CMSSM

In the light of 13 TeV LHC and LUX WS2014-16

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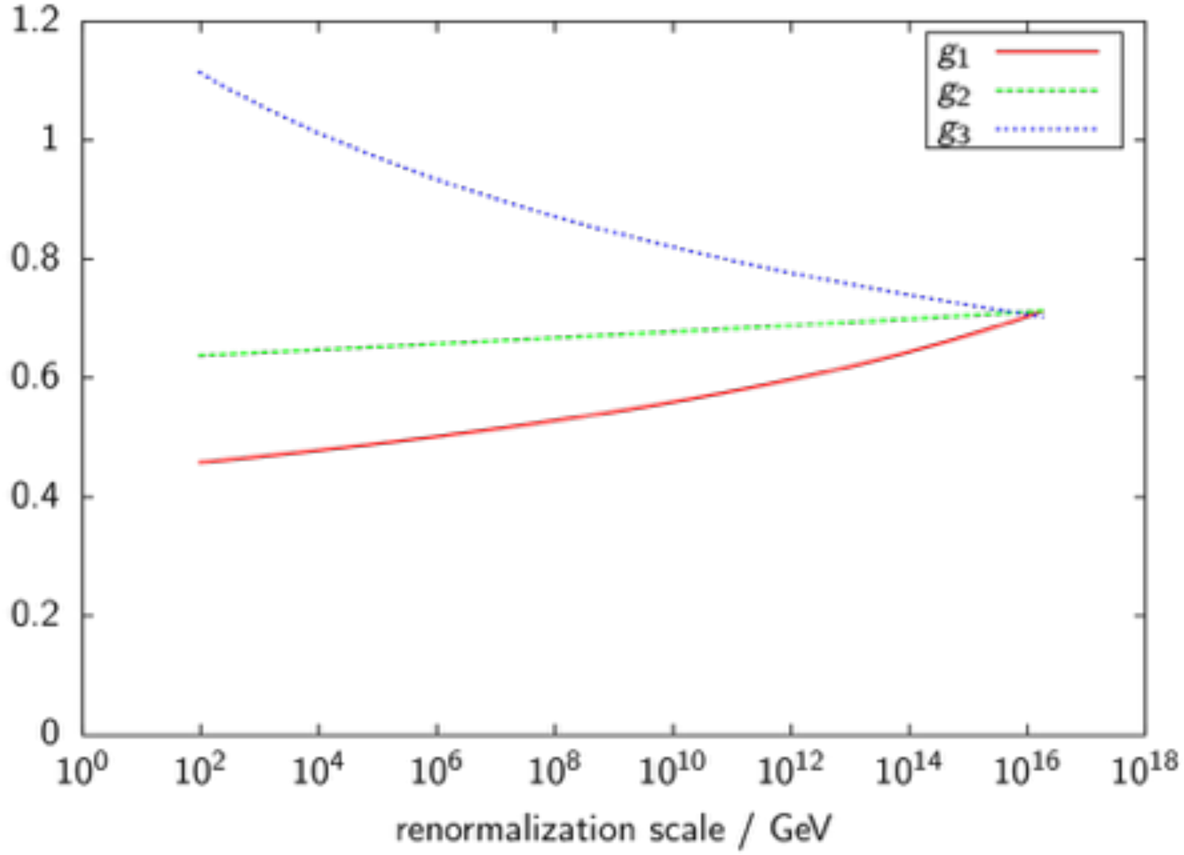
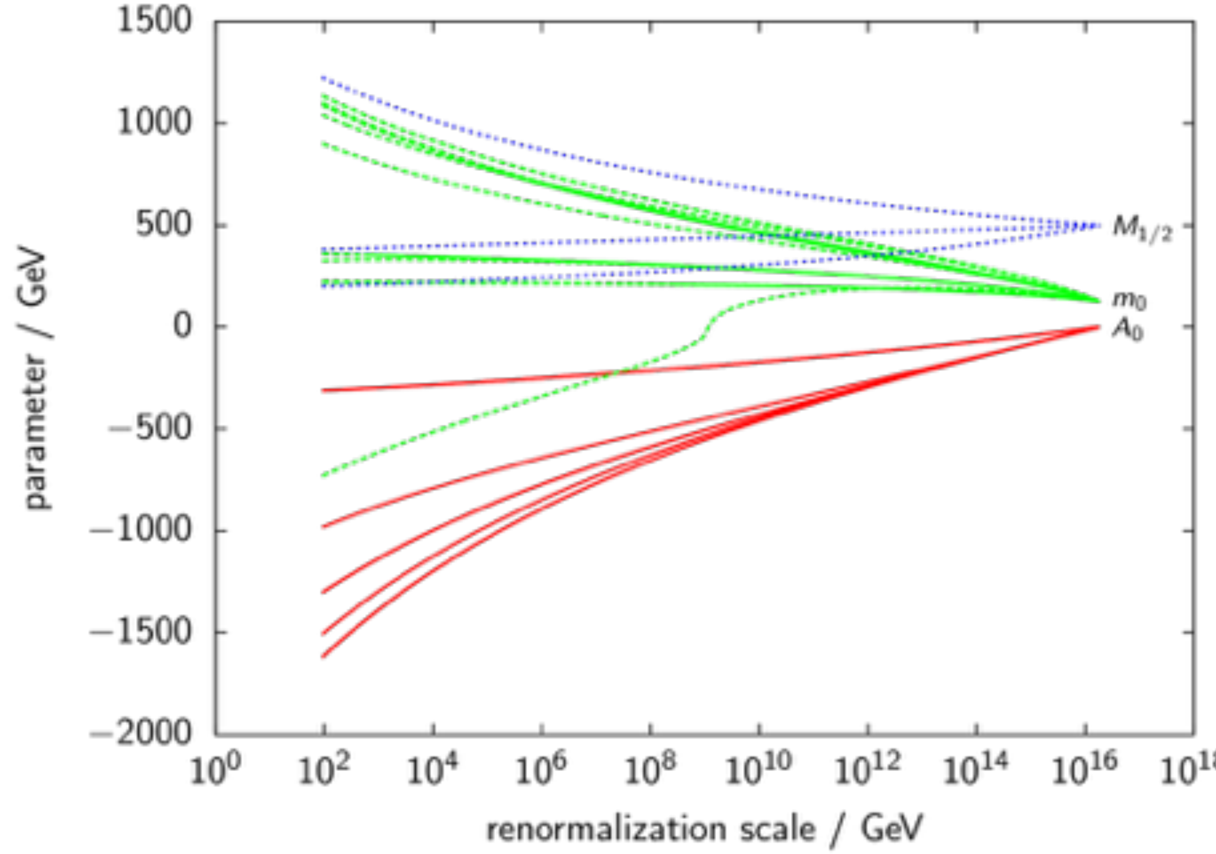
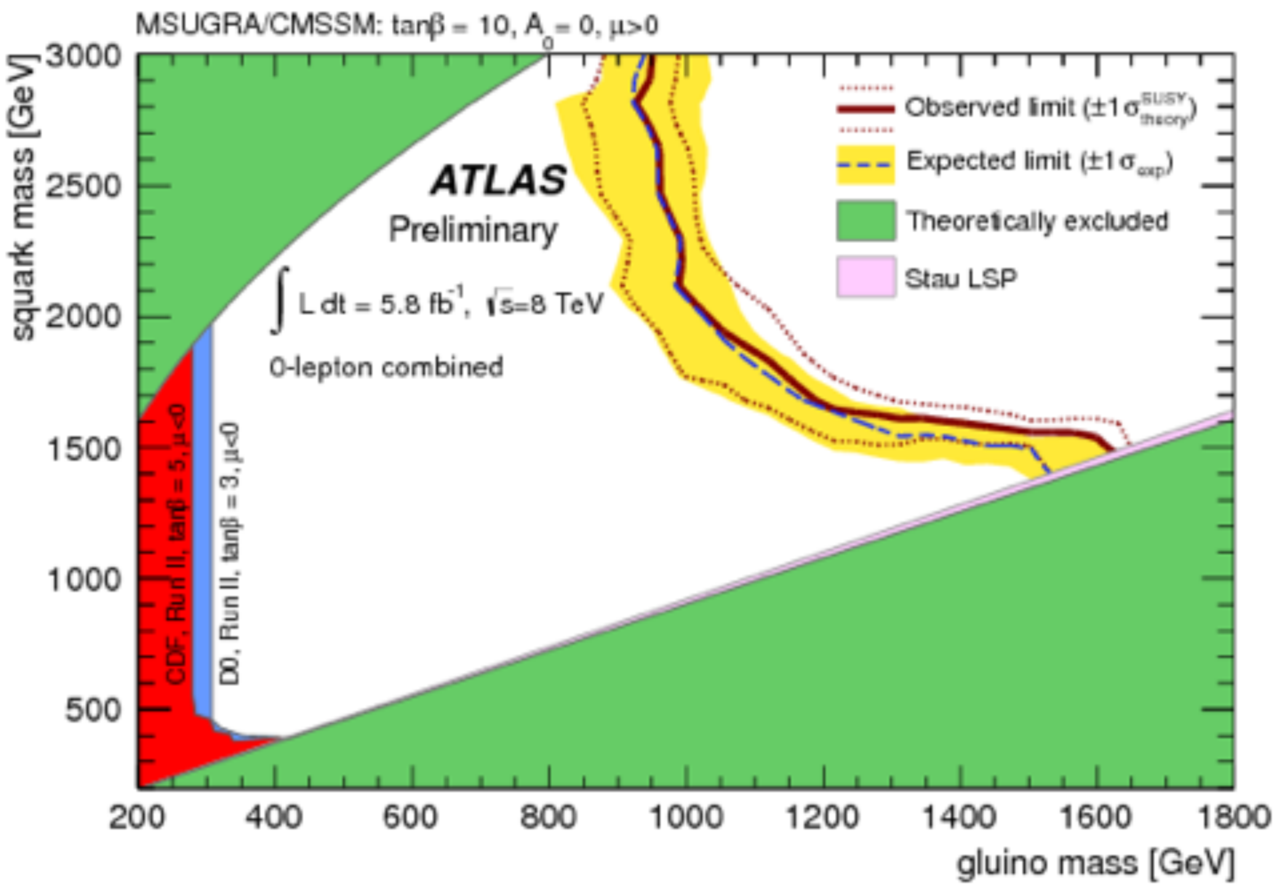
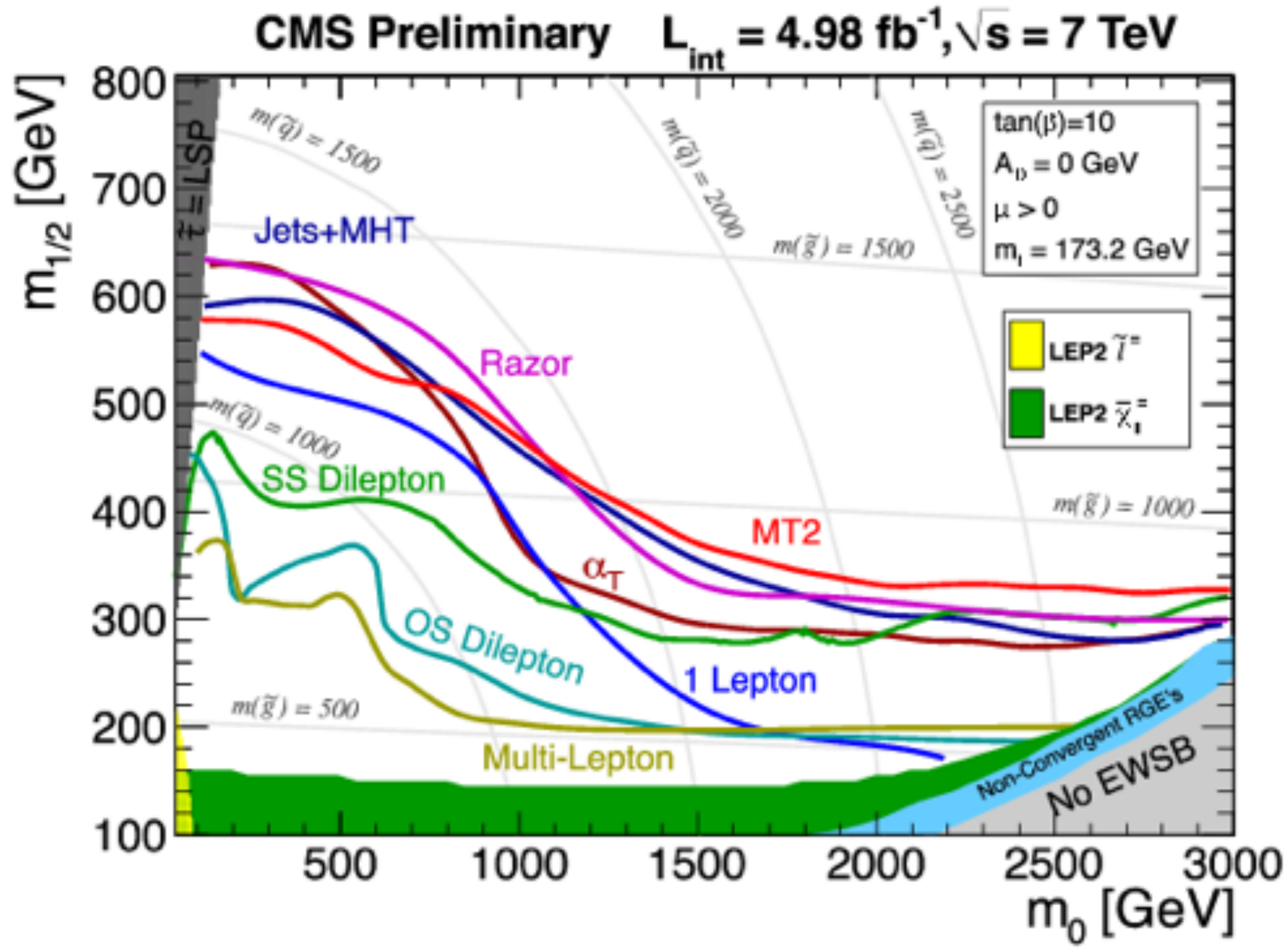
INTRODUCTION

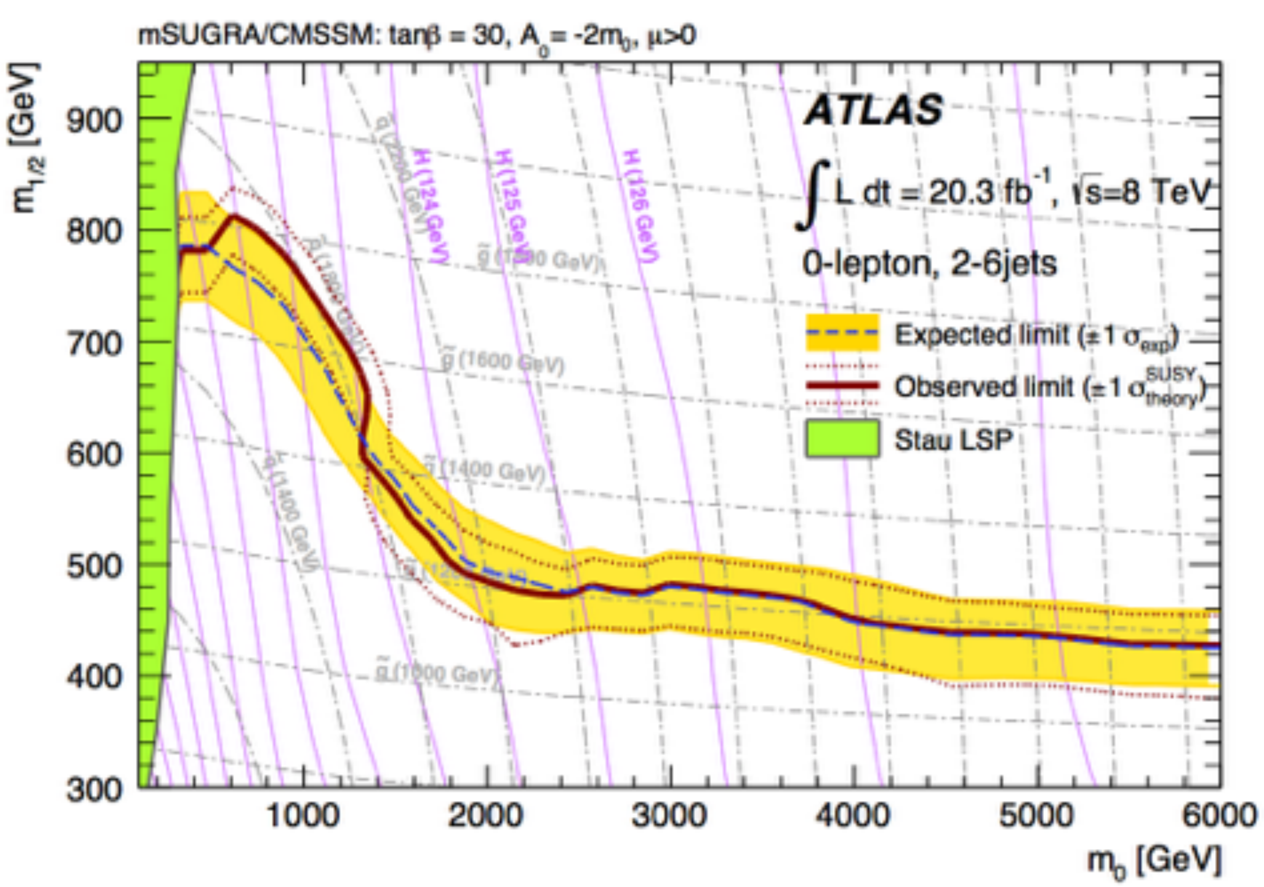


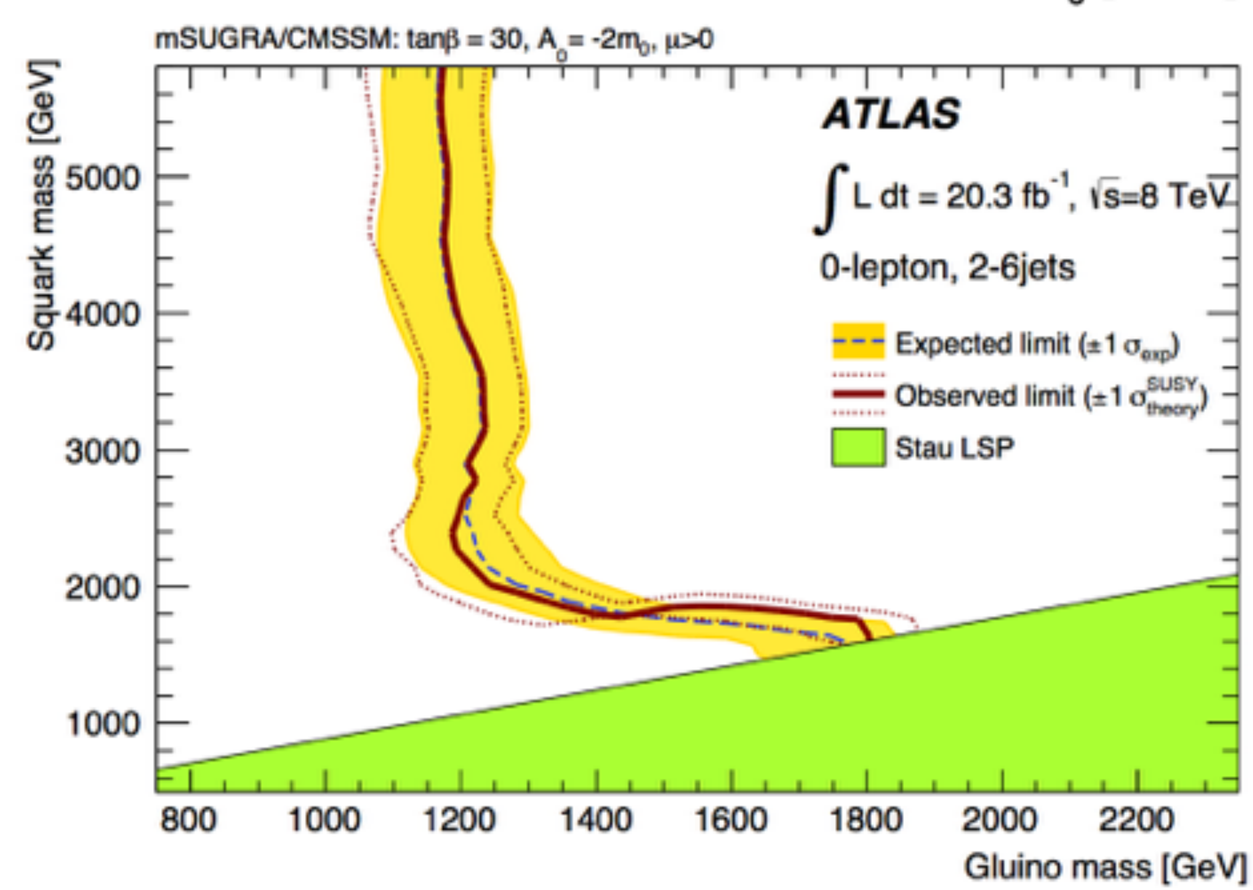


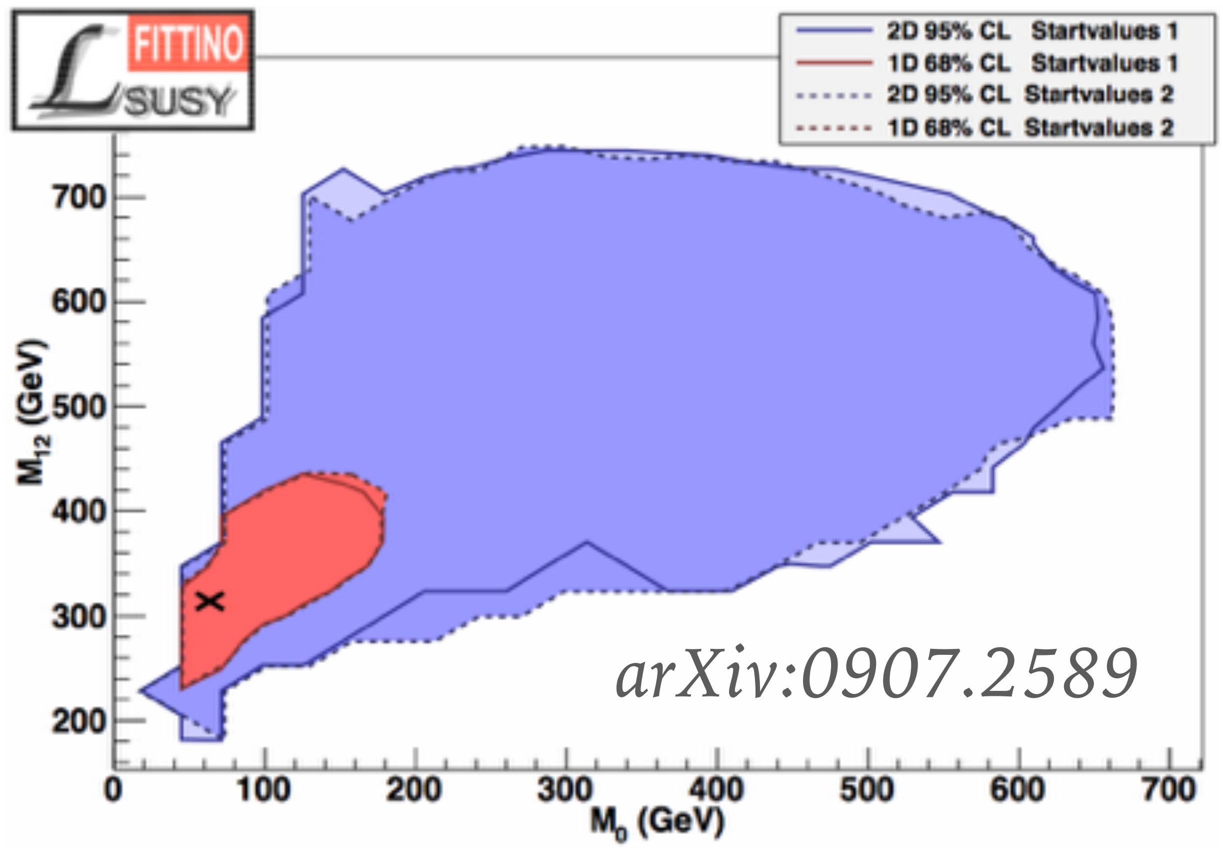
The CMSSM is famous for the small number of parameters, only including four and 'half' parameters at Grand Unification(GUT) scale, the universal scaler and gaugino mass parameters M_0 and $M_{1/2}$, the universal trilinear coupling A_0, the ratio of two Higgs doublet vacuum expectation value $tan\beta$, and the sign of the Higgs/Higgsino mass parameter $sign(\mu)$.


MSUGRA/CMSSM: tanβ = 10, A0 = 0, μ>0
ATLAS
Preliminary
∫ L dt = 5.8 fb⁻¹, √s=8 TeV
0-lepton combined
Observed limit (±1 σ theory SUSY)
Expected limit (±1 σexp)
Theoretically excluded
Stau LSP
CDF, Run II, tanβ = 5, μ<0
D0, Run II, tanβ = 3, μ<0
squark mass [GeV]
gluino mass [GeV]
200 400 600 800 1000 1200 1400 1600 1800
500 1000 1500 2000 2500 3000


CMS Preliminary L int = 4.98 fb⁻¹, √s = 7 TeV
m1/2 [GeV]
m0 [GeV]
tan(β)=10
A0 = 0 GeV
μ > 0
mt = 173.2 GeV
LEP2 l̃±
LEP2 χ̃1±
τ̃ = LSP
Jets+MHT
Razor
SS Dilepton
MT2
αT
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB
m(q̃) = 1500
m(q̃) = 2000
m(q̃) = 2500
m(g̃) = 1500
m(q̃) = 1000
m(g̃) = 1000
m(g̃) = 500
100 200 300 400 500 600 700 800
500 1000 1500 2000 2500 3000


mSUGRA/CMSSM: tanβ = 30, A0 = -2m0, μ>0
ATLAS
∫ L dt = 20.3 fb⁻¹, √s=8 TeV
0-lepton, 2-6jets
Expected limit (±1 σexp)
Observed limit (±1 σ theory SUSY)
Stau LSP
H (124 GeV)
H (125 GeV)
H (126 GeV)
g̃ (1800 GeV)
g̃ (1600 GeV)
g̃ (1400 GeV)
g̃ (1000 GeV)
m1/2 [GeV]
m0 [GeV]
1000 2000 3000 4000 5000 6000
300 400 500 600 700 800 900

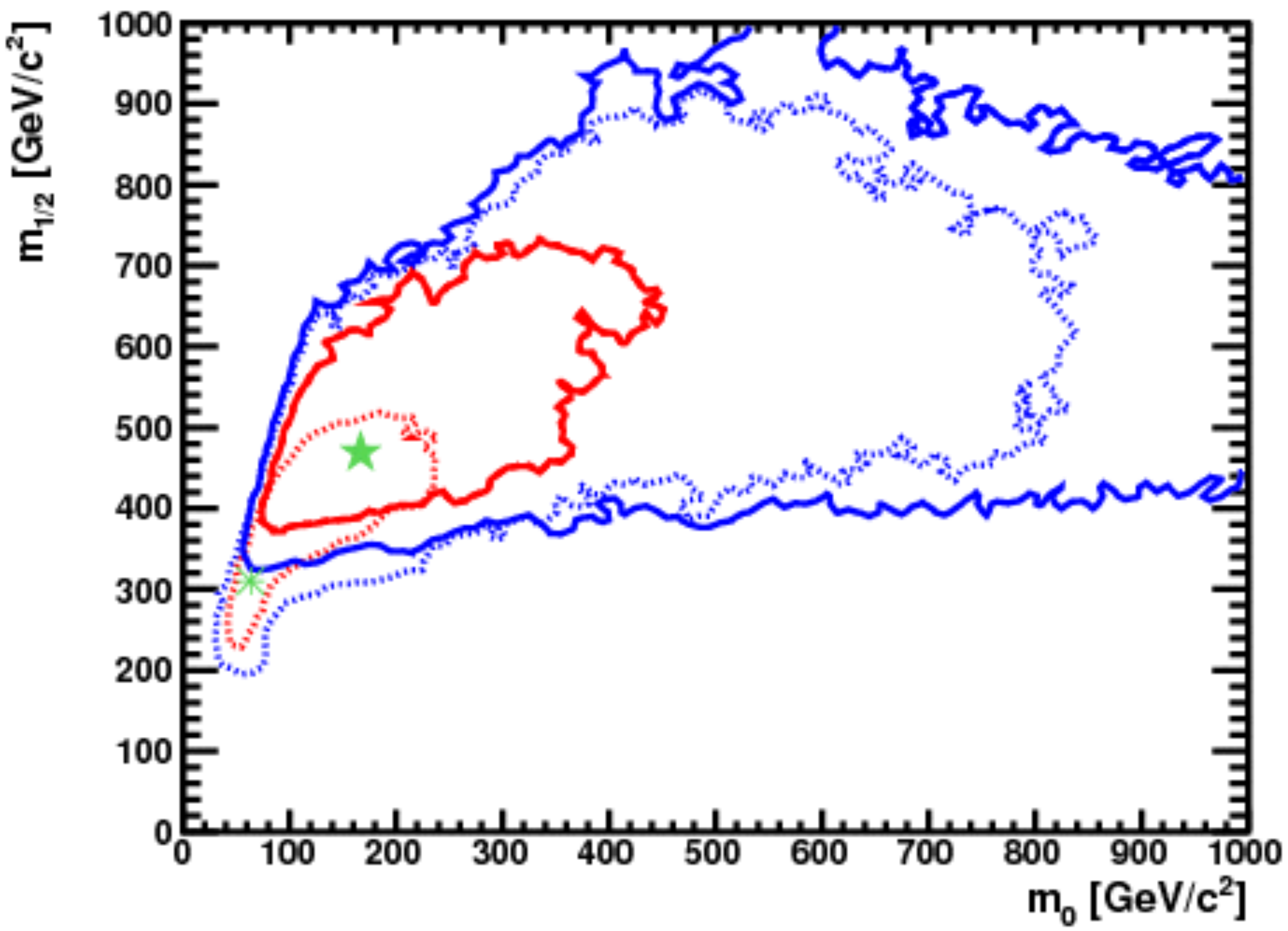

mSUGRA/CMSSM: tanβ = 30, A0 = -2m0, μ>0
ATLAS
∫ L dt = 20.3 fb⁻¹, √s=8 TeV
0-lepton, 2-6jets
Expected limit (±1 σexp)
Observed limit (±1 σ theory SUSY)
Stau LSP
Squark mass [GeV]
Gluino mass [GeV]
800 1000 1200 1400 1600 1800 2000 2200
1000 2000 3000 4000 5000

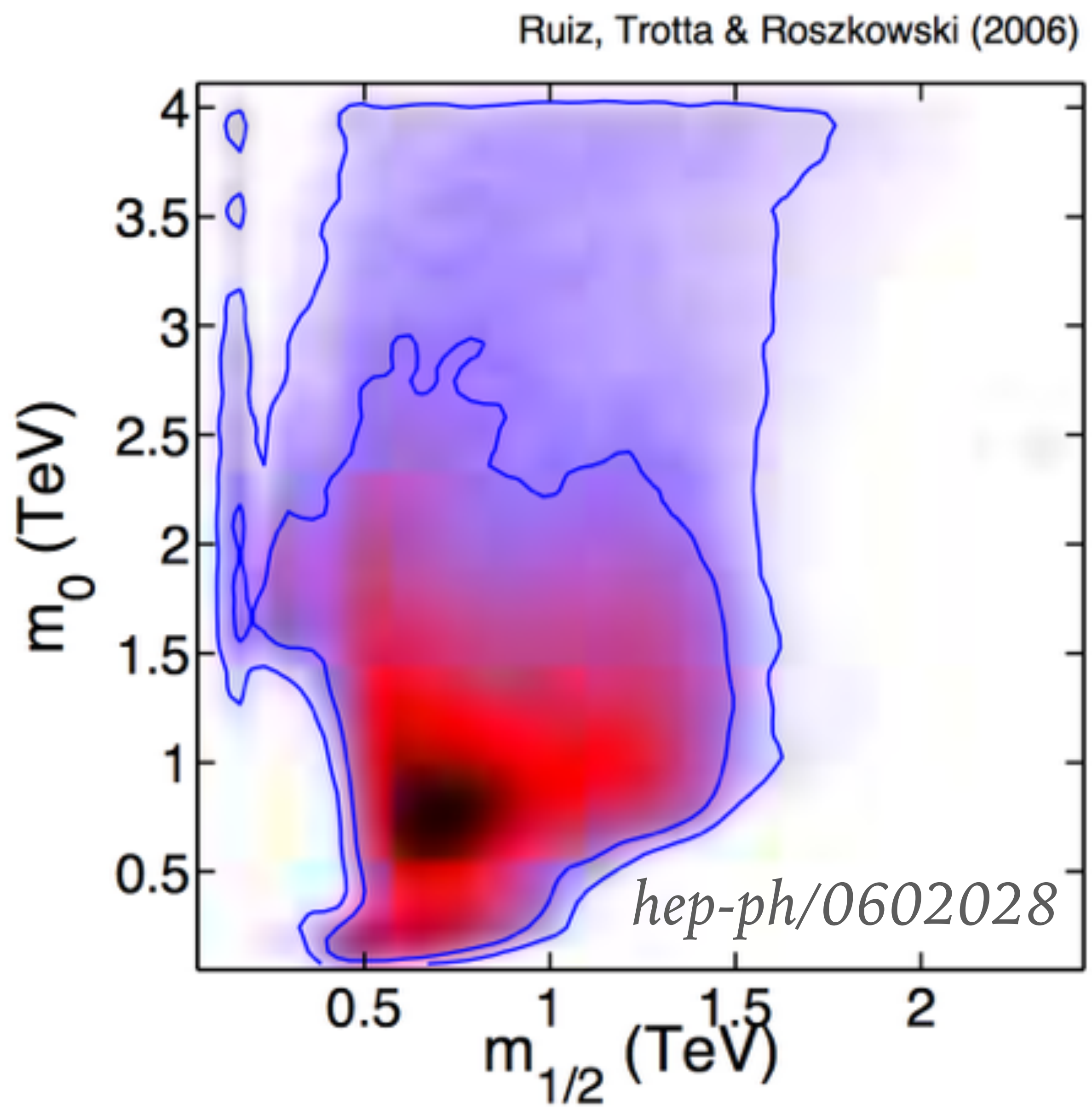


SuperBayes/BayesFit

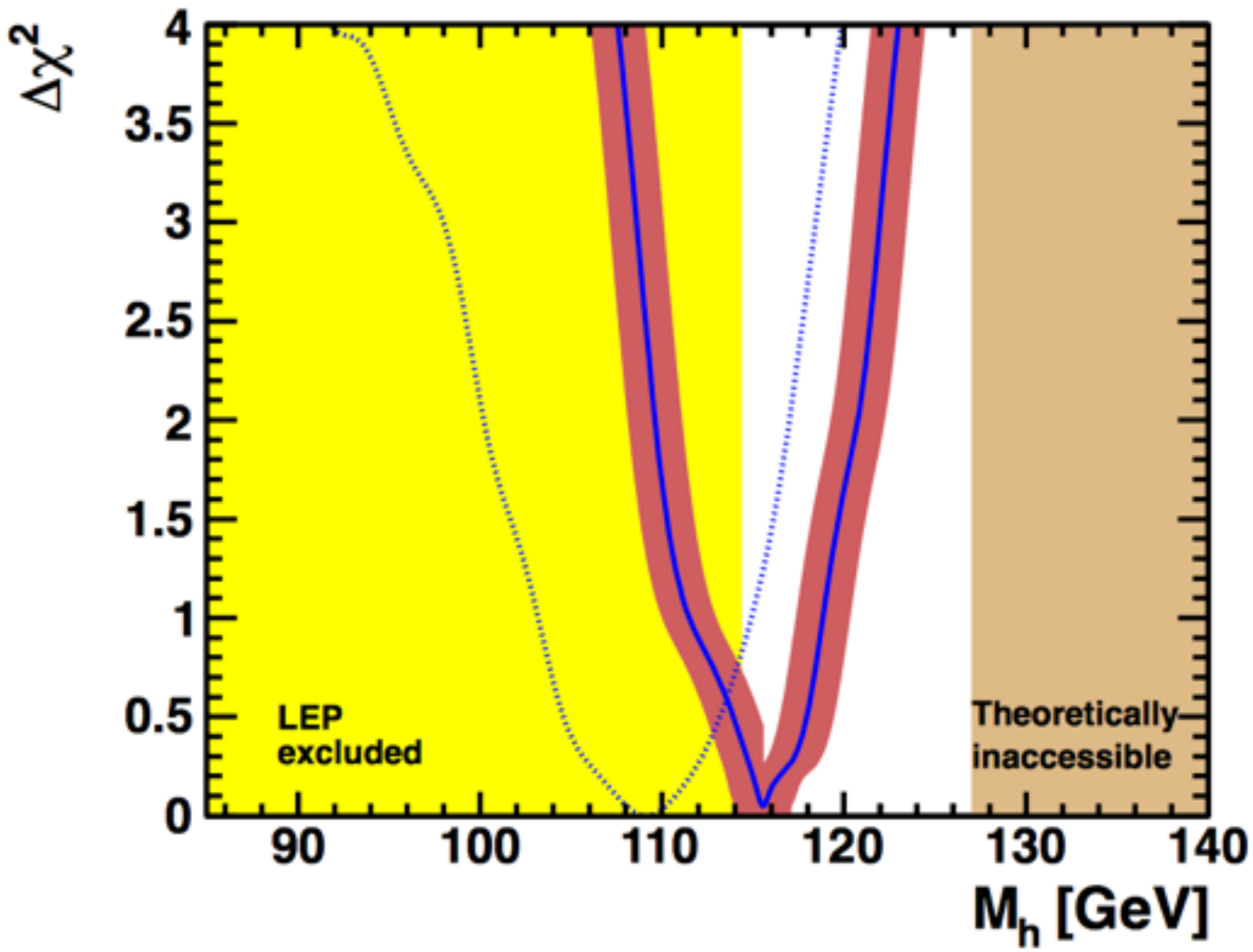
MasterCode

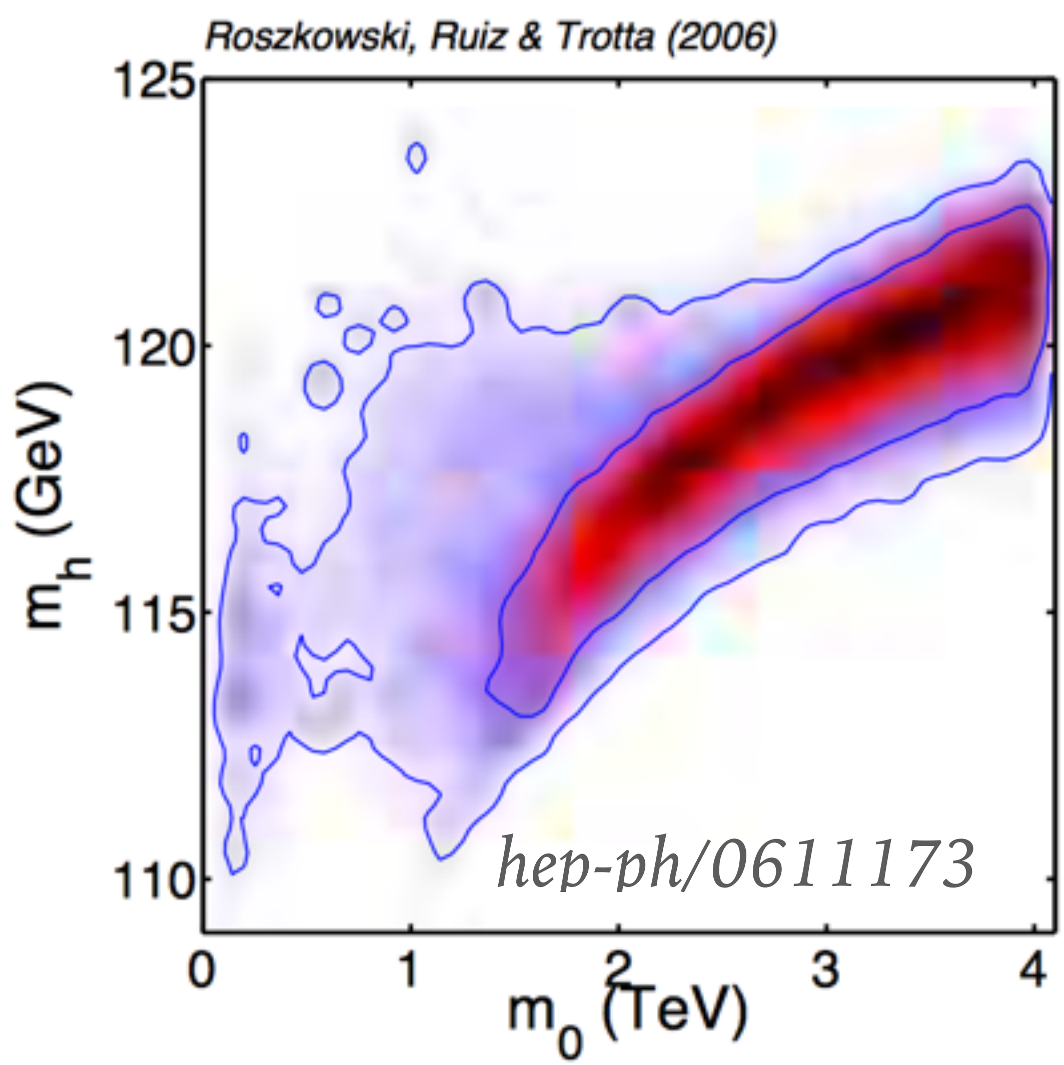
Fittino



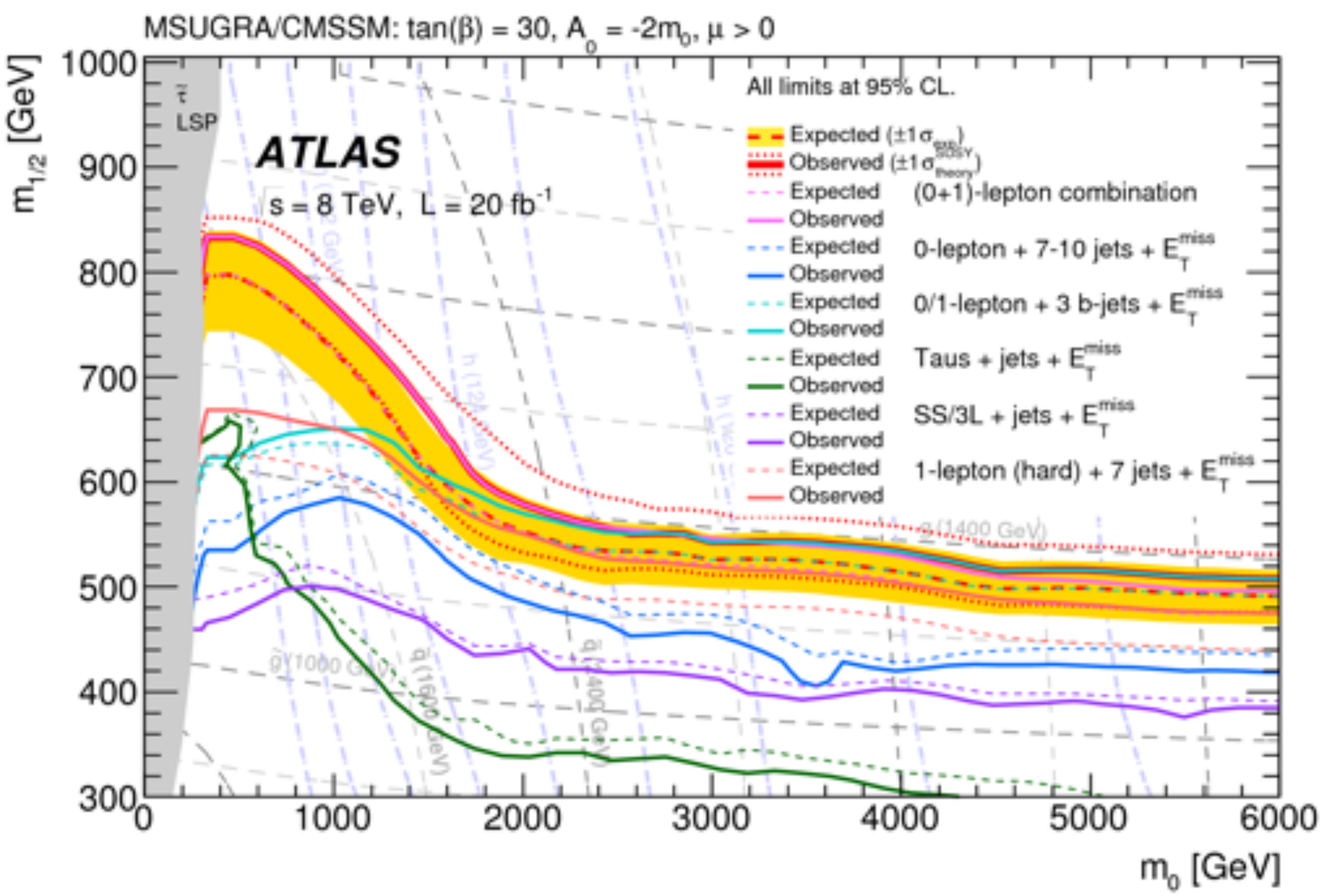


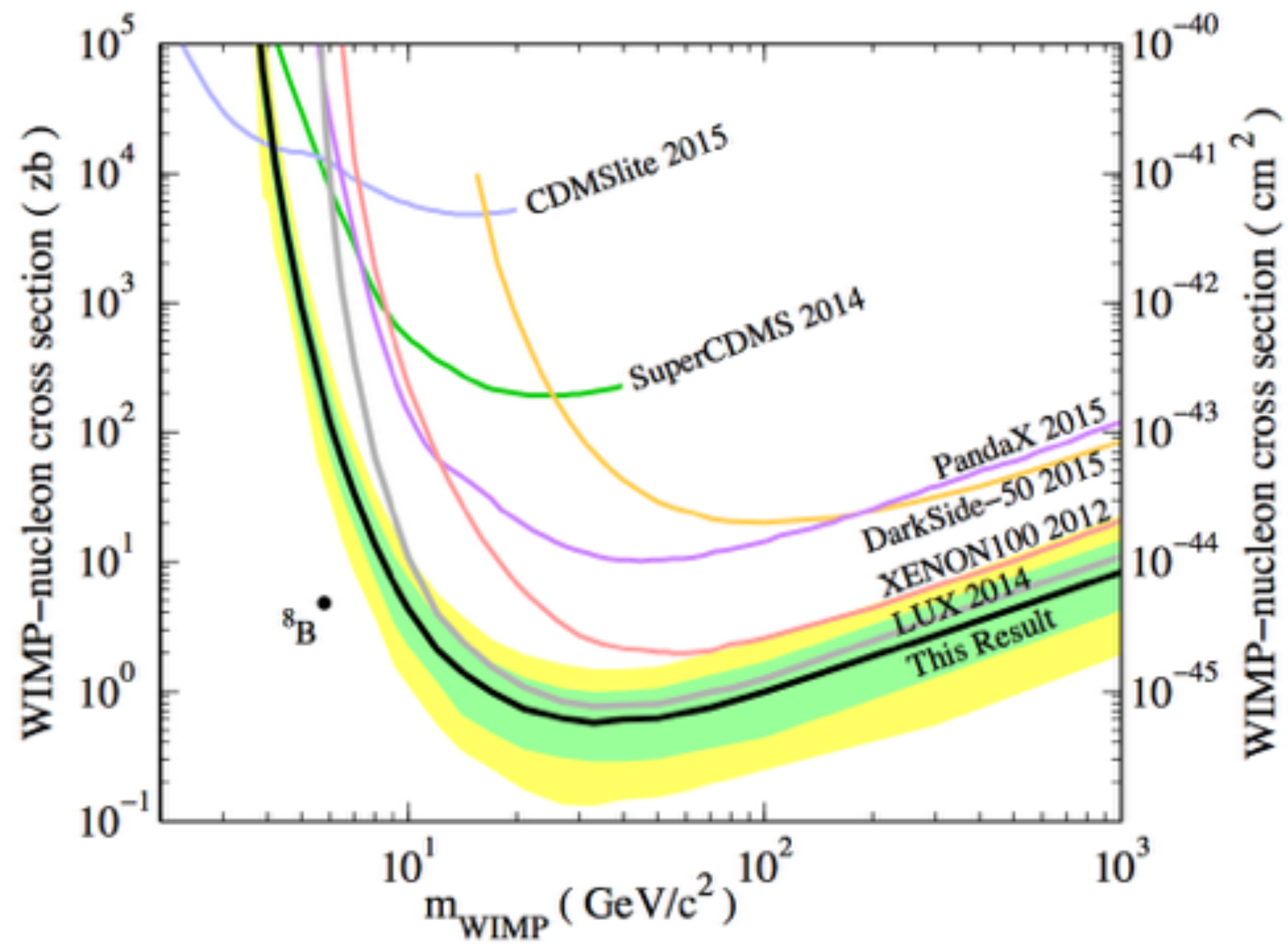
Then the 125 GeV Higgs is discovered at LHC …



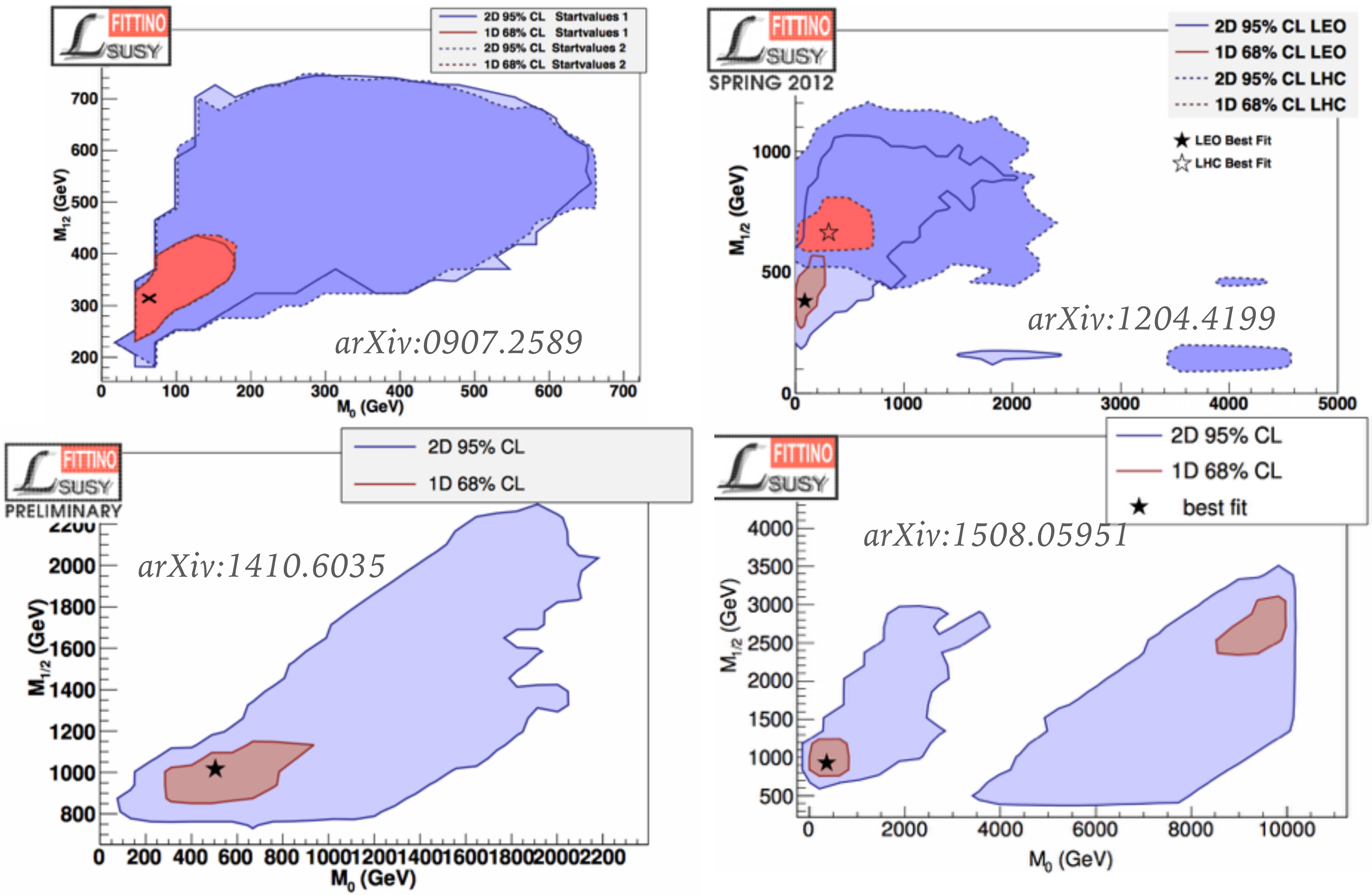


And no significant signals have been observed in SUSY searches at LHC and DM direct searches.

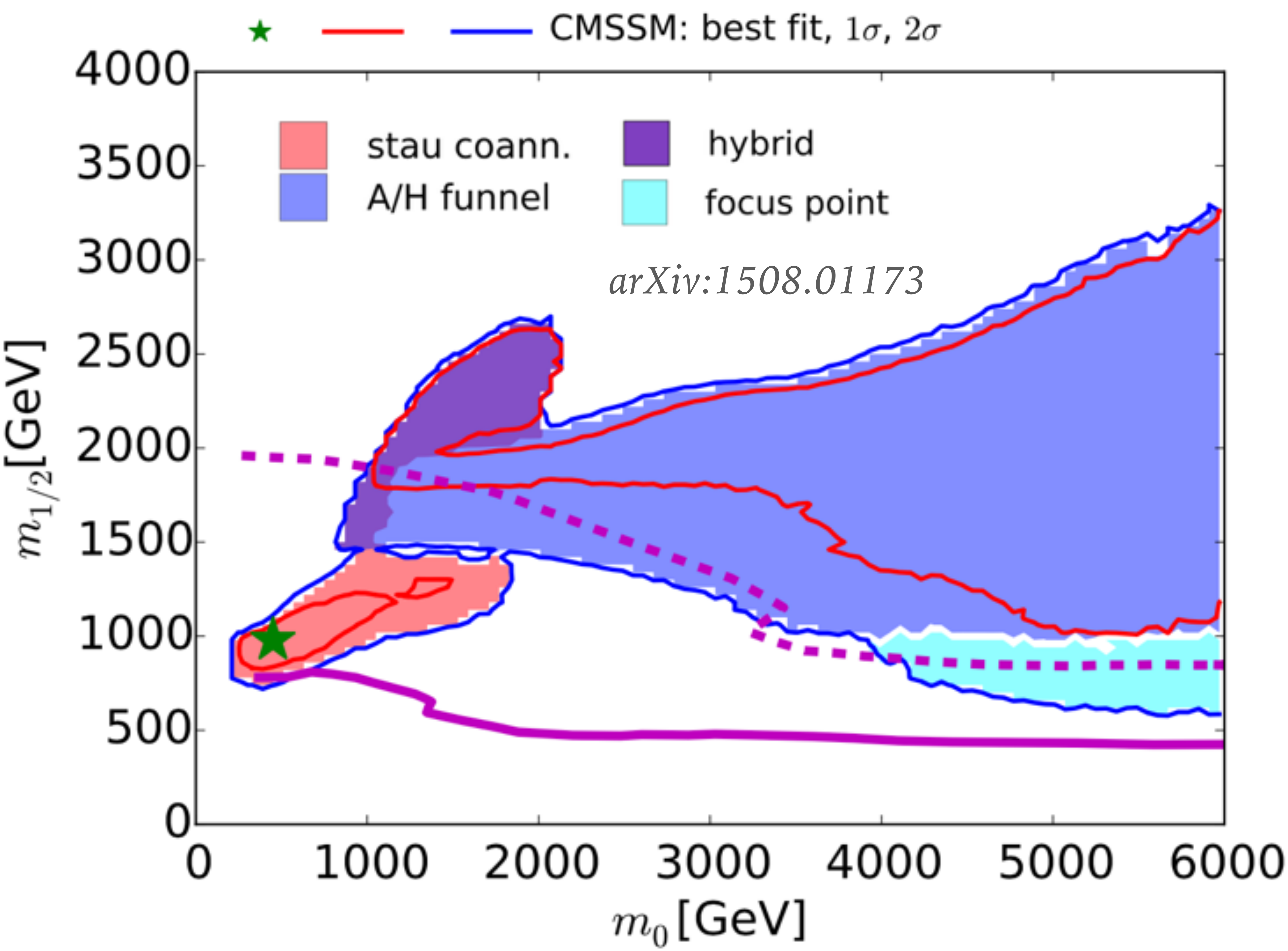




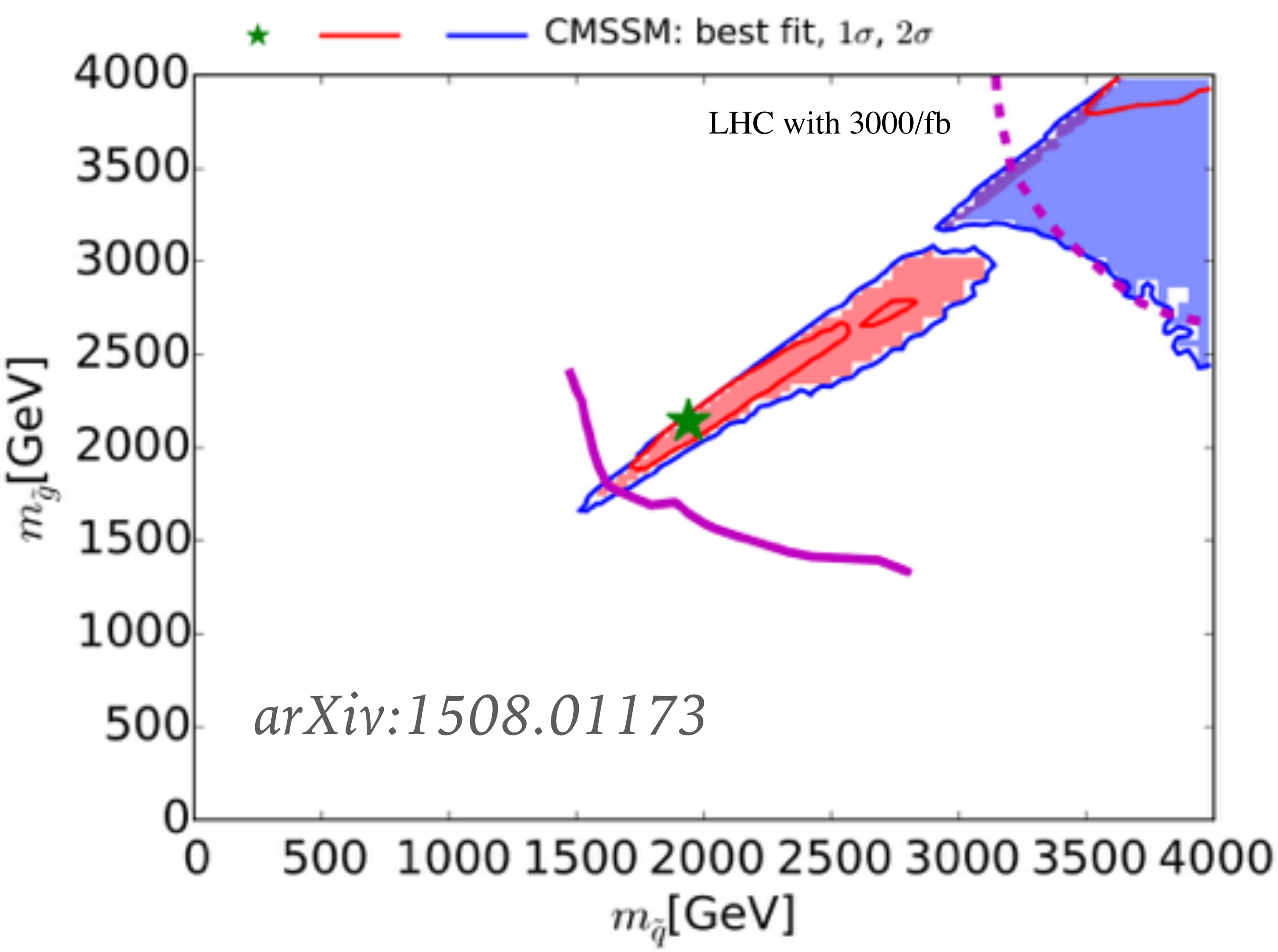
The favored parameter space changed …

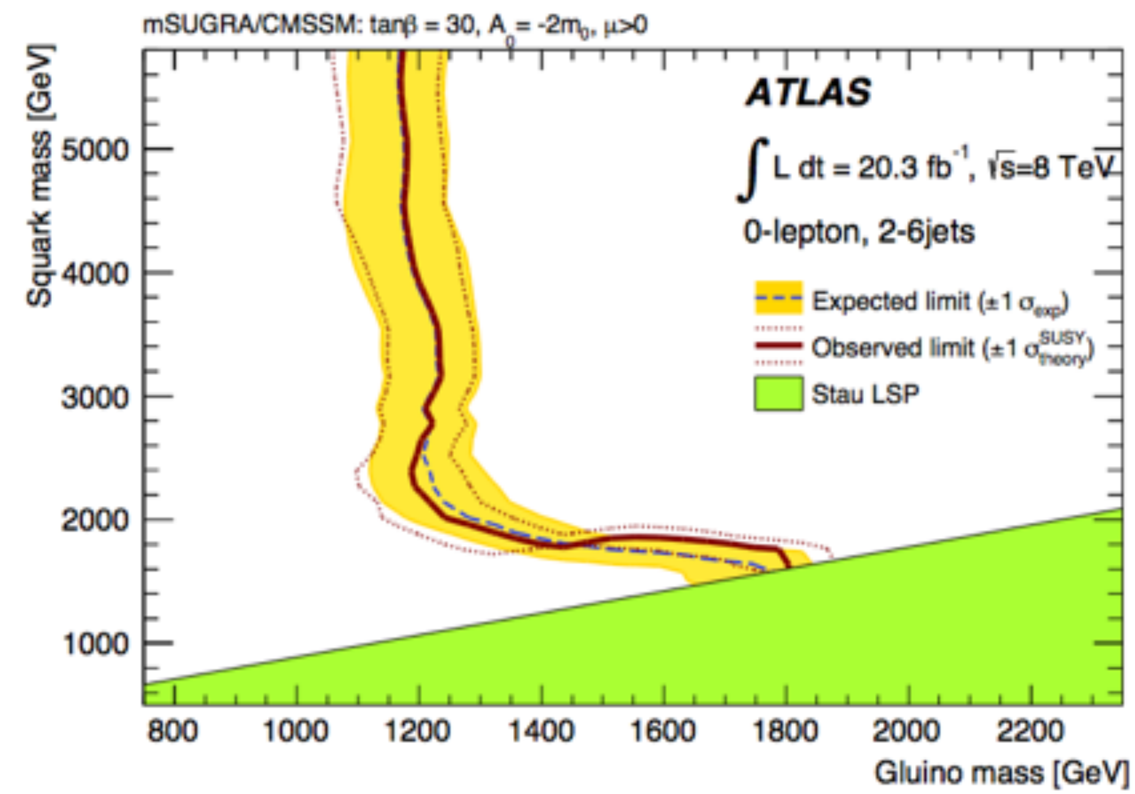


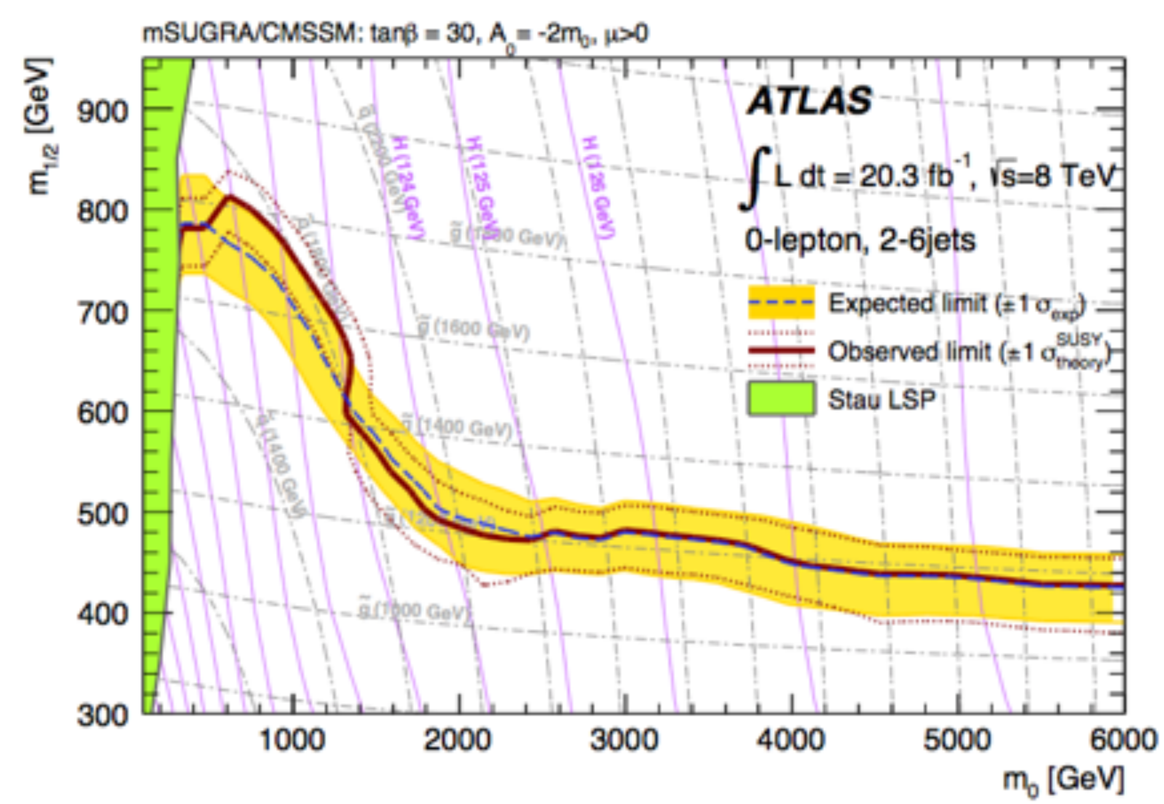
Dark matter annihilation mechanisms



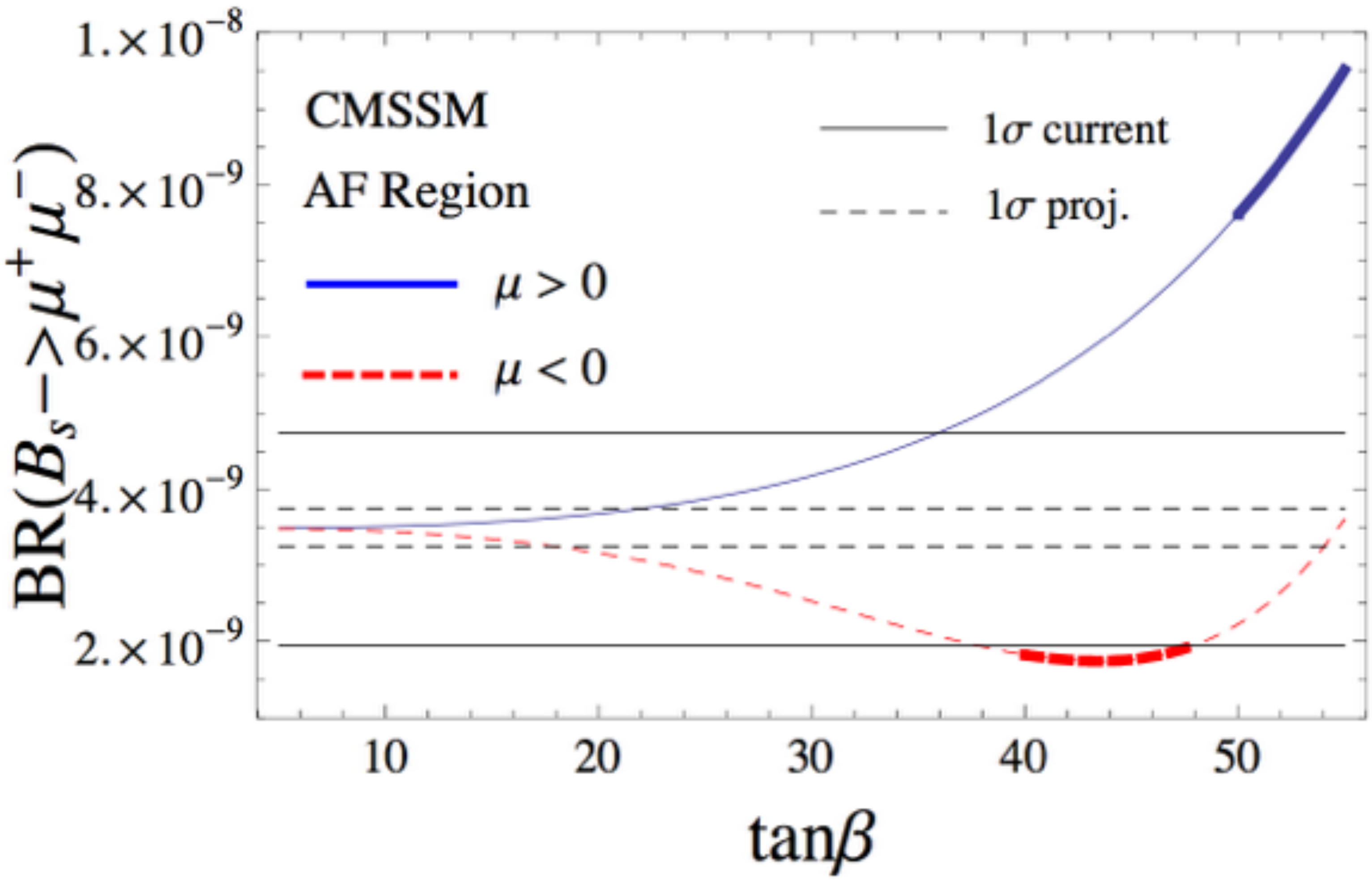
Stau coannihilation and LHC

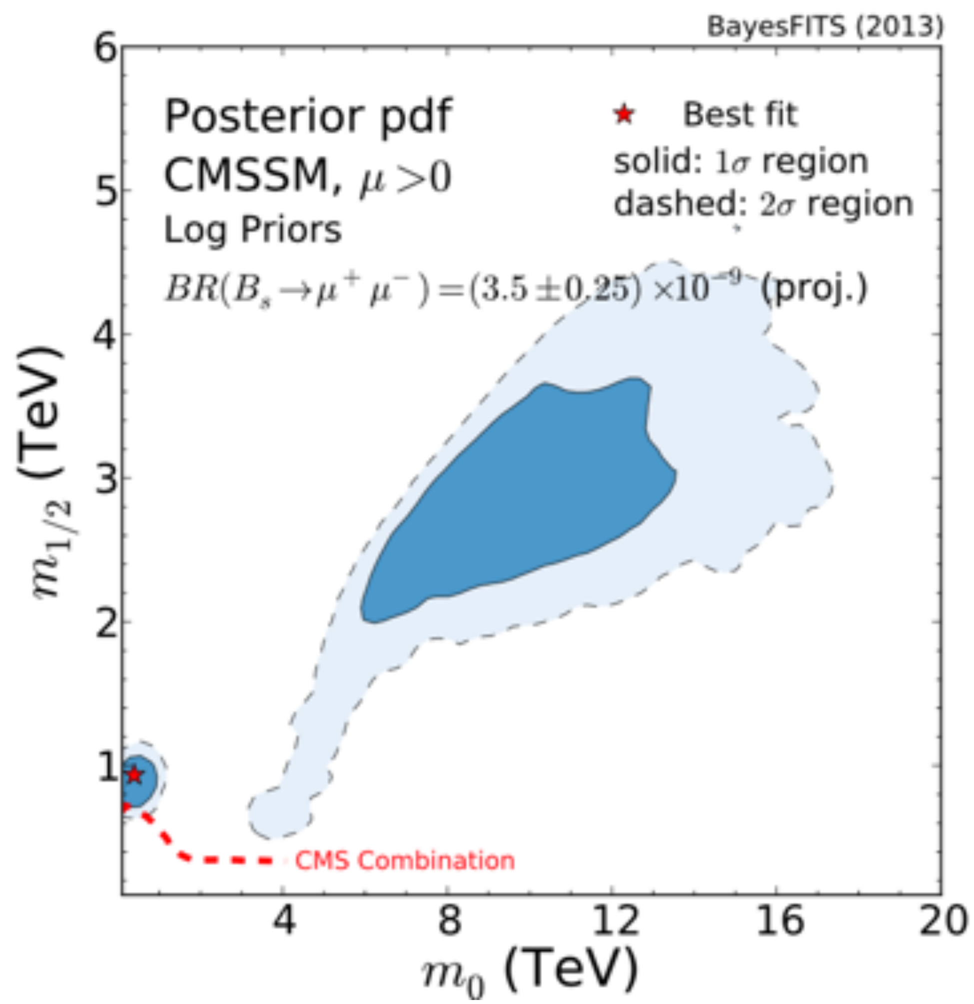




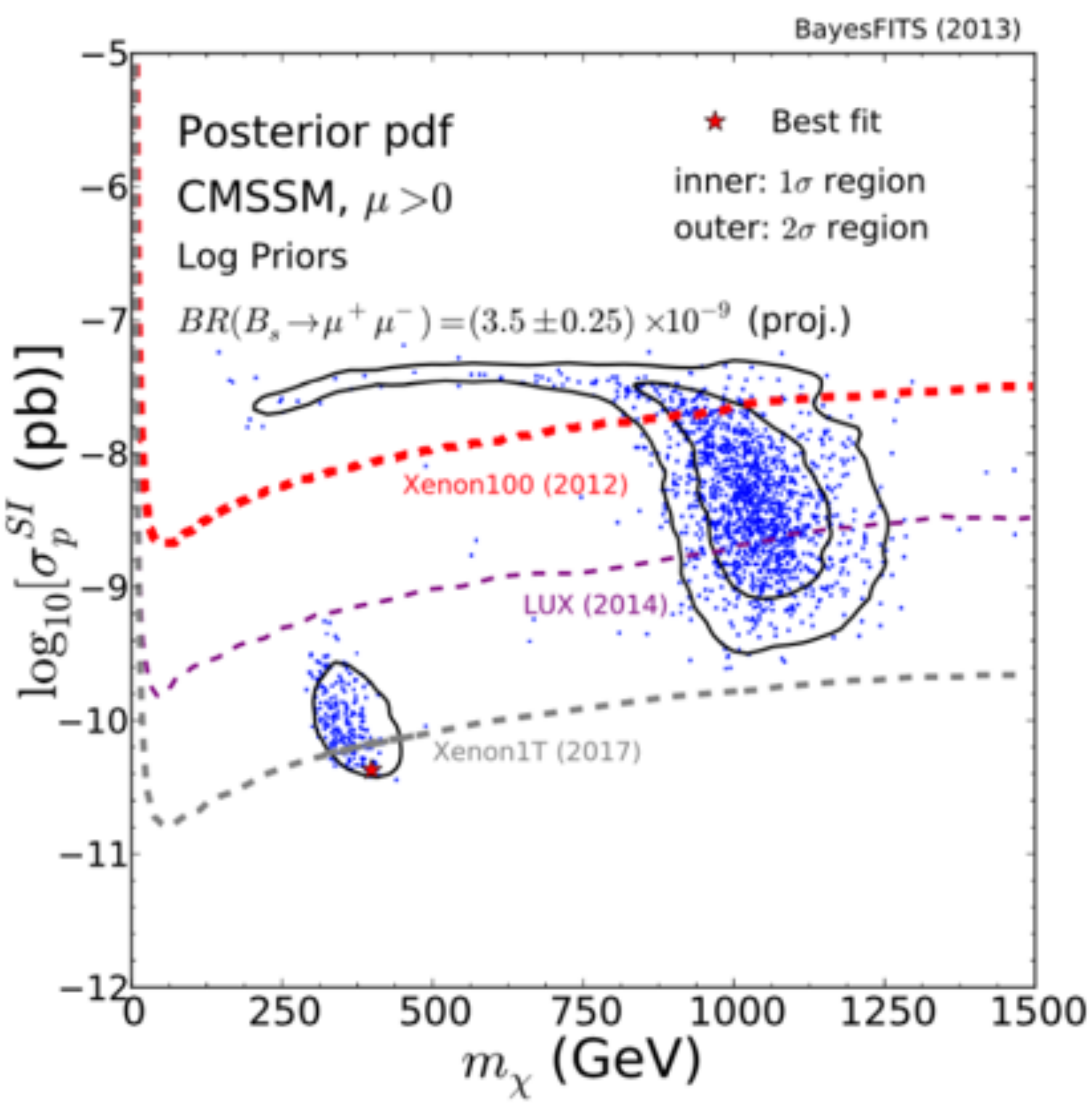


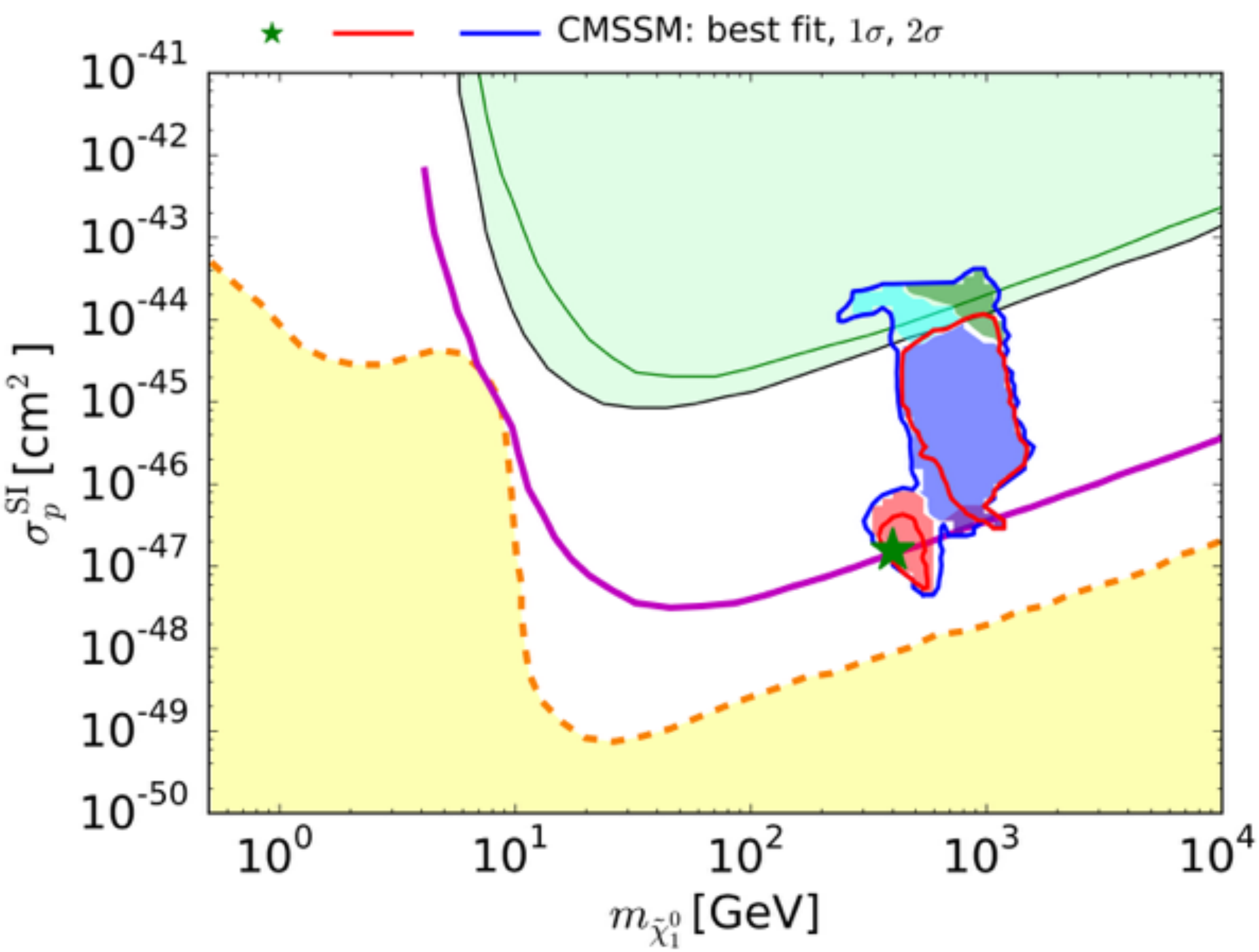
A/H Funnel and B decay



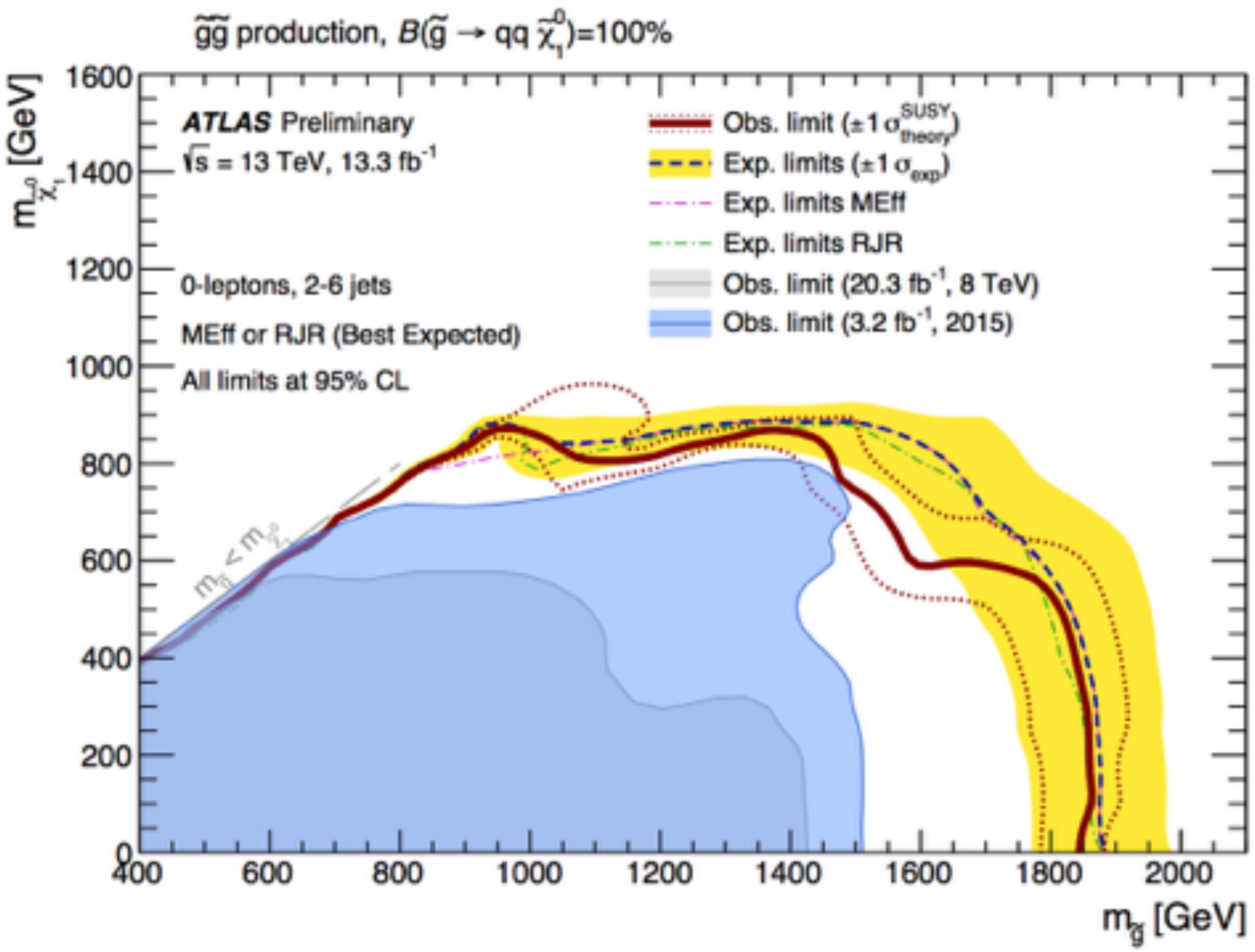


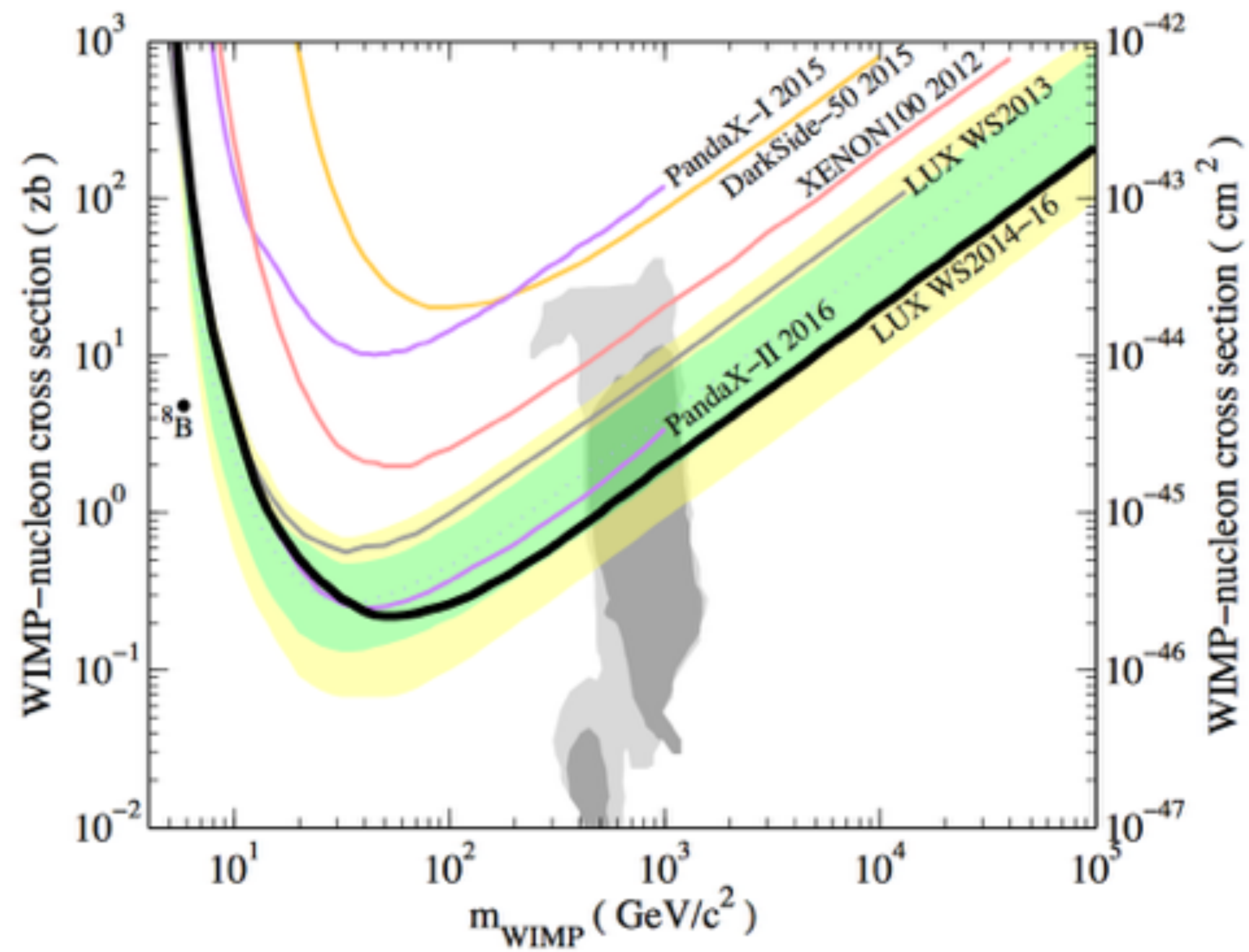
Focus point region and DM direct detection





13 TeV LHC and LUX 2016

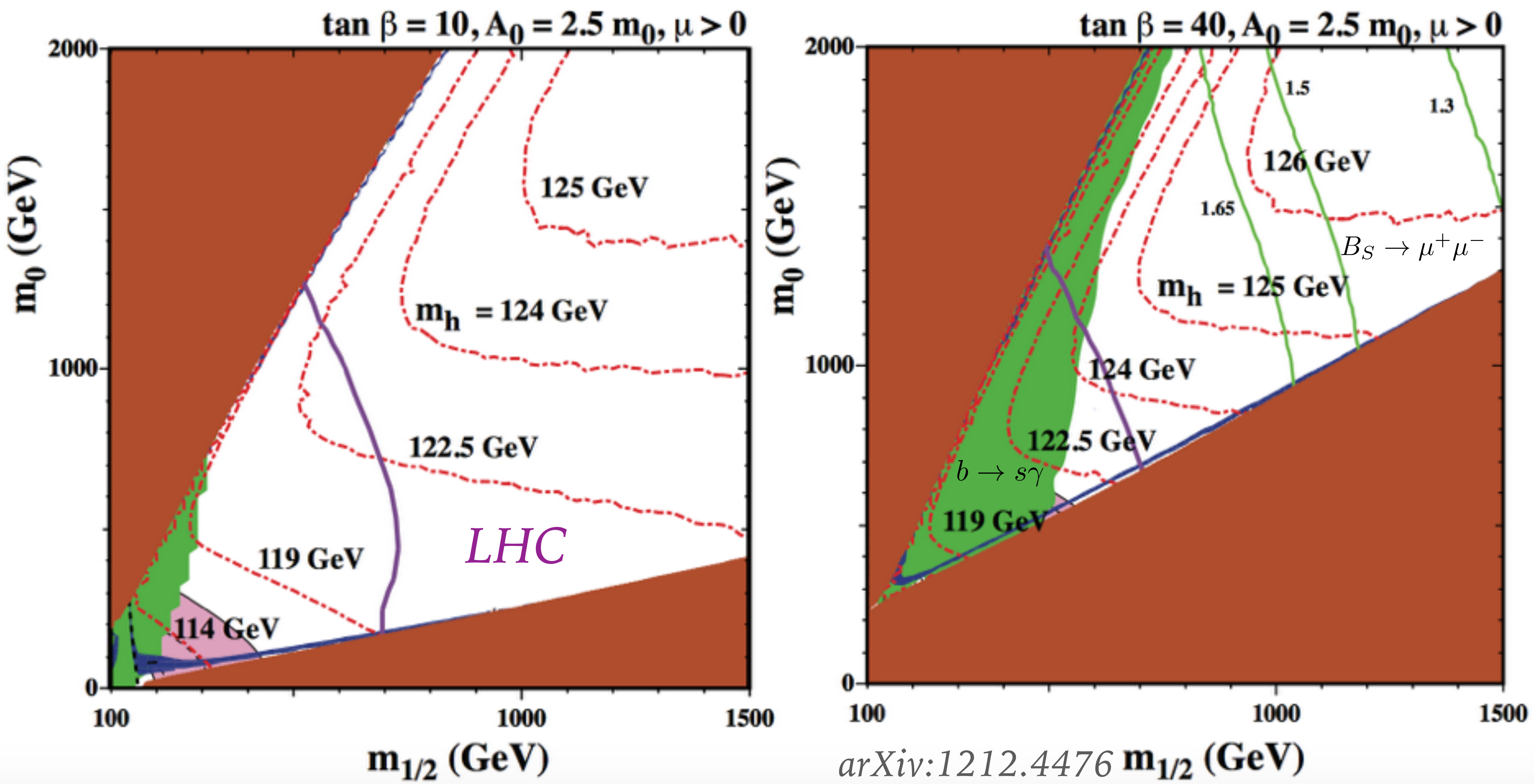




Stau coannihilation

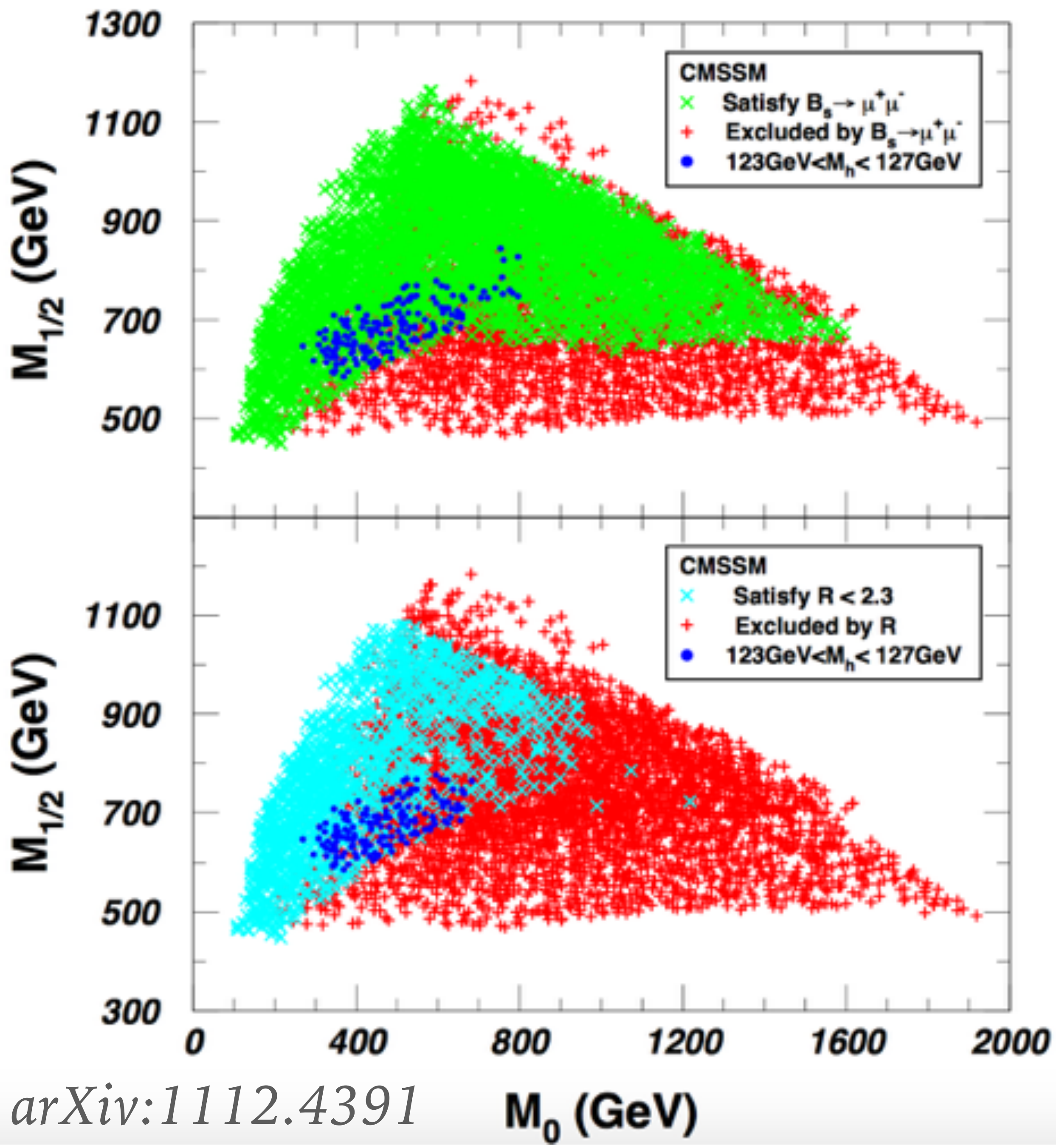
Focus point region

Statistical framework



arXiv:1212.4476

Statistical framework

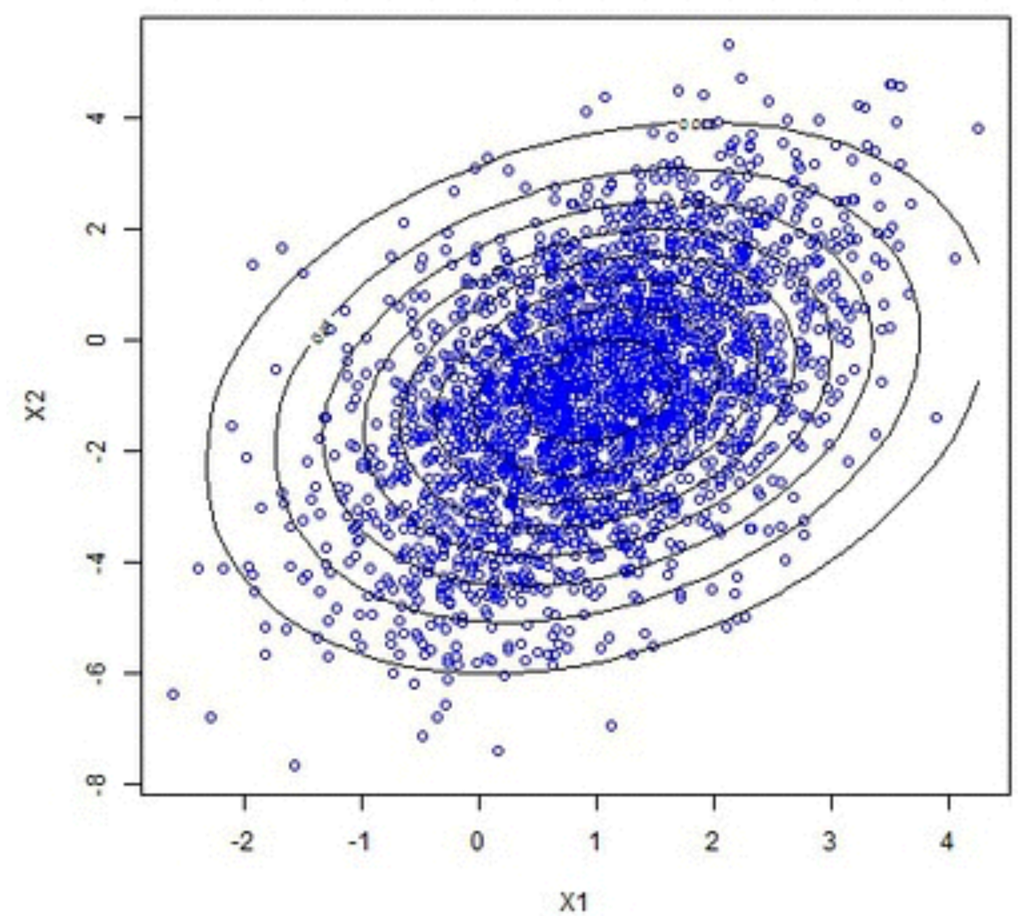


arXiv:1112.4391

Junjie Cao, Zhaoxia Heng, Dongwei Li, Jin Min Yang

Markov chain Monte Carlo(MCMC)

Multinest



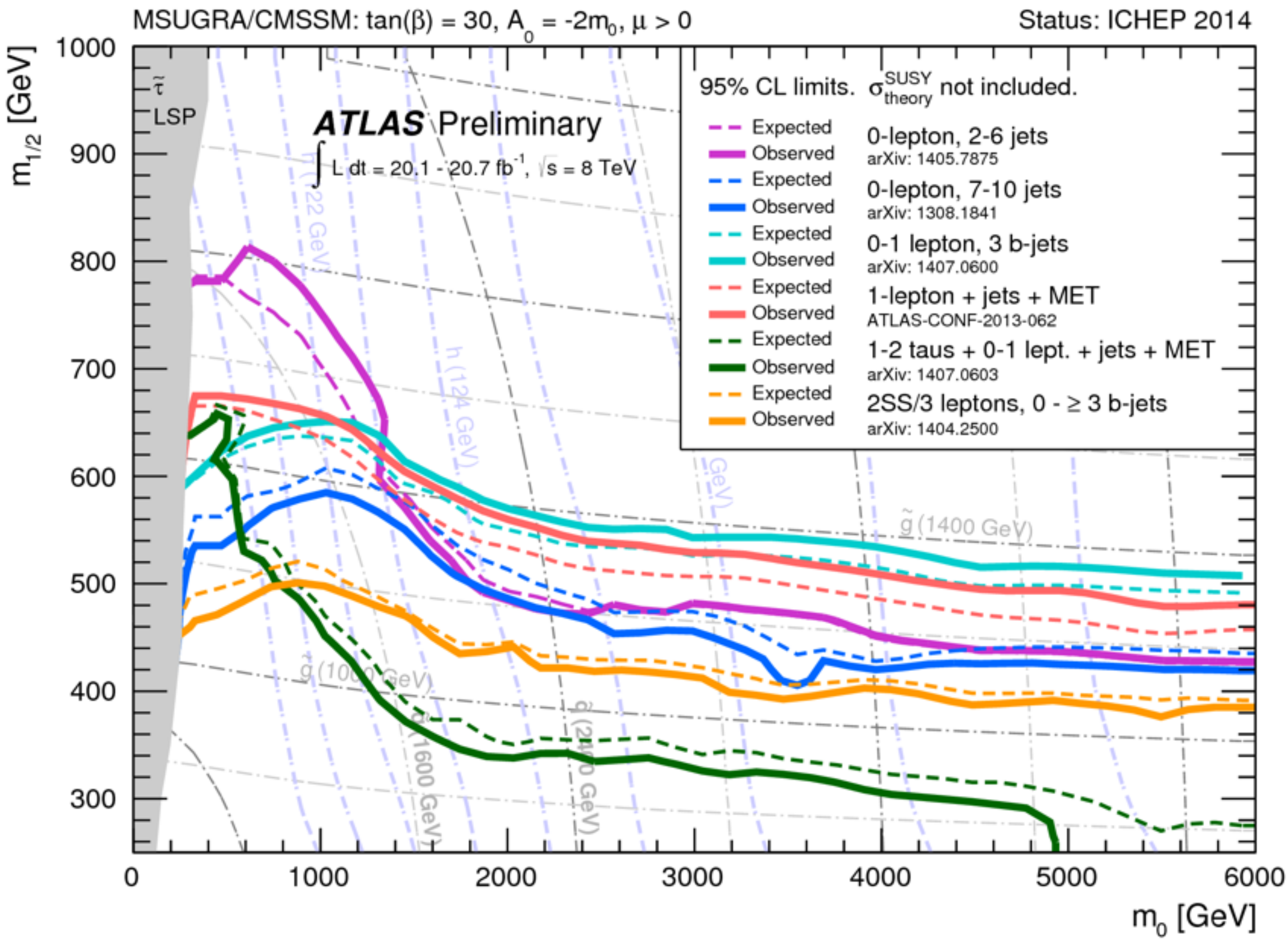
Likelihood function

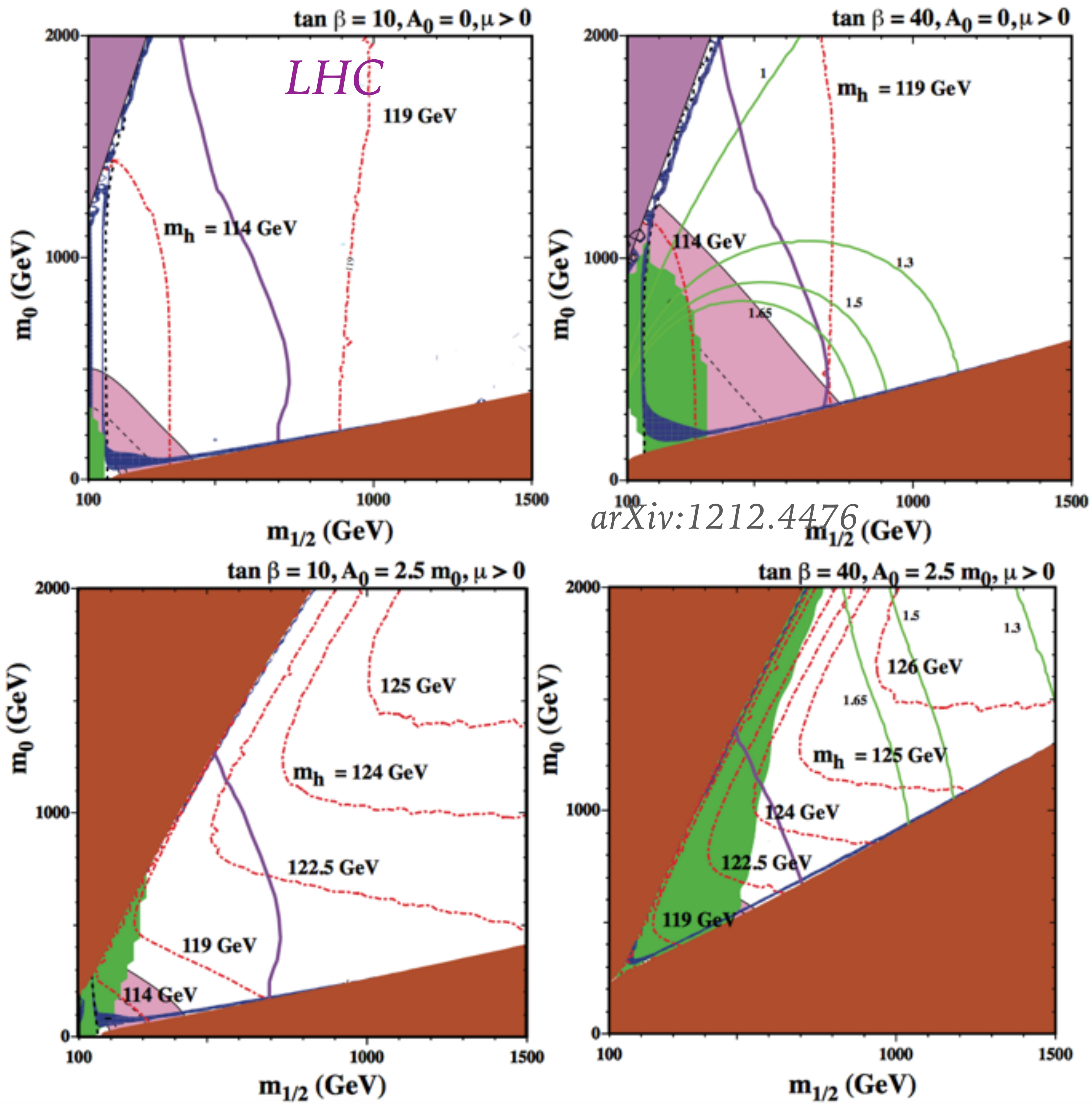
$$p(\mathbf{\Theta}|\mathbf{D}) = \frac{p(\mathbf{D}|\mathbf{\Theta})p(\mathbf{\Theta})}{p(\mathbf{D})} \qquad p(\mathbf{D}|\mathbf{\Theta}) \equiv \mathcal{L}(\mathbf{\Theta})$$

$$ln\mathcal{L} = ln\mathcal{L}_{WMAP} + ln\mathcal{L}_{EW} + ln\mathcal{L}_{B} + ln\mathcal{L}_{g-2} + ln\mathcal{L}_{m_h} + ln\mathcal{L}_{LHC} + ln\mathcal{L}_{LUX} + ln\mathcal{L}_{LEP} + ln\mathcal{L}_{HiggsCoupling}$$

Observable	μ	σ(exp)	τ(th)	References
$\Omega_\chi h^2$	0.1186	0.0031	0.012	arXiv:1303.5076
$\Delta a_\mu \times 10^{10}$	28.7	8	10.0	Eur.Phys.J. C71, 1515 (2011)
$BR(B \to X_s\gamma) \times 10^4$	3.43	0.22	0.24	arXiv:1412.7515
$BR(B_s^0 \to \mu^+\mu^-) \times 10^9$	2.9	0.7	0.29	arXiv:1411.4413
$R(B^- \to \tau^-\hat{\nu}_\tau)$	1.04	0.24	0.24	arXiv:1412.7515
m_h	125.36	0.41	2.0	arXiv:1406.3827
M_W	80.385	0.015	0.01	Chin. Phys. C 38 (2014) 090001
$sin^2\hat{\theta}(M_Z)(\overline{MS})$	0.23153	0.00016	0.00010	arXiv:hep-ex/0509008

Limits from LHC SUSY search





LHC
arXiv:1212.4476
tan β = 10, A0 = 0, μ > 0
tan β = 40, A0 = 0, μ > 0
tan β = 10, A0 = 2.5 m0, μ > 0
tan β = 40, A0 = 2.5 m0, μ > 0
m0 (GeV)
m1/2 (GeV)
mh = 114 GeV
119 GeV
mh = 119 GeV
114 GeV
1
1.3
1.5
1.65
125 GeV
mh = 124 GeV
122.5 GeV
126 GeV
mh = 125 GeV
124 GeV
0
100
1000
1500
2000

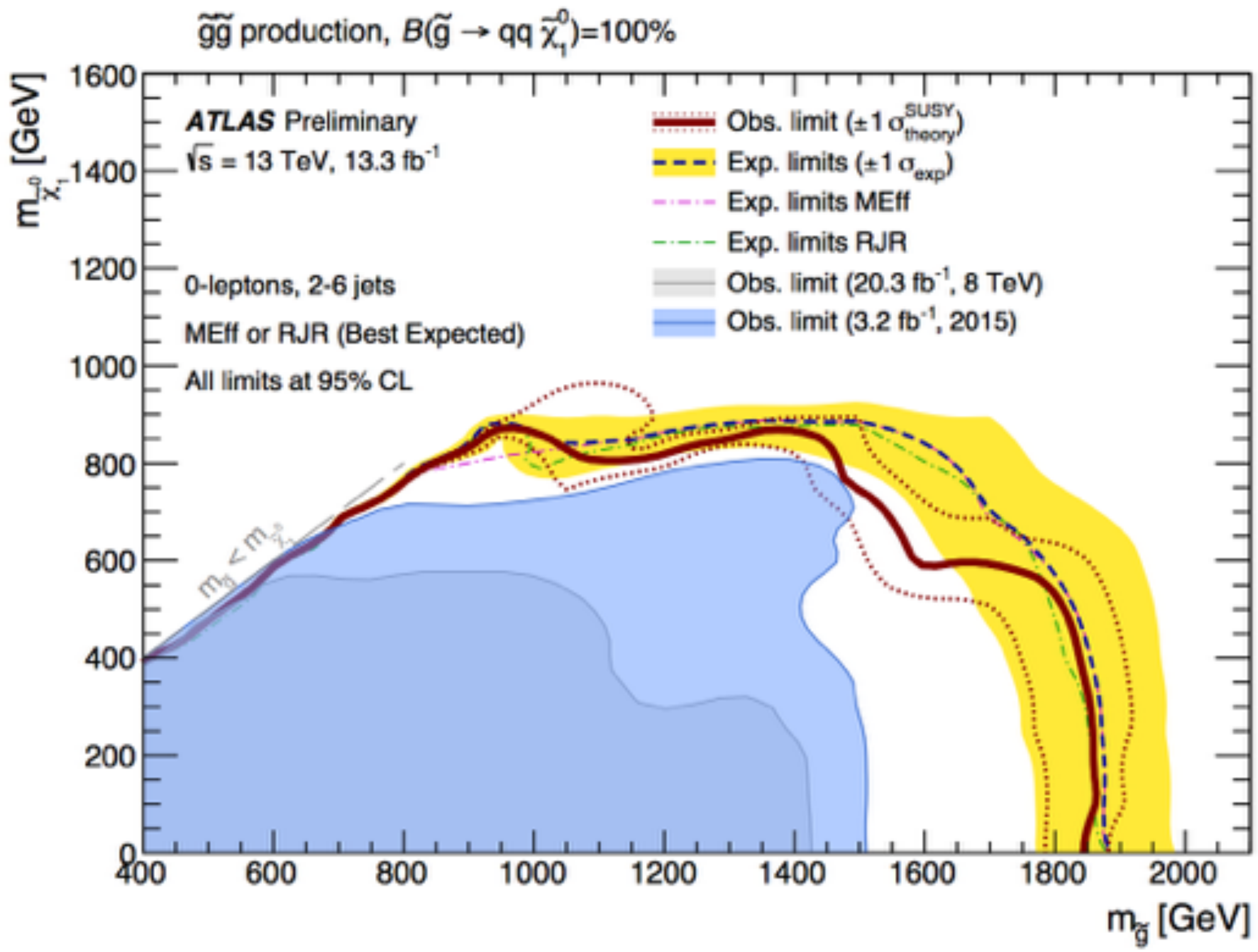
ATLAS 13TeV 13.3 /fb 2~6 jets + MET

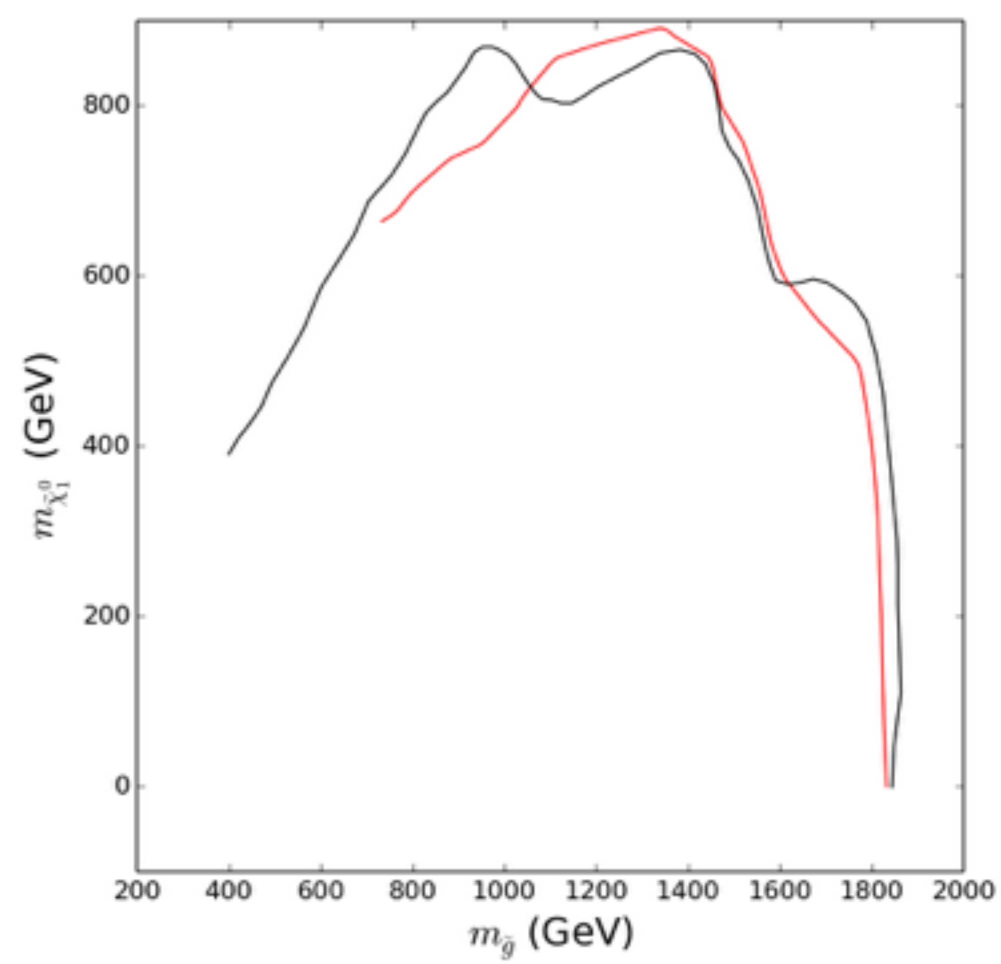
The jets+E^{miss} Meff-based search

Targeted signal	$\tilde{q}\bar{\tilde{q}}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$				
Requirement	Signal Region				
	Meff-2j-800	Meff-2j-1200	Meff-2j-1600	Meff-2j-2000	Meff-3j-1200
E_T^{miss} [GeV] >	250				
$p_T(j_1)$ [GeV] >	200	250			600
$p_T(j_2)$ [GeV] >	200	250			50
$p_T(j_3)$ [GeV] >	–				50
$\lvert\eta(j_{1,2})\rvert$ <	0.8	1.2			–
$\Delta\phi(\mathrm{jet}_{1,2,(3)}, E_T^{\mathrm{miss}})_{\mathrm{min}}$ >	0.8				0.4
$\Delta\phi(\mathrm{jet}_{i>3}, E_T^{\mathrm{miss}})_{\mathrm{min}}$ >	0.4				0.2
$E_T^{\mathrm{miss}}/\sqrt{H_T}$ [GeV$^{1/2}$] >	14	16	18	20	16
m_{eff}(incl.) [GeV] >	800	1200	1600	2000	1200

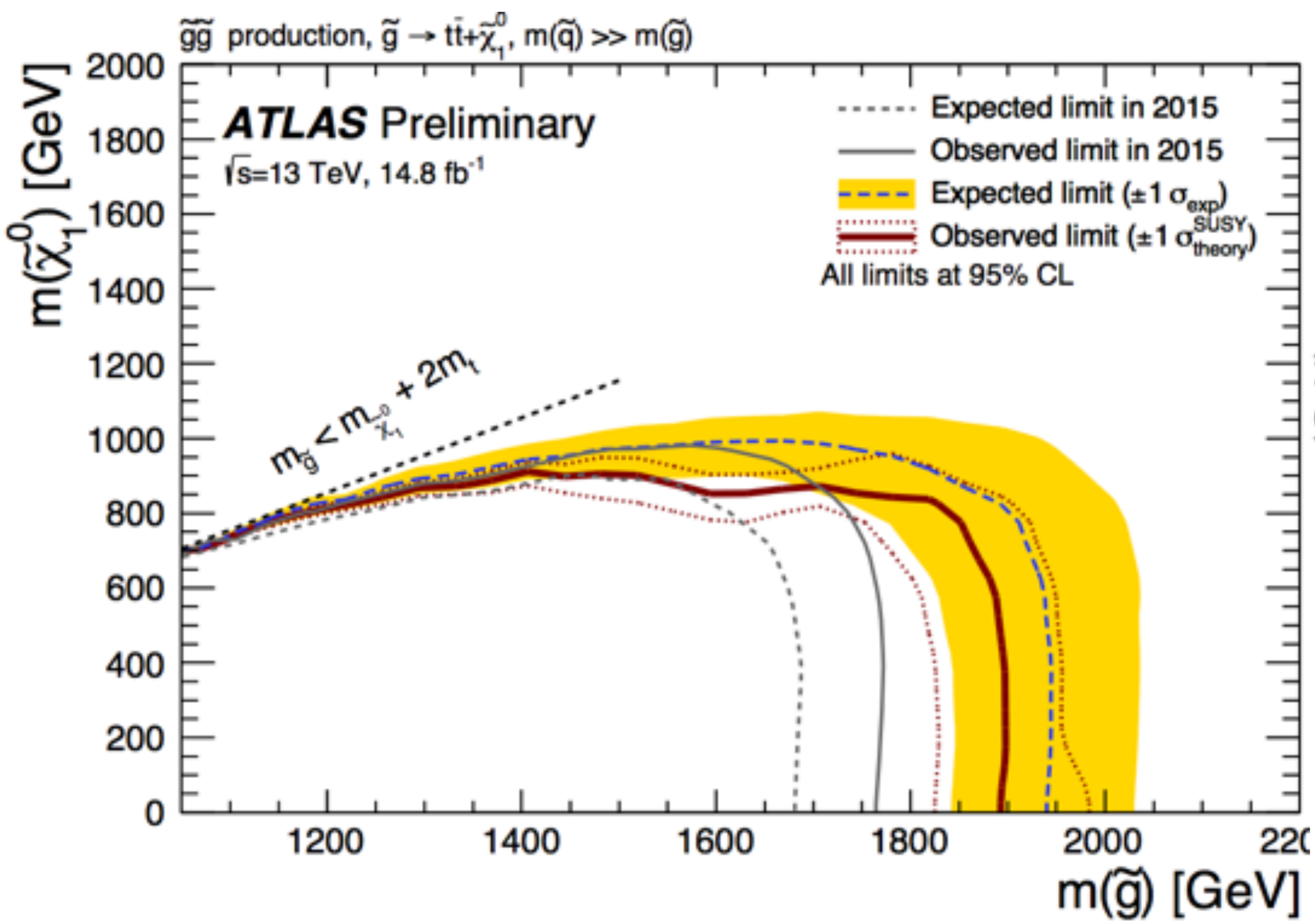
The Recursive Jigsaw Reconstruction technique

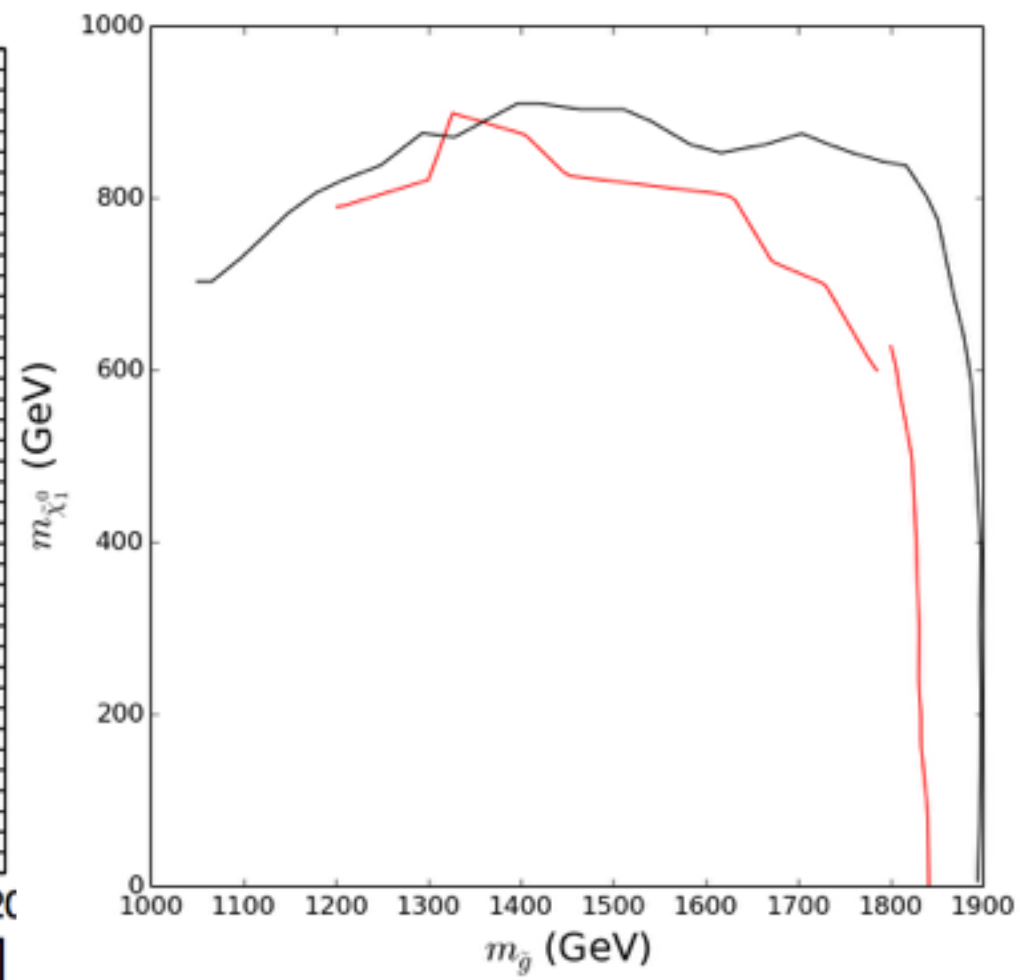
Targeted signal	$\tilde{q}\bar{\tilde{q}}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$					
Requirement	Signal Region					
	RJR-S1		RJR-S2		RJR-S3	
$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}} \geq$	0.6		0.55		0.5	
$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}} \leq$	0.95		0.96		0.98	
$p_{\mathrm{PP},z}^{\mathrm{lab}}/\left(p_{\mathrm{PP},z}^{\mathrm{lab}} + H_{T\,2,1}^{\mathrm{PP}}\right) \leq$	0.5		0.55		0.6	
$p_{j2,T}^{\mathrm{PP}}/H_{T\,2,1}^{\mathrm{PP}} \geq$	0.16		0.15		0.13	
Δ_{QCD} >	0.001					
	RJR-S1a	RJR-S1b	RJR-S2a	RJR-S2b	RJR-S3a	RJR-S3b
$H_{T\,2,1}^{\mathrm{PP}}$ [GeV] >	1000	1200	1400	1600	1800	2000
$H_{1,1}^{\mathrm{PP}}$ [GeV] >	1000		1400		1600	



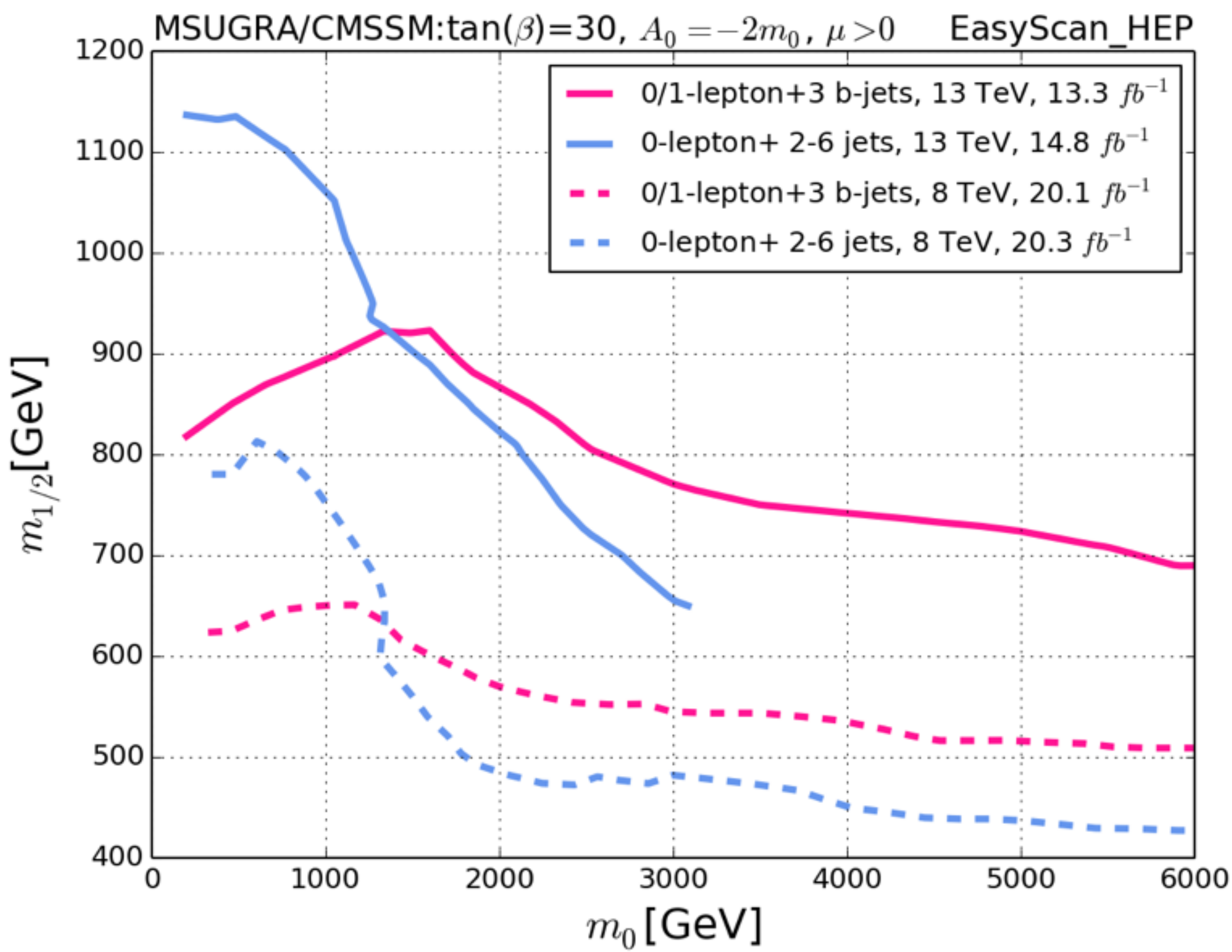


ATLAS 13TeV 14.8 /fb 0/1 lepton + 3 bjets + MET

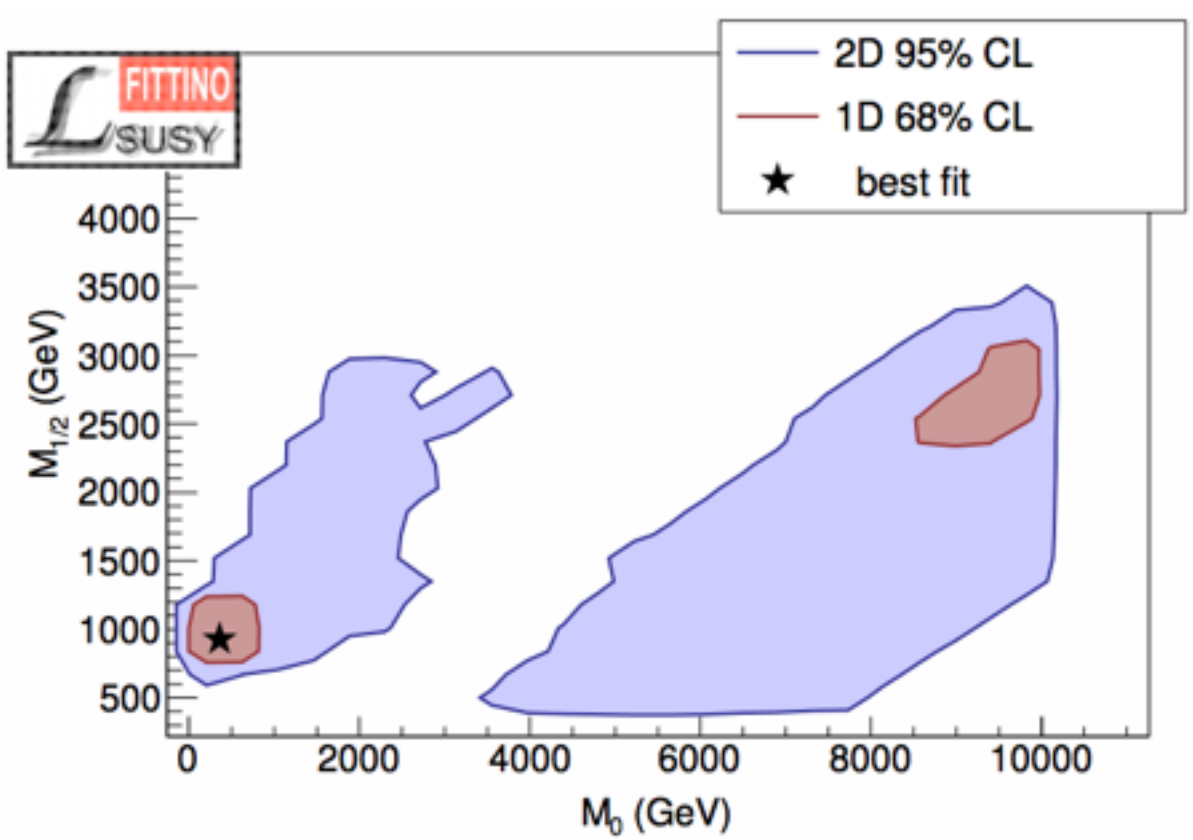


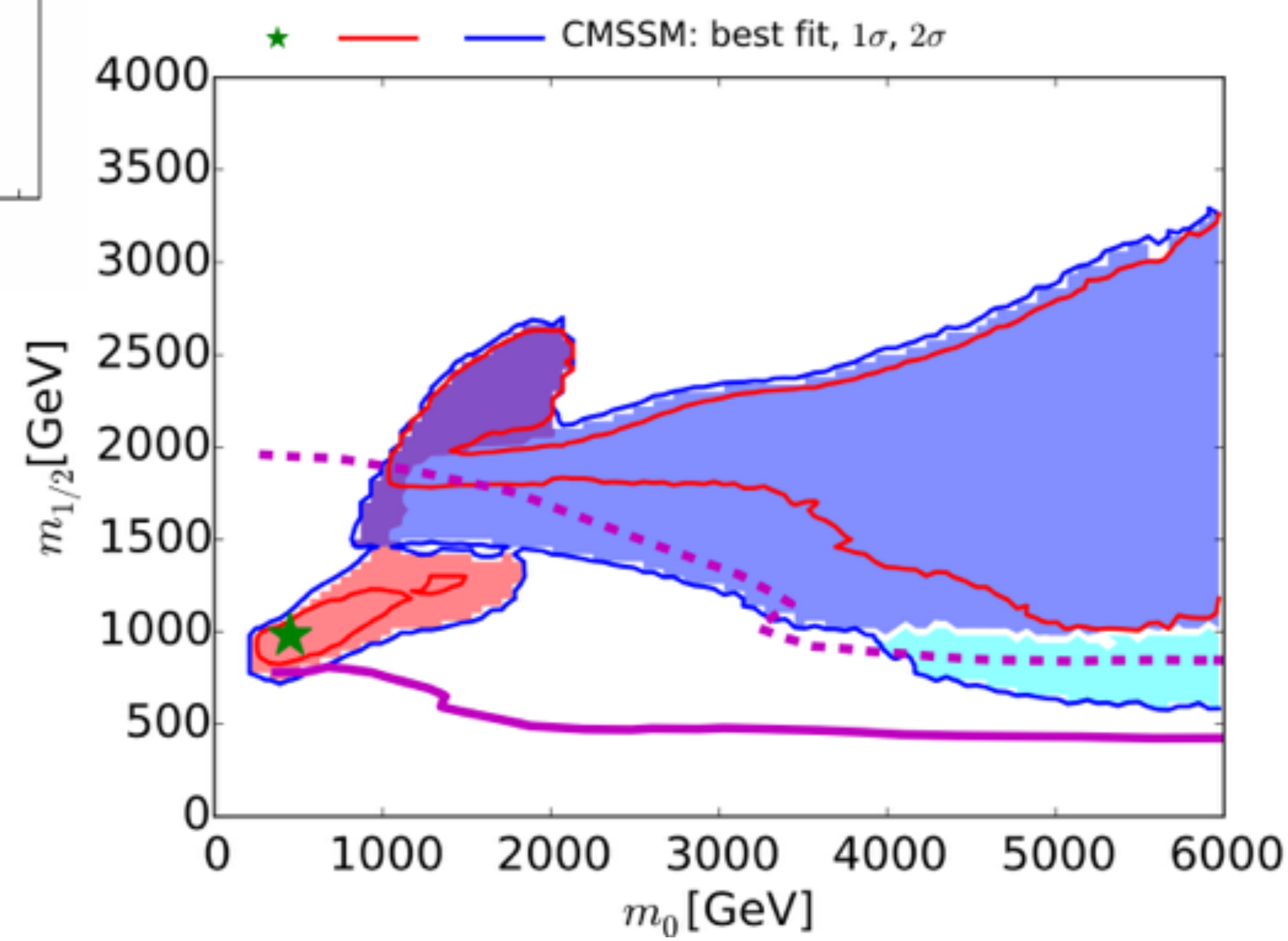


Limits from LHC SUSY search



Estimate the impact of 13 TeV LHC





Impact of 13 TeV LHC and LUX WS2014-16

Input parameter	Prior fuction	Range
M_0 (GeV)	Flat, Log	100, 10000
$M_{1/2}$ (GeV)	Flat, Log	100, 4000
A_0 (GeV)	Flat	-10000, 10000
$\tan\beta$	FLAS	2.0, 65.0
sign(μ)	Fixed	+1
m_t	Gaussian	172.9±0.91

CMSSM	ATLAS 7 TeV	32.6/23	8.8%	340	910	2670	12
$\mu > 0$	$\text{ATLAS}_{20/\text{fb}}$ (low)	35.8/23	4.3%	670	1040	3440	21
	$\text{ATLAS}_{20/\text{fb}}$ (high)	35.1/23	5.1%	5650	2100	-780	51
CMSSM	$\text{ATLAS}_{20/\text{fb}}$ (low)	38.9/23	2.0%	330	970	3070	10
$\mu < 0$	$\text{ATLAS}_{20/\text{fb}}$ (high)	36.6/23	3.6%	6650	2550	-3150	39

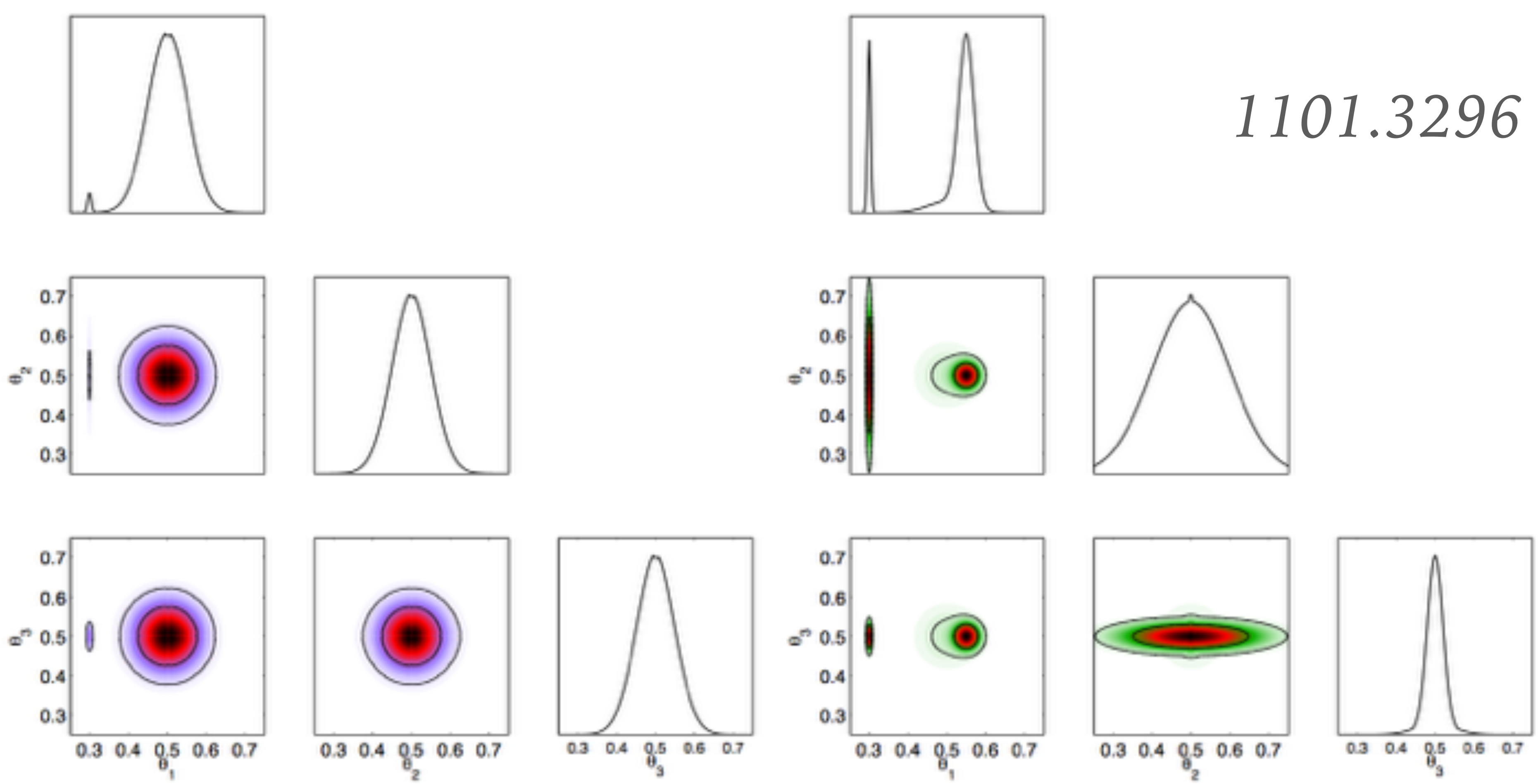
Constraints on a single parameter of interest

The Bayesian marginal pdf:

$$p(\theta_i|\mathbf{D}) = \int p(\mathbf{\Theta}|\mathbf{D}) d\theta_1 ... d\theta_{i-1} d\theta_{i+1} ... d\theta_n.$$

The frequentist profile likelihood function:

$$\mathcal{L}(\theta_i) = \max_{\theta_1,...,\theta_{i-1},\theta_{i+1},...,\theta_n} \mathcal{L}(\mathbf{\Theta}).$$



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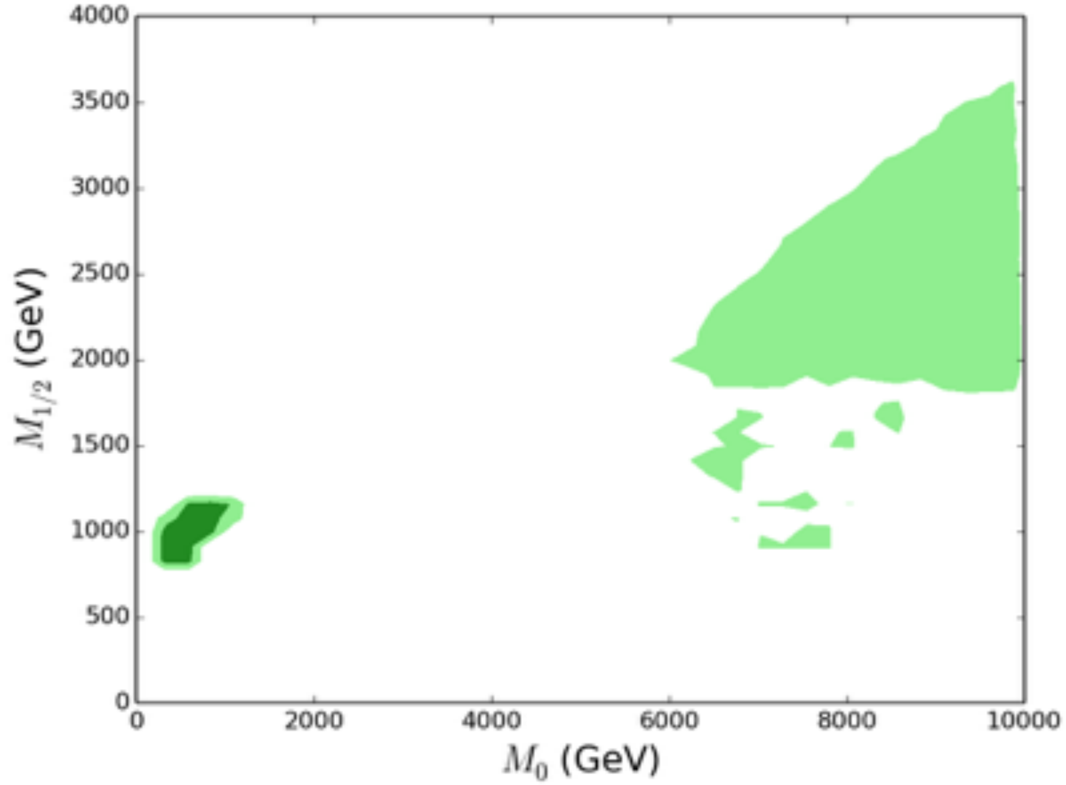
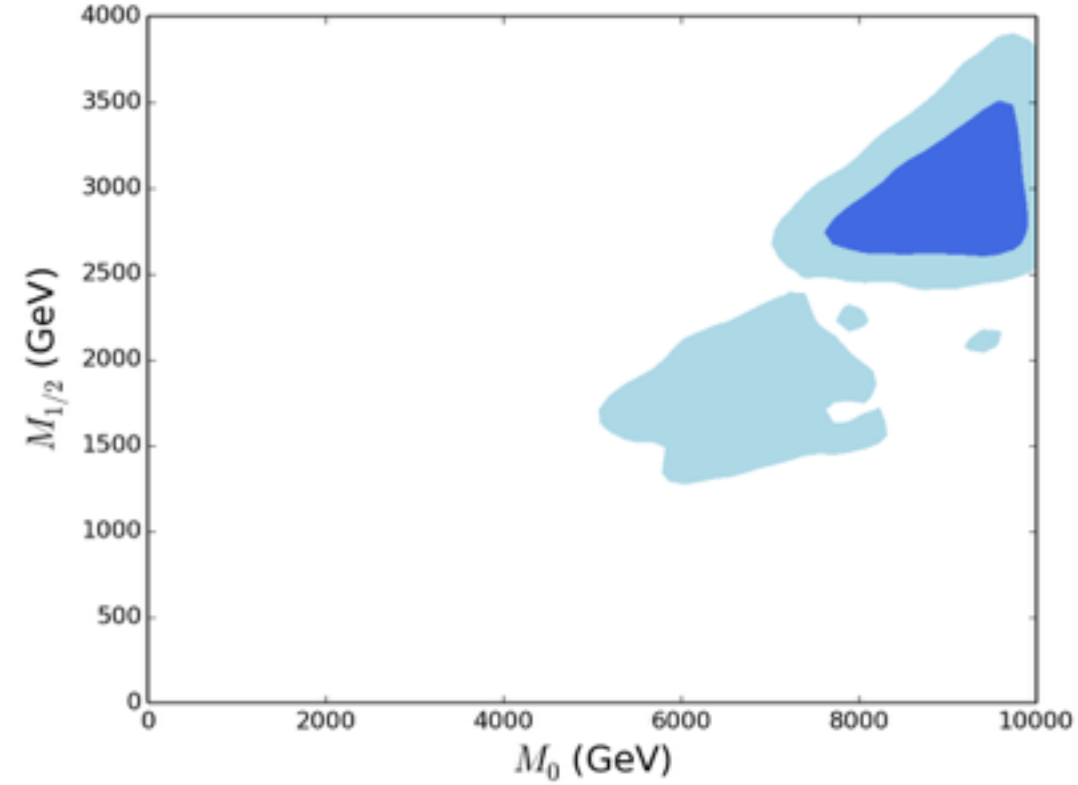
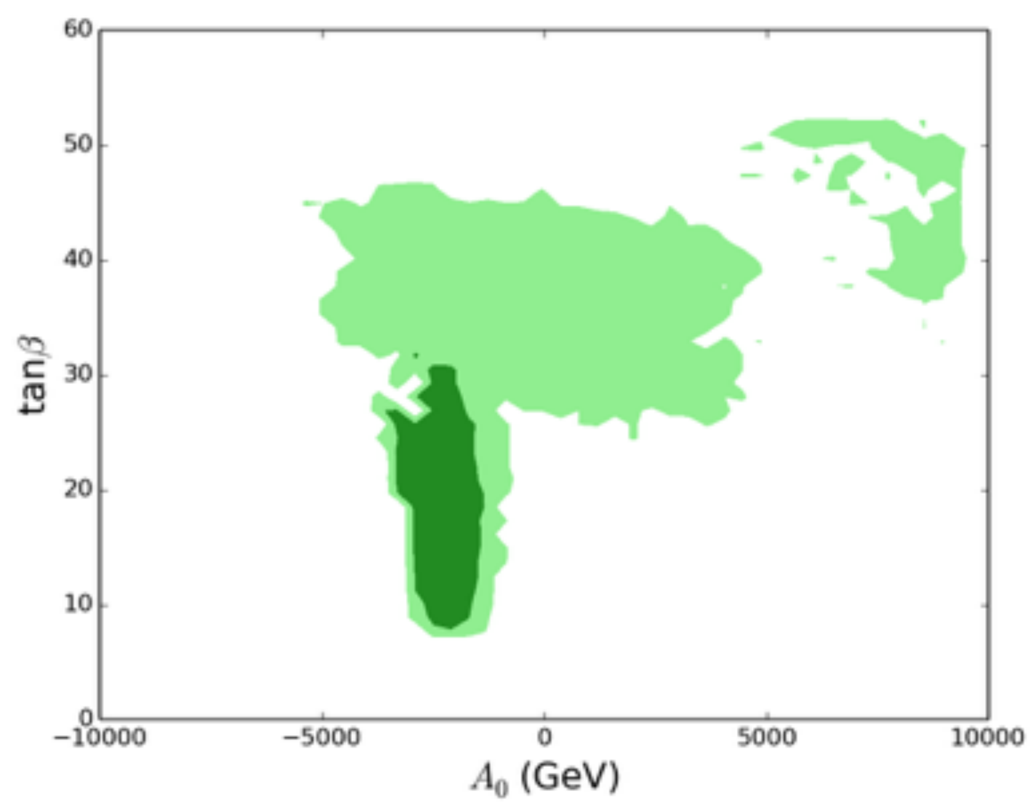
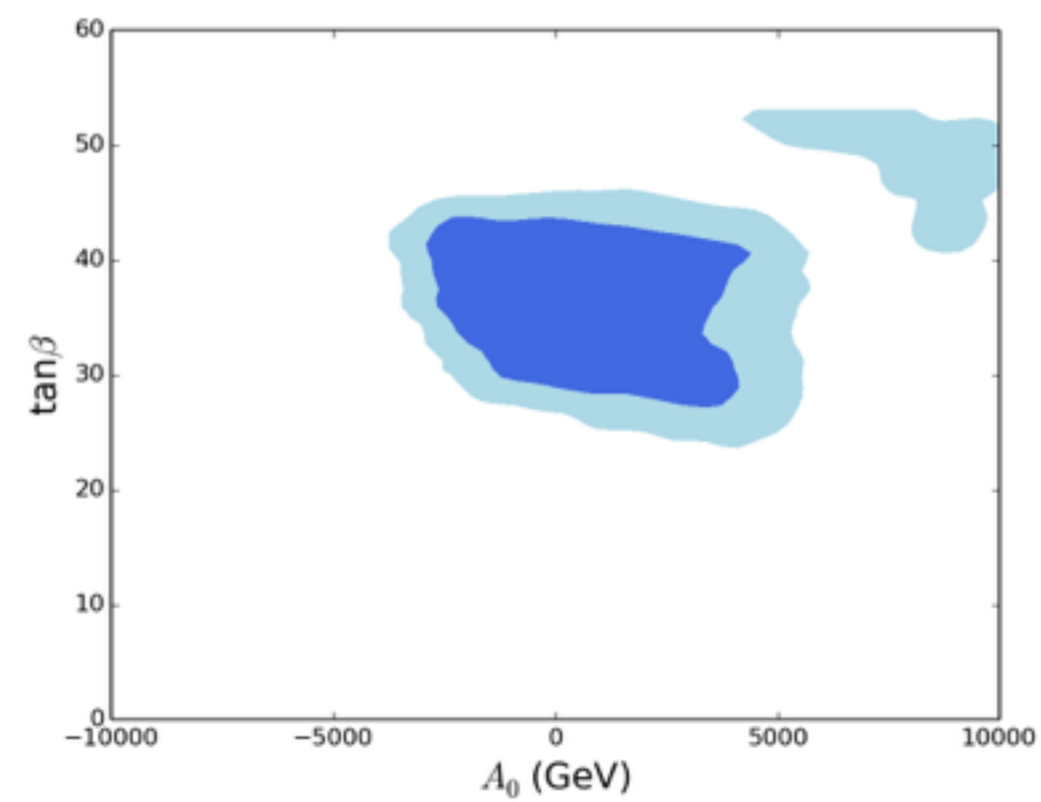
Impact of 13 TeV LHC and LUX WS2014-16



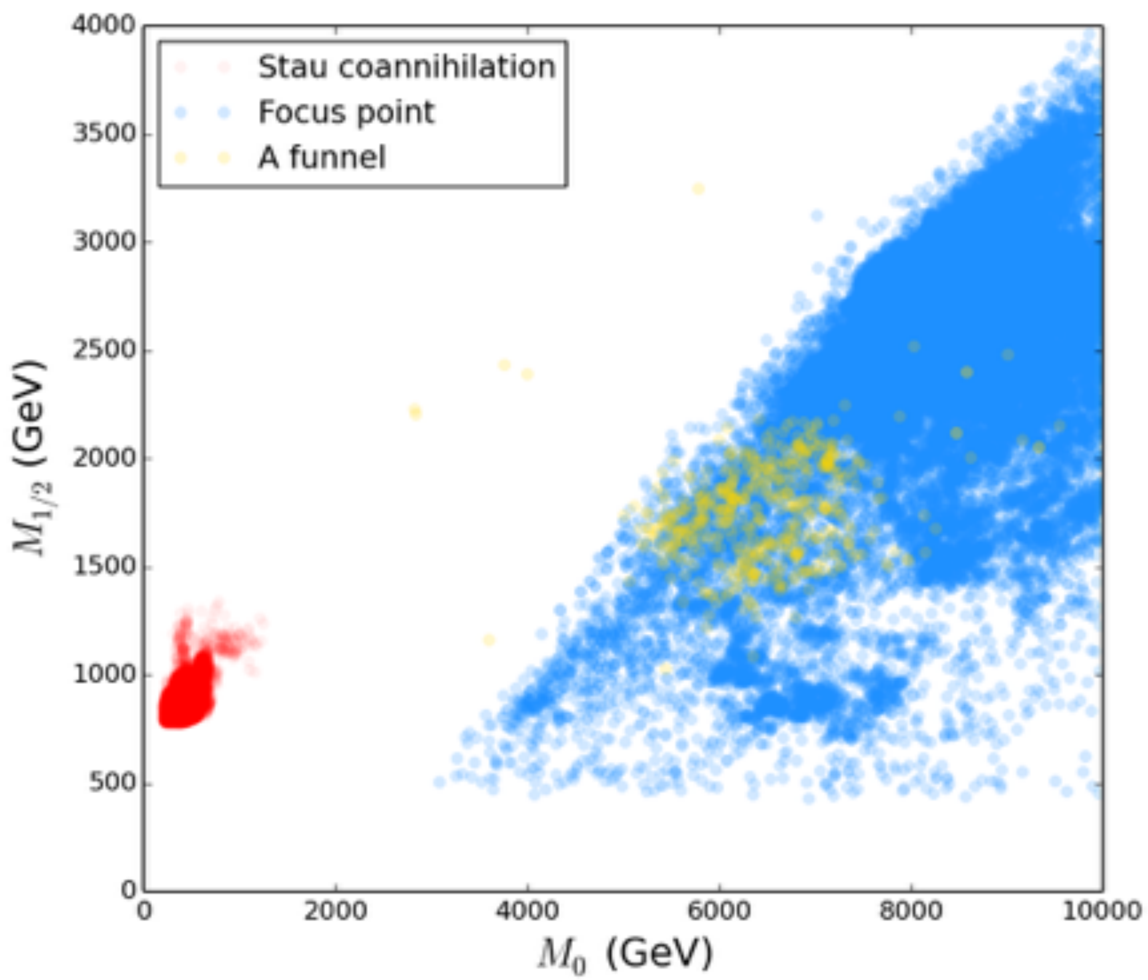


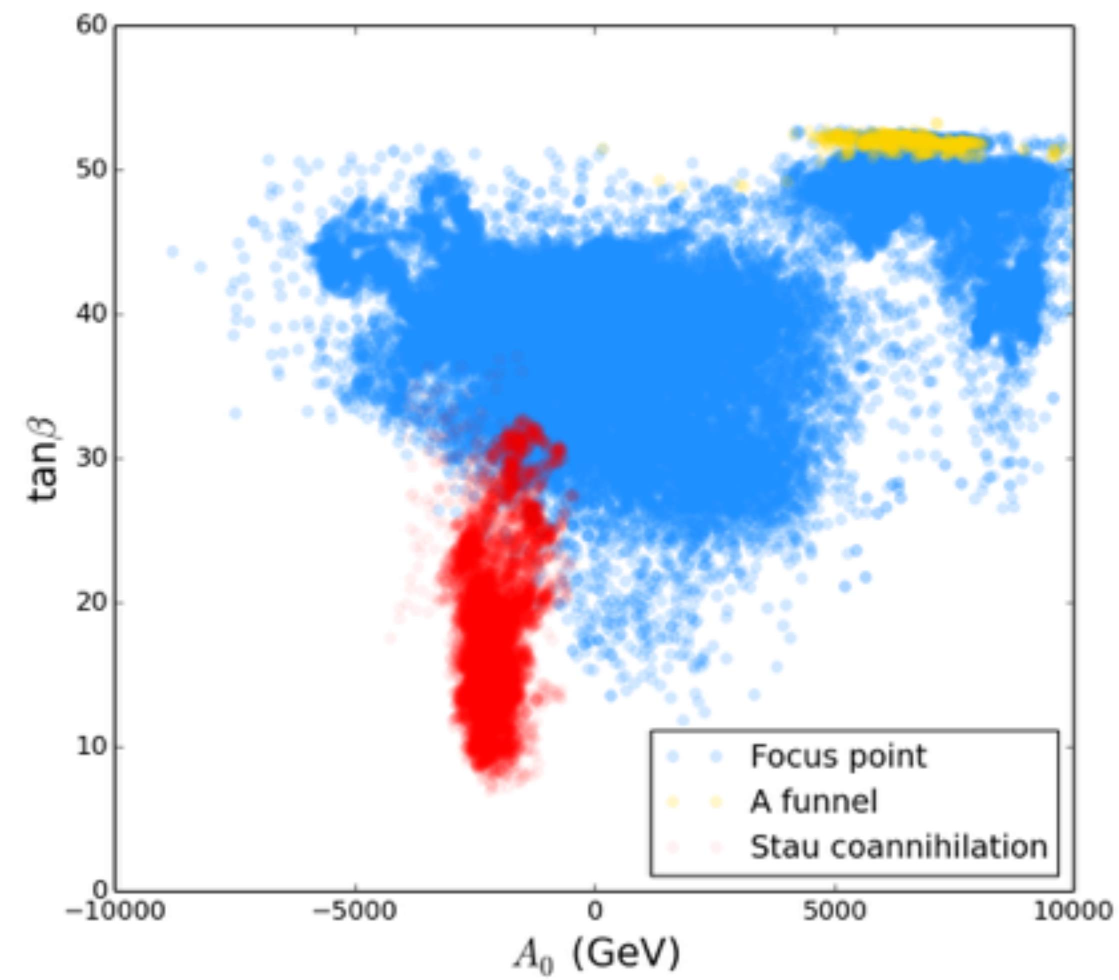




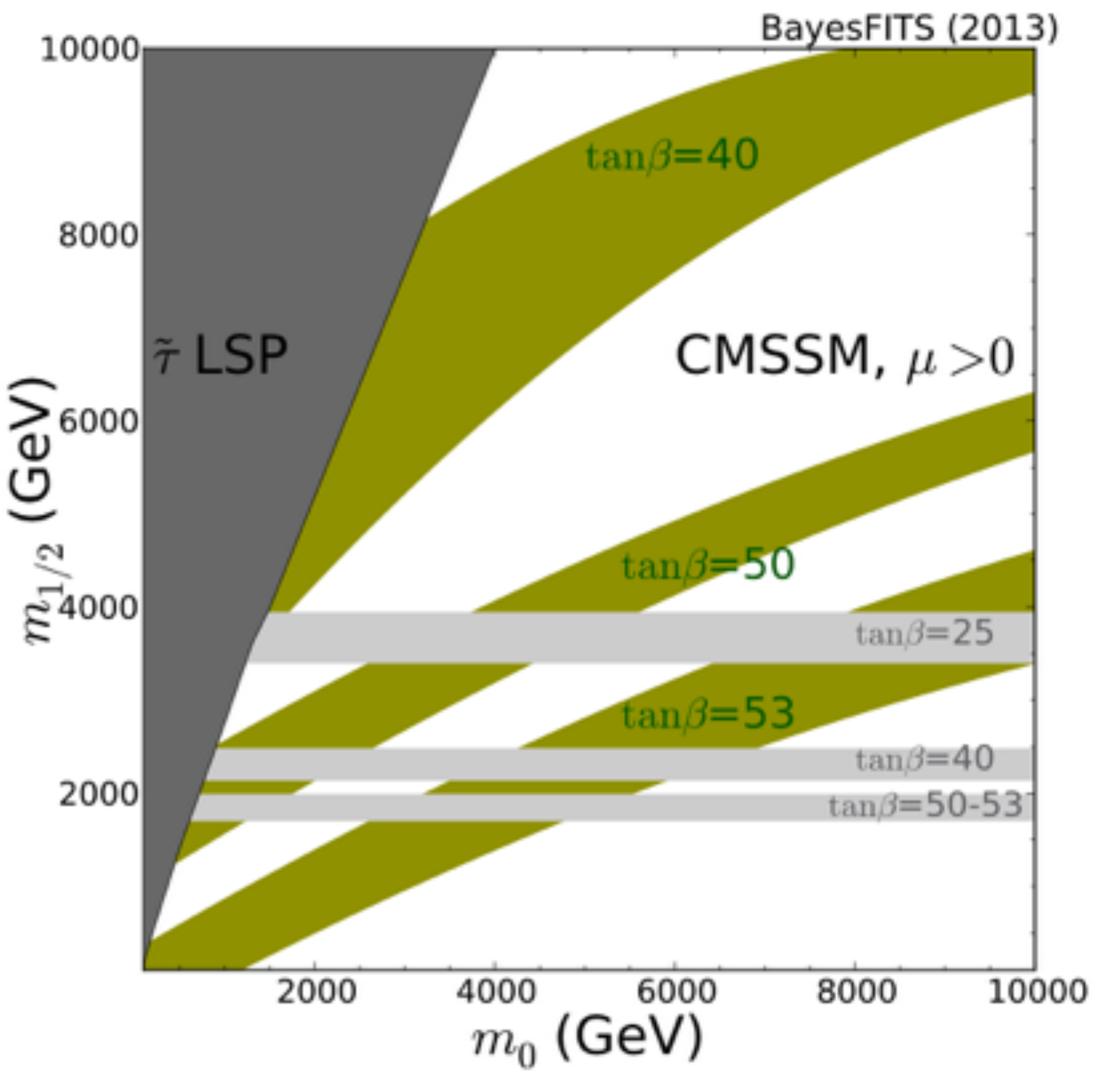
Dark matter annihilation mechanisms

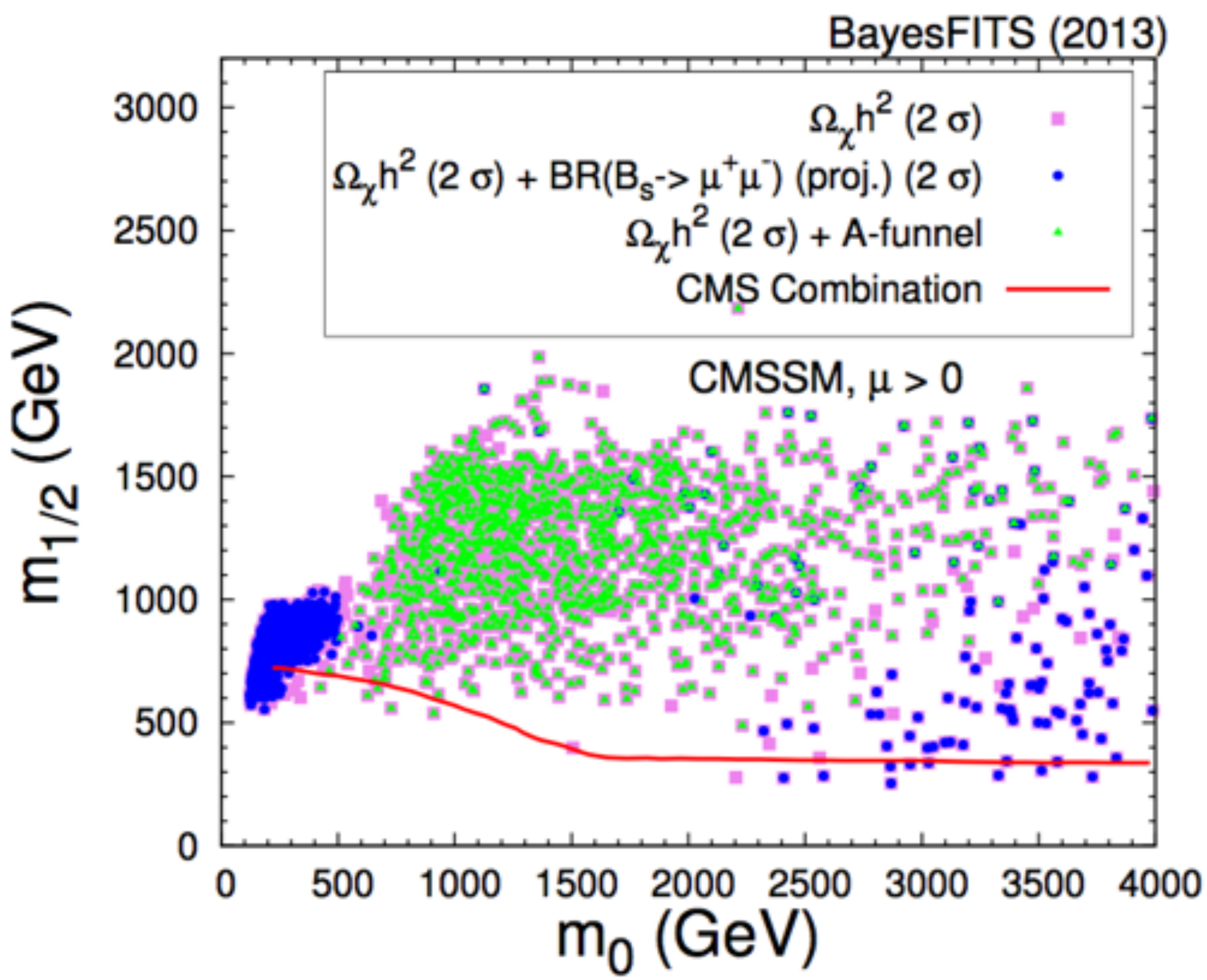
$\tilde{\tau}_1$ coannihilation: $m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0} - 1 < 0.15$
A/H funnel: $|m_A/2m_{\tilde{\chi}_1^0} - 1| < 0.2$
Focus Point: $|\mu/m_{\tilde{\chi}_1^0} - 1| < 0.4$





A Funnel region





$\text{BR}\left(B_s \to \mu^+\mu^-\right)_{\text{current}} \times 10^9$	3.2	+1.5 − 1.2, 10% (0.32)	Gaussian	[5]
$\text{BR}\left(B_s \to \mu^+\mu^-\right)_{\text{proj}} \times 10^9$	3.5 (3.2*)	0.18 (0.16*), 5% [0.18 (0.16*)]	Gaussian	[5]

$$3.5 + \sqrt{0.18^2 + 0.18^2} = 4$$

$BR(B_s^0 \to \mu^+\mu^-) \times 10^9$	2.9	0.7	0.29	arXiv:1411.4413

$$2.9 + \sqrt{0.7^2 + 0.29^2} = 4.4$$

Before the conclusion

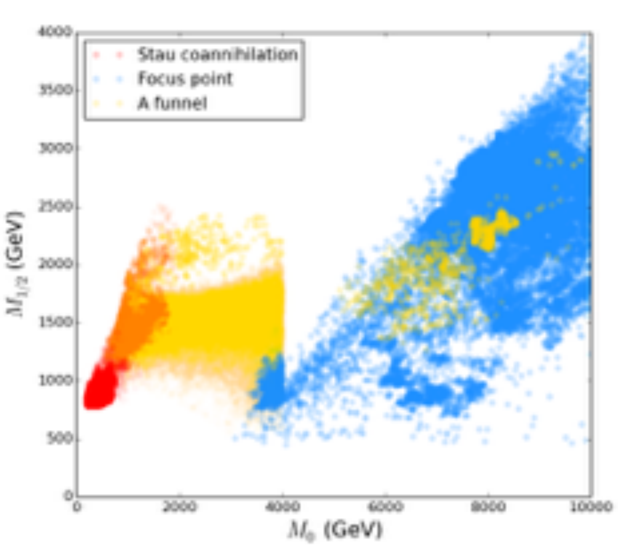
Observable	Mean value	Standard deviation Experimental	Standard deviation Theoretical	Ref.
m_W [GeV]	80.385	0.015	0.01	[57]
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.231 53	0.00016	0.00010	[58]
Γ_Z [GeV]	2.495 2	0.0023	0.001	[59]
$\Gamma_Z^{\rm inv}$ [GeV]	0.499	0.0015	0.001	[57]
$\sigma^0_{\rm had}$ [nb]	41.540	0.037	-	[59]
R^0_ℓ	20.767	0.025	-	[59]
R^0_b	0.216 29	0.00066	-	[59]
R^0_c	0.172 1	0.003	-	[59]
$BR(B \to X_s\gamma) \times 10^4$	3.55	0.26	0.30	[57]
$\frac{BR(B_u\to\tau\nu)}{BR(B_u\to\tau\nu)_{\rm SM}}$	1.62	0.57	-	[60]
$BR(B^0_s \to \mu^+\mu^-) \times 10^9$	2.9	1.1	0.38	[61]
$\Omega_\chi h^2$	0.118 6	0.0031	0.012	[62]
m_h [GeV]	125.36	0.41	2.0	[63]

1508.05951

$a_\mu - a_\mu^{\rm SM}$	$(28.7 \pm 8.0) \times 10^{-10}$	[82, 83]
$\sin^2\theta_{\rm eff}$	0.23113 ± 0.00021	[84]
m_t	$(173.34 \pm 0.27 \pm 0.71)$ GeV	[85]
m_W	(80.385 ± 0.015) GeV	[86]
Δm_s	$(17.719 \pm 0.036 \pm 0.023)\,{\rm ps}^{-1}$	[87]
$\mathscr{B}(B_s \to \mu\mu)$	$(2.90 \pm 0.70) \times 10^{-9}$	[88]
$\mathscr{B}(b \to s\gamma)$	$(3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$	[89]
$\mathscr{B}(B \to \tau\nu)$	$(1.05 \pm 0.25) \times 10^{-4}$	[87]

1606.03577

1608.00872



i	Observable $\mu_i(\theta)$	Constraint $D_i^{\rm non\text{-}DCS}$	Likelihood function $L[D_i^{\rm non\text{-}DCS}\|\mu_i(\theta)]$	Comment
1	$\mathcal{B}({\rm b}\to{\rm s}\gamma)$ [45]	$(3.43 \pm 0.21^{\rm stat} \pm 0.24^{\rm th} \pm 0.07^{\rm sys}) \times 10^{-4}$	Gaussian	reweight
2	$\mathcal{B}({\rm B_s}\to\mu\mu)$ [46]	$(2.9 \pm 0.7 \pm 0.29^{\rm th}) \times 10^{-9}$	Gaussian	reweight
3	$R({\rm B}\to\tau\nu)$[45]	1.04 ± 0.34	Gaussian	reweight
4	Δa_μ [47]	$(26.1 \pm 6.3^{\rm exp} \pm 4.9^{\rm SM} \pm 10.0^{\rm SUSY}) \times 10^{-10}$	Gaussian	
5	$\alpha_s(m_Z)$ [48]	0.1184 ± 0.0007	Gaussian	
6	m_t [49]	$173.20 \pm 0.87^{\rm stat} \pm 1.3^{\rm sys}$ GeV	Gaussian	reweight
7	$m_b(m_b)$ [48]	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian	
8	m_h	LHC: $m_h^{\rm low} = 120$ GeV, $m_h^{\rm high} = 130$ GeV	1 if $m_h^{\rm low} \leq m_h \leq m_h^{\rm high}$ 0 if $m_h < m_h^{\rm low}$ or $m_h > m_h^{\rm high}$	reweight
9	μ_h	CMS and ATLAS in LHC Run 1, Tevatron	LILITH 1.01 [50, 51]	post-MCMC
10	sparticle masses	LEP [52] (via MICROMEGAs [53–55])	1 if allowed 0 if excluded	

13 TeV LHC and LUX WS2014-16

CMSSM

Most of the Stau coannihilation are excluded by 13 TeV LHC.

Some of the focus point region are excluded by the new LUX data.

There are some parameter space in A funnel region which will be very hard to be detected.

13 TeV LHC and LUX WS2014-16

CMSSM

TANK YOU!

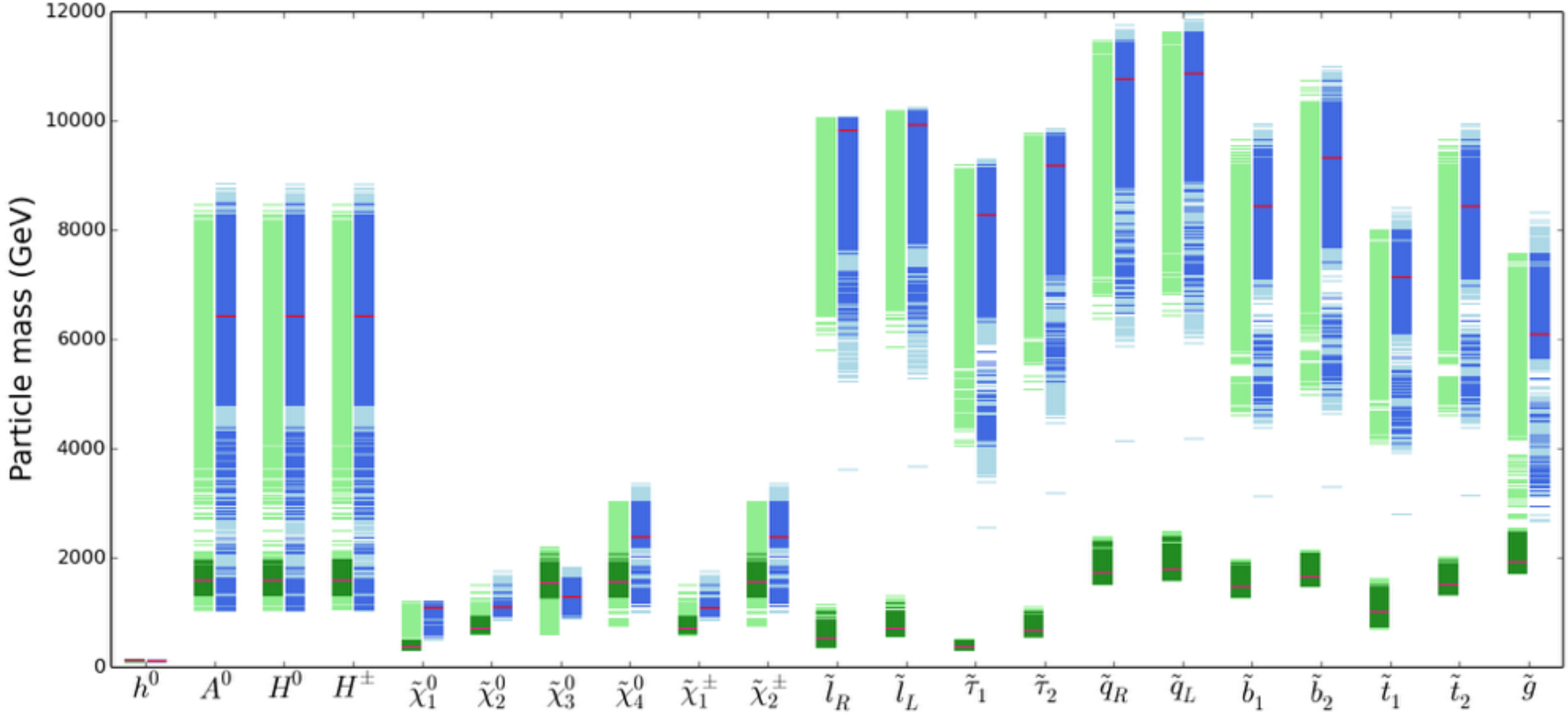
张阳

中科院理论物理所

2016.09.23 郑州大学

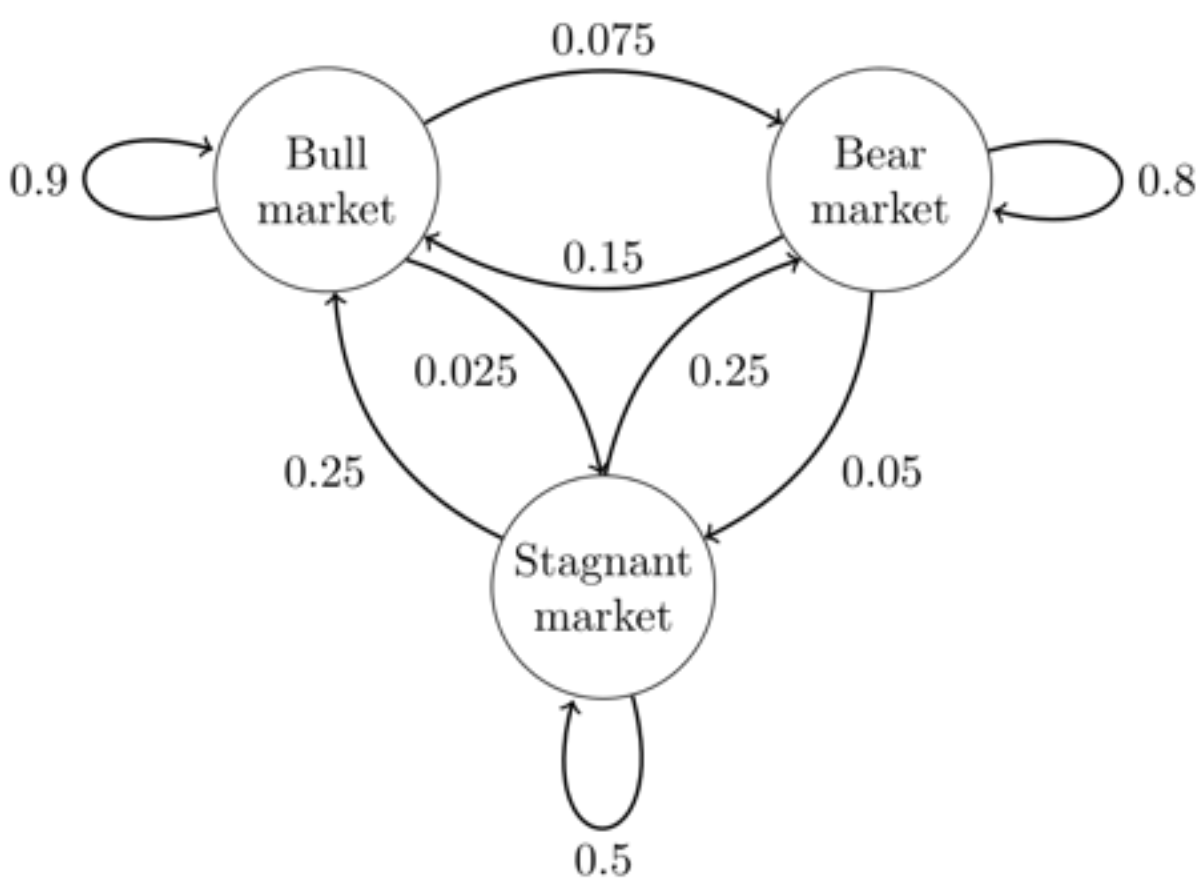
BACKUP

The Higgs and supersymmetric particle mass spectrum



MARKOV CHAIN

A discrete-time Markov chain is a sequence of random variables X1, X2, X3, … with the Markov property, namely that the probability of moving to next state depends only on the present state and not on the previous states.



$$\begin{aligned} x^{(n+3)} &= \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0.9 & 0.075 & 0.025 \\ 0.15 & 0.8 & 0.05 \\ 0.25 & 0.25 & 0.5 \end{bmatrix}^3 \\ &= \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0.7745 & 0.17875 & 0.04675 \\ 0.3575 & 0.56825 & 0.07425 \\ 0.4675 & 0.37125 & 0.16125 \end{bmatrix} \\ &= \begin{bmatrix} 0.3575 & 0.56825 & 0.07425 \end{bmatrix}. \end{aligned}$$

$$\lim_{N \to \infty} P^N = \begin{bmatrix} 0.625 & 0.3125 & 0.0625 \\ 0.625 & 0.3125 & 0.0625 \\ 0.625 & 0.3125 & 0.0625 \end{bmatrix}$$

MARKOV CHAIN MONTE CARLO

构造一个转移矩阵为P的马氏链，使得该马氏链的平稳分布恰好是p(x), 那么我们从任何一个初始状态x0出发沿着马氏链转移, 得到一个转移序列 x0,x1,x2,⋯xn,xn+1⋯,， 如果马氏链在第n步已经收敛了，于是我们就得到了 π(x) 的样本xn,xn+1⋯。

MetropolisHastingsSampler(π_0, q, T, x_0)

1 $\mathcal{S} \leftarrow \emptyset$.

2 **for** $t \leftarrow 1$ **to** T,

3 Sample $x_* \sim q(.|x_{t-1})$ and $u \sim \mathcal{U}_{(0,1)}$.

4 Form the acceptance ratio

$$\rho = \min\left(1, \frac{\pi_0(x_*)}{q(x_*|x_{t-1})} \frac{q(x_{t-1}|x_*)}{\pi_0(x_{t-1})}\right).$$

5 **if** $u < \rho$, **then** $x_t \leftarrow x_*$ **else** $x_t \leftarrow x_{t-1}$.

6 $\mathcal{S} \leftarrow \mathcal{S} \cup \{x_t\}$.