Current status of MSSM Higgs bosons and future

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Kavli IPMU, The University of Tokyo, 23rd May 2018

Plan

- Status of 125 GeV Higgs boson
- Bounds on MSSM Higgs bosons
- SUSY decay modes of MSSM Higgs bosons
- Higgs self coupling measurements and new physics effects
- Conclusion

Current status

We have found the (a) Higgs boson

Properties: consistent with SM Higgs boson

New Physics:No evidence so far

Many experiments : UA, LEP, HERA, Tevatron, LHC, Xenon, ···

Search results are translated to exclusion limits

Higgs boson: current status

Spin parity ?

New decay modes ?

Differential distributions ?

Total decay width ?

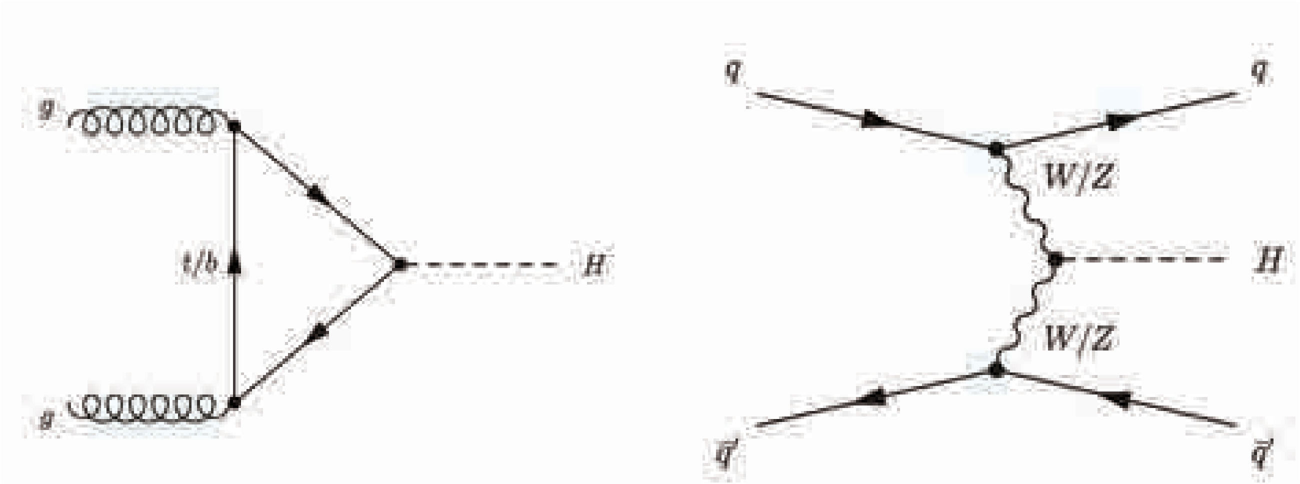
Couplings ?

Additional Higgs bosons ?

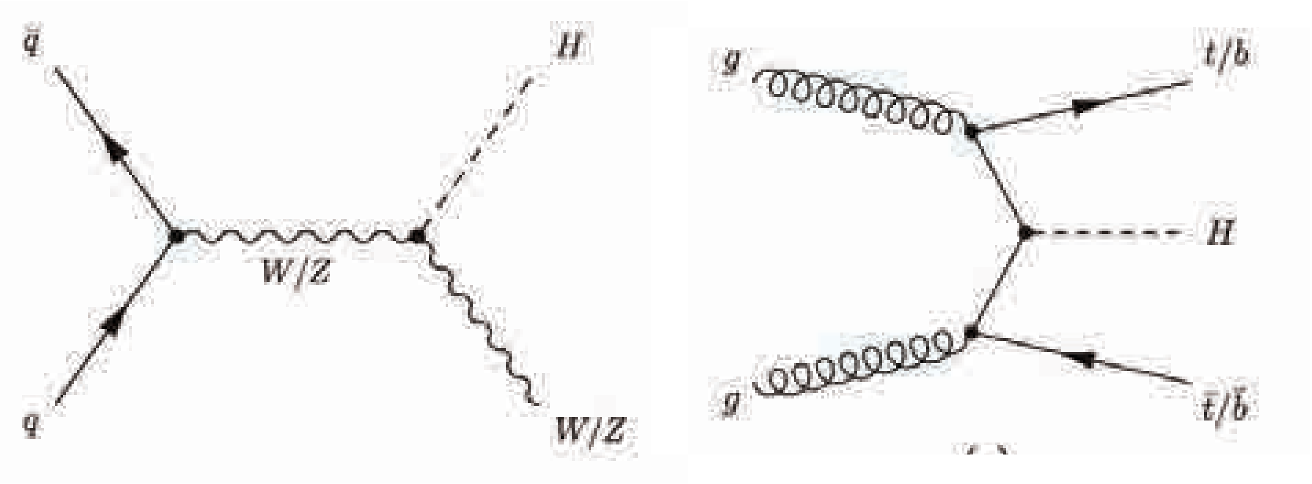
Higgs boson at the LHC

1606.02266

Higgs productions :



dominant



subdominant

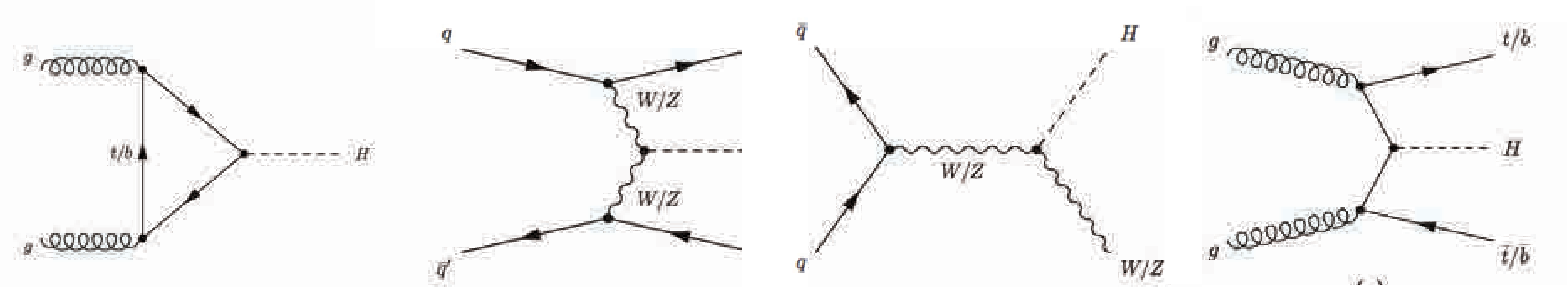
$$\sigma(pp \to H) :\sim 21pb \overset{8\ TeV \to 13\ TeV}{\longrightarrow} 49pb$$

$$\sigma(pp \to ttH) :\sim 130fb \overset{8\ TeV \to 13\ TeV}{\longrightarrow} 507fb$$

1606.02266

Higgs boson at the LHC

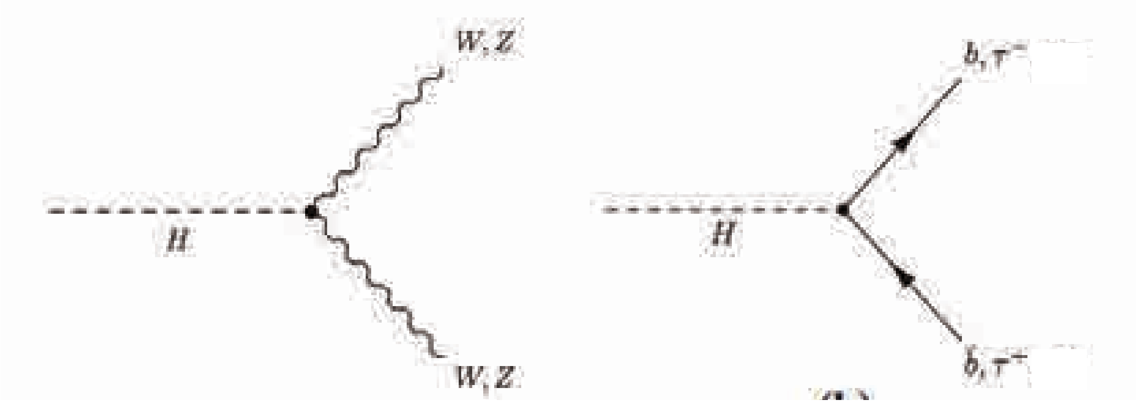
Higgs productions :



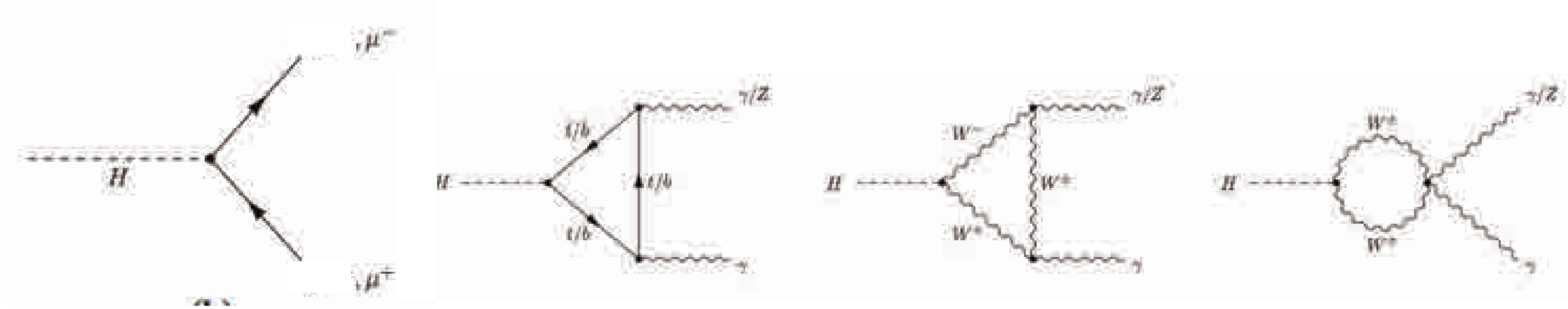
$$\sigma(pp\to H) :\sim 21pb \overset{8\ TeV\to 13\ TeV}{\longrightarrow} 49pb$$

$$\sigma(pp\to ttH) :\sim 130fb \overset{8\ TeV\to 13\ TeV}{\longrightarrow} 507fb$$

Higgs Decays :



dominant



rare

Higgs measurements: signal strength variables

Consider a process g g -> H -> Z Z*

Signal strength: μ

$$\mu_{gg} = \frac{\sigma(gg \rightarrow h) Br(h \rightarrow ZZ^{*})}{\sigma(gg \rightarrow h)_{SM} Br(h \rightarrow ZZ^{*})_{SM}}$$

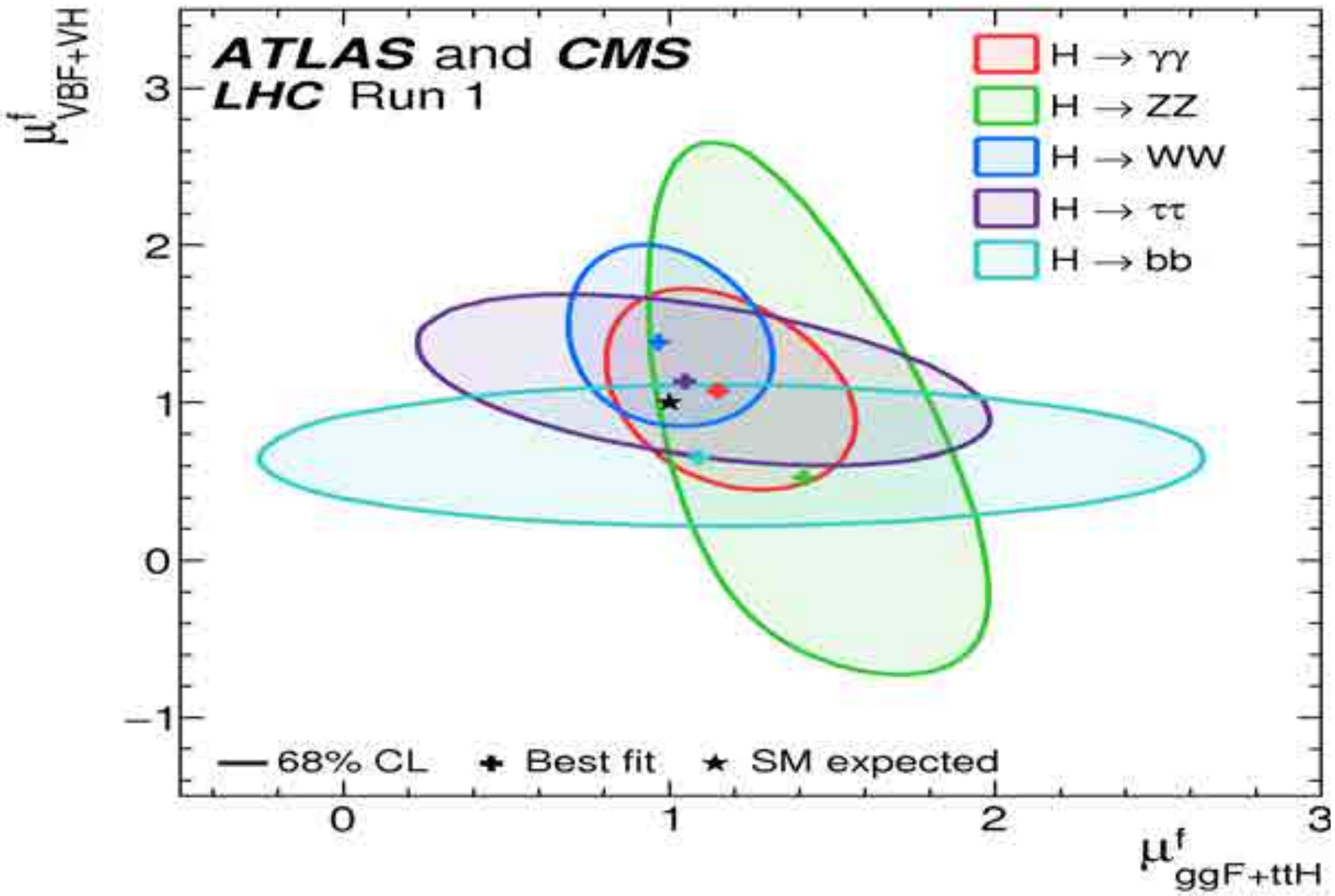
Observed

Expected

Combine different production and decay process

Expectation for SM Higgs : μ for all channels ~ 1.

Higgs measurements: Run I



Combination of ATLAS+ CMS run I data (68% CL)

1606.02266

Observations : Large deviations are excluded but signal strengths < 1 and ~1.5 -2 are not ruled out everywhere

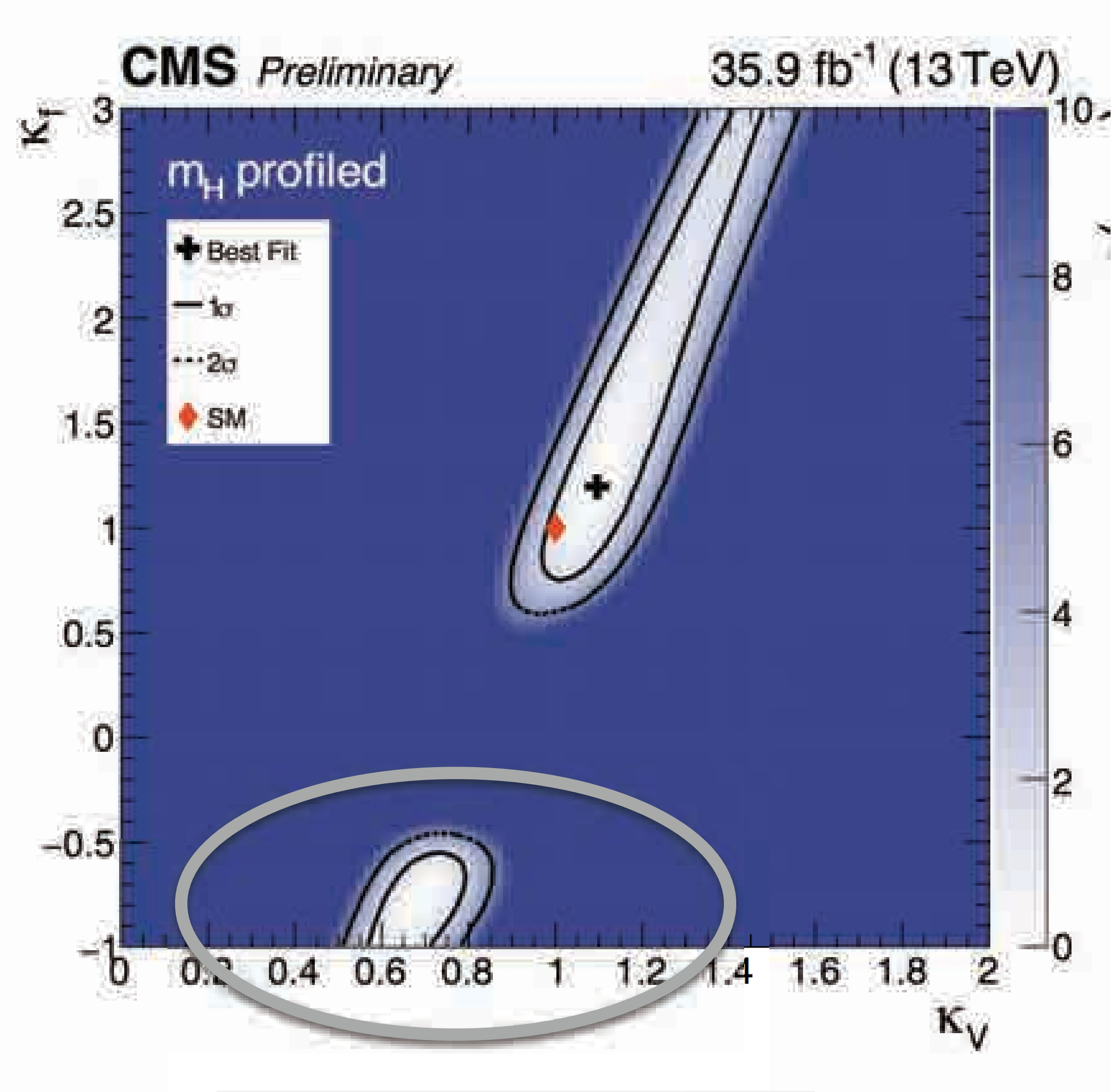
Note: signal strength of an individual channel ~1 may be possible in BSM model

Higgs measurements: Run II

$$H \to \gamma\gamma$$

$$g_{VVH} = \kappa_V * g^{SM}_{VVH}$$

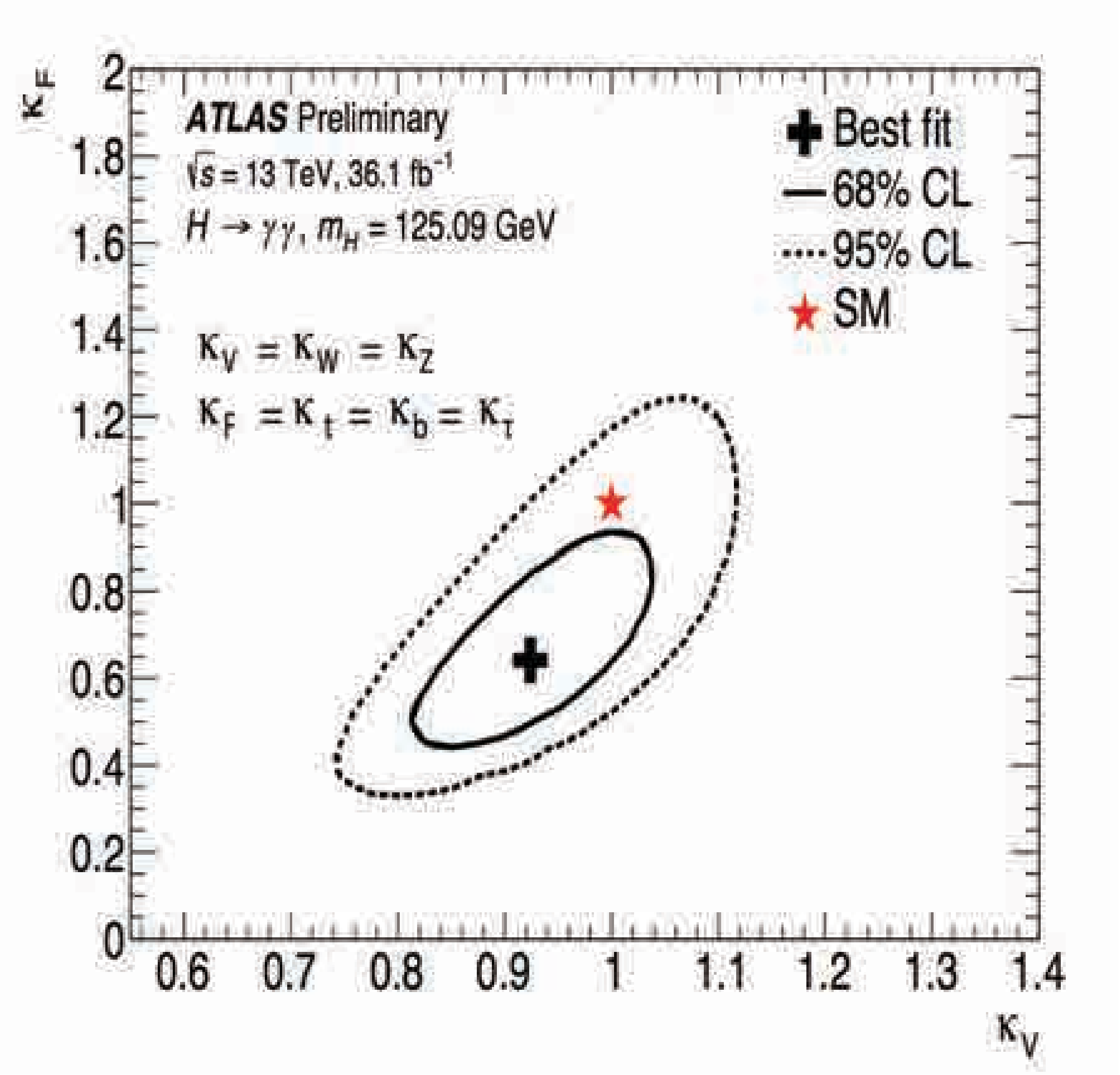
$$\mu_{\gamma\gamma} = 1.16^{+0.15}_{-0.14}$$



CMS PAS HIG-16-040

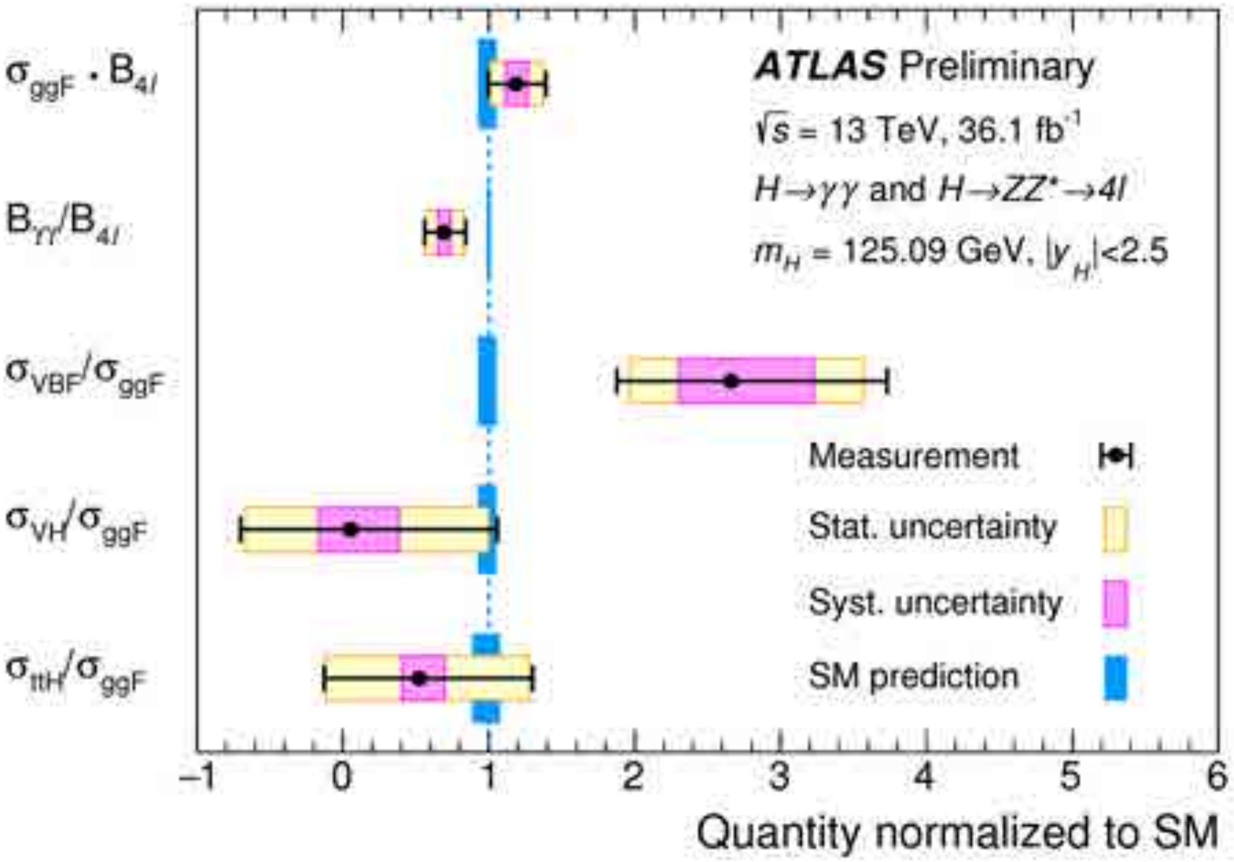
$$g_{ffH} = \kappa_f * g^{SM}_{ffH}$$

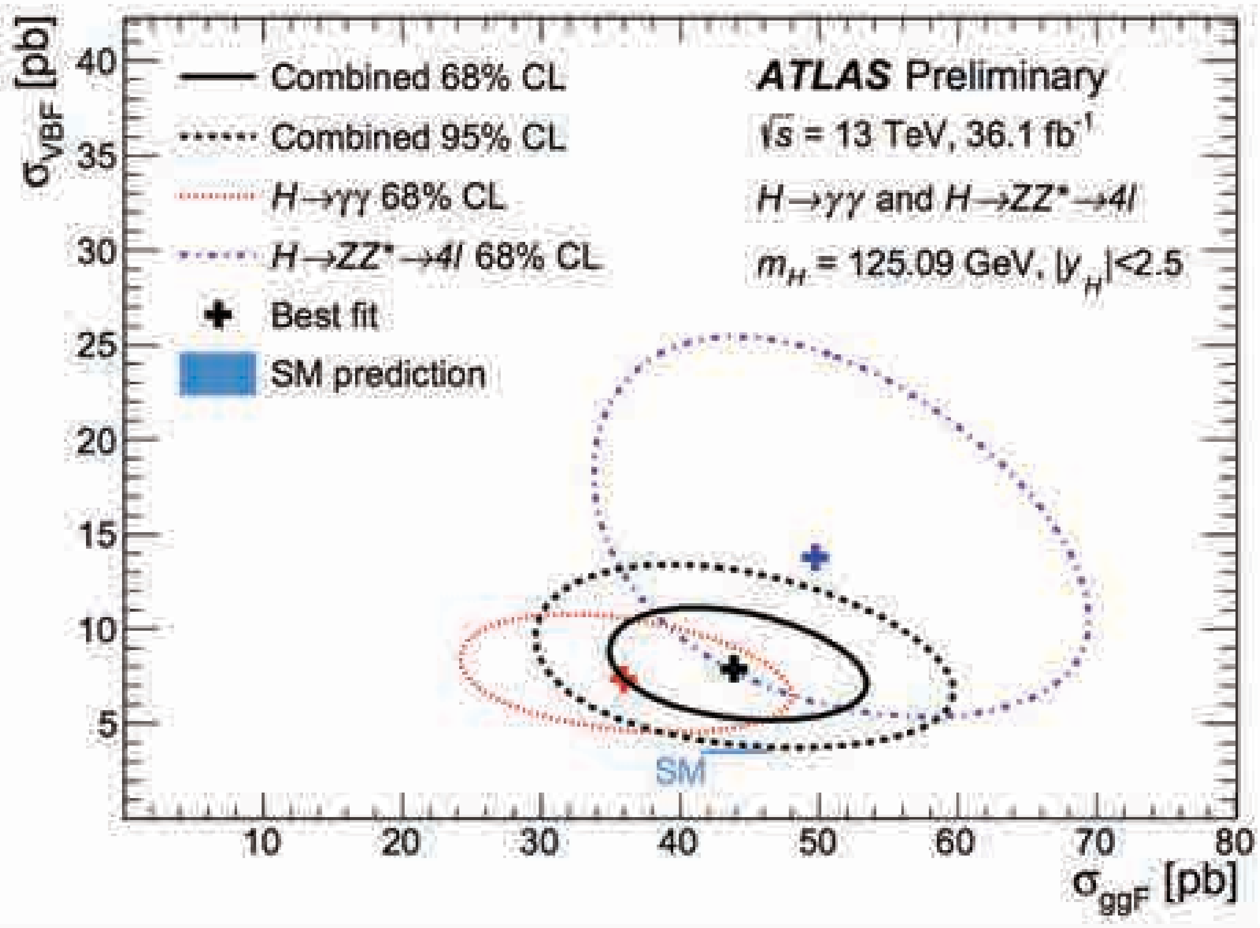
$$\mu_{\gamma\gamma} = 0.99^{(\sim+0.15)}_{(\sim-0.13)}$$



Higgs measurements: Run II

$$H \to ZZ^*$$





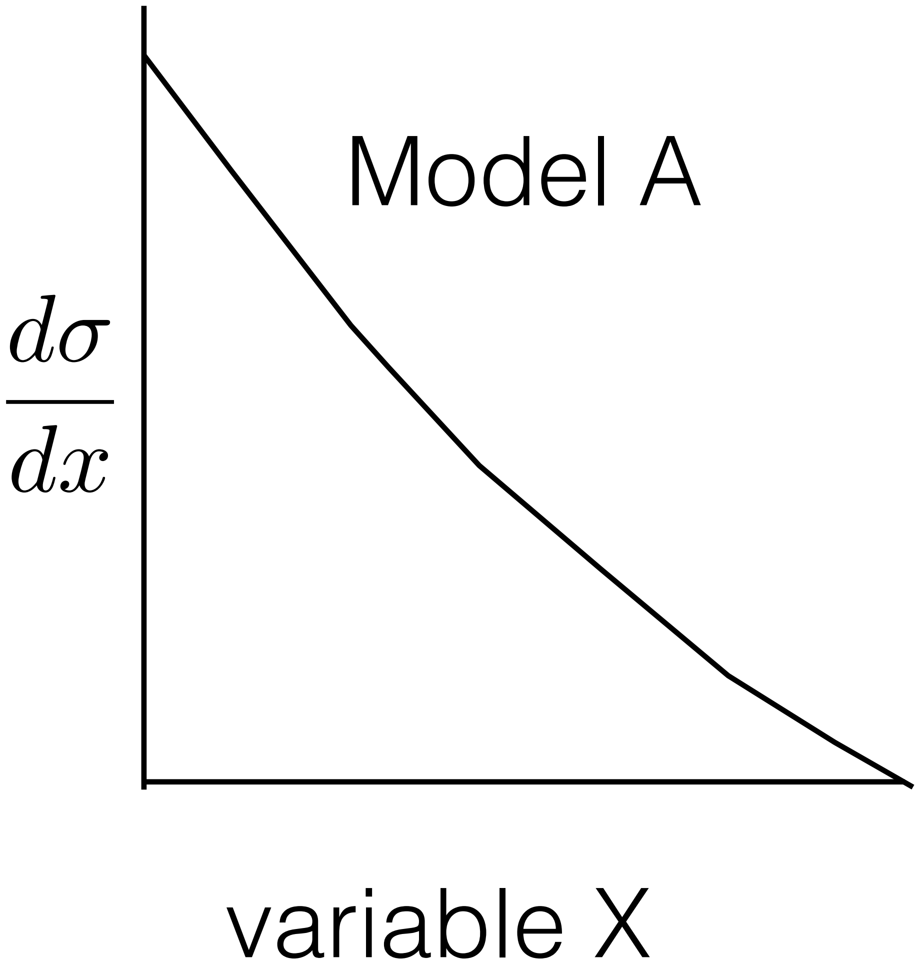
ATLAS-CONF-2017-047

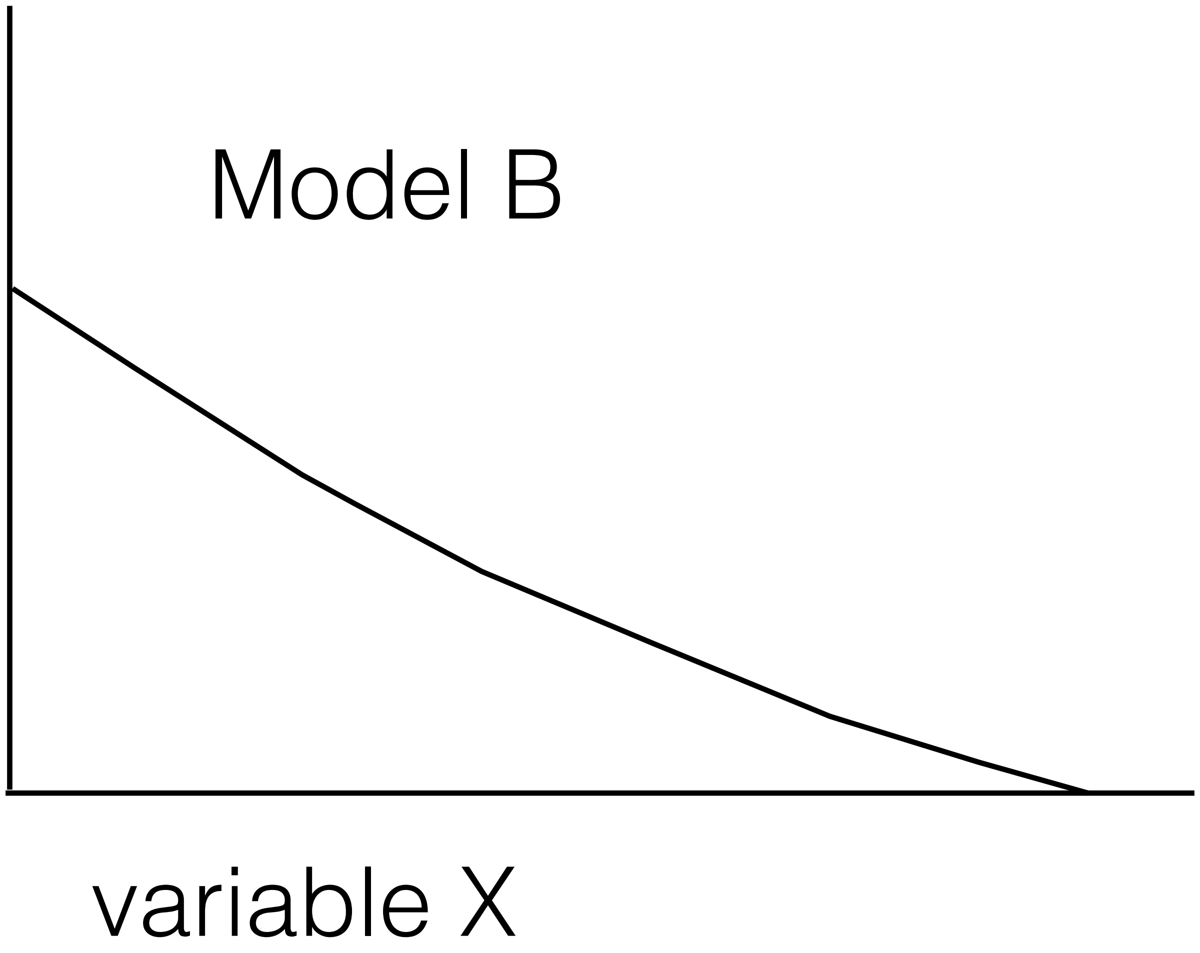
some upward fluctuation in VBF channel,

ggF is consistent with SM

Inclusive vs differential

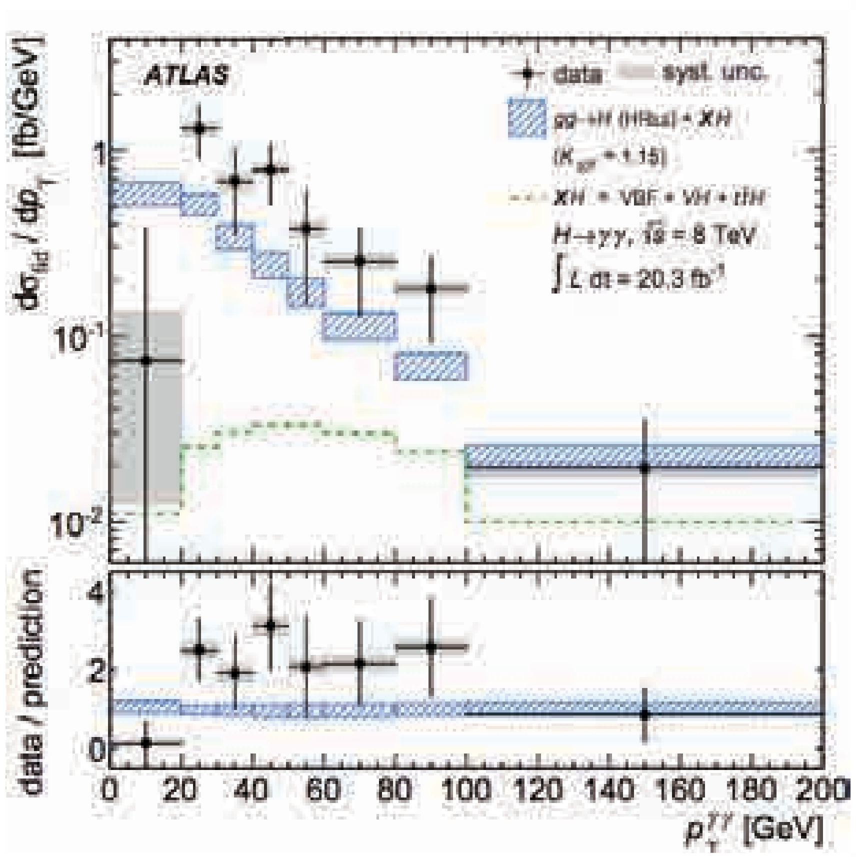
Inclusive cross section $\int \frac{d\sigma}{dx} dx = \sigma$

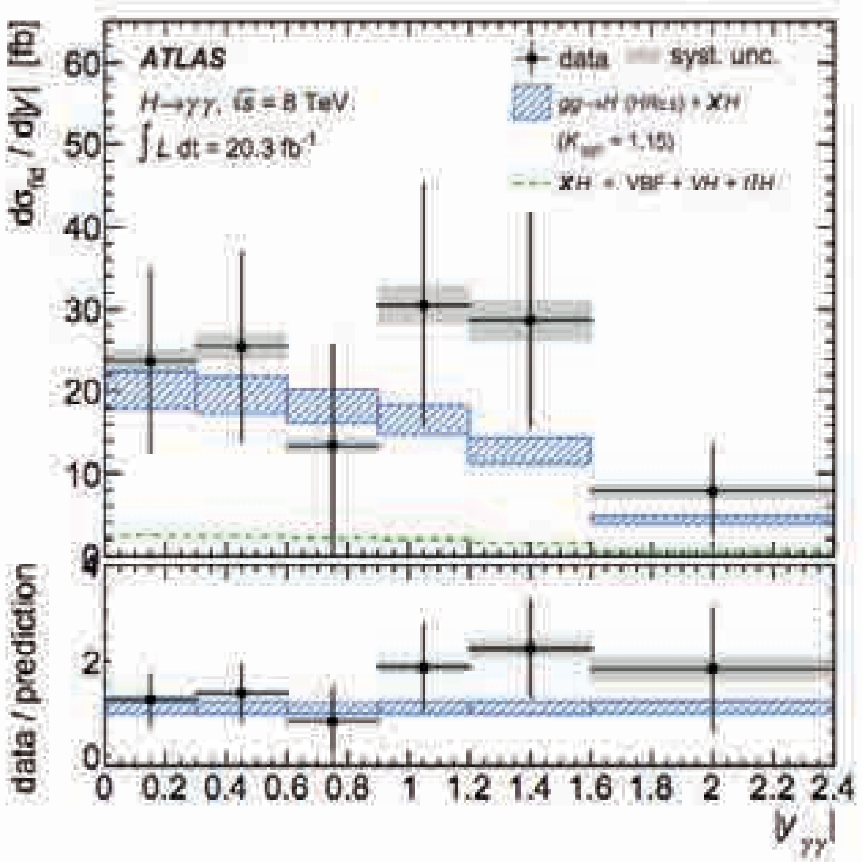


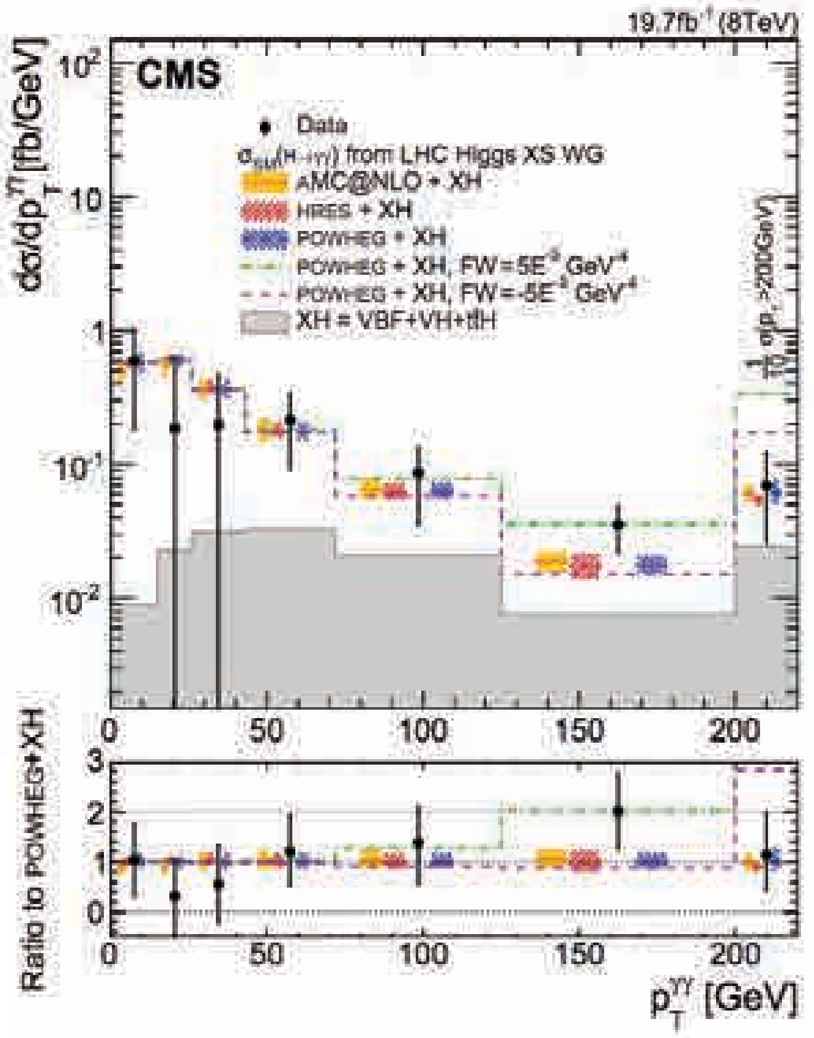


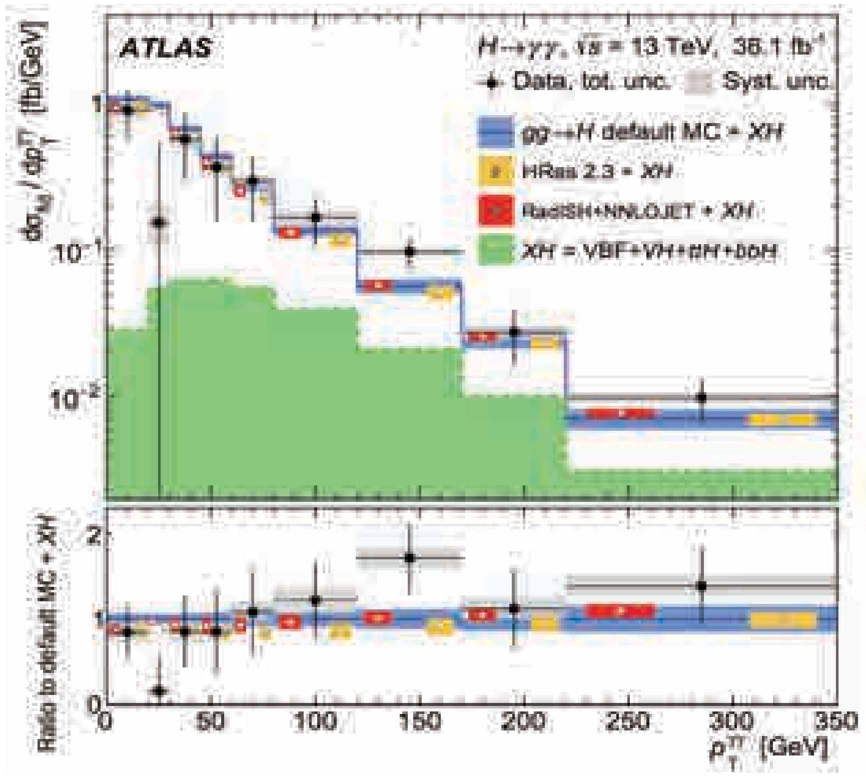
Inclusive cross section same but not the differential cs

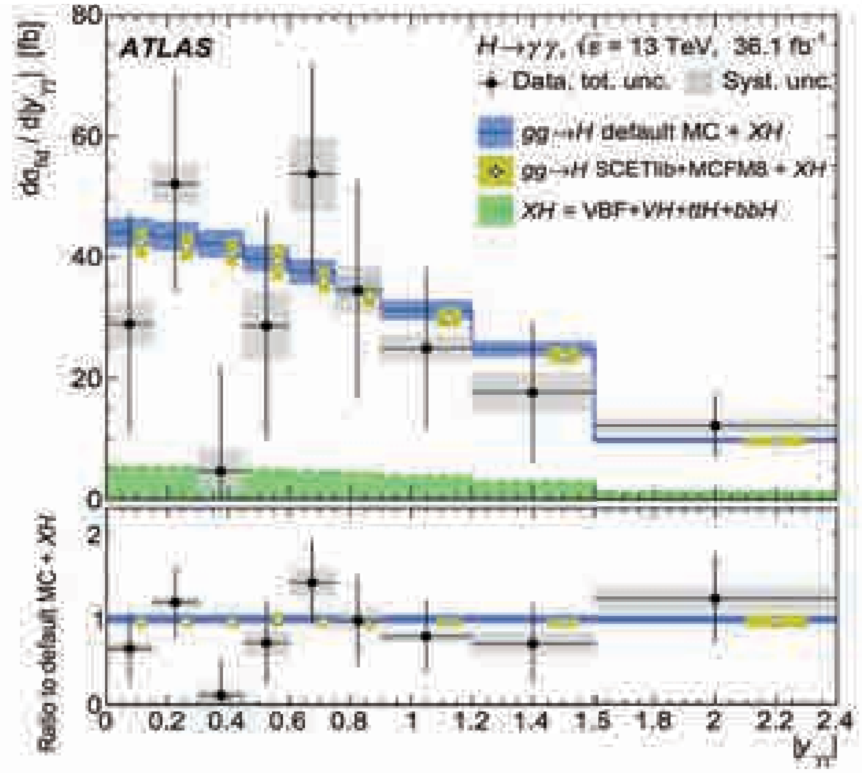
Higgs boson differential distributions











1802.04146

Total decay width of Higgs boson

(SM Higgs Width ~ 4 MeV)

Direct measurement : Determination of Higgs width by fitting Higgs(ZZ, gamma gamma) invariant mass distribution

Detector resolution very important

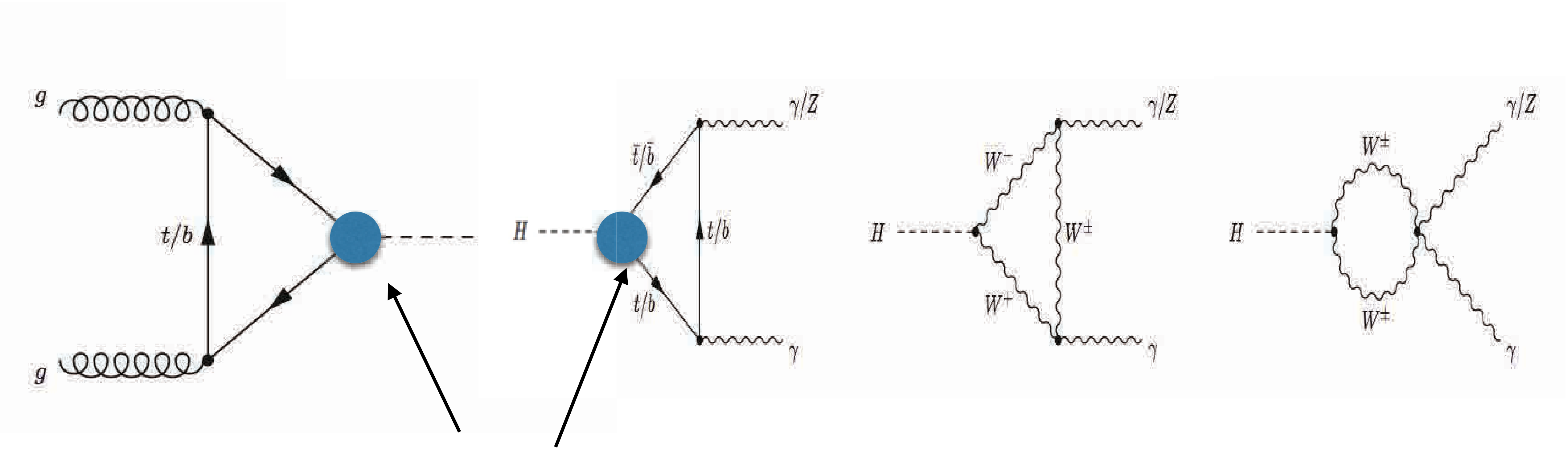
↓

Upper limit on Higgs width ~ GeV

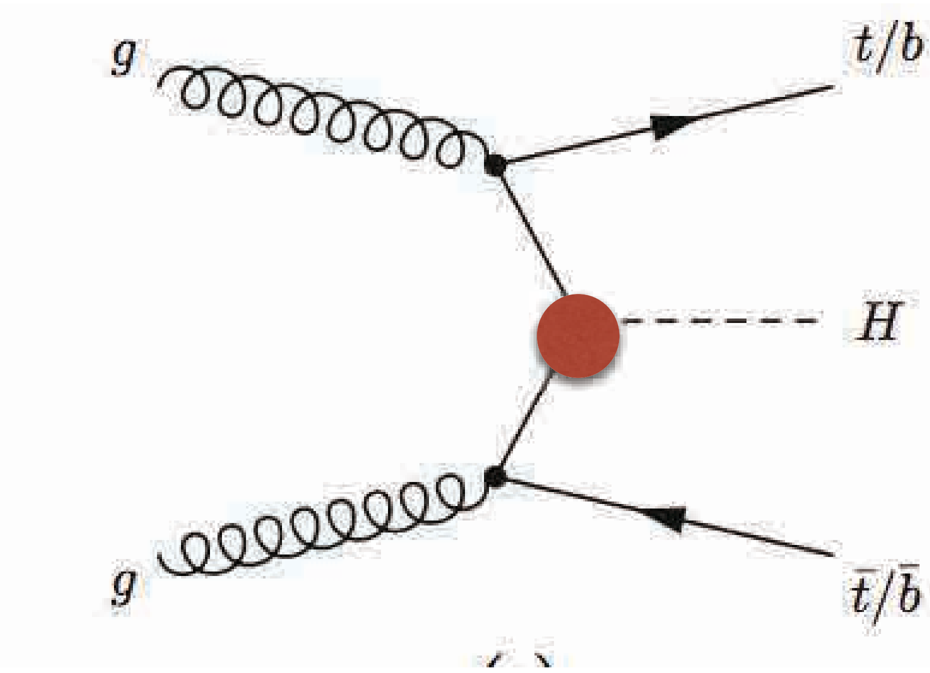
Indirect measurement : calculated from the ratio of on-shell and off-shell cross sections ~22-23 MeV

CMS-HIG-14-002 **1503.01060**

gluon fusion vs ttH process



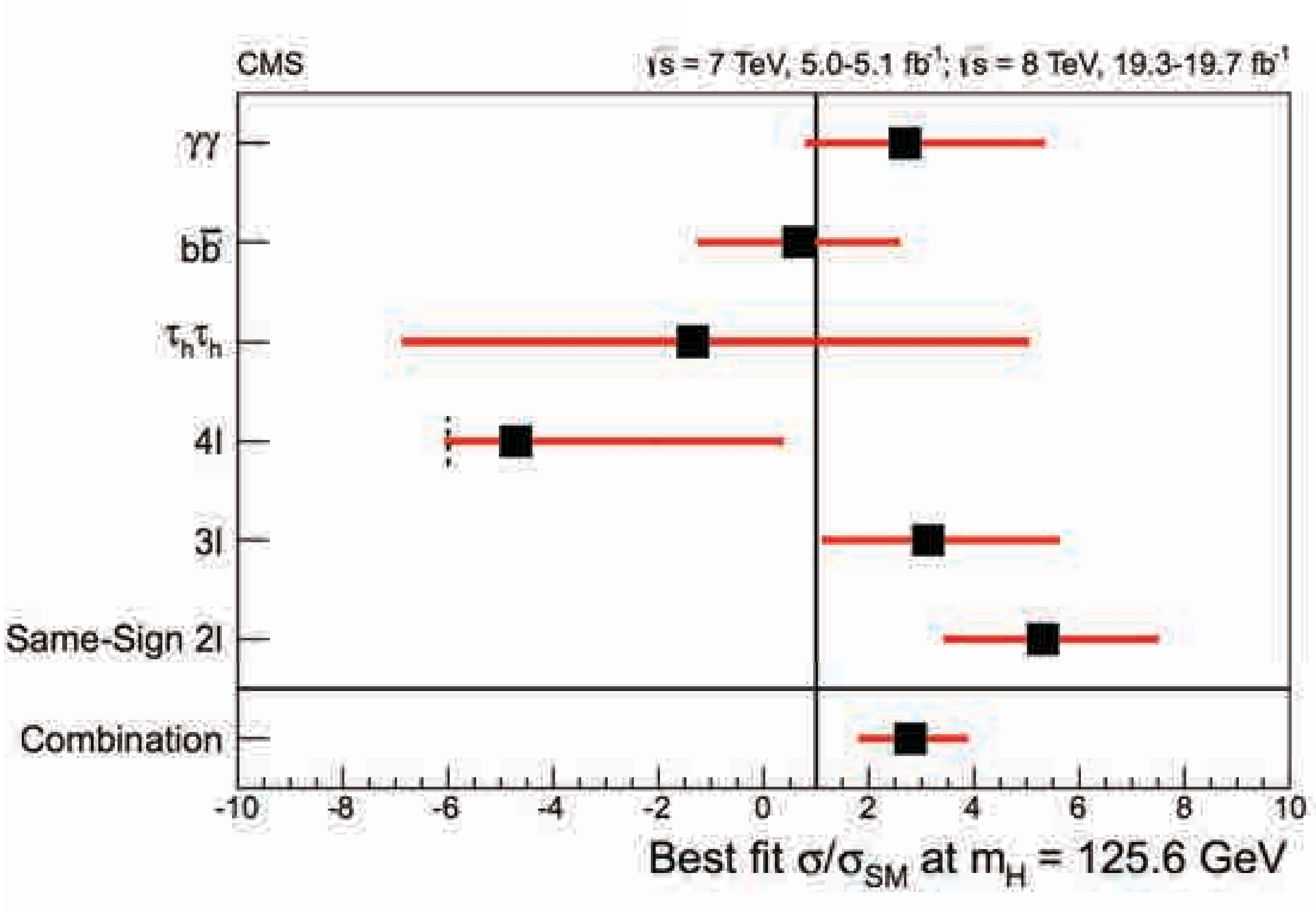
Indirect measurement of y_t

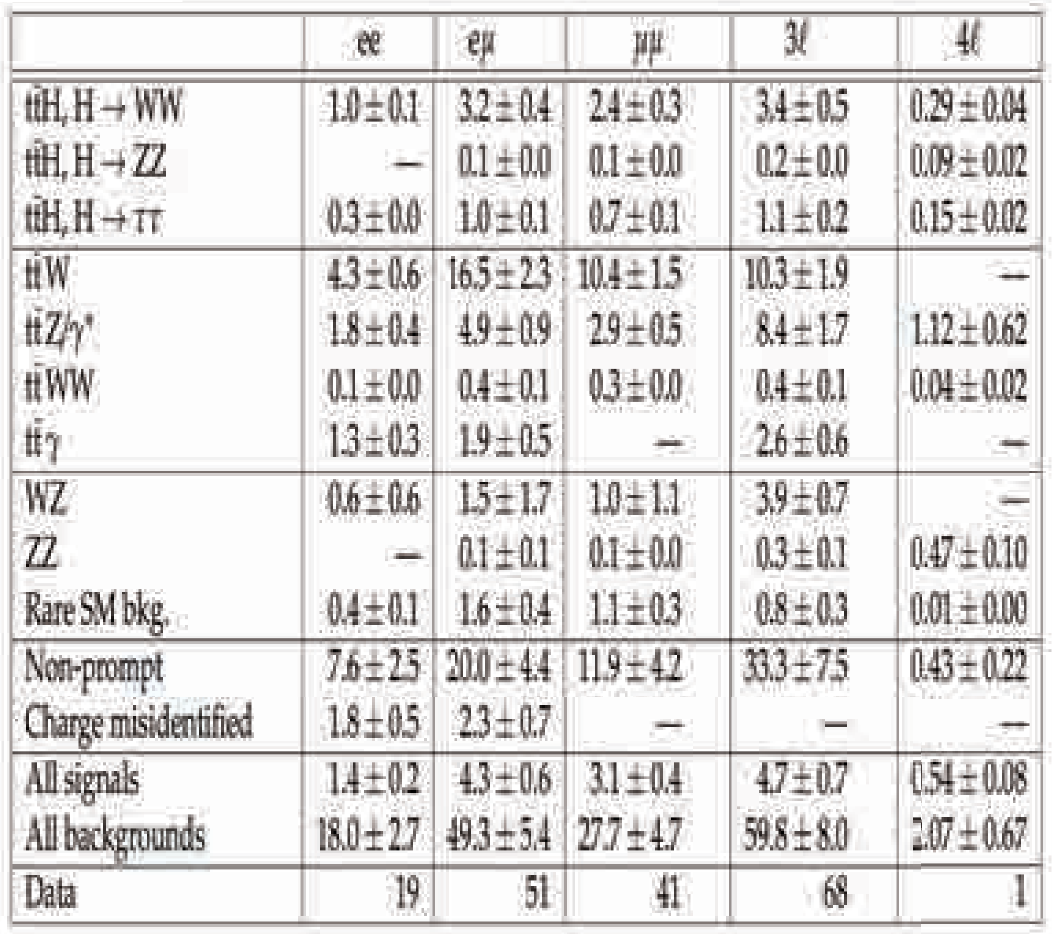


Direct measurement of top Yukawa

ttH (CMS 8 TeV)

1408.1682

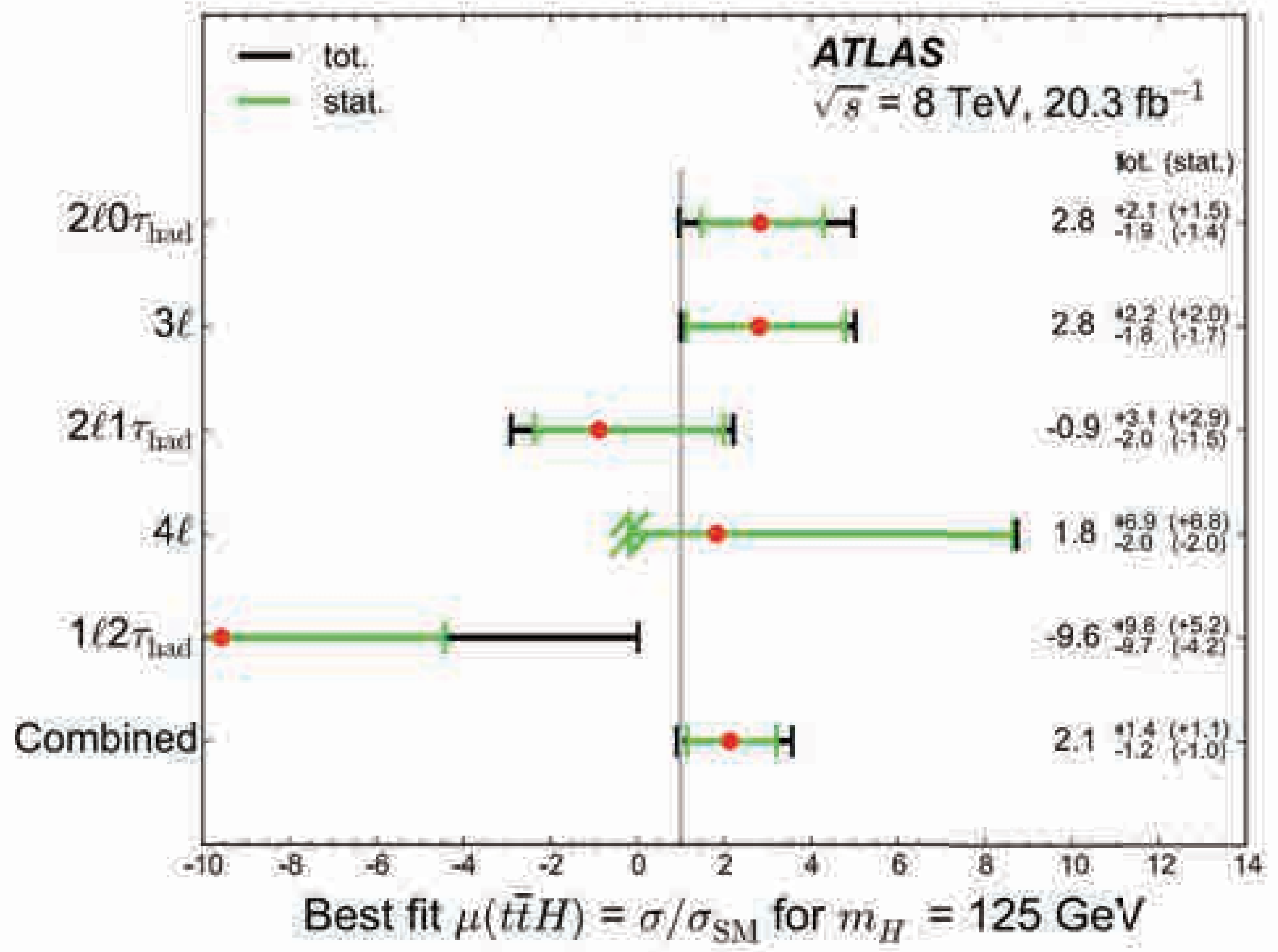




	ee	$e\mu$	$\mu\mu$	3ℓ	4ℓ
$t\bar{t}H$, $H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H$, $H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H$, $H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

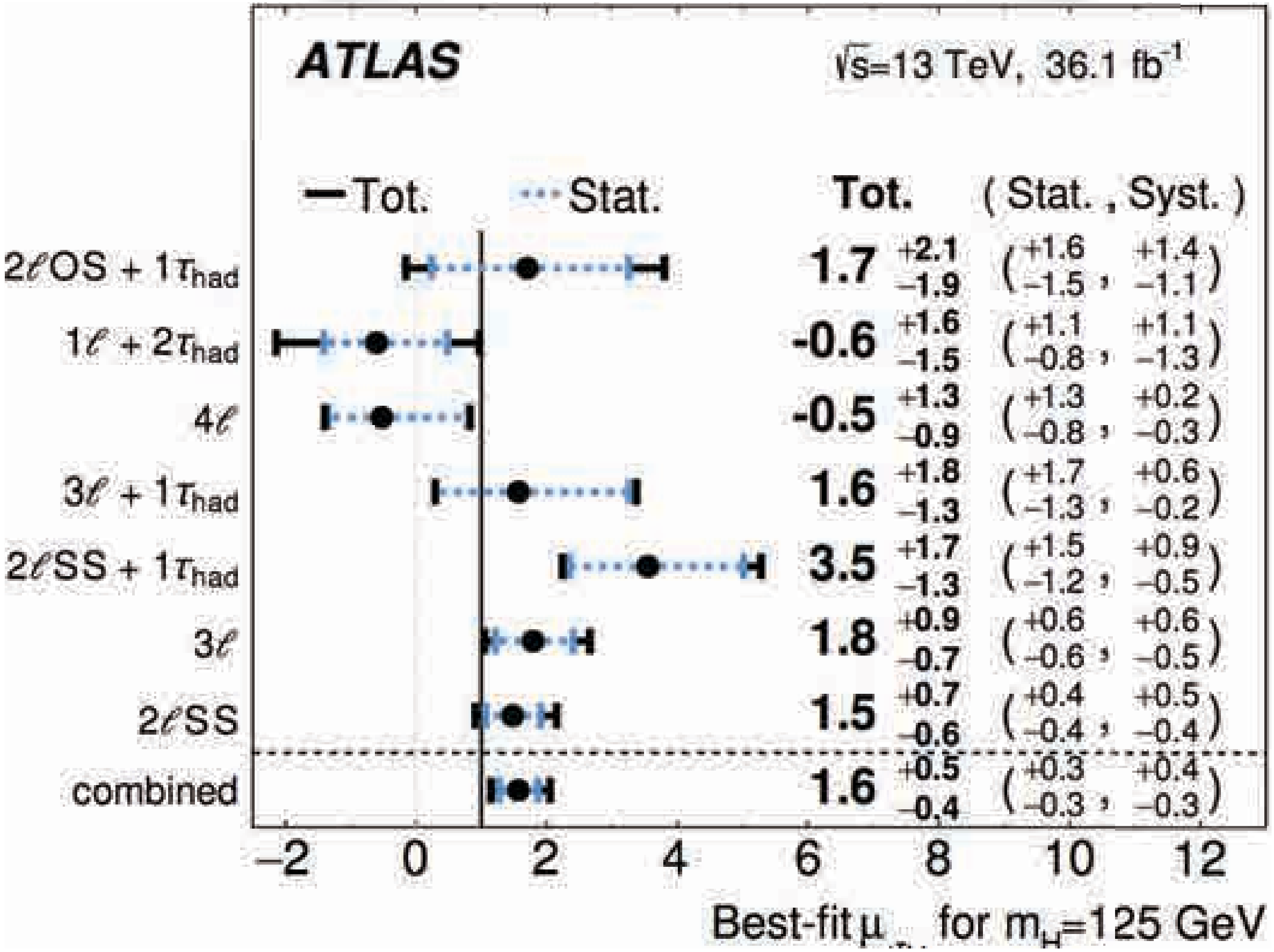
ttH (ATLAS 8 TeV)

1506.05988

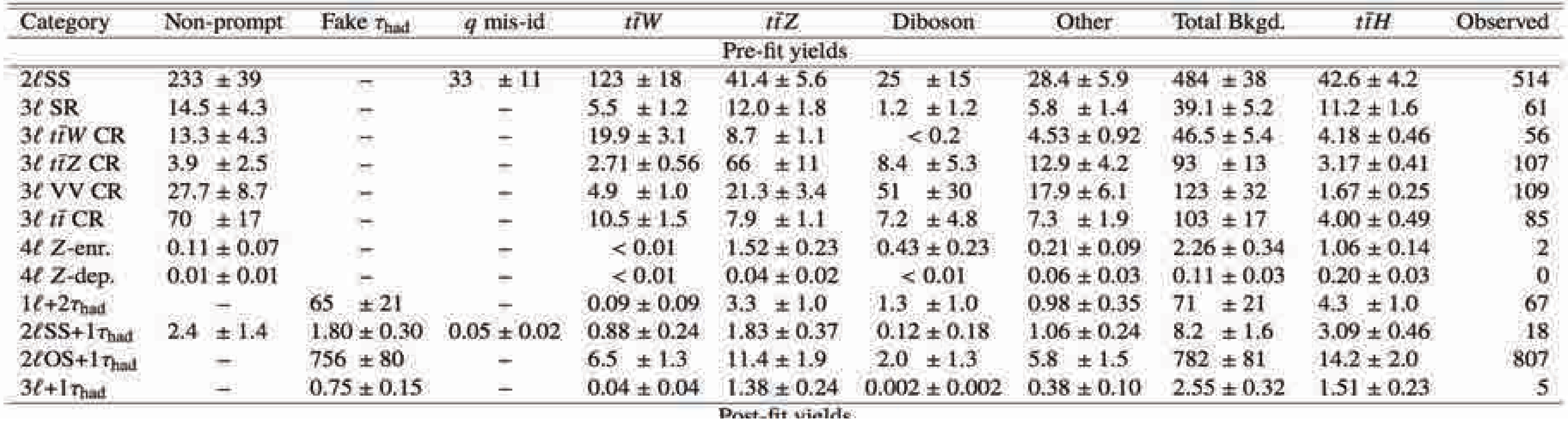


Category	q mis-id	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected bkg.	$t\bar{t}H$ ($\mu = 1$)	Observed
$ee + \geq 5j$	1.1 ± 0.5	2.3 ± 1.2	1.4 ± 0.4	0.98 ± 0.26	0.47 ± 0.29	6.5 ± 1.8	0.73 ± 0.14	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.2	2.1 ± 0.5	0.38 ± 0.30	15 ± 3	2.13 ± 0.41	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 0.9	0.95 ± 0.25	0.69 ± 0.39	8.6 ± 2.2	1.41 ± 0.28	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.20	0.74 ± 0.42	9.1 ± 2.1	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 1.0	1.5 ± 0.3	1.9 ± 1.0	24 ± 5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.22	0.53 ± 0.30	12.7 ± 2.9	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.7	3.9 ± 0.8	0.86 ± 0.55	11.4 ± 2.3	2.34 ± 0.35	18
$2\ell 1\tau_{\rm had}$	–	$0.4\,^{+0.6}_{-0.4}$	0.38 ± 0.12	0.37 ± 0.08	0.12 ± 0.11	1.4 ± 0.6	0.47 ± 0.08	1
$1\ell 2\tau_{\rm had}$	–	15 ± 5	0.17 ± 0.06	0.37 ± 0.09	0.41 ± 0.42	16 ± 5	0.68 ± 0.13	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.12	0.05 ± 0.02	0.55 ± 0.15	0.17 ± 0.02	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.025 ± 0.003	0

ttH(ATLAS13 TeV)



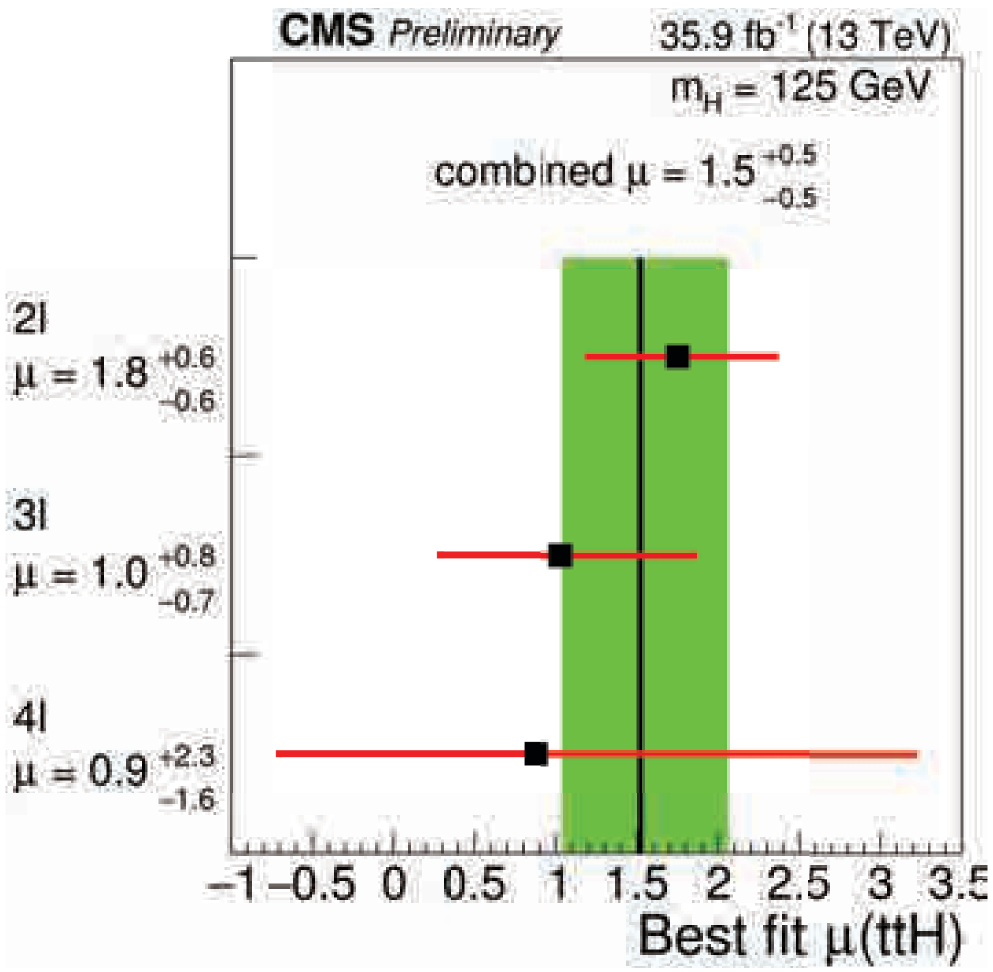
1712.08891

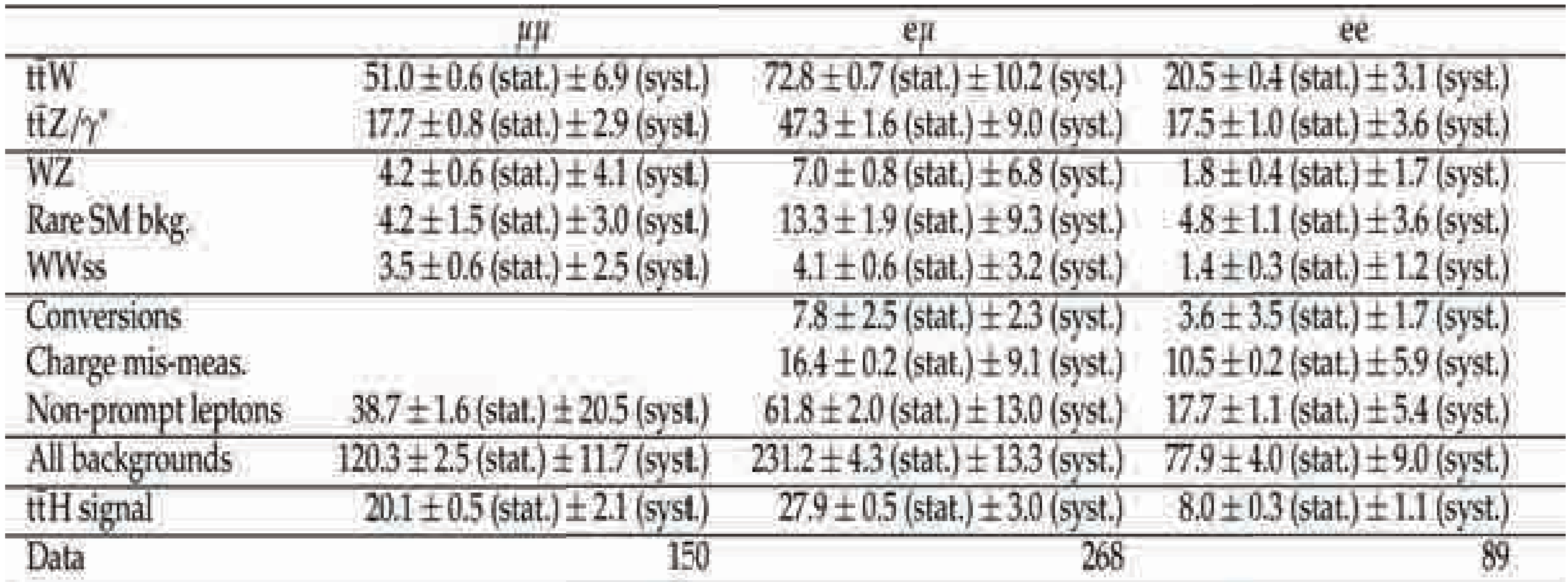


Category	Non-prompt	Fake τ_{had}	q mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
Pre-fit yields										
2ℓSS	233 ± 39	–	33 ± 11	123 ± 18	41.4 ± 5.6	25 ± 15	28.4 ± 5.9	484 ± 38	42.6 ± 4.2	514
3ℓ SR	14.5 ± 4.3	–	–	5.5 ± 1.2	12.0 ± 1.8	1.2 ± 1.2	5.8 ± 1.4	39.1 ± 5.2	11.2 ± 1.6	61
3ℓ $t\bar{t}W$ CR	13.3 ± 4.3	–	–	19.9 ± 3.1	8.7 ± 1.1	< 0.2	4.53 ± 0.92	46.5 ± 5.4	4.18 ± 0.46	56
3ℓ $t\bar{t}Z$ CR	3.9 ± 2.5	–	–	2.71 ± 0.56	66 ± 11	8.4 ± 5.3	12.9 ± 4.2	93 ± 13	3.17 ± 0.41	107
3ℓ VV CR	27.7 ± 8.7	–	–	4.9 ± 1.0	21.3 ± 3.4	51 ± 30	17.9 ± 6.1	123 ± 32	1.67 ± 0.25	109
3ℓ $t\bar{t}$ CR	70 ± 17	–	–	10.5 ± 1.5	7.9 ± 1.1	7.2 ± 4.8	7.3 ± 1.9	103 ± 17	4.00 ± 0.49	85
4ℓ Z-enr.	0.11 ± 0.07	–	–	< 0.01	1.52 ± 0.23	0.43 ± 0.23	0.21 ± 0.09	2.26 ± 0.34	1.06 ± 0.14	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	< 0.01	0.04 ± 0.02	< 0.01	0.06 ± 0.03	0.11 ± 0.03	0.20 ± 0.03	0
1ℓ+$2\tau_{\text{had}}$	–	65 ± 21	–	0.09 ± 0.09	3.3 ± 1.0	1.3 ± 1.0	0.98 ± 0.35	71 ± 21	4.3 ± 1.0	67
2ℓSS+$1\tau_{\text{had}}$	2.4 ± 1.4	1.80 ± 0.30	0.05 ± 0.02	0.88 ± 0.24	1.83 ± 0.37	0.12 ± 0.18	1.06 ± 0.24	8.2 ± 1.6	3.09 ± 0.46	18
2ℓOS+$1\tau_{\text{had}}$	–	756 ± 80	–	6.5 ± 1.3	11.4 ± 1.9	2.0 ± 1.3	5.8 ± 1.5	782 ± 81	14.2 ± 2.0	807
3ℓ+$1\tau_{\text{had}}$	–	0.75 ± 0.15	–	0.04 ± 0.04	1.38 ± 0.24	0.002 ± 0.002	0.38 ± 0.10	2.55 ± 0.32	1.51 ± 0.23	5
Post-fit yields										

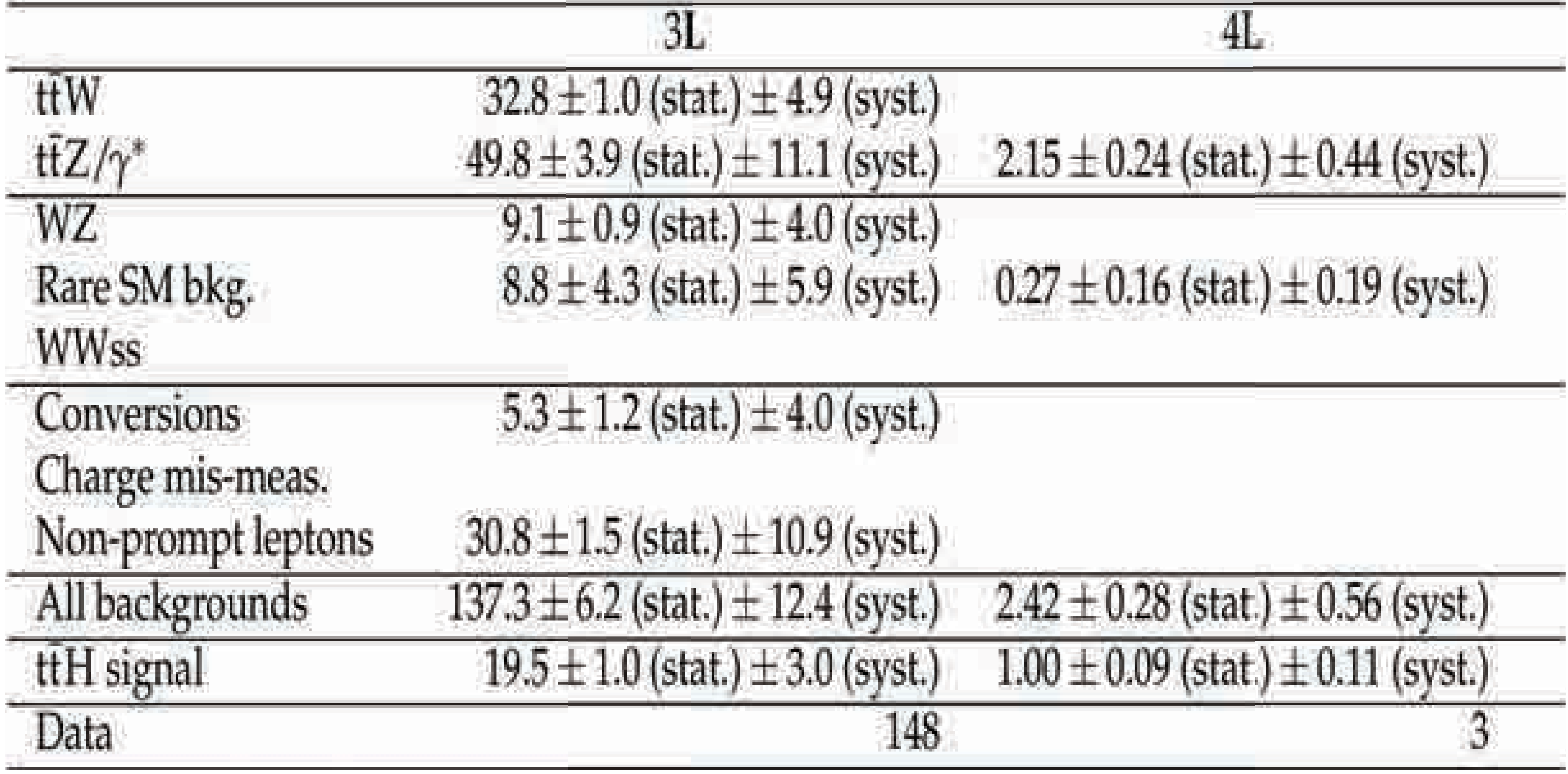
ttH(CMS 13 TeV)

HIG-17-004-pas





	$\mu\mu$	$e\mu$	ee
$t\bar{t}W$	51.0 ± 0.6 (stat.) ± 6.9 (syst.)	72.8 ± 0.7 (stat.) ± 10.2 (syst.)	20.5 ± 0.4 (stat.) ± 3.1 (syst.)
$t\bar{t}Z/\gamma^*$	17.7 ± 0.8 (stat.) ± 2.9 (syst.)	47.3 ± 1.6 (stat.) ± 9.0 (syst.)	17.5 ± 1.0 (stat.) ± 3.6 (syst.)
WZ	4.2 ± 0.6 (stat.) ± 4.1 (syst.)	7.0 ± 0.8 (stat.) ± 6.8 (syst.)	1.8 ± 0.4 (stat.) ± 1.7 (syst.)
Rare SM bkg.	4.2 ± 1.5 (stat.) ± 3.0 (syst.)	13.3 ± 1.9 (stat.) ± 9.3 (syst.)	4.8 ± 1.1 (stat.) ± 3.6 (syst.)
WWss	3.5 ± 0.6 (stat.) ± 2.5 (syst.)	4.1 ± 0.6 (stat.) ± 3.2 (syst.)	1.4 ± 0.3 (stat.) ± 1.2 (syst.)
Conversions		7.8 ± 2.5 (stat.) ± 2.3 (syst.)	3.6 ± 3.5 (stat.) ± 1.7 (syst.)
Charge mis-meas.		16.4 ± 0.2 (stat.) ± 9.1 (syst.)	10.5 ± 0.2 (stat.) ± 5.9 (syst.)
Non-prompt leptons	38.7 ± 1.6 (stat.) ± 20.5 (syst.)	61.8 ± 2.0 (stat.) ± 13.0 (syst.)	17.7 ± 1.1 (stat.) ± 5.4 (syst.)
All backgrounds	120.3 ± 2.5 (stat.) ± 11.7 (syst.)	231.2 ± 4.3 (stat.) ± 13.3 (syst.)	77.9 ± 4.0 (stat.) ± 9.0 (syst.)
$t\bar{t}H$ signal	20.1 ± 0.5 (stat.) ± 2.1 (syst.)	27.9 ± 0.5 (stat.) ± 3.0 (syst.)	8.0 ± 0.3 (stat.) ± 1.1 (syst.)
Data	150	268	89



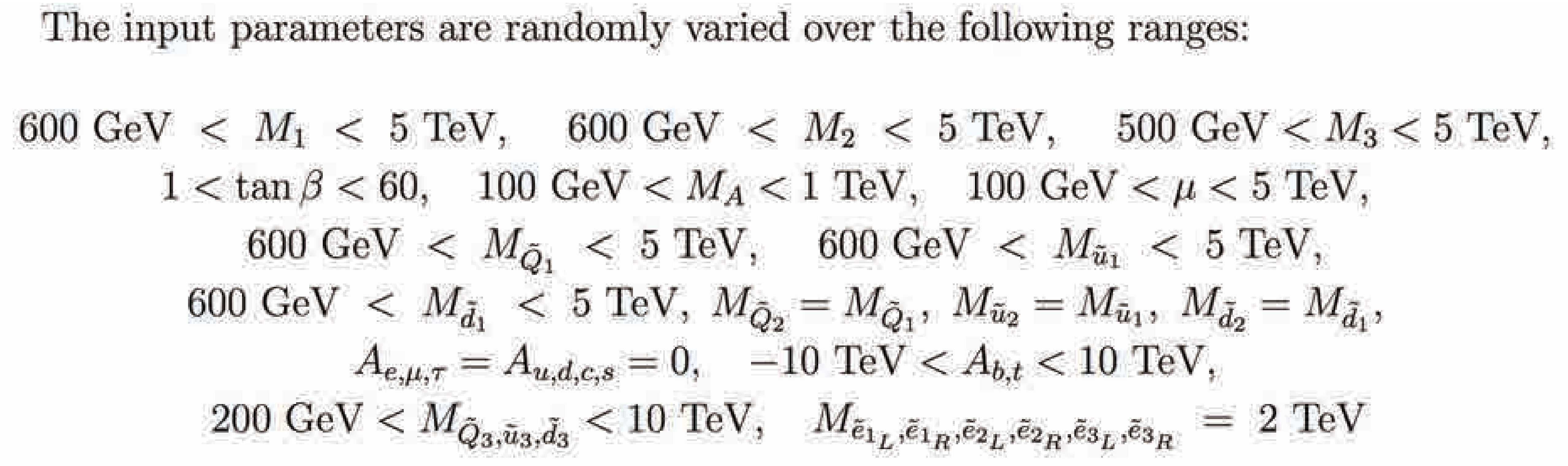
	3L	4L
$t\bar{t}W$	32.8 ± 1.0 (stat.) ± 4.9 (syst.)	
$t\bar{t}Z/\gamma^*$	49.8 ± 3.9 (stat.) ± 11.1 (syst.)	2.15 ± 0.24 (stat.) ± 0.44 (syst.)
WZ	9.1 ± 0.9 (stat.) ± 4.0 (syst.)	
Rare SM bkg.	8.8 ± 4.3 (stat.) ± 5.9 (syst.)	0.27 ± 0.16 (stat.) ± 0.19 (syst.)
WWss		
Conversions	5.3 ± 1.2 (stat.) ± 4.0 (syst.)	
Charge mis-meas.		
Non-prompt leptons	30.8 ± 1.5 (stat.) ± 10.9 (syst.)	
All backgrounds	137.3 ± 6.2 (stat.) ± 12.4 (syst.)	2.42 ± 0.28 (stat.) ± 0.56 (syst.)
$t\bar{t}H$ signal	19.5 ± 1.0 (stat.) ± 3.0 (syst.)	1.00 ± 0.09 (stat.) ± 0.11 (syst.)
Data	148	3

Higgs sector of MSSM

Higgs sector of MSSM

Higgs sector of the phenomenological Minimal Supersymmetric Standard Model, in light of the recent Higgs data, on and above the existing Run-I data **Barman, BB, Choudhury, Chowdhury, Lahiri, Ray 1608.02573**

We keep Heavy Higgs Higgs bosons below 1 TeV in our scan



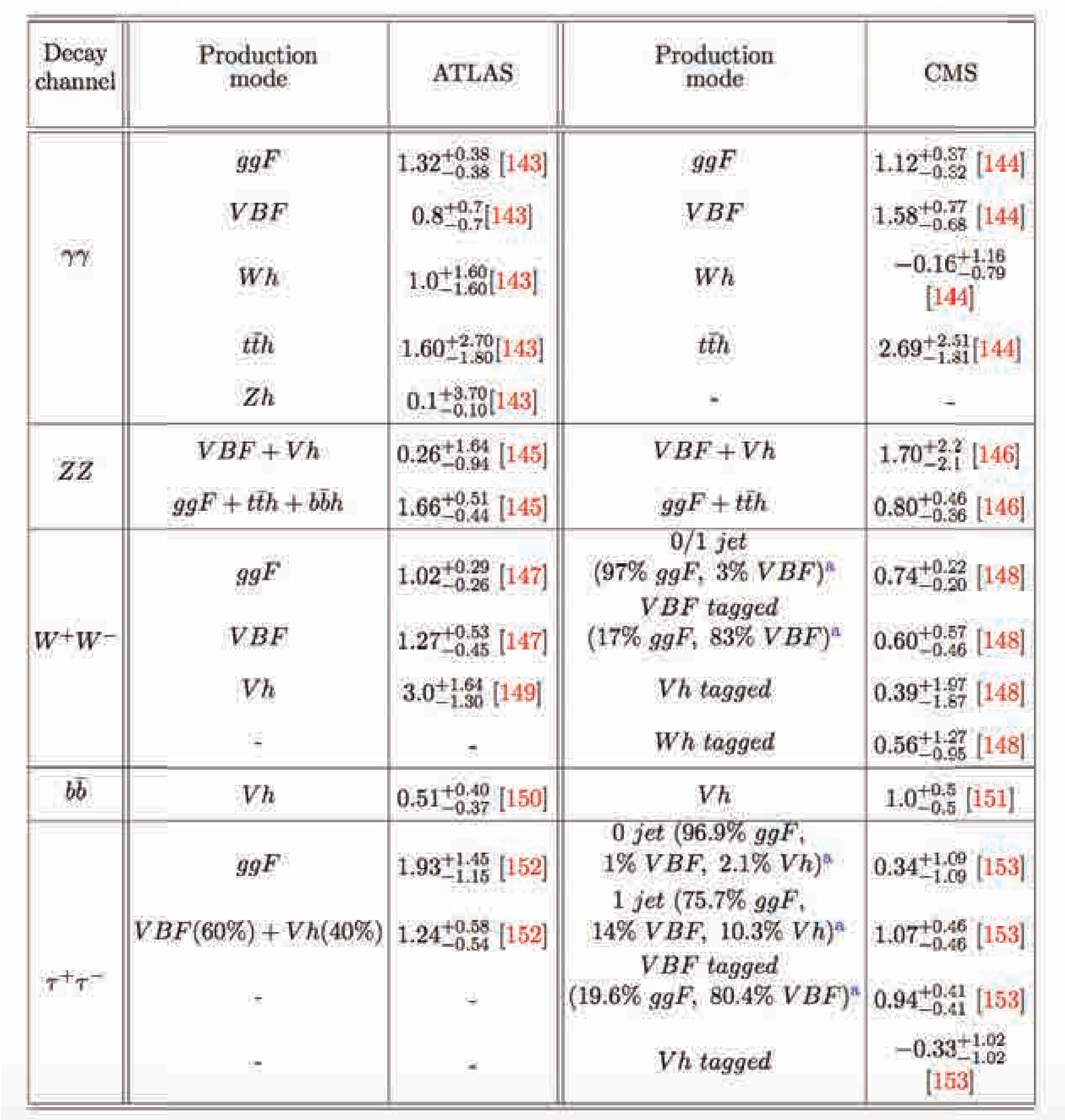
The input parameters are randomly varied over the following ranges:

$$\begin{gathered}
600\text{ GeV} < M_1 < 5\text{ TeV}, \quad 600\text{ GeV} < M_2 < 5\text{ TeV}, \quad 500\text{ GeV} < M_3 < 5\text{ TeV}, \\
1 < \tan\beta < 60, \quad 100\text{ GeV} < M_A < 1\text{ TeV}, \quad 100\text{ GeV} < \mu < 5\text{ TeV}, \\
600\text{ GeV} < M_{\tilde{Q}_1} < 5\text{ TeV}, \quad 600\text{ GeV} < M_{\tilde{u}_1} < 5\text{ TeV}, \\
600\text{ GeV} < M_{\tilde{d}_1} < 5\text{ TeV}, \; M_{\tilde{Q}_2} = M_{\tilde{Q}_1}, \; M_{\tilde{u}_2} = M_{\tilde{u}_1}, \; M_{\tilde{d}_2} = M_{\tilde{d}_1}, \\
A_{e,\mu,\tau} = A_{u,d,c,s} = 0, \quad -10\text{ TeV} < A_{b,t} < 10\text{ TeV}, \\
200\text{ GeV} < M_{\tilde{Q}_3,\tilde{u}_3,\tilde{d}_3} < 10\text{ TeV}, \quad M_{\tilde{e}_{1_L},\tilde{e}_{1_R},\tilde{e}_{2_L},\tilde{e}_{2_R},\tilde{e}_{3_L},\tilde{e}_{3_R}} = 2\text{ TeV}
\end{gathered}$$

FeynHiggs 2.12.0: for spectrum generation and cross section calculation

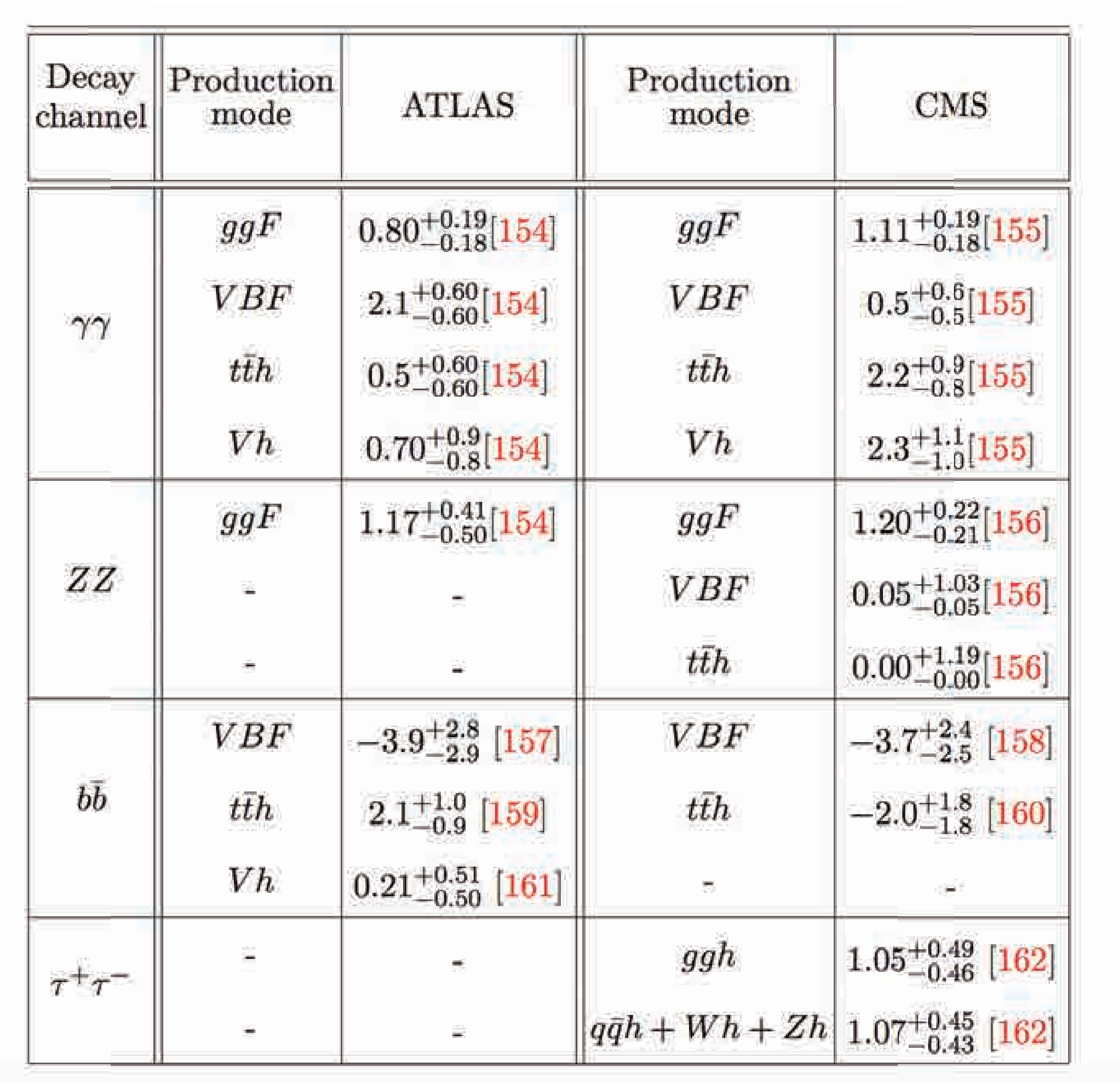
Micromegas 4.1.8 for flavour physics

Run I signal strength data



Decay channel	Production mode	ATLAS	Production mode	CMS
$\gamma\gamma$	ggF	$1.32^{+0.38}_{-0.38}$ [143]	ggF	$1.12^{+0.37}_{-0.32}$ [144]
	VBF	$0.8^{+0.7}_{-0.7}$[143]	VBF	$1.58^{+0.77}_{-0.68}$ [144]
	Wh	$1.0^{+1.60}_{-1.60}$[143]	Wh	$-0.16^{+1.16}_{-0.79}$ [144]
	$t\bar{t}h$	$1.60^{+2.70}_{-1.80}$[143]	$t\bar{t}h$	$2.69^{+2.51}_{-1.81}$[144]
	Zh	$0.1^{+3.70}_{-0.10}$[143]	-	-
ZZ	$VBF + Vh$	$0.26^{+1.64}_{-0.94}$ [145]	$VBF + Vh$	$1.70^{+2.2}_{-2.1}$ [146]
	$ggF + t\bar{t}h + b\bar{b}h$	$1.66^{+0.51}_{-0.44}$ [145]	$ggF + t\bar{t}h$	$0.80^{+0.46}_{-0.36}$ [146]
W^+W^-	ggF	$1.02^{+0.29}_{-0.26}$ [147]	0/1 *jet* (97% ggF, 3% VBF)[a]	$0.74^{+0.22}_{-0.20}$ [148]
	VBF	$1.27^{+0.53}_{-0.45}$ [147]	VBF *tagged* (17% ggF, 83% VBF)[a]	$0.60^{+0.57}_{-0.46}$ [148]
	Vh	$3.0^{+1.64}_{-1.30}$ [149]	Vh *tagged*	$0.39^{+1.97}_{-1.87}$ [148]
	-	-	Wh *tagged*	$0.56^{+1.27}_{-0.95}$ [148]
$b\bar{b}$	Vh	$0.51^{+0.40}_{-0.37}$ [150]	Vh	$1.0^{+0.5}_{-0.5}$ [151]
$\tau^+\tau^-$	ggF	$1.93^{+1.45}_{-1.15}$ [152]	0 *jet* (96.9% ggF, 1% VBF, 2.1% Vh)[a]	$0.34^{+1.09}_{-1.09}$ [153]
	$VBF(60\%) + Vh(40\%)$	$1.24^{+0.58}_{-0.54}$ [152]	1 *jet* (75.7% ggF, 14% VBF, 10.3% Vh)[a]	$1.07^{+0.46}_{-0.46}$ [153]
	-	-	VBF *tagged* (19.6% ggF, 80.4% VBF)[a]	$0.94^{+0.41}_{-0.41}$ [153]
	-	-	Vh *tagged*	$-0.33^{+1.02}_{-1.02}$ [153]

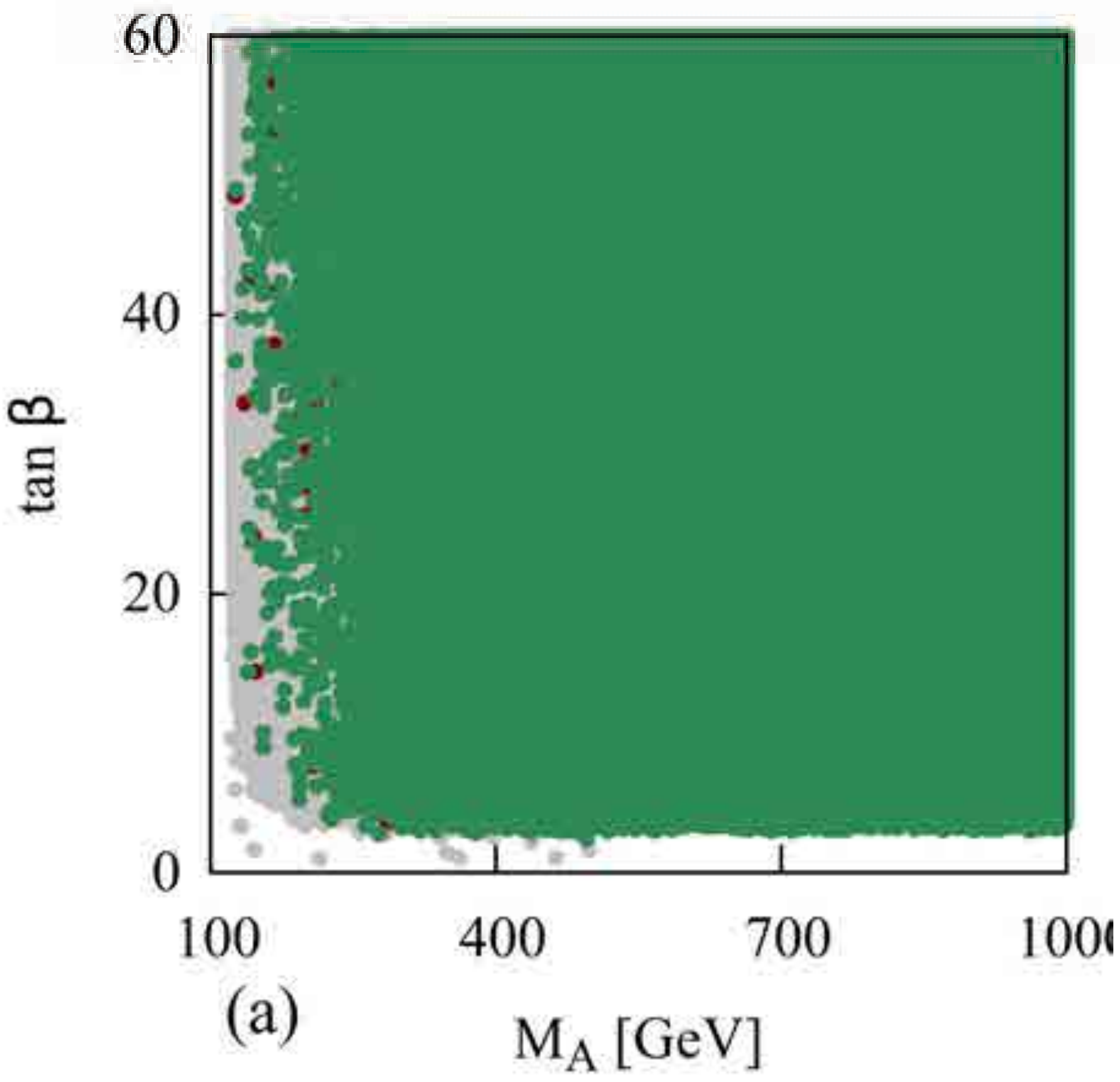
Run II signal strength data



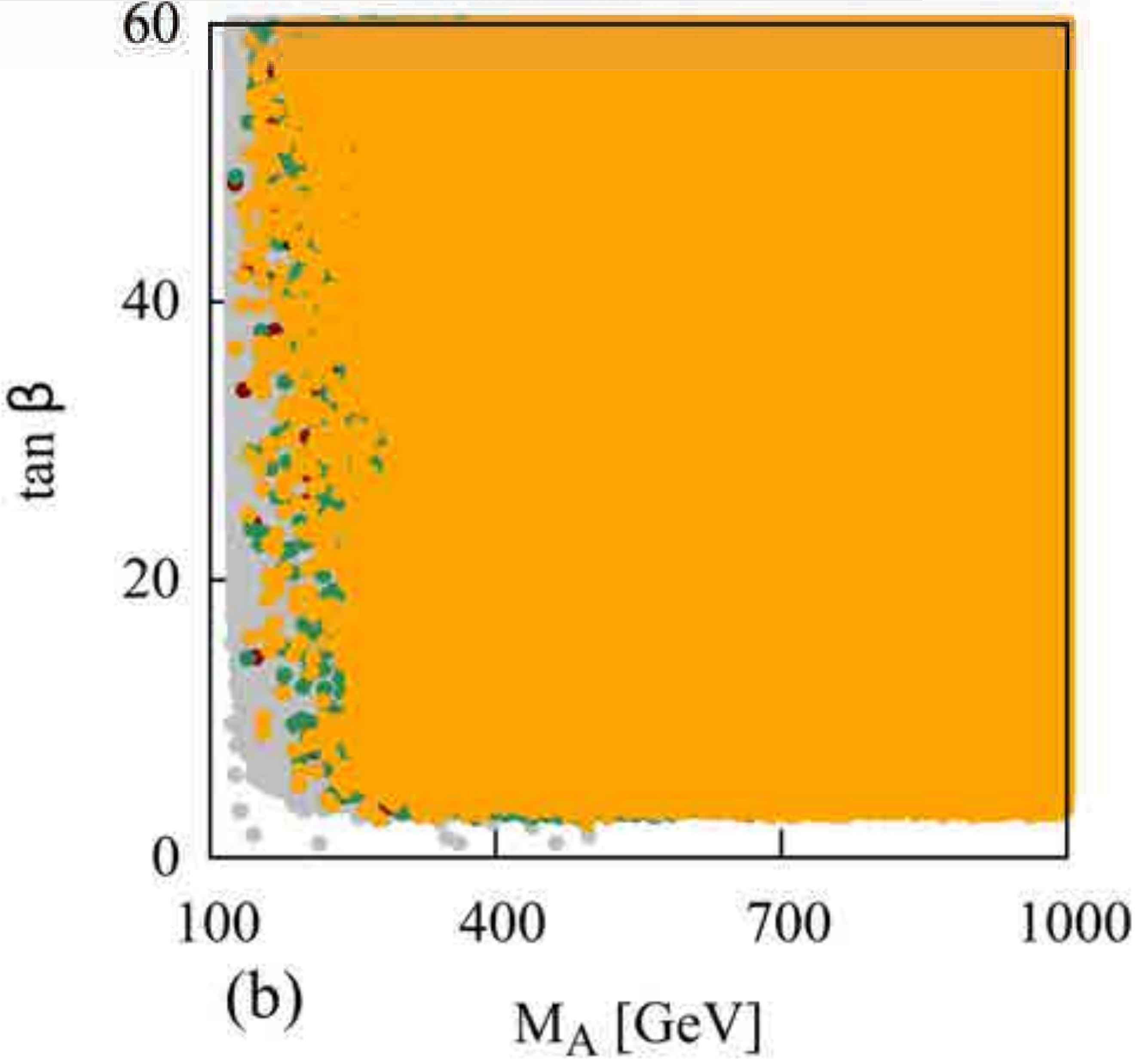
Decay channel	Production mode	ATLAS	Production mode	CMS
$\gamma\gamma$	ggF	$0.80^{+0.19}_{-0.18}$[154]	ggF	$1.11^{+0.19}_{-0.18}$[155]
	VBF	$2.1^{+0.60}_{-0.60}$[154]	VBF	$0.5^{+0.6}_{-0.5}$[155]
	$t\bar{t}h$	$0.5^{+0.60}_{-0.60}$[154]	$t\bar{t}h$	$2.2^{+0.9}_{-0.8}$[155]
	Vh	$0.70^{+0.9}_{-0.8}$[154]	Vh	$2.3^{+1.1}_{-1.0}$[155]
ZZ	ggF	$1.17^{+0.41}_{-0.50}$[154]	ggF	$1.20^{+0.22}_{-0.21}$[156]
	-	-	VBF	$0.05^{+1.03}_{-0.05}$[156]
	-	-	$t\bar{t}h$	$0.00^{+1.19}_{-0.00}$[156]
$b\bar{b}$	VBF	$-3.9^{+2.8}_{-2.9}$ [157]	VBF	$-3.7^{+2.4}_{-2.5}$ [158]
	$t\bar{t}h$	$2.1^{+1.0}_{-0.9}$ [159]	$t\bar{t}h$	$-2.0^{+1.8}_{-1.8}$ [160]
	Vh	$0.21^{+0.51}_{-0.50}$ [161]	-	-
$\tau^+\tau^-$	-	-	ggh	$1.05^{+0.49}_{-0.46}$ [162]
	-	-	$q\bar{q}h + Wh + Zh$	$1.07^{+0.45}_{-0.43}$ [162]

Allowed parameter space: bounds from signal strengths

Barman, BB, Choudhury, Chowdhury, Lahiri, Ray (1608.02573)



(a)



(b)

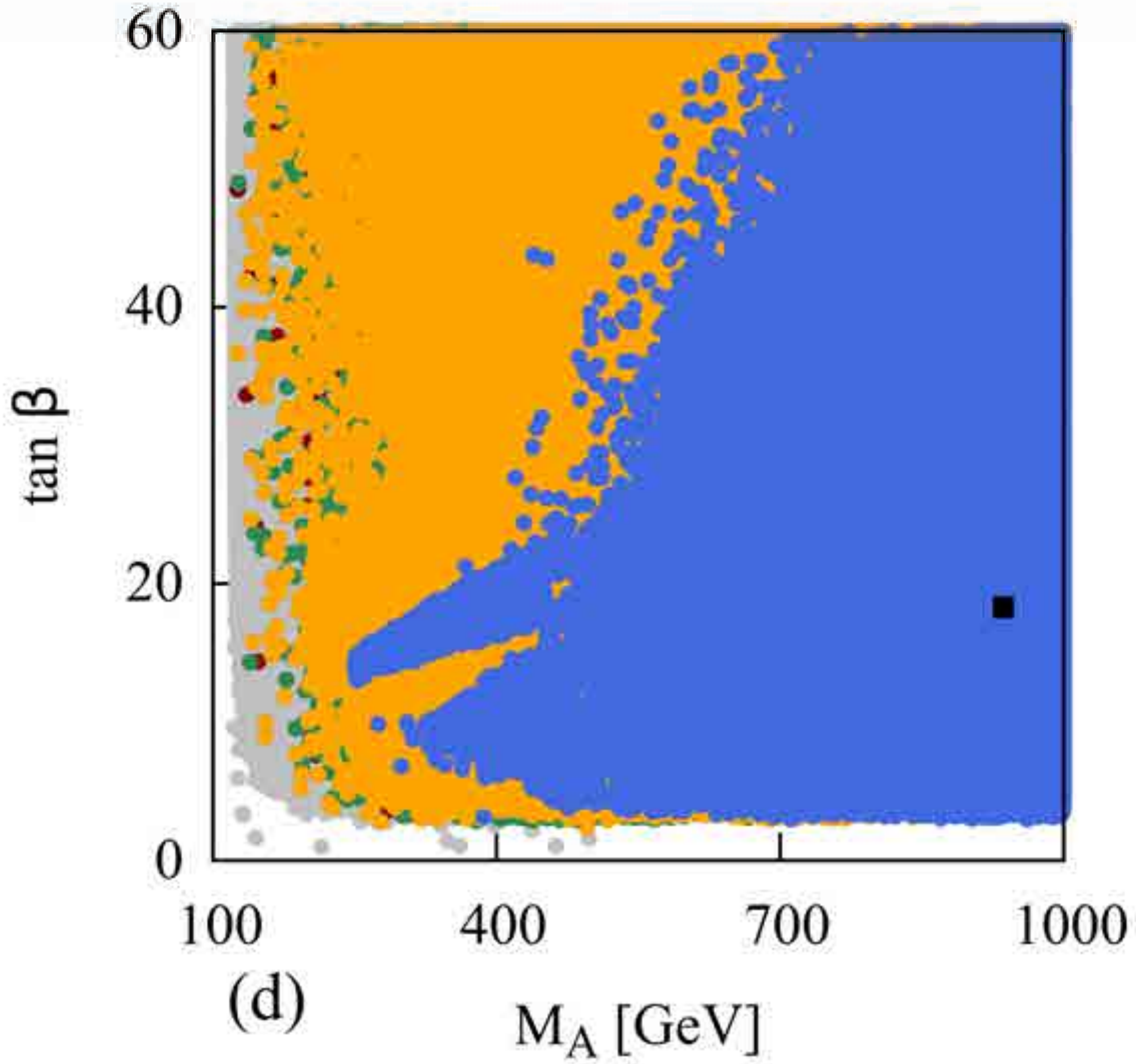
grey points: satisfy the light Higgs mass constraint.

red points : only LHC Run-II data

green points: only LHC Run-I data

yellow points : combined Run-I and Run-II.

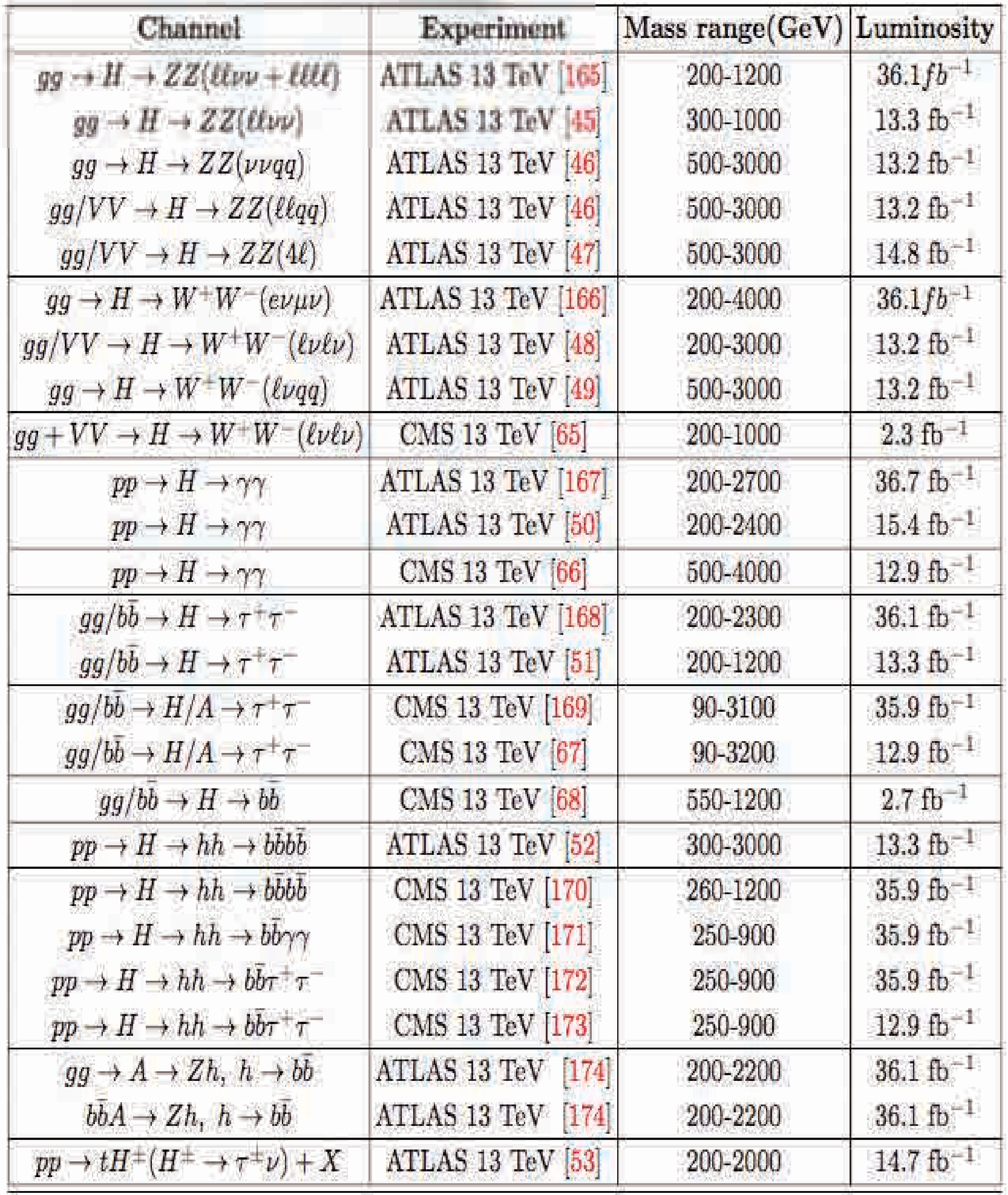
Allowed parameter space: bounds from flavour physics



Barman, BB, Choudhury, Chowdhury, Lahiri, Ray (1608.02573)

Heavy Higgs searches at the LHC

Channel	Experiment	Mass range (GeV)	Luminosity
$gg \to H/A \to \tau^+\tau^-$	ATLAS 8 TeV [28]	90-1000	19.5-20.3 fb^{-1}
	CMS 8 TeV [55]	90-1000	19.7 fb^{-1}
	ATLAS 13 TeV [29]	200-1200	3.2 fb^{-1}
	CMS 13 TeV [56]	100-3000	2.3 fb^{-1}
$b\bar{b} \to H/A \to \tau^+\tau^-$	ATLAS 8 TeV [28]	90-1000	19.5-20.3 fb^{-1}
	CMS 8 TeV [55]	90-1000	19.7 fb^{-1}
	ATLAS 13 TeV [29]	200-1200	3.2 fb^{-1}
	CMS 13 TeV [56]	100-3000	2.3 fb^{-1}
$gg \to H/A \to \gamma\gamma$	ATLAS 8 TeV [30]	65-600	20.3 fb^{-1}
	CMS 8+13 TeV [57]	500-4000	19.7+3.3 fb^{-1}
	ATLAS 13 TeV [31]	200-2000	3.2 fb^{-1}
$pp \to bH/A(H/A \to b\bar{b})$	CMS 8 TeV [58]	100-900	19.7 fb^{-1}
$gg \to H \to W^+W^-$	ATLAS 8 TeV [32]	300-1500	20.3 fb^{-1}
	ATLAS 13 TeV [33]	500-3000	3.2 fb^{-1}
$W^+W^-/ZZ \to H \to W^+W^-$	ATLAS 8 TeV [32]	300-1500	20.3 fb^{-1}
	ATLAS 13 TeV[33]	500-3000	3.2 fb^{-1}
$gg \to H \to ZZ$	ATLAS 8 TeV [34]	160-1000	20.3 fb^{-1}
$gg \to H \to ZZ \to (\ell\ell)(qq)$	ATLAS 13 TeV [35]	300-1000	3.2 fb^{-1}
$gg \to H \to ZZ \to (\ell\ell)(\nu\nu)$	ATLAS 13 TeV [36]	300-1000	3.2 fb^{-1}
$pp \to H \to Z\gamma$	ATLAS 13 TeV [37]	250-2750	3.2 fb^{-1}
$W^+W^-/ZZ \to H \to ZZ$	ATLAS 8 TeV [34]	160-1000	20.3 fb^{-1}
$pp \to H \to ZZ$	CMS 8 TeV [59]	150-1000	5.1 fb^{-1}
$pp \to H \to W^+W^-$	CMS 8 TeV [59]	150-1000	5.1 fb^{-1}
$gg \to H \to hh$	ATLAS 8 TeV [38]	260-1000	20.3 fb^{-1}
$pp \to H \to hh \to (b\bar{b})(b\bar{b})$	ATLAS 13 TeV [39]	500-3000	3.2 fb^{-1}
$pp \to H \to hh \to (\gamma\gamma)(b\bar{b})$	CMS 8 TeV [60]	250-1100	19.7 fb^{-1}
$pp \to H \to hh \to (b\bar{b})(b\bar{b})$	CMS 8 TeV [61]	270-1100	17.9 fb^{-1}
$gg \to H \to hh \to (b\bar{b})(\tau^+\tau^-)$	CMS 8 TeV [62]	260-350	19.7 fb^{-1}
$gg \to A \to Zh \to (\tau^+\tau^-)(\ell\ell)$	CMS 8 TeV [62]	220-350	19.7 fb^{-1}
$gg \to A \to Zh \to (b\bar{b})(\ell\ell)$	CMS 8 TeV [63]	225-600	19.7 fb^{-1}
$gg \to A \to Zh \to Z(\tau^+\tau^-)$	ATLAS 8 TeV [40]	220-1000	20.3 fb^{-1}
$gg \to A \to Zh \to Z(b\bar{b})$	ATLAS 8 TeV [40]	220-1000	20.3 fb^{-1}
	ATLAS 13 TeV [41]	200-2000	3.2 fb^{-1}
$pp \to Ab\bar{b} \to Zhb\bar{b} \to Z(b\bar{b})(b\bar{b})$	ATLAS 13 TeV [41]	200-1000	3.2 fb^{-1}
$pp \to tH^\pm(H^\pm \to \tau^\pm\nu) + X$	ATLAS 8 TeV [42]	180-1000	19.5 fb^{-1}
$pp \to tbH^\pm(H^\pm \to \tau^\pm\nu)$	ATLAS 13 TeV [43]	200-2000	3.2 fb^{-1}
	CMS 8 TeV [64]	200-600	19.7 ± 0.5 fb^{-1}
$gb \to tH^\pm(H^\pm \to tb)$	ATLAS 8 TeV [44]	200-600	20.3 fb^{-1}
$qq' \to H^\pm(H^\pm \to tb) \to (l + \text{jets})$	ATLAS 8 TeV [44]	400-2000	20.3 fb^{-1}
$qq' \to H^\pm(H^\pm \to tb) \to (\text{all had.})$	ATLAS 8 TeV [44]	400-2000	20.3 fb^{-1}
$pp \to \bar{t}bH^\pm(H^\pm \to tb)$	CMS 8 TeV [64]	200-600	19.7 ± 0.5 fb^{-1}

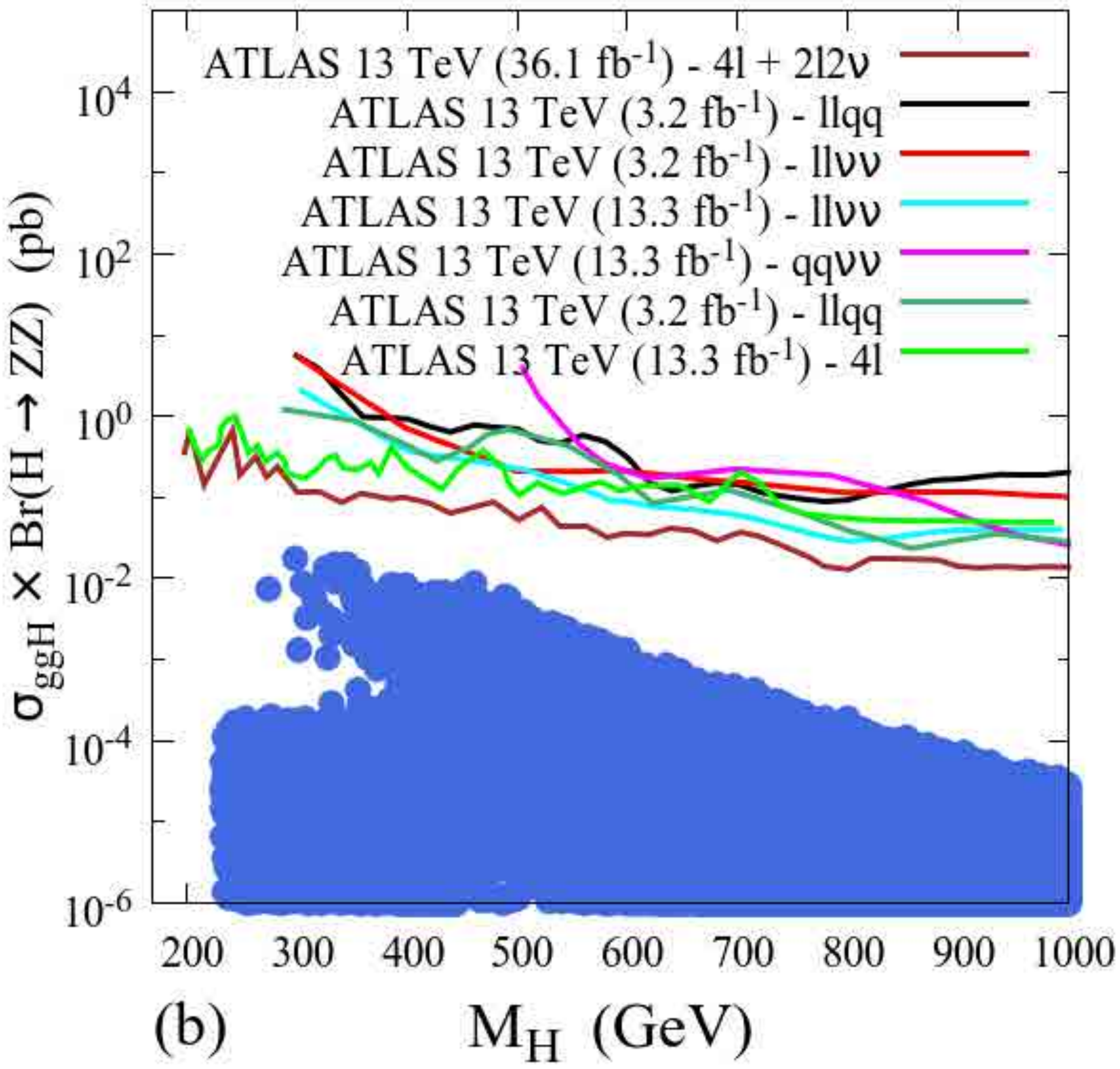


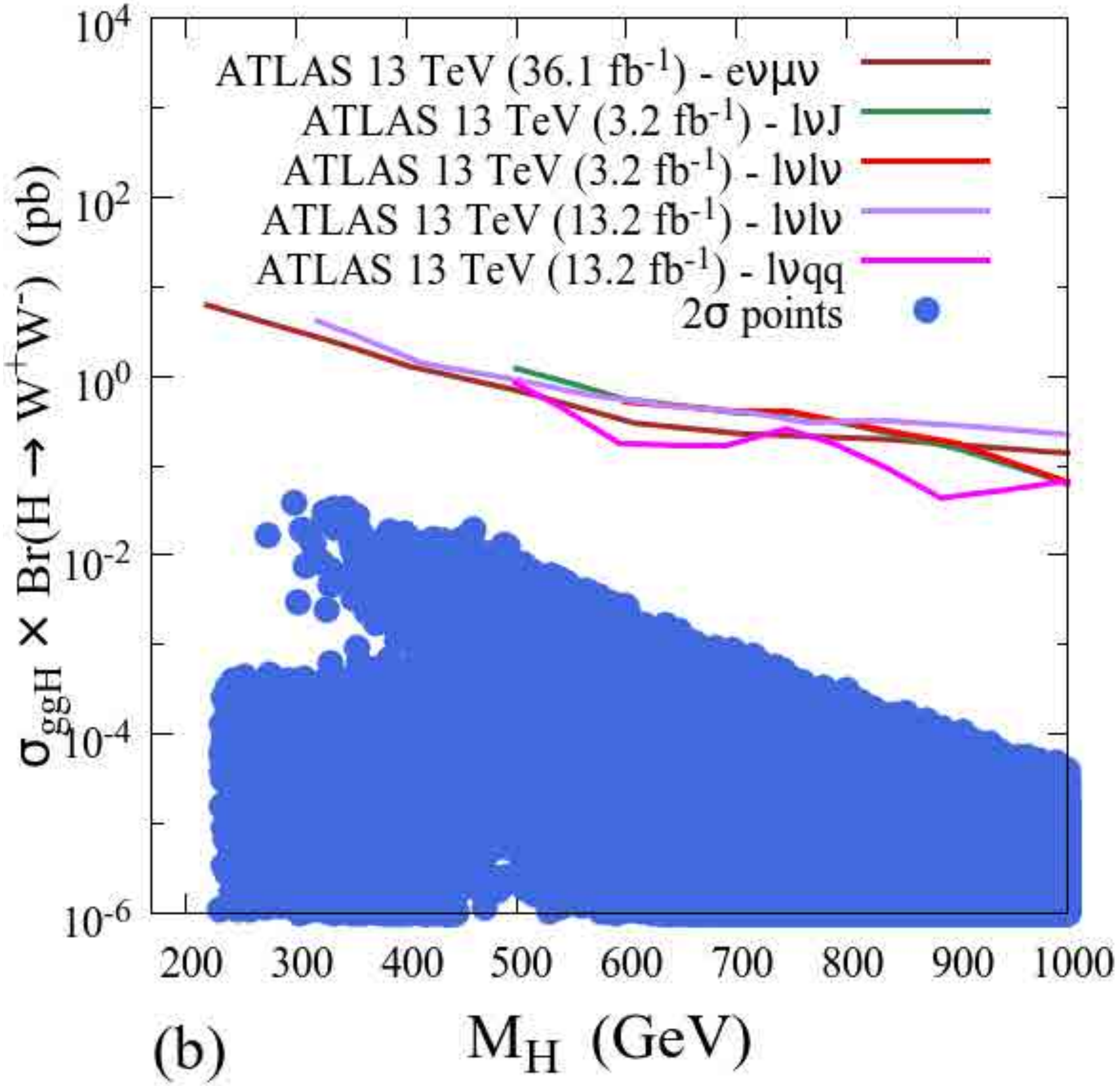
Channel	Experiment	Mass range(GeV)	Luminosity
$gg \to H \to ZZ(\ell\ell\nu\nu + \ell\ell\ell\ell)$	ATLAS 13 TeV [165]	200-1200	$36.1 fb^{-1}$
$gg \to H \to ZZ(\ell\ell\nu\nu)$	ATLAS 13 TeV [45]	300-1000	13.3 fb^{-1}
$gg \to H \to ZZ(\nu\nu qq)$	ATLAS 13 TeV [46]	500-3000	13.2 fb^{-1}
$gg/VV \to H \to ZZ(\ell\ell qq)$	ATLAS 13 TeV [46]	500-3000	13.2 fb^{-1}
$gg/VV \to H \to ZZ(4\ell)$	ATLAS 13 TeV [47]	500-3000	14.8 fb^{-1}
$gg \to H \to W^+W^-(e\nu\mu\nu)$	ATLAS 13 TeV [166]	200-4000	$36.1 fb^{-1}$
$gg/VV \to H \to W^+W^-(\ell\nu\ell\nu)$	ATLAS 13 TeV [48]	200-3000	13.2 fb^{-1}
$gg \to H \to W^+W^-(\ell\nu qq)$	ATLAS 13 TeV [49]	500-3000	13.2 fb^{-1}
$gg + VV \to H \to W^+W^-(\ell\nu\ell\nu)$	CMS 13 TeV [65]	200-1000	2.3 fb^{-1}
$pp \to H \to \gamma\gamma$	ATLAS 13 TeV [167]	200-2700	36.7 fb^{-1}
$pp \to H \to \gamma\gamma$	ATLAS 13 TeV [50]	200-2400	15.4 fb^{-1}
$pp \to H \to \gamma\gamma$	CMS 13 TeV [66]	500-4000	12.9 fb^{-1}
$gg/b\bar{b} \to H \to \tau^+\tau^-$	ATLAS 13 TeV [168]	200-2300	36.1 fb^{-1}
$gg/b\bar{b} \to H \to \tau^+\tau^-$	ATLAS 13 TeV [51]	200-1200	13.3 fb^{-1}
$gg/b\bar{b} \to H/A \to \tau^+\tau^-$	CMS 13 TeV [169]	90-3100	35.9 fb^{-1}
$gg/b\bar{b} \to H/A \to \tau^+\tau^-$	CMS 13 TeV [67]	90-3200	12.9 fb^{-1}
$gg/b\bar{b} \to H \to b\bar{b}$	CMS 13 TeV [68]	550-1200	2.7 fb^{-1}
$pp \to H \to hh \to b\bar{b}b\bar{b}$	ATLAS 13 TeV [52]	300-3000	13.3 fb^{-1}
$pp \to H \to hh \to b\bar{b}b\bar{b}$	CMS 13 TeV [170]	260-1200	35.9 fb^{-1}
$pp \to H \to hh \to b\bar{b}\gamma\gamma$	CMS 13 TeV [171]	250-900	35.9 fb^{-1}
$pp \to H \to hh \to b\bar{b}\tau^+\tau^-$	CMS 13 TeV [172]	250-900	35.9 fb^{-1}
$pp \to H \to hh \to b\bar{b}\tau^+\tau^-$	CMS 13 TeV [173]	250-900	12.9 fb^{-1}
$gg \to A \to Zh,\ h \to b\bar{b}$	ATLAS 13 TeV [174]	200-2200	36.1 fb^{-1}
$b\bar{b}A \to Zh,\ h \to b\bar{b}$	ATLAS 13 TeV [174]	200-2200	36.1 fb^{-1}
$pp \to tH^\pm(H^\pm \to \tau^\pm\nu) + X$	ATLAS 13 TeV [53]	200-2000	14.7 fb^{-1}

66 analyses in total

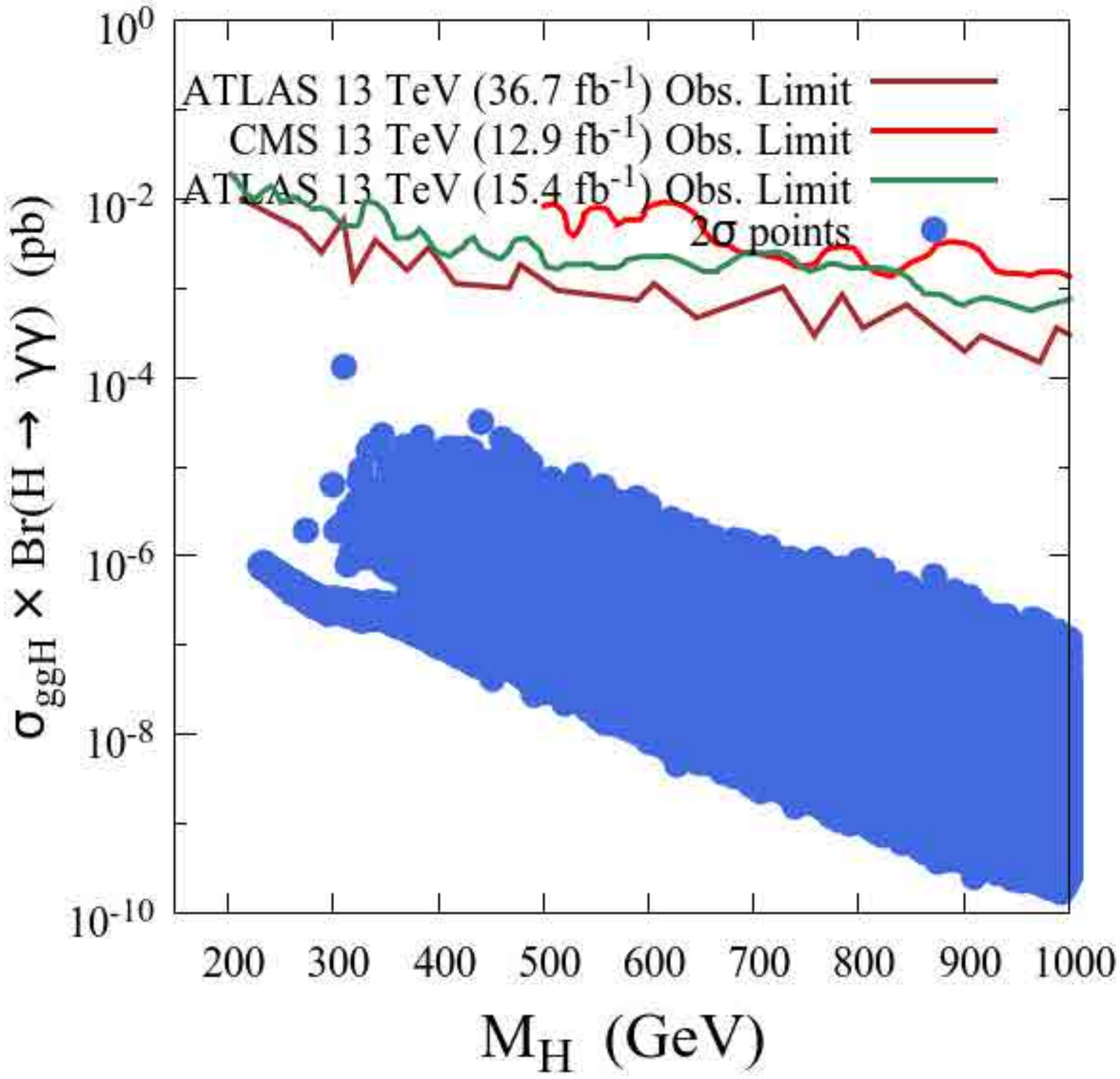
(CMS + ATLAS: 8 + 13 TeV)

Heavy Higgs searches at the LHC

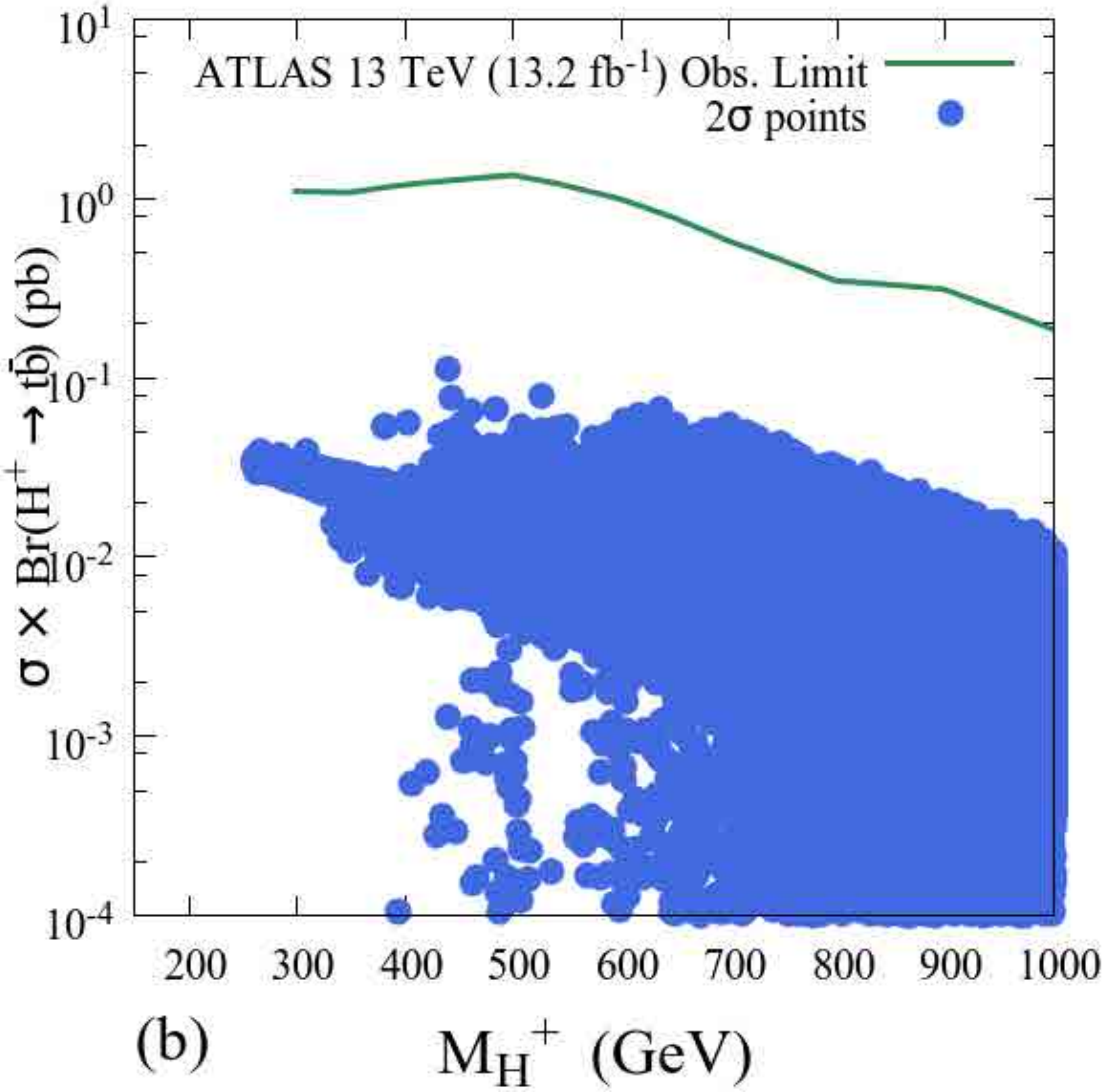




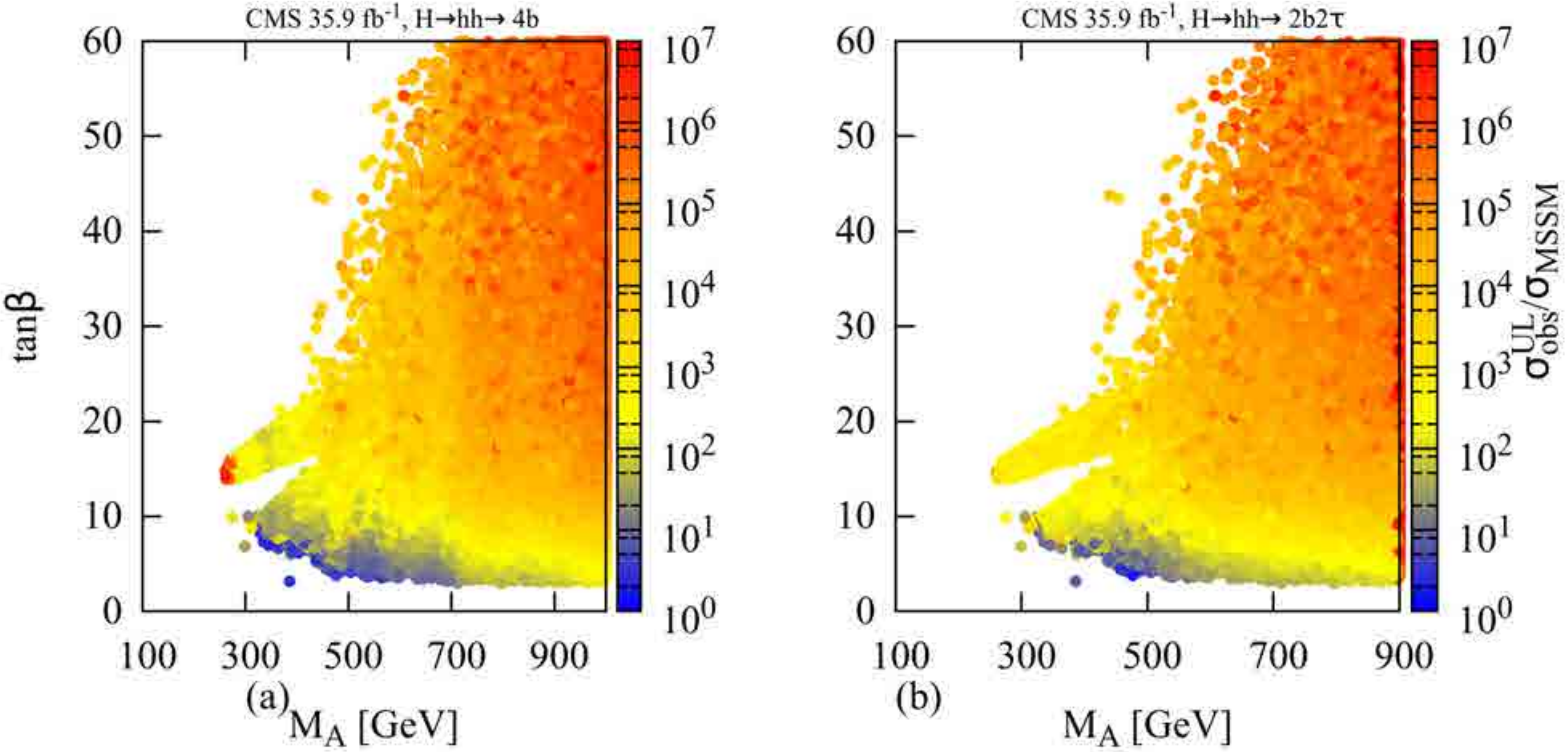
Heavy Higgs searches at the LHC



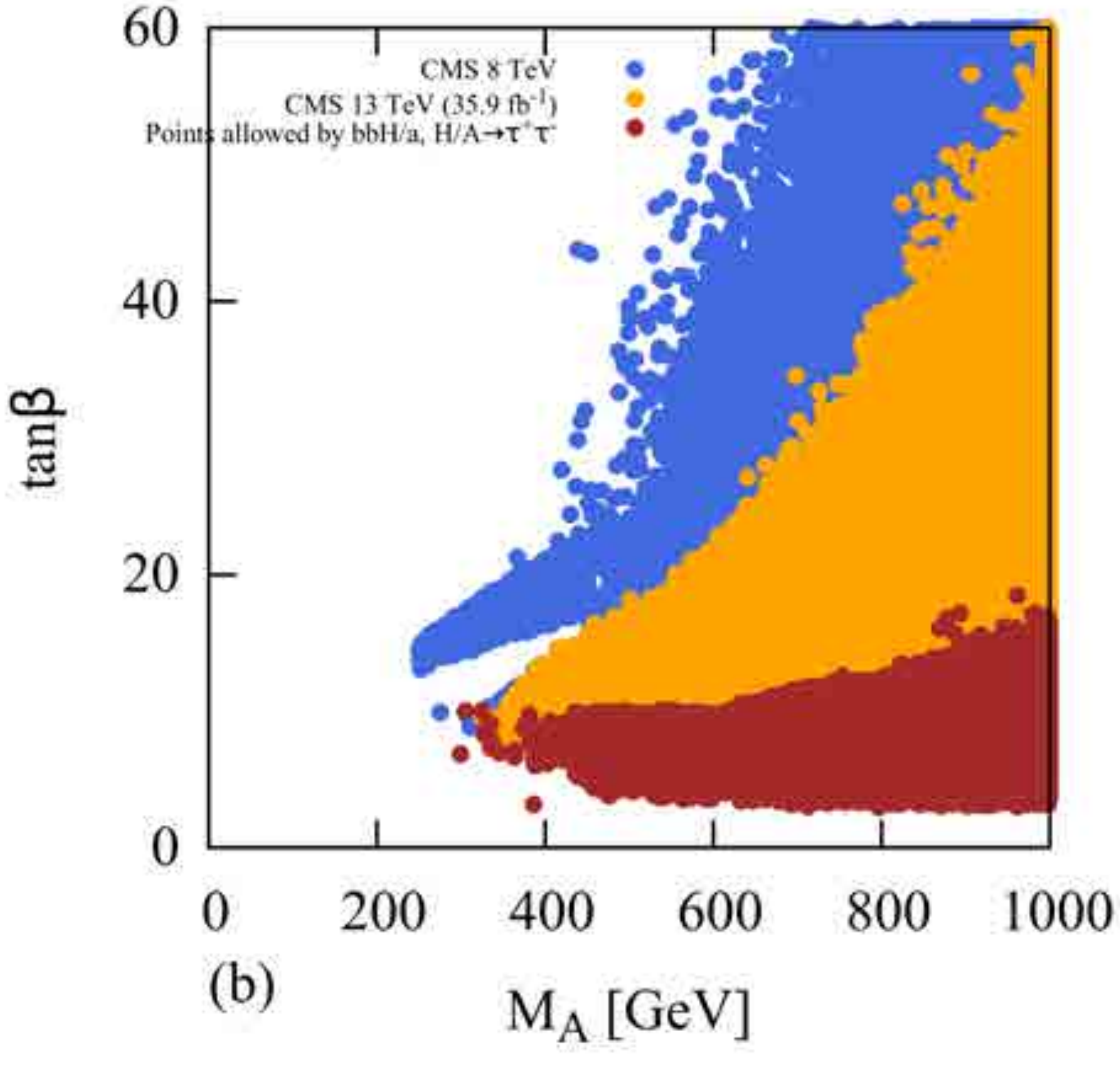
Heavy Higgs searches at the LHC



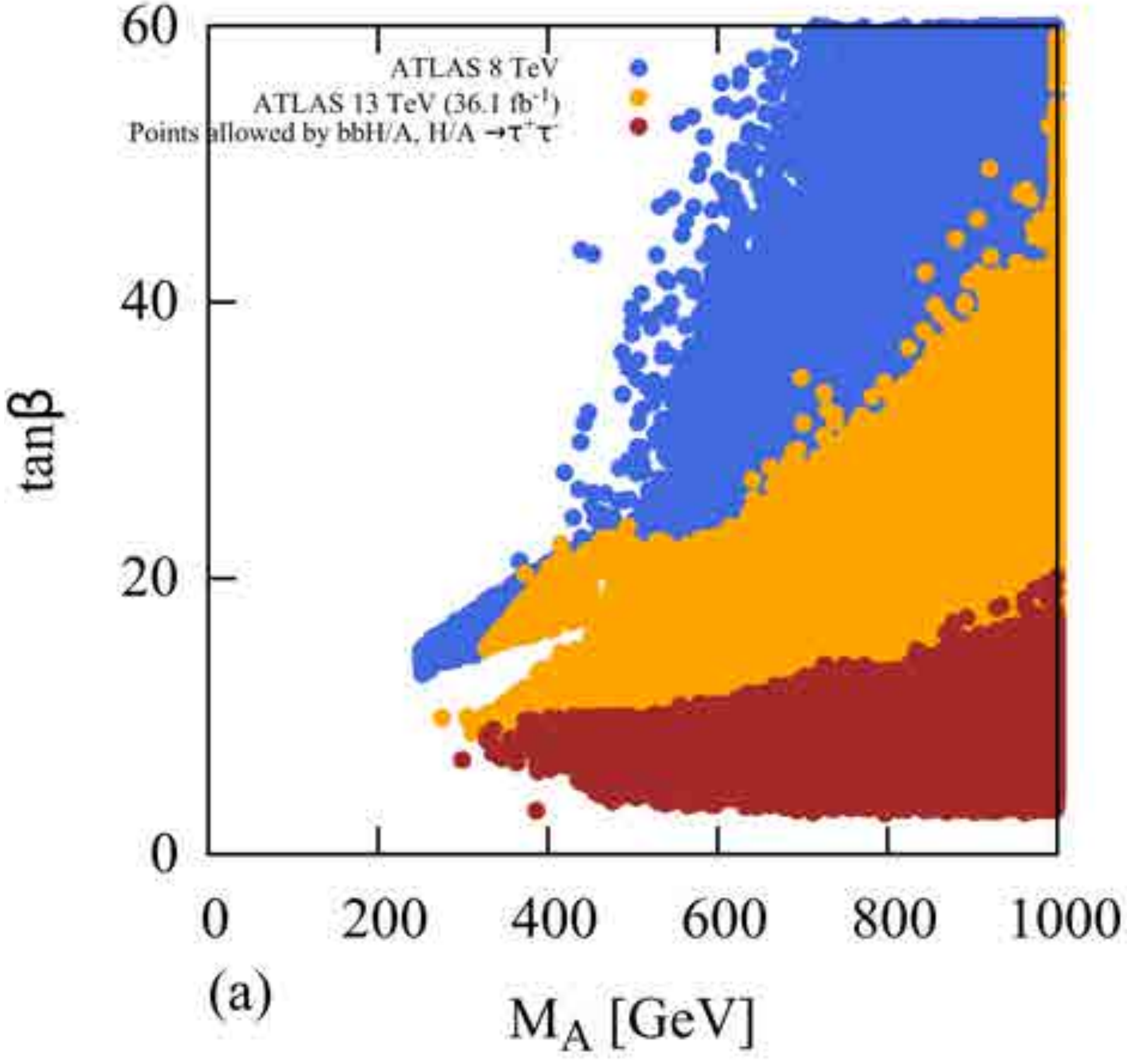
SUSY HIGGS: Heavy Higgs searches



SUSY HIGGS: Heavy Higgs searches

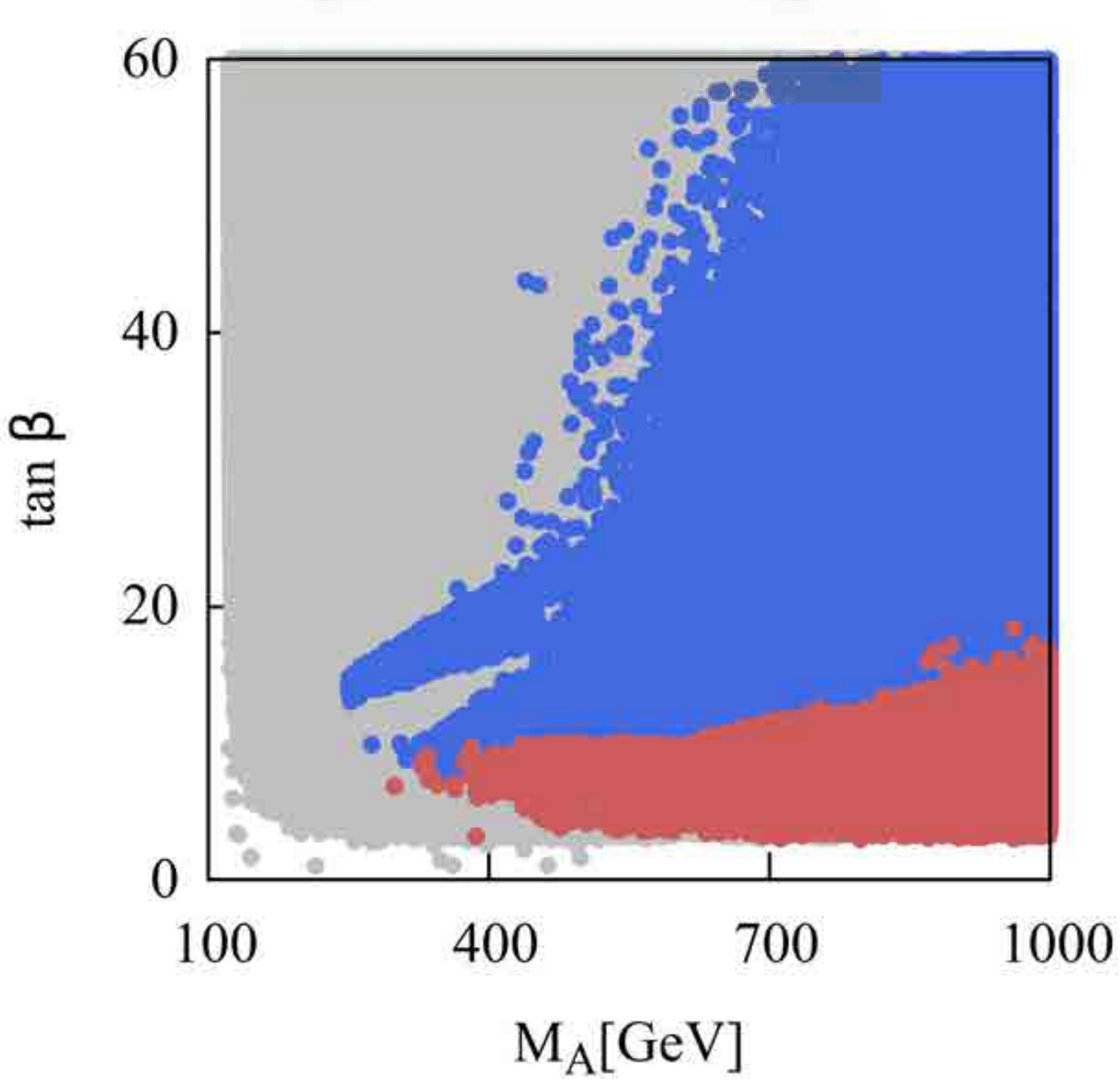


(b)



(a)

Current status



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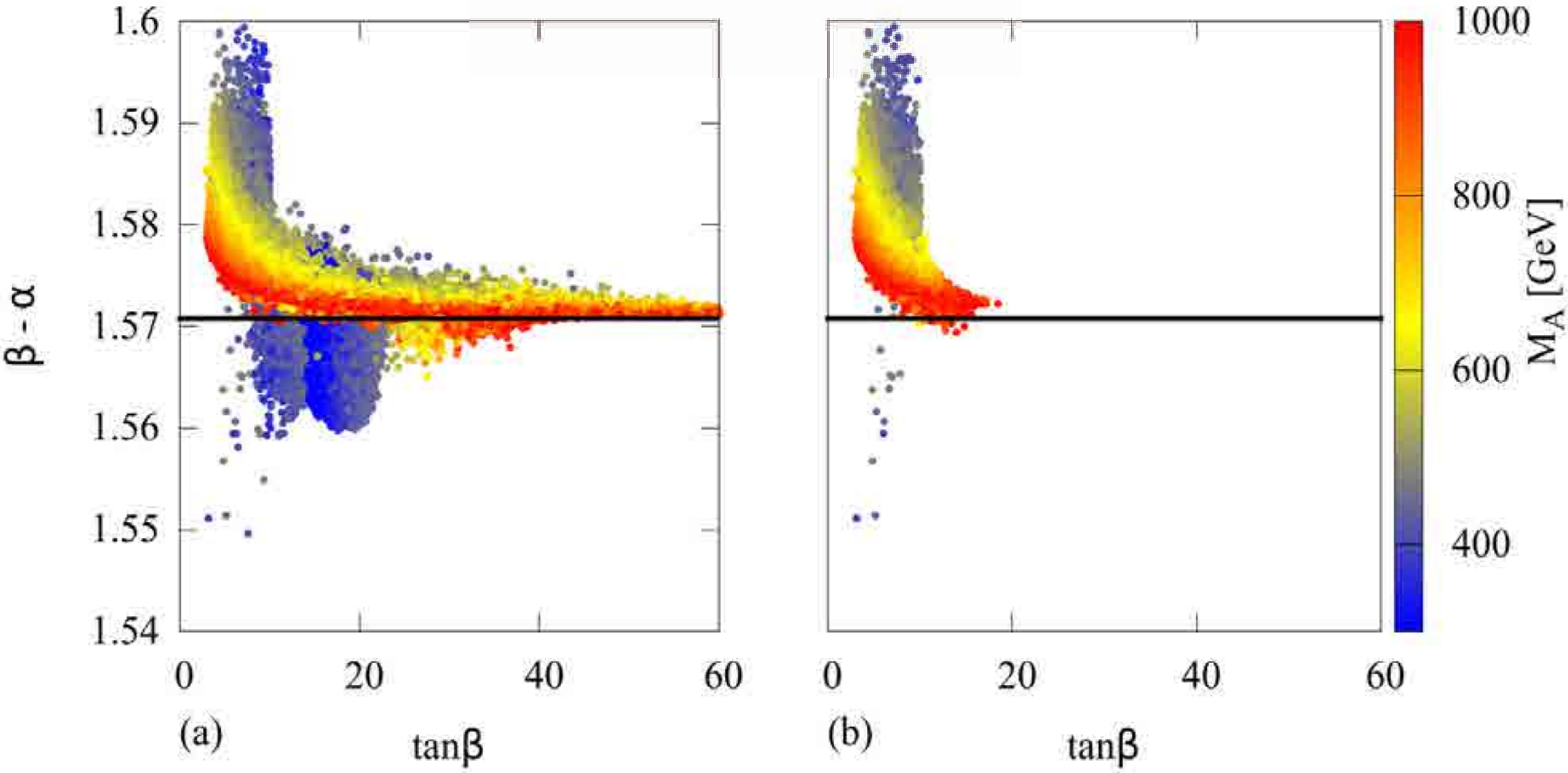
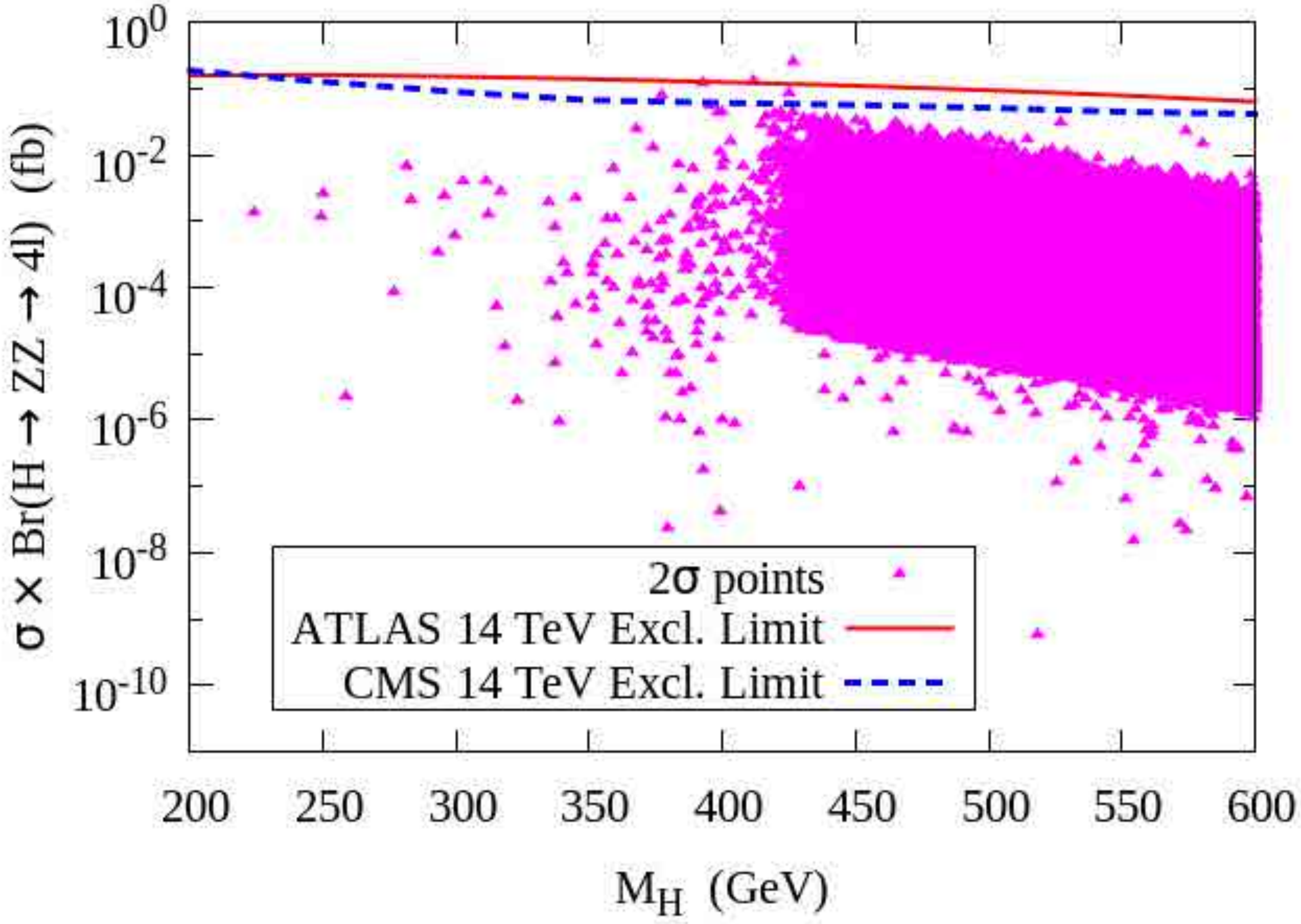
Current status



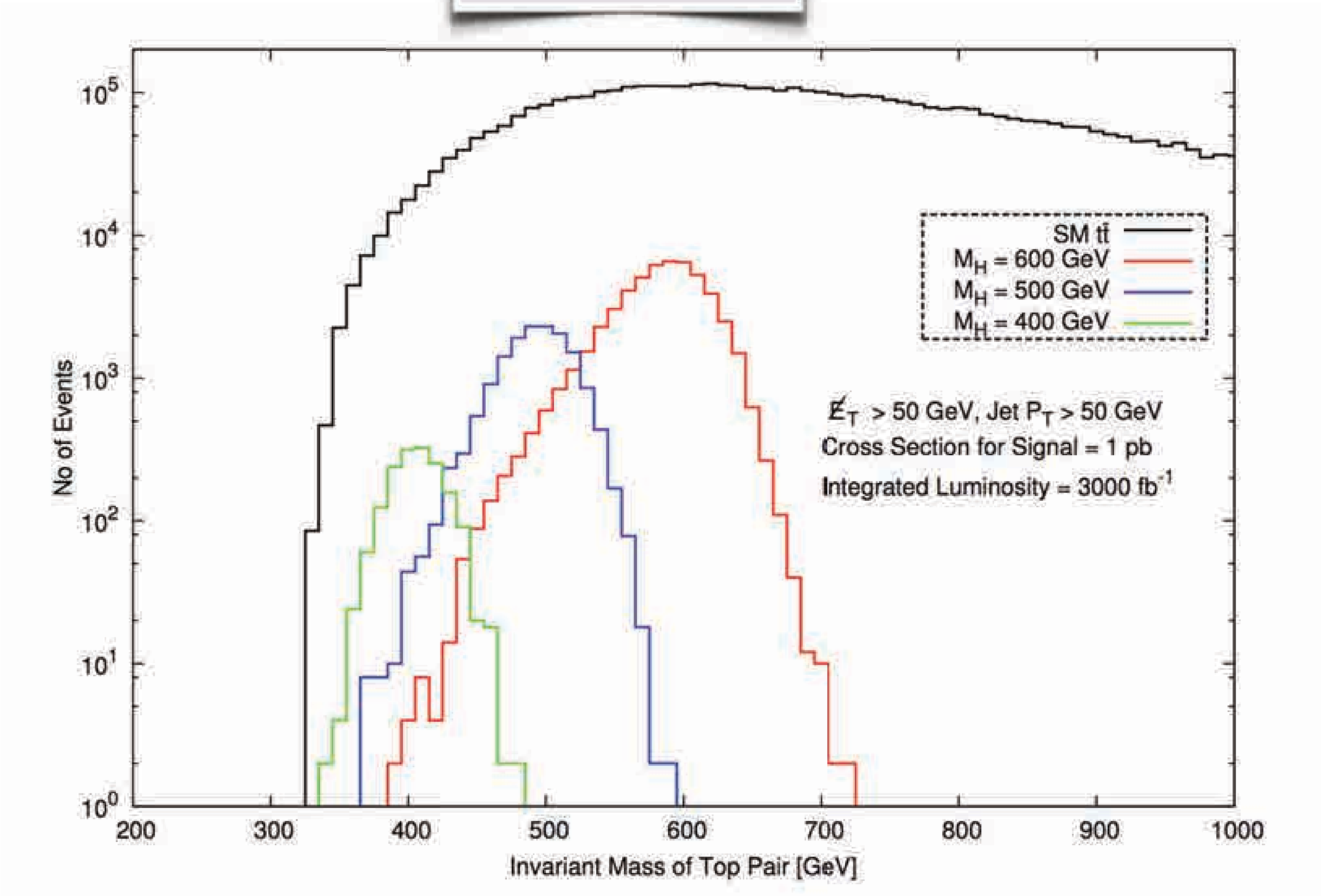
signal strength : about 20 % variation still possible

Future limits



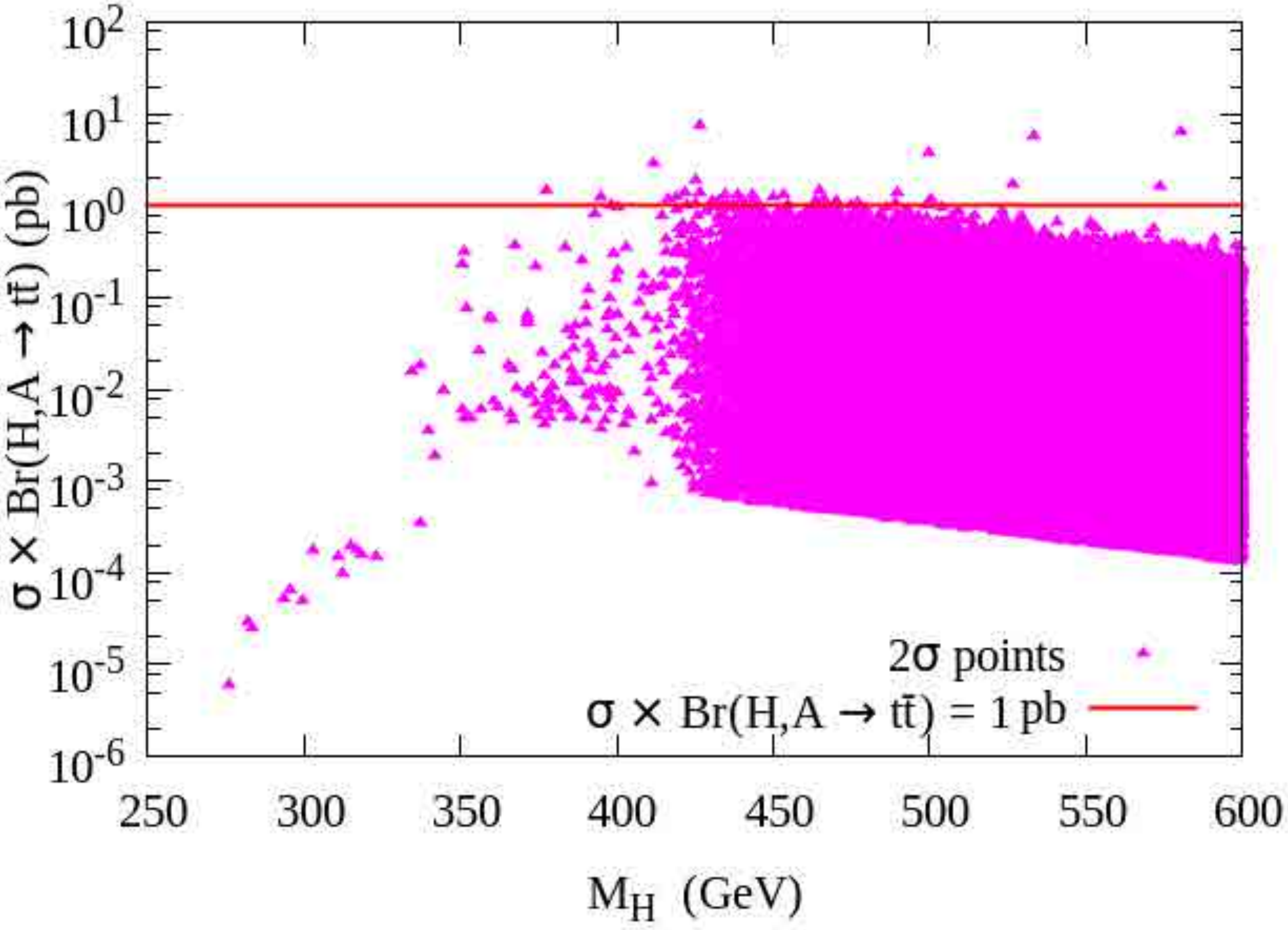
BB, Chakraborty, Choudhury Phys.Rev. D92 (2015) no.9, 093007

Future limits



BB, Chakraborty, Choudhury Phys.Rev. D92 (2015) no.9, 093007

Future limits



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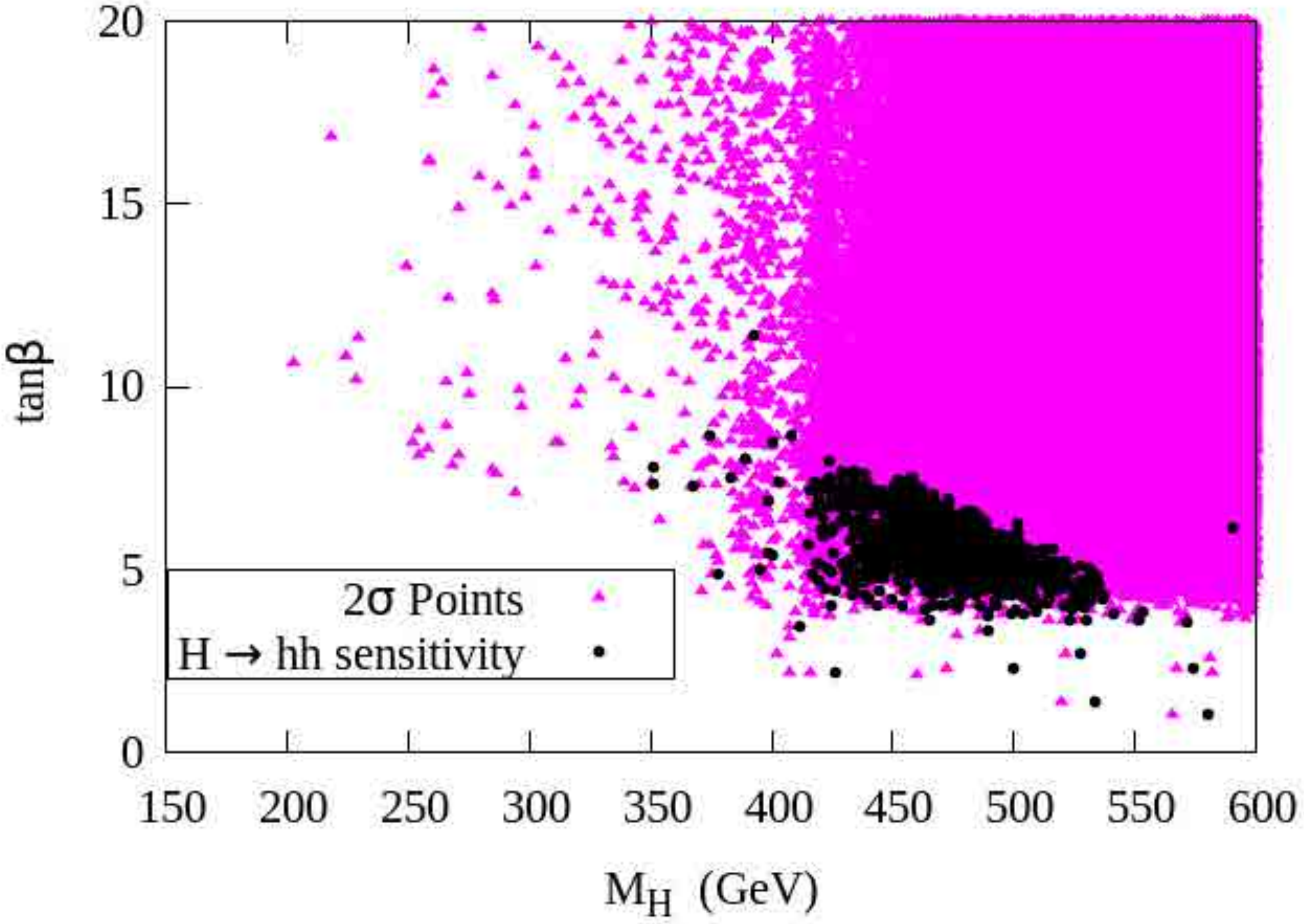
Future limits



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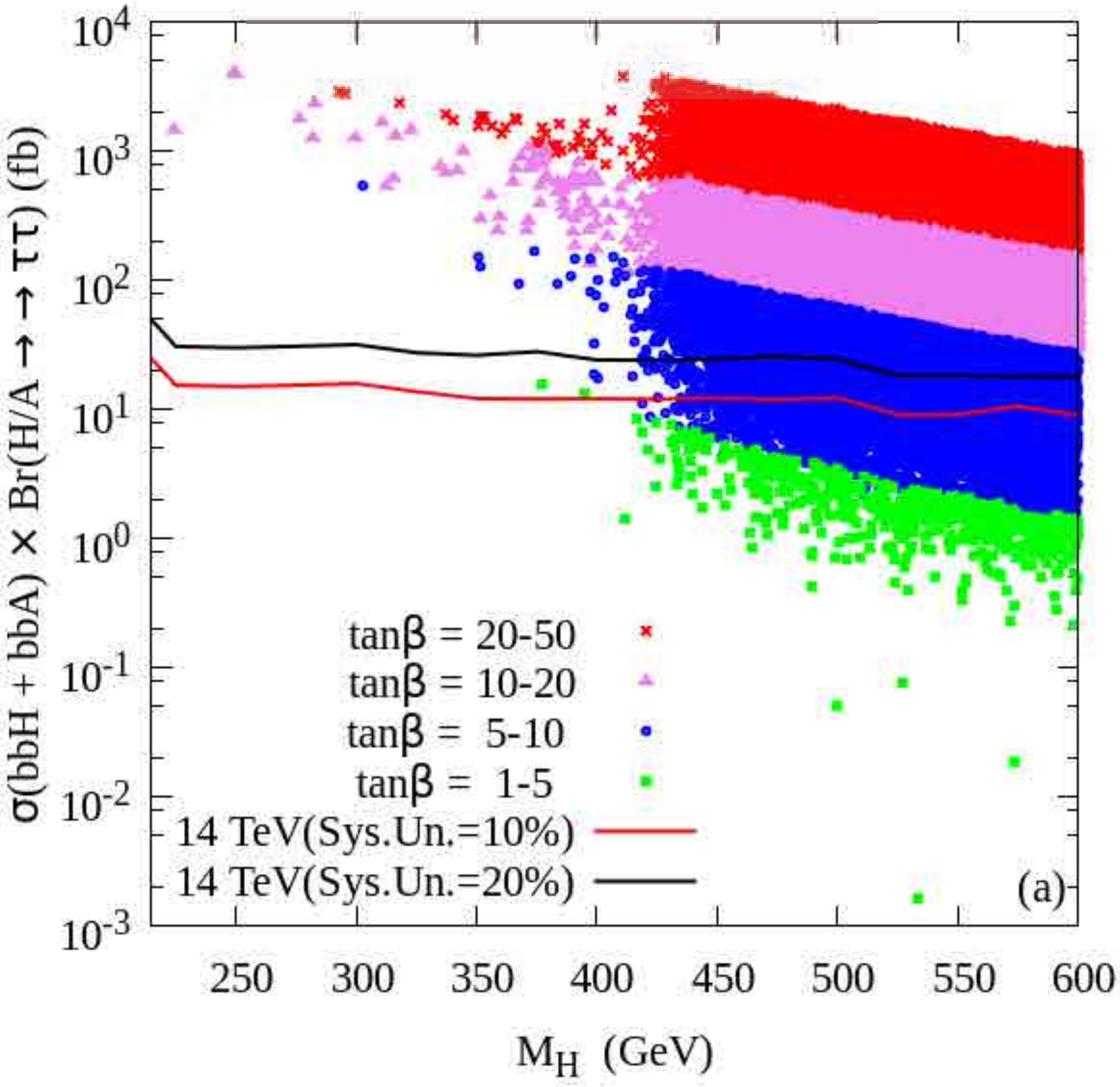
Future limits



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Additional decay modes of Heavy Higgs bosons

The heavy Higgs limits are derived by assuming 100% decay to SM particles

SUSY particles can be lighter than Heavy Higgs bosons

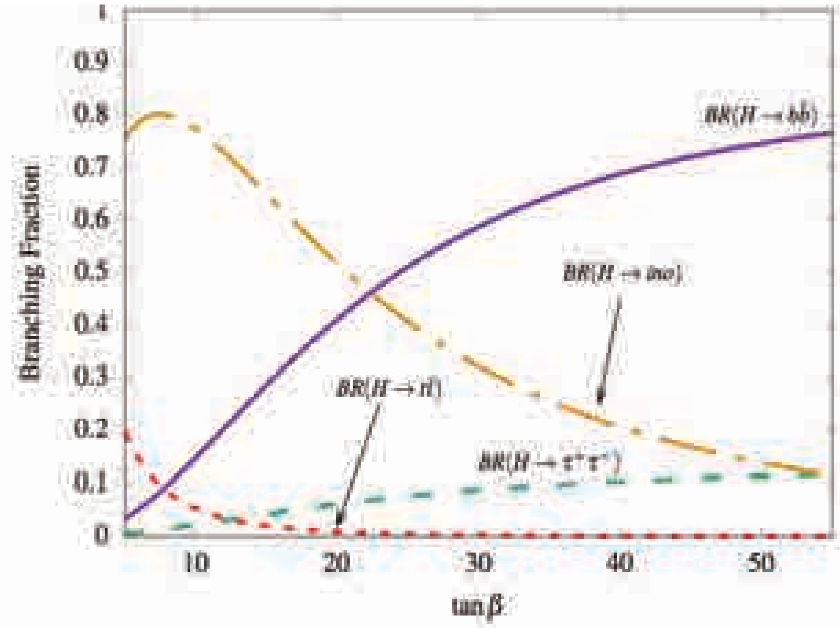
Heavy Higgs -> sparticles possible

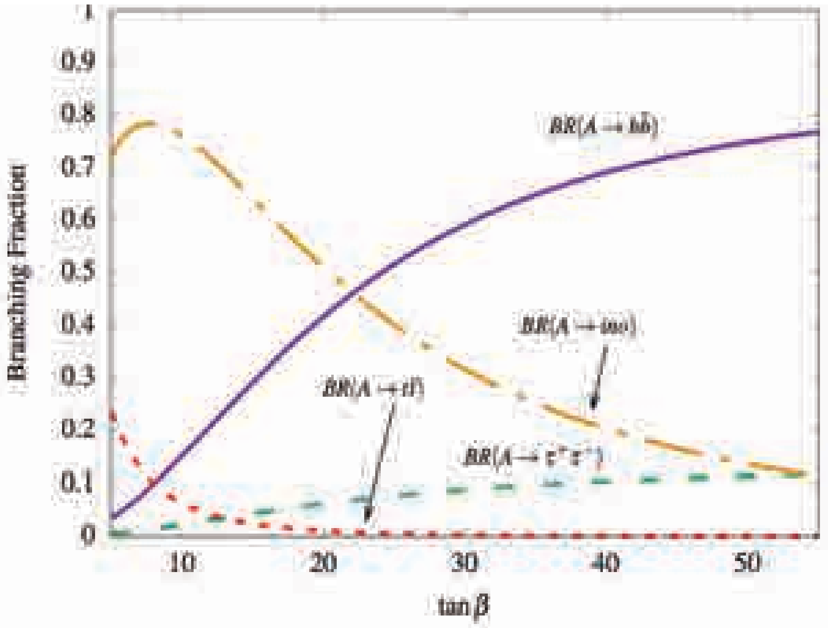
Here we will consider Heavy Higgs -> electroweak inos

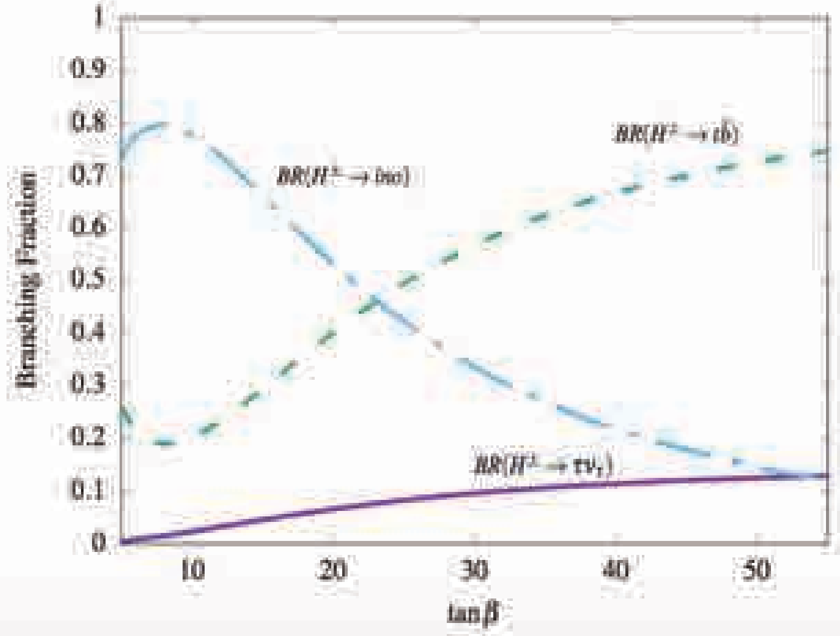
Heavy Higgs decay to Electrowikinos

$$\Gamma(H_k \to \widetilde{\chi}_i \widetilde{\chi}_j) \sim M_{H_k} \left[\left(\left(g^L_{ijk}\right)^2 + \left(g^R_{ijk}\right)^2 \right) \left(1 - \frac{m^2_{\widetilde{\chi}_i}}{M^2_{H_k}} - \frac{m^2_{\widetilde{\chi}_j}}{M^2_{H_k}} \right) - 4\epsilon_i \epsilon_j g^L_{ijk} g^R_{ijk} \frac{m_{\widetilde{\chi}_i} m_{\widetilde{\chi}_j}}{M^2_{H_k}} \right]$$

$$g^L_{\widetilde{\chi}^0_i \widetilde{\chi}^0_j H_\ell} = \frac{1}{2 s_w} \left(N_{j2} - \tan\theta_w N_{j1} \right) \left(e_\ell N_{i3} + d_\ell N_{i4} \right) + i \leftrightarrow j$$





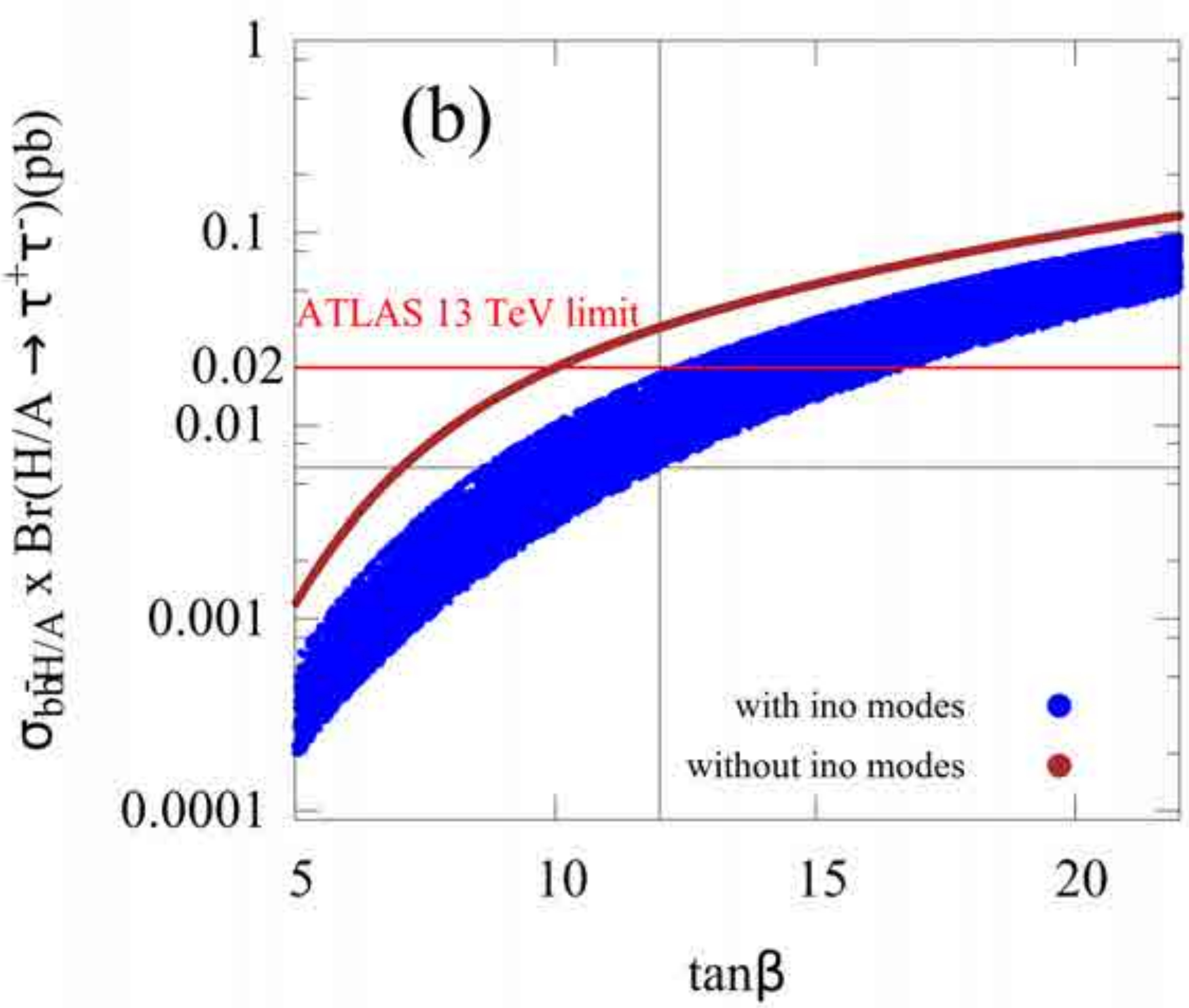


Barman, BB, Chowdhury, Chakraborty,
Phys.Rev. D94 (2016) no.7, 075013

$M_A = 650$ GeV, $M_1 = 500$ GeV, $M_2 = 150$ GeV, $\mu = 300$ GeV,
$M_3 = 5$ TeV, $m_{\tilde{Q}_{3L}} = m_{\tilde{t}_R} = m_{\tilde{b}_R} = 5$ TeV,
$A_t = -5$ TeV, $A_b = A_\tau = 0.$

Heavy Higgs decay to Electrowikinos

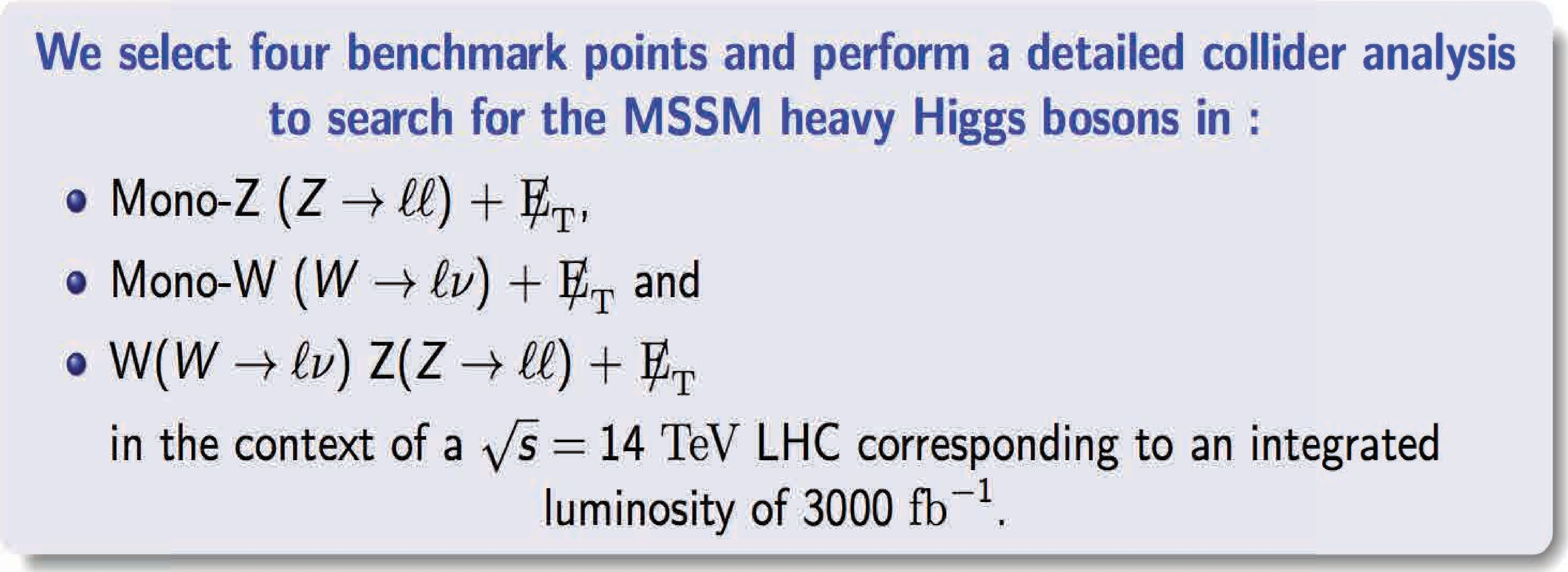
MA= 600 GeV



limit is weaker in case of H-> electrowino

Barman, BB, Choudhury, Chowdhury, Lahiri, Ray (1608.02573)

Heavy Higgs decay to Electrowikinos



We select four benchmark points and perform a detailed collider analysis to search for the MSSM heavy Higgs bosons in :

- Mono-Z $(Z \to \ell\ell) + \not\!\!E_{\mathrm{T}}$,
- Mono-W $(W \to \ell\nu) + \not\!\!E_{\mathrm{T}}$ and
- W$(W \to \ell\nu)$ Z$(Z \to \ell\ell) + \not\!\!E_{\mathrm{T}}$

in the context of a $\sqrt{s} = 14$ TeV LHC corresponding to an integrated luminosity of 3000 fb^{-1}.

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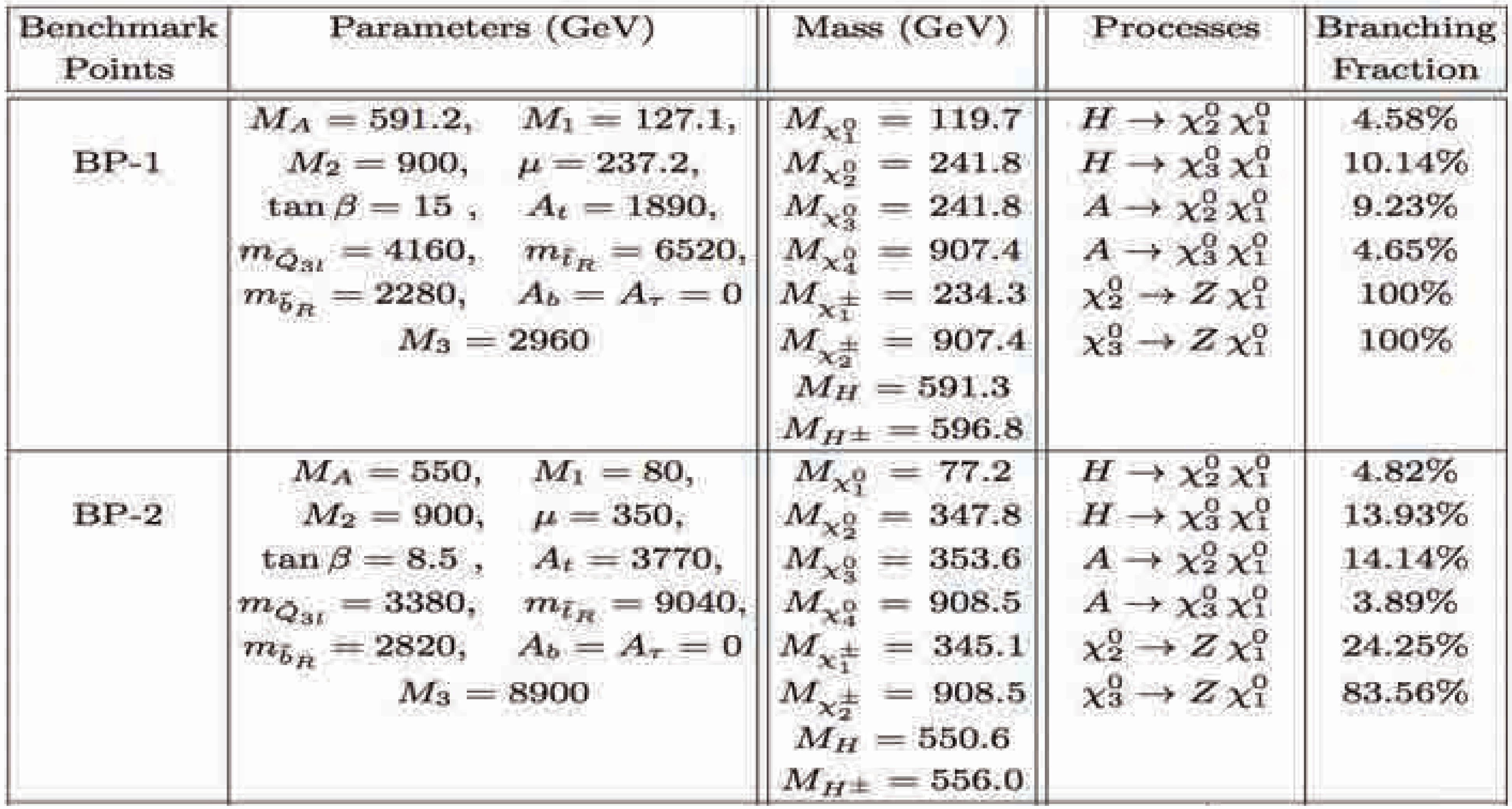
Heavy Higgs decay to Electrowikinos

$$pp \rightarrow H/A, \quad H/A \rightarrow \widetilde{\chi}^0_{2,3}\widetilde{\chi}^0_1, \quad \widetilde{\chi}^0_{2,3} \rightarrow \widetilde{\chi}^0_1 Z.$$

Signal : mono Z + MET (typically used for DM searches)

Benchmark point

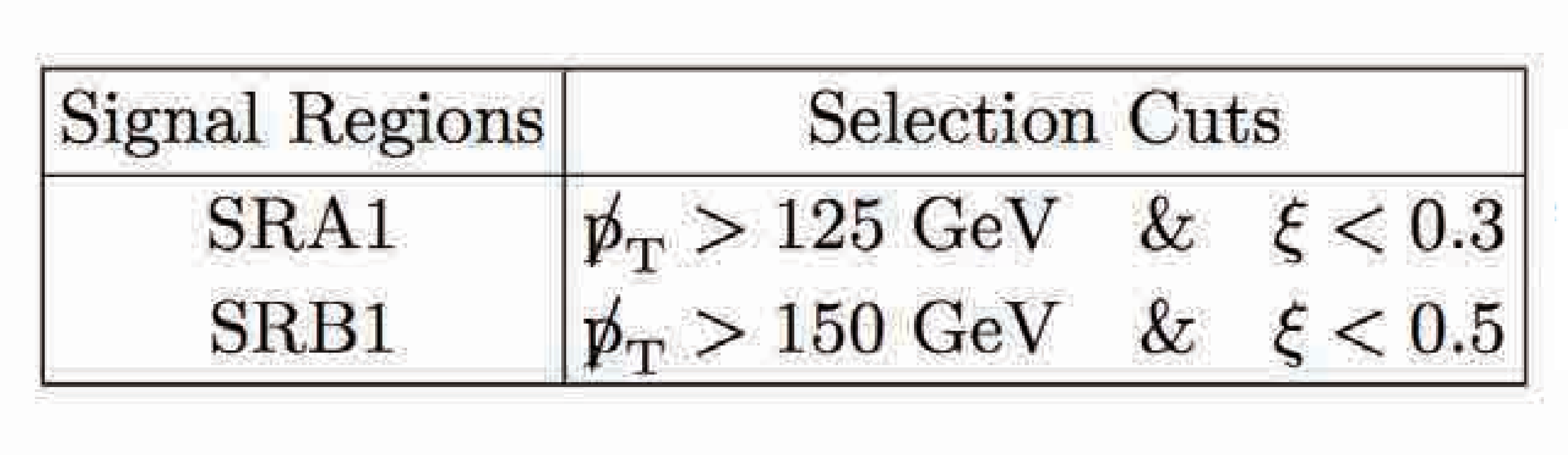


Benchmark Points	Parameters (GeV)		Mass (GeV)	Processes	Branching Fraction
BP-1	$M_A = 591.2,$	$M_1 = 127.1,$	$M_{\chi^0_1} = 119.7$	$H \rightarrow \chi^0_2\,\chi^0_1$	4.58%
	$M_2 = 900,$	$\mu = 237.2,$	$M_{\chi^0_2} = 241.8$	$H \rightarrow \chi^0_3\,\chi^0_1$	10.14%
	$\tan\beta = 15$,	$A_t = 1890,$	$M_{\chi^0_3} = 241.8$	$A \rightarrow \chi^0_2\,\chi^0_1$	9.23%
	$m_{\tilde{Q}_{3L}} = 4160,$	$m_{\tilde{t}_R} = 6520,$	$M_{\chi^0_4} = 907.4$	$A \rightarrow \chi^0_3\,\chi^0_1$	4.65%
	$m_{\tilde{b}_R} = 2280,$	$A_b = A_\tau = 0$	$M_{\chi^\pm_1} = 234.3$	$\chi^0_2 \rightarrow Z\,\chi^0_1$	100%
	$M_3 = 2960$		$M_{\chi^\pm_2} = 907.4$	$\chi^0_3 \rightarrow Z\,\chi^0_1$	100%
			$M_H = 591.3$		
			$M_{H^\pm} = 596.8$		
BP-2	$M_A = 550,$	$M_1 = 80,$	$M_{\chi^0_1} = 77.2$	$H \rightarrow \chi^0_2\,\chi^0_1$	4.82%
	$M_2 = 900,$	$\mu = 350,$	$M_{\chi^0_2} = 347.8$	$H \rightarrow \chi^0_3\,\chi^0_1$	13.93%
	$\tan\beta = 8.5$,	$A_t = 3770,$	$M_{\chi^0_3} = 353.6$	$A \rightarrow \chi^0_2\,\chi^0_1$	14.14%
	$m_{\tilde{Q}_{3L}} = 3380,$	$m_{\tilde{t}_R} = 9040,$	$M_{\chi^0_4} = 908.5$	$A \rightarrow \chi^0_3\,\chi^0_1$	3.89%
	$m_{\tilde{b}_R} = 2820,$	$A_b = A_\tau = 0$	$M_{\chi^\pm_1} = 345.1$	$\chi^0_2 \rightarrow Z\,\chi^0_1$	24.25%
	$M_3 = 8900$		$M_{\chi^\pm_2} = 908.5$	$\chi^0_3 \rightarrow Z\,\chi^0_1$	83.56%
			$M_H = 550.6$		
			$M_{H^\pm} = 556.0$		

Barman, BB, Chowdhury, Chakraborty, Phys.Rev. D94 (2016) no.7, 075013

Heavy Higgs decay to Electrowikinos

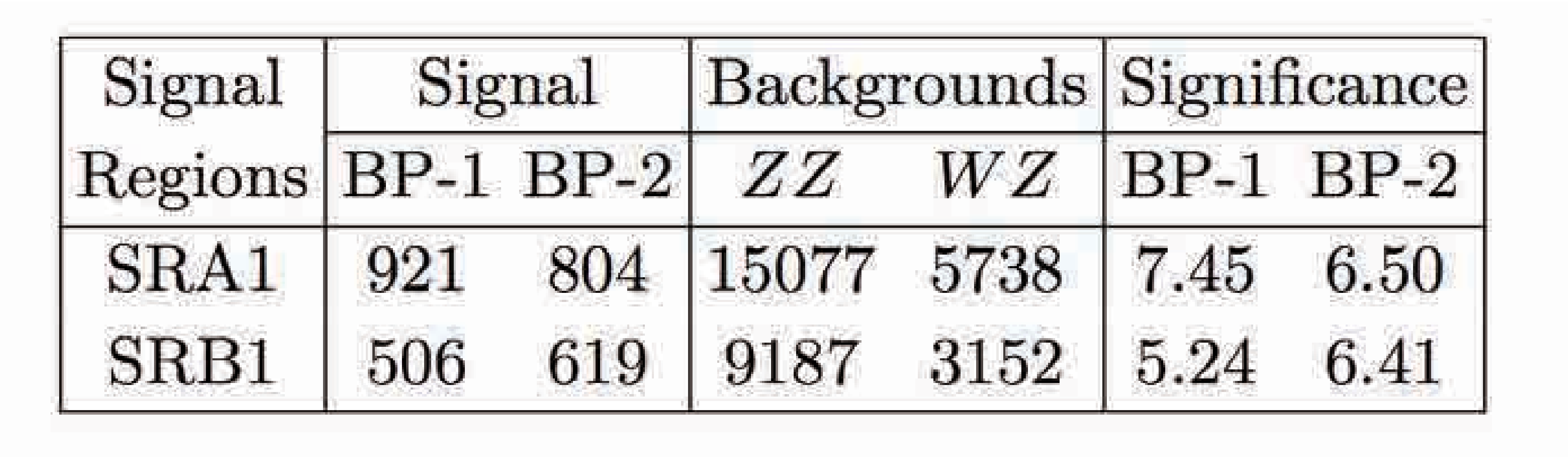
CUTS



Signal Regions	Selection Cuts
SRA1	$\not{p}_T > 125$ GeV & $\xi < 0.3$
SRB1	$\not{p}_T > 150$ GeV & $\xi < 0.5$

$$\xi = \frac{|p_T^{\ell\ell} - \not{p}_T|}{p_T^{\ell\ell}}$$

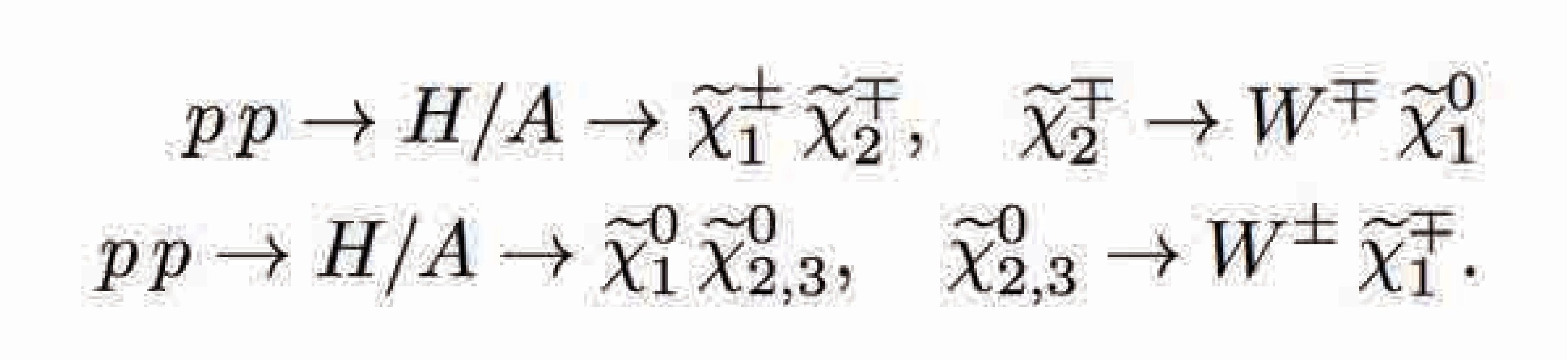
Results



Signal	Signal		Backgrounds		Significance	
Regions	BP-1	BP-2	ZZ	WZ	BP-1	BP-2
SRA1	921	804	15077	5738	7.45	6.50
SRB1	506	619	9187	3152	5.24	6.41

This channel has some potential to search for Heavy Higgs boson

Heavy Higgs decay to Electrowikinos

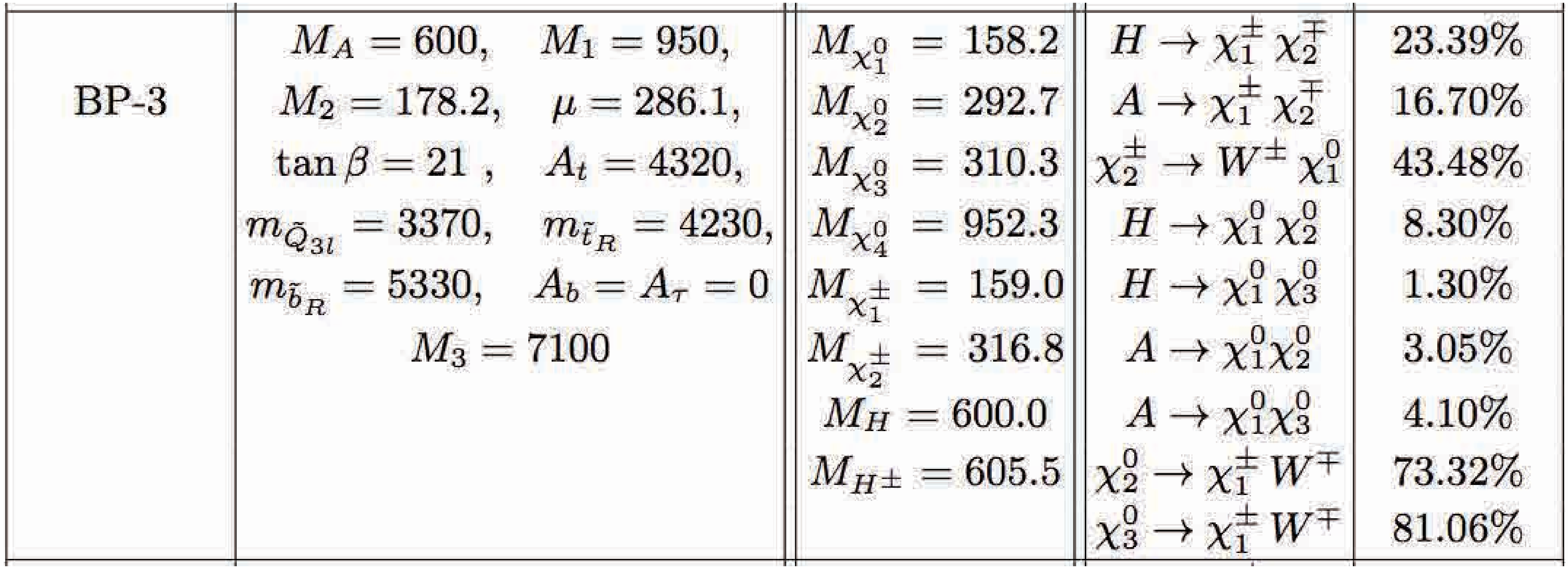


$$pp \to H/A \to \widetilde{\chi}_1^{\pm}\,\widetilde{\chi}_2^{\mp}, \quad \widetilde{\chi}_2^{\mp} \to W^{\mp}\,\widetilde{\chi}_1^0$$

$$pp \to H/A \to \widetilde{\chi}_1^0\,\widetilde{\chi}_{2,3}^0, \quad \widetilde{\chi}_{2,3}^0 \to W^{\pm}\,\widetilde{\chi}_1^{\mp}.$$

Signal : mono lepton + MET (typically used for W' search)

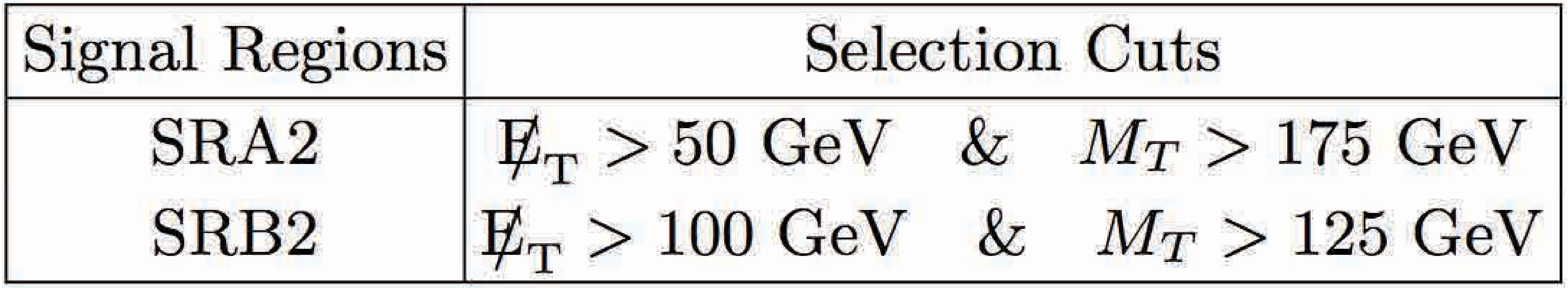
Benchmark point



BP-3	$M_A = 600, \quad M_1 = 950,$	$M_{\chi_1^0} = 158.2$	$H \to \chi_1^{\pm}\chi_2^{\mp}$	23.39%
	$M_2 = 178.2, \quad \mu = 286.1,$	$M_{\chi_2^0} = 292.7$	$A \to \chi_1^{\pm}\chi_2^{\mp}$	16.70%
	$\tan\beta = 21\ , \quad A_t = 4320,$	$M_{\chi_3^0} = 310.3$	$\chi_2^{\pm} \to W^{\pm}\chi_1^0$	43.48%
	$m_{\tilde{Q}_{3l}} = 3370, \quad m_{\tilde{t}_R} = 4230,$	$M_{\chi_4^0} = 952.3$	$H \to \chi_1^0\chi_2^0$	8.30%
	$m_{\tilde{b}_R} = 5330, \quad A_b = A_\tau = 0$	$M_{\chi_1^{\pm}} = 159.0$	$H \to \chi_1^0\chi_3^0$	1.30%
	$M_3 = 7100$	$M_{\chi_2^{\pm}} = 316.8$	$A \to \chi_1^0\chi_2^0$	3.05%
		$M_H = 600.0$	$A \to \chi_1^0\chi_3^0$	4.10%
		$M_{H^{\pm}} = 605.5$	$\chi_2^0 \to \chi_1^{\pm}W^{\mp}$	73.32%
			$\chi_3^0 \to \chi_1^{\pm}W^{\mp}$	81.06%

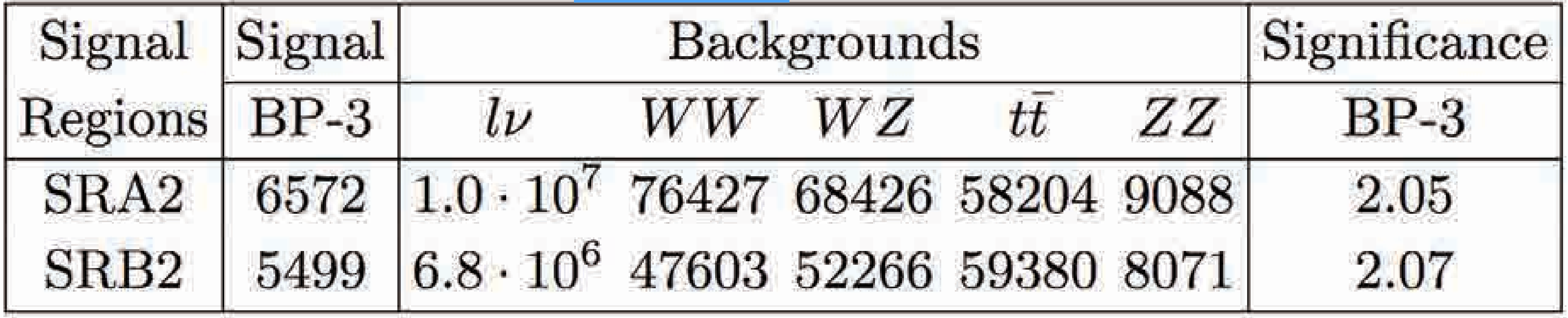
Heavy Higgs decay to Electrowikinos

CUTS



Signal Regions	Selection Cuts
SRA2	$\not\!\!E_T > 50$ GeV & $M_T > 175$ GeV
SRB2	$\not\!\!E_T > 100$ GeV & $M_T > 125$ GeV

Results



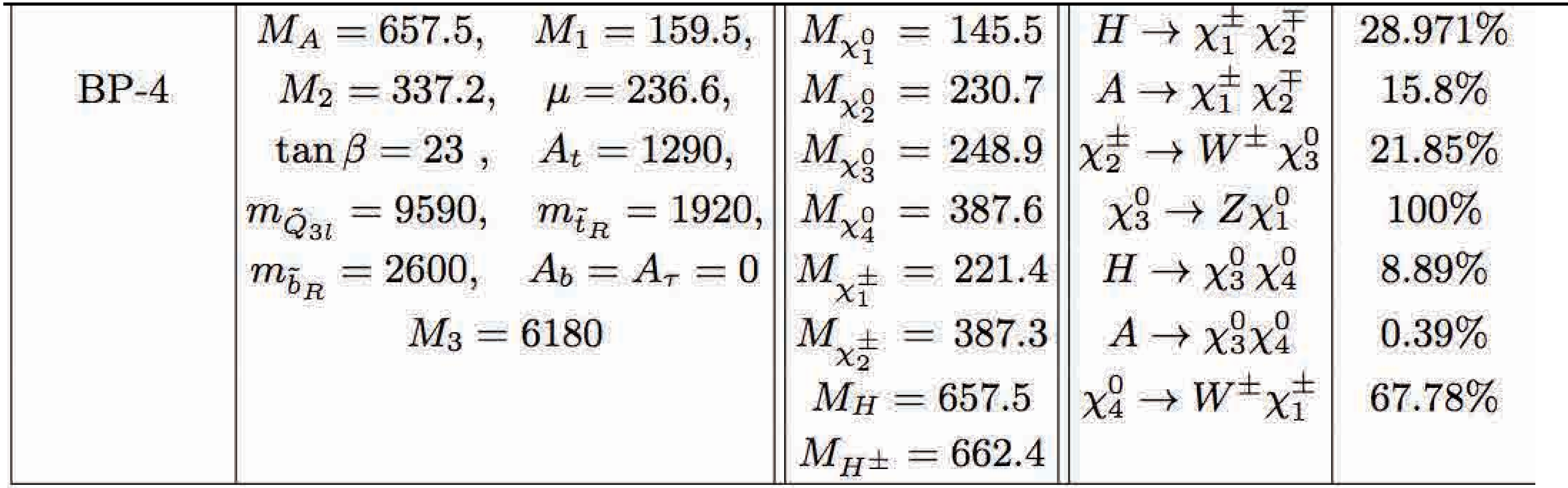
Signal	Signal	Backgrounds					Significance
Regions	BP-3	$l\nu$	WW	WZ	$t\bar{t}$	ZZ	BP-3
SRA2	6572	$1.0 \cdot 10^7$	76427	68426	58204	9088	2.05
SRB2	5499	$6.8 \cdot 10^6$	47603	52266	59380	8071	2.07

This channel has suffered from huge SM background: probably not very useful

Heavy Higgs decay to Electrowikinos

$$pp \to H/A, \quad H/A \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^{\mp}, \quad \tilde{\chi}_2^{\mp} \to W^{\mp}\, \tilde{\chi}_3^0, \quad \tilde{\chi}_3^0 \to Z\, \tilde{\chi}_1^0$$
$$pp \to H/A, \quad H/A \to \tilde{\chi}_3^0\, \tilde{\chi}_4^0, \quad \tilde{\chi}_3^0 \to Z\, \tilde{\chi}_1^0, \quad \tilde{\chi}_4^0 \to W^{\pm}\, \tilde{\chi}_1^{\mp},$$

Benchmark point

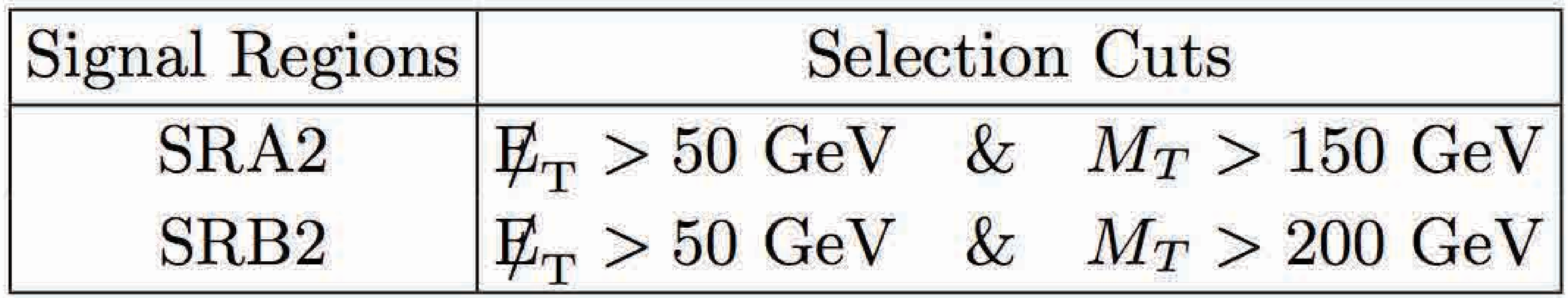


BP-4	$M_A = 657.5, \quad M_1 = 159.5,$	$M_{\chi_1^0} = 145.5$	$H \to \chi_1^{\pm}\, \chi_2^{\mp}$	28.971%
	$M_2 = 337.2, \quad \mu = 236.6,$	$M_{\chi_2^0} = 230.7$	$A \to \chi_1^{\pm}\, \chi_2^{\mp}$	15.8%
	$\tan\beta = 23\ , \quad A_t = 1290,$	$M_{\chi_3^0} = 248.9$	$\chi_2^{\pm} \to W^{\pm}\, \chi_3^0$	21.85%
	$m_{\tilde{Q}_{3l}} = 9590, \quad m_{\tilde{t}_R} = 1920,$	$M_{\chi_4^0} = 387.6$	$\chi_3^0 \to Z \chi_1^0$	100%
	$m_{\tilde{b}_R} = 2600, \quad A_b = A_\tau = 0$	$M_{\chi_1^{\pm}} = 221.4$	$H \to \chi_3^0\, \chi_4^0$	8.89%
	$M_3 = 6180$	$M_{\chi_2^{\pm}} = 387.3$	$A \to \chi_3^0 \chi_4^0$	0.39%
		$M_H = 657.5$	$\chi_4^0 \to W^{\pm} \chi_1^{\pm}$	67.78%
		$M_{H^{\pm}} = 662.4$		

Barman, BB, Chowdhury, Chakraborty, Phys.Rev. D94 (2016) no.7, 075013

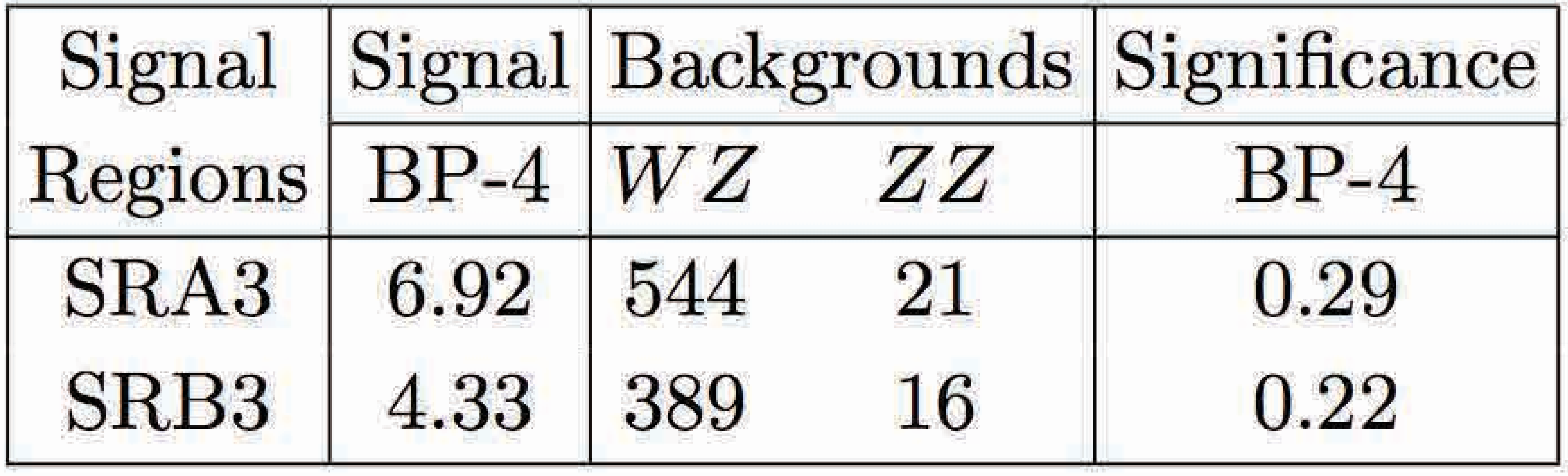
Heavy Higgs decay to Electrowikinos

CUTS



Signal Regions	Selection Cuts
SRA2	$\not{E}_{\rm T} > 50$ GeV & $M_T > 150$ GeV
SRB2	$\not{E}_{\rm T} > 50$ GeV & $M_T > 200$ GeV

Results



Signal Regions	Signal	Backgrounds		Significance
	BP-4	WZ	ZZ	BP-4
SRA3	6.92	544	21	0.29
SRB3	4.33	389	16	0.22

Number of signal events is very small, may not be useful

Barman, BB, Chowdhury, Chakraborty, Phys.Rev. D94 (2016) no.7, 075013

Invisible decay of 125 GeV Higgs boson

for very light neutralino $h_{125} \to \chi_1^0 \chi_1^0$ possible

$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = g\left(N_{11} - \tan\theta_W N_{12}\right)\left(\sin\alpha N_{13} + \cos\alpha N_{14}\right)$$

light neutralino will also couple to Z boson

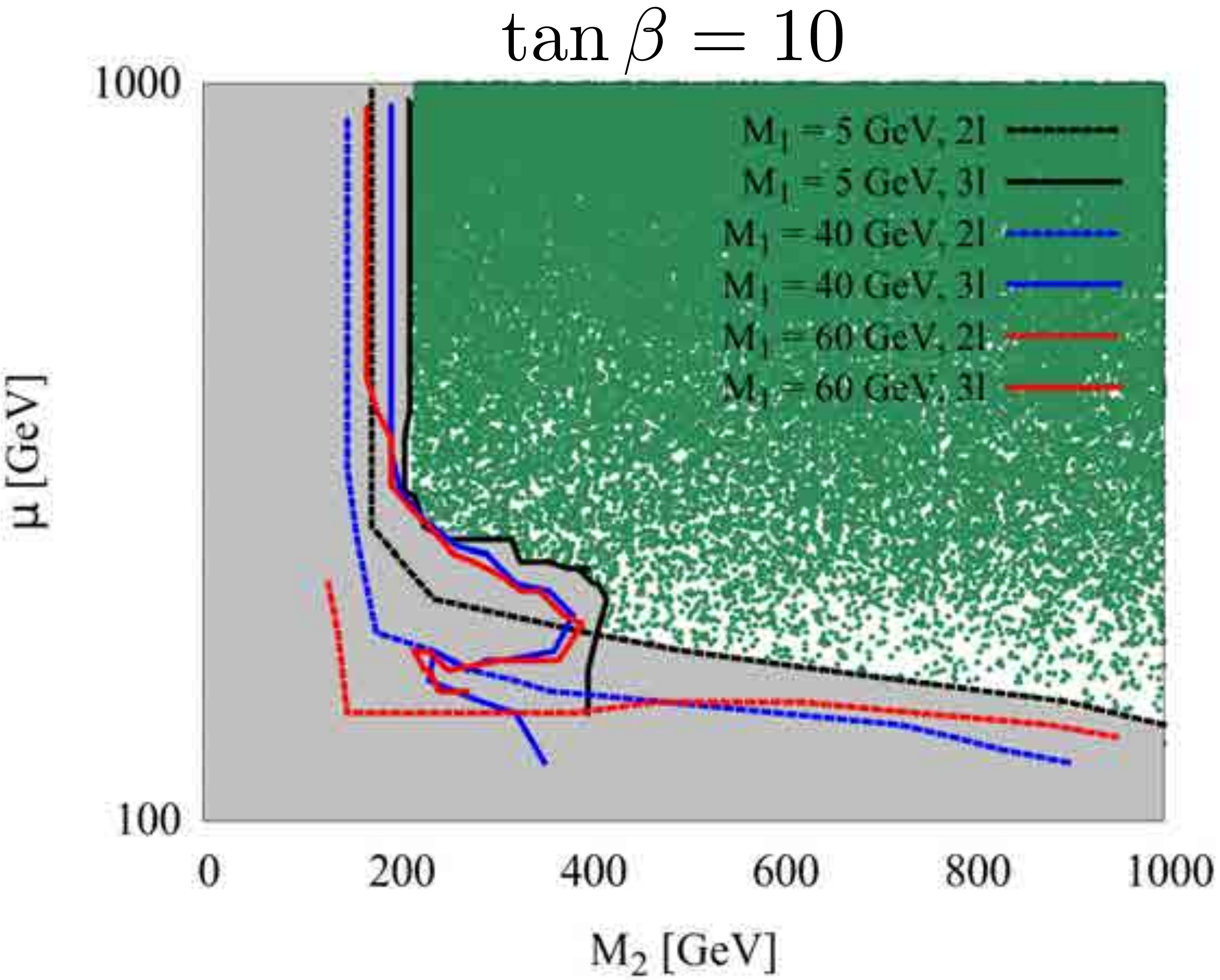
$$g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = \frac{g}{2\cos\theta_W}\left(|N_{13}|^2 - |N_{14}|^2\right)$$

Two possibilities : thermal dark matter and non standard cosmological model

Barman, Belanger, BB, Godbole, Mendiratta, Sengupta Phys.Rev. D95 (2017) no.9, 095018

Invisible decay of 125 GeV Higgs boson

bounds :Z decay , LEP limit, Higgs signal strength, direct detection, electrowikino searches(8 TeV)



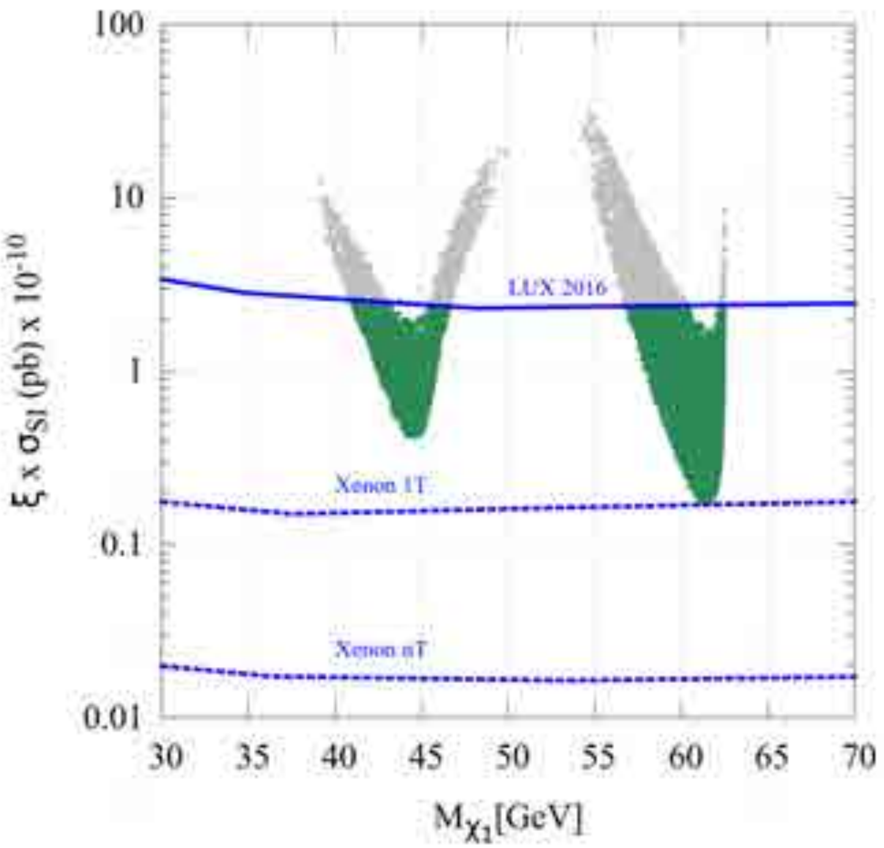
Barman, Belanger, BB, Godbole, Mendiratta, Sengupta Phys.Rev. D95 (2017) no.9, 095018

Invisible decay of 125 GeV Higgs boson

LHC limit on Higgs -> invisible~ 10 % from Higgs global fit

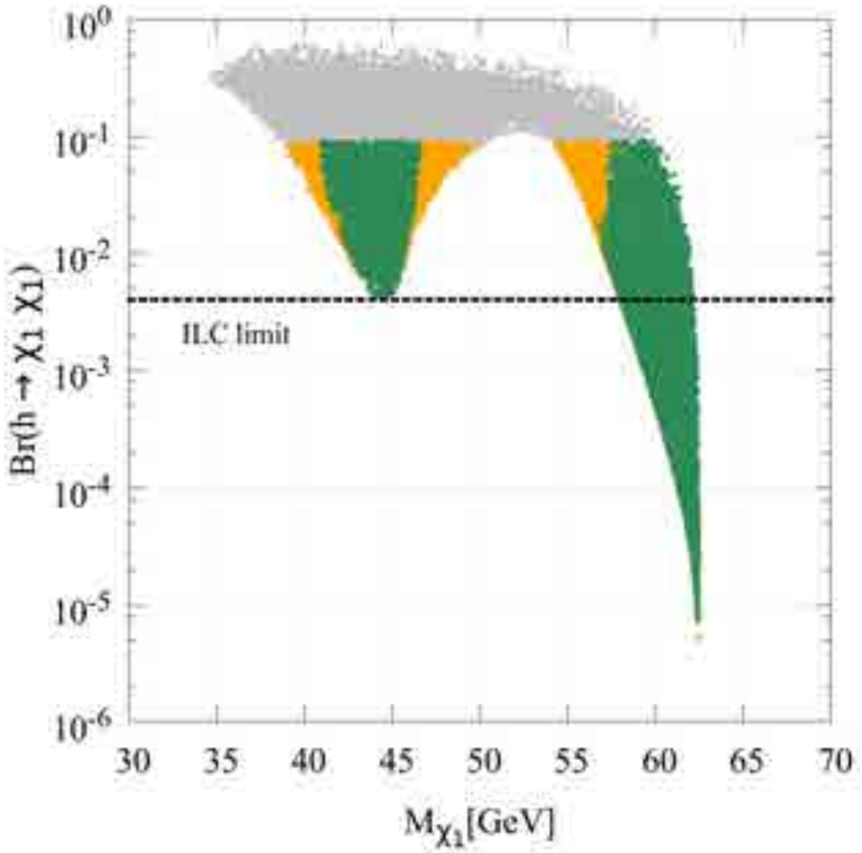
Direct search limit ~ 24 % (3000 ifb limit ~ 3-5 %)

For thermal relic only 2 possibilities: Z pole and Higgs pole



Current and future

direct detection bounds



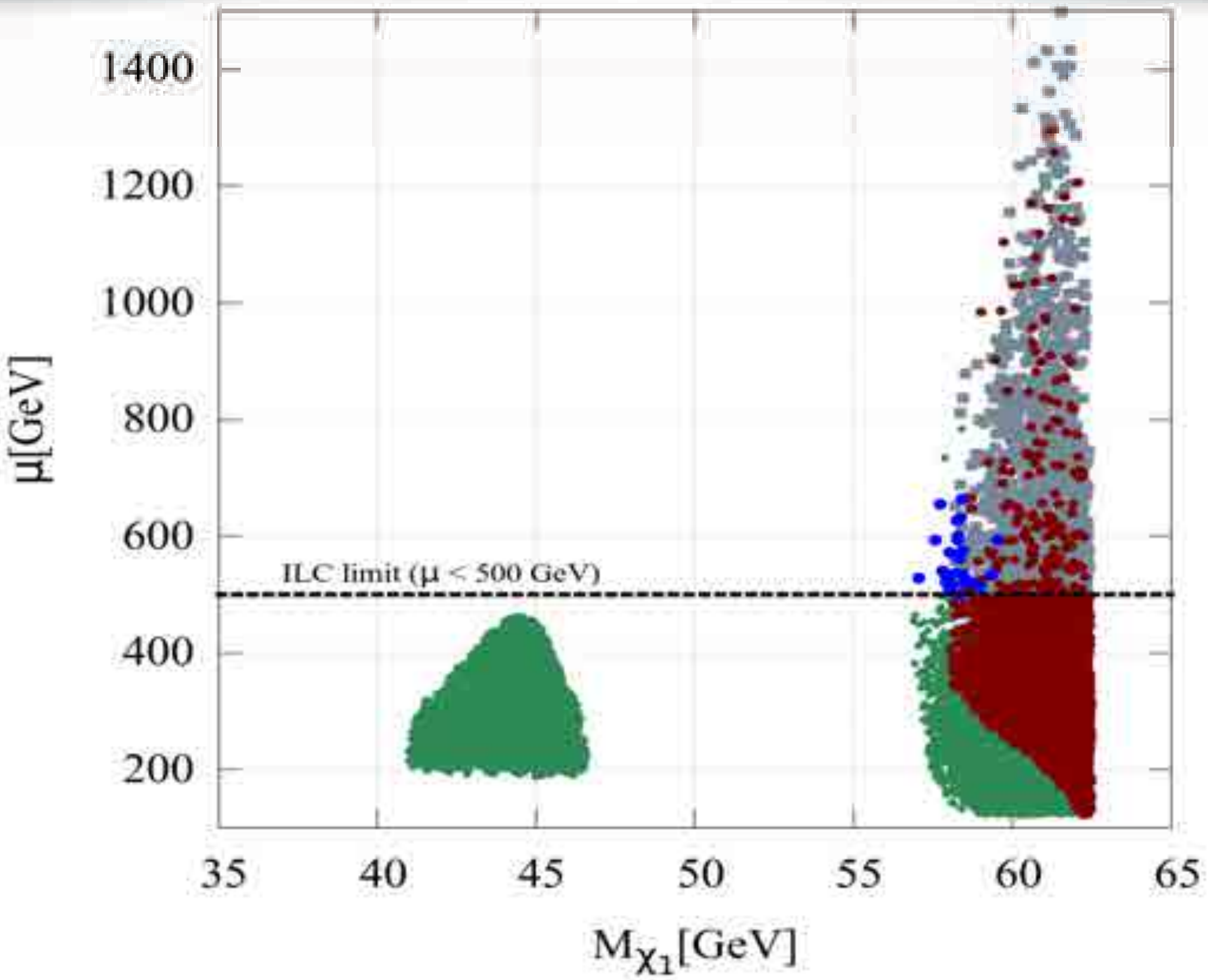
ILC limit

Higgs -> invisible

spin dependent direct detection experiments can probe Z resonance region

Barman, Belanger, BB, Godbole, Mendiratta, Sengupta Phys.Rev. D95 (2017) no.9, 095018

Invisible decay of 125 GeV Higgs boson: ILC direct search



grey points: Can not be probed by ILC

brown points : only via higgsino/wino searches

green points: both invisible branching and higgsino search

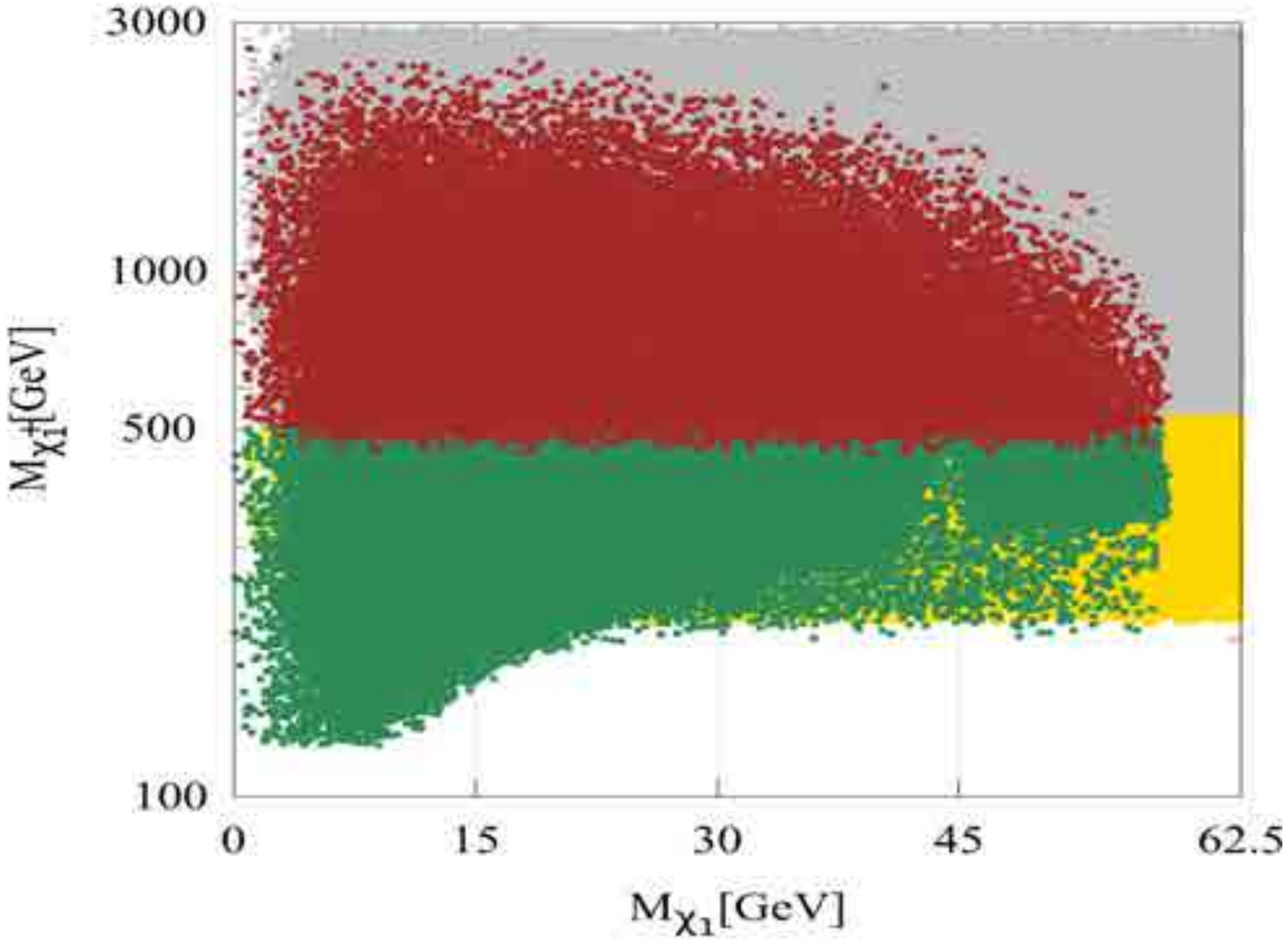
blue points : only Higgs invisible

Non standard Cosmology :

relic density condition : bino-like neutralinos lighter than about 40 GeV are ruled out

Non standard cosmological models : the lower bound on the lightest neutralino mass is lifted and we obtain LSP's with masses that span the whole range of the scan

Neutralino with mass ~ a few GeV is possible (weaker bound from direct detection cross section)



grey points: Can not be probed by ILC

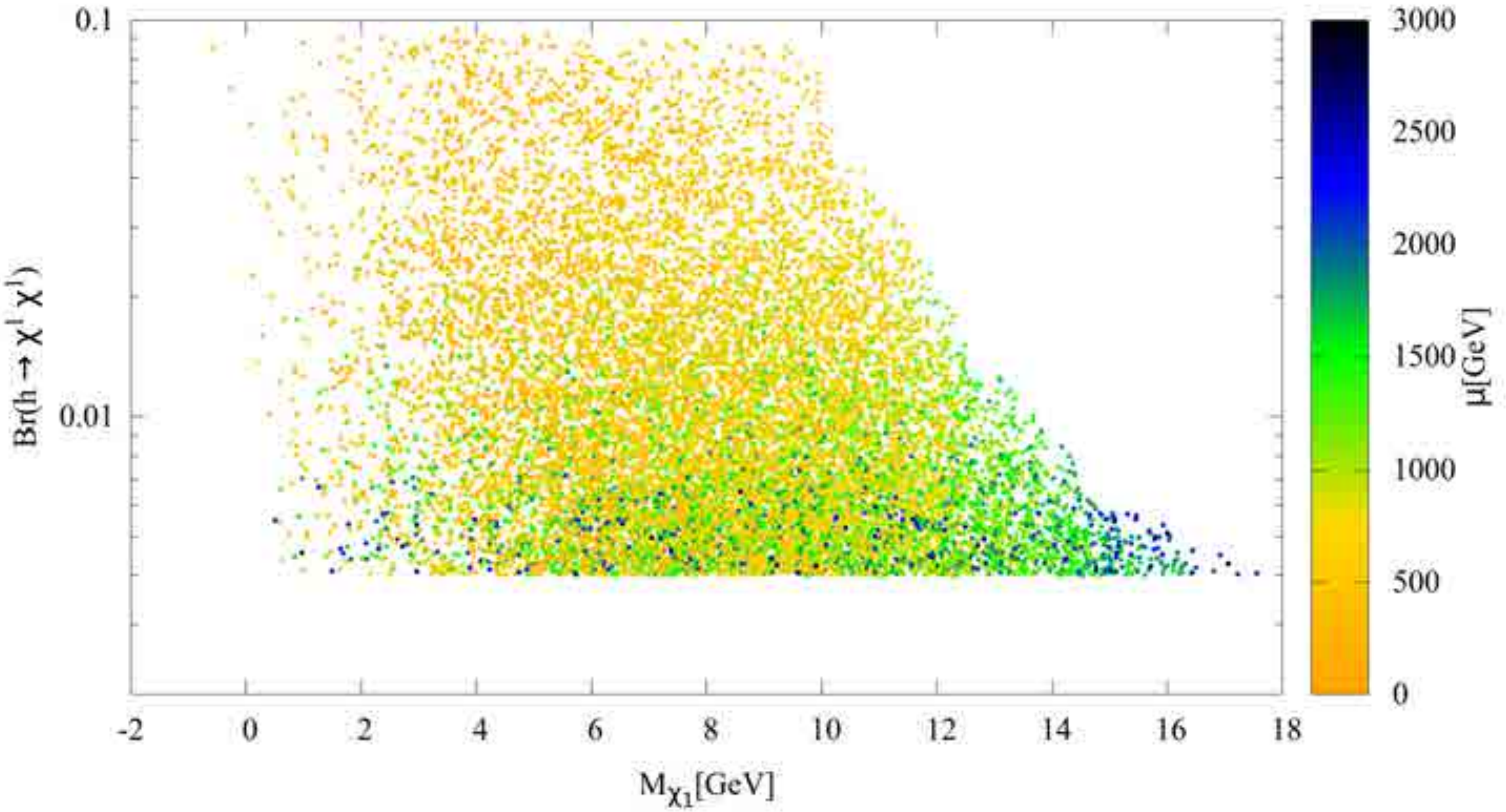
yellow points : only via higgsino/wino searches

green points: invisible branching + higgsino search

brown points : only Higgs invisible

Complementarity of future experiments in probing dark matter

One example : signal in ILC only



Light neutralino , large value of Higgs -> invisible possible

No Direct detection , It will indicate non standard cosmological model

Many such possibilities exist : detailed discussion in Phys.Rev. D95 (2017) no.9, 095018

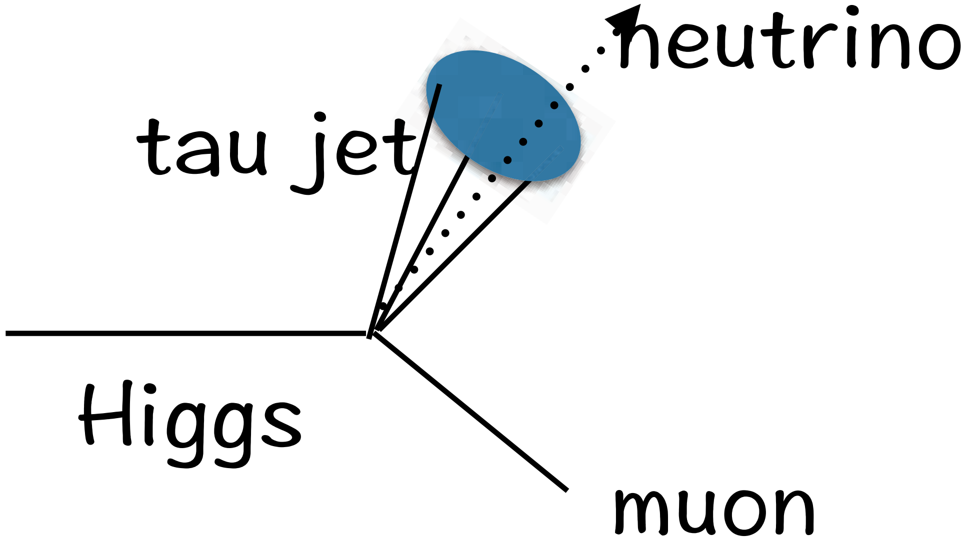
LFV Higgs decay

In SM, lepton flavour violating decays are extremely suppressed

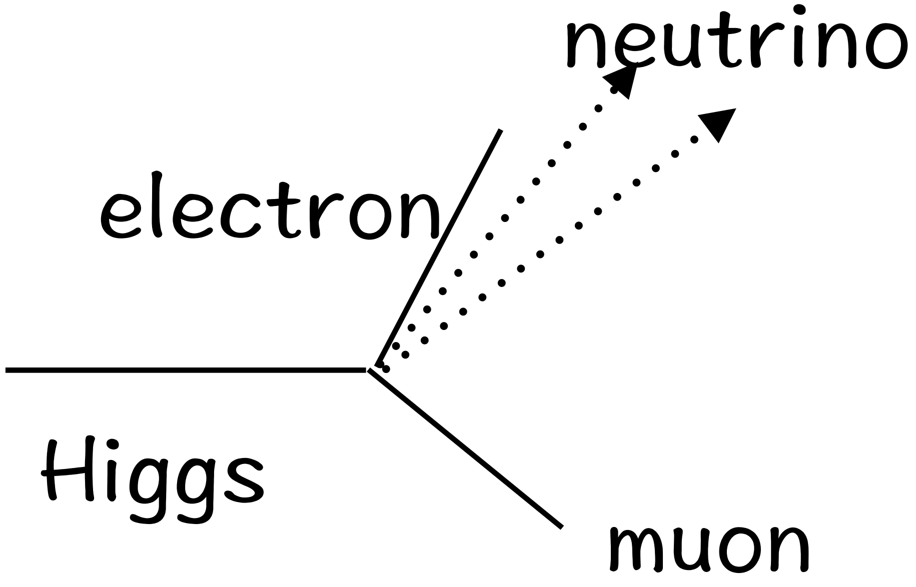
A large number of BSM theories can give rise to LFV in the range of current experimental limits

LFV is an interesting way to search for new physics!

$$H \to l_i l_j$$



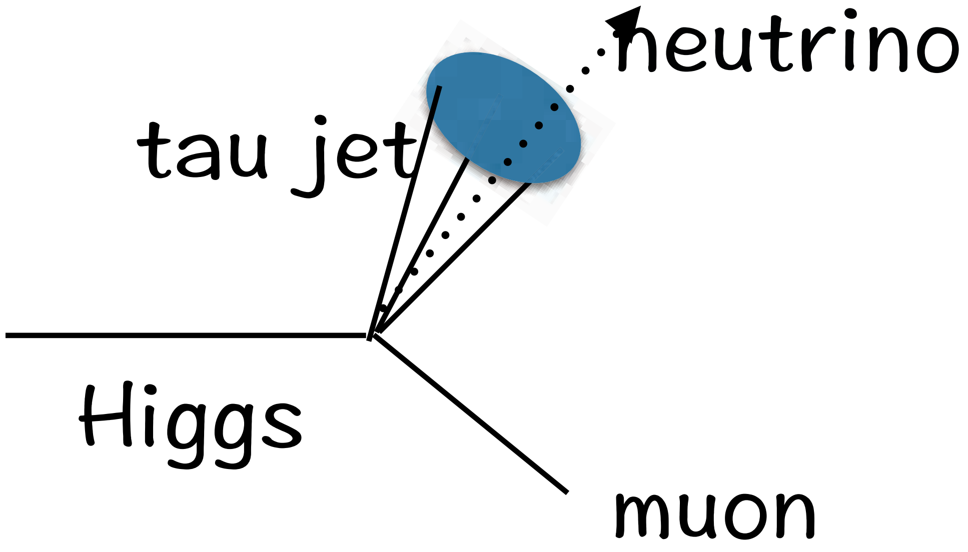
H-> muon + tau jet

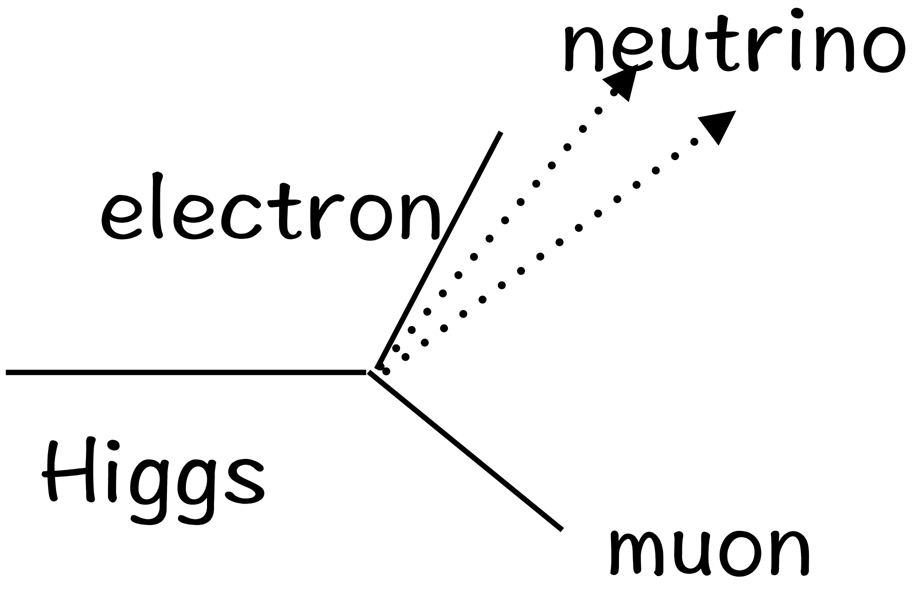


H-> muon + electron

LFV Higgs decay

CMS PAS HIG-14-005





H-> muon + tau jet

H-> muon + electron

Charge of tau/electron + muon =0

CMS : A slight excess of signal events with a significance of 2.5 sigma is observed (In the collinear mass window 100 -150 GeV)

95 % Upper limit on branching (Higgs to Mu tau) = 1.57 %

ATLAS : slight excess in one of the signal regions (no excess in other)

95 % Upper limit on branching (Higgs to Mu tau) = 1.85 % (1508.03372)

Excess in ttH in leptonic channel and LFV decay of Higgs may be correlated [BB, Chakraborty, Mukherjee arXiv:1505.02688]

LFV Higgs decay LHC (H-> e tau)

LHC 14 TeV L = 3000 ifb

(effective operators)

$$L_V \equiv -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h$$

$$e\mu + MET channel: \quad L = 3000 fb^{-1}$$

$$signal(Br(H \to e\tau) = 0.1\%) \sim 1600 \qquad SM\ \ bkg \sim 48000$$

$$\frac{s}{\sqrt{B}} \sim 2\ \ for\ \ Br(H \to e\tau) = 0.03\%$$

$$\frac{s}{\sqrt{B + k^2 B^2}}\ with\ \ k = 0.1,\ \ \sim 2\sigma\ \ for\ \ Br(h \to e\tau) = 0.6\%$$

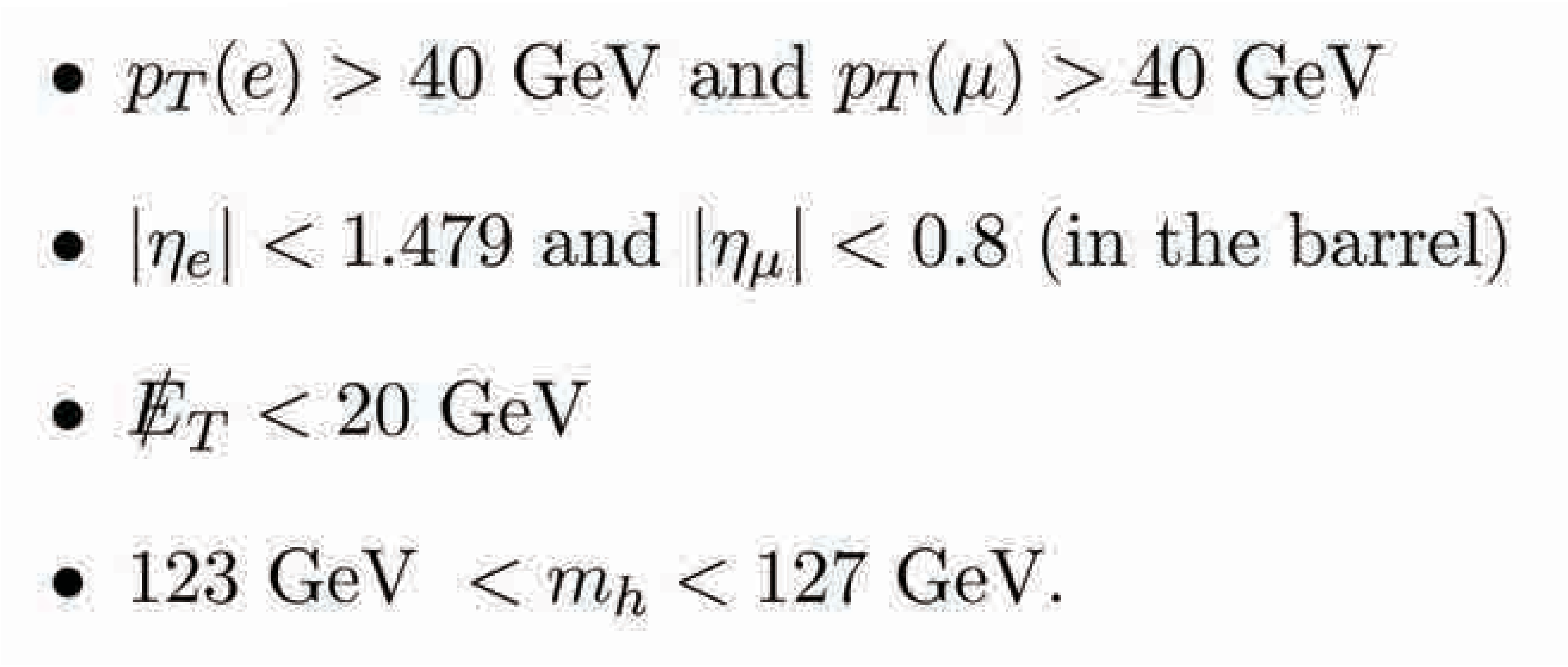
Limit from hadronic channel is weaker than the leptonic channel Combination will help to strengthen the limit

H-> tau mu : Direct search limit is already stronger than low energy bounds

H-> e mu: Low energy limit is much better than direct search results

LFV Higgs decay LHC (H-> e mu)

p p -> h -> e mu



- $p_T(e) > 40$ GeV and $p_T(\mu) > 40$ GeV
- $|\eta_e| < 1.479$ and $|\eta_\mu| < 0.8$ (in the barrel)
- $\cancel{E}_T < 20$ GeV
- 123 GeV $< m_h <$ 127 GeV.

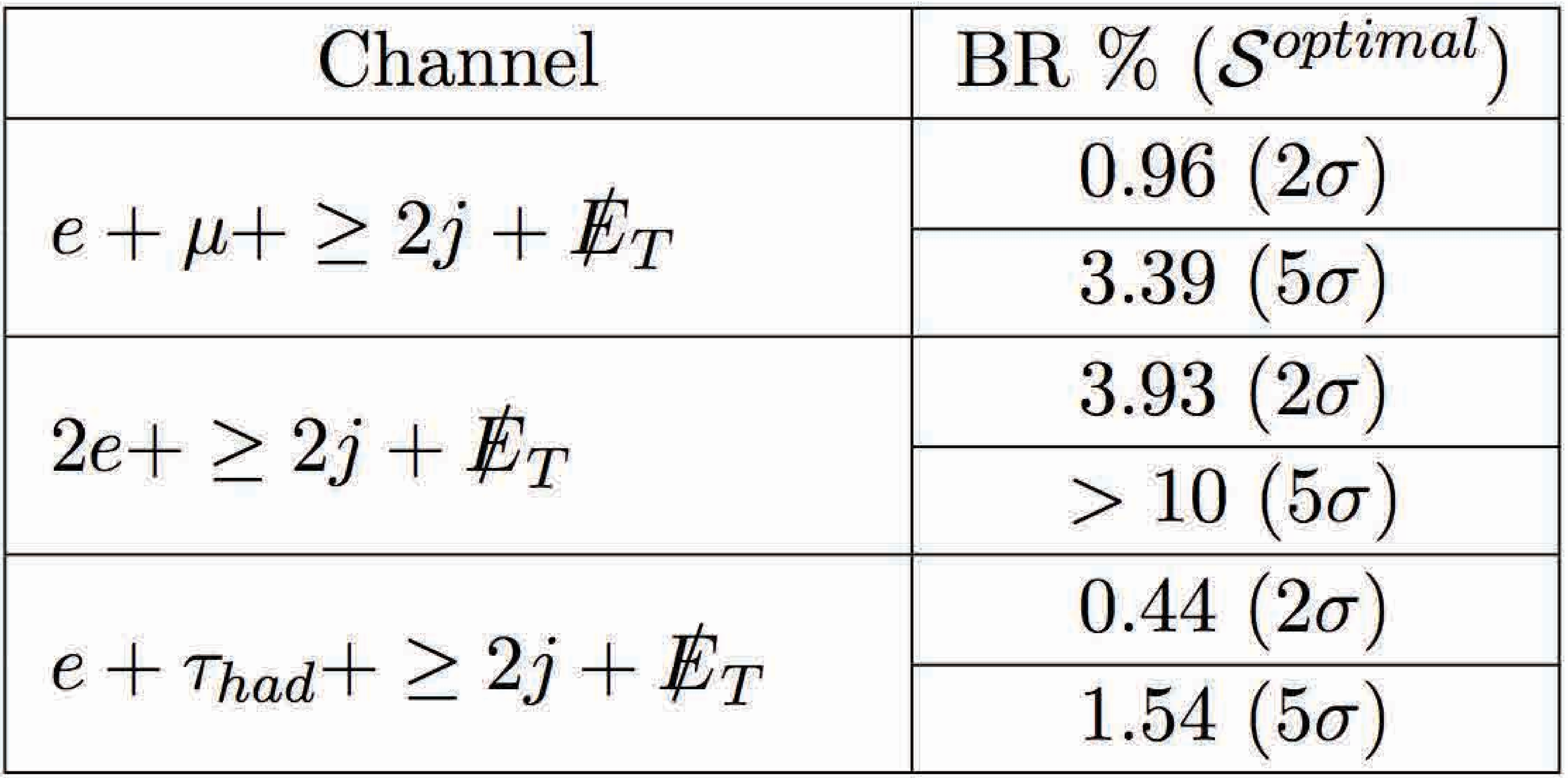
signal = 1435 for Br(H-> e mu) =0.01 % and bkg ~13900

2 sigma w.o systematic uncertainty .0017%

Banerjee,BB, Mitra, Spannowsky JHEP 1607 (2016) 059

LFV Higgs decay ILC 250 GeV (H-> e tau)

- $e^+e^- \to Zh, h \to \tau e$, with $Z \to$ $2j$ and $\tau \to e\nu, \mu\nu$ or τ tagged as τ_{had}

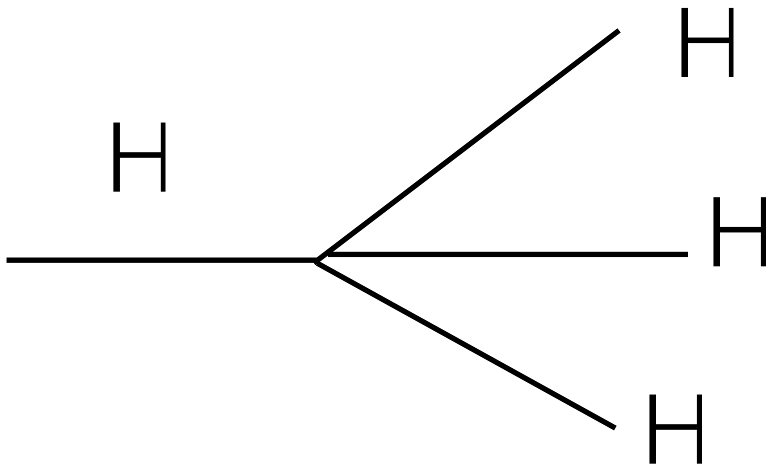


Channel	BR % ($\mathcal{S}^{optimal}$)
$e + \mu + \geq 2j + \not{E}_T$	0.96 (2σ)
	3.39 (5σ)
$2e + \geq 2j + \not{E}_T$	3.93 (2σ)
	$>$ 10 (5σ)
$e + \tau_{had} + \geq 2j + \not{E}_T$	0.44 (2σ)
	1.54 (5σ)

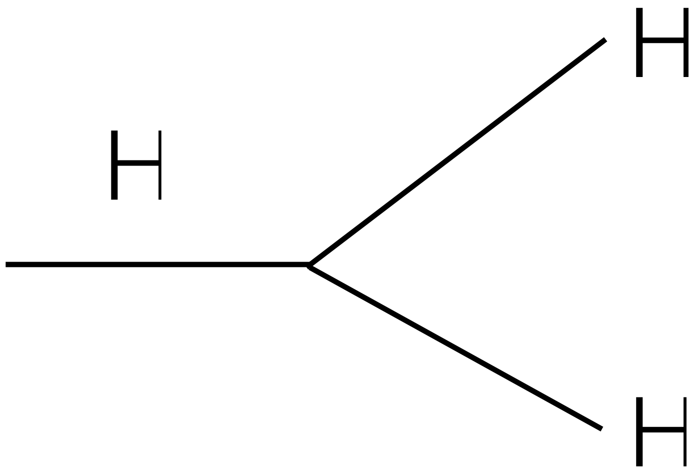
Limited by statistics

Measurement of Higgs self coupling

Direct Measurement of Higgs boson self coupling necessary to verify SM

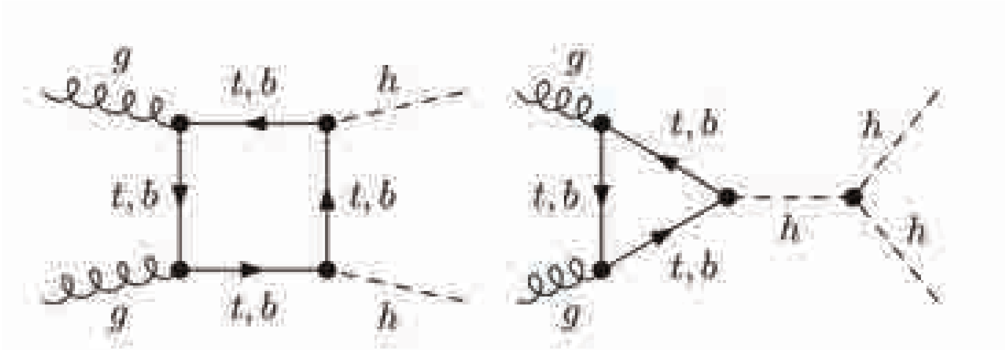


Direct Measurement of 4-Higgs boson vertex at HL-LHC not possible



Verification of SM Measurement of tri Higgs boson vertex only possible at HL-LHC

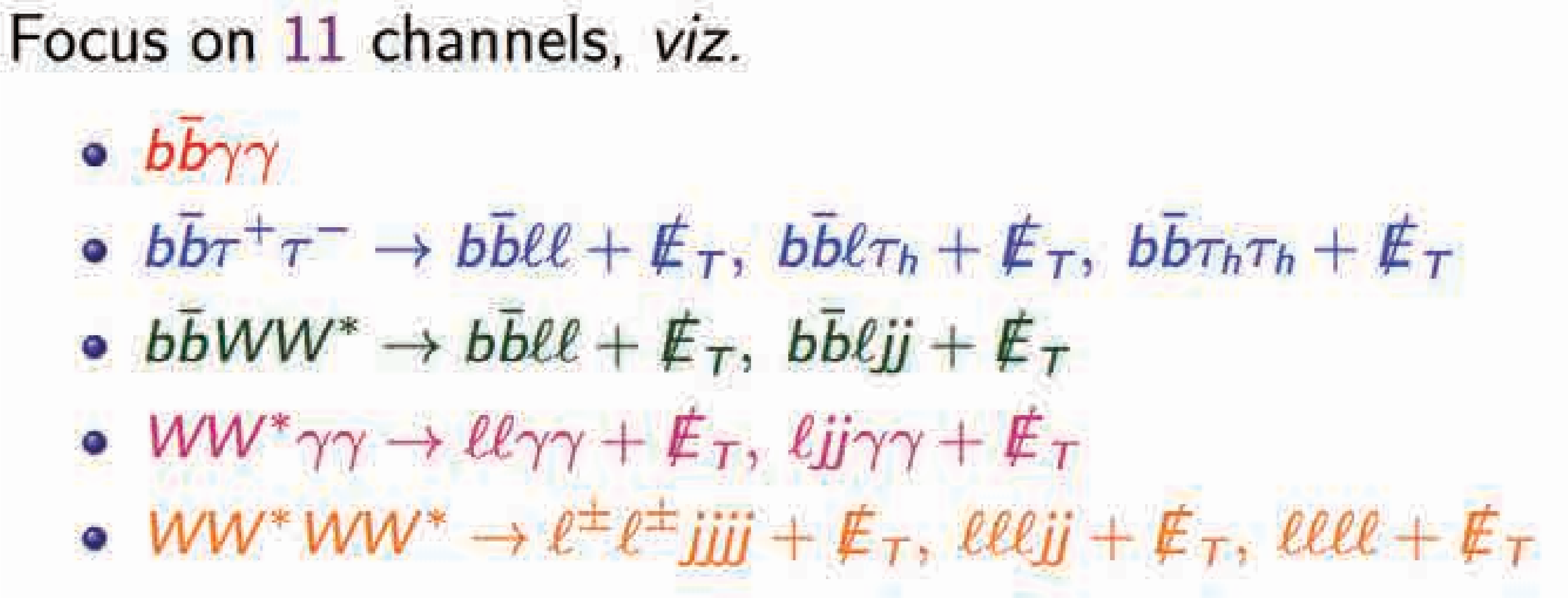
di-Higgs production



SM cross section ~ 39 fb

Di-Higgs production at the LHC

We choose final states based on rate and cleanliness
(contains photon or/and letpton)



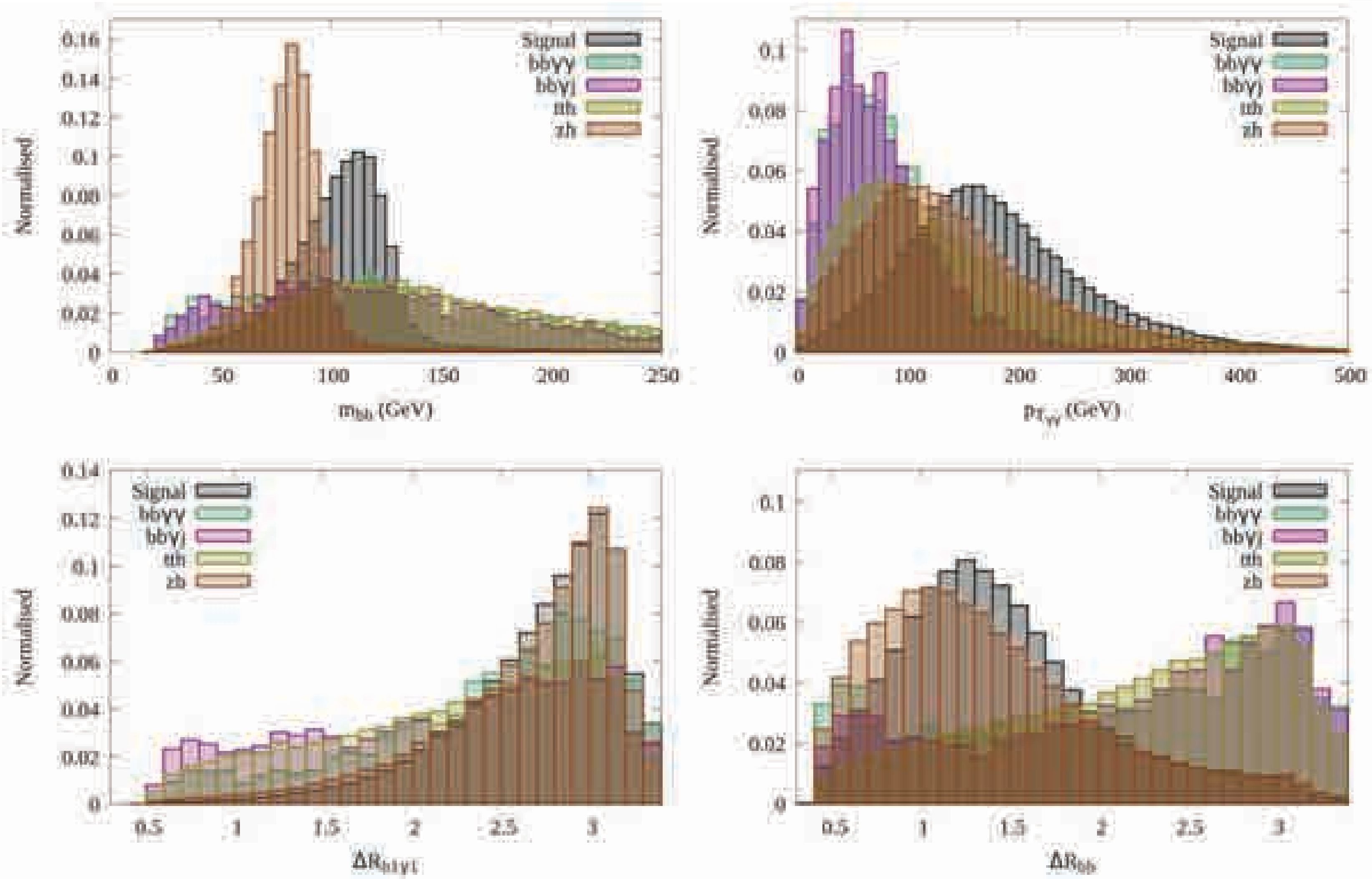
Focus on 11 channels, *viz.*

- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau^+\tau^- \to b\bar{b}\ell\ell + \not{E}_T$, $b\bar{b}\ell\tau_h + \not{E}_T$, $b\bar{b}\tau_h\tau_h + \not{E}_T$
- $b\bar{b}WW^* \to b\bar{b}\ell\ell + \not{E}_T$, $b\bar{b}\ell jj + \not{E}_T$
- $WW^*\gamma\gamma \to \ell\ell\gamma\gamma + \not{E}_T$, $\ell jj\gamma\gamma + \not{E}_T$
- $WW^*WW^* \to \ell^\pm\ell^\pm jjjj + \not{E}_T$, $\ell\ell\ell jj + \not{E}_T$, $\ell\ell\ell\ell + \not{E}_T$

Results are quoted for 3000 ifb (14 TeV)

Adhikary, Banerjee, Barman, BB, Niyogi 1712.05346

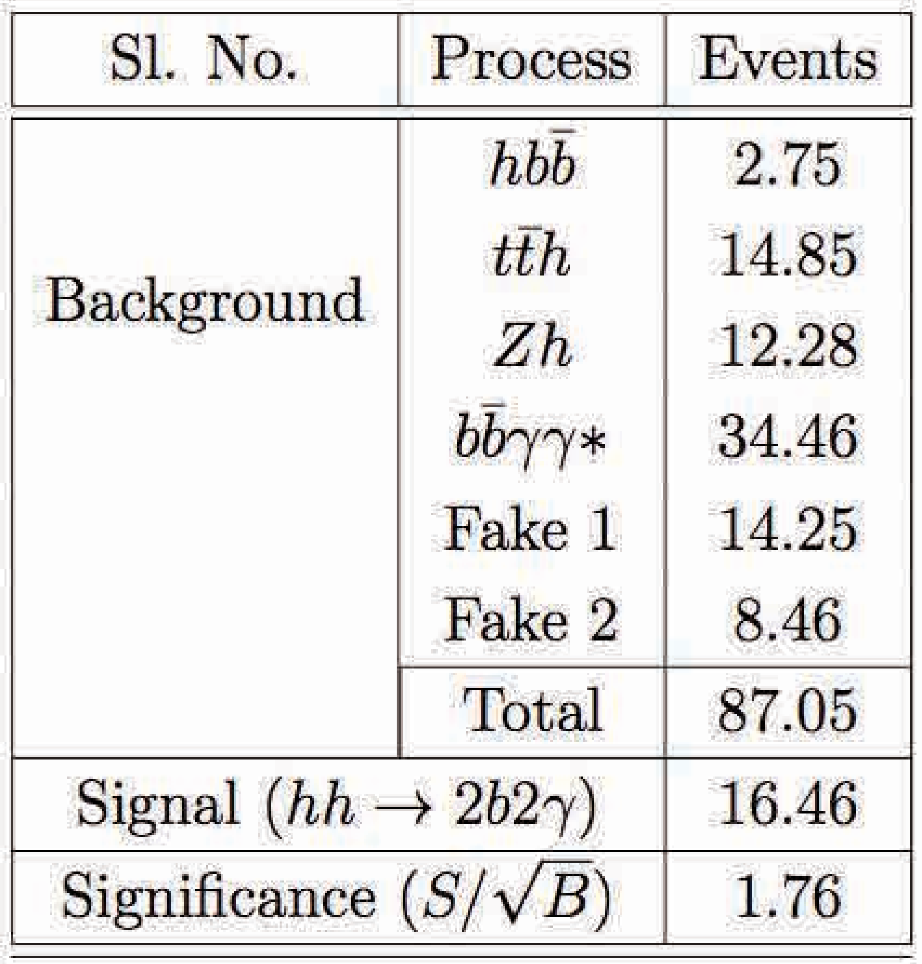
Di-Higgs production at the LHC: bb gamma gamma



Cut flow	Event rates with 3000 fb^{-1} of integrated luminosity							$\frac{S}{\sqrt{B}}$
	Signal	SM Backgrounds						
	$hh \to 2b2\gamma$	$hb\bar{b}$	$t\bar{t}h$	Zh	$b\bar{b}\gamma\gamma*$ [3]	Fake 1 [4]	Fake 2 [5]	
Order	NNLO [70]	NNLO (5FS) + NLO (4FS) [111]	NLO [111]	NNLO (QCD) + NLO EW [111]	LO	LO	LO	
$2b + 2\gamma$	31.63	21.20	324.91	39.32	25890.31	1141.18	393.79	0.19
lepton veto	31.63	21.20	255.66	39.32	25889.94	1141.18	393.79	0.19
$N_j < 6$	31.04	21	192.05	39.23	25352.78	1064.64	167.32	0.19
ΔR cuts	22.19	7.75	38.71	23.48	4715.21	130.10	28.81	0.31
m_{bb}	12.71	1.53	13.80	1.09	862.37	22.11	6.88	0.42
$m_{\gamma\gamma}$	12.36	1.5	13.16	1.06	26.54	22.11	6.88	1.46
$p_{T,bb}, p_{T,\gamma\gamma}$	12.32	1.48	13.03	1.06	26.54	21.82	6.88	1.46

Di-Higgs production at the LHC: bb gamma gamma

Significance can be slightly improved if we use BDT



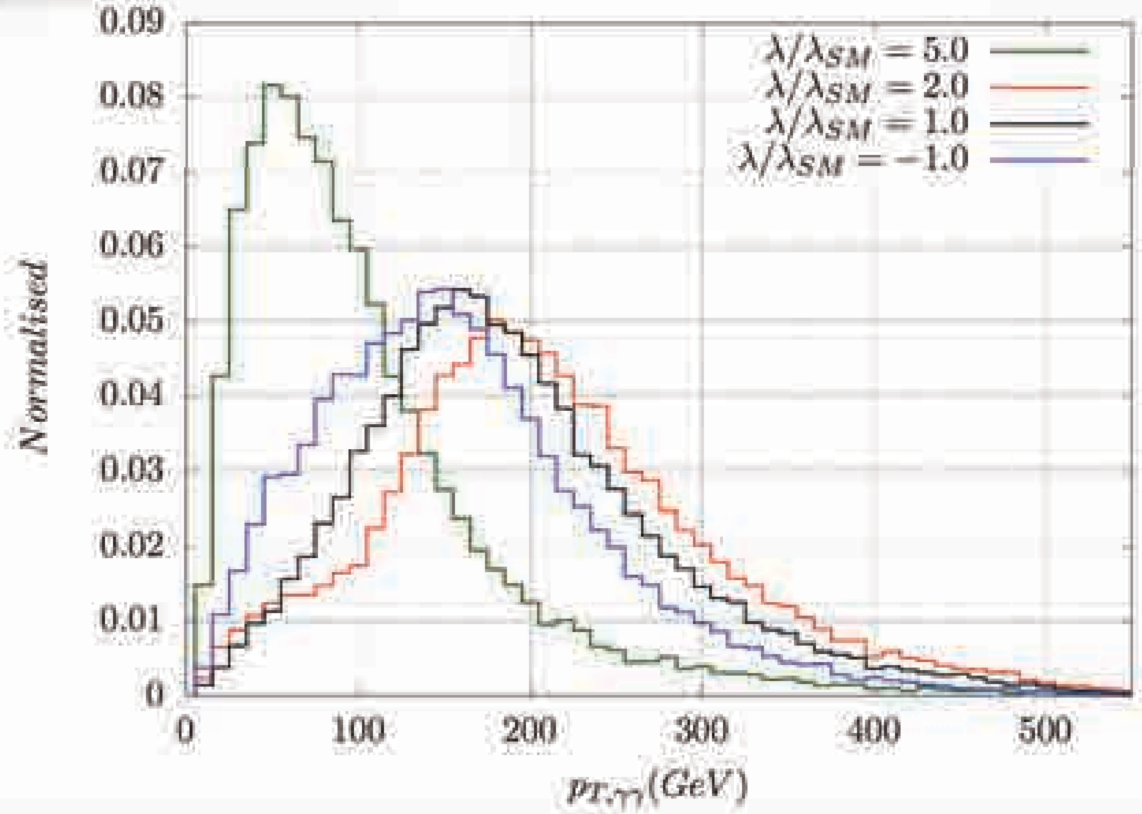
Sl. No.	Process	Events
Background	$hb\bar{b}$	2.75
	$t\bar{t}h$	14.85
	Zh	12.28
	$b\bar{b}\gamma\gamma*$	34.46
	Fake 1	14.25
	Fake 2	8.46
	Total	87.05
Signal ($hh \to 2b2\gamma$)		16.46
Significance ($S/\sqrt{B}$)		1.76

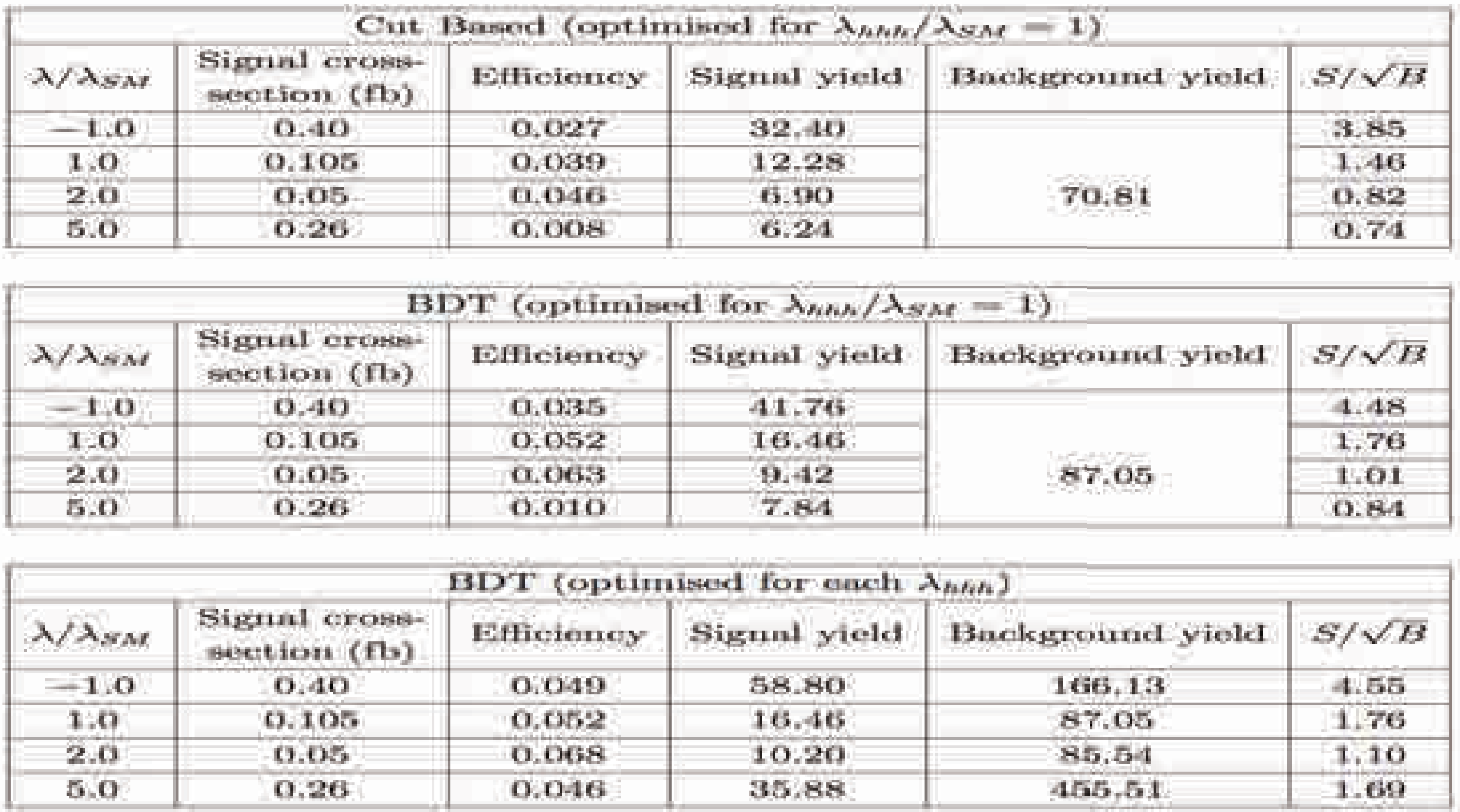
Variables used in our analysis

m_{bb}, $p_{T,\gamma\gamma}$, $\Delta R_{\gamma\gamma}$, $p_{T,bb}$, $\Delta R_{b_1\gamma_1}$, p_{T,γ_1}, ΔR_{bb}, p_{T,γ_2}, $\Delta R_{b_2\gamma_1}$, $\Delta R_{b_2\gamma_2}$, p_{T,b_1}, $\Delta R_{b_1\gamma_2}$, p_{T,b_2}, $\not{E}_T$

Adhikary, Banerjee, Barman, BB, Niyogi 1712.05346

Di-Higgs production: variation of self-coupling





Cut Based (optimised for $\lambda_{hhh}/\lambda_{SM} = 1$)					
λ/λ_{SM}	Signal cross-section (fb)	Efficiency	Signal yield	Background yield	$S/\sqrt{B}$
−1.0	0.40	0.027	32.40	70.81	3.85
1.0	0.105	0.039	12.28		1.46
2.0	0.05	0.046	6.90		0.82
5.0	0.26	0.008	6.24		0.74

BDT (optimised for $\lambda_{hhh}/\lambda_{SM} = 1$)					
λ/λ_{SM}	Signal cross-section (fb)	Efficiency	Signal yield	Background yield	$S/\sqrt{B}$
−1.0	0.40	0.035	41.76	87.05	4.48
1.0	0.105	0.052	16.46		1.76
2.0	0.05	0.063	9.42		1.01
5.0	0.26	0.010	7.84		0.84

BDT (optimised for each λ_{hhh})					
λ/λ_{SM}	Signal cross-section (fb)	Efficiency	Signal yield	Background yield	$S/\sqrt{B}$
−1.0	0.40	0.049	58.80	166.13	4.55
1.0	0.105	0.052	16.46	87.05	1.76
2.0	0.05	0.068	10.20	85.54	1.10
5.0	0.26	0.046	35.88	455.51	1.69

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Higgs self coupling measurement: contamination from BSM physics

Higgs self coupling: measured from di-Higgs cross section

Number of events in a particular channel coming from SM di-Higgs prouction is small—> only number counting possible (not possible to study differential distributions)

New physics can alter the self-coupling or top Higgs coupling (fairly restricted already)-> change in the number of events

New physics can also generate the same final state -> Can be interpreted as a change in Higgs self coupling
some totally different new physics scenarios can mimic some or all SM di-Higgs final states

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Higgs self coupling measurement: contamination from BSM physics

Three possibilities :

a). New physics cross section is large and no overlap with SM counterpart: possible to measure Higgs self coupling as well as new physics signals

b). New physics cross section is large and kinematic variables overlaps with SM counterpart: discovery of new physics possible but not the measurement Higgs self coupling

c). New physics cross section is small and kinematic variables overlaps with SM counterpart: Most challenging scenario, can be interpreted as modified Higgs self coupling

Q: How much contamination possible ?

Q: Which method is better : cut based vs BDT performed to maximise SM di-Higgs?

Correlations possible: Some non-resonant channels will incur contamination from more new physics scenarios than others

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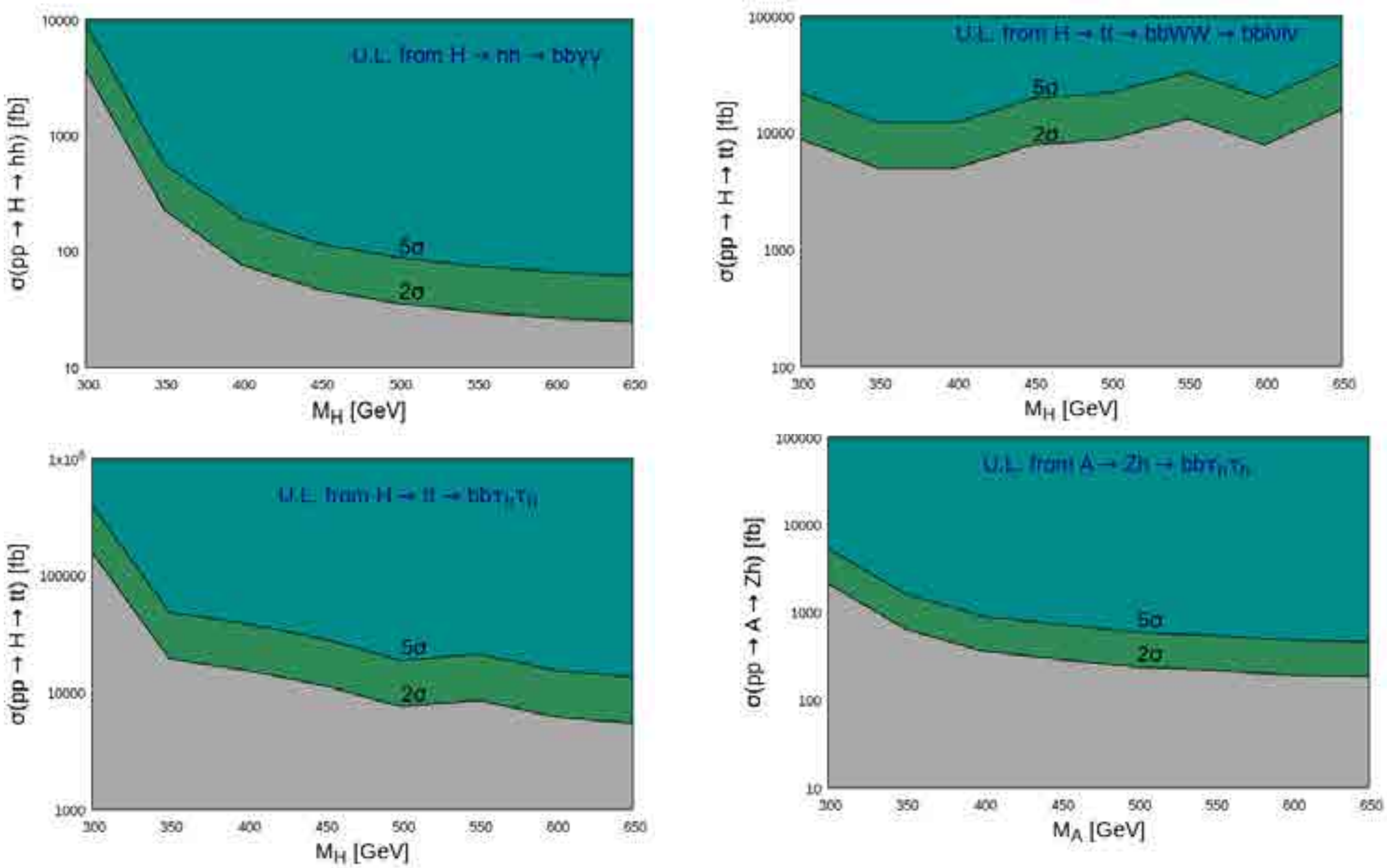
Higgs self coupling measurement: contamination from BSM physics

- Double Higgs production, pp → hh(+X) through resonant or non-resonant production modes H -> hh , di-Higgs production from SUSY cascade
- Single Higgs production in association with some other particles, pp → h + X (A->Zh)
- Null Higgs scenario, pp → X, yielding some of the final states (H-> top pair)



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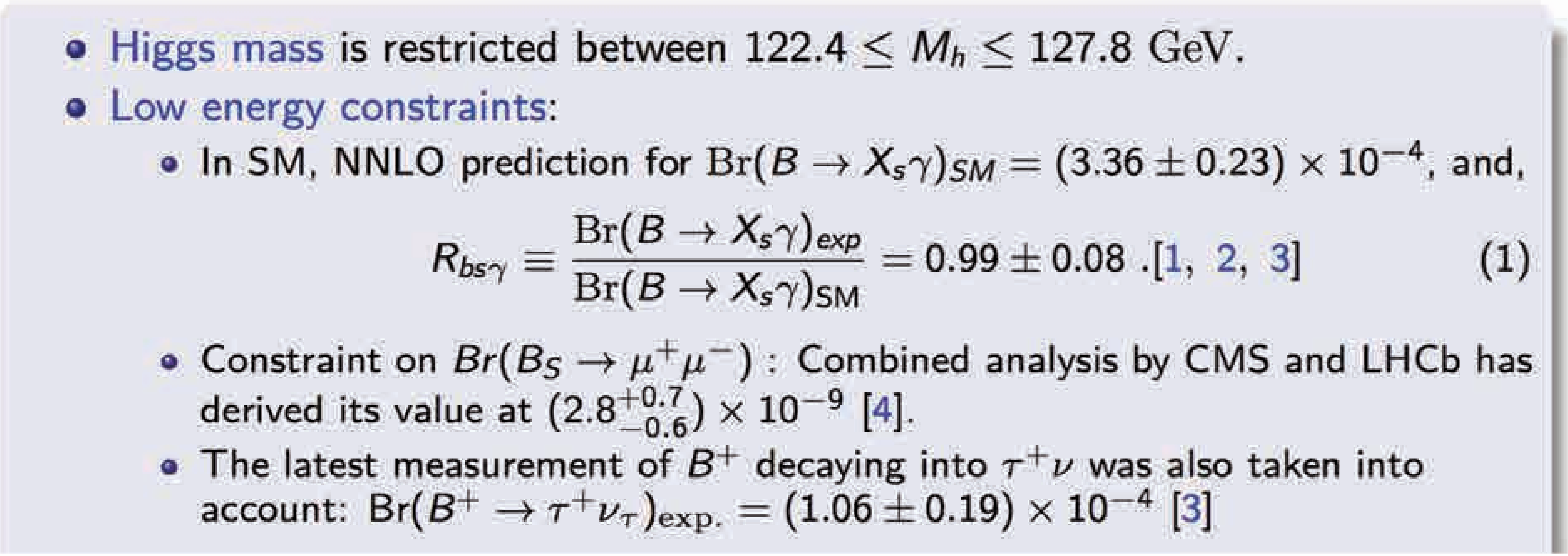
Conclusion

- ✳ The observed Higgs boson is consistent with SM , still some room for BSM physics in the Higgs sector
- ✳ The effect of Higgs coupling measurements is mild on MSSM Higgs bosons, flavour physics impose stronger bound than signal strength measurements
- ✳ Heavy Higgs production in association with b quark(s) put very strong constraint and rule out high tan beta region
- ✳ H-> h h has the potential to rule out low tan beta region
- ✳ The limits on Heavy Higgs bosons can be weakened in the presence of additional SUSY decay modes. Further analysis required in this direction.
- ✳ Measurement of Higgs self coupling via di-Higgs production can be contaminated by new physics

Thank You !

BACKUP



- Higgs mass is restricted between $122.4 \le M_h \le 127.8\ \mathrm{GeV}$.
- Low energy constraints:
    - In SM, NNLO prediction for $\mathrm{Br}(B \to X_s\gamma)_{SM} = (3.36 \pm 0.23) \times 10^{-4}$, and,

$$R_{bs\gamma} \equiv \frac{\mathrm{Br}(B \to X_s\gamma)_{exp}}{\mathrm{Br}(B \to X_s\gamma)_{\mathrm{SM}}} = 0.99 \pm 0.08\ .\text{[1, 2, 3]} \qquad (1)$$

    - Constraint on $Br(B_S \to \mu^+\mu^-)$: Combined analysis by CMS and LHCb has derived its value at $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$ [4].
    - The latest measurement of B^+ decaying into $\tau^+\nu$ was also taken into account: $\mathrm{Br}(B^+ \to \tau^+\nu_\tau)_{\mathrm{exp.}} = (1.06 \pm 0.19) \times 10^{-4}$ [3]

Taken from RKB