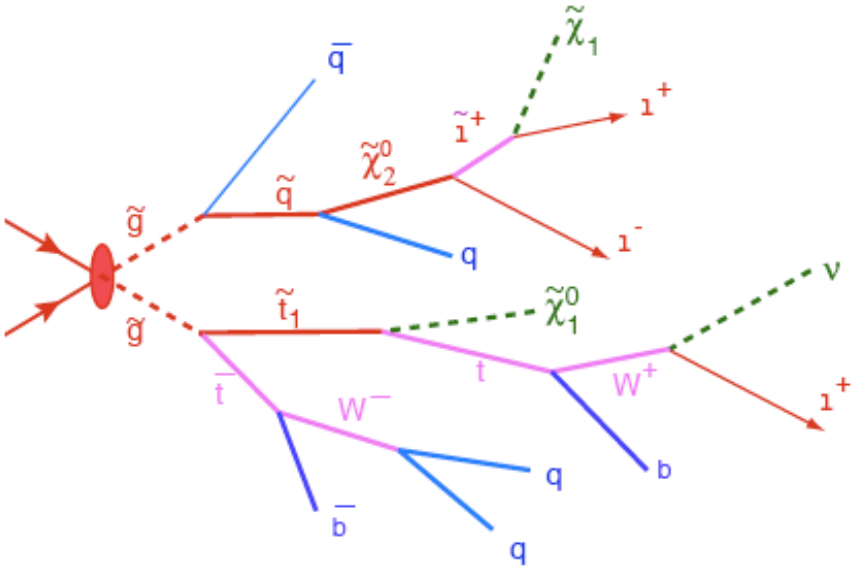
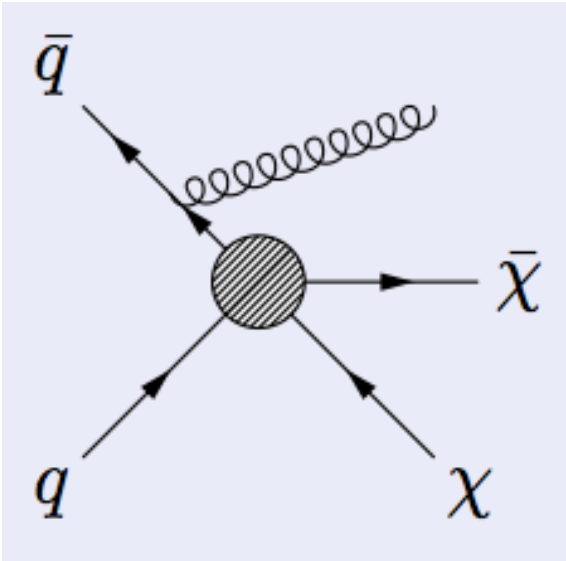
Oliver Buchmueller, Imperial College London

SEARCHES FOR DARK MATTER PRODUCTION AT THE LHC





Fundamental Open Questions in Particle Physics

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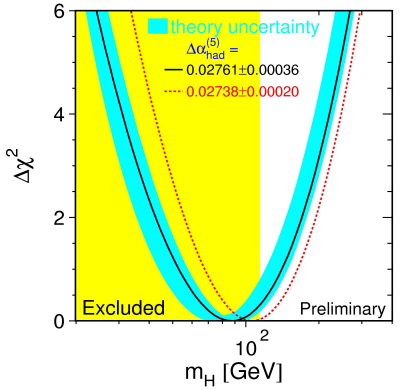
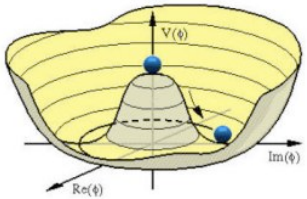
- *Why are the vector bosons Z and W are massive whereas the photon is massless?*
- *Is there a Higgs boson - or even more of them ?*





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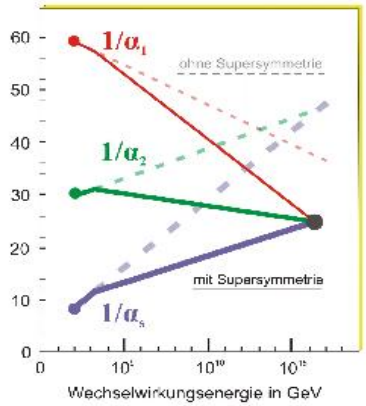

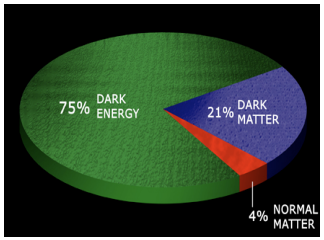

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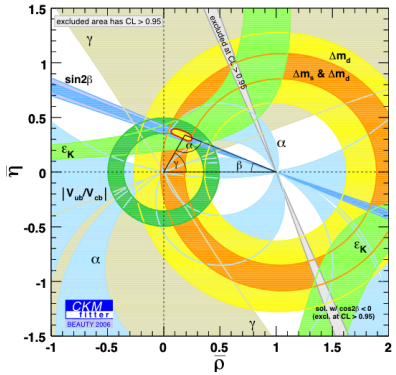

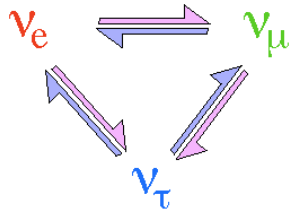

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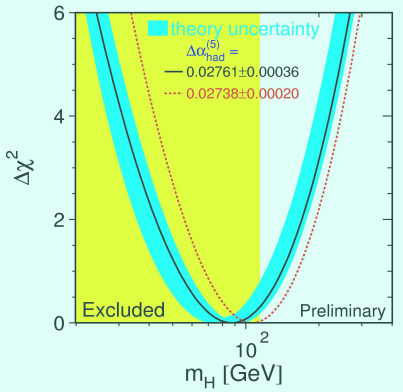

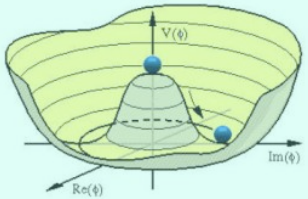

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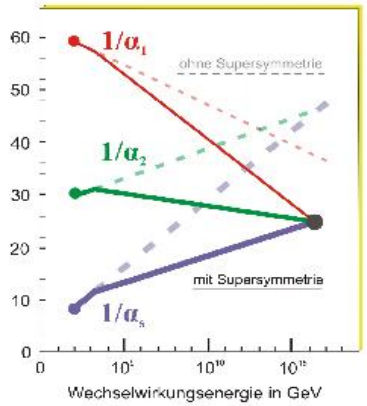

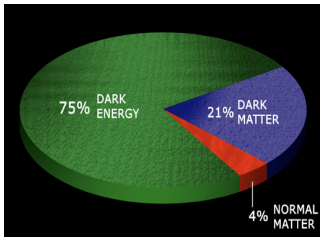

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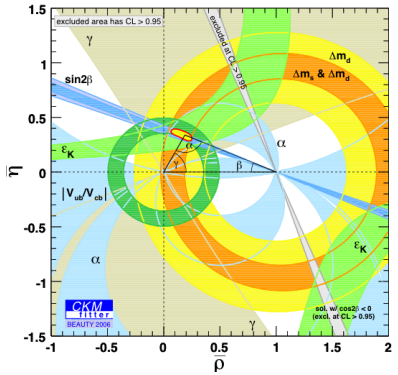

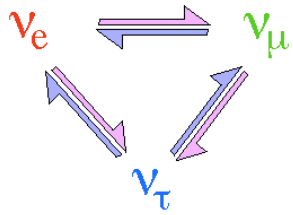

The Large Hadron Collider at CERN

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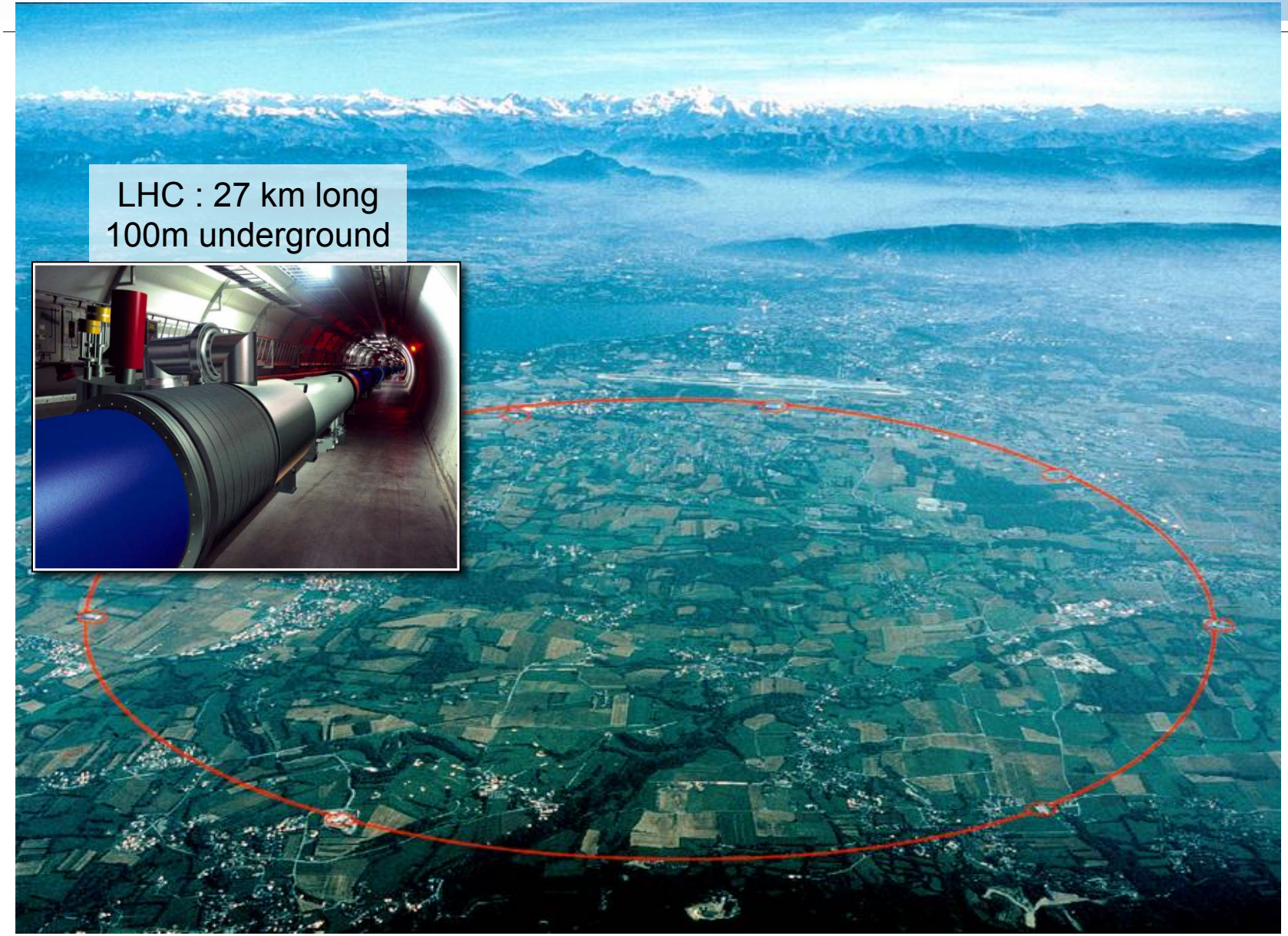
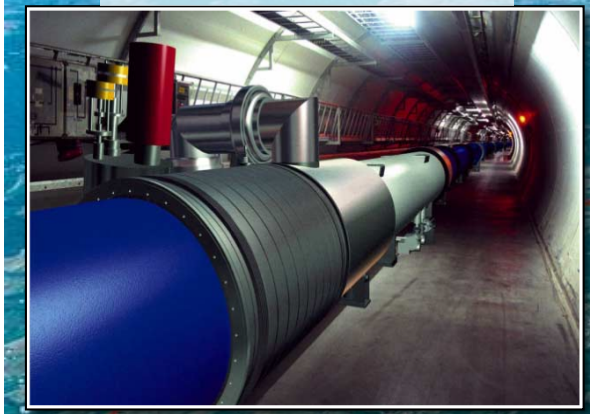
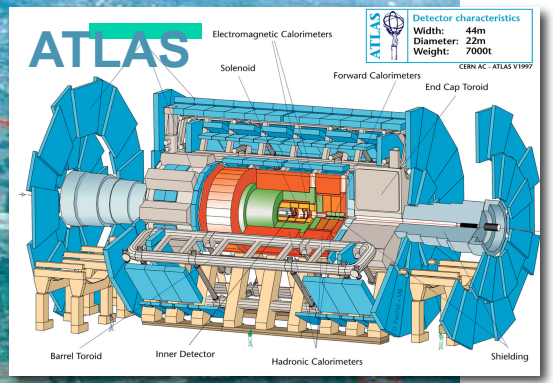


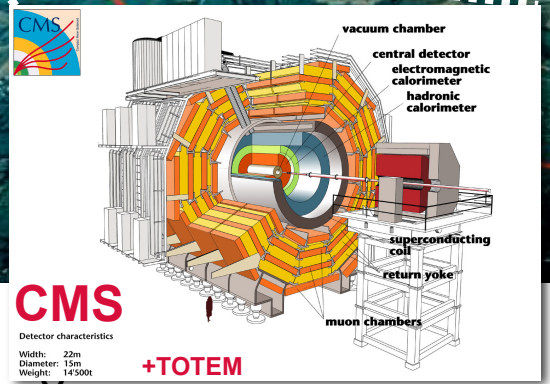
The Large Hadron Collider at CERN

LHC : 27 km long
100m underground





General Purpose,
pp, heavy ions



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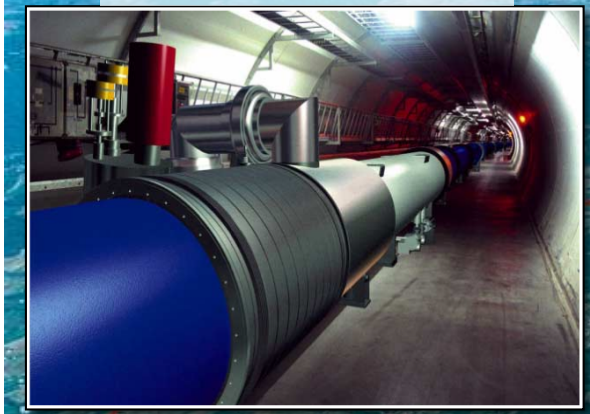

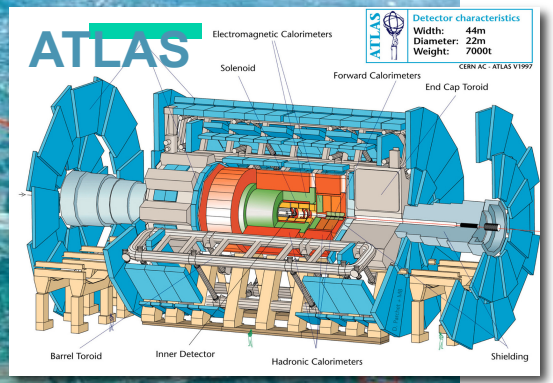

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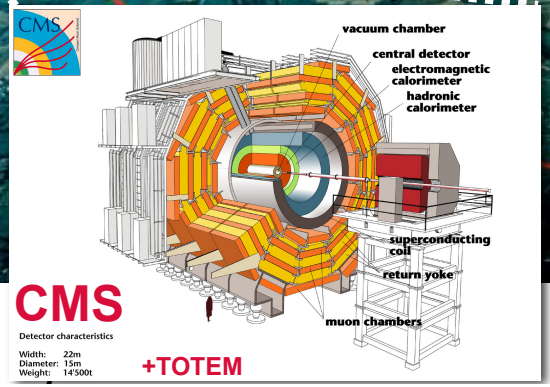
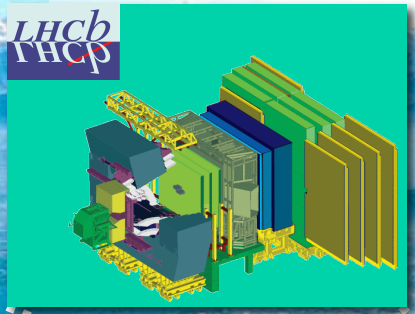


Heavy ions, pp

The Large Hadron Collider at CERN

pp, B-Physics,
CP Violation



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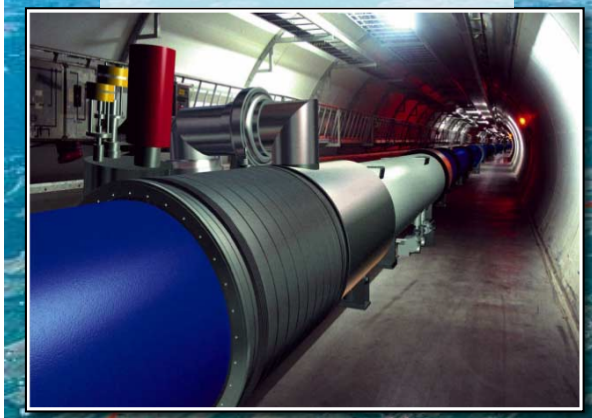

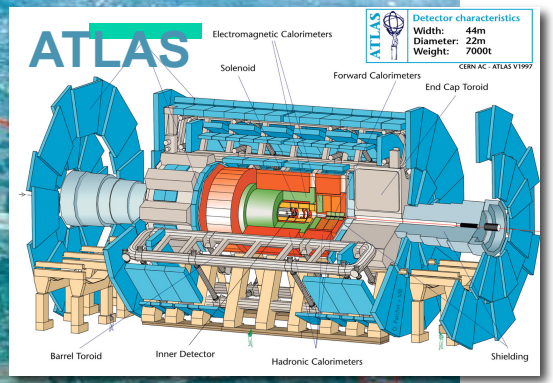

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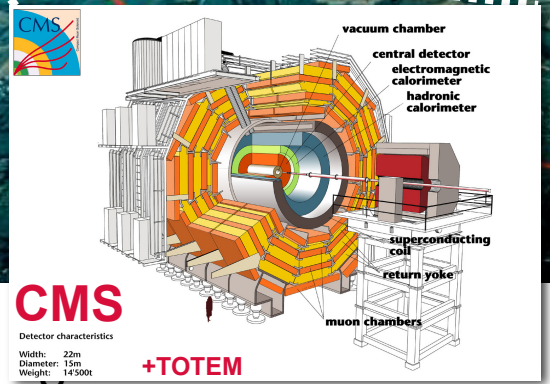
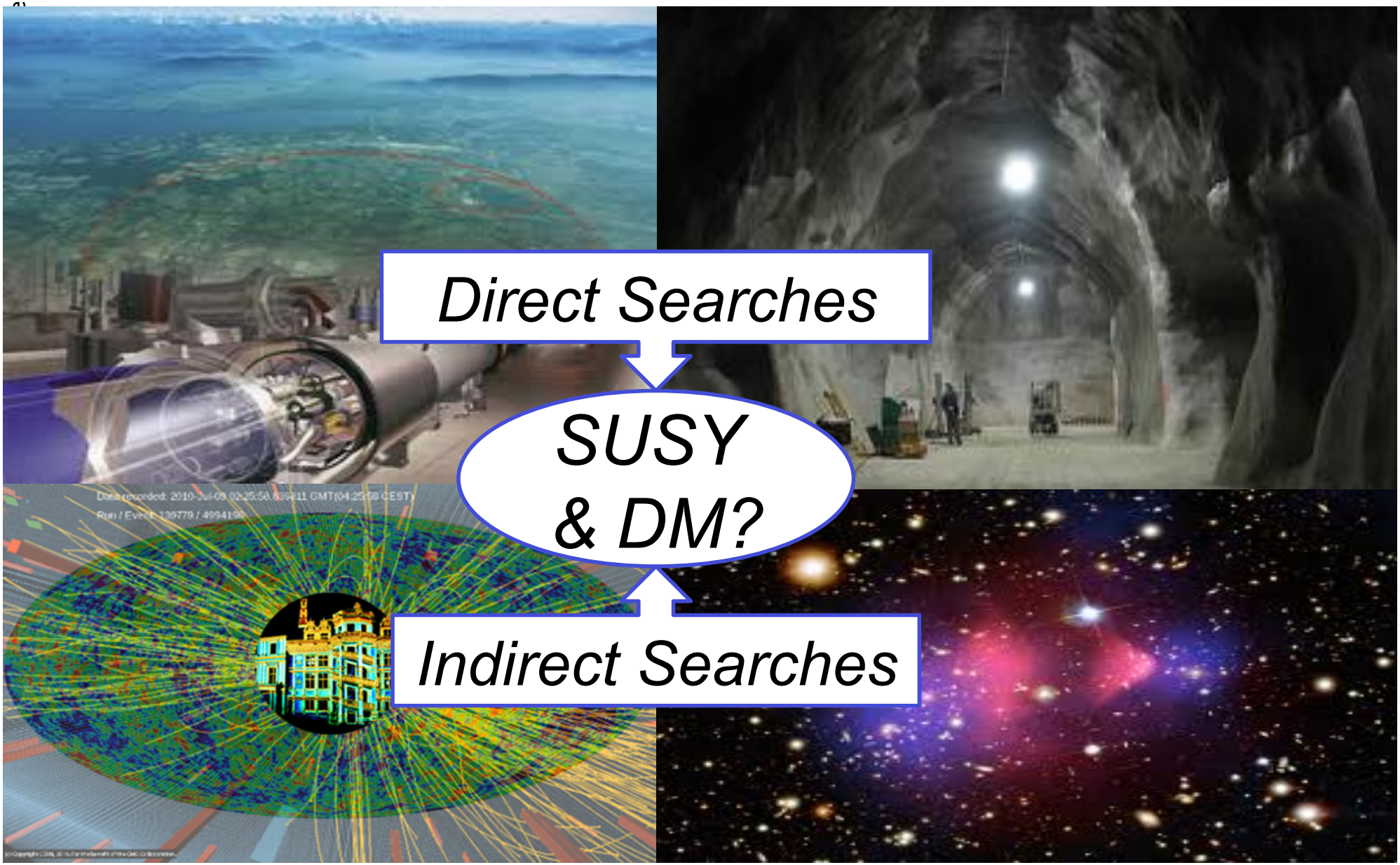


Heavy ions, pp

Imperial College London

Searches for SUSY (& DM)



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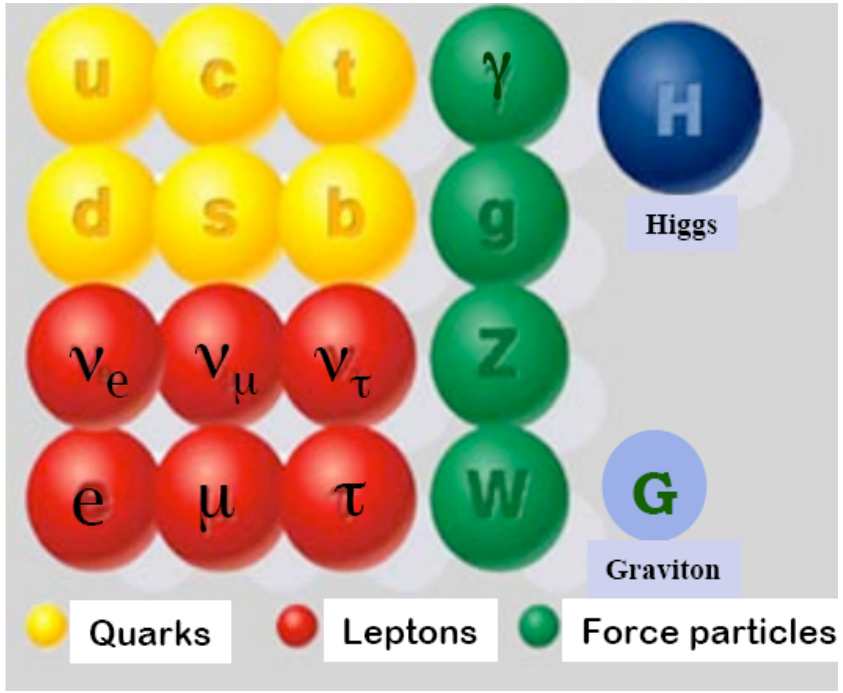
Searches for SUSY (& DM)

Supersymmetry

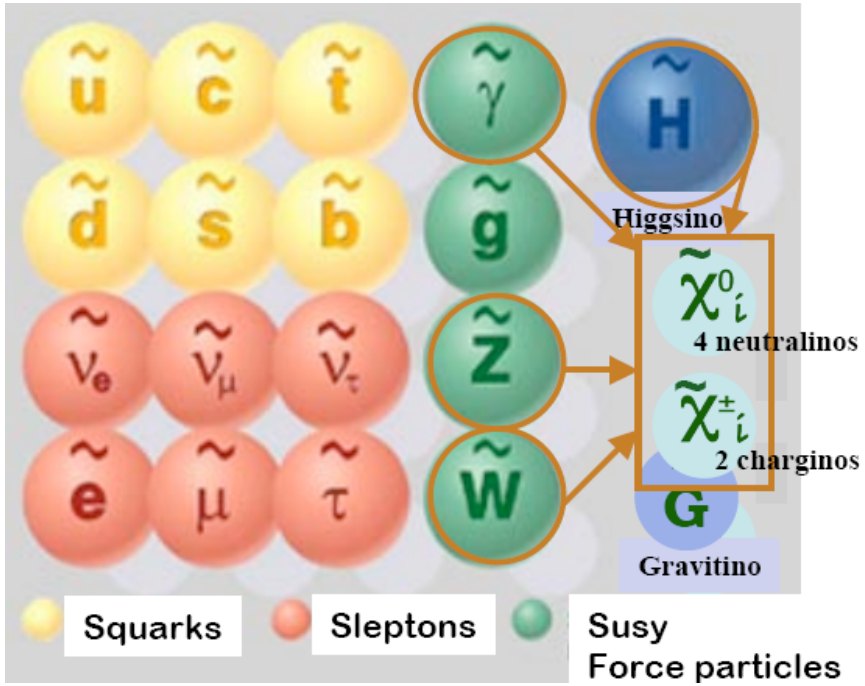
Extension of the Standard Model: Introduce a new symmetry

Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



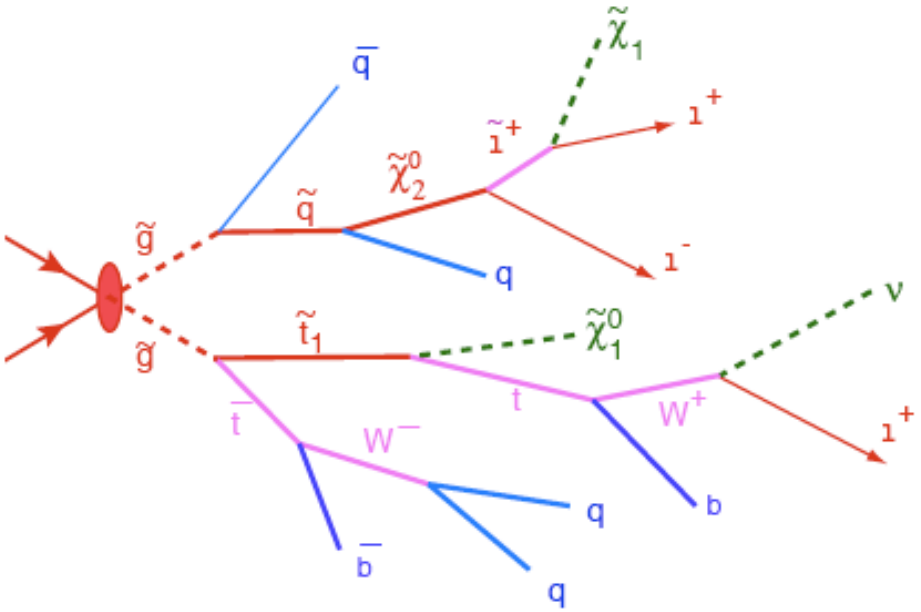
New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles, - 1 SUSY particles

R-parity conservation:

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

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*

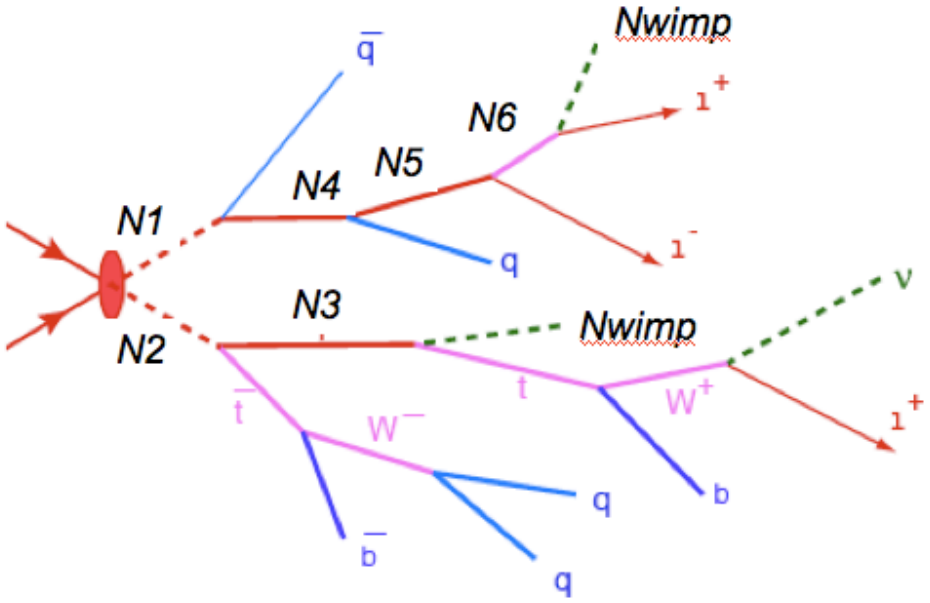
Multi-Jet:
- *from cascade decay (gaugino)*

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.

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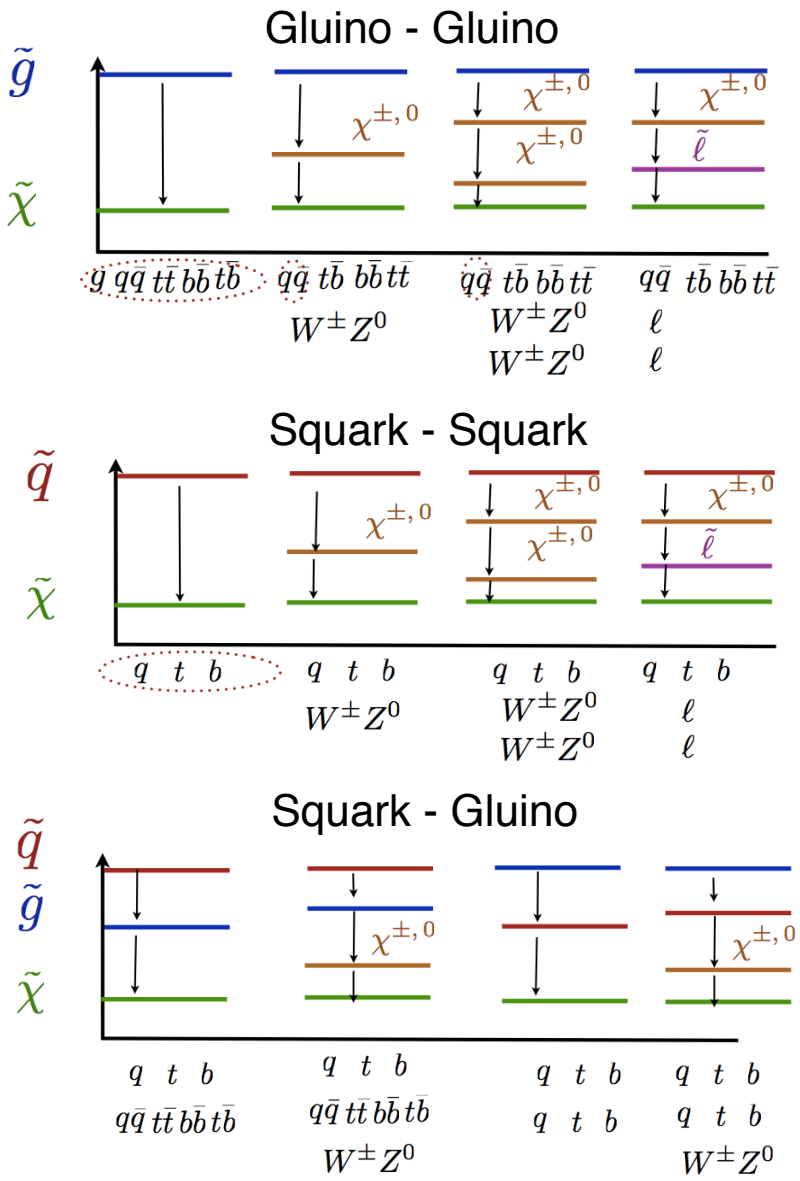
Early SUSY Search Strategy at the LHC

SUSY & DM Searches, @ LHC O. Buchmüller



Search Signatures

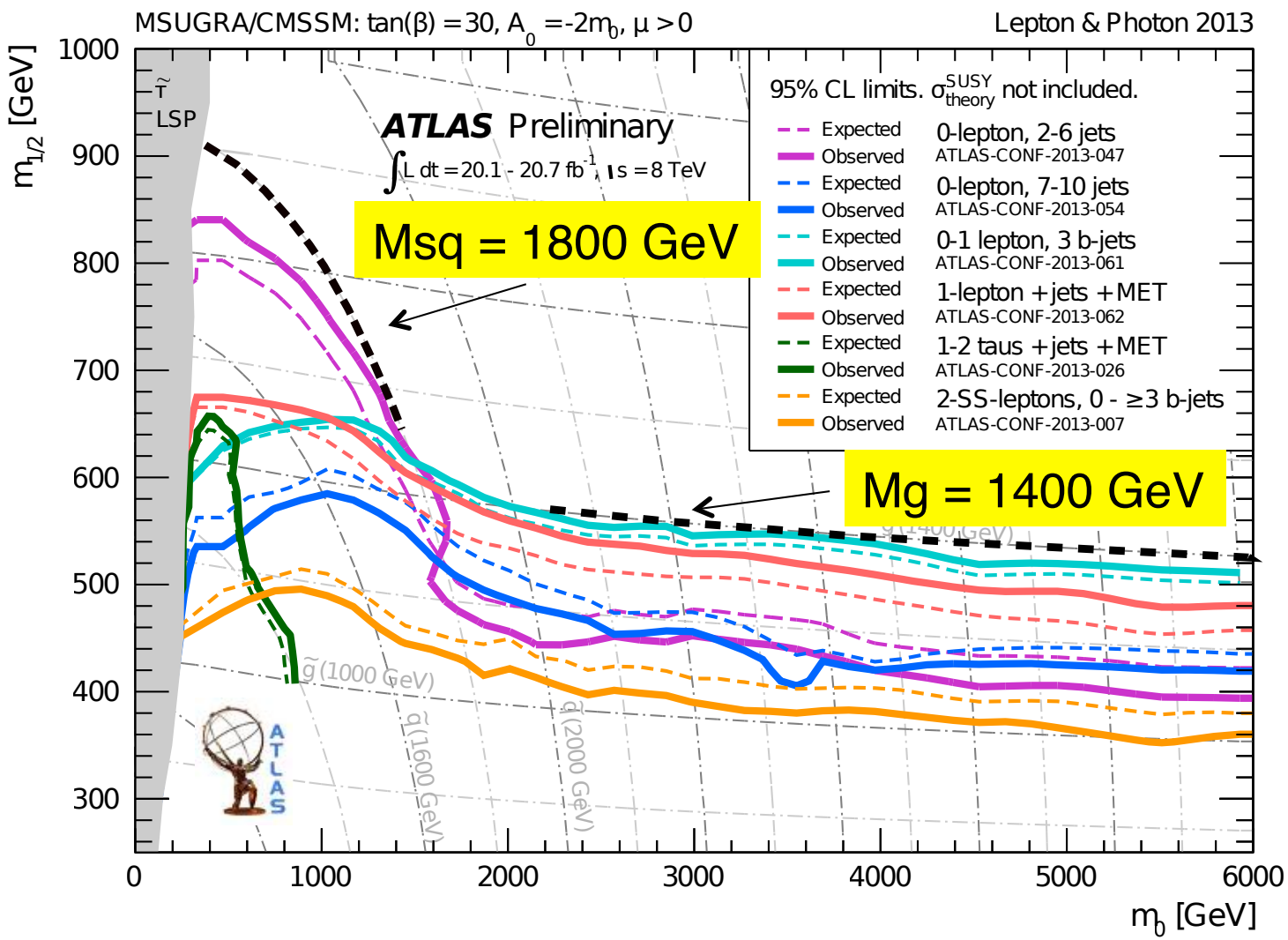
- SUSY-like decay chains range from short to long and simple to very complicated.
- All physics objects, MET, jets, leptons, photons, b's taus, tops, W, Z, etc are involved
- Comprehensive coverage of all possible signature requires a topology oriented search strategy:

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"!

Inclusive SUSY Searches in 2013



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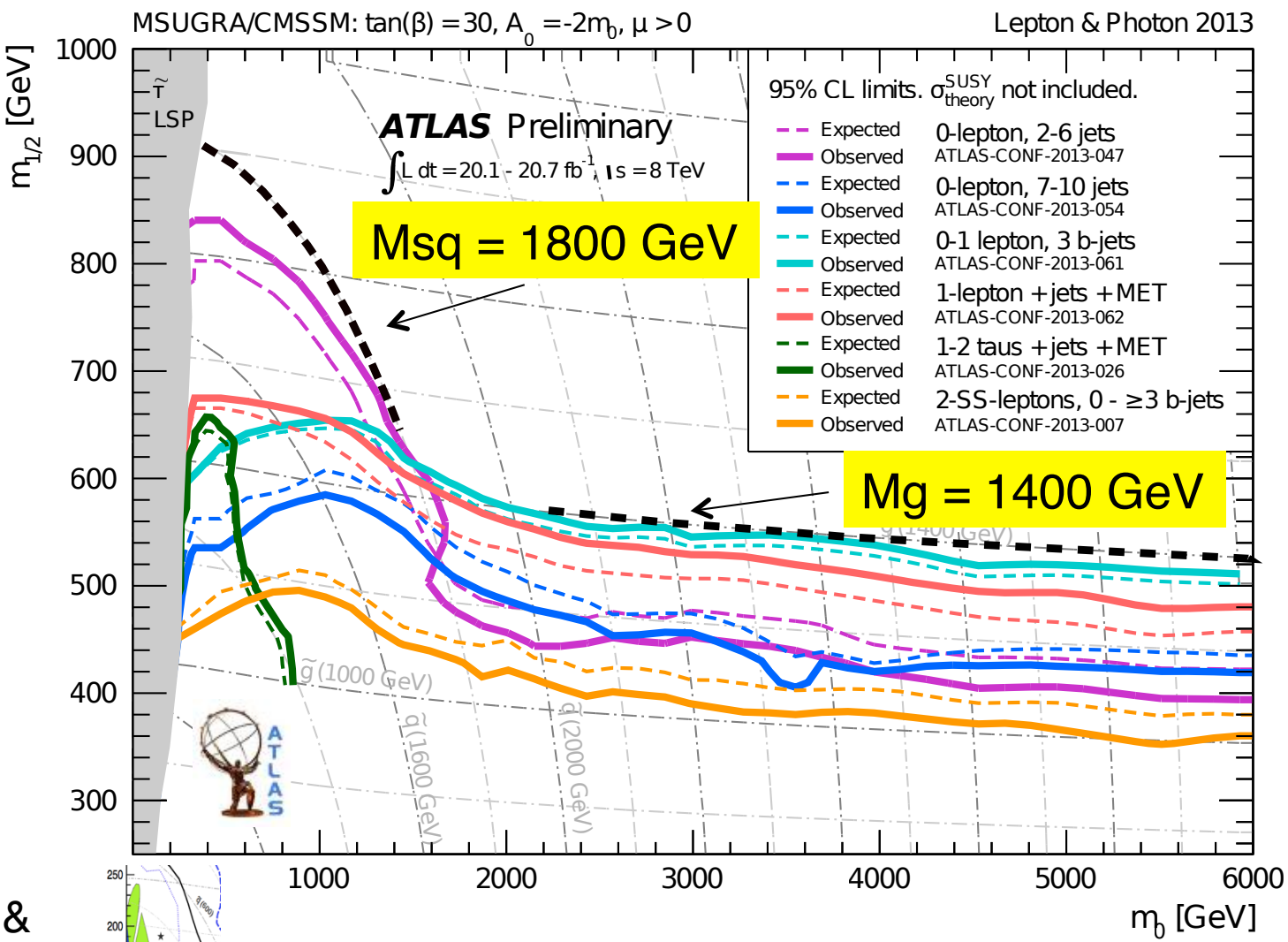
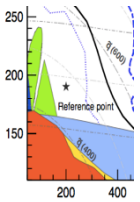


LEP & Tevatron



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

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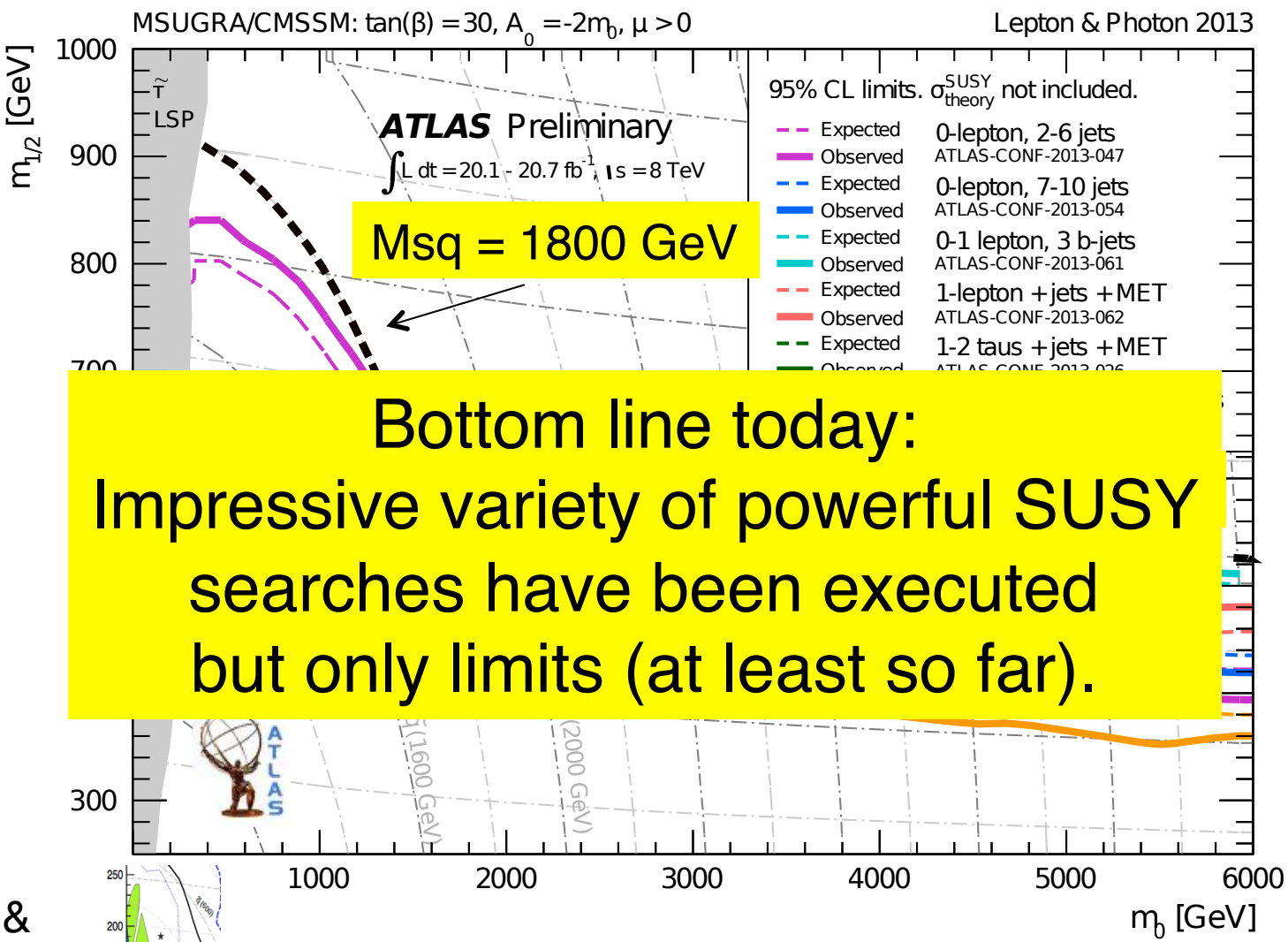

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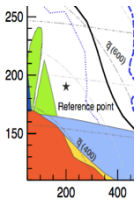

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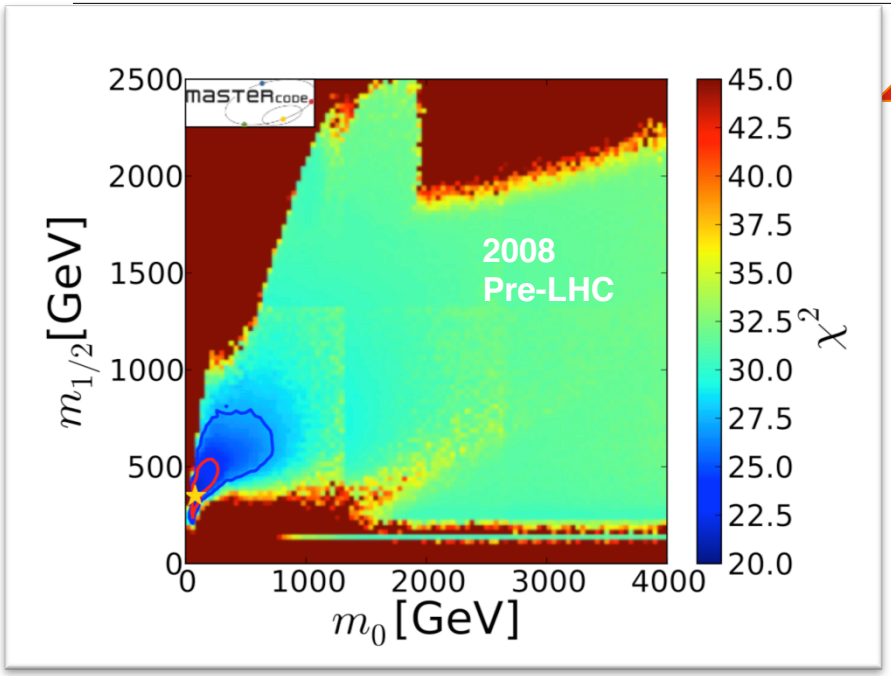
CMSSM: Evolution with time



X^2 increase from bluish to reddish

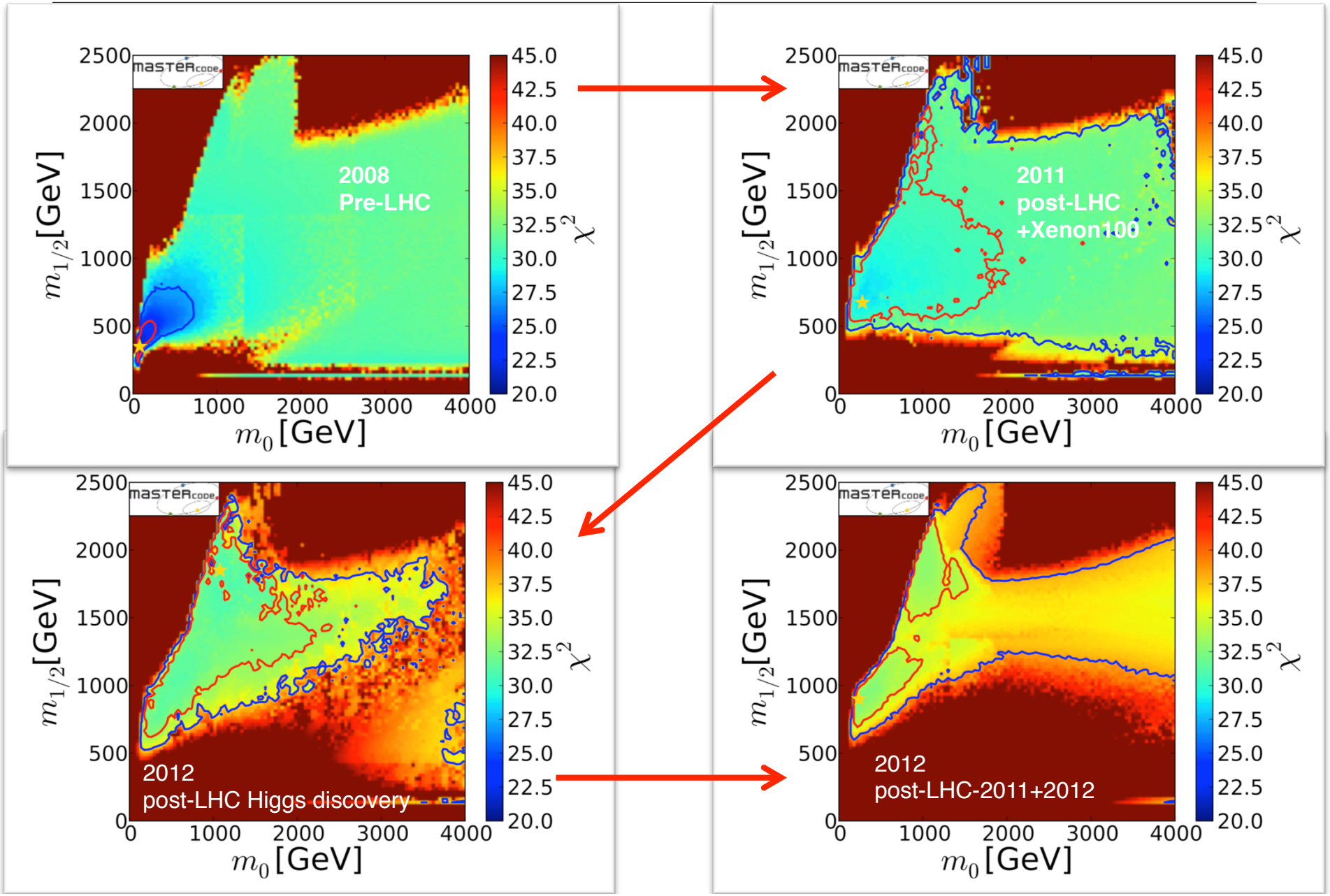
Source: http://mastercode.web.cern.ch/mastercode/

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	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$	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
$\sin^2\theta^\ell_{\rm eff}(Q_{fb})$	26 / 44	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	26 / 44	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$	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	$> 114.4[\pm1.5_{\rm SUSY}]$	0.0	0.0	0.0
$BR^{\rm EXP/SM}_{b\to s\gamma}$	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
$BR(B_s \to \mu^+\mu^-)$	29 / 41	CMS & LHCb	0.04	0.44	0.01
$BR^{\rm EXP/SM}_{B\to\tau\nu}$	29 / 46	$1.43 \pm 0.43_{\rm EXP+TH}$	1.43	1.59	1.00
$BR(B_d \to \mu^+\mu^-)$	29 / 46	$< 4.6[\pm0.01_{\rm SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR^{\rm EXP/SM}_{B\to X_s\ell\ell}$	47 / 46	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{\rm EXP/SM}_{K\to\mu\nu}$	29 / 48	$1.008 \pm 0.014_{\rm EXP+TH}$	0.39	0.42	0.33
$BR^{\rm EXP/SM}_{K\to\tau\nu}$	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	$\ll 0.01$
$\Delta\epsilon_K^{\rm EXP/SM}$	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
σ_p^{SI}	25	$(m_{\chi^0}, \sigma_p^{SI})$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	18,20	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	21	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

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

CMSSM: Evolution with time

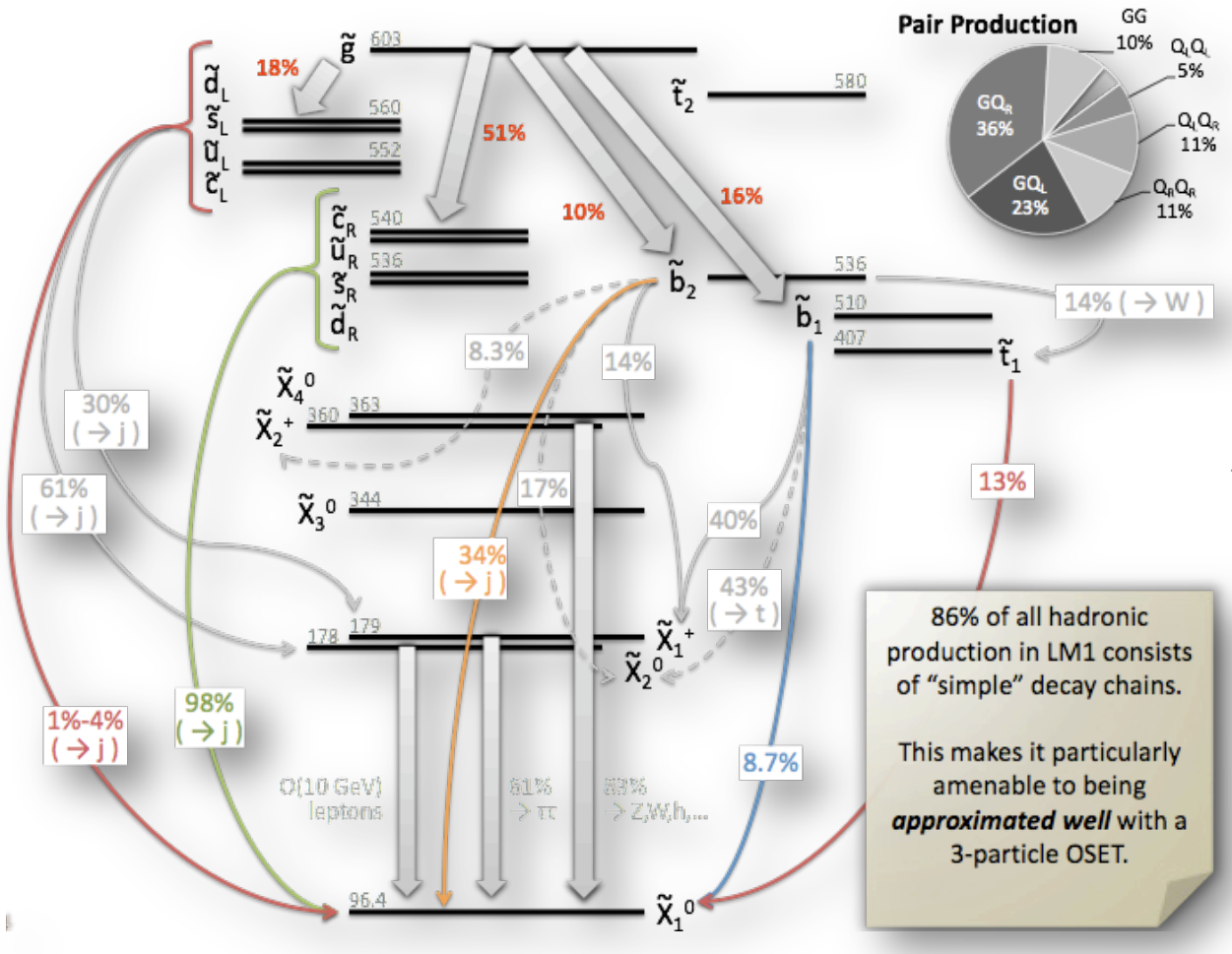


SUSY Status – post 7 TeV LHC data

- Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!
- Experiments 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

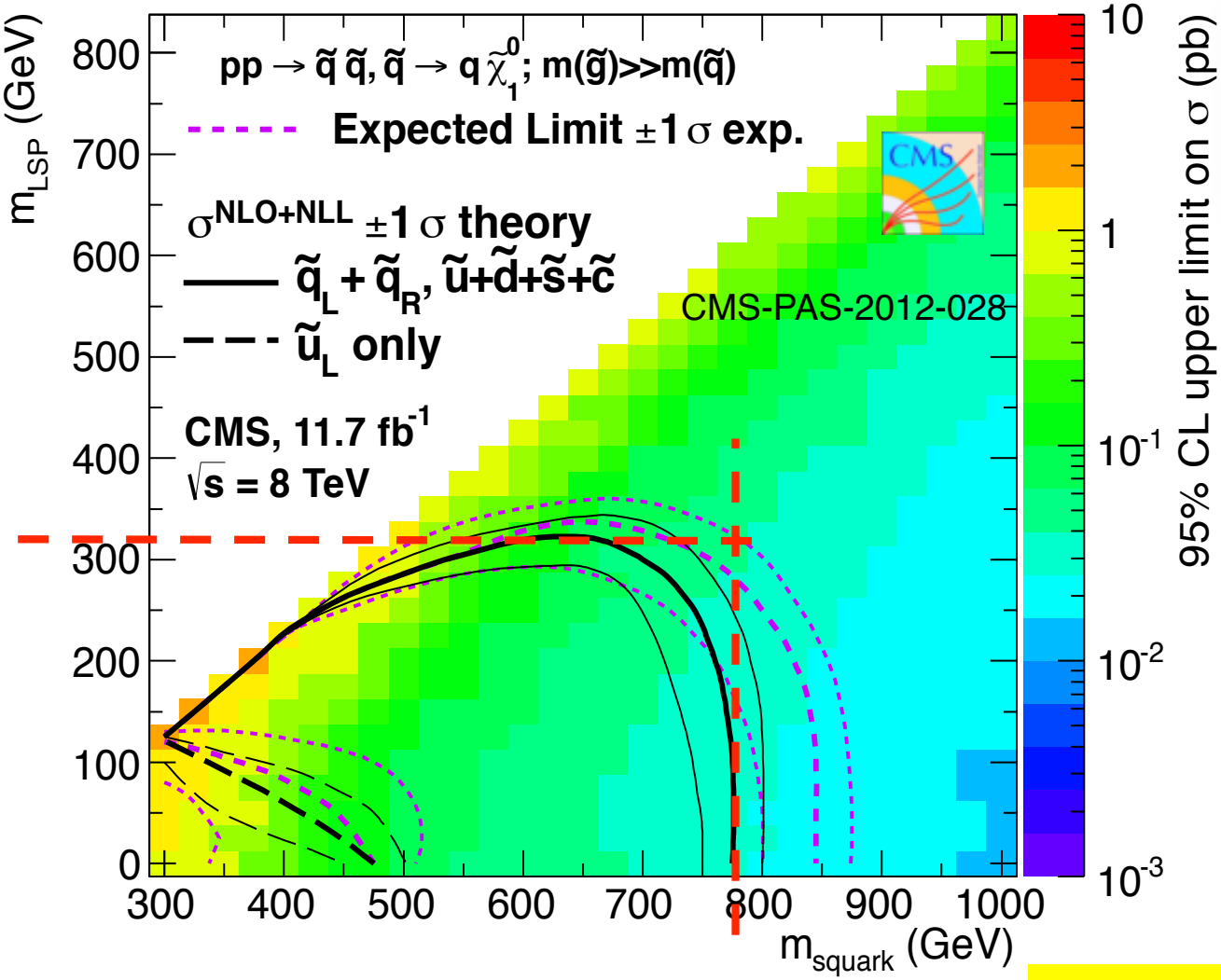


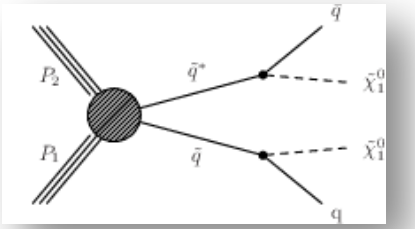
Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

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

SMS: a few interesting features

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





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

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

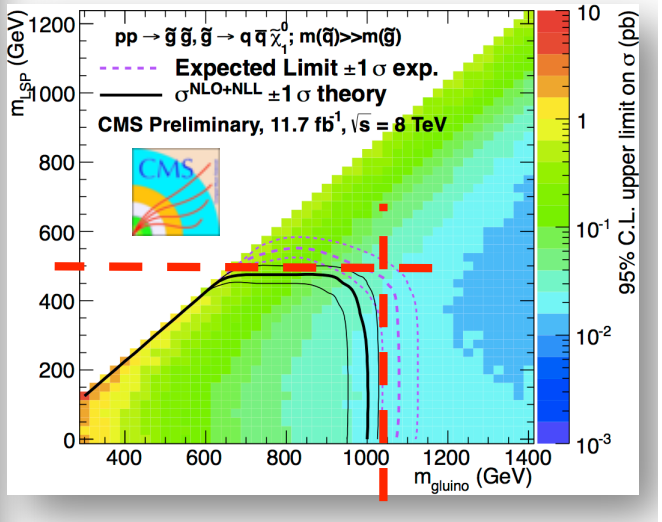
Assumes 100% BR for decay chain considered.

How to summarize SMS limits?

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

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

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



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

How to summarize SMS limits?

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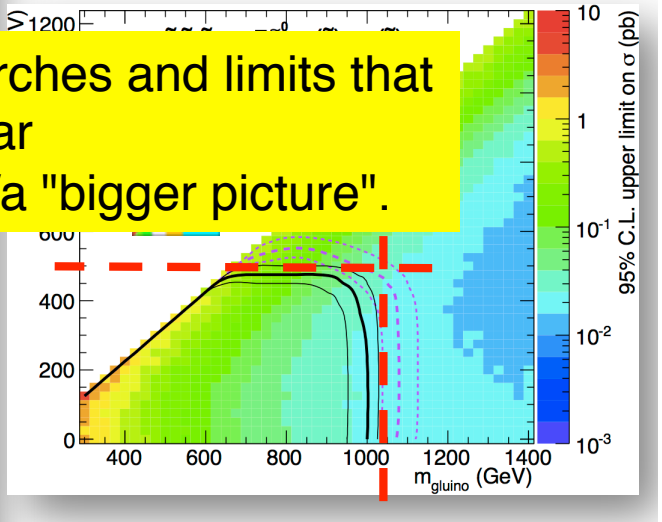
Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
CMSSM	all $m_{\tilde{q}}$		800
Simpli			
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}}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

SUSY & DM Searches, @ LHC O. Buchmüller

m_{LSP} [GeV]

1000

750

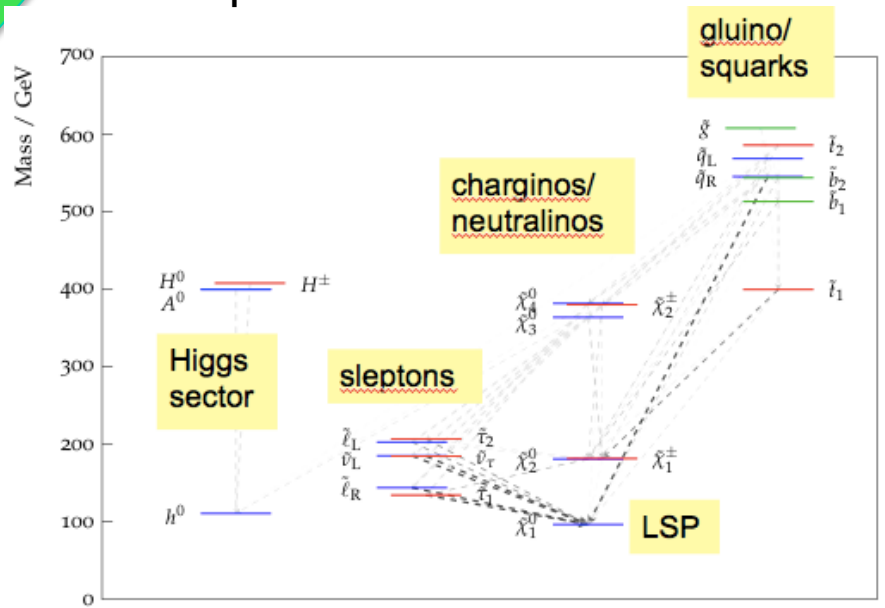
500

250

0

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

What are representative SMS limits on the different particles?



0 250 500 750 1000 1250 1500

m_{SUSY} [GeV]

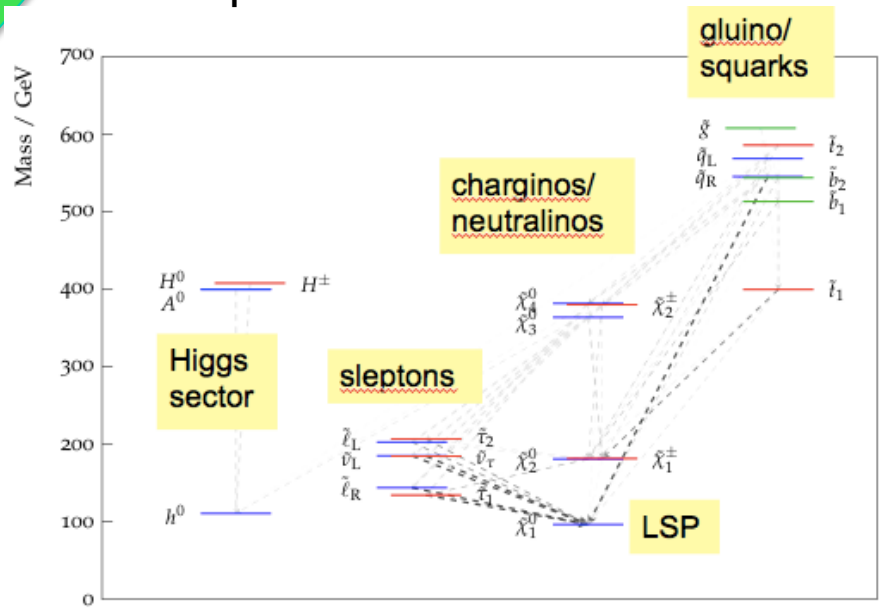
m_{LSP} [GeV]

Note: The following results are based on PDG review September 2013.

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

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

What are representative SMS limits on the different particles?



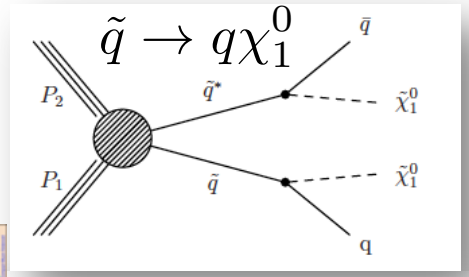
m_{SUSY} [GeV]

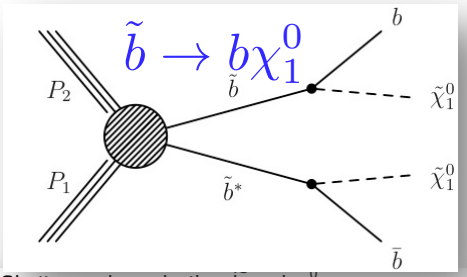
0 250 500 750 1000 1250 1500

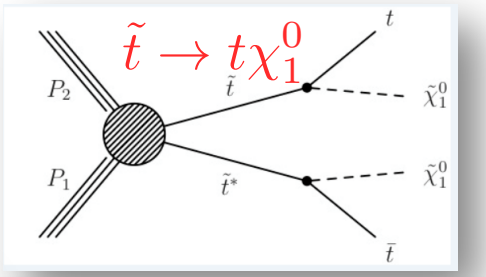
Imperial College London

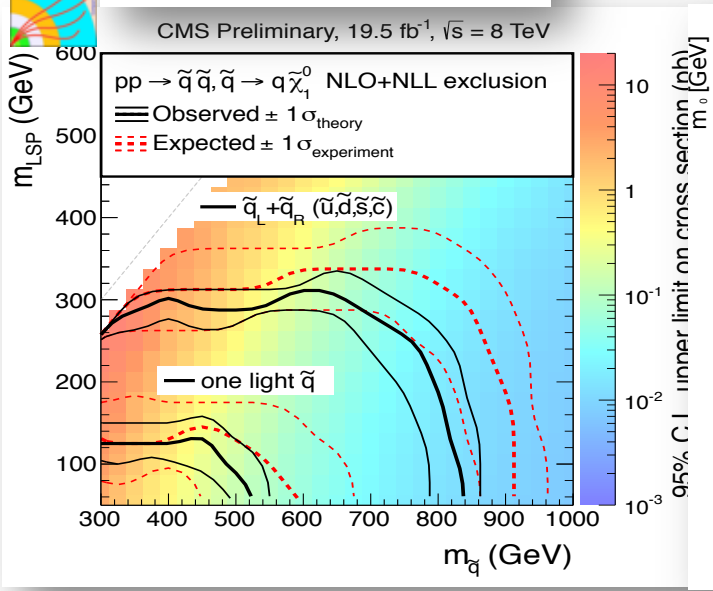
Direct squark production – chosen limits

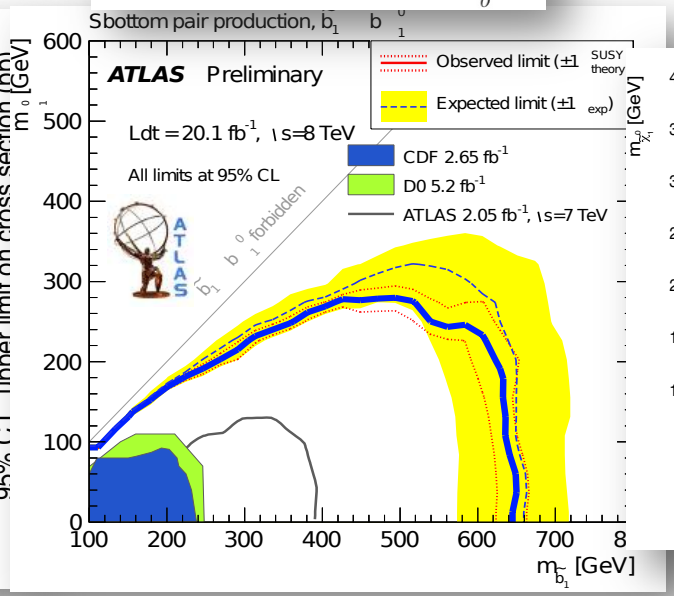
SUSY & DM Searches, @ LHC O. Buchmüller

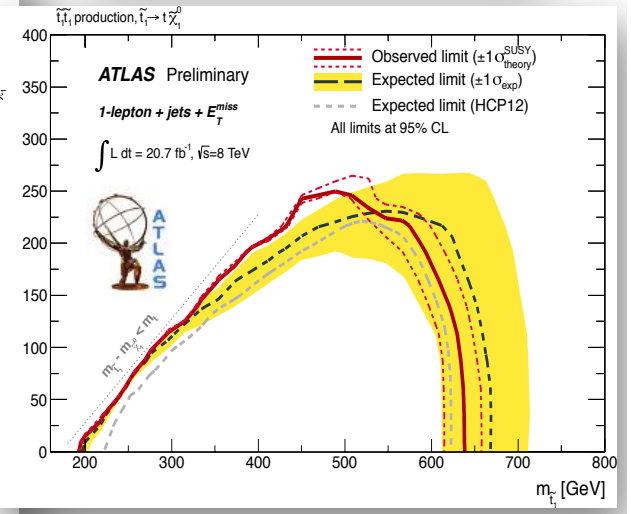








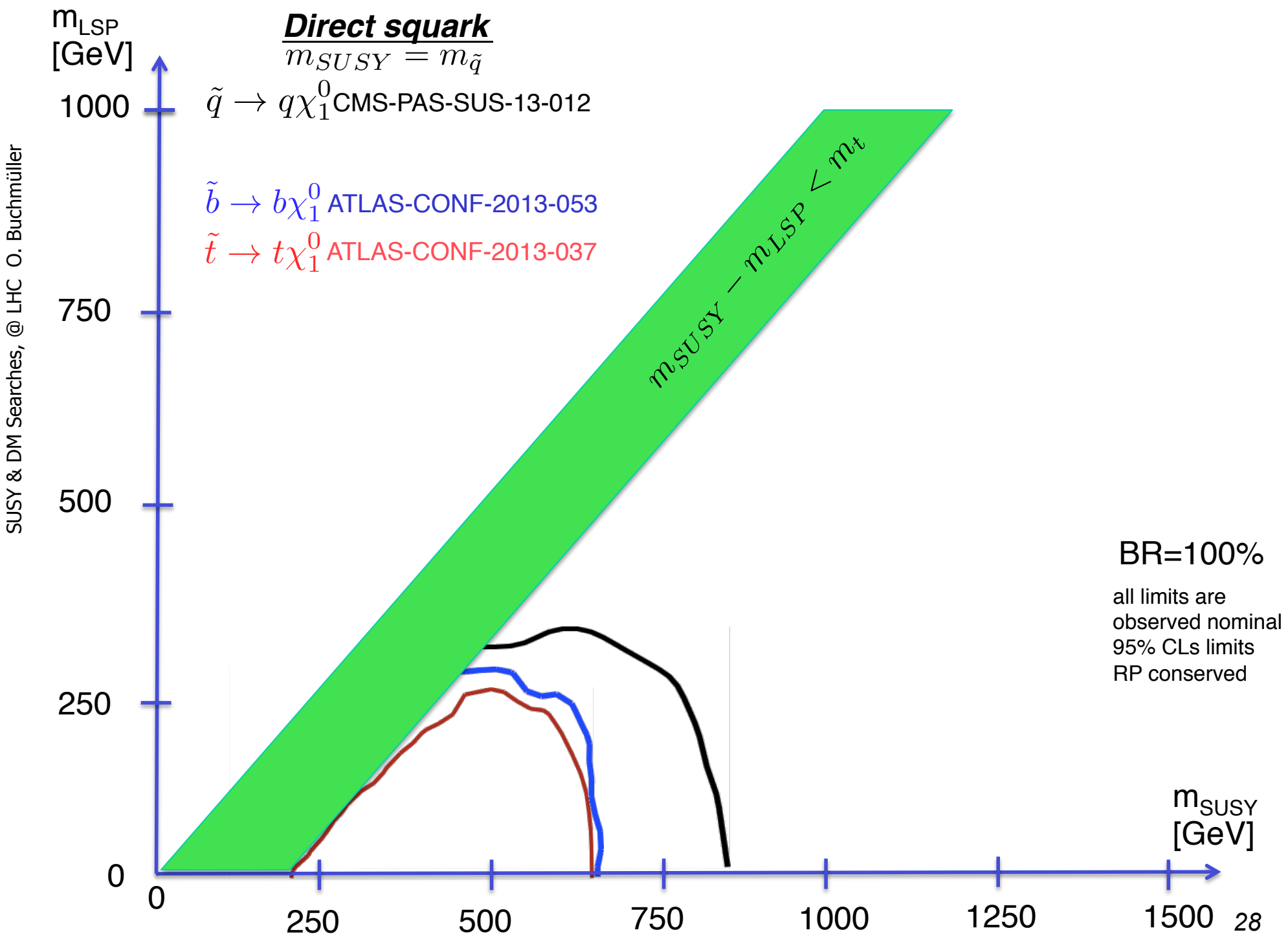




CMS-SUS-PAS-13-012
Signature: Jets + E_t^{miss} + H_T
Limit assumes all 1st & 2nd gen squarks to be mass degenerate or only one light squark!

ATLAS-CONF-2013-053
Signature: 2 b-jets + E_T^{mis}

ATLAS-CONF-2013-037
Signature: 1Lepton + jets + E_T^{mis}


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \rightarrow b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
$m_{SUSY} - m_{LSP} < m_t$
SUSY & DM Searches, @ LHC O. Buchmüller
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved

Direct squark

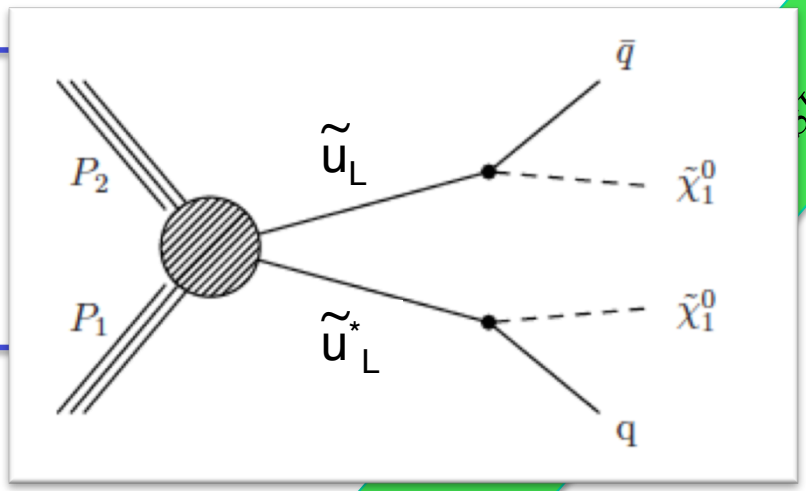
$m_{SUSY} = m_{\tilde{q}}$

$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012 (8x mass

$\tilde{u}_L \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012

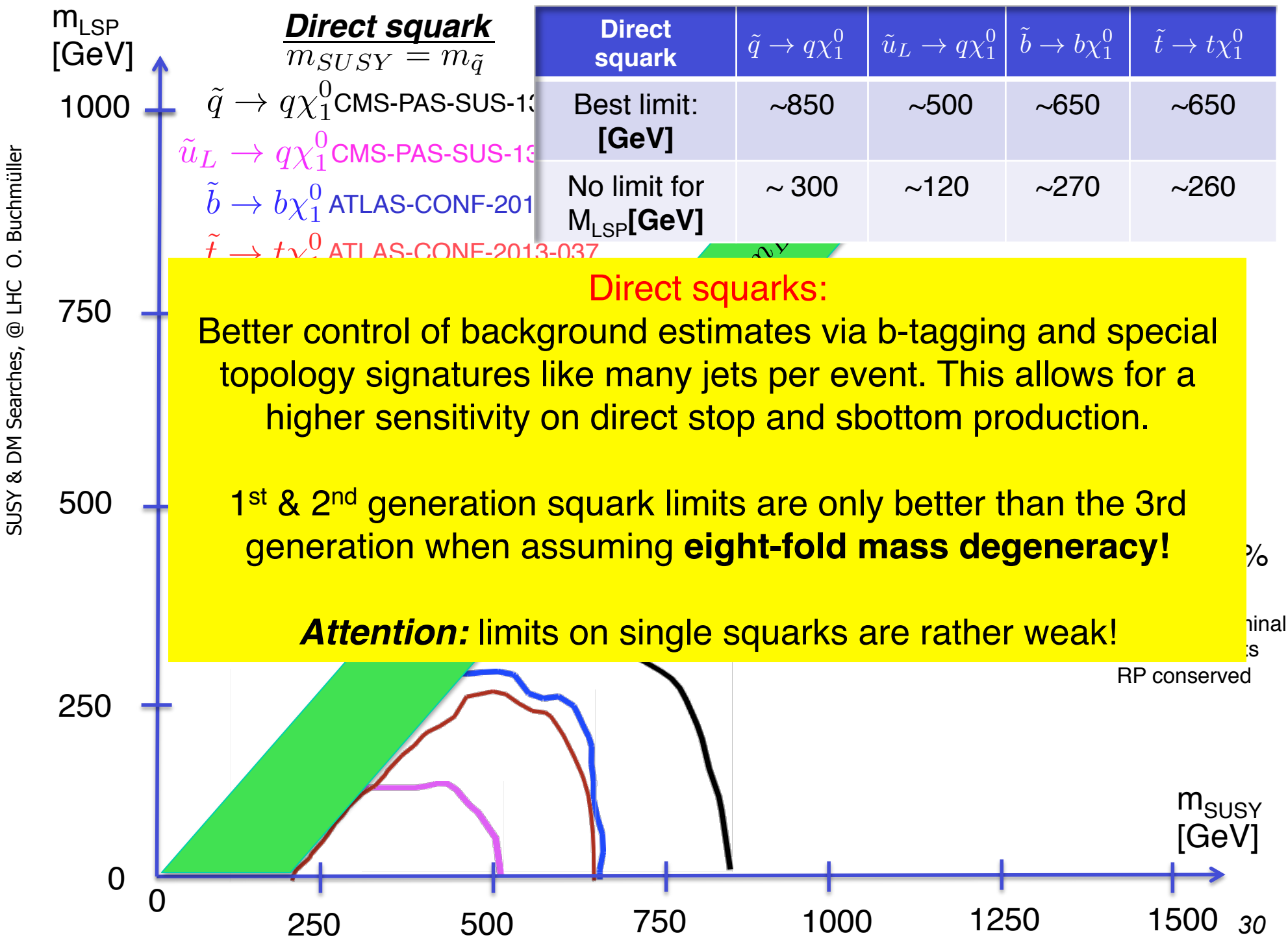
$\tilde{b} \rightarrow b\chi_1^0$ ATLAS-CONF-2013-053

$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037



CMS-SUS-PAS-13-012
Signature: Jets + E_t^{miss}

Limit assumes only one light squark (e.g. u_L) and decoupled gluino (as before).



Direct squark	$\tilde{q} \to q\chi_1^0$	$\tilde{u}_L \to q\chi_1^0$	$\tilde{b} \to b\chi_1^0$	$\tilde{t} \to t\chi_1^0$
Best limit: **[GeV]**	~850	~500	~650	~650
No limit for M_{LSP}**[GeV]**	~ 300	~120	~270	~260

Direct squarks:

Better control of background estimates via b-tagging and special topology signatures like many jets per event. This allows for a higher sensitivity on direct stop and sbottom production.

1st & 2nd generation squark limits are only better than the 3rd generation when assuming **eight-fold mass degeneracy!**

Attention: limits on single squarks are rather weak!

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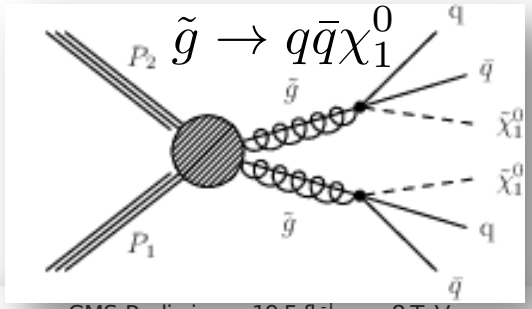
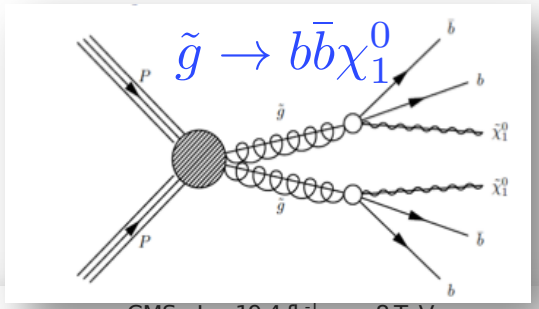
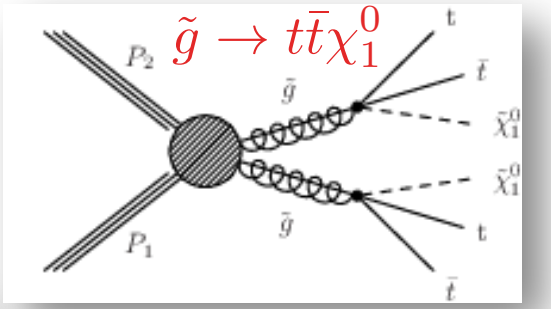
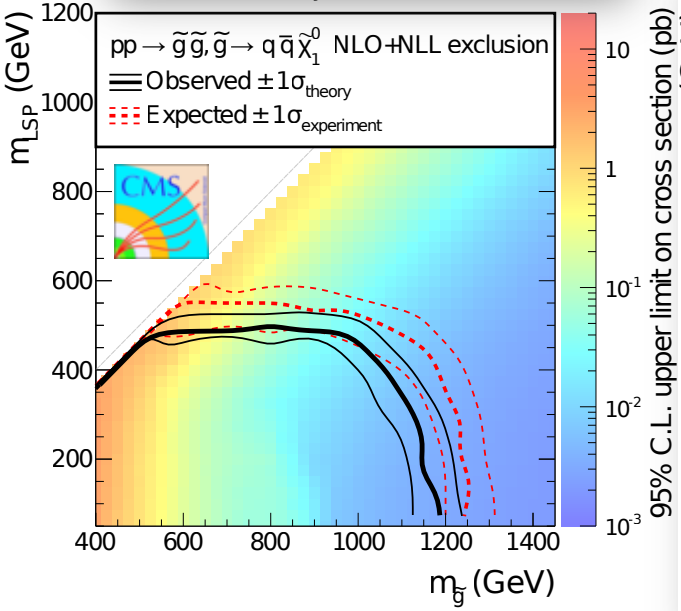
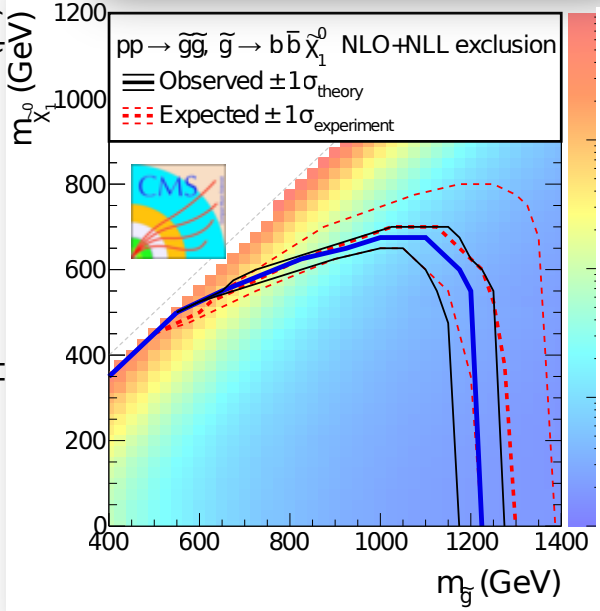
Gluino mediated squark production – limits chosen

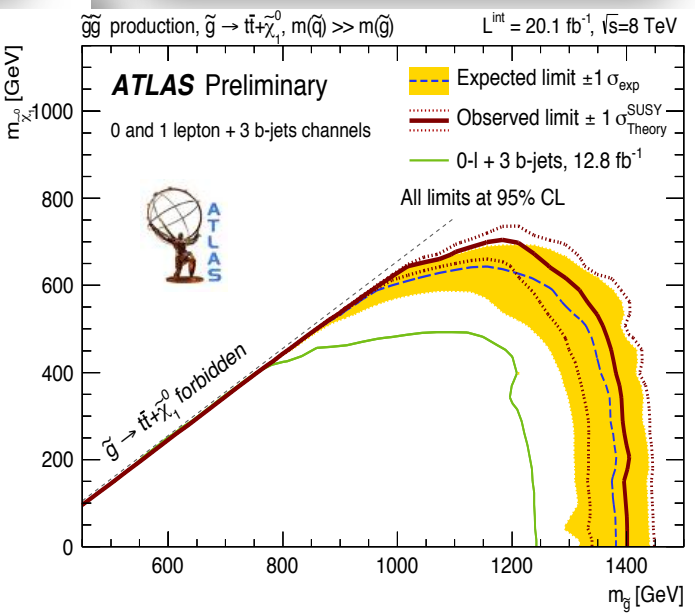








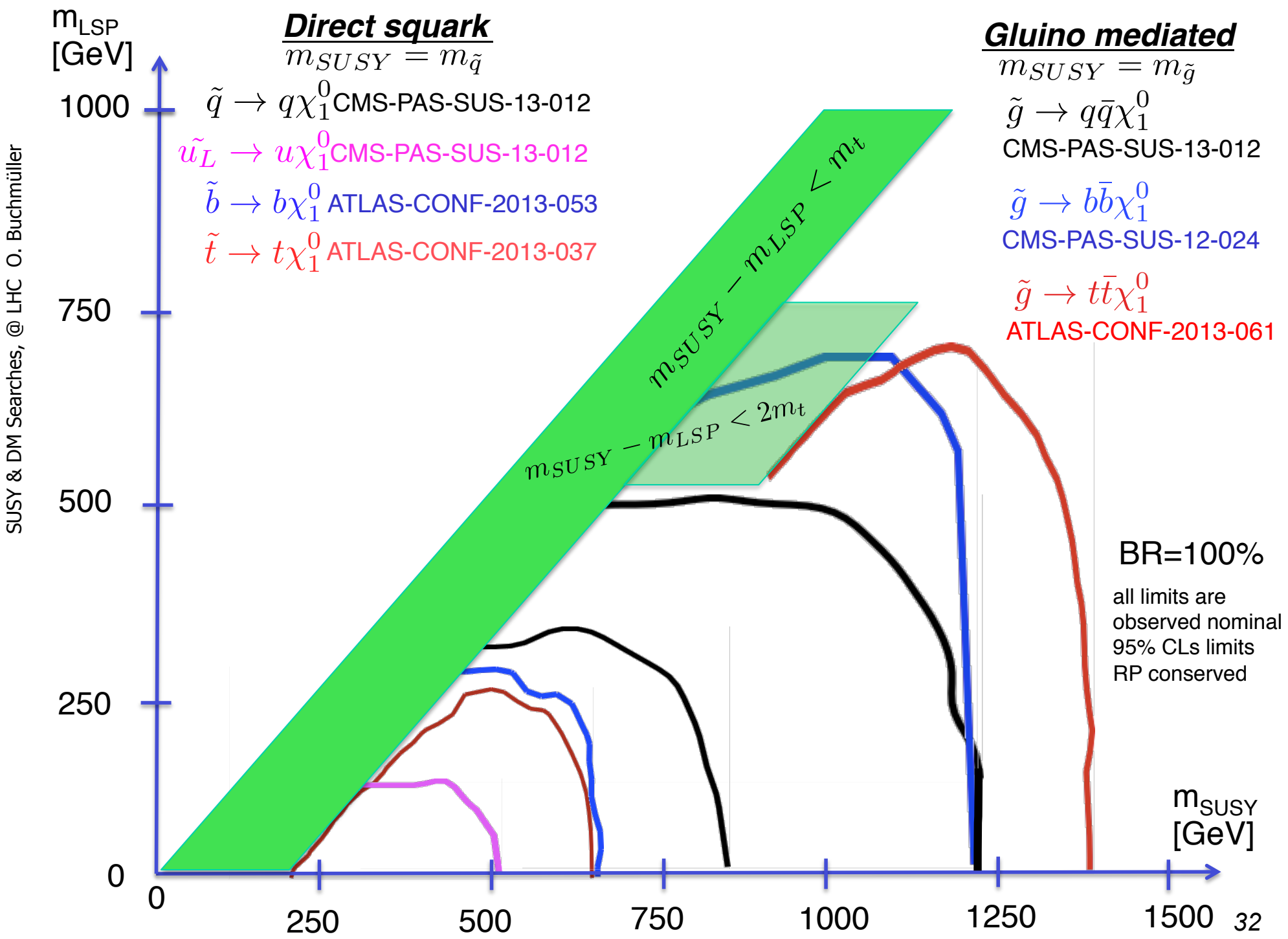




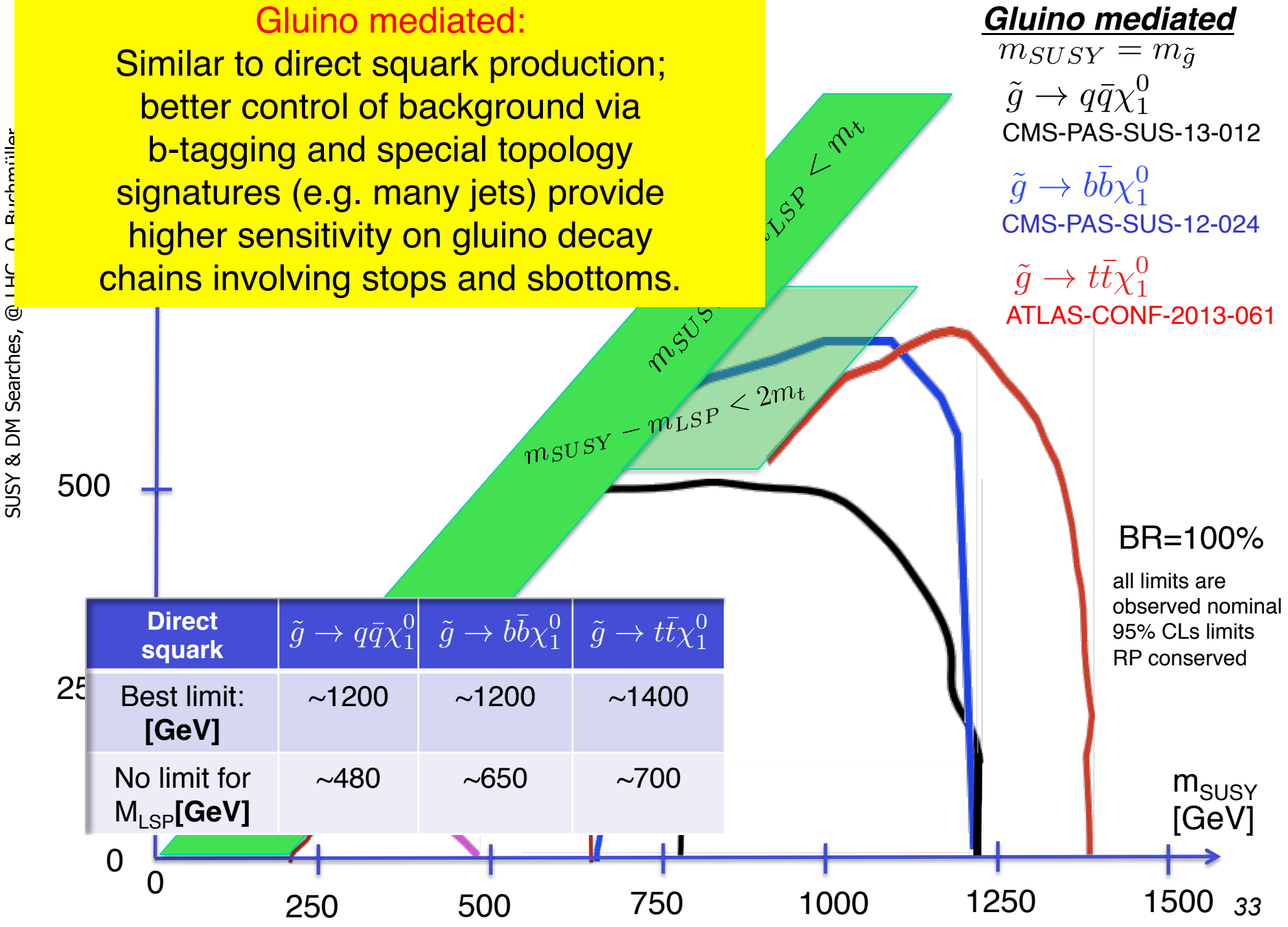
CMS-SUS-PAS-13-012
Signature: Jets + H_T + E_t^{miss}

CMS-SUS-PAS-12-024
Signature: : Jets + b-tag + E_t^{miss}

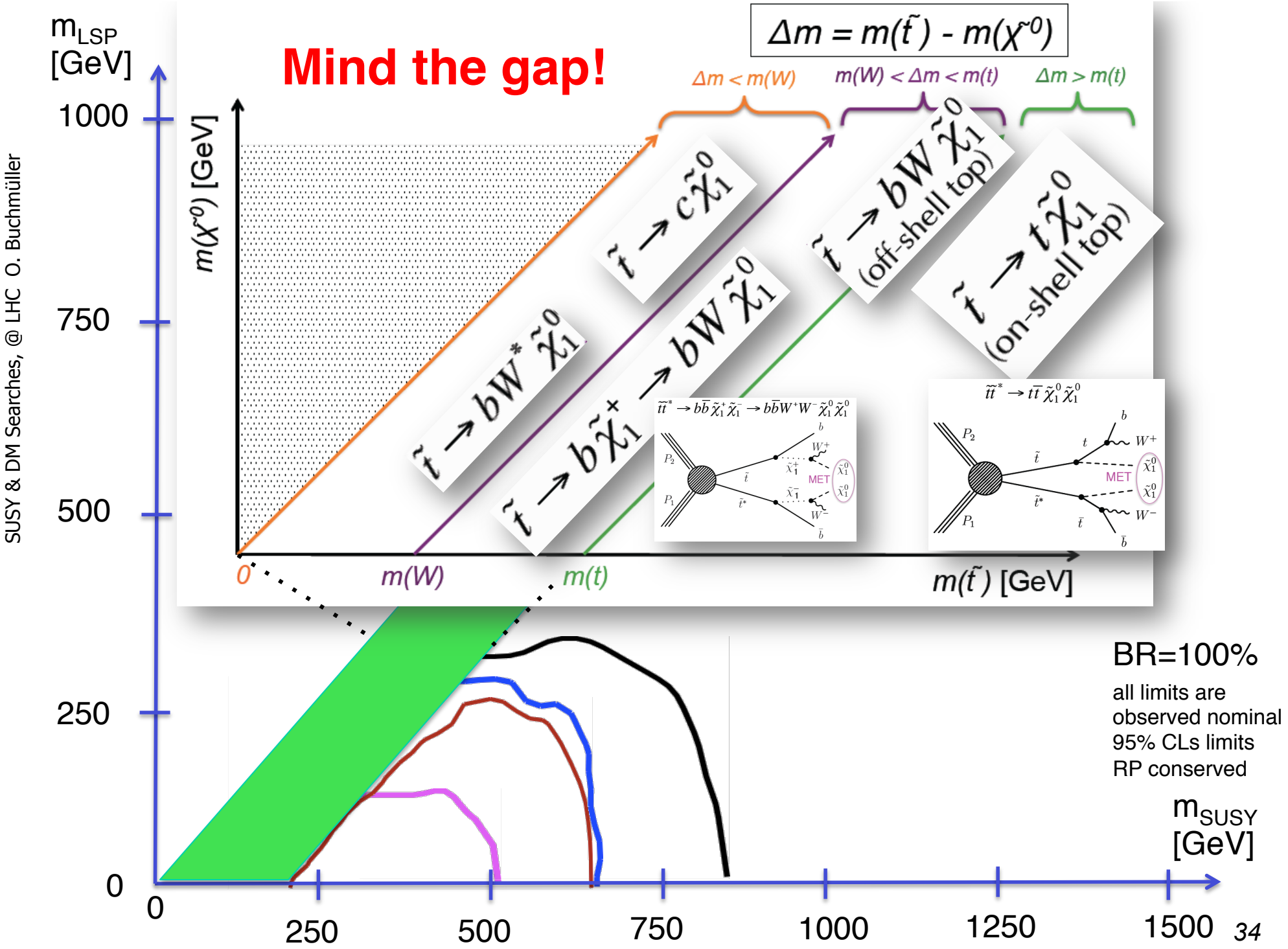
ATLAS-CONF-2013-061
Signature: 0/1 Leptons + 3 b-tag + E_t^{mis}


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
CMS-PAS-SUS-13-012
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500
SUSY & DM Searches, @ LHC O. Buchmüller
32

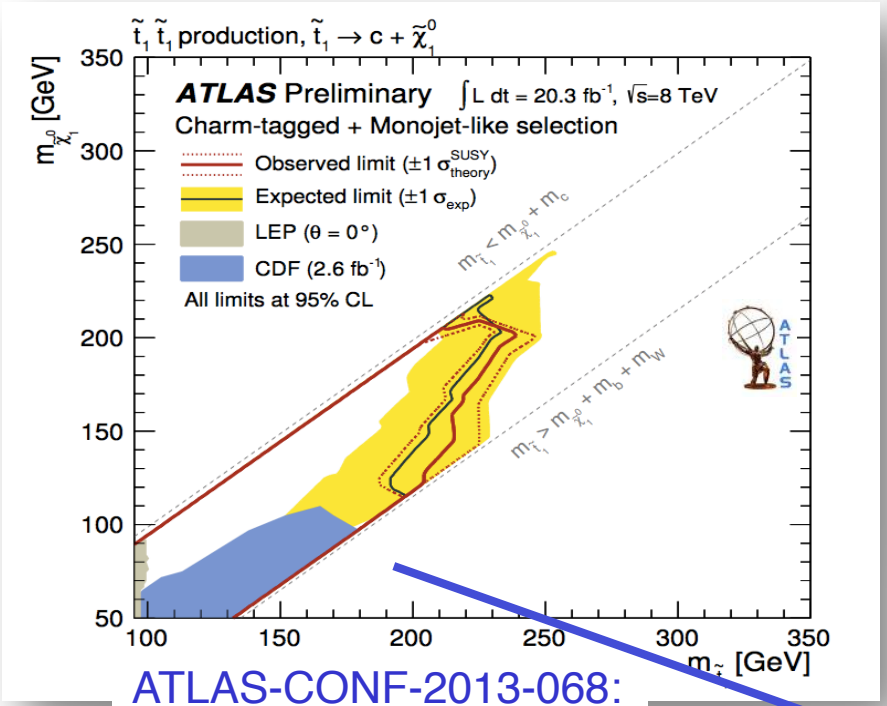
Gluino mediated:
Similar to direct squark production; better control of background via b-tagging and special topology signatures (e.g. many jets) provide higher sensitivity on gluino decay chains involving stops and sbottoms.

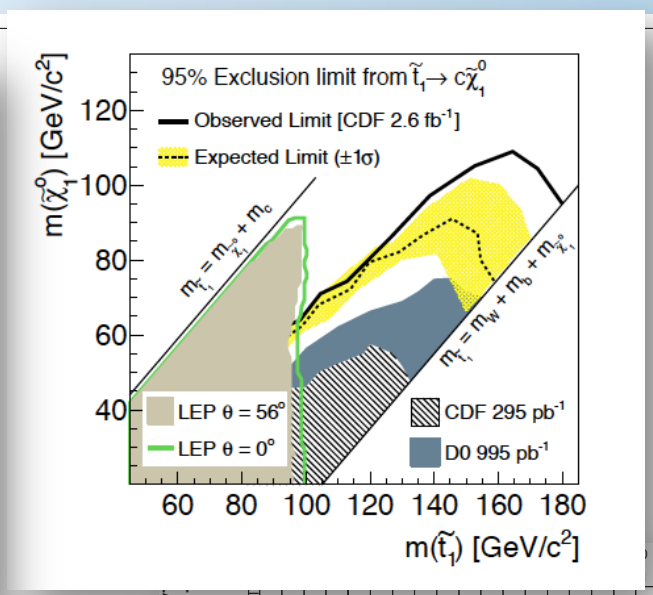


Direct squark	$\tilde{g} \to q\bar{q}\chi_1^0$	$\tilde{g} \to b\bar{b}\chi_1^0$	$\tilde{g} \to t\bar{t}\chi_1^0$
Best limit: **[GeV]**	~1200	~1200	~1400
No limit for M_{LSP}**[GeV]**	~480	~650	~700


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

Dedicated searches for direct stop-pair production

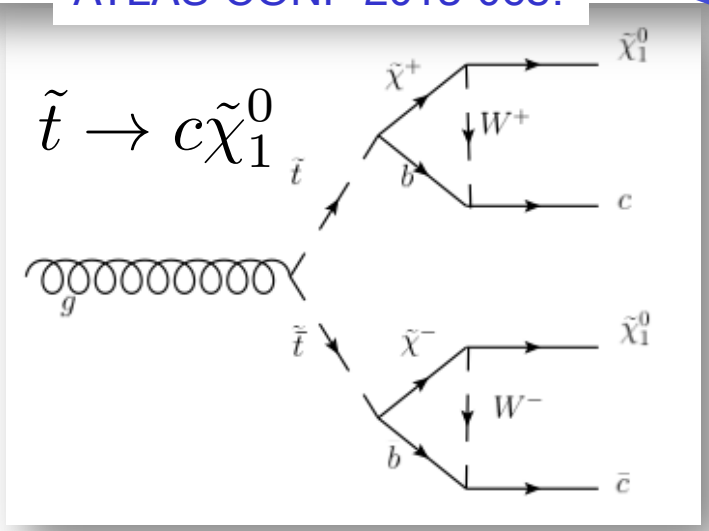


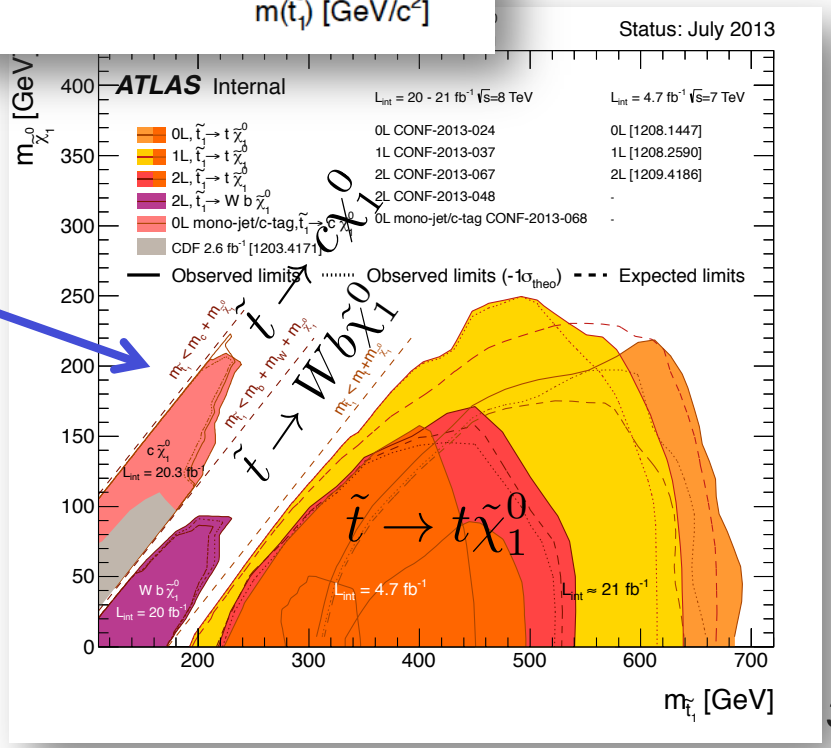


LEP:
LEPSUSY
WG/04-01.1

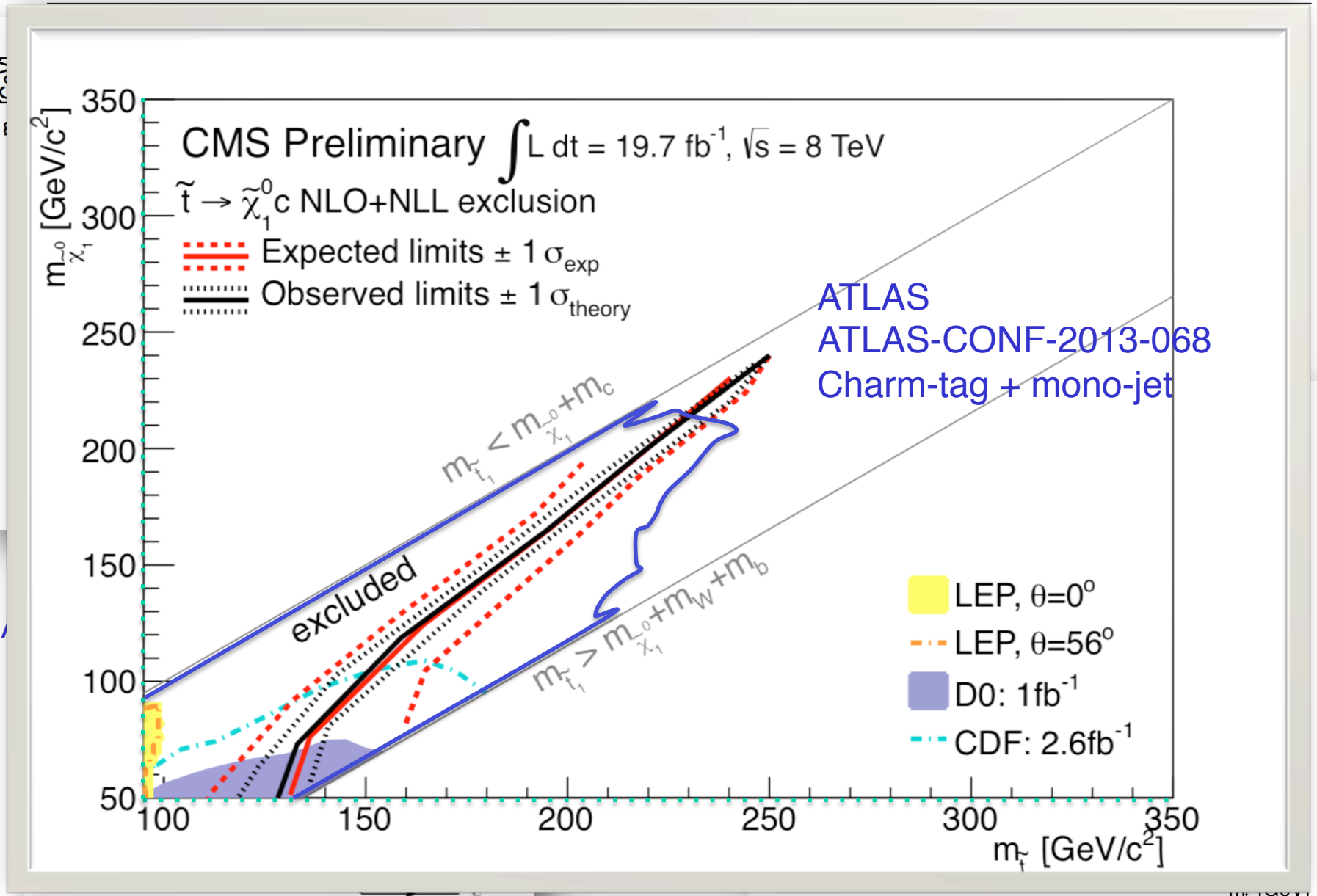
CDF:
1203.4171
D0:
0803.2263

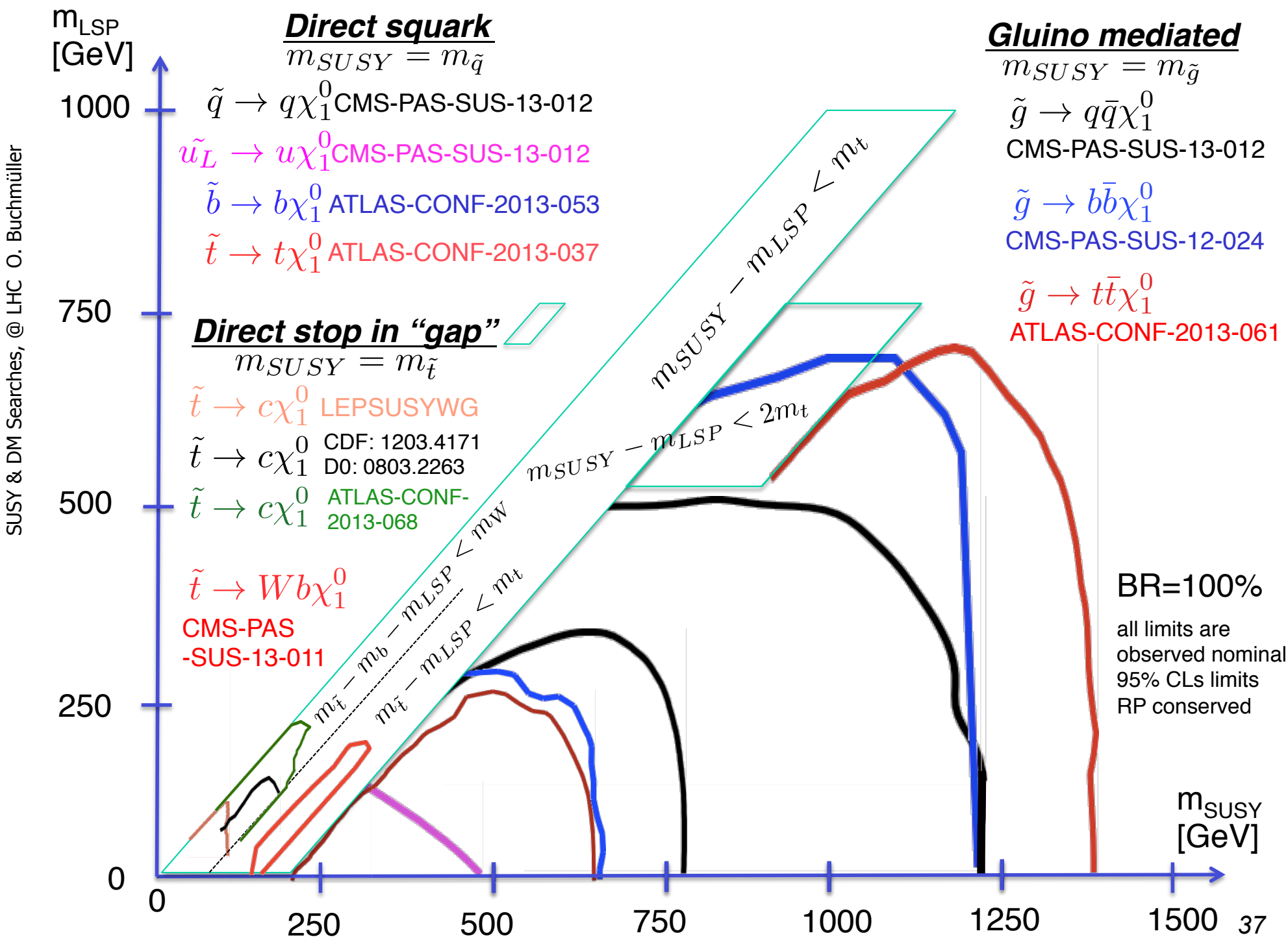
ATLAS-CONF-2013-068:

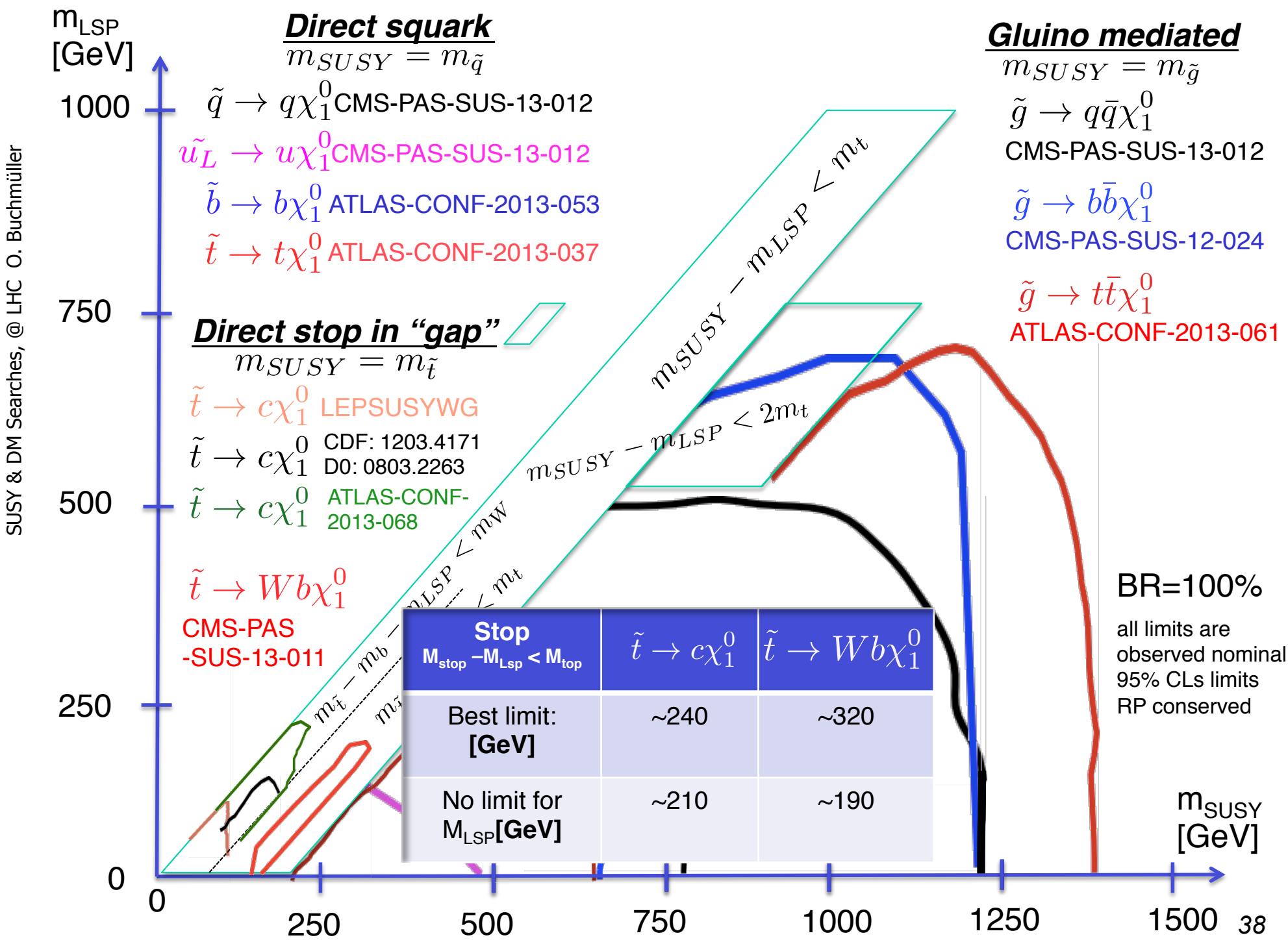




Dedicated searches for direct stop-pair production




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-PAS-SUS-13-012
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$ LEPSUSYWG
$\tilde{t} \to c\chi_1^0$ CDF: 1203.4171 D0: 0803.2263
$\tilde{t} \to c\chi_1^0$ ATLAS-CONF-2013-068
$\tilde{t} \to Wb\chi_1^0$
CMS-PAS -SUS-13-011
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
CMS-PAS-SUS-13-012
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved


m_LSP [GeV]
1000
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$m_{\tilde{t}} - m_b$
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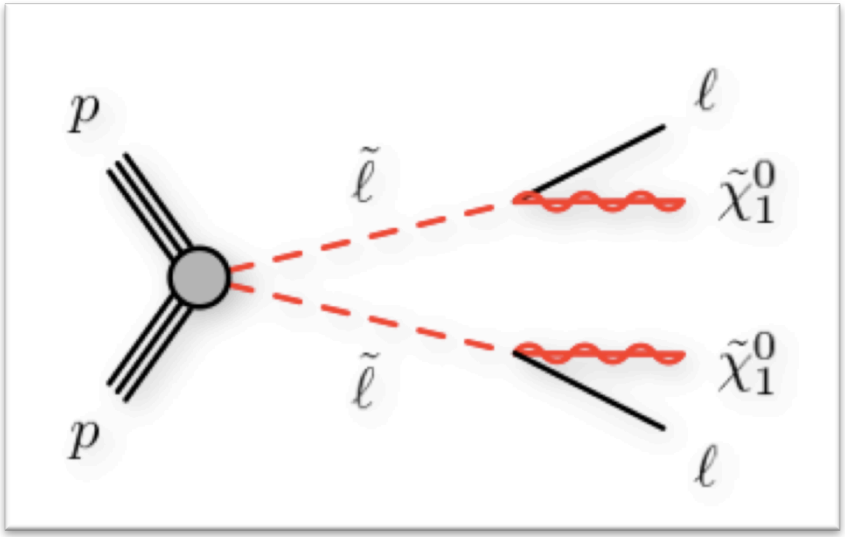
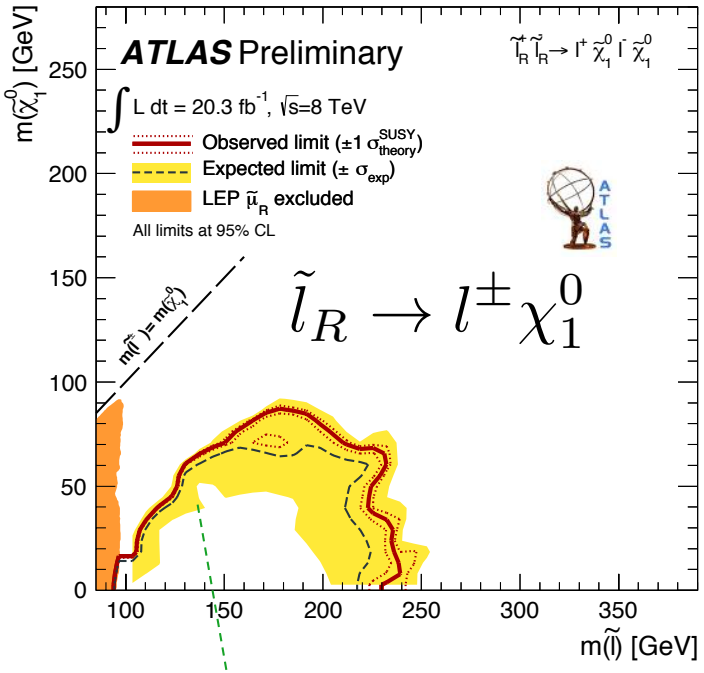
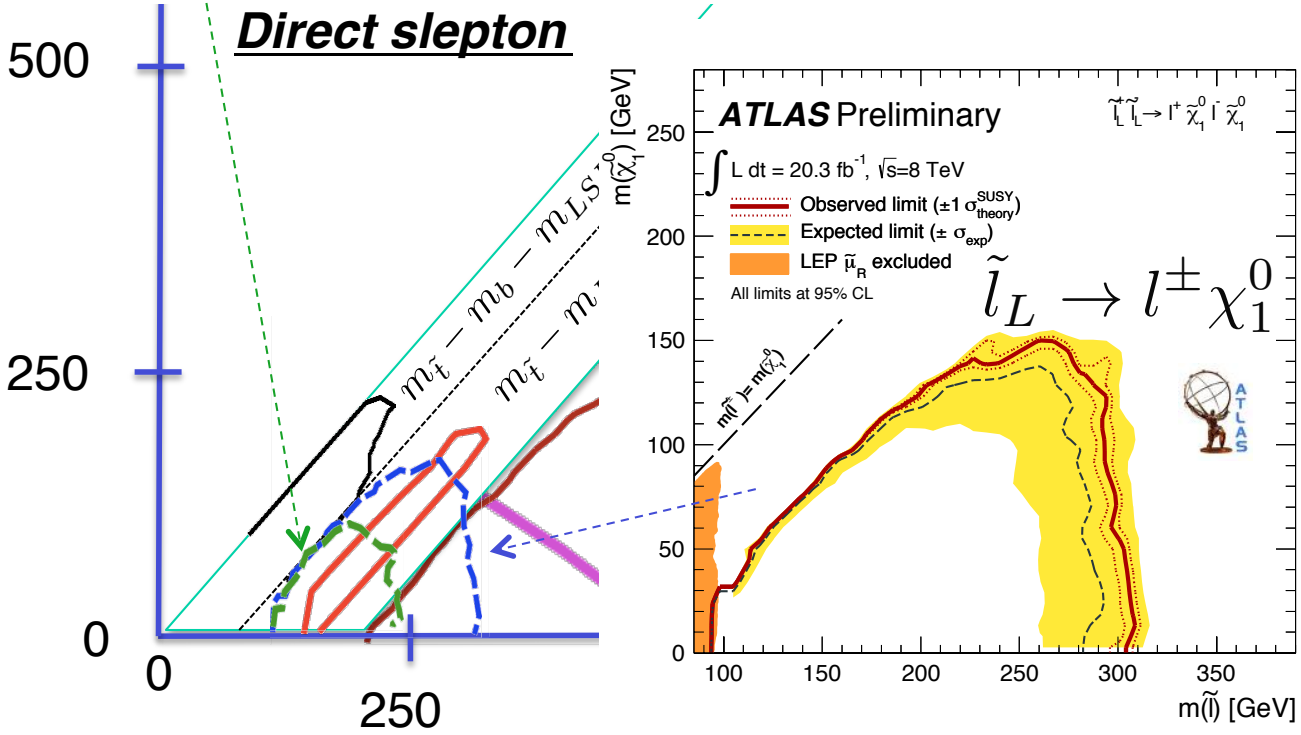
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
Stop
$M_{stop} - M_{Lsp} < M_{top}$
$\tilde{t} \to c\chi_1^0$
$\tilde{t} \to Wb\chi_1^0$
Best limit: [GeV]
~240
~320
No limit for M_{LSP}[GeV]
~210
~190
38

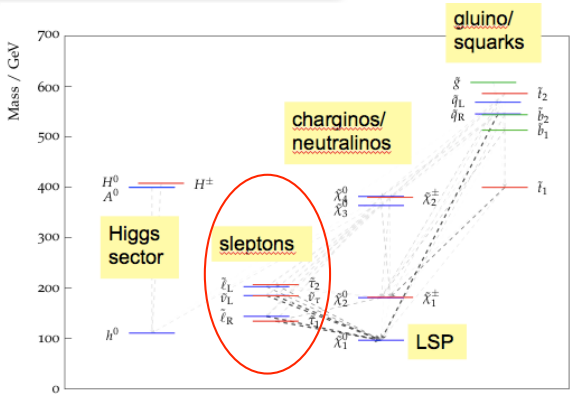
Direct slepton production



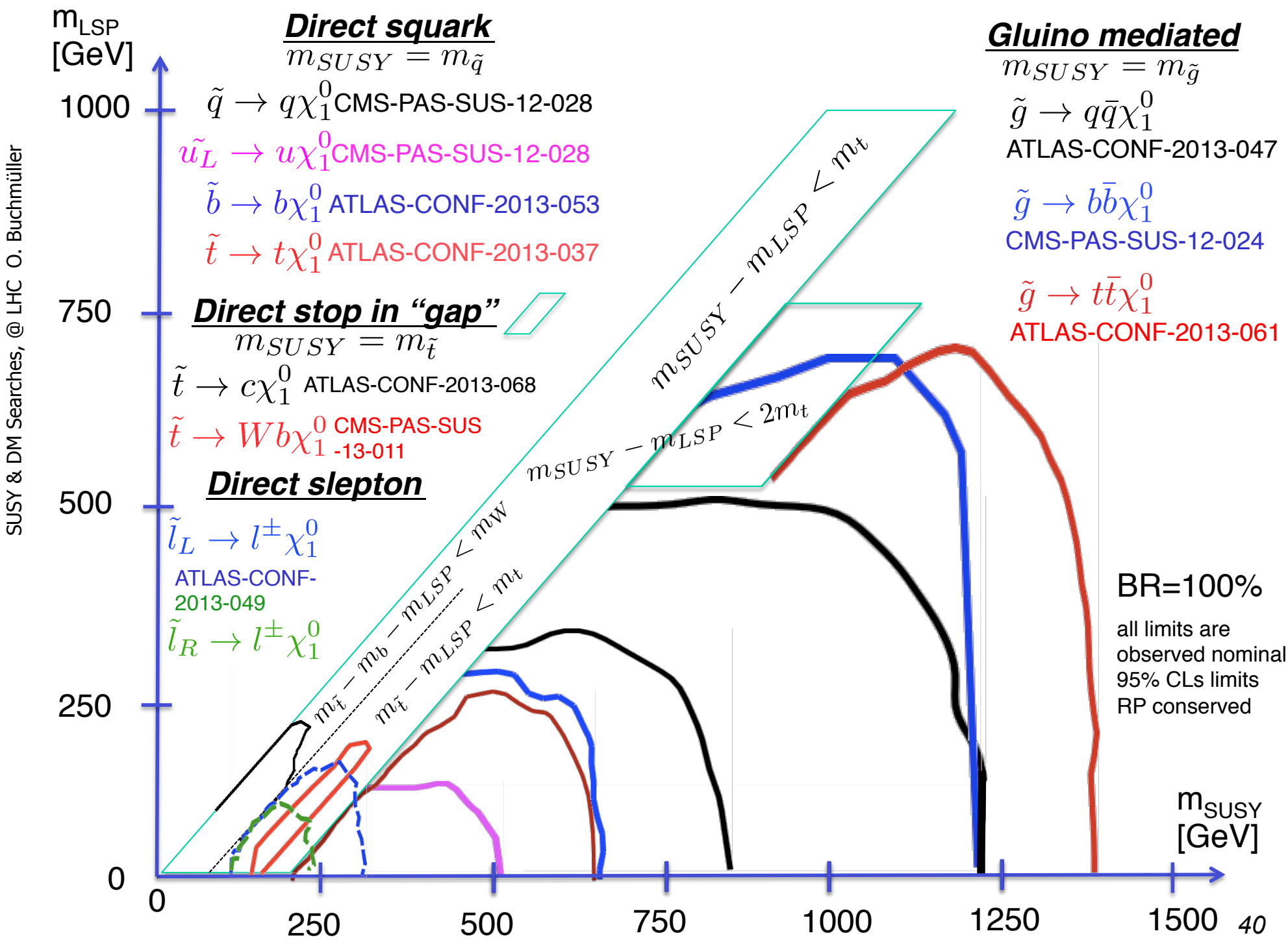


Direct slepton





ATLAS-CONF-2013-049
Signature
2 lepton + E_T^{miss}


m_LSP [GeV]
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m_SUSY [GeV]
SUSY & DM Searches, @ LHC O. Buchmüller
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$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
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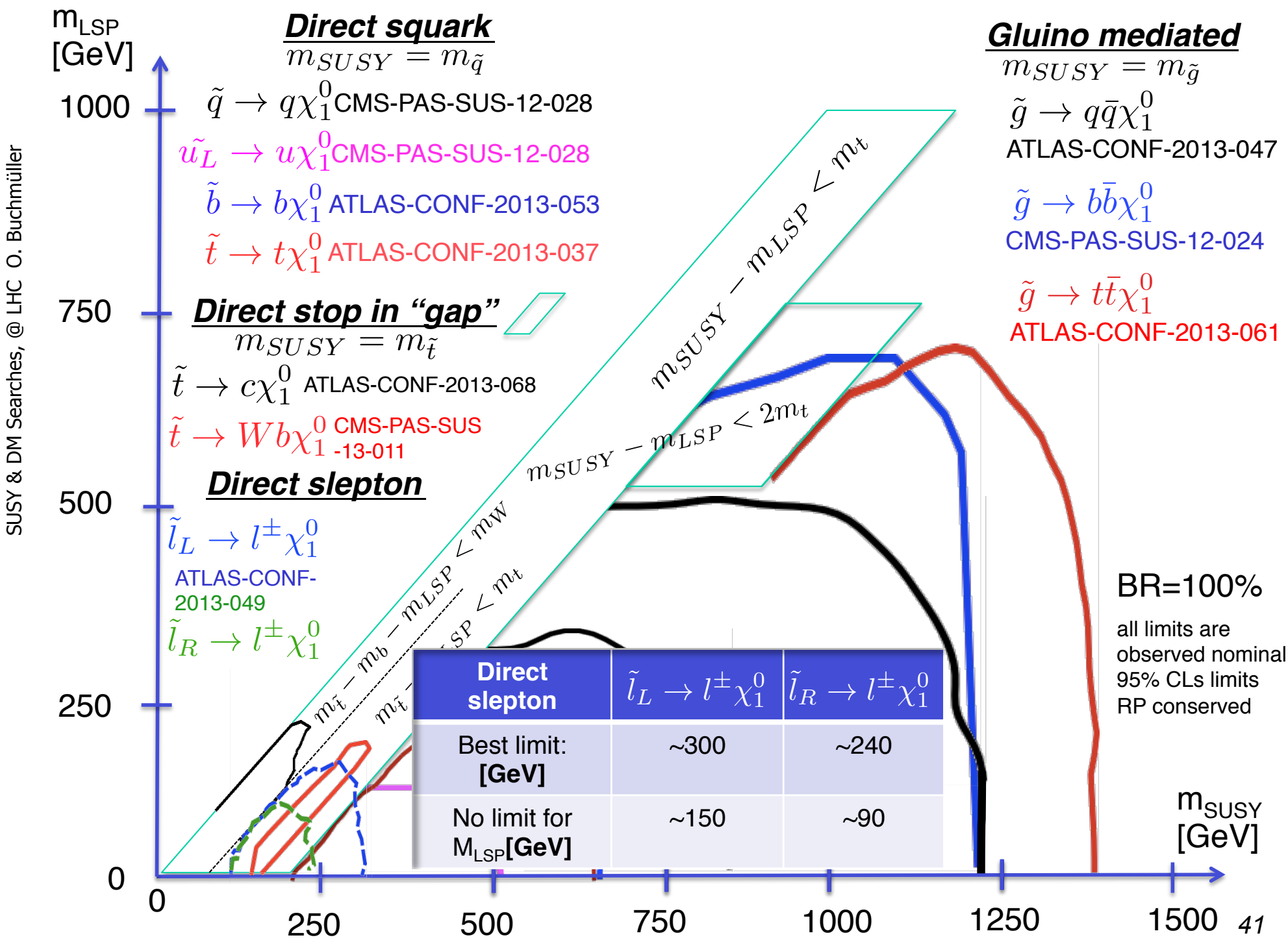
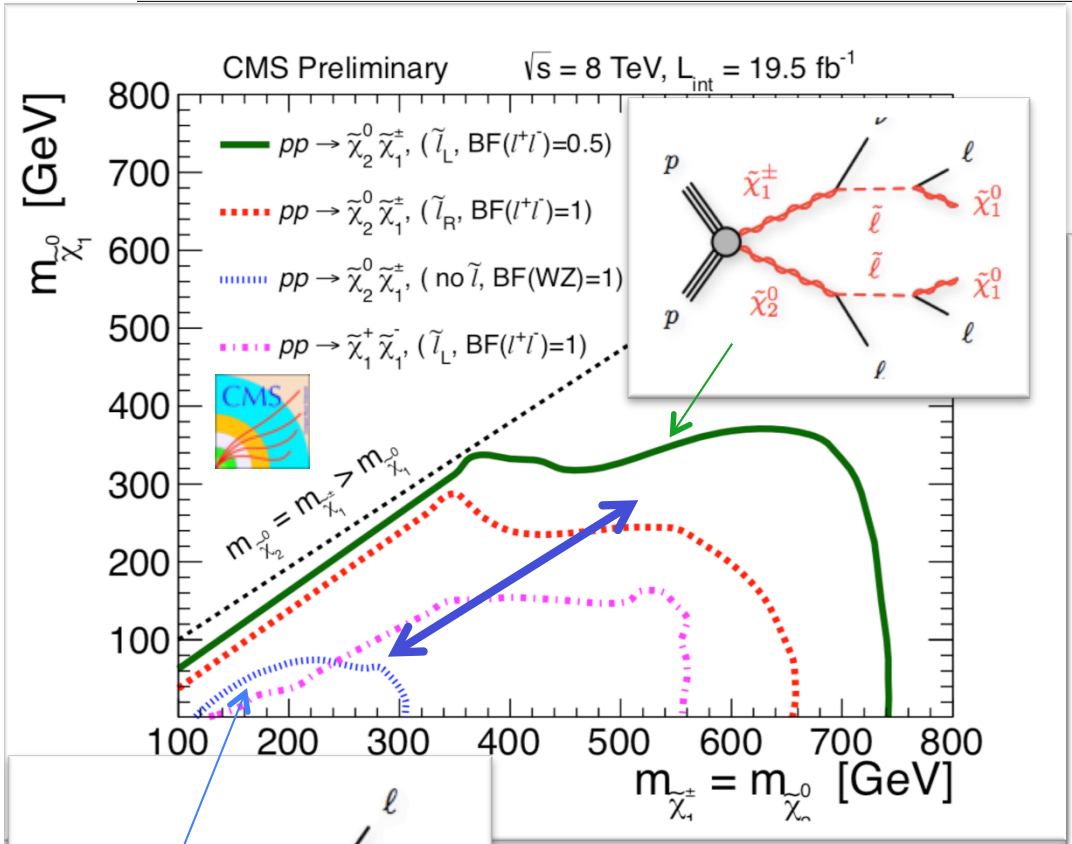
$\tilde{t} \to Wb\chi_1^0$ CMS-PAS-SUS-13-011
Direct slepton
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS-CONF-2013-049
$\tilde{l}_R \to l^{\pm}\chi_1^0$
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2013-047
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved

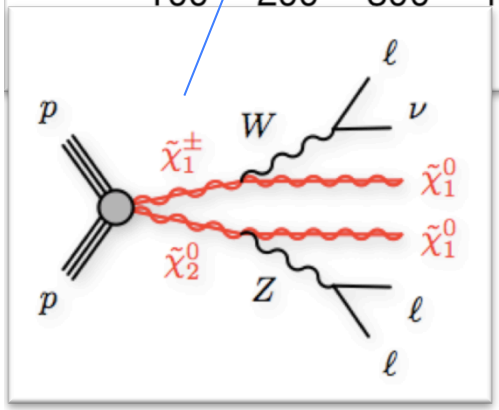


Direct slepton	$\tilde{l}_L \to l^{\pm}\chi_1^0$	$\tilde{l}_R \to l^{\pm}\chi_1^0$
Best limit: **[GeV]**	~300	~240
No limit for M_{LSP}**[GeV]**	~150	~90

Imperial College London

Direct chargino/neutralino production





heavy slepton“hard(er)”

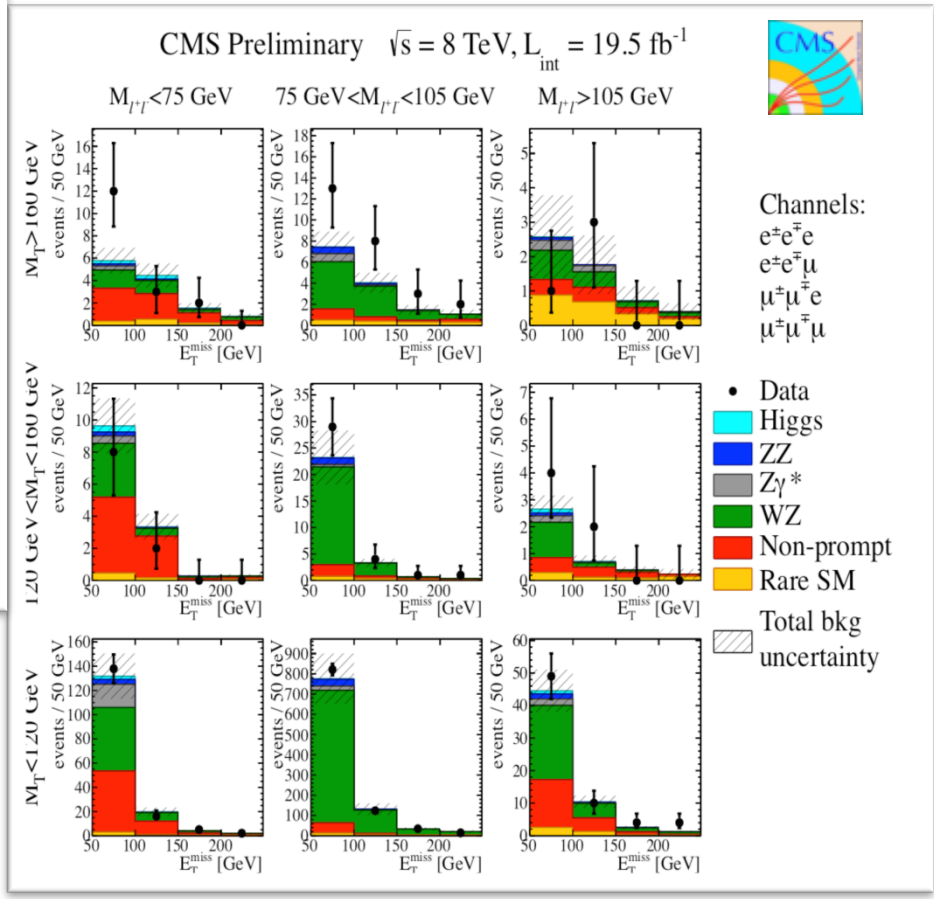
Add Z(l⁺l⁻)+2jets topology in bins of E_t^{miss} to increase sensitivity for “heavy” slepton case

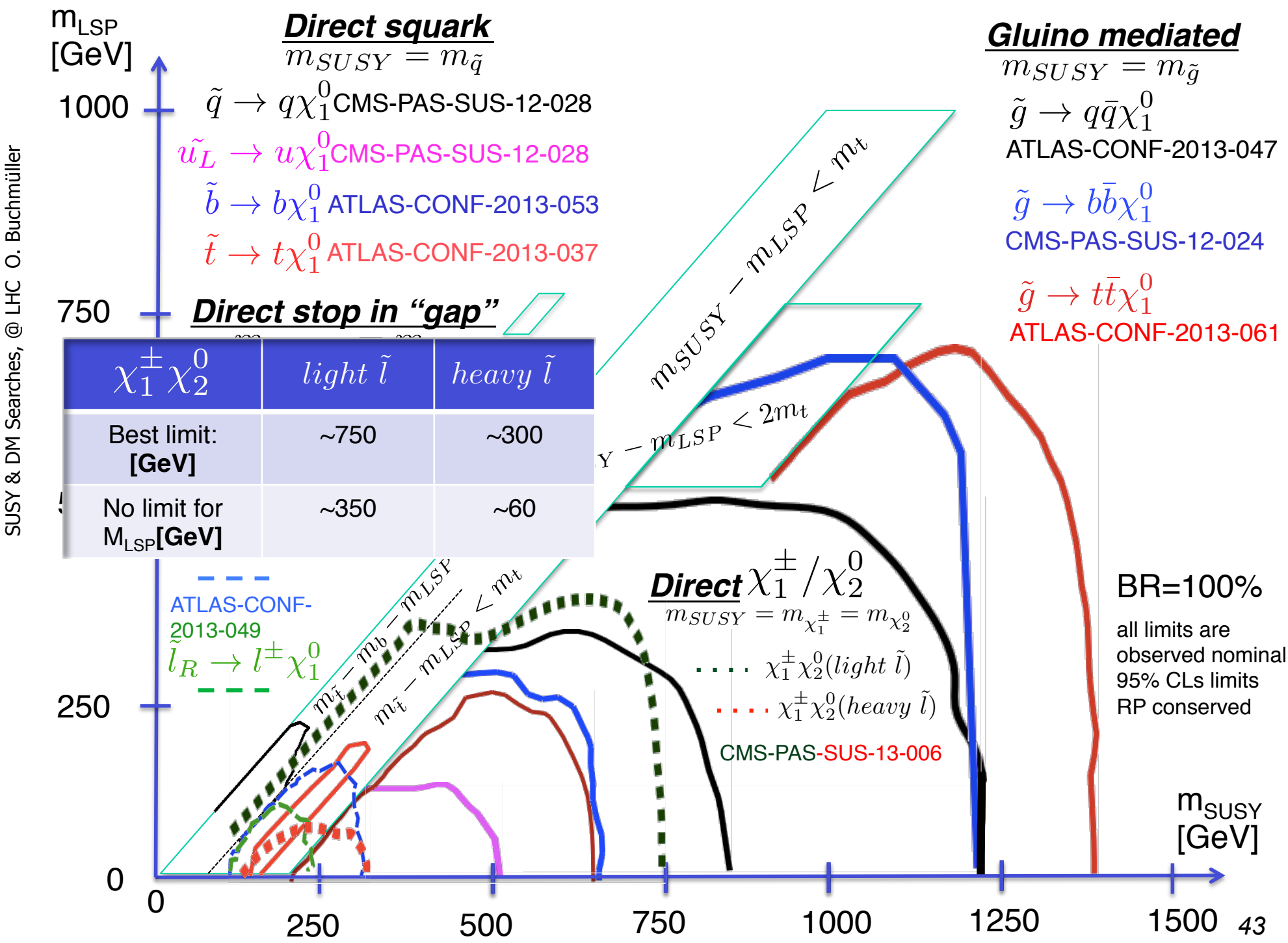
light slepton “easy”

CMS-PAS-SUS-13-006

NEW

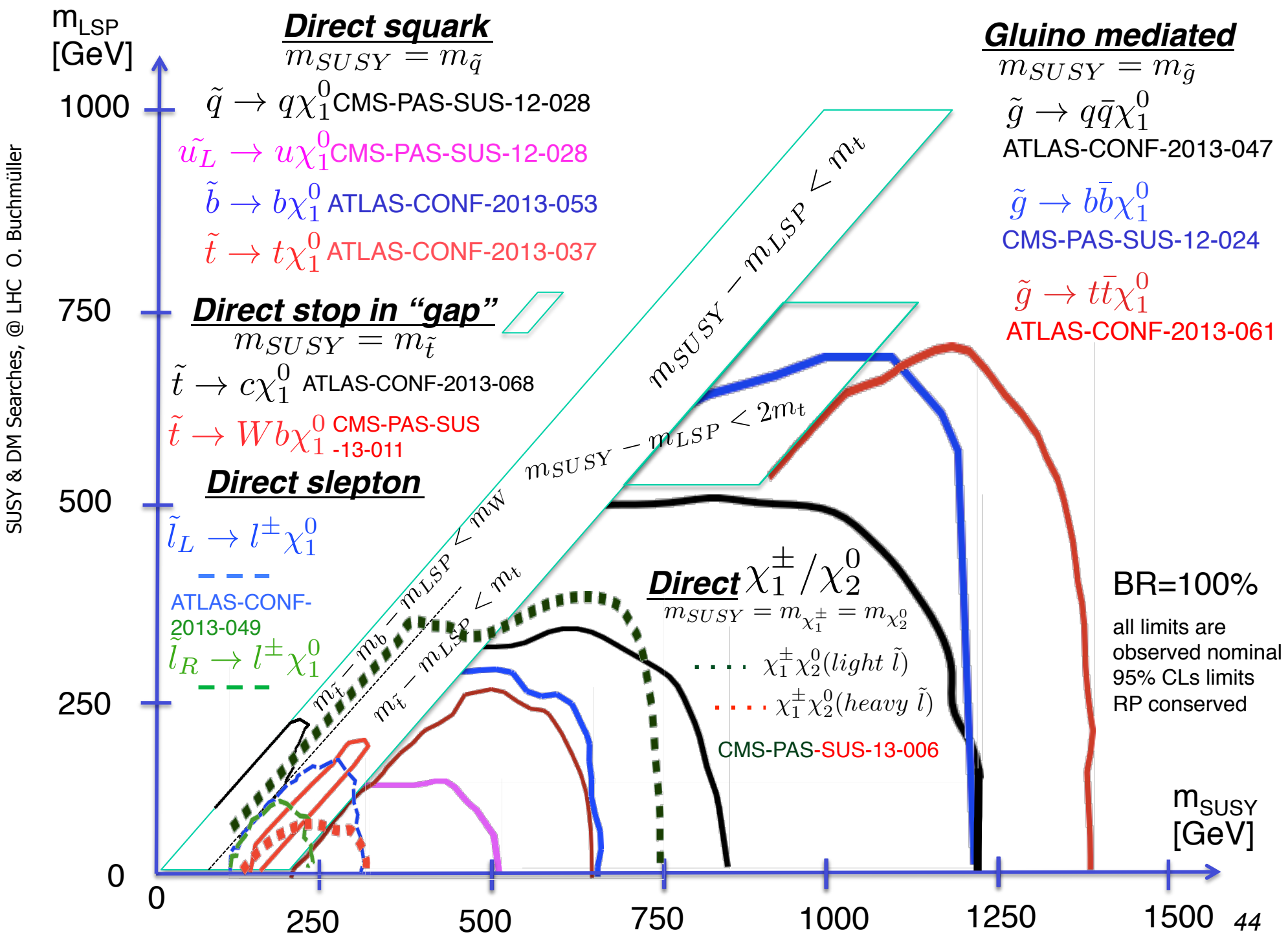
3l OSSF categorised in bins of M_{ll}, MT, and ETmis





$\chi_1^{\pm}\chi_2^0$	*light* $\tilde{l}$	*heavy* $\tilde{l}$
Best limit: **[GeV]**	~750	~300
No limit for M_{LSP} **[GeV]**	~350	~60

SUSY & DM Searches, @ LHC O. Buchmüller


m_LSP [GeV]
SUSY & DM Searches, @ LHC O. Buchmüller
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
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Direct stop in "gap"
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$\tilde{l}_L \to l^{\pm}\chi_1^0$
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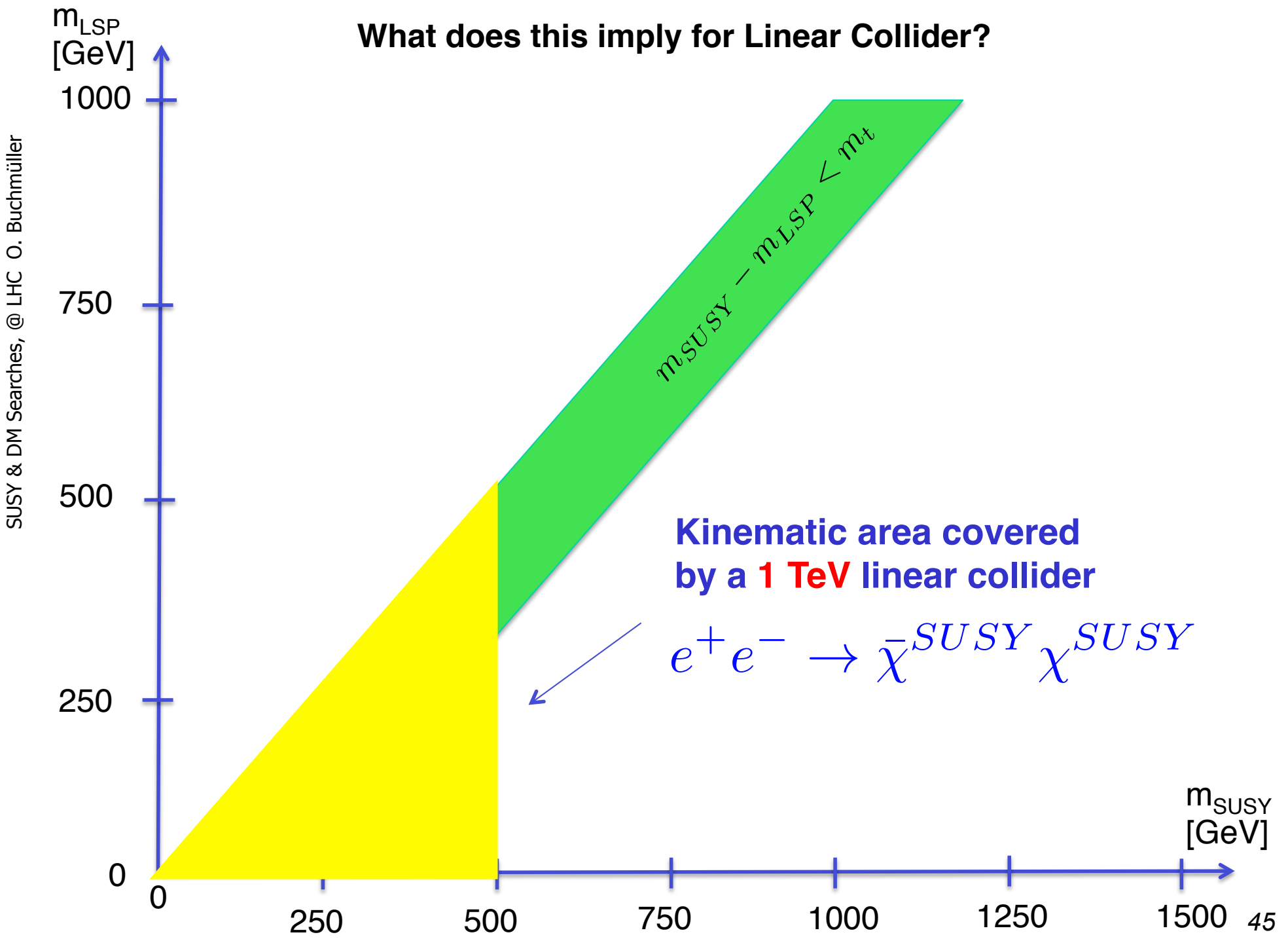
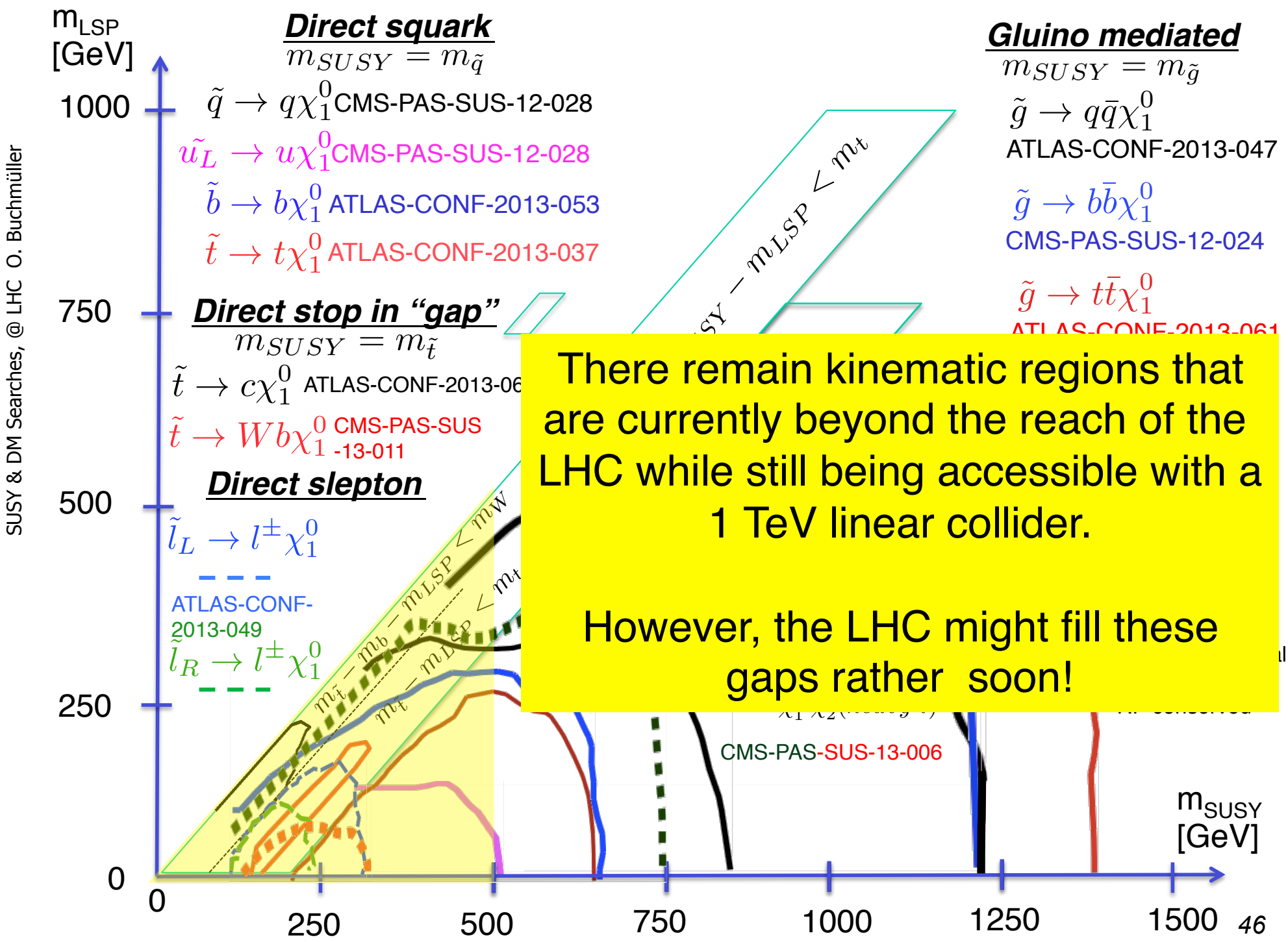
$\tilde{l}_R \to l^{\pm}\chi_1^0$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{SUSY} - m_{LSP} < m_W$
$m_{\tilde{t}} - m_b - m_{LSP} < m_t$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0(light\ \tilde{l})$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2013-047
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500
44

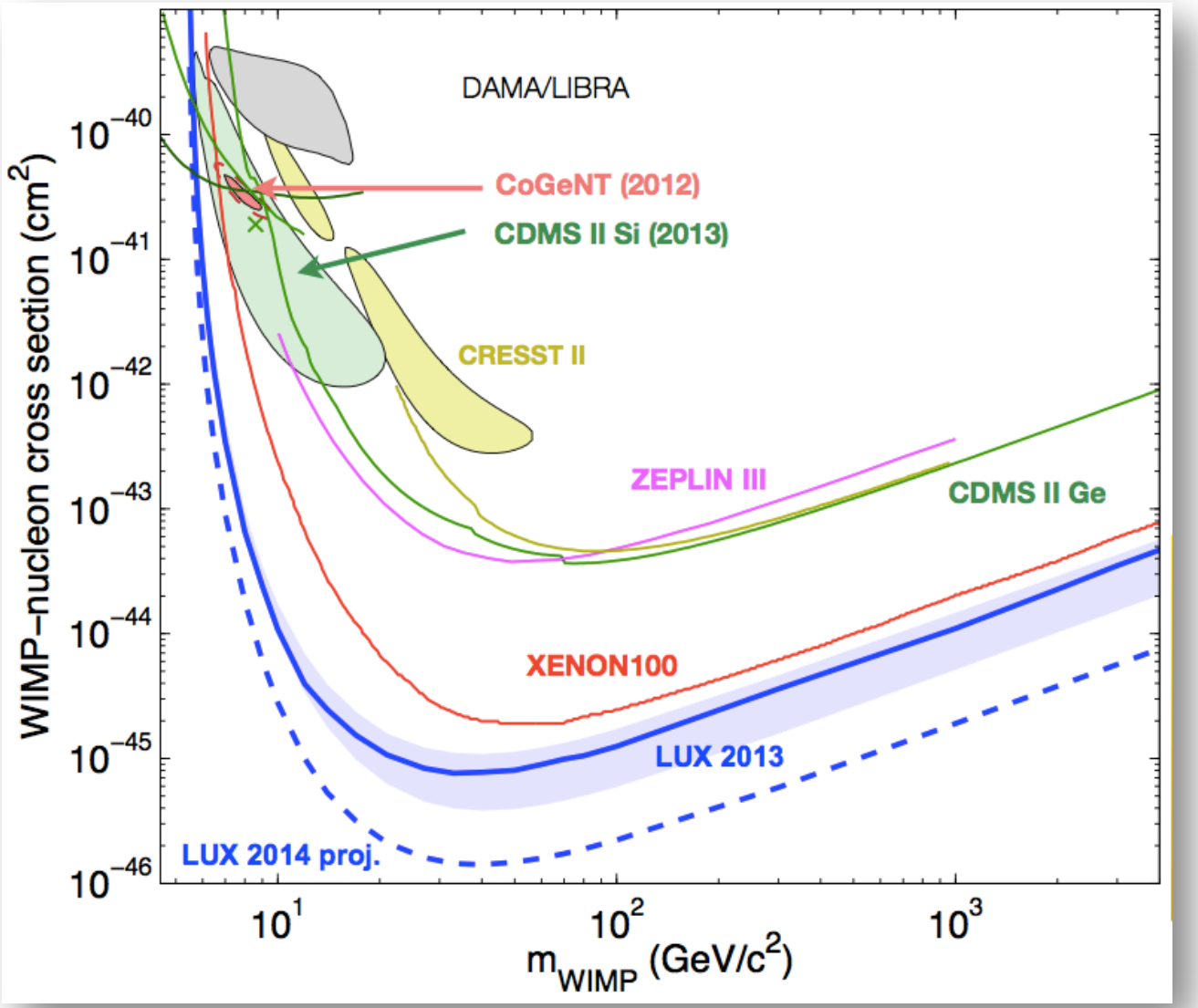

What does this imply for Linear Collider?
m_LSP [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]
SUSY & DM Searches, @ LHC O. Buchmüller
$m_{SUSY} - m_{LSP} < m_t$
Kinematic area covered
by a 1 TeV linear collider
$e^+e^- \to \bar{\chi}^{SUSY}\chi^{SUSY}$



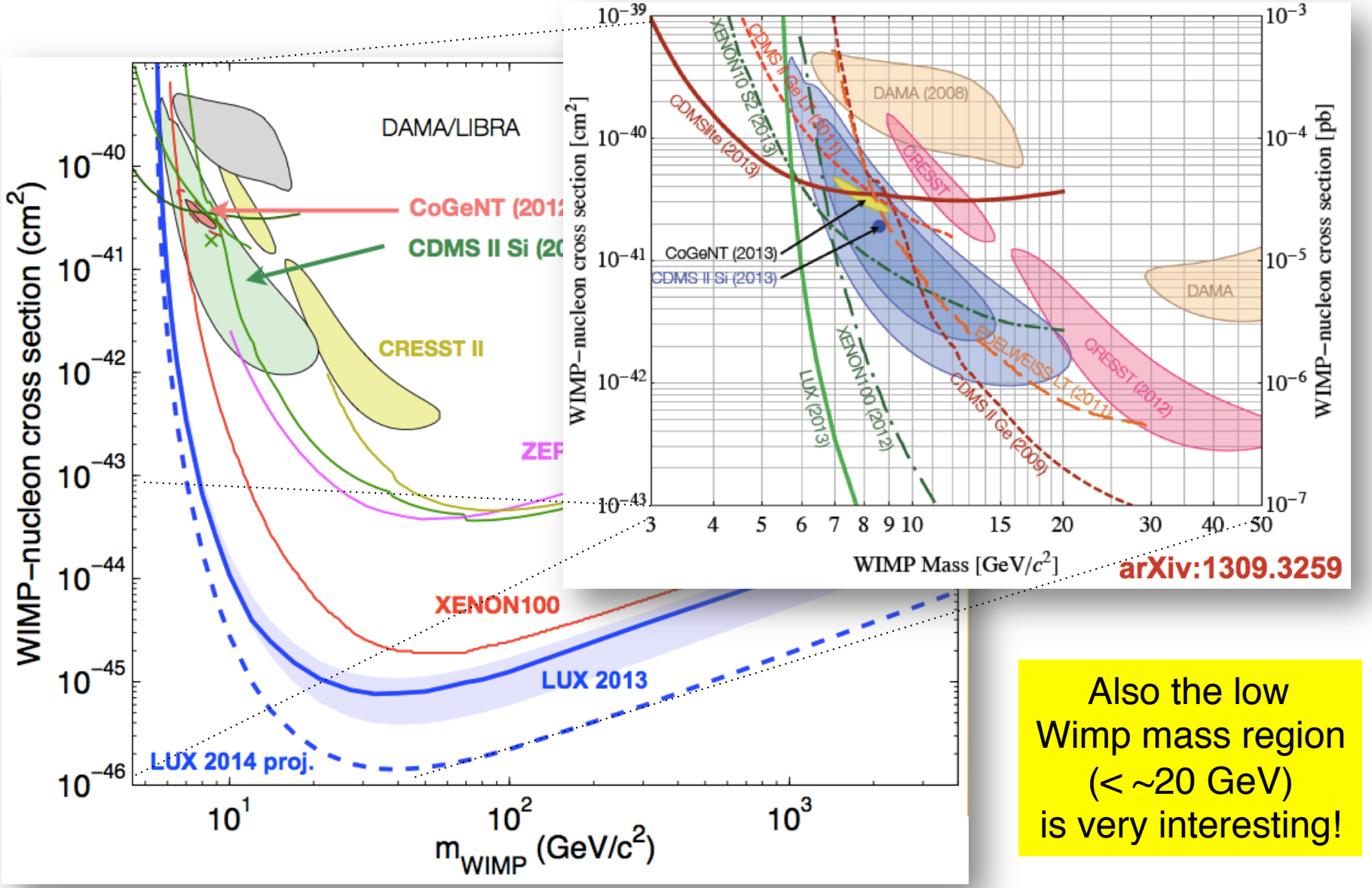
There remain kinematic regions that are currently beyond the reach of the LHC while still being accessible with a 1 TeV linear collider.

However, the LHC might fill these gaps rather soon!

Dark Matter Searches: Direct Detection Experiments

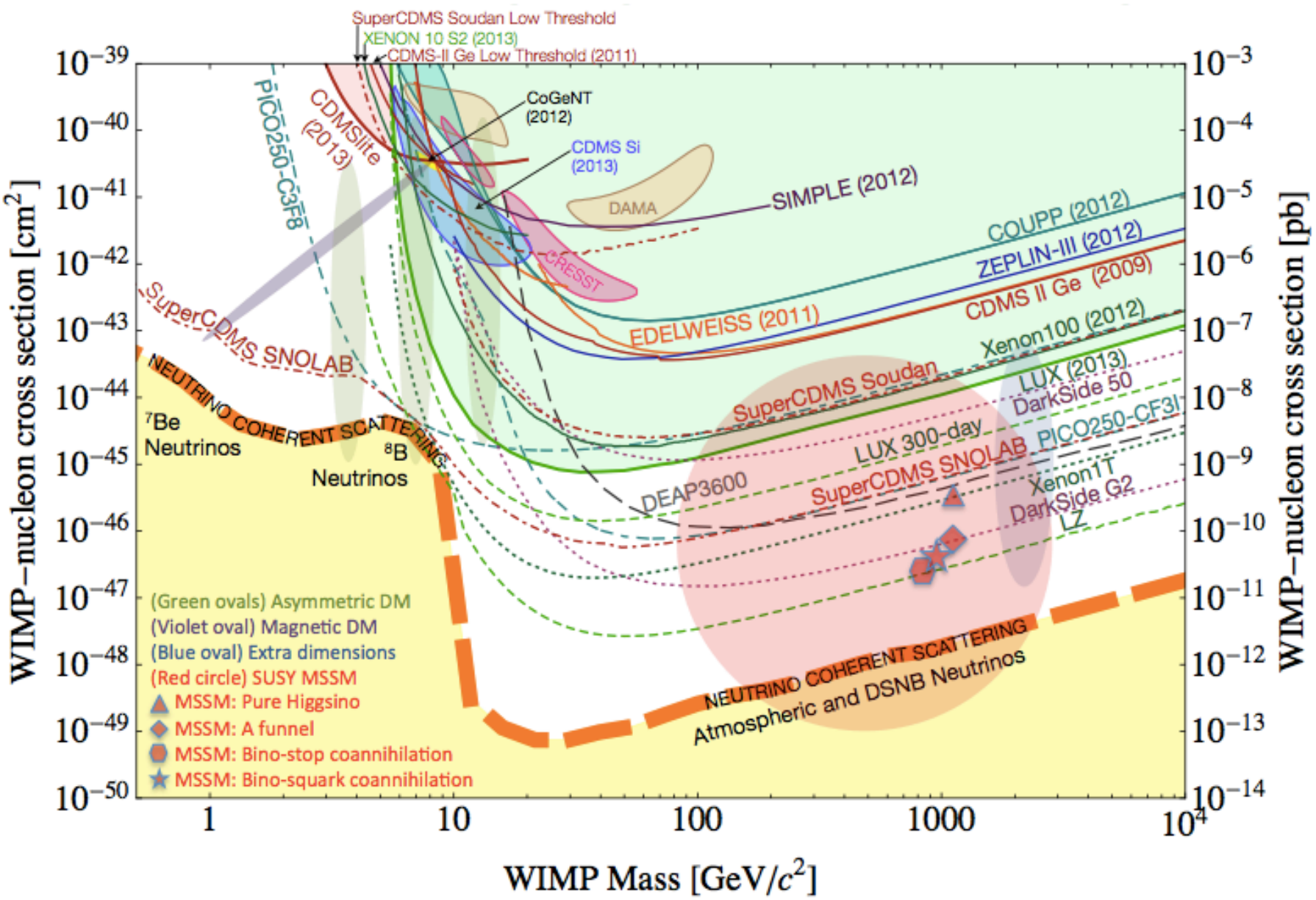


Dark Matter Searches: Direct Detection Experiments

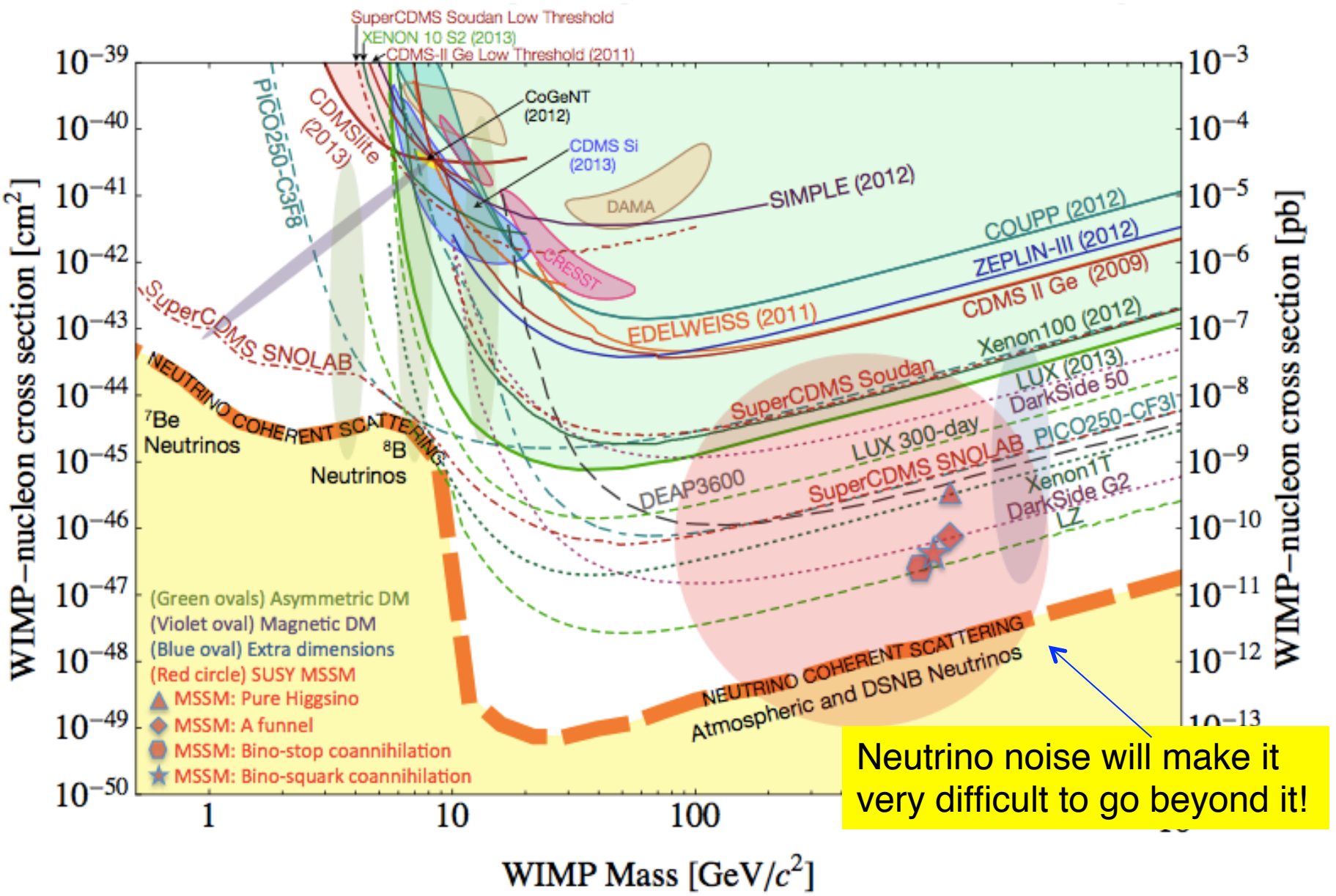


Also the low Wimp mass region (< ~20 GeV) is very interesting!

Direct Detection Landscape in a nutshell!

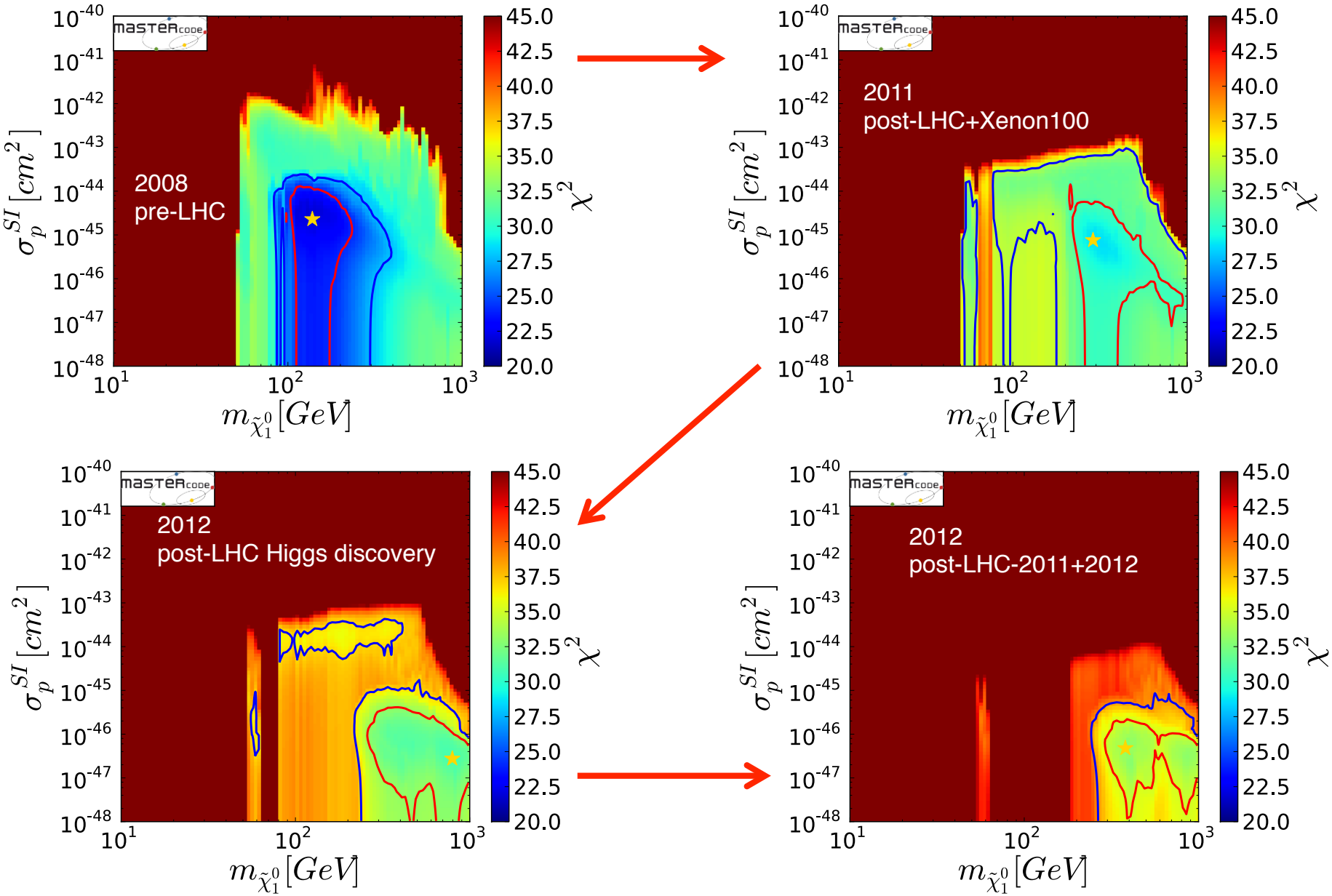


Direct Detection Landscape in a nutshell!

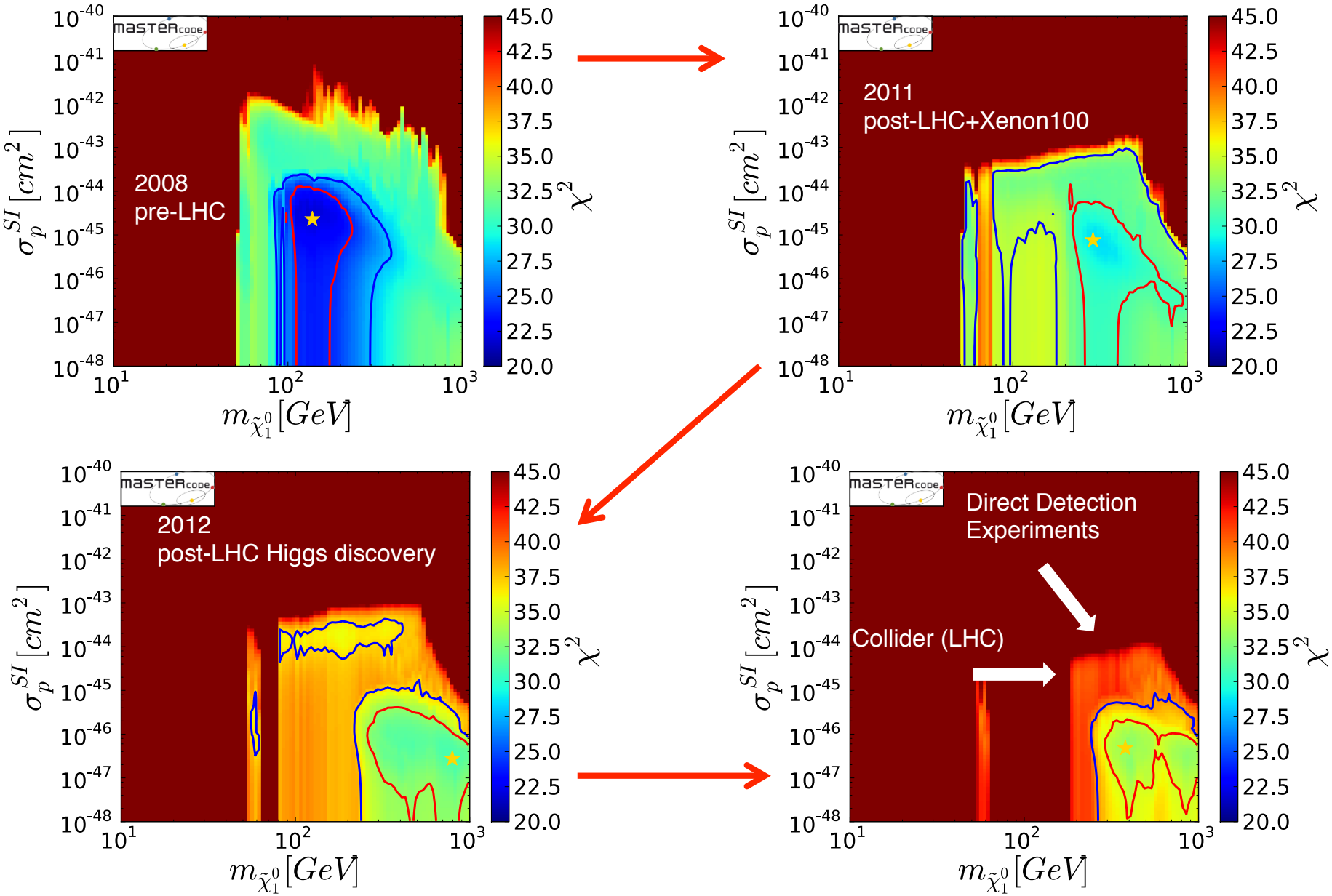


Neutrino noise will make it very difficult to go beyond it!

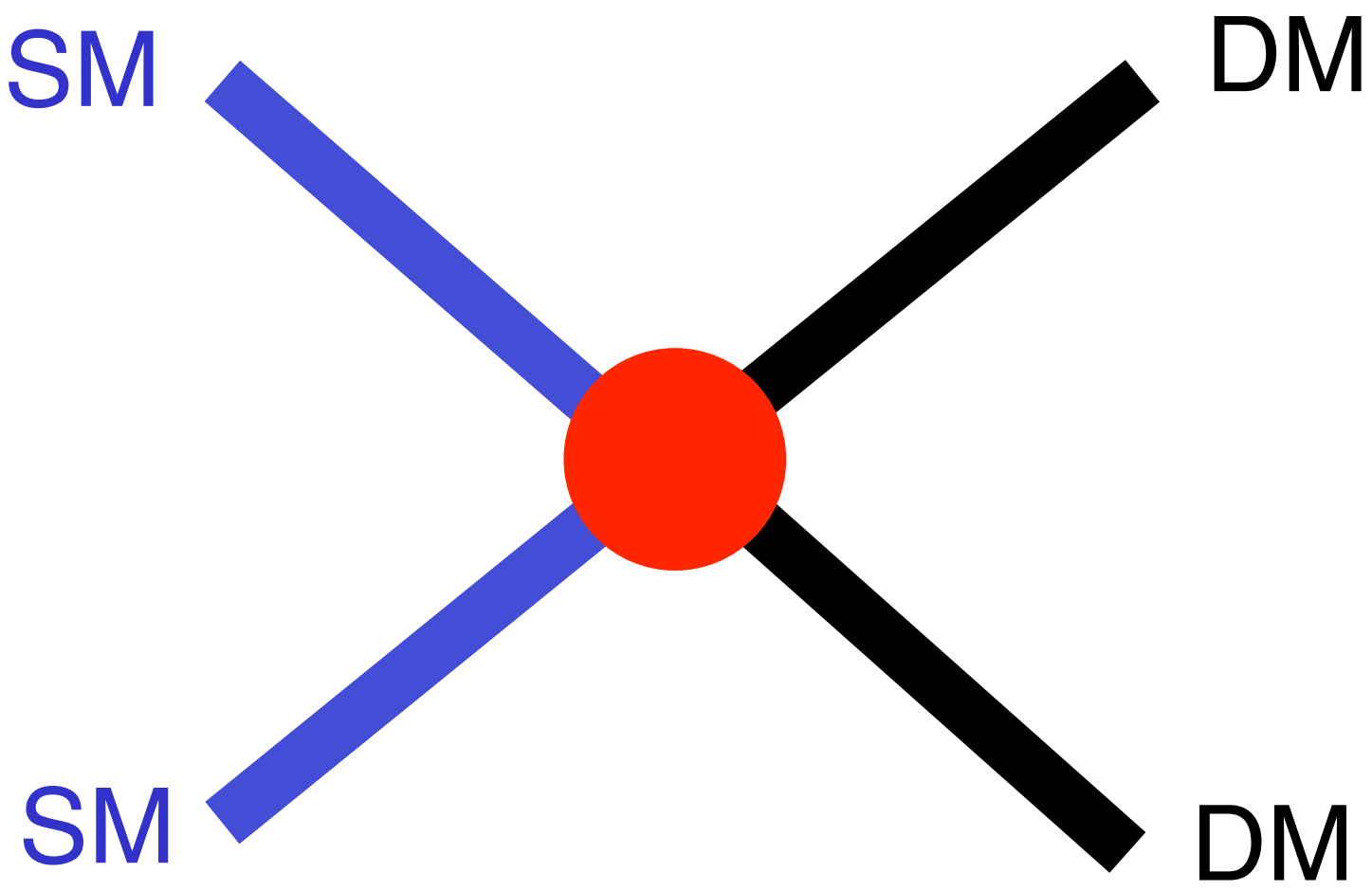
SUSY & Dark Matter: Evolution with time



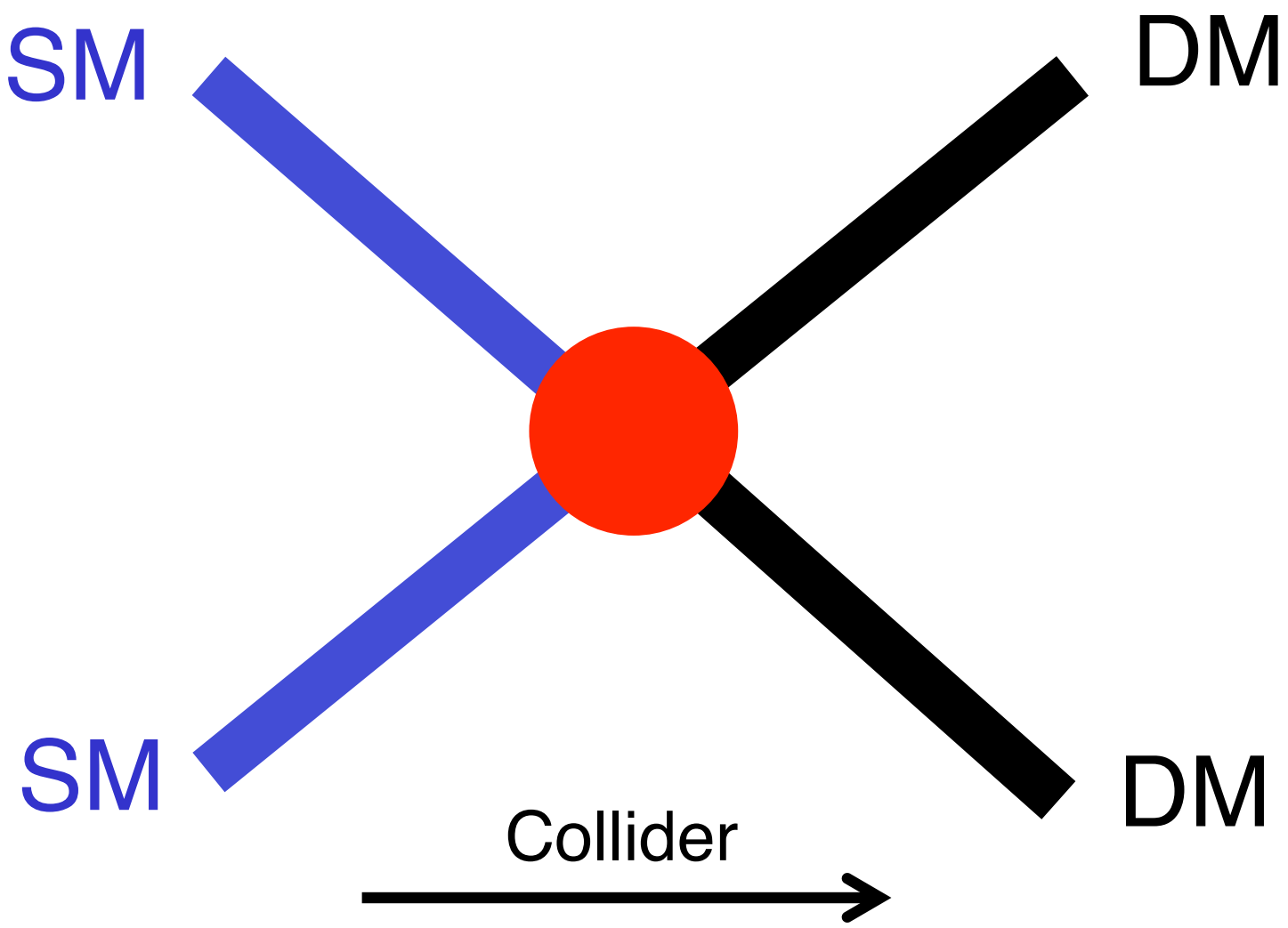
SUSY & Dark Matter: Evolution with time



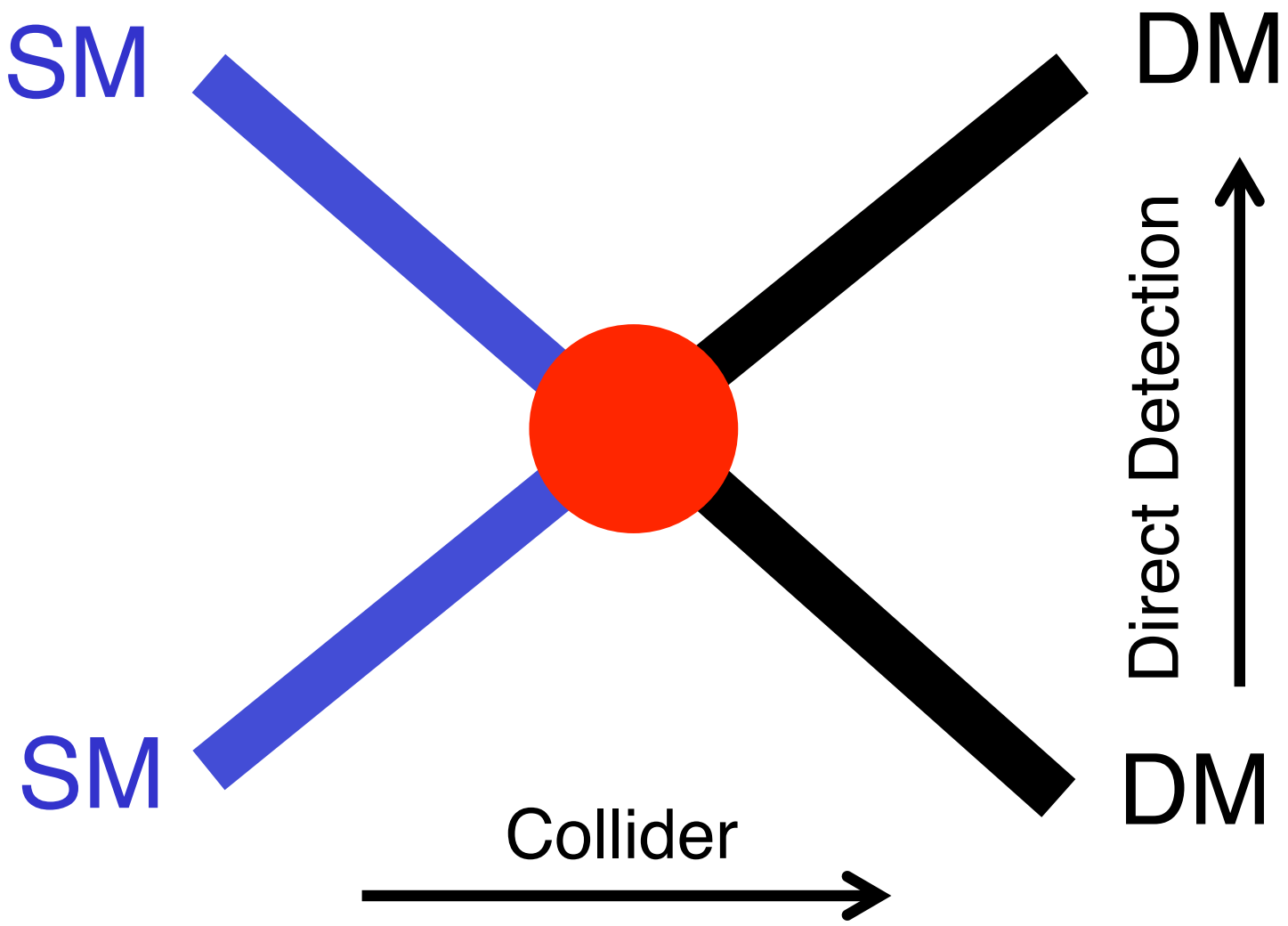
Dark Matter Searches



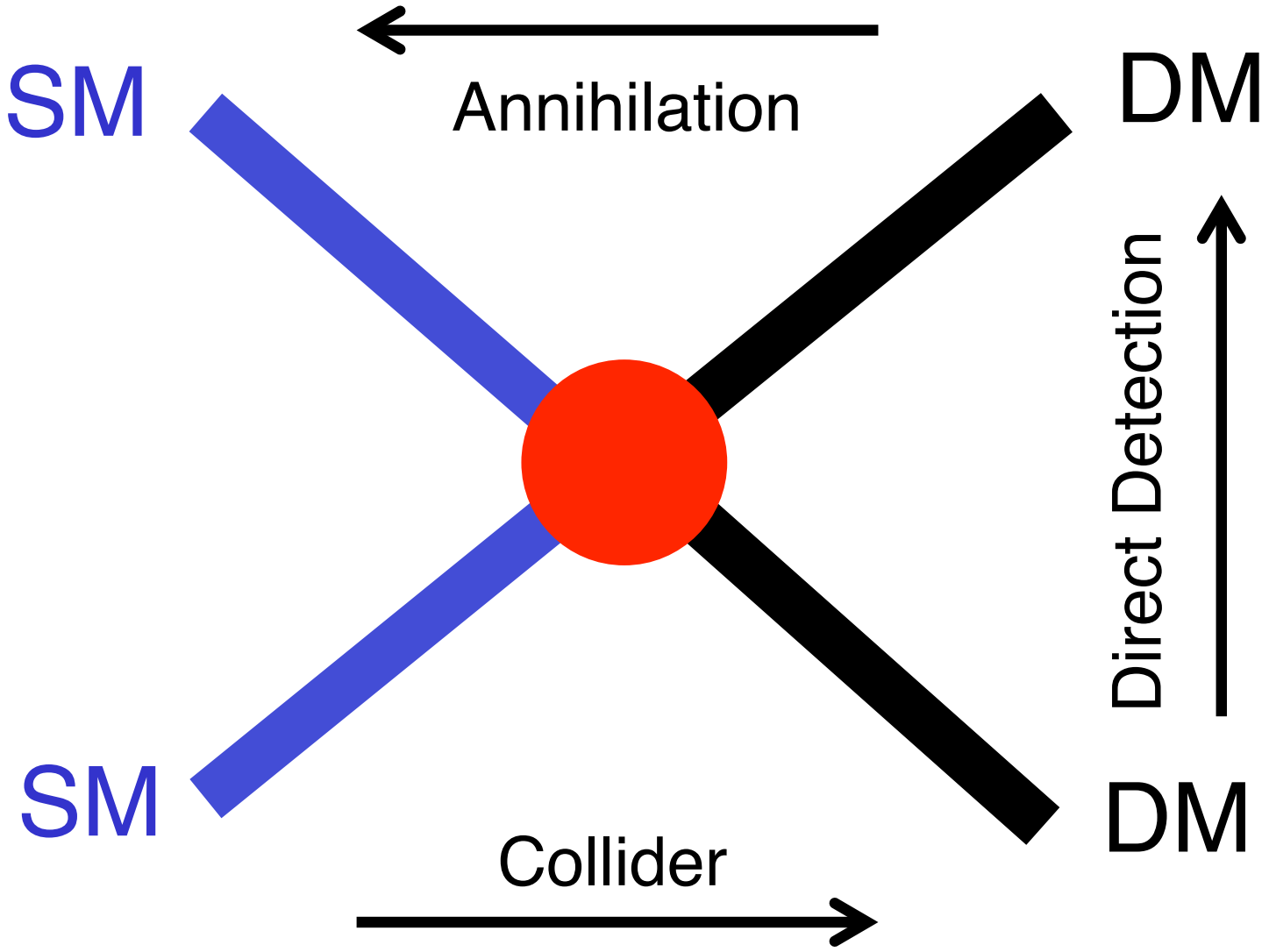
Dark Matter Searches



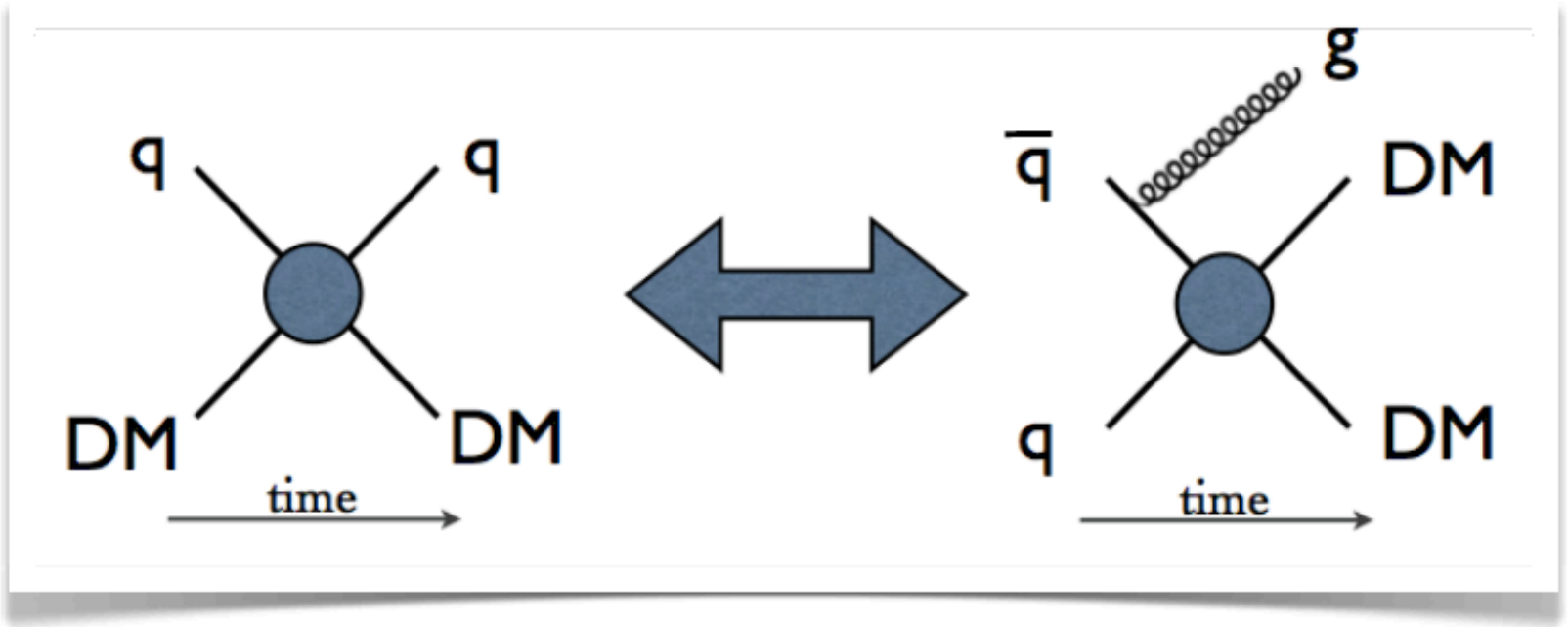
Dark Matter Searches



Dark Matter Searches

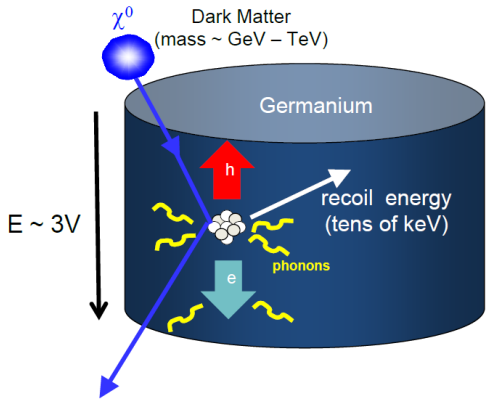


Dark Matter Searches: Direct Detection vs Colliders



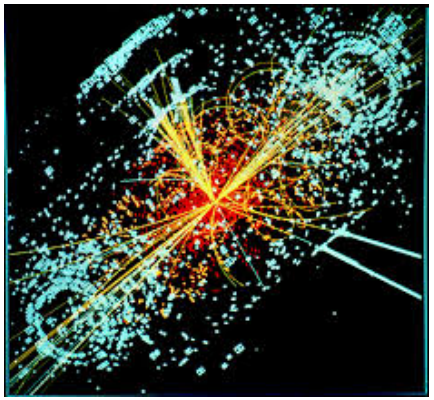
Direct Detection Experiments

- DM-nucleus scattering



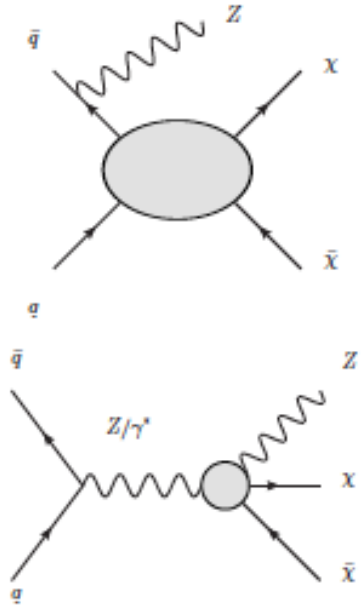
Collider Experiments

- Pair-production of DM
- missing energy signature

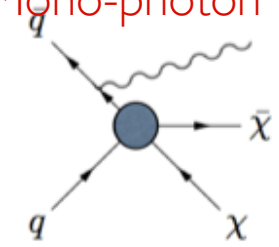


Mono-Mania (at the LHC)

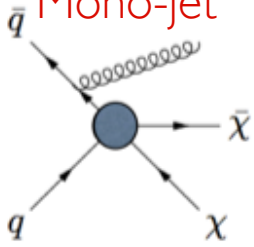
Mono-Z



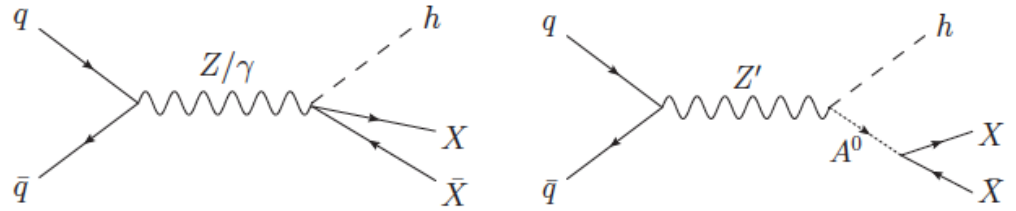
Mono-photon



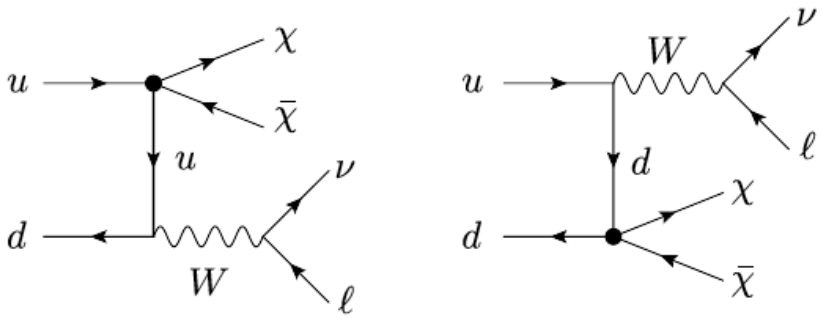
Mono-jet



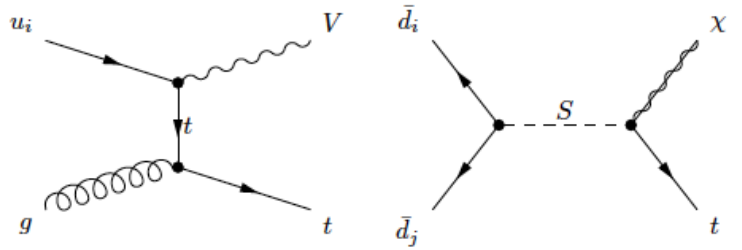
Mono-Higgs



Mono-W

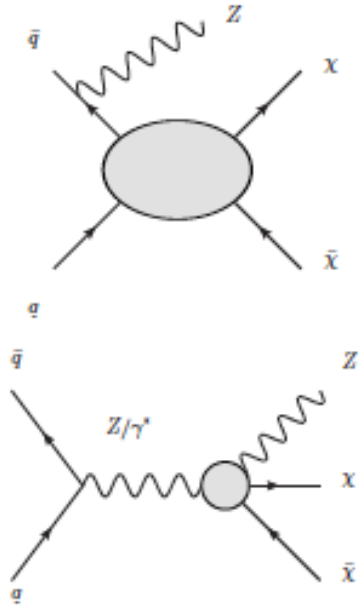


Mono-top

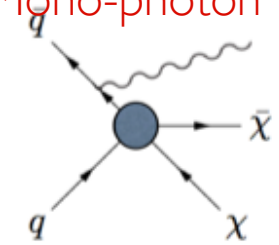


Mono-Mania (at the LHC)

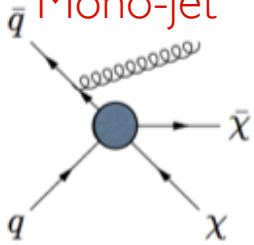
Mono-Z



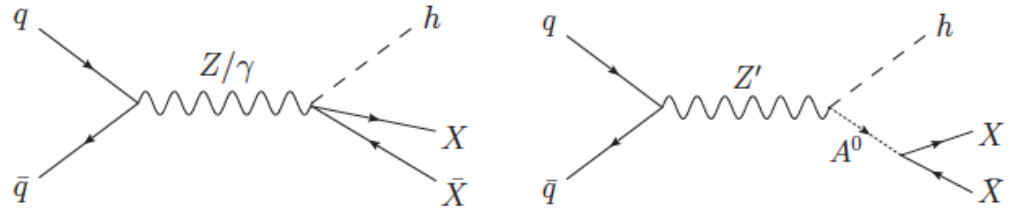
Mono-photon



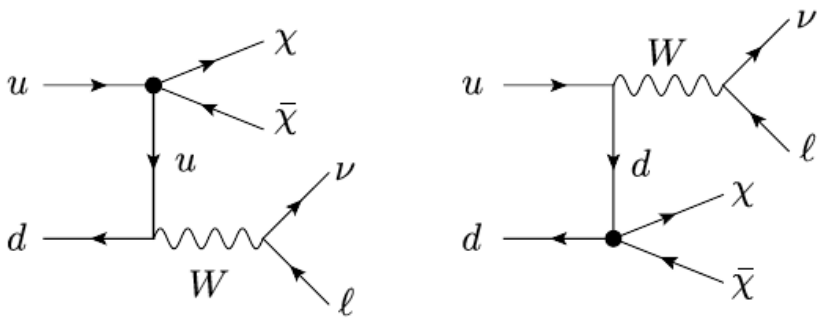
Mono-jet



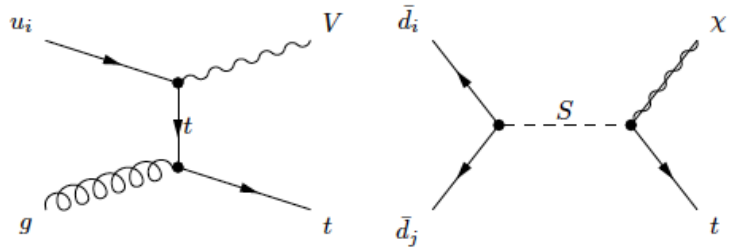
Mono-Higgs



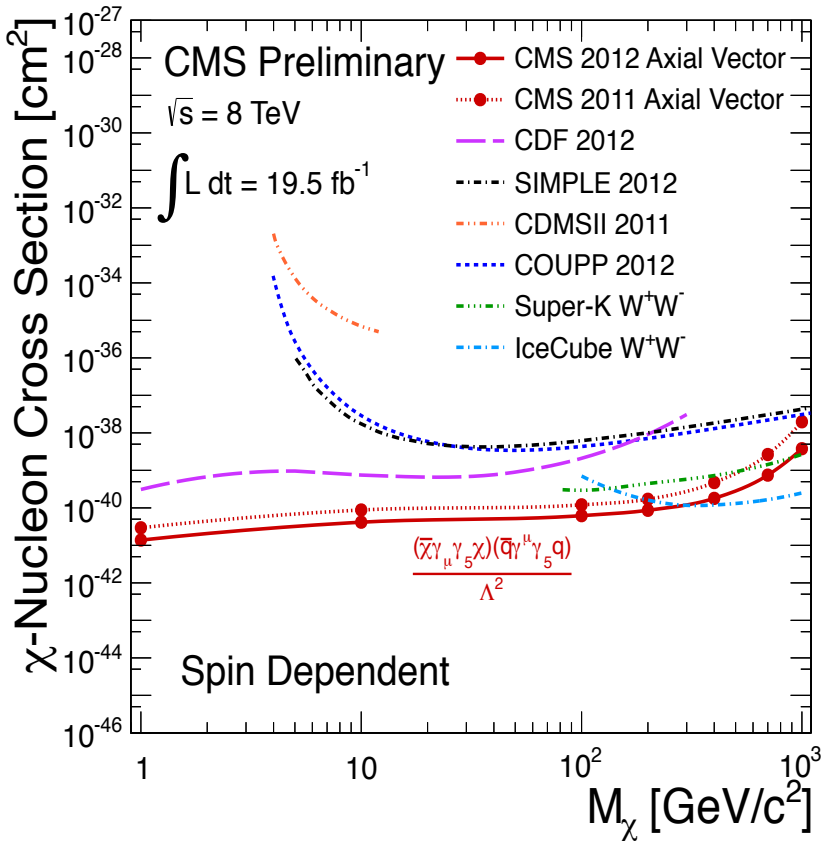
Mono-W

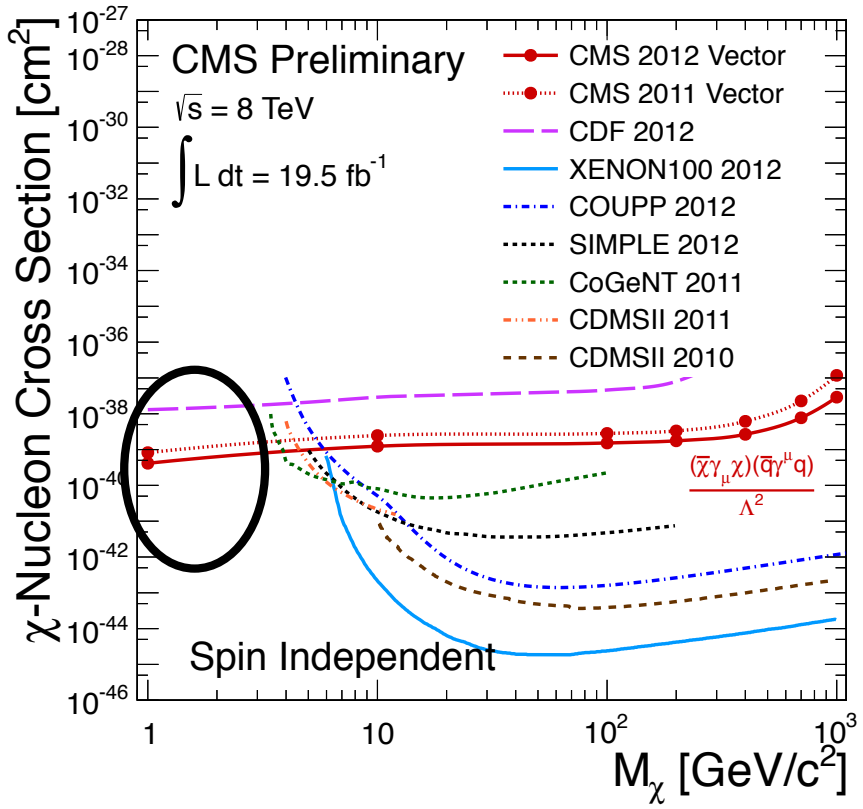


Mono-top



Monojet analyses better than direct detection?!



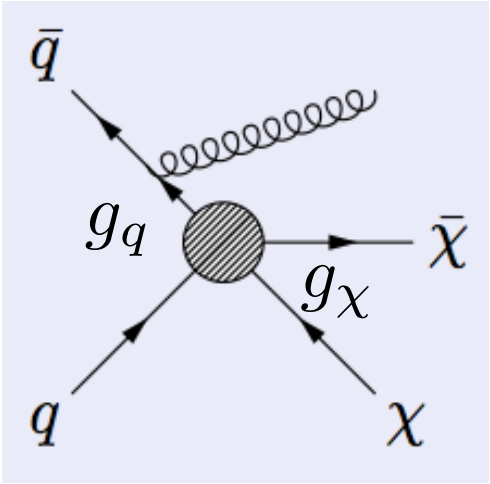


Claim [often made]:
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

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:

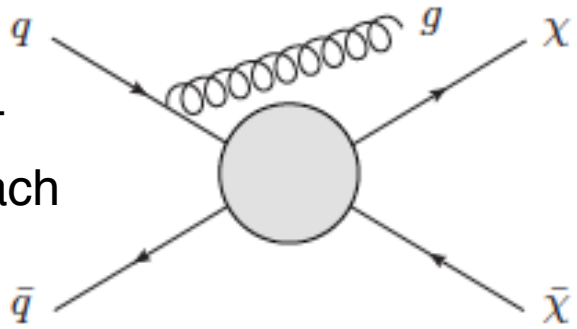
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

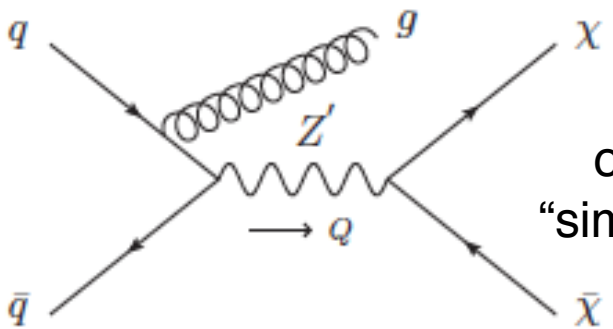
Validity of Effective Field Theory Limits

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

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

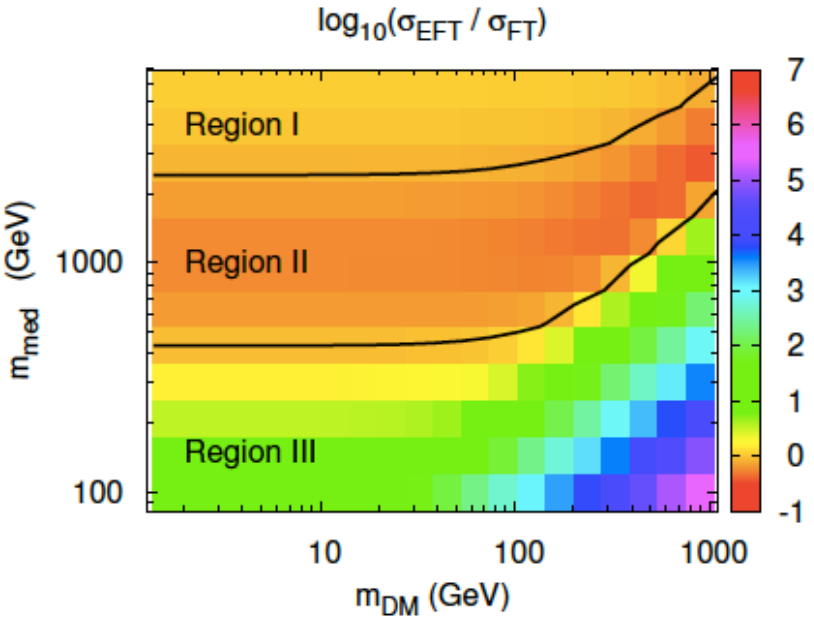
EFT approach





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

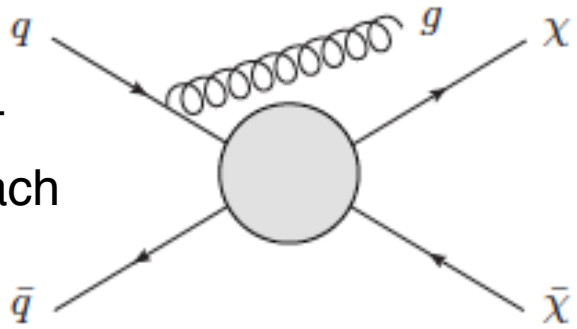
- EFT limits are too aggressive!

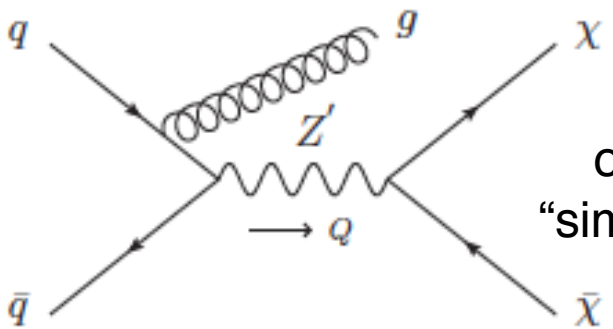
Validity of Effective Field Theory Limits

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

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

EFT approach





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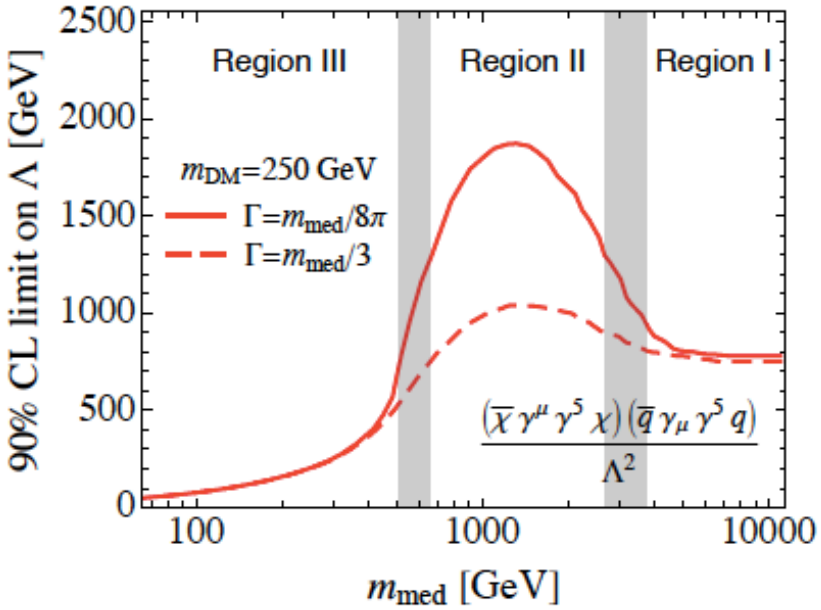


Three Regions as function of mediator mass:

Region I: Heavy m_{med}

- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

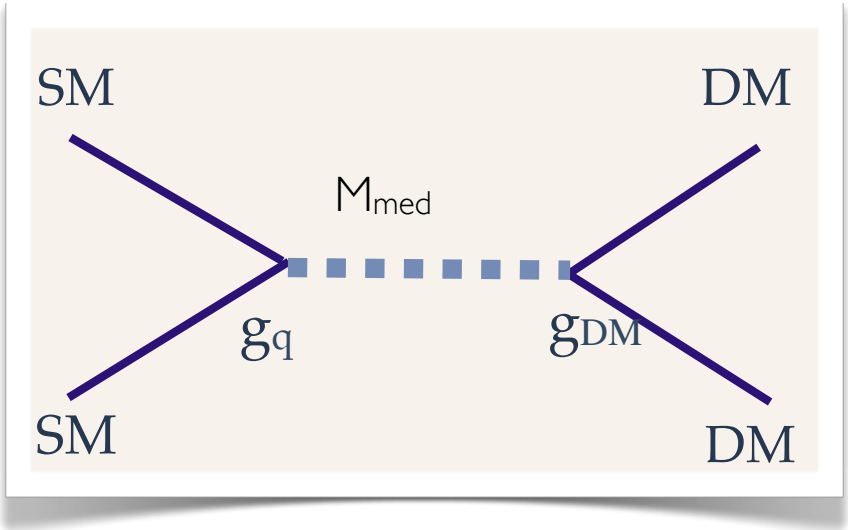
- EFT limits are too conservative!

Region III: Low m_{med}

- EFT limits are too aggressive!

Minimal Simplified Dark Matter Model

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



s-channel

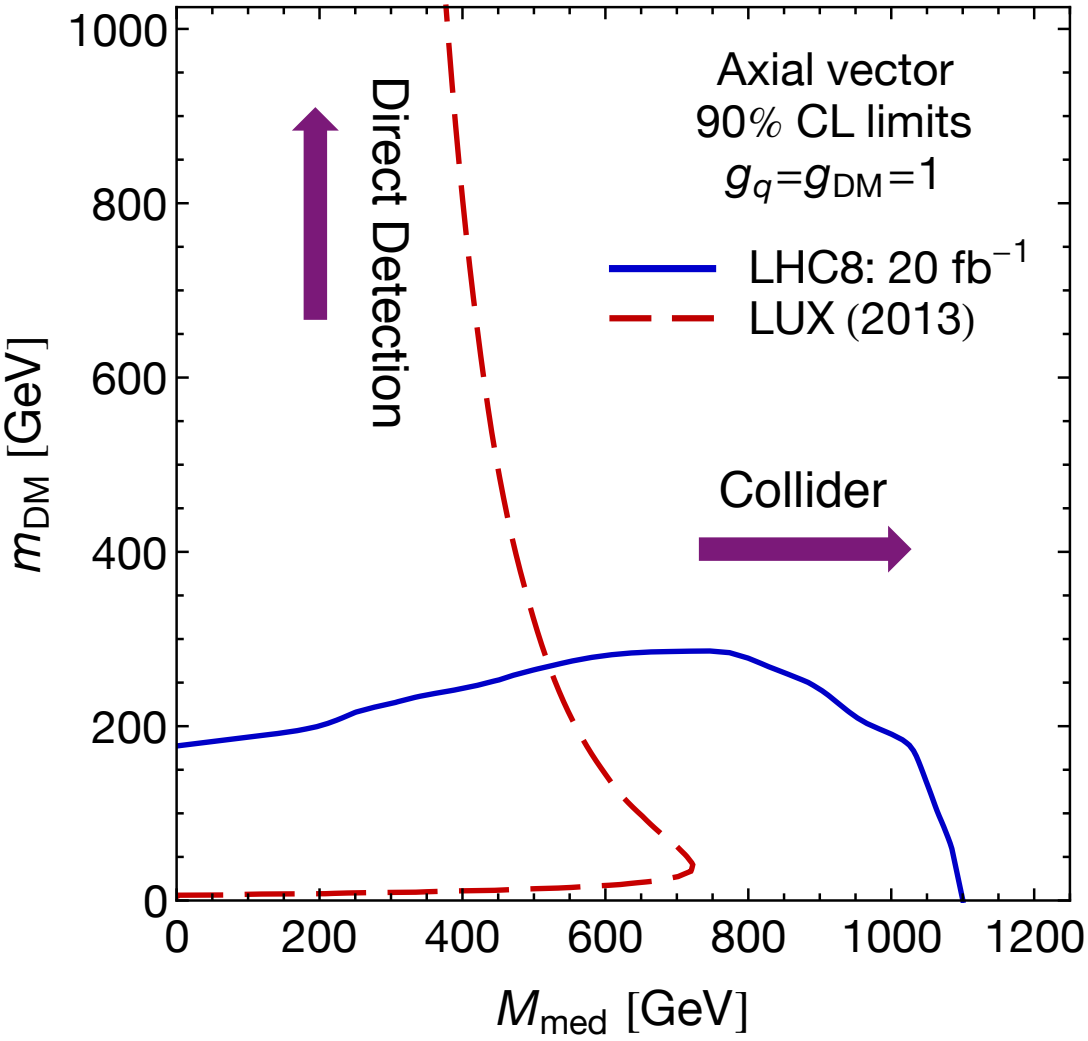
Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

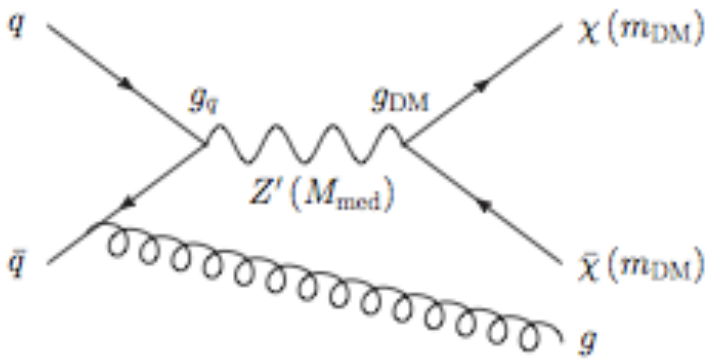
DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

Dark Matter Limits from Direct Searches: Today

Examples: CMS monojet search and recent LUX result: interpretation in simplified models



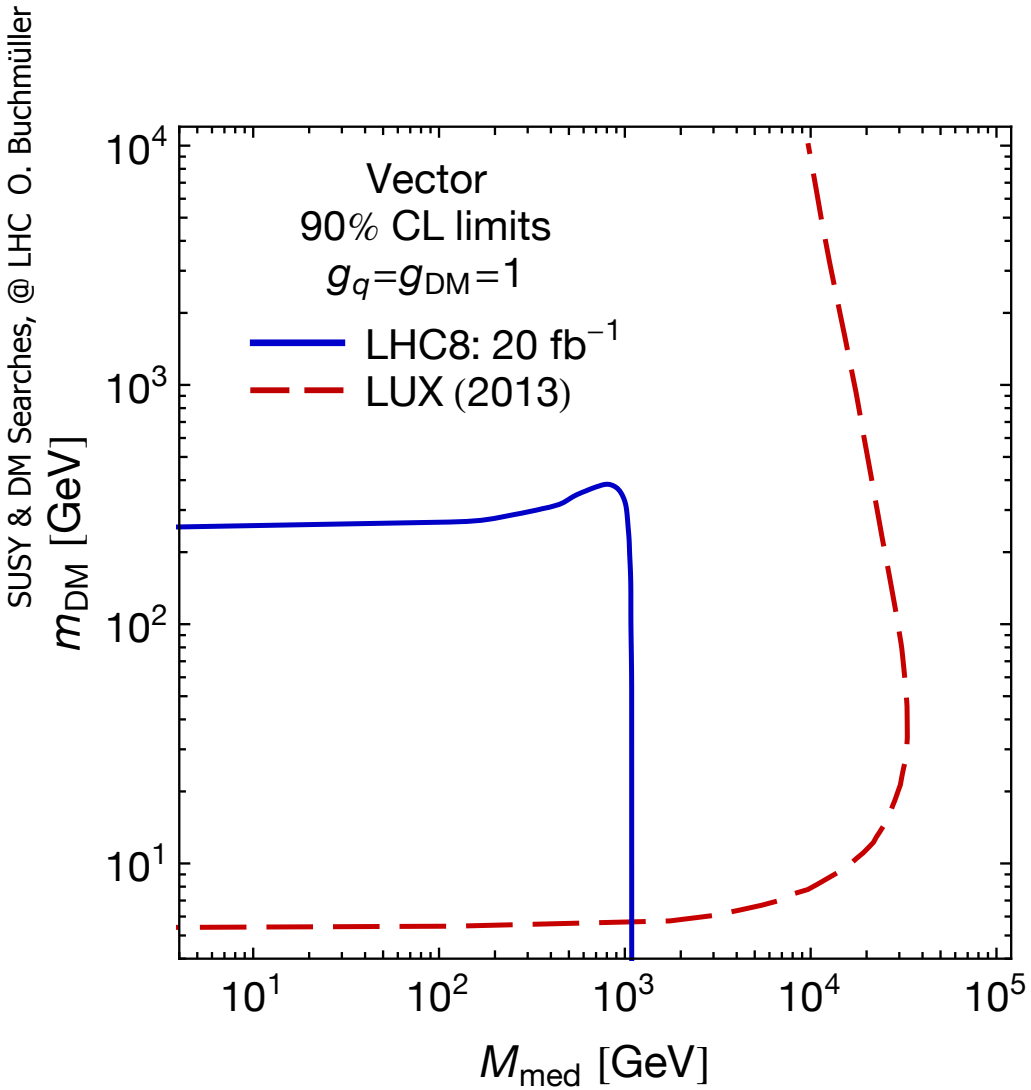


Assumes:

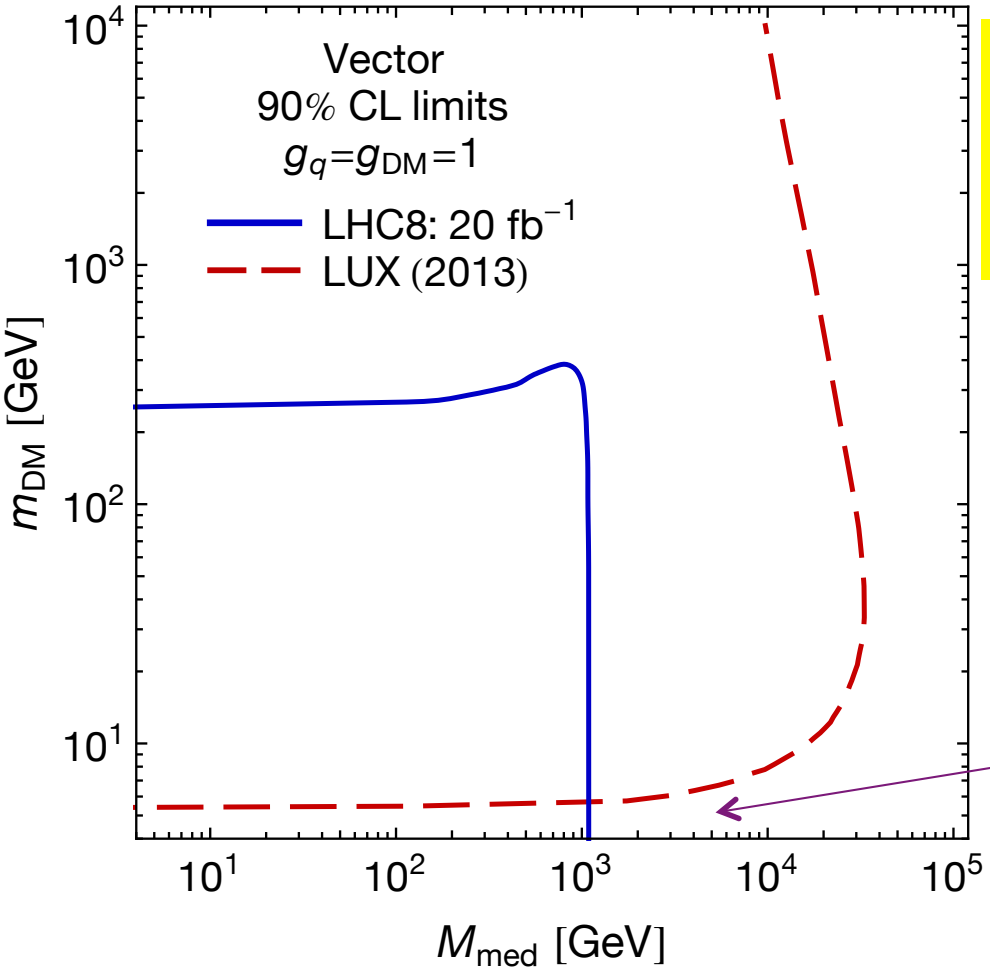
- couplings to all quarks
- g_q=g_{DM}=1
- width calculated from g

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

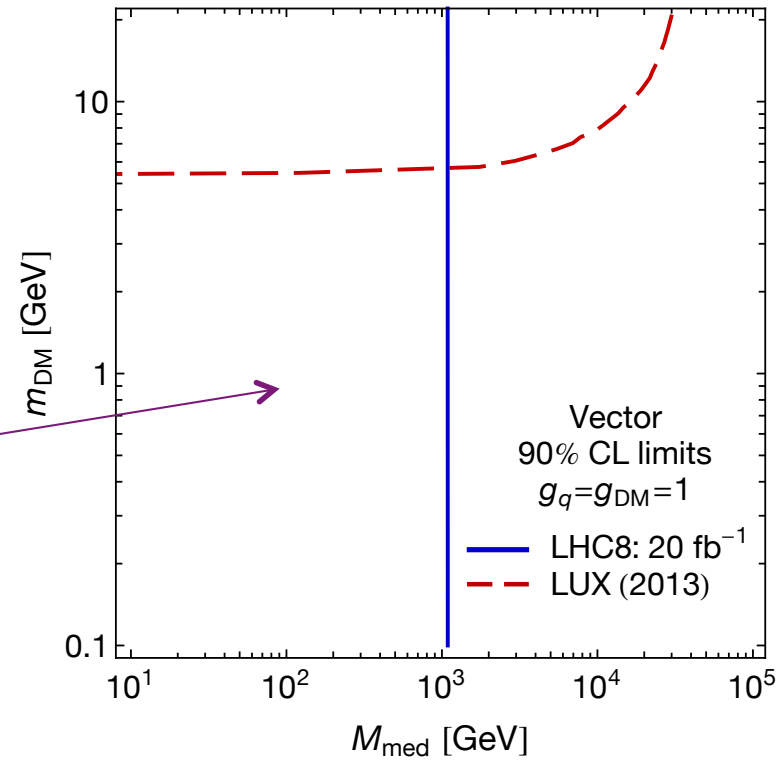
The Vector Case



The Vector Case

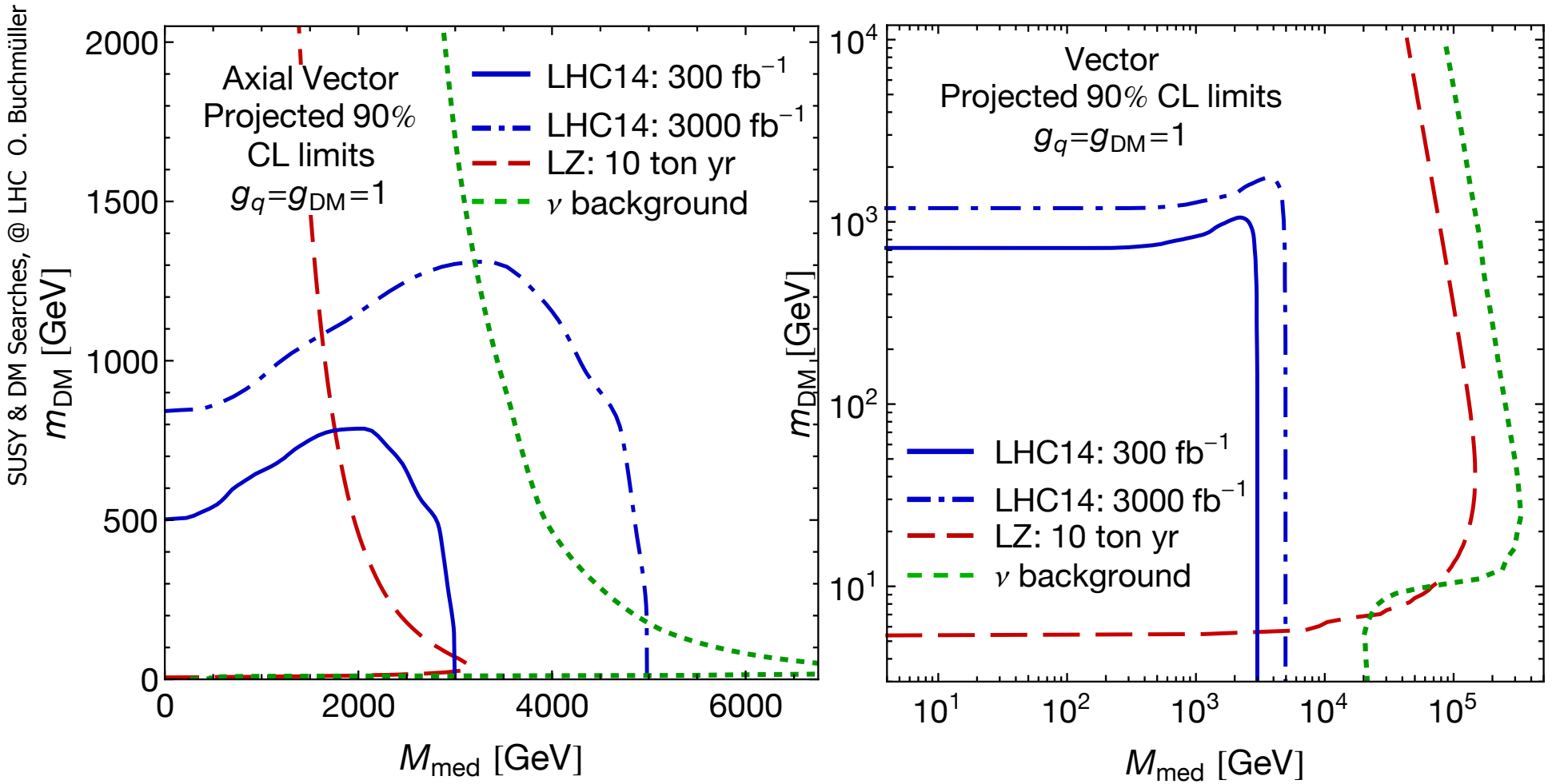


While for Axial-Vector collider and DD are complementary in the full parameter space, for the pure Vector case, DD limits are strong EXCEPT for low DM masses!



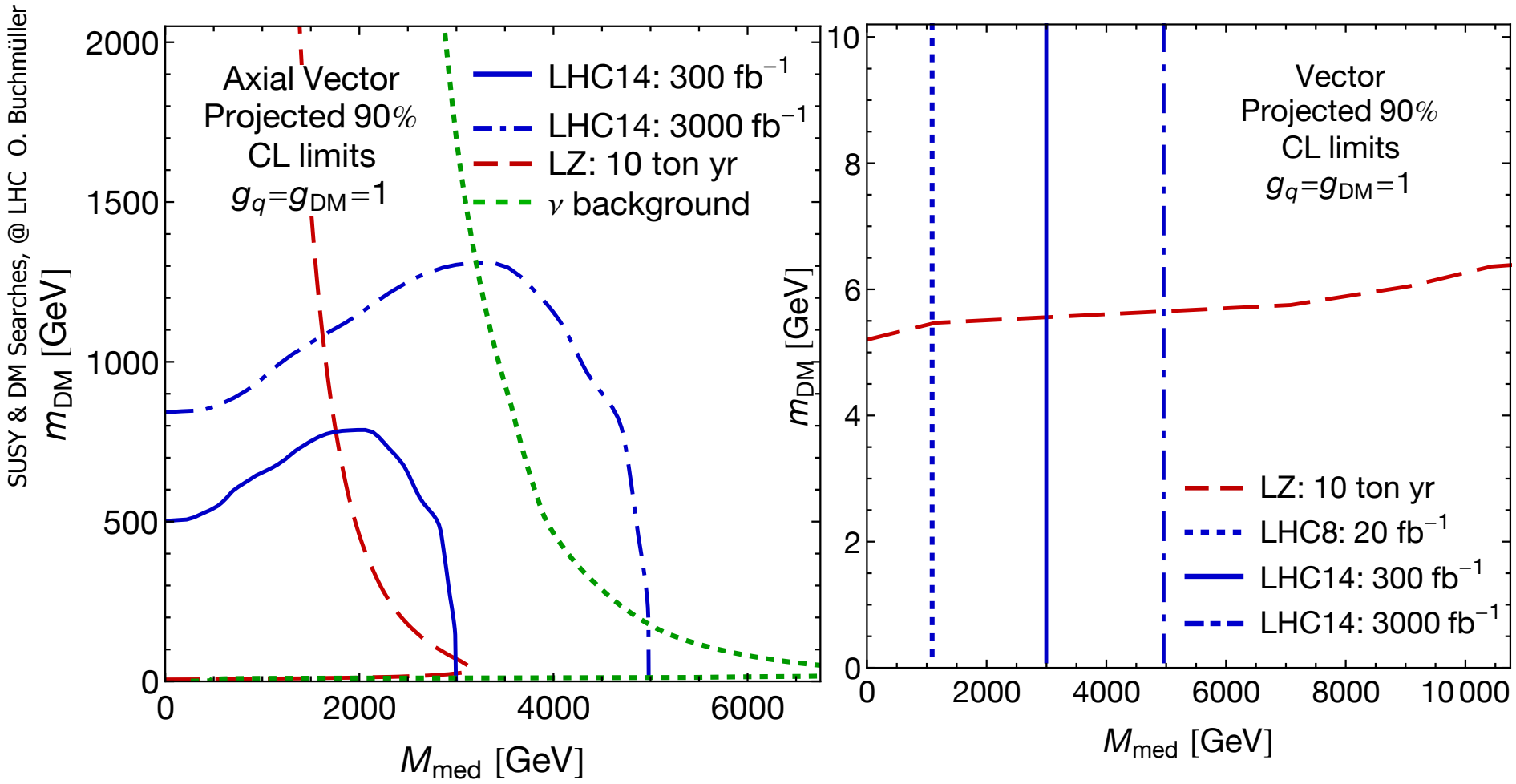
Note: Vector scales like Atomic number squared (~130^2) while AV scales like the spin (~1).

Future Projections



Compare:
LHC @ 300/fb and HL-LHC@/3000/fb
with Direct Detection:
Lux-Zeppline (~2025) and Neutrino noise border

Future Projections



Important complementarity of the two experimental approaches will allow good coverage of the relevant parameter space!

Big discovery potential!

Outlook: 8 TeV vs 14 TeV

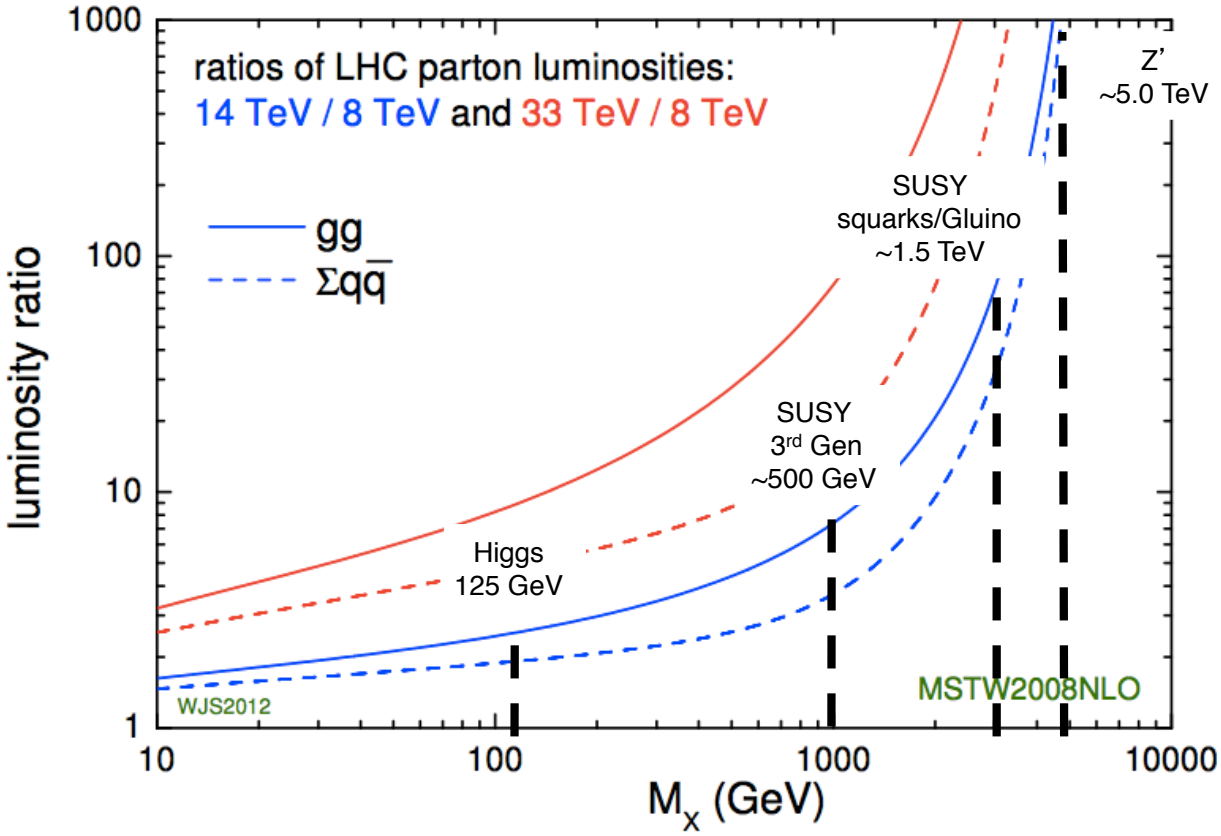
Use parton luminosities to illustrate the gain of 14 vs 8 TeV

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

SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

Z' :
Mass scale ~ 5 TeV
qq: factor ~1000



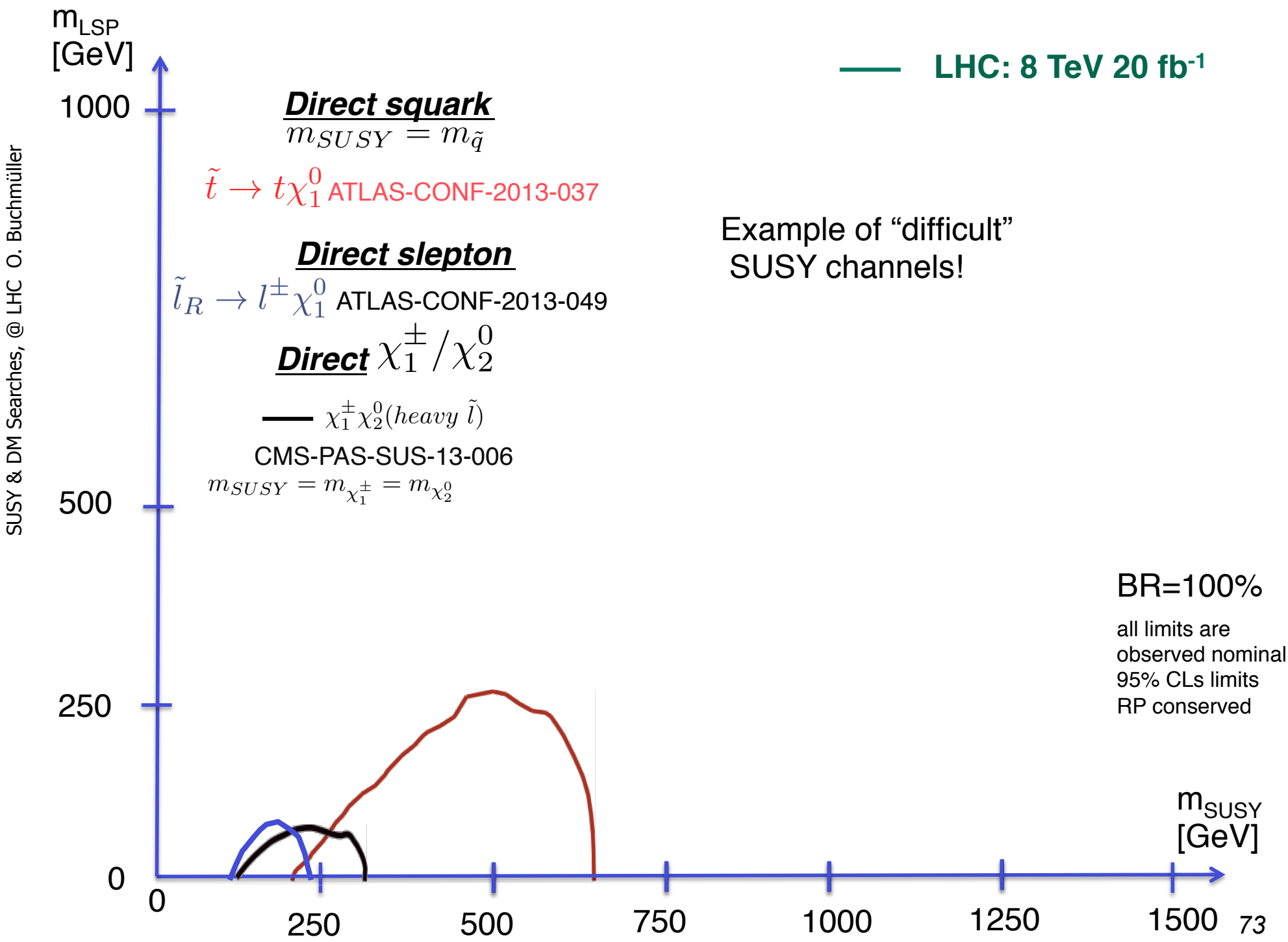
Increase in energy will help a lot!
Not just for SUSY...

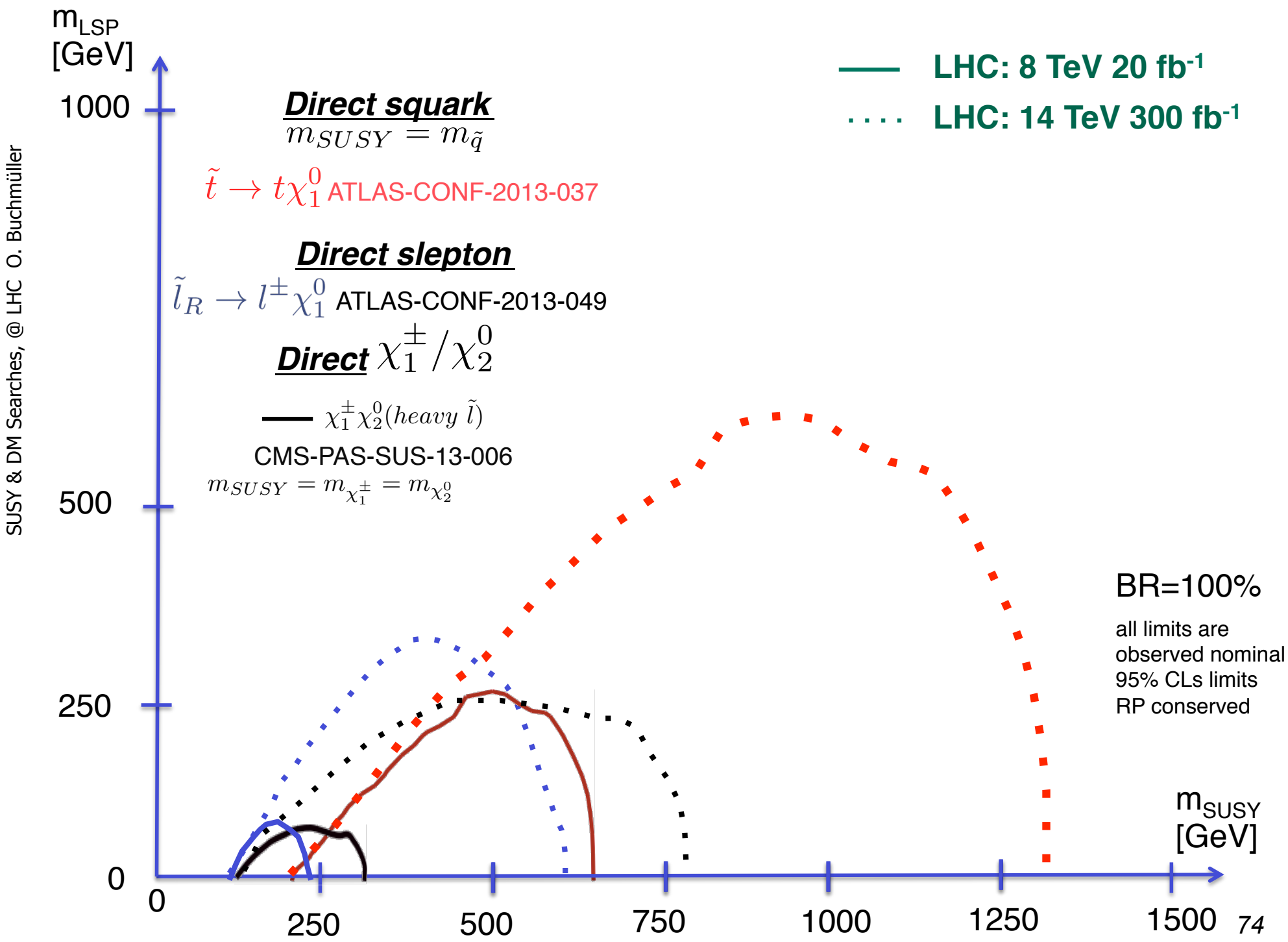
Summary

- 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!

BACKUP


m_LSP [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]
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
SUSY & DM Searches, @ LHC O. Buchmüller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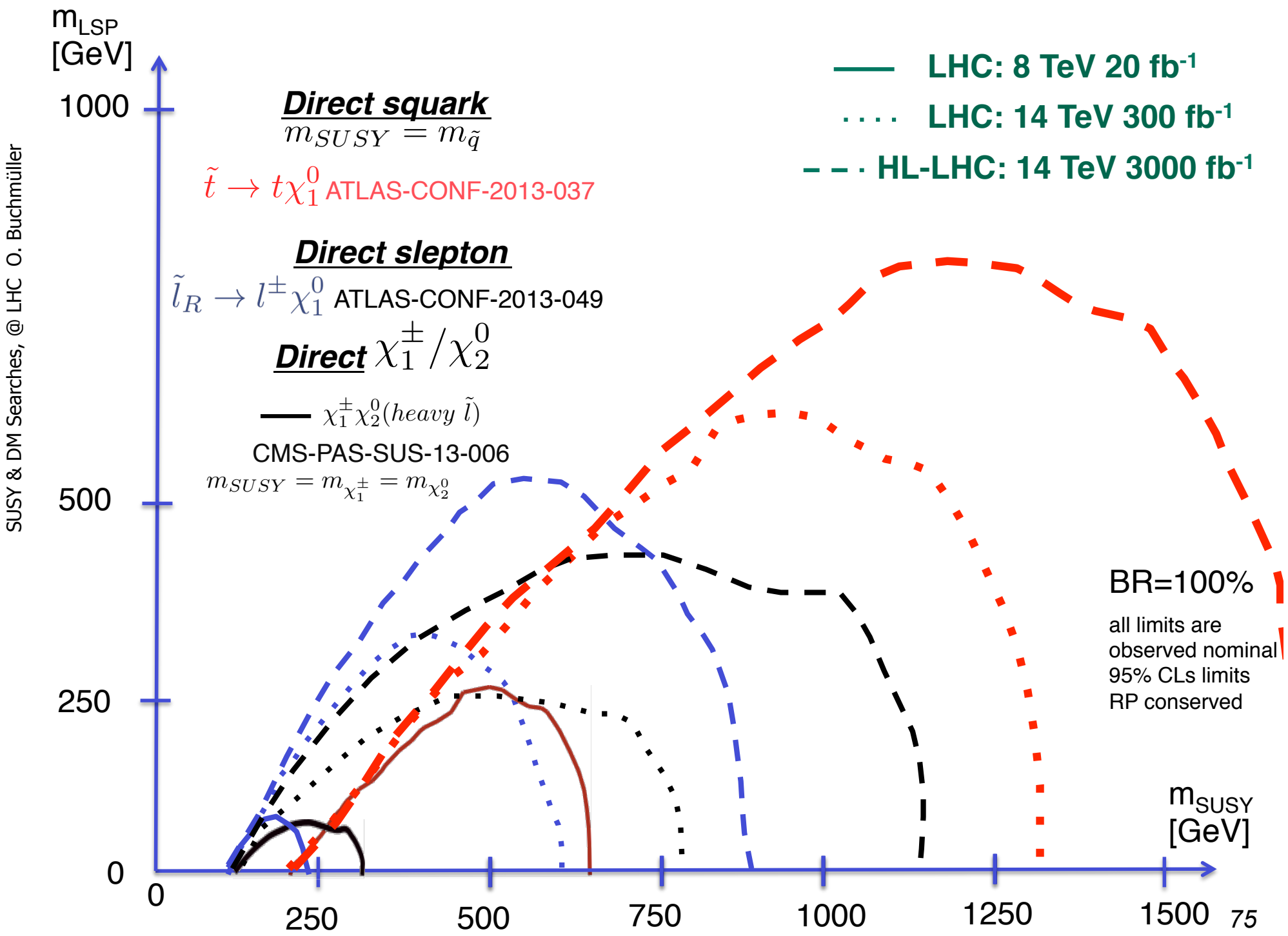
SUSY & DM Searches, @ LHC O. Buchmüller
74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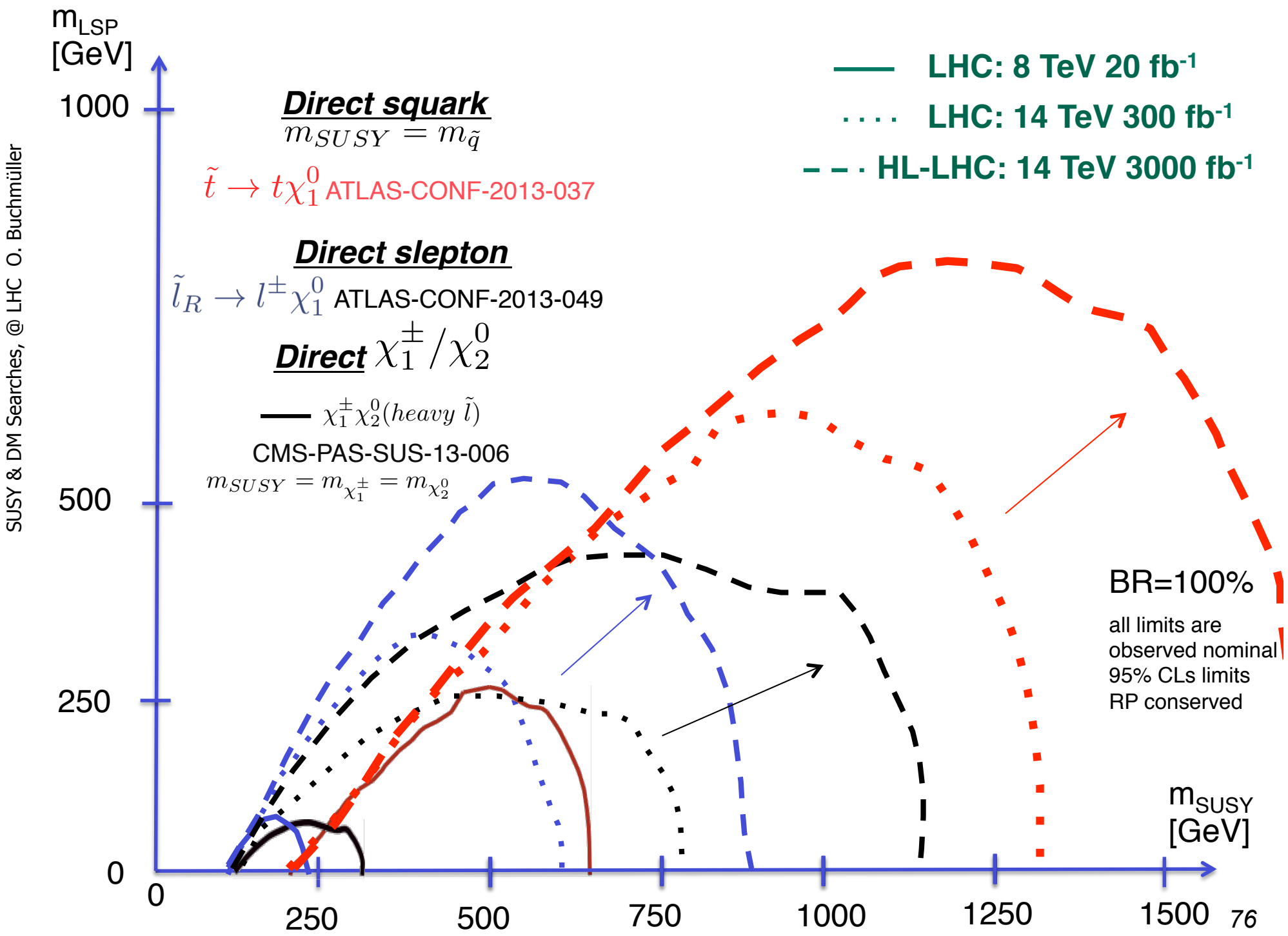
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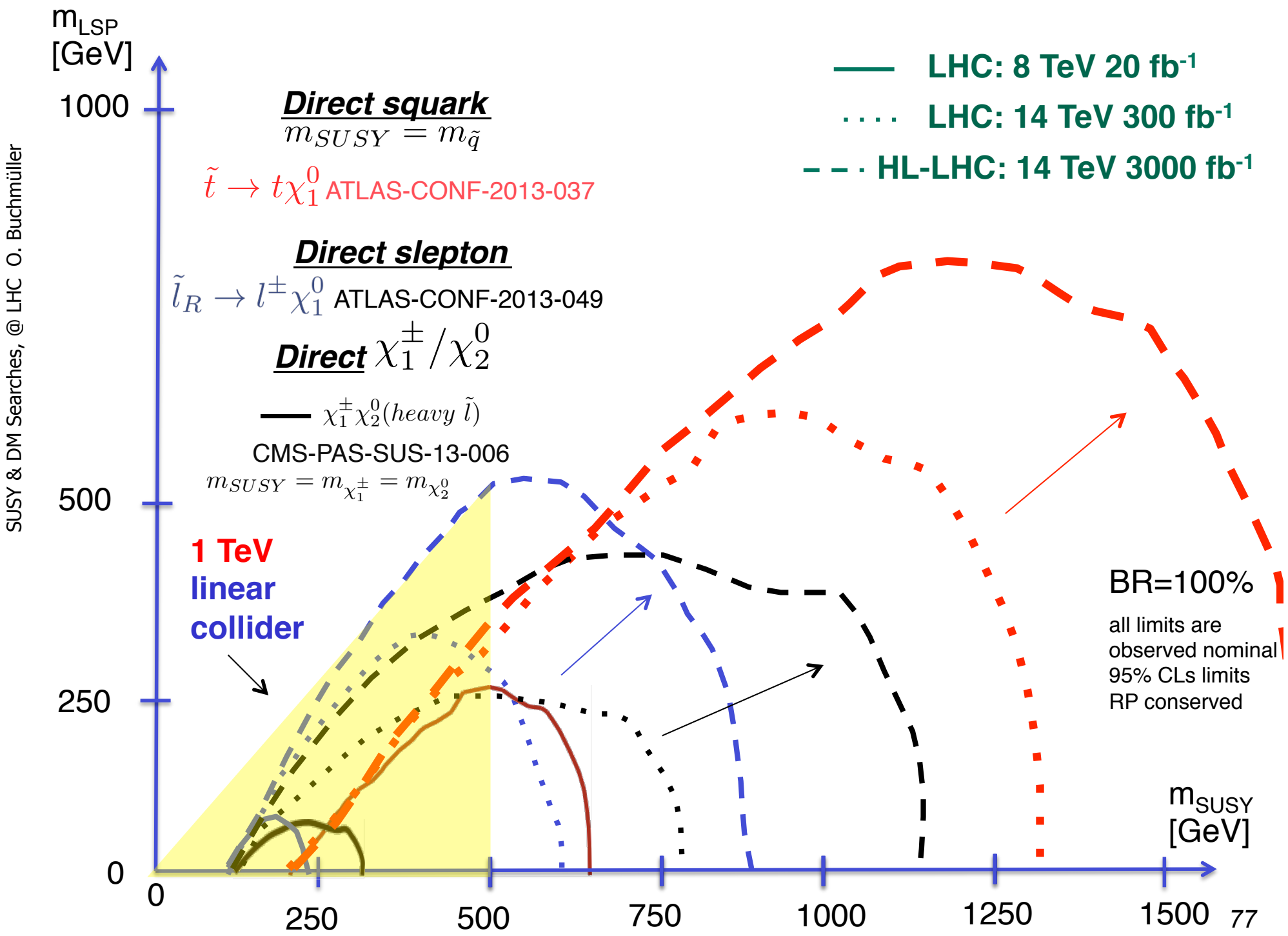
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CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
1 TeV linear collider
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved

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

ATLAS Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (4.4 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$)<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tanβ>18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	m($\tilde{\chi}_1^0$)>50 GeV	1209.0753
	GGM (wino NLSP)	1 e, μ + γ	0	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	m($\tilde{\chi}_1^0$) <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2013-053
	$b_1b_1, b_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	m($\tilde{\chi}_1^0$)>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	m($\tilde{t}_1$)=m($\tilde{\chi}_1^0$)+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{l}_{L,R}\tilde{l}_{L,R}, \tilde{l}\to l\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{l}$ 85-315 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{l}\nu(l\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{l}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{l}_L\nu\tilde{l}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{l}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{l}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0Z^*\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm<cτ<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 e, μ + τ	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e, μ + τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

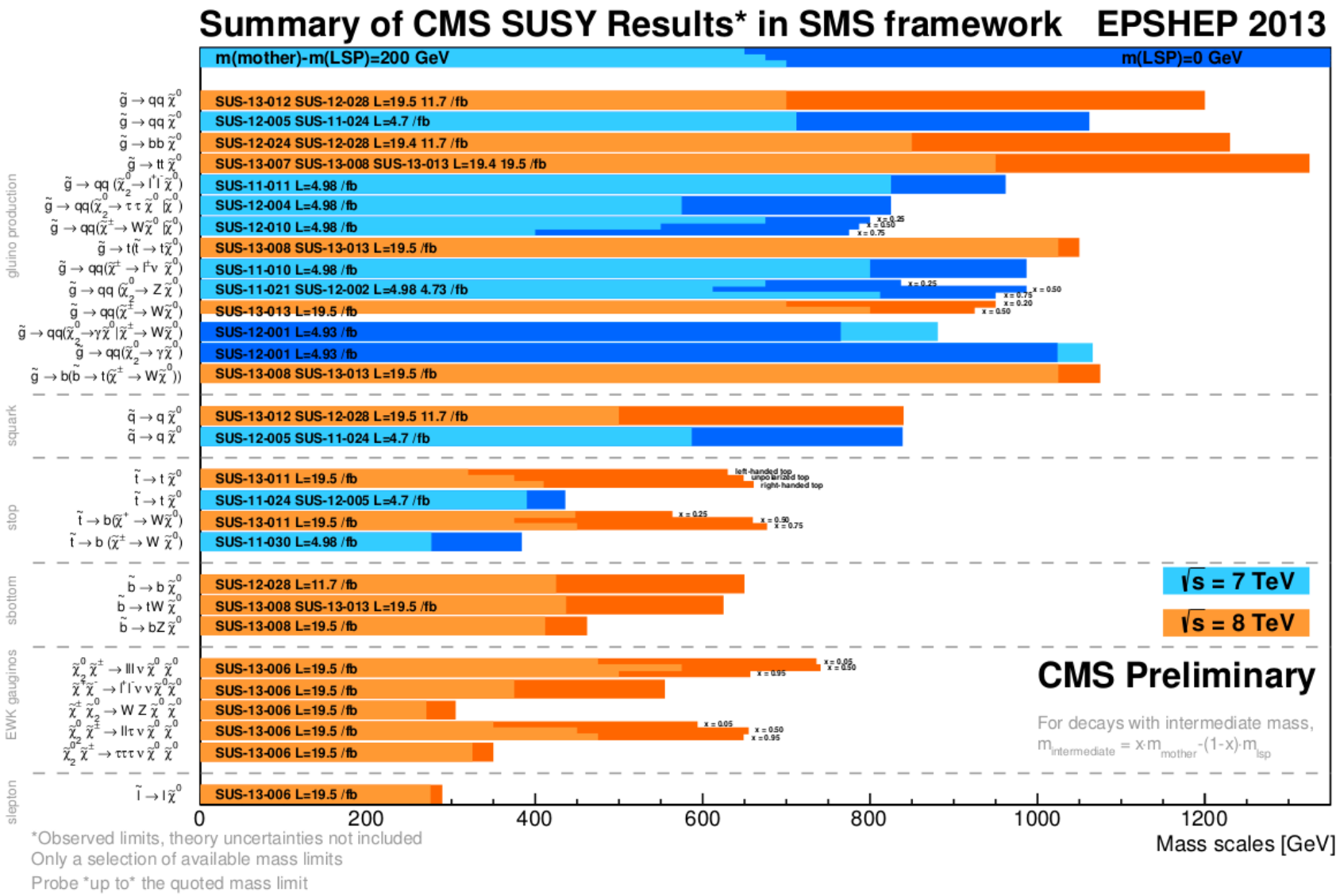
10^{-1} 1

Mass scale [TeV]

√s = 7 TeV full data | √s = 8 TeV partial data | √s = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

CMS Summary


Summary of CMS SUSY Results* in SMS framework EPSHEP 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-12-024 SUS-12-028 L=19.4 11.7 /fb
SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
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SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother -(1-x)·m_lsp
0
200
400
600
800
1000
1200
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Summary

Slide from 2007
EPS Plenary talk in Manchester
LHC Detectors
Commissioning & Physics
pre-accident & 14 TeV assumption

- LHC&Experiments are on track for first collisions in 2008
  - Challenge: commissioning of machine and detectors of unprecedented complexity, technology and performance
- The LHC will discover (or exclude) the Higgs by ~2010
  - Electro Weak Symmetry Breaking
  - Large phase space can already be excluded with only ~1fb^{-1}
- The LHC will discover low energy SUSY (if it exists)
  - Could be easy; could also take more time and ingenuity before we can claim a discovery
  - First signals might emerge already in the first data
  - 1-3 TeV can be covered already with <10fb^{-1}
- The LHC will cover a new physics scale of 1-3 TeV
  - Many new physics models; Black hole, Extra Dimensions,Little Higgs, Split Susy, New Bosons, Technicolour, etc ...

In other words; the next five years will be an exciting time for particle physics . . .

(Best) mass limits in a nutshell (RP conserving)

Direct squark	$\tilde{q} \to q\chi_1^0$	$\tilde{u}_L \to q\chi_1^0$	$\tilde{b} \to b\chi_1^0$	$\tilde{t} \to t\chi_1^0$
Best limit: **[GeV]**	~850	~500	~650	~650
No limit for M_{LSP}**[GeV]**	~ 300	~120	~270	~260

coloured sparticle production

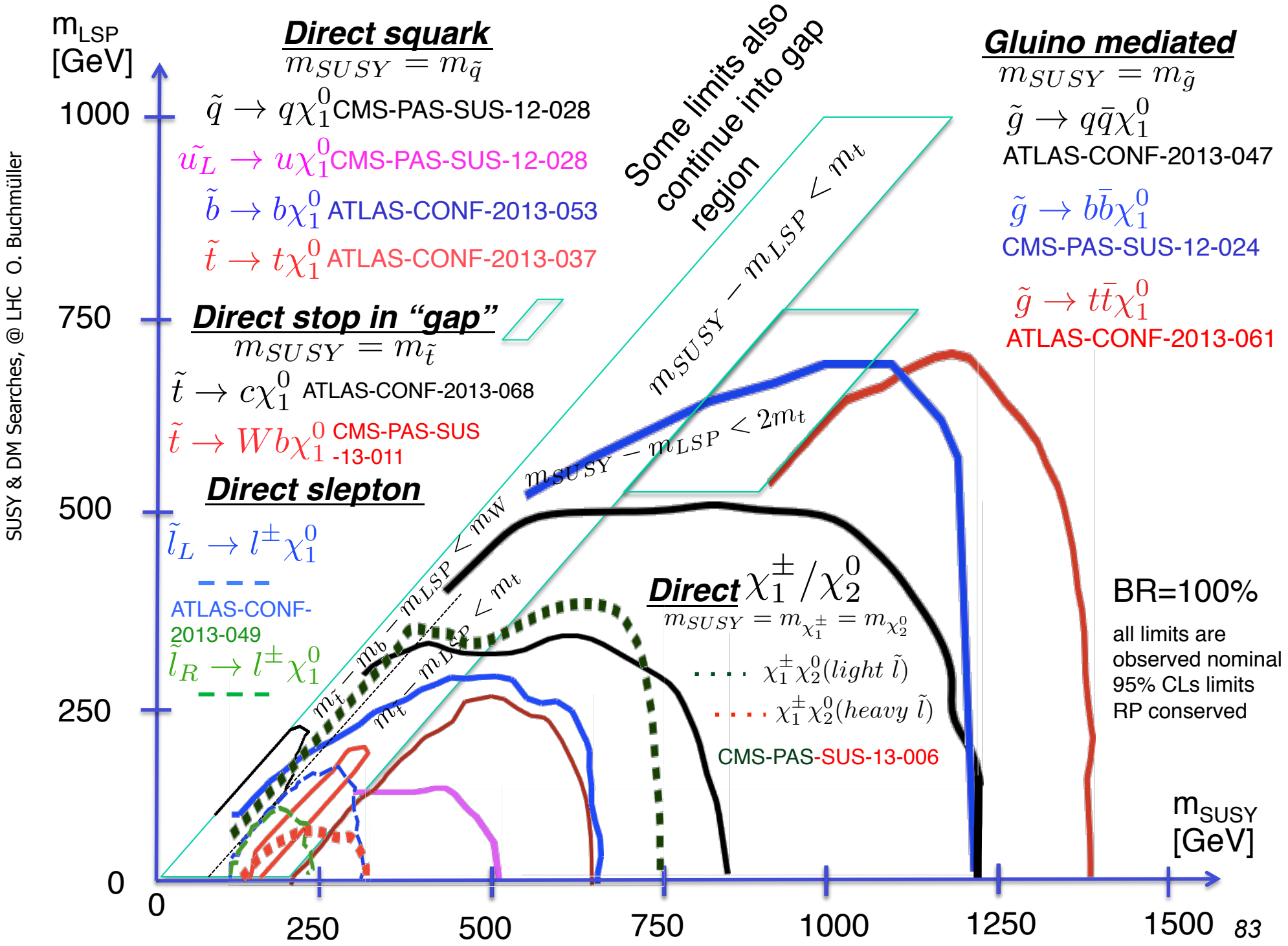
Direct squark	$\tilde{g} \to q\bar{q}\chi_1^0$	$\tilde{g} \to b\bar{b}\chi_1^0$	$\tilde{g} \to t\bar{t}\chi_1^0$
Best limit: **[GeV]**	~1200	~1200	~1400
No limit for M_{LSP}**[GeV]**	~480	~650	~700

Stop $M_{stop} - M_{Lsp} < M_{top}$	$\tilde{t} \to c\chi_1^0$	$\tilde{t} \to Wb\chi_1^0$
Best limit: **[GeV]**	~240	~320
No limit for M_{LSP}**[GeV]**	~210	~190

EWK sparticle production

Direct slepton	$\tilde{l}_L \to l^{\pm}\chi_1^0$	$\tilde{l}_R \to l^{\pm}\chi_1^0$
Best limit: **[GeV]**	~300	~240
No limit for M_{LSP}**[GeV]**	~150	~90

$\chi_1^{\pm}\chi_2^0$	$light\ \tilde{l}$	$heavy\ \tilde{l}$
Best limit: **[GeV]**	~750	~300
No limit for M_{LSP}**[GeV]**	~350	~60


SUSY & DM Searches, @ LHC O. Buchmüller
m_LSP [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$ ATLAS-CONF-2013-068
$\tilde{t} \to Wb\chi_1^0$ CMS-PAS-SUS-13-011
Direct slepton
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS-CONF-2013-049
$\tilde{l}_R \to l^{\pm}\chi_1^0$
Some limits also continue into gap region
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{SUSY} - m_{LSP} < m_W$
$m_{\tilde{t}} - m_b - m_{LSP} < m_t$
$m_t - m_{LSP} < m_b$
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0(light\ \tilde{l})$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2013-047
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
BR=100%
all limits are observed nominal 95% CLs limits
RP conserved
83

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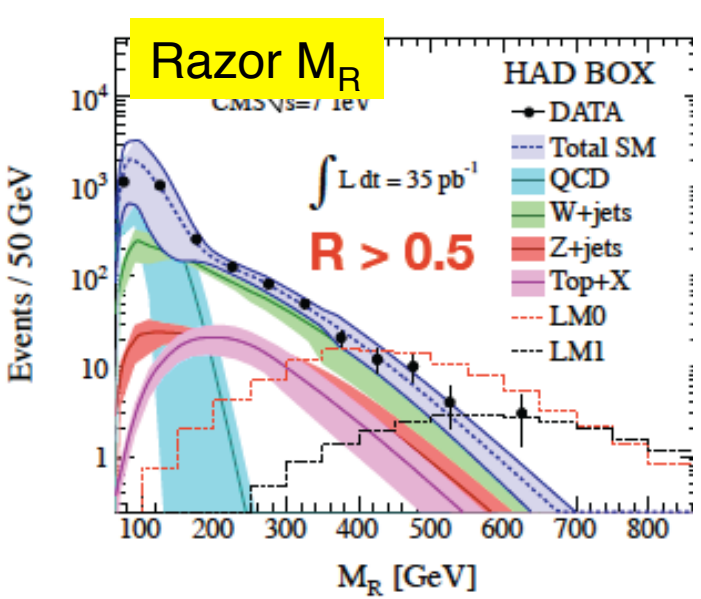
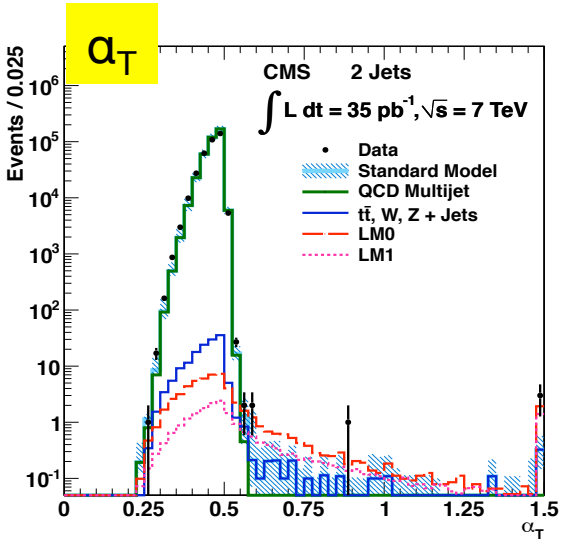
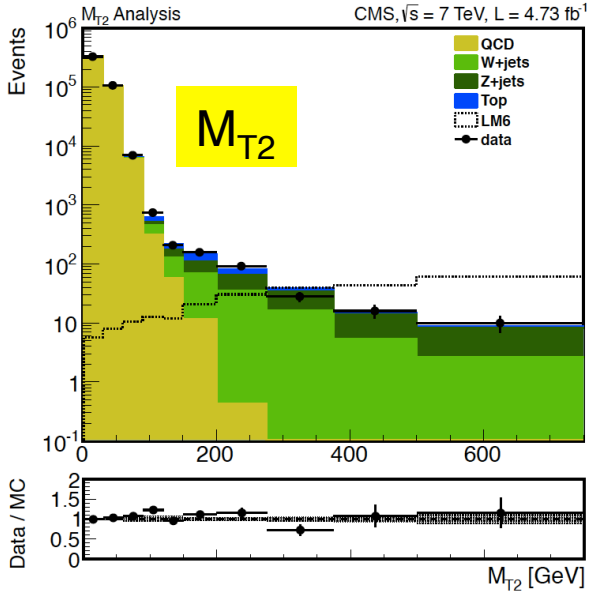
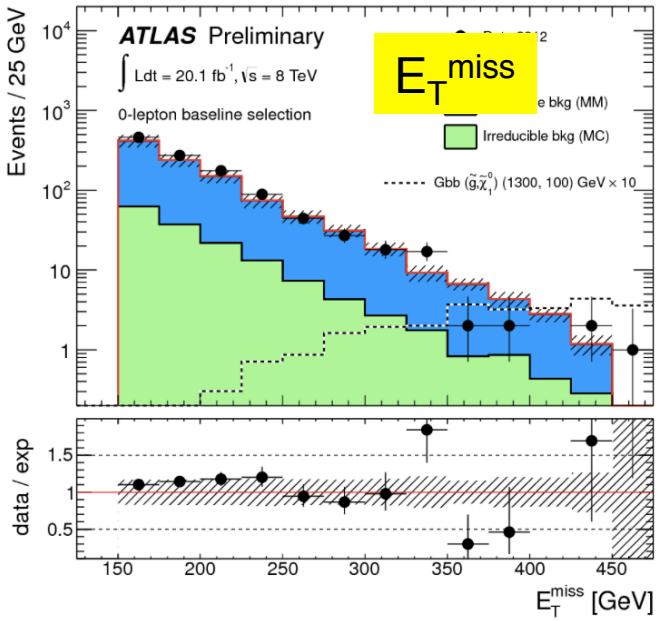
Many Different Kinematic Variables

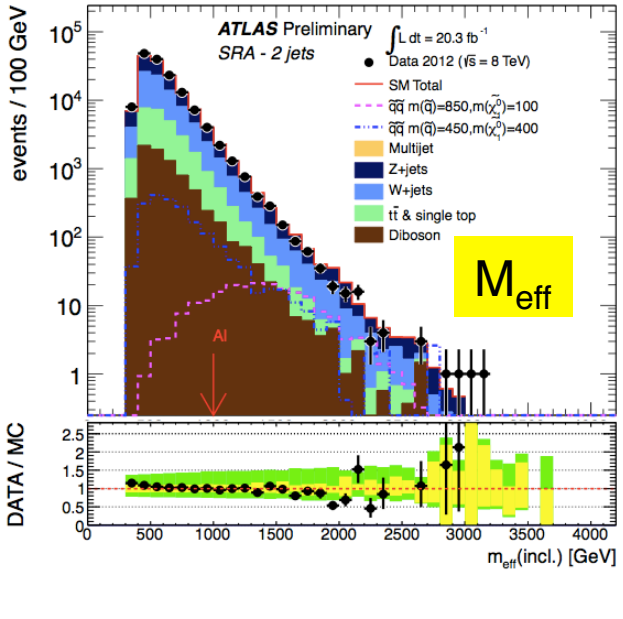
SUSY & DM Searches, @ LHC O. Buchmüller

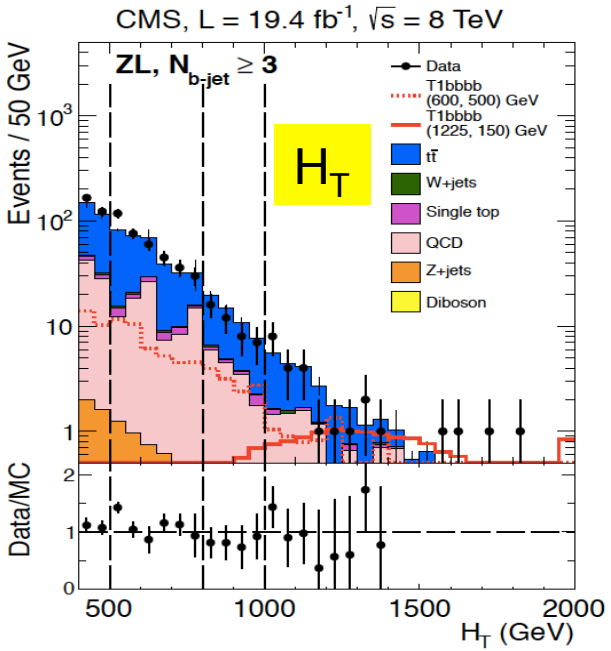












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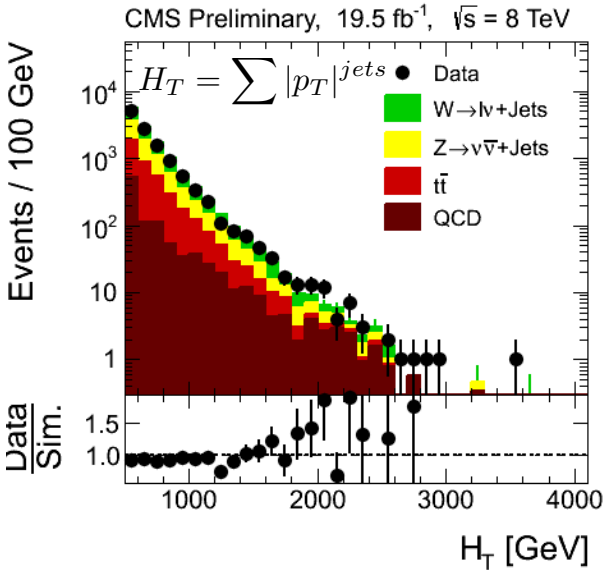
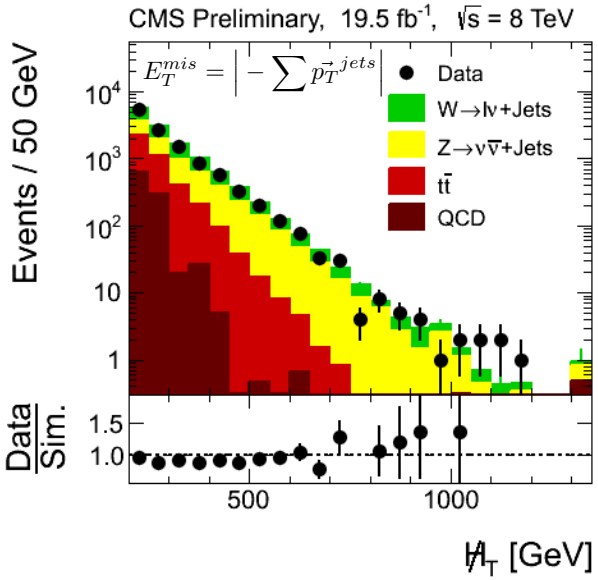
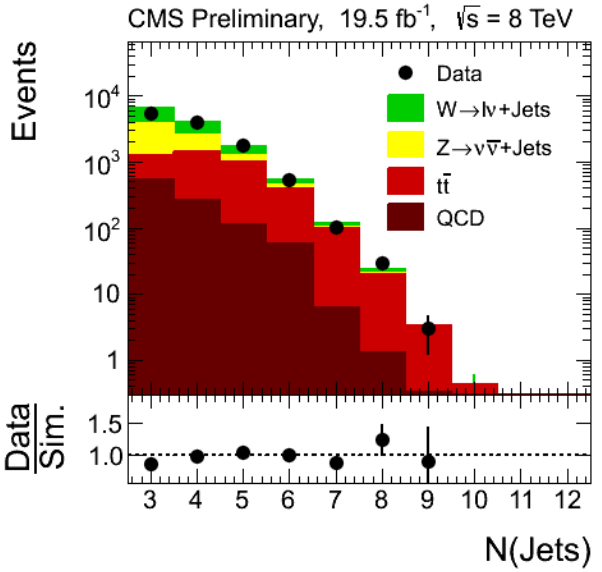
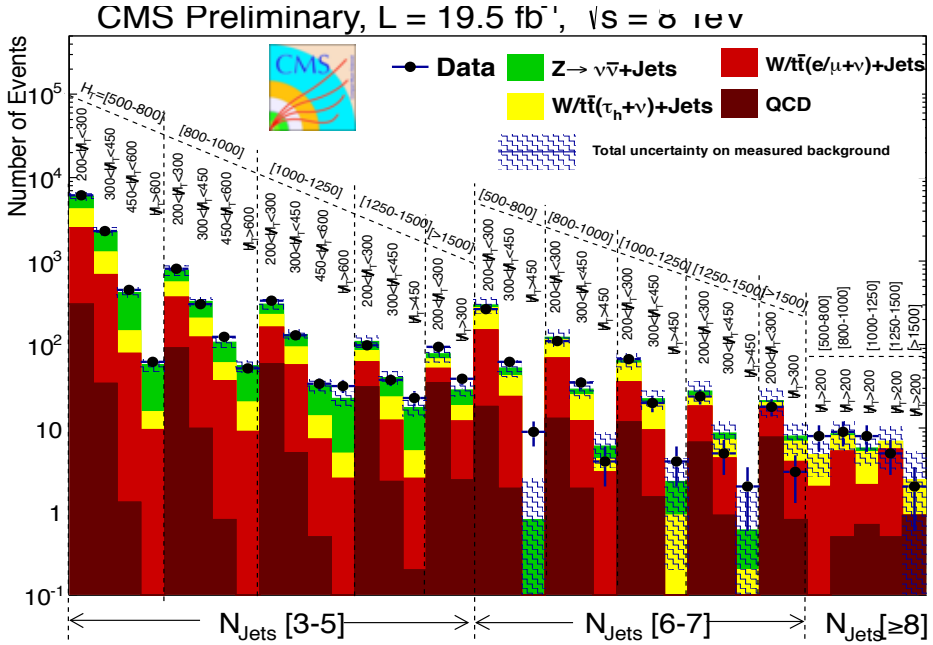
Multijets & missing energy search









Traditional inclusive Jets + E_t^{mis} search, which uses simple kinematic variables to categories the events.

Main backgrounds QCD, W/Z+jet and ttbar are estimated using data-driven techniques.

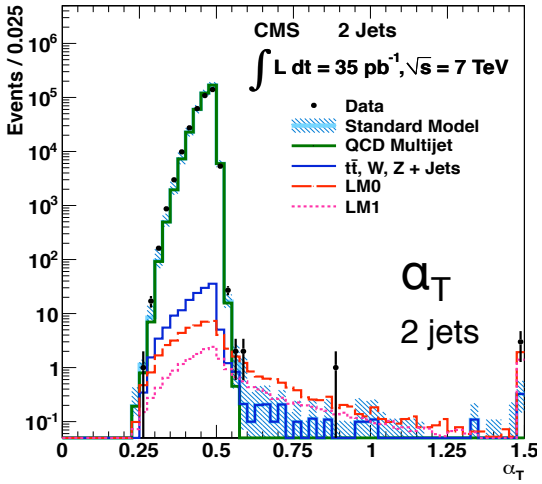
NEW

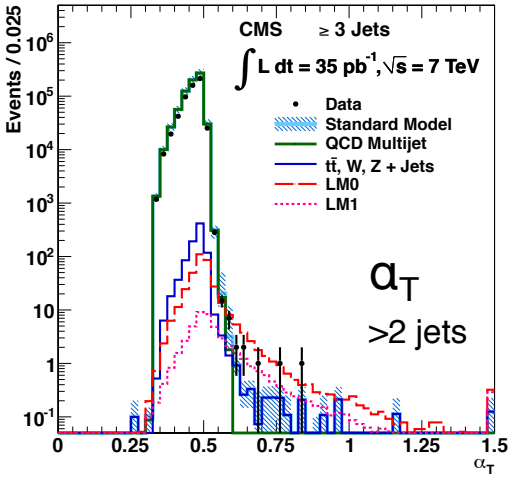
CMS-SUS-PAS-13-012

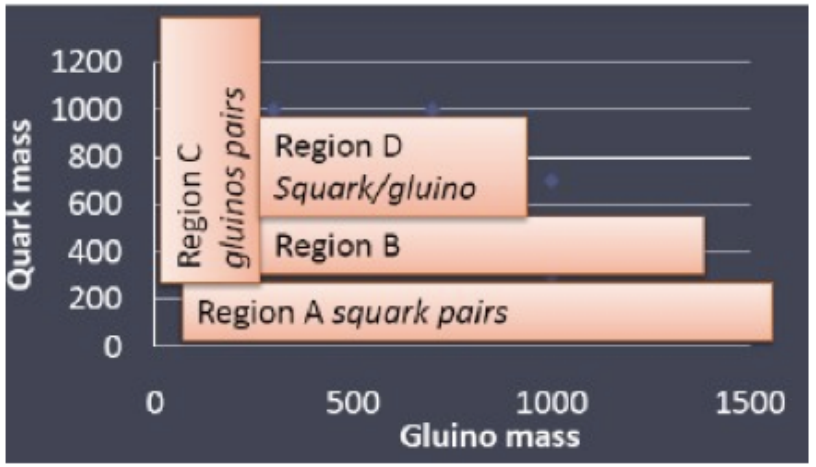
See parallel talk for details:
C. Autermann

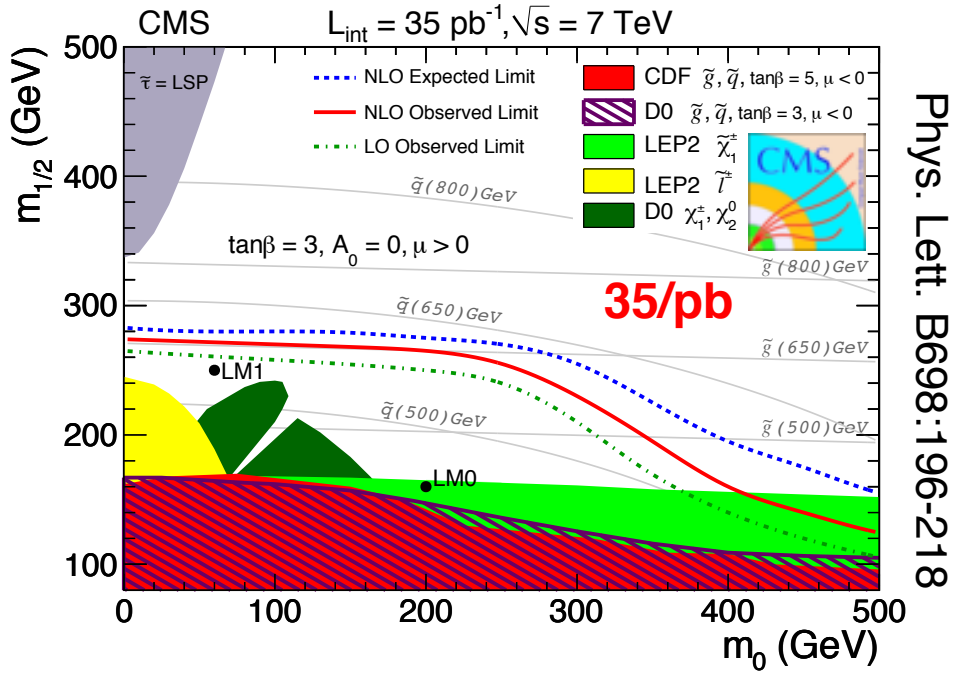
Imperial College London

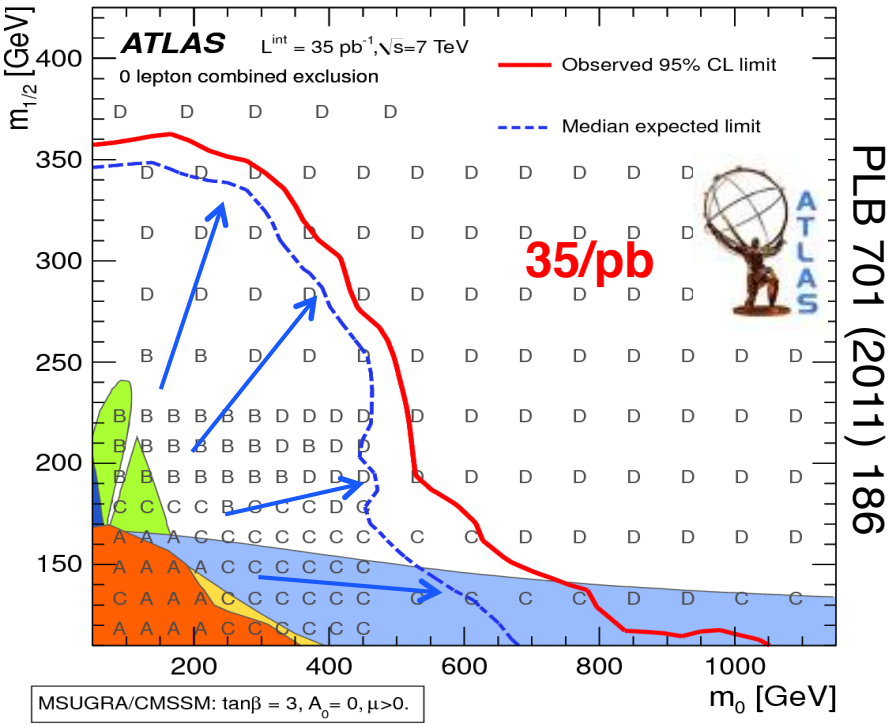
2010: Entering New Territory at the LHC!



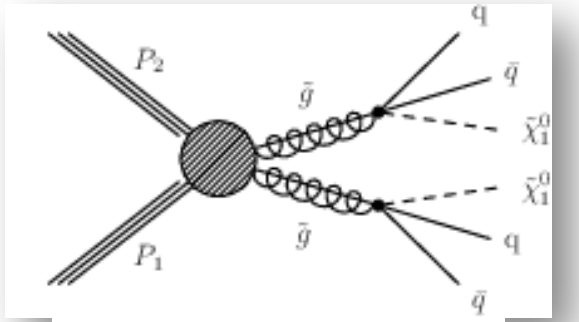




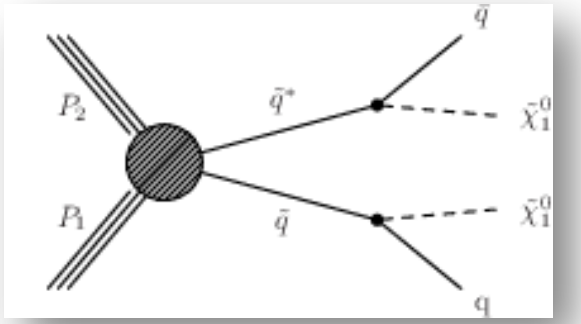




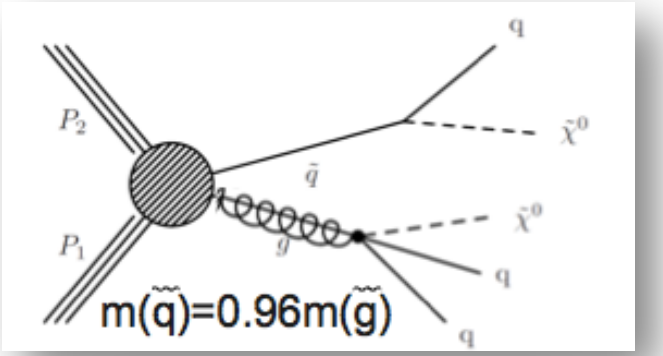
Simplified Model Spectra (SMS)



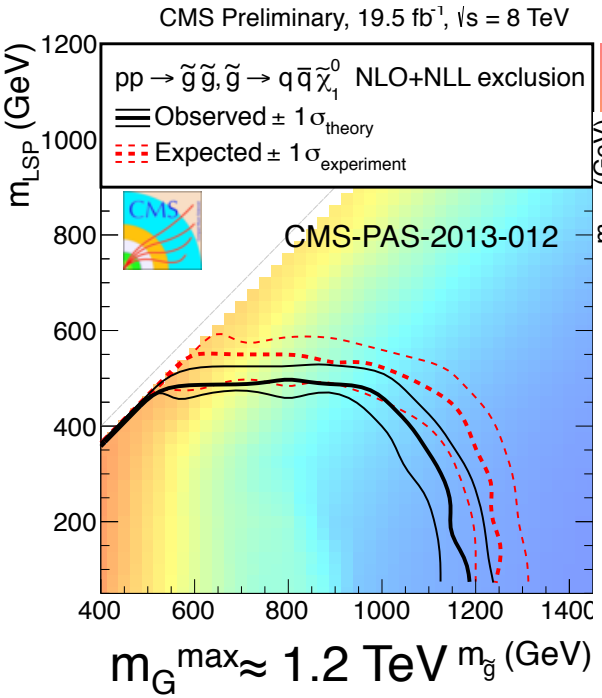
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$



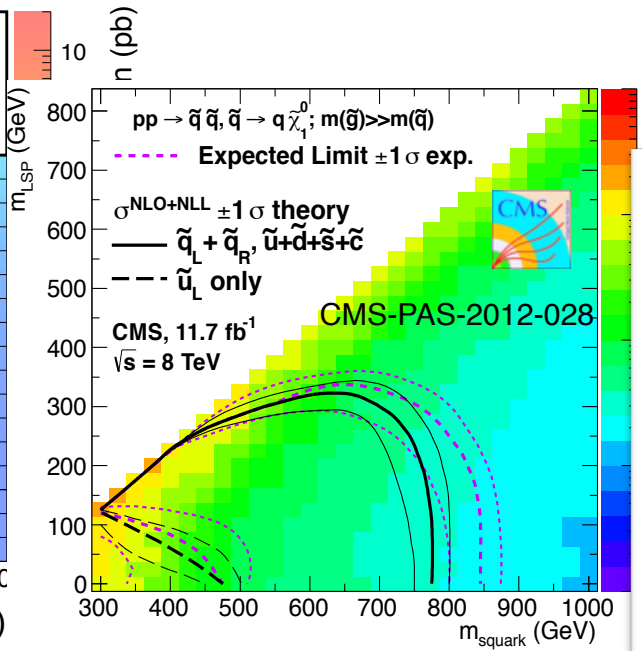
$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0 \bar{q}\tilde{\chi}^0$



$\tilde{q} \rightarrow q\,\tilde{\chi}_1^0, \tilde{g} \rightarrow q\,q\,\tilde{\chi}_1^0$

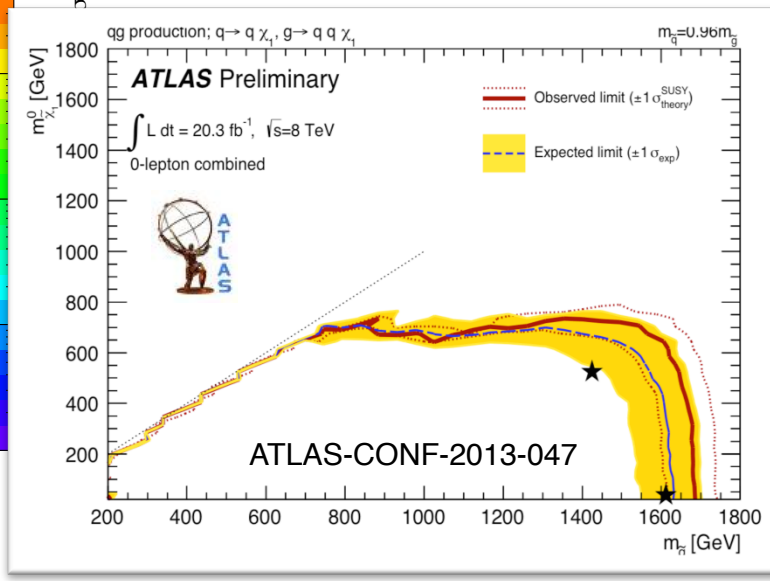


$m_G^{max} \approx 1.2$ TeV



$m_{sq}^{max} \approx 0.8$ TeV

$m_G^{max} \approx 1.7$ TeV



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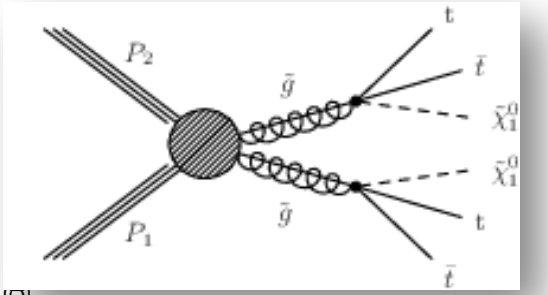
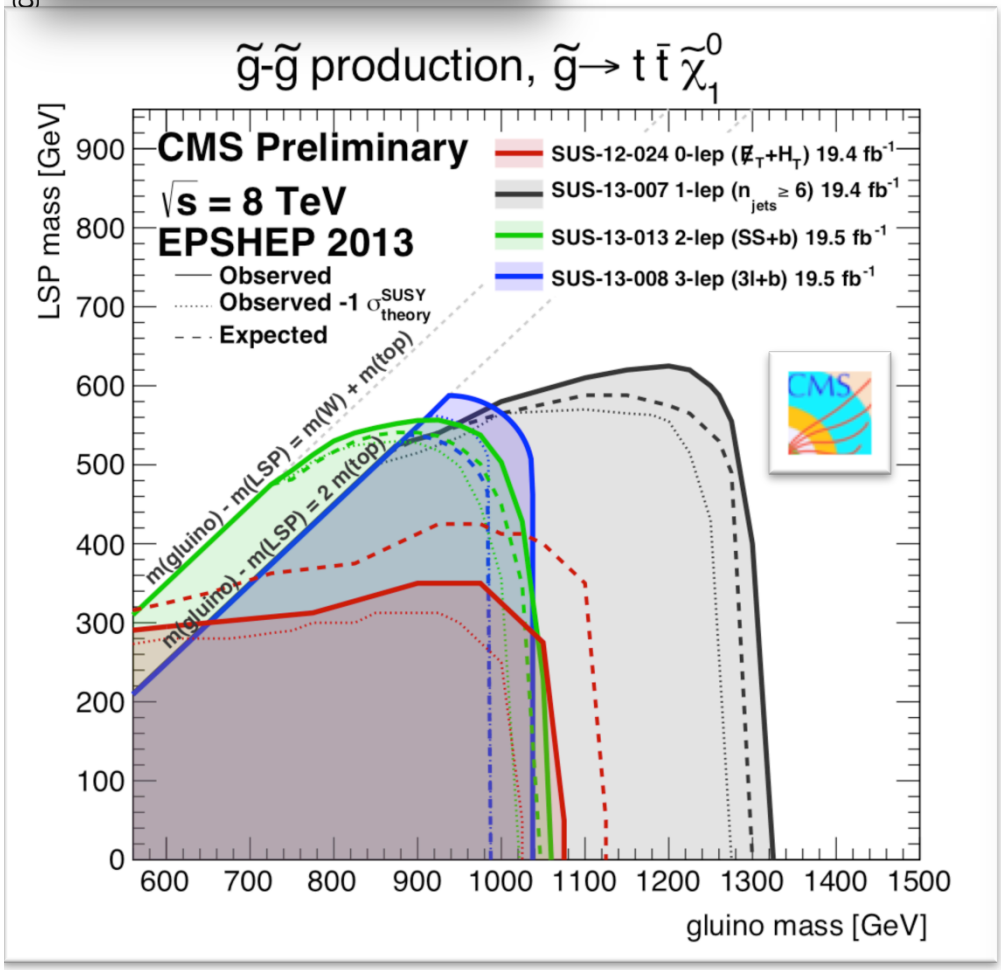
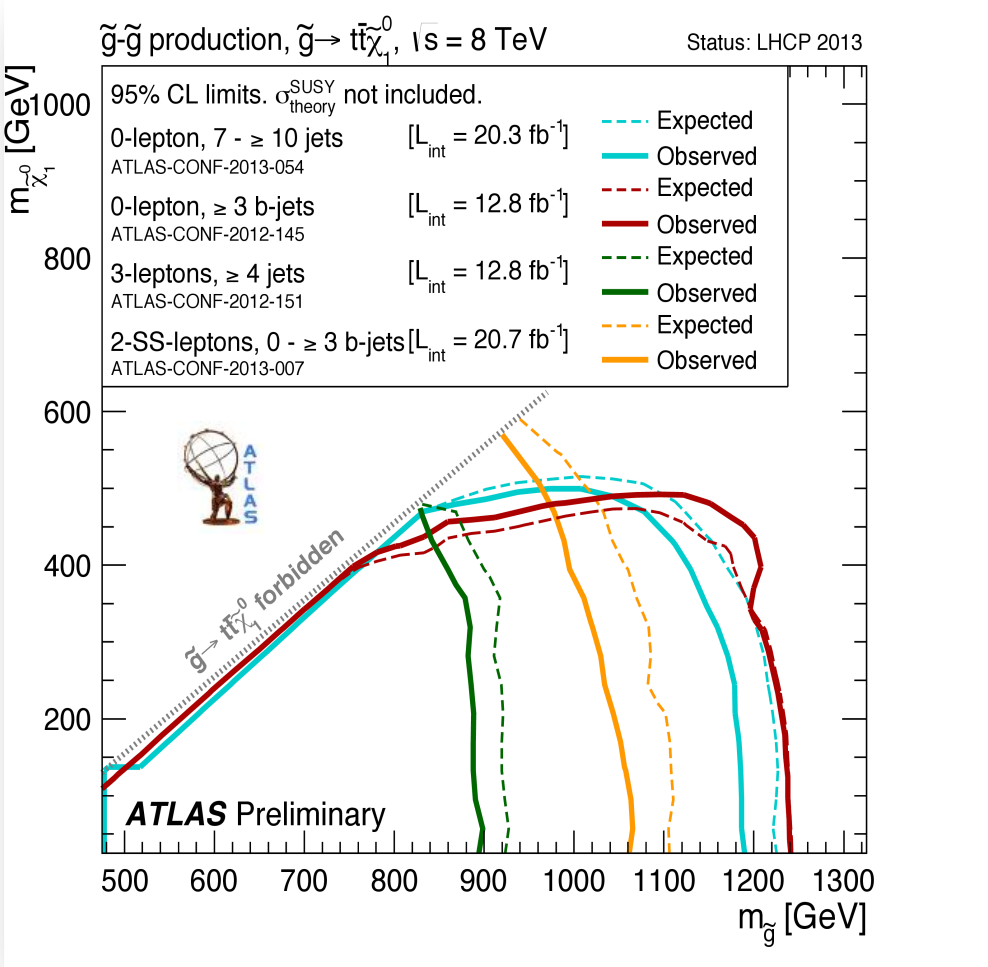
Today: many more SMS and many more searches



Example: $\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\chi_1^0\chi_1^0$

Several searches are interpret in this particular SMS!

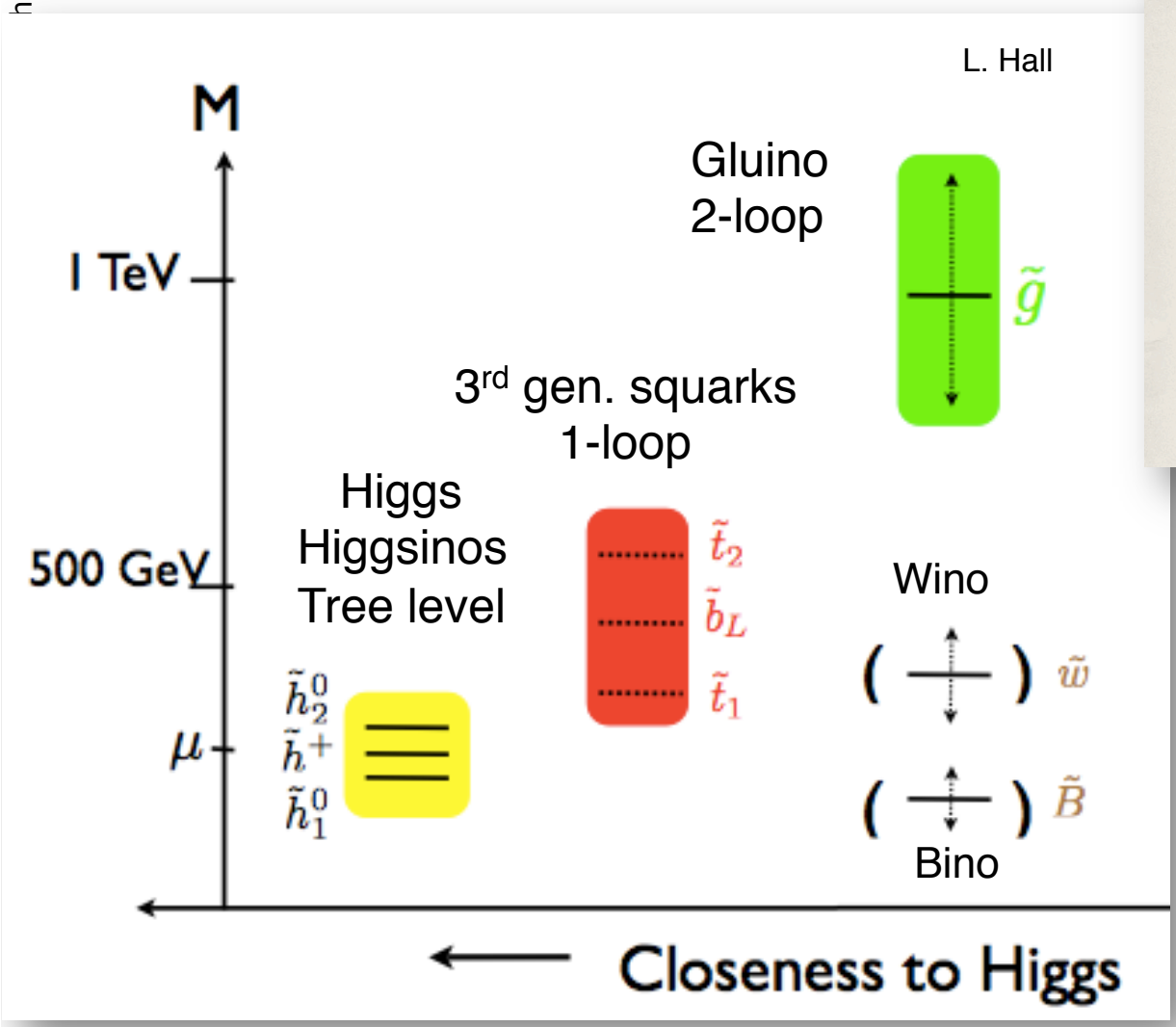




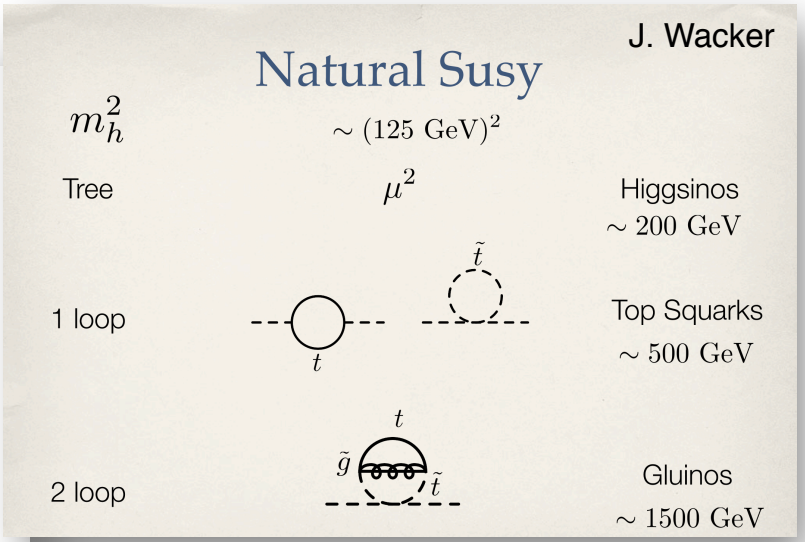
(Minimal) Natural SUSY Spectrum

hmüller

L. Hall



J. Wacker

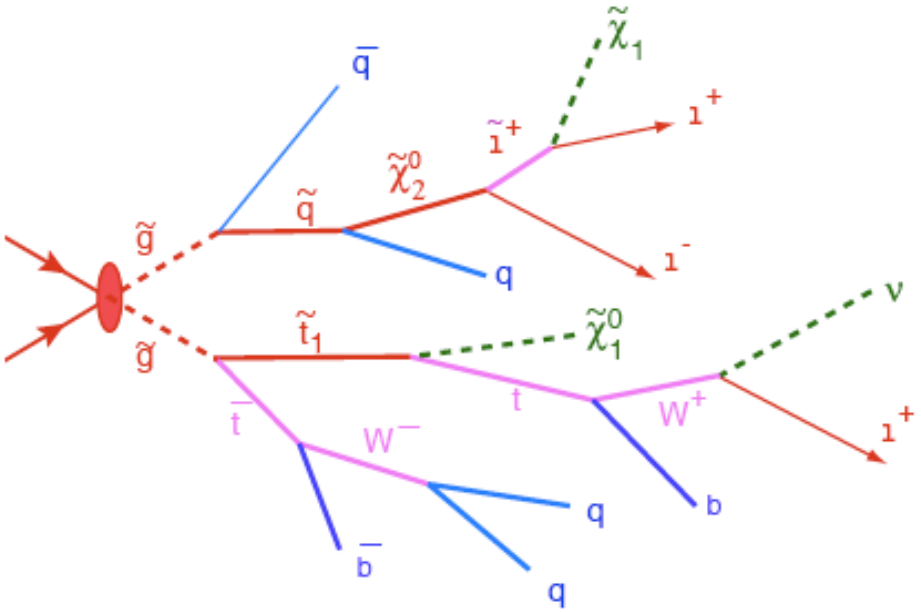


Use the argument of "naturalness" (i.e. fine-tuning) to motivate light 3rd generation squarks (especially stop) and a rather light gluino!

More in Gian Guidice talk!

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*

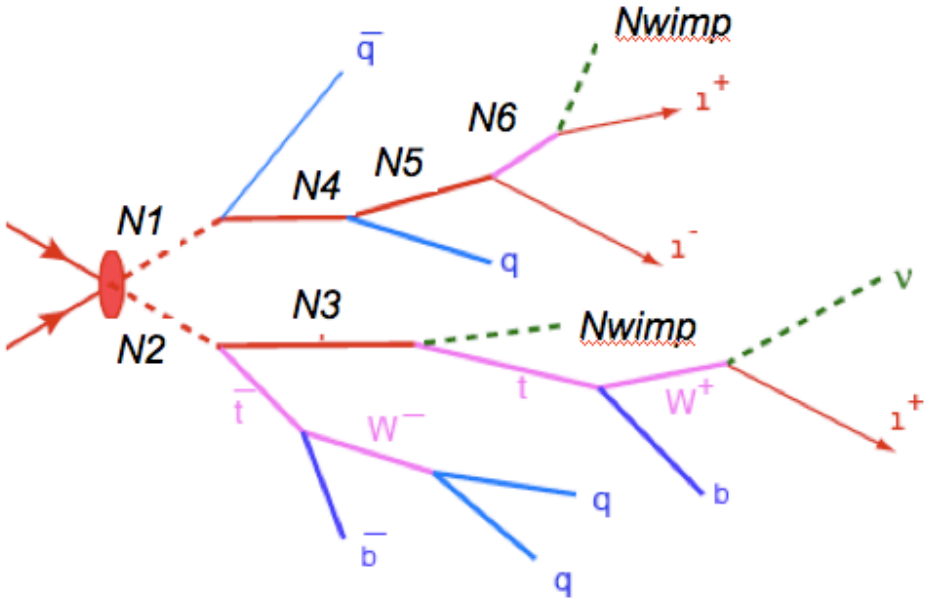
Multi-Jet:
- *from cascade decay (gaugino)*

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:

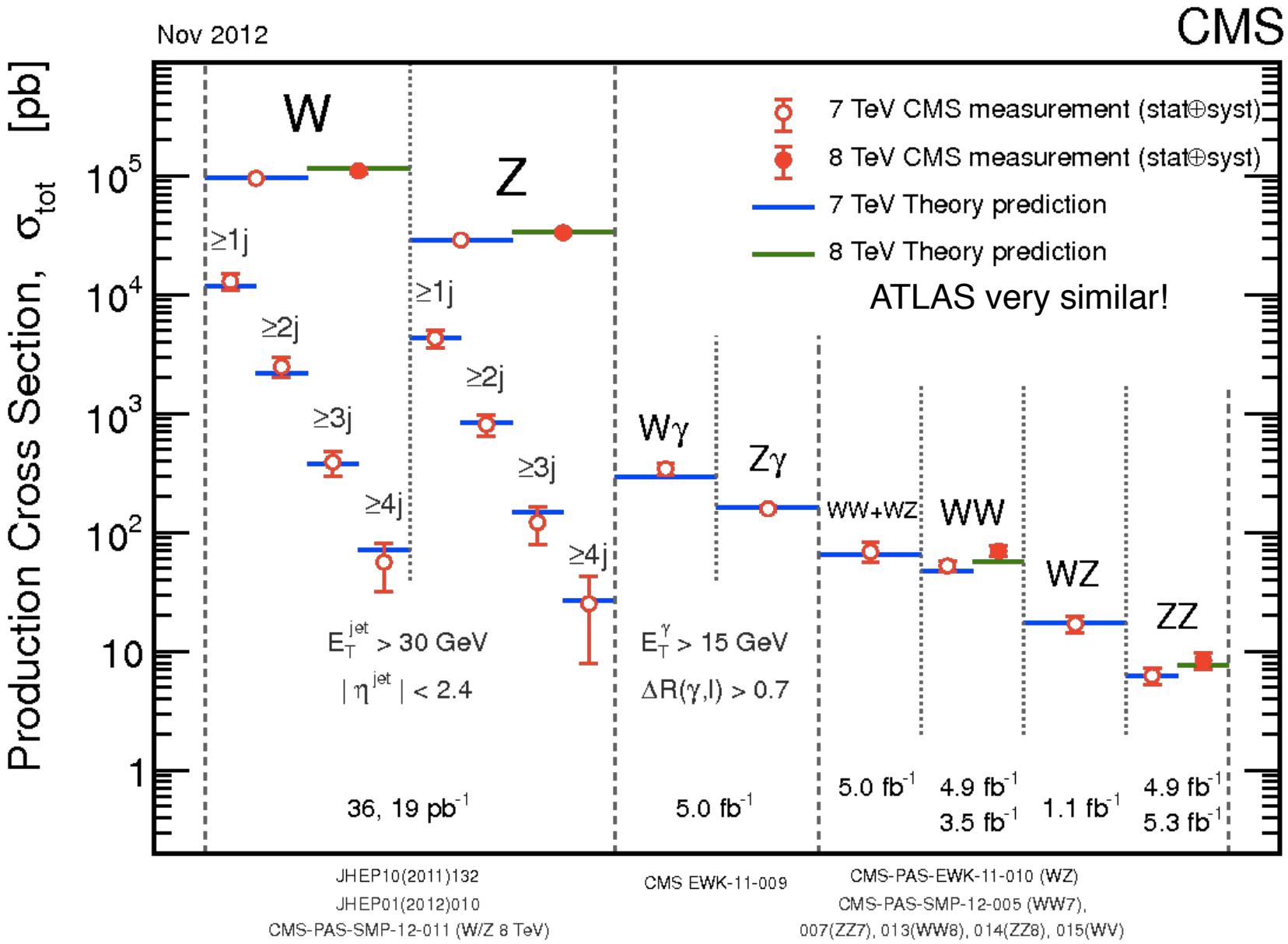
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

Multi-Leptons:

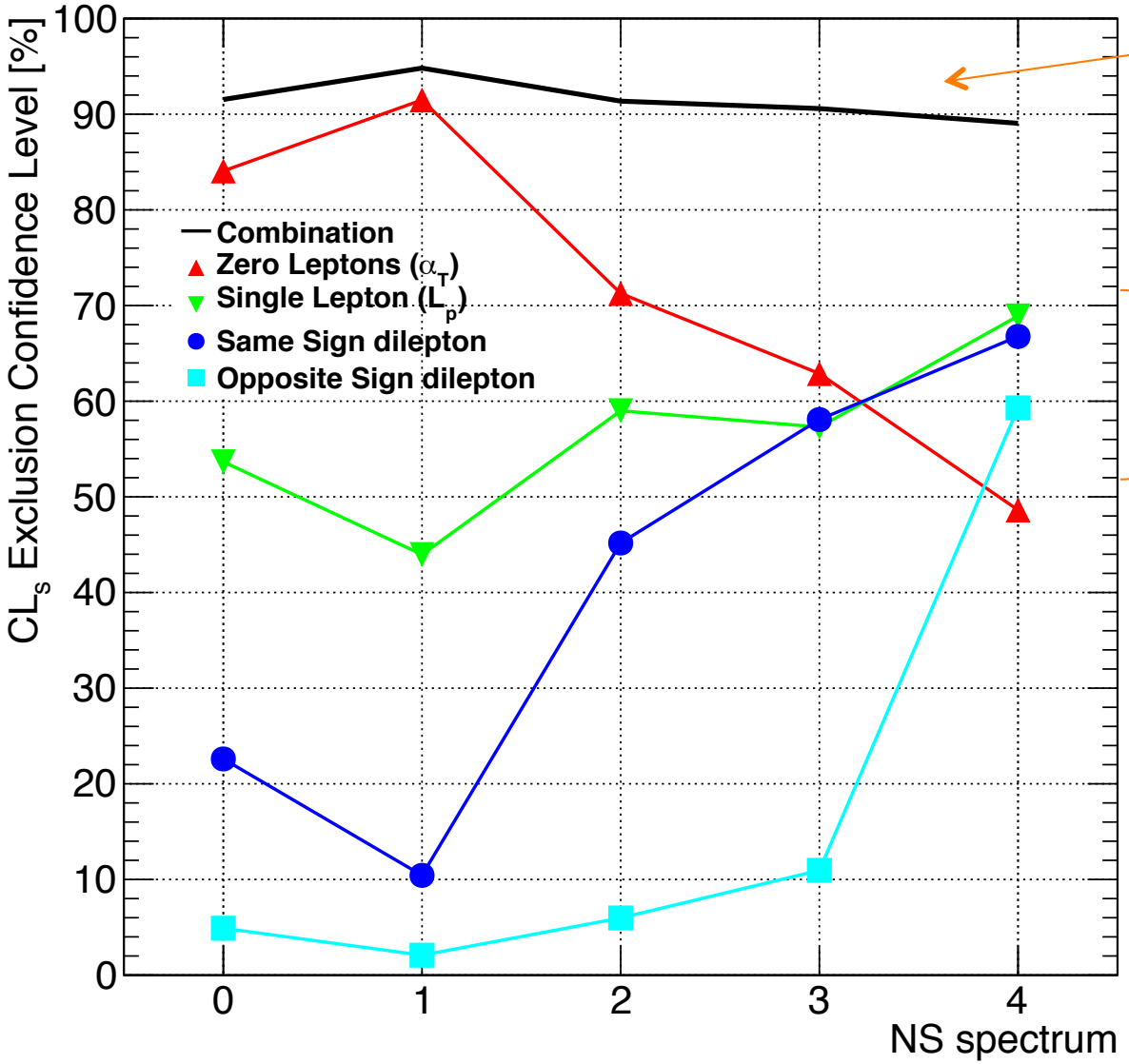
- *from decay of the N's*

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

Rediscovery of the SM at a new energy frontier



Combination vs individual search



Combination of searches stable

Individual searches exhibit large variations

Combinations is stable vs. complexity while individual searches are NOT!

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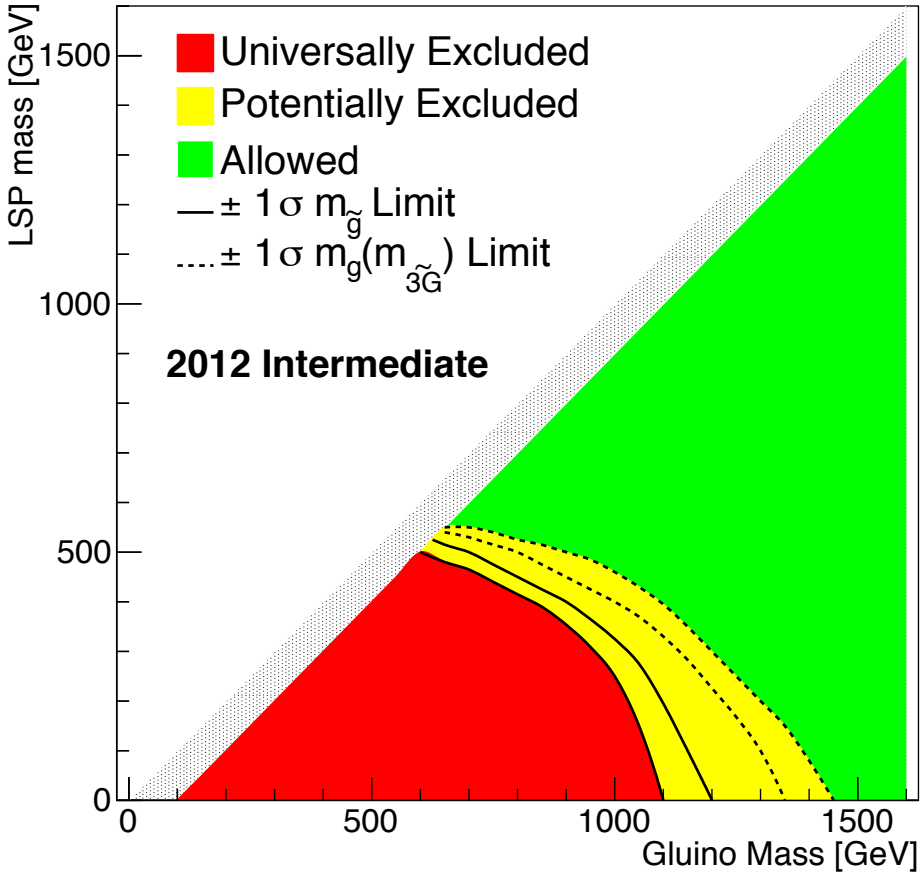
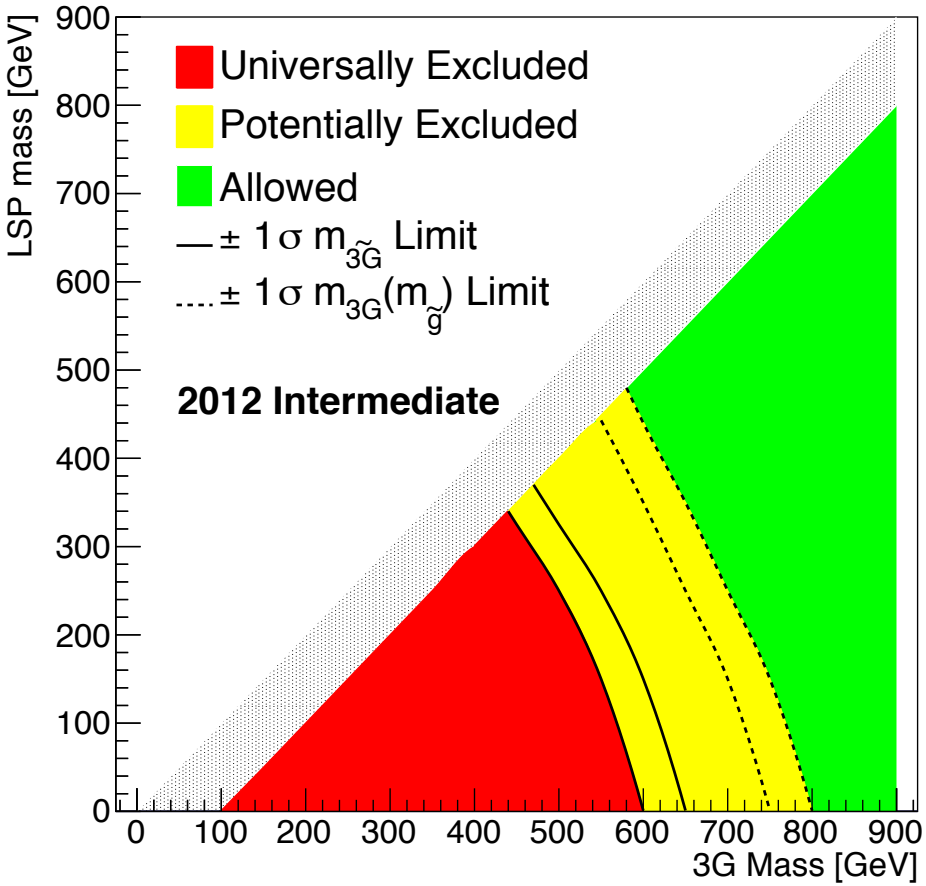
Natural SUSY: universal limits

Buchmueller

If the gluino mass OR 3G mass lies in the red band, the point is excluded.
If the gluino mass AND 3G mass lie in the yellow band the point may or may not be excluded. Otherwise the point is not excluded.





Combining with the latest published 8 TeV results:

Outlook: 8 TeV vs 14 TeV

Use 30/fb for 2011/2012 for comparison

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

SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

Z' :
Mass scale ~ 5 TeV
qq: factor ~1000

Higgs:
15/fb@14 TeV to match 2011/2012
mainly gg: factor ~2

SUSY – 3rd Generation:
5/fb to 10/fb@14 TeV to match 2011/2012
qq and gg: factor ~3 to 6

SUSY – Squarks/Gluino:
0.4/fb to 0.8/fb@14 TeV to match 2011/2012
qq,gg,qg: factor ~40 to 80

Z' :
O(1/pb) @14 TeV to match 2011/2012
qq: factor ~1000

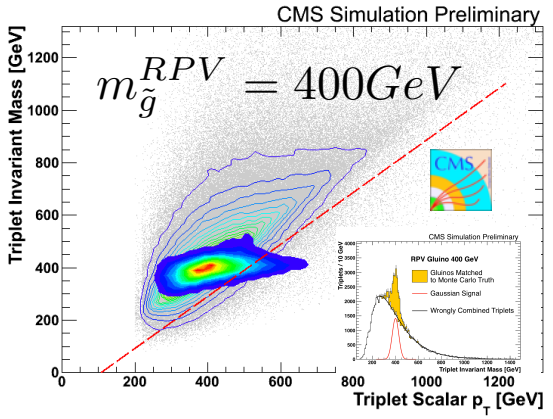
RP-violating searches/interpretation

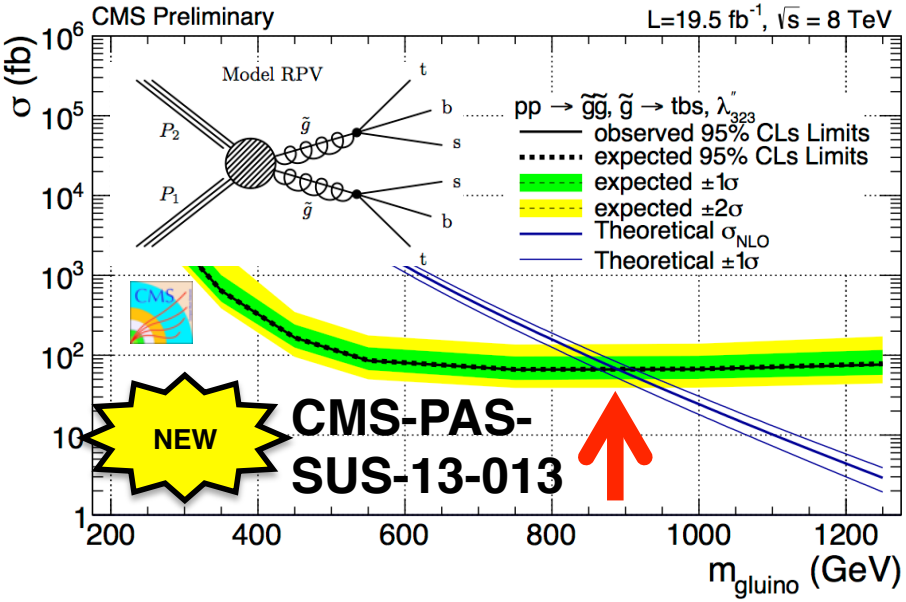
Generic same-sign di-lepton search with different signal regions

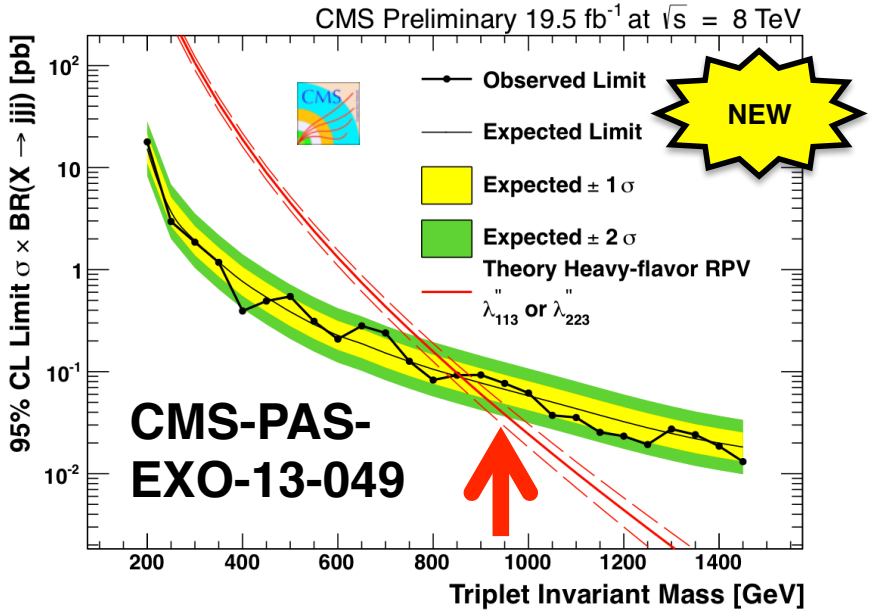
SR	Expected	Observed
RPV0	38 ± 14	35
RPV2	5.3 ± 2.1	5
SStop1	160 ± 59	152
SStop1++	90 ± 32	92
SStop2	40 ± 13	52
SStop2++	22 ± 8	25

$\tilde{g} \rightarrow 3\ jets$

Take all triplets,
QCD: $M_{3j} \sim \Sigma P_T^j$;
SUSY: $M_{3j} \sim M_g$
$M_{3j} < \Sigma P_T^j - 160$ GeV







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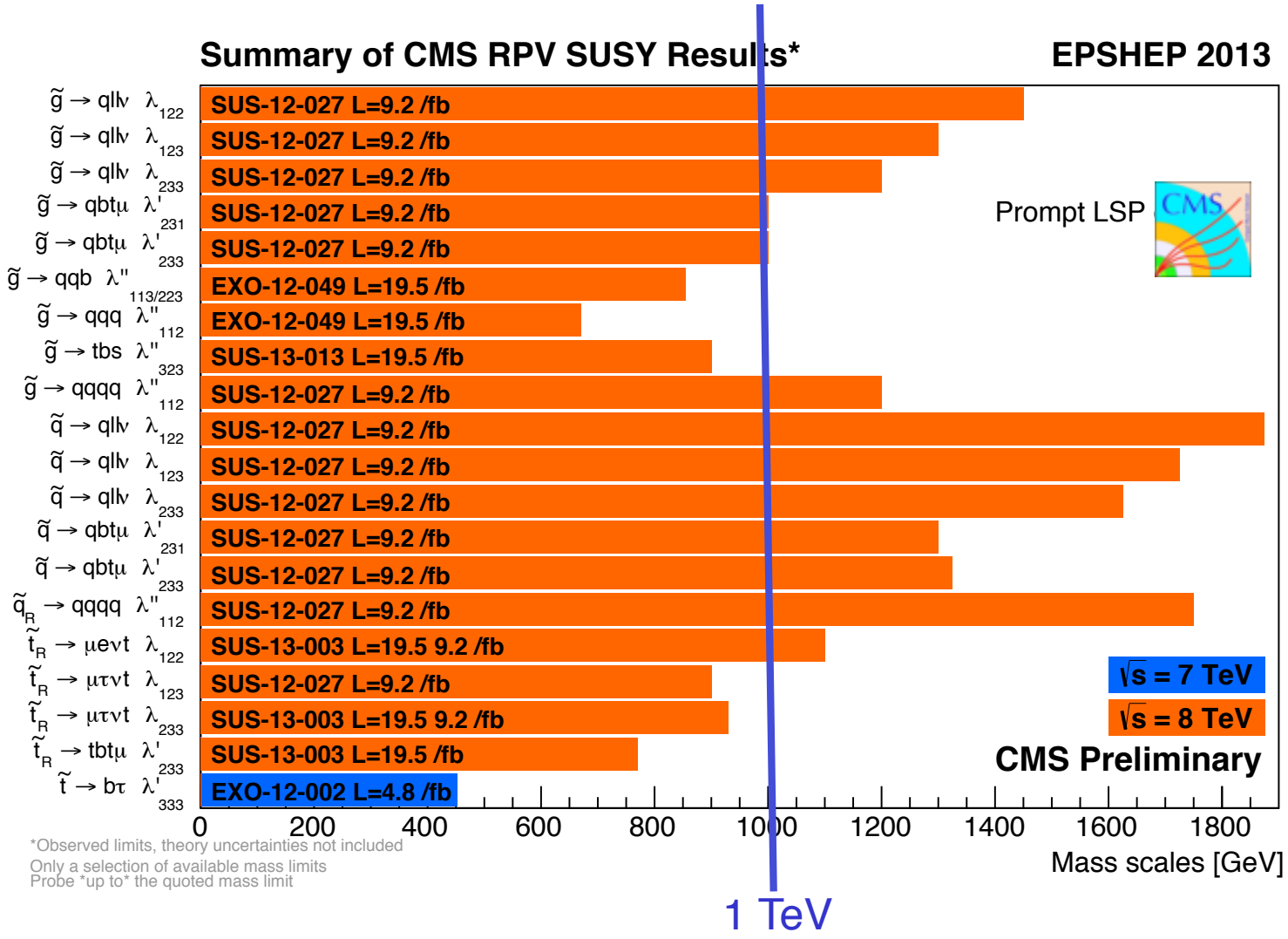
RP violation searches: Summary

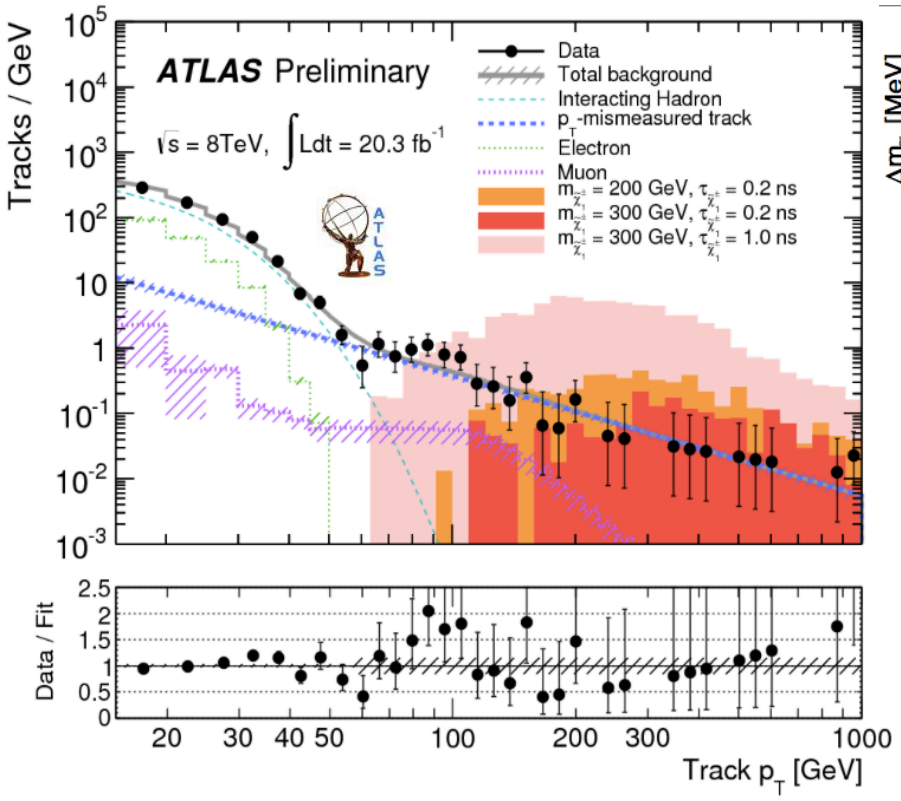
SUSY & DM Searches, @ LHC O. Buchmüller

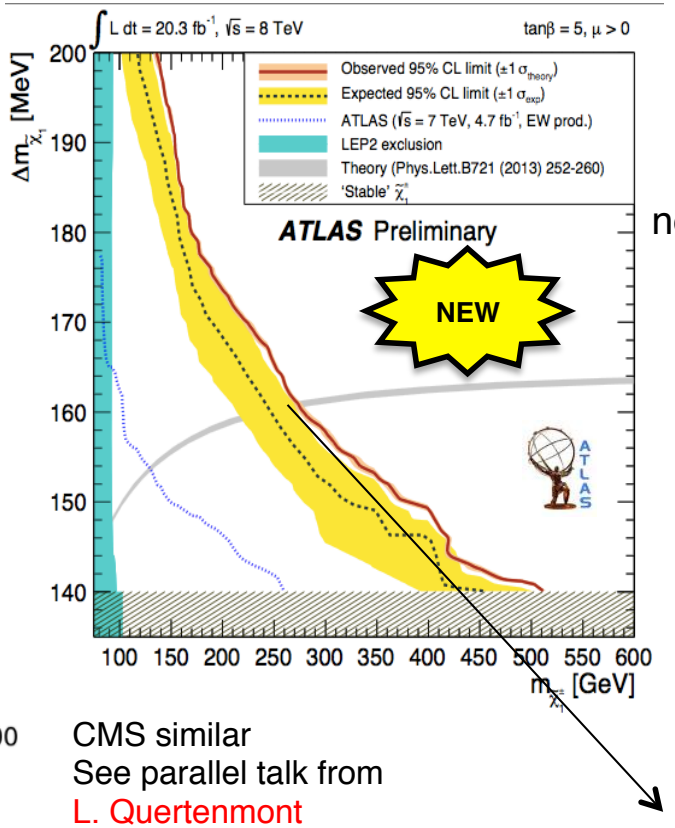


ATLAS similar

Like RP conserving searches, these searches are also probing the 1 TeV scale and even beyond!

Long-lived particle (SUSY) searches





ATLAS-CONF -2013-069

nearly mass-degenerate

$\chi_1^{\pm}\chi_1^0$

search based on disappearing-track signature

CMS similar
See parallel talk from
L. Quertenmont

Long-lived particles						
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV
Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	857 GeV
GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0 \to \tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}_1^0$	475 GeV
GMSB, $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV
$\tilde{\chi}_1^0 \to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$	700 GeV

1 TeV

$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
10<tanβ<50	ATLAS-CONF-2013-058
0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451

About to probe the 1 TeV scale

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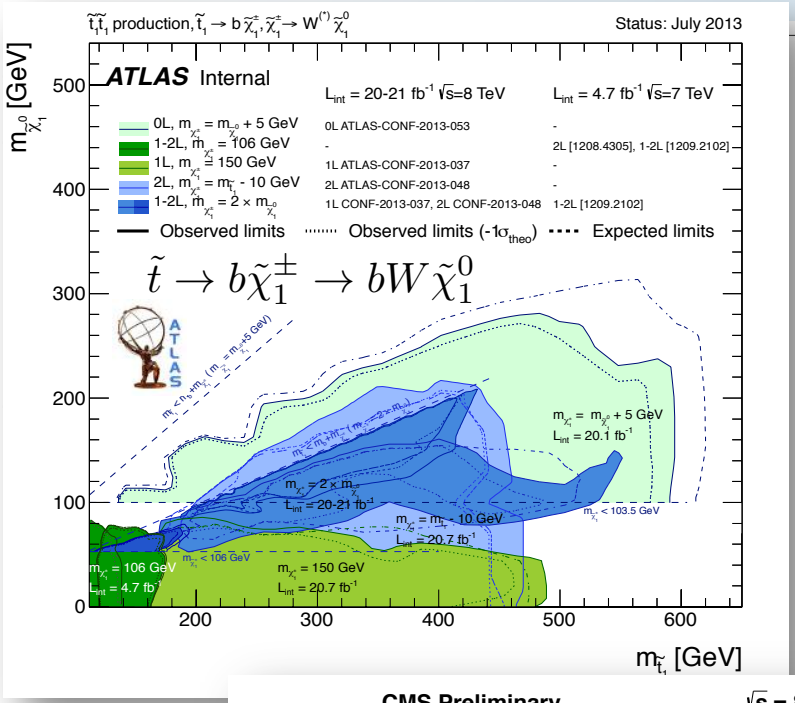
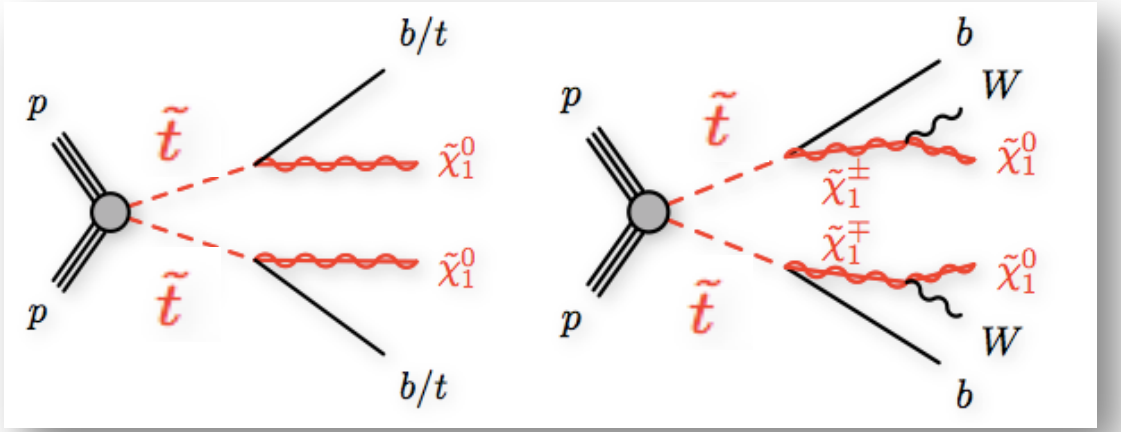
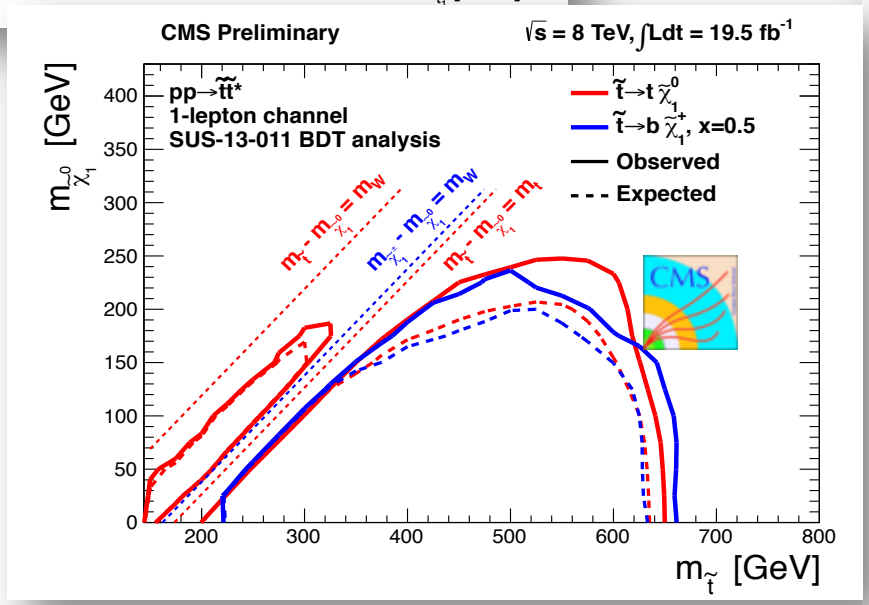
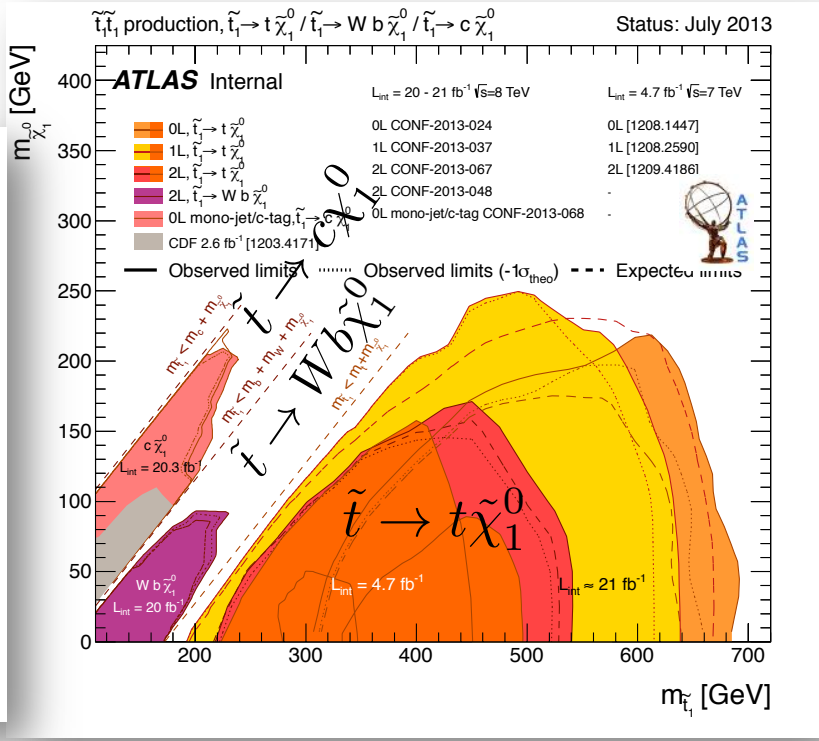
Dedicated searches for direct stop-pair production









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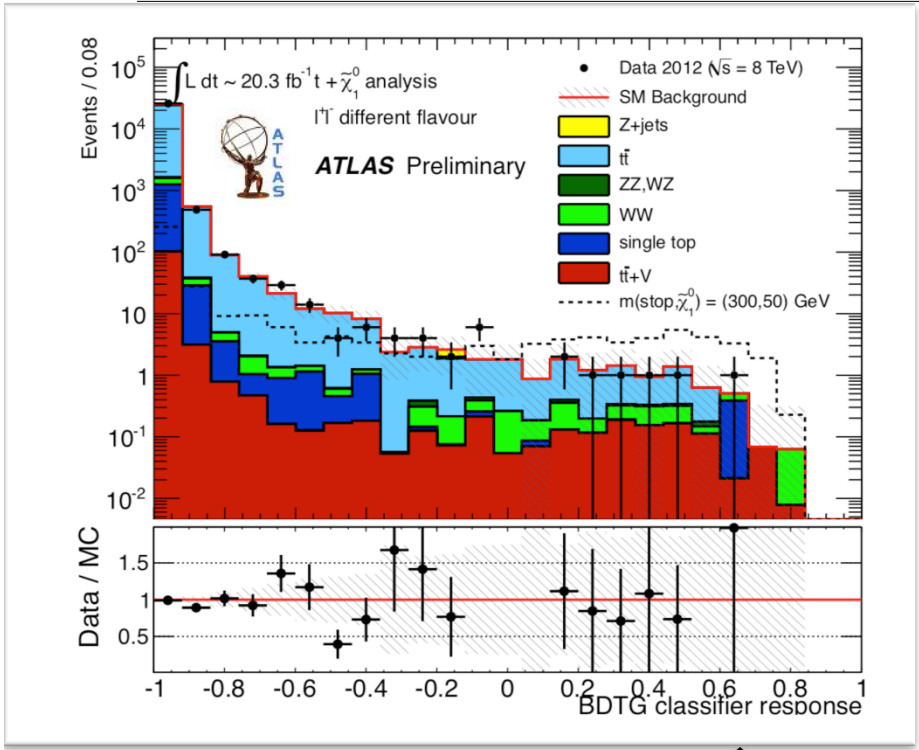
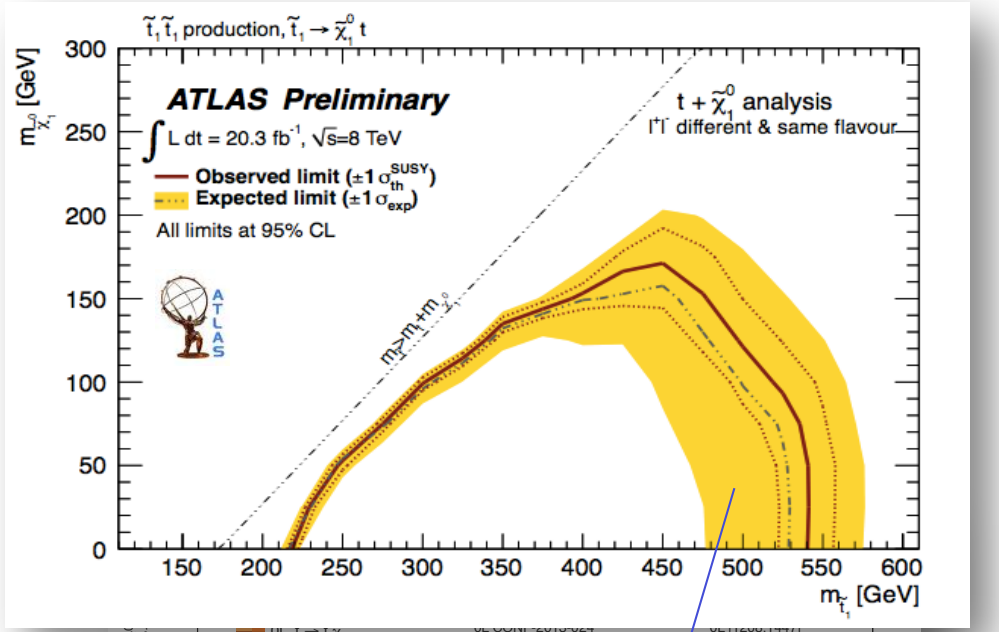
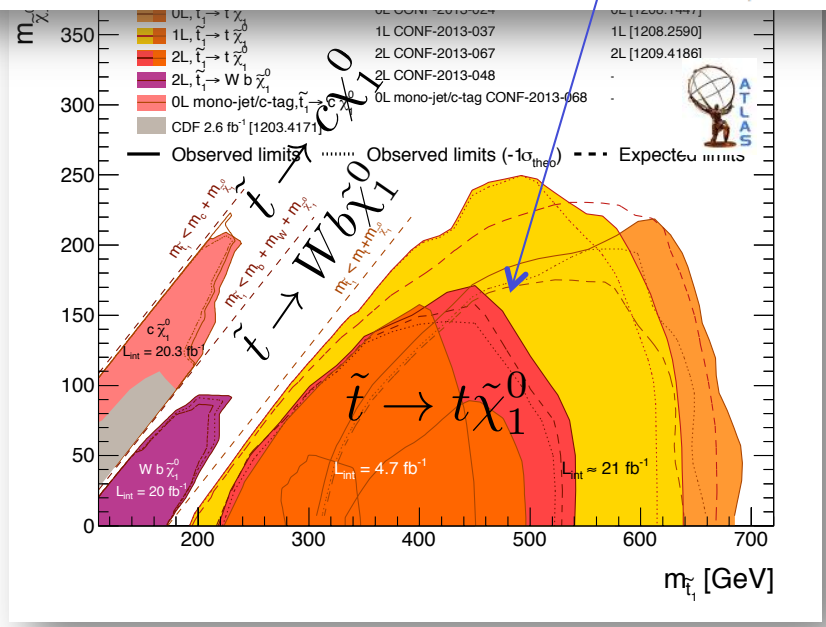
Dedicated searches for direct stop-pair production



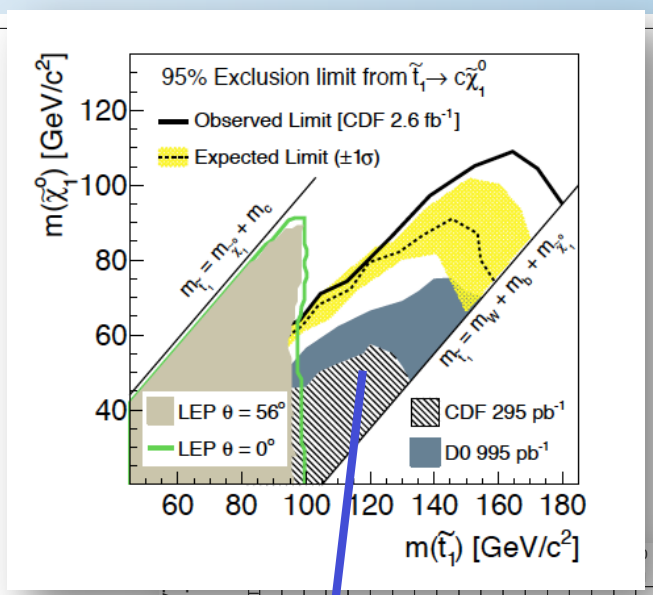




NEW

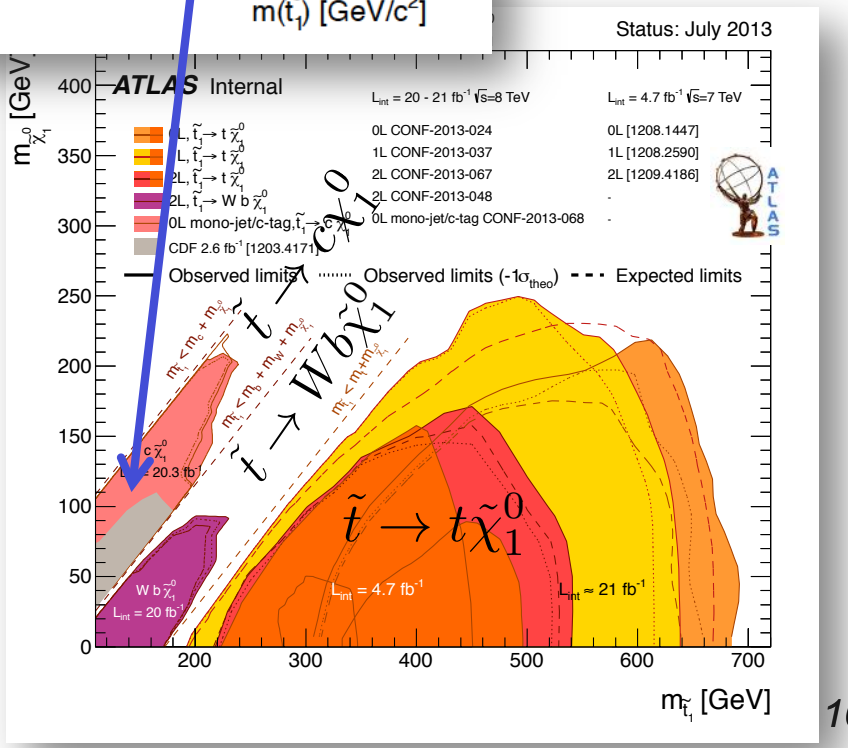
ATLAS-CONF-2013-065:
Scalar stop analysis with two leptons in the final state using a MVA technique.

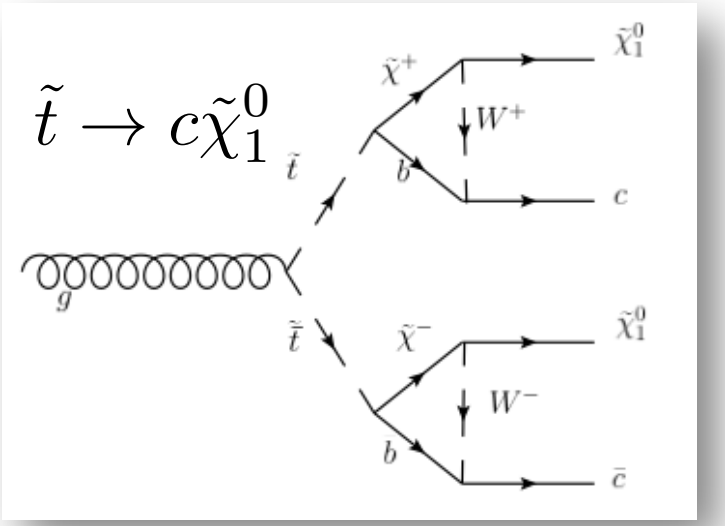
Dedicated searches for direct stop-pair production



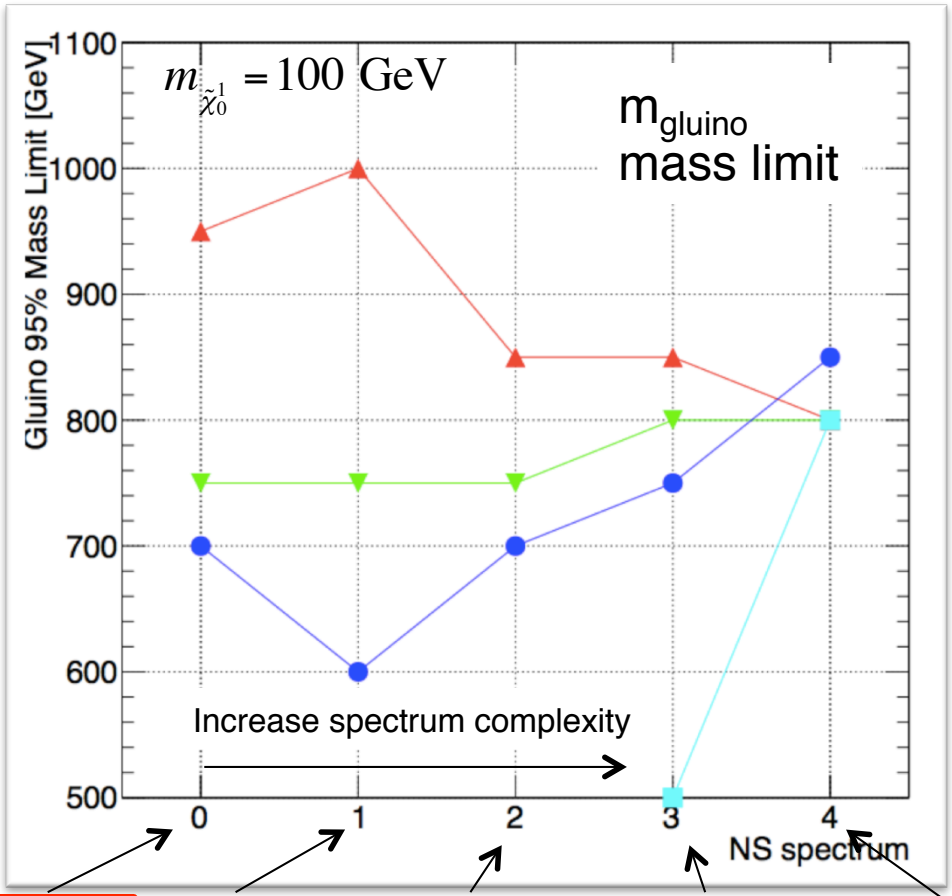
LEP:
LEPSUSY
WG/04-01.1

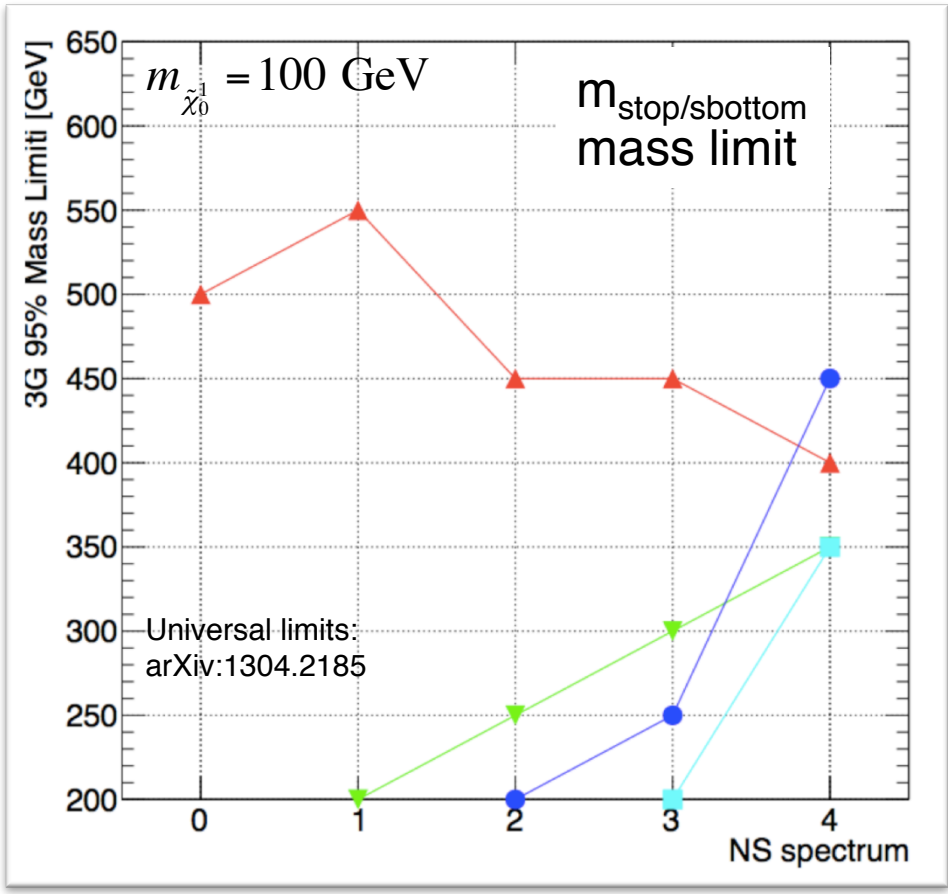
CDF:
1203.4171
D0:
0803.2263





SMS limits: A word of caution!





NS0	NS1	NS2	NS3	NS4
$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$
$\tilde{t_1}, \tilde{t_2}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}, \tilde{b_2}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}, \tilde{b_2}$
		$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$
		$\tilde{\chi}^{\pm}$	$\tilde{\chi}^{\pm}$	$\tilde{\chi}^{\pm}, \tilde{\ell}_{L,R}$
$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$

Used inclusive searches from 2011:

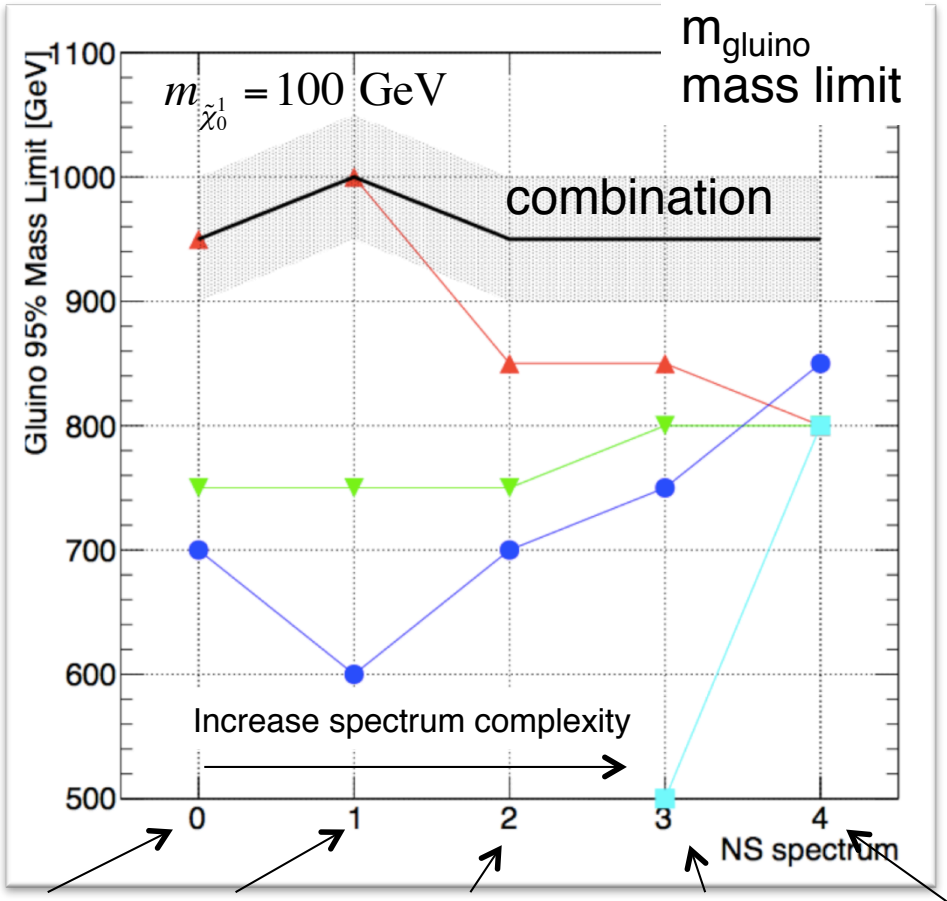
0-Lepton CMS-SUS-11-022

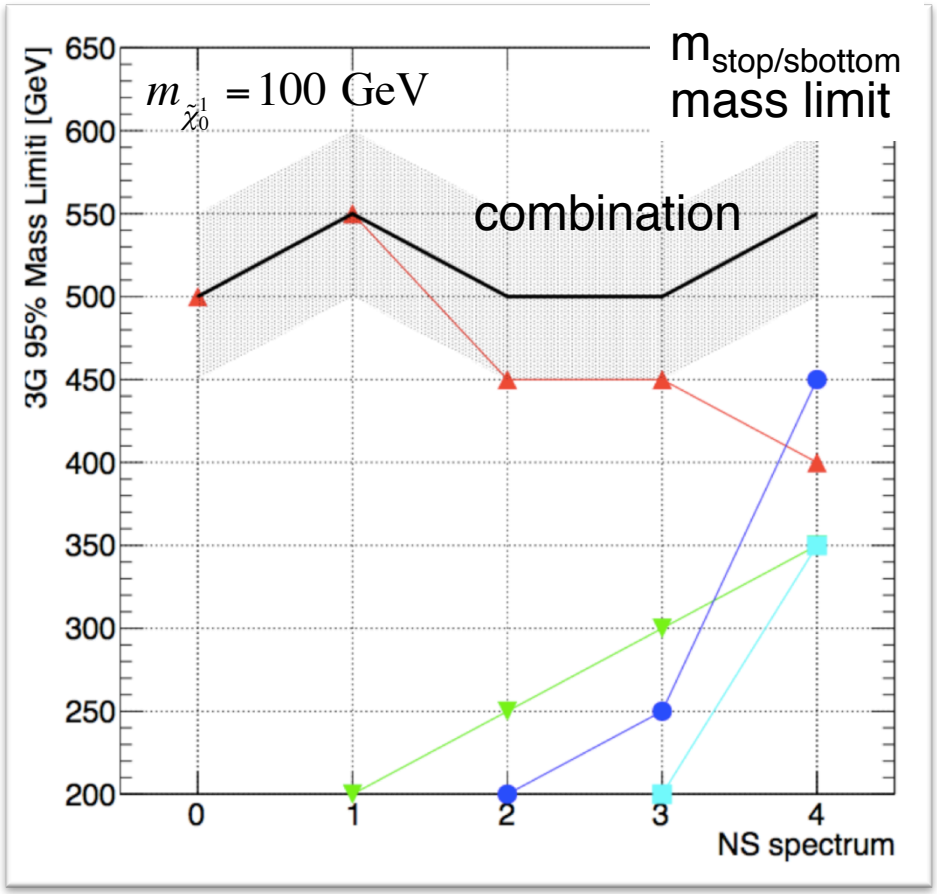
1-Lepton CMS-SUS-12-010

2-Lepton SS CMS-SUS-11-010

2-Lelpton OS CMS-SUS-11-011

Combining Searches = less model dependence





NS0	NS1	NS2	NS3	NS4
$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$
$\tilde{t_1}, \tilde{t_2}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}, \tilde{b_2}$	$\tilde{t_1}, \tilde{t_2}, \tilde{b_1}, \tilde{b_2}$
		$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$
		$\tilde{\chi}^{\pm}$	$\tilde{\chi}^{\pm}$	$\tilde{\chi}^{\pm}, \tilde{\ell}_{L,R}$
$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$

Used inclusive searches from 2011:

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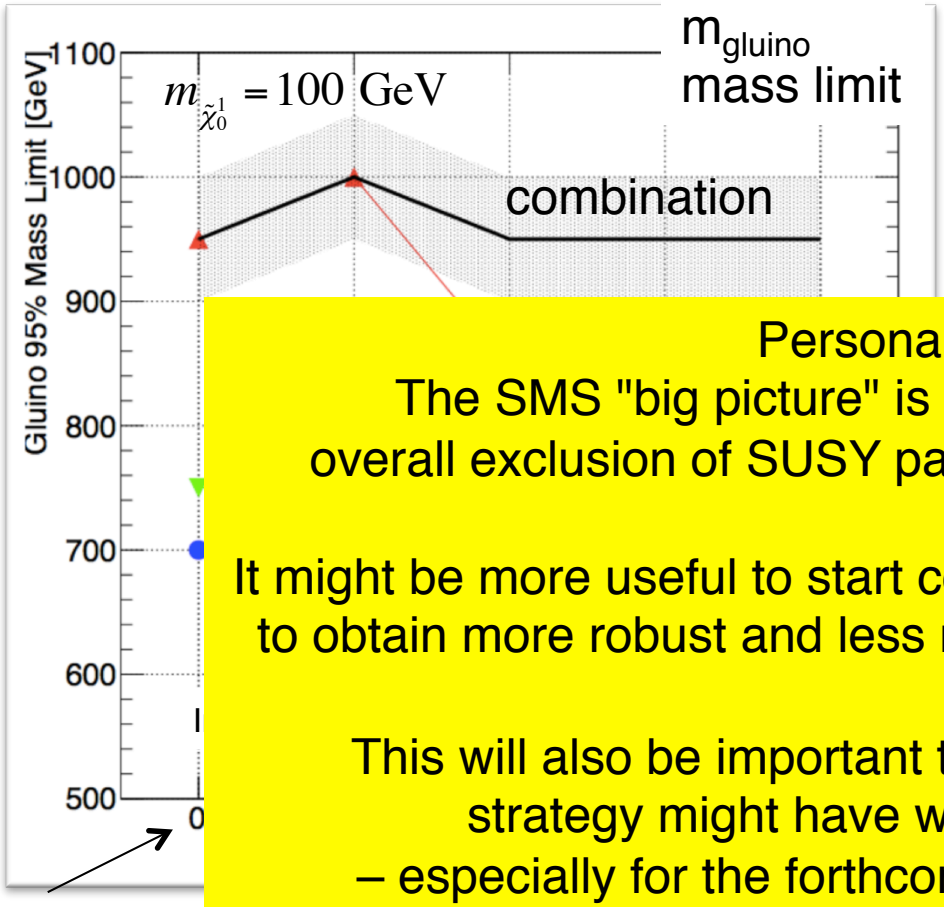
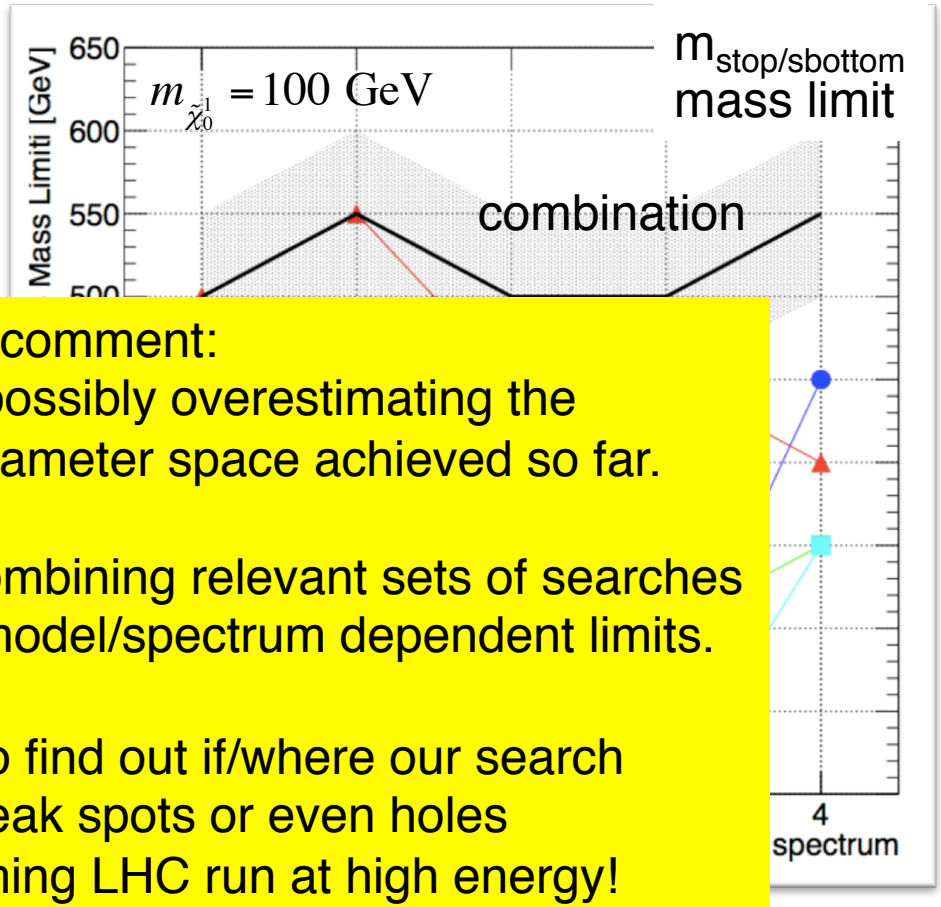


m_{gluino} mass limit



$m_{stop/sbottom}$ mass limit

Personal comment:
The SMS "big picture" is possibly overestimating the overall exclusion of SUSY parameter space achieved so far.

It might be more useful to start combining relevant sets of searches to obtain more robust and less model/spectrum dependent limits.

This will also be important to find out if/where our search strategy might have weak spots or even holes – especially for the forthcoming LHC run at high energy!

NS0				
$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$
$\tilde{t}_1, \tilde{t}_2$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
		$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$
		$\tilde{\chi}^\pm$	$\tilde{\chi}^\pm$	$\tilde{\chi}^\pm, \tilde{\ell}_{L,R}$
$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$

2011:

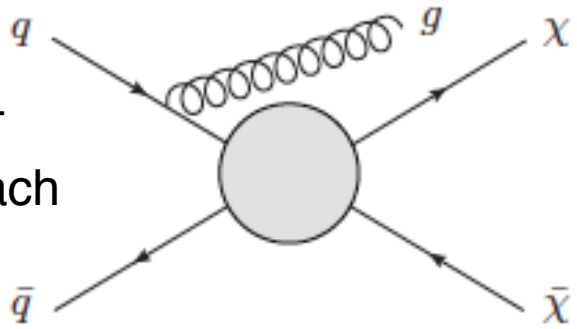
0-Lepton CMS-SUS-11-022
1-Lepton CMS-SUS-12-010
2-Lepton SS CMS-SUS-11-010
2-Lelpton OS CMS-SUS-11-011

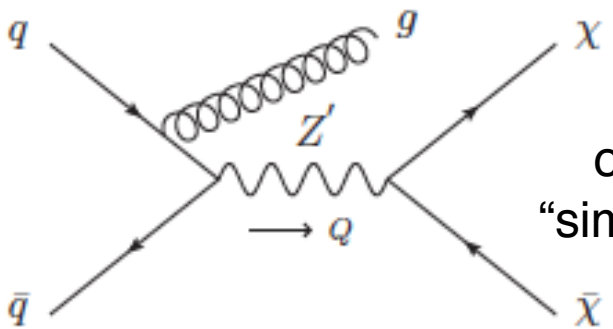
Validity of Effective Field Theory Limits

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

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

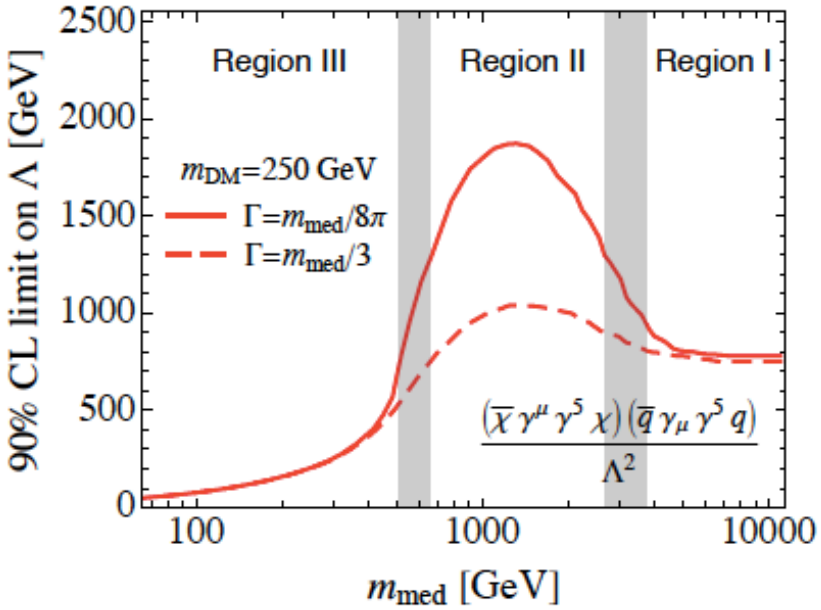
EFT approach





FT
one diagram
"simplified model"

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



Three Regions as function of mediator mass:

Region I: Heavy m_{med}

- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

- EFT limits are too conservative!

Region III: Low m_{med}

- EFT limits are too aggressive!

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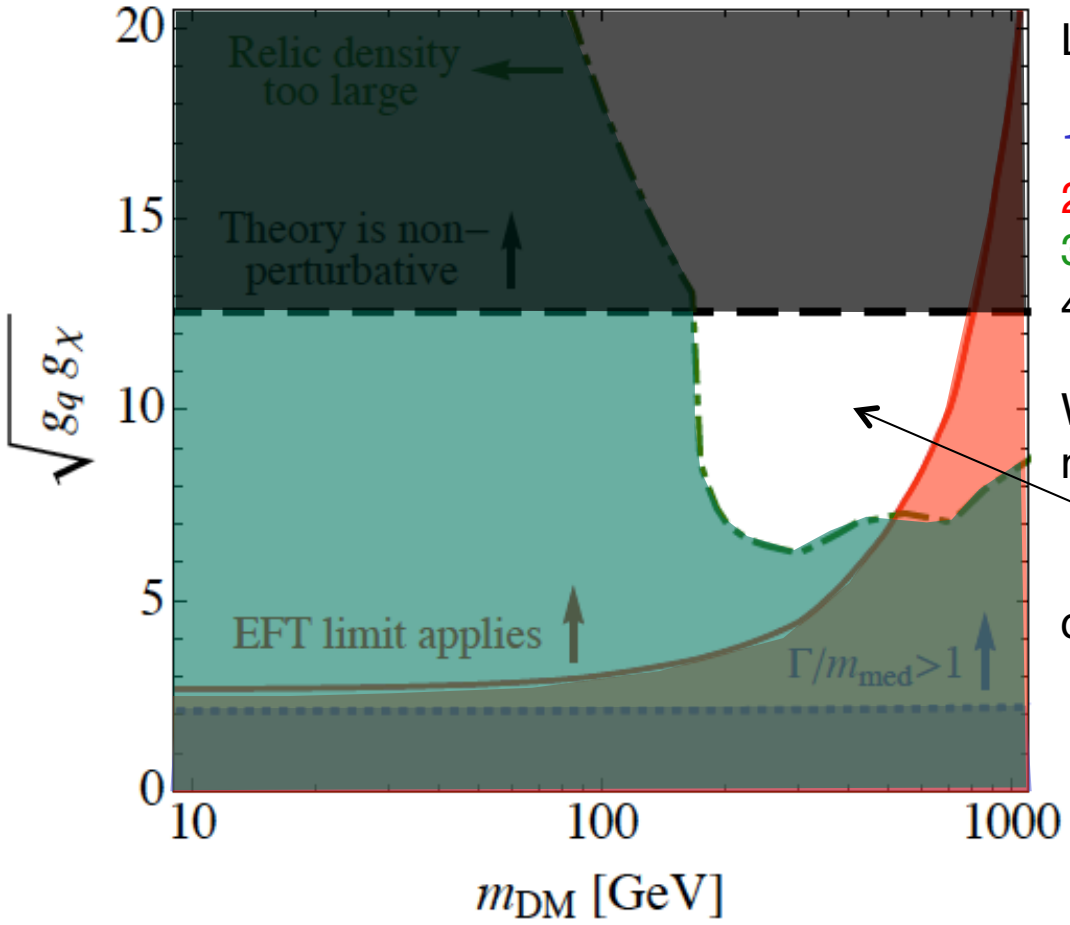
What those this imply on model-dependences of EFT limits?



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:

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

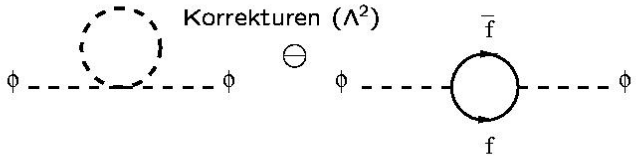
only a very small region is left!

This together with the observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ leads to the conclusion the the EFT only applies to a very (as in VERY) small class of DM models.
EFT limits of monojet searches are therefore highly model-depended!

Why is SUSY so attractive?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

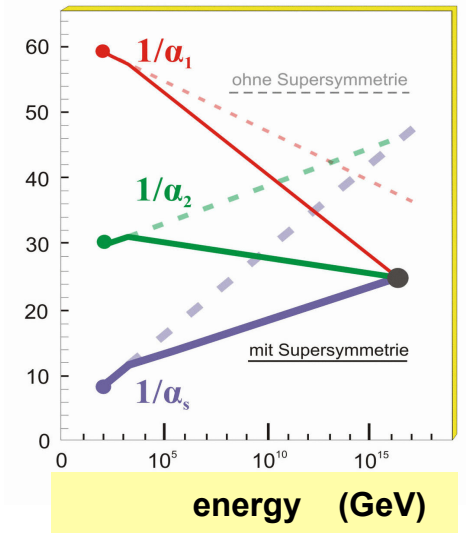
$$\Delta m_H = f(m_B^2 - m_f^2)$$



(Hierarchy or naturalness problem)

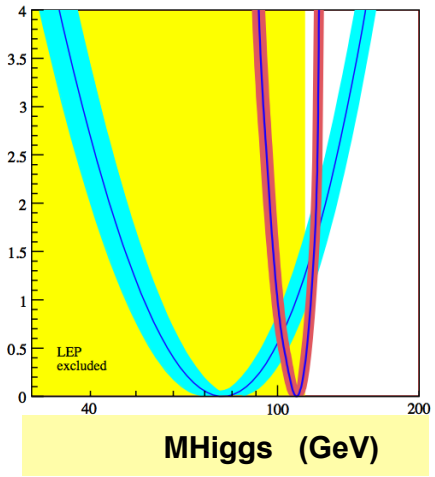
2. Unification of coupling constants of the three interactions seems possible

m_{SUSY} ~ 1 TeV



3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)



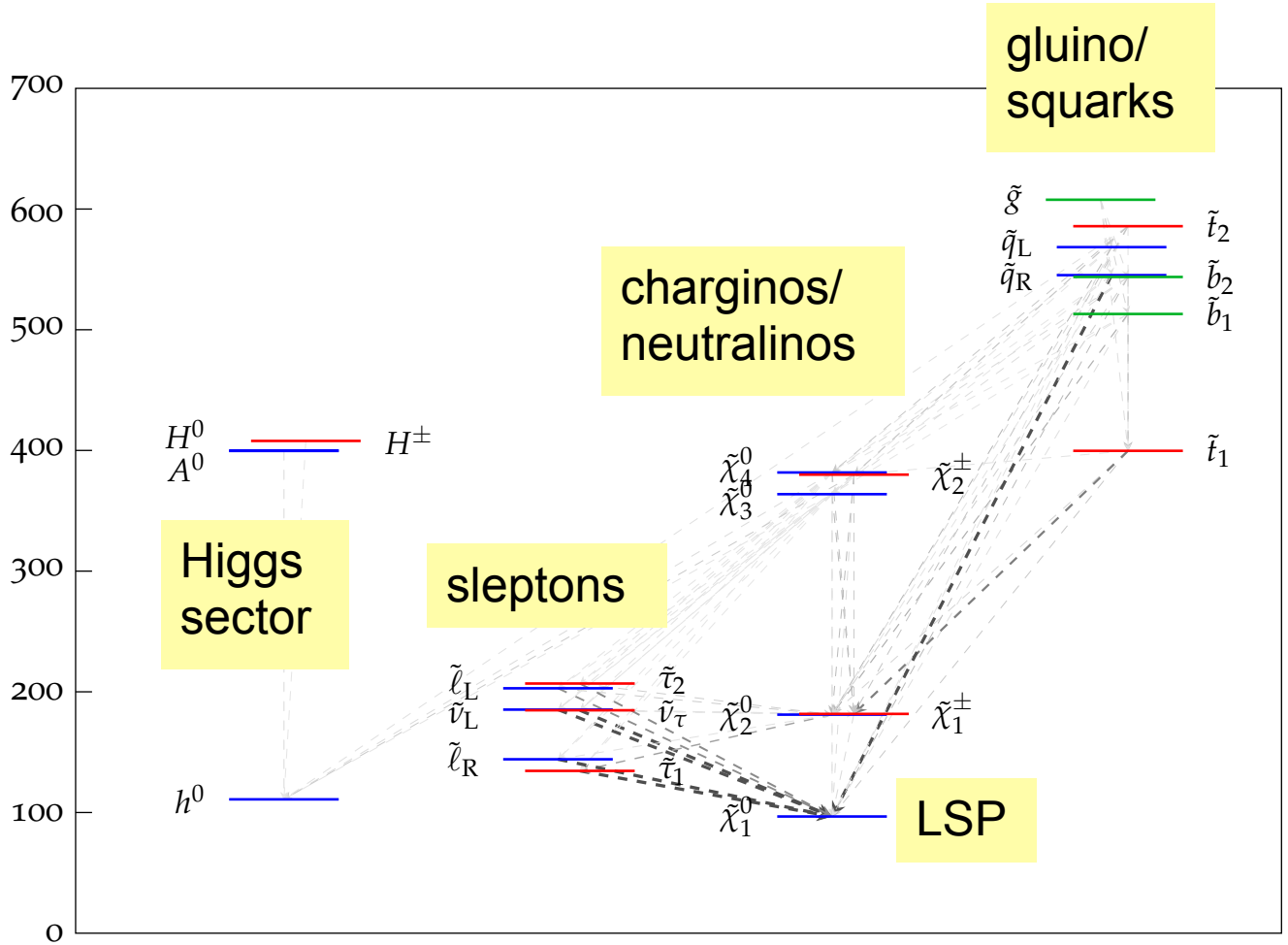
4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

A "typical" SUSY Spectrum

Use the famous SPS1a benchmark point for illustration [m_0=100, m_{12}=250, tanβ=10, A_0=-100, μ>0]

CMSSM

$m_0, m_{1/2}, \tan\beta, A_0, sign(\mu)$



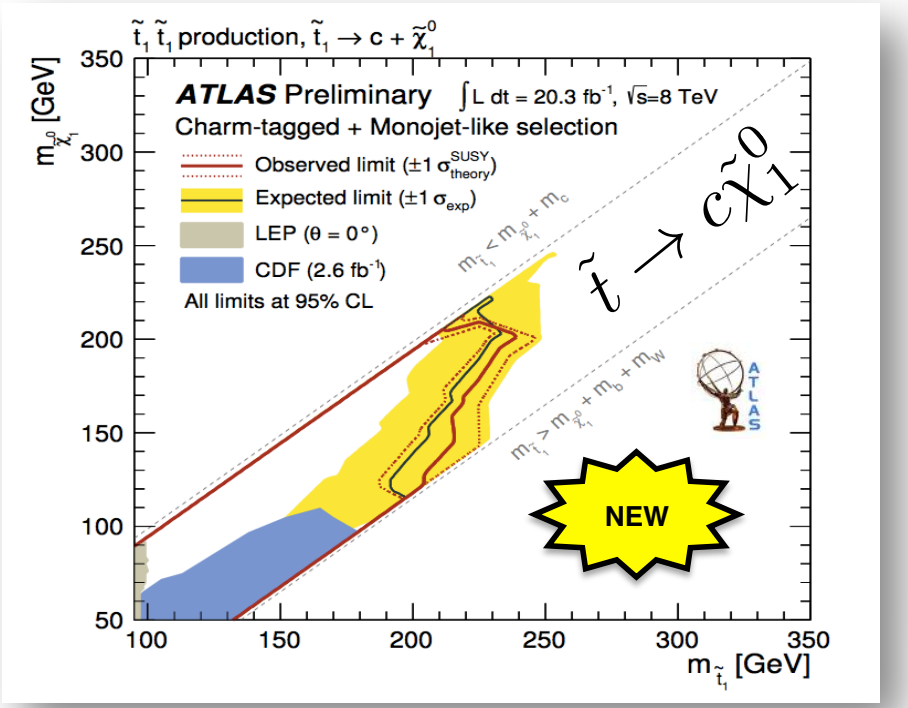
Advantage:

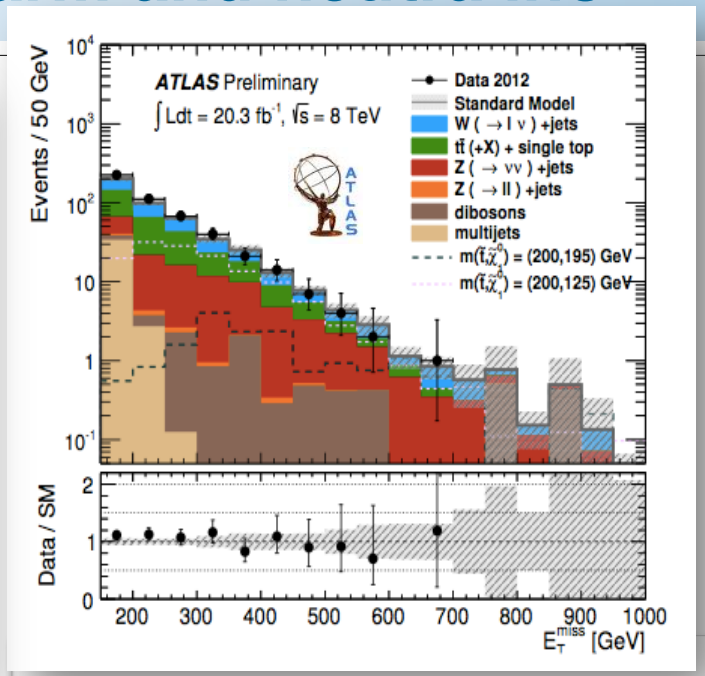
- Only four free parameters (when sign(μ) fixed)
- One of the most studied incarnations of the MSSM

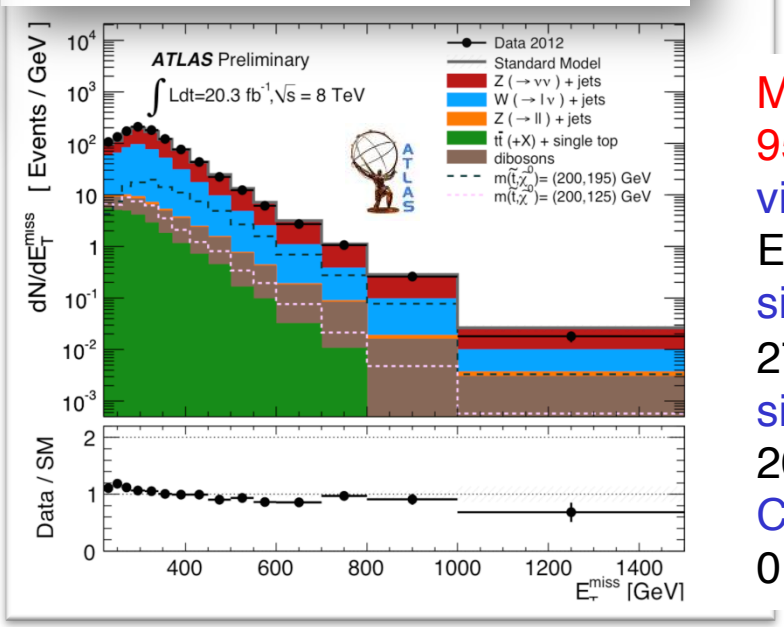
Disadvantage:

- Not generally representative of SUSY (e.g. fixed mass relation between M_{gluion} and M_{LSP})

Stop decay to charm and neutralino







ATLAS-CONF-2013-068:
Two different selections:

- Monojet-like selection

to cover region close to ‘diagonal”

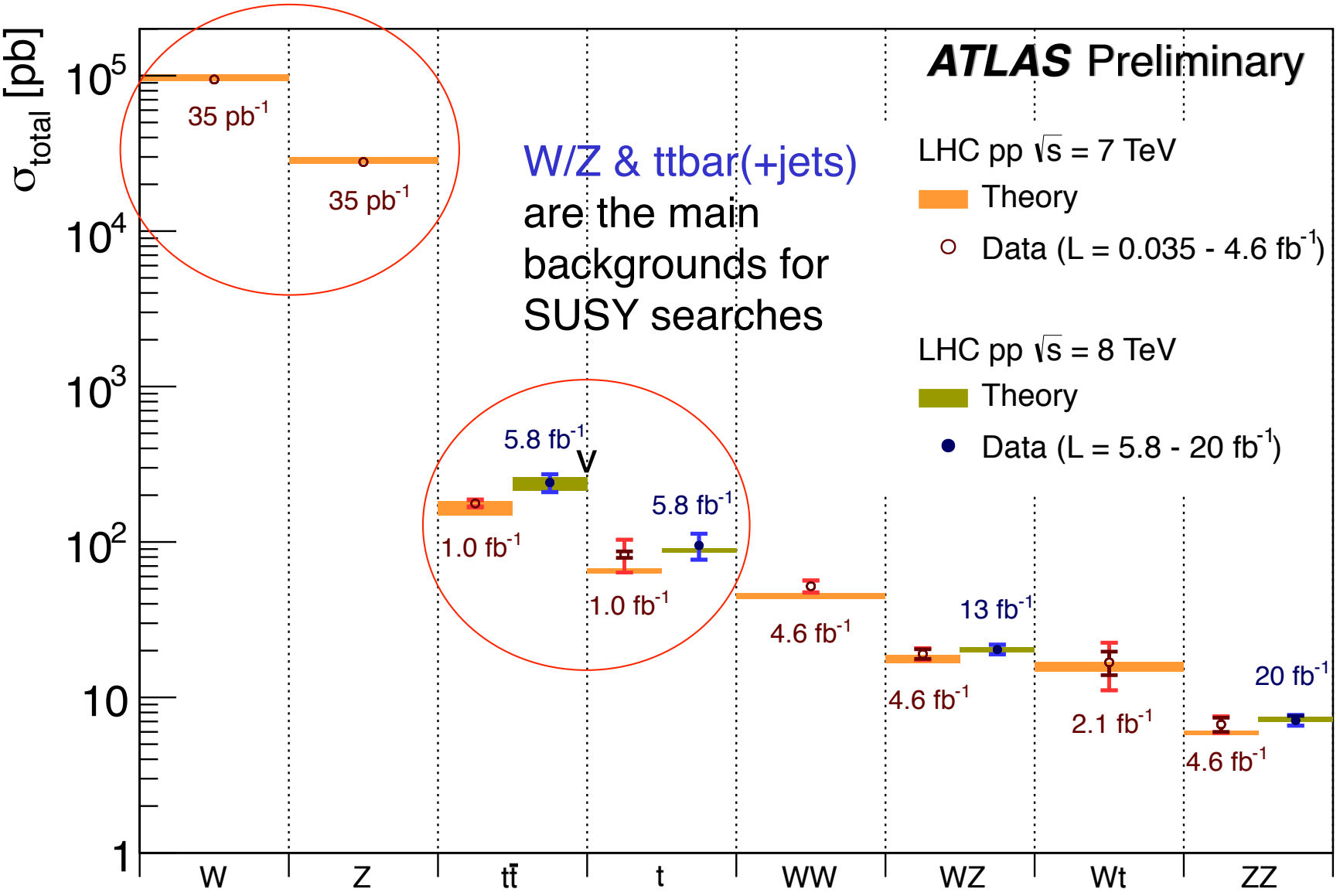
- MVA based c-tag selection

for remaining region

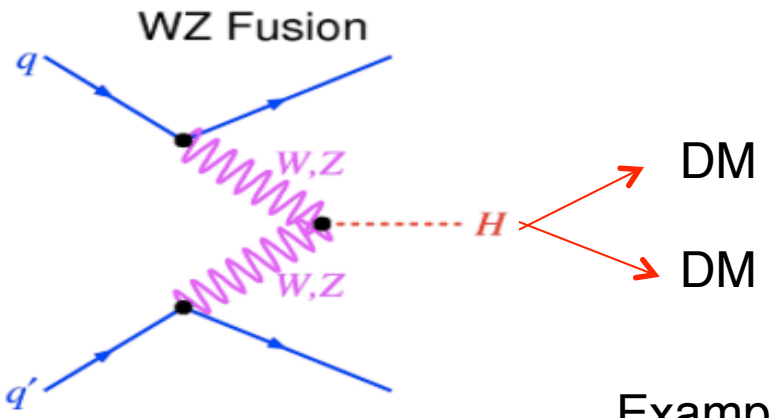
c-Tag:
95% excl. visible XS:
εσ=0.7fb
signal obs:
13 events
signal exp:
14^{+5}_{-4} events
CL_B:
0.45

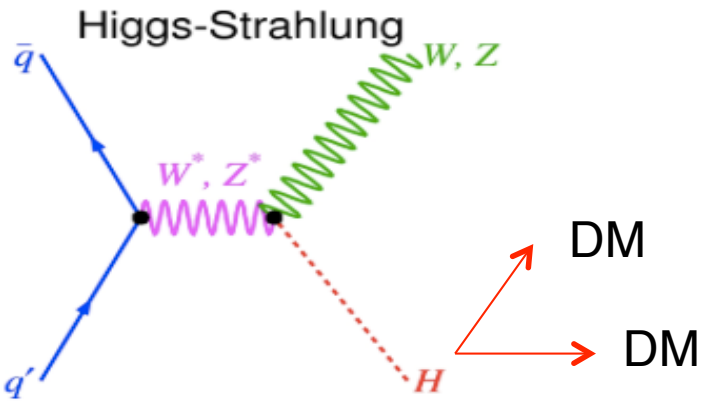
Monojet
95% excl. visible XS:
Eσ=136fb
signal obs:
2770 events
signal exp:
2060^{+780}_{-560}
CL_B:
0.86

Rediscovery of the SM at a new energy frontier

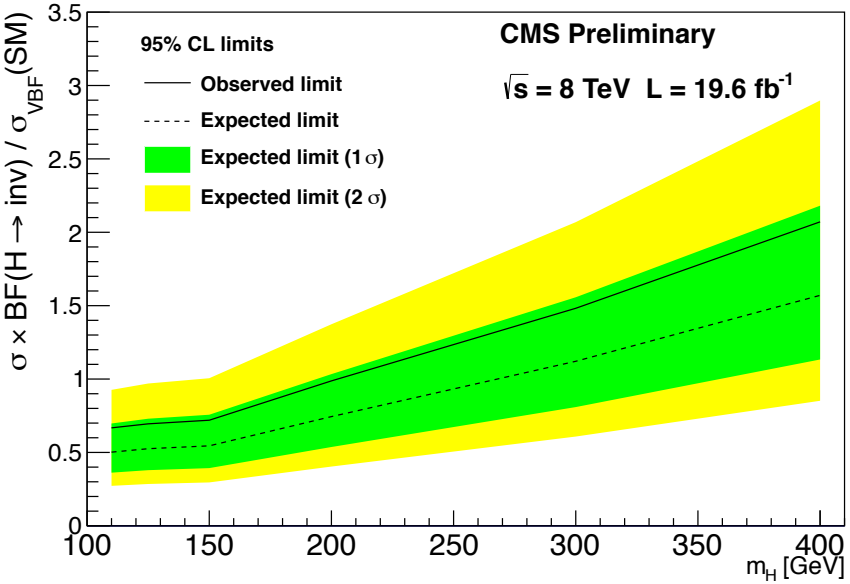


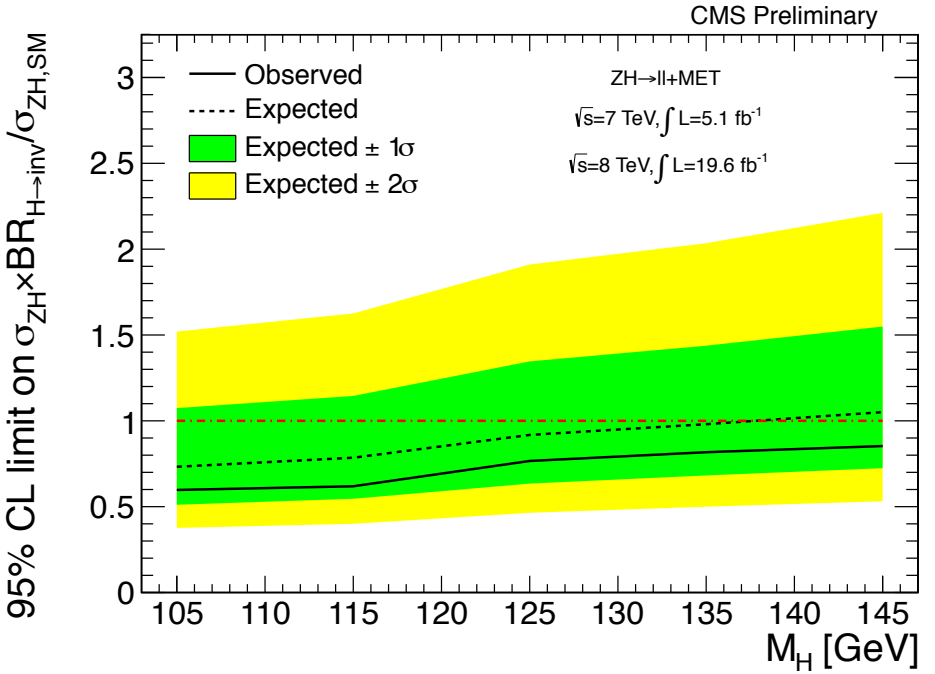
Dark Matter from invisible Higgs searches





Example CMS





BR(H->invisible) < 68% @ 95%CL

BR(H->invisible) < 75% @ 95%CL

Dark Matter from invisible Higgs searches

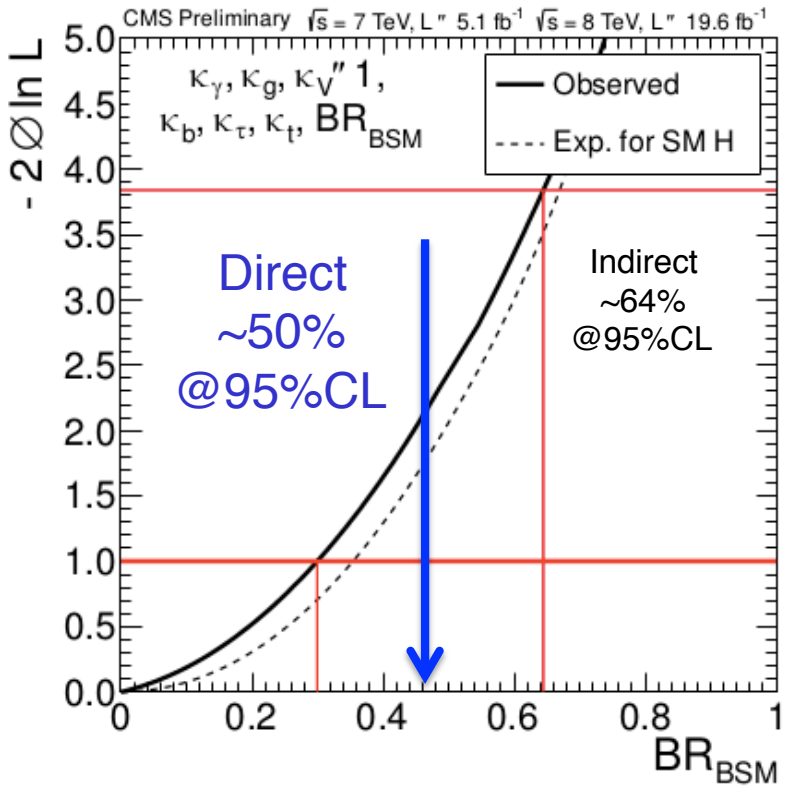
Status 2012 CMS only:

VBF: $BR_{H->invisible} < 68\%$ @ 95%CL

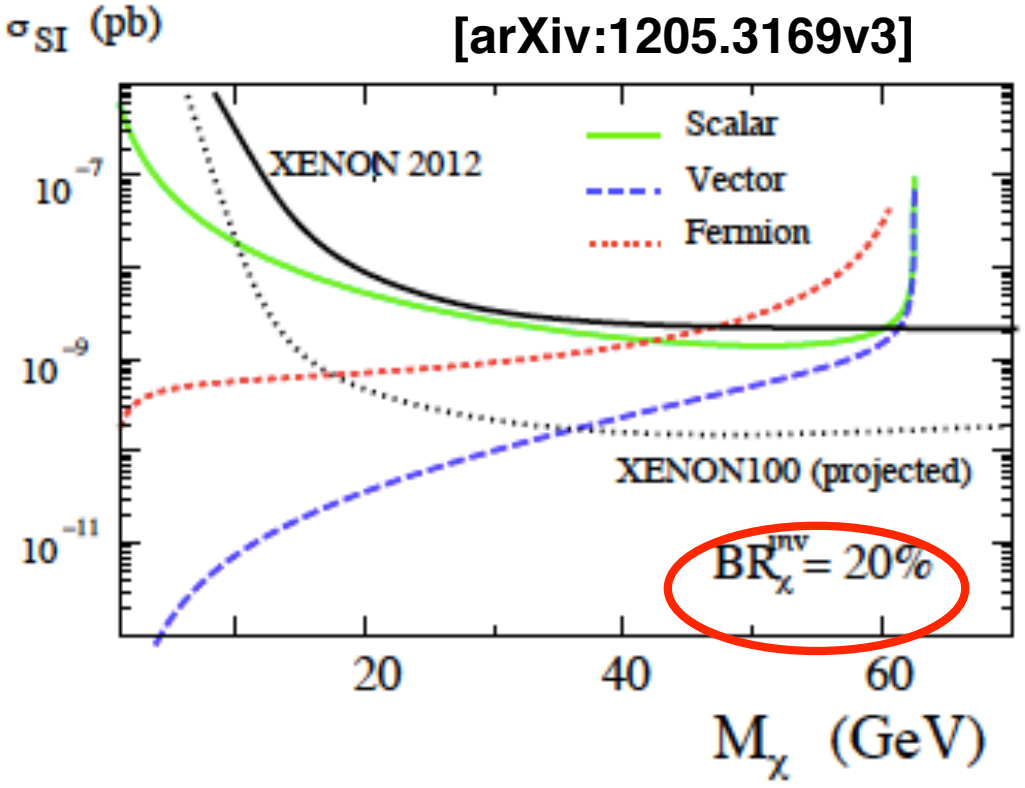
VH: $BR_{H->invisible} < 75\%$ @ 95%CL

Naïve combination: ~ 50% @ 95% CL

$BR_{H->invisible}$ Direct vs Indirect

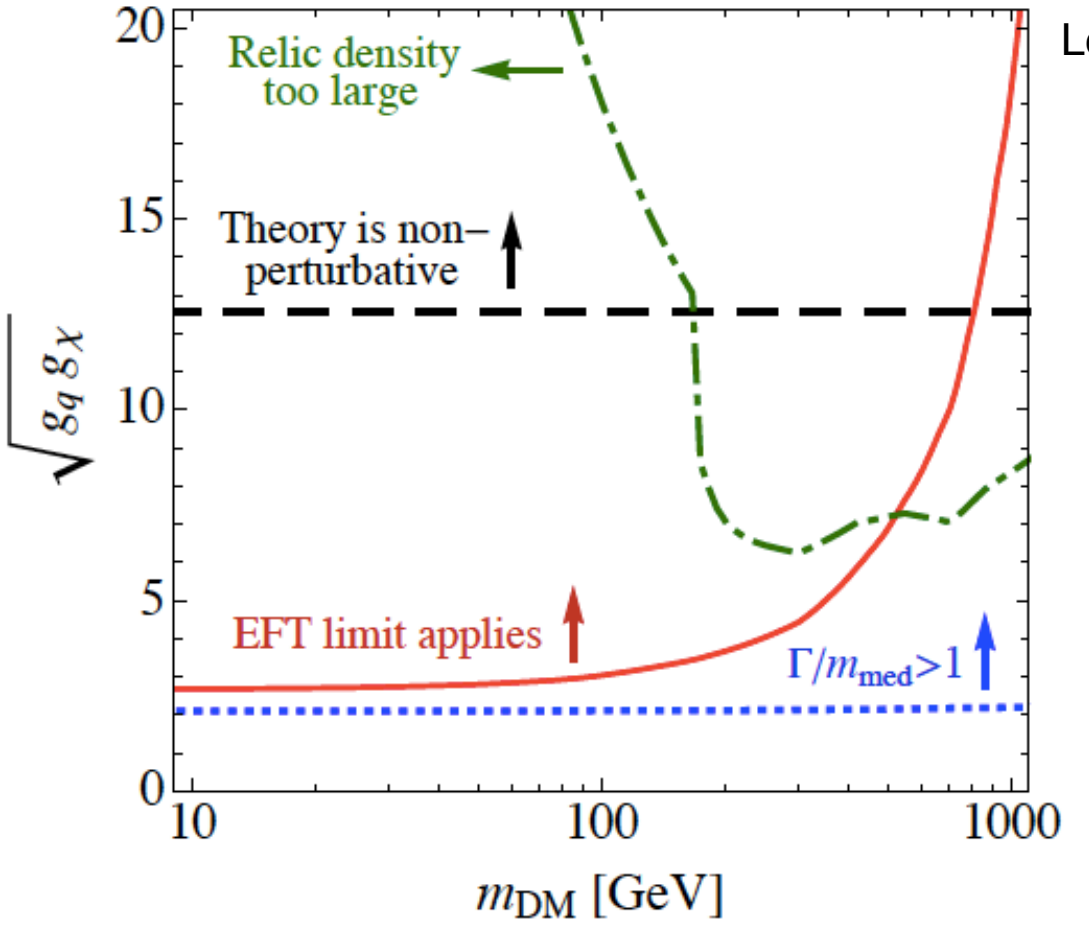


[arXiv:1205.3169v3]



Assuming the experiments are able to maintain trigger and analysis acceptances, the LHC will provide a VERY powerful comparison of indirect & direct measurement of $\Gamma_{H->invisible}$. In the (near) future this might provide a stringent constraint for $M_{DM} < M_H/2$

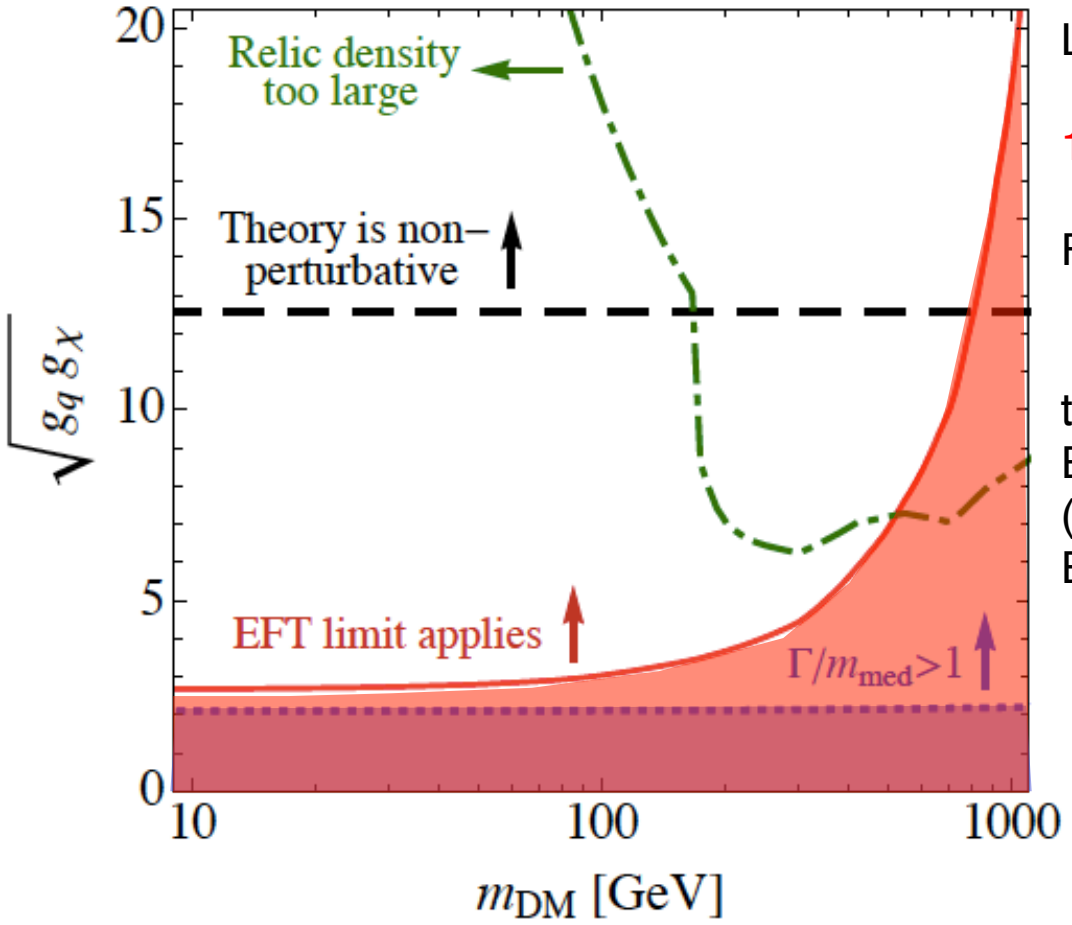
What those this imply on model-dependences of EFT limits?



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

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

Model-dependences of EFT limits



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

1. Region in which EFT is valid

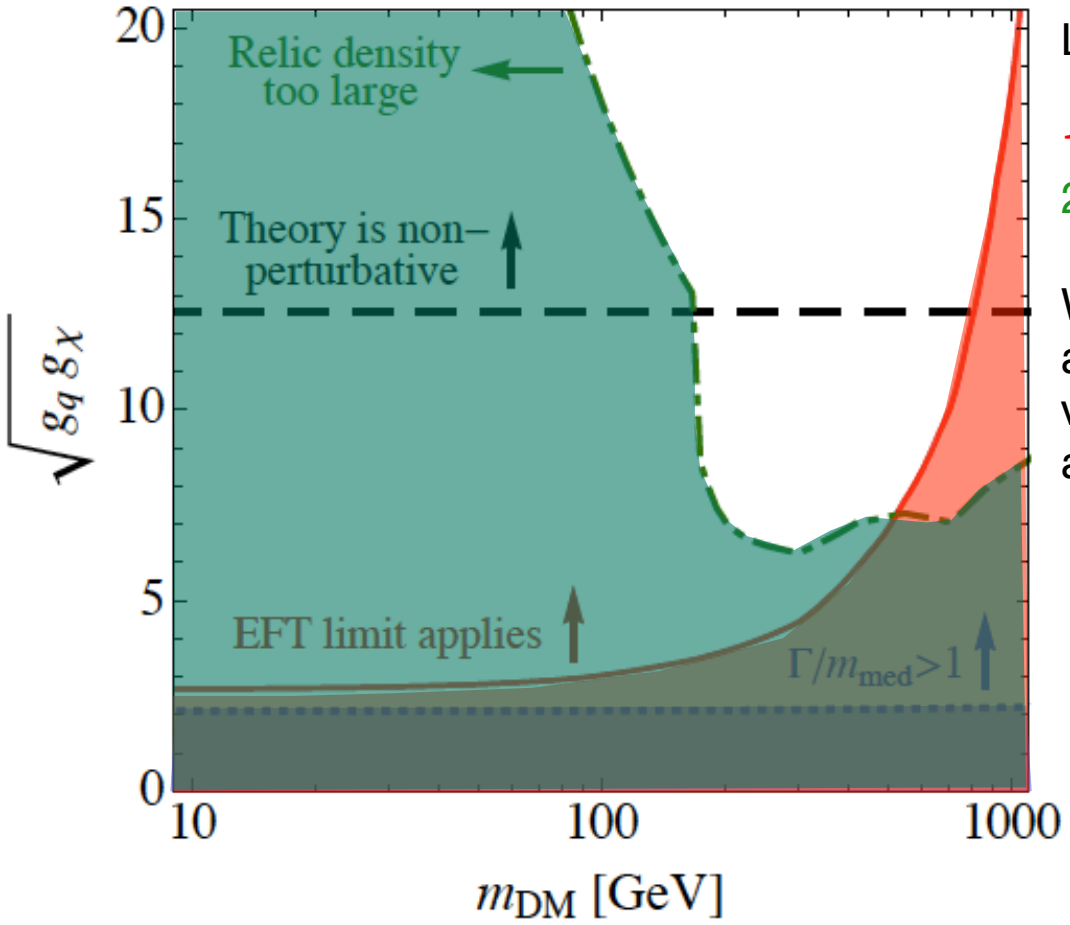
For this we calculate the minimum coupling

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

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

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

Model-dependences of EFT limits



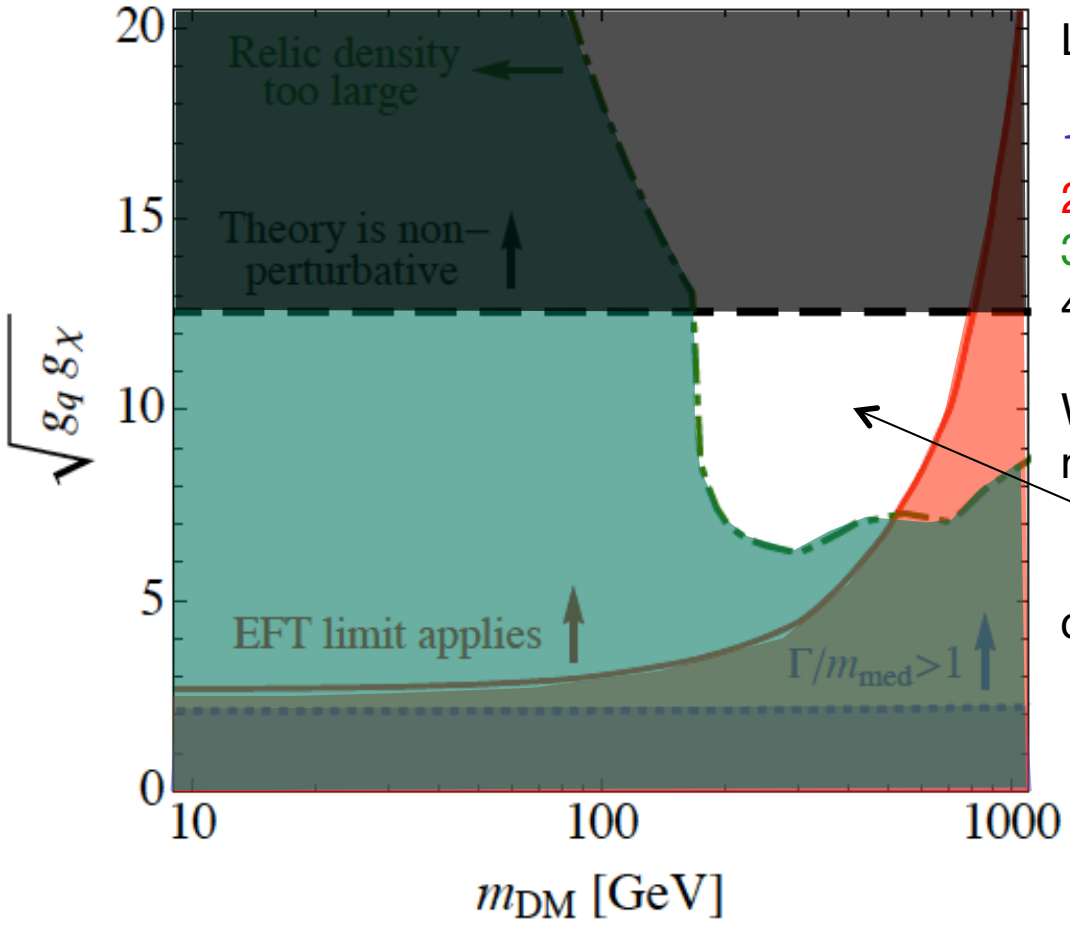
Look at EFT validity in m_{DM} – coupling* plane!

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

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

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

Model-dependences of EFT limits



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

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

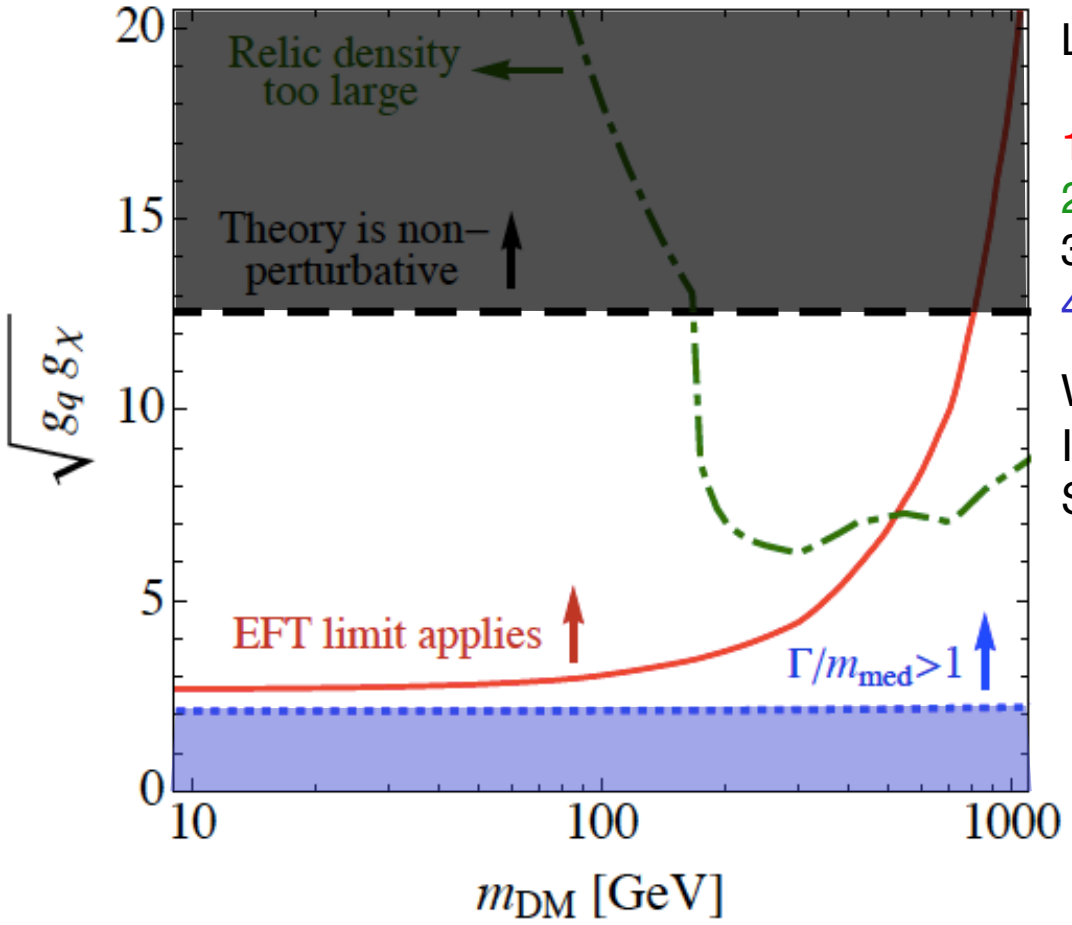
When we also require that the region/theory must be perturbative:

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

only a very small region is left!

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

Model-dependences of EFT limits



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

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

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

In the reaming part of the plot:

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

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

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

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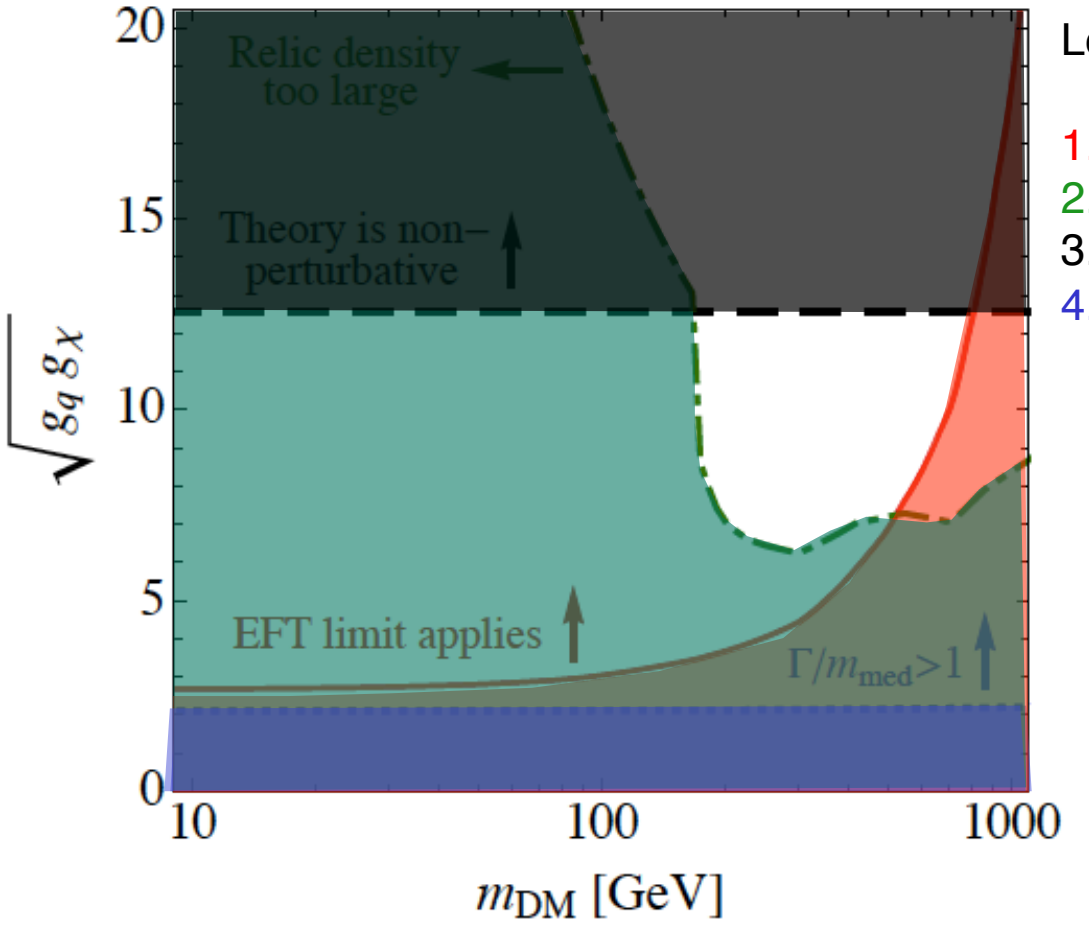
What those this imply on model-dependences of EFT limits?



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

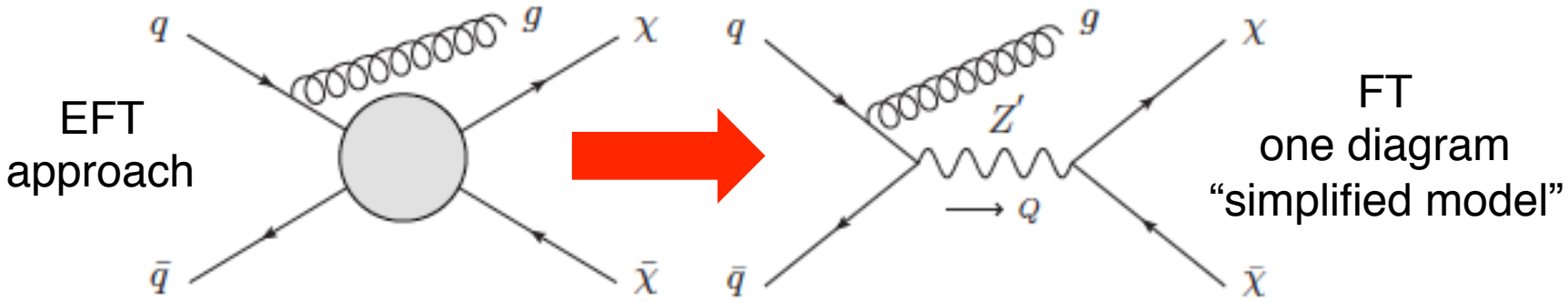
1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

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!

Alternative Interpretation Ansatz: Simplified models

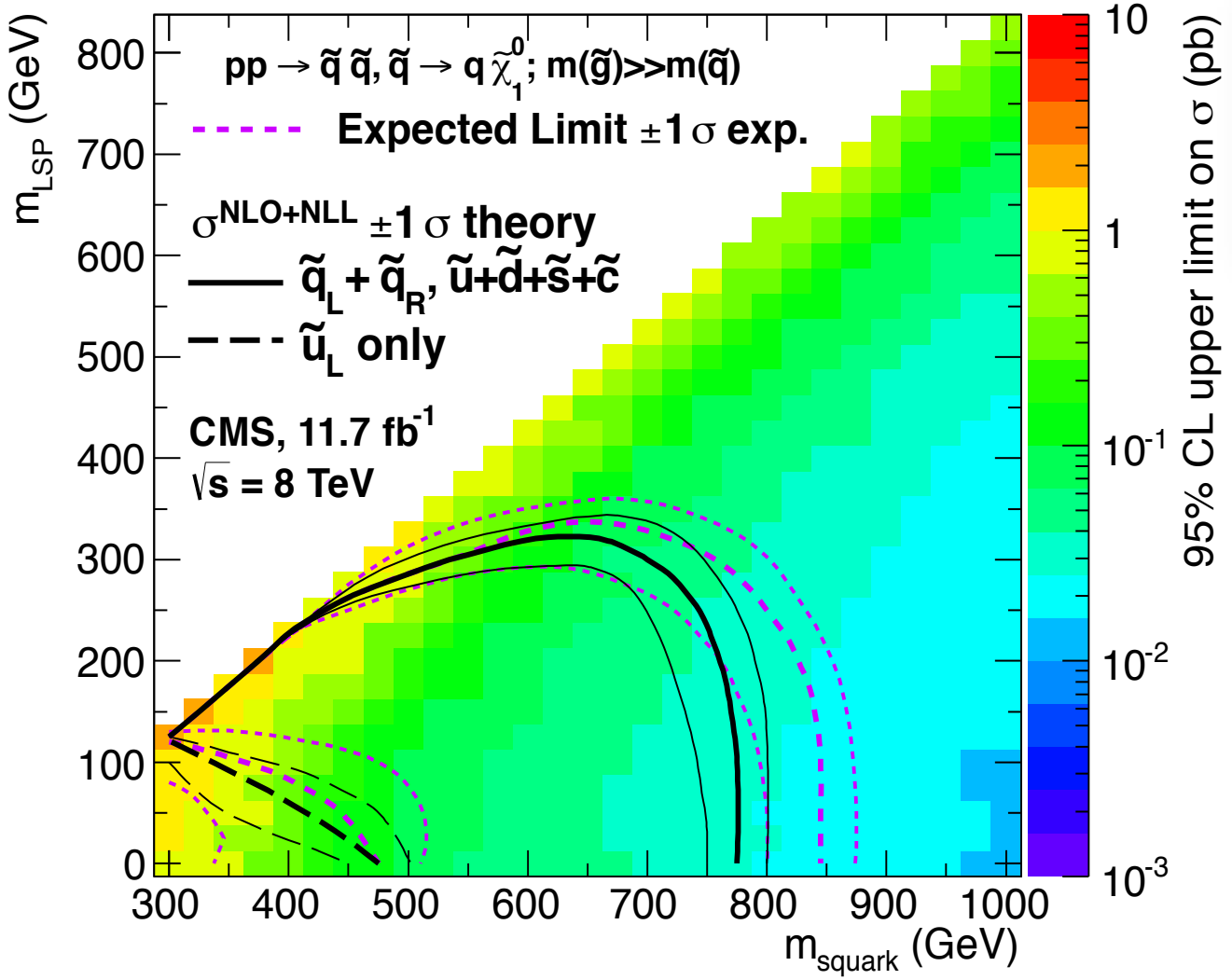
Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

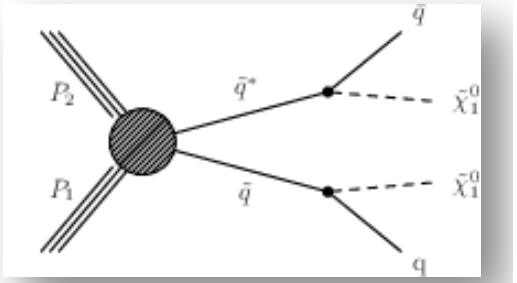
- Compare Effective Field Theory (EFT) with Full Theory (FT)



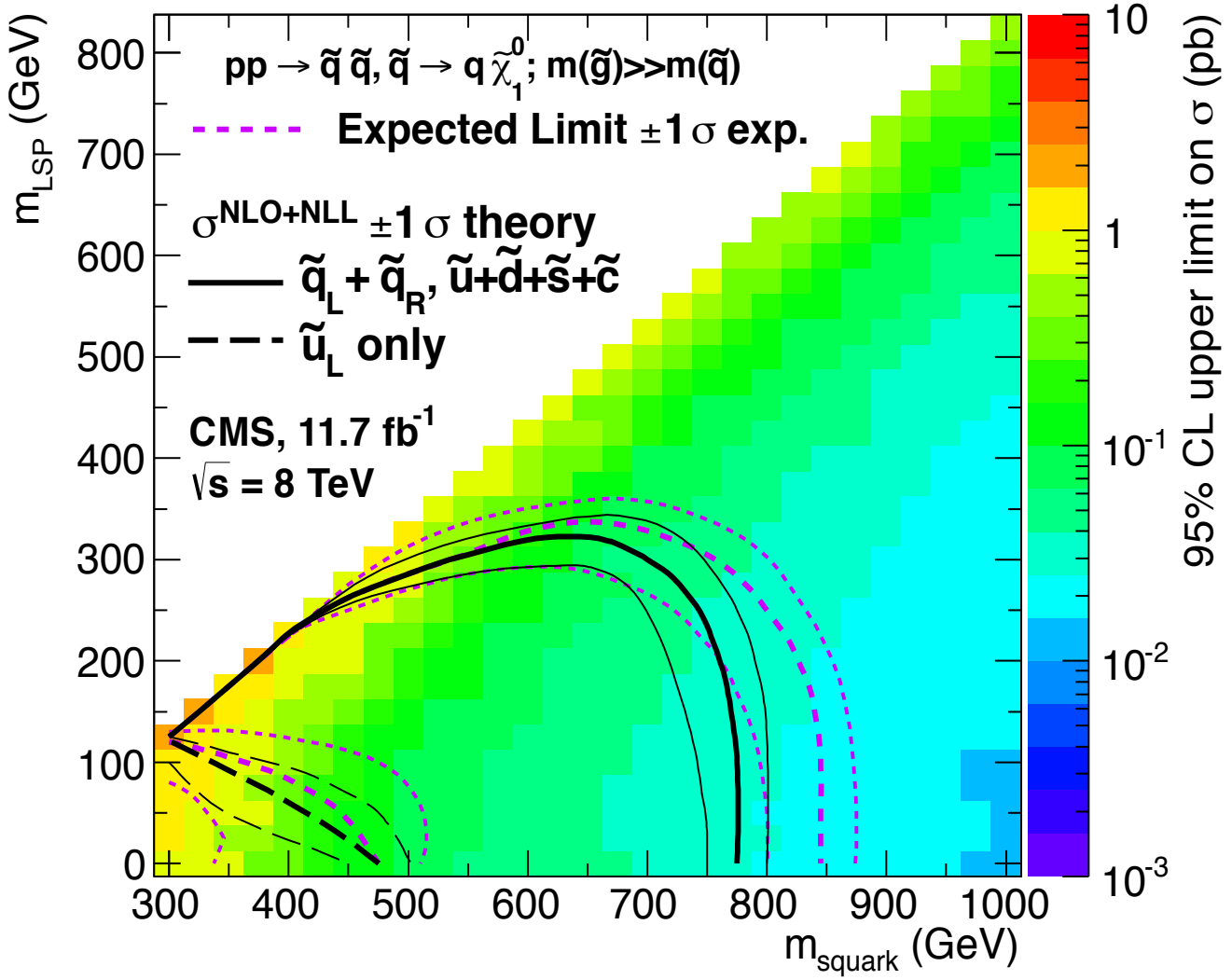
After three years of operation at the LHC the landscape for interpretation of searches has changed dramatically – new superior & modern approaches have replaced in many areas longstanding traditional ones (e.g. SUSY searches)

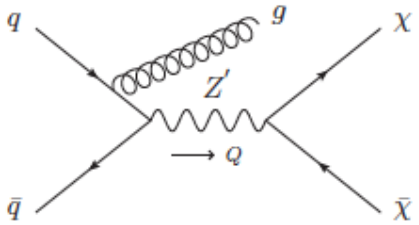
The proposal



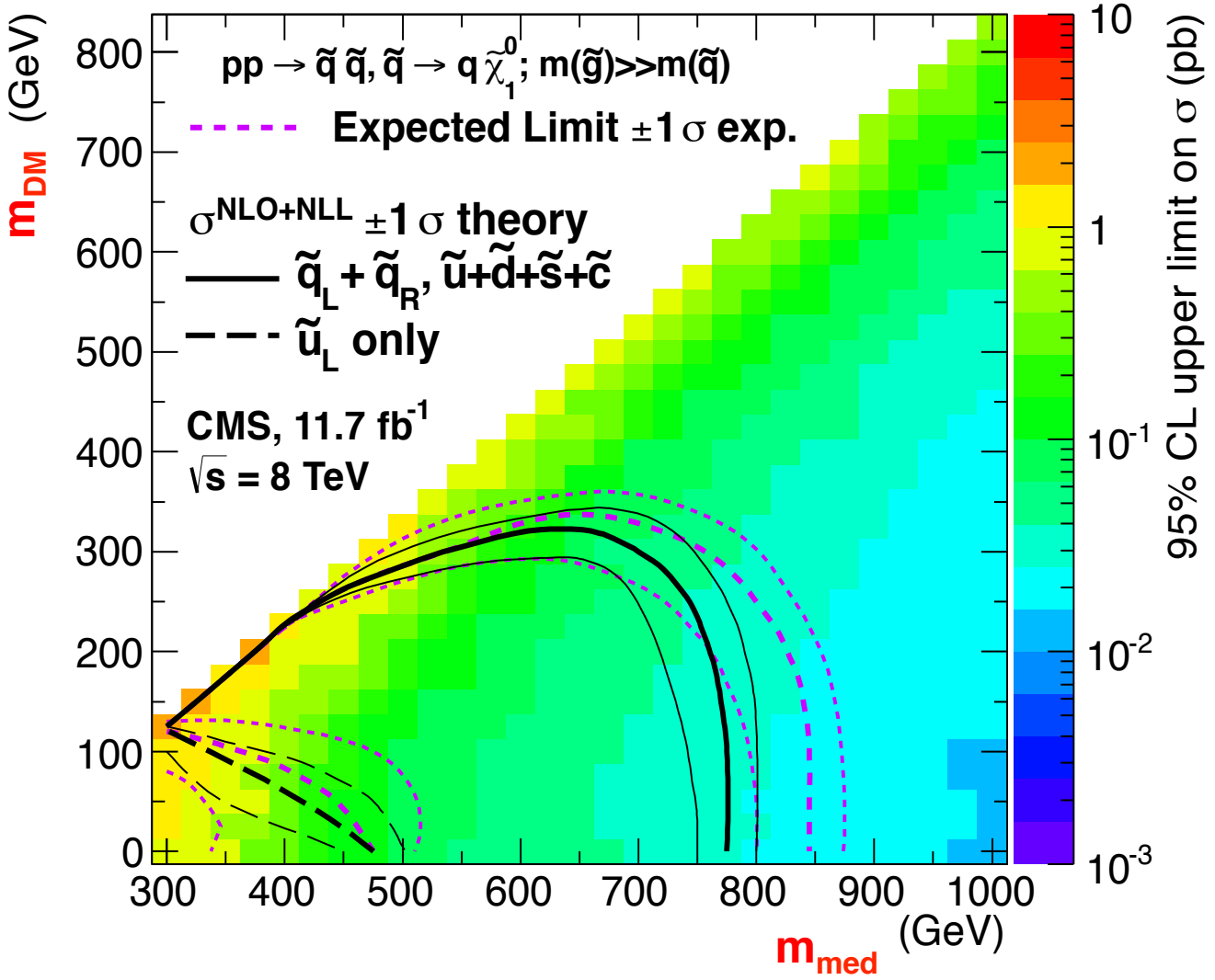


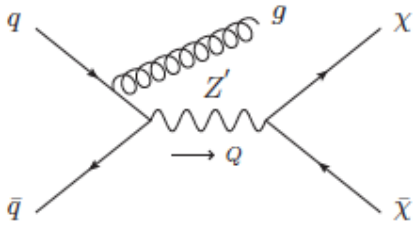
The proposal



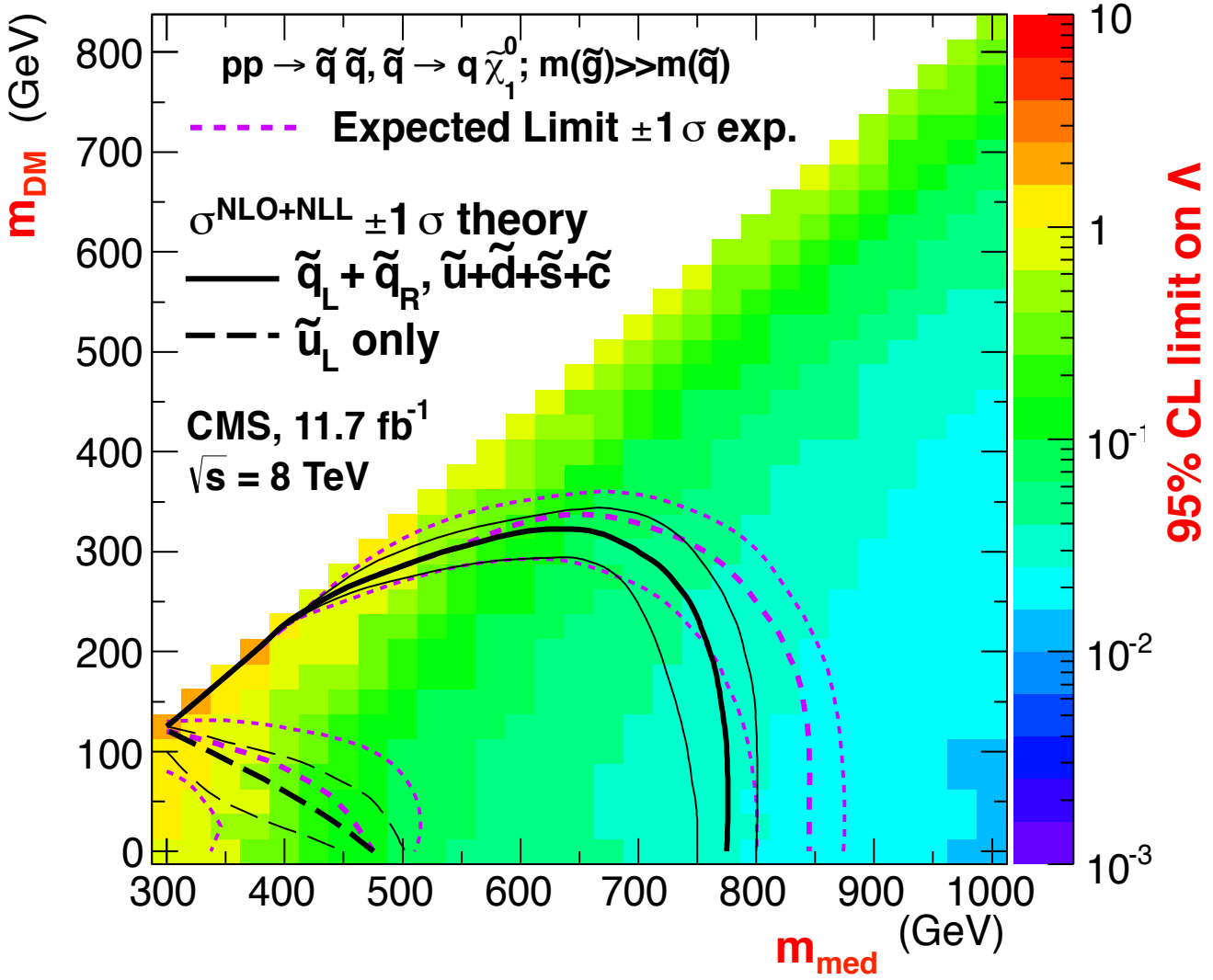


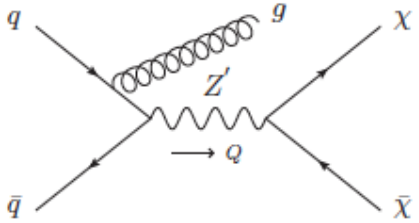
The proposal





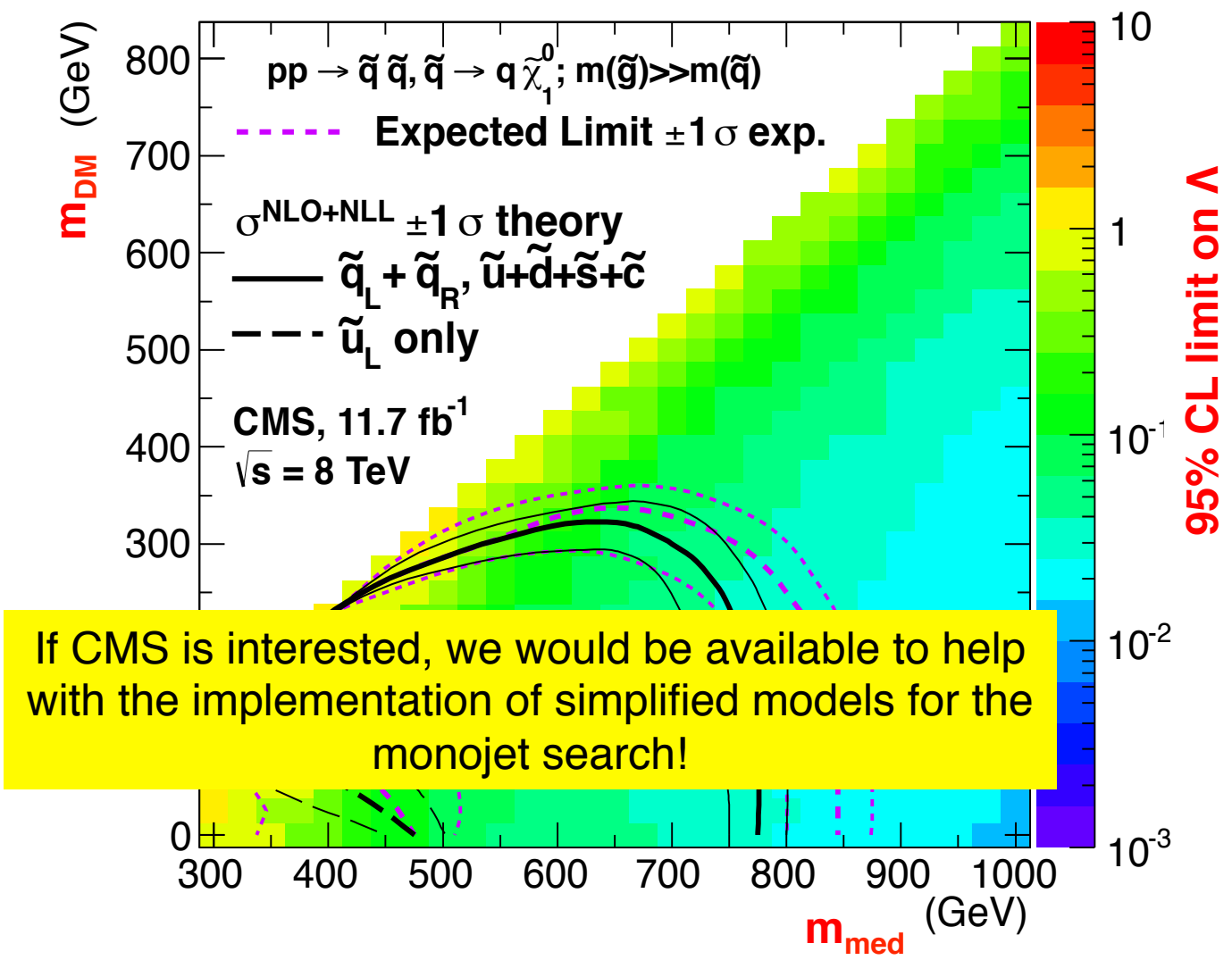
The proposal

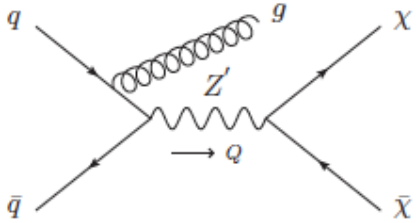




Very similar to limits in SUSY simplified models – m_{med}, m_{DM}, Λ and possibly some variation of Γ_{med} will cover the full problem!

The proposal





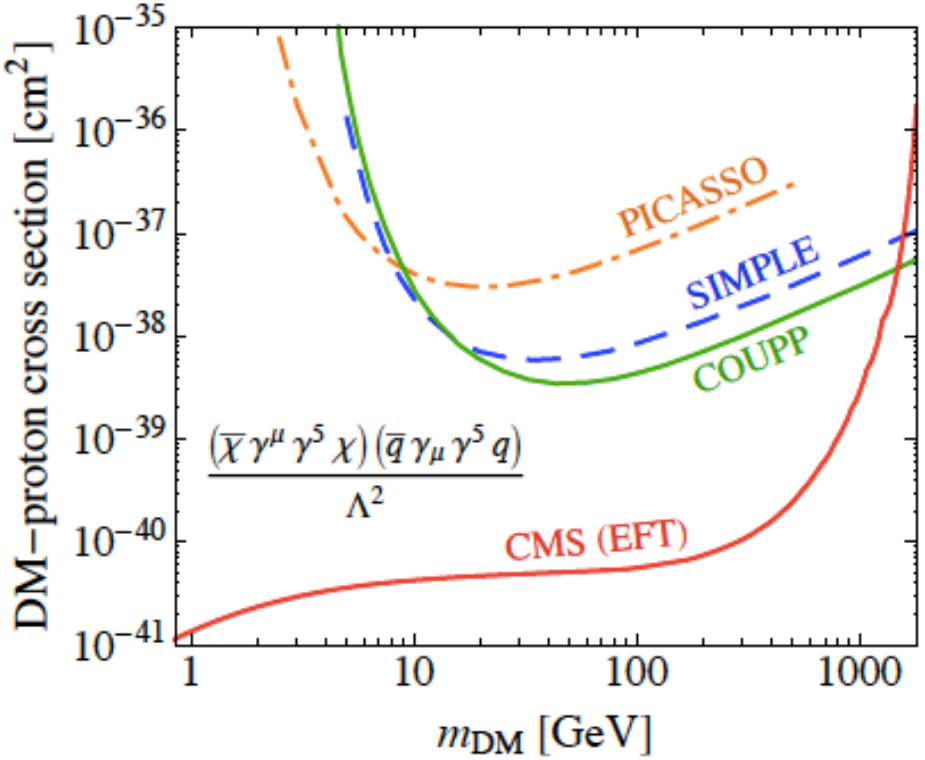
If CMS is interested, we would be available to help with the implementation of simplified models for the monojet search!

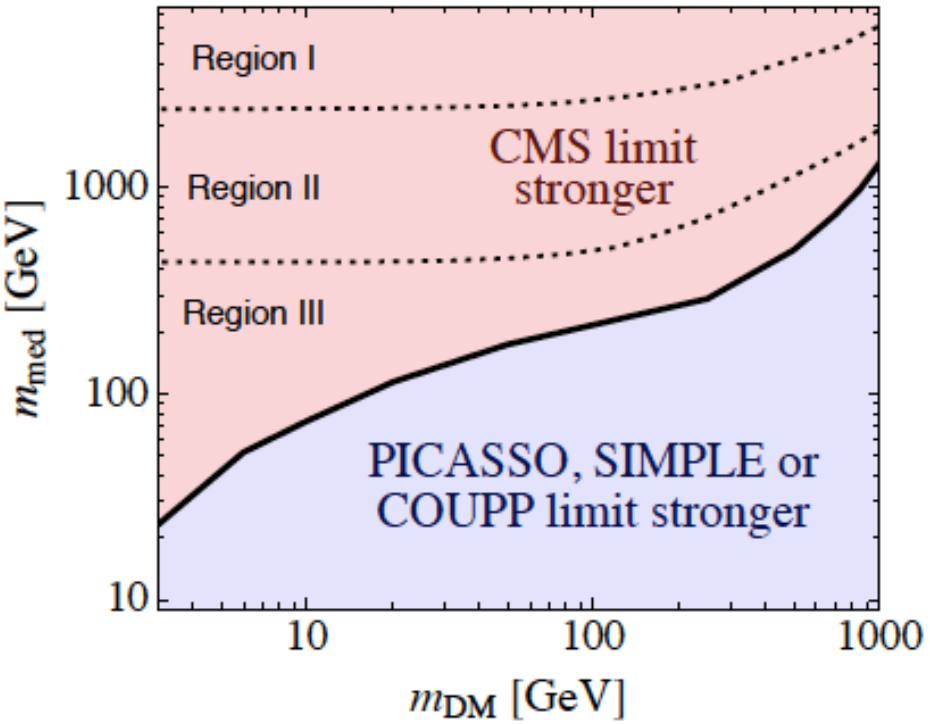
Very similar to limits in SUSY simplified models – m_{med}, m_{DM}, Λ and possibly some variation of Γ_{med} will cover the full problem!

Beyond EFT limits: Simplified models

Buchmüller

Working out the complementarity between direct DM detection experiments and collider based DM searches!





EFT limits give the impression that monsjet searches outperform direct detection BUT EFT only applies a VERY small class of DM models.

Simplified model limits give a much better Account of the REAL complementarity and thus seem superior for a comparison.

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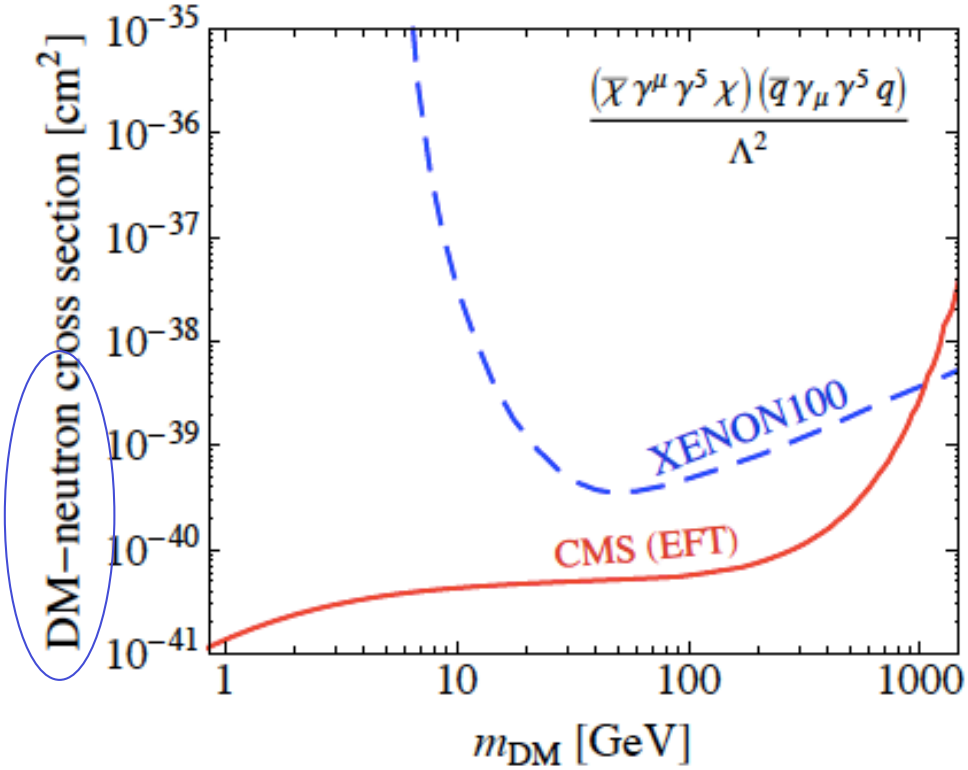

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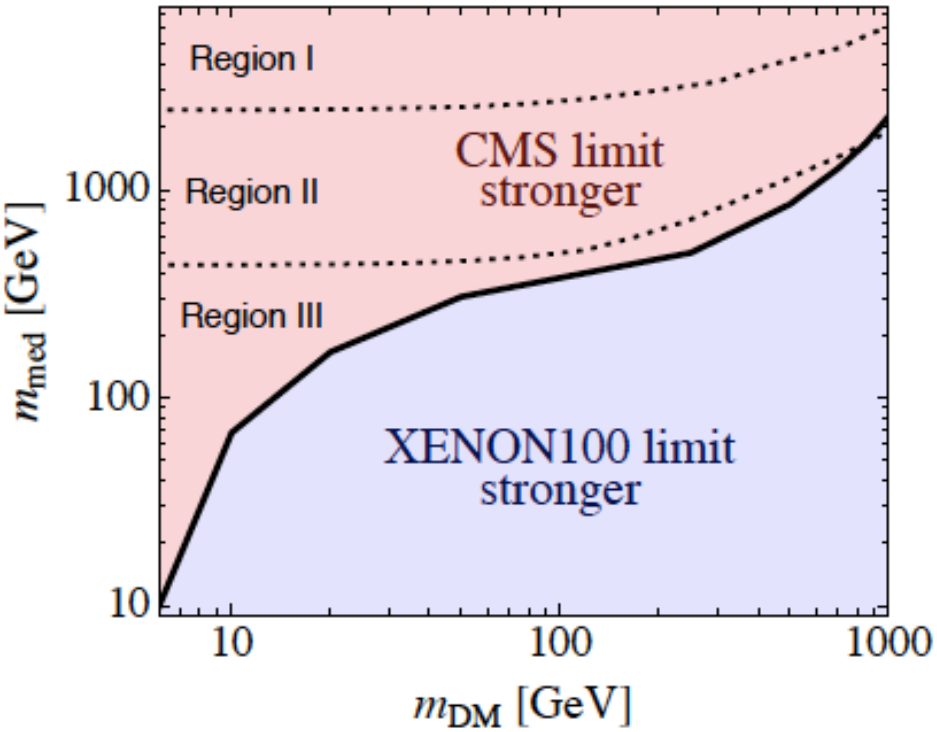

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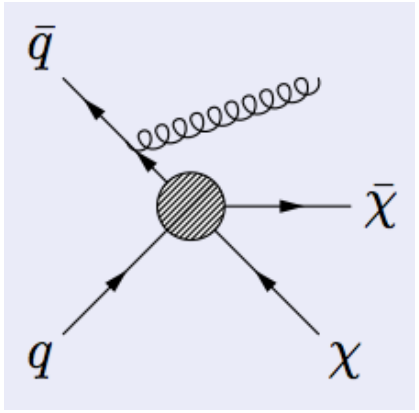
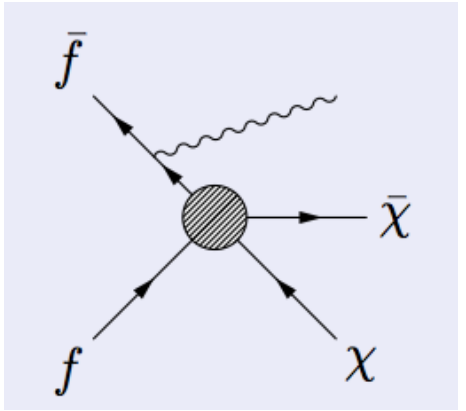
Monojet and Monophoto (plus E_T^{miss})

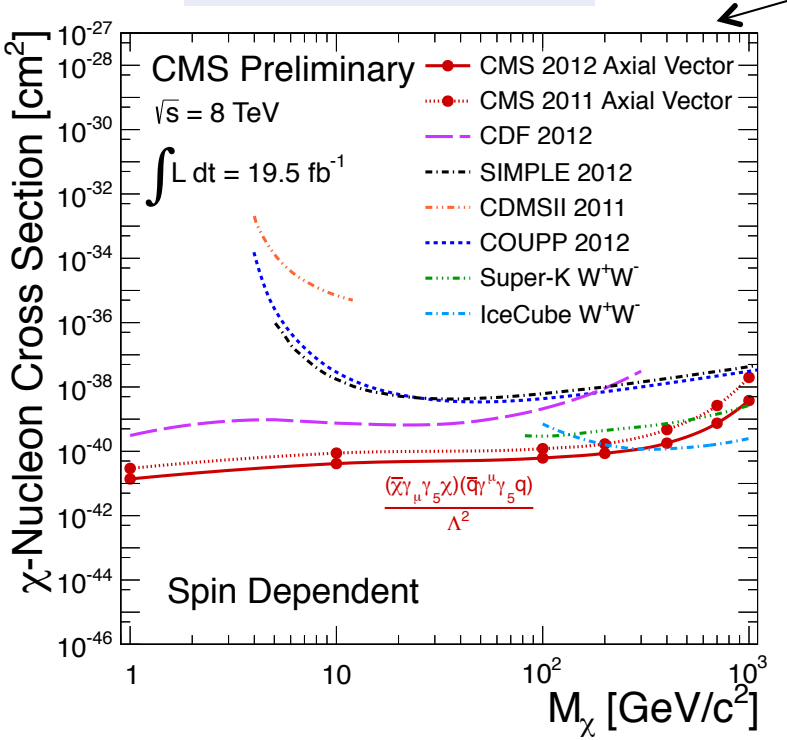
Monojet: hard jet + E_T^{miss}

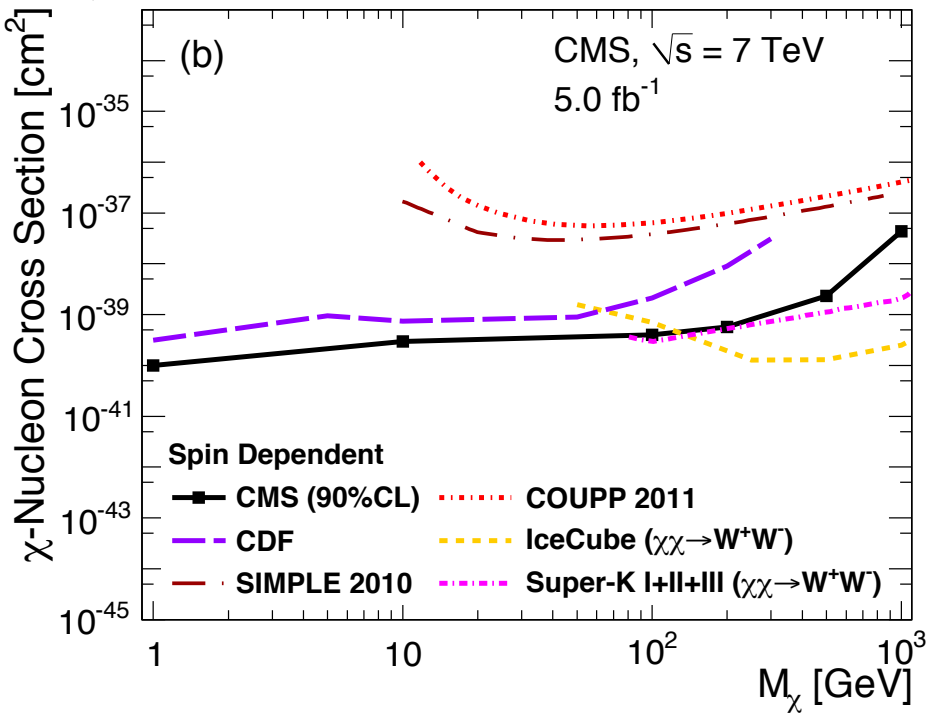


Monphoton: hard photon + E_T^{miss}



Note different y scale





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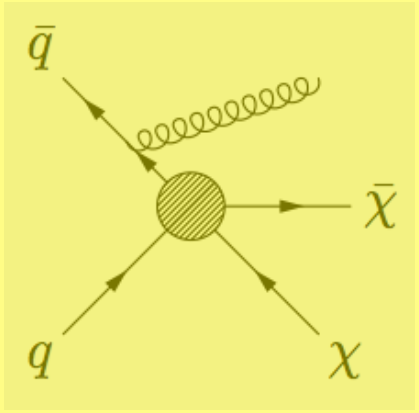

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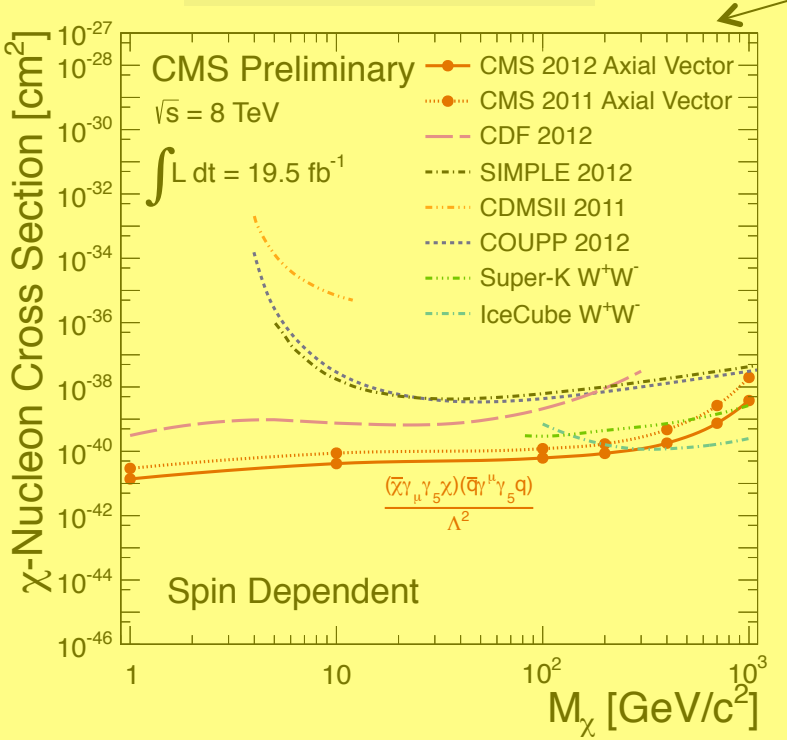

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