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MITCHELL INSTITUTE
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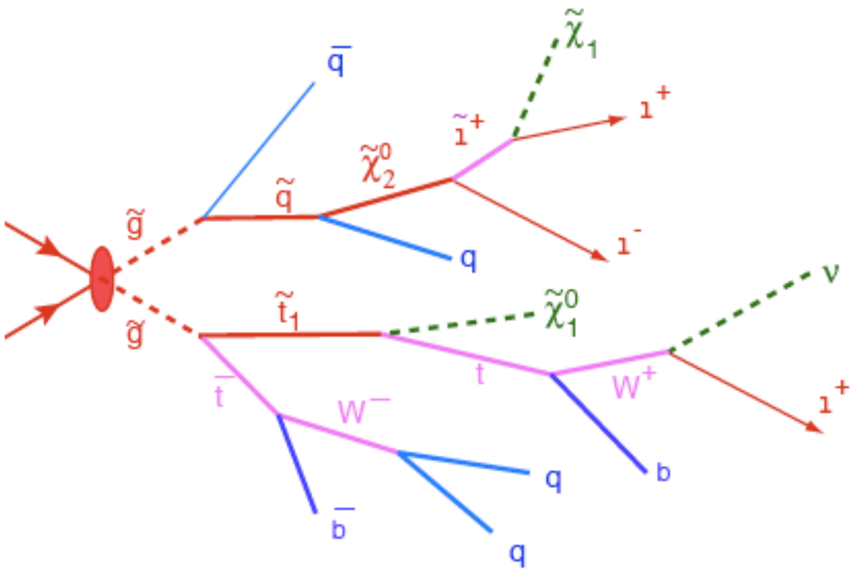
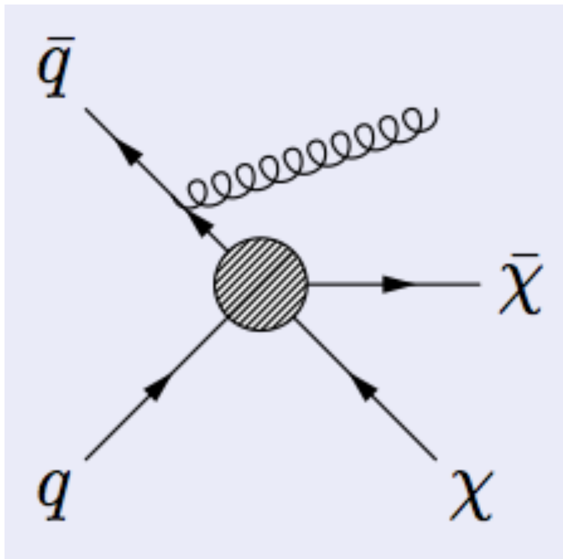
DM Searches @ LHC O. Buchmüller

Oliver Buchmueller, Imperial College London

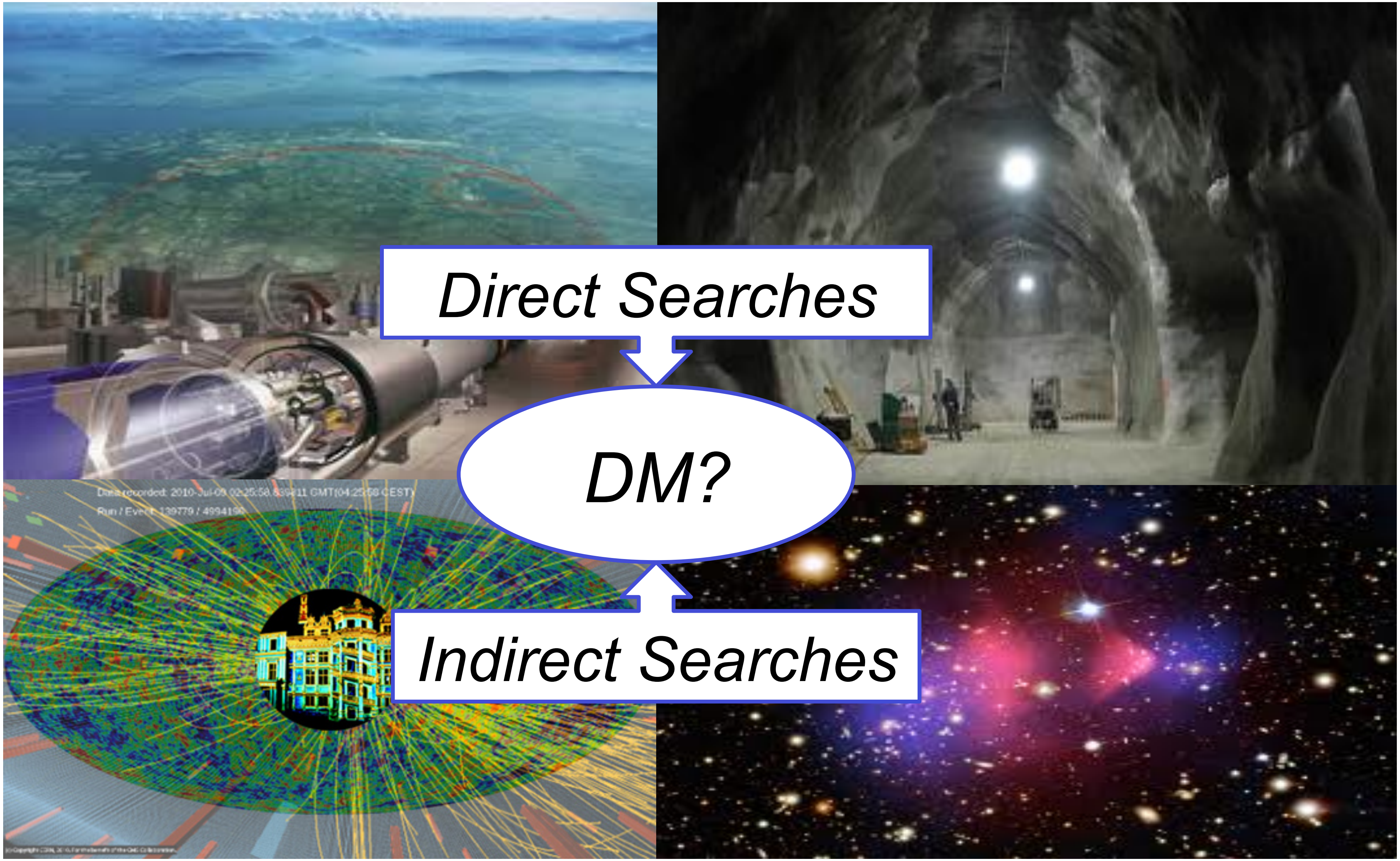
SEARCHES FOR DARK MATTER PRODUCTION AT THE LHC

MITCHELL WORKSHOP ON COLLIDER AND DARK MATTER PHYSICS 2015





Searches for Dark Matter (&SUSY)

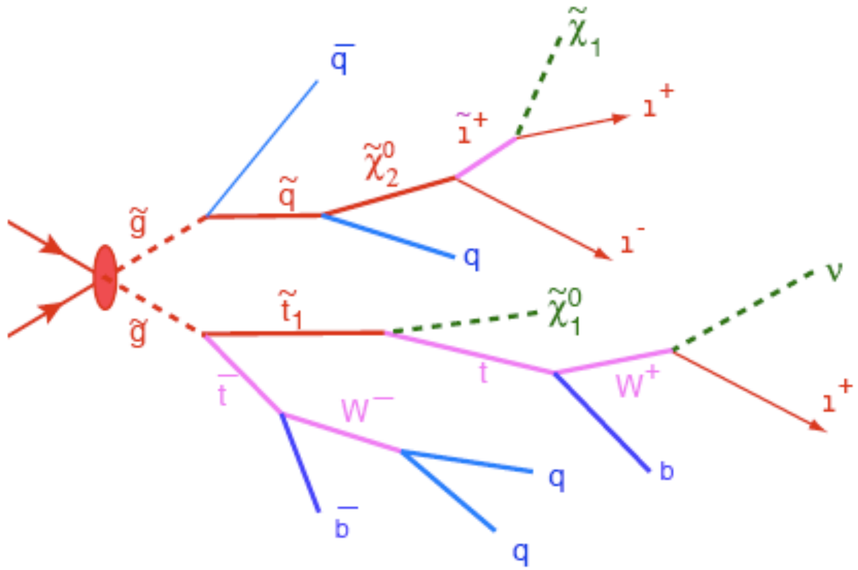


Searches for Dark Matter (&SUSY)

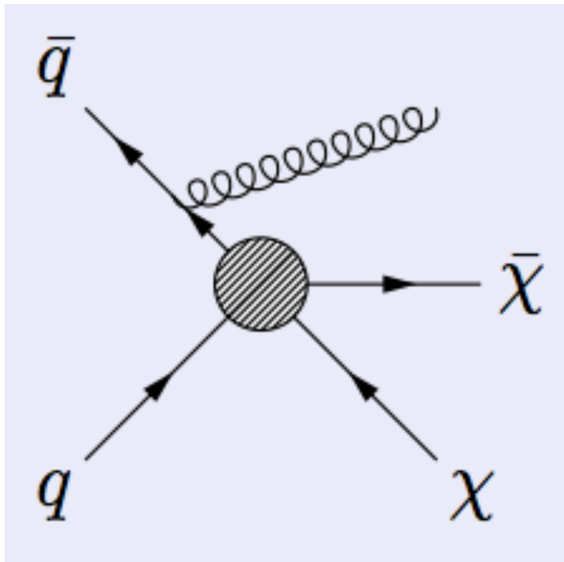
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY



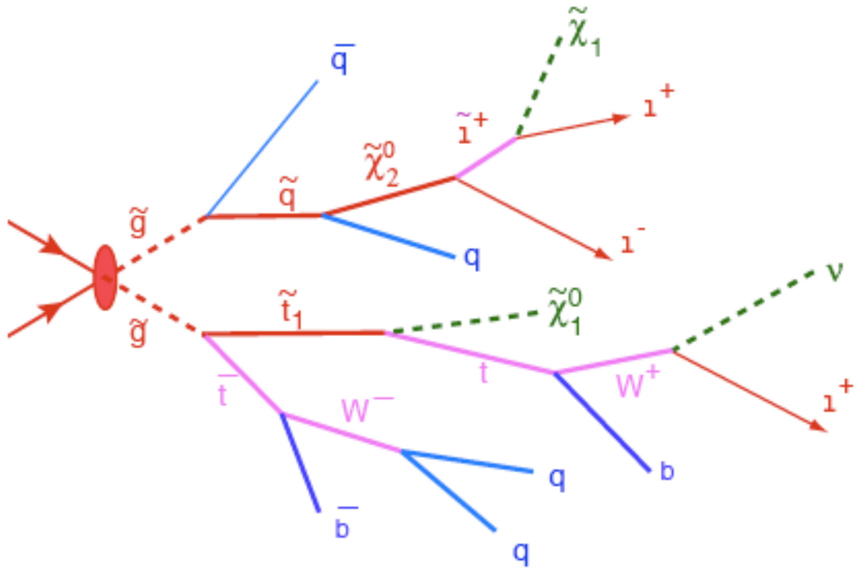
Example:
Effective Field Theory
Simplified models



Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY



Example:
Effective Field Theory
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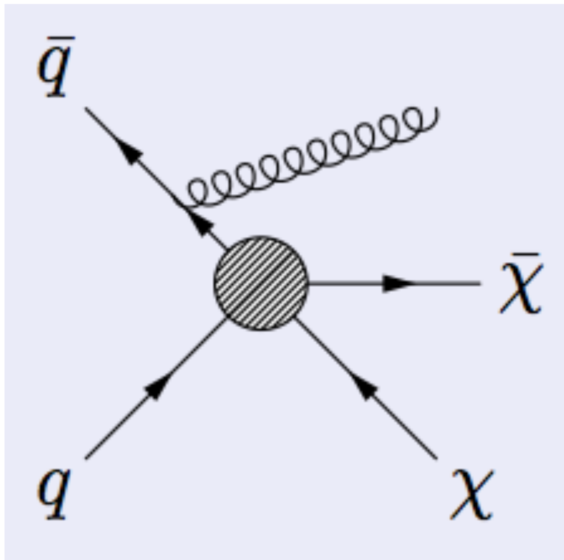
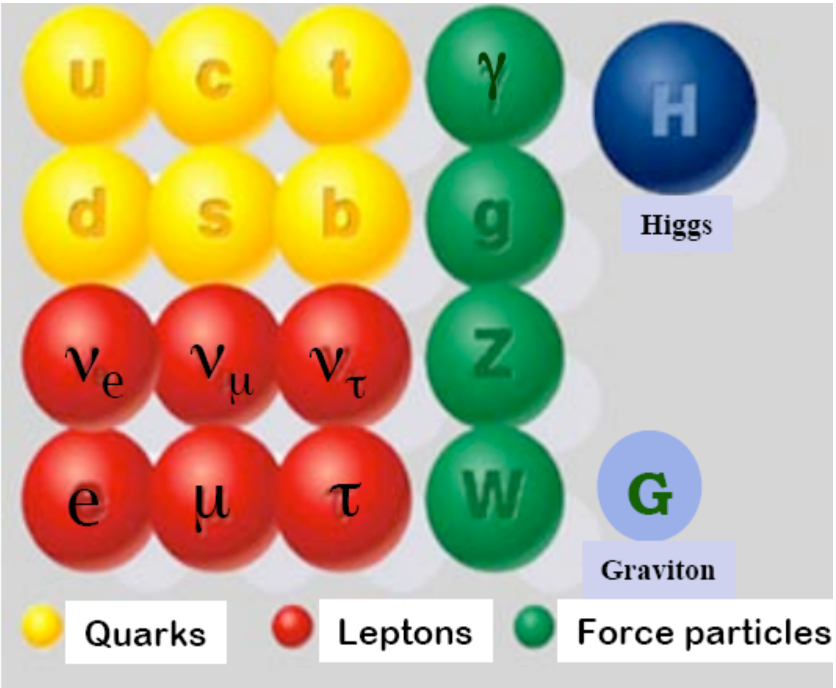
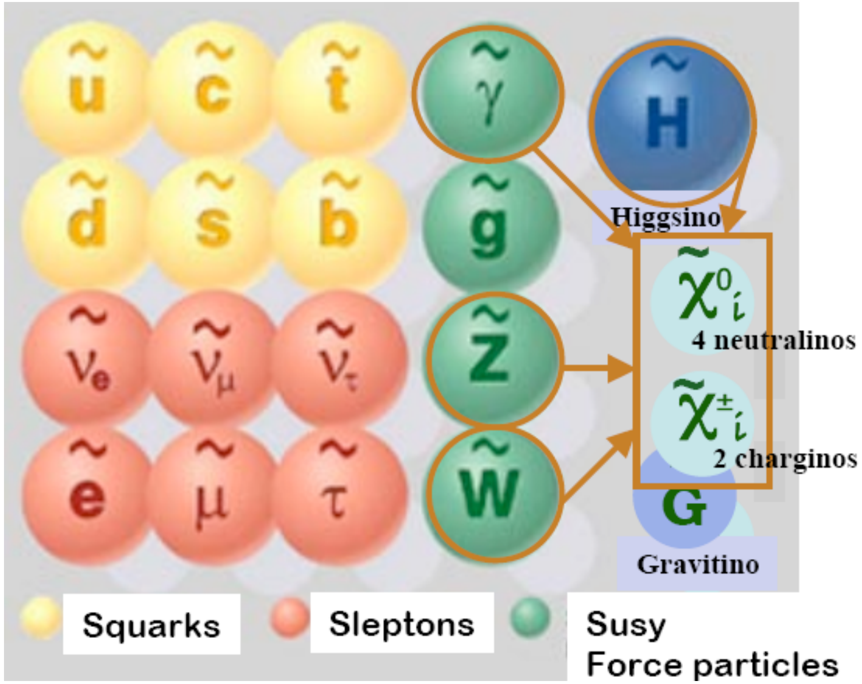


Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles **SUSY particles**





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

R-parity conservation:
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

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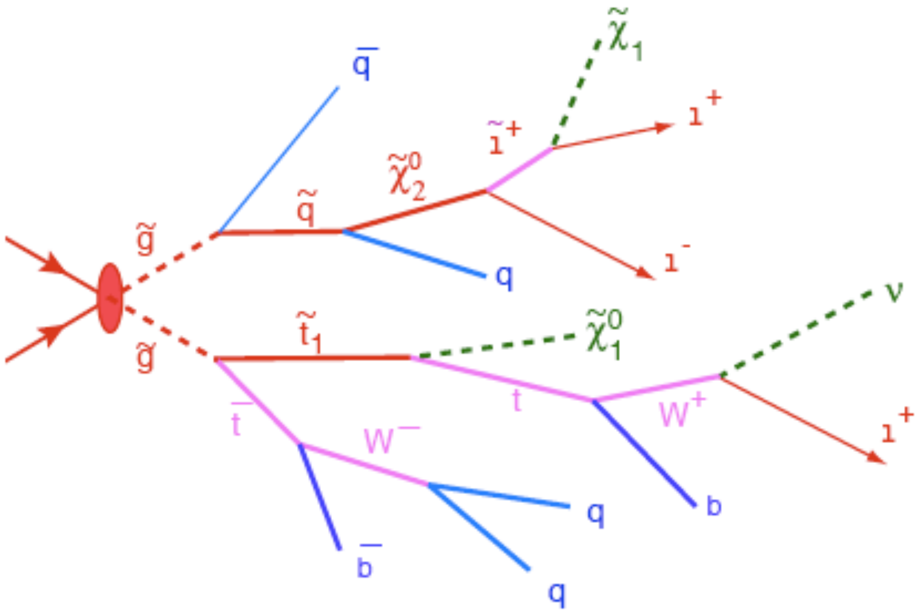
What do we call a "SUSY search"?

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



Missing Energy:
- *from LSP*

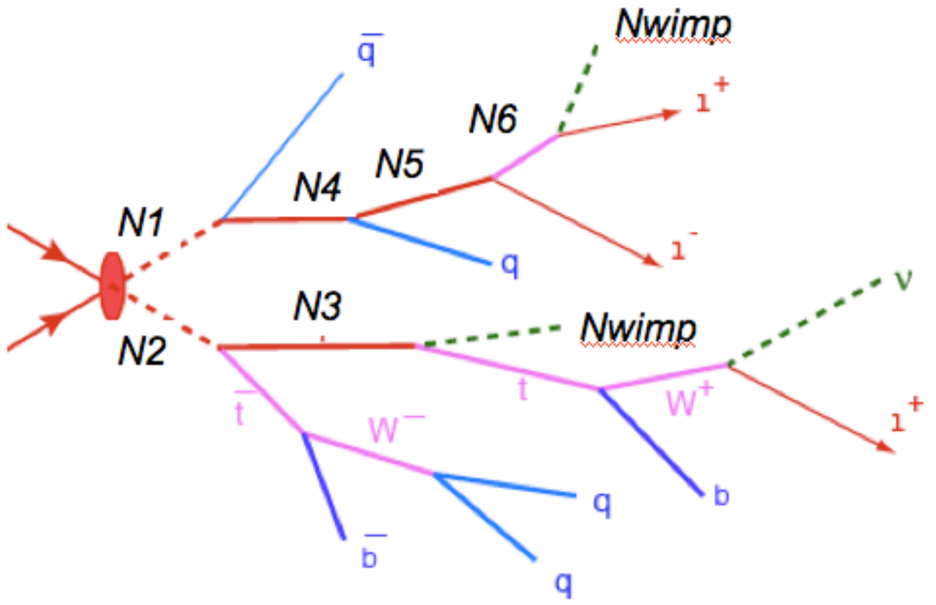
Multi-Jet:
- *from cascade decay (gaugino)*

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



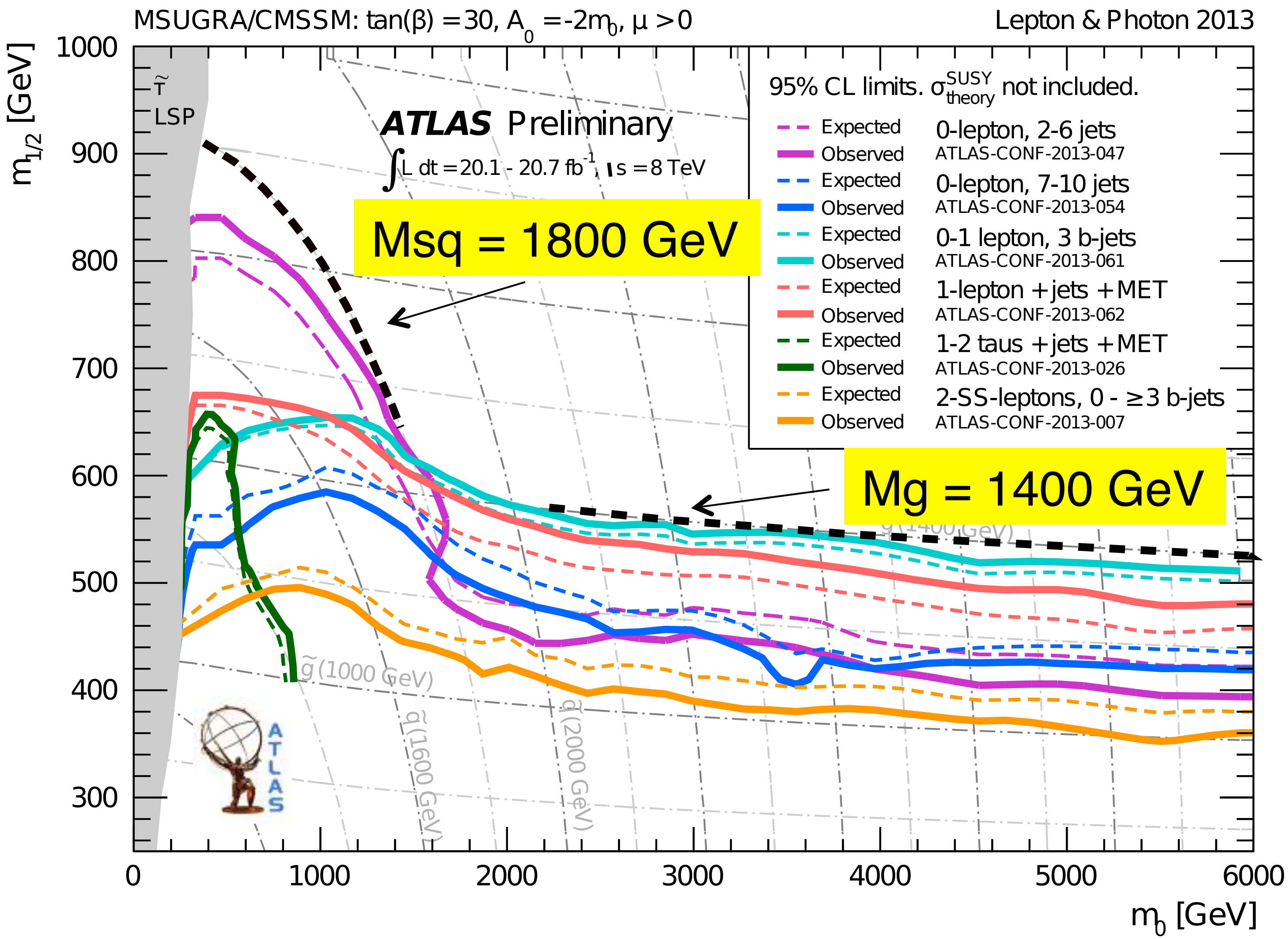
Missing Energy:
- *Nwimp - end of the cascade*

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



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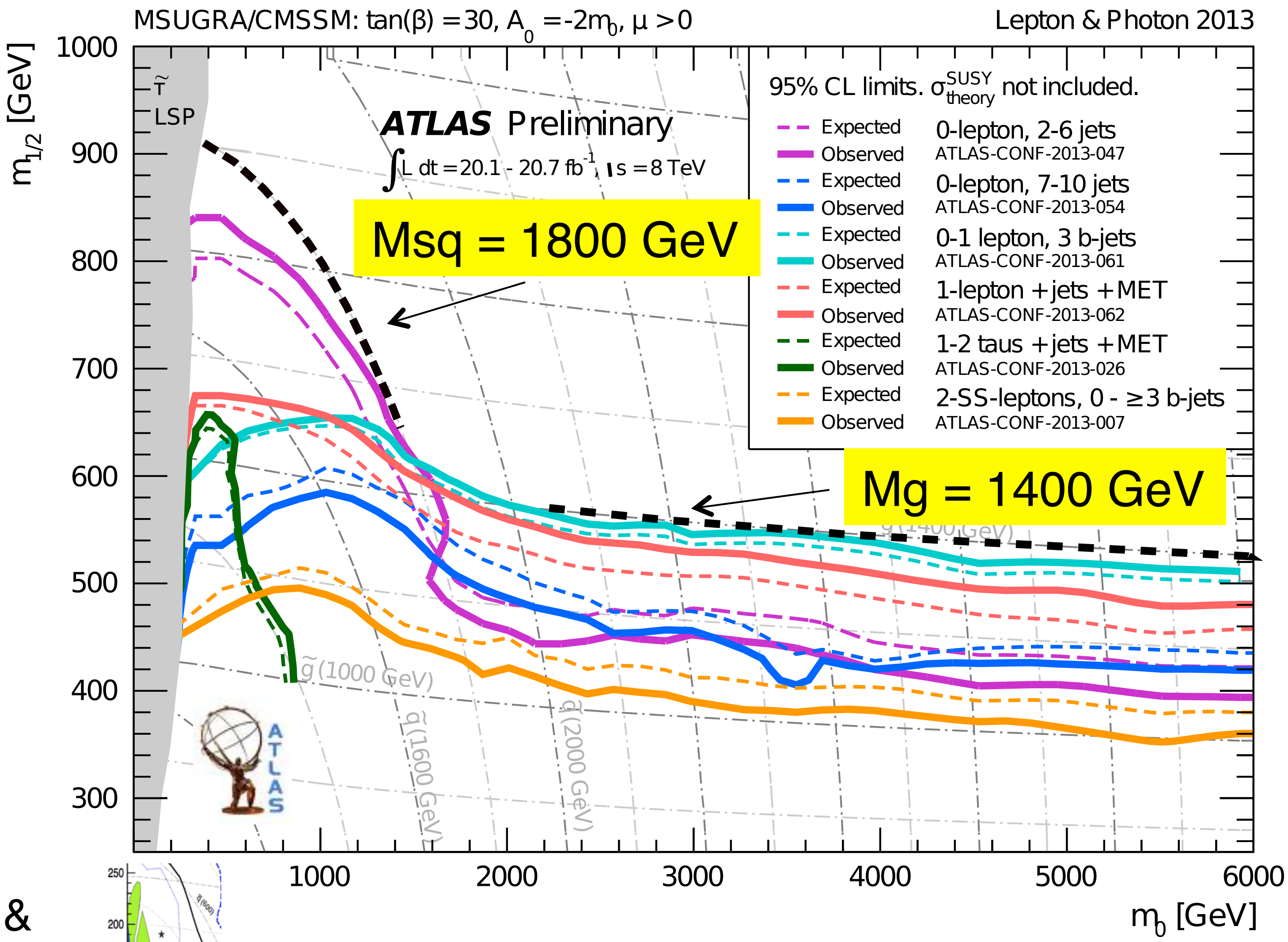
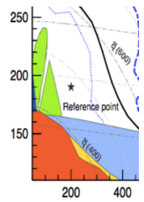
Inclusive SUSY Searches in 2013

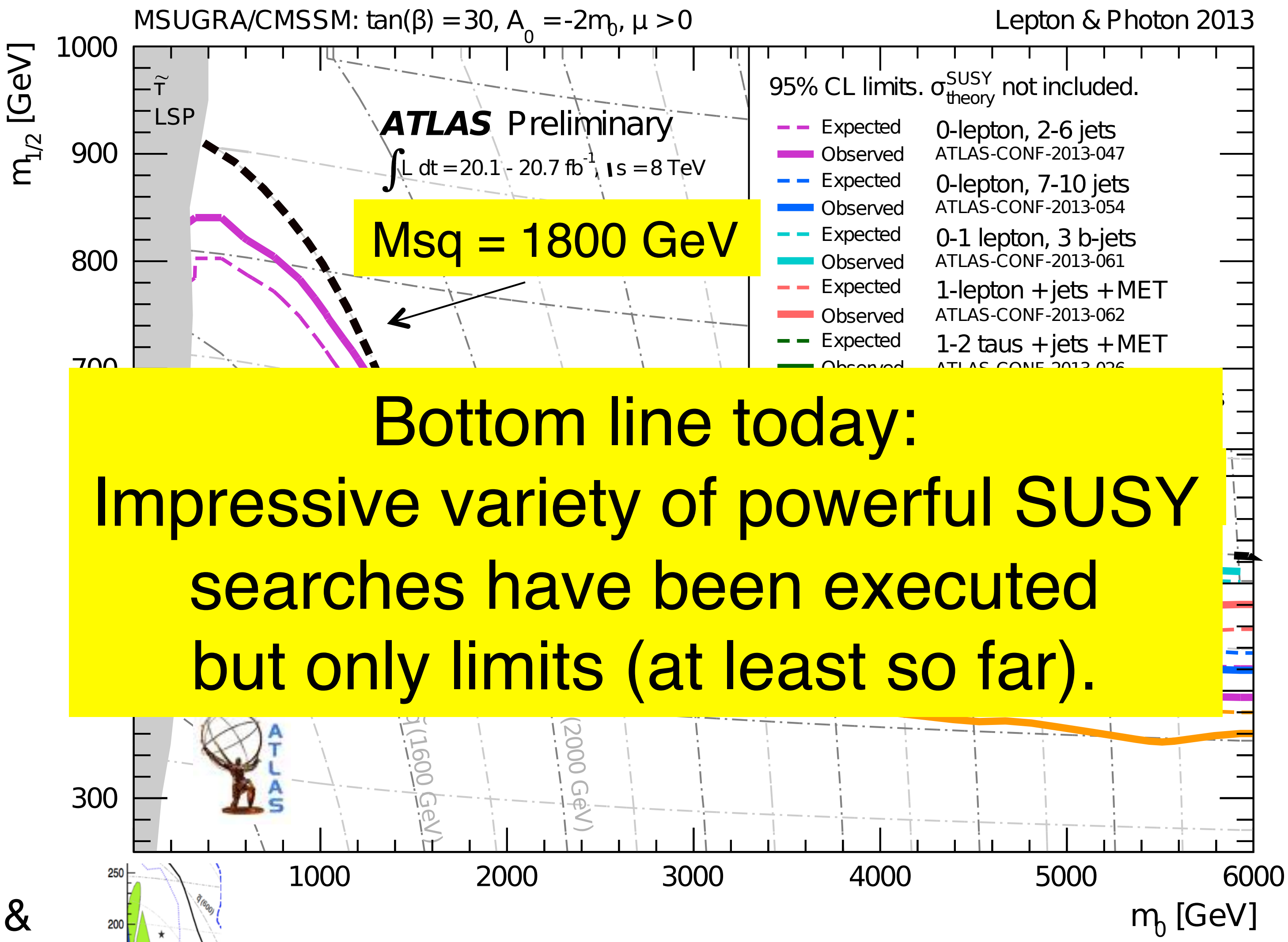


LEP &
Tevatron



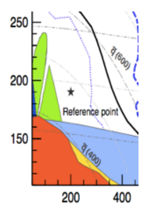
The LHC has pushed the mass scale in constraint SUSY models to a new level!

Inclusive SUSY Searches in 2013



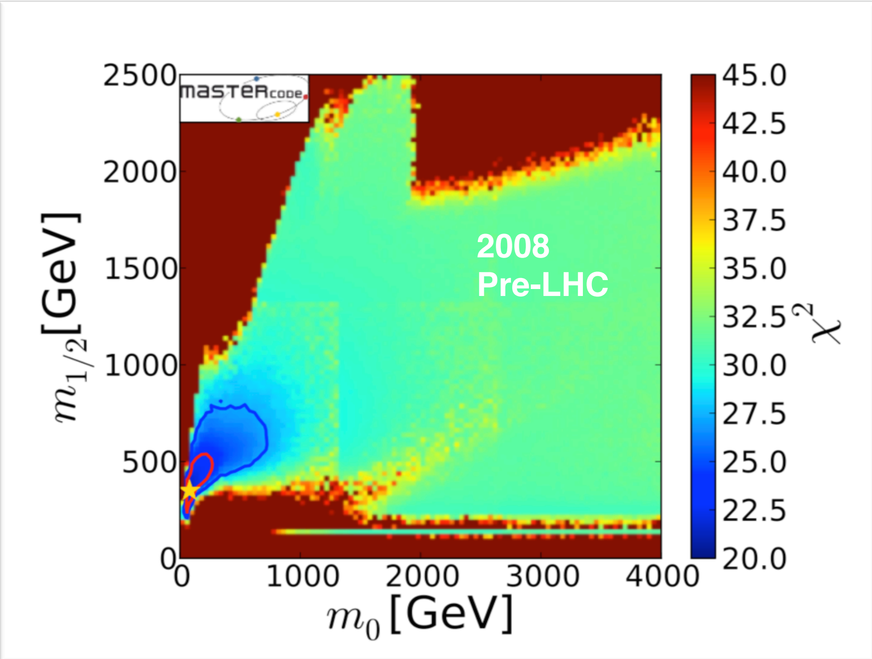
Bottom line today:
Impressive variety of powerful SUSY searches have been executed but only limits (at least so far).

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	-
$\Delta\alpha^{(5)}_{had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{SUSY}$	0.078	0.047	0.14
σ^0_{had} [nb]	[26] / [44]	41.540 ± 0.037	2.50	2.57	2.54
R_l	[26] / [44]	20.767 ± 0.025	1.05	1.08	1.08
$A_{fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
$A_\ell(P_\tau)$	[26] / [44]	0.1465 ± 0.0032	0.11	0.13	0.07
R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{fb}(c)$	[26] / [44]	0.0707 ± 0.0035	0.86	0.88	0.80
A_b	[26] / [44]	0.923 ± 0.020	0.36	0.36	0.35
A_c	[26] / [44]	0.670 ± 0.027	0.005	0.005	0.005
A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{SUSY}$	1.77	1.39	2.08
$a^{EXP}_\mu - a^{SM}_\mu$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4[\pm 1.5_{SUSY}]$	0.0	0.0	0.0
$BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{EXP}$ $\pm 0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
$BR(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$BR^{EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{EXP+TH}$	1.43	1.59	1.00
$BR(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6[\pm 0.01_{SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR^{EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
σ^{SI}_p	[25]	$(m_{\chi^0_1}, \sigma^{SI}_p)$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

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

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CMSSM: Evolution with time

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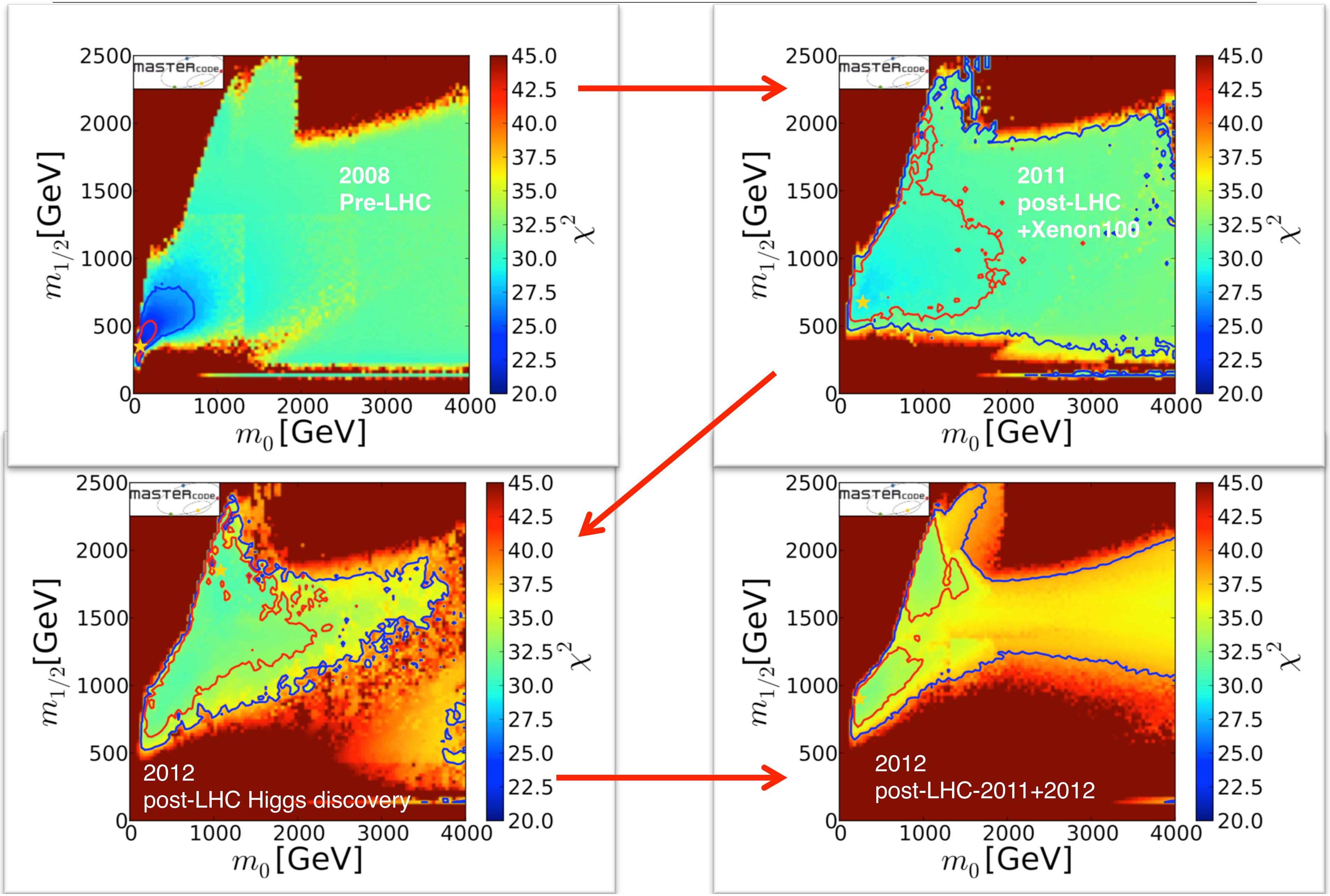
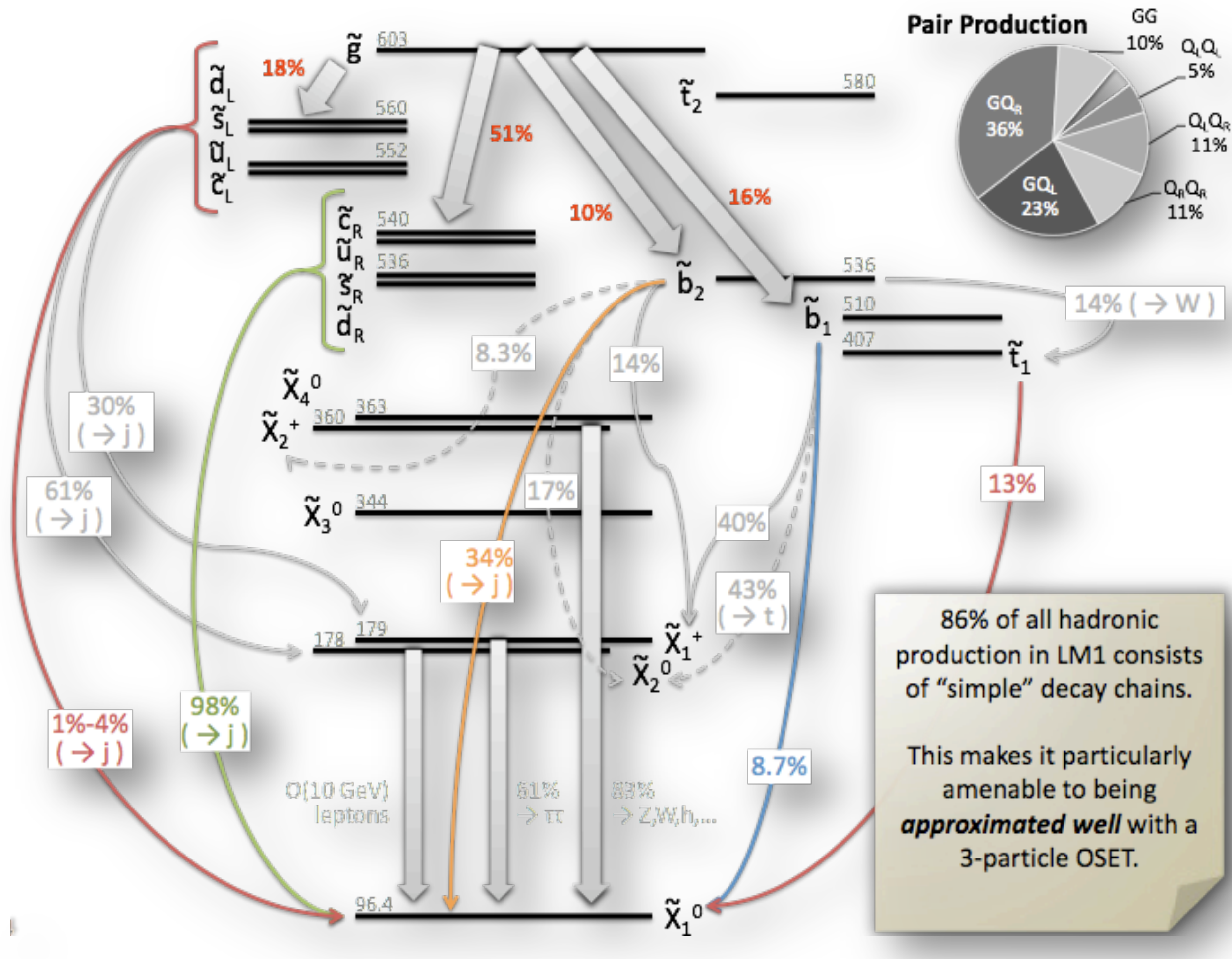


SUSY Status – post 7 TeV LHC data

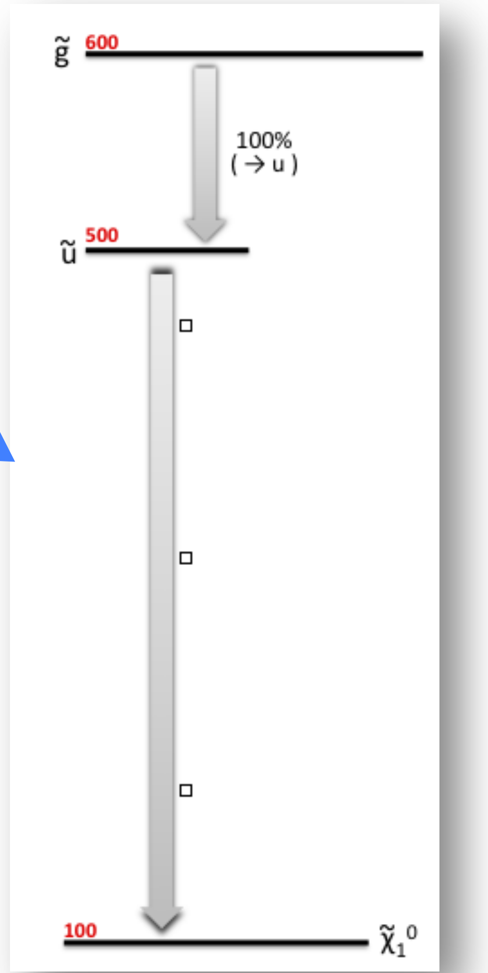
- Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!
- Experiments define new benchmarks and less complex SUSY models in order to present the interpretation of their searches.
- Aided by the discovery of a Higgs boson, the focus of the experimental search strategy and corresponding interpretation shifts towards other scenarios like "Natural SUSY" (i.e. 3rd generation squark searches).

Interpretation in Simplified Models

CMSSM



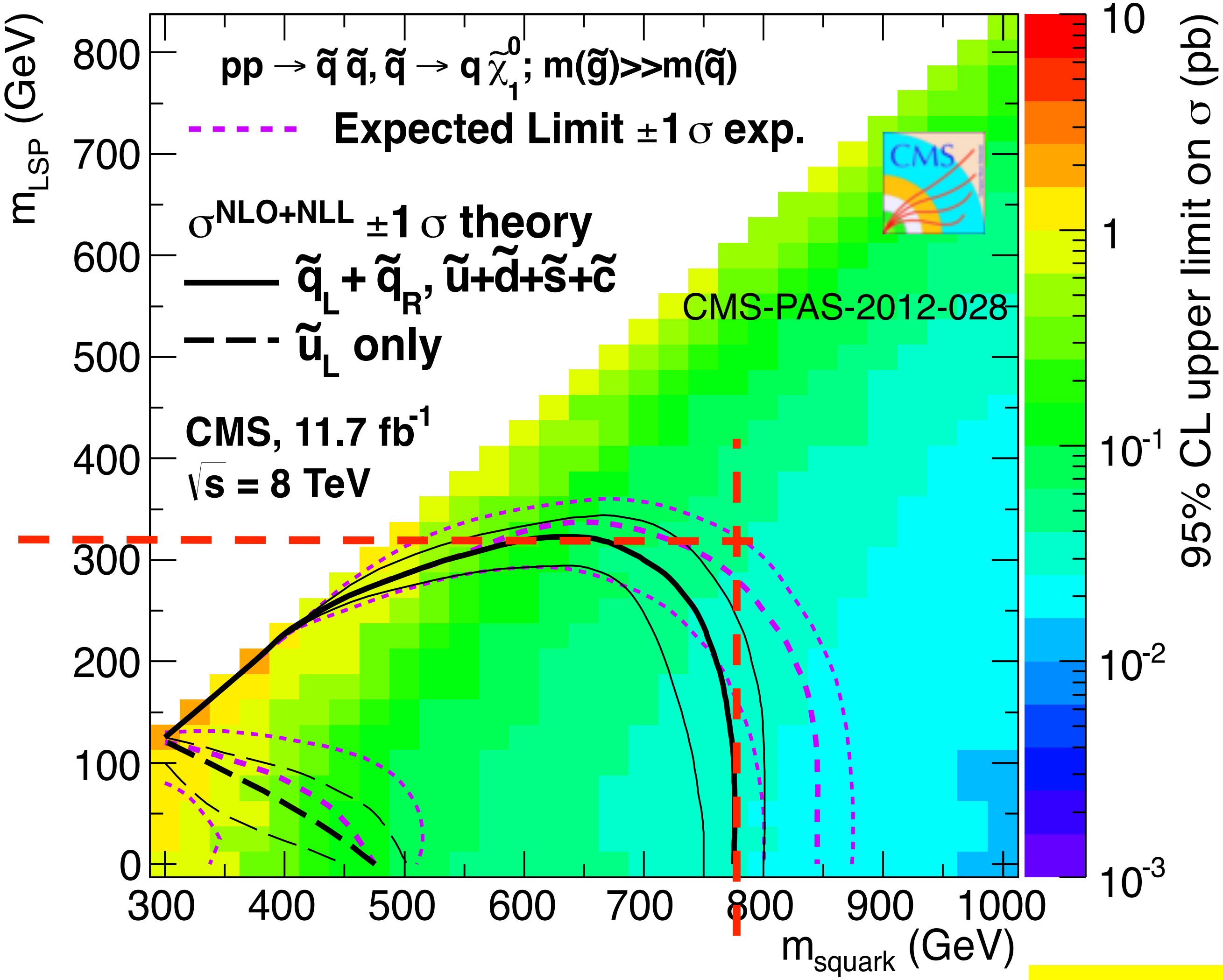
What the individual searches are sensitive to is much more simple…

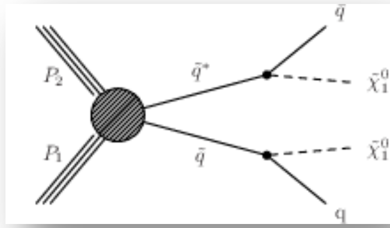


Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

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

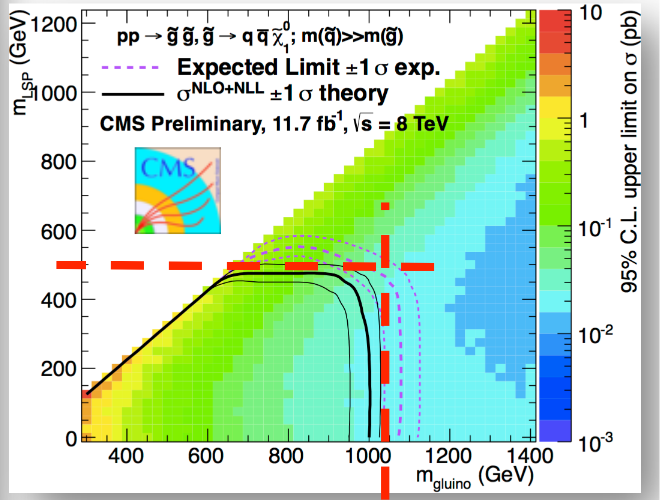
Assumes 100% BR for decay chain considered.

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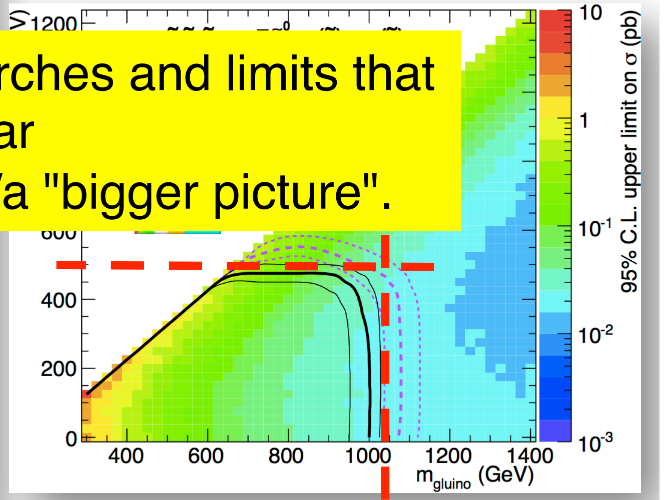
Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
CMSSM	all $m_{\tilde{q}}$		800
Simpli			
Simplified model $\tilde{q}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$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



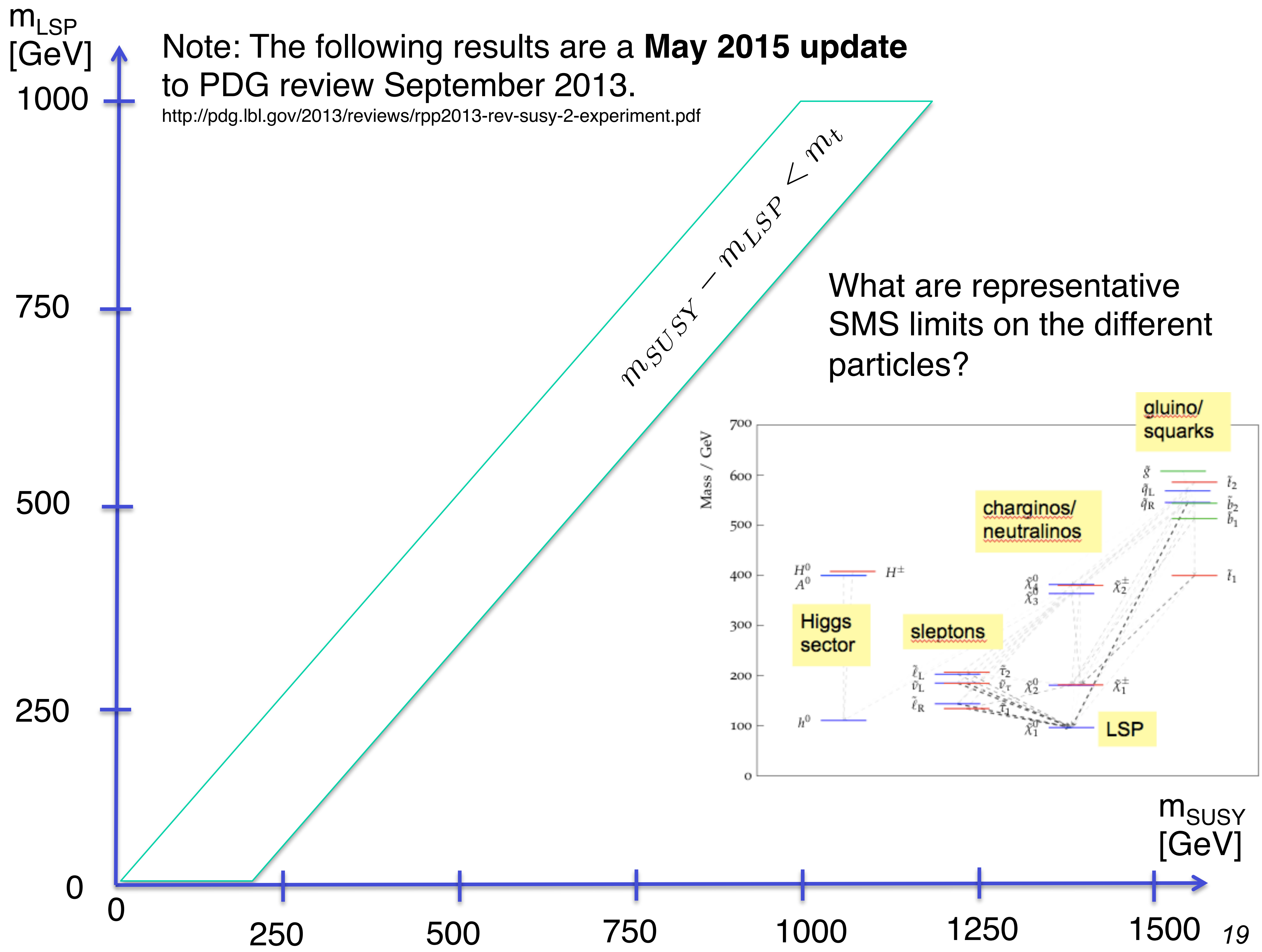
It is a challenge to do justice to the many searches and limits that have been established so far
- even more so to put it all together into the/a "bigger picture".

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

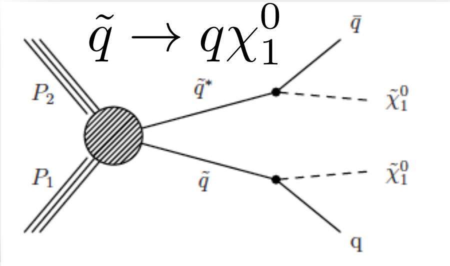
Note: The following results are a **May 2015 update** to PDG review September 2013.

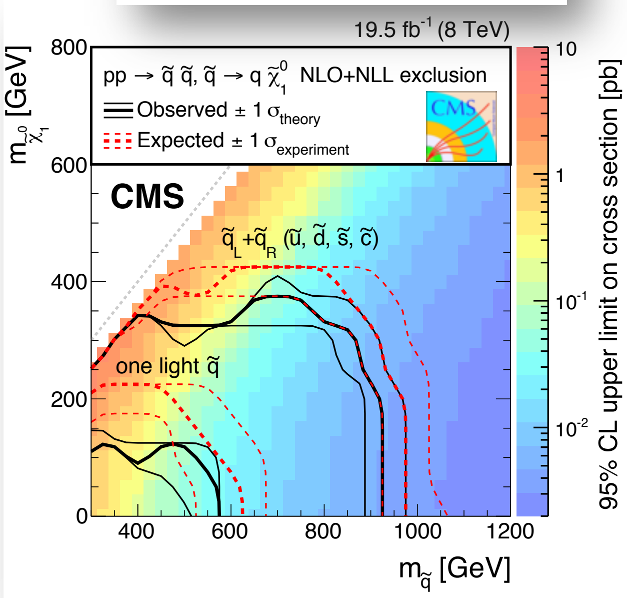
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

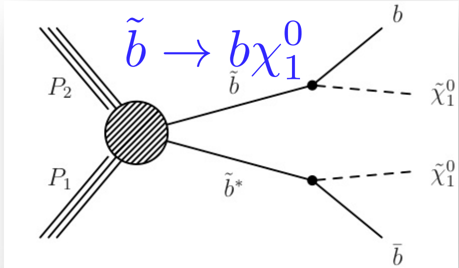
What are representative SMS limits on the different particles?

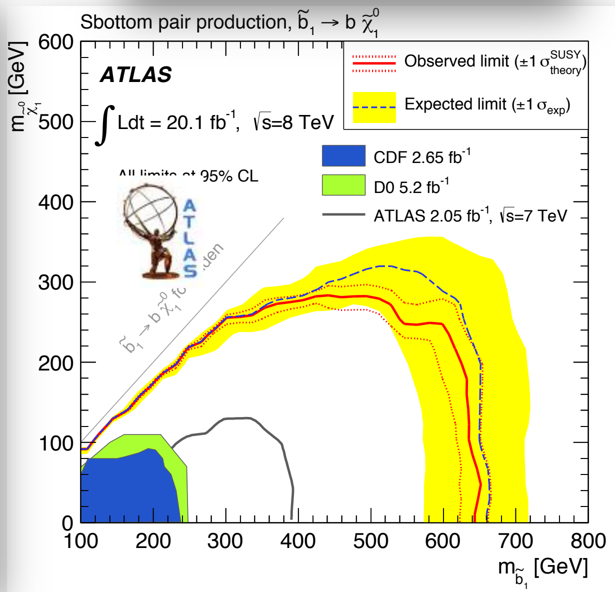


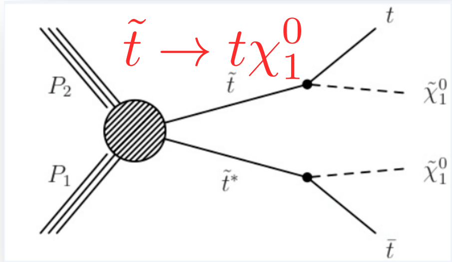
Direct squark production – chosen limits

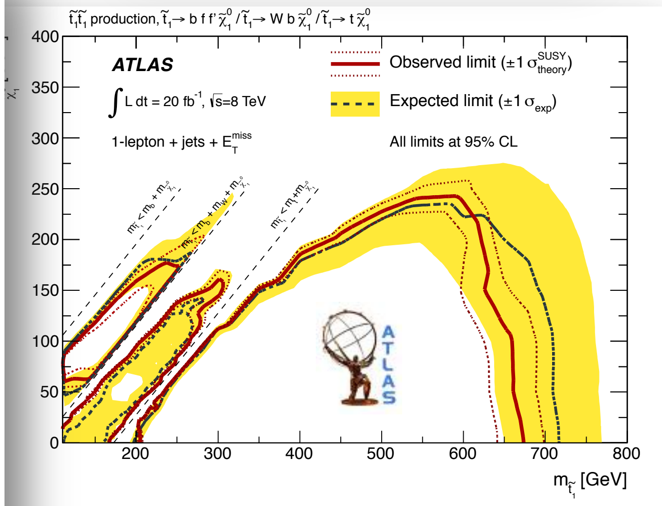








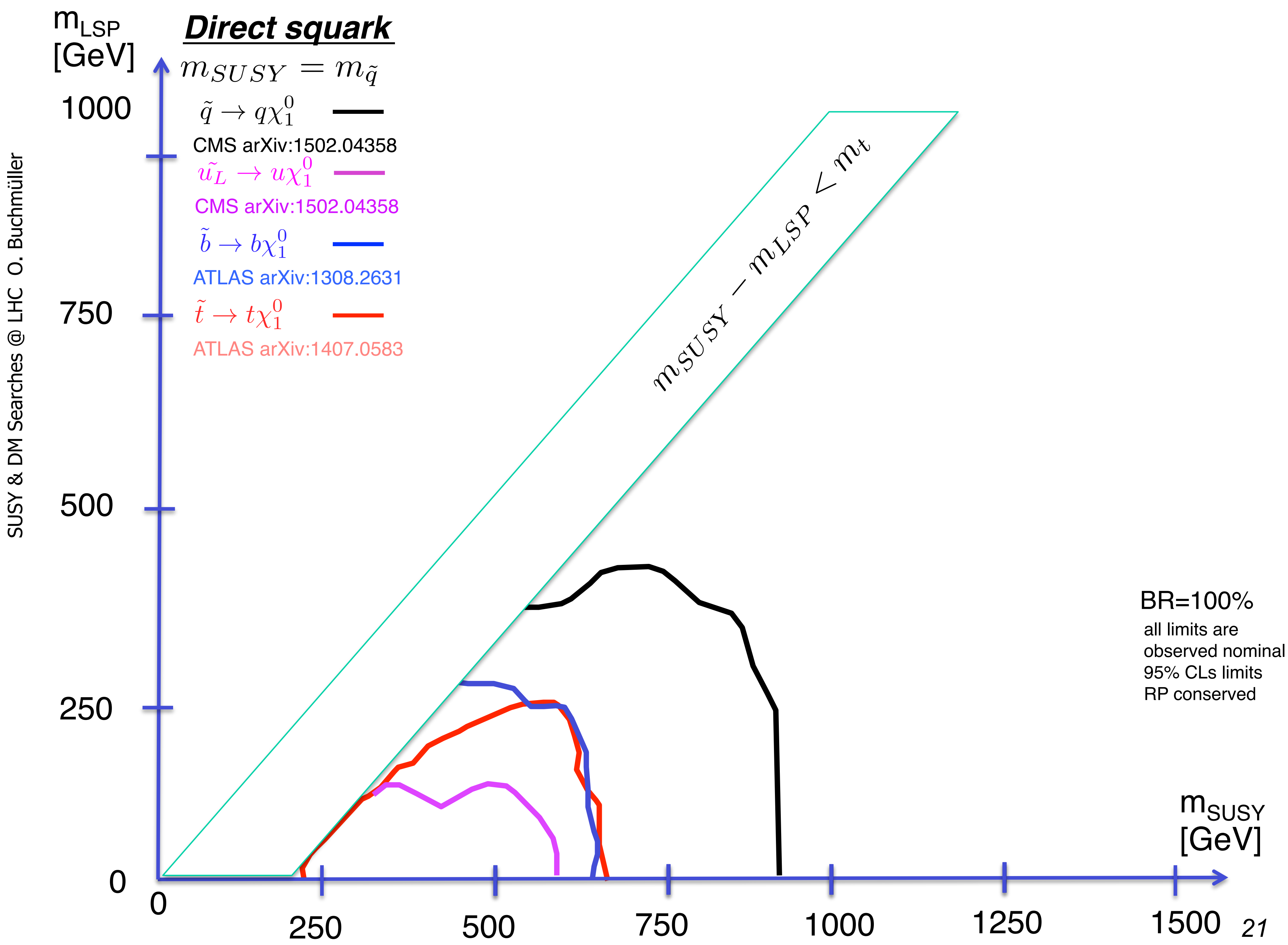




CMS arXiv:1502.04358
Signature: Jets + E_t^{miss} with M_{T2}
Limit assumes all 1st & 2nd gen squarks to be mass degenerate [or only one light squark]!

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

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



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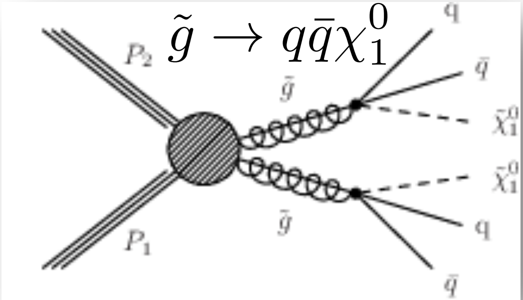
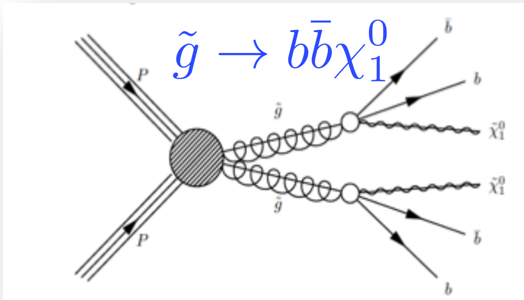
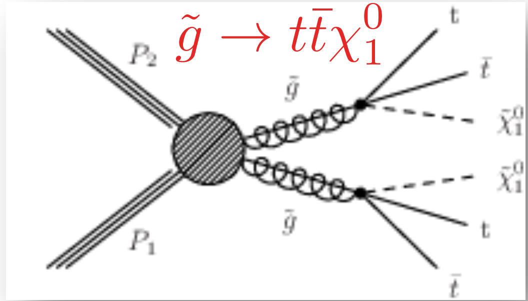
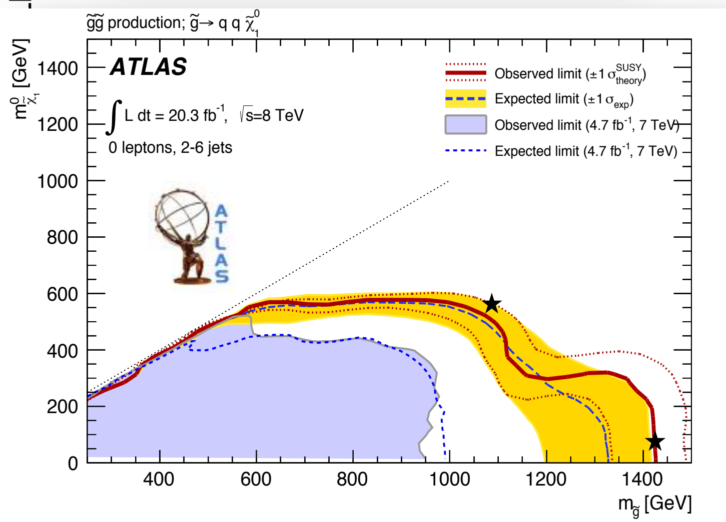
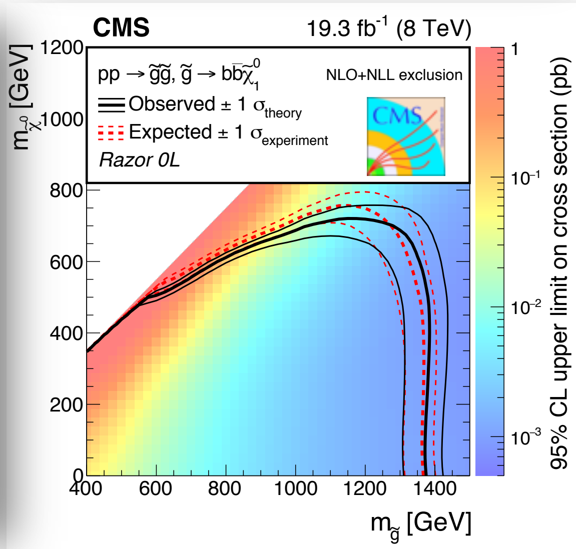
Gluino mediated squark production – limits chosen

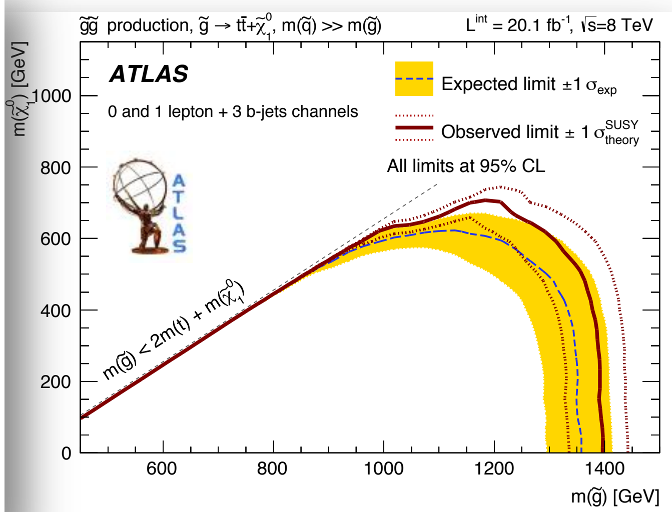








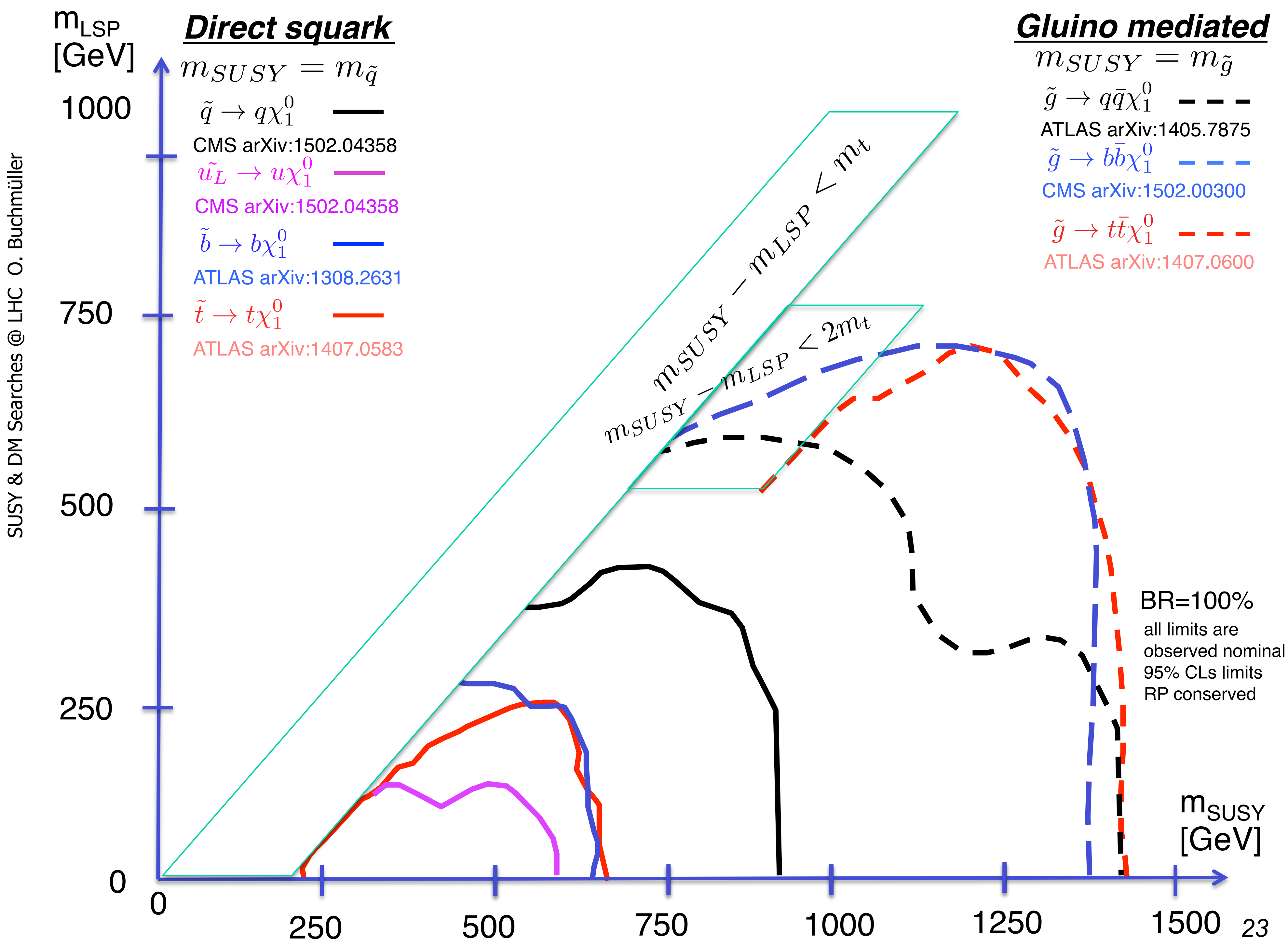




ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets + E_t^{miss}

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

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



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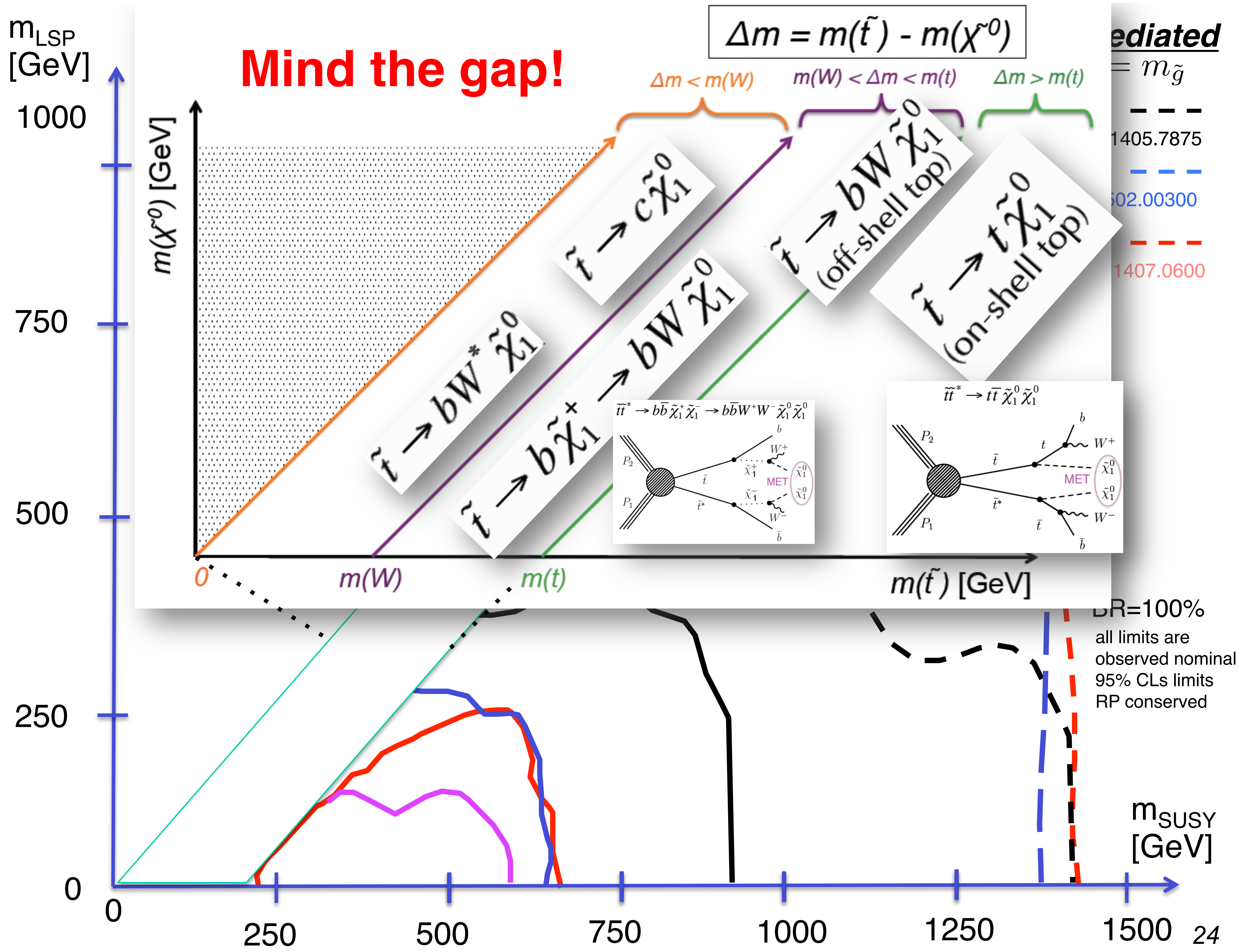
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
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_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



Mind the gap!
Δm = m(t̃) - m(χ̃⁰)
Δm < m(W)
m(W) < Δm < m(t)
Δm > m(t)
m(χ̃⁰) [GeV]
m(t̃) [GeV]
0
m(W)
m(t)
t̃ → bW* χ̃₁⁰
t̃ → cχ̃₁⁰
t̃ → bχ̃₁⁺
t̃ → bW χ̃₁⁰
t̃ → bW χ̃₁⁰ (off-shell top)
t̃ → tχ̃₁⁰ (on-shell top)
MET
m_LSP [GeV]
m_SUSY [GeV]
1405.7875
1407.0600
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
0
250
500
750
1000
1250
1500

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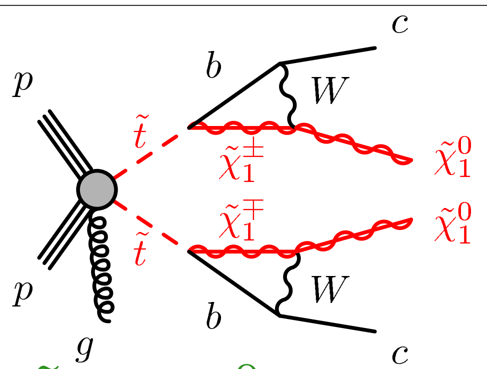
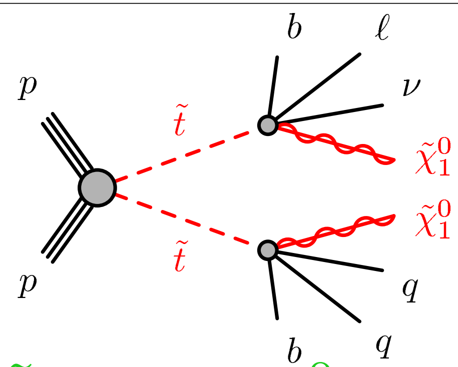
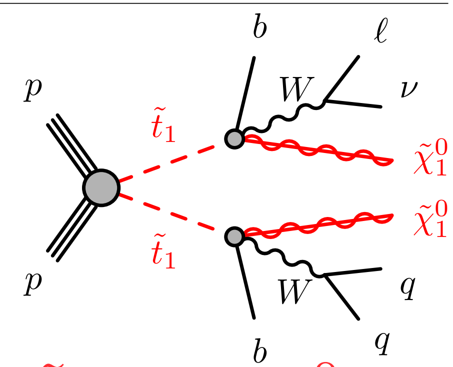
Compressed stop – mind the gap!



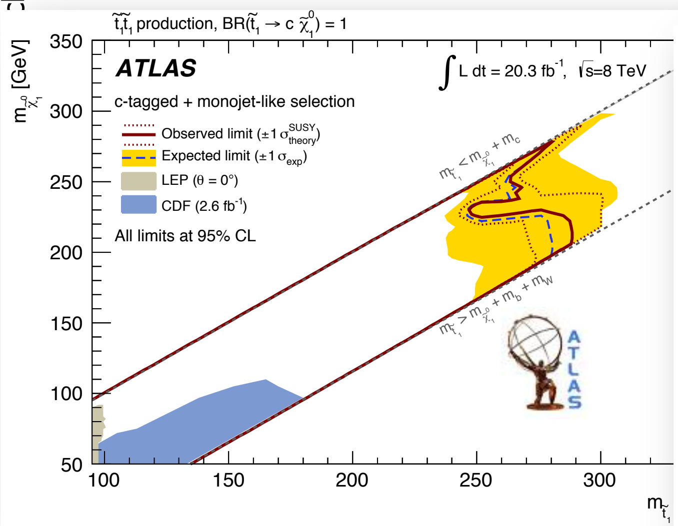
$\tilde{t} \to c\chi_1^0$

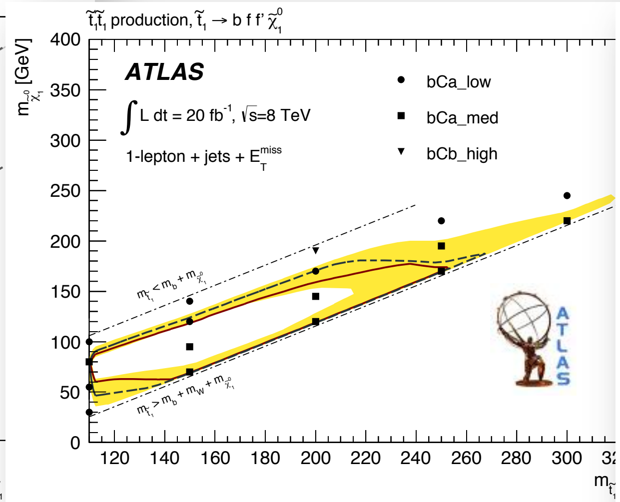


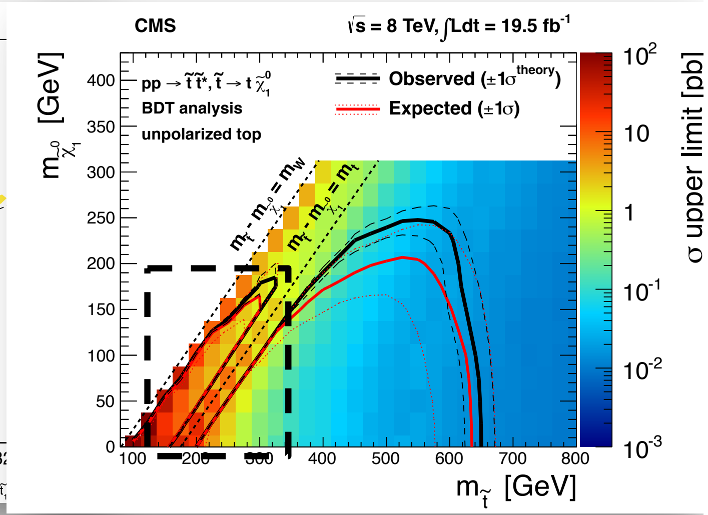
$\tilde{t} \to b f f' \chi_1^0$



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



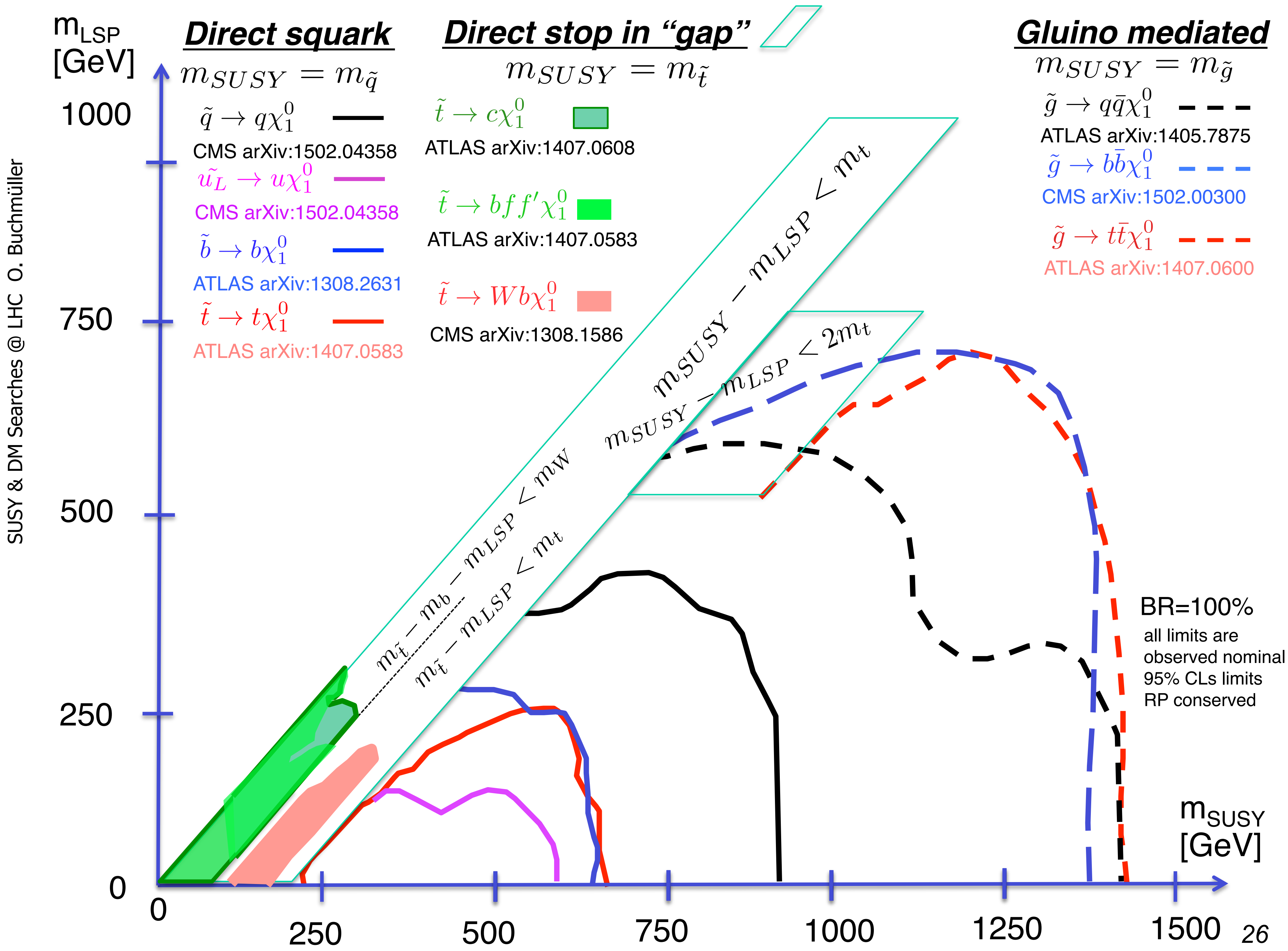




ATLAS arXiv:1407.0608
Mono-jet & c-tag combined

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
$\tilde{t} \to Wb\chi_1^0$
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Gluino mediated
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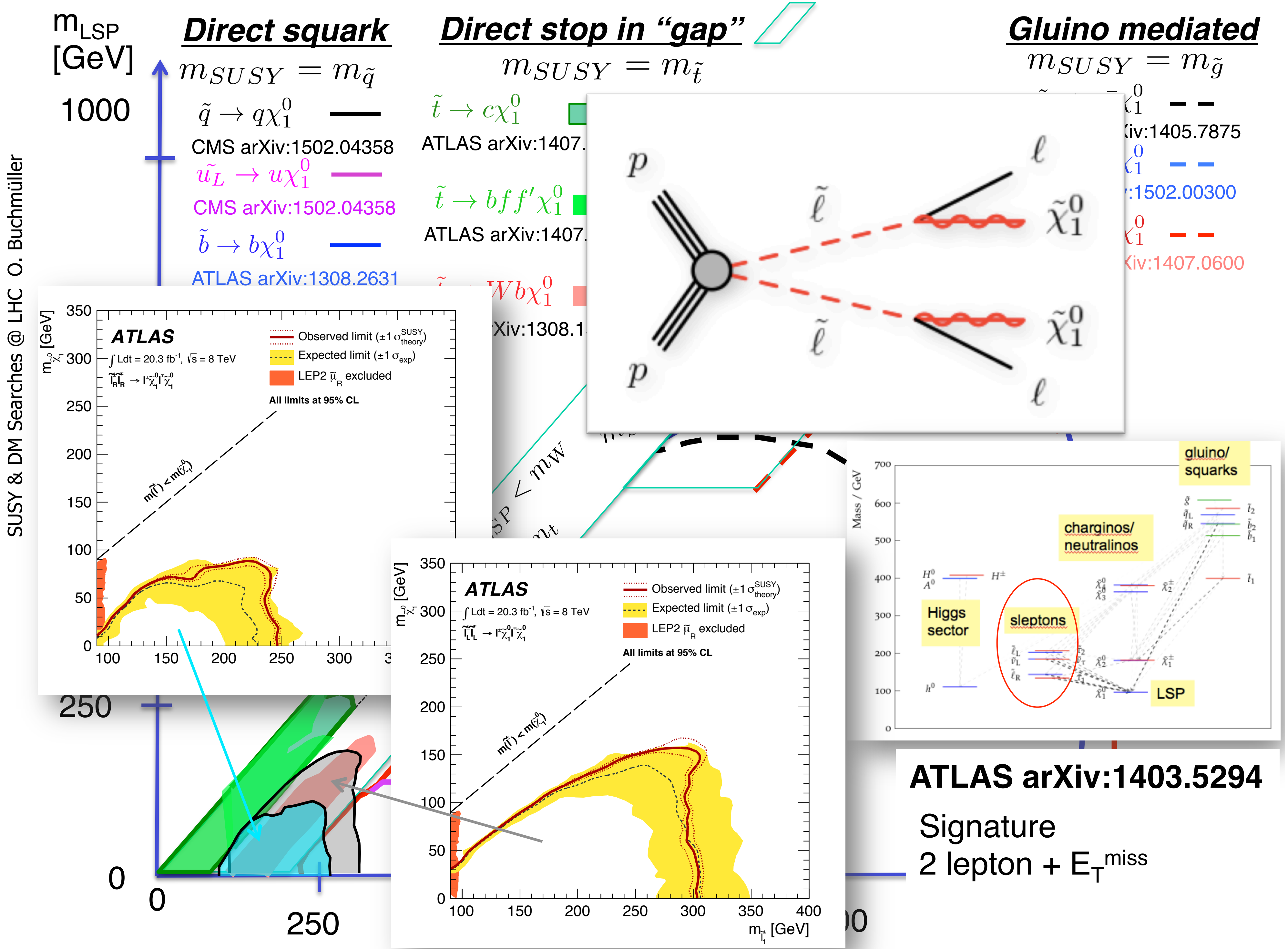
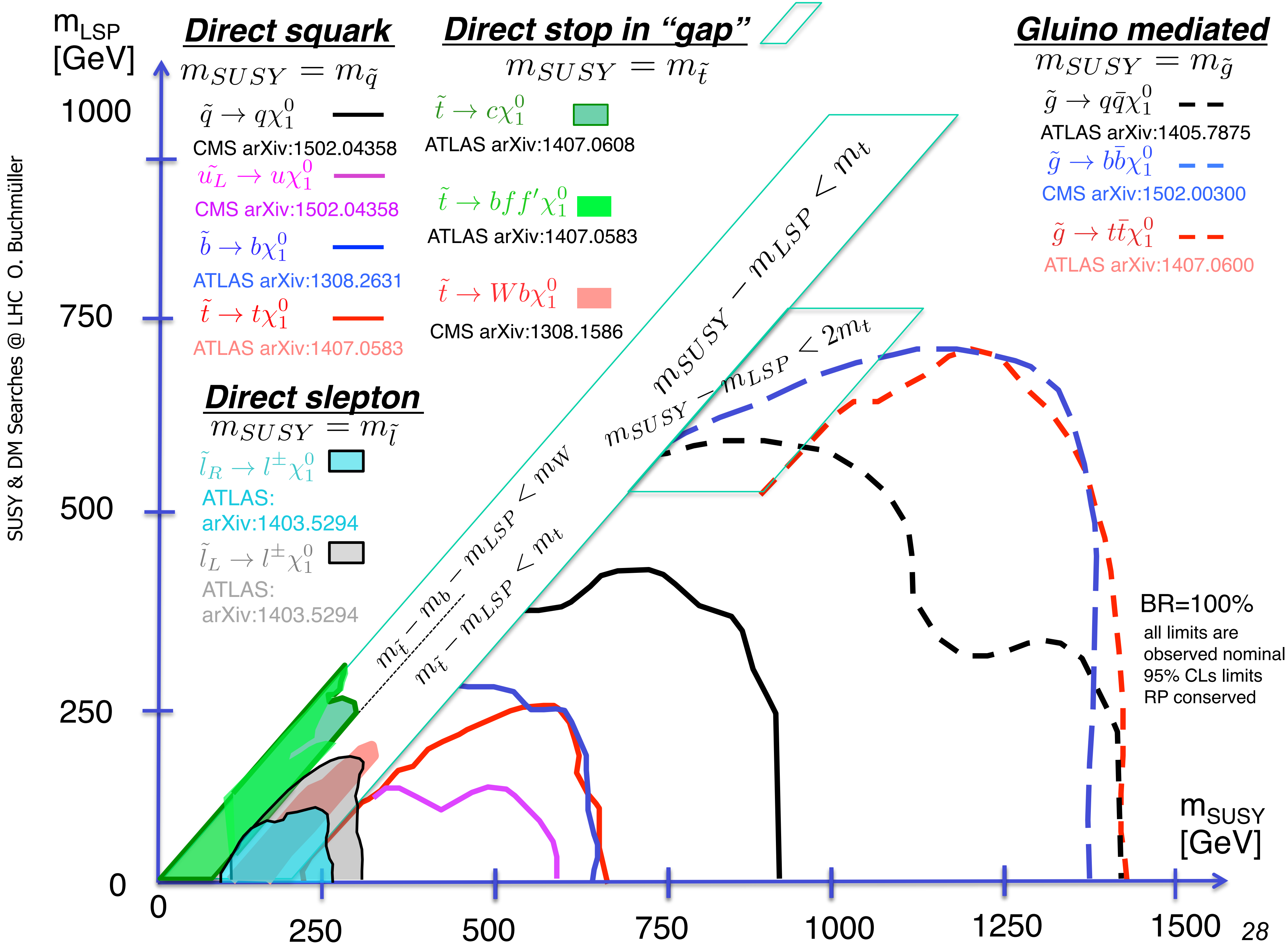
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
SUSY & DM Searches @ LHC O. Buchmüller



m_LSP [GeV]
Direct squark
Direct stop in "gap"
Gluino mediated
$m_{SUSY} = m_{\tilde{q}}$
$m_{SUSY} = m_{\tilde{t}}$
$m_{SUSY} = m_{\tilde{g}}$
1000
$\tilde{q} \to q\chi_1^0$
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
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.
SUSY & DM Searches @ LHC O. Buchmüller
ATLAS
Observed limit (±1 σ^SUSY_theory)
Expected limit (±1 σ_exp)
LEP2 μ̃_R excluded
All limits at 95% CL
∫ Ldt = 20.3 fb⁻¹, √s = 8 TeV
m_χ̃⁰₁ [GeV]
m_l̃ [GeV]
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
Mass / GeV
ATLAS arXiv:1403.5294
Signature
2 lepton + E_T^{miss}
250
0



m_{LSP} [GeV]
Direct squark
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$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
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ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
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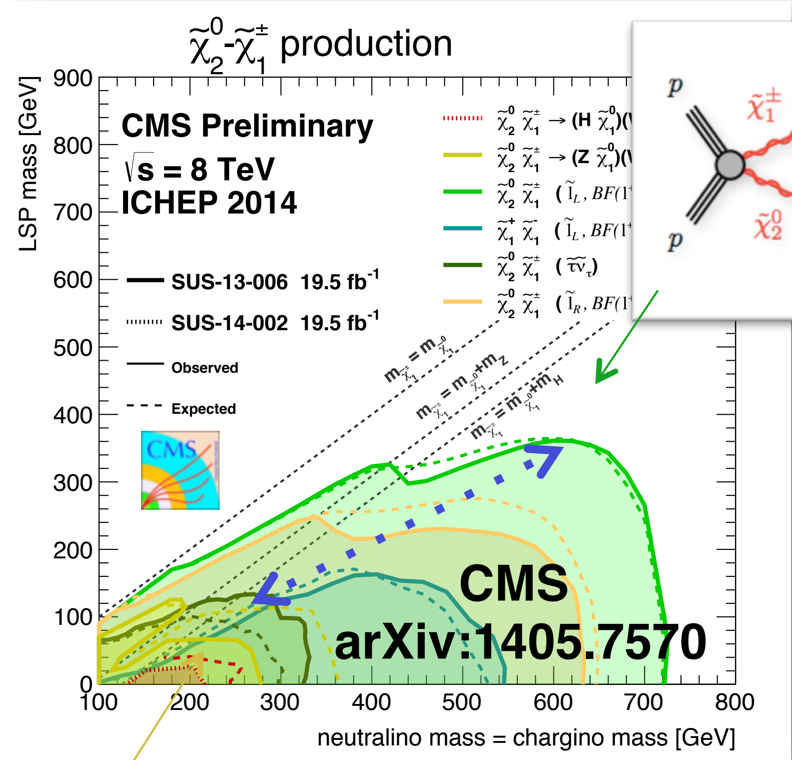
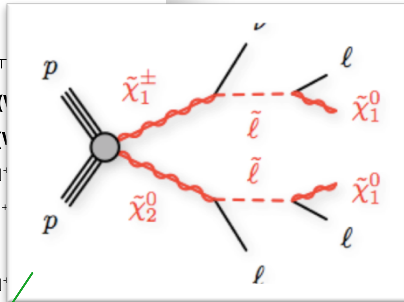
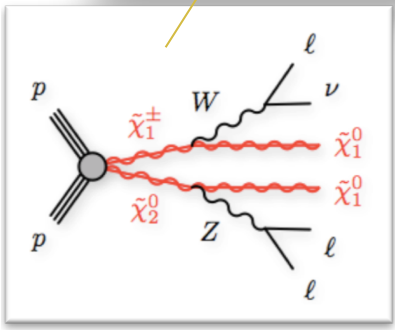
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
SUSY & DM Searches @ LHC O. Buchmüller

Direct chargino/neutralino production

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





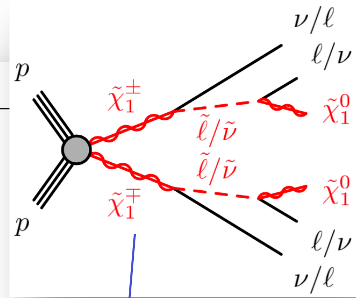


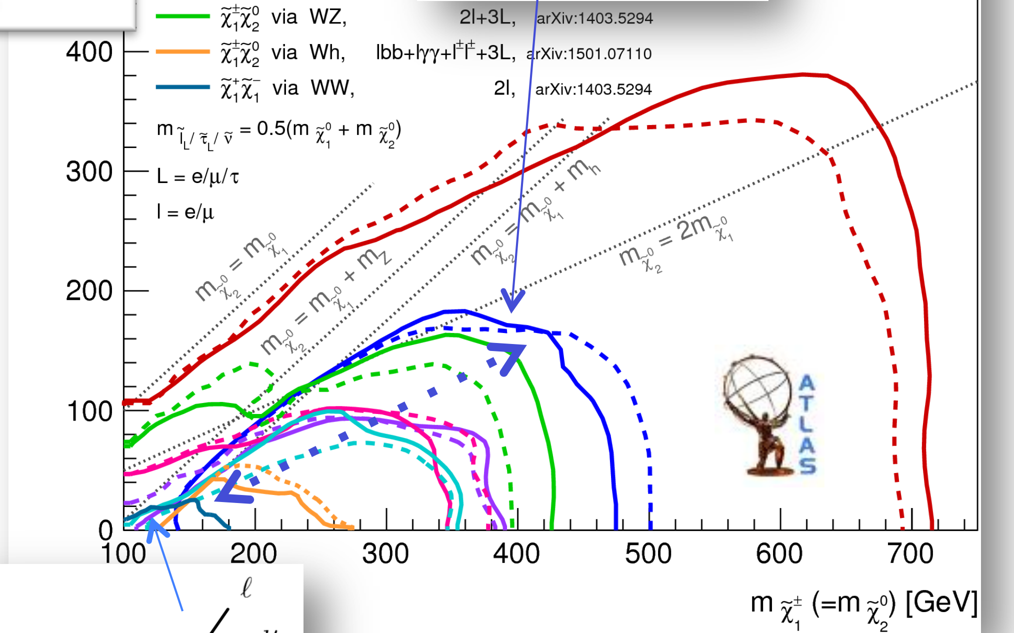
heavy slepton"hard(er)"

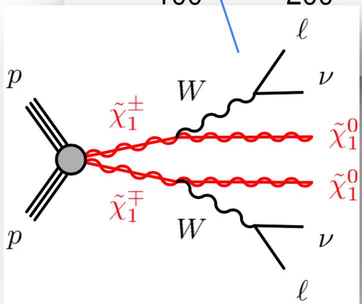
Add $Z(l^+l^-)$+2jets topology in bins of E_t^{miss} to increase sensitivity for "heavy" slepton case

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

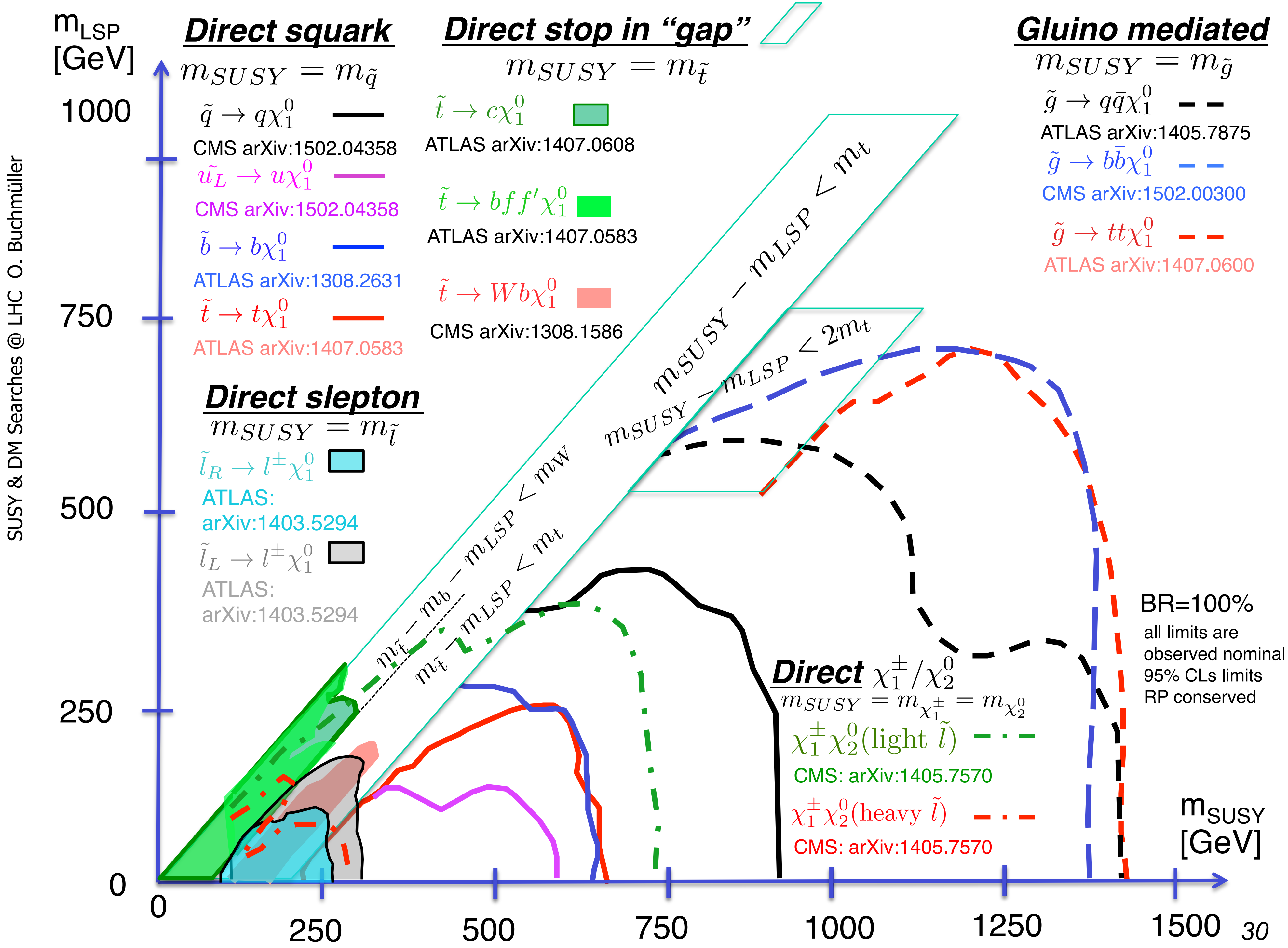
light slepton "easy"







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
$\tilde{t} \to Wb\chi_1^0$
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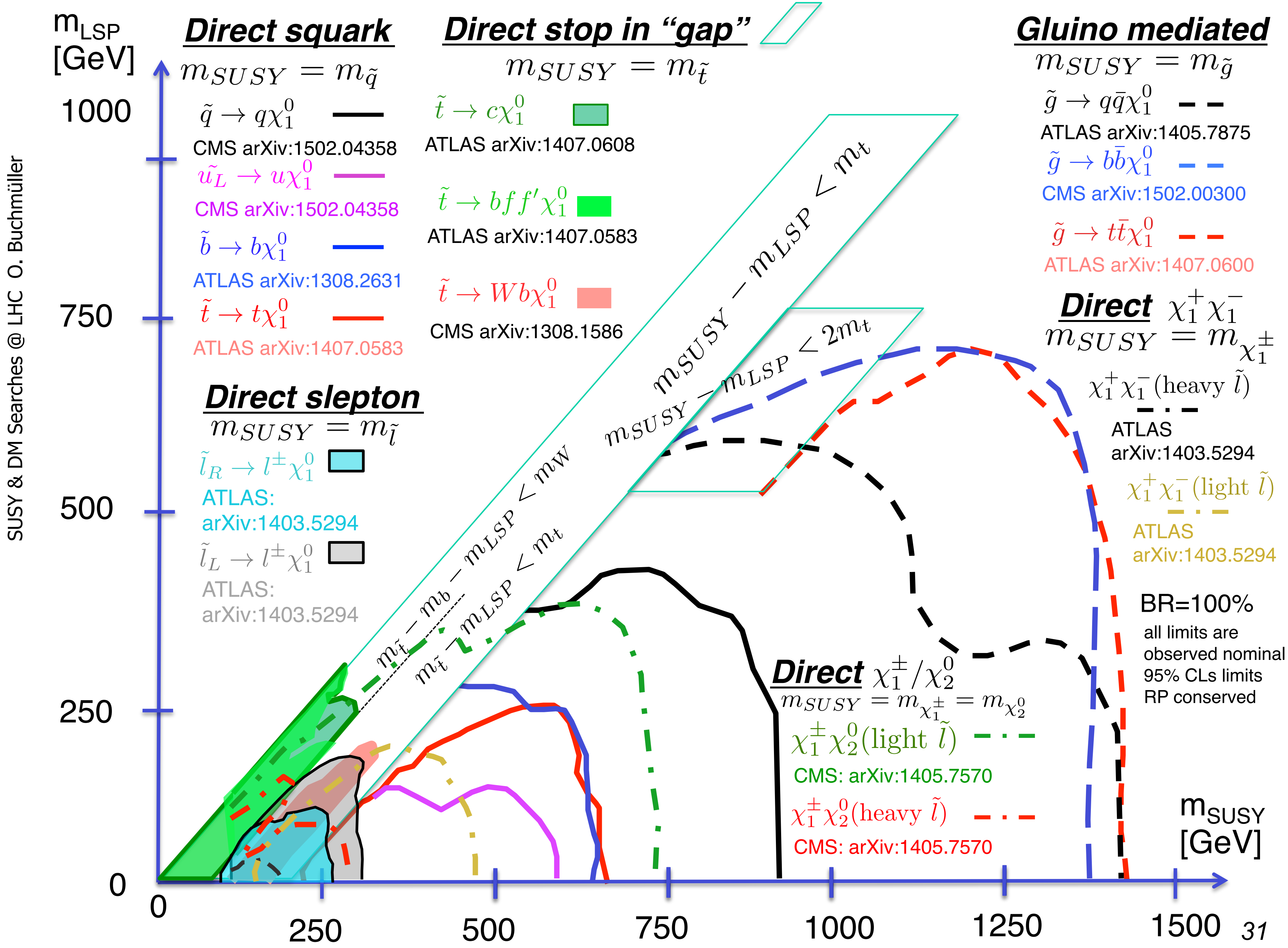
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
$\chi_1^\pm\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^\pm\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
SUSY & DM Searches @ LHC O. Buchmüller
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



m_LSP [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]
SUSY & DM Searches @ LHC O. Buchmüller
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
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$\tilde{t} \to bff'\chi_1^0$
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Gluino mediated
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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
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
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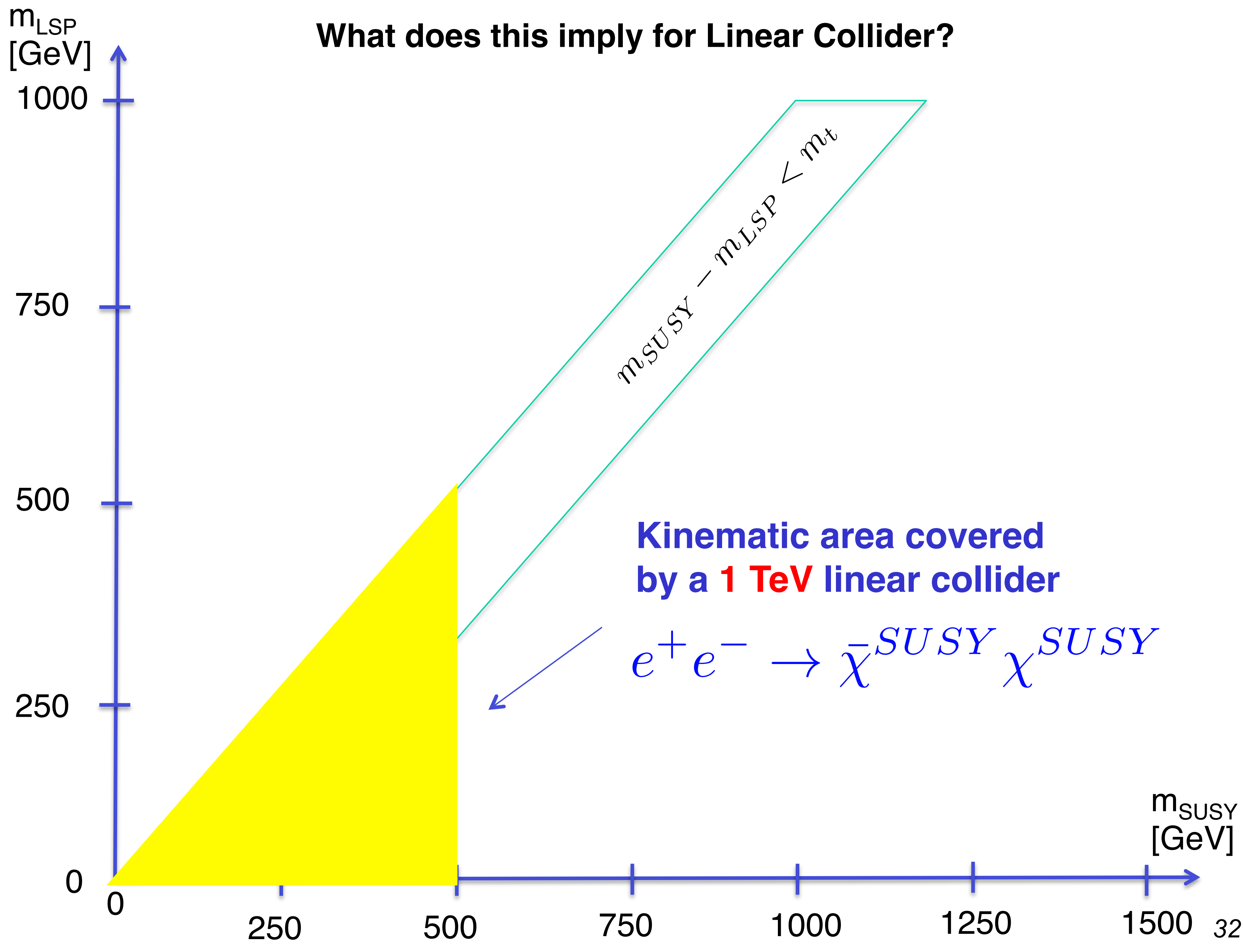
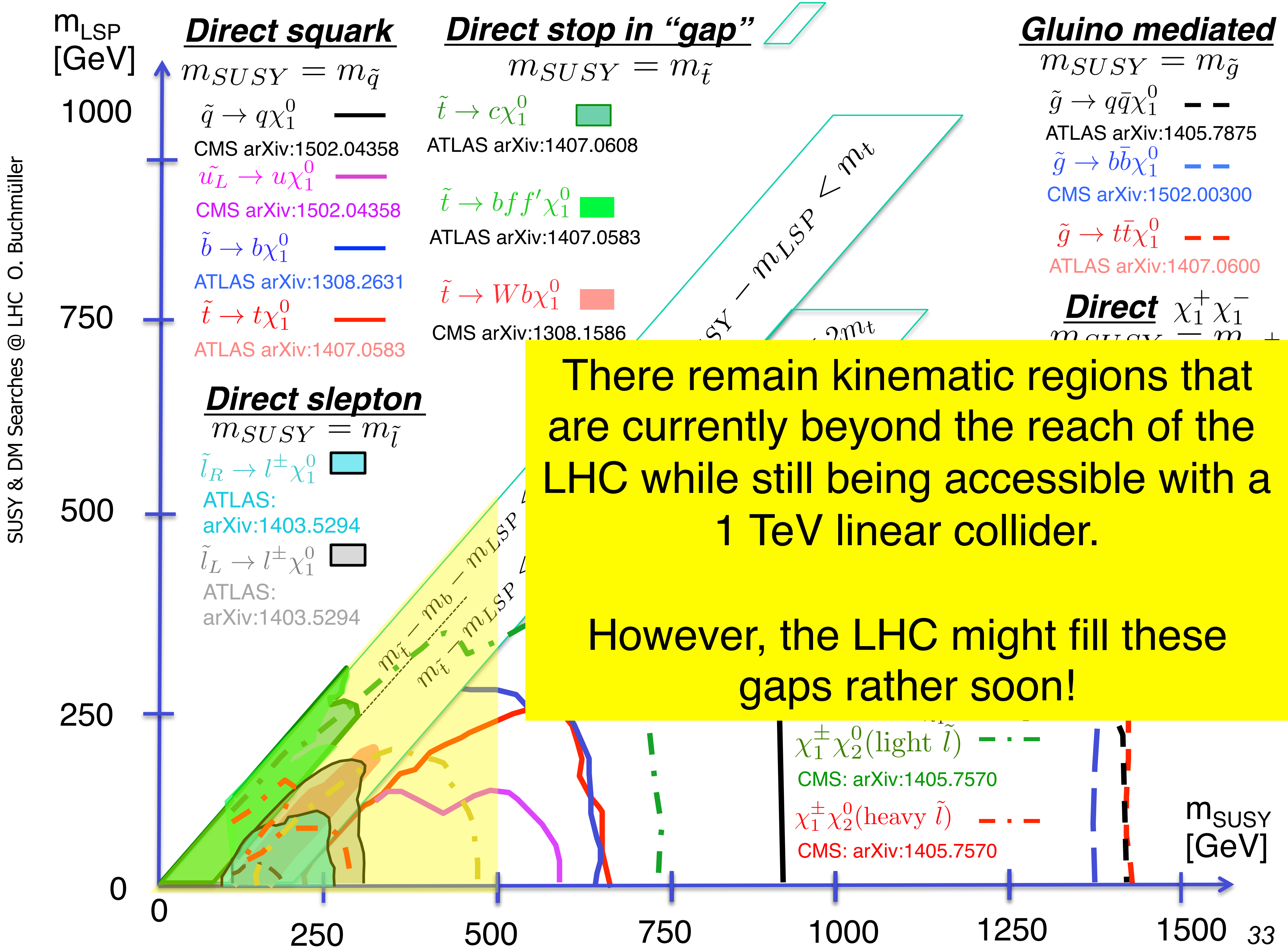
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
Direct $\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
$\chi_1^\pm\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^\pm\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570

What does this imply for Linear Collider?





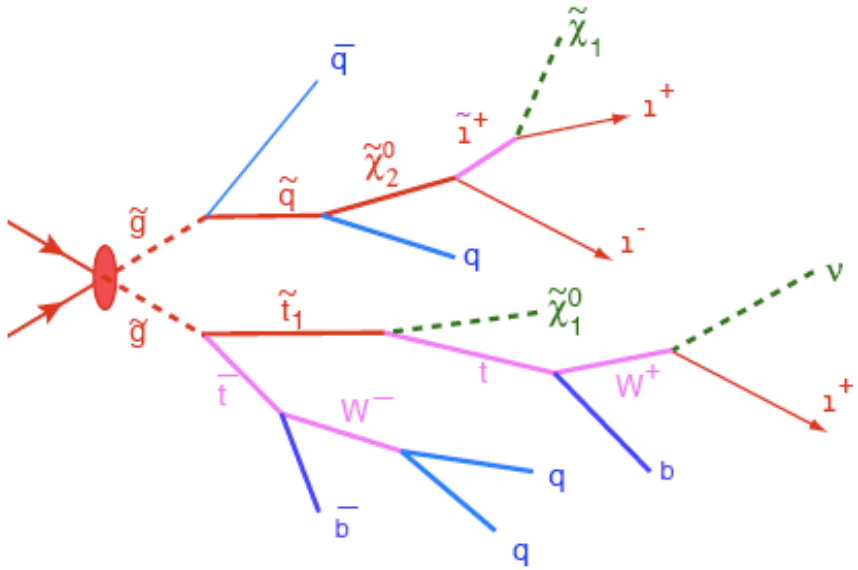
There remain kinematic regions that are currently beyond the reach of the LHC while still being accessible with a 1 TeV linear collider.

However, the LHC might fill these gaps rather soon!

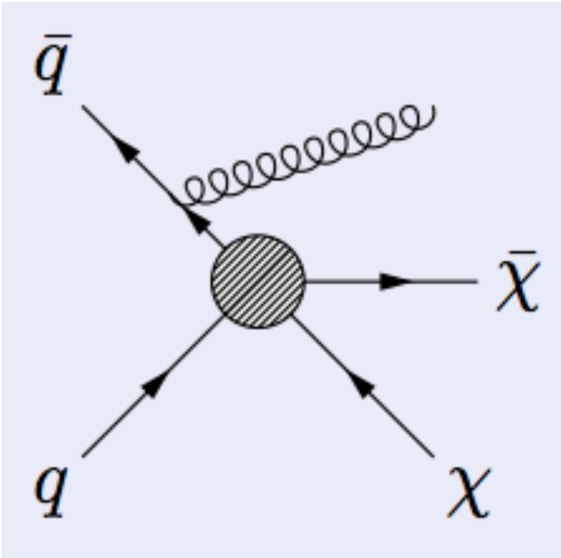
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY

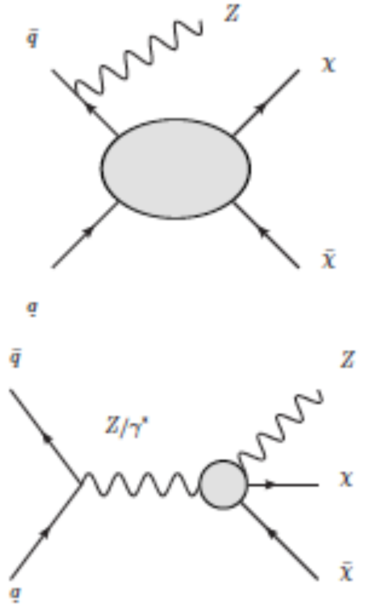


Example:
Effective Field Theory
Simplified models



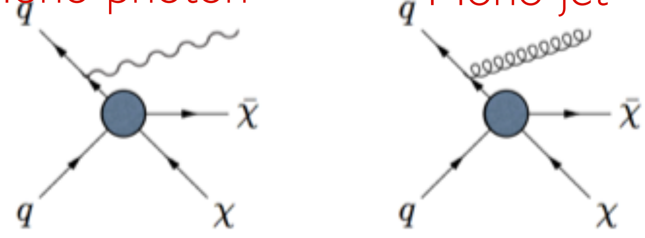
Mono-Mania (at the LHC)

Mono-Z

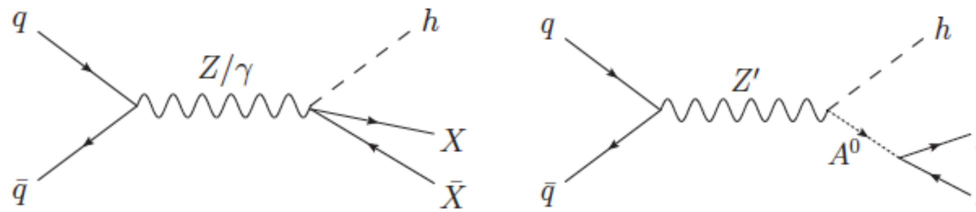


Mono-photon

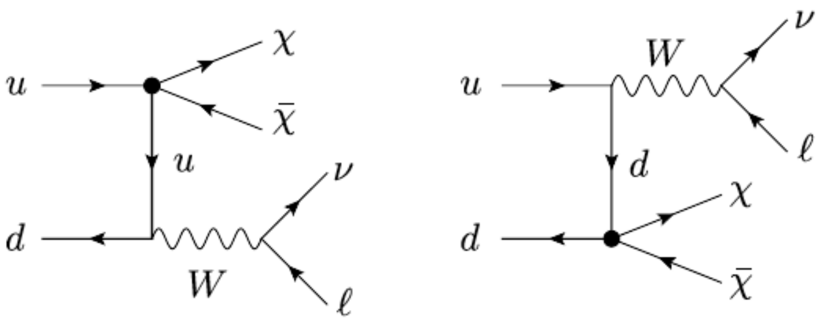
Mono-jet



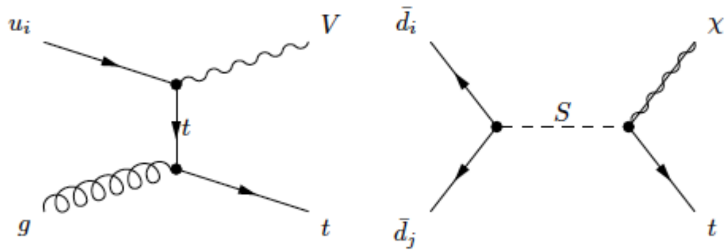
Mono-Higgs



Mono-W

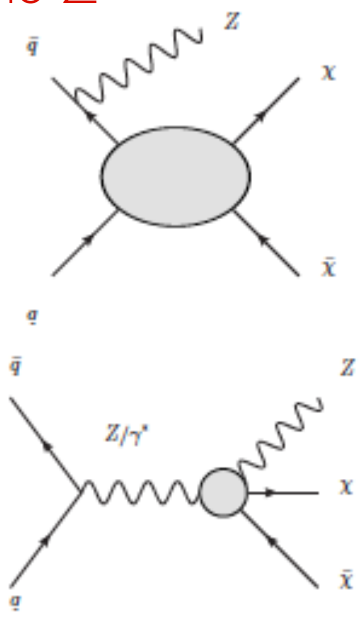


Mono-top



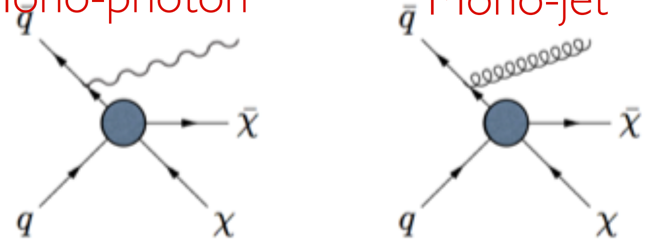
Mono-Mania (at the LHC)

Mono-Z

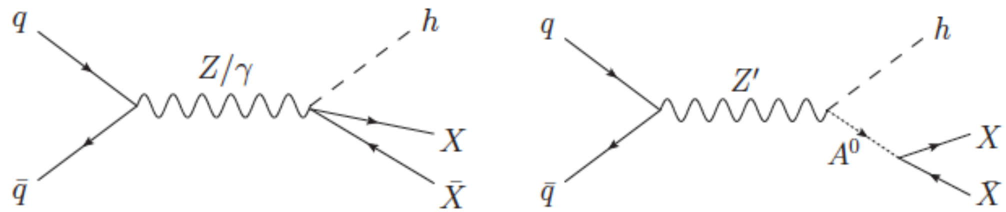


Mono-photon

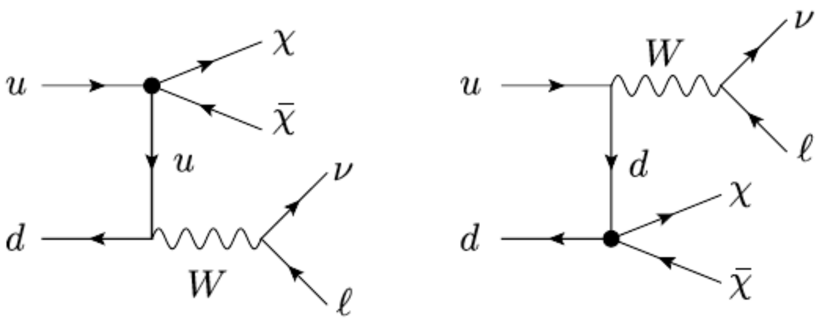
Mono-jet



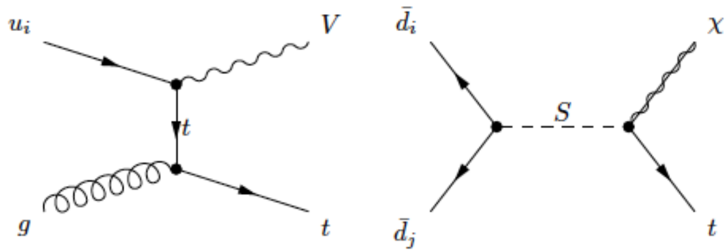
Mono-Higgs



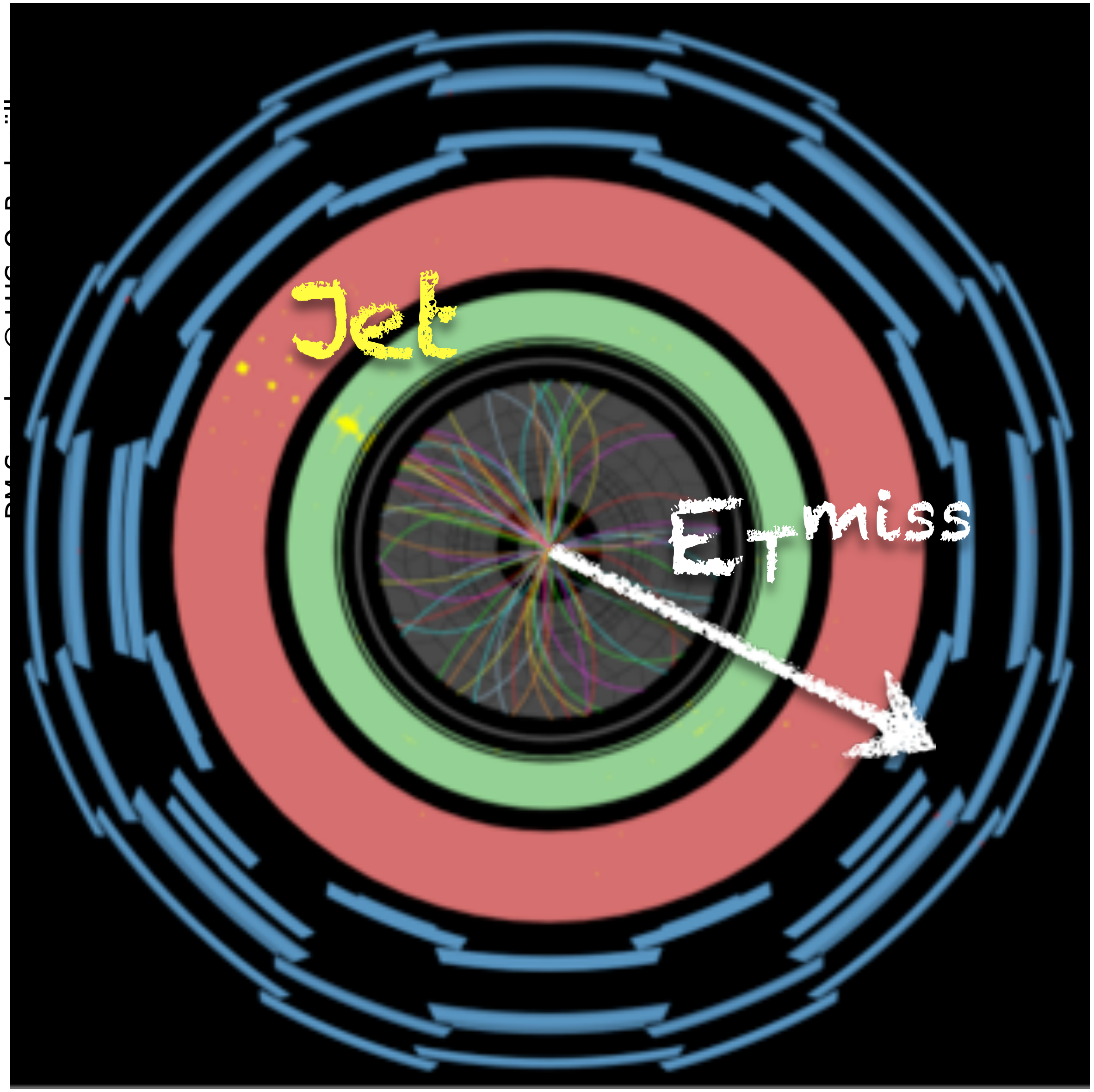
Mono-W



Mono-top



Mono-X searches at colliders



E_T^{miss} trigger

Example Monojet

(8 TeV, 20.3 fb-1)

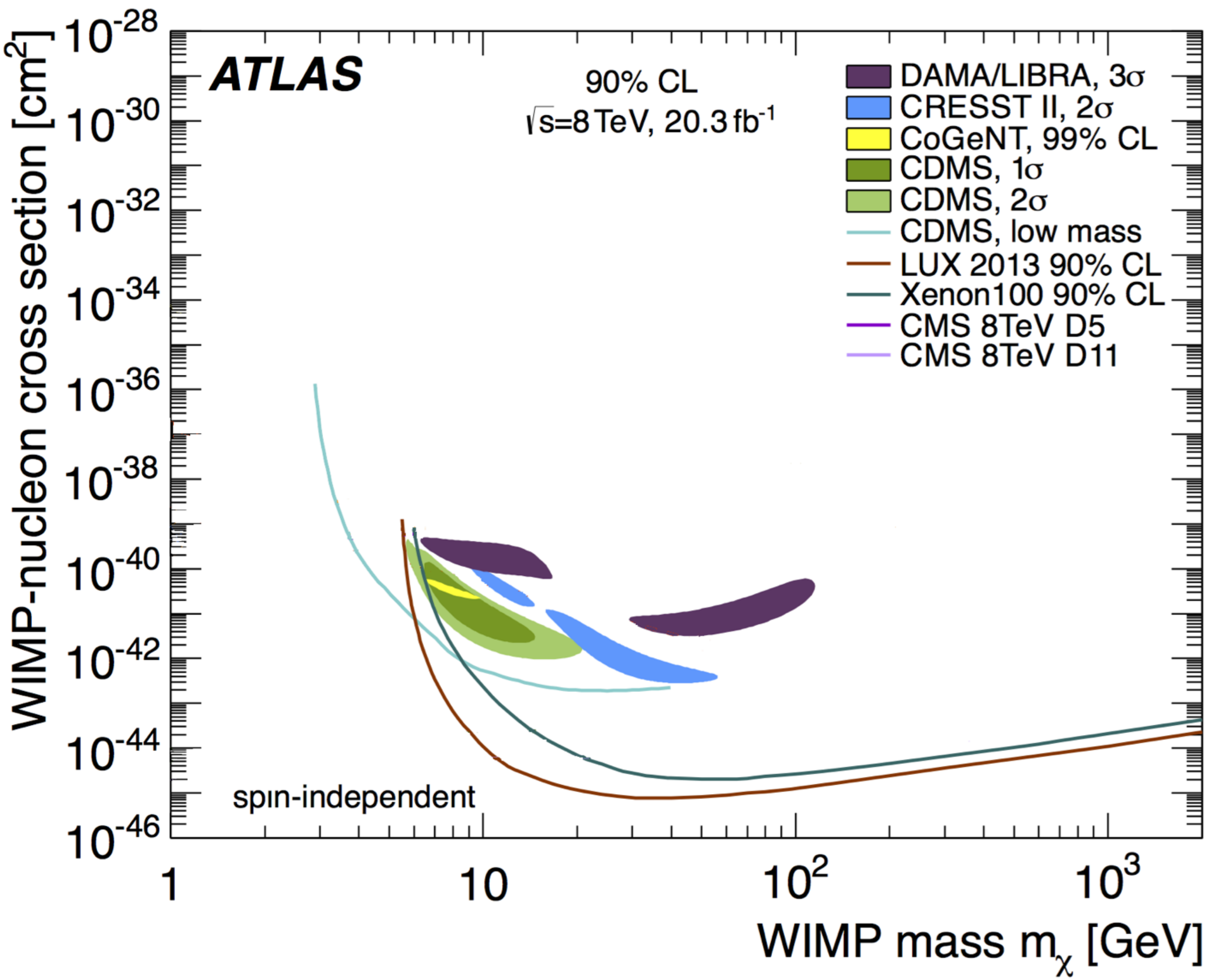
- E_T^{miss} , $p_T(j)$ > 150 - 900 GeV
- 1 or 2 jets (anti-k_T, R=0.4, p_T>30 GeV)
- $|\Delta\phi(E_T^{miss}, j_2)| > 0.5$

Example Monophoton

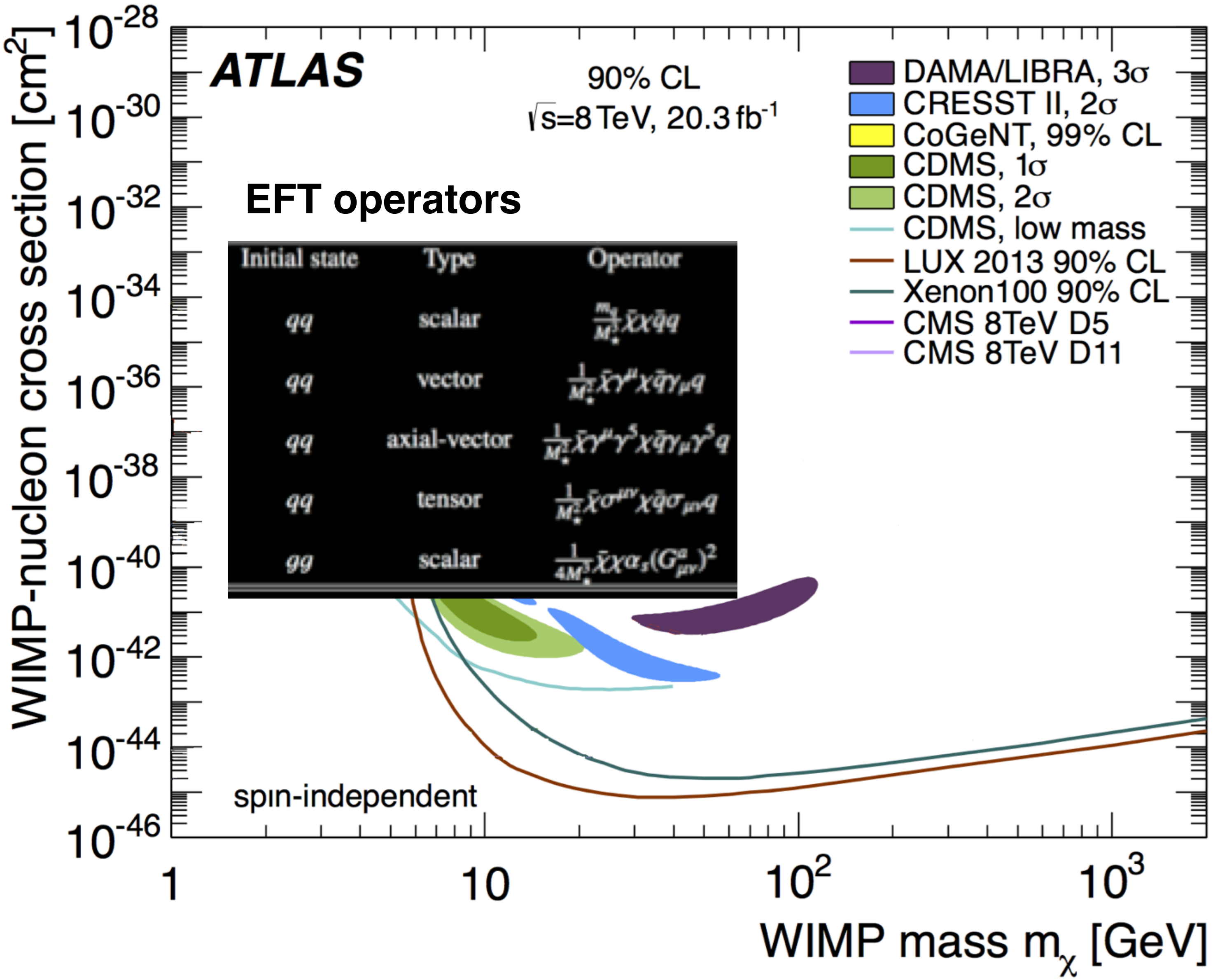
(8 TeV, 19.6 fb^{-1}):

- 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)

ATLAS Mono-Jet: Comparison with Direct Detection

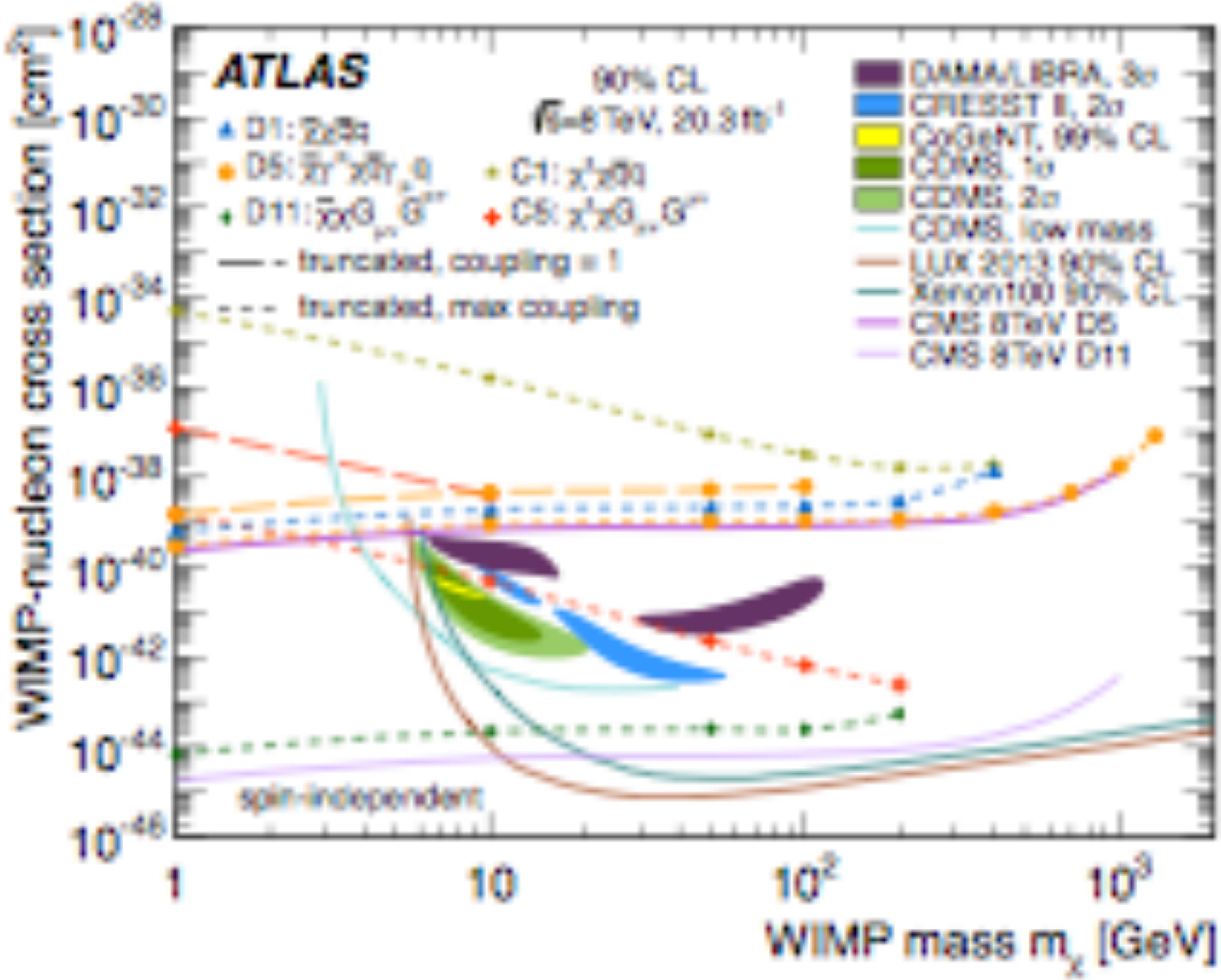


ATLAS Mono-Jet: Comparison with Direct Detection



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



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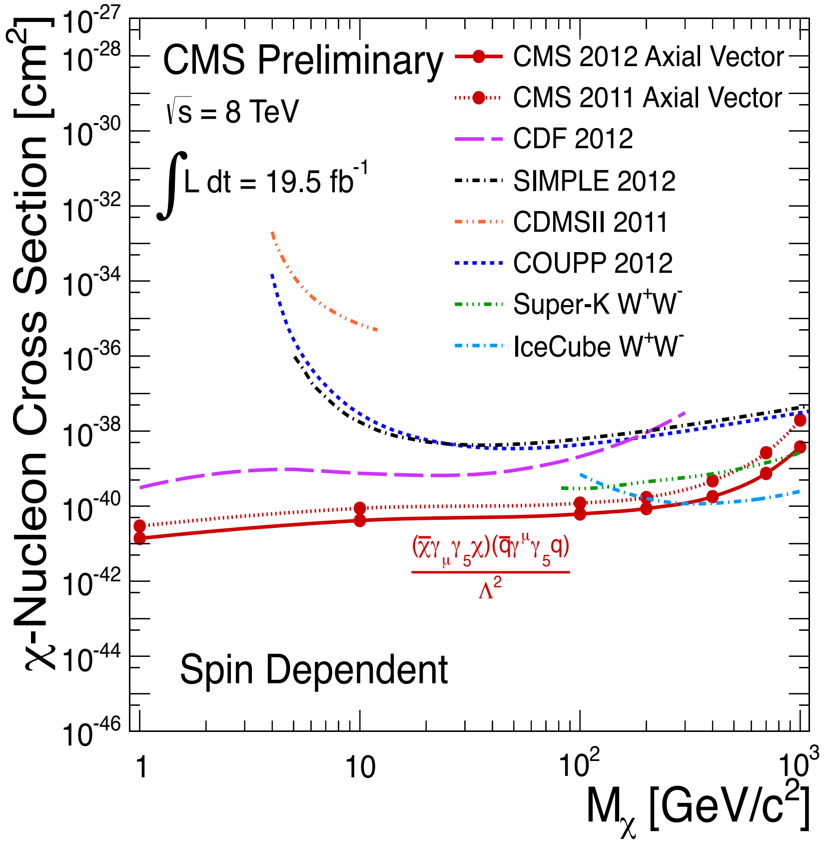
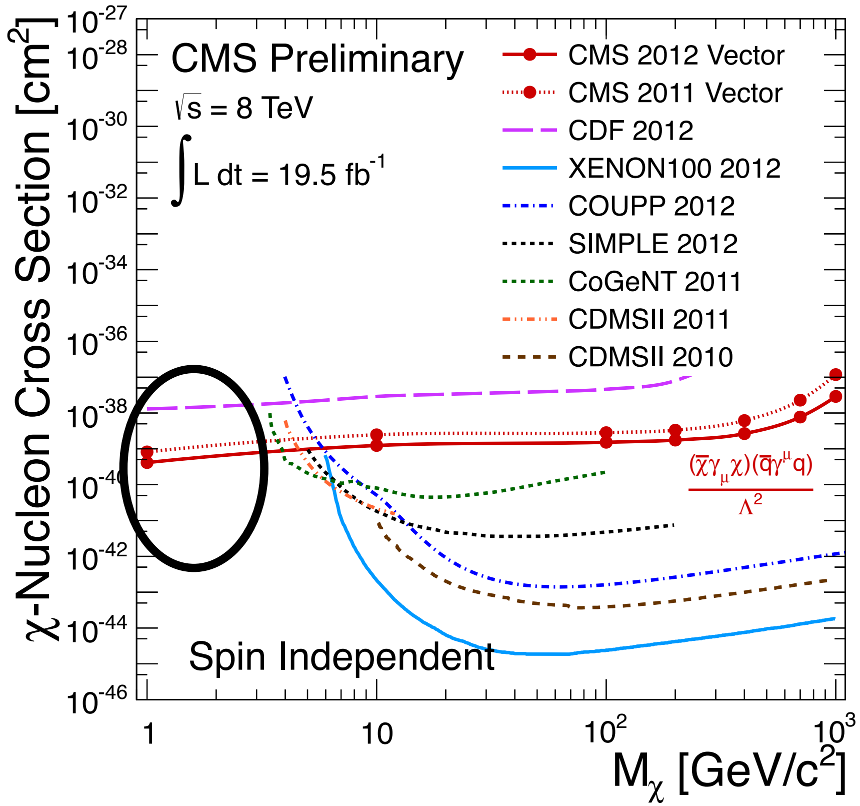
Mono-Jet analyses better than direct detection?!



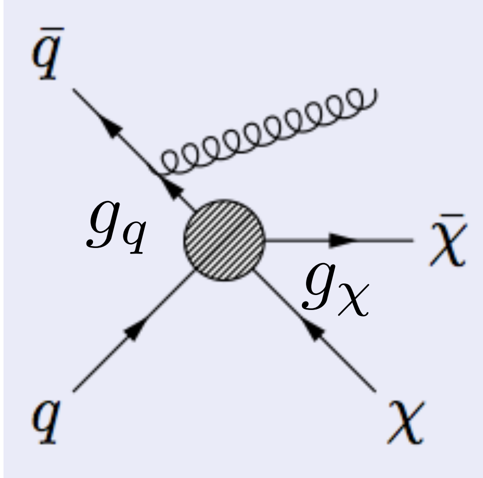


Claim [often made]:

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:

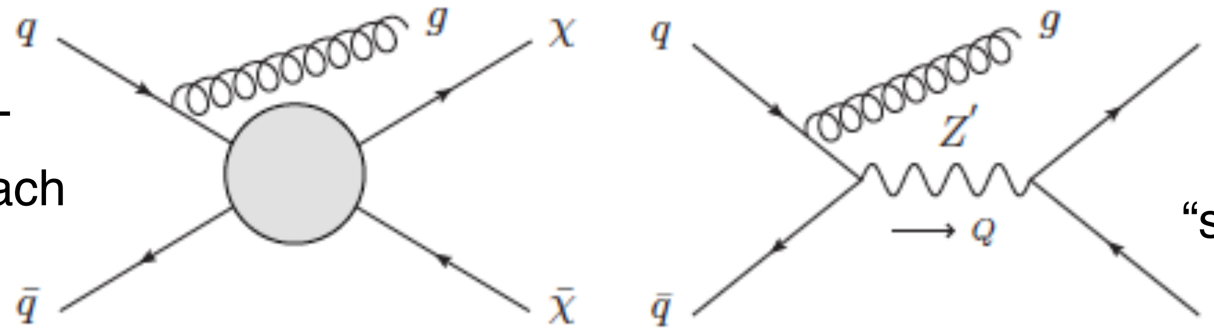
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Validity of Effective Field Theory Limits

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

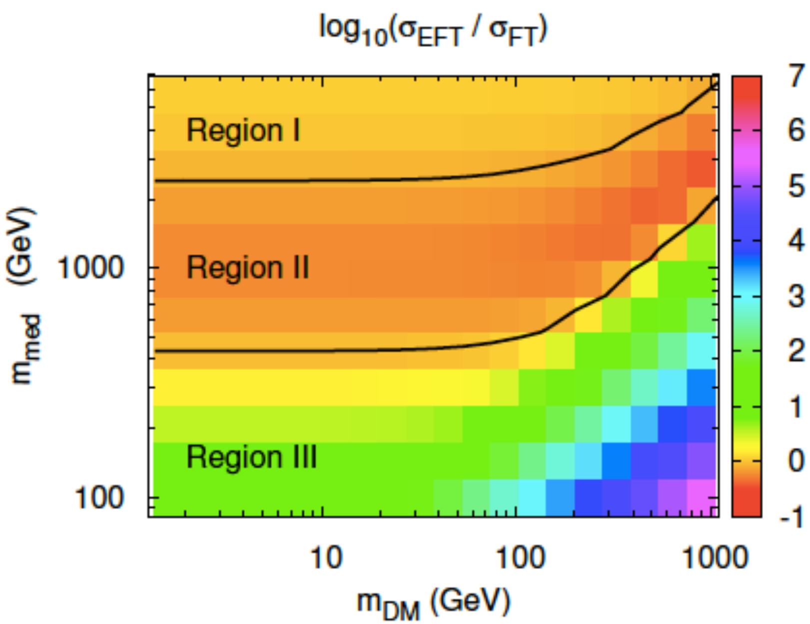
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

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!

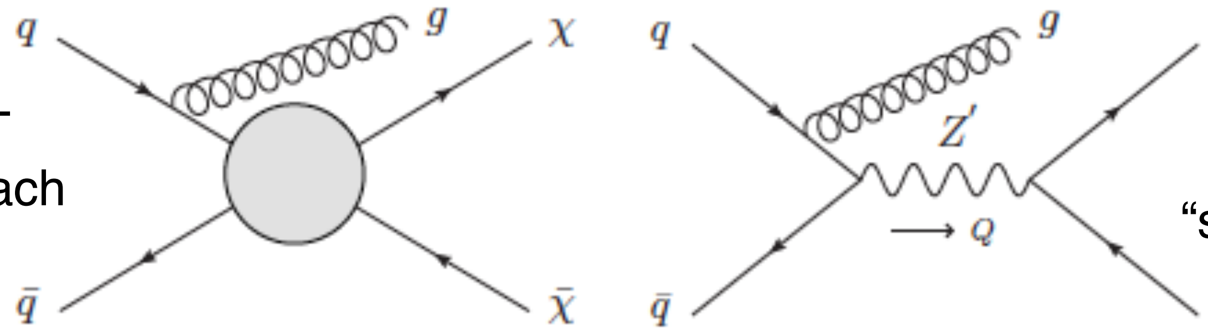
Region III: EFT yields significant stronger limits then FT
➢ EFT limits are too aggressive!

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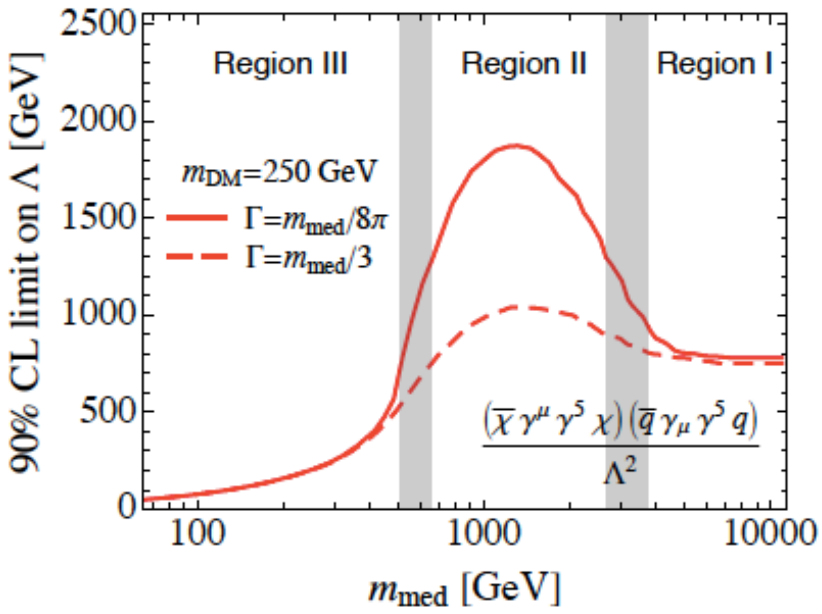
Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



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!

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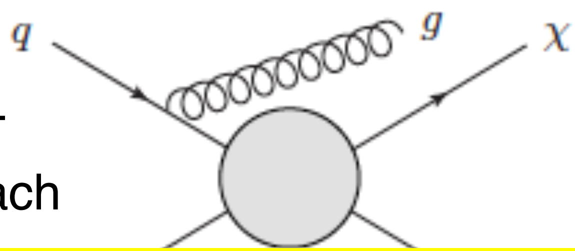
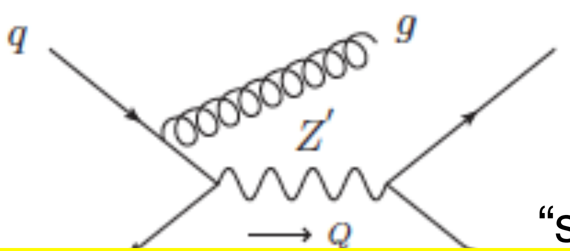
Validity of Effective Field Theory Limits

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

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

EFT approach



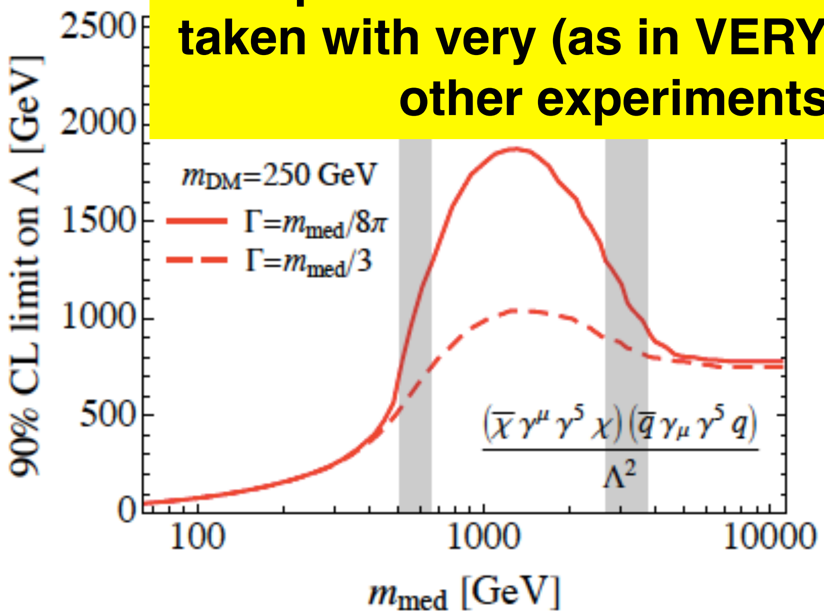


FT
one diagram
“simplified model”

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

Use v … clusion!

… :



Region I: Heavy m_{med}

➢ EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

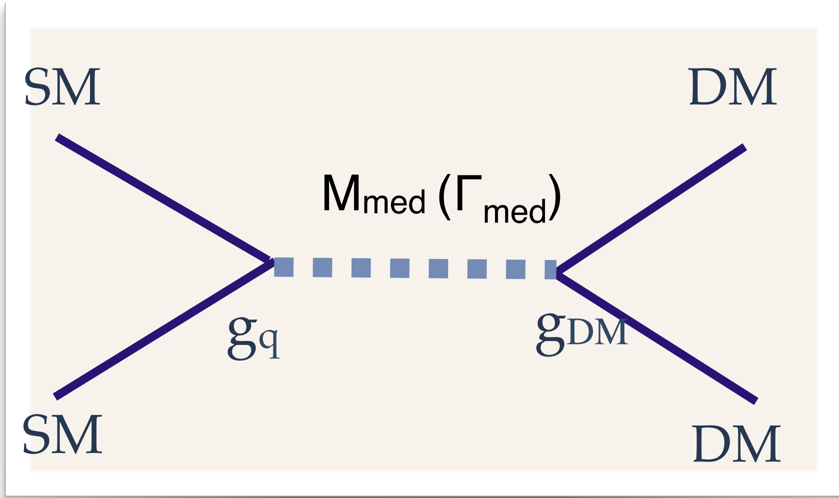
➢ EFT limits are too conservative!

Region III: Low m_{med}

➢ EFT limits are too aggressive!

Minimal Simplified Dark Matter Model

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

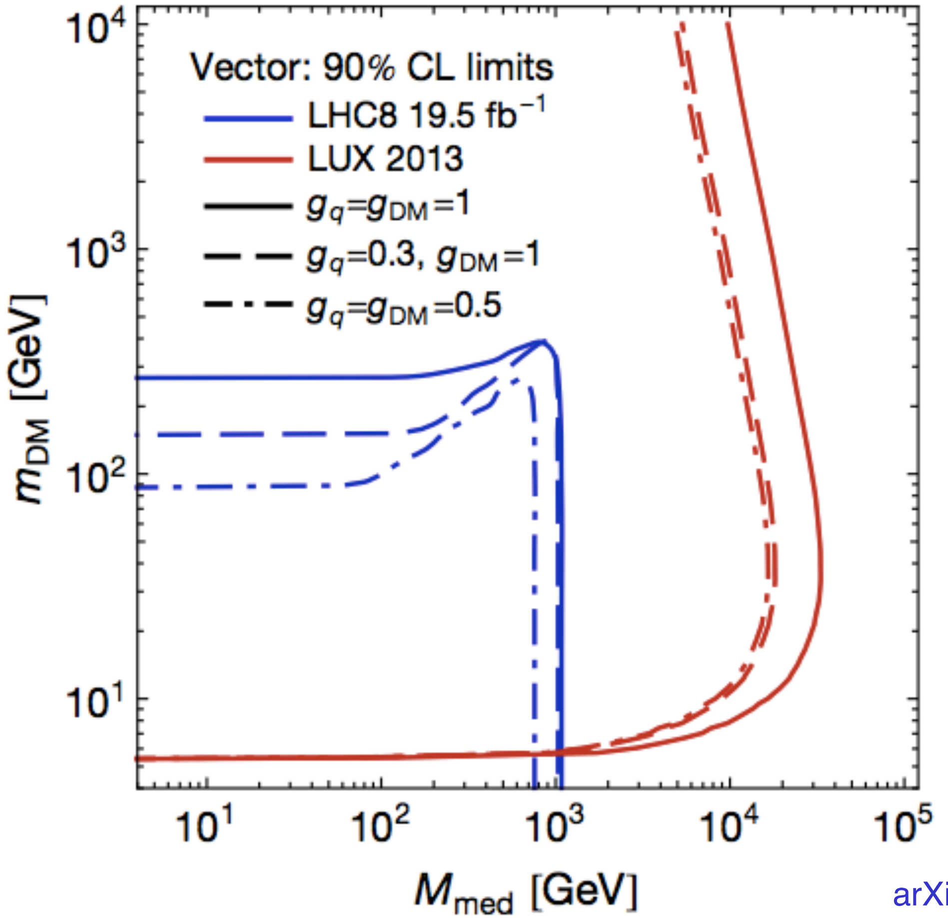
(Γ_{med} can also be free as long
As $\Gamma_{med} < M_{med}$)

Collider vs Direct Detection

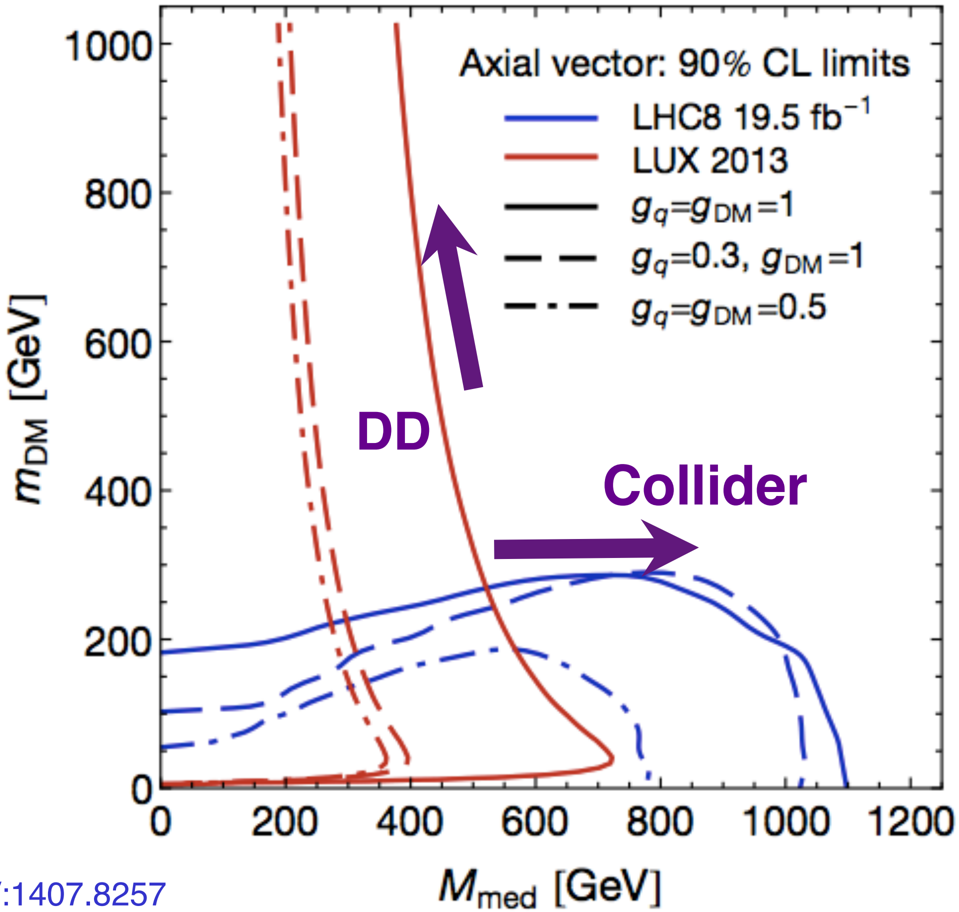
M_{DM}	M_{med}
g_q	g_{DM}

nmüller

Vector



Axial vector

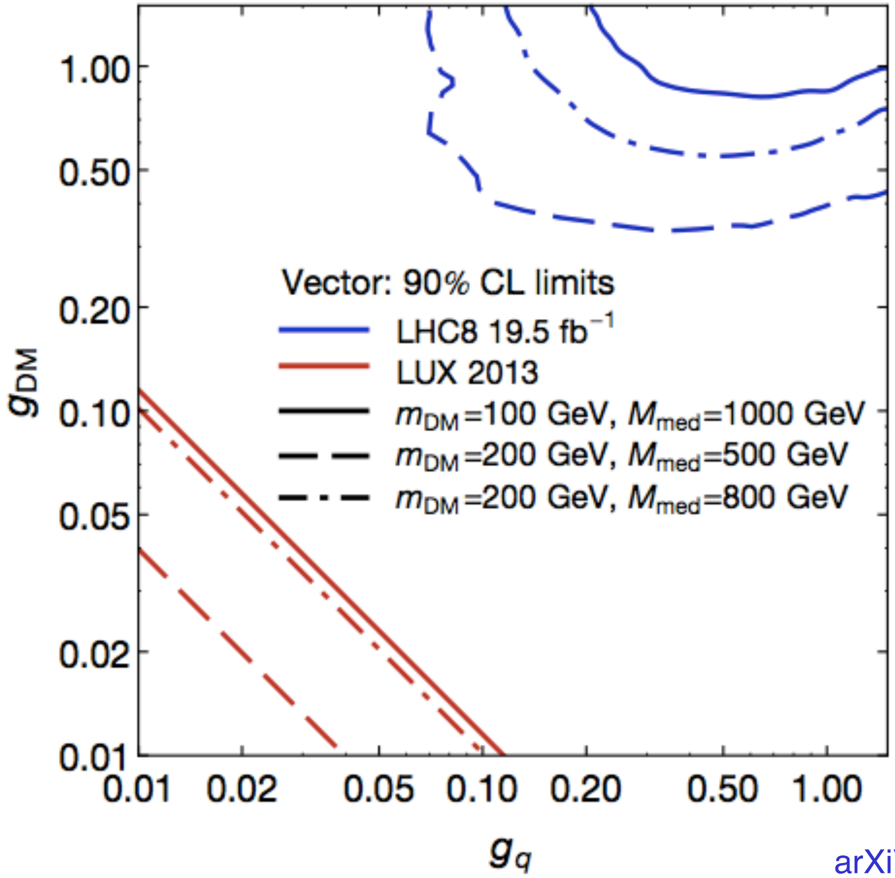


arXiV:1407.8257

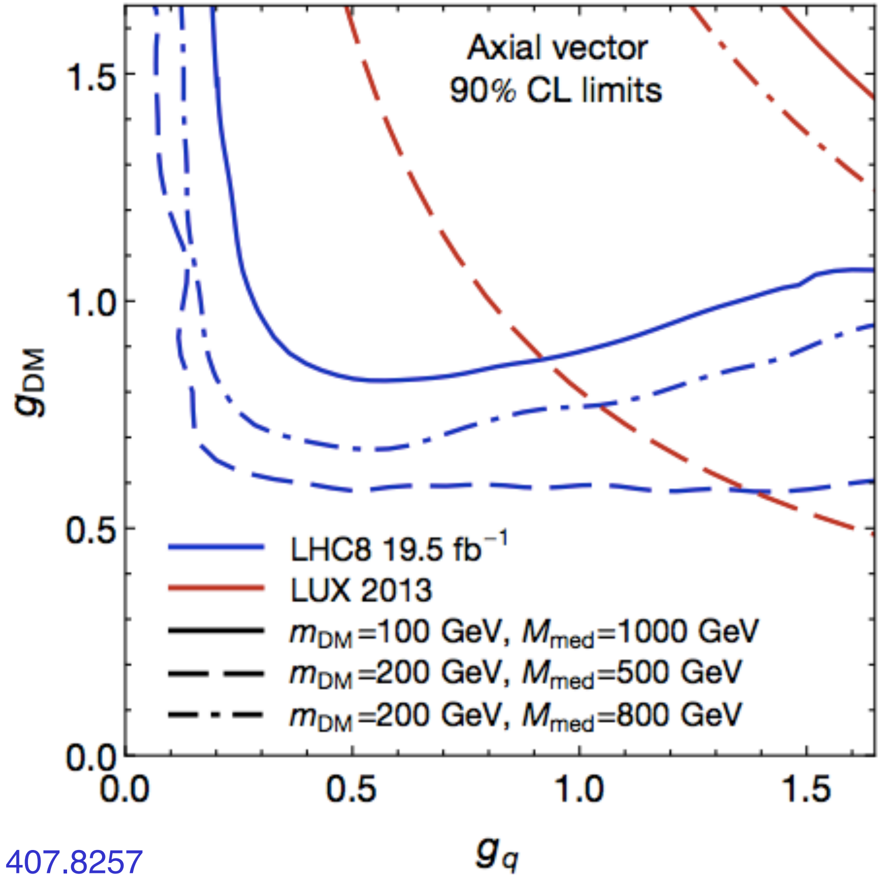
Collider vs Direct Detection

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

Vector



Axial vector



arXiV:1407.8257

Scalar and Pseudoscalar

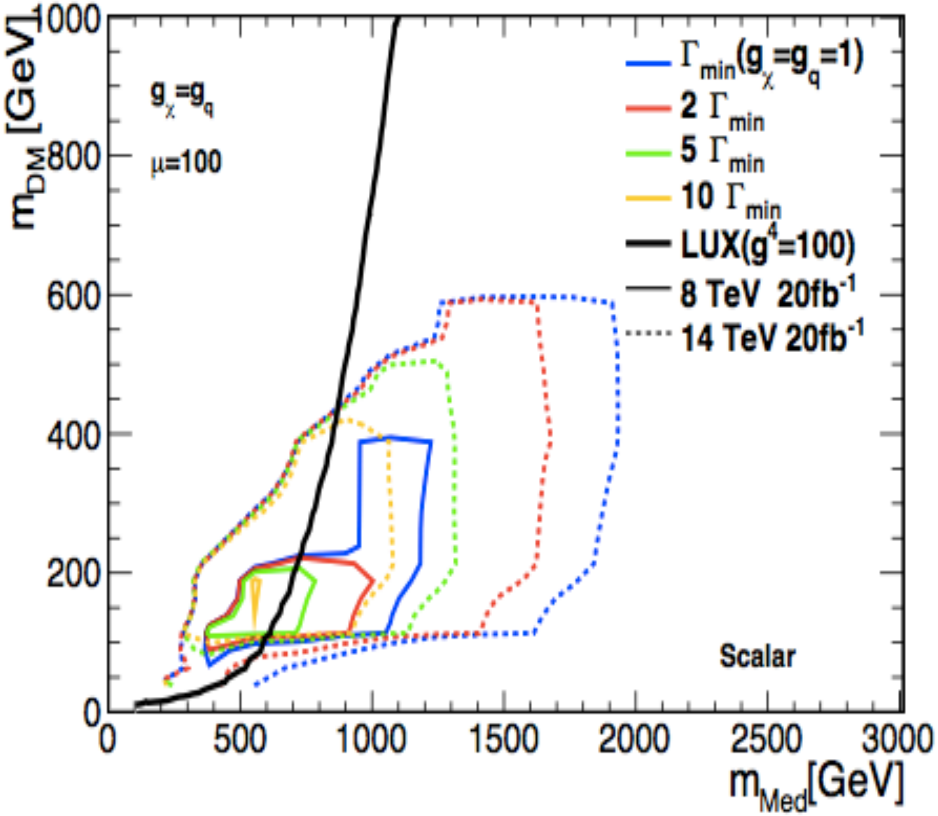
Philip Harris, Valentin V. Khoze,
Michael Spannowsky, Ciaran Williams

arXiv:1411.0535

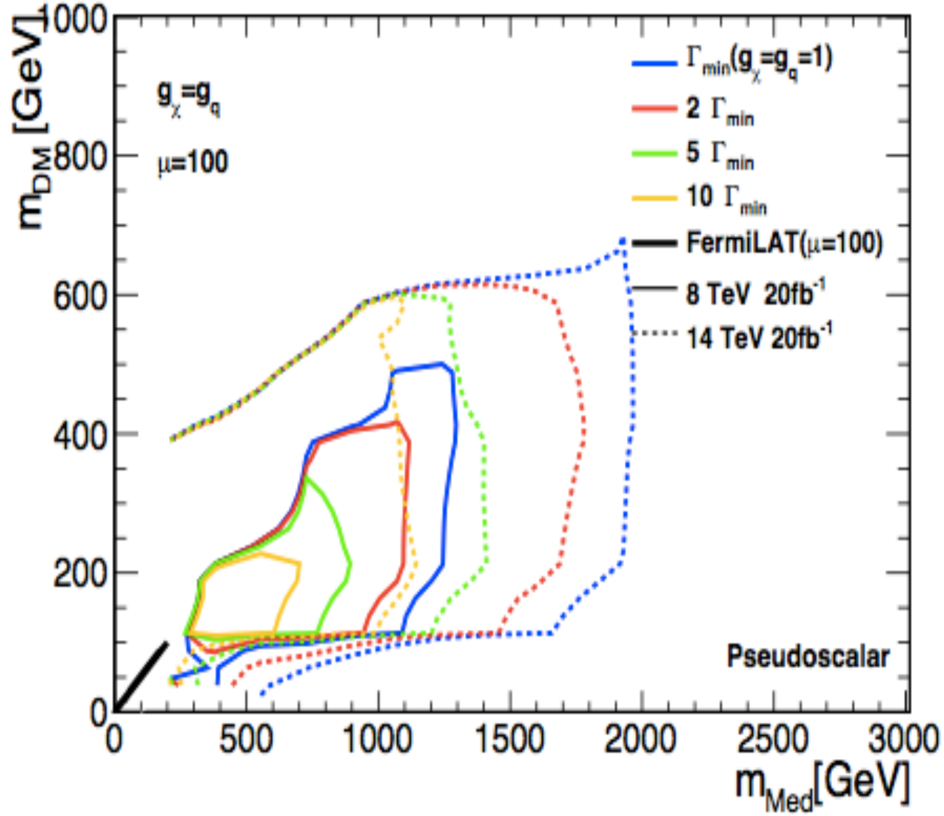
See also Buckley et al
arXiv:1410.6497

chmüller

Scalar



Pseudoscalar



Projections for Future Experiments: M_{med} vs M_{DM}

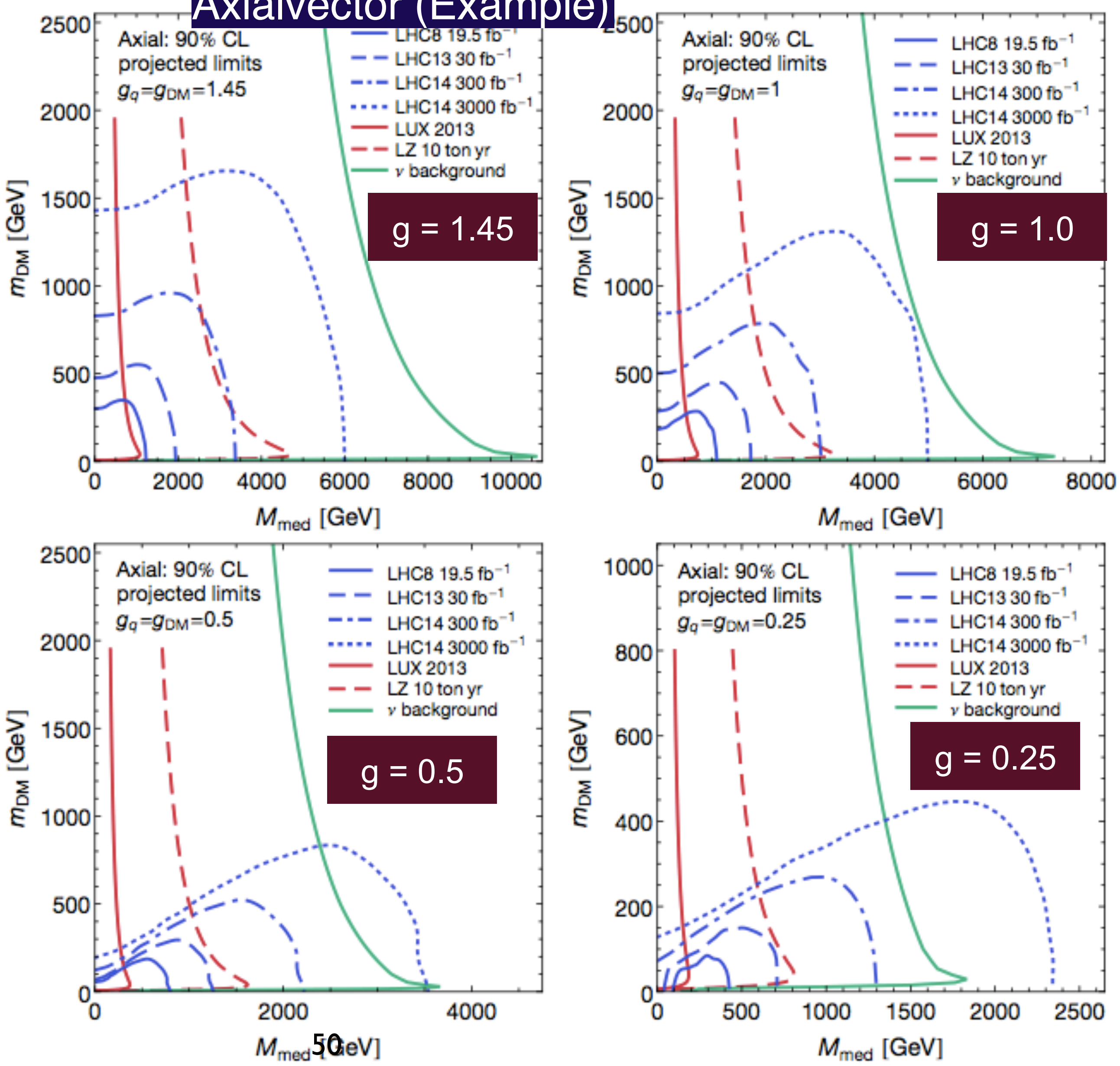
Based on work from : S. Malik, OB, M.Dolan, C.McCabe et al arXiV:1409.4075

Limits from 8 TeV monojet search and projected limits for 3 LHC scenarios:
- 13 TeV 30 fb^{-1}
- 14 TeV, 300 fb^{-1}
- 14 TeV, 3000 fb^{-1}

LUX 2013 limits and projected limits for LZ assuming 10 tonne-year exposure

Discovery reach accounting for coherent neutrino scattering

Axialvector (Example)



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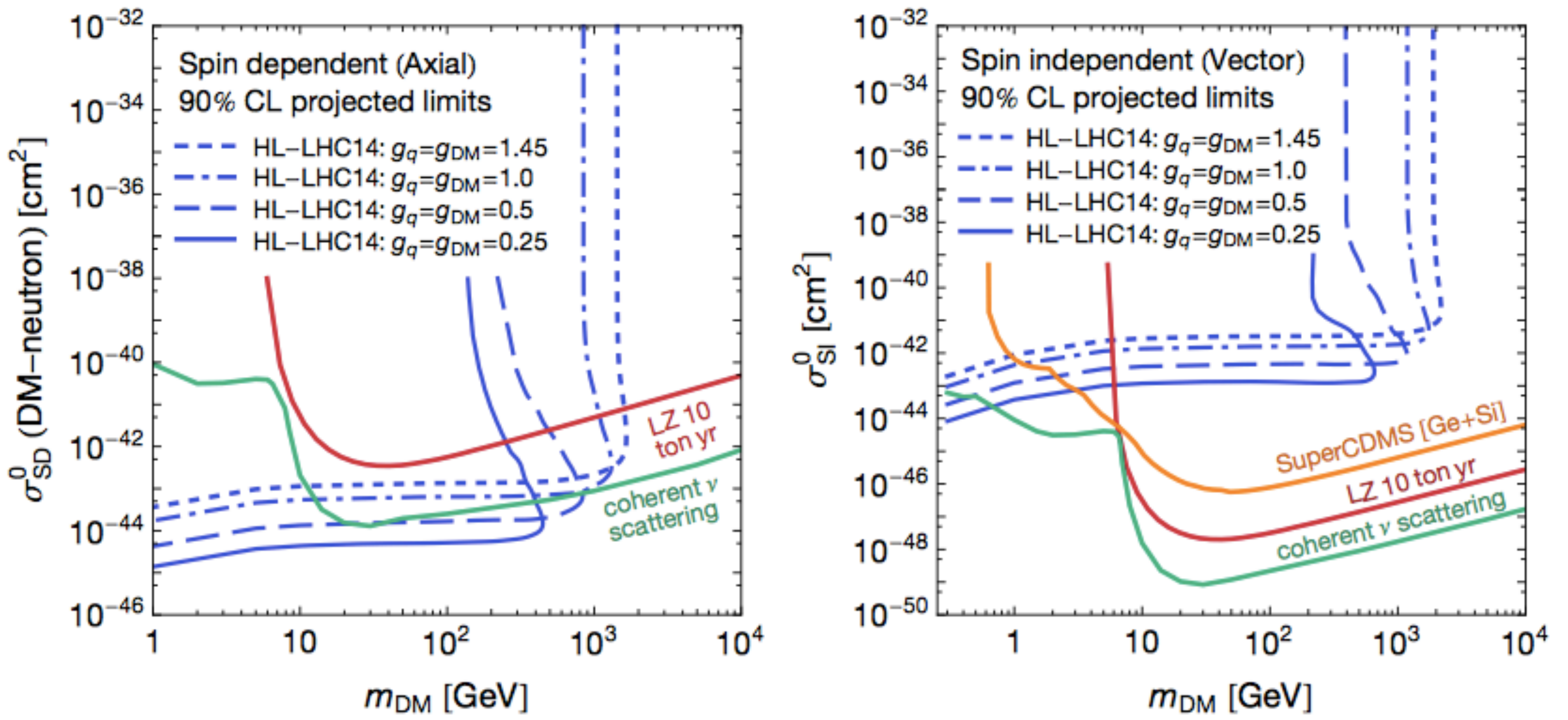
Projections for Future Experiments: σ vs M_{DM}

Can be also shown in the σ vs M_{DM} plane …



Direct Detection experiments and collider are complementary!
They are probing different regions of the relevant parameter space!

Summary for most basic Mediator Interactions

… in a nutshell!

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

Outlook: 8 TeV vs 14 TeV

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

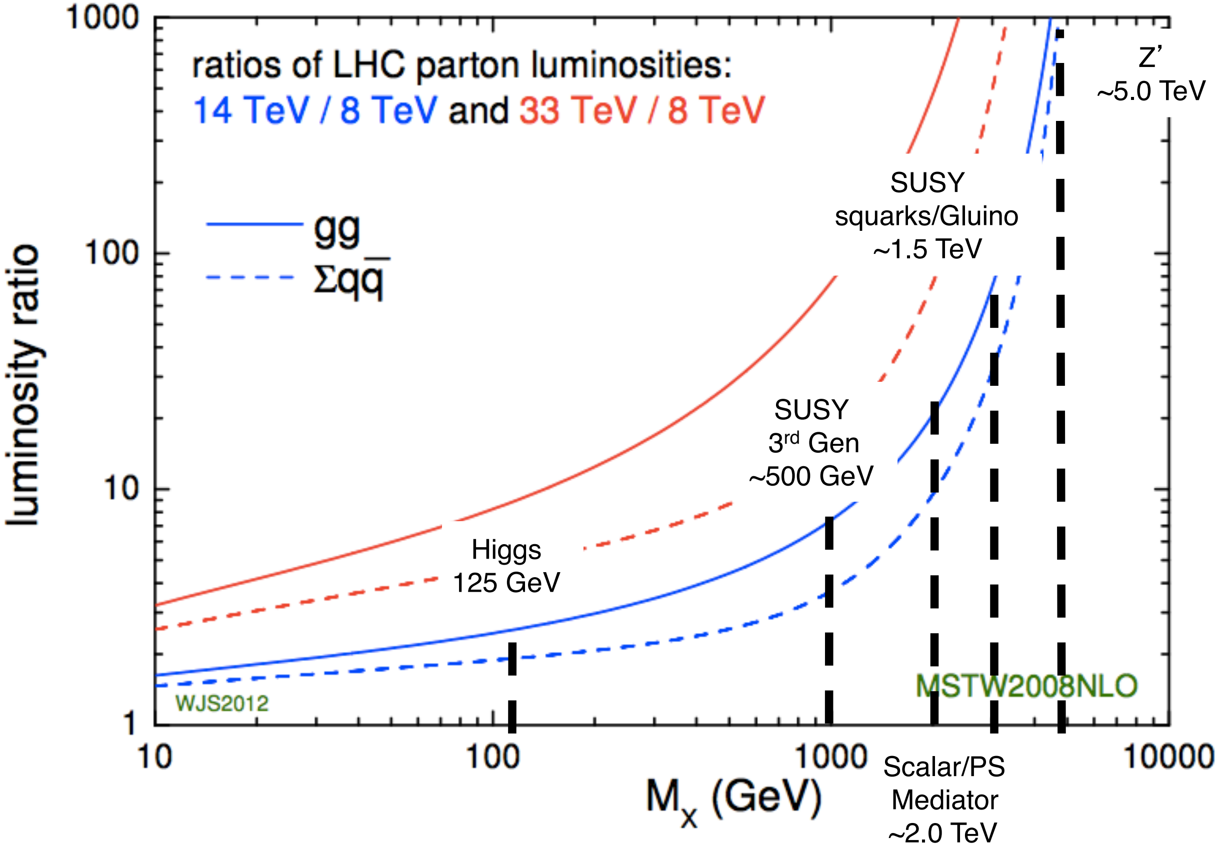
Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

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!
  - Even by 2010 the LHC has enter 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 find out 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 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!

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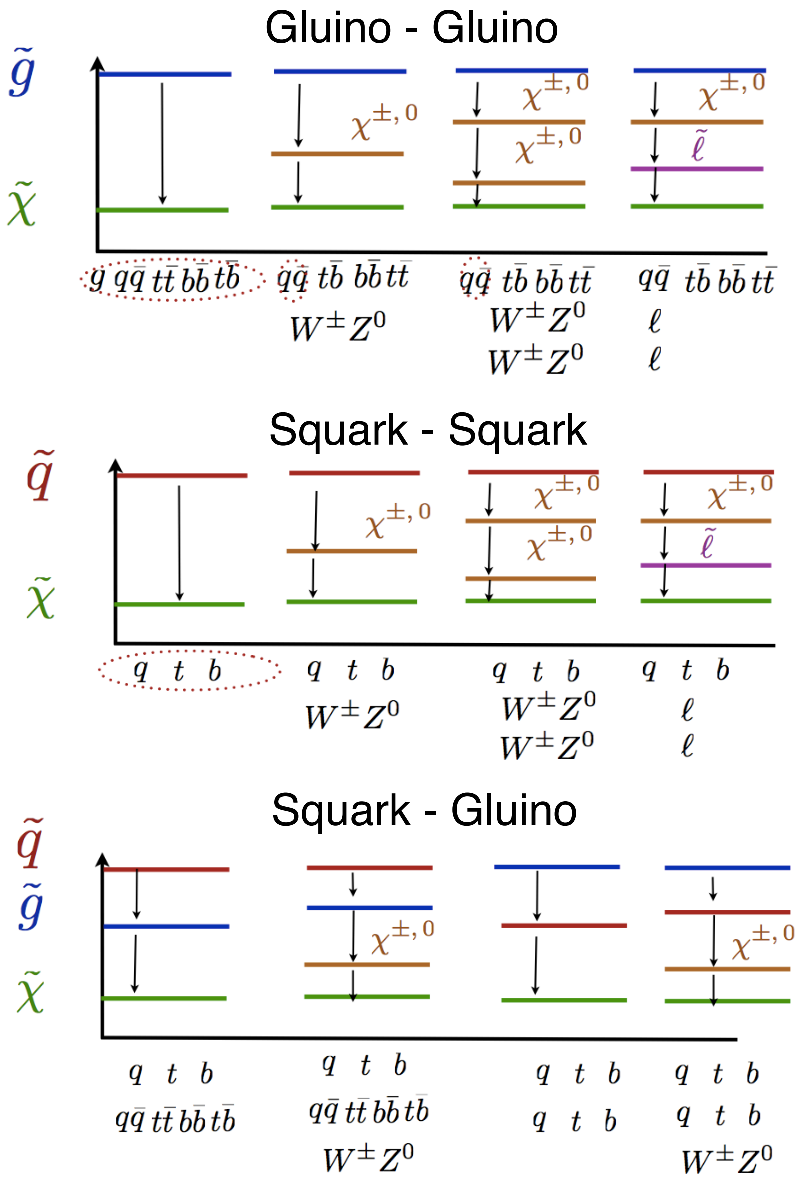
BACKUP

Early SUSY Search Strategy at the LHC



Search Signatures

- SUSY-like decay chains range from short to long and simple to very complicated.
- All physics objects, MET, jets, leptons, photons, b's taus, tops, W, Z, etc are involved
- Comprehensive coverage of all possible signature requires a topology oriented search strategy:

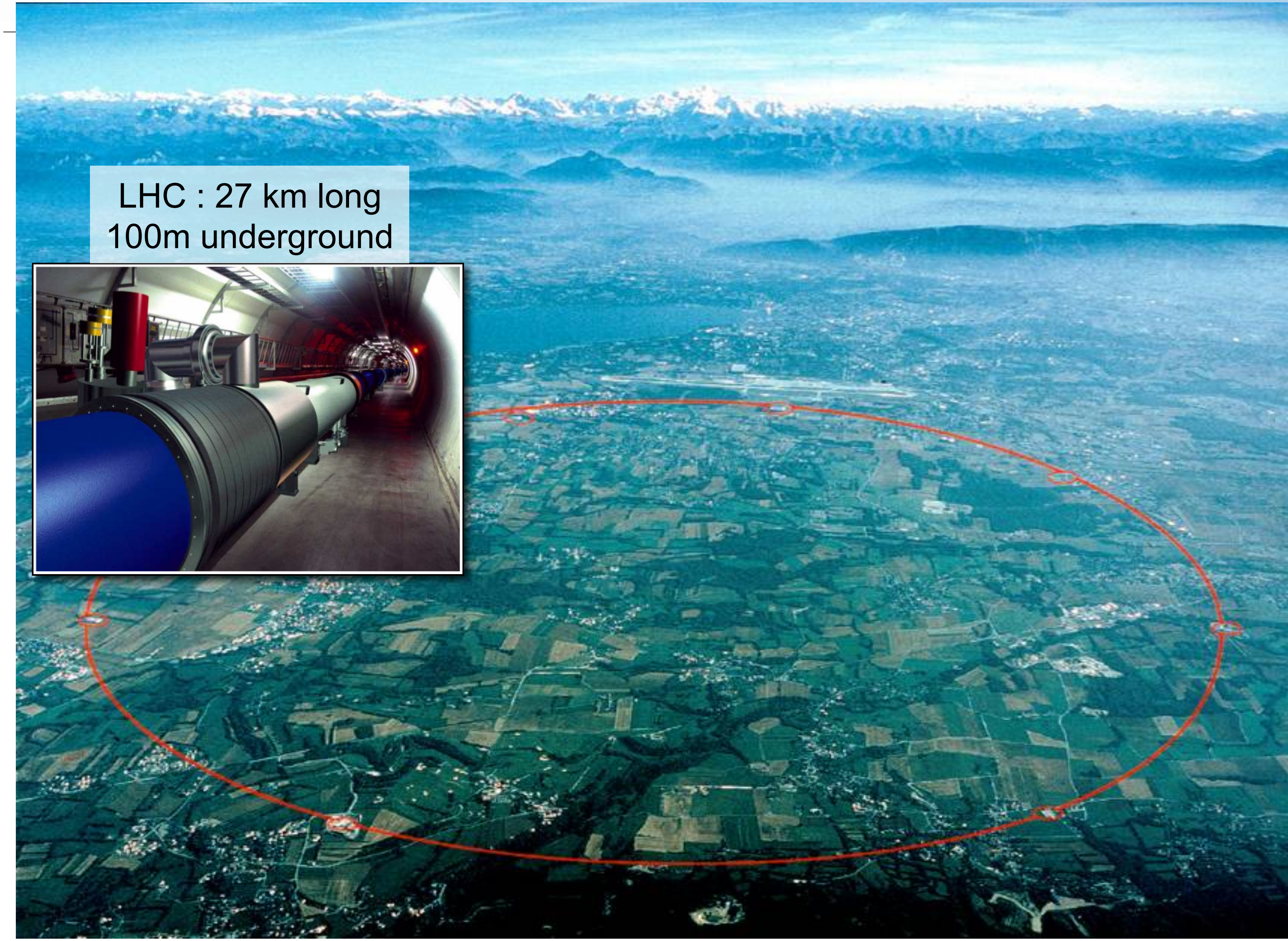
References Analyses

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

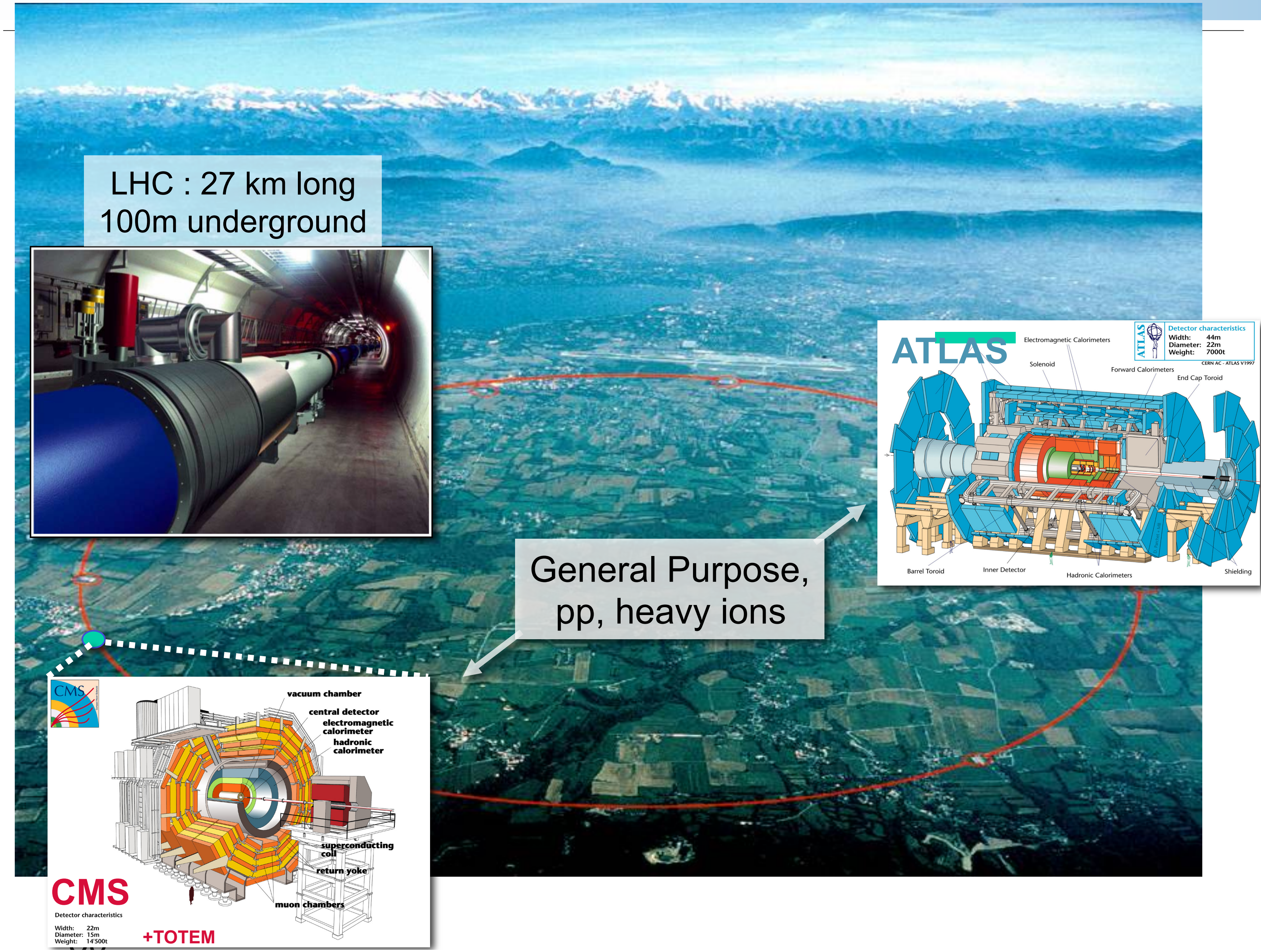
Already in less then two years of operation ATLAS & CMS managed to carry out the full list of these core "SUSY References Analyses"!

The Large Hadron Collider at CERN

The Large Hadron Collider at CERN



The Large Hadron Collider at CERN



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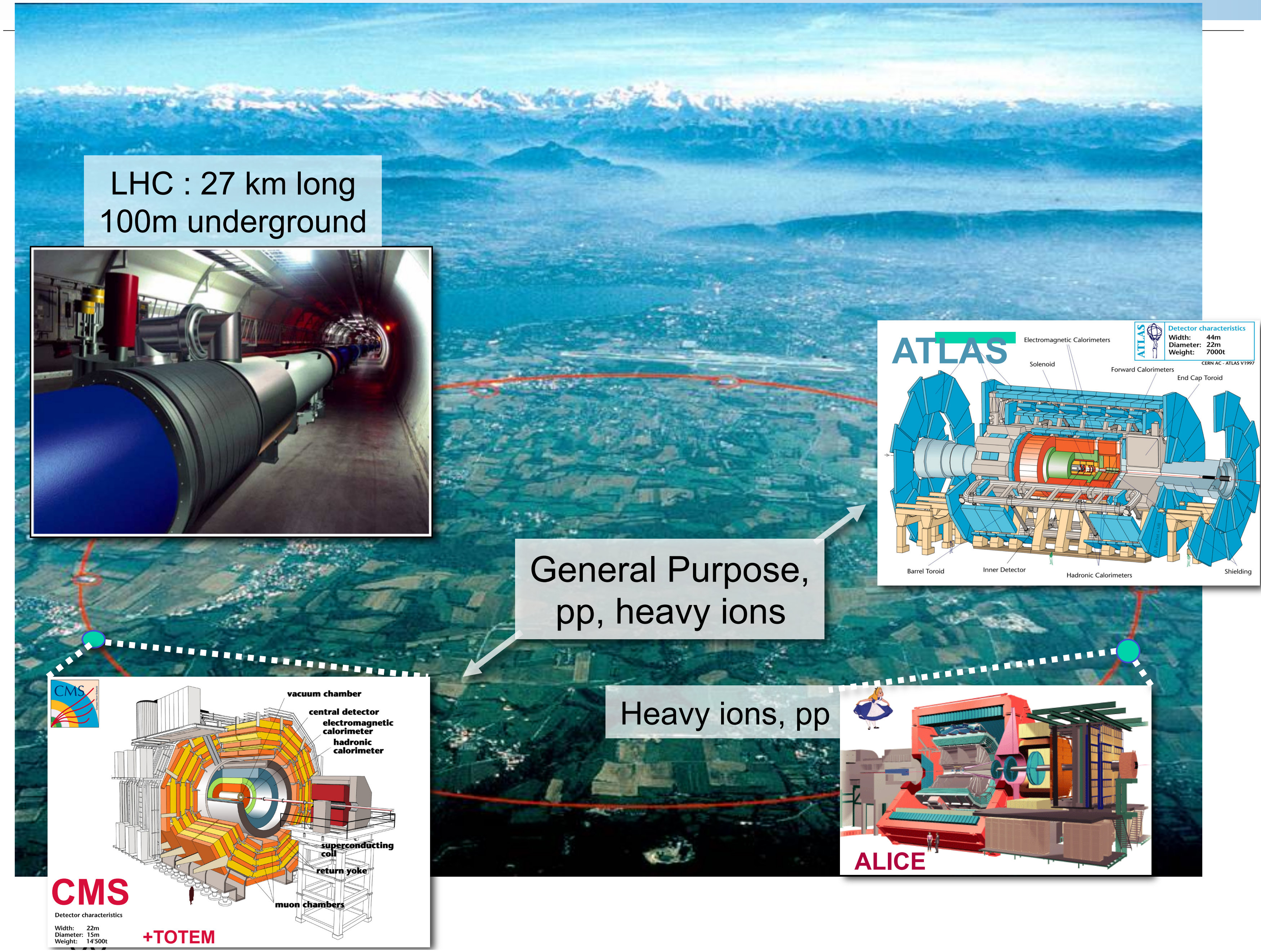

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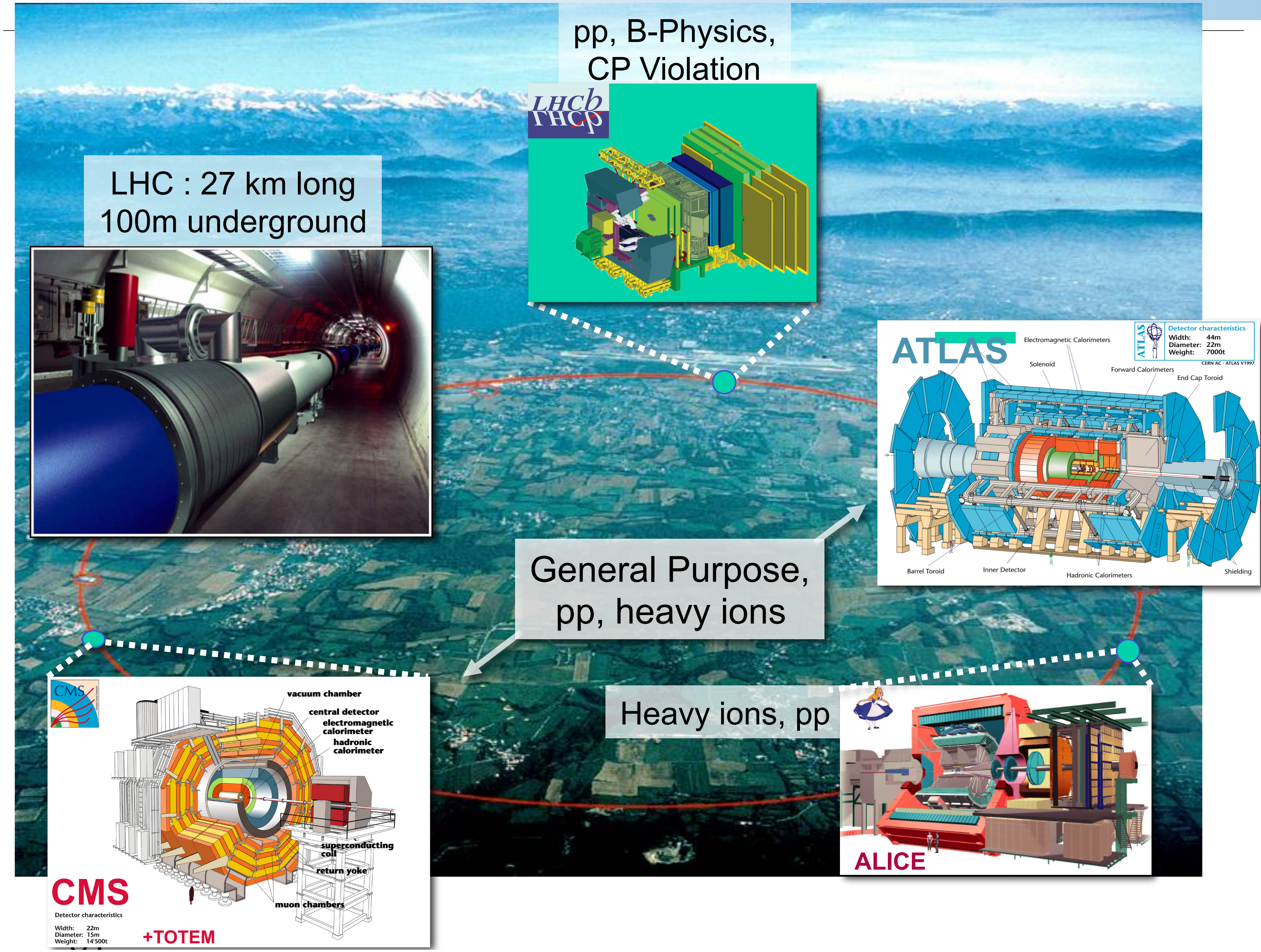
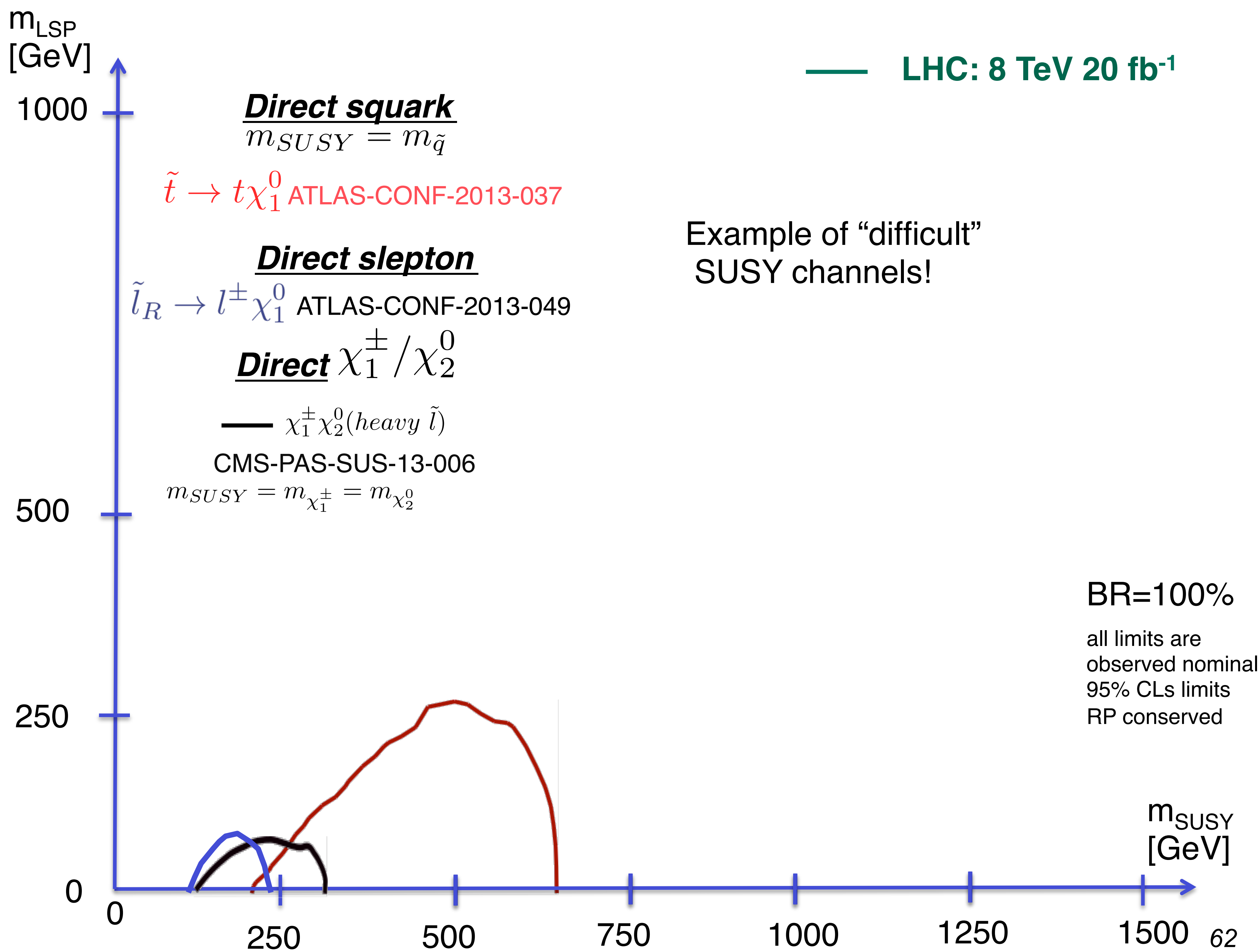
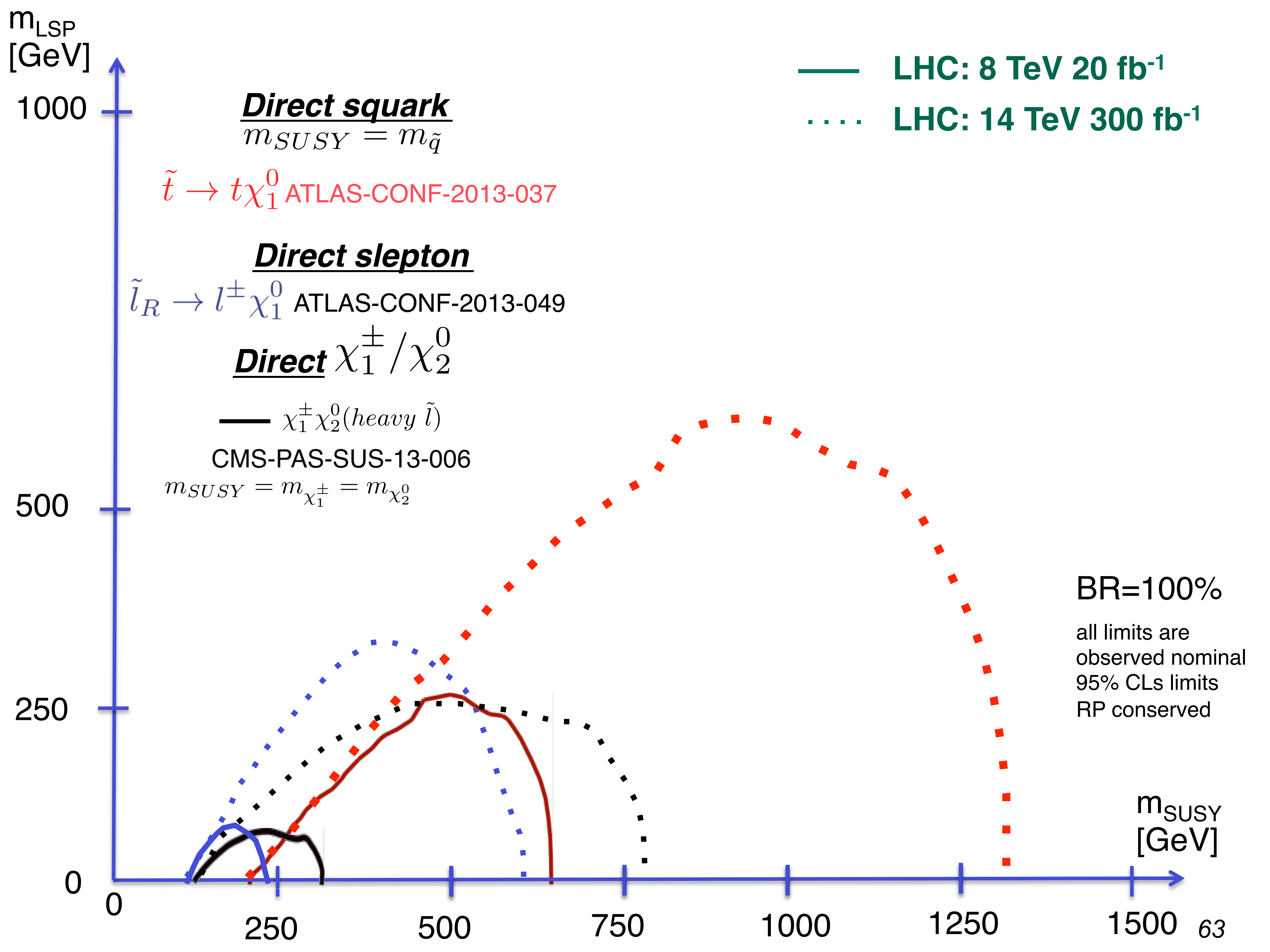




m_LSP [GeV]
1000
500
250
0
LHC: 8 TeV 20 fb-1
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
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]
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
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500
250
0
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500
750
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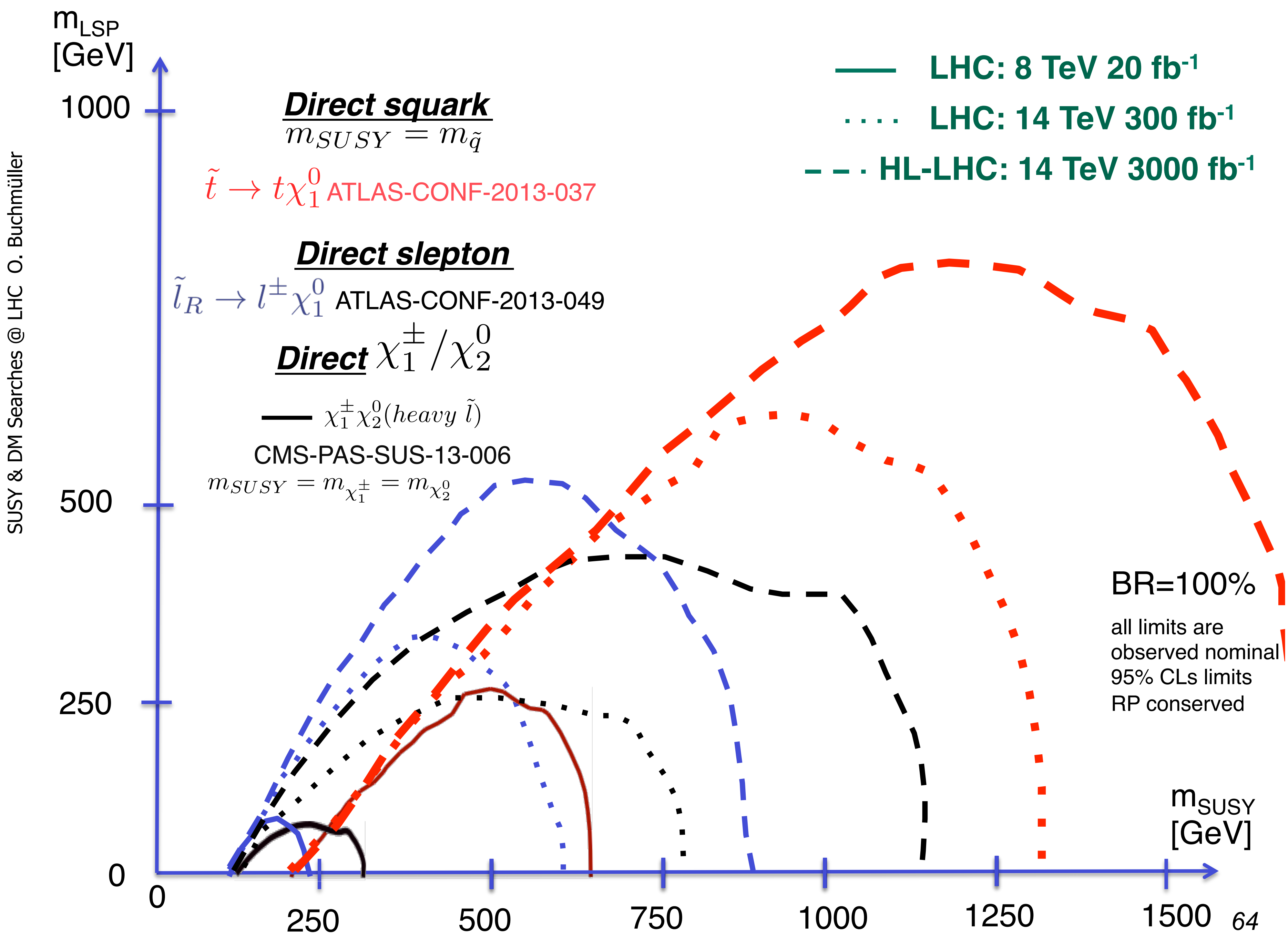
1250
1500



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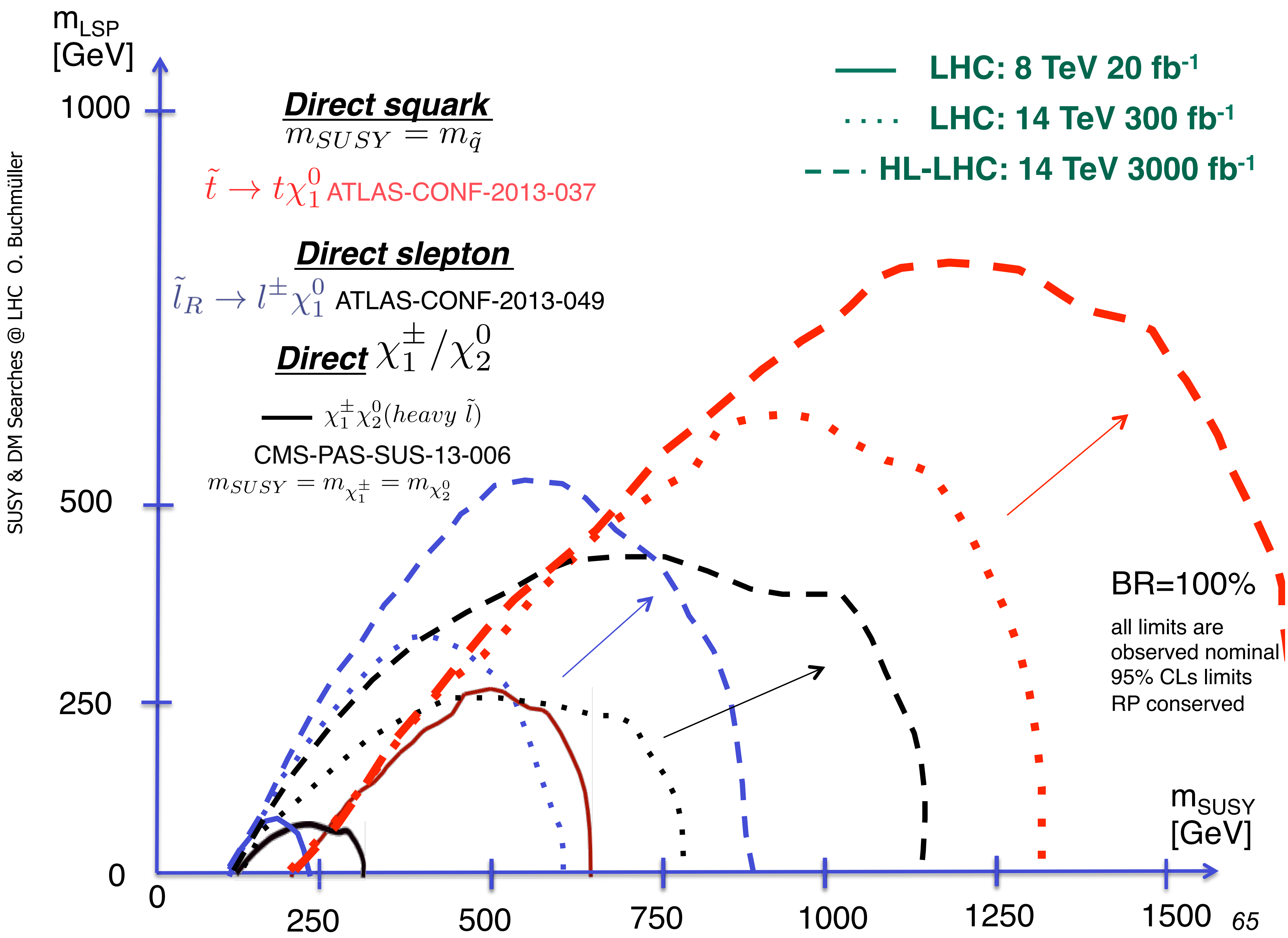
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500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



m_{LSP} [GeV]
1000
500
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0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
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Direct $\chi_1^{\pm}/\chi_2^0$
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$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
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LHC: 14 TeV 300 fb^{-1}
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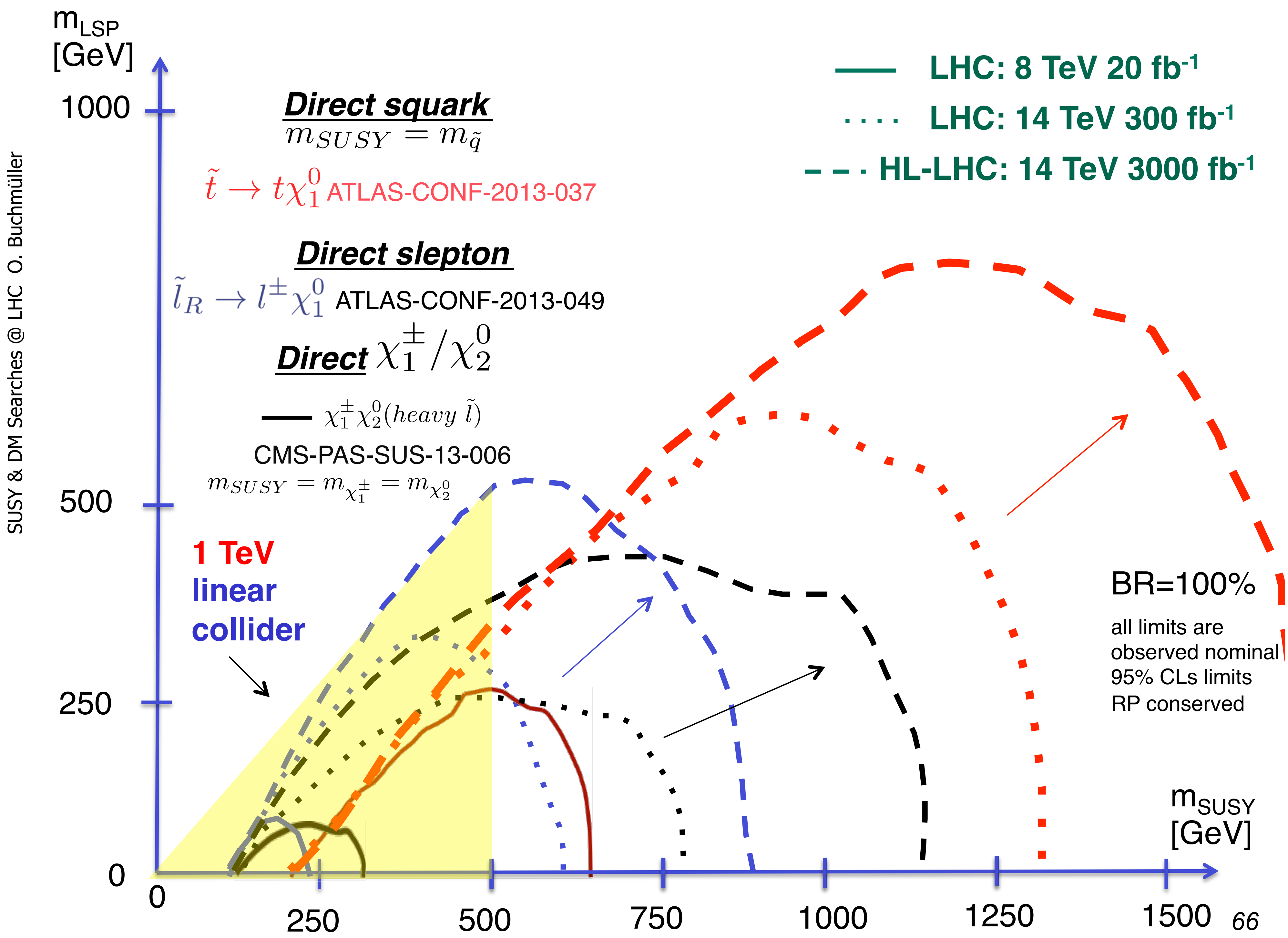
SUSY & DM Searches @ LHC O. Buchmüller



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Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
1 TeV
linear
collider
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
SUSY & DM Searches @ LHC O. Buchmüller

ATLAS & CMS public results

All 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

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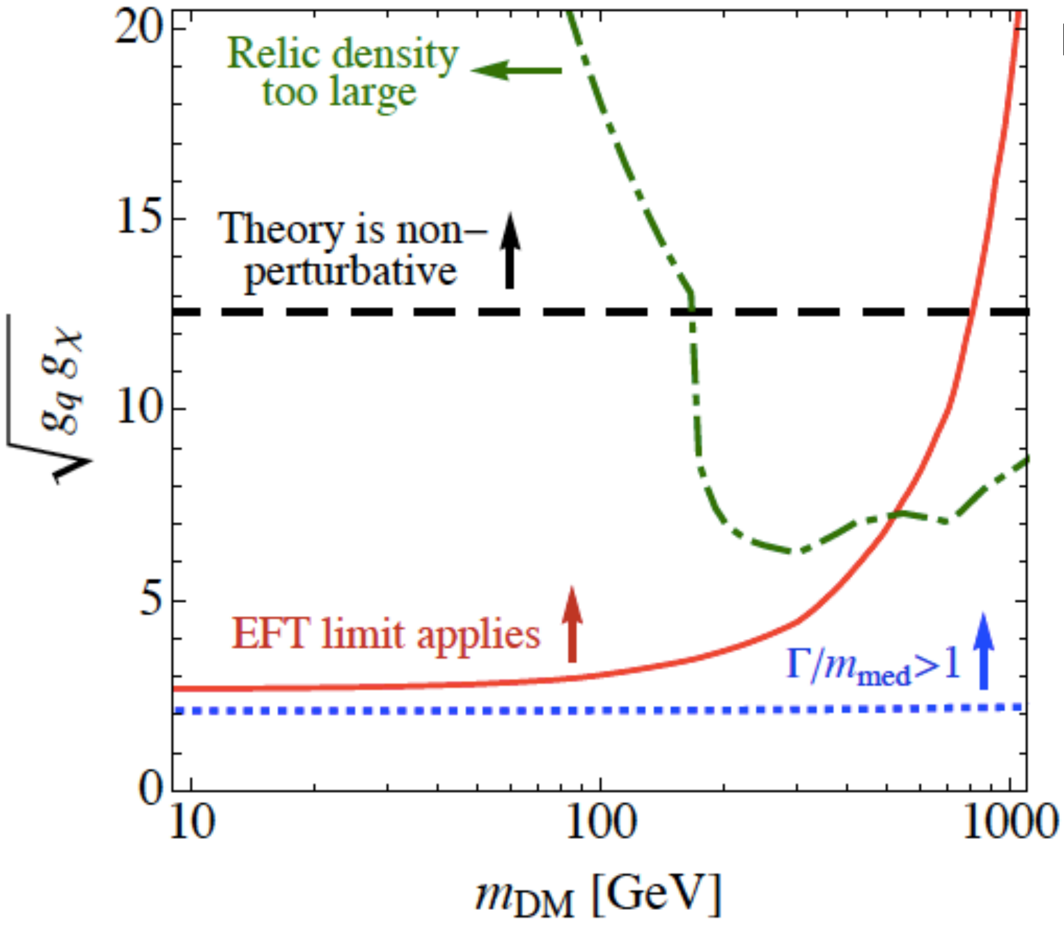
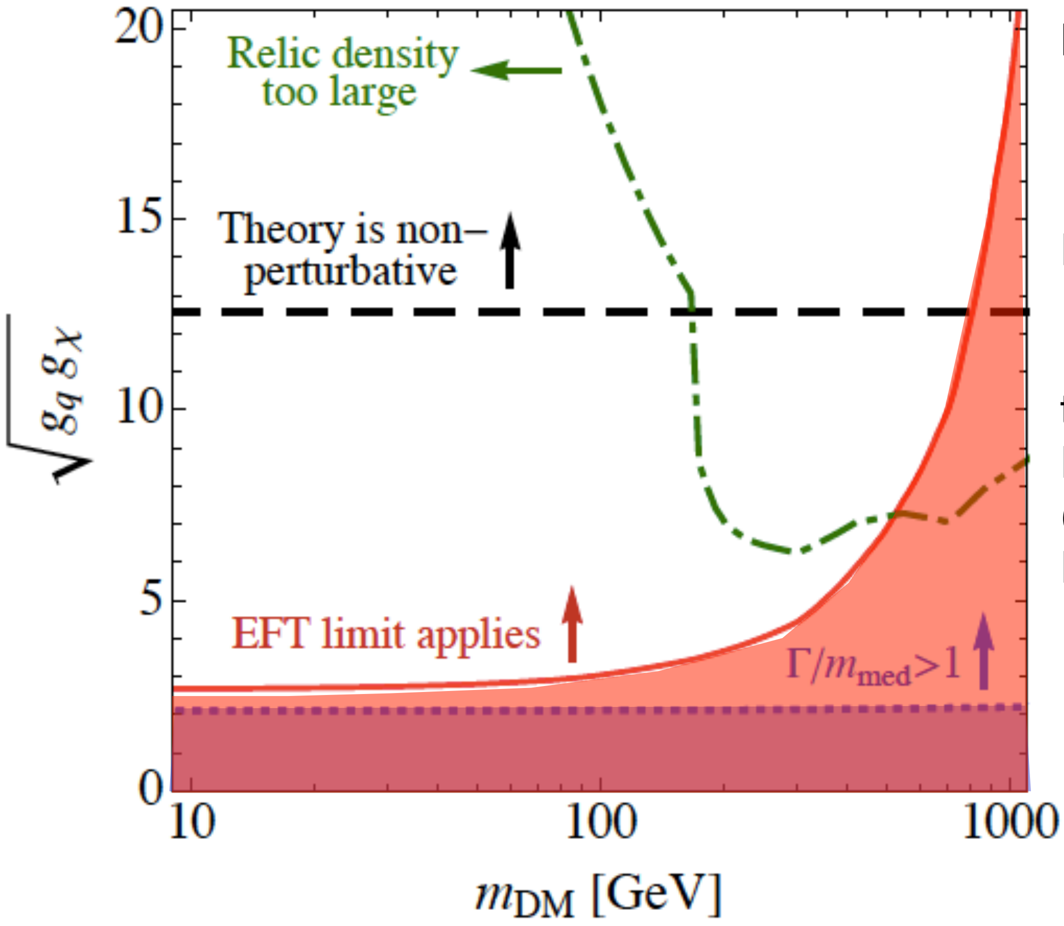
What those this imply on model-dependences of EFT limits?



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

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

Model-dependences of EFT limits



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

1. Region in which EFT is valid

For this we calculate the minimum coupling

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

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

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

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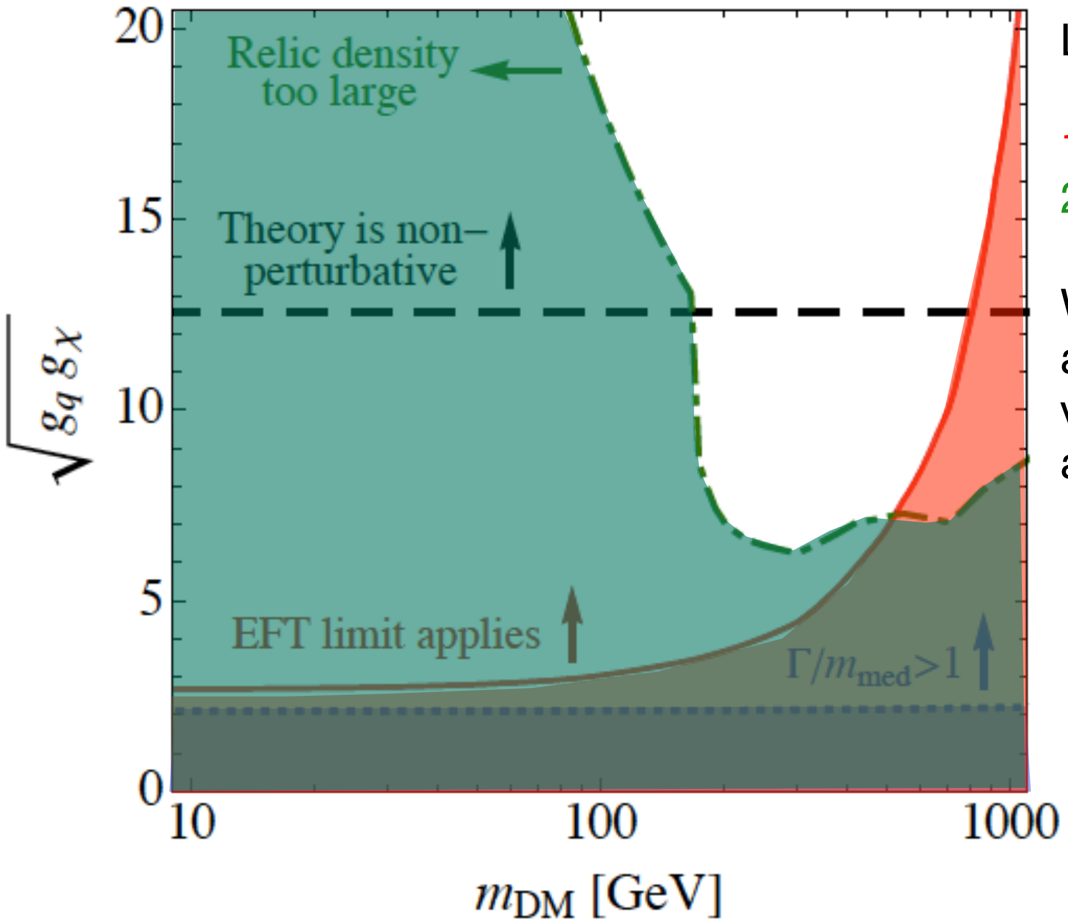
Model-dependences of EFT limits



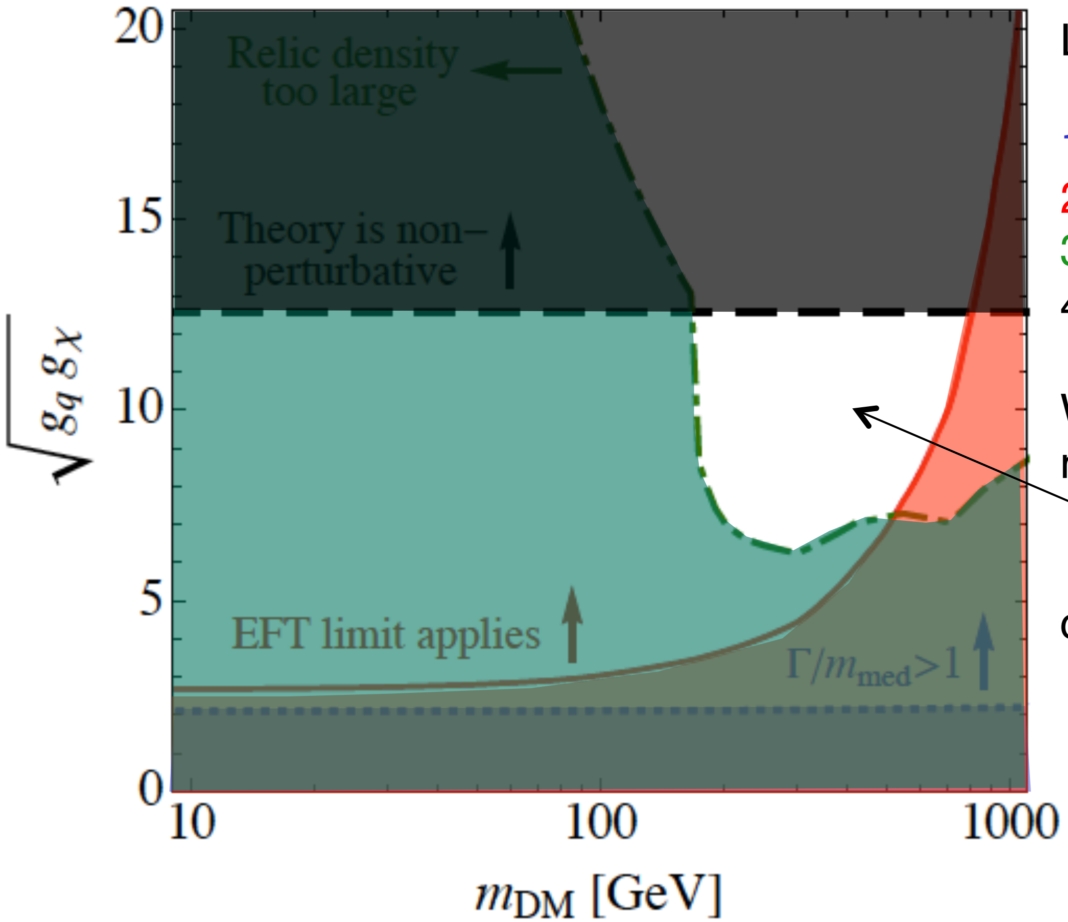
Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (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)

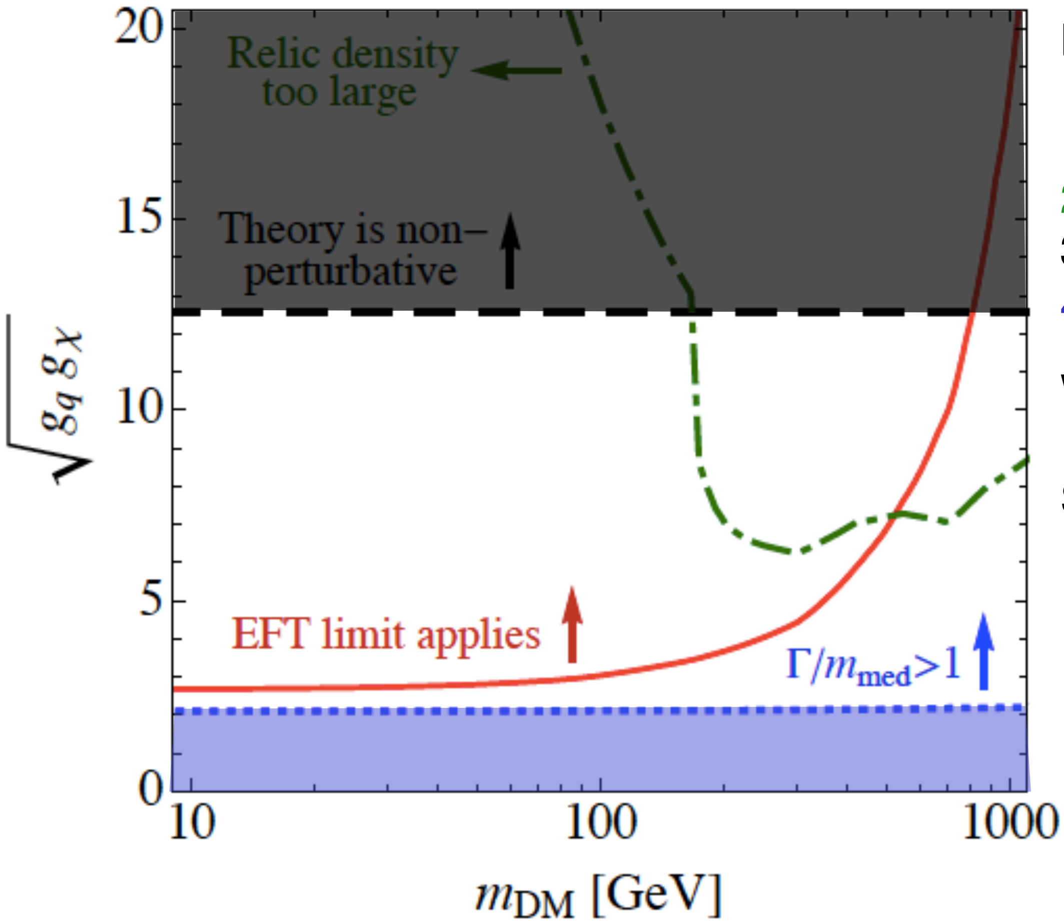
When we also require that the region/theory must be perturbative:

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

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.

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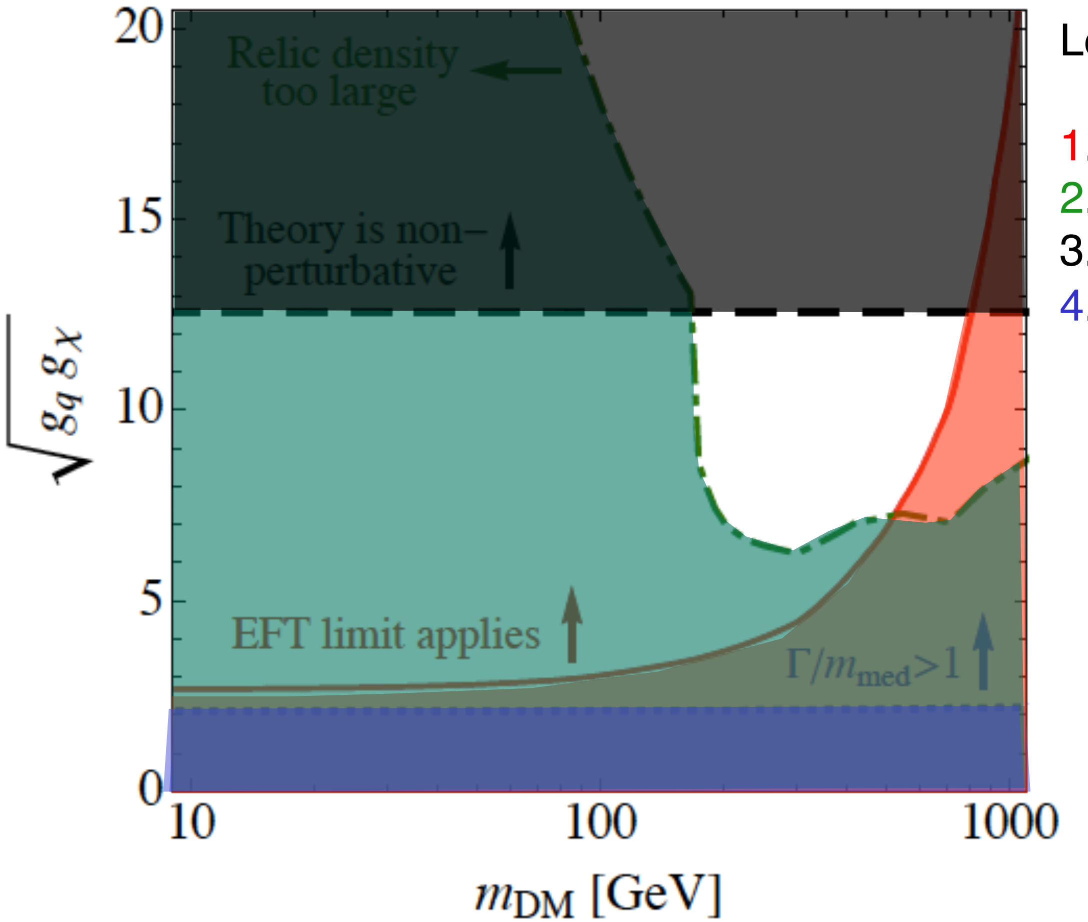
What those this imply on model-dependences of EFT limits?



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!