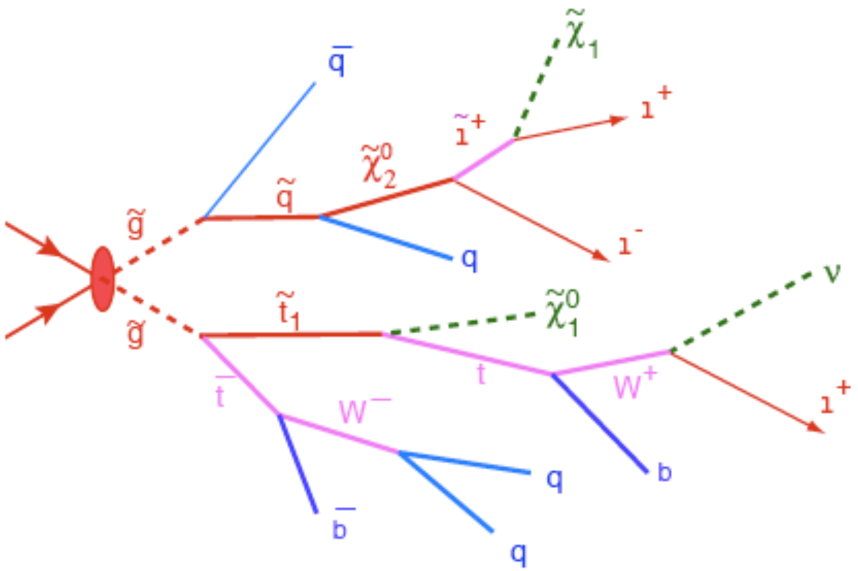
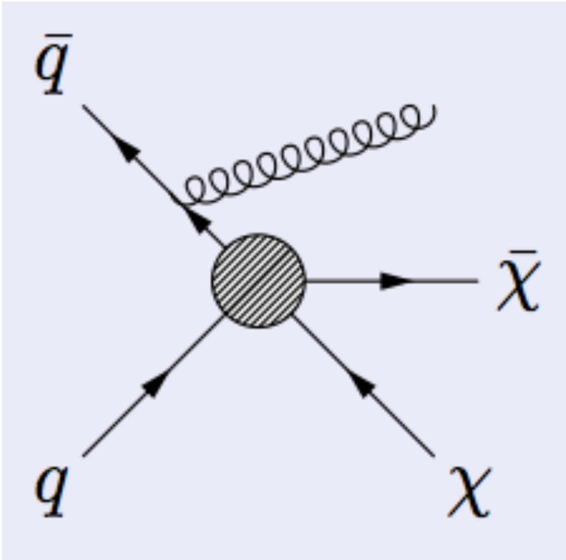
Oliver Buchmueller, Imperial College London

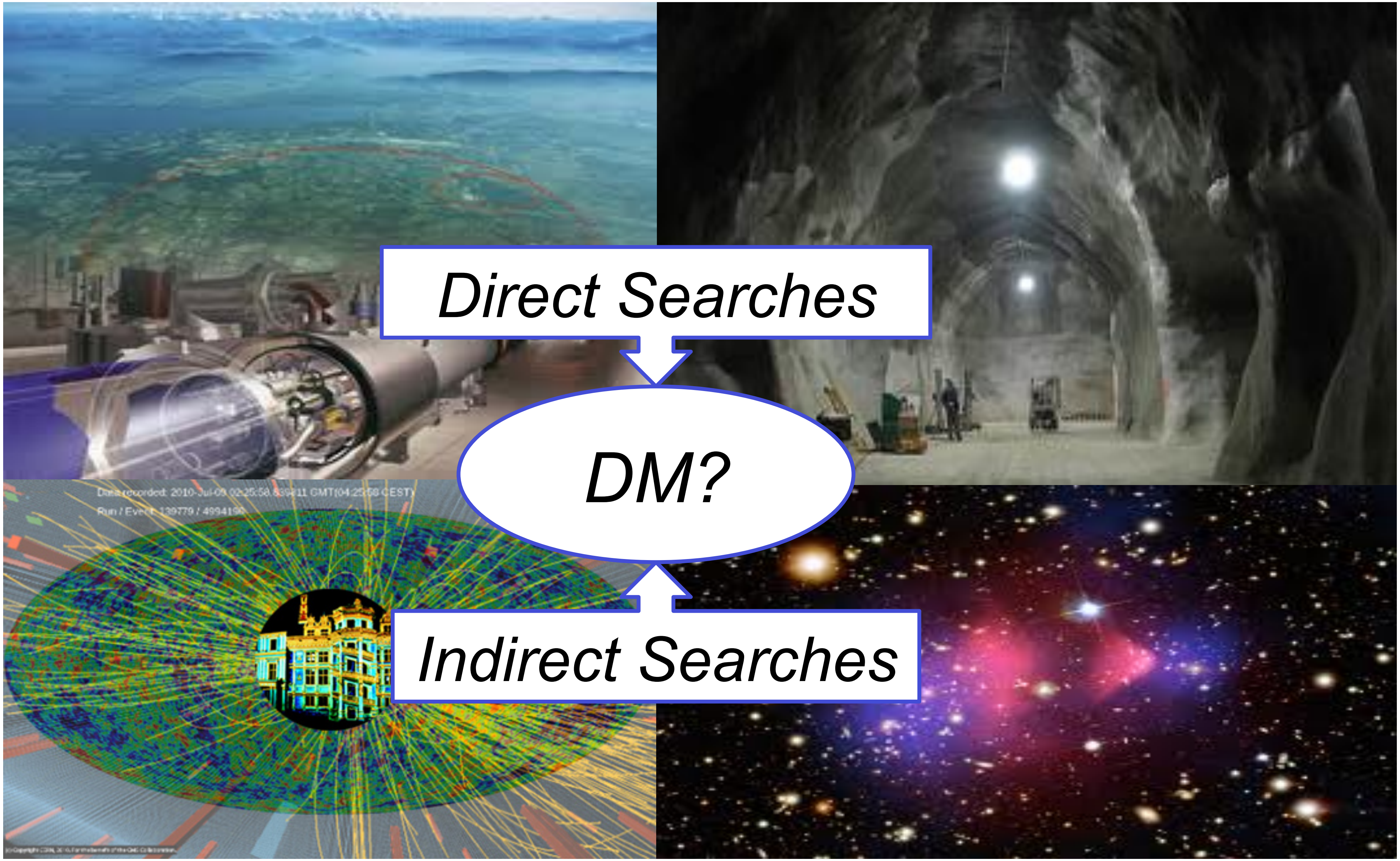
SEARCHES FOR DARK MATTER PRODUCTION AT THE LHC

FERMILAB DM AT FUTURE COLLIDERS WORKSHOP DECEMBER 4-6





Searches for Dark Matter (&SUSY)



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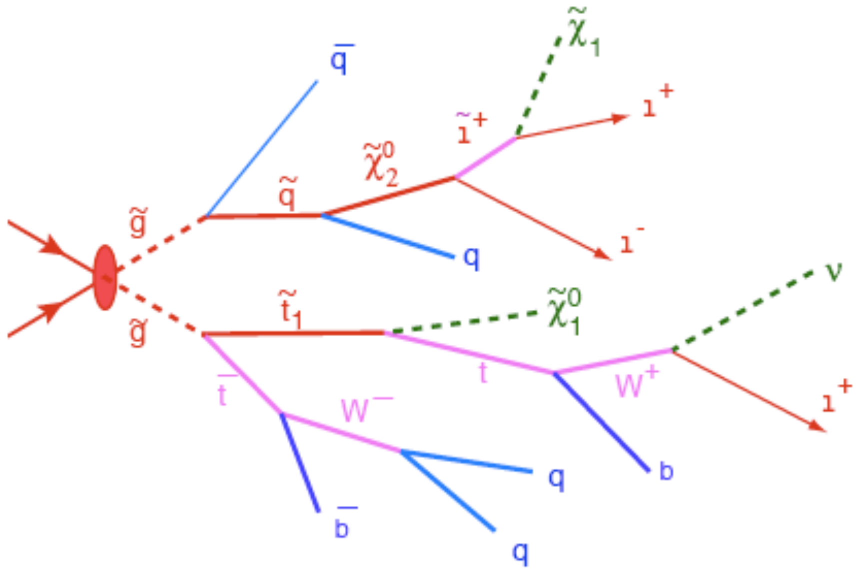
Searches for Dark Matter (&SUSY)

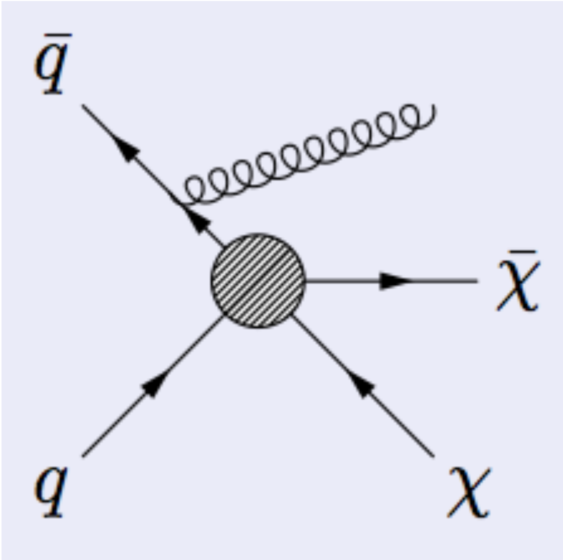
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY



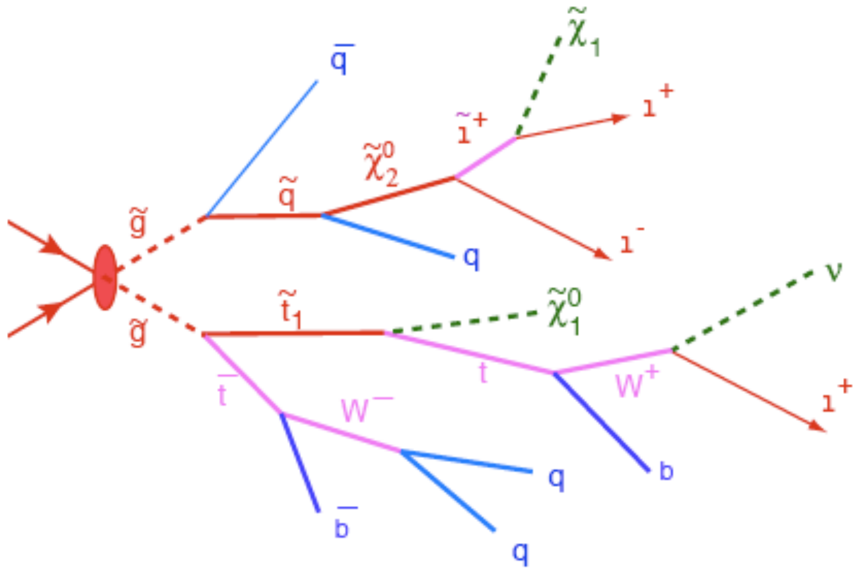
Example:
Effective Field Theory
Simplified models



Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY



Example:
Effective Field Theory
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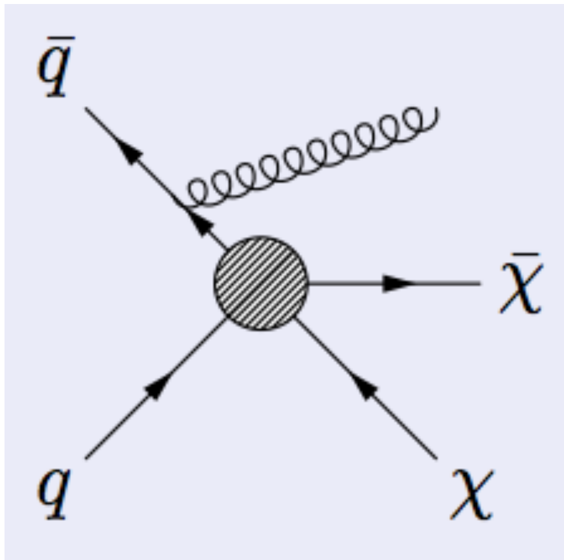
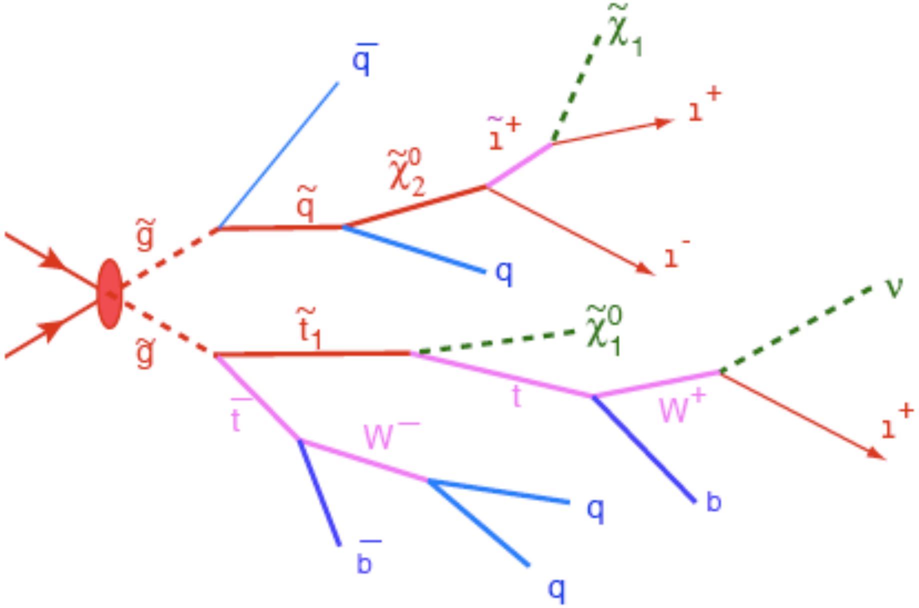


What do we call a "SUSY search"?

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)*

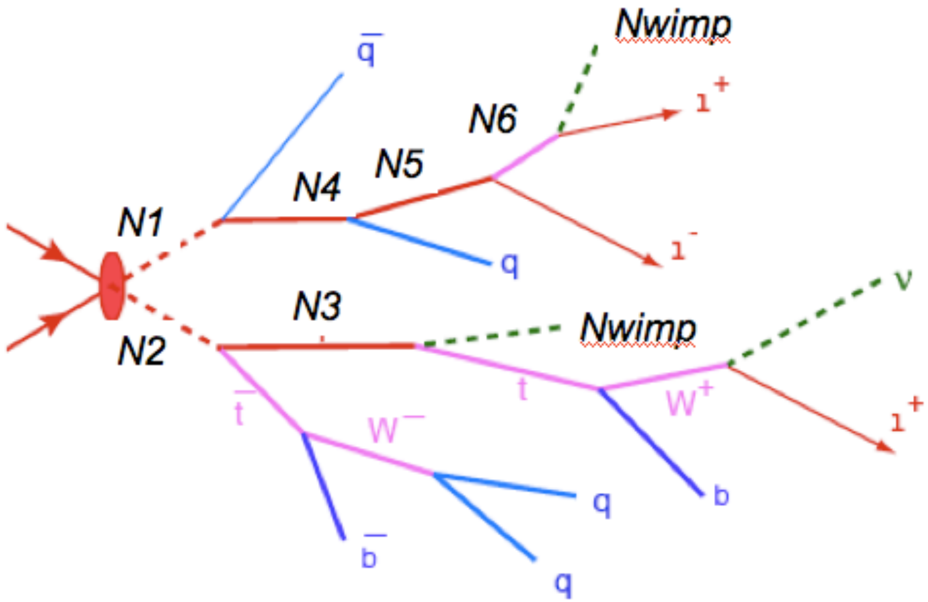
Multi-Leptons:
- *from decay of charginos/neutralios*

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



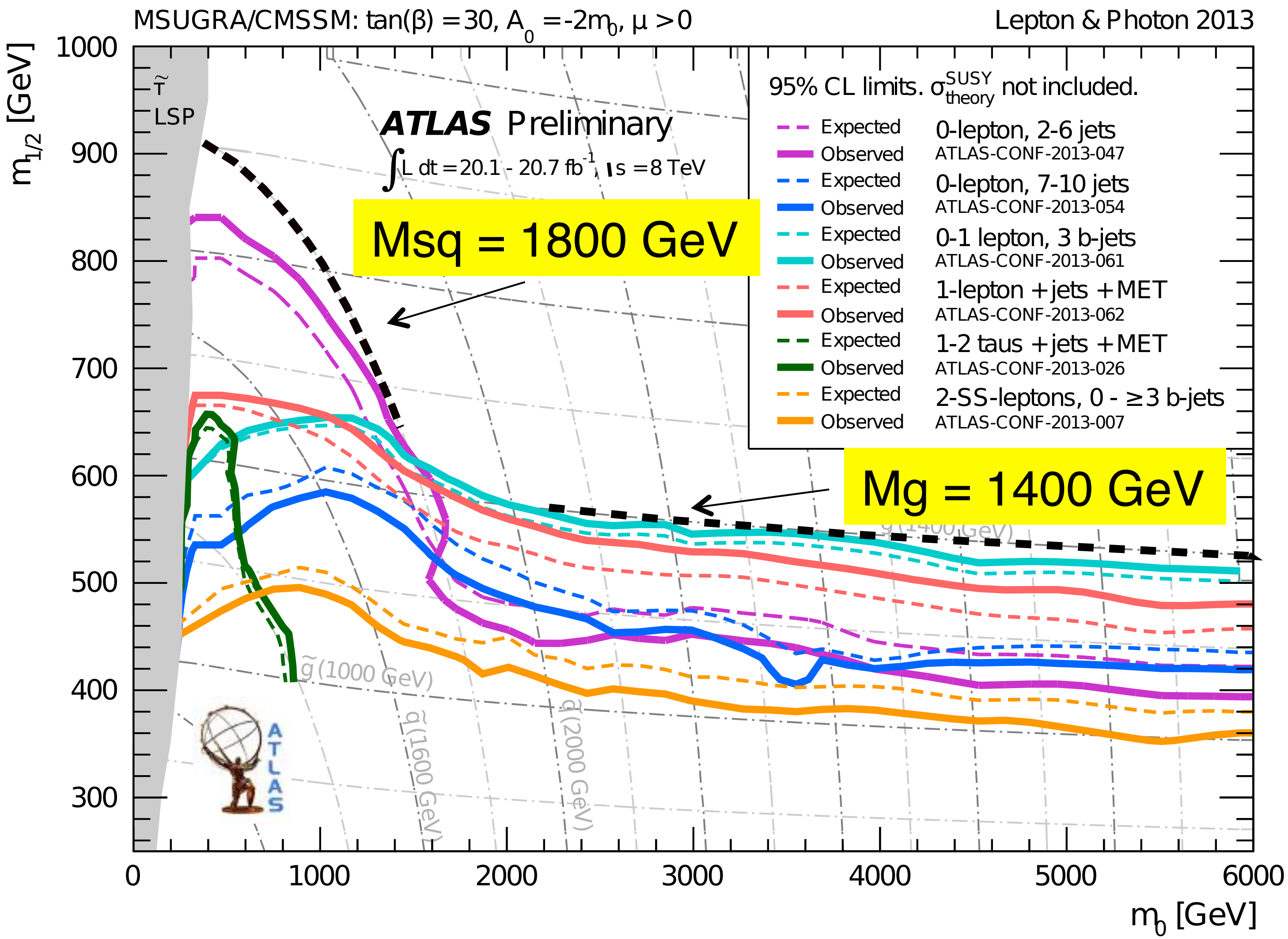
Missing Energy:
- *Nwimp - end of the cascade*

Multi-Jet:
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

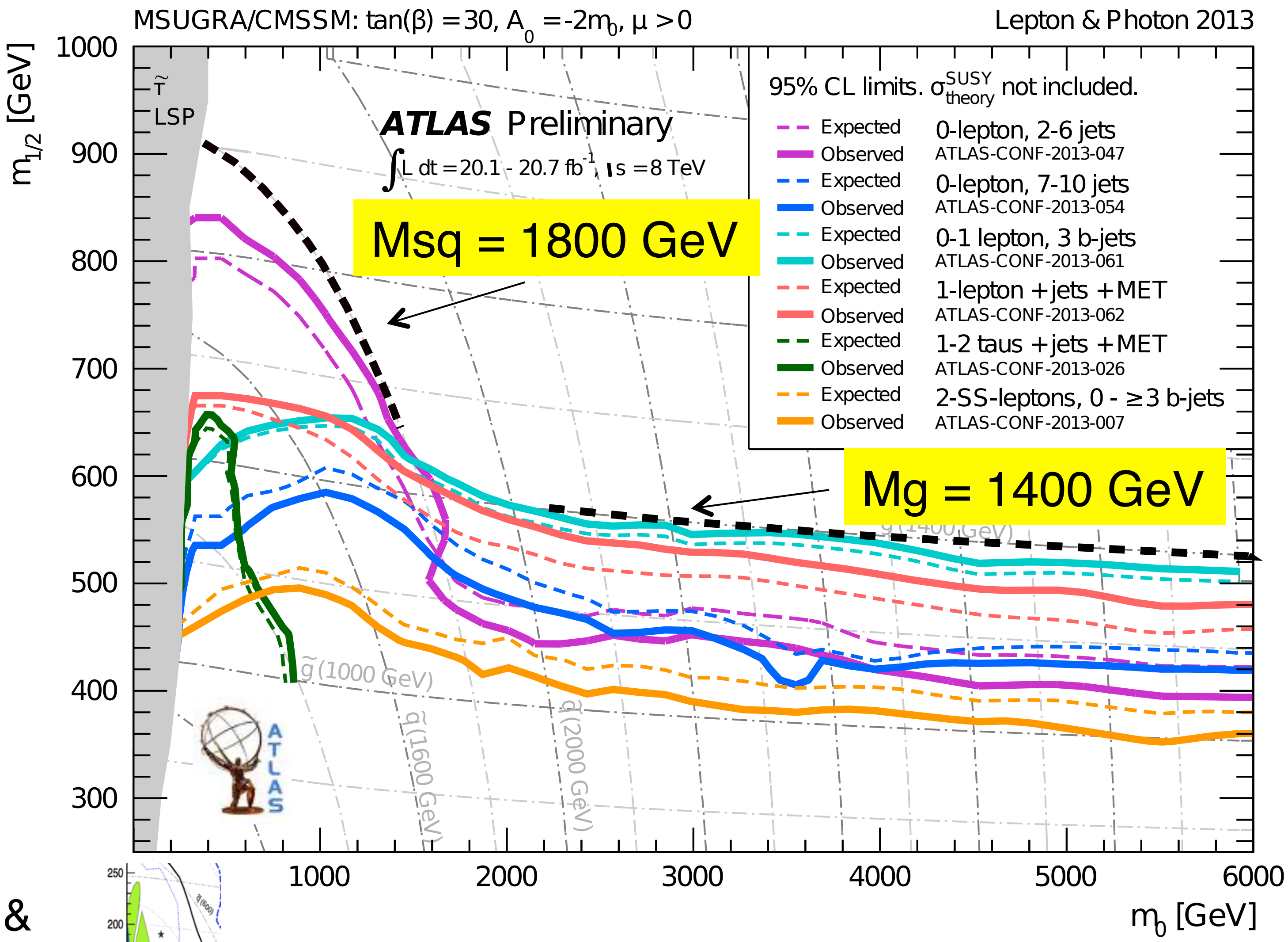
Multi-Leptons:
- *from decay of the N's*

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

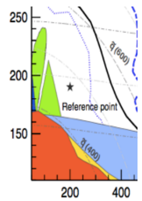
Inclusive SUSY Searches in 2013



Inclusive SUSY Searches in 2013

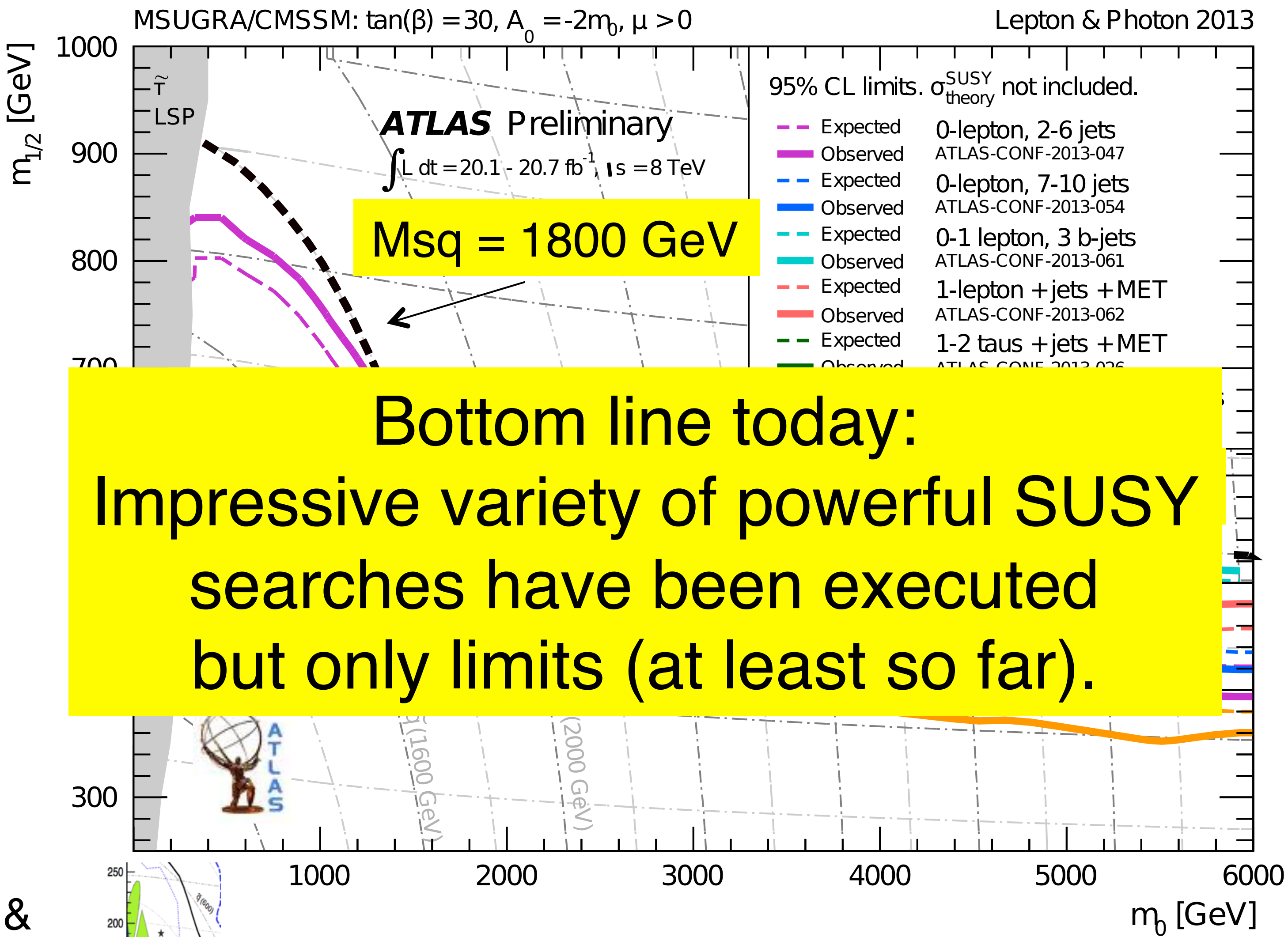


LEP & Tevatron



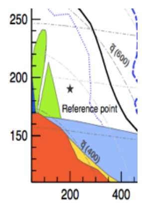
The LHC has pushed the mass scale in constraint SUSY models to a new level!

Inclusive SUSY Searches in 2013



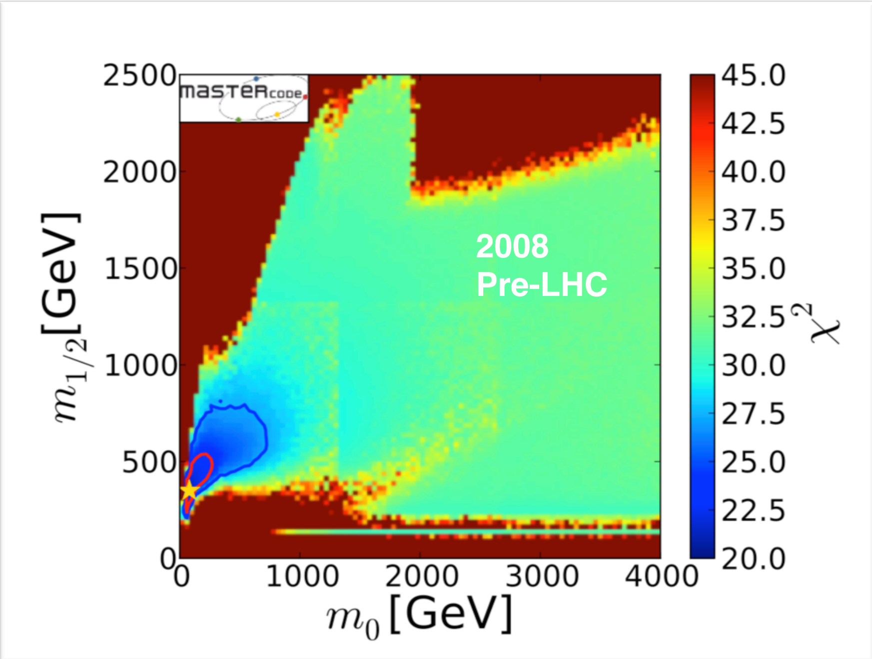
Bottom line today:
Impressive variety of powerful SUSY searches have been executed but only limits (at least so far).

LEP & Tevatron



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

CMSSM: Evolution with time



X^2 increase from bluish to reddish

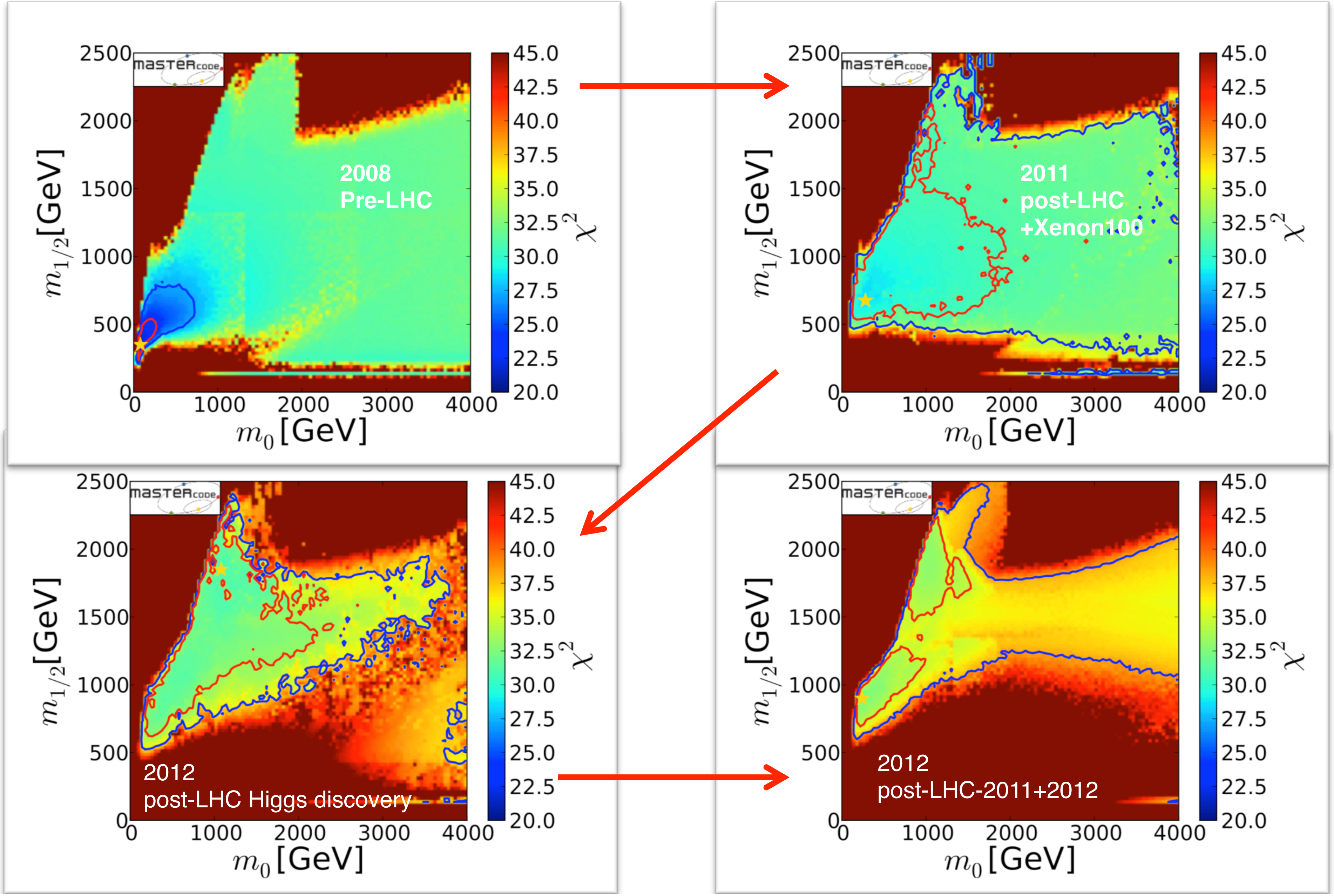
Source:
http://mastercode.web.cern.ch/mastercode/

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	-
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	[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]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$	0.078	0.047	0.14
$\sigma^0_{\rm had}$ [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
$A_{\rm fb}(\ell)$	[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
$A_{\rm fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{\rm fb}(c)$	[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
$\sin^2\theta^\ell_w(Q_{\rm fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$	1.77	1.39	2.08
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4 [\pm 1.5_{\rm SUSY}]$	0.0	0.0	0.0
${\rm BR}^{\rm EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$	1.83	1.09	0.94
${\rm BR}(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
${\rm BR}^{\rm EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{\rm EXP+TH}$	1.43	1.59	1.00
${\rm BR}(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6 [\pm 0.01_{\rm SUSY}] \times 10^{-9}$	0.0	0.0	0.0
${\rm BR}^{\rm EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
${\rm BR}^{\rm EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{\rm EXP+TH}$	0.39	0.42	0.33
${\rm BR}^{\rm EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{\rm EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$	0.02	0.02	0.01
$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{\rm EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{\rm EXP+TH}$	0.27	0.37	0.33
$\Omega_{\rm CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{\rm SUSY}$	8.4×10^{-4}	0.1	N/A
$\sigma_p^{\rm SI}$	[25]	$(m_{\chi^0_1}, \sigma_p^{\rm SI})$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

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

CMSSM: Evolution with time



SUSY Status – post 7 TeV LHC data

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

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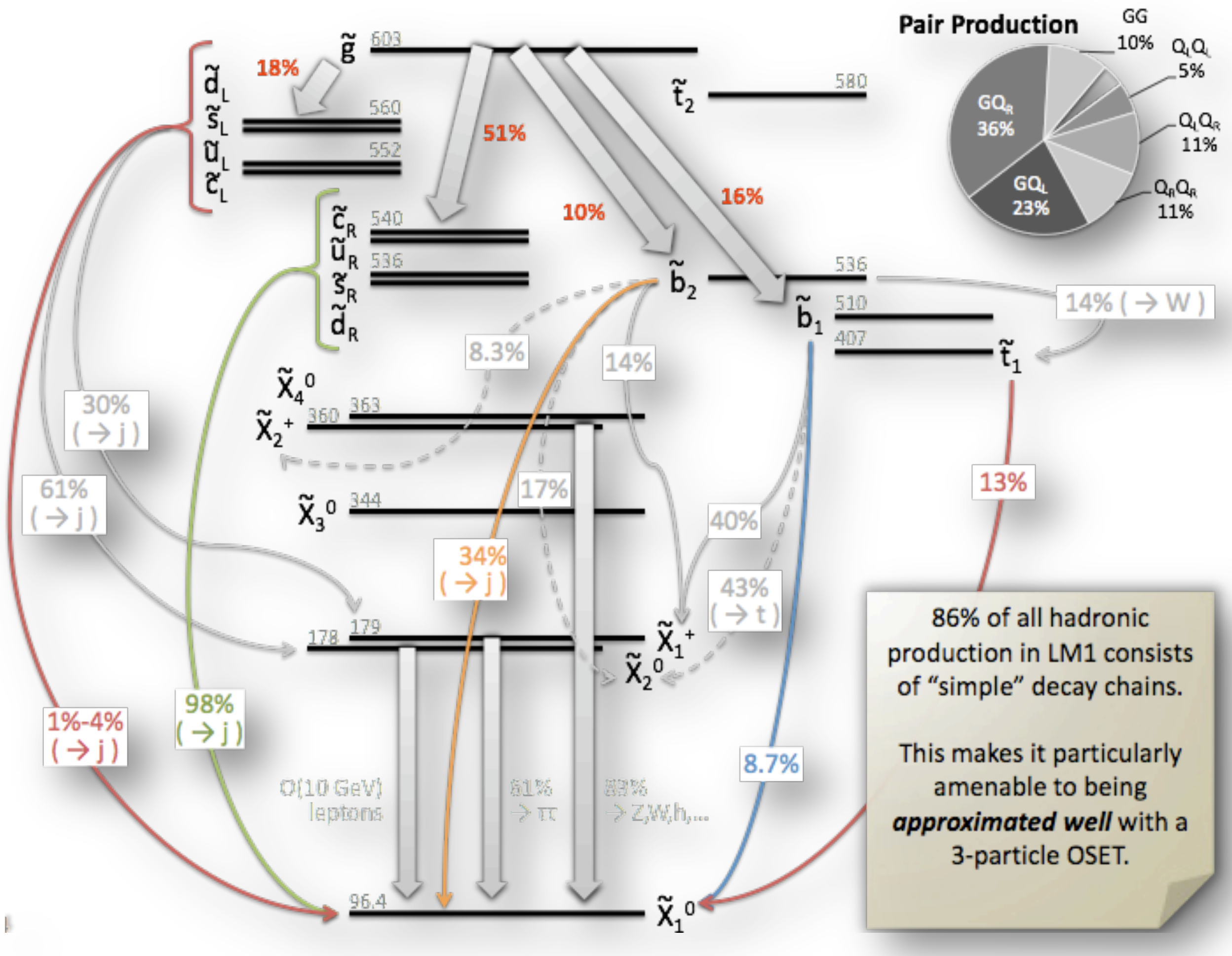
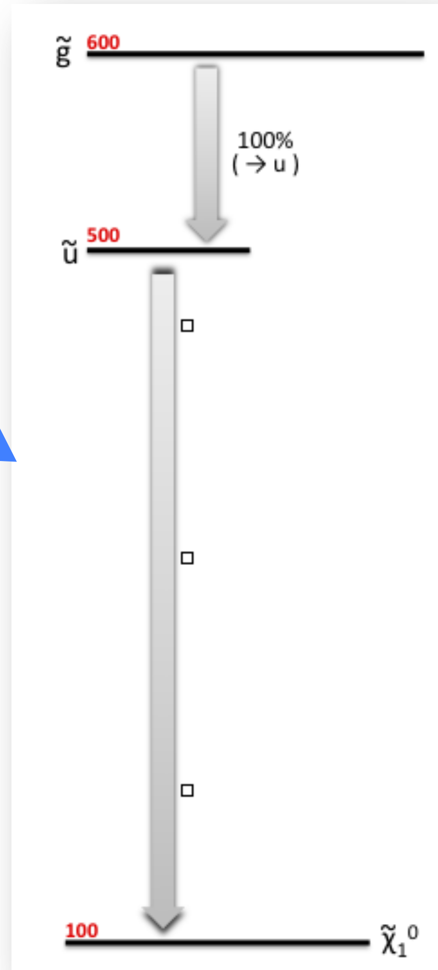
Interpretation in Simplified Models

CMSSM



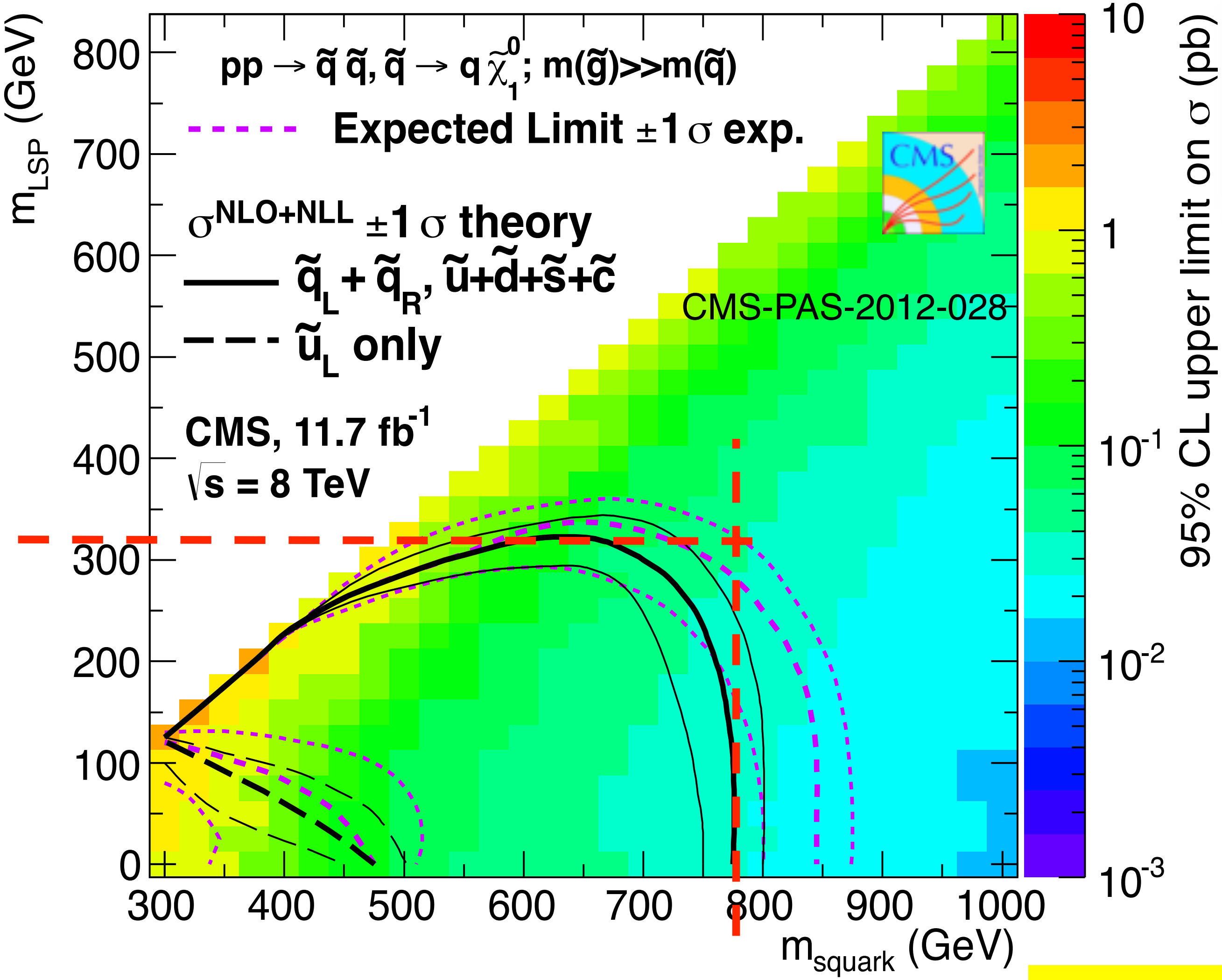
What the individual searches are sensitive to is much more simple…

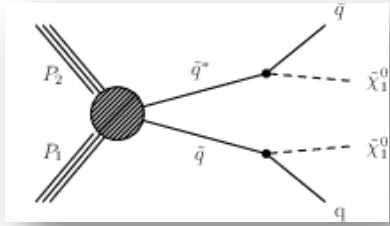


Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

SMS: a few interesting features

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





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

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

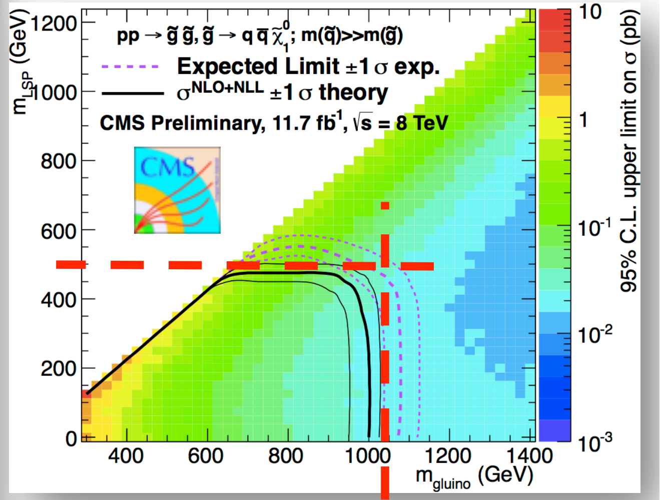
Assumes 100% BR for decay chain considered.

How to summarize SMS limits?

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

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

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



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

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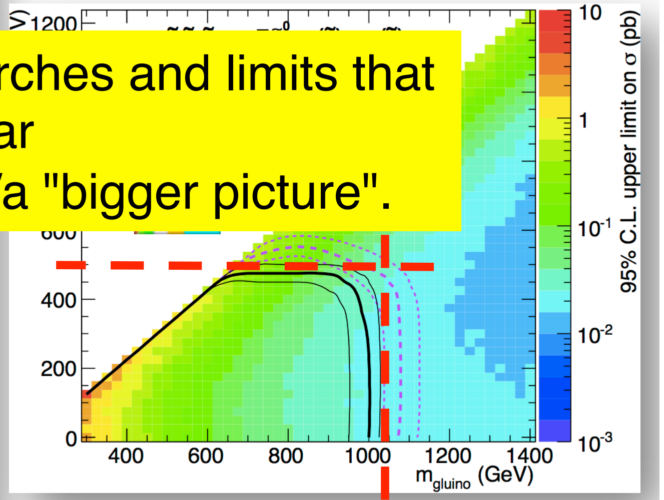
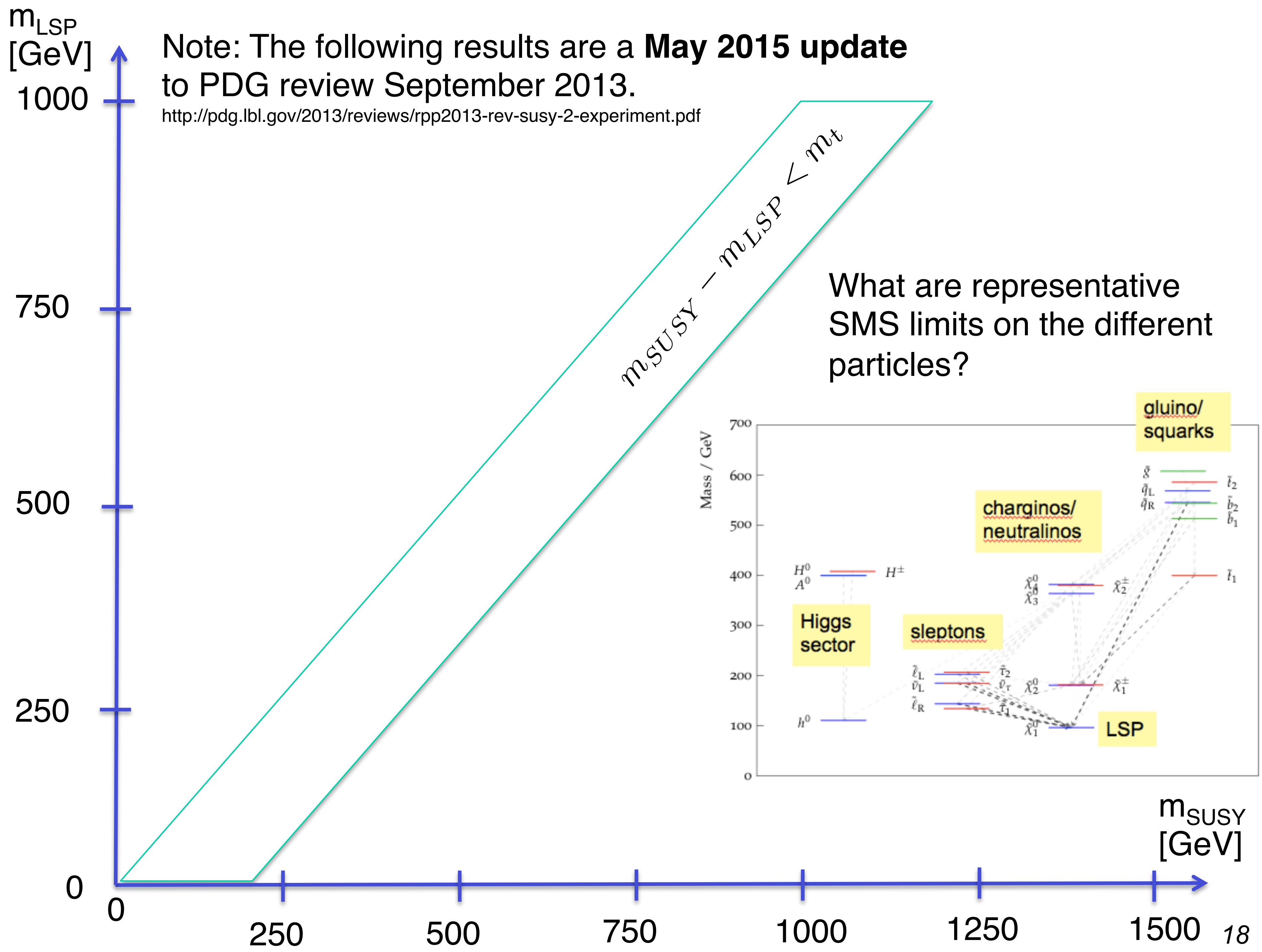
Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$		800
Simpli…	[illegible]	[illegible]	[illegible]
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model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

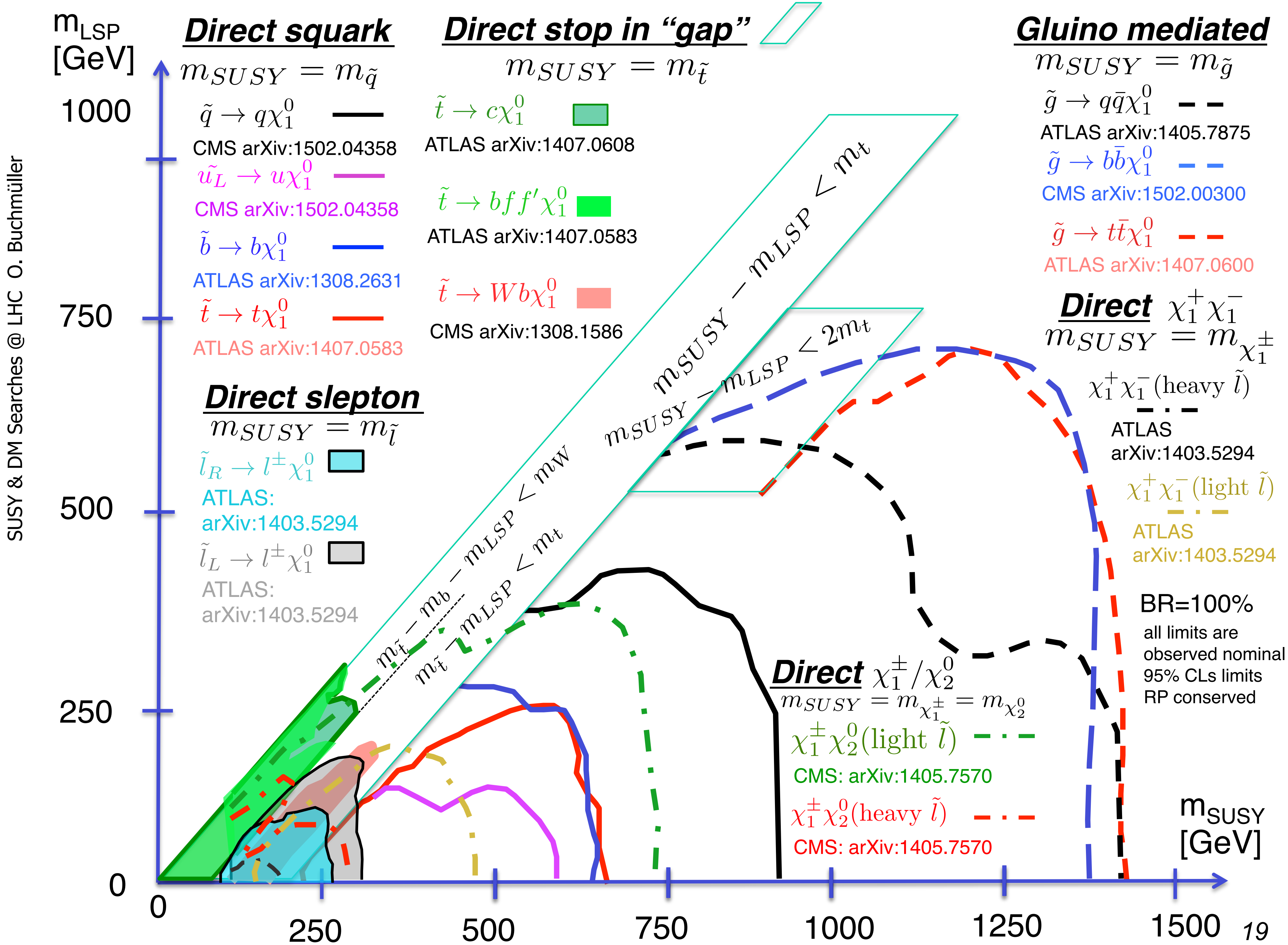


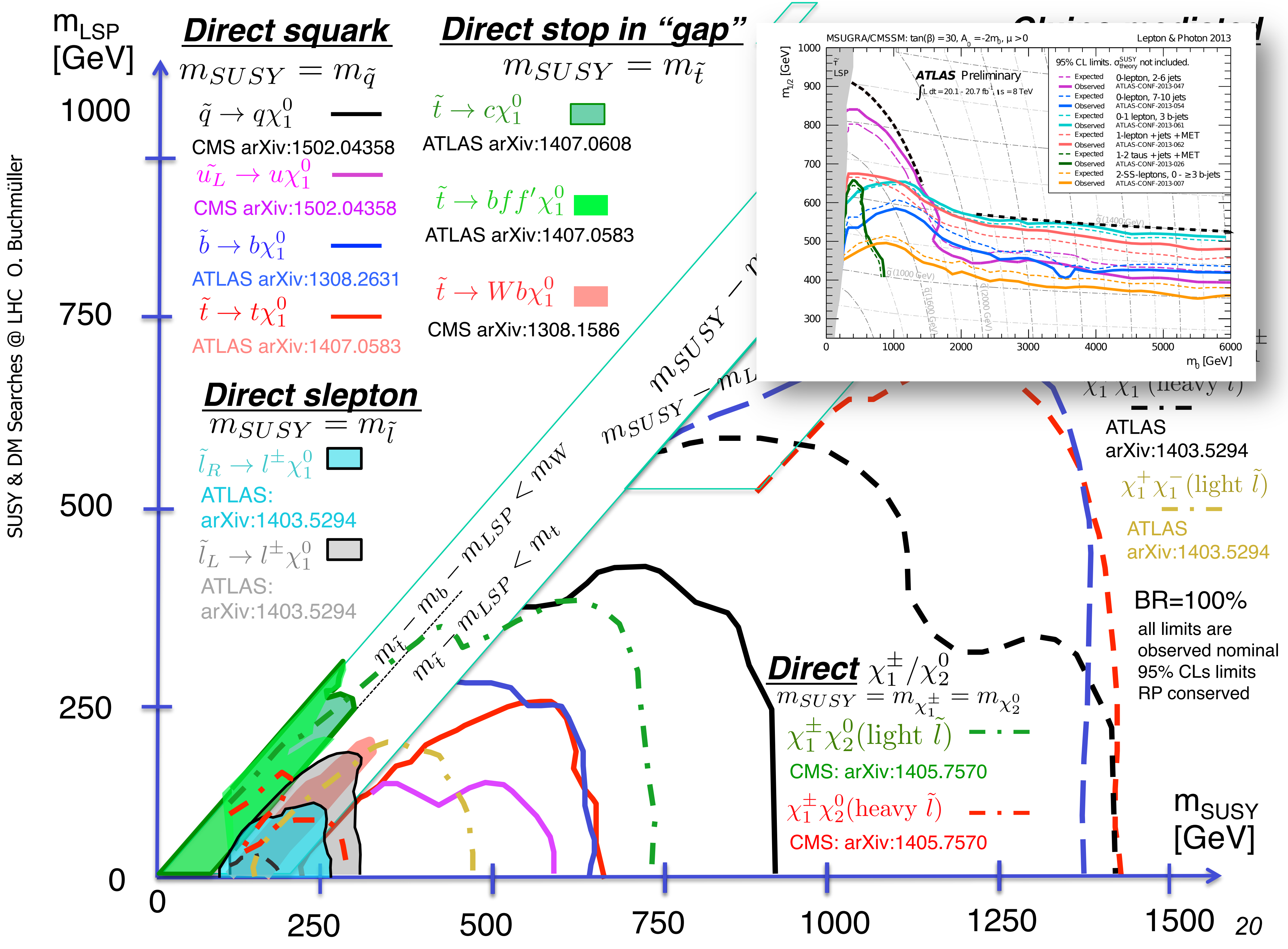
It is a challenge to do justice to the many searches and limits that have been established so far
- even more so to put it all together into the/a "bigger picture".

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



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?
m_{LSP} [GeV]
1000
750
500
250
0
$m_{SUSY} - m_{LSP} < m_t$
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
Mass / GeV
700
600
500
400
300
200
100
0
Higgs sector
sleptons
charginos/ neutralinos
gluino/ squarks
LSP


SUSY & DM Searches @ LHC O. Buchmüller
m_LSP [GeV]
1000
750
500
250
0
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
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
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
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
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 [GeV]
0
250
500
750
1000
1250
1500


SUSY & DM Searches @ LHC O. Buchmüller
m_LSP [GeV]
1000
750
500
250
0
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
$\tilde{b} \to b\chi_1^0$
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$\tilde{t} \to t\chi_1^0$
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Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
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$\tilde{t} \to bff'\chi_1^0$
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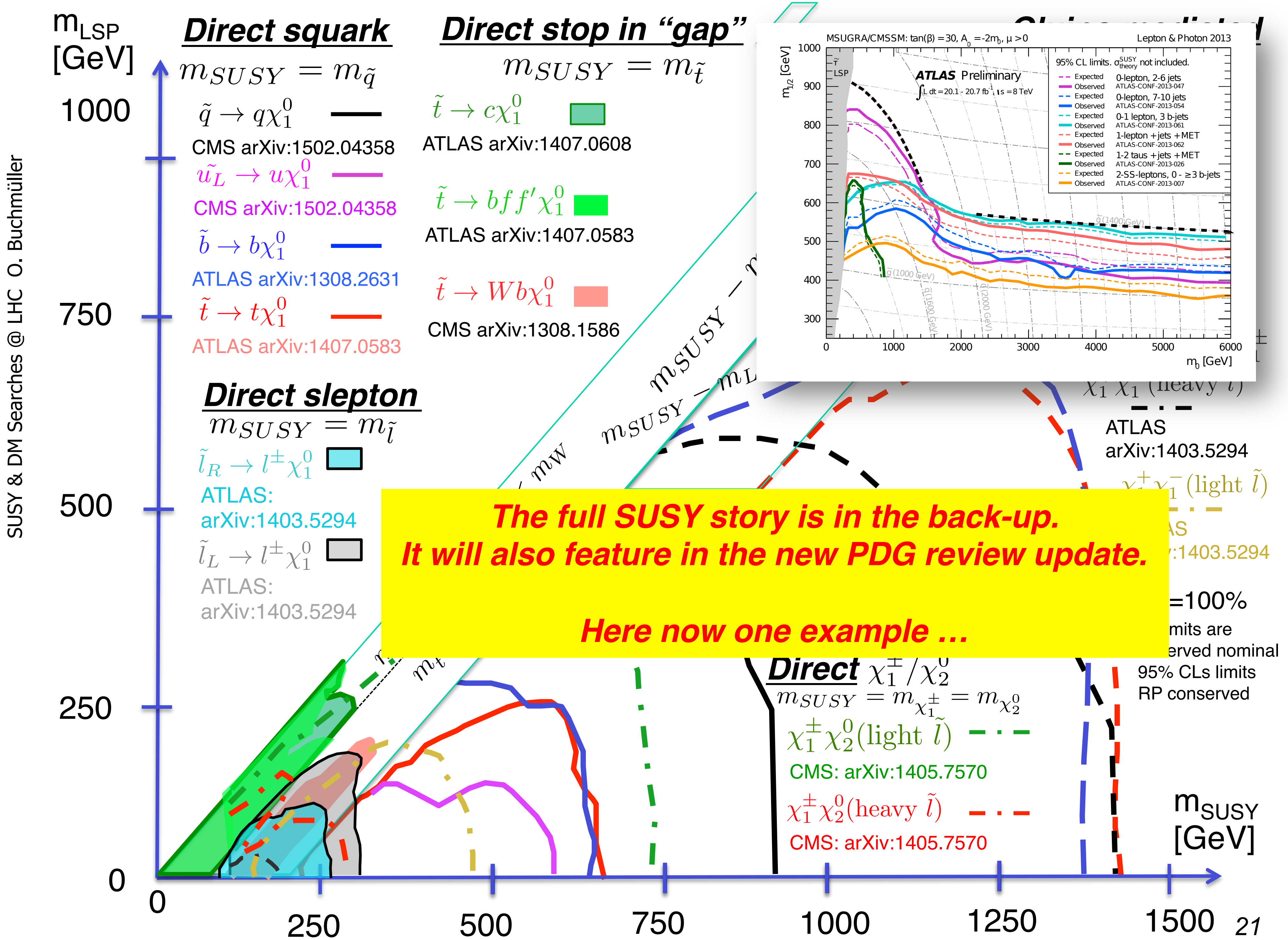
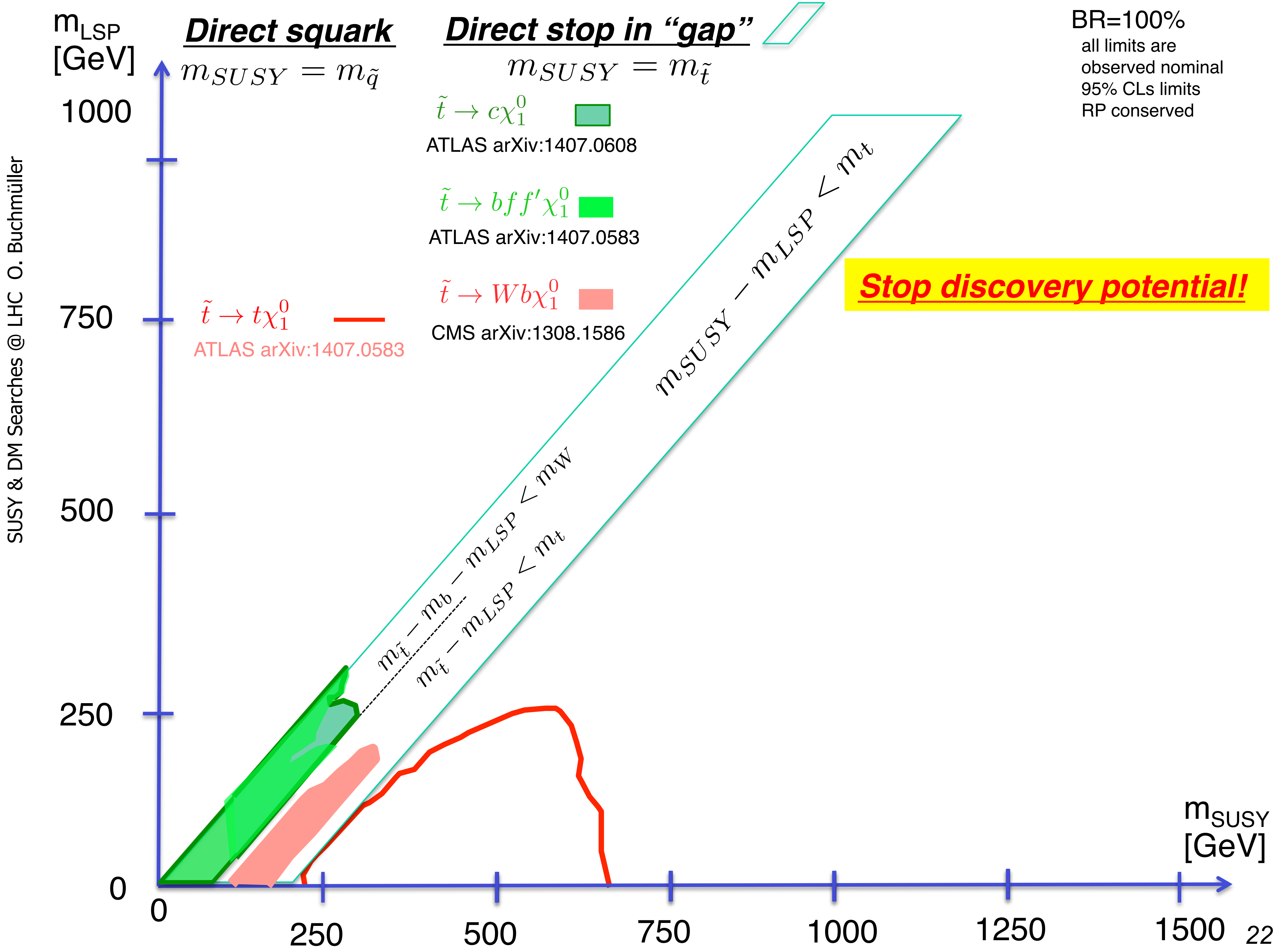
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP}$
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^+\chi_1^-$(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_SUSY [GeV]
0
250
500
750
1000
1250
1500
MSUGRA/CMSSM: tan(β) = 30, A0 = -2m0, μ > 0
Lepton & Photon 2013
ATLAS Preliminary
∫L dt = 20.1 - 20.7 fb⁻¹, √s = 8 TeV
95% CL limits. σ^SUSY_theory not included.
0-lepton, 2-6 jets ATLAS-CONF-2013-047
0-lepton, 7-10 jets ATLAS-CONF-2013-054
0-1 lepton, 3 b-jets ATLAS-CONF-2013-061
1-lepton + jets + MET ATLAS-CONF-2013-062
1-2 taus + jets + MET ATLAS-CONF-2013-026
2-SS-leptons, 0 - ≥3 b-jets ATLAS-CONF-2013-007
Expected
Observed
$\tilde{\tau}$ LSP
m_1/2 [GeV]
m_0 [GeV]
300
400
500
600
700
800
900
1000
0
1000
2000
3000
4000
5000
6000

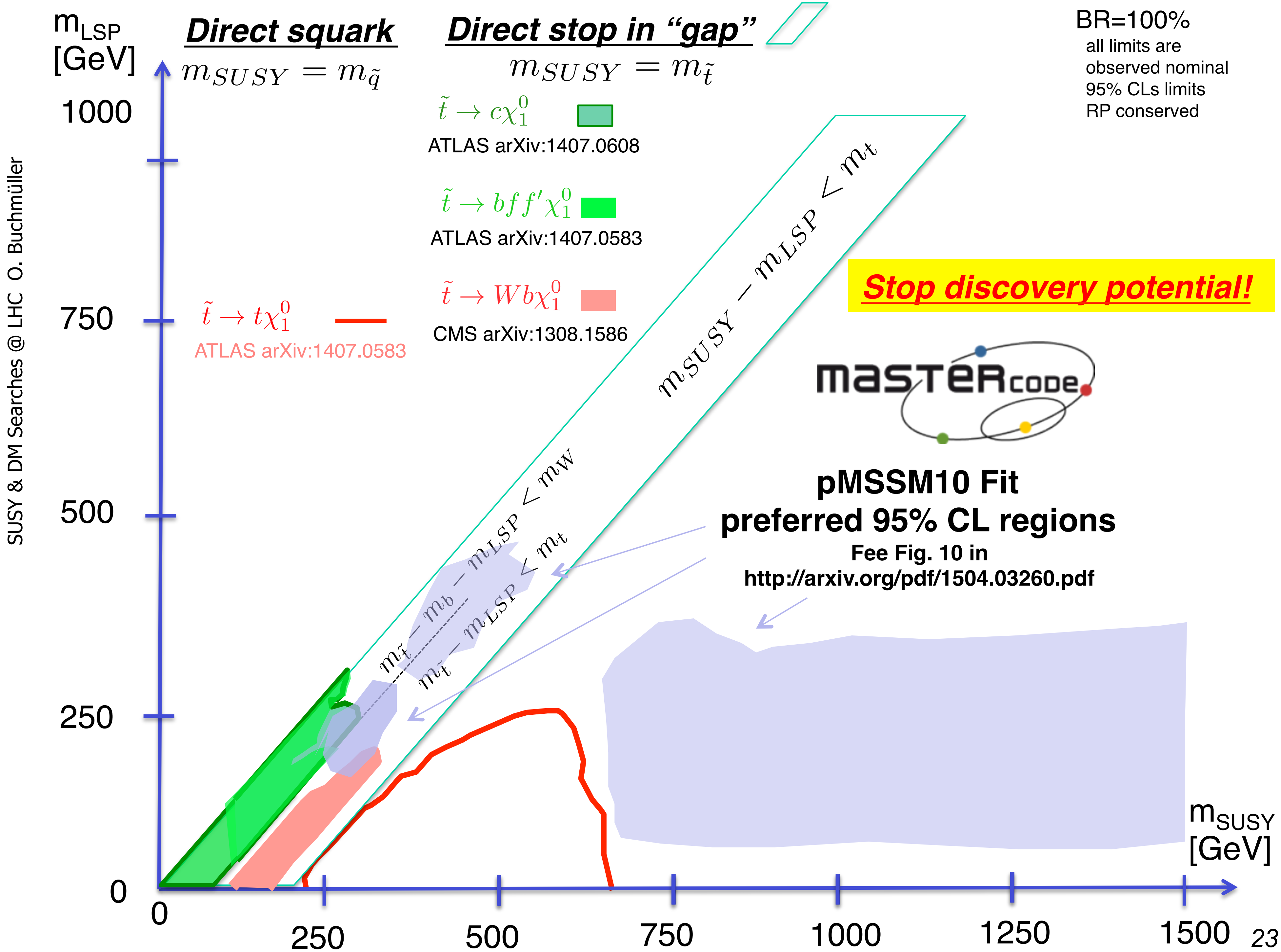


The full SUSY story is in the back-up.
It will also feature in the new PDG review update.

Here now one example …



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!
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
SUSY & DM Searches @ LHC O. Buchmüller



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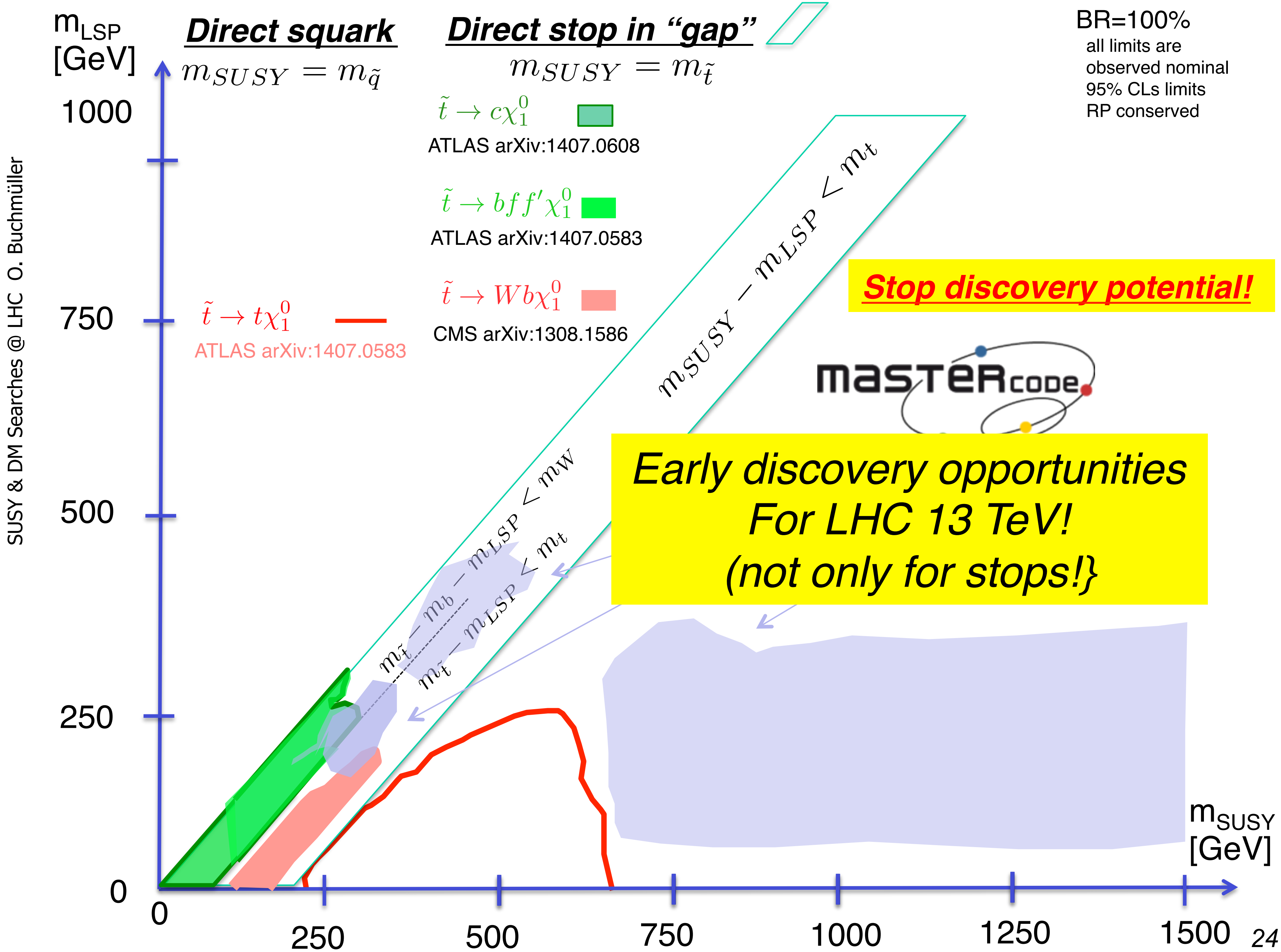
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
$m_{SUSY} - m_{LSP} < m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Stop discovery potential!
mastercode
pMSSM10 Fit preferred 95% CL regions
Fee Fig. 10 in http://arxiv.org/pdf/1504.03260.pdf
SUSY & DM Searches @ LHC O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]

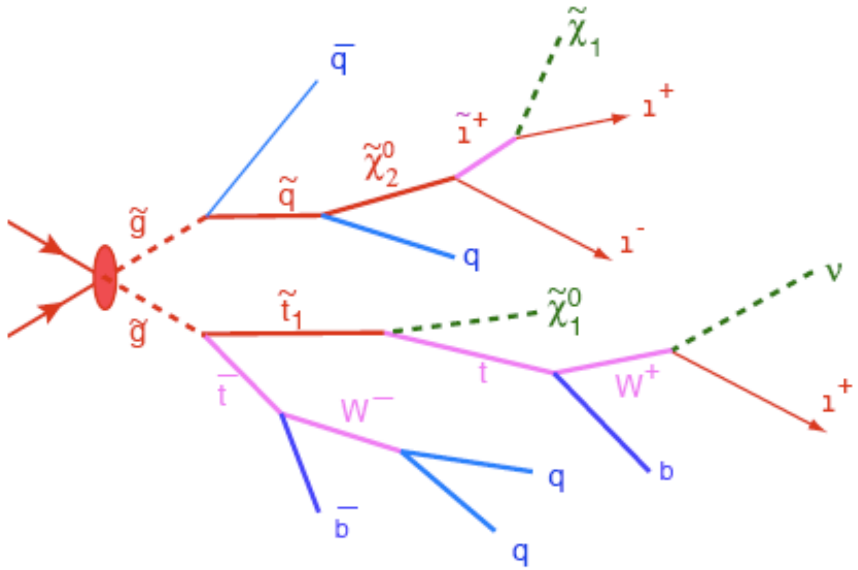


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
$m_{SUSY} - m_{LSP} < m_t$
$m_t - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Stop discovery potential!
MasterCode
Early discovery opportunities For LHC 13 TeV! (not only for stops!}
SUSY & DM Searches @ LHC O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]

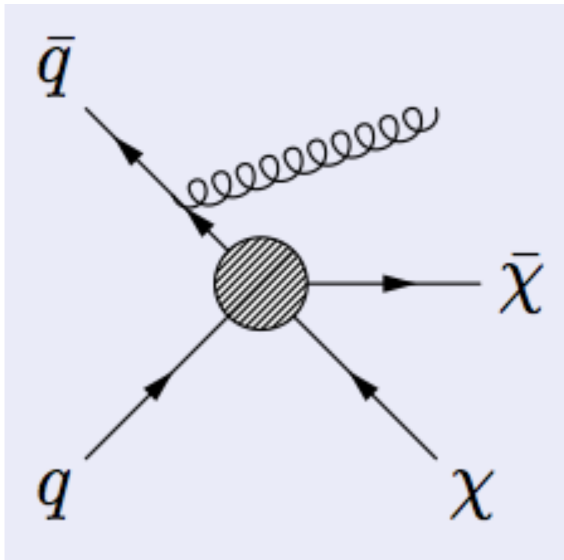
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

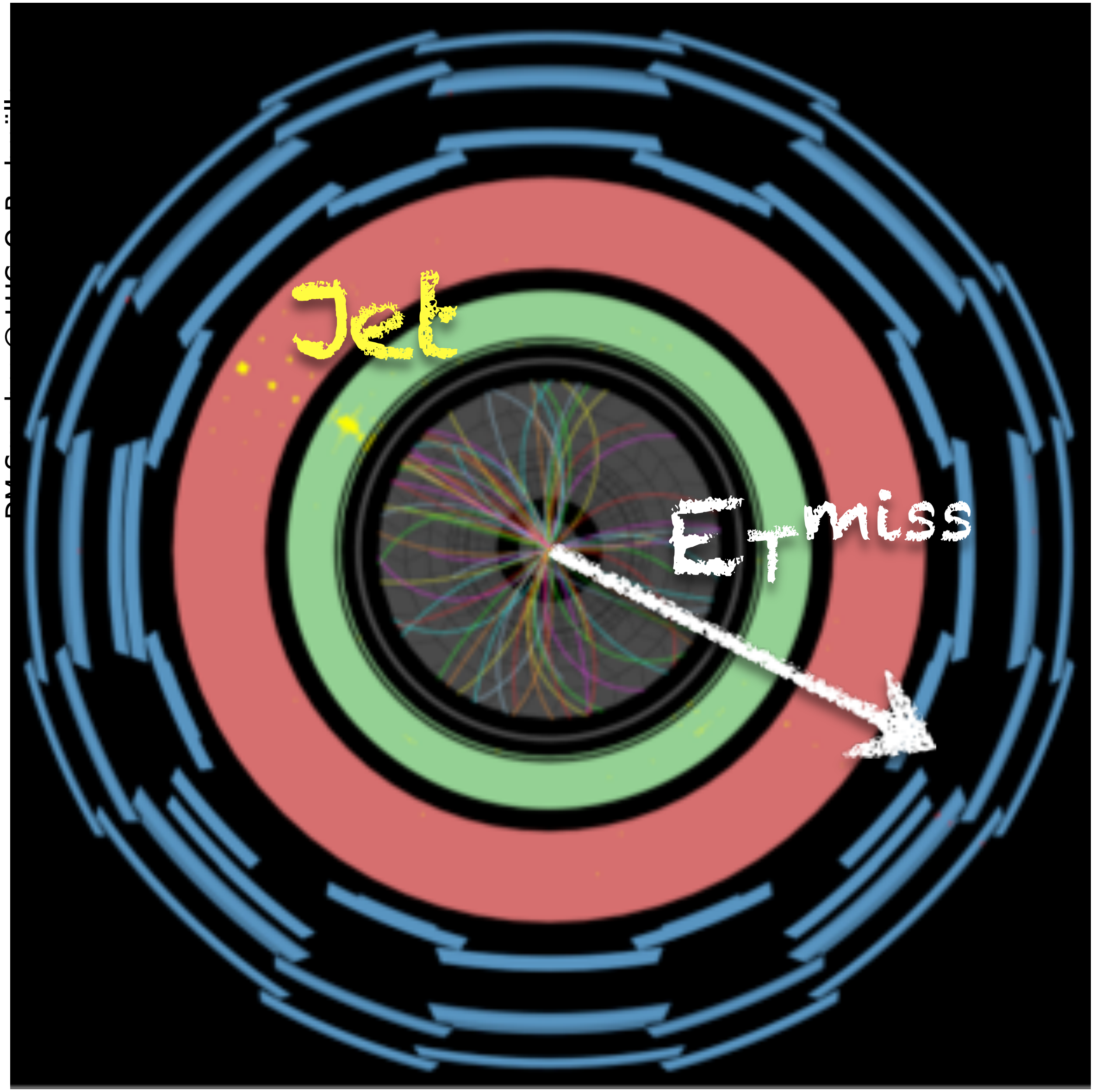
SUSY



Example:
Effective Field Theory
Simplified models



Mono-X searches at colliders



E_T^{miss} trigger

Example Monojet (8 TeV, 20.3 fb-1)

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

Example Monophoton (8 TeV, 19.6 fb^{-1}):

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

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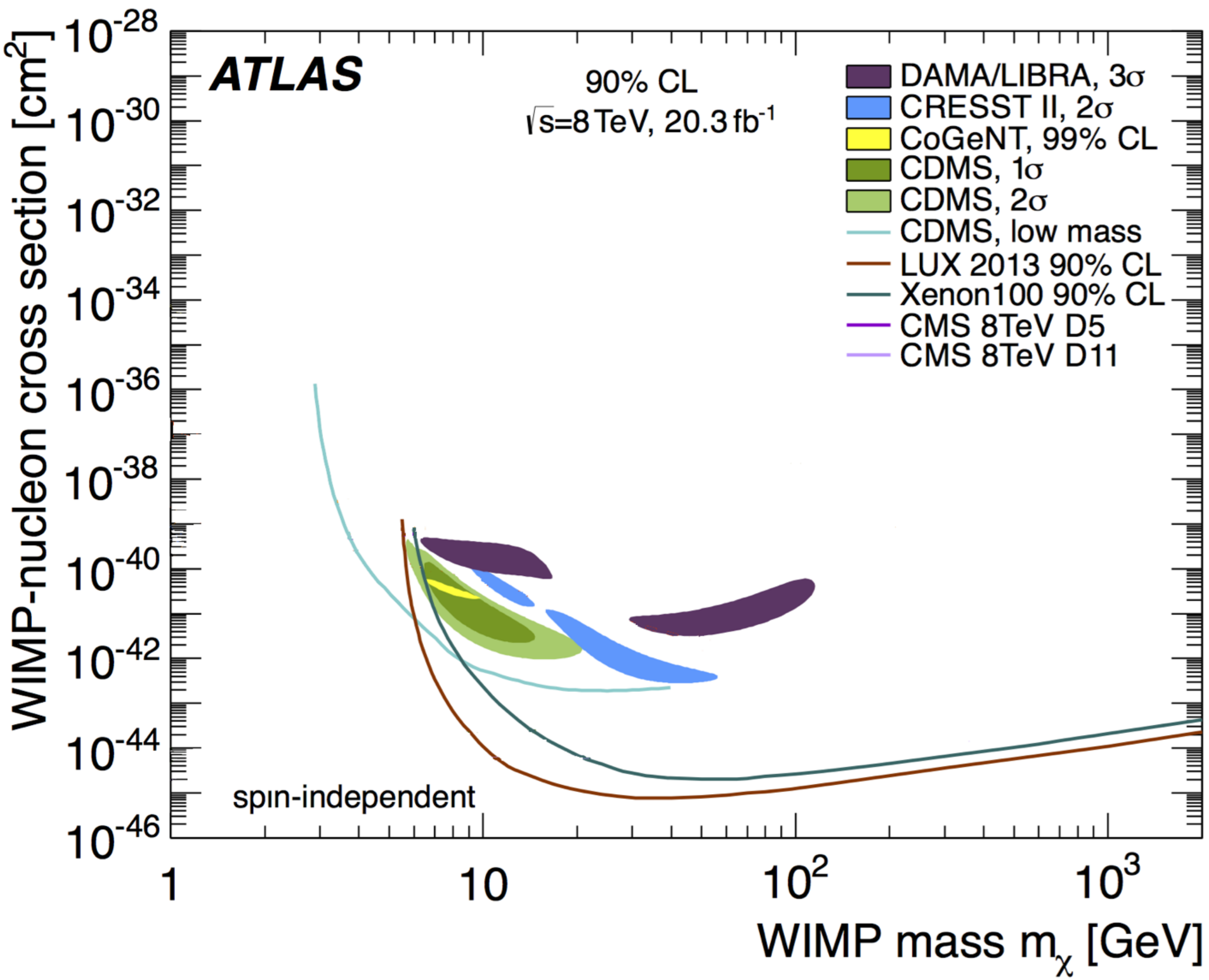
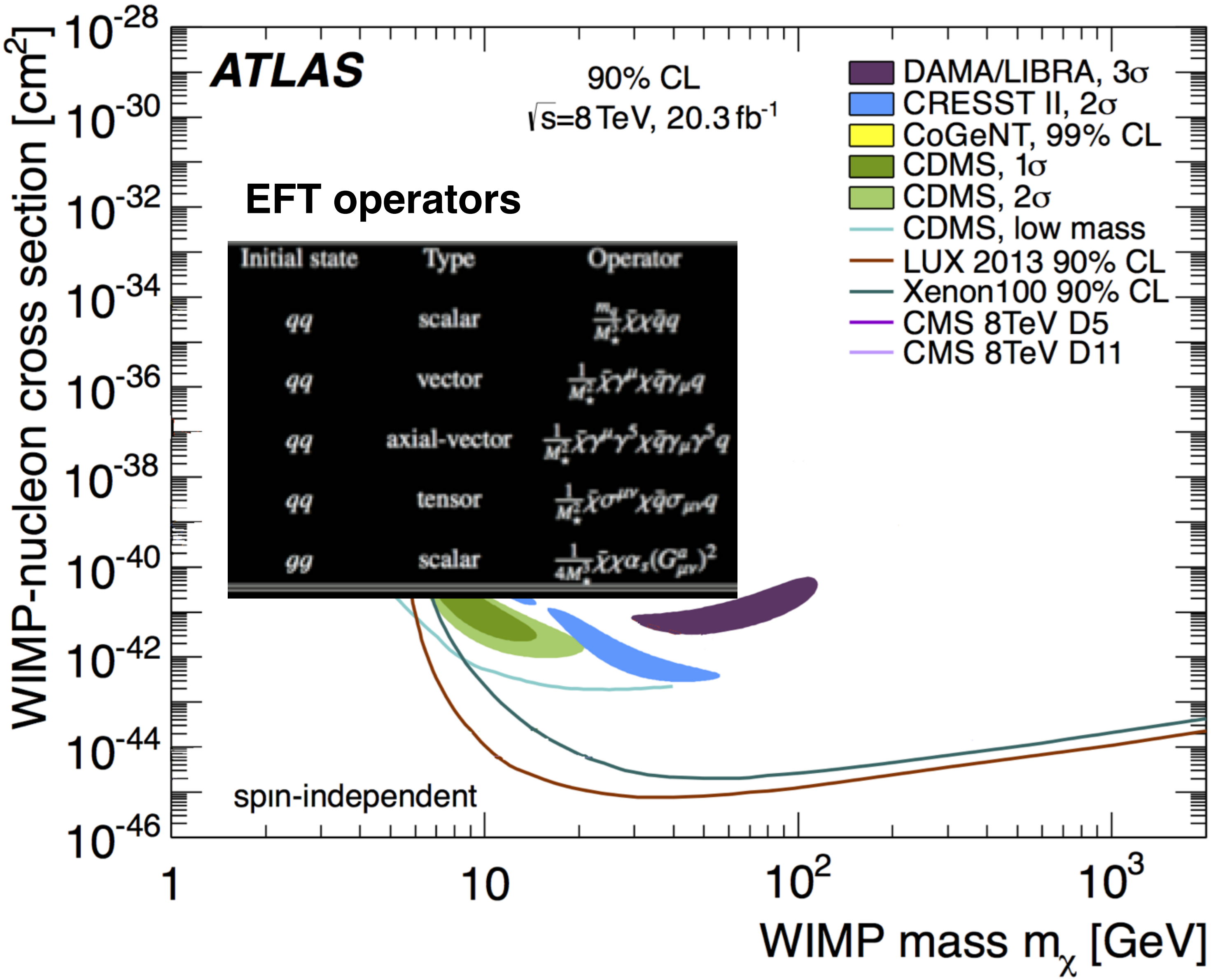
ATLAS Mono-Jet: Comparison with Direct Detection

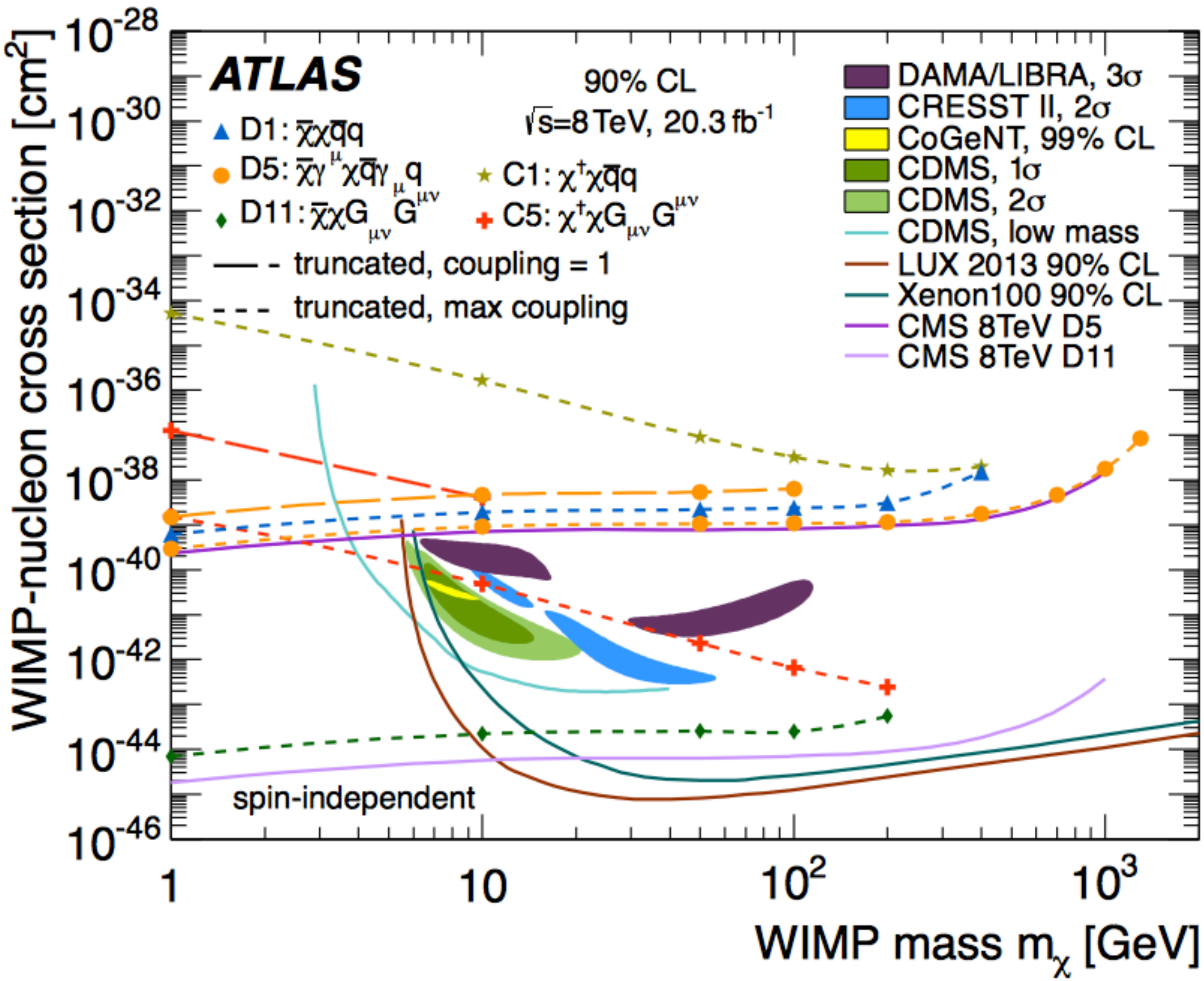


ATLAS Mono-Jet: Comparison with Direct Detection

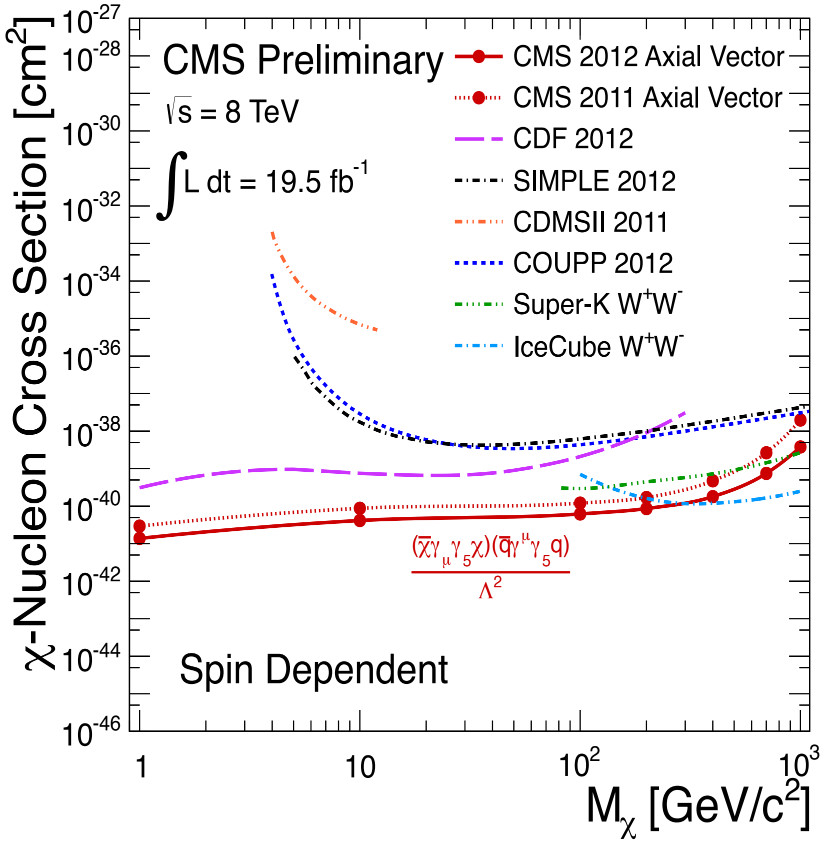


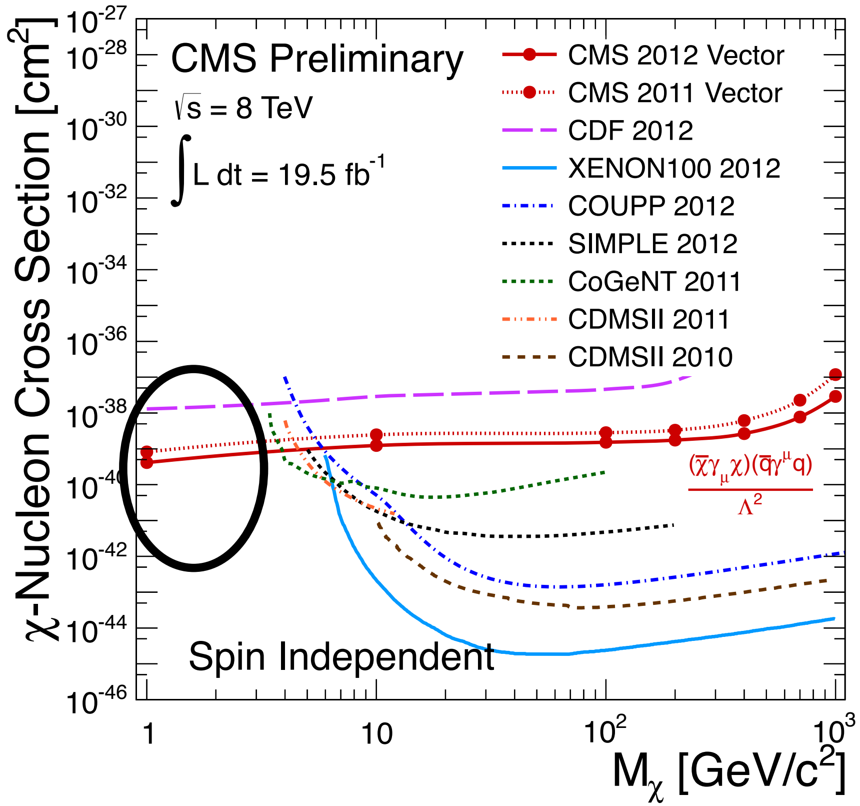
Initial state	Type	Operator
qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

ATLAS Mono-Jet: Comparison with Direct Detection



Mono-Jet analyses better than direct detection?!



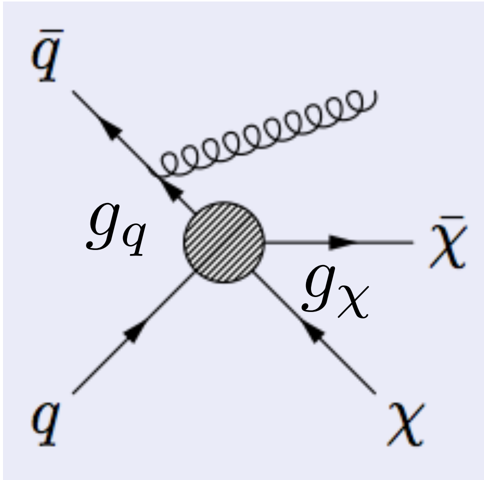


Claim [often made]:
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ 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:

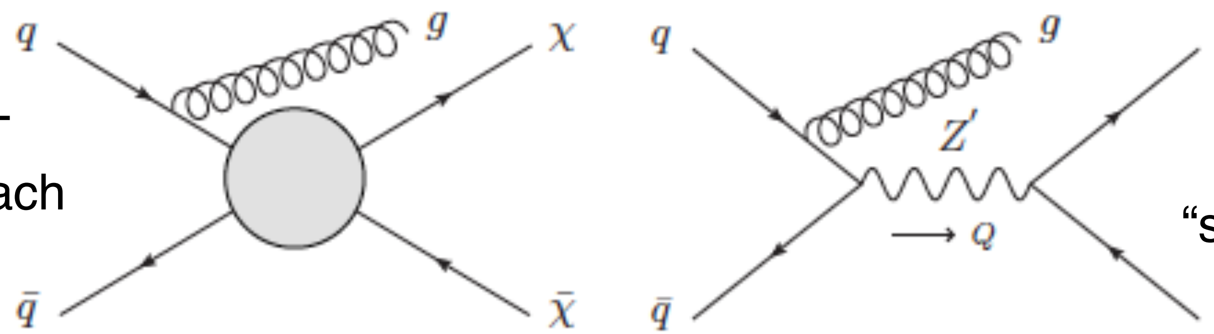
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Validity of Effective Field Theory Limits

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

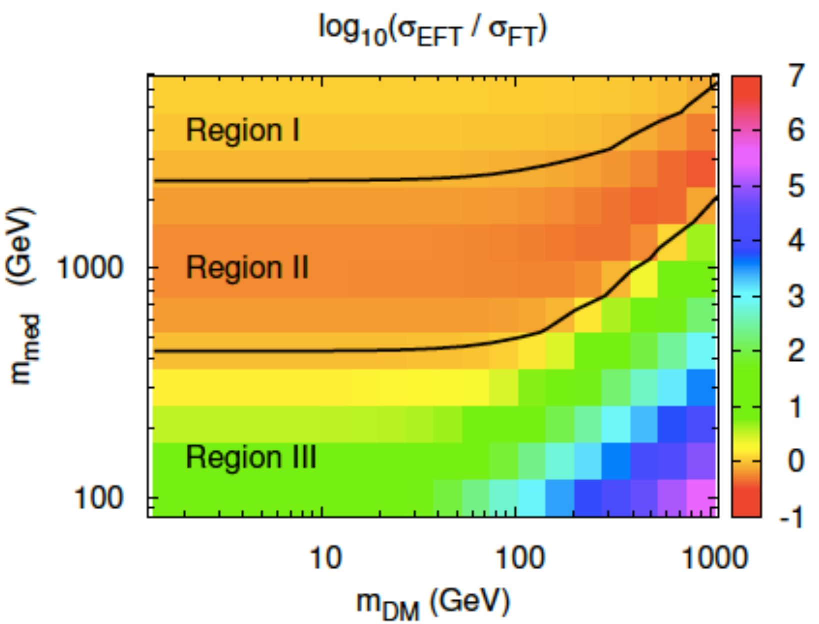
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

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

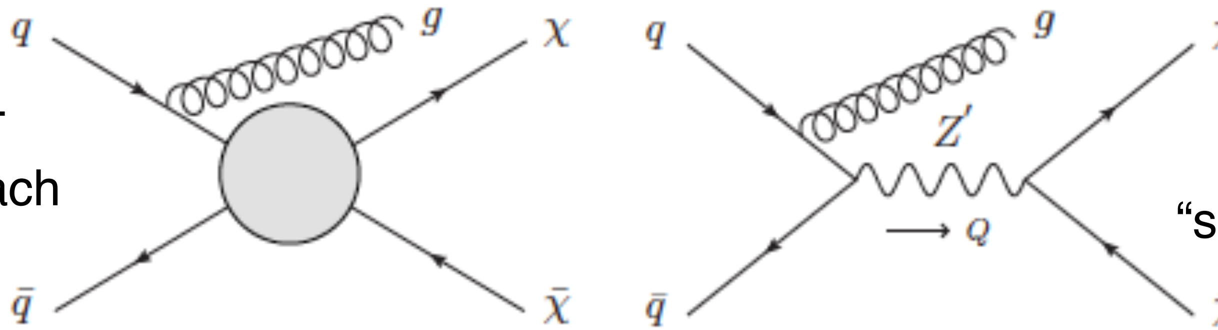
➢ EFT limits are too aggressive!

Validity of Effective Field Theory Limits

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

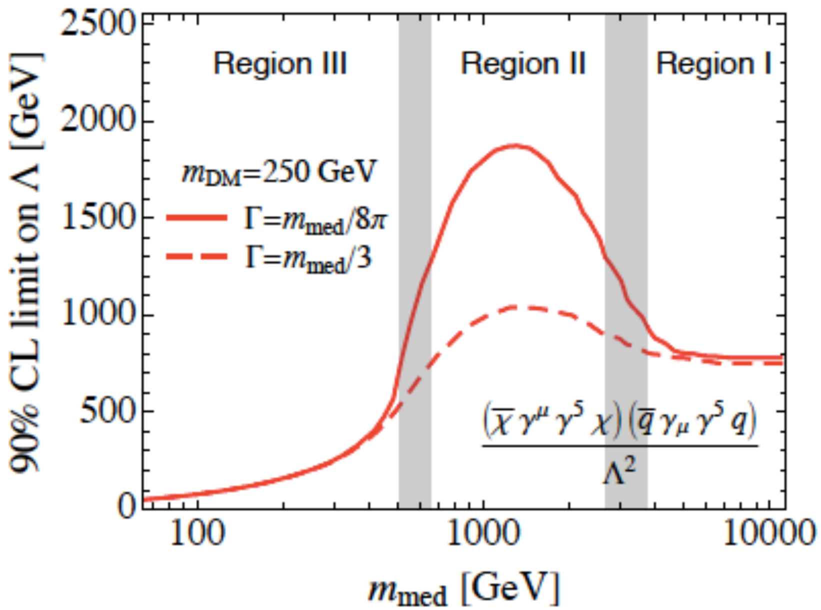
- Compare Effective Field Theory (EFT) with Full Theory (FT)

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!

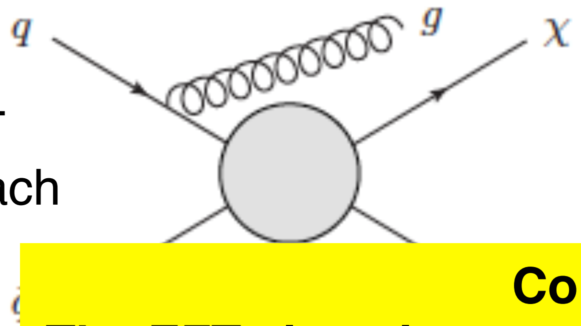
Region III: Low m_{med}

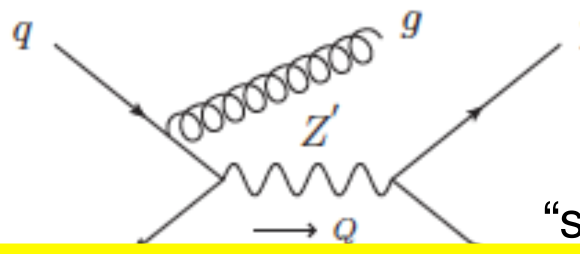
- EFT limits are far too aggressive!

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





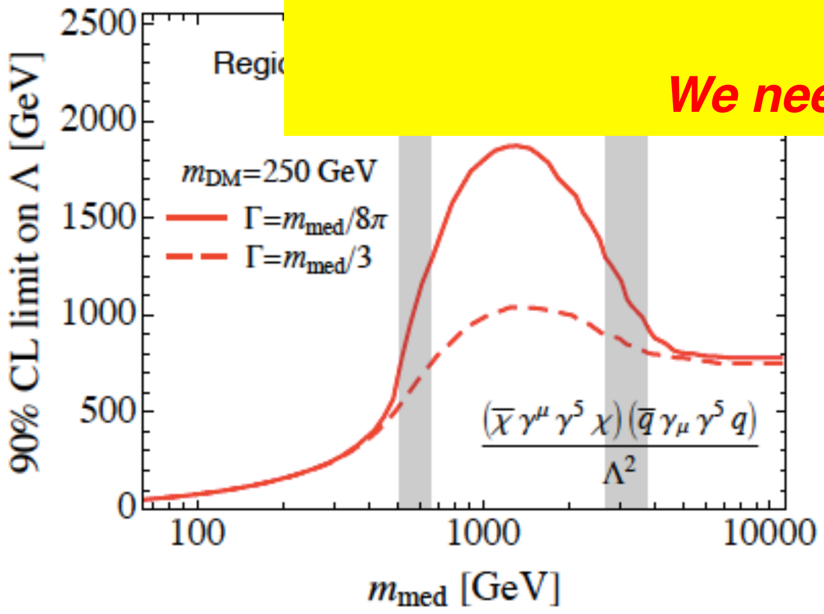
FT
one diagram
“simplified model”

Use vector a … in conclusion!

… r mass:

Conclusion:
The EFT alone is not sufficient for a comprehensive characterization of DM searches at colliders!

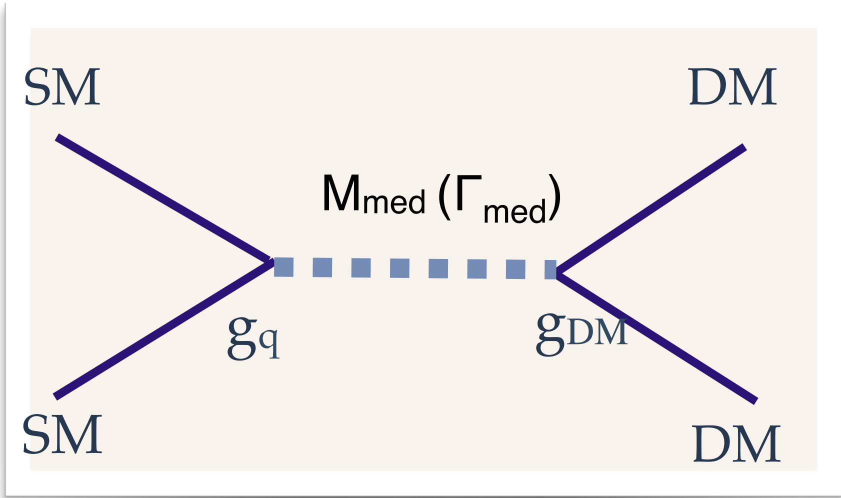
We need alternatives!



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 far too aggressive!

Minimal Simplified Dark Matter Model

See also DM forum report which brought together experimentalist from ATLAS and CMS as well as theorists. See: arXiv:1507.00966



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 Γ_{med}<M_{med})

Imperial College London

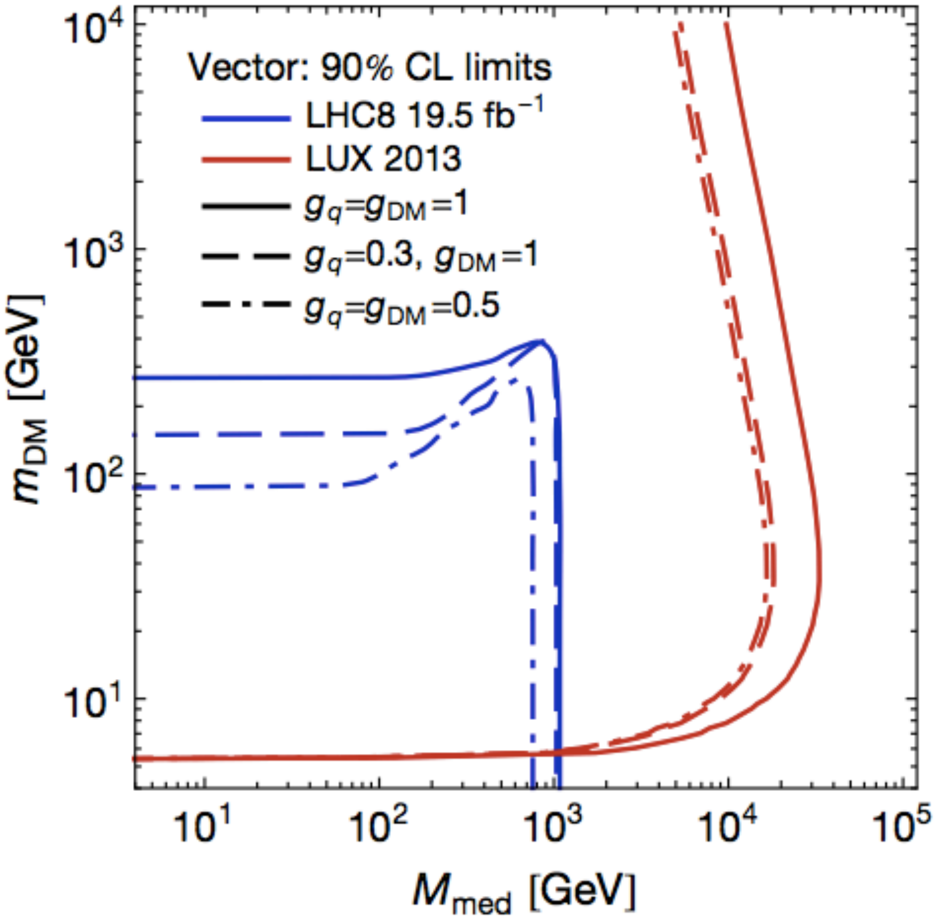
Collider vs Direct Detection

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

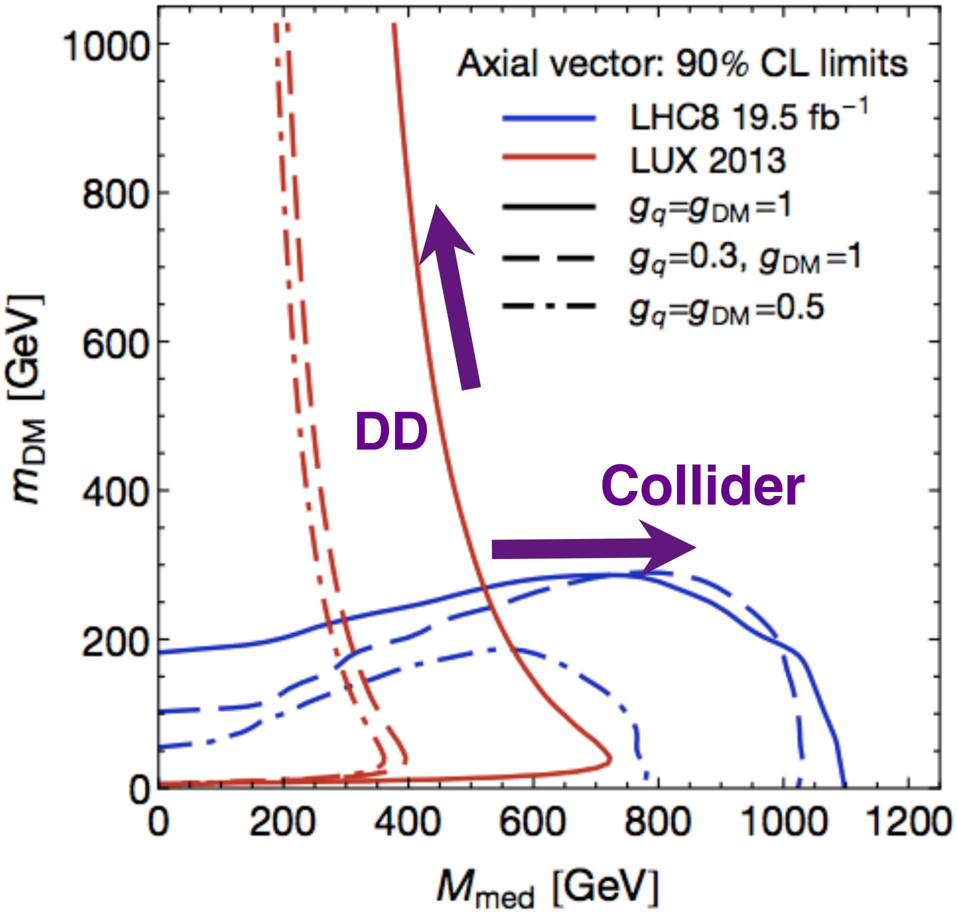
M_{DM}	M_{med}
g_q	g_{DM}

nmüller

Vector



Axial vector



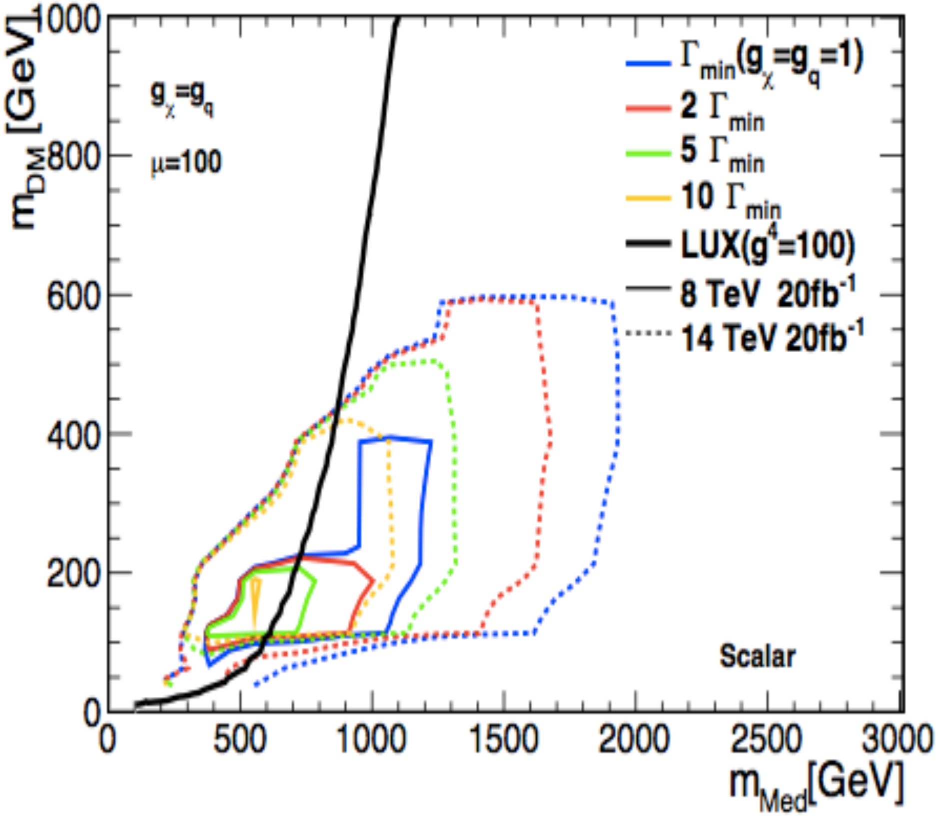
Scalar and Pseudoscalar

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

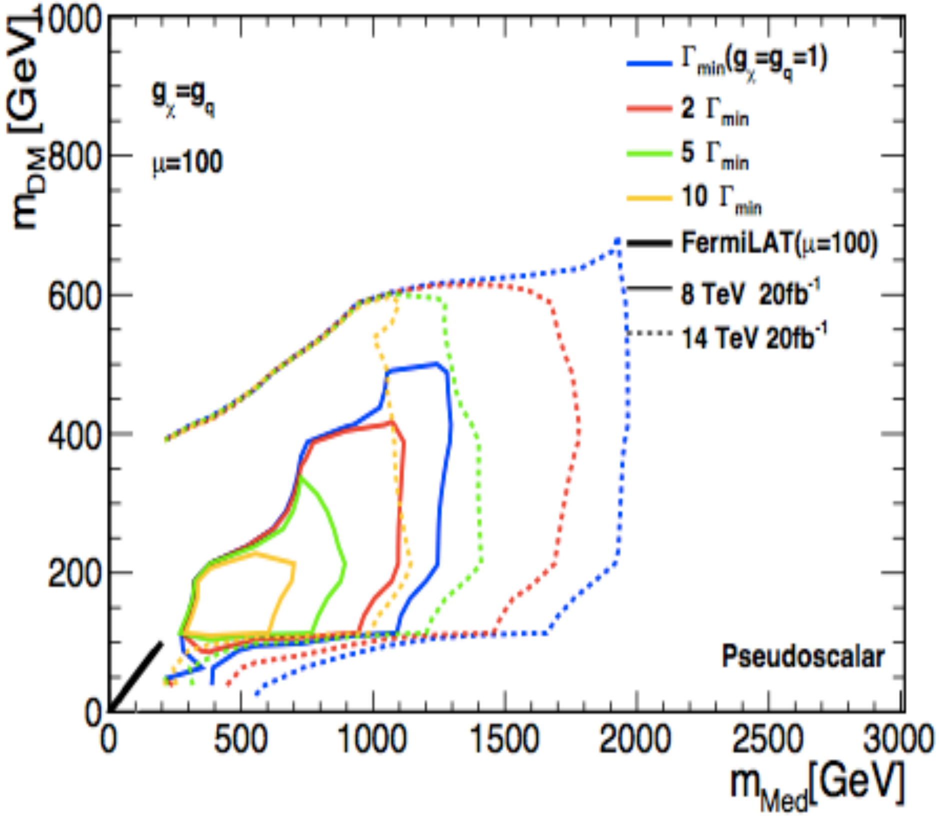
See also Buckley et al
arXiv:1410.6497

chmüller

Scalar



Pseudoscalar



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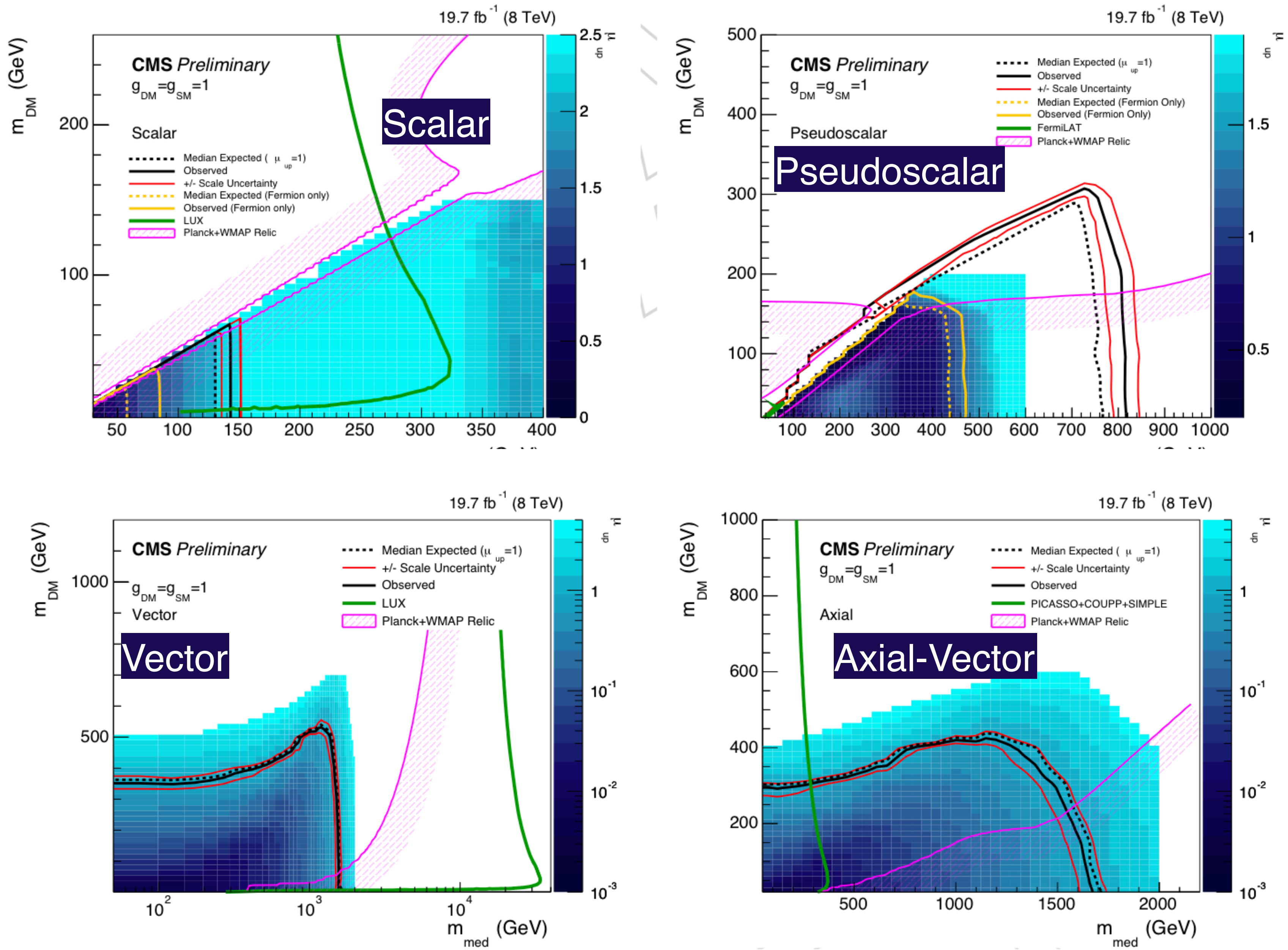
Recent released CMS “mono-jet” result 8 TeV



CMS PAS-EXO-12-055

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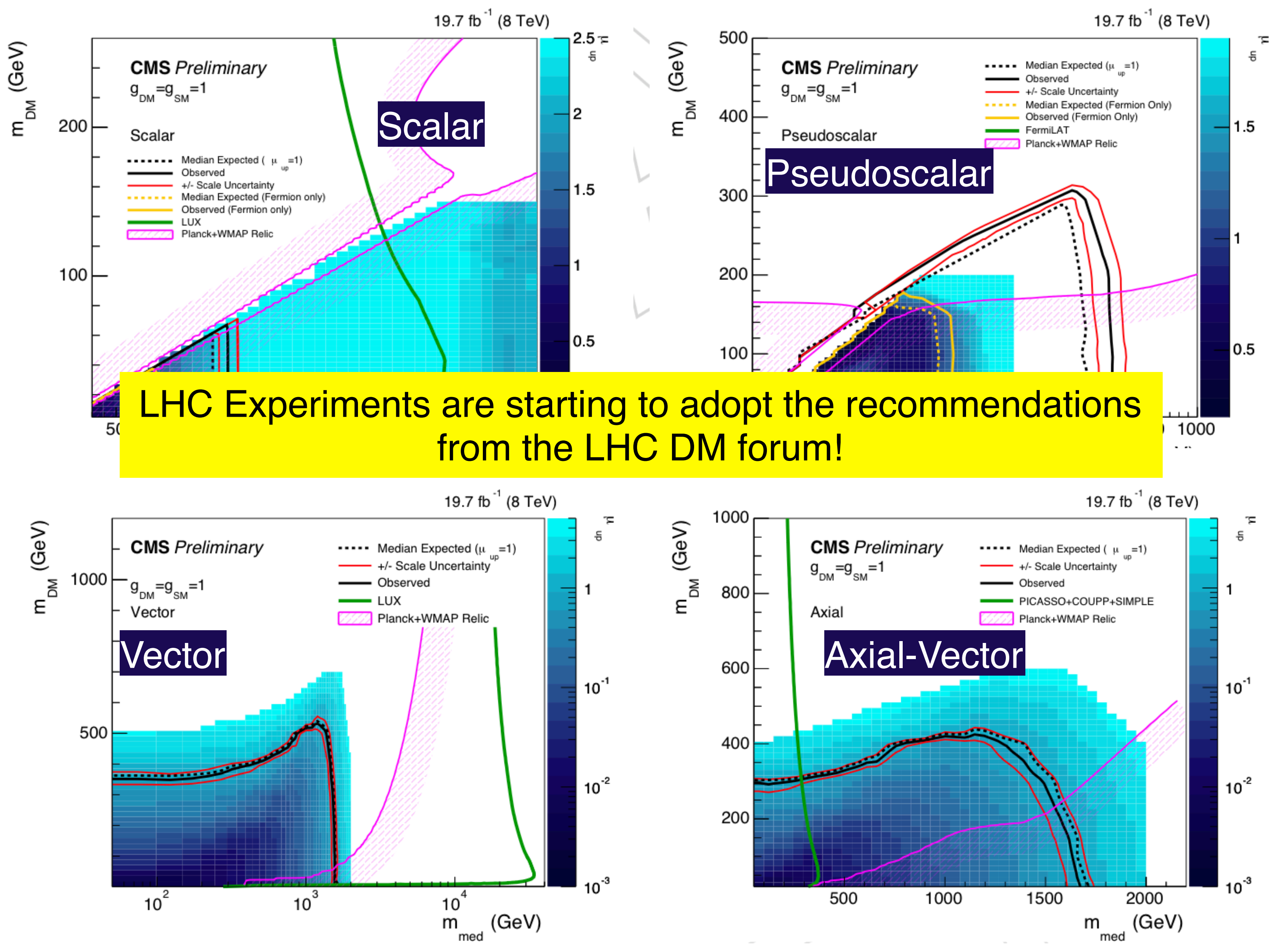
Recent released CMS "mono-jet" result 8 TeV



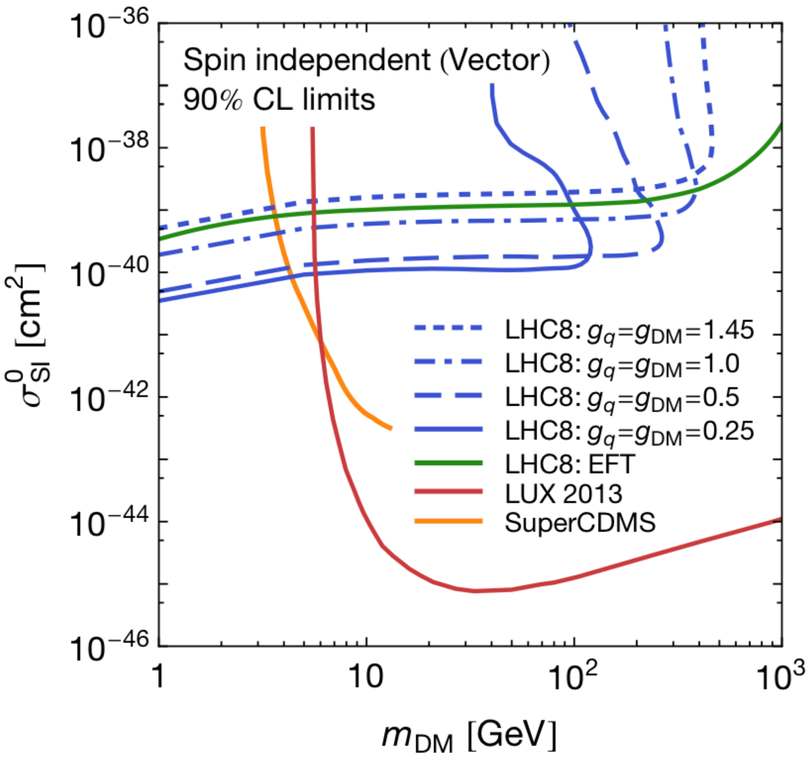
LHC Experiments are starting to adopt the recommendations from the LHC DM forum!

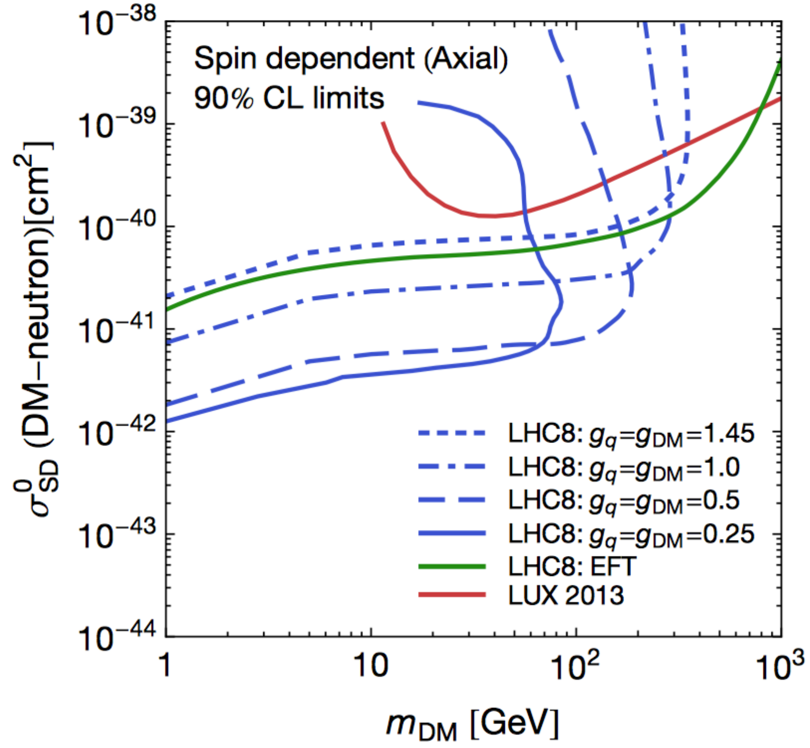
CMS PAS-EXO-12-055

Comparison of collider with DD and ID

"Direct translation of M_{med}-M_{DM} collider limits into $\sigma_{SI/SD}$ planes

arXiv:1407.8257
arXiv:1409.4075

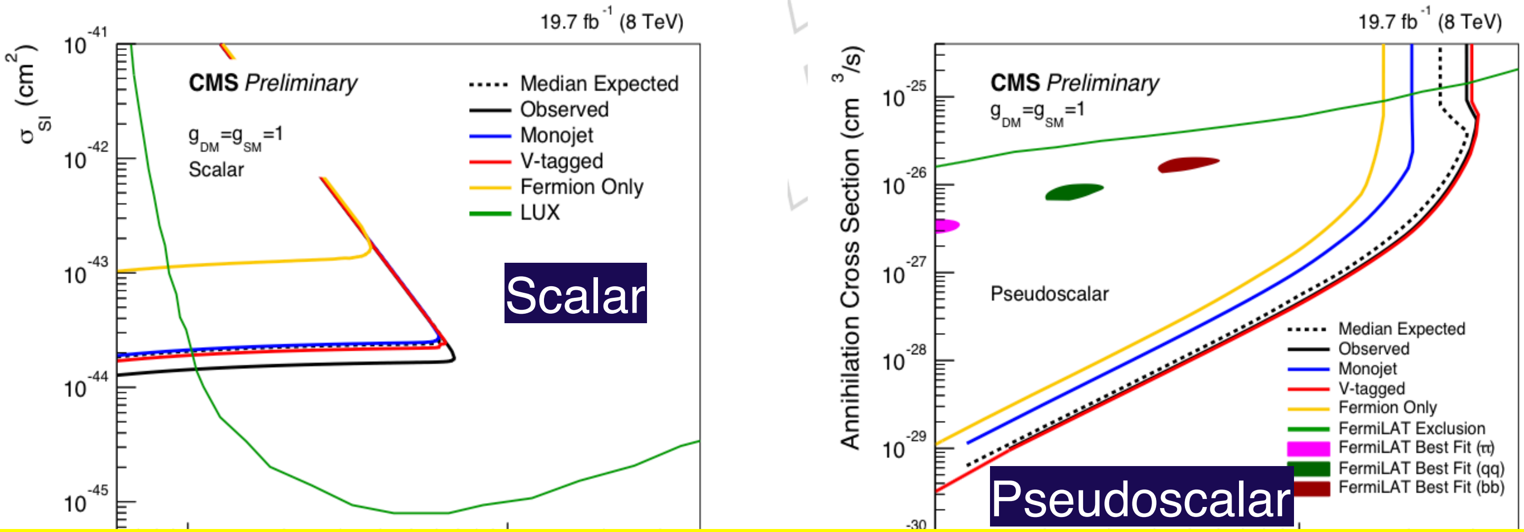




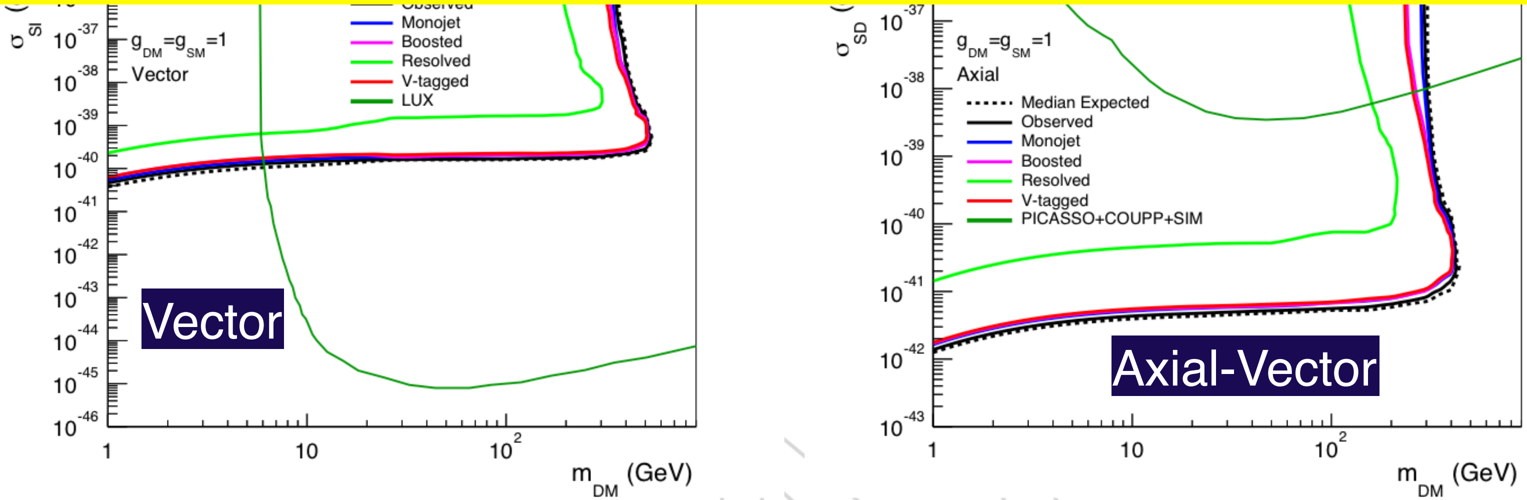
$$\sigma^0_{\rm SI} = \frac{9\, g^2_{\rm DM}\, g^2_q\, \mu^2_{n\chi}}{\pi M^4_{\rm med}} \approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

$$\sigma^0_{\rm SD} = \frac{3\, g^2_{\rm DM}\, g^2_q (\Delta_u + \Delta_d + \Delta_s)^2\, \mu^2_{n\chi}}{\pi M^4_{\rm med}} \approx 4.6 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

Comparison of collider with DD and ID (II)

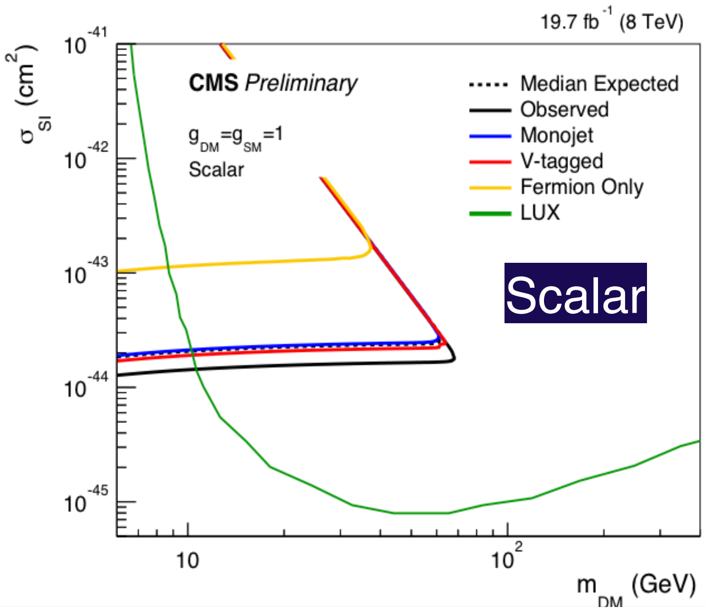


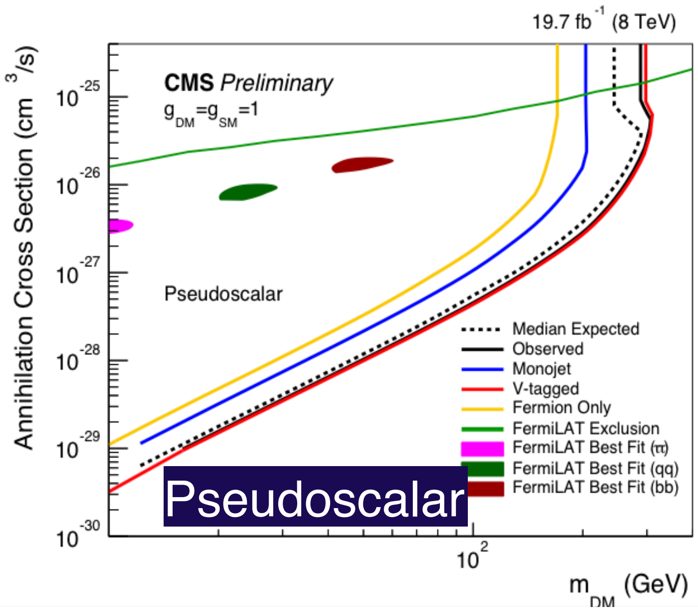
The comparison of collider DM results with Direct Detection and Indirect Detection experiments will be subject of discussion at the forthcoming
LPCC DM WG Workshop at CERN next week.

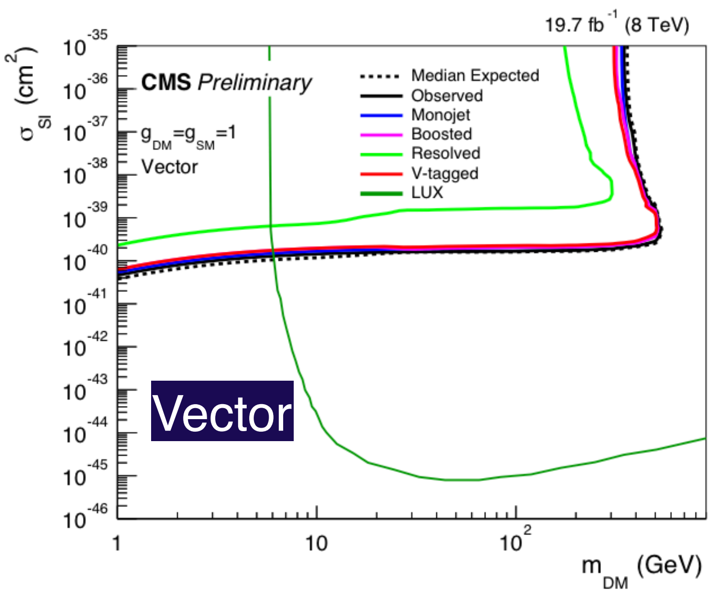


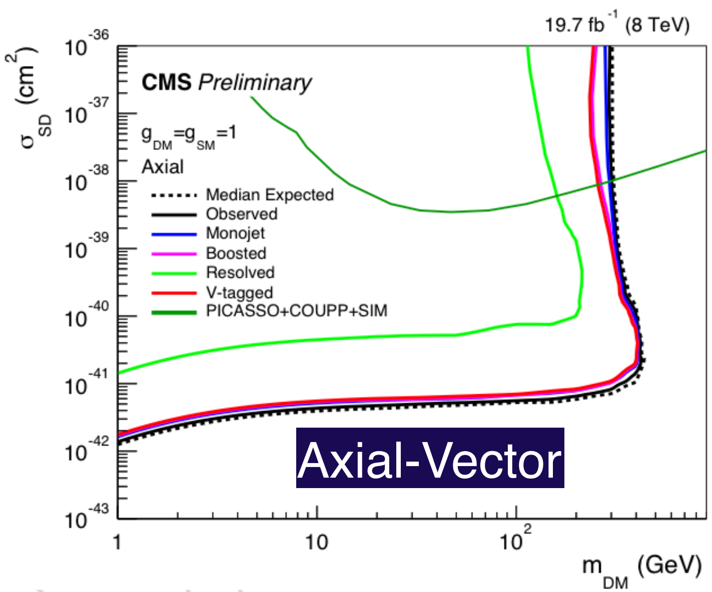
CMS P... -12-055

Comparison of collider with DD and ID (II)









New LPCC Dark Matter Working Group

This Working Group brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC. More details can be found at this page:

http://lpcc.web.cern.ch/LPCC/index.php?page=dm_wg

and the mailing list (which now also includes the lhc-dmf@cern.ch mailing list recipients) is lhc-dmwg@cern.ch.

Our first goal is to discuss and agree upon the presentation of collider searches for DM between ATLAS and CMS. Both LHC experiment and theory community will collaborate, in order to decide upon the best format for comparison between collider and non-collider results and on the usability of the material that is made public for the Winter conferences 2016.

We will have a short workshop on this topic at CERN on December 10th-11th.

The developing agenda can be found here: https://indico.cern.ch/event/459037/

Collider vs DD Complementarity in a nutshell (so far)!

Common ground (almost)

- Axial-Vector mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

- Scalar mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

Exclusive domains (almost)

- Vector mediator

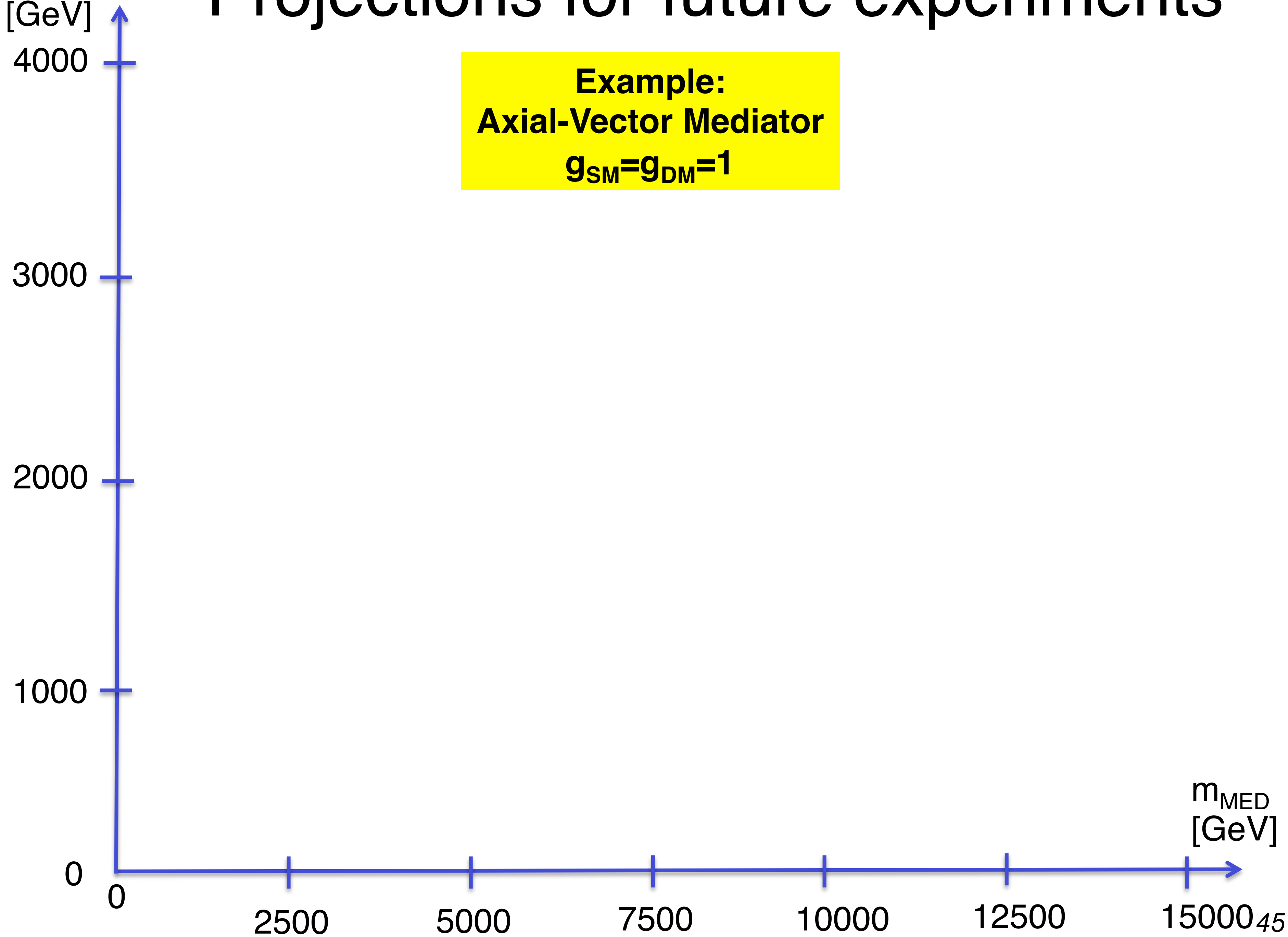
  Besides very low DM masses DD wins clearly over collider

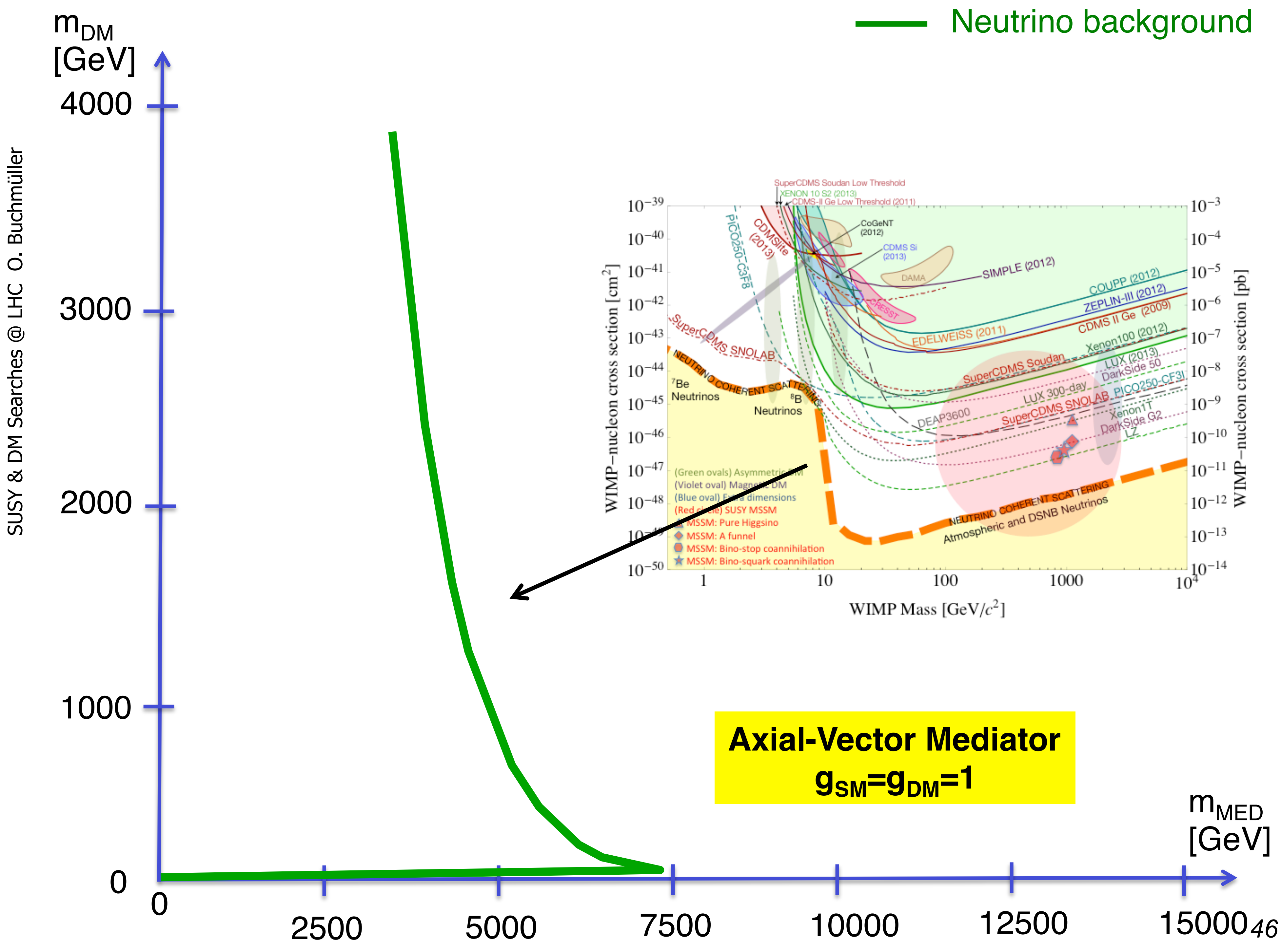
- Pseudo-Scalar mediator

  No competitive limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits

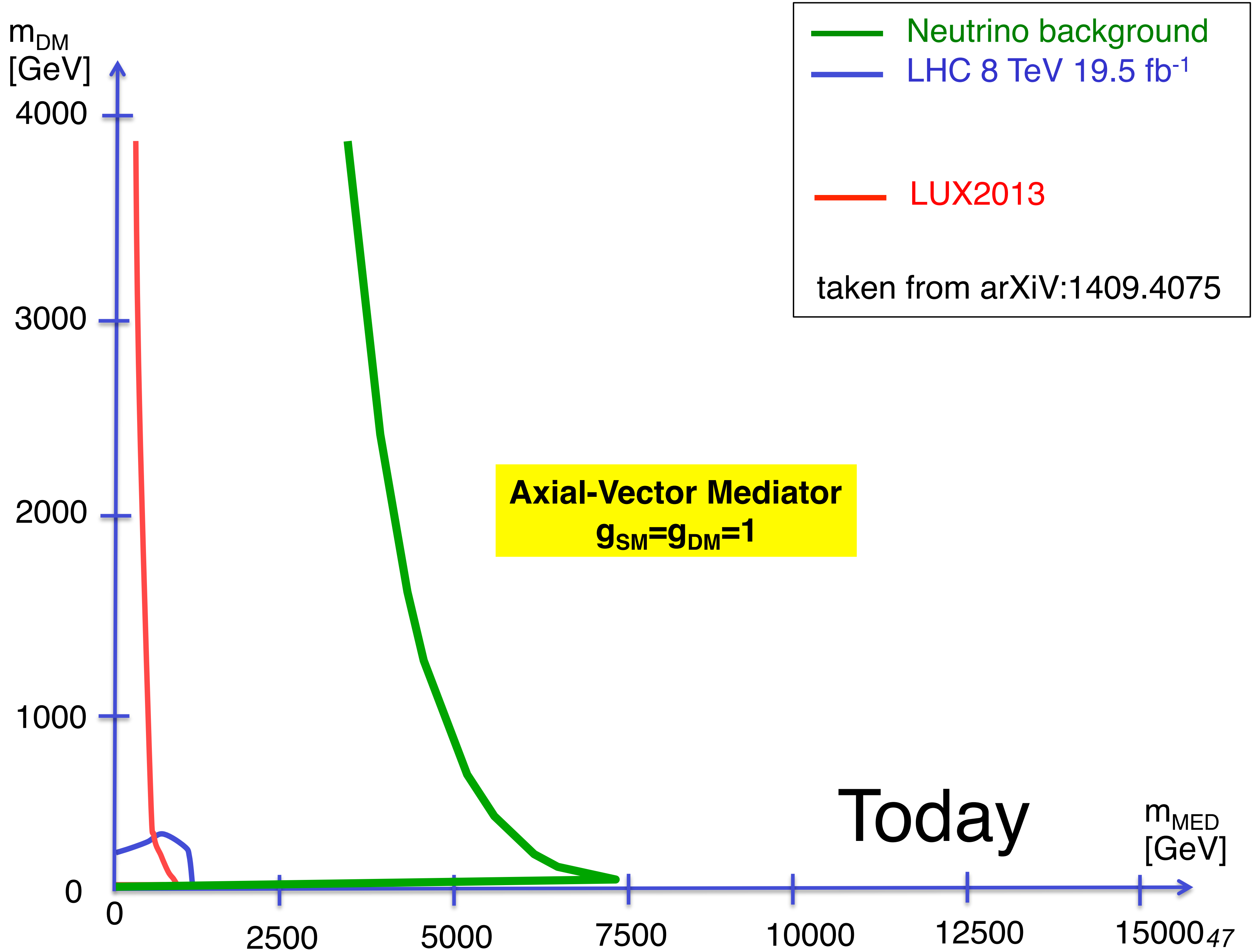
Projections for future experiments

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

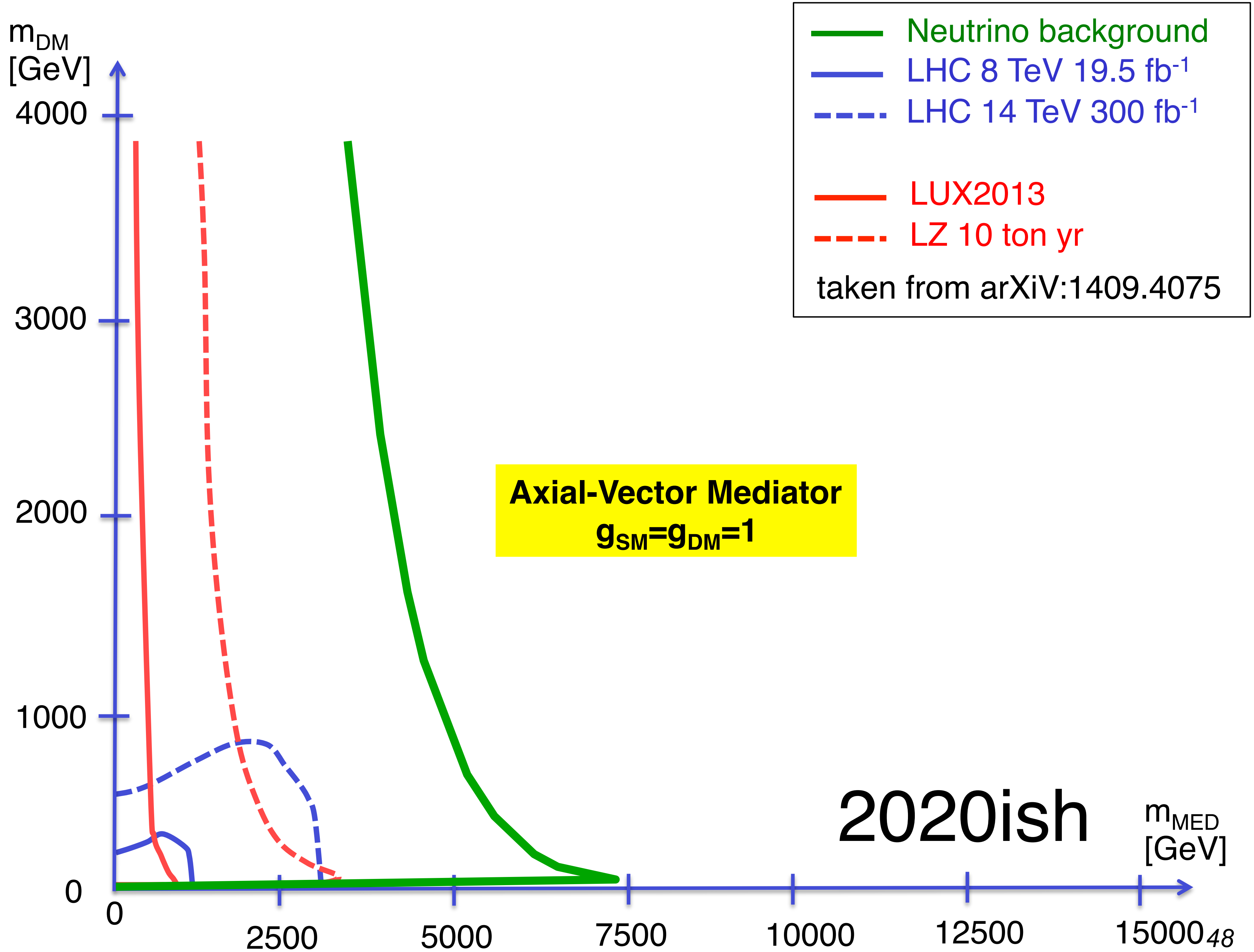




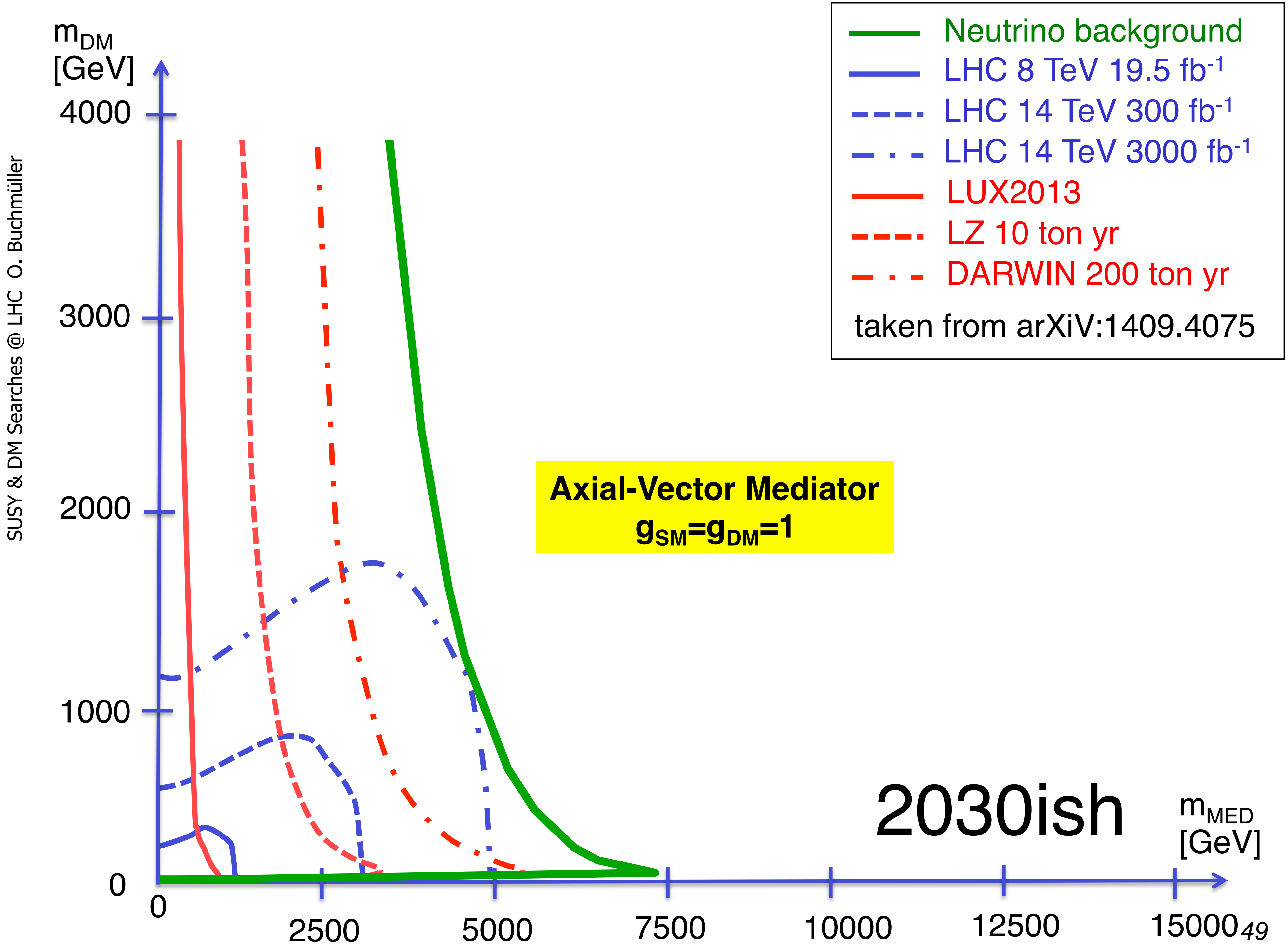
Neutrino background
m_{DM} [GeV]
4000
3000
2000
1000
0
SUSY & DM Searches @ LHC O. Buchmüller
0
2500
5000
7500
10000
12500
15000
m_{MED} [GeV]
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
CRESST
CDMSlite (2013)
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
LUX (2013)
DarkSide 50
PICO250-CF3I
LUX 300-day
SuperCDMS SNOLAB
Xenon1T
DarkSide G2
LZ
DEAP3600
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-50}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4



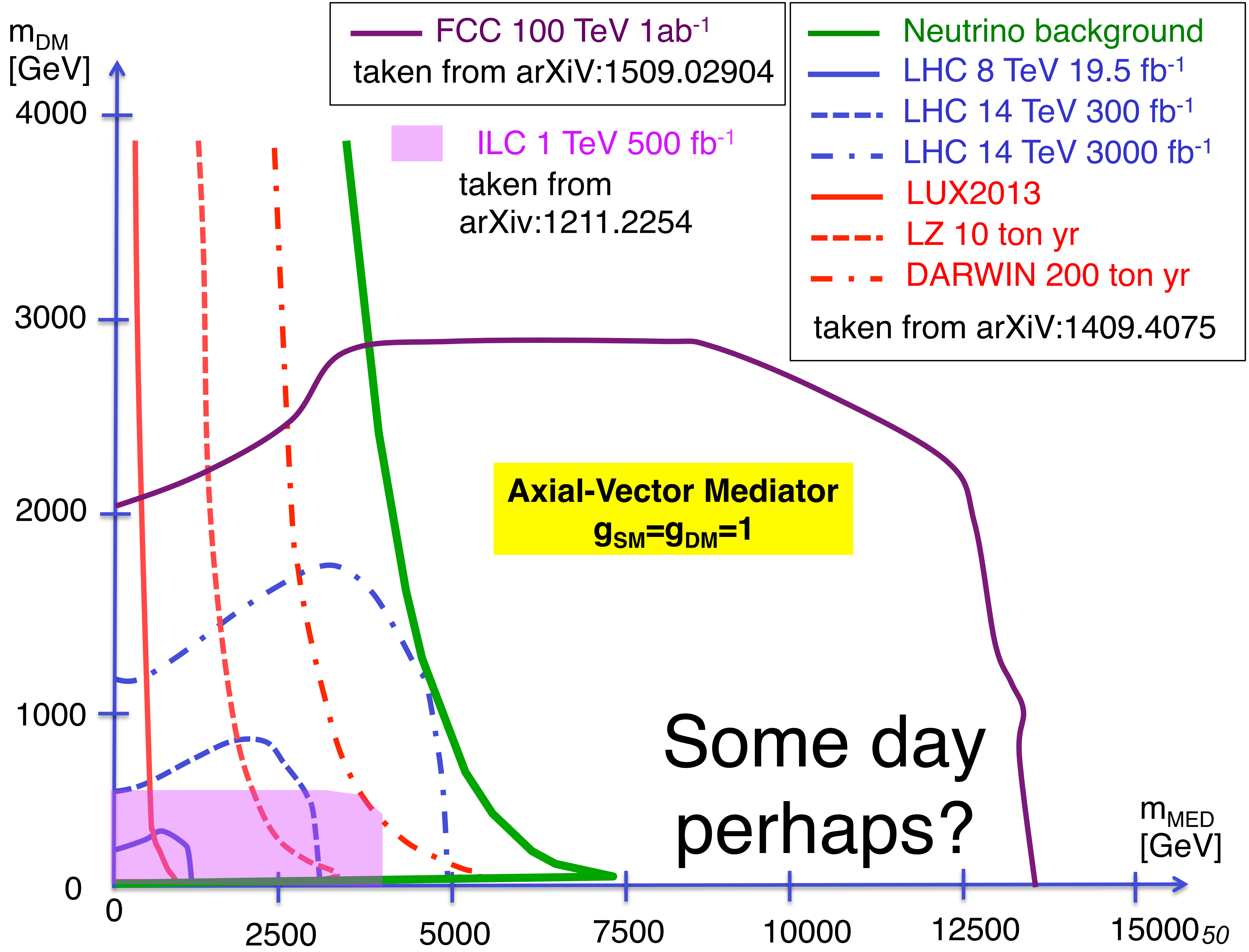
m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LUX2013
taken from arXiV:1409.4075
Axial-Vector Mediator
g_SM=g_DM=1
Today



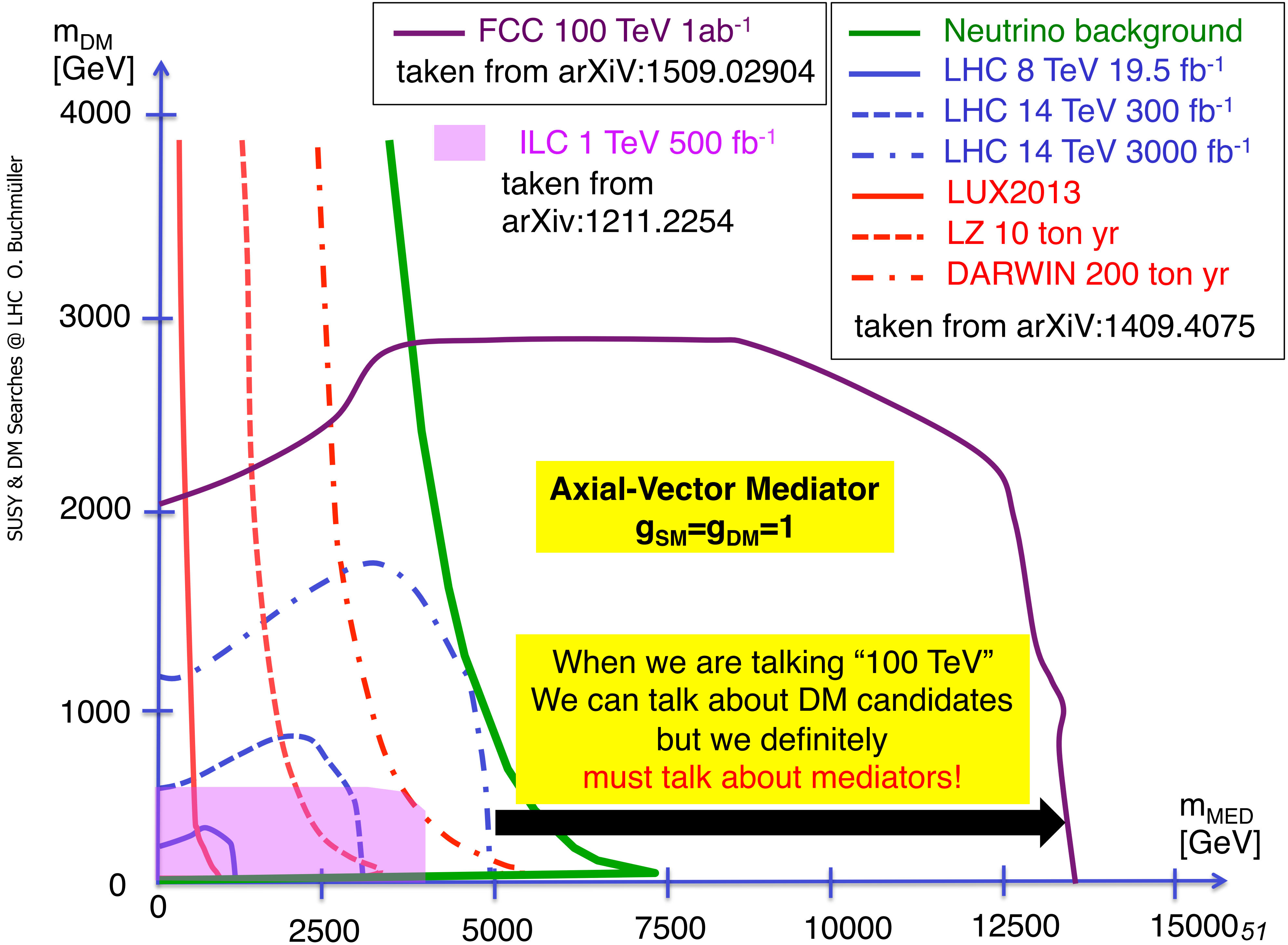
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LUX2013
LZ 10 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
gSM=gDM=1
2020ish
mDM [GeV]
mMED [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000



m_{DM} [GeV]
4000
3000
2000
1000
0
SUSY & DM Searches @ LHC O. Buchmüller
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
$g_{SM}=g_{DM}=1$
2030ish
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000



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
ILC 1 TeV 500 fb-1
taken from
arXiv:1211.2254
Axial-Vector Mediator
gSM=gDM=1
Some day
perhaps?
mDM
[GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
mMED
[GeV]



m_{DM} [GeV]
4000
3000
2000
1000
0
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
ILC 1 TeV 500 fb^{-1}
taken from arXiv:1211.2254
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
When we are talking "100 TeV"
We can talk about DM candidates
but we definitely
must talk about mediators!
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000
SUSY & DM Searches @ LHC O. Buchmüller

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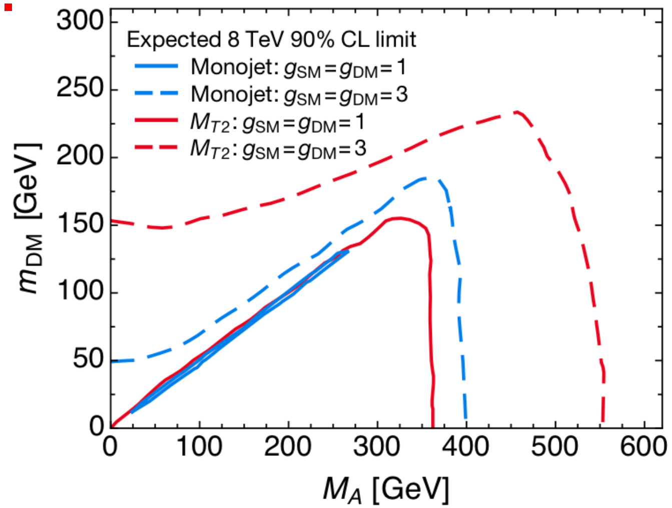
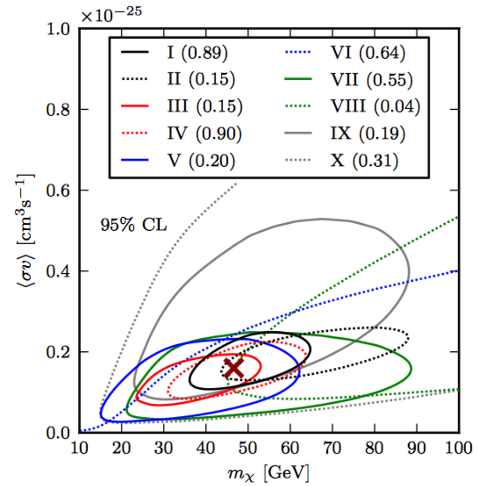
Fermi-Lat Excess: Indirect Detection vs Collider

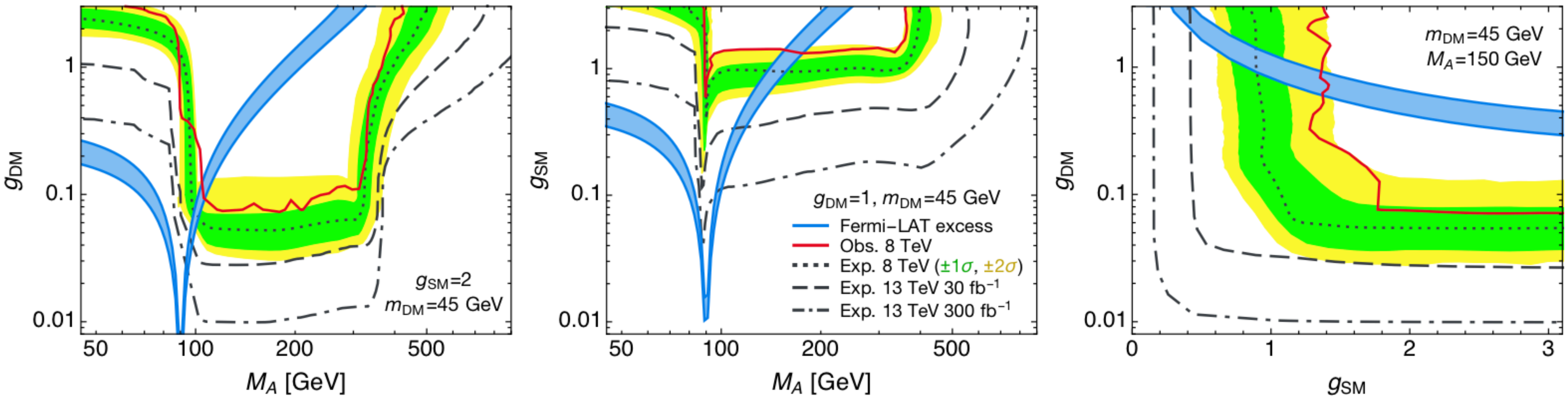
Constraining the Fermi-LAT excess with collider data.

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



$M_{DM} \sim 45$ GeV
arXiv:1409.0042





Fermi-Lat Excess: Indirect Detection vs Collider

Constraining the Fermi-LAT excess with collider data.

Based on work from :
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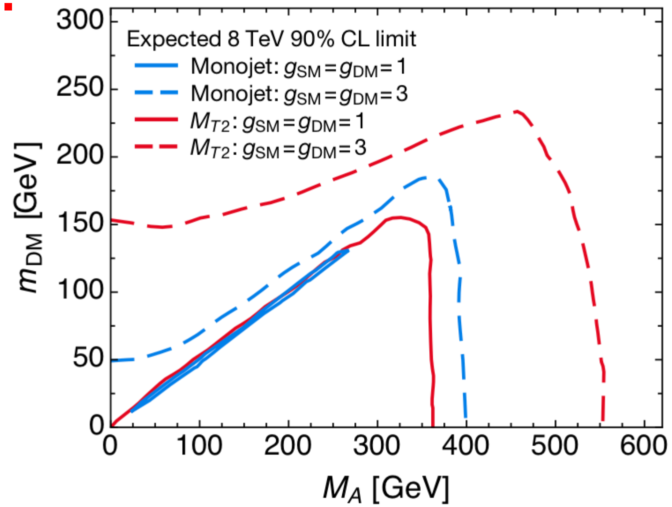
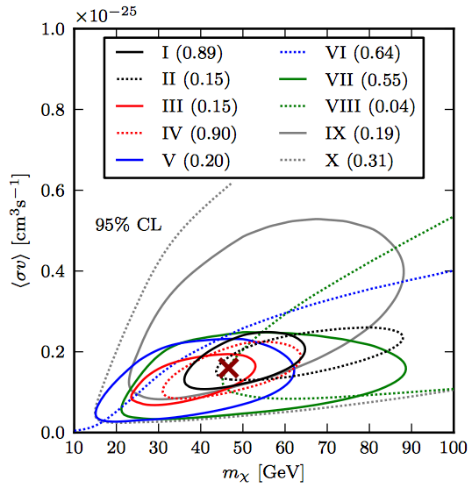
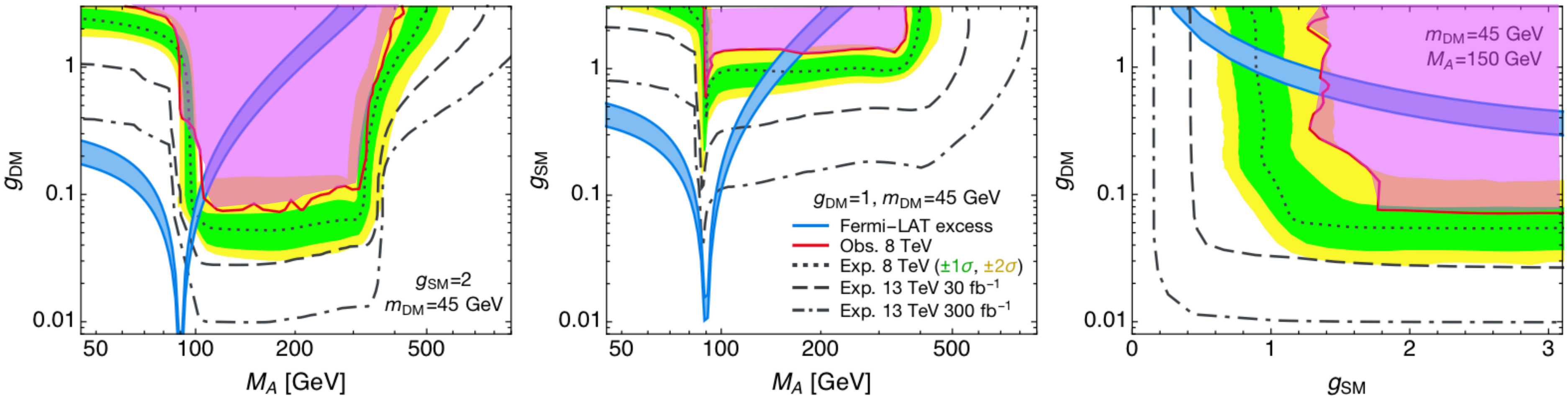


$M_{DM} \sim 45$ GeV
arXiv:1409.0042



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

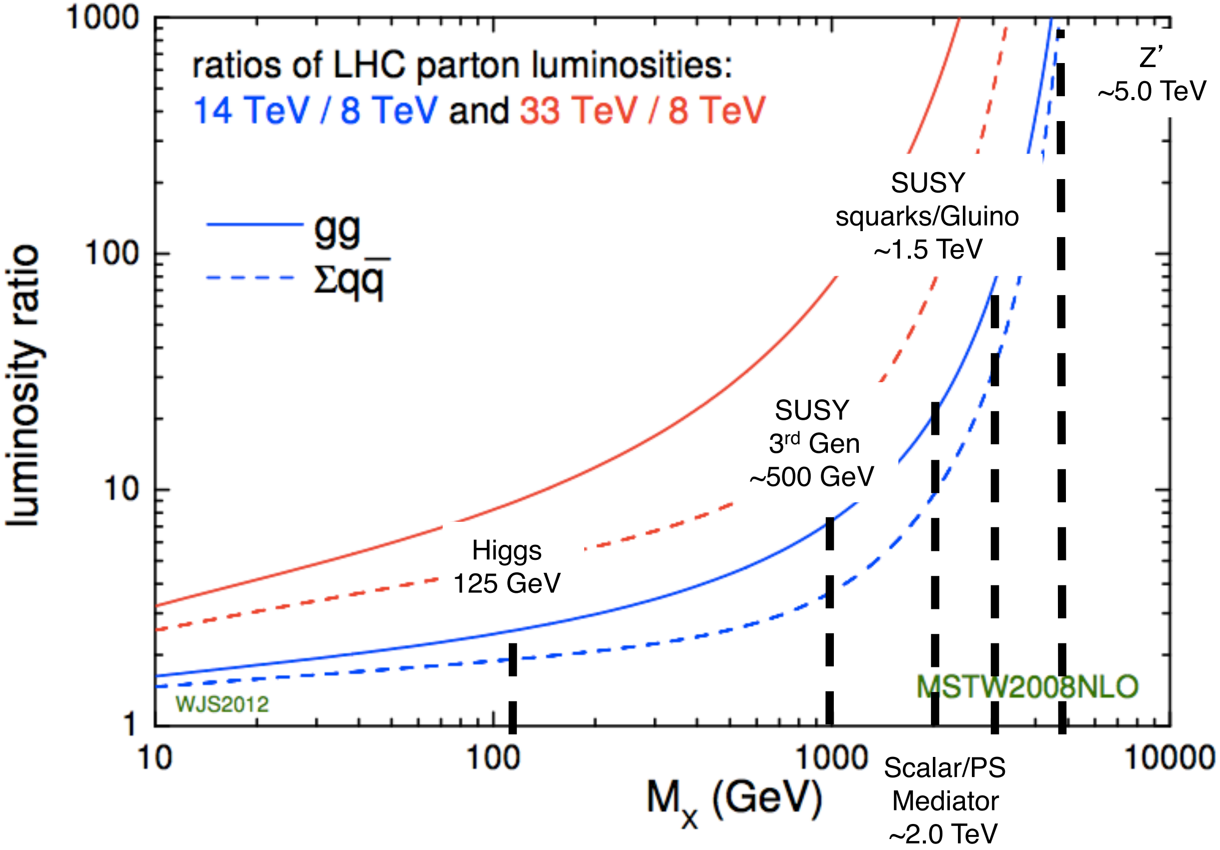
Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

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!
  - In 2010 the LHC has enter new territory for New Physics searches and since then pushed e.g. the (coloured) mass scale to the ~1 TeV scale and in some cases even beyond.
- The LHC experiments have established an impressive variety of very powerful direct searches for many different final states!
  - So far many of these searches are only interpret in dedicated models, while they do possess also sensitivity for other scenarios. A good example are the missing (transverse) energy searches, which, so far, predominately have been interpret in the context of "SUSY" only.
  - 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 MEANIGFUL comparison with other experiments – important example are DM searches!
  - The LHC DM forum has made a first important step in this direction!
- The high energy running of the LHC is our next very (as in VERY) real chance for discovery!

The story continues … stay tuned!

BACKUP

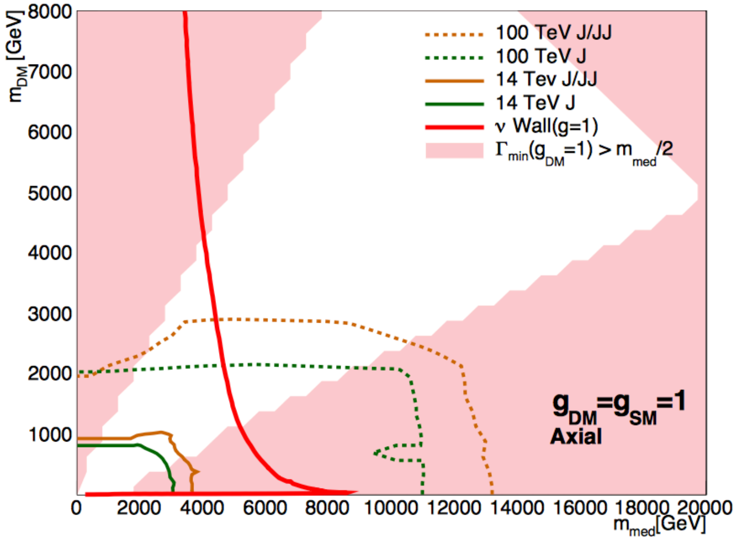
ATLAS & CMS public results

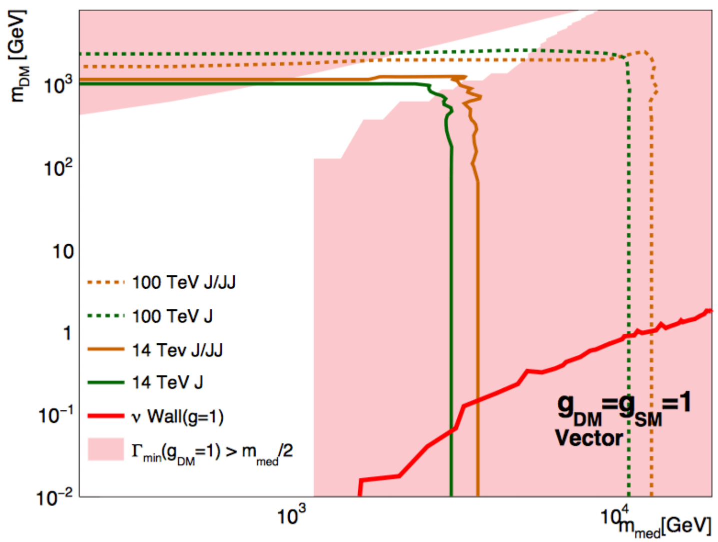
Most results presented in this talk (and many more) can be accessed via the public page of the ATLAS and CMS experiments:

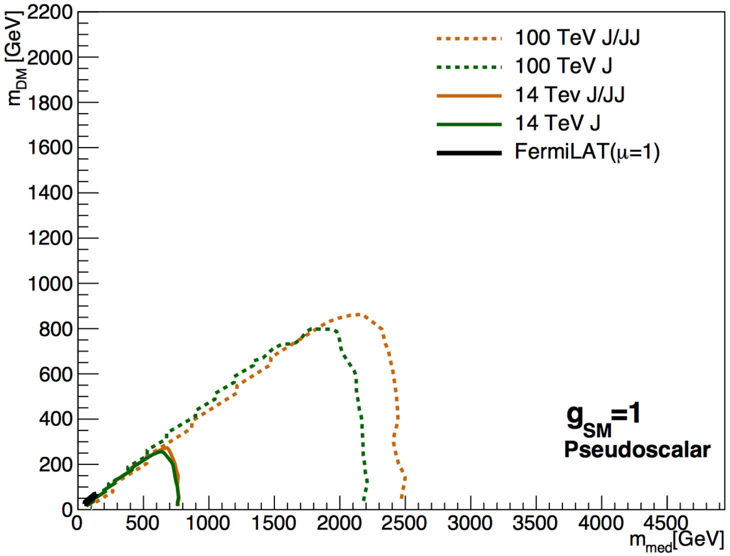
ATLAS SUSY: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

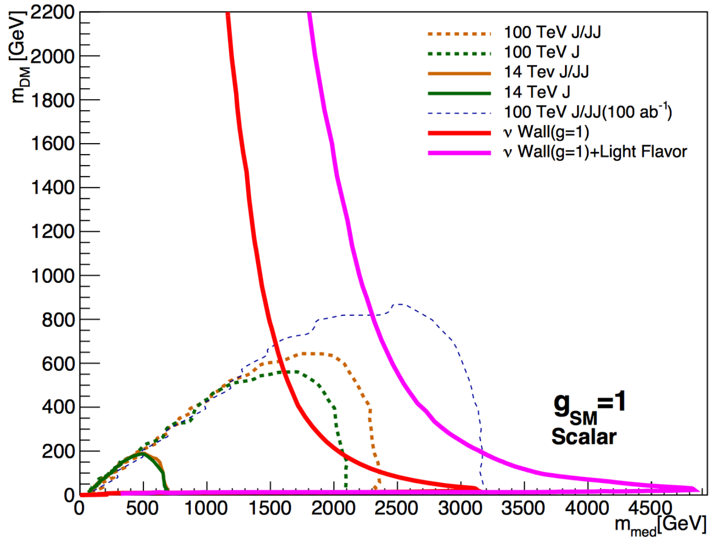
CMS SUSY :https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

100 TeV Prediction from arXiv:1509.02904









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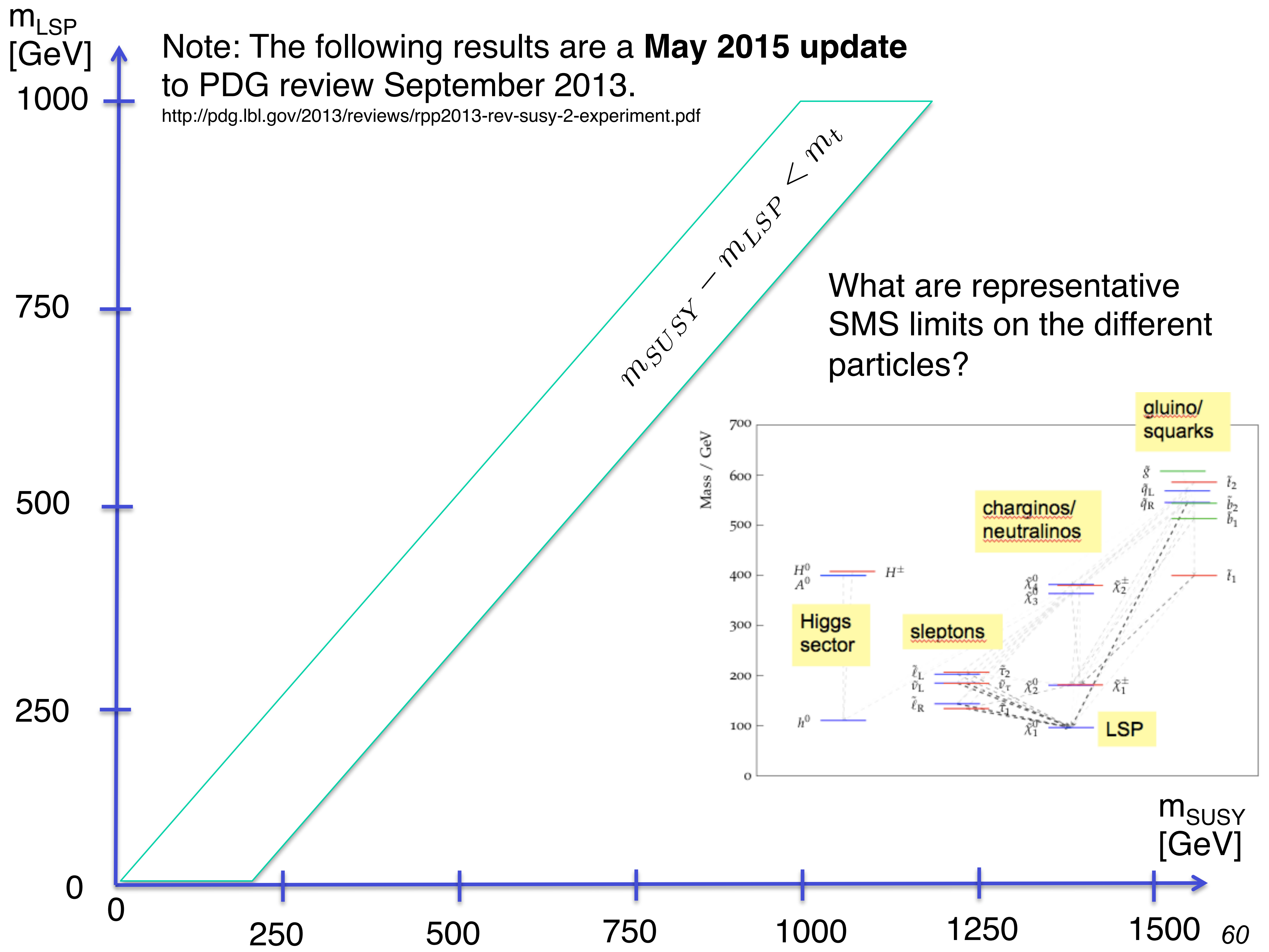
The full story

SUSY SUMMARY PLOT

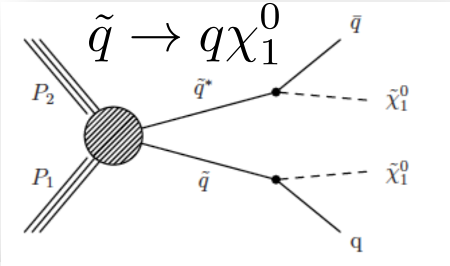
Note: The following results are a **May 2015 update** to PDG review September 2013.

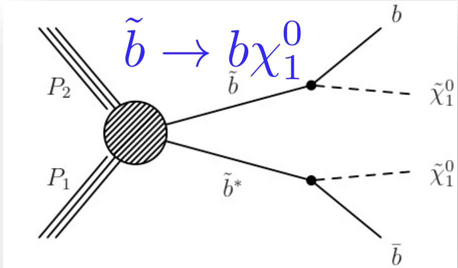
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

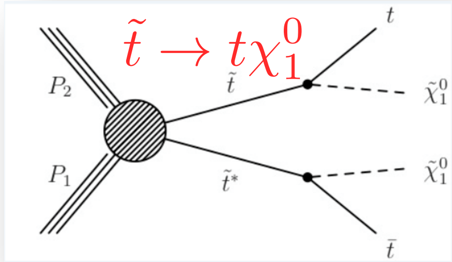
What are representative SMS limits on the different particles?

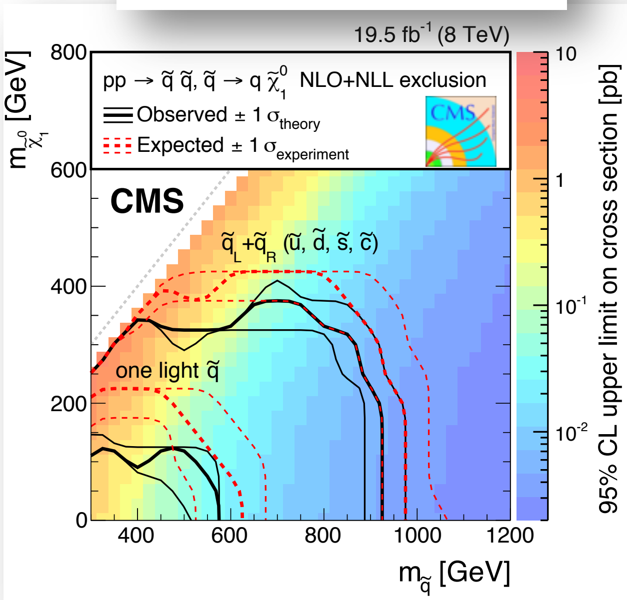


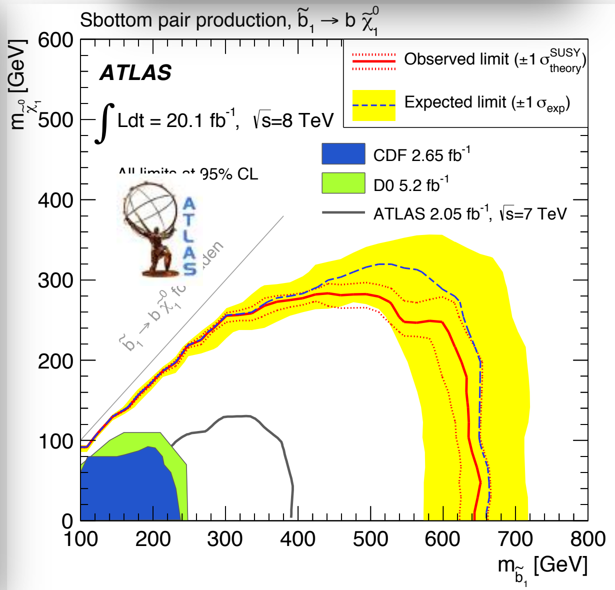
Direct squark production – chosen limits

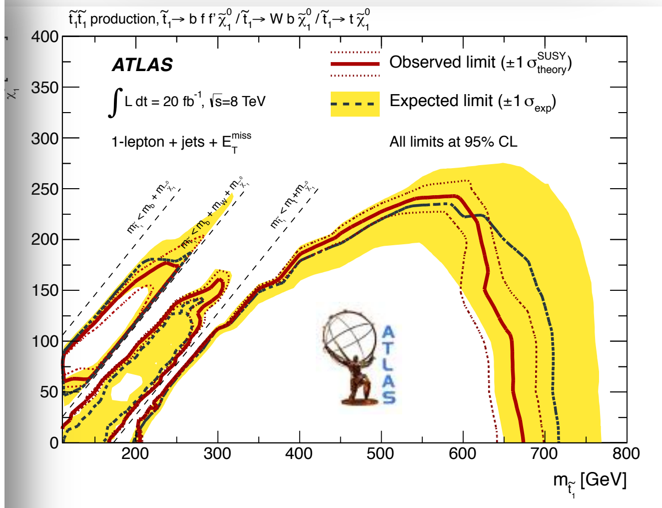








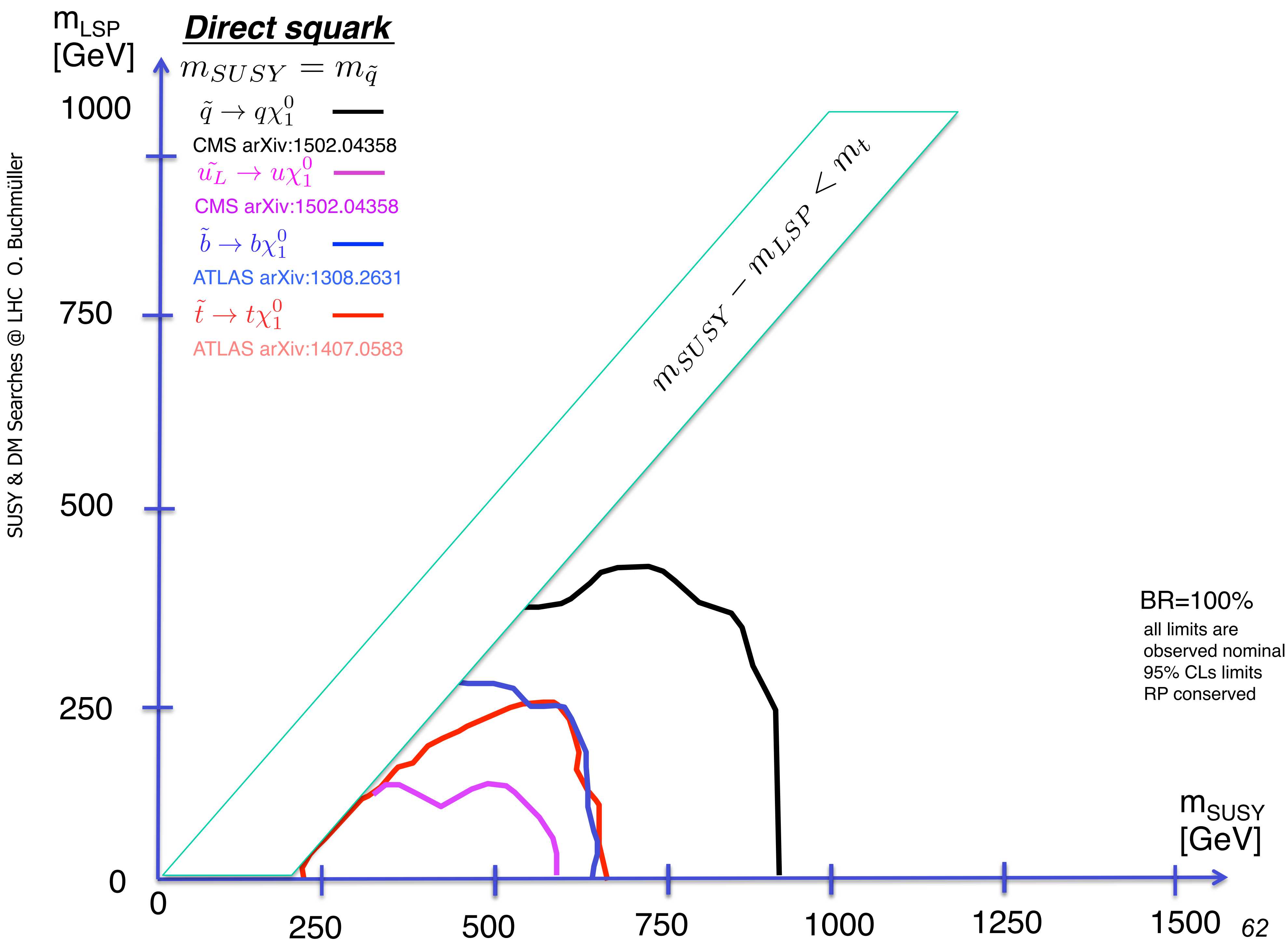




CMS arXiv:1502.04358
Signature: Jets + E_t^{miss} with M_{T2}
Limit assumes all 1st & 2nd gen squarks to be mass degenerate [or only one light squark]!

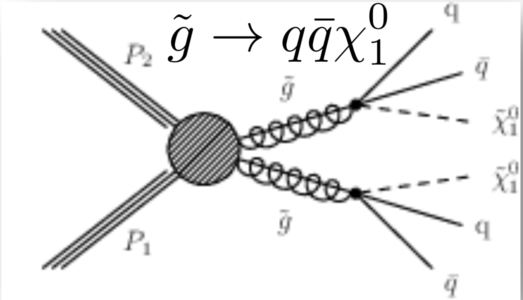
ATLAS arXiv:1308.2631
Signature: 2 b-jets + E_T^{mis}

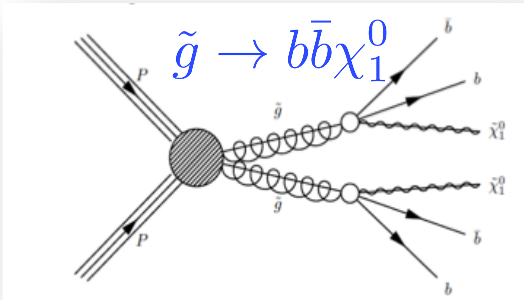
ATLAS arXiv:1407.0583
Signature: 1Lepton + jets + E_T^{mis}

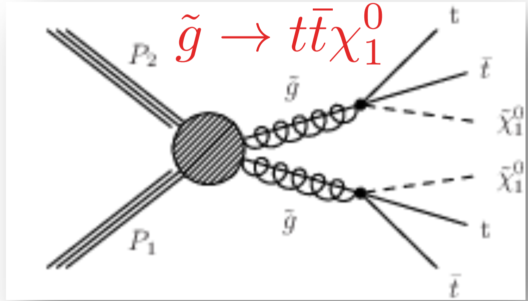


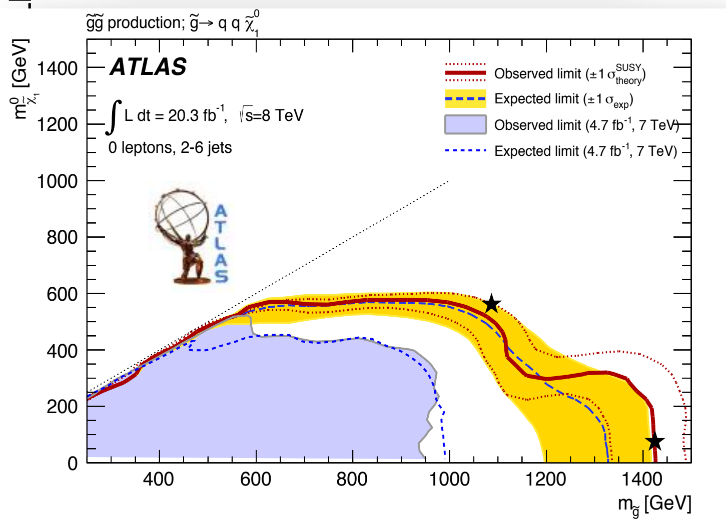
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
m_{LSP} [GeV]
1000
750
500
250
0
$m_{SUSY}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

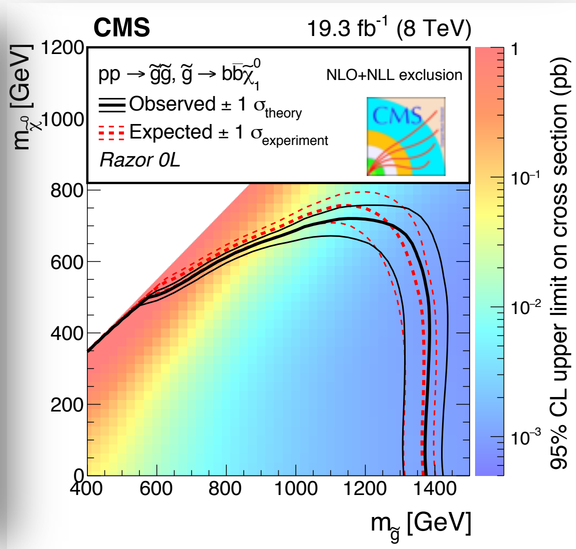
Gluino mediated squark production – limits chosen

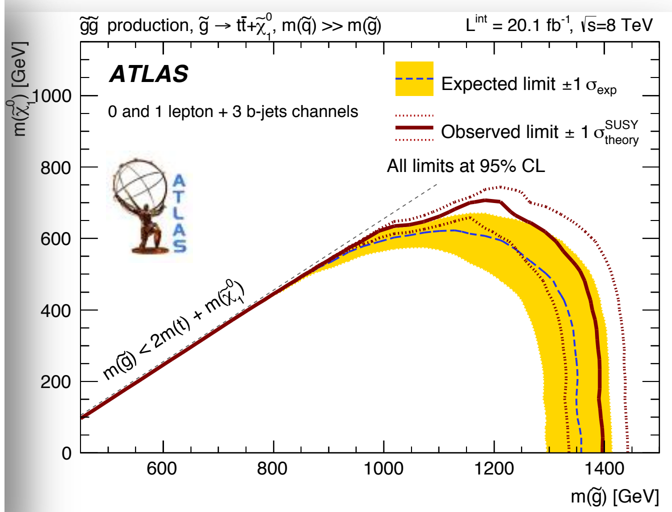








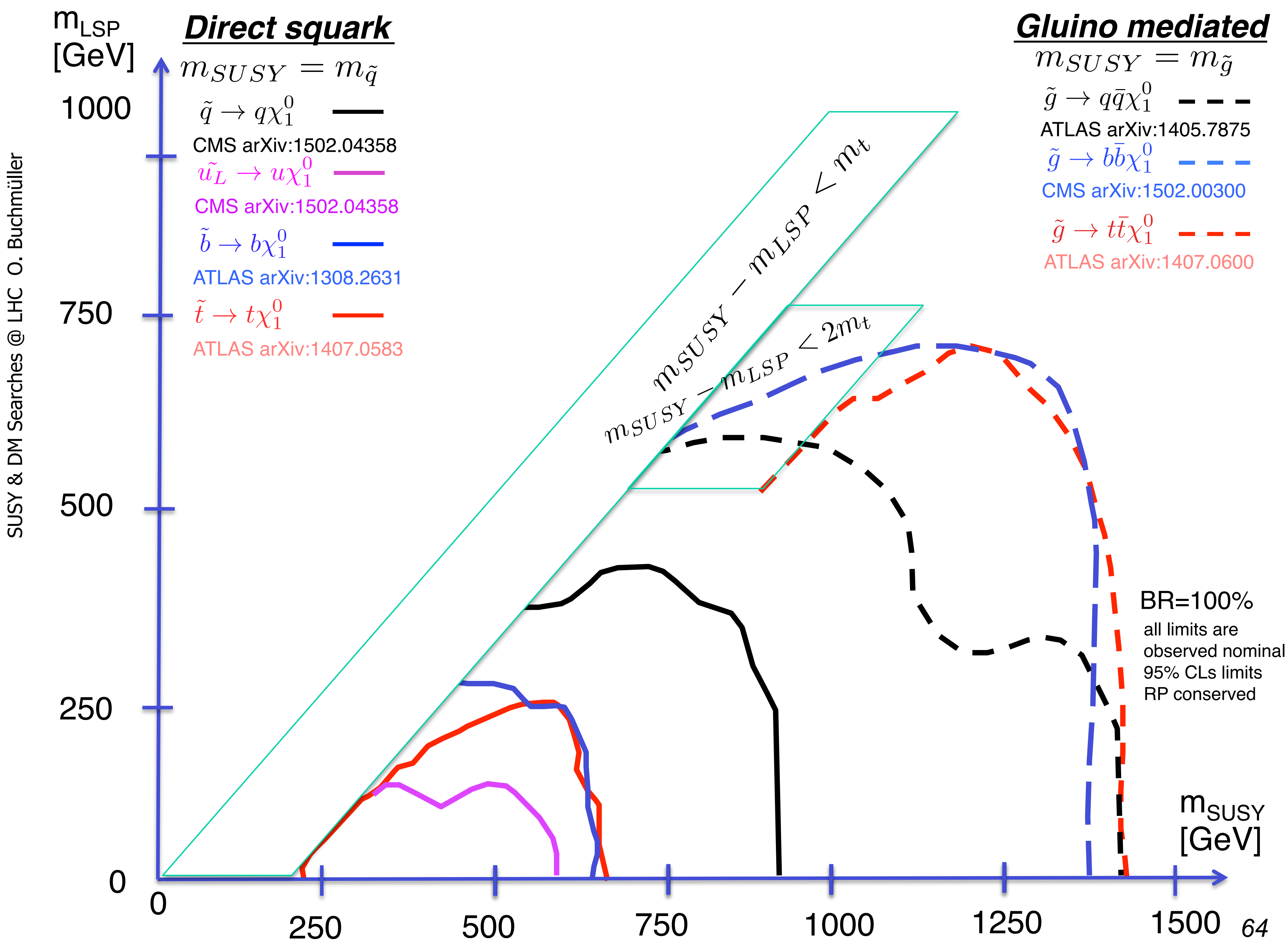




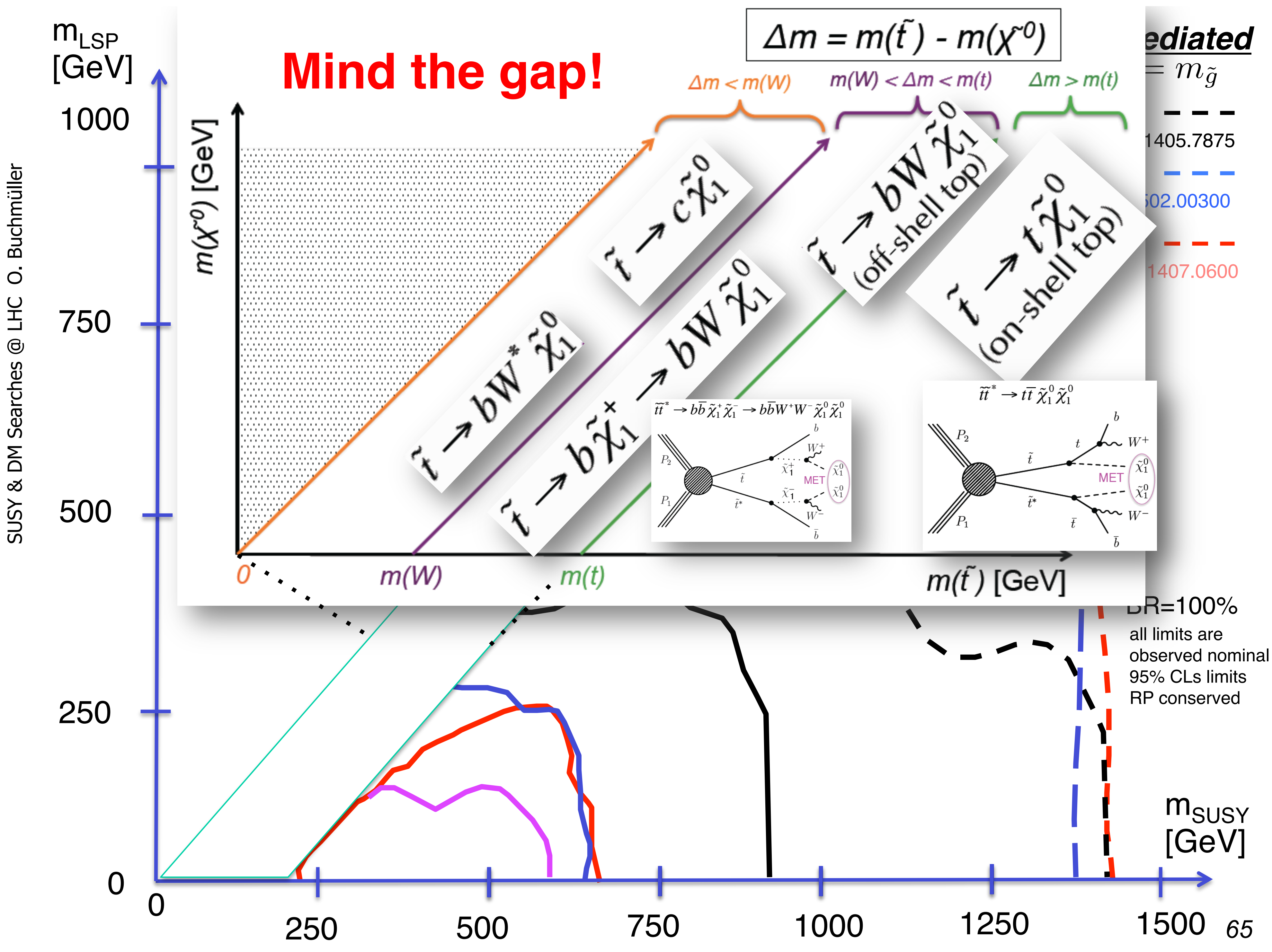
ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets + E_t^{miss}

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

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



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
m_{LSP} [GeV]
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
SUSY & DM Searches @ LHC O. Buchmüller


Mind the gap!
Δm = m(t̃) - m(χ̃⁰)
Δm < m(W)
m(W) < Δm < m(t)
Δm > m(t)
m(χ̃⁰) [GeV]
m(t̃) [GeV]
0
m(W)
m(t)
(off-shell top)
(on-shell top)
MET
mLSP [GeV]
mSUSY [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
1405.7875
1502.00300
1407.0600
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
SUSY & DM Searches @ LHC O. Buchmüller

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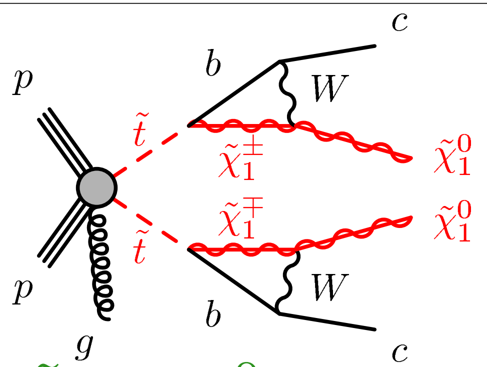
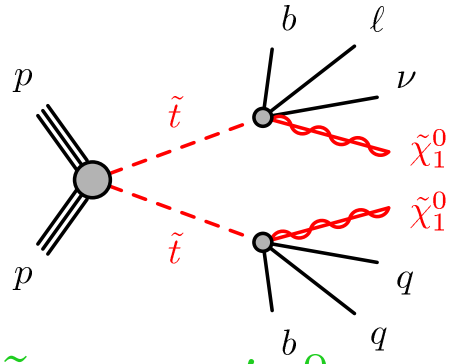
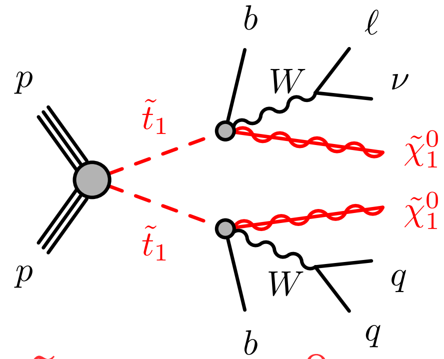
Compressed stop – mind the gap!



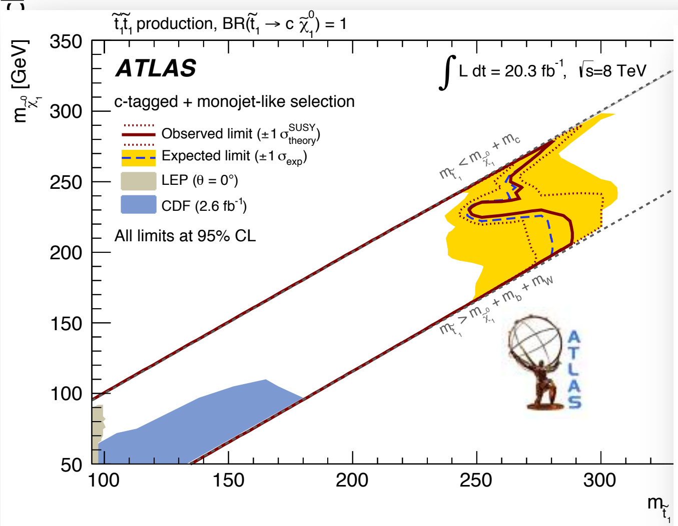
$\tilde{t} \rightarrow c\chi_1^0$

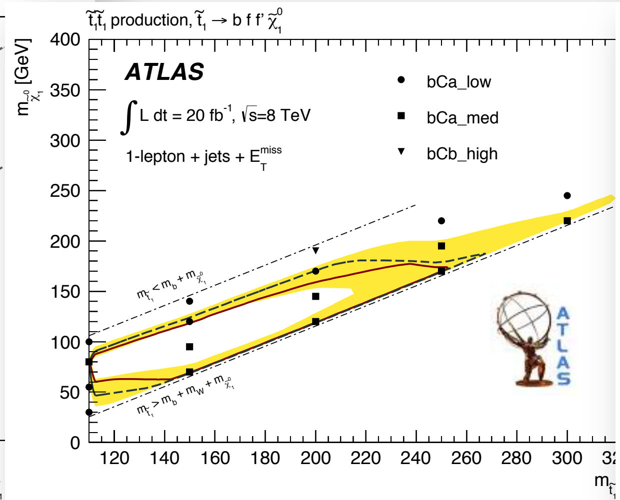


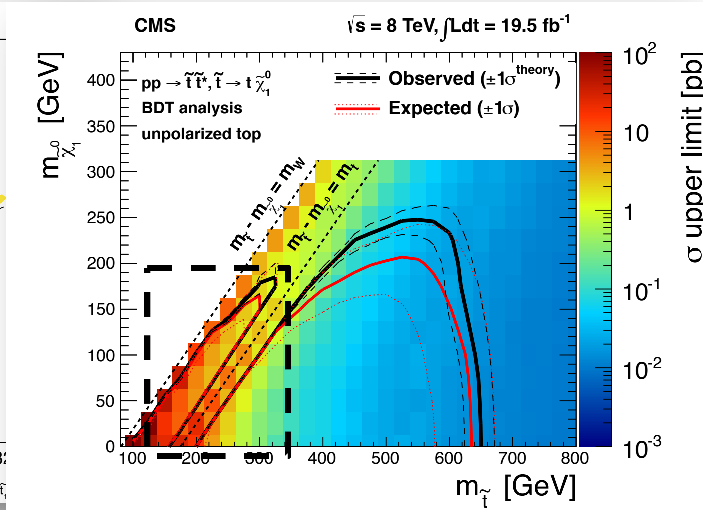
$\tilde{t} \rightarrow b f f' \chi_1^0$



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



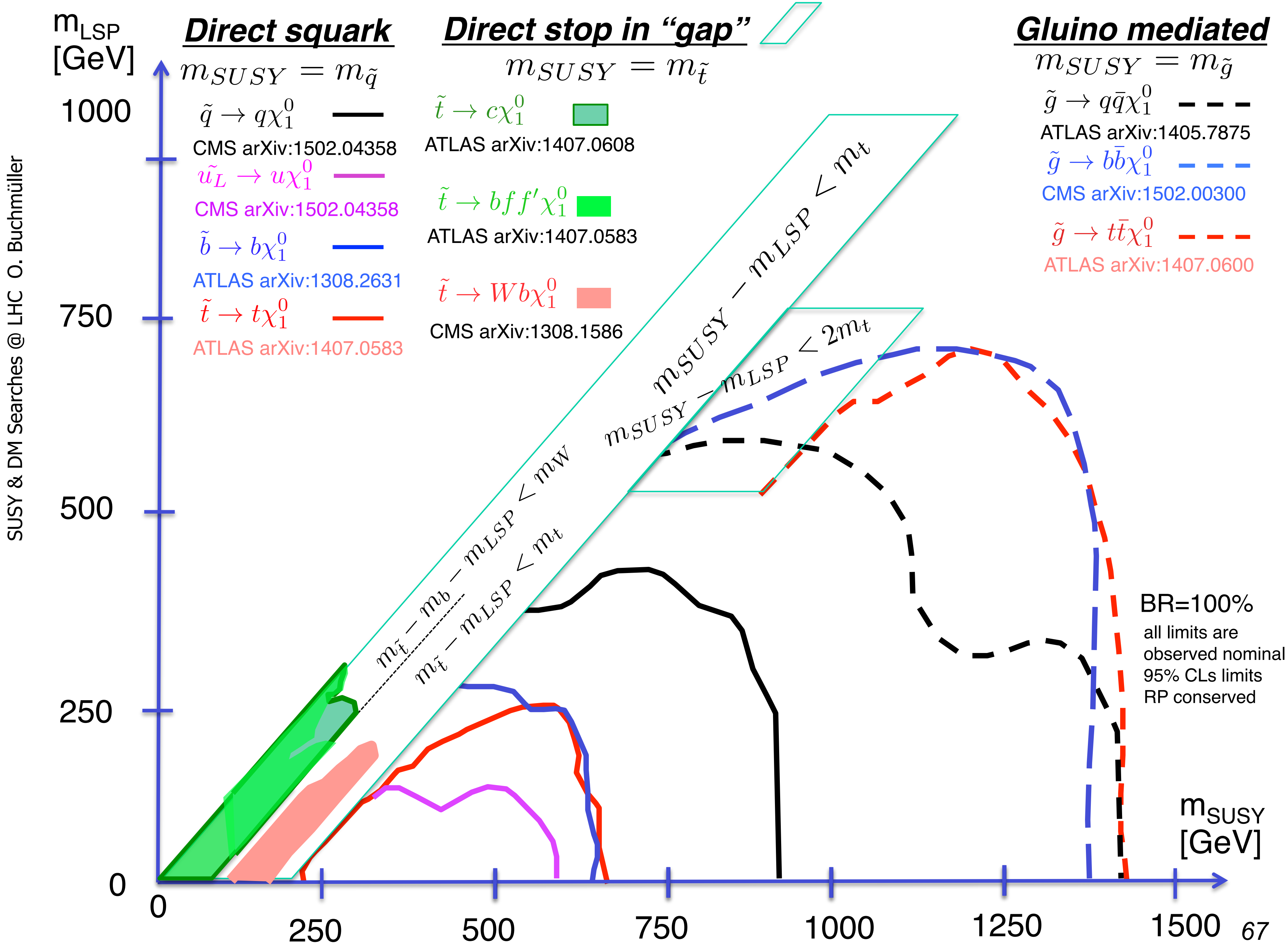




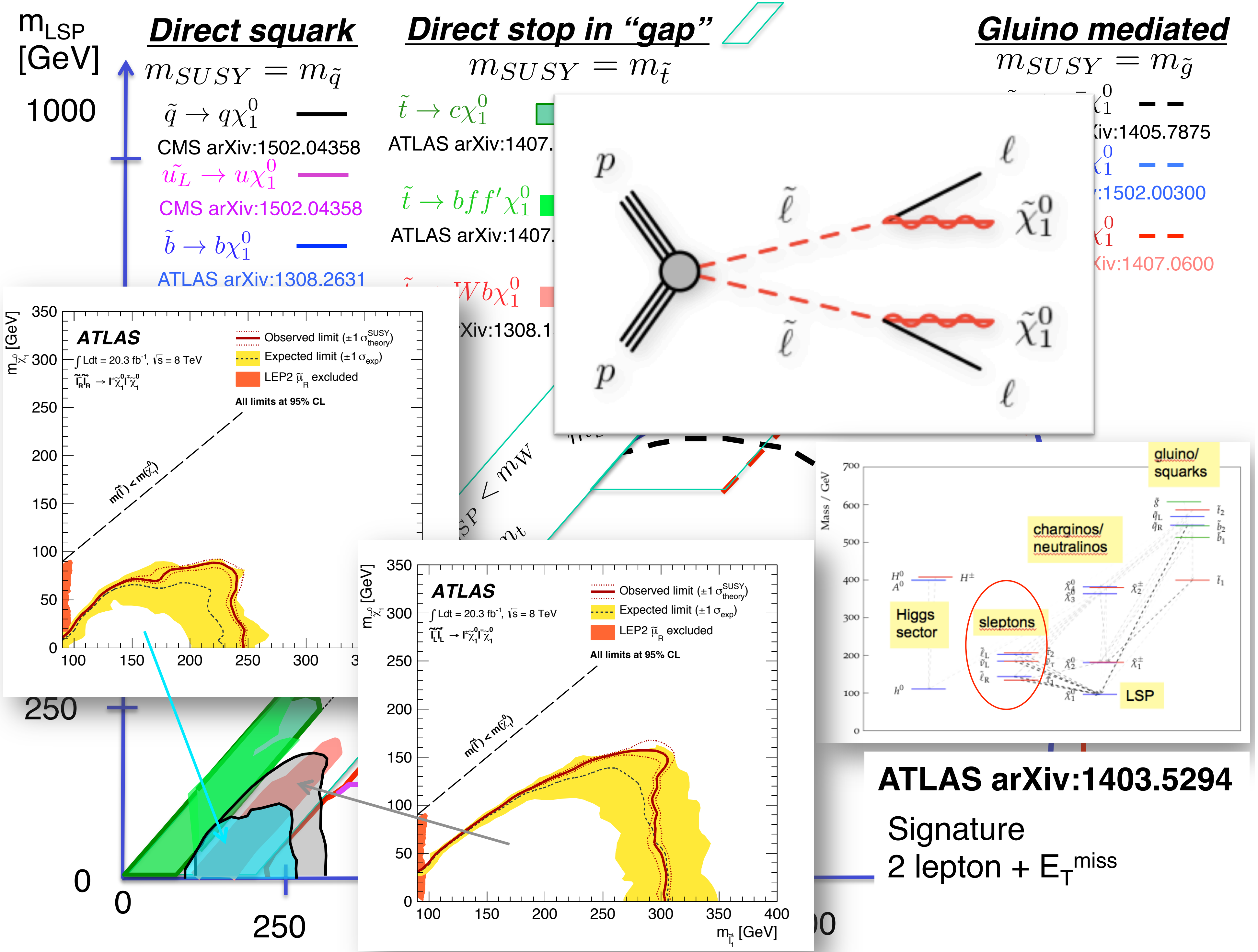
ATLAS arXiv:1407.0608
Mono-jet & c-tag combined

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

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

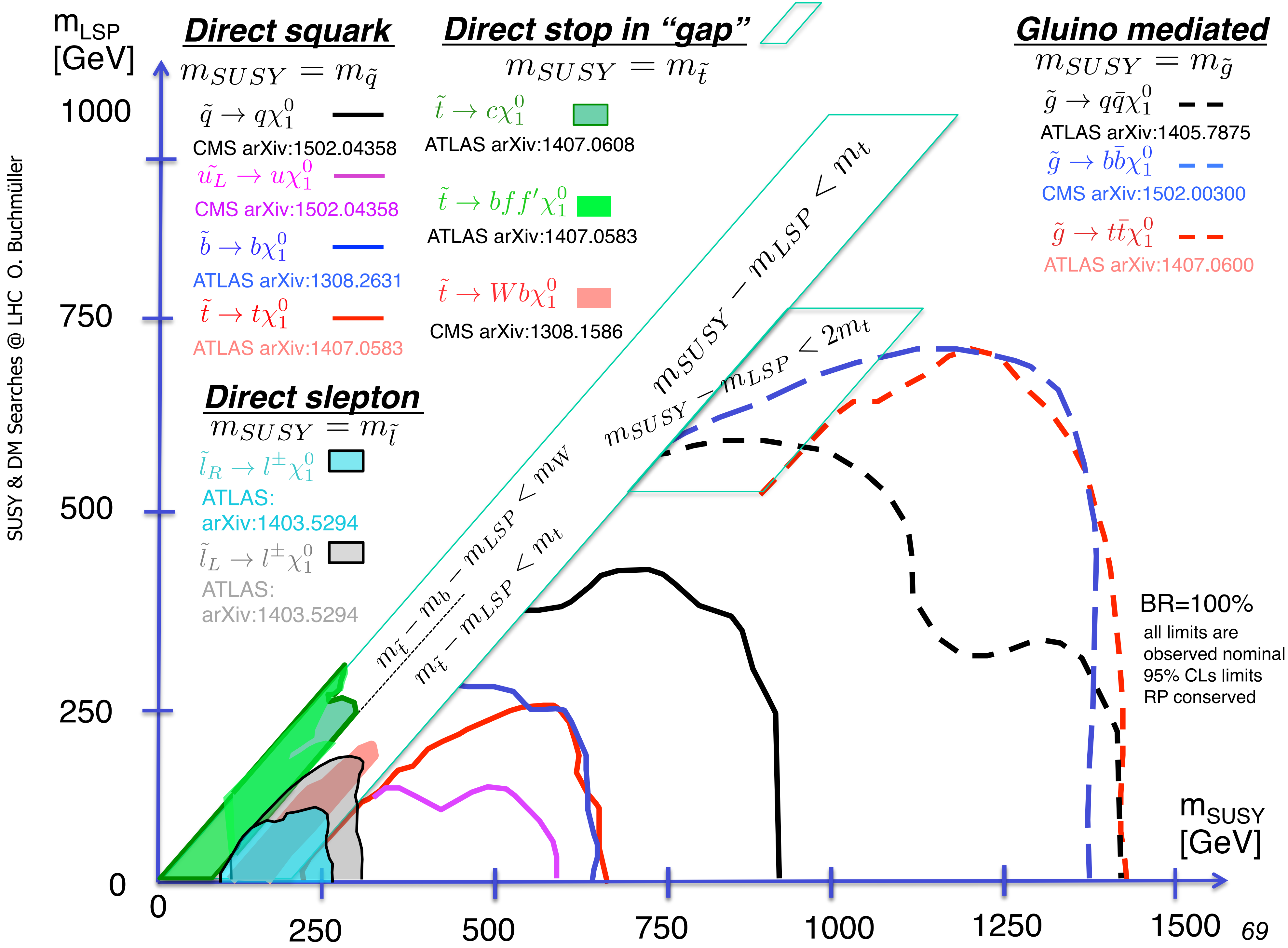


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
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
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
SUSY & DM Searches @ LHC O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]



ATLAS arXiv:1403.5294

Signature
2 lepton + E_T^{miss}



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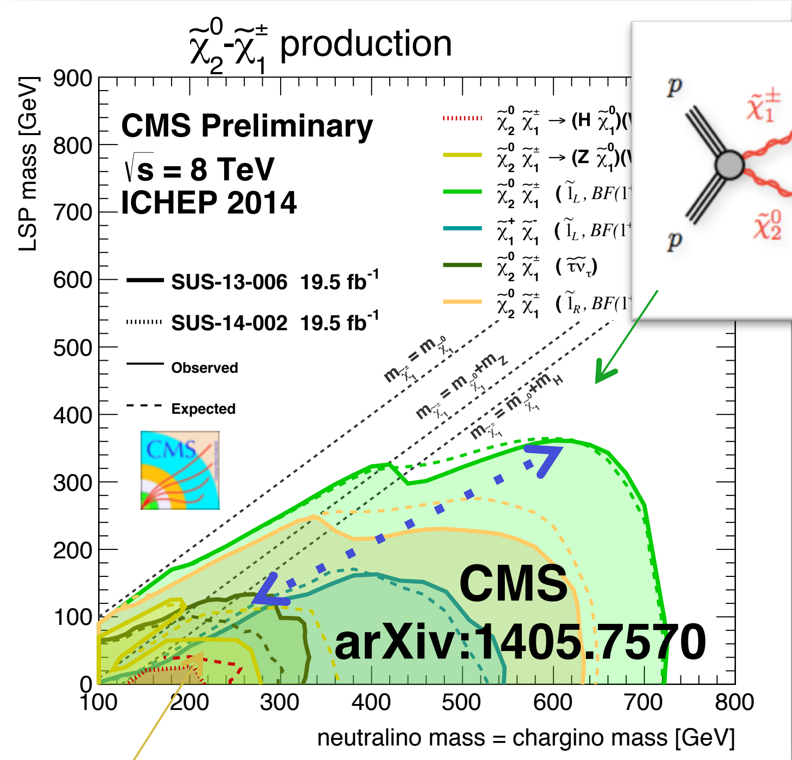
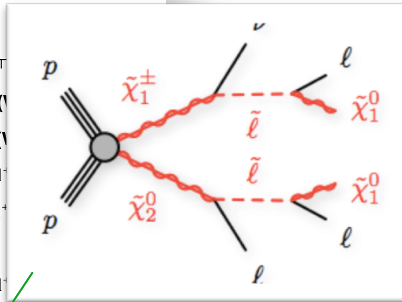
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
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
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

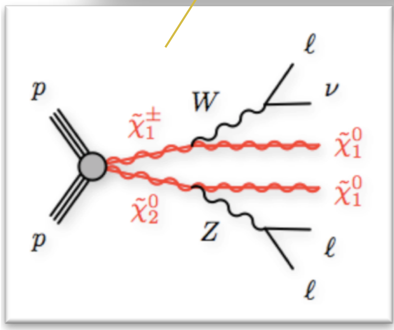
Direct chargino/neutralino production

DM Searches @ LHC O. Buchmüller

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





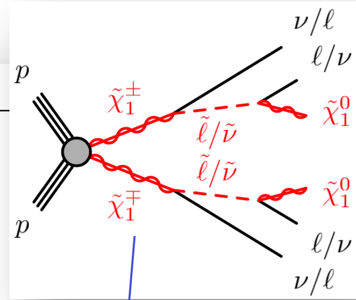


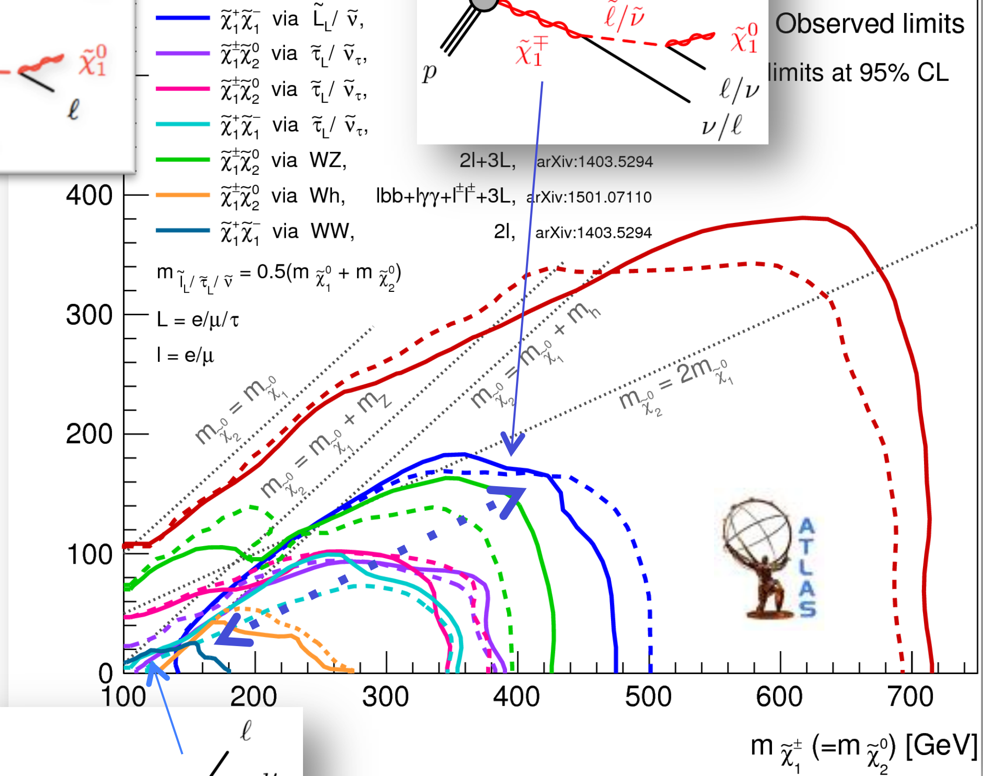
heavy slepton"hard(er)"

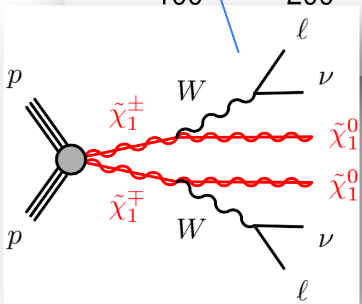
Add Z(l+l-)+2jets topology in bins of E_t^{miss} to increase sensitivity for "heavy" slepton case

$X_1^+ X_1^-$ production

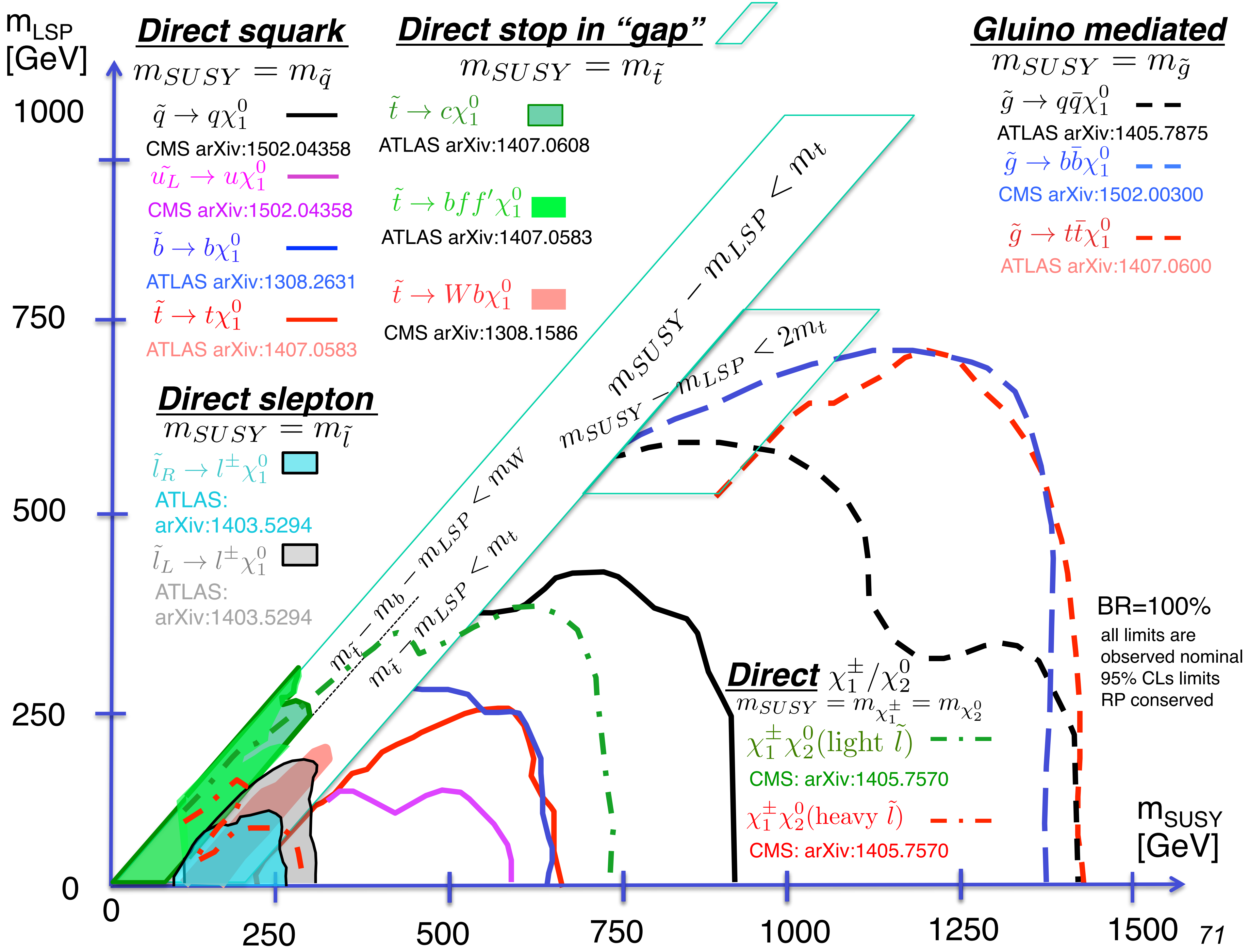
light slepton "easy"







ATLAS arXiv:1403.5294



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
$\tilde{g} \to t\bar{t}\chi_1^0$
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Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
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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
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
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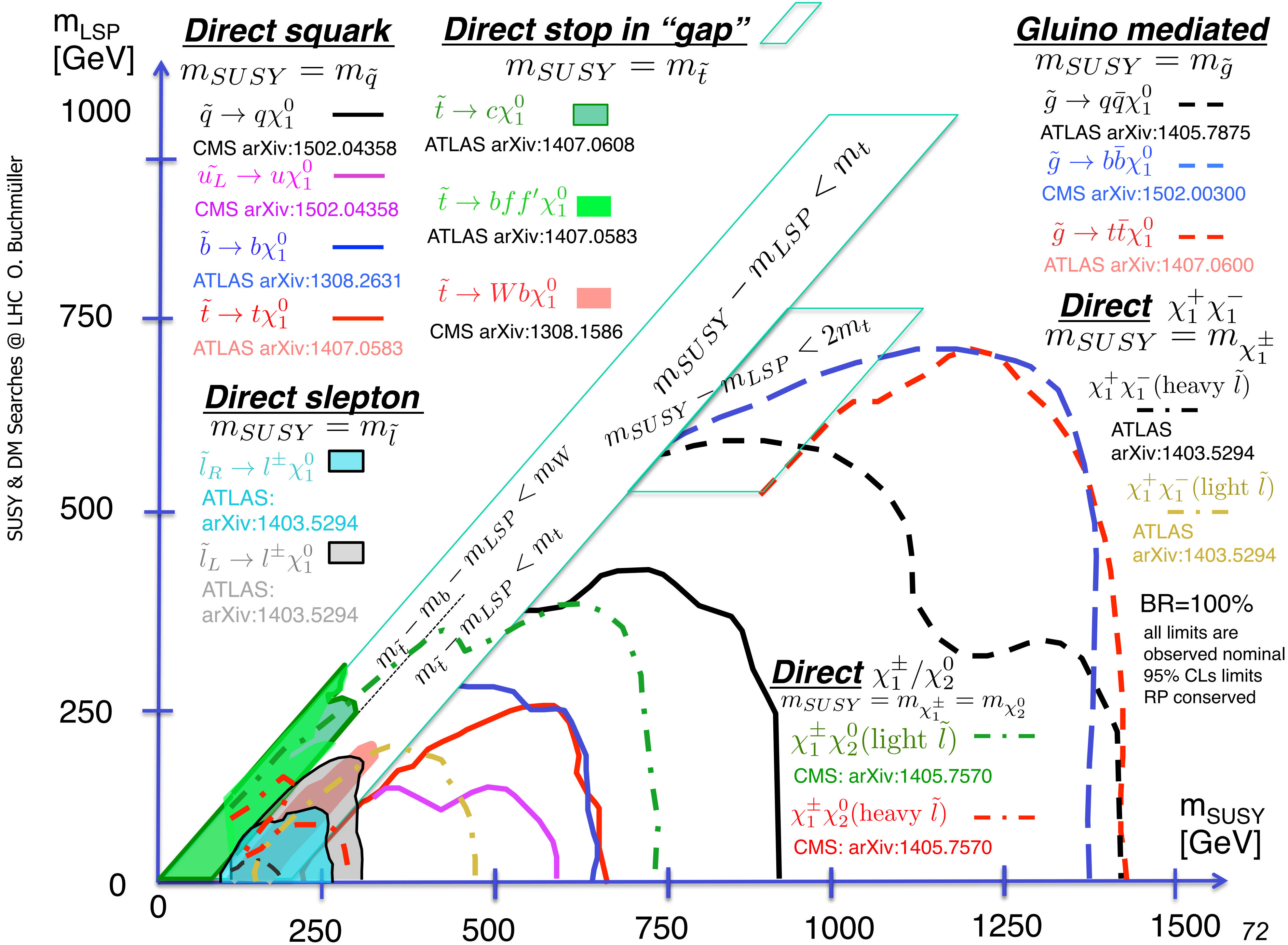
CMS: arXiv:1405.7570
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500



SUSY & DM Searches @ LHC O. Buchmüller
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$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
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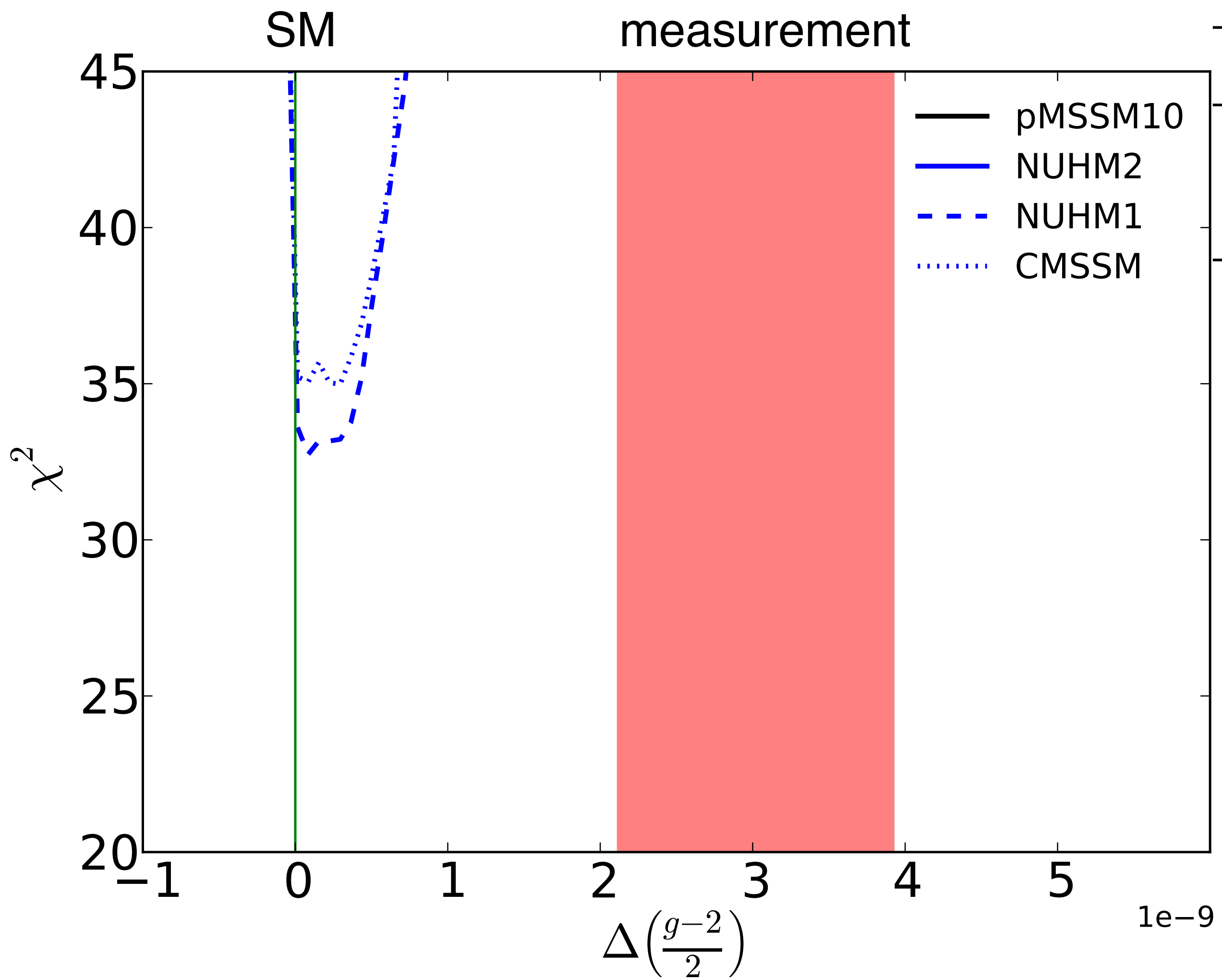
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500

MASTERCODE

Resolving tension (g-2) and LHC

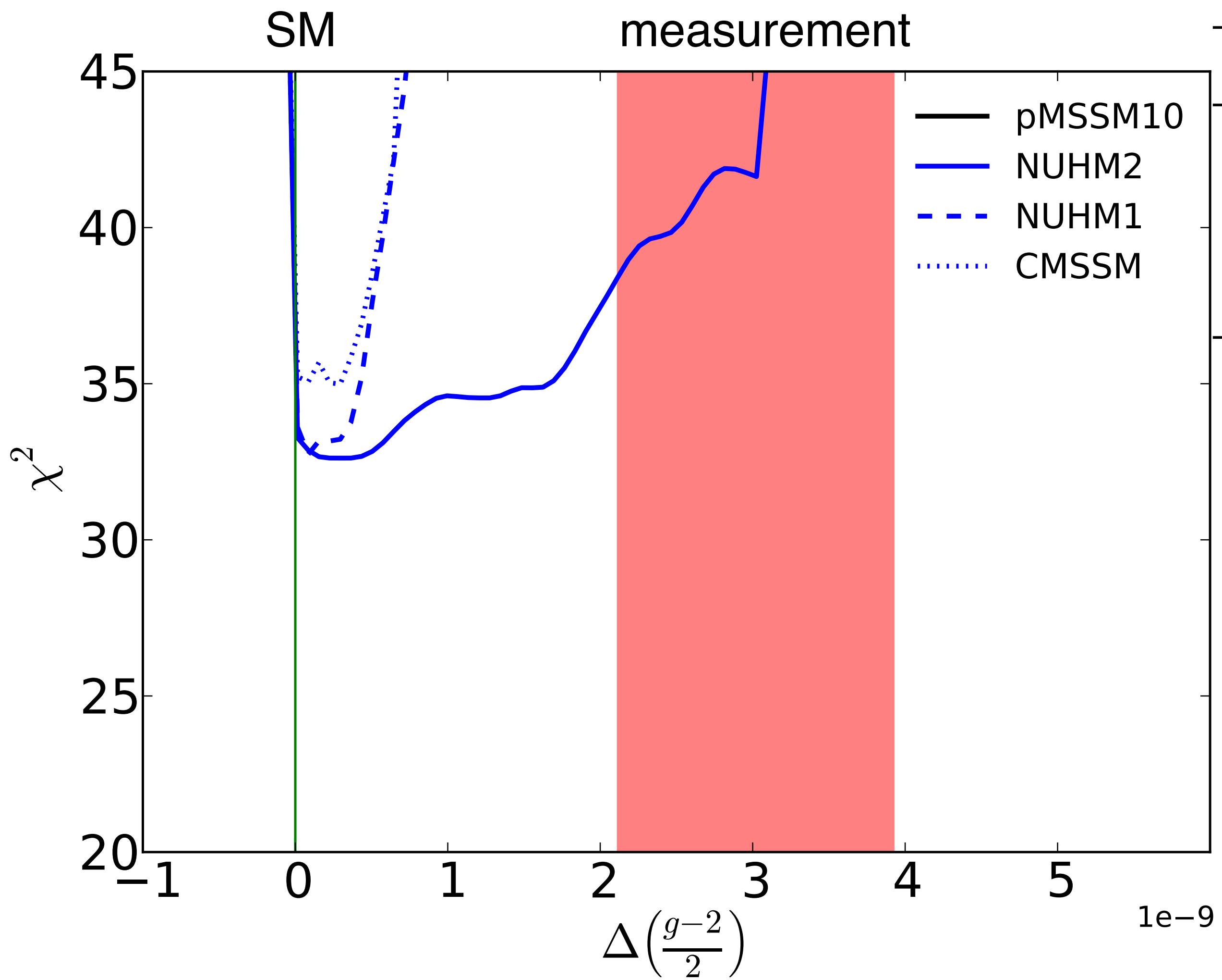


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

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

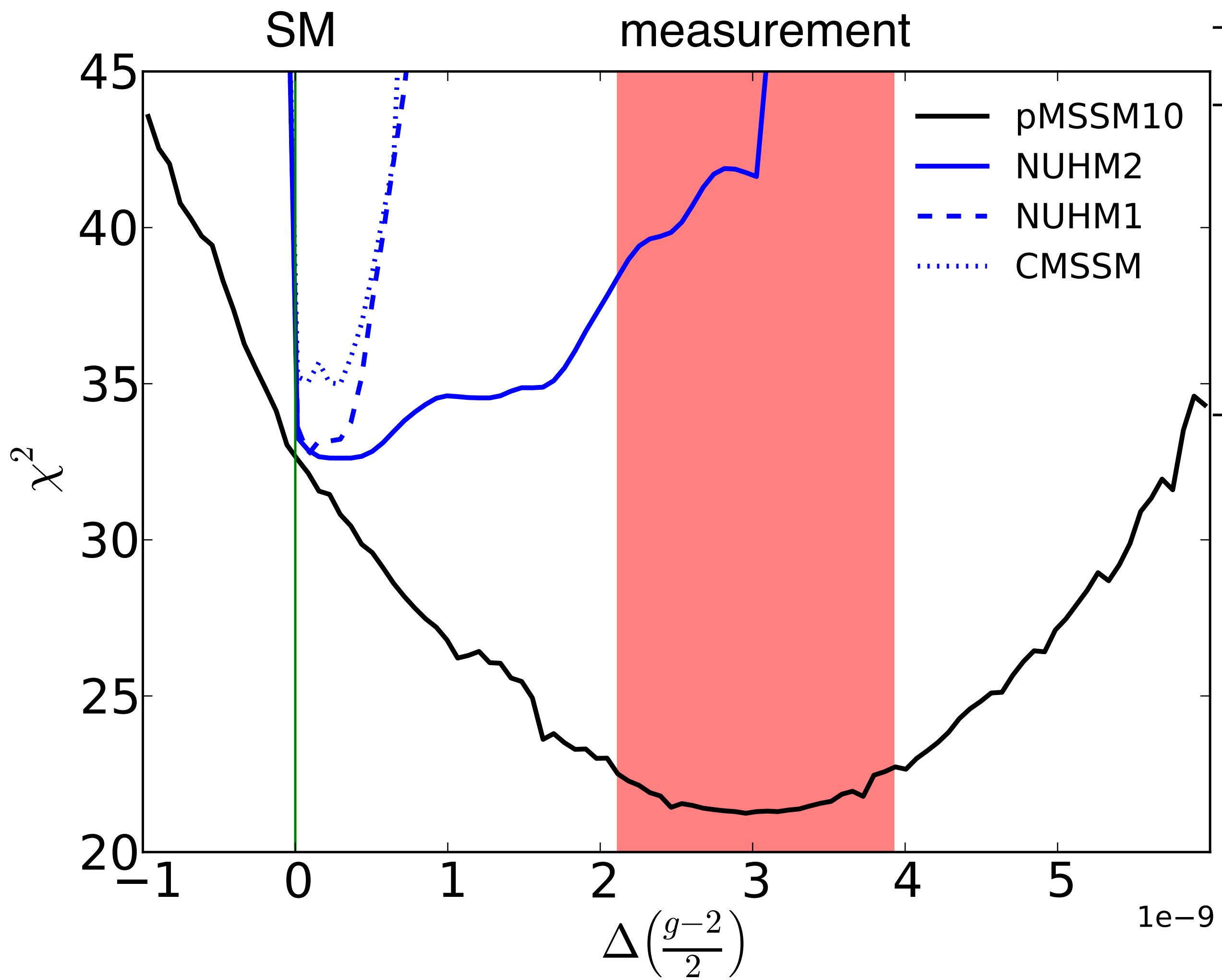


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

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

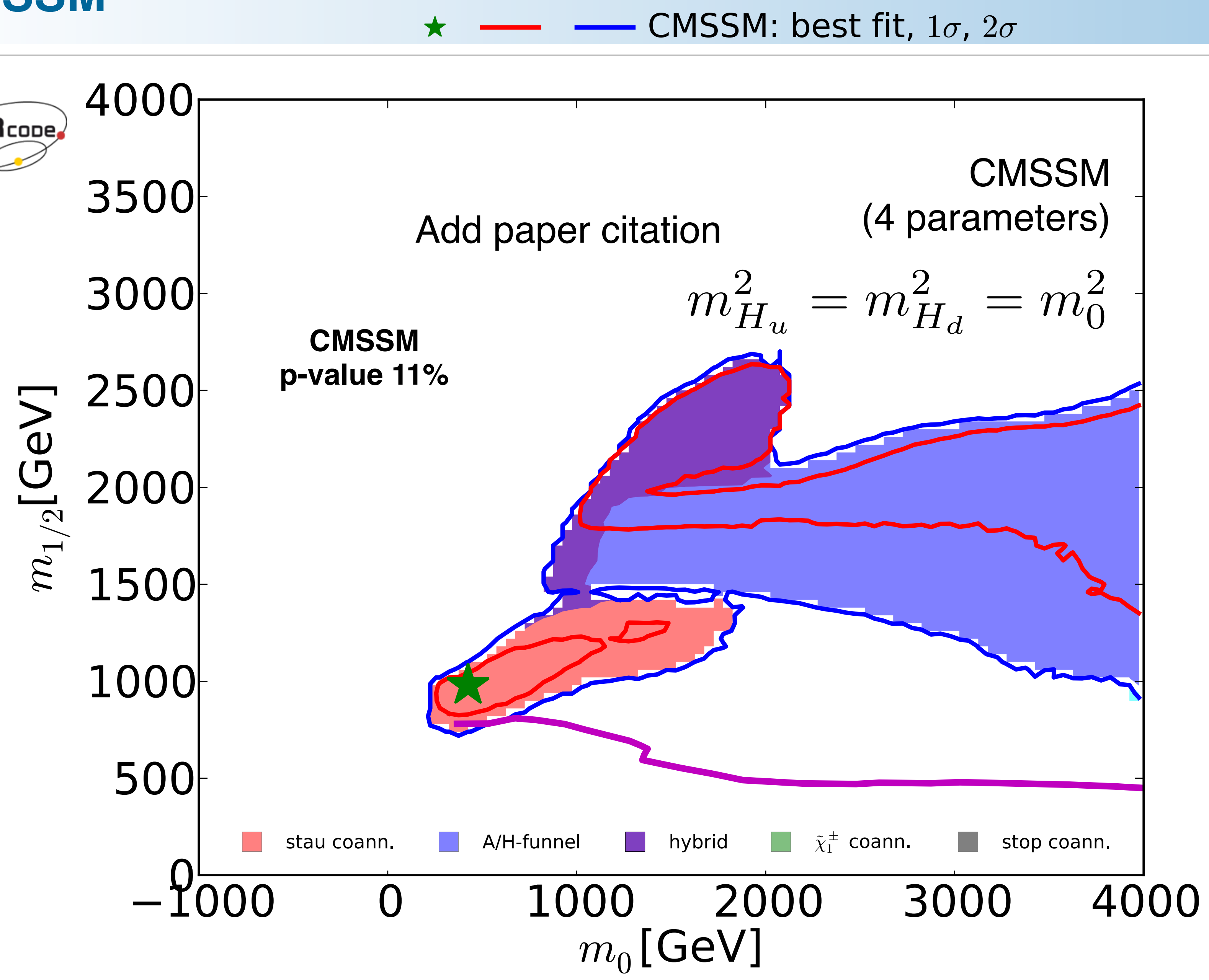


	χ^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	**20.5/18**	**31 %**

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



From MasterCode papers:
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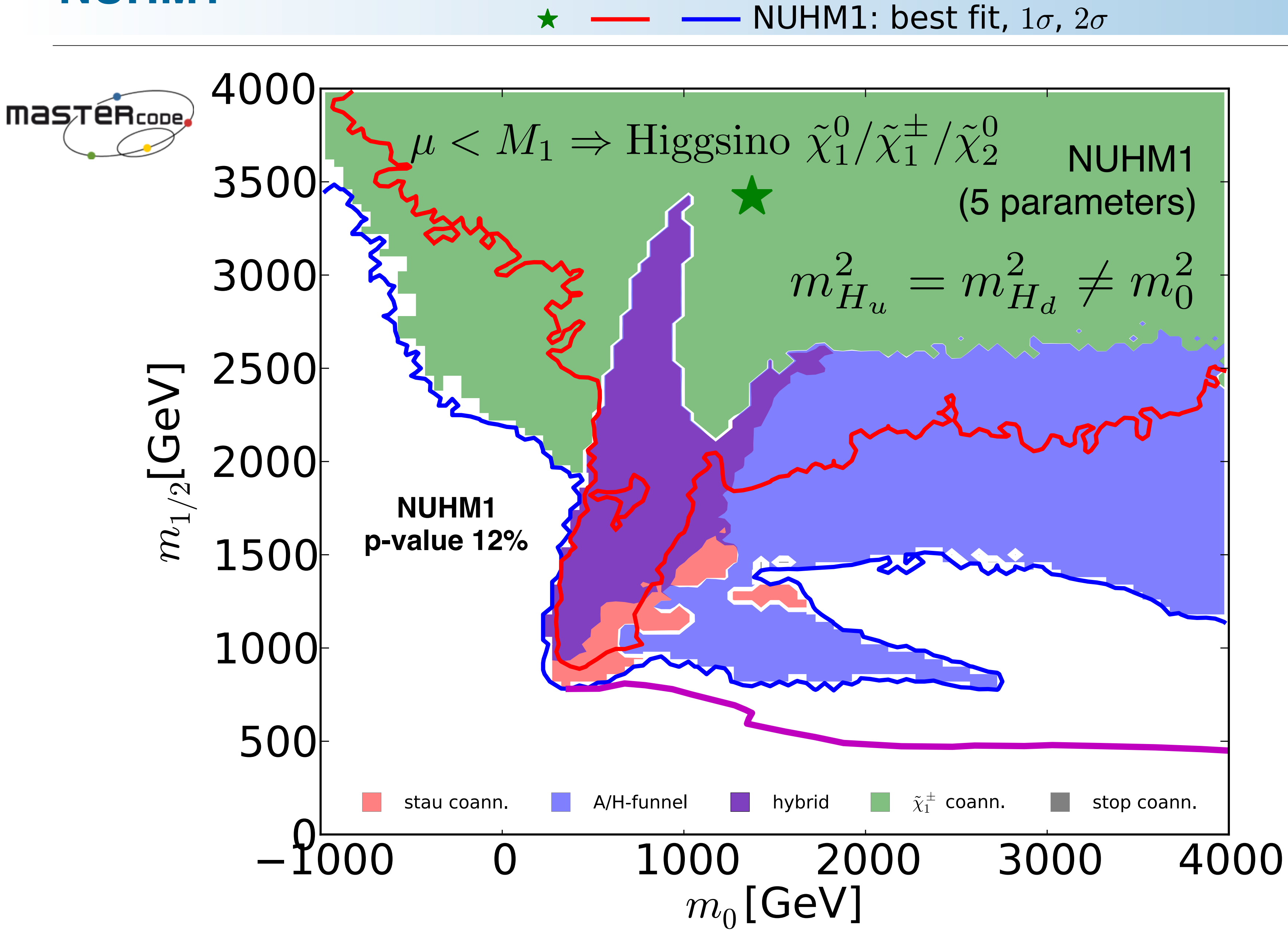
NUHM1



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NUHM2

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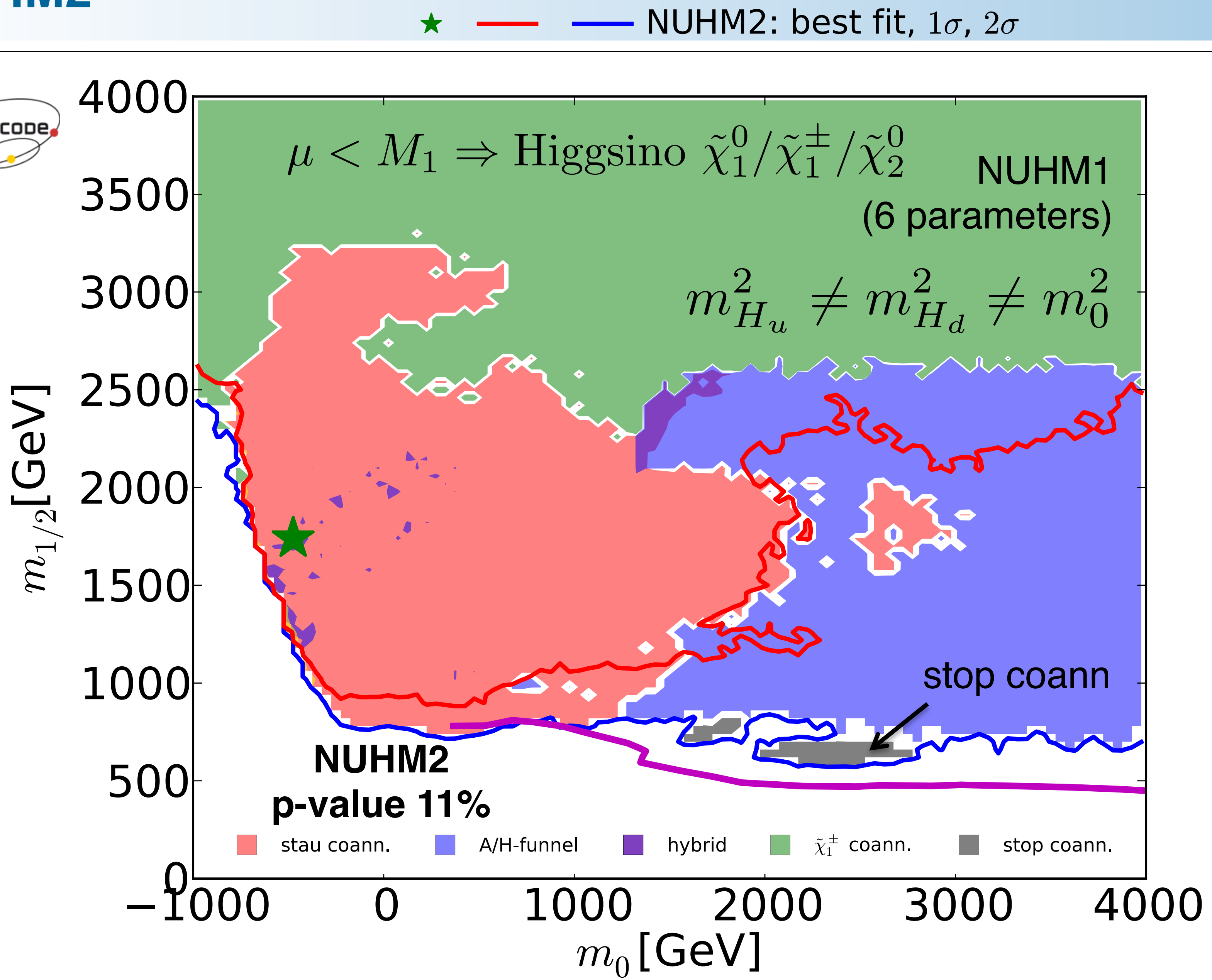


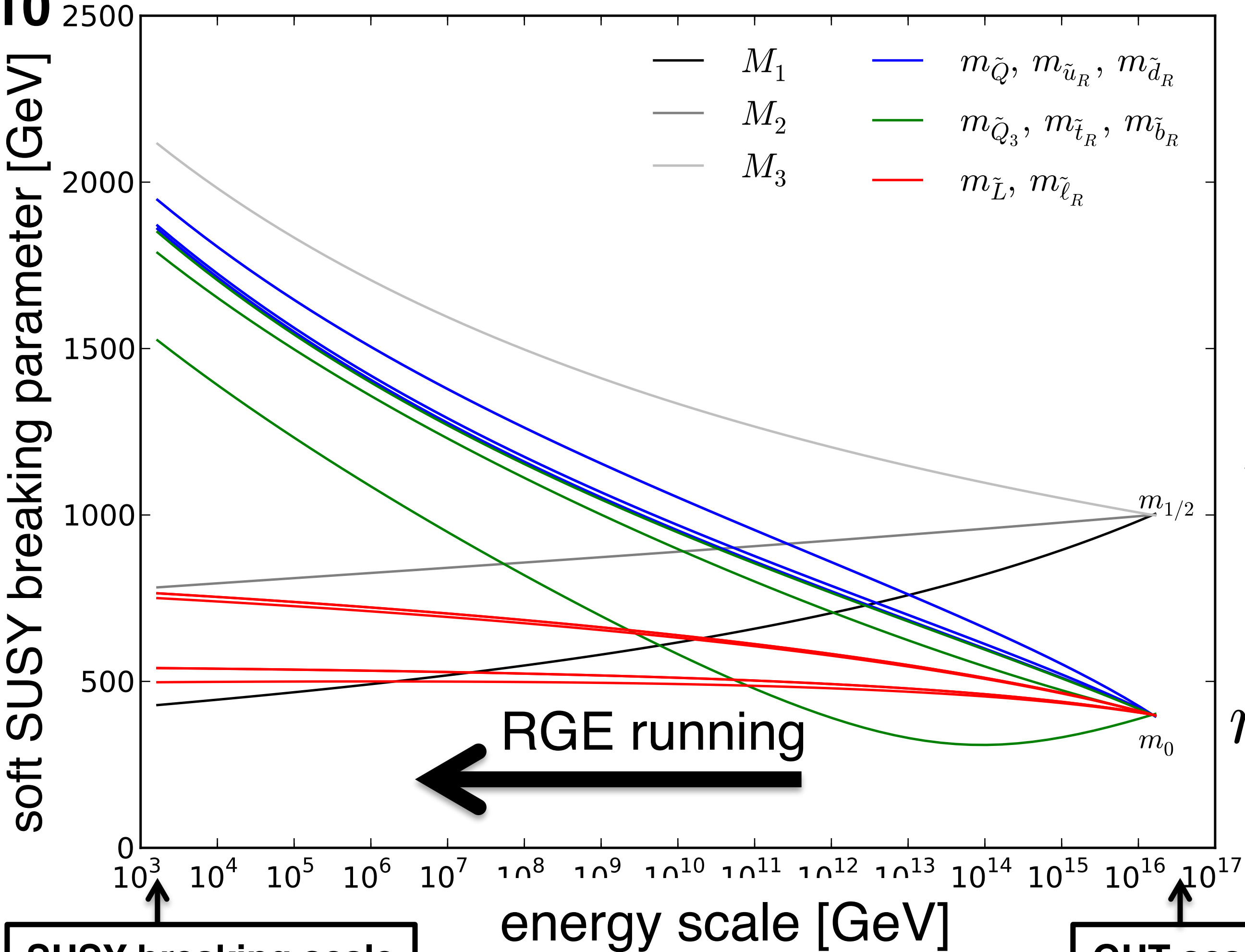
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

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

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

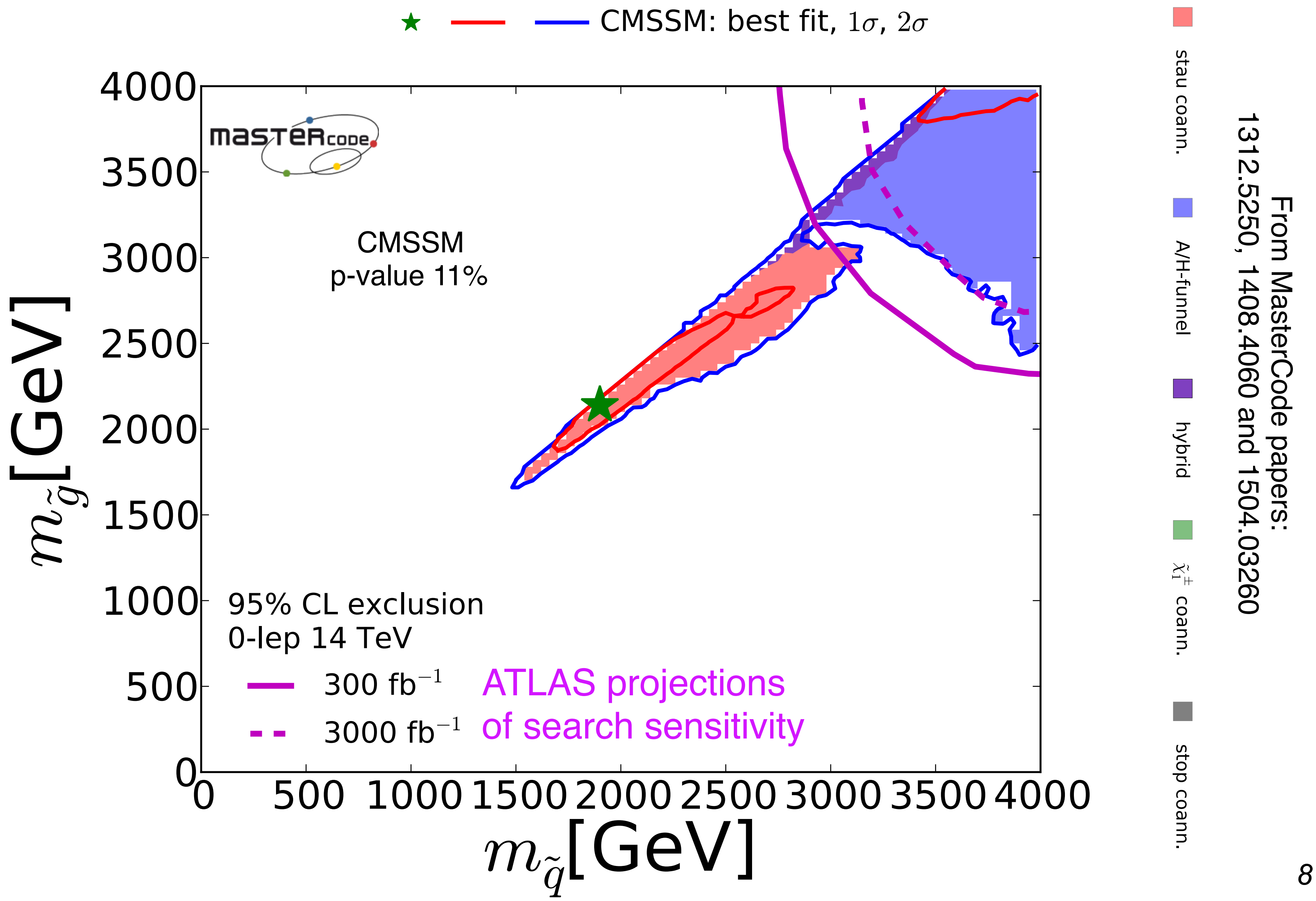
NUHM1

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

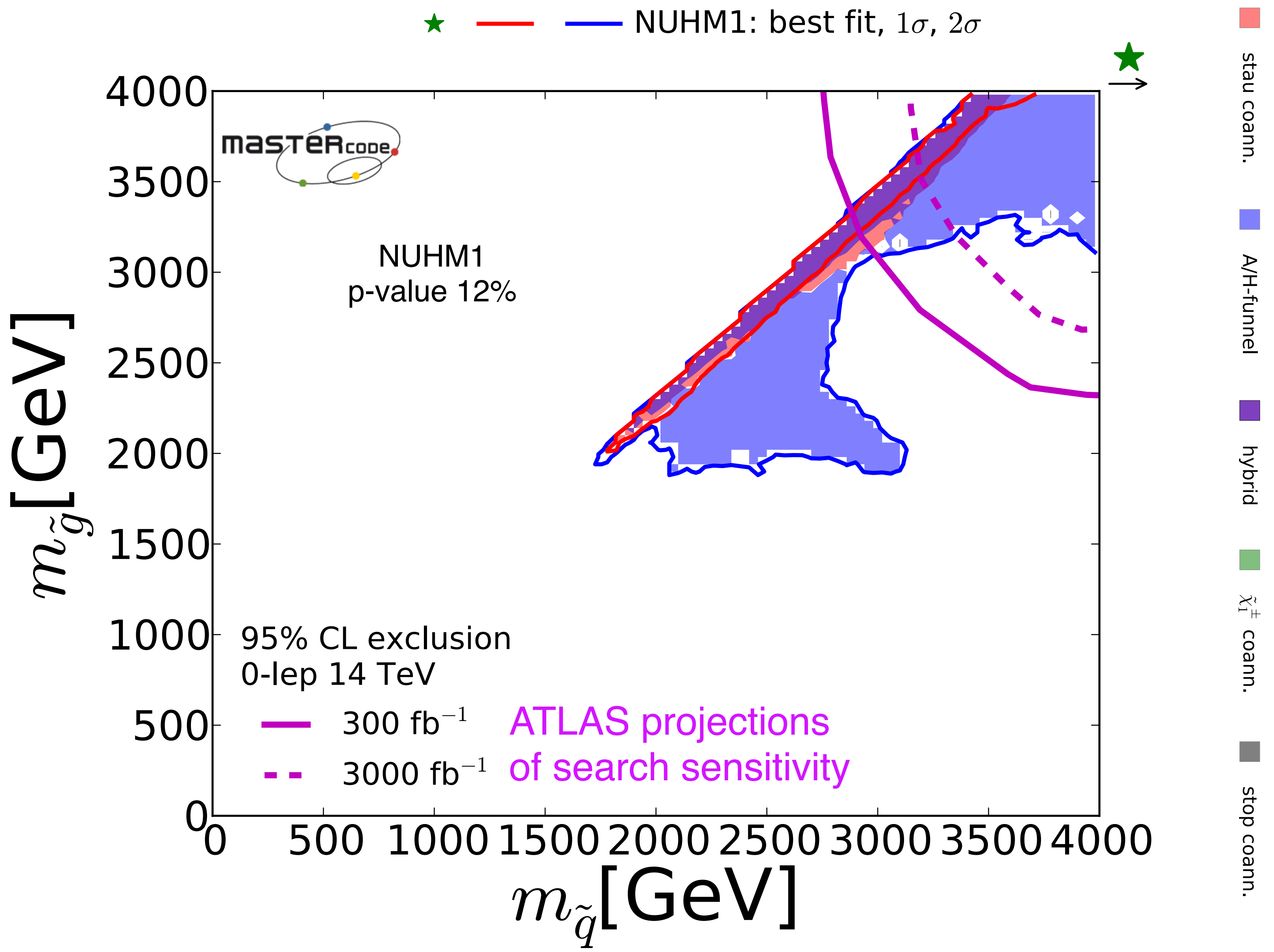
NUHM2

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

CMSSM Today: Mq-Mg Search plane

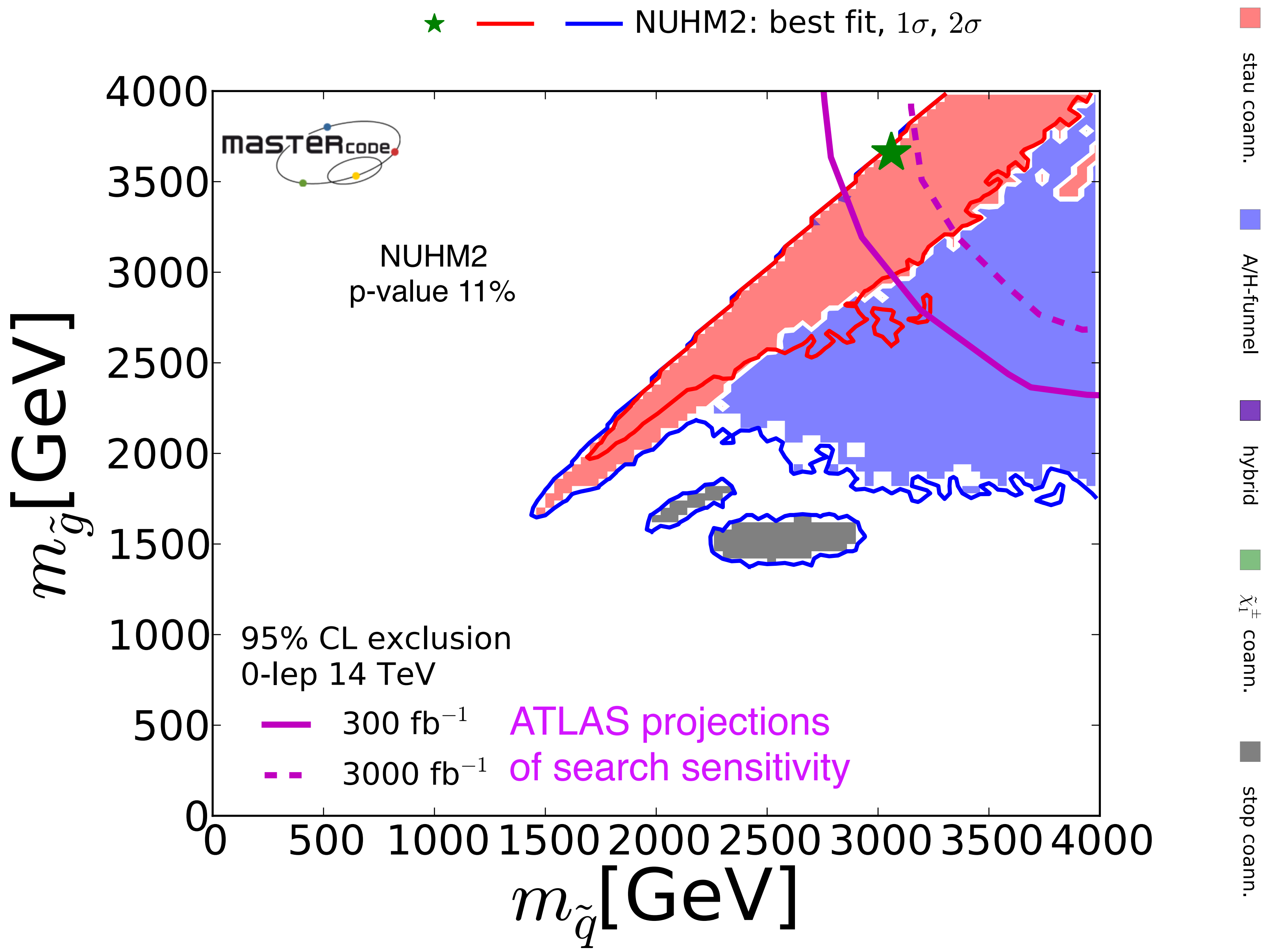


CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



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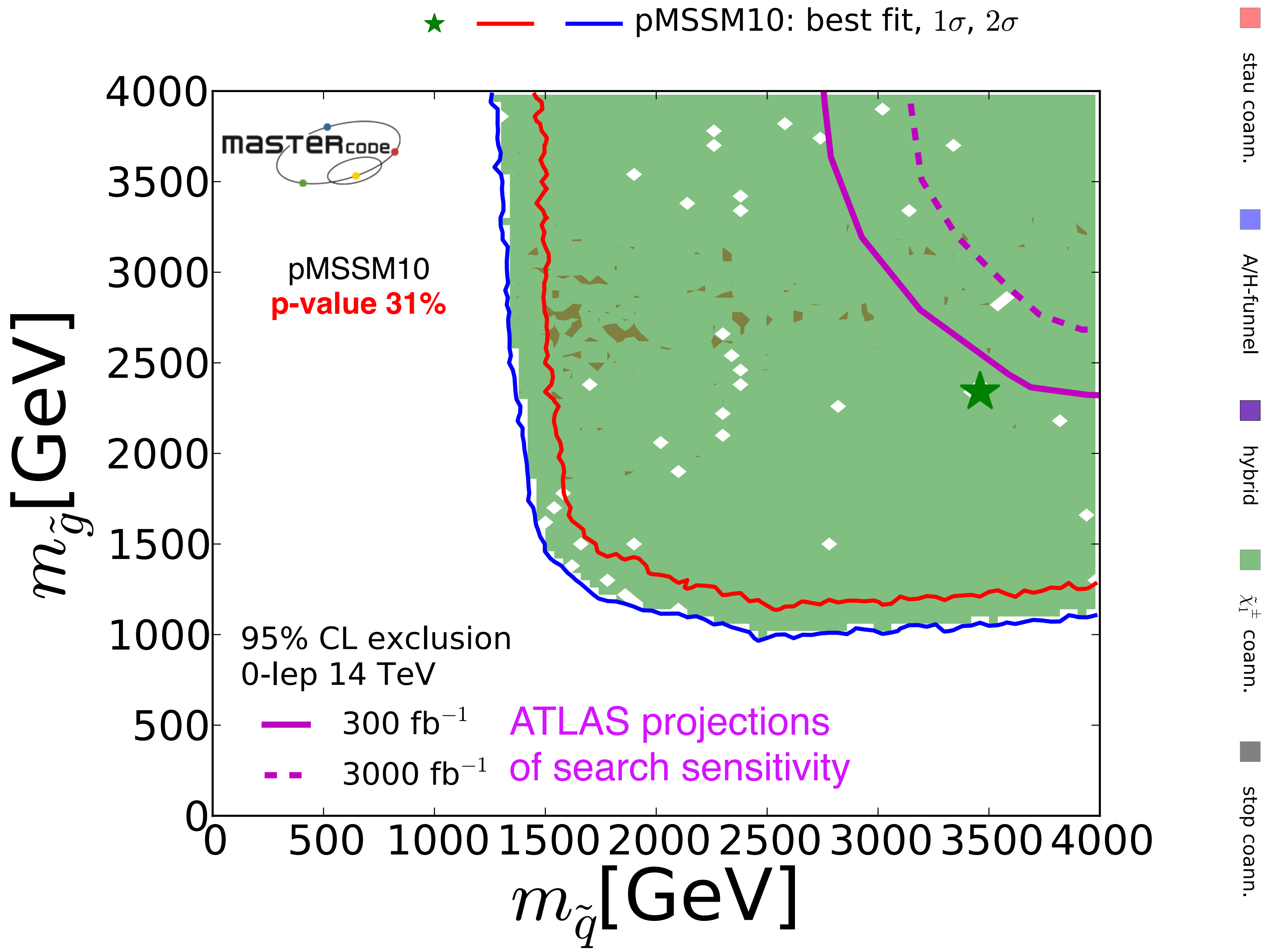
1312.5250, 1408.4060 and 1504.03260

Imperial College London

CMSSM Today: Mq-Mg Search plane



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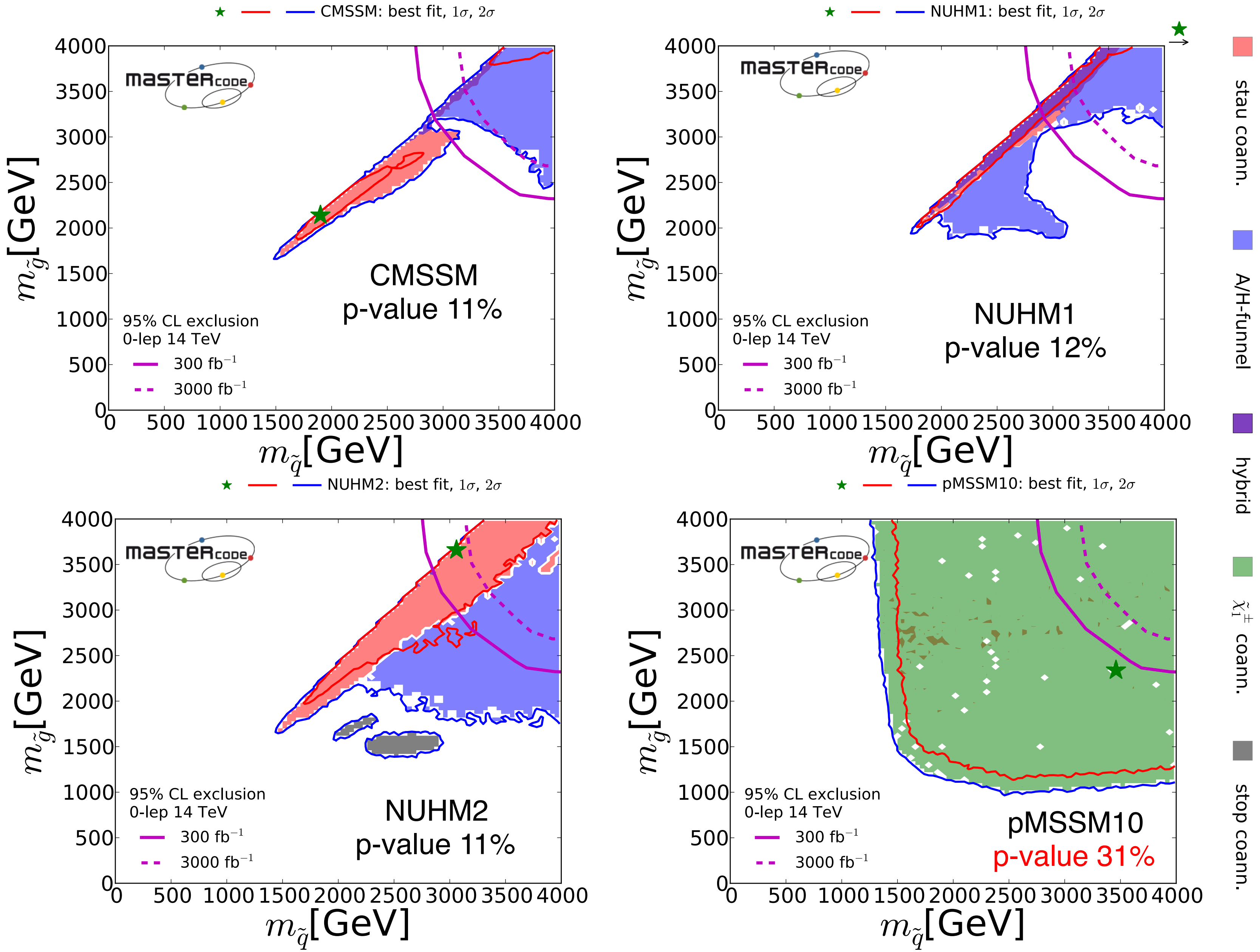
Models in Comparison in "Mq-Mg Search plane"



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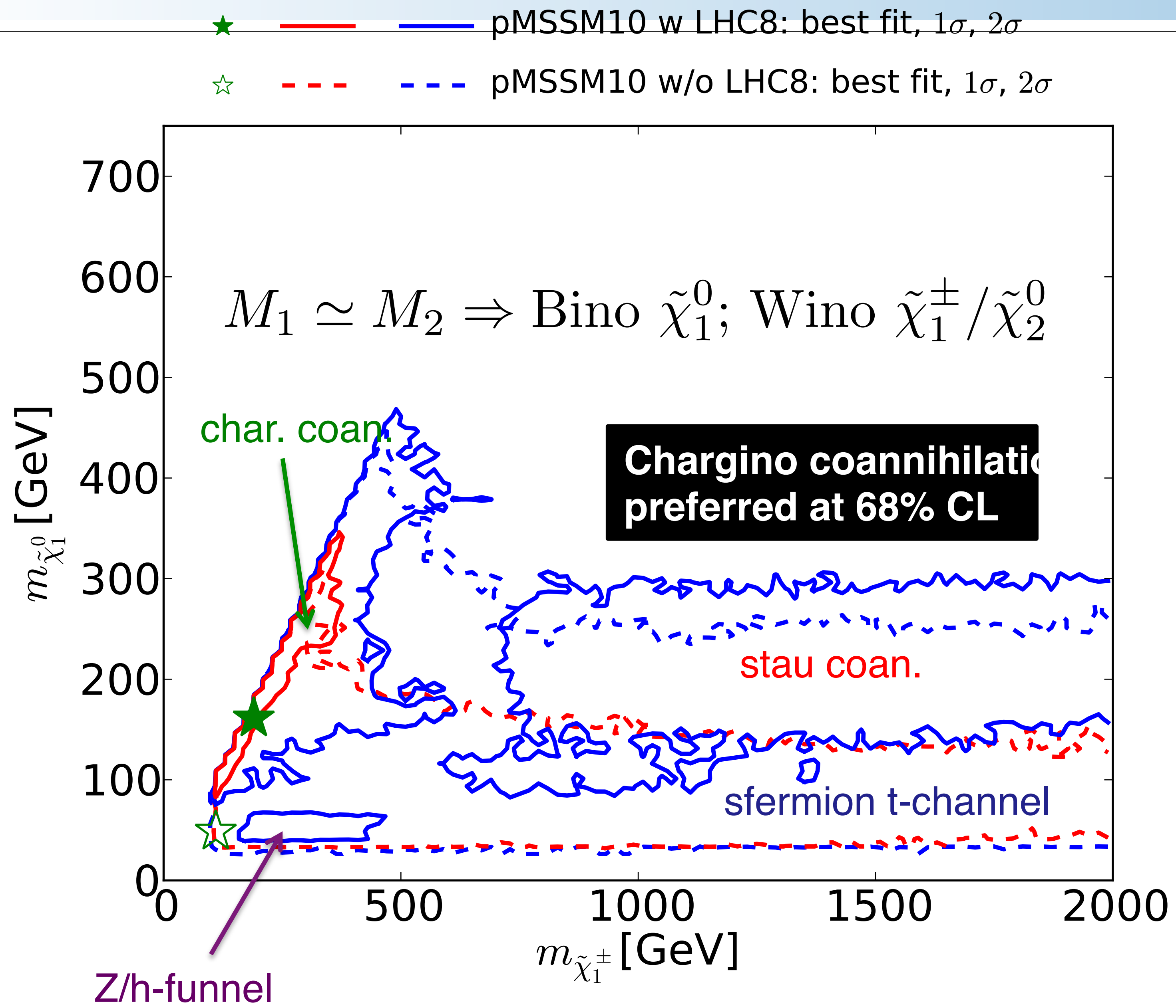
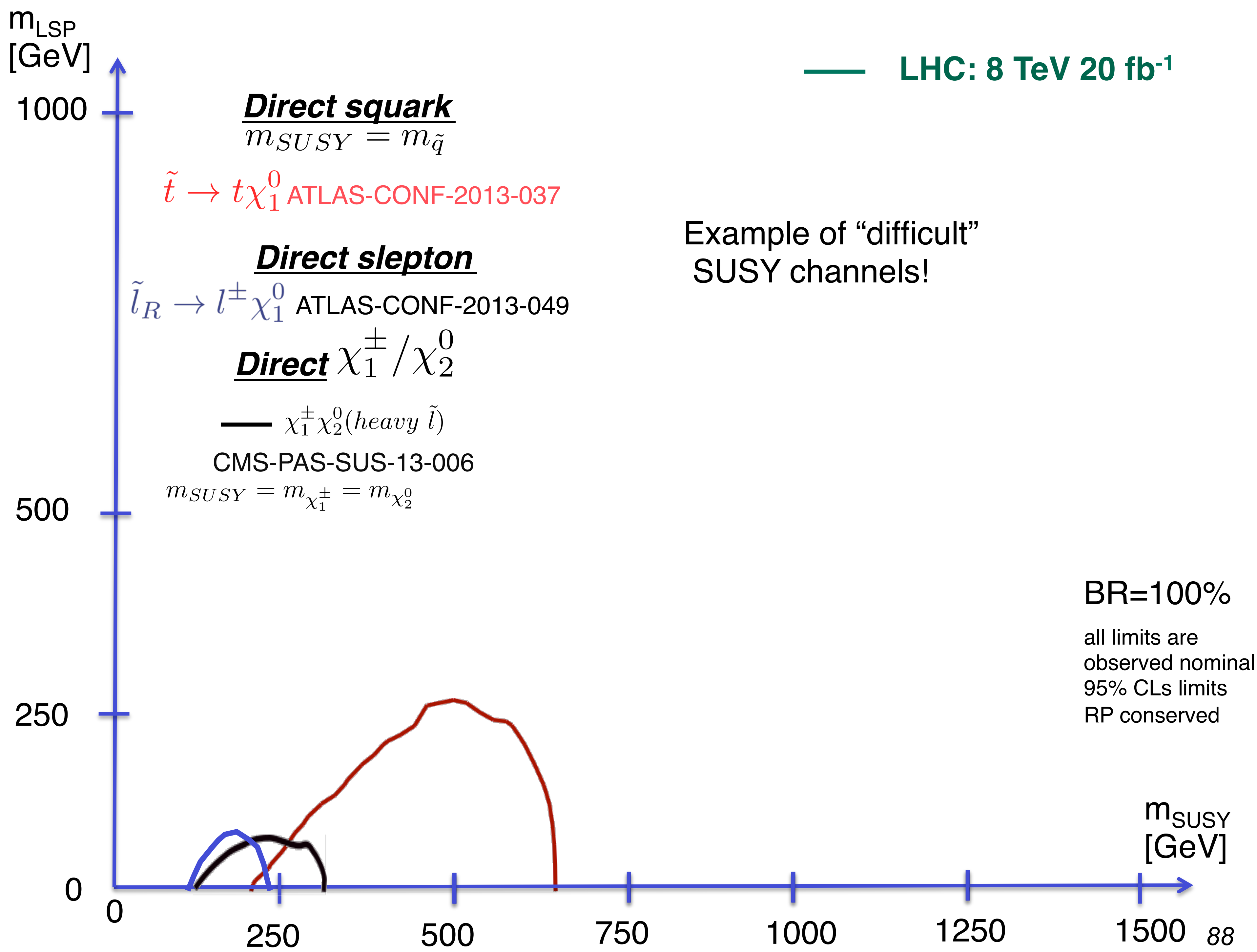
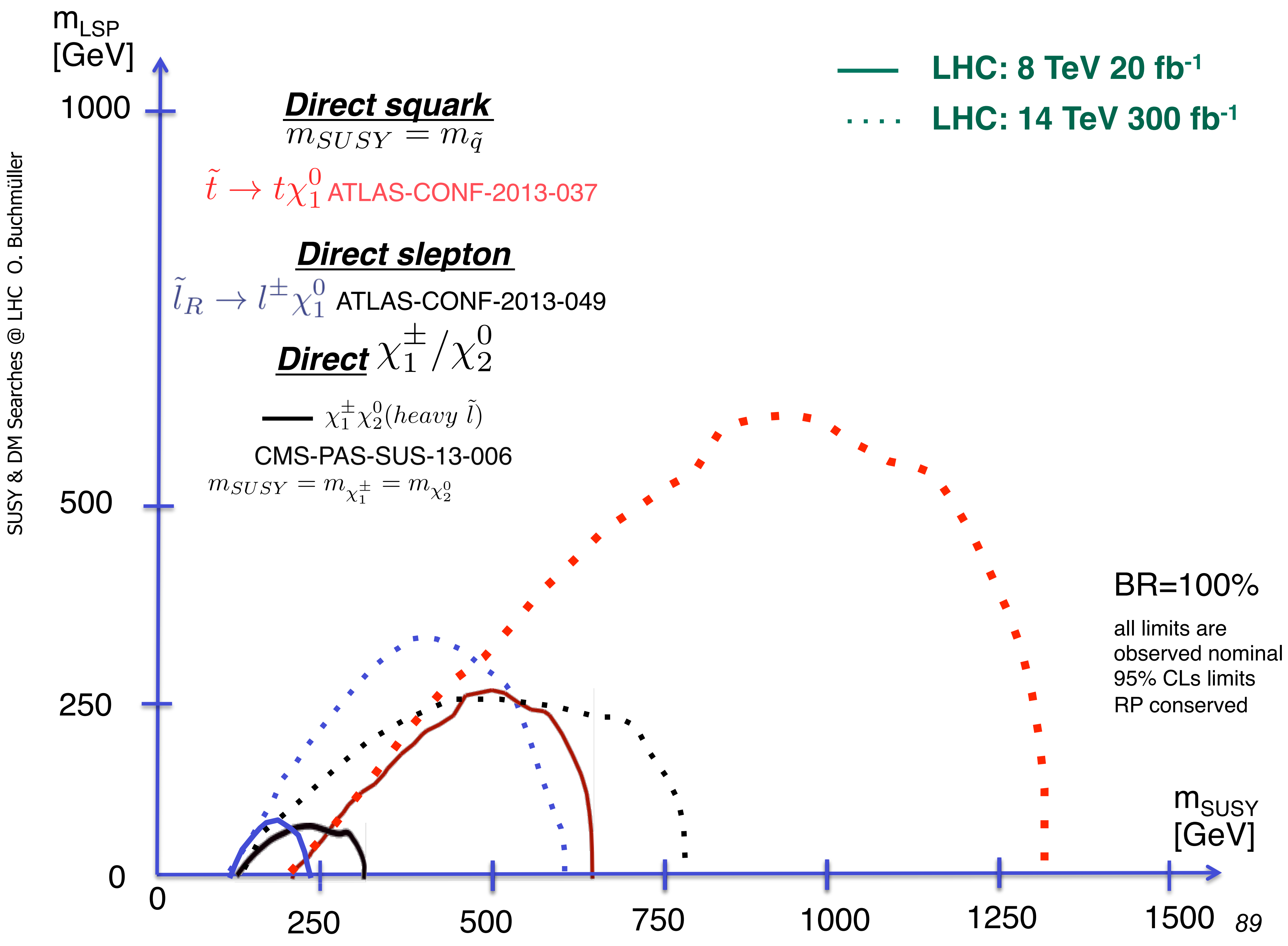
pMSSM10: parameter space



SUSY PROJECTION OF DIFFICULT CHANNELS



m_{LSP} [GeV]
1000
500
250
0
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_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



m_LSP [GeV]
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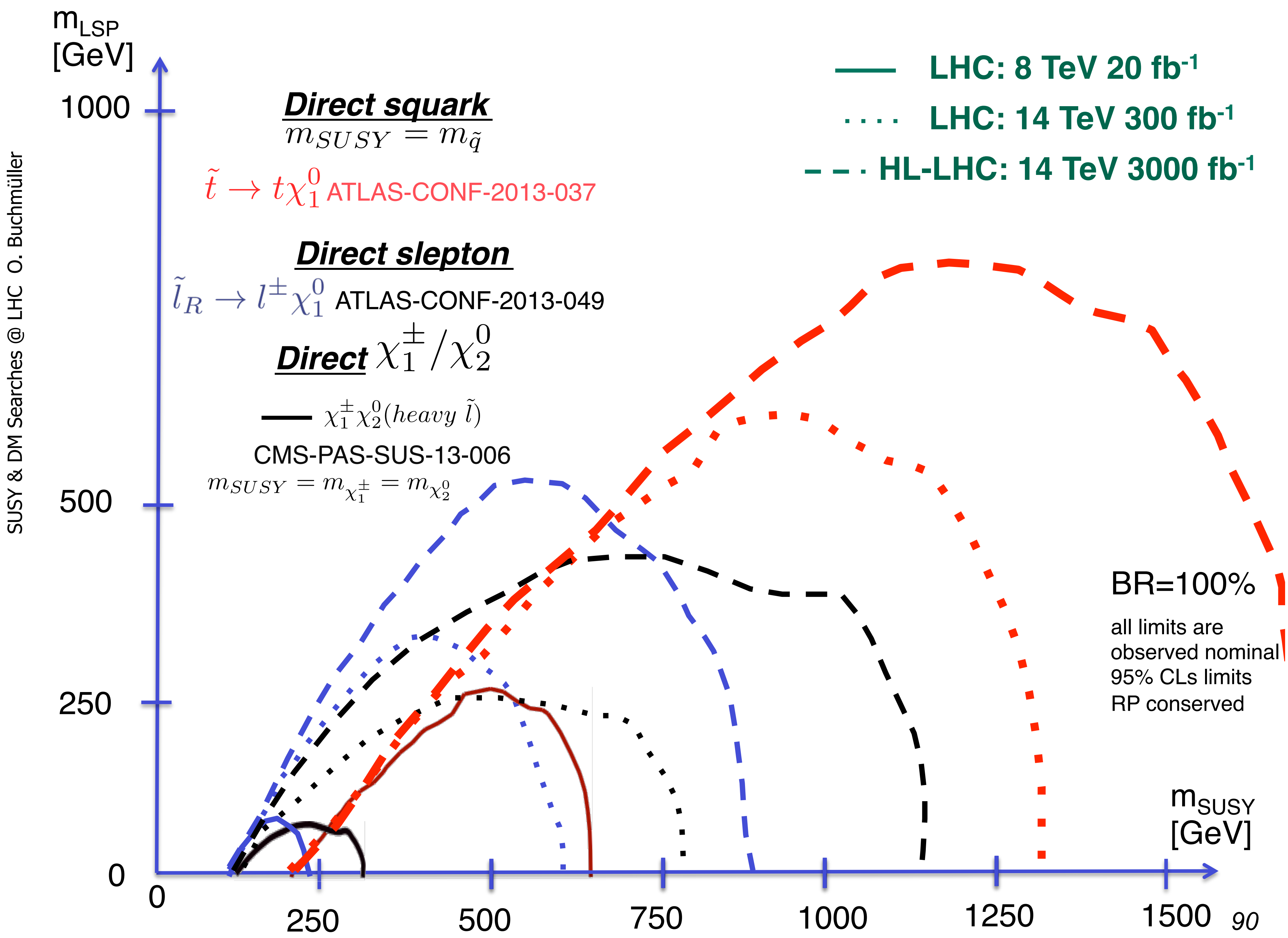
SUSY & DM Searches @ LHC O. Buchmüller



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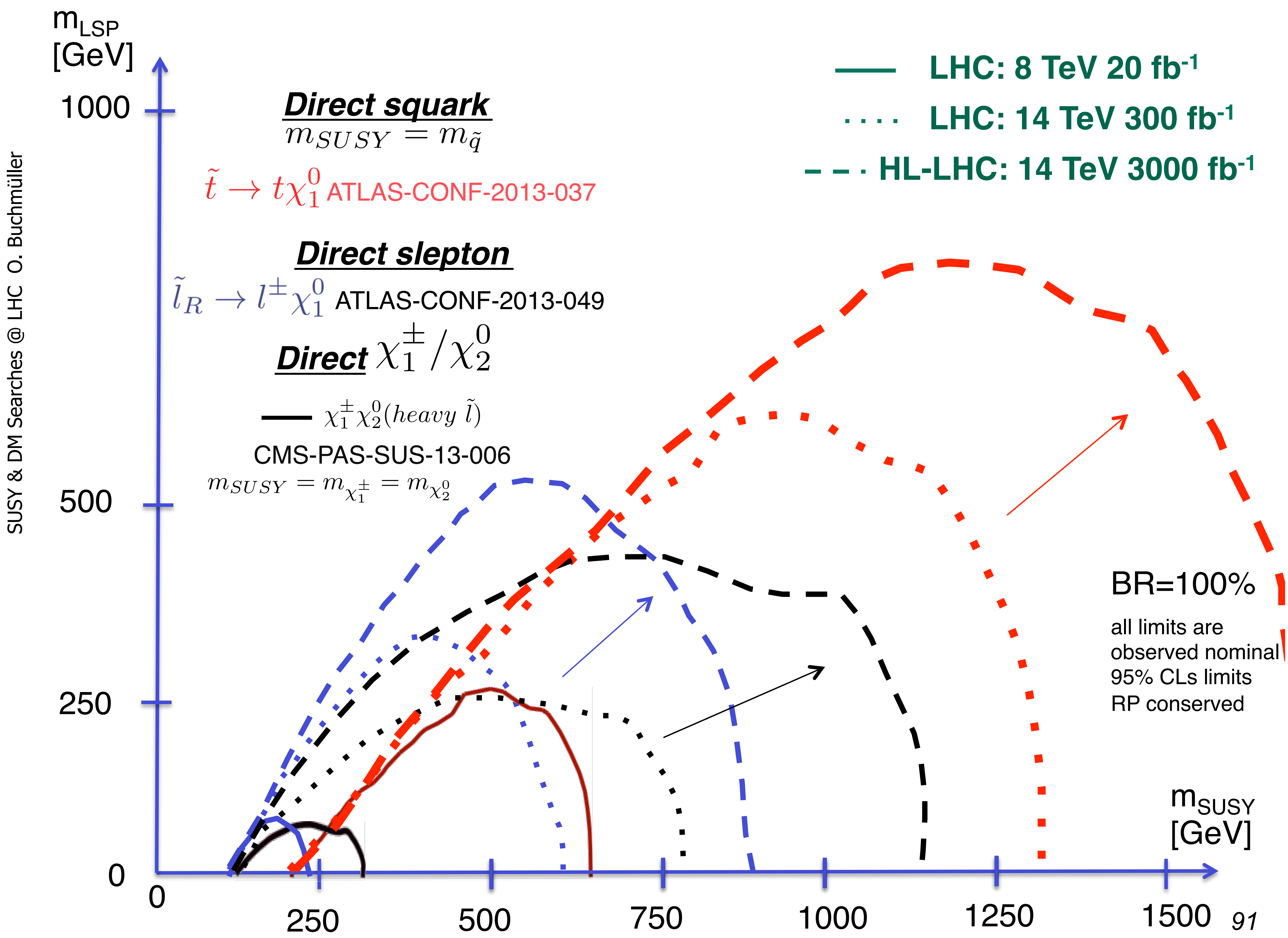
SUSY & DM Searches @ LHC O. Buchmüller
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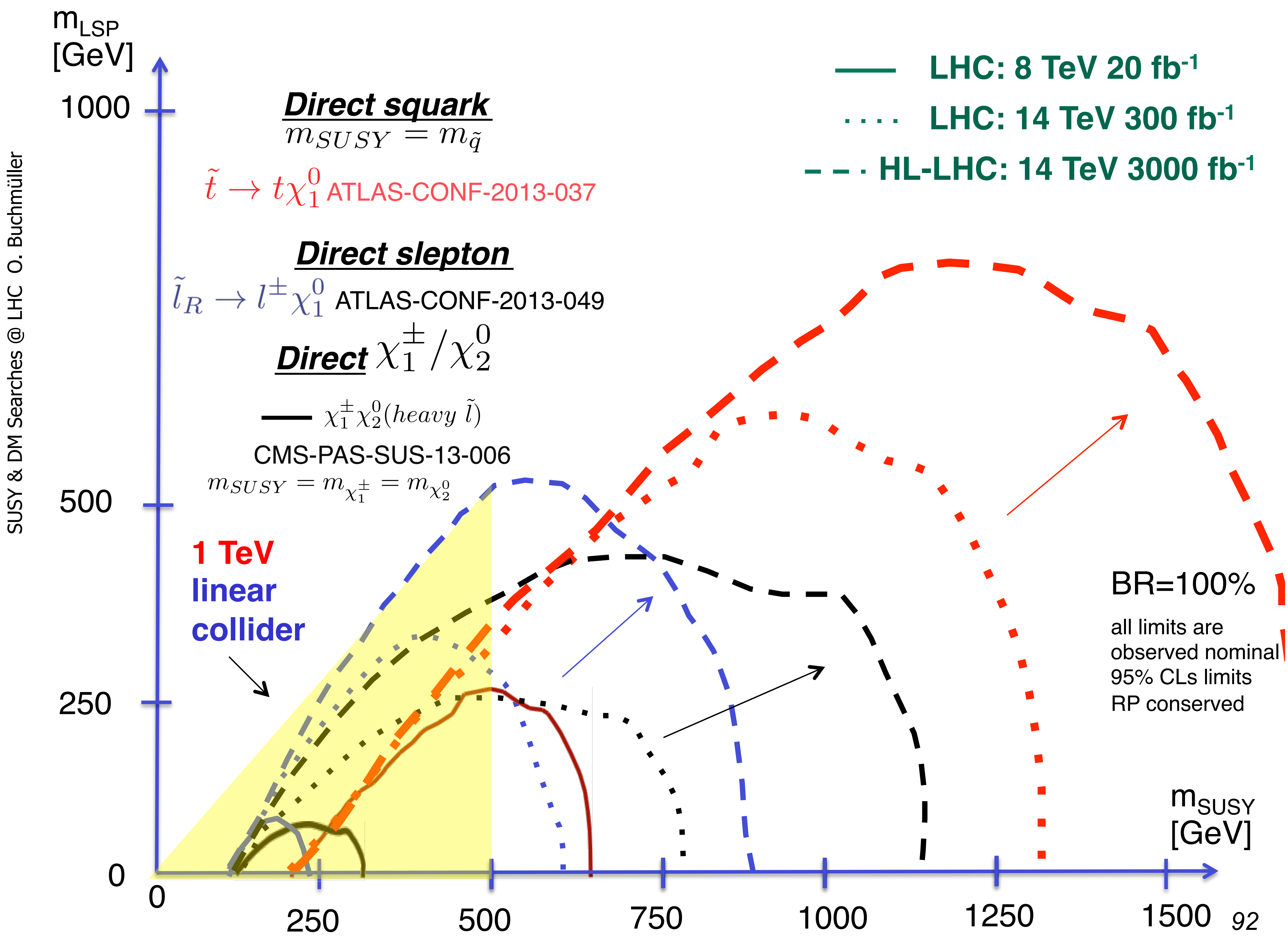

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1 TeV linear collider
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0
250
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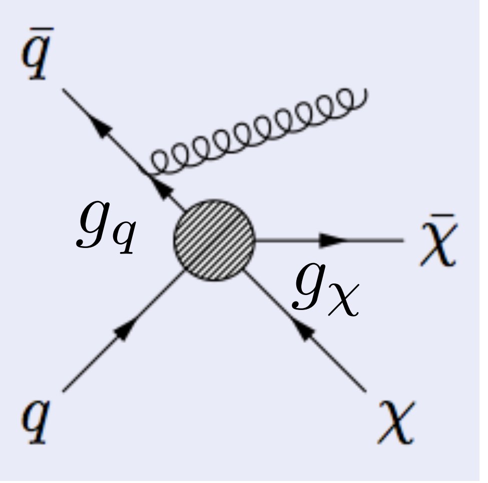
1000
1250
1500

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:

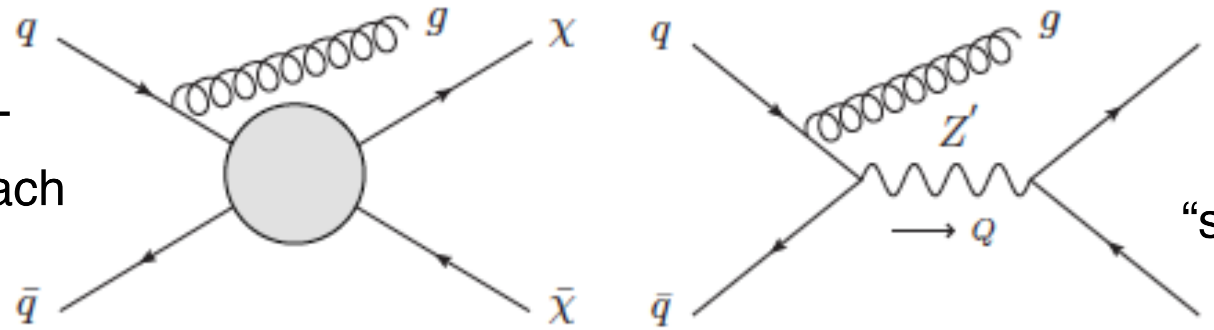
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Validity of Effective Field Theory Limits

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

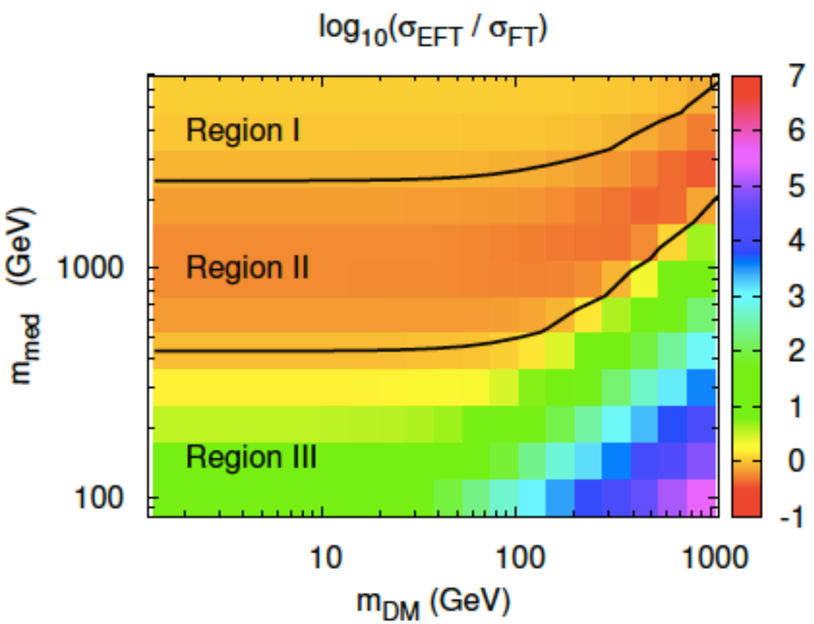
- Compare Effective Field Theory (EFT) with Full Theory (FT)

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!

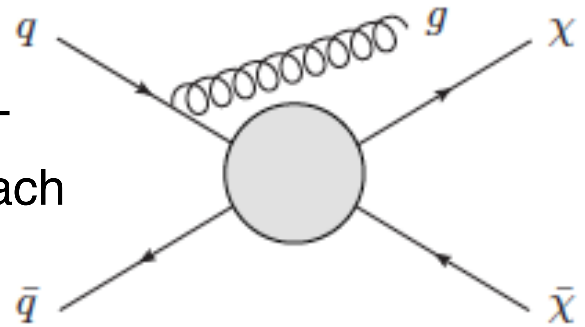
Region III: EFT yields significant stronger limits then FT

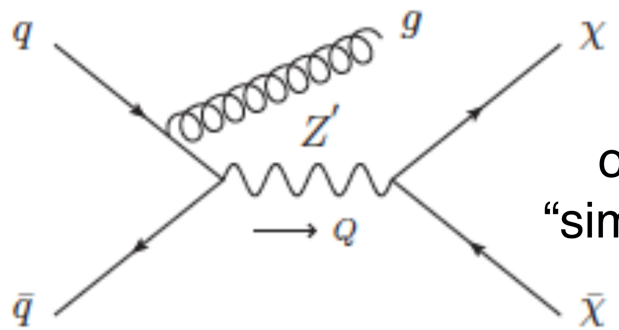
- EFT limits are too aggressive!

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
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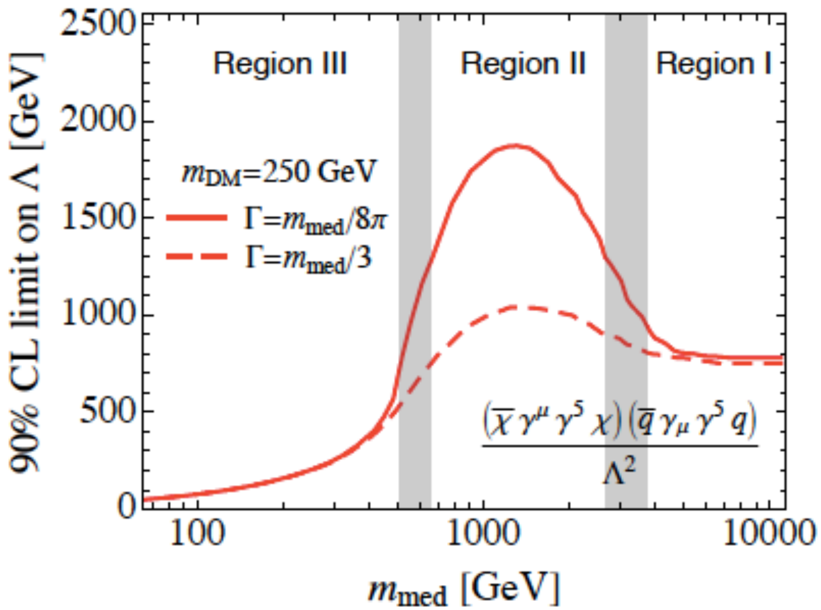


Three Regions as function of mediator mass:

Region I: Heavy m_{med}
➢ EFT is valid!

Region II: Medium m_{med} – Resonant enhancement
➢ EFT limits are too conservative!

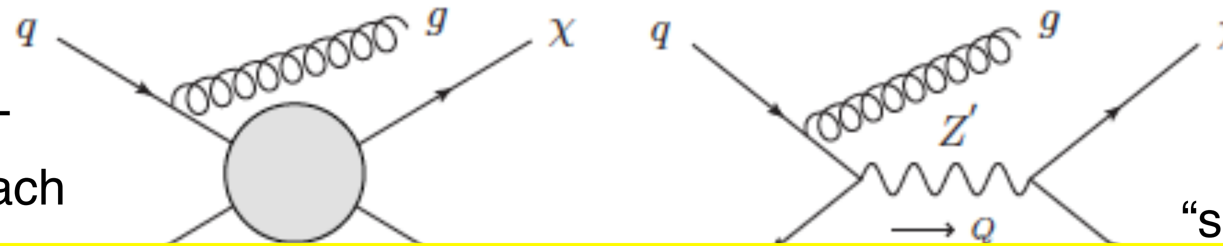
Region III: Low m_{med}
➢ EFT limits are too aggressive!

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

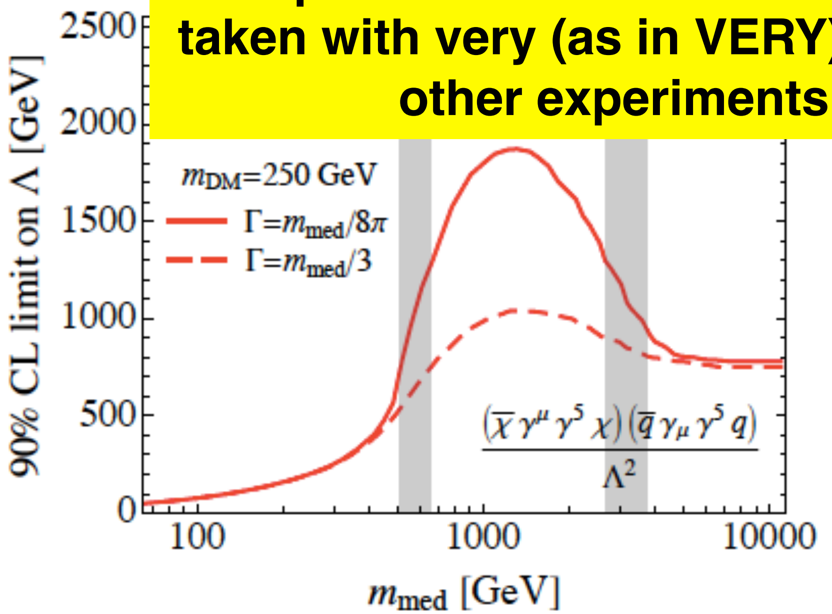


FT one diagram "simplified model"

Use v... clusion!

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!

...s:



Region I: Heavy m_{med}

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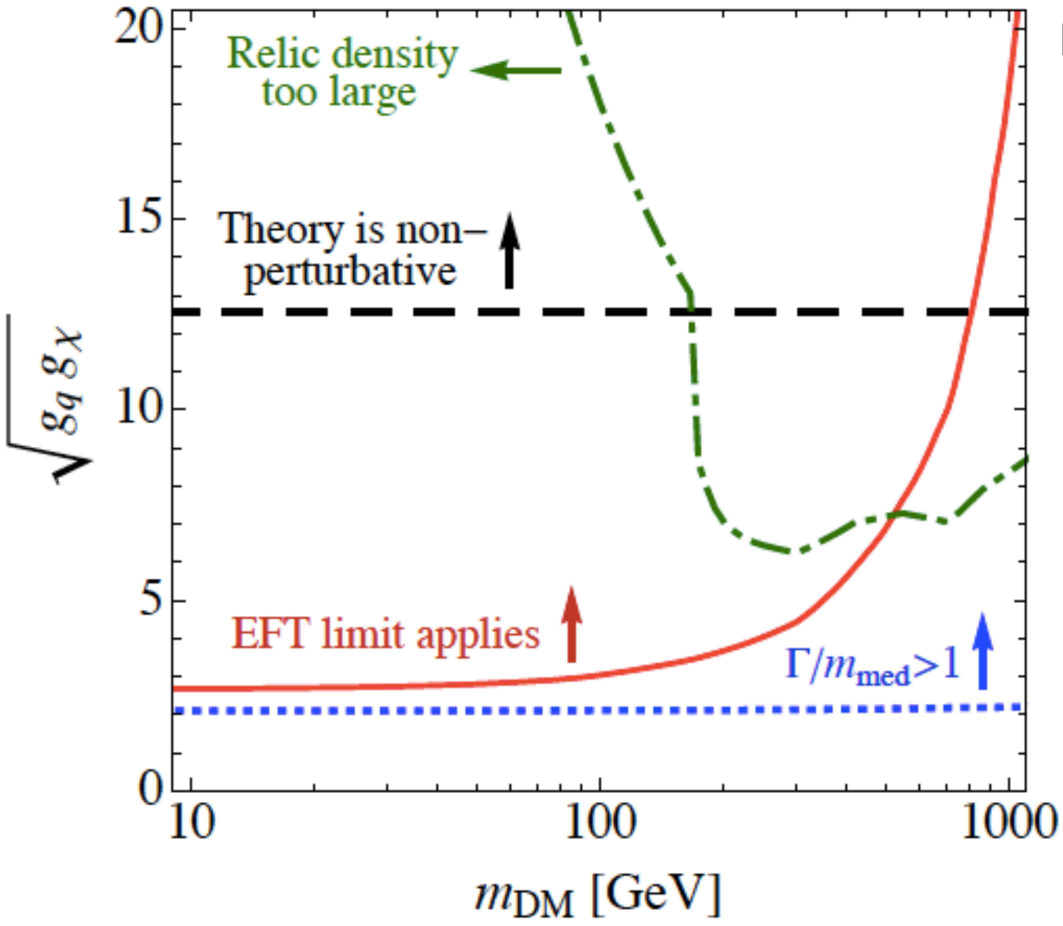
Region II: Medium m_{med} – Resonant enhancement

- 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

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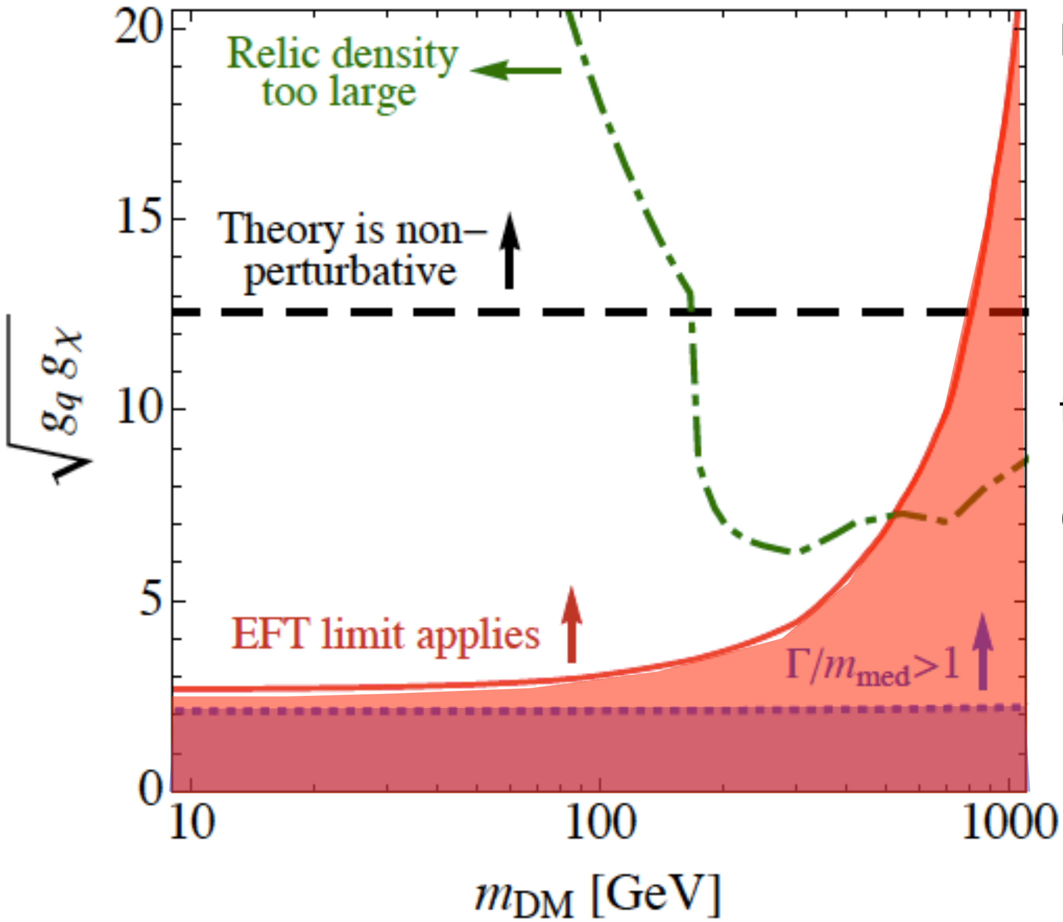
Model-dependences of EFT limits



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

1. Region in which EFT is valid

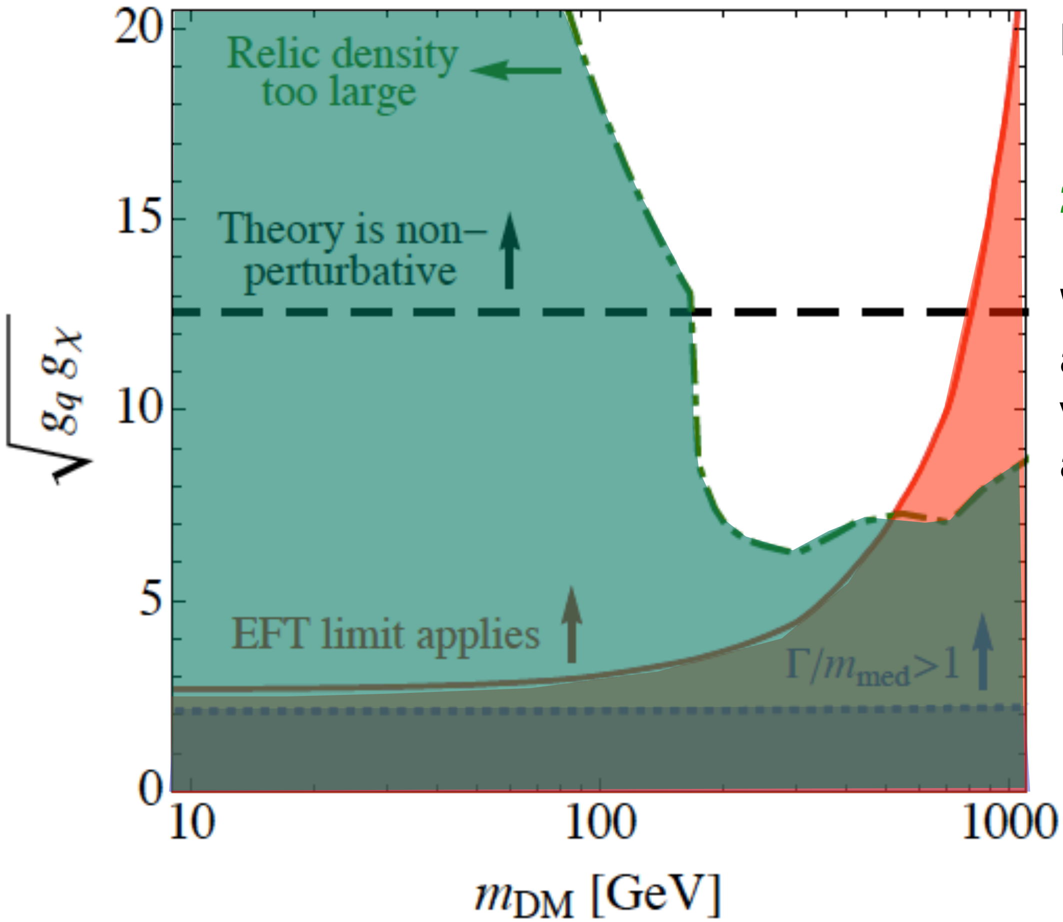
For this we calculate the minimum coupling

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

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



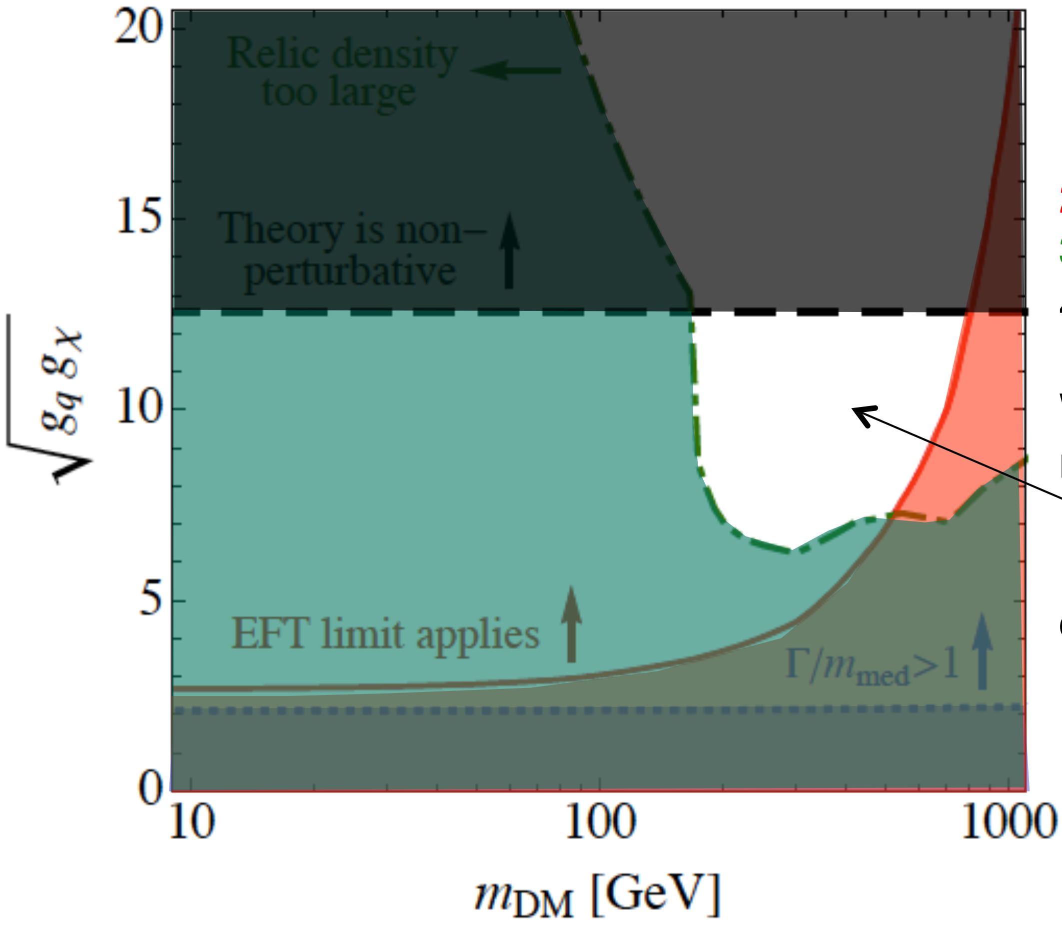
Look at EFT validity in m_{DM} – coupling* plane!

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 $\Omega_{XX}h^2 = 0.119$ 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_{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)

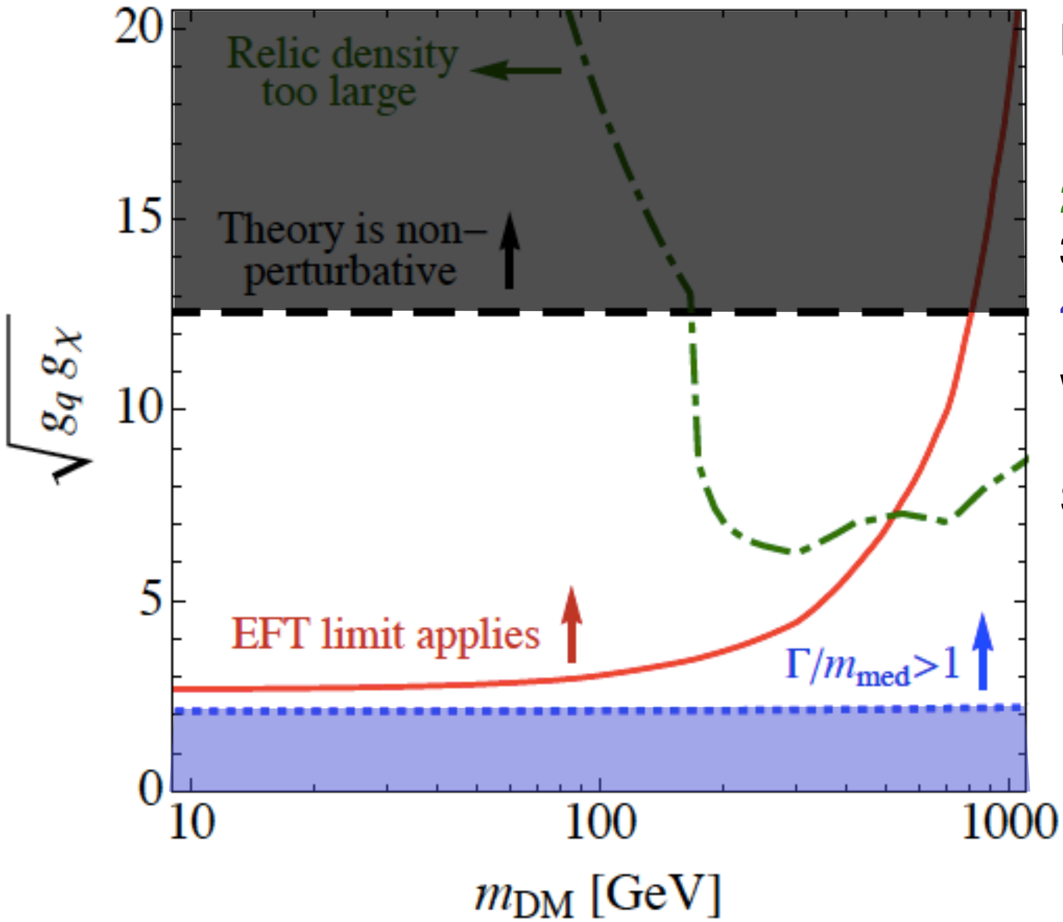
When we also require that the region/theory must be perturbative:

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

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!

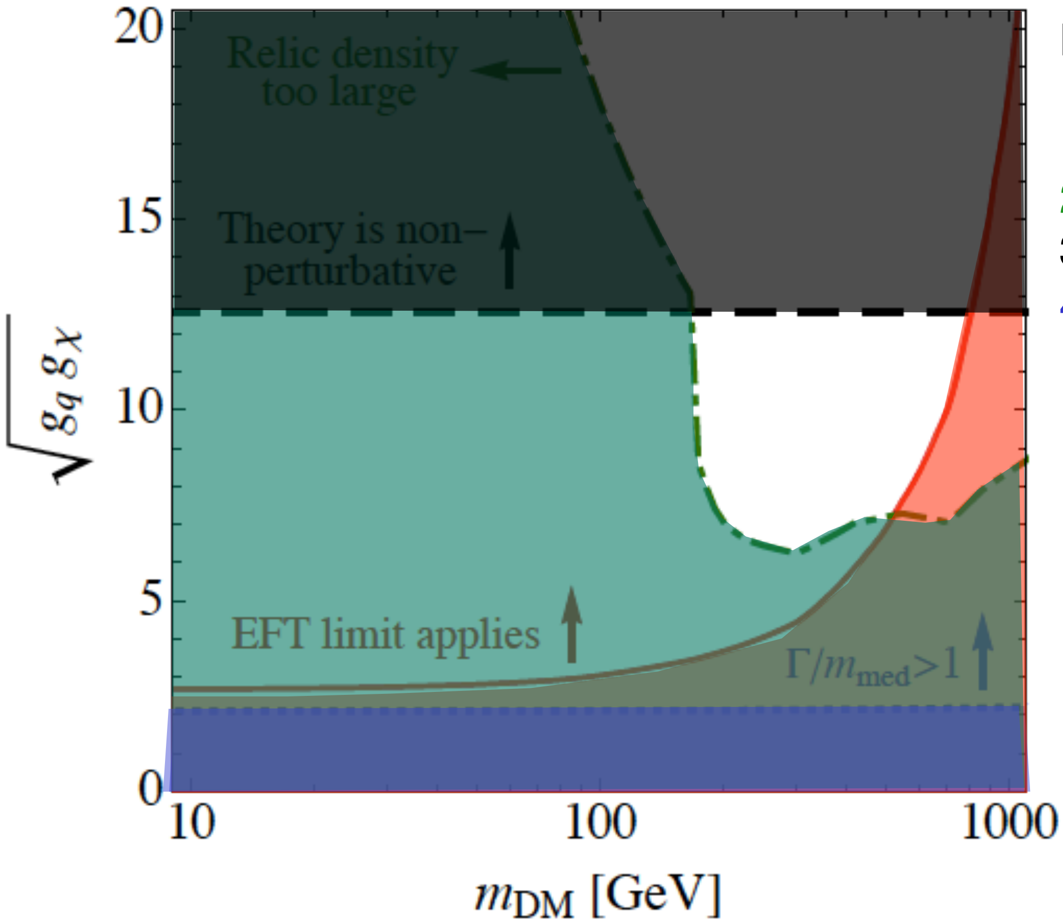
In the reaming part of the plot:

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

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!

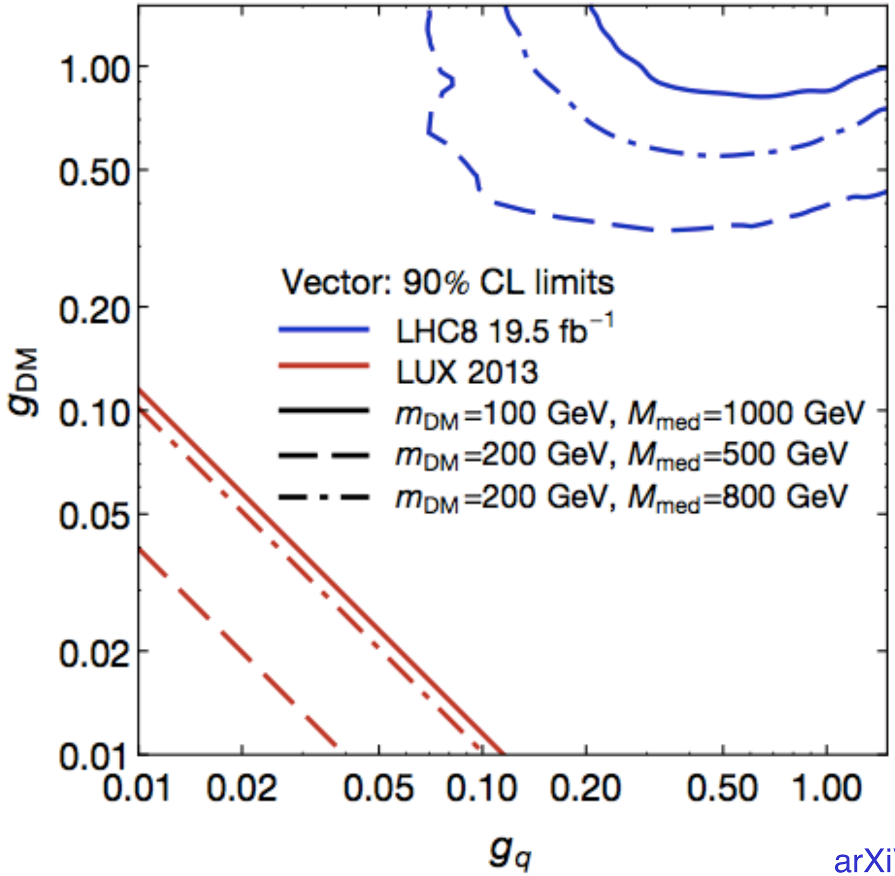
The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.

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

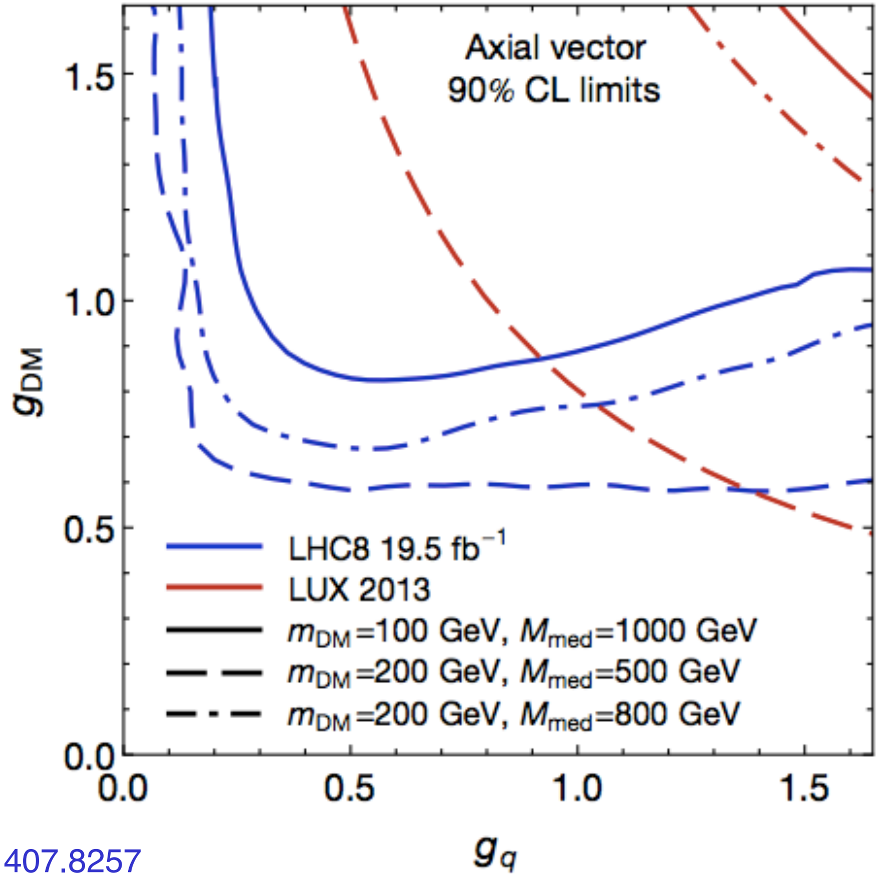
Collider vs Direct Detection

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

Vector



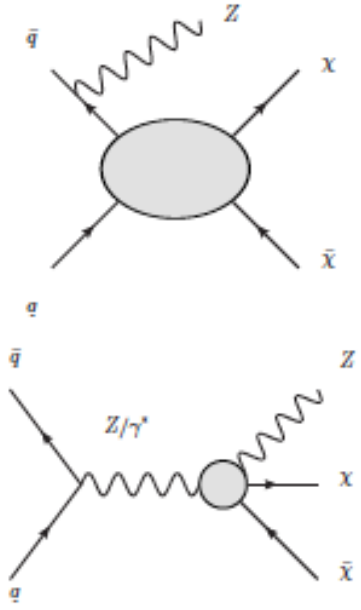
Axial vector



arXiV:1407.8257

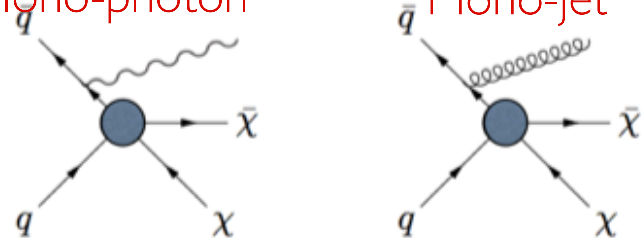
Mono-Mania (at the LHC)

Mono-Z

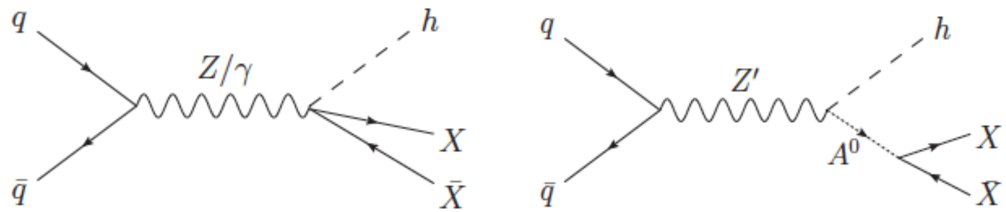


Mono-photon

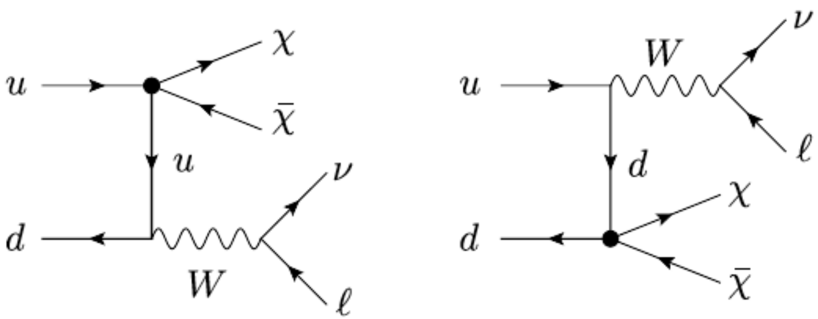
Mono-jet



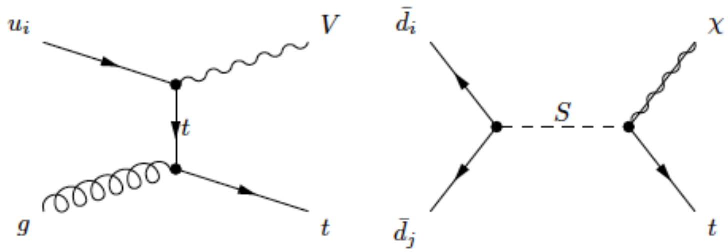
Mono-Higgs



Mono-W

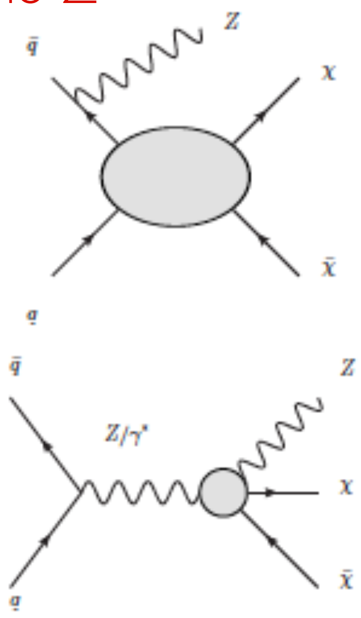


Mono-top



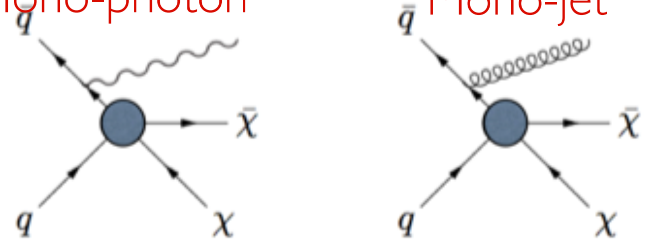
Mono-Mania (at the LHC)

Mono-Z

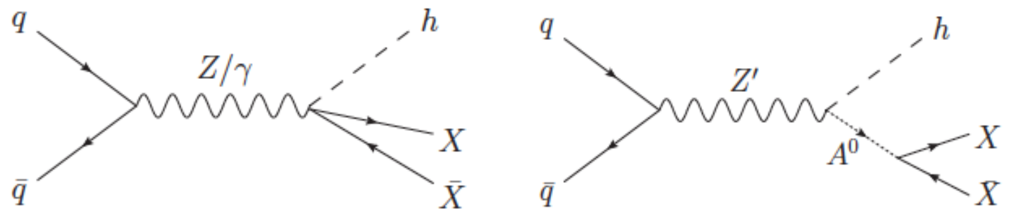


Mono-photon

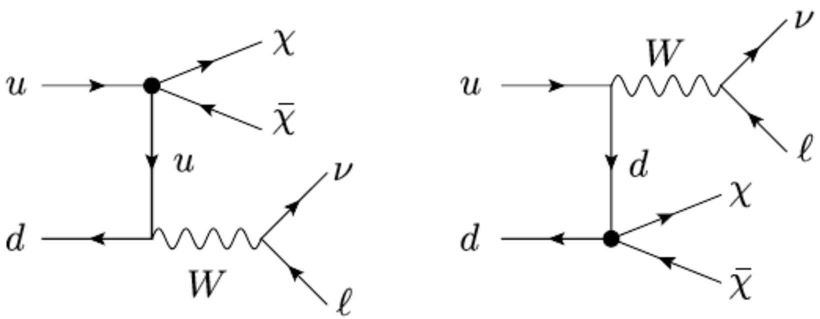
Mono-jet



Mono-Higgs



Mono-W



Mono-top