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Oliver Buchmueller, Imperial College London

DIRECT SEARCHES FOR SUPERSYMMETRY – WHERE ARE WE TODAY?

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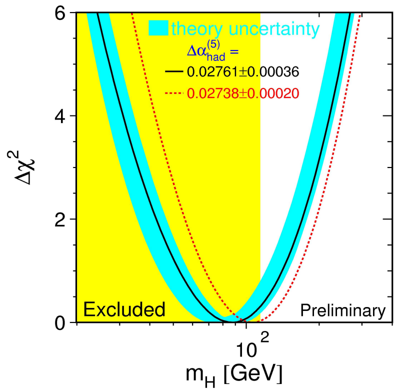
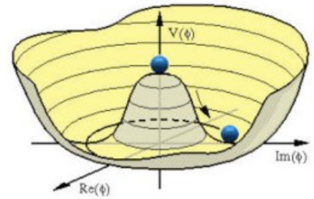
Fundamental Open Questions in Particle Physics

I. What is the origin of mass?

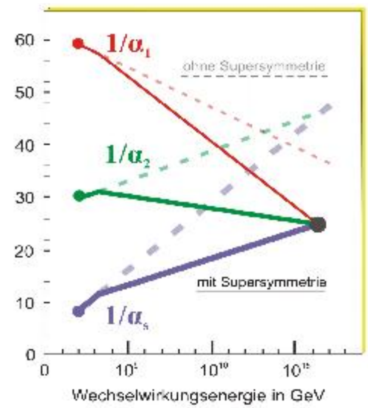
- *Why are the vector bosons Z and W are massive whereas the photon is massless?*
- *Is there a Higgs boson - or even more of them ?*

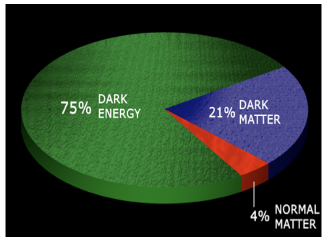




I. Is there a new symmetry - Supersymmetry ?

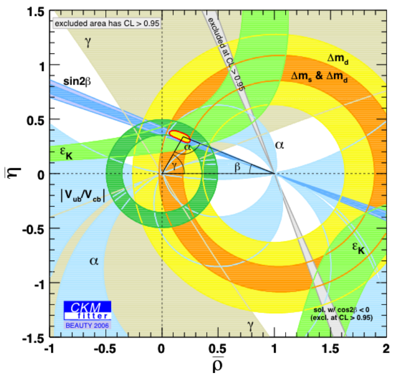
- *Can we get experimental evidence to support the Grand Unification of all fundamental forces?*
- *What is the origin of Dark Matter in the Universe?*
  $\rightarrow$ *Is a fundamental particle responsible for it?*

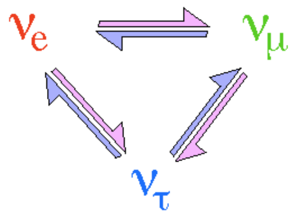




III. What is the origin of the matter-anti-matter asymmetry in our Universe?

- *Does the answer lie in in CP violation?*
- *Neutrino masses and mixing - how do they fit in the picture?*





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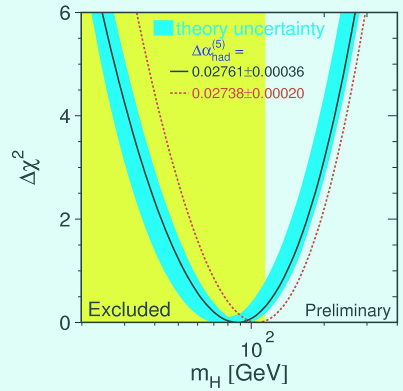

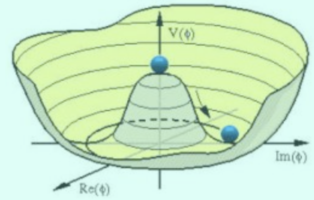

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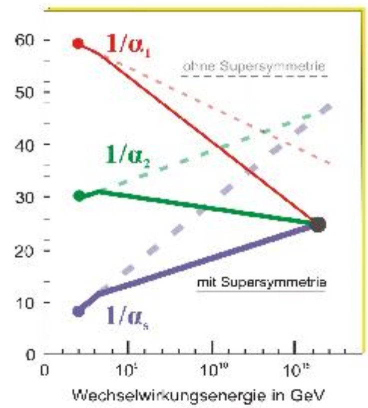

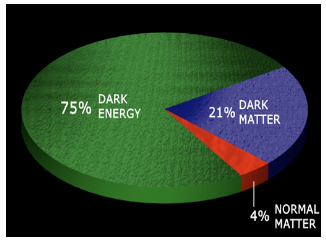

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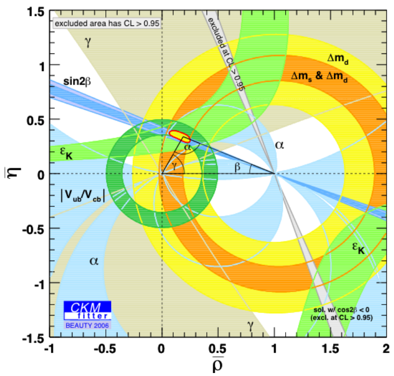
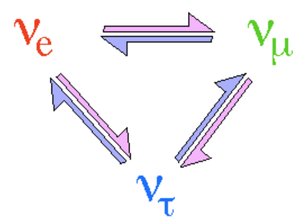
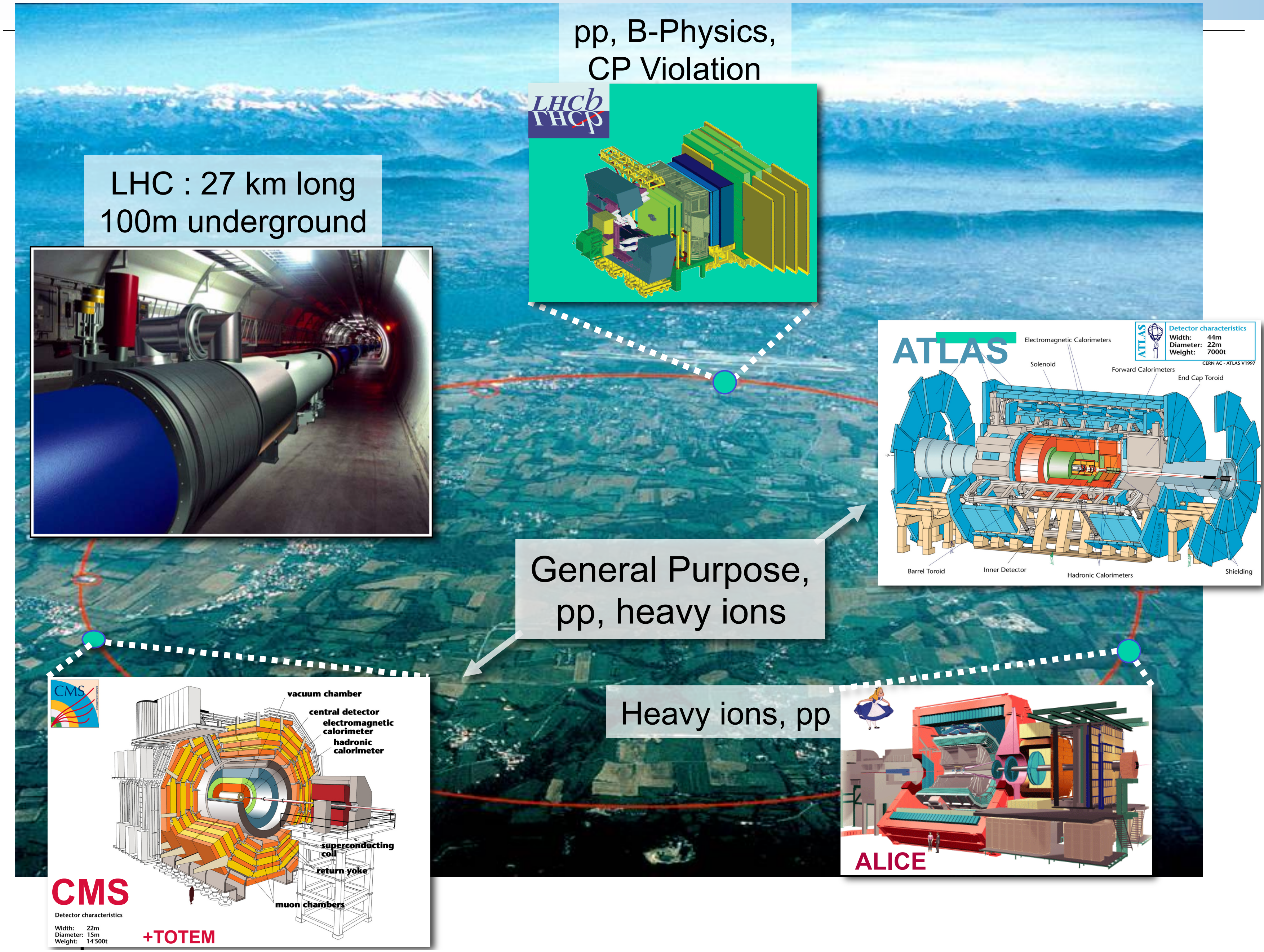
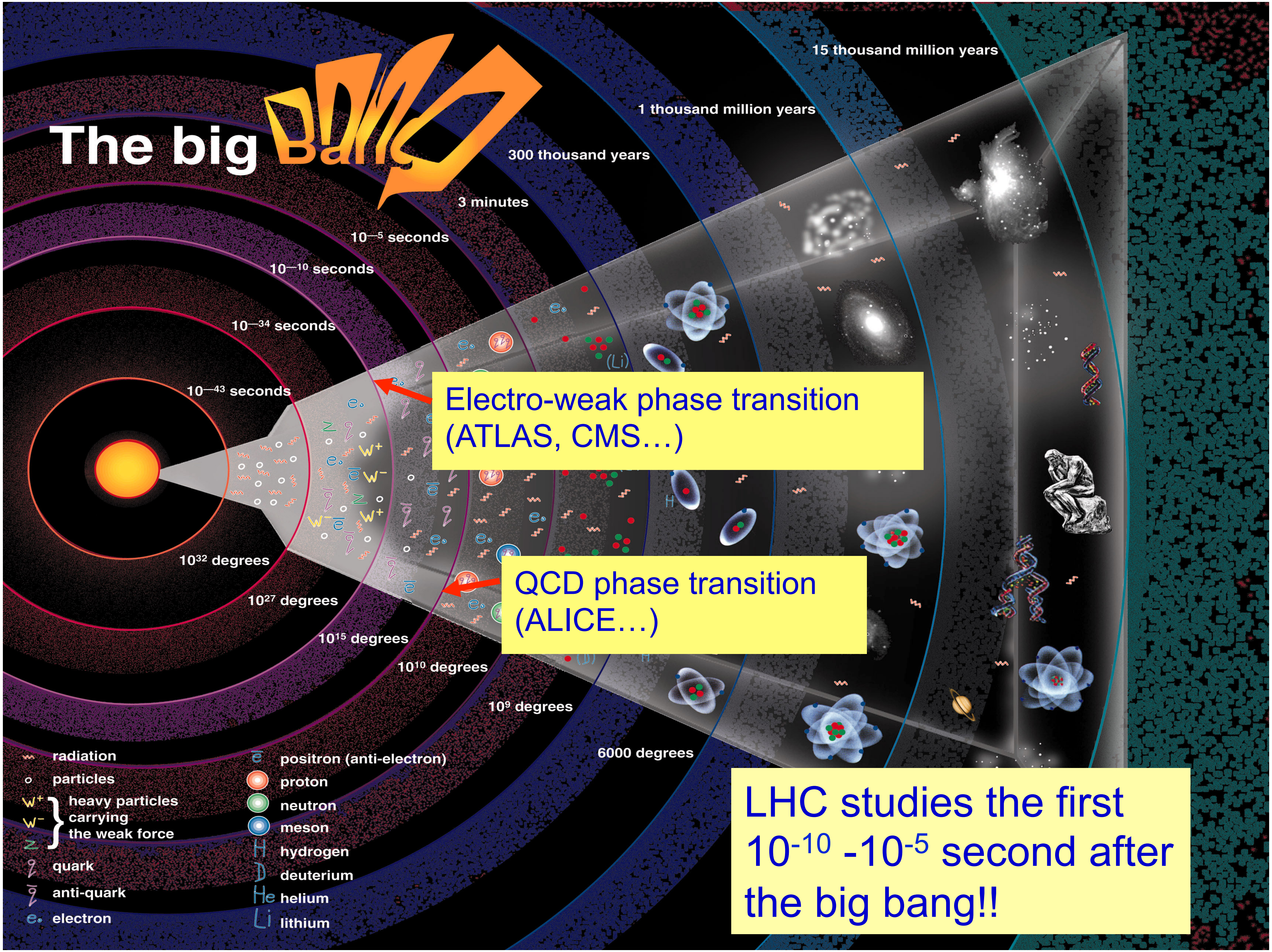




The Large Hadron Collider at CERN




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
Electro-weak phase transition (ATLAS, CMS…)
QCD phase transition (ALICE…)
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
LHC studies the first 10⁻¹⁰ -10⁻⁵ second after the big bang!!

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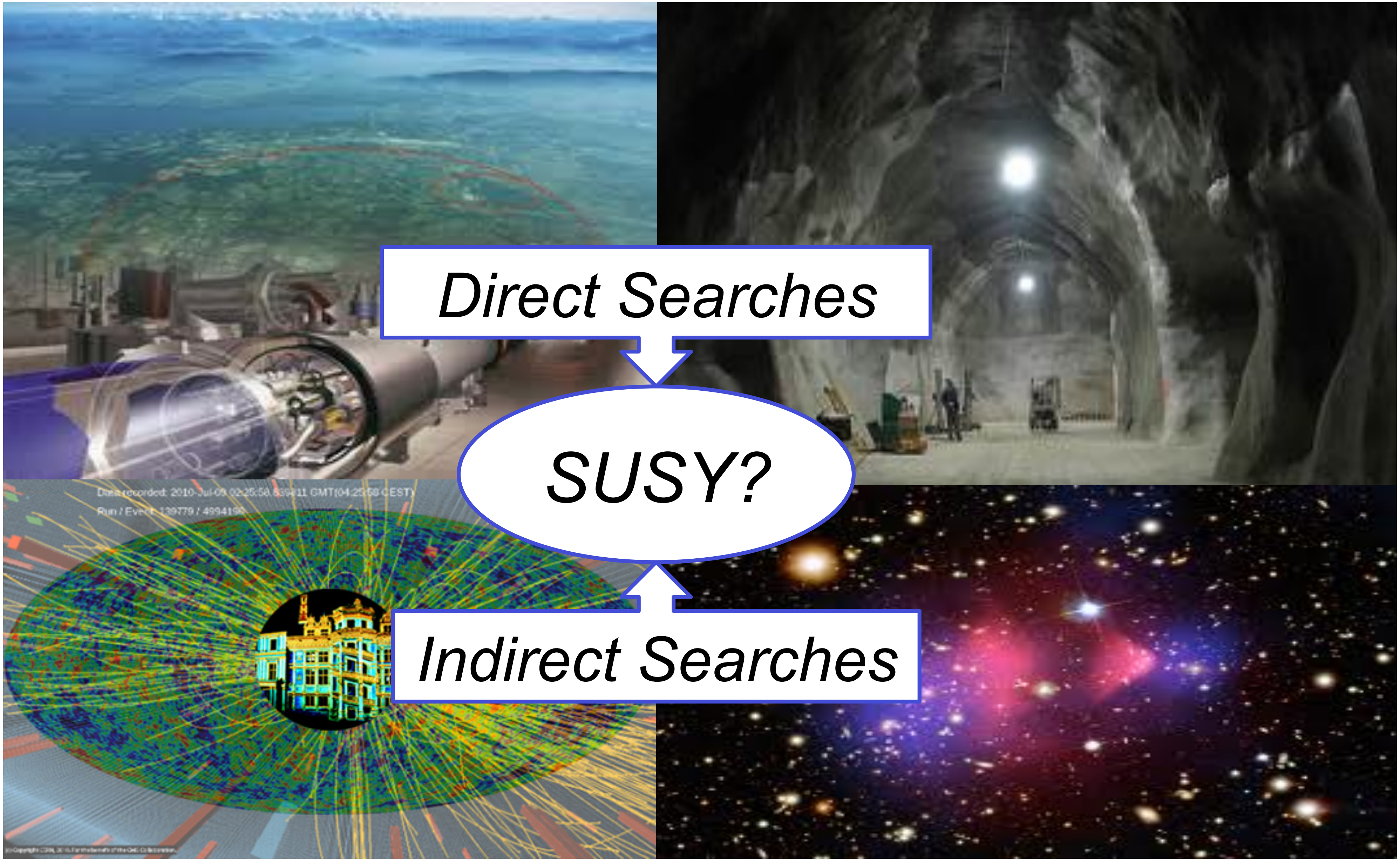
Searches for SUSY

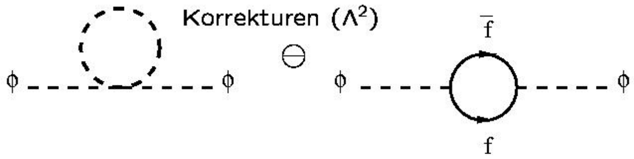


Searches for SUSY

Why is SUSY so attractive?

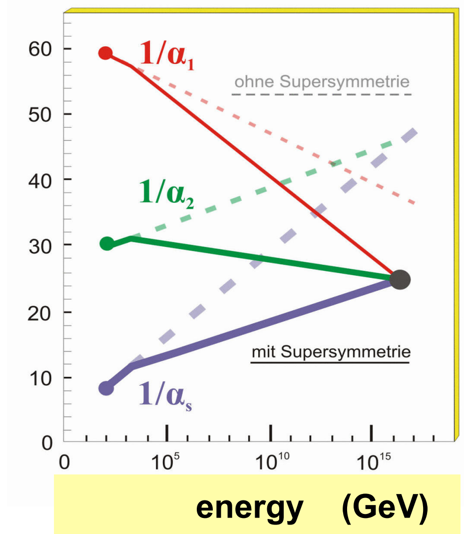
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

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



(Hierarchy or naturalness problem)

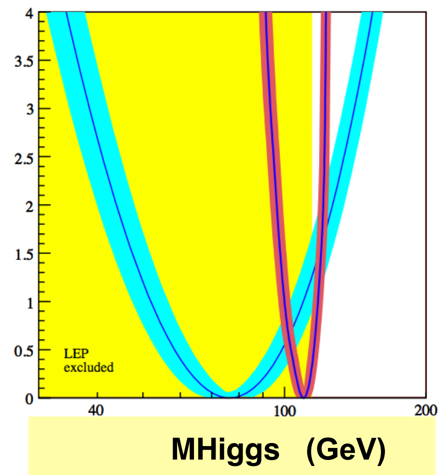
$m_{SUSY} \sim 1$ TeV



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

3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)



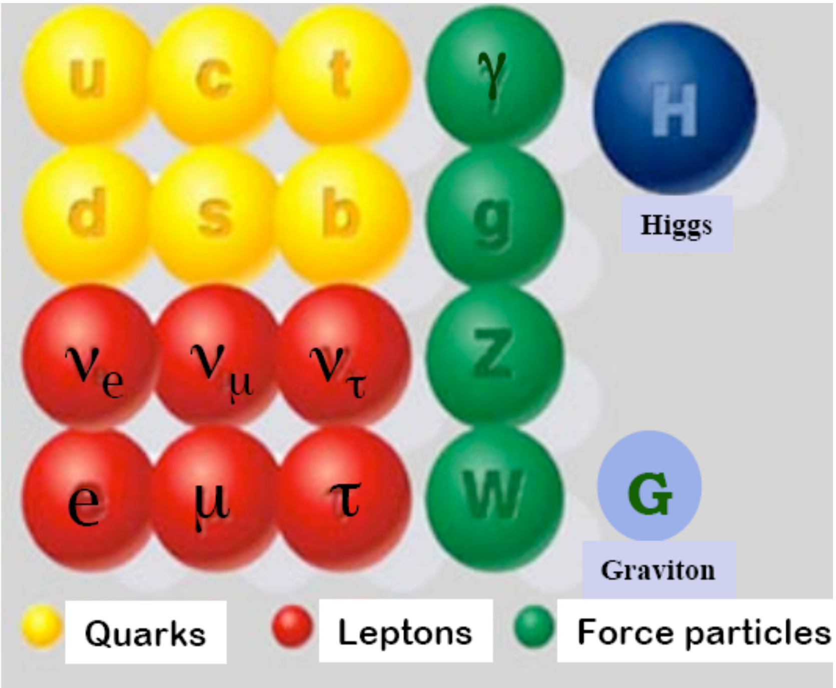
4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

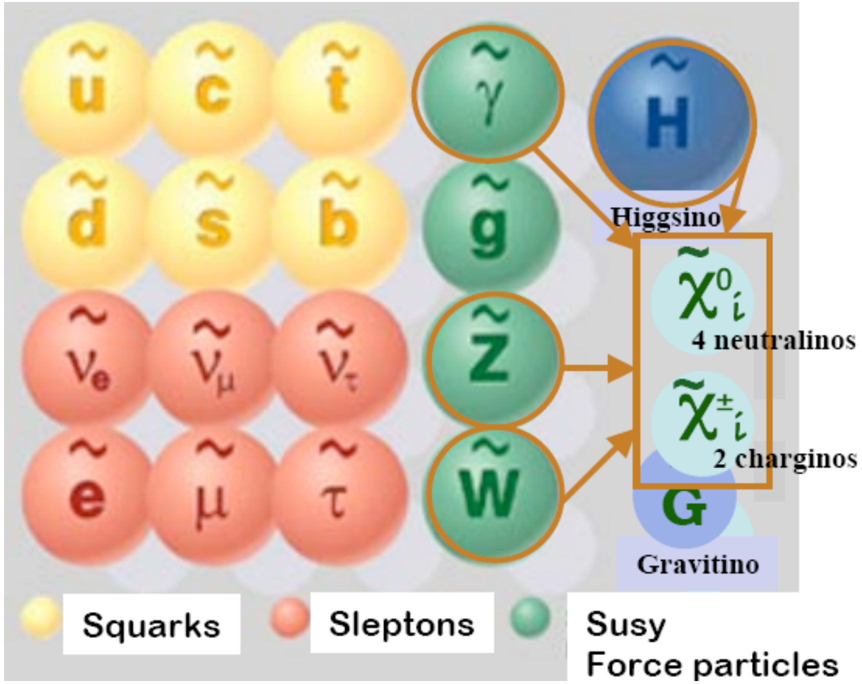
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry

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

Standard Model particles | **SUSY particles**





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

R-parity conservation:

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

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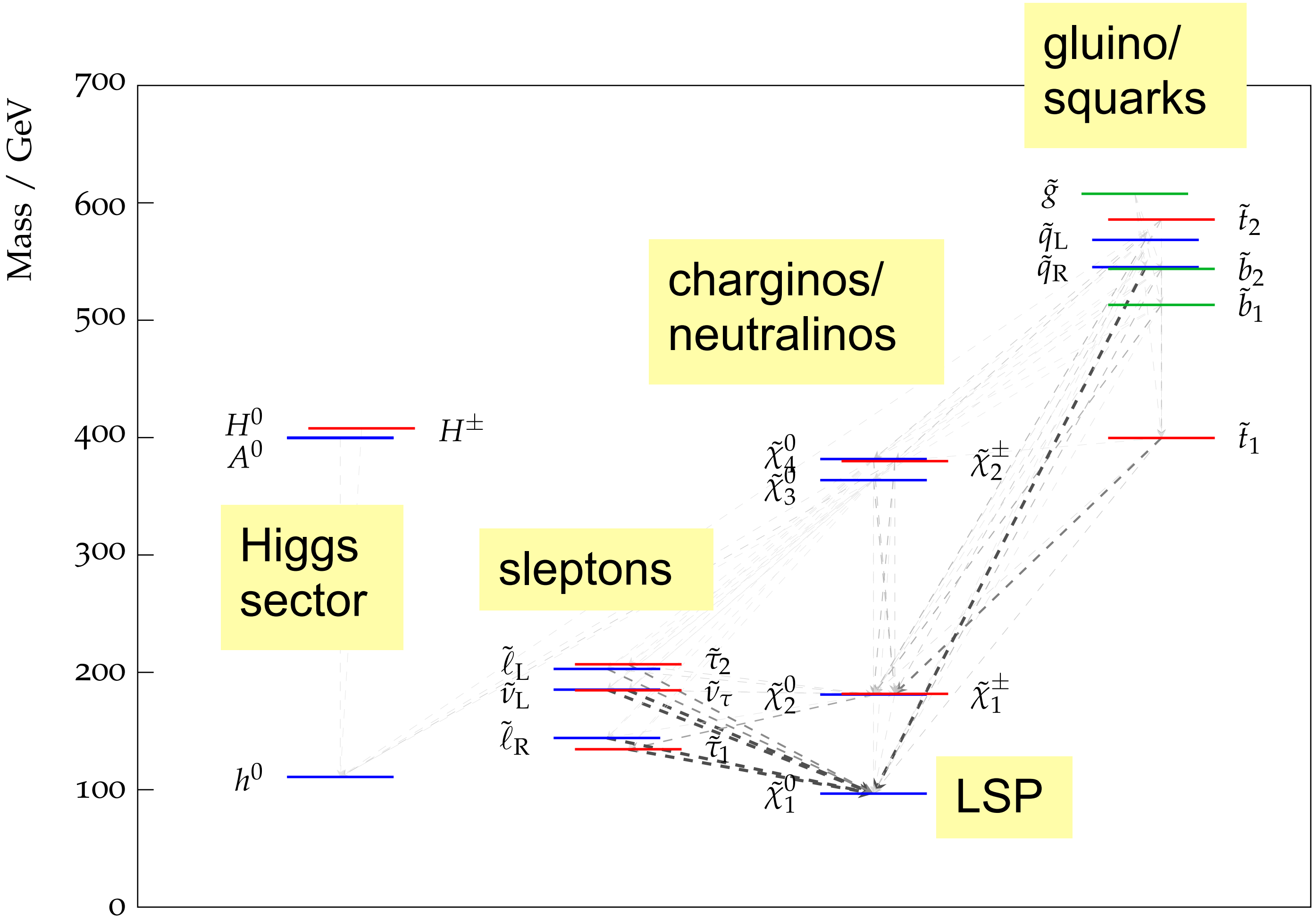
A "typical" SUSY Spectrum

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



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

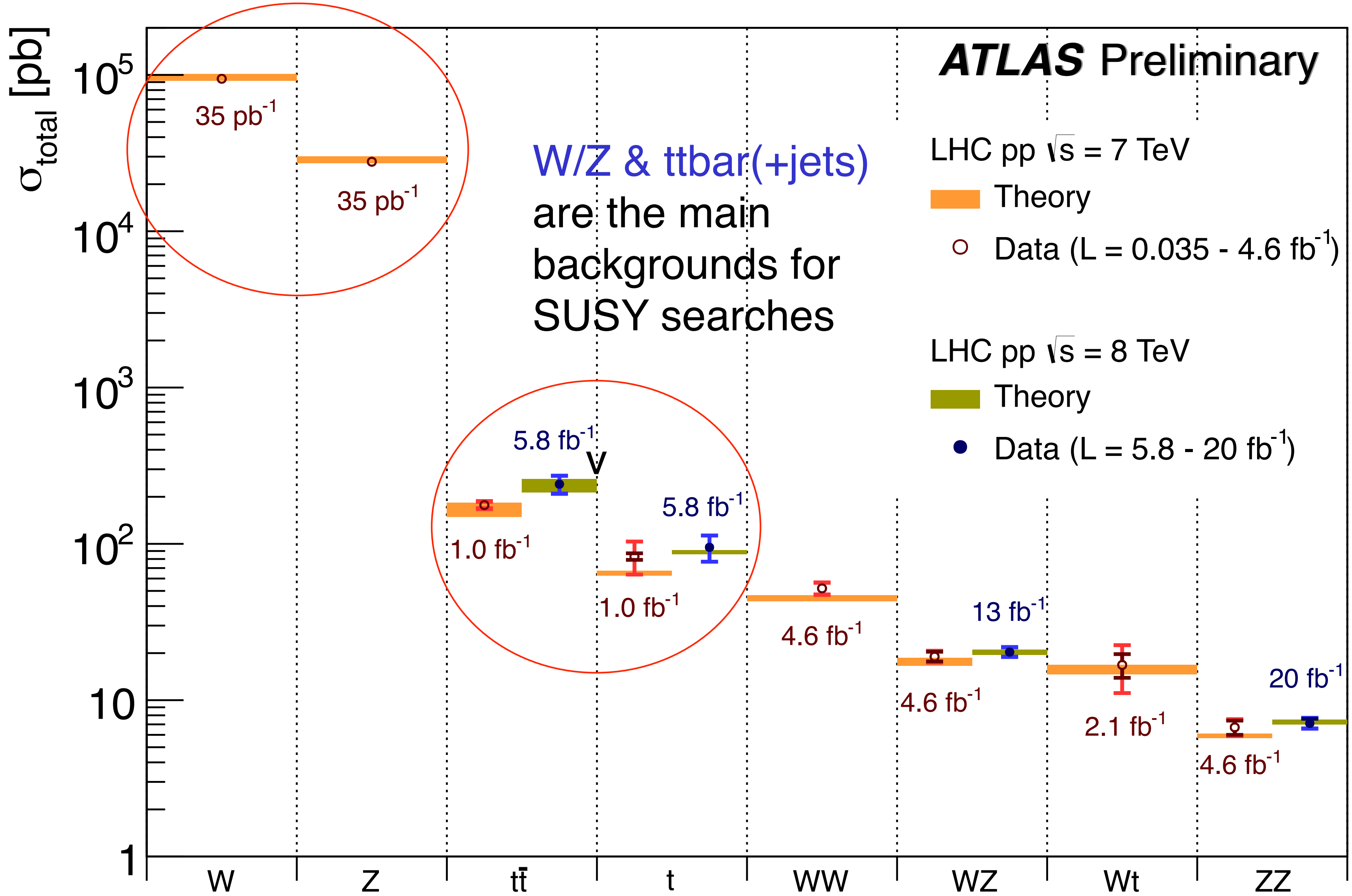
Advantage:

- ➢ 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})

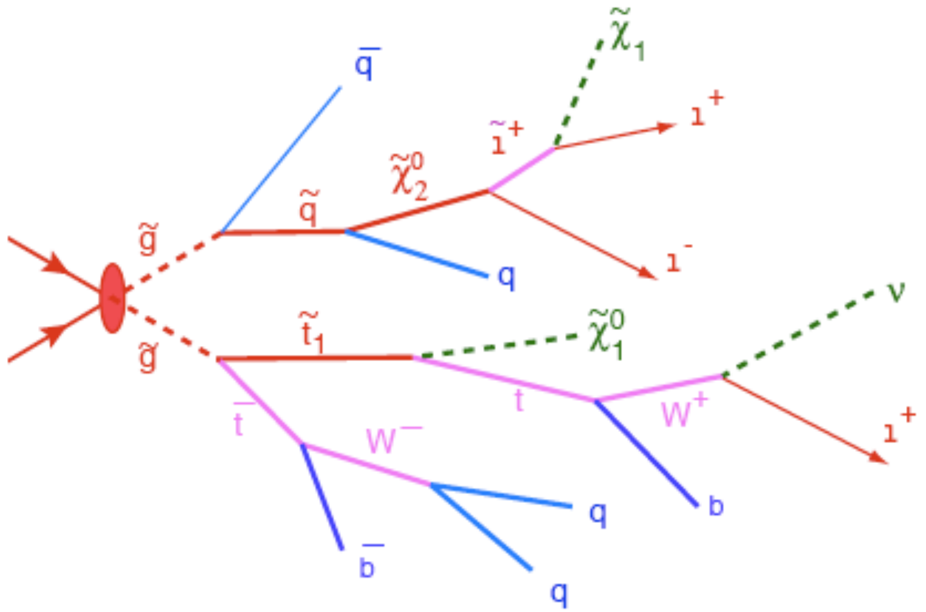
Rediscovery of the SM at a new energy frontier



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*

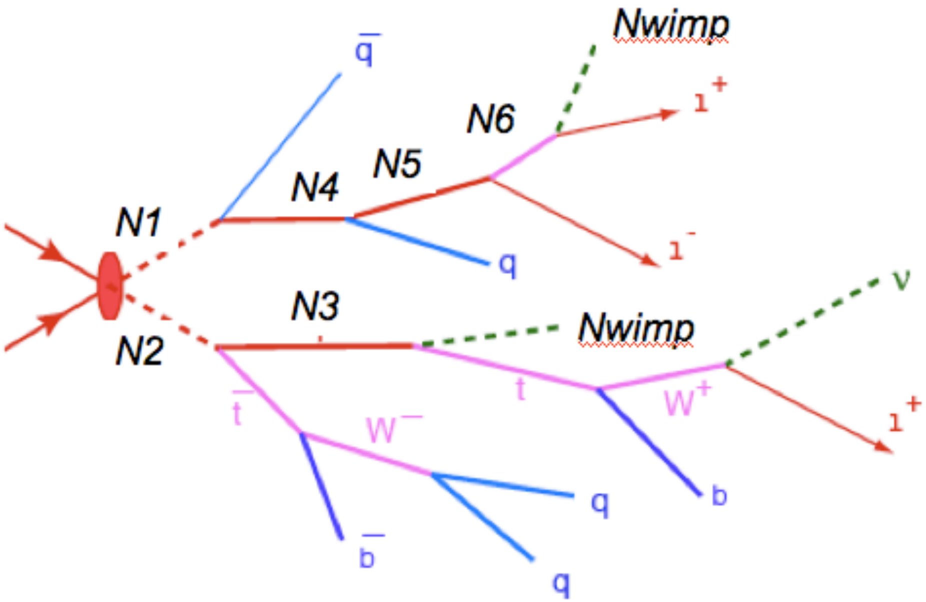
Multi-Jet:
- *from cascade decay (gaugino)*

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*

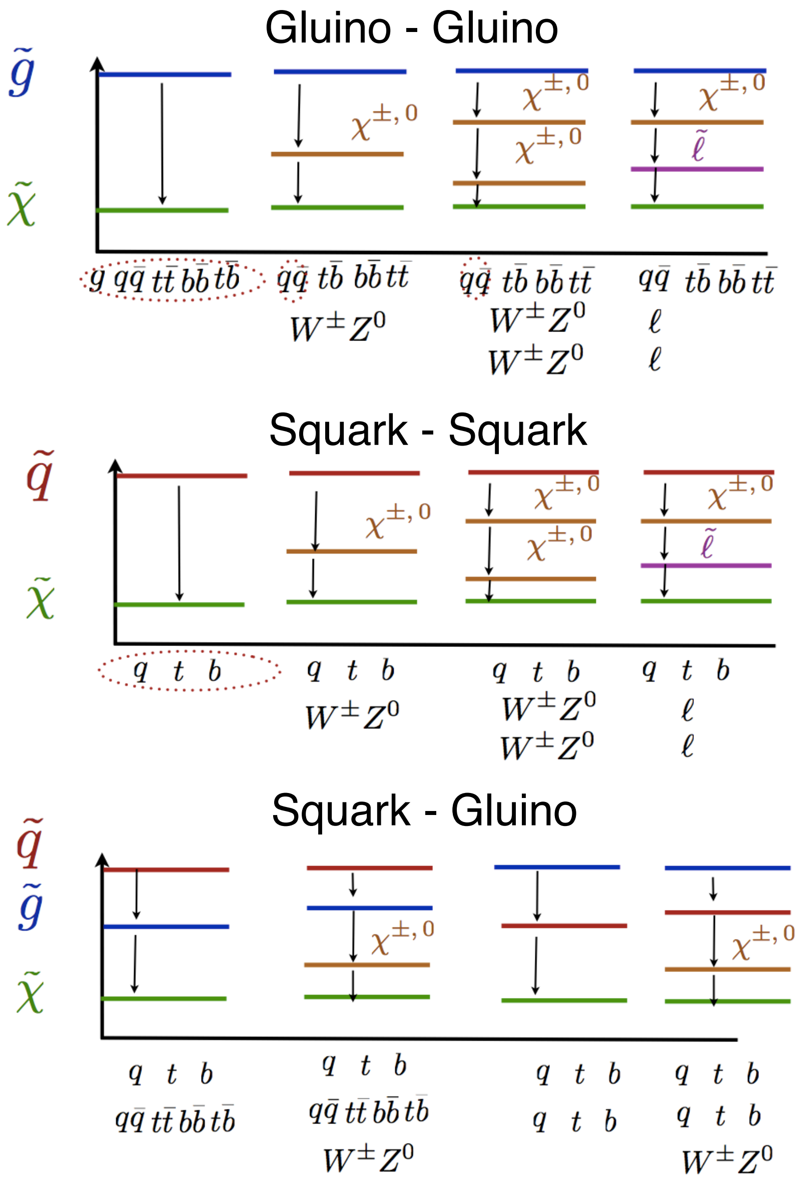
Multi-Jet:
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

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.

Early SUSY Search Strategy at the LHC

Direct SUSY Searches, O. Buchmüller



Search Signatures

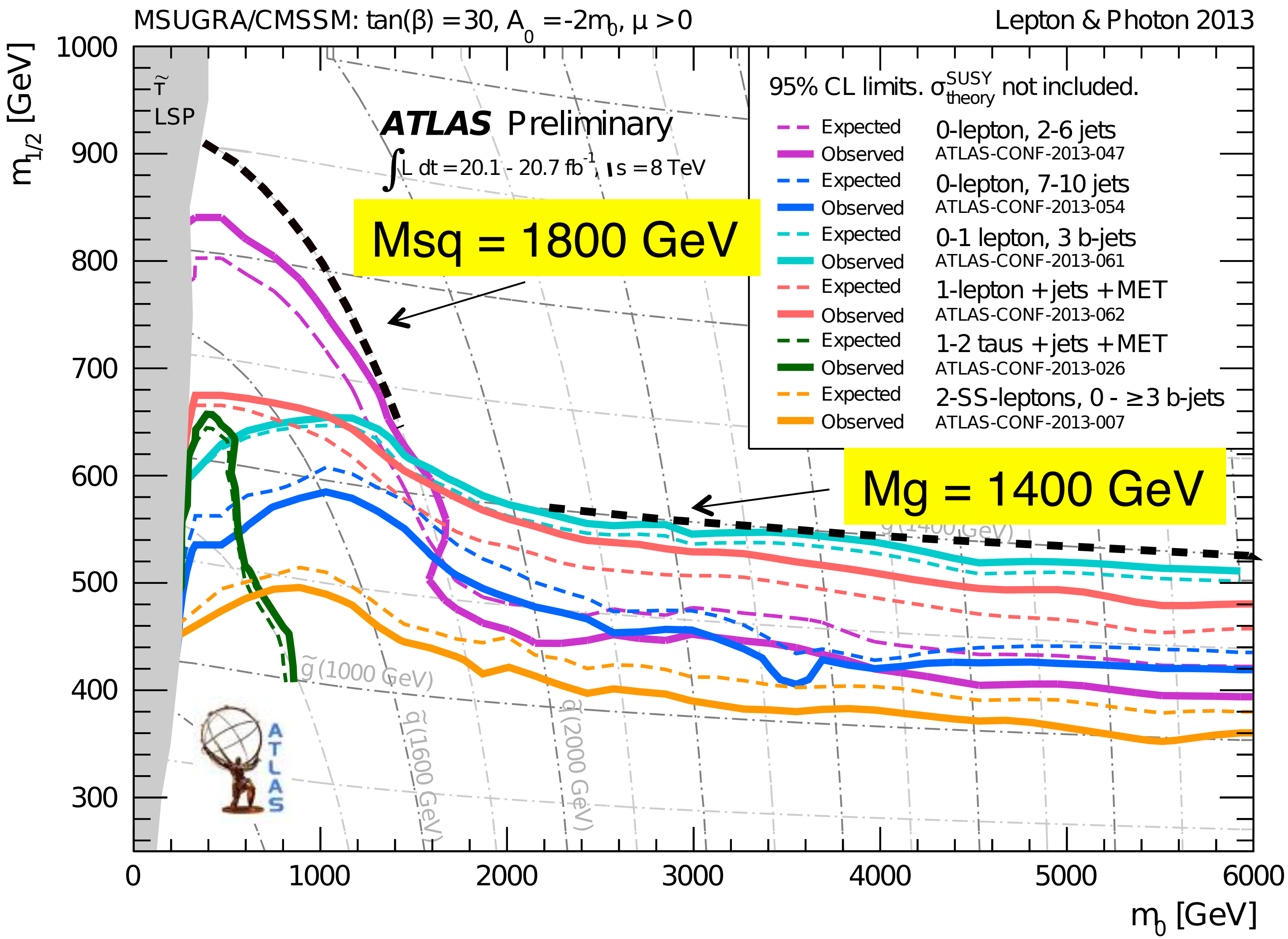
- SUSY-like decay chains range from short to long and simple to very complicated.
- All physics objects, MET, jets, leptons, photons, b's taus, tops, W, Z, etc are involved
- Comprehensive coverage of all possible signature requires a topology oriented search strategy:

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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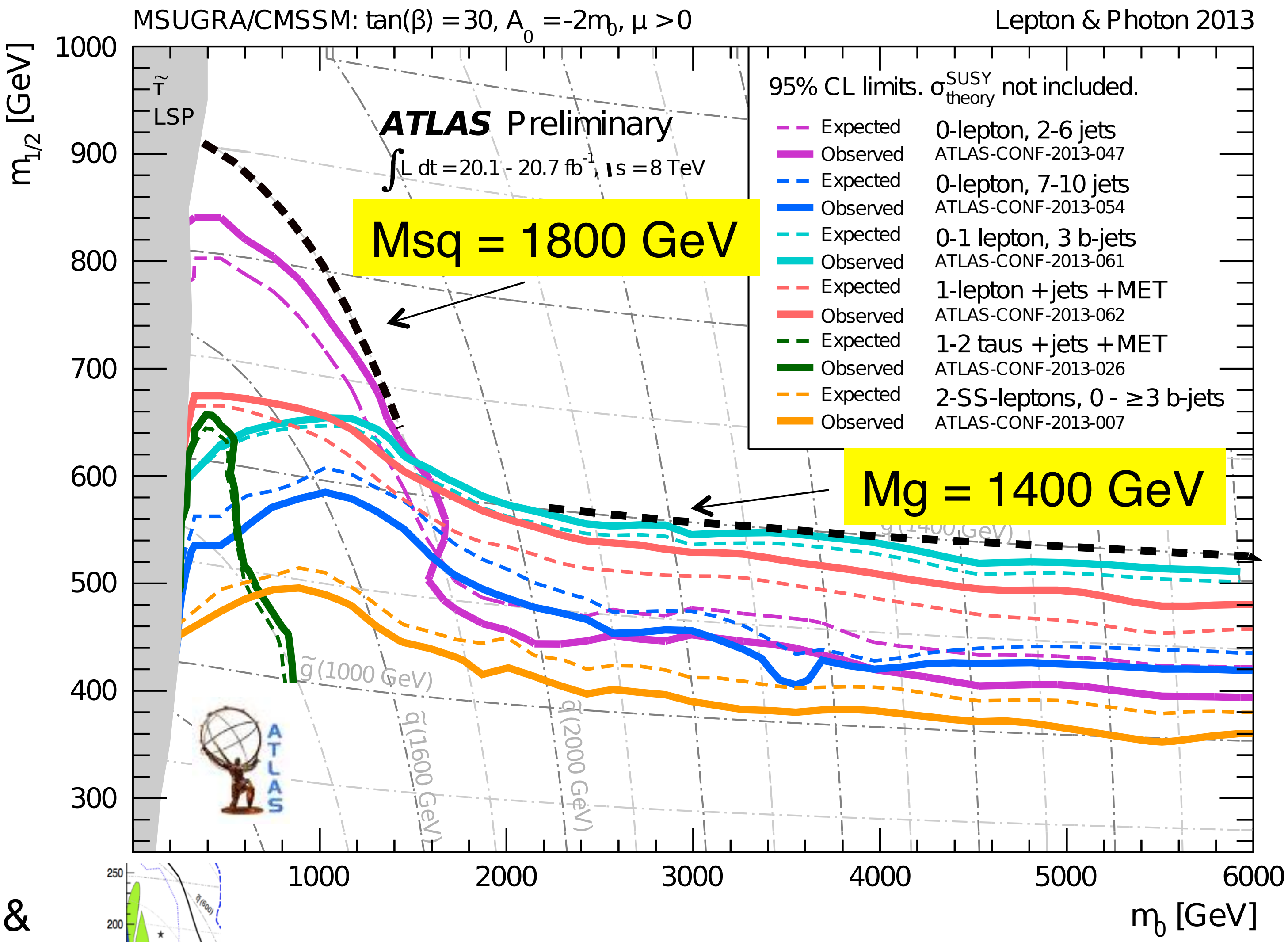
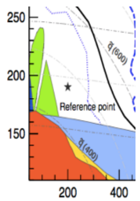


LEP & Tevatron



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

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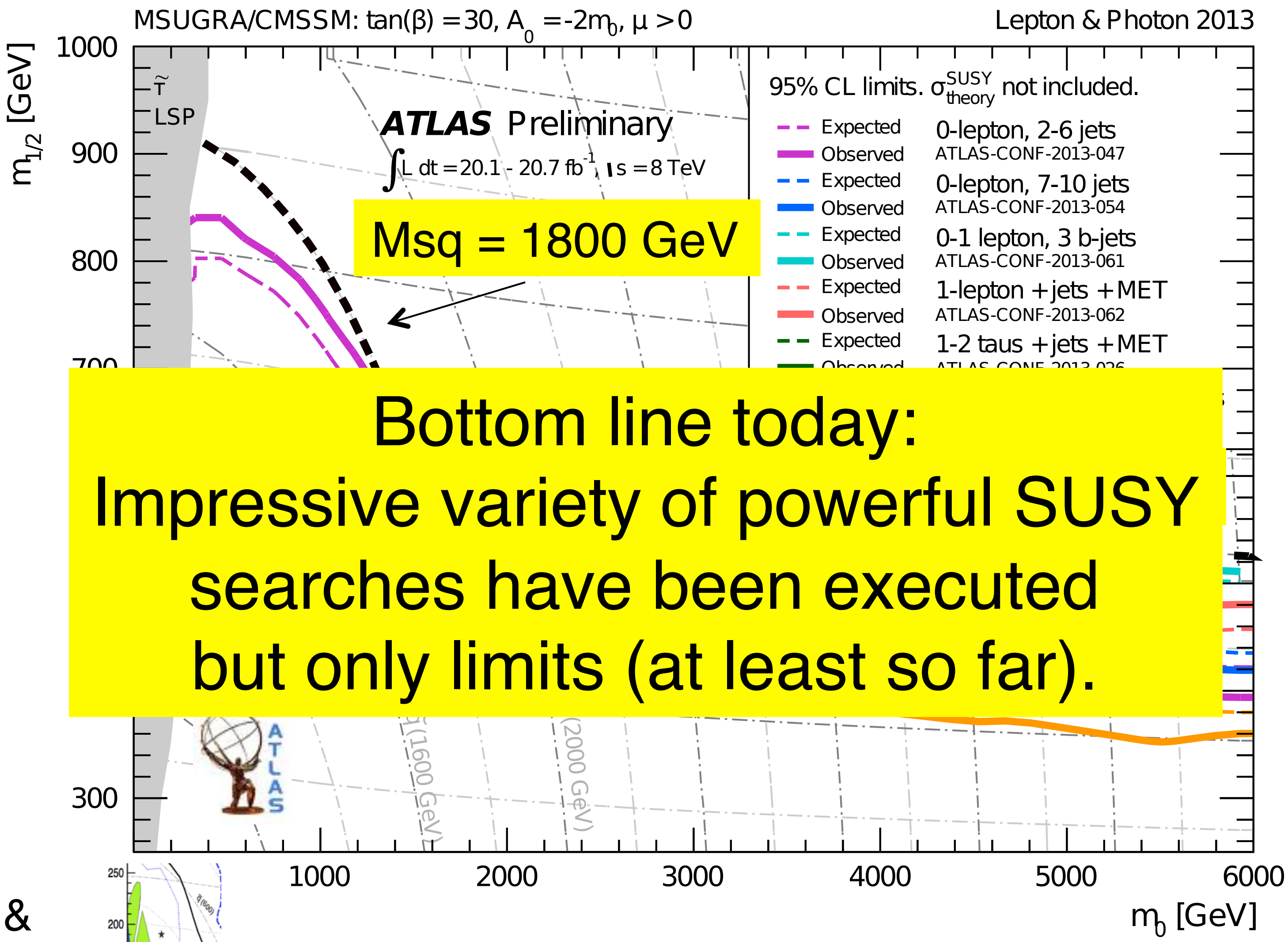
Inclusive SUSY Searches in 2013

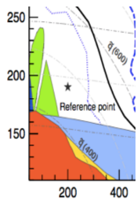
Direct SUSY Searches, O. Buchmüller



Msq = 1800 GeV

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

LEP & Tevatron



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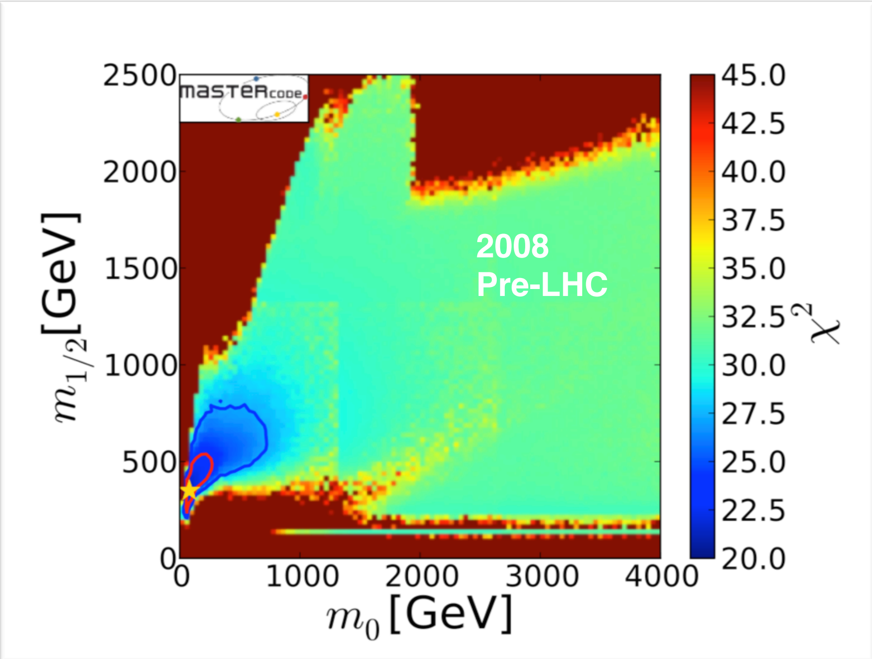
CMSSM: Evolution with time

Direct SUSY Searches, O. Buchmüller



X^2 increase from bluish to reddish

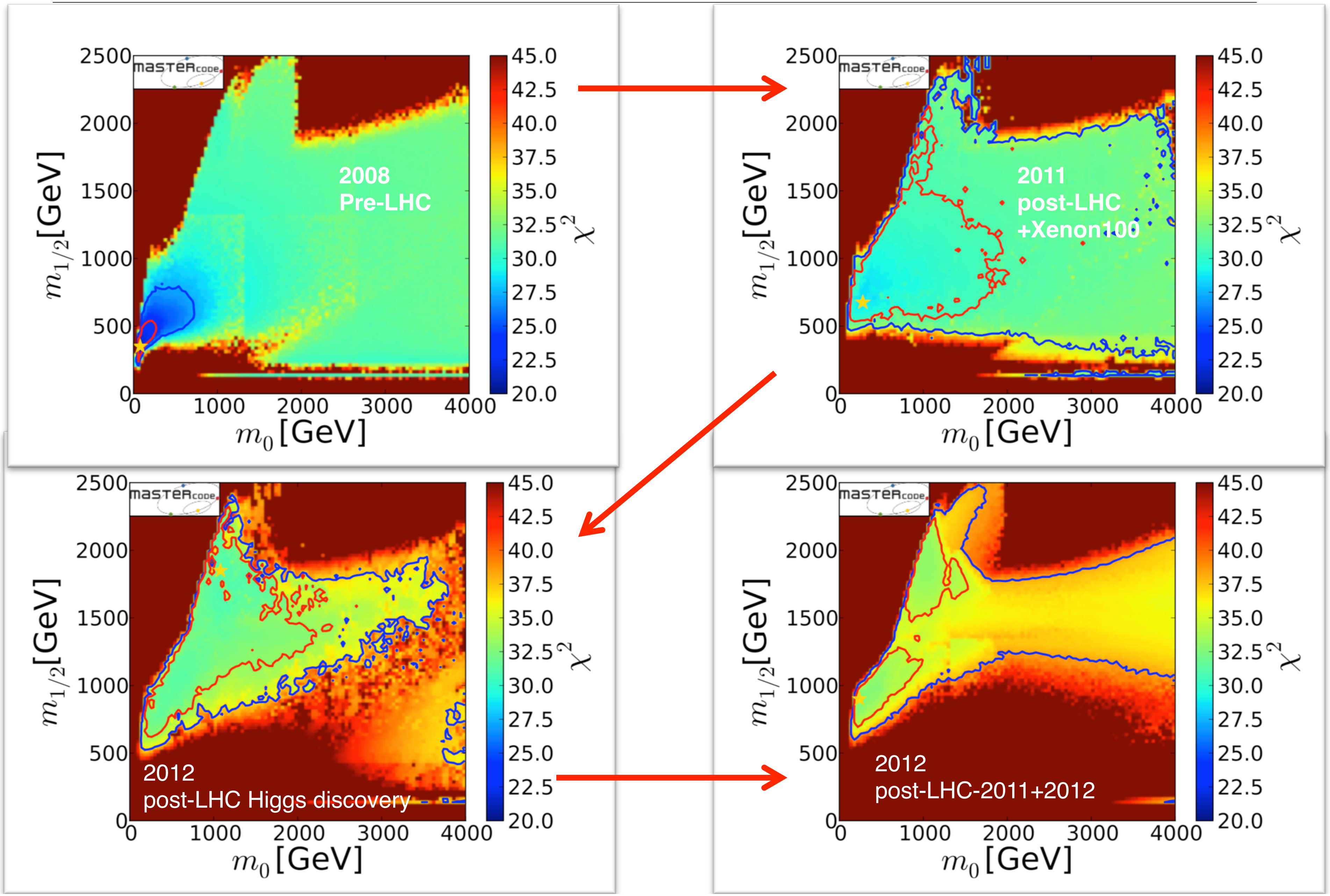
Source:
http://mastercode.web.cern.ch/mastercode/

Observable	Source Th./Ex.	Constraint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
m_t [GeV]	[43]	173.2 ± 0.90	0.05	0.06	-
$\Delta\alpha^{(5)}_{had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{SUSY}$	0.078	0.047	0.14
σ^0_{had} [nb]	[26] / [44]	41.540 ± 0.037	2.50	2.57	2.54
R_l	[26] / [44]	20.767 ± 0.025	1.05	1.08	1.08
$A_{fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
$A_\ell(P_\tau)$	[26] / [44]	0.1465 ± 0.0032	0.11	0.13	0.07
R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{fb}(c)$	[26] / [44]	0.0707 ± 0.0035	0.86	0.88	0.80
A_b	[26] / [44]	0.923 ± 0.020	0.36	0.36	0.35
A_c	[26] / [44]	0.670 ± 0.027	0.005	0.005	0.005
A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{SUSY}$	1.77	1.39	2.08
$a^{EXP}_\mu - a^{SM}_\mu$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4[\pm1.5_{SUSY}]$	0.0	0.0	0.0
$BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{EXP}$ $\pm0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
$BR(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$BR^{EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{EXP+TH}$	1.43	1.59	1.00
$BR(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6[\pm0.01_{SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR^{EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
σ^{SI}_p	[25]	$(m_{\chi^0_1}, \sigma^{SI}_p)$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

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

CMSSM: Evolution with time



Direct SUSY Searches, O. Buchmüller

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).

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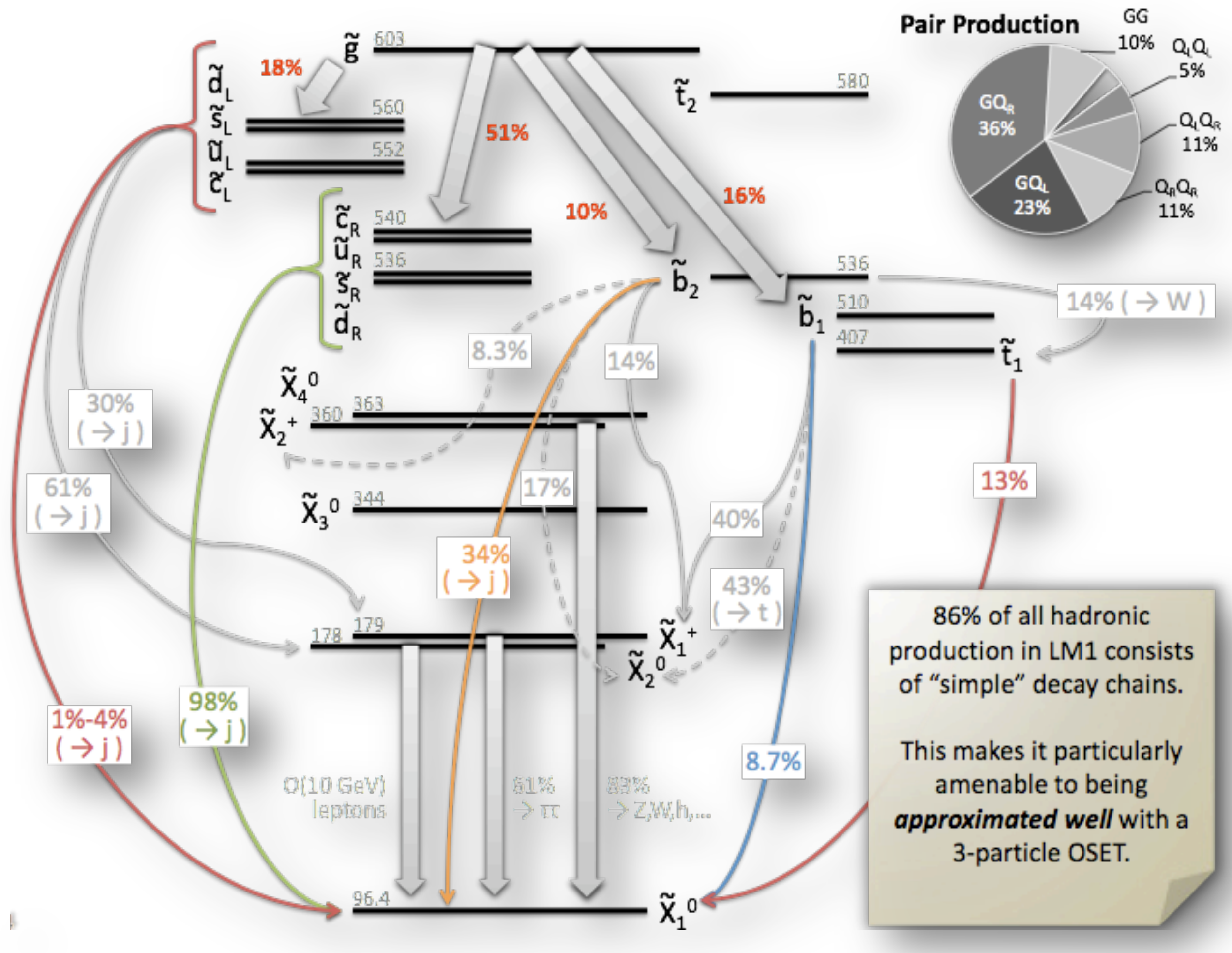
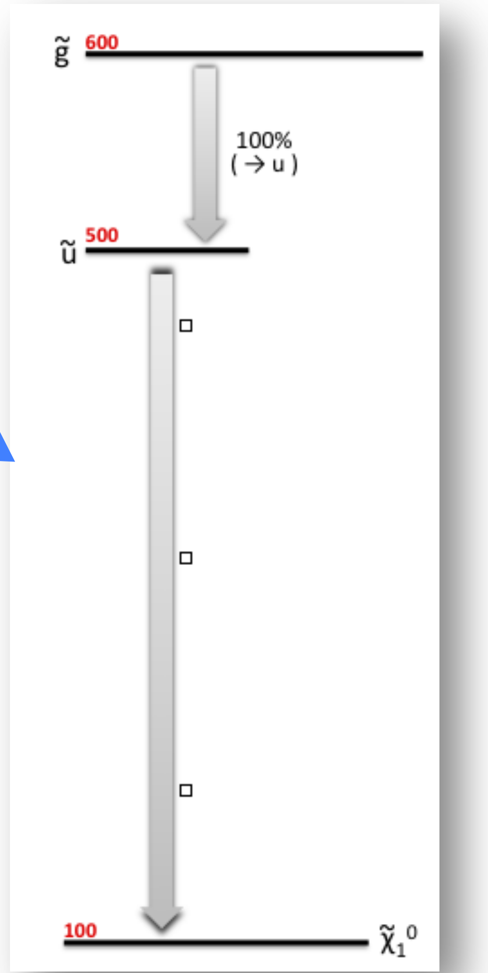
Interpretation in Simplified Models

CMSSM

Direct SUSY Searches, O. Buchmüller



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



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

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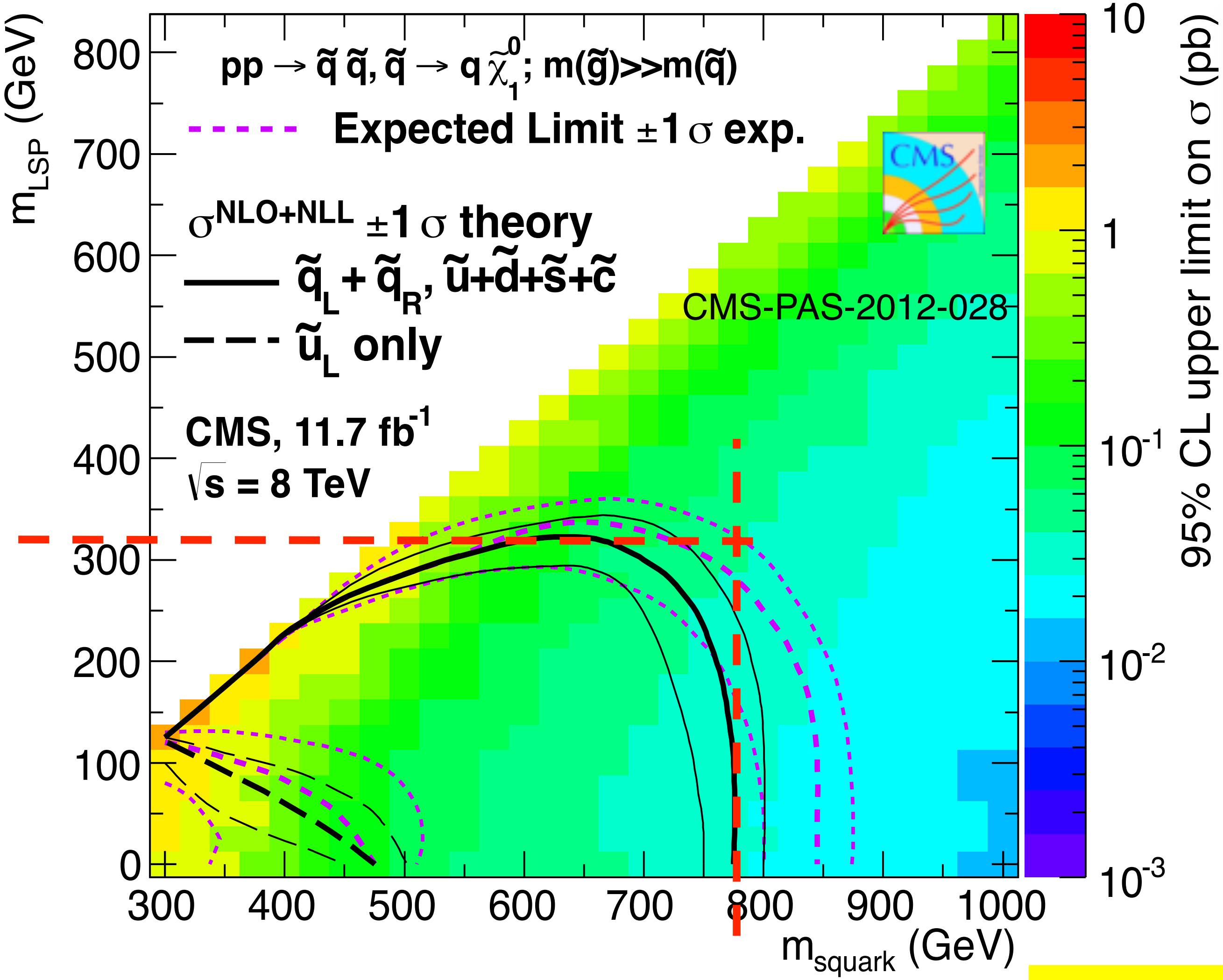
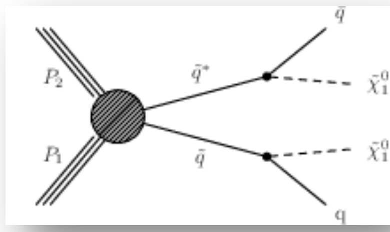
SMS: a few interesting features

$m_{LSP}^{max} \approx 0.3$ 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

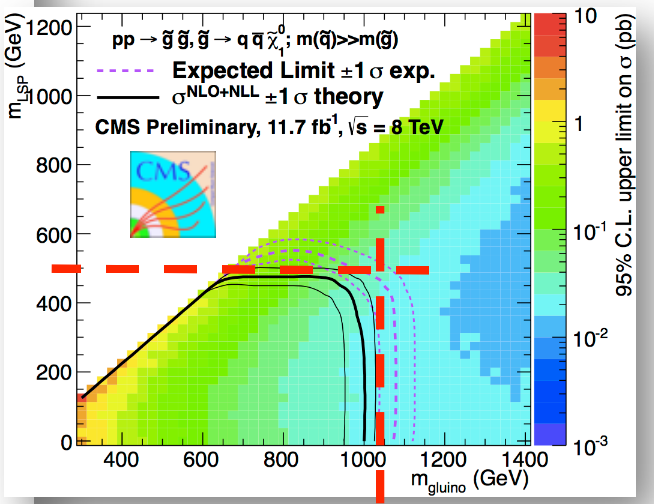
Assumes 100% BR for decay chain considered.

How to summarize SMS limits?

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

http://pdg.lbl.gov/2012/reviews/rpp2012-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 $\tilde{q}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$= 0, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0}$= 0, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0}$= 0, all $m_{\tilde{q}}$	-	900



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

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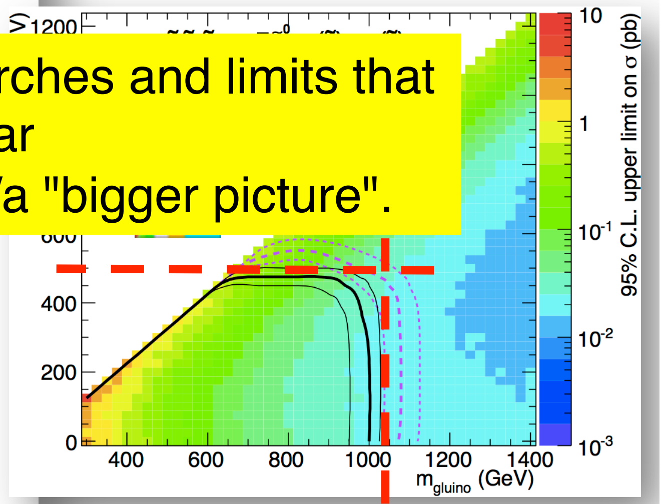
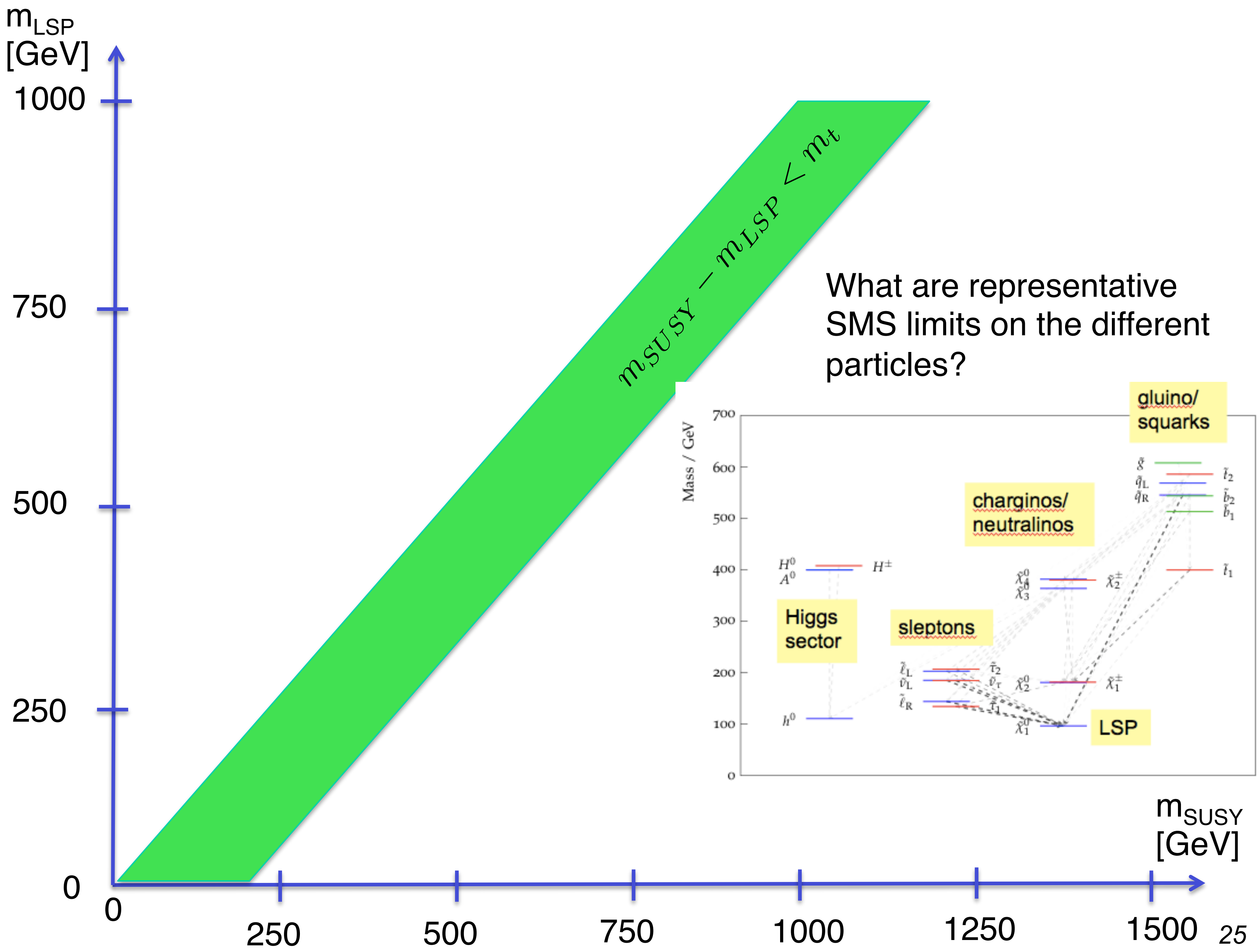
Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$	-	800
Simplifi[illegible]	[illegible]	[illegible]	[illegible]
Simplified model $\tilde{q}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit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



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

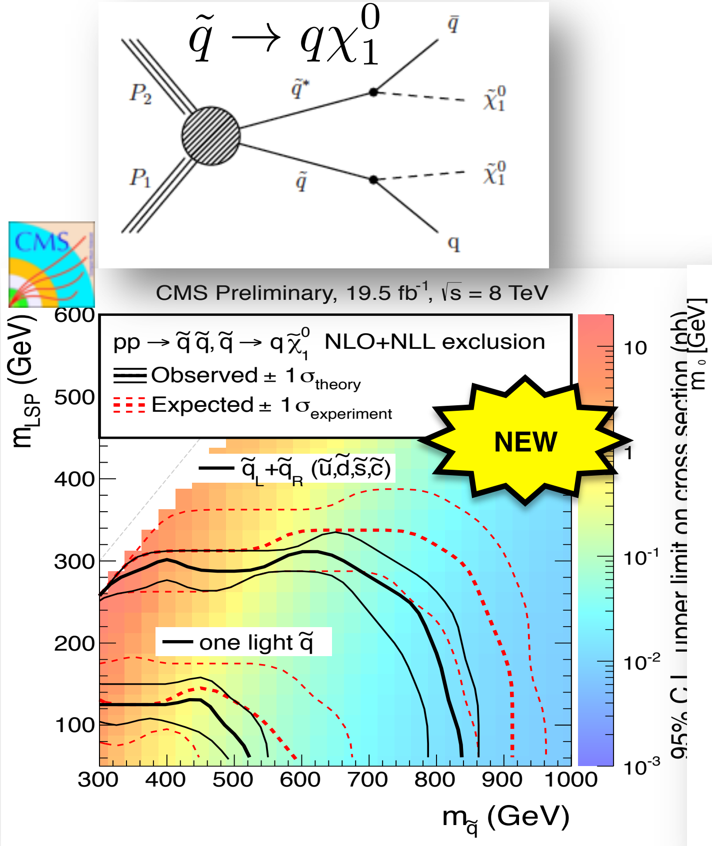
This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).



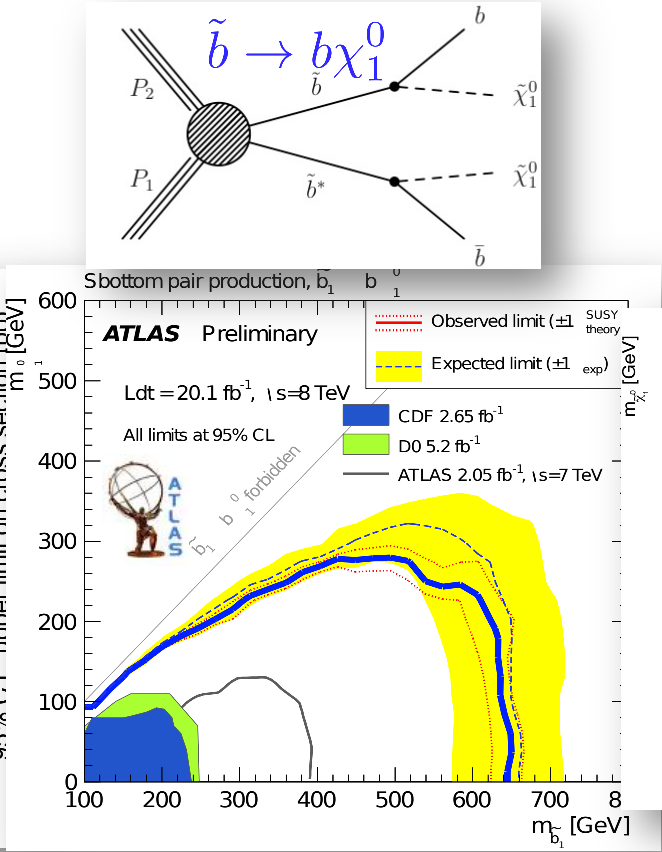
What are representative SMS limits on the different particles?

Direct squark production – chosen limits

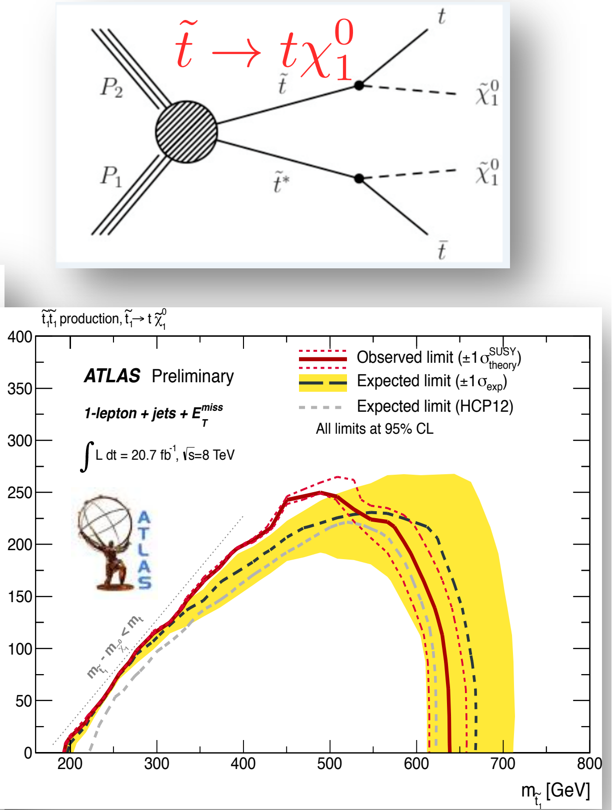
Direct SUSY Searches, O. Buchmüller



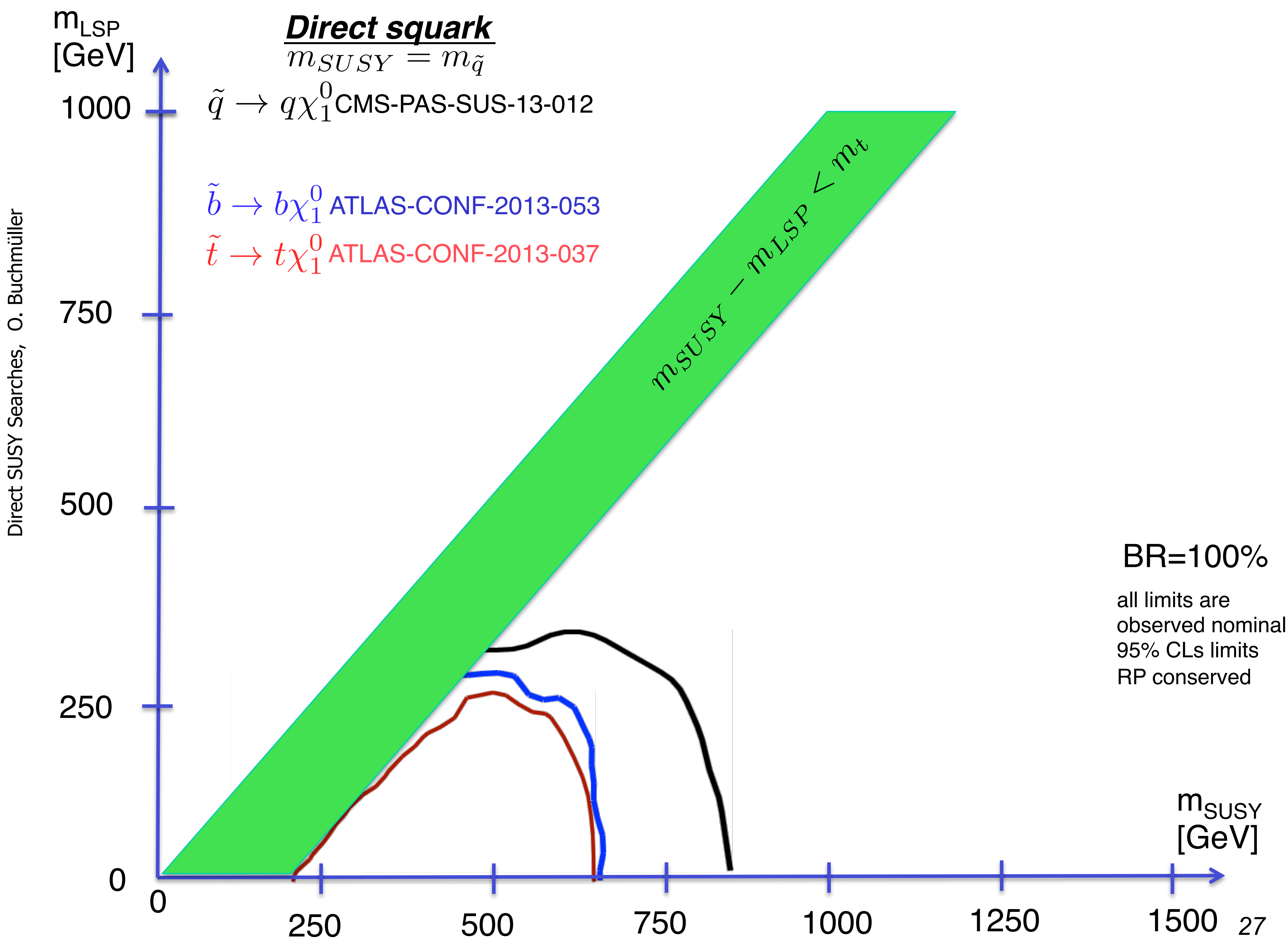
CMS-SUS-PAS-13-012
Signature: Jets + E_t^{miss} + H_T
Limit assumes all 1st & 2nd gen squarks to be mass degenerate or only one light squark!



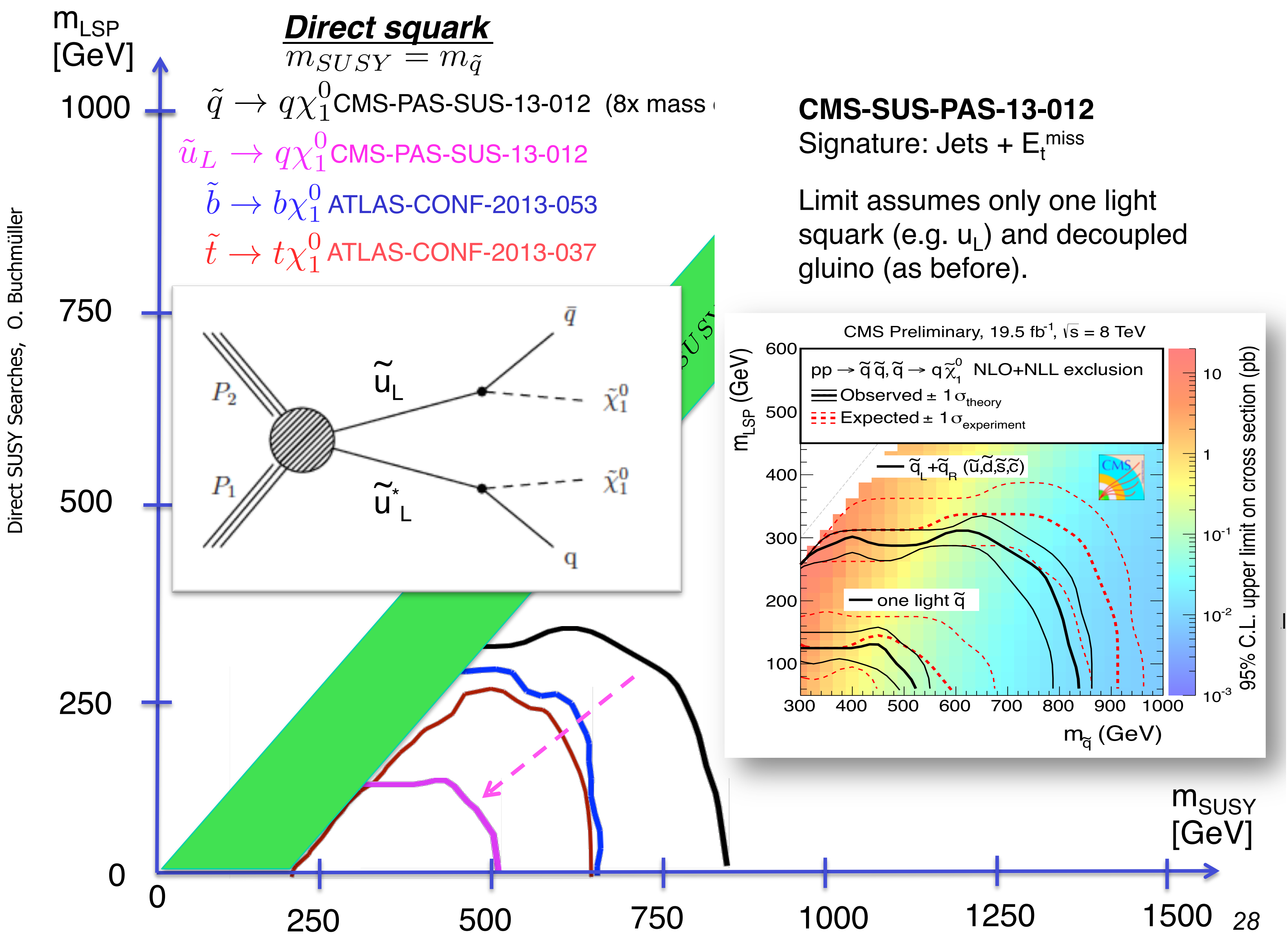
ATLAS-CONF-2013-053
Signature: 2 b-jets + E_T^{mis}

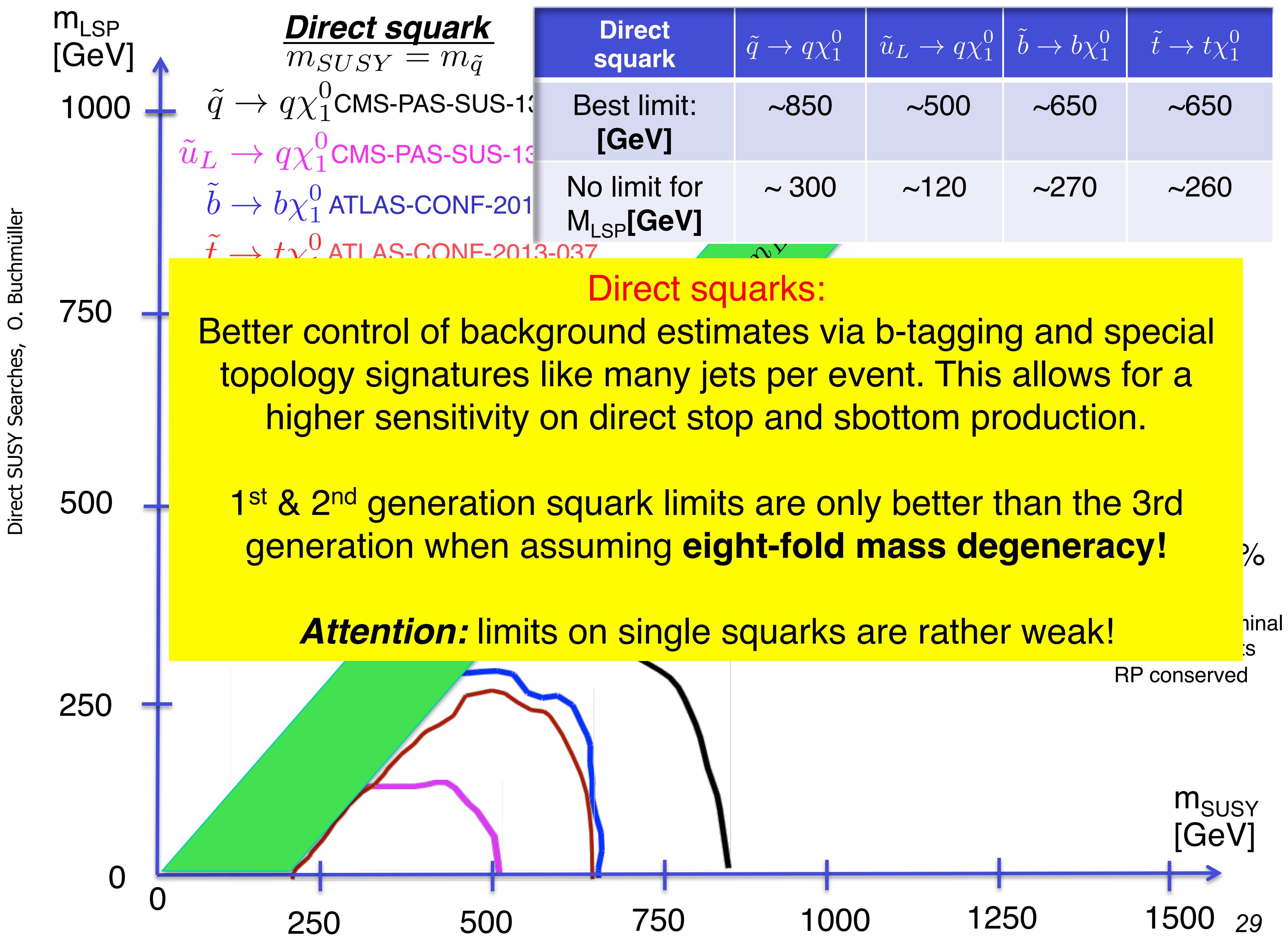


ATLAS-CONF-2013-037
Signature: 1Lepton + jets + E_T^{mis}



Direct squark
$m_{SUSY} = m_{\tilde{q}}$
m_{LSP} [GeV]
$\tilde{q} \to q\chi_1^0$ 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
$m_{SUSY} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
Direct SUSY Searches, O. Buchmüller


Direct SUSY Searches, O. Buchmüller
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
m_{LSP} [GeV]
1000
750
500
250
0
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
P_2
P_1
$\tilde{u}_L$
$\tilde{u}^*_L$
$\bar{q}$
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
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).
CMS Preliminary, 19.5 fb^{-1}, $\sqrt{s}$ = 8 TeV
$pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$\tilde{q}_L + \tilde{q}_R$ ($\tilde{u},\tilde{d},\tilde{s},\tilde{c}$)
one light $\tilde{q}$
m_{LSP} (GeV)
$m_{\tilde{q}}$ (GeV)
95% C.L. upper limit on cross section (pb)



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

Direct squarks:

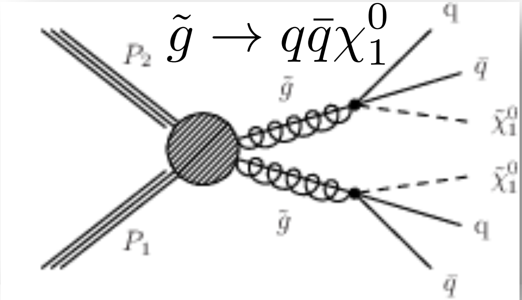
Better control of background estimates via b-tagging and special topology signatures like many jets per event. This allows for a higher sensitivity on direct stop and sbottom production.

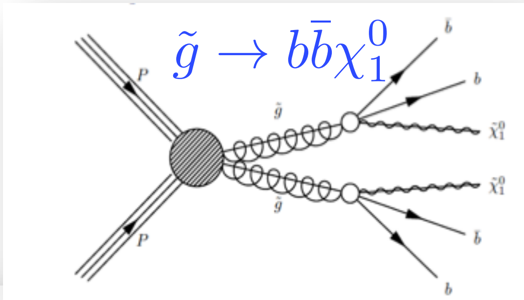
1st & 2nd generation squark limits are only better than the 3rd generation when assuming **eight-fold mass degeneracy!**

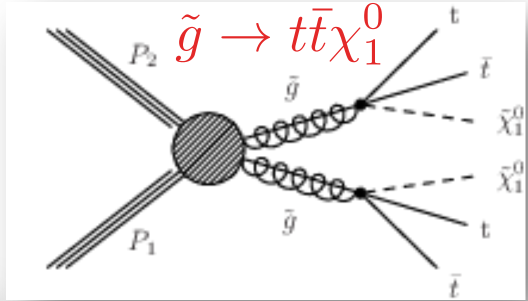
Attention: limits on single squarks are rather weak!

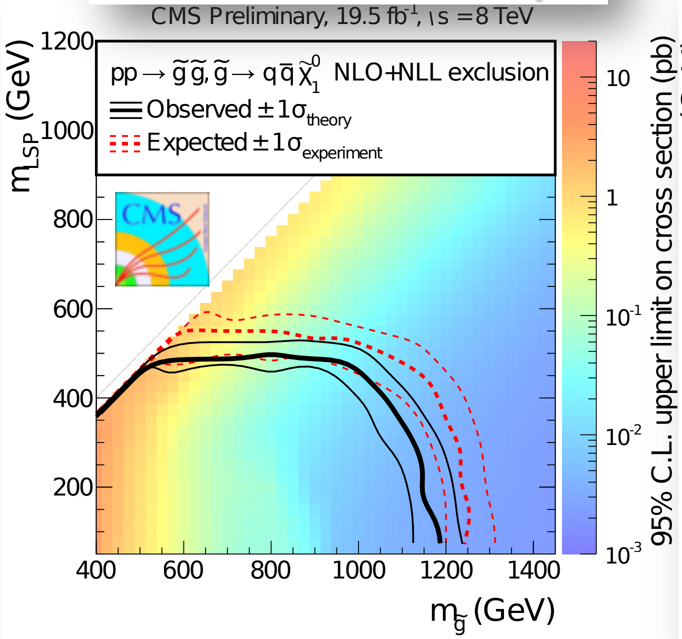
Gluino mediated squark production – limits chosen

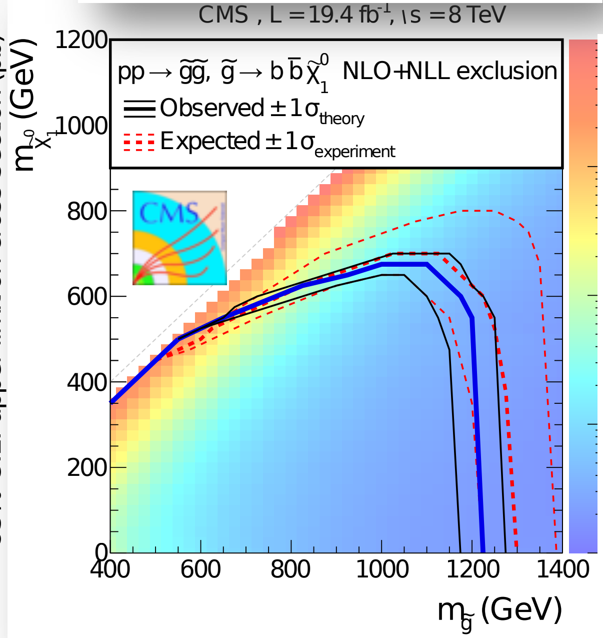
D. Buchmüller

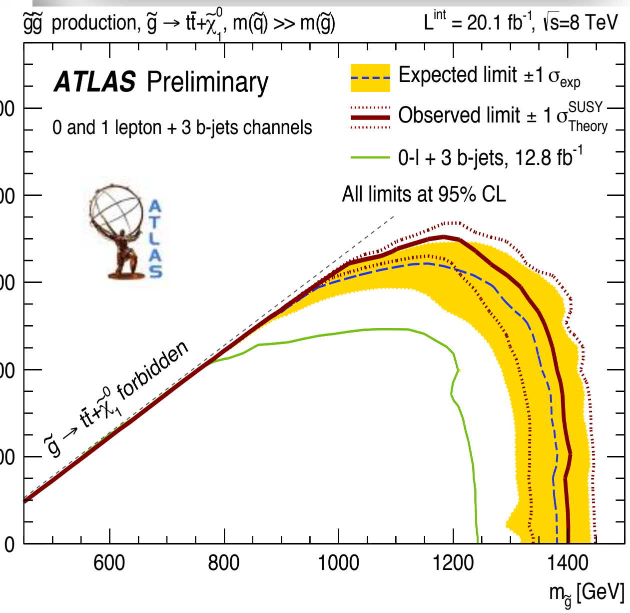








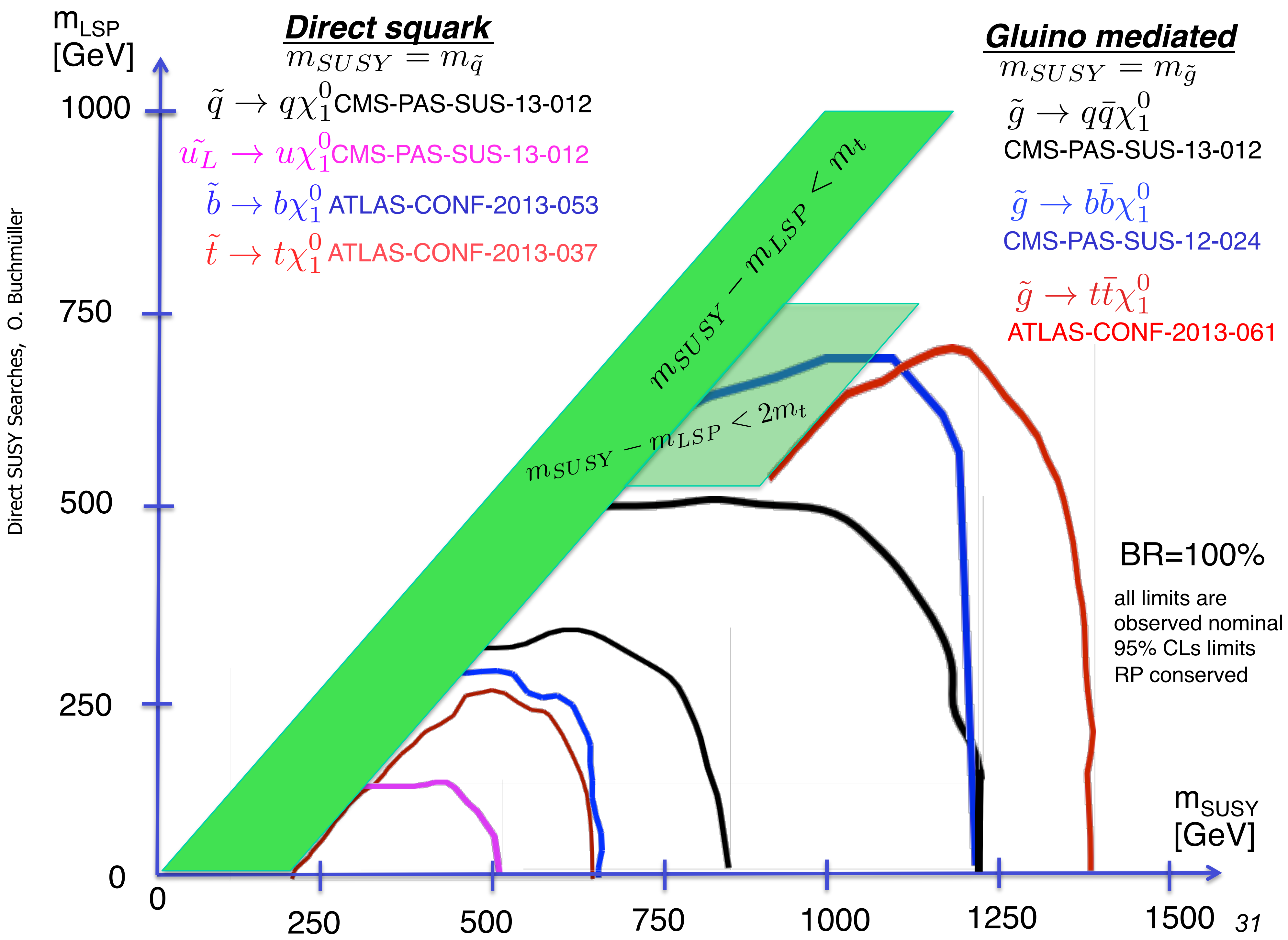




CMS-SUS-PAS-13-012
Signature: Jets + H_T + E_t^{miss}

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

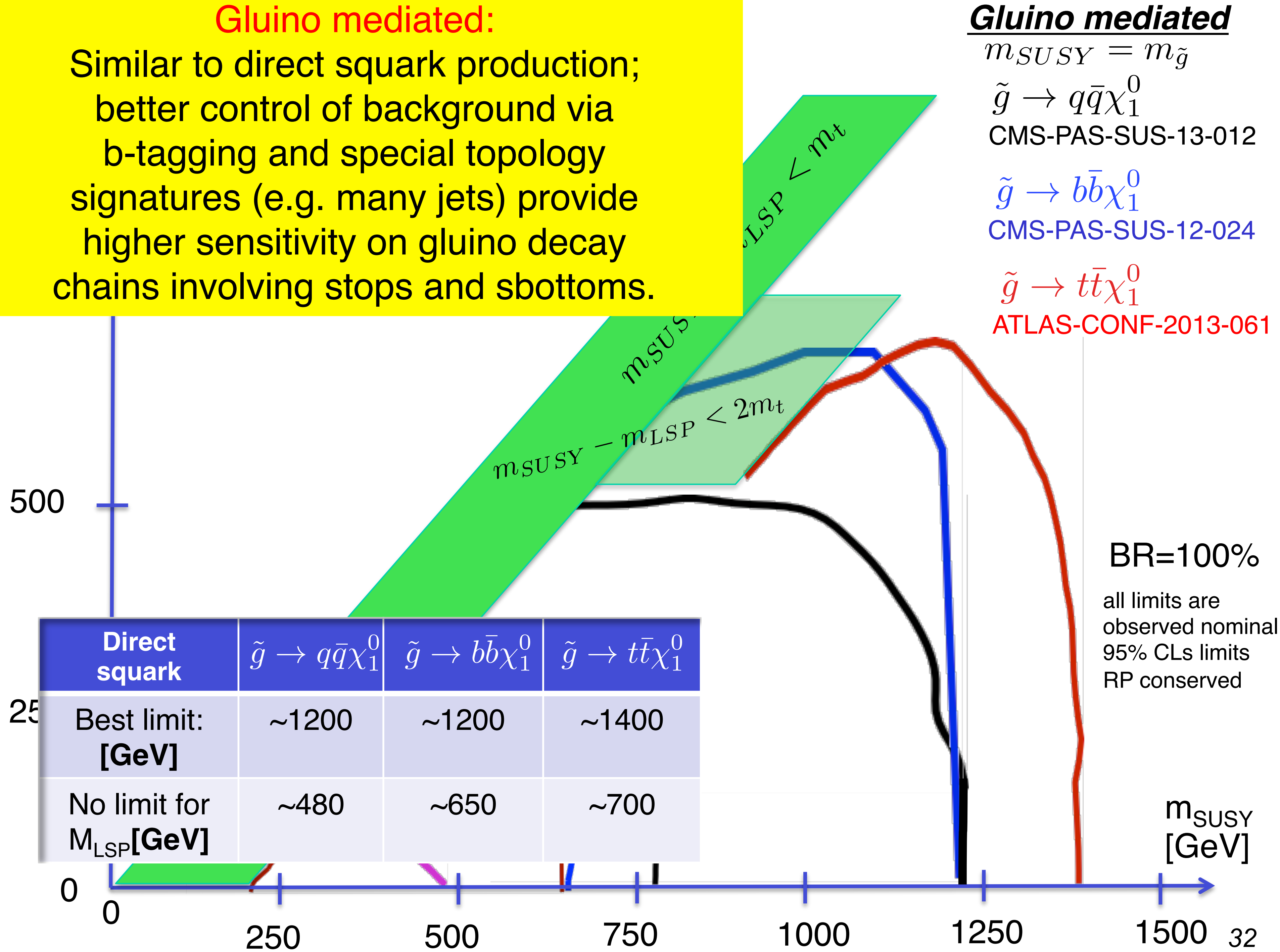
ATLAS-CONF-2013-061
Signature: 0/1 Leptons + 3 b-tag + E_t^{mis}



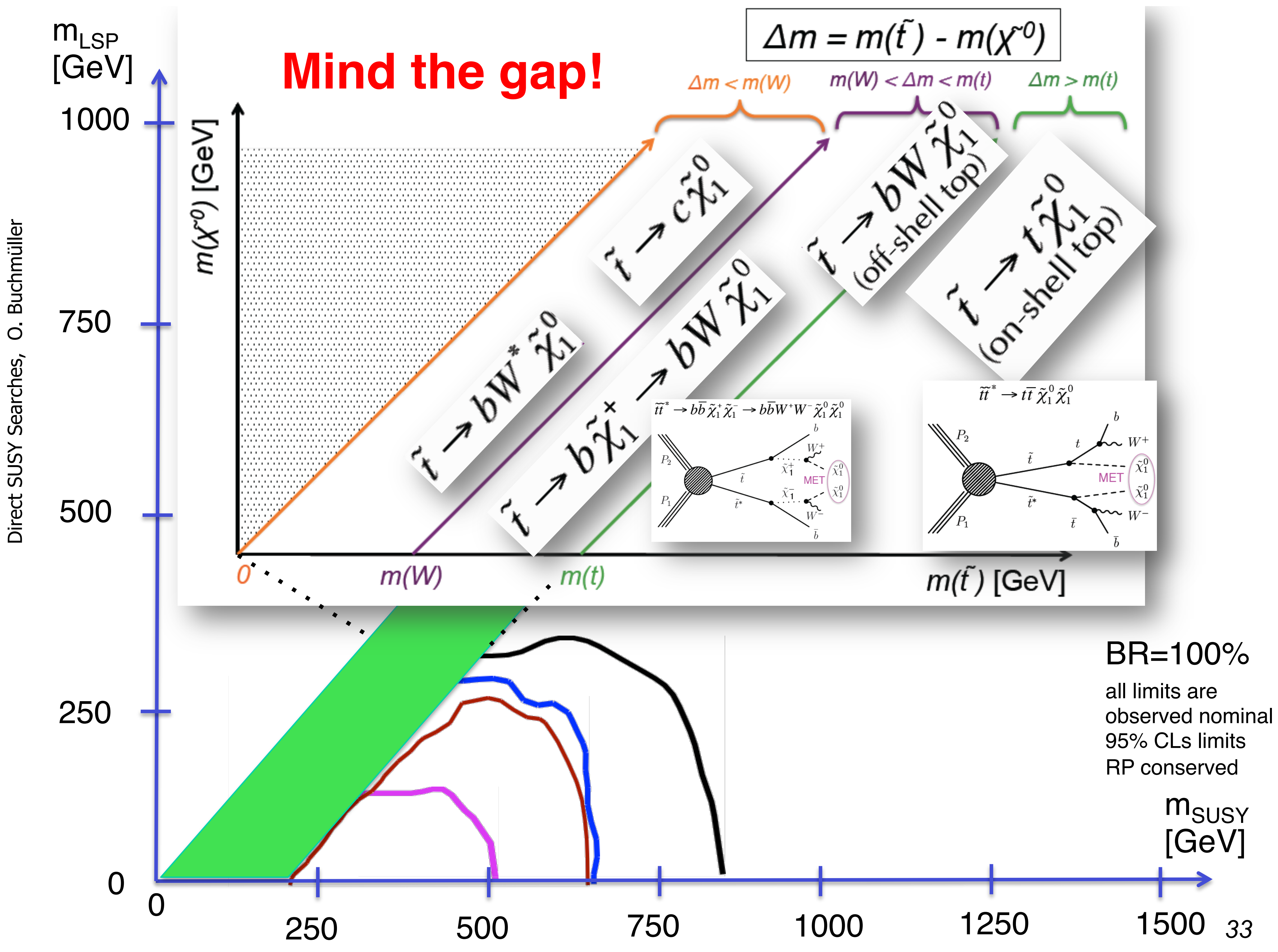
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{u_L} \rightarrow u\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \rightarrow b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
CMS-PAS-SUS-13-012
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
m_{LSP} [GeV]
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 SUSY Searches, O. Buchmüller

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.

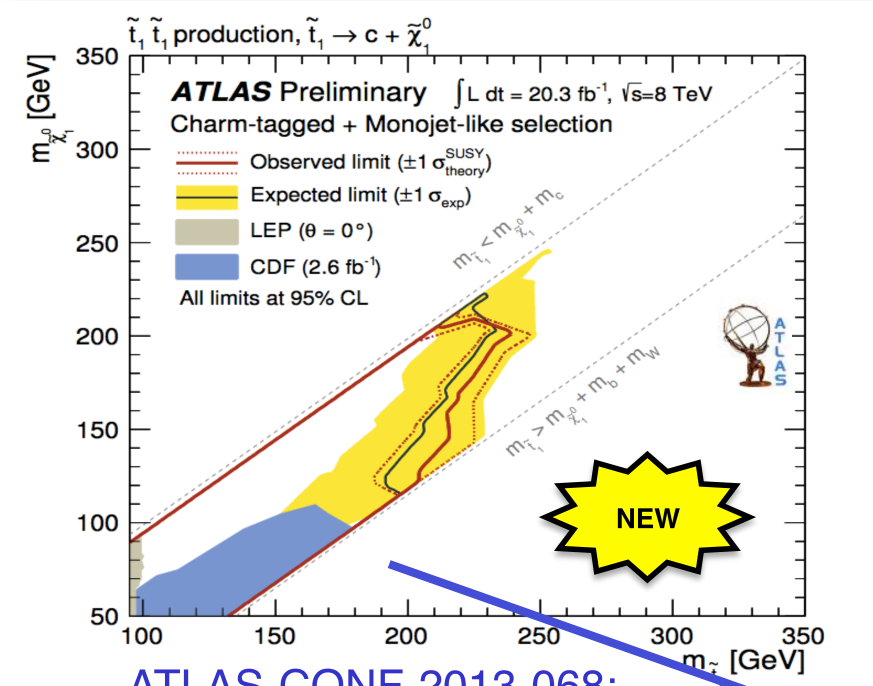


Direct squark	$\tilde{g} \rightarrow q\bar{q}\chi_1^0$	$\tilde{g} \rightarrow b\bar{b}\chi_1^0$	$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
Best limit: **[GeV]**	~1200	~1200	~1400
No limit for M_{LSP}**[GeV]**	~480	~650	~700

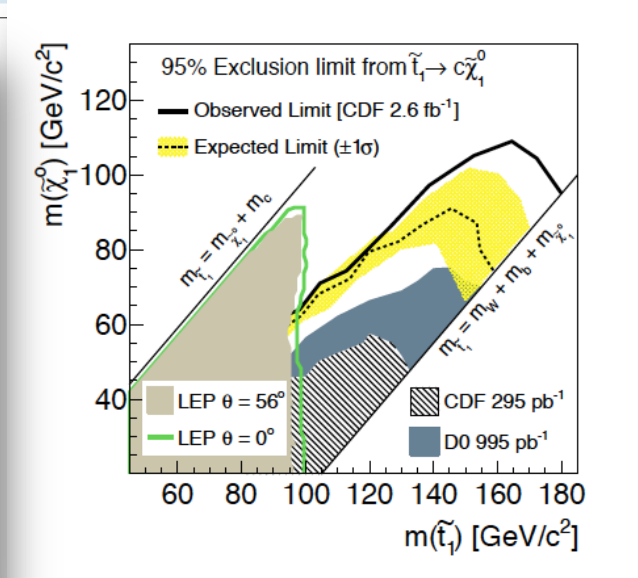


Mind the gap!
$\Delta m = m(\tilde{t}) - m(\tilde{\chi}^0)$
$\Delta m < m(W)$
$m(W) < \Delta m < m(t)$
$\Delta m > m(t)$
$m(\tilde{\chi}^0)$ [GeV]
$m(\tilde{t})$ [GeV]
0
m(W)
m(t)
$\tilde{t} \to c\tilde{\chi}_1^0$
$\tilde{t} \to bW^*\tilde{\chi}_1^0$
$\tilde{t} \to bW\tilde{\chi}_1^0$ (off-shell top)
$\tilde{t} \to t\tilde{\chi}_1^0$ (on-shell top)
$\tilde{t} \to b\tilde{\chi}_1^+ \to bW\tilde{\chi}_1^0$
$\tilde{t}\tilde{t}^* \to b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \to b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
$\tilde{t}\tilde{t}^* \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$
MET
m_{LSP} [GeV]
1000
750
500
250
0
m_{SUSY} [GeV]
250
500
750
1000
1250
1500
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
Direct SUSY Searches, O. Buchmüller

Dedicated searches for direct stop-pair production



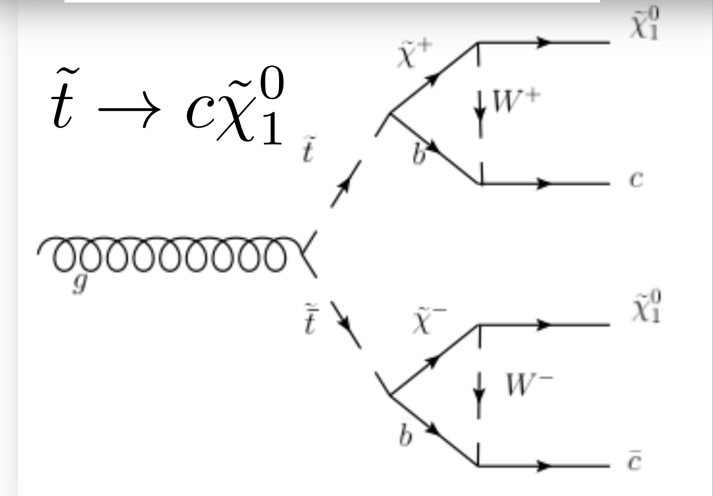
ATLAS-CONF-2013-068:

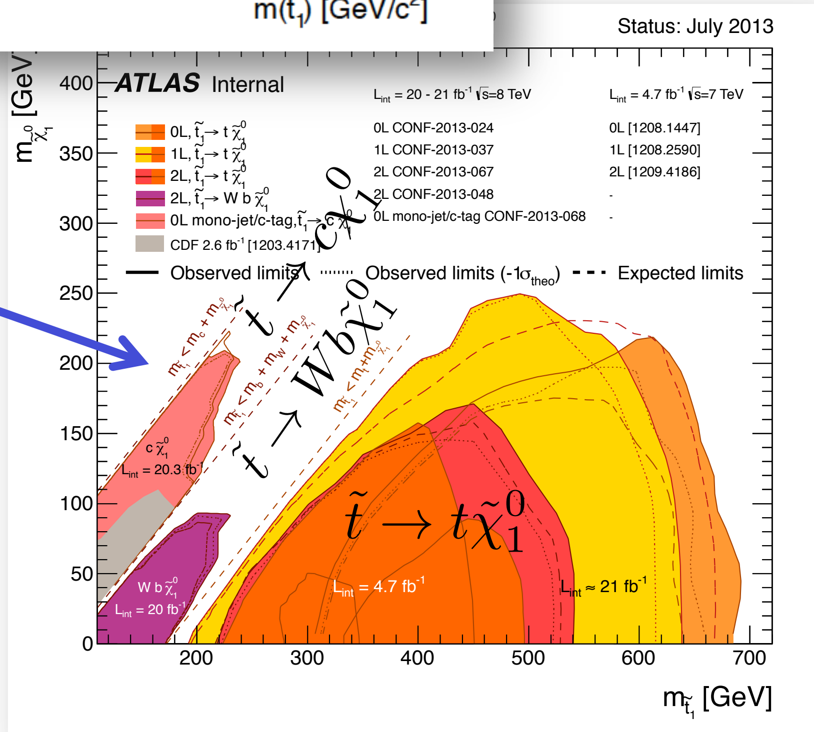


LEP: LEPSUSY WG/04-01.1

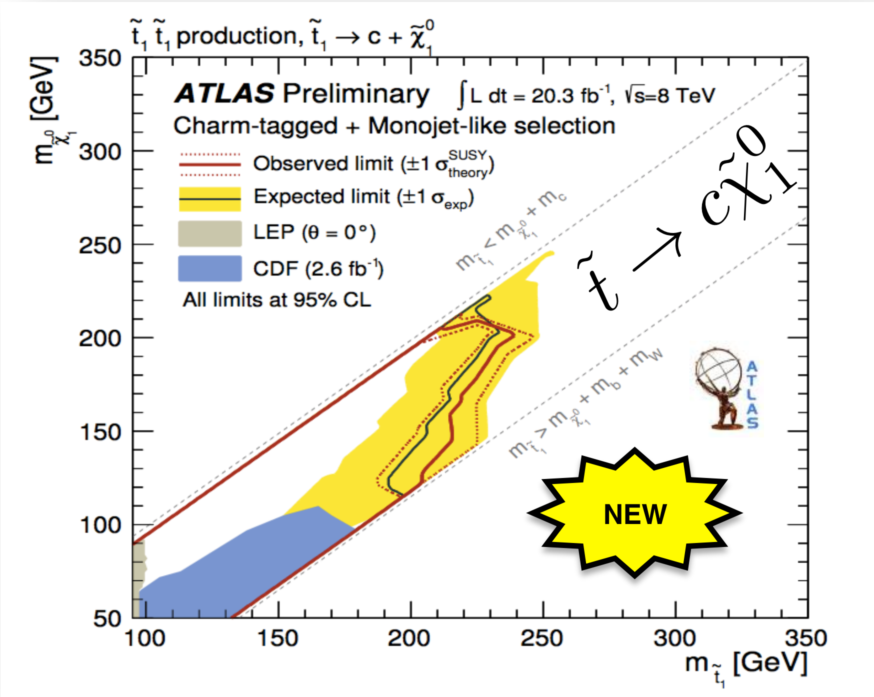
CDF: 1203.4171

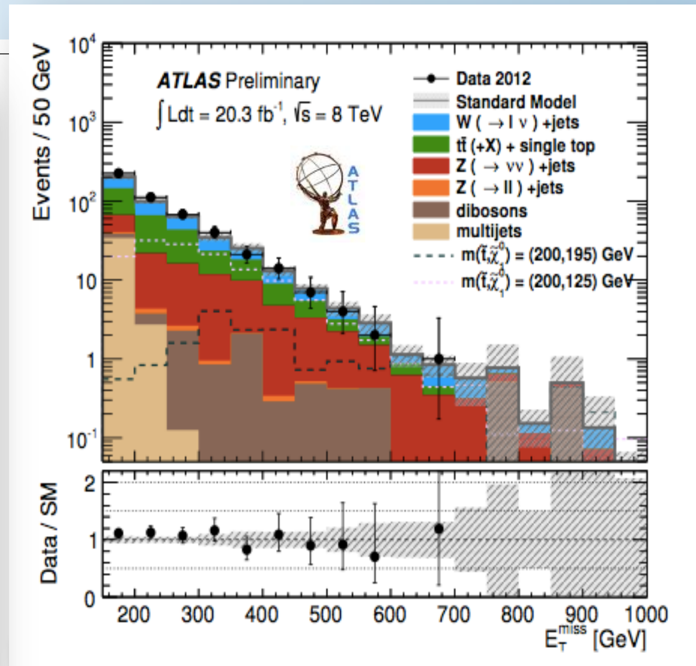
D0: 0803.2263





Stop decay to charm and neutralino



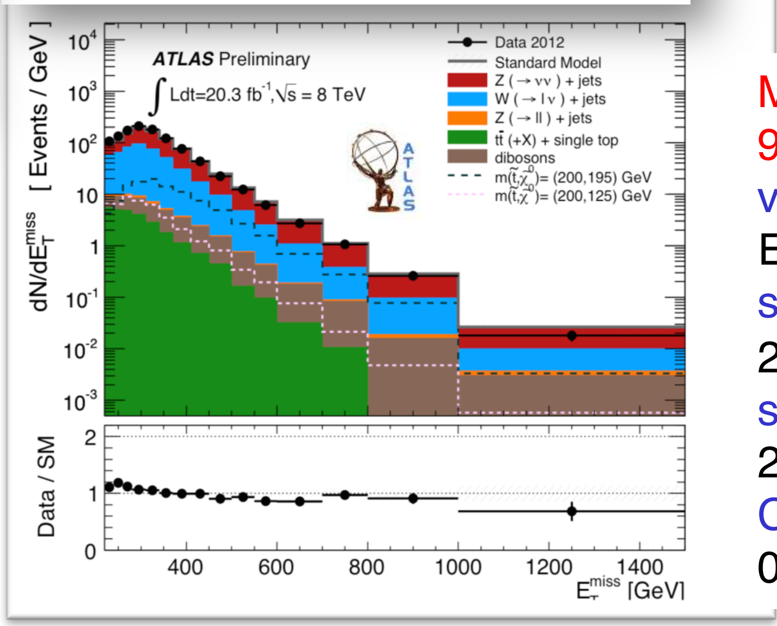


c-Tag:
95% excl.
visible XS:
$\epsilon\sigma$=0.7fb
signal obs:
13 events
signal exp:
14^{+5}_{-4} events
CL_B:
0.45

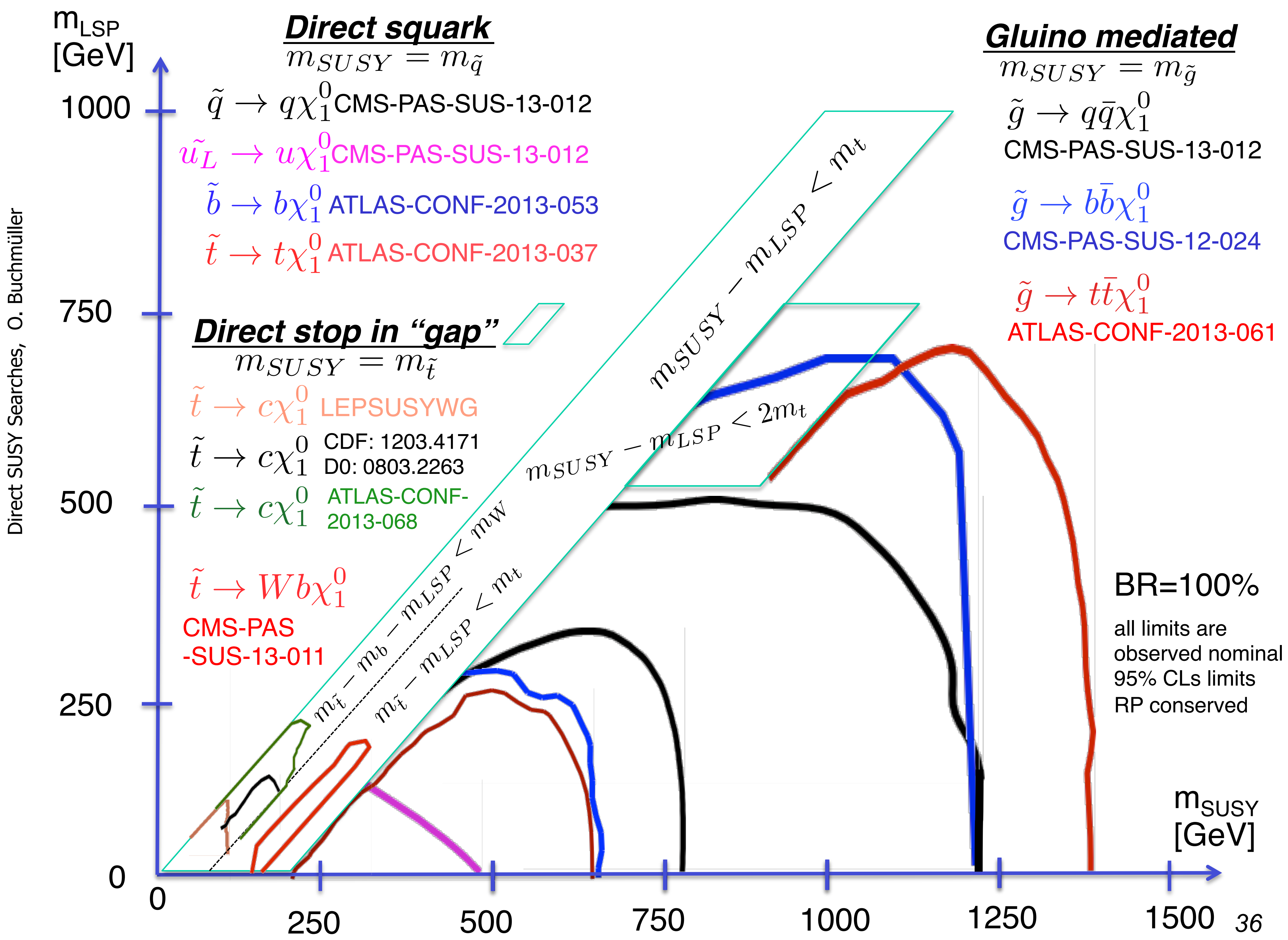
ATLAS-CONF-2013-068:
Two different selections:
- Monojet-like selection

to cover region close to 'diagonal"
- MVA based c-tag selection

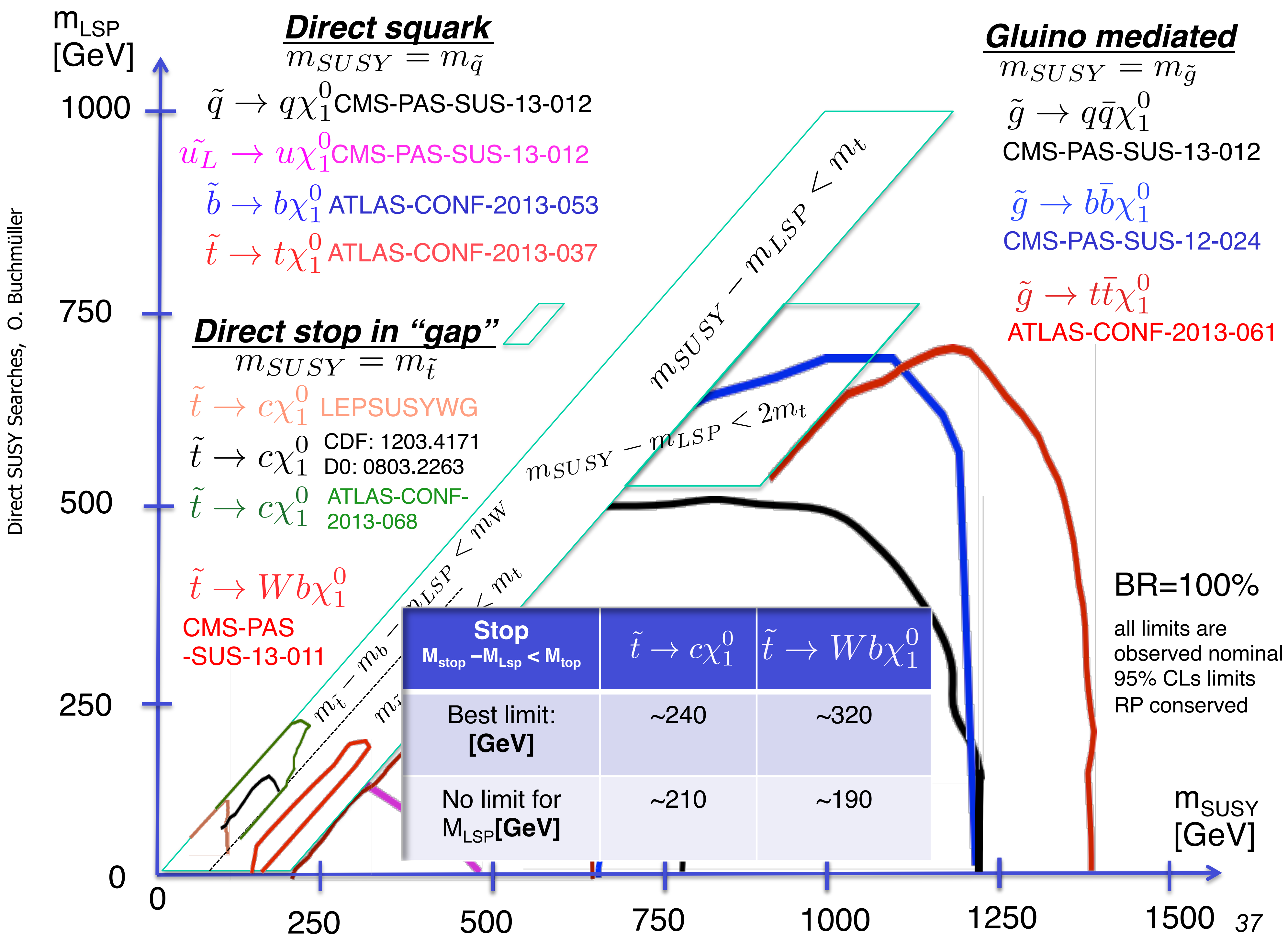
for remaining region



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

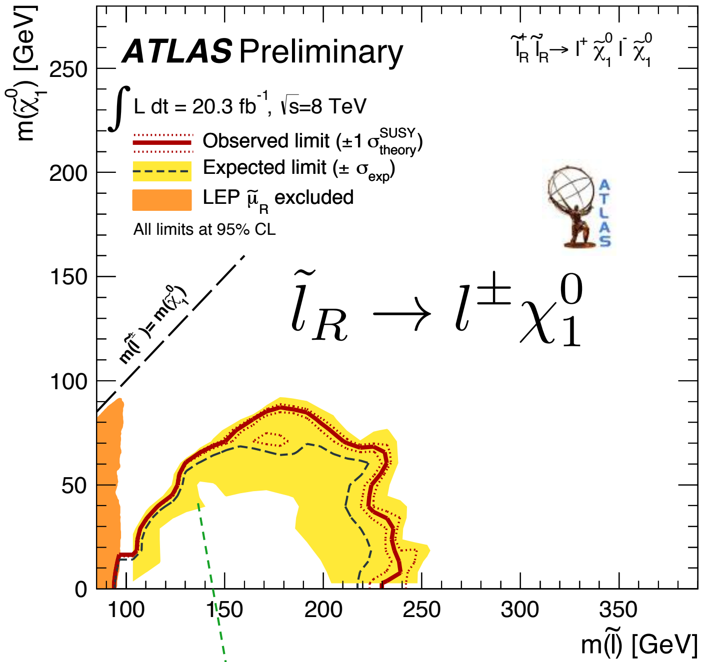


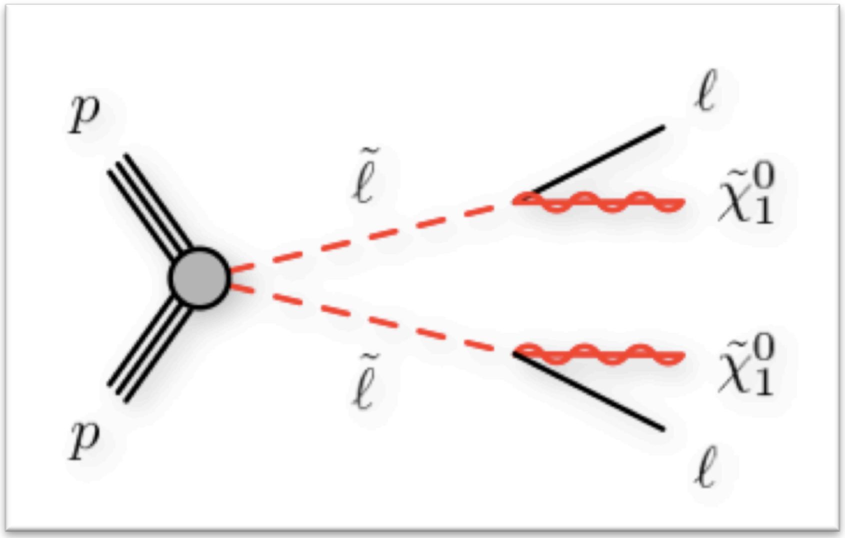
m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$ 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
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
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_SUSY [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
Direct SUSY Searches, O. Buchmüller


Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{u_L} \rightarrow u\chi_1^0$ 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
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$ LEPSUSYWG
$\tilde{t} \rightarrow c\chi_1^0$ CDF: 1203.4171 D0: 0803.2263
$\tilde{t} \rightarrow c\chi_1^0$ ATLAS-CONF-2013-068
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS-PAS -SUS-13-011
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
CMS-PAS-SUS-13-012
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
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
m_{LSP} [GeV]
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500
Direct SUSY Searches, O. Buchmüller
Stop $M_{stop} - M_{Lsp} < M_{top}$
$\tilde{t} \rightarrow c\chi_1^0$
$\tilde{t} \rightarrow Wb\chi_1^0$
Best limit: [GeV]
~240
~320
No limit for M_{LSP} [GeV]
~210
~190

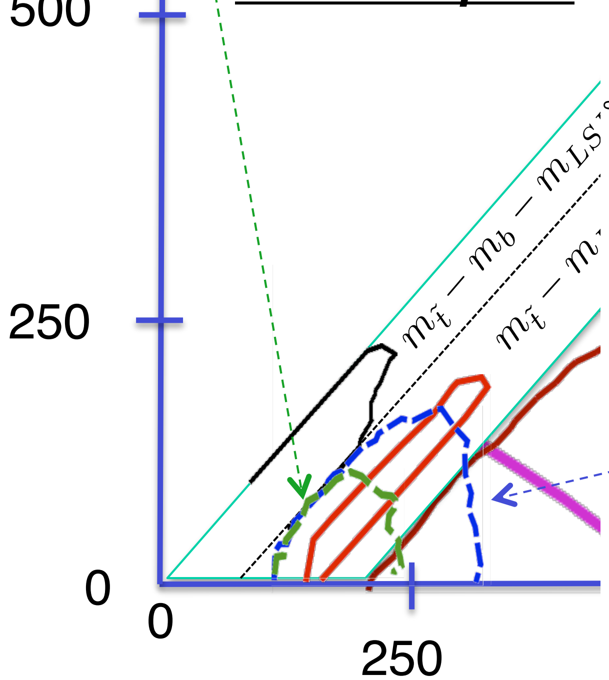
Direct SUSY Searches, O. Buchmüller

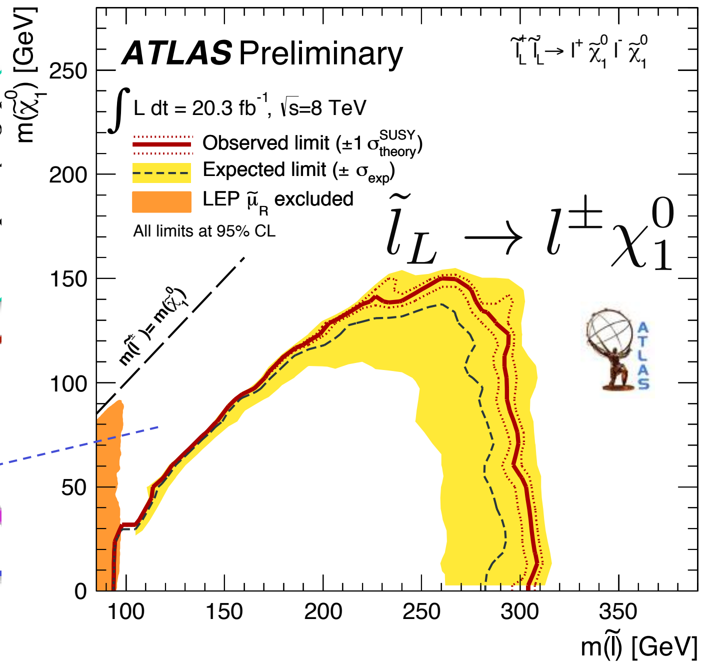
Direct slepton production

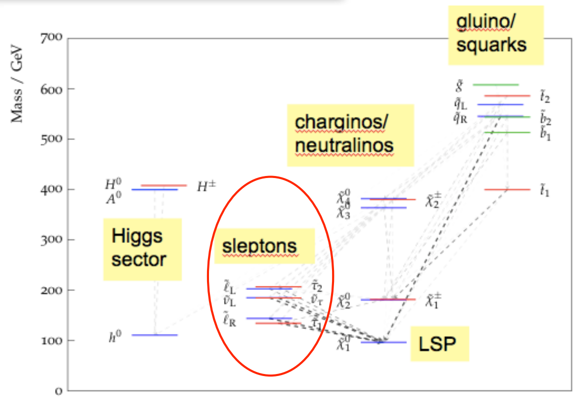




Direct slepton



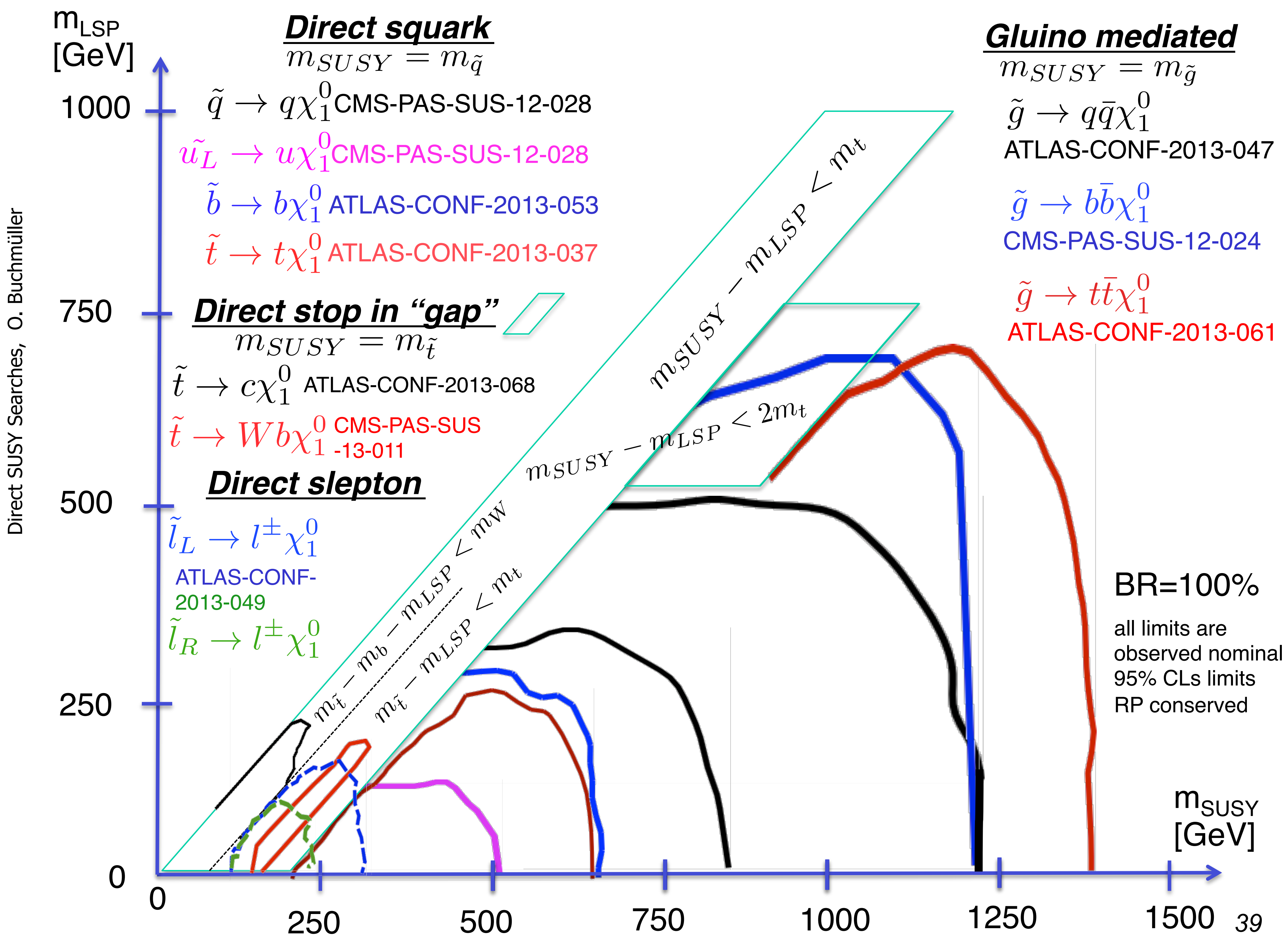




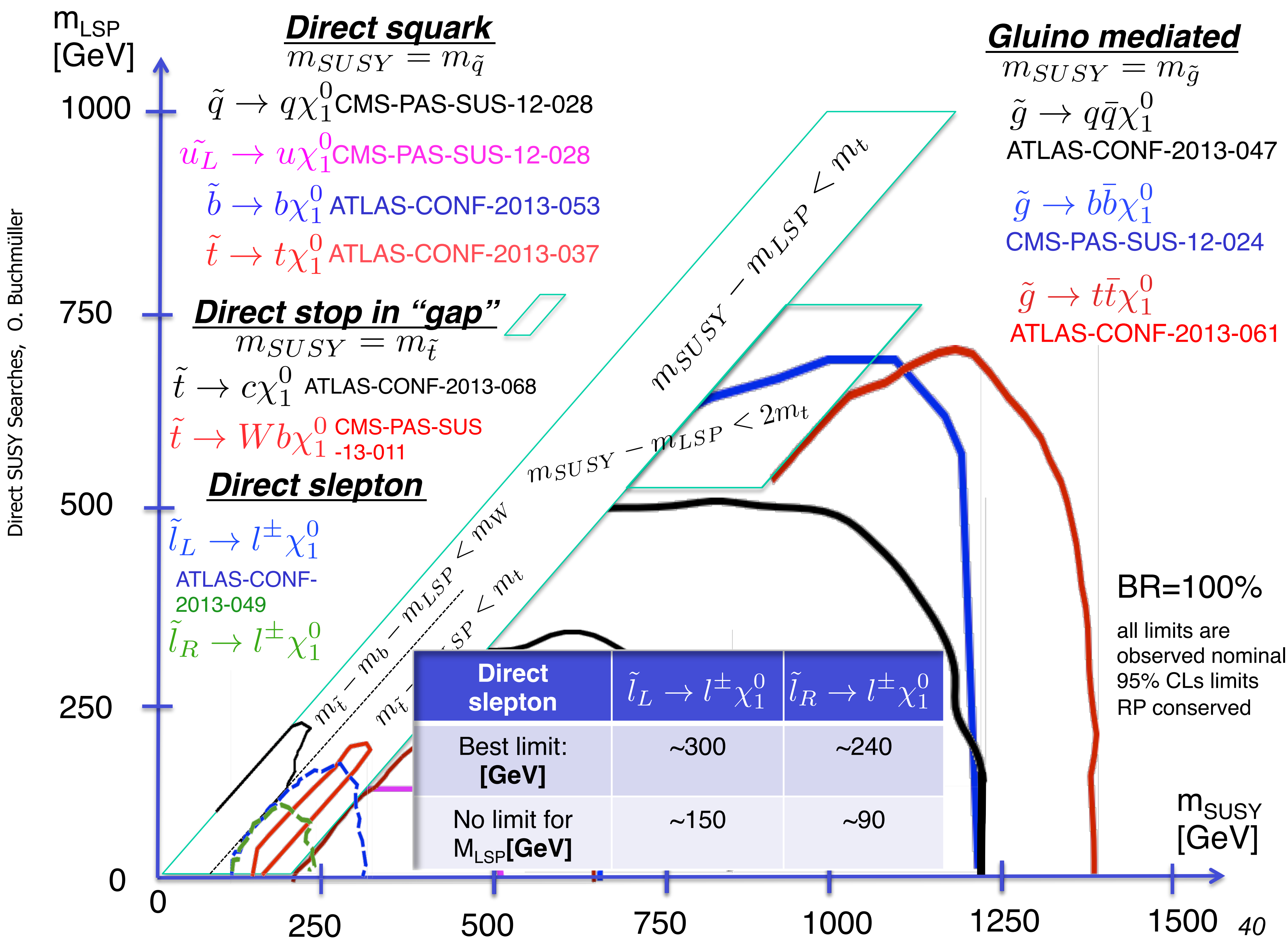
ATLAS-CONF-2013-049

Signature

2 lepton + E_T^{miss}

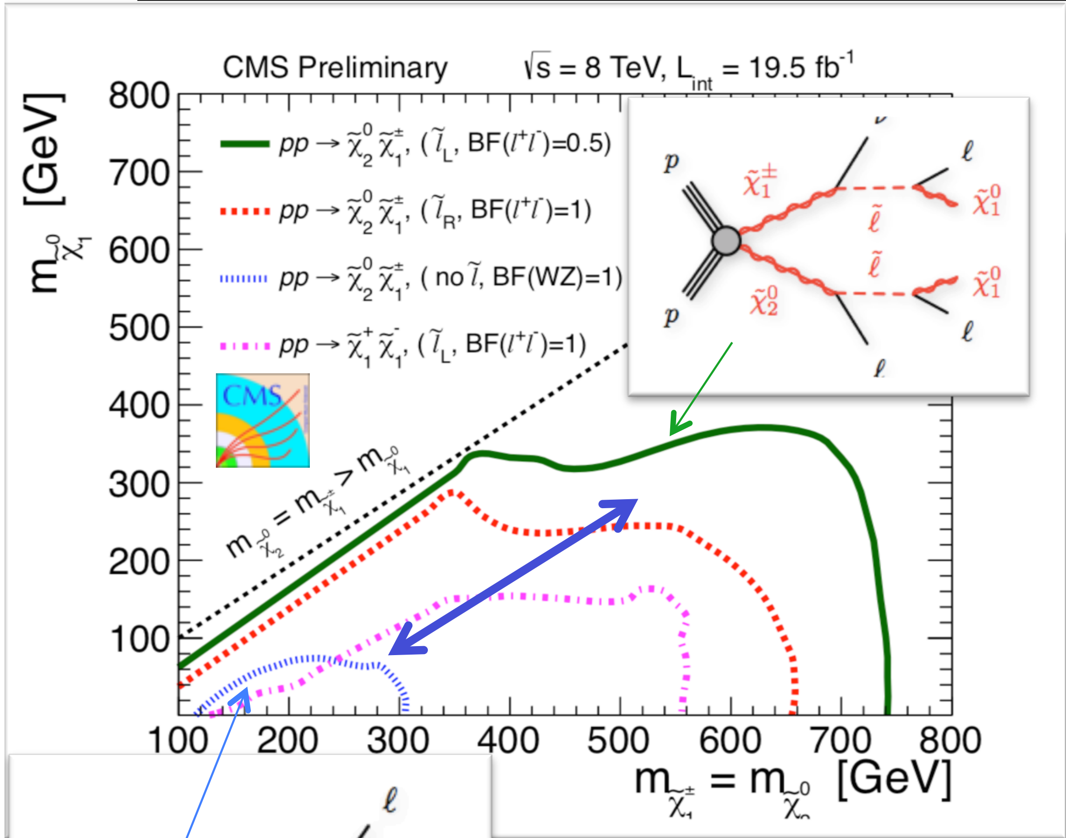


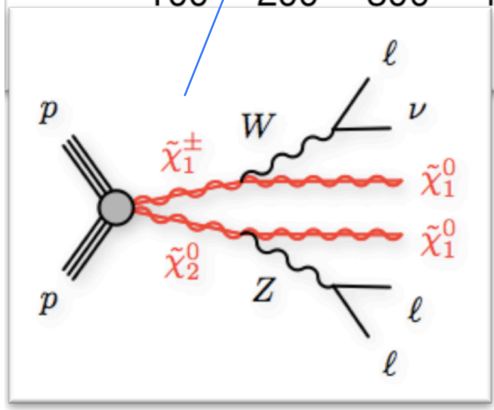
Direct SUSY Searches, O. Buchmüller
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$ 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
$\tilde{l}_R \to l^{\pm}\chi_1^0$
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
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500



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

Direct chargino/neutralino production



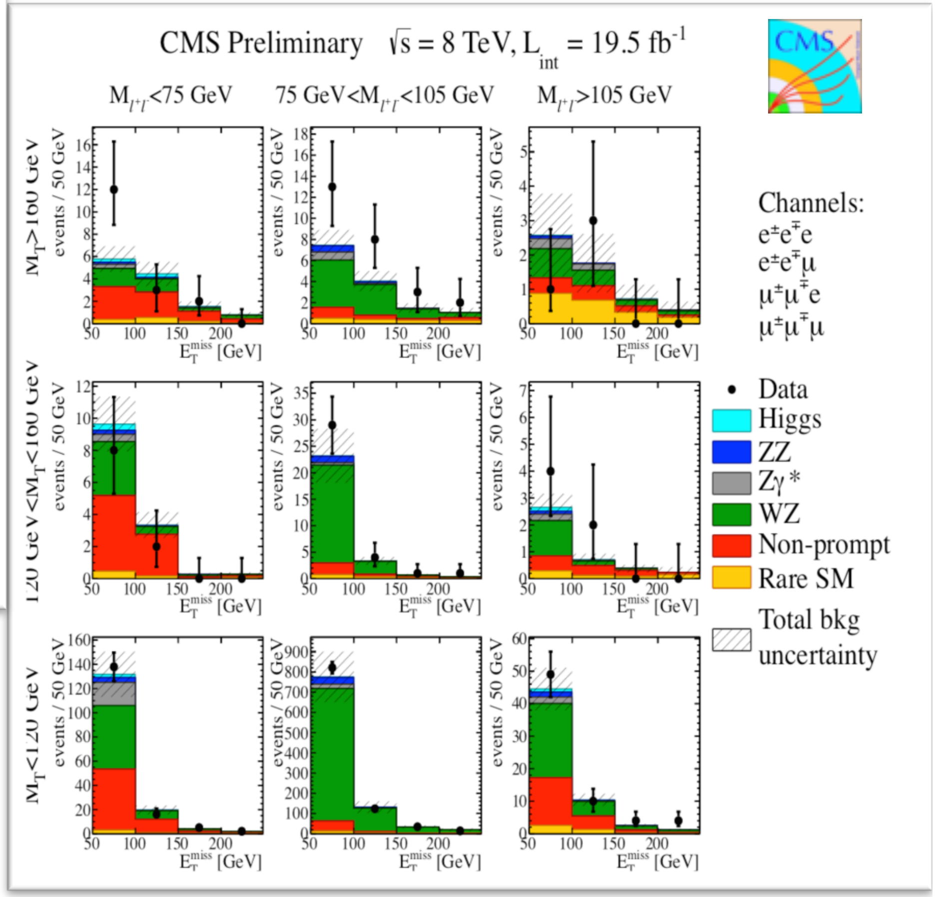


light slepton "easy"

CMS-PAS-SUS-13-006

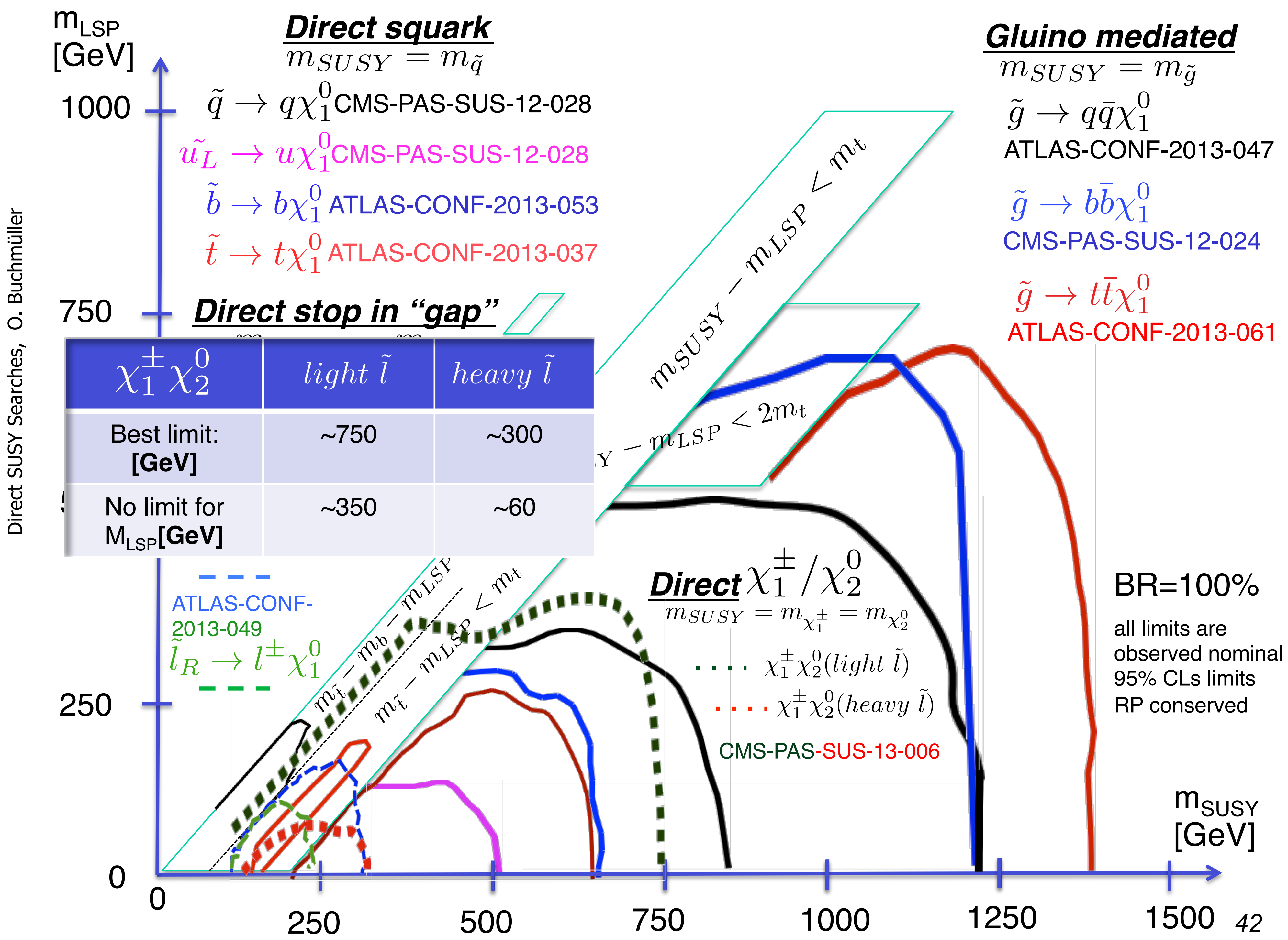
NEW

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

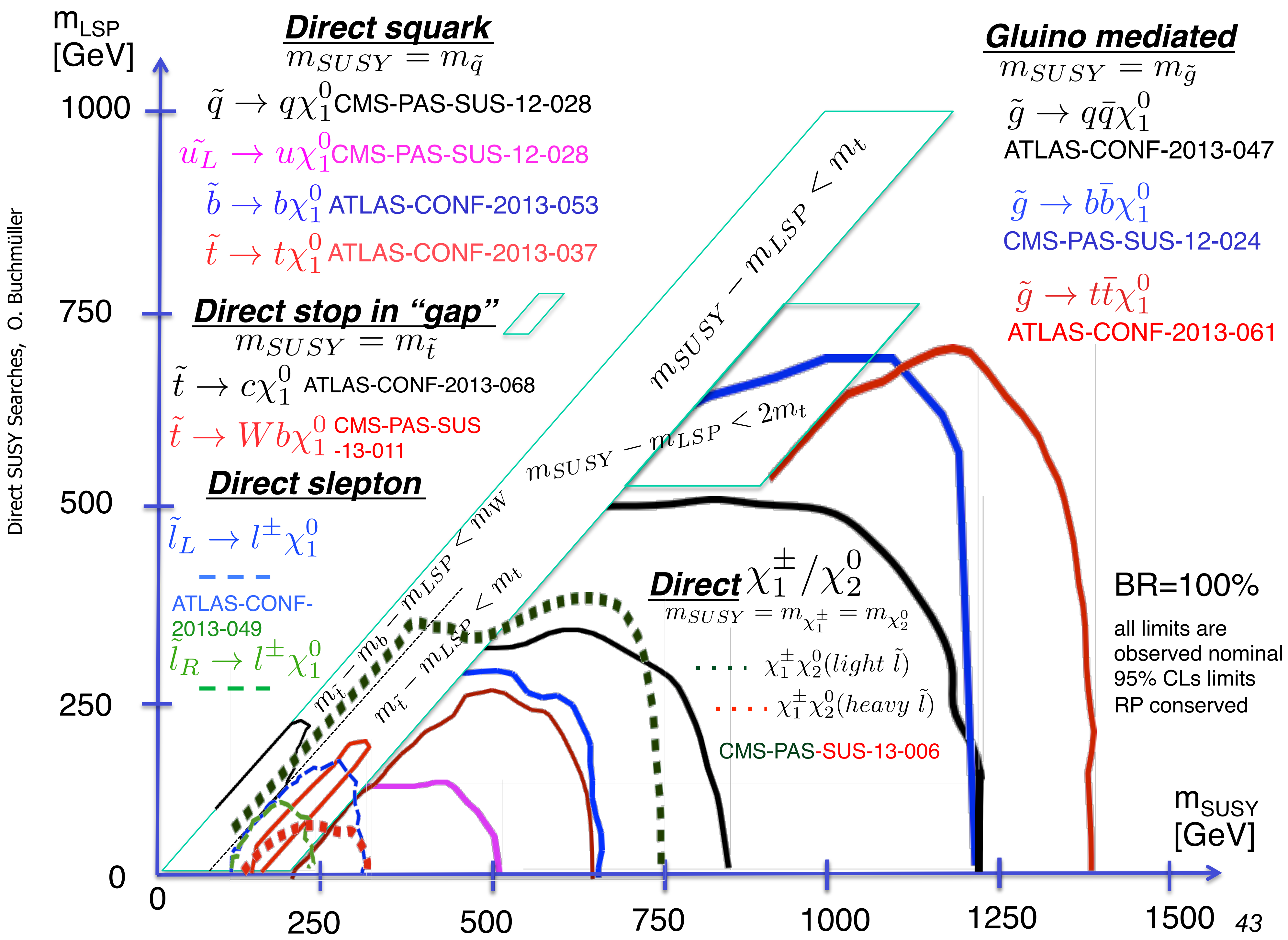


heavy slepton "hard(er)"

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

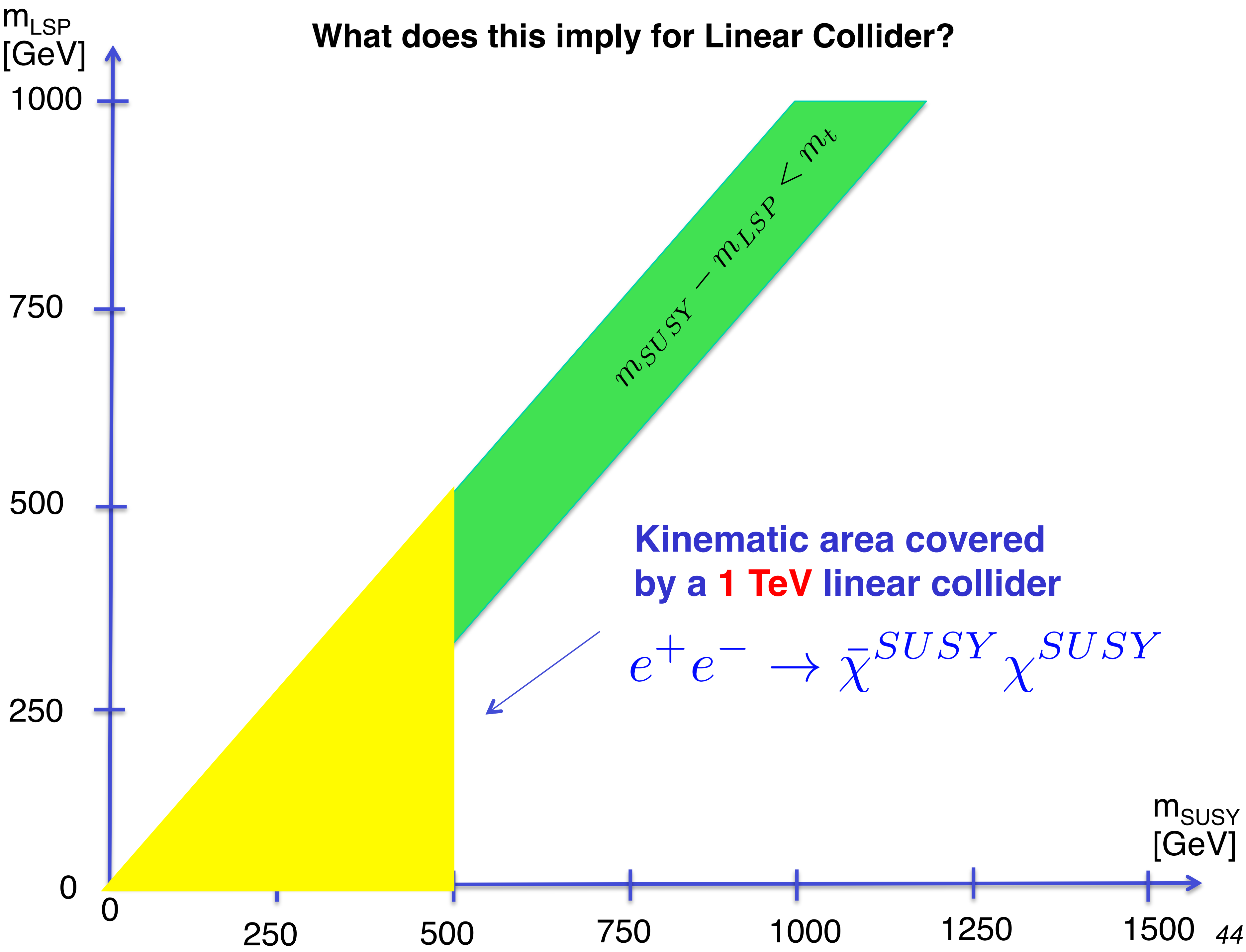


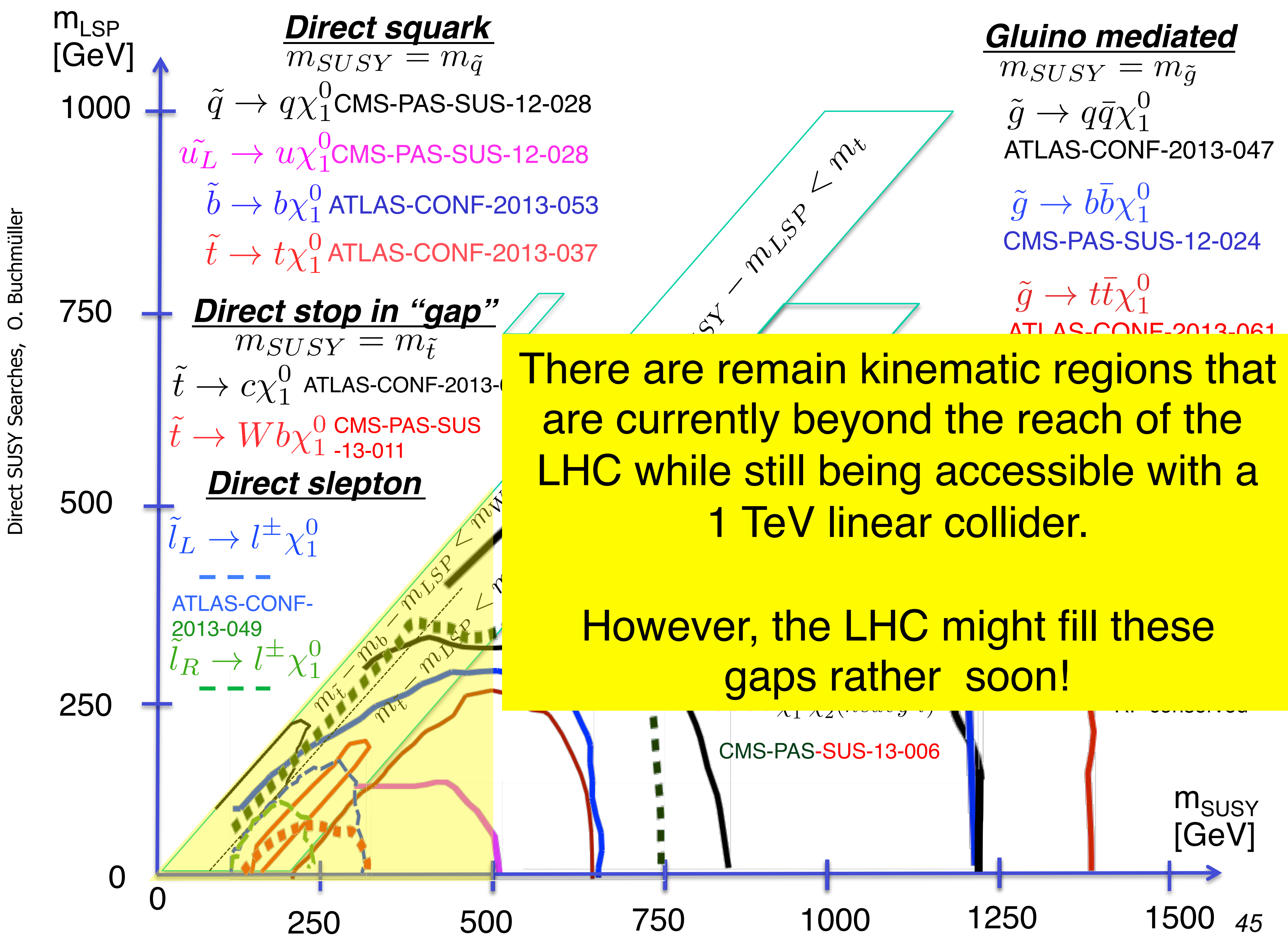
$\chi_1^{\pm}\chi_2^0$	$light\ \tilde{l}$	$heavy\ \tilde{l}$
Best limit: **[GeV]**	~750	~300
No limit for M_{LSP}**[GeV]**	~350	~60



m_{LSP} [GeV]
Direct SUSY Searches, O. Buchmüller
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
$\tilde{l}_R \to l^\pm\chi_1^0$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
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
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
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

What does this imply for Linear Collider?





There are 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!

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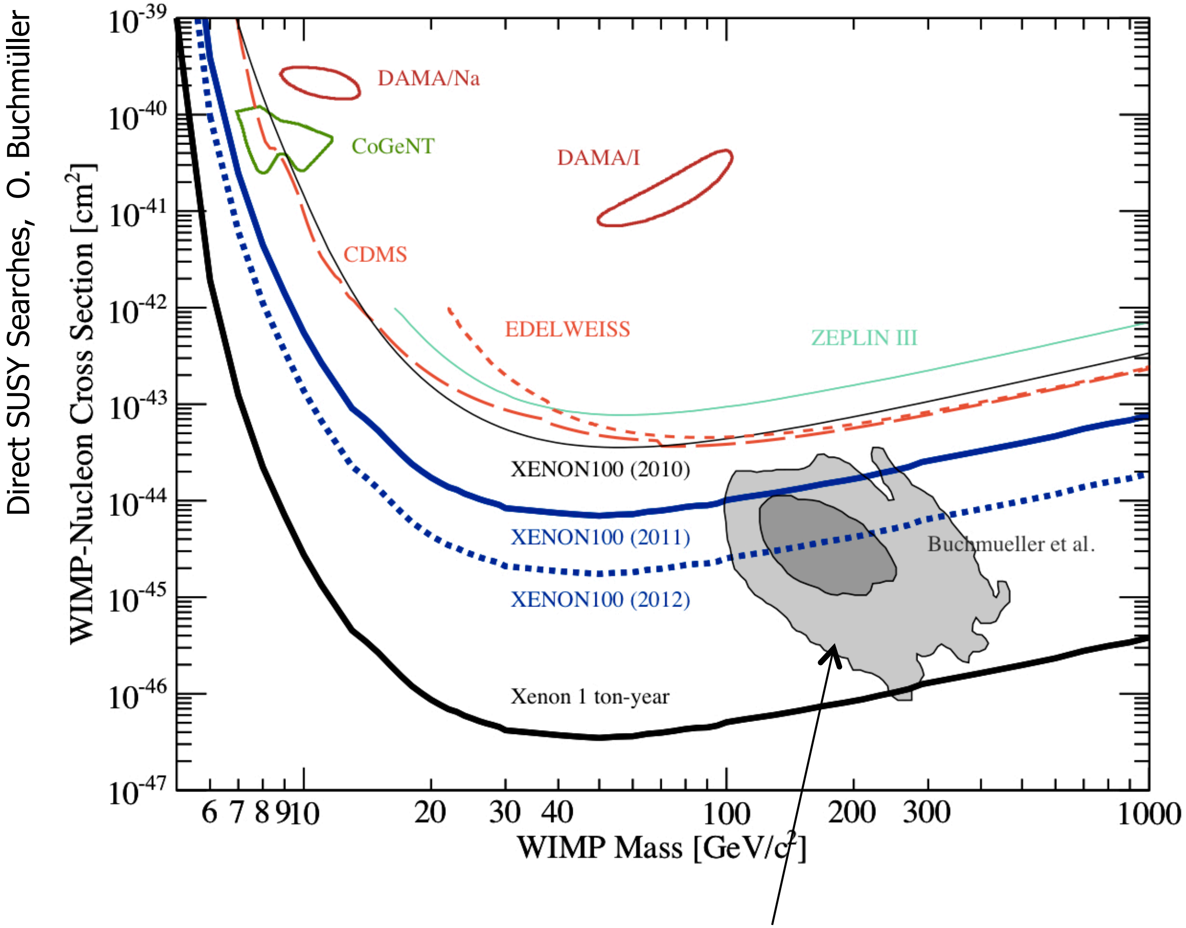
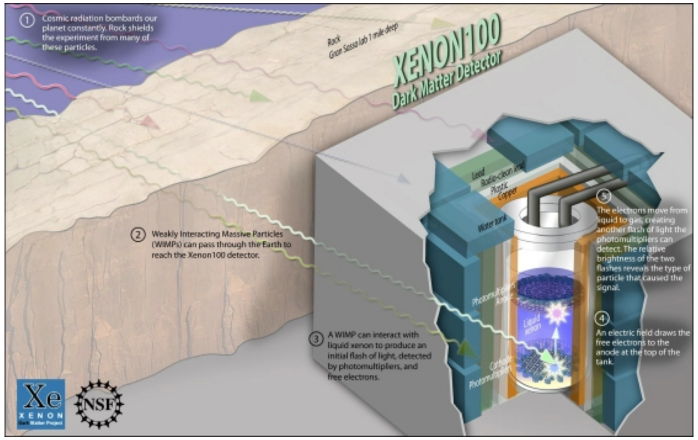
Direct Dark Matter Detection Experiments



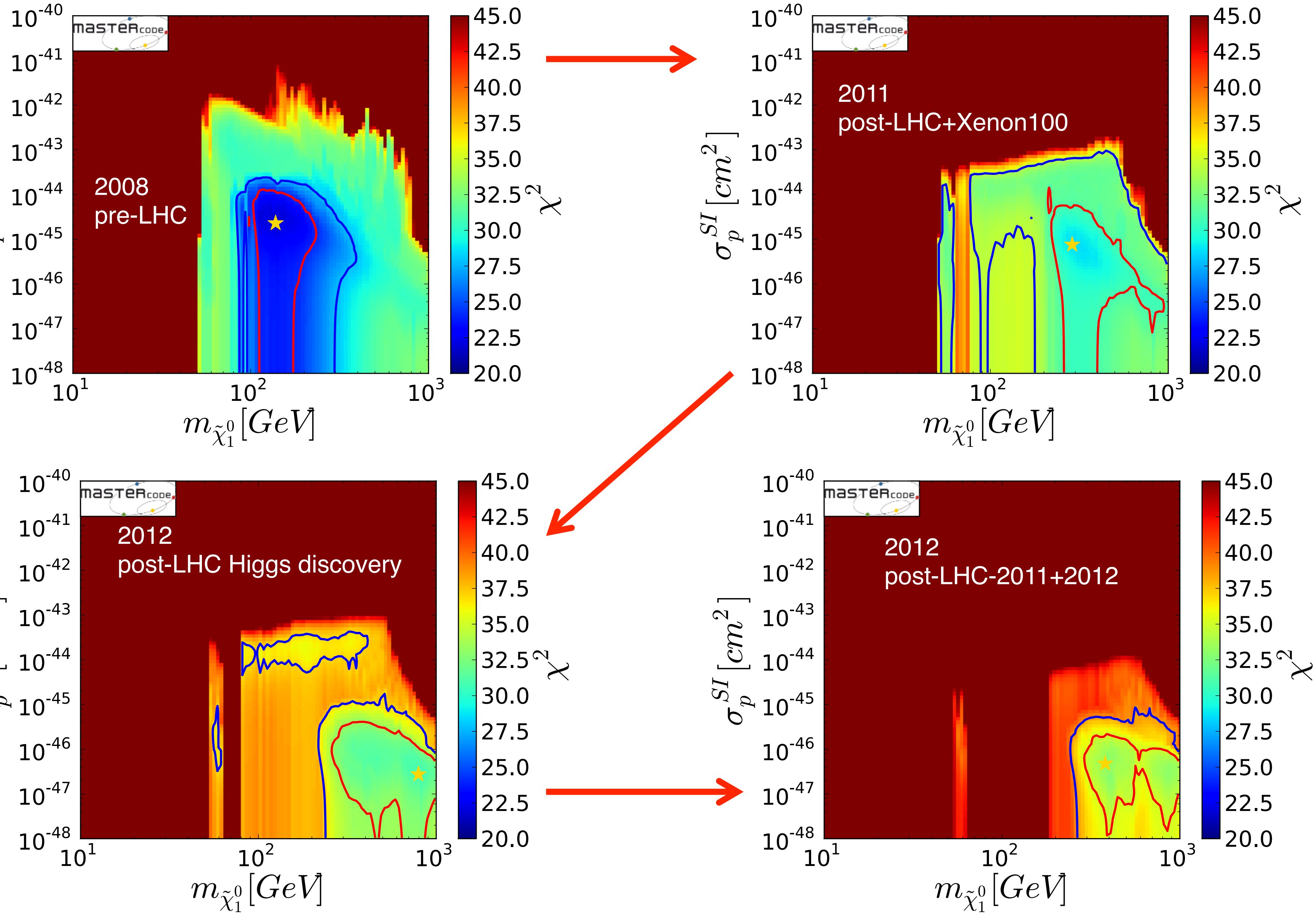
Expectation from global SUSY fits in the CMSSM



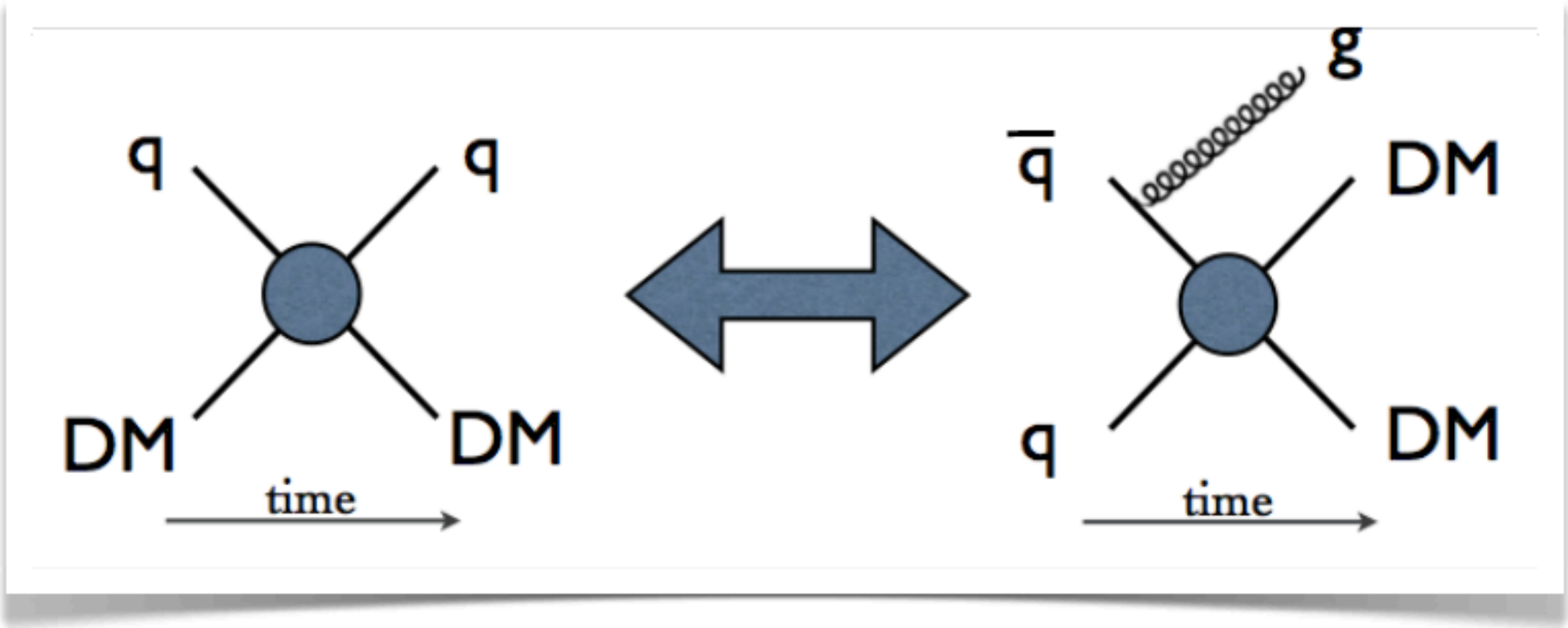
Example:
The XENON100 experiment is located deep underground at the Gran Sasso National Laboratory in Italy.

62 kg liquid Xenon target
100 days of data taking
1.8±0.6 events expected
3 events observed
$\Rightarrow$Exclude 7.0×10^{-45} cm^2
for a $M_{WIMP} = 50$ GeV at 90% CL.

SUSY & Dark Matter: Evolution with time

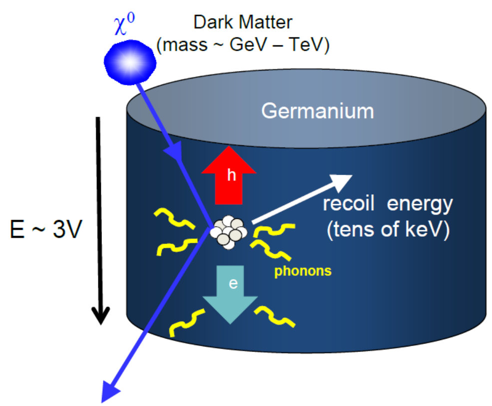


Dark Matter Searches: Direct Detection vs Colliders



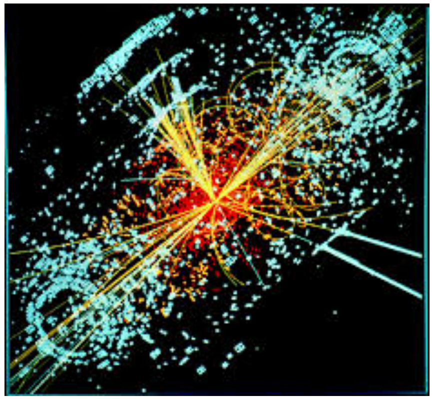
Direct Detection Experiments

- DM-nucleus scattering

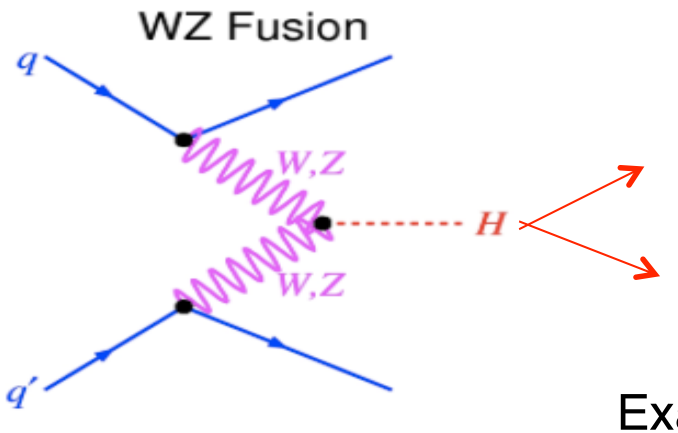


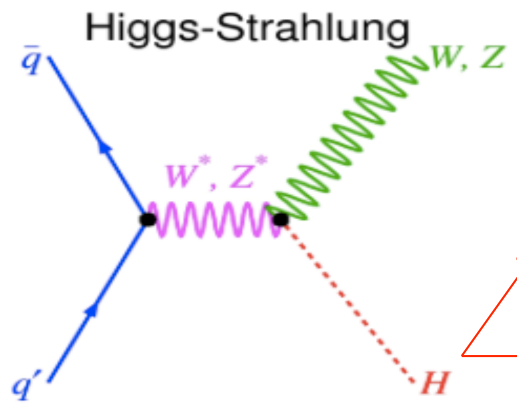
Collider Experiments

- Pair-production of DM
- missing energy signature

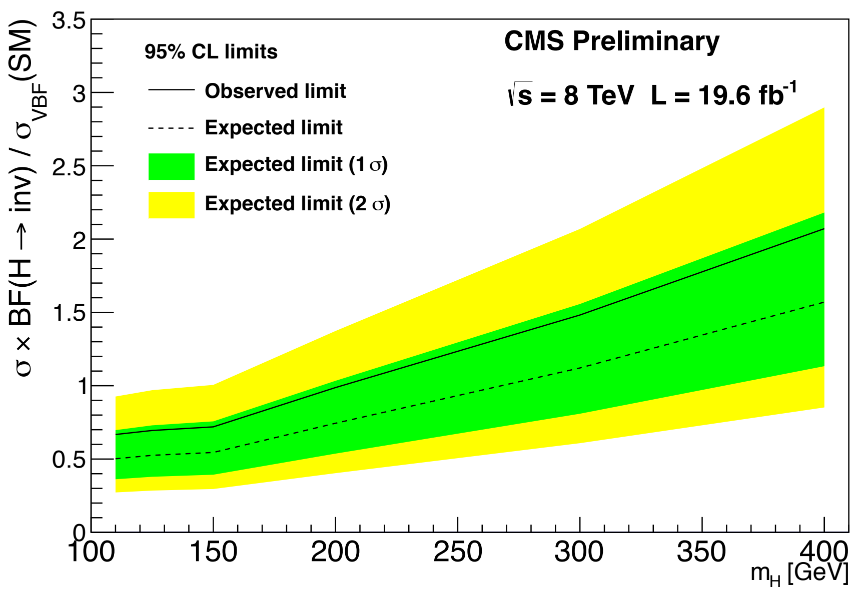


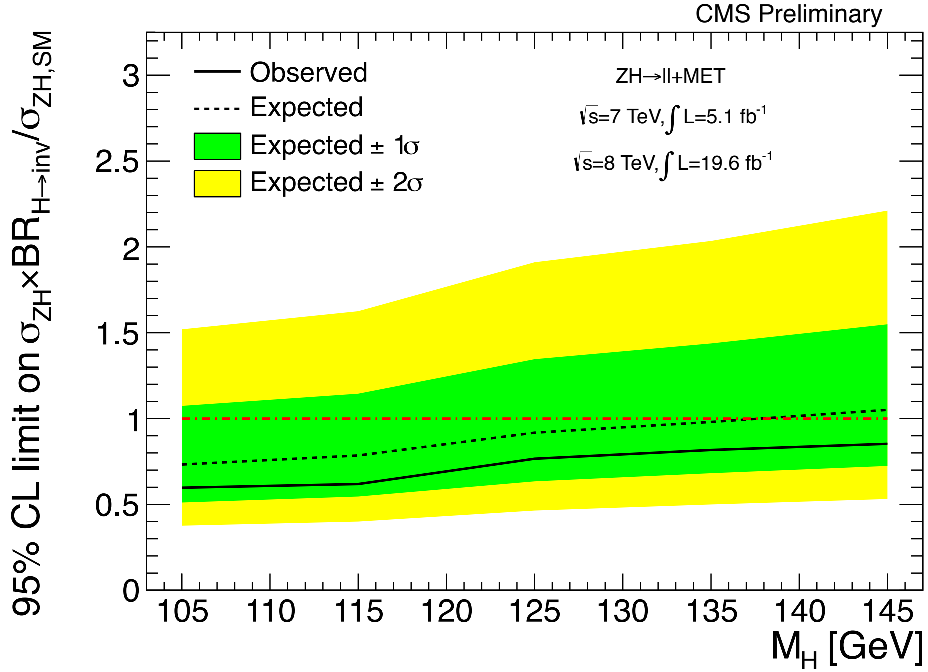
Dark Matter from invisible Higgs searches





Example CMS





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

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

Dark Matter from invisible Higgs searches

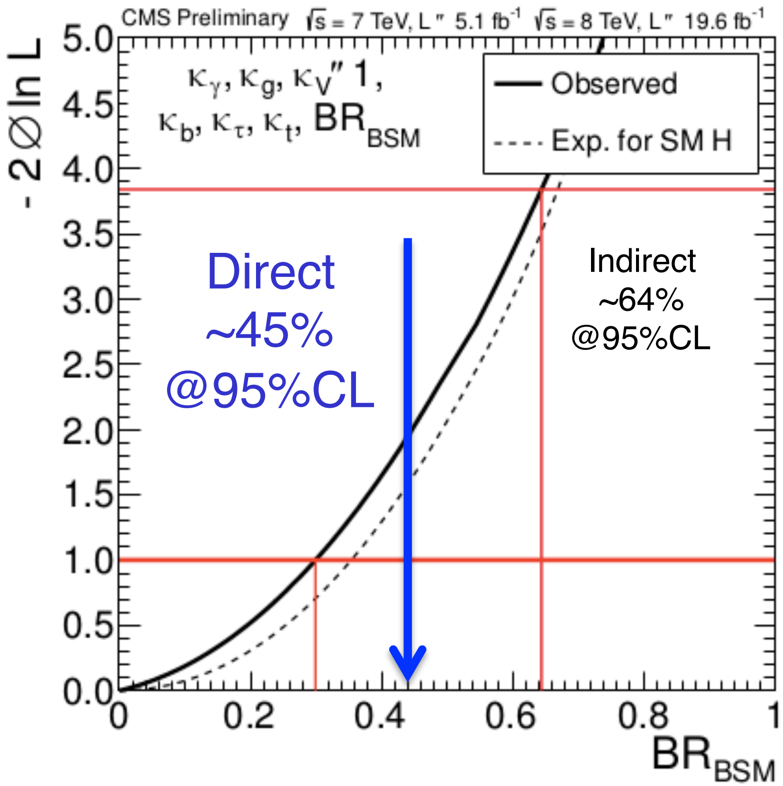
Status 2012 CMS only:

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

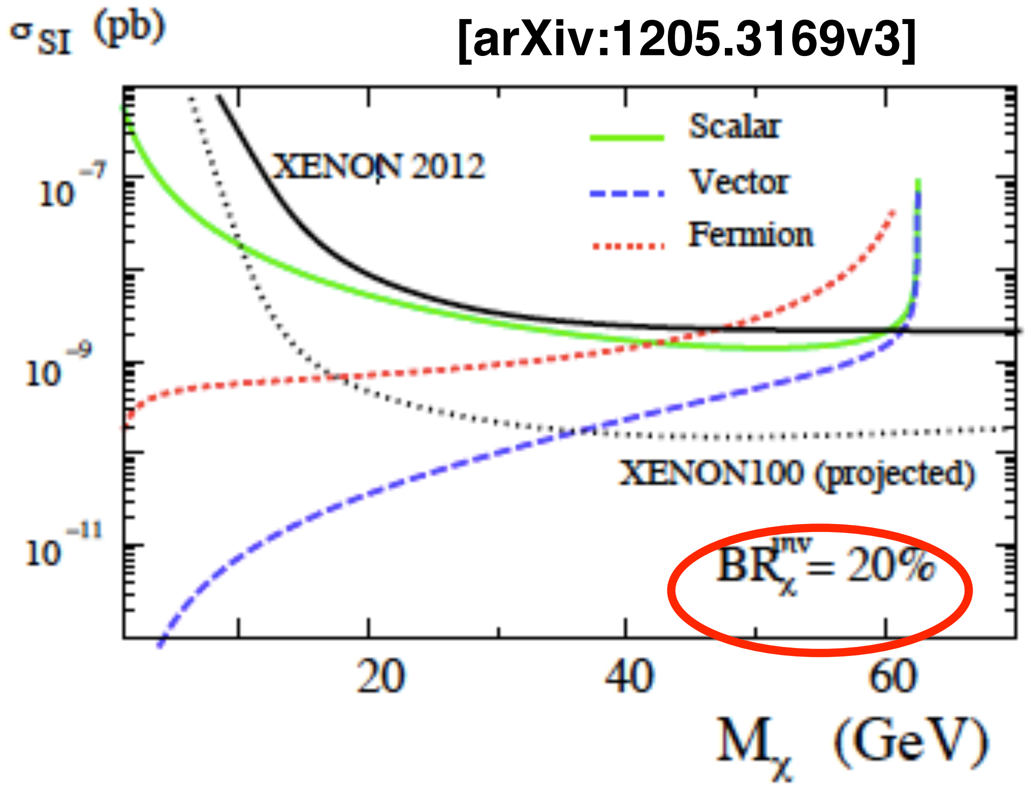
VH: $BR_{H\text{->}invisible} < 75\%$ @ 95%CL

Naïve combination: ~ <45% @ 95% CL

$BR_{H\text{->}invisible}$ 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 $\Gamma_{H\text{->}invisible}$.
In the (near) future this might provide a stringent constraint for $M_{DM} < M_H/2$

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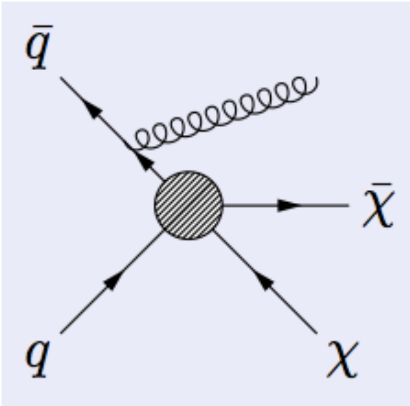
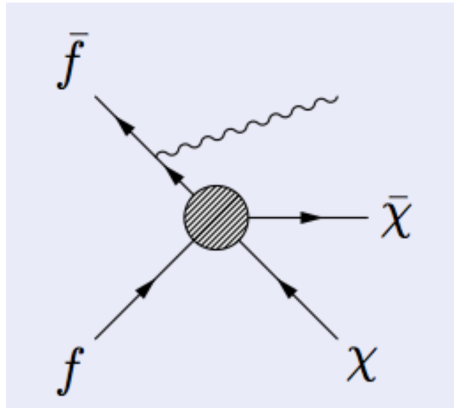
Monojet and Monophoto (plus E_T^{miss})

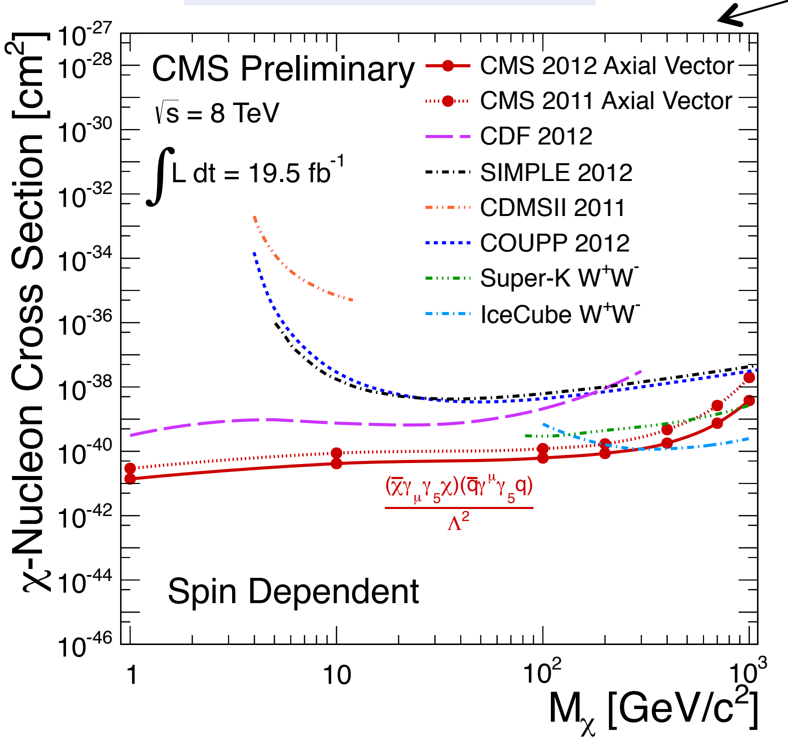
Monojet: hard jet + E_T^{miss}

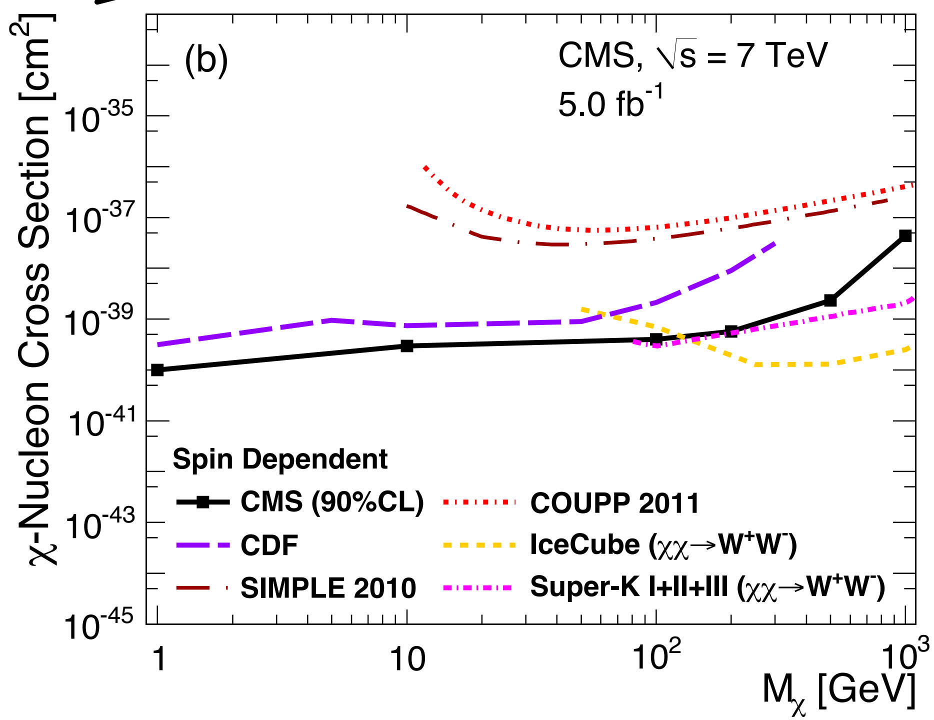


Monphoton: hard photon + E_T^{miss}



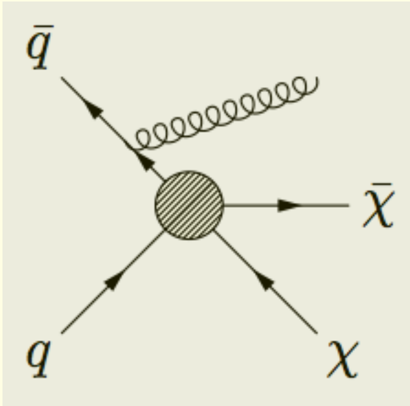
Note different y scale

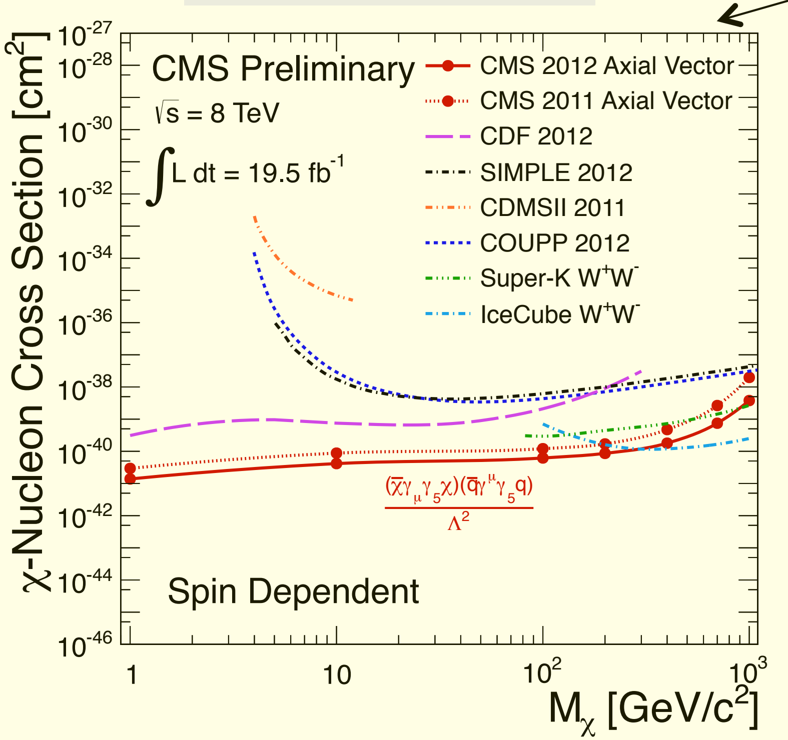




Monojet and Monophoto (plus E_T^{miss})

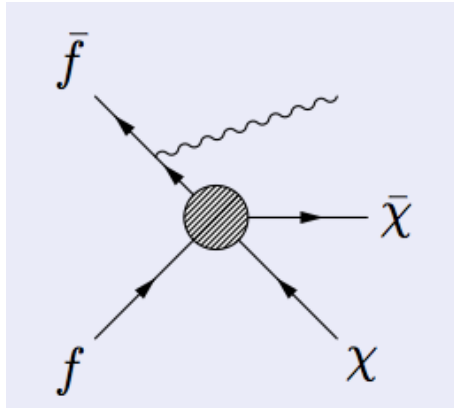
Monojet: hard jet + E_T^{miss}

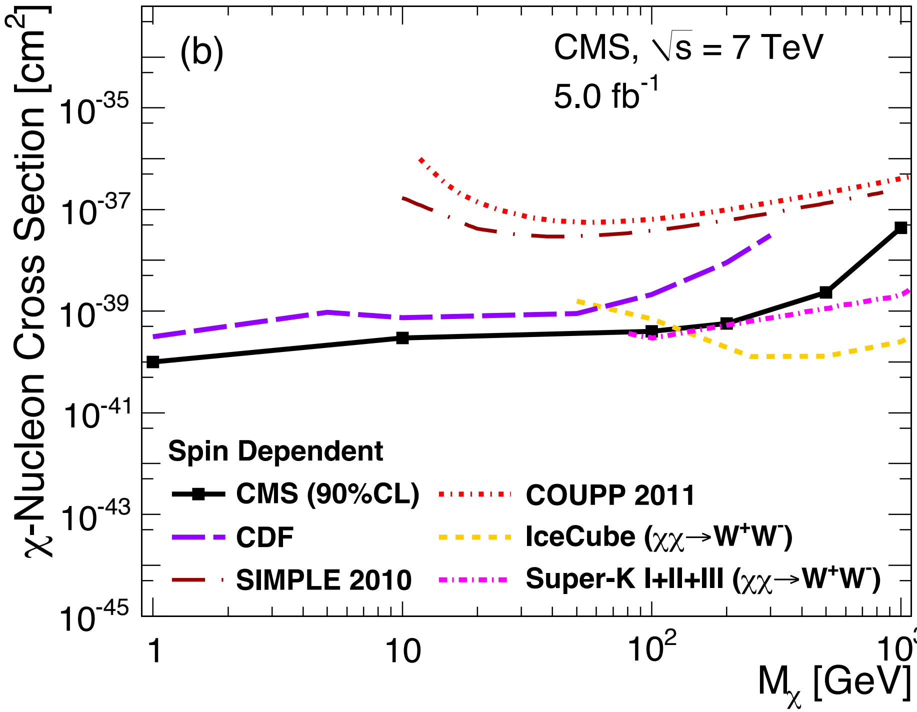




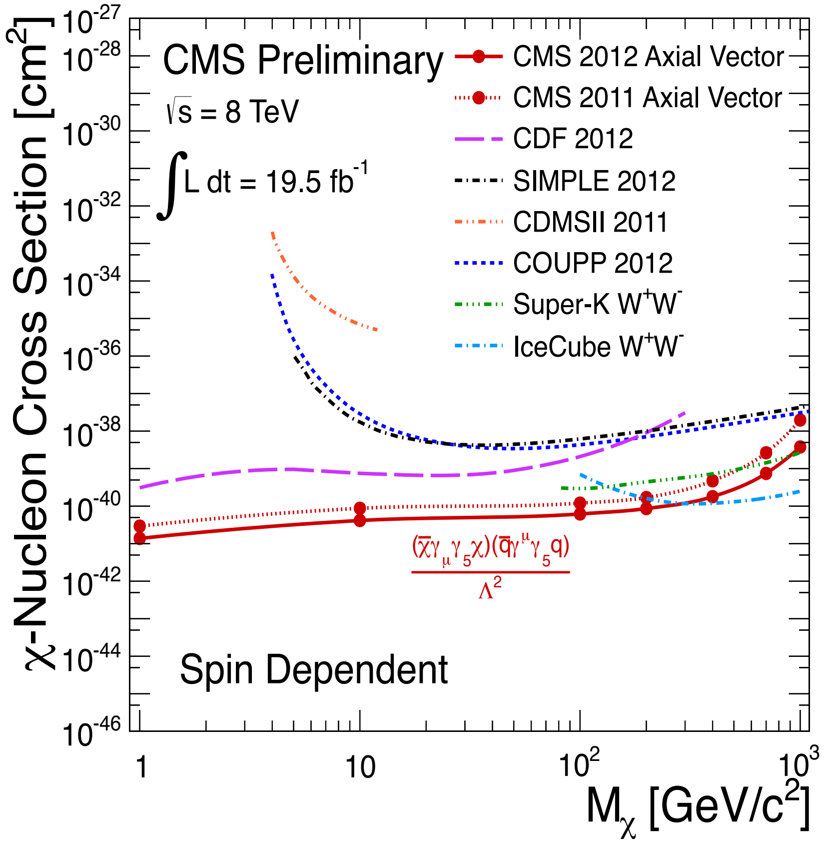
Note different y scale

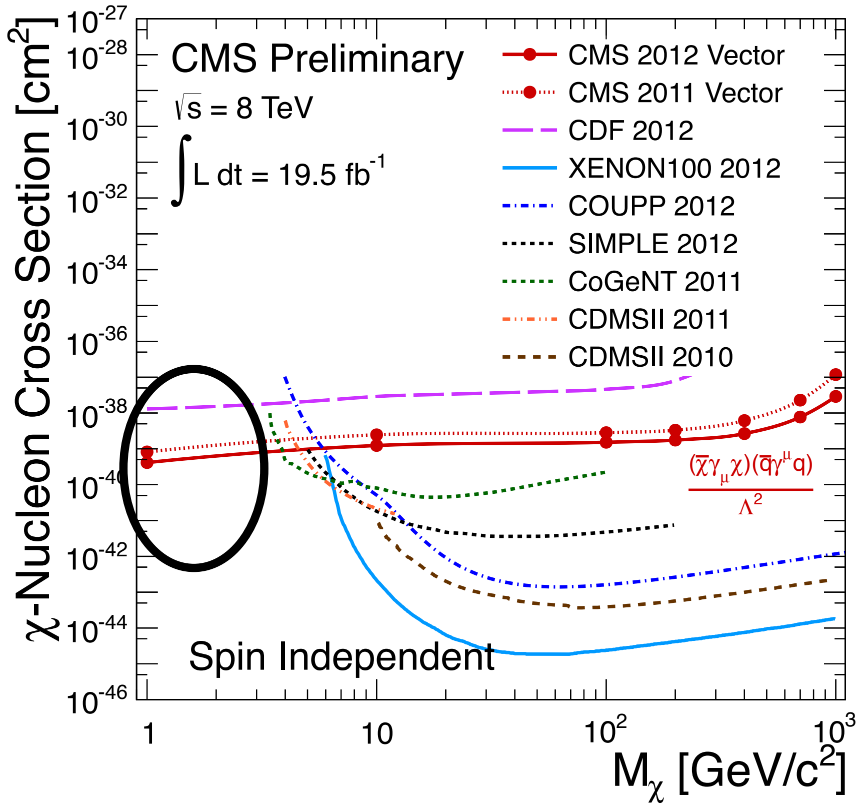
Monphoton: hard photon + E_T^{miss}





Monojet analyses better than direct detection?!





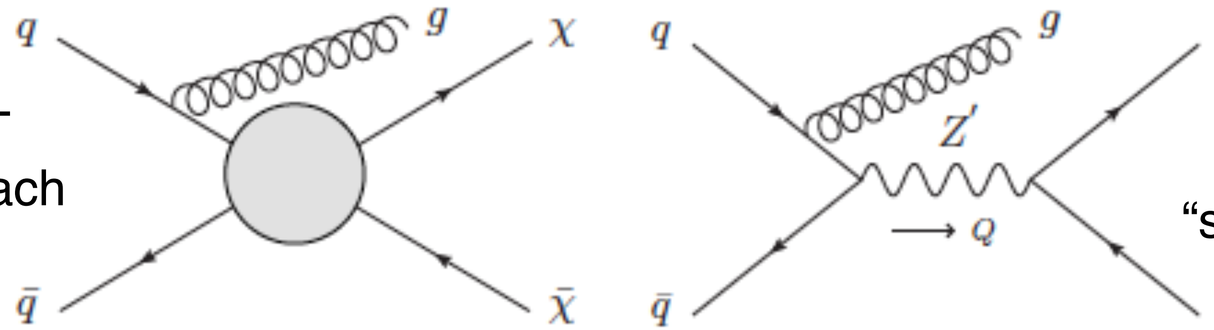
Claim [often made]:
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

Validity of Effective Field Theory Limits

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

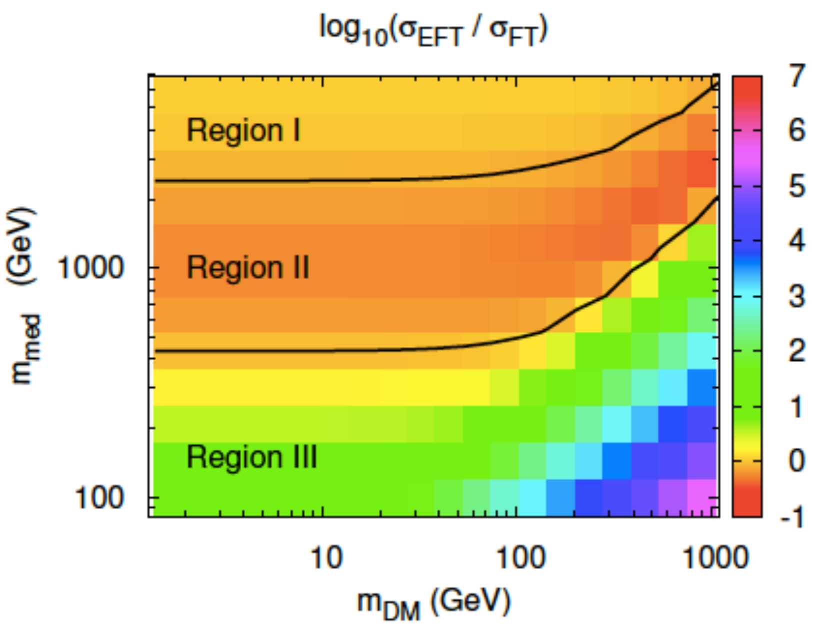
- Compare Effective Field Theory (EFT) with Full Theory (FT)

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!

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Beyond EFT limits: Simplified models

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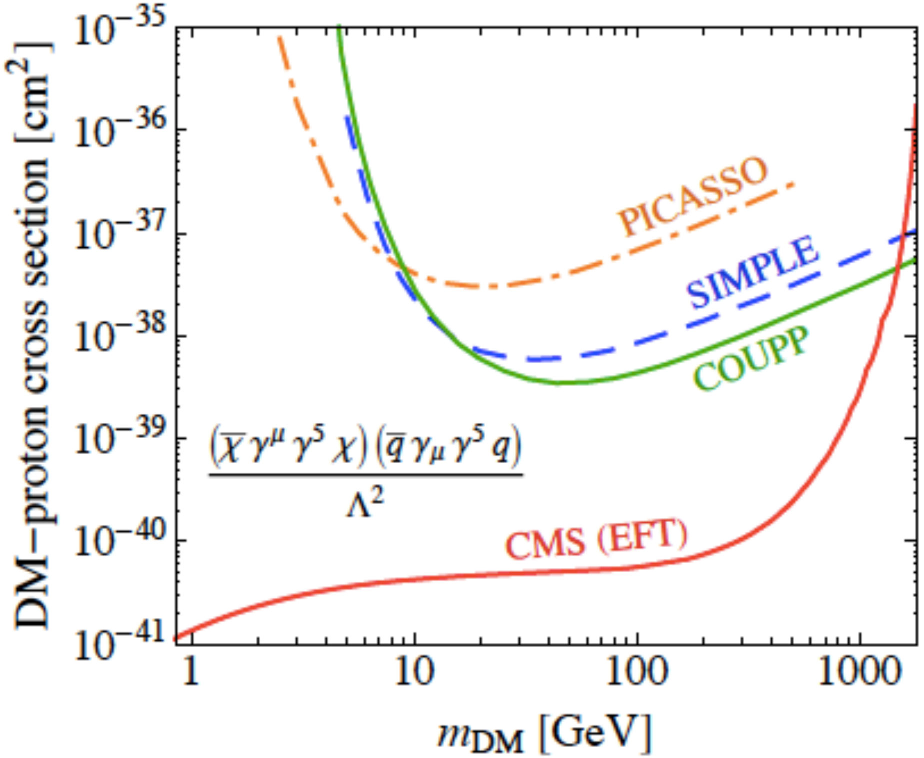
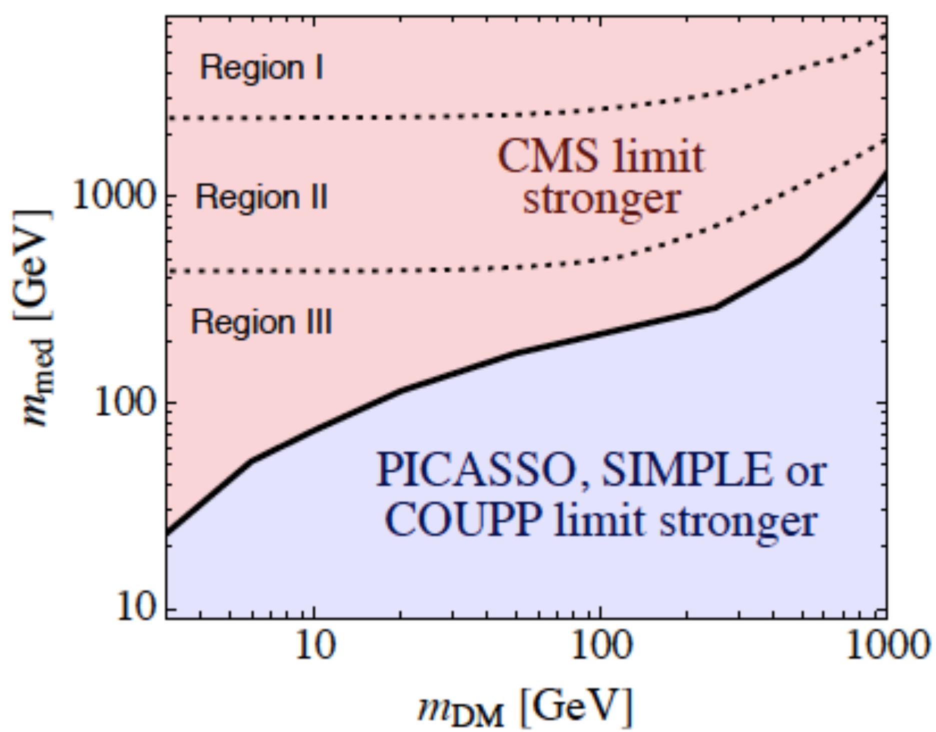
Working out the complementarity between direct DM detection experiments and collider based DM searches!





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.

Beyond EFT limits: Simplified models

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

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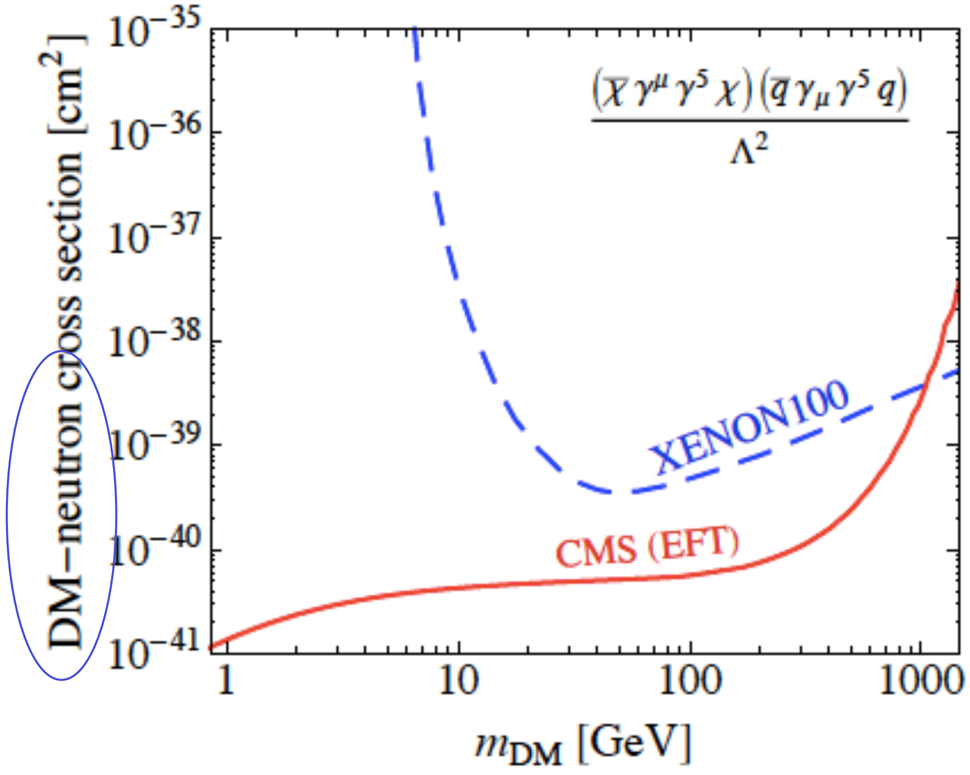
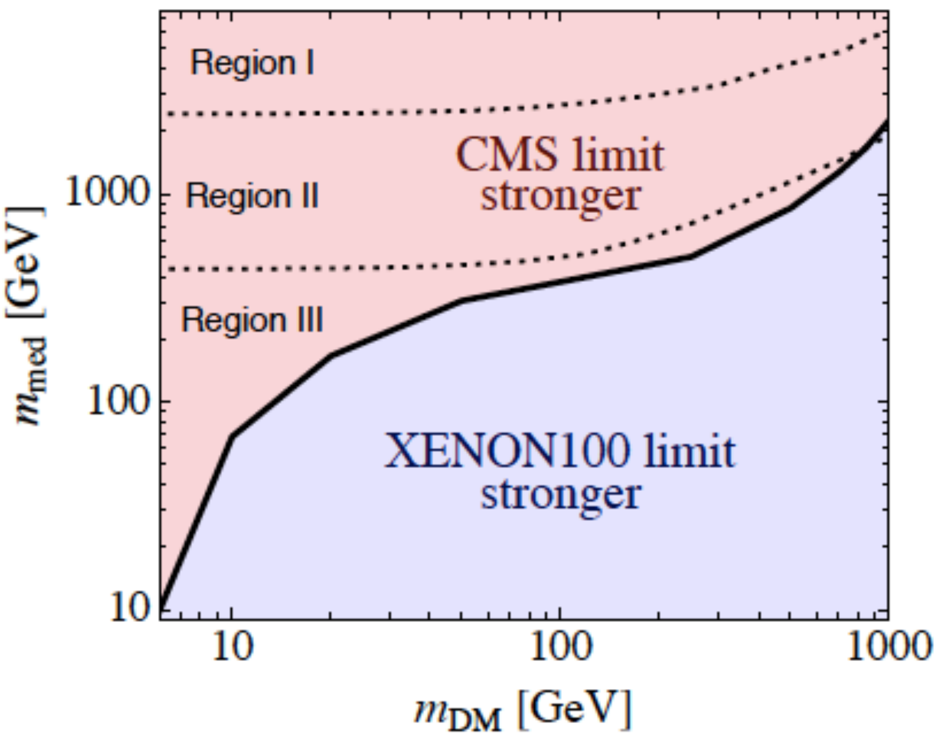




EFT limits give the impression that monsjet searches outperform direct detection BUT EFT only applies a VERY small class of DM models.

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

Outlook: 8 TeV vs 14 TeV

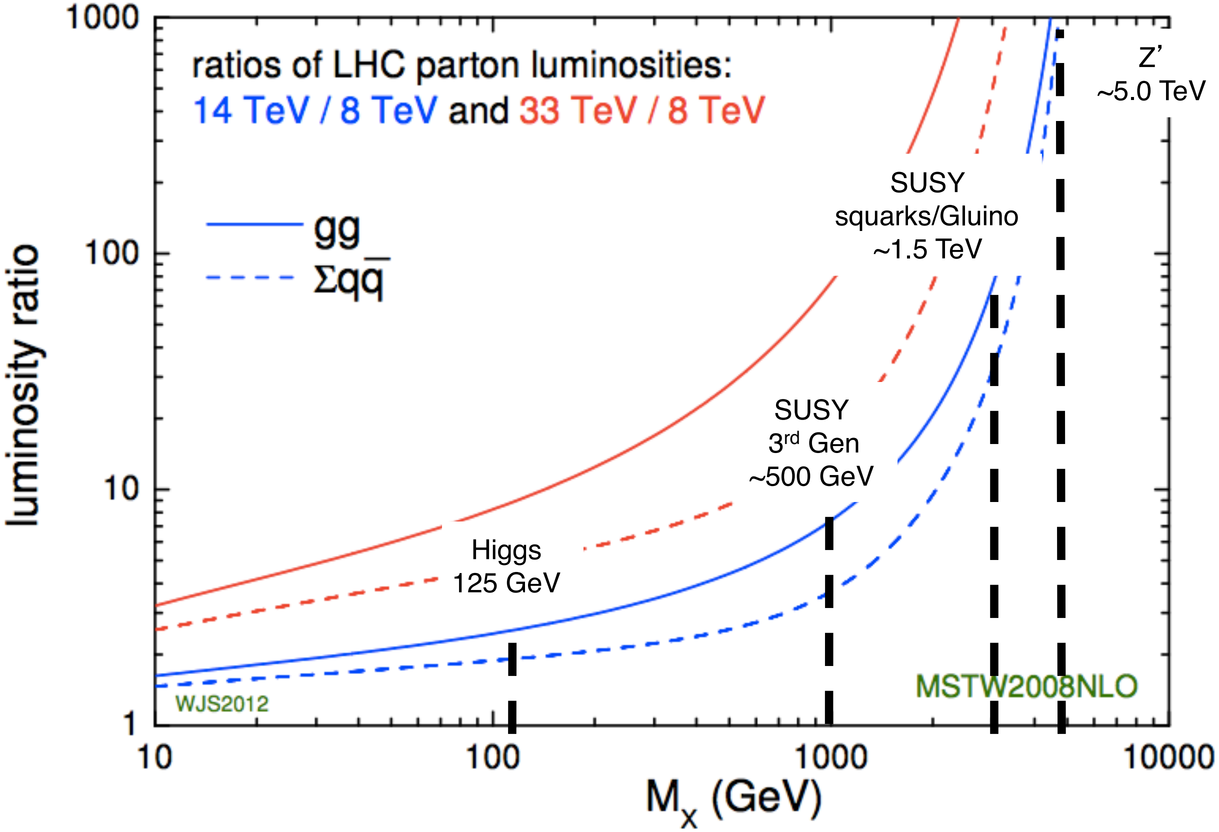
Use parton luminosities to illustrate the gain of 14 vs 8 TeV

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 SUSY has not revealed itself!
  - Even by 2010 the LHC has enter new territory for SUSY searches and since pushed 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 SUSY exist)
- The LHC experiments have established an impressive variety of very powerful direct searches for many different final states (very hard work)!
  - 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!
- The high energy running of the LHC starting 2015 will be our next very (as in very) real chance for discovery!

The SUSY (&DM) story continues … stay tuned!

BACKUP

ATLAS & CMS public results

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

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

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

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ATLAS Summary

Direct SUSY Searches, O. Buchmüller

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

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

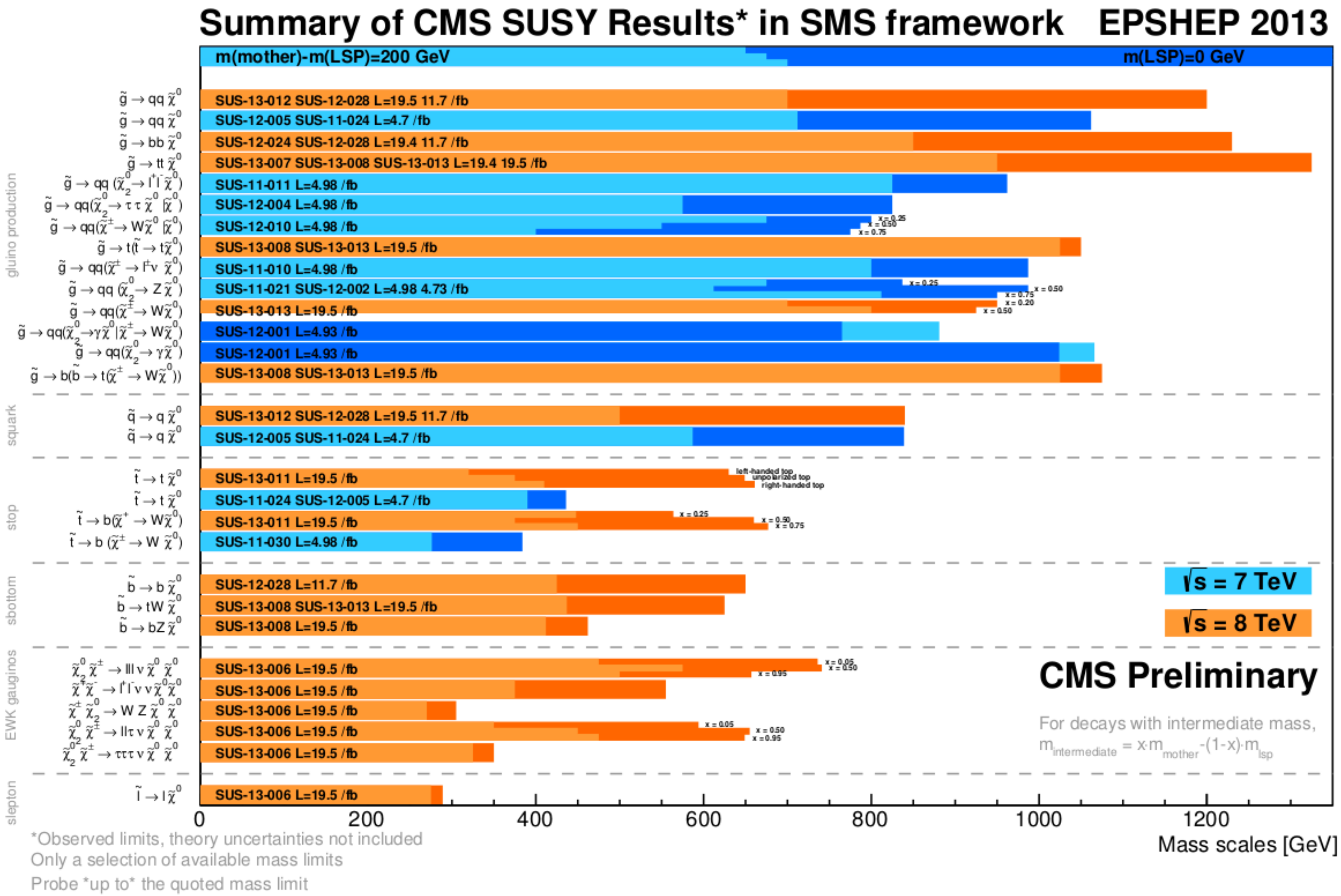
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	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	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >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 $e, \mu + \gamma$	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
3^{rd} 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
3^{rd} 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
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	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	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	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, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	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, $\tau(\tilde{\chi}_1^\pm)$=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<$\tau(\tilde{g})$<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<$\tan\beta$<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<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$	700 GeV	1 mm<$c\tau$<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 $e, \mu + \tau$	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 $e, \mu + \tau$	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	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

Mass scale [TeV] (10^{-1}, 1)

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 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
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /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
left-handed top
unpolarized top
right-handed top
√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	$\tilde{q} \rightarrow q\chi_1^0$	$\tilde{u}_L \rightarrow q\chi_1^0$	$\tilde{b} \rightarrow b\chi_1^0$	$\tilde{t} \rightarrow t\chi_1^0$
Best limit: **[GeV]**	~850	~500	~650	~650
No limit for M_{LSP}**[GeV]**	~ 300	~120	~270	~260

coloured sparticle production

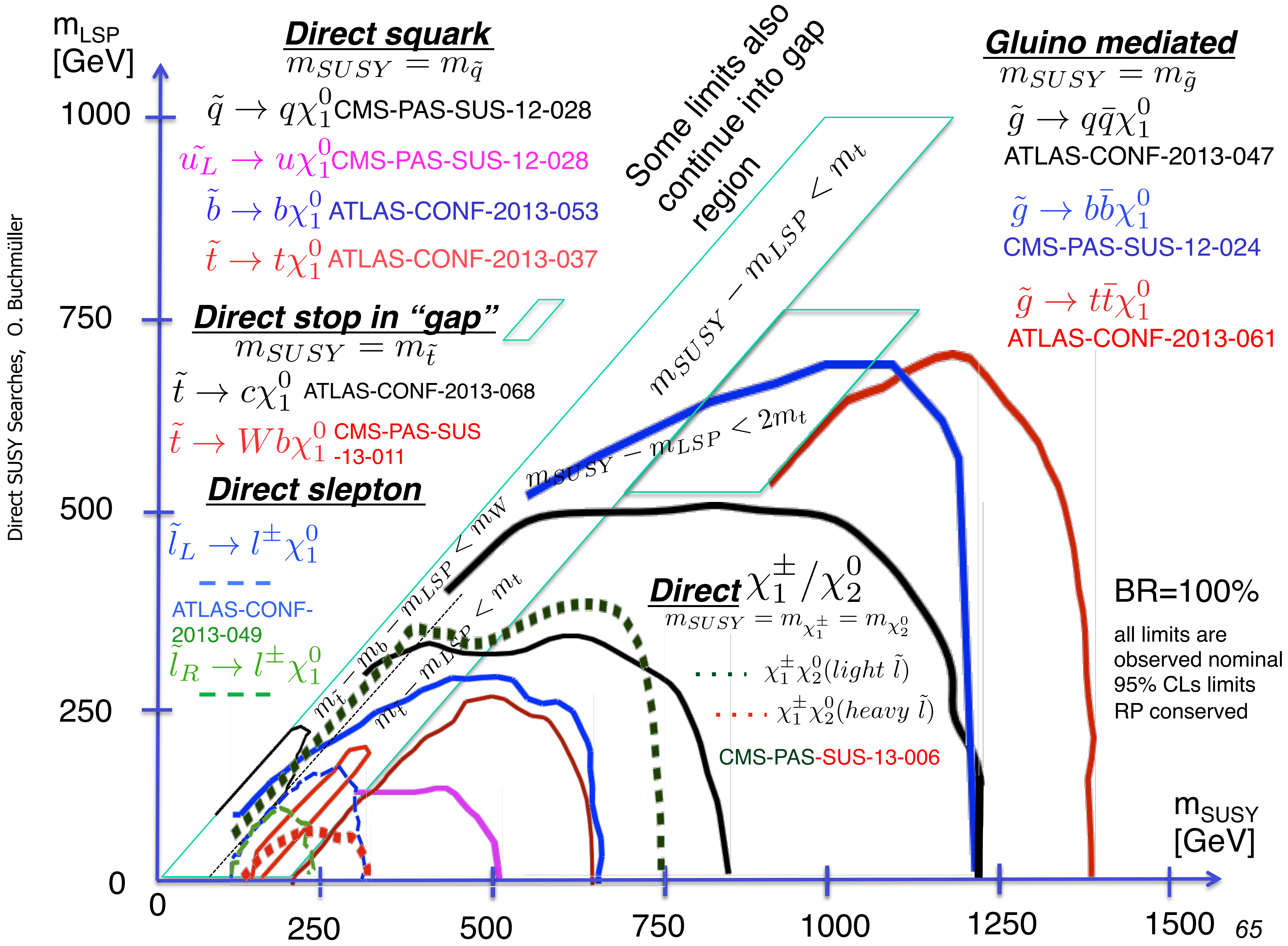
Direct squark	$\tilde{g} \rightarrow q\bar{q}\chi_1^0$	$\tilde{g} \rightarrow b\bar{b}\chi_1^0$	$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
Best limit: **[GeV]**	~1200	~1200	~1400
No limit for M_{LSP}**[GeV]**	~480	~650	~700

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

EWK sparticle production

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



Direct SUSY Searches, O. Buchmüller
m_LSP [GeV]
1000
750
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-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
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
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
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
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500

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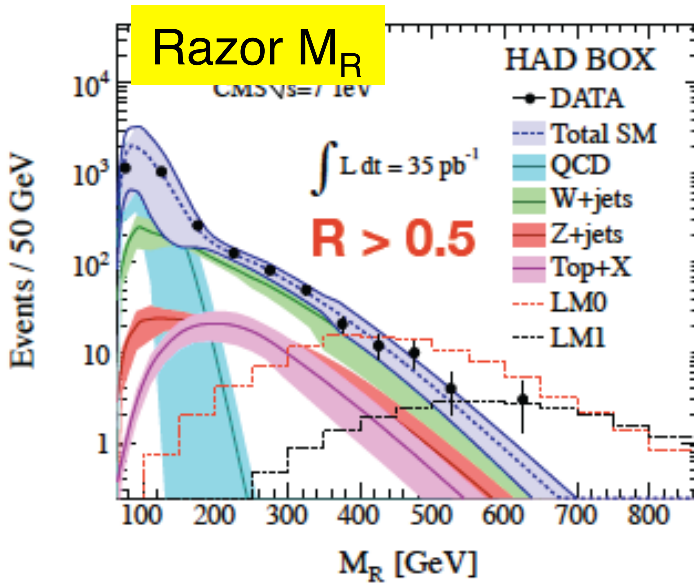
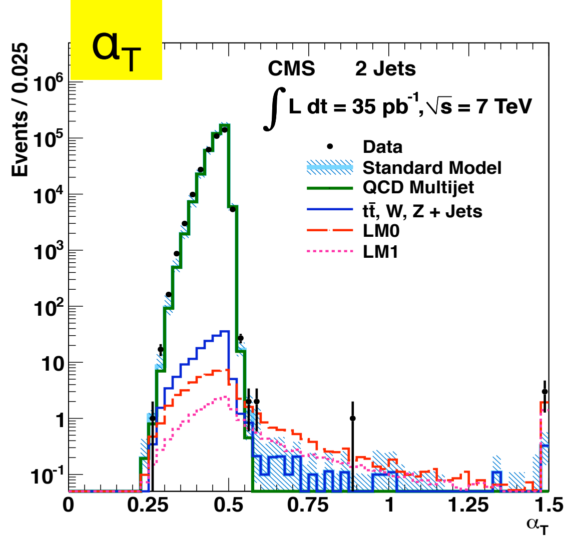
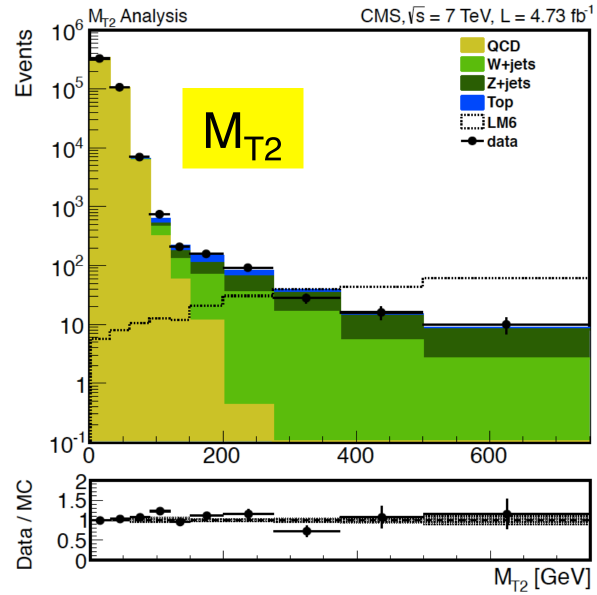
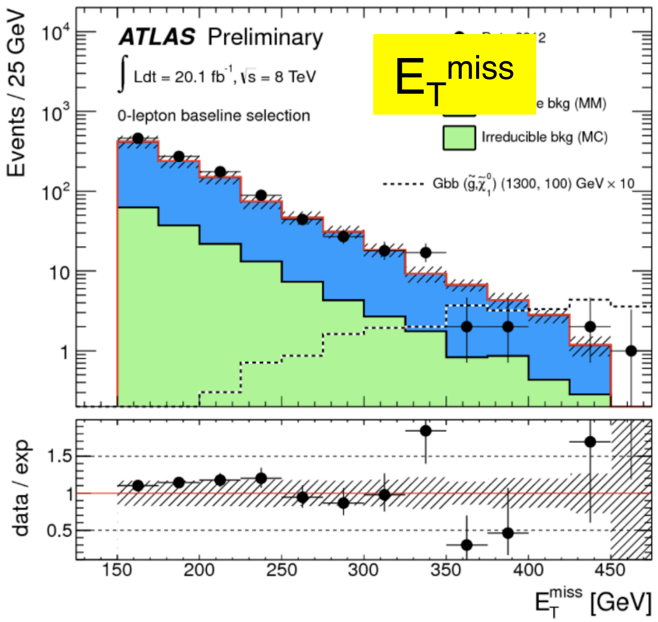
Many Different Kinematic Variables

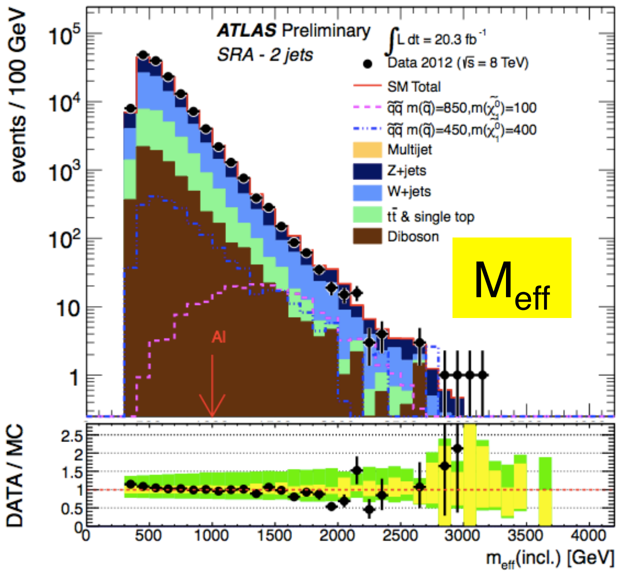
Direct SUSY Searches, O. Buchmüller

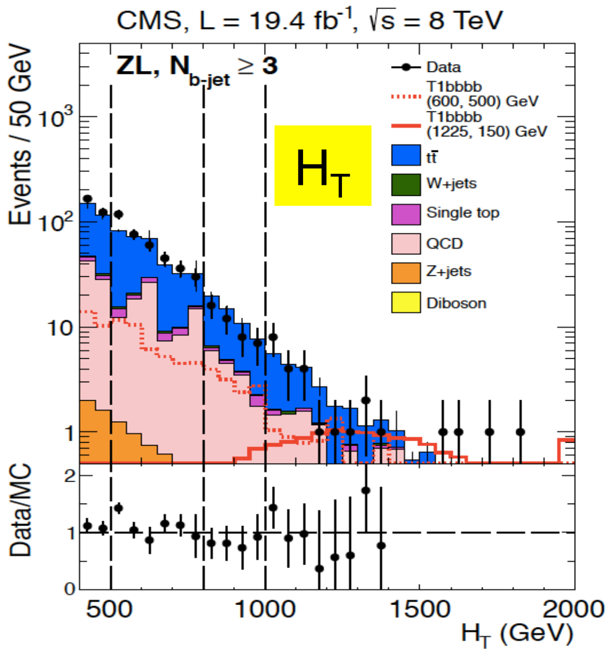












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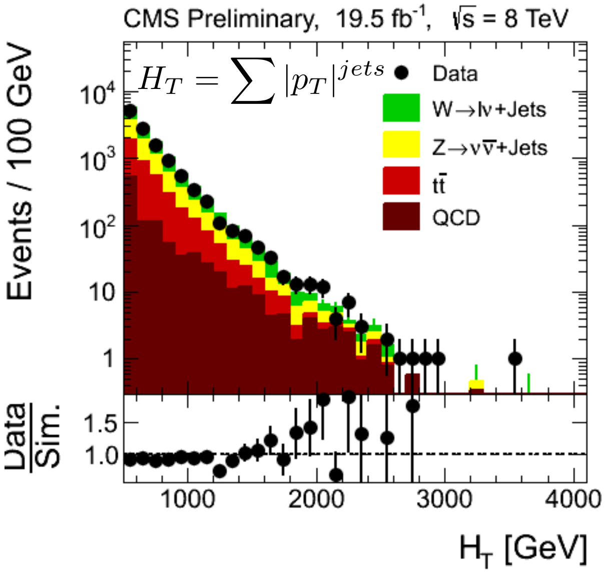
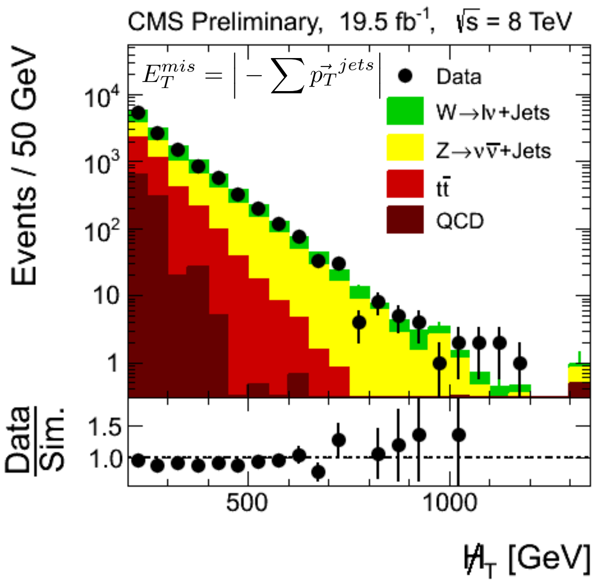
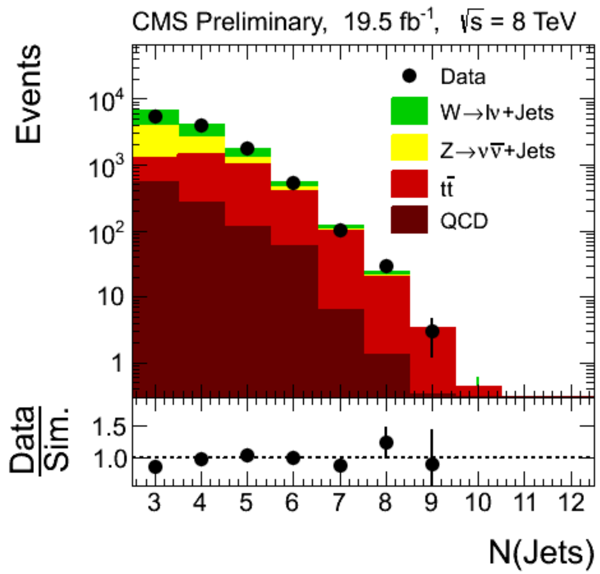
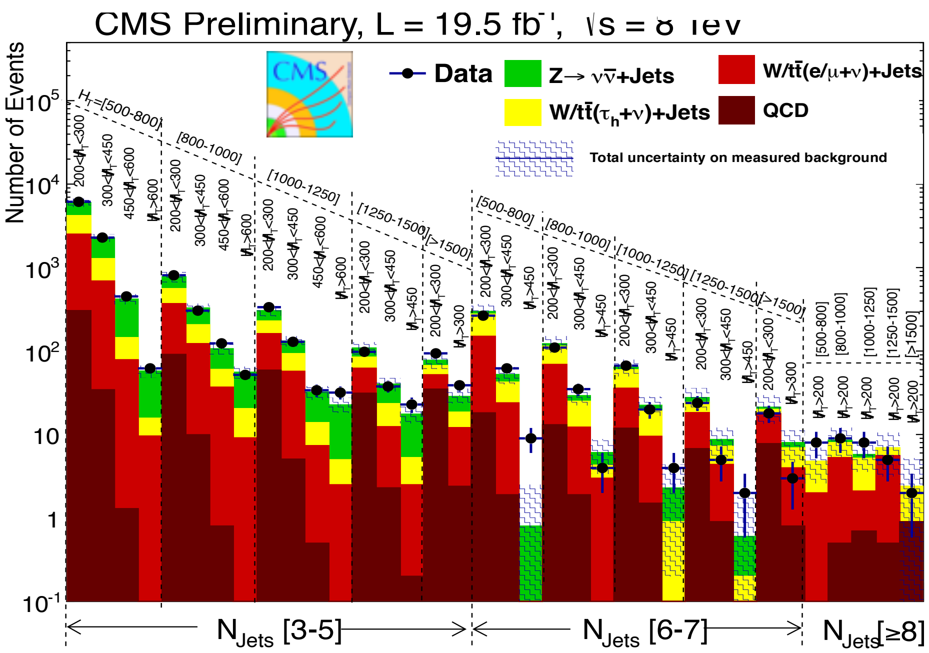
Multijets & missing energy search









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

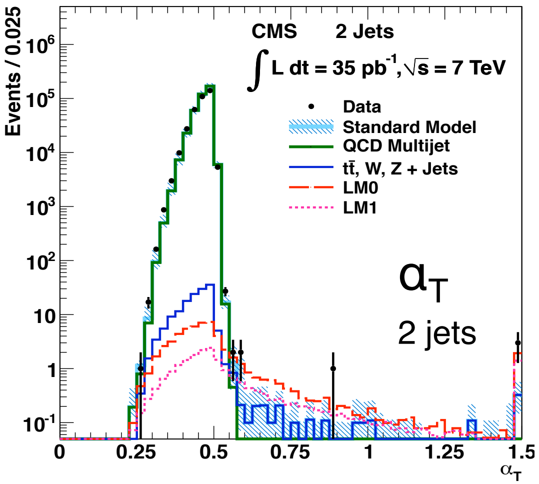
CMS-SUS-PAS-13-012

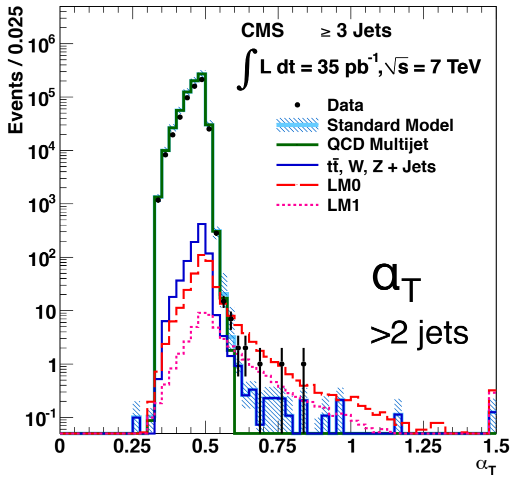
See parallel talk for details:

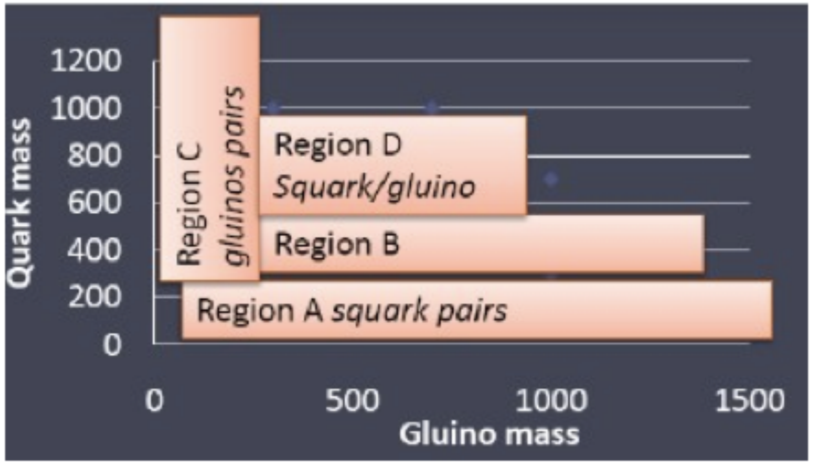
C. Autermann

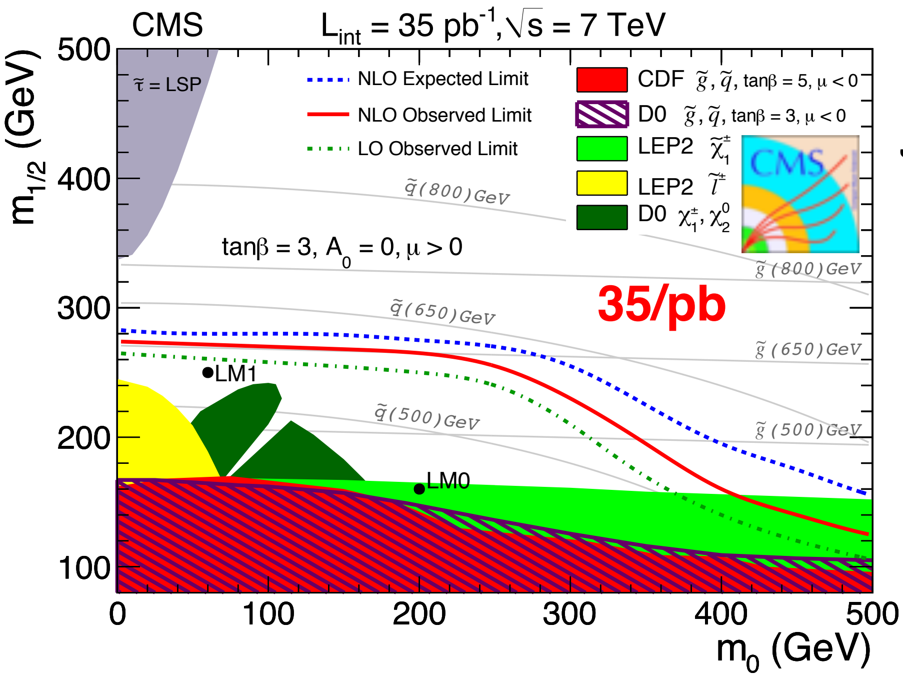
Imperial College London

2010: Entering New Territory at the LHC!

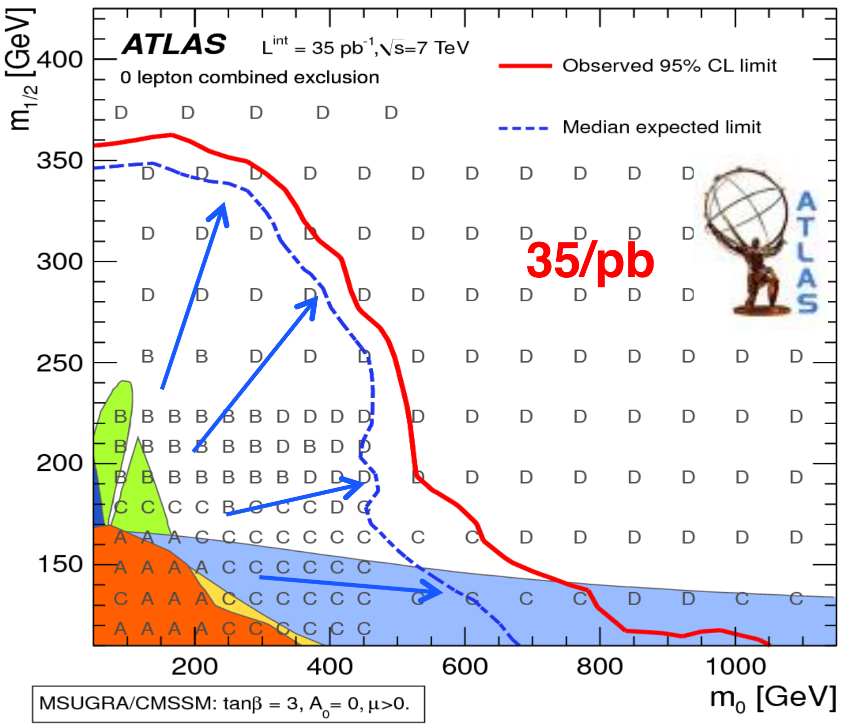








Phys. Lett. B698:196-218



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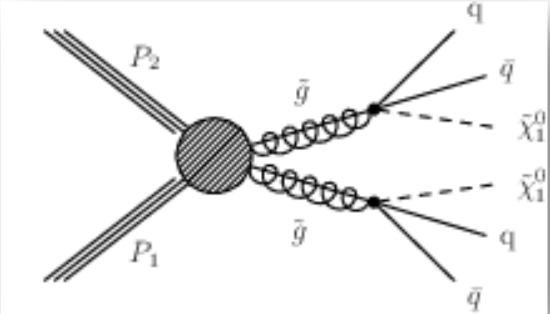
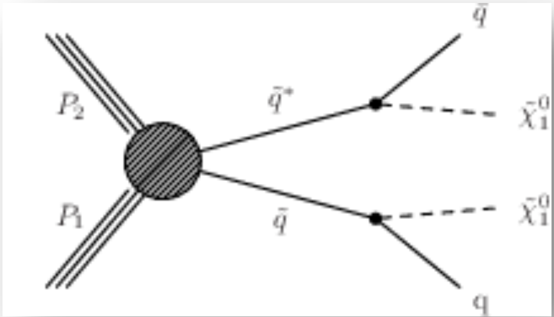
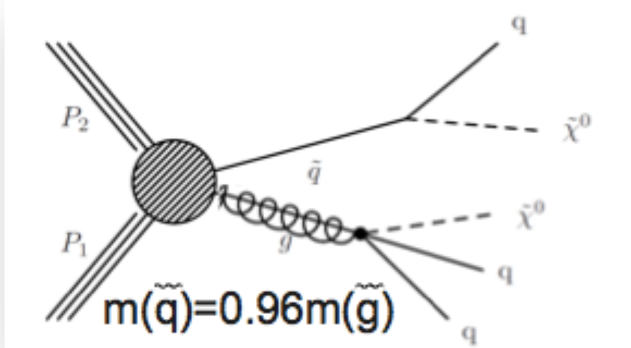
Simplified Model Spectra (SMS)



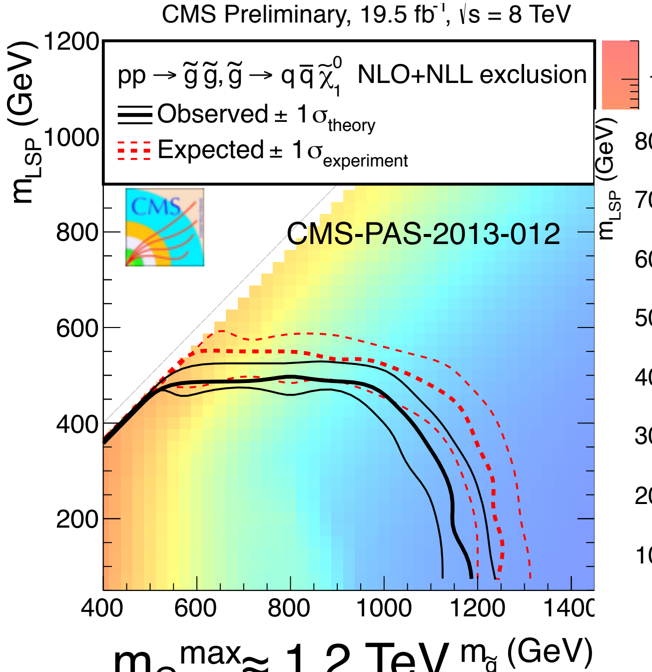
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$



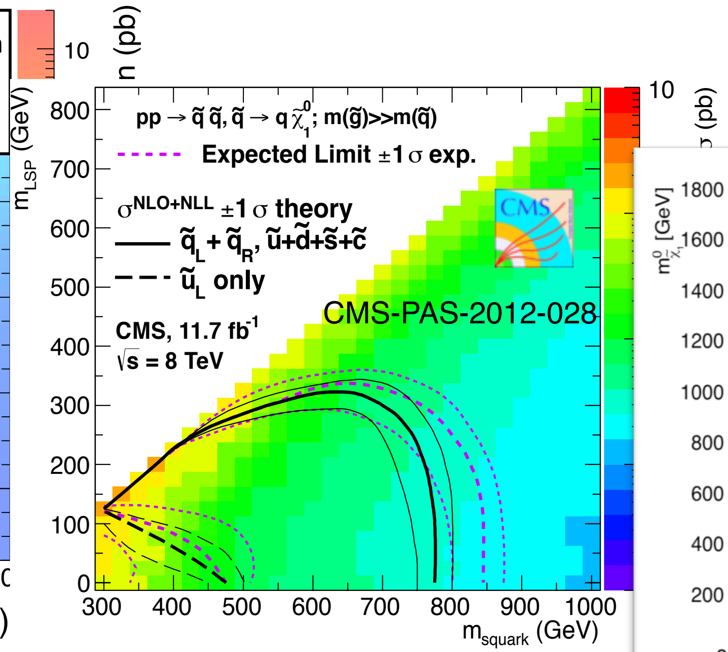
$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$



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

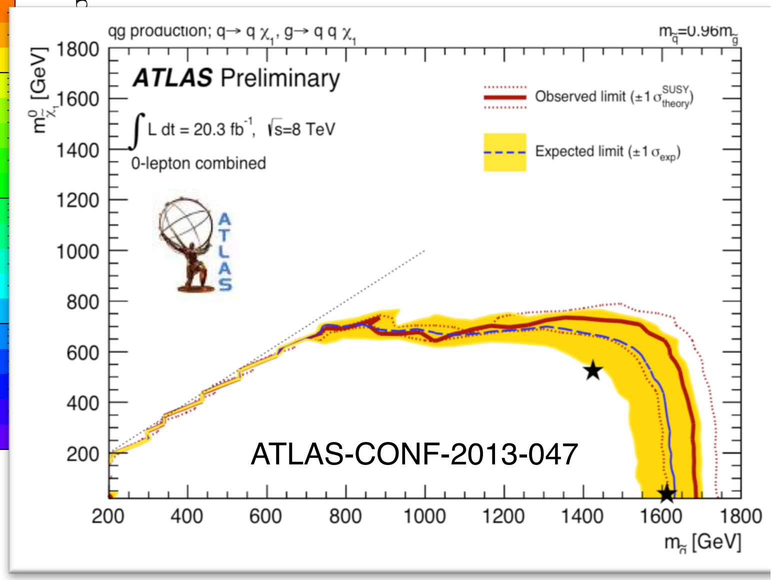


$m_G^{max} \approx 1.2$ TeV



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

$m_G^{max} \approx 1.7$ TeV



earches, O. Buchmüller

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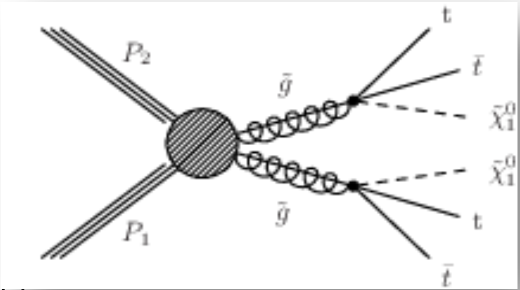
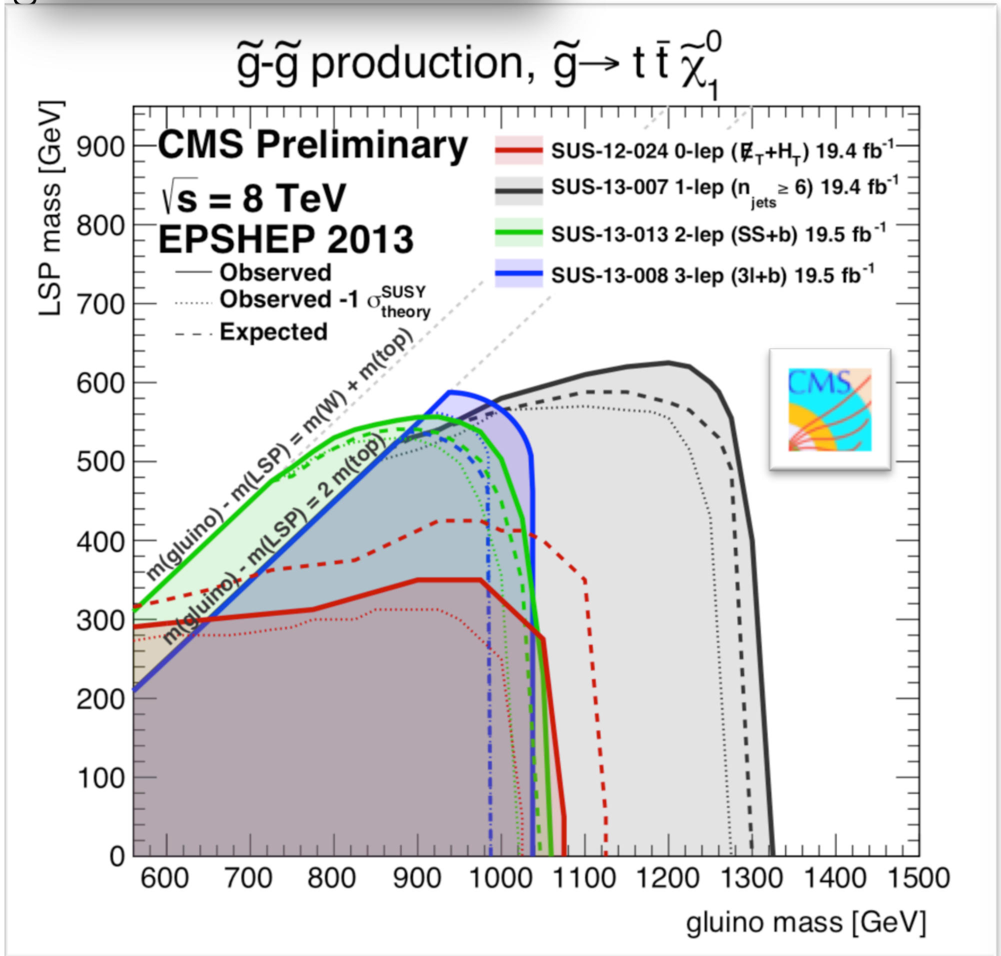
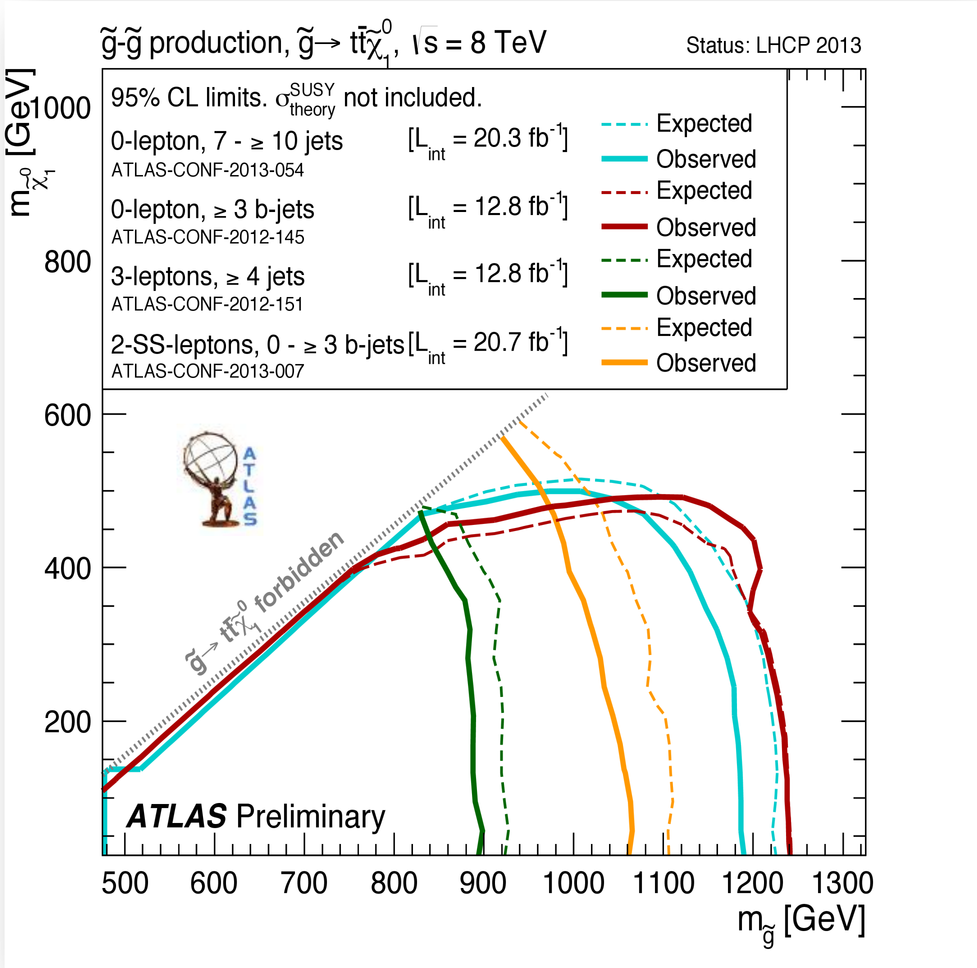
Today: many more SMS and many more searches



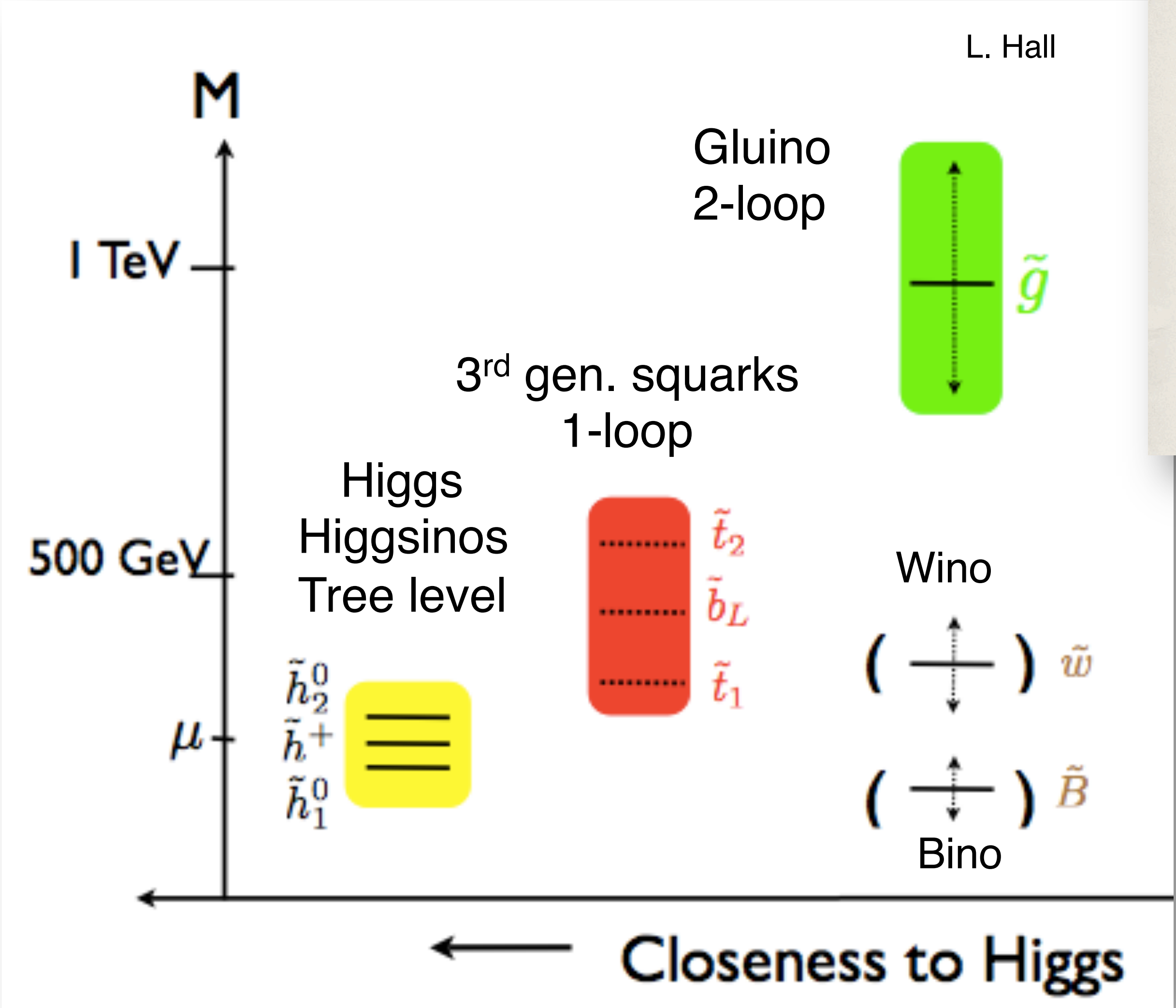
Example: $\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\chi_1^0\chi_1^0$

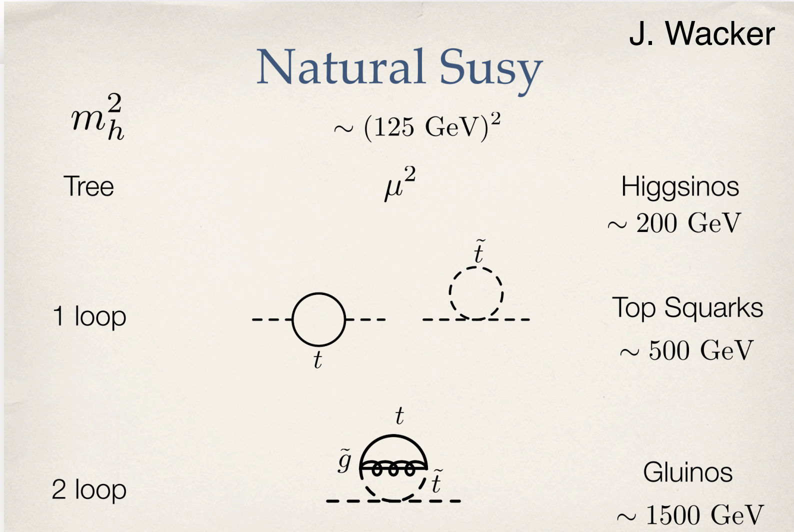
Several searches are interpret in this particular SMS!





(Minimal) Natural SUSY Spectrum





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!

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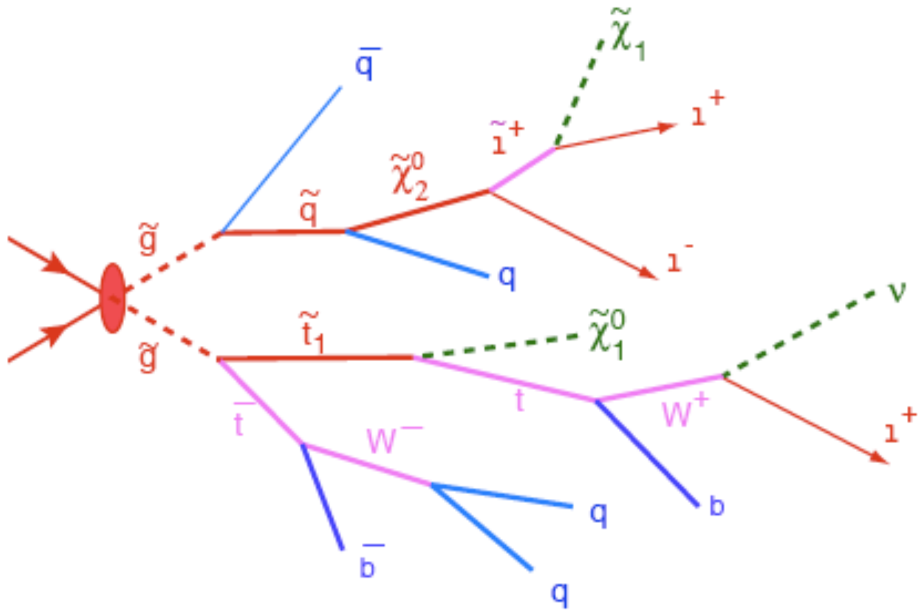
What do we call a "SUSY search"?

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

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



Missing Energy:
- *from LSP*

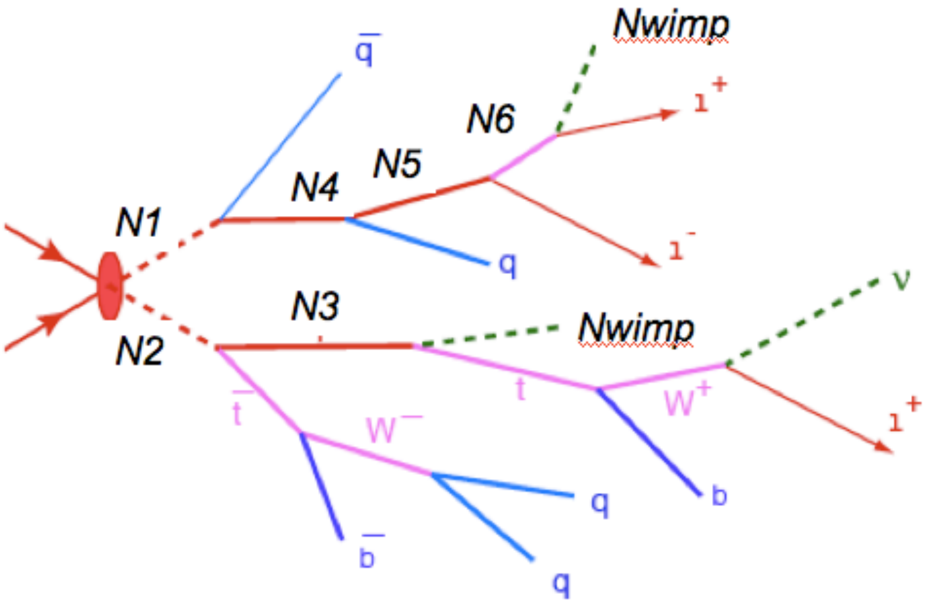
Multi-Jet:
- *from cascade decay (gaugino)*

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

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

What is its experimental signature?

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



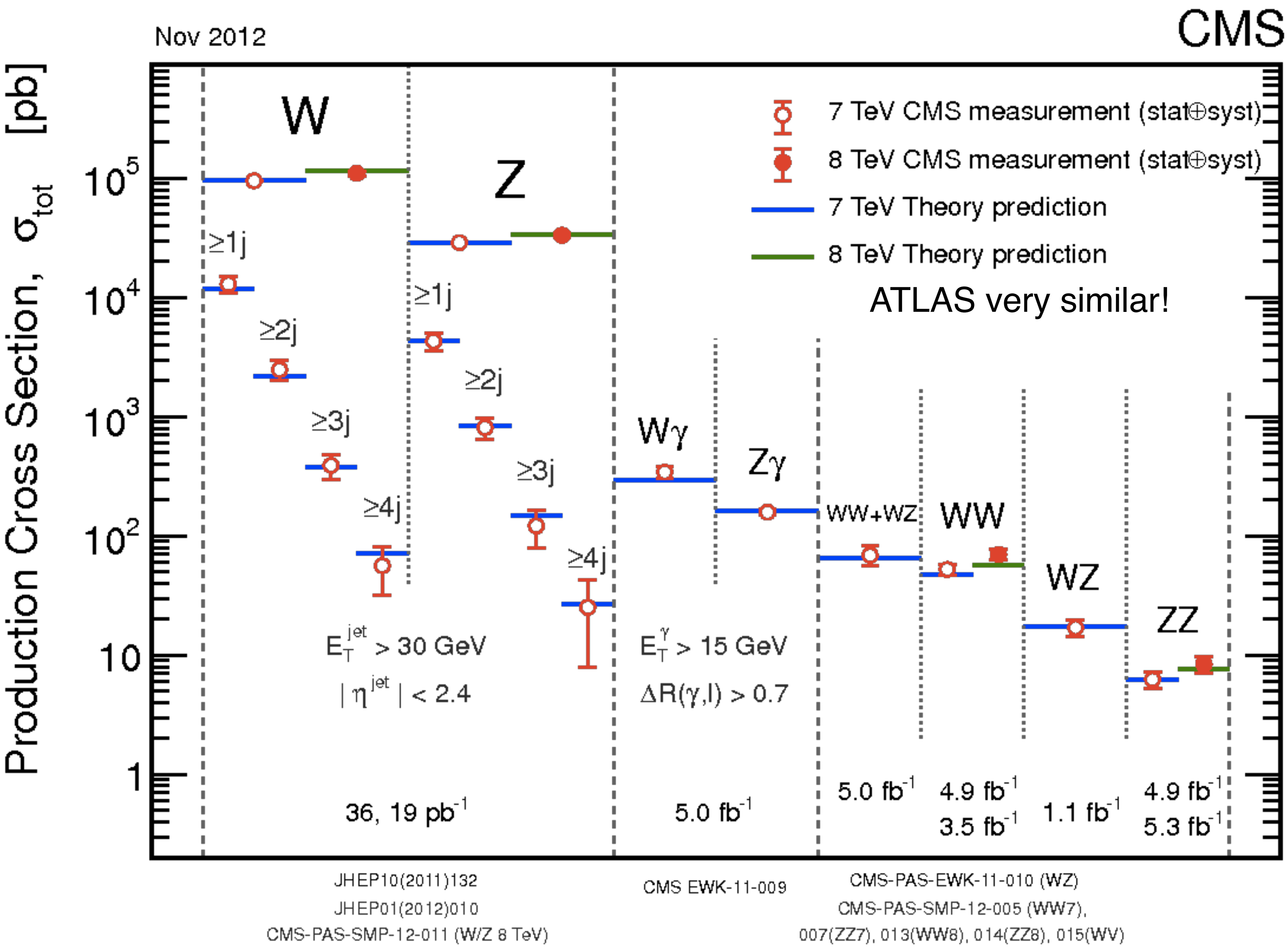
Missing Energy:
- *Nwimp - end of the cascade*

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

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

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

Rediscovery of the SM at a new energy frontier



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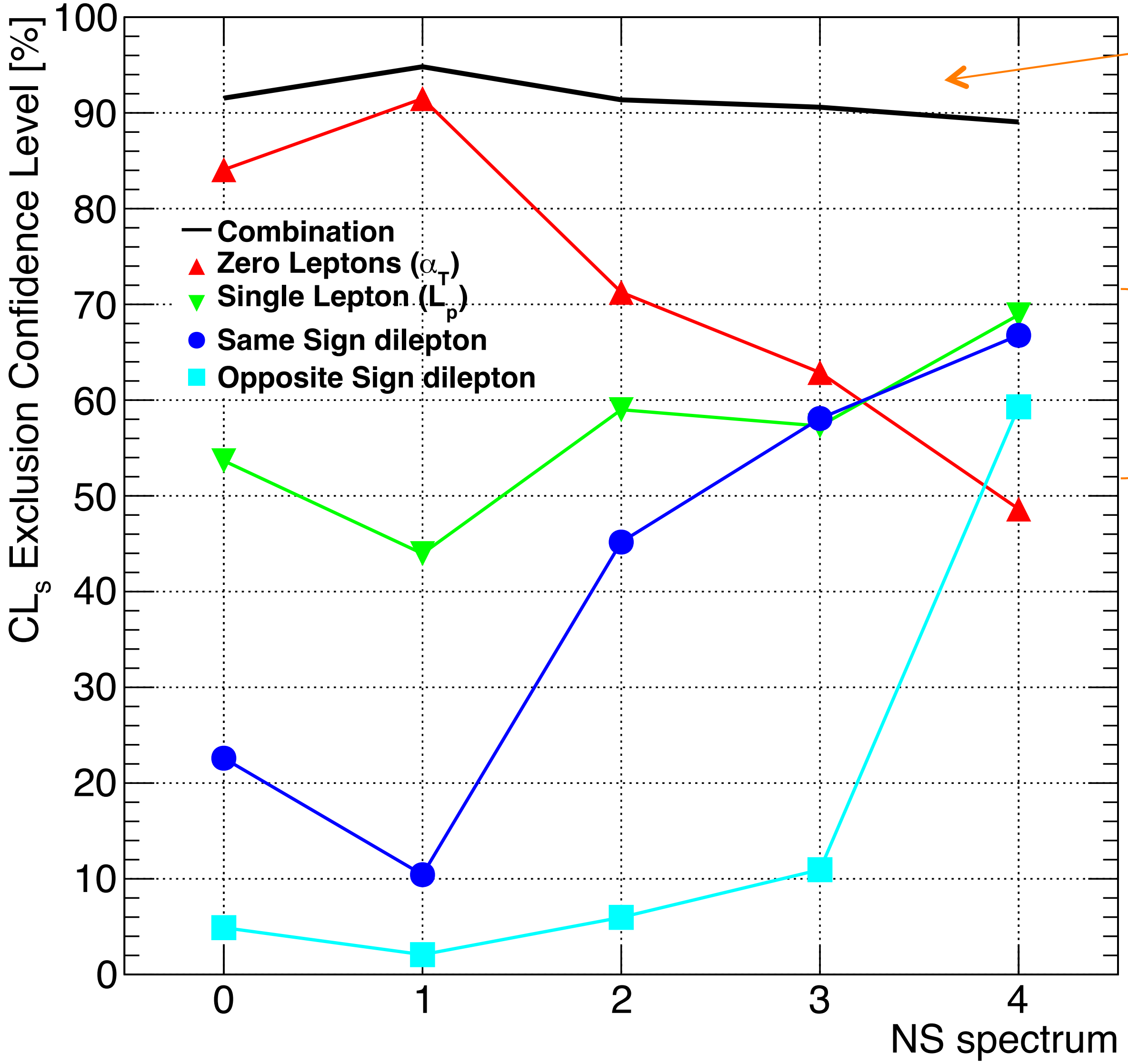
Combination vs individual search



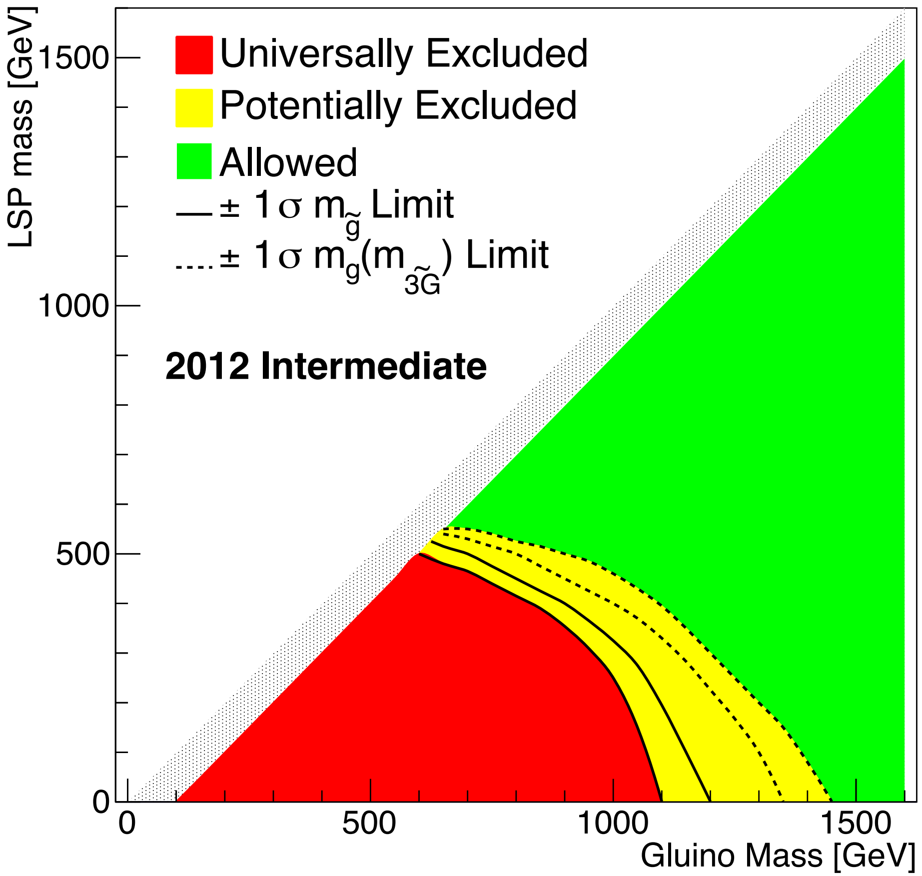
Combination of searches stable

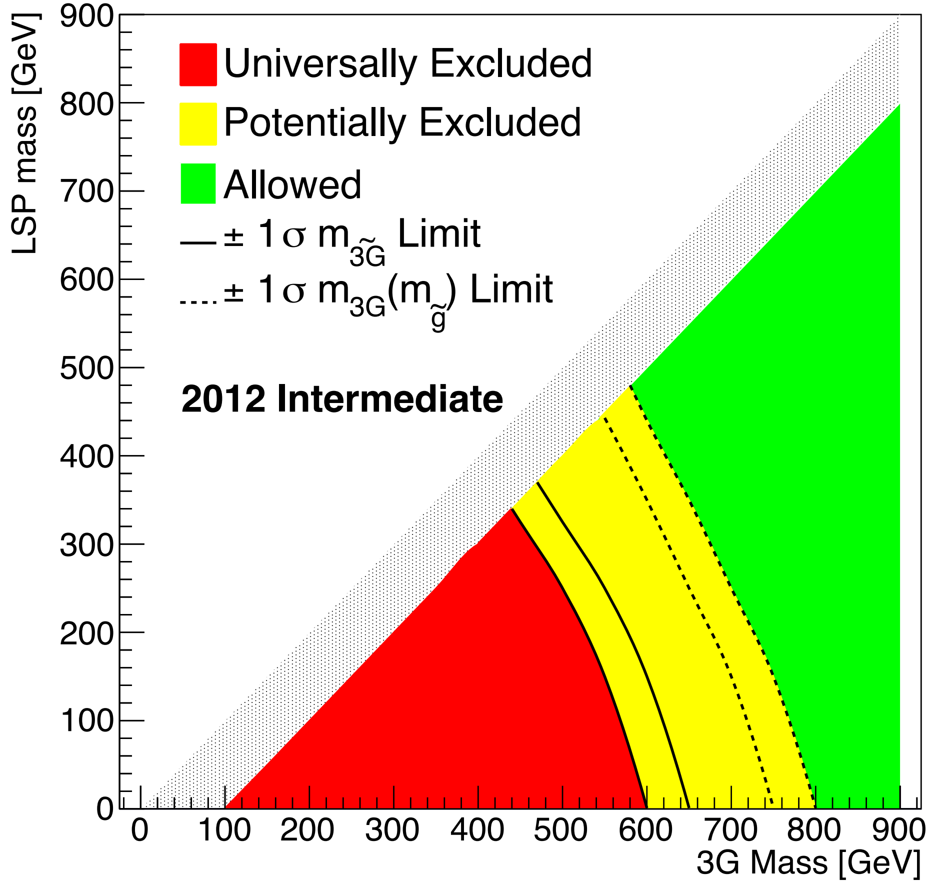
Individual searches exhibit large variations

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

Natural SUSY: universal limits

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

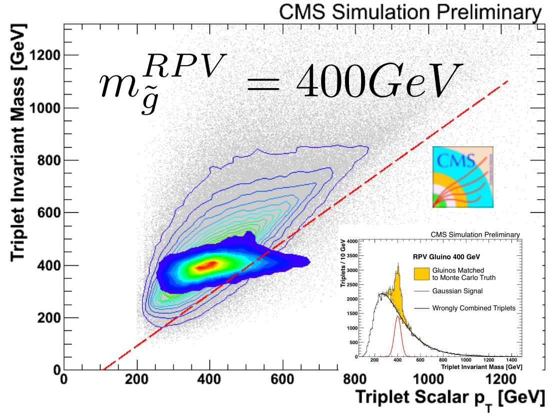
Searches, O. Buchmüller

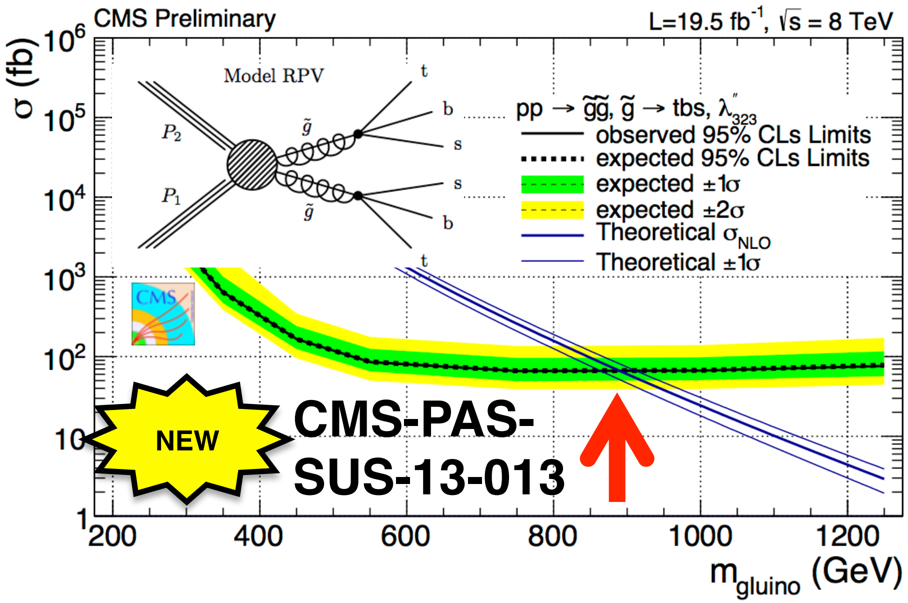
Generic same-sign di-lepton search with different signal regions

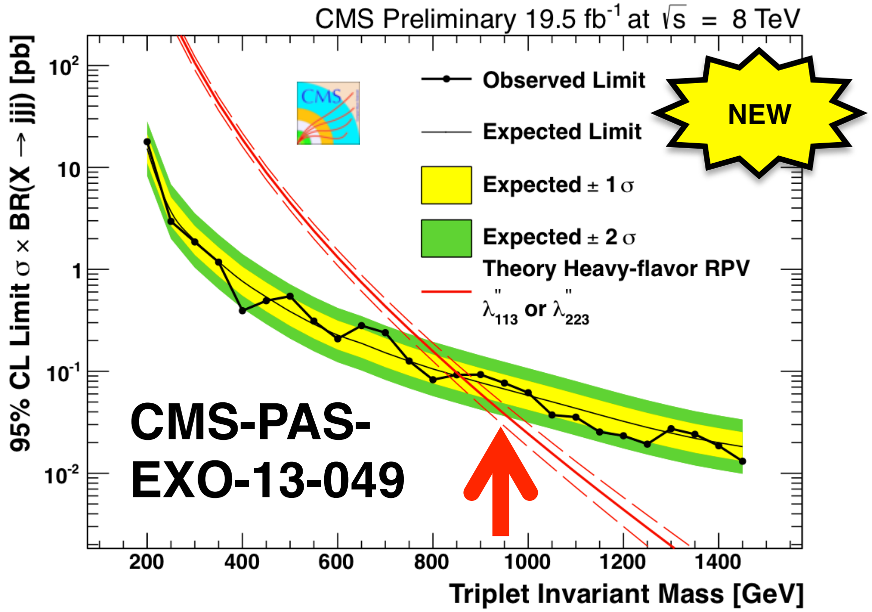
SR	Expected			Observed
RPV0	38	±	14	35
RPV2	5.3	±	2.1	5
SStop1	160	±	59	152
SStop1++	90	±	32	92
SStop2	40	±	13	52
SStop2++	22	±	8	25

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

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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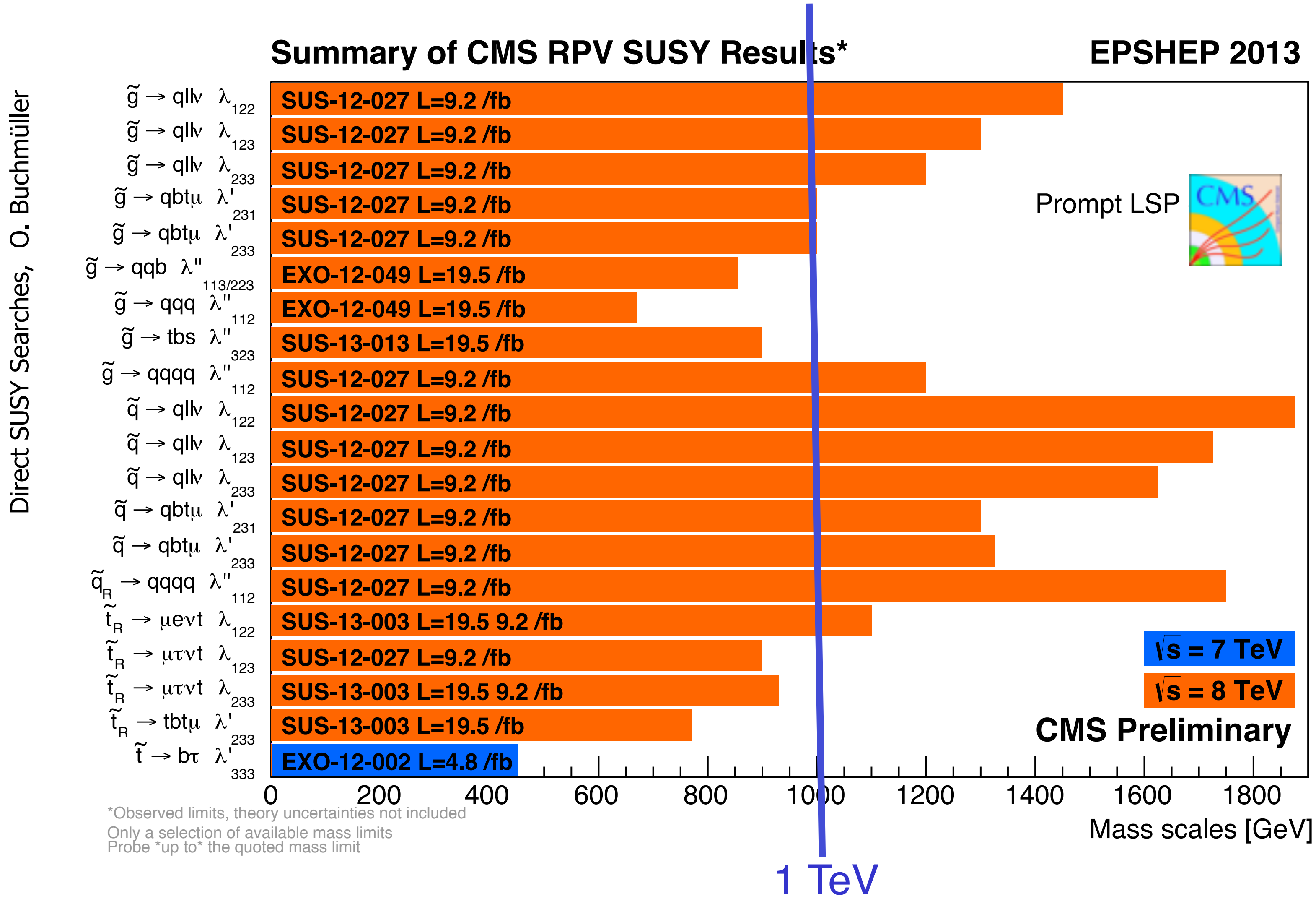
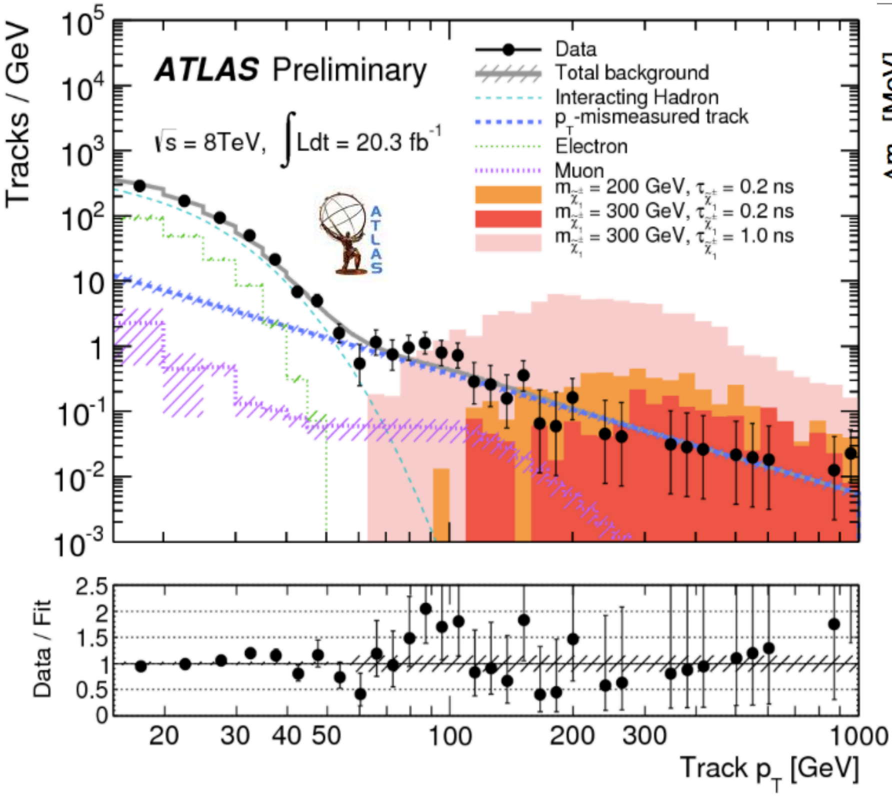
RP violation searches: Summary

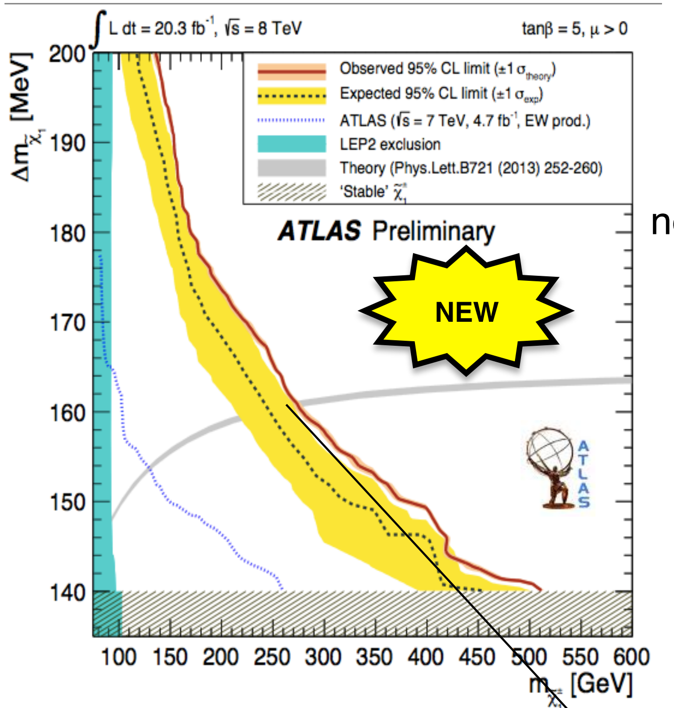


ATLAS similar

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

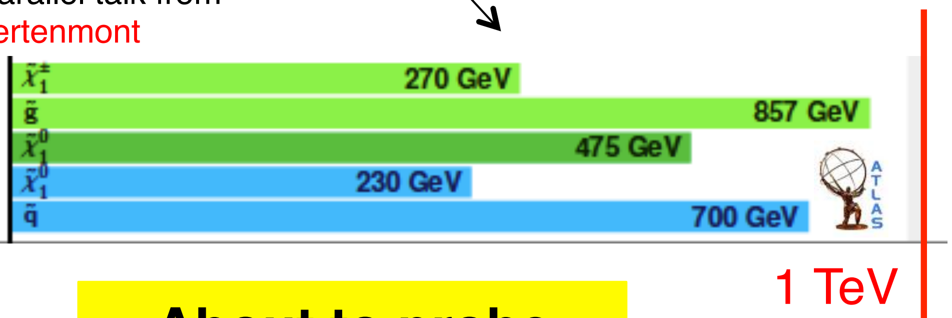
nearly mass-degenerate

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

search based on disappearing-track signature

CMS similar
See parallel talk from
L. Quertenmont

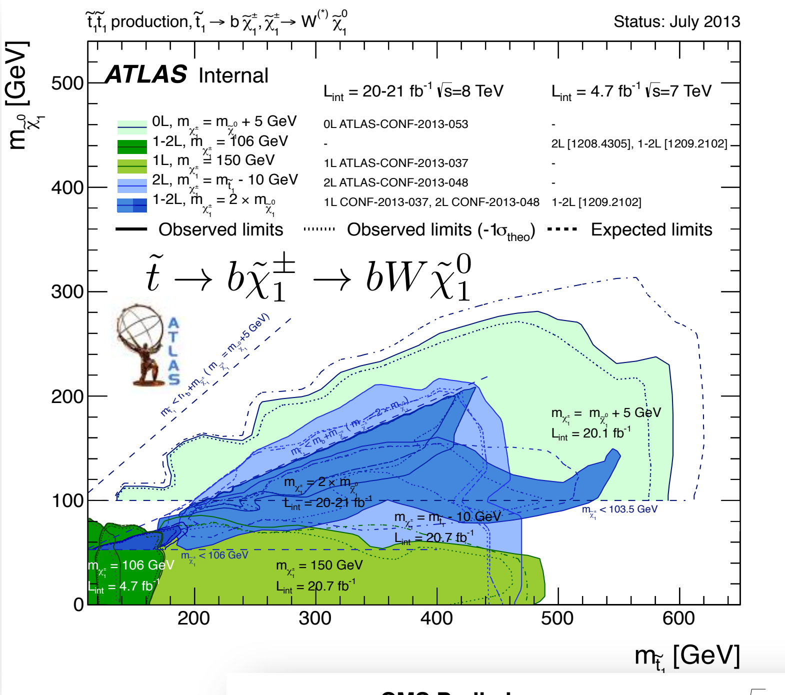
Long-lived particles					
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV
Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV
GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	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

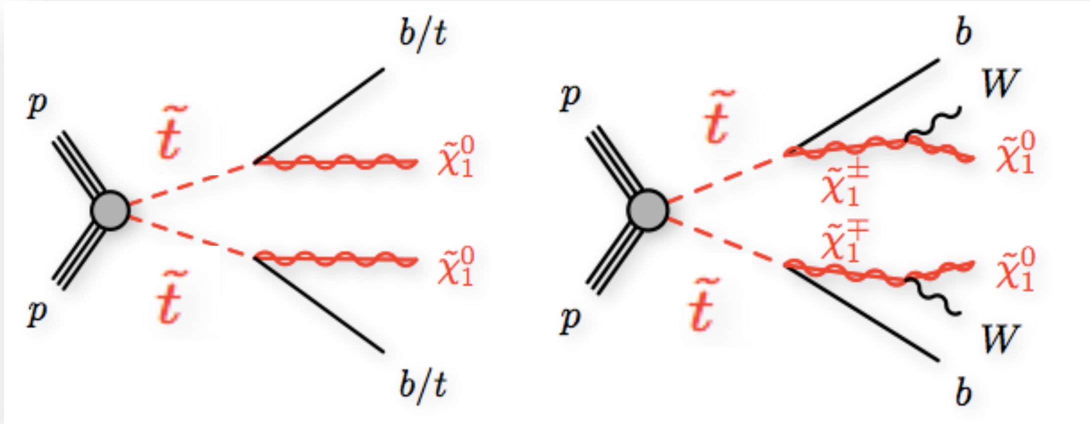


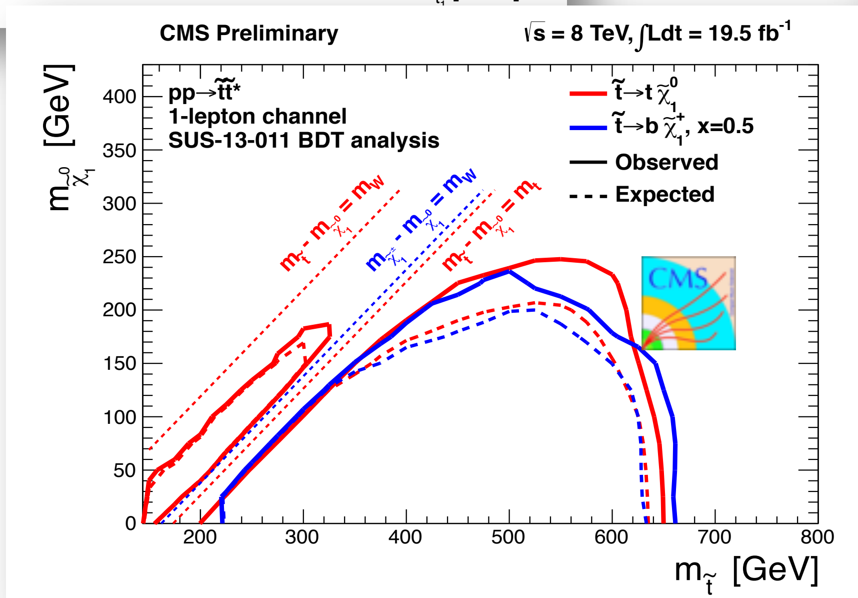
$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
10<tanβ<50	ATLAS-CONF-2013-058
0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
1 mm<cτ<1 m, $\tilde{g}$ decoupled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

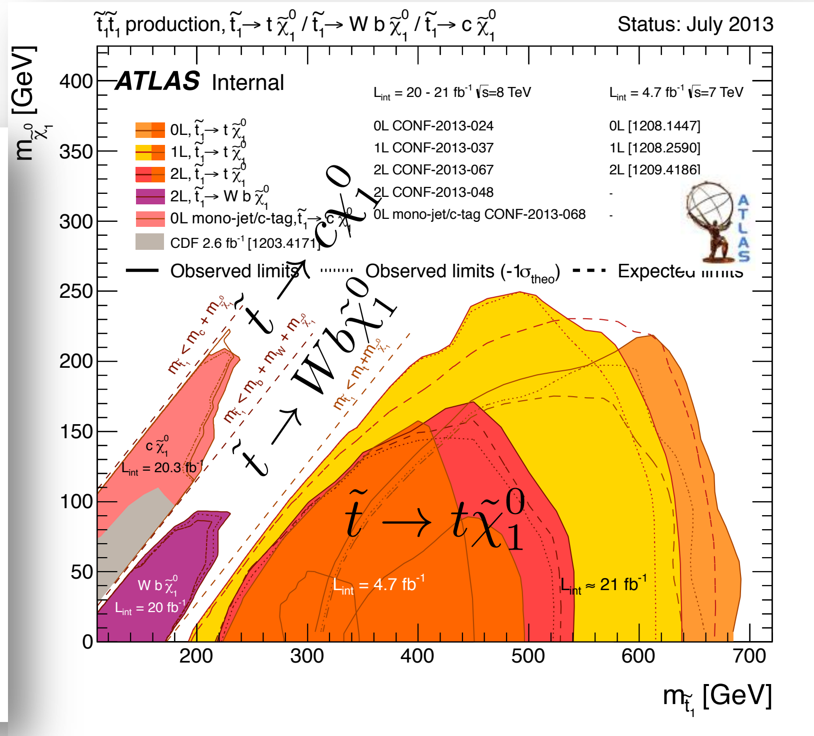
About to probe the 1 TeV scale

Dedicated searches for direct stop-pair production









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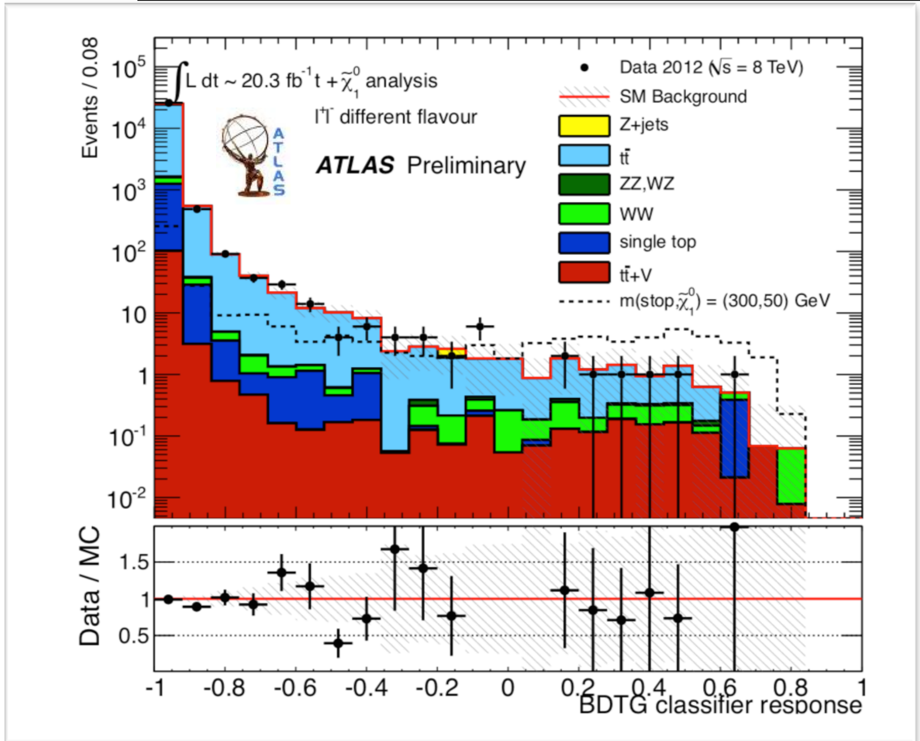
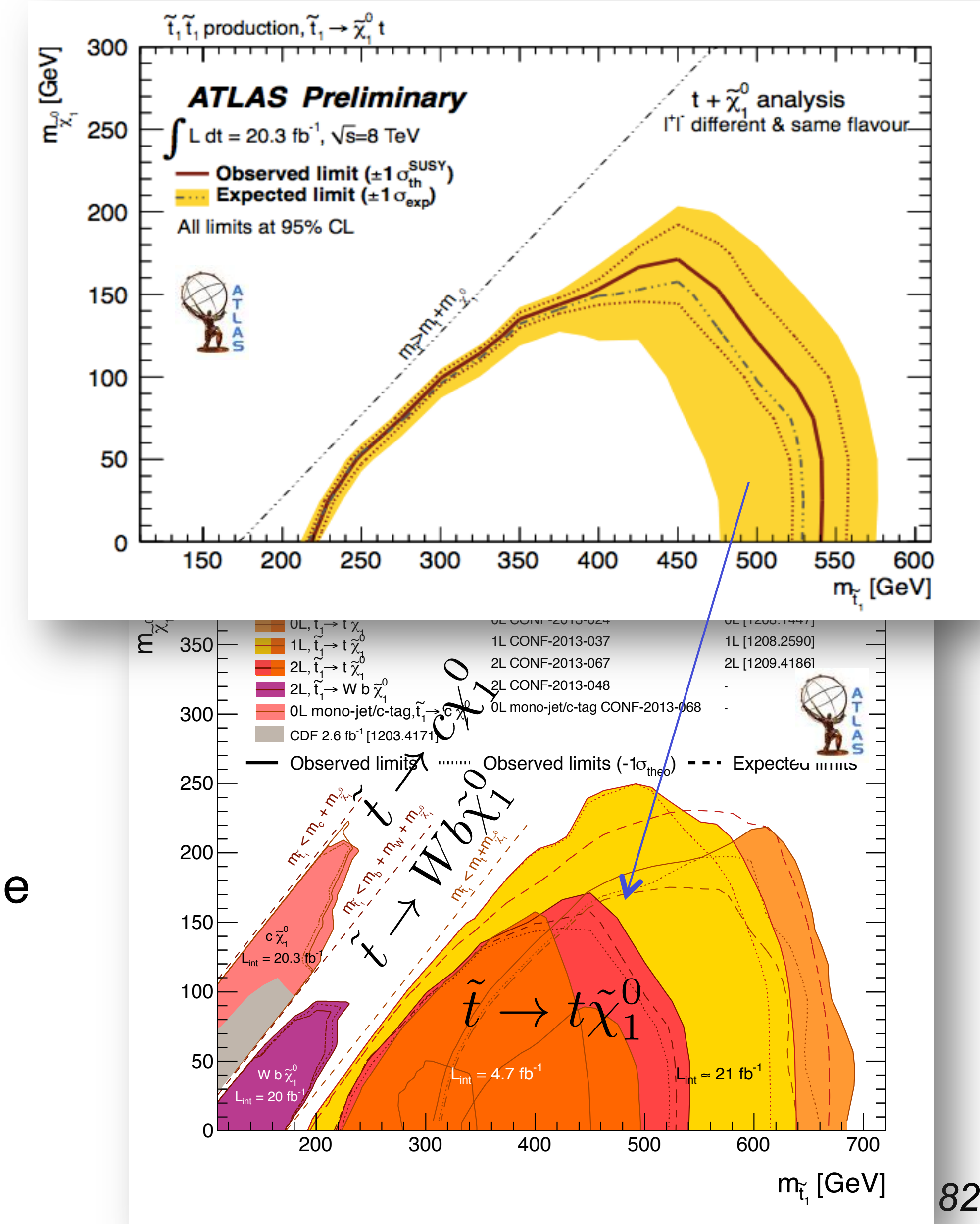
Dedicated searches for direct stop-pair production

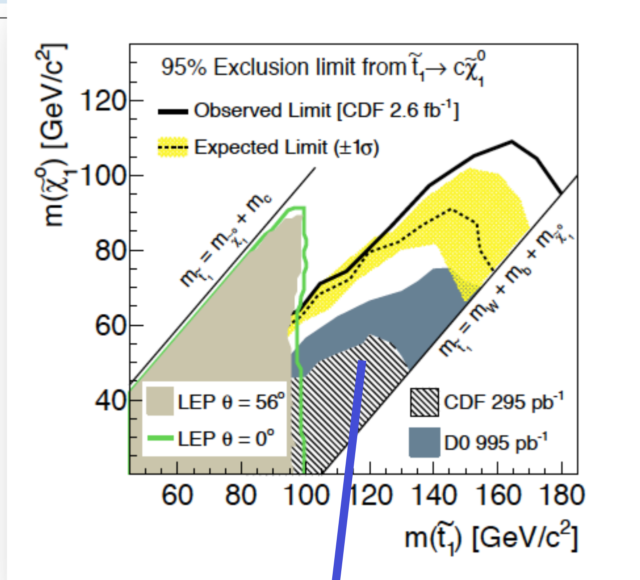




NEW

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

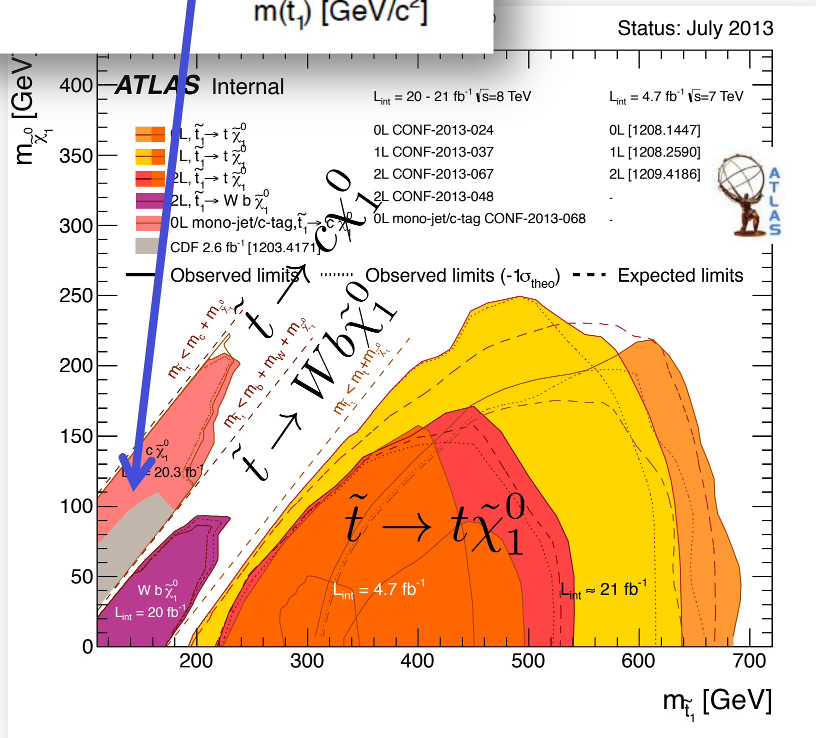
Dedicated searches for direct stop-pair production

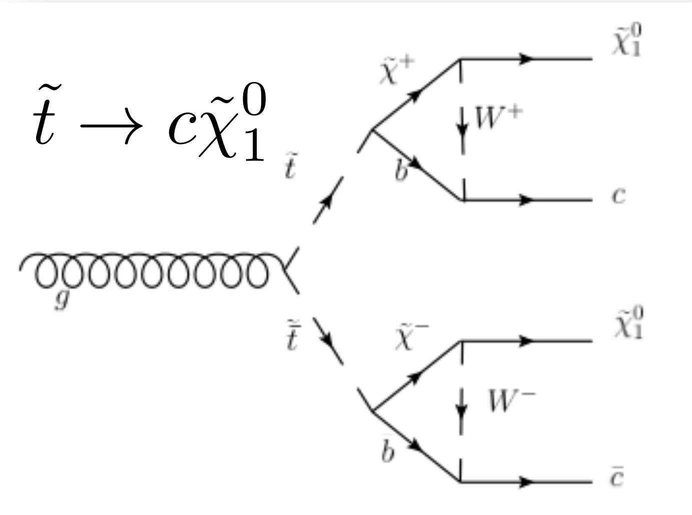


LEP:
LEPSUSY WG/04-01.1

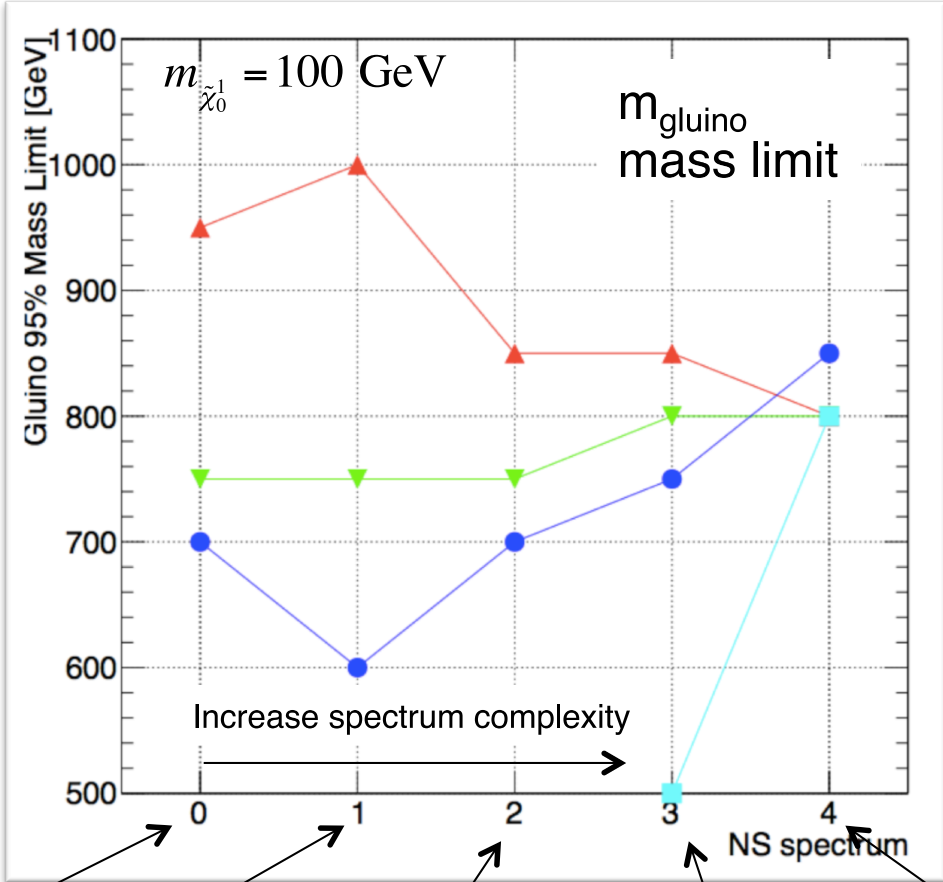
CDF:
1203.4171

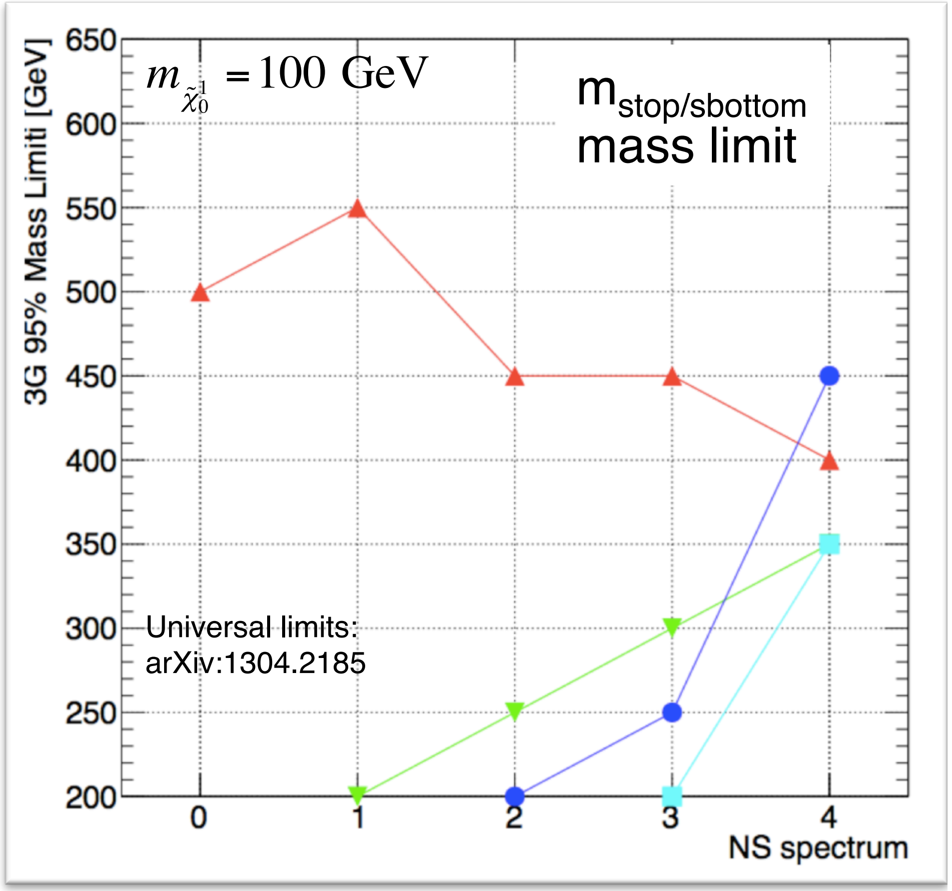
D0:
0803.2263





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

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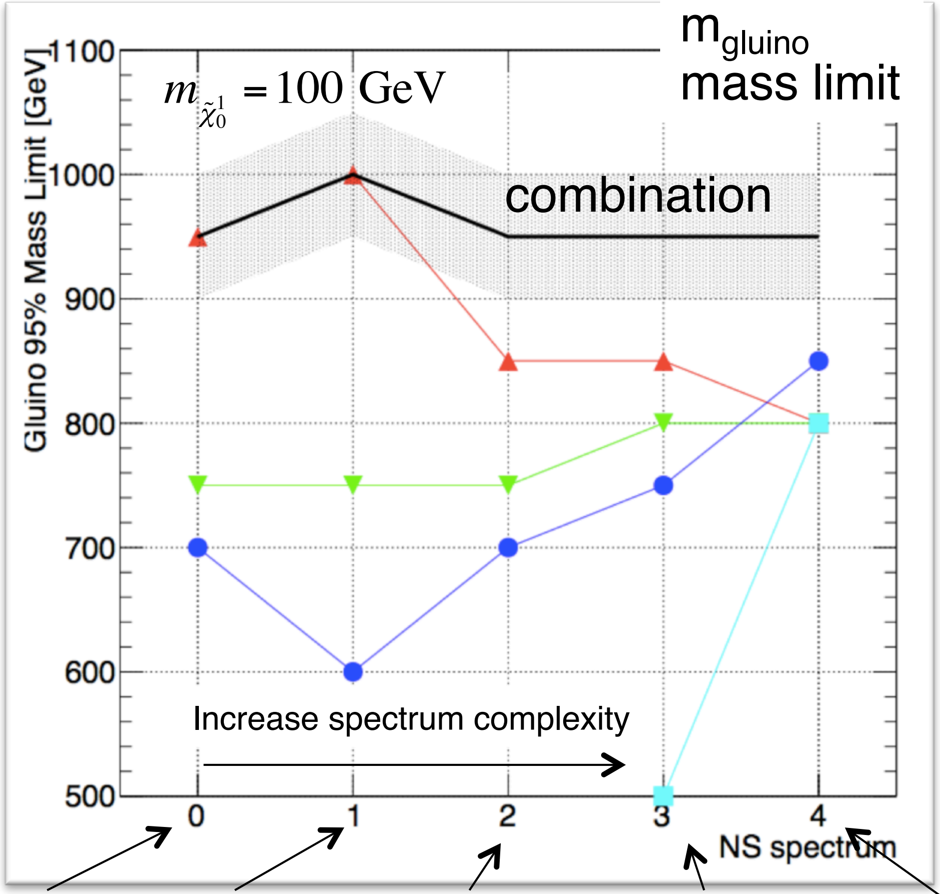
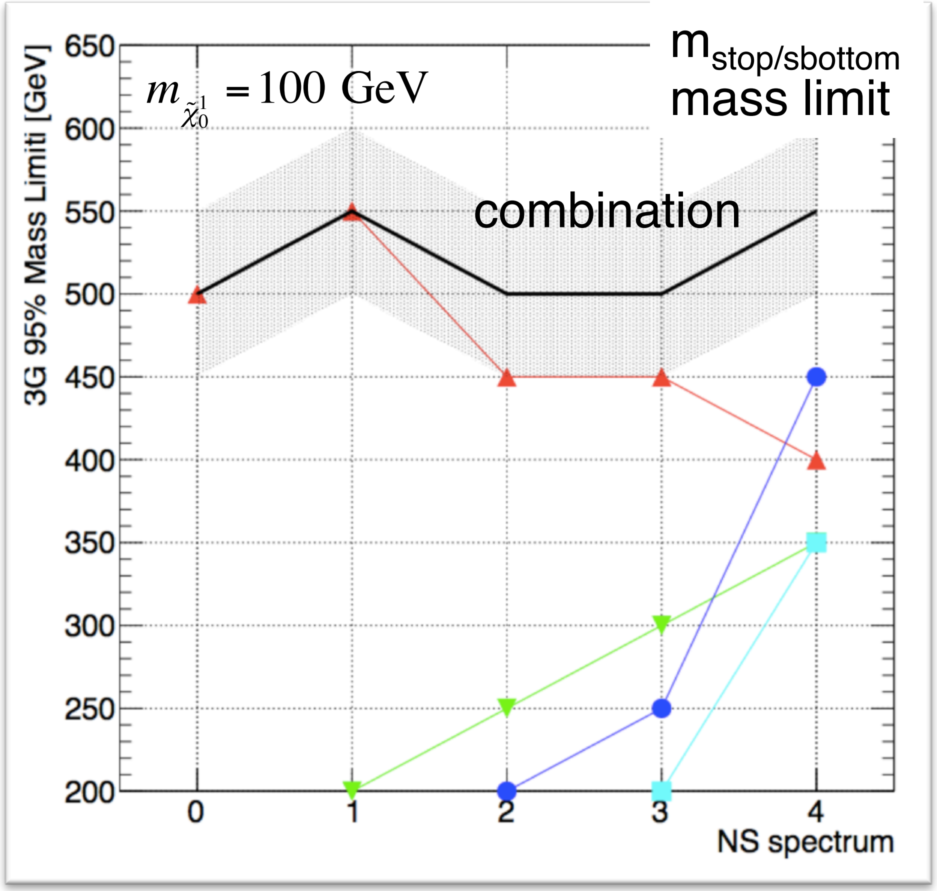
Combining Searches = less model dependence

Direct SUSY Searches, O. Buchmüller





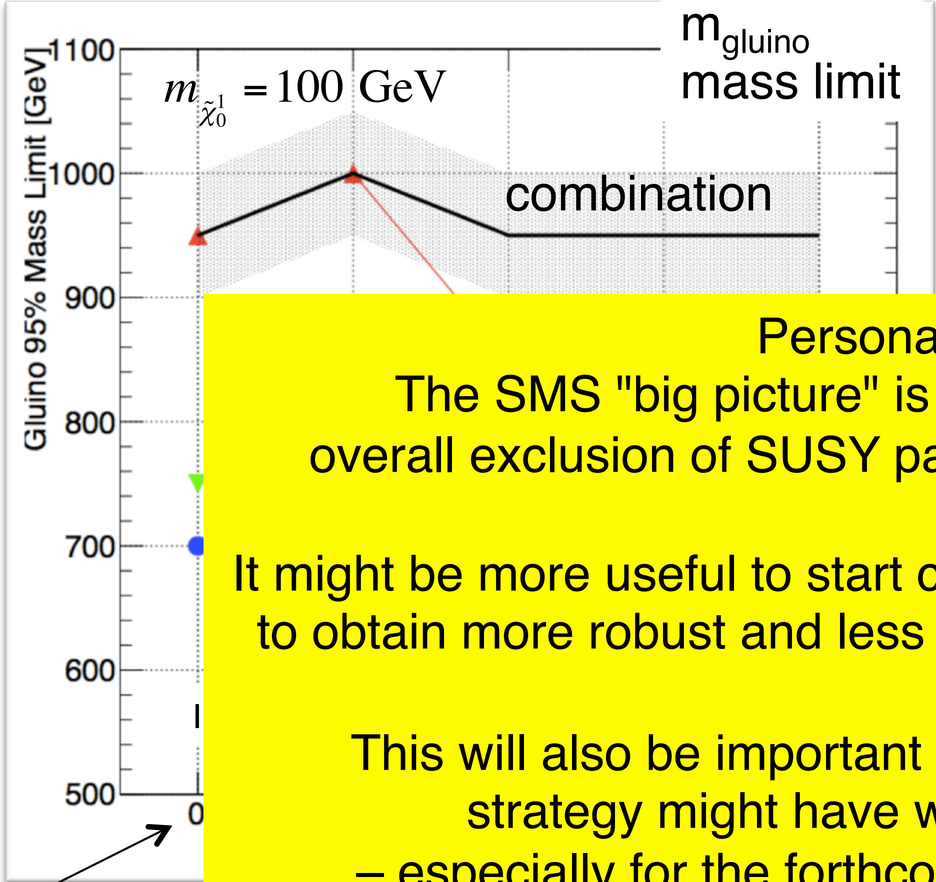
NS0	NS1	NS2	NS3	NS4
$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$
$\tilde{t}_1, \tilde{t}_2$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
		$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$	$\tilde{\chi}_0^2$
		$\tilde{\chi}^{\pm}$	$\tilde{\chi}^{\pm}$	$\tilde{\chi}^{\pm}, \tilde{\ell}_{L,R}$
$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$	$\tilde{\chi}_0^1$

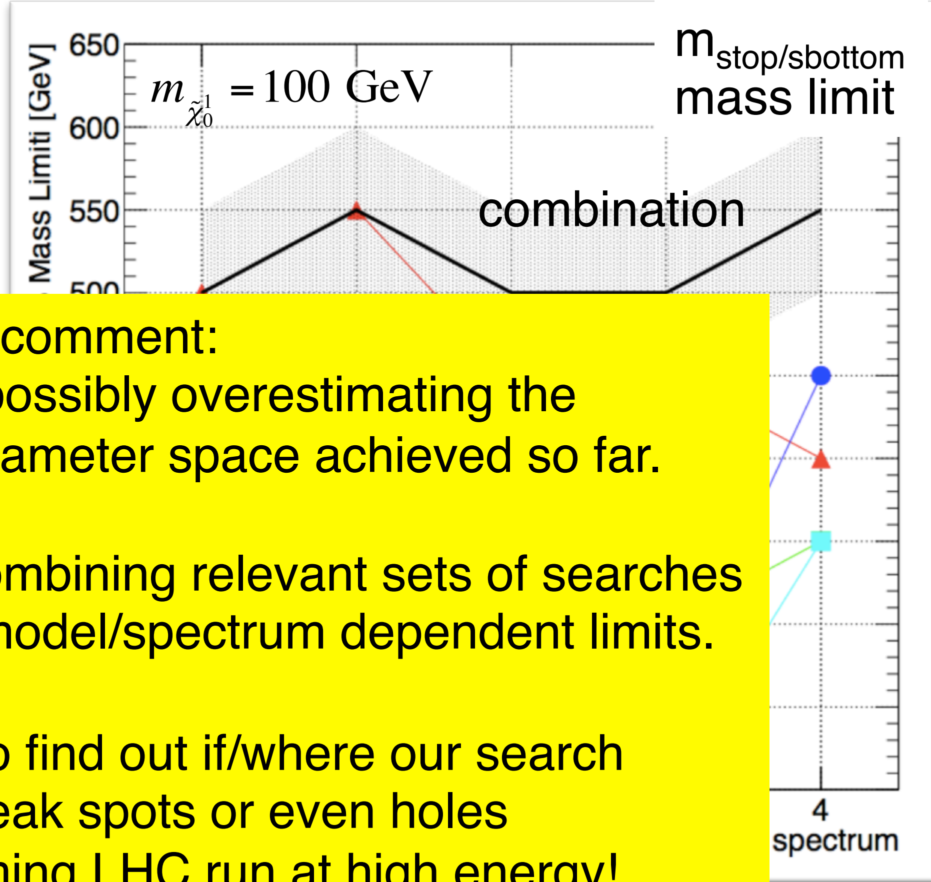
<u>Used inclusive searches from 2011:</u>

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

Direct SUSY Searches, O. Buchmüller





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

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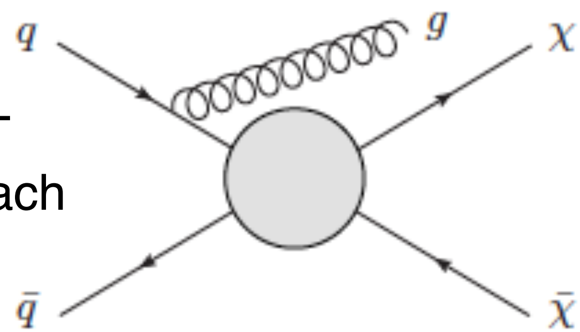
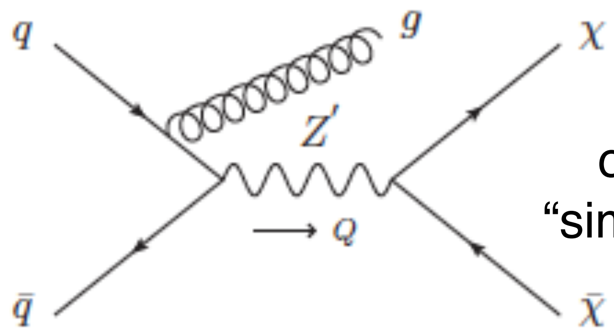
Validity of Effective Field Theory Limits

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

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

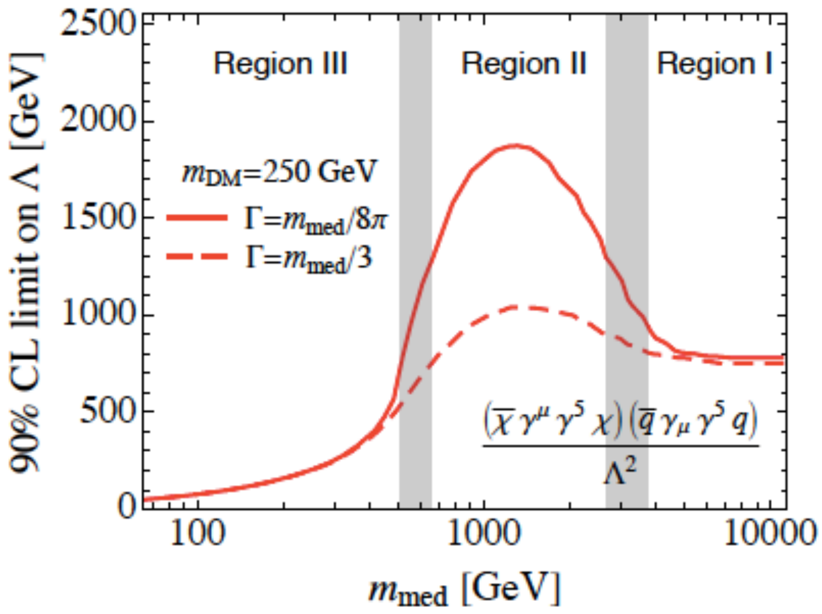
EFT approach





FT one diagram "simplified model"

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!

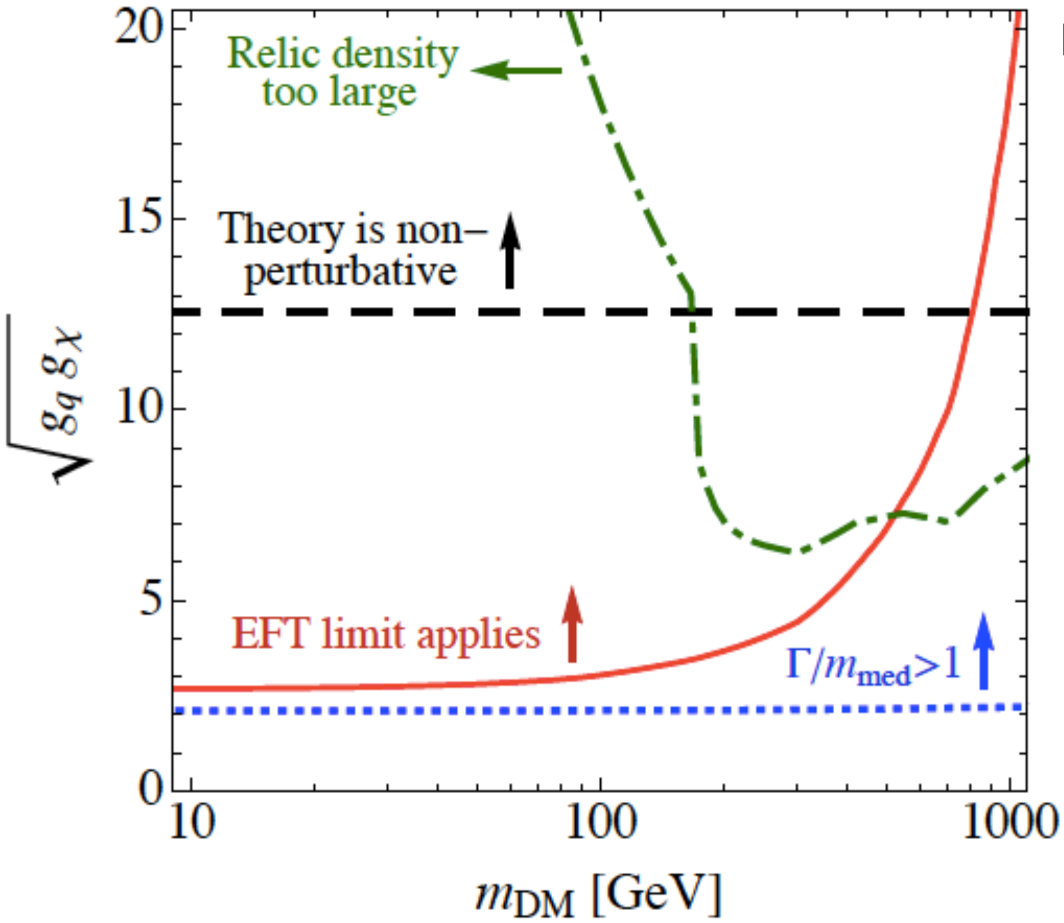
Region II: Medium m_{med} – Resonant enhancement

➢ EFT limits are too conservative!

Region III: Low m_{med}

➢ EFT limits are too aggressive!

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



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

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

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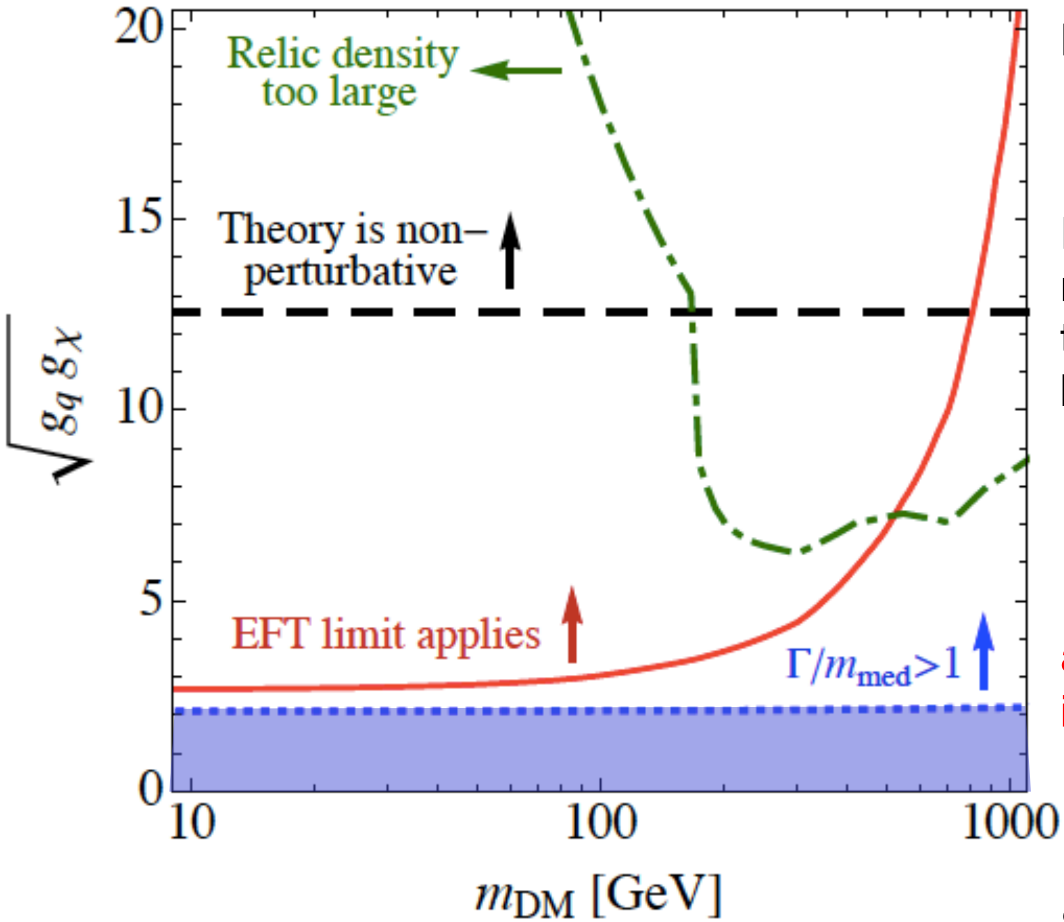
What those this imply on model-dependences of EFT limits?



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

1. Must require $m_{med} < \Gamma_{med}$

First we define the region in which mediator mass is larger then its width. Therefore, only this region a well-defined theory of PF can be straightforwardly established.

In the reaming part of the plot:

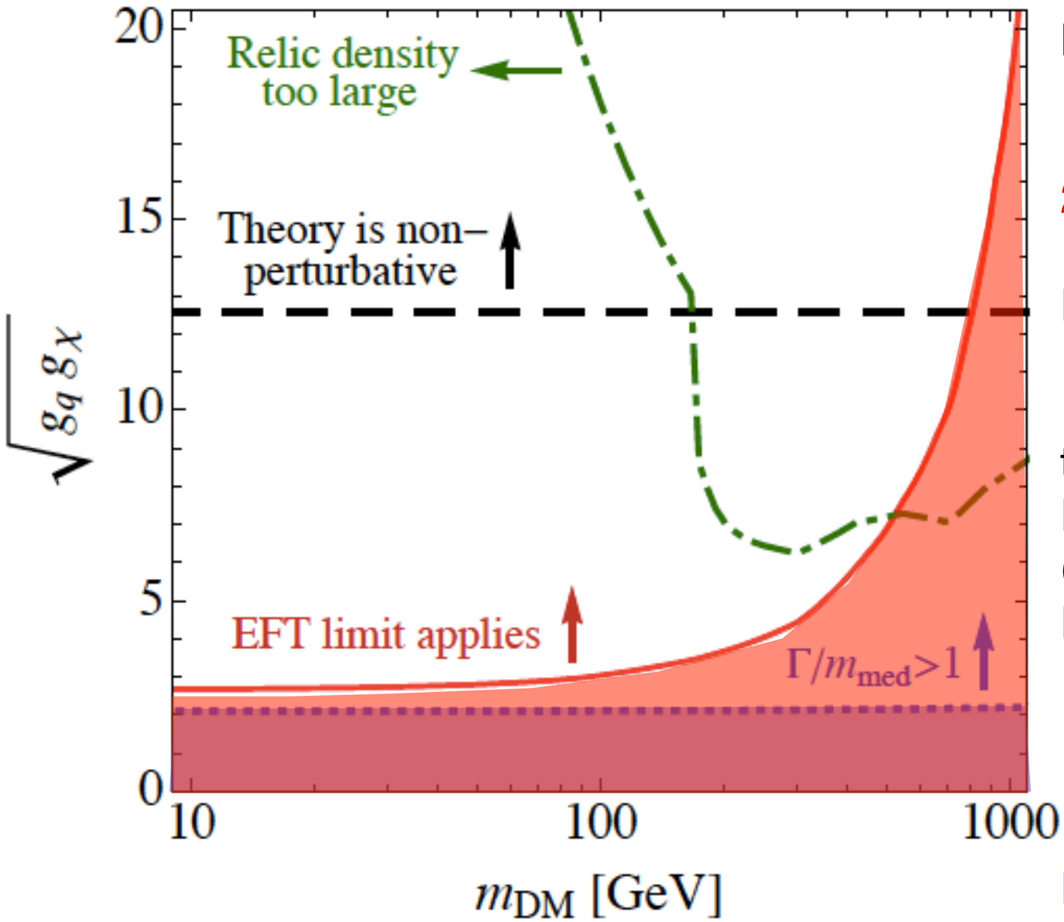
$$\sqrt{g_q g_\chi} > 2$$

a particle-like interpretation of the mediator is doubtful!

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

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

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

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).

First important observation:
The EFT is only valid in the region in which mediator width is larger than mediator mass!

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

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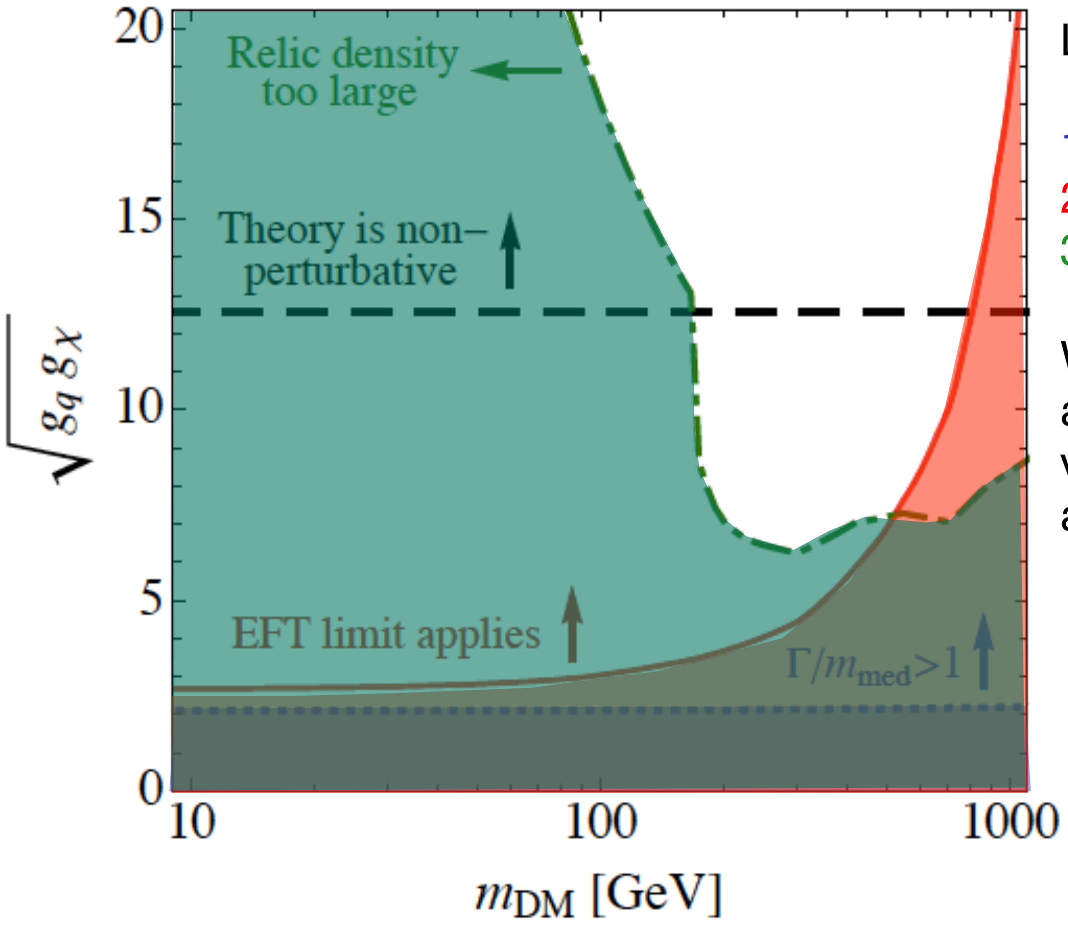
What those this imply on model-dependences of EFT limits?



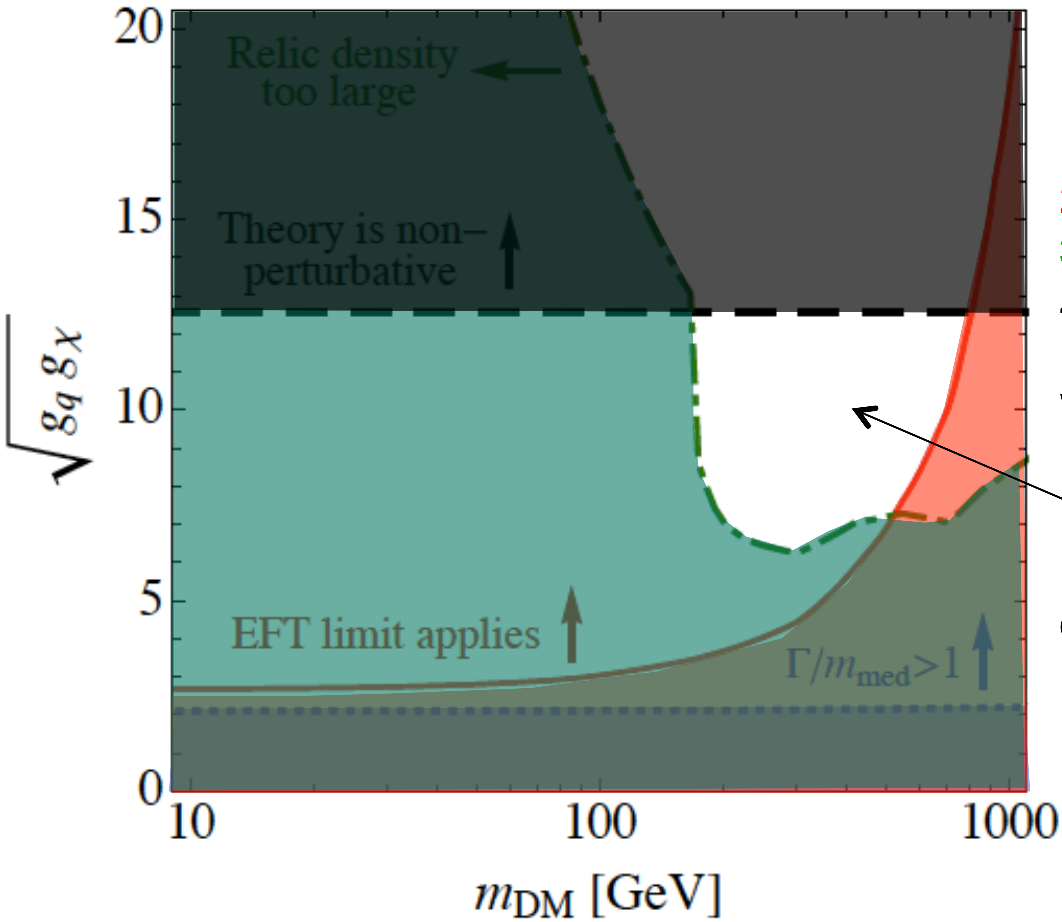
Look at EFT validity in m_{DM} – coupling* plane!

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

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

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

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!