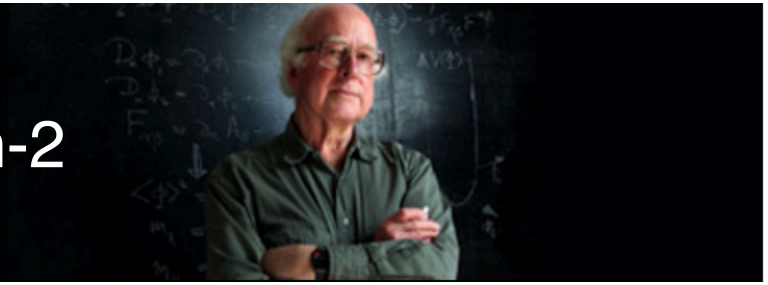
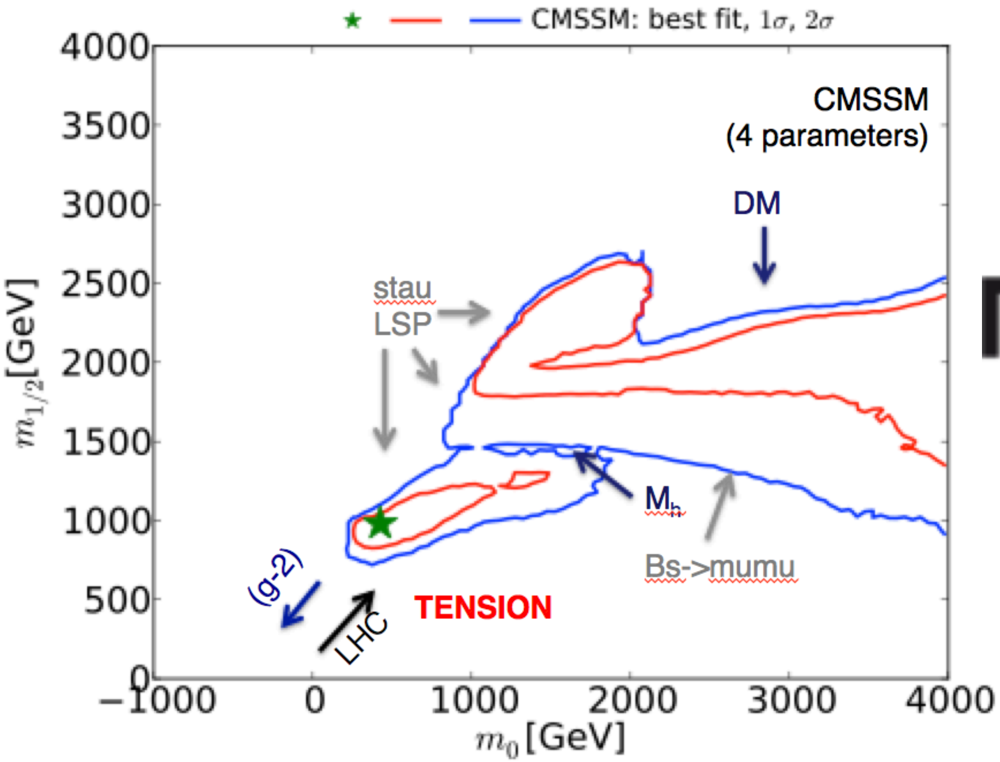
Higgs Centre
for Theoretical Physics



Fit(s) for LHC run-2

Oliver Buchmueller, Imperial College London

MATERCODE @ LHC



masterCODE

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)

MasterCode Collaboration Today

E. Bagnaschi[a], M. Borsato[b], O. Buchmueller[c], R. Cavanaugh[d,e], V. Chobanova[b], M. Citron[c], J.C. Costa[c], A. De Roeck[f], M.J. Dolan[g], J.R. Ellis[h], H. Flächer[i], S. Heinemeyer[j], G. Isidori[k], M. Lucio[b], D. Martínez Santos[b], K.A. Olive[l], A. Richards[c], K. Sakurai[m,n] G. Weiglein[a]

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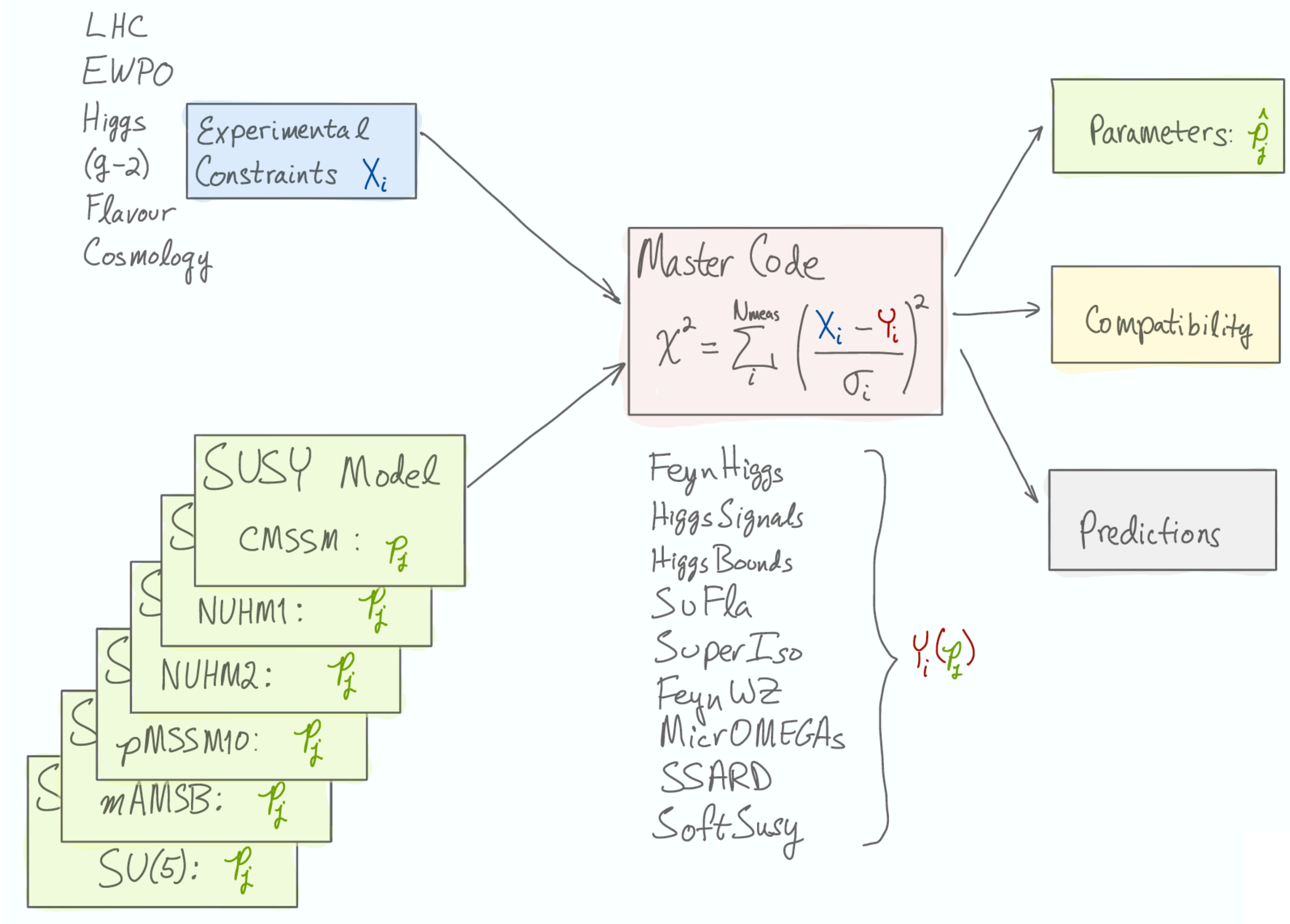
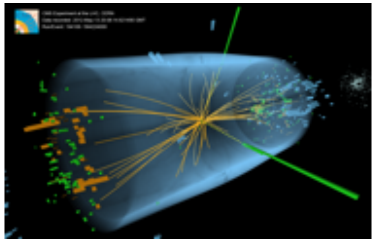
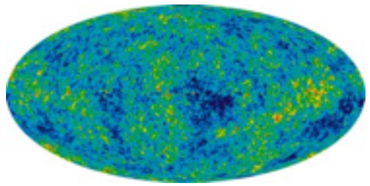
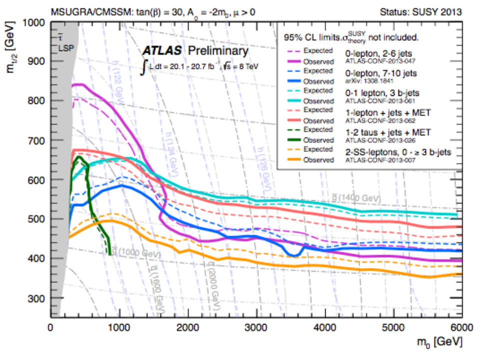
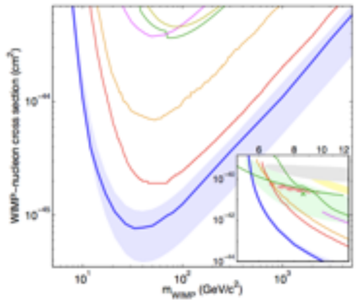
[n] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL–02–093 Warsaw, Poland*

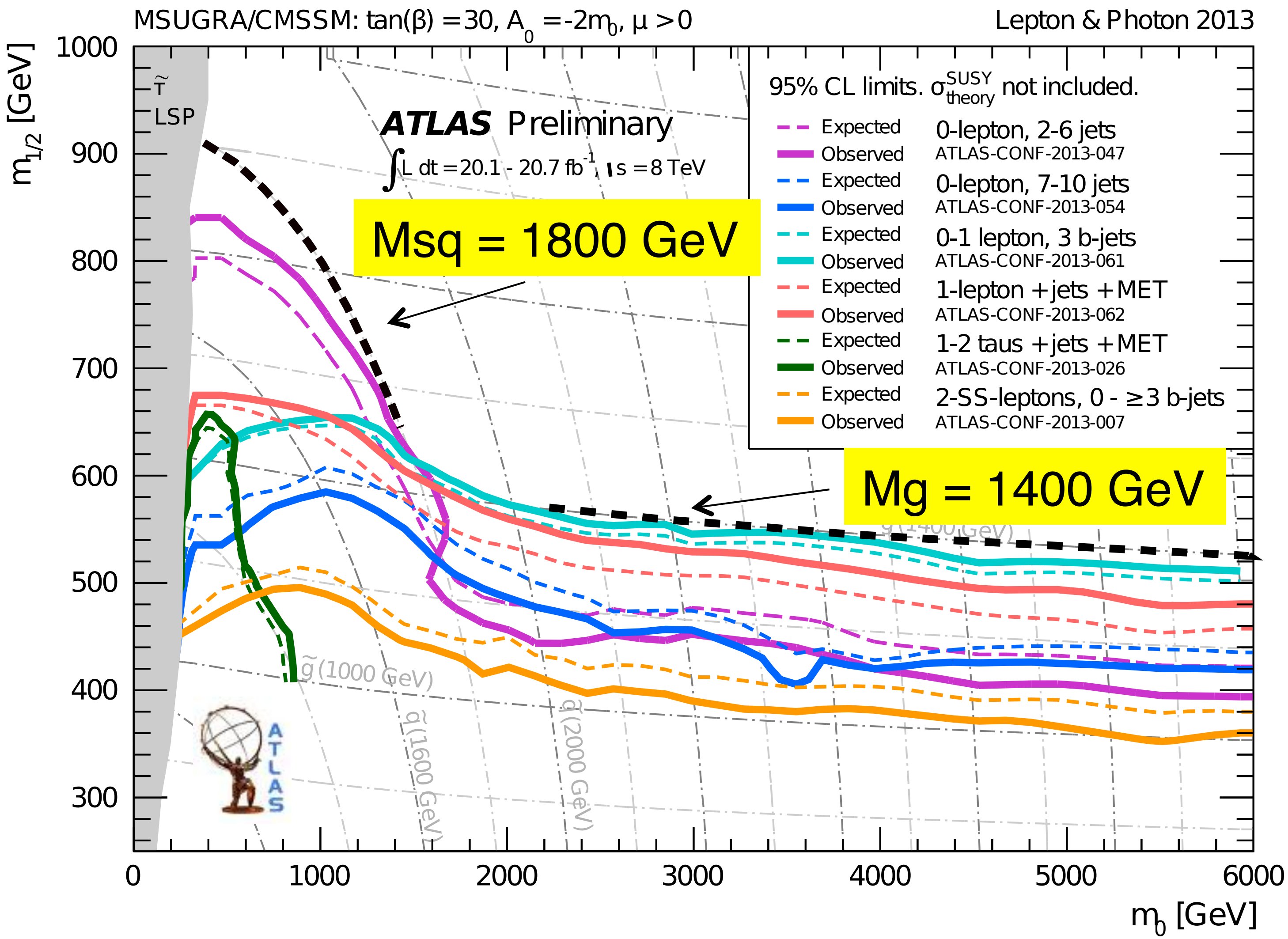
MasterCode Framework



Experimental Constraints

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

Inclusive SUSY Searches in 2013



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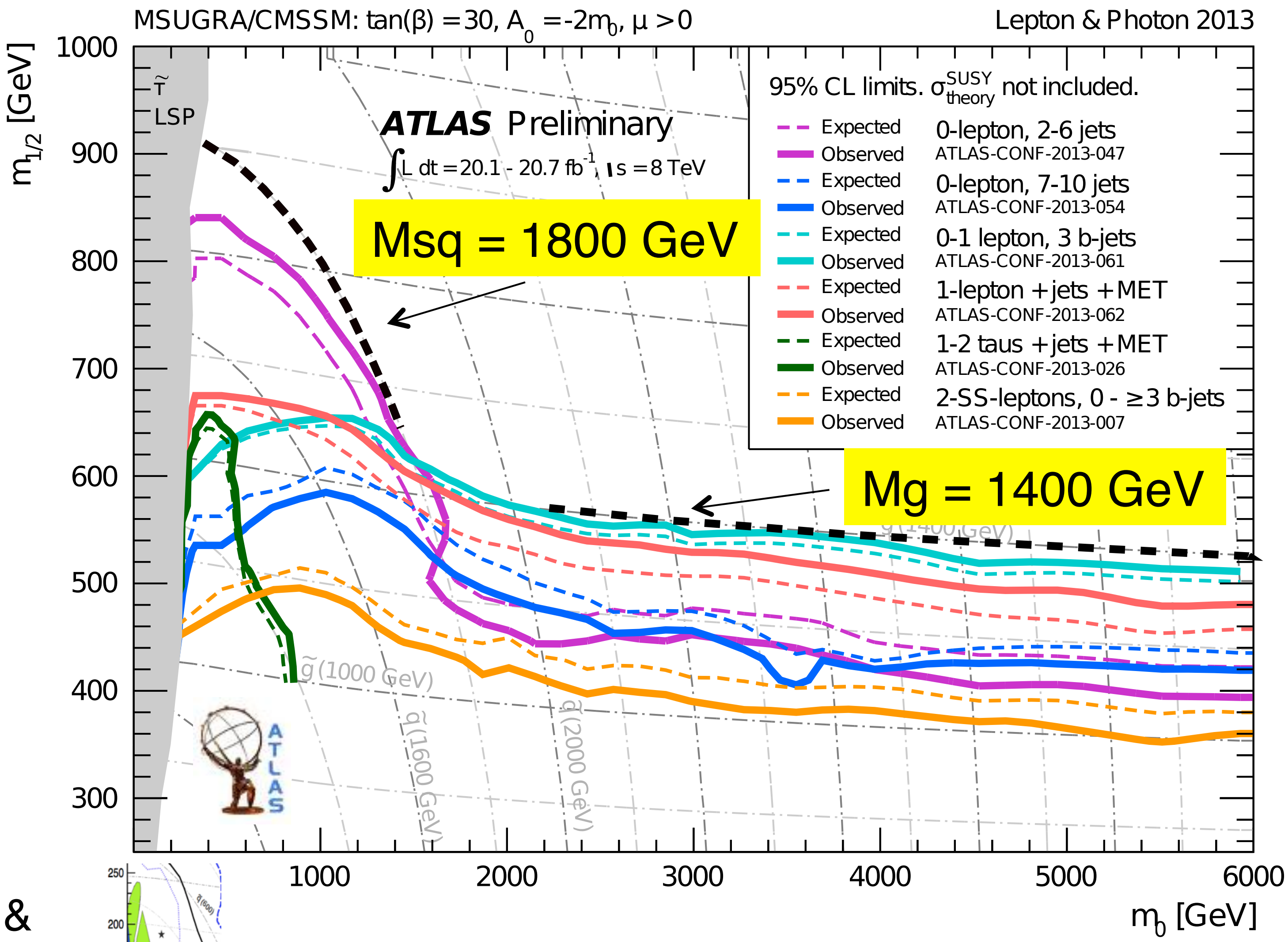
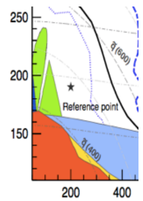
Inclusive SUSY Searches in 2013



LEP & Tevatron



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

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Inclusive SUSY Searches in 2013

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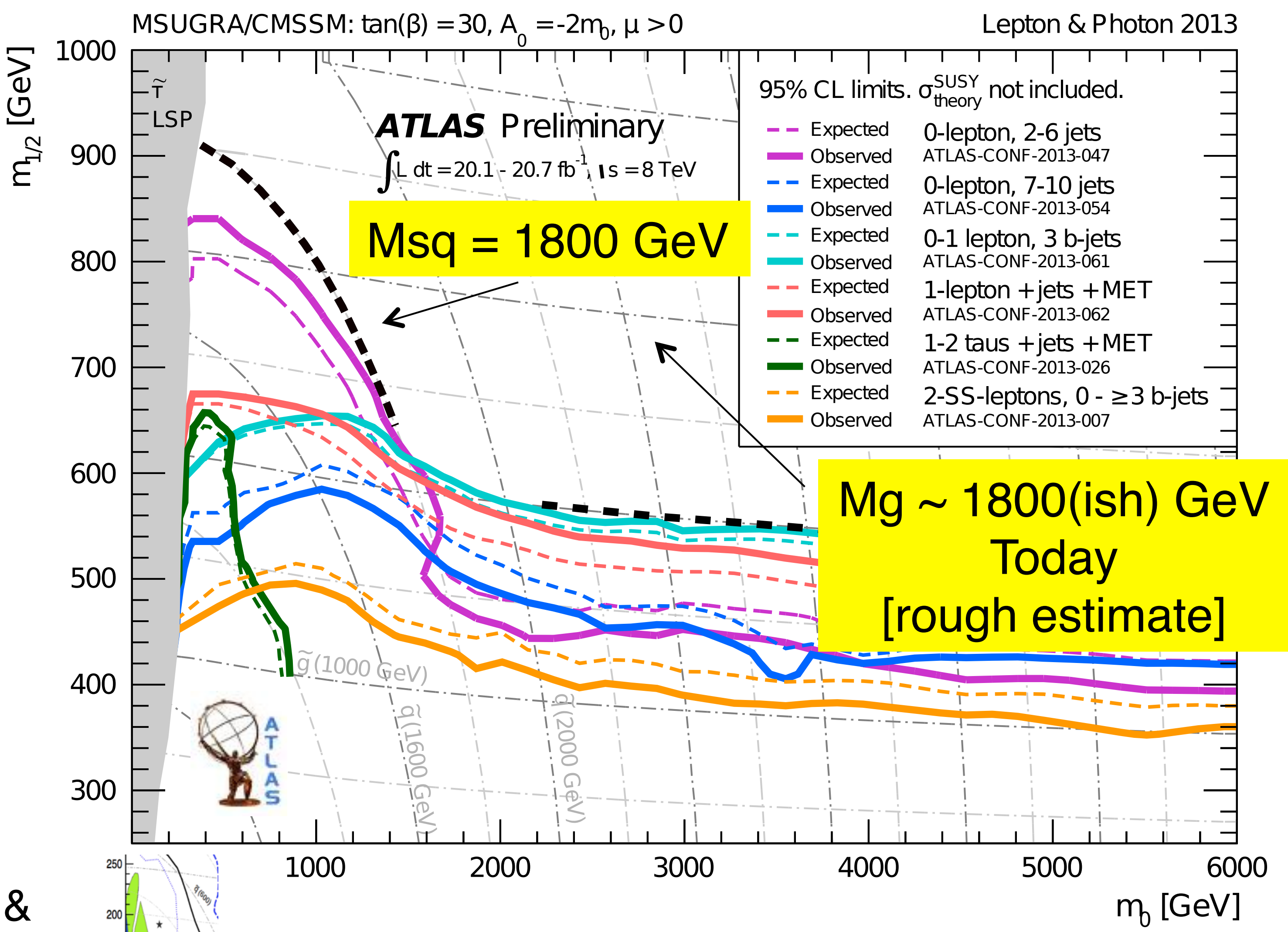
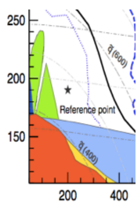


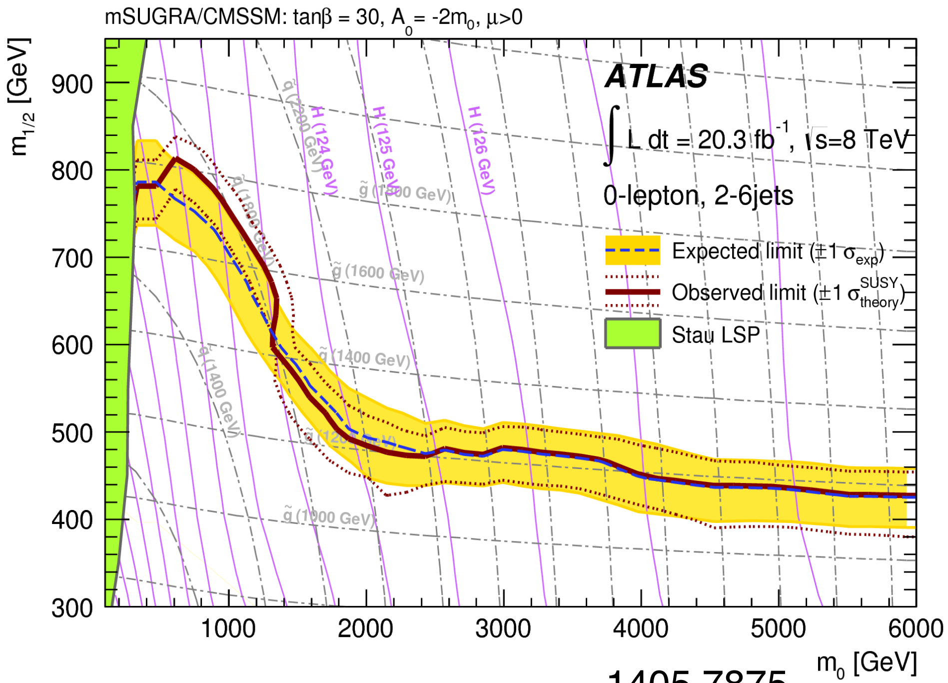
LEP & Tevatron



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

Implementation of LHC searches

GUT models



1405.7875

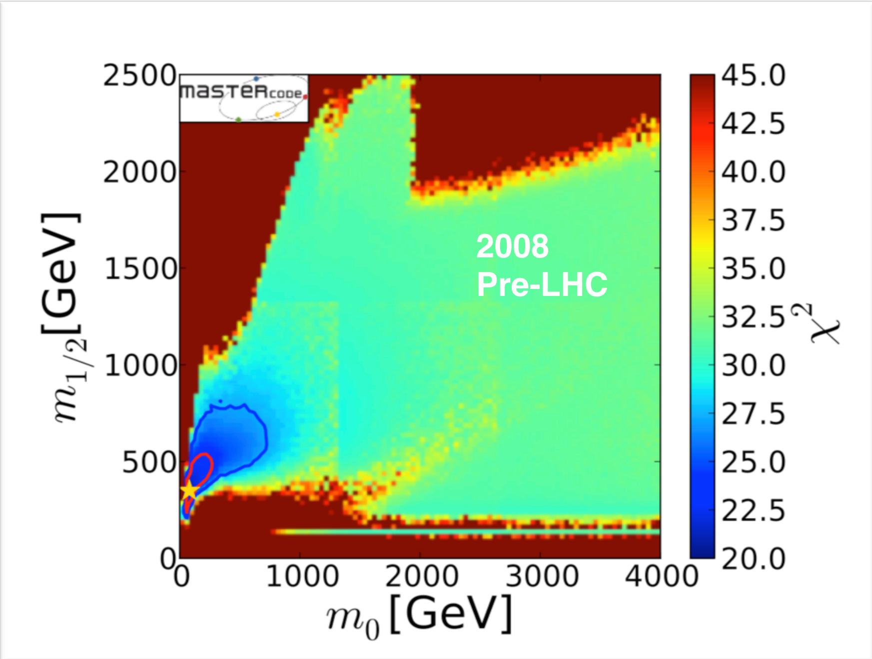
- Limits are independent of
  $$A_0, \ \tan\beta, \ m^2_{H_u}, \ m^2_{H_d}$$
- Mass limits on **squarks and gluinos** constrain implicitly those on **sleptons, neutralinos** and **charginos**

pMSSM10

- **squarks and gluinos**
  $$\chi^2(\mathrm{LHC8_{col}})$$
- **sleptons, charginos, and neutralinos**
  $$\chi^2(\mathrm{LHC8_{EWK}})$$
- **compressed-stop spectra**
  $$\chi^2(\mathrm{LHC8_{stop}})$$

CMSSM: Evolution with time

MasterCode O. Buchmüller



X^2 increase from bluish to reddish

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

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
$A_\ell(P_\tau)$	[26] / [44]	0.1465 ± 0.0032	0.11	0.13	0.07
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]	$> 114.4[\pm1.5_{SUSY}]$	0.0	0.0	0.0
$BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{EXP}$ $\pm0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
$BR(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$BR^{EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{EXP+TH}$	1.43	1.59	1.00
$BR(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6[\pm0.01_{SUSY}] \times 10^{-9}$	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^{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%)

Global Fit to indirect and direct constraints on SUSY!

Other "fitter" groups find very similar results: e.g.
SuperBayeS: **arXiv:1212.2636**
Fittino group: **arXiv:1204.4199**

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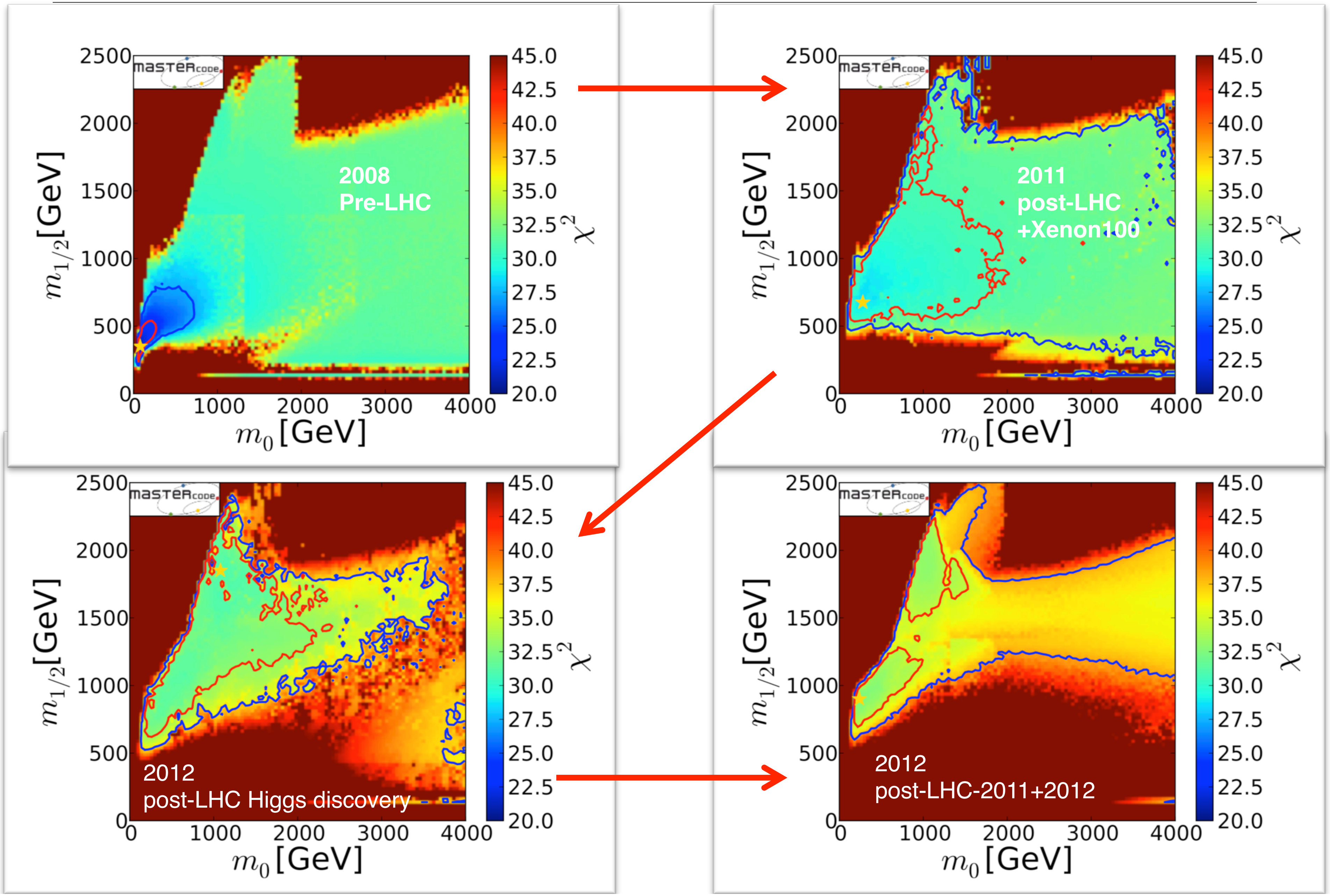
CMSSM: Evolution with time



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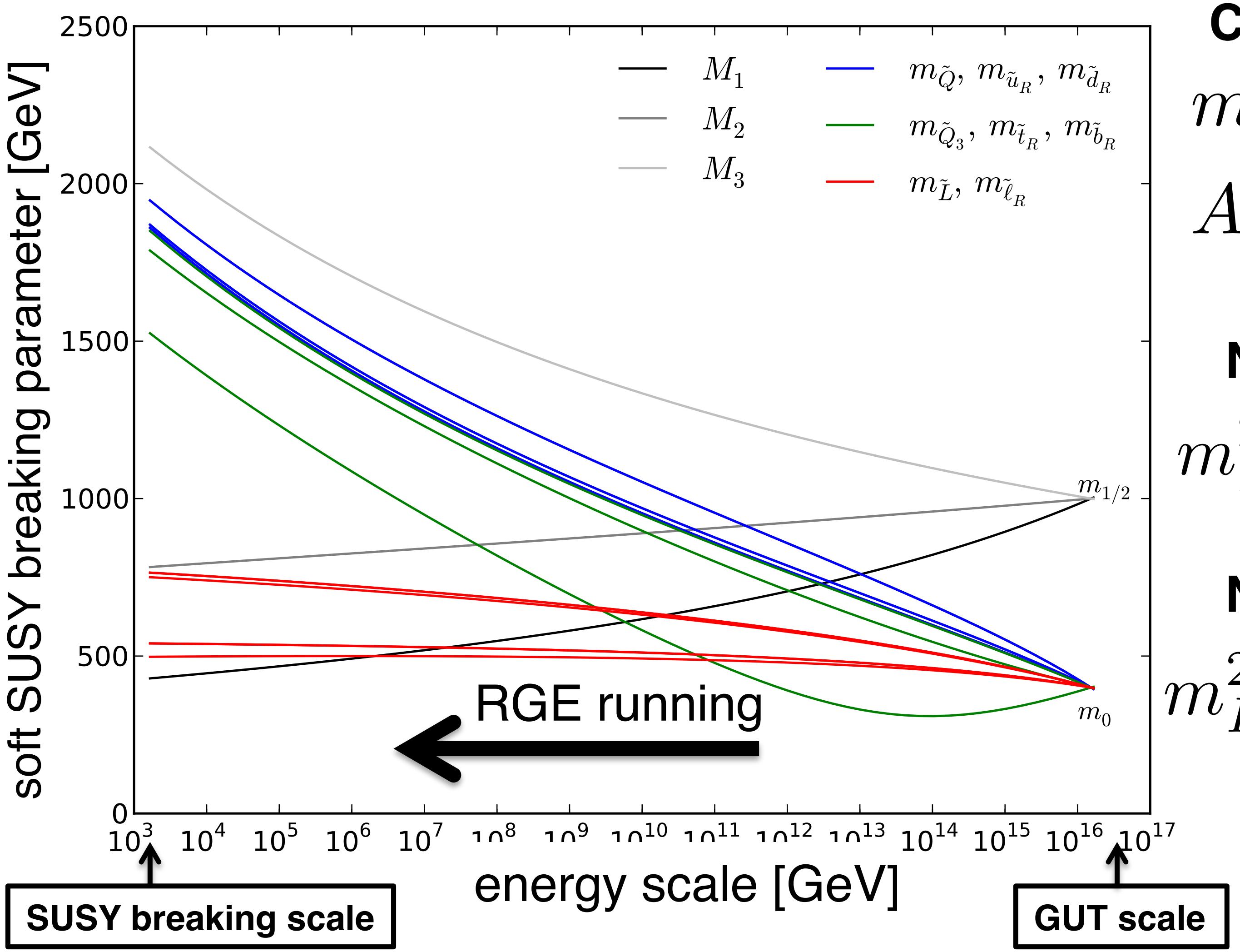
MasterCode: The two worlds of SUSY models

"GUT scale"



CMSSM

$$m_0, \; m_{1/2}, \; A_0, \; \tan\beta$$

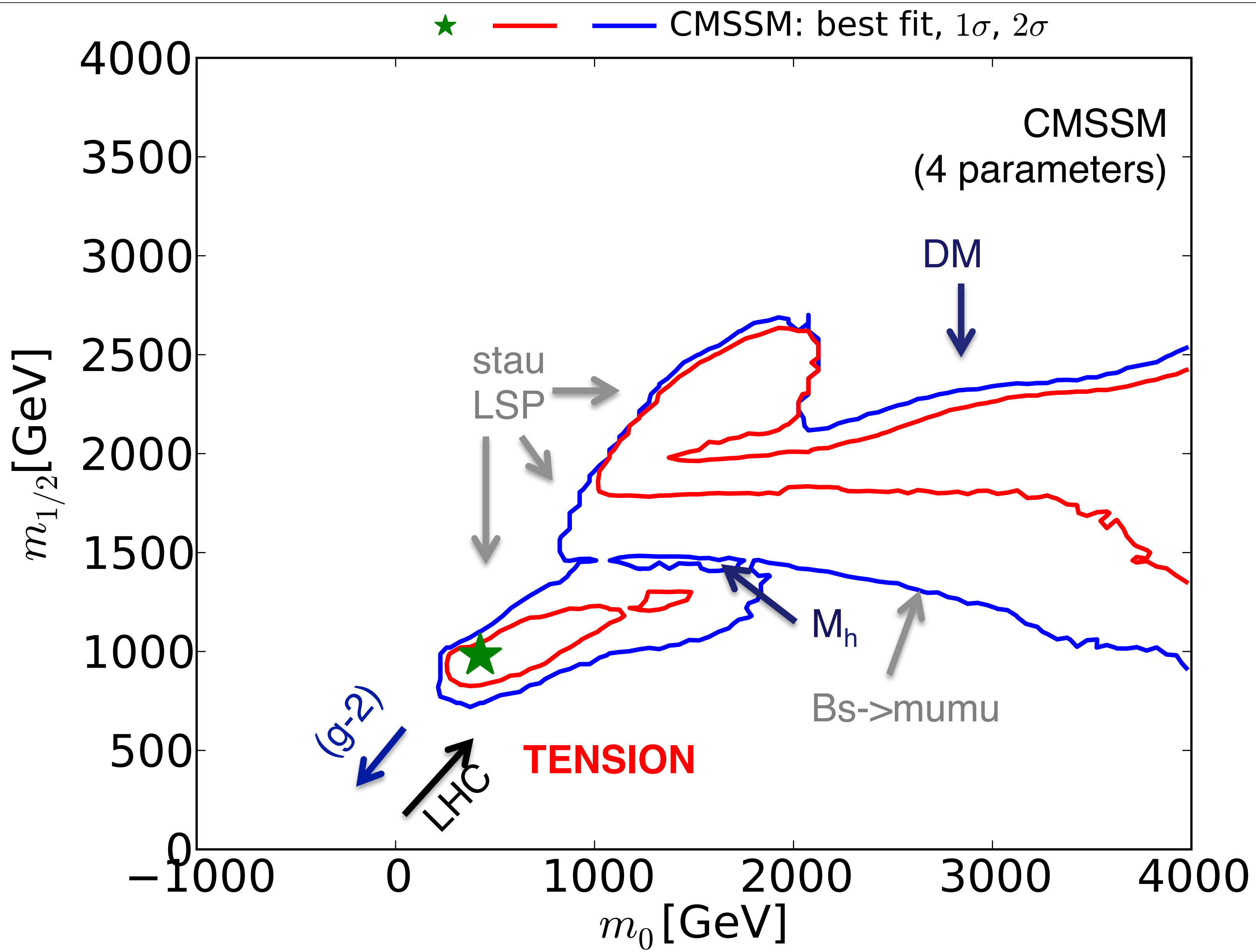
NUHM1

$$m_{H_u}^2 = m_{H_d}^2$$

NUHM2

$$m_{H_u}^2 \neq m_{H_d}^2$$

Interplay of constraints



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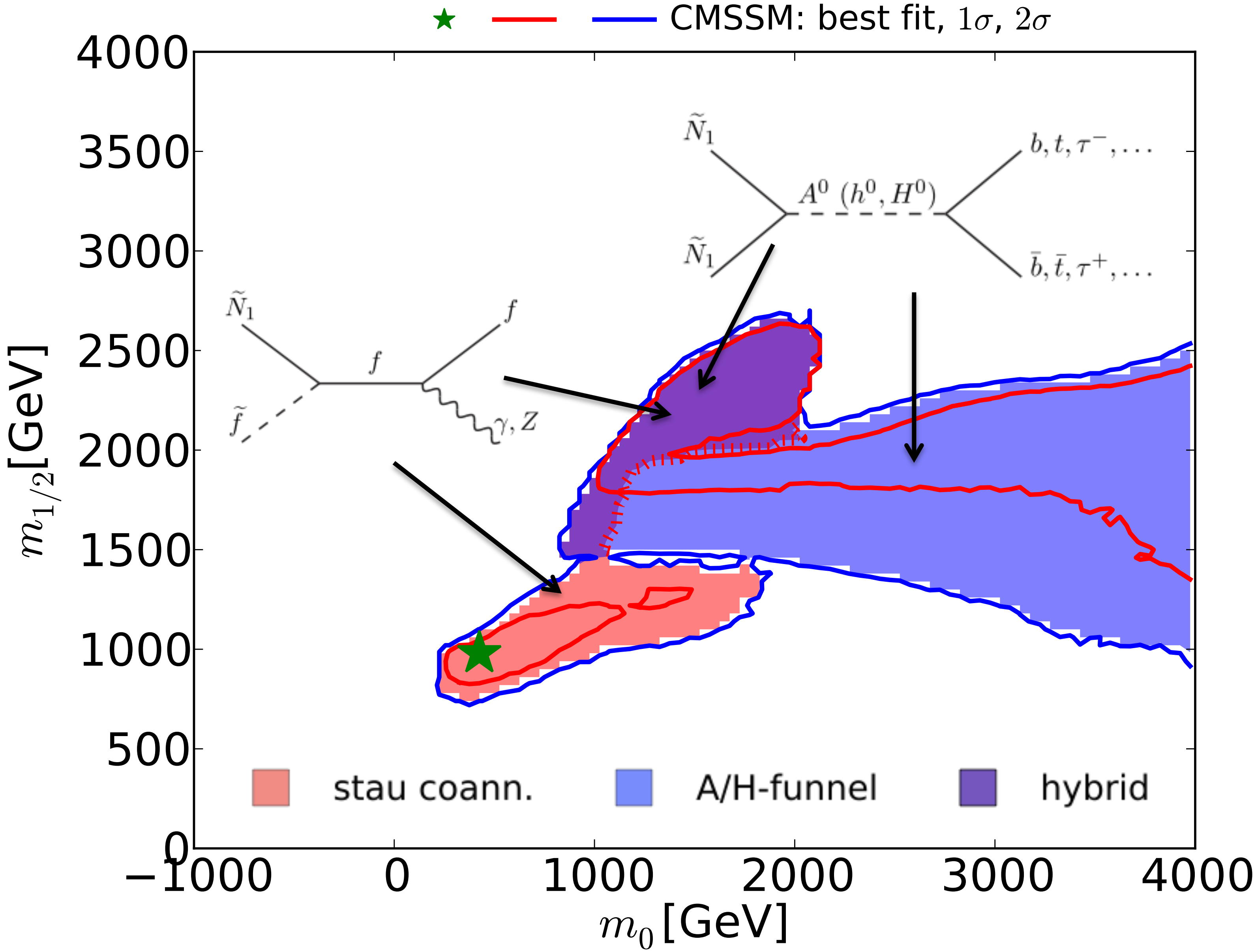
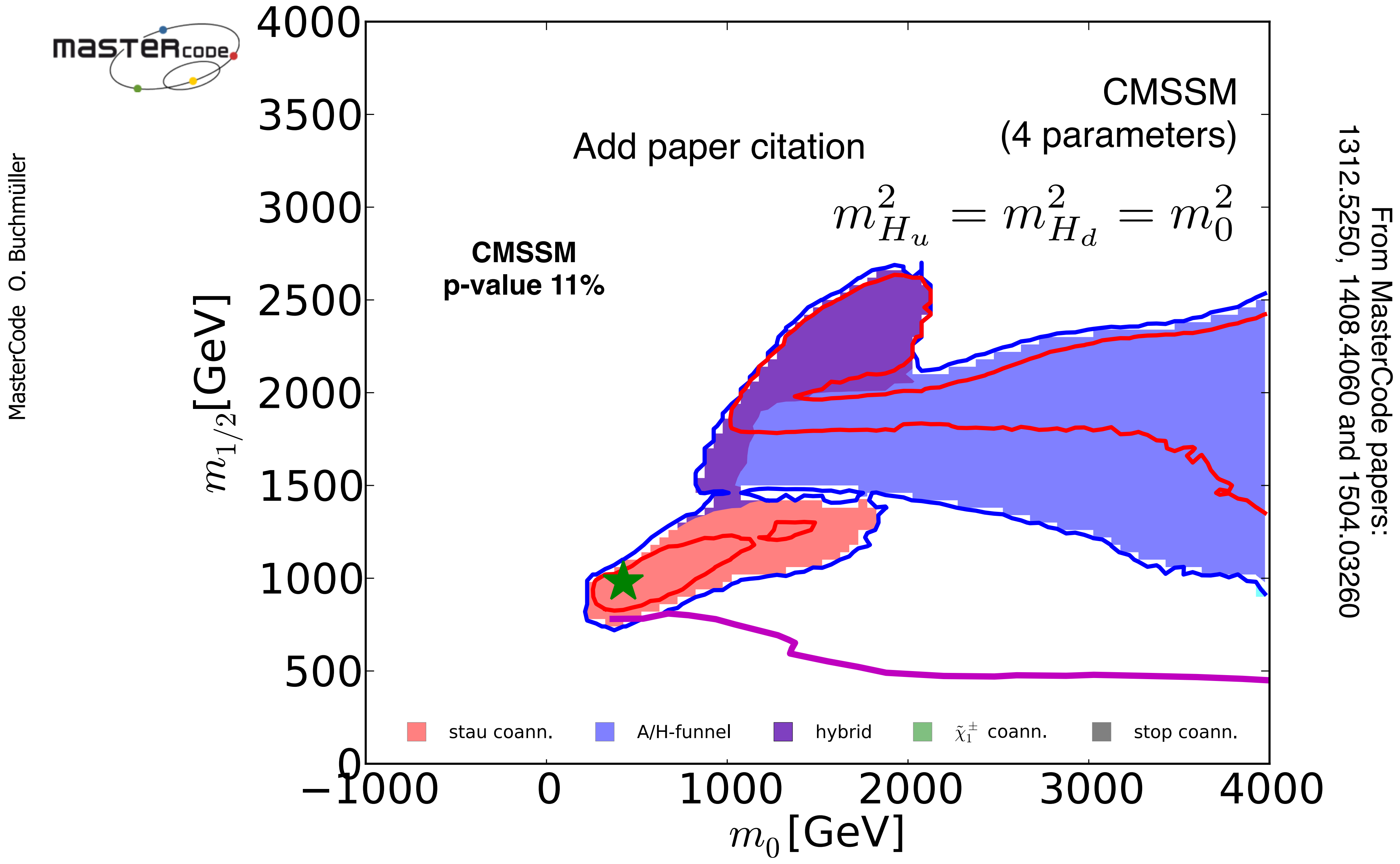
Mechanisms for relic dark matter density fulfillment in the CMSSM

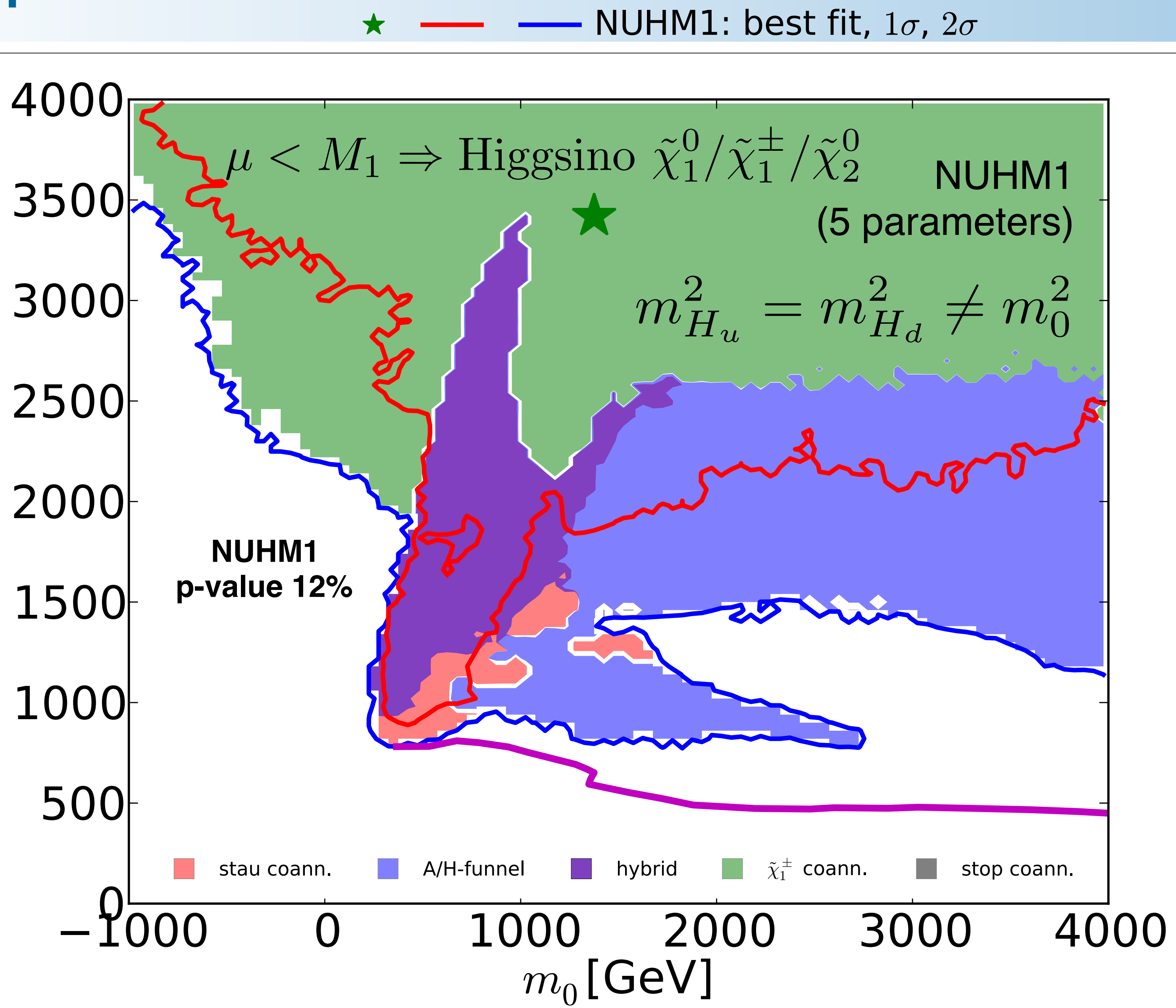


CMSSM

★ — — CMSSM: best fit, 1σ, 2σ



NUHM1



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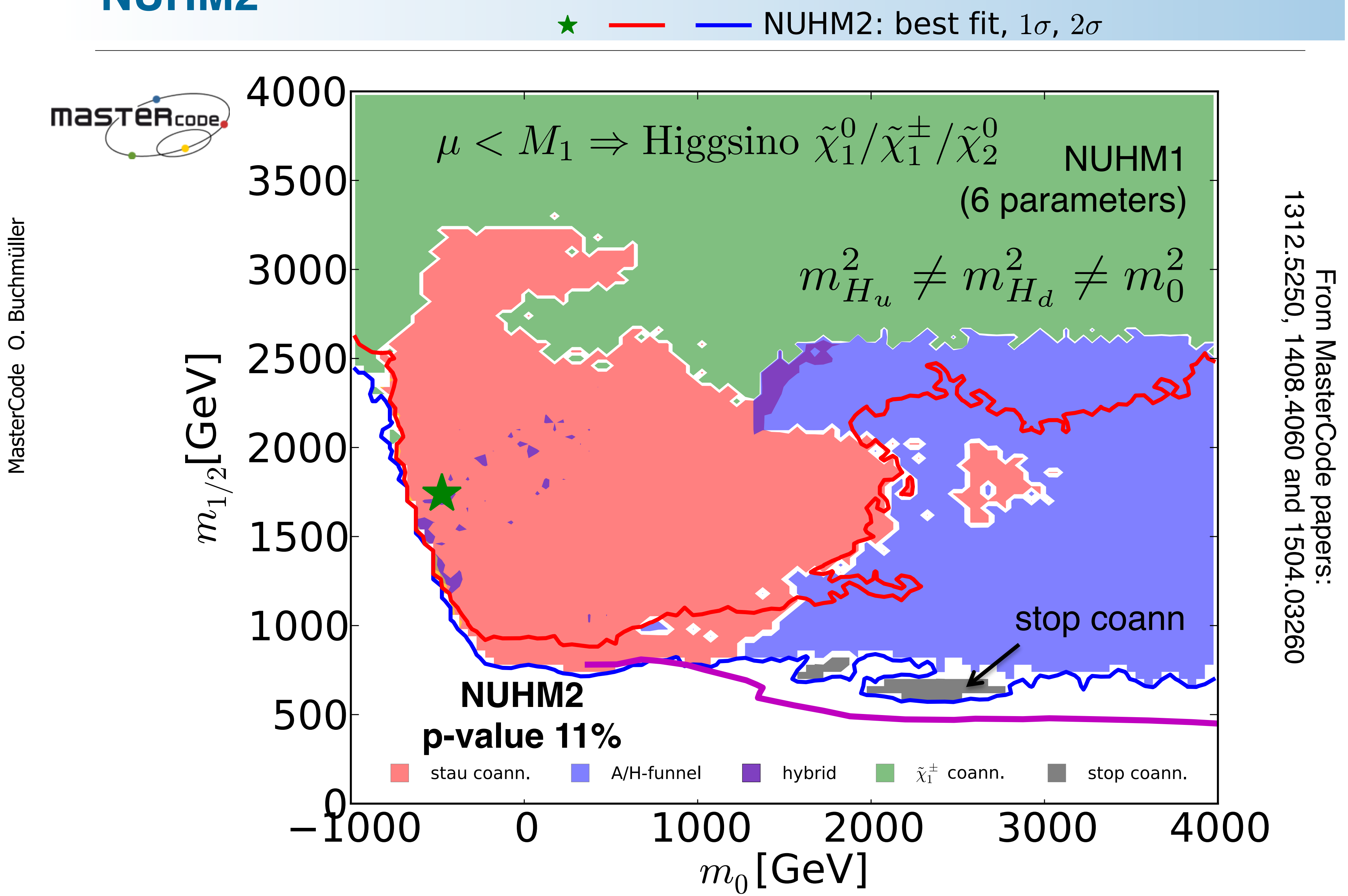
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

NUHM2


NUHM2: best fit, 1σ, 2σ
$\mu < M_1 \Rightarrow$ Higgsino $\tilde{\chi}^0_1/\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$
NUHM1
(6 parameters)
$m^2_{H_u} \neq m^2_{H_d} \neq m^2_0$
stop coann
NUHM2
p-value 11%
stau coann.
A/H-funnel
hybrid
$\tilde{\chi}^\pm_1$ coann.
stop coann.
$m_{1/2}$[GeV]
m_0 [GeV]
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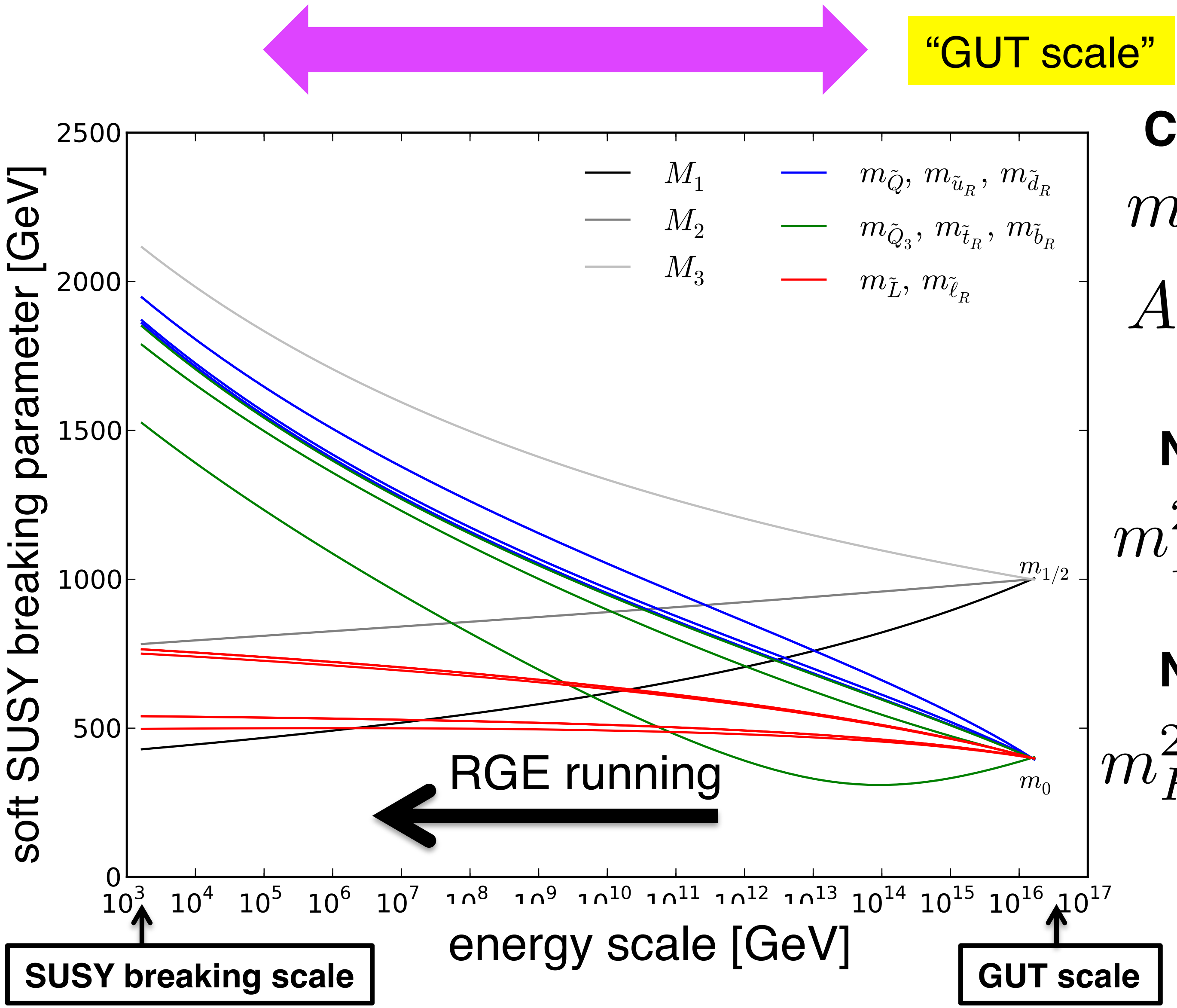
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

MasterCode: The two worlds of SUSY models



CMSSM

$$m_0, \; m_{1/2}, \; A_0, \; \tan\beta$$

NUHM1

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

NUHM2

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

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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

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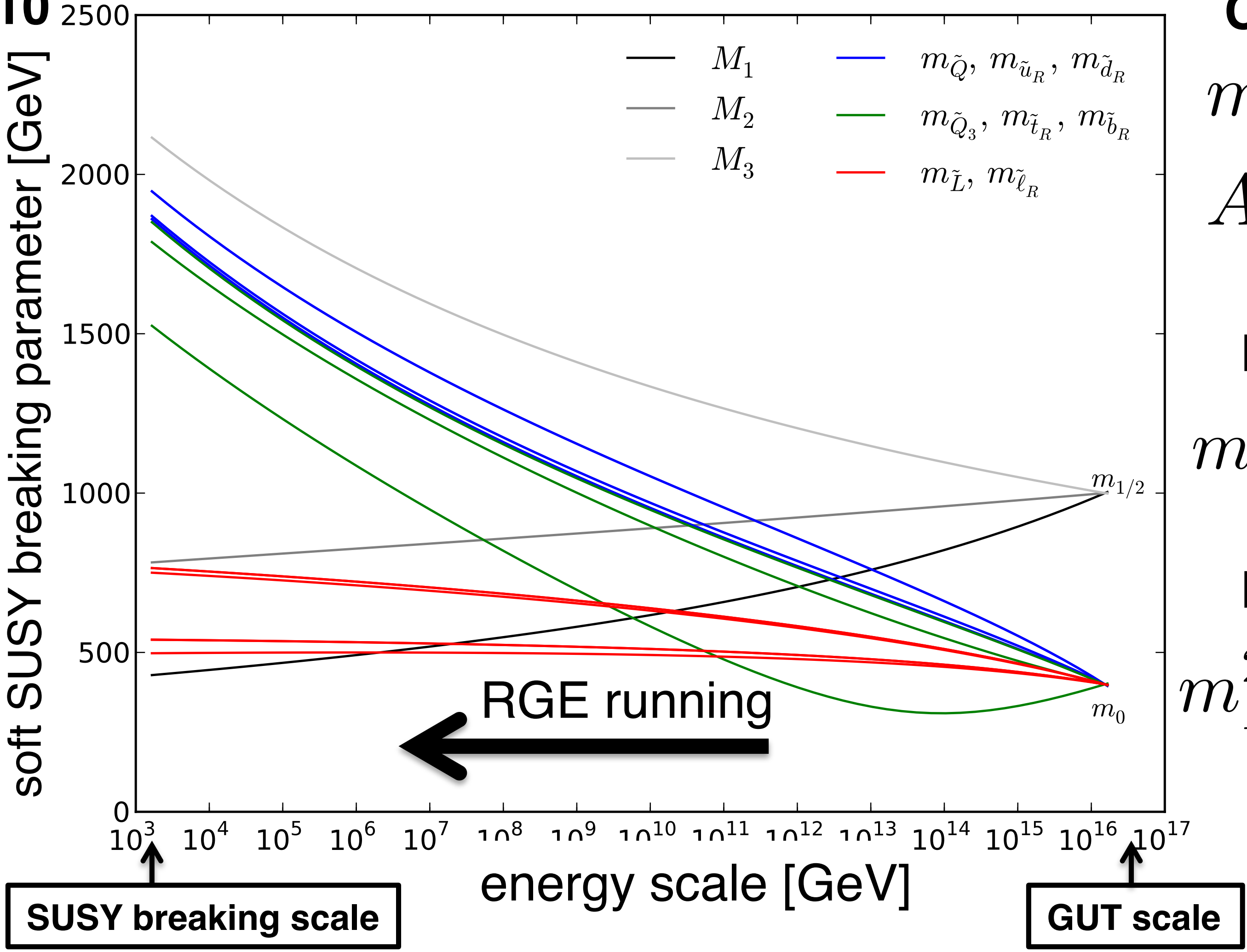


CMSSM

m_0, $m_{1/2}$, A_0, $\tan\beta$

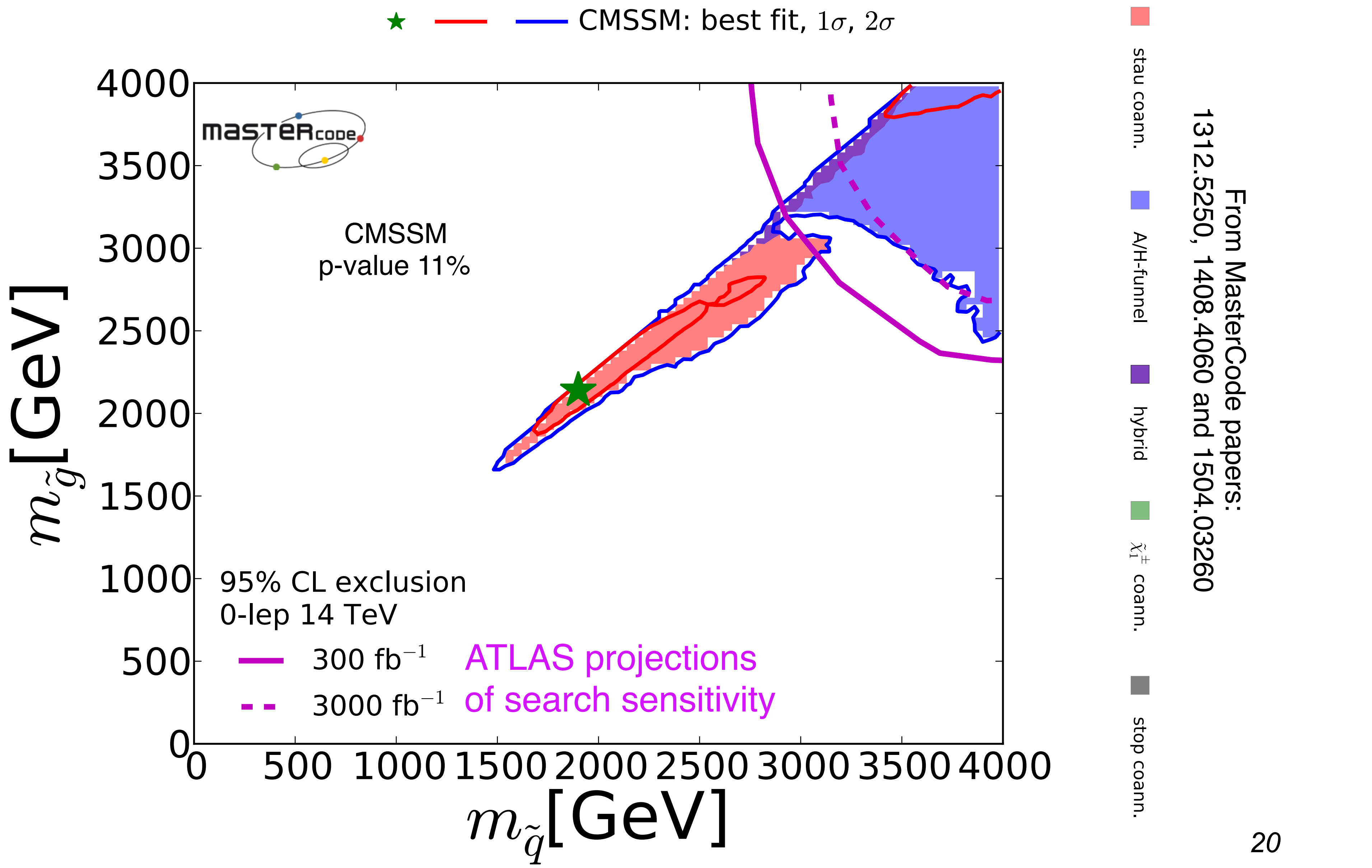
NUHM1

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

NUHM2

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

CMSSM Today: Mq-Mg Search plane



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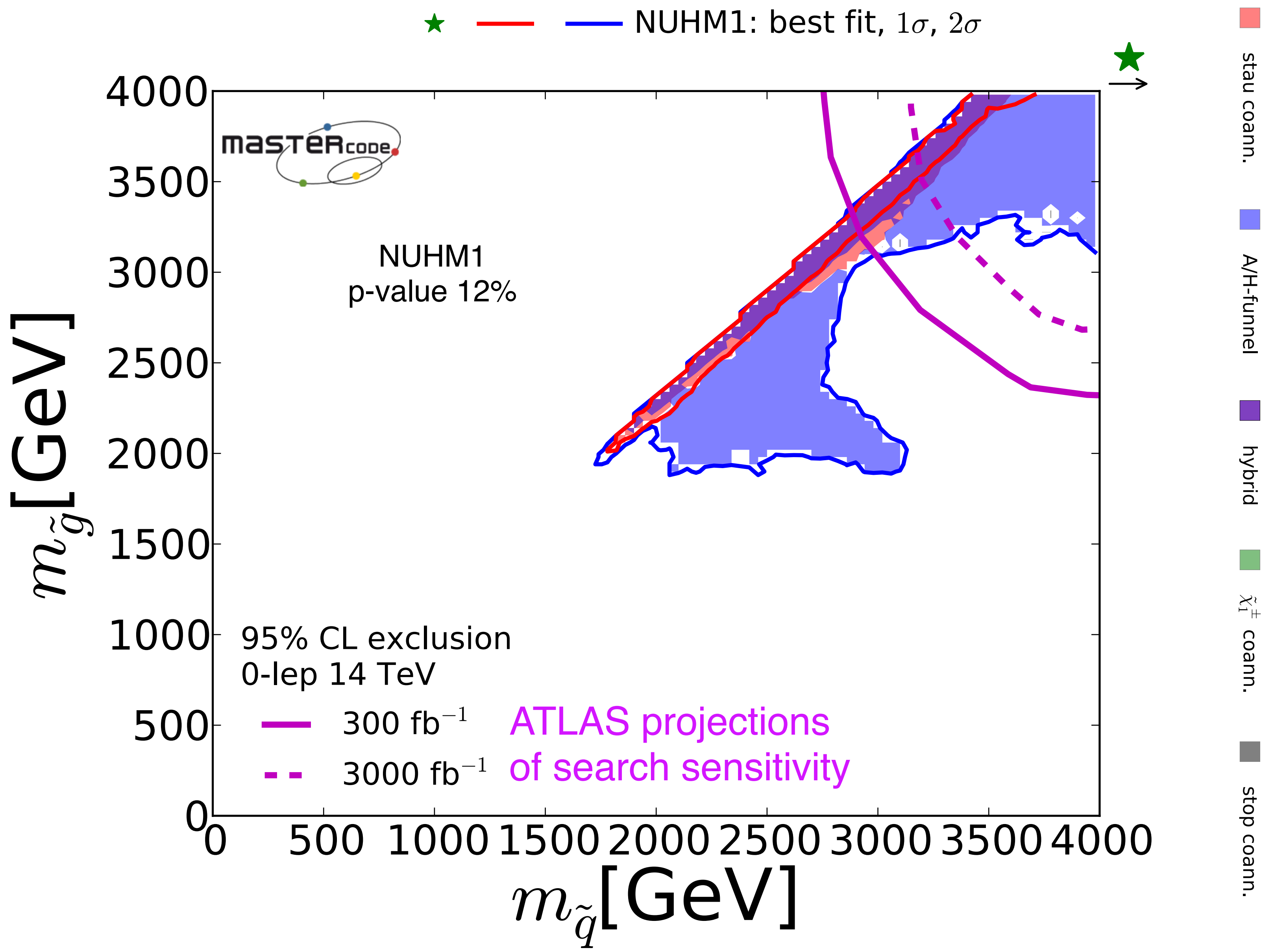
CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

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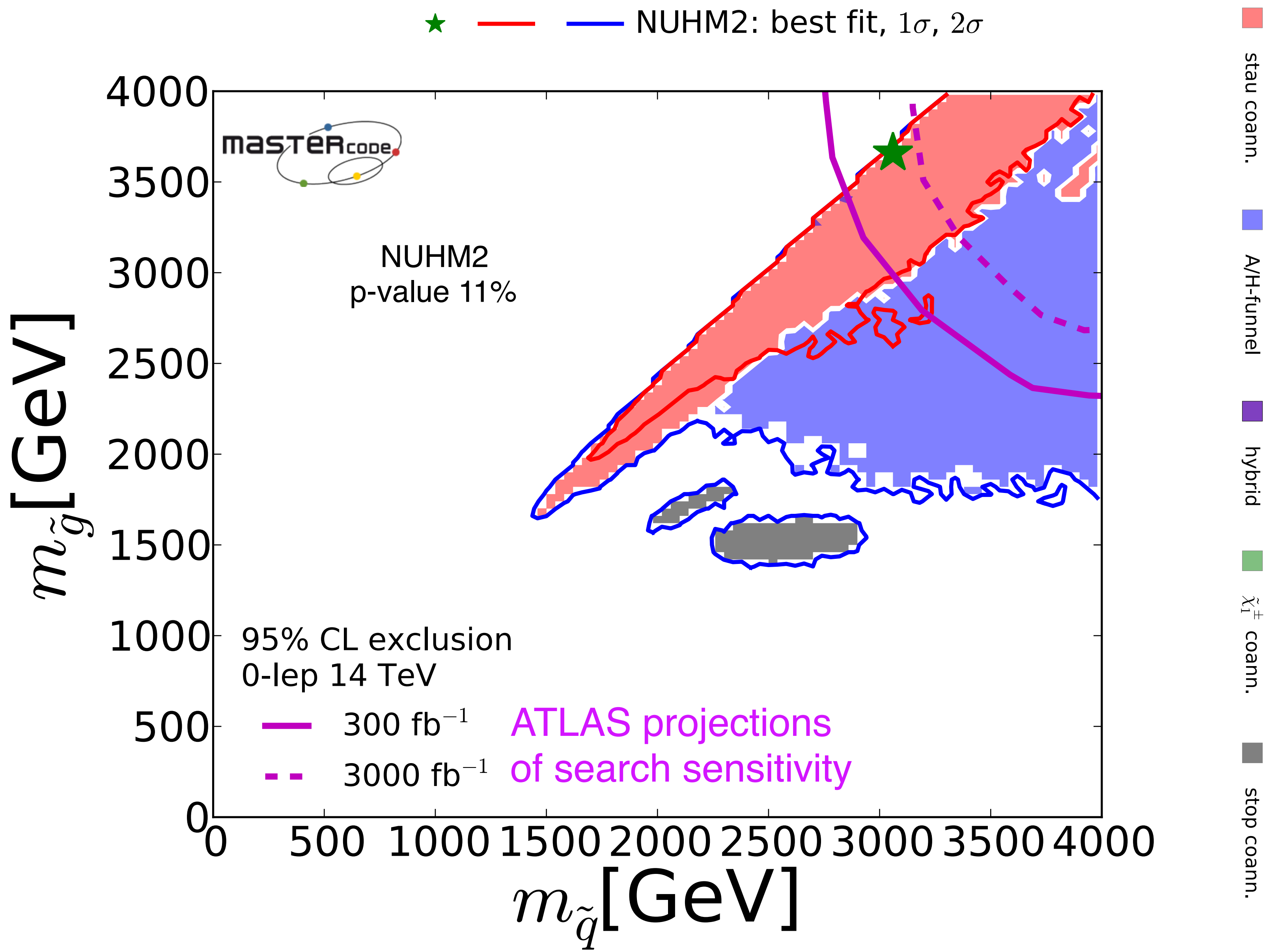
CMSSM Today: Mq-Mg Search plane



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CMSSM Today: Mq-Mg Search plane

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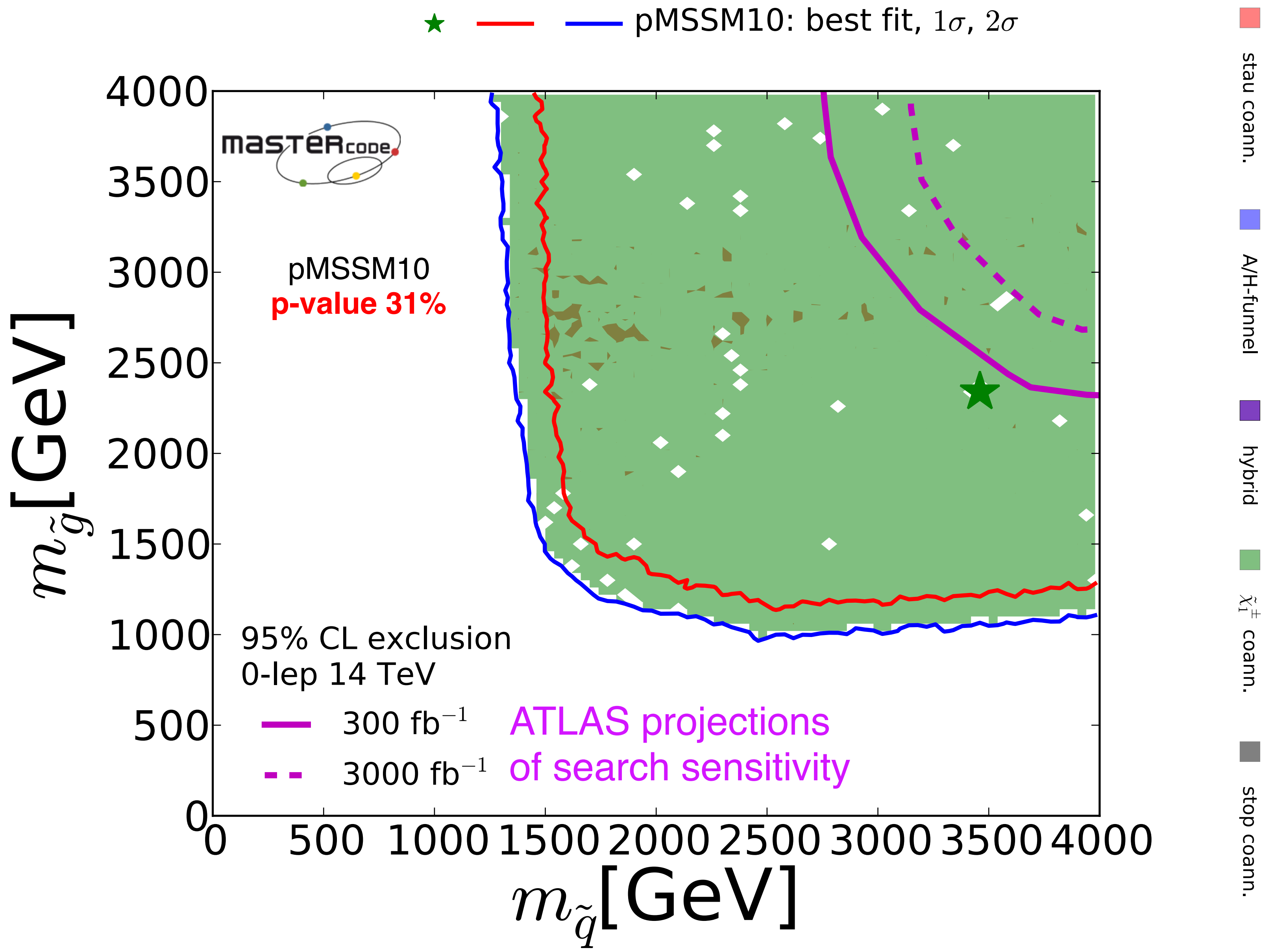

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Models in Comparison in "Mq-Mg Search plane"

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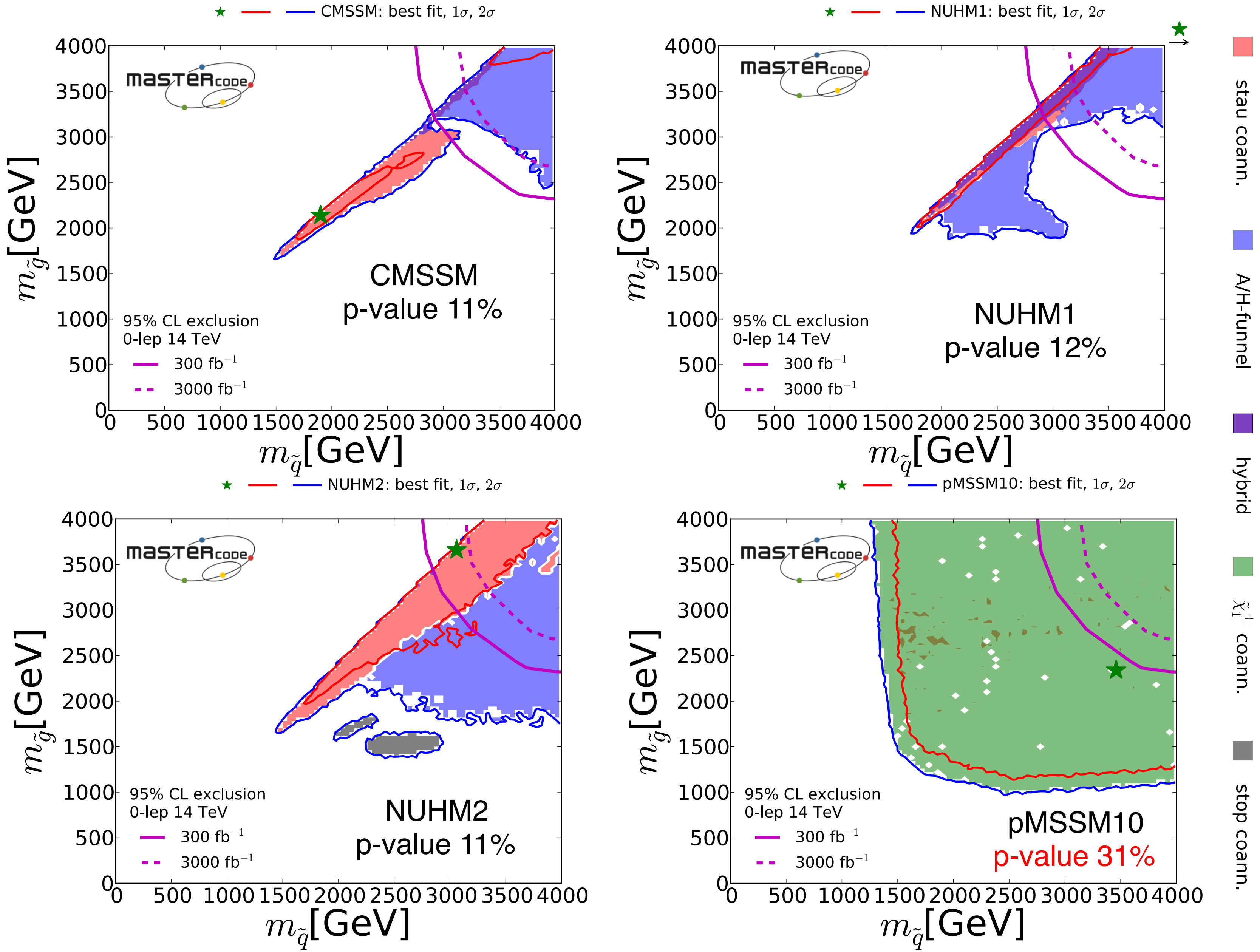

From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

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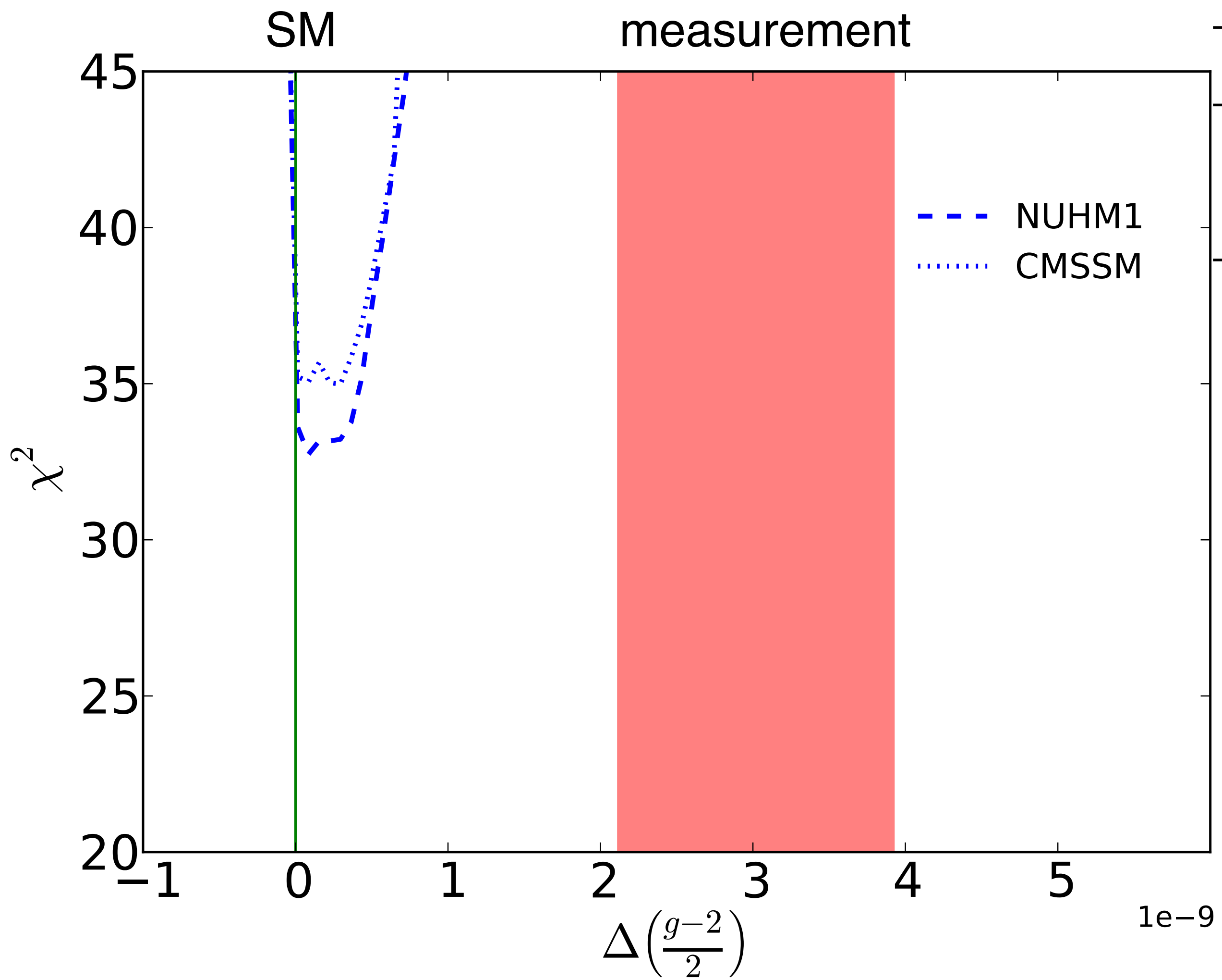
Resolving tension (g-2) and LHC

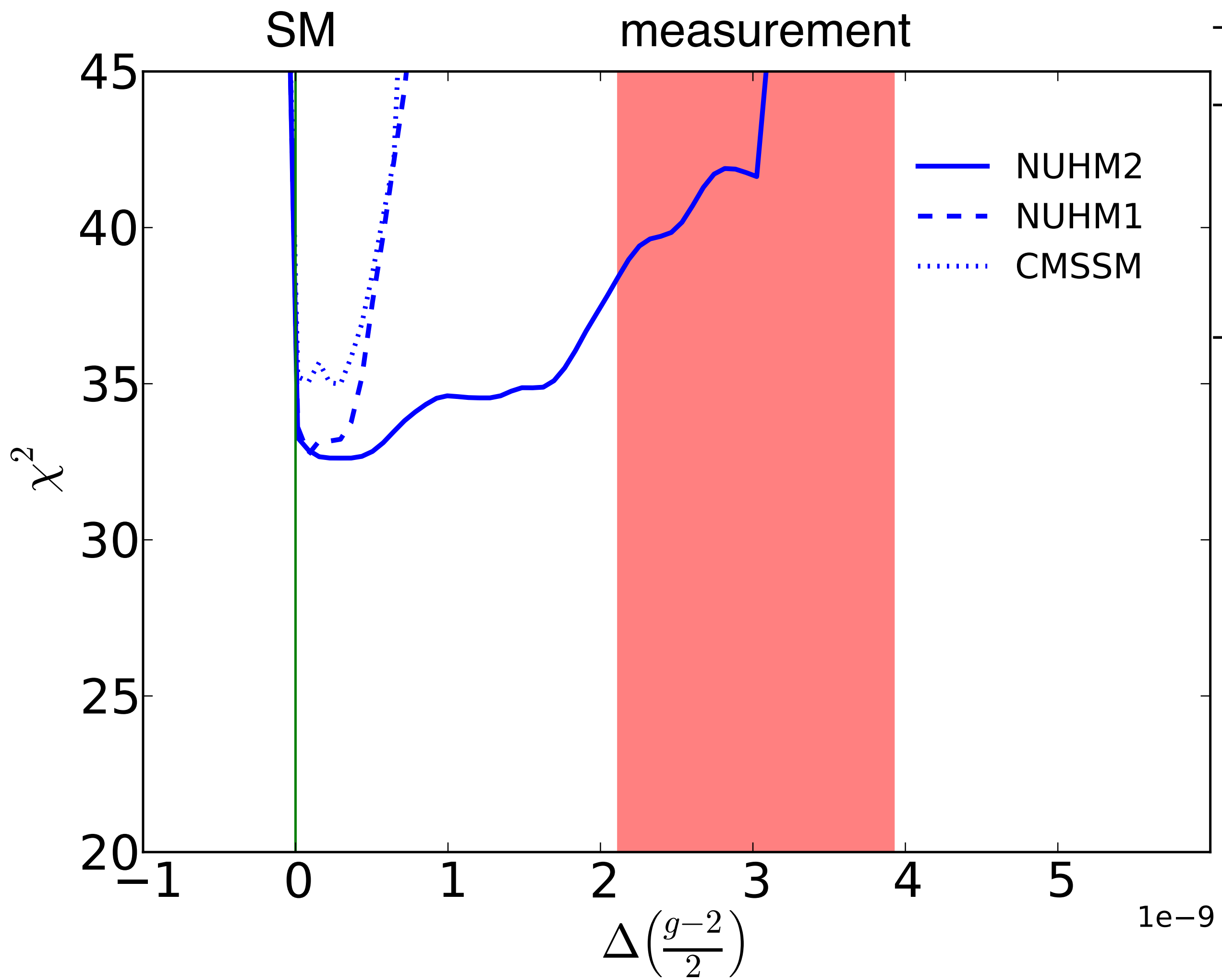


	χ^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

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

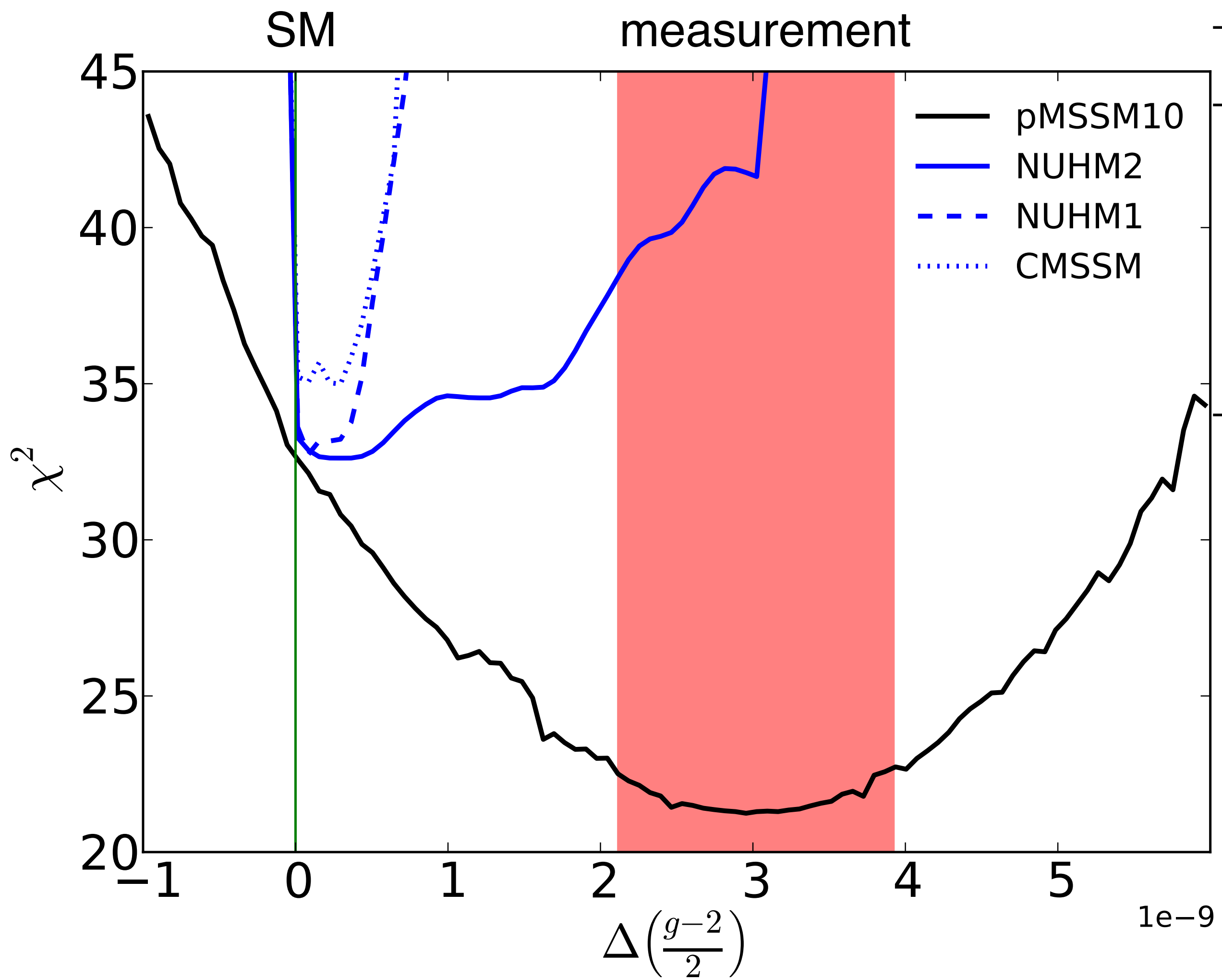


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

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

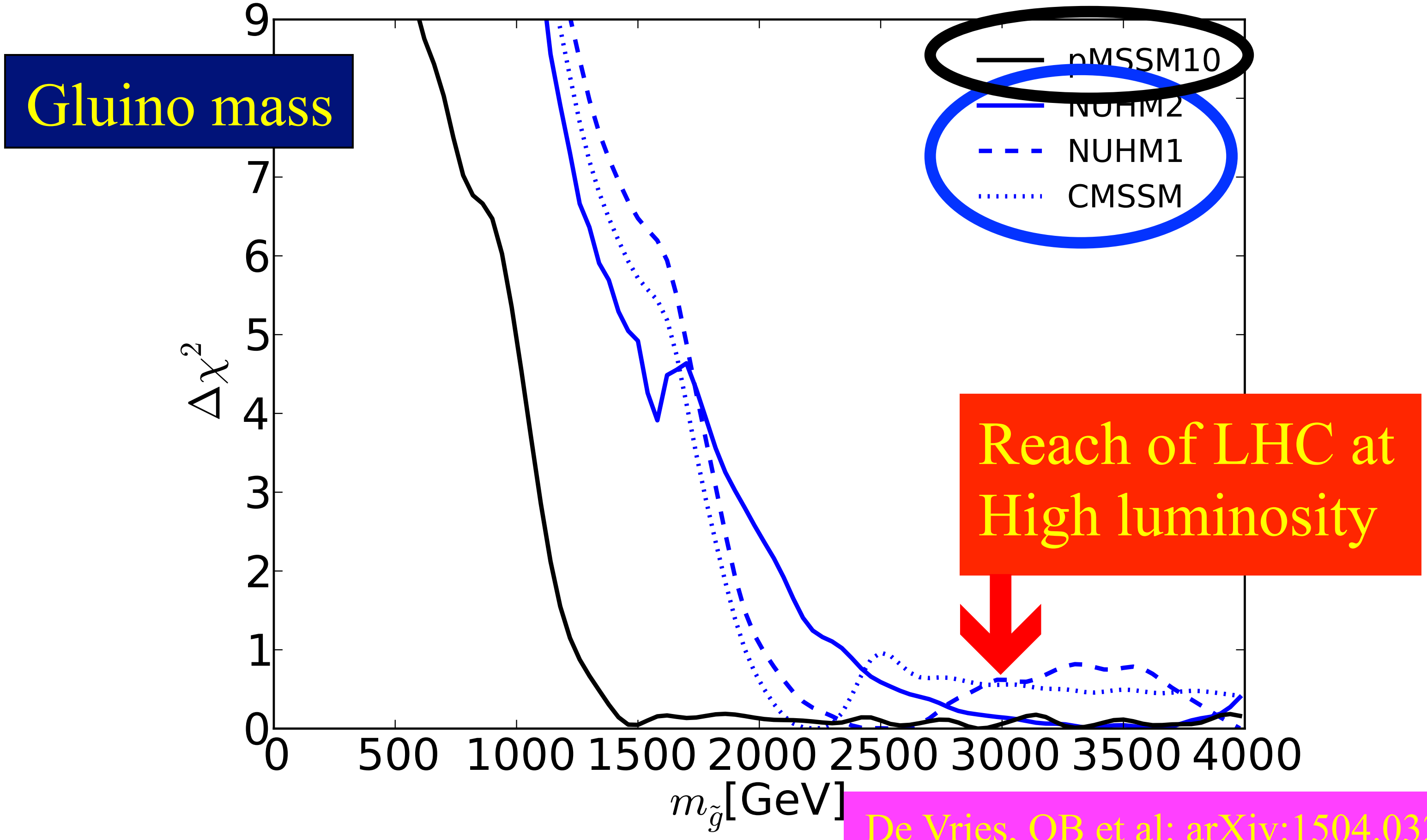


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	**20.5/18**	**31 %**

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

Gluino Mass 2012

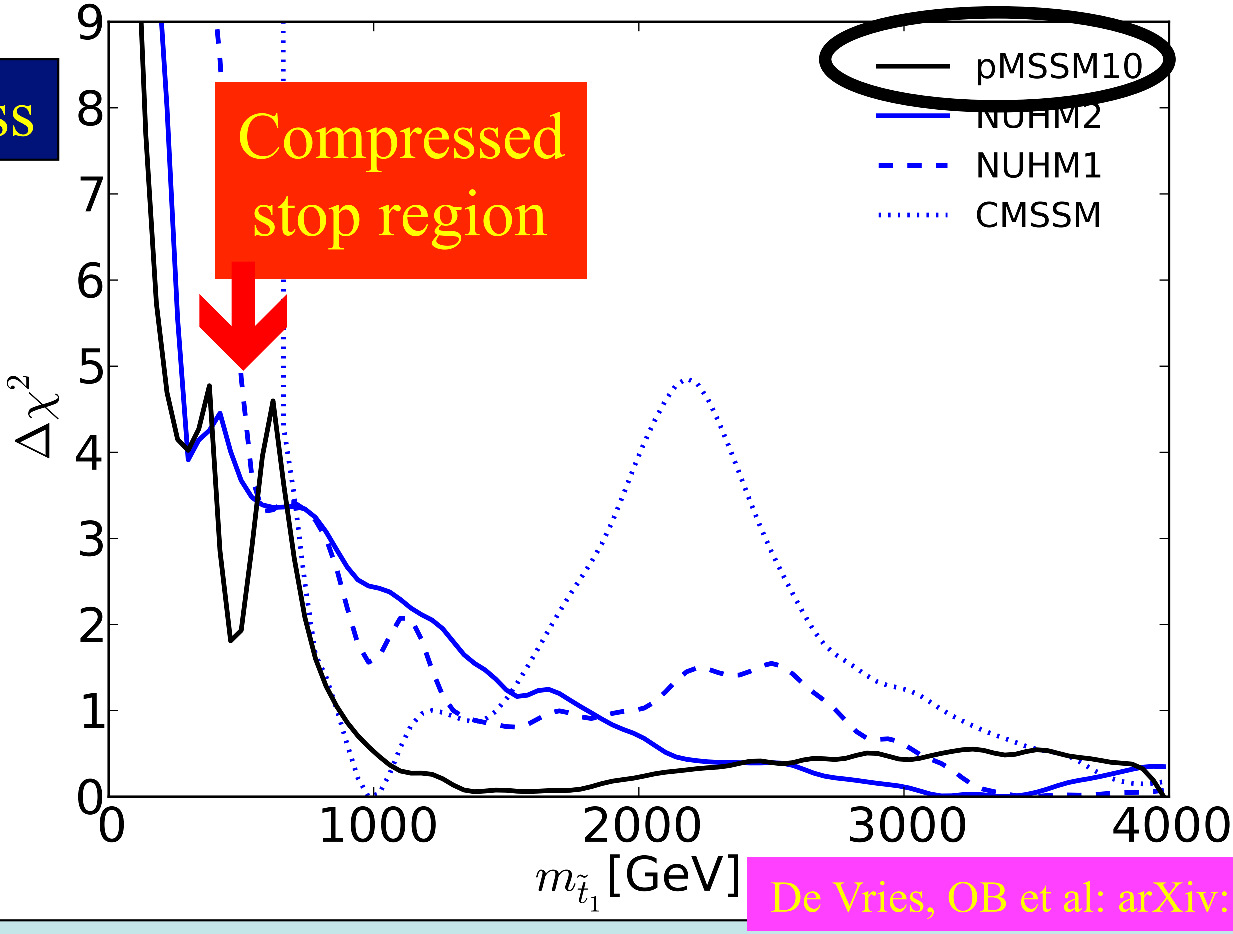


De Vries, OB et al: arXiv:1504.03260

Favoured values of gluino mass also significantly above pre-LHC, > 1.2 TeV

Stop Mass 2016

Stop mass



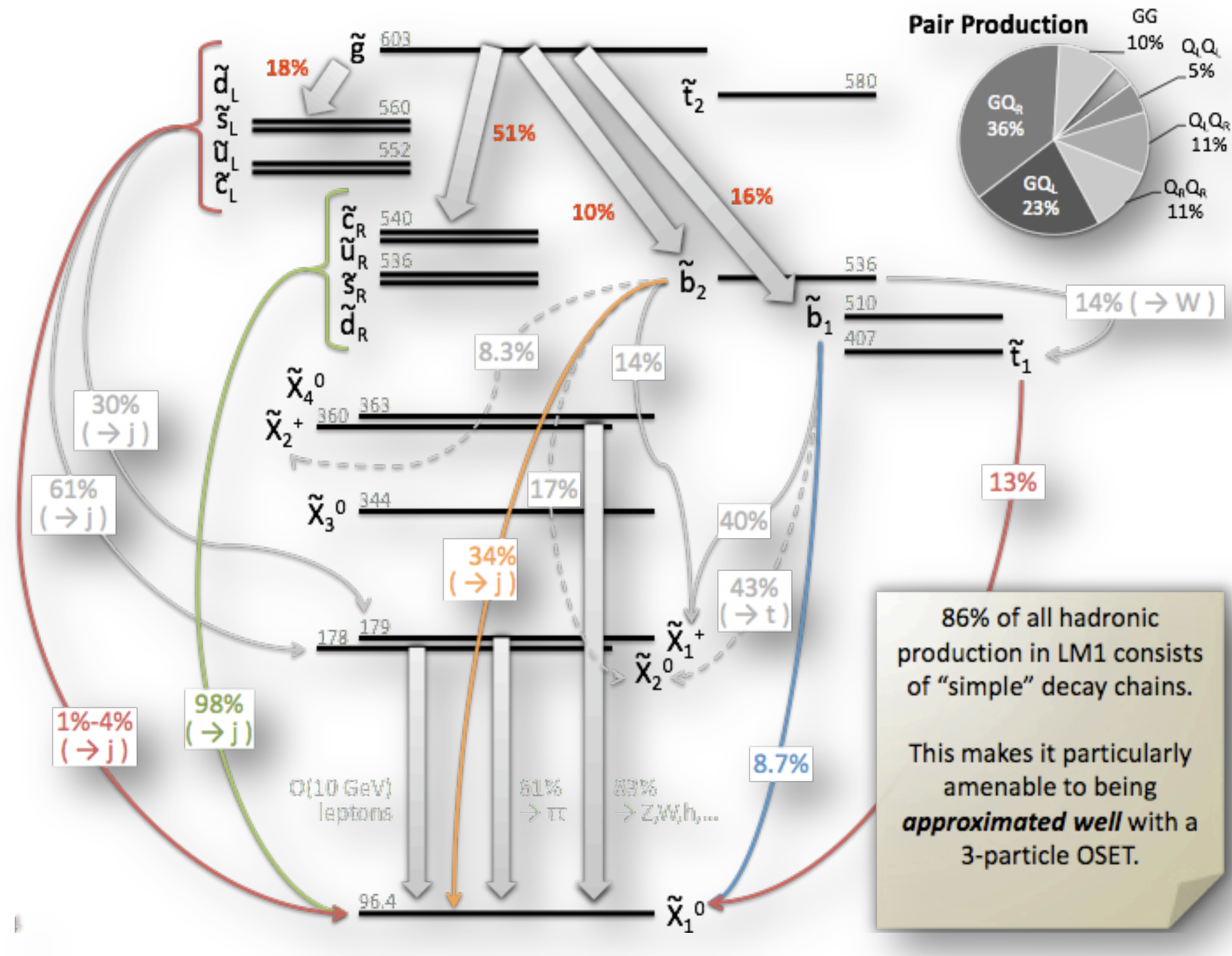
De Vries, OB et al: arXiv:1504.03260

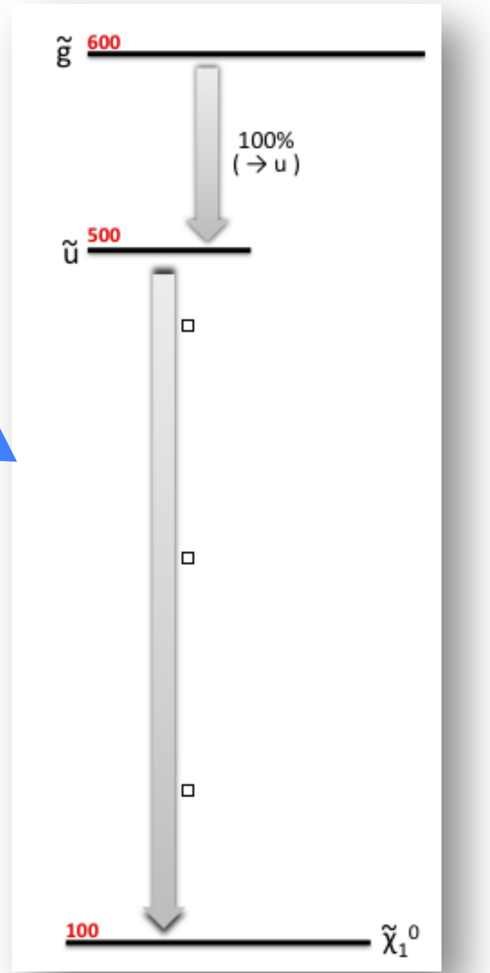
Remaining possibility of a light "natural" stop weighing ~ 400 GeV

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

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SMS: a few interesting features

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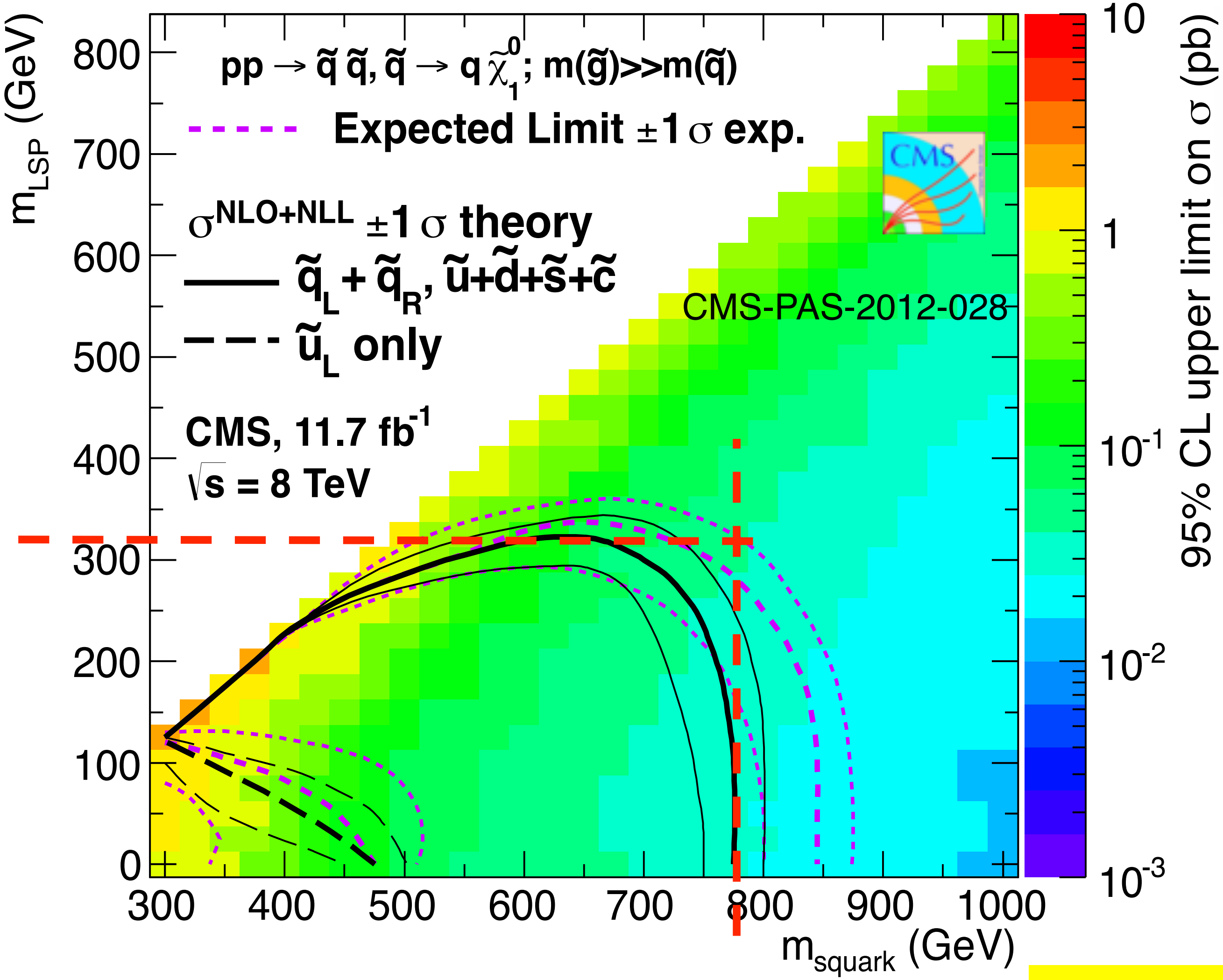
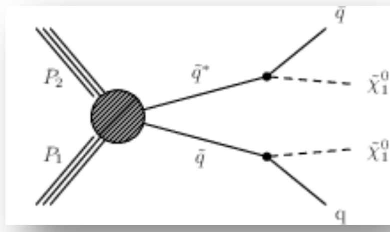
$m_{LSP}^{max} \approx 0.3$ TeV : LSP mass above which there is NO limit anymore



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

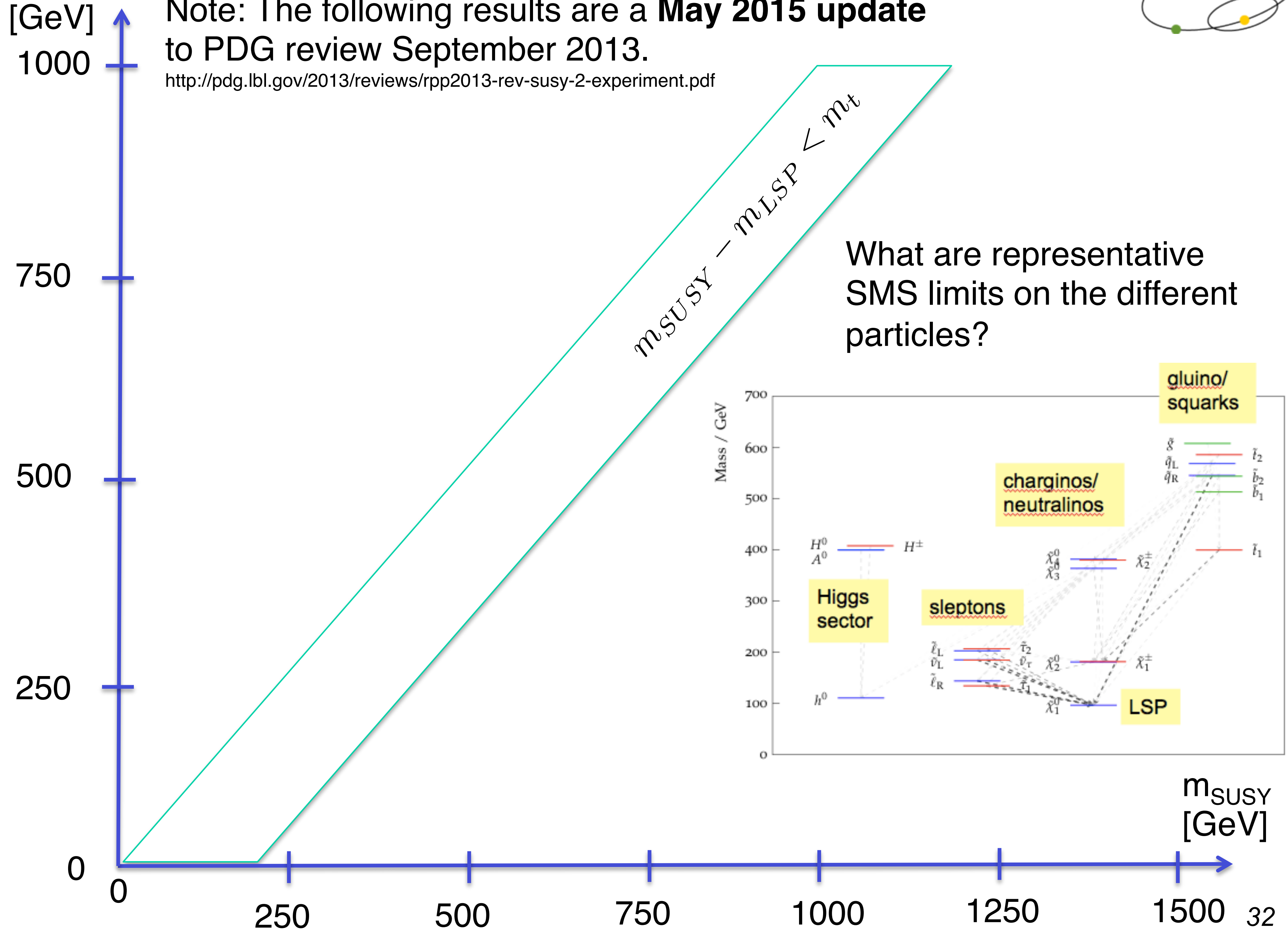


$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0 \bar{q}\tilde{\chi}^0$

Assumes 100% BR for decay chain considered.

Note: The following results are a **May 2015 update** to PDG review September 2013.
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

What are representative SMS limits on the different particles?



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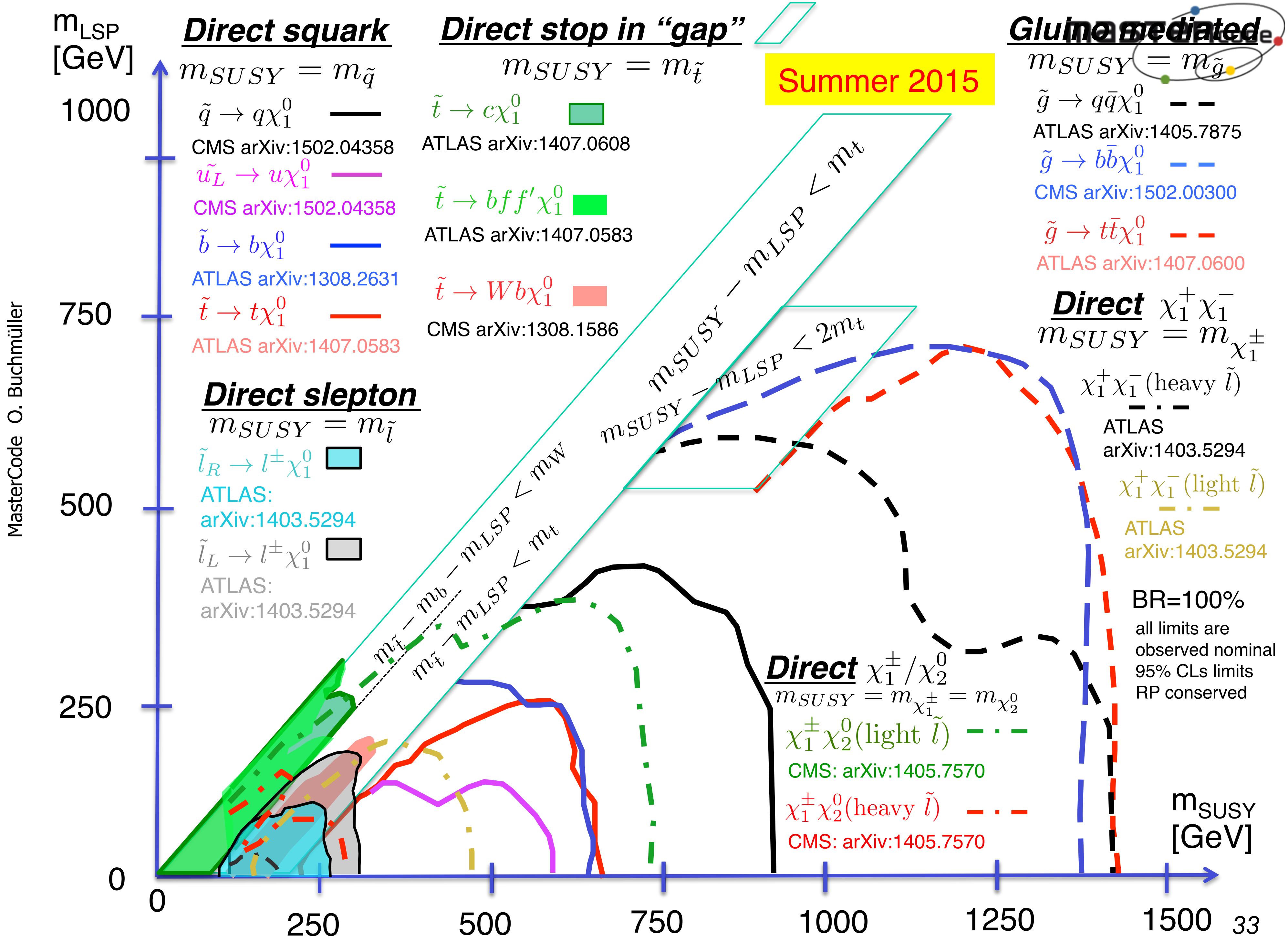
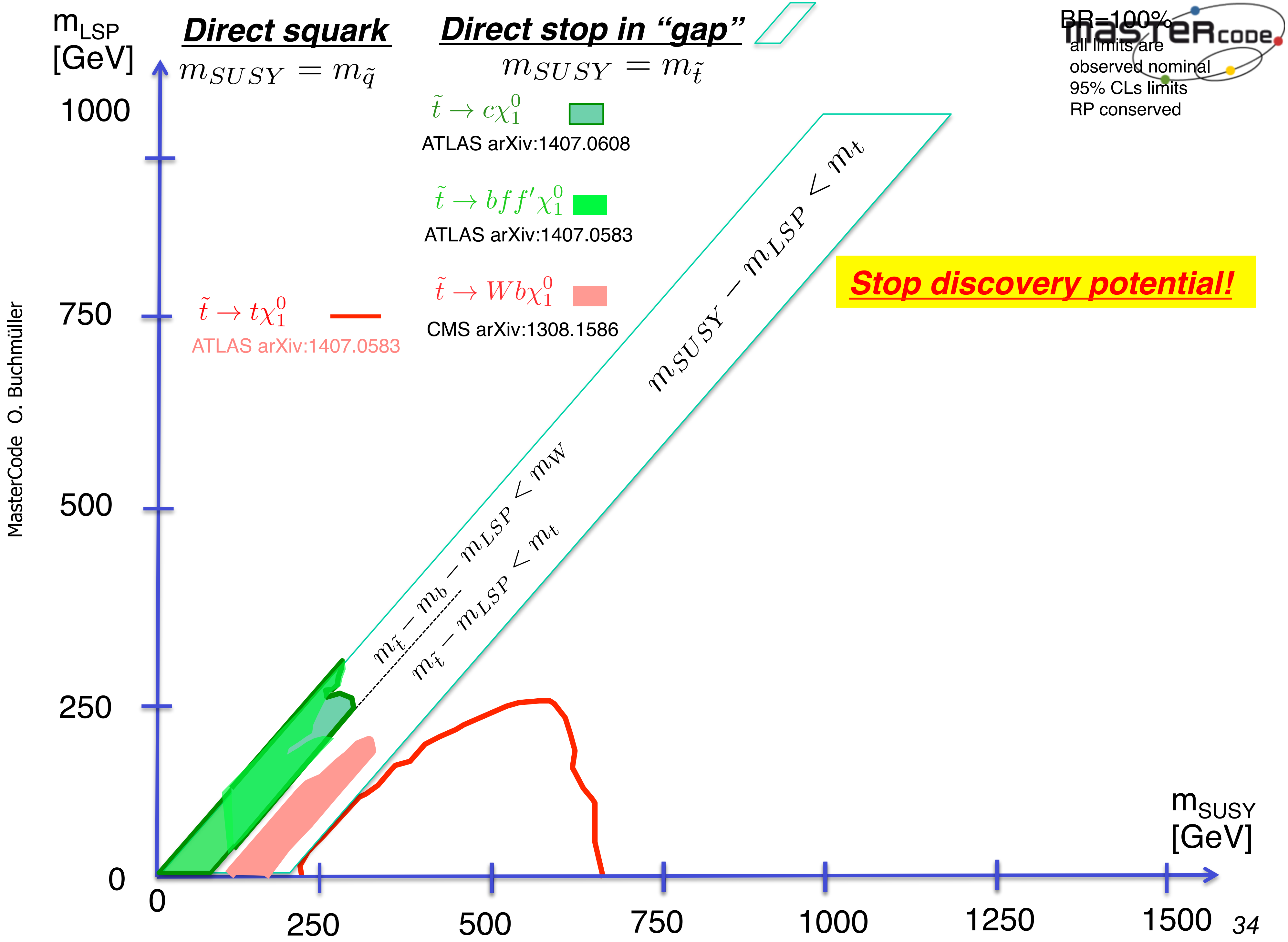
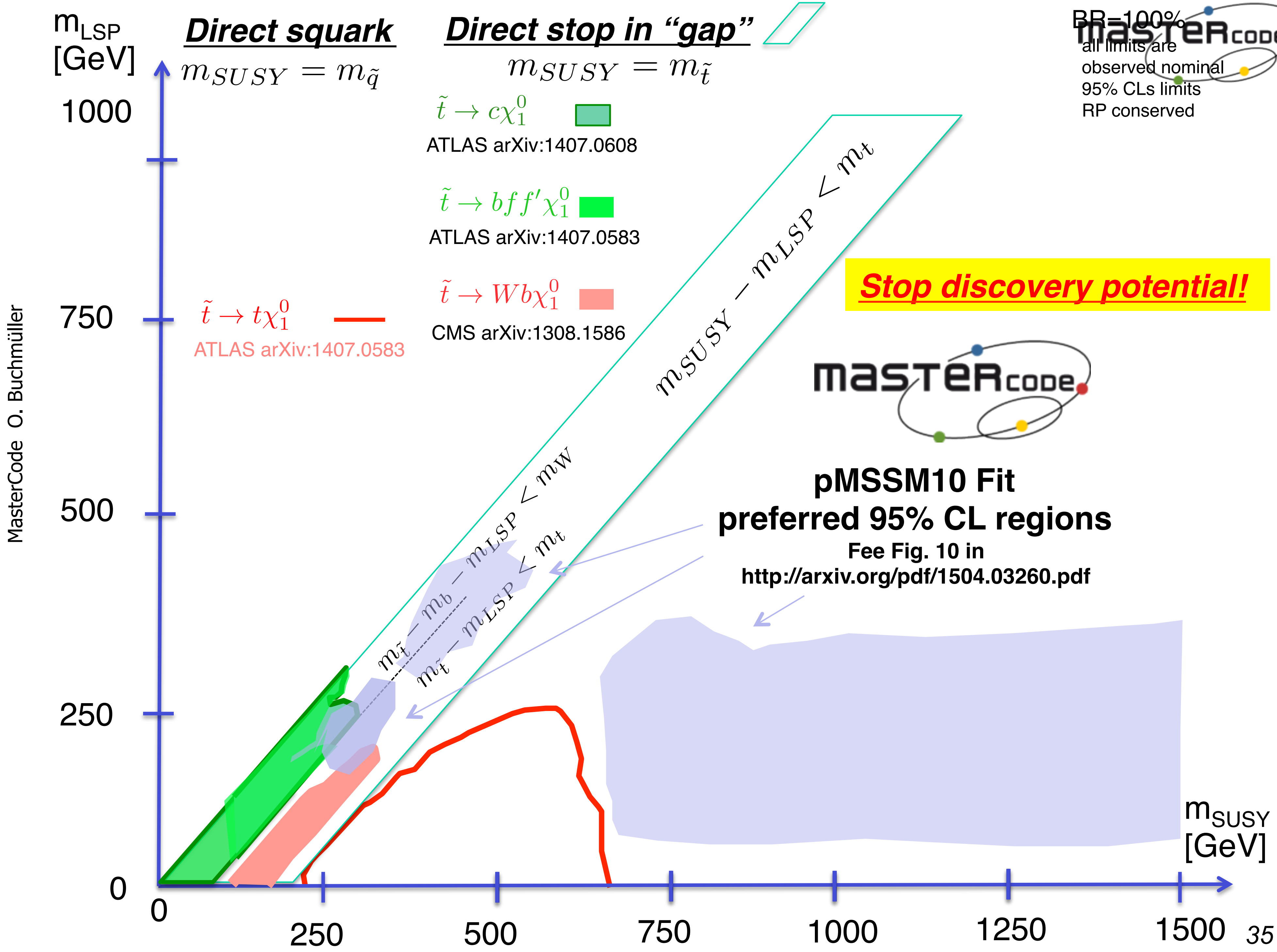


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde q}$
$\tilde q \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde b \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde t \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde t}$
$\tilde t \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde t \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde t \to Wb\chi_1^0$
CMS arXiv:1308.1586
Summer 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 $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^\pm}$
$\chi_1^+\chi_1^-$(heavy $\tilde l$)
ATLAS arXiv:1403.5294
$\chi_1^+\chi_1^-$(light $\tilde l$)
ATLAS arXiv:1403.5294
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde l}$
$\tilde l_R \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde l_L \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde t} - m_b - m_{LSP} < m_W$
$m_{\tilde t} - m_{LSP} < m_t$
Direct $\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
$\chi_1^\pm\chi_2^0$(light $\tilde l$)
CMS: arXiv:1405.7570
$\chi_1^\pm\chi_2^0$(heavy $\tilde l$)
CMS: arXiv:1405.7570
MasterCode O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]



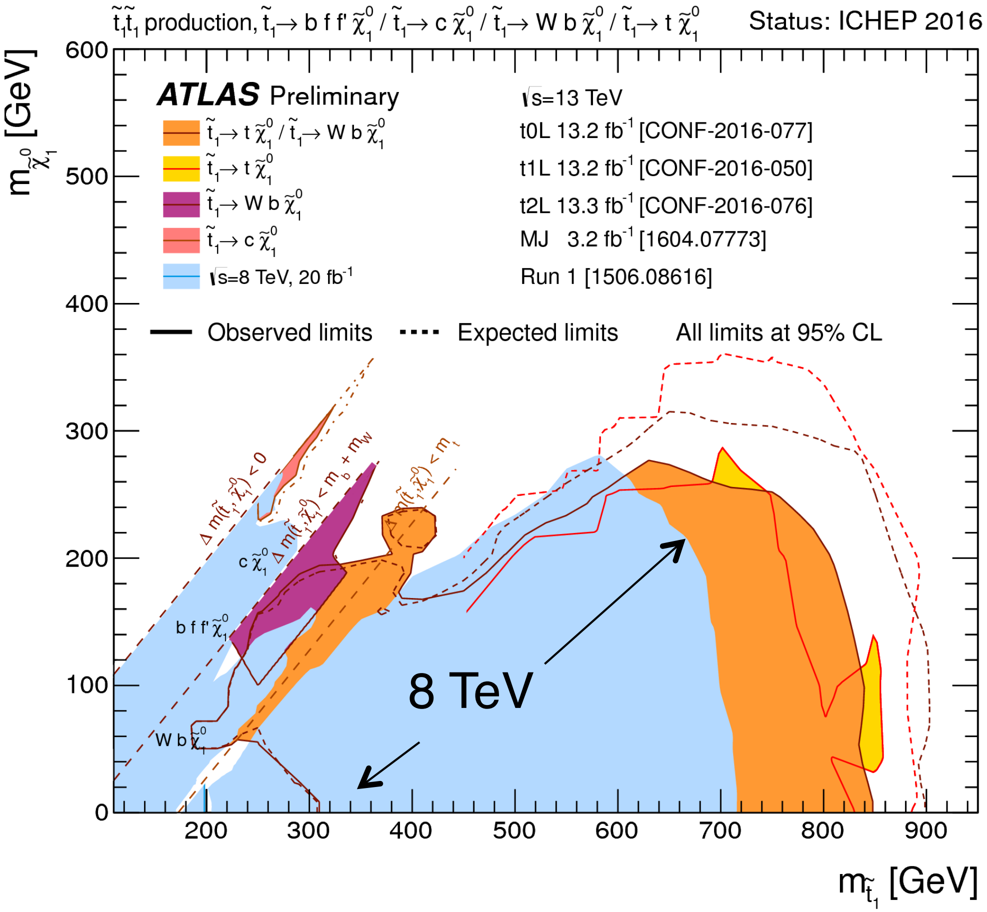
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS arXiv:1308.1586
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Stop discovery potential!
$m_{SUSY} - m_{LSP} < m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
MasterCode O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]

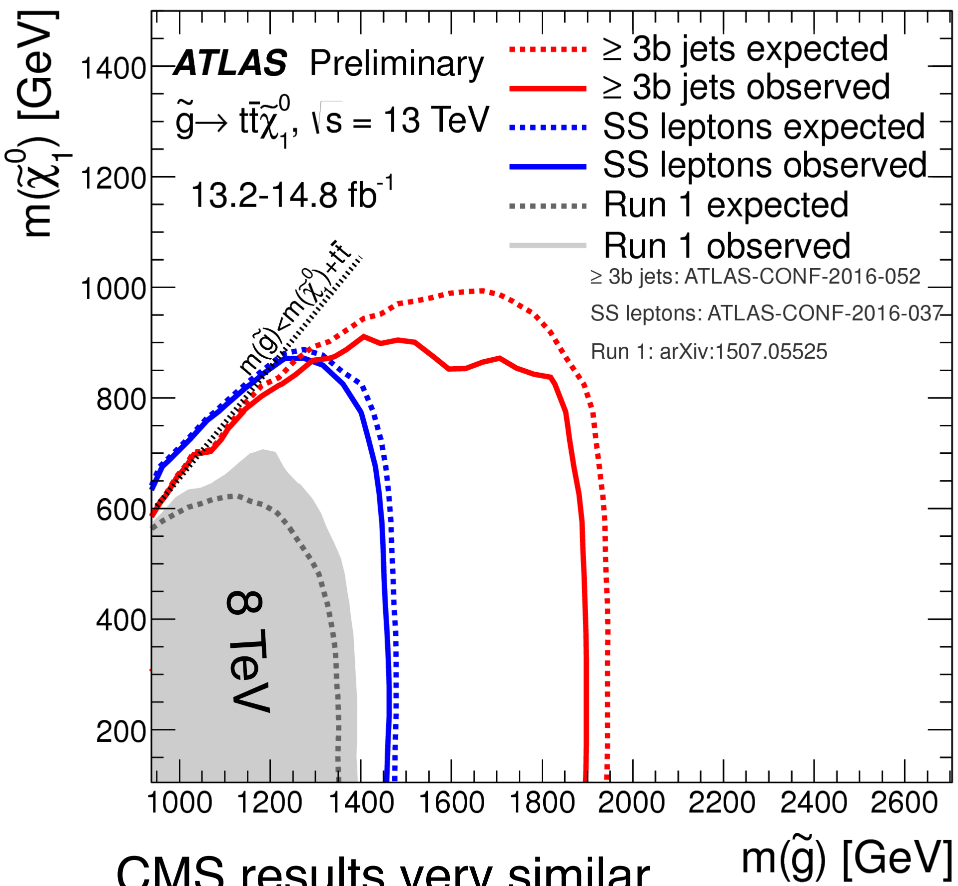


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
Direct stop in “gap”
$m_{SUSY} = m_{\tilde{t}}$
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
$m_{SUSY} - m_{LSP} < m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Stop discovery potential!
pMSSM10 Fit
preferred 95% CL regions
Fee Fig. 10 in
http://arxiv.org/pdf/1504.03260.pdf
MasterCode O. Buchmüller
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

SUSY Summer 2016

“Tough” vs “Easy”





CMS results very similar

Energy increase has pushed significantly sensitivity for high-mass sparticles like gluions and squarks but other signatures, like stop production, are still a challenge needing much more data and possibly also more ingenuity.

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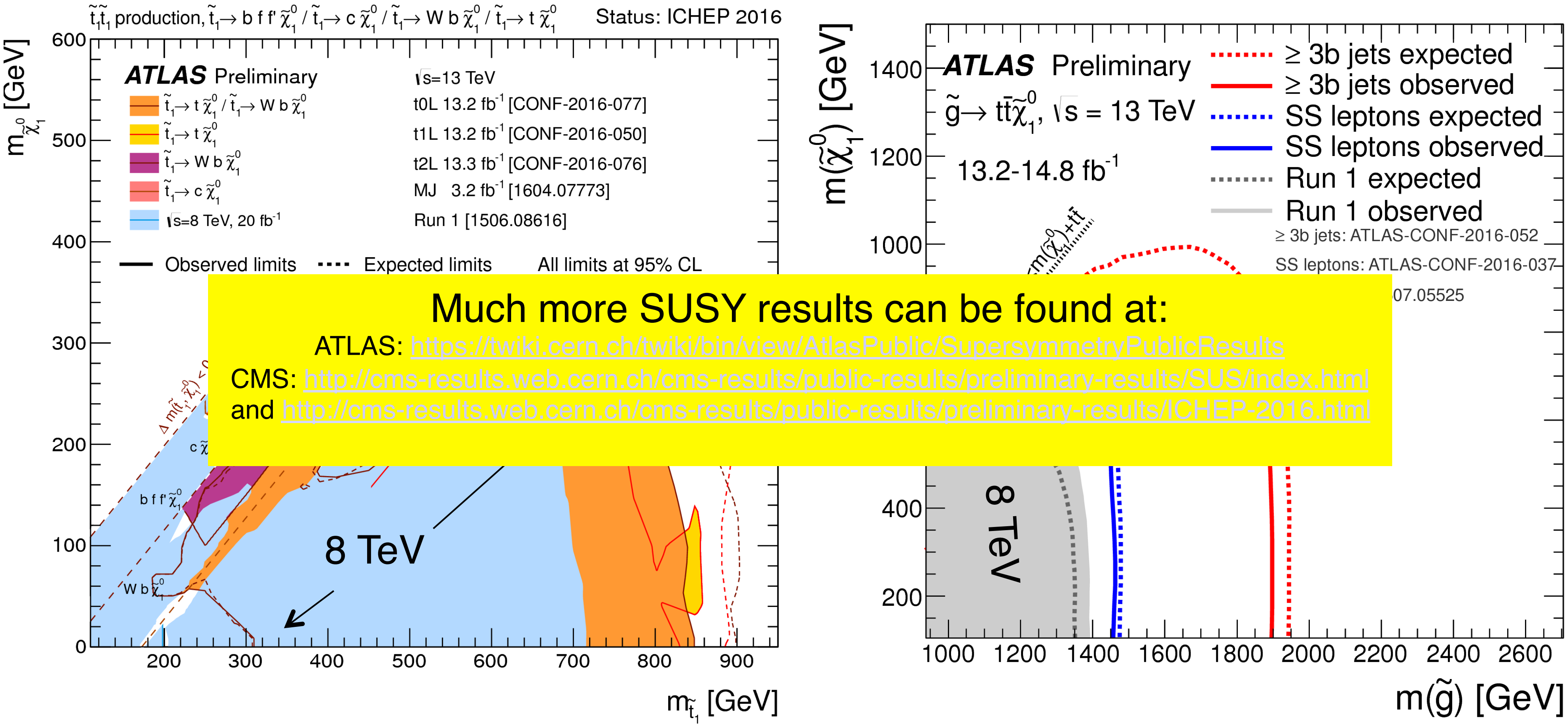
SUSY Summer 2016

“Easy” vs “Though”



Much more SUSY results can be found at:

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

CMS: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html

and http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/ICHEP-2016.html

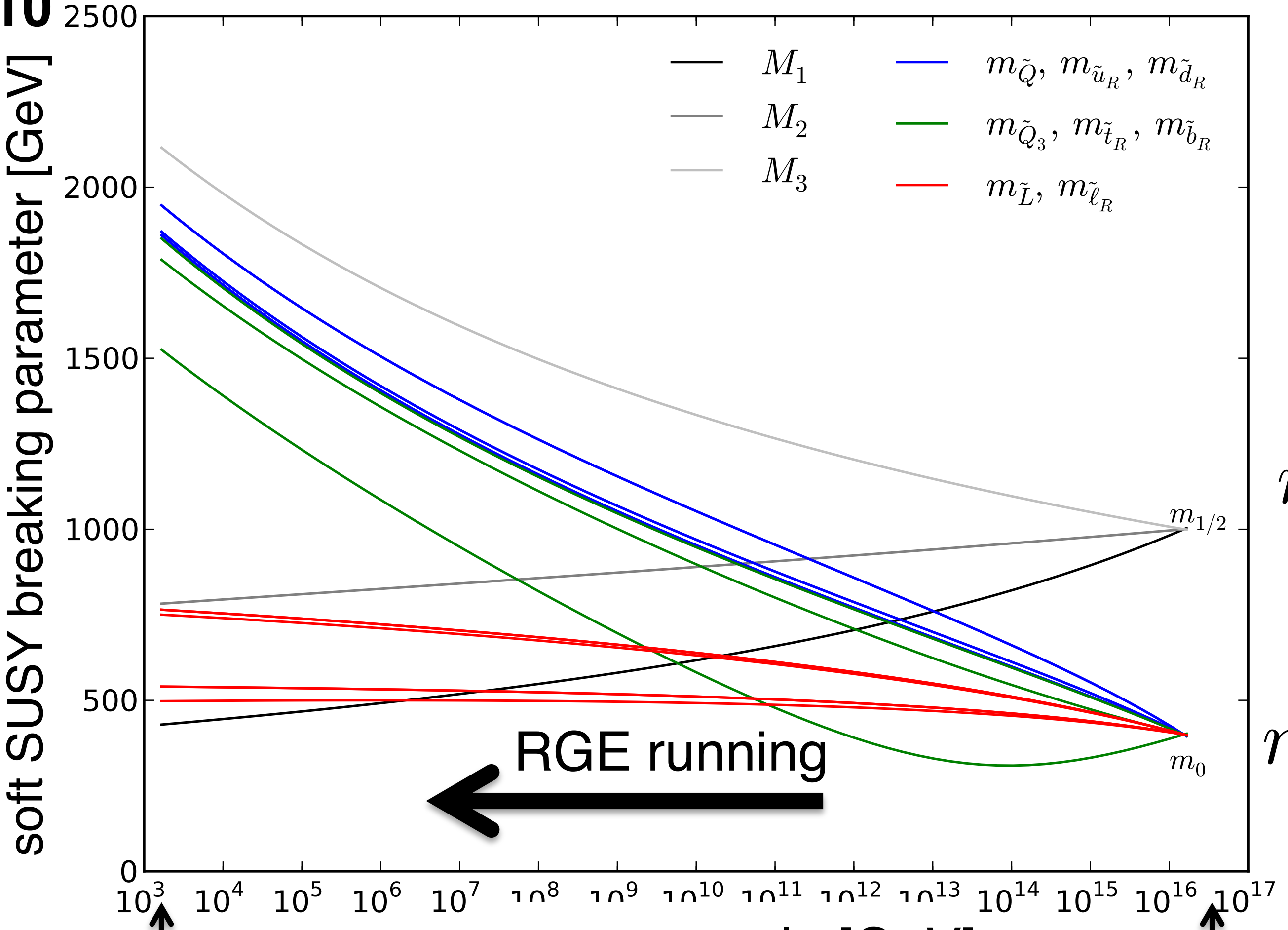
Energy increase has pushed significantly sensitivity for high-mass sparticles like gluions but other signatures, like stop production, are still a challenge needing much more data and possibly also more ingenuity. .

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



SUSY breaking scale **GUT scale**

CMSSM

$m_0, \ m_{1/2}, \ A_0, \ \tan\beta$

NUHM1

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

NUHM2

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

SU5
m_0: m_5, m_{10}

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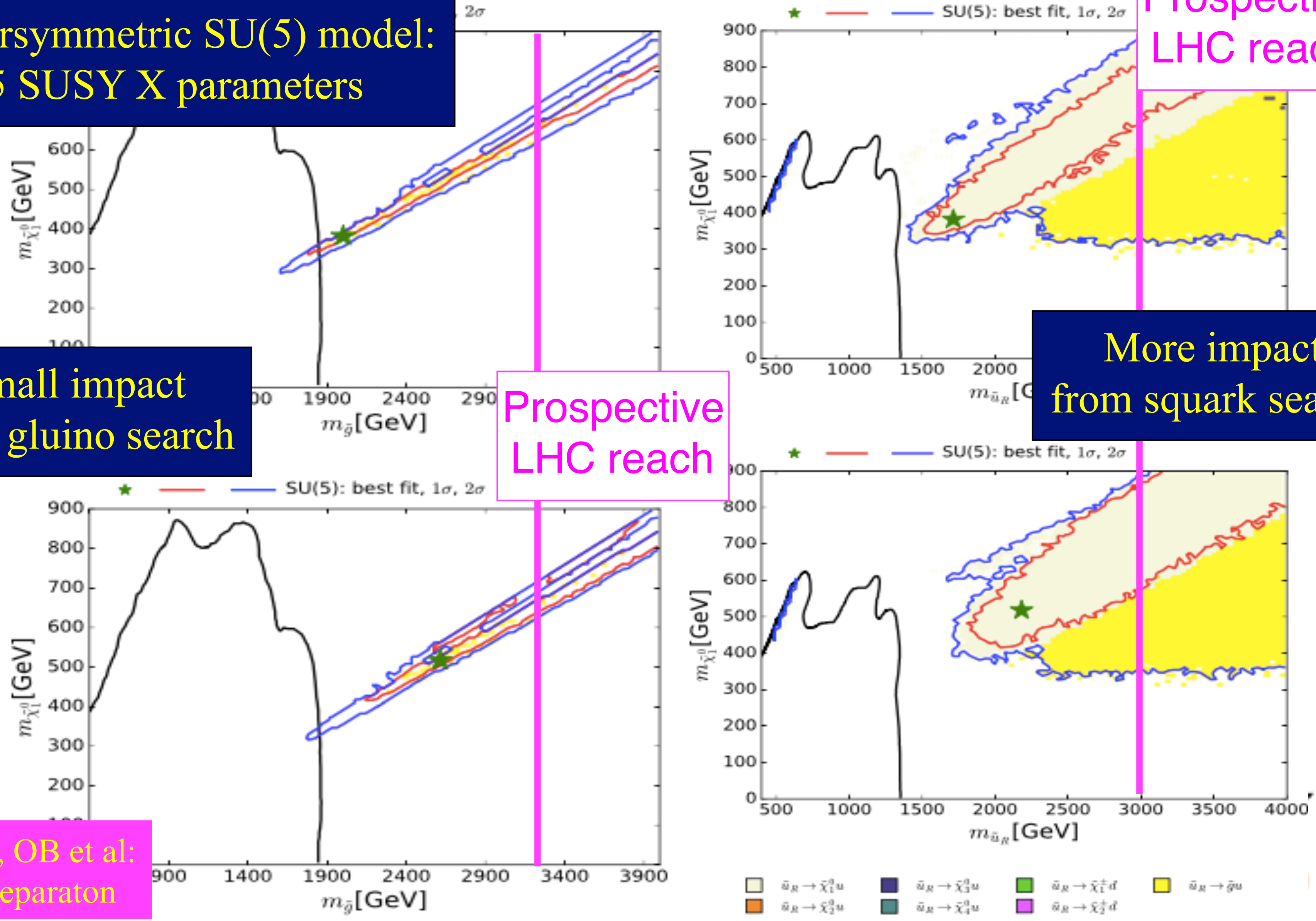
Constraints from ICHEP2016

2016 ATLAS with **13/fb** LHC Data

Supersymmetric SU(5) model:
5 SUSY X parameters



Small impact
from gluino search

Prospective
LHC reach

Prospective
LHC reach

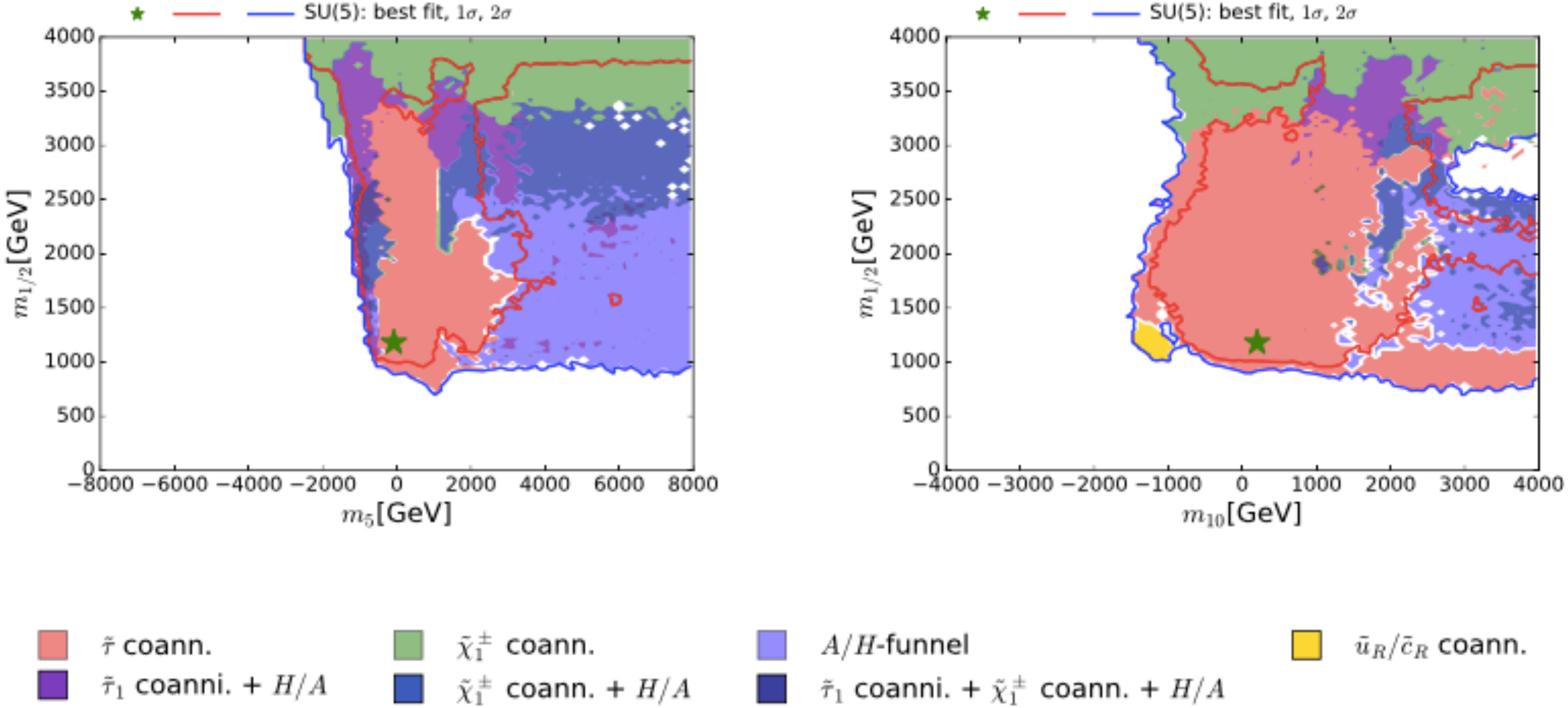
More impact
from squark search

Costa, OB et al:
in preparaton

Constraints from ICHEP2016

2016 ATLAS with 13/fb LHC Data

Parameter planes in supersymmetric SU(5) model

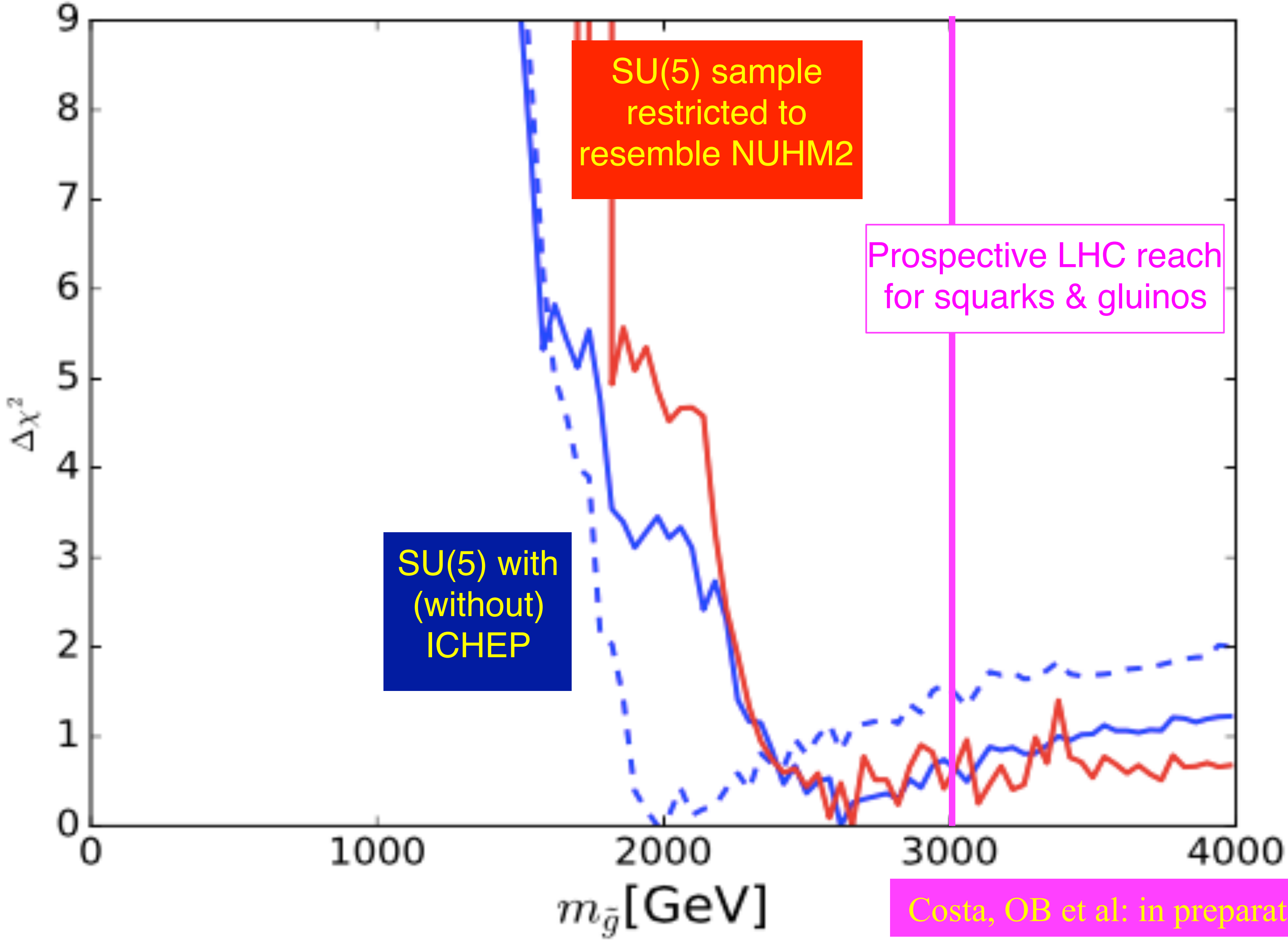


Colour-coded according to dominant mechanisms

Costa, OB et al: in preparaton

Constraints from ICHEP2016

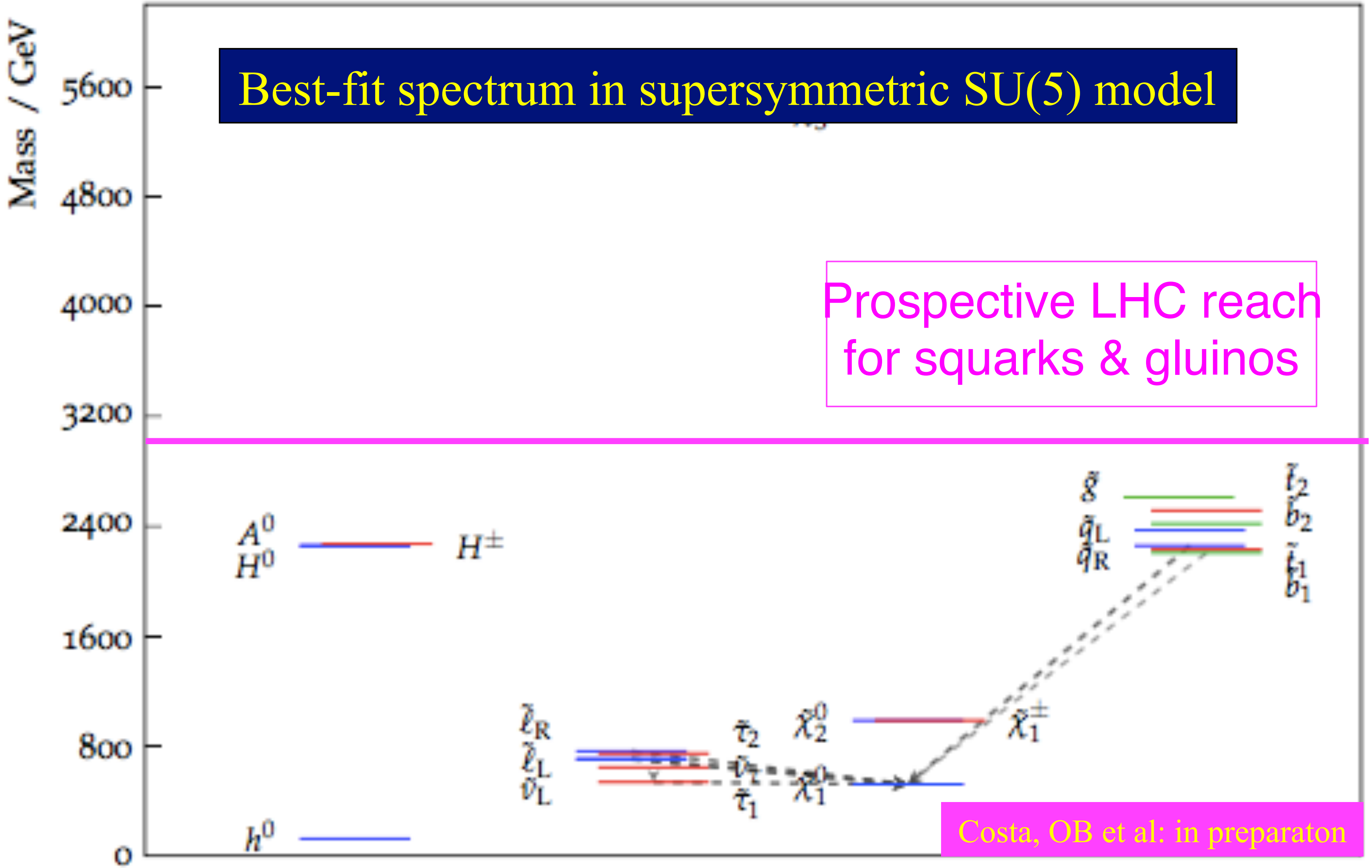
2016 ATLAS with 13/fb LHC Data



Costa, OB et al: in preparaton

Constraints from ICHEP2016

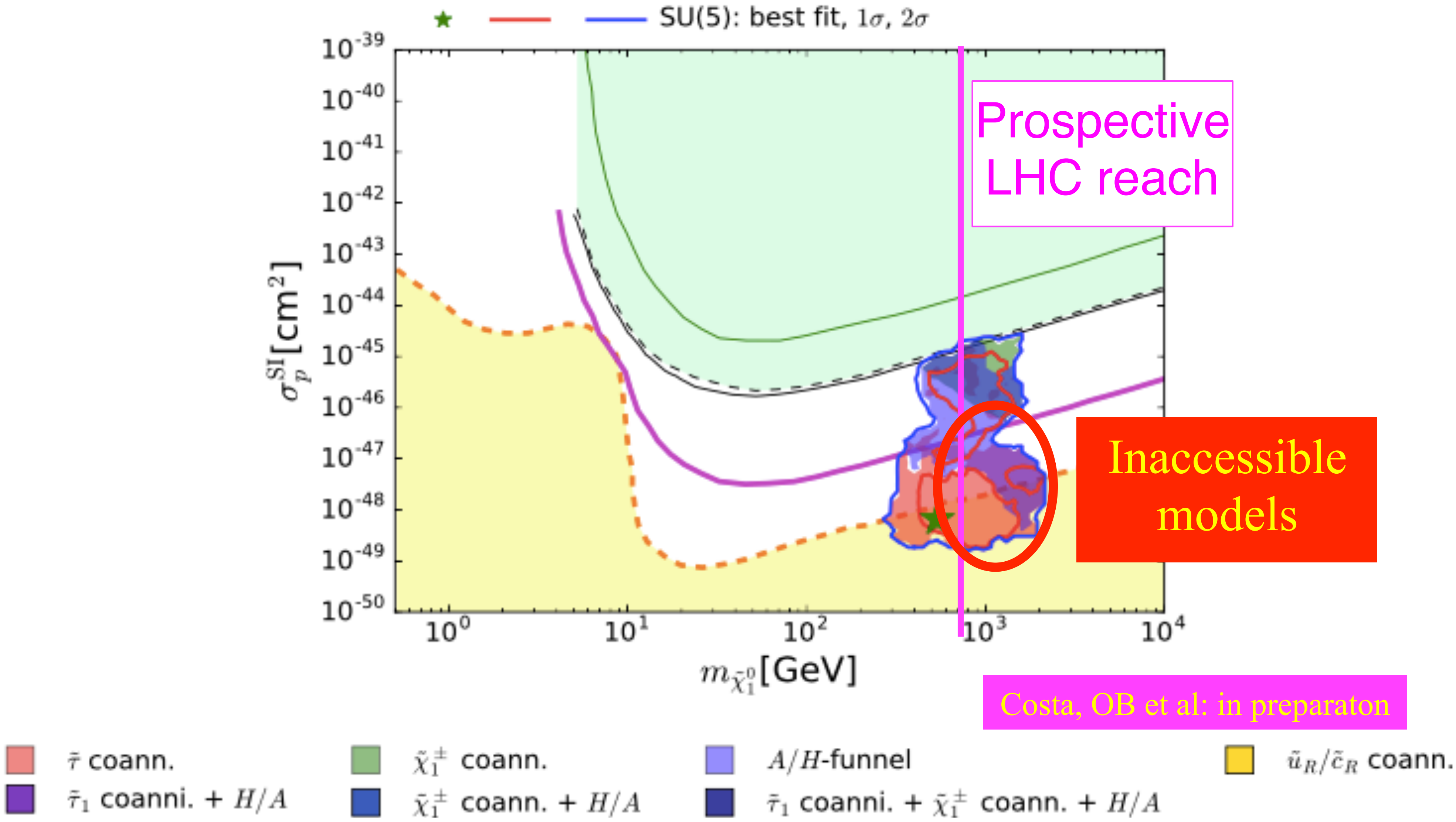
2016 ATLAS with 13/fb LHC Data



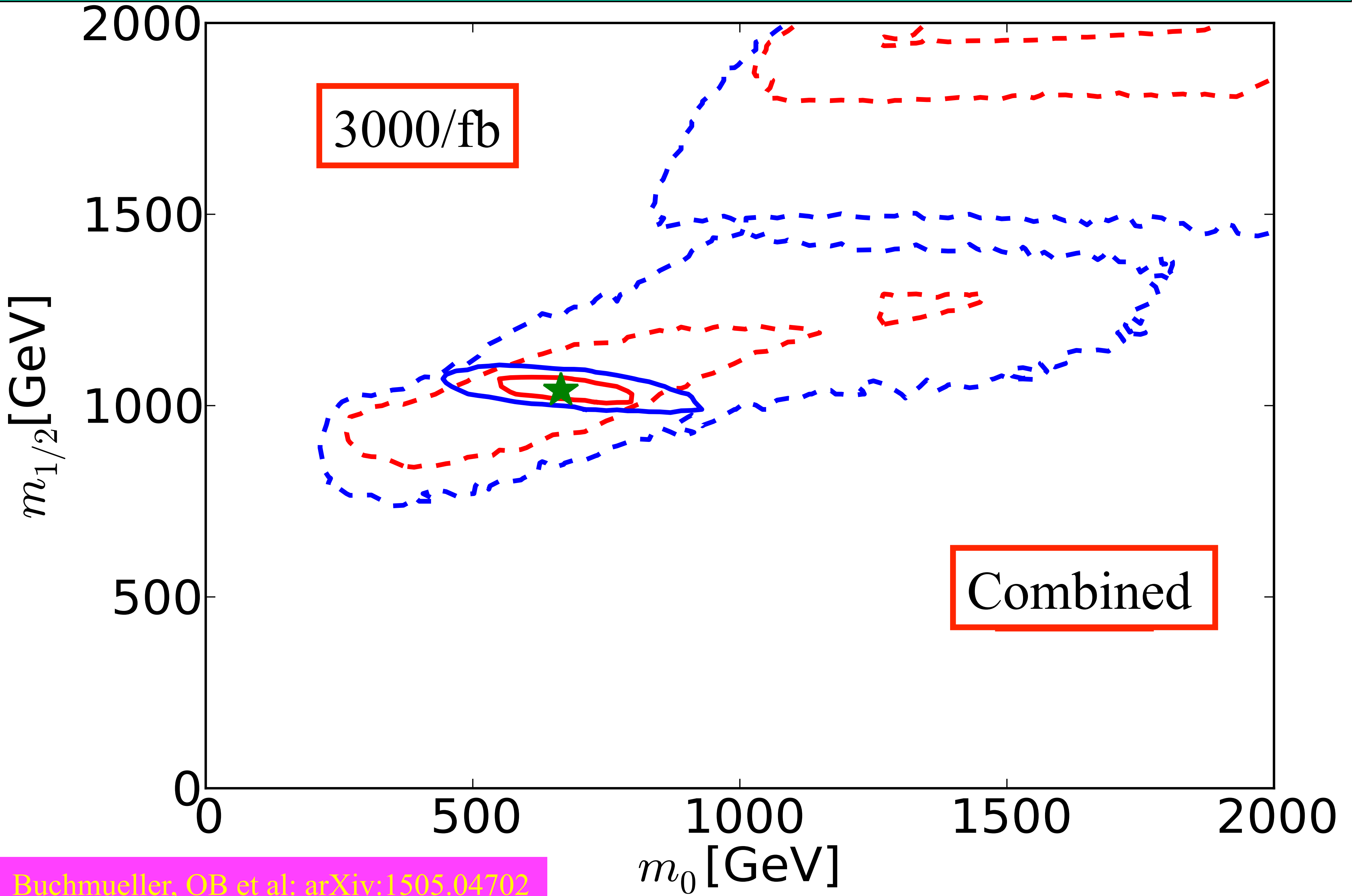
Constraints from ICHEP2016

2016 ATLAS with 13/fb LHC Data

Direct Dark Matter scattering in supersymmetric SU(5) model



Measuring the CMSSM with the LHC

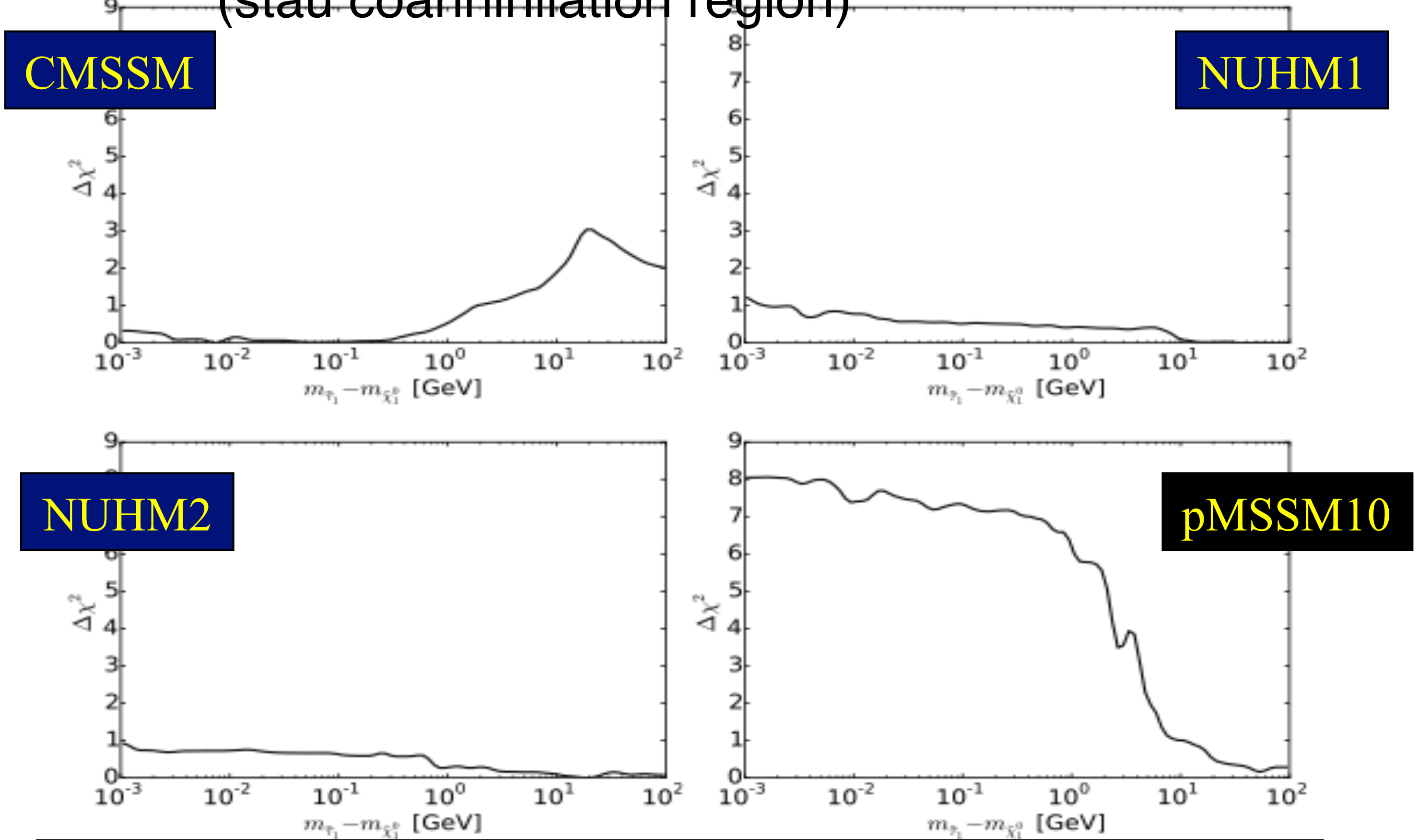


Buchmueller, OB et al: arXiv:1505.04702

Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{stau} - m_{LSP} < m_{\tau}$
Generic possibility in CMSSM, NUHM1, NUHM2
(stau coannihilation region)

Bagnaschi, OB et al: arXiv:1508. 01173



$\tau_{stau} > 10^3$ s gives problems with nucleosynthesis
$\tau_{stau} > 10^{-7}$ s gives separated vertex signature

Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{stau} - m_{LSP} < m_\tau$
Generic possibility in CMSSM, NUHM
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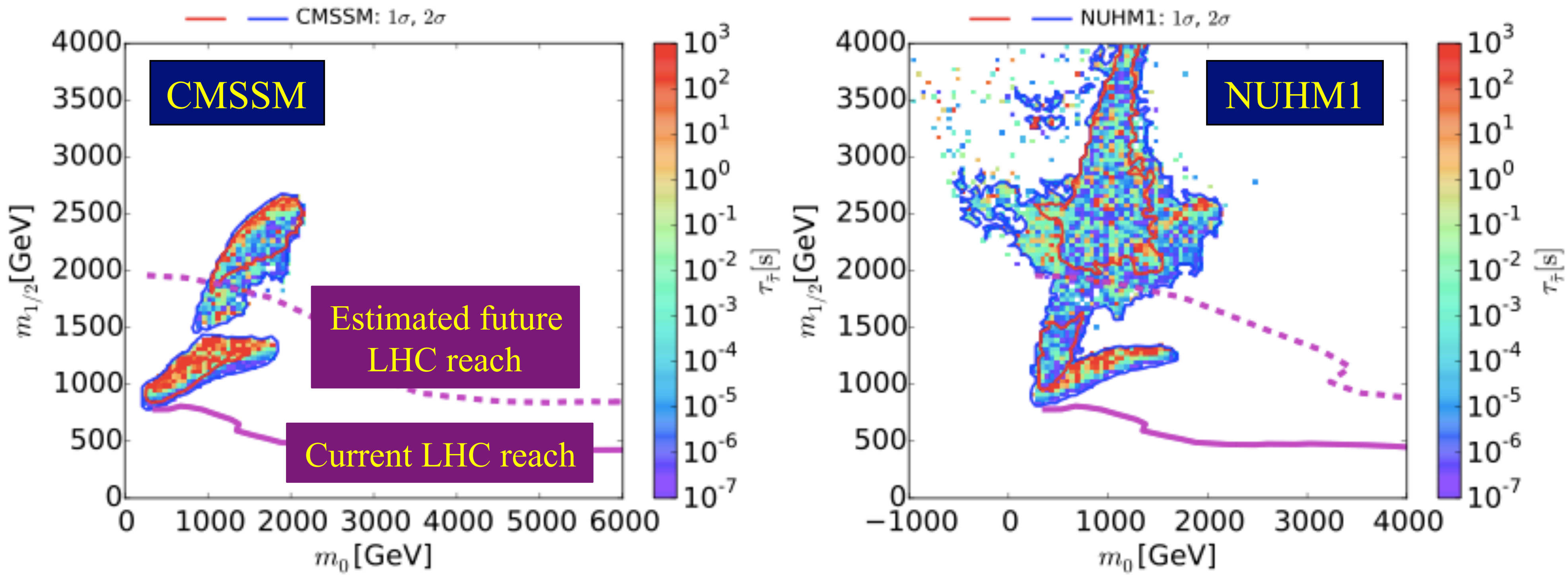
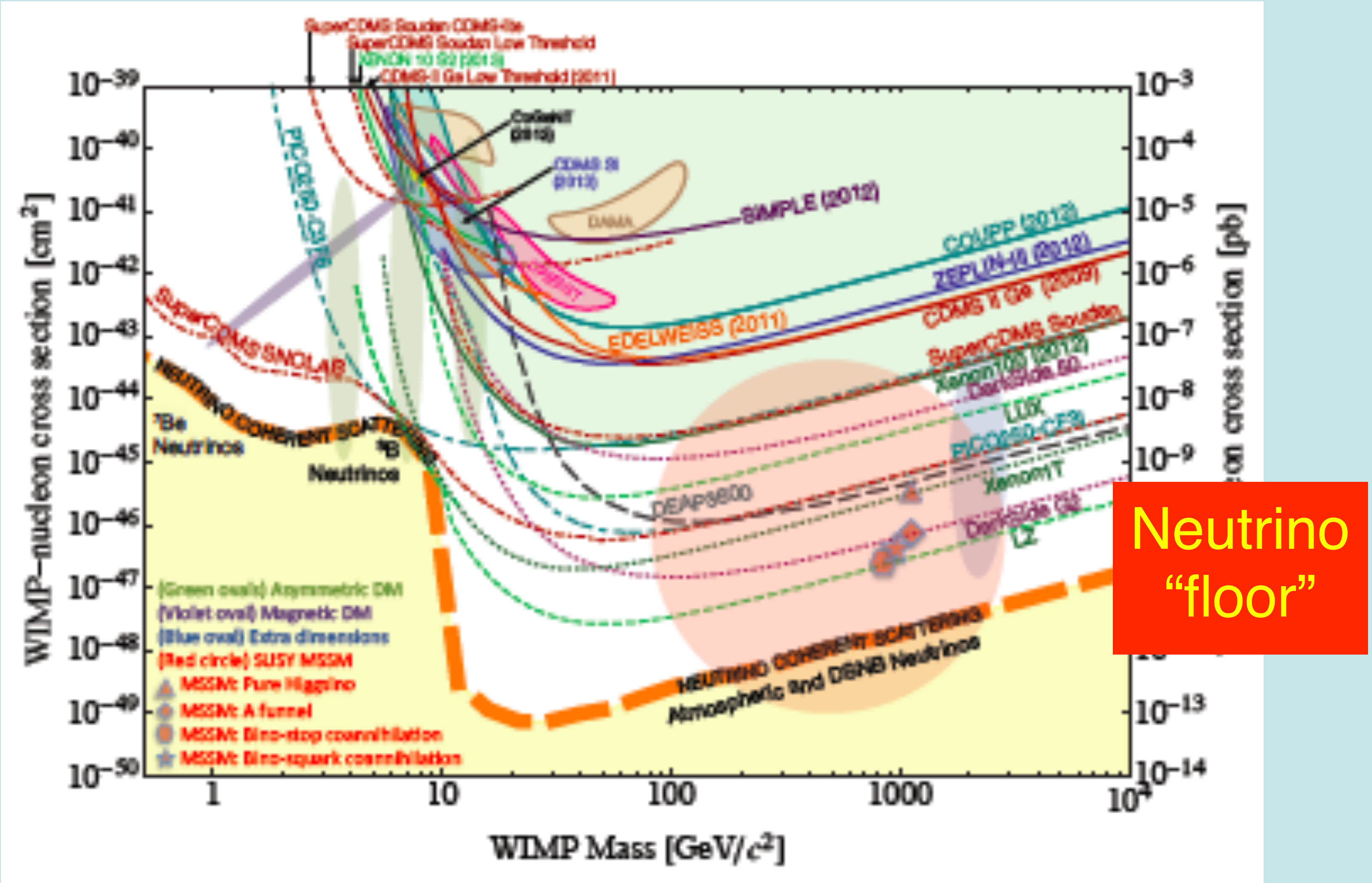


$\tau_{stau} > 10^3$ s gives problems with nucleosynthesis
$\tau_{stau} > 10^{-7}$ s gives separated vertex signature for τ-like decays

Bagnaschi, OB et al: arXiv:1508. 01173

Direct Dark Matter Searches

Compilation of present and future sensitivities



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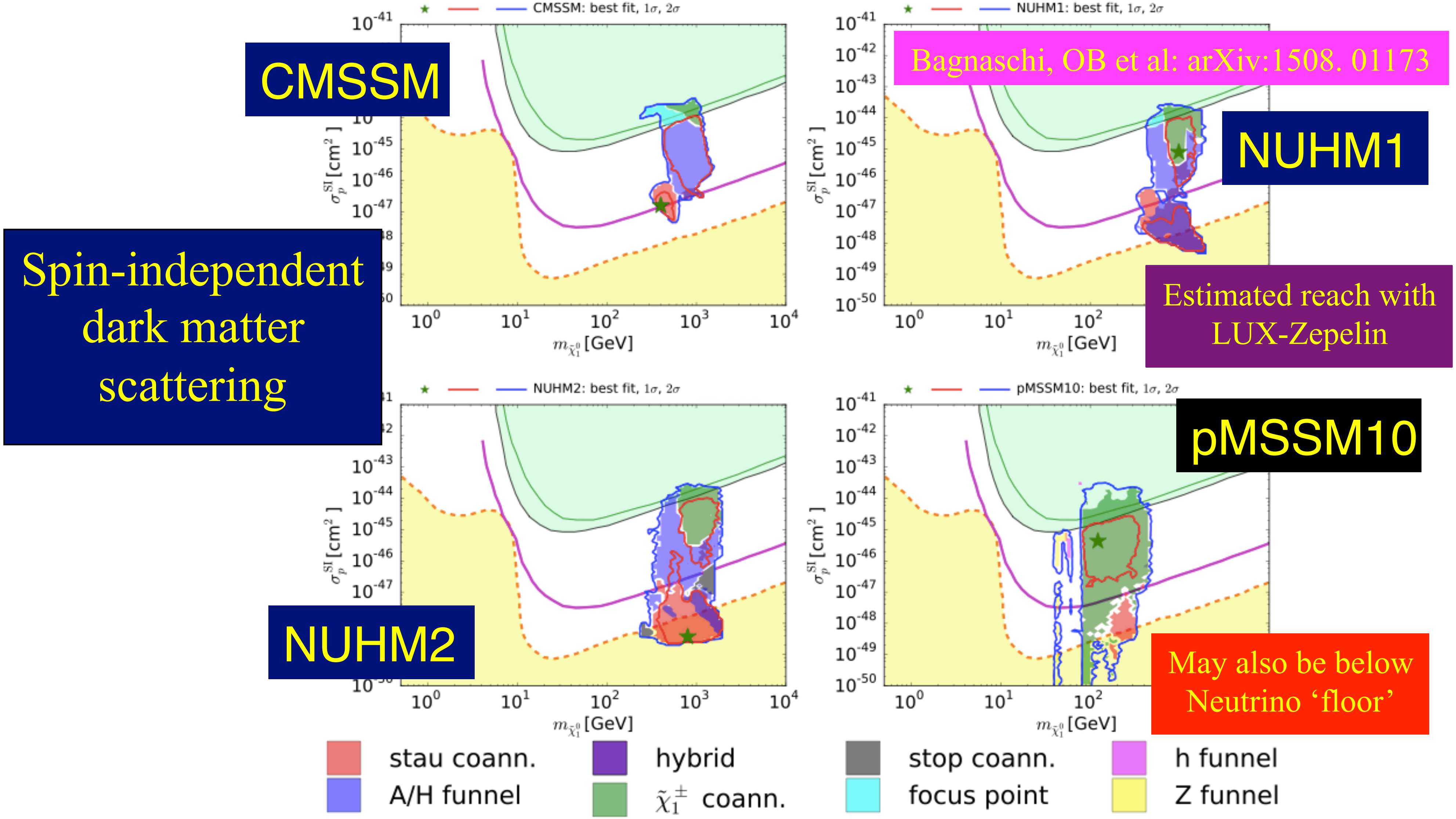
Direct Dark Matter Search



Direct scattering cross-section may be very close to LUX upper limit, accessible to LZ experiment

Prospects for SUSY Searches

Different models, various dark matter mechanisms

DM mechanism	Exp't	Models: CMSSM	NUHM1	NUHM2	pMSSM10
$\tilde{\tau}_1$ coann.	LHC	$\checkmark\ \not{E}_T$, $\checkmark$ LL	($\checkmark\ \not{E}_T$, $\checkmark$ LL)	($\checkmark\ \not{E}_T$, $\checkmark$ LL)	($\checkmark\ \not{E}_T$), $\times$ LL
	DM	($\checkmark$)	($\checkmark$)	$\times$	$\times$
$\tilde{\chi}_1^{\pm}$ coann.	LHC	–	$\times$	$\times$	($\checkmark\ \not{E}_T$)
	DM	–	$\checkmark$	$\checkmark$	($\checkmark$)
$\tilde{t}_1$ coann.	LHC	–	–	$\checkmark\ \not{E}_T$	–
	DM	–	–	$\times$	–
A/H funnel	LHC	$\checkmark$ A/H	($\checkmark$ A/H)	($\checkmark$ A/H)	–
	DM	$\checkmark$	$\checkmark$	($\checkmark$)	–
Focus point	LHC	($\checkmark\ \not{E}_T$)	–	–	–
	DM	$\checkmark$	–	–	–
h, Z funnels	LHC	–	–	–	($\checkmark\ \not{E}_T$)
	DM	–	–	–	($\checkmark$)

Bagnaschi, OB et al: arXiv:1508. 01173

BACKUP

LHC 8 TEV CONSTRAINTS

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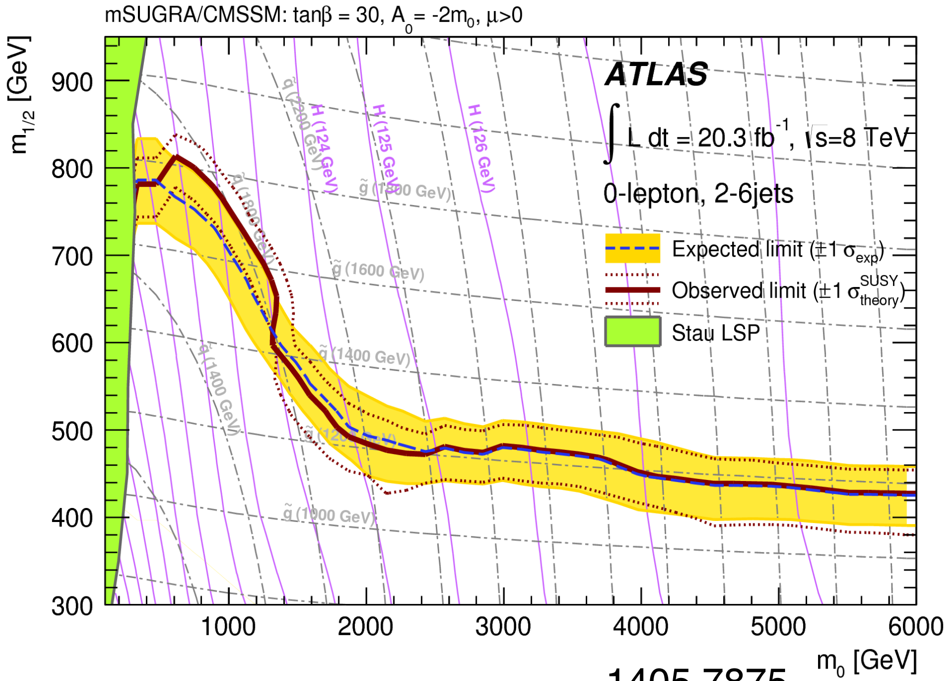
Implementation of LHC searches

GUT models



1405.7875

- Limits are independent of

$$A_0,\ \tan\beta,\ m^2_{H_u},\ m^2_{H_d}$$

- Mass limits on **squarks and gluinos** constrain implicitly those on **sleptons, neutralinos** and **charginos**

pMSSM10

- **squarks and gluinos**

$$\chi^2(\mathrm{LHC8_{col}})$$

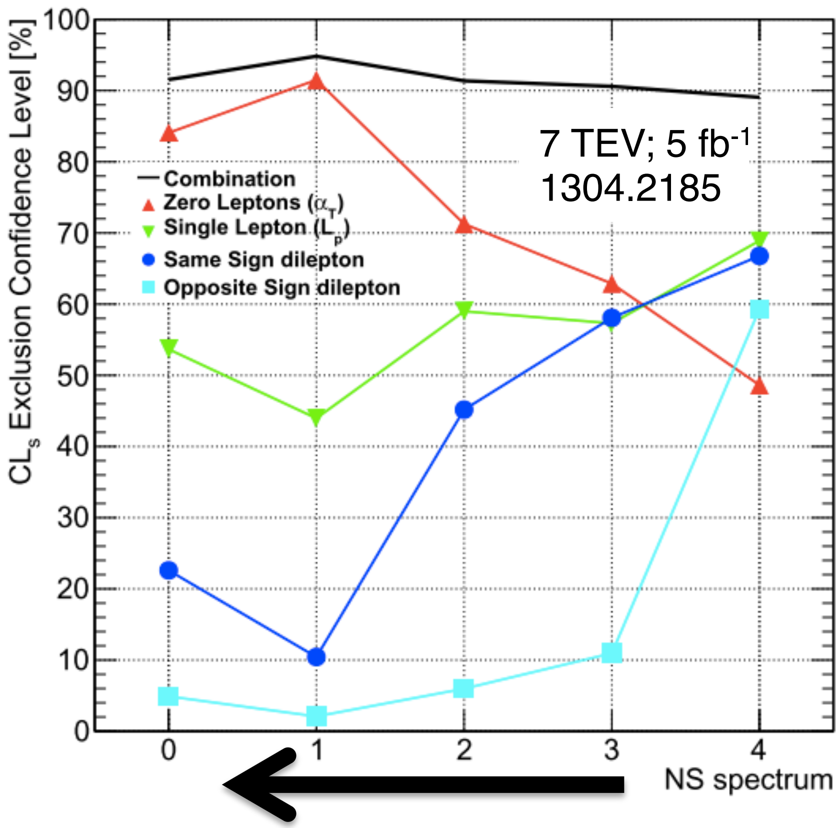
- **sleptons, charginos, and neutralinos**

$$\chi^2(\mathrm{LHC8_{EWK}})$$

- **compressed-stop spectra**

$$\chi^2(\mathrm{LHC8_{stop}})$$

LHC8$_{col}$: squarks and gluinos



removing sleptons, neutralinos, charginos from the spectrum

Combine CMS searches (8 TeV; 20 fb^{-1})

- 0-lep M_{T2}
- 1-lep M^W_{T2}
- 2-lep OS/SS
- >=3 lep

4 dimensional lookup table

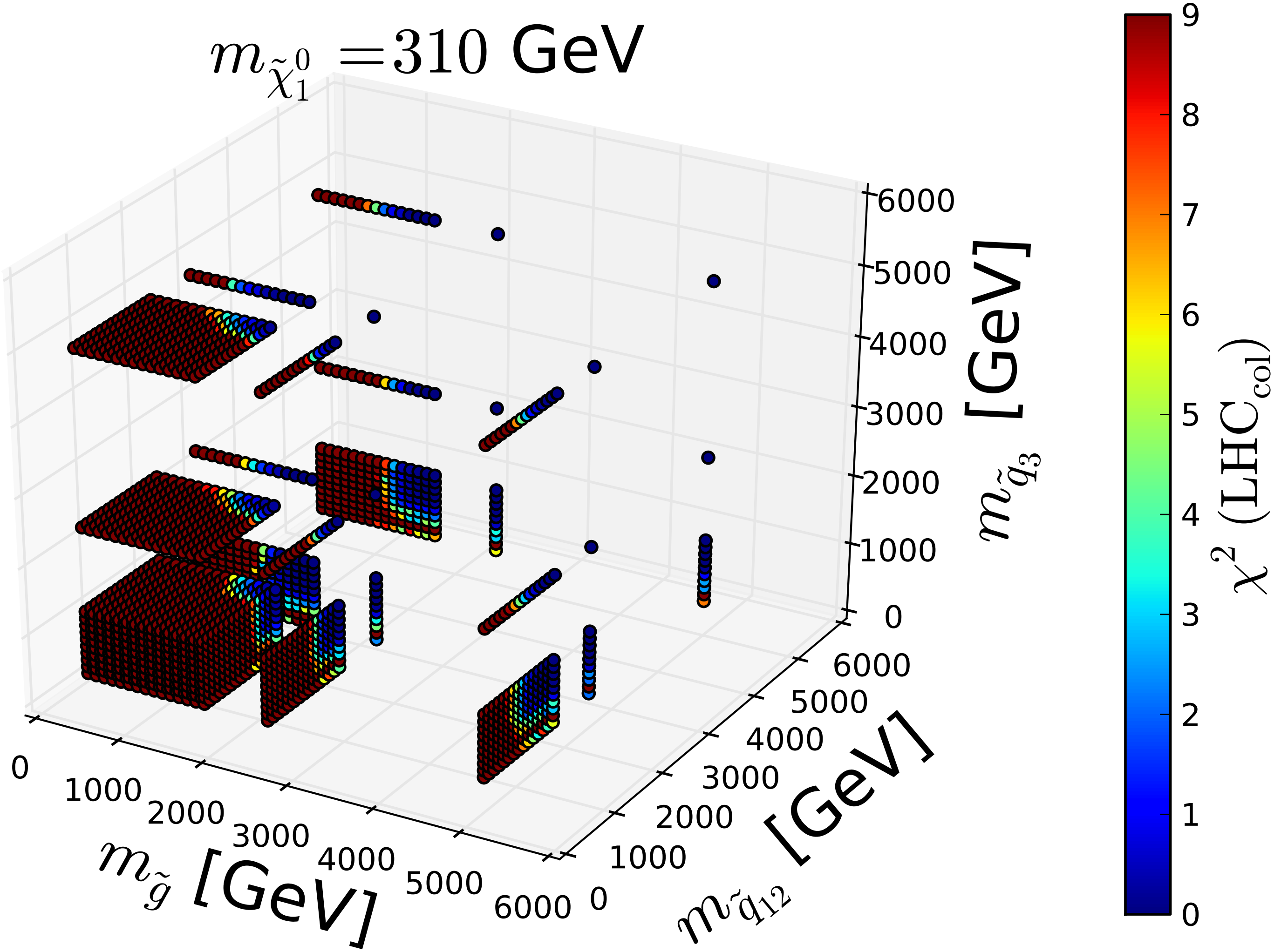
- LSP mass
- gluino mass
- 1st and 2nd generation squark mass
- 3rd generation squark mass

(production cross-section weighted average)

Compressed-stop scenario

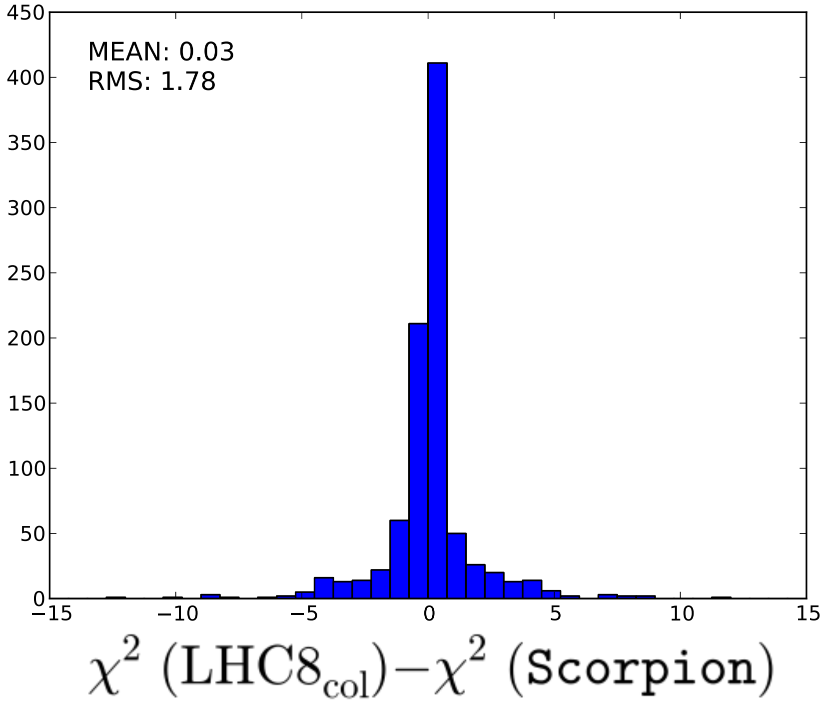
- treat separately
- set stop cross-section to zero

LHC8$_{col}$: 4 dimensional lookup



$LHC8_{col}$: validation

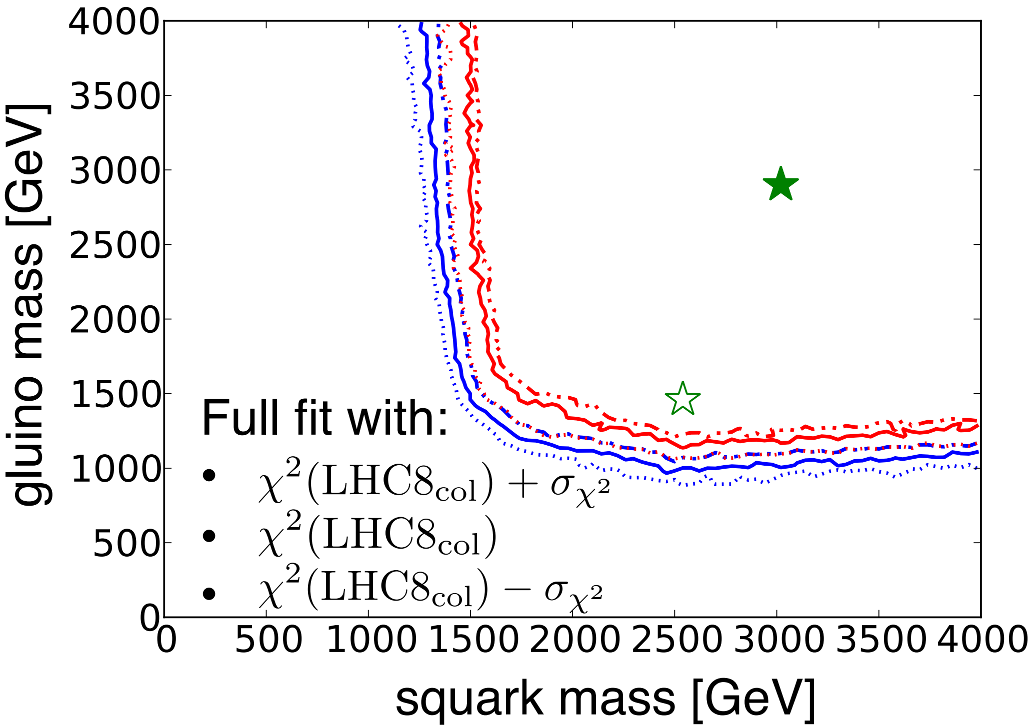
1000 randomly chosen points from our pMSSM10 sample



Lookup table

Point-by-point reinterpretation

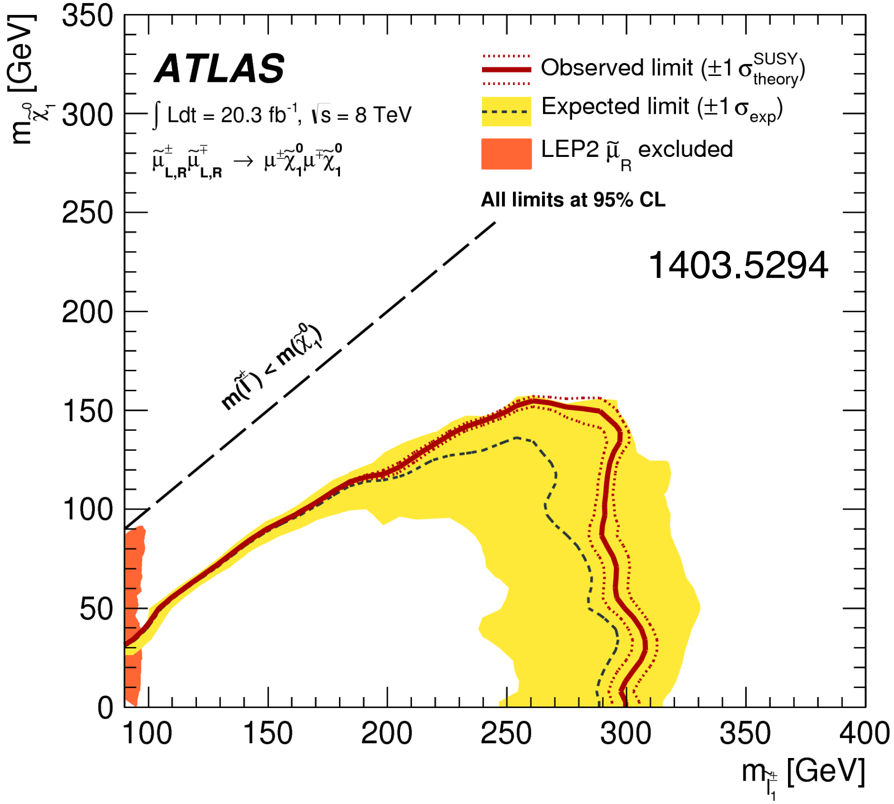
Uncertainty on mass lower limits

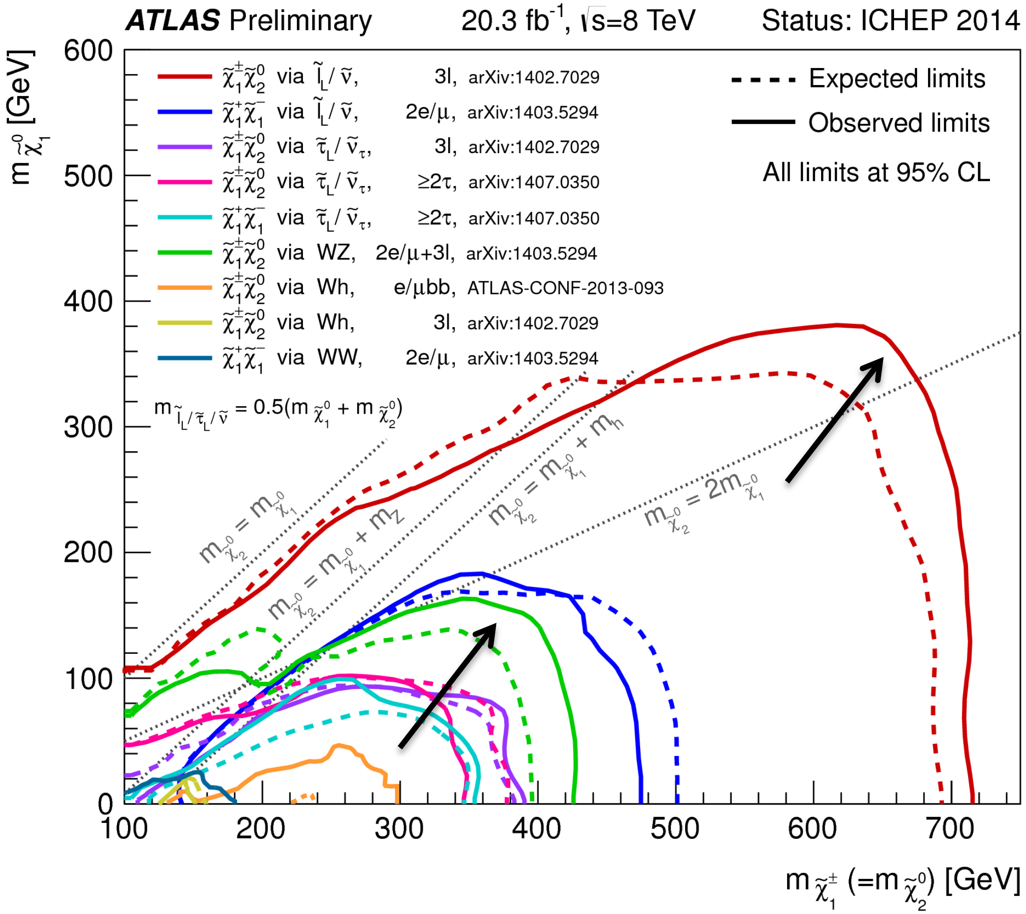


σ_{χ^2} : RMS in bins of $\chi^2(\mathrm{LHC8_{col}})$

LHC_{col}: uncertain of O(50 GeV)

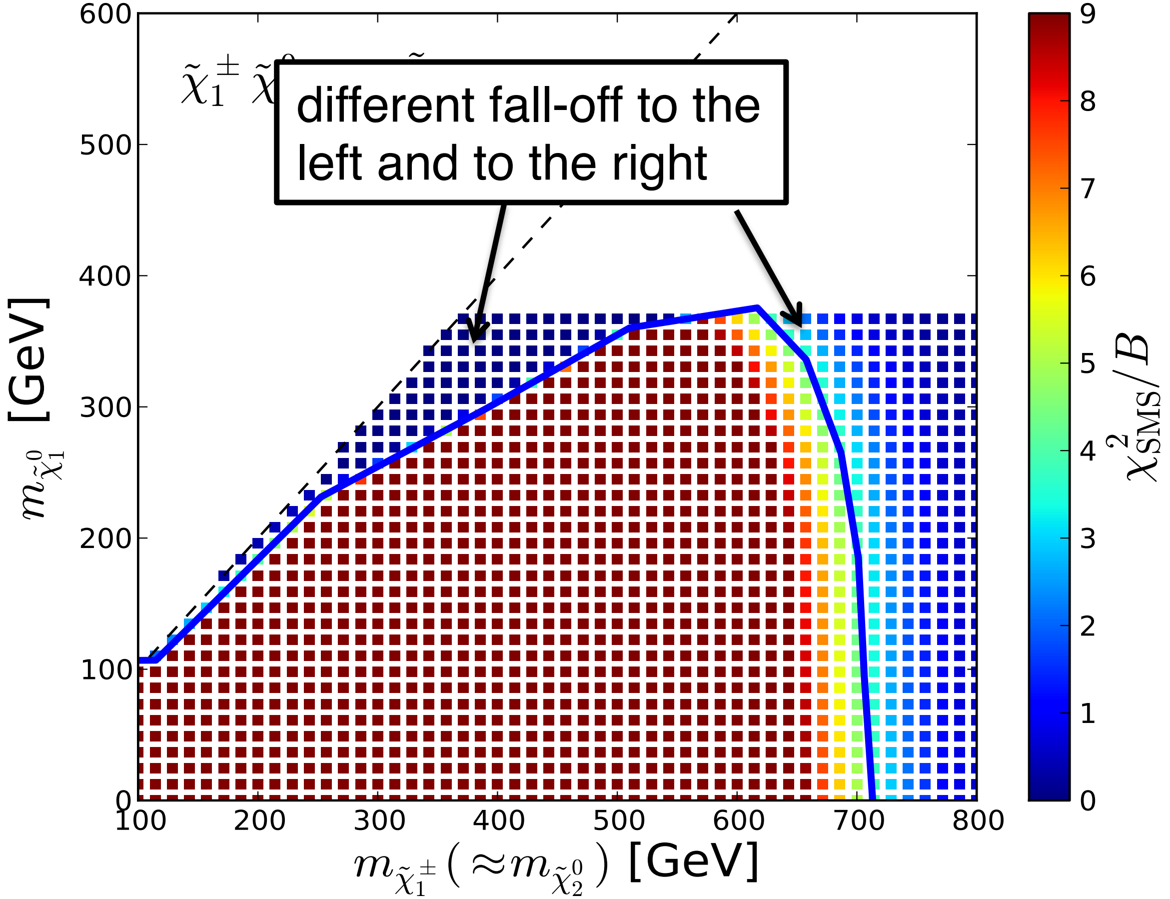
$LHC8_{EWK}$: apply SMS limits





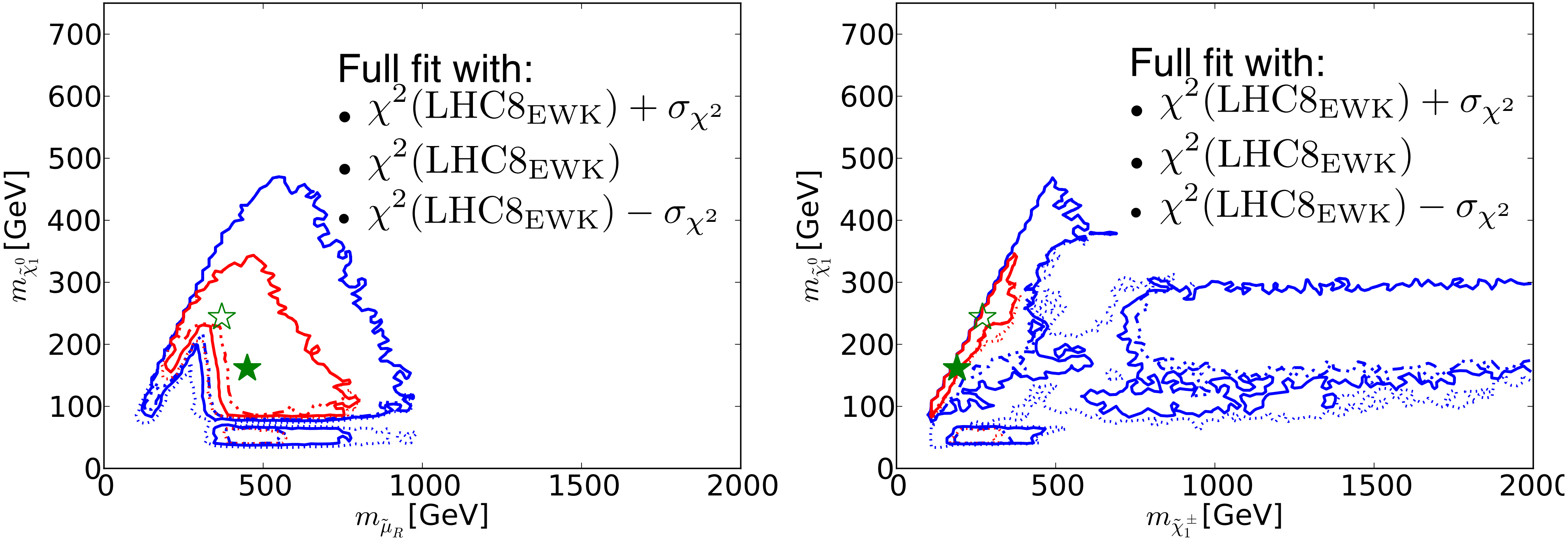
- **SMS limits (from ATLAS)**
  - motivation: very different **sensitivity** depending on decay chain
  - only the **hierarchy** between **chargino/neutralino** and **slepton** masses need to be constrained

LHC8$_{EWK}$: implementation



scaling with branching ration

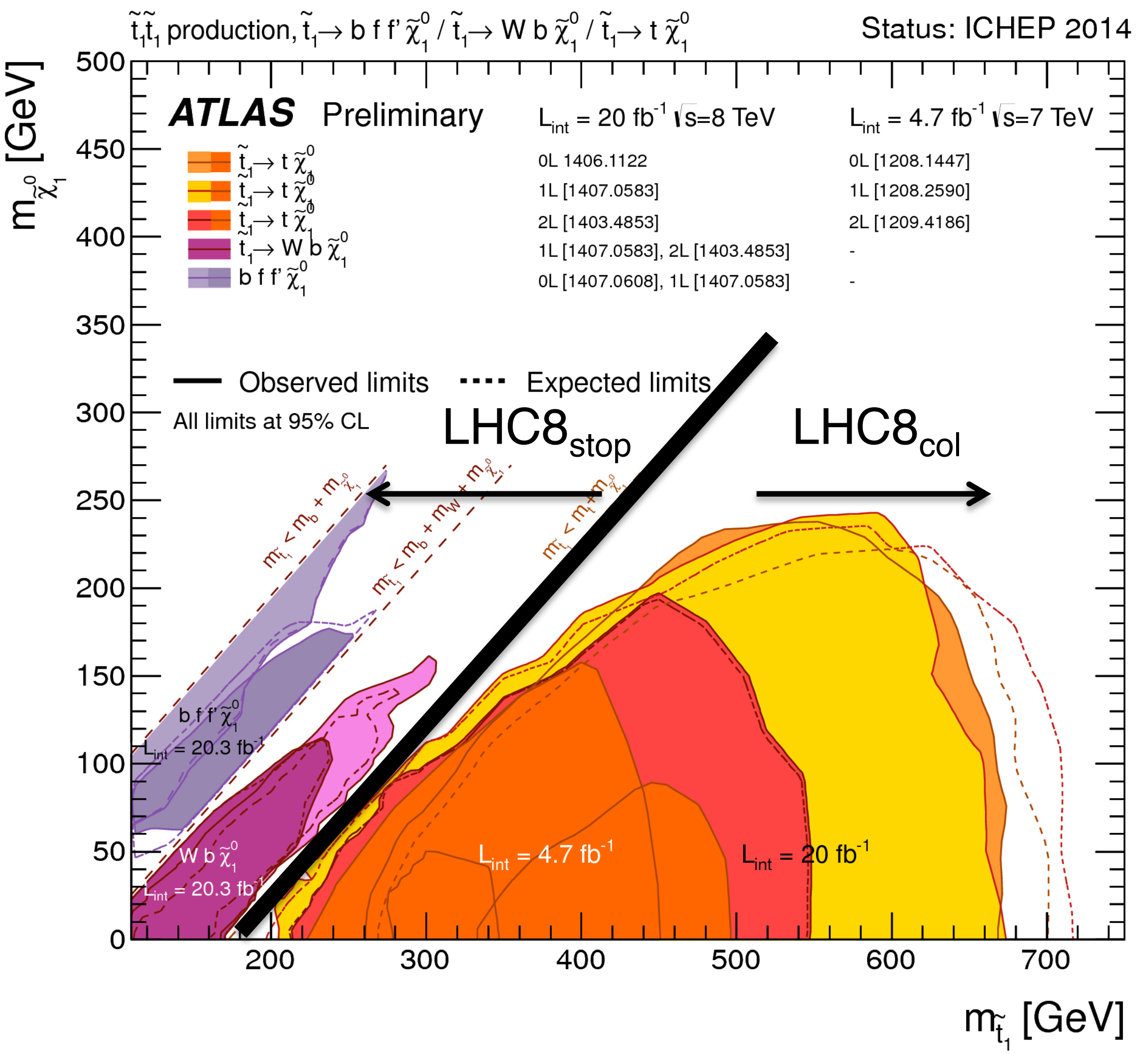
$LHC8_{EWK}$: validation



- 1000 random points
  - point-by-point reinterpretation (see backup) yields good agreement
  - propagate binned uncertainties into mass planes

LHC8$_{stop}$: compressed-stop scenario

- compressed-stop
  - only the **lightest** stop treated separately from LHC8$_{col}$
  - LCH8$_{EWK}$ still applies
  - LHC8$_{col}$ applies still to heavier stops and sbottoms



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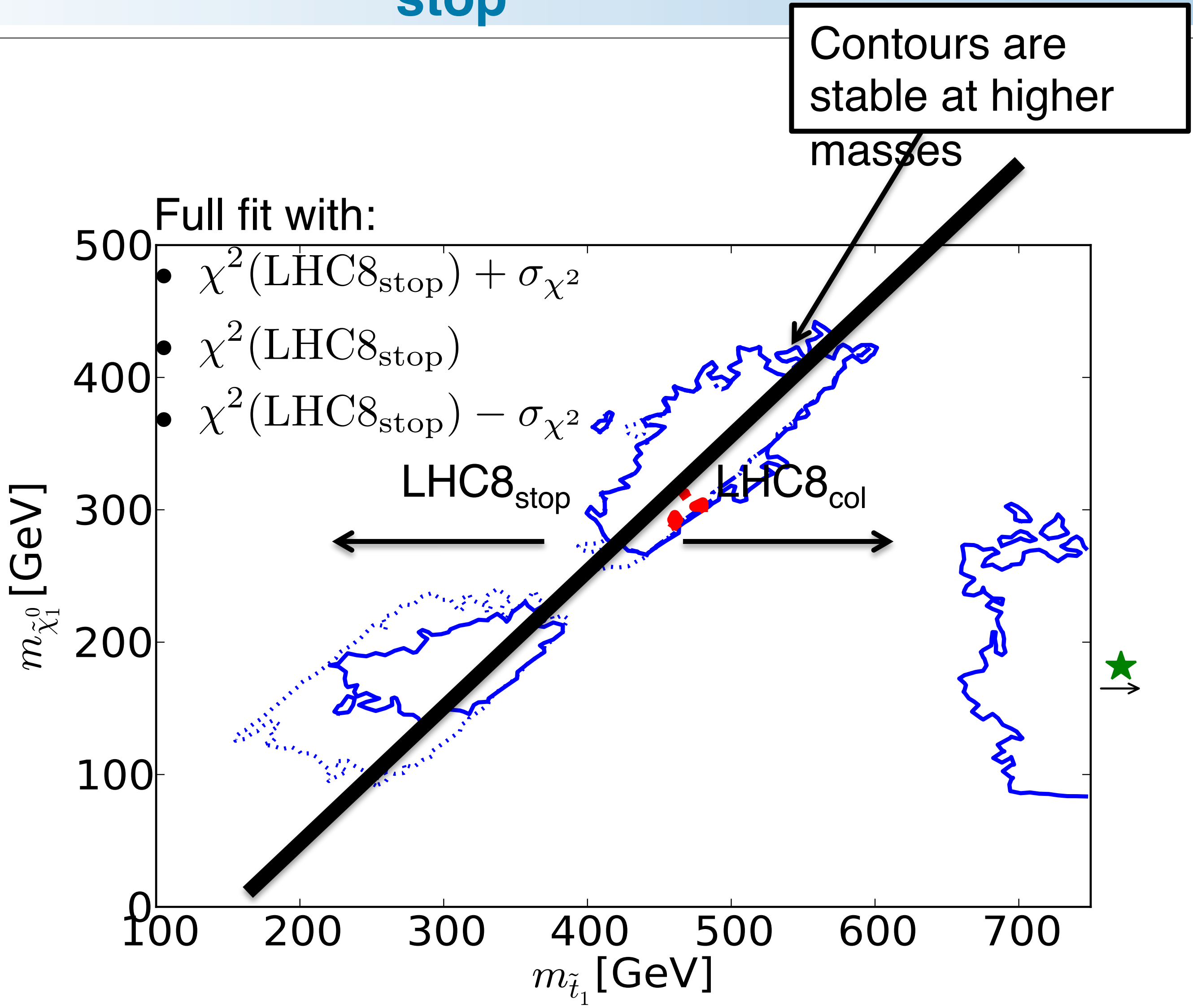
LHC8$_{stop}$: validation



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Projections for future experiments

Example:
Axial-Vector Mediator
g_{SM}=g_{DM}=1

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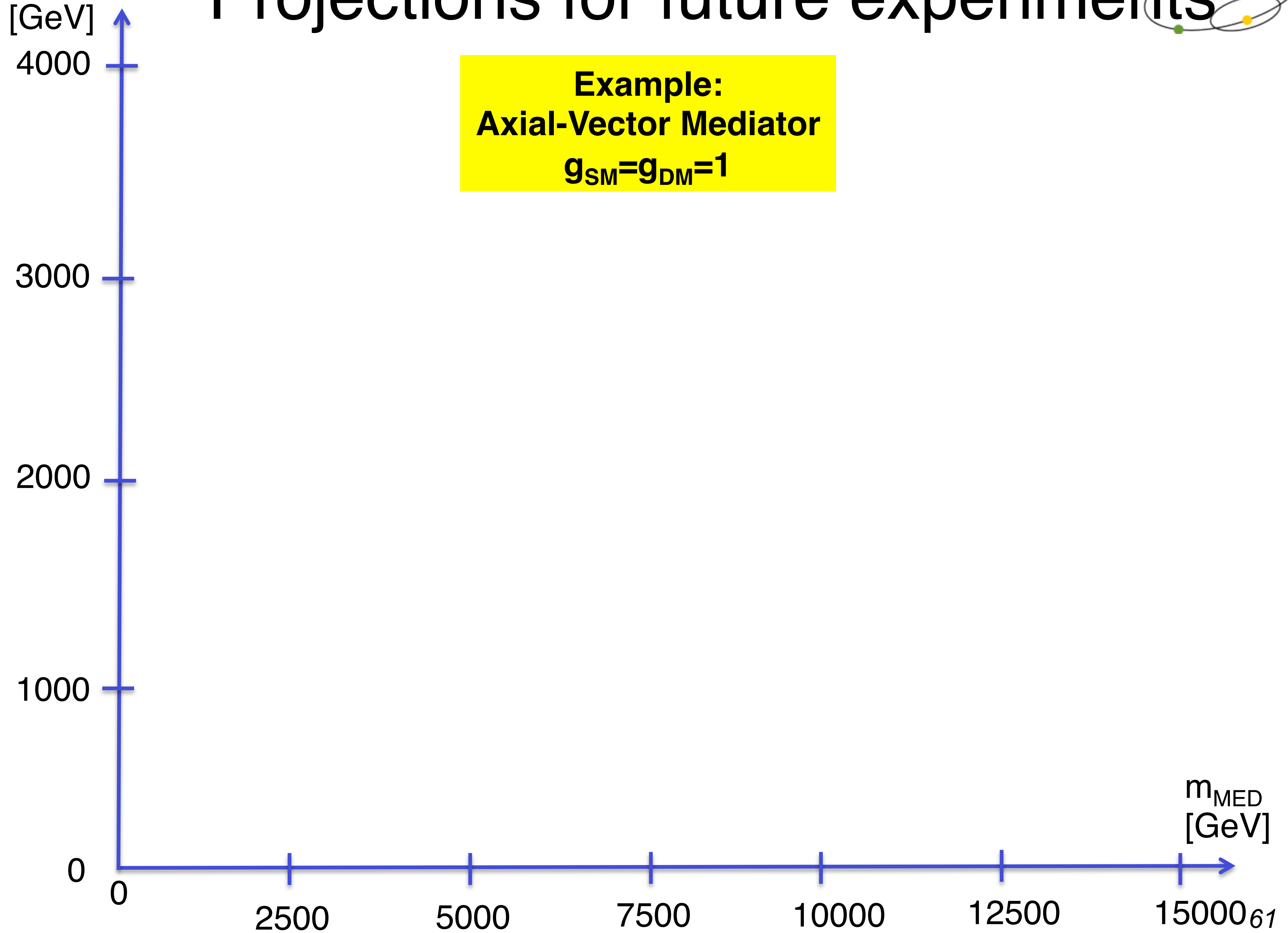

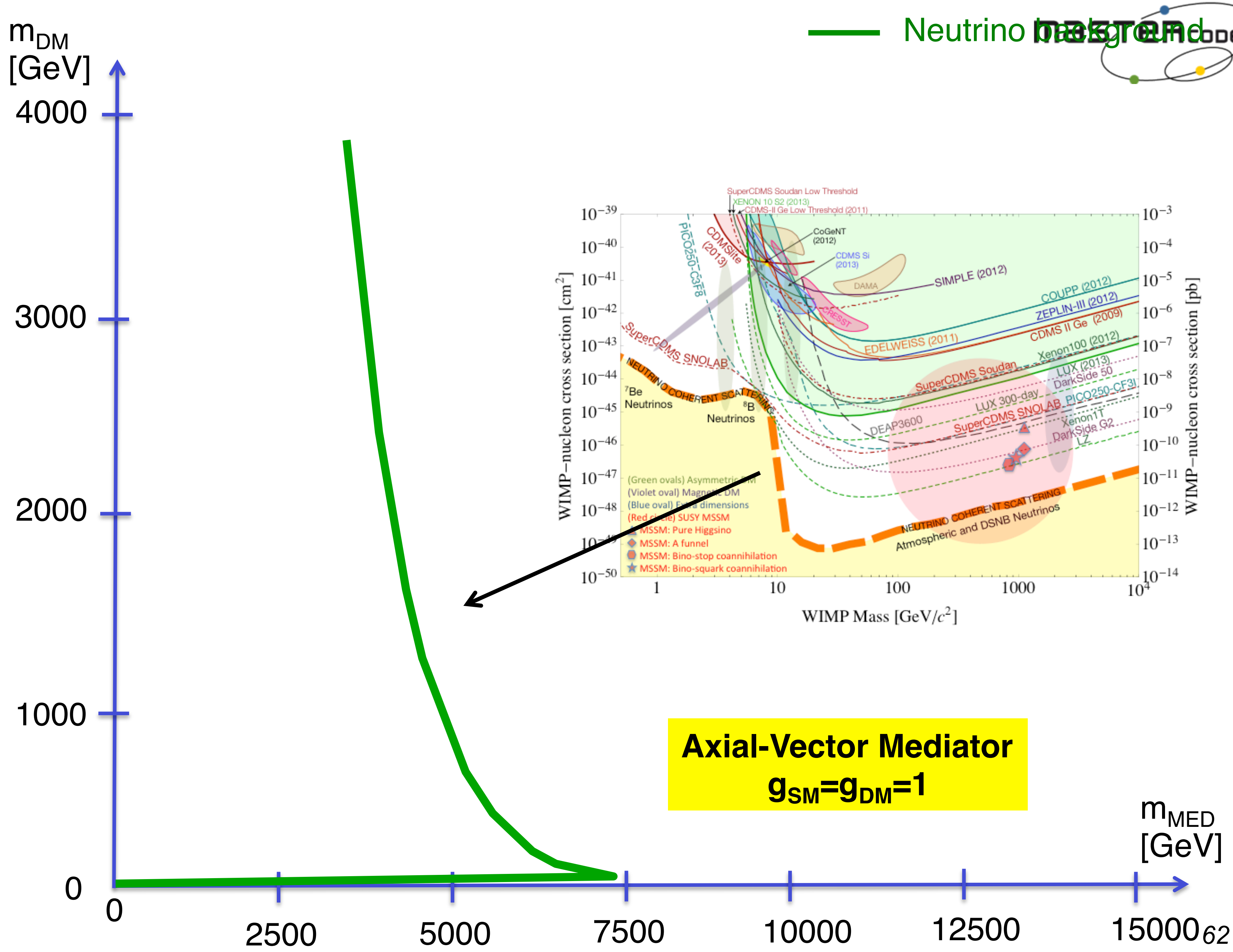

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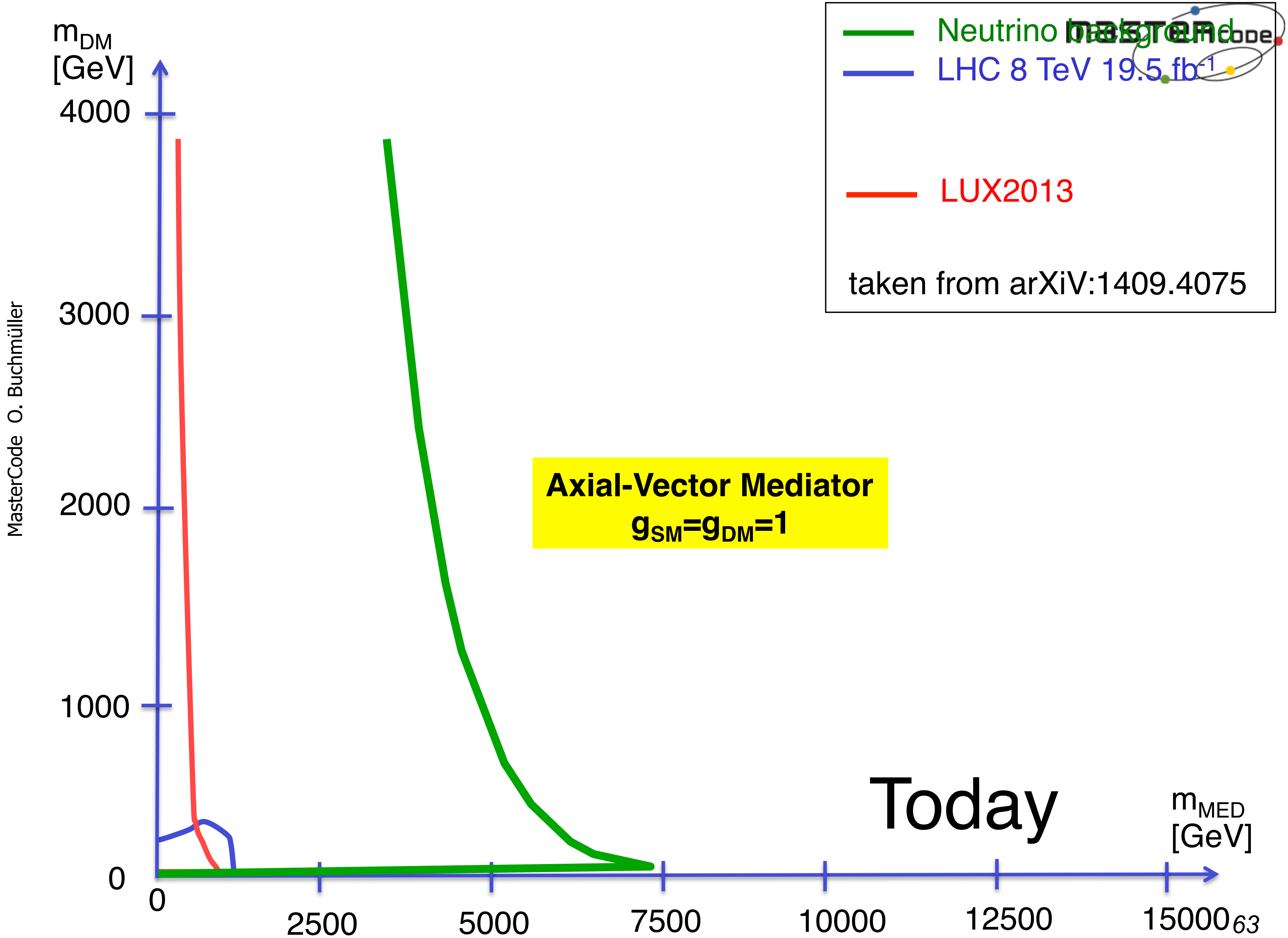
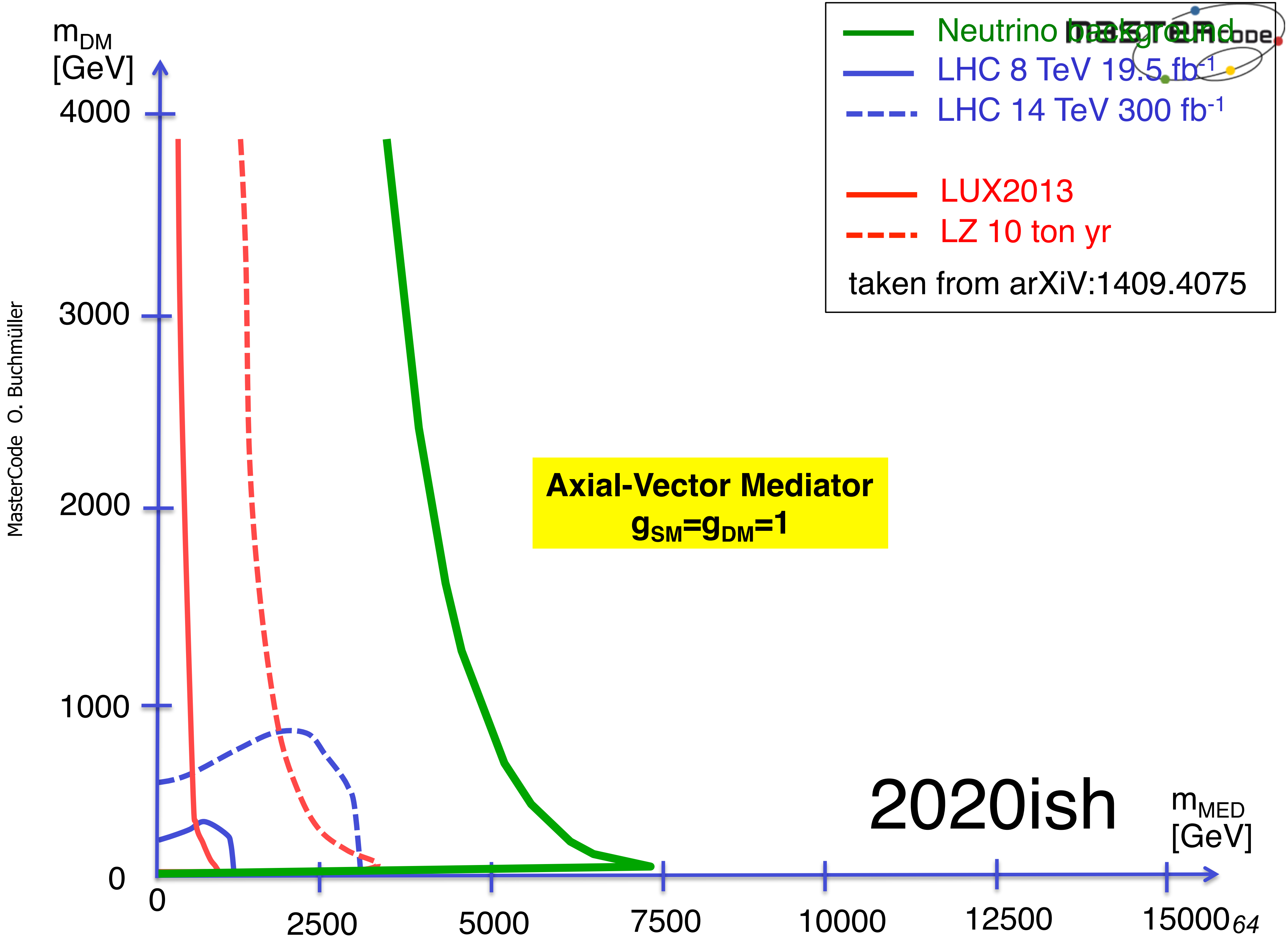
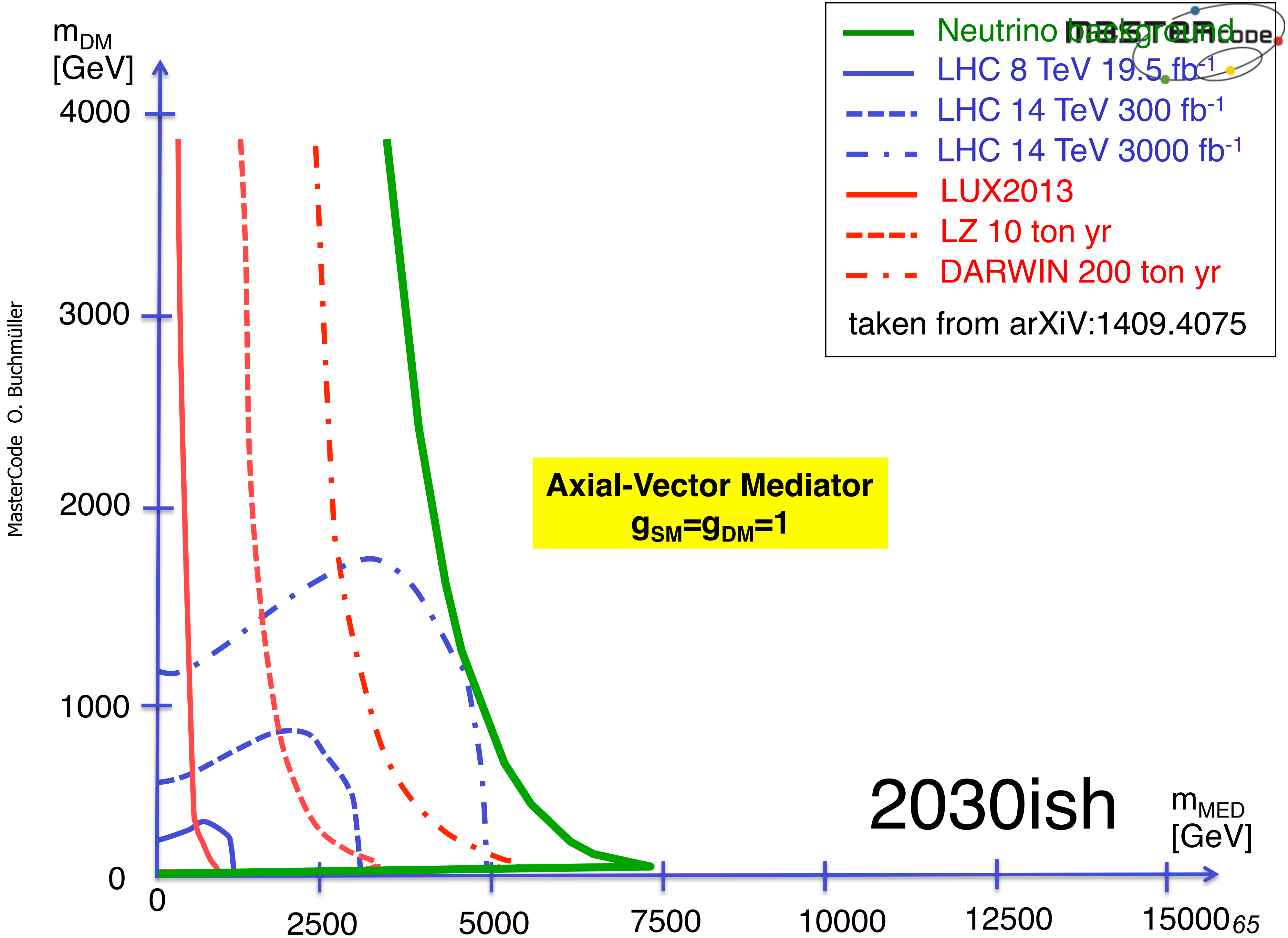


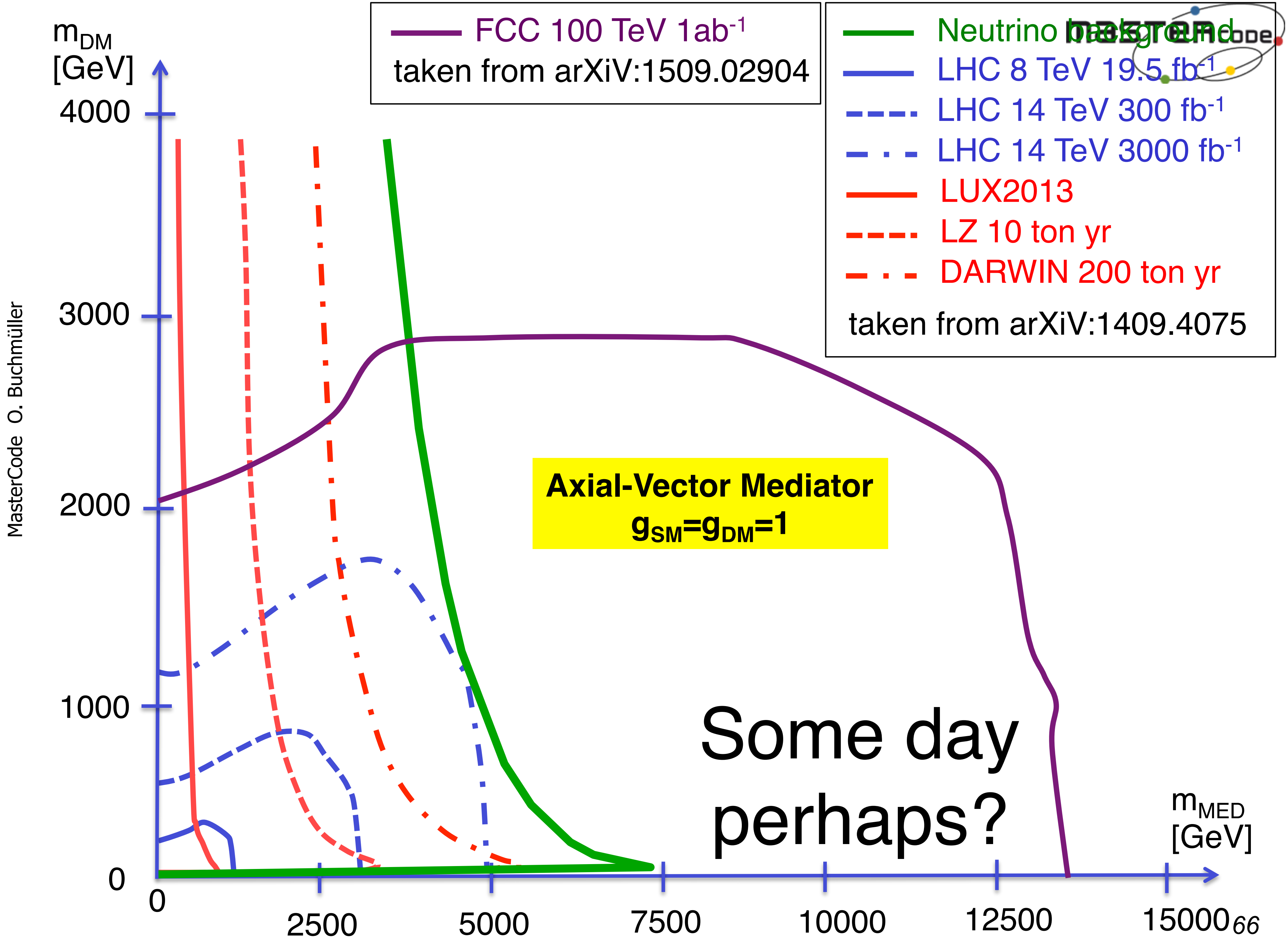
m_{DM} [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_{MED} [GeV]
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LUX2013
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
Today
MasterCode O. Buchmüller



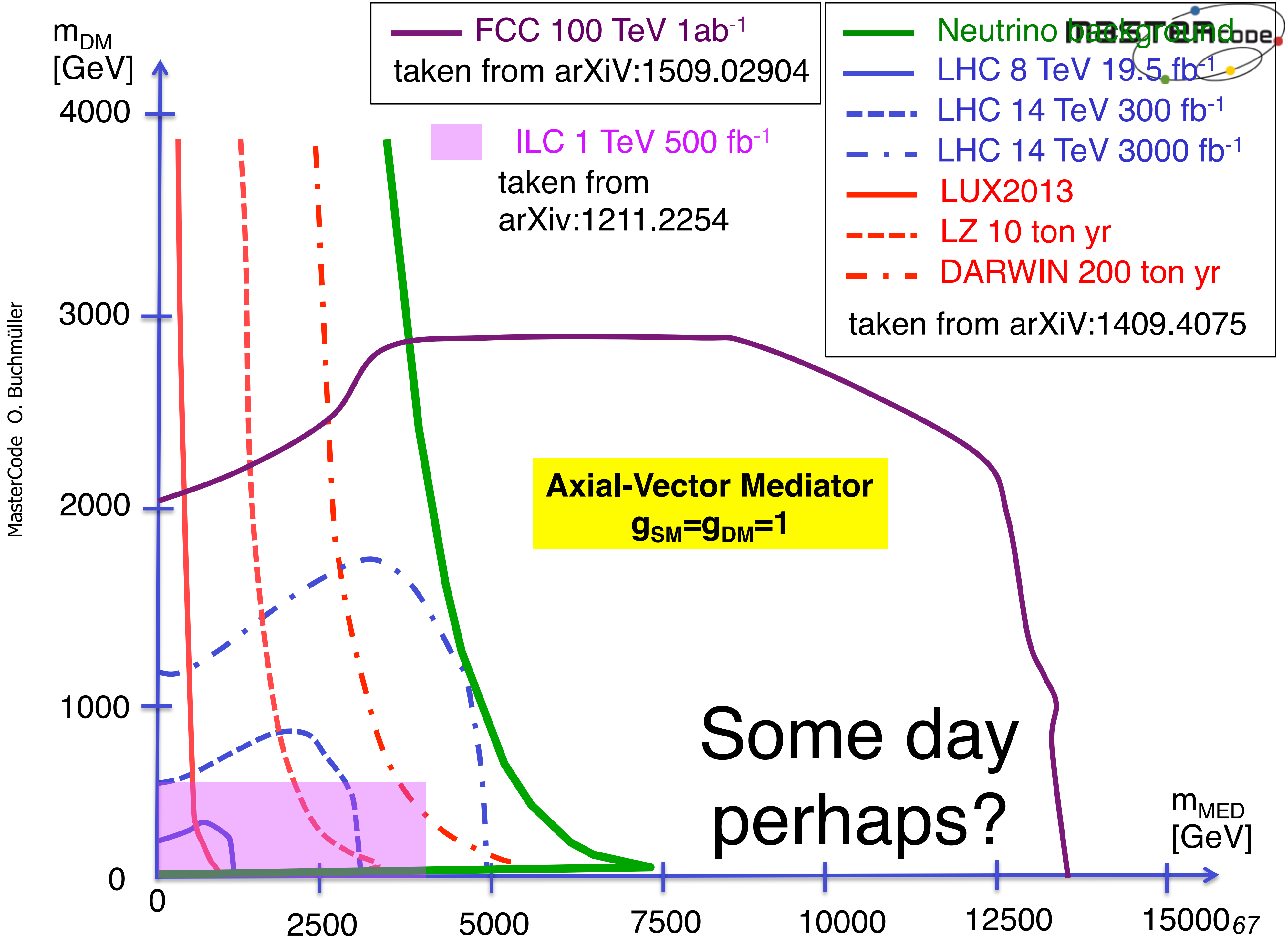
m_{DM} [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_{MED} [GeV]
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LHC 14 TeV 300 fb^{-1}
LUX2013
LZ 10 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
2020ish
MasterCode O. Buchmüller



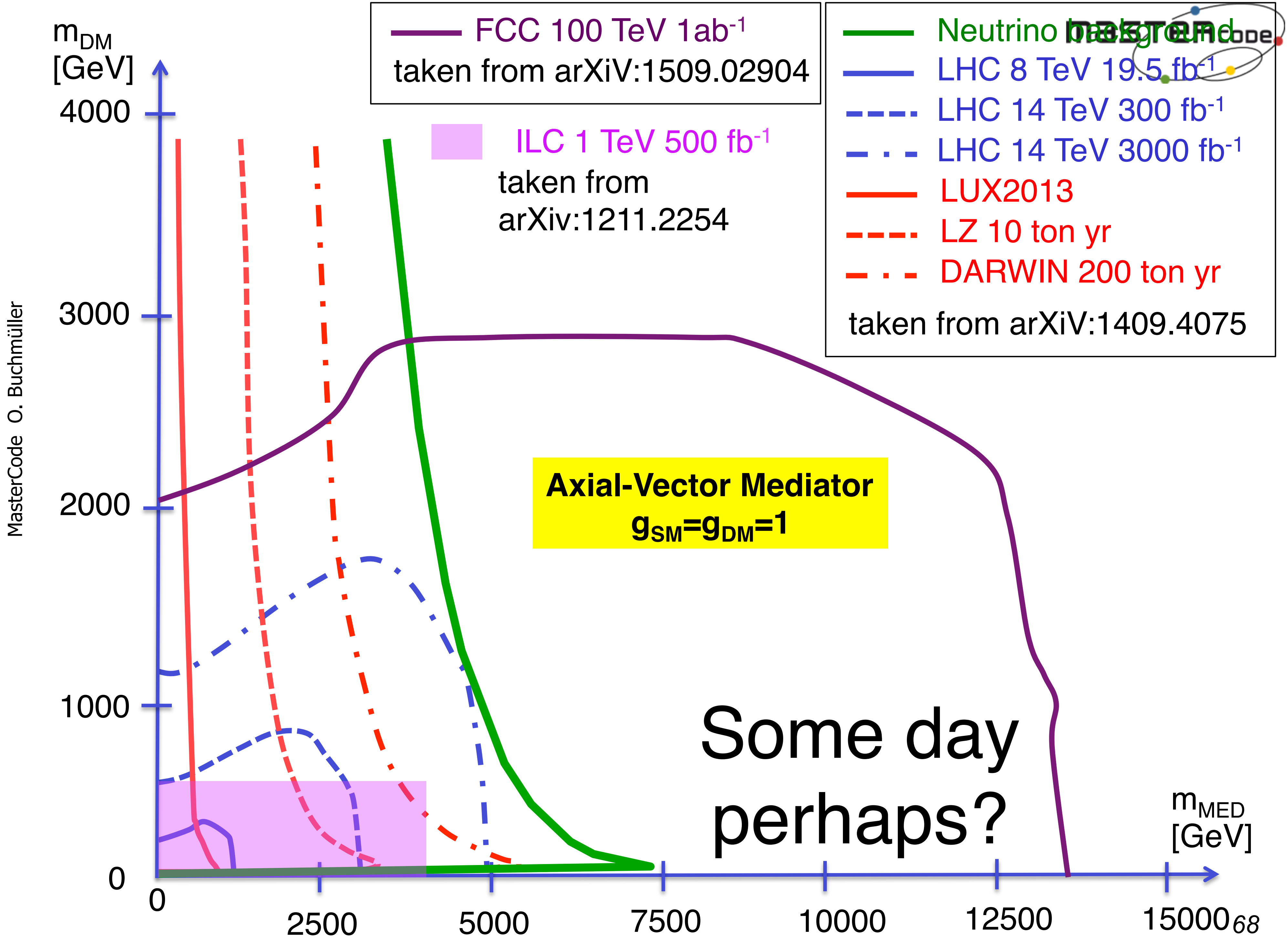
m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
gSM=gDM=1
2030ish
MasterCode O. Buchmüller



FCC 100 TeV 1ab-1
taken from arXiV:1509.02904
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
mDM [GeV]
4000
3000
2000
1000
0
Axial-Vector Mediator
gSM=gDM=1
Some day perhaps?
mMED [GeV]
0
2500
5000
7500
10000
12500
15000
MasterCode O. Buchmüller



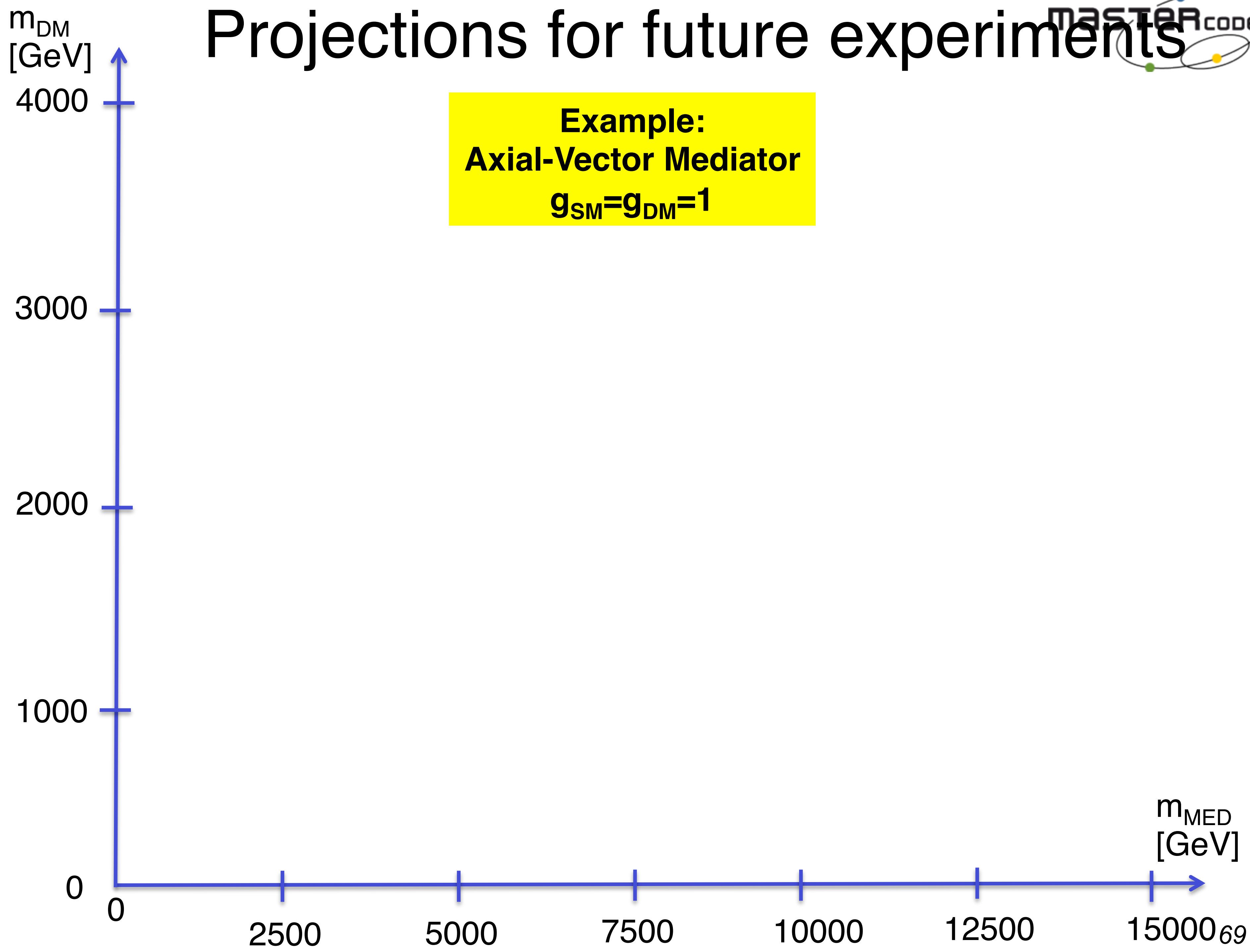
m_{DM} [GeV]
4000
3000
2000
1000
0
FCC 100 TeV 1ab^{-1}
taken from arXiV:1509.02904
ILC 1 TeV 500 fb^{-1}
taken from arXiv:1211.2254
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LHC 14 TeV 300 fb^{-1}
LHC 14 TeV 3000 fb^{-1}
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
Some day perhaps?
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000
MasterCode O. Buchmüller

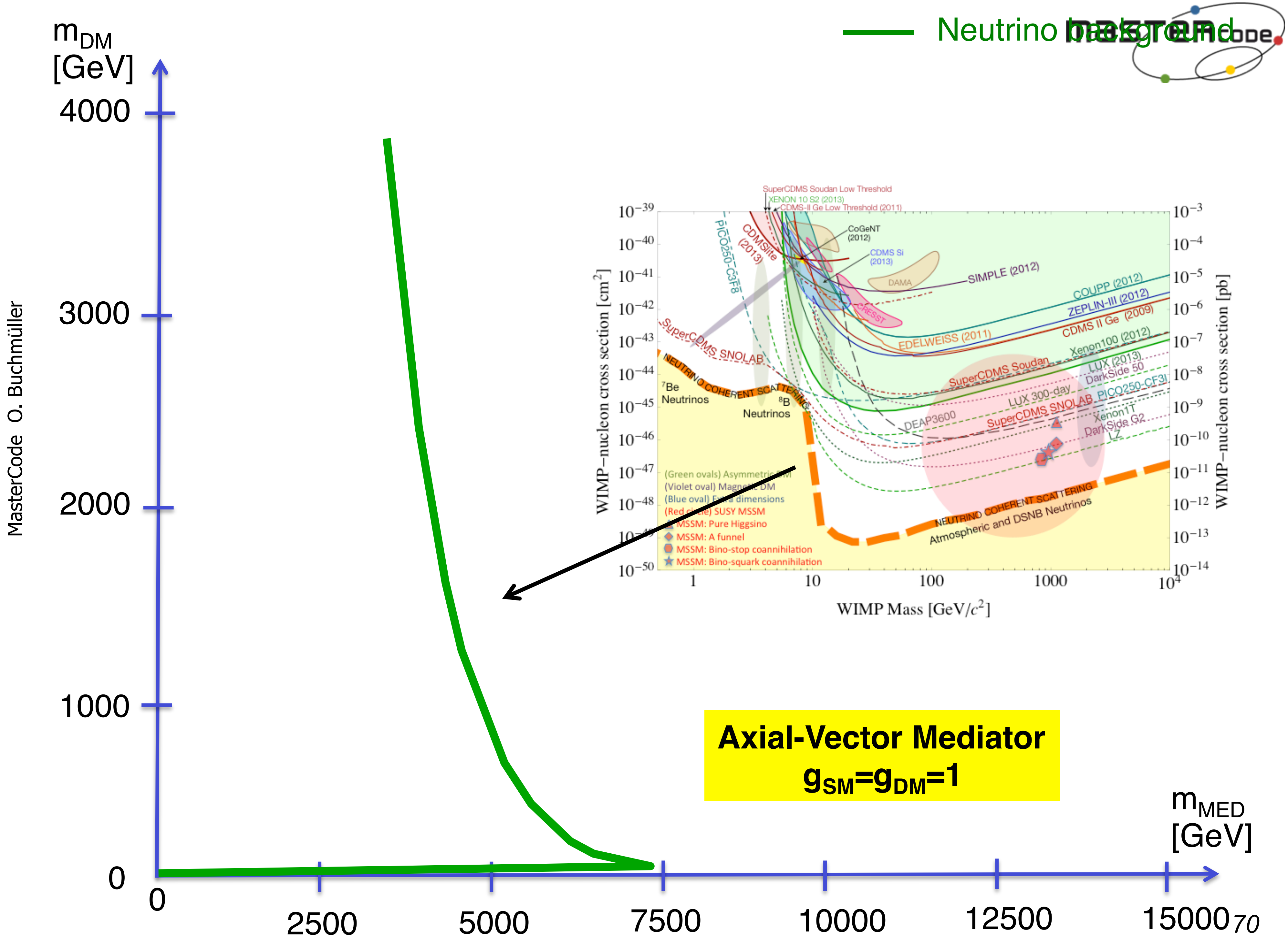


m_{DM} [GeV]
4000
3000
2000
1000
0
FCC 100 TeV 1ab^{-1}
taken from arXiV:1509.02904
ILC 1 TeV 500 fb^{-1}
taken from arXiv:1211.2254
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LHC 14 TeV 300 fb^{-1}
LHC 14 TeV 3000 fb^{-1}
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
Some day perhaps?
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000
MasterCode O. Buchmüller

Projections for future experiments

Example:
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$





Axial-Vector Mediator
g_{SM}=g_{DM}=1

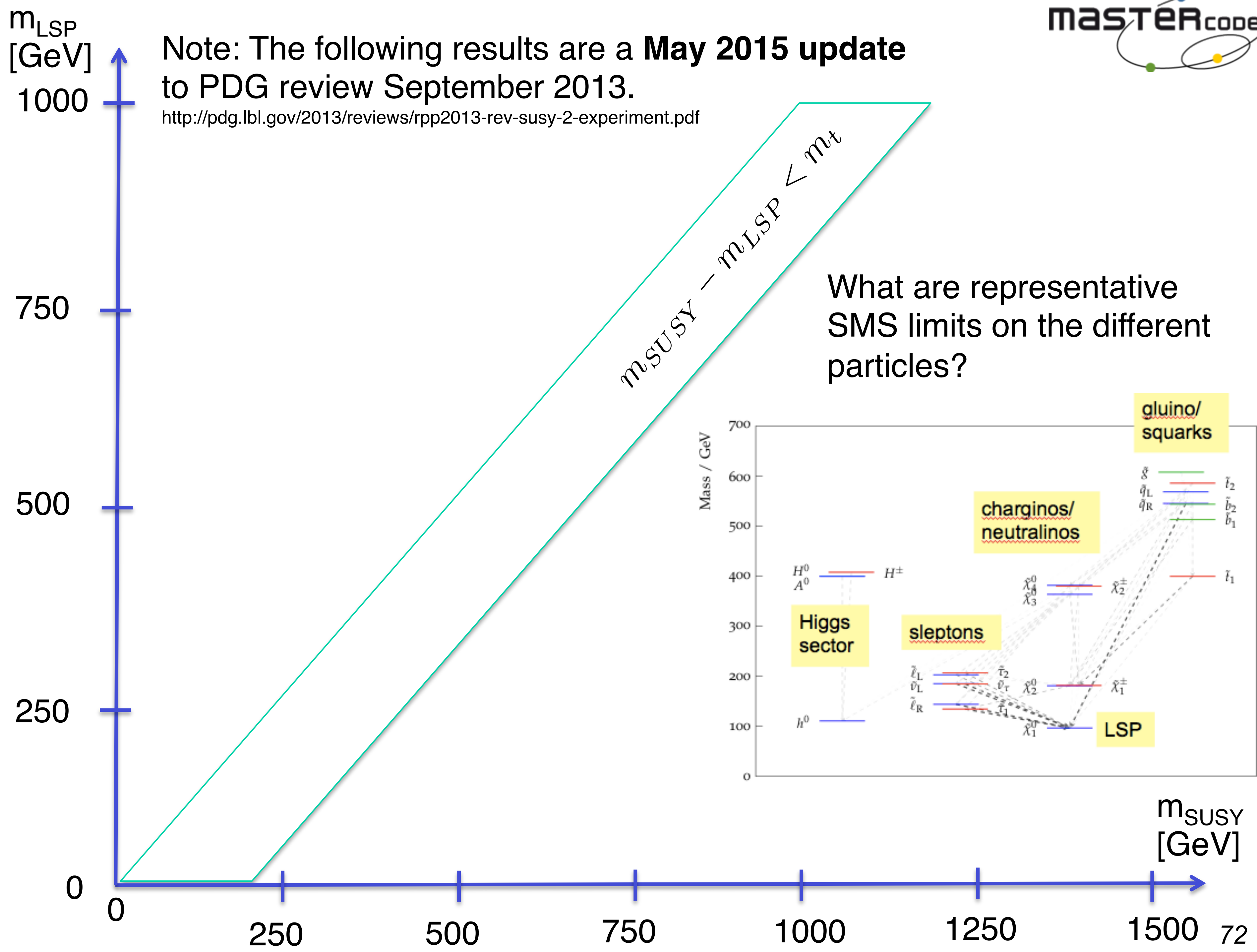
The full story

SUSY SUMMARY PLOT

Note: The following results are a **May 2015 update** to PDG review September 2013.

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

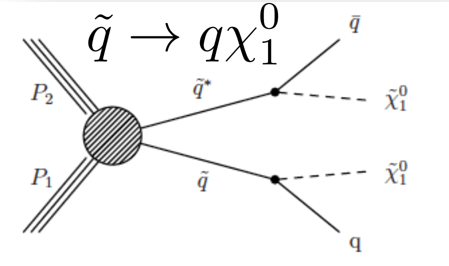
What are representative SMS limits on the different particles?

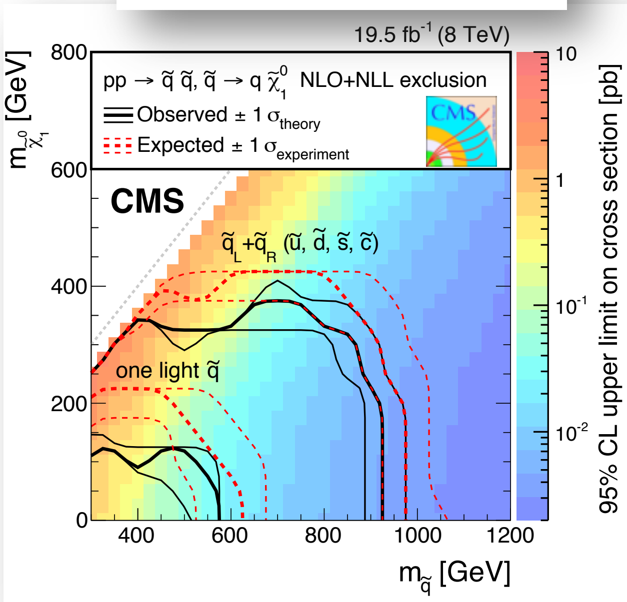


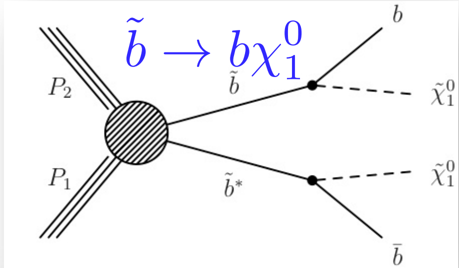
MasterCode O. Buchmüller

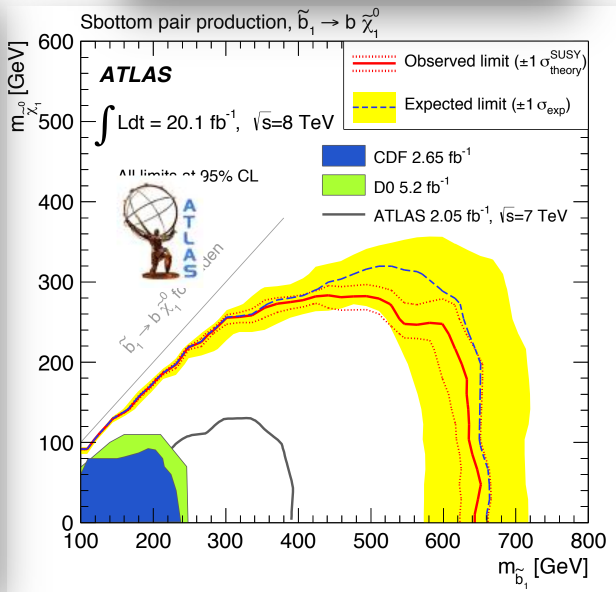
Direct squark production – chosen limits

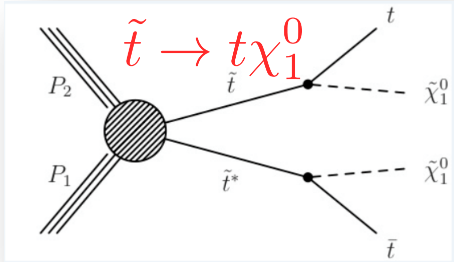
MasterCode O. Buchmüller

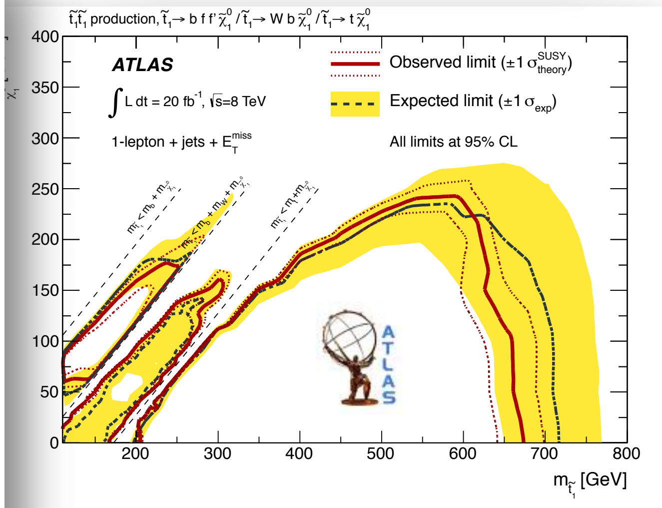








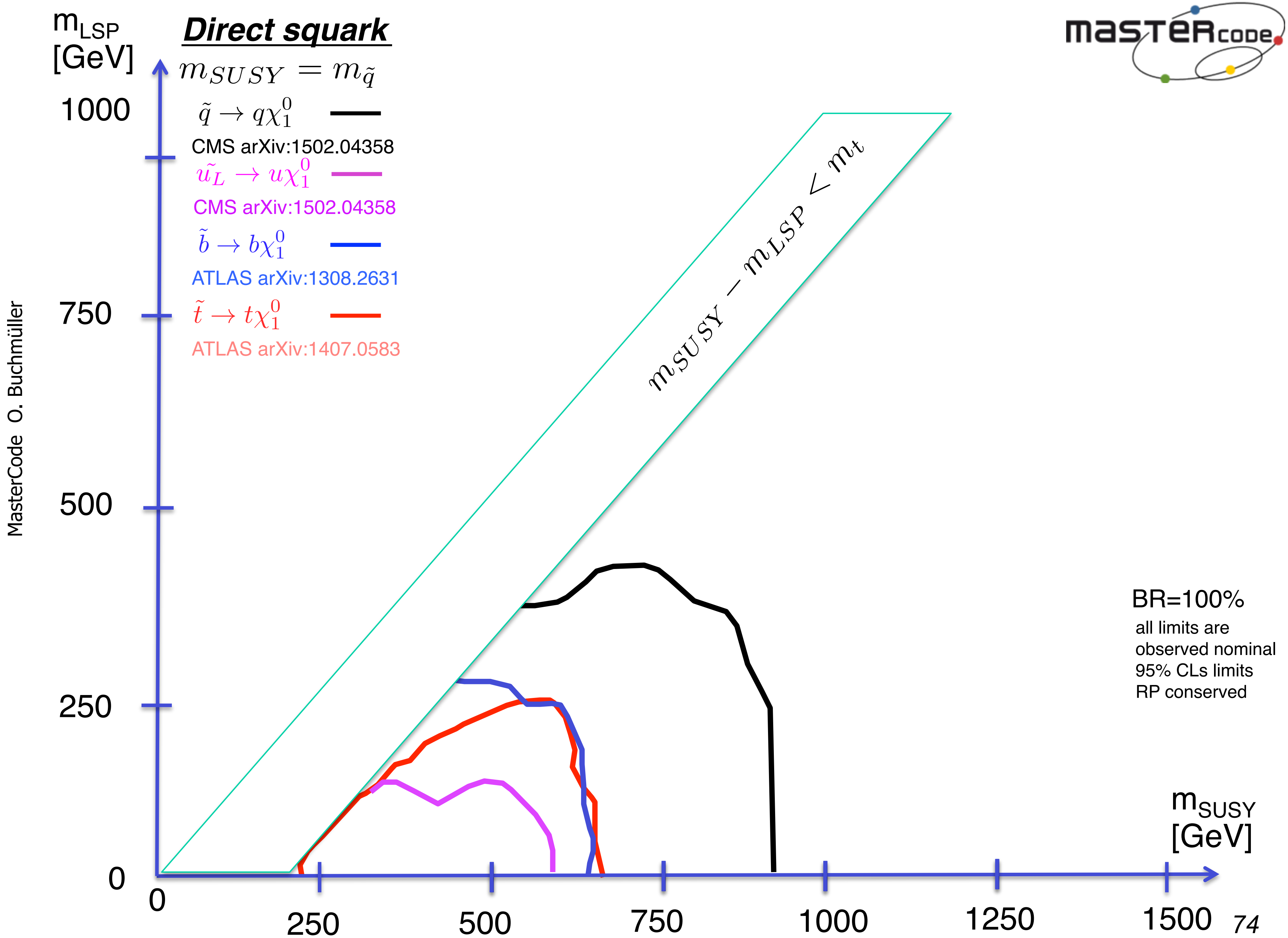




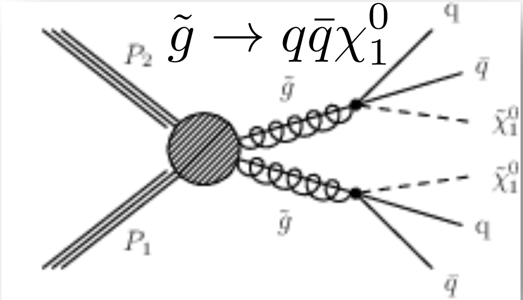
CMS arXiv:1502.04358
Signature: Jets + E_t^{miss} with M_{T2}
Limit assumes all 1st & 2nd gen squarks to be mass degenerate [or only one light squark]!

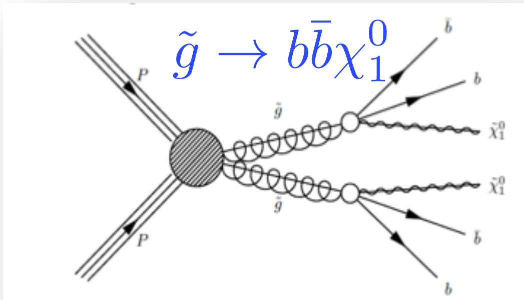
ATLAS arXiv:1308.2631
Signature: 2 b-jets + E_T^{mis}

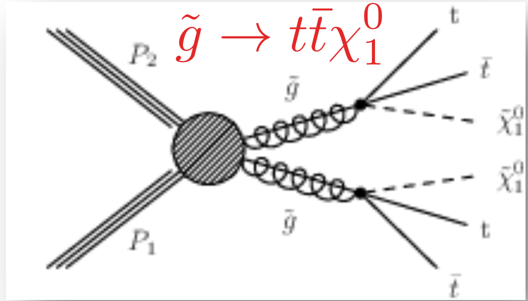
ATLAS arXiv:1407.0583
Signature: 1Lepton + jets + E_T^{mis}

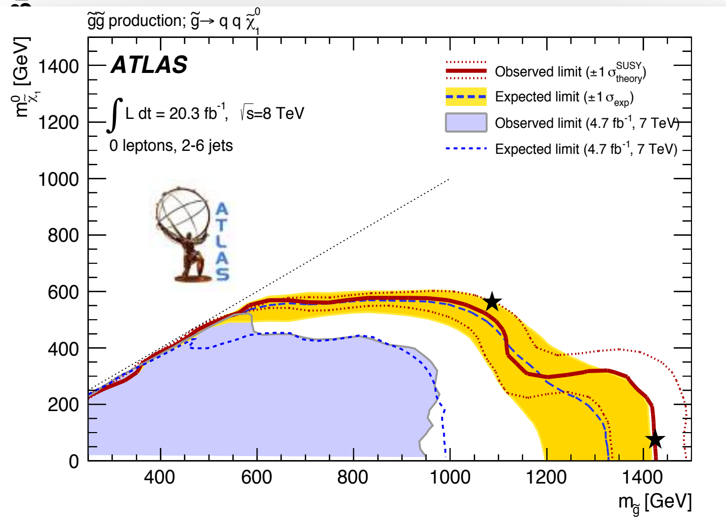

Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
m_{LSP} [GeV]
1000
750
500
250
0
$m_{SUSY} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
MasterCode O. Buchmüller

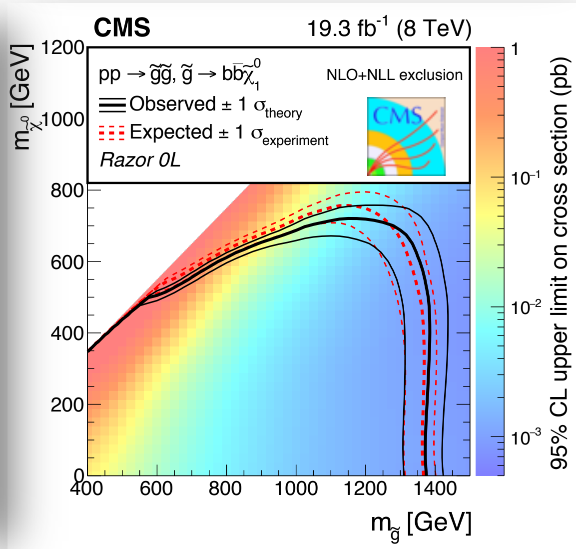
Gluino mediated squark production – limits chosen

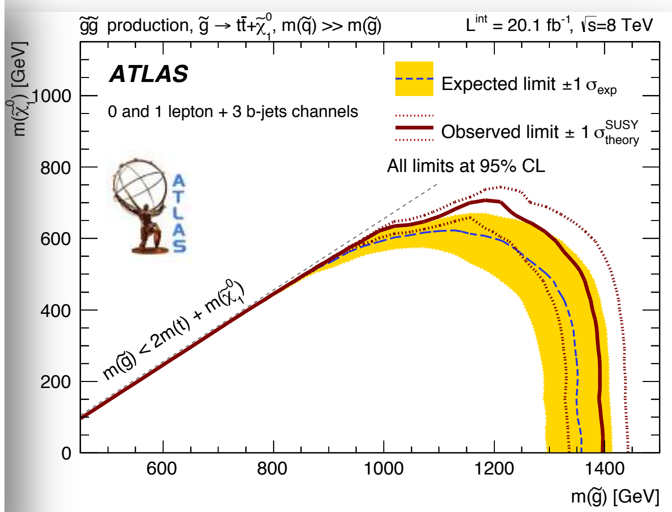








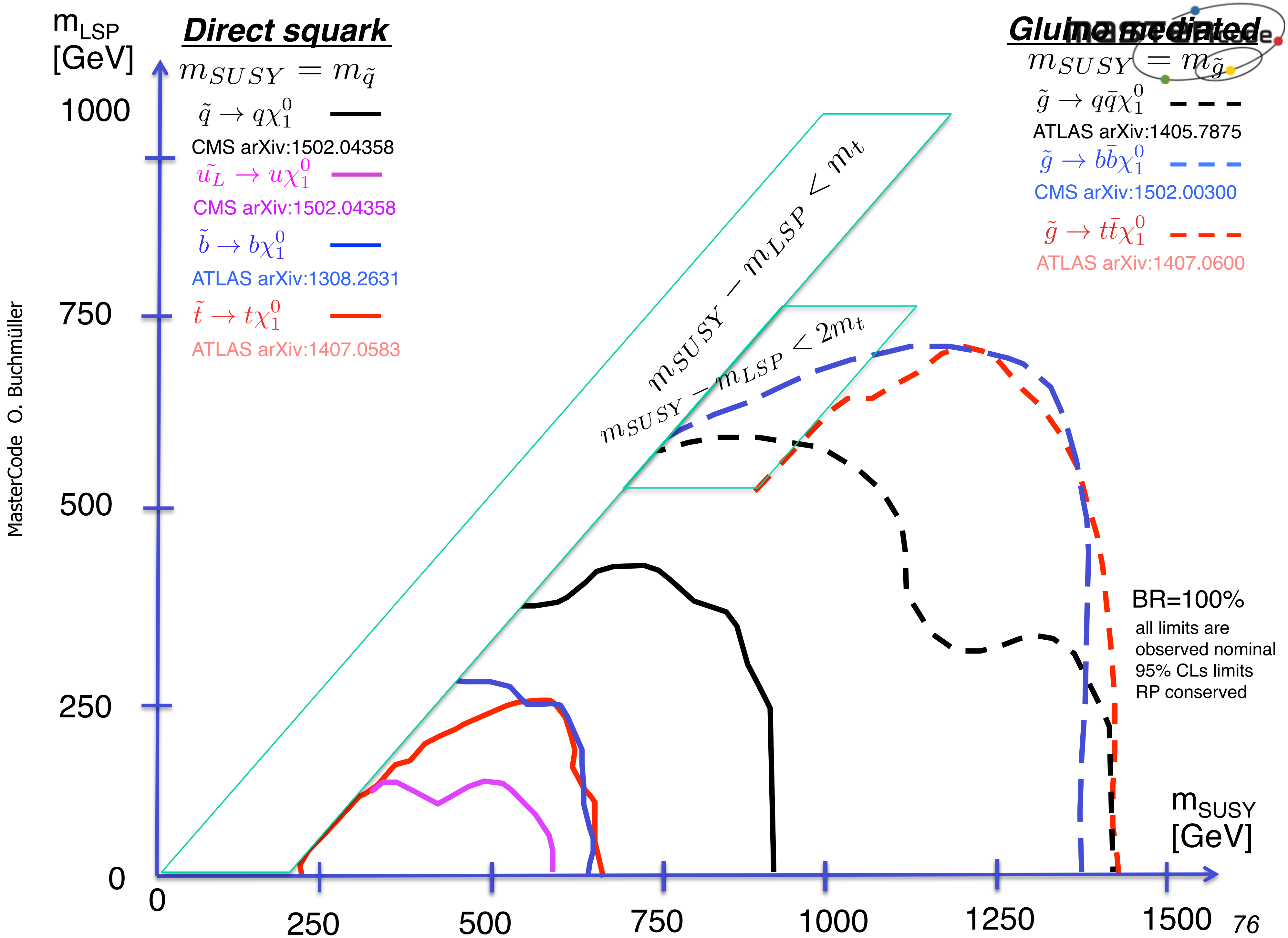




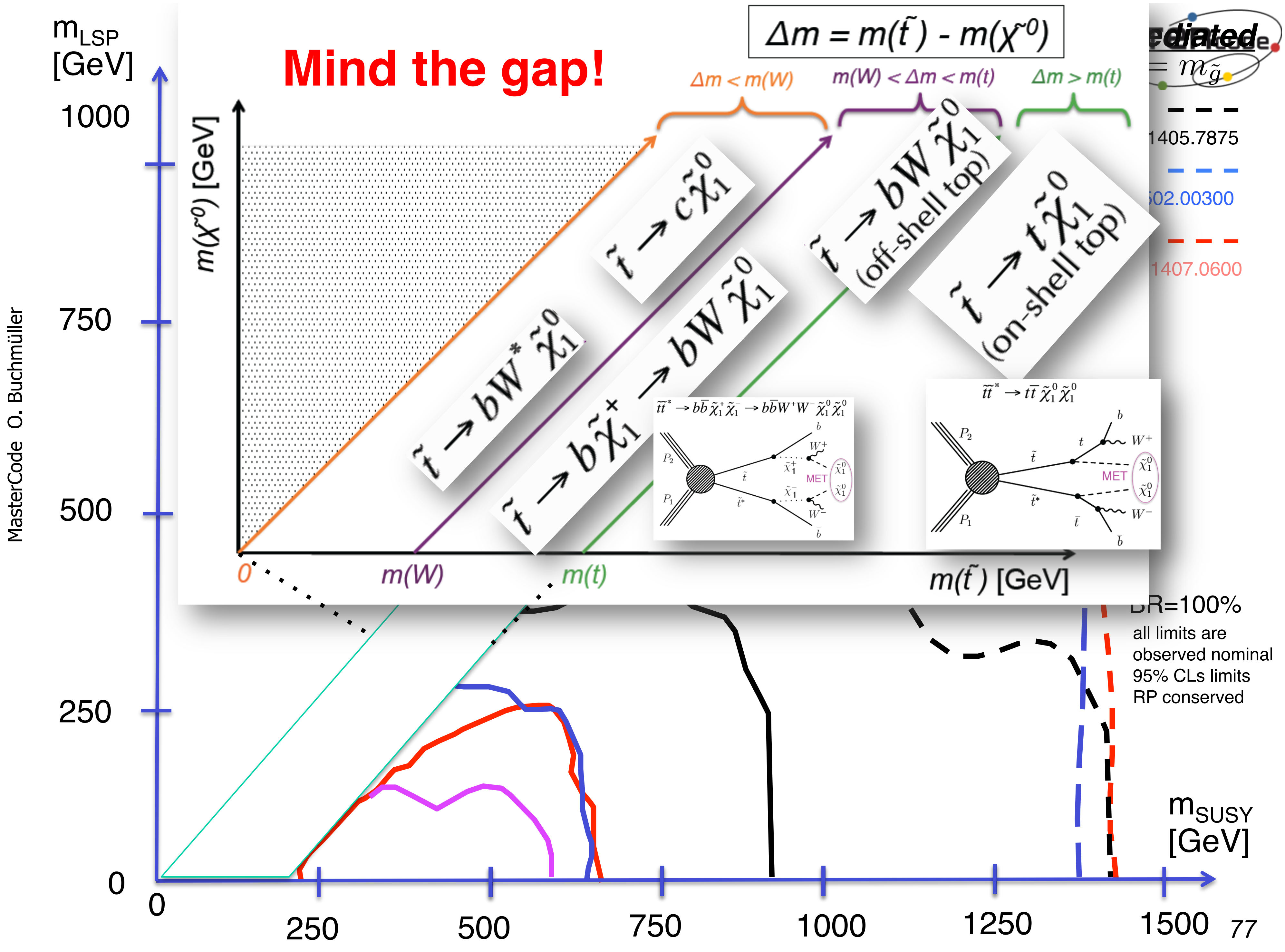
ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets + E_t^{miss}

CMS arXiv:1502.00300
Signature: : 0L + Razor + b-tag

Signature: 0/1 Leptons + 3 b-tag + E_t^{mis}

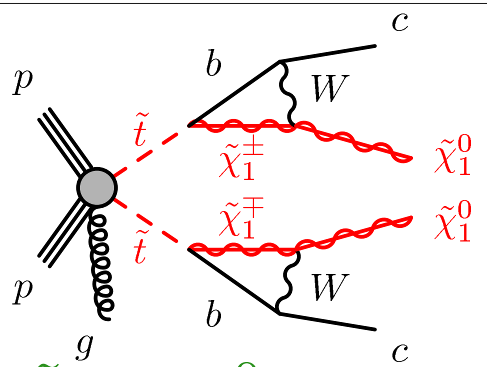


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
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
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
MasterCode O. Buchmüller
m_SUSY [GeV]
0
250
500
750
1000
1250
1500

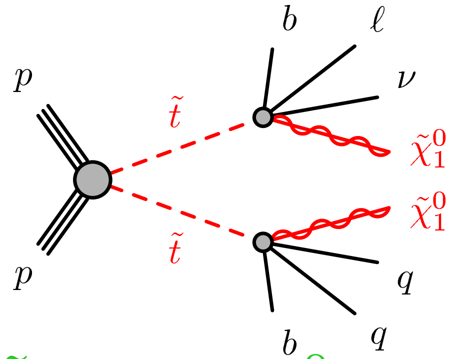


Mind the gap!
Δm = m(t̃) - m(χ̃⁰)
Δm < m(W)
m(W) < Δm < m(t)
Δm > m(t)
t̃ → c χ̃₁⁰
t̃ → bW* χ̃₁⁰
t̃ → bW χ̃₁⁰ (off-shell top)
t̃ → b χ̃₁⁺ → bW χ̃₁⁰
t̃ → t χ̃₁⁰ (on-shell top)
m(χ̃⁰) [GeV]
m(t̃) [GeV]
0
m(W)
m(t)
MET
m_LSP [GeV]
m_SUSY [GeV]
1405.7875
1407.0600
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
MasterCode O. Buchmüller
0
250
500
750
1000
1250
1500

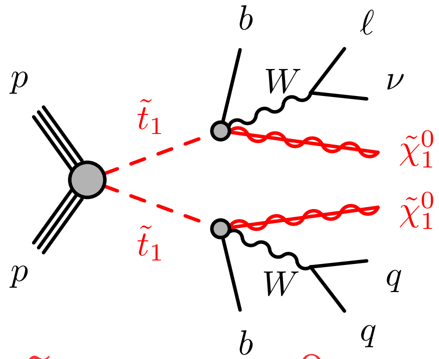
Compressed stop – mind the gap!



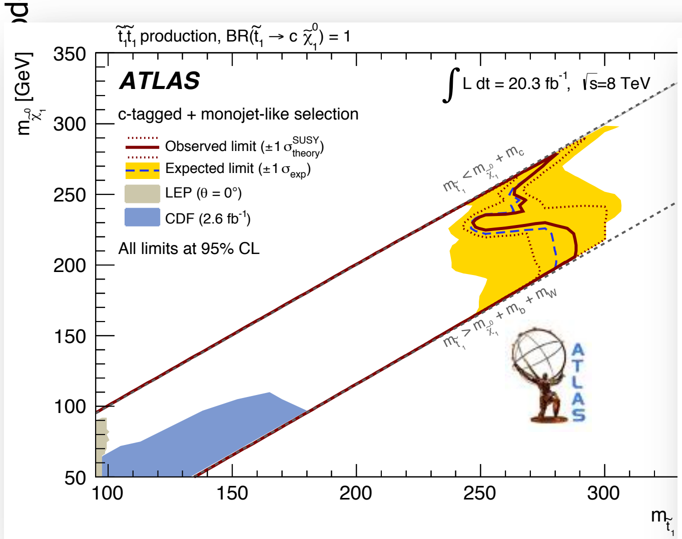
$\tilde{t} \to c\chi_1^0$

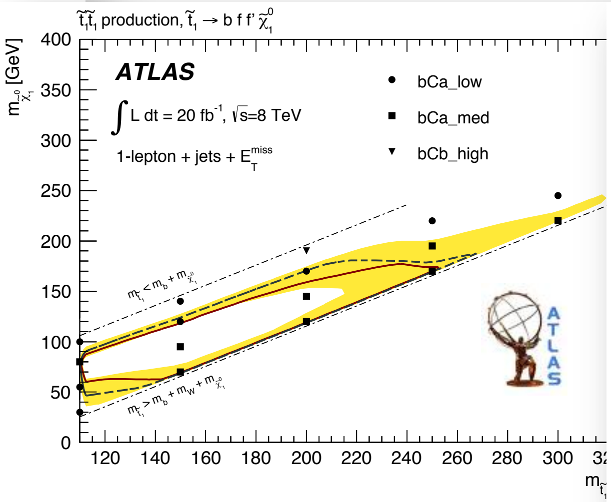


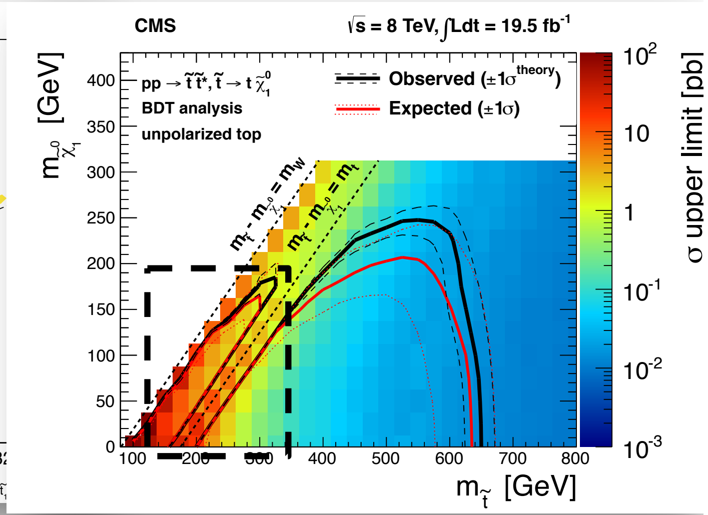
$\tilde{t} \to bff'\chi_1^0$



$\tilde{t} \to Wb\chi_1^0$



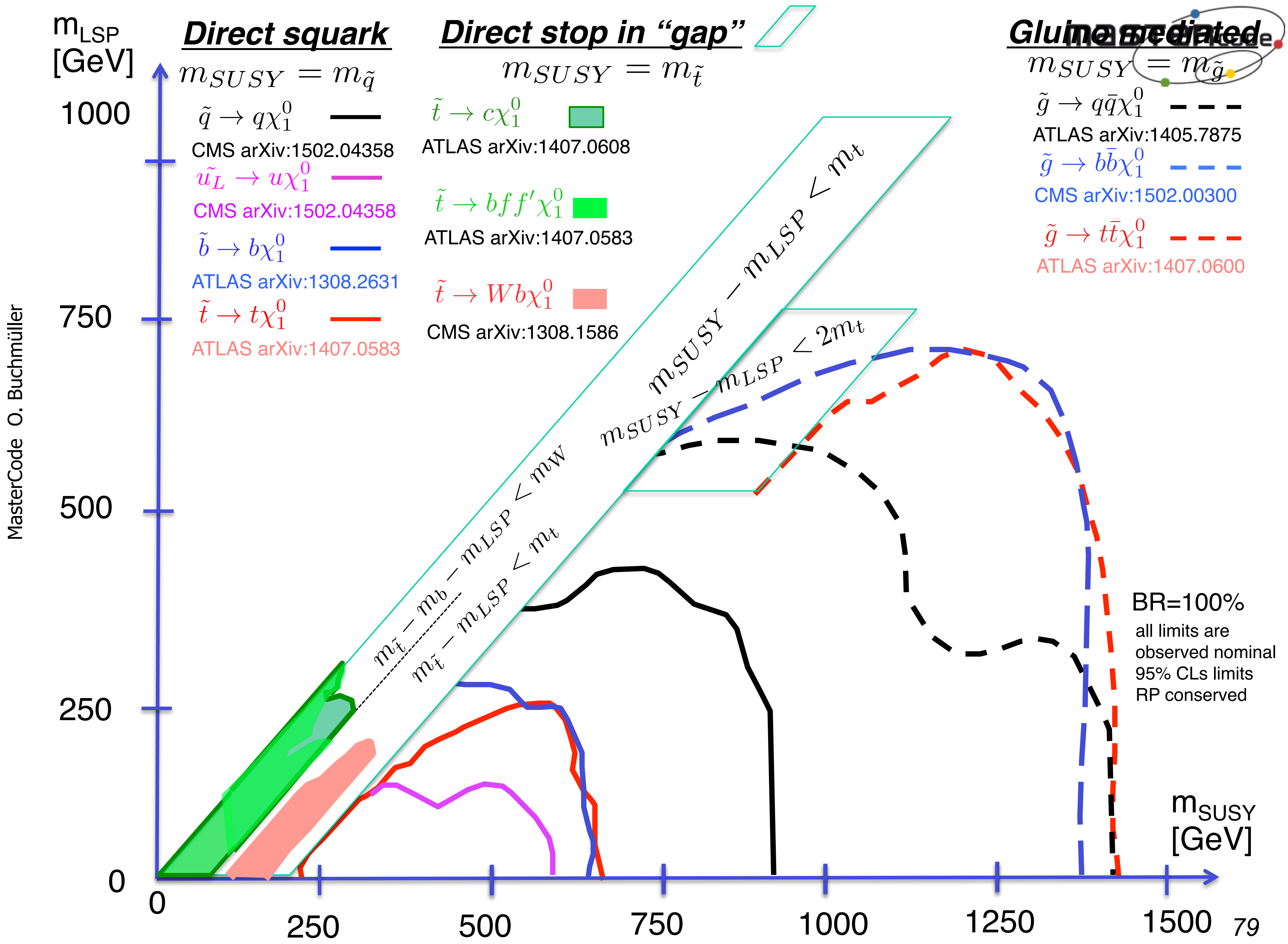




ATLAS arXiv:1407.0608
Mono-jet & c-tag combined

ATLAS: arXiv:1407.0583
1L + E_t^{mis} & b-tag

CMS arXiv:1308.1586
1L + E_t^{mis} and BDT & b-tag



m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
MasterCode O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
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

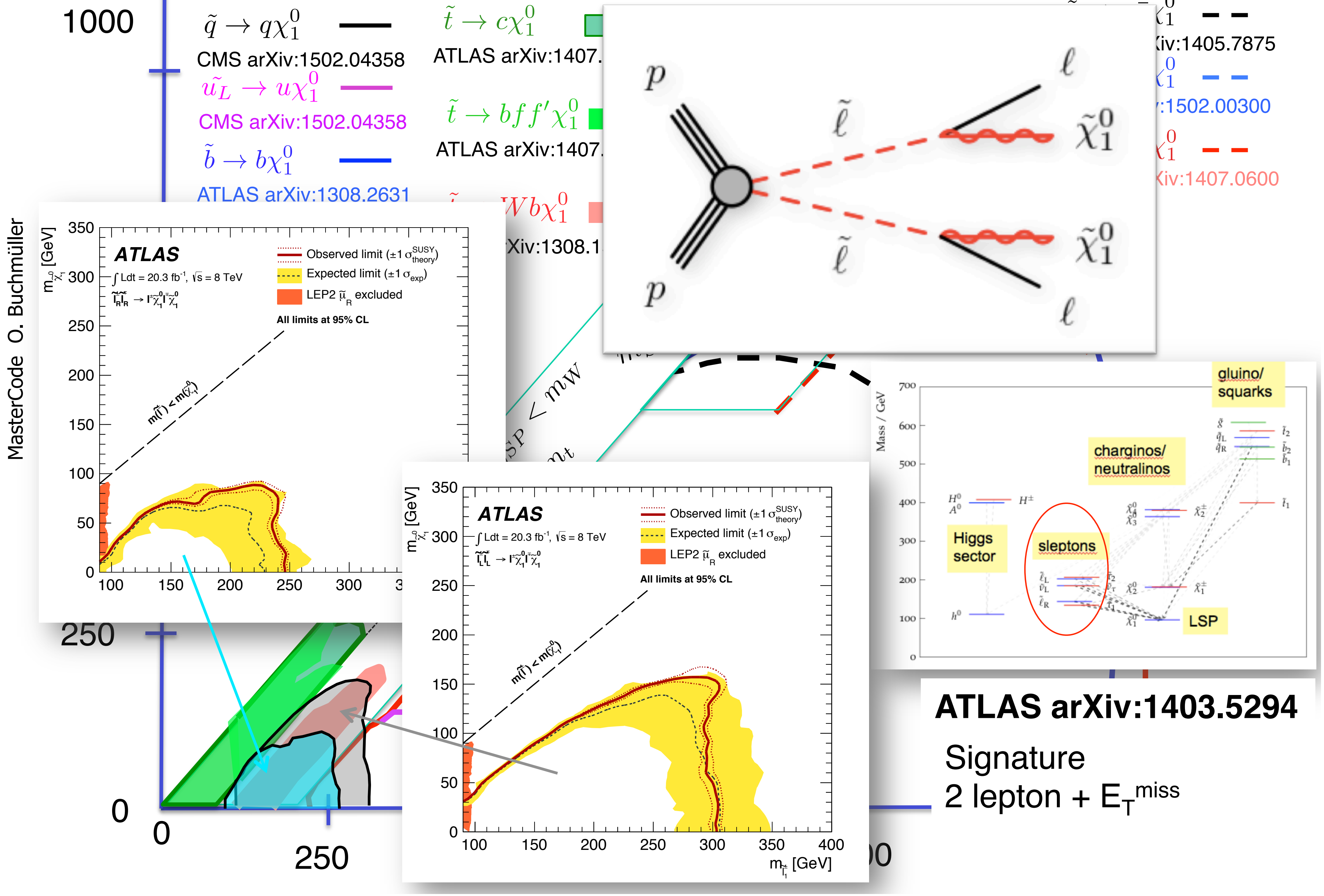
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631

Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$

$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.

$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.

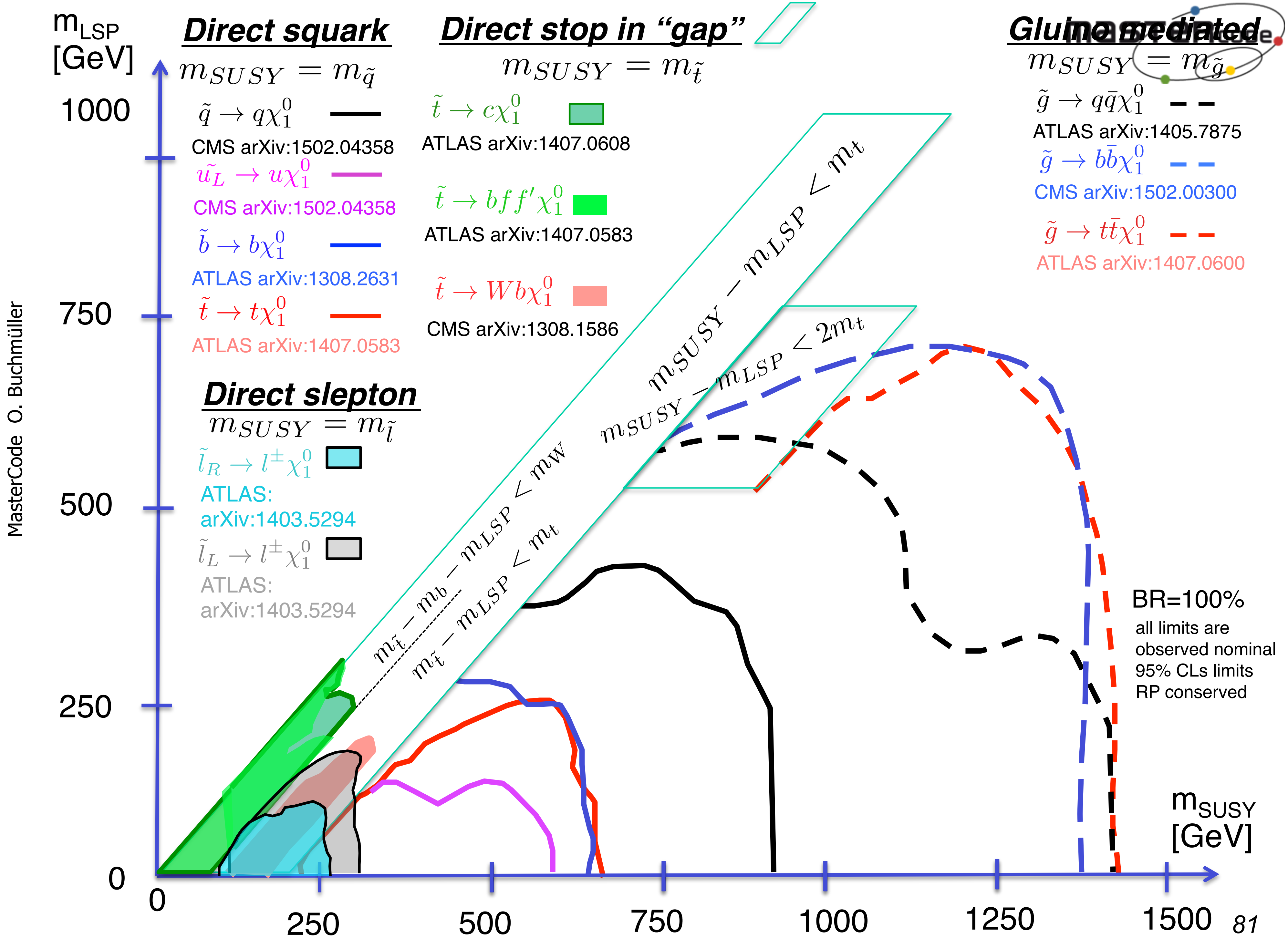
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$



ATLAS arXiv:1403.5294

Signature

2 lepton + E_T^{miss}

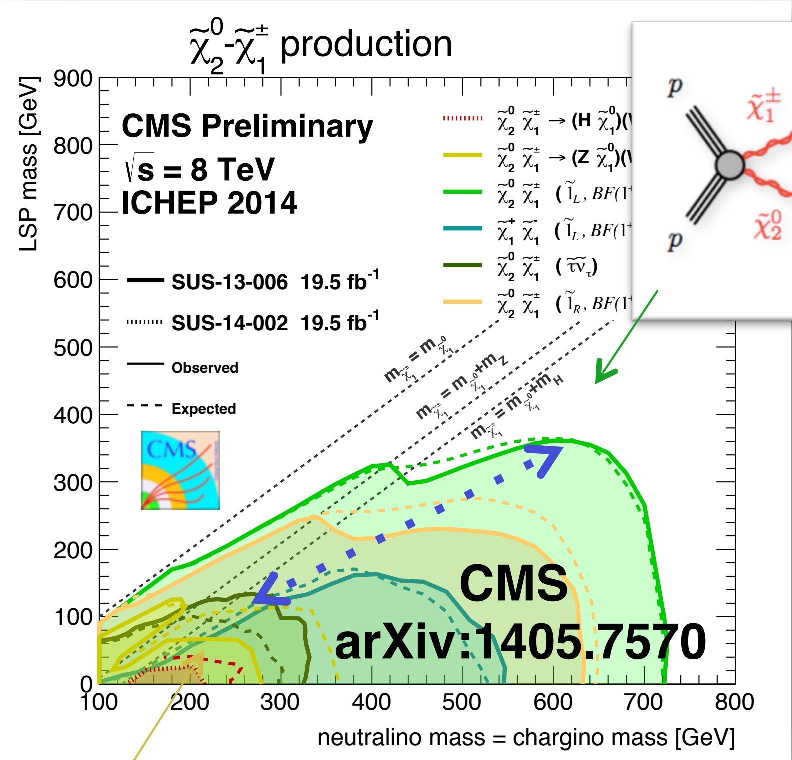


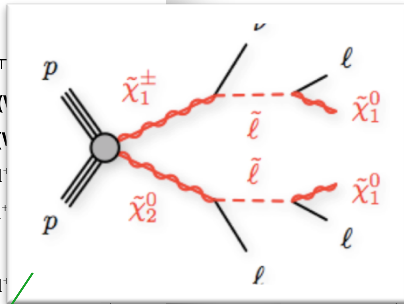
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
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 slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
MasterCode O. Buchmüller

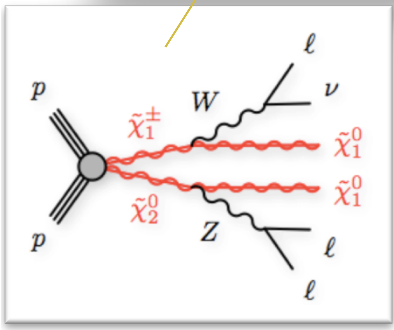
Direct chargino/neutralino production

MasterCode O. Buchmüller

$\chi_2^0\,\chi_1^{+-}$ production

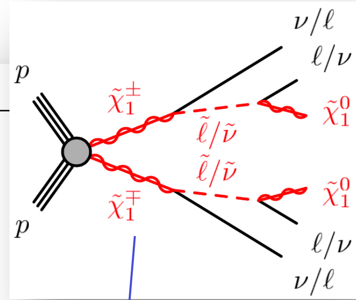


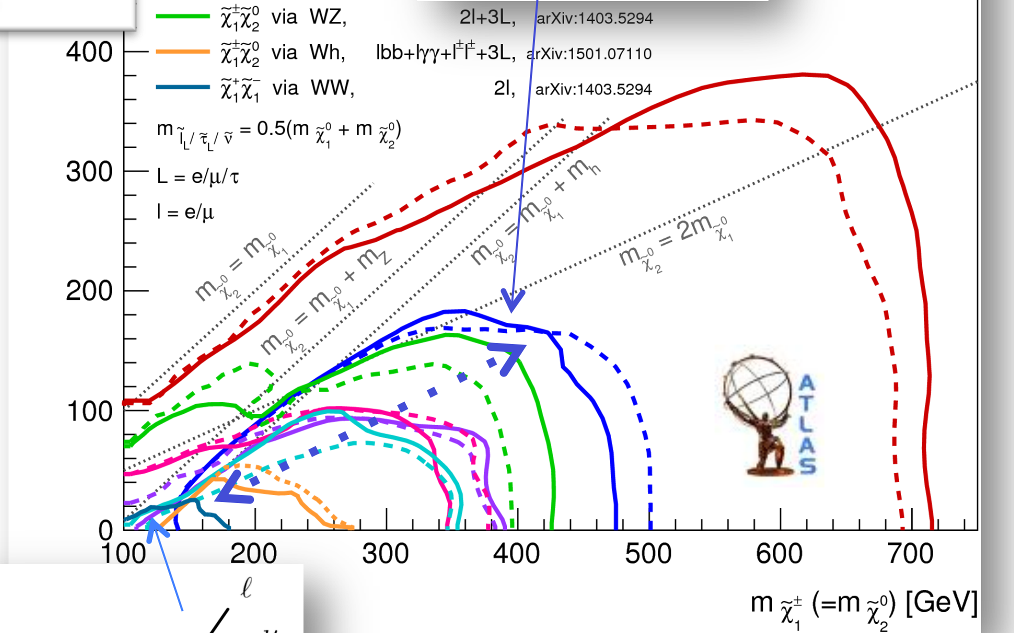




$\chi_1^+\,\chi_1^-$ production

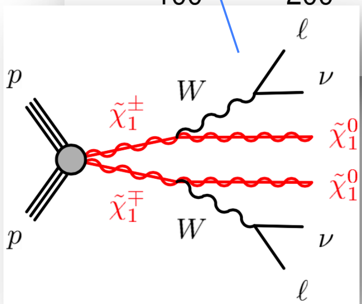
light slepton "easy"



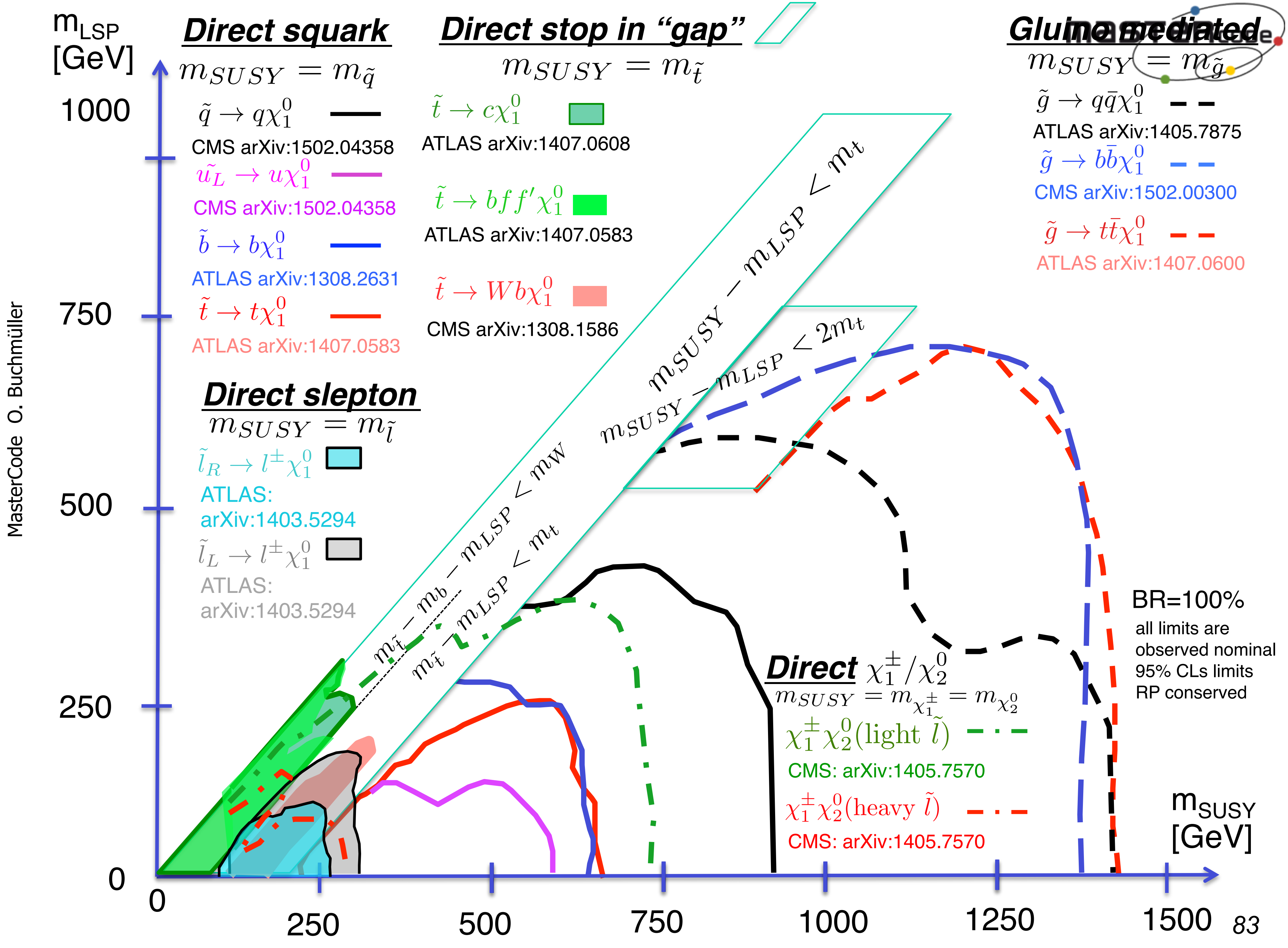


heavy slepton "hard(er)"

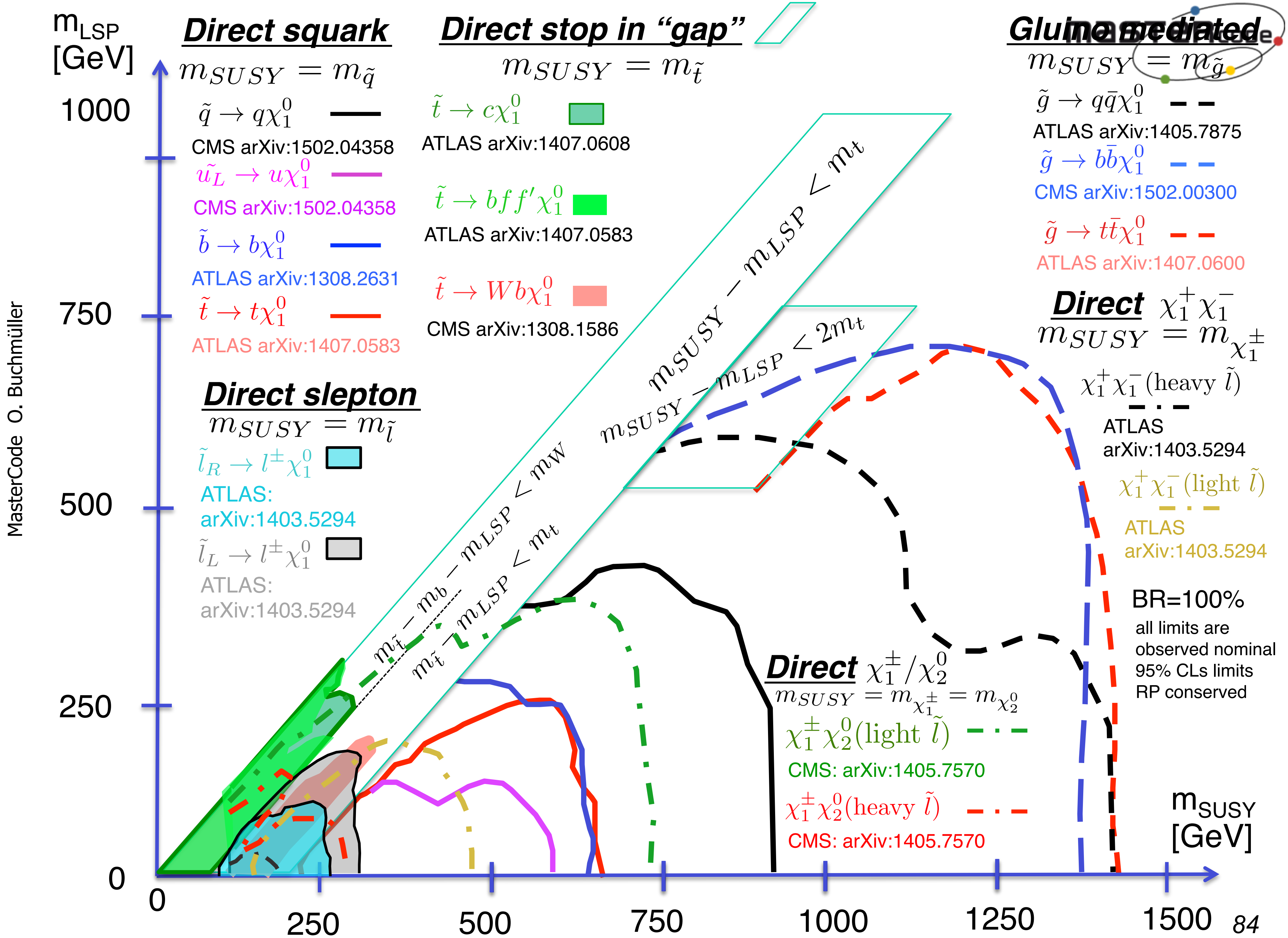
Add Z(l$^+$l$^-$)+2jets topology in bins of E_t^{miss} to increase sensitivity for "heavy" slepton case



ATLAS arXiv:1403.5294



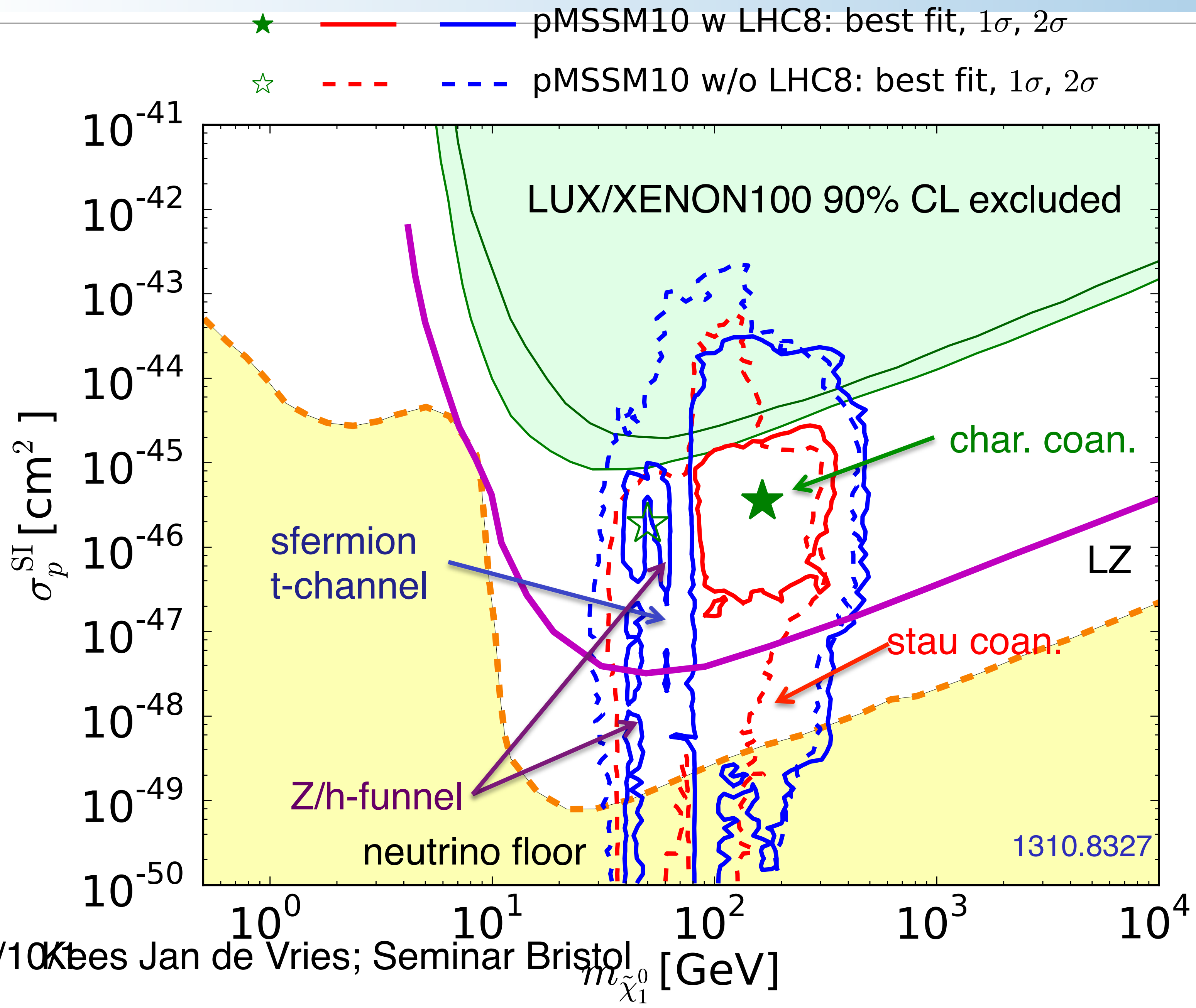
m_{LSP} [GeV]
1000
750
500
250
0
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
MasterCode O. Buchmüller
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
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
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
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 slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570
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 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
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
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
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
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 $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^\pm}$
$\chi_1^+\chi_1^-$(heavy $\tilde{l}$)
ATLAS arXiv:1403.5294
$\chi_1^+\chi_1^-$(light $\tilde{l}$)
ATLAS arXiv:1403.5294
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
Direct $\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
$\chi_1^\pm\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^\pm\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
MasterCode O. Buchmüller
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500

MASTERCODE

pMSSM10: direct DM detection



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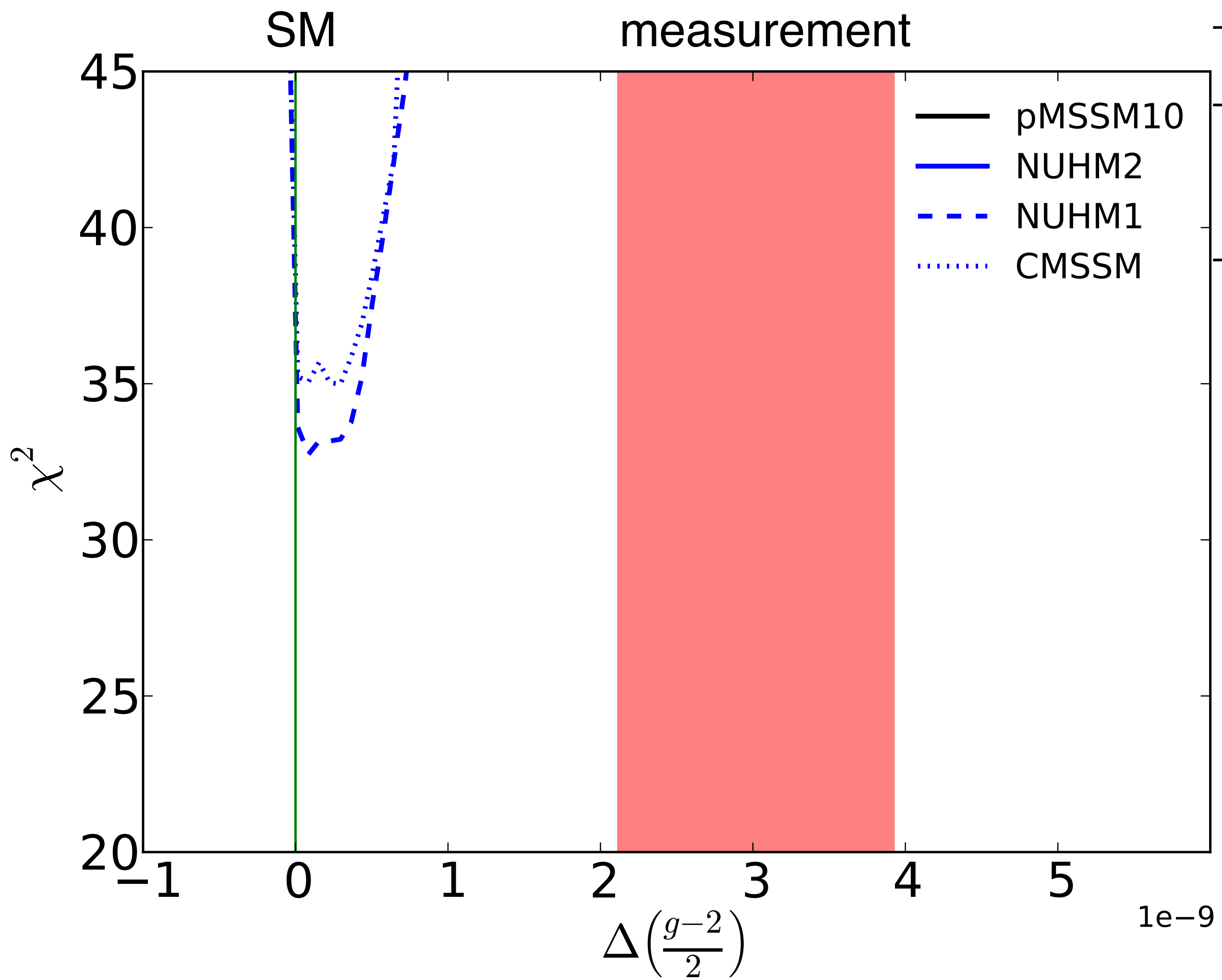
Resolving tension (g-2) and LHC

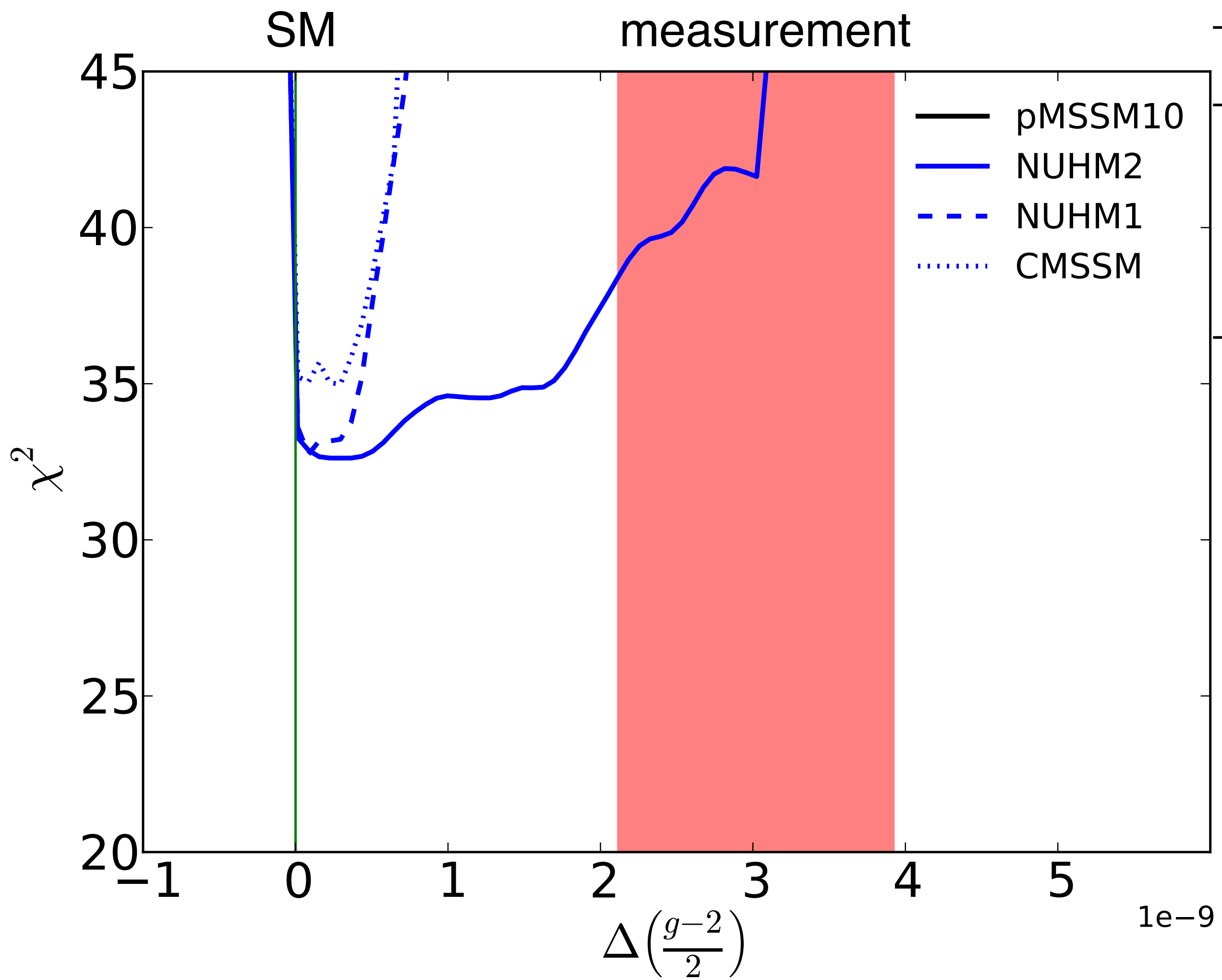


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

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

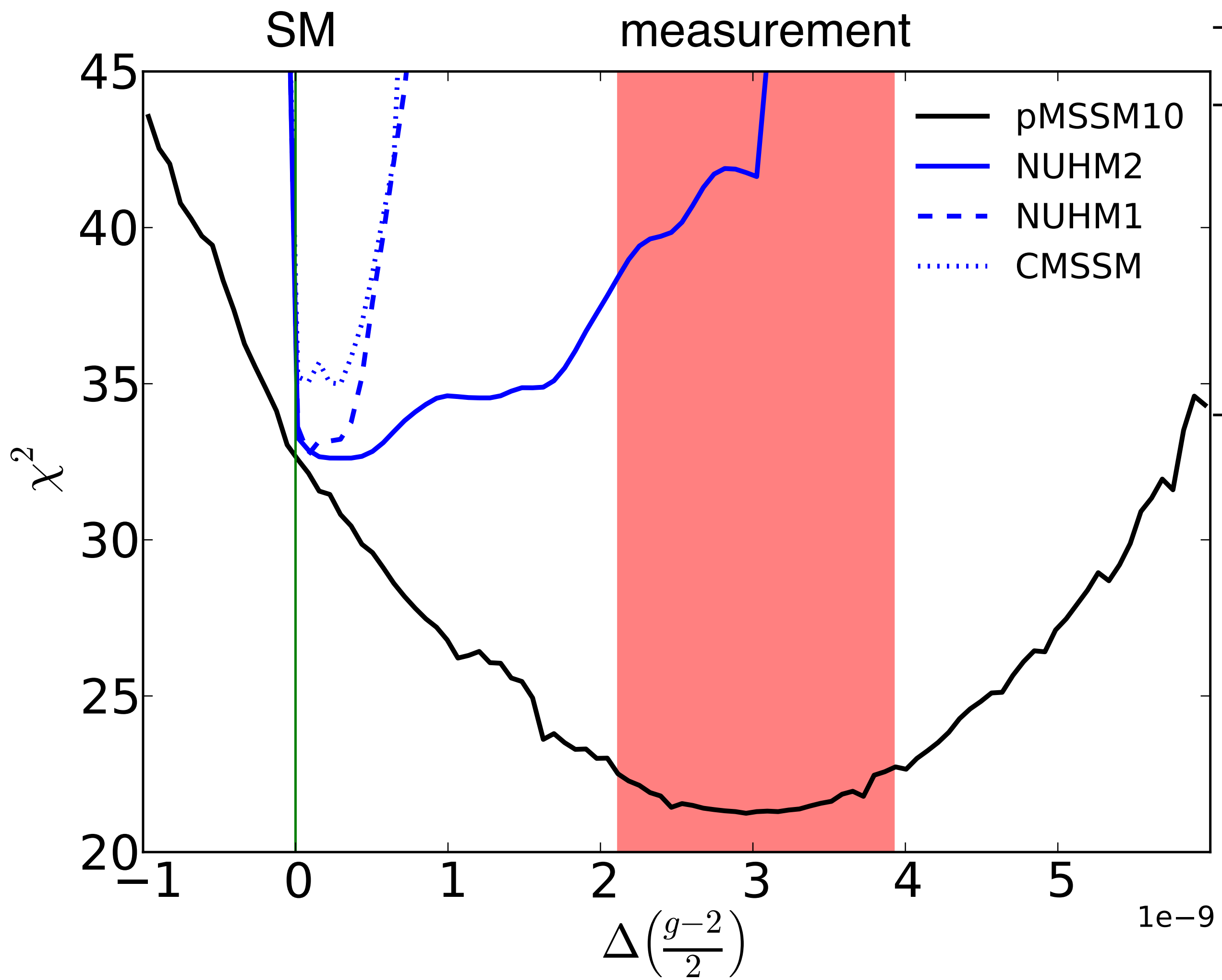


	χ^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

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

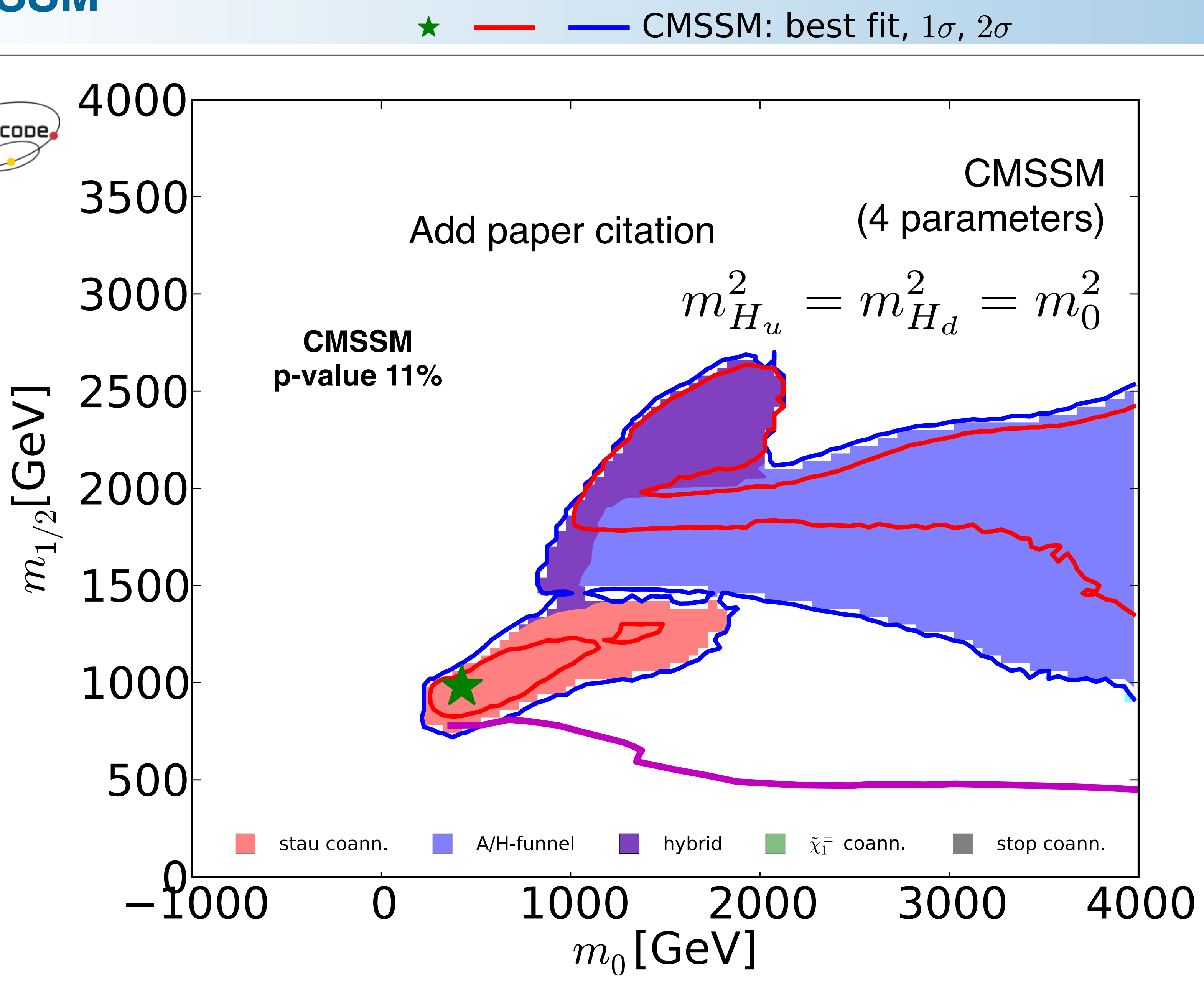


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	**20.5/18**	**31 %**

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

CMSSM



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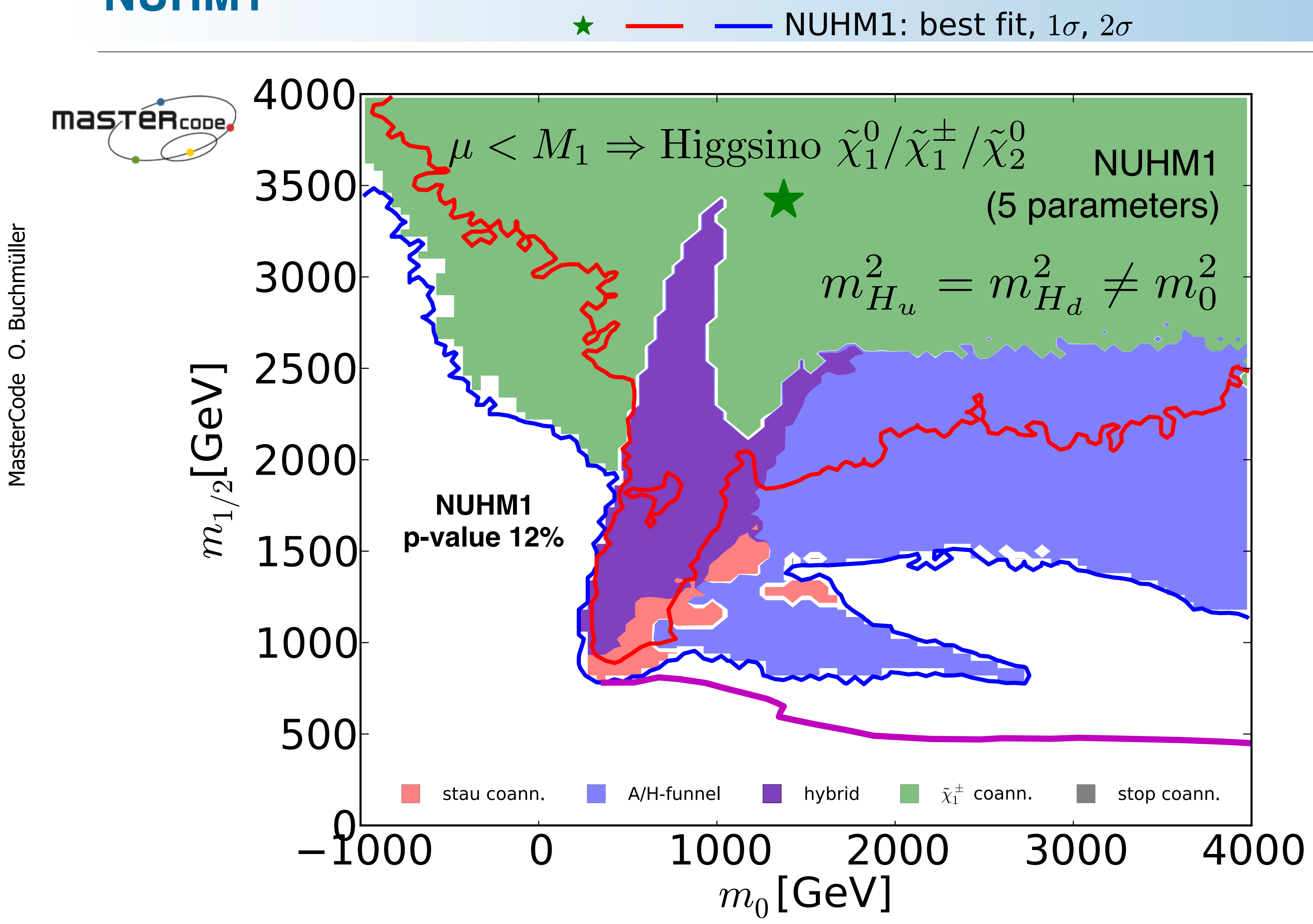
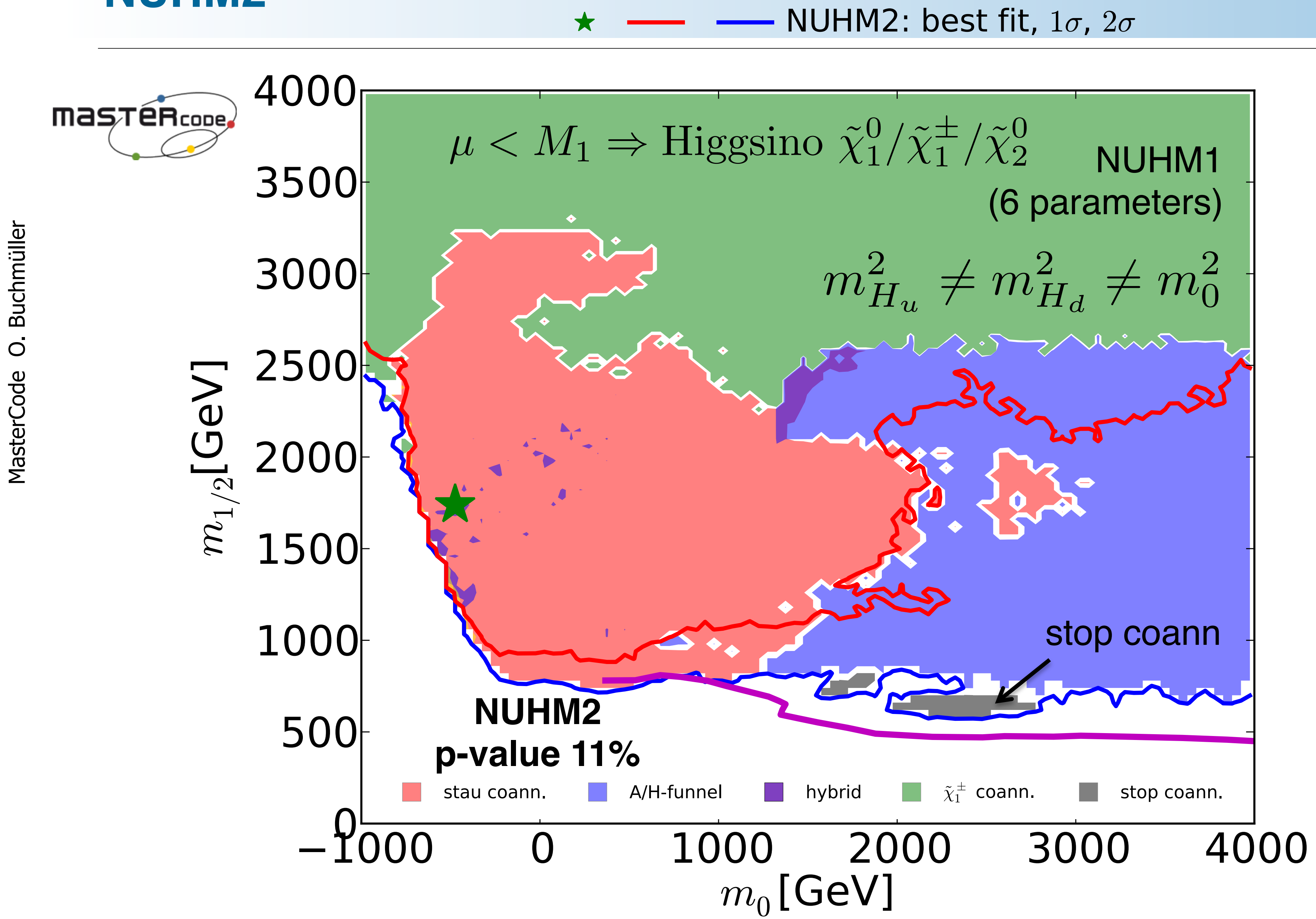
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

NUHM1



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

NUHM2



From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

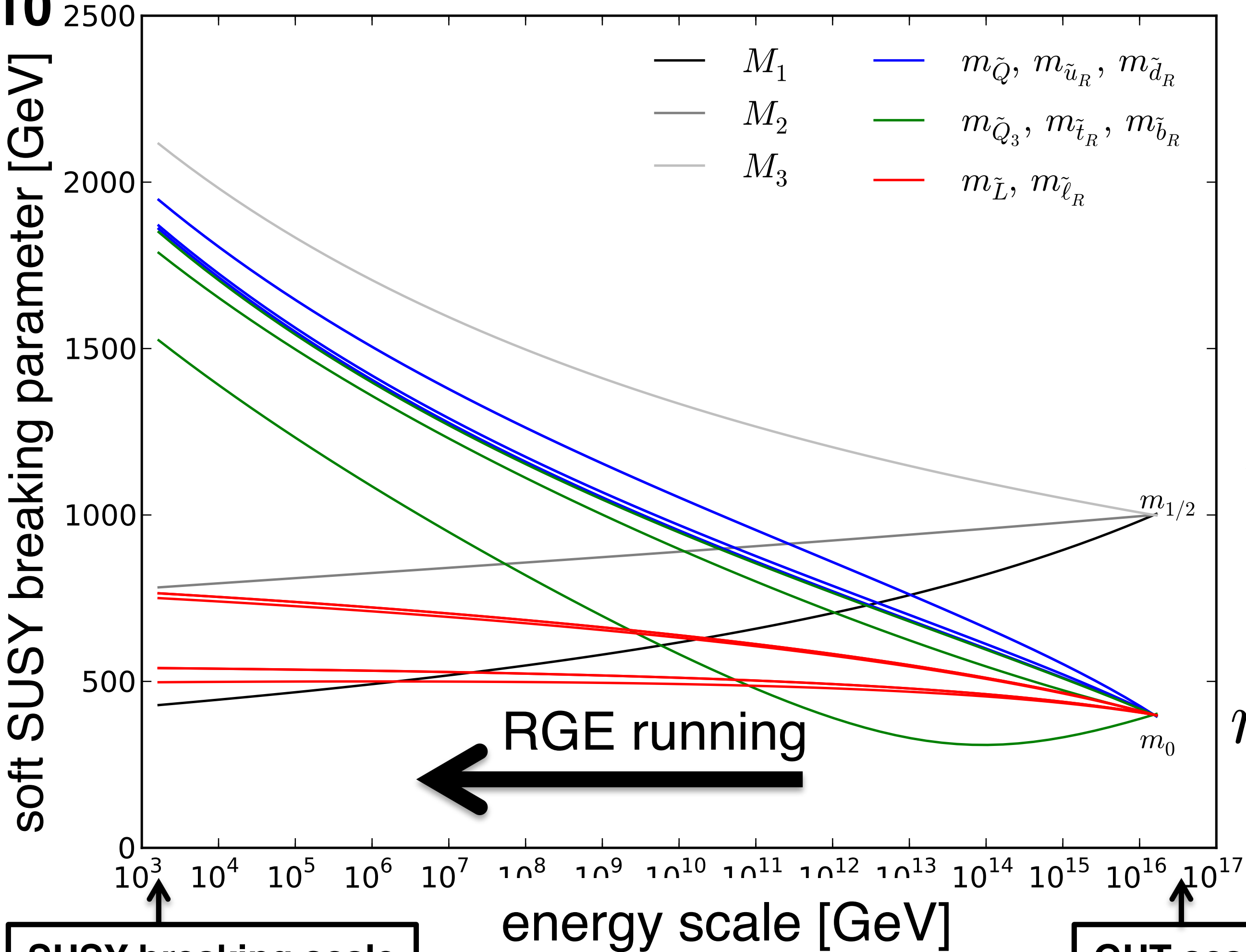
MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

MasterCode O. Buchmüller

pMSSM10

$M_1,$ $M_2,$ $M_3,$ $m_{\tilde{q}_{12}},$ $m_{\tilde{q}_3},$ $m_{\tilde{\ell}},$ $A,$ $M_A,$ $\tan\beta$ μ



SUSY breaking scale

GUT scale

CMSSM

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

$A_0,\ \tan\beta$

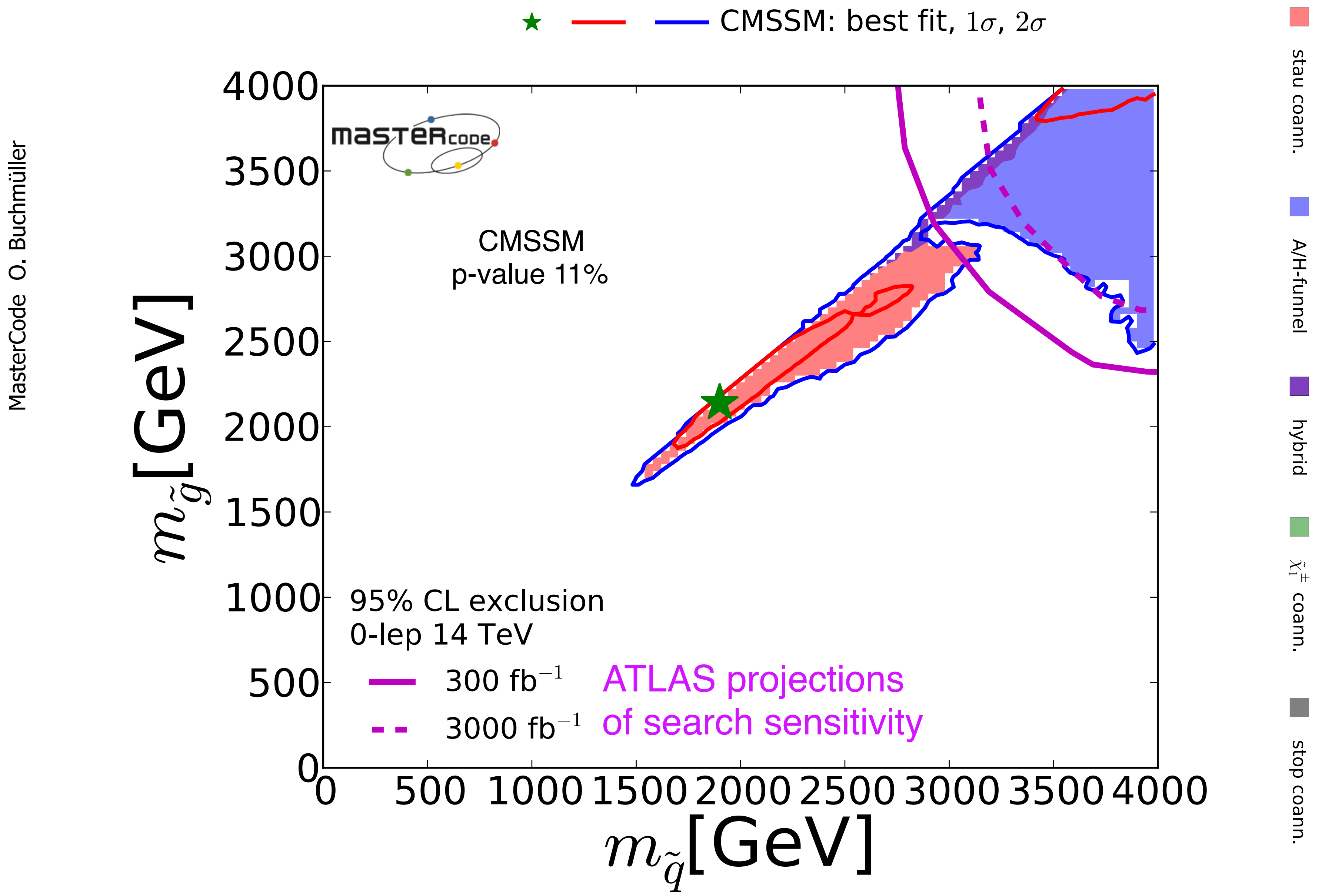
NUHM1

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

NUHM2

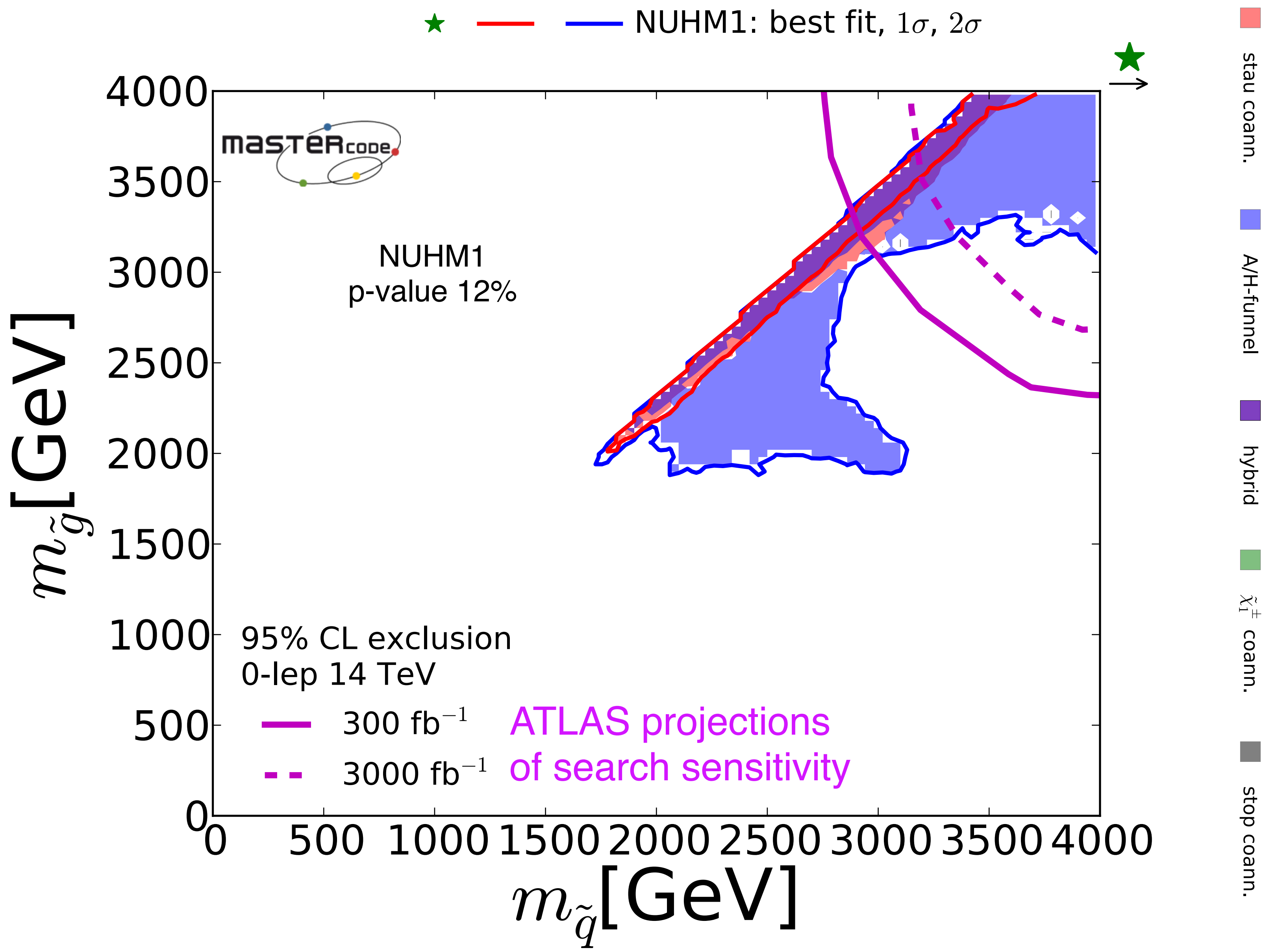
$$m^2_{H_u} \neq m^2_{H_d}$$

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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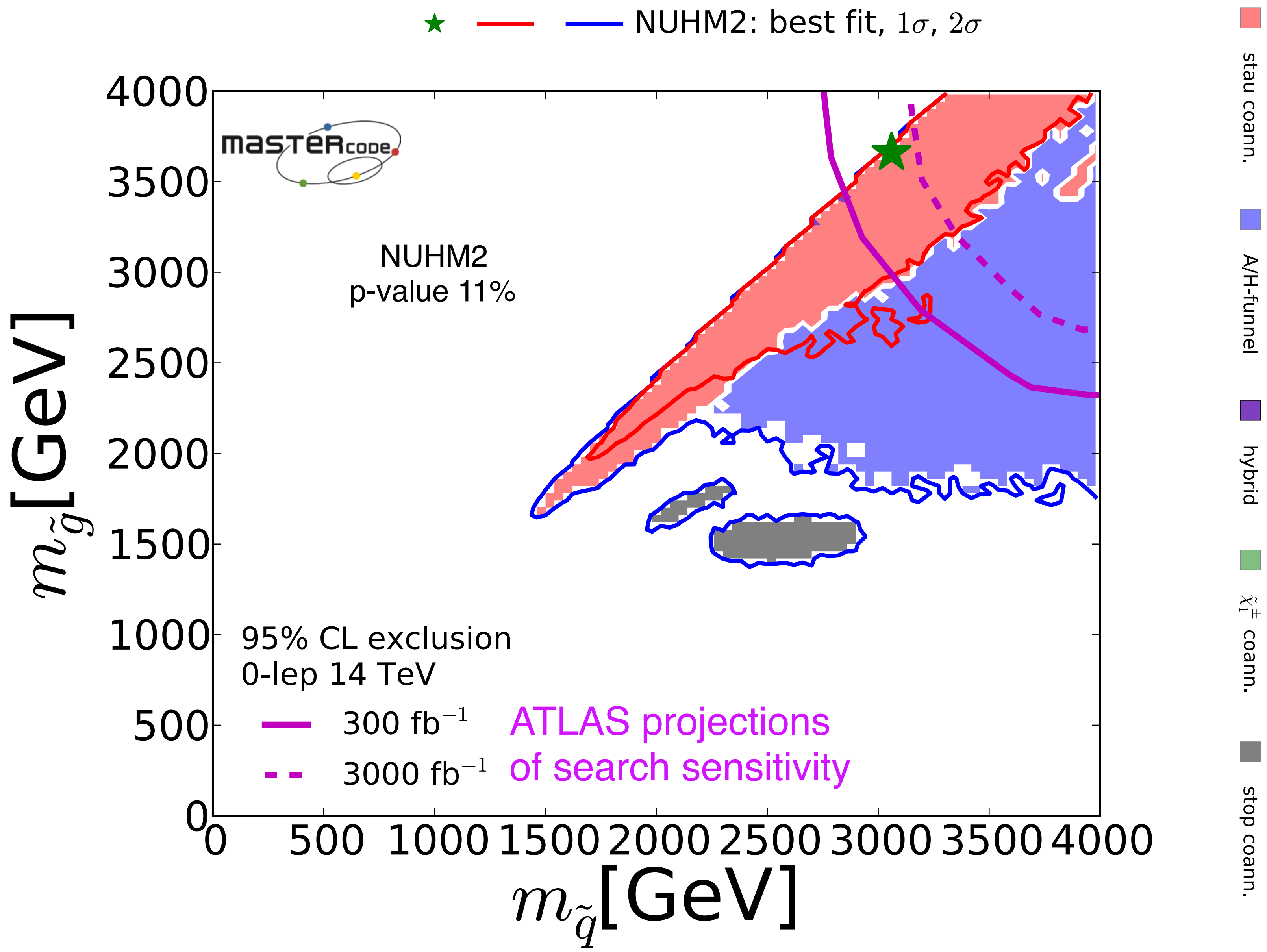
CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

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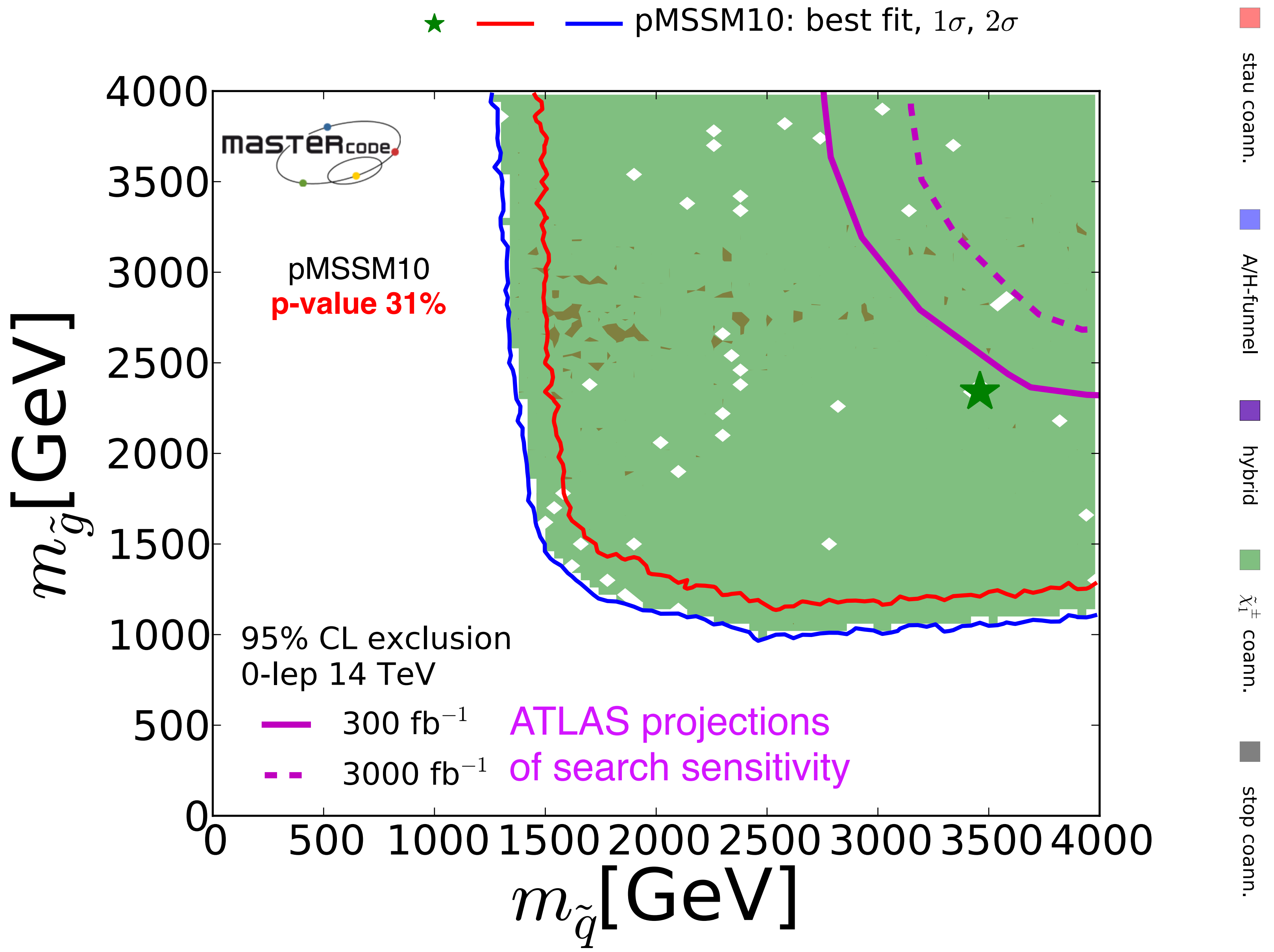
CMSSM Today: Mq-Mg Search plane



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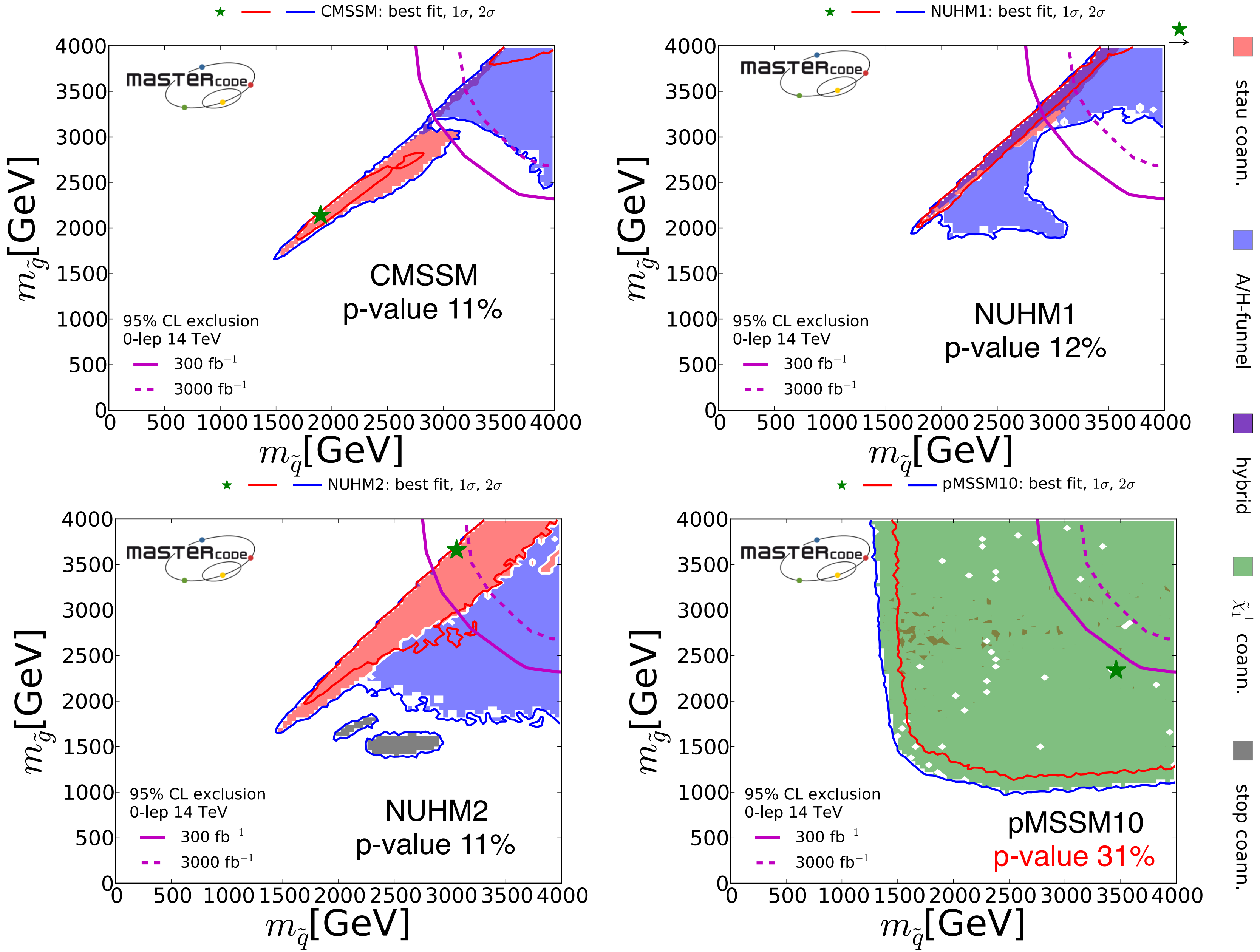
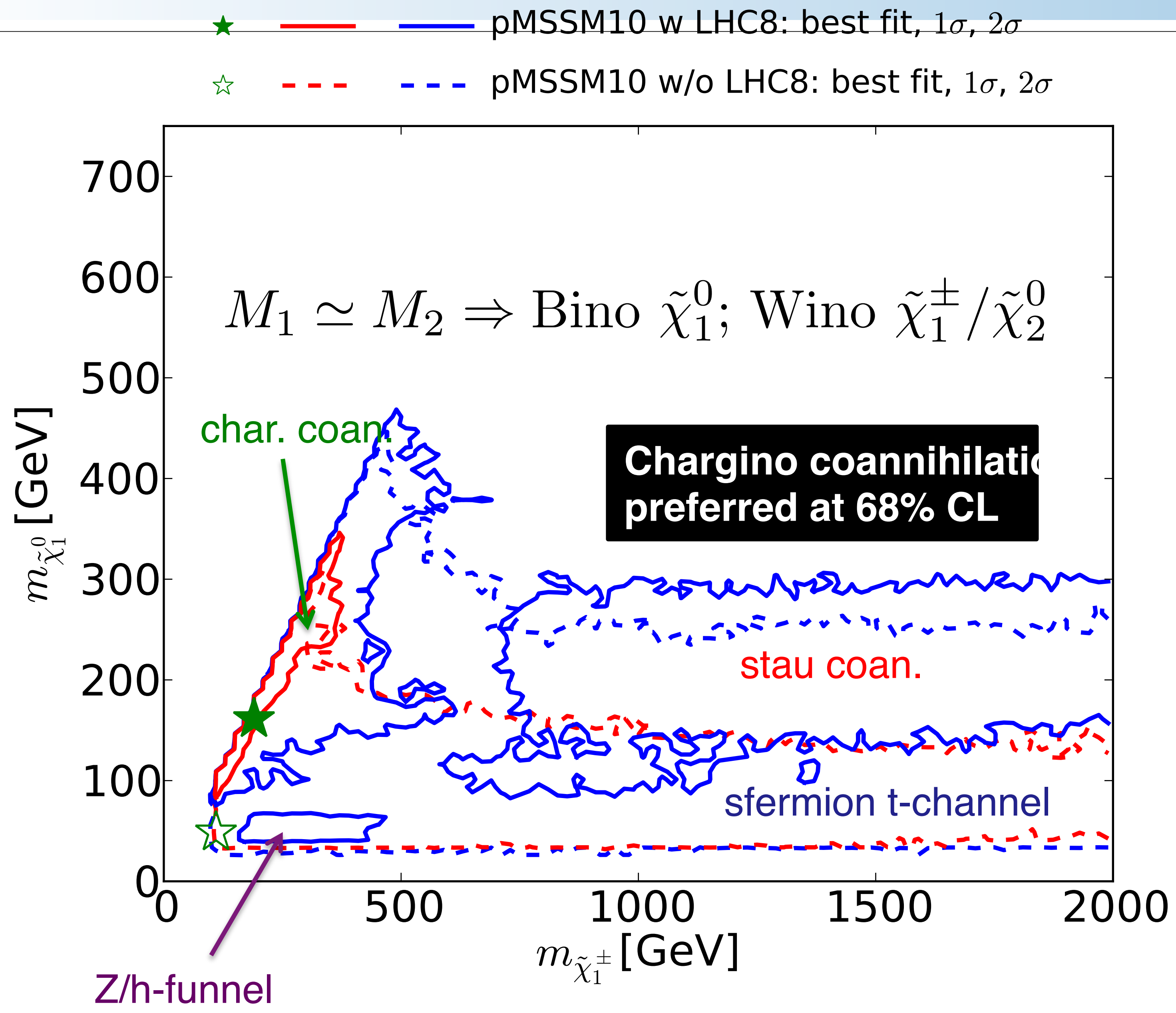
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Models in Comparison in "Mq-Mg Search plane"

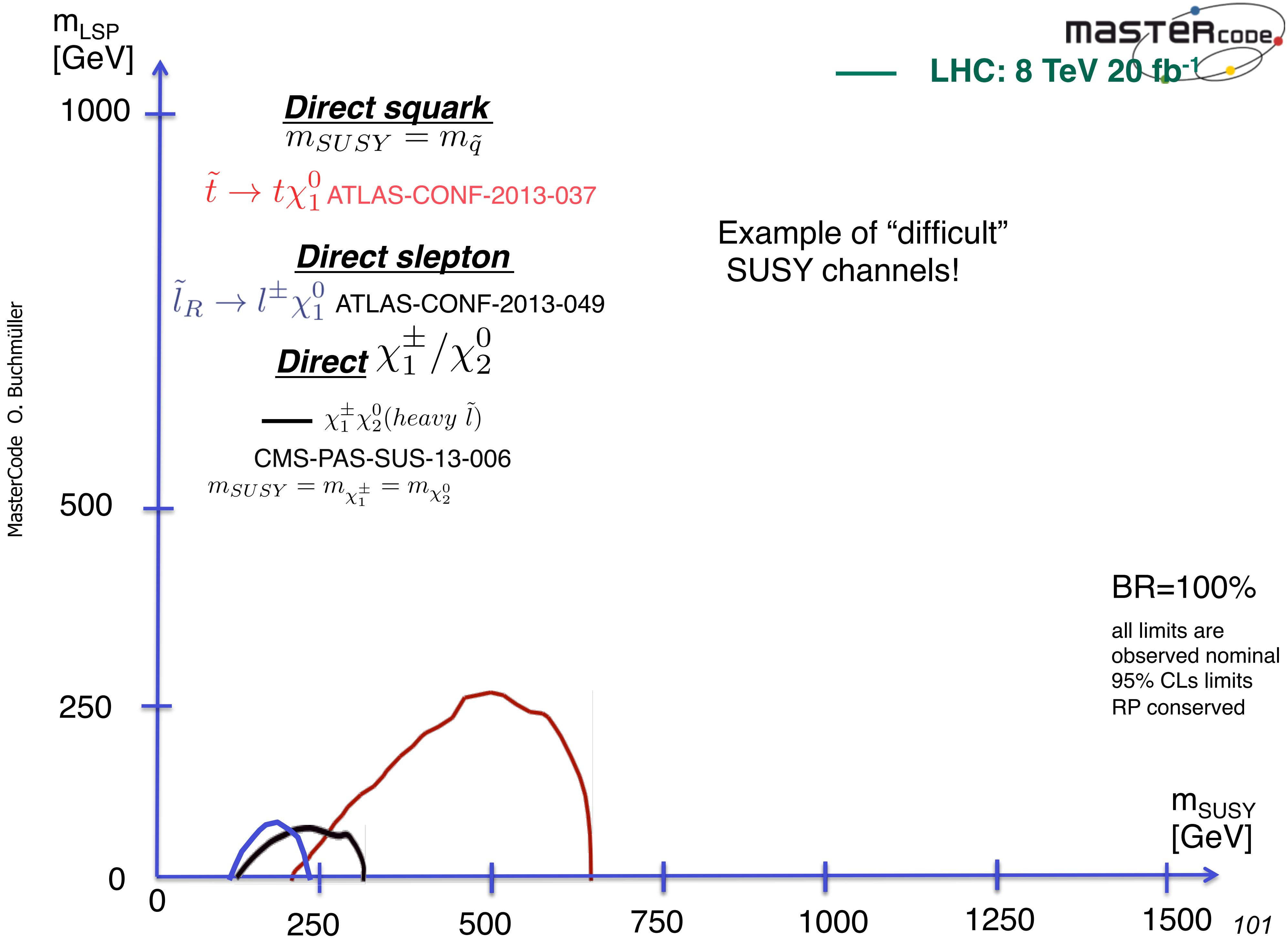


From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

pMSSM10: parameter space

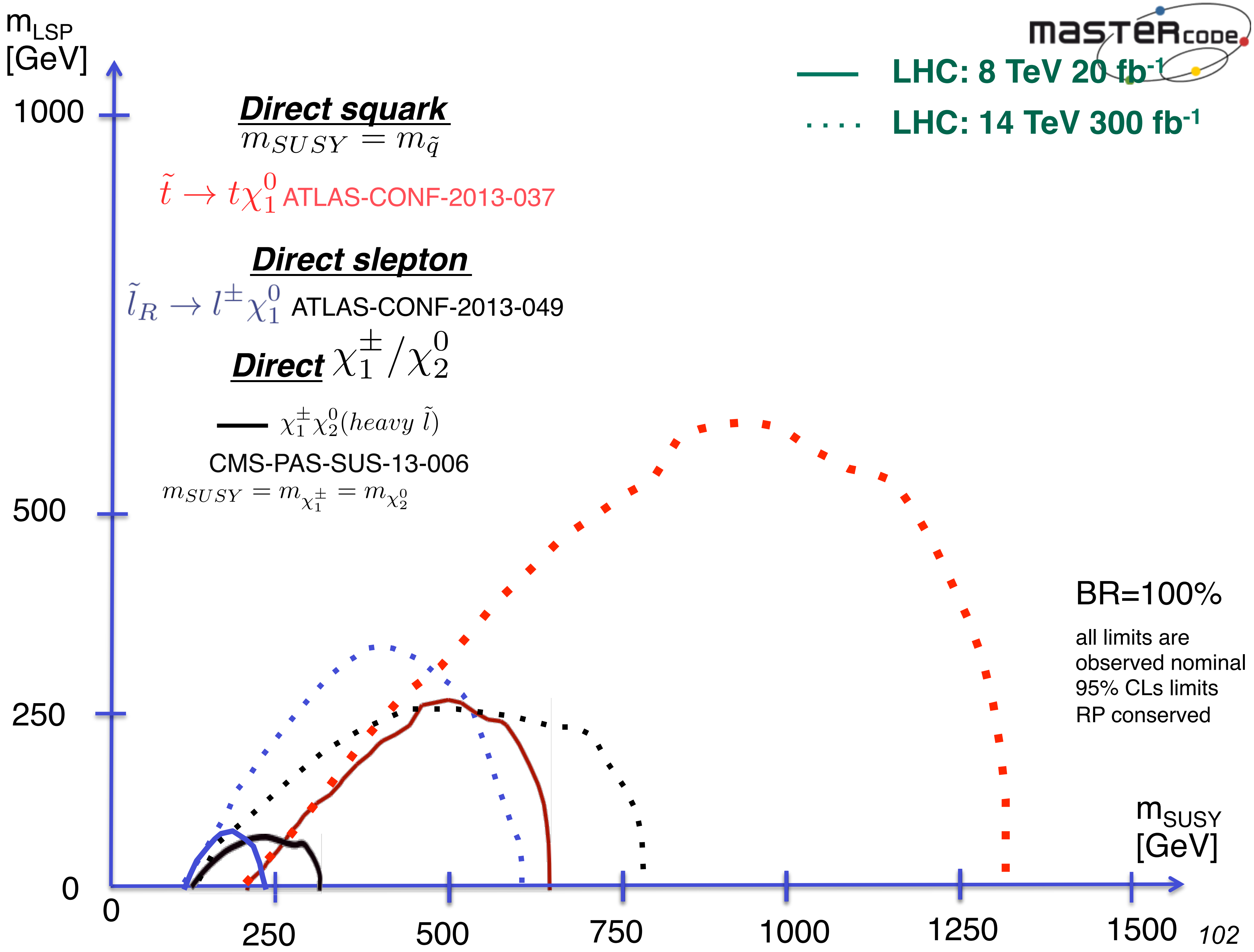


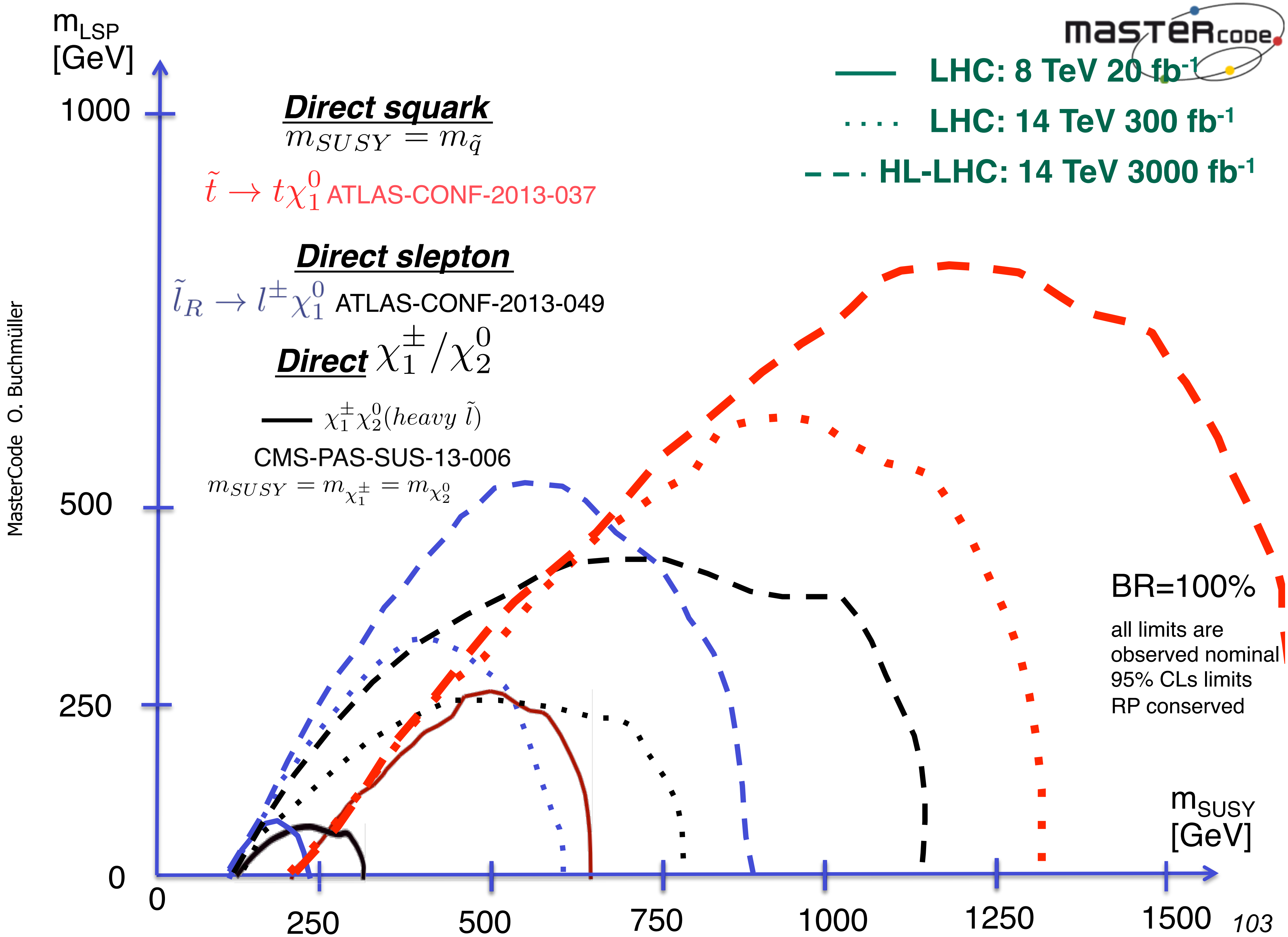
SUSY PROJECTION OF DIFFICULT CHANNELS



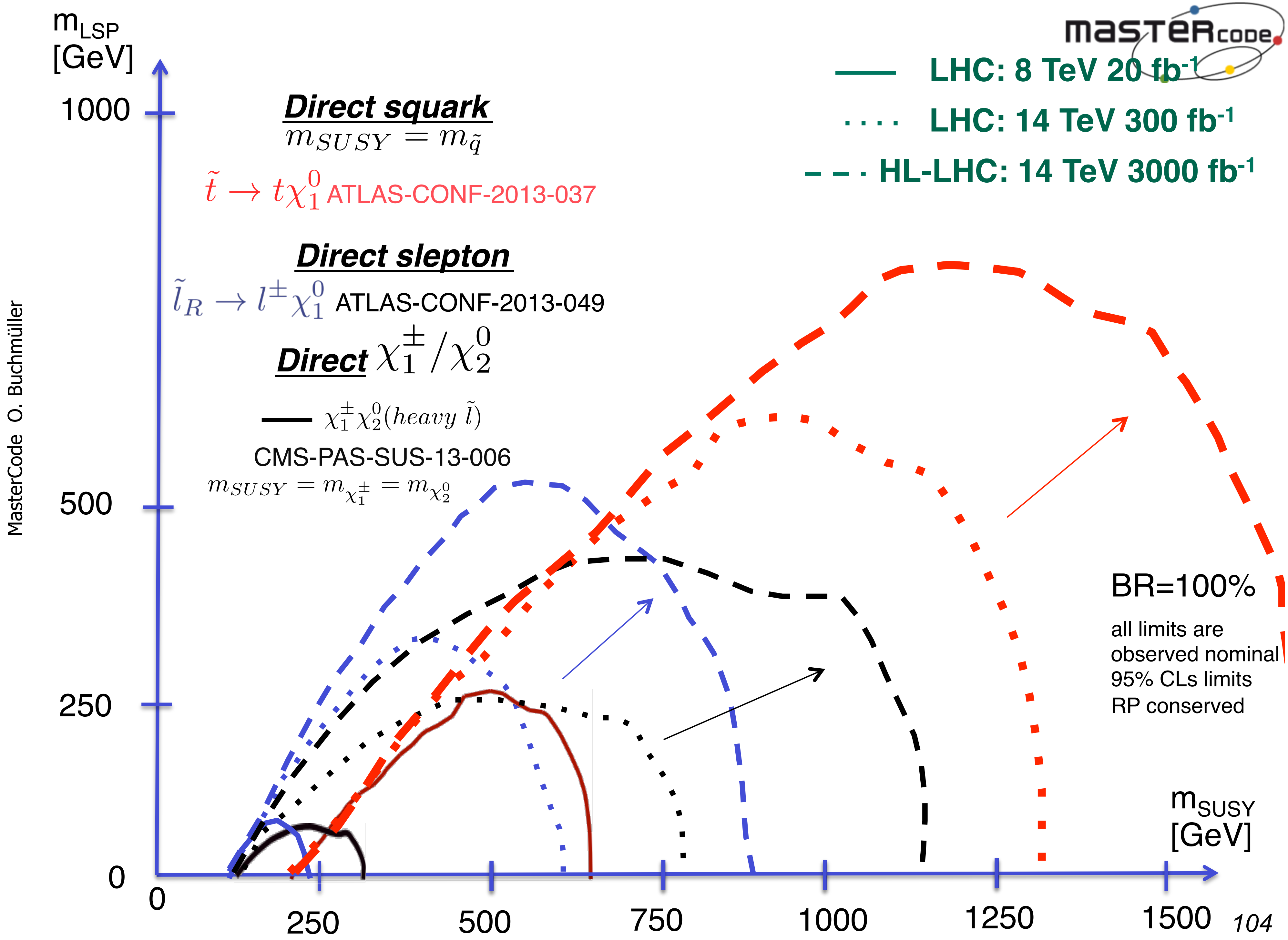
LHC: 8 TeV 20 fb-1
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
Example of “difficult” SUSY channels!
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{LSP} [GeV]
m_{SUSY} [GeV]
0
250
500
1000
750
1250
1500
MasterCode O. Buchmüller

MasterCode O. Buchmüller

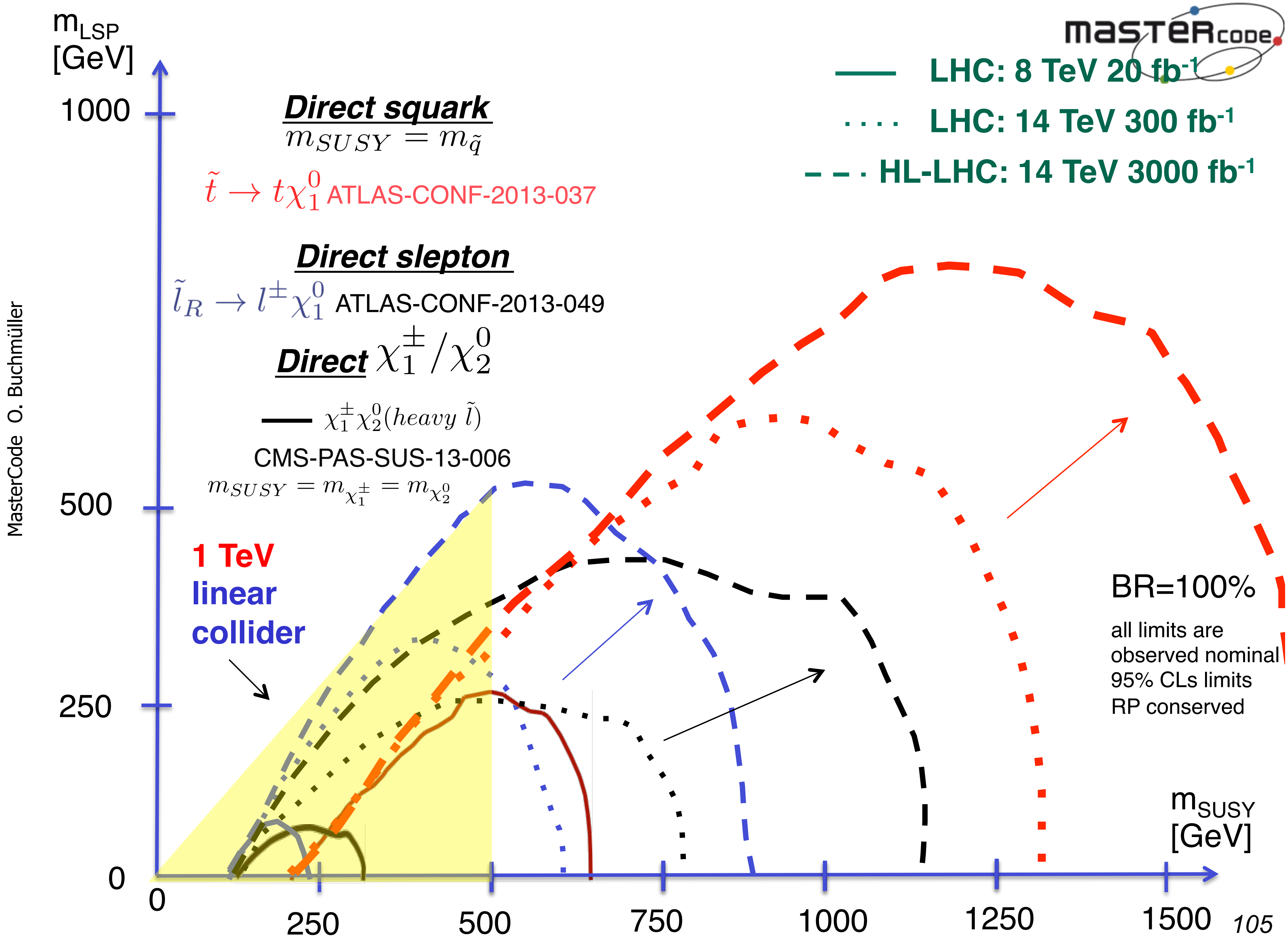




MasterCode O. Buchmüller
mastercode
m_{LSP} [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved



m_{LSP} [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
MasterCode O. Buchmüller



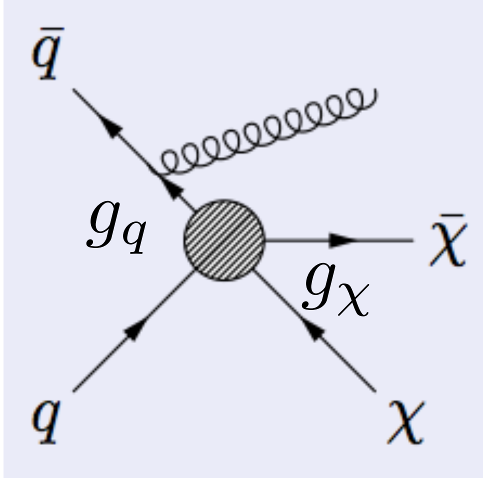
m_{LSP} [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
1 TeV linear collider
MasterCode O. Buchmüller
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

EFT VALIDITY REGION ILLUSTRATED

Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel



$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

Assumption of EFT

If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

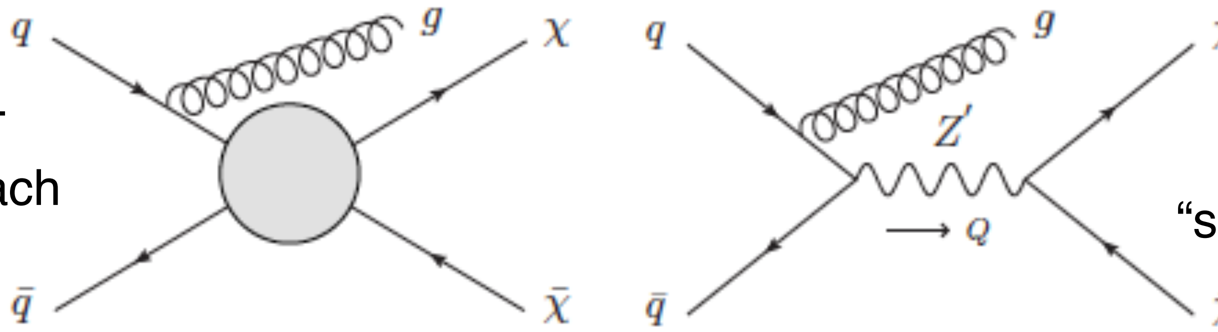
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

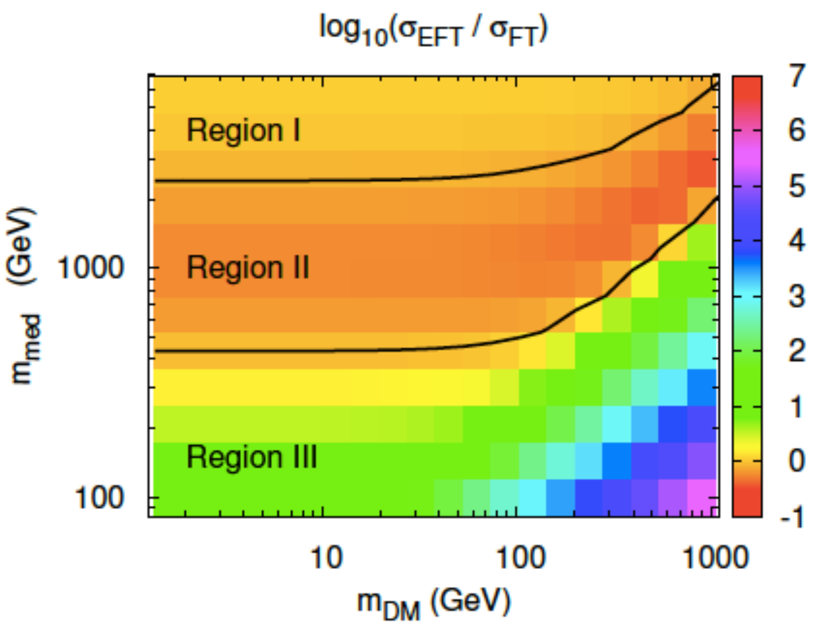
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach



FT
one diagram
“simplified model”

Use vector and axial-vector mediators (e.g. Z’) as example - scalar are similar in conclusion!



Compare prediction of FT with EFT in m_{med} – m_{DM} plane.
Three regions become visible:

Region I: EFT and FT agree better then 20%
- EFT is valid!

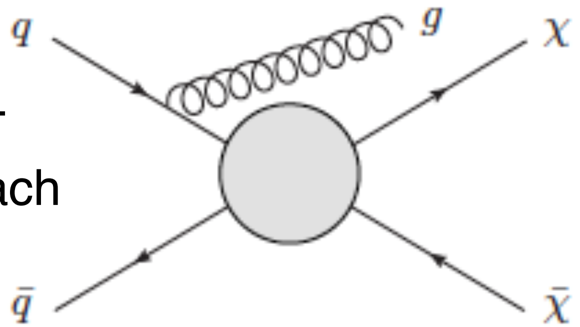
Region II: EFT yields significant weaker limits then FT
- EFT limits are too conservative!

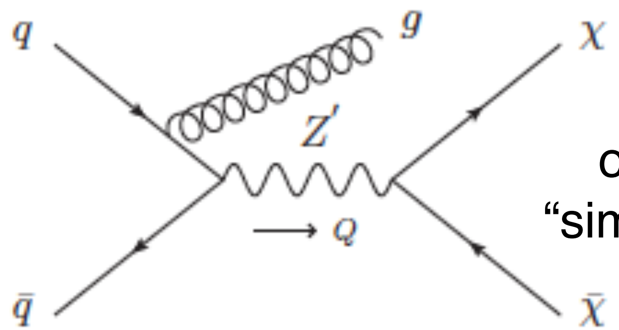
Region III: EFT yields significant stronger limits then FT
- EFT limits are too aggressive!

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

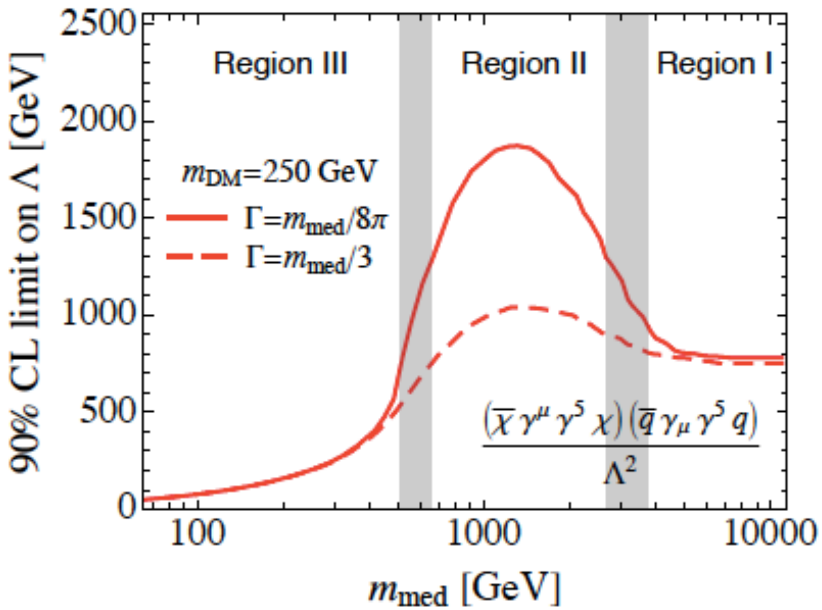
EFT approach





FT
one diagram
"simplified model"

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Three Regions as function of mediator mass:

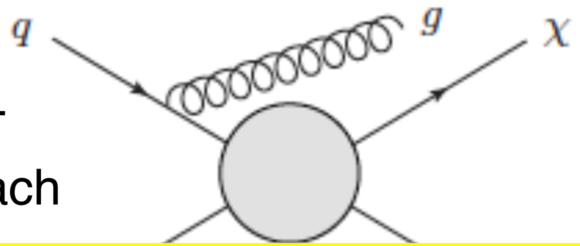
Region I: Heavy m_{med}
➢ EFT is valid!
Region II: Medium m_{med} – Resonant enhancement
➢ EFT limits are too conservative!
Region III: Low m_{med}
➢ EFT limits are too aggressive!

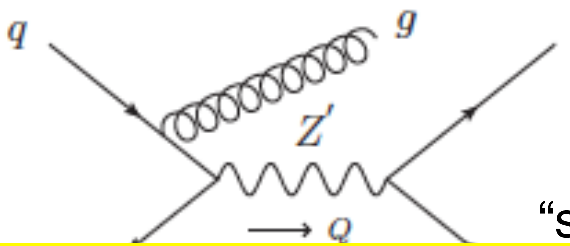
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

➤ Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach





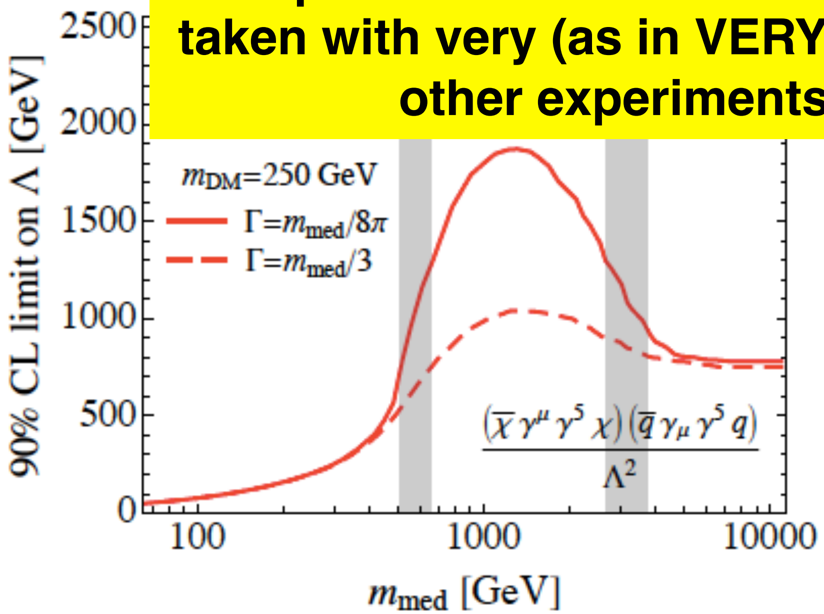
FT
one diagram
“simplified model”

Conclusion:
The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!

Use v

clusion!

:



Region I: Heavy m_{med}

➤ EFT is valid!

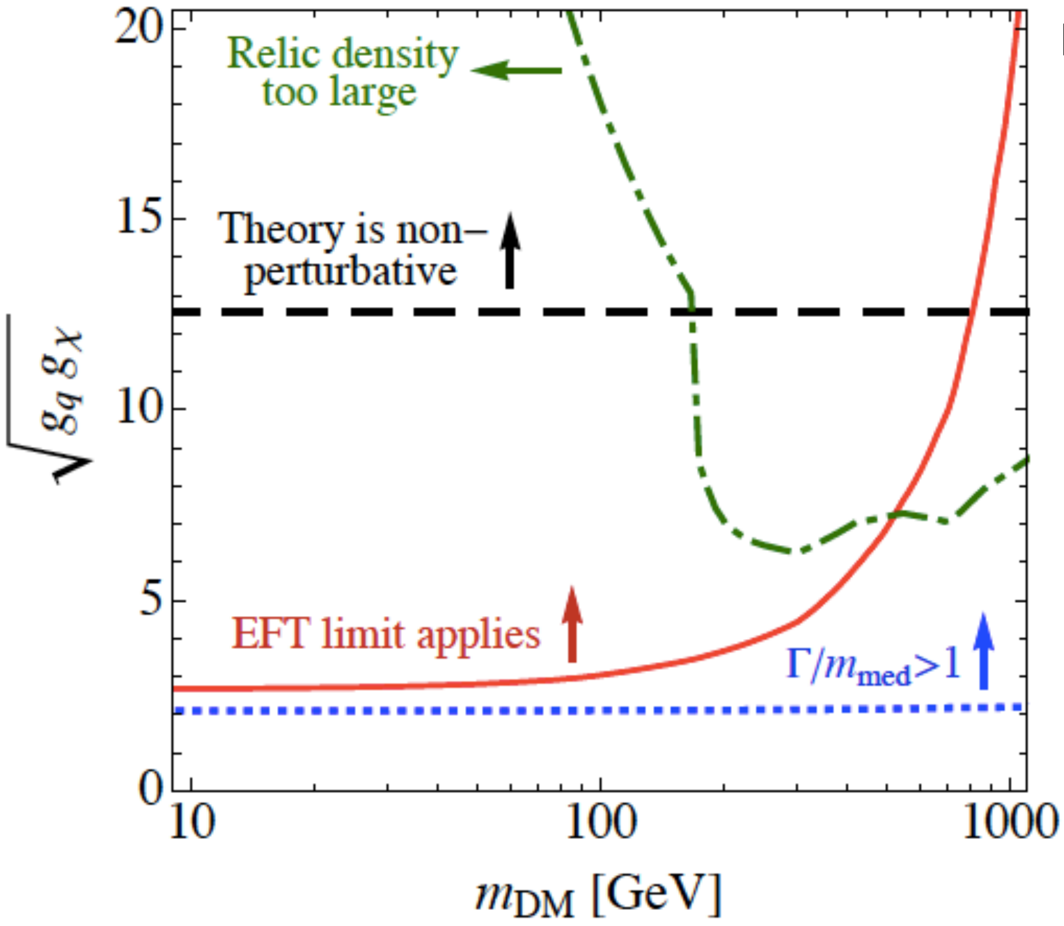
Region II: Medium m_{med} – Resonant enhancement

➤ EFT limits are too conservative!

Region III: Low m_{med}

➤ EFT limits are too aggressive!

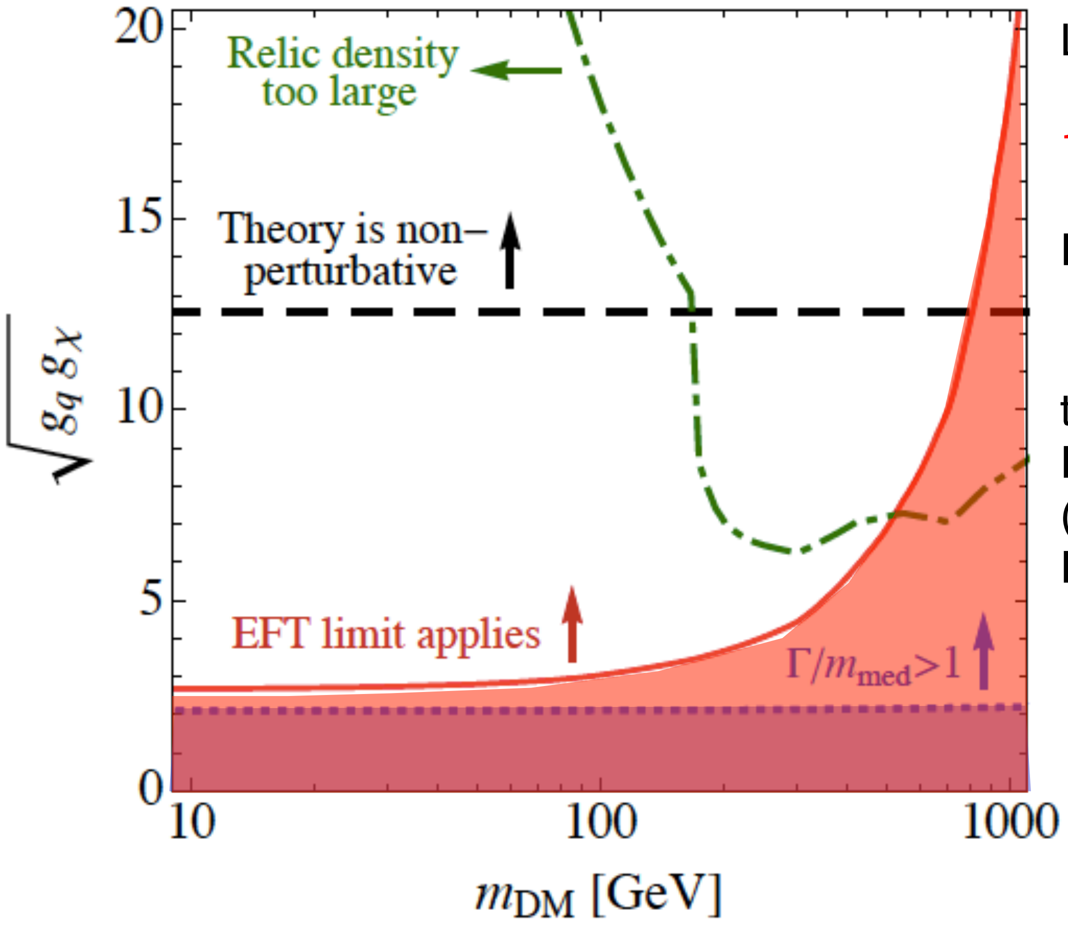
What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid

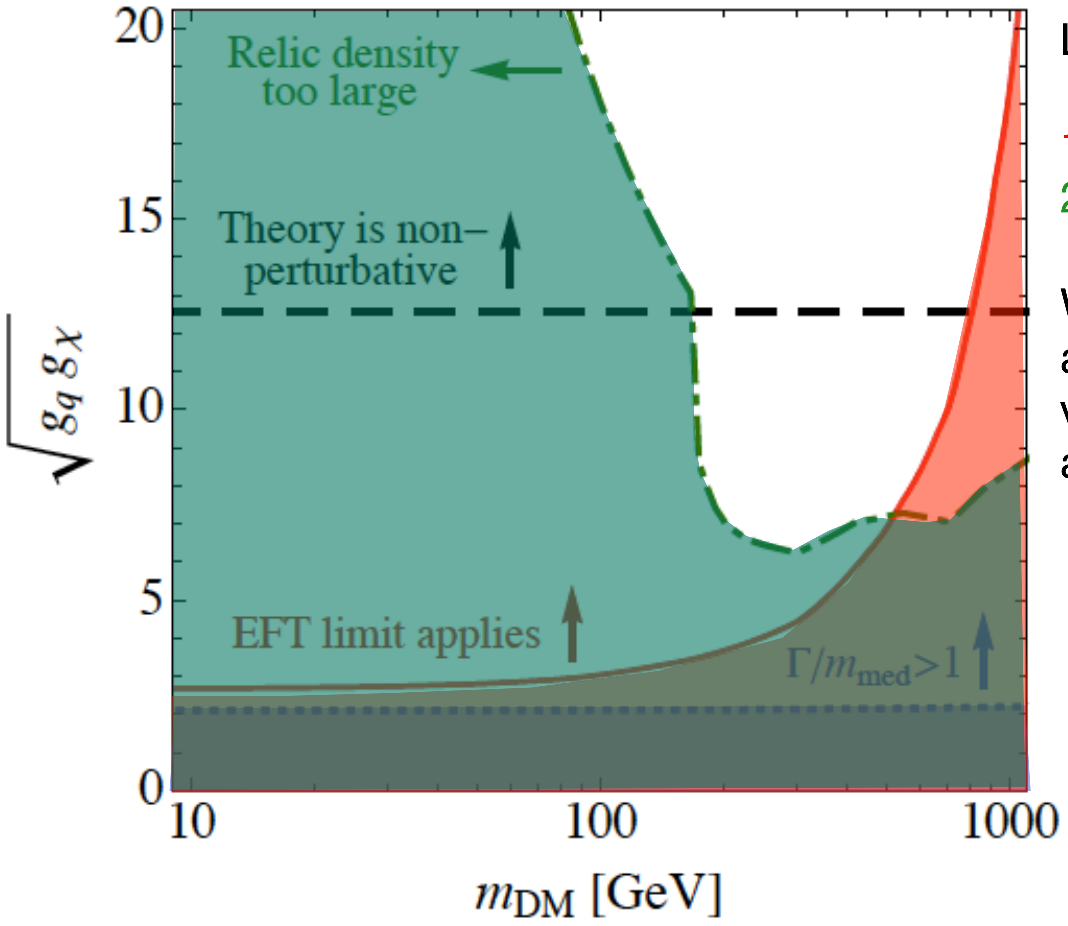
For this we calculate the minimum coupling

$$\sqrt{g_q g_\chi} = m_{med}/\Lambda_{CMS}$$

that the simplified model must have for the EFT limits to apply. This is defined by region I (i.e. better then 20% agreement of FT and EFT).

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



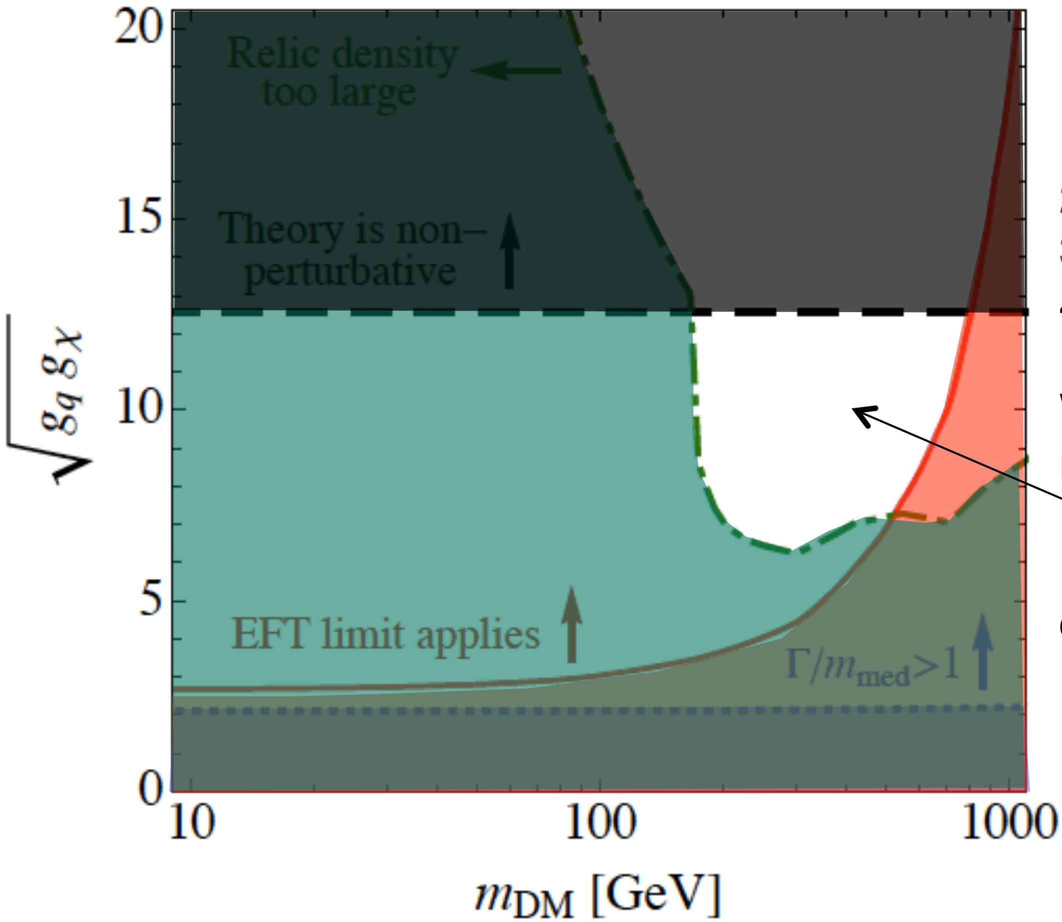
Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density

When exclude the region in which relic abundance is larger then the observed value of $\Omega_{\chi\chi}h^2 = 0.119$ only mediator masses above a few hundred GeV fulfill this.

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Must require $m_{med} < \Gamma_{med}$
2. Region in which EFT is valid (20%)
3. Require compatibility with relic density
4. Require theory to be perturbative (<4π)

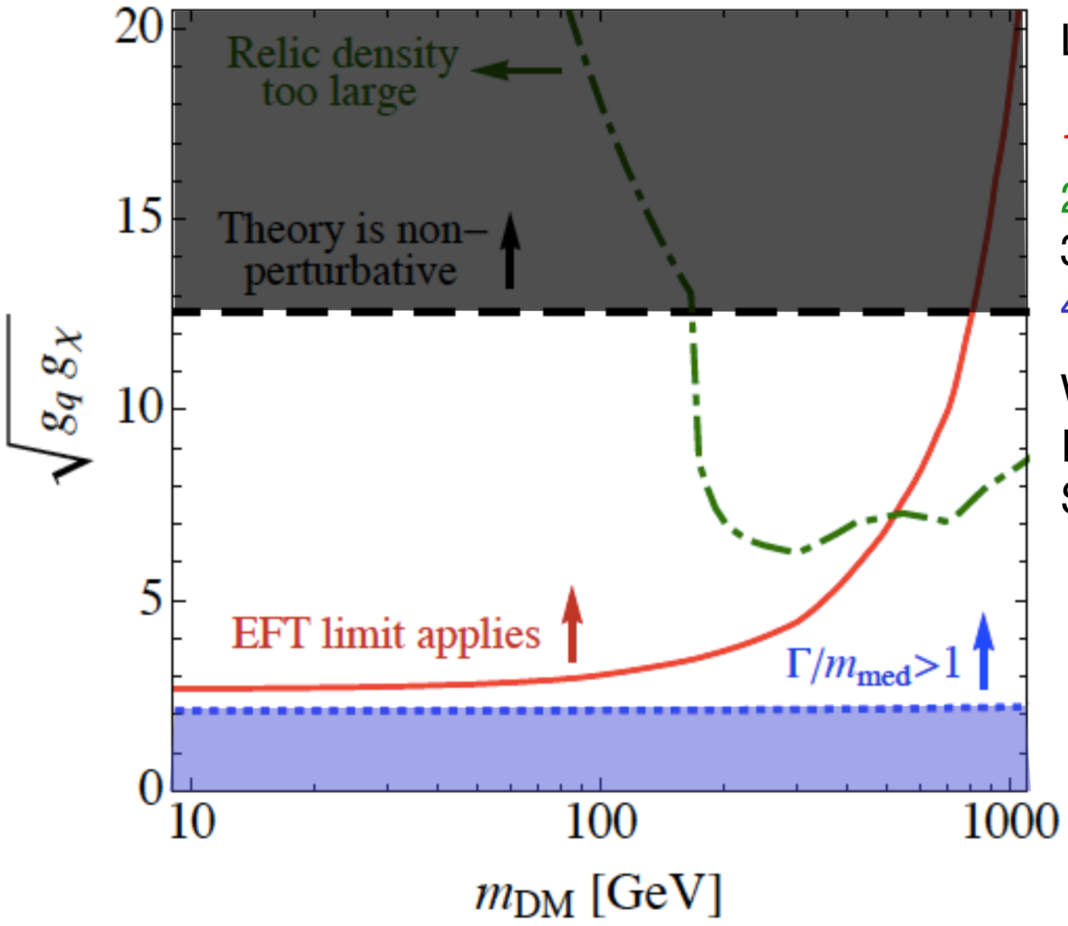
When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

EFT limits of monojet searches only apply to a very (as in VERY) small class of DM models!

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT Is valid the mass of the mediator must be Smaller than its width!

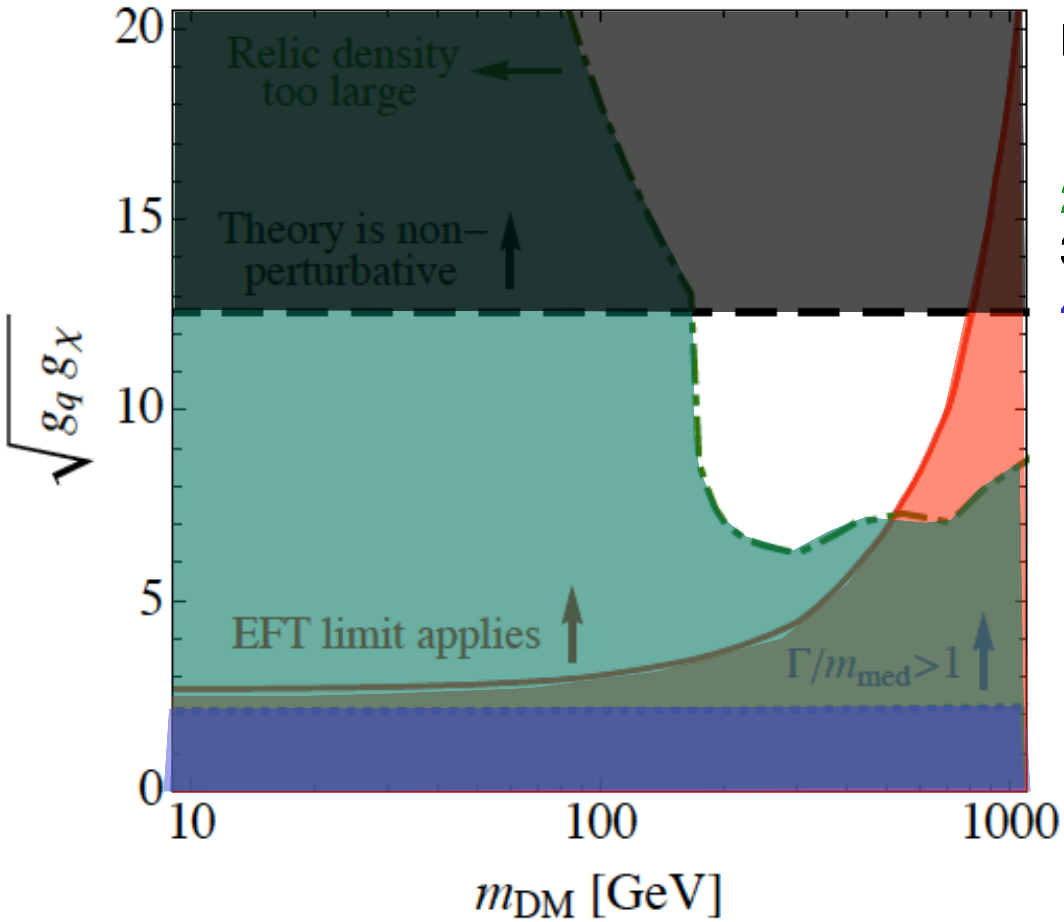
In the reaming part of the plot:

$$\sqrt{g_q g_\chi} > 2$$

a particle-like interpretation of the mediator is doubtful because of $m_{med} < \Gamma_{med}$!

See discussion about equation 3.5 in arXiv:1308.6799 for further details.

What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

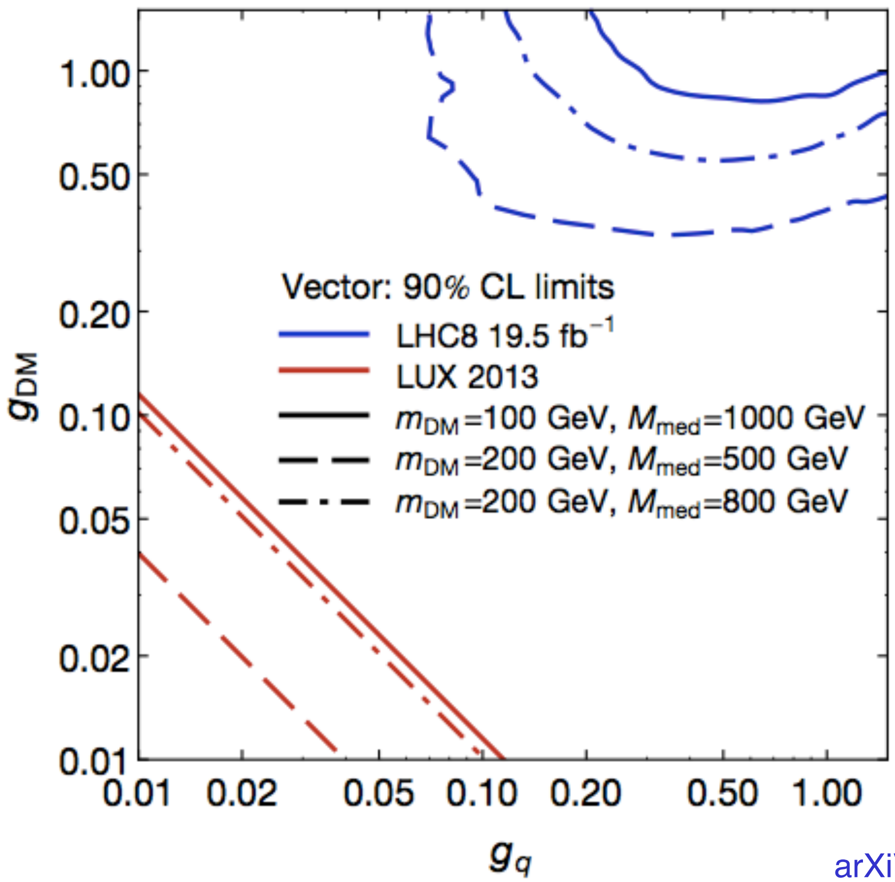
The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.

EFT limits of monojet searches are therefore highly model-depended!

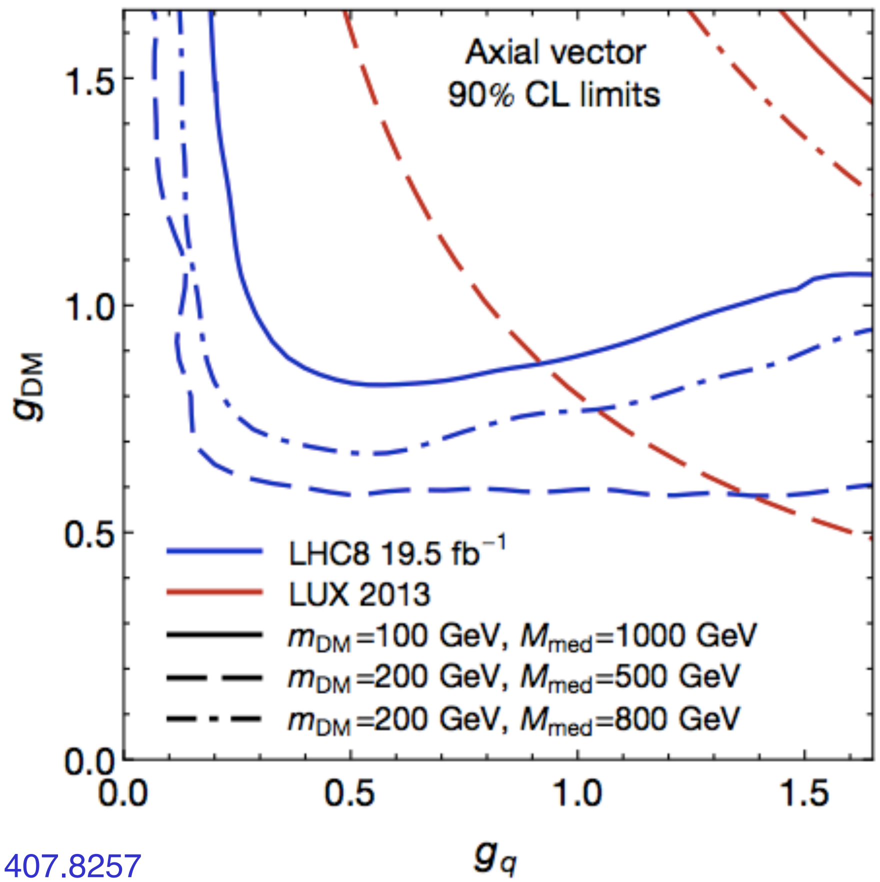
Collider vs Direct Detection

M_{DM}	M_{med}
g_q	g_{DM}

Vector



Axial vector



arXiV:1407.8257

MasterCode, O. Buchmüller