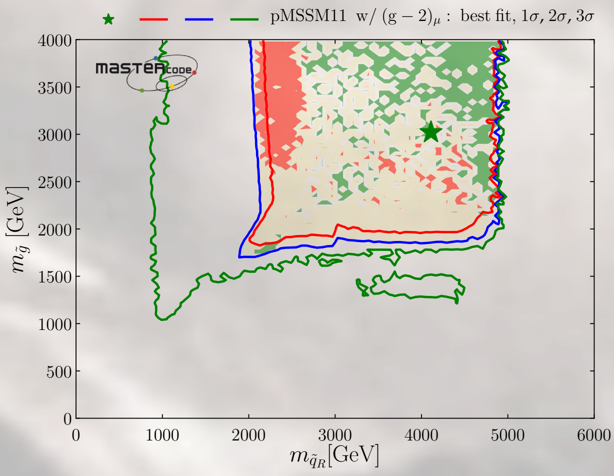
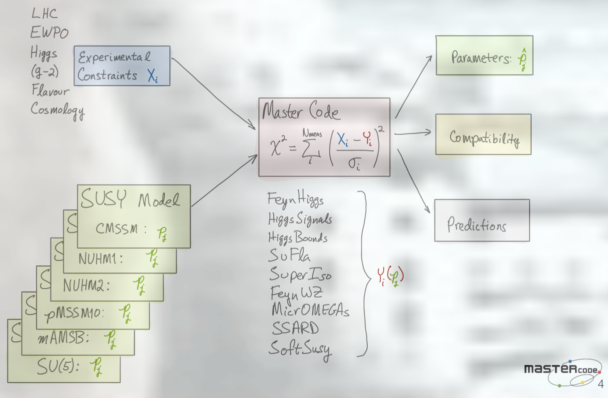
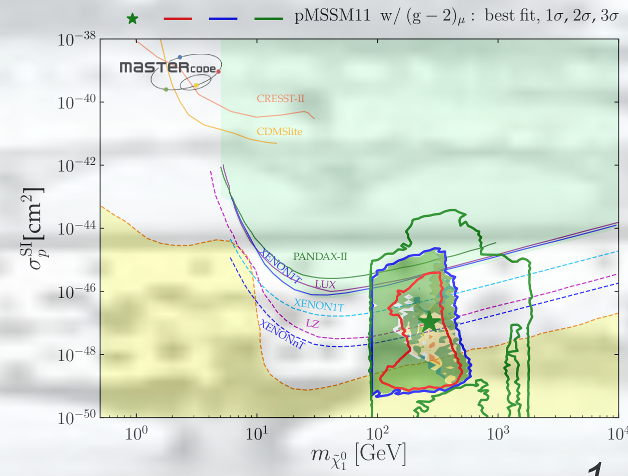
STATISTICAL ANALYSIS OF THE MSSM AFTER THE LHC 13 TEV DATA WITH MASTERCODE

Oliver Buchmueller, Imperial College London

GALILEO GALILEI INSTITUTE CONFERENCE: "COLLIDER PHYSICS AND THE COSMOS" OCT 9-13, 2017

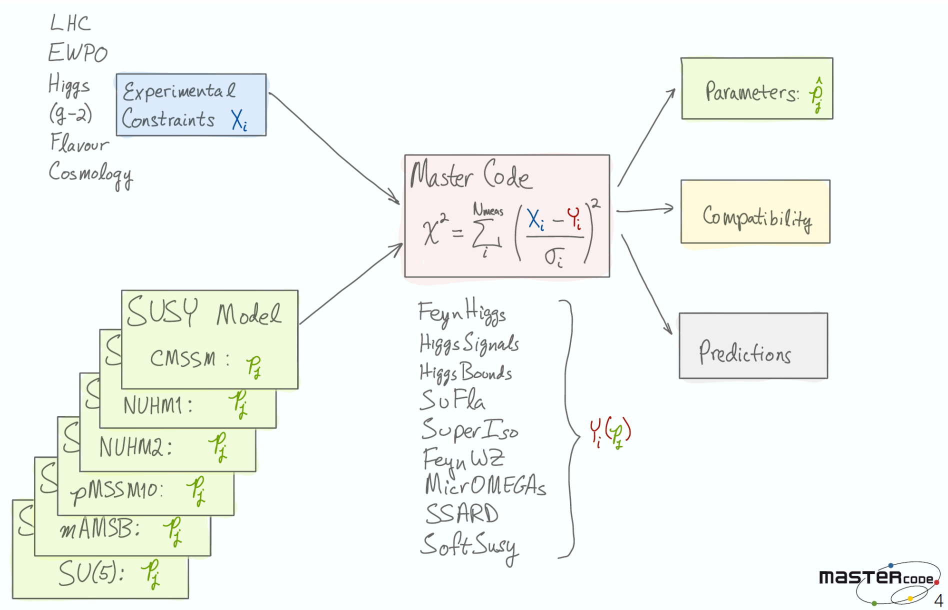




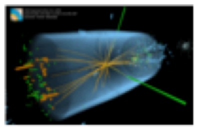
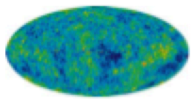
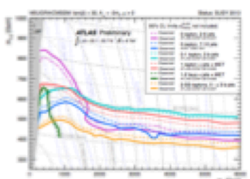
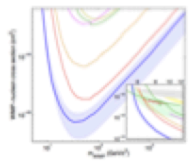


MasterCode in a Nutshell

Global Fit to indirect and direct constraints on SUSY!



Source:
http://mastercode.web.cern.ch/mastercode/

Direct Constraints	Indirect Constraints	Dark Matter Constraints
 Lightest Higgs	Mw, Z-pole $(g-2)_\mu$ Electroweak observables	 CMB
 SUSY particles	Flavour observables	 Direct Detection

Observable	Source Th./Ex.	Constraint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
m_t [GeV]	[43]	173.2 ± 0.90	0.05	0.06	-
$\Delta\alpha^{(5)}_{had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{SUSY}$	0.078	0.047	0.14
σ^0_{had} [nb]	[26] / [44]	41.540 ± 0.037	2.50	2.57	2.54
R_l	[26] / [44]	20.767 ± 0.025	1.05	1.08	1.08
$A_{fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
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R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{fb}(c)$	[26] / [44]	0.0707 ± 0.0035	0.86	0.88	0.80
A_b	[26] / [44]	0.923 ± 0.020	0.36	0.36	0.35
A_c	[26] / [44]	0.670 ± 0.027	0.005	0.005	0.005
A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{SUSY}$	1.77	1.39	2.08
$a^{EXP}_\mu - a^{SM}_\mu$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4 [\pm 1.5_{SUSY}]$	0.0	0.0	0.0
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$BR(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
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$BR^{EXP/SM}_{B\to X_s \ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
σ^{SI}_p	[25]	$(m_{\chi^0_1}, \sigma^{SI}_p)$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Dark Matter in Supersymmetry with MasterCode

Global Fit to indirect and direct constraints on SUSY!

O. Buchmueller[a], R. Cavanaugh[b,c], A. De Roeck[d,e], M.J. Dolan[f], J.R. Ellis[g,d], H. Flächer[h], S. Heinemeyer[i], G. Isidori[j,d], J. Marrouche[a], D. Martínez Santos[k], K.A. Olive[l], S. Rogerson[a], F.J. Ronga[m], K.J. de Vries[a], G. Weiglein[n]

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[l]William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

[m]Institute for Particle Physics, ETH Zürich, CH–8093 Zürich, Switzerland

[n]DESY, Notkestrasse 85, D–22607 Hamburg, Germany

…b.cern.ch/mastercode/

…straint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
± 0.90	0.05	0.06	-
± 0.00010	0.009	0.004	-
± 0.0021	2.7×10^{-5}	0.26	-
…23 $\pm 0.001_{SUSY}$	0.078	0.047	0.14
± 0.037	2.50	2.57	2.54
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…4.5	0.0	0.0	0.0
…$_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
…$_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
…14_{EXP+TH}	0.27	0.37	0.33
…56 $\pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
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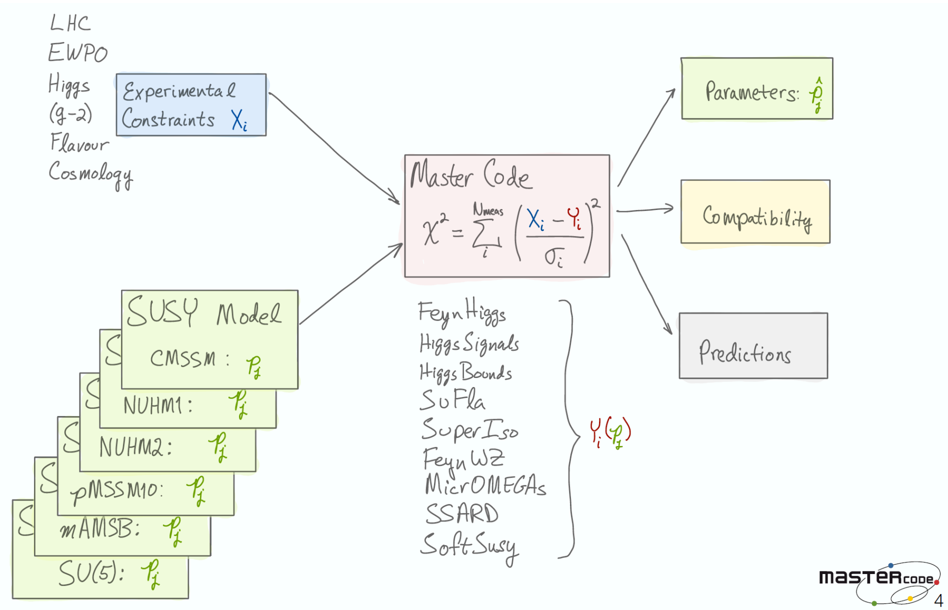

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Direct Constraints | Indirect Constraints | Dark Matter Constraints

Other "global Fitters" with similar studies are:
Fittino group: [see e.g. arXiv:1508.05951]
http://flcwiki.desy.de/Fittino
Gambit group: [see e.g. arXiv:1705.07917]
https://gambit.hepforge.org
SuperBayeS: [see e.g. arXiv:1507.07008]

SUSY particles | Flavour observables | Direct Detection

MasterCode Collaboration Today

Some History:

- Founded by interested experimentalists and theorists in 2007

- Has produced more than a dozen of publications (so far)

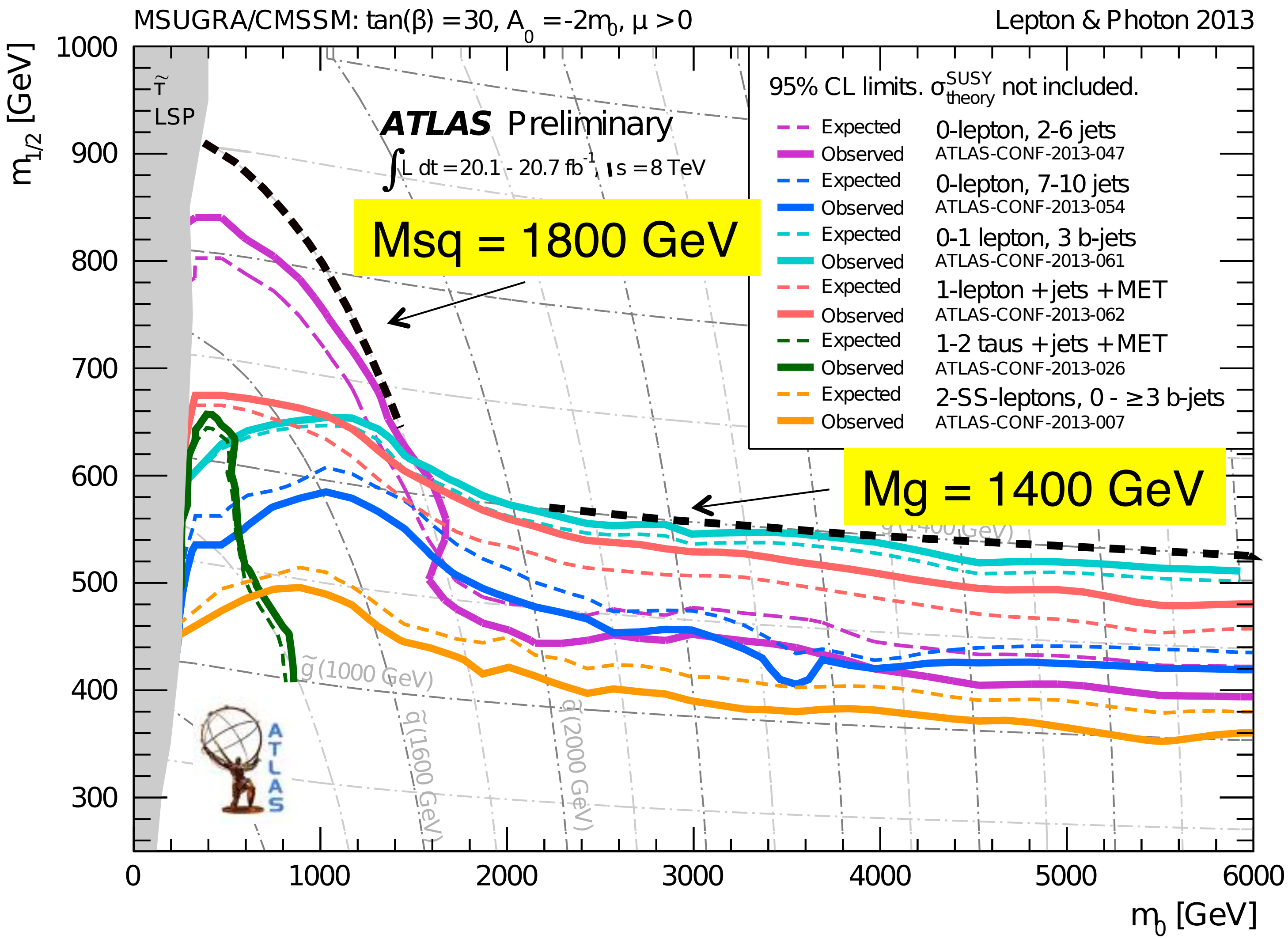
- Total citations >1000 (so far)

[0] MasterCode Collaboration, http://mastercode.web.cern.ch/mastercode
[1] Eur. Phys. J. C77, no.4 (2017), 1612.05210
[2] Eur. Phys. J. C77, no.4 (2017), 1610.10084
[3] Eur. Phys. J. C75, 500 (2015), 1508.01173
[4] Eur. Phys. J. C75, 9, 422 (2015), 1504.03260
[5] Eur.Phys.J. C74, 12, 3212 (2014), 1408.4060
[6] Eur.Phys.J. C74, 6, 2922 (2014), 1312.5250
[7] Eur.Phys.J. C74, 3, 2809 (2014), 1312.5233
[8] Eur.Phys.J. C72, 2243 (2012), 1207.7315
[9] Eur.Phys.J. C72, 2020 (2012), 1112.3564
[10] Eur.Phys.J. C72, 1878 (2012), 1110.3568
[11] Eur.Phys.J. C71, 1722 (2011), 1106.2529
[12] Eur.Phys.J. C71, 1634 (2011), 1102.4585
[13] Eur.Phys.J. C71, 1583 (2011), 1011.6118
[14] Phys.Rev. D81, 035009 (2010), 0912.1036
[15] Eur.Phys.J. C64, 391 (2009), 0907.5568
[16] JHEP 0809, 117 (2008), 0808.4128
[17] Phys.Lett. B657, 87 (2007), 0707.3447

Note: all MasterCode shown this part are published.

IMPACT OF LHC RUN 1 ON SUSY PARAMETER SPACE

Inclusive SUSY Searches in 2013



Imperial College London

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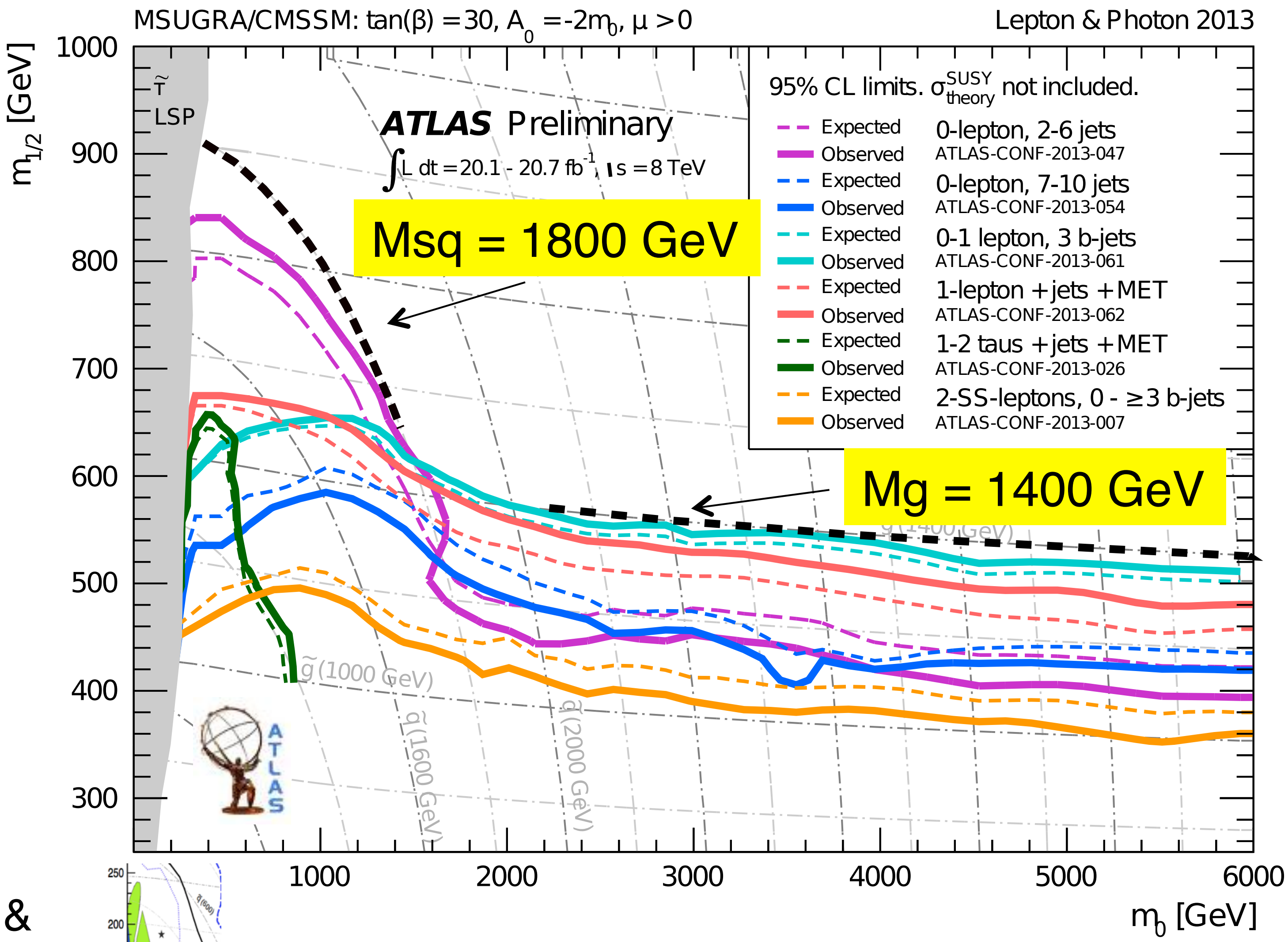
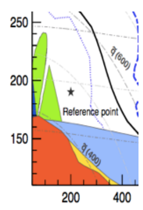


LEP & Tevatron



The LHC has pushed the mass scale in constraint SUSY models to a new level!

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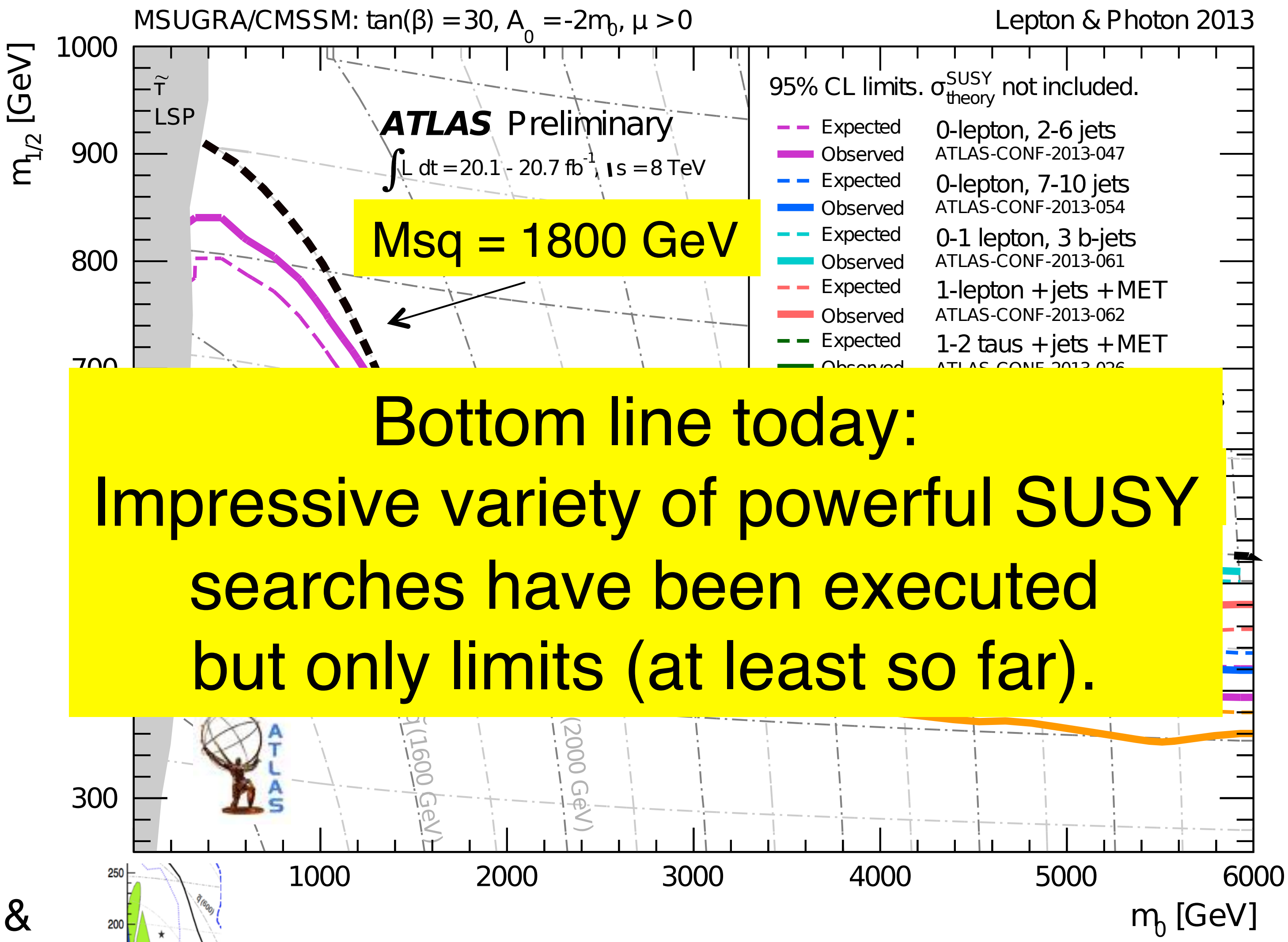
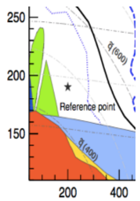


Bottom line today:
Impressive variety of powerful SUSY searches have been executed but only limits (at least so far).

LEP & Tevatron



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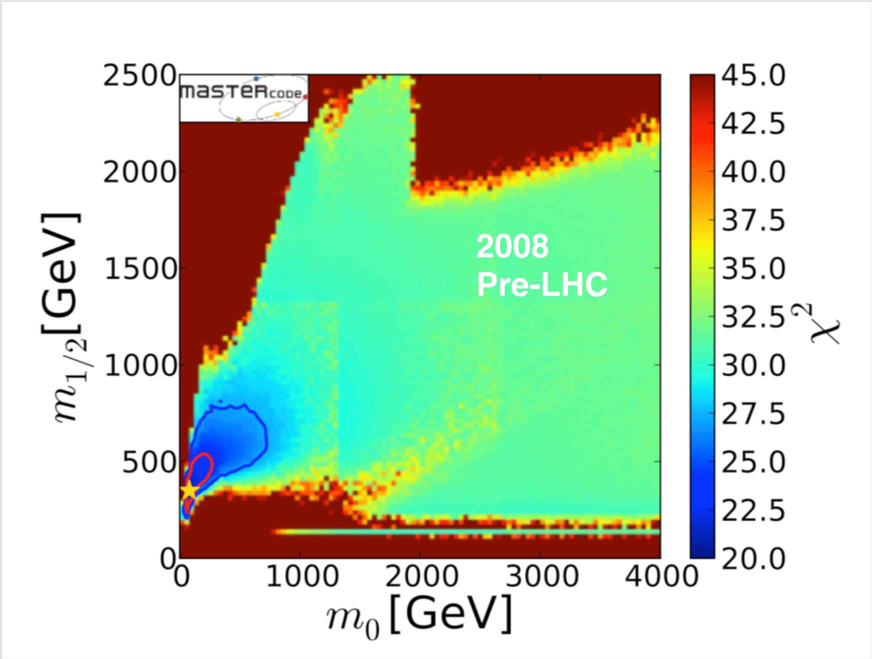
CMSSM: Evolution with time



X[2] increase from bluish to reddish

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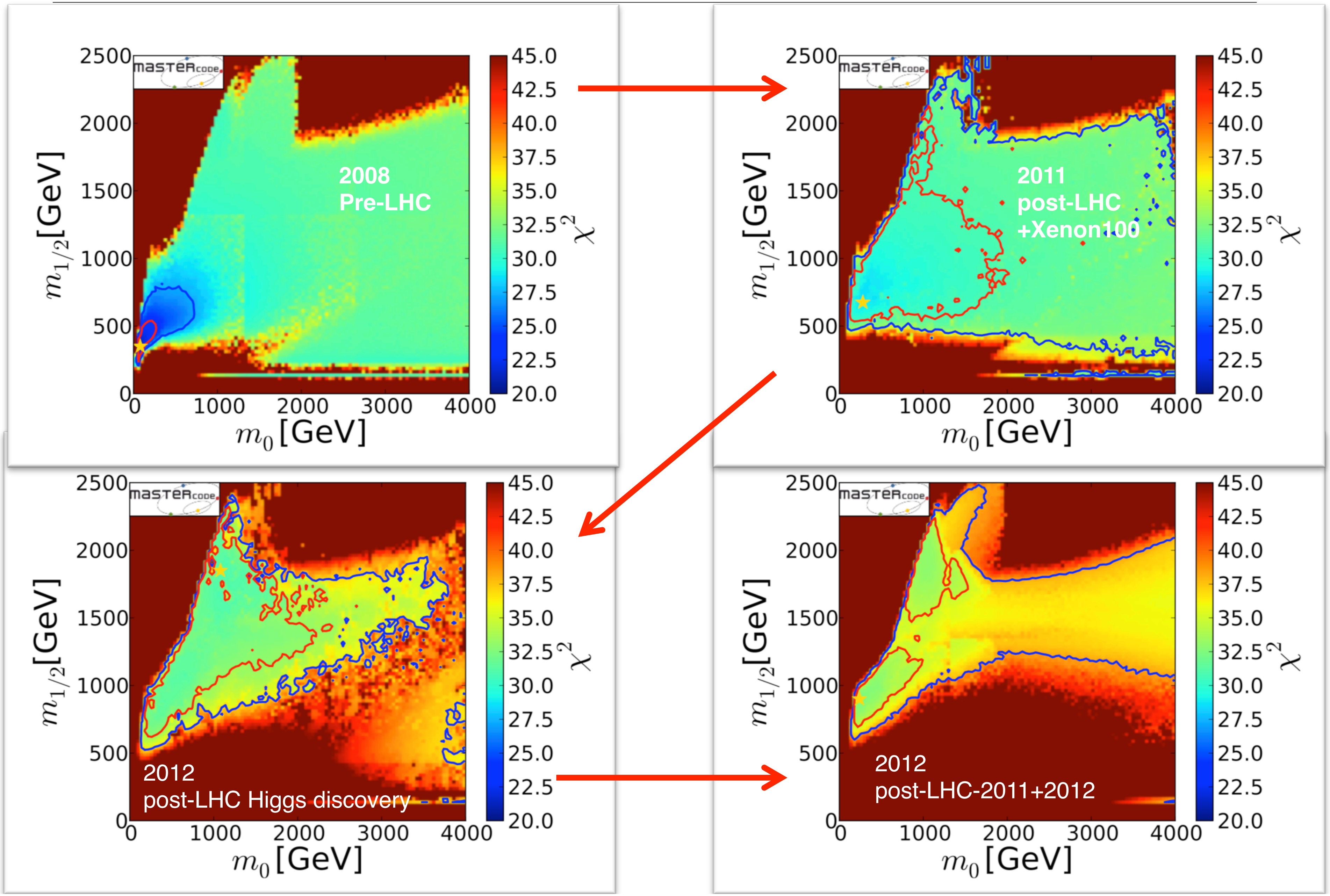
$BR(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6 [\pm 0.01_{SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR^{EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
σ_p^{SI}	[25]	$(m_{\chi^0_1}, \sigma_p^{SI})$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

Other "fitter" groups fond very similar Results for this time frame: e.g.
SuperBayeS: **arXiv:1212.2636**
Fittino group: **arXiv:1204.4199**

CMSSM: Evolution with time



MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

pMSSM10

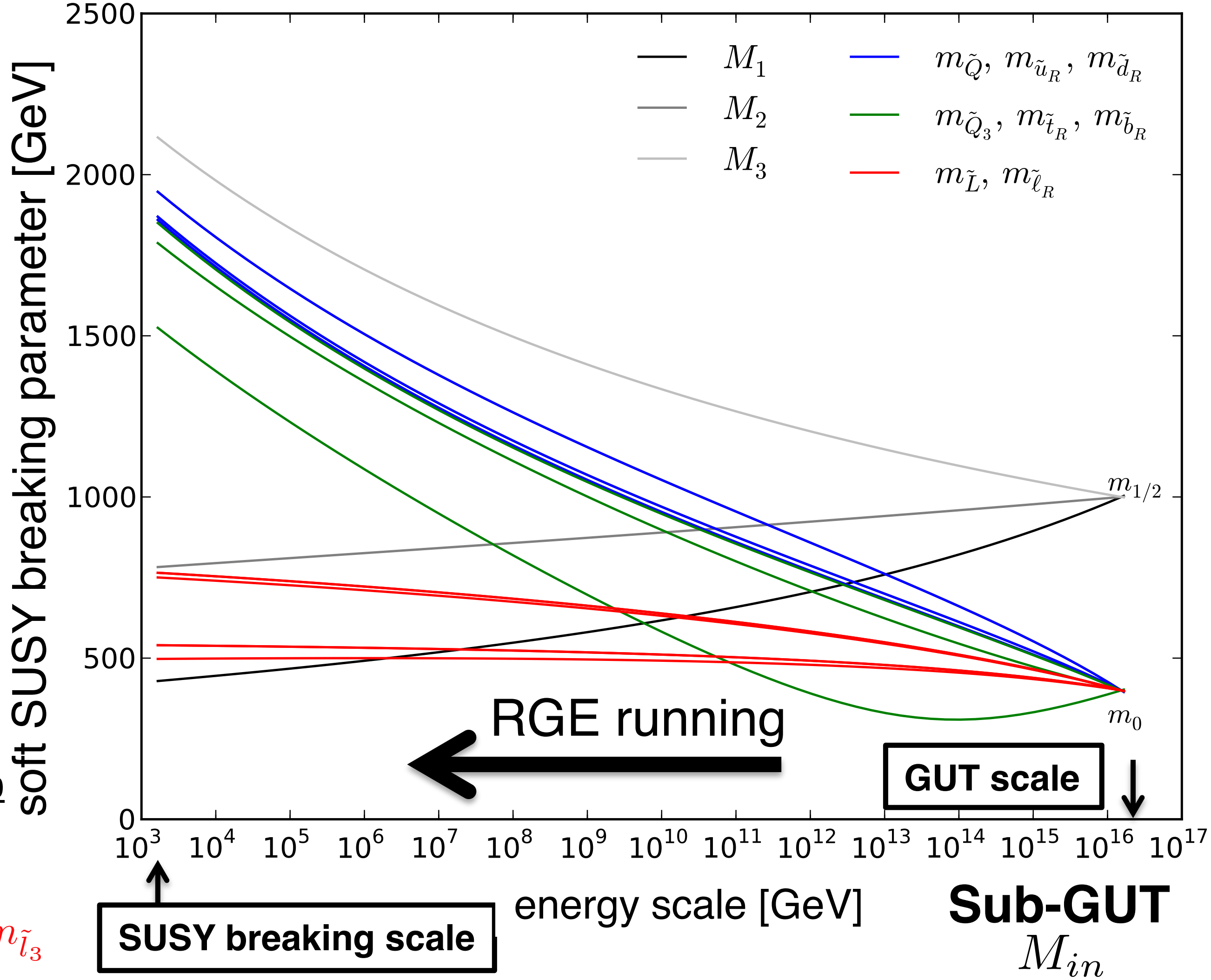
M_1, M_2, M_3, $m_{\tilde{q}12}$, $m_{\tilde{q}3}$, $m_{\tilde{\ell}}$, A, M_A, $\tan\beta$, μ

arXiv:1504.03260

pMSSM11

$m_{\tilde{l}} \to m_{\tilde{l}_{12}}, m_{\tilde{l}_3}$

in preparation



Sub-GUT

M_{in}

in preparation

CMSSM

$m_0, \; m_{1/2},$

$A_0, \; \tan\beta$

arXiv:1312.5250

NUHM1

$m^2_{H_u} = m^2_{H_d}$

arXiv:1312.5250

NUHM2

$m^2_{H_u} \neq m^2_{H_d}$

arXiv:1408.4060

SU5

$m_0 \to m_5, m_{10}$

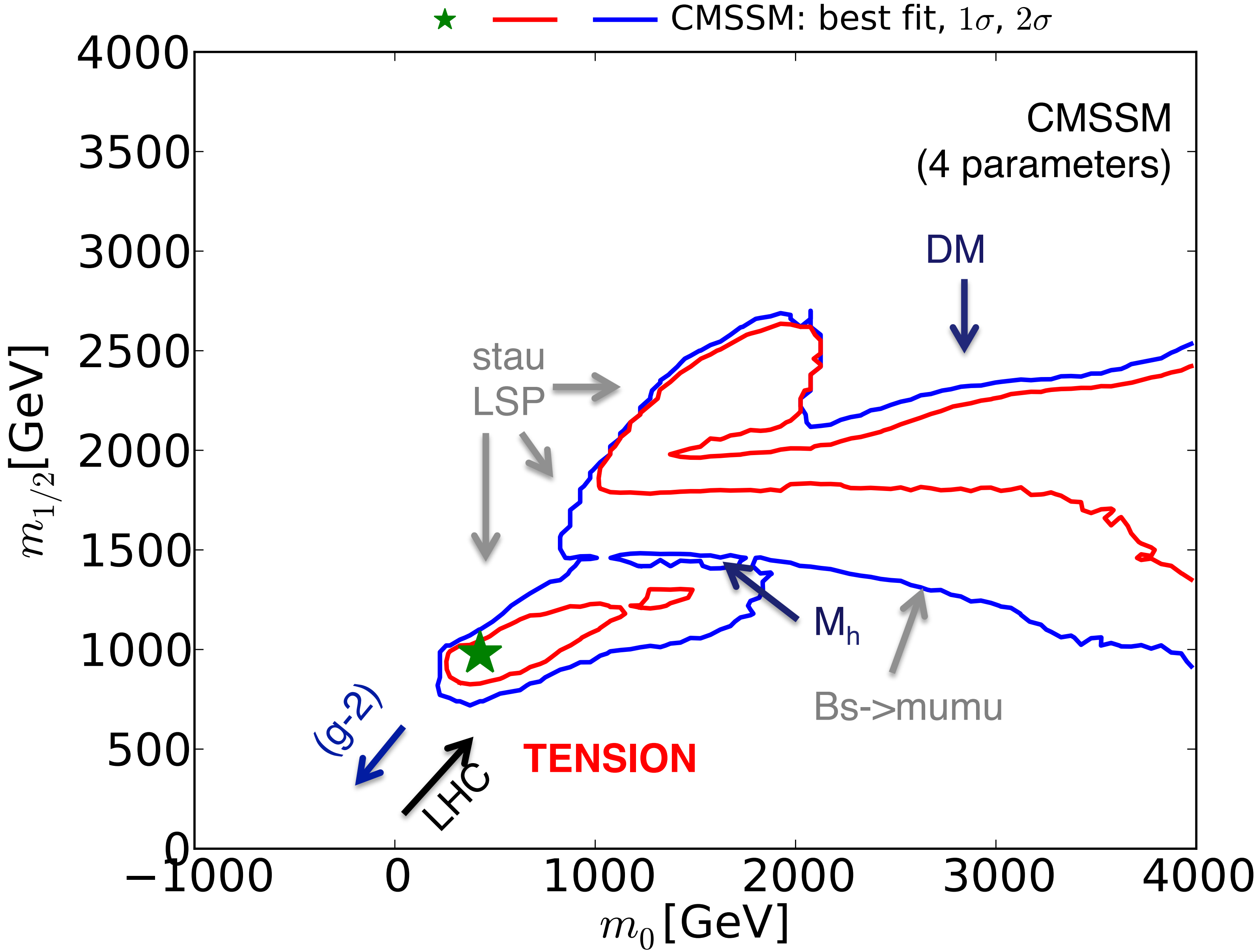
arXiv:1610.10084

AMSB

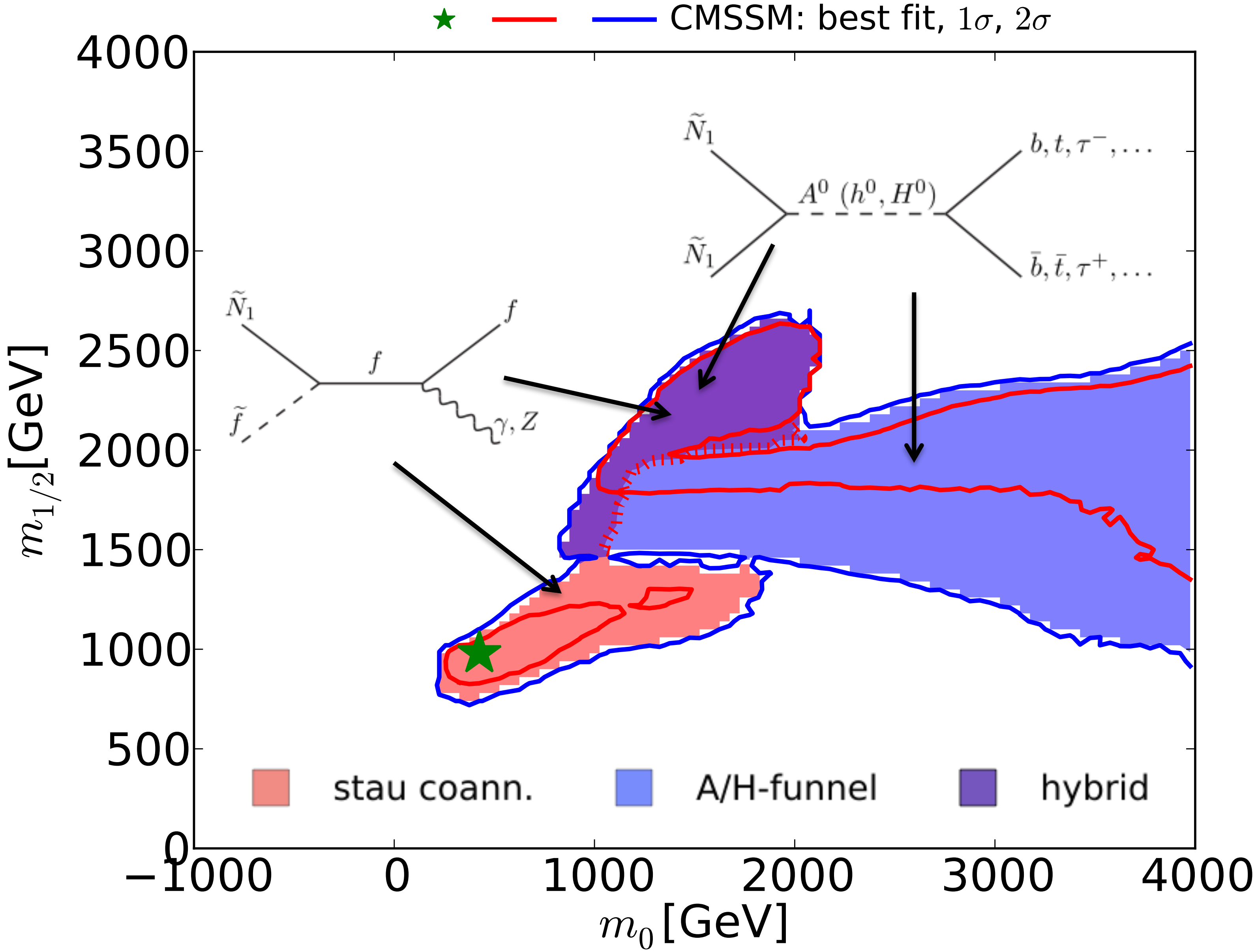
$m_0, m_{3/2}, tan\beta$

arXiv:1612.05210

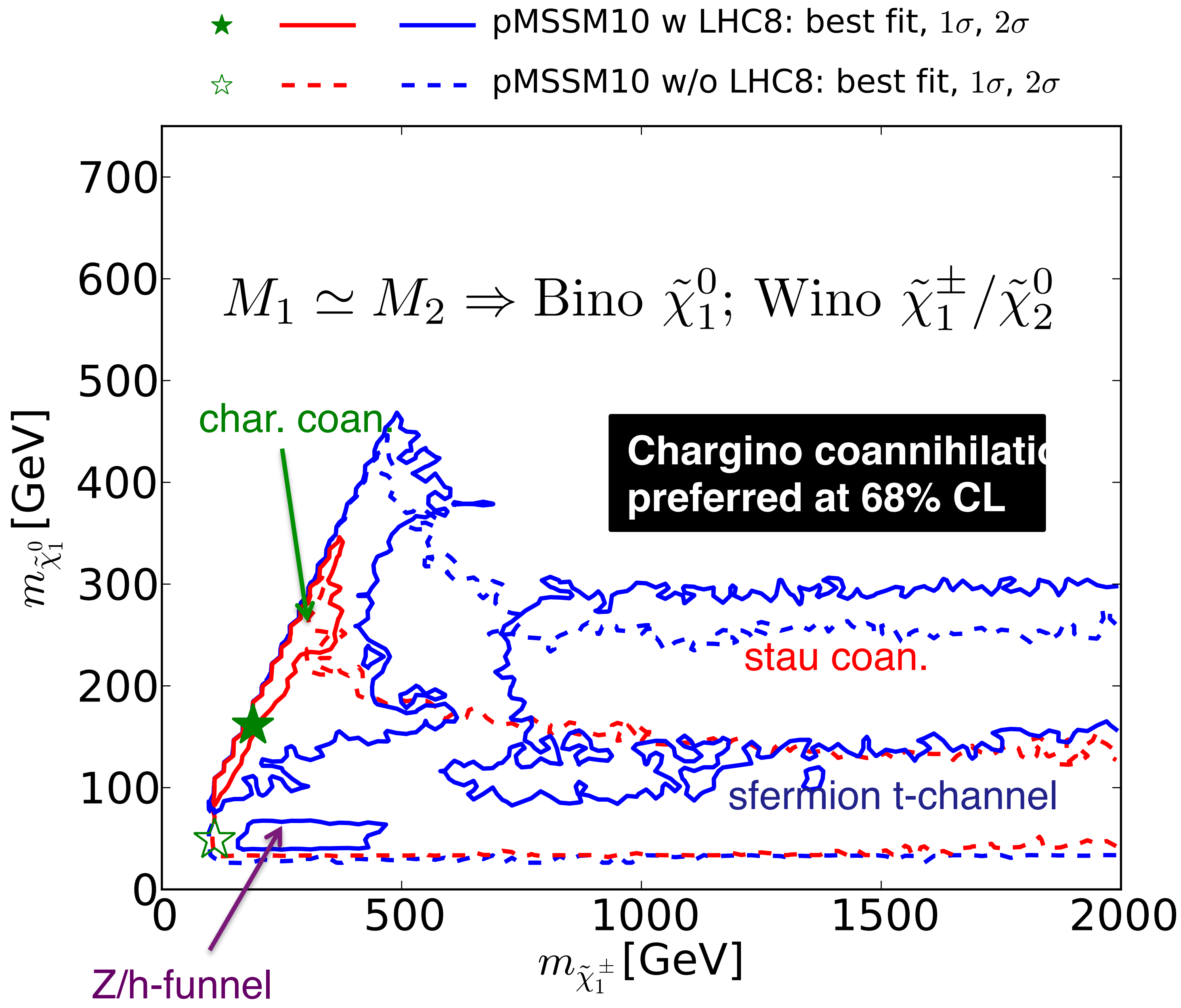
Interplay of constraints: CMSSM LHC RUN1 (2013)



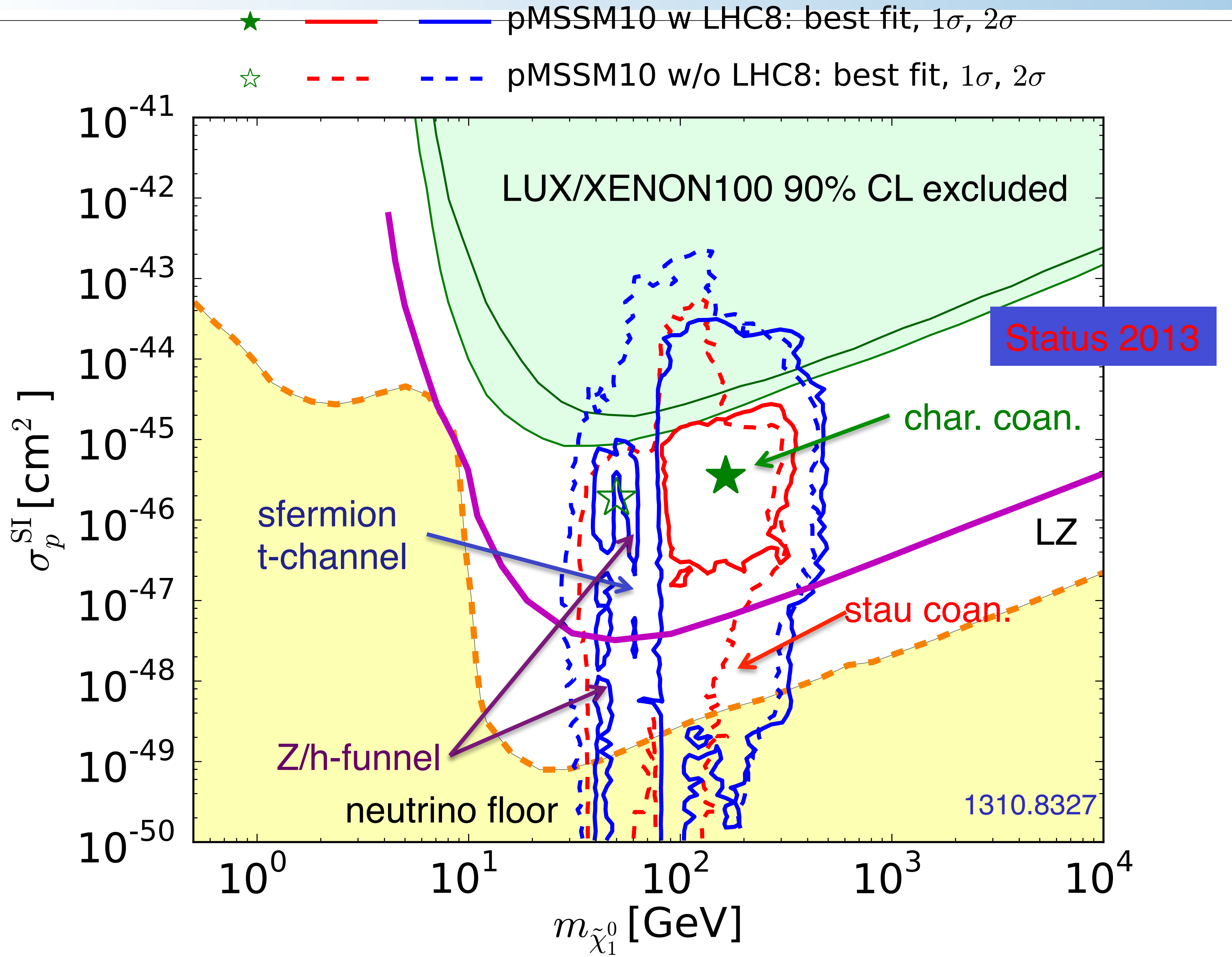
Mechanisms for relic dark matter density fulfillment in the CMSSM



pMSSM10: parameter space



pMSSM10: direct DM detection



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DM Mechanisms

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.

$$\left(\frac{M_{\tilde{\tau}}}{m_{\chi_1^0}} - 1\right) < 0.15$$

Stau coannihilation

$$\left|\frac{M_B}{m_{\chi_1^0}} - 2\right| < 0.4$$

B = h, Z or H/A funnel

$$\left(\frac{M_{\chi_1^{\pm}}}{m_{\chi_1^0}} - 1\right) < 0.25$$

Chargino Co-annihilation

$$\left|\frac{\mu}{m_{\chi_1^0}} - 1\right| < 0.30$$

Higgsino enriched "focus-point" like

$$\left(\frac{M_{\tilde{l}}}{m_{\chi_1^0}} - 1\right) < 0.15$$

Slepton Co-annihilation

$$\left(\frac{M_{\tilde{g}}}{m_{\chi_1^0}} - 1\right) < 0.25$$

Gluino Co-annihilation

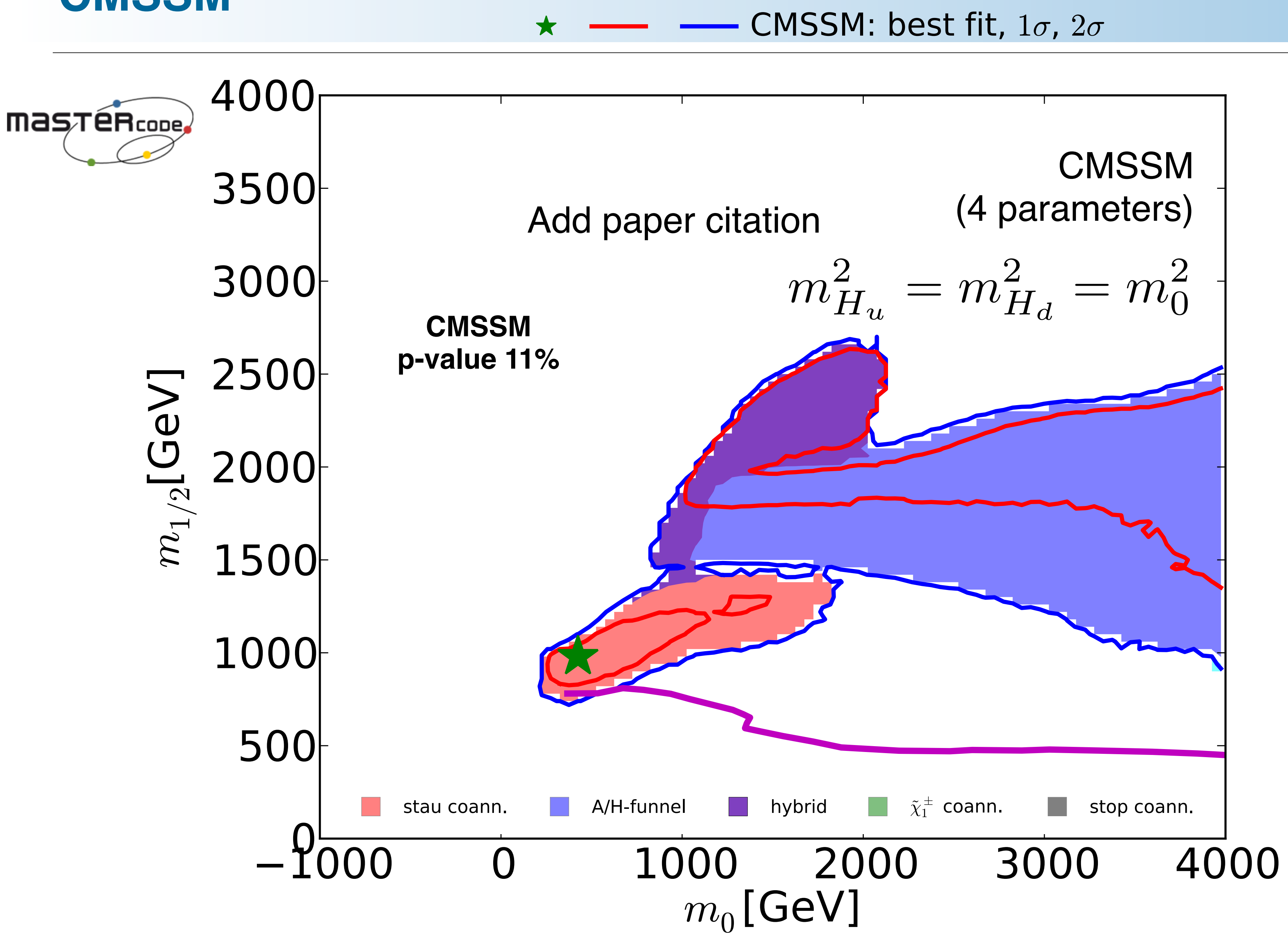
$$\left(\frac{M_{\tilde{q}}}{m_{\chi_1^0}} - 1\right) < 0.20$$

Squark Co-annihilation

Hybrid regions:
In addition to the `primary' regions where only one of the conditions is satisfied, there are also `hybrid' regions where more than one condition is satisfied. These are indicated using combined colours.

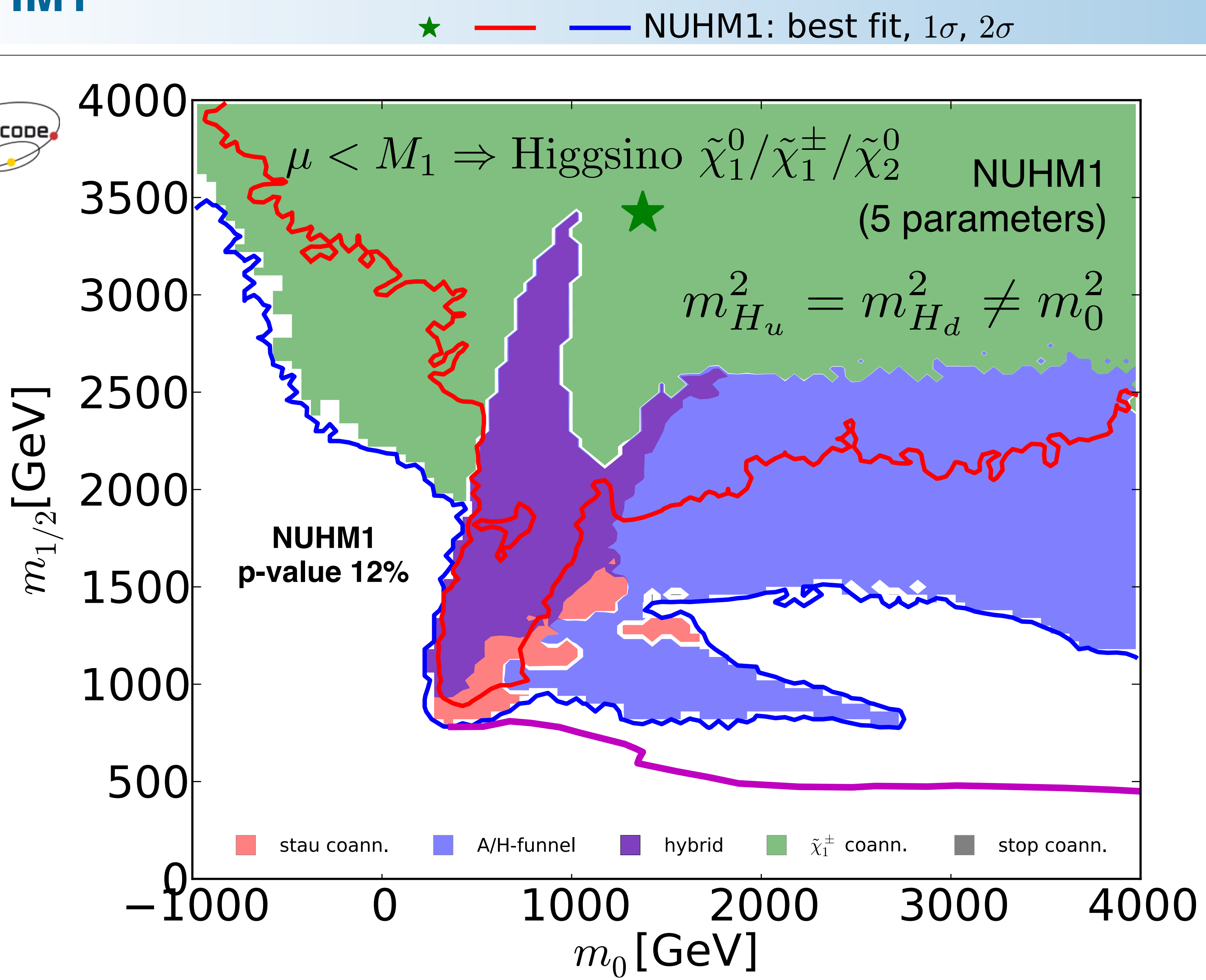
See also arXiv:1508.01173 for further details

CMSSM



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

NUHM1



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

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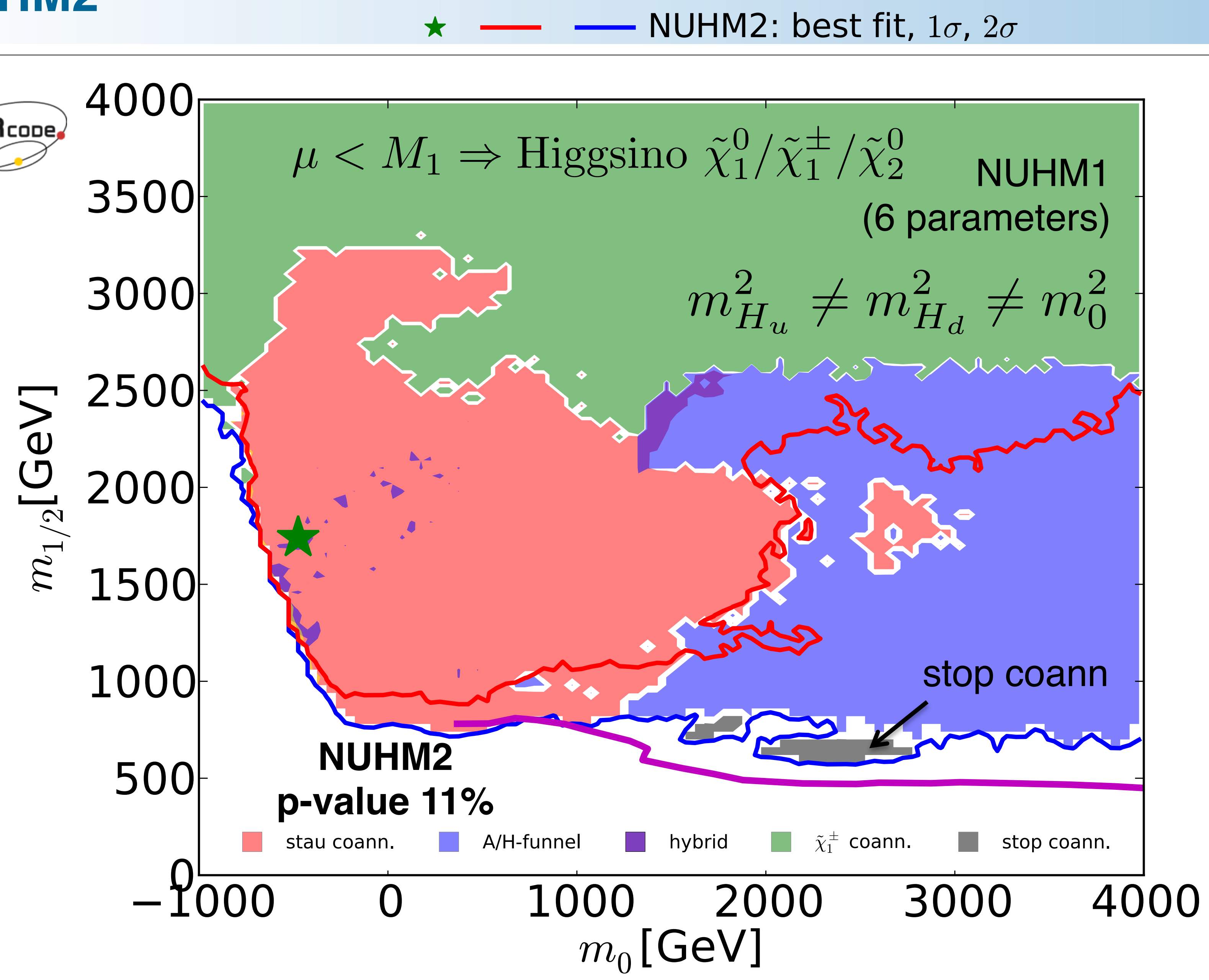
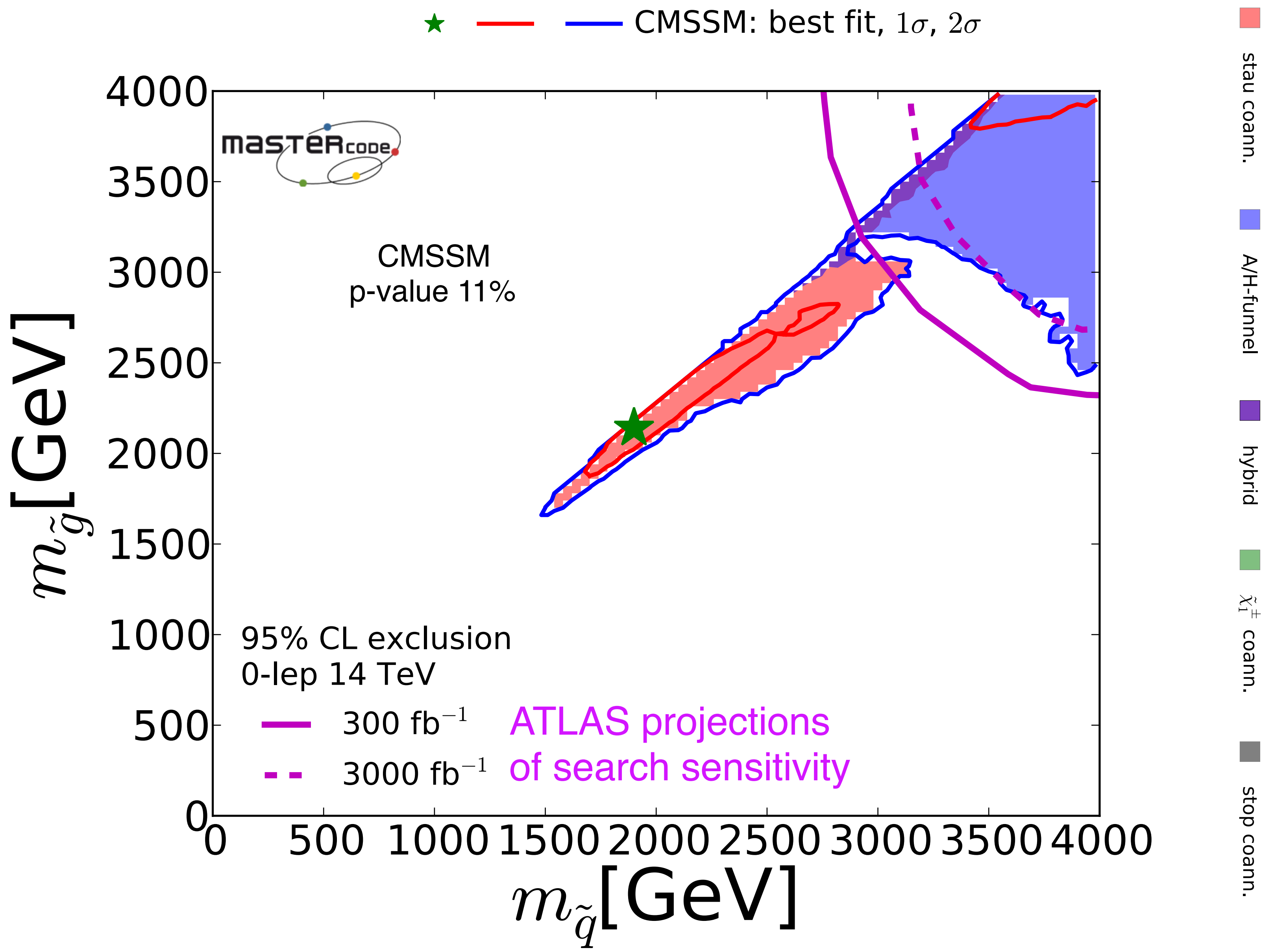
NUHM2



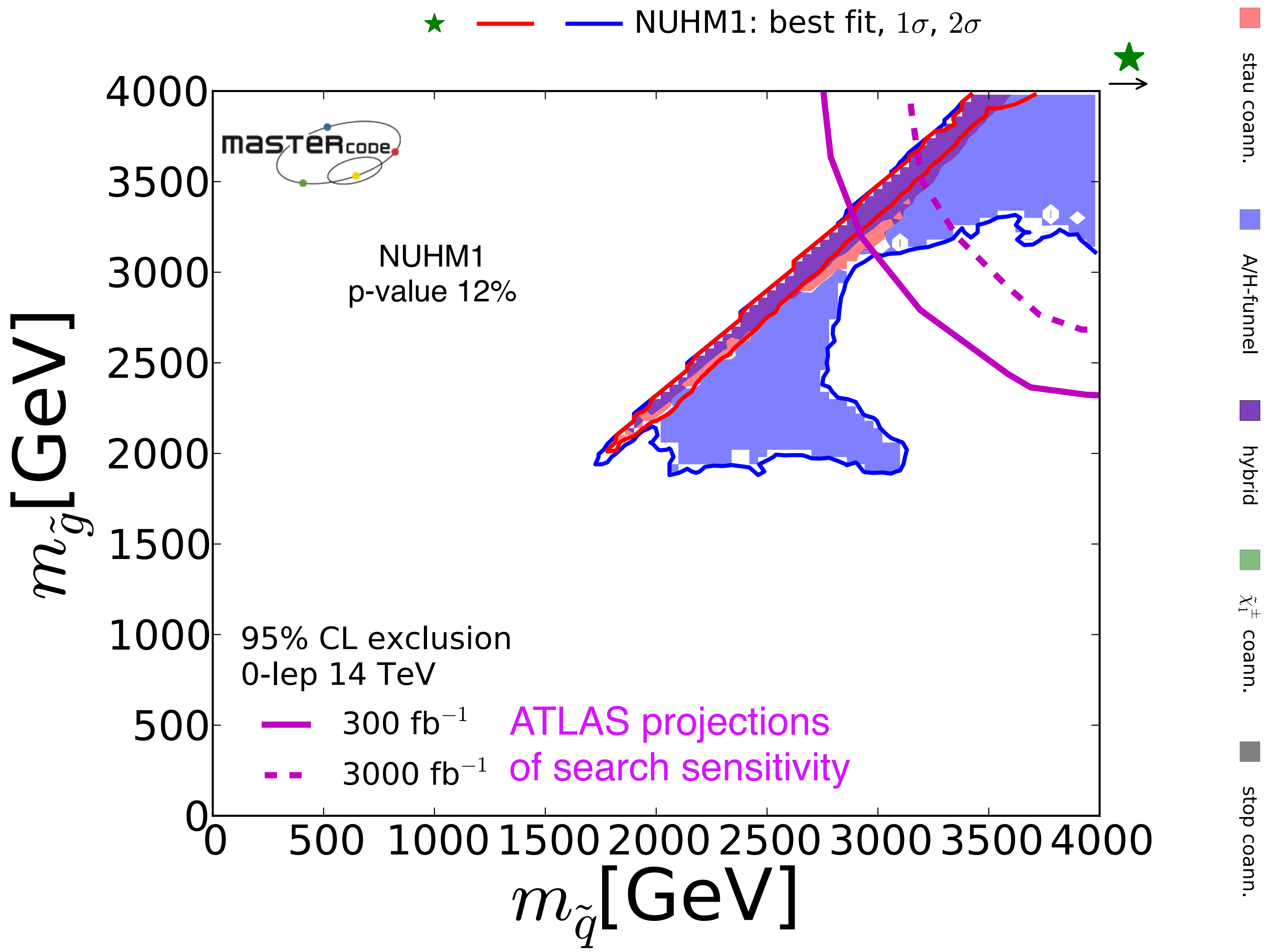
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

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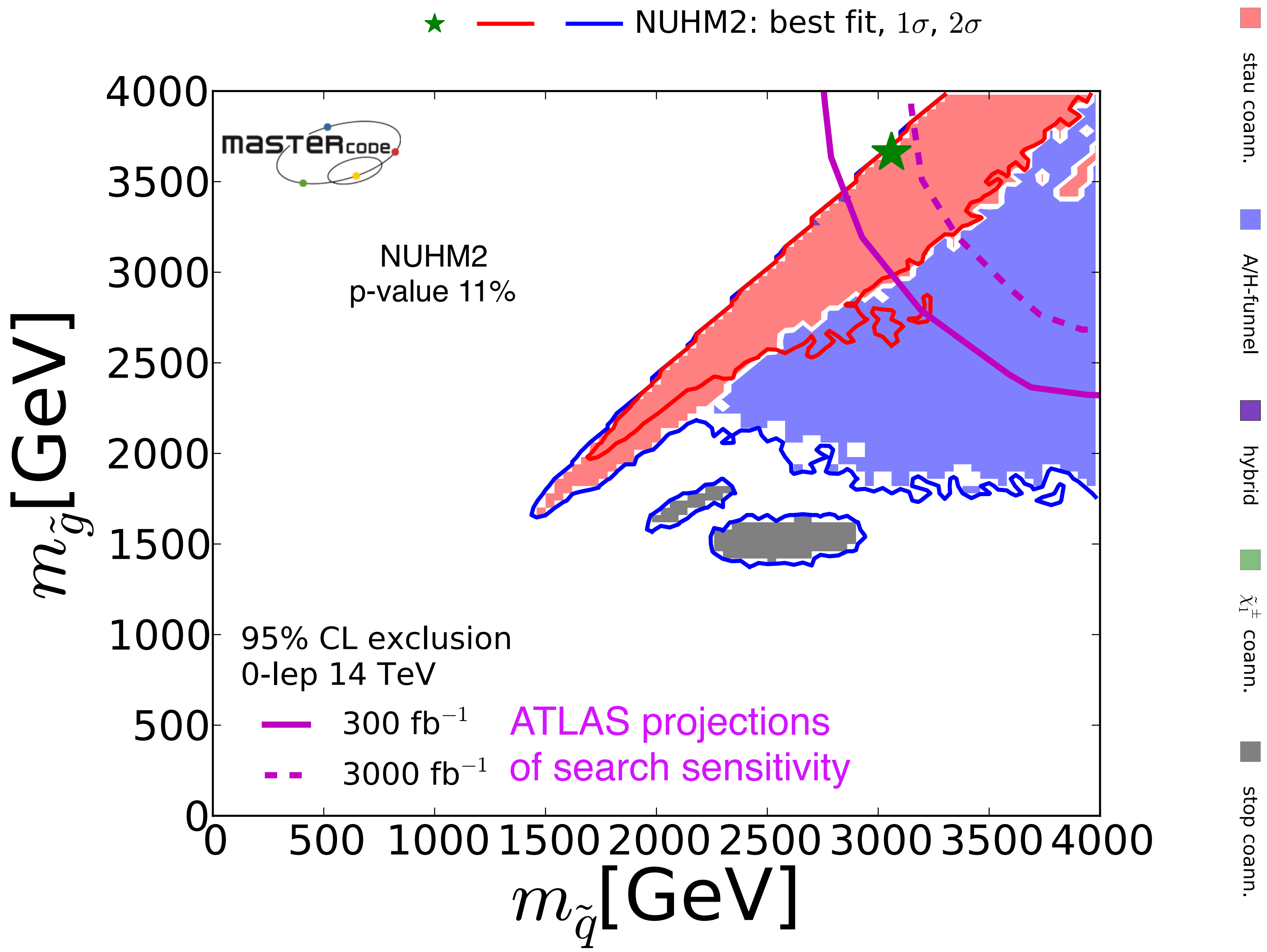
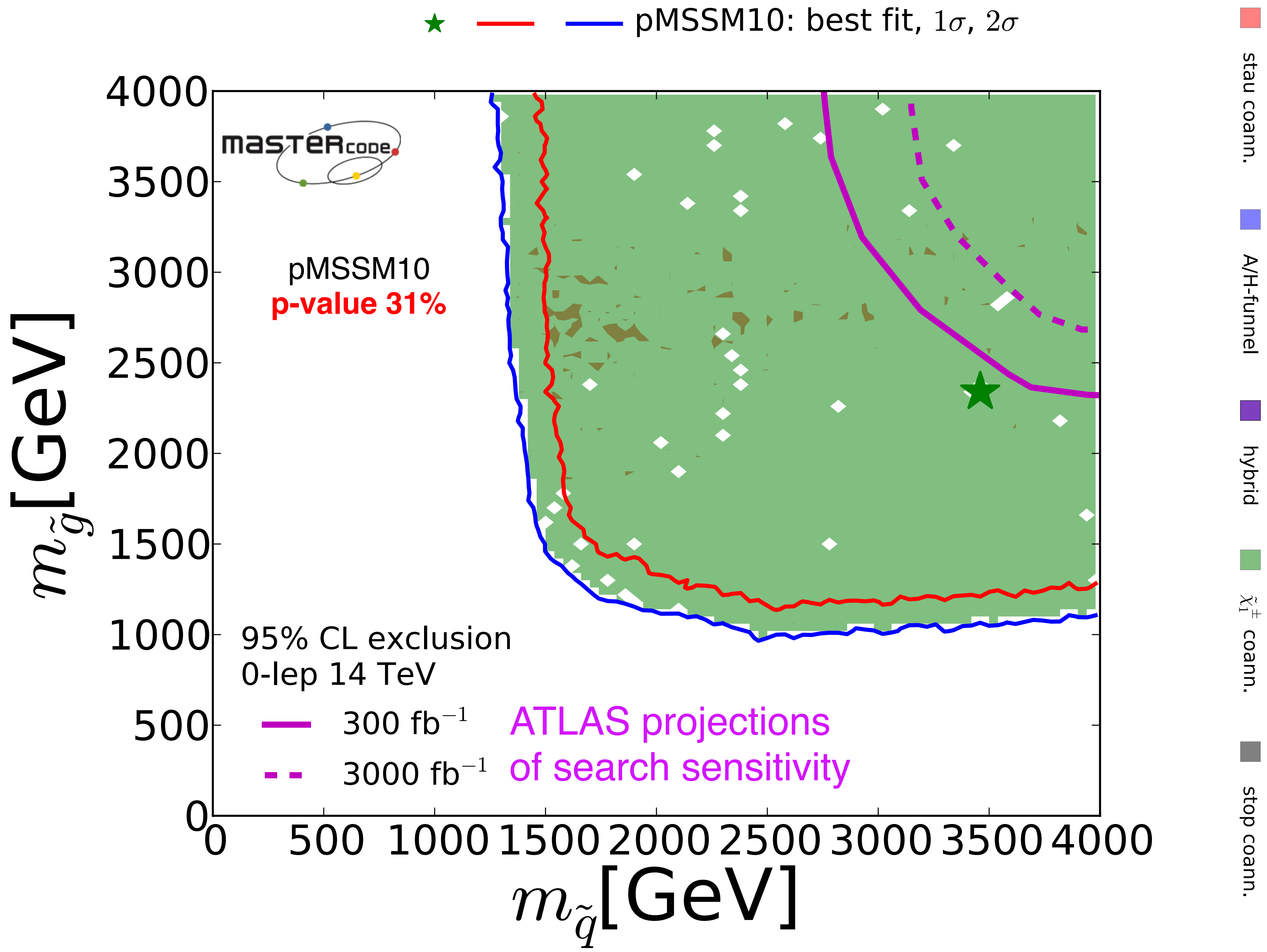
CMSSM Today: Mq-Mg Search plane



From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

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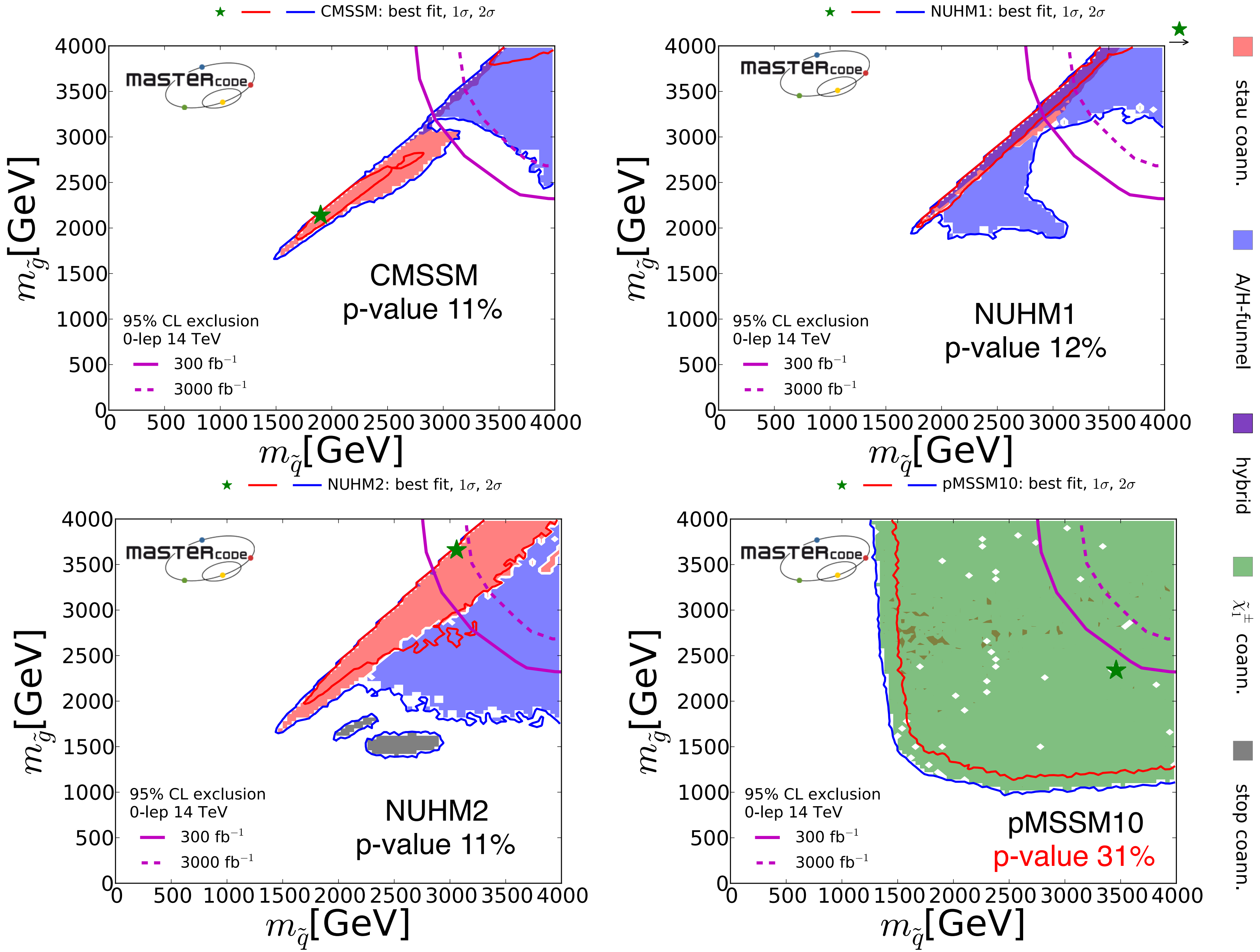
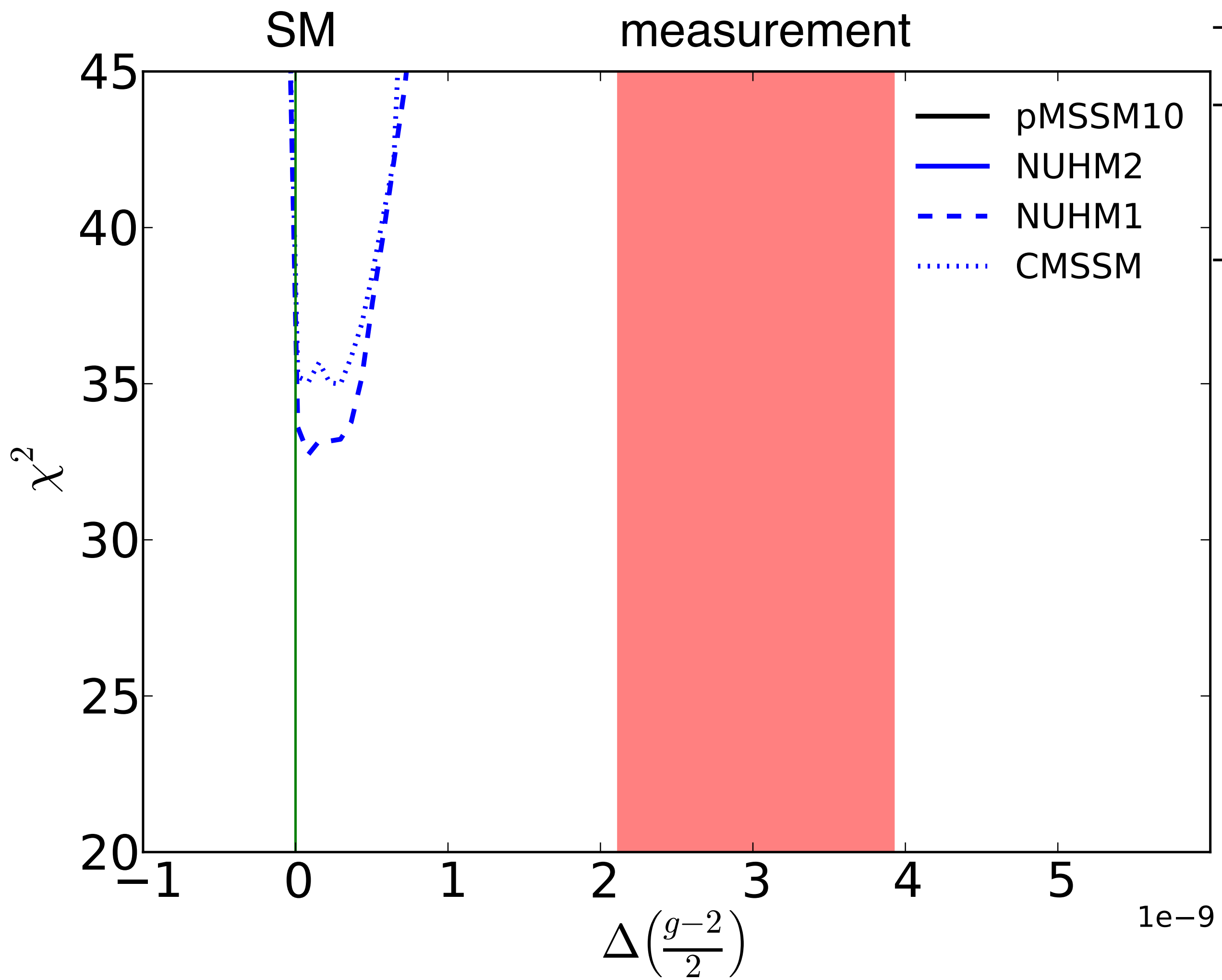
Models in Comparison in “Mq-Mg Search plane”



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Resolving tension (g-2) and LHC

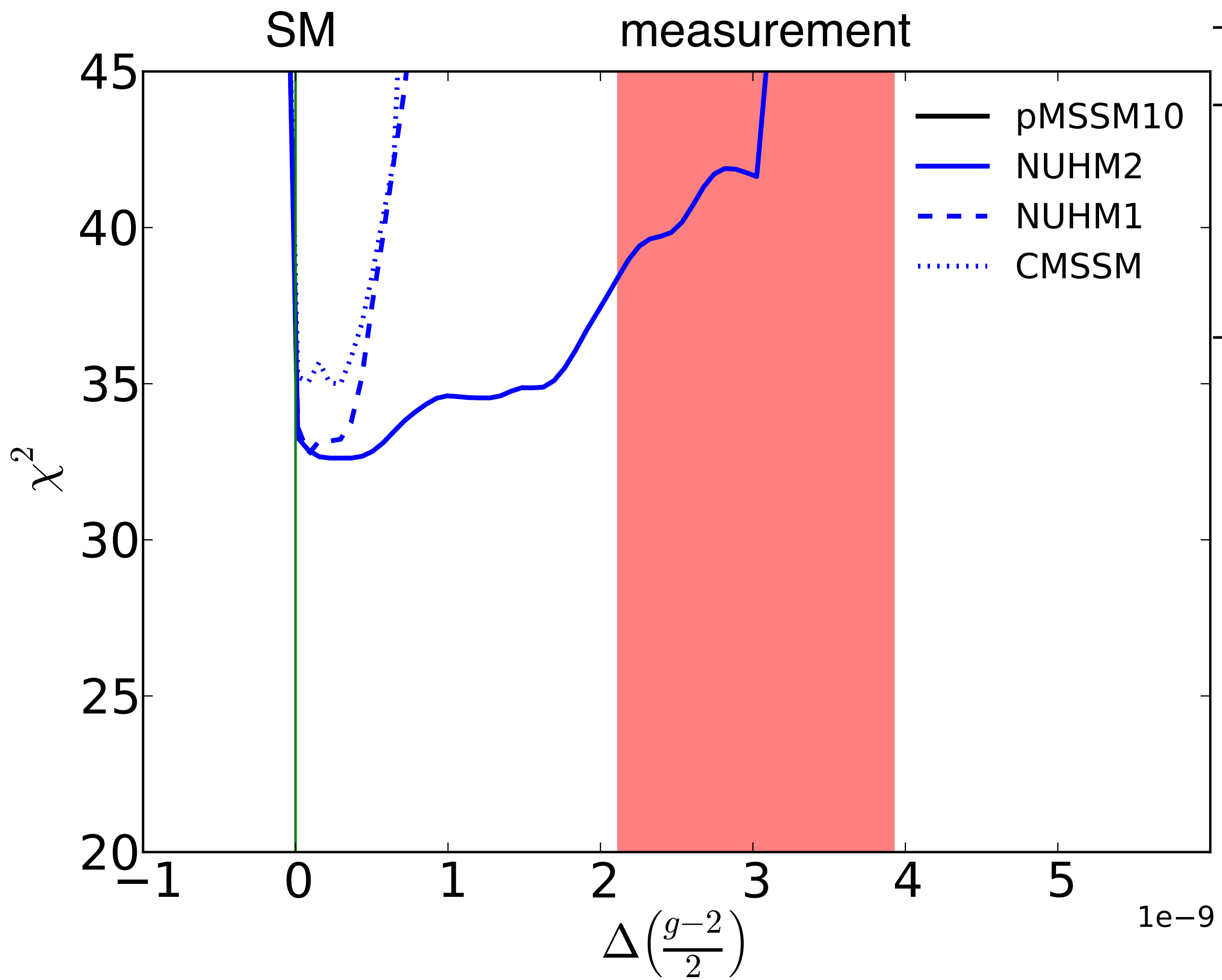


	χ^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

Can adding extra parameters resolve the tension between (g-2) and jets+MET constraints?

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Resolving tension (g-2) and LHC

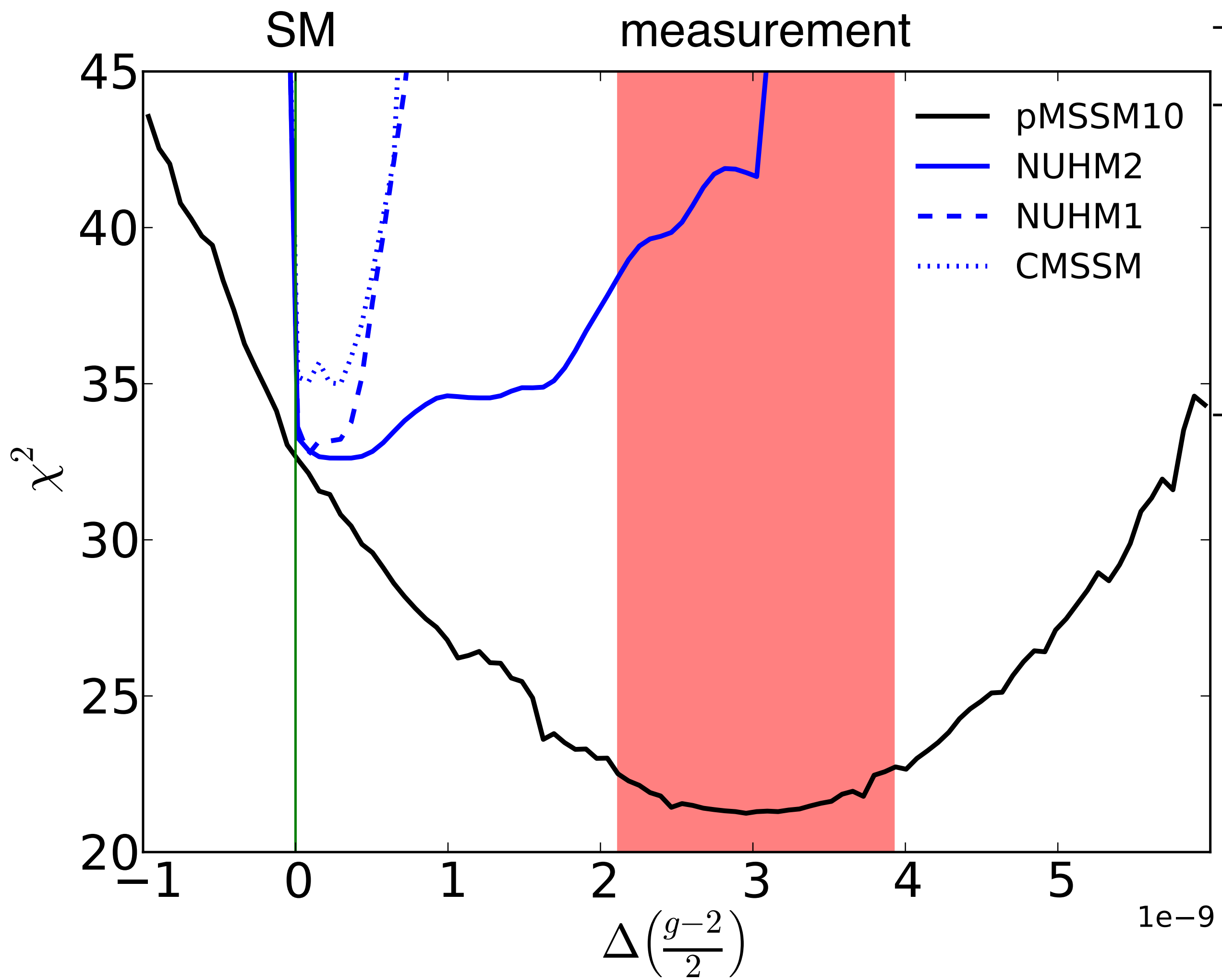


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

NUHM2 can get (g-2) right but only at the expense of M_h and jets + MET constraints.

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Resolving tension (g-2) and LHC



	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	**20.5/18**	**31 %**

pMSSM10 resolves the tension between (g-2) and LHC constraints. This significantly improves the fit.

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Note: will mainly focus on pMSSM11 results which will soon be published.

SUSY PARAMTER SPACE TODAY

SUSY Status – post 7 TeV LHC data

- Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!
- Experiments need to define new benchmarks and to present the interpretation of their searches.
- A bottom-up approach, using so-called simplified models, was adopted but ATLAS and CMS as the primary vehicle to present SUSY searches!

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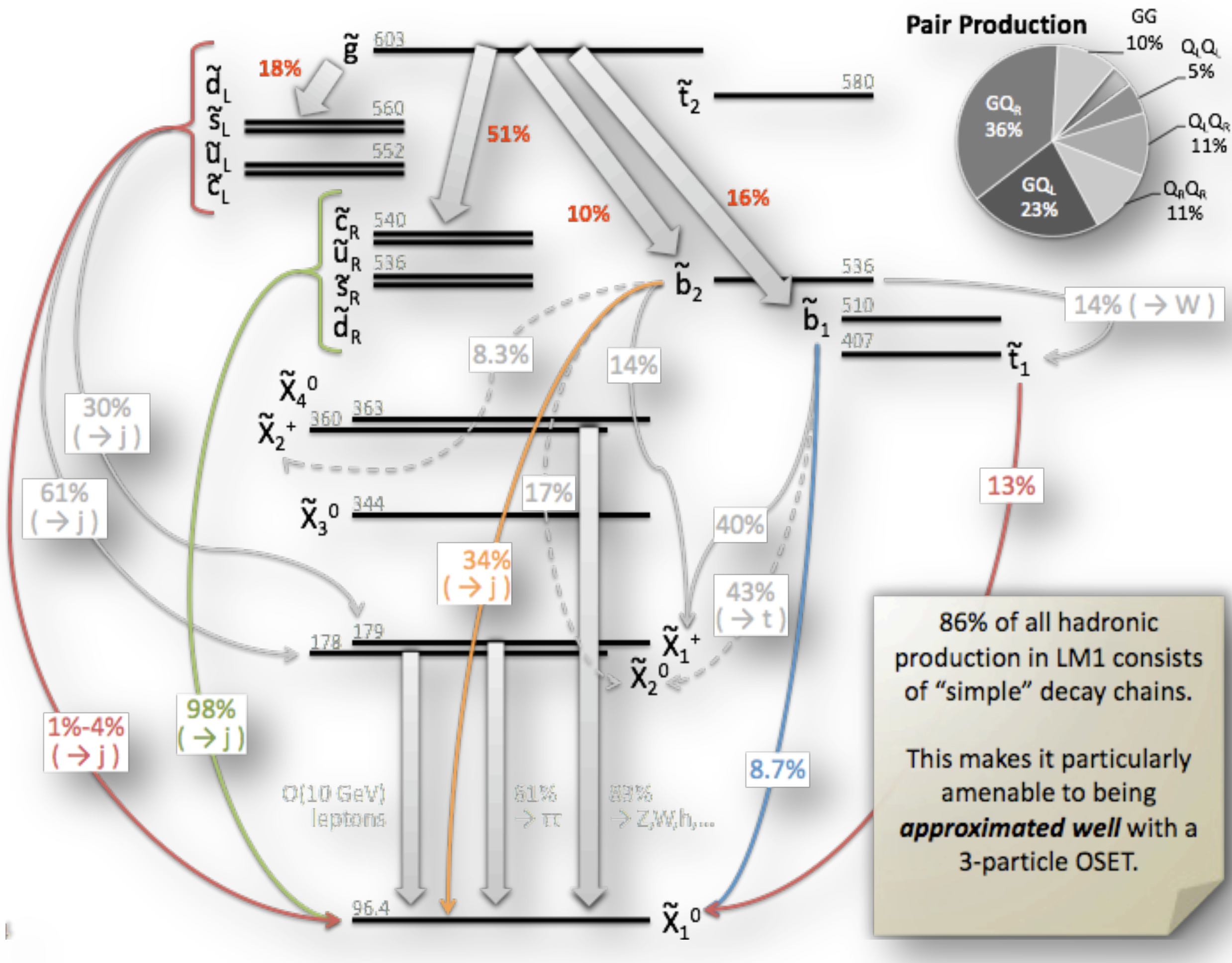
Interpretation in Simplified Models

CMSSM

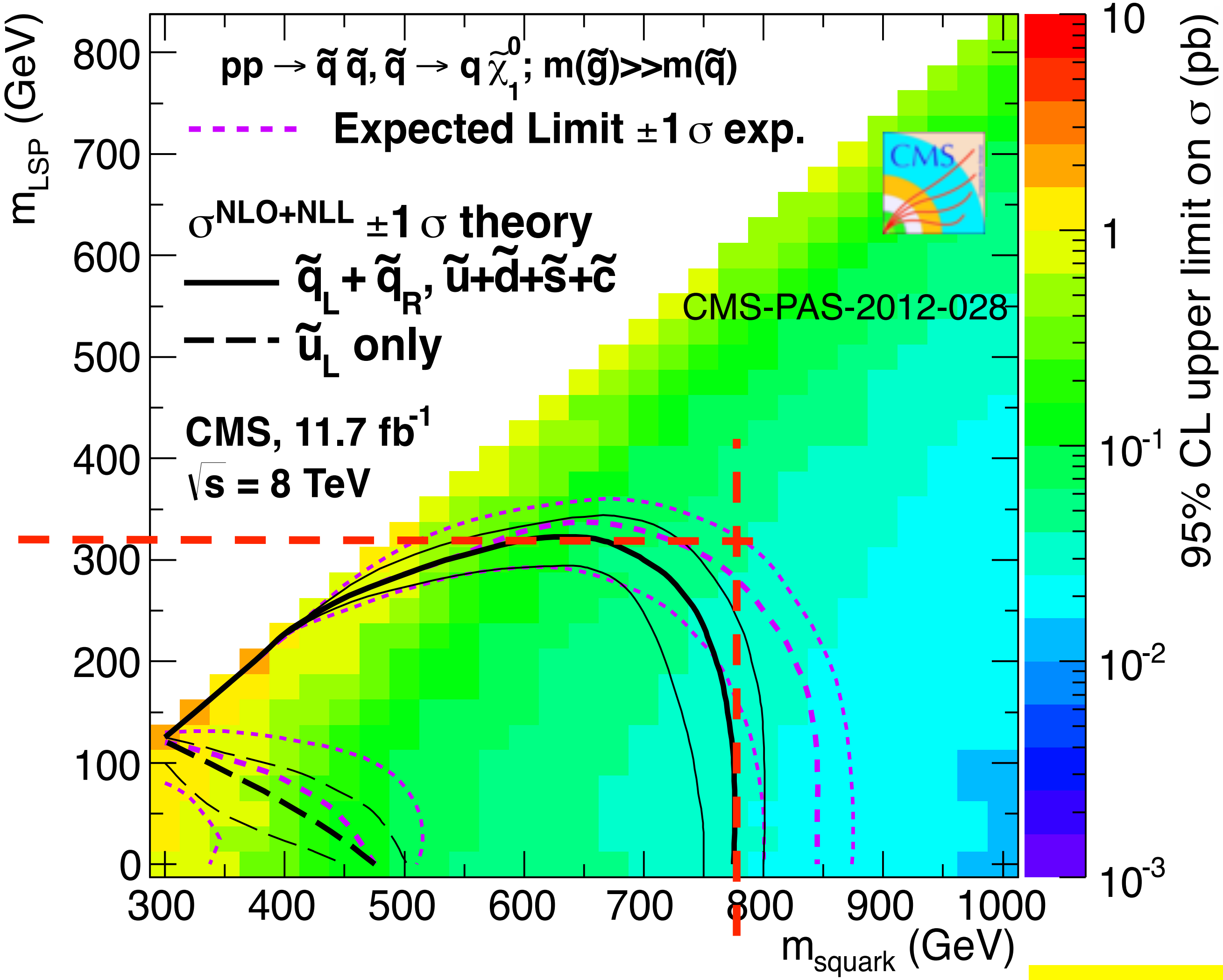


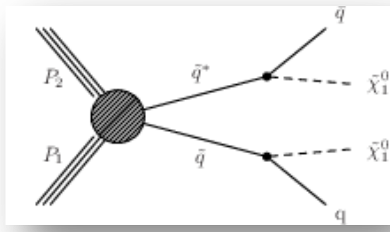
What the individual searches are sensitive to is much more simple…

Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

SMS: a few interesting features

$m_{LSP}^{max} \approx 0.3$ TeV : LSP mass above which there is NO limit anymore





$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$

$m_G^{max} \approx 0.8$ TeV : Best limit in plane

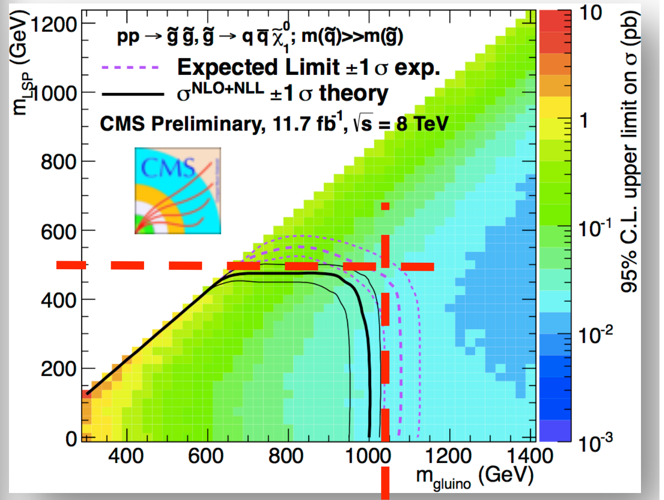
Assumes 100% BR for decay chain considered.

How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$	-	800
	all $m_{\tilde{g}}$	1300	-
Simplified model $\tilde{g}\tilde{g}$	$m_{\tilde{\chi}_1^0} = 0$	-	900
	$m_{\tilde{\chi}_1^0} > 300$	-	no limit
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900



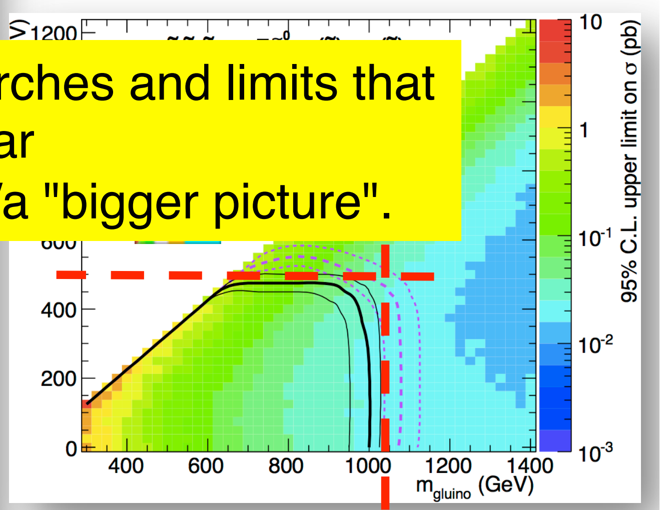
This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:

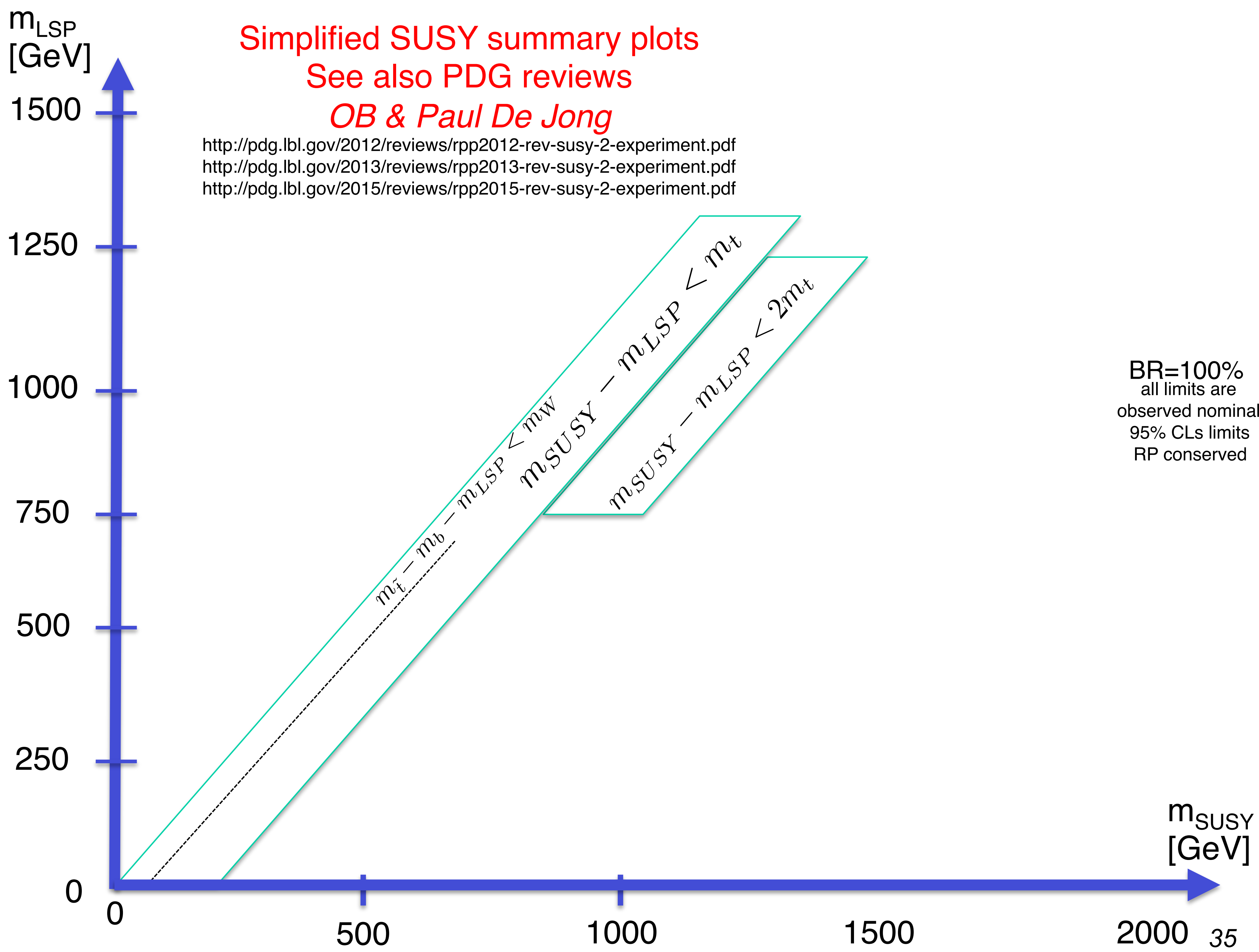
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2015/reviews/rpp2015-rev-susy-2-experiment.pdf

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
CMSSM	all $m_{\tilde{q}}$		800
Simpli[illegible]	[illegible]	[illegible]	[illegible]
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900

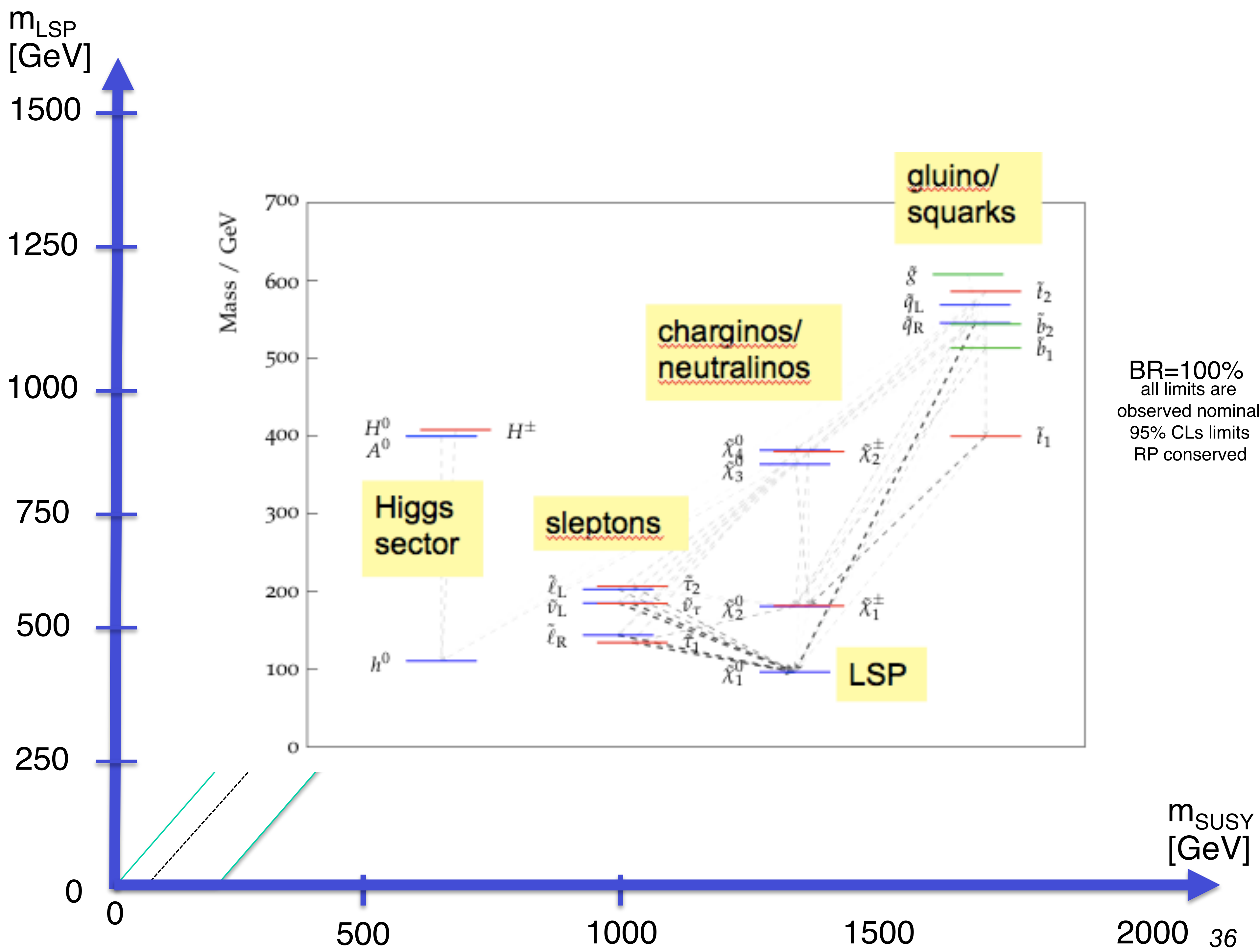


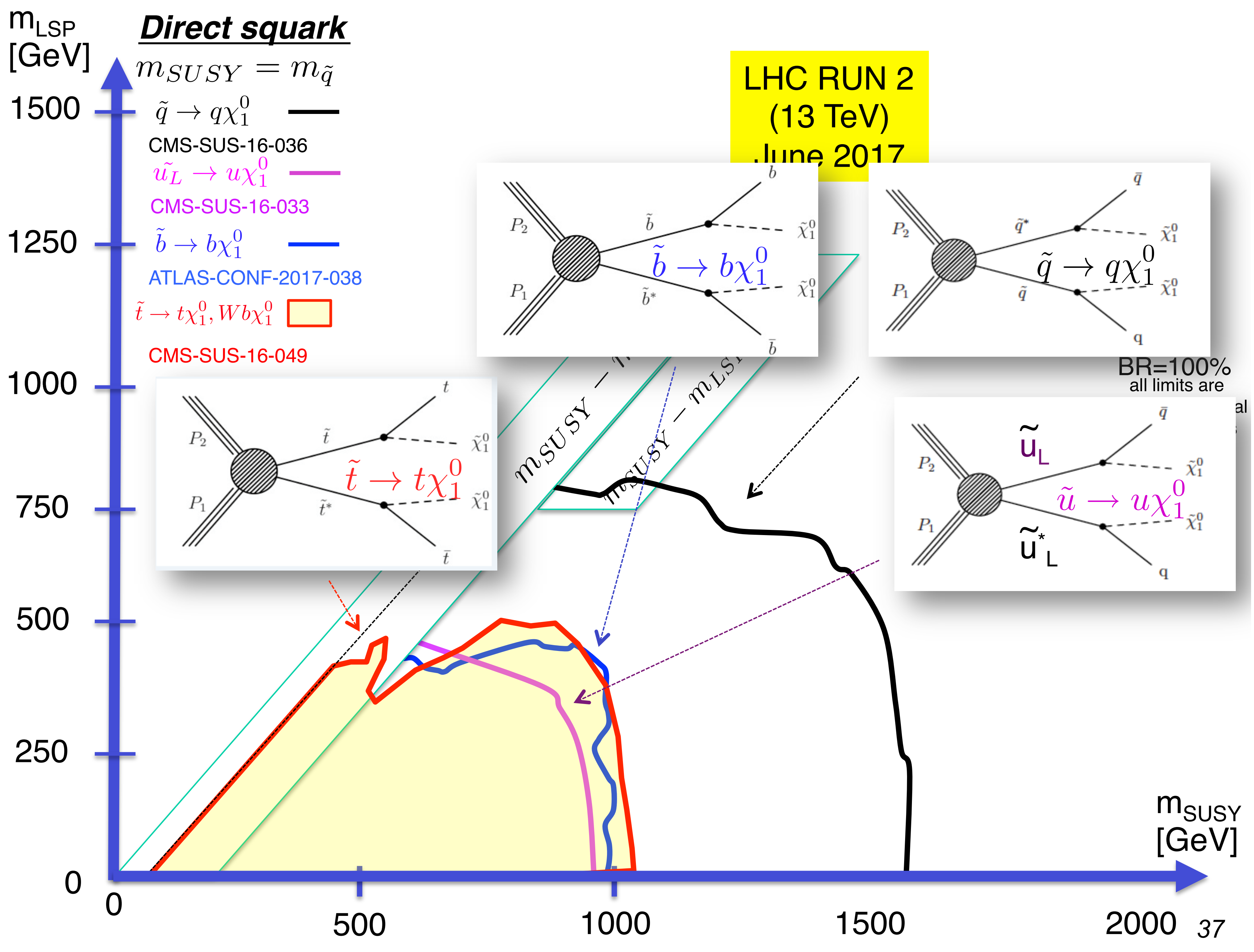
It is a challenge to do justice to the many searches and limits that have been established so far
- even more so to put it all together into the/a "bigger picture".

This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

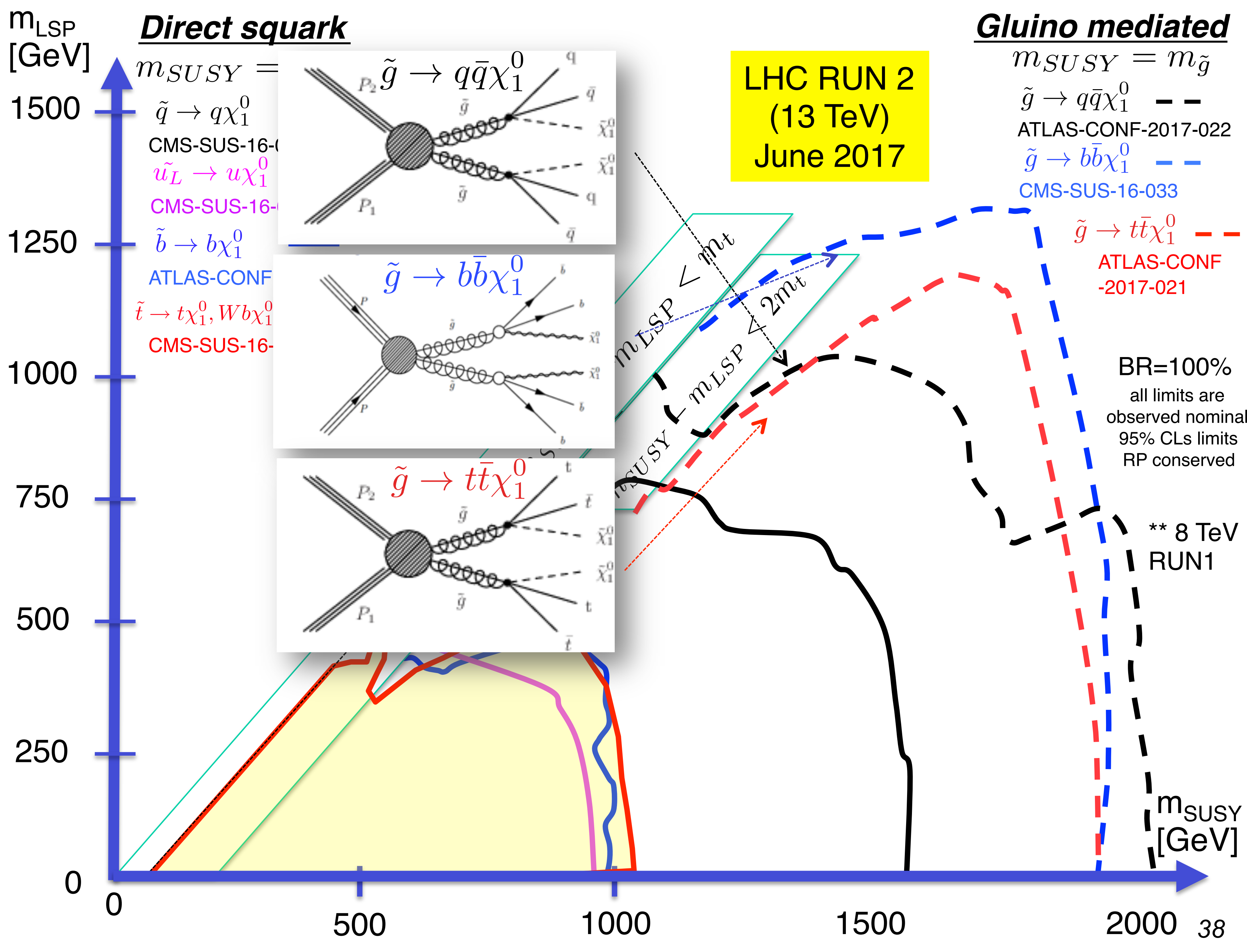


Simplified SUSY summary plots
See also PDG reviews
OB & Paul De Jong
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2015/reviews/rpp2015-rev-susy-2-experiment.pdf
m_{LSP} [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_{SUSY} [GeV]
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved

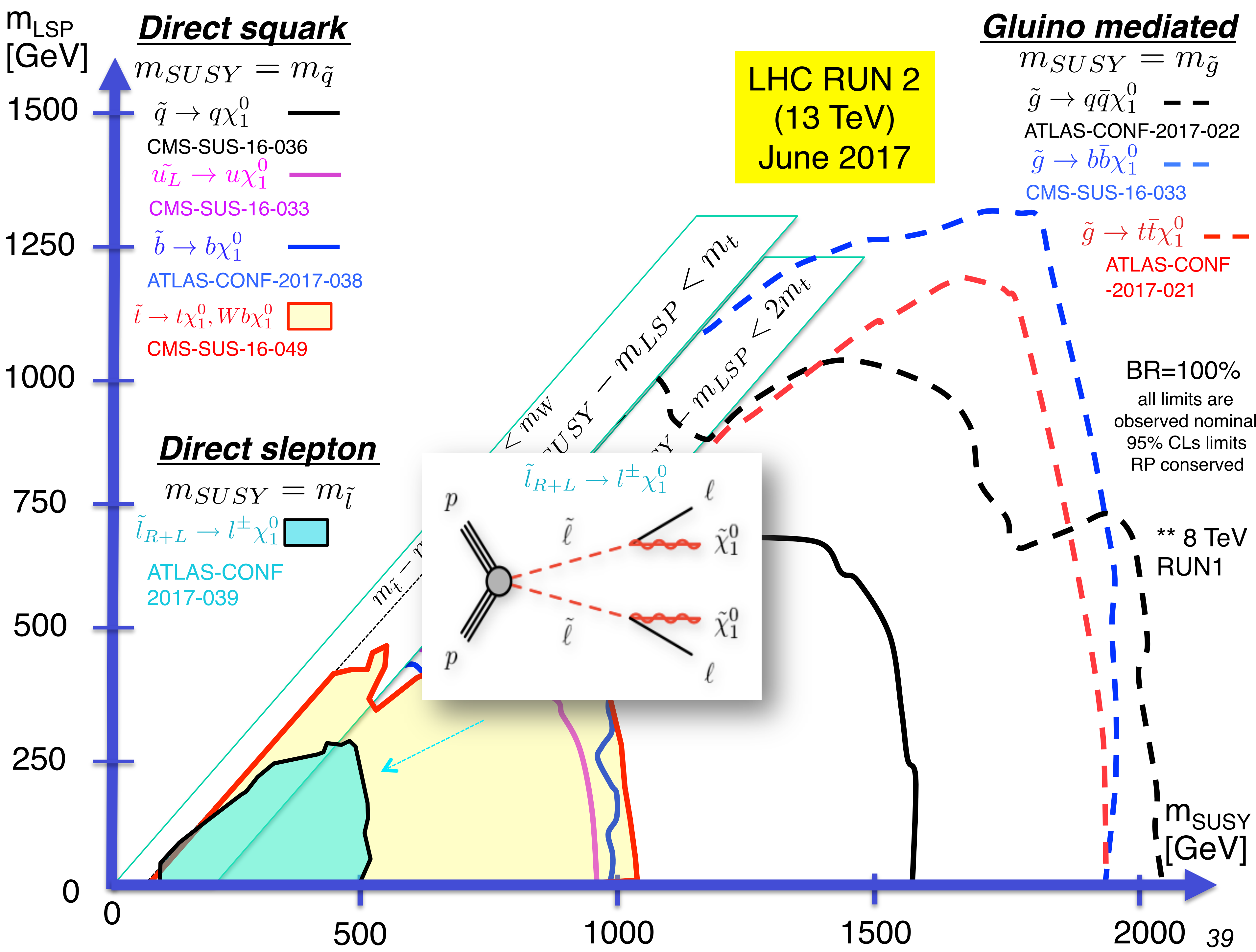

m_LSP [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_SUSY [GeV]
Mass / GeV
700
600
500
400
300
200
100
0
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved



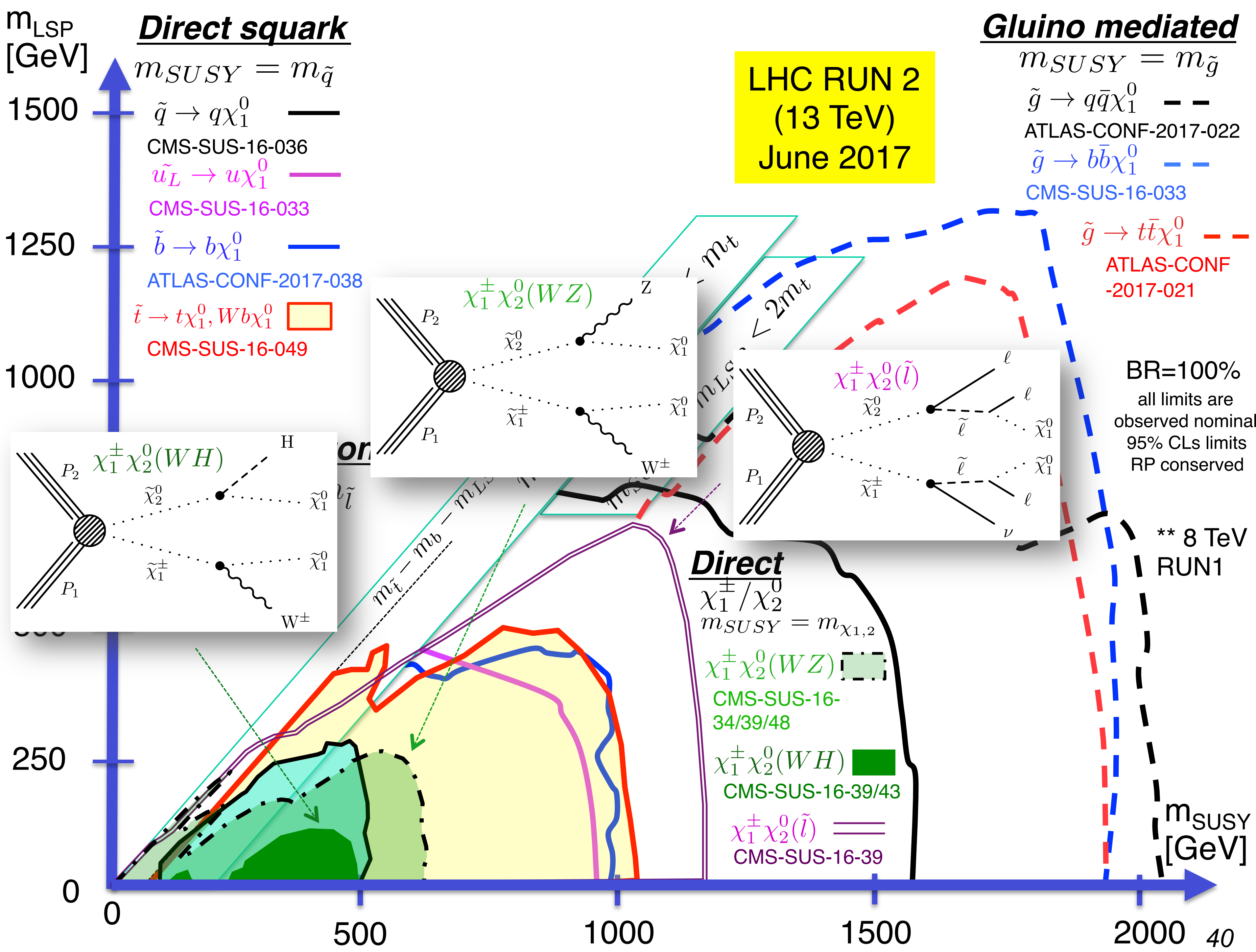
m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
$\tilde{b} \to b\chi_1^0$
$\tilde{q} \to q\chi_1^0$
BR=100%
all limits are
$\tilde{t} \to t\chi_1^0$
$\tilde{u} \to u\chi_1^0$
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_SUSY [GeV]



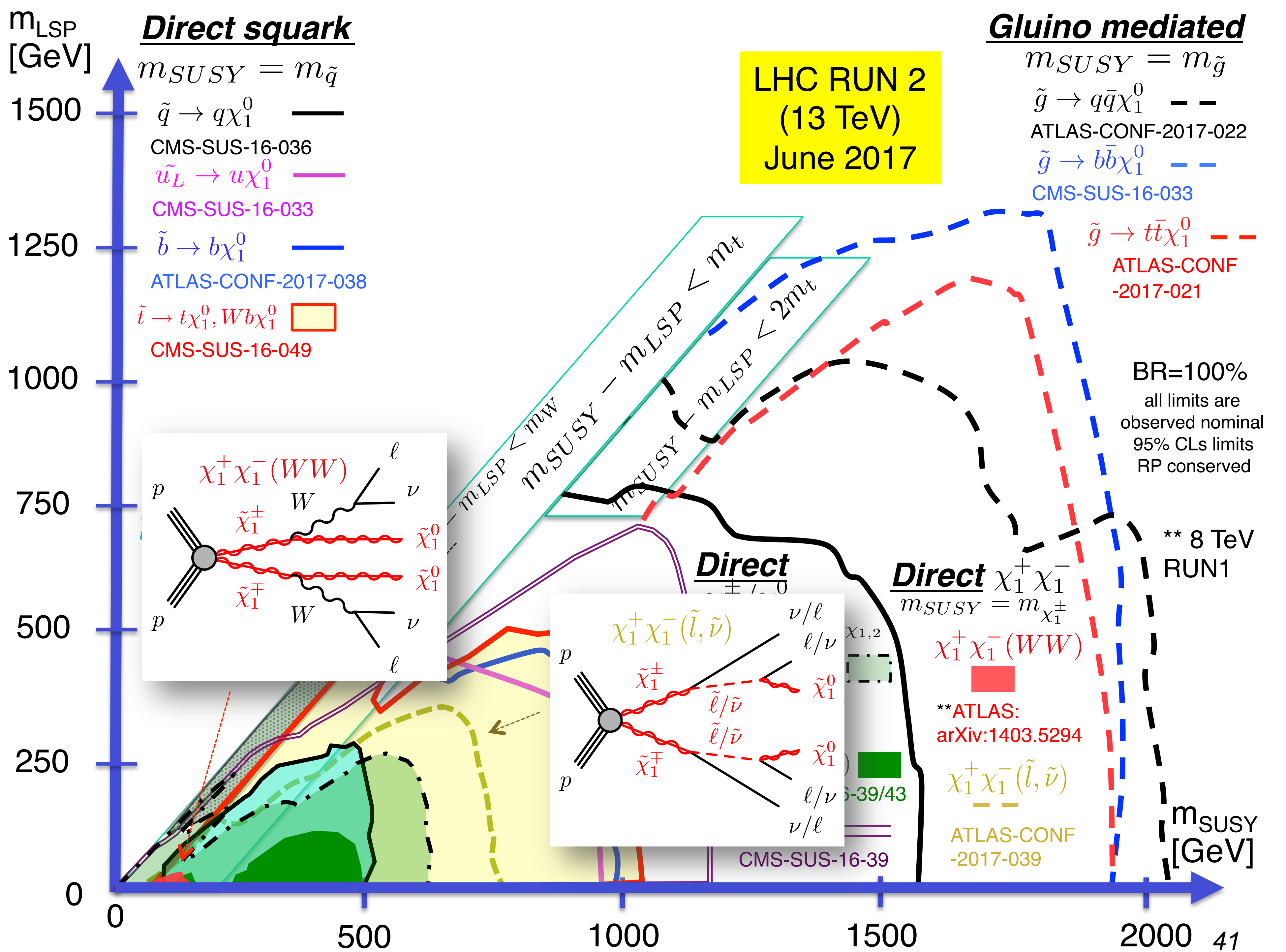
m_{LSP} [GeV]
Direct squark
$m_{SUSY} =$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-
$\tilde{g} \to q\bar{q}\chi_1^0$
$\tilde{g} \to b\bar{b}\chi_1^0$
$\tilde{g} \to t\bar{t}\chi_1^0$
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{LSP} < m_t$
$m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
0
500
1000
1500
2000



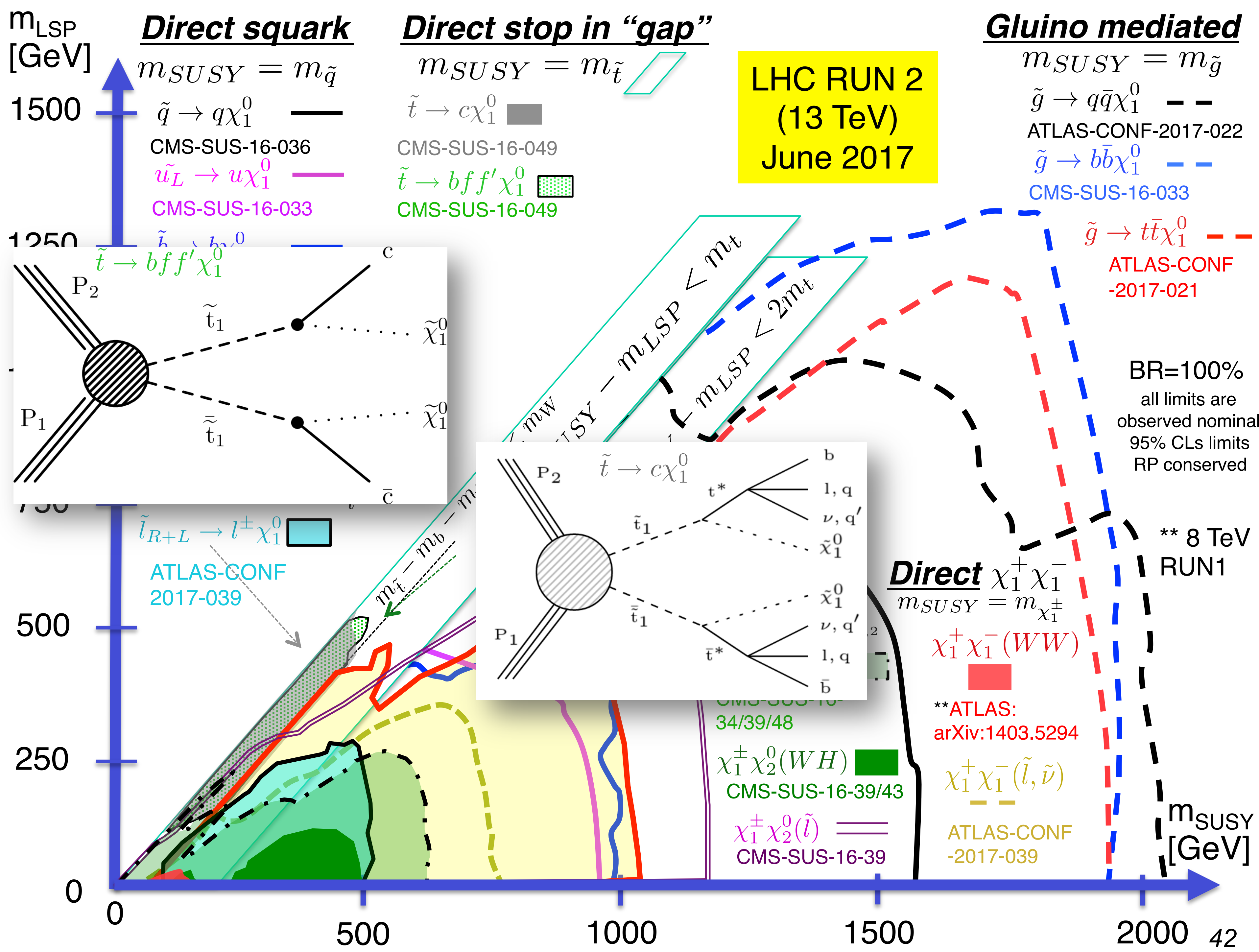
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$< m_W$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
p
p
$\tilde{\ell}$
$\tilde{\ell}$
ℓ
ℓ
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_{SUSY} [GeV]



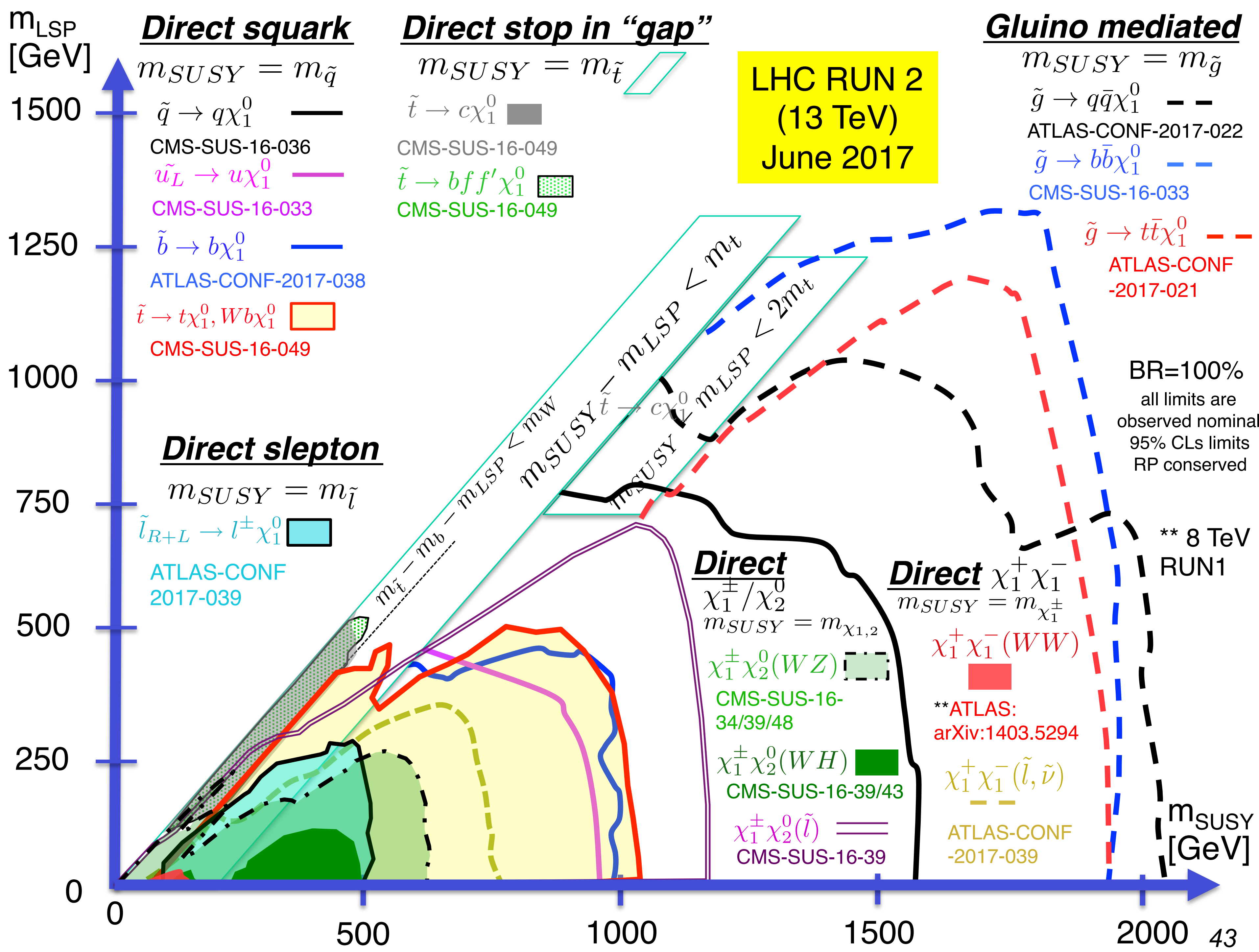
m_LSP [GeV]
1500
1250
1000
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS-SUS-16-036
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \rightarrow t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$\chi_1^\pm\chi_2^0(WZ)$
$\chi_1^\pm\chi_2^0(WH)$
$\chi_1^\pm\chi_2^0(\tilde{l})$
$m_{\tilde{t}} - m_b - m_{LSP}$
$< 2m_t$
Direct
$\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^\pm\chi_2^0(WZ)$
CMS-SUS-16-
34/39/48
$\chi_1^\pm\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^\pm\chi_2^0(\tilde{l})$
CMS-SUS-16-39
m_SUSY [GeV]
0
500
1000
1500
2000



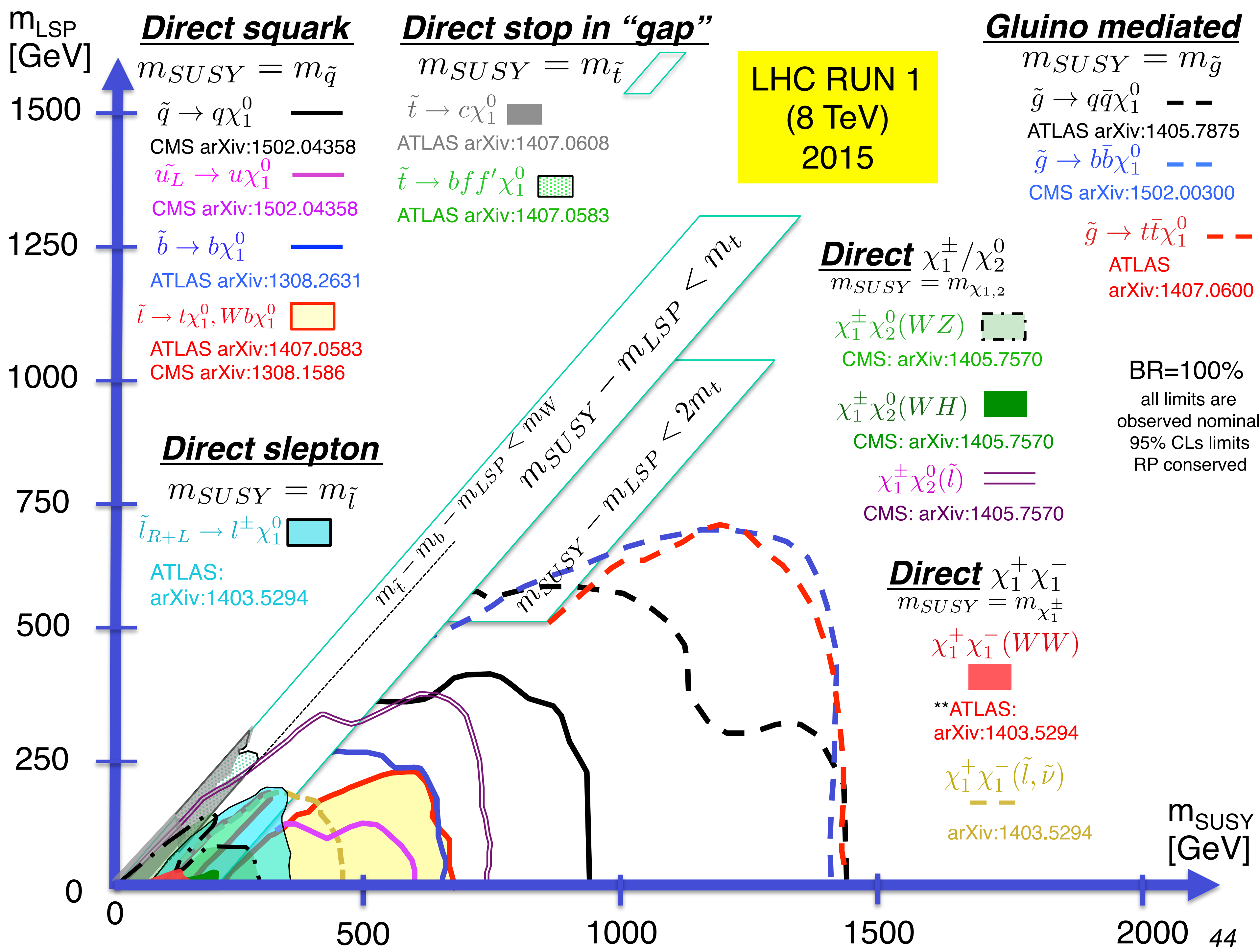
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u_L} \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{SUSY} - m_{LSP} < m_W$
Direct
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^\pm}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
CMS-SUS-16-39
$\chi_1^+\chi_1^-(WW)$
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
0
500
1000
1500
2000



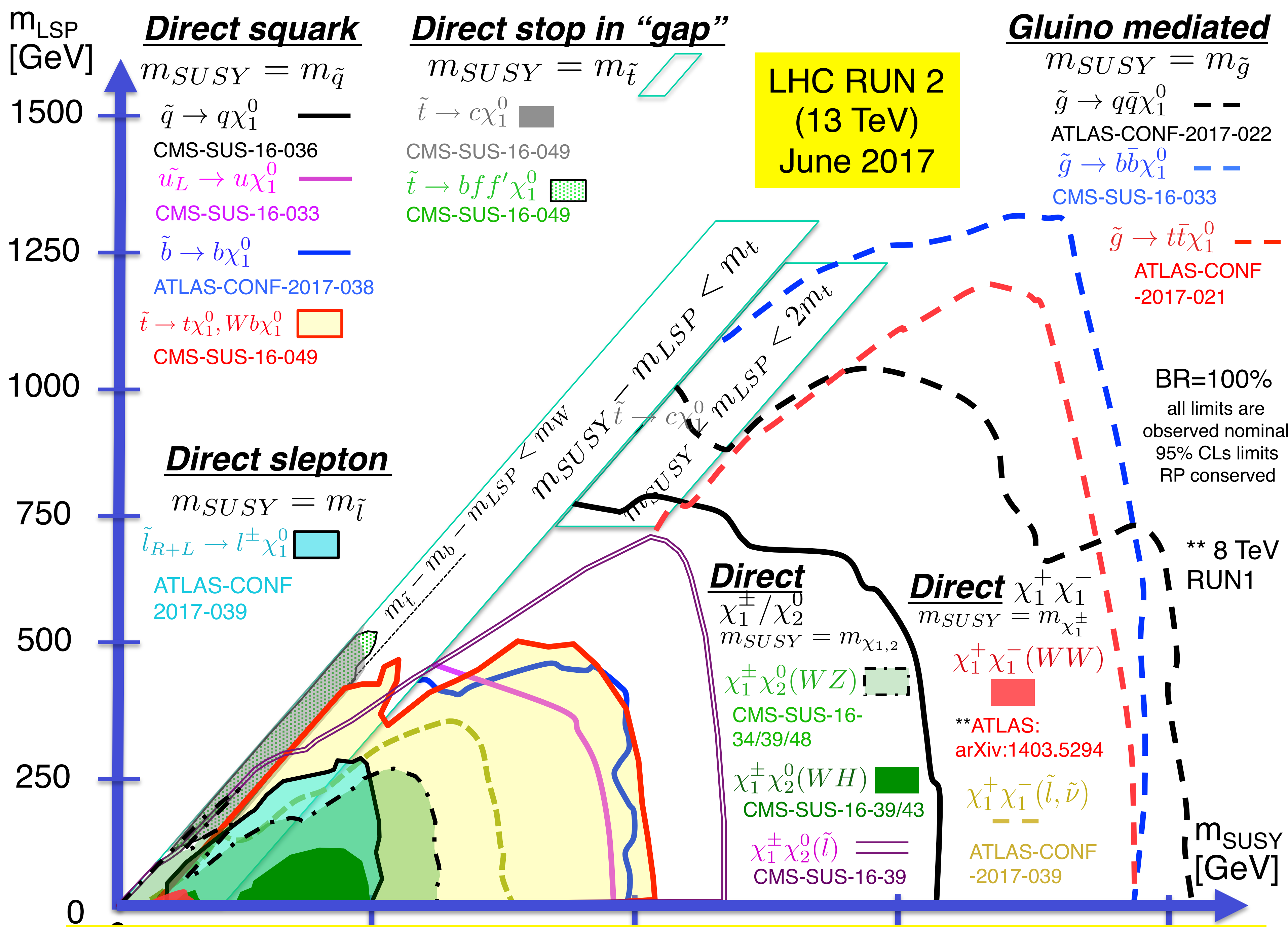
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u_L} \to u\chi_1^0$
CMS-SUS-16-033
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
CMS-SUS-16-049
$\tilde{t} \to bff'\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{SUSY} - m_{LSP} < m_t$
$m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
$m_{\tilde{t}} - m_b$
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
34/39/48
$\chi_1^{\pm}\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS-SUS-16-39
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
m_{SUSY} [GeV]
1500
1250
500
250
0
0
500
1000
1500
2000
P$_2$
P$_1$
$\tilde{t}_1$
$\bar{\tilde{t}}_1$
$\tilde{\chi}_1^0$
c
$\bar{c}$
t*
b
l, q
ν, q'



m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS-SUS-16-036
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \rightarrow t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
CMS-SUS-16-049
$\tilde{t} \rightarrow bff'\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$\tilde{t} \rightarrow c\chi_1^0$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \rightarrow l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
Direct
$\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^{\pm}\chi_2^0(WZ)$
CMS-SUS-16-
34/39/48
$\chi_1^{\pm}\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS-SUS-16-39
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
** 8 TeV
RUN1
m_{SUSY} [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000



m_{LSP} [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_{SUSY} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
ATLAS arXiv:1407.0583
CMS arXiv:1308.1586
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
LHC RUN 1
(8 TeV)
2015
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS
arXiv:1407.0600
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^{\pm}\chi_2^0(WZ)$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(WH)$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS: arXiv:1405.7570
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
arXiv:1403.5294



Check out the new PDG experimental SUSY review for for further details!

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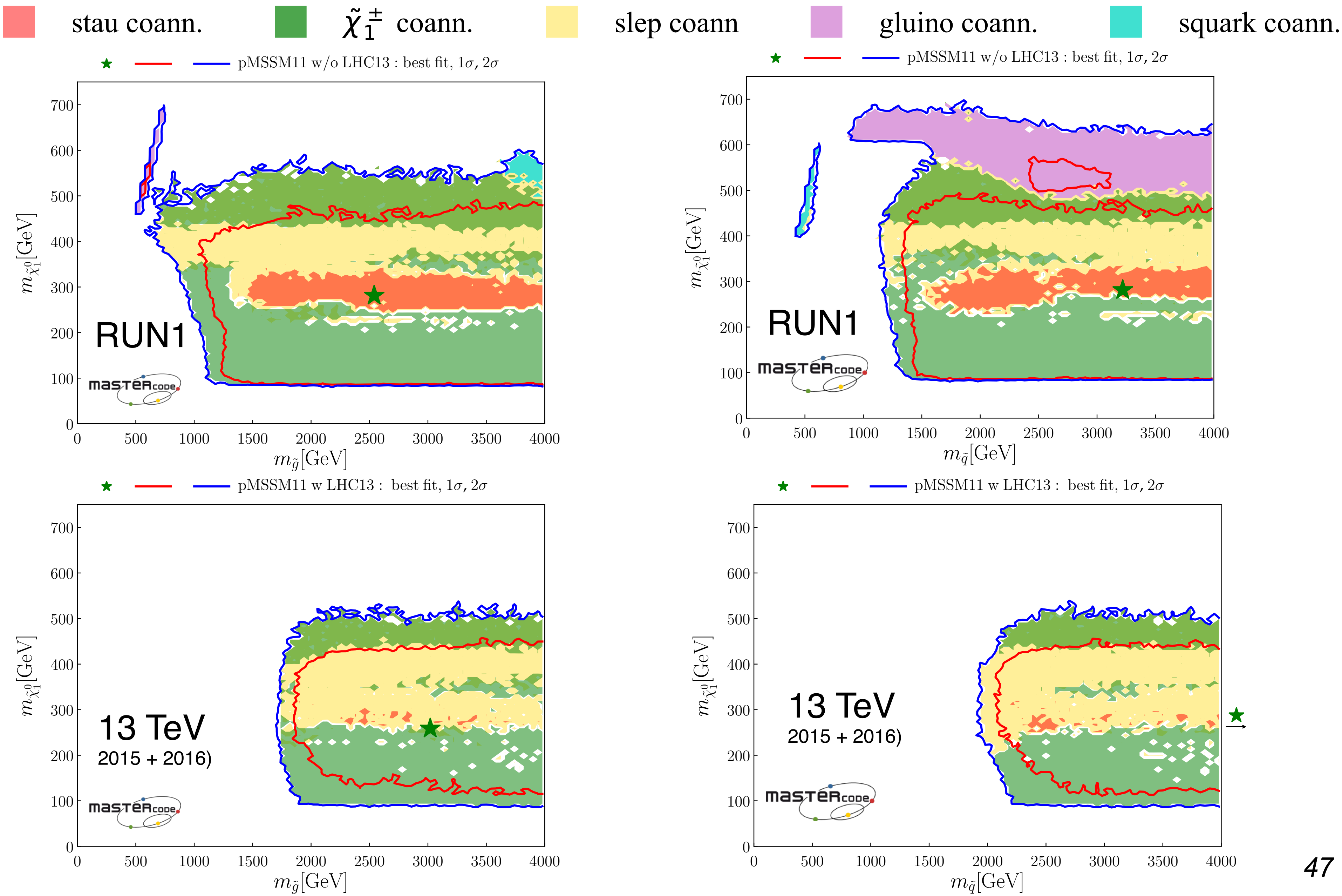
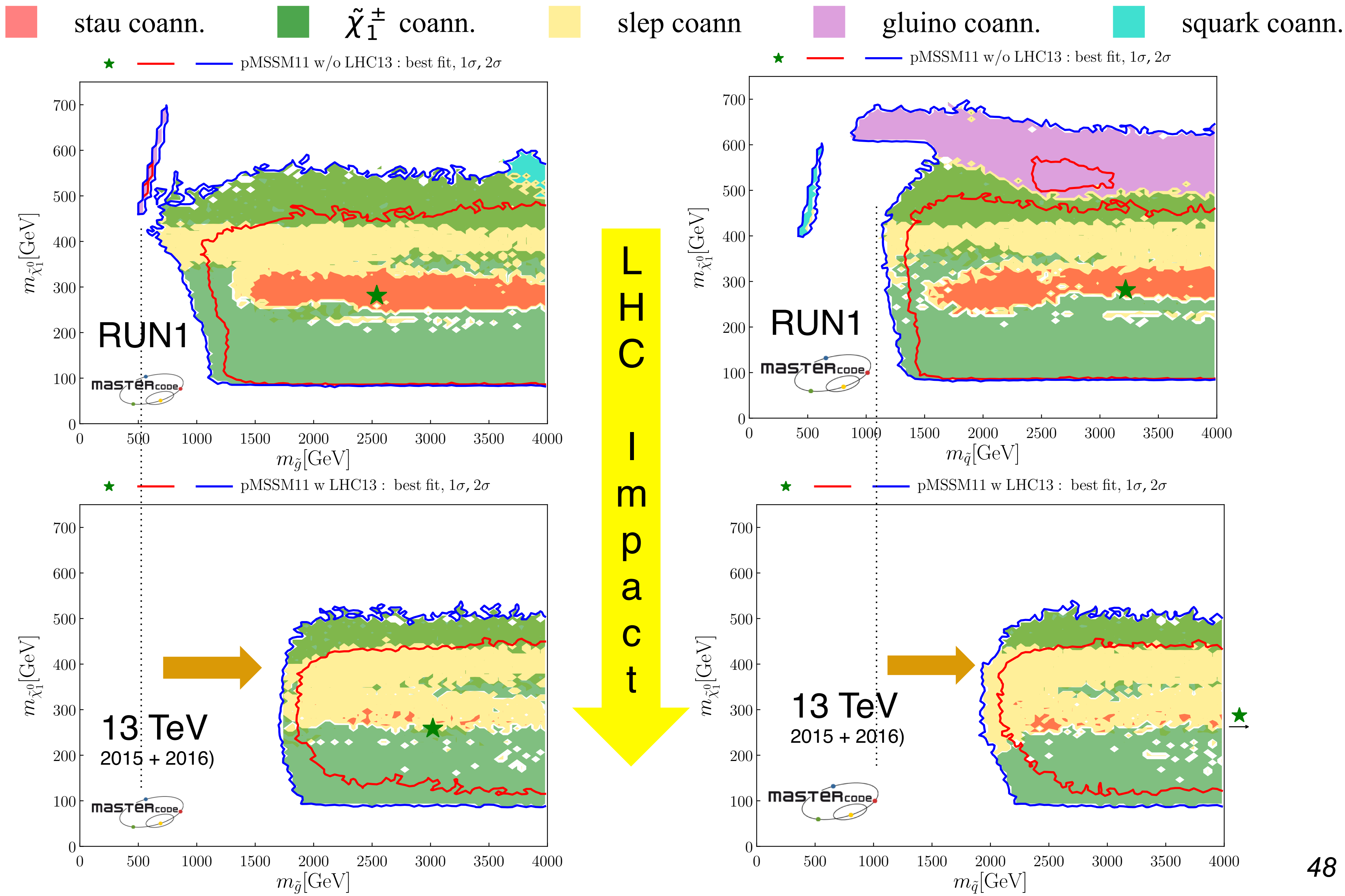
NOTE: Results based on about 1 billion points

IMPACT OF LHC13 TEV CONSTRAINTS ON PMSSM11.

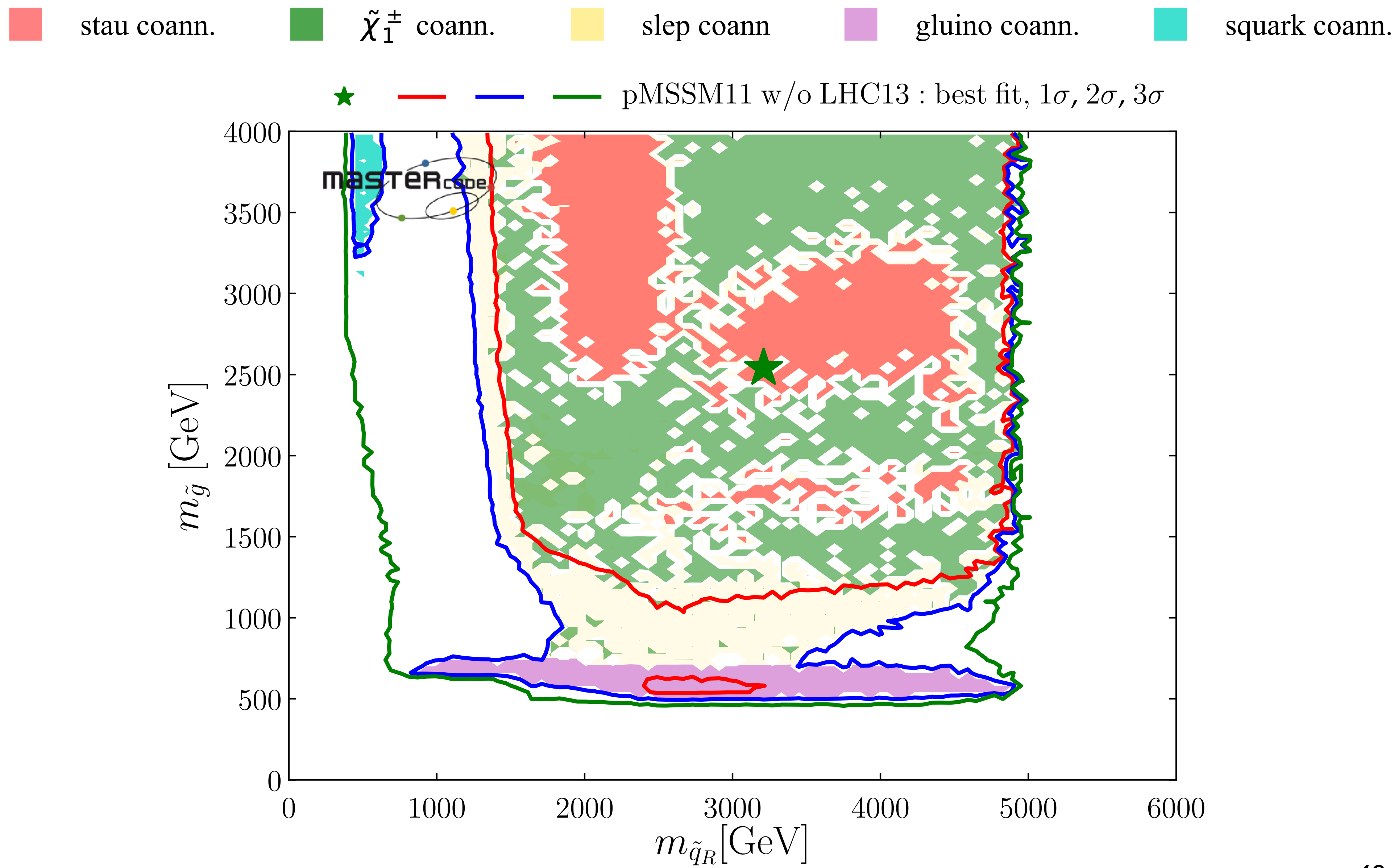
pMSSM11: RUN1 vs 13 TeV (2015 + 2016)



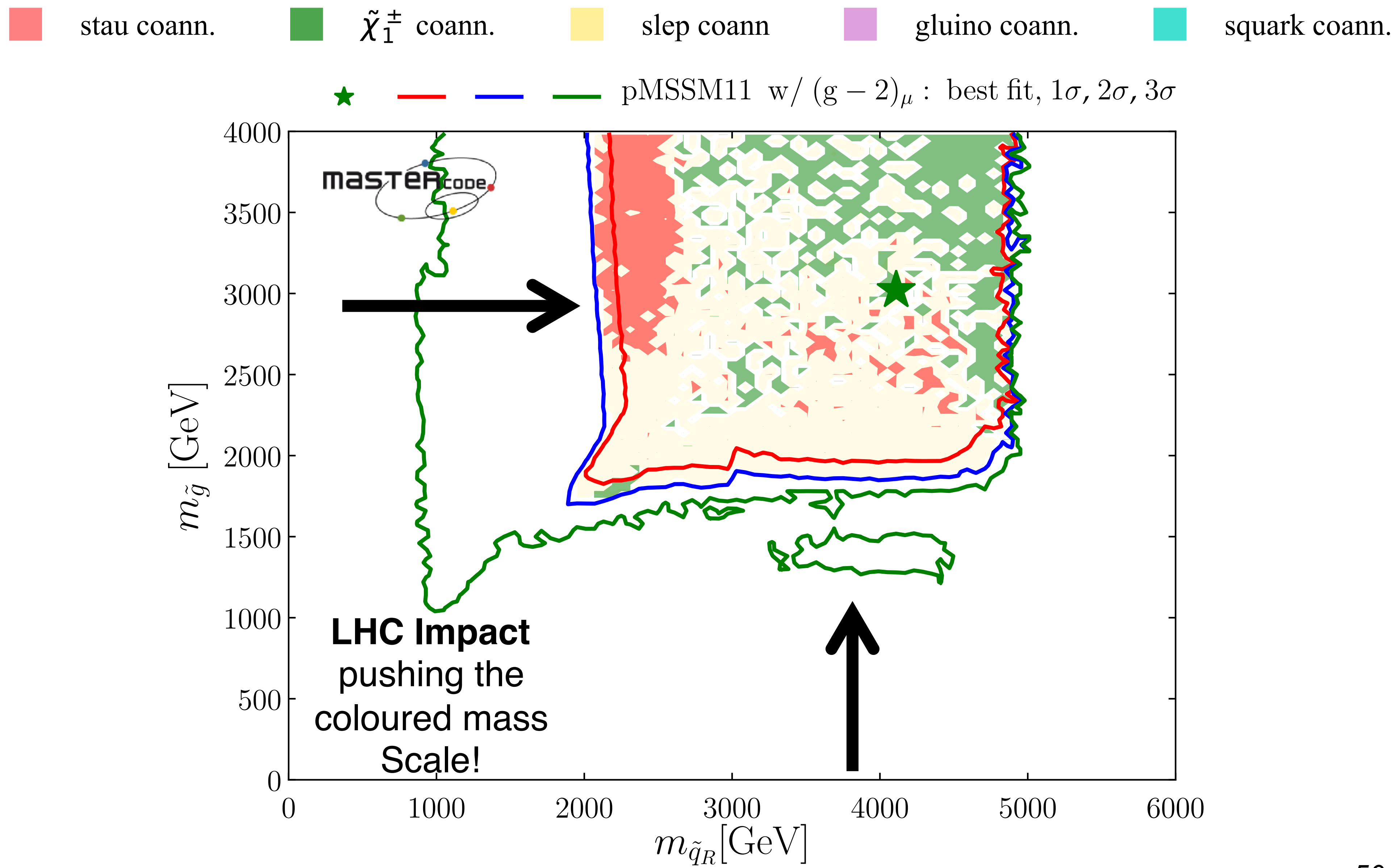
pMSSM11: RUN1 vs 13 TeV (2015 + 2016)



Gluino vs Squark: LHC RUN 1



Gluino vs Squark: LHC RUN 2 (2015 + 2016 data)



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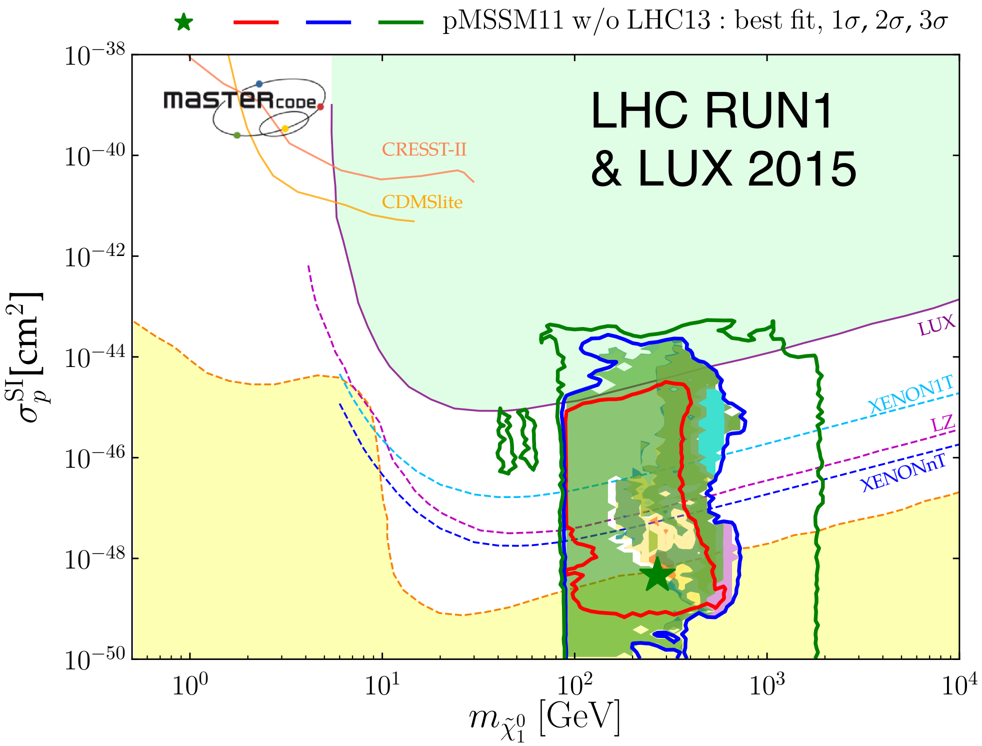
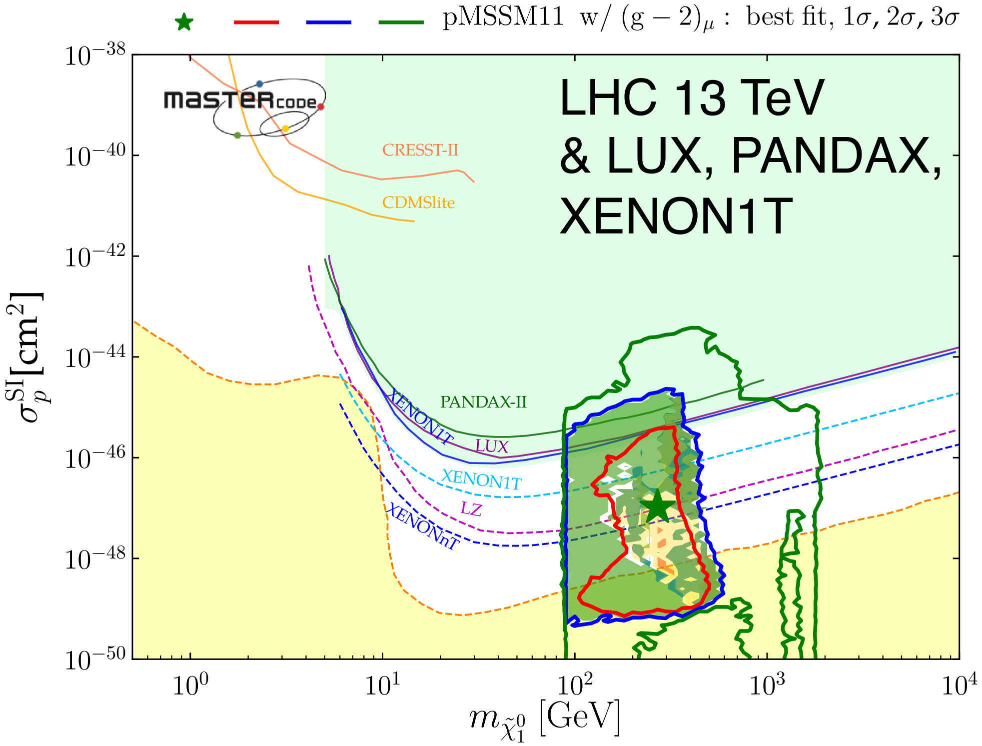
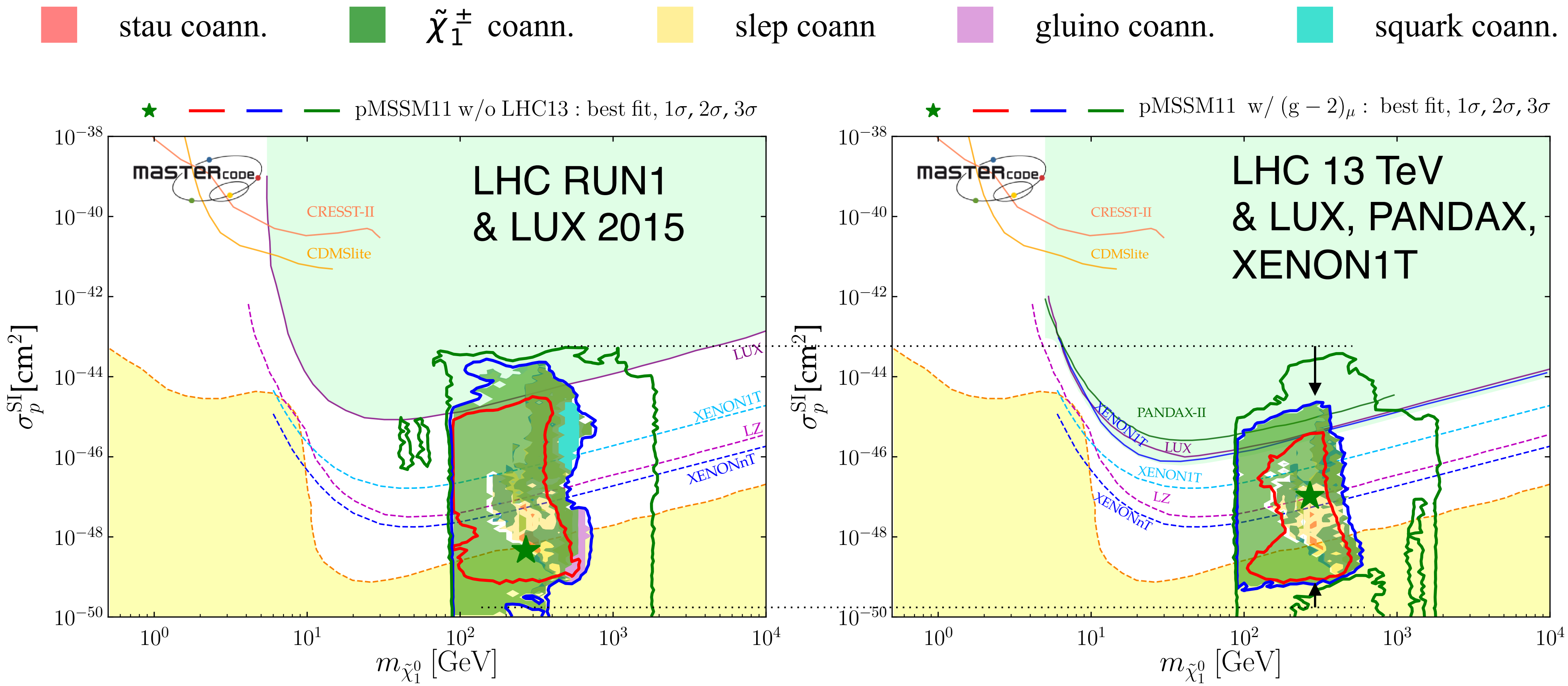
pMSSM11: σ_{SI} vs m_{DM}

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.





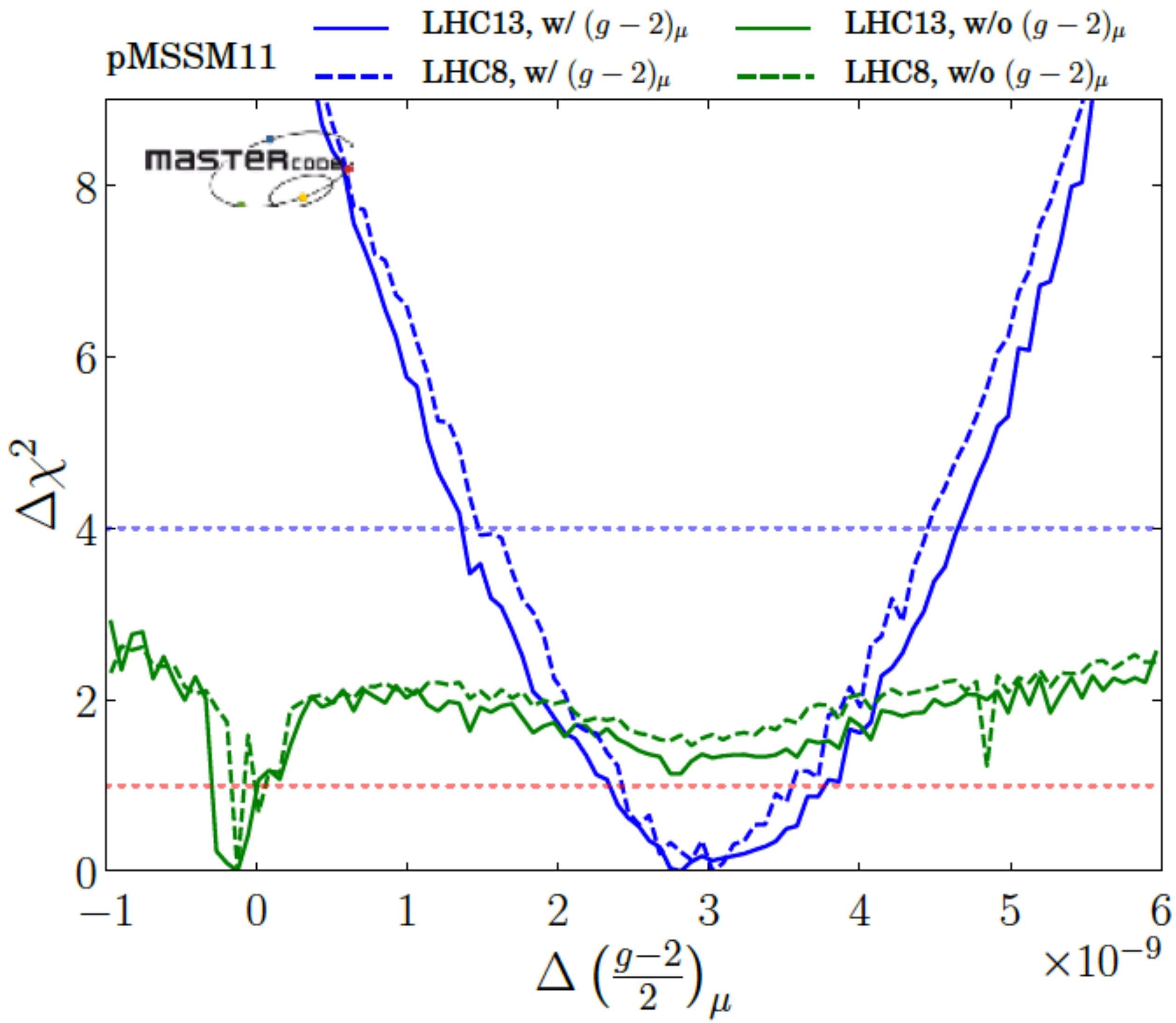
pMSSM11: σ_{SI} vs m_{DM}



Clear complementarity of collider and DD constraints:

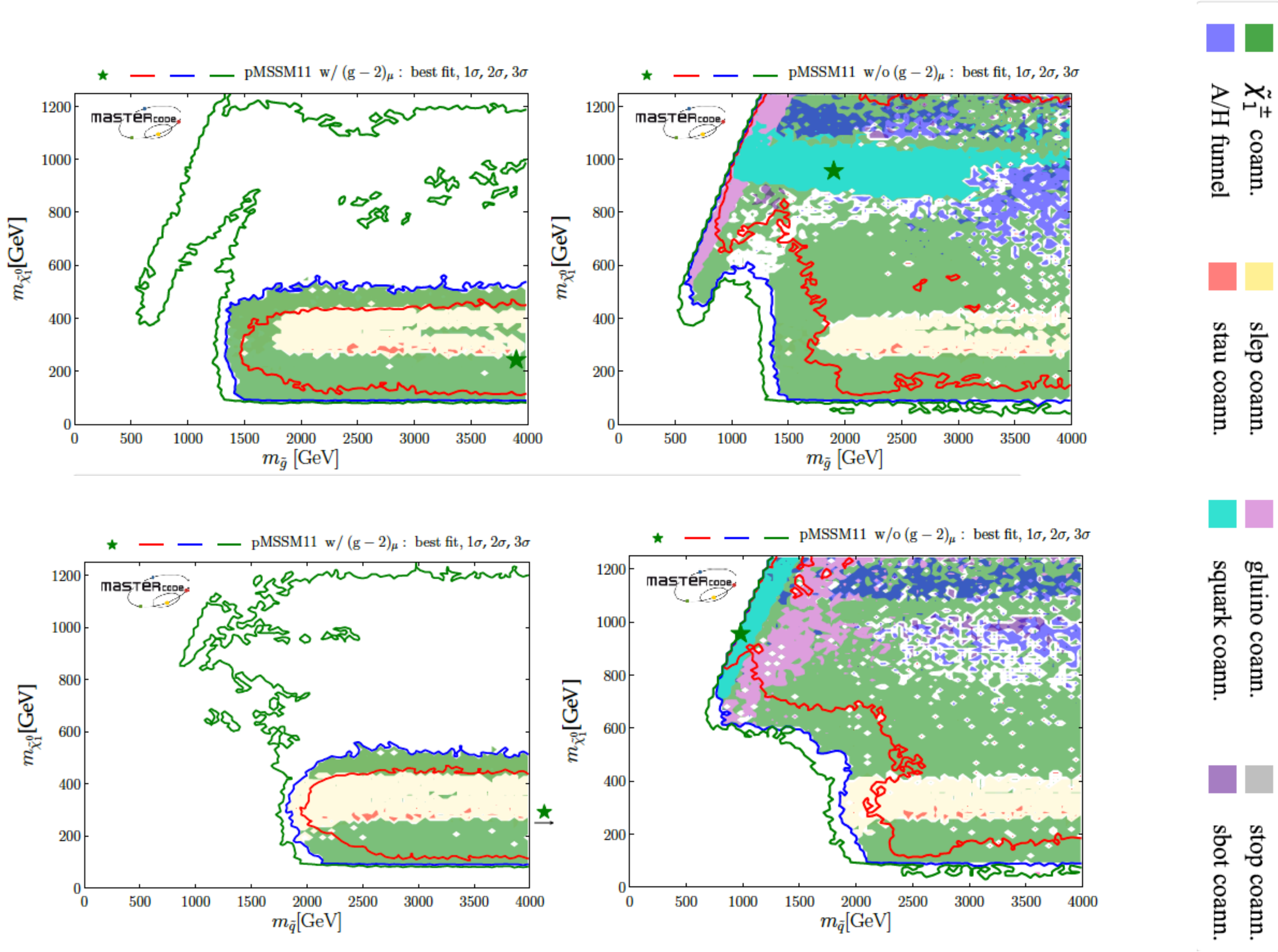
- Collider covers regions not easily or not at all accessible to DD experiments (i.e. low m_{DM} and also very small σ_{SI})
- On the other hand, DD experiments push strongly the preferred region to lower σ_{SI} (and will continue to do so in the future)

With and Without g-2

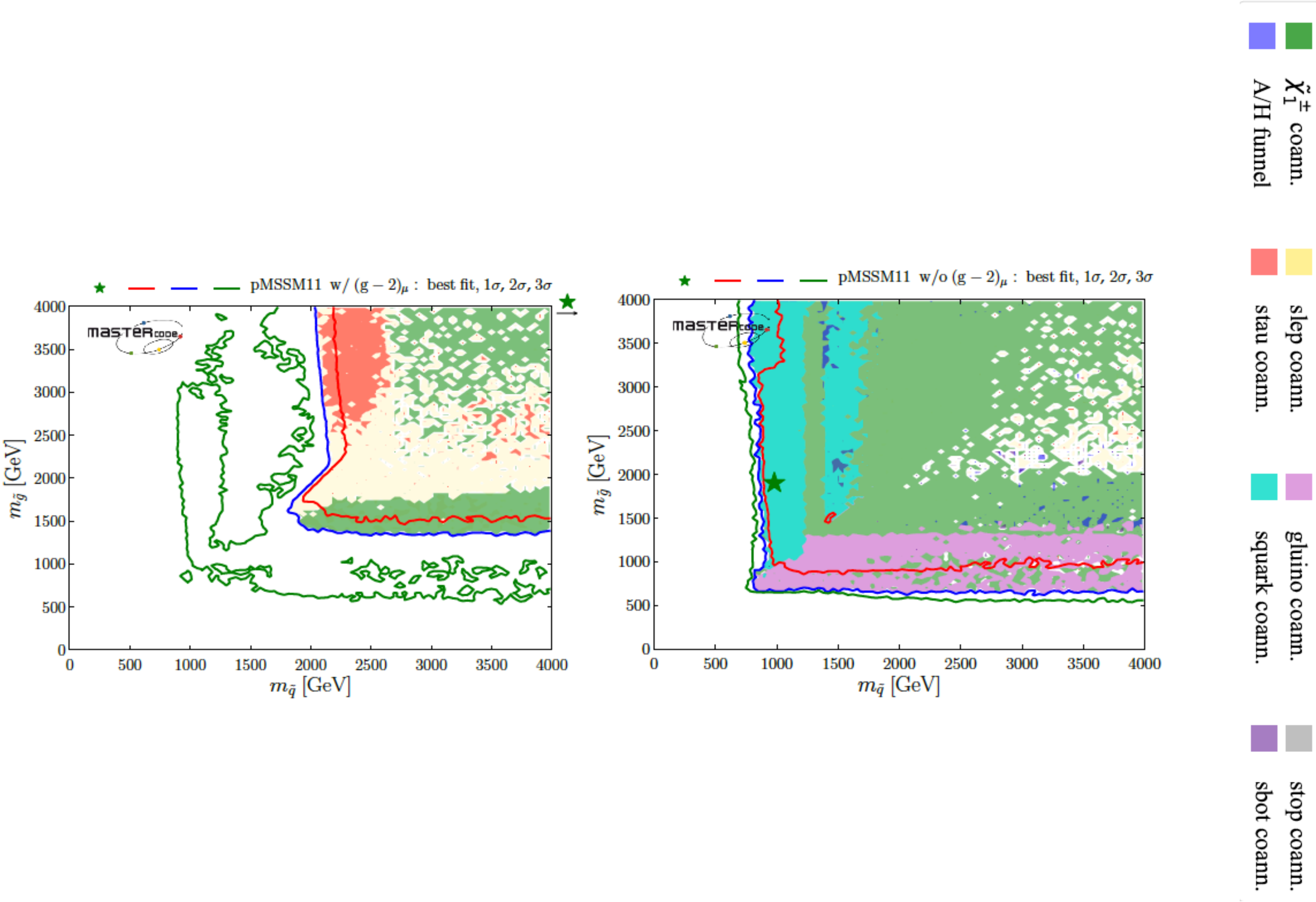


As before, also in the LHC 13 TeV era g-2 constraint plays a critical role in defining allowed SUSY parameter space.

With and Without g-2



With and Without g-2



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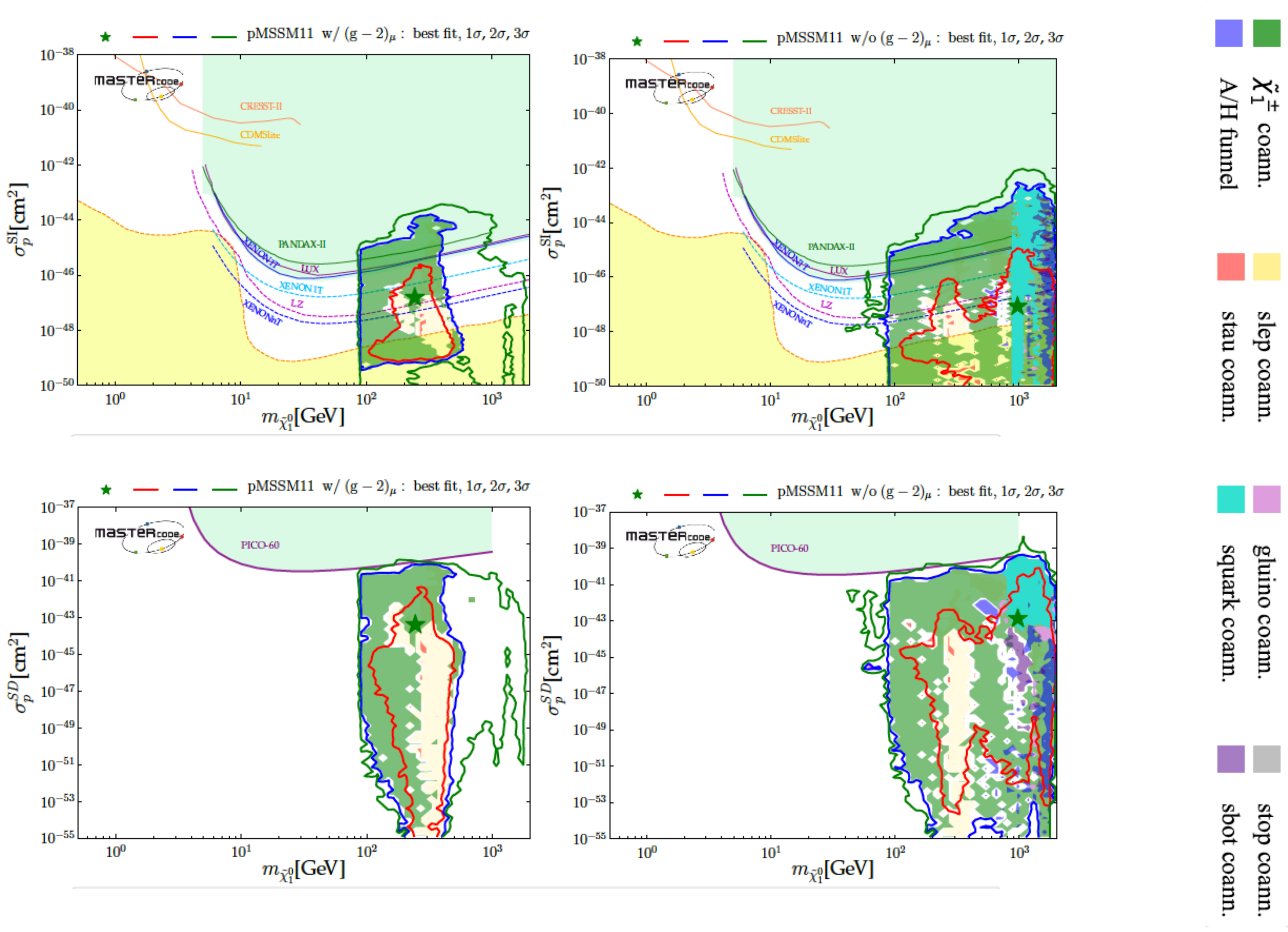
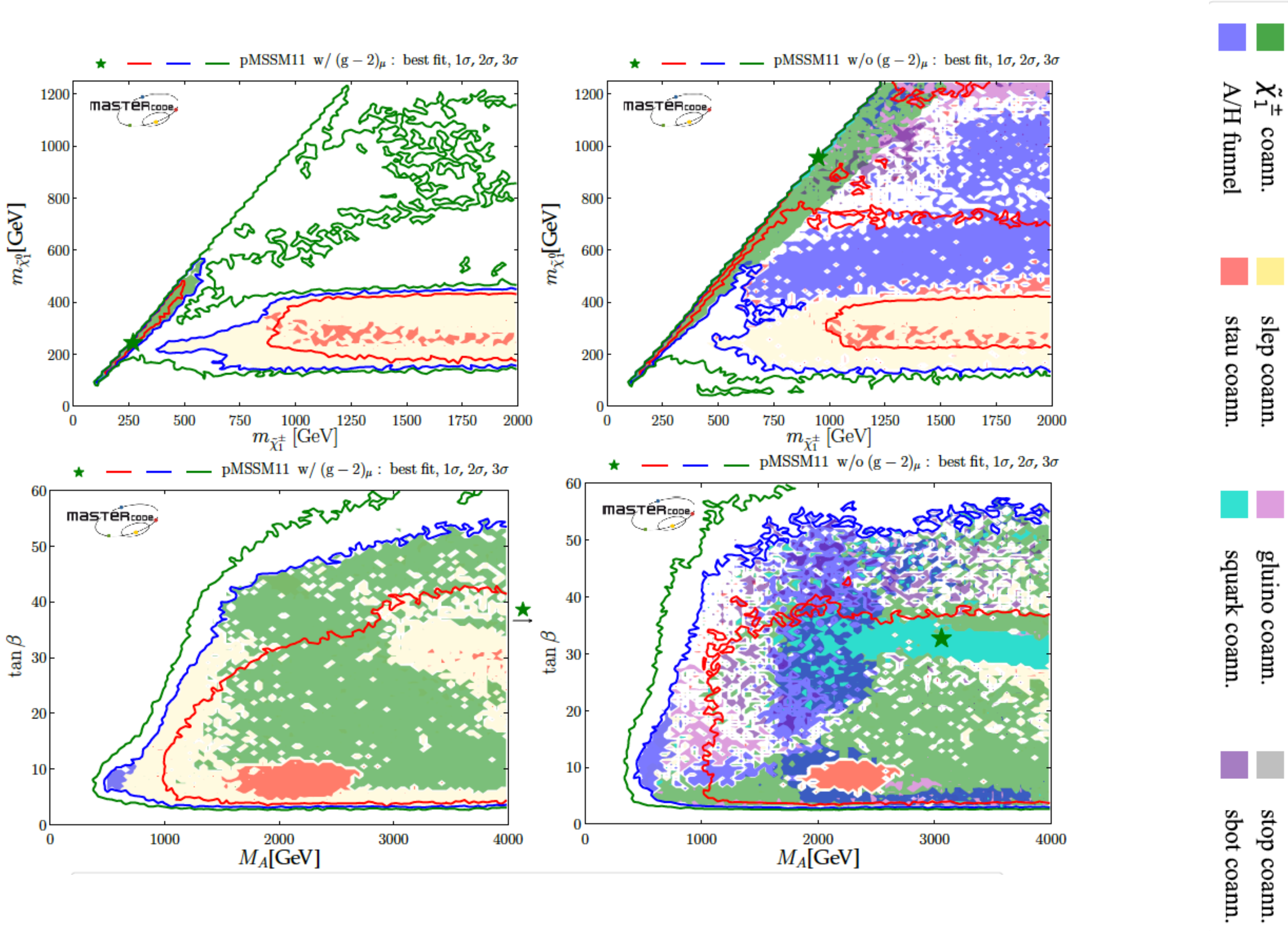
With and Without g-2



With and Without g-2



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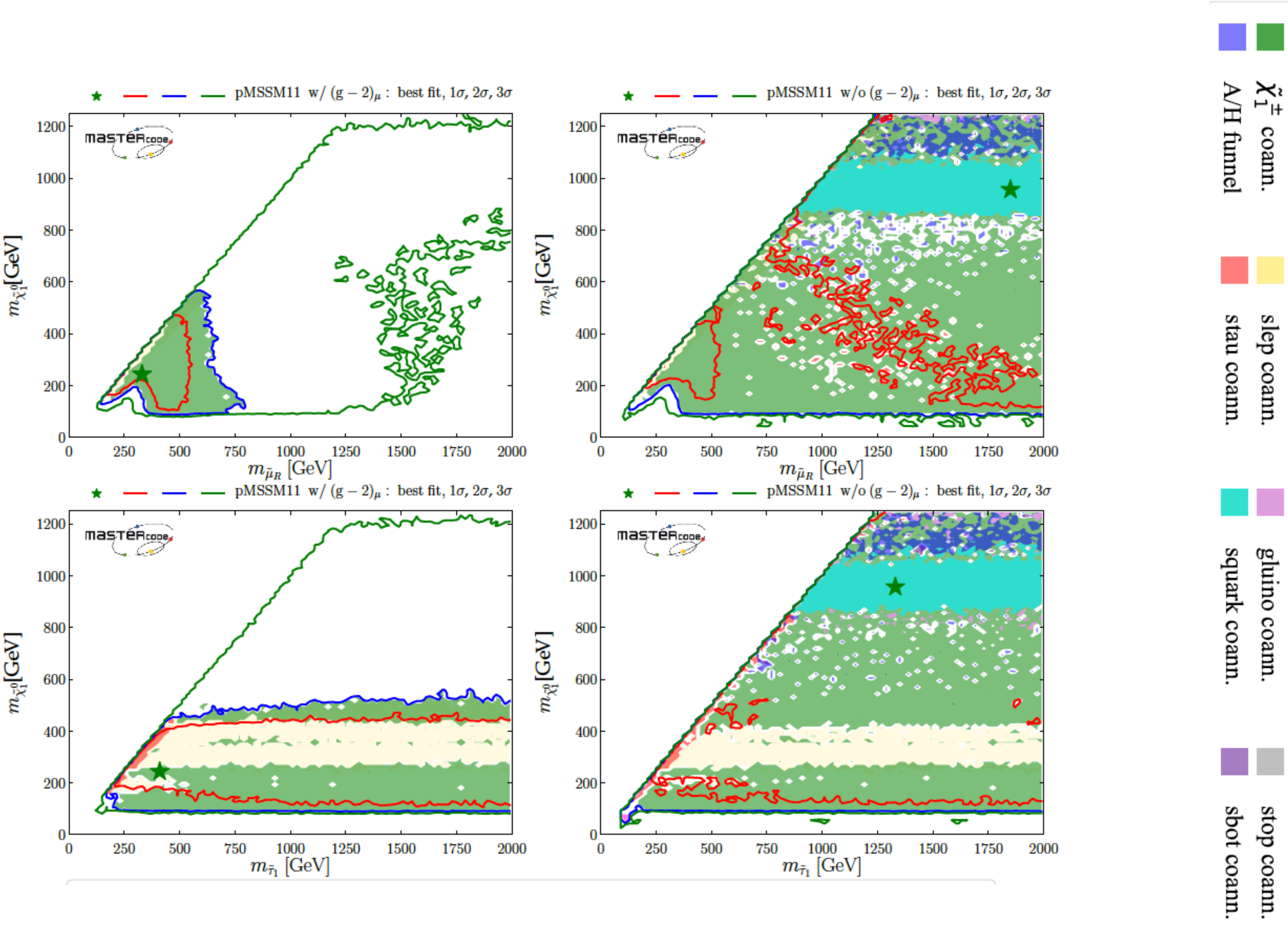
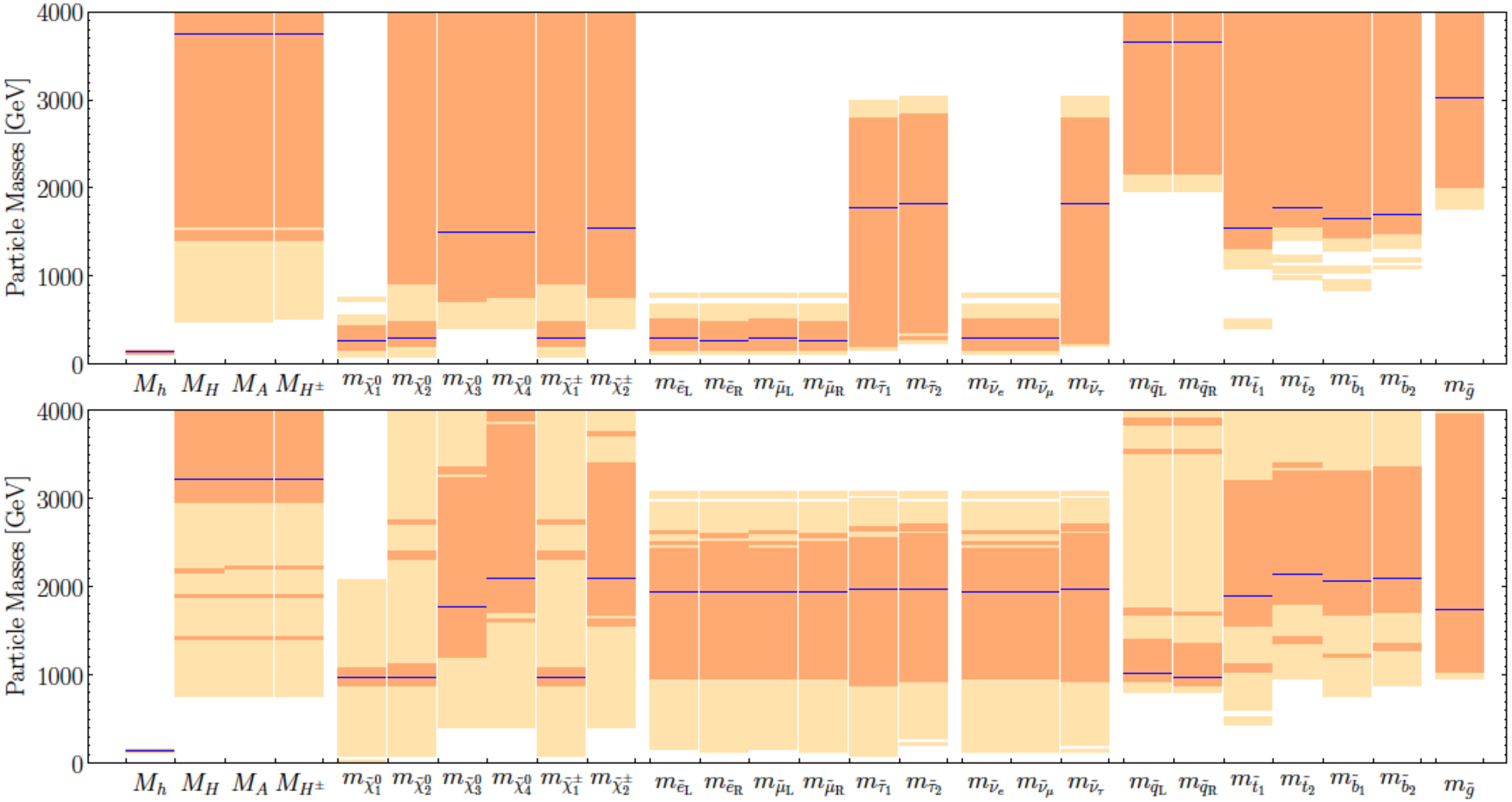
With and Without g-2



Best-Fit Point(s)

**Higgs and sparticle spectrum for the pMSSM11
with and without the (g-2) constraint.**

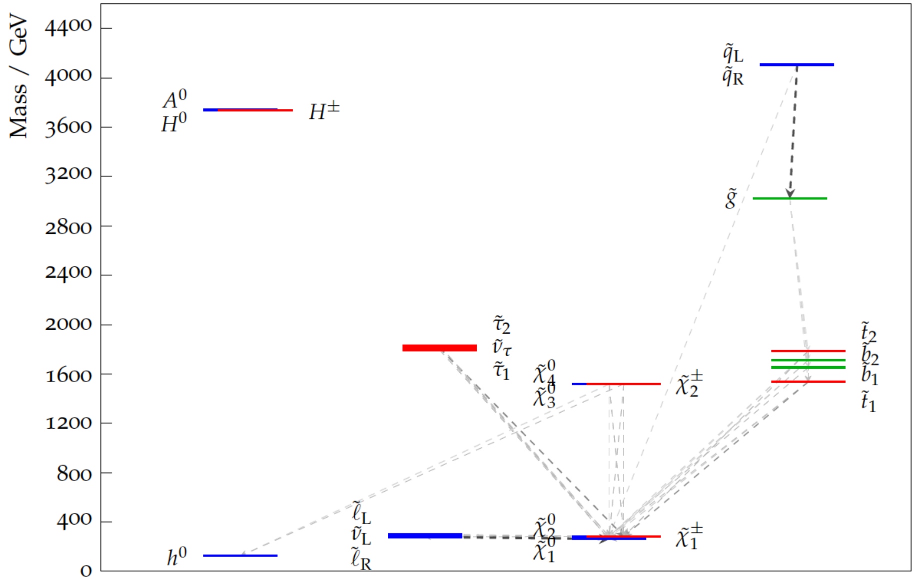
The values at the best-fit points are indicated by blue lines, the 68% CL ranges by orange bands, and the 95% CL ranges by yellow bands.



Best-Fit Point with g-2

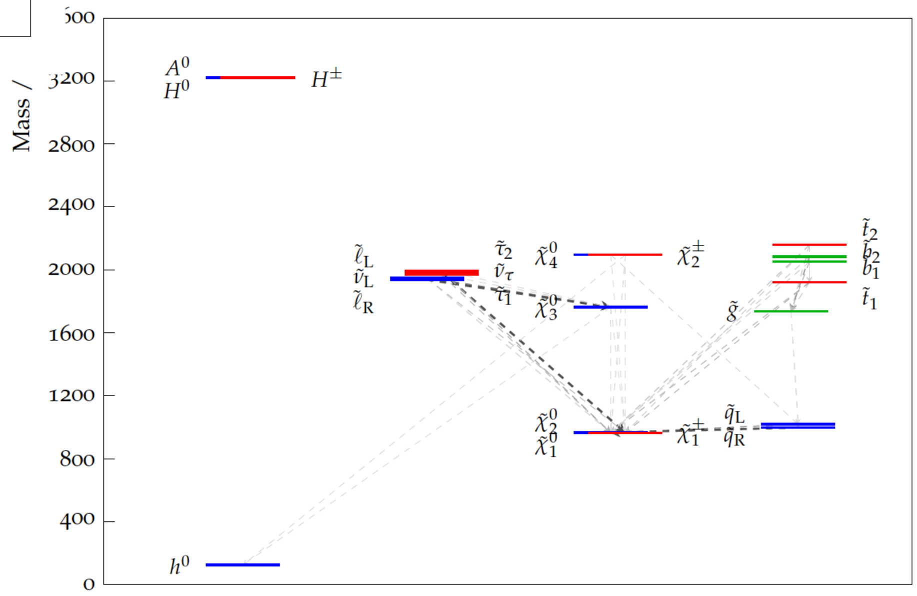
Best-Fit Point without g-2

Best-Fit Point(s) Spectra



Best-Fit Point
With g-2

Best-Fit Point
Without g-2



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Chi2 contribution breakdown

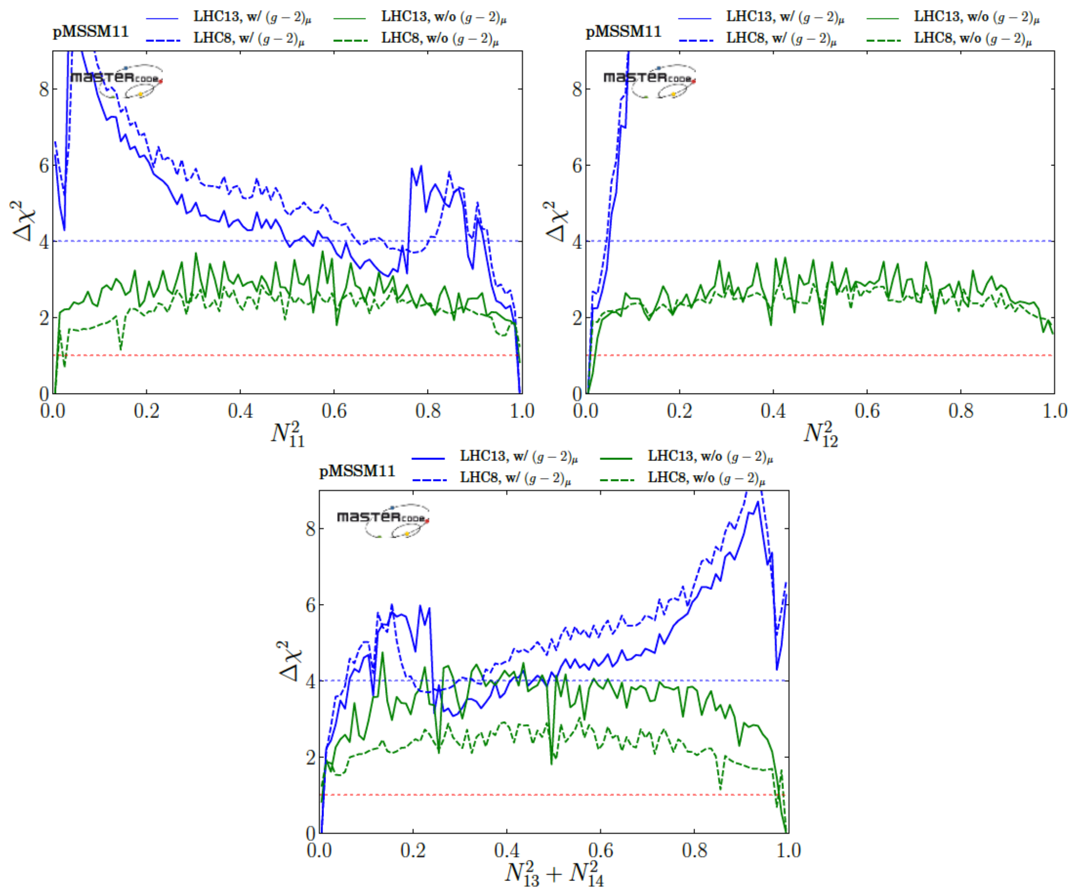
Summary

- So far New Physics has not revealed itself!
  - By 2010 the LHC has enter new territory for New Physics searches and since pushed e.g. the (coloured) SUSY mass scale well below the ~1 TeV scale
  - We were well prepared for an early discovery but we also knew that it could take more time and ingenuity before we can claim a discovery (if NP exist)
- The LHC experiments have established an impressive variety of very powerful direct searches for many different final states!
- Global Fits as e.g. executed by MasterCode are important tools to gauge the impact of these searches on the parameter space, which, in turn, informs the "big picture".
  - So far the main focus was on the MSSM but soon other models like more generic DM scenarios will follow.
- Last but not least, The LHC has still almost two decades of data taking in front of it, with a factor 100 increase of statistic still to come!

The story continues …

BACKUP

LSP composition



$$\tilde{\chi}^0_1 \; = \; N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_u + N_{14}\tilde{H}_d \; ,$$

In the LHC 13-TeV case an almost pure ~B composition of the ~01 is preferred, N11 -> 1, though the possibility that this component is almost absent is also allowed at the level Dchi2 ~ 4.

On the other hand, before the LHC 13-TeV data there would have been a mild preference for N11 -> 0.

The upper right panel shows that a small W3 component in is preferred in all cases.

Finally, the lower panel confirms that small Hud components are preferred when the LHC 13-TeV data are used, whereas there would have been a preference for these components to dominate in the absence of the LHC 13-TeV data.