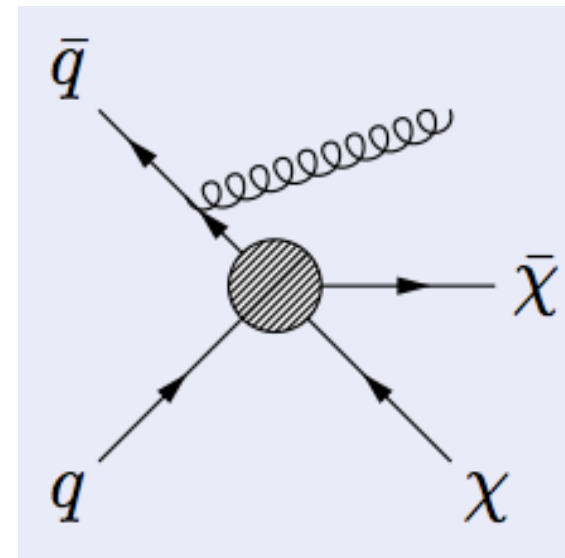
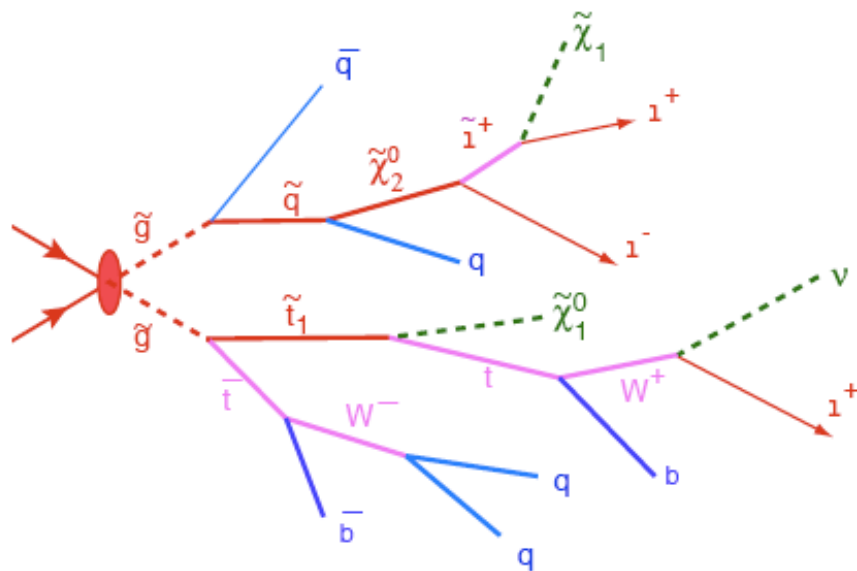


Oliver Buchmueller, Imperial College London

SEARCHES FOR DARK MATTER PRODUCTION AT THE LHC

DESY SEMINAR OCTOBER 27, 2015

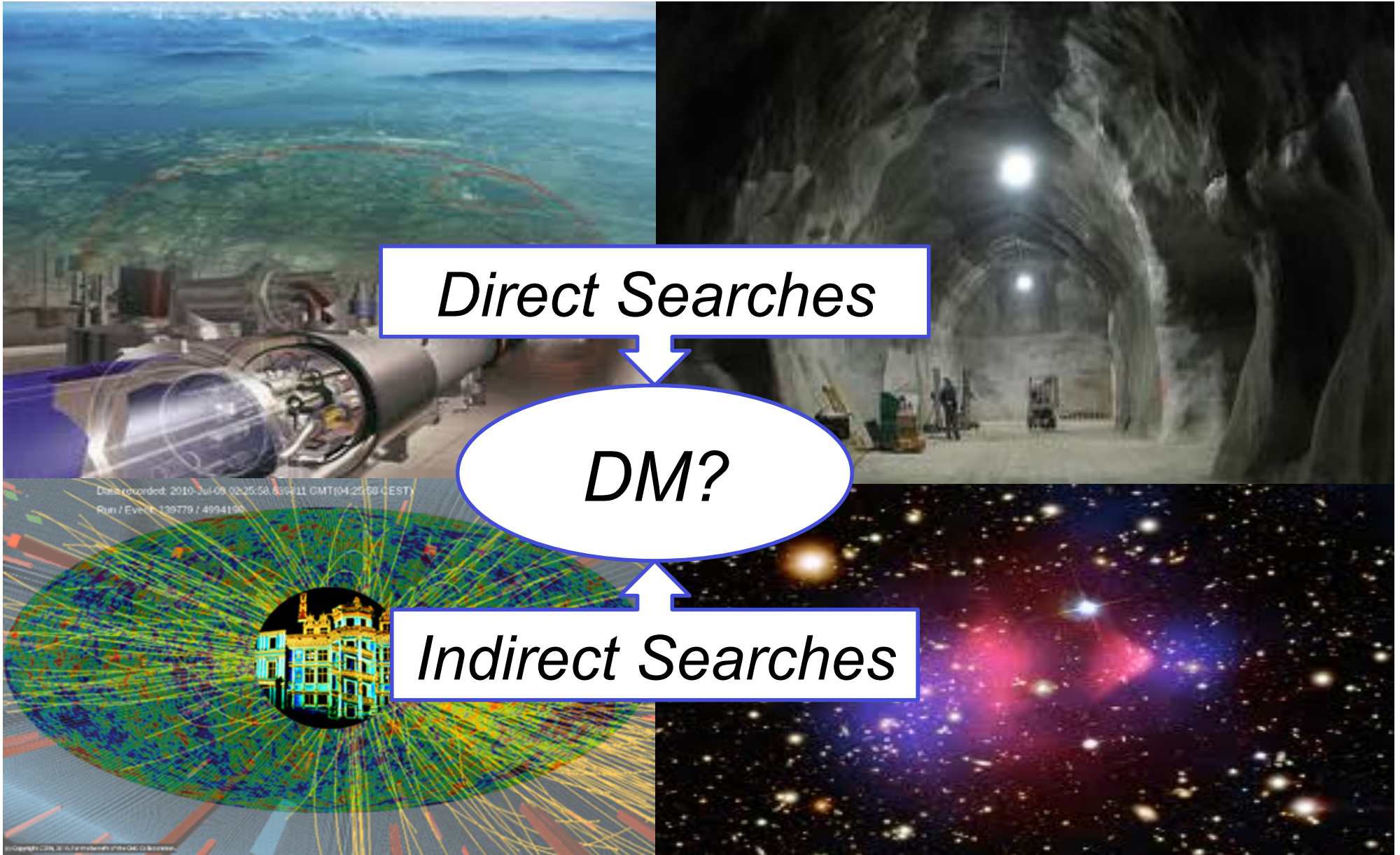


Searches for Dark Matter (& SUSY)

Direct Searches

DM?

Indirect Searches



Searches for Dark Matter (&SUSY)

Direct Searches

DM?

Indirect Searches

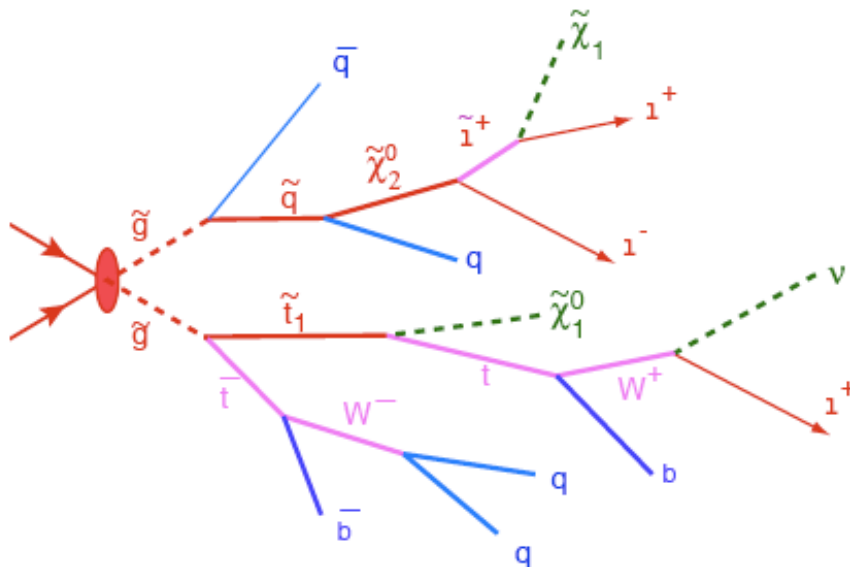


Characterizing Dark Matter Searches

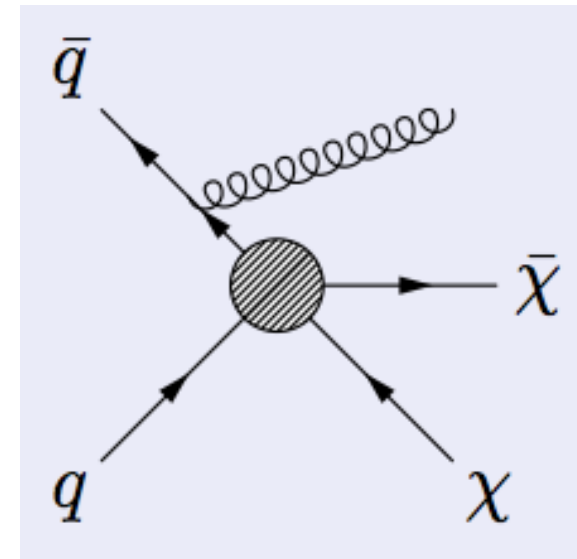
complete theory vs. simple interpretations



SUSY



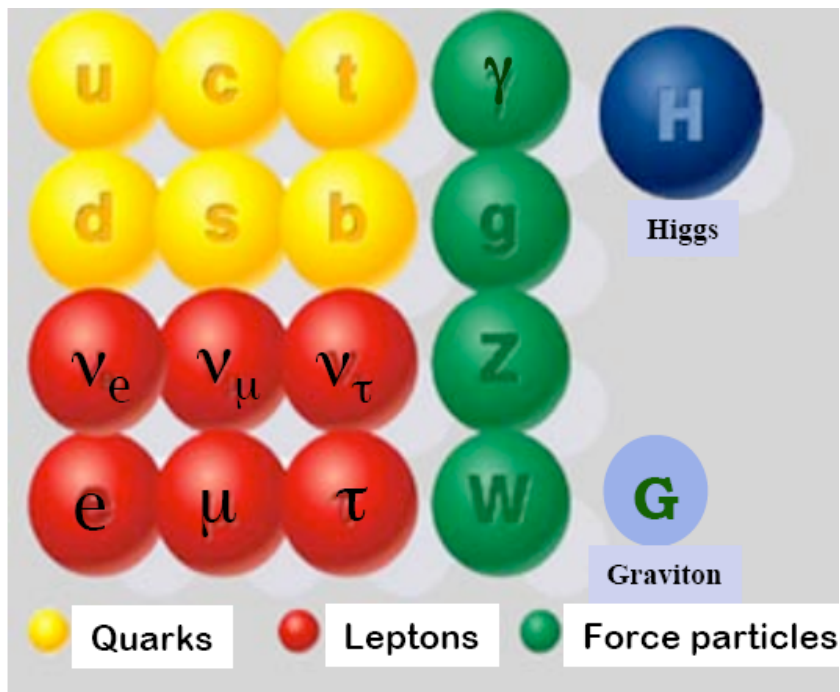
Example:
Effective Field Theory
Simplified models



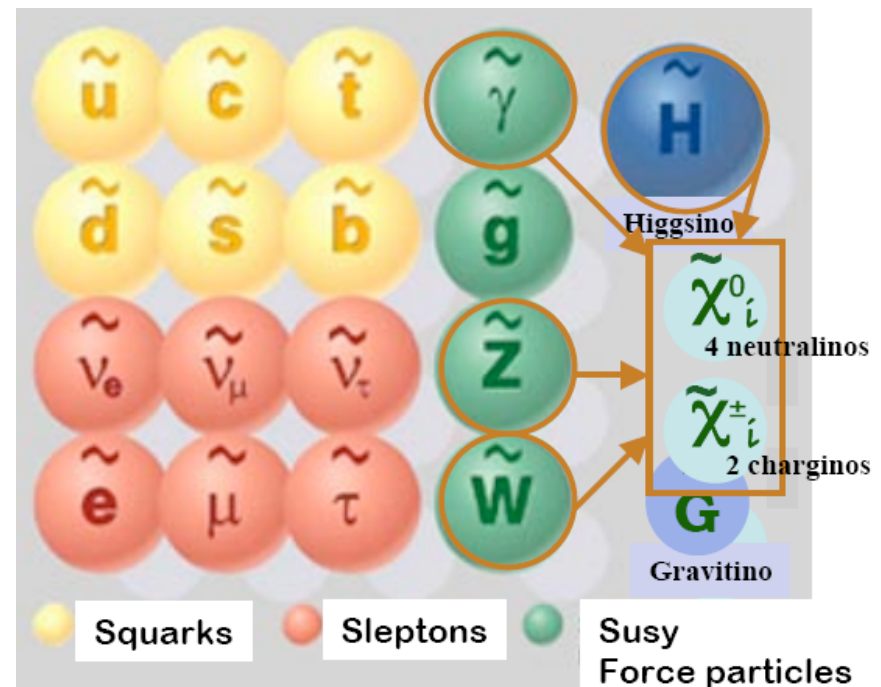
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin 1/2 matter particles (fermions) $\Leftrightarrow$ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s} = +1$ SM particles
R-parity conservation: -1 SUSY particles

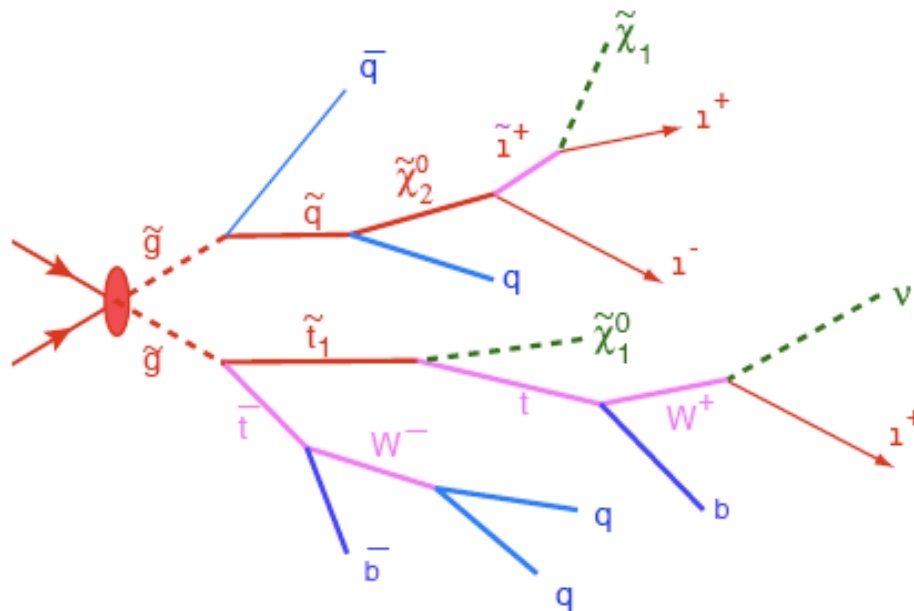
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

What do we call a “SUSY search”?

*The definition is purely derived from the experimental signature.
Therefore, a “SUSY search signature” is characterized by*

Lots of missing energy, many jets, and possibly leptons in the final state

Slides from 2007



Missing Energy:

- from LSP

Multi-Jet:

- from cascade decay (gaugino)

Multi-Leptons:

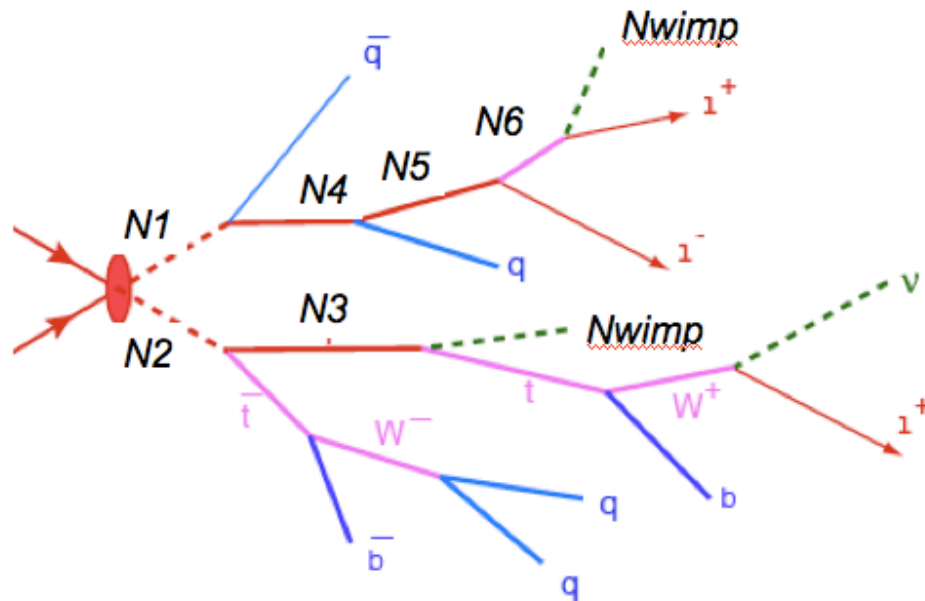
- from decay of charginos/neutralinos

RP-Conserving SUSY is a very prominent example predicting this famous signature but ...

What is its experimental signature?

... by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature

Slides from 2007



Missing Energy:

- $Nwimp$ - end of the cascade

Multi-Jet:

- from decay of the N s (possibly via heavy SM particles like top, W/Z)

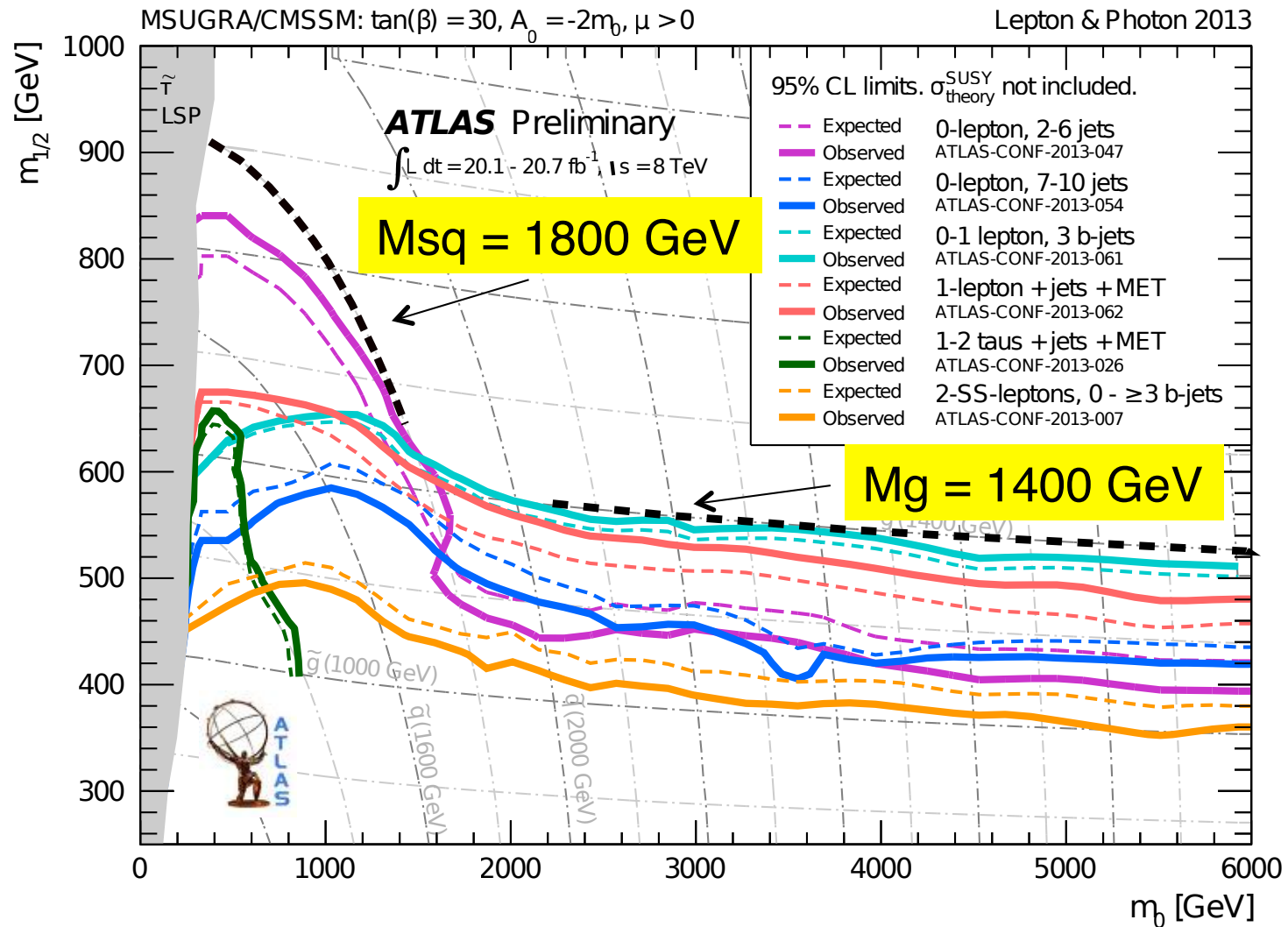
Multi-Leptons:

- from decay of the N 's

Model examples are Extra dimensions, Little Higgs, Technicolour, etc
but a more generic definition for this signature is as follows.

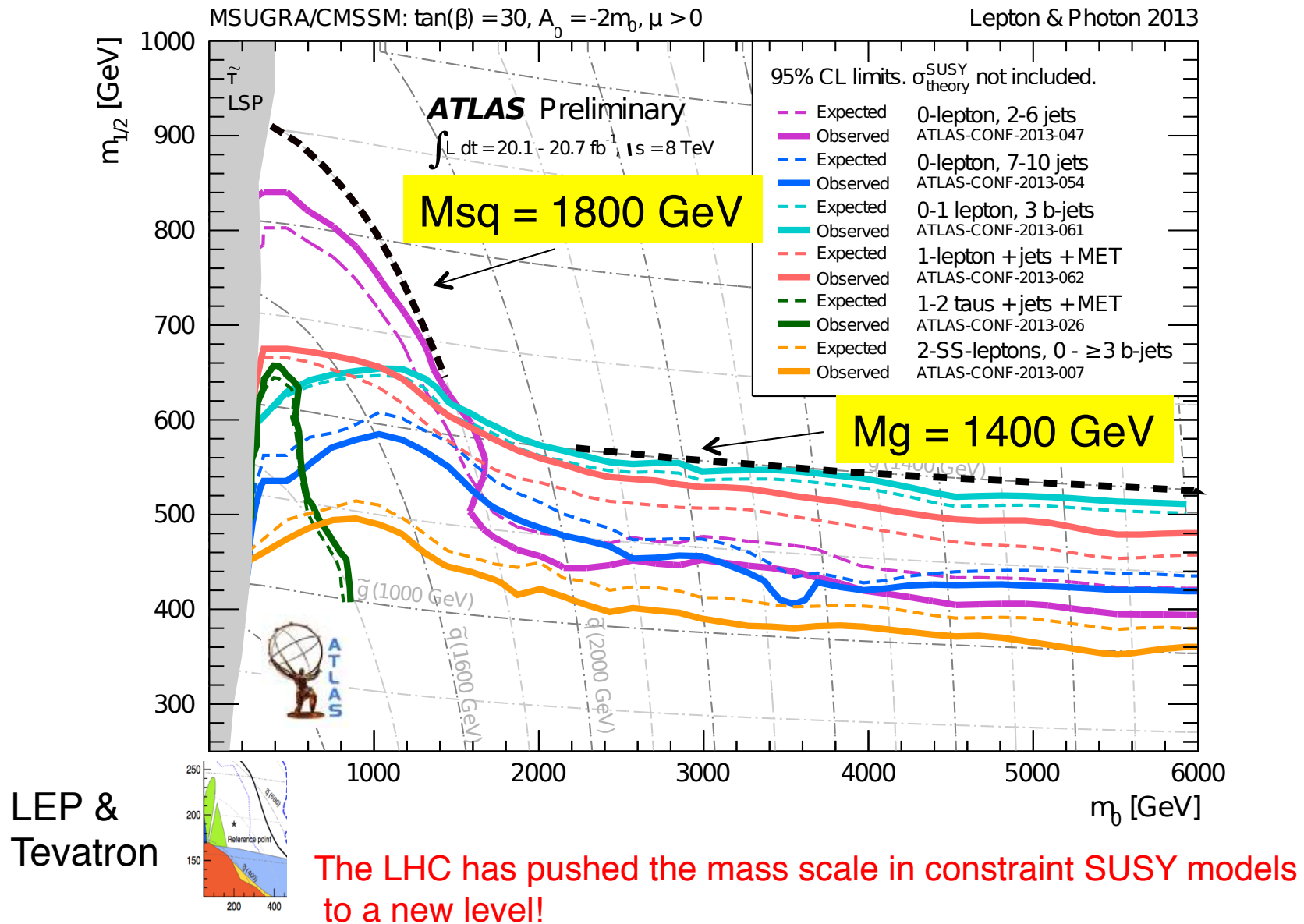
Inclusive SUSY Searches in 2013

DM Searches @ LHC O. Buchmüller



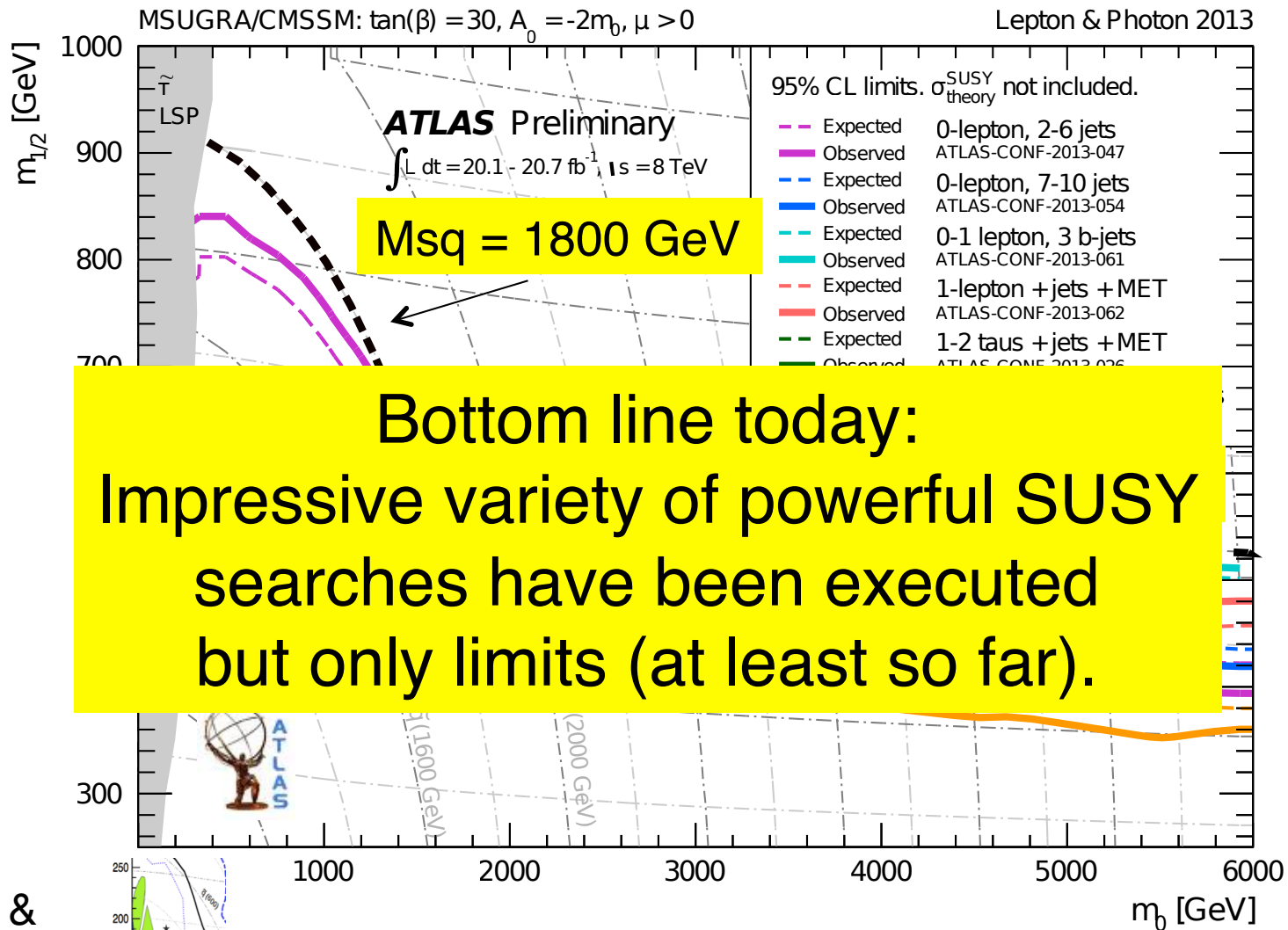
Inclusive SUSY Searches in 2013

DM Searches @ LHC O. Buchmüller



Inclusive SUSY Searches in 2013

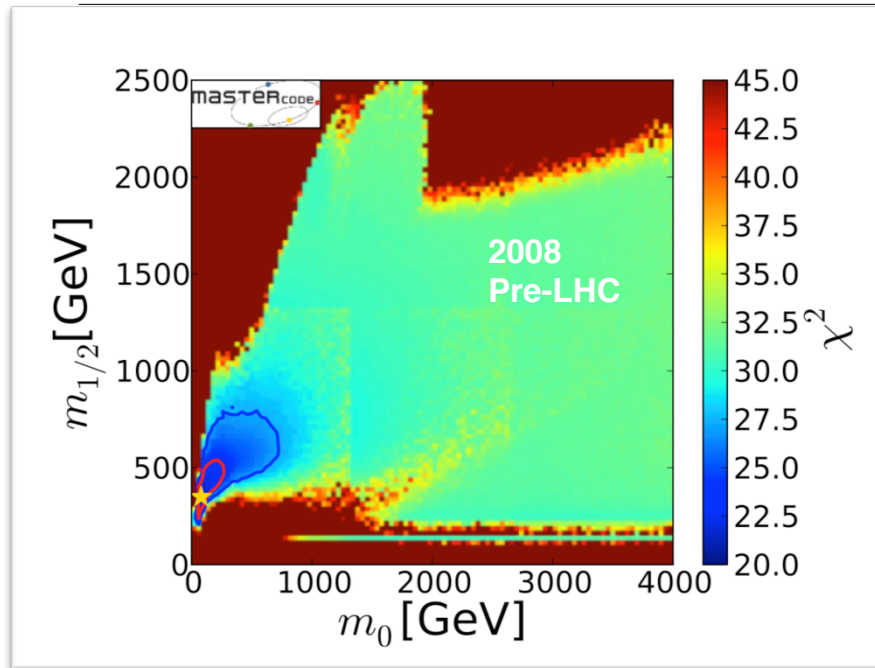
DM Searches @ LHC O. Buchmüller



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

CMSSM: Evolution with time

DM Searches @ LHC O. Buchmüller



χ^2 increase from
bluish to reddish



Source:

<http://mastercode.web.cern.ch/mastercode/>

Global Fit to indirect and direct constraints on SUSY!

Other “fitter” groups find very similar results: e.g.

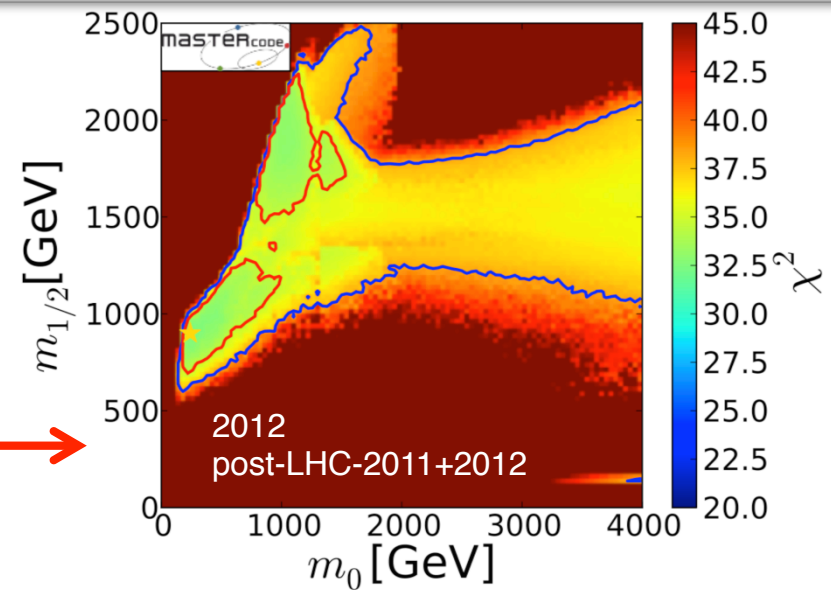
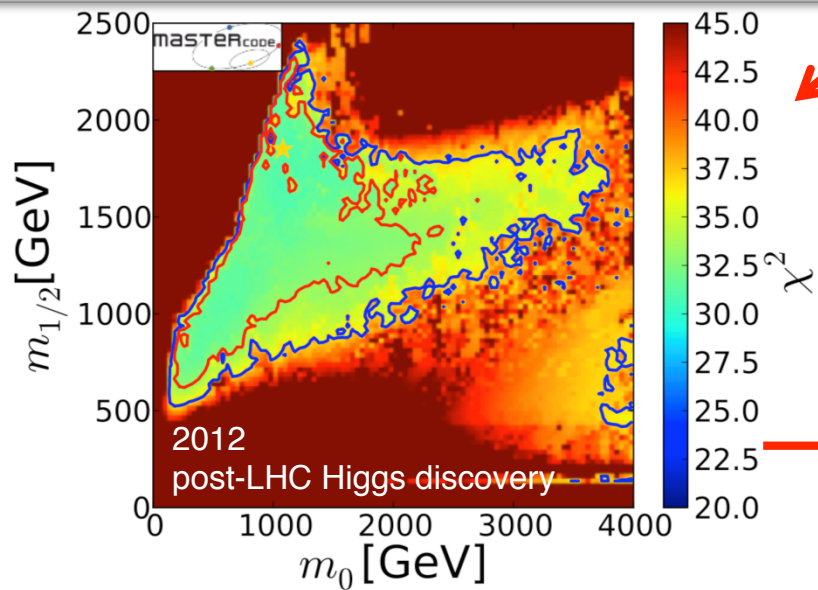
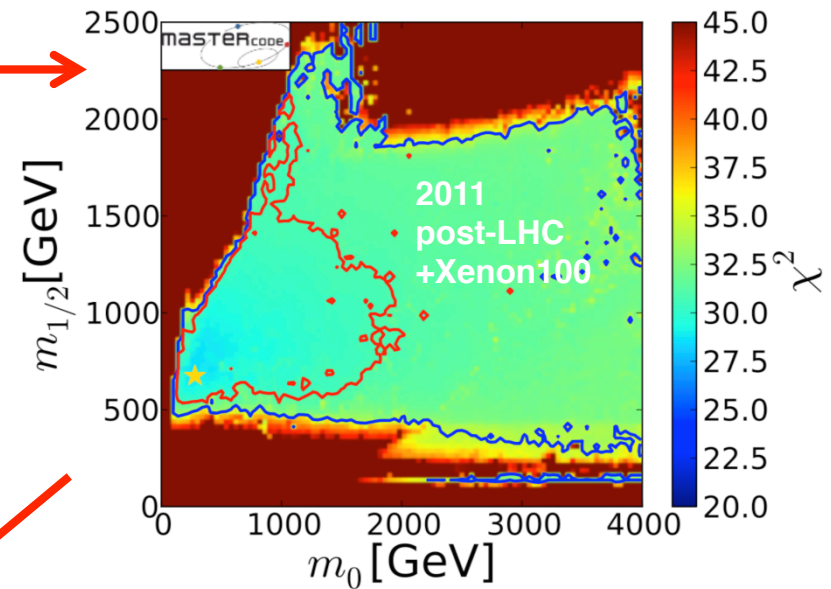
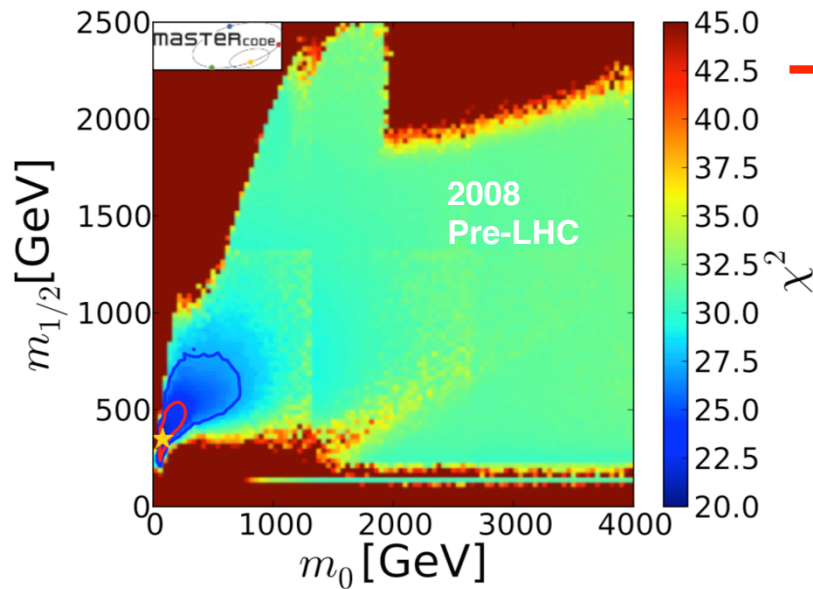
SuperBayeS: [arXiv:1212.2636](https://arxiv.org/abs/1212.2636)

Fittino group: [arXiv:1204.4199](https://arxiv.org/abs/1204.4199)

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	-
$\Delta\alpha_{\text{had}}^{(5)}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-2}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{\text{SUSY}}$	0.078	0.047	0.14
σ_{had}^0 [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
$A_{\text{fb}}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
$A_{\text{fb}}(P_\tau)$	[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
$A_{\text{fb}}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{\text{fb}}(c)$	[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
$A_{\text{fb}}(\text{SLD})$	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2 \theta_{\text{eff}}^e(Q_{\text{fb}})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{\text{SUSY}}$	1.77	1.99	2.08
$a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}}$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{\text{SUSY}}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4[\pm 1.5_{\text{SUSY}}]$	0.0	0.0	0.0
$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$	[45] / [46]	$1.117 \pm 0.076_{\text{EXP}} \pm 0.082_{\text{SM}} \pm 0.050_{\text{SUSY}}$	1.83	1.09	0.94
$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$\text{BR}_{\text{B-L}}^{\text{EXP/SM}}$	[29] / [46]	$1.43 \pm 0.43_{\text{EXP+TH}}$	1.43	1.59	1.00
$\text{BR}(B_d \rightarrow \mu^+ \mu^-)$	[29] / [46]	$< 4.6[\pm 0.01_{\text{SUSY}}] \times 10^{-9}$	0.0	0.0	0.0
$\text{BR}_{\text{B-L}}^{\text{EXP/SM}}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$\text{BR}_{K-L}^{\text{EXP/SM}}$	[29] / [48]	$1.008 \pm 0.014_{\text{EXP+TH}}$	0.39	0.42	0.33
$\text{BR}_{K-L}^{\text{EXP/SM}}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M_{B_s}^{\text{EXP/SM}}$	[49] / [51,52]	$0.97 \pm 0.01_{\text{EXP}} \pm 0.27_{\text{SM}}$	0.02	0.02	0.01
$\frac{\Delta M_{B_s}^{\text{EXP/SM}}}{\Delta M_{B_d}^{\text{EXP/SM}}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{\text{EXP}} \pm 0.13_{\text{SM}}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta M_K^{\text{EXP/SM}}$	[49] / [51,52]	$1.08 \pm 0.14_{\text{EXP+TH}}$	0.27	0.37	0.33
$\Omega_{\text{CDM}} h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{\text{SUSY}}$	8.4×10^{-4}	0.1	N/A
σ_p^{SI}	[25]	$(m_{\chi_1^0}, \sigma_p^{\text{SI}})$ plane	0.13	0.13	N/A
jets + 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 $\chi^2/\text{d.o.f.}$	All	All	28.8/22	27.3/21	32.7/23 (21.5/22)
p-values			15%	16%	9% (49%)

CMSSM: Evolution with time

DM Searches @ LHC O. Buchmüller



MasterCode: The two worlds of SUSY models

DM Searches @ LHC O. Buchmüller

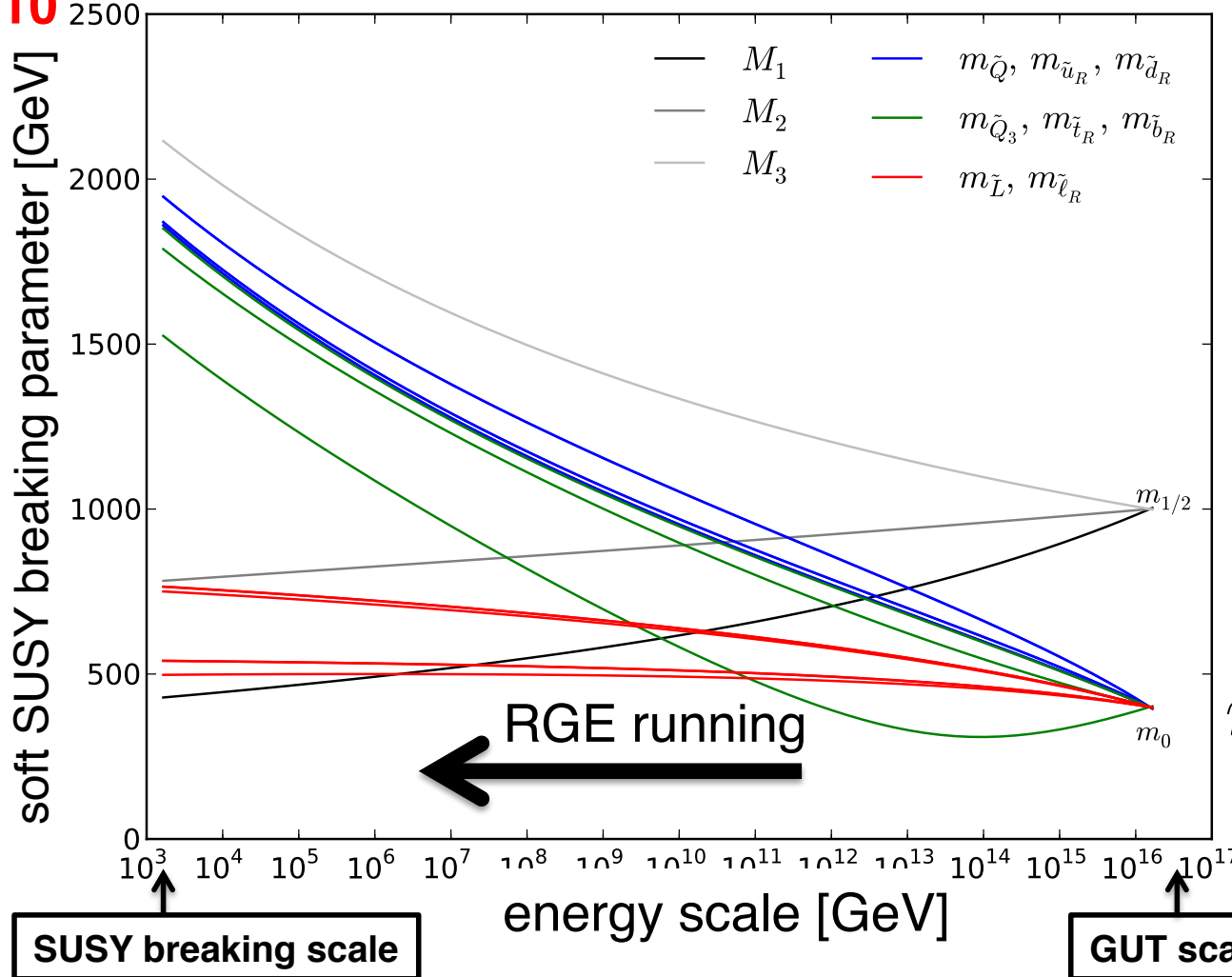
“Soft scale”

“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



CMSSM

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

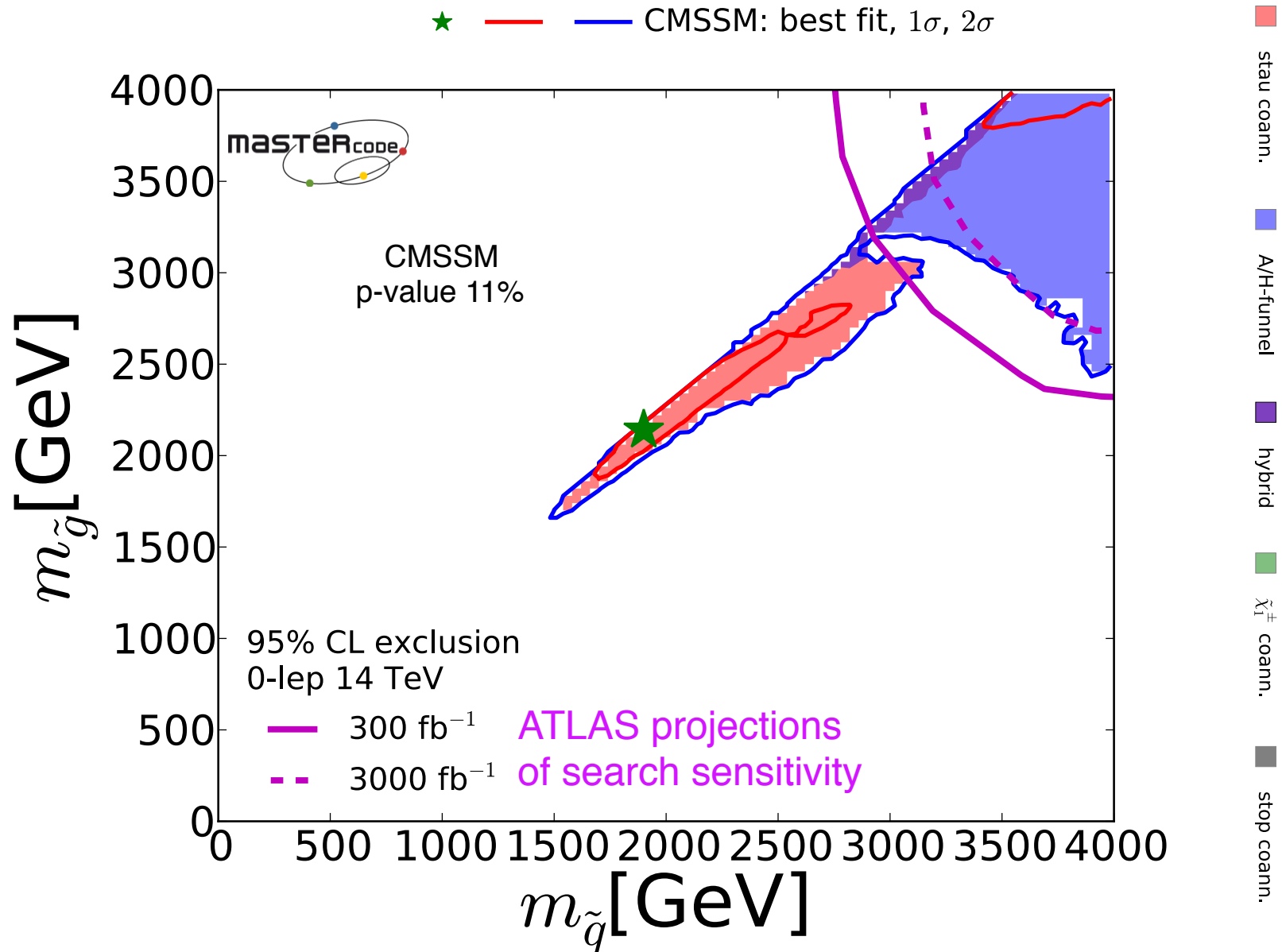
NUHM1

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

NUHM2

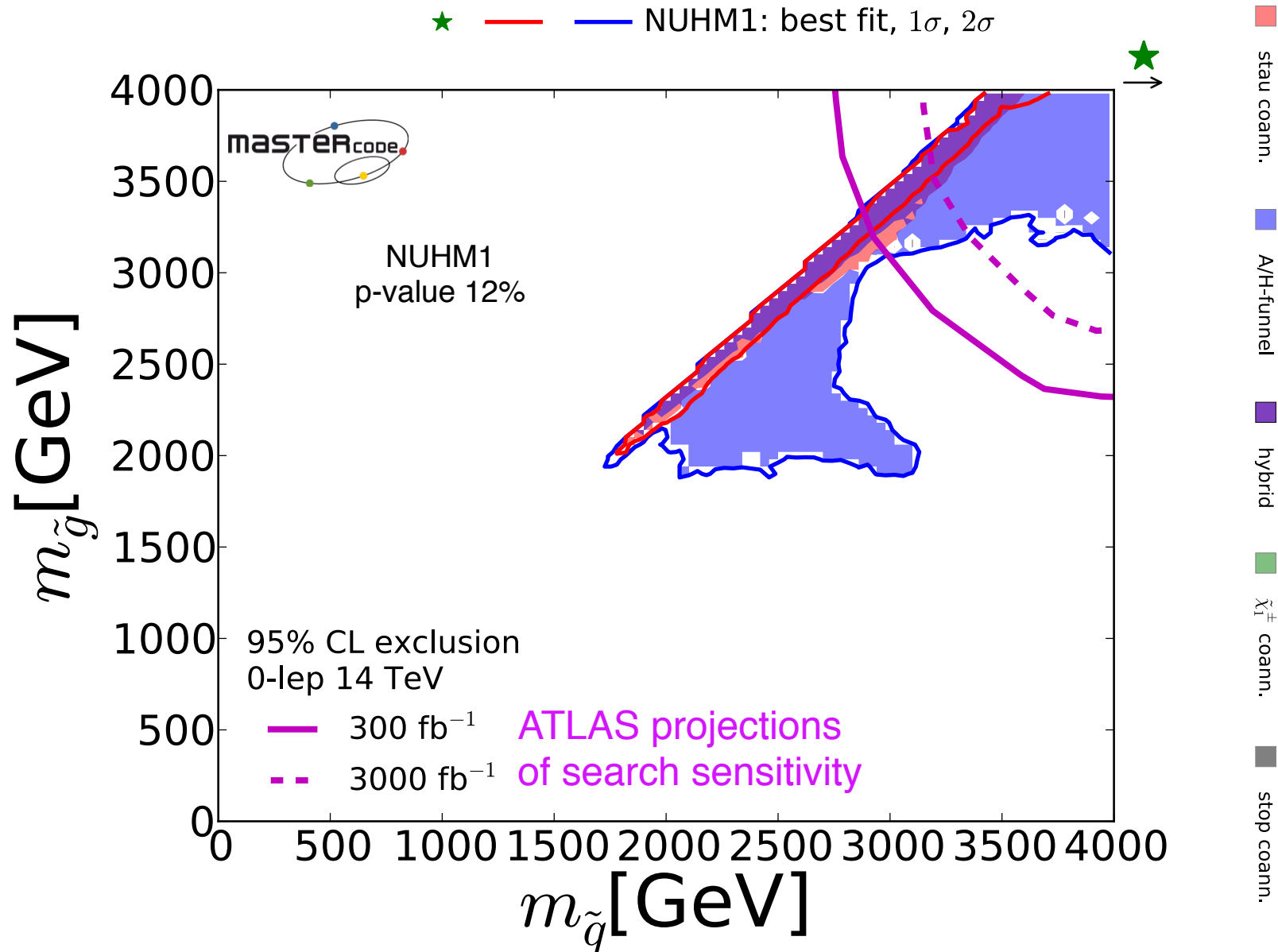
$m_{H_u}^2 \neq m_{H_d}^2$

CMSSM Today: M_q - M_g Search plane



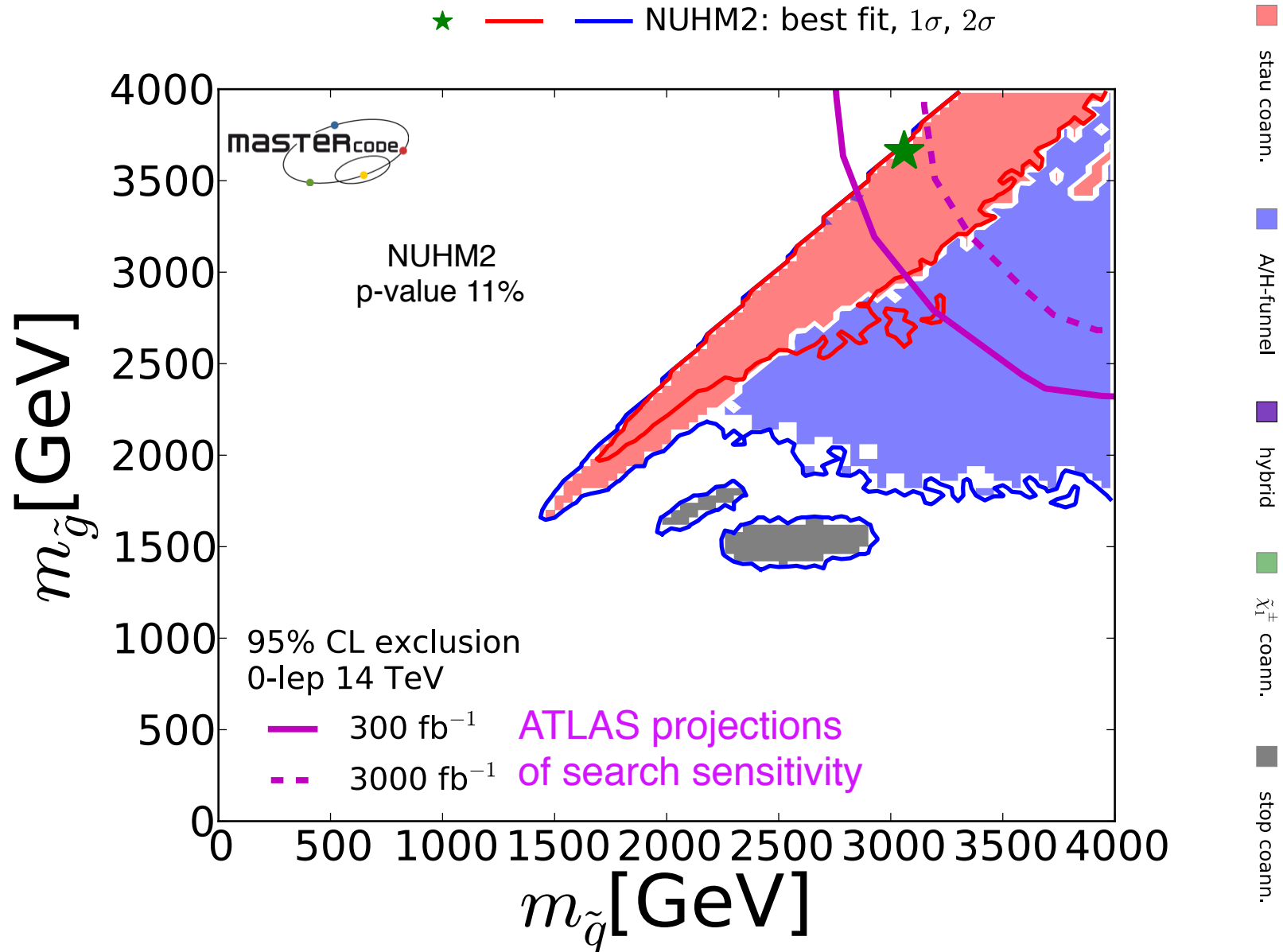
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



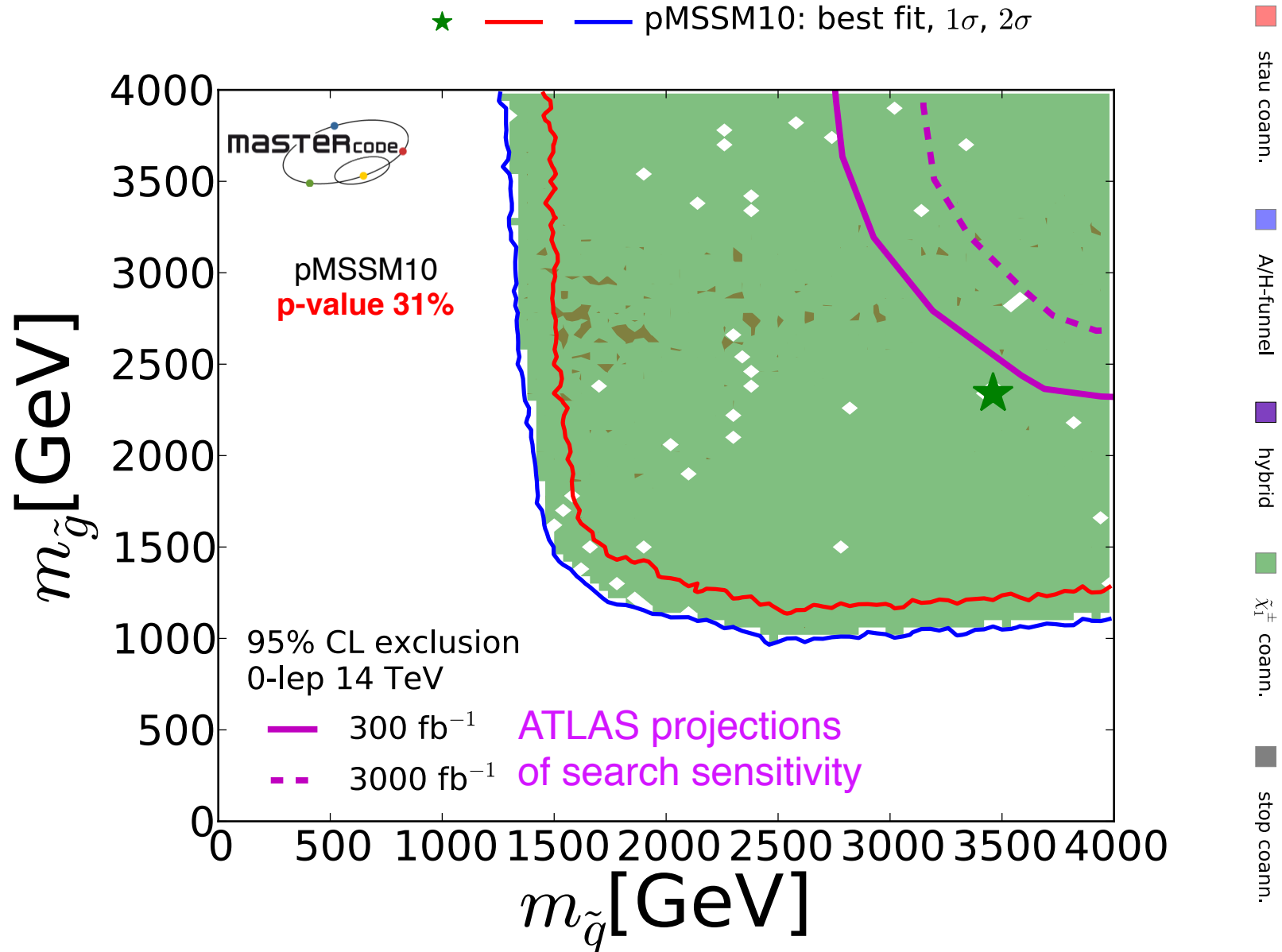
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

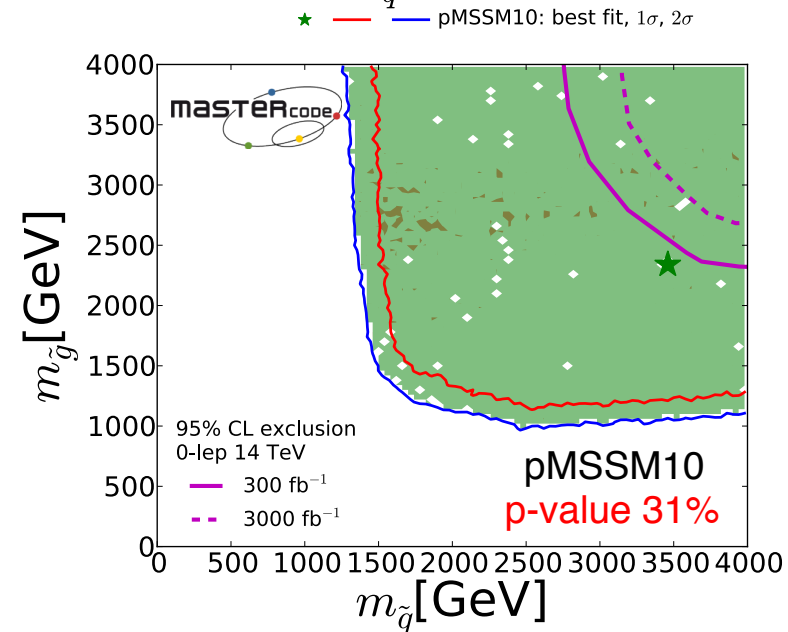
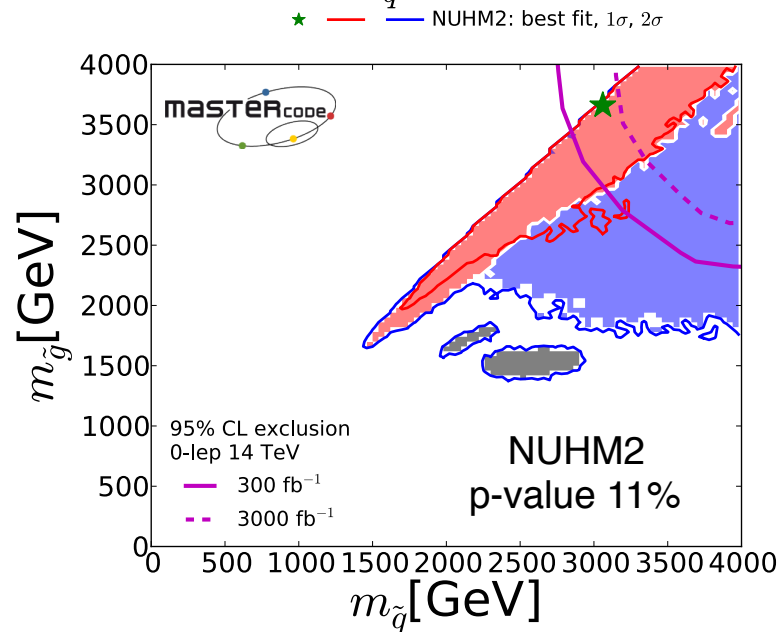
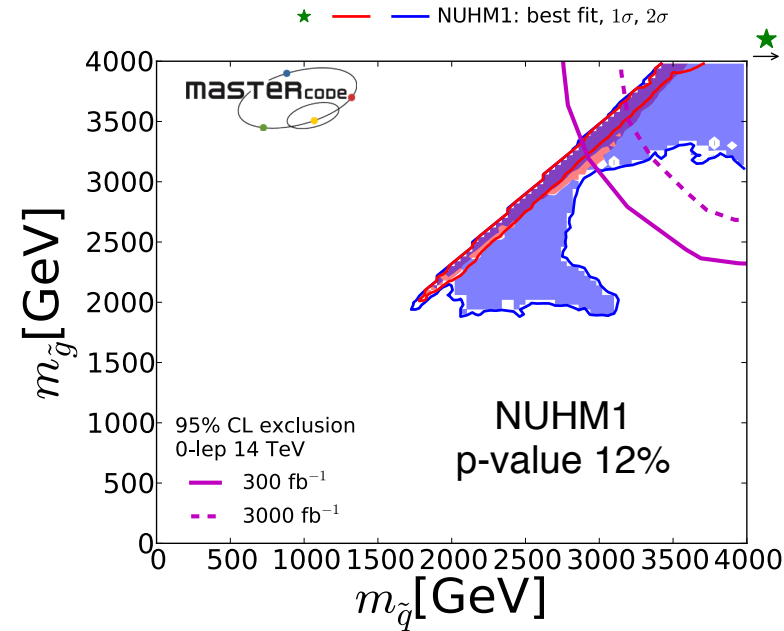
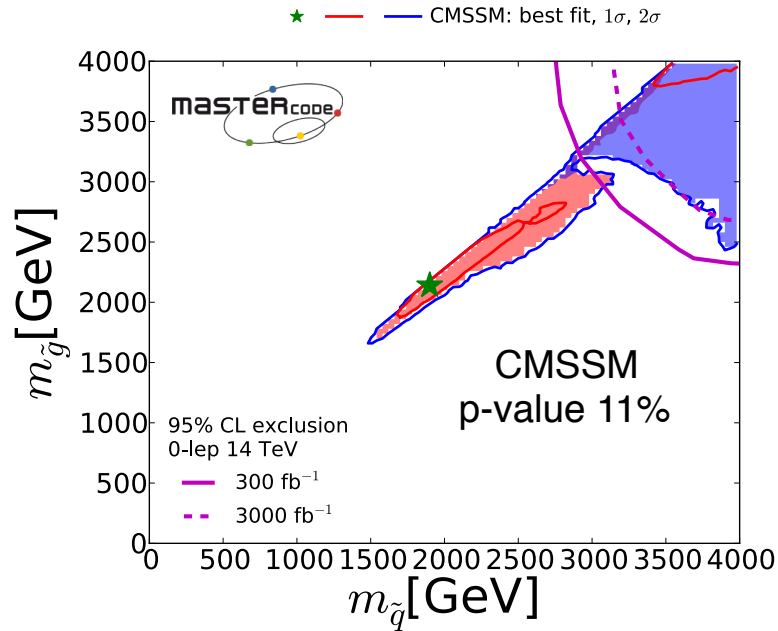
CMSSM Today: M_q - M_g Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Models in Comparison in “Mq-Mg Search plane”

DM Searches @ LHC O. Buchmüller



■ stau coann.
■ A/H-funnel
■ hybrid
■ $\tilde{\chi}_1^\pm$ coann.
■ stop coann.

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

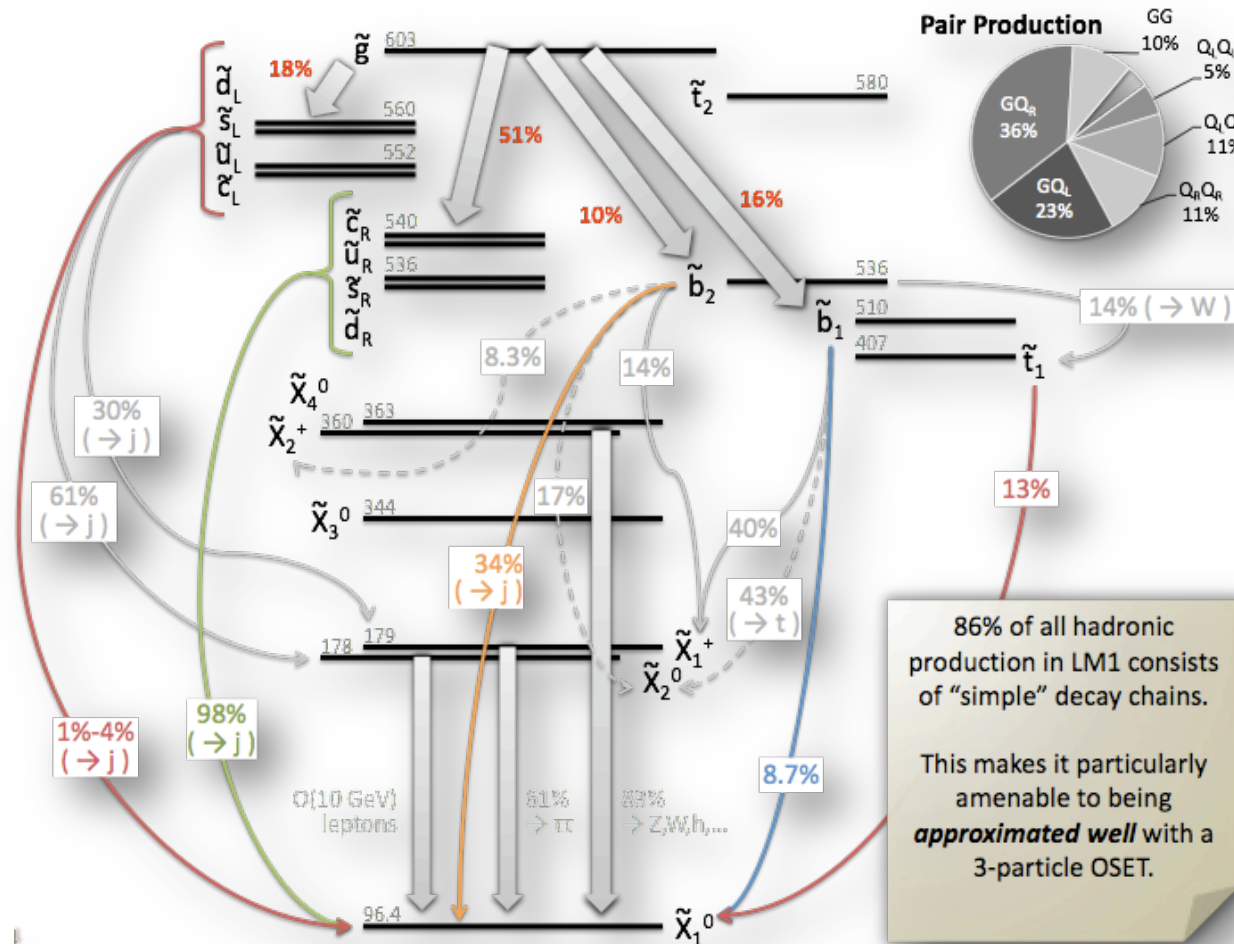
SUSY Status – post 7 TeV LHC data

- 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!

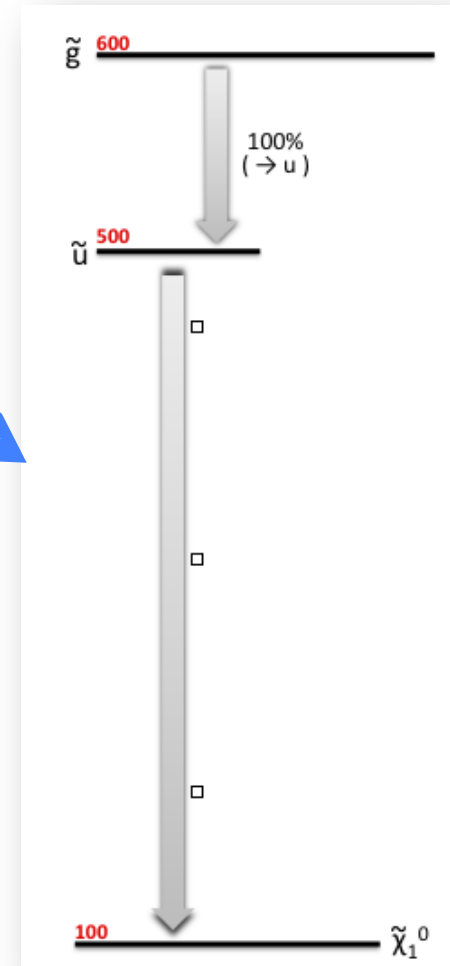
Interpretation in Simplified Models

DM Searches @ LHC O. Buchmüller

CMSSM



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

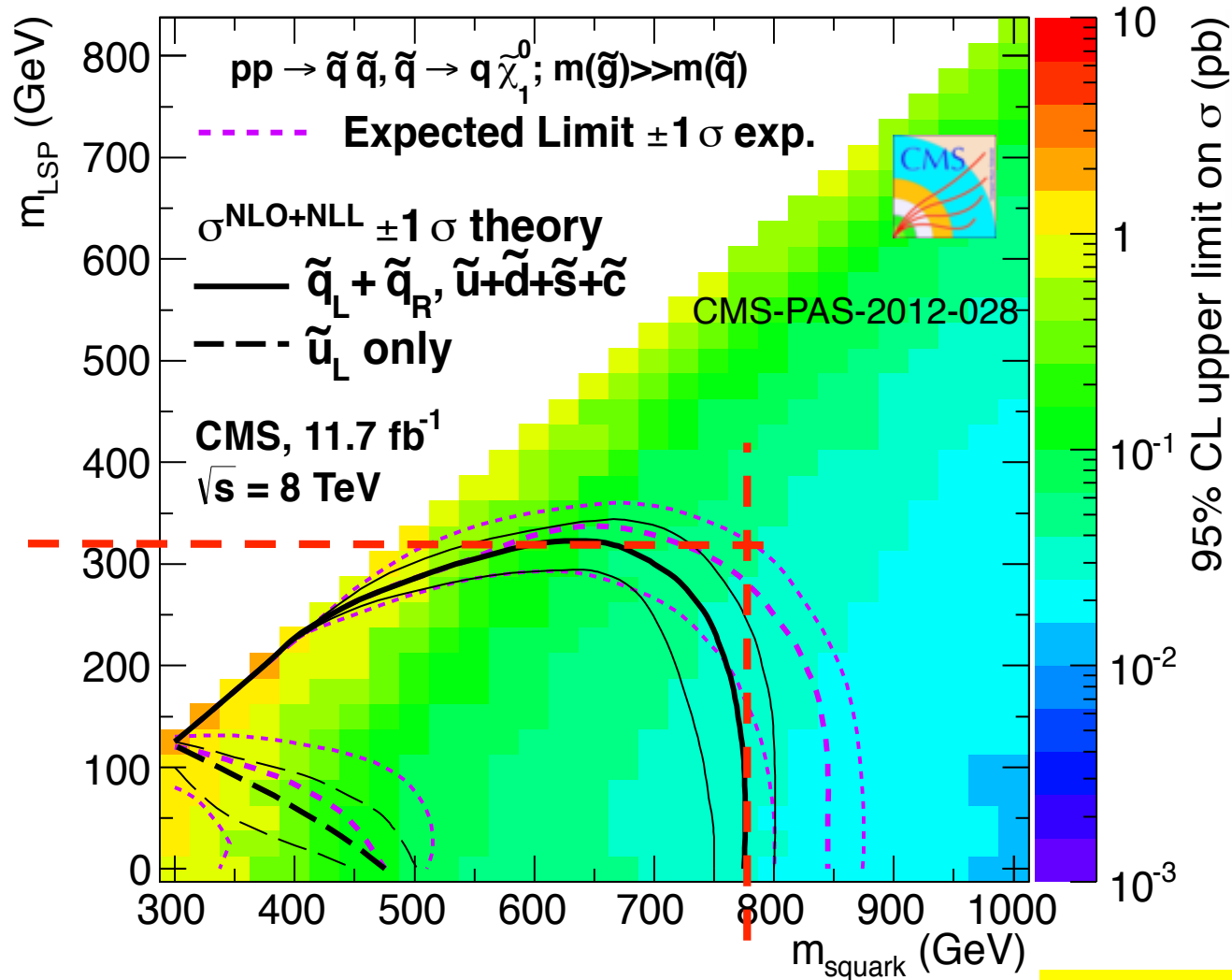


Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

SMS: a few interesting features

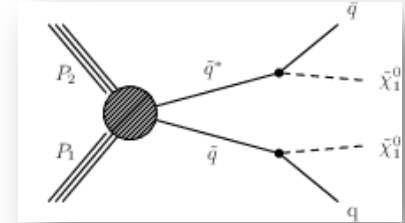
DM Searches @ LHC O. Buchmüller

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



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

Assumes 100%
BR for decay chain
considered.



$$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$$

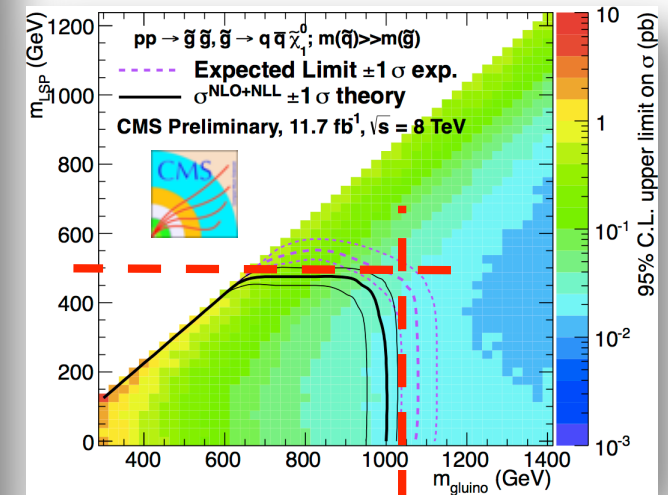
How to summarize SMS limits?

*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 $\tilde{g}\tilde{q}, \tilde{g}\tilde{\bar{q}}$	$m_{\tilde{\chi}_1^0} = 0, m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0, \text{all } m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0, \text{all } m_{\tilde{q}}$	-	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>

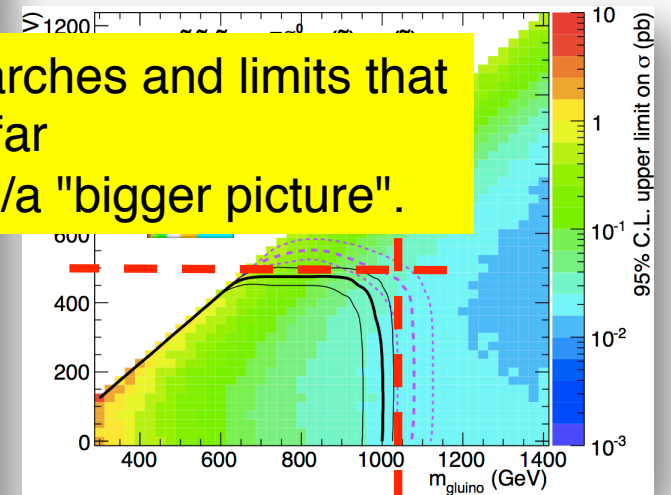
<http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf>

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
CMSSM	all m	800	800

Simpli

Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\tilde{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0, m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0, \text{all } m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0, \text{all } m_{\tilde{q}}$	-	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).

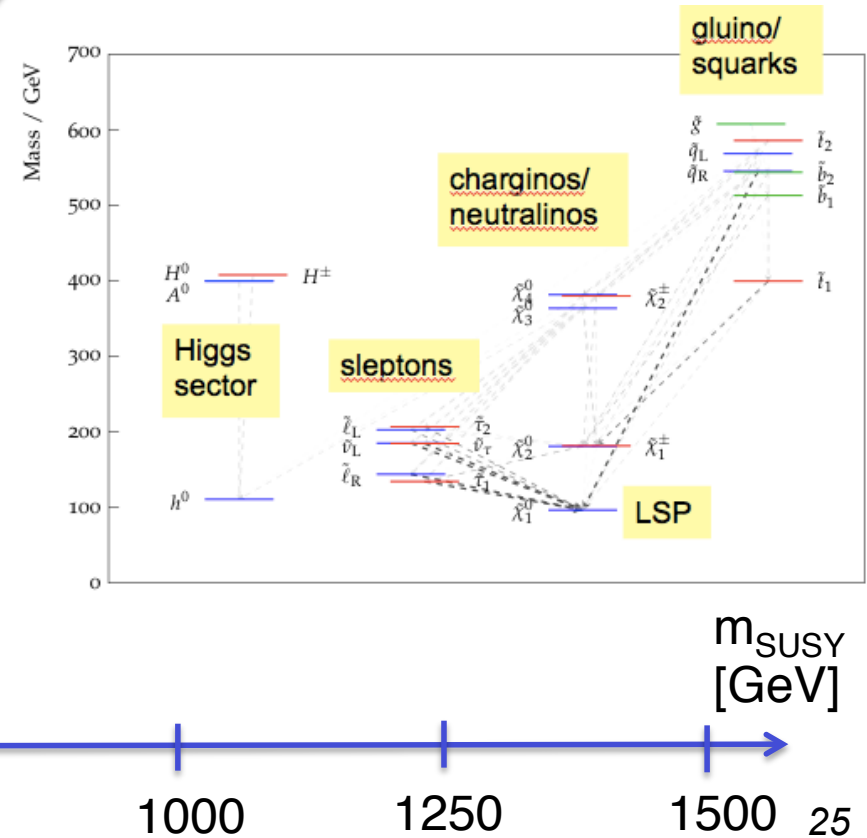
m_{LSP}
[GeV]

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>

$$m_{\text{SUSY}} - m_{\text{LSP}} < m_t$$

What are representative
SMS limits on the different
particles?



Direct stop in “gap”

$$m_{SUSY} = m_{\tilde{q}}$$

$$m_{SUSY} = m_{\tilde{t}}$$

$$\tilde{t} \rightarrow t\chi_1^0$$

$\tilde{t} \rightarrow b f f' \chi_1^0$ 

ATLAS arXiv:1407.0583

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

CMS arXiv:1308.1586

Direct slepton

$$m_{SUSY} = m_{\tilde{l}}$$

$\tilde{l}_R \rightarrow l^\pm \chi_1^0$ 

ATLAS:
arXiv:1403.5294

$\tilde{l}_L \rightarrow l^\pm \chi_1^0$ 

ATLAS:
arXiv:1403.5294

Direct $\chi_1^\pm / \chi_2^0$
 $m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$

$\chi_1^\pm \chi_2^0(\text{light } \tilde{l})$ —
CMS: arXiv:1405.7570

$\chi_1^\pm \chi_2^0(\text{heavy } \tilde{l})$ — . —
CMS: arXiv:1405.7570

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

$$\underline{\textbf{Direct}} \quad \chi_1^+ \chi_1^-$$

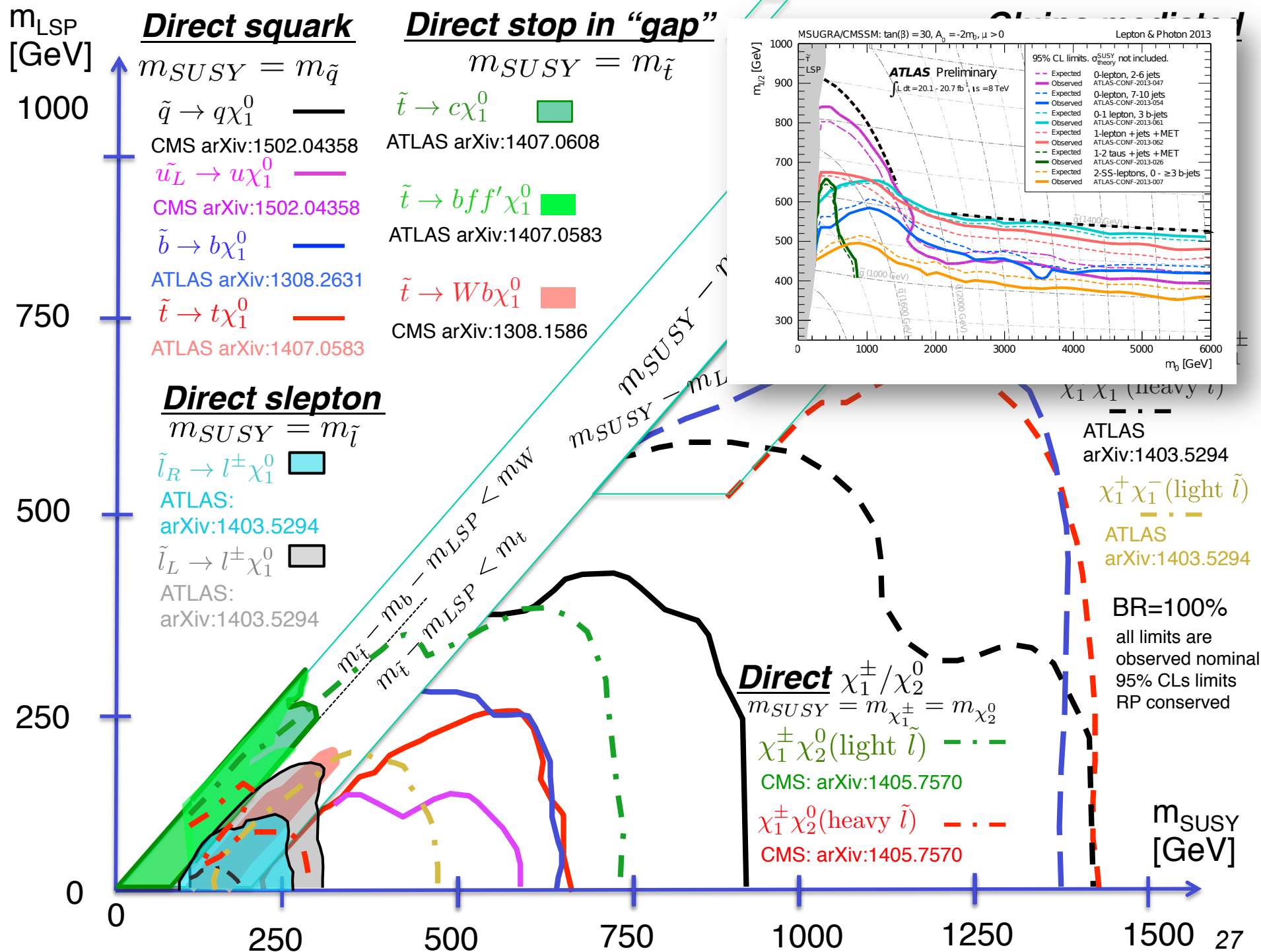
$\chi_1^+ \chi_1^-$ (heavy $\tilde{l}$)
ATLAS
arXiv:1403.5294

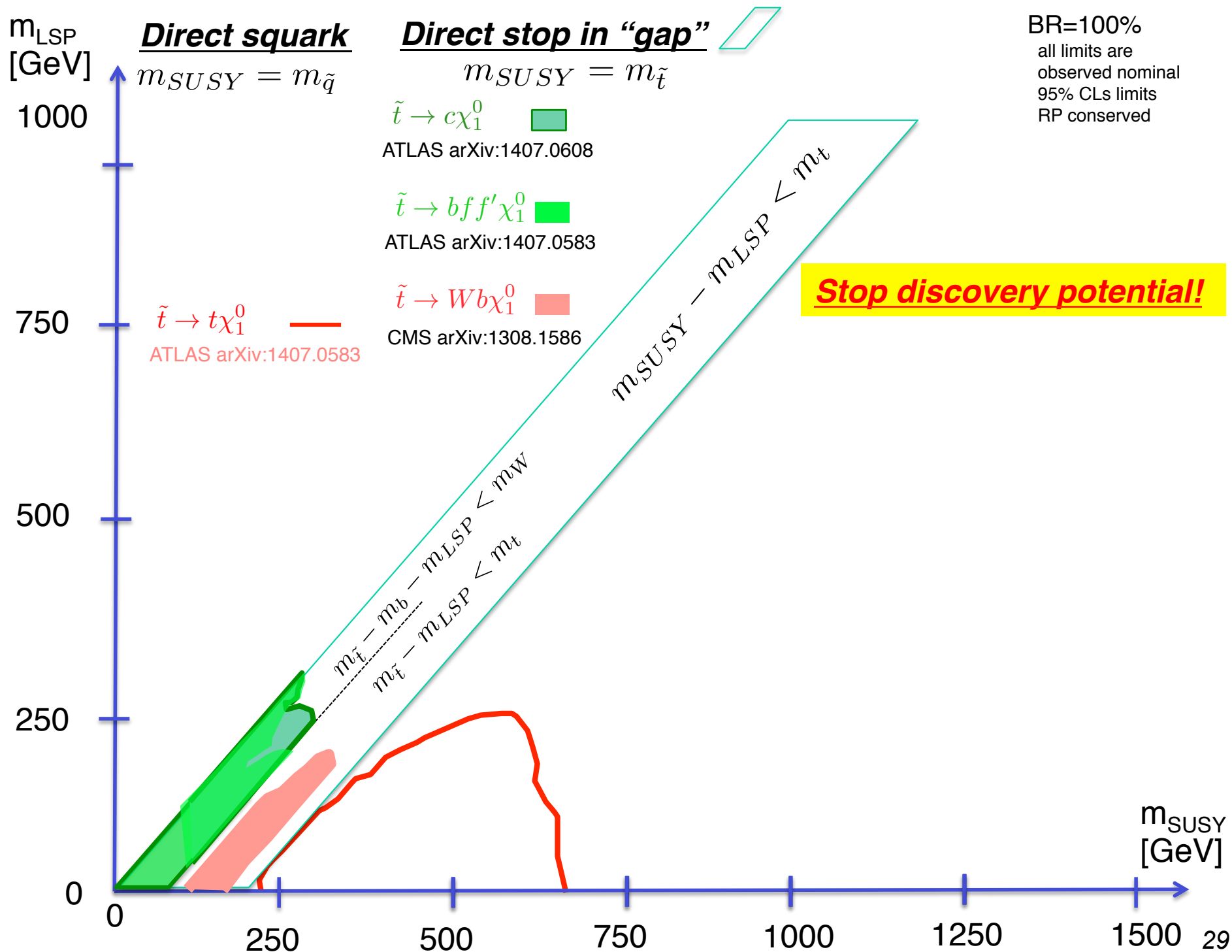
$\chi_1^+ \chi_1^-$ (light $\tilde{l}$)
 ATLAS
 arXiv:1403.5294

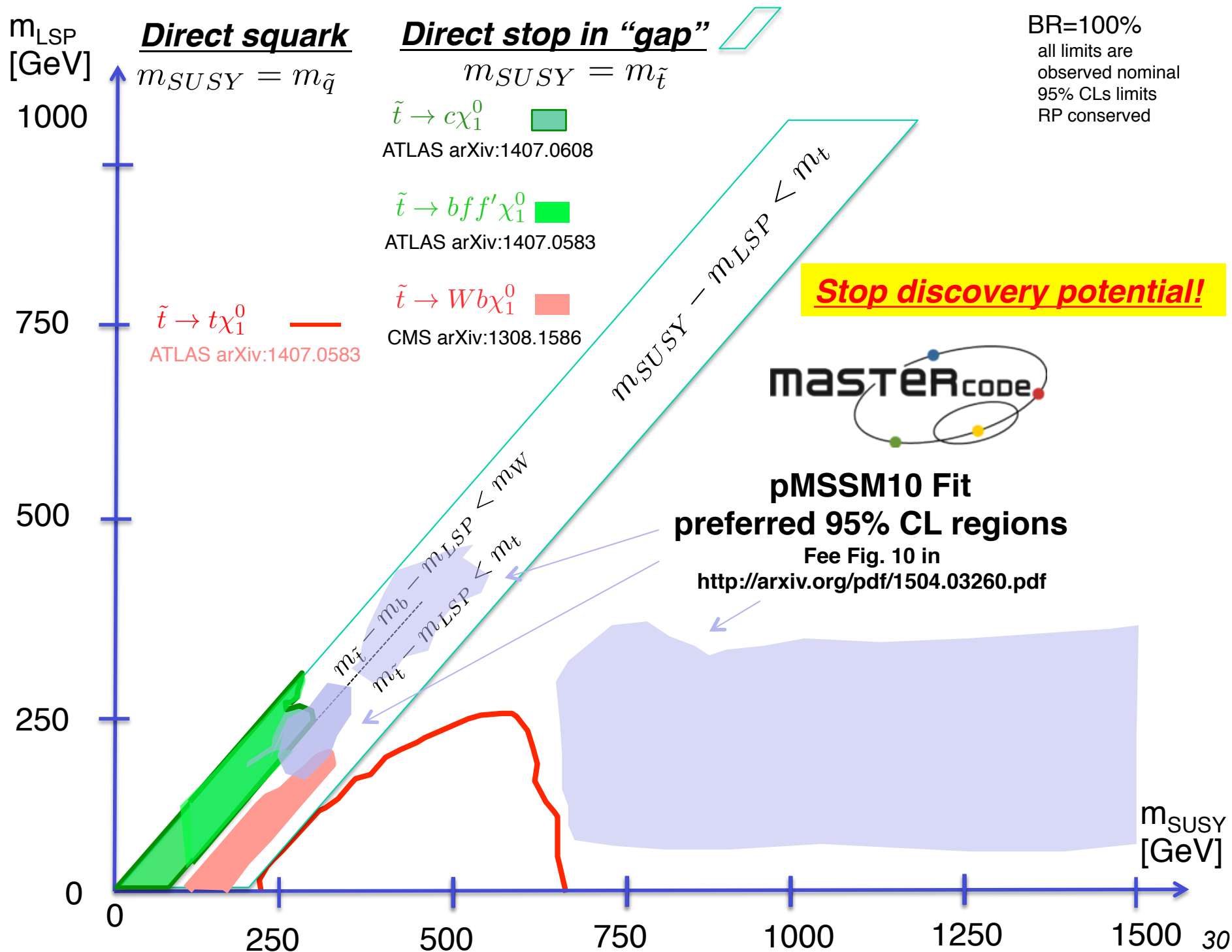
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved

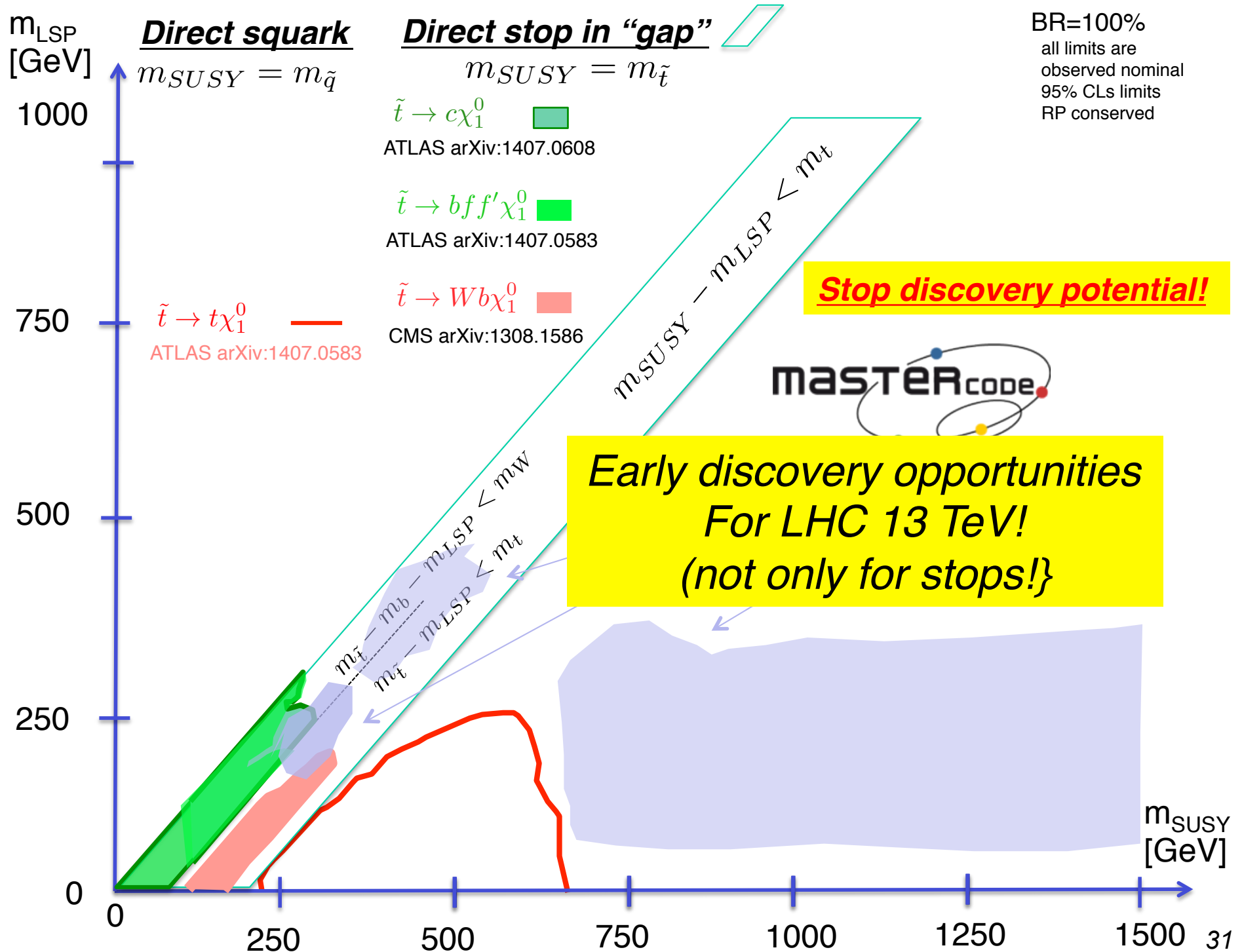
$$m_{\text{SUSY}}$$

$$[\text{GeV}]$$

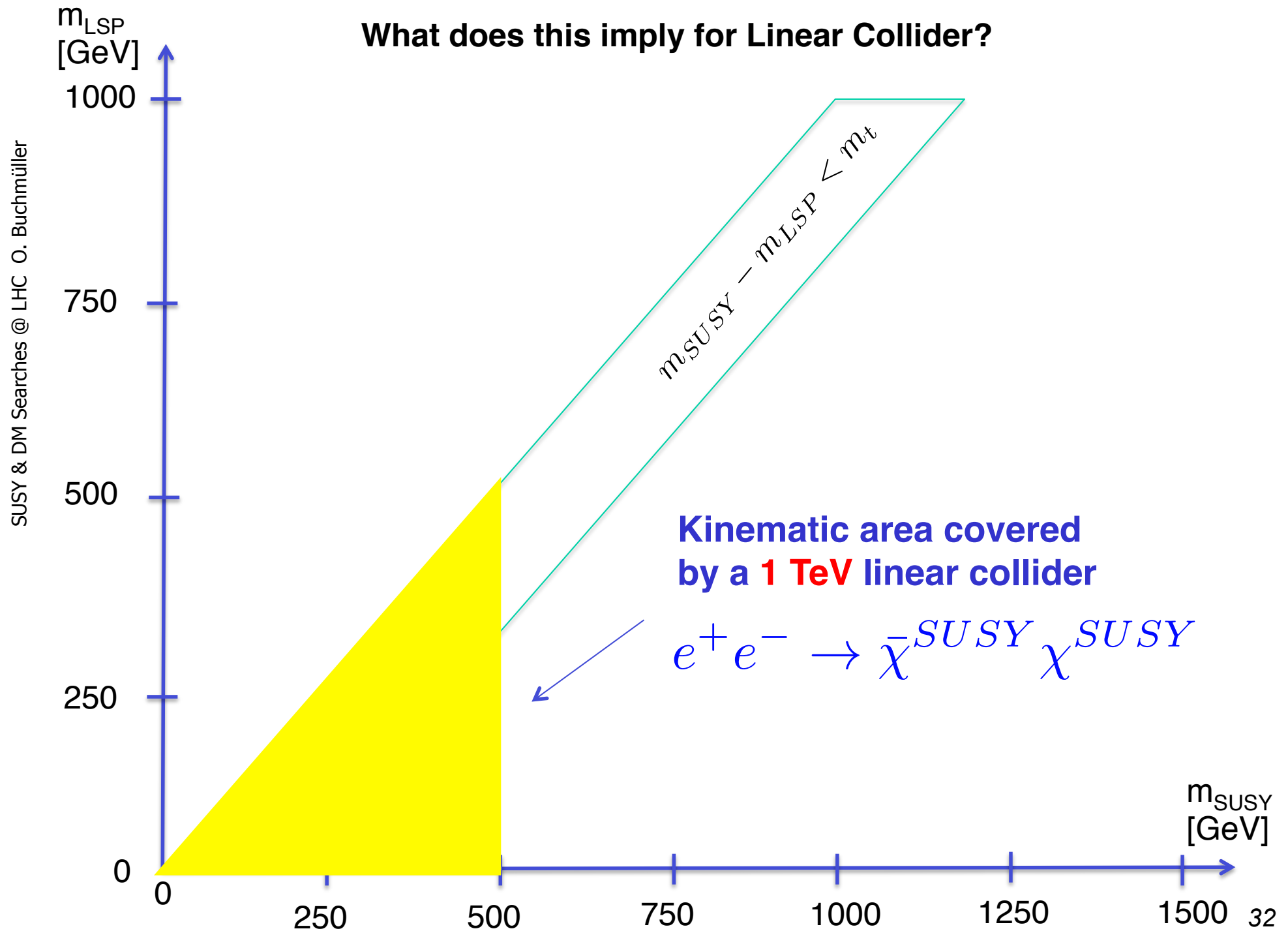



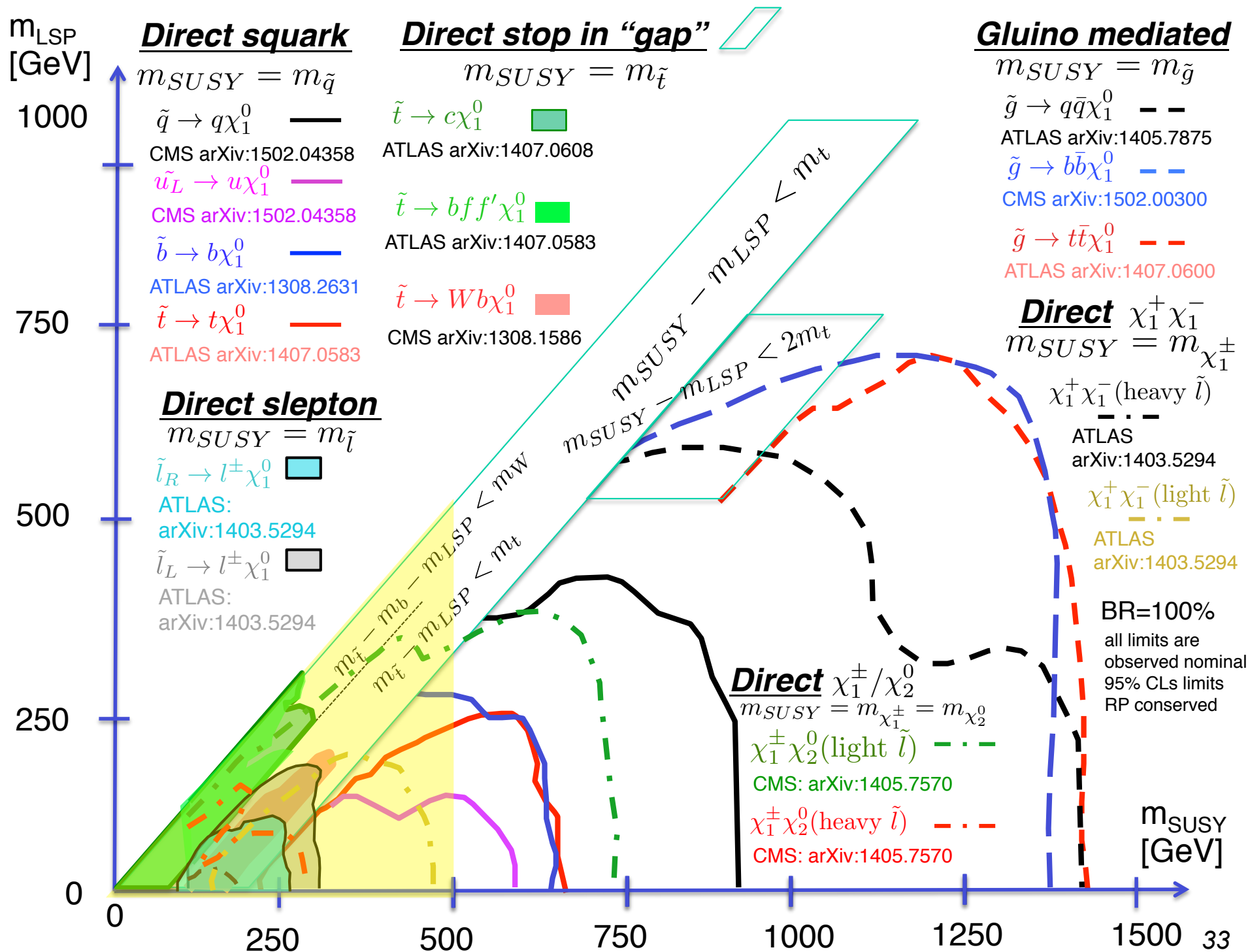


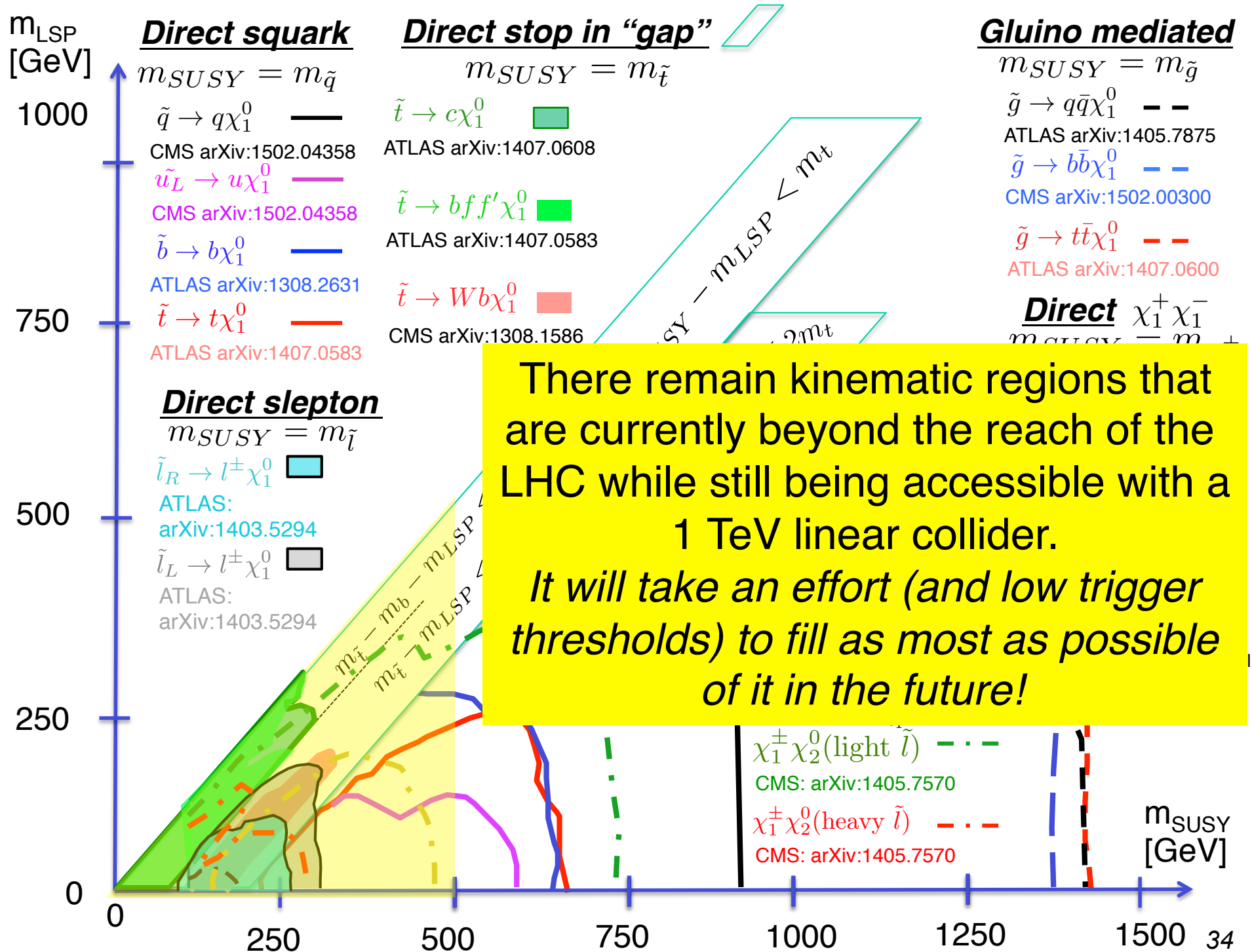




What does this imply for Linear Collider?





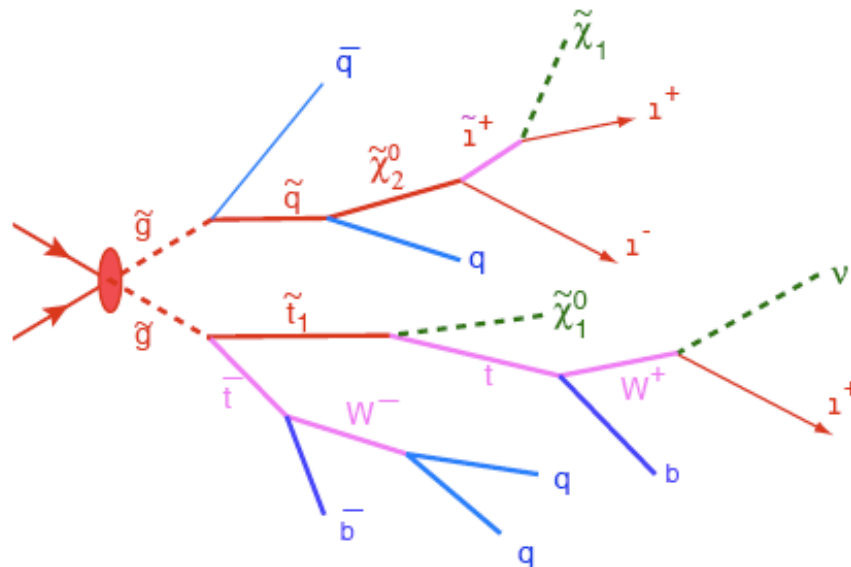


Characterizing Dark Matter Searches

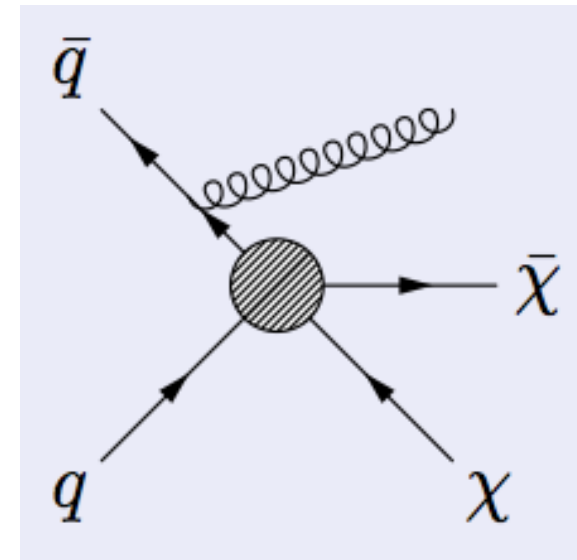
complete theory vs. simple interpretations



SUSY



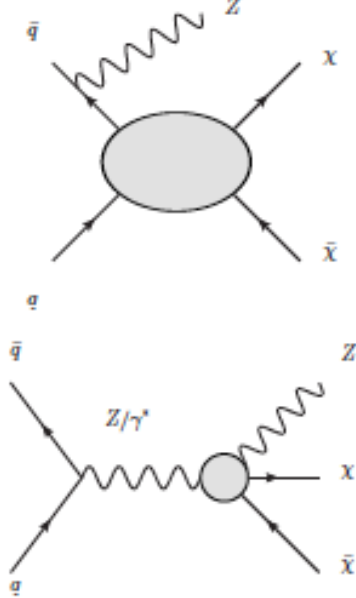
**Example:
Effective Field Theory
Simplified models**



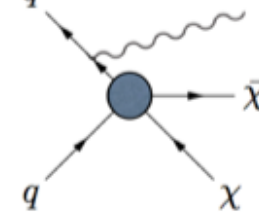
Mono-Mania (at the LHC)

DM Searches @ LHC O. Buchmüller

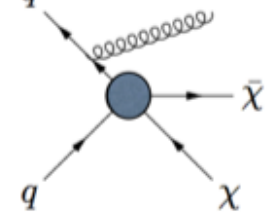
Mono-Z



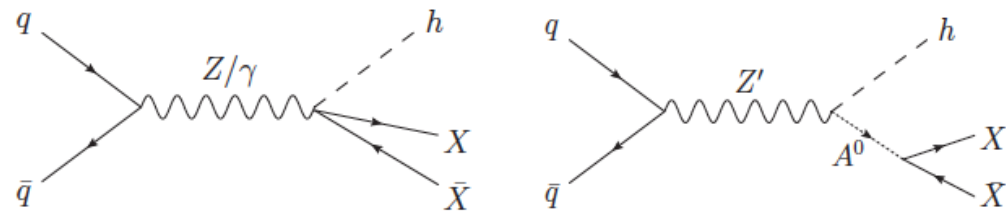
Mono-photon



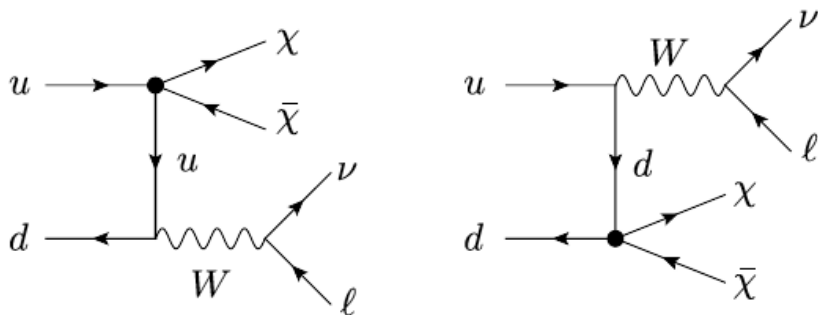
Mono-jet



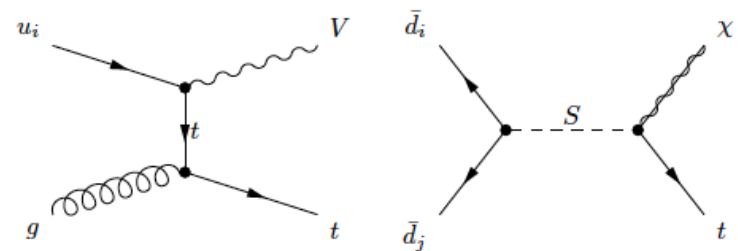
Mono-Higgs



Mono-W



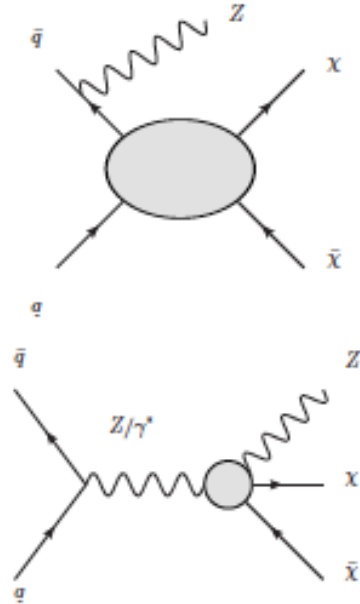
Mono-top



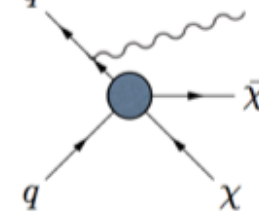
Mono-Mania (at the LHC)

DM Searches @ LHC O. Buchmüller

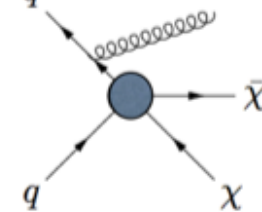
Mono-Z



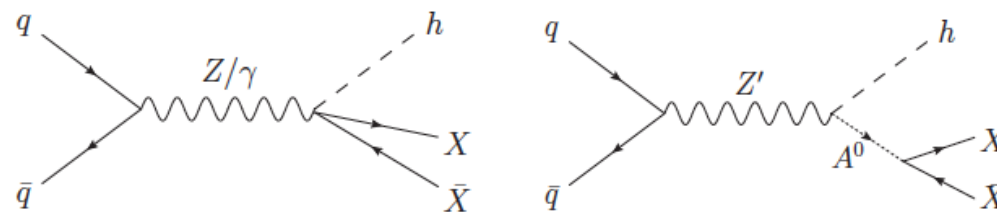
Mono-photon



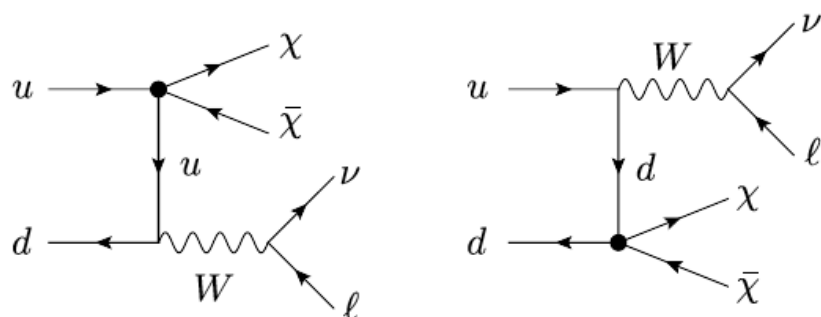
Mono-jet



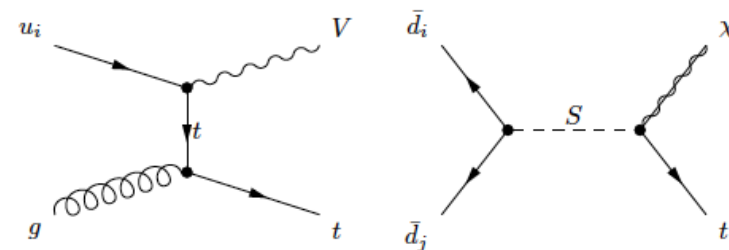
Mono-Higgs



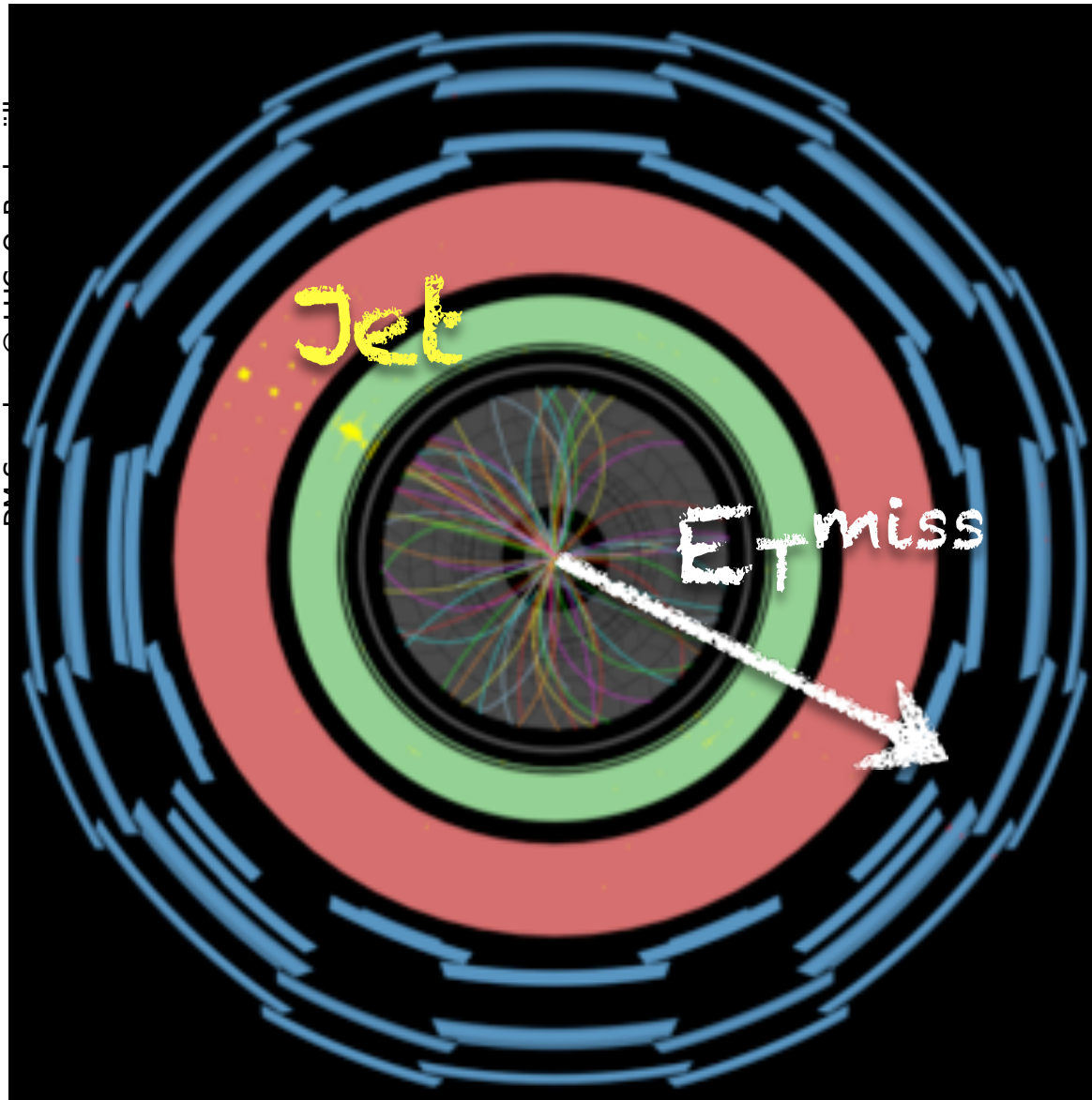
Mono-W



Mono-top



Mono-X searches at colliders



E_T^{miss} trigger

**Example Monojet
(8 TeV, 20.3 fb⁻¹)**

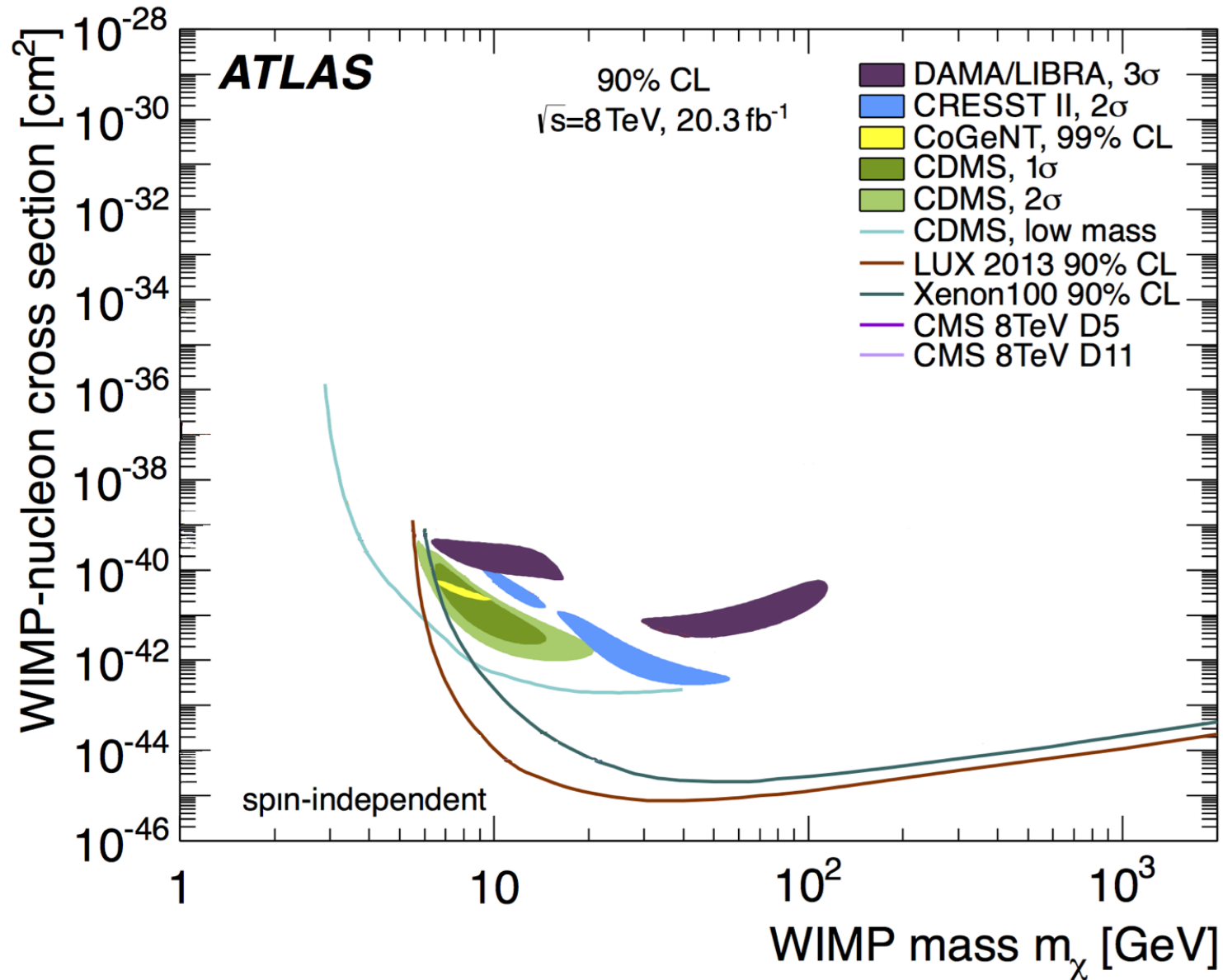
$E_T^{\text{miss}}, p_T(j) > 150 - 900 \text{ GeV}$
1 or 2 jets (anti- k_T ,
 $R=0.4, p_T > 30 \text{ GeV}$)
 $|\Delta\phi(E_T^{\text{miss}}, j_2)| > 0.5$

**Example Monophoton
(8 TeV, 19.6 fb⁻¹):**

$E_T^{\text{miss}}, p_T(\gamma) > 140 \text{ GeV},$
 $N_{\text{jet}} < 2$ (anti- $k_T, R=0.5,$
 $p_T > 30 \text{ GeV}$)
 $\Delta\phi(\gamma, E_T^{\text{miss}}) > 2,$
 $(X^2, \Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.4)$

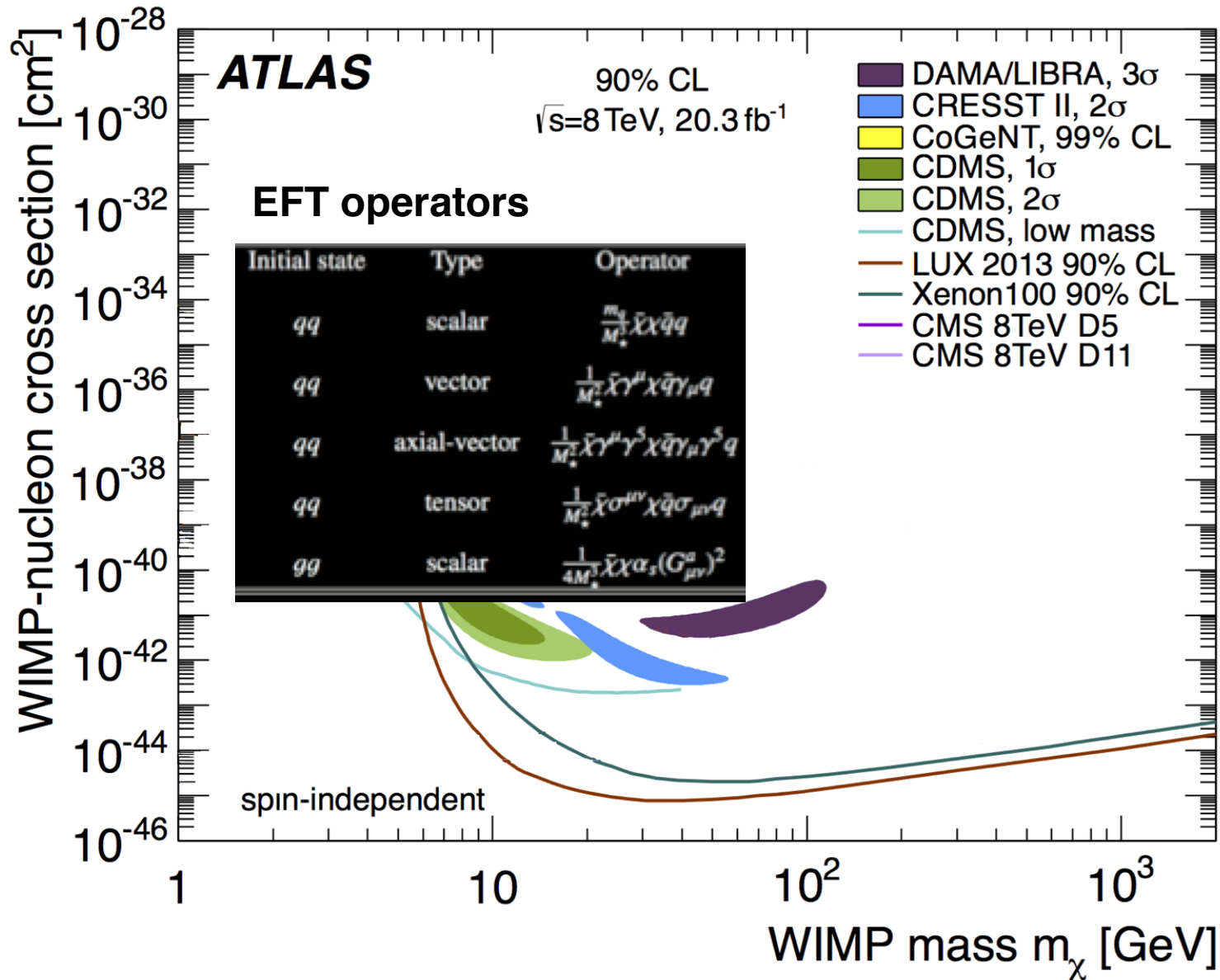
ATLAS Mono-Jet: Comparison with Direct Detection

DM Searches @ LHC O. Buchmüller

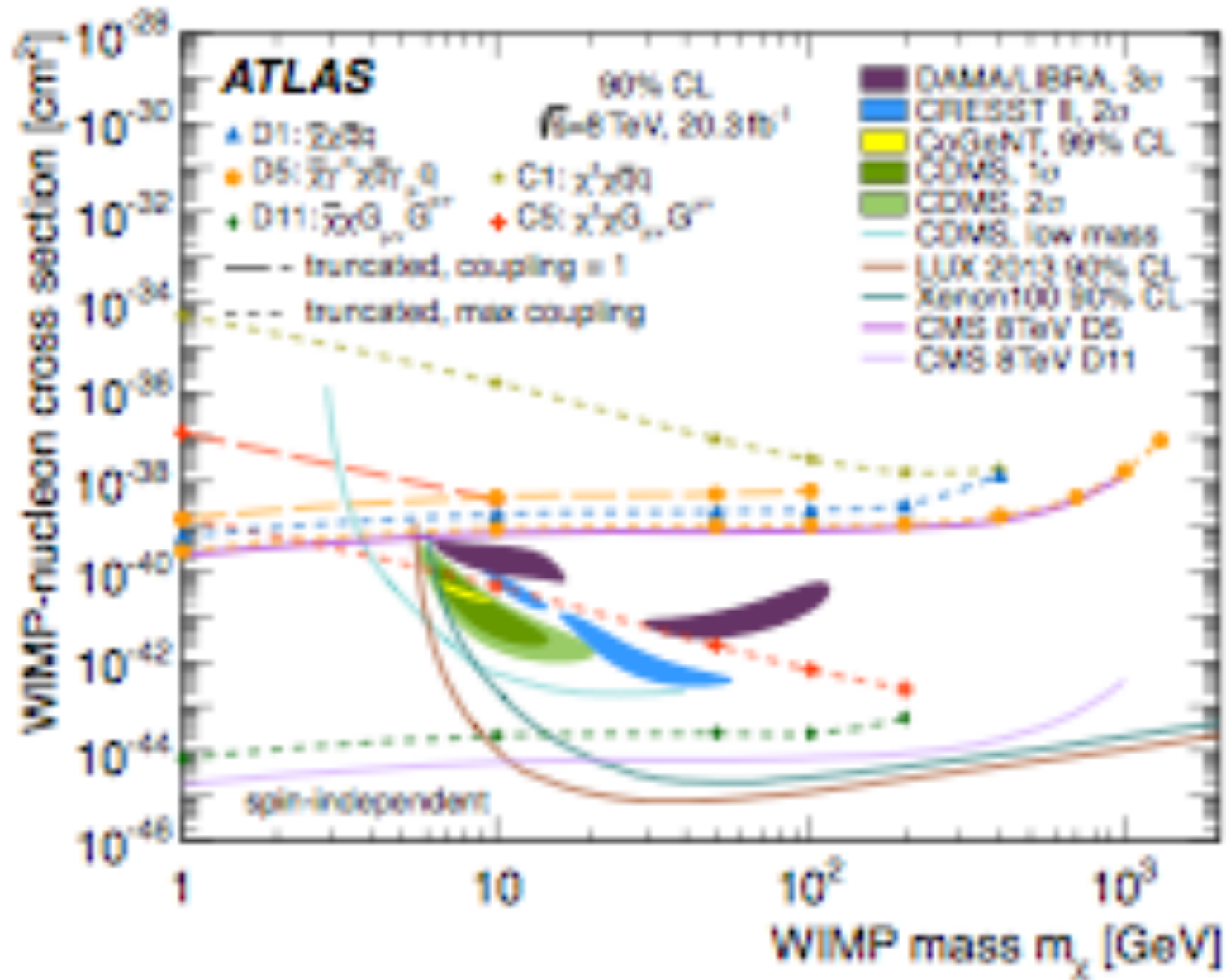


ATLAS Mono-Jet: Comparison with Direct Detection

DM Searches @ LHC O. Buchmüller

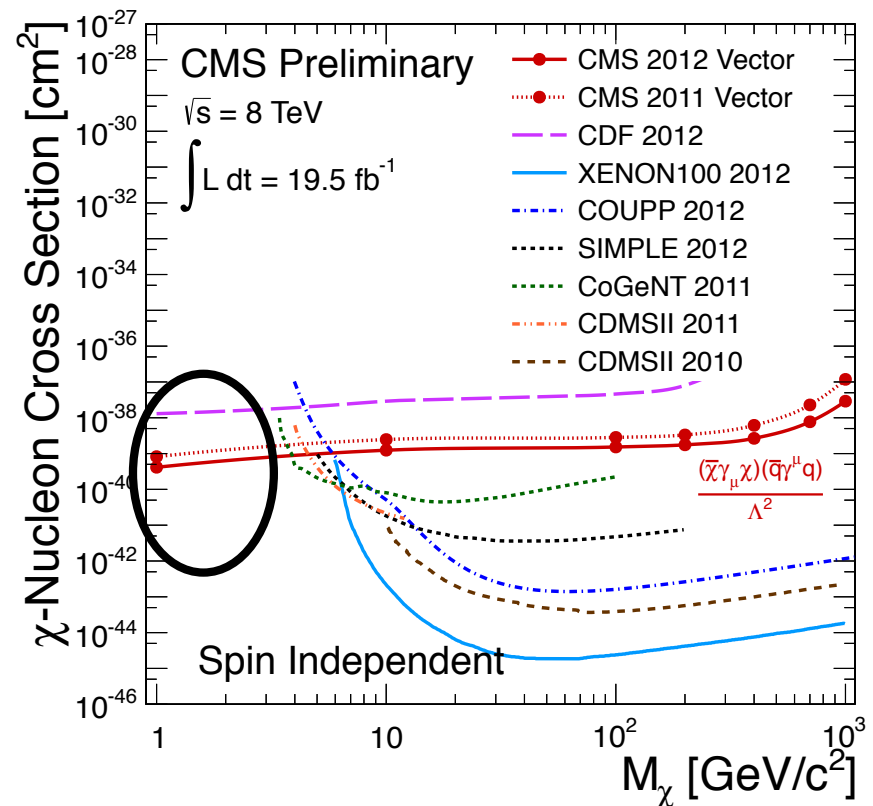
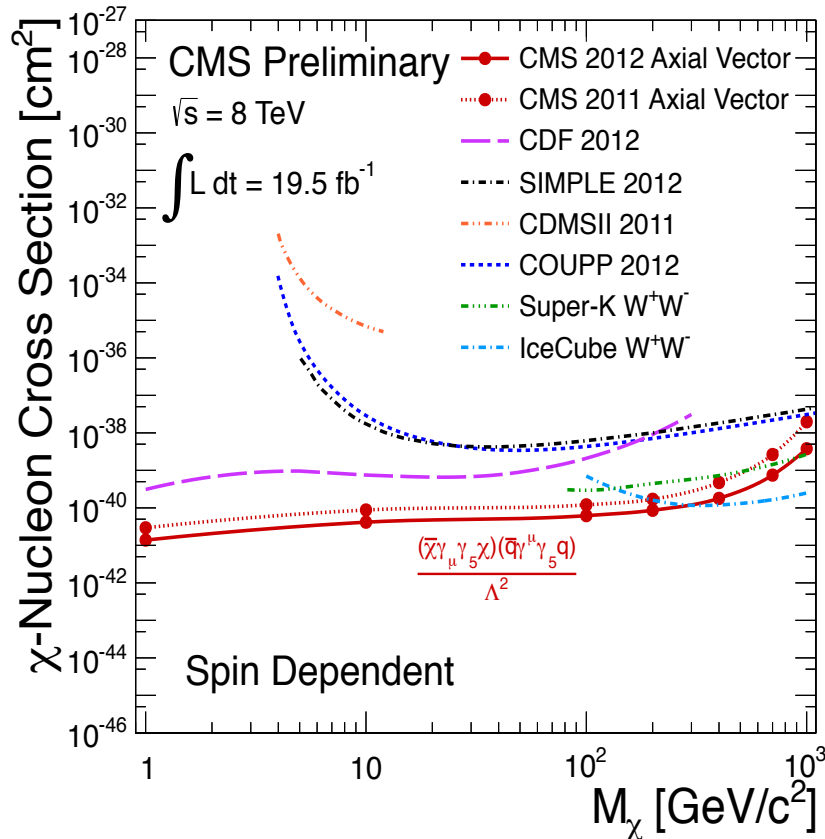


ATLAS Mono-Jet: Comparison with Direct Detection



Mono-Jet analyses better than direct detection?!

DM Searches @ LHC O. Buchmüller



Claim [often made]:

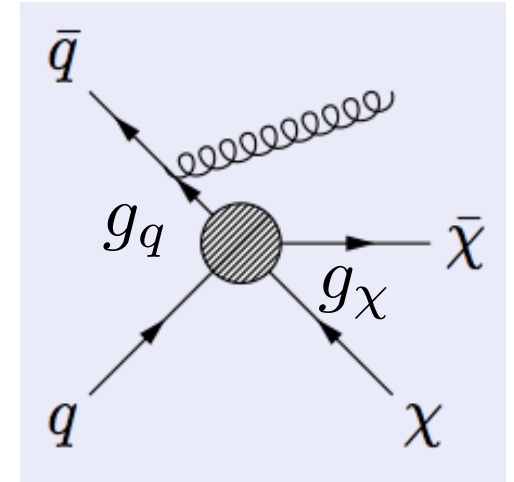
For **low mass** and the entire **spin-dependent** case monojet limits are stronger than direct detection limits!

Effective Field Theory (EFT) Interpretation

Example of considered operators:

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

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



Assumption of EFT

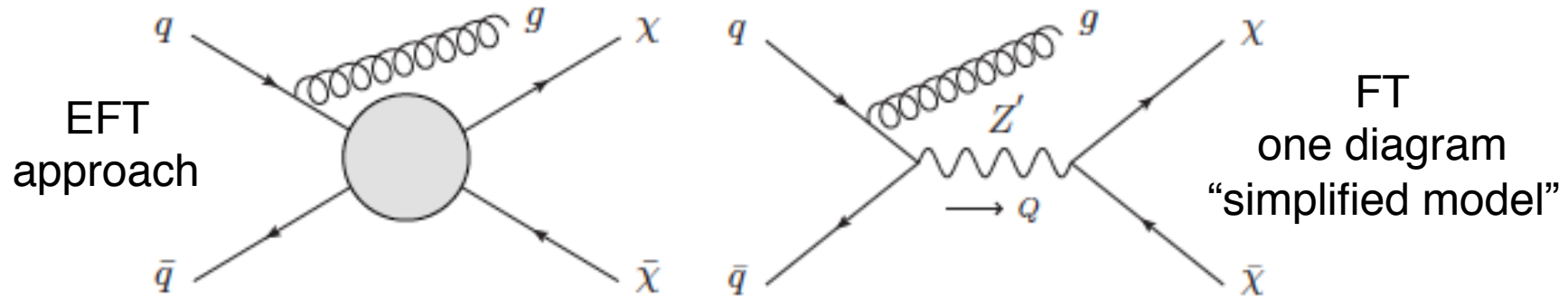
If the operator (e.g. V or AV) mediator is **suitably(!!)** heavy it can be integrated out to obtain the effective V or AV contact operator. **In this case (and only this case)**, the contact interaction scale Λ is related to the parameters entering the Lagrangian:

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

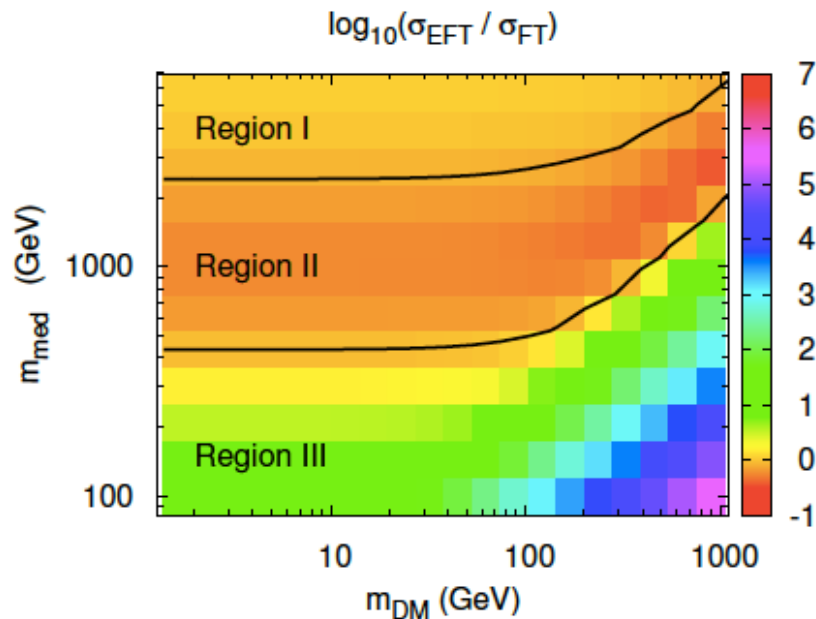
Validity of Effective Field Theory Limits

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

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



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



Compare prediction of FT with EFT in $m_{\text{med}} - m_{\text{DM}}$ plane. Three regions become visible:

Region I: EFT and FT agree better than 20%

➤ EFT is valid!

Region II: EFT yields significant weaker limits than FT

➤ EFT limits are too conservative!

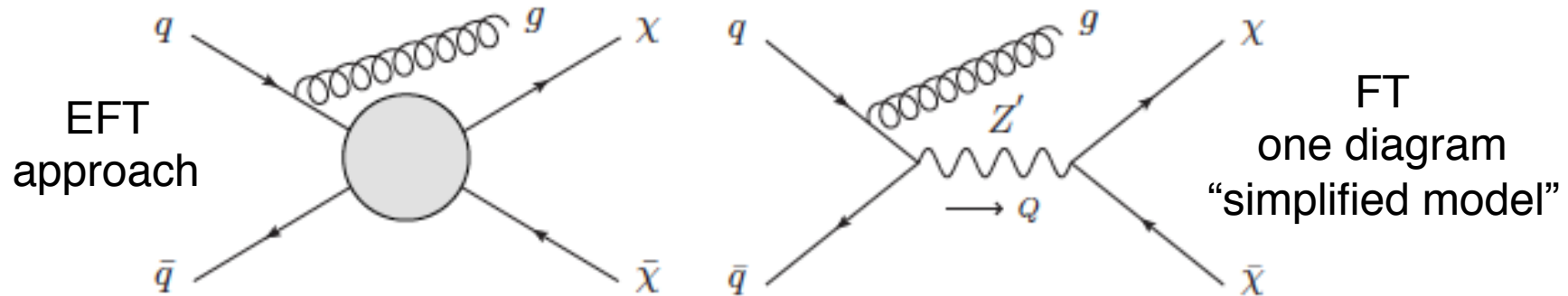
Region III: EFT yields significant stronger limits than FT

➤ EFT limits are too aggressive!

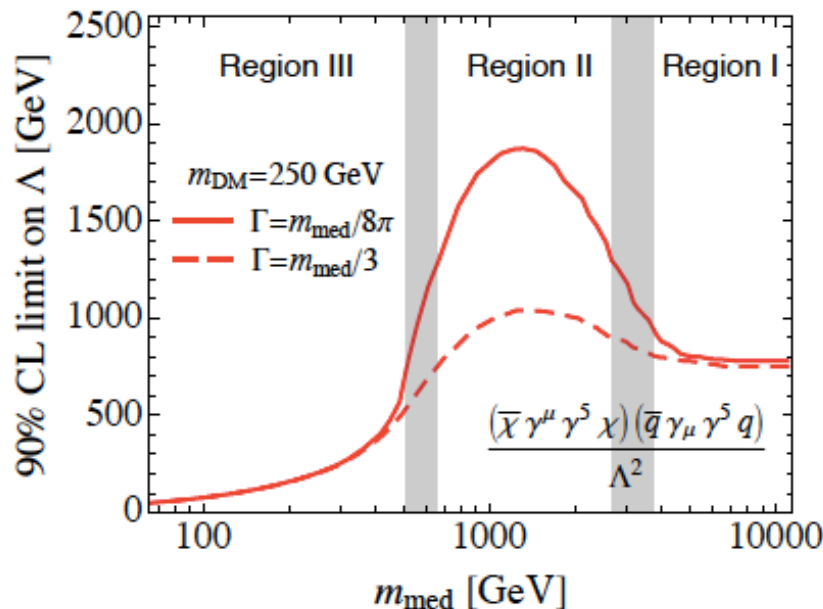
Validity of Effective Field Theory Limits

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

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



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!

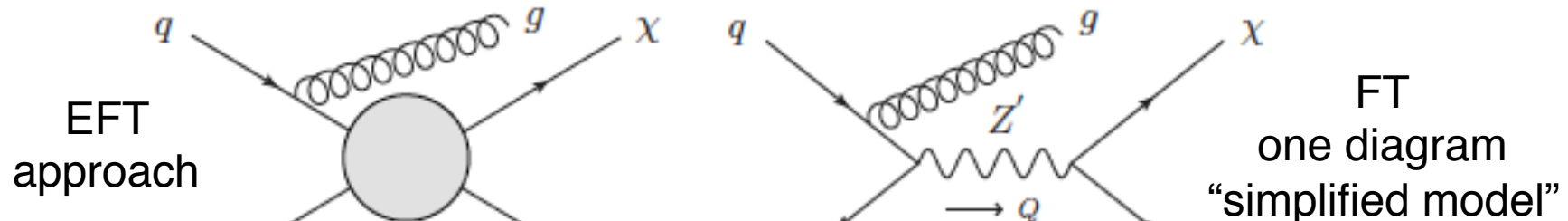
Region III: Low m_{med}

➤ EFT limits are too aggressive!

Validity of Effective Field Theory Limits

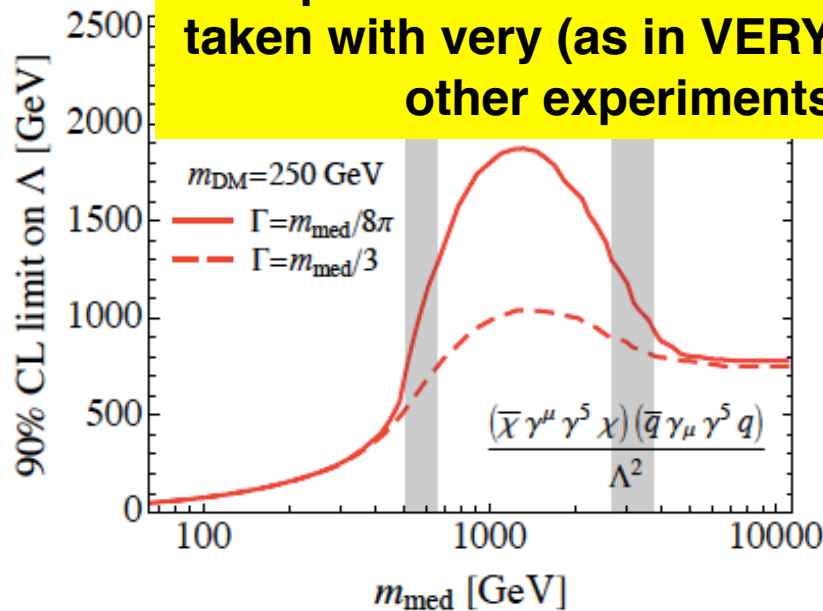
Recent work from OB, M.Dolan, C.McCabe: arXiv:1308.6799

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



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!



Region I: Heavy m_{med}

➤ EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

➤ EFT limits are too conservative!

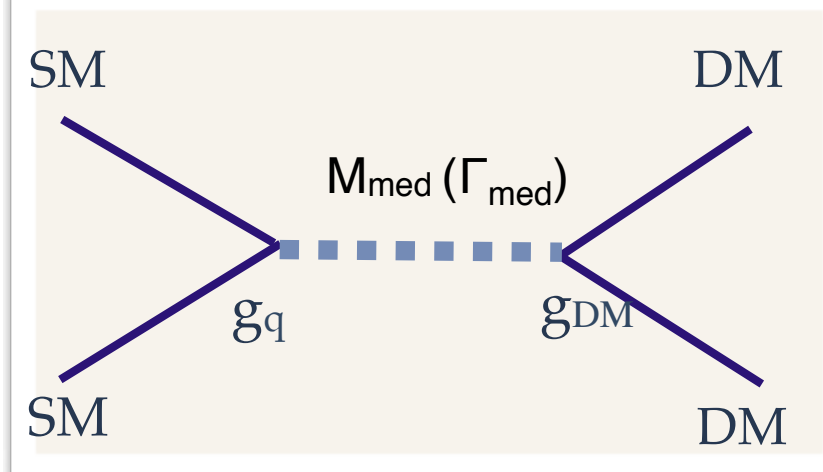
Region III: Low m_{med}

➤ EFT limits are too aggressive!

Minimal Simplified Dark Matter Model

DM Searches @ LHC O. Buchmüller

Based on work from :
OB, S. Malik,
M.Dolan,C.McCabe
arXiv:1407.8257



s-channel

Define simplified model with
(minimum) 4 parameters

Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

DM

Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set
of diagrams for mediator

Vector	Axial-vector
Scalar	Pseudoscalar

(Γ_{med} can also be free as long
As $\Gamma_{\text{med}} < M_{\text{med}}$)

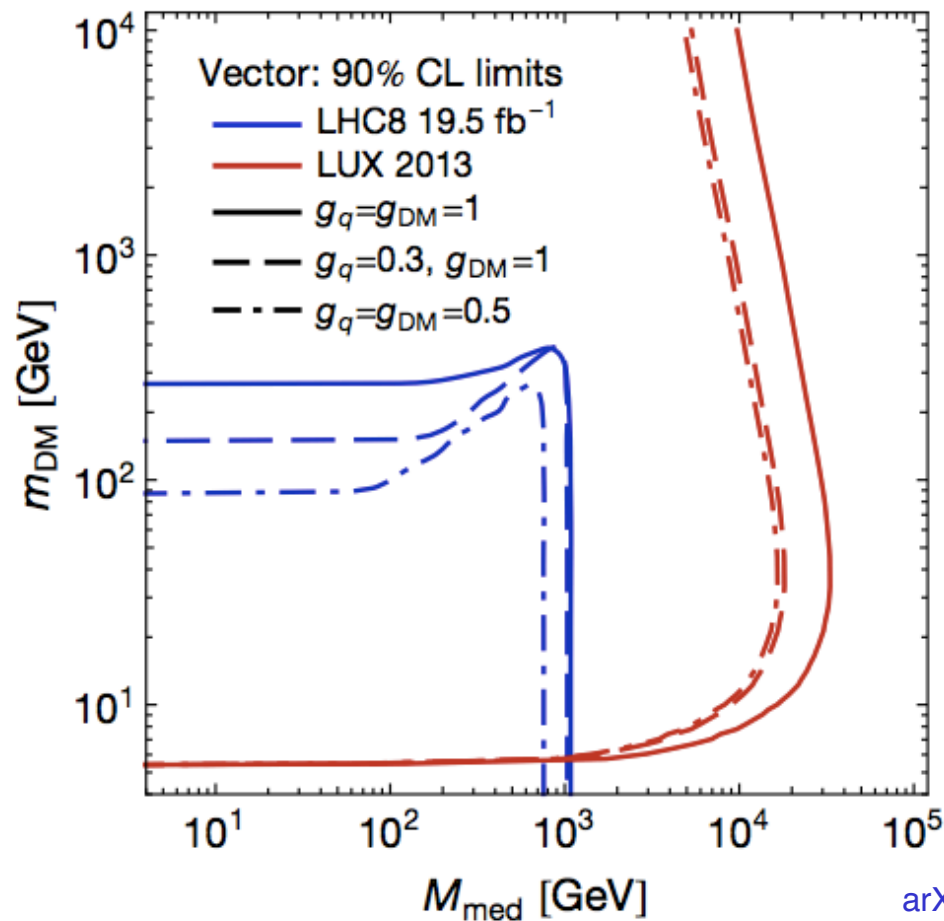
Collider vs Direct Detection

γmüller

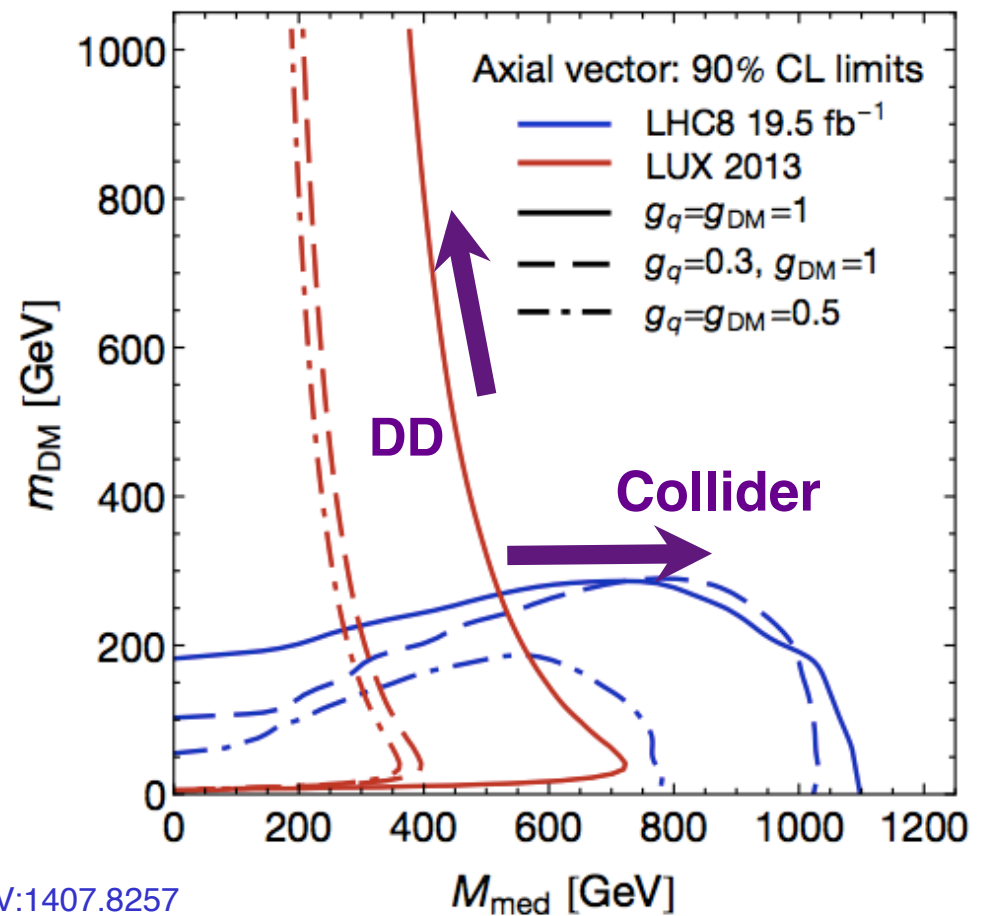
Vector

Axial vector

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



arXiv:1407.8257



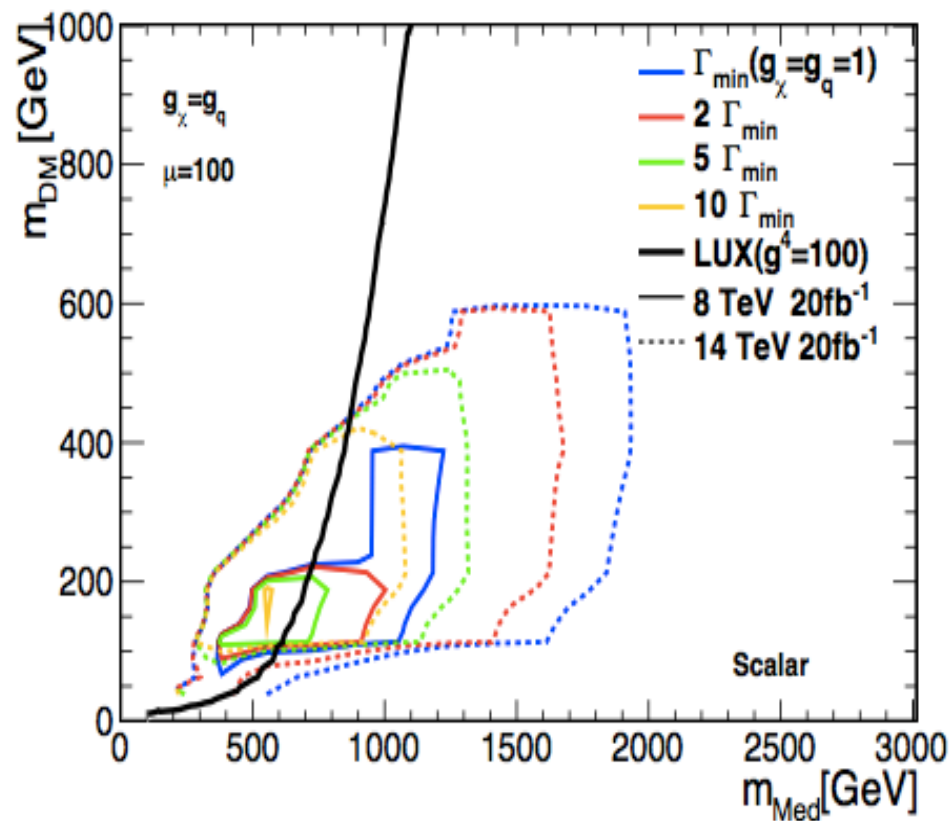
Scalar and Pseudoscalar

Philip Harris, Valentin V. Khoze,
Michael Spannowsky, Ciaran Williams
arXiv:1411.0535

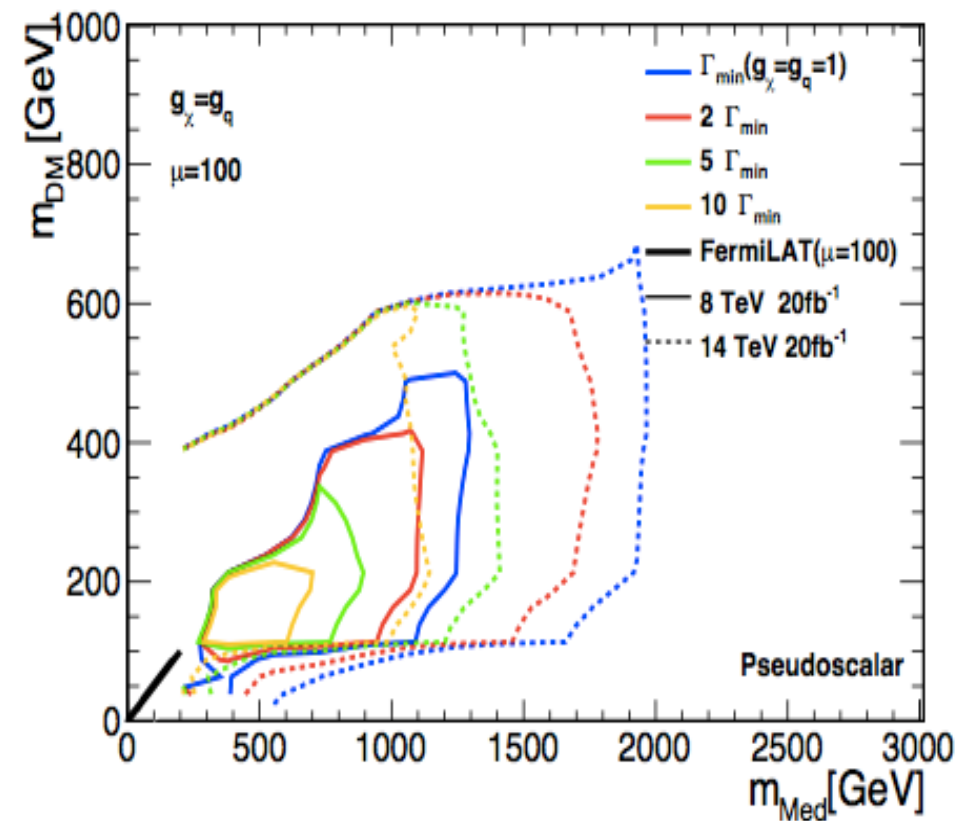
See also Buckley et al
arXiv:1410.6497

chmüller

Scalar



Pseudoscalar



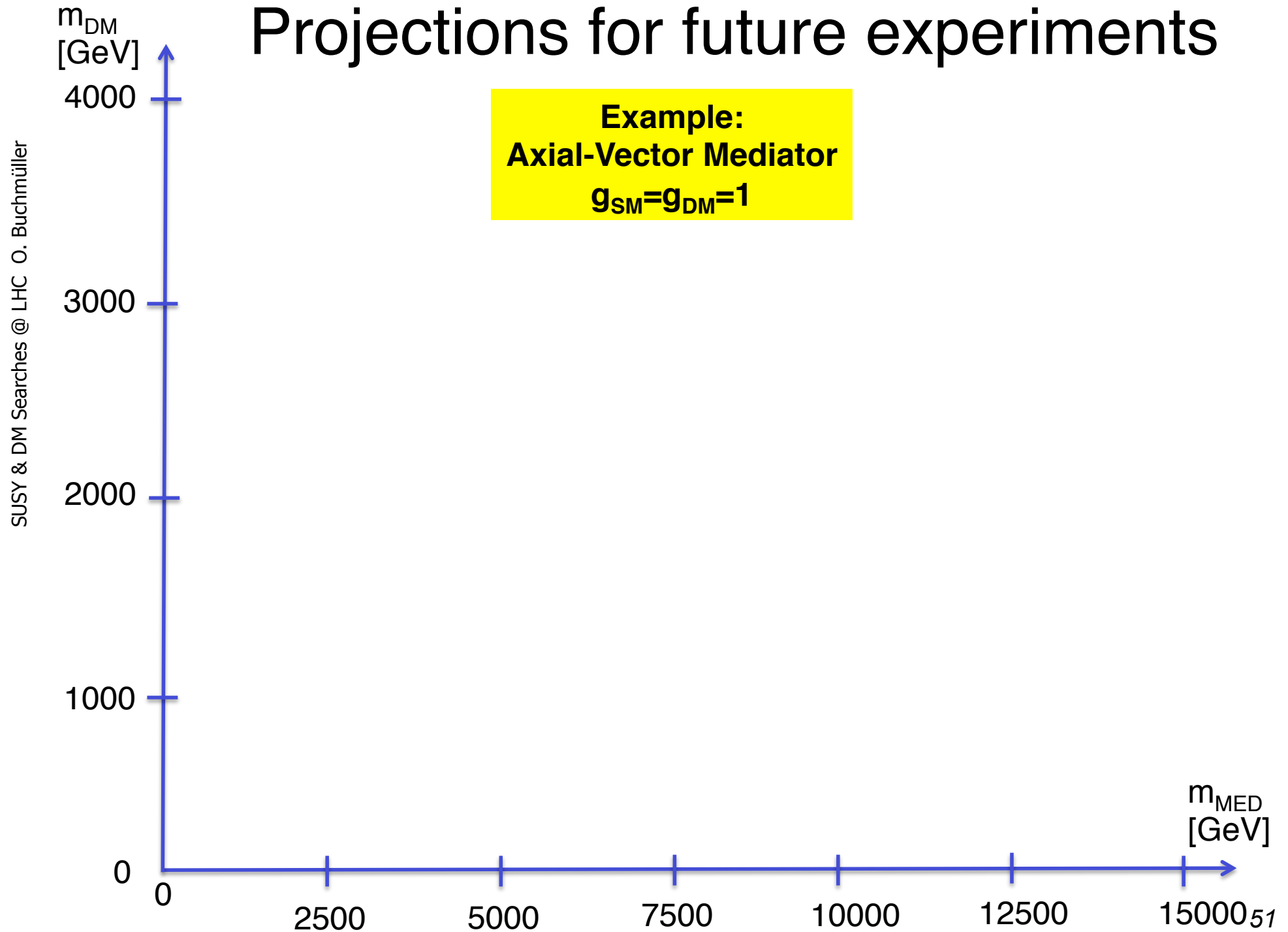
Summary for most basic Mediator Interactions

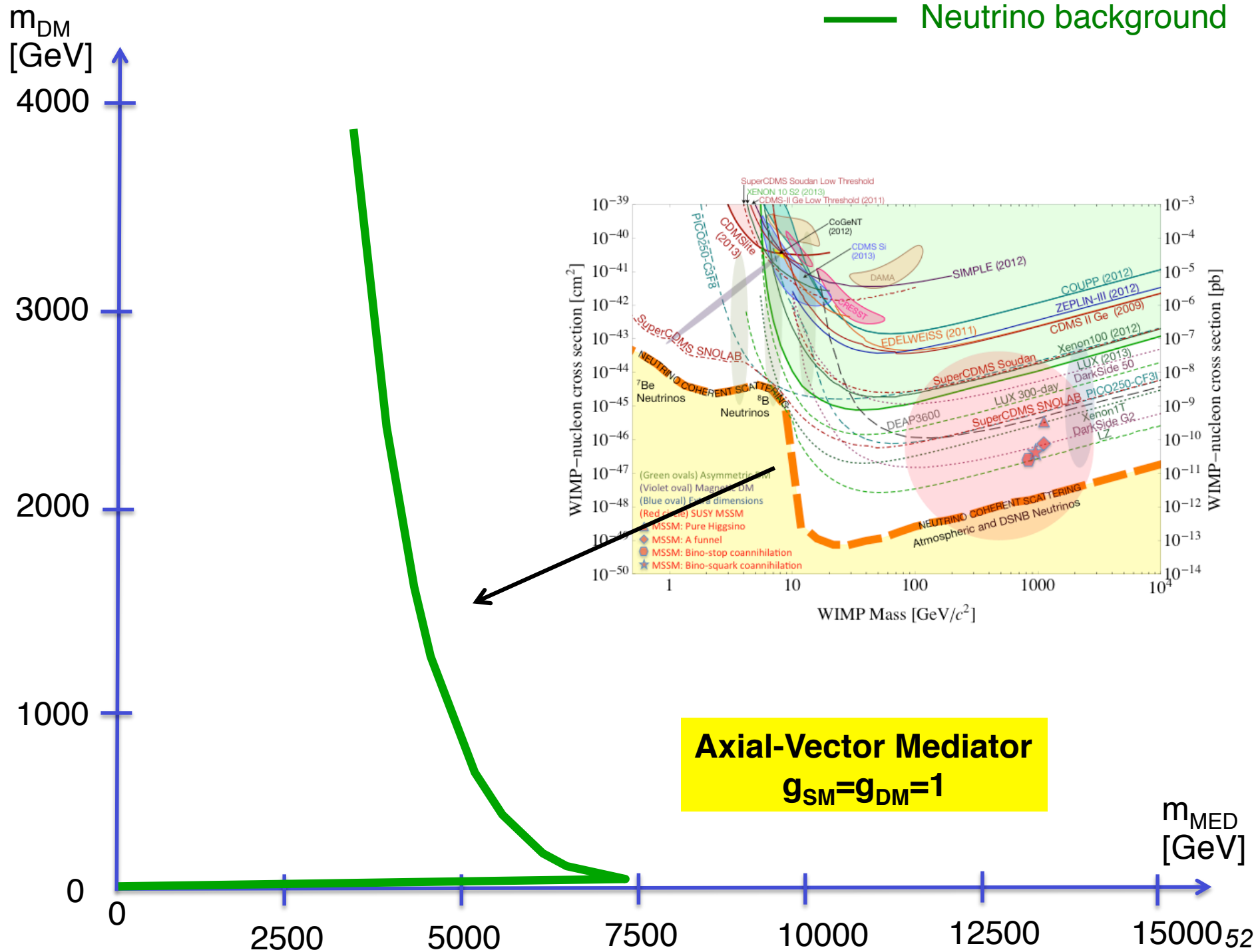
... in a nutshell!

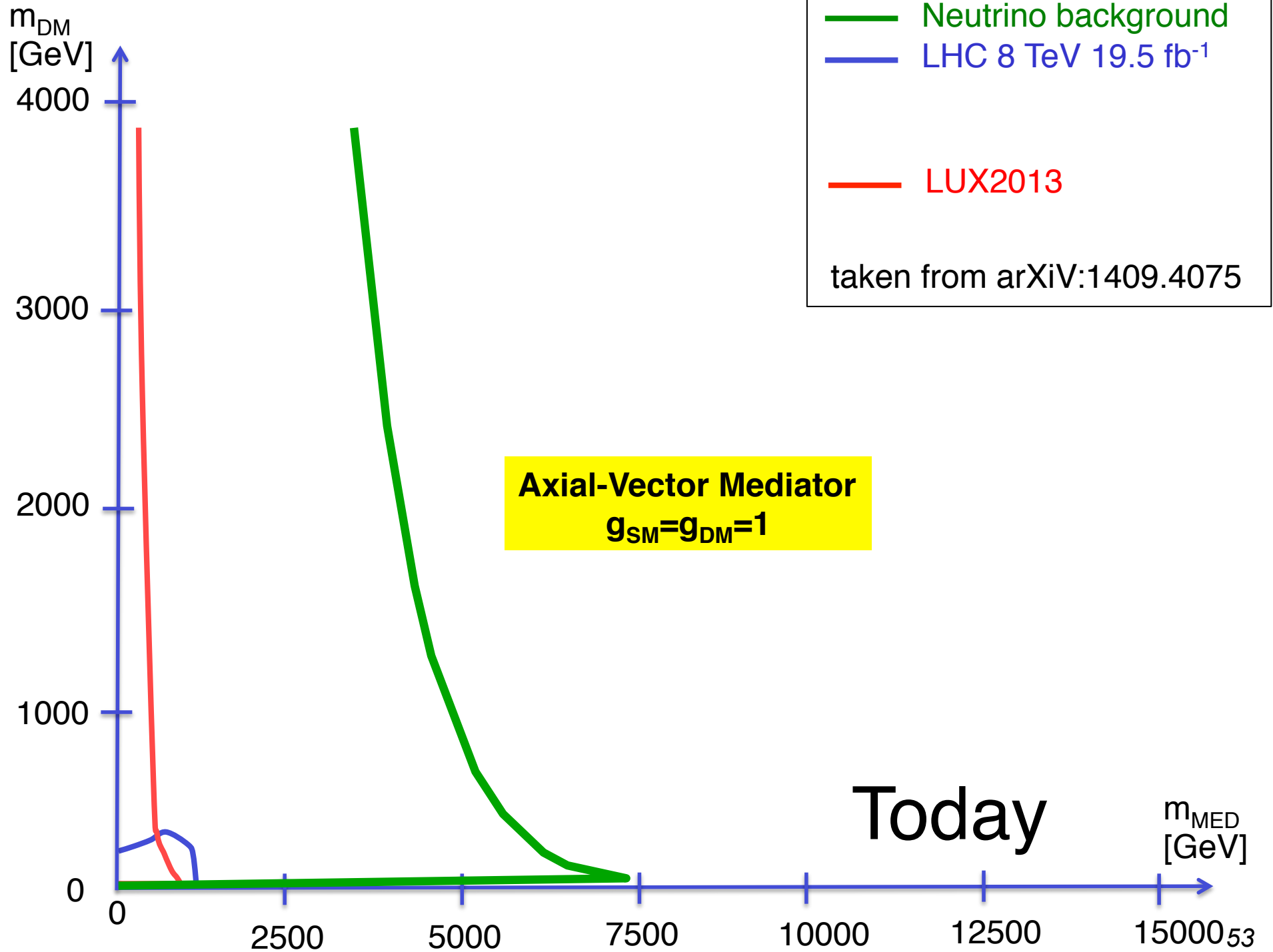
DM Searches @ LHC O. Buchmüller

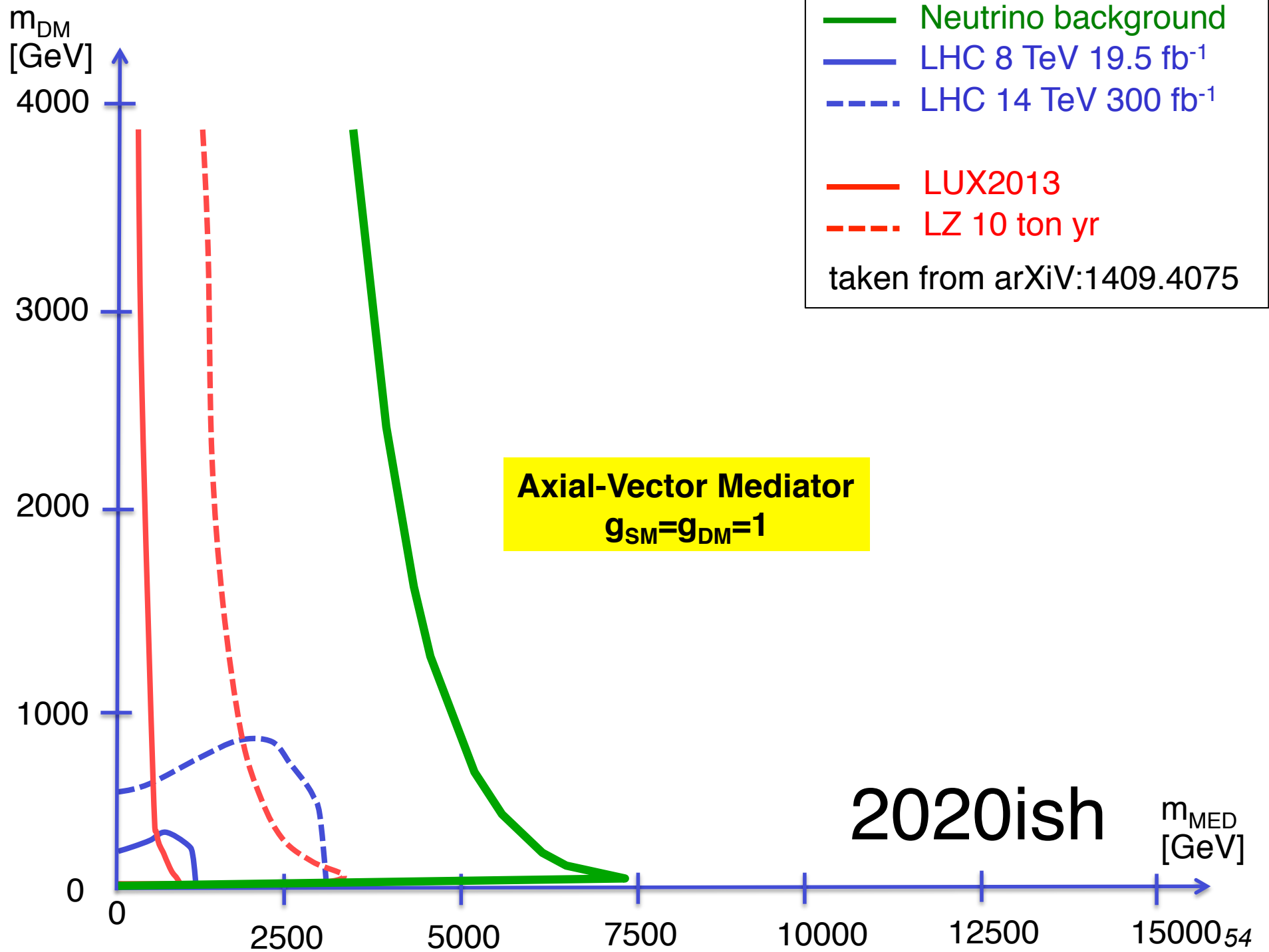
Basic Mediators	
<u>Vector</u> EWK like coupling (assumed equal to all leptons). <i>Besides very low DM masses DD wins clearly over collider!</i>	<u>Axial-vector</u> EWK like coupling (assumed equal to all leptons). <i>DD and collider are equal in overall sensitivity but probe different regions of parameter space!</i>
<u>Scalar</u> Yukawa like coupling on SM side (mass based on SM side) <i>DD and collider are equal in overall sensitivity but probe different regions of parameter space!</i>	<u>Pseudoscalar</u> Yukawa like coupling on SM side (mass based on SM side) <i>No limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits</i>

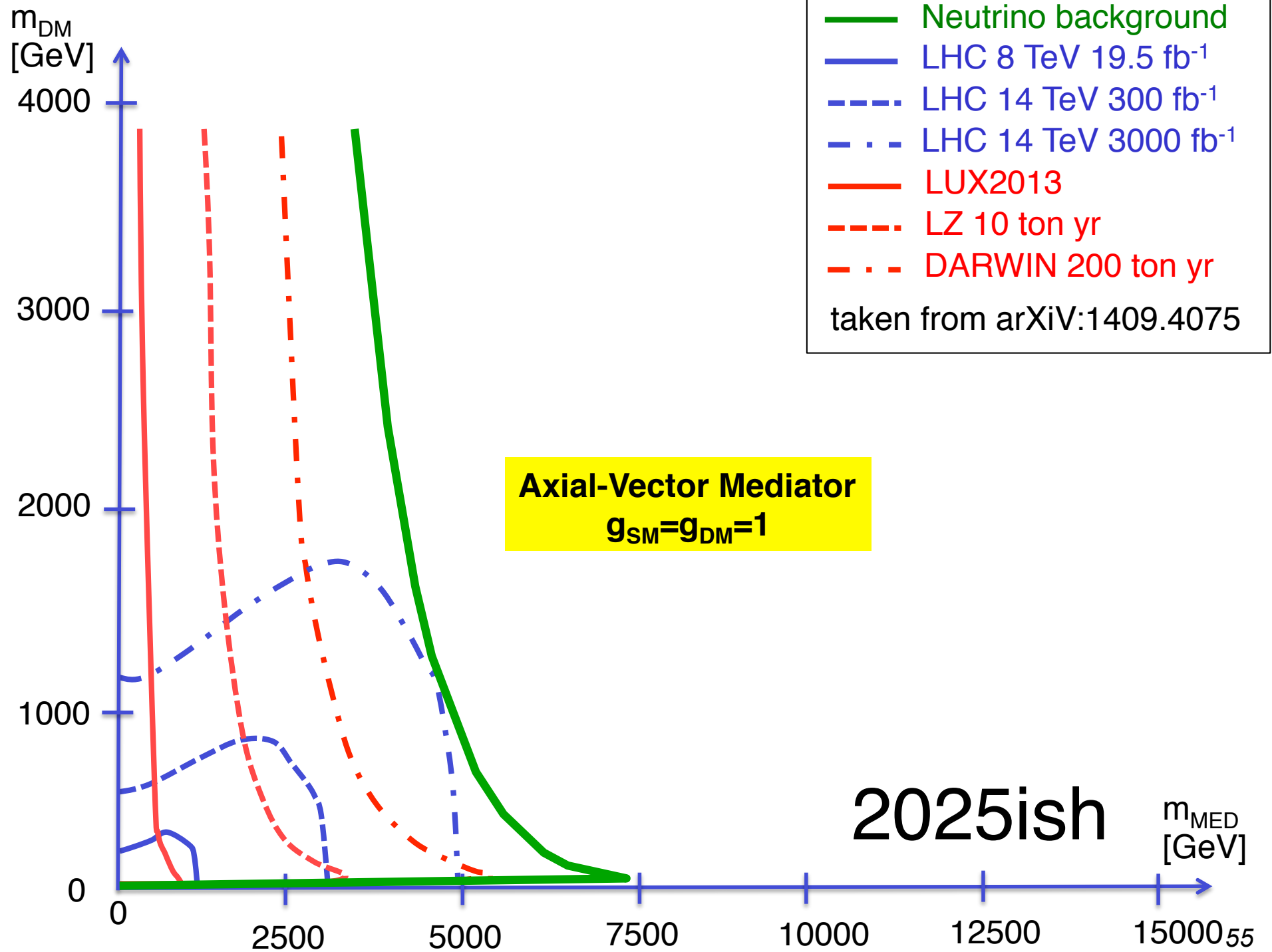
Projections for future experiments

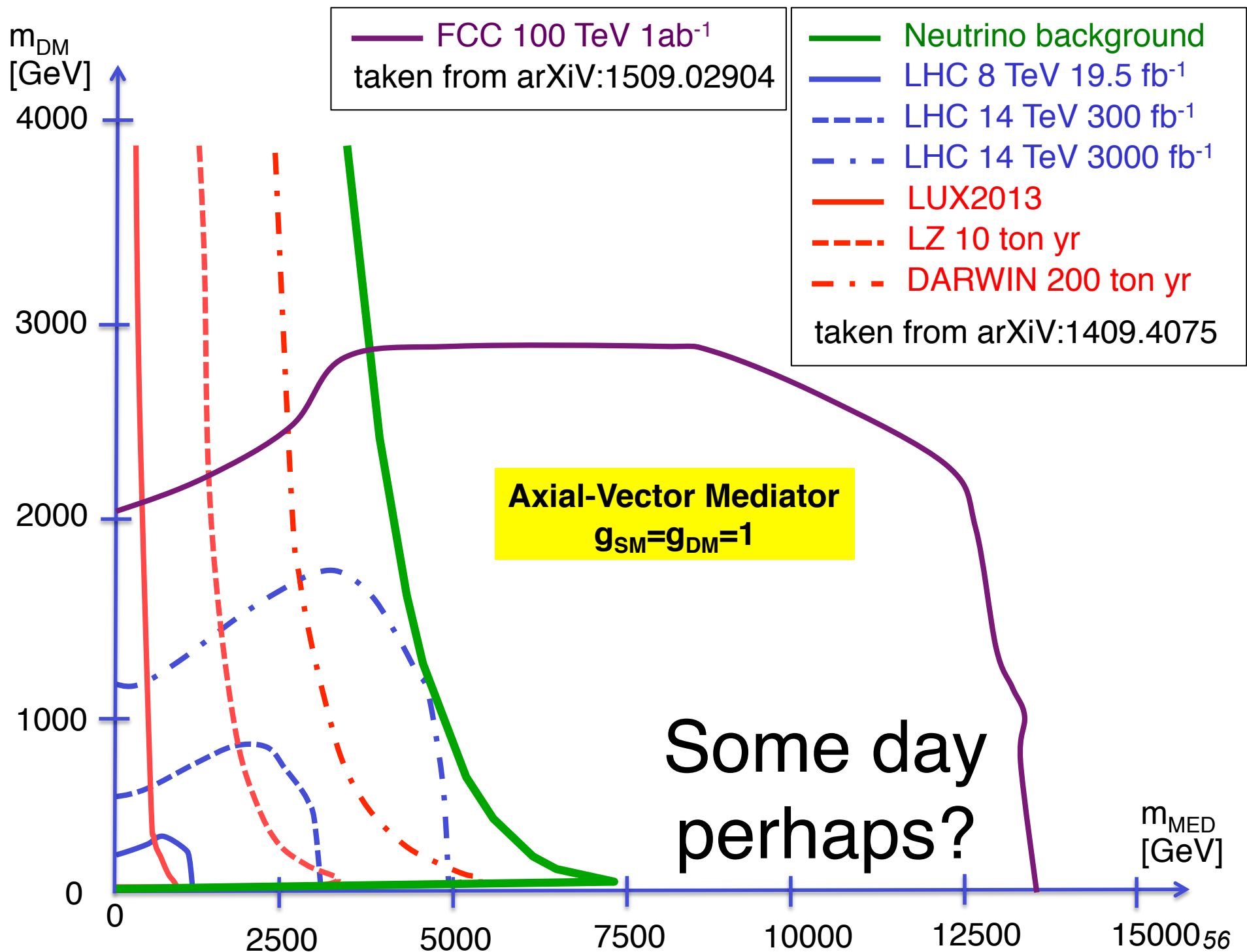










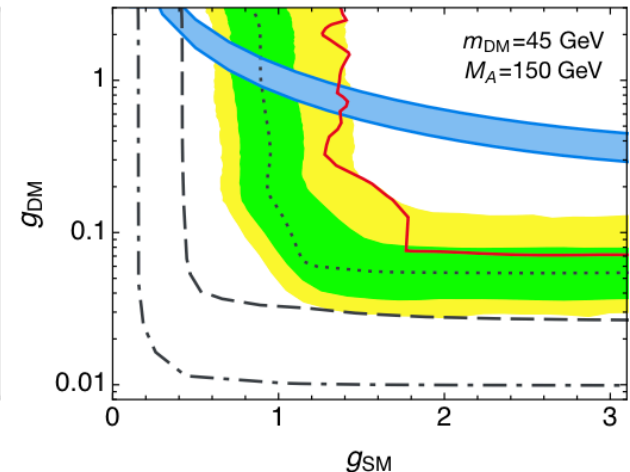
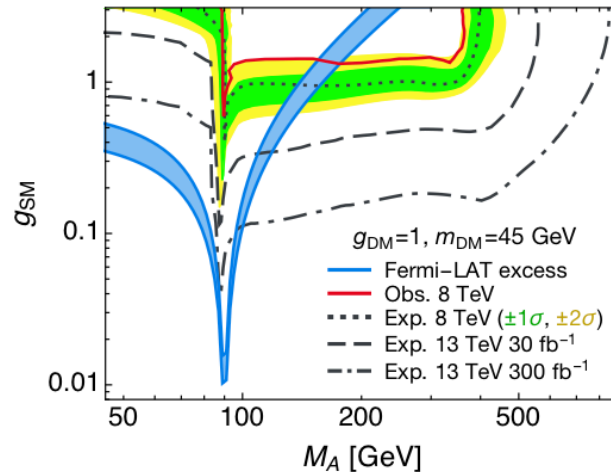
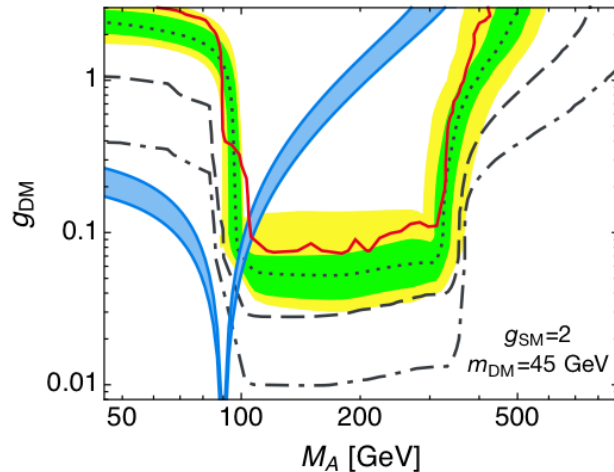
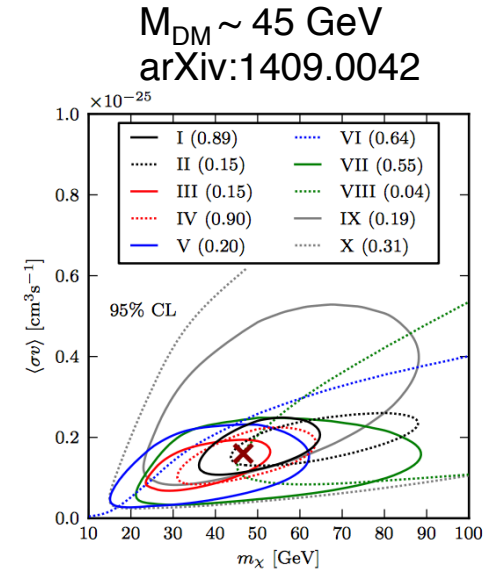
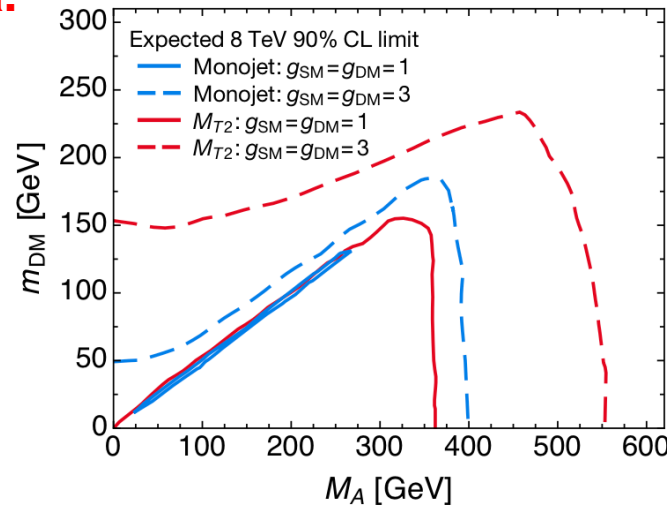


Fermi-Lat Excess: Indirect Detection vs Collider

Constraining the Fermi-LAT excess with collider data.

Based on work from :
OB, S. Malik, C. McCabe,
and B. Penning
arXiv:1505.07826
Accepted for publication
in PRL

DM Searches @ LHC O. Buchmüller

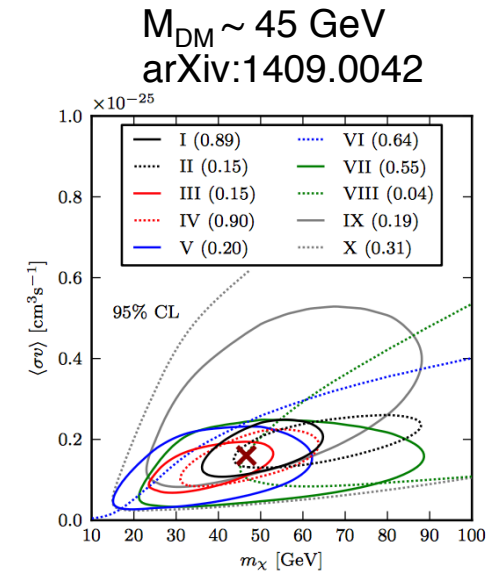
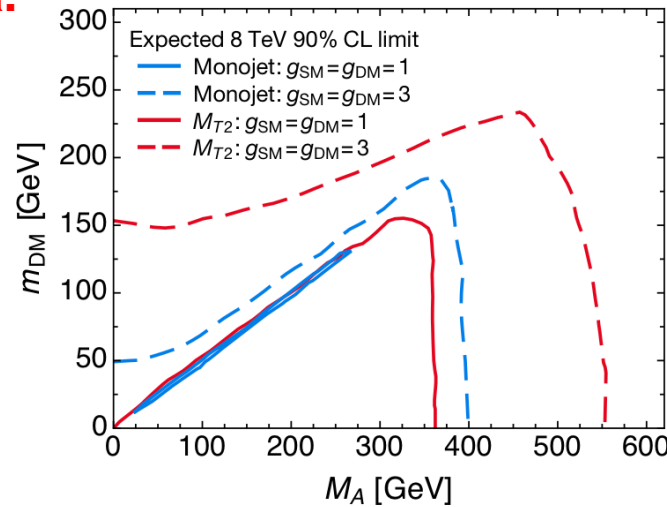


Fermi-Lat Excess: Indirect Detection vs Collider

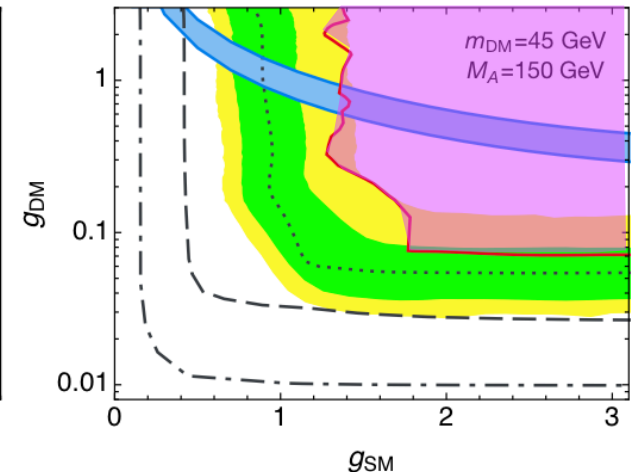
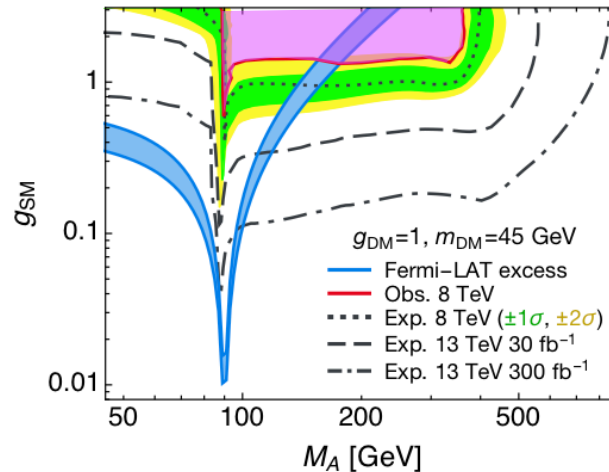
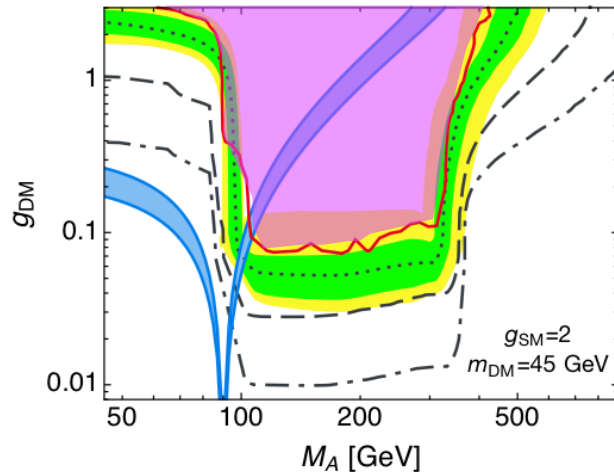
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Based on work from :
OB, S. Malik, C. McCabe,
and B. Penning
arXiv:1505.07826
Accepted for publication
in PRL

DM Searches @ LHC O. Buchmüller



Region excluded for pseudo-scalar model interpretation:



Outlook: 8 TeV vs 14 TeV

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

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Higgs:

$pp \rightarrow H, H \rightarrow WW, ZZ$ and $\gamma\gamma$

mainly gg : factor ~ 2

SUSY – 3rd Generation:

Mass scale ~ 500 GeV

qq and gg : factor ~ 3 to 6

Scalar/Pseudoscalar Mediator

Mass scale ~ 2.0 TeV

gg : factor ~ 20

SUSY – Squarks/Gluino:

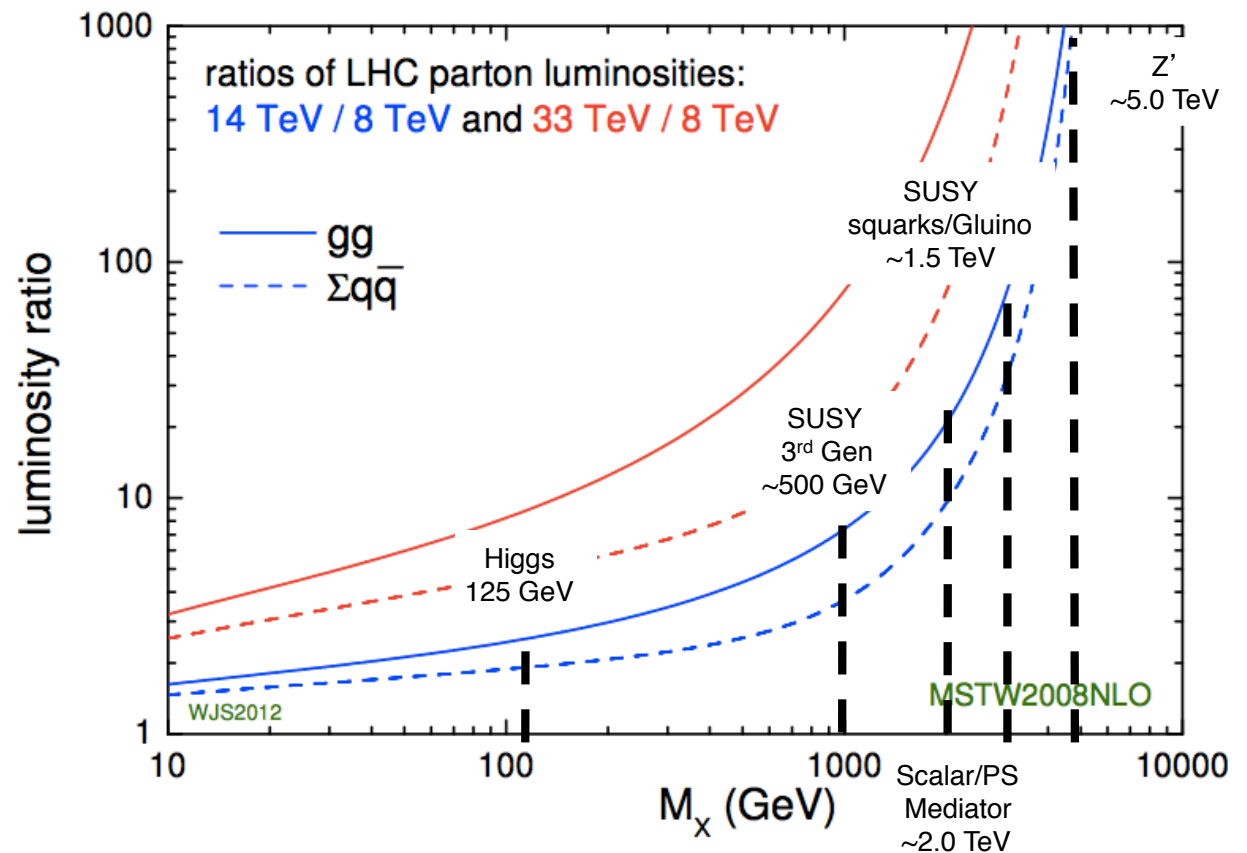
Mass scale ~ 1.5 TeV

qq, gg, qg : factor ~ 40 to 80

Vector/Axialvector a la Z' :

Mass scale ~ 5 TeV

qq : factor ~ 1000



Increase in energy will help a lot!

Summary

- So far New Physics has not revealed itself!
 - Even by 2010 the LHC has entered new territory for New Physics searches and since pushed e.g. the (coloured) SUSY mass scale to 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!
 - Based on these results we need to establish the “big picture” in order to understand if/where our search strategy might have weak spots or even holes!
 - This requires appropriate interpretations of the searches and a MEANINGFUL comparison with other experiments – important example DM searches!
- The high energy running of the LHC starting 2015 will be our next very (as in VERY) real chance for discovery!

The story continues ... stay tuned!

BACKUP

ATLAS & CMS public results

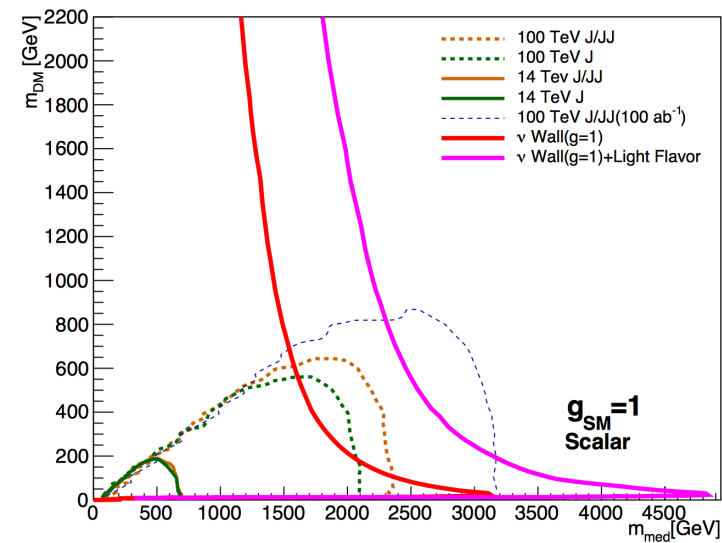
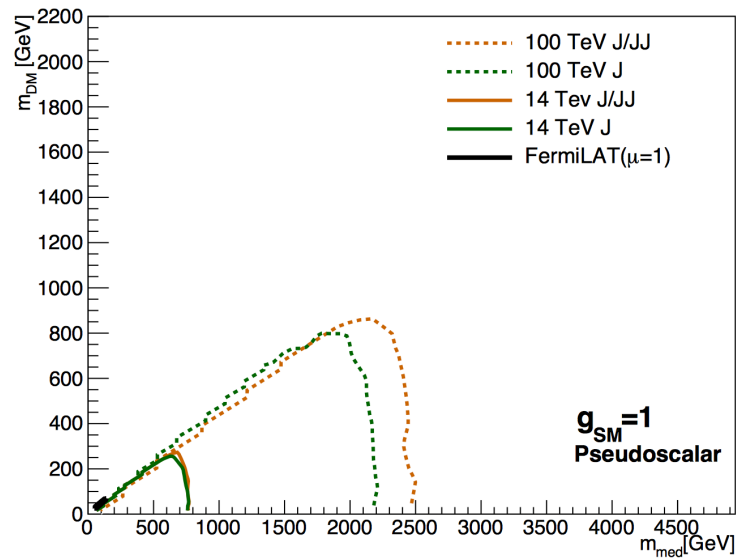
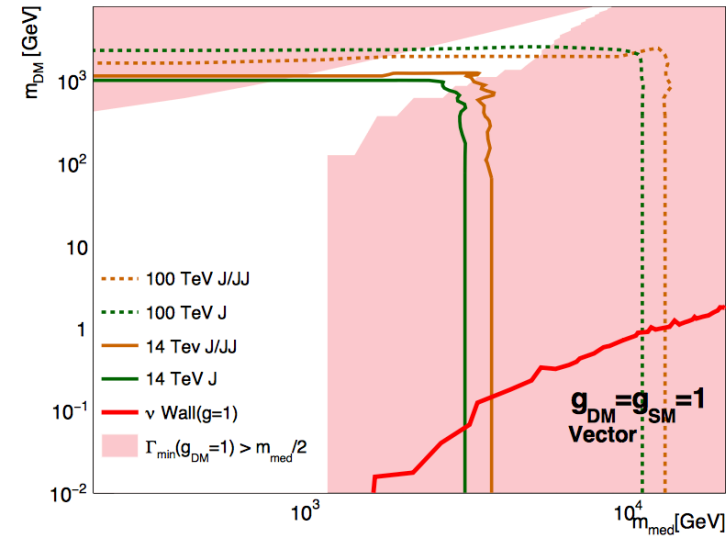
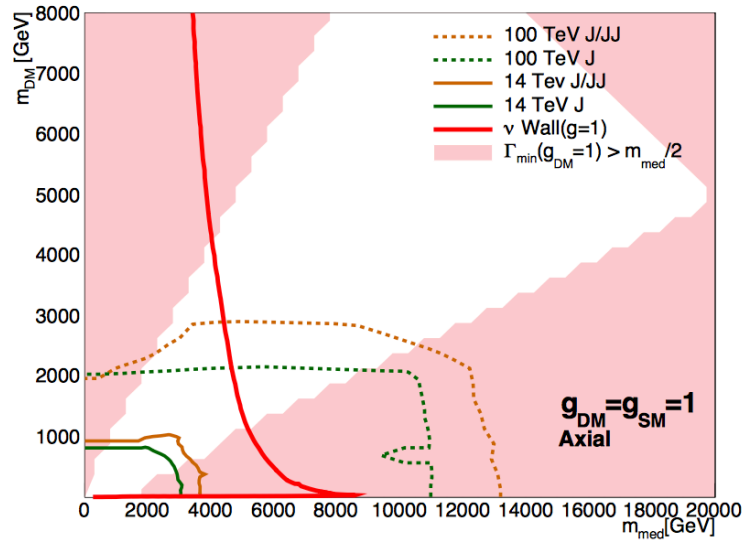
Most results presented in this talk (and many more)
can be accessed via the public page of the
ATLAS and CMS experiments:

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

CMS SUSY: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

100 TeV Prediction from arXiv:1509.02904

DM Searches @ LHC O. Buchmüller



The full story

SUSY SUMMARY PLOT

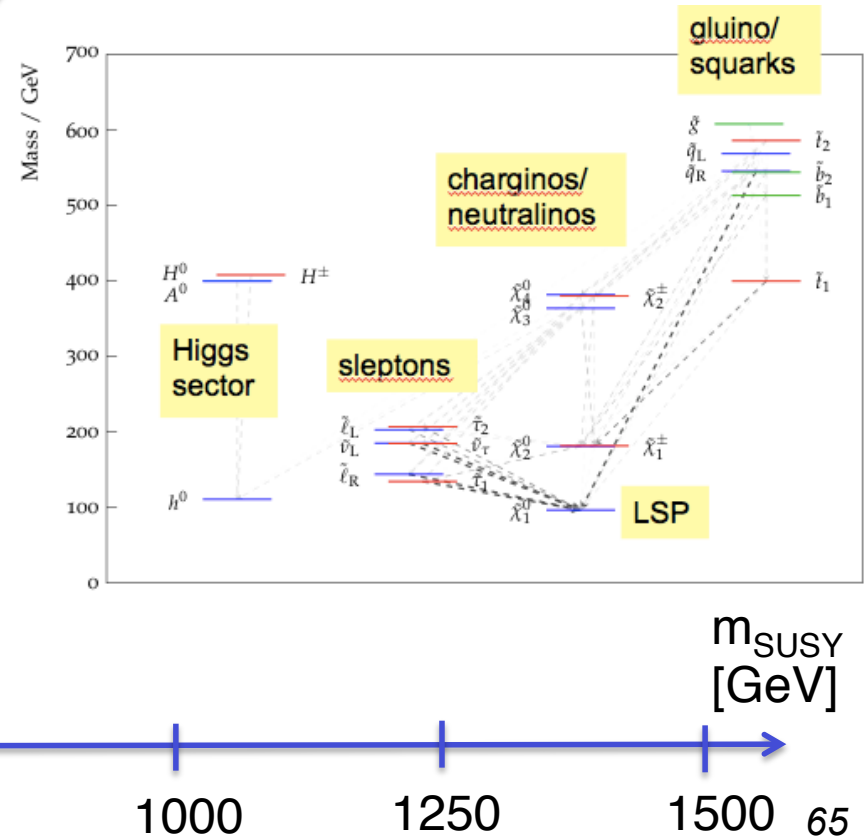
m_{LSP}
[GeV]

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>

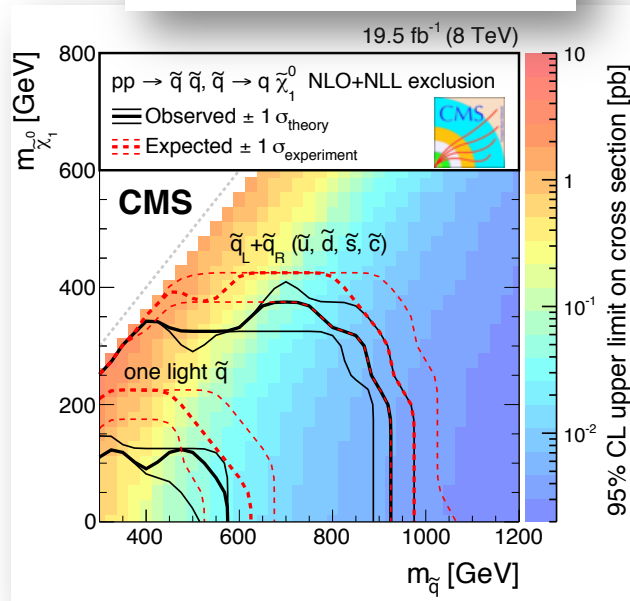
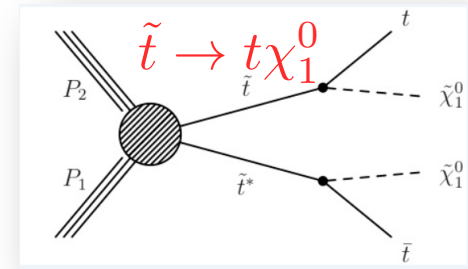
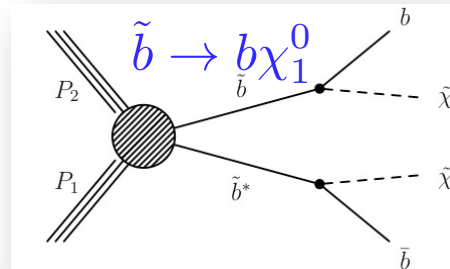
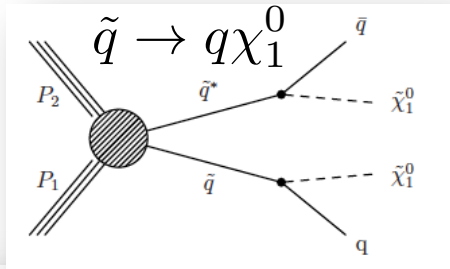
$$m_{\text{SUSY}} - m_{\text{LSP}} < m_t$$

What are representative
SMS limits on the different
particles?



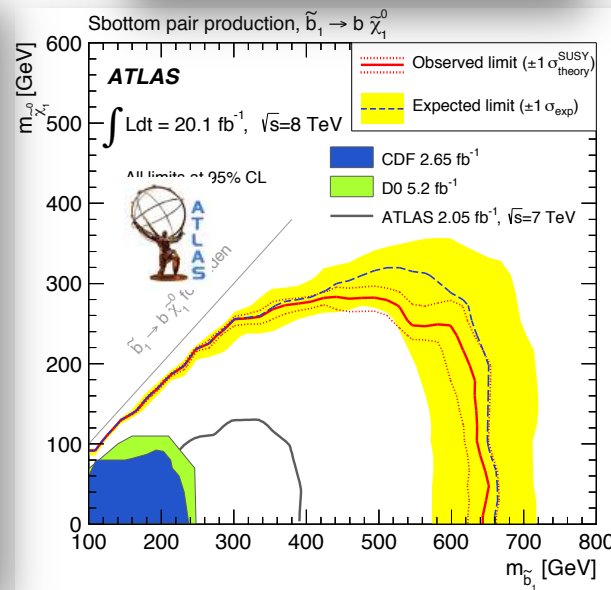
Direct squark production – chosen limits

DM Searches @ LHC O. Buchmüller



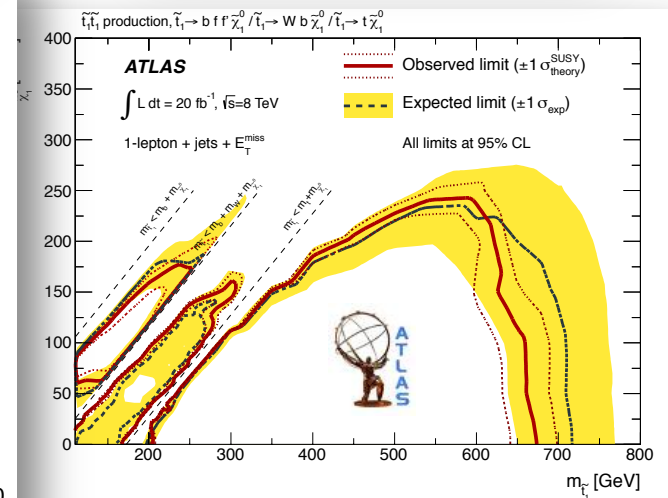
CMS arXiv:1502.04358

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



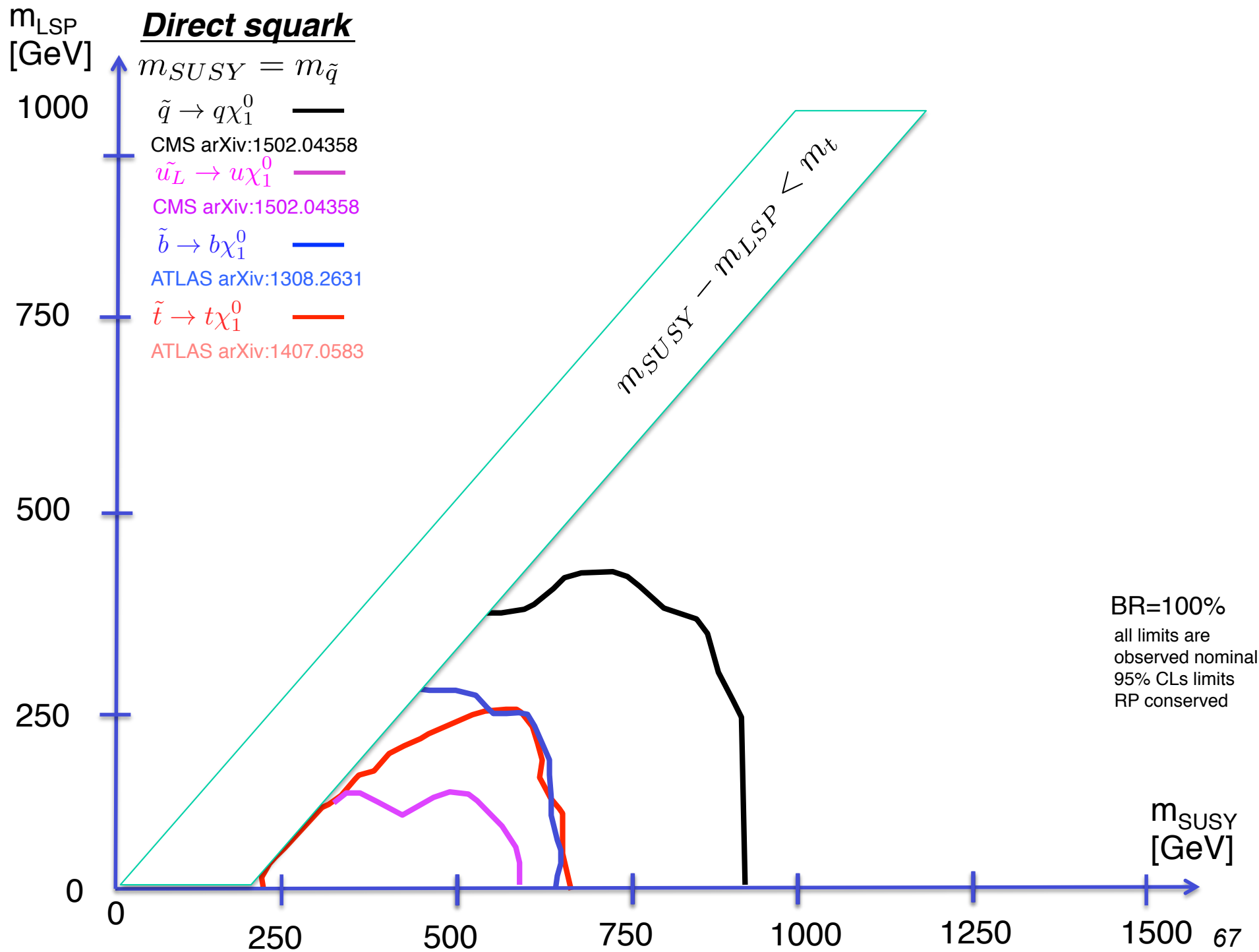
ATLAS arXiv:1308.2631

Signature: 2 b-jets + E_T^{miss}



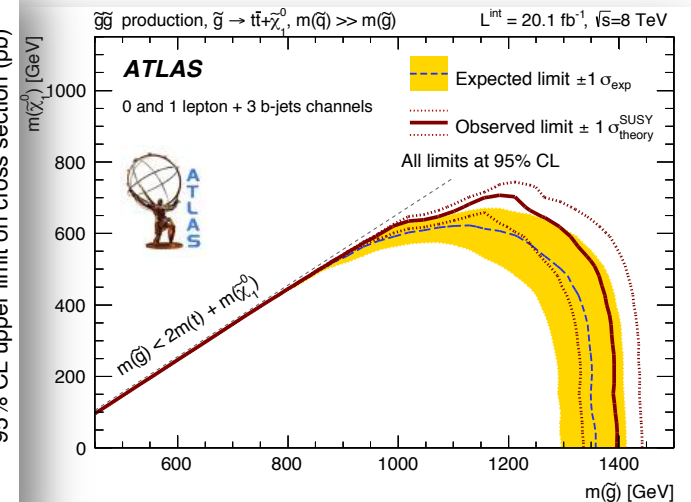
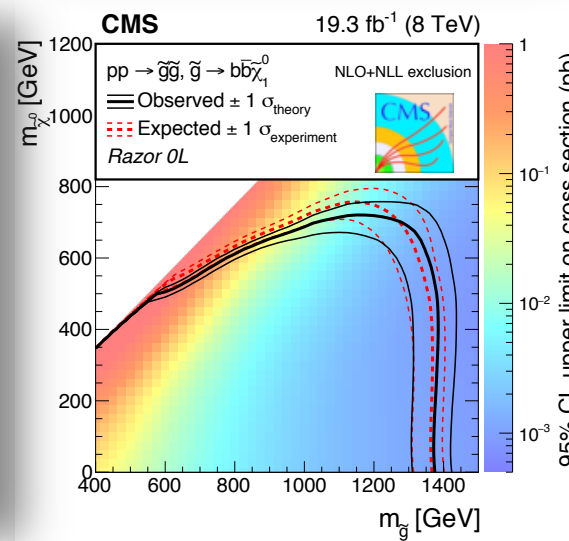
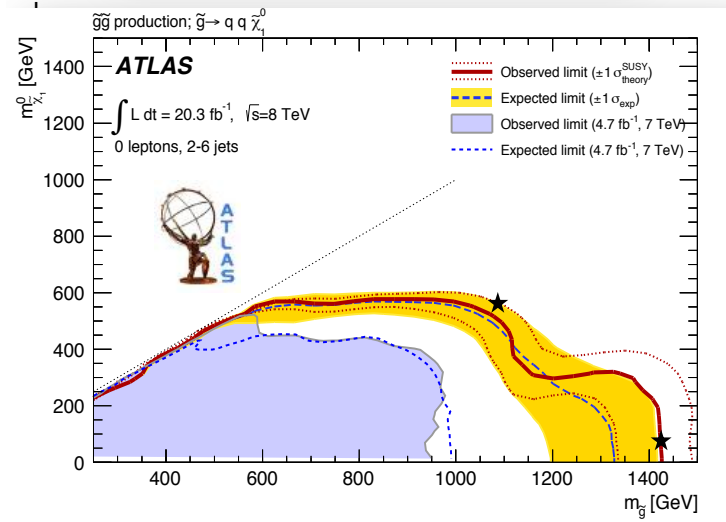
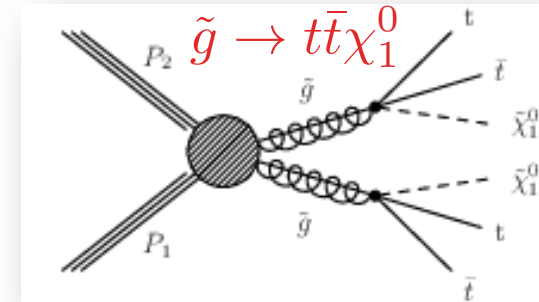
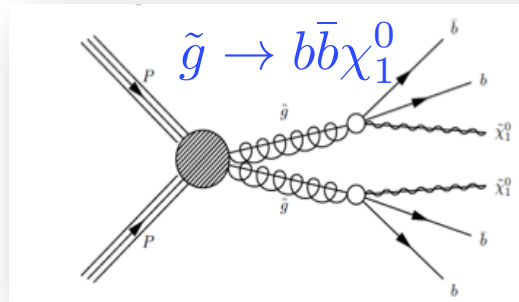
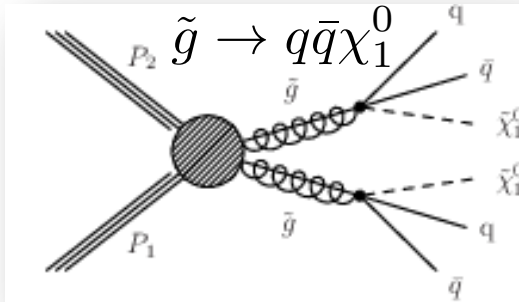
ATLAS arXiv:1407.0583

Signature: 1 Lepton + jets + E_T^{miss}



Gluino mediated squark production – limits chosen

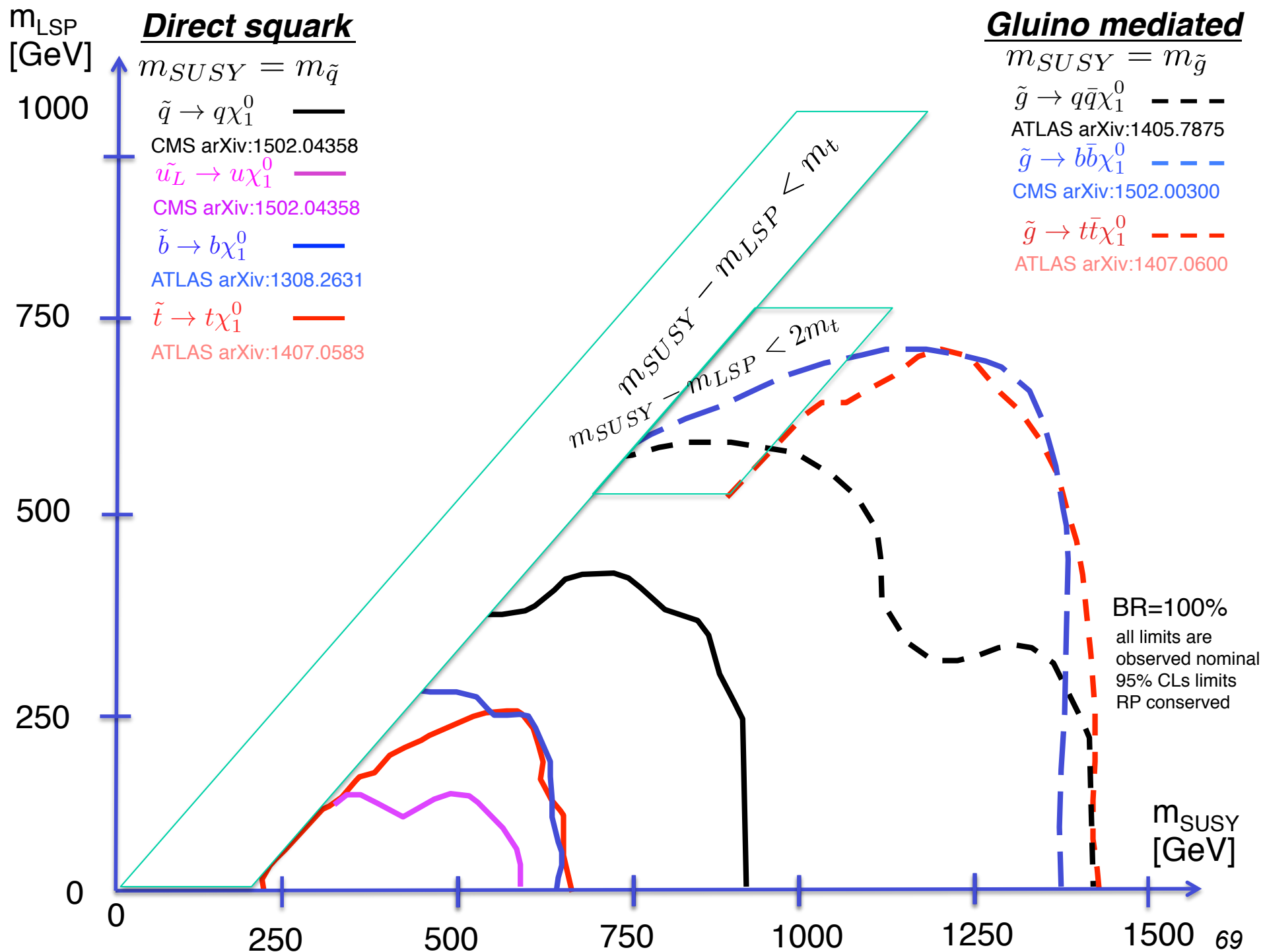
HC O. Buchmüller

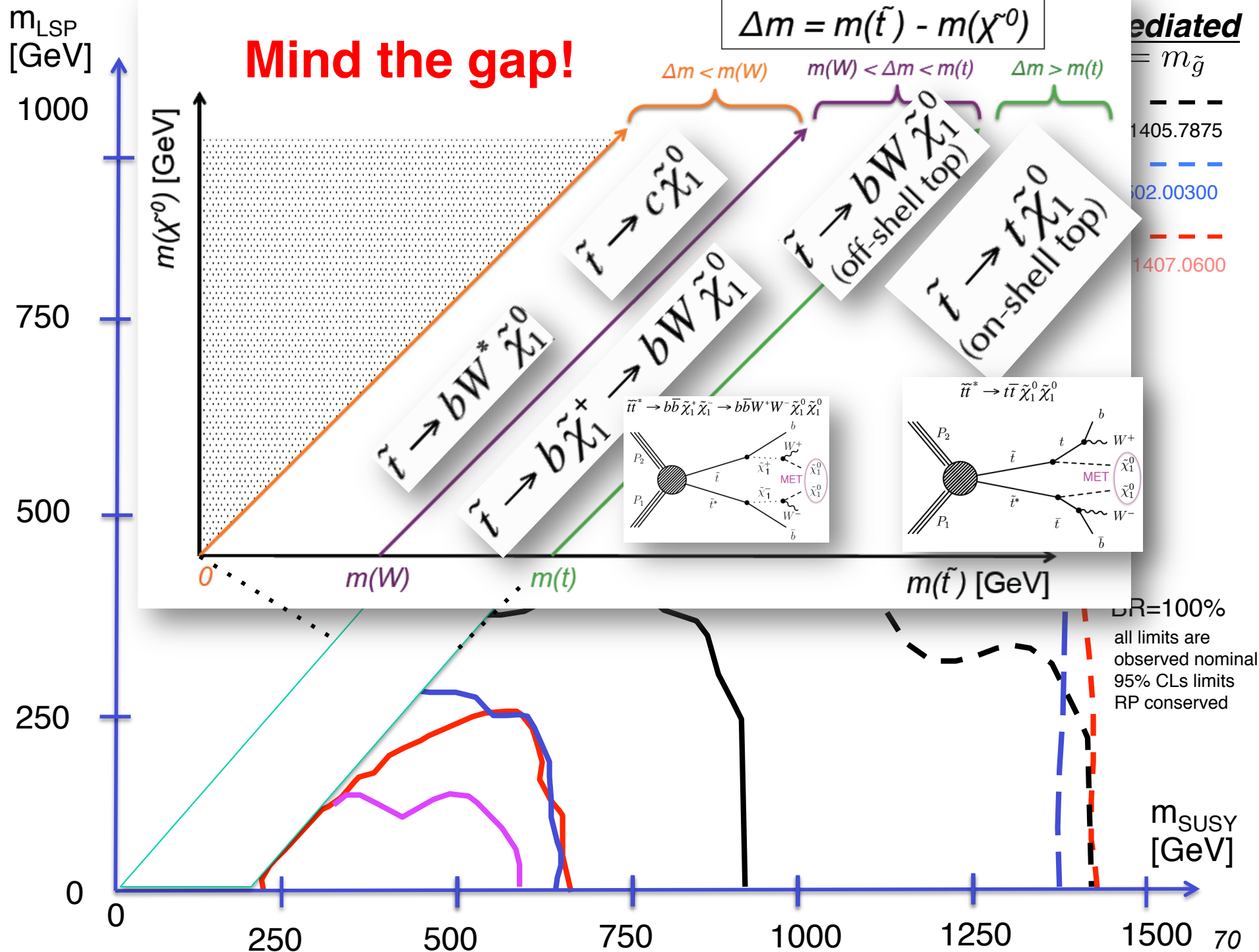


ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets
+ E_t^{miss}

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

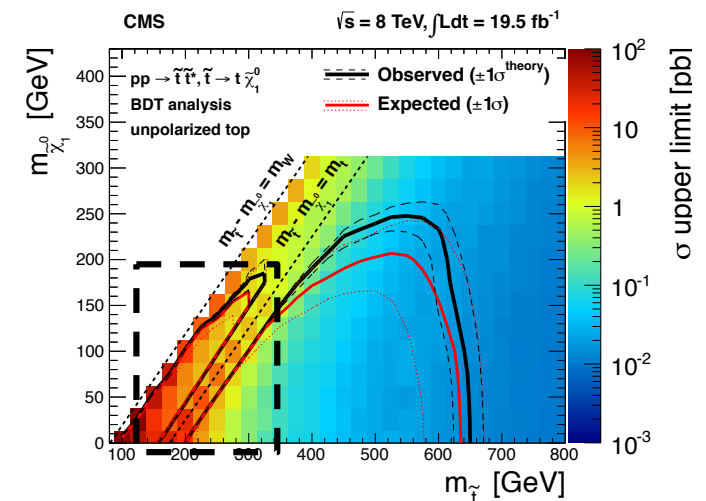
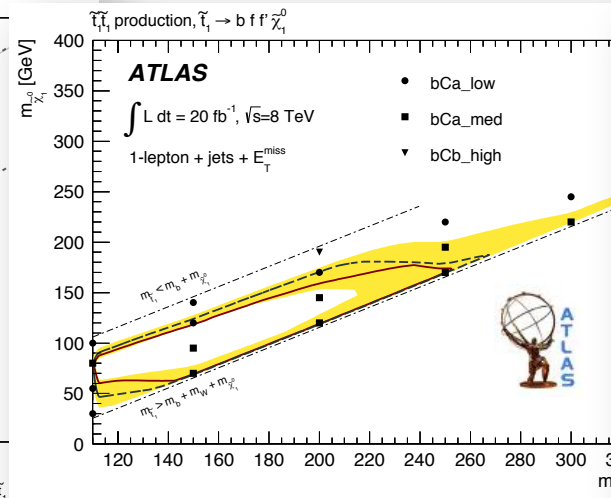
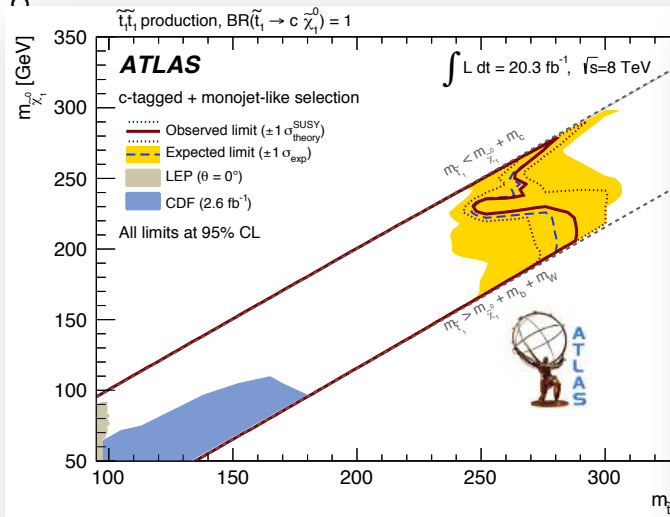
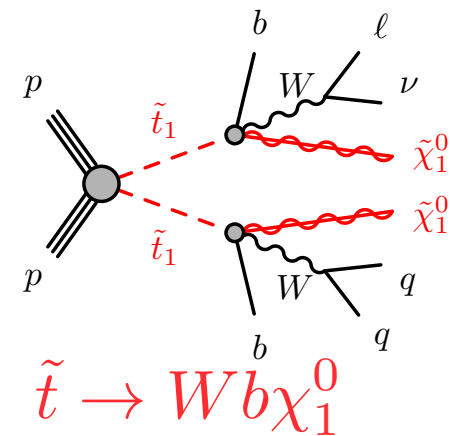
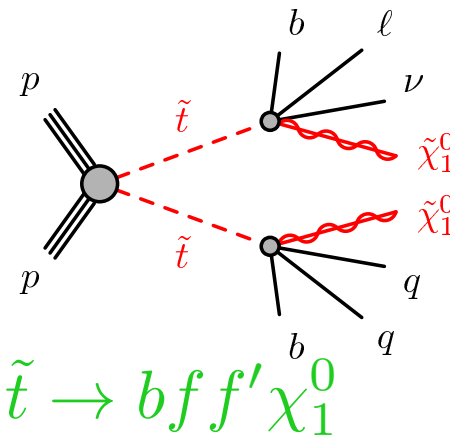
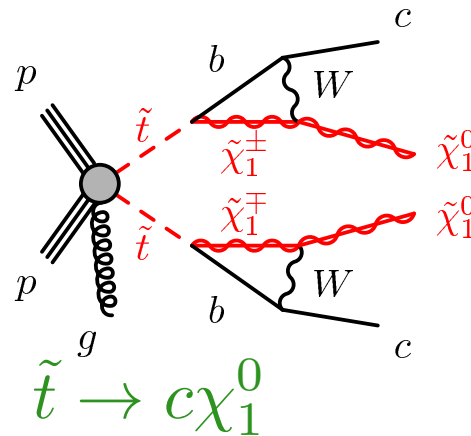
Signature: 0/1 Leptons +
3 b-tag + E_t^{mis}





Compressed stop – mind the gap!

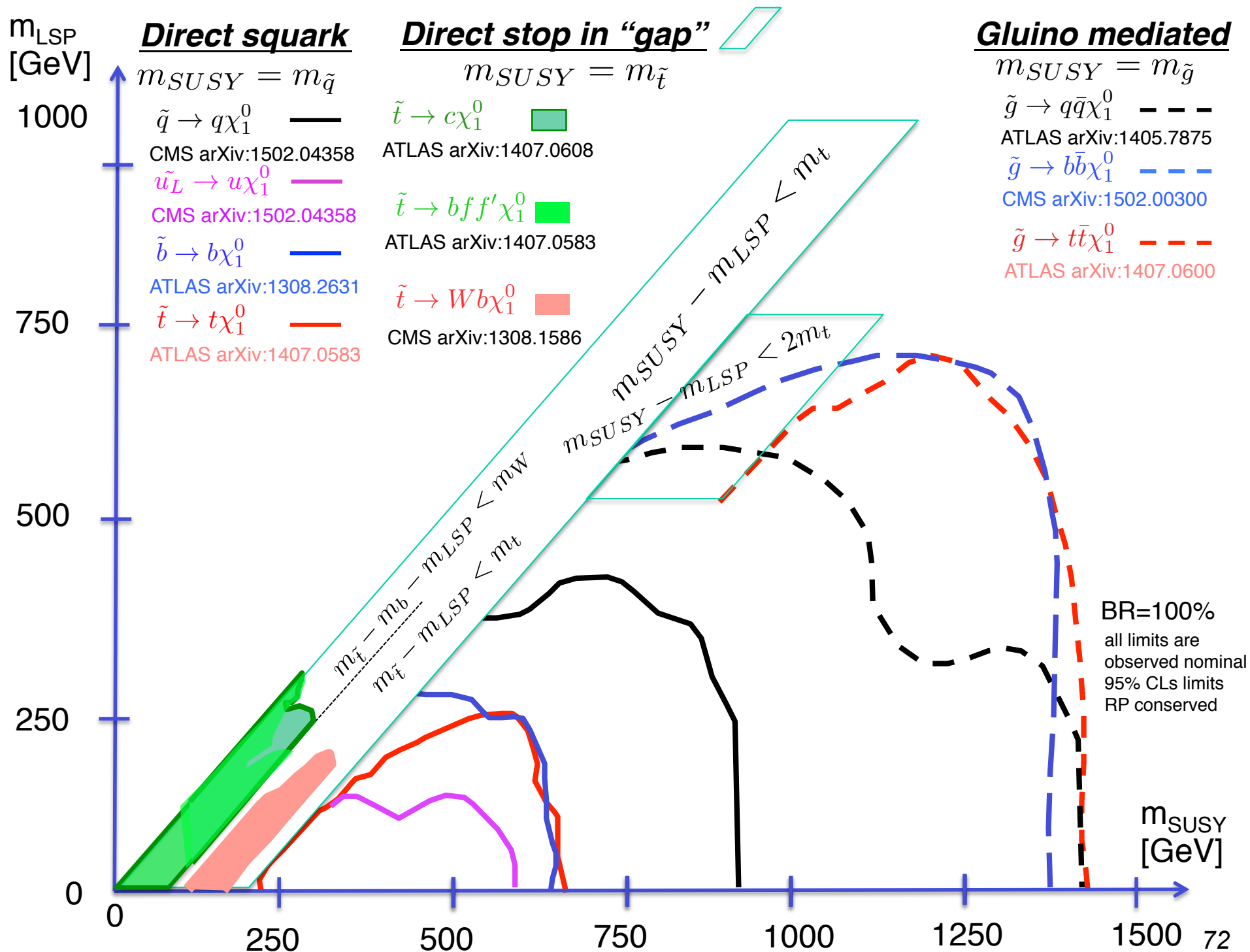
ches @ LHC O. Buchmüller



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

$$m_{\text{SUSY}} = m_{\tilde{q}}$$

$$\tilde{q} \rightarrow q\chi_1^0$$

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

Direct stop in "gap"

$$m_{\text{SUSY}} = m_{\tilde{t}}$$

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

ATLAS arXiv:1407.

$$\tilde{t} \rightarrow b f f' \chi_1^0$$

ATLAS arXiv:1407.

Gluino mediated

$$m_{\text{SUSY}} = m_{\tilde{g}}$$

$$\tilde{g} \rightarrow q\bar{q}\chi_1^0$$

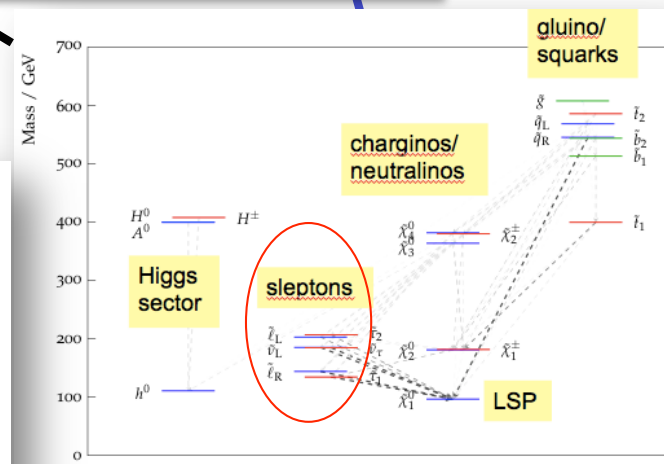
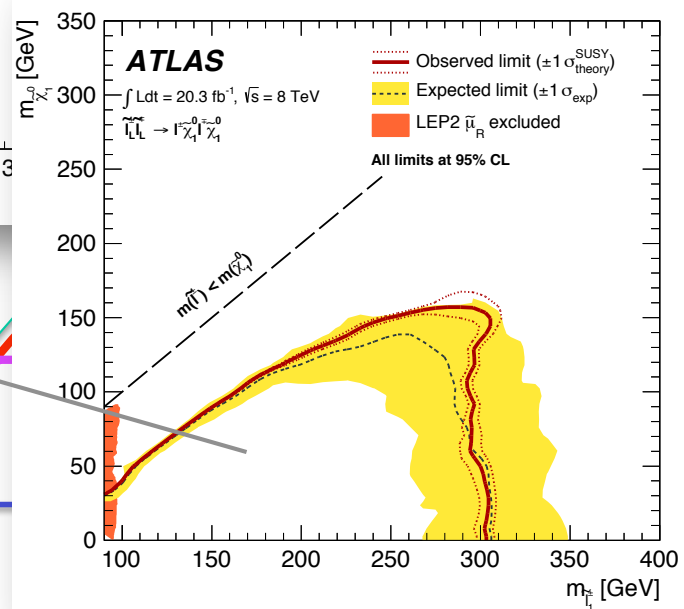
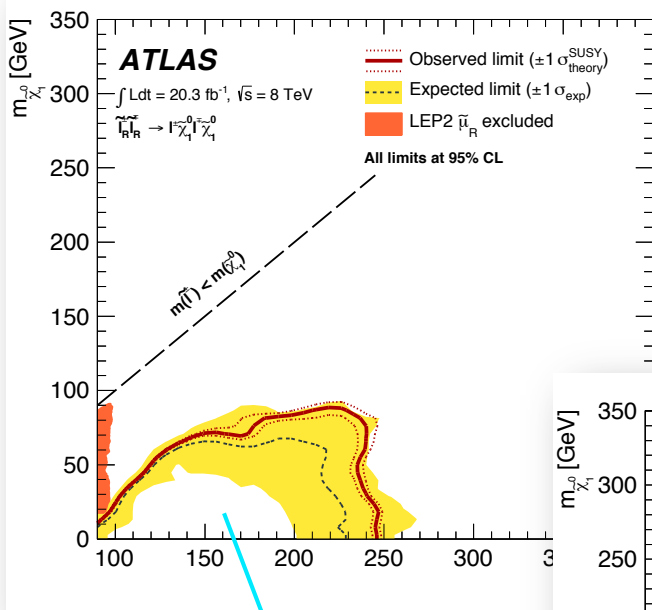
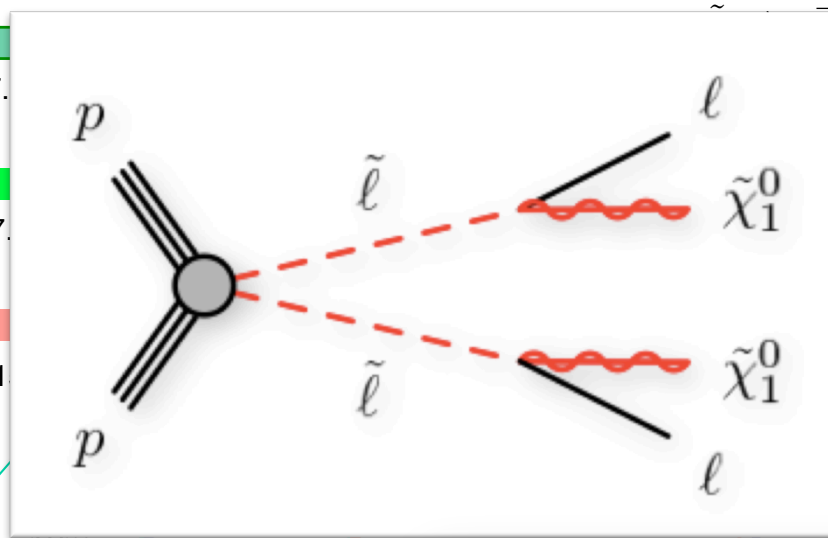
ATLAS arXiv:1405.7875

$$\tilde{g} \rightarrow q\bar{q}\chi_1^0$$

ATLAS arXiv:1502.00300

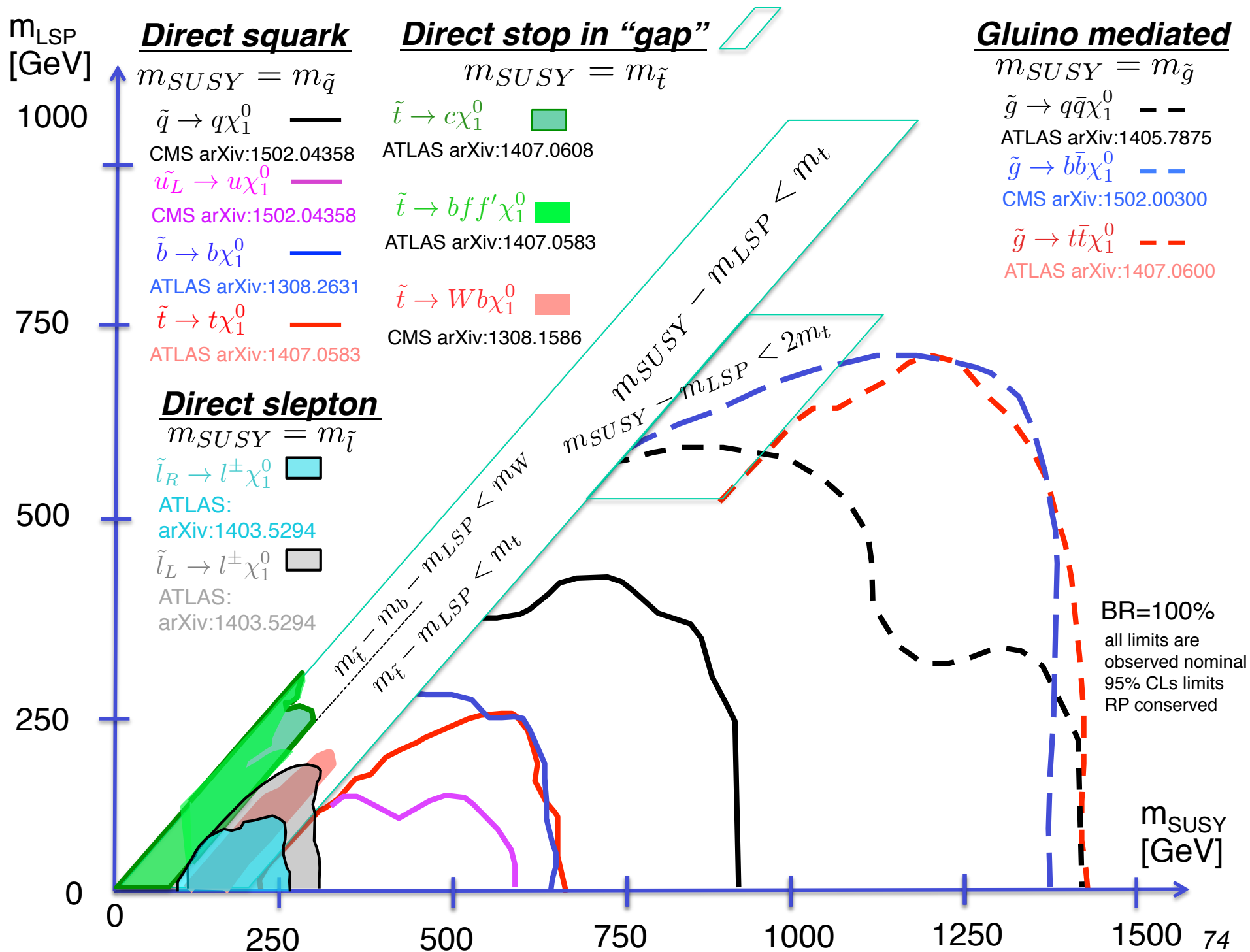
$$\tilde{g} \rightarrow q\bar{q}\chi_1^0$$

ATLAS arXiv:1407.0600



ATLAS arXiv:1403.5294

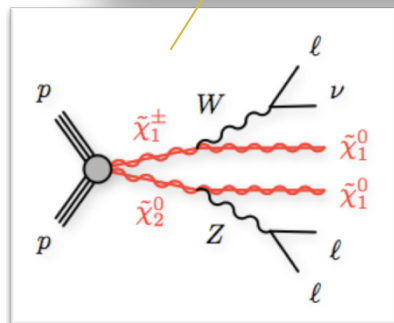
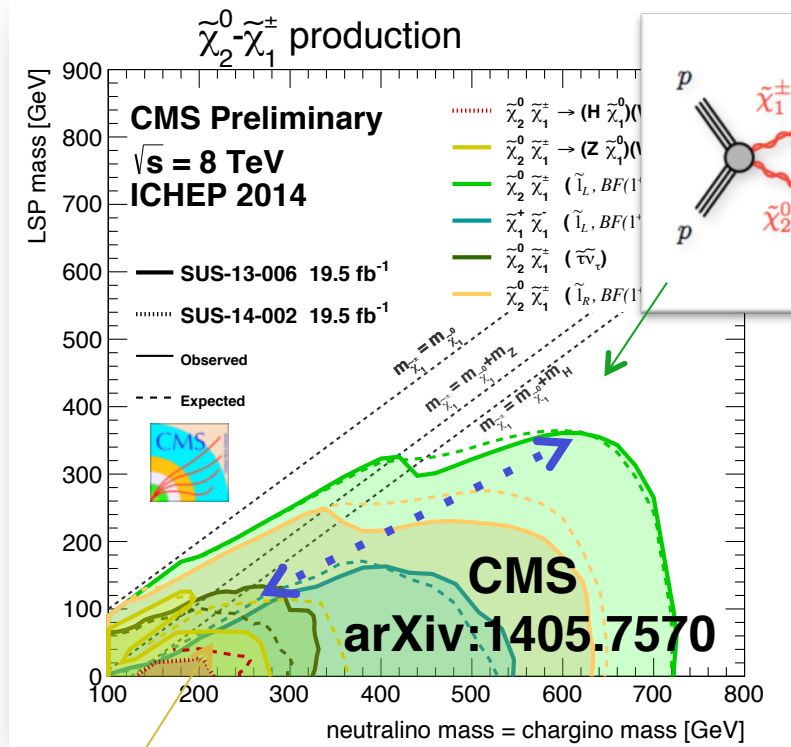
Signature
2 lepton + E_T^{miss}



Direct chargino/neutralino production

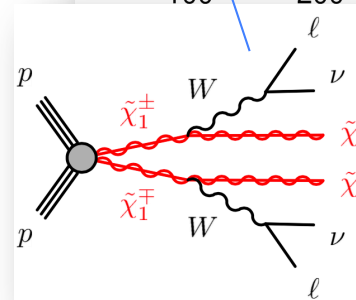
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production

DM Searches @ LHC O. Buchmüller



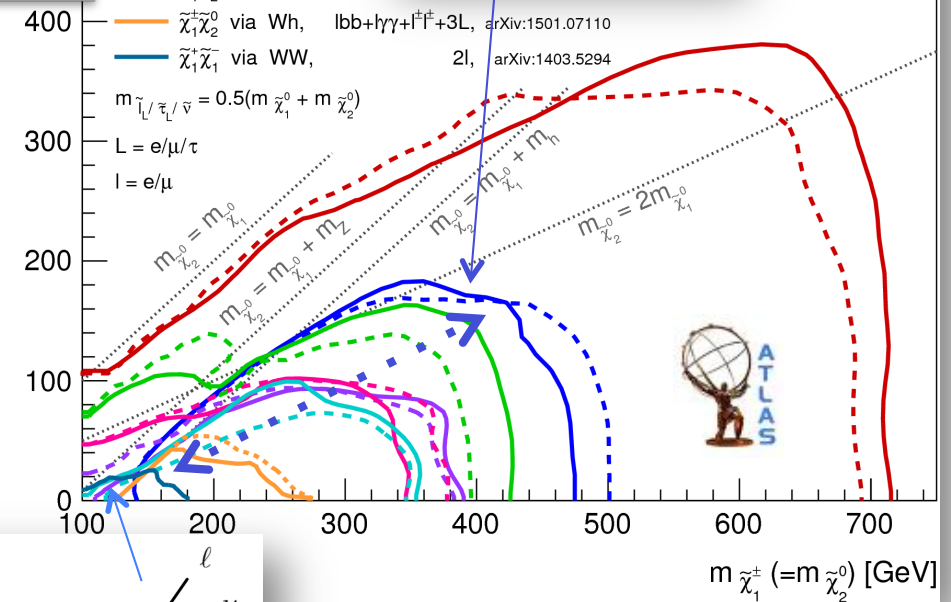
heavy slepton “hard(er)”

Add $Z(\ell^+\ell^-)+2\text{jets}$
topology in bins of
 E_t^{miss} to increase
sensitivity for
“heavy” slepton case

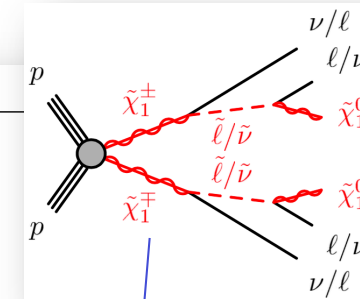


light
slepton
“easy”

- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $\tilde{L}_L / \tilde{\nu}_\tau$
- $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via $\tilde{L}_L / \tilde{\nu}_\tau$
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $\tilde{\tau}_L / \tilde{\nu}_\tau$
- $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via $\tilde{\tau}_L / \tilde{\nu}_\tau$
- $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via $\tilde{\tau}_R / \tilde{\nu}_\tau$
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $\tilde{\tau}_R / \tilde{\nu}_\tau$
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh
- $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ via WW

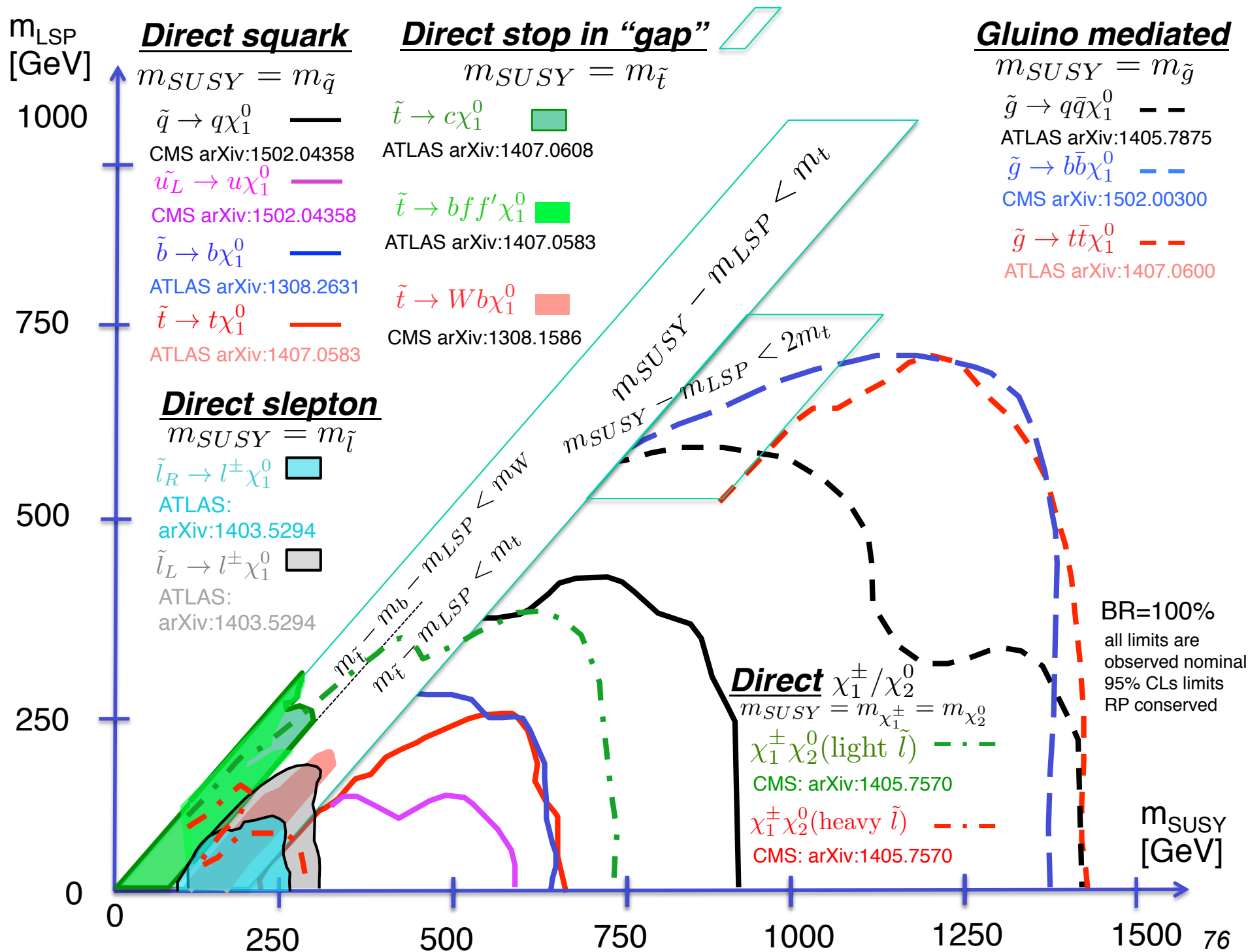


$\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production



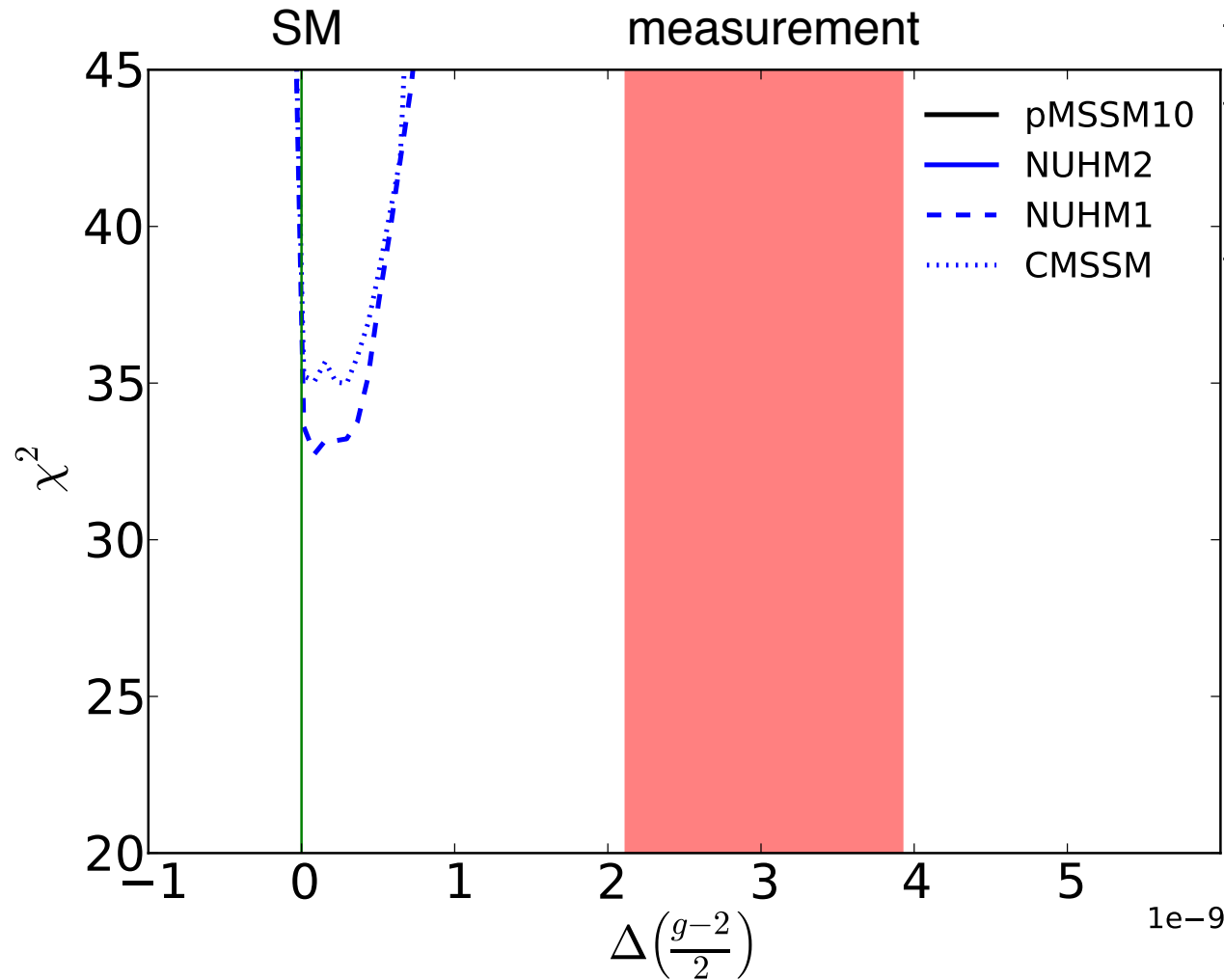
Status: Feb 2015
Expected limits
Observed limits
limits at 95% CL

ATLAS arXiv:1403.5294



MASTERCODE

Resolving tension (g-2) and LHC



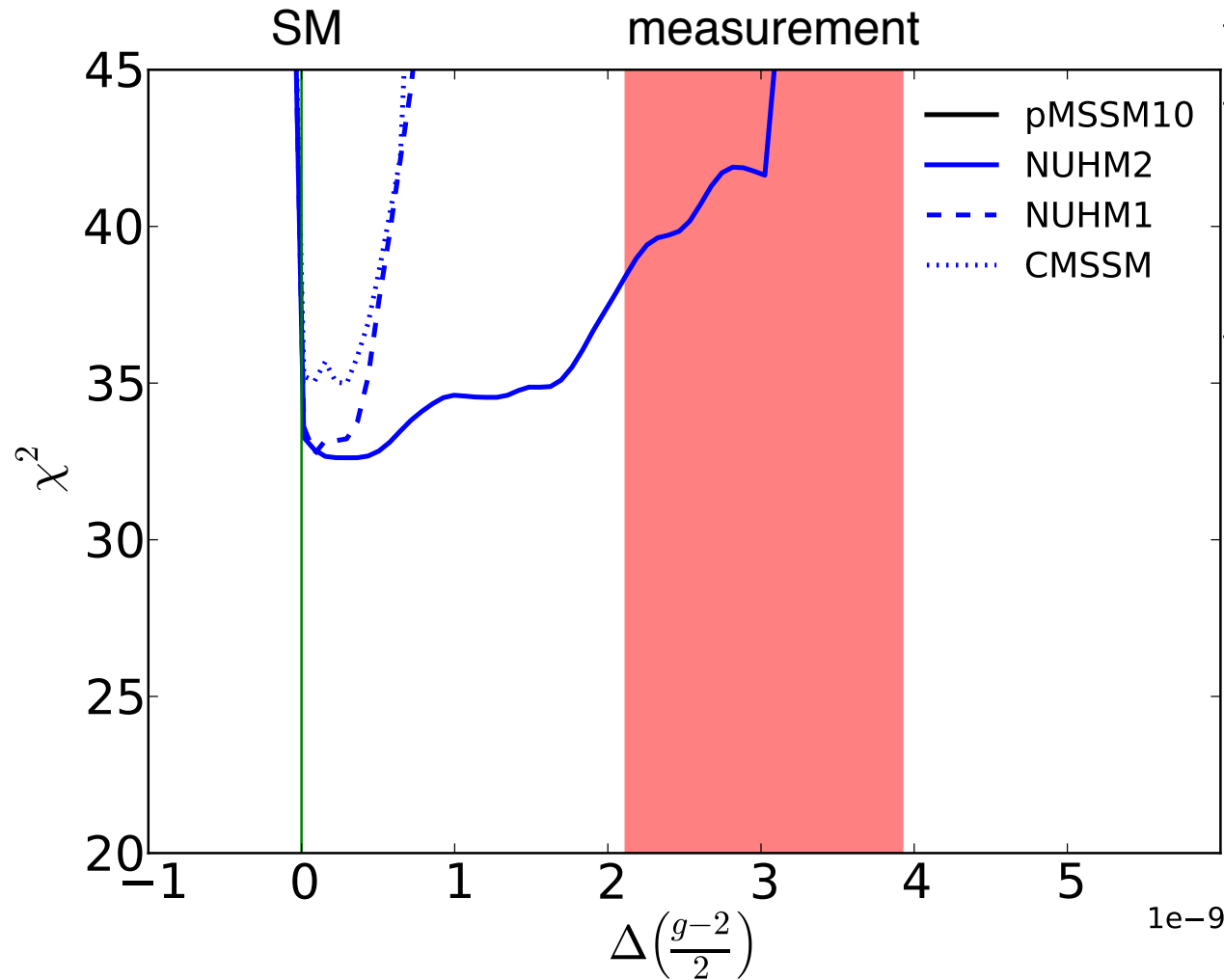
	χ^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

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



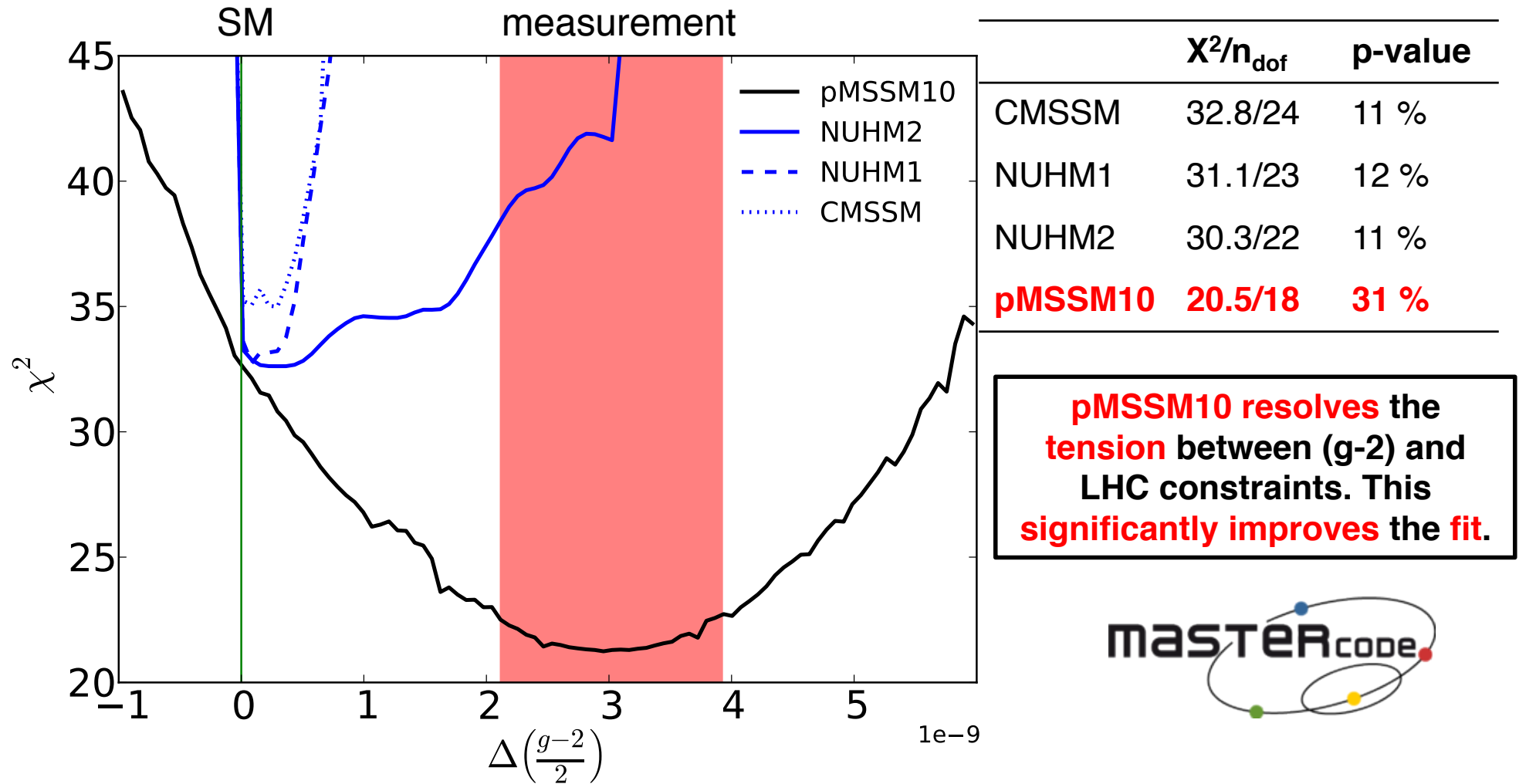
	χ^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

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

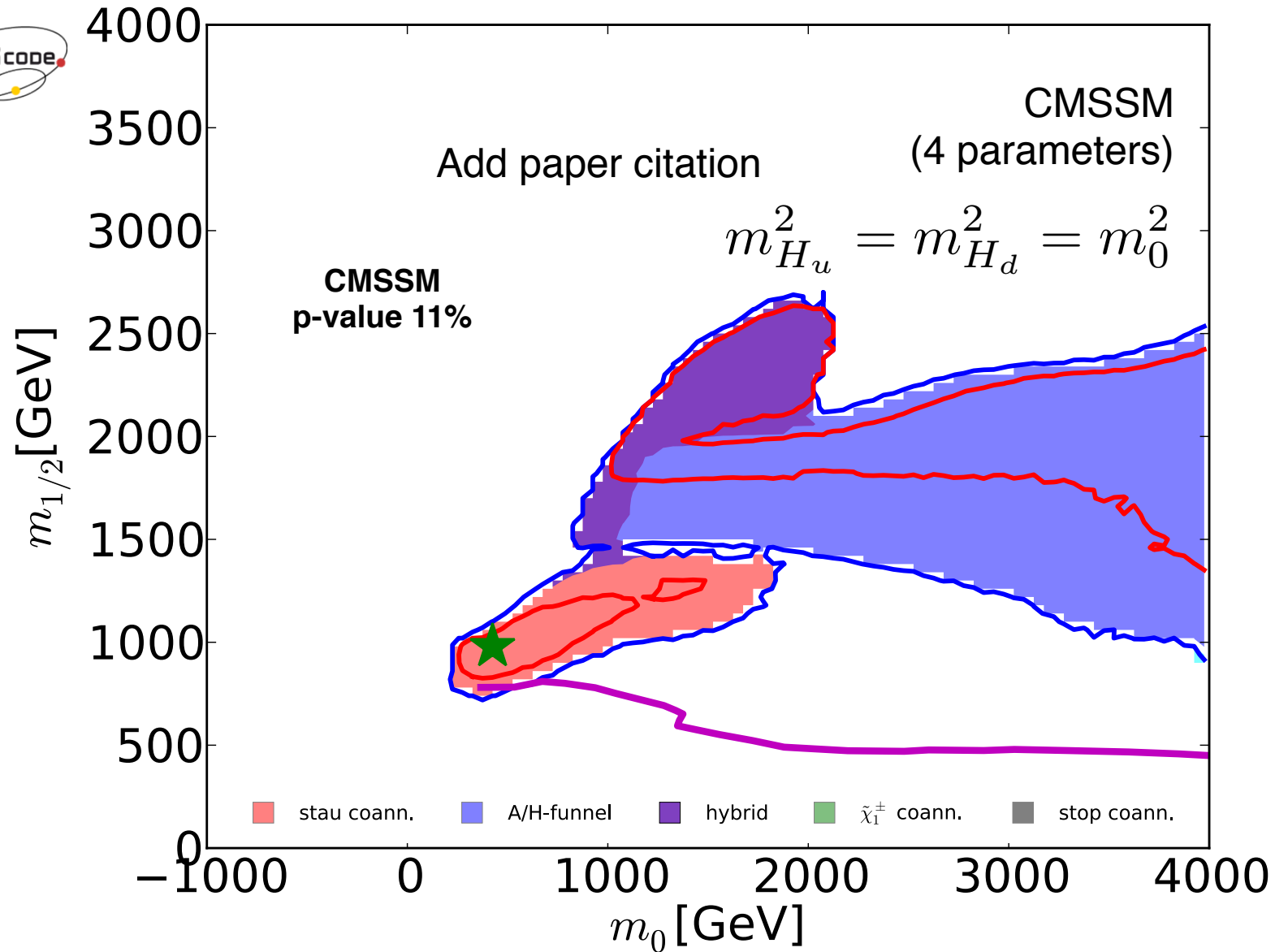


From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM

★ — CMSSM: best fit, 1σ , 2σ

DM Searches @ LHC O. Buchmüller



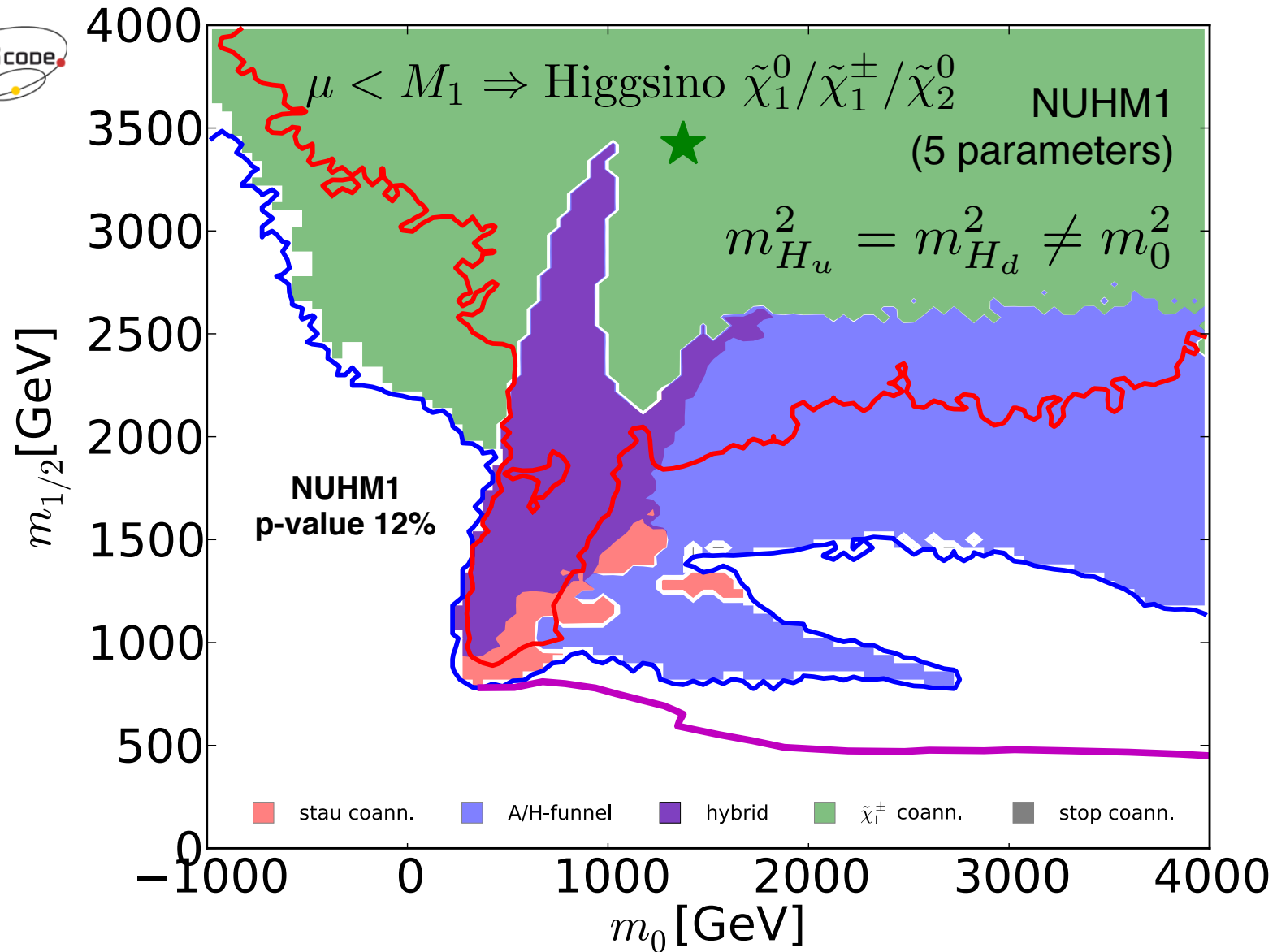
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

NUHM1

★ ——— NUHM1: best fit, 1σ , 2σ



DM Searches @ LHC O. Buchmüller



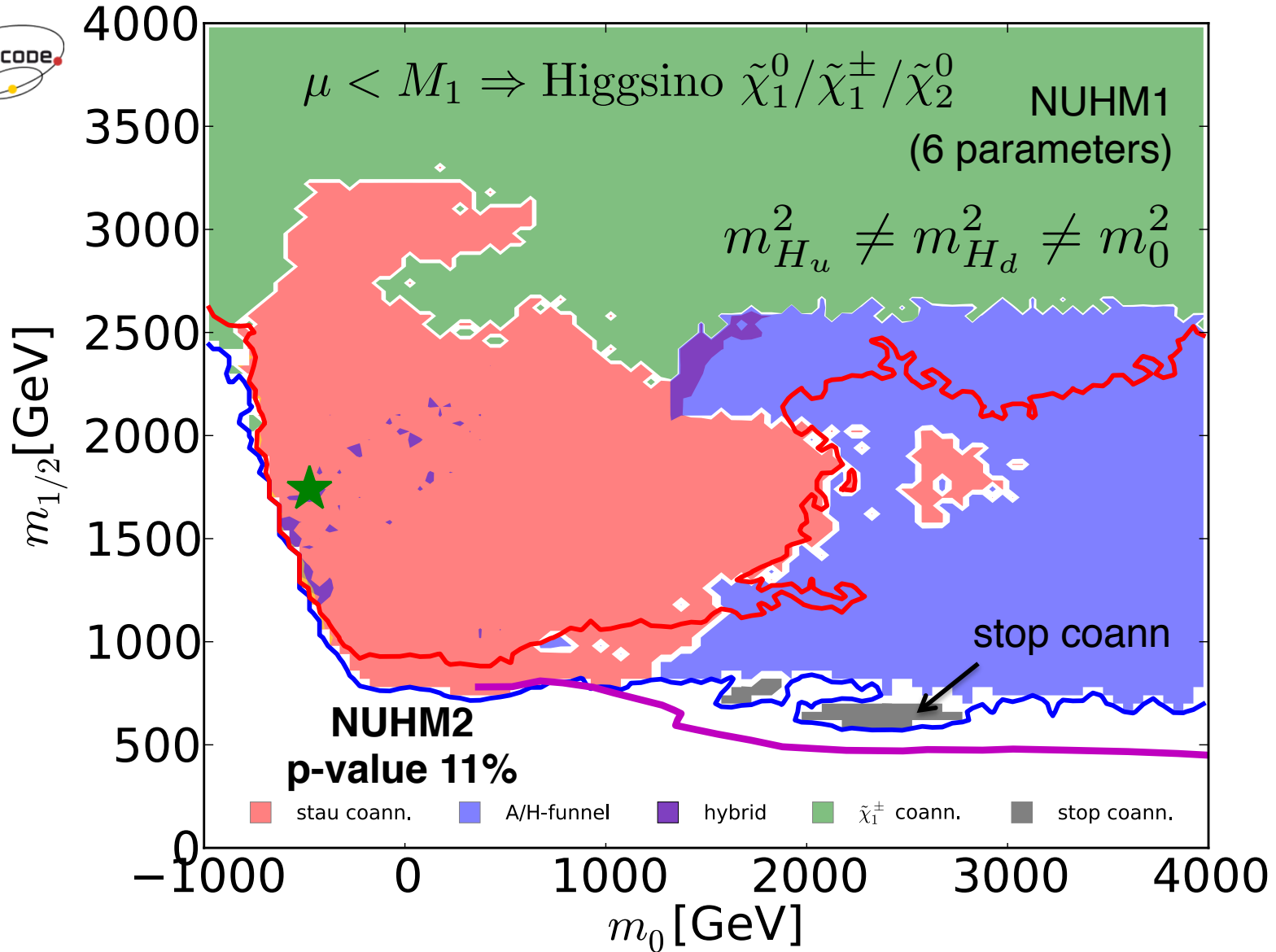
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

NUHM2

★ ——— NUHM2: best fit, 1σ , 2σ



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From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

MasterCode: The two worlds of SUSY models

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“Soft scale”

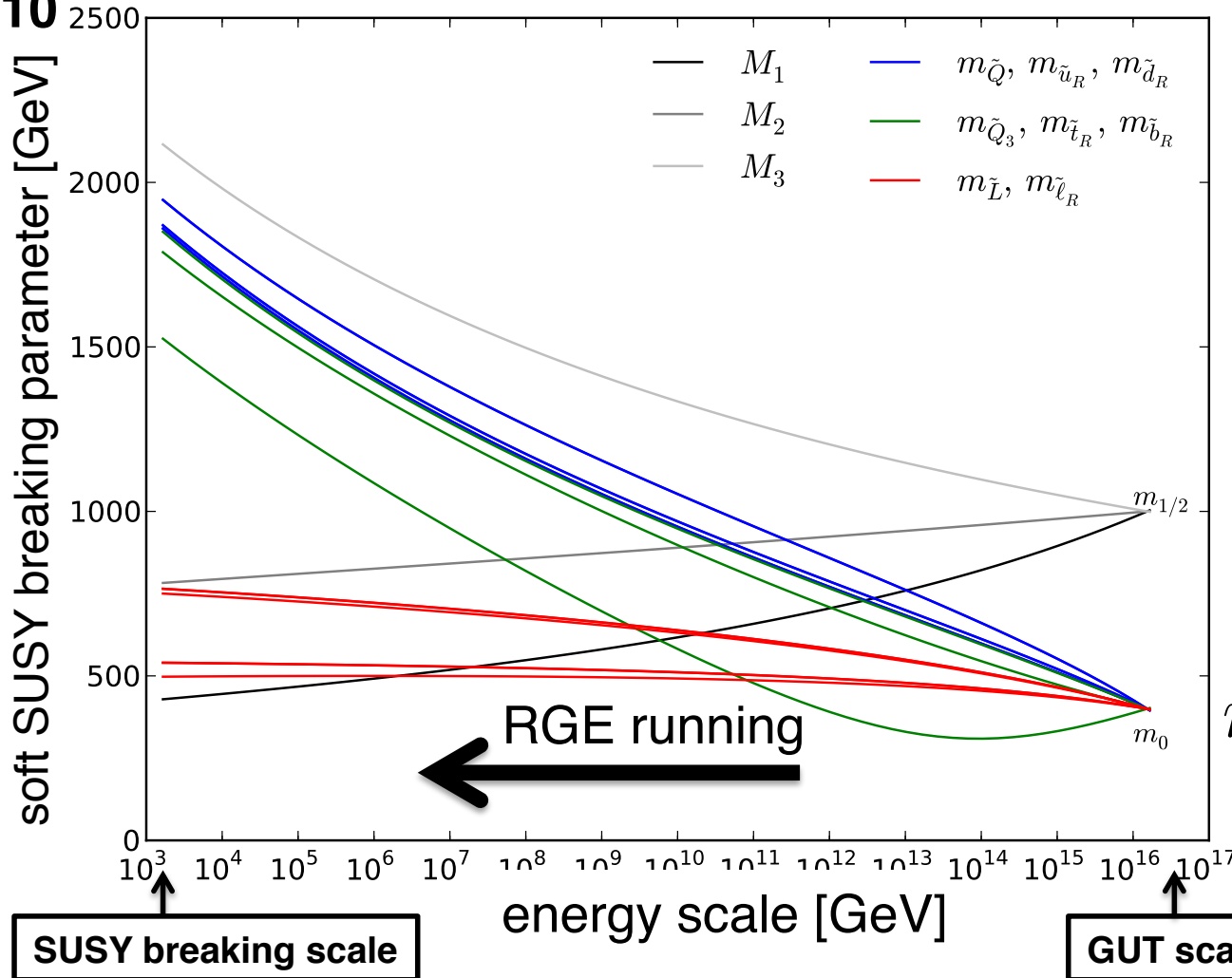


“GUT scale”



pMSSM10

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



CMSSM

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

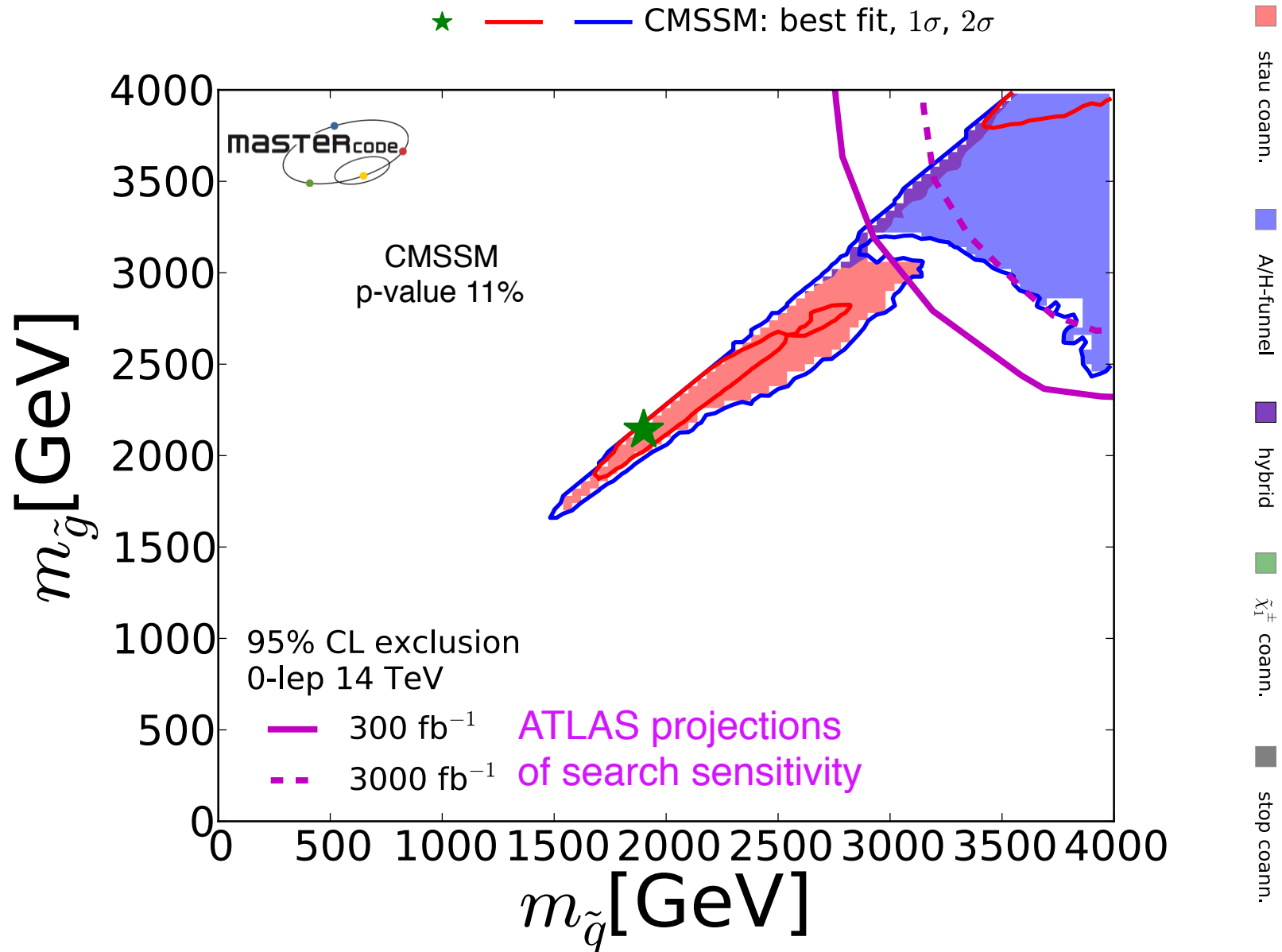
NUHM1

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

NUHM2

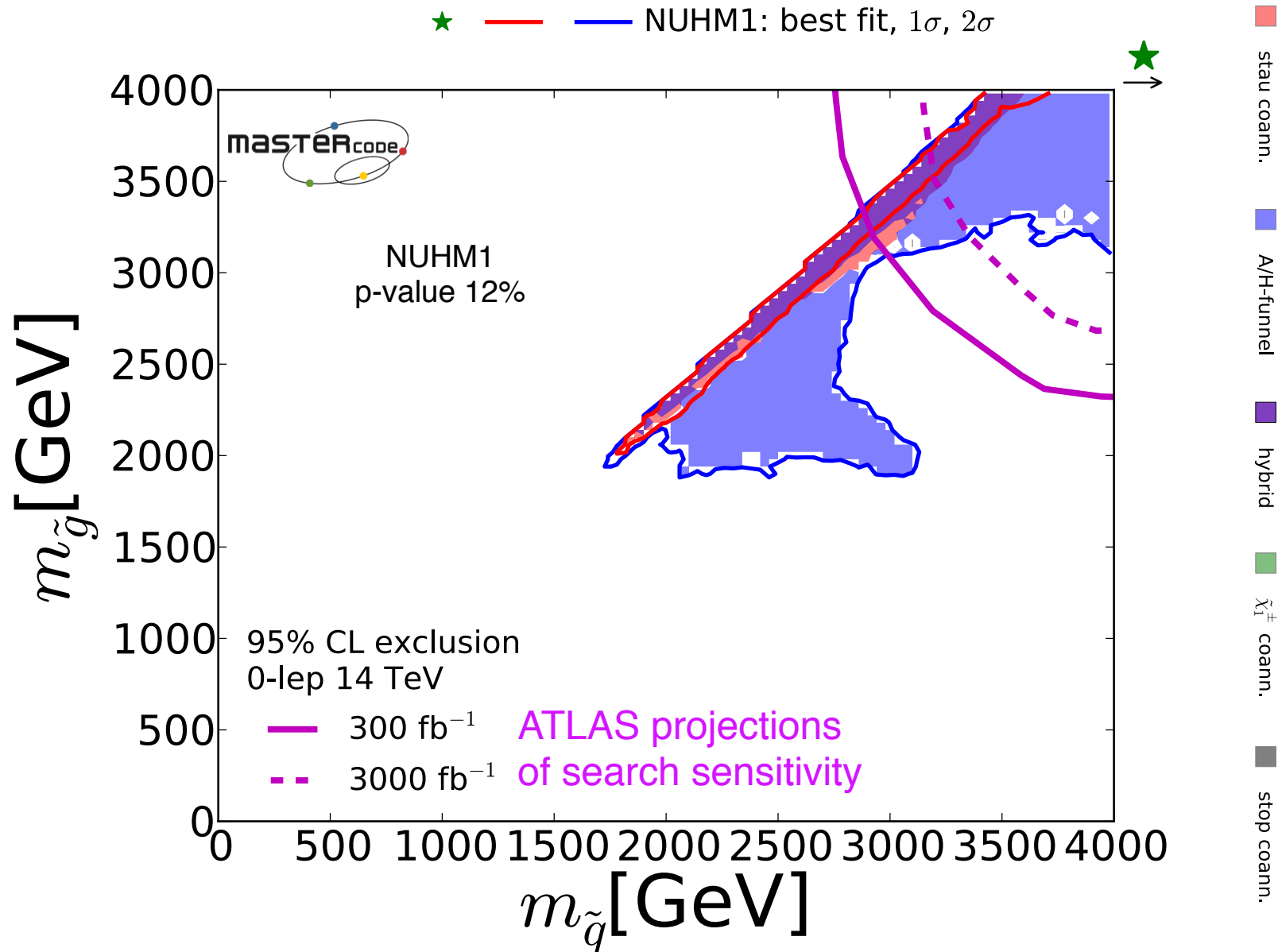
$m_{H_u}^2 \neq m_{H_d}^2$

CMSSM Today: M_q - M_g Search plane



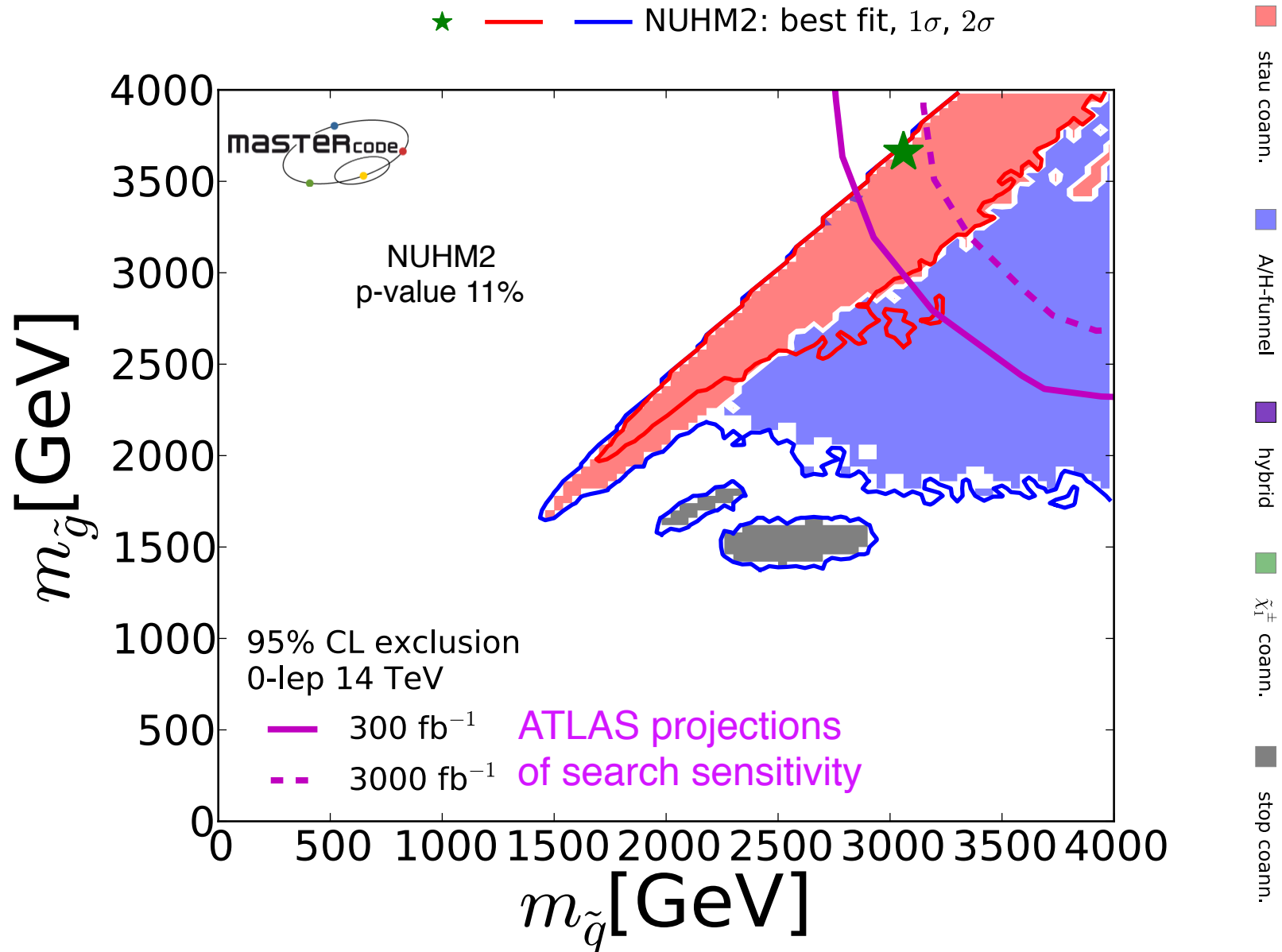
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: M_q - M_g Search plane



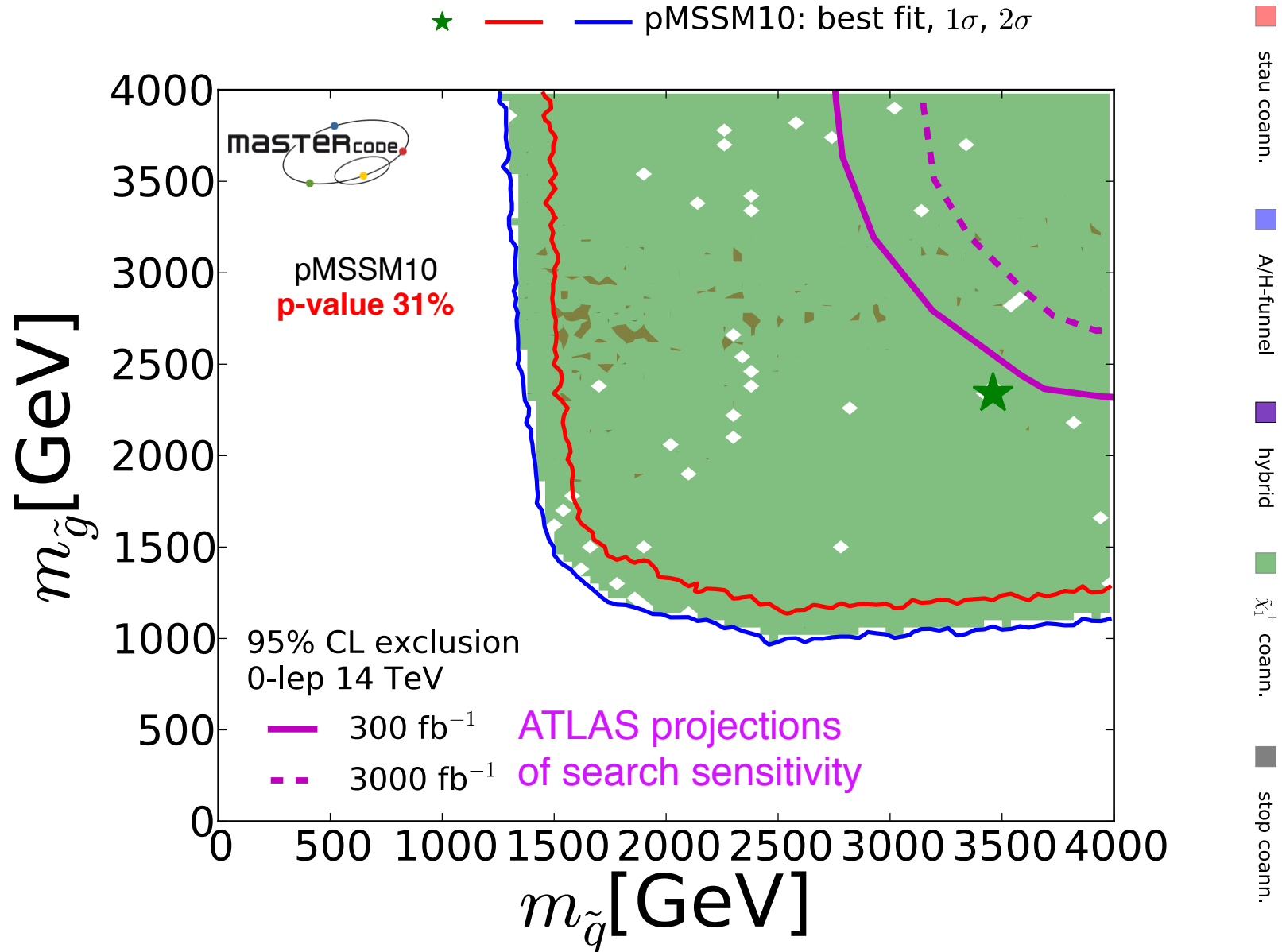
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

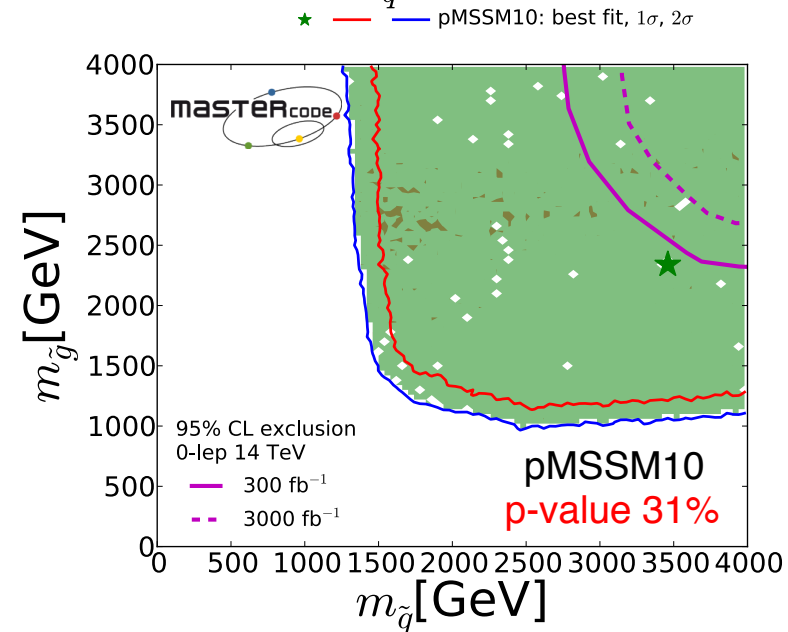
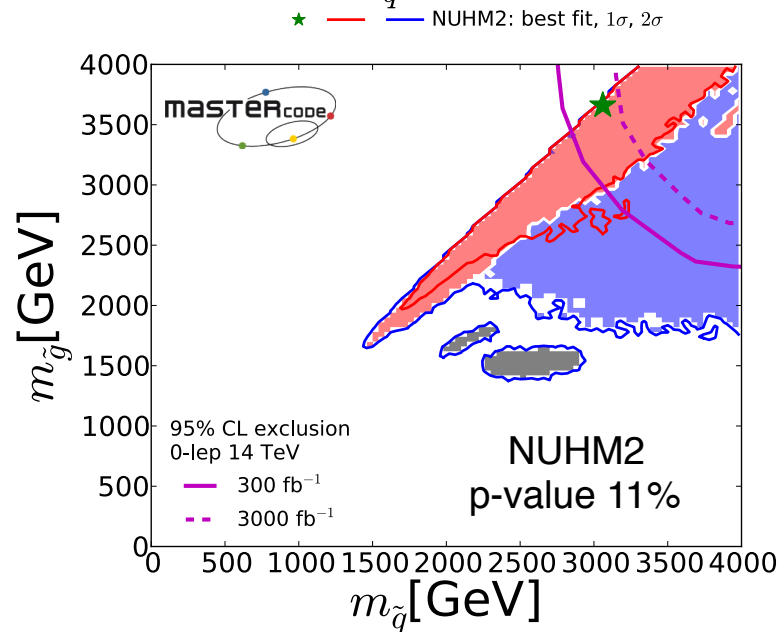
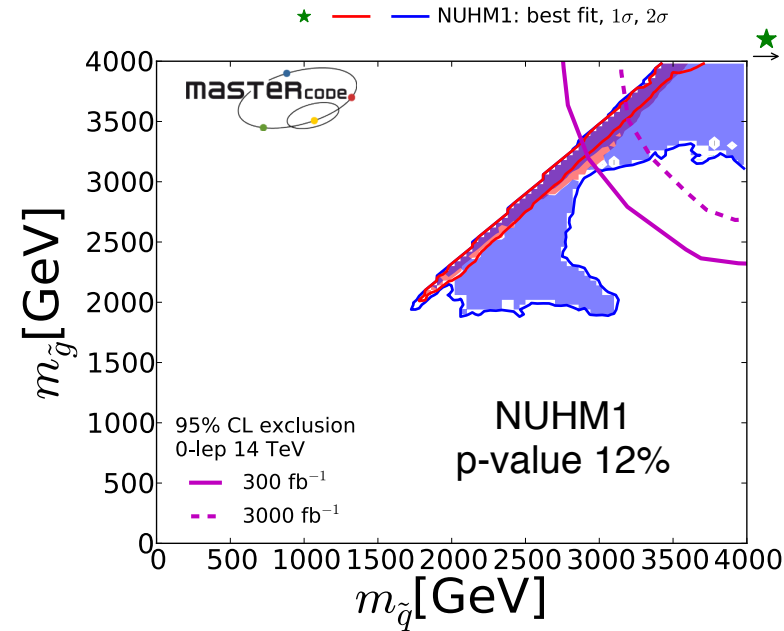
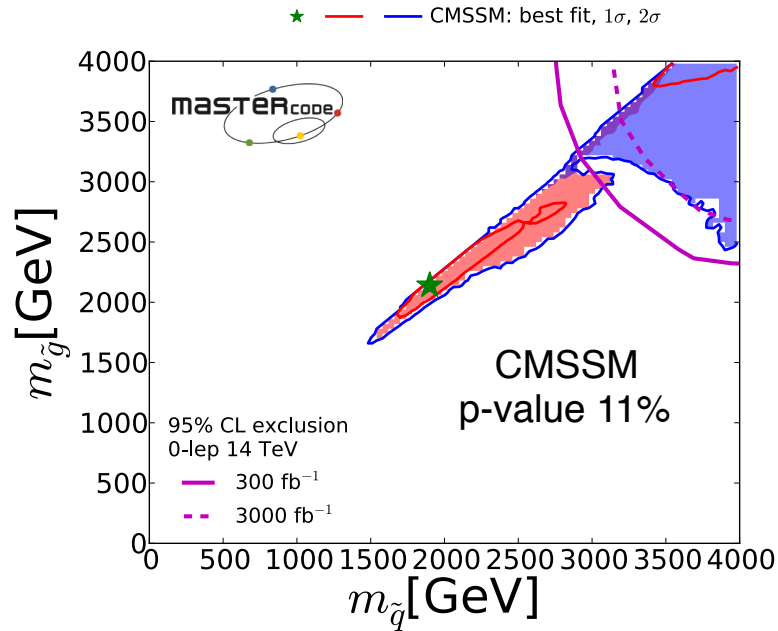
CMSSM Today: M_q - M_g Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Models in Comparison in “Mq-Mg Search plane”

DM Searches @ LHC O. Buchmüller

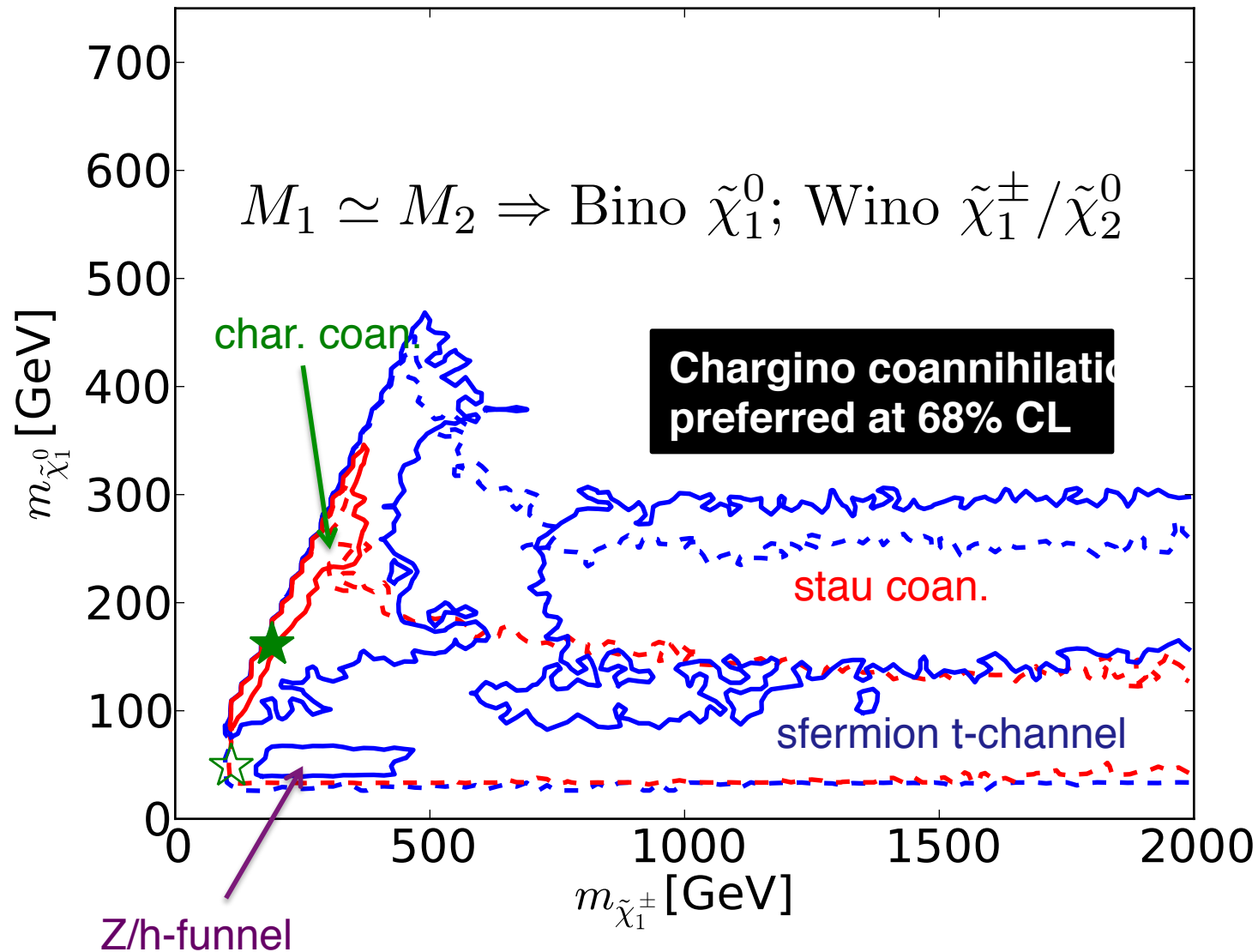


■ stau coann.
■ A/H-funnel
■ hybrid
■ $\tilde{\chi}_1^\pm$ coann.
■ stop coann.

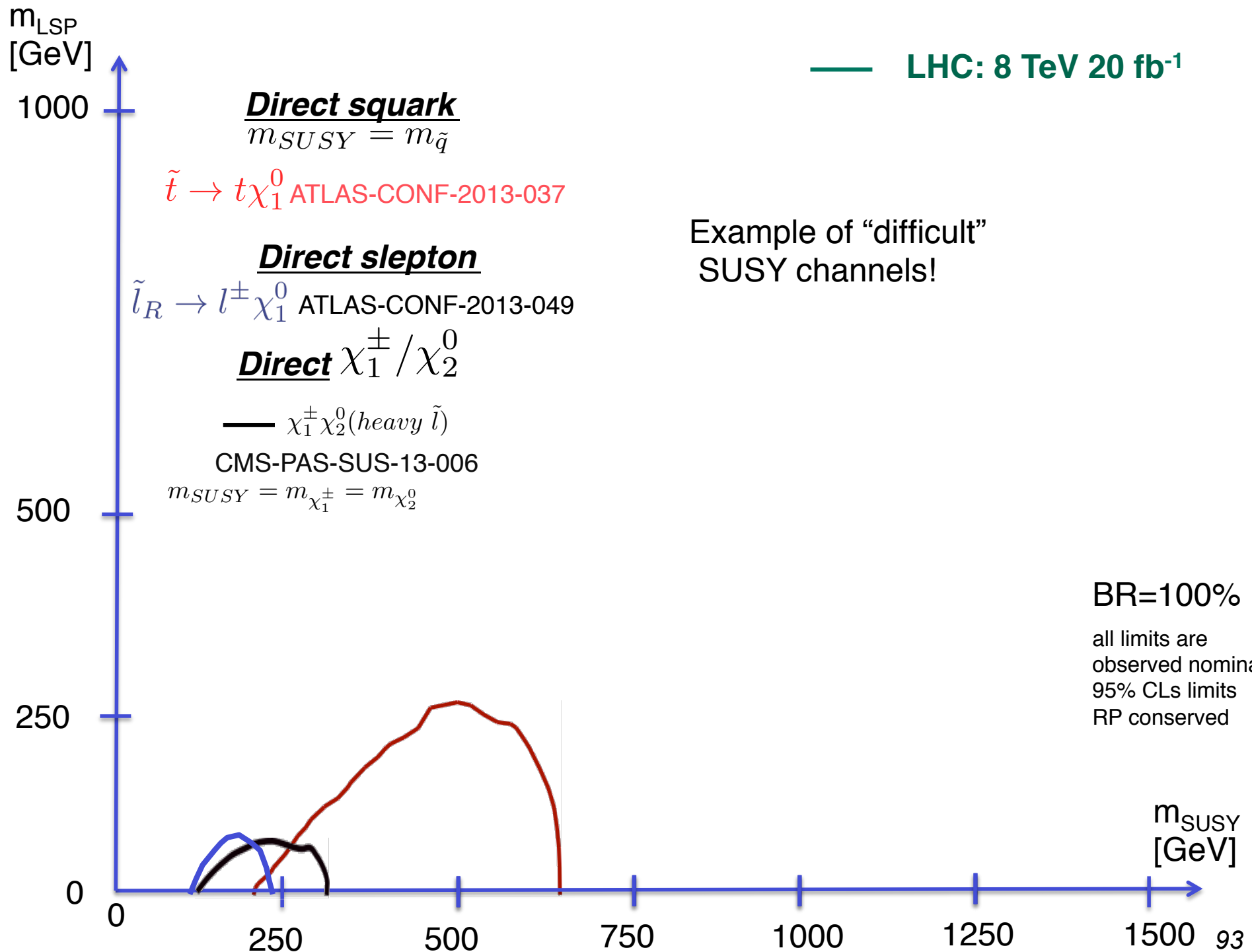
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

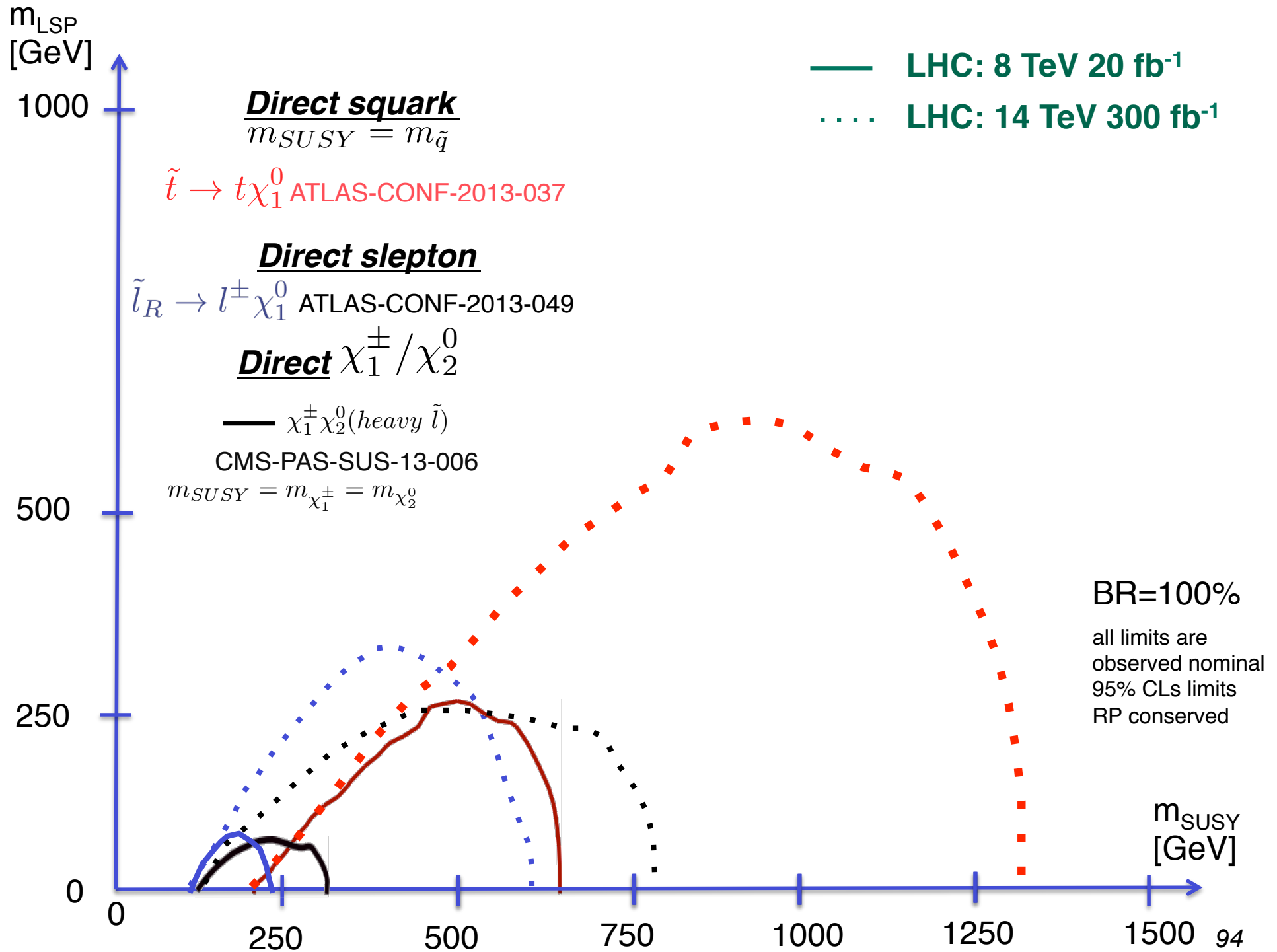
pMSSM10: parameter space

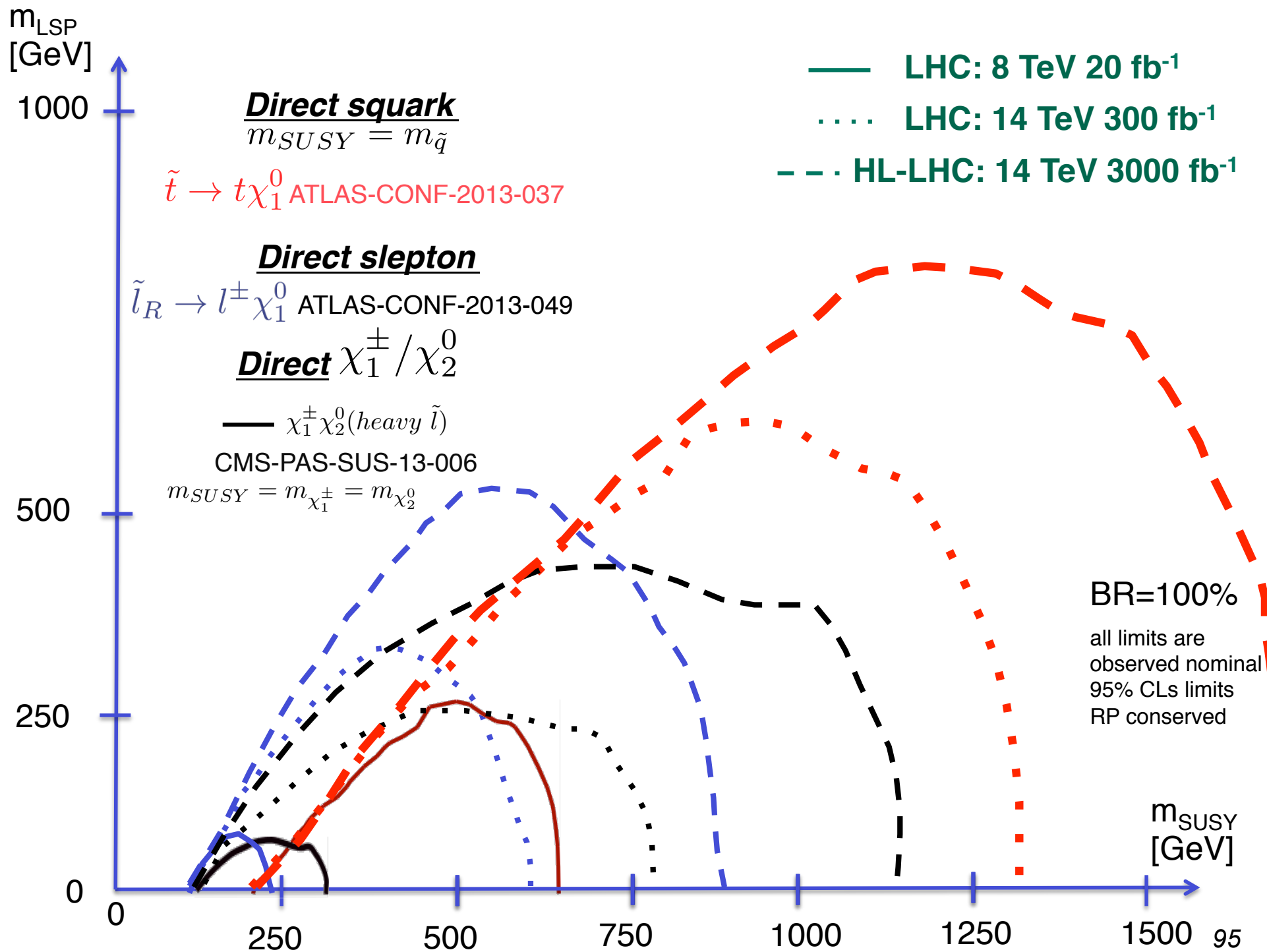
★ — pMSSM10 w LHC8: best fit, 1σ , 2σ
 ☆ - - - pMSSM10 w/o LHC8: best fit, 1σ , 2σ

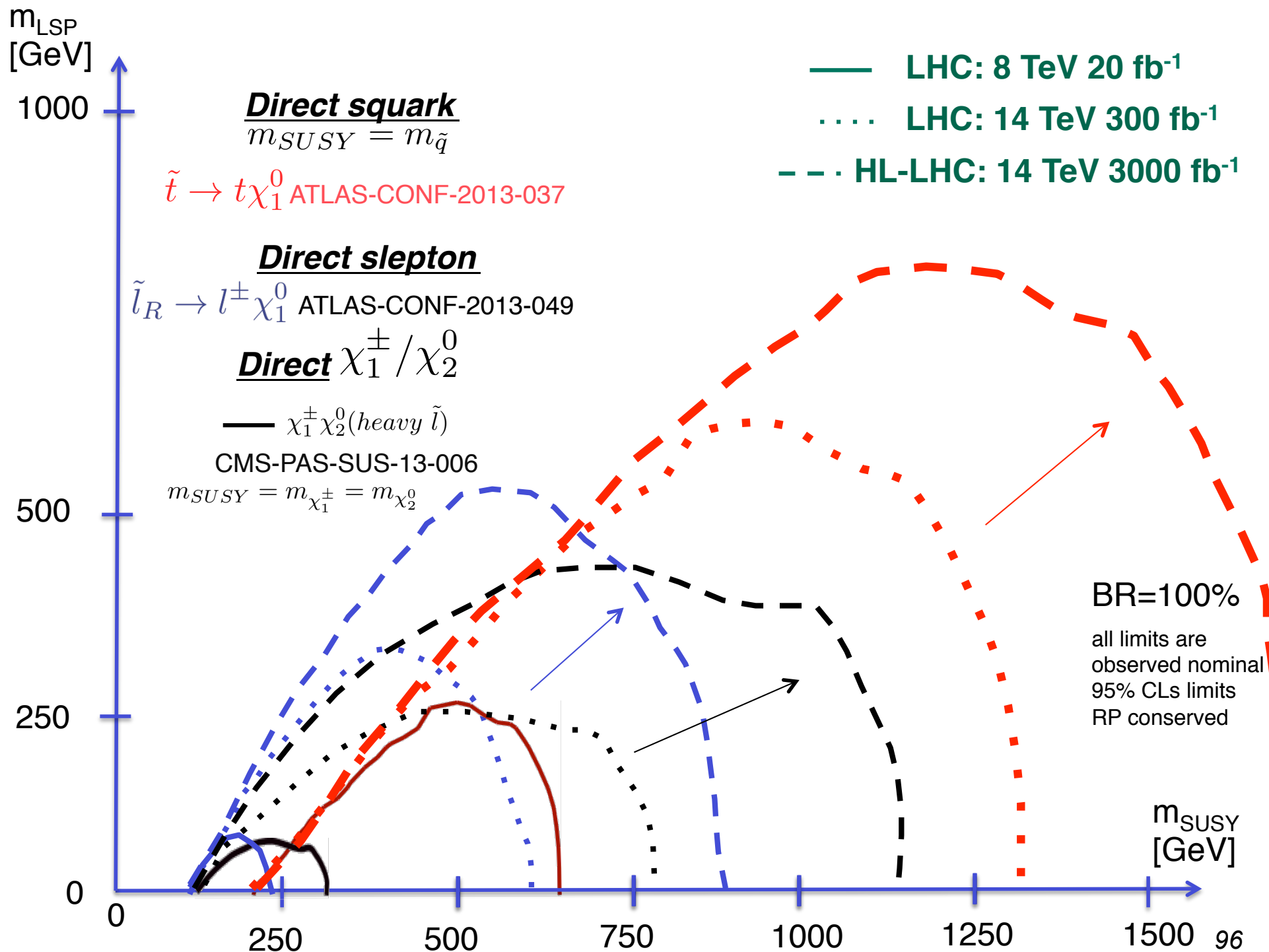


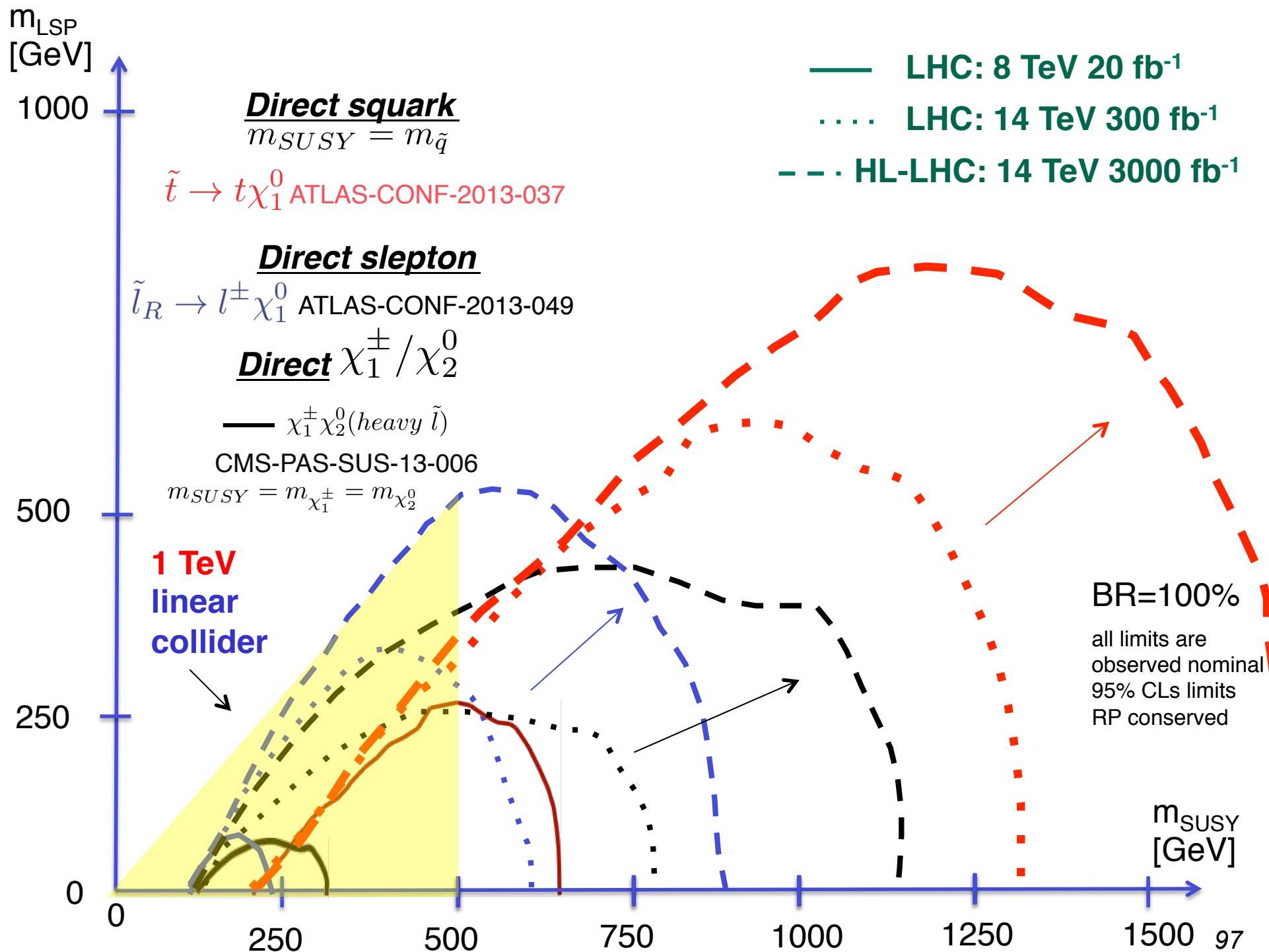
SUSY PROJECTION OF DIFFICULT CHANNELS











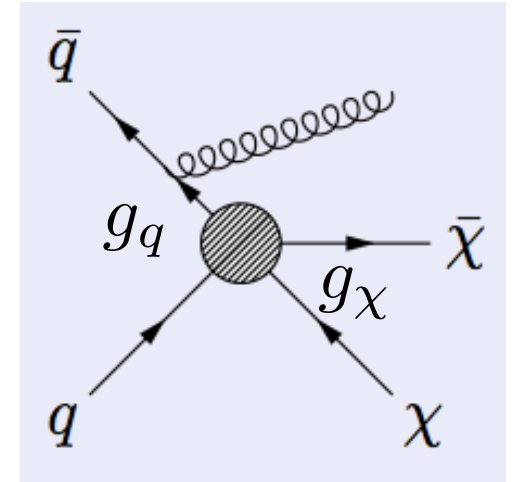
EFT VALIDITY REGION ILLUSTRATED

Effective Field Theory (EFT) Interpretation

Example of considered operators:

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

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



Assumption of EFT

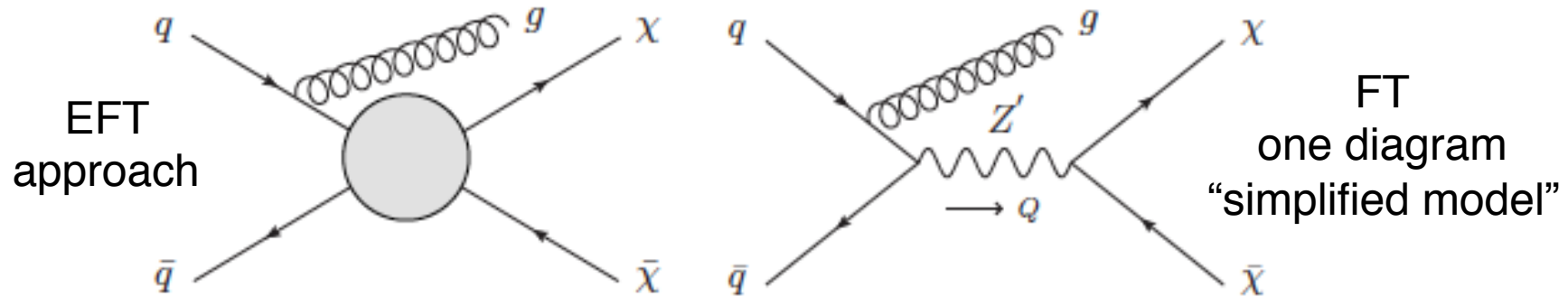
If the operator (e.g. V or AV) mediator is **suitably(!!)** heavy it can be integrated out to obtain the effective V or AV contact operator. **In this case (and only this case)**, the contact interaction scale Λ is related to the parameters entering the Lagrangian:

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

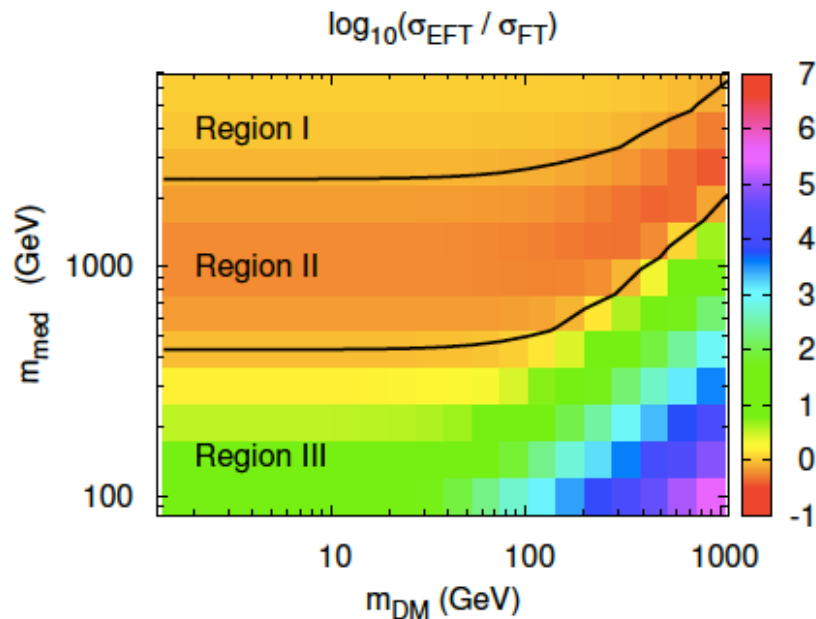
Validity of Effective Field Theory Limits

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

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



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



Compare prediction of FT with EFT in $m_{\text{med}} - m_{\text{DM}}$ plane. Three regions become visible:

Region I: EFT and FT agree better than 20%

➤ EFT is valid!

Region II: EFT yields significant weaker limits than FT

➤ EFT limits are too conservative!

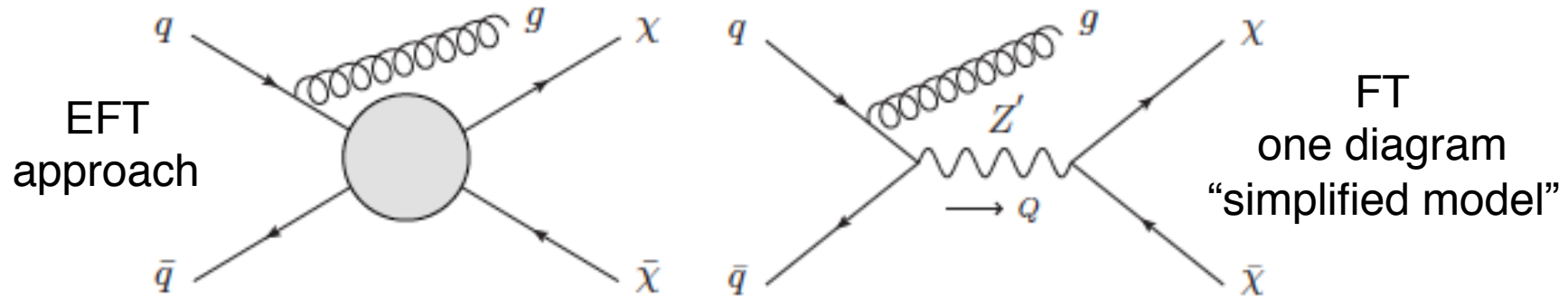
Region III: EFT yields significant stronger limits than FT

➤ EFT limits are too aggressive!

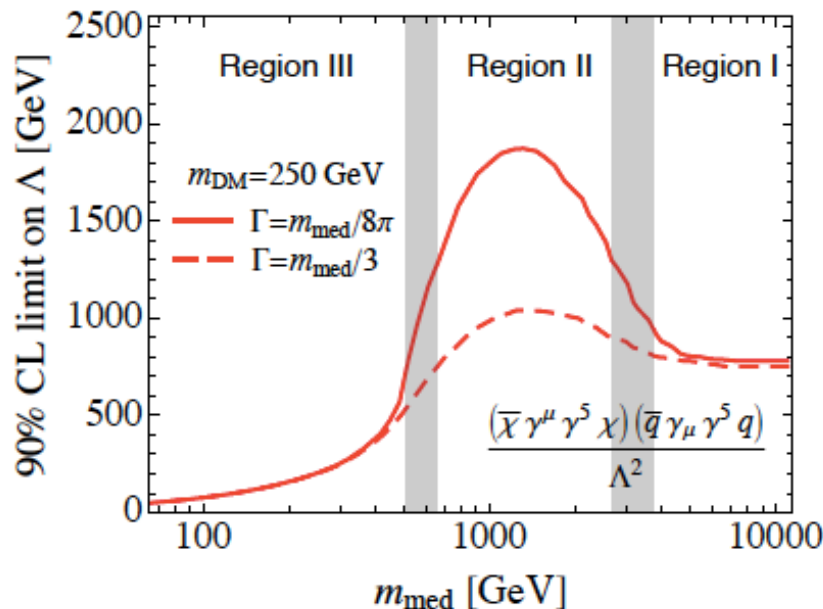
Validity of Effective Field Theory Limits

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

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



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!

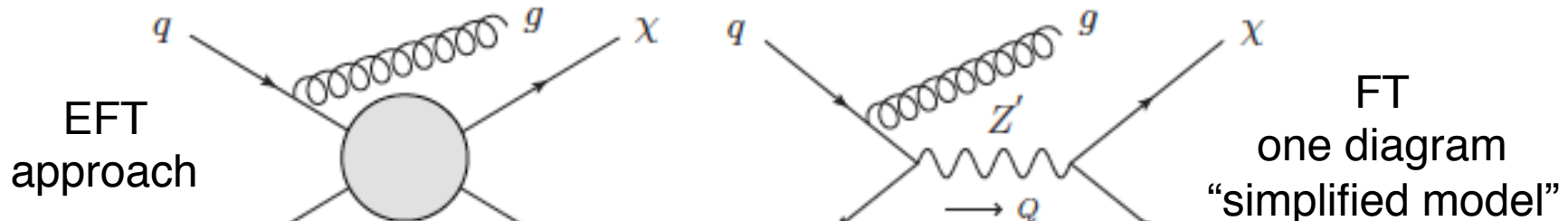
Region III: Low m_{med}

➤ EFT limits are too aggressive!

Validity of Effective Field Theory Limits

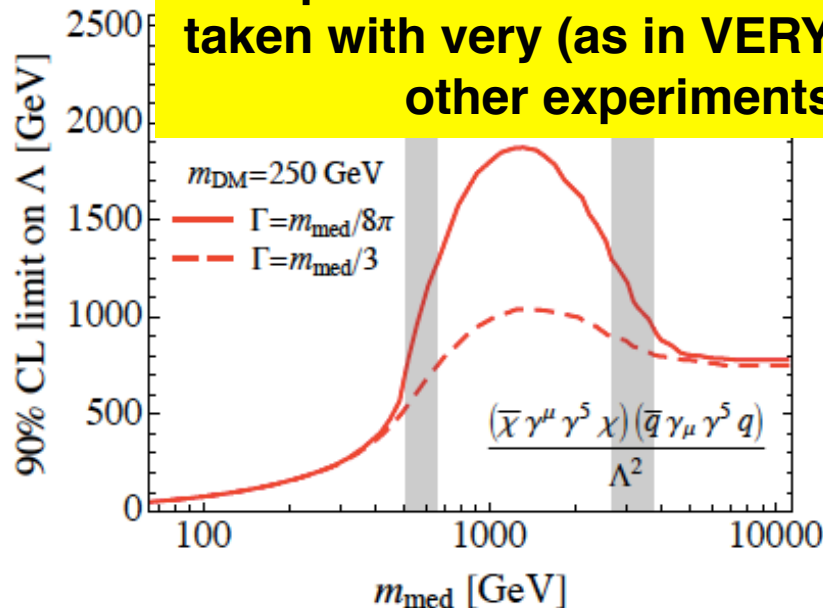
Recent work from OB, M.Dolan, C.McCabe: arXiv:1308.6799

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



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!



Region I: Heavy m_{med}

➤ EFT is valid!

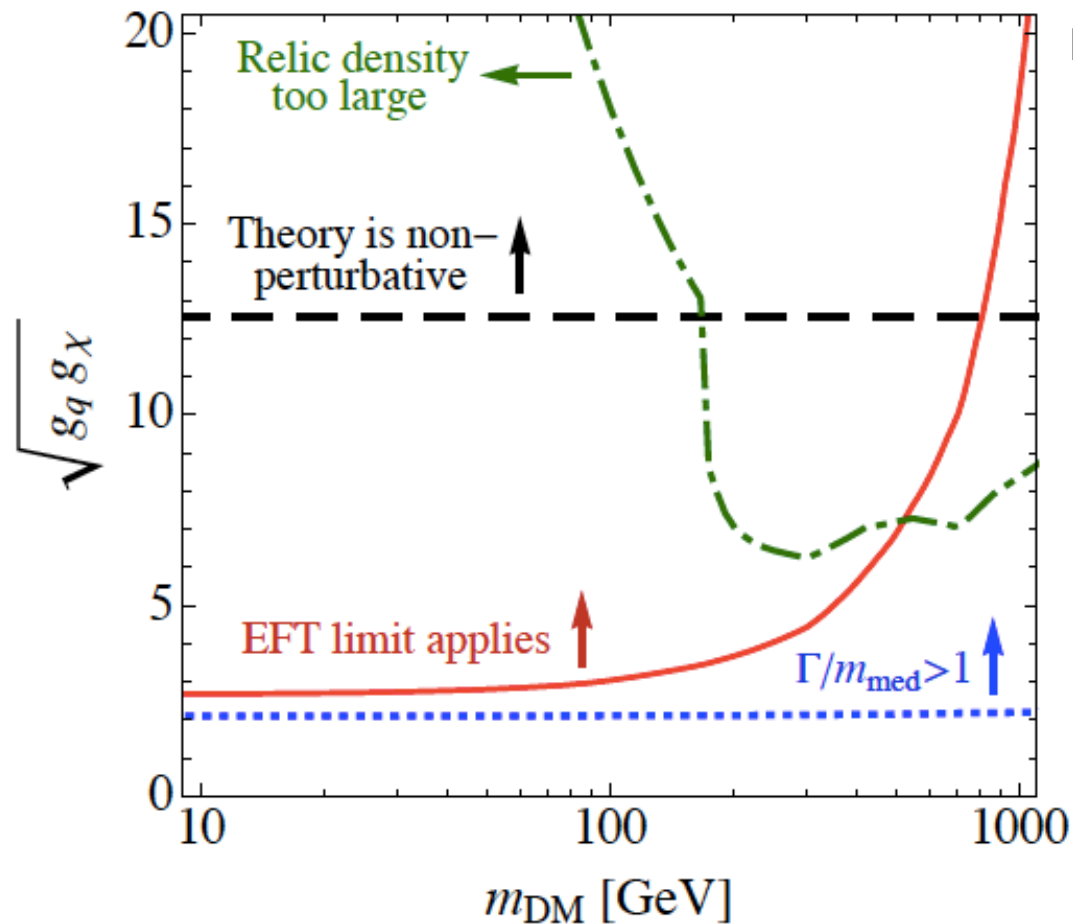
Region II: Medium m_{med} – Resonant enhancement

➤ EFT limits are too conservative!

Region III: Low m_{med}

➤ EFT limits are too aggressive!

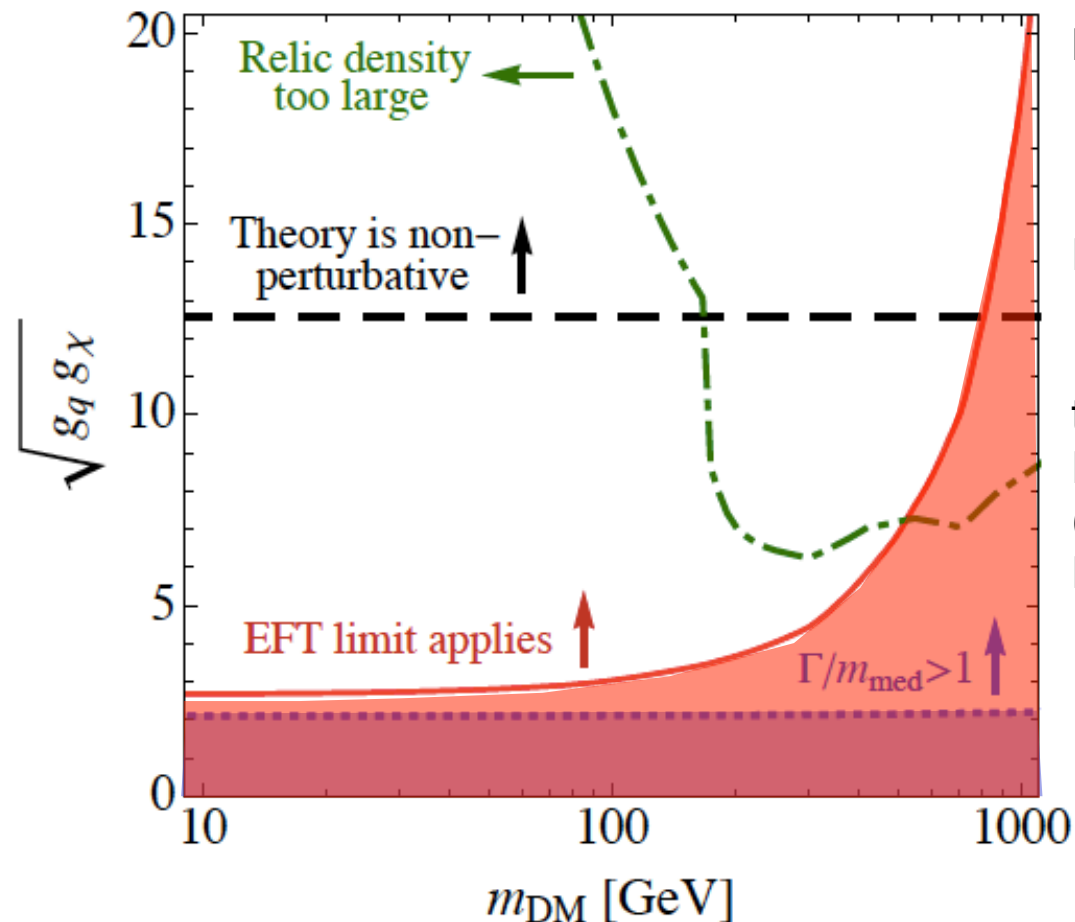
What those this imply on model-dependences of EFT limits?



Look at EFT validity in $m_{\text{DM}} - \text{coupling}^*$ plane!

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

Model-dependences of EFT limits



Look at EFT validity in $m_{\text{DM}} - \text{coupling}^*$ plane!

1. Region in which EFT is valid

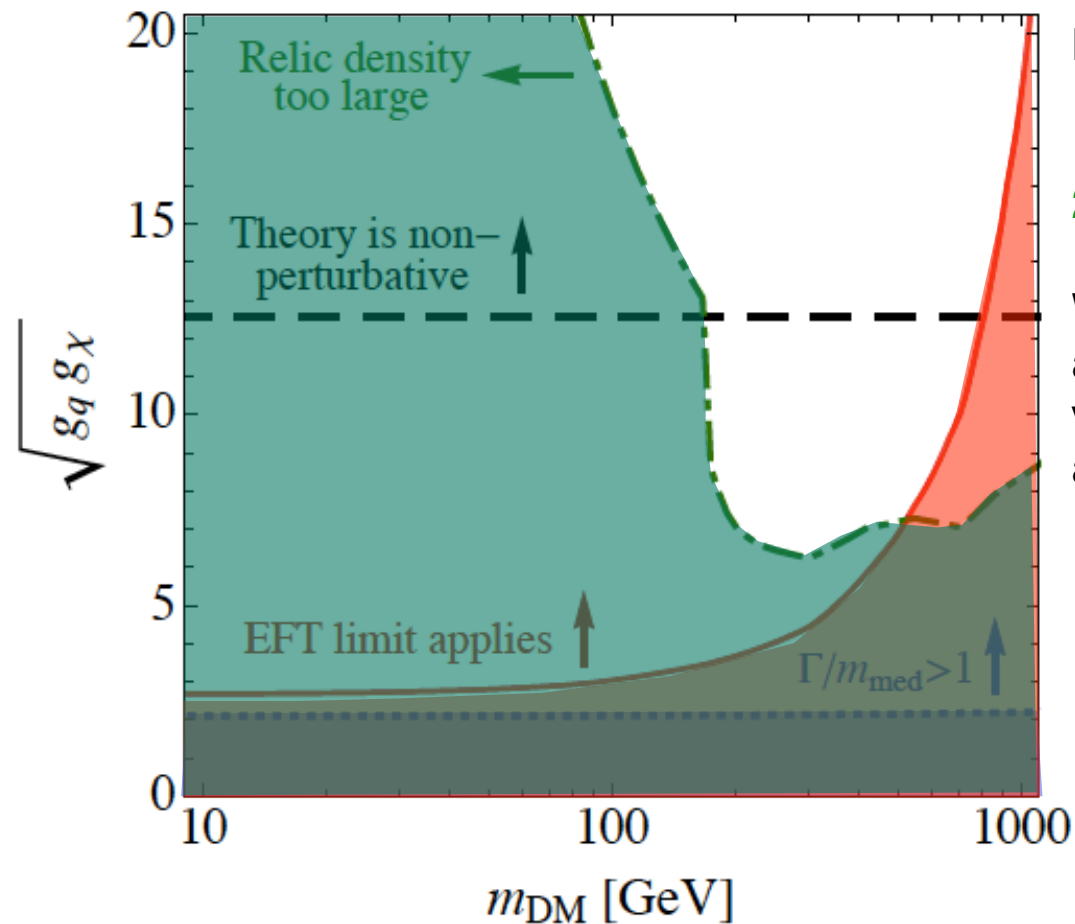
For this we calculate the minimum coupling

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

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

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

Model-dependences of EFT limits



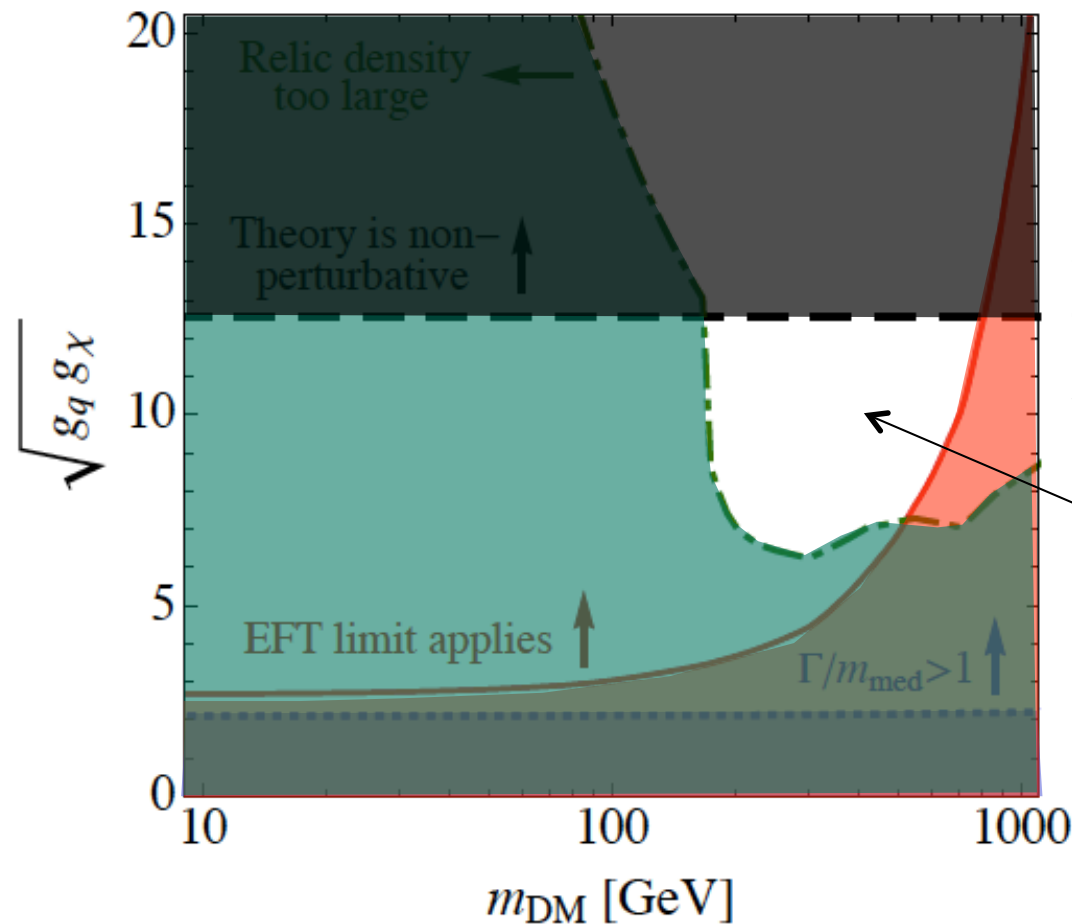
Look at EFT validity in $m_{\text{DM}} - \text{coupling}^*$ plane!

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

When exclude the region in which relic abundance is larger than the observed value of $\Omega_{\text{xx}} h^2 = 0.119$ 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 $m_{\text{DM}} - \text{coupling}^*$ plane!

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

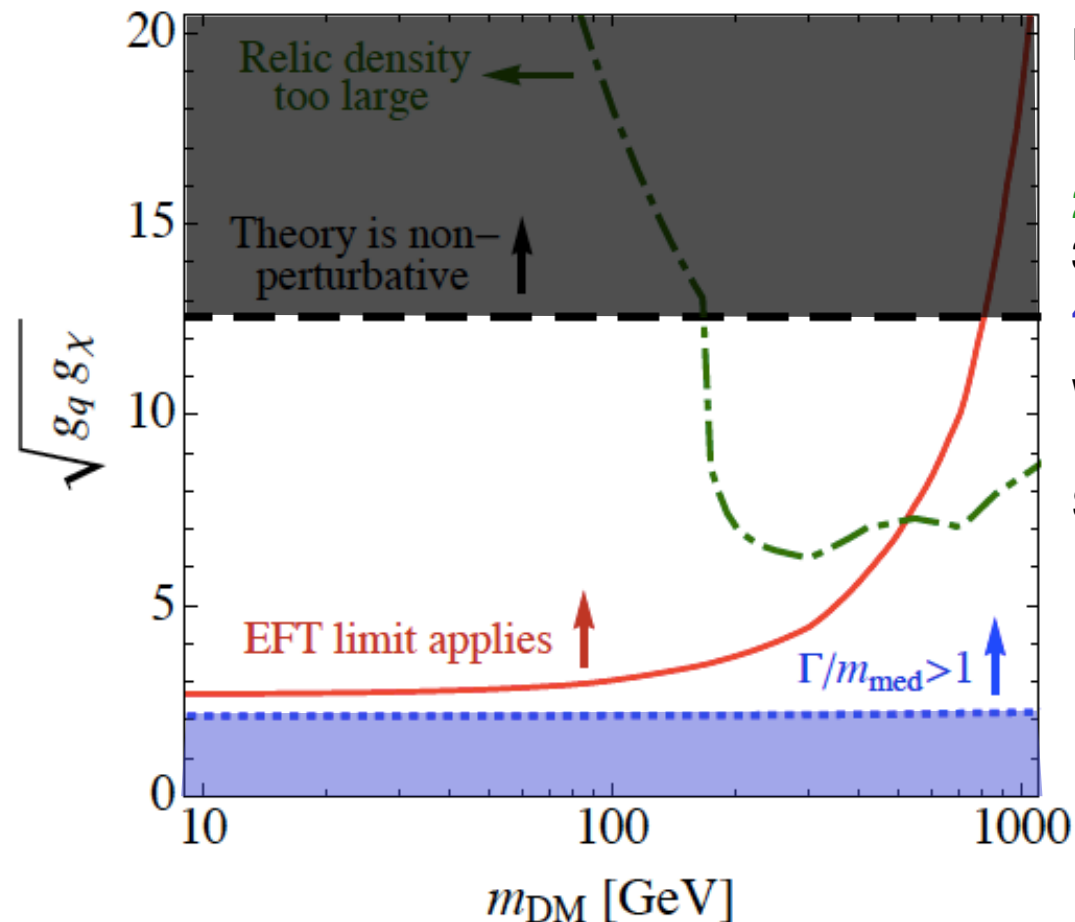
When we also require that the region/theory must be perturbative:

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

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 $m_{\text{DM}} - \text{coupling}^*$ plane!

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

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

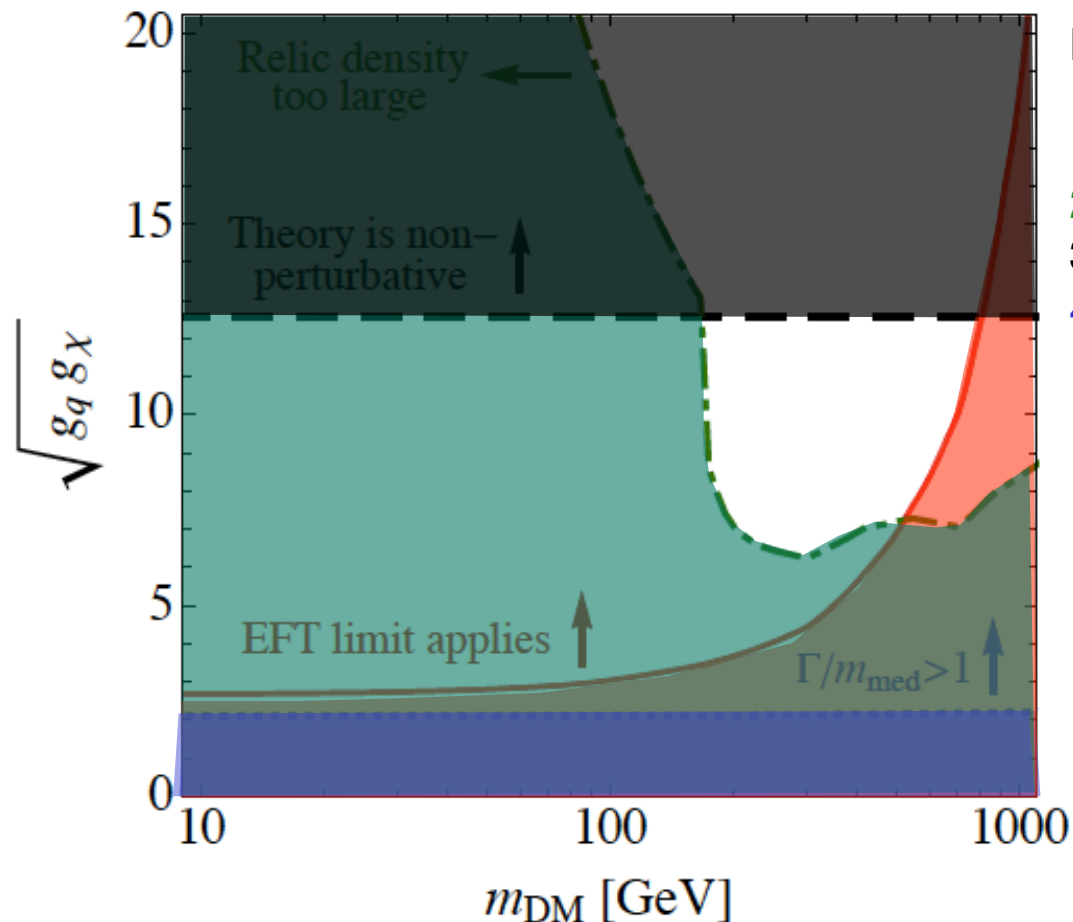
In the remaining part of the plot:

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

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

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 $m_{\text{DM}} - \text{coupling}^*$ plane!

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

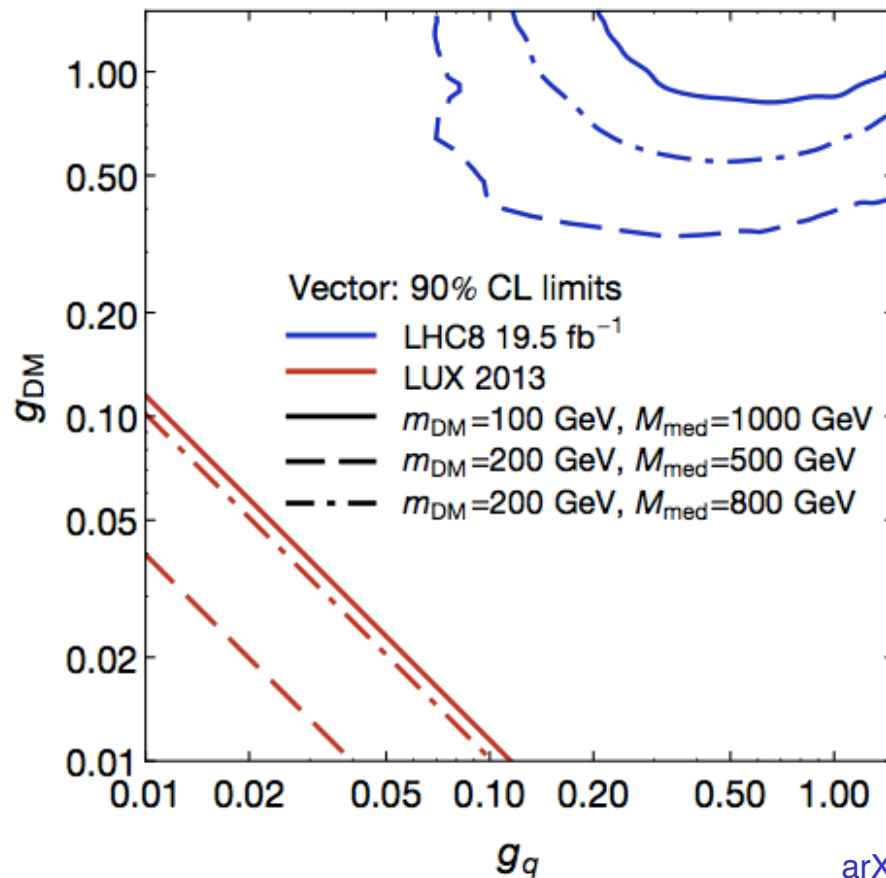
The observation that all DM theories for which the EFT is valid must have $m_{\text{med}} < \Gamma_{\text{med}}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.

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

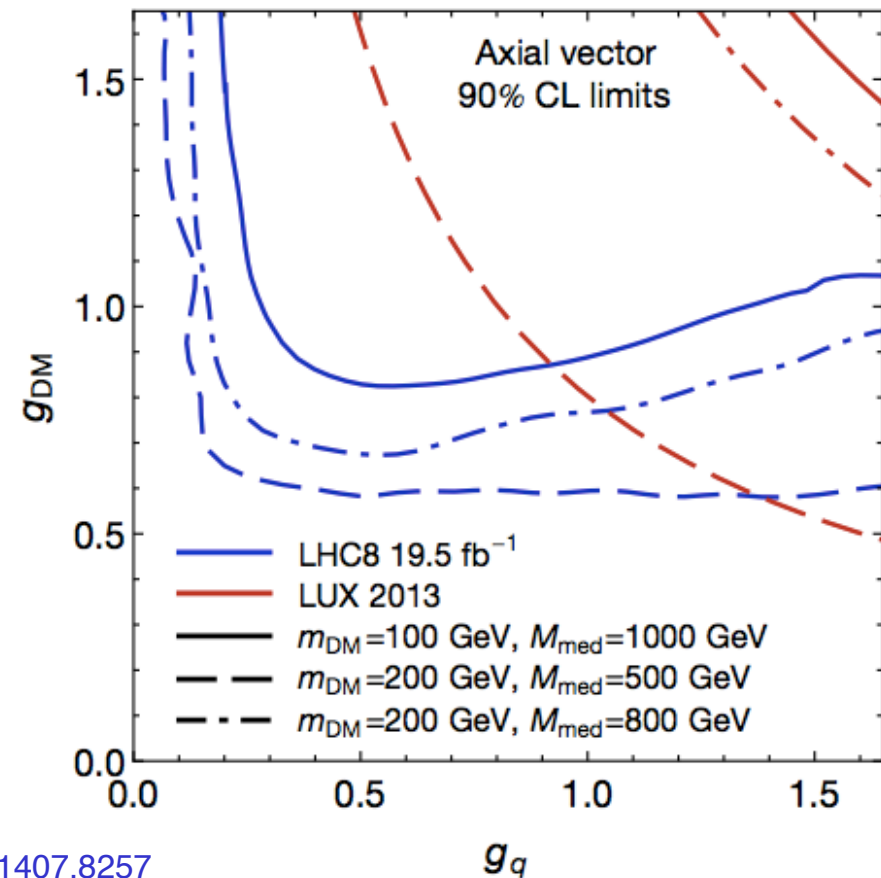
Collider vs Direct Detection

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

Vector



Axial vector



arXiv:1407.8257

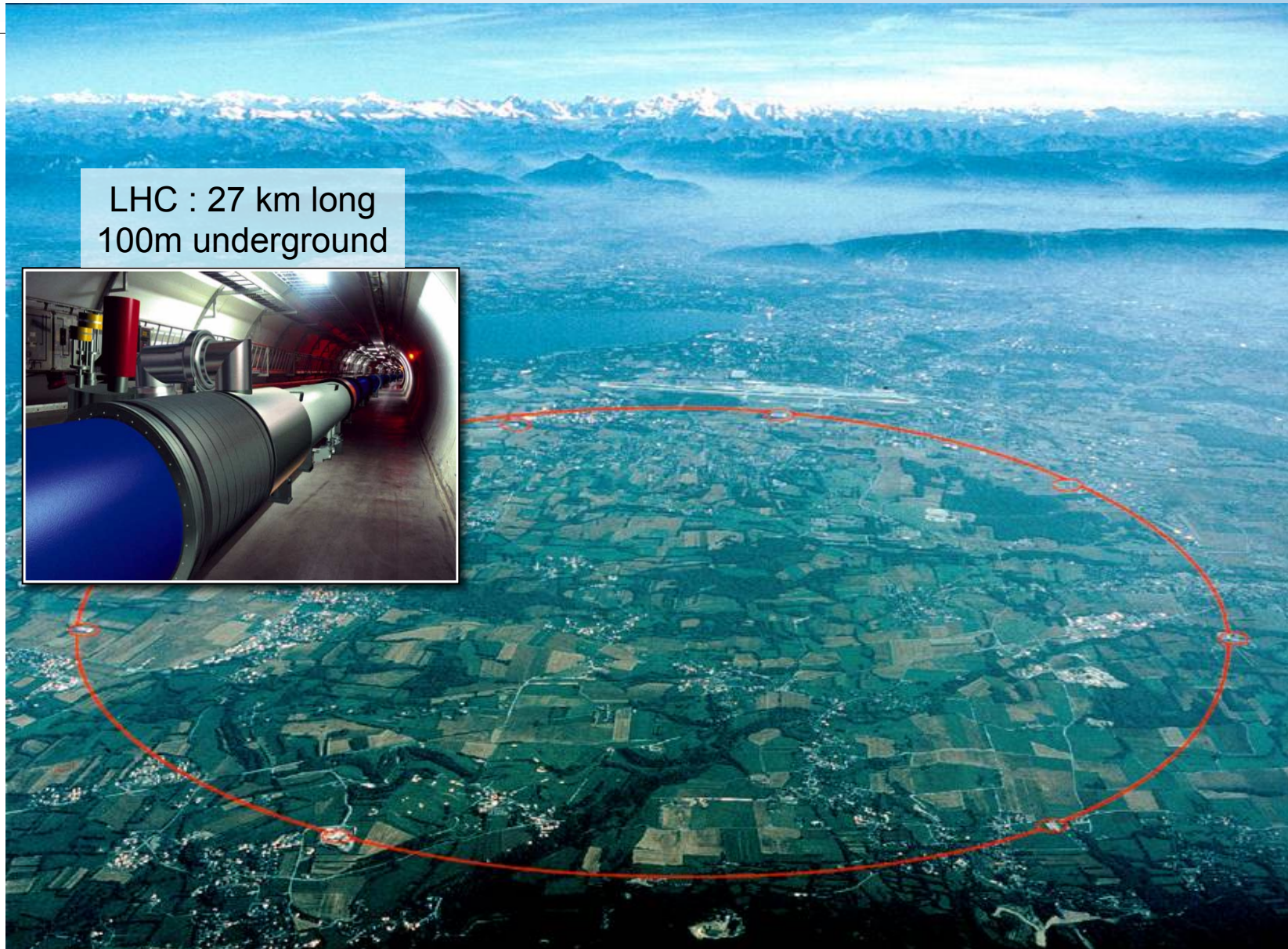
LHC

The Large Hadron Collider at CERN

DM Searches @ LHC O. Buchmüller



The Large Hadron Collider at CERN

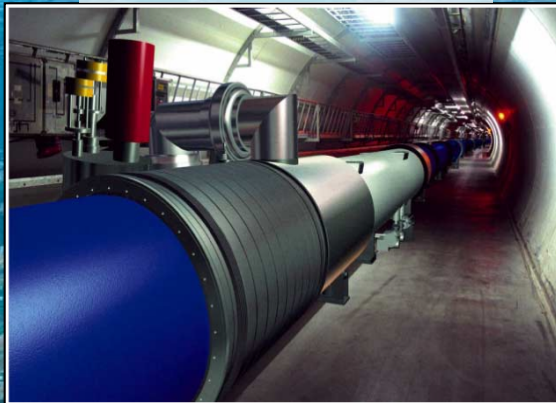


LHC : 27 km long
100m underground

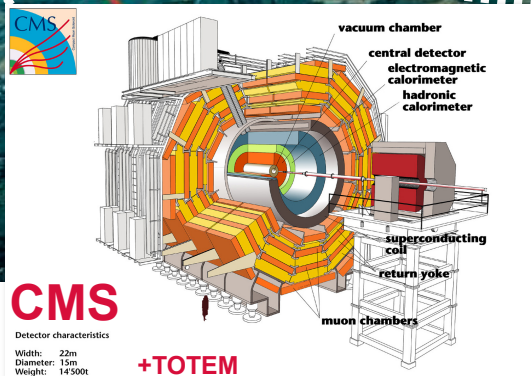
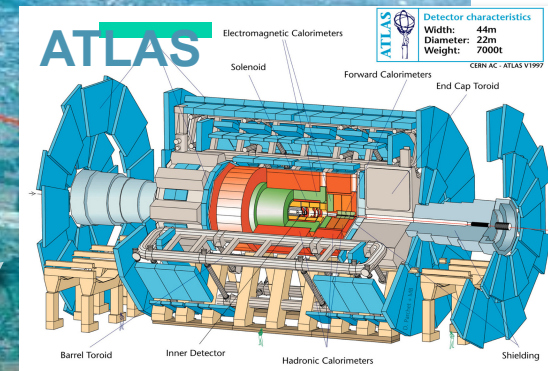
The Large Hadron Collider at CERN

DM Searches @ LHC O. Buchmüller

LHC : 27 km long
100m underground

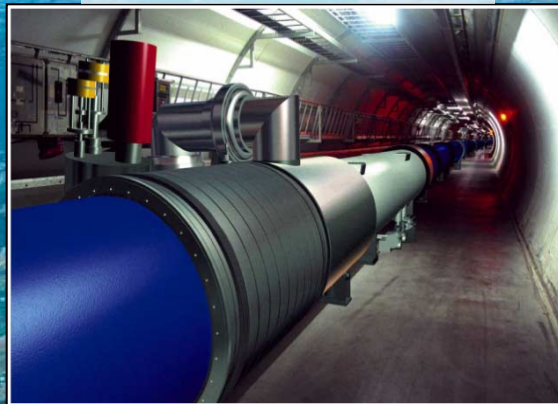


General Purpose,
pp, heavy ions

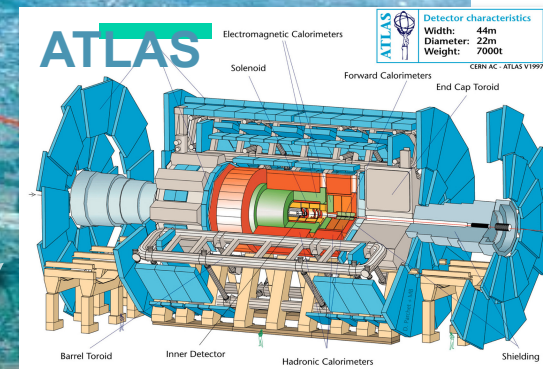


The Large Hadron Collider at CERN

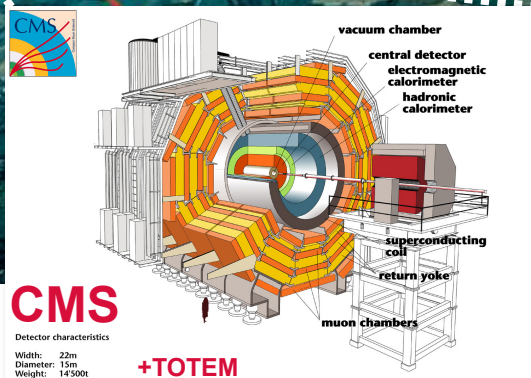
LHC : 27 km long
100m underground



General Purpose,
pp, heavy ions



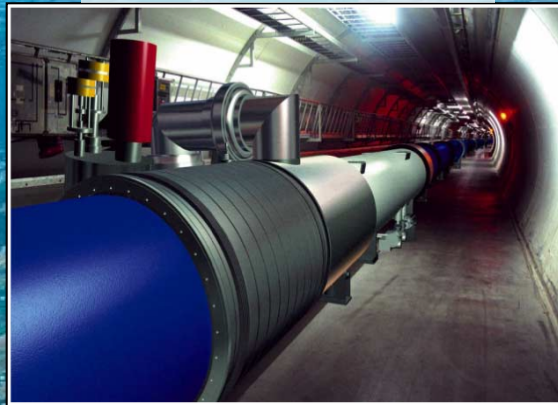
Heavy ions, pp



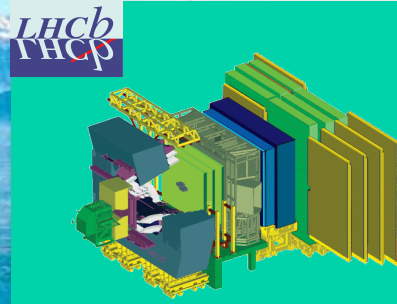
The Large Hadron Collider at CERN

DM Searches @ LHC O. Buchmüller

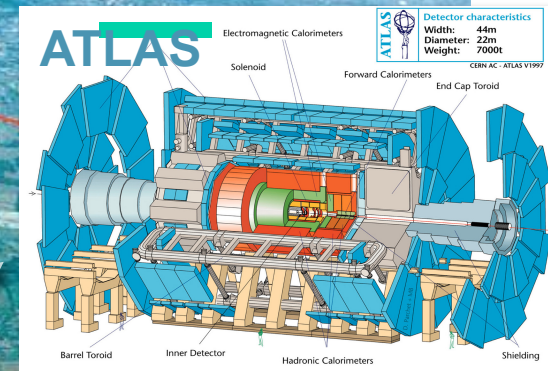
LHC : 27 km long
100m underground



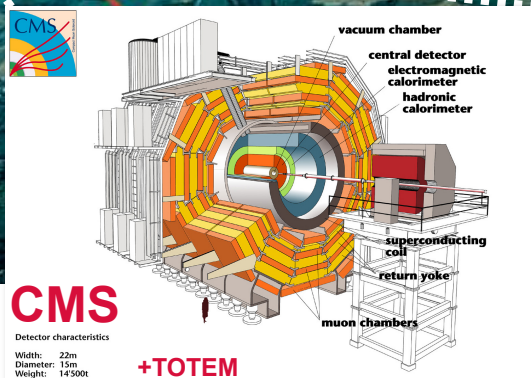
pp, B-Physics,
CP Violation



General Purpose,
pp, heavy ions



Heavy ions, pp



The big Bang

