LHC results and intriguing anomalies from collider experiments

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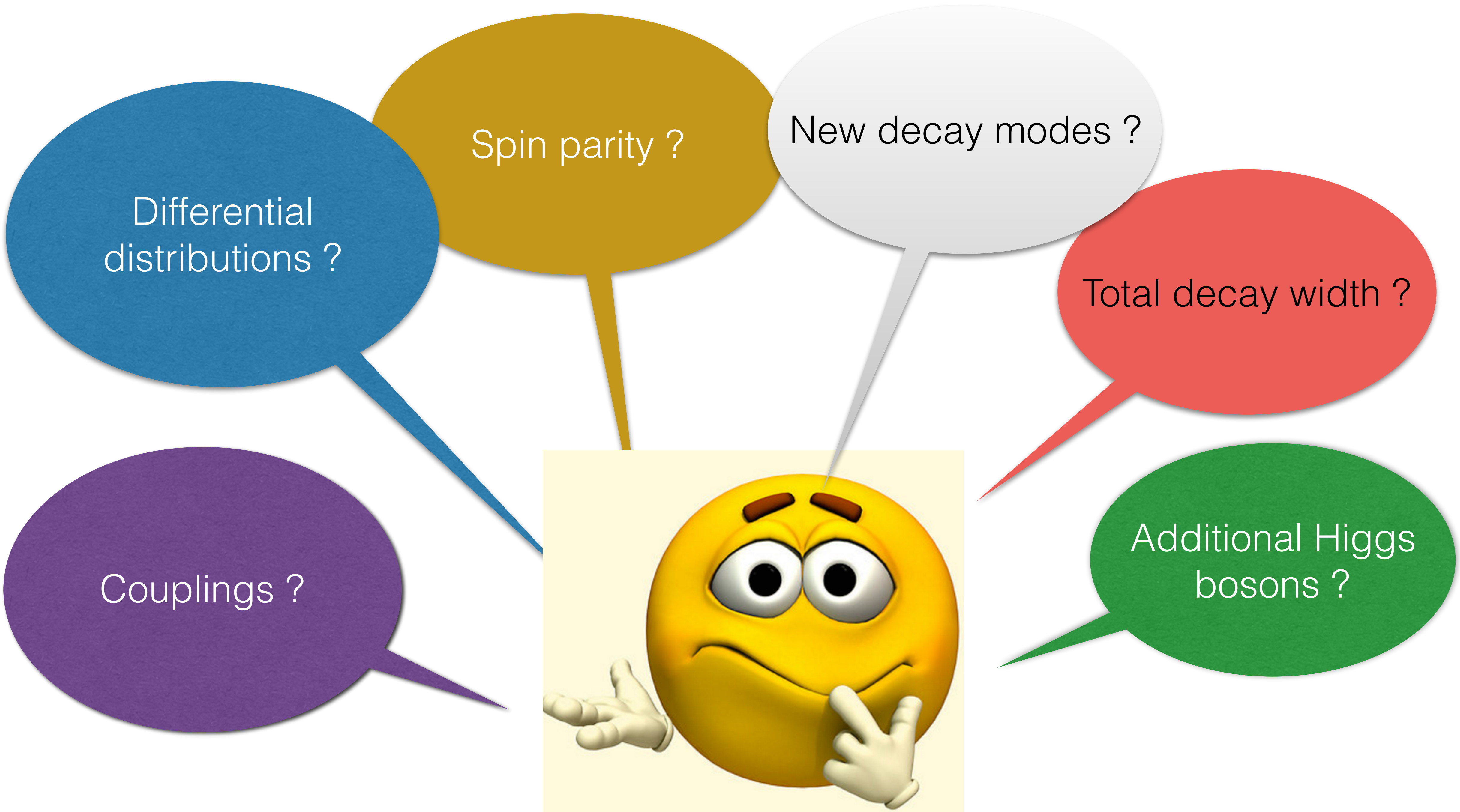
IMHEP 2019
IOP Bhubaneswar January 17-22 ,2019

Higgs boson: current status

We have found the (a) Higgs boson

Properties: consistent with SM Higgs boson

Many more consistency checks required



di-Higgs limits

Adhikary, Barman, Banerjee, Bhattacherjee 1812.05640

Channel	CMS (NR) ($\times$SM)	CMS (R) [fb, (GeV)]	ATLAS (NR) ($\times$SM)	ATLAS (R) [fb, (GeV)]
$b\bar{b}b\bar{b}$	75	1500-45 (260-1200)	13	2000-2 (260-3000)
$b\bar{b}\gamma\gamma$	24	240-290 (250-900)	22	1100-120 (260-1000)
$b\bar{b}\tau^+\tau^-$	30	3110-70 (250-900)	12.7	1780-100 (260-1000)
$\gamma\gamma WW^*$ [135]			200	40000-6100 (260-500)
$b\bar{b}\ell\nu\ell\nu$	79	20500-800 (300-900)	300	6000-170 (500-3000)
WW^*WW^*			160	9300-2800 (260-500)

HL-LHC will not be able to measure Higgs self coupling precisely
require 27 TeV/100 TeV colliders

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 production is small—> only number counting possible (not possible to study differential distributions)

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

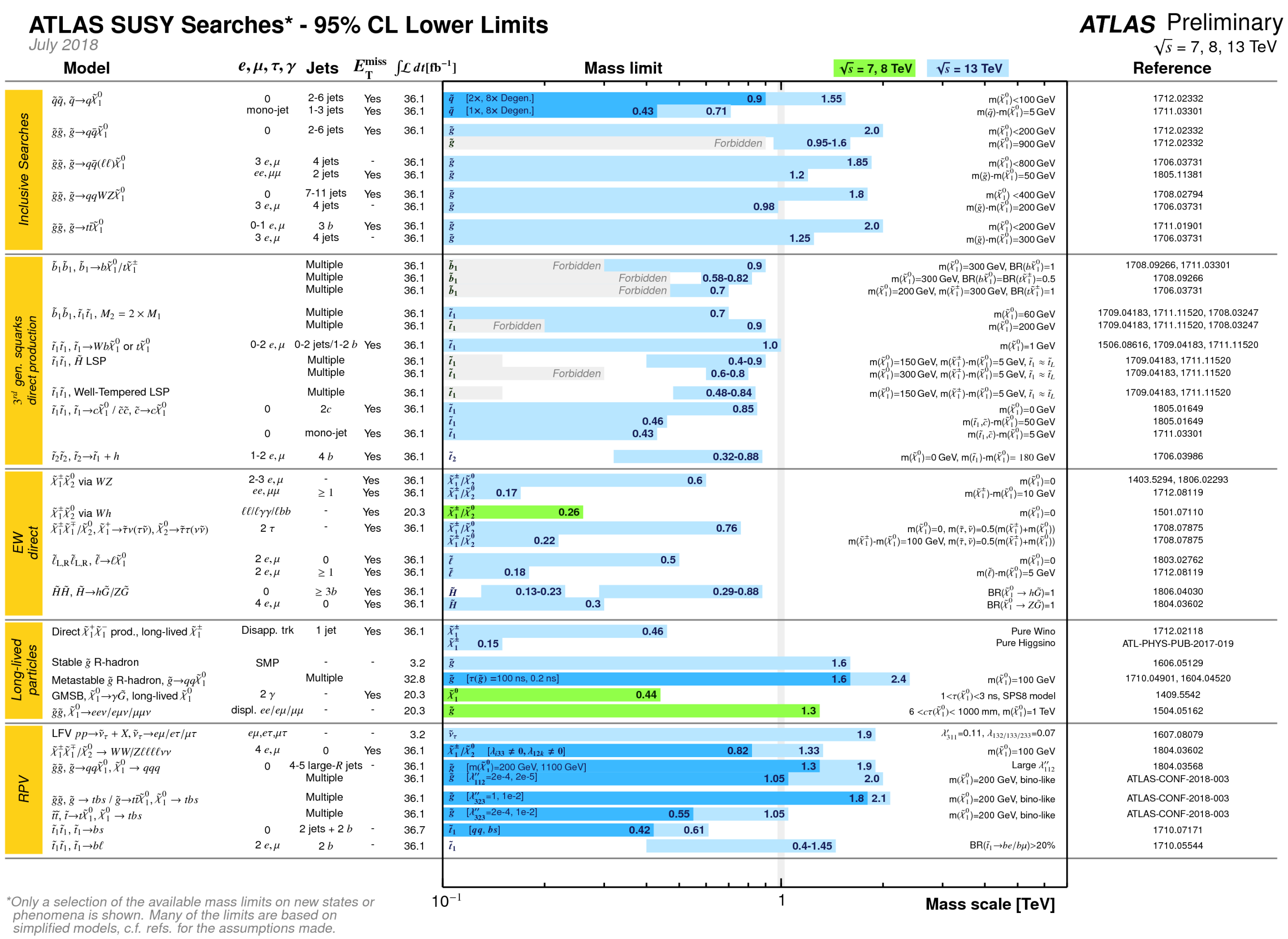
SUSY processes can also generate the same final state -> Can be interpreted as a change in Higgs self coupling some totally different new physics scenarios can mimic some or all SM di-Higgs final states

BB , Choudhury Phys.Rev. D(2015) and Adhikary, Banerjee, Barman, BB, Niyogi JHEP(2018)

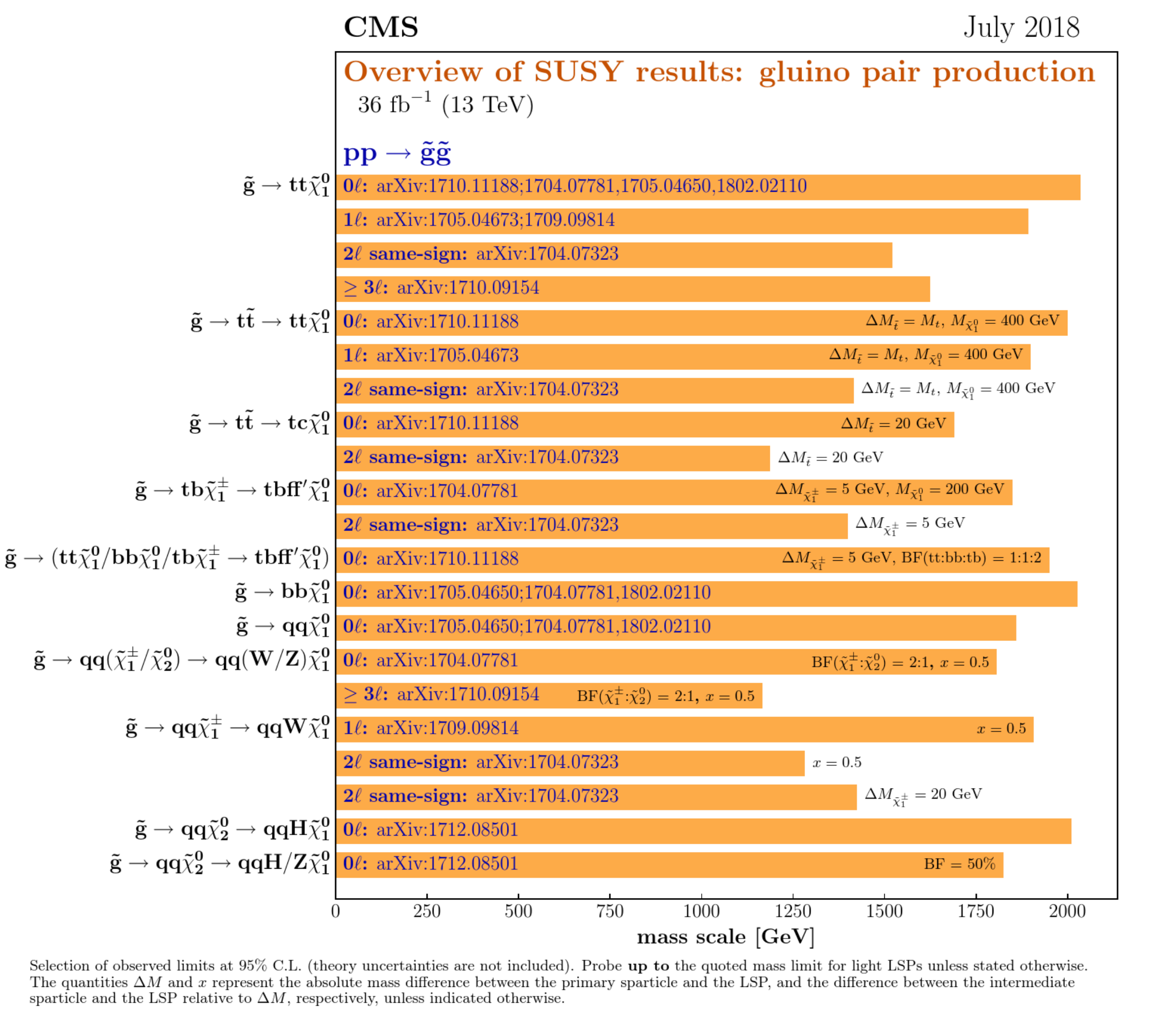
SUSY: Current status

SUSY: No evidence so far

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



ATLAS SUSY Summary



CMS SUSY Summary(only gluino)

Search results are translated into exclusion limits

Bounds on Light SUSY particles

How to put bounds on SUSY particles ?

Lower limits → Higgs Mass
Direct searches

Upper limits → Dark Matter
Naturalness

Higgs mass in MSSM

Tree level mass $M_H \leq M_Z$

dominant contribution from Stop squarks

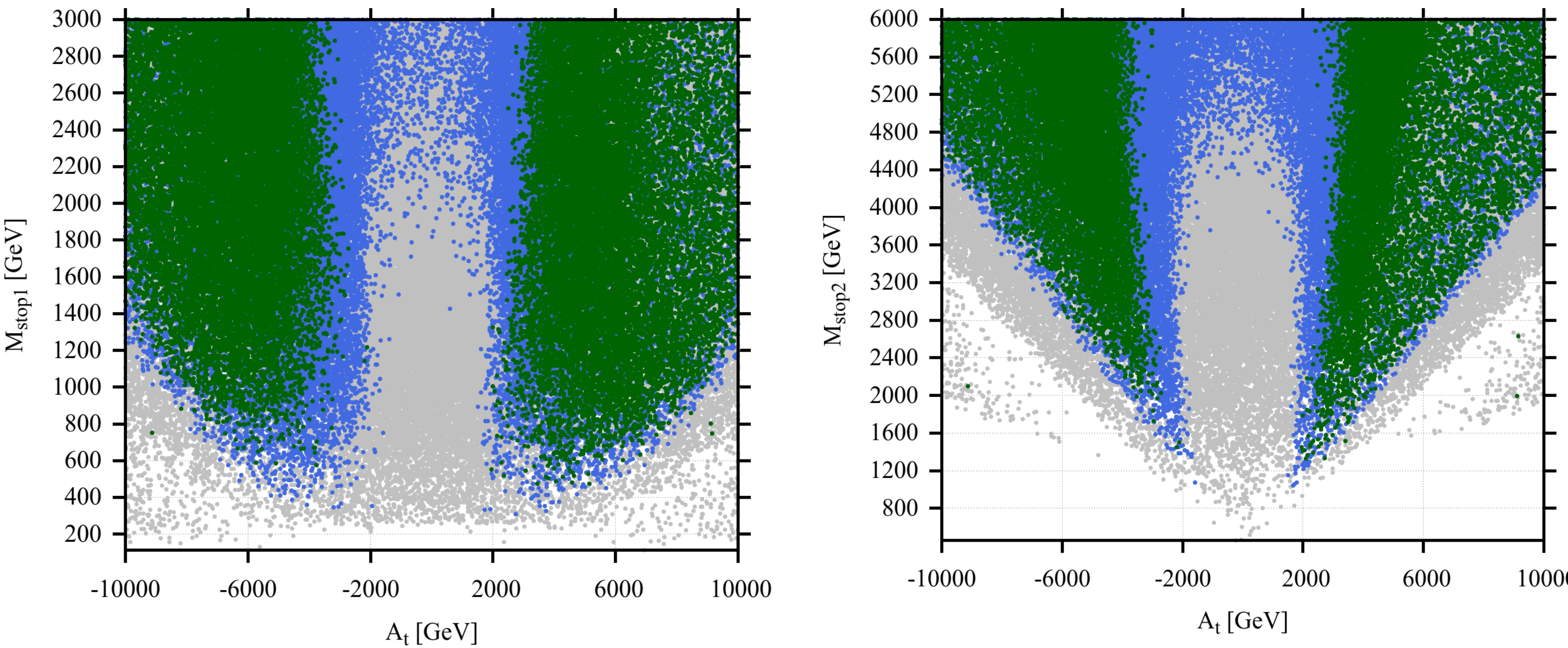
$$m_h^2 \simeq M_Z^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)\right]$$

assuming

$$\cos^2(2\beta) \simeq 1$$

and $M_A > M_Z$

$M_{SUSY}^2 \rightarrow$ averaged stop squared mass $\quad X_t = A_t - \mu/\tan\beta \rightarrow$ stop mixing parameter



More refined computation including 2-loop and leading 3 loop available, EFT calculations

For a recent review, see P. Draper and H. Rzehak, Phys. Reports 619, 1 (2016).

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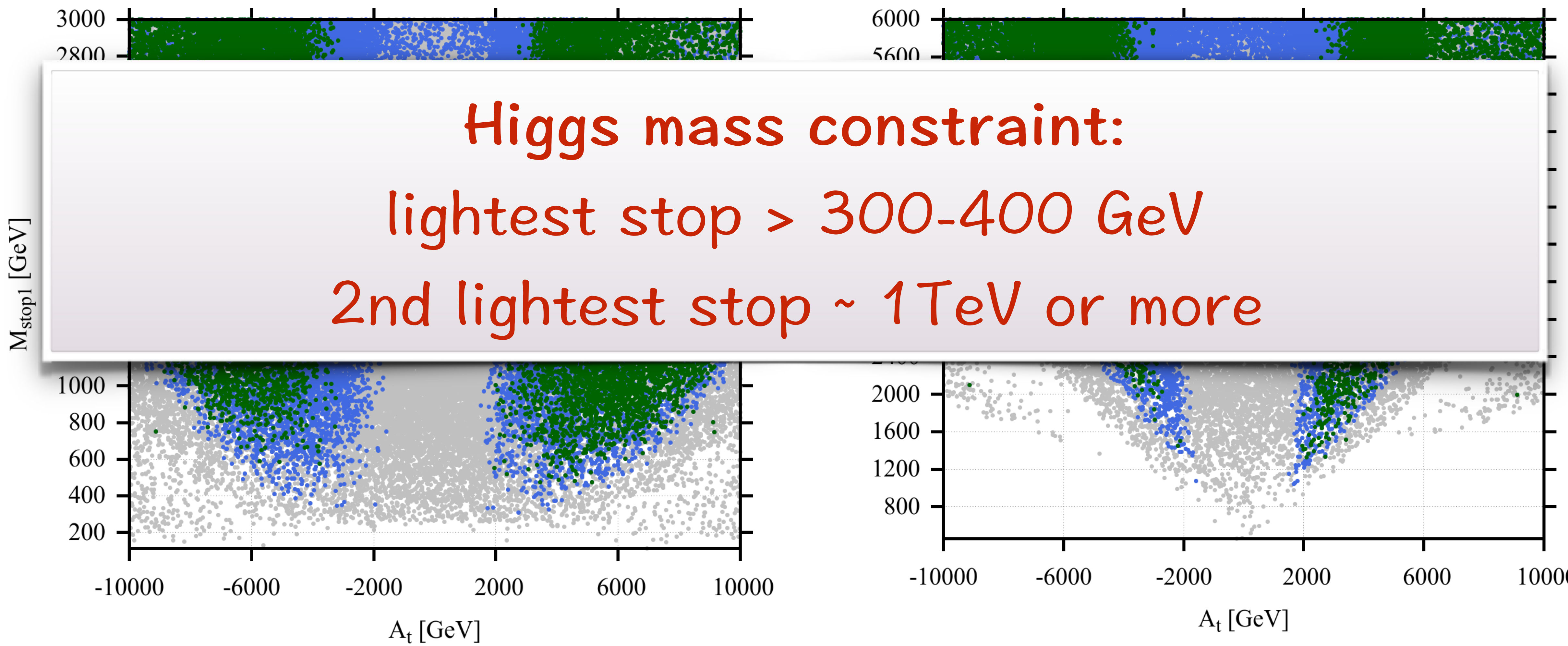

Higgs mass constraint:

lightest stop > 300-400 GeV

2nd lightest stop ~ 1TeV or more

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For a recent review, see P. Draper and H. Rzehak, Phys. Reports 619, 1 (2016).

Electroweak fine tuning

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

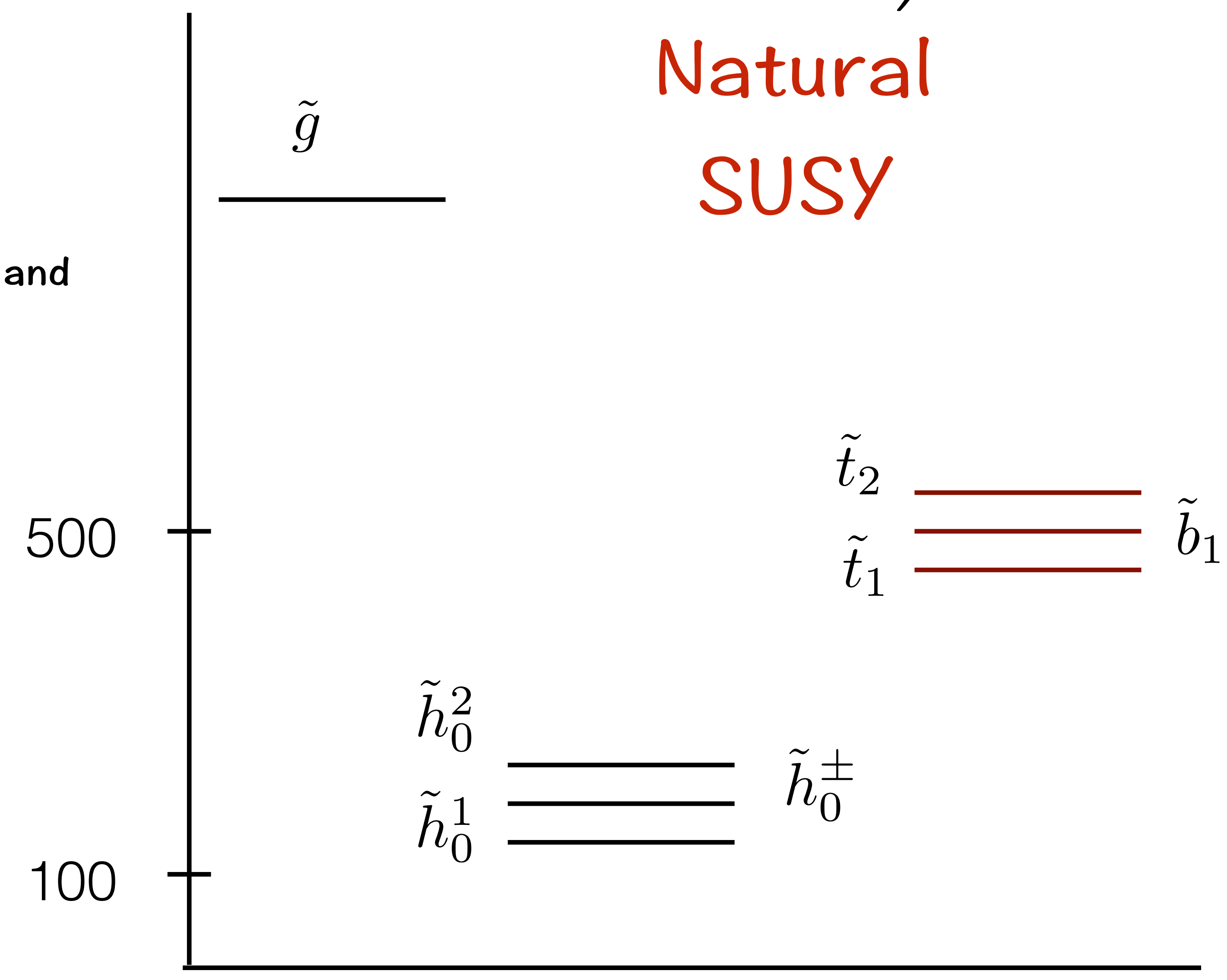
$$C_i = \left(\mu^2, \frac{m_{H_d}^2}{\tan^2\beta - 1}, \frac{\Sigma_d^d}{\tan^2\beta - 1}, \ldots\right)$$

$$\Delta_{EW} = max(|C_i|/(M_Z^2/2))$$

H. Baer, V. Barger, P. Huang, A. Mustafayev, and X. Tata PRL 2012

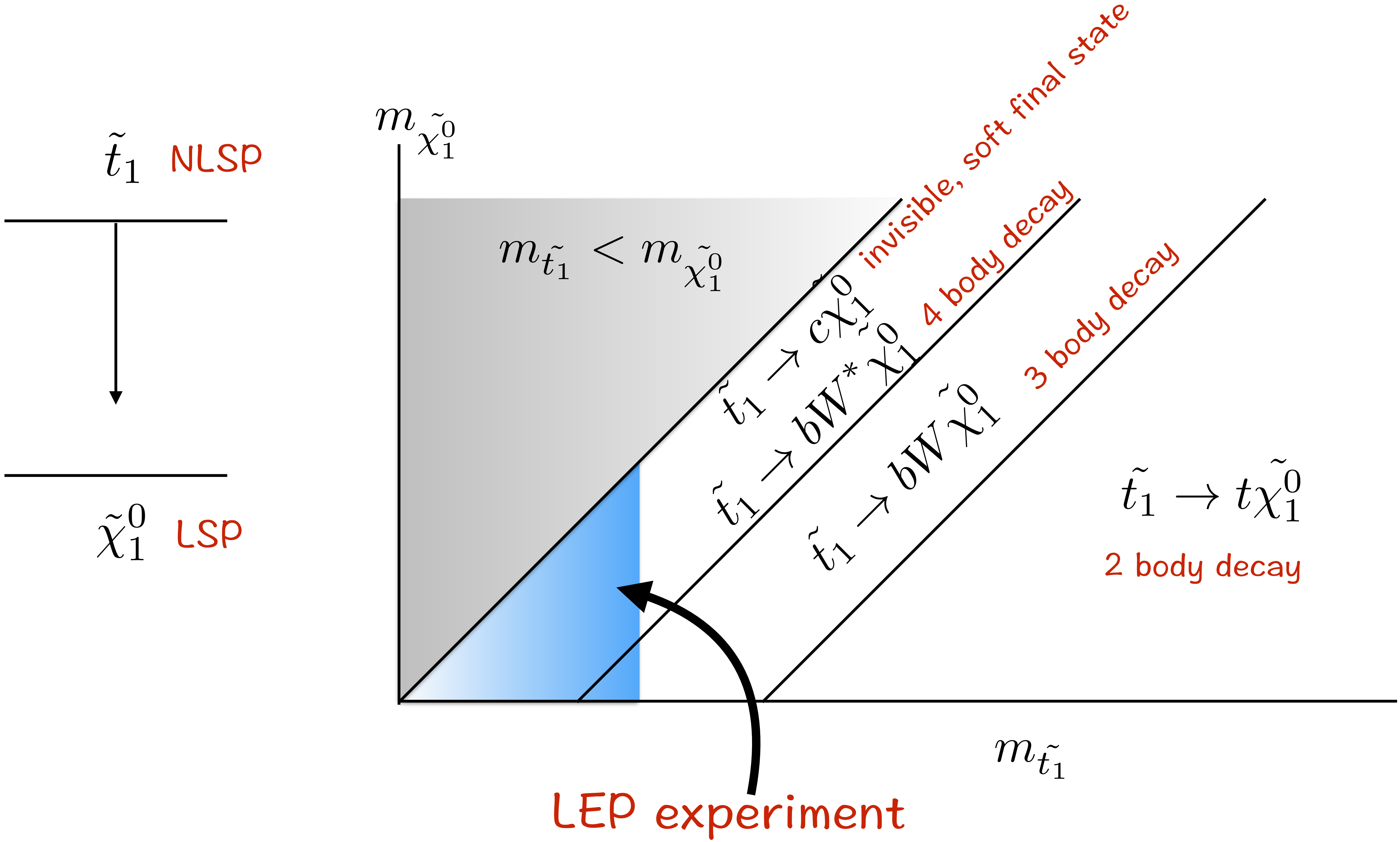
J. R. Ellis, K. Enqvist, D. V. Nanopoulos, and F. Zwirner (1986) .

R. Barbieri and G. F. Giudice, Nucl. Phys. B (1988) .

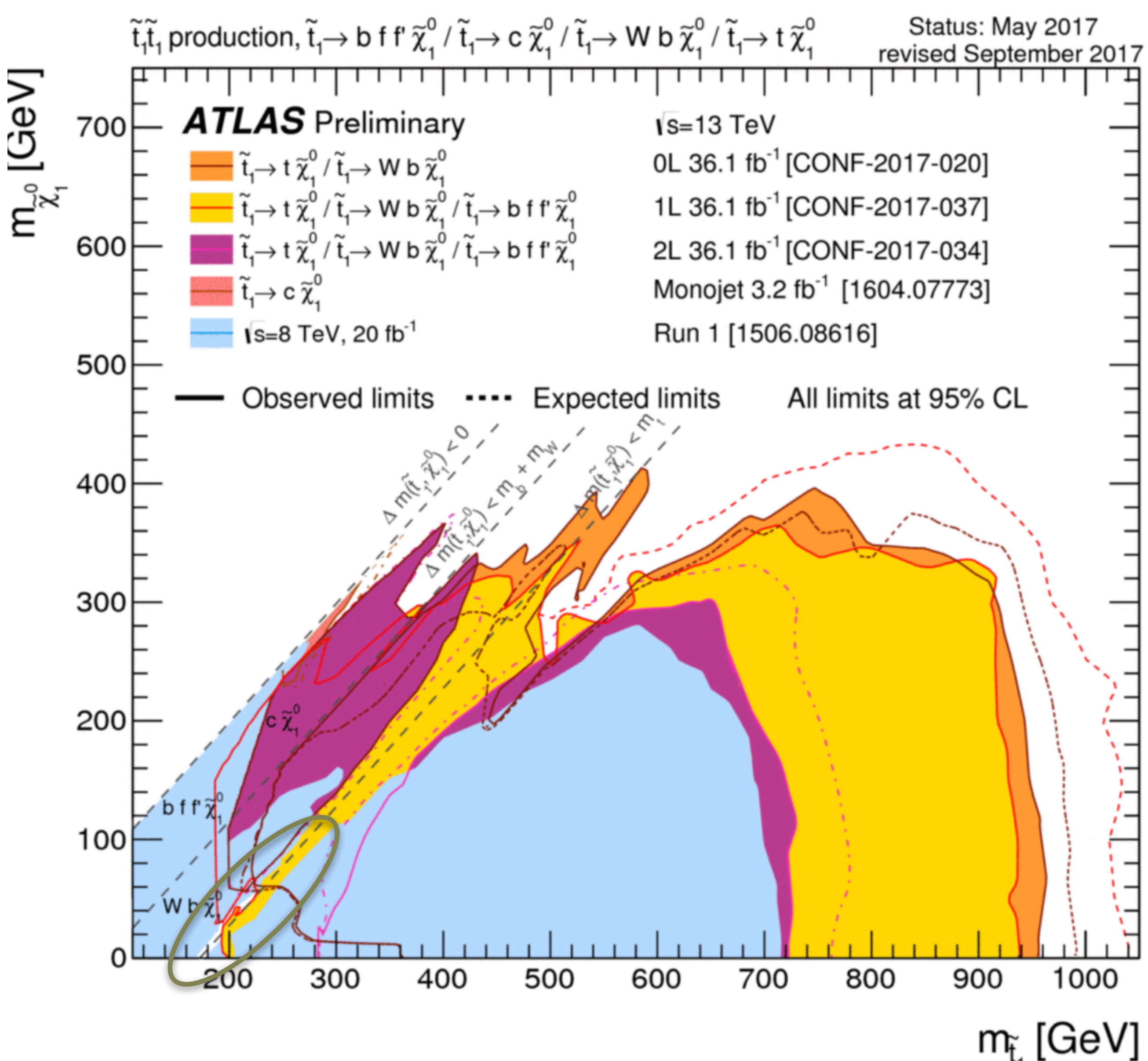


Stop searches at the LHC

Stop searches are complicated (most of the searches focus on lights stop)



Current limits on lightest Stop



Many recent results

$$\tilde{t}_2 \to \tilde{t}_1\ h/Z$$

$$\tilde{t}_1 \to \tilde{\chi}_2^0 t,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ h \quad \tilde{t}_1 \to \tilde{\chi}_1^{\pm} b$$

(1706.03986, 1710.11188 ,1708.03247..)

interesting scenario: stop mass is close to the sum of the neutralino mass and the top quark mass

An equal-velocity scenario for hiding dark matter at the LHC

by Hagiwara, Yamada (1307.1553)

Similar limits from CMS

for sbottom search see for example (1708.09266)

Future Sensitivity ~1.5 TeV (ATL-COM-PHYS-2014-555)

stop mass limits up to 3 TeV(33 TeV) and 5.7 TeV(100 TeV) (1606.00947)

Gluino searches at the LHC

CMS-SUS-16-038 for natural SUSY

Important decay modes for natural SUSY

$$p\,p \to \tilde{g}\tilde{g},\ \tilde{g} \to q\bar{q}\chi_1^0$$

$$p\,p \to \tilde{g}\tilde{g},\ \tilde{g} \to b\bar{b}\chi_1^0$$

$$p\,p \to \tilde{g}\tilde{g},\ \tilde{g} \to t\bar{t}\chi_1^0$$

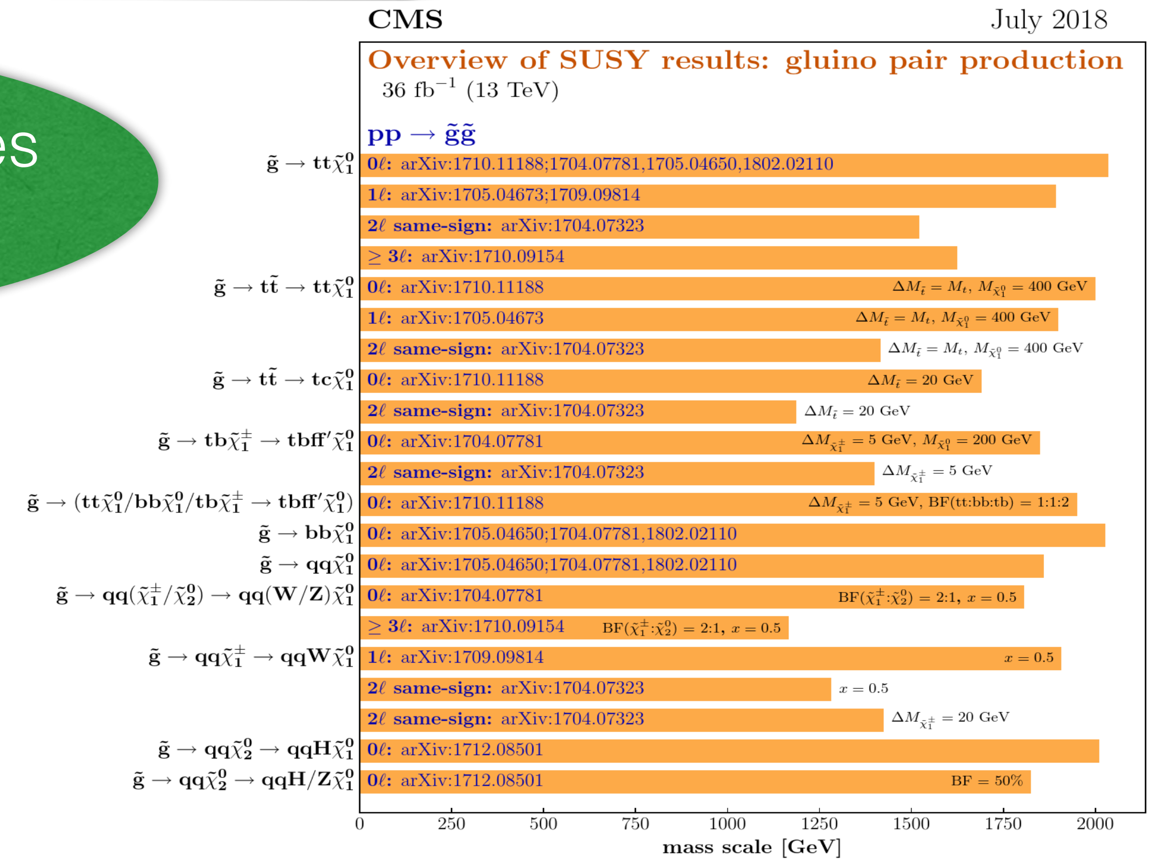
$$p\,p \to \tilde{q}\tilde{g},\ \tilde{g} \to q\bar{q}\chi_1^0,\ \tilde{q} \to q\chi_1^0$$

$$p\,p \to \tilde{q}\tilde{g},\ \tilde{g} \to q\bar{q}\chi_2^0$$

direct /associated production

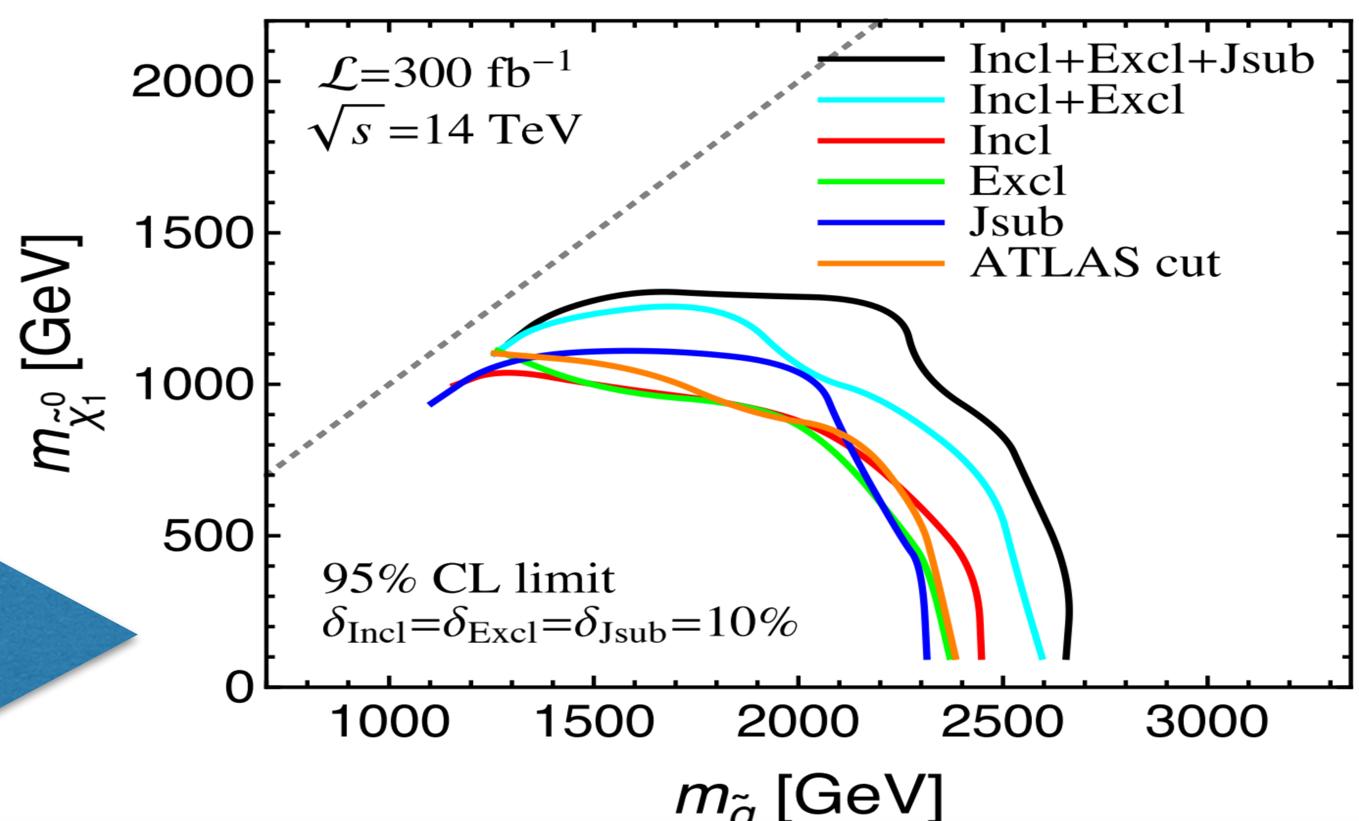
Many search channels :
multiple-b, top, leptonic final states
considered strongest limit ~ 2 TeV
(CMS and ATLAS)

Theory proposal: use of quark gluon tagging



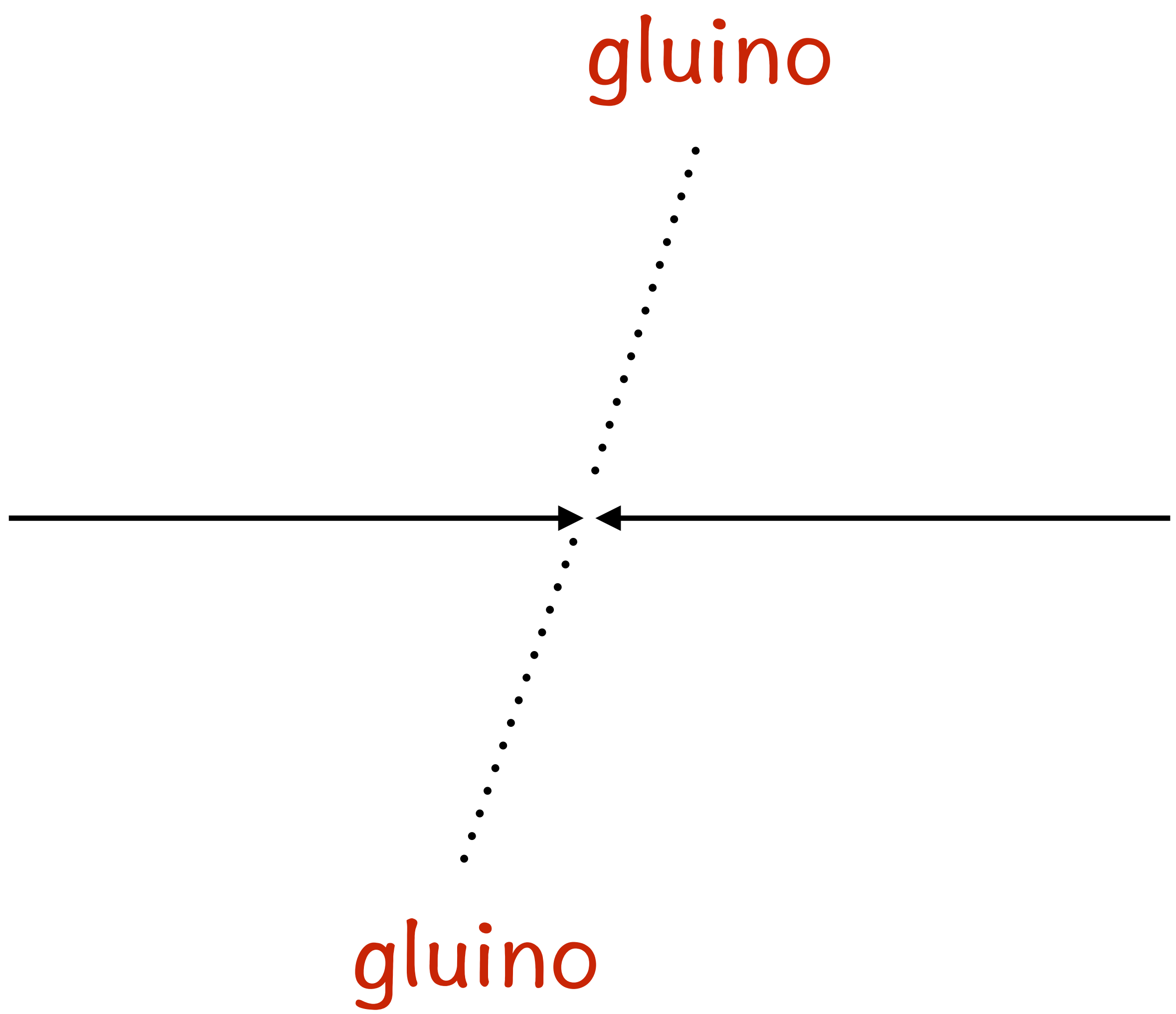
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

BB, Mukhopadhyay, Nojiri, Sakakie and Webber JHEP17

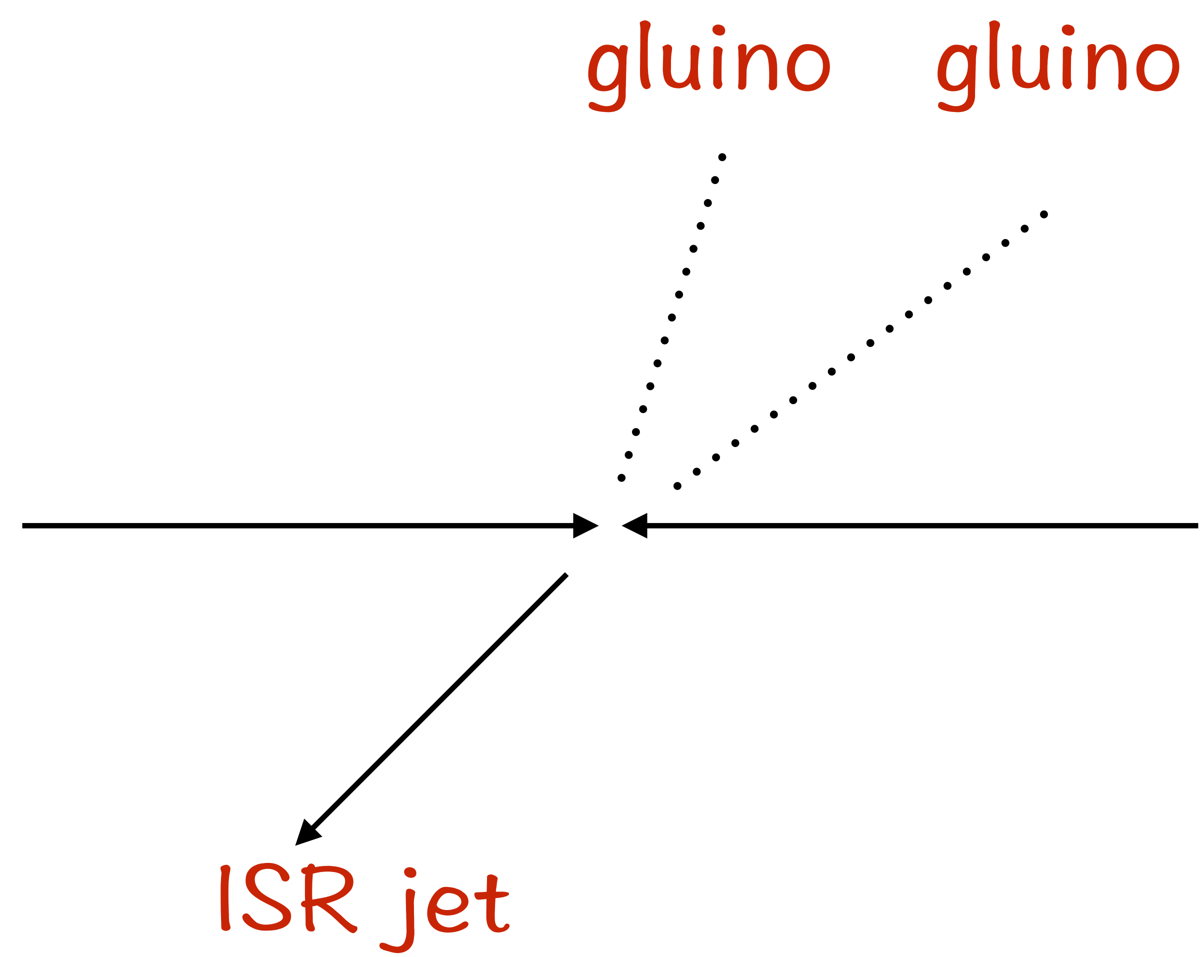


Degenerate gluino production

gluino pair production



gluino pair + ISR



back to back in the transverse plane

> no transverse missing energy

recoil of gluing pair against ISR jet

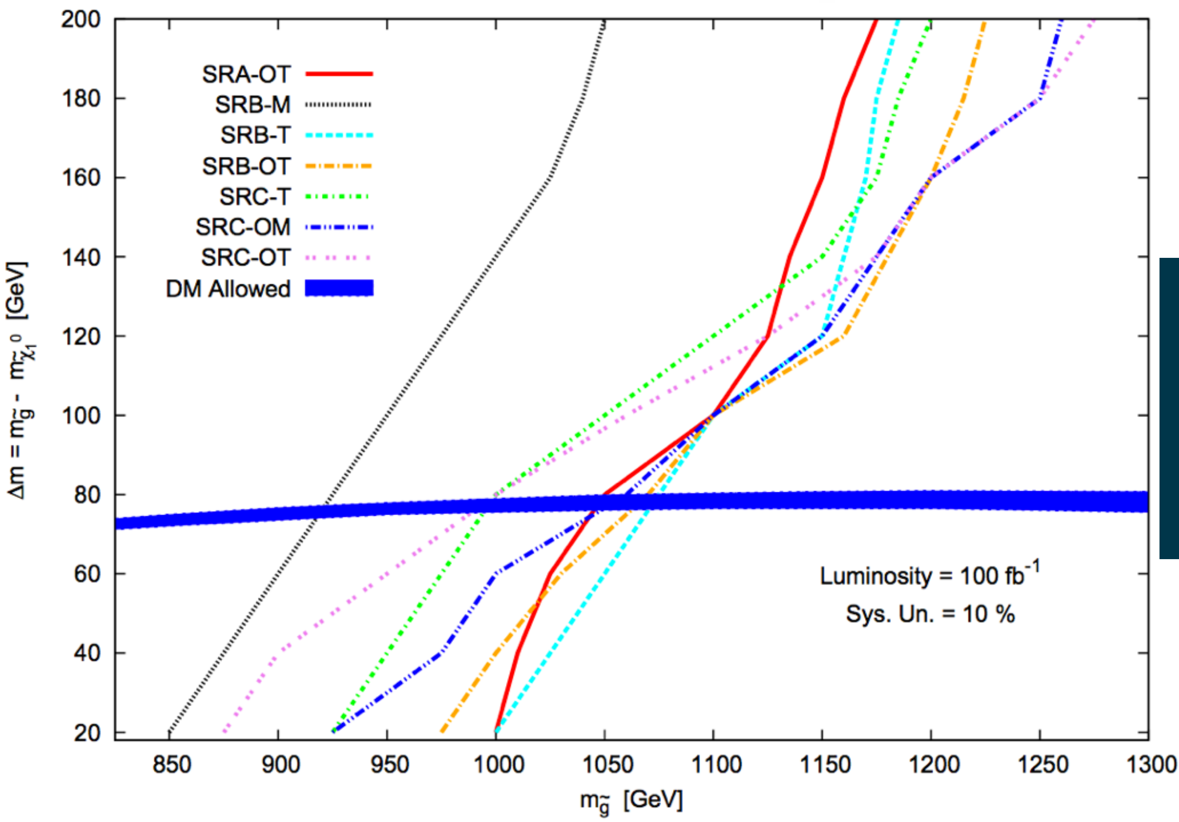
-> transverse missing energy

REMEMBER LEP SERCH FOR DEGENERATE CHARGINO

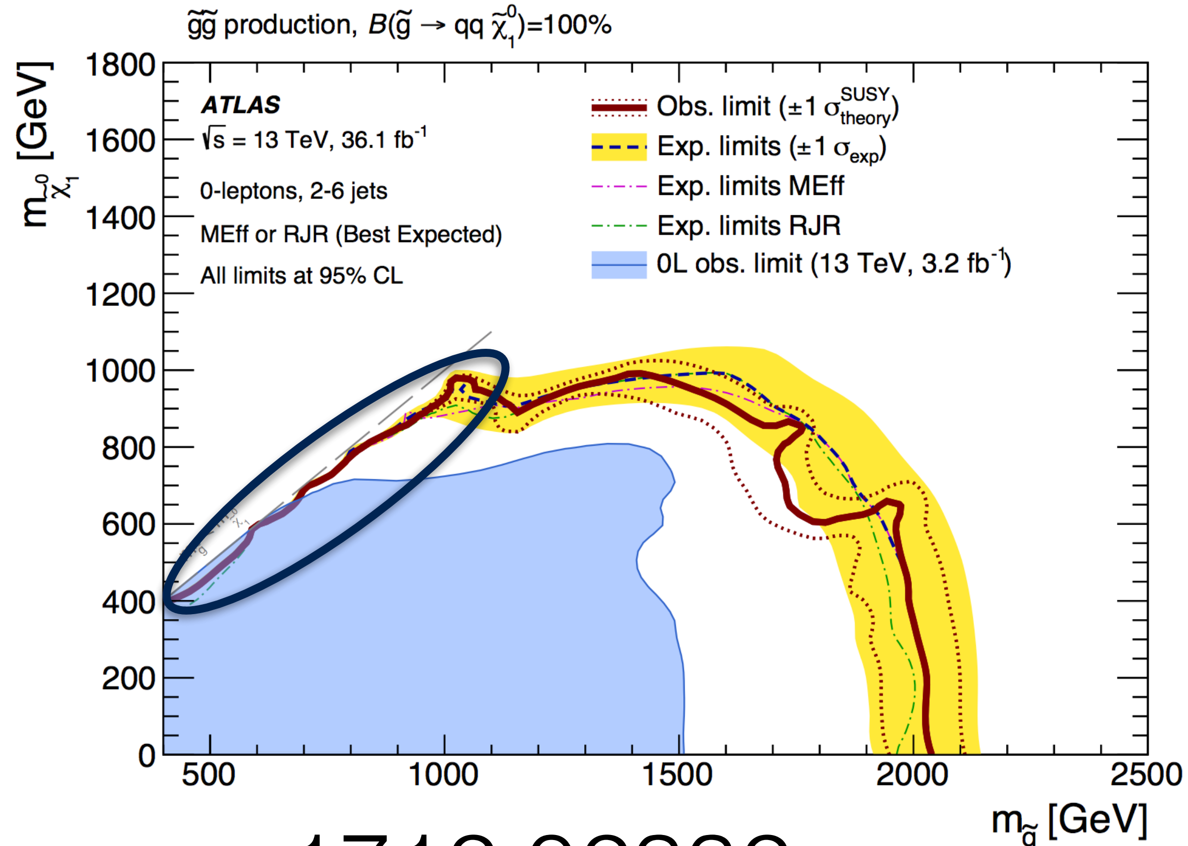
Uncertainty in the momentum distribution will be highly reduced after jet matching

(Dreiner, Kramer,Tattersall PRD12)

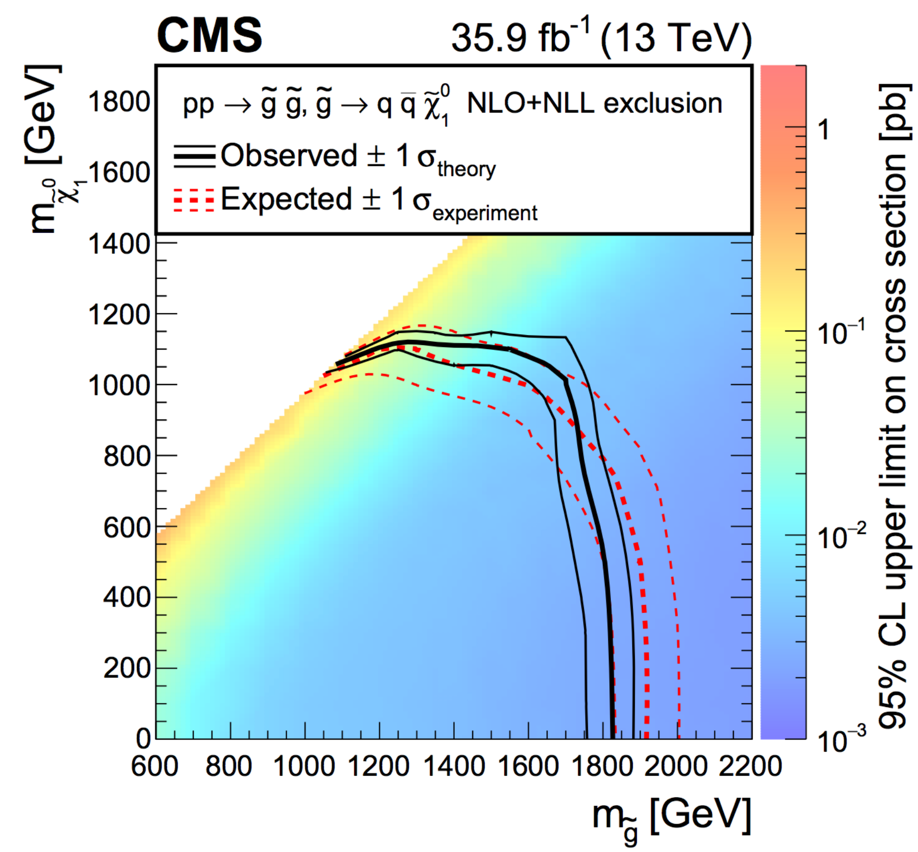
Future limit



14 TeV



1712.02332



CMS:1704.07781

BB, Chaudhury, Ghosh, Poddar
PRD14(1308.1526)

7/8 TeV bound on gluino ~ 500-600 GeV

Dark matter: degenerate SUSY can produce correct relic density (new co-annihilation regions) [S. Profumo, C. E. Yaguna PRD 14]

LHC 33 TeV High luminosity option (T. Cohen et.al., 1311.6480): extremely degenerate gluino with mass up to 1.8 TeV can be exclude
(discovery reach ~ 1.4 TeV)

Higgsino searches

mass difference between charged and neutral higgsino

for heavy wino, bino

Typically $$\Delta m(\chi_1^{\pm}, \chi_1^0) \sim \frac{m_W^2}{min(m_1, m_2)}$$ 1401.1235

μ -> 100 to 1000 GeV : decay length 20 to 7 mm

Sum of NLO-NLL chargino neutralino

sqrt(s) = 13 TeV, cross section in fb

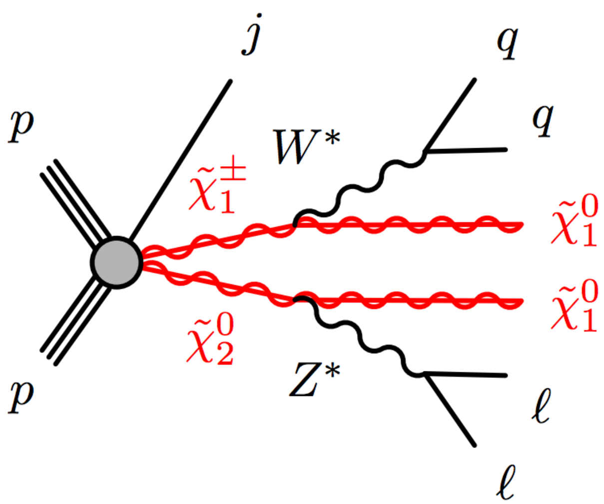
wino-like chargino neutralino	wino-like chargino pair	higgsino-like chargino neutralino	higgsino-like chargino pair
150 5118	150 2612	150 1215	150 689
200 1779	200 902	200 424	200 244
500 45	500 22	500 11	500 6
700 9	700 4.4	700 2.2	700 1.25
1000 1.3	1000 0.6	1000 0.31	1000 0.18

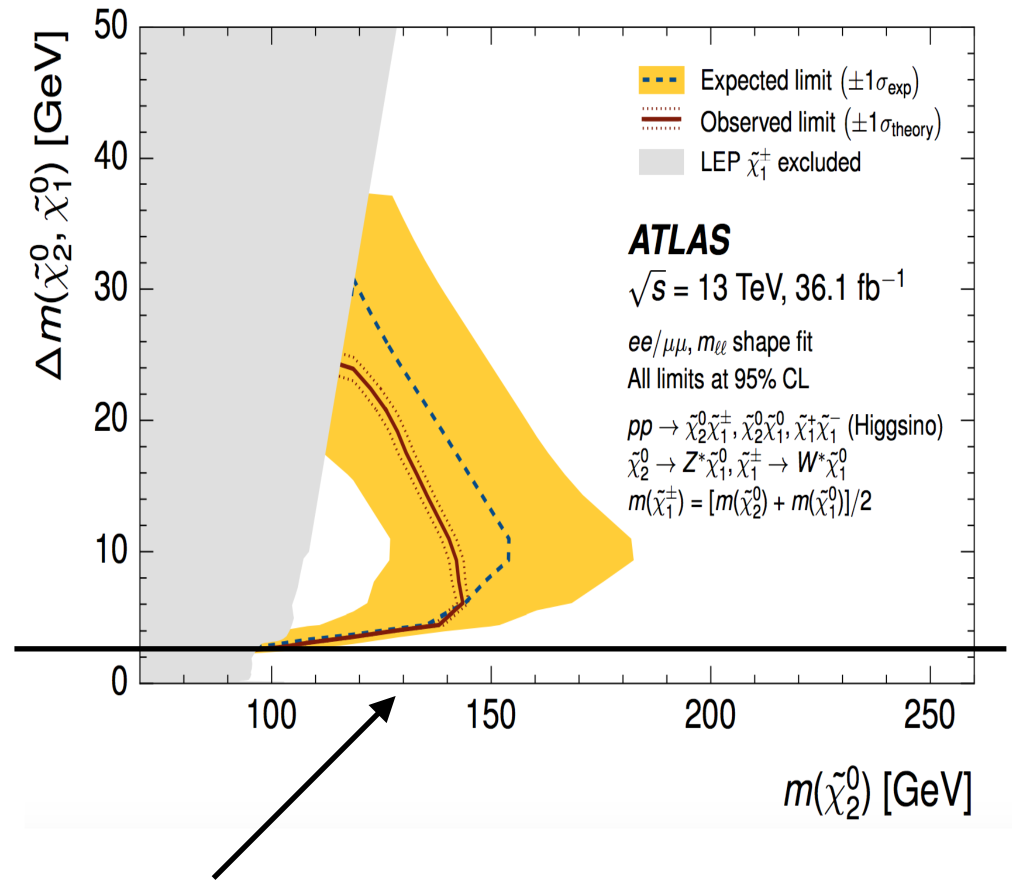
smaller cross section

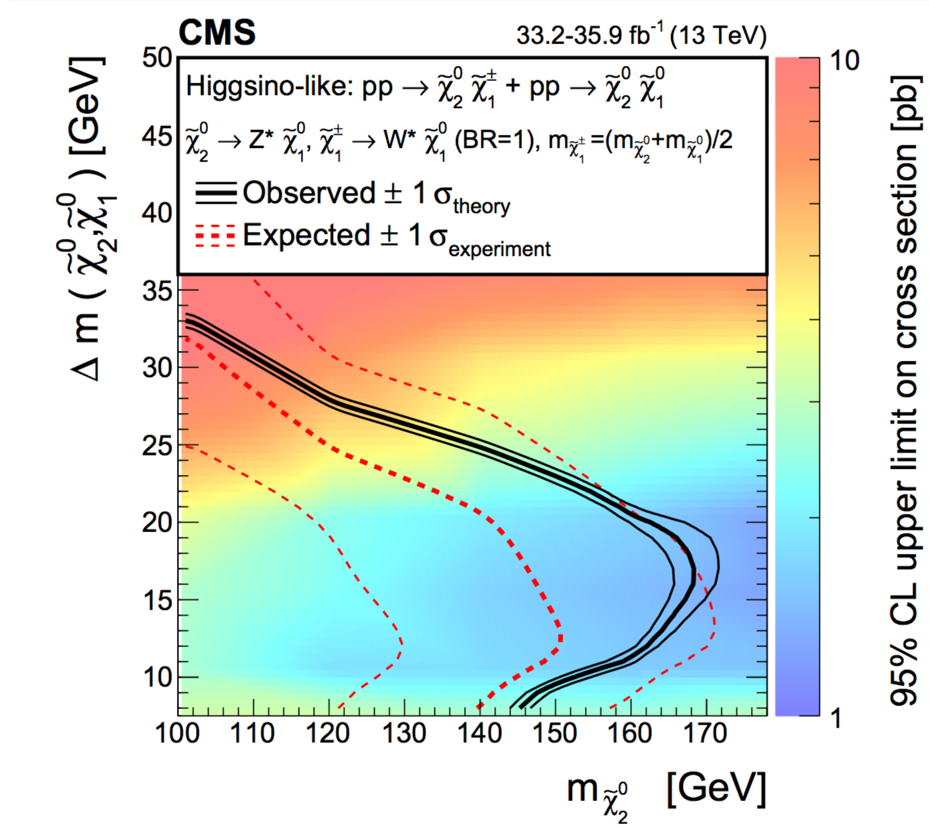
compared to wino

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

Higgsino searches : soft di-lepton(1712.08119 and 1801.01846)





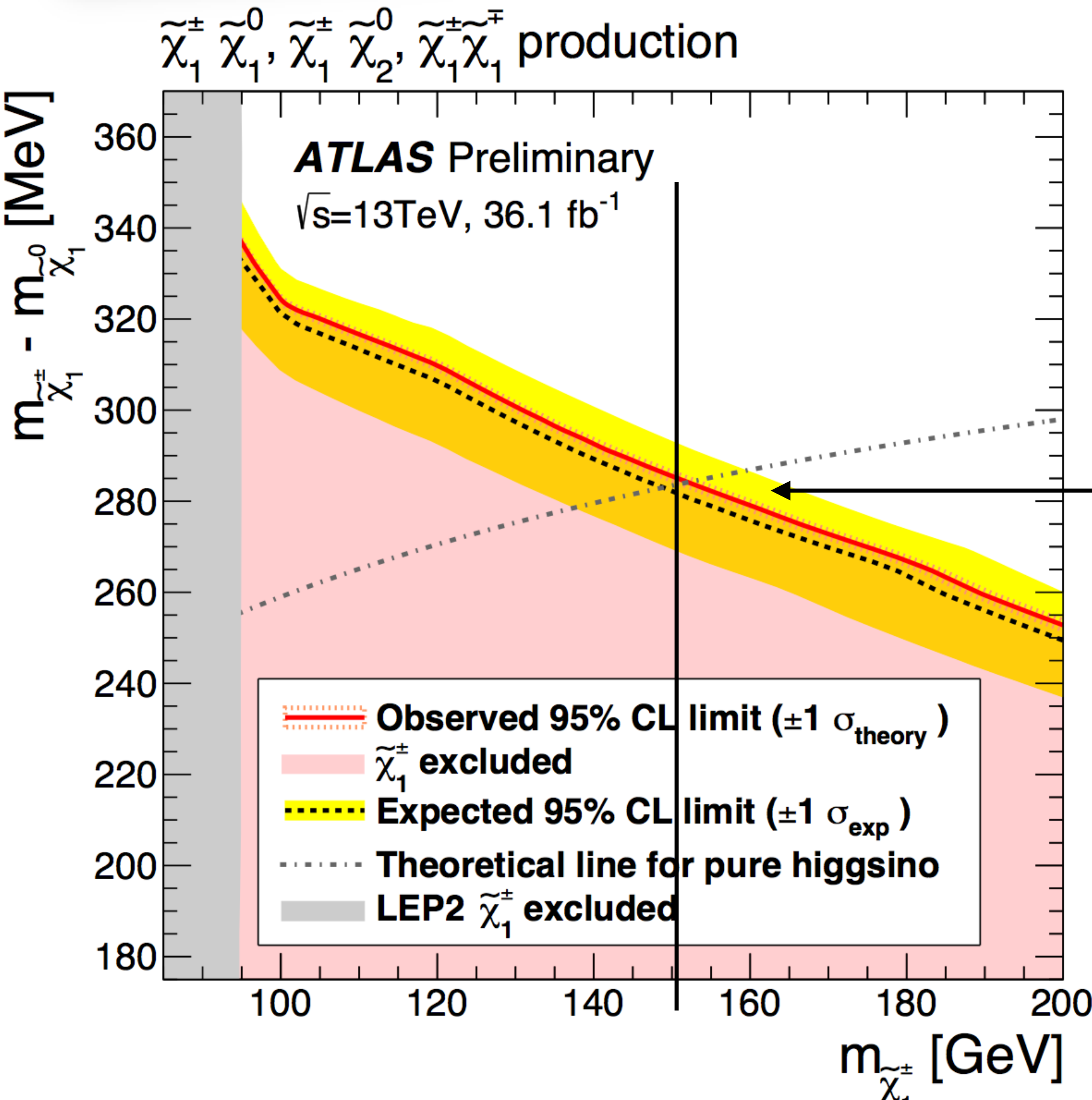


very low sensitivity below 2-3 GeV

soft lepton, robust fake lepton modelling and di-lepton invariant mass distribution(kinematic endpoint) increase the sensitivity

Other possible option to search in mono-jet +MET (1310.4274, 1401.1162), soft 1 lepton/ 3 lepton channels (any other options ?)

ATLAS Higgsino searches : disappearing charged track



mass limit

is about 150 GeV

reinterpretation of ATLAS wino search using tracklets

ATL-PHYS-PUB-2017-019

100 TeV collider: disappearing track search within the inner 10 cm of detector volume resulting in around 10 events for 1.1 TeV thermal Higgsinos. (1703.05327)

Possibility 1 : make everything degenerate

lowest possible mass

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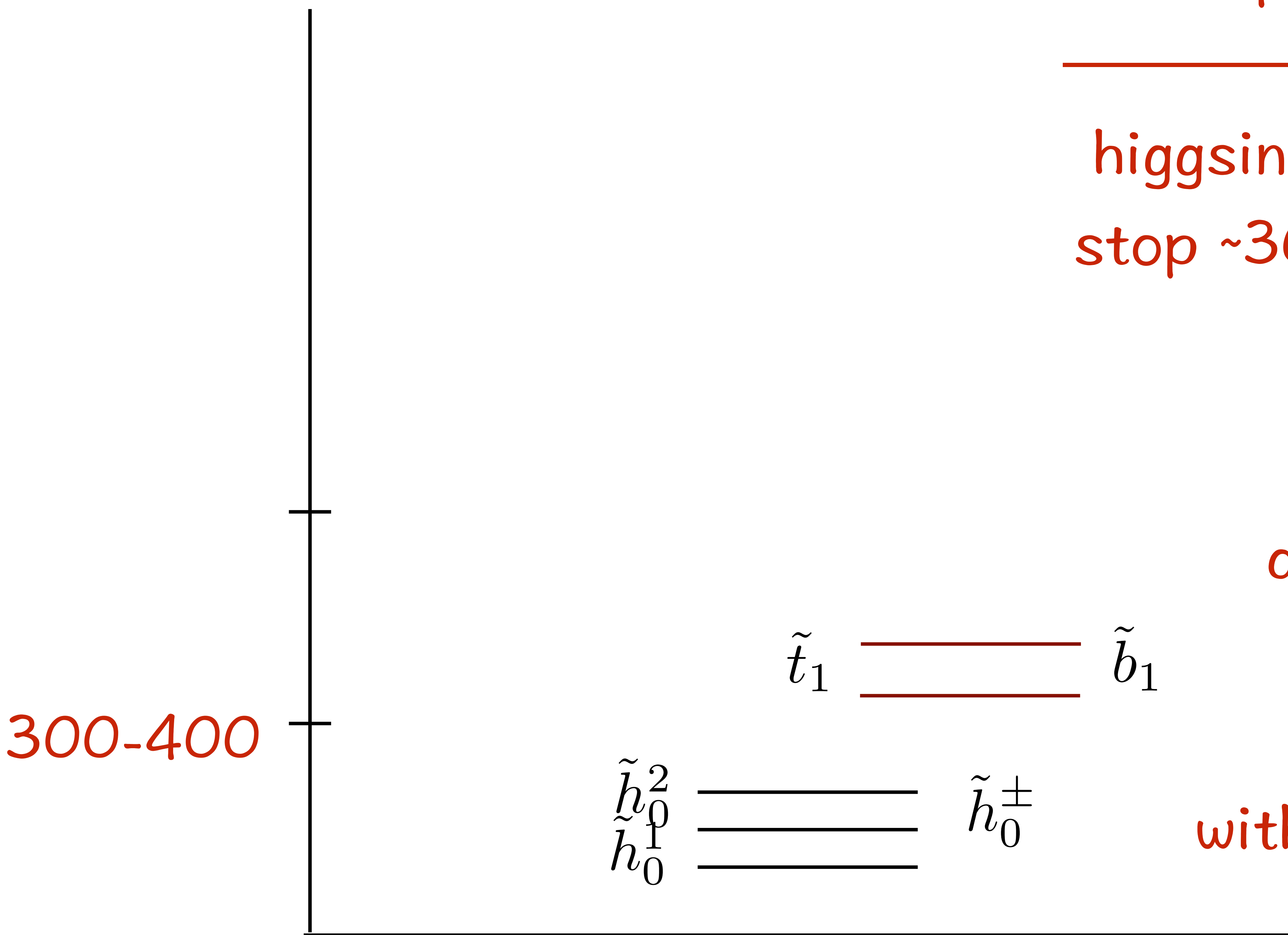
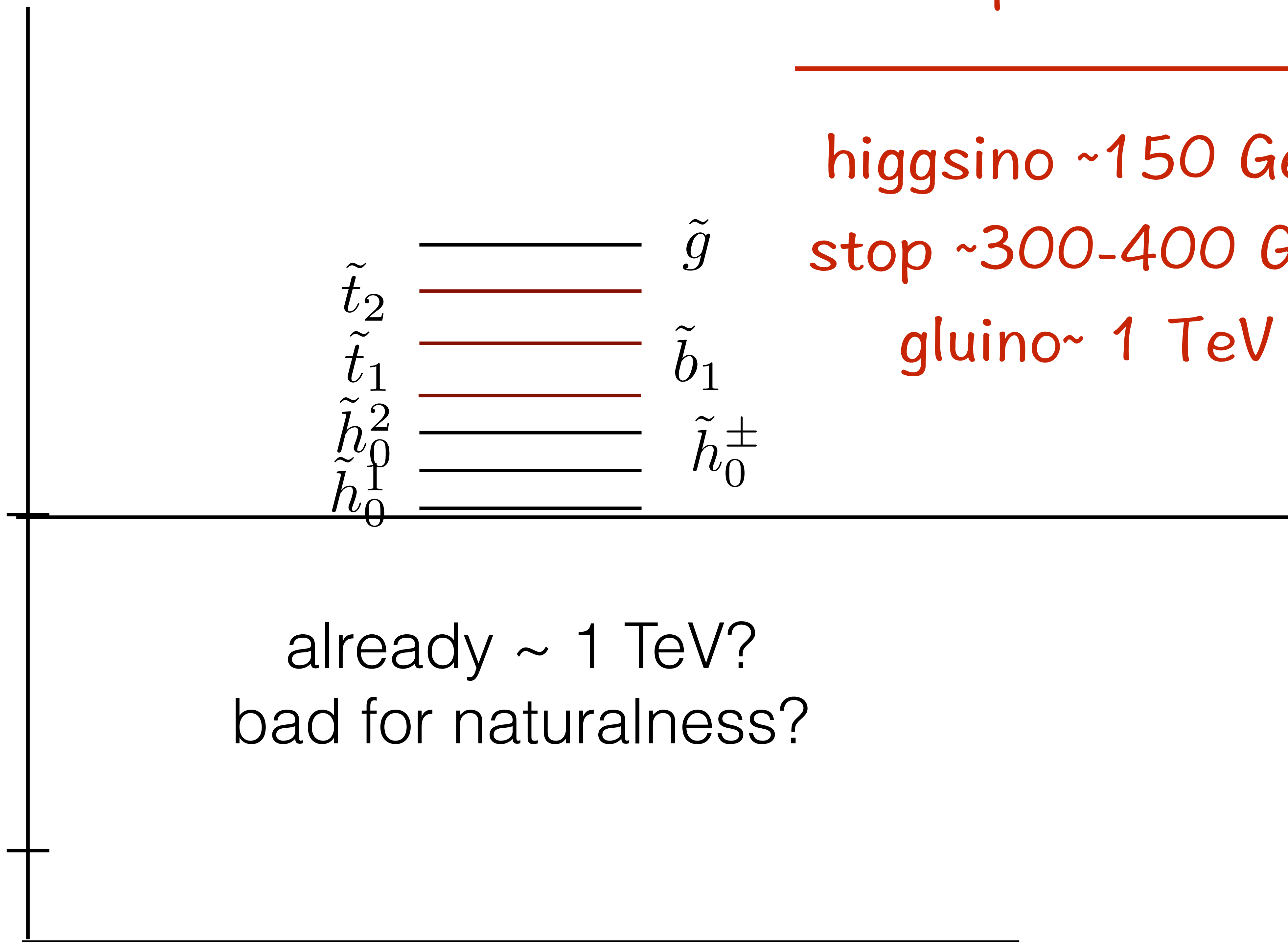
higgsino ~150 GeV

stop ~300-400 GeV



degenerate stop and higgsino with mass ~ 400 GeV

Possibility 1 : make everything degenerate



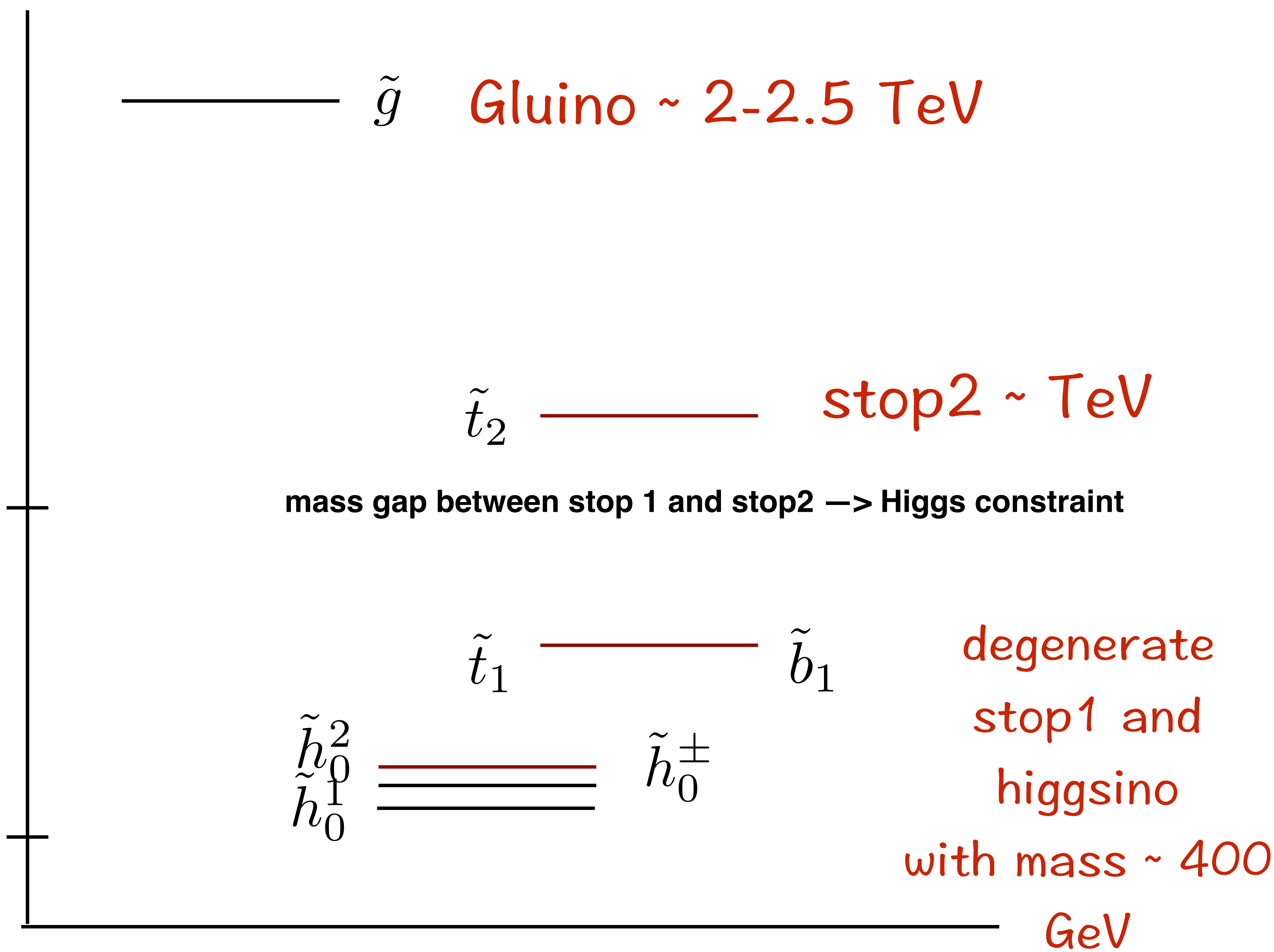
lowest possible mass

higgsino ~150 GeV

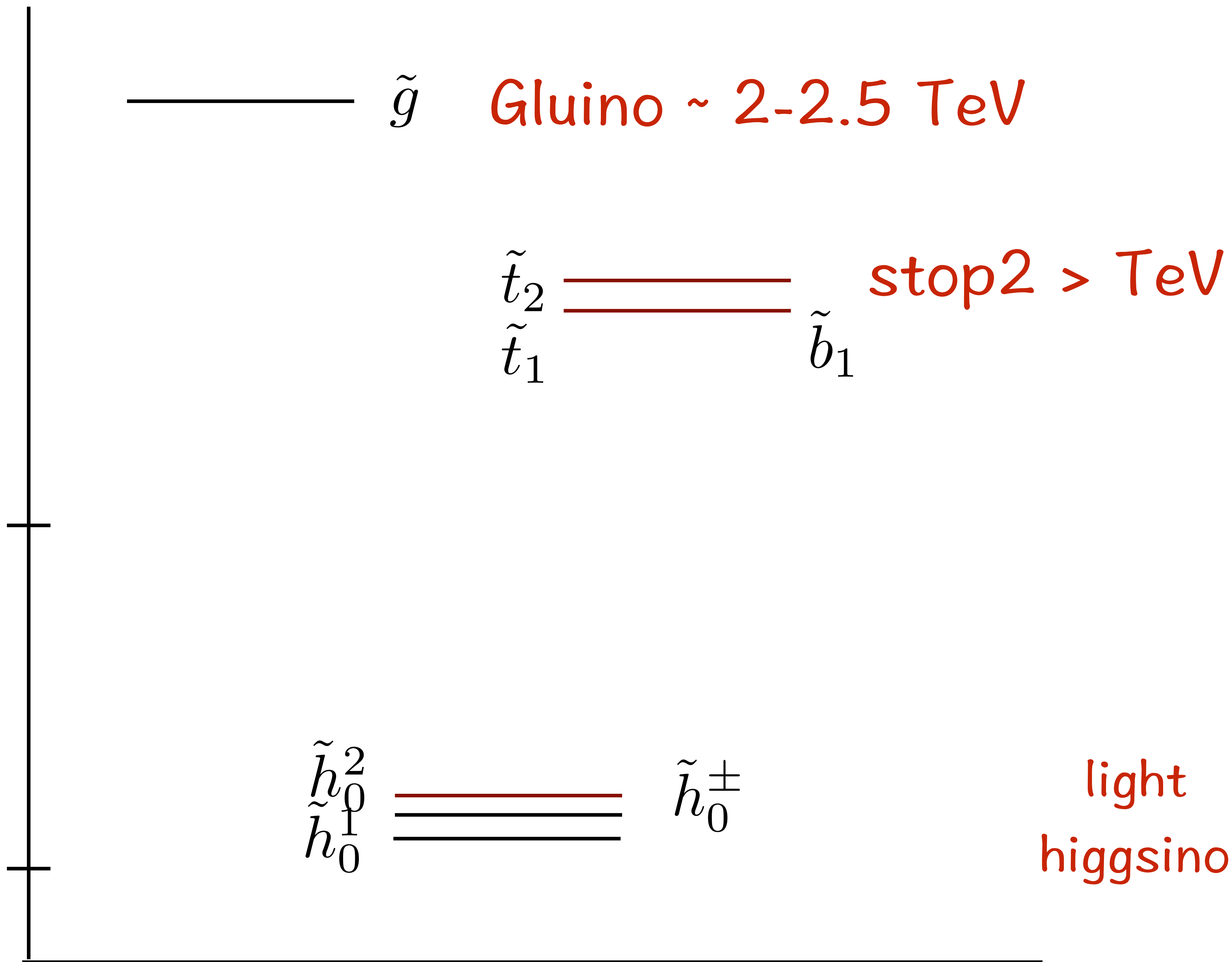
stop ~300-400 GeV

gluino~ 1 TeV

Possibility 2 : degenerate higgsino stop + heavy gluino



Possibility 3 : light higgsino + heavy stop and gluino



4-5 TeV gluino and 2 TeV stops are fine with $\Delta_{EW} < 30$

Higgs sector of MSSM

What are the current bounds on MSSM Higgs bosons

Large mixing with 125 GeV Higgs boson allowed ?

We have done a random scan on pMSSM parameter space

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

FeynHiggs 2.12.0: for spectrum generation and cross section calculation

Micromegas 4.1.8 for flavour physics

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

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

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]

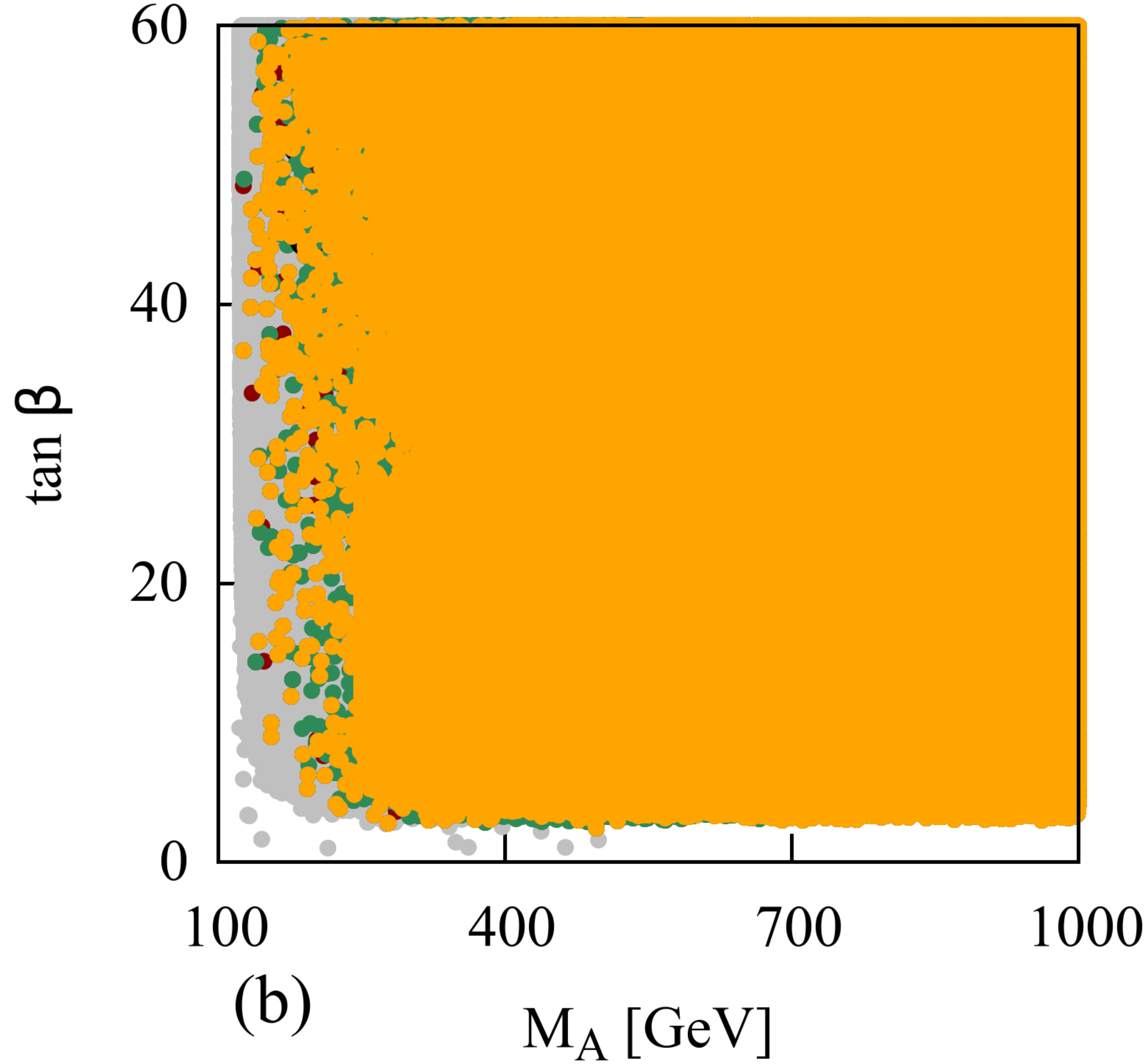
Run I

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]

Run II

Allowed parameter space

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



grey points: satisfy the light Higgs mass constraint.

green points: only LHC Run-I data

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

falvour data more stringent than Higgs data

Heavy Higgs searches at the LHC

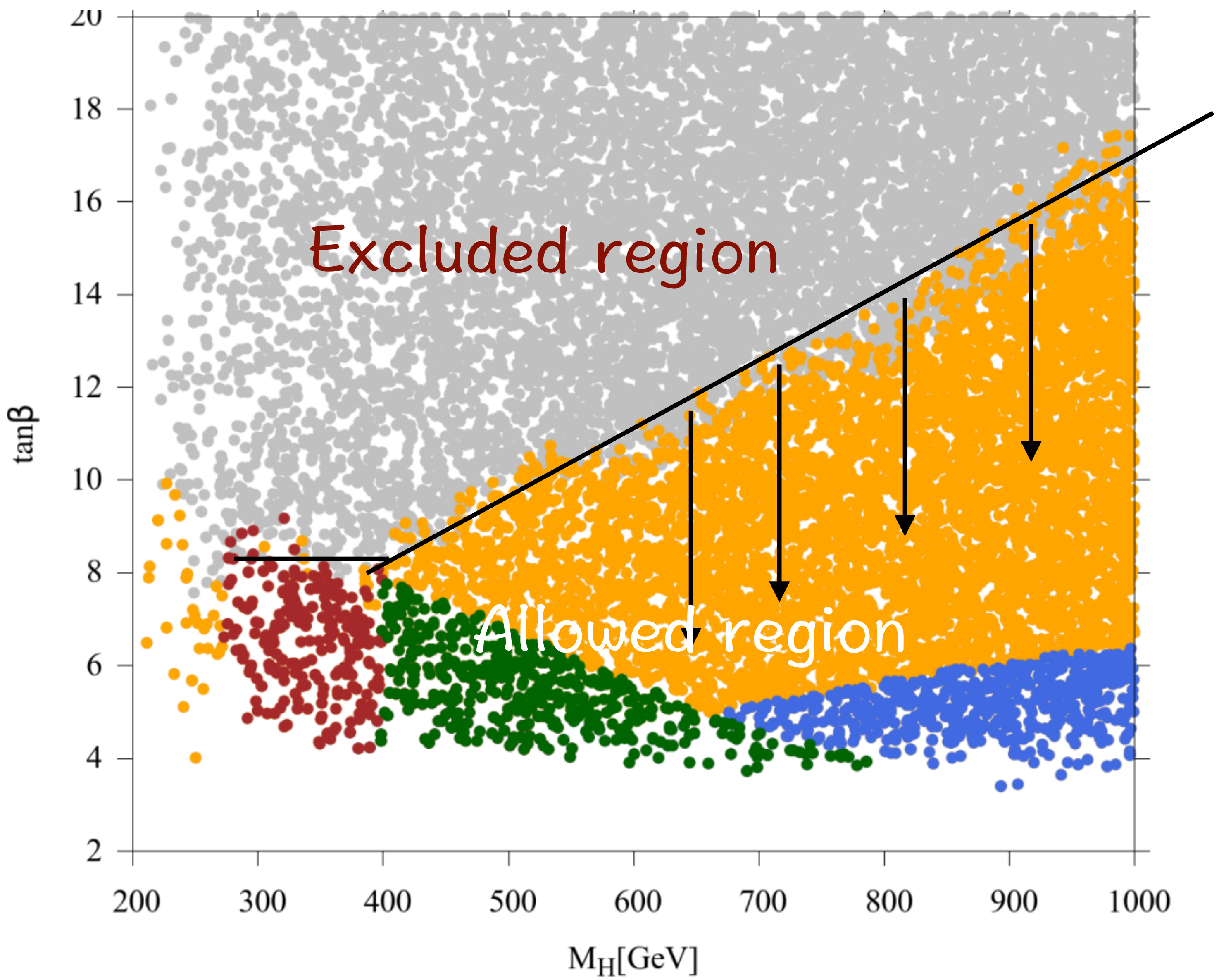
Channel	Experiment	Mass range (GeV)	Luminosity
$gg \to H/A \to \tau^+\tau^-$	ATLAS 8 TeV [28]	90-1000	19.5-20.3 fb^{-1}
	CMS 8 TeV [55]	90-1000	19.7 fb^{-1}
	ATLAS 13 TeV [29]	200-1200	3.2 fb^{-1}
	CMS 13 TeV [56]	100-3000	2.3 fb^{-1}
$b\bar{b} \to H/A \to \tau^+\tau^-$	ATLAS 8 TeV [28]	90-1000	19.5-20.3 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

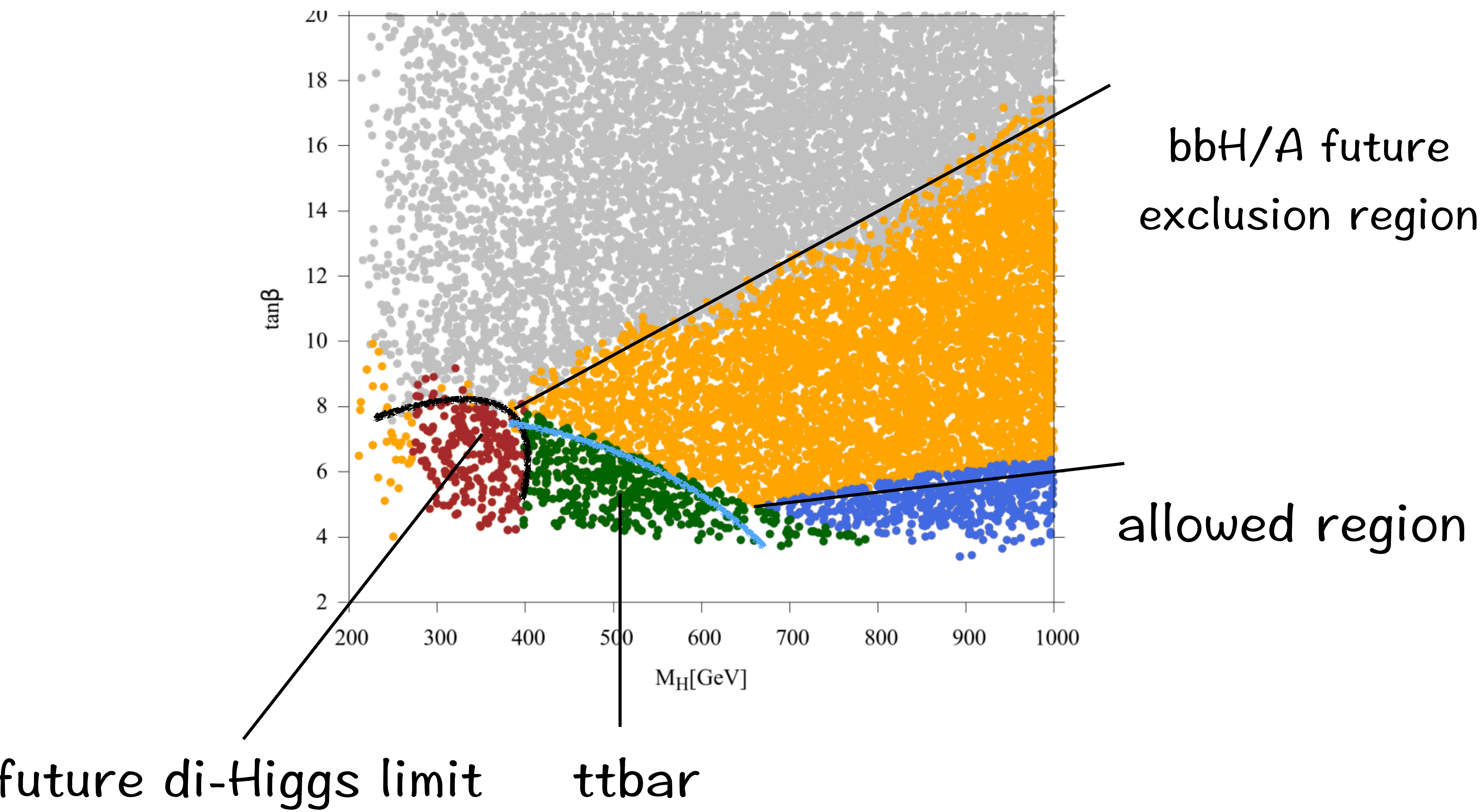
(CMS + ATLAS: 8 + 13 TeV)

MSSM Heavy Higgs bosons : current bound



Adhikary, Barman, Banerjee, Bhattacherjee 1812.05640

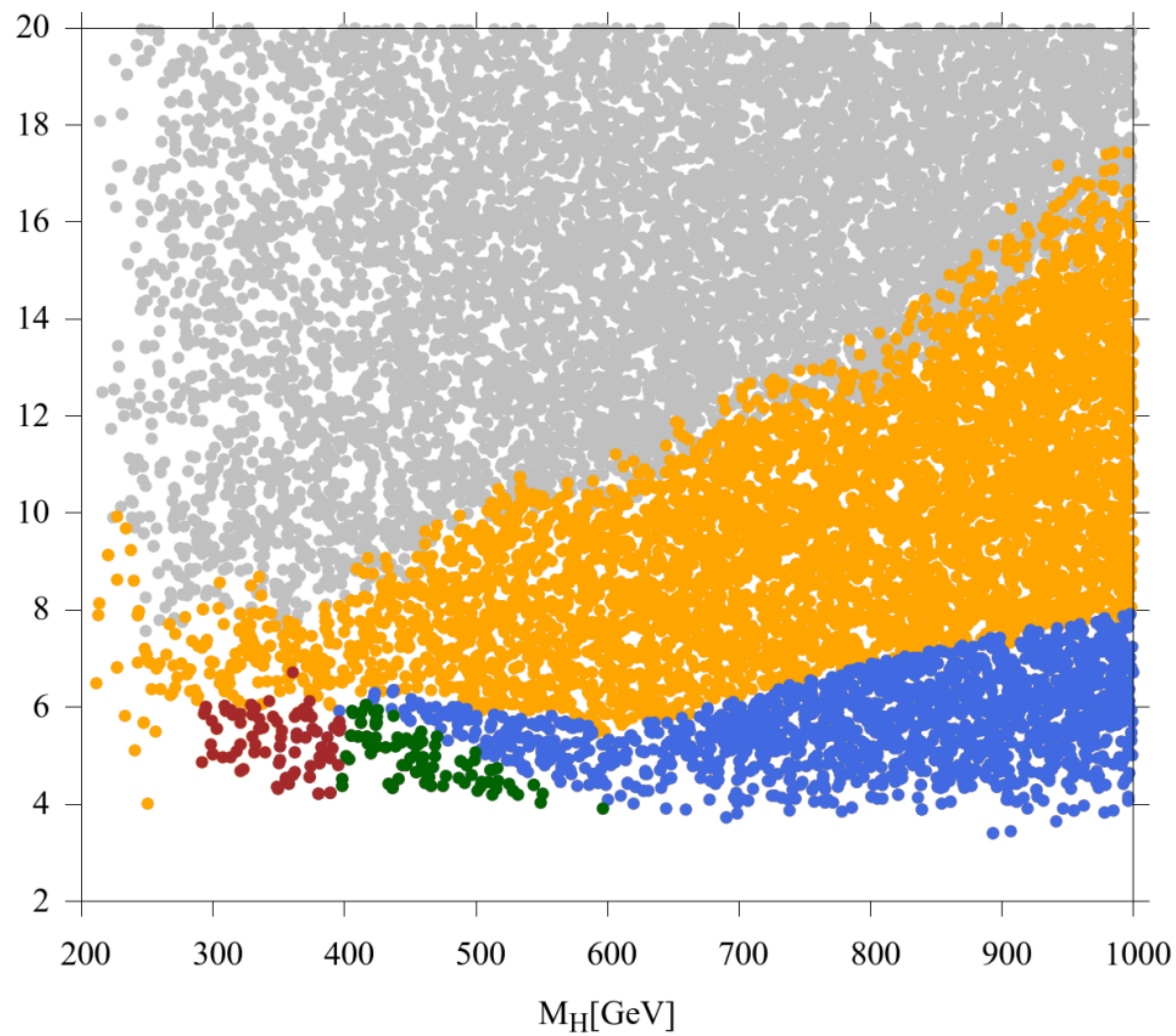
Future limits



Adhikary, Barman, Banerjee, Bhattacherjee 1812.05640

Future limit in the presence of BSM decay modes

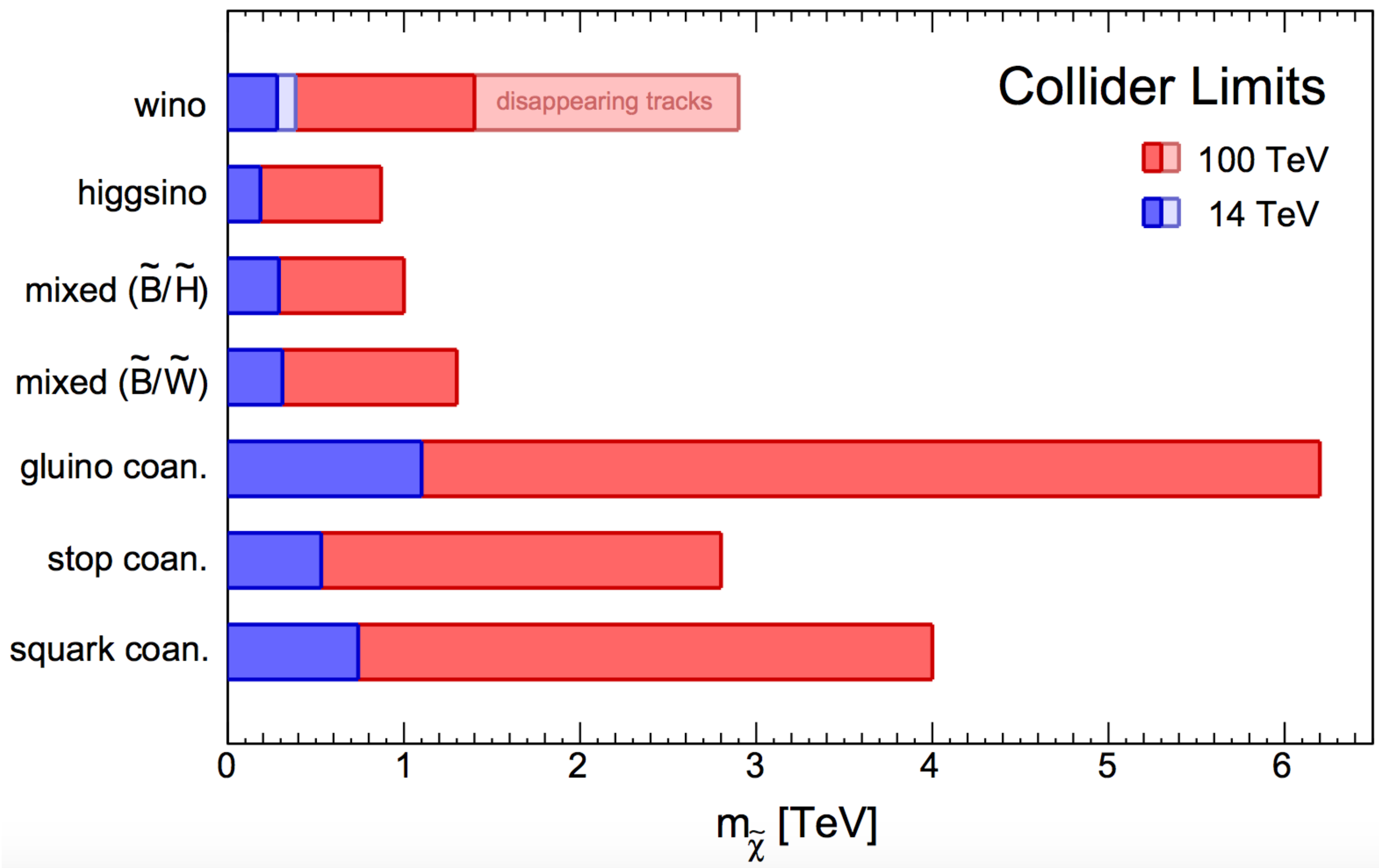
Branching(H/A-> non-SM) = can be > 50%



Barman, Bhattacherjee,Chakraborty, Choudhury PRD 2016
Adhikary, Barman, Banerjee, Bhattacherjee 1812.05640

Neutralino dark matter: collider bounds

Low, Wang 1404.0682



recent review on
Higgsino dark matter
1802.04097

100 TeV can not fully cover the allowed parameter space: some part of the bino-higgsino and wino-higgsino portions of the surface un-discoverable at a 100 TeV collider(1412.4789)

some of the relic neutralino sector will be uncovered by the direct detection experiments like Xenon1T, as well as indirect detection (1510.03460)

Conventional SUSY Searches

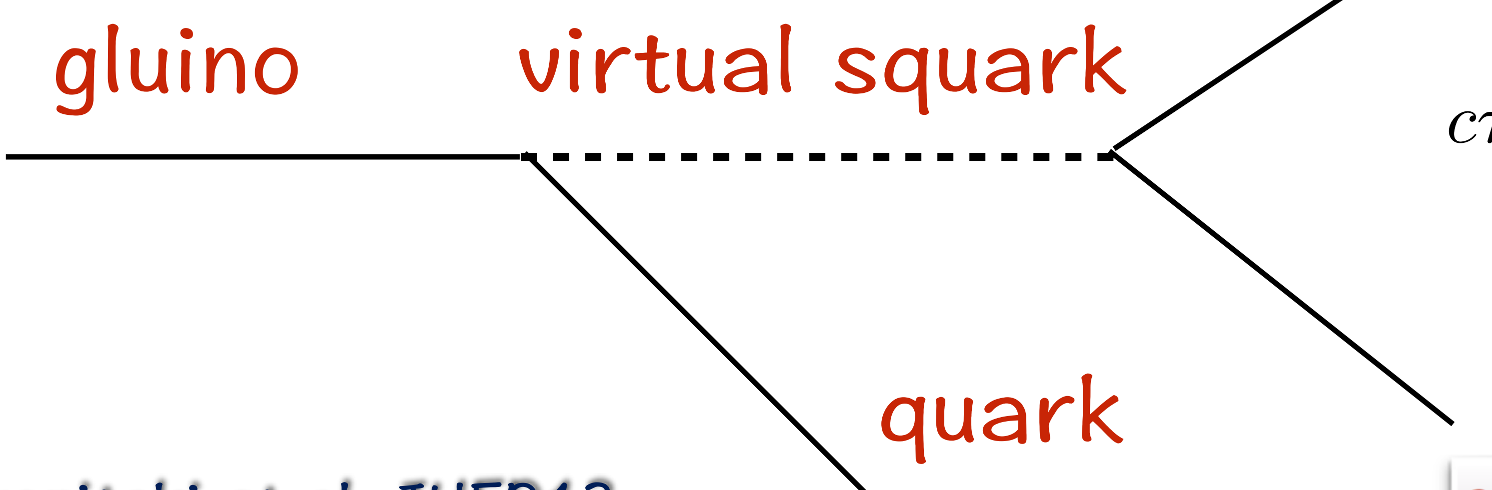
Features:

- Mostly NSLP decay to LSP assuming 100% branching
- Reasonable mass difference assumed in most of the cases(large MET, high effective mass …)
- Mass degenerate squarks (8 in total) => enhancement in cross section
- Mostly wino production considered (larger cross section than higgsino)
- Mostly prompt decays of SUSY particles considered

    - Many un-conventional scenarios are possible : RPV, long lived particles, stealth SUSY… Not fully explored at the LHC

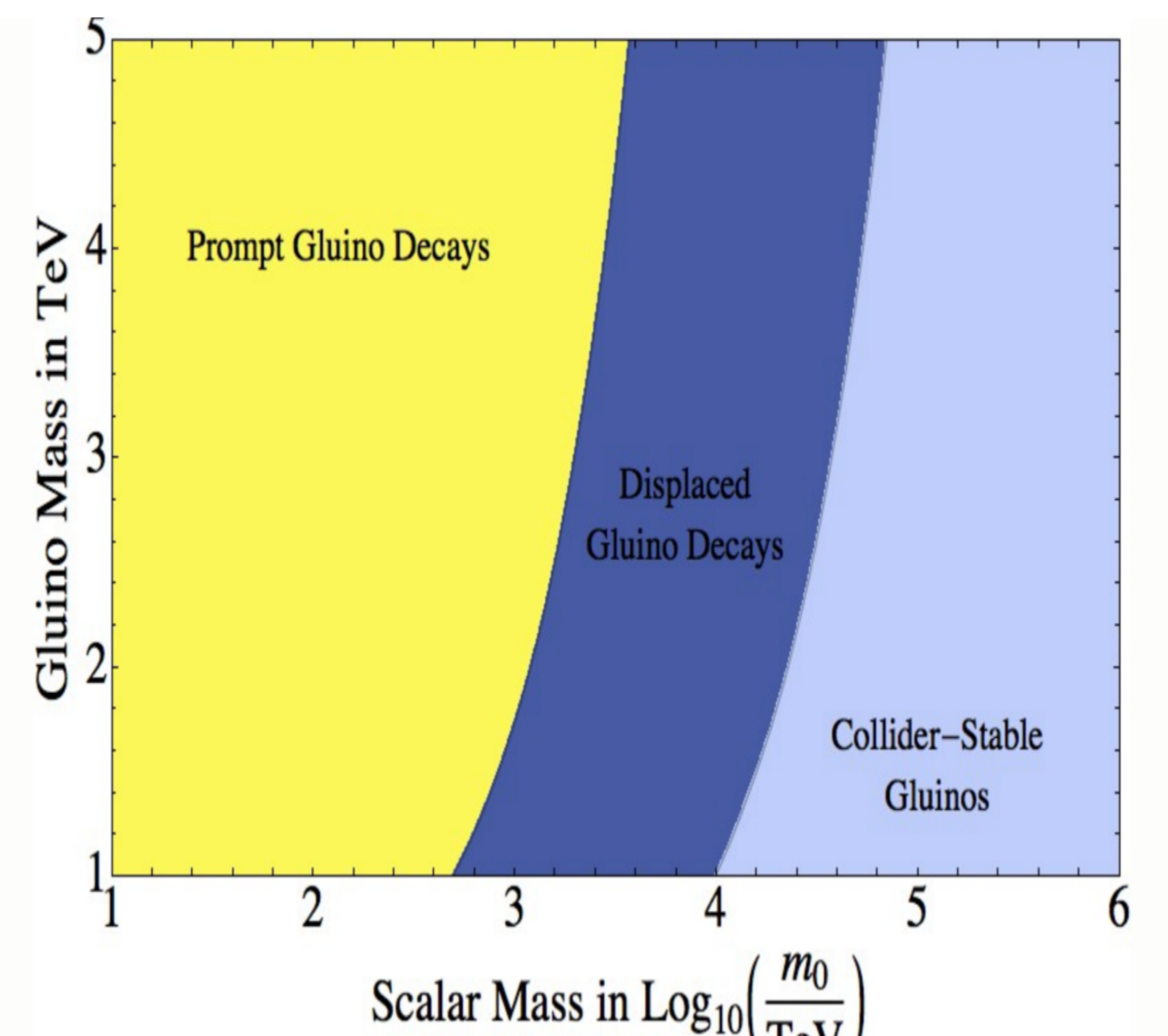
Example of unusual signature: Long lived gluino

gluino decay for heavy sfermions



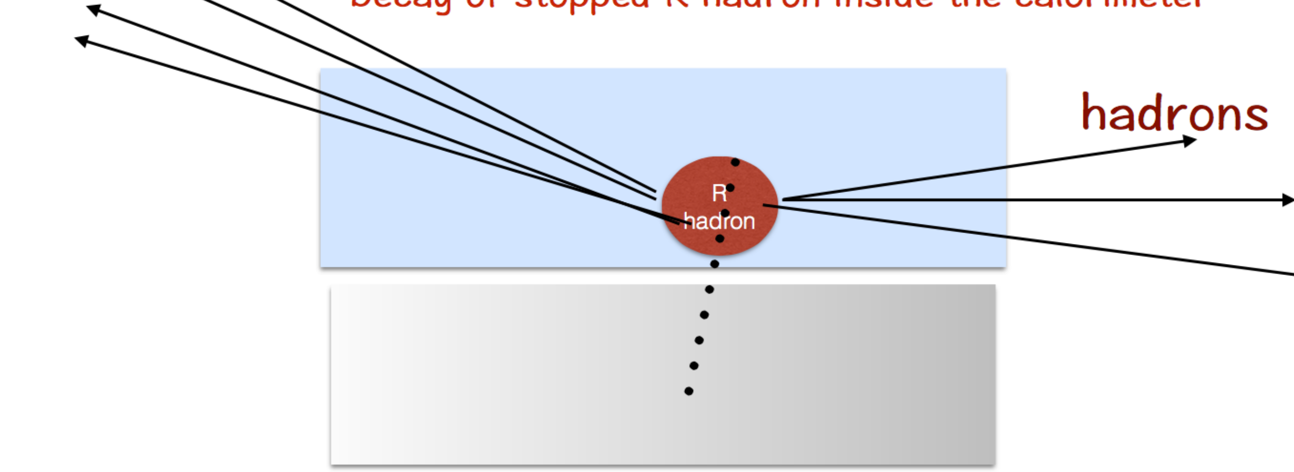
$$c\tau \simeq 10^{-5} m \left(\frac{m_{\tilde{q}}}{PeV}\right)^4 \left(\frac{TeV}{m_{\tilde{g}}}\right)^5$$

Arvanitaki et al. JHEP13



Stopped gluino search

Decay of stopped R hadron inside the calorimeter



signature : randomly-timed, relatively large energy response

most easily observed at times between pp collisions.

During these times the detector should be mostly quiet

(possible activity : :cosmic rays, beam-related backgrounds, and instrumental noise)

searched by D0 of Tevatron , ATLAS, CMS : limits also depend on lifetime

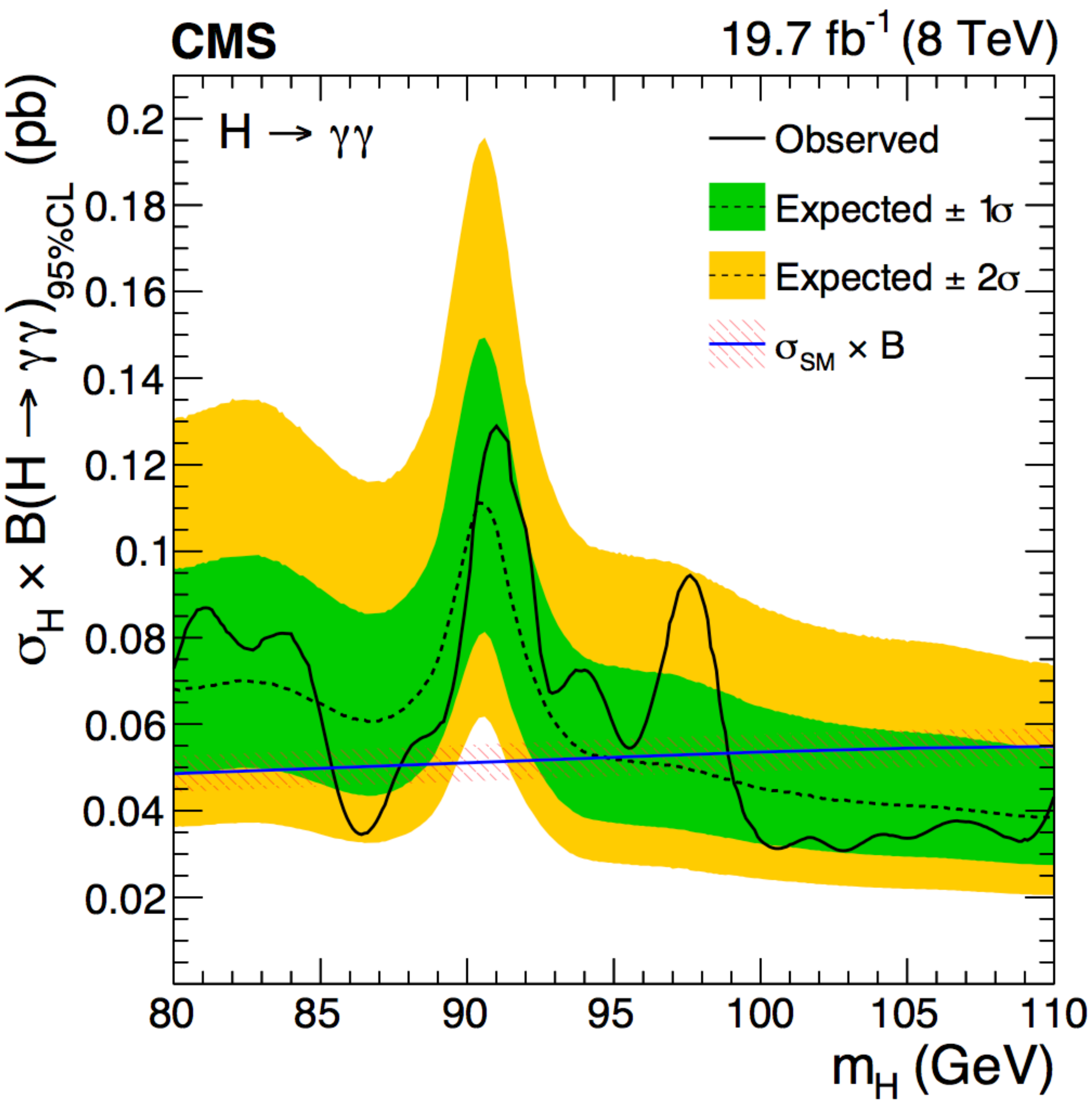
hep-ex: 1501.05603, https://inspirehep.net/record/1599661/files/EXO-16-004-pas.pdf

Collider anomalies
My watch list

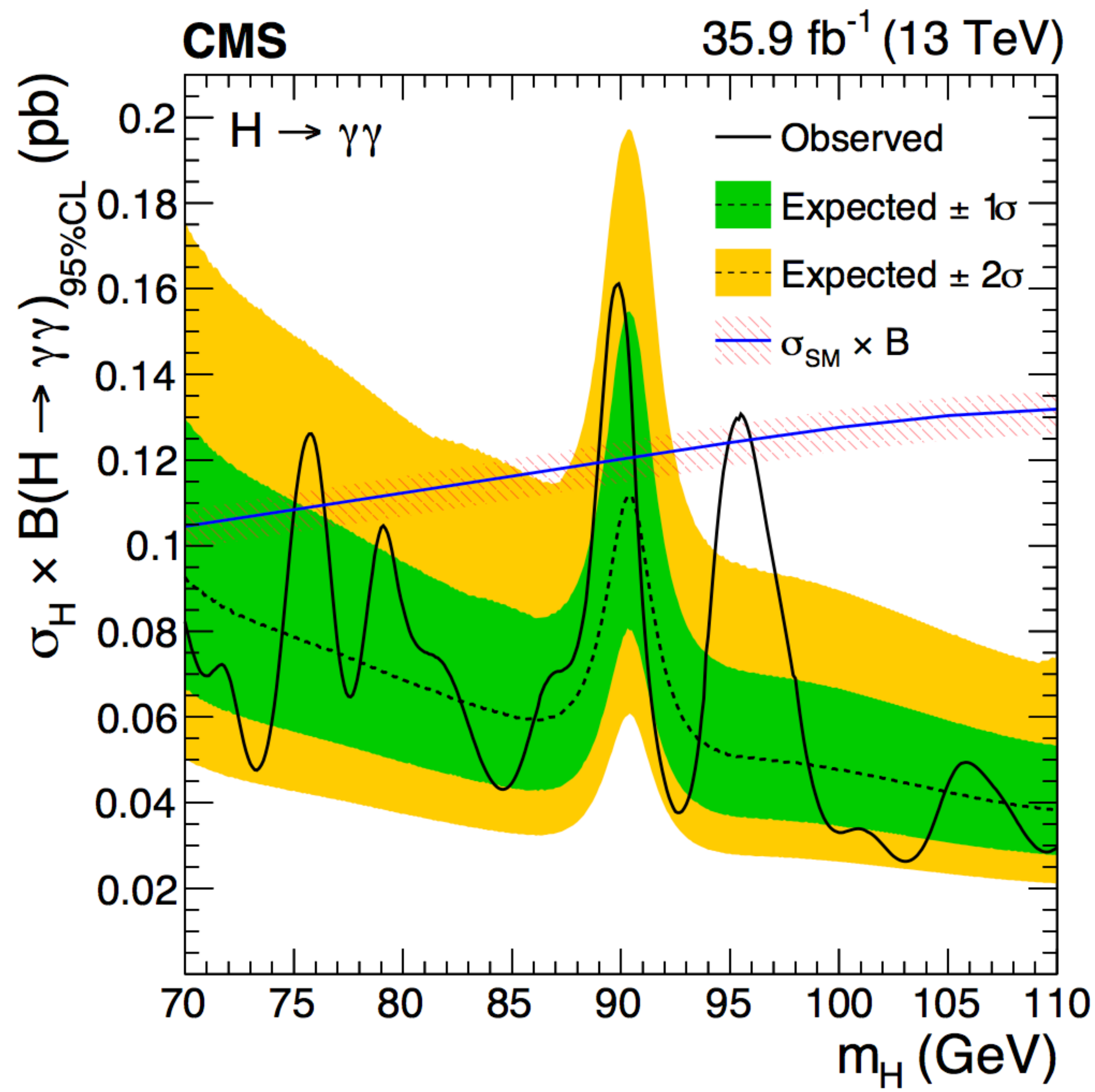
Warning: may be just statistical fluctuations !!

CMS low mass di-photon search below 110 GeV

$$pp \to \gamma\gamma$$



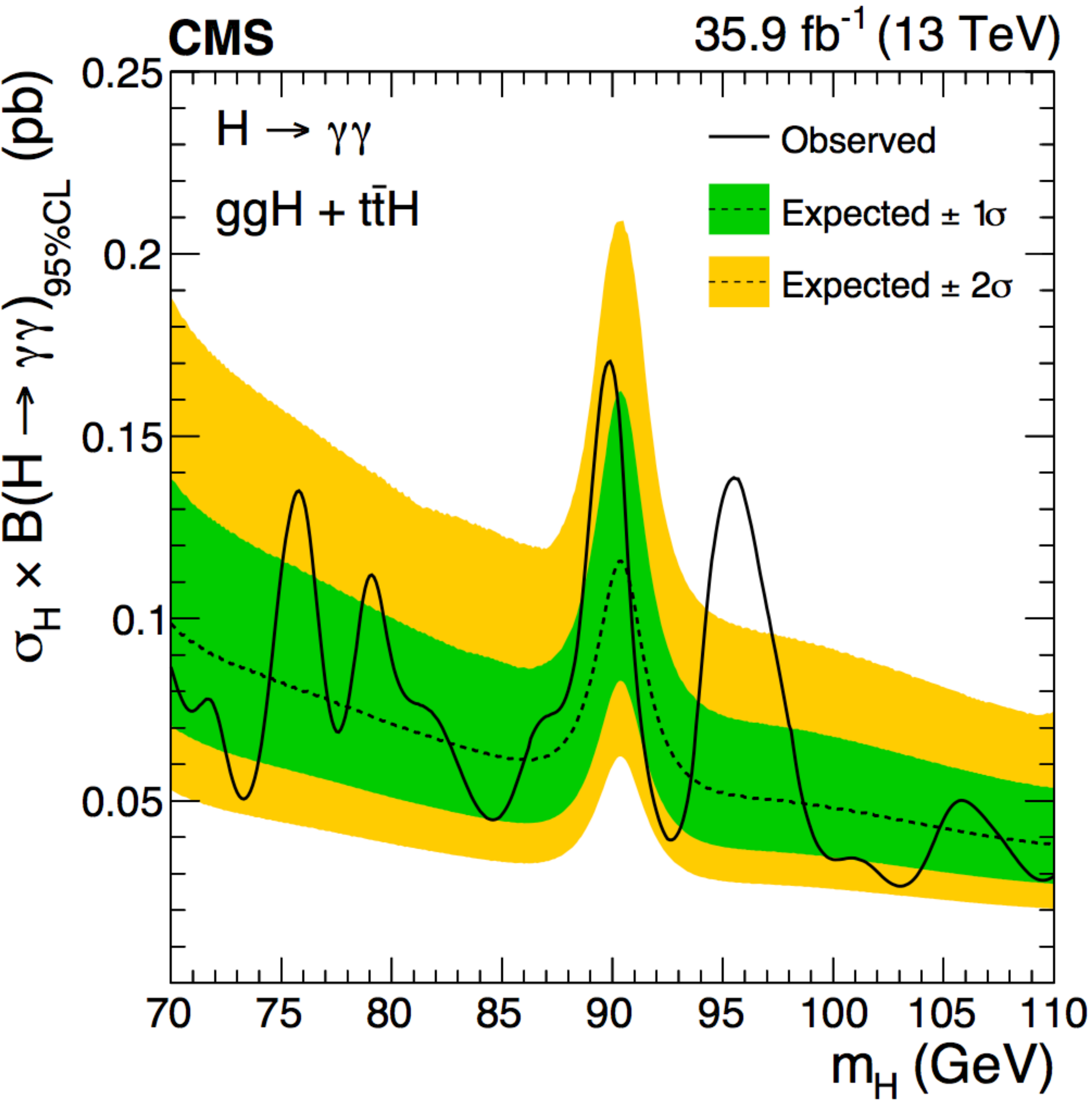
Run I : local excess ~ 2σ

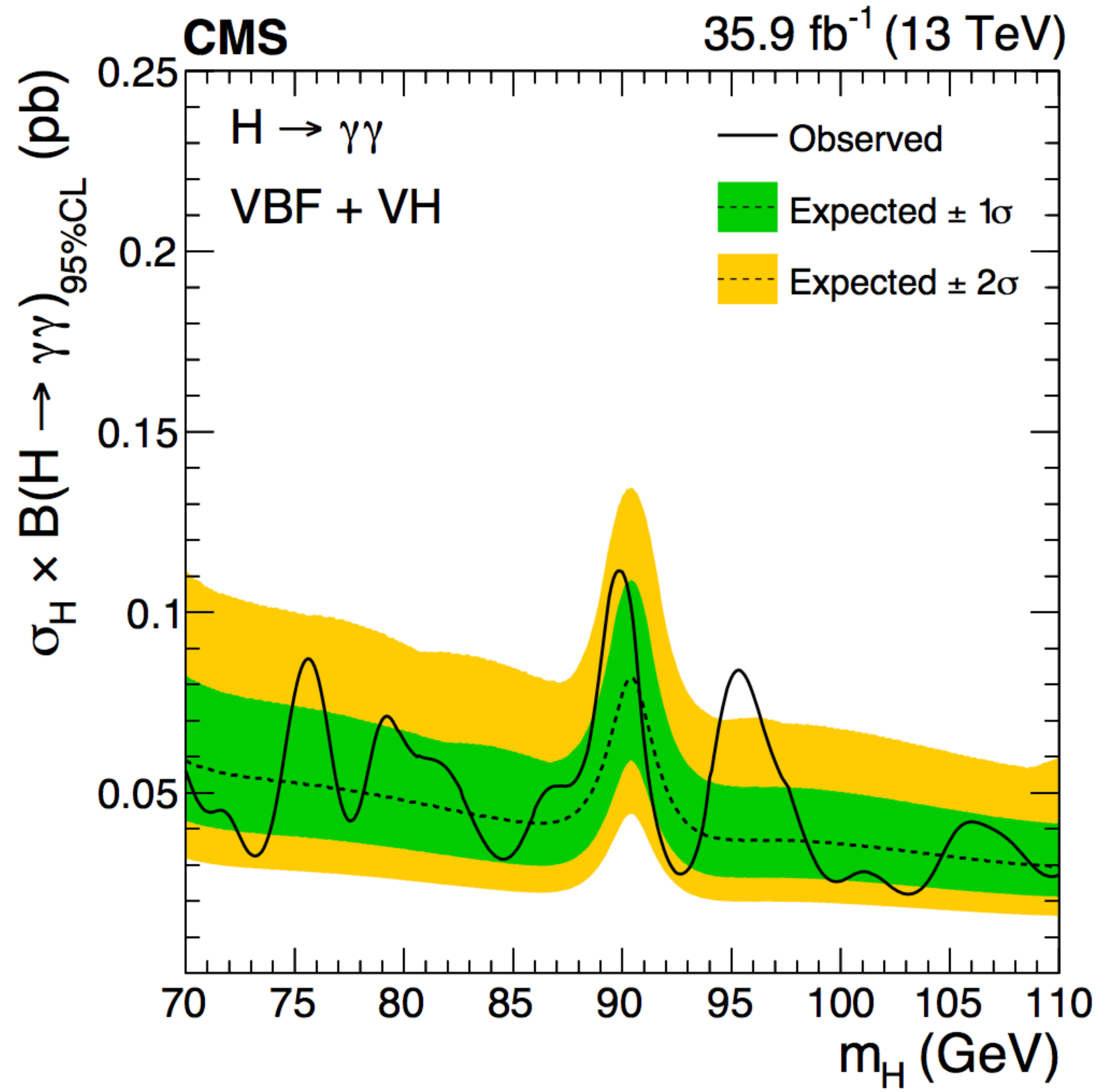


Run II : local excess ~ 3σ

CMS Higgs to gamma gamma search below 110 GeV

$$pp \to \gamma\gamma$$

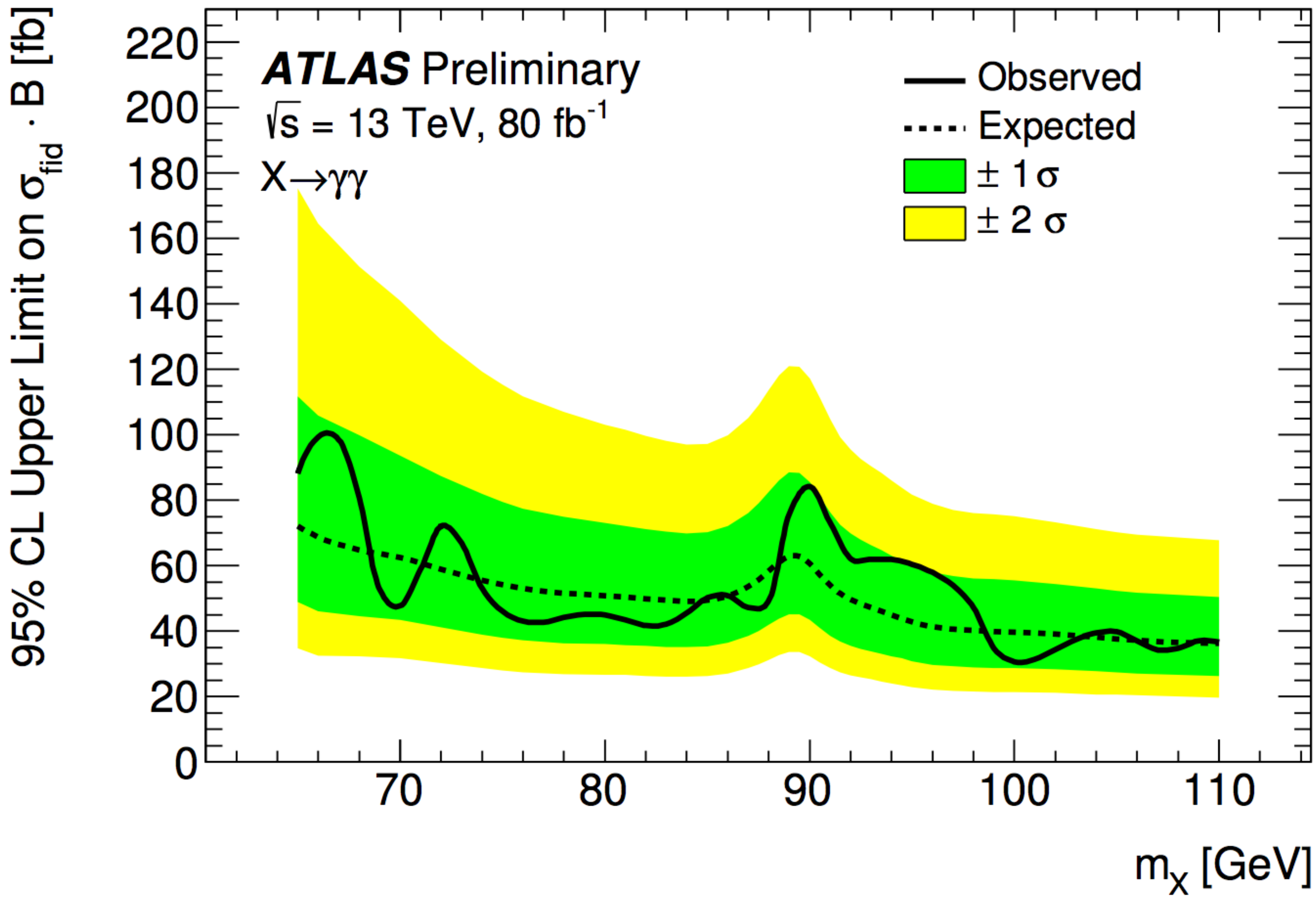




Channel wise search results

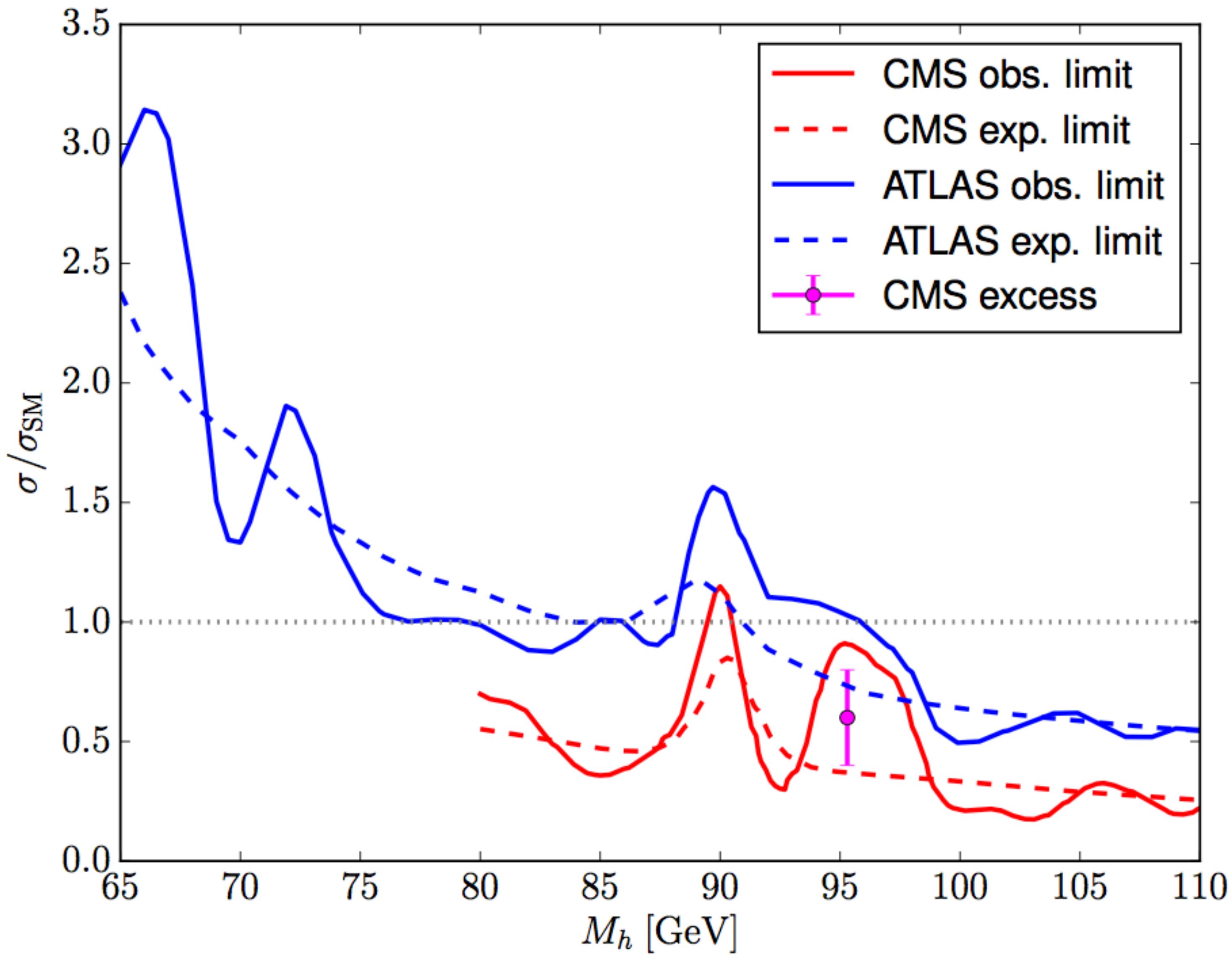
ATLAS di-photon search below 110 GeV

$pp \to \gamma\gamma$ ATLAS-CONF-2018-025



Comparison of CMS vs ATLAS results

$pp \to \gamma\gamma$ Heinmeyer and Stefaniak 1812.05864



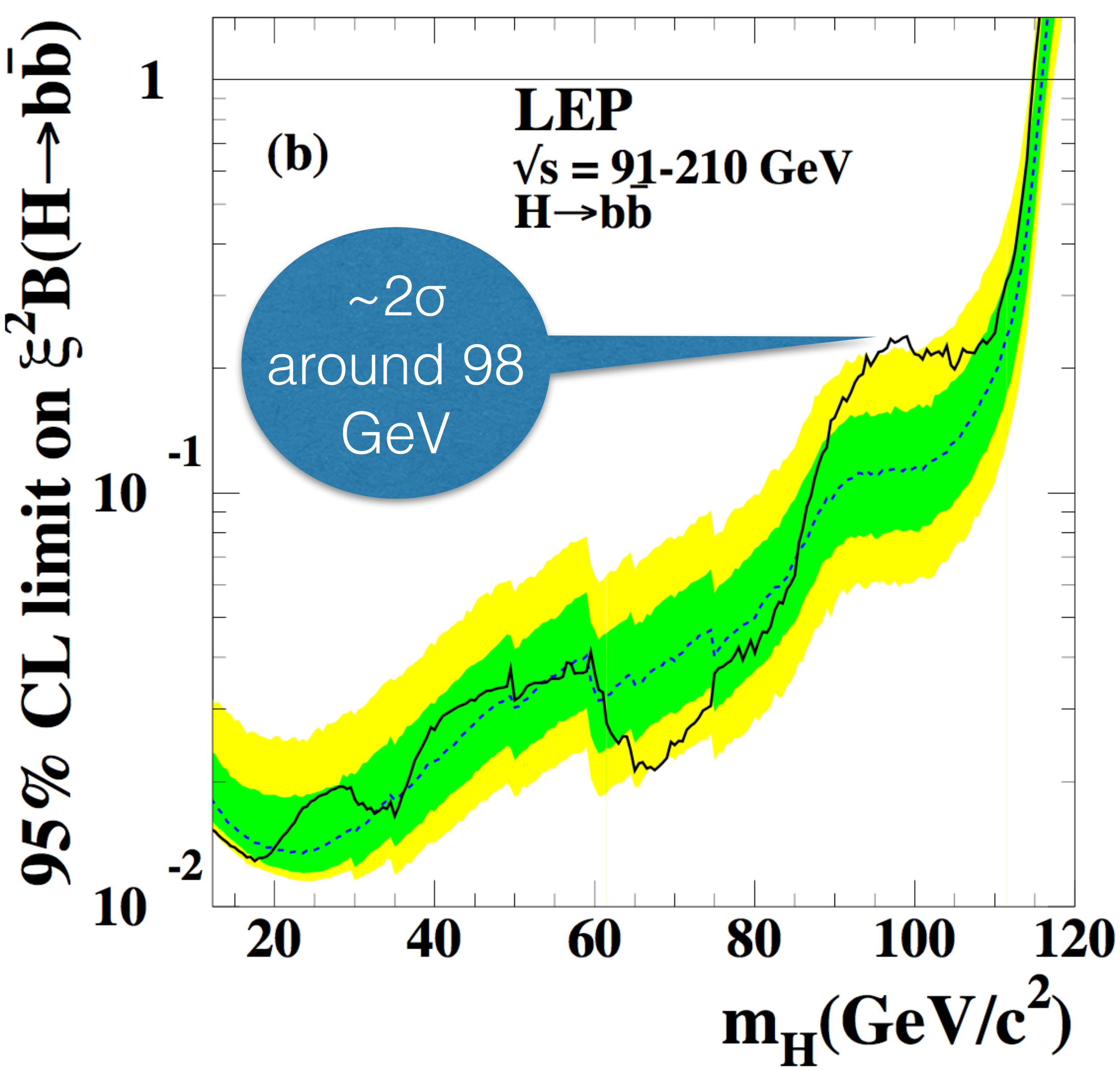
Many possible explanations ··· will not be discussed here

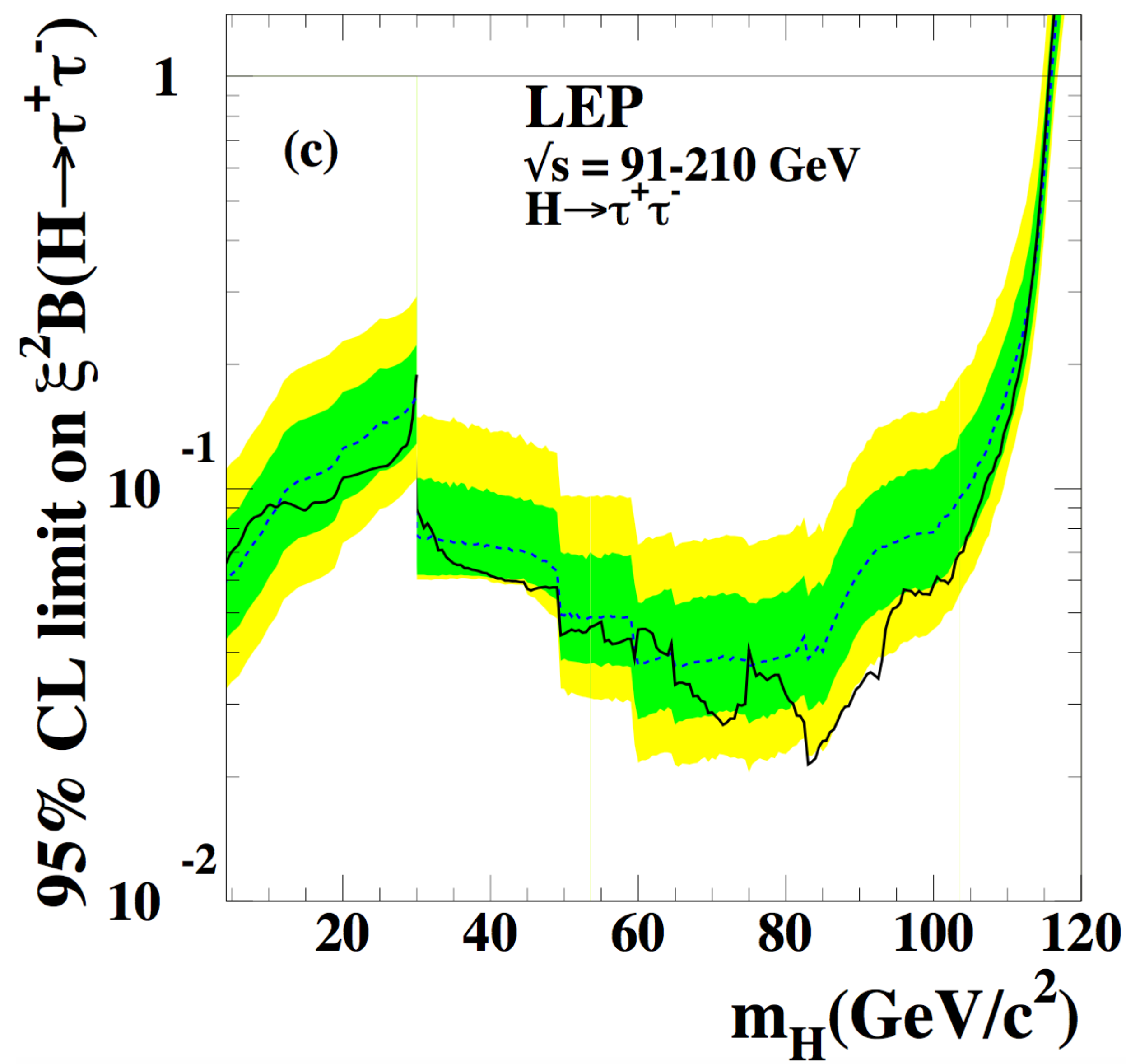
LEP anomaly around ~ 100 GeV

LEP Higgs working group hep-ex: 0306033

$$e^+e^- \to Zh$$

$$\xi^2 = (g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}^{\mathrm{SM}})^2$$





CMS di-muon resonance search

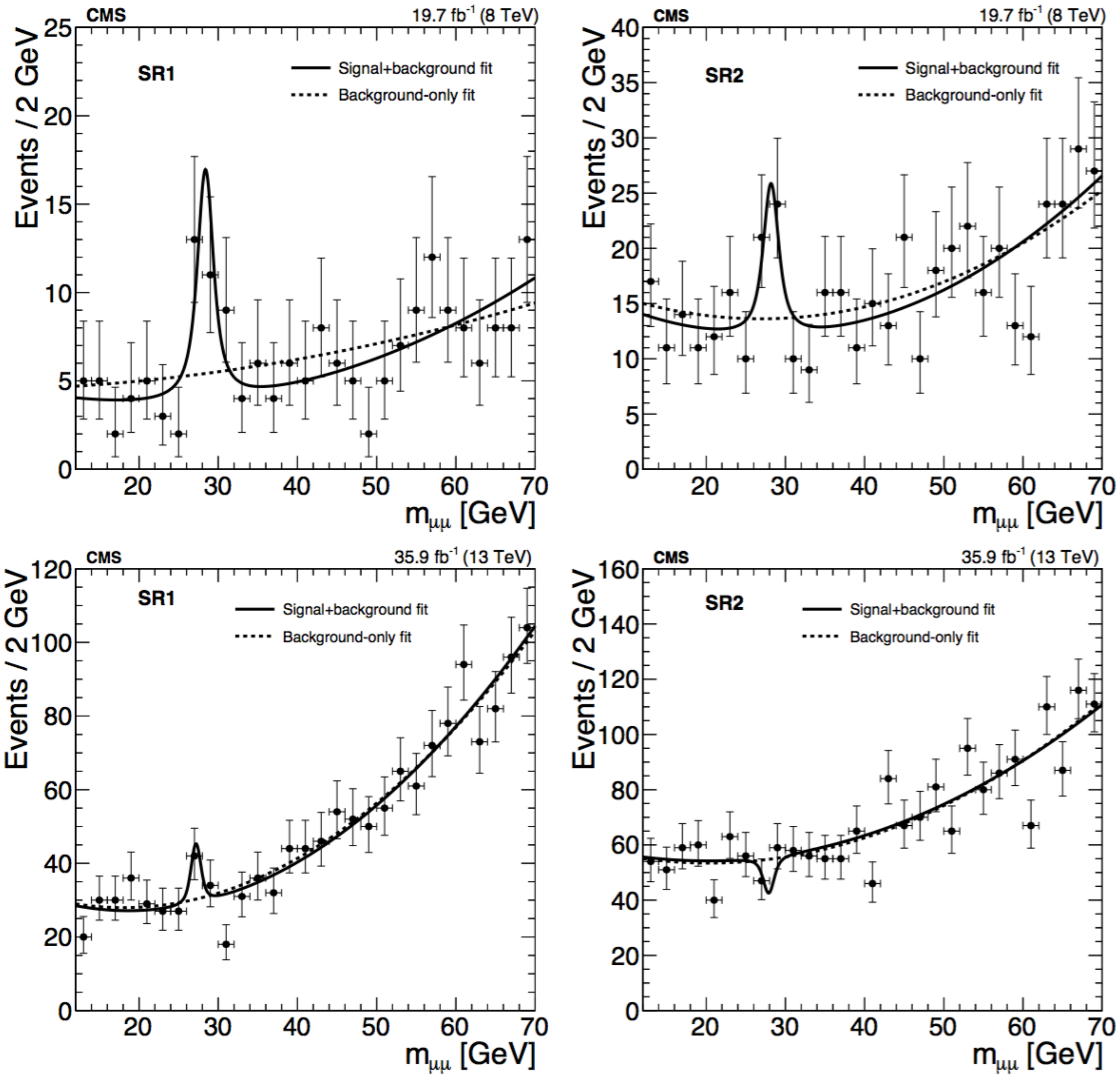
Final state : b quark jet and a second jet, and decaying to a muon pair

Mass range: 12—70 GeV

category 1: a b quark jet in the central region ($|\eta| \leq 2.4$) and at least one jet in the forward region ($|\eta| > 2.4$).

category 2: two jets in the central region, at least one of which is identified as a b quark jet, no jets in the forward region, and low missing transverse momentum.

CMS di-muon resonance search



An excess near a dimuon mass of 28 GeV in the 8 TeV data:

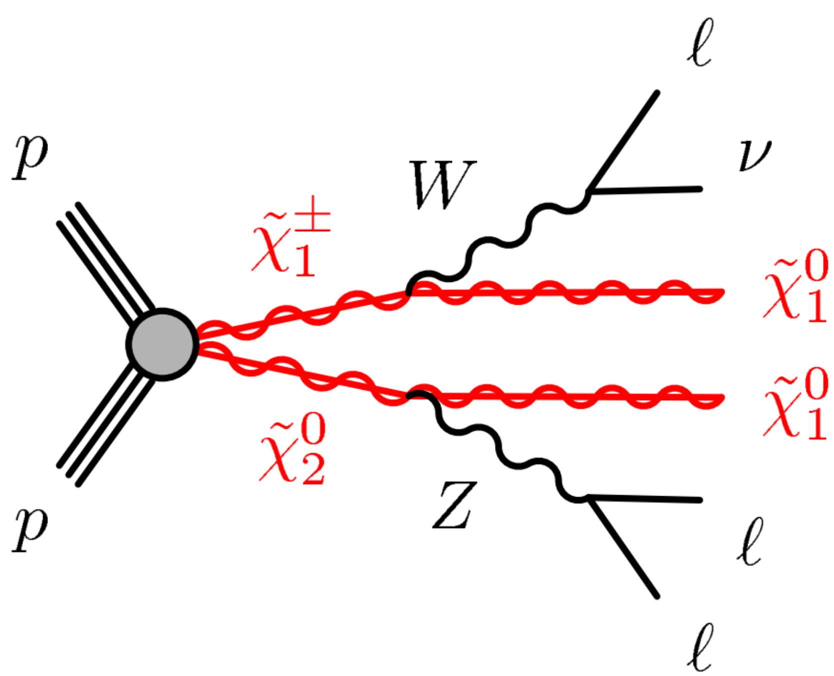
local significances of 4.2(category I) and 2.9 standard

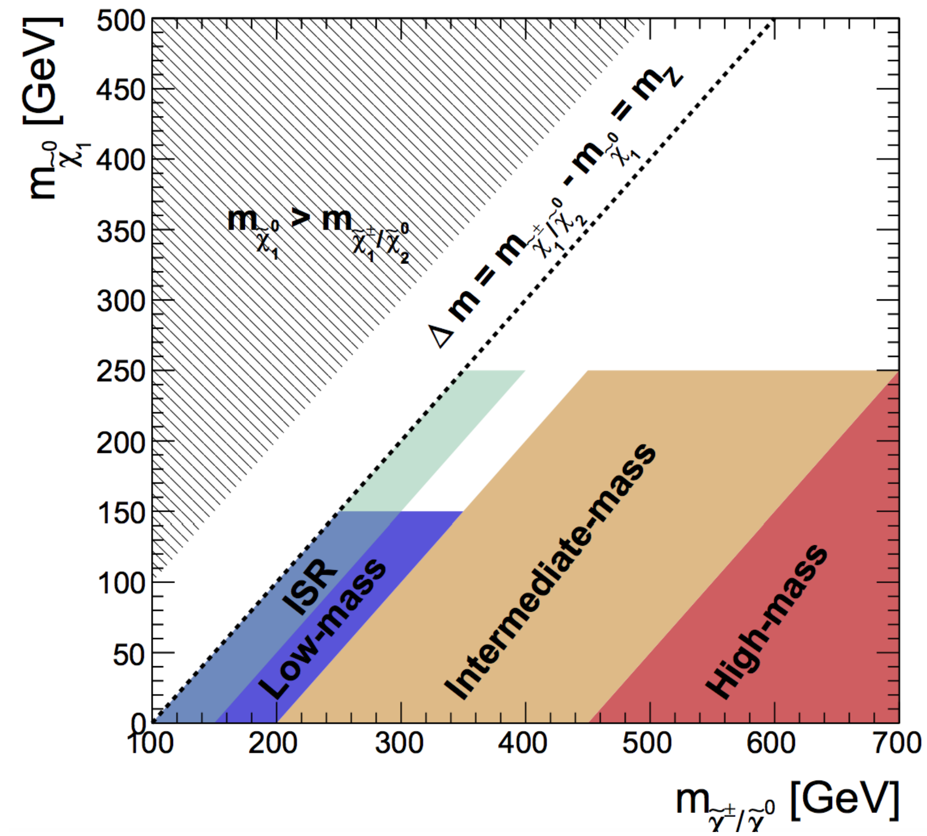
deviations for the category II

13 TeV data :

a mild excess in the category I (local significance of 2.0 standard deviations) second category results in a 1.4 standard deviation deficit.

ATLAS Electrowikino searches(1806.02293)





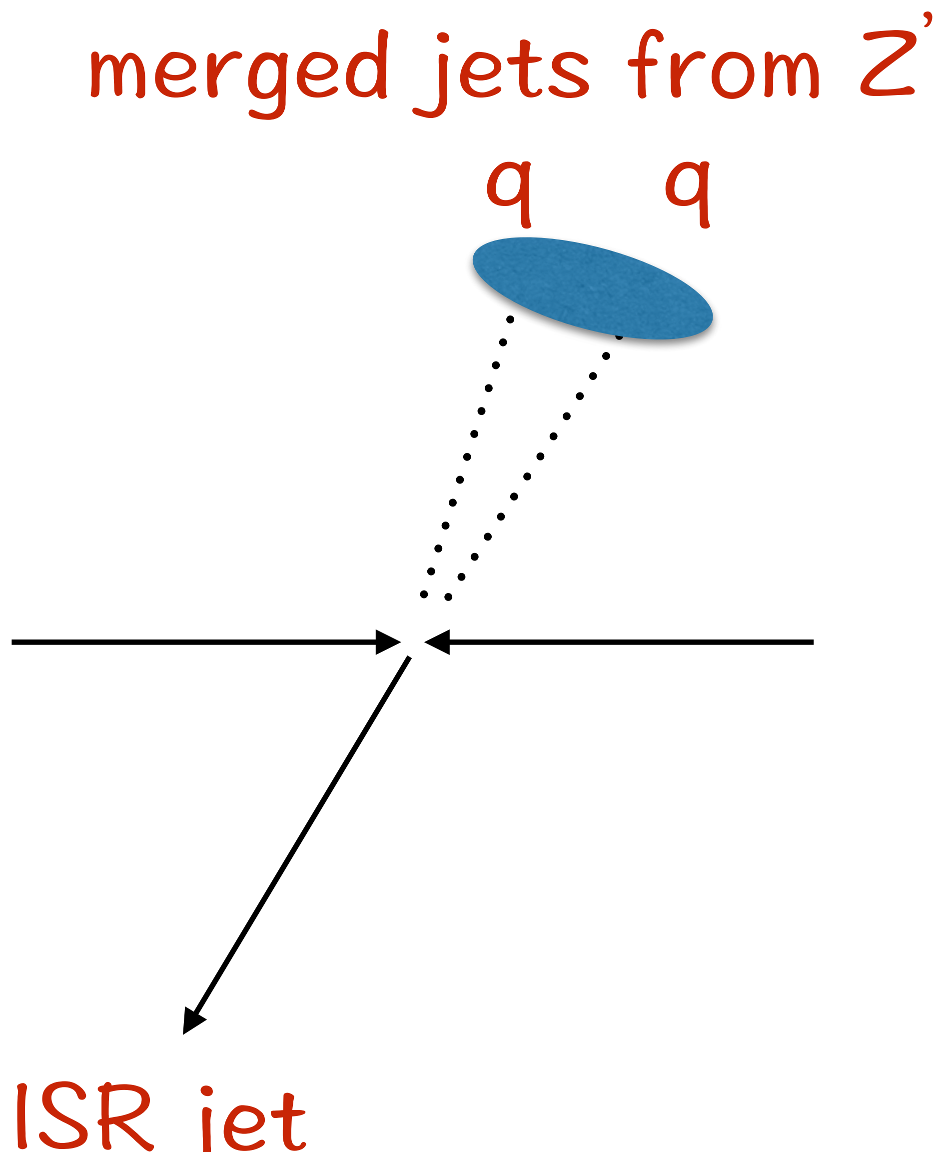
An excess of events above the background estimate is observed in each of the four low-mass and ISR signal regions

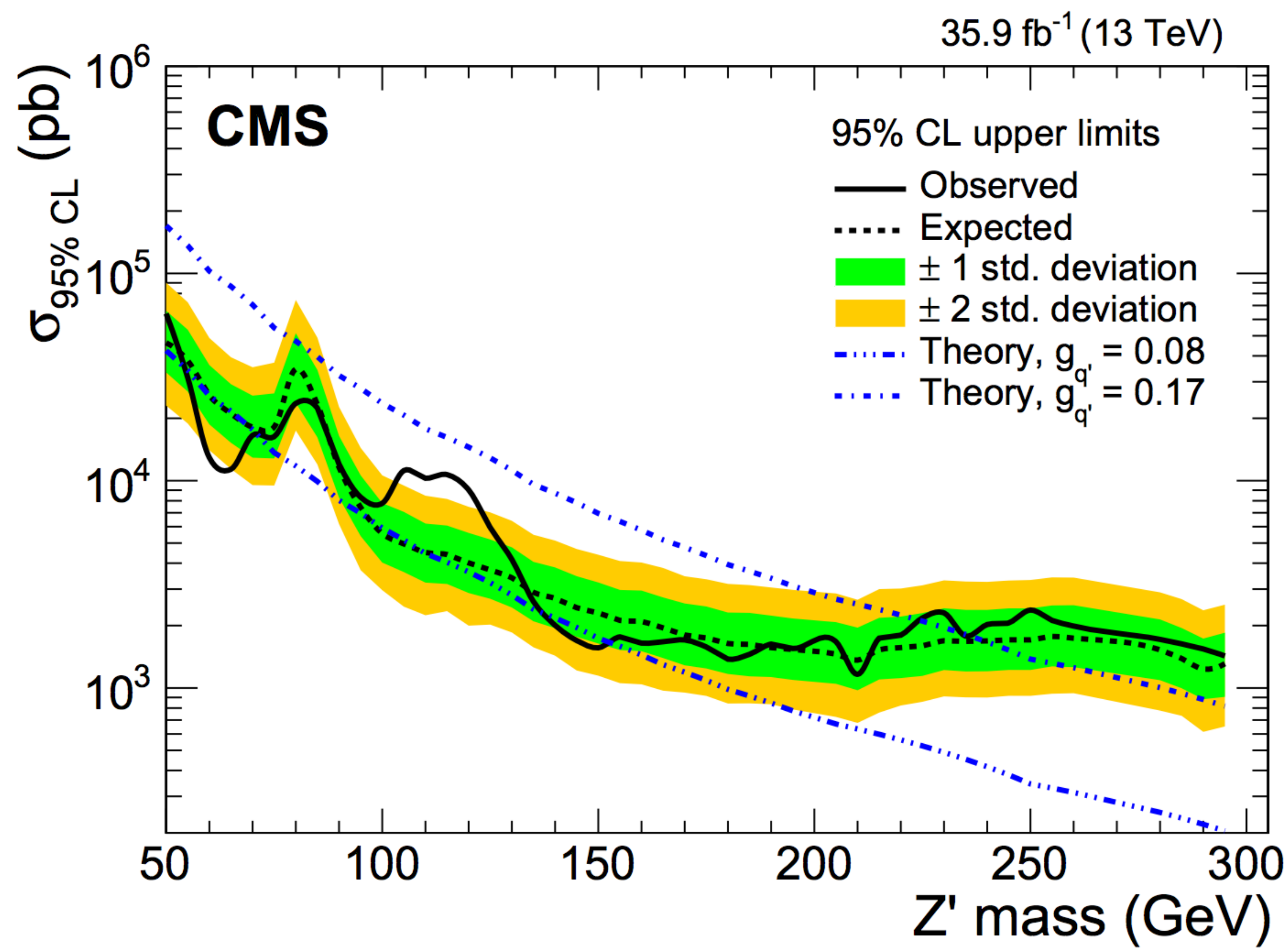
Table 16: Expected and observed yields from the background-only fit for the 3ℓ SRs. The errors shown are the statistical plus systematic uncertainties. Uncertainties in the predicted background event yields are quoted as symmetric, except where the negative error reaches down to zero predicted events, in which case the negative error is truncated.

Signal region	SR3ℓ_High	SR3ℓ_Int	SR3ℓ_Low	SR3ℓ_ISR
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0
Other	$0.03^{+0.07}_{-0.03}$	0.04 ± 0.02	$0.02^{+0.34}_{-0.02}$	$0.06^{+0.19}_{-0.06}$
Triboson	0.19 ± 0.07	0.32 ± 0.06	0.25 ± 0.03	0.08 ± 0.04
Fit output, *VV*	0.83 ± 0.39	1.9 ± 0.5	10 ± 2	3.8 ± 1.0
Fit input, *VV*	0.76	1.8	9.2	3.4

CMS light Z' search(1710.00159)

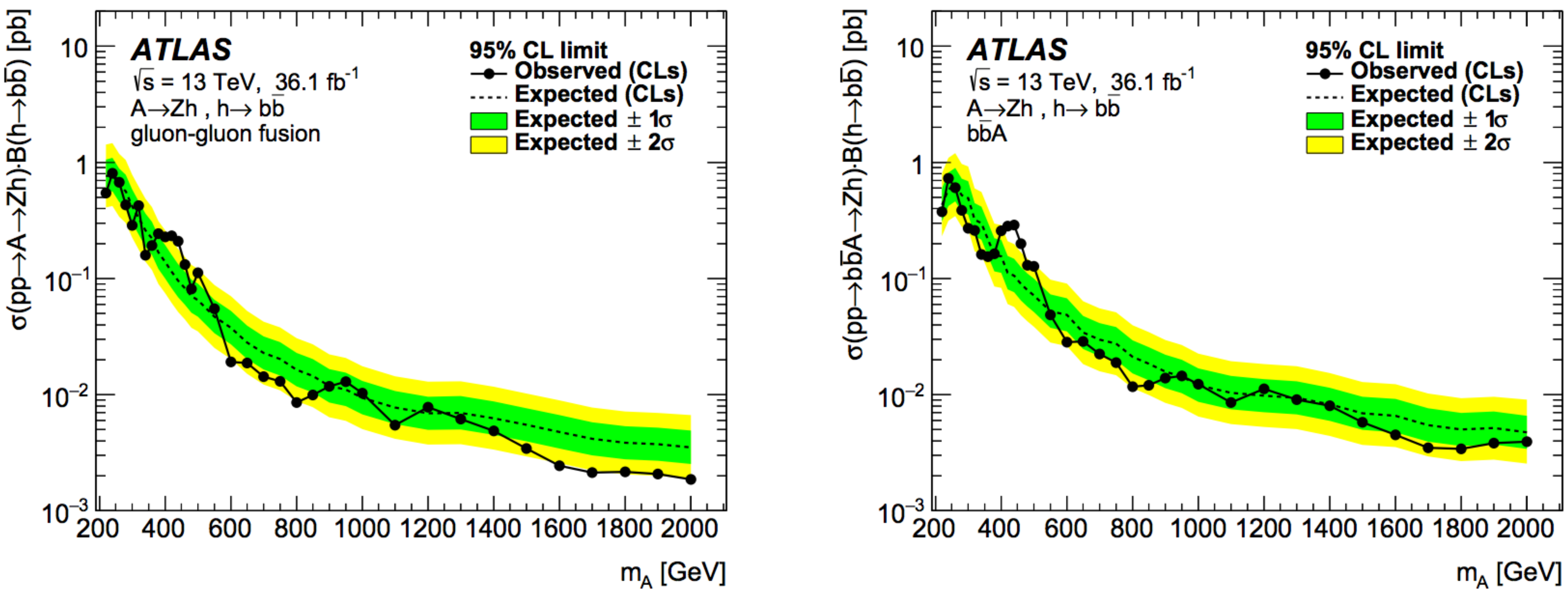
$$pp \to Z^{'} + \text{ISR Jet}, \quad (Z^{'} \to q\bar{q})$$





ATLAS Heavy Higgs search(1712.06518)

$$pp \to W/Z + h, \quad (h \to b\bar{b}), \quad (W/Z \to leptons)$$



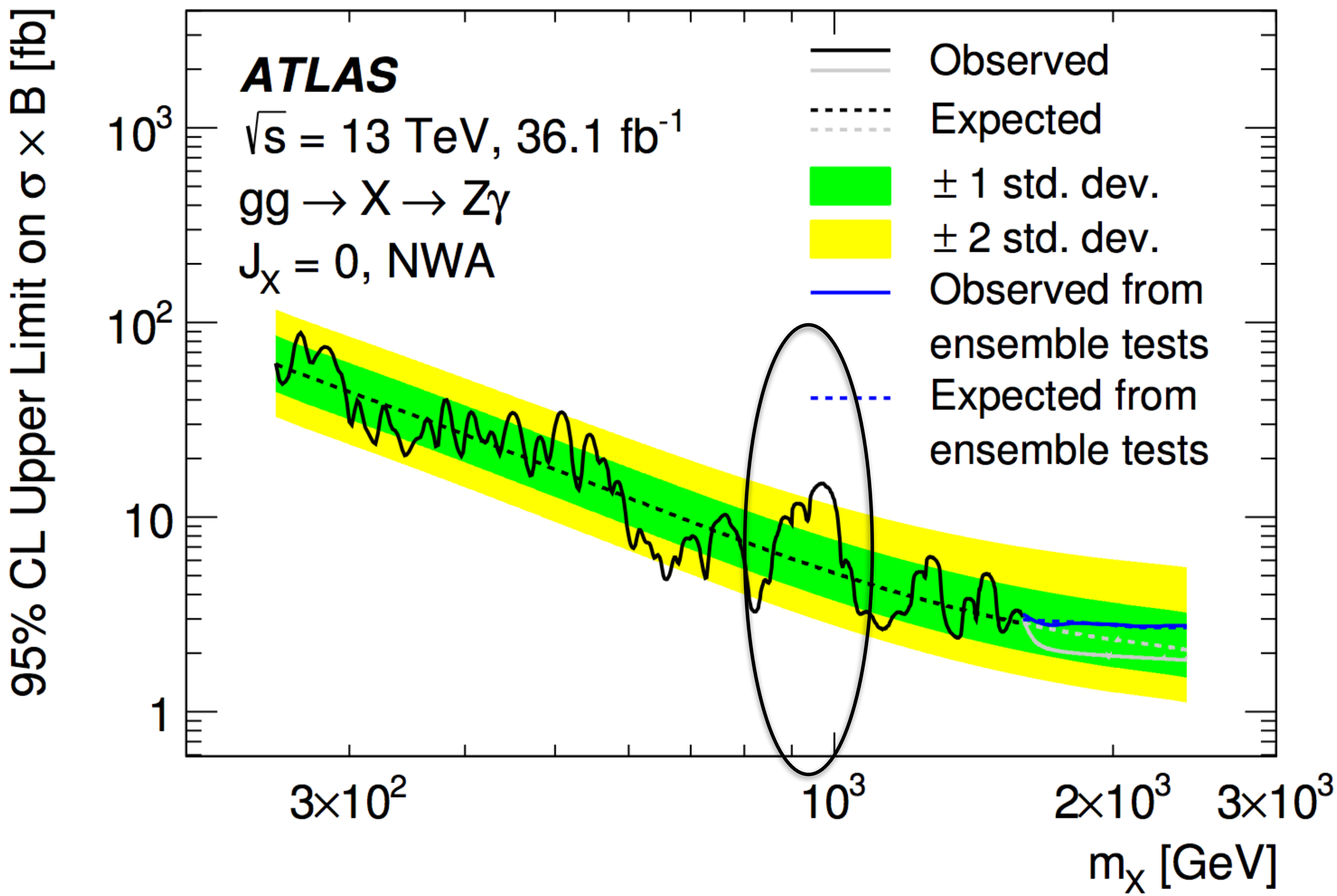
(a) Pure gluon–gluon fusion production

(b) Pure b-quark associated production

Figure 6: Upper limits at the 95% CL on the product of the production cross-section for $pp \to A$ and the branching fractions for $A \to Zh$ and $h \to b\bar{b}$ evaluated by combining the 0-lepton and 2-lepton channels. The possible signal components of the data are interpreted assuming (a) pure gluon–gluon fusion production, and (b) pure b-quark associated production.

ATLAS Z gamma search (1708.00212)

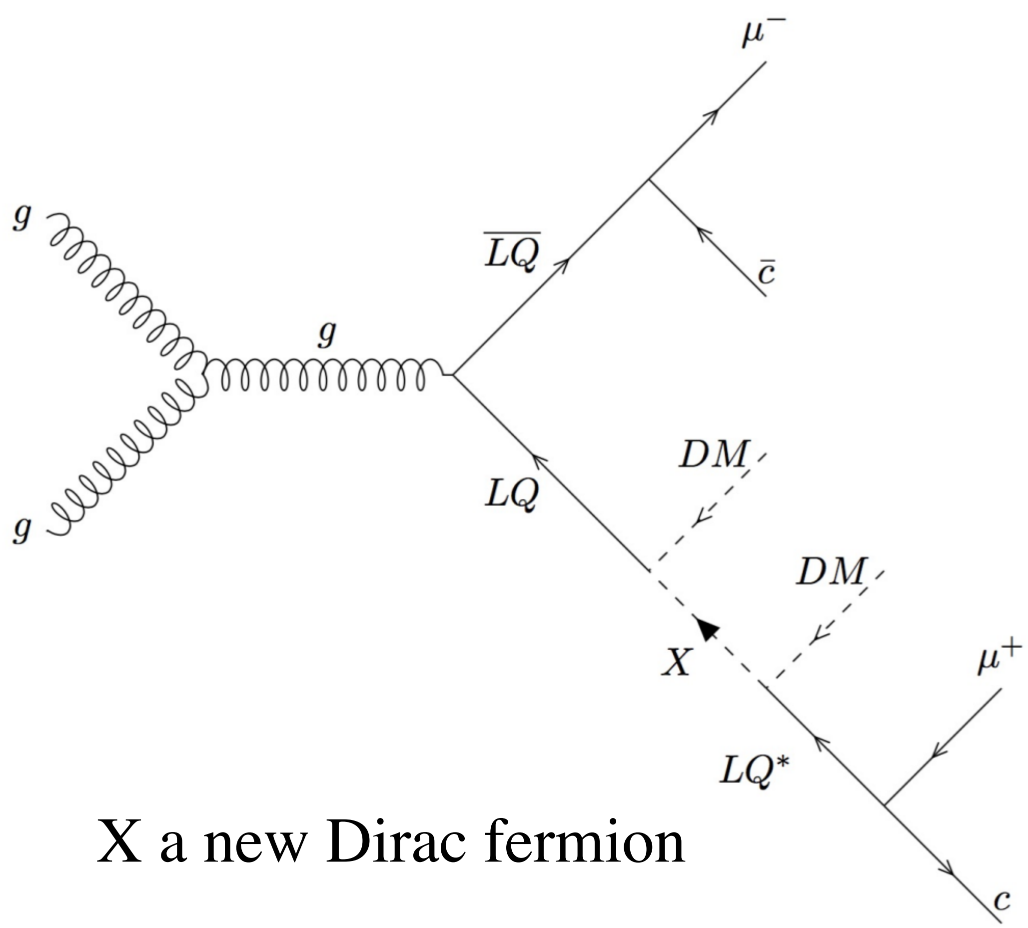
$$pp \to X \to Z\gamma, (Z \to ll)$$



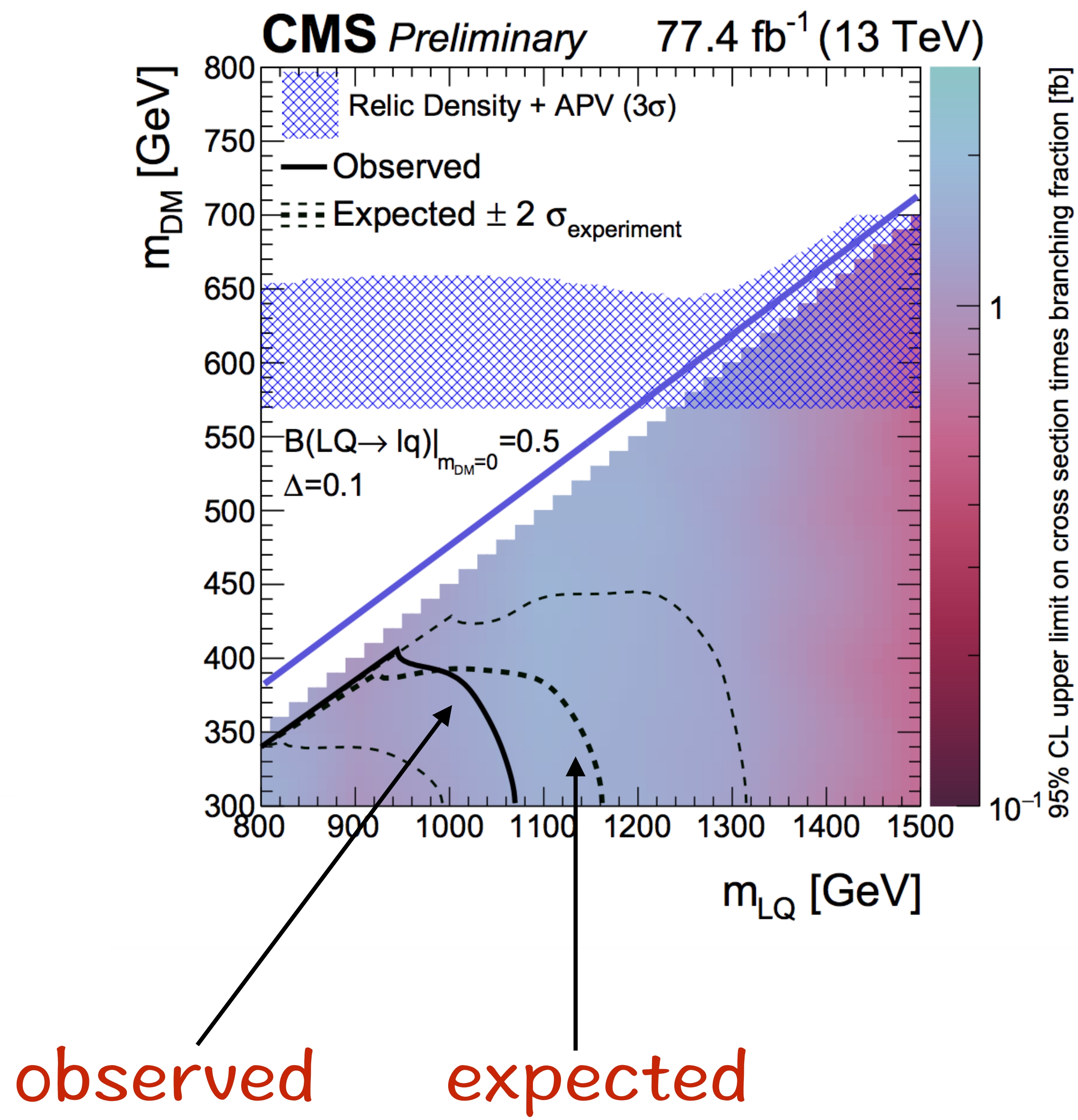
CMS leptoquark search(CMS-EXO-17-015-pas)

One leptoquark decays to a muon and a jet while the other decays to dark matter

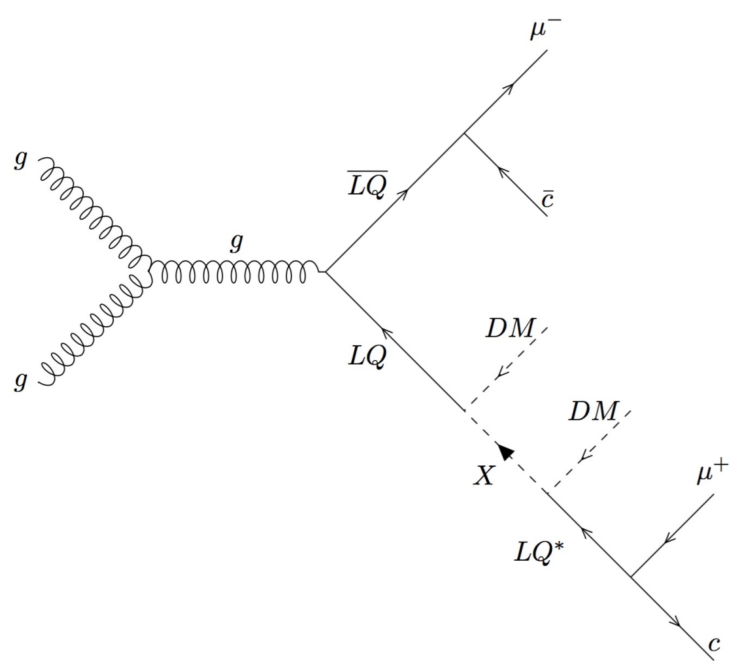
and soft standard model particles

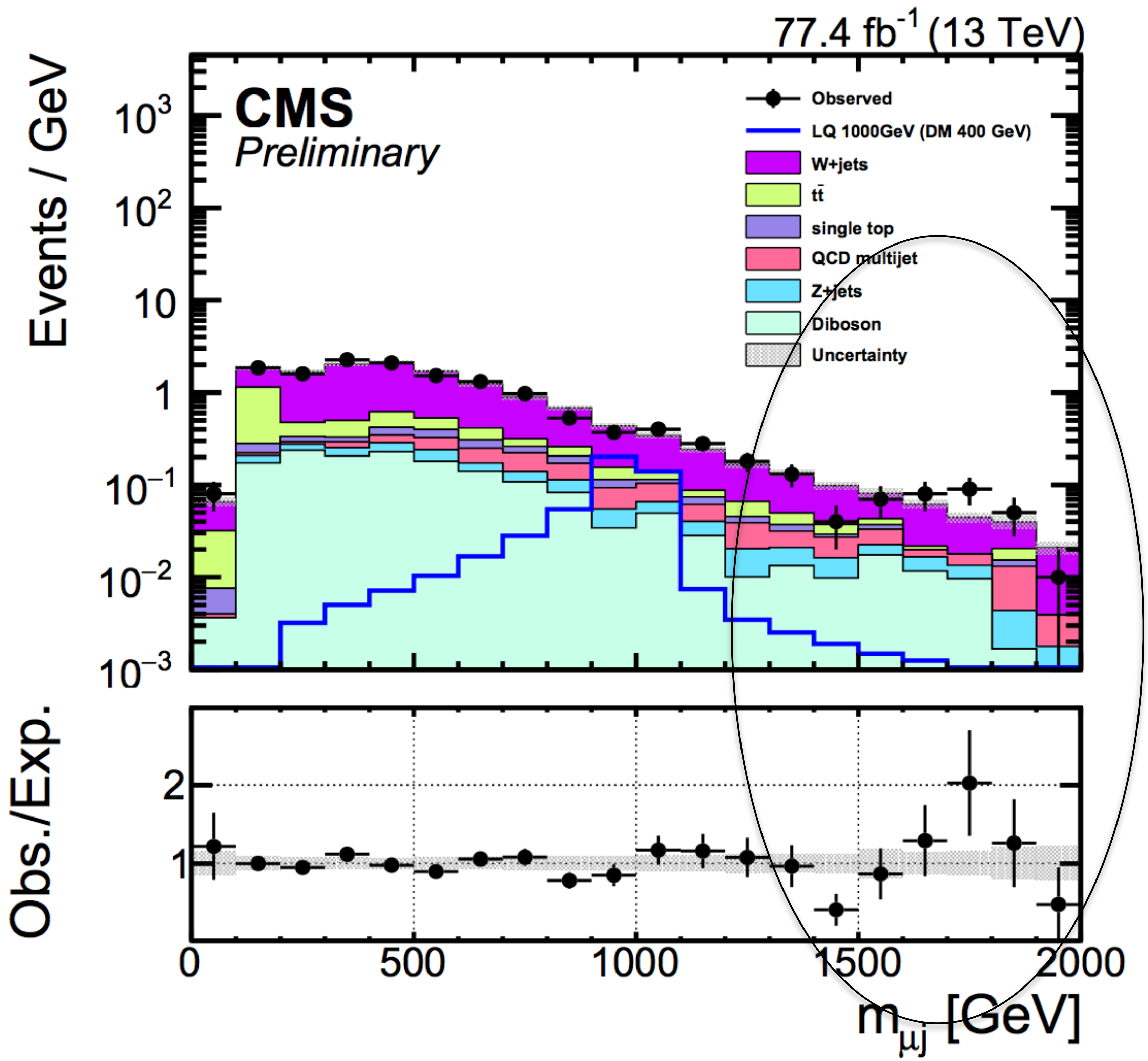


X a new Dirac fermion

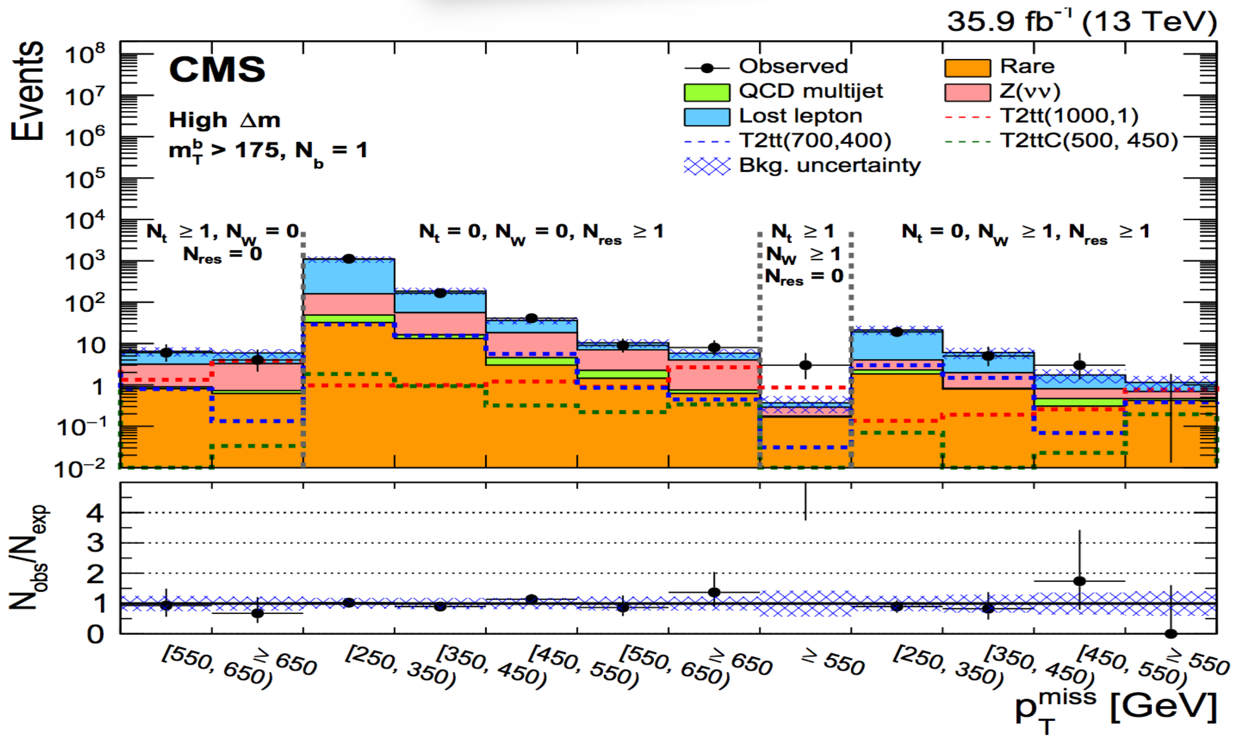


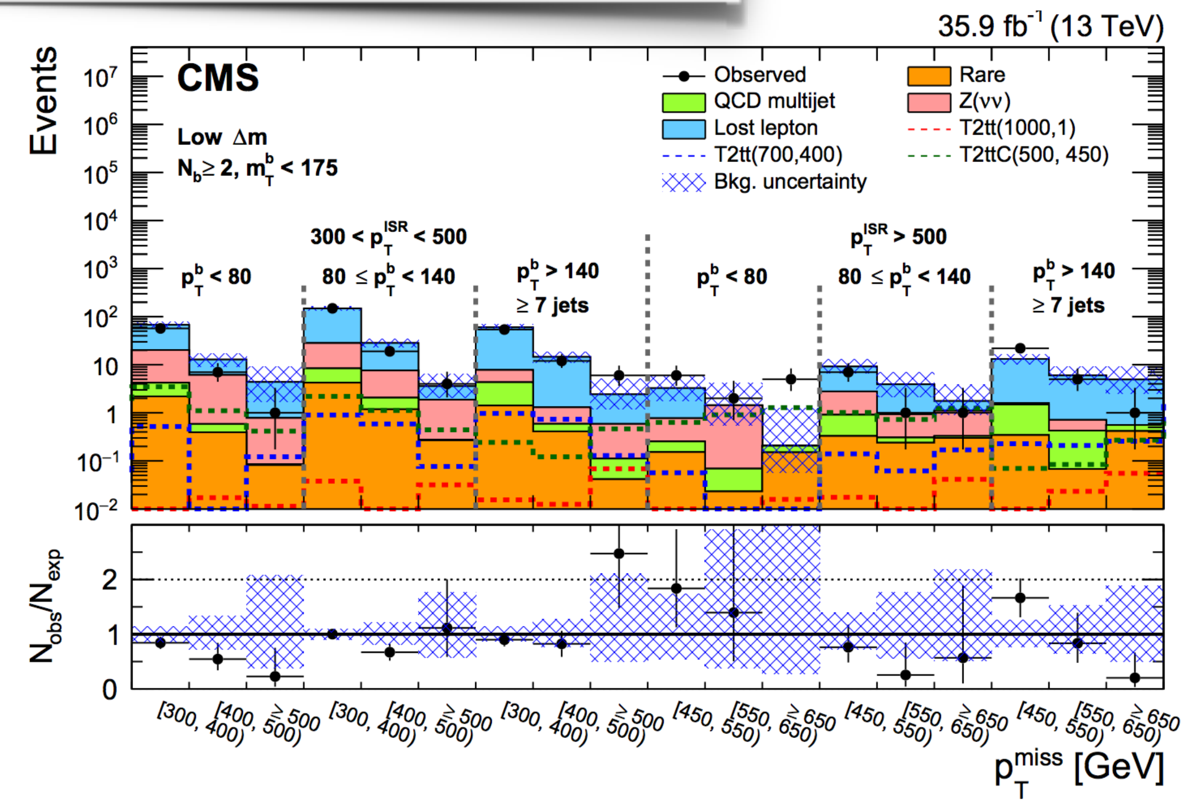
leptoquark +DM search by CMS(CMS-EXO-17-015-pas)





CMS Stop searches (1707.03316)





p_T^{miss} [GeV]	Lost lepton	$Z(\nu\nu)$	Rare	QCD multijet	Total SM	N_{data}
$N_b = 1, m_T^b \geq 175\,GeV, N_t \geq 1, N_{res} = 0, N_W \geq 1$						
≥ 550	0.08 ± 0.07	0.11 ± 0.08	0.17 ± 0.07	0.01 ± 0.01	0.37 ± 0.16	3
$N_b \geq 2, m_T^b < 175\,GeV, p_T^{ISR} \geq 500\,GeV, p_T^b < 80\,GeV$						
450-550	$2.5^{+2.2}_{-1.4}$	$0.52^{+0.46}_{-0.31}$	0.15 ± 0.08	$0.1^{+0.13}_{-0.09}$	$3.3^{+2.4}_{-1.5}$	6
550-650	<1.59	$1.4^{+1.5}_{-0.9}$	0.02 ± 0.06	$0.05^{+0.07}_{-0.04}$	$1.4^{+2.7}_{-0.9}$	2
≥ 650	<0.75	<0.33	0.15 ± 0.14	$0.06^{+0.09}_{-0.06}$	$0.2^{+1.0}_{-0.2}$	5

8 Results and interpretation

The event counts observed in data and those predicted for SM backgrounds are summarized graphically in Figs. 5-8, and numerically in Tables 5 and 6. The observed event counts are in general agreement with the predictions. The two search regions with most significant discrepancies are the low Δm SR defined by the selection $N_b \geq 2$, $m_T^b < 175\,GeV$, $p_T^{ISR} \geq 500\,GeV$, $p_T^b < 80\,GeV$, $p_T^{miss} \geq 650\,GeV$, and the high Δm SR defined by $N_b = 1$, $m_T^b \geq 175\,GeV$, $N_t \geq 1$, $N_{res} = 0$, $N_W \geq 1$, $p_T^{miss} \geq 550\,GeV$. For these two SR, observed excesses over the predicted event counts correspond to local significances of 2.3 and 1.9 standard deviations, respectively. These can be attributed to statistical fluctuations of the SM backgrounds alone, given the number of search regions employed in this analysis.

Summary

Generic SUSY: hard jets+ leptons + high MET + high Effective mass (Not always true)

Many possible unusual signals: displaced vertex,disappearing charged tracks, very high multiplicity events (hidden valley, RPV), multi-particle resonance, collider stable sparticles, fat jets, ...

New techniques can improve the sensitivity of the LHC analysis

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

The limits on Heavy Higgs bosons can be weakened in the presence of additional SUSY decay modes. Further analysis required in this direction.

Dark matter direct detection and indirect detection experiments can be complimentary to LHC experiment

Several 2-3 sigma fluctuations exist -> New run II results might reveal something interesting

Thank you

Additional slides

Future limits

results form1407.5066

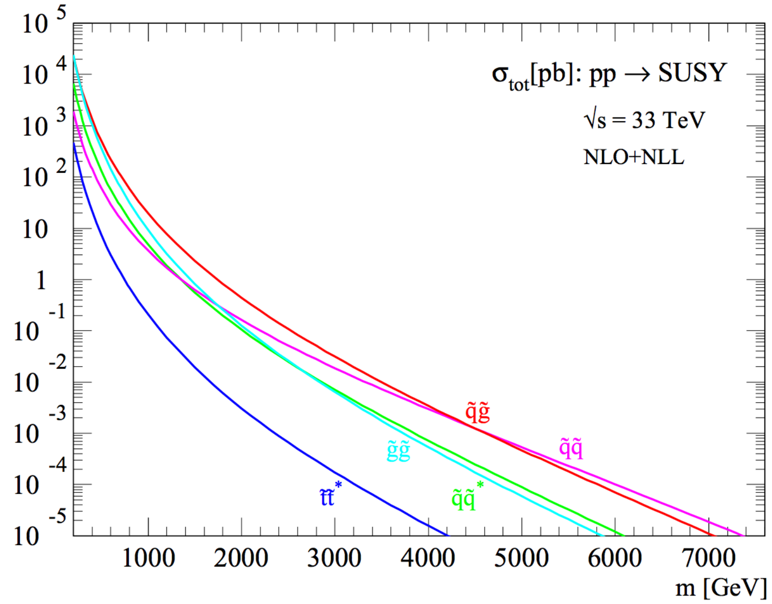
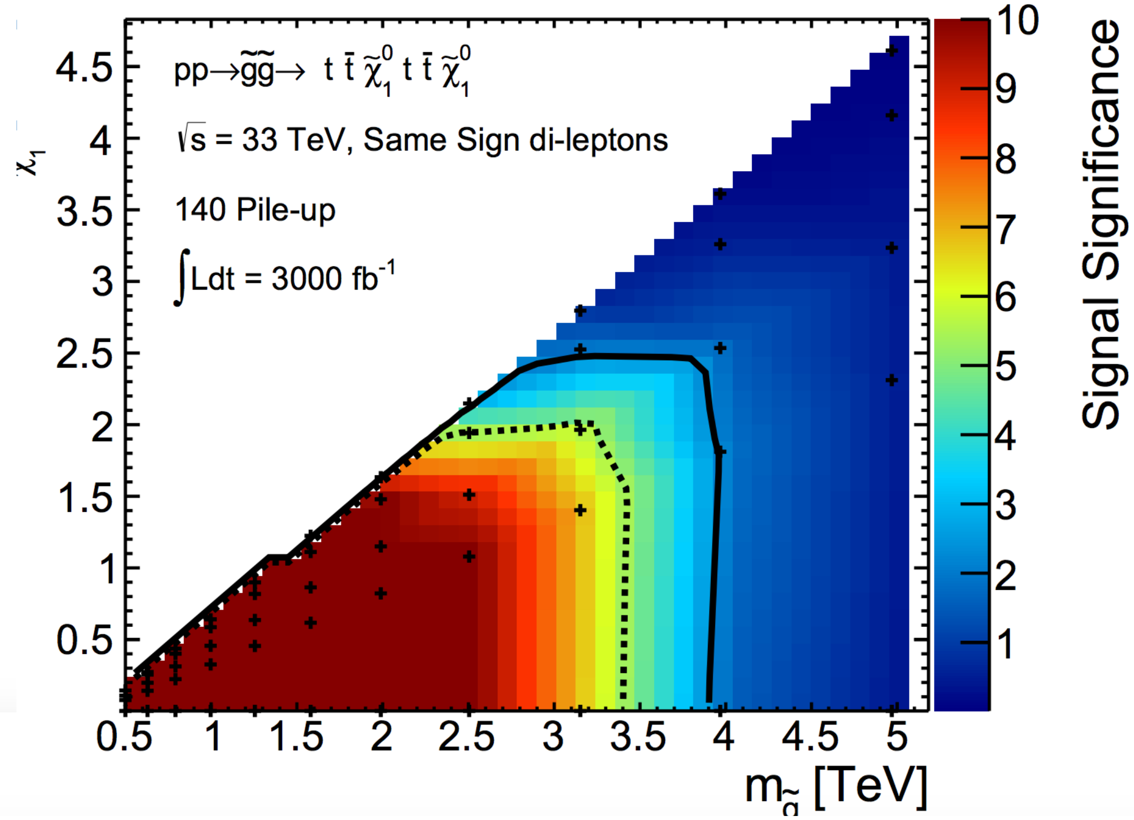


Figure 3: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 33$ TeV.



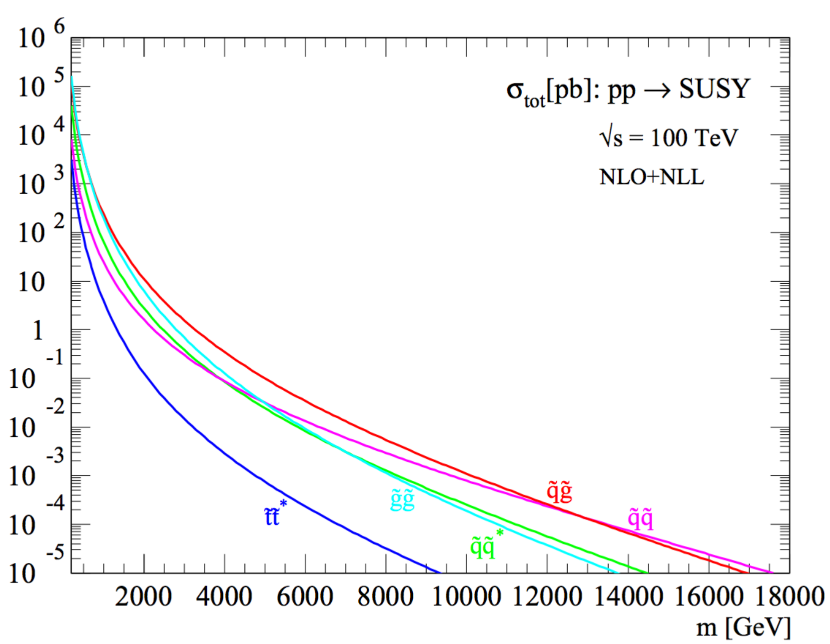
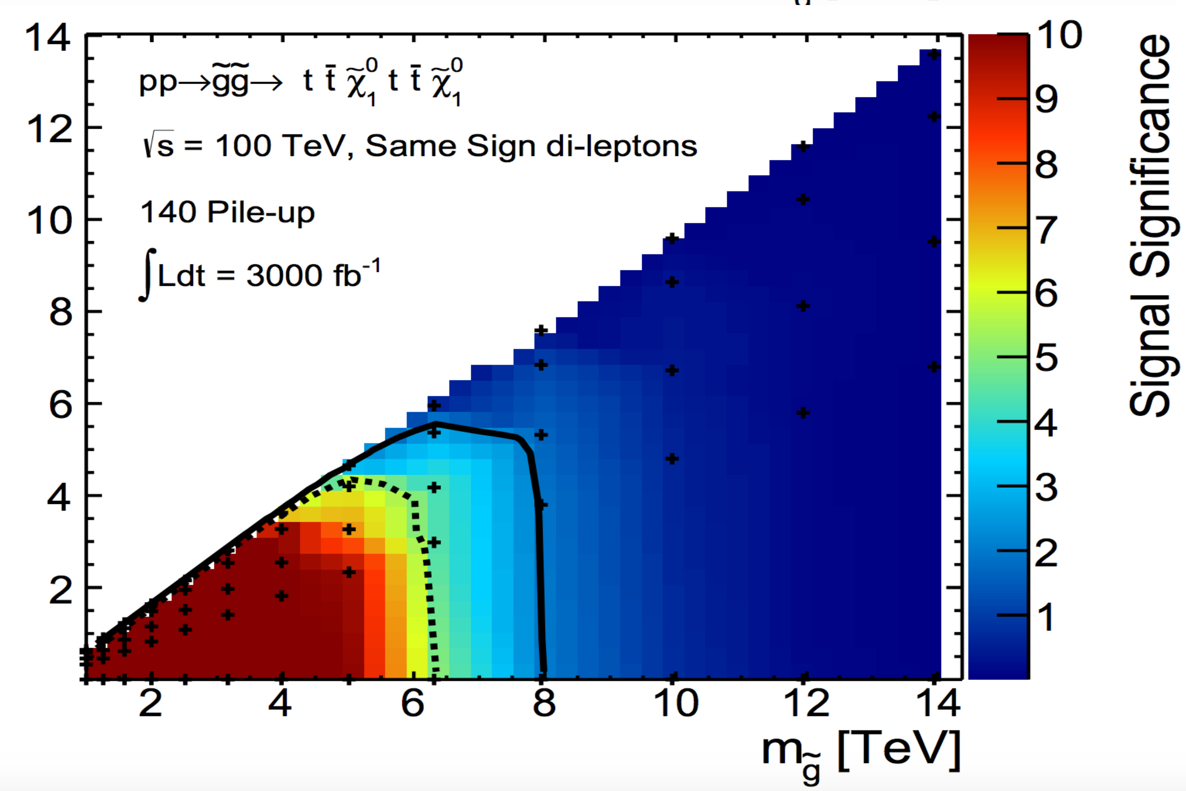


Figure 4: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 100$ TeV.



limits from 1311.480

see also 1506.02644,1704.03014 , 1606.00947 for other possibilities

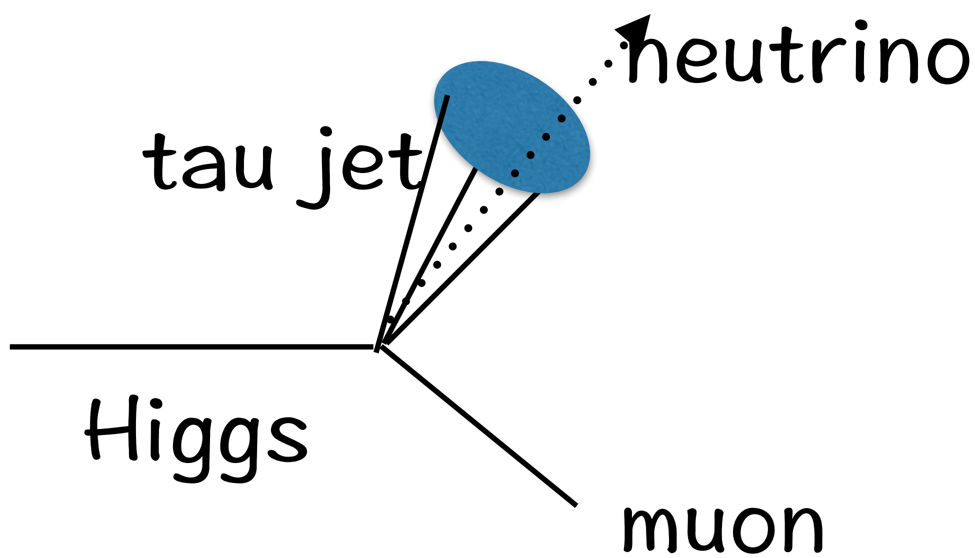
LFV Higgs decay

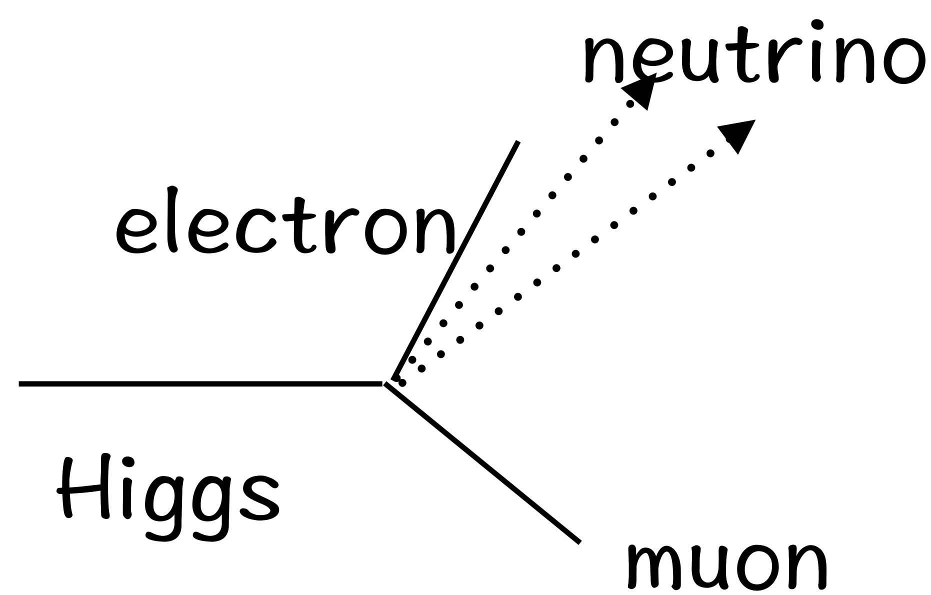
In SM, lepton flavour violating decays are extremely suppressed

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

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

<u>95 % Upper limit on branching (Higgs to Mu tau) = 1.57 %</u>

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

<u>95 % Upper limit on branching (Higgs to Mu tau) = 1.85 % (1508.03372)</u>

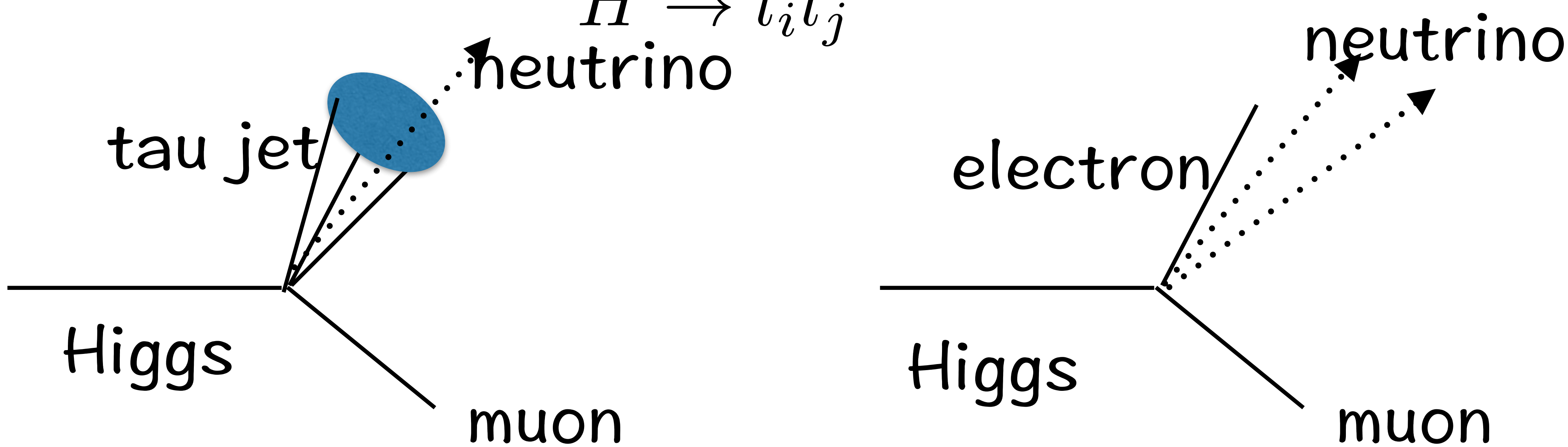
LFV Higgs decay

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!

$$H \rightarrow l_i l_j$$



H-> muon + tau jet

H-> muon + electron

CMS : A slight excess of signal events with a significance of 2.5 sigma is observed (In th

95 % … u) = 1.57 %

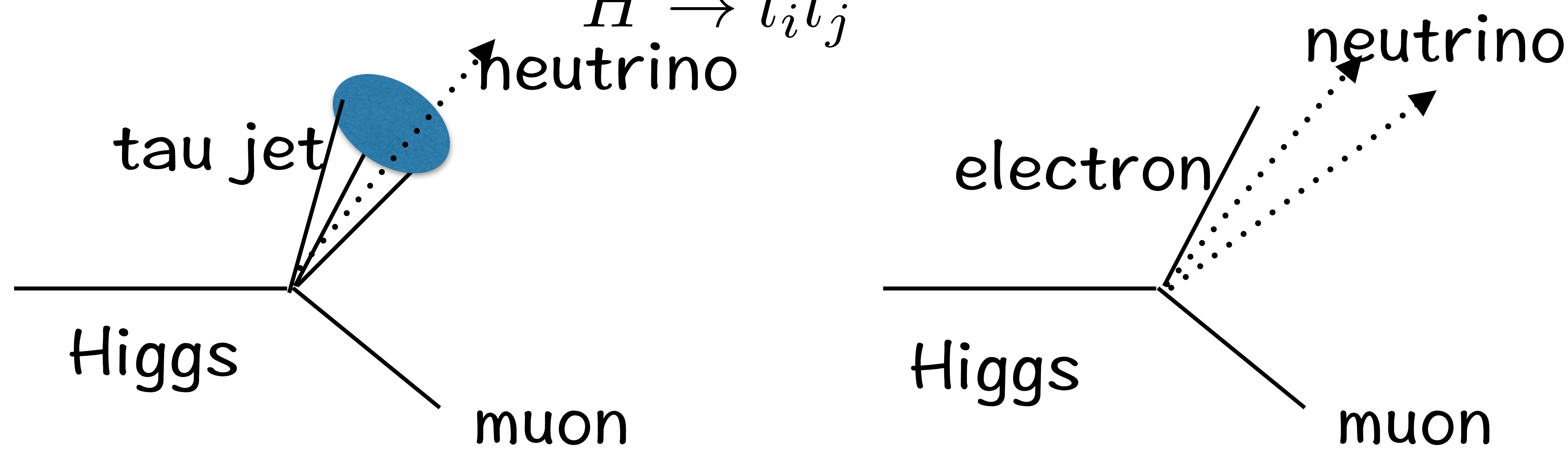
The Excess disappeared at 13 TeV

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)

LFV Higgs decay

$$H \to l_i l_j$$



H-> muon + tau jet

H-> muon + electron

$$95\%\ exclusion\ limit\ on\ Br(H \to \tau\mu/e) \sim 0.03\%$$

$$(14\ TeV\ LHC,\ \mathcal{L}\ =\ 3000\ fb^{-1})$$

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)
- $\not{E}_T < 20$ 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