

Oliver Buchmueller, Imperial College London

# **DIRECT SEARCHES FOR SUPERSYMMETRY – WHERE ARE WE TODAY?**

**INPUT FROM ATLAS, CMS, CDF AND D0**



**HEP 2013  
Stockholm  
18-24 July 2013**  
( [info@eps-hep2013.eu](mailto:info@eps-hep2013.eu) )



# “SUSY searches”: Talks in the parallel sessions

## Thursday 18/07

### Search for new physics in multijet final states

*Claudia Seitz*

<http://indico.cern.ch/getFile.py/access?contribId=206&sessionId=15&resId=0&materialId=slides&confId=218030>

### Inclusive searches for squarks and gluinos with the ATLAS detector

*Aleksej KOUTSMAN*

<http://indico.cern.ch/getFile.py/access?contribId=348&sessionId=15&resId=0&materialId=slides&confId=218030>

### Inclusive SUSY searches at the LHC using the CMS detector

*Christian AUTERMANN*

<http://indico.cern.ch/getFile.py/access?contribId=496&sessionId=15&resId=0&materialId=slides&confId=218030>

## Friday 19/07

### Search for RP violating Supersymmetry

*Altan CAKIR*

<http://indico.cern.ch/getFile.py/access?contribId=147&sessionId=15&resId=0&materialId=slides&confId=218030>

### Searches for SUSY in R-parity violating signatures

*Wolfgang EHRENFELD*

<http://indico.cern.ch/getFile.py/access?contribId=353&sessionId=15&resId=0&materialId=slides&confId=218030>

### Searches for highly displaced jets with the ATLAS detector

*Massimo CORRADI*

<http://indico.cern.ch/getFile.py/access?contribId=341&sessionId=15&resId=0&materialId=slides&confId=218030>

### Search for long-lived particles at CMS

*Loic QUERTENMONT*

<http://indico.cern.ch/getFile.py/access?contribId=205&sessionId=15&resId=0&materialId=slides&confId=218030>

### Search for Natural SUSY with inclusive search strategies at the LHC using the CMS detector

*Sezen SEKMEN*

<http://indico.cern.ch/getFile.py/access?contribId=495&sessionId=15&resId=0&materialId=slides&confId=218030>

### Searches for electroweak production of SUSY neutralinos, charginos and sleptons

*Samuel KING*

<http://indico.cern.ch/getFile.py/access?contribId=352&sessionId=15&resId=0&materialId=slides&confId=218030>

### SUSY searches for EWK production of Gauginos and Sleptons at the LHC

*Lesya SHCHUTSKA*

<http://indico.cern.ch/getFile.py/access?contribId=148&sessionId=15&resId=0&materialId=slides&confId=218030>

## Saturday 20/07

### Searches for direct pair production of third generation squarks with the ATLAS detector

*Tommaso LARI*

<http://indico.cern.ch/getFile.py/access?contribId=350&sessionId=15&resId=0&materialId=slides&confId=218030>

### Search for direct stop pair production at the LHC using the CMS detector

*Hongxuan LIU*

<http://indico.cern.ch/getFile.py/access?contribId=167&sessionId=15&resId=0&materialId=slides&confId=218030>

### Searches for gluino-mediated production of third generation squarks with ATLAS

*David COTE*

<http://indico.cern.ch/getFile.py/access?contribId=349&sessionId=15&resId=0&materialId=slides&confId=218030>

### Search for Supersymmetry in the four W and multiple b-quark final state

*Keith ULMER*

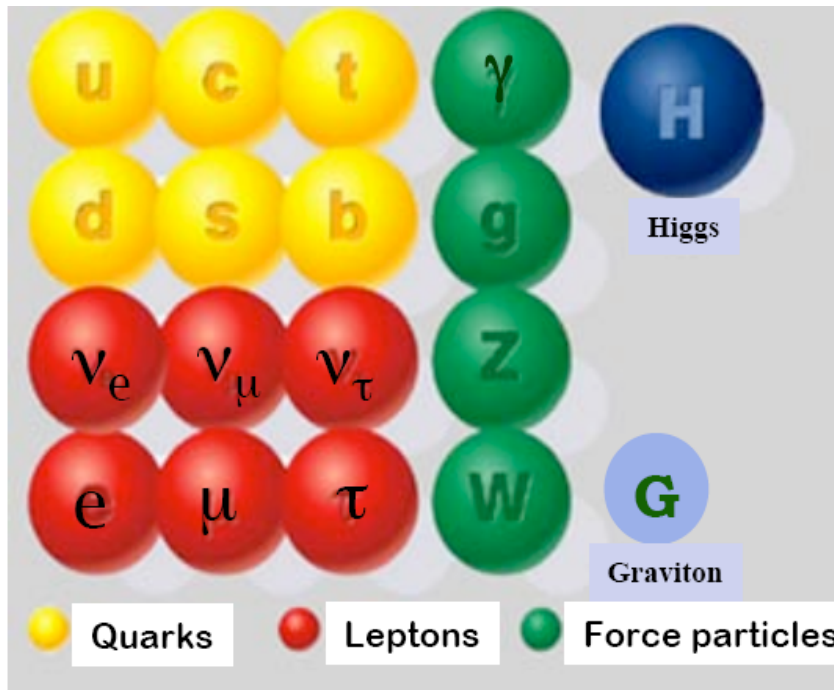
<http://indico.cern.ch/getFile.py/access?contribId=146&sessionId=15&resId=0&materialId=slides&confId=218030>

...and many other related talks presented in the parallel session “Higgs and New Physics”

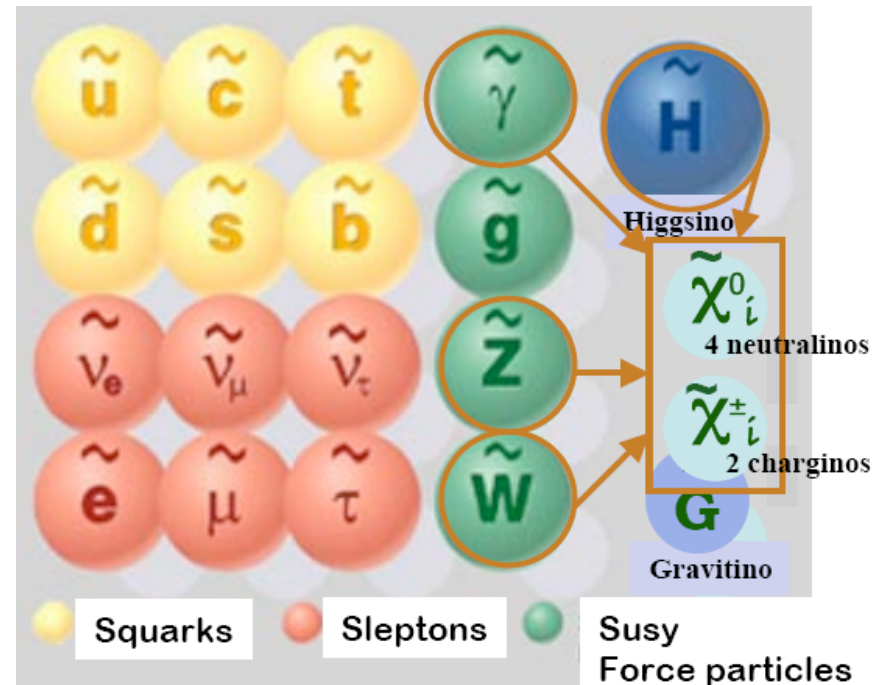
# Supersymmetry

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

## Standard Model particles



## SUSY particles



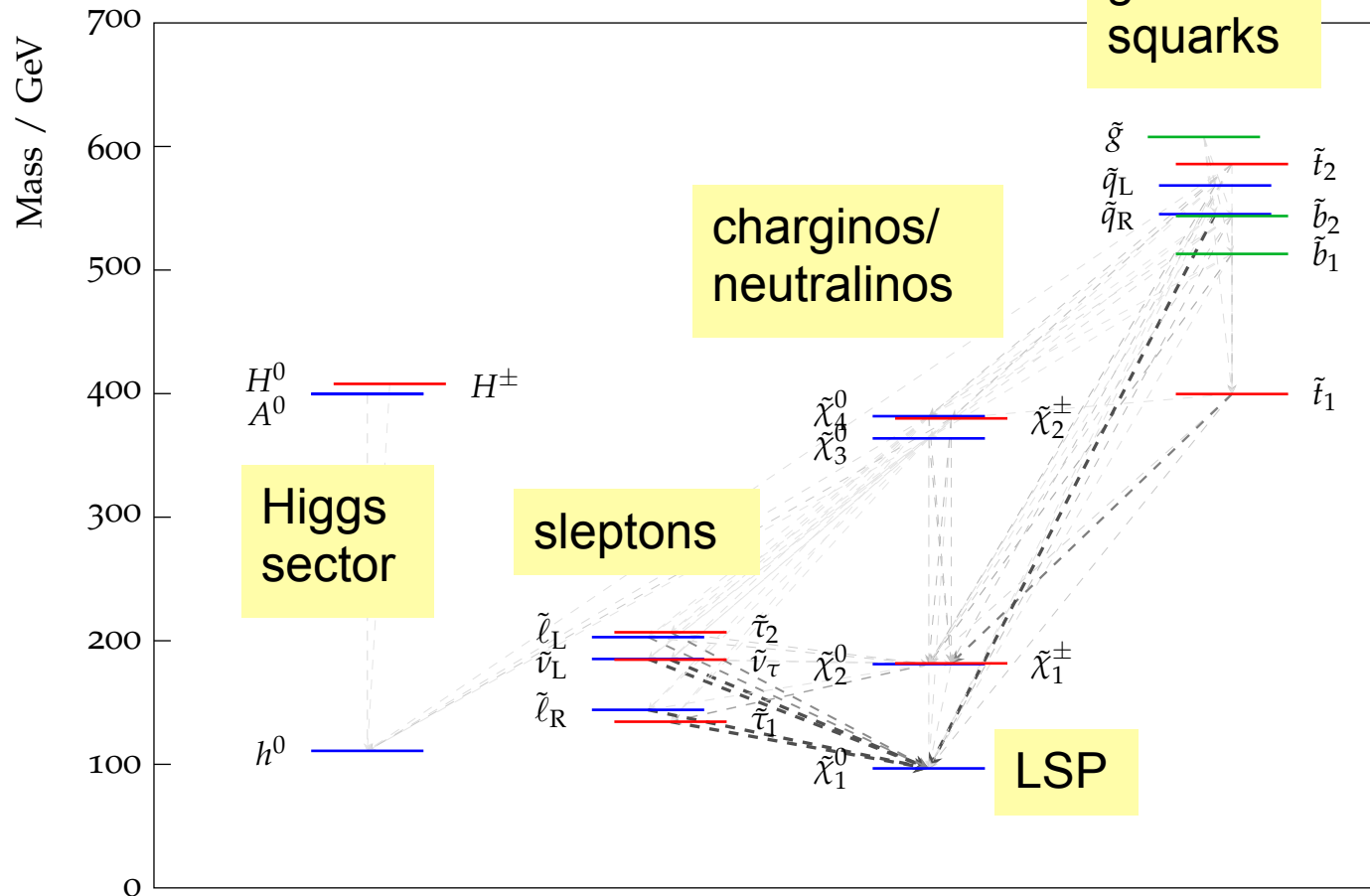
New Quantum number: R-parity:  $R_p = (-1)^{B+L+2s} = +1$  SM particles  
 R-parity conservation:  $-1$  SUSY particles

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

# A “typical” SUSY Spectrum

Use the famous SPS1a benchmark point for illustration  
 $[m_0=100, m_{1/2}=250, \tan\beta=10, A_0=-100, \mu>0]$

EPS 2013 Direct SUSY Searches, O. Buchmüller



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

## Advantage:

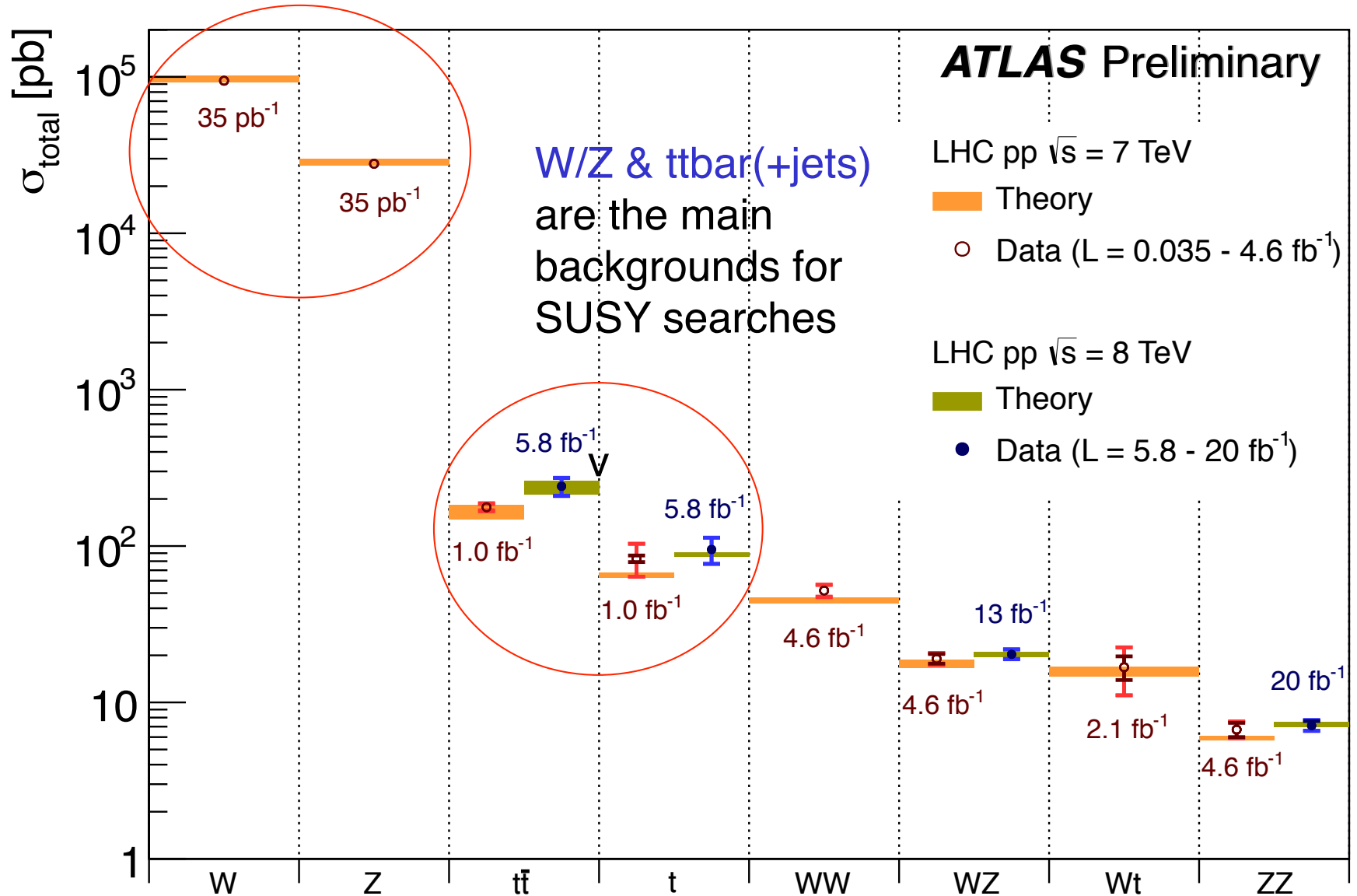
- Only four free parameters (when  $\text{sign}(\mu)$  fixed)
- One of the most studied incarnations of the MSSM

## Disadvantage:

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

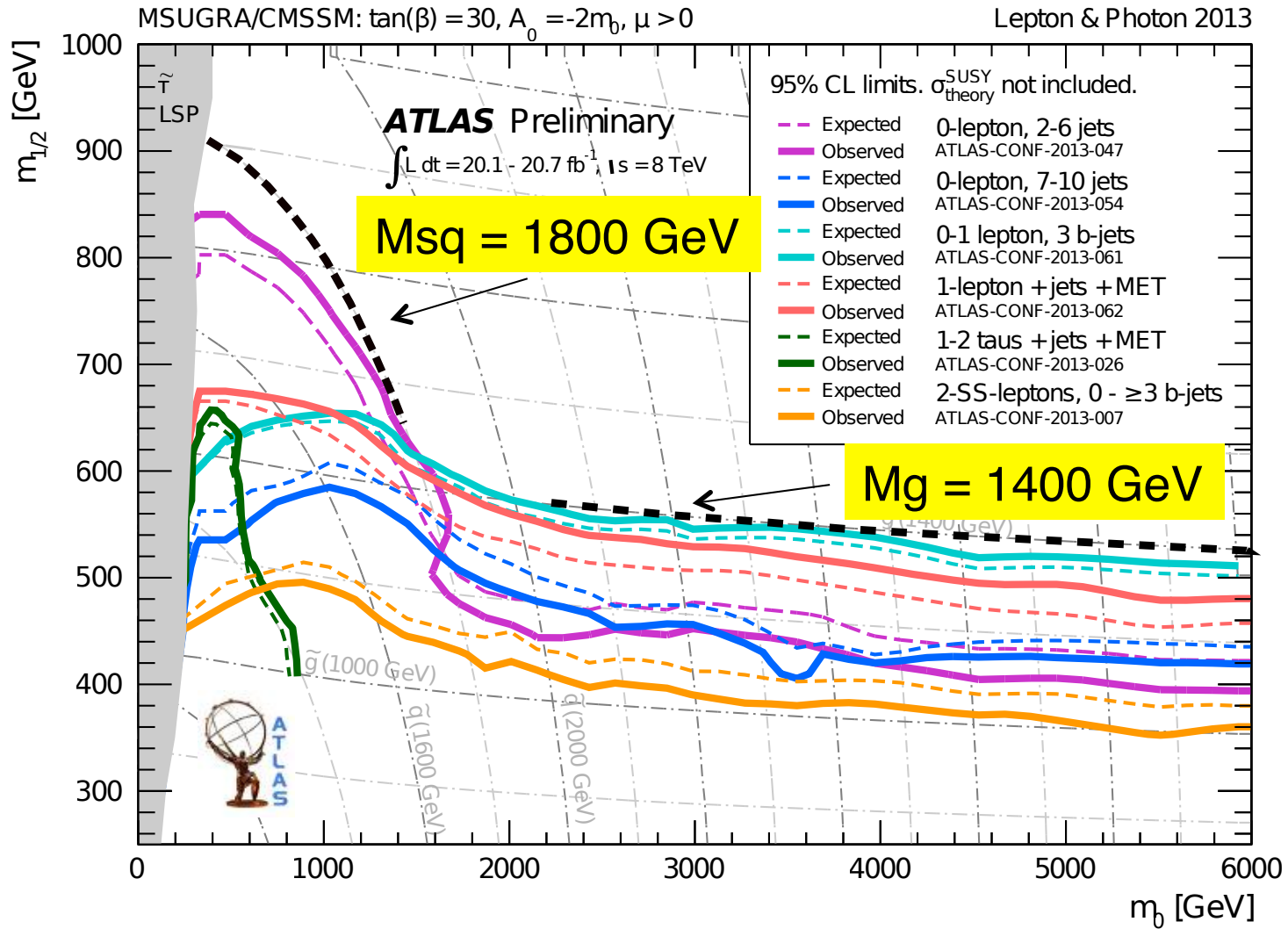
# Rediscovery of the SM at a new energy frontier

EPS 2013 Direct SUSY Searches, O. Buchmüller



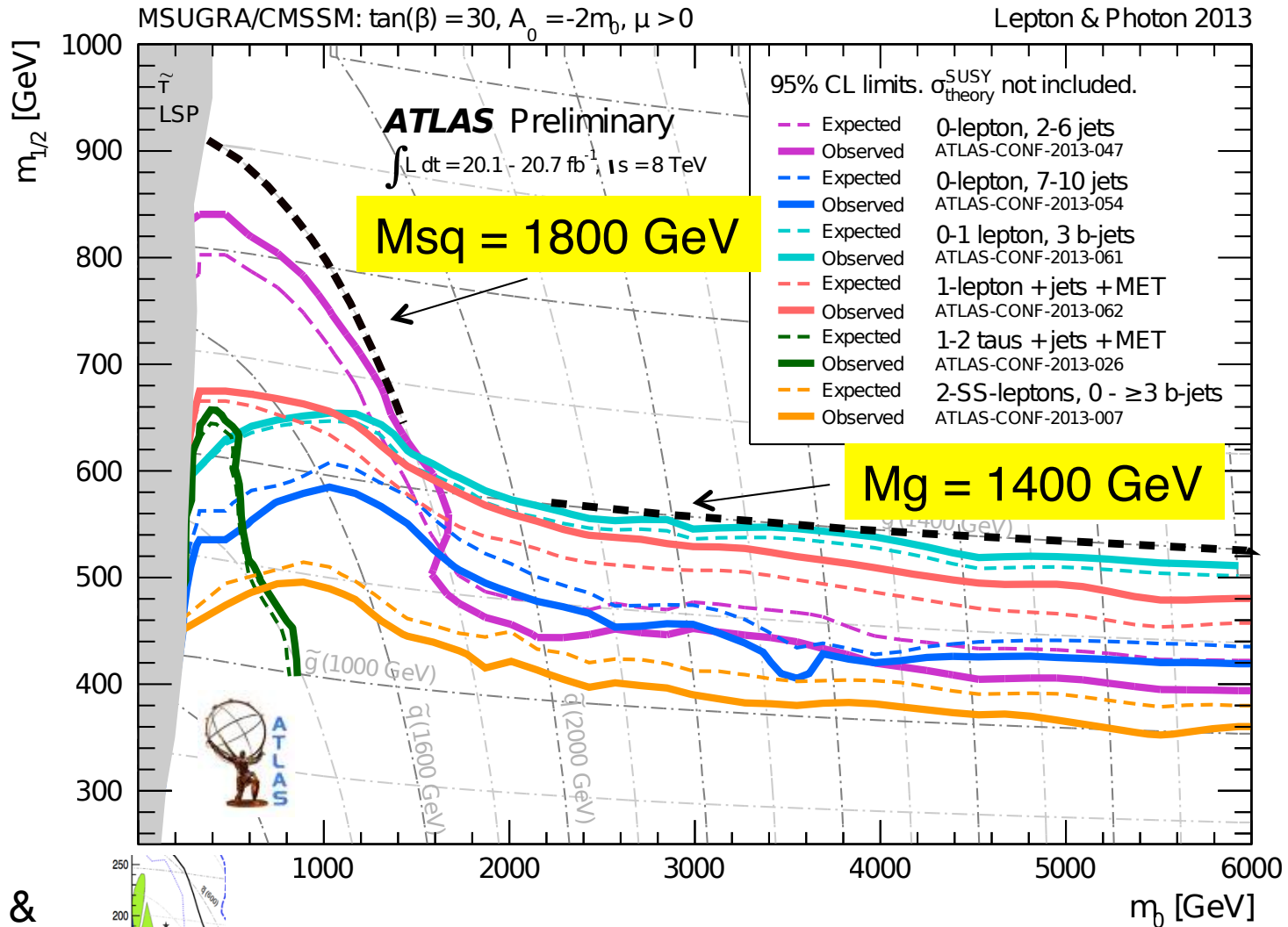
# Inclusive SUSY Searches in 2013

EPS 2013 Direct SUSY Searches, O. Buchmüller



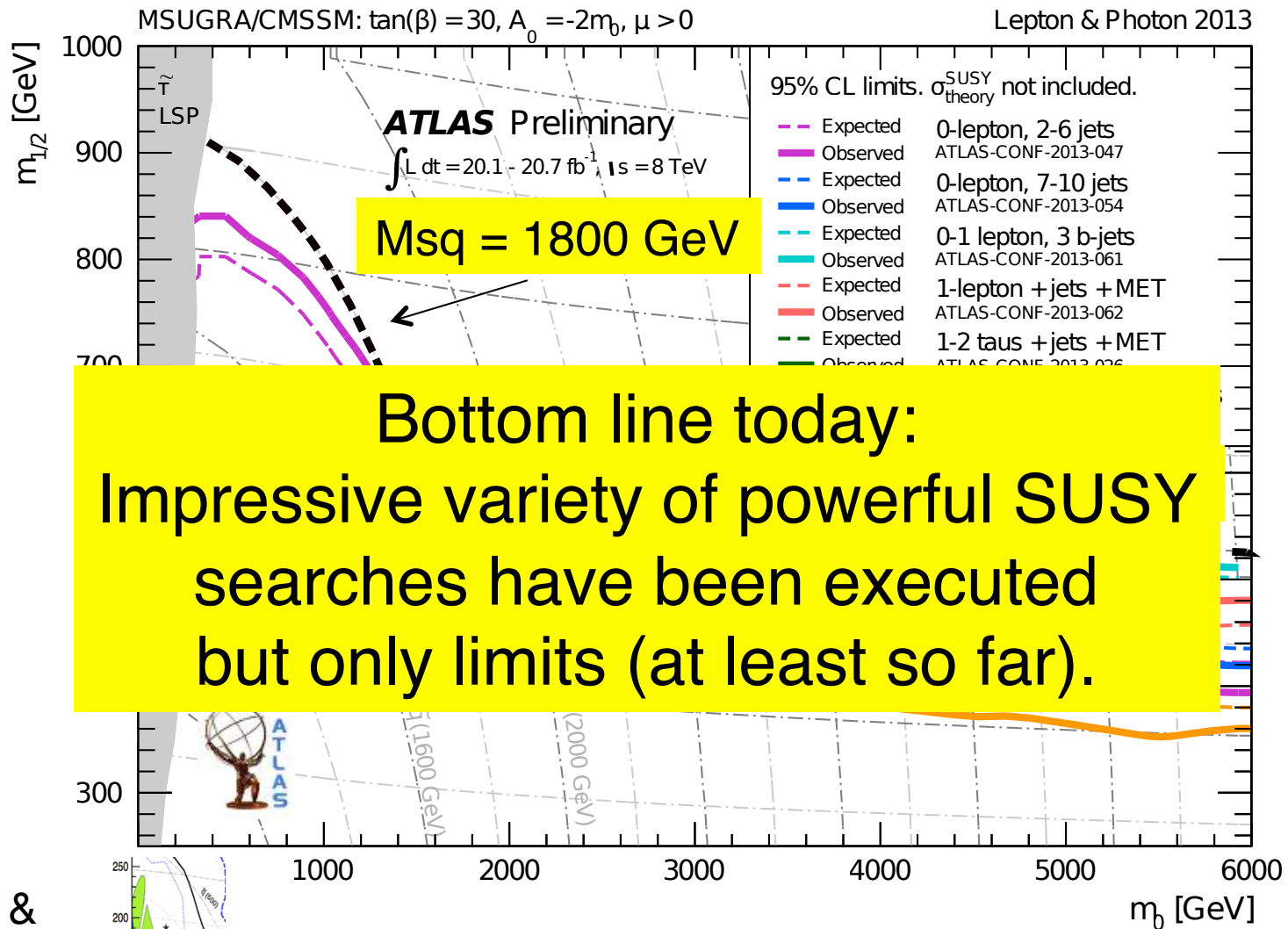
# Inclusive SUSY Searches in 2013

EPS 2013 Direct SUSY Searches, O. Buchmüller



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

# Inclusive SUSY Searches in 2013

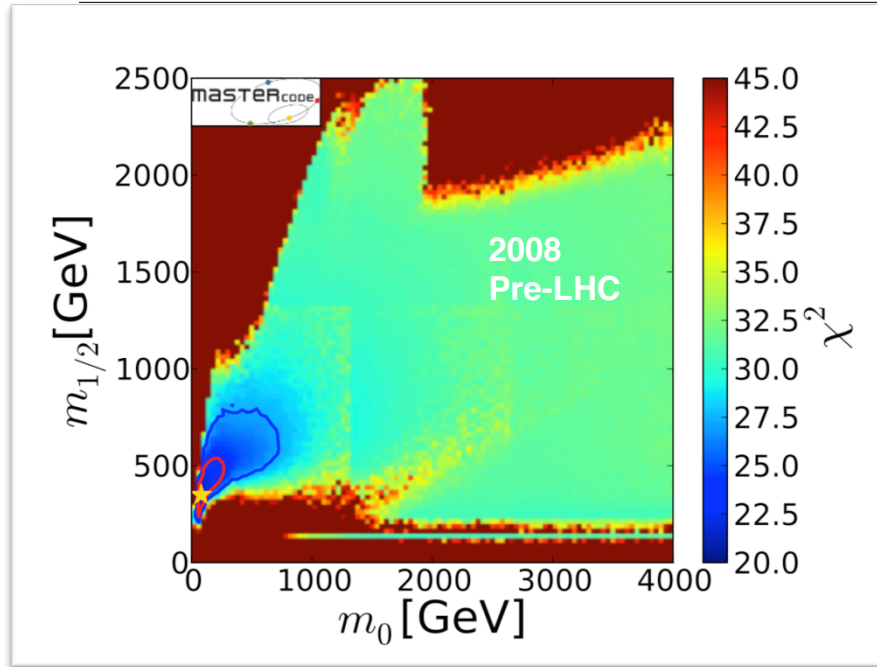


The LHC has pushed the mass scale in constraint SUSY models to a new level!



# CMSSM: Evolution with time

EPS 2013 Direct SUSY Searches, O. Buchmüller



$\chi^2$  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]	$173.2 \pm 0.90$	0.05	0.06	-
$\Delta\alpha_{had}^{(5)}(M_Z)$	[42]	$0.02749 \pm 0.00010$	0.009	0.004	-
$M_Z$ [GeV]	[44]	$91.1875 \pm 0.0021$	$2.7 \times 10^{-11}$	0.26	-
$\Gamma_Z$ [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{SUSY}$	0.078	0.047	0.14
$\sigma_{had}^{inb}$	[26] / [44]	$41.540 \pm 0.037$	2.50	2.57	2.54
$R_t$	[26] / [44]	$20.767 \pm 0.025$	1.05	1.08	1.08
$A_{fb}(\ell)$	[26] / [44]	$0.01714 \pm 0.00095$	0.72	0.69	0.81
$A_{FB}(P_T)$	[26] / [44]	$0.1465 \pm 0.0032$	0.11	0.13	0.07
$R_b$	[26] / [44]	$0.21629 \pm 0.00066$	0.26	0.29	0.27
$R_c$	[26] / [44]	$0.1721 \pm 0.0030$	0.002	0.002	0.002
$A_{FB}(b)$	[26] / [44]	$0.0992 \pm 0.0016$	7.17	7.37	6.63
$A_{FB}(c)$	[26] / [44]	$0.0707 \pm 0.0035$	0.86	0.88	0.80
$A_b$	[26] / [44]	$0.923 \pm 0.020$	0.36	0.36	0.35
$A_c$	[26] / [44]	$0.670 \pm 0.027$	0.005	0.005	0.005
$A_{FB}(SLD)$	[26] / [44]	$0.1513 \pm 0.0021$	3.16	3.03	3.51
$\sin^2 \theta_{eff}^e(Q_{FB})$	[26] / [44]	$0.2324 \pm 0.0012$	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
$a_{\mu}^{exp} - a_{\mu}^{SM}$	[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] / [53,56]	$> 114.4[\pm 1.5_{SUSY}]$	0.0	0.0	0.0
$BR_{b \rightarrow sy}^{EXP/SM}$	[45] / [46]	$1.117 \pm 0.076_{EXP} \pm 0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
$BR(B_s \rightarrow \mu^+ \mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$BR_{B \rightarrow \tau \nu}^{EXP/SM}$	[29] / [46]	$1.43 \pm 0.43_{EXP+TH}$	1.43	1.59	1.00
$BR(B_d \rightarrow \mu^+ \mu^-)$	[29] / [46]	$< 4.6[\pm 0.1_{SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR_{\mu \rightarrow X \gamma}^{EXP/SM}$	[47] / [46]	$0.99 \pm 0.32$	0.02	$\ll 0.01$	$\ll 0.01$
$BR_{K \rightarrow \mu \nu}^{EXP/SM}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR_{K \rightarrow \pi \nu \nu}^{EXP/SM}$	[49] / [50]	$< 4.5$	0.0	0.0	0.0
$\Delta M_{B_s}^{EXP/SM}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\Delta M_{B_d}^{EXP/SM}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta c_K^{EXP/SM}$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM} h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	$8.4 \times 10^{-4}$	0.1	N/A
$\sigma_8$	[25]	$(m_{\tilde{g}}, \sigma_8^{21})$ plane	0.13	0.13	N/A
jets + $B_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan \beta)$ plane	0.0	0.0	N/A
Total $\chi^2/d.o.f.$	All	All	28.8/22	27.3/21	32.7/23 (21.5/22)
p-values			15%	16%	9% (49%)

**Global Fit to indirect and direct constraints on SUSY!**

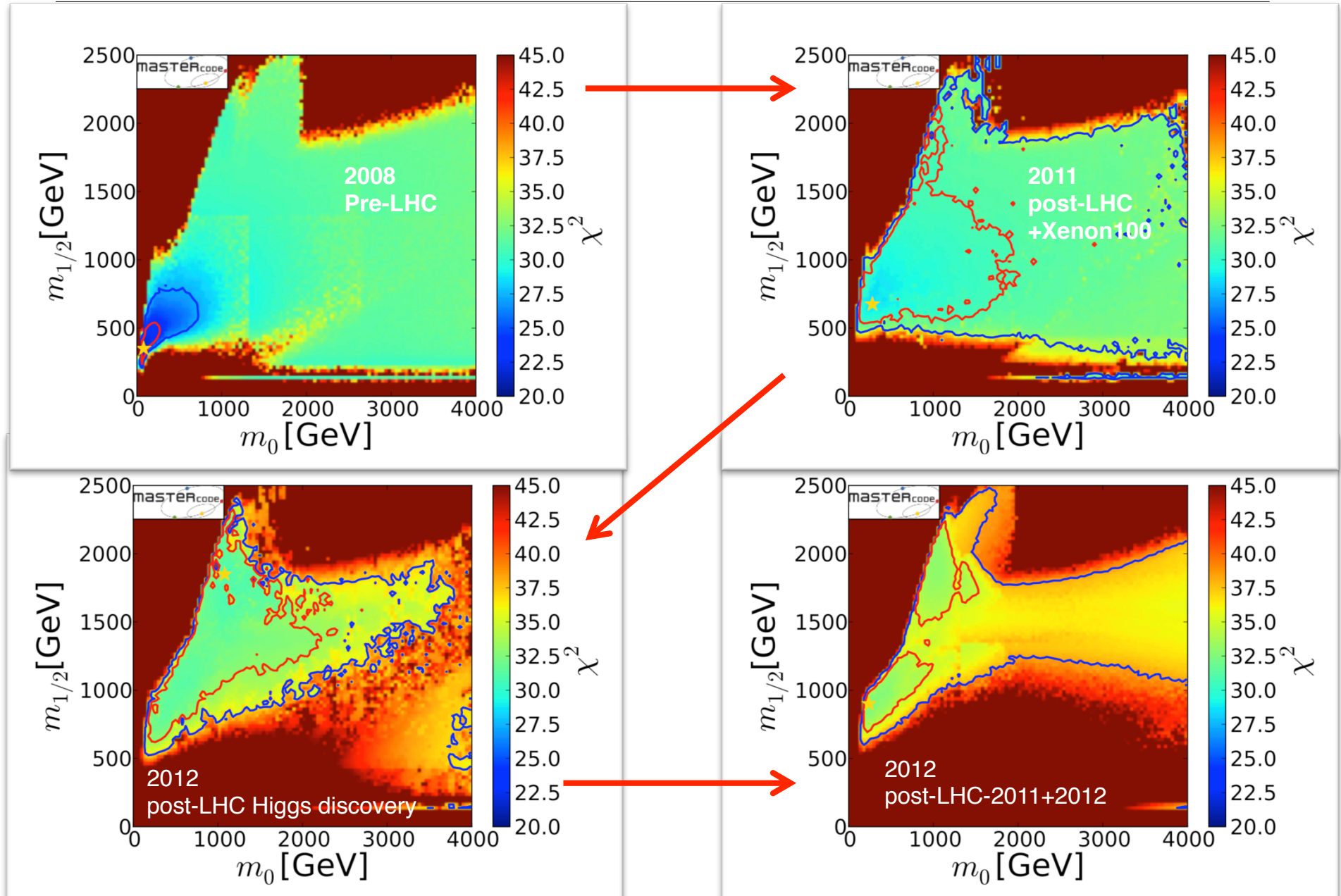
Other "fitter" groups find very similar results: e.g.

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

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

# CMSSM: Evolution with time

EPS 2013 Direct SUSY Searches, O. Buchmüller



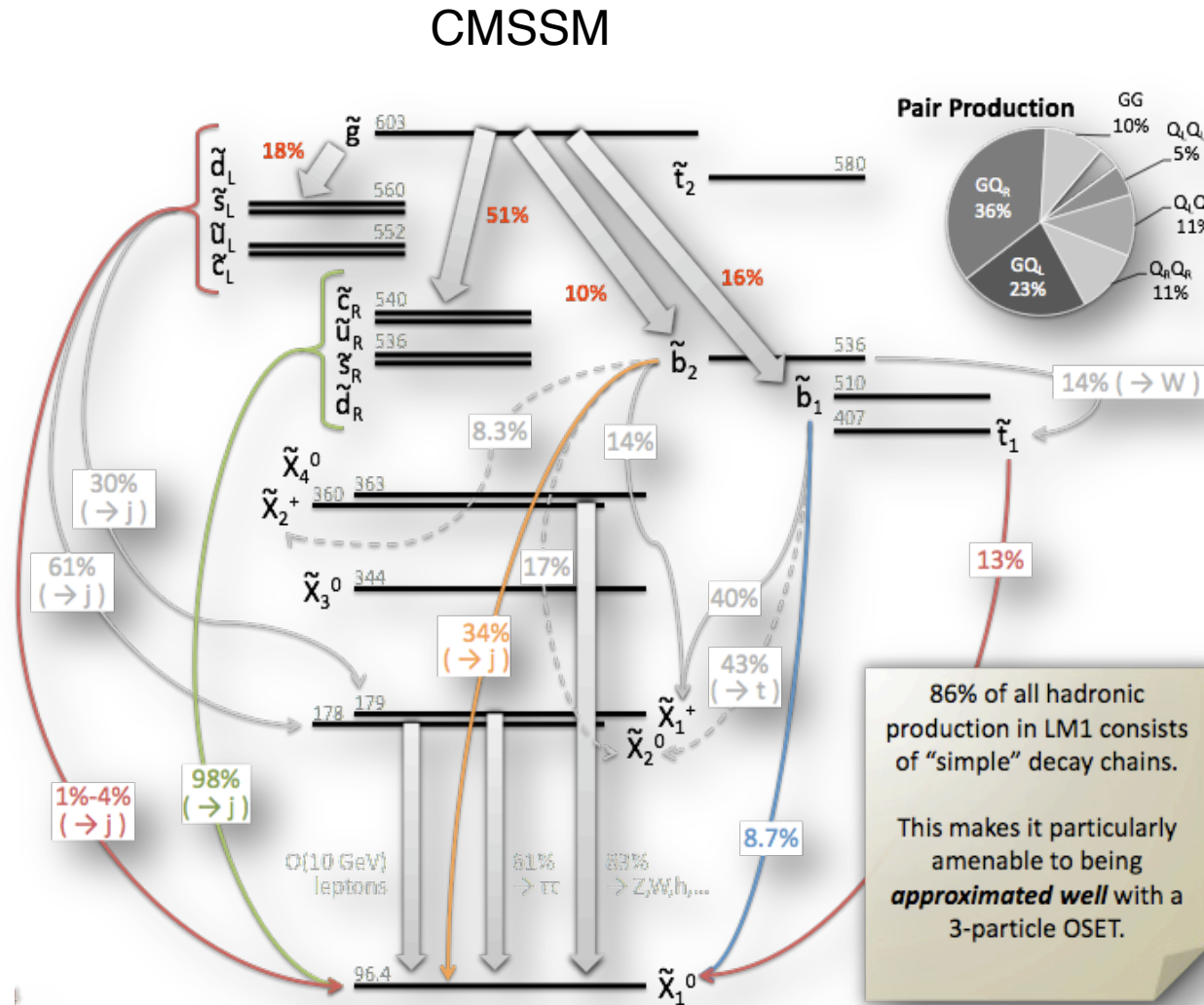
## SUSY Status – post 7 TeV LHC data

- 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. 3<sup>rd</sup> generation squark searches).

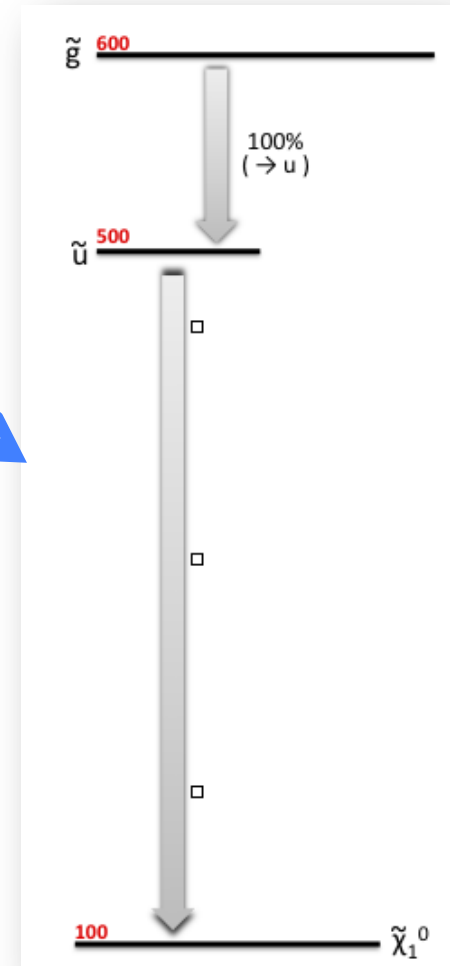
More in Gian Giudice talk!

# Interpretation in Simplified Models

EPS 2013 Direct SUSY Searches, O. Buchmüller



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

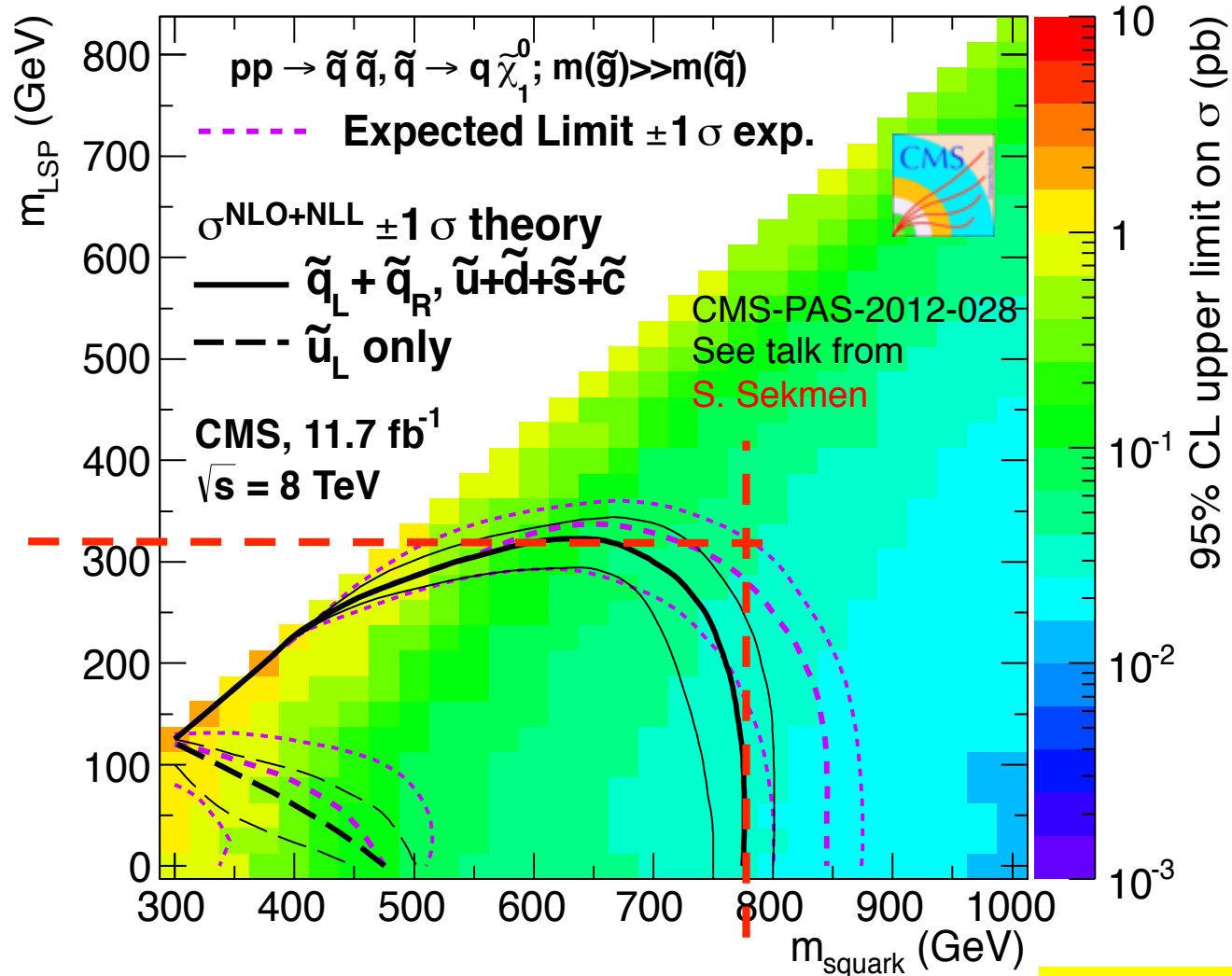


**Simplified model spectrum (SMS)**  
with 3 particles, 2 decay modes

# SMS: a few interesting features

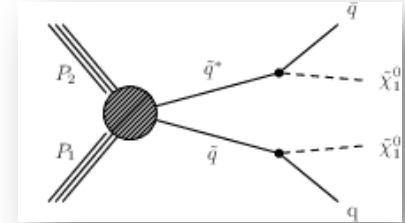
EPS 2013 Direct SUSY Searches, O. Buchmüller

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



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

Assumes 100%  
BR for decay chain  
considered.



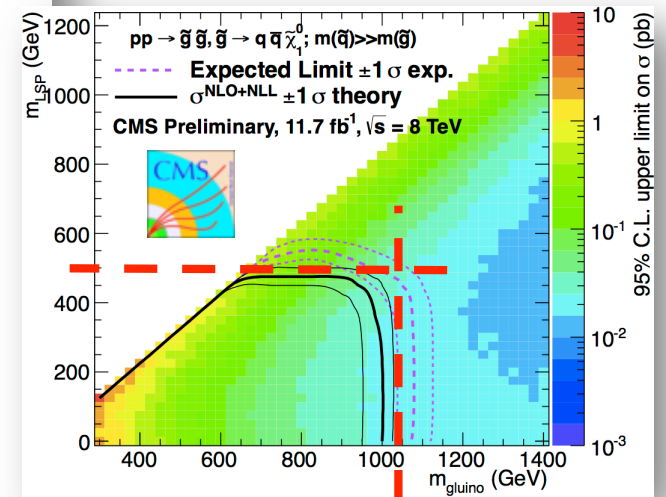
$$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$$

## How to summarize SMS limits?

*Approach taken in the 2012 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 $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\tilde{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0, m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0, \text{all } m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0, \text{all } m_{\tilde{q}}$	-	900



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

## How to summarize SMS limits?

*Approach taken in the 2012 Experimental SUSY PDG review  
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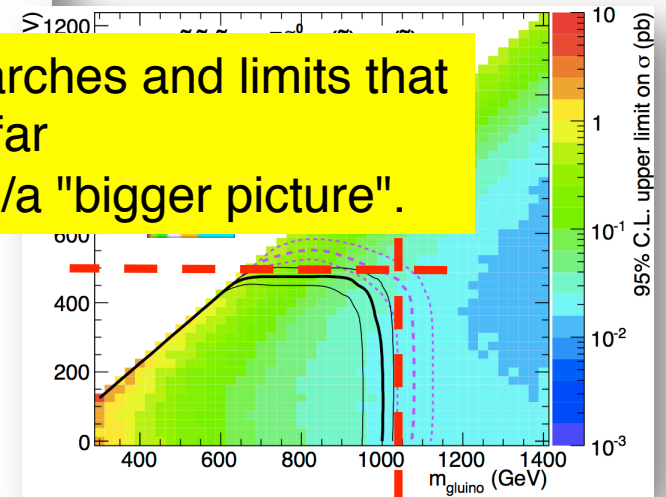
<http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf>

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

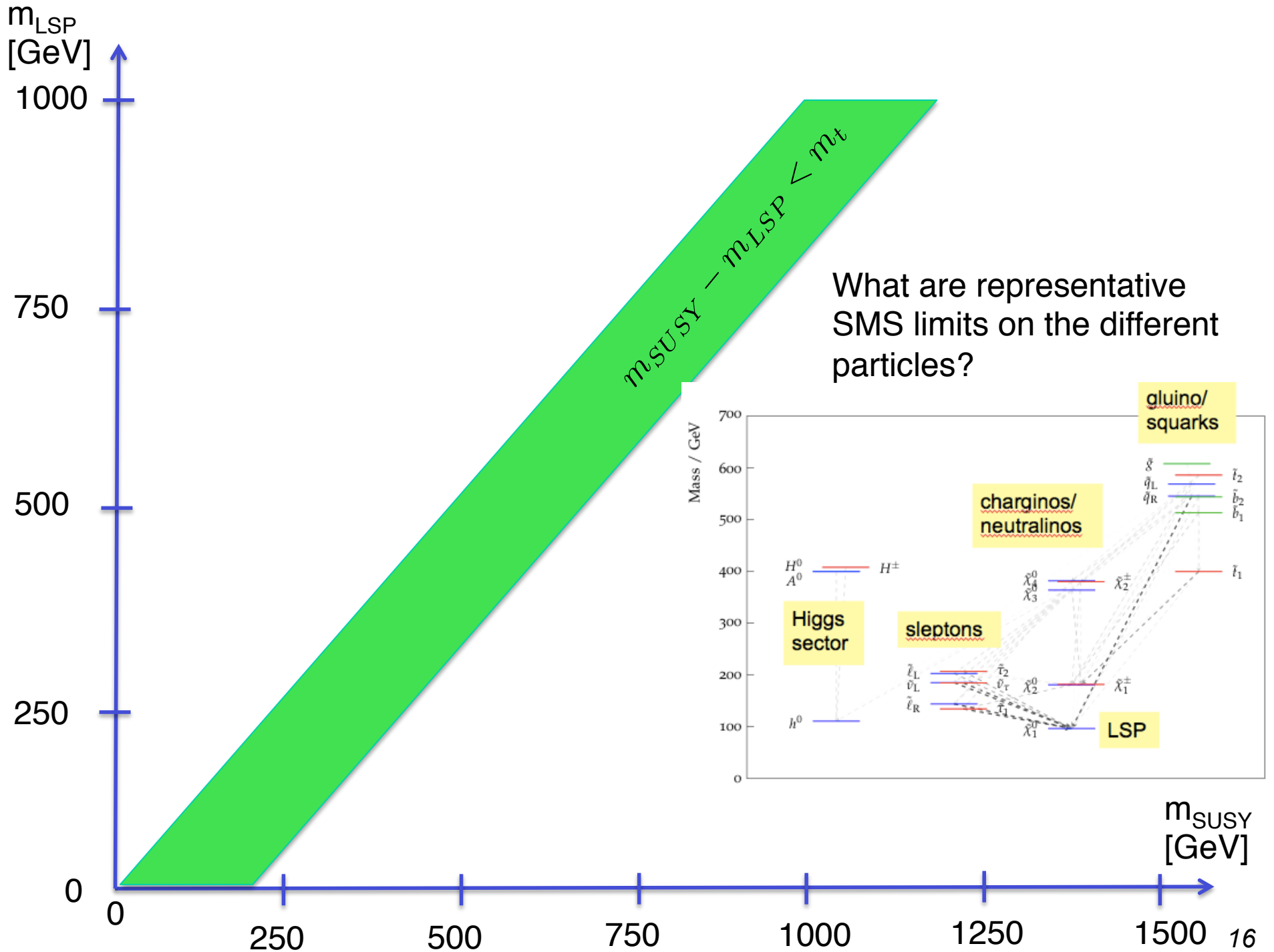
Simplified

Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\tilde{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0, m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0, \text{ all } m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0, \text{ all } m_{\tilde{q}}$	-	900

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



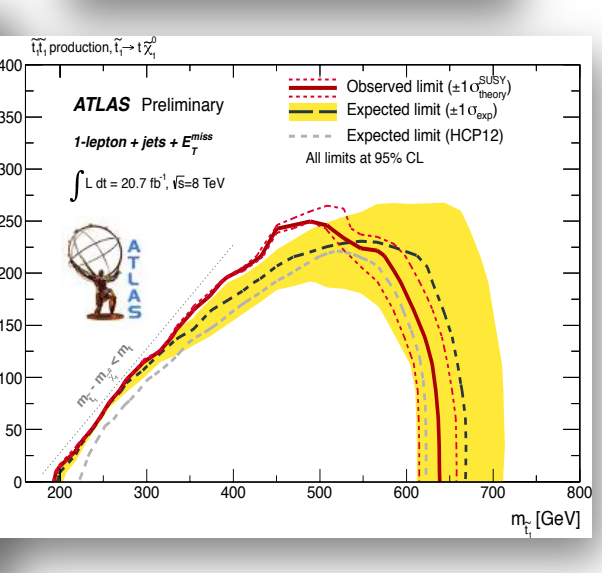
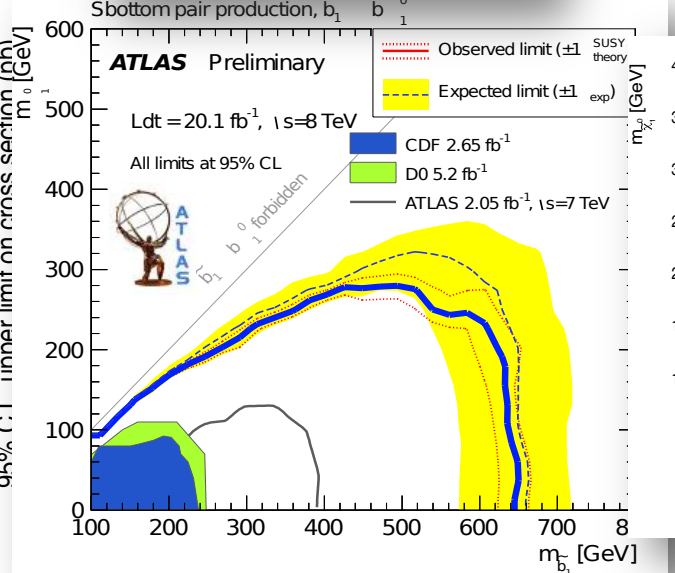
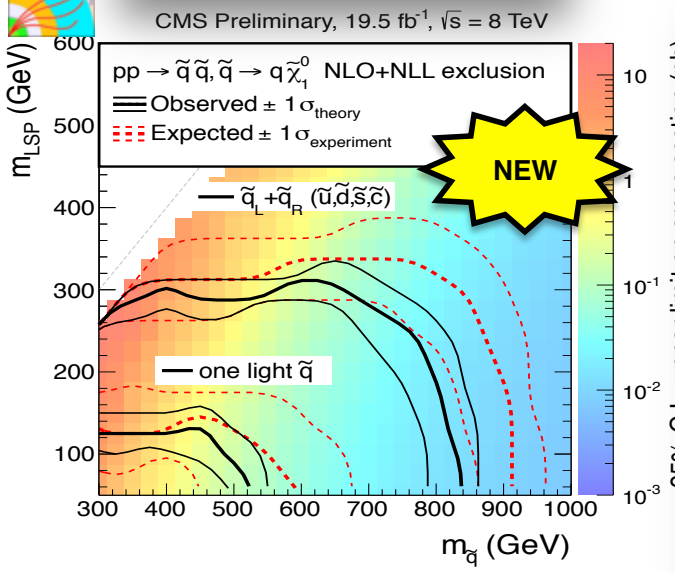
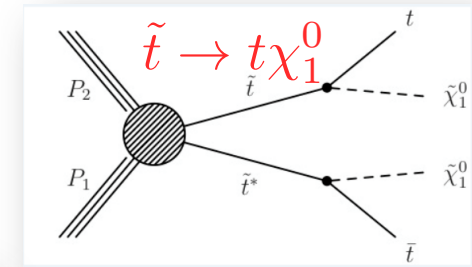
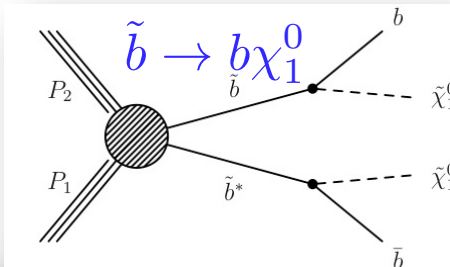
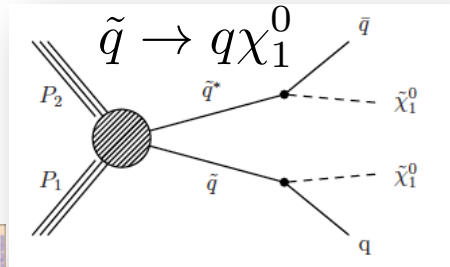
This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).





# Direct squark production – chosen limits

EPS 2013 Direct SUSY Searches, O. Buchmüller



## CMS-SUS-PAS-13-012

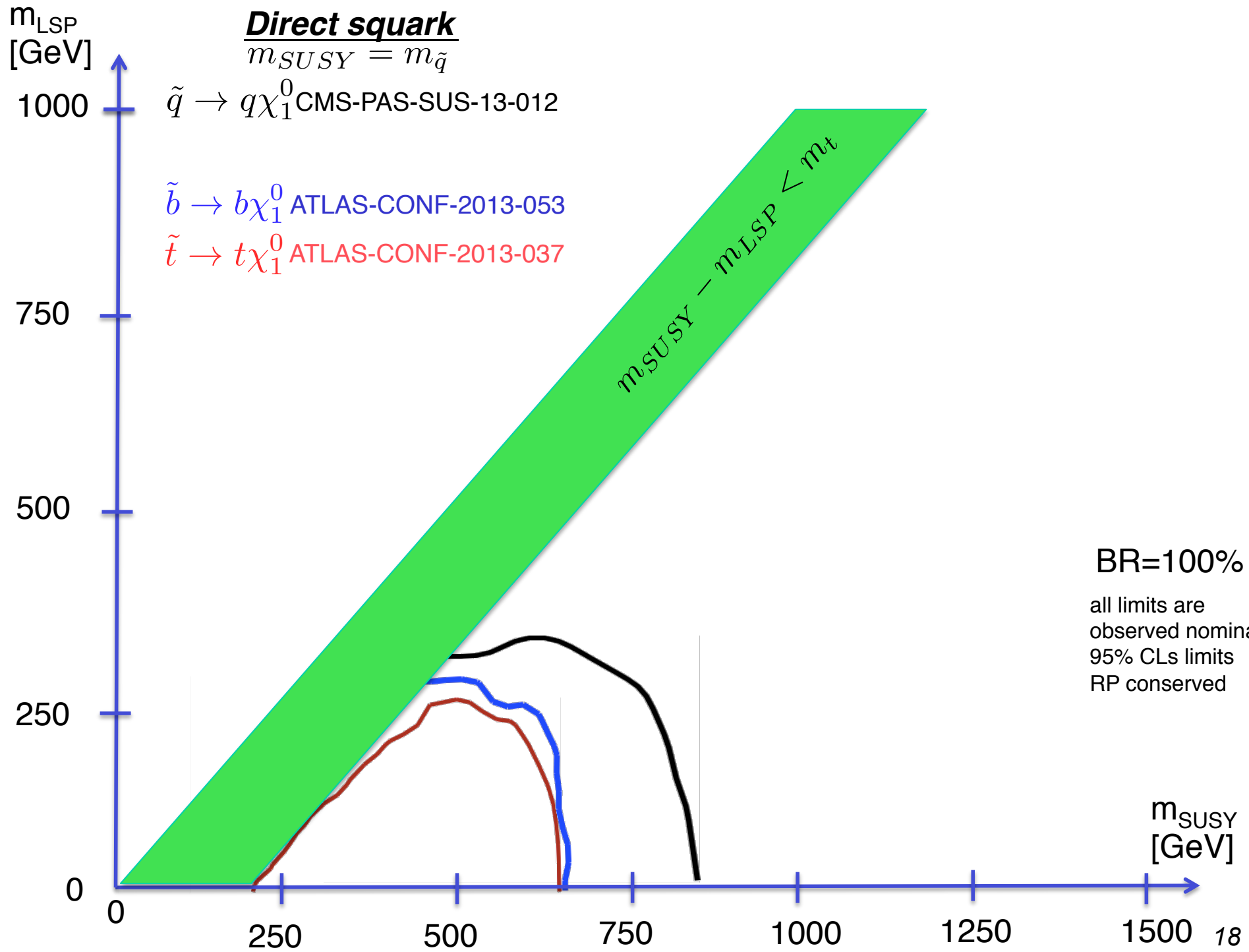
Signature: Jets +  $E_T^{\text{miss}}$  +  $H_T$   
Limit assumes all 1<sup>st</sup> & 2<sup>nd</sup> gen squarks to be mass degenerate or only one light squark!  
See parallel talk for details:  
**C. Autermann**

## ATLAS-CONF-2013-053

Signature: 2 b-jets +  $E_T^{\text{mis}}$   
See parallel talk for further  
Details: **T. Lari**

## ATLAS-CONF-2013-037

Signature: 1Lepton + jets +  $E_T^{\text{mis}}$   
See parallel talk for further  
Details: **T.Lari**



$m_{LSP}$   
[GeV]

**Direct squark**

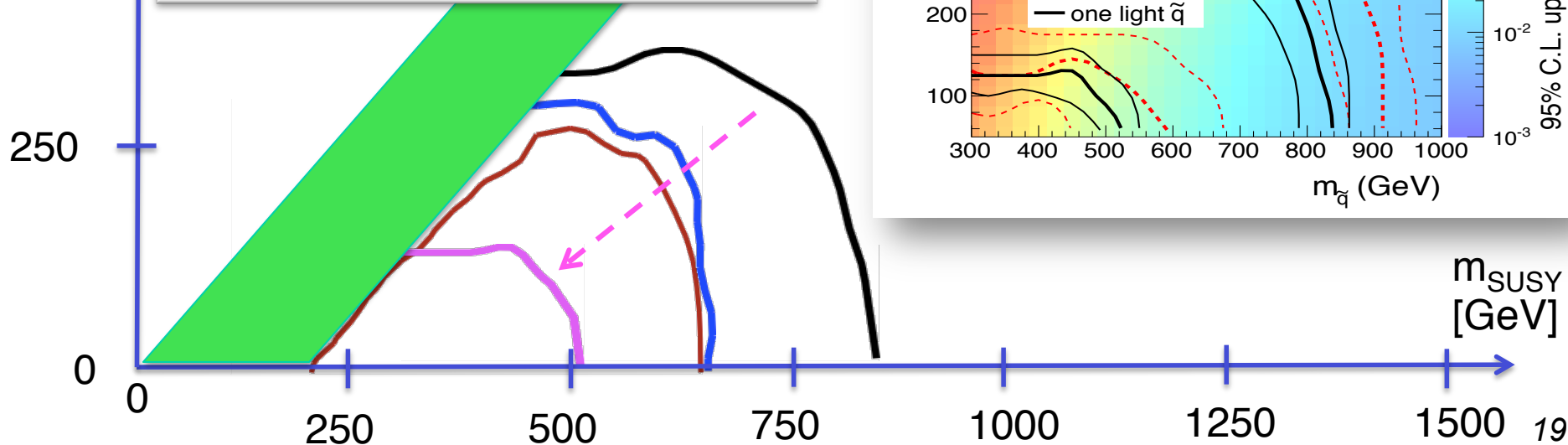
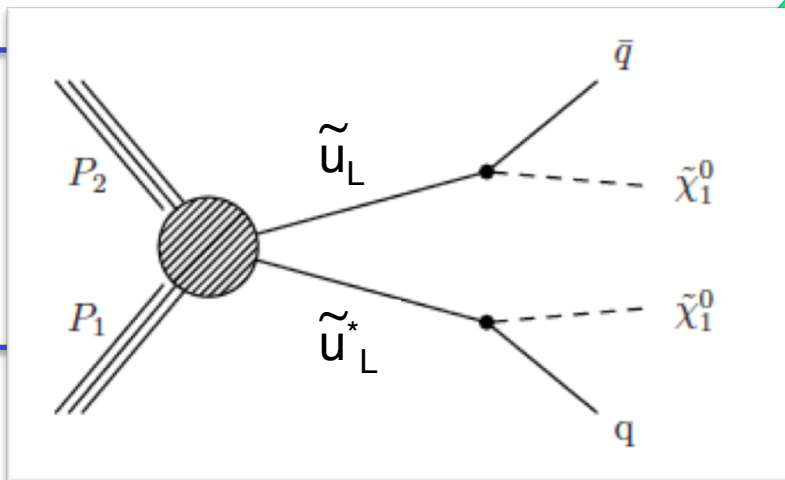
$m_{SUSY} = m_{\tilde{q}}$

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

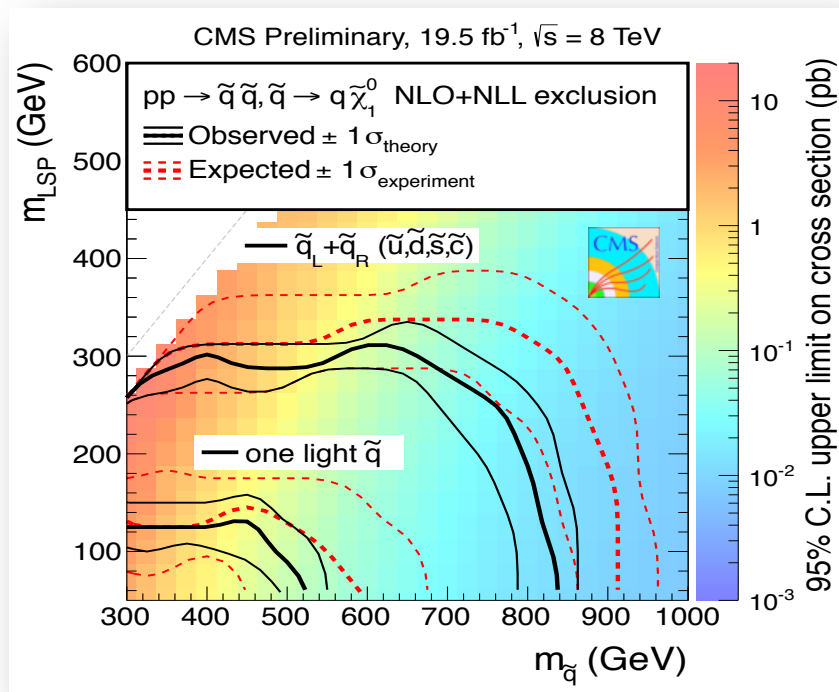
$\tilde{t} \rightarrow t\chi_1^0$  ATLAS-CONF-2013-037

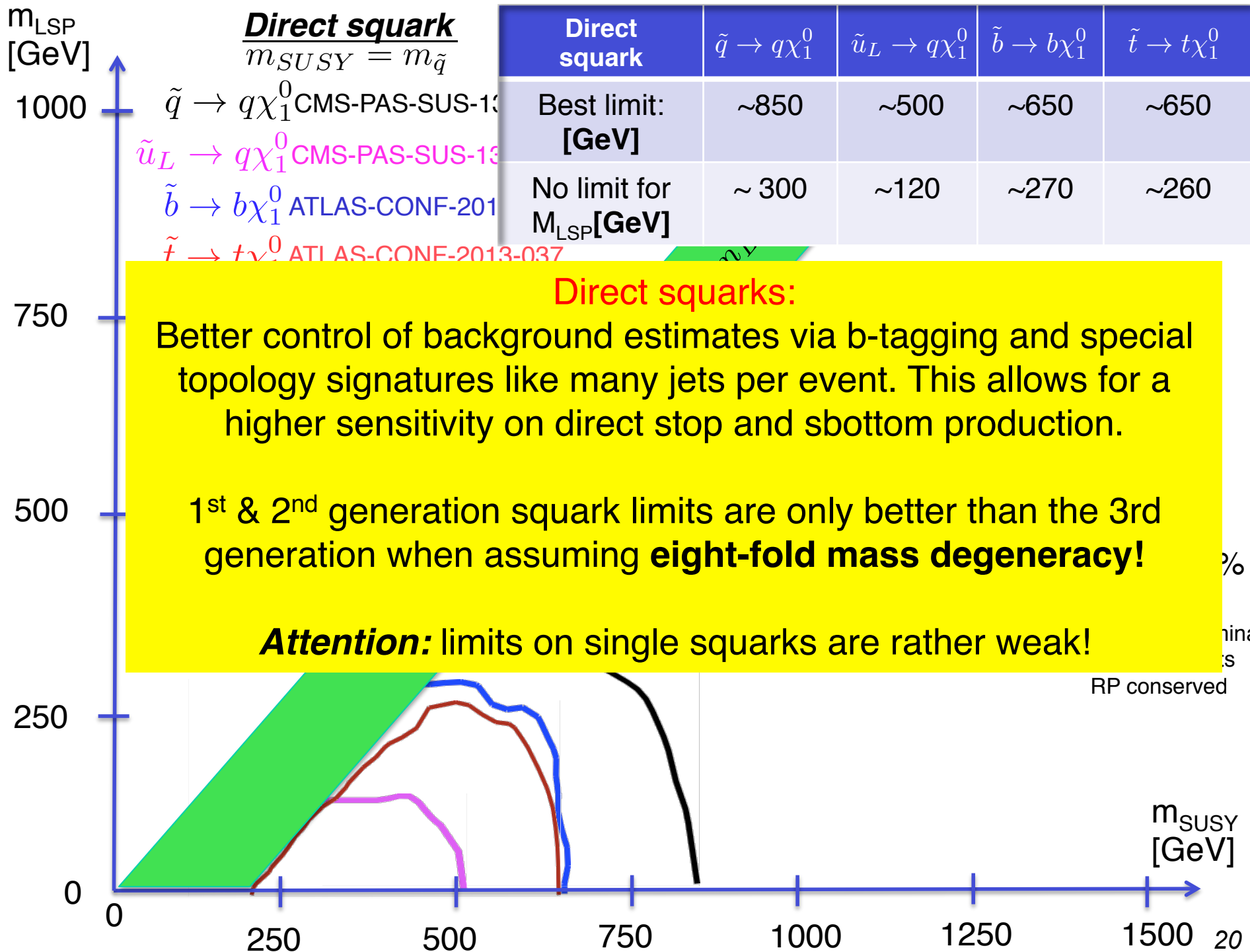


**CMS-SUS-PAS-13-012**

Signature: Jets +  $E_t^{miss}$

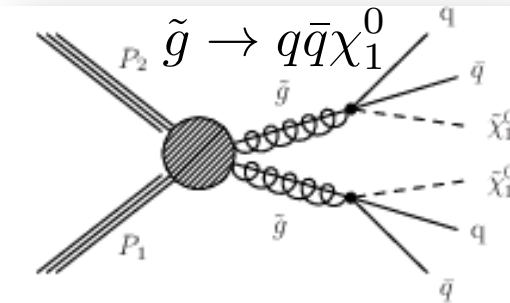
Limit assumes only one light squark (e.g.  $u_L$ ) and decoupled gluino (as before).



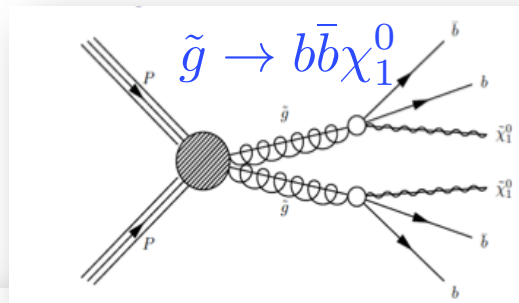


# Glino mediated squark production – limits chosen

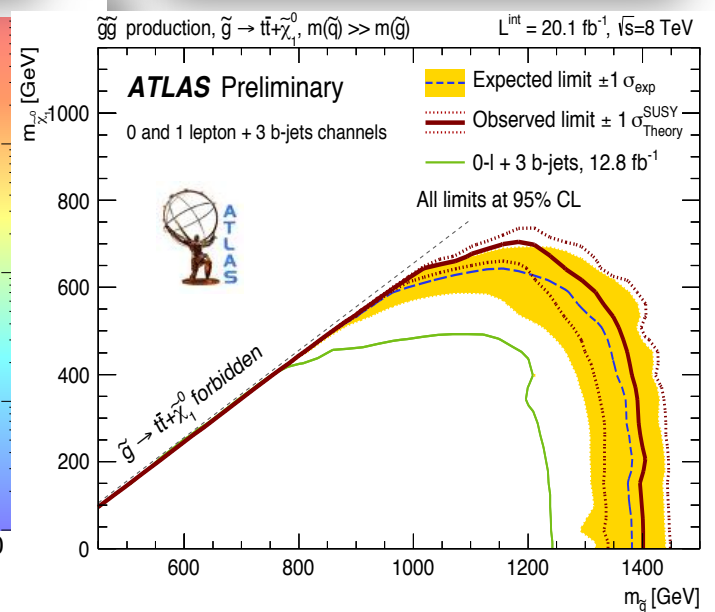
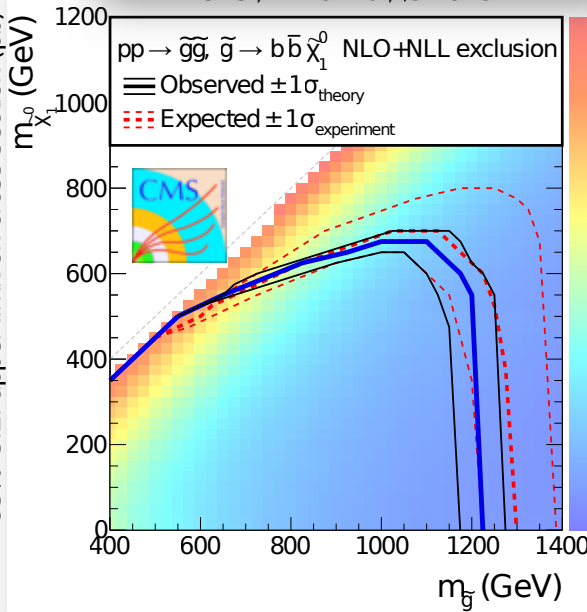
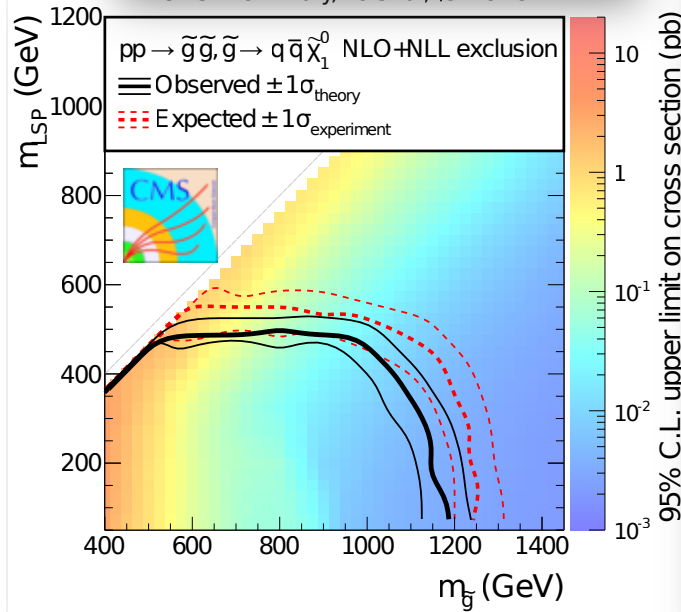
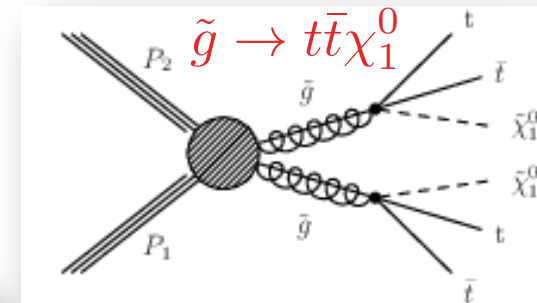
Marches, O. Buchmüller



CMS Preliminary, 19.5 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV



CMS, L = 19.4 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV



## CMS-SUS-PAS-13-012

Signature: Jets +  $H_T$  +  $E_t^{\text{miss}}$

See also parallel talk:

[C. Autermann](#)

## CMS-SUS-PAS-12-024

Signature: : Jets + b-tag +  $E_t^{\text{miss}}$

See parallel talk for details:

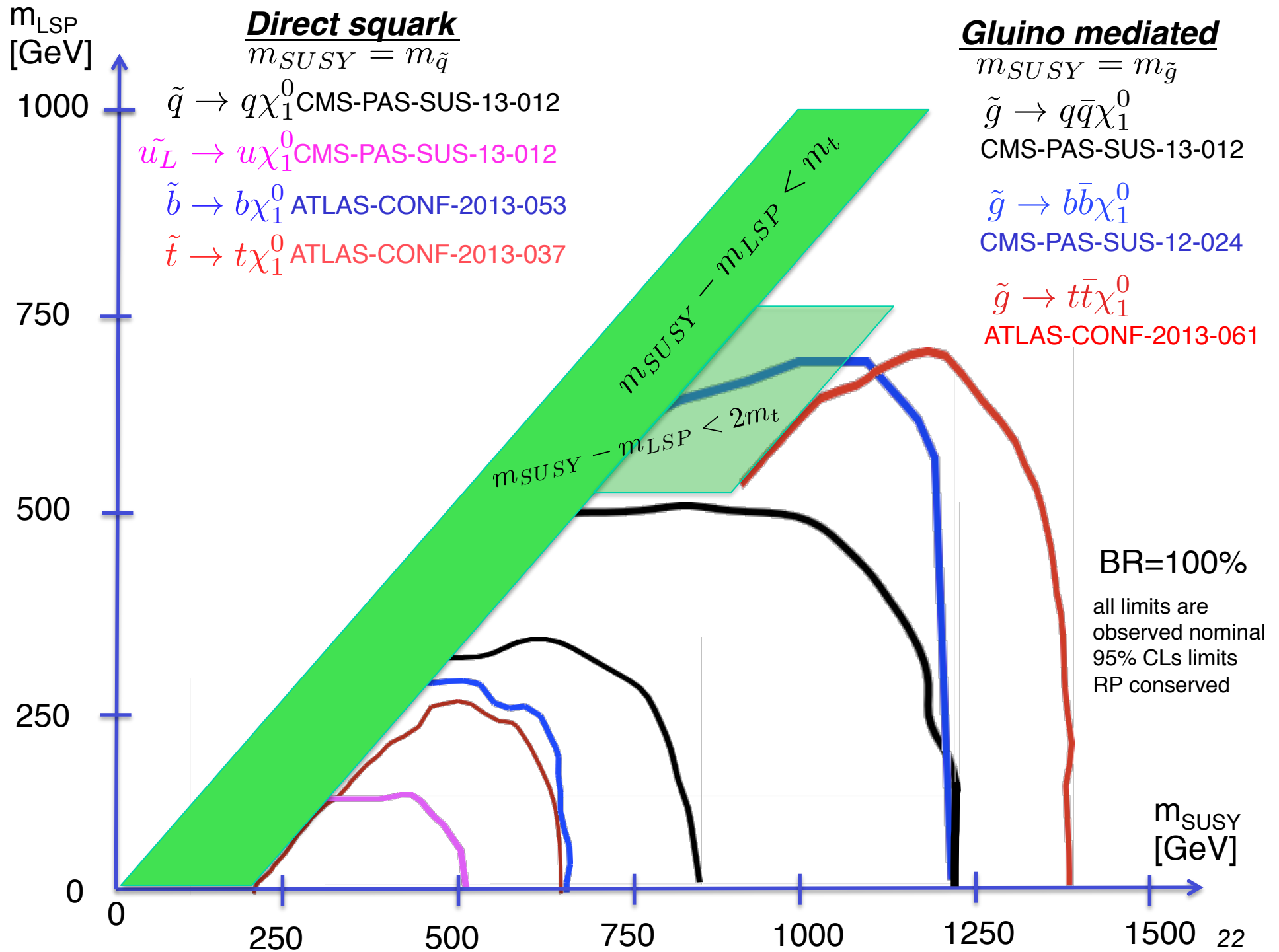
[S. Sekmen](#)

## ATLAS-CONF-2013-061

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

See parallel talk for details:

[D. Cote](#)



**Glauino 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.

**Glauino mediated**

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

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

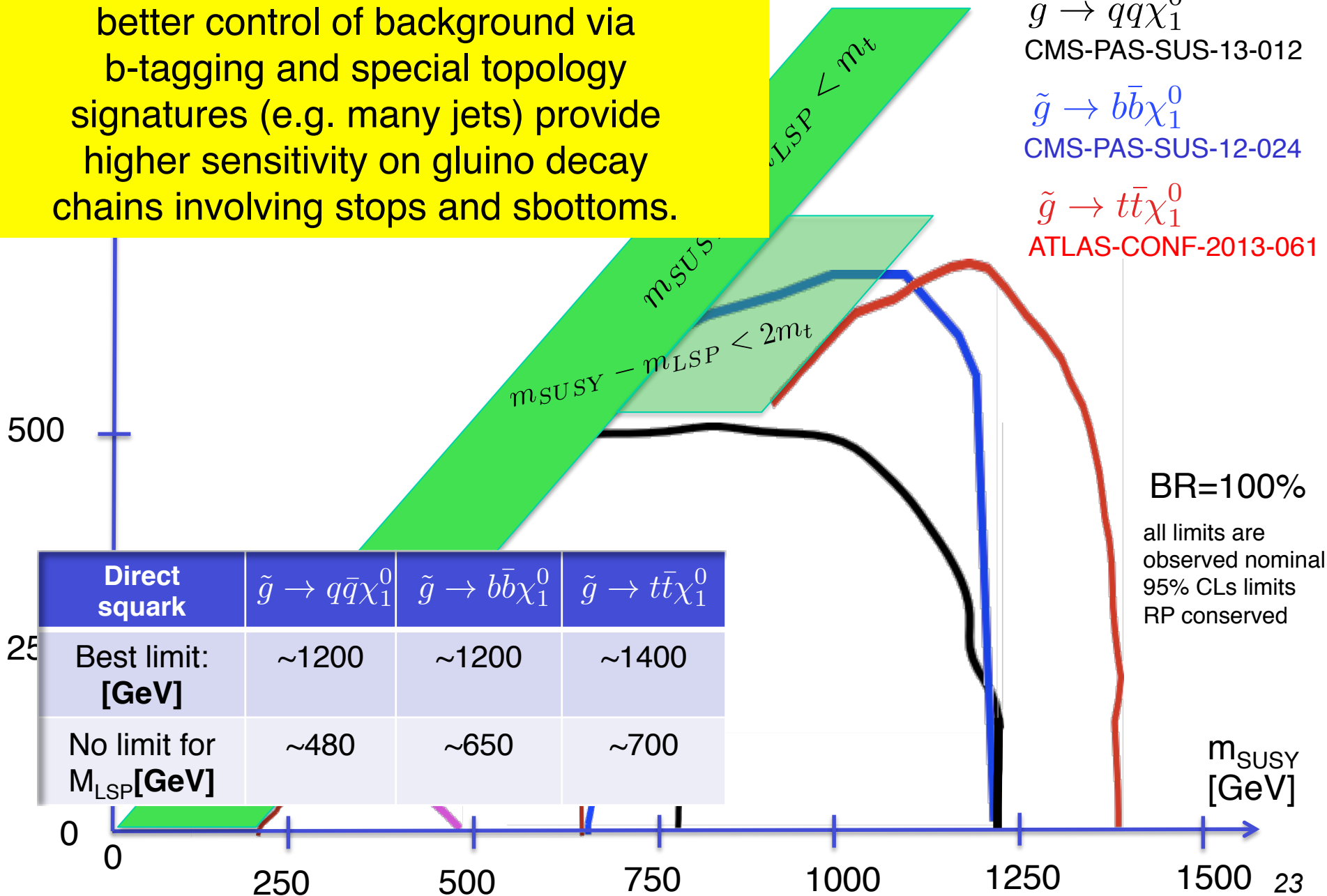
CMS-PAS-SUS-13-012

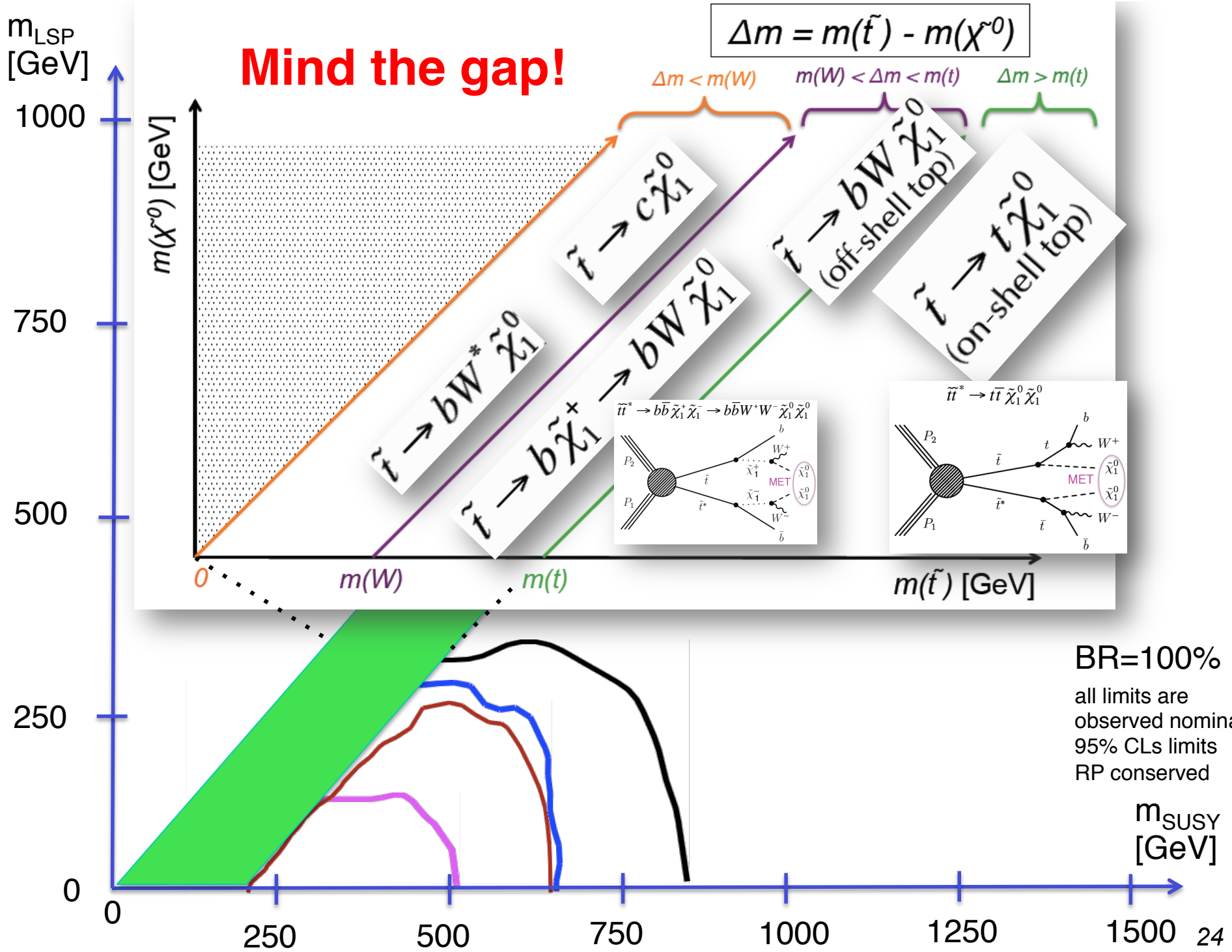
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$

CMS-PAS-SUS-12-024

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

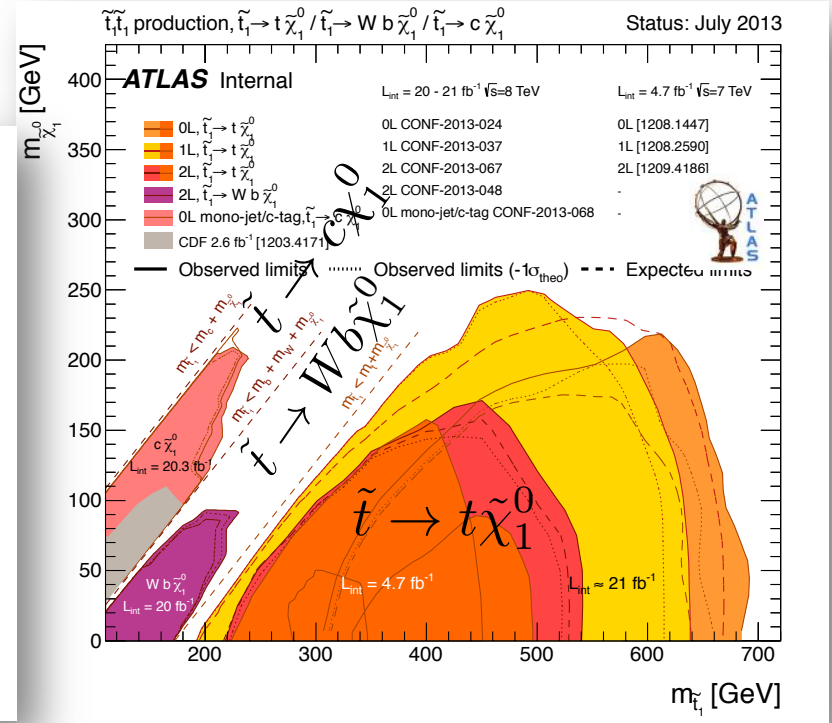
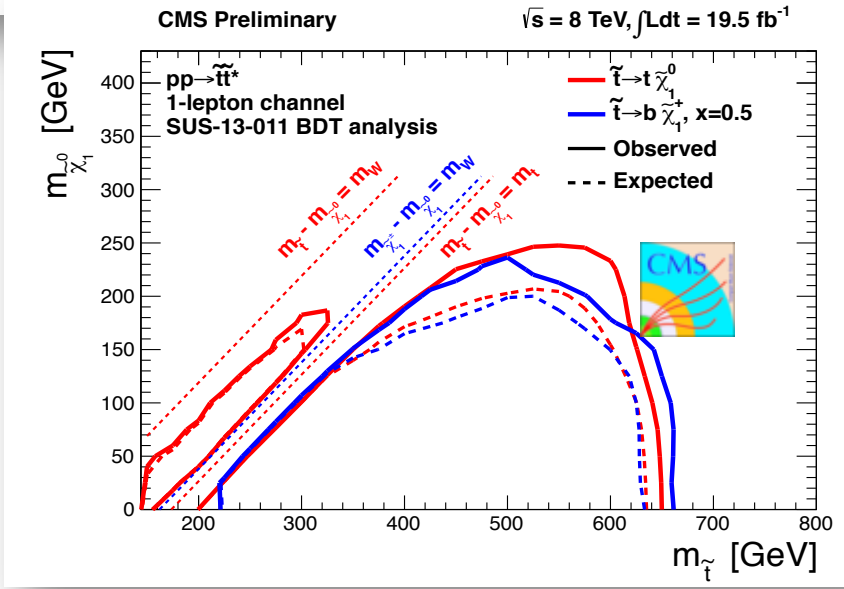
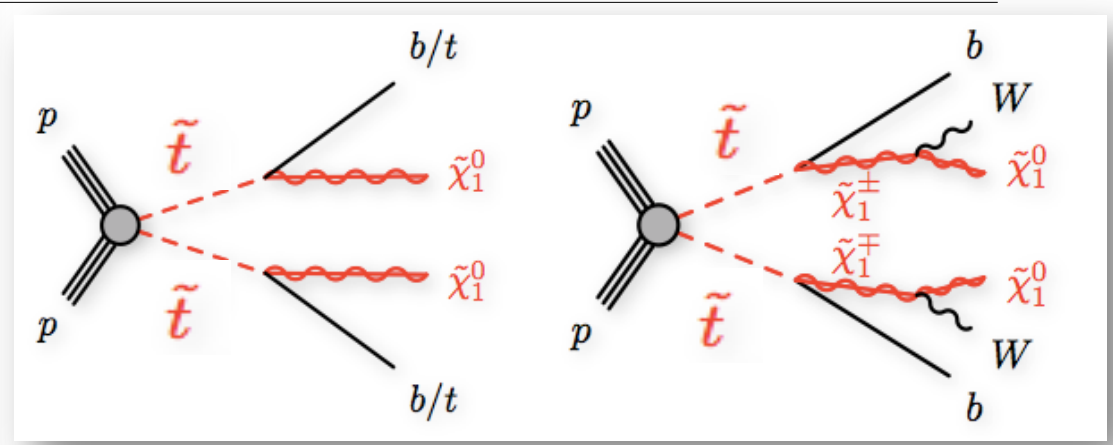
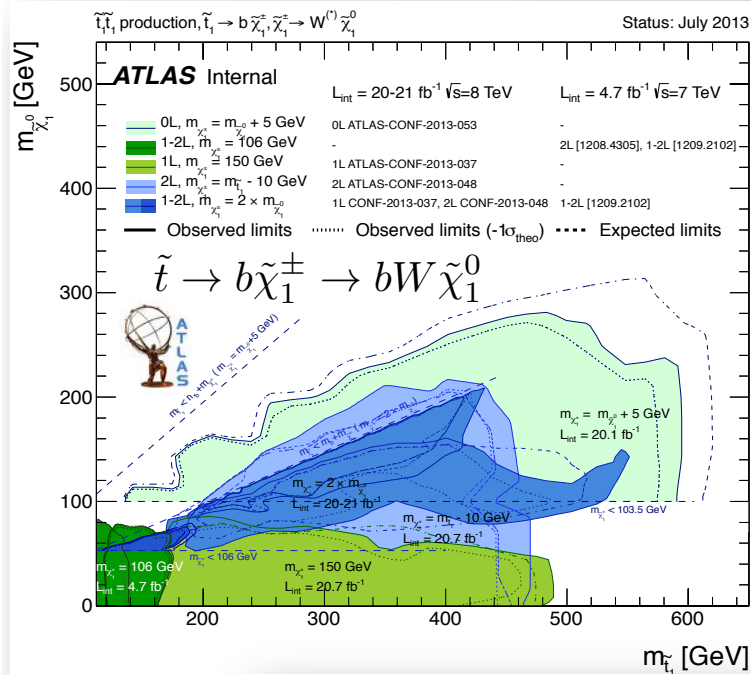
ATLAS-CONF-2013-061





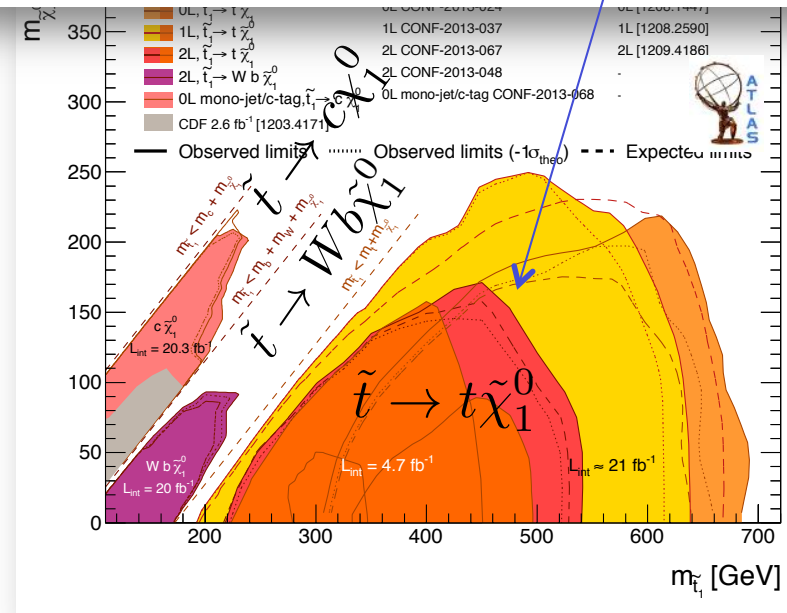
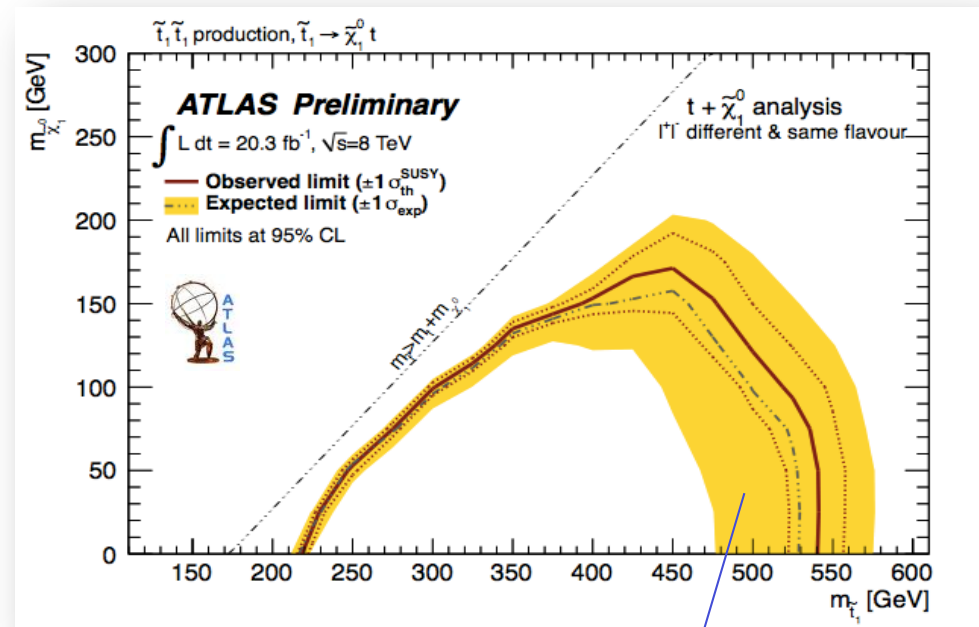
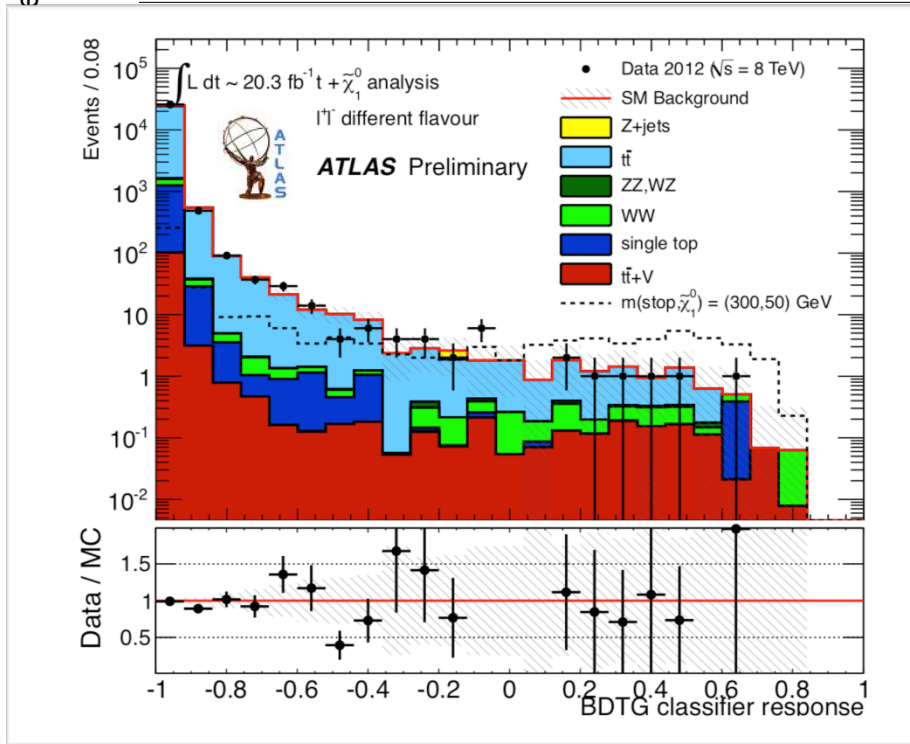


# Dedicated searches for direct stop-pair production



# Dedicated searches for direct stop-pair production

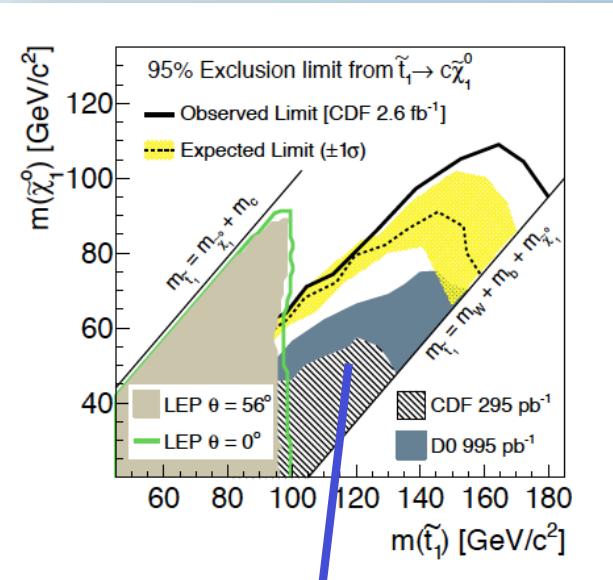
er



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

See talk from **T. Lari** in parallel session  
for further details

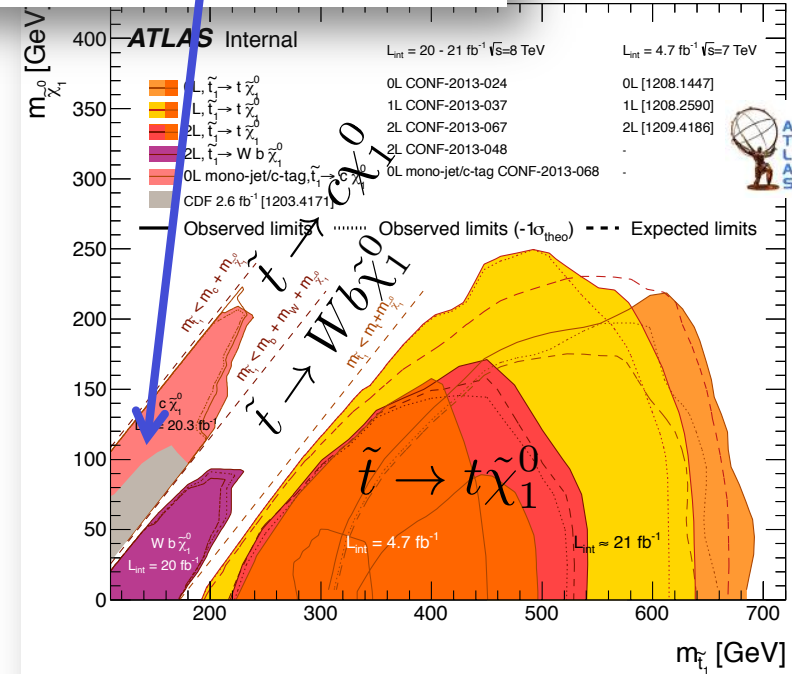
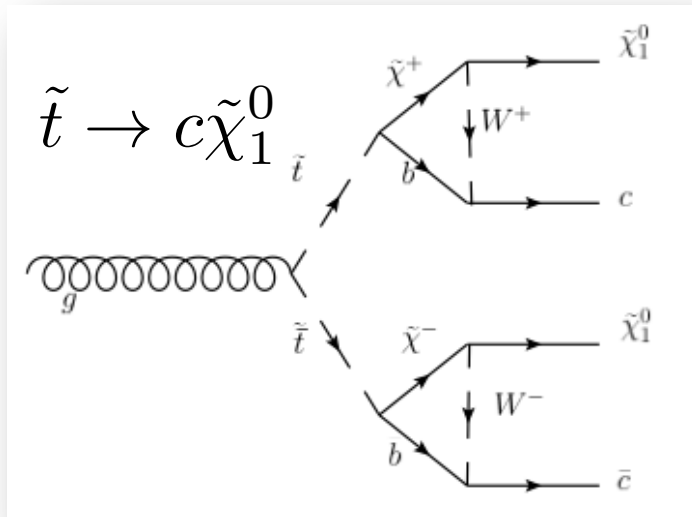
# Dedicated searches for direct stop-pair production



LEP:  
LEPSUSY  
WG/04-01.1

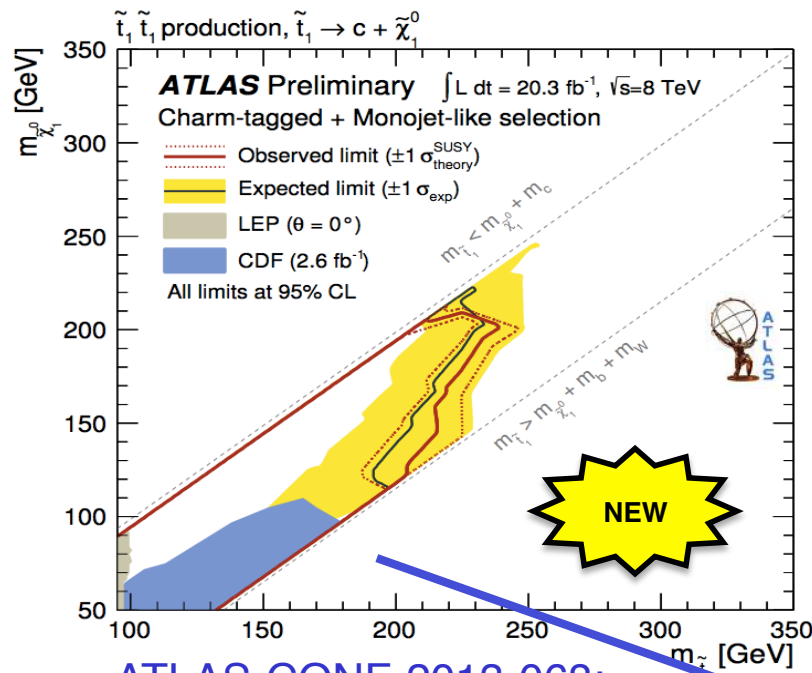
CDF:  
1203.4171  
D0:  
0803.2263

Status: July 2013

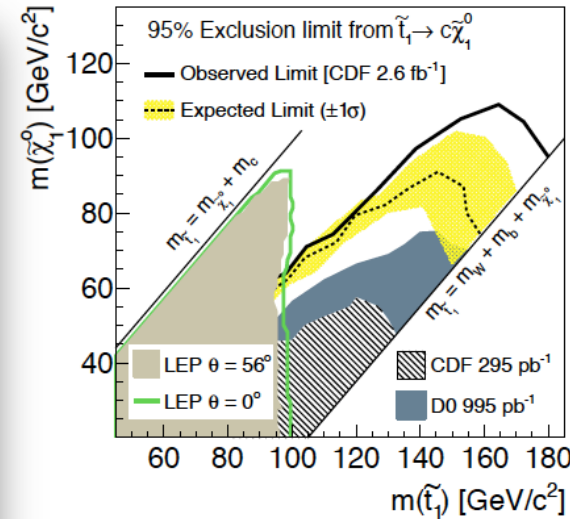


# Dedicated searches for direct stop-pair production

EPS 2013 Direct SUSY Searches, O. Buchmüller



ATLAS-CONF-2013-068:

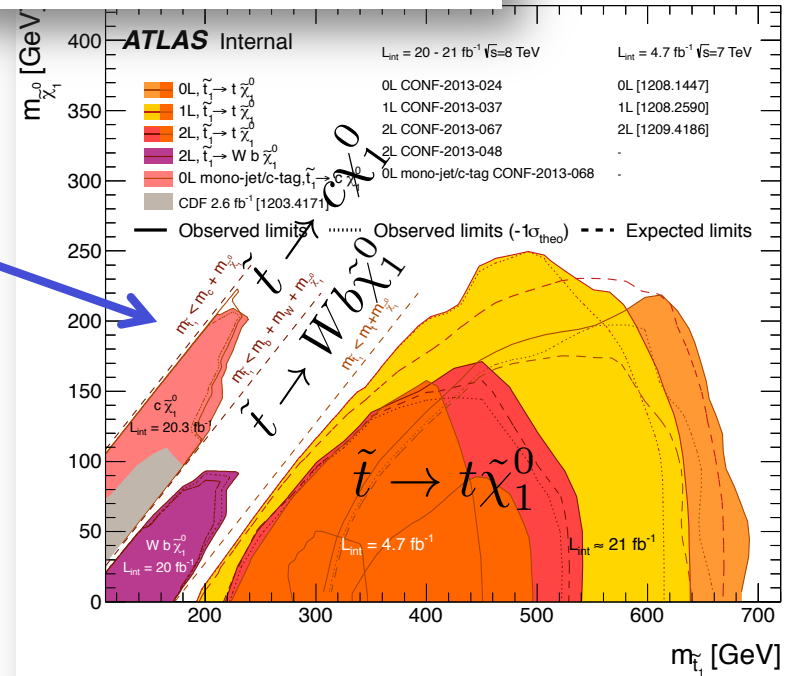
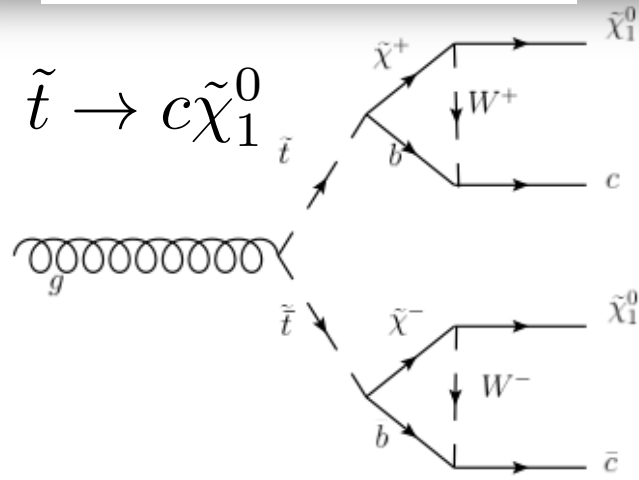


LEP:  
LEPSUSY  
WG/04-01.1

CDF:  
1203.4171

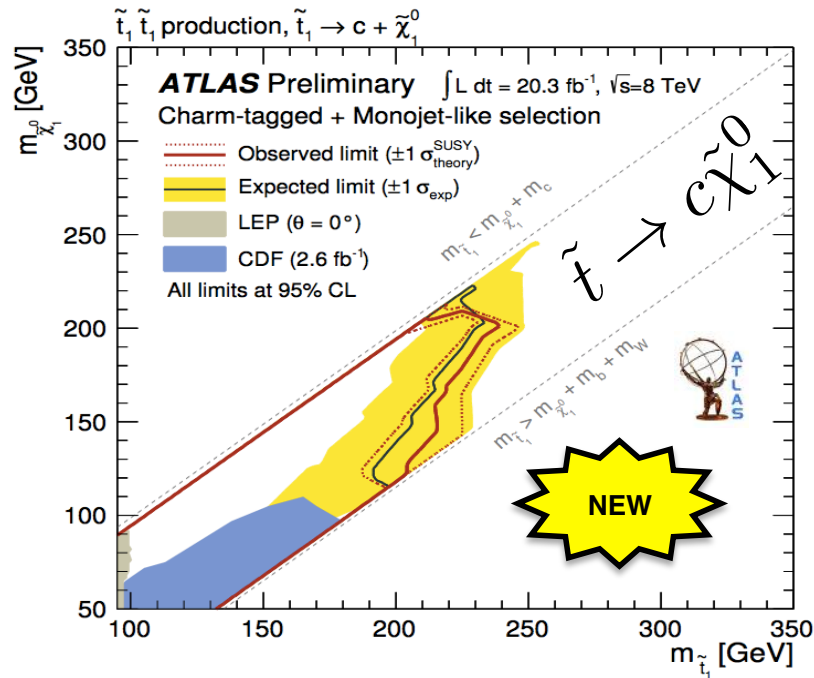
D0:  
0803.2263

Status: July 2013



# Stop decay to charm and neutralino

EPS 2013 Direct SUSY Searches, O. Buchmüller

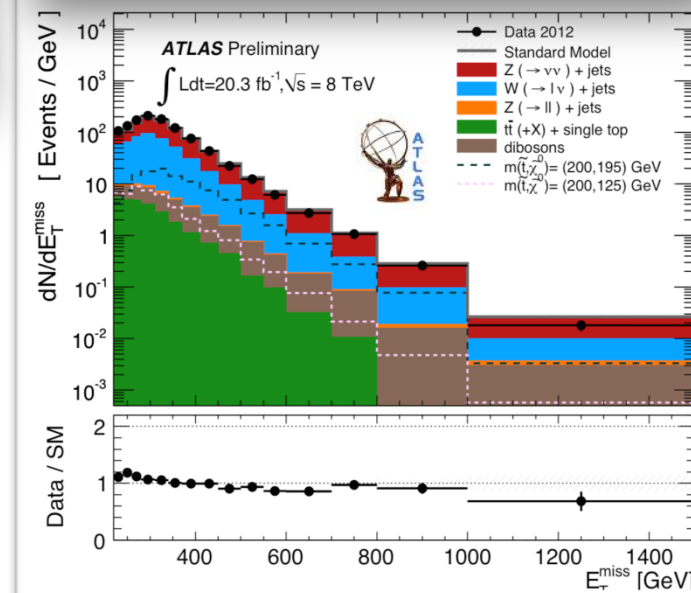
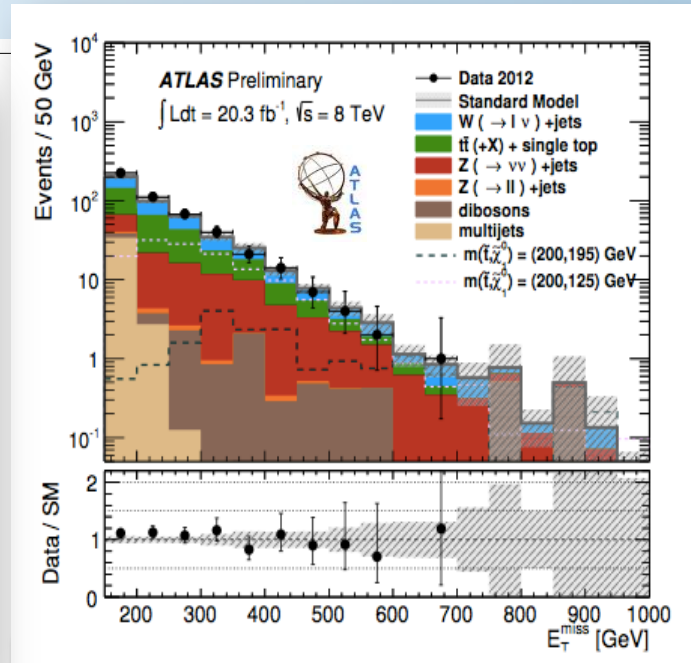


ATLAS-CONF-2013-068:

Two different selections:

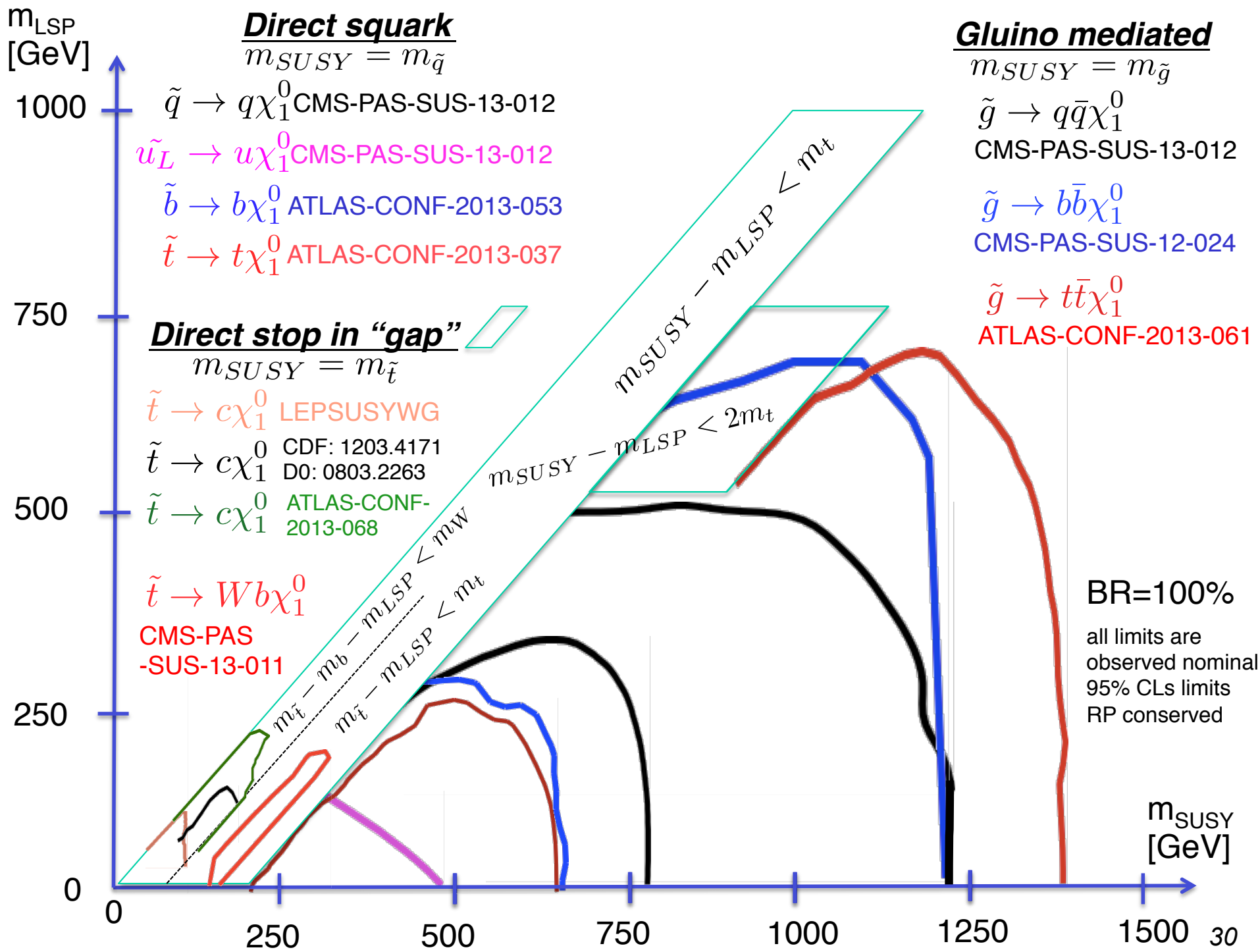
- Monojet-like selection to cover region close to ‘diagonal’
- MVA based c-tag selection for remaining region

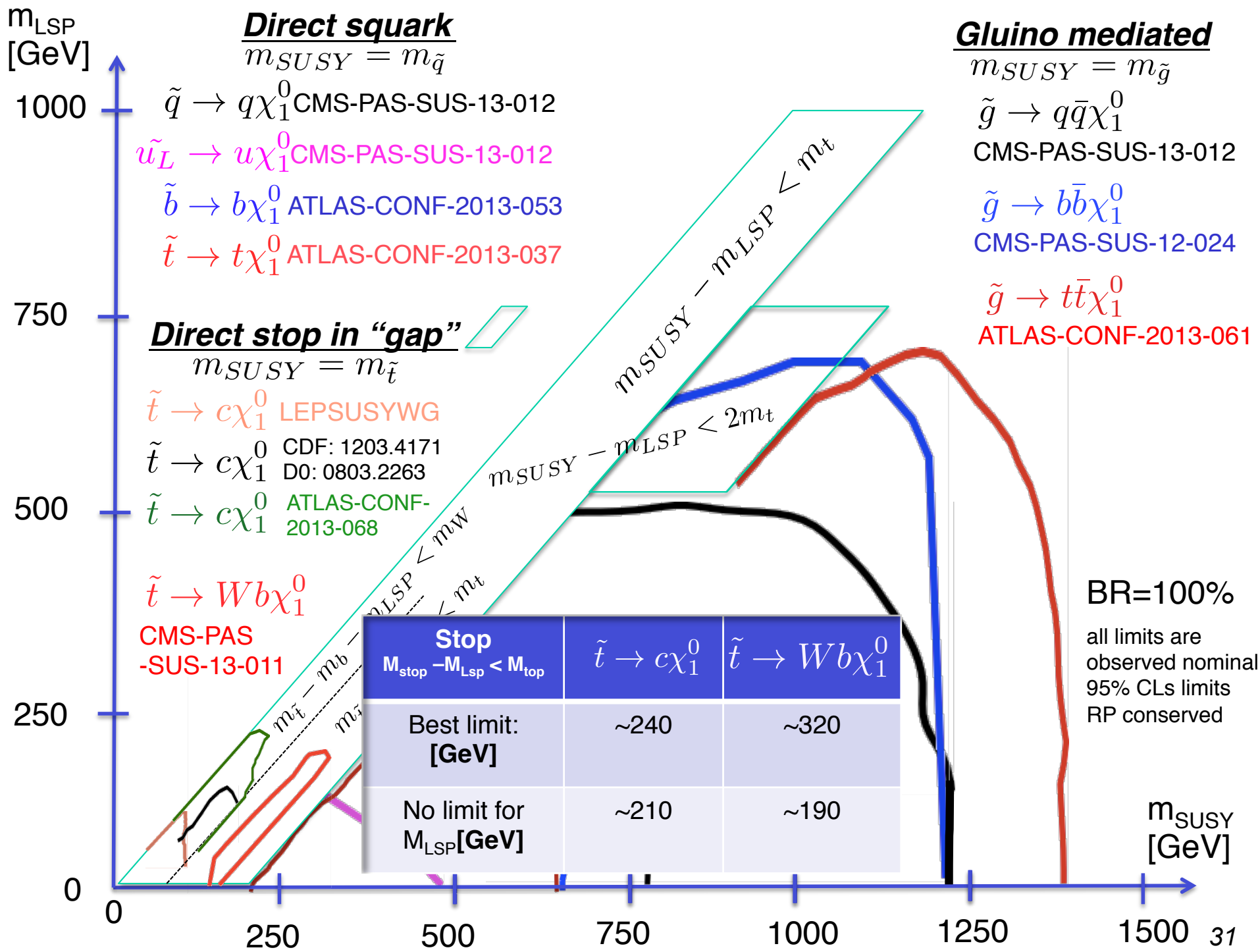
See also parallel talk from **T. Lari**



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

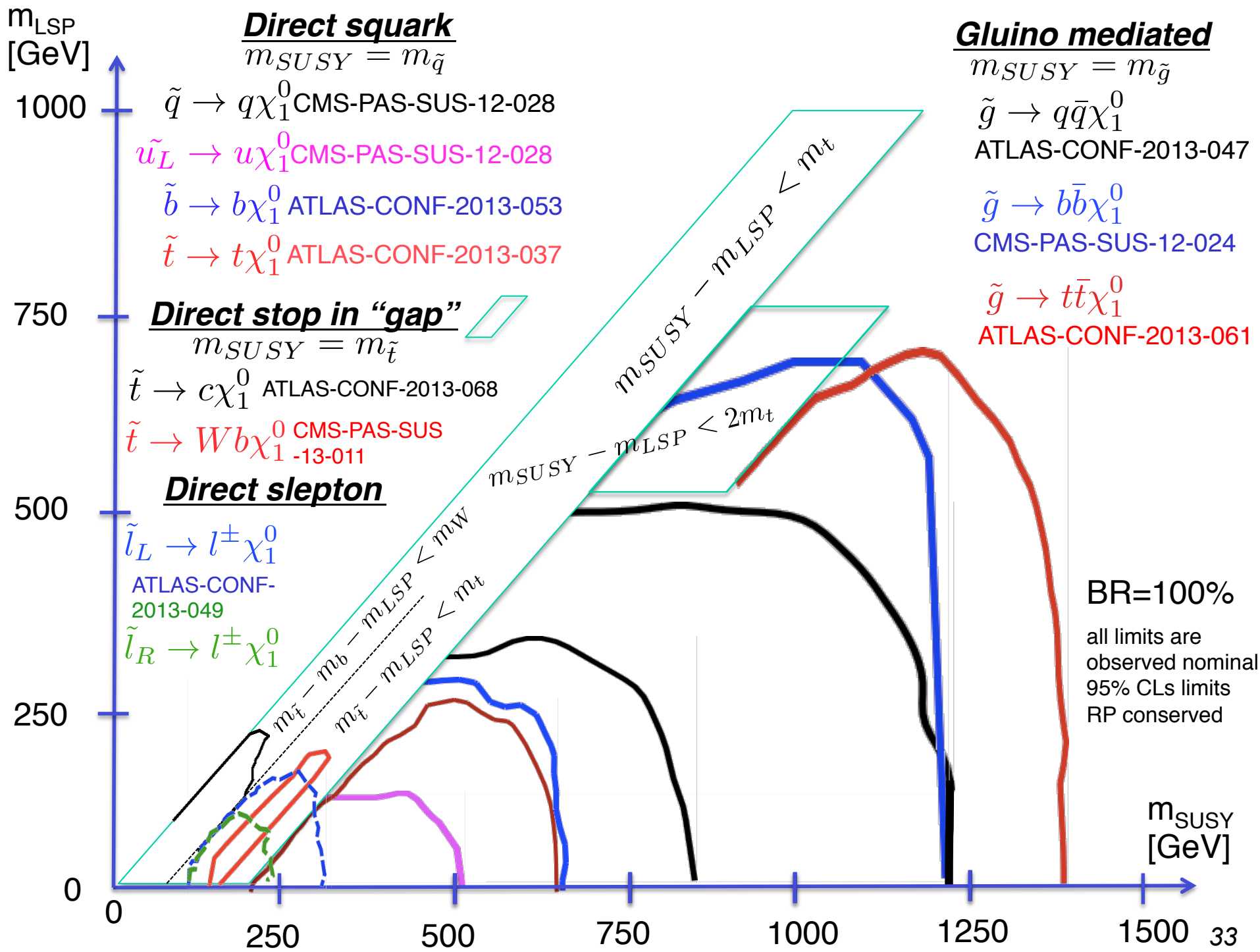
**Monojet**  
 95% excl.  
 visible XS:  
 $\epsilon\sigma = 136 \text{ fb}$   
 signal obs:  
 2770 events  
 signal exp:  
 $2060^{+780}_{-560}$   
 $CL_B$ :  
 0.86

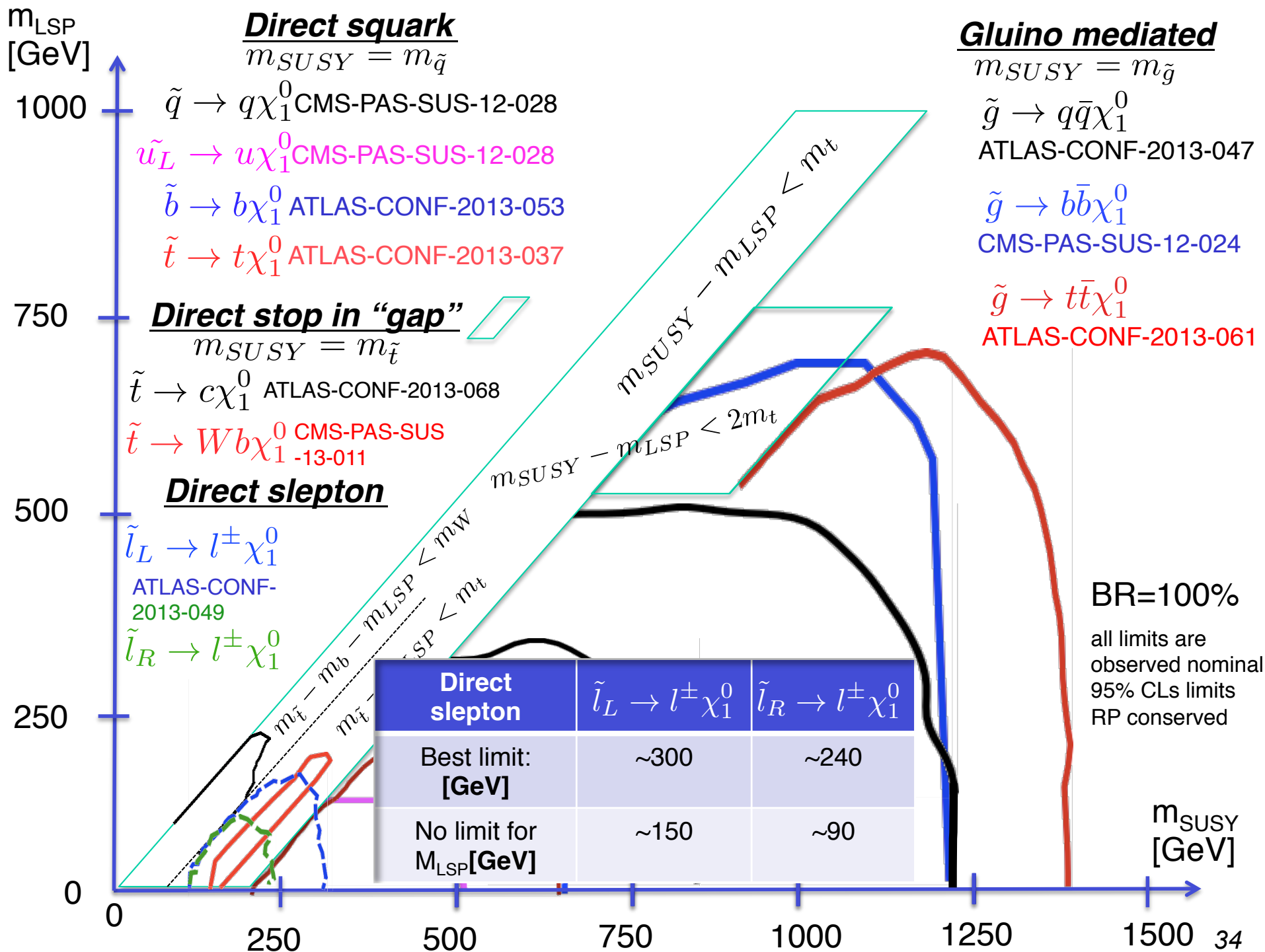




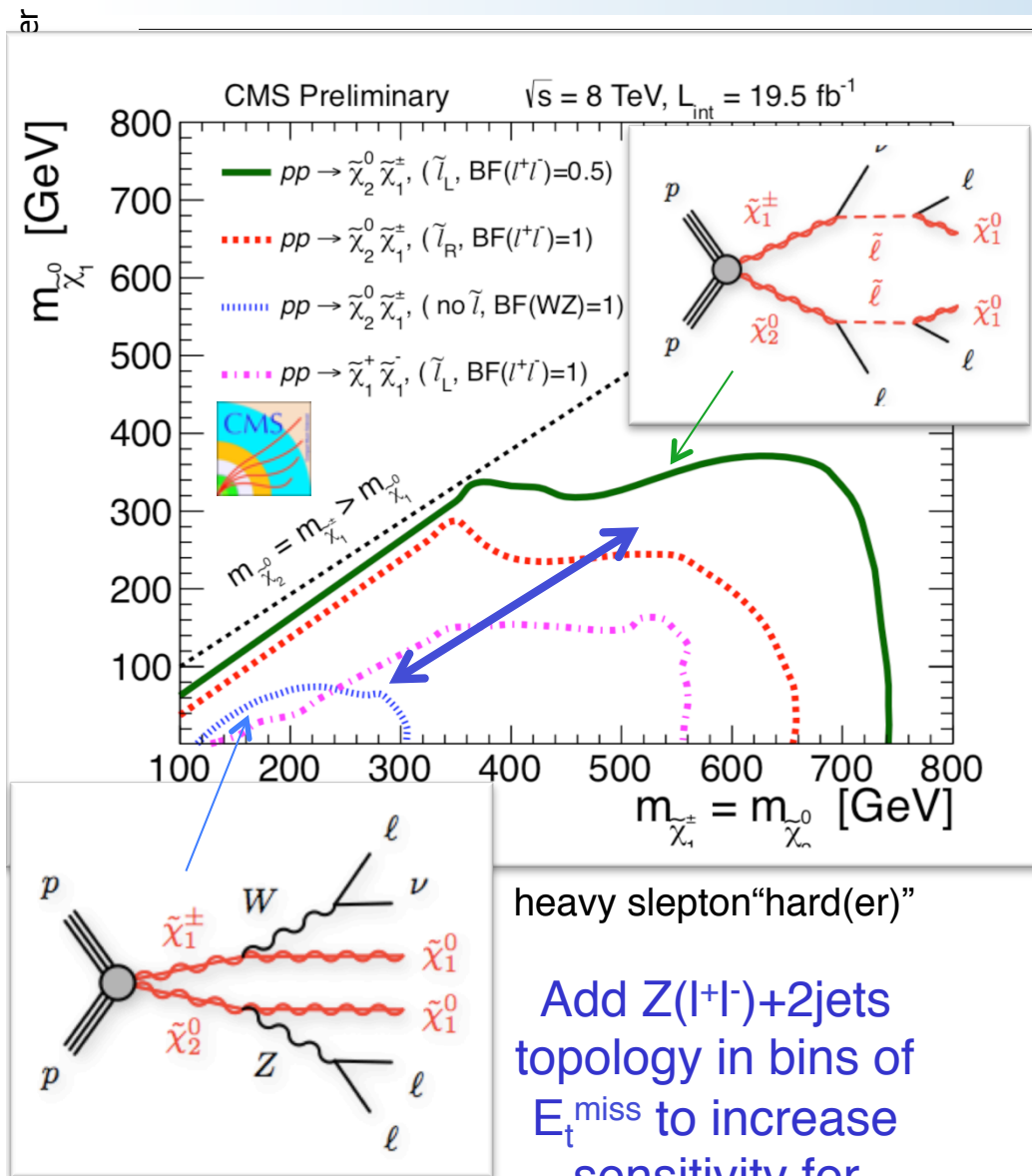






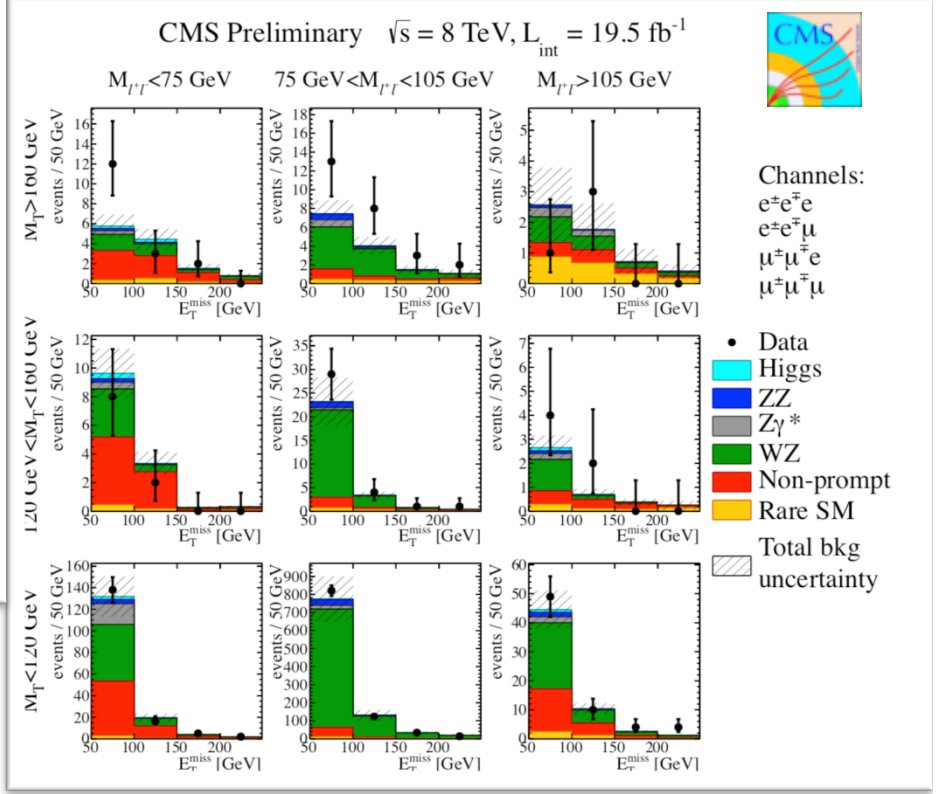


# Direct chargino/neutralino production

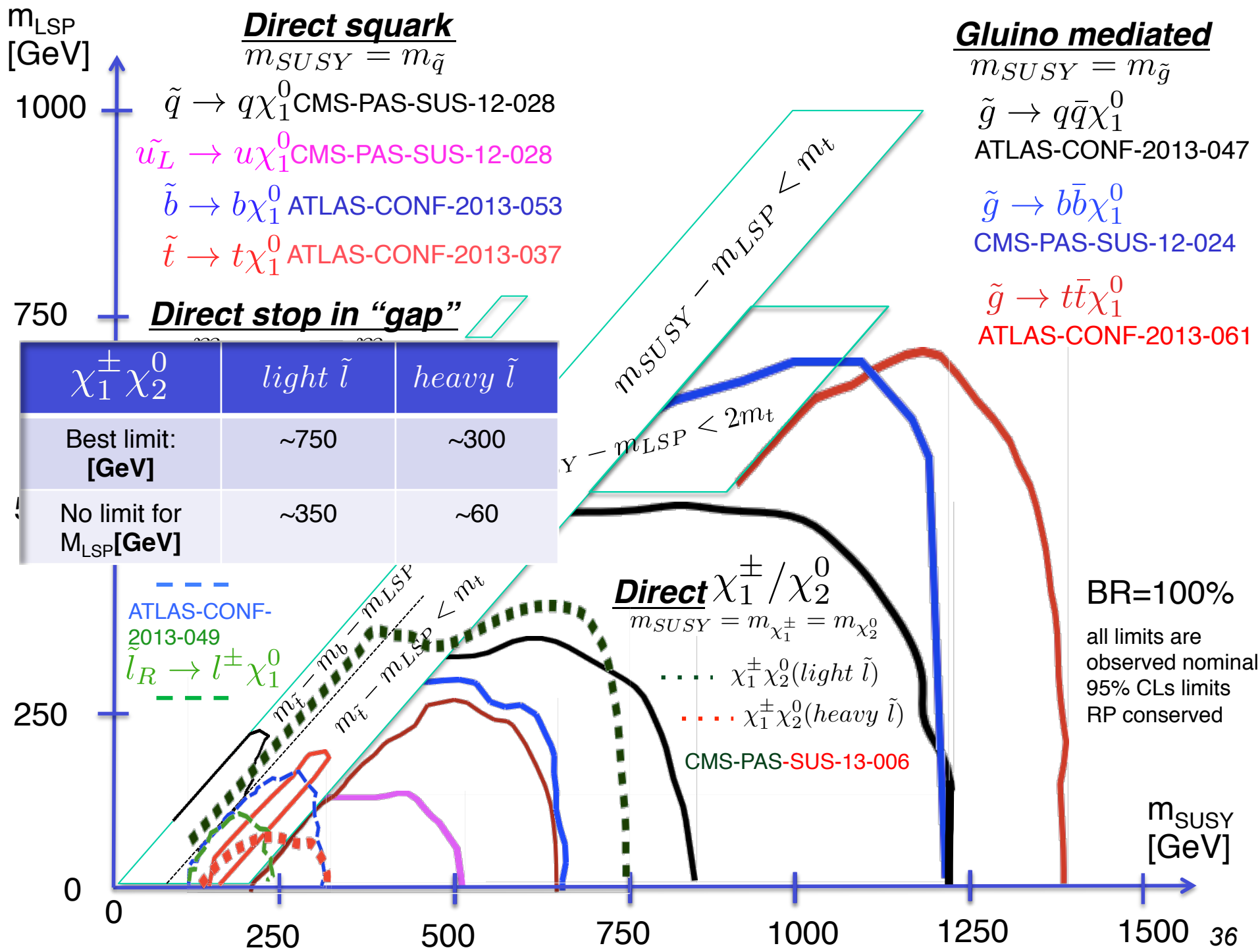


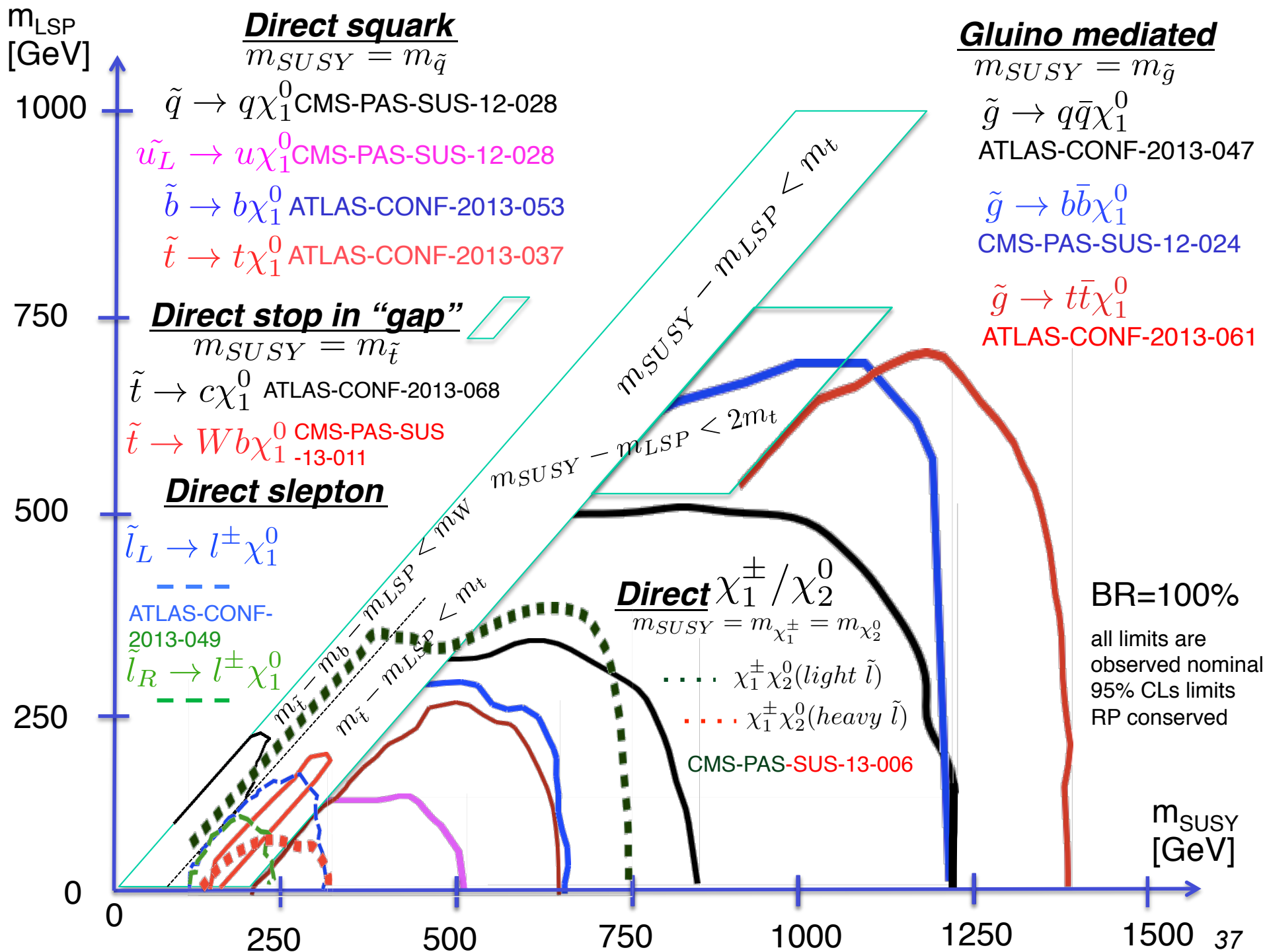
light slepton "easy"

CMS-PAS-SUS-13-006  
3l OSSF categorised in bins of  $M_{ll}$ , MT, and ETmis



See parallel talk for details:  
**L. Shchutska**  
 see also **S. King**





# RP-violating searches/interpretation

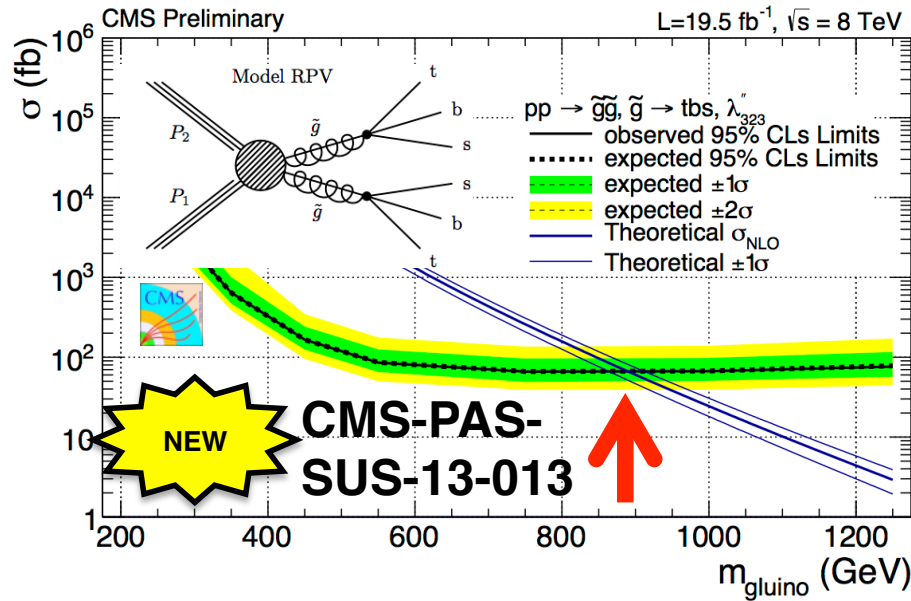
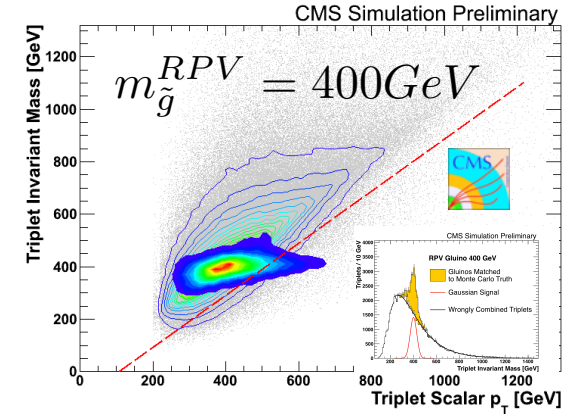
Direct SUSY Searches, O. Buchmüller

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

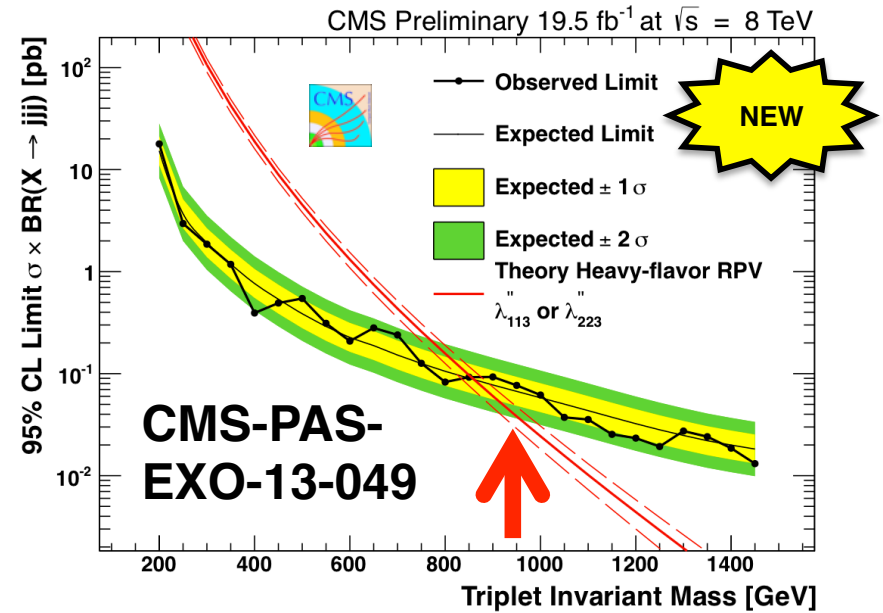
SR	Expected	Observed
RPV0	38 ± 14	35
RPV2	5.3 ± 2.1	5
SStop1	160 ± 59	152
SStop1++	90 ± 32	92
SStop2	40 ± 13	52
SStop2++	22 ± 8	25

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

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



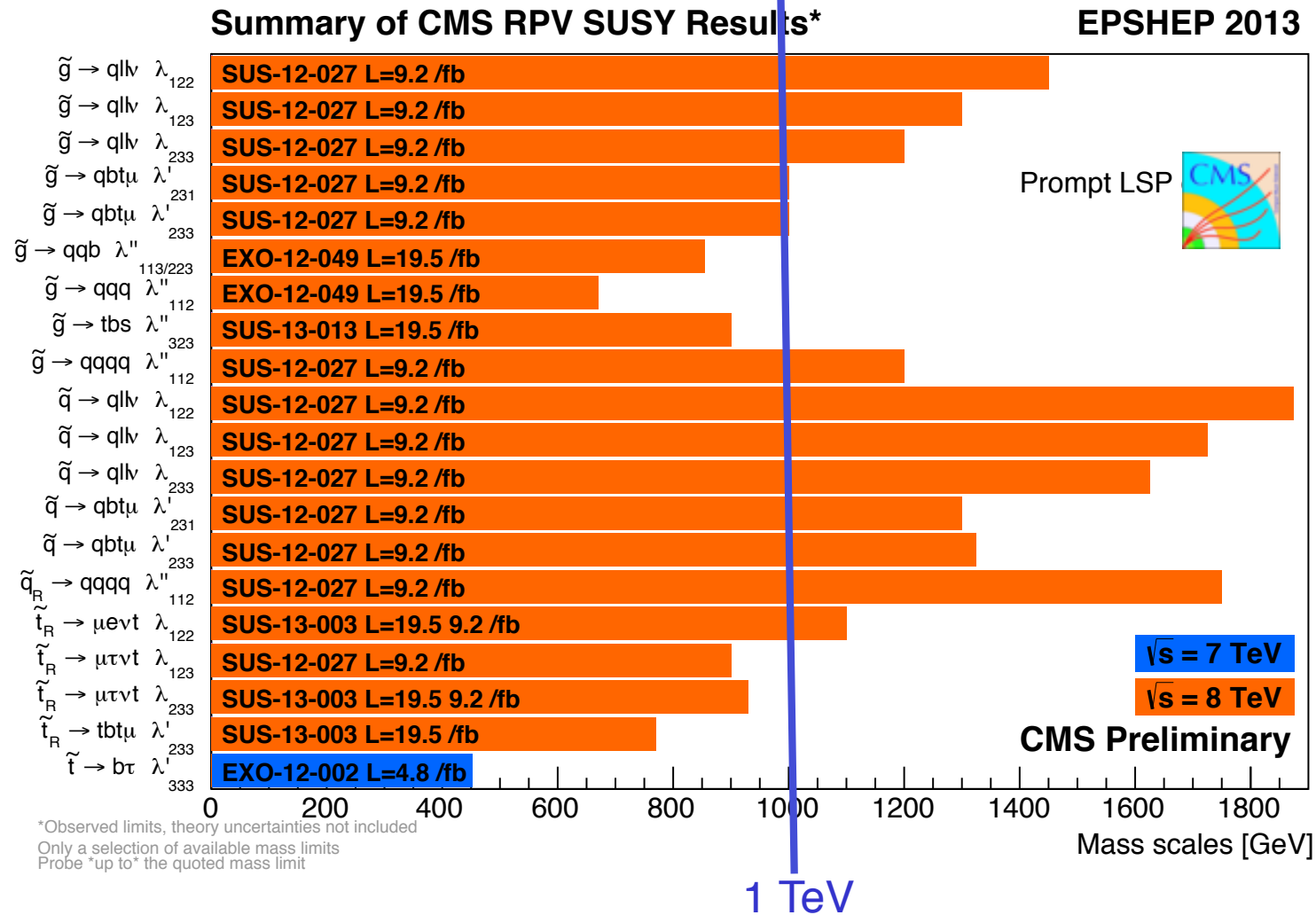
See talk from **K. Ulmer** in parallel session for further details.



See talk from **C. Seitz** in parallel session for further details.

# RP violation searches: Summary

EPS 2013 Direct SUSY Searches, O. Buchmüller

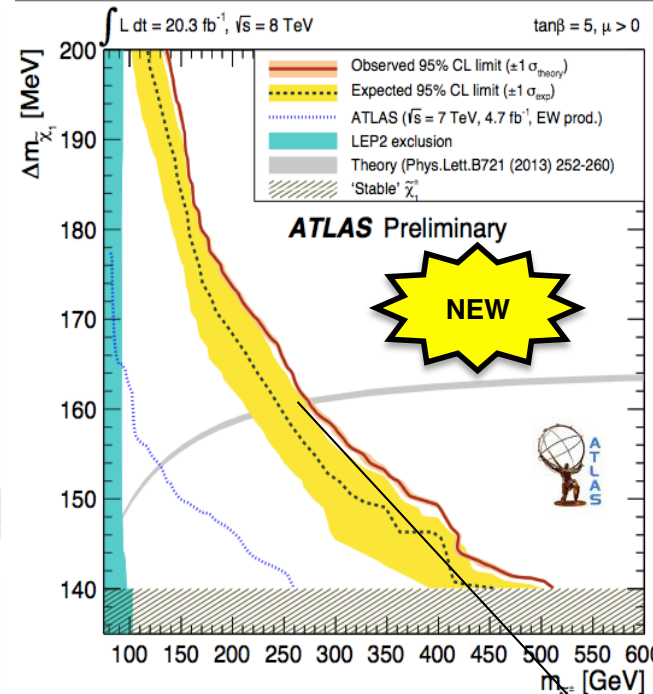
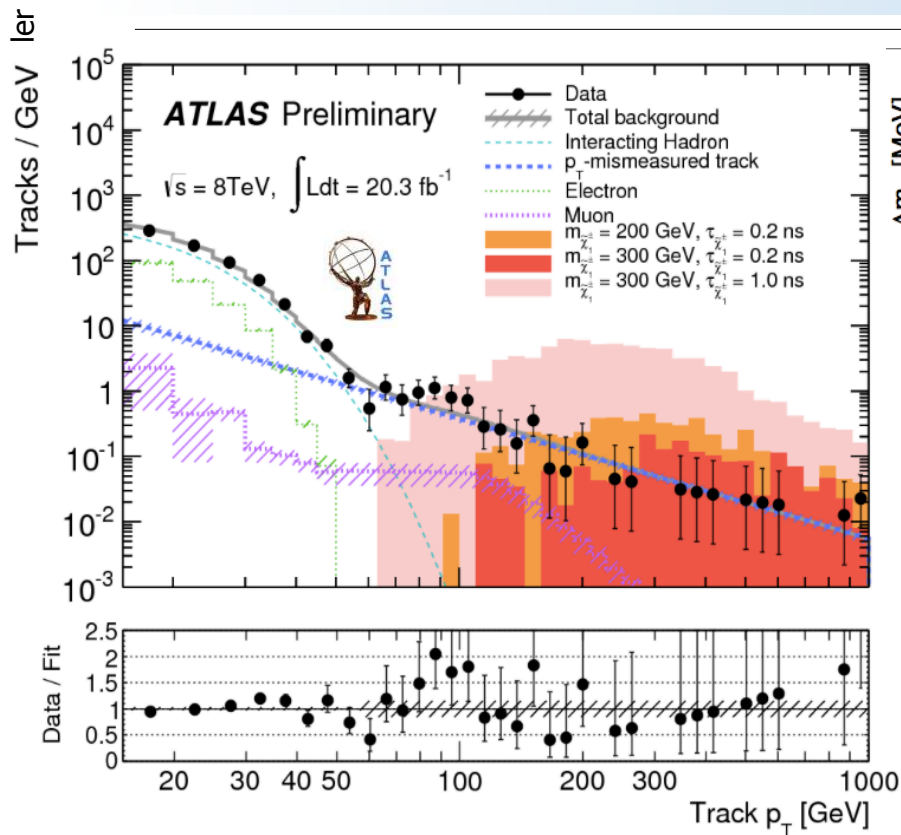


ATLAS  
similar

See also talks  
from e.g.  
**A. Cakir,**  
**W. Ehrenfeld**

**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

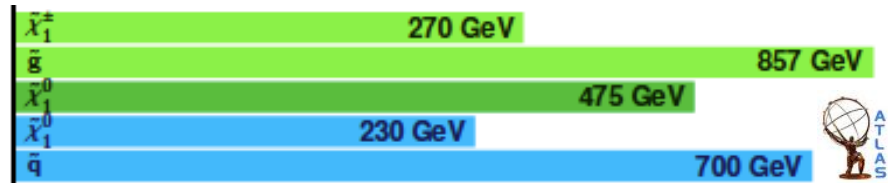
$$\chi_{1\pm}^{\pm} \chi_{10}^0$$

search based on  
disappearing-track  
signature

See parallel talk  
from [W. Ehrenfeld](#)  
for further details.

CMS similar  
See parallel talk from  
[L. Quertenmont](#)

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



$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) = 160$  MeV,  $\tau(\tilde{\chi}_1^{\pm}) = 0.2$  ns  
 $m(\tilde{\chi}_1^0) = 100$  GeV,  $10 \mu s < \tau(\tilde{g}) < 1000$  s  
 $10 < \tan\beta < 50$   
 $0.4 < \tau(\tilde{\chi}_1^0) < 2$  ns  
 $1 \text{ mm} < c\tau < 1$  m,  $\tilde{g}$  decoupled

ATLAS-CONF-2013-069  
 ATLAS-CONF-2013-057  
 ATLAS-CONF-2013-058  
 1304.6310  
 1210.7451

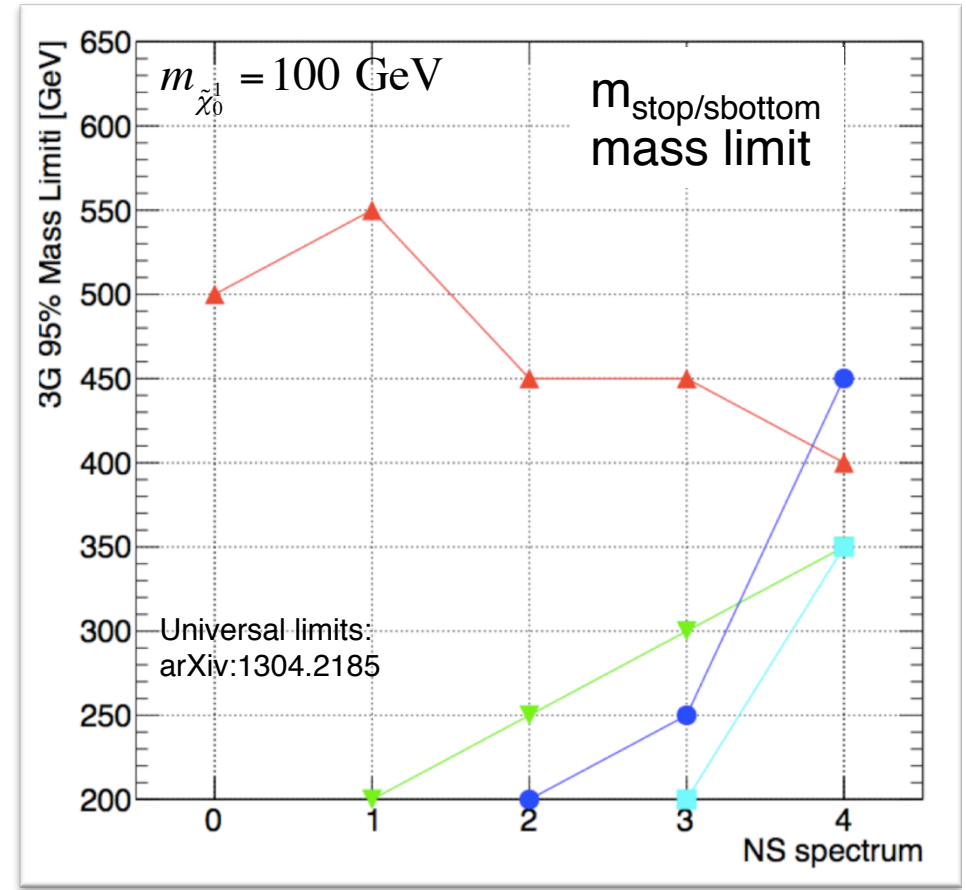
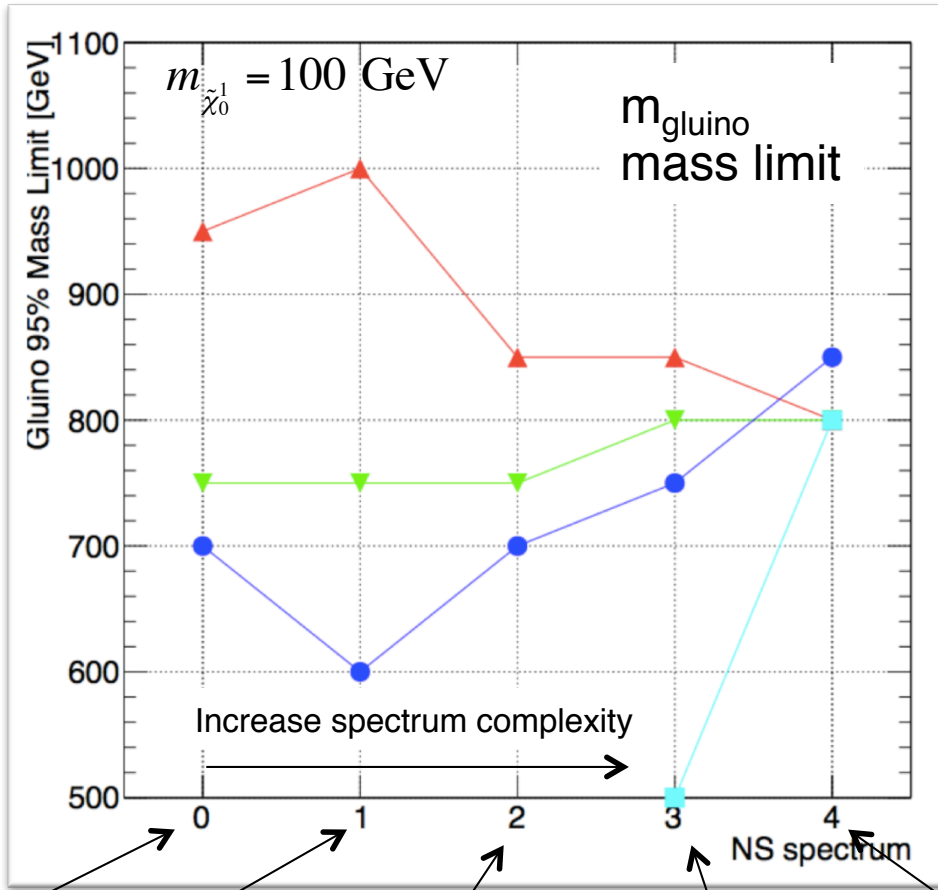
About to probe  
the 1 TeV scale

1 TeV



# SMS limits: A word of caution!

EPS 2013 Direct SUSY Searches, O. Buchmüller



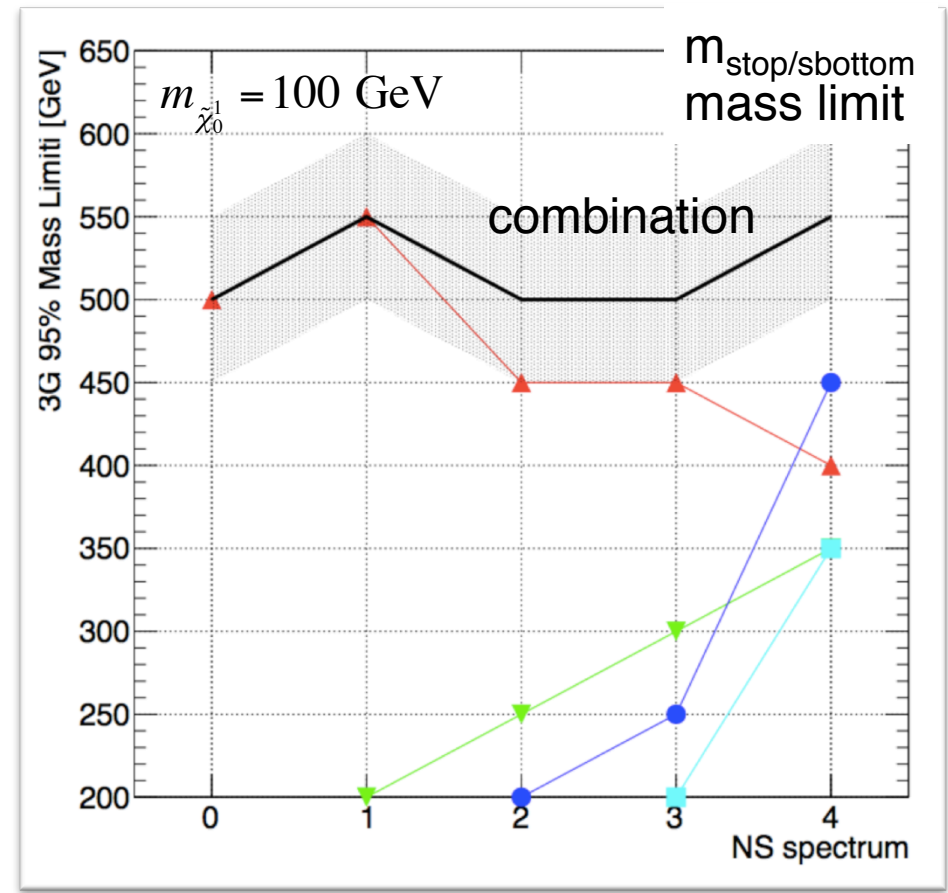
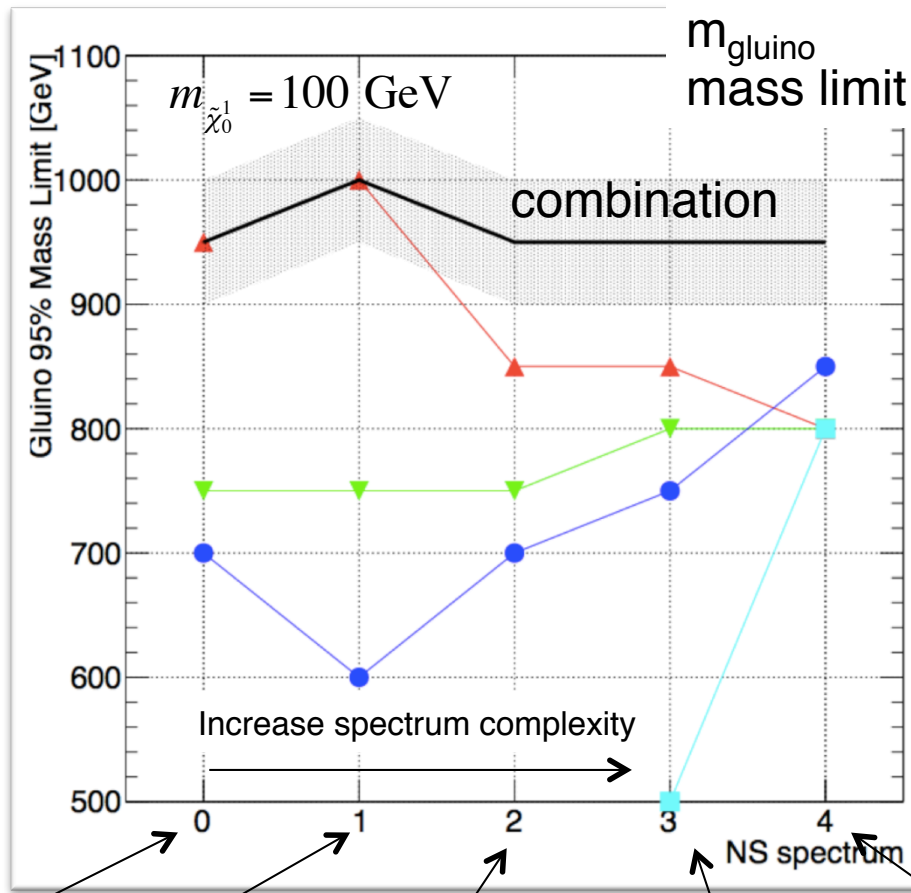
NS0	NS1	NS2	NS3	NS4
$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$	$\tilde{g}$
$\tilde{t}_1, \tilde{t}_2$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
		$\tilde{\chi}_0^2$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

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-Lepton OS CMS-SUS-11-011

# Combining Searches = less model dependence

EPS 2013 Direct SUSY Searches, O. Buchmüller



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

Used inclusive searches from 2011:

0-Lepton CMS-SUS-11-022

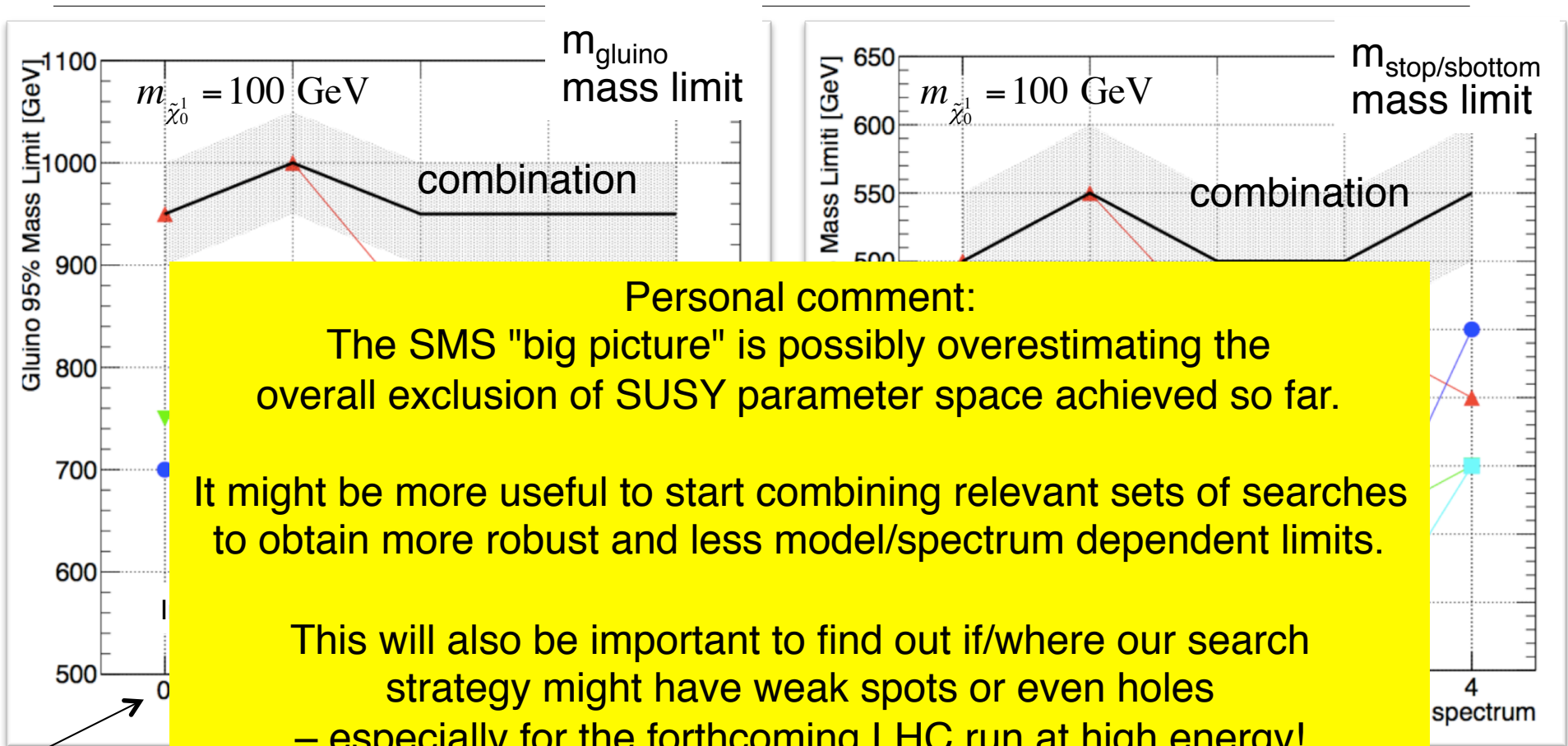
1-Lepton CMS-SUS-12-010

2-Lepton SS CMS-SUS-11-010

2-Lepton OS CMS-SUS-11-011

# Combining Searches = less model dependence

EPS 2013 Direct SUSY Searches, O. Buchmüller



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-Lepton OS CMS-SUS-11-011

# Outlook: 8 TeV vs 14 TeV

EPS 2013 Direct SUSY Searches, O. Buchmüller

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

## Higgs:

$pp \rightarrow H, H \rightarrow WW, ZZ$  and  $\gamma\gamma$   
mainly  $gg$ : factor  $\sim 2$

## SUSY – 3<sup>rd</sup> Generation:

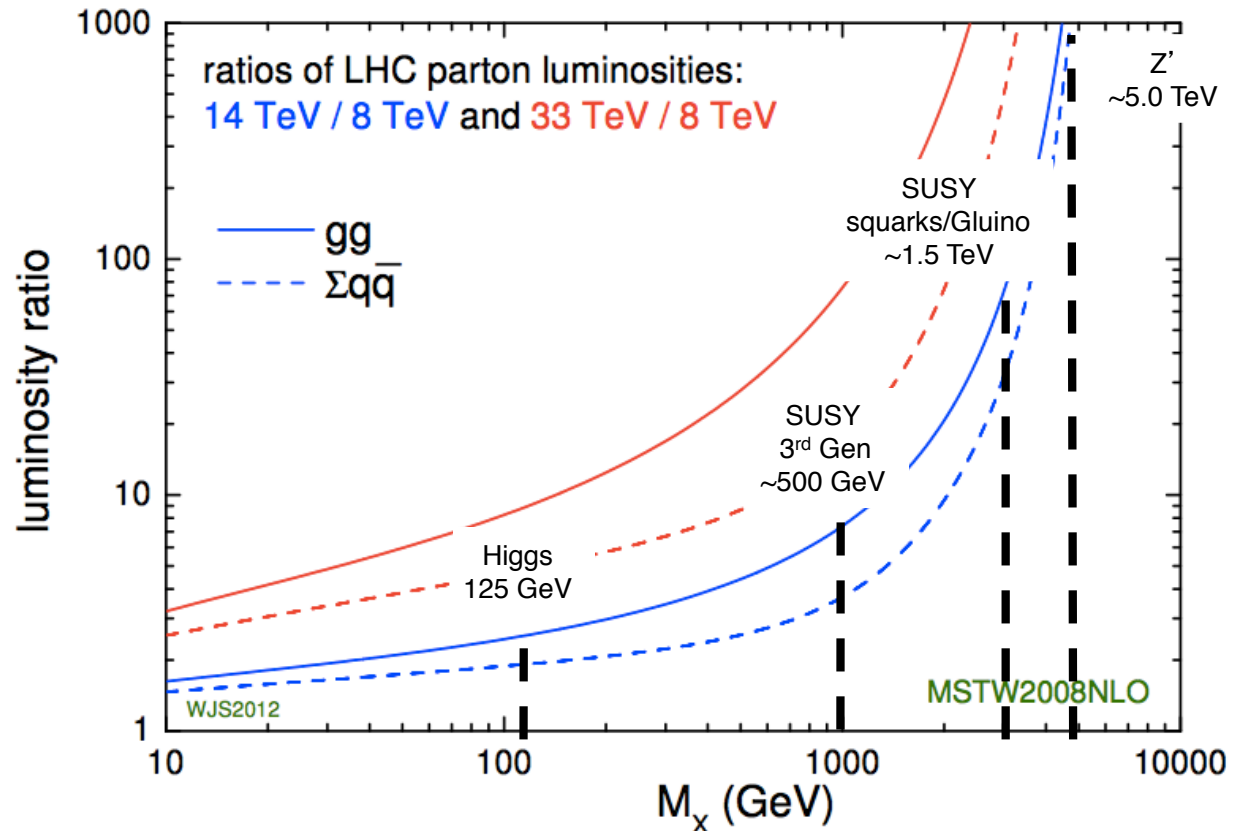
Mass scale  $\sim 500$  GeV  
 $qq$  and  $gg$ : factor  $\sim 3$  to 6

## SUSY – Squarks/Gluino:

Mass scale  $\sim 1.5$  TeV  
 $qq, gg, qg$ : factor  $\sim 40$  to 80

## Z' :

Mass scale  $\sim 5$  TeV  
 $qq$ : factor  $\sim 1000$



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 entered new territory for SUSY searches and since pushed the (coloured) SUSY mass scale to the  $\sim 1$  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 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>

# ATLAS Summary

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

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

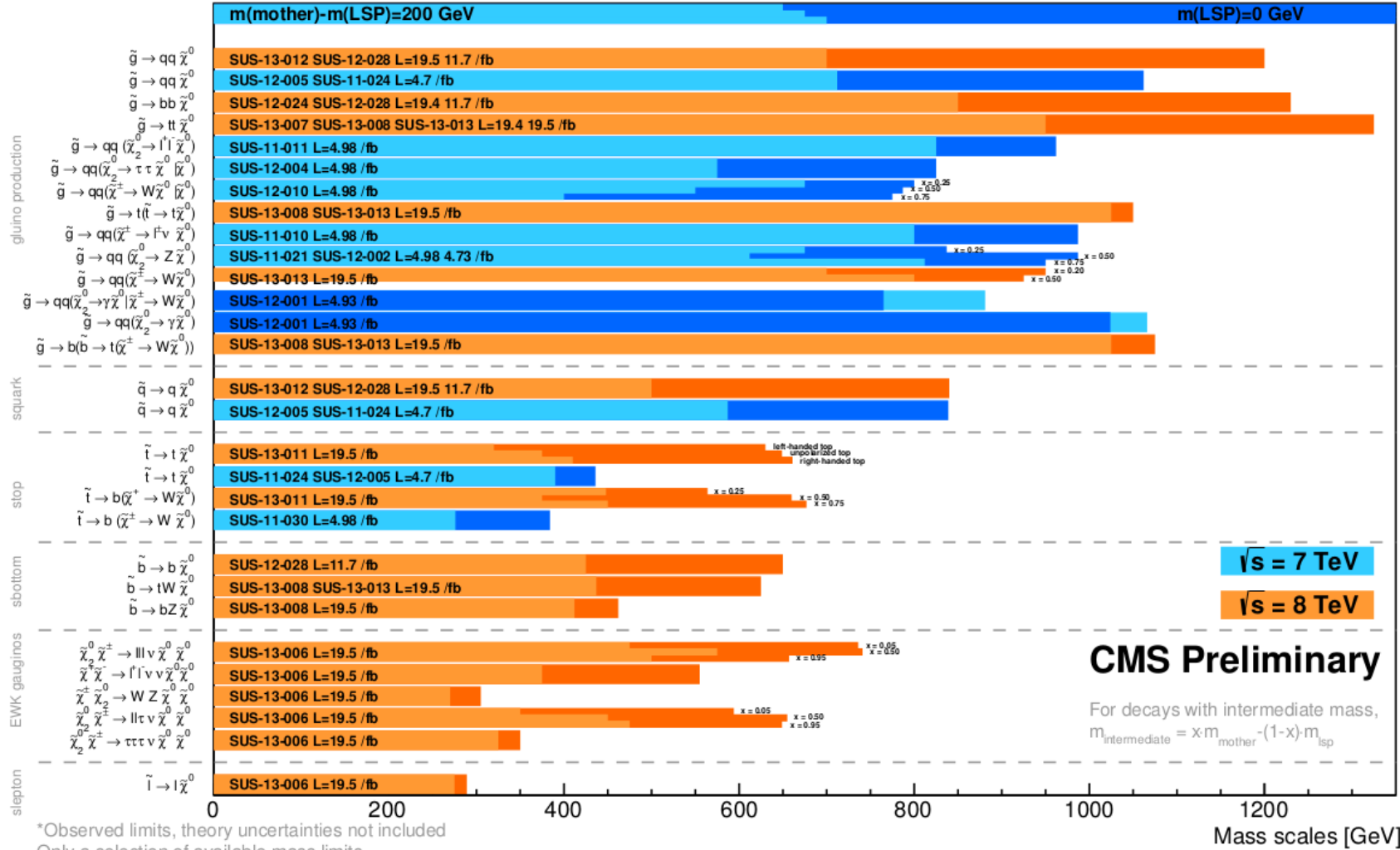
Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$
	MSUGRA/CMSSM	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$
	$\tilde{g}\tilde{g} \rightarrow qq\tilde{q}\tilde{\ell}(\tilde{\ell})\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 $e, \mu$ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0) < 650 \text{ GeV}$
	GMSB ( $\tilde{\ell}$ NLSP)	2 $e, \mu$	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta < 15$
	GMSB ( $\tilde{\tau}$ NLSP)	1-2 $\tau$	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta > 18$
	GGM (bino NLSP)	2 $\gamma$	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) > 220 \text{ GeV}$
	GGM (higgsino NLSP)	2 $e, \mu$ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(H) > 200 \text{ GeV}$
Gravitino LSP	0	mono-jet	Yes	10.5	$E_T^{1/2}$ scale 645 GeV	$m(\tilde{g}) > 10^{-4} \text{ eV}$	
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^\pm$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^\pm$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}_1^0) < 100 \text{ GeV}$
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}_1^0) = 2 m(\tilde{\chi}_1^\pm)$
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	1-2 $e, \mu$	1-2 $b$	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}_1^0) = 55 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{t}_1) - m(W) - 50 \text{ GeV}, m(\tilde{t}_1) < m(\tilde{\chi}_1^\pm)$
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	0	2 $b$	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^\pm$	1 $e, \mu$	1 $b$	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0	2 $b$	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 200 GeV	$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < 85 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 $b$	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180 \text{ GeV}$	
EIW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\nu})$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\nu})$	2 $\tau$	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\tilde{\nu}\nu), \tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 $e, \mu$	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ 600 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	3 $e, \mu$	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ 315 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0) = 0, \text{ sleptons decoupled}$
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_1^\pm) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(e, \mu) + \tau$	1-2 $\mu$	0	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	$10 < \tan\beta < 50$
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma G$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4 < \tau(\tilde{\chi}_1^0) < 2 \text{ ns}$
$\tilde{\chi}_1^0 \rightarrow q\tilde{q}$ (RPV)	1 $\mu$	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm $< c\tau < 1 \text{ m}, \tilde{g}$ decoupled	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda'_{311} = 0.10, \lambda_{132} = 0.05$
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda'_{311} = 0.10, \lambda_{1(2)33} = 0.05$
	Bilinear RPV CMSSM	1 $e, \mu$	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q}) = m(\tilde{g}), c\tau_{\text{LSP}} < 1 \text{ mm}$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0) > 300 \text{ GeV}, \lambda_{121} > 0$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^\pm\tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_e, e\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0) > 80 \text{ GeV}, \lambda_{133} > 0$
	$\tilde{g} \rightarrow qq\tilde{q}$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV	
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.7	$\tilde{g}$ 880 GeV	
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693
	WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$M^*$ scale 704 GeV	$m(\chi) < 80 \text{ GeV}$ , limit of $\sim 687 \text{ GeV}$ for D8

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



# CMS Summary

## Summary of CMS SUSY Results\* in SMS framework EPSHEP 2013



\*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  $\sim 1\text{fb}^{-1}$
- 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  $< 10\text{fb}^{-1}$
- 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)

EPS 2013 Direct SUSY Searches, O. Buchmüller

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

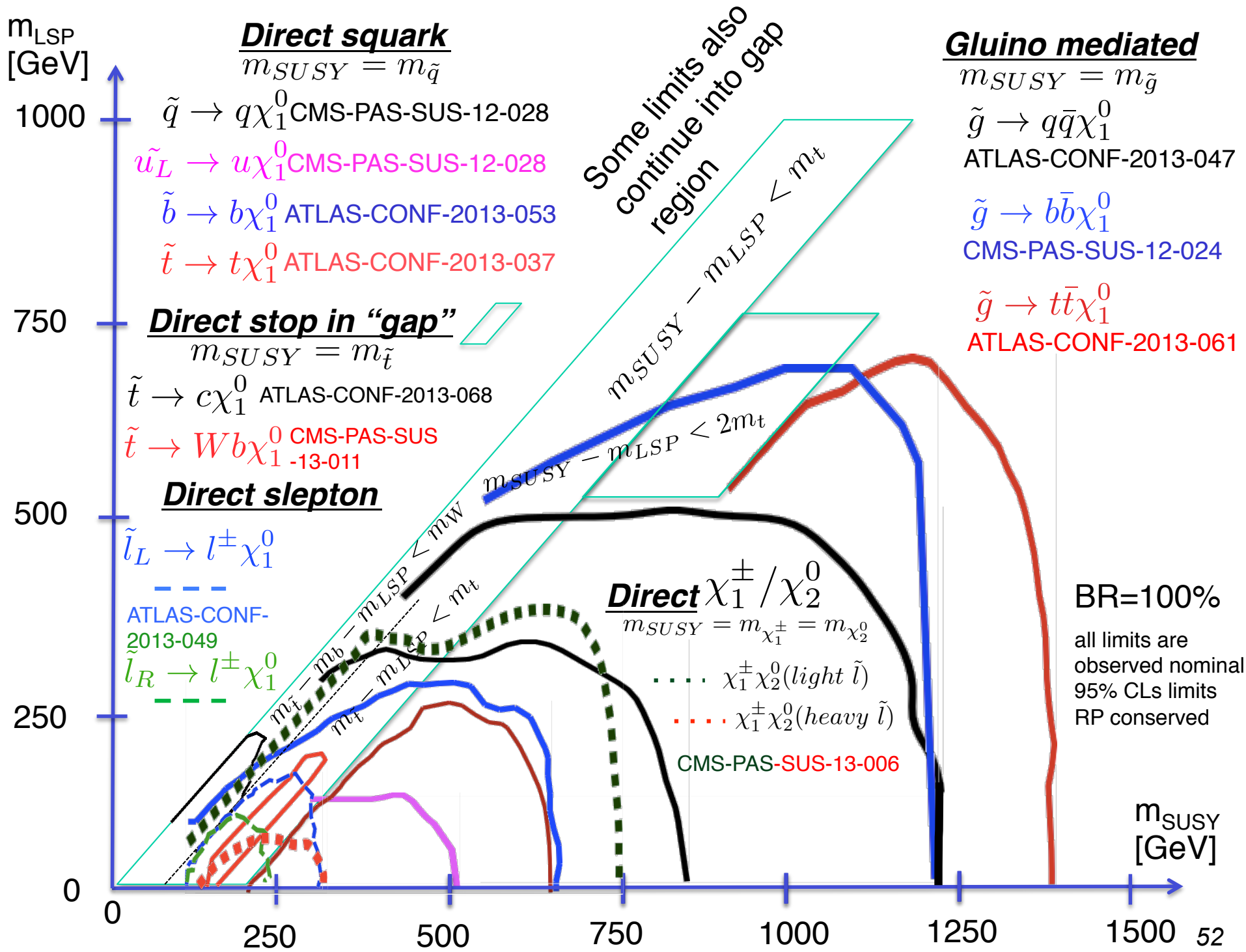
Direct squark	$\tilde{g} \rightarrow q\bar{q}\chi_1^0$	$\tilde{g} \rightarrow b\bar{b}\chi_1^0$	$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
Best limit: [GeV]	~1200	~1200	~1400
No limit for $M_{LSP}$ [GeV]	~480	~650	~700

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

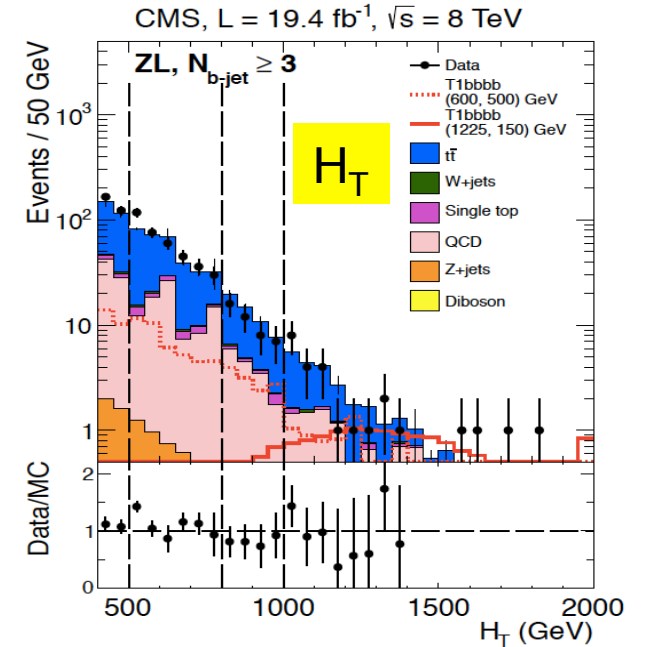
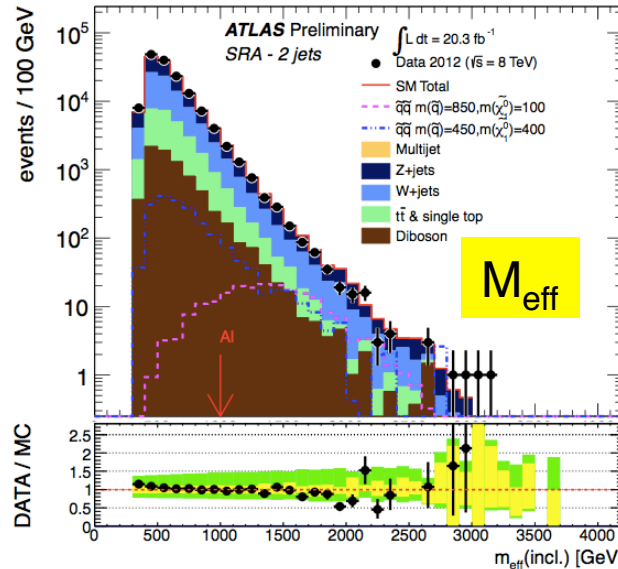
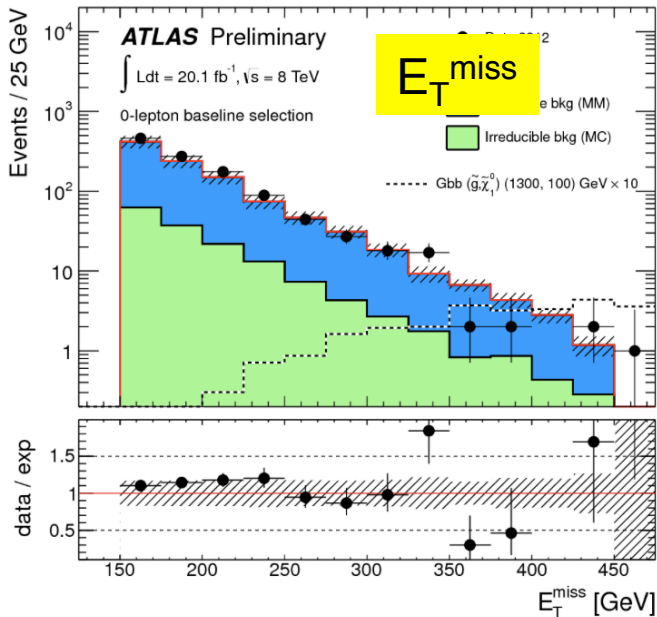
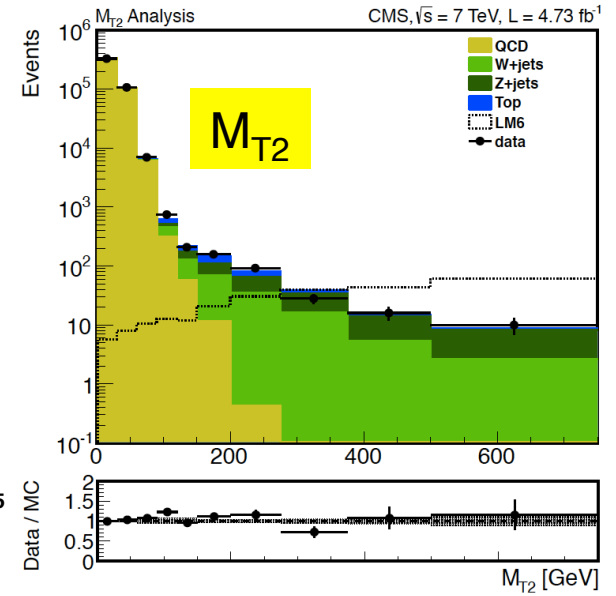
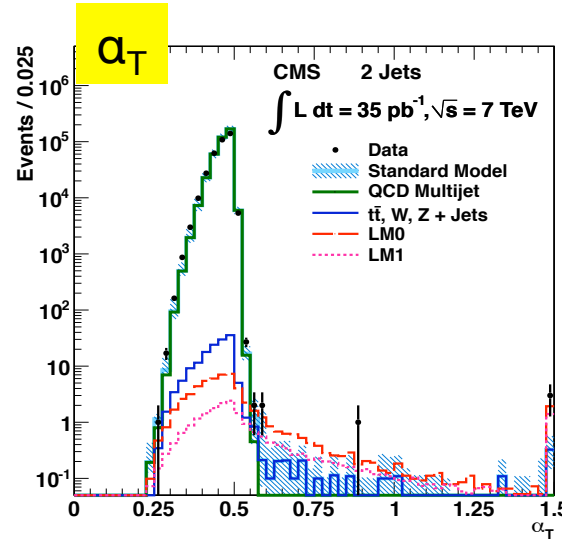
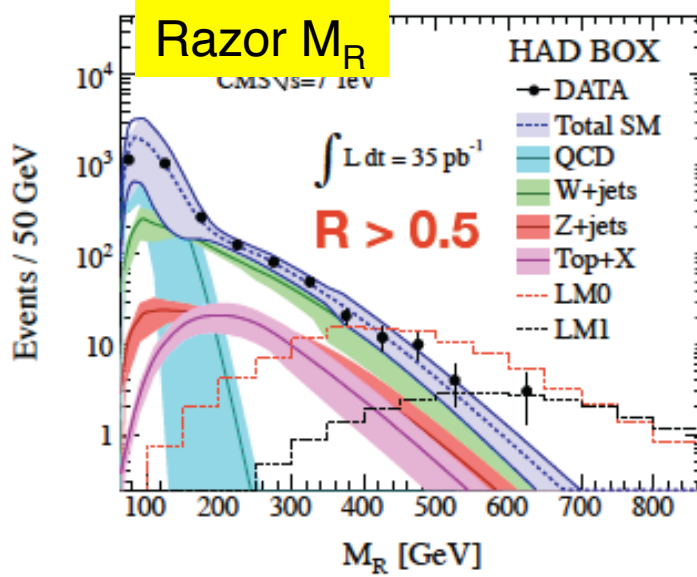
Direct slepton	$\tilde{l}_L \rightarrow l^\pm\chi_1^0$	$\tilde{l}_R \rightarrow l^\pm\chi_1^0$
Best limit: [GeV]	~300	~240
No limit for $M_{LSP}$ [GeV]	~150	~90

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

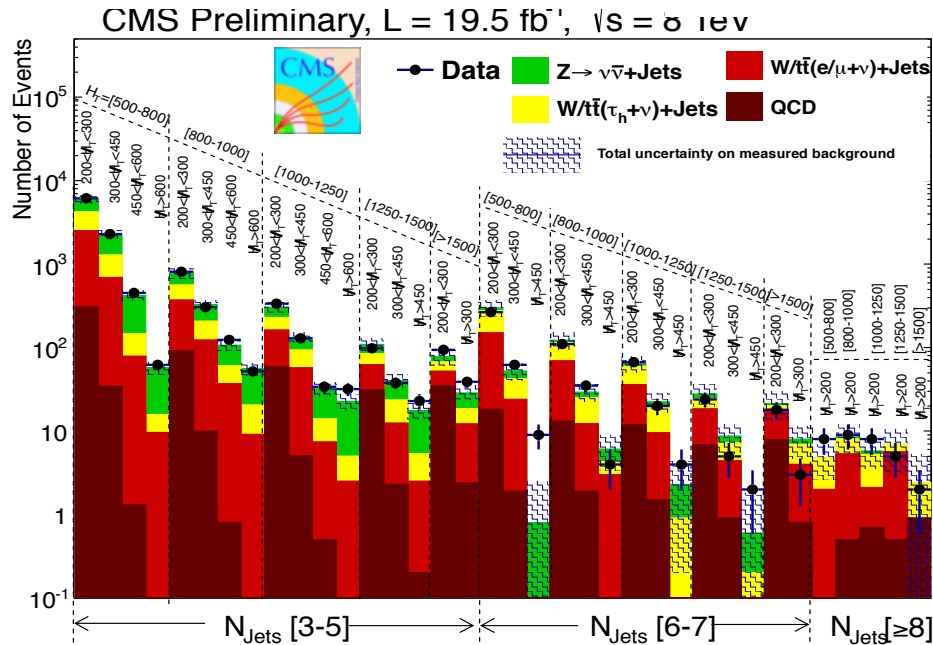
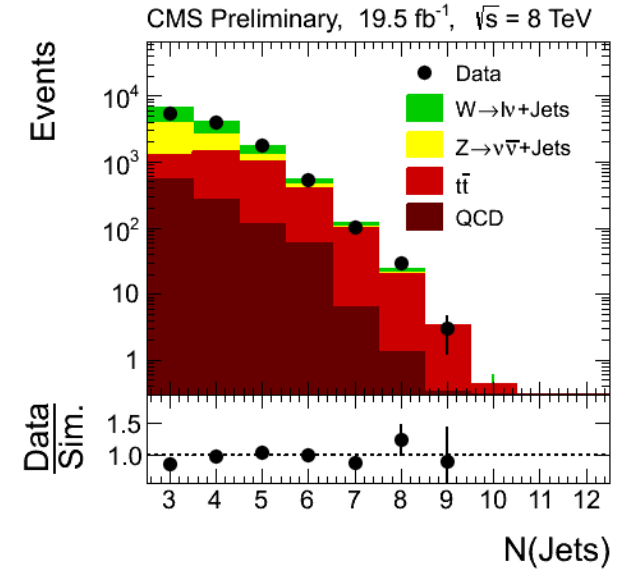
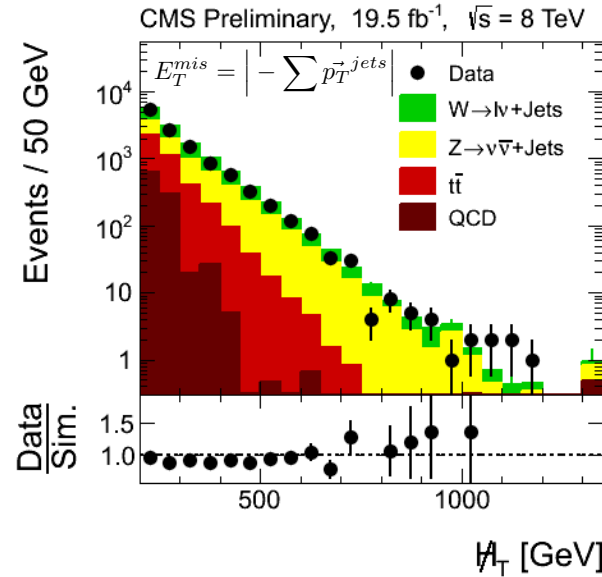
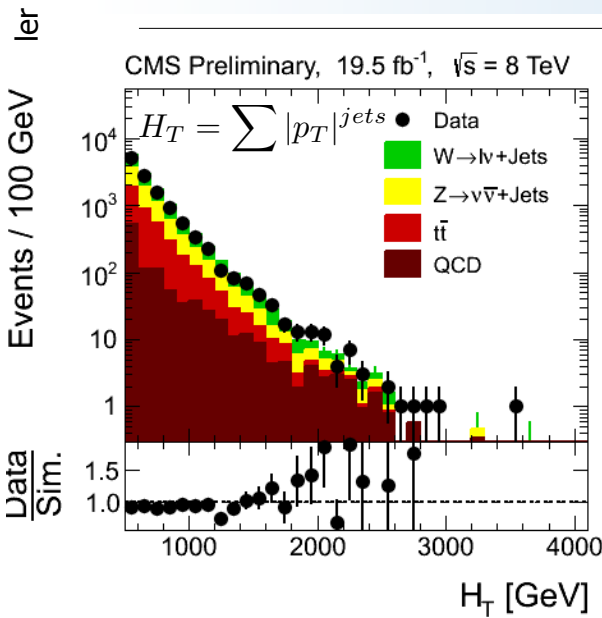


# Many Different Kinematic Variables

EPS 2013 Direct SUSY Searches, O. Buchmüller



# Multijets & missing energy search



Traditional inclusive Jets +  $E_T^{mis}$  search, which uses simple kinematic variables to categorize the events.

Main backgrounds QCD, W/Z+jet and t $\bar{t}$  are estimated using data-driven techniques.



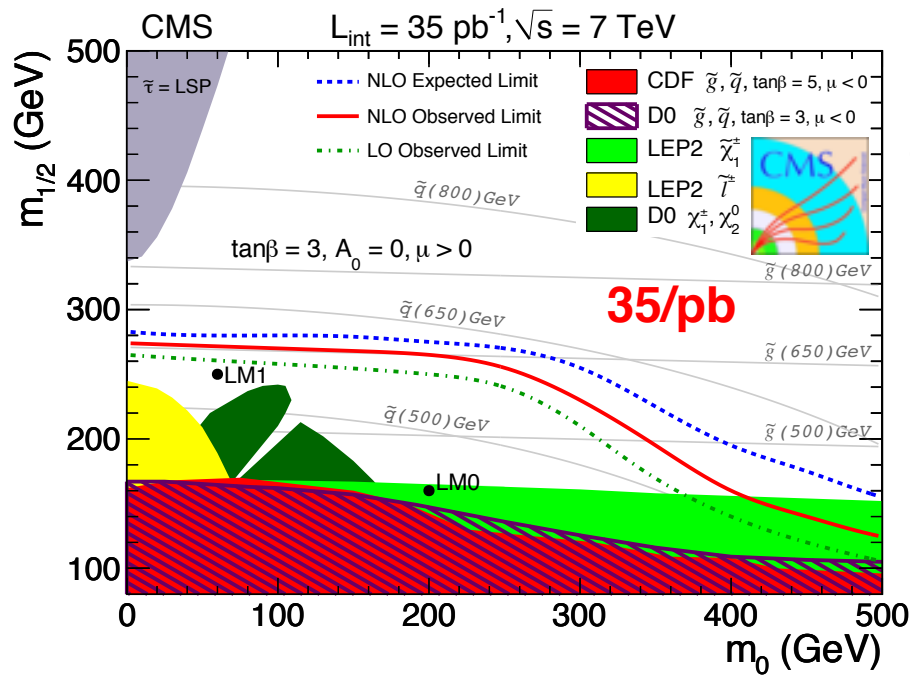
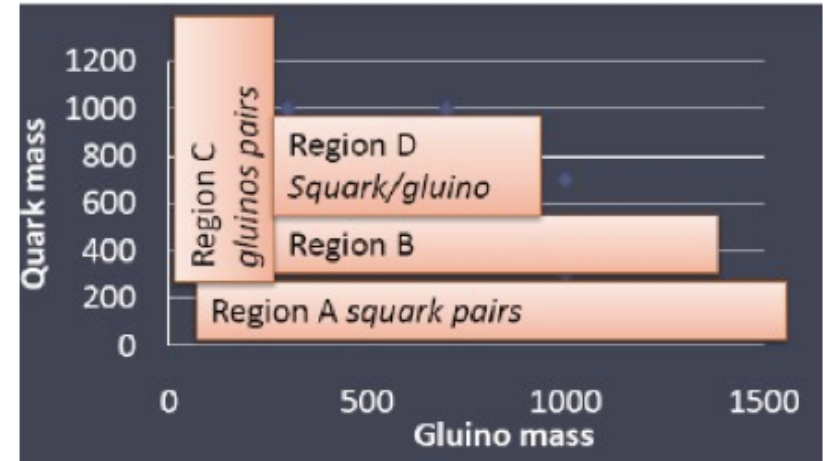
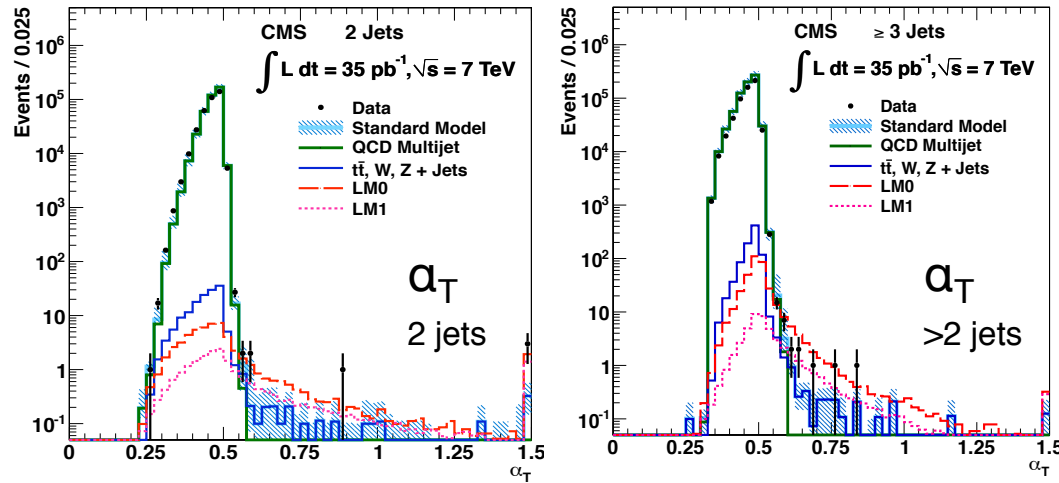
**CMS-SUS-PAS-13-012**

See parallel talk for details:

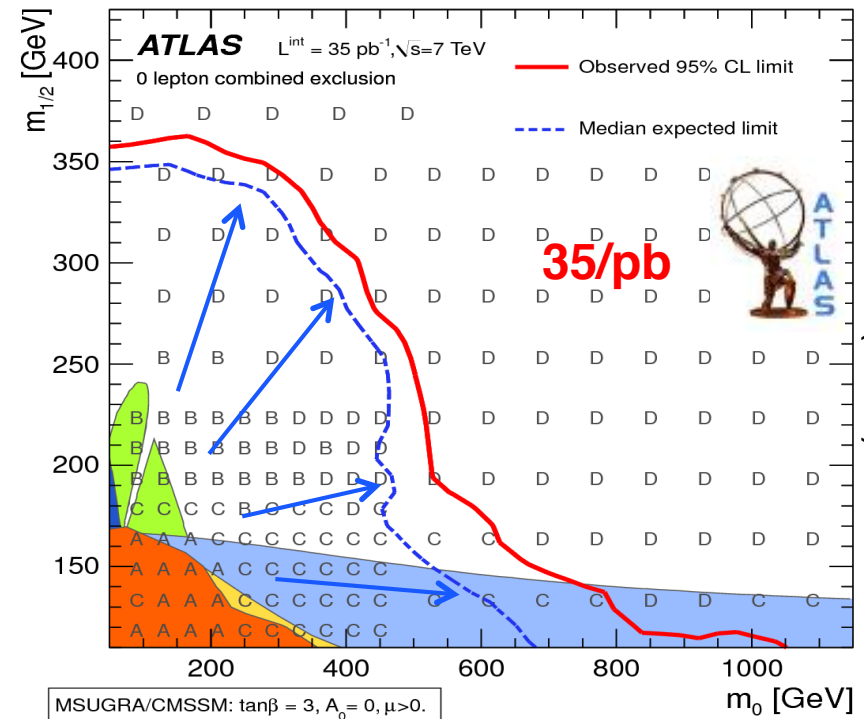
C. Autermann

# 2010: Entering New Territory at the LHC!

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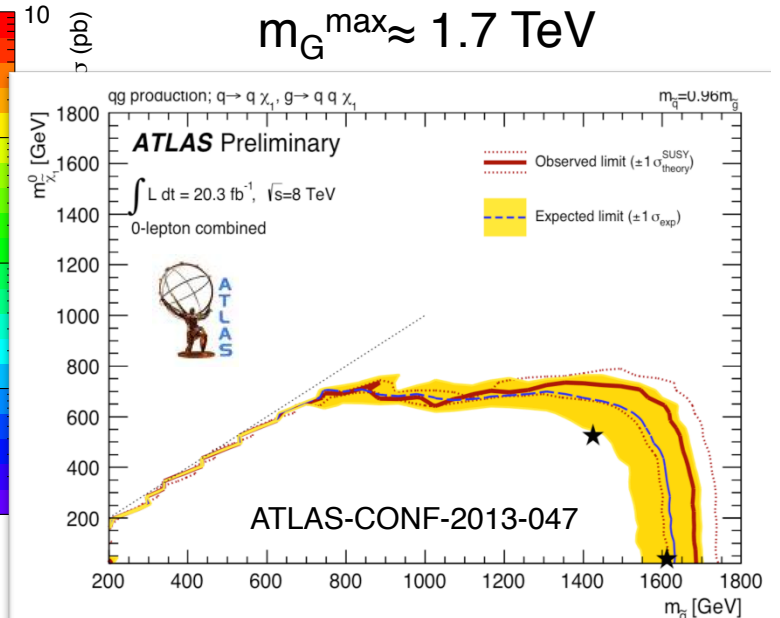
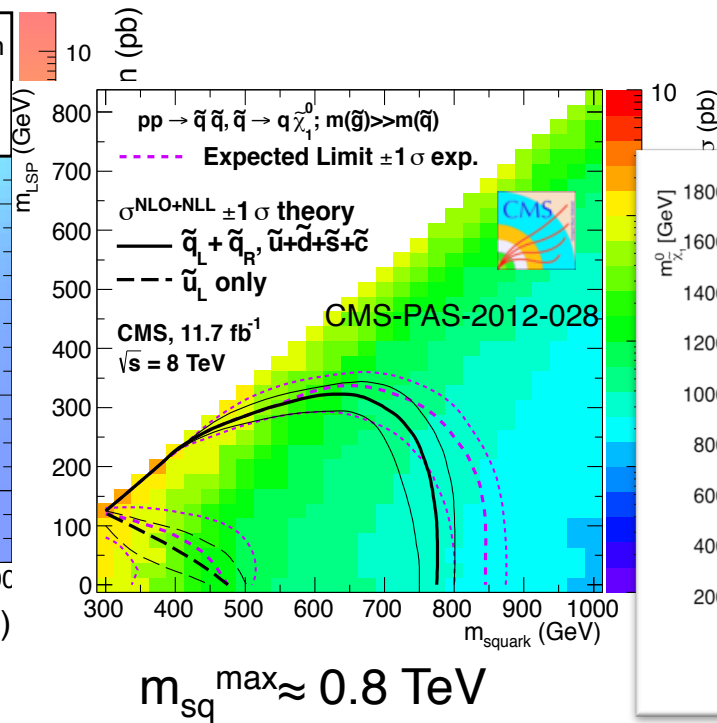
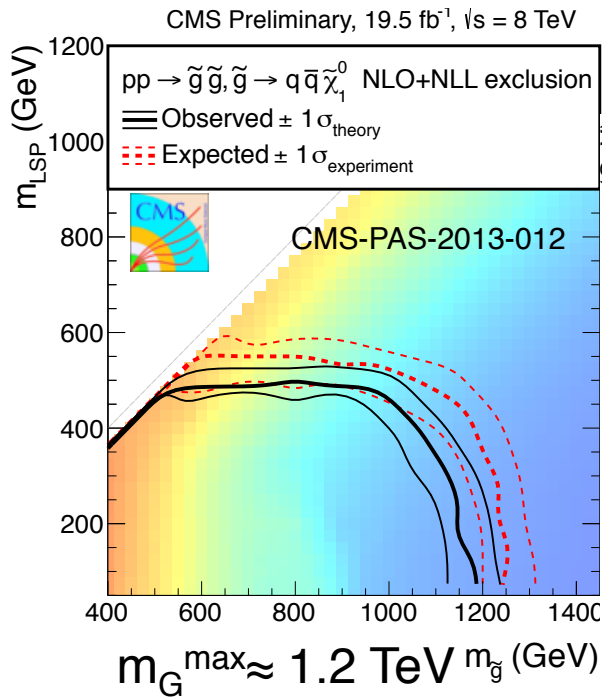
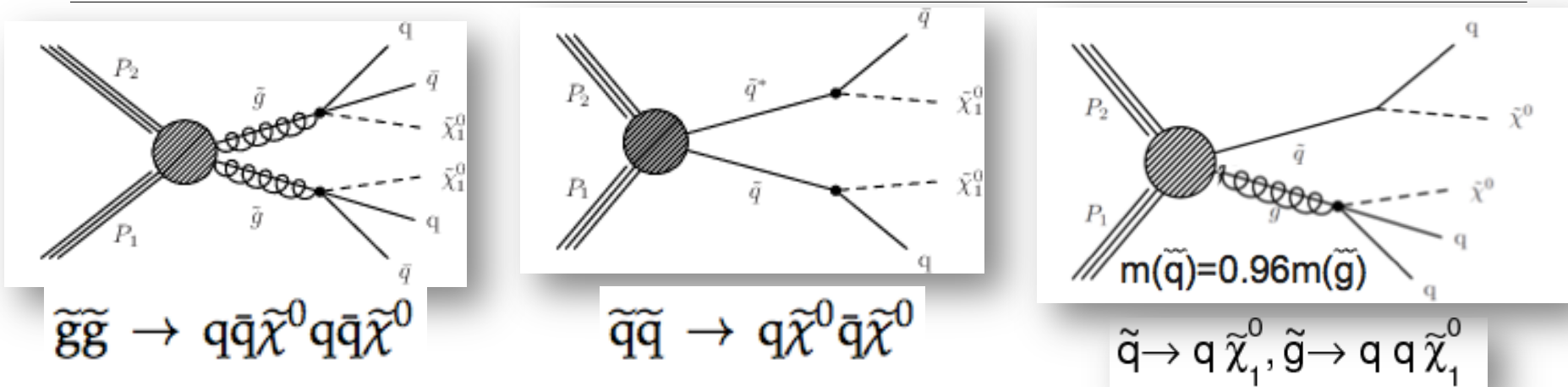
Phys. Lett. B698:196-218



PLB 701 (2011) 186

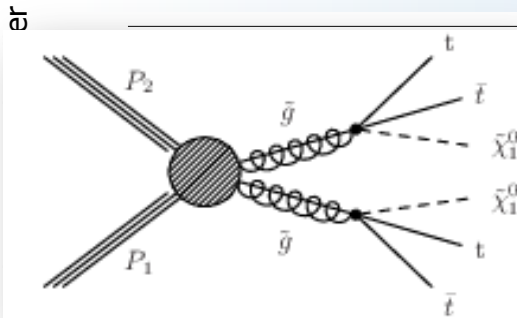
# Simplified Model Spectra (SMS)

Direct SUSY Searches, O. Buchmüller



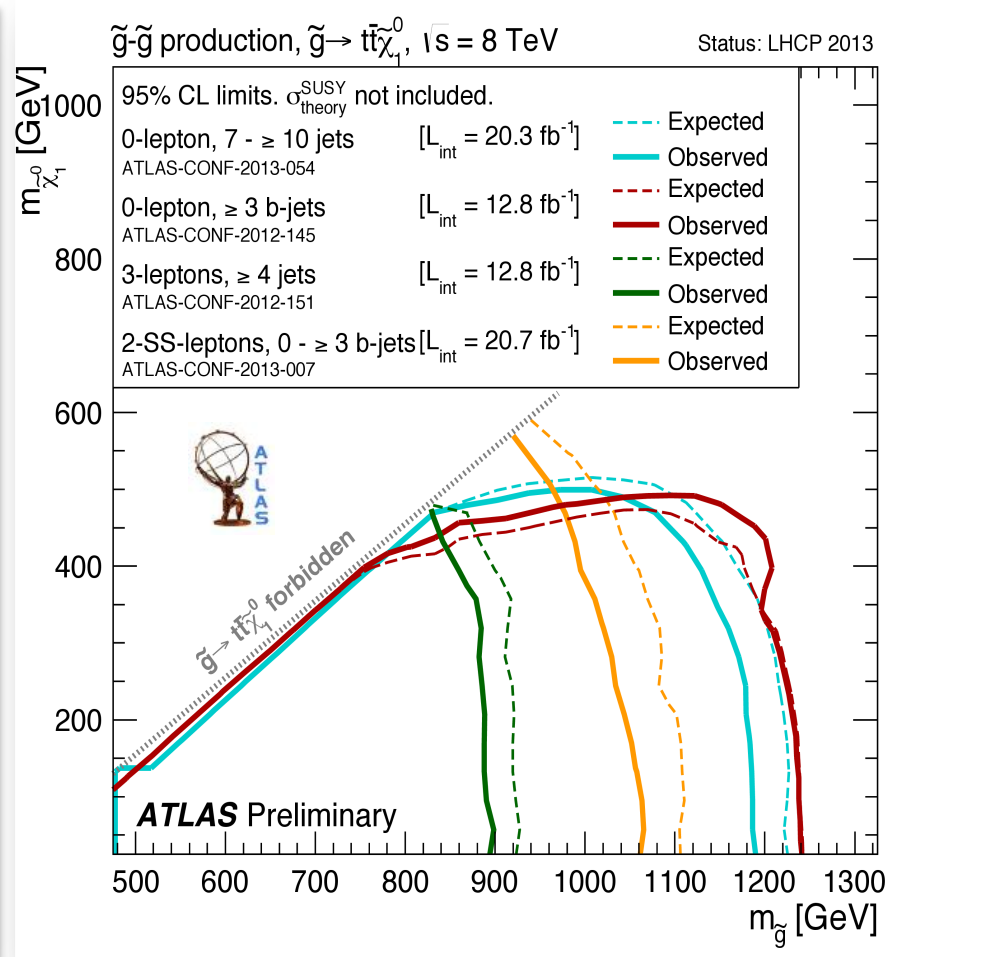
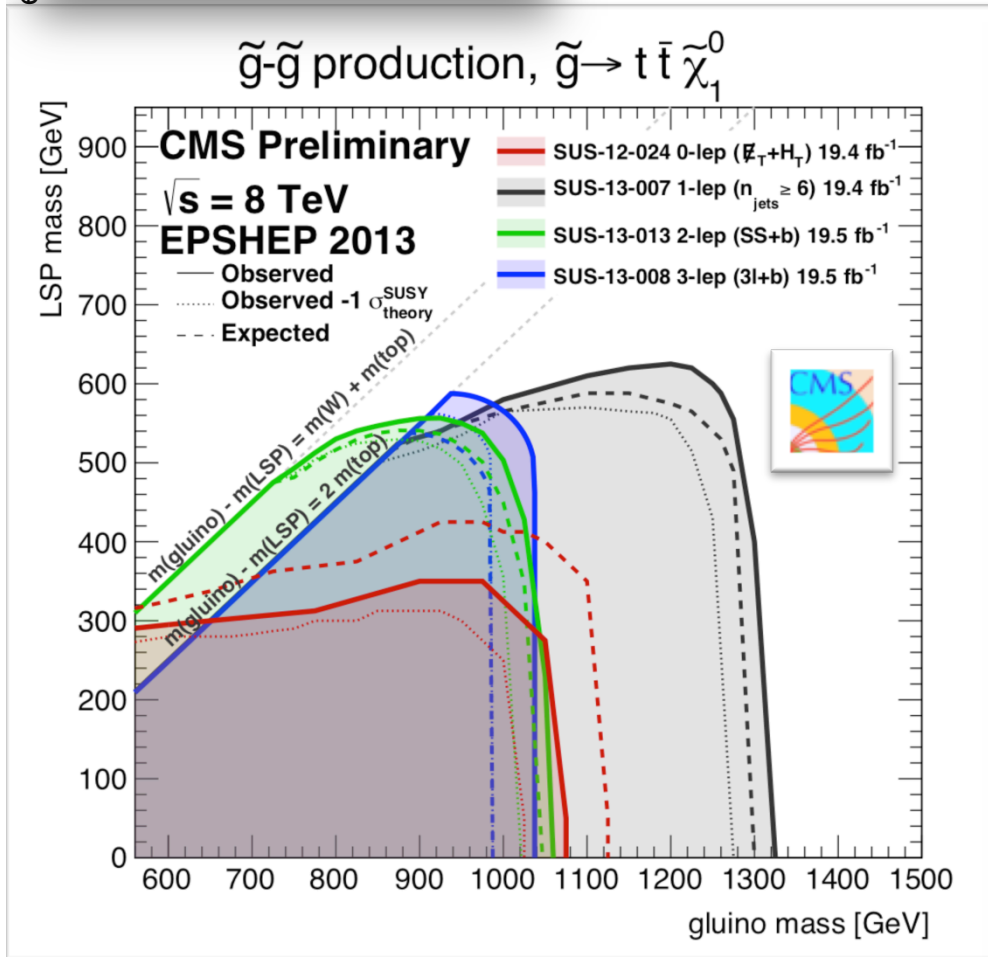


# Today: many more SMS and many more searches



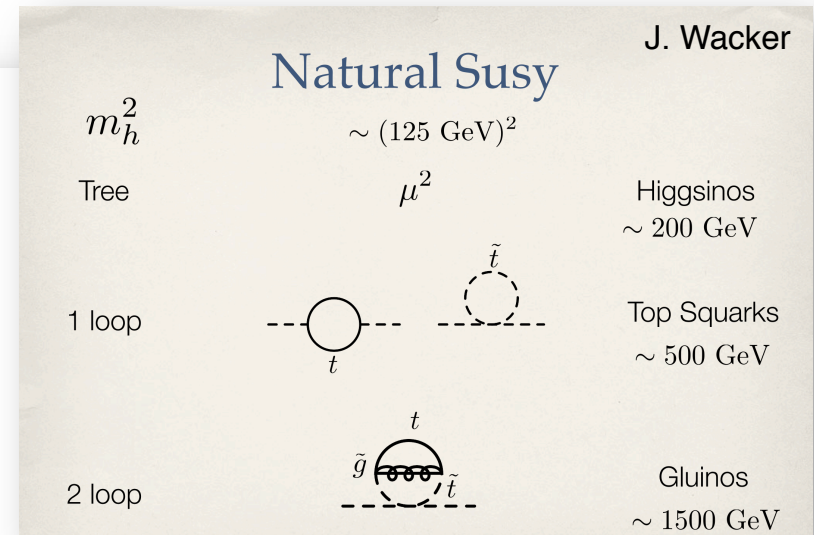
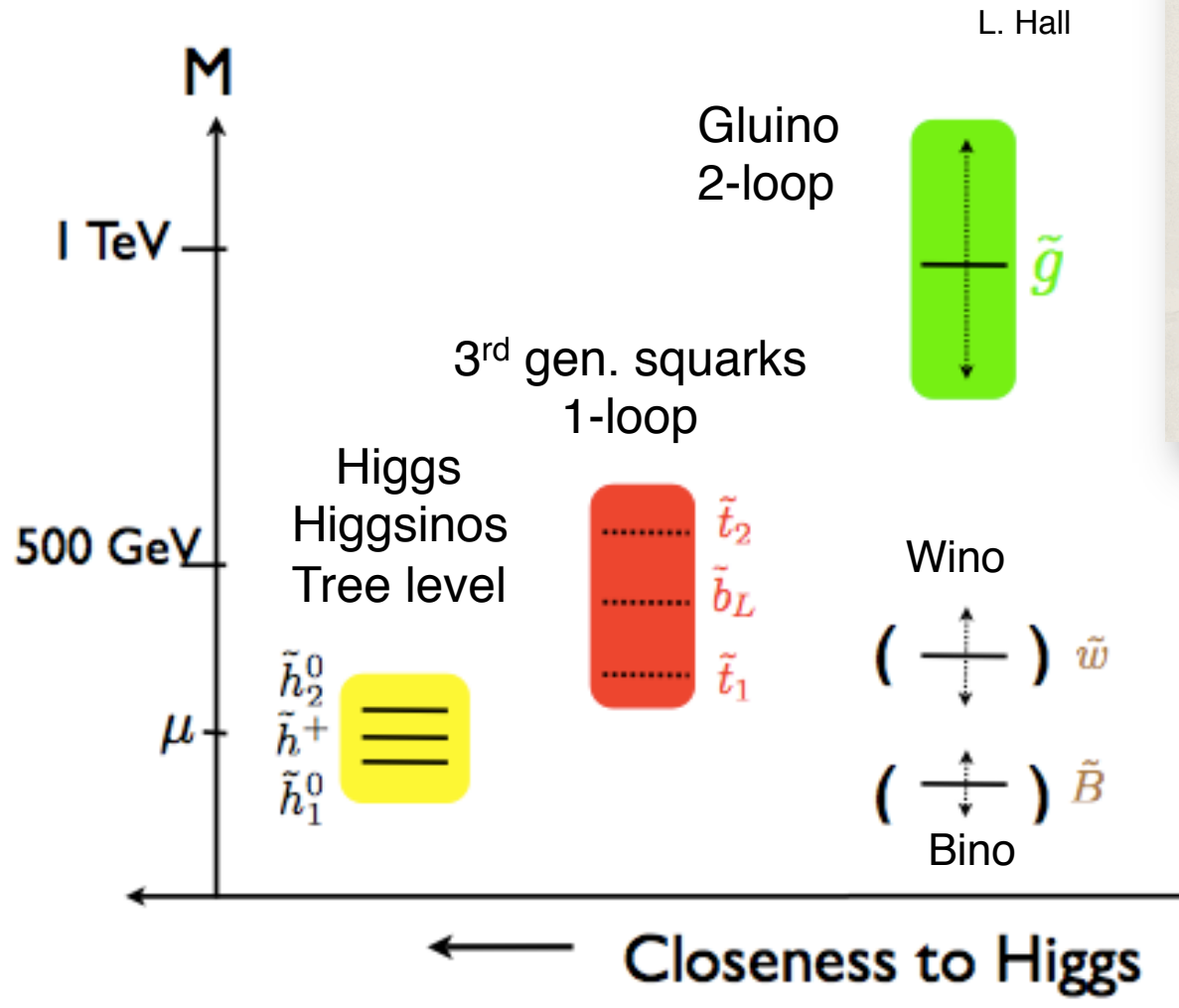
Example:  $\tilde{g}\tilde{g} \rightarrow t\bar{t}\bar{t}\bar{t}\chi_1^0\chi_1^0$

Several searches are interpreted in this particular SMS!



# (Minimal) Natural SUSY Spectrum

uchmüller

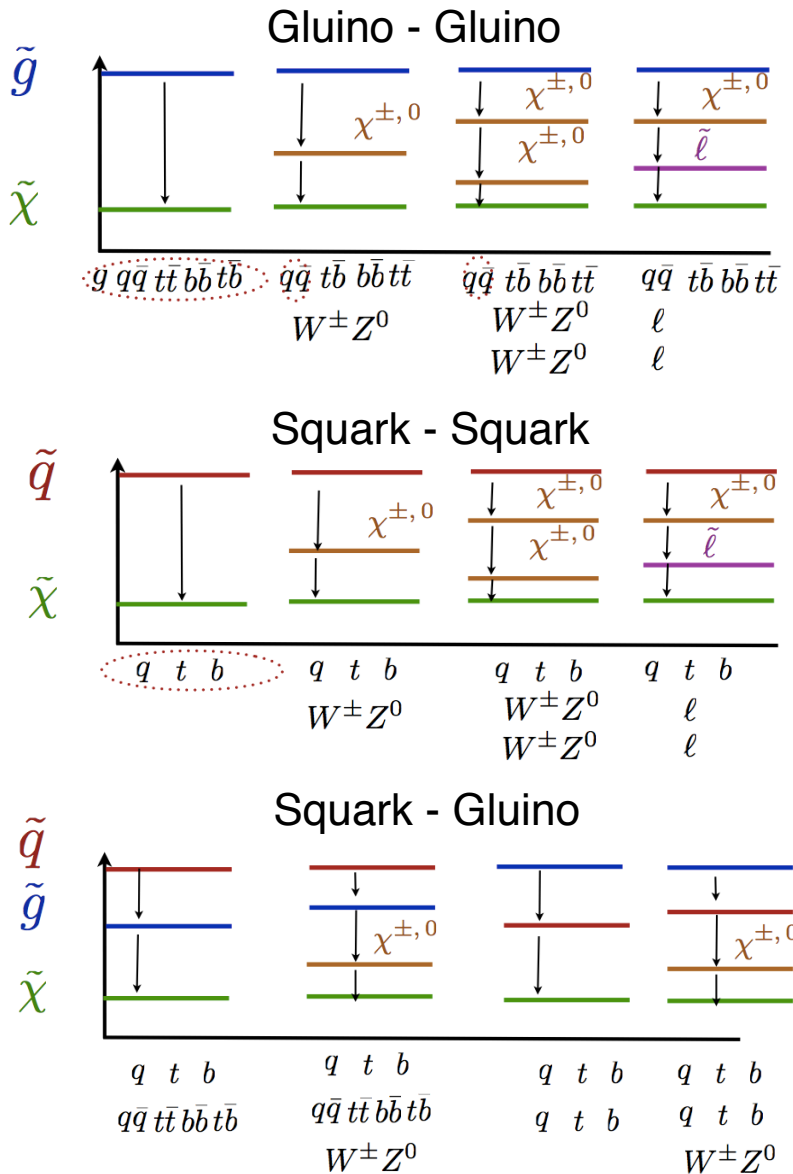


Use the argument of “naturalness” (i.e. fine-tuning) to motivate light **3<sup>rd</sup> generation squarks** (especially stop) and a rather light **gluino!**

More in Gian Giudice talk!

# Early SUSY Search Strategy at the LHC

EPS 2013 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

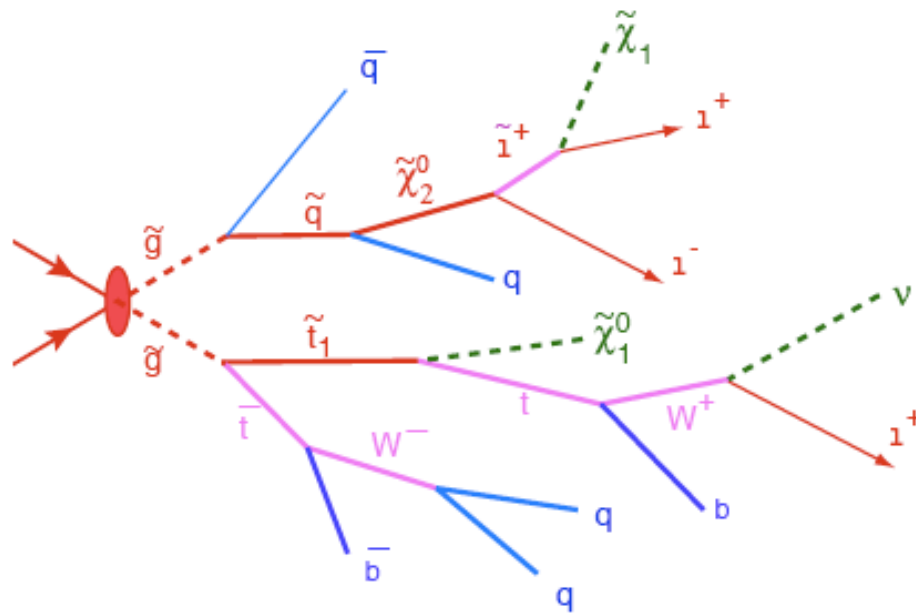
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

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

## 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)

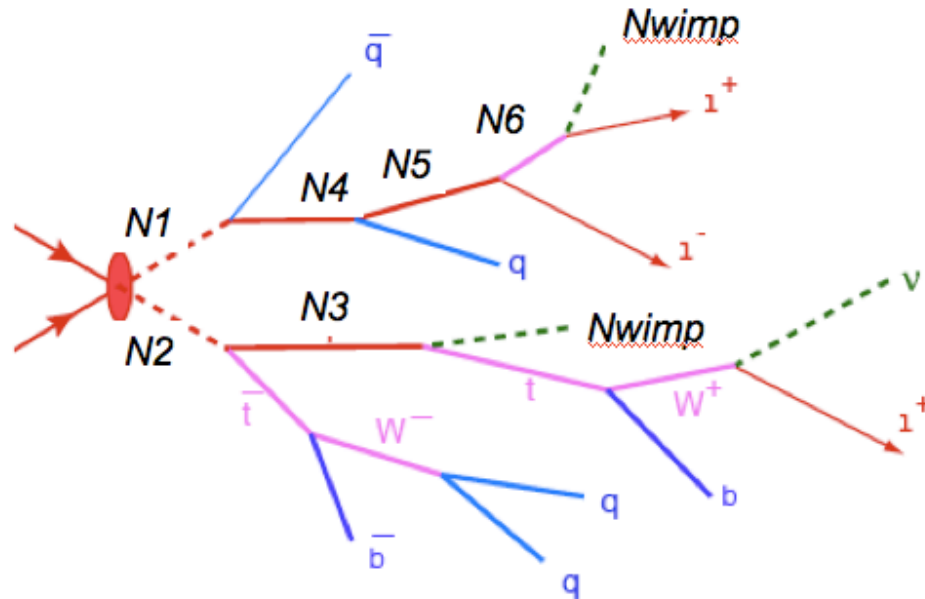
### Multi-Leptons:

- 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 *N*s (possibly via heavy SM particles like top, *W/Z*)

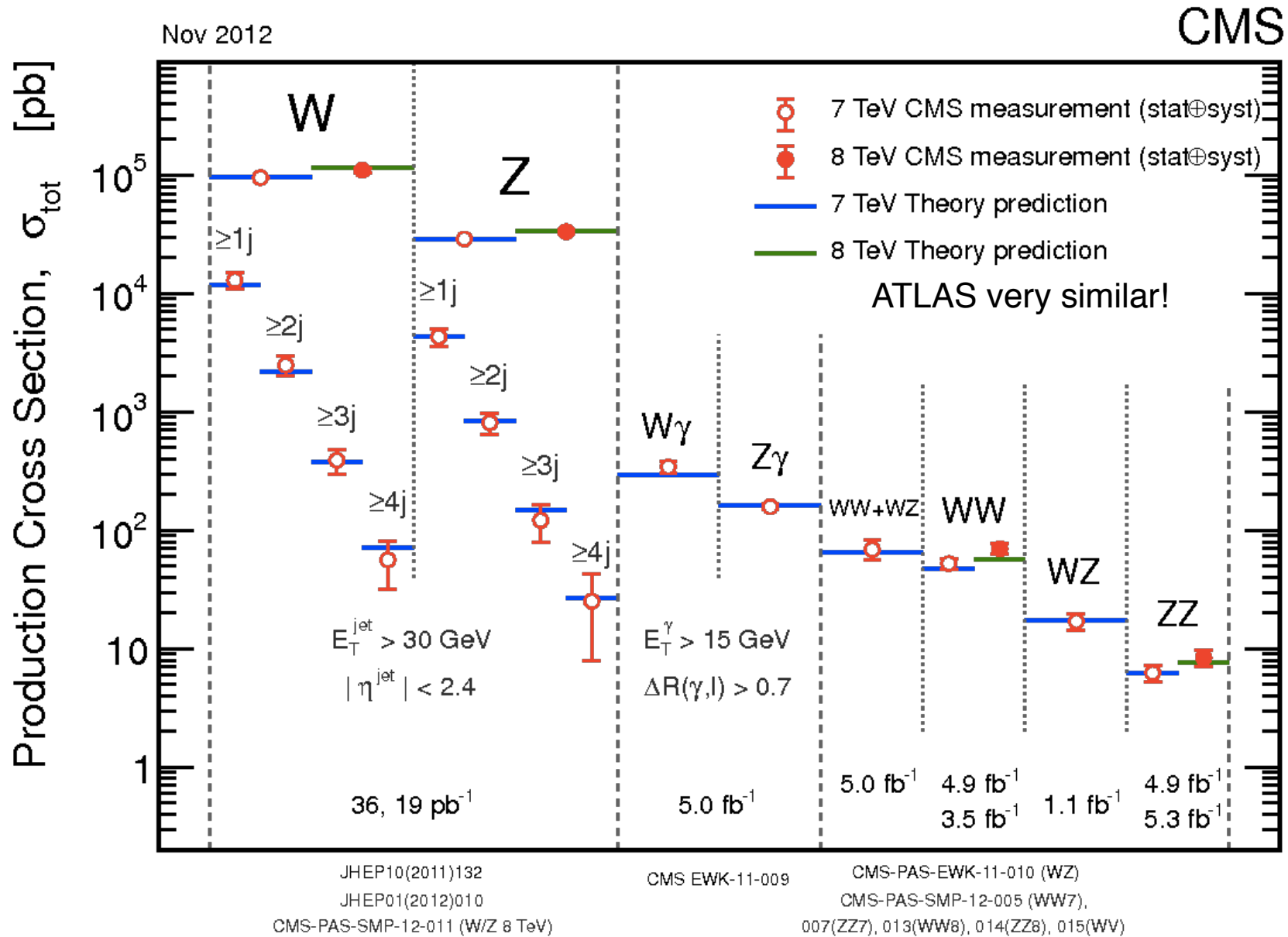
### Multi-Leptons:

- from decay of the *N*'s

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

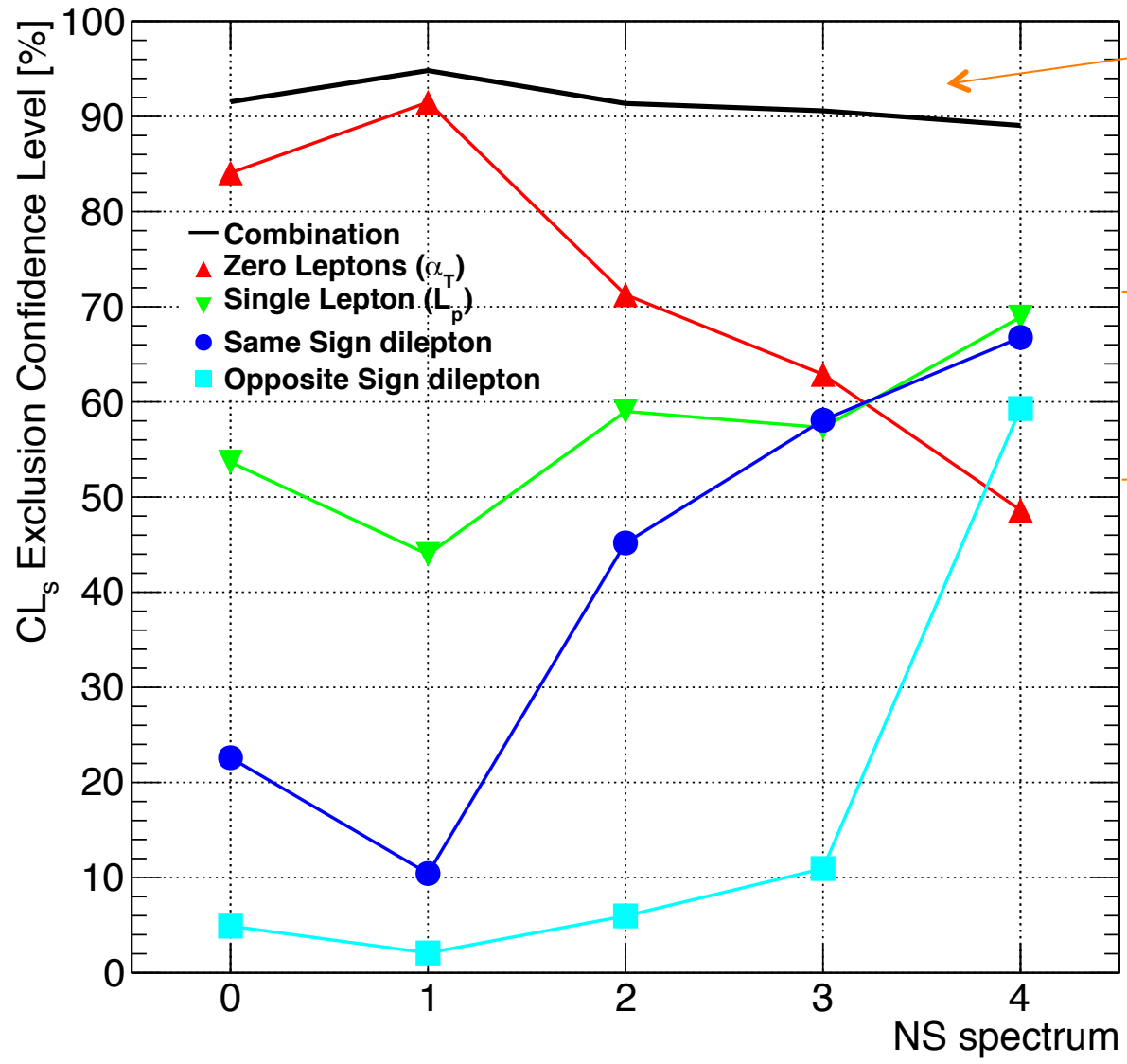
# Rediscovery of the SM at a new energy frontier

EPS 2013 Direct SUSY Searches, O. Buchmüller



# Combination vs individual search

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Combination of searches stable

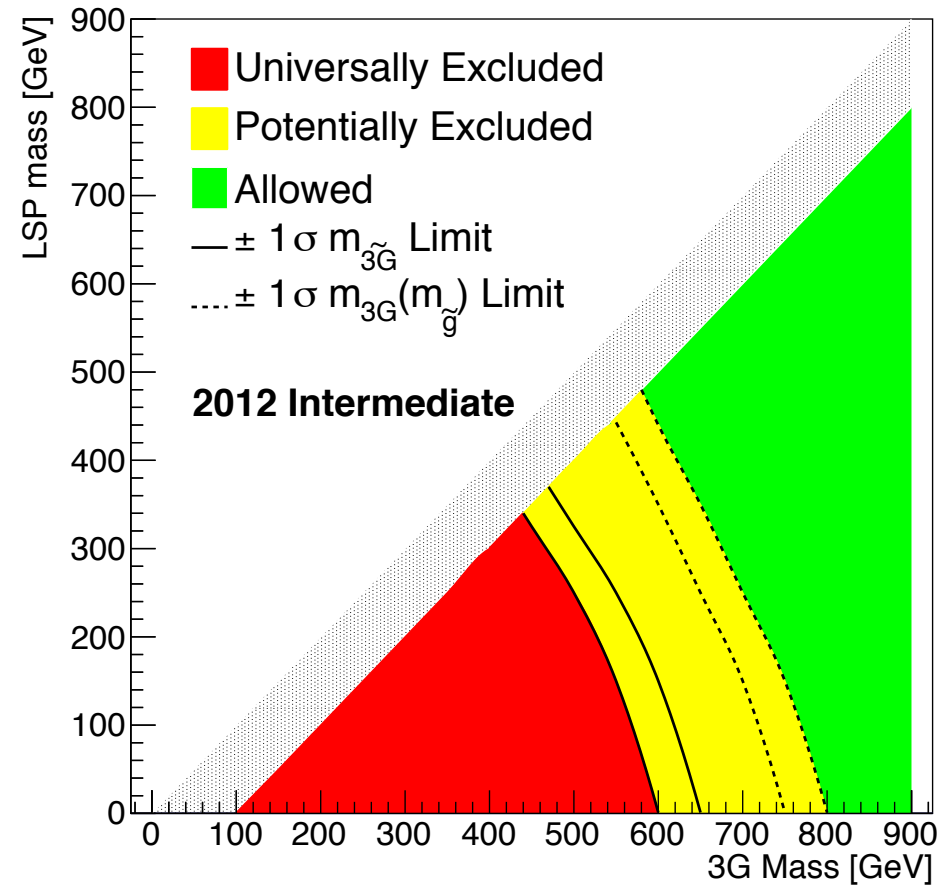
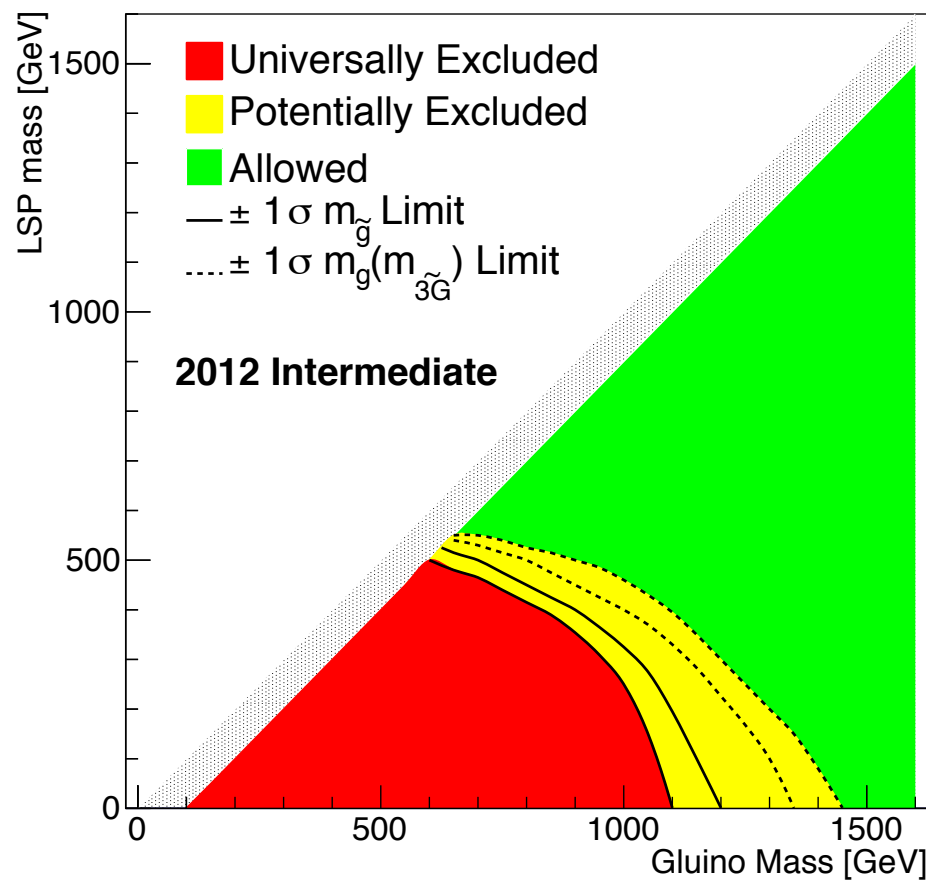
Individual searches exhibit large variations

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

# Natural SUSY: universal limits

O. Buchmüller

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  $\rightarrow$  H, H $\rightarrow$ WW, ZZ and  $\gamma\gamma$   
mainly gg: factor  $\sim 2$

SUSY – 3<sup>rd</sup> Generation:

Mass scale  $\sim$  500 GeV  
qq and gg: factor  $\sim 3$  to 6

SUSY – Squarks/Gluino:

Mass scale  $\sim$  1.5 TeV  
qq,gg,qq: factor  $\sim 40$  to 80

Z' :

Mass scale  $\sim$  5 TeV  
qq: factor  $\sim 1000$

Higgs:

**15/fb@14 TeV to match 2011/2012**  
mainly gg: factor  $\sim 2$

SUSY – 3<sup>rd</sup> Generation:

**5/fb to 10/fb@14 TeV to match 2011/2012**  
qq and gg: factor  $\sim 3$  to 6

SUSY – Squarks/Gluino:

**0.4/fb to 0.8/fb@14 TeV to match 2011/2012**  
qq,gg,qq: factor  $\sim 40$  to 80

Z' :

**0(1/pb) @14 TeV to match 2011/2012**  
qq: factor  $\sim 1000$