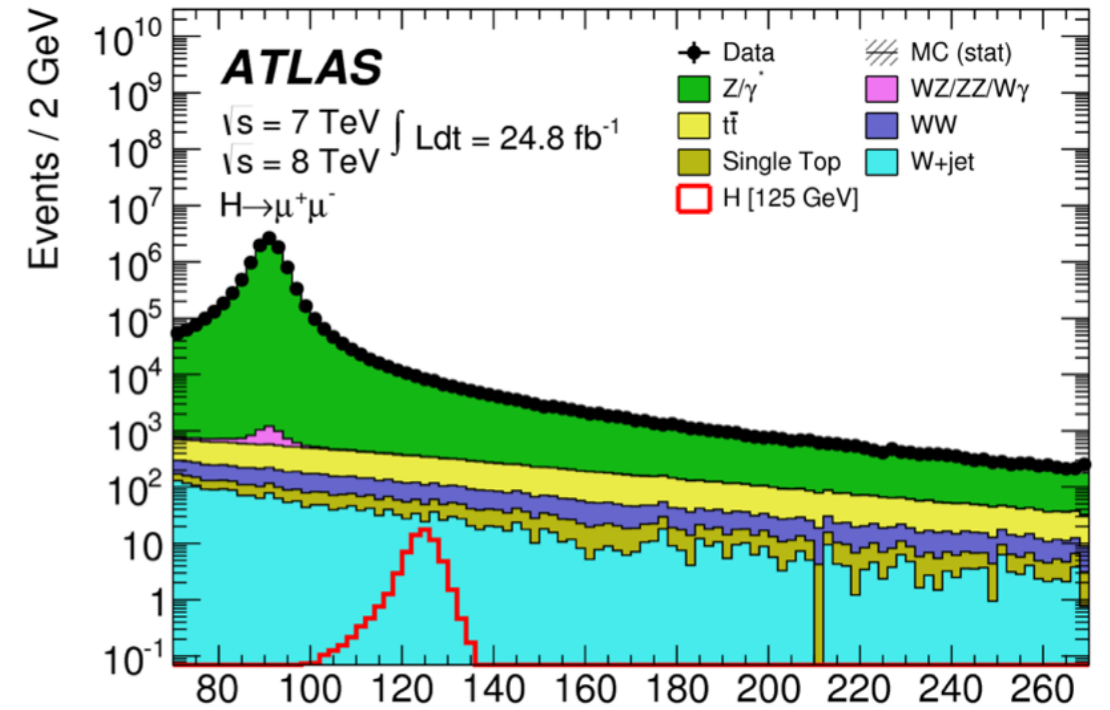
$H(125) \rightarrow \mu\mu$ 95% CL observed
(expected) limits on σ/σ_{SM}

ATLAS: PLB 738 (2015)	7.0(7.2)
CMS: arXiv:1410.6679	7.4(6.5)

Together with evidence of $H \rightarrow \tau\tau$, confirm lepton non-universality

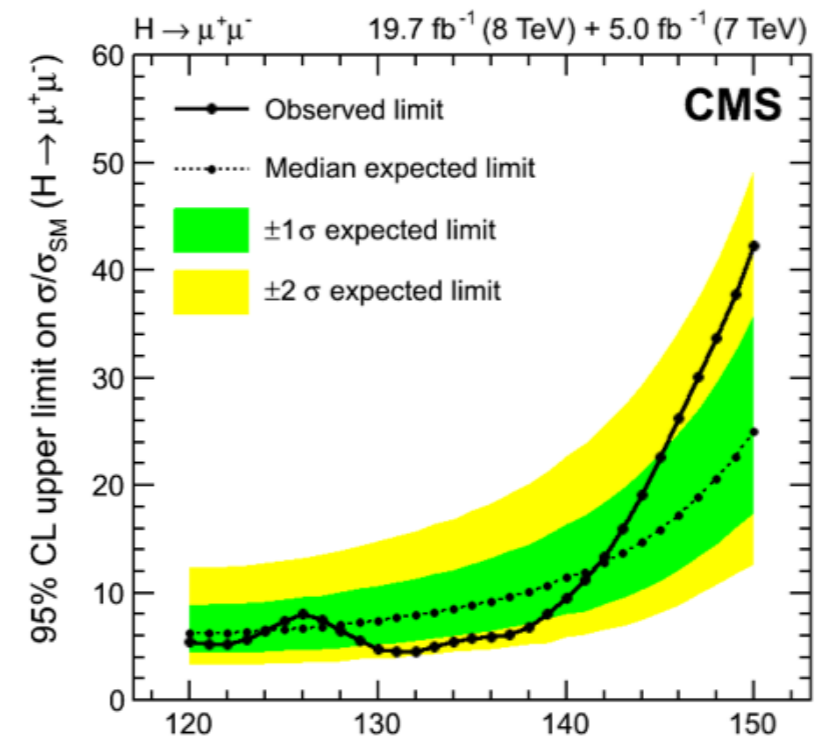
With 300 fb^{-1} @ 13 TeV sensitivity to ~exclude $H \rightarrow \mu\mu$

$H \rightarrow ee$: CMS put 95% CL exclusion limit on $\sigma \times BR(H(125) \rightarrow ee) = 41 \text{ fb}$



ATLAS: PLB 738 (2015) 68

$m_{\mu^+\mu^-}$ [GeV]



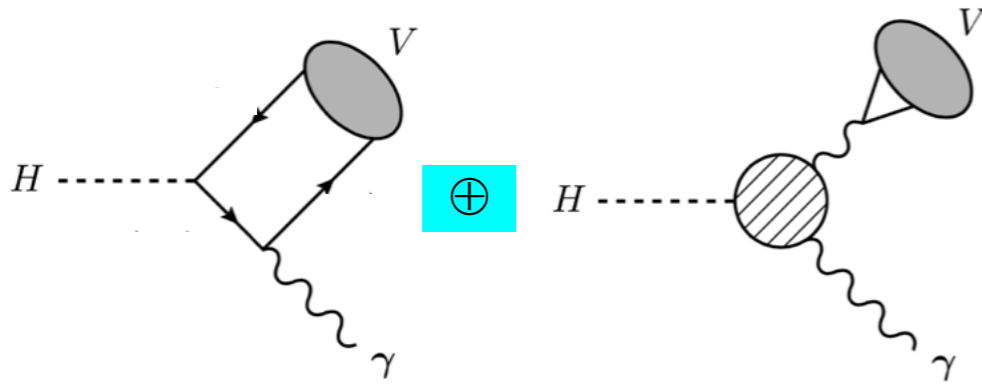
CMS: arXiv:1410.6679

m_H [GeV]

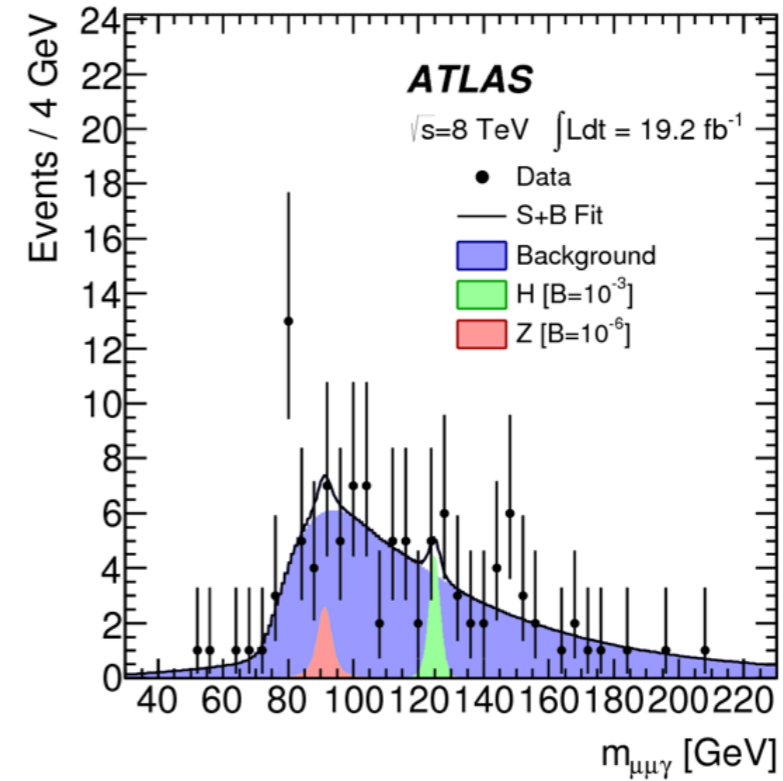
$H \rightarrow J/\psi \gamma, \Upsilon \gamma$

Very small BR

$$\text{BR}(H \rightarrow J/\psi \gamma) \sim 3 \times 10^{-6}$$

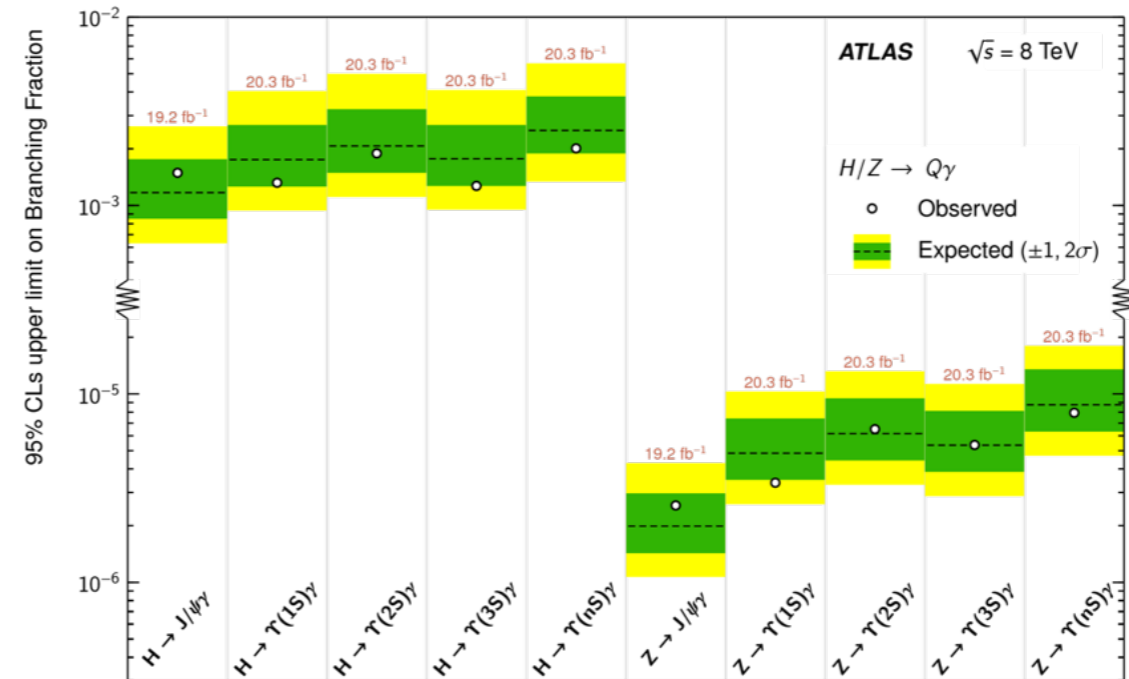


J/psi + gamma candidates



Limit on $H(\rightarrow J/\psi \gamma) \sim \times 540 \text{ SM}$

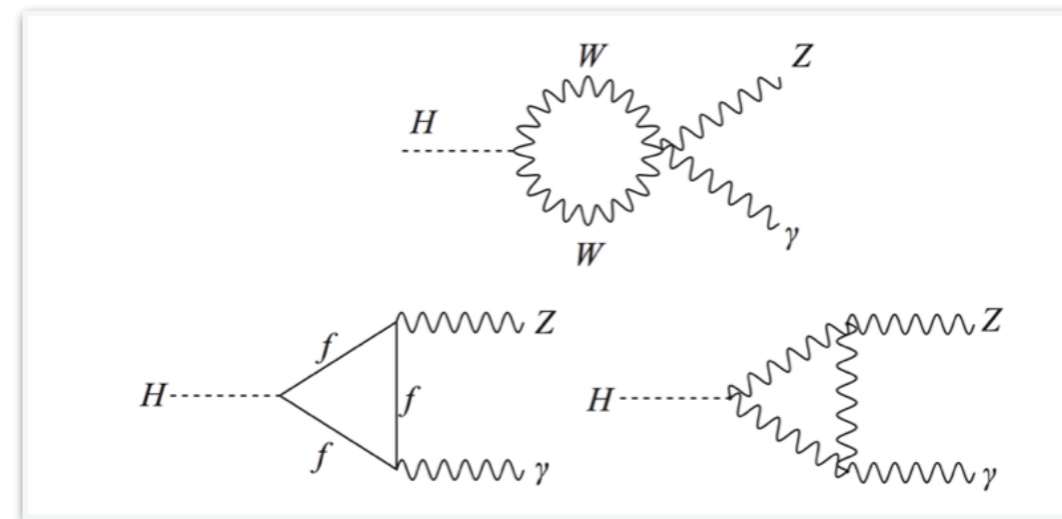
95% CLs Upper Limit on Branching Ratio



95% CLs Upper Limit on Branching Ratio

RARE HIGGS DECAYS: $H \rightarrow Z\gamma$ & $H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$

- Search performed in $Z(\rightarrow ee)+\gamma$ and $Z(\rightarrow \mu\mu)+\gamma$ channel
- Very small BR expected in SM $\sim 0.1\%$.
 - New particles/couplings (e.g composite higgs) can be revealed in decays involving loop

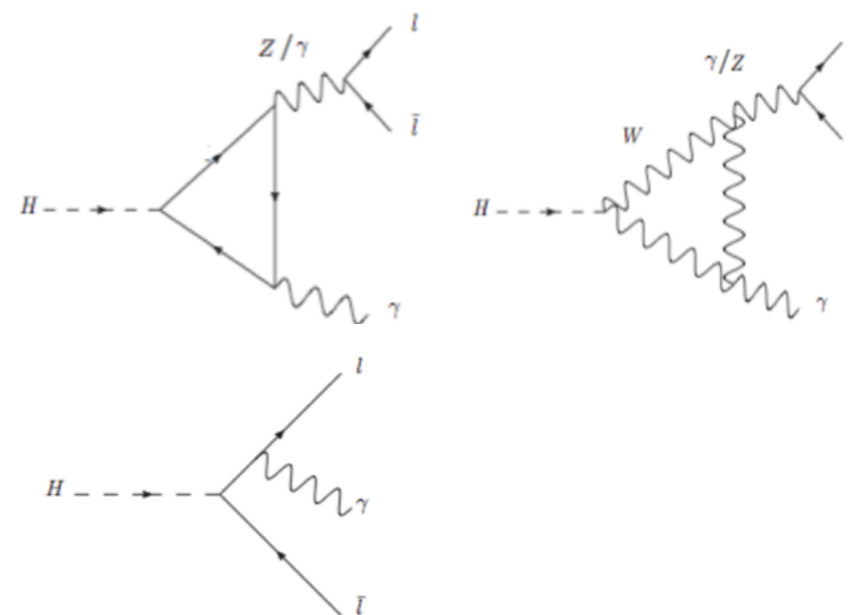


- For $h(125)$ excluding BR enhancement $> \sim x10$ @ 95% CL

ATLAS: arXiv:1402.3051	>11(9)
CMS: Phys. Lett. B 726(2013) 587	>9.5(10)

Dalitz decay

- different contributions to the same final state, not yet disentangled
- wrt to $Z\gamma$: $m_{\mu\mu} < 20$ GeV



- Sensitivity similar to $Z\gamma$: excluding $>x11$ @ 95% CL

CMS HIG-14-003	>11(7)	NEW
----------------	--------	------------

H → DARK/HIDDEN SECTOR

ATLAS Exotics Long-lived Particle Searches* - 95% CL Exclusion

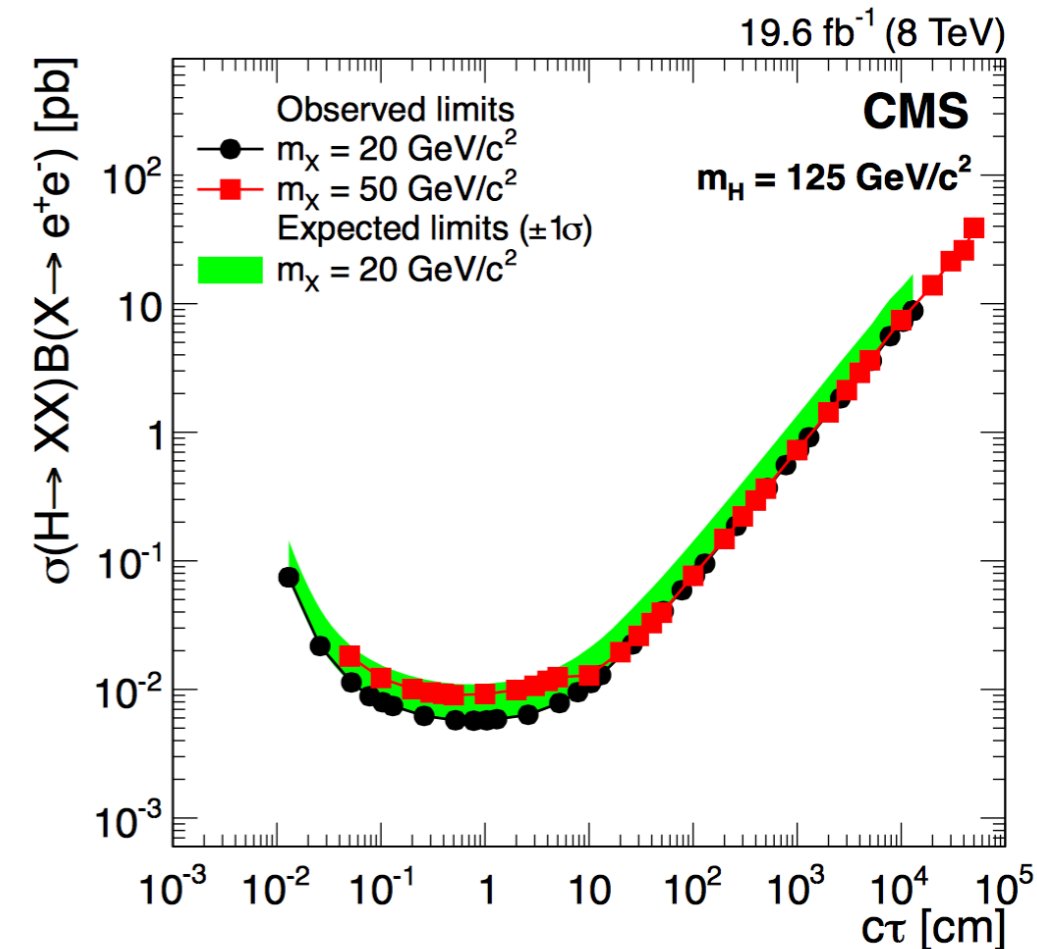
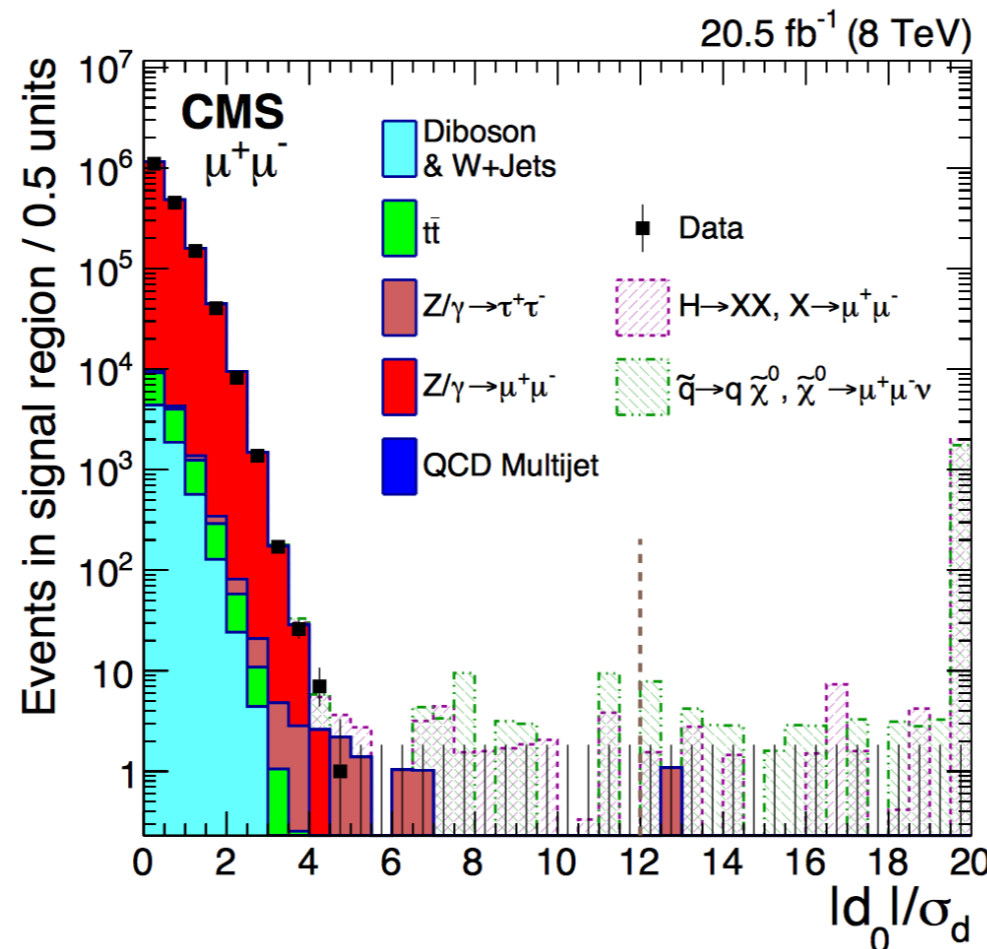
Status: March 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (19.5 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Lifetime limit	Reference
Higgs BR = 10%	Hidden Valley $H \rightarrow \pi_\nu \pi_\nu$	2 low-EMF trackless jets	π_ν lifetime: 0.41-7.57 m	$m(\pi_\nu) = 25 \text{ GeV}$ 1501.04020
	Hidden Valley $H \rightarrow \pi_\nu \pi_\nu$	2 ID/MS vertices	π_ν lifetime: 0.31-25.4 m	$m(\pi_\nu) = 25 \text{ GeV}$ Preliminary
	FRVZ $H \rightarrow 2\gamma_d + X$	2 e^-, μ^-, π^- -jets	γ_d lifetime: 14-140 mm	$H \rightarrow 2\gamma_d + X, m(\gamma_d) = 400 \text{ MeV}$ 1409.0746
	FRVZ $H \rightarrow 4\gamma_d + X$	2 e^-, μ^-, π^- -jets	γ_d lifetime: 15-260 mm	$H \rightarrow 4\gamma_d + X, m(\gamma_d) = 400 \text{ MeV}$ 1409.0746

Displaced lepton pairs



H → DARK SECTOR

If dark sector, e.g. new a $U(1)_d$ gauge boson, Higgs could decay to its dark boson Z_d

$U(1)_d$ unbroken: $H \rightarrow ZZ_d$, coupling via kinematic mixing

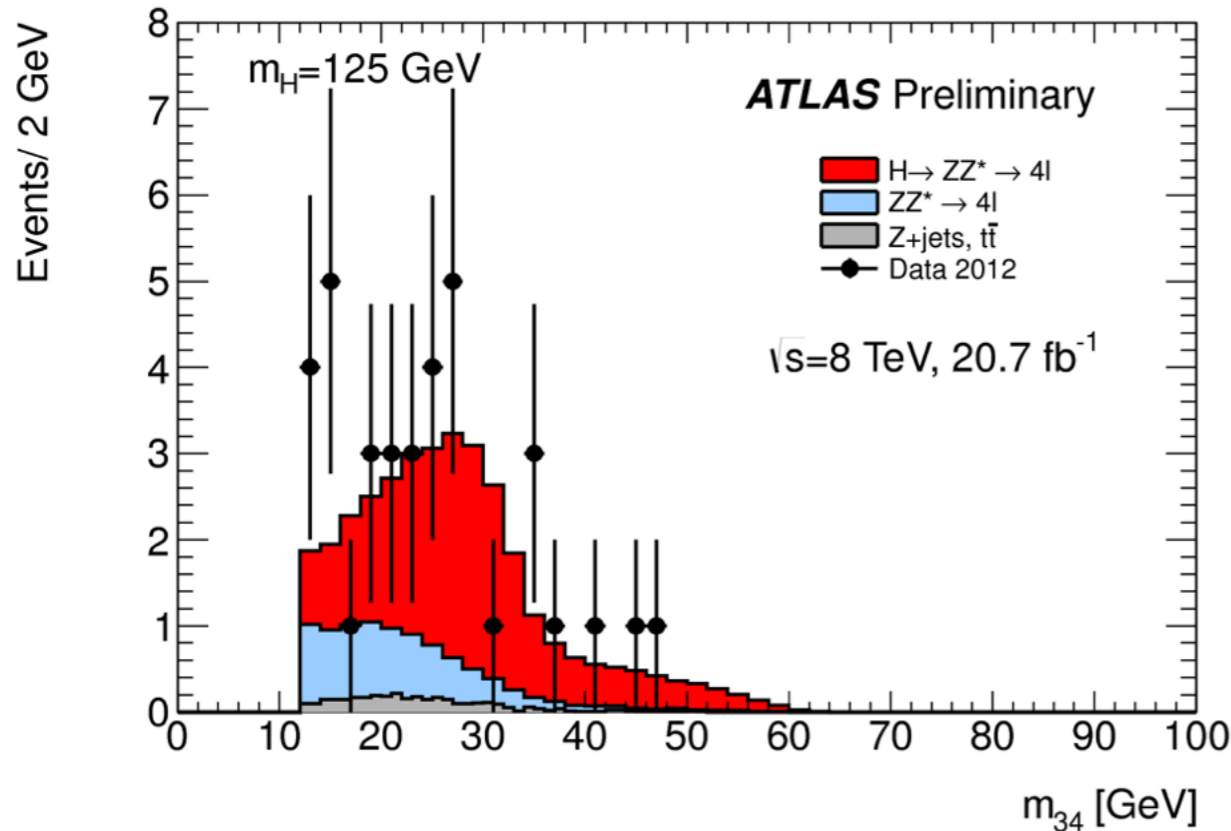
$U(1)_d$ broken: H mixing with dark Higgs, $H \rightarrow Z_d Z_d$

ATLAS-CONF-2015-003

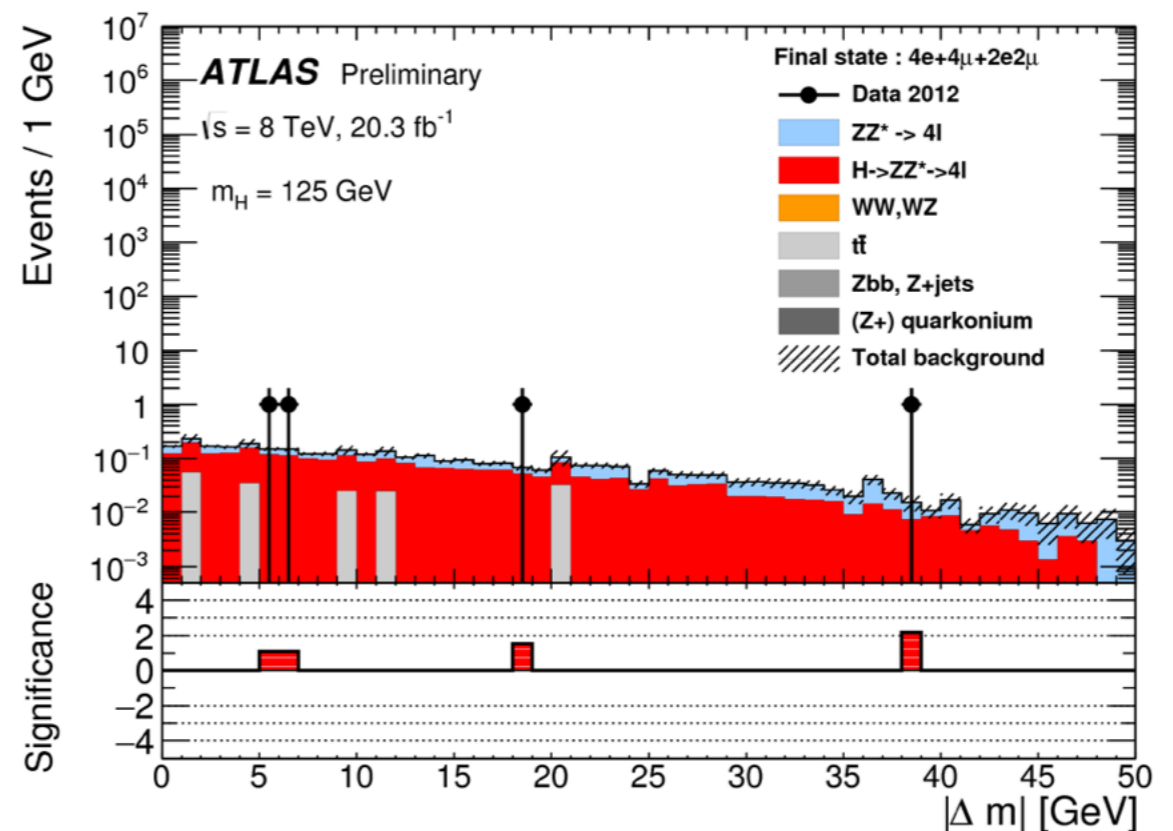
$H \rightarrow ZZ_d \rightarrow 4l$: same selection as Higgs

$H \rightarrow ZZ^* \rightarrow 4l$, look for a bump in m_{34}

$H \rightarrow Z_d Z_d \rightarrow 4l$: small Δm between pairs of opposite sign same flavour leptons



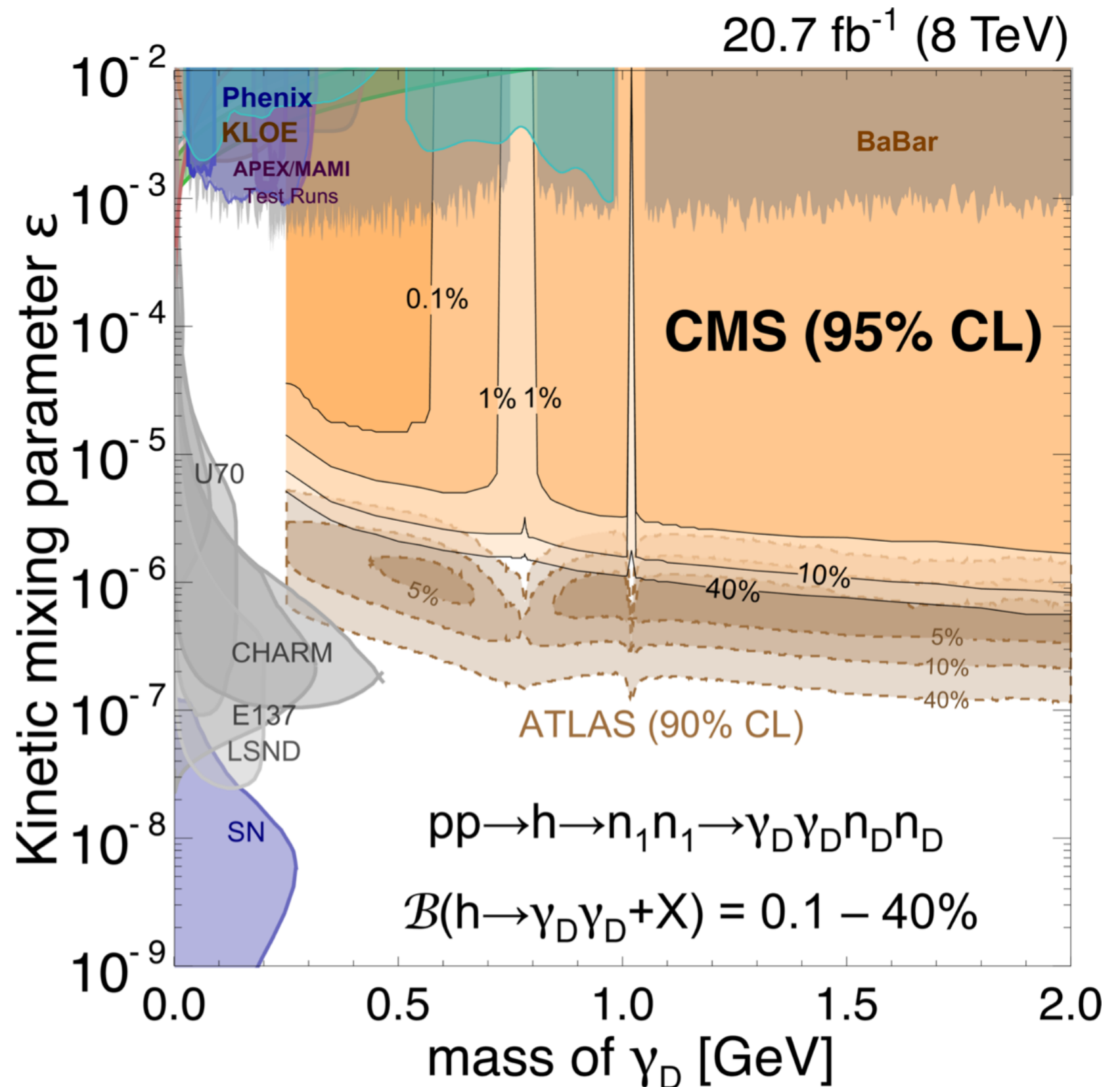
Limit on $BR(H \rightarrow ZZ_d) \sim 10-40\%$ for m_{Z_d} in 15-60 GeV range



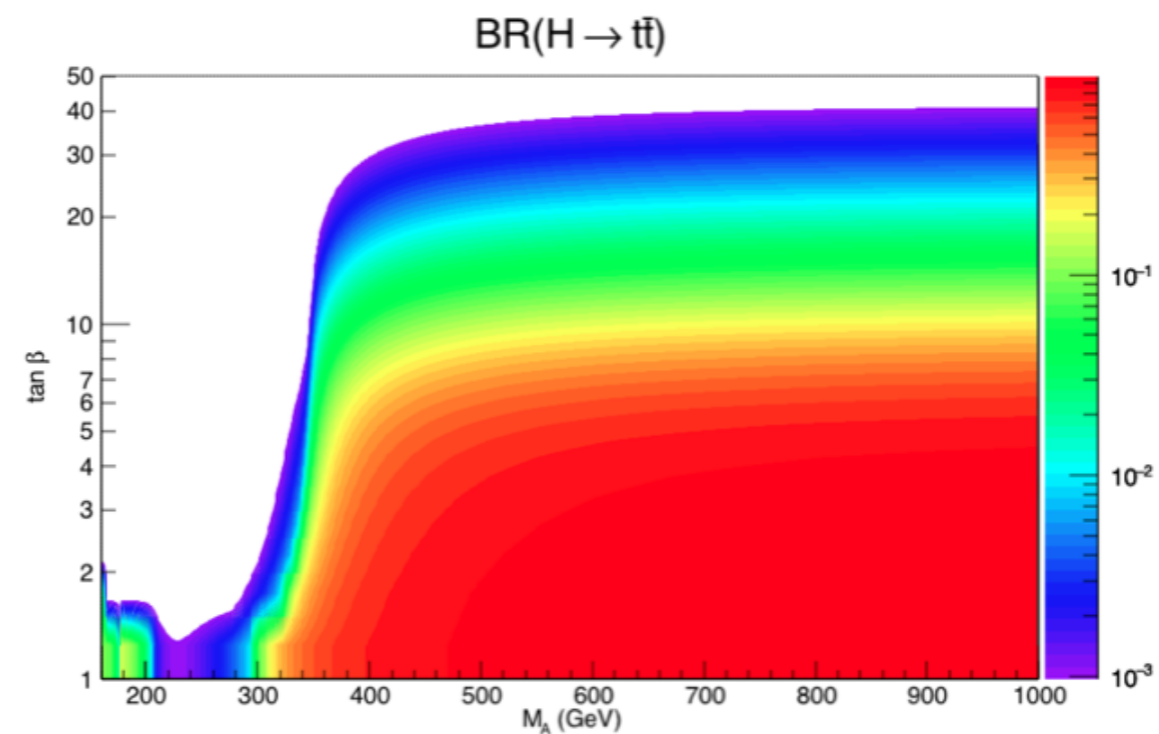
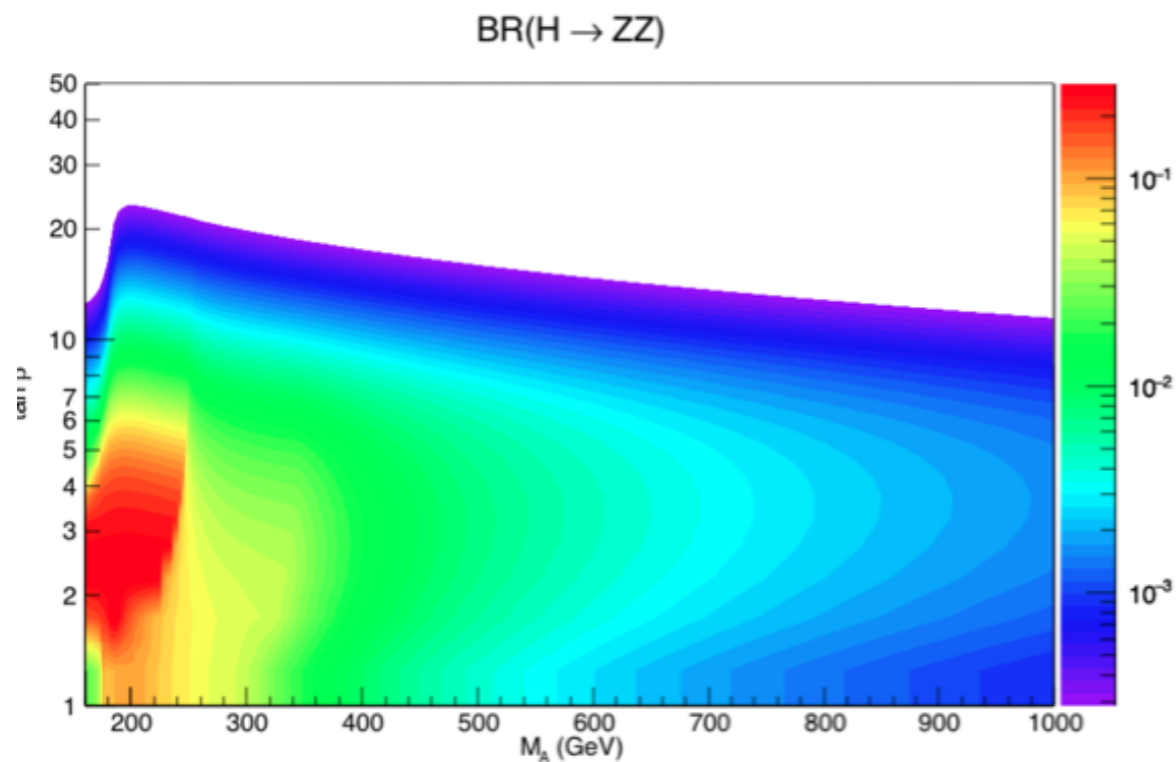
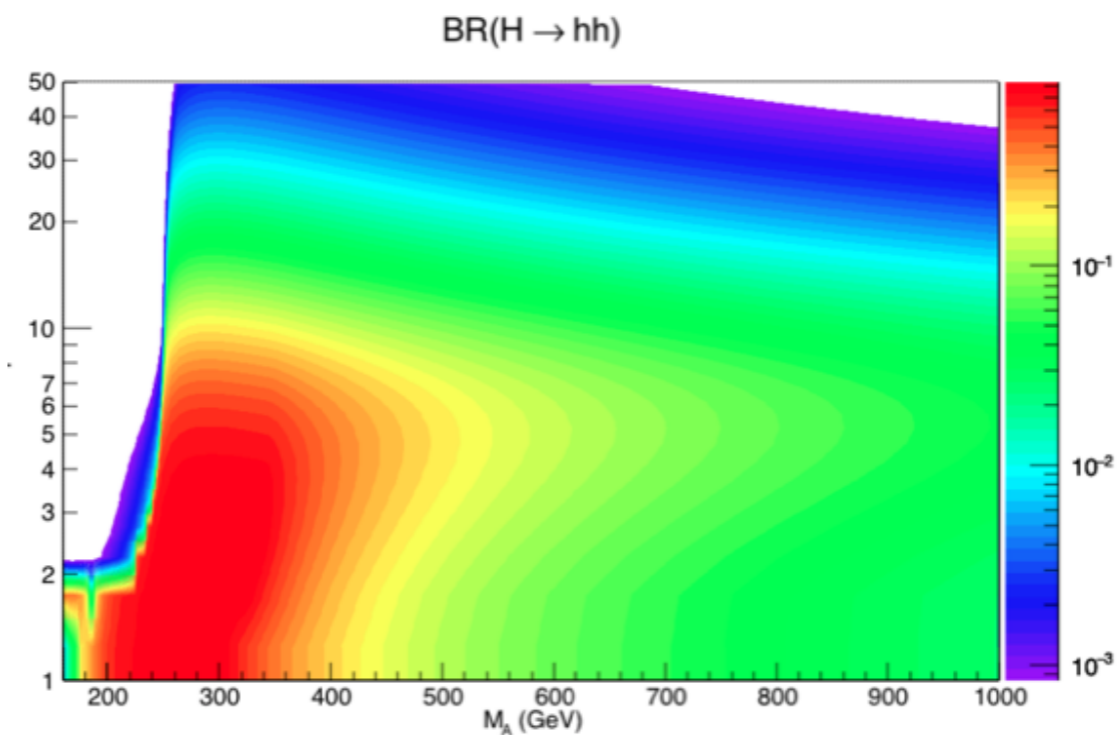
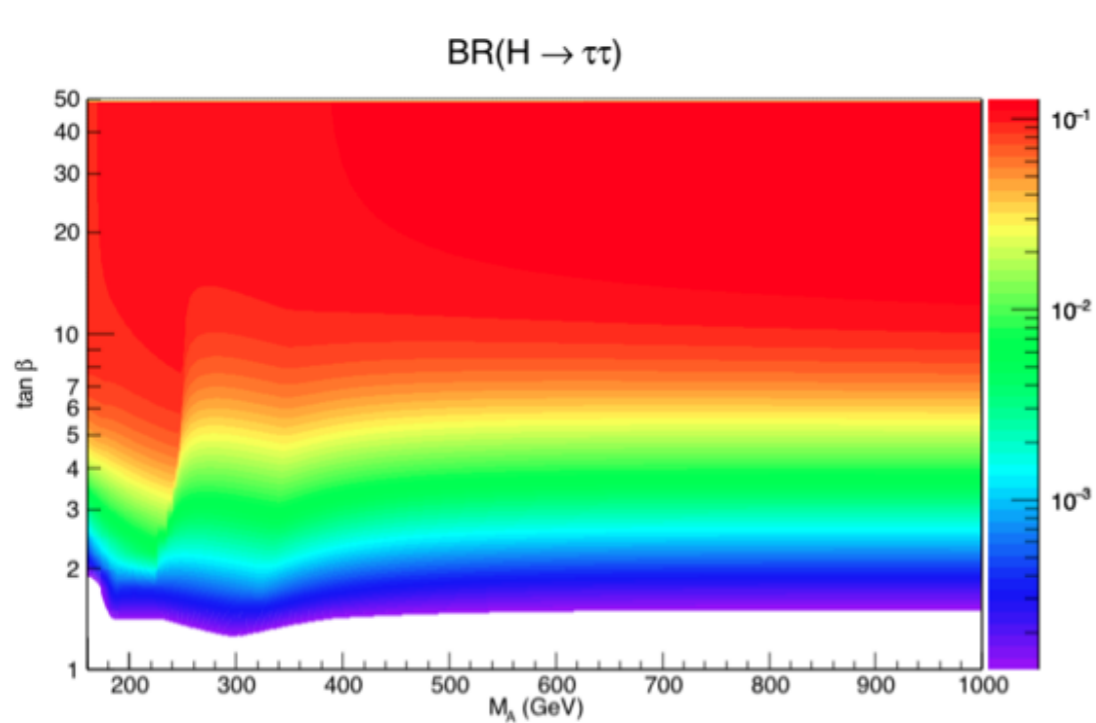
Limit on $BR(H \rightarrow Z_d Z_d) \sim 20\%$ for m_{Z_d} in 15-60 GeV range

H → DARK SECTOR

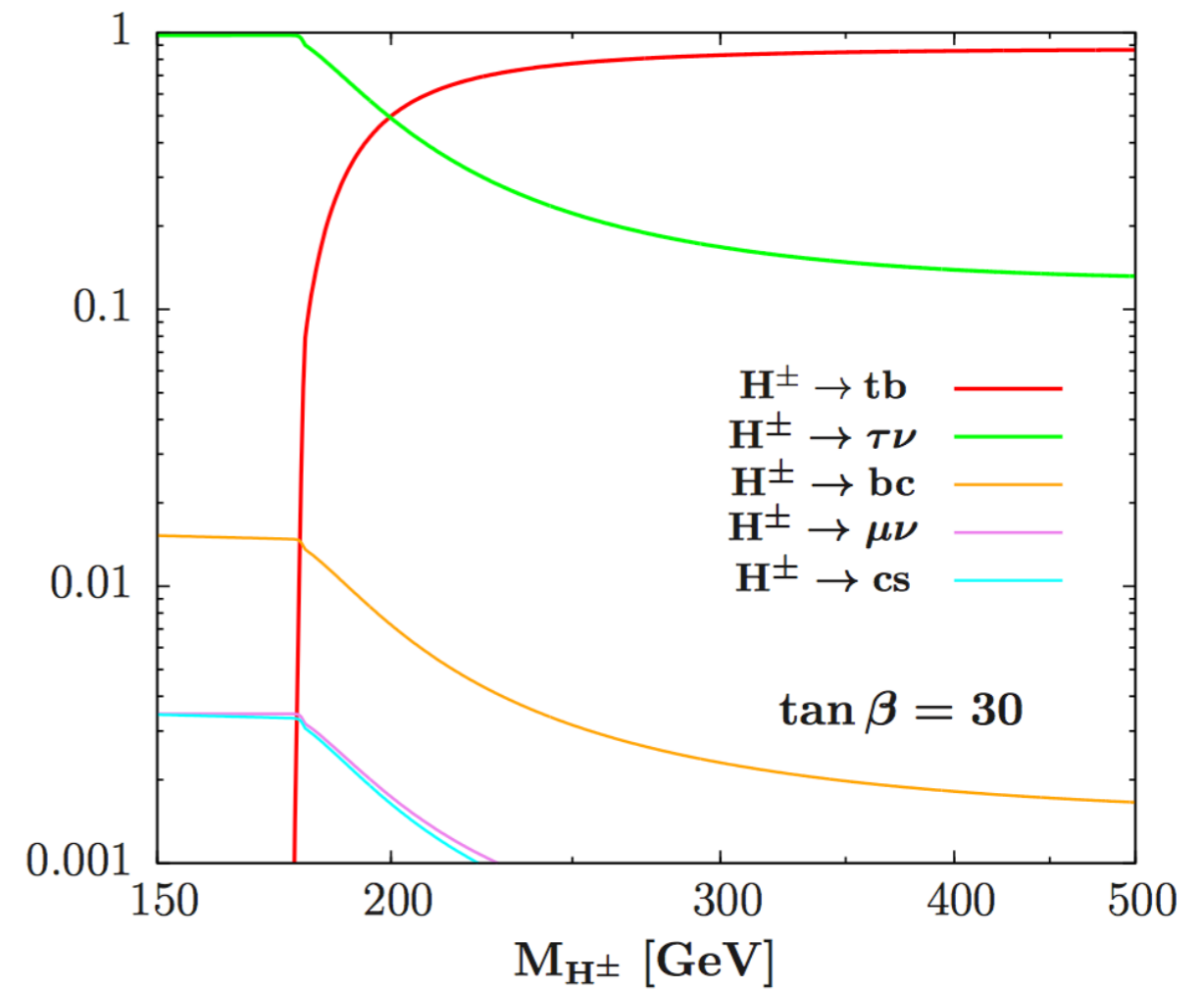
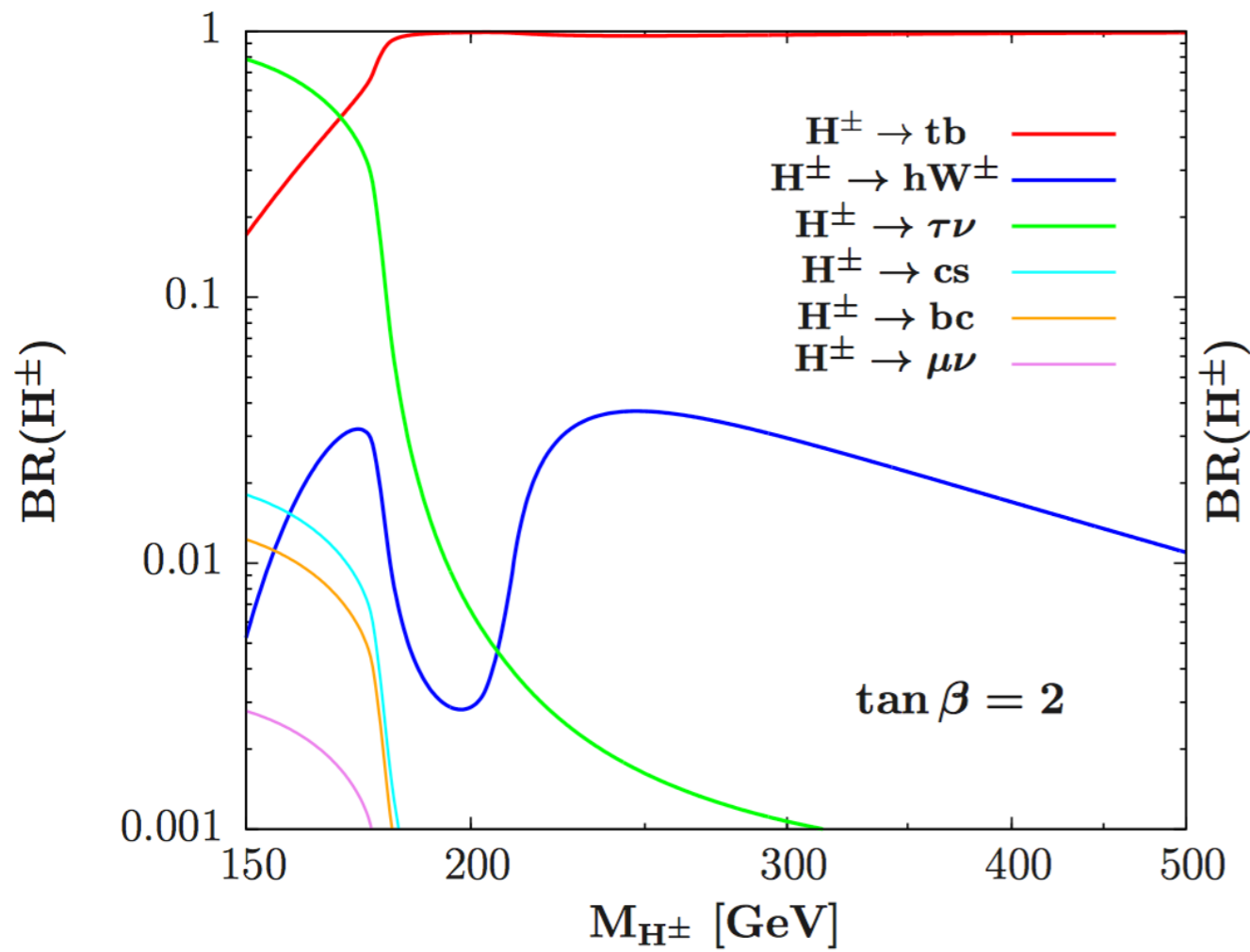
$$H \rightarrow 2\gamma_d (\rightarrow \mu\mu) + X$$



HMSSM: HEAVY HIGGS DECAYS



MSSM: CHARGED HIGGS DECAY



CHARGED HIGGS

High m_{H^+} mass: $H^+ \rightarrow tb$

di-lepton + b-jets final state

sensitive to both $H^+ \rightarrow tb$ & $H^+ \rightarrow \tau\nu$

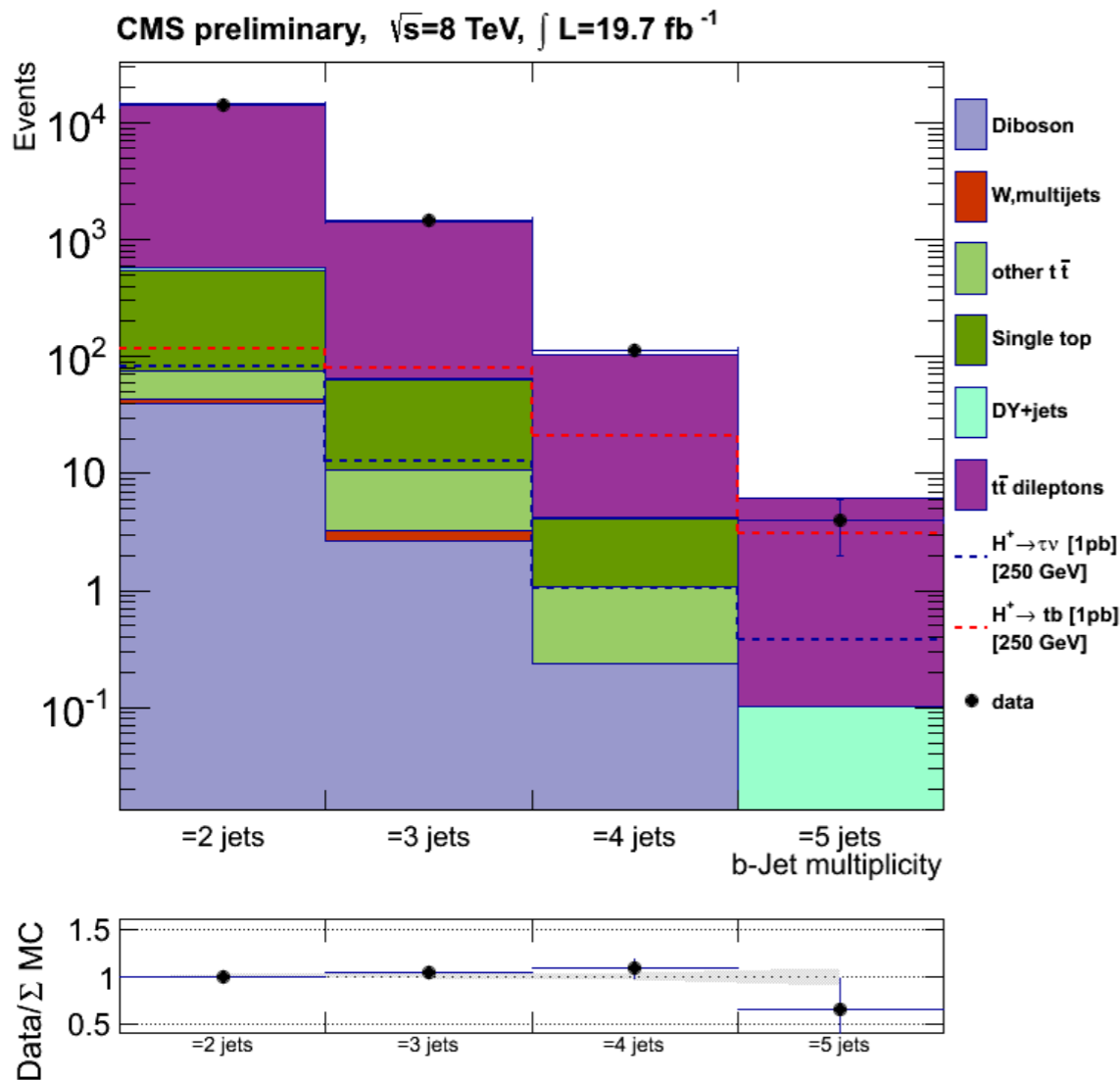
interpretation provided for $BR(H^+ \rightarrow tb)=1$ or $BR(H^+ \rightarrow \tau\nu)=1$

Higgs triplet model: $H^\pm \rightarrow W^\pm Z$

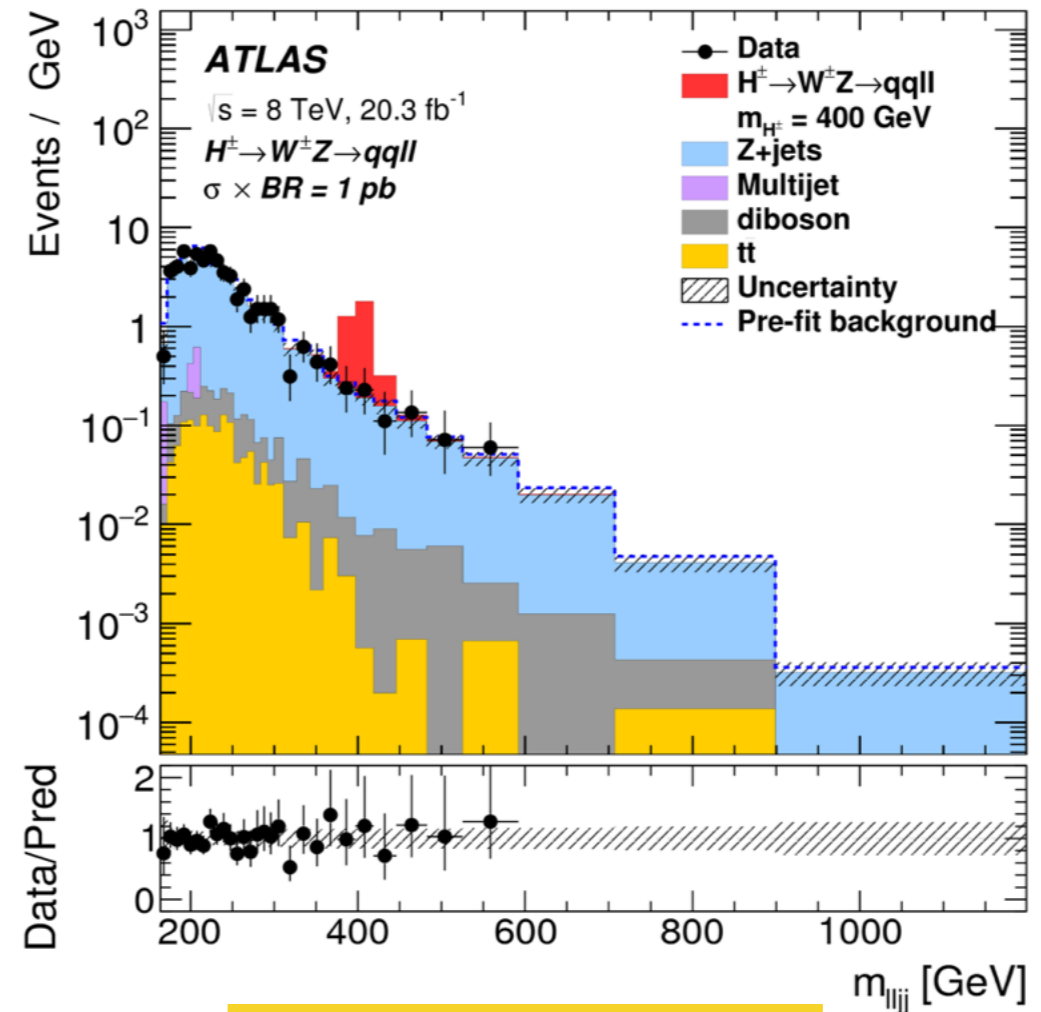
allowed at tree level

Search performed with VBF production of charged Higgs

2 jets (VBF topology), 2 central jets (W decay), 2 leptons (Z)



CMS-HIG-13-026

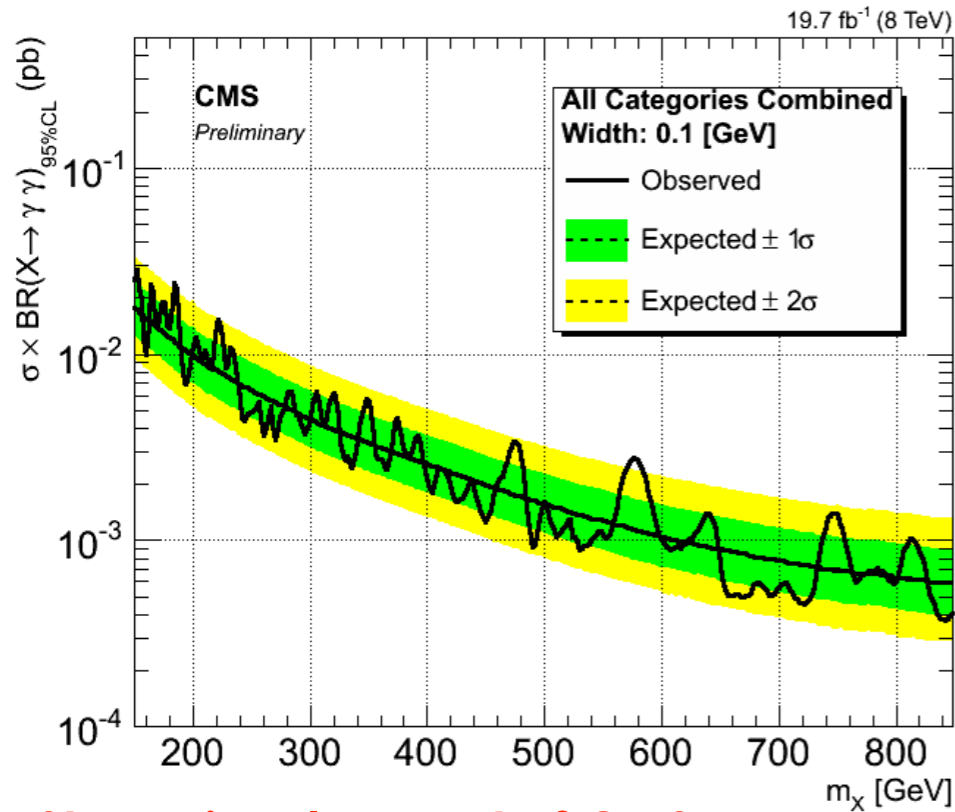


ATLAS-HIGG-2014-13

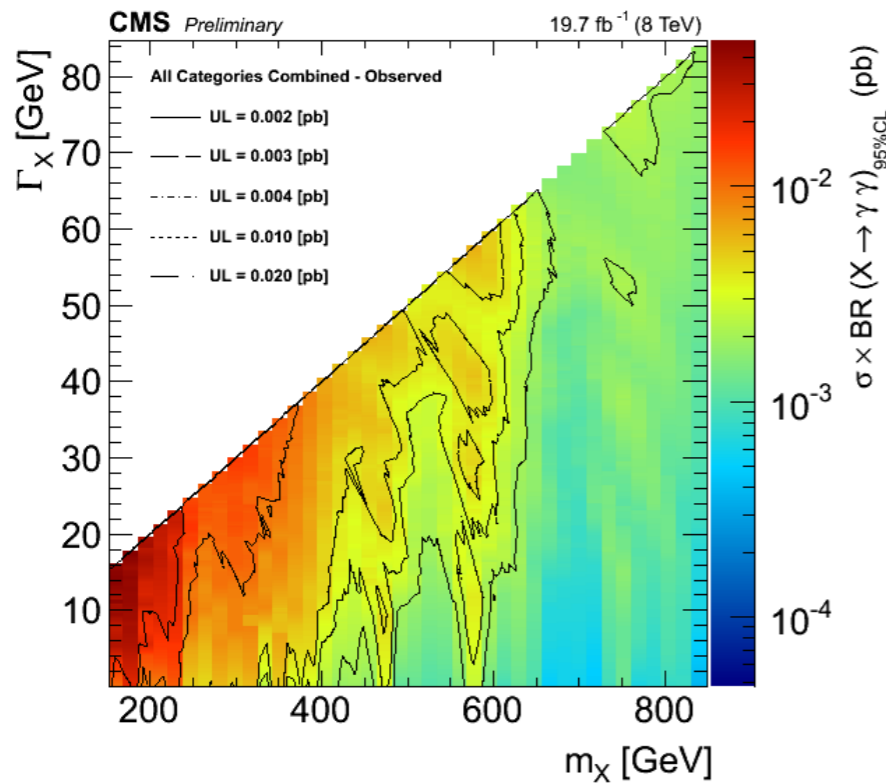
$$\phi \rightarrow \gamma\gamma, \phi \rightarrow Z\gamma$$

$\phi \rightarrow \gamma\gamma$

CMS-HIG-14-006

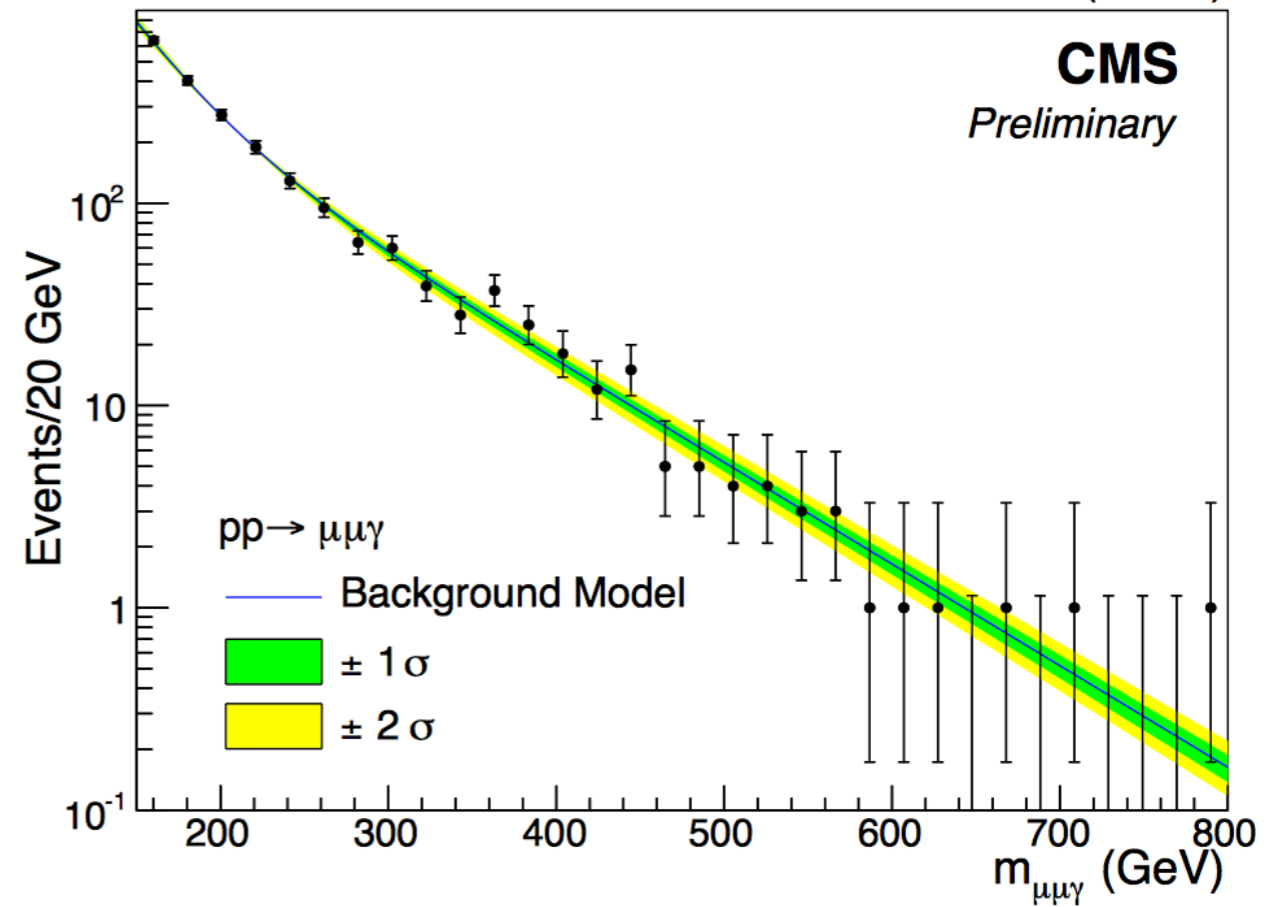


Strong involvement of CMS Rome group



$A \rightarrow Z(\rightarrow \mu\mu)\gamma$

19.7 fb⁻¹ (8 TeV)



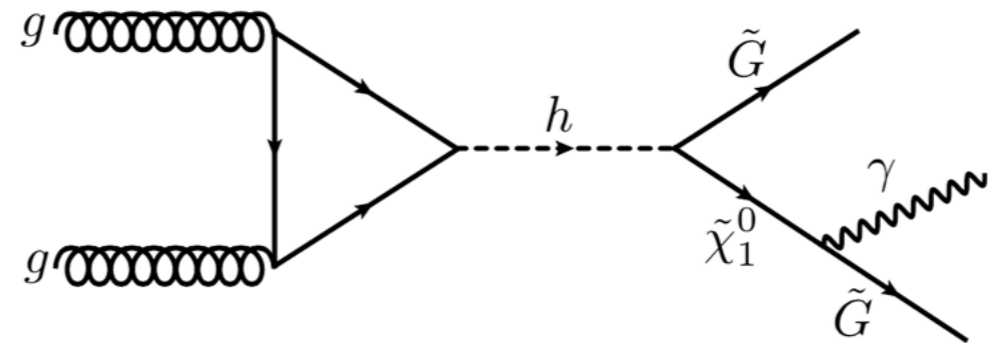
CMS-HIG-14-031

H → γ + MET

Higgs decays to neutralinos/gravitinos: γ + MET final state

GMSB $h \rightarrow \tilde{G} \tilde{\chi}^0 \rightarrow \tilde{G} \tilde{G} \gamma$

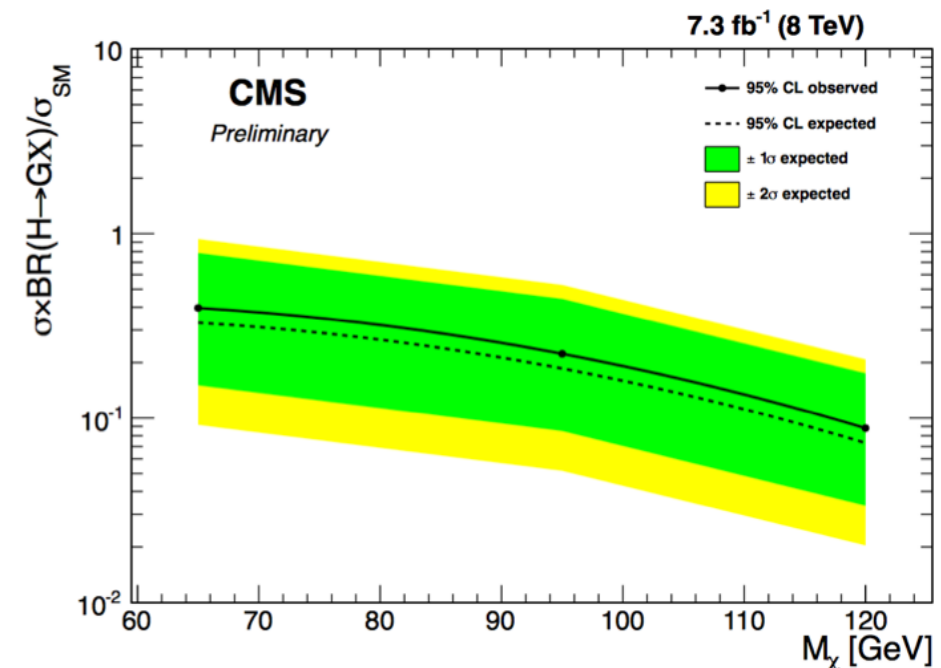
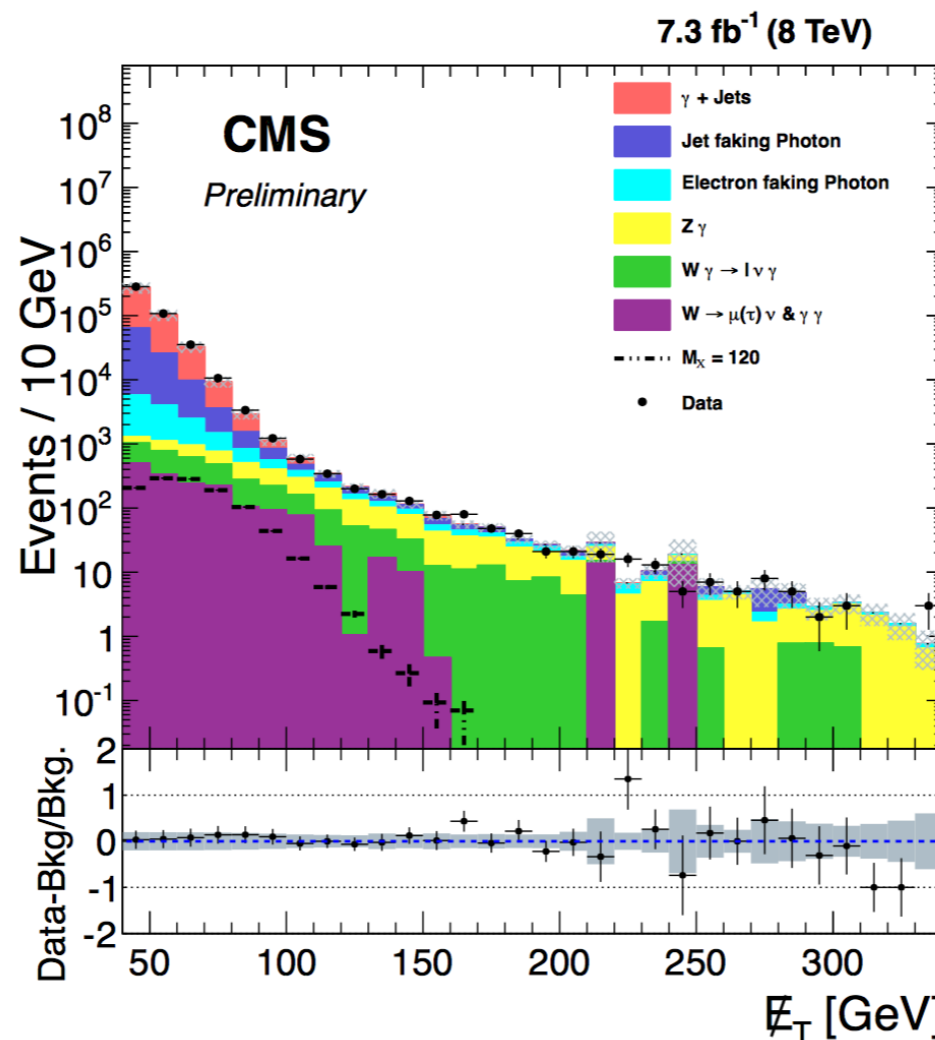
NMSSM $h \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$



CMS: inclusive analysis

γ $p_T > 45$ GeV

ATLAS: associated VBF production



Optimized for $m_h/2 < m_{\tilde{\chi}_1^0} < m_h$
below $\gamma\gamma + \text{MET}$ will dominate

CMS: HIG-14-024