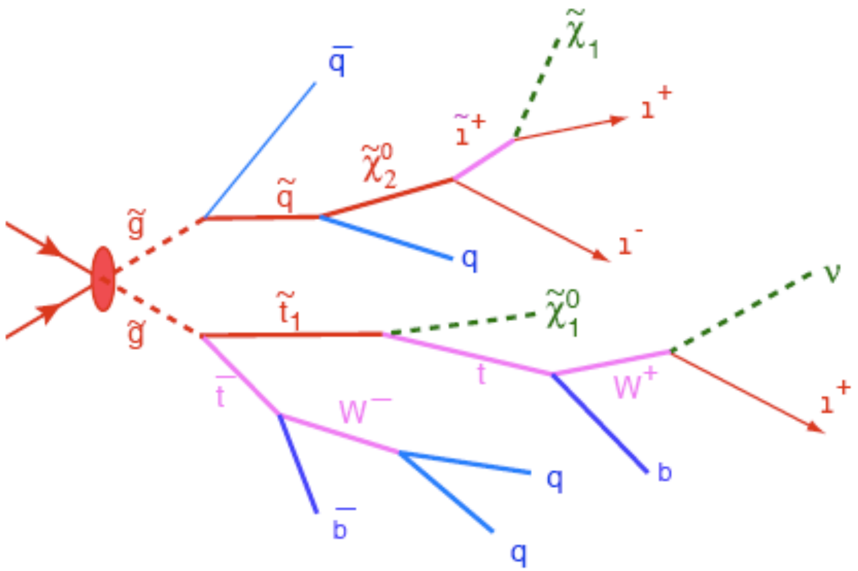
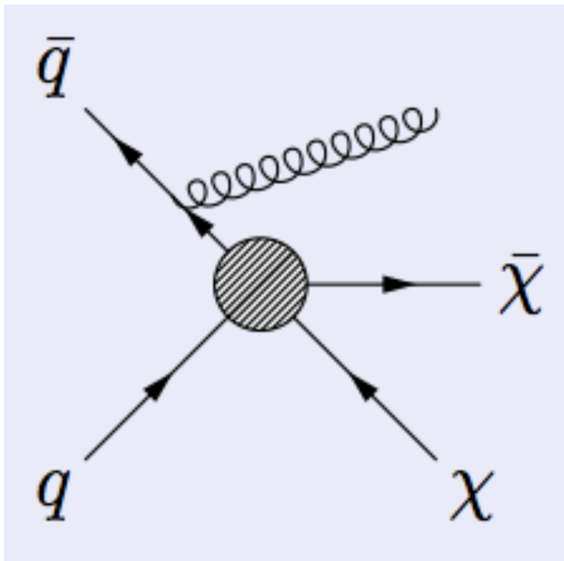
Oliver Buchmueller, Imperial College London

# SEARCHES FOR DARK MATTER PRODUCTION AT THE LHC



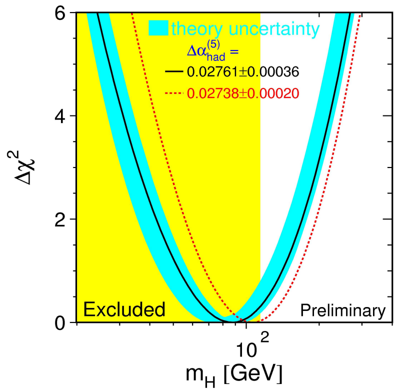



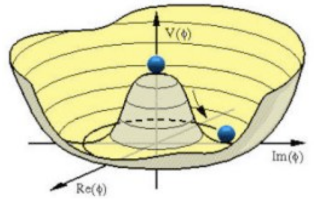
# Fundamental Open Questions in Particle Physics



## *I. What is the origin of mass?*

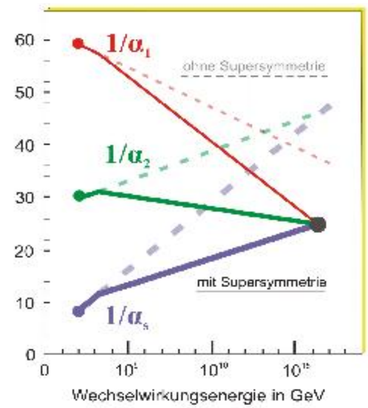
- *Why are the vector bosons Z and W are massive whereas the photon is massless?*
- *Is there a Higgs boson - or even more of them ?*

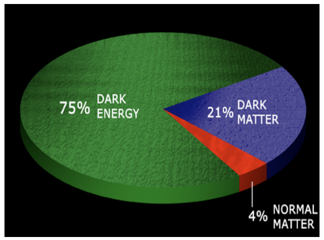



## *I. Is there a new symmetry - Supersymmetry ?*

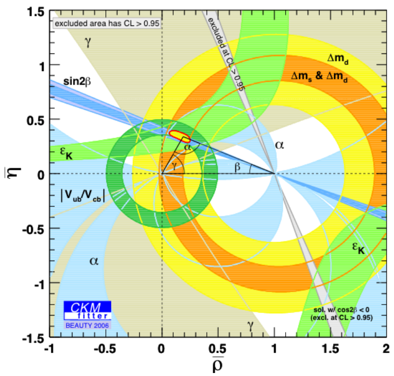
- *Can we get experimental evidence to support the Grand Unification of all fundamental forces?*
- *What is the origin of Dark Matter in the Universe?*
  → *Is a fundamental particle responsible for it?*

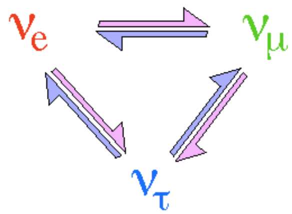



## *III. What is the origin of the matter-anti-matter asymmetry in our Universe?*

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



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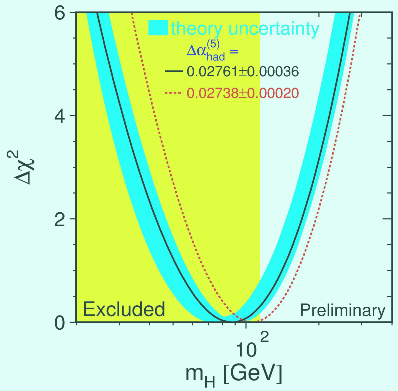


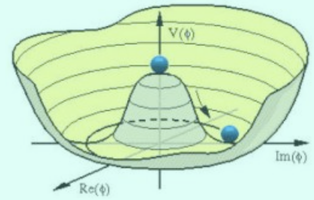


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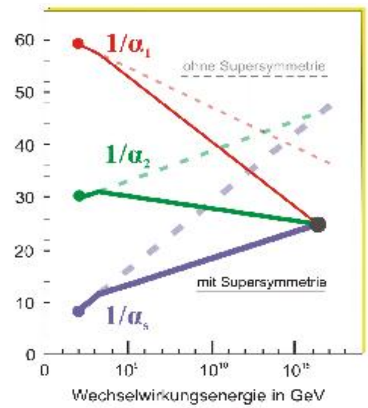


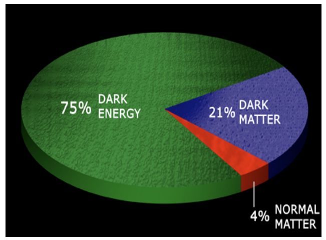


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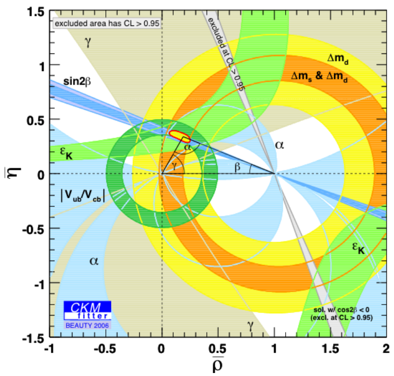


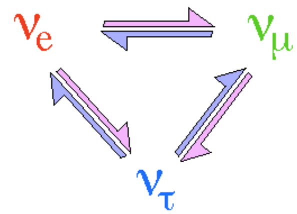

# The Large Hadron Collider at CERN

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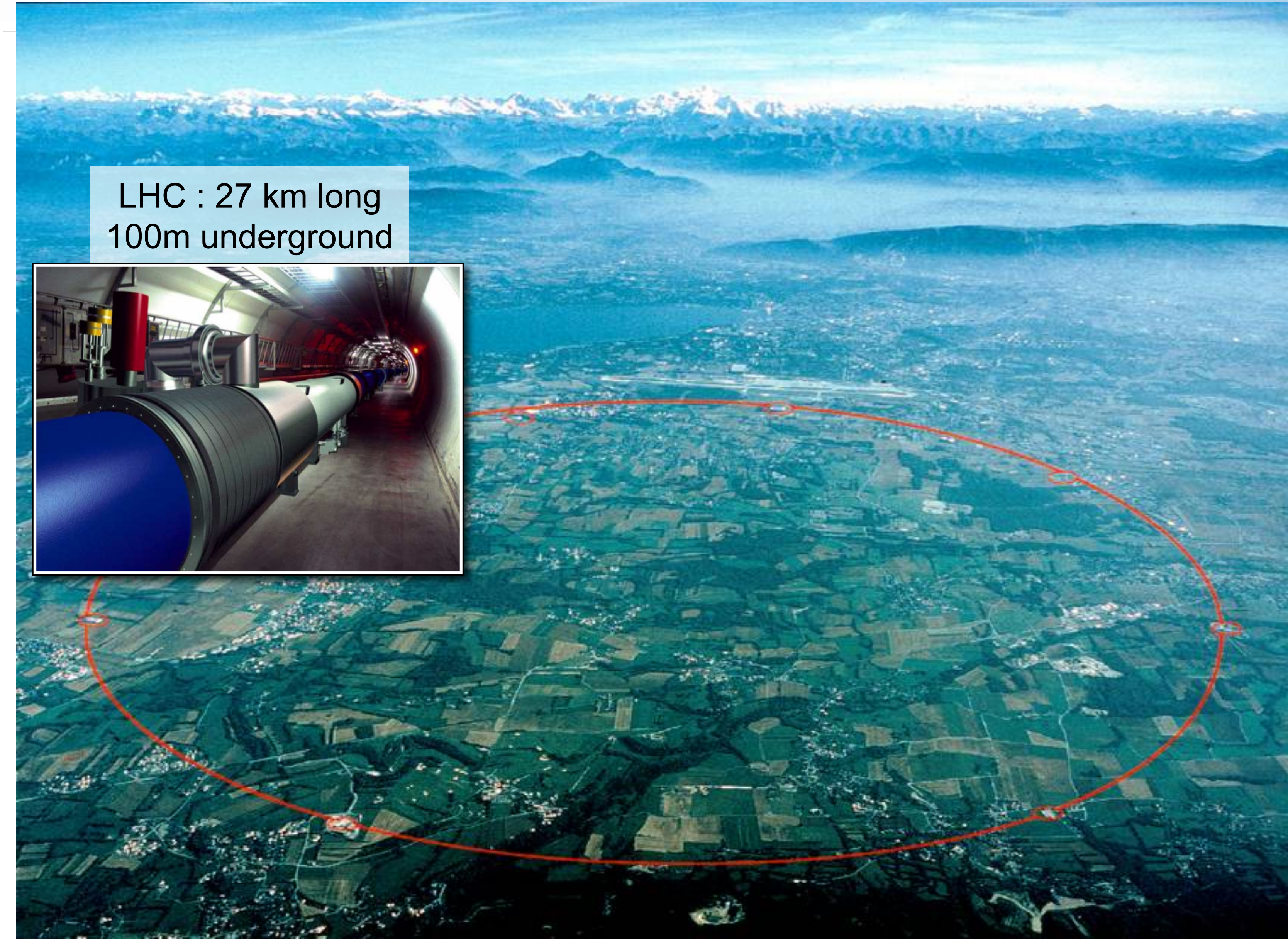

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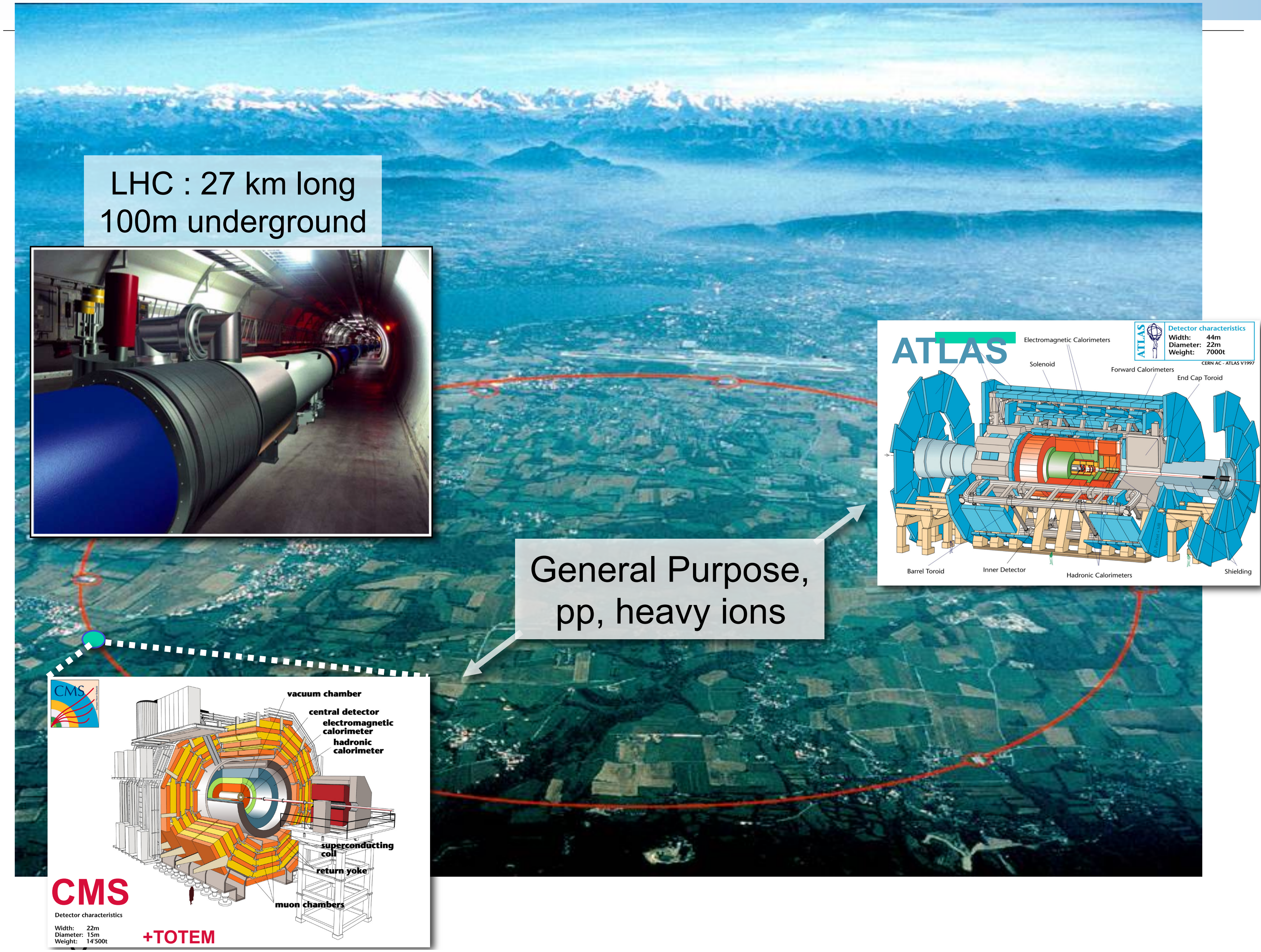

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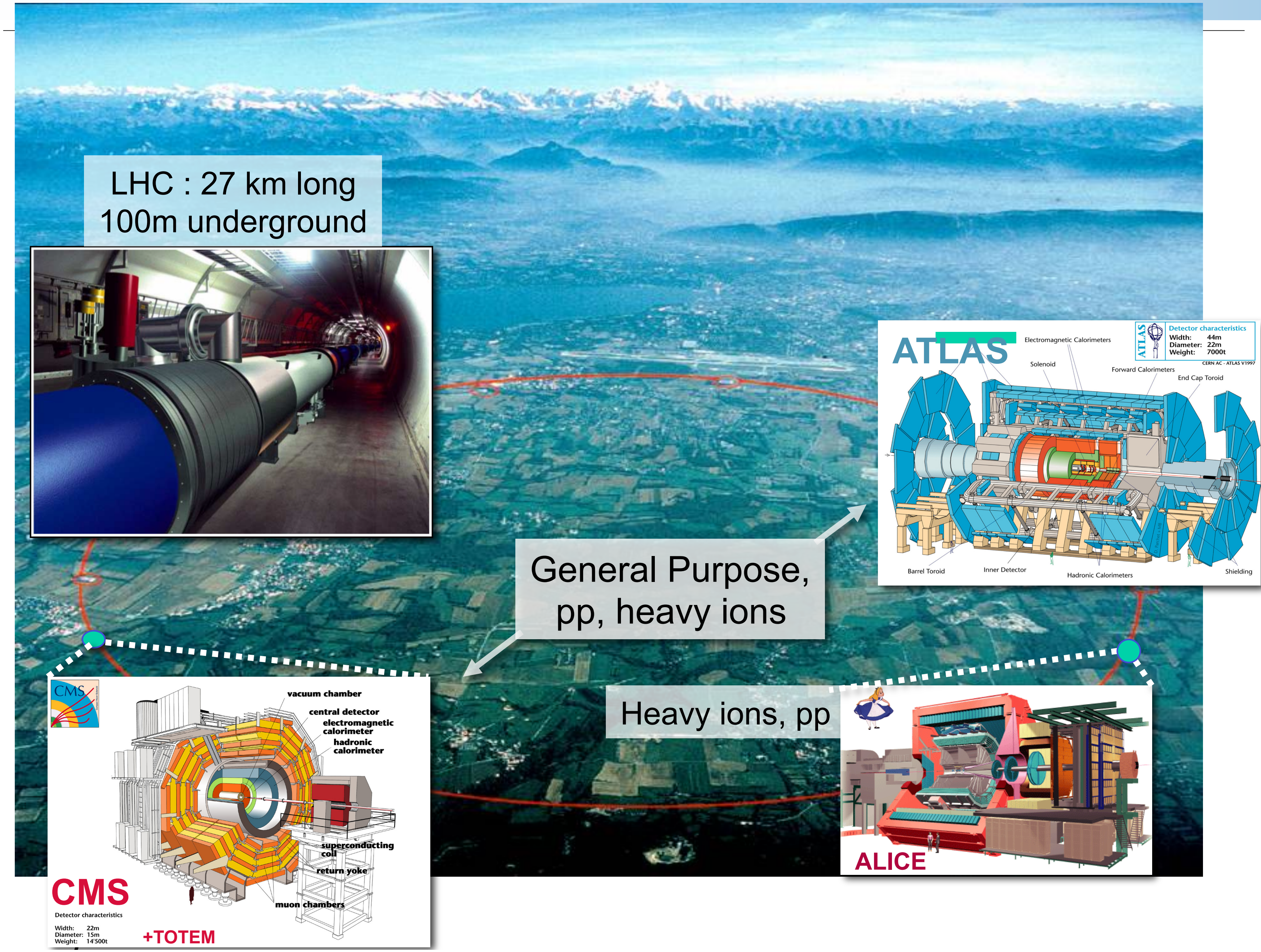

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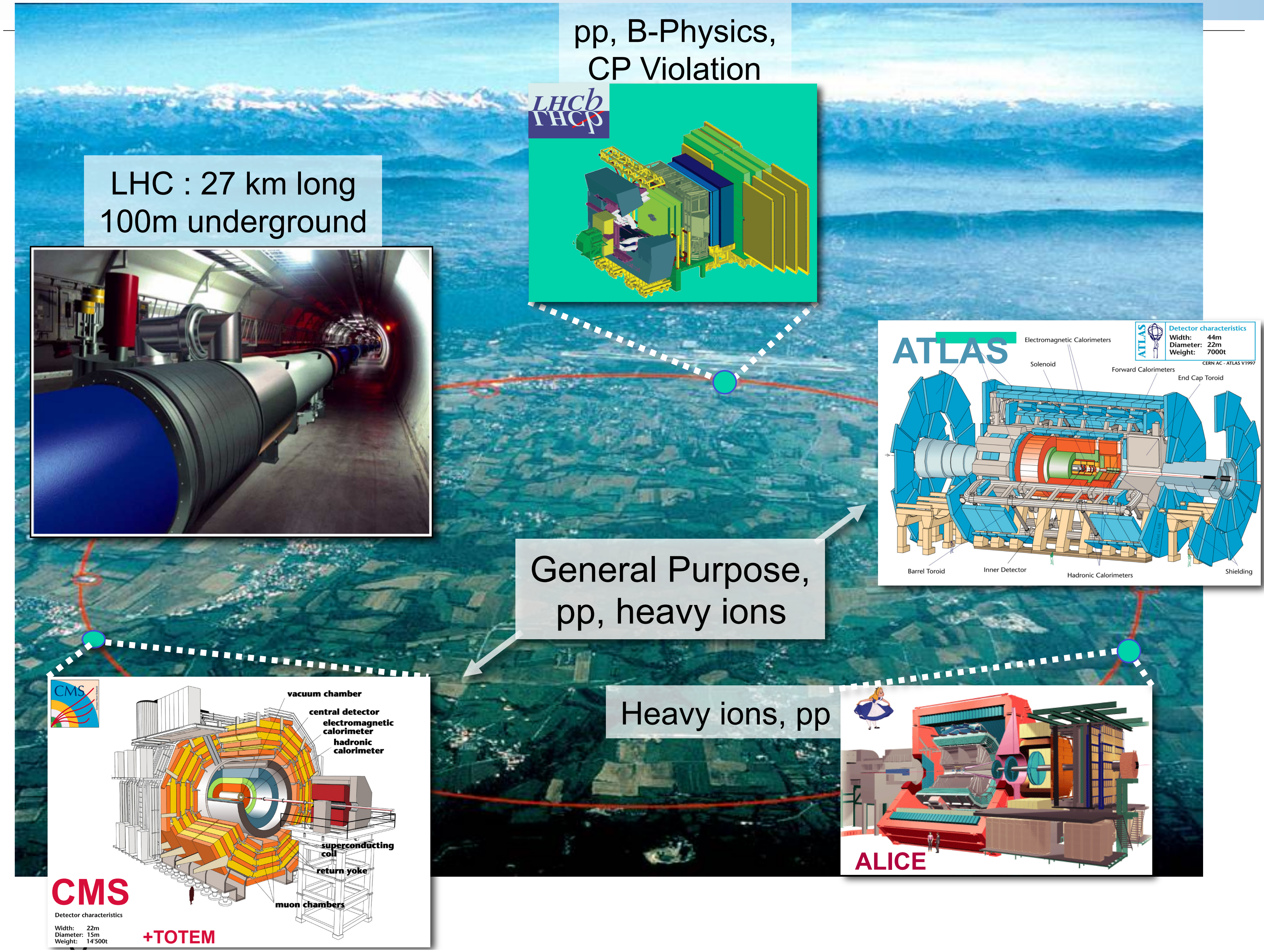
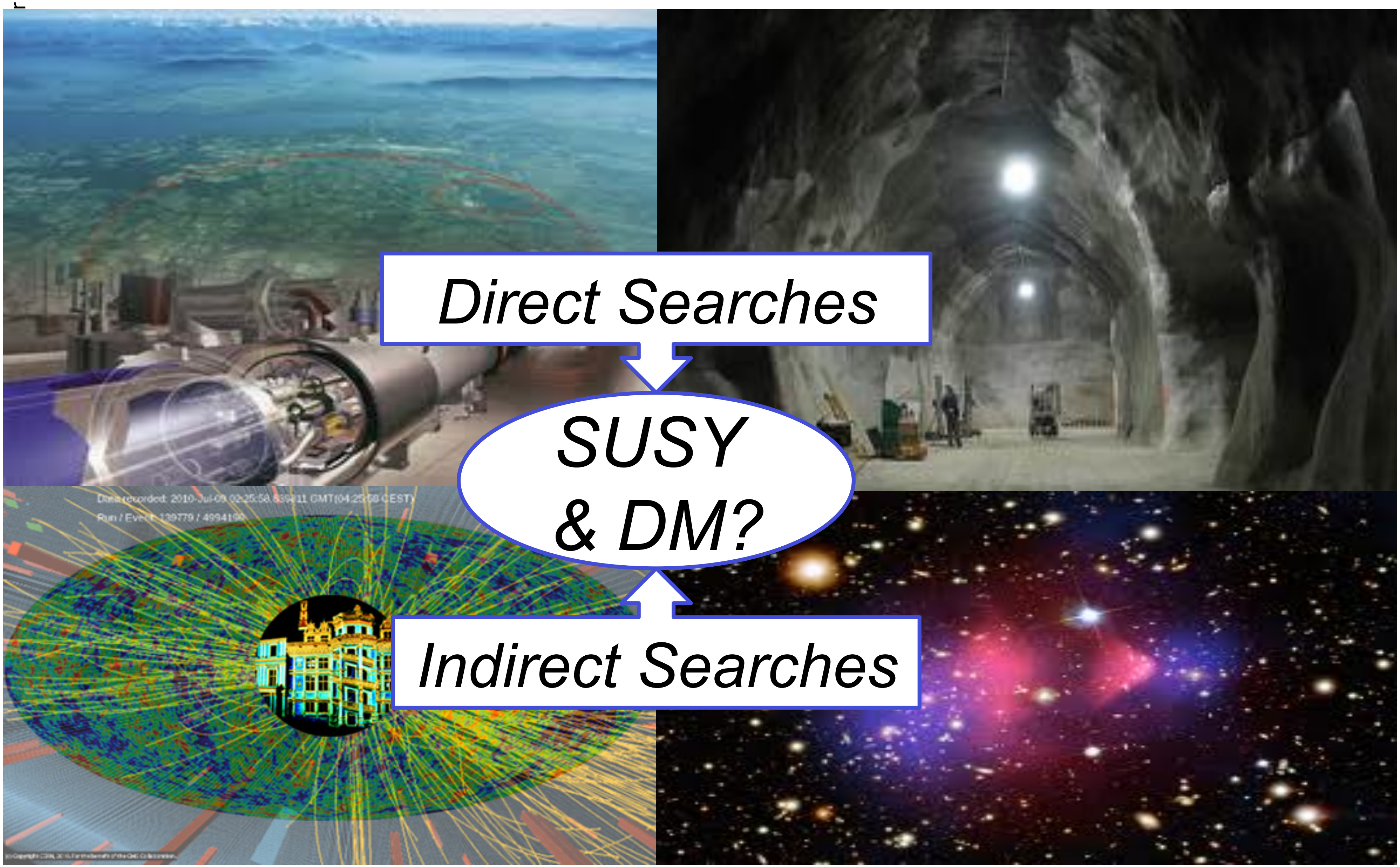


# Searches for SUSY (& DM)



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# Searches for SUSY (& DM)

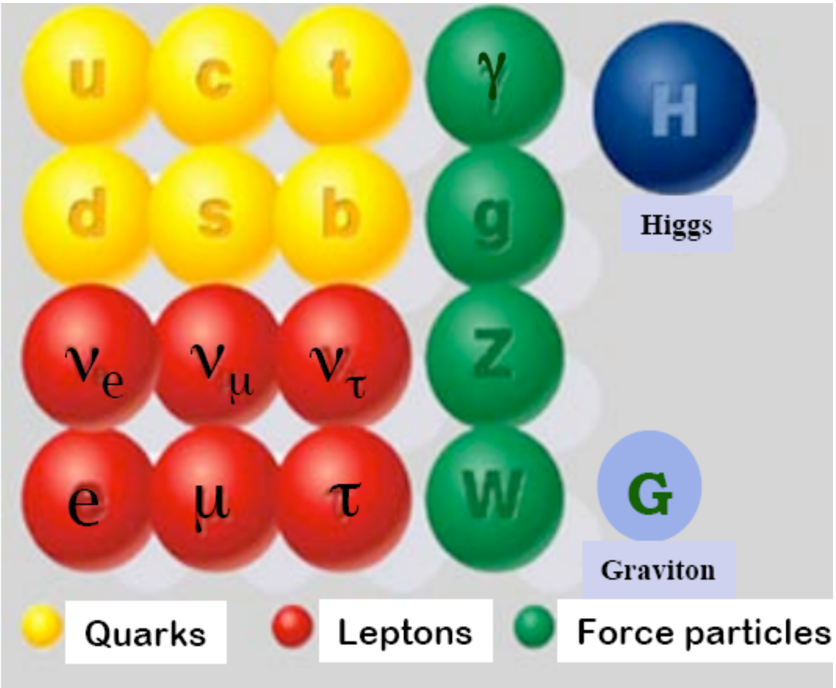
# Supersymmetry

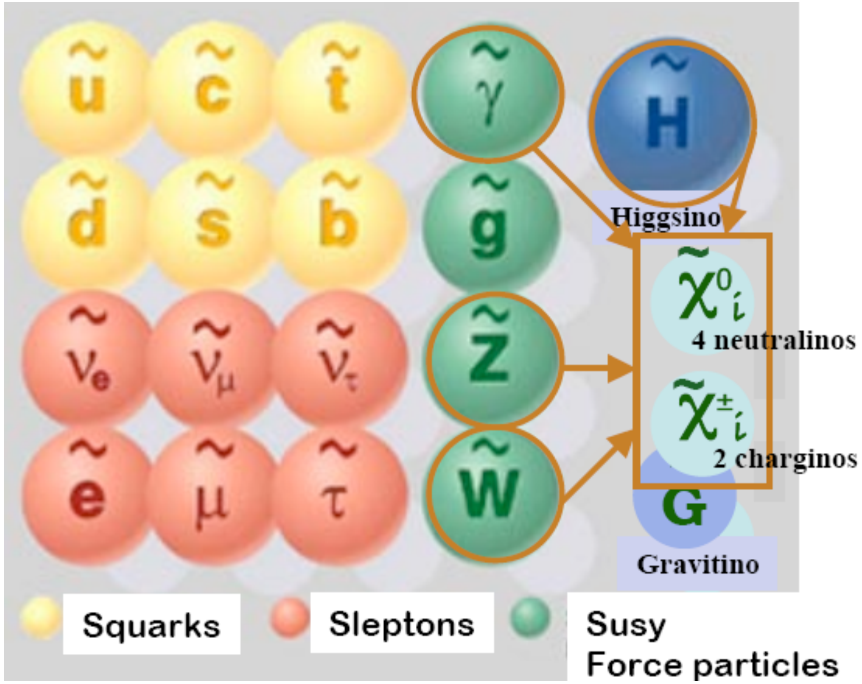


Extension of the Standard Model: Introduce a new symmetry

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

**Standard Model particles** **SUSY particles**




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

- 1 SUSY particles

R-parity conservation:

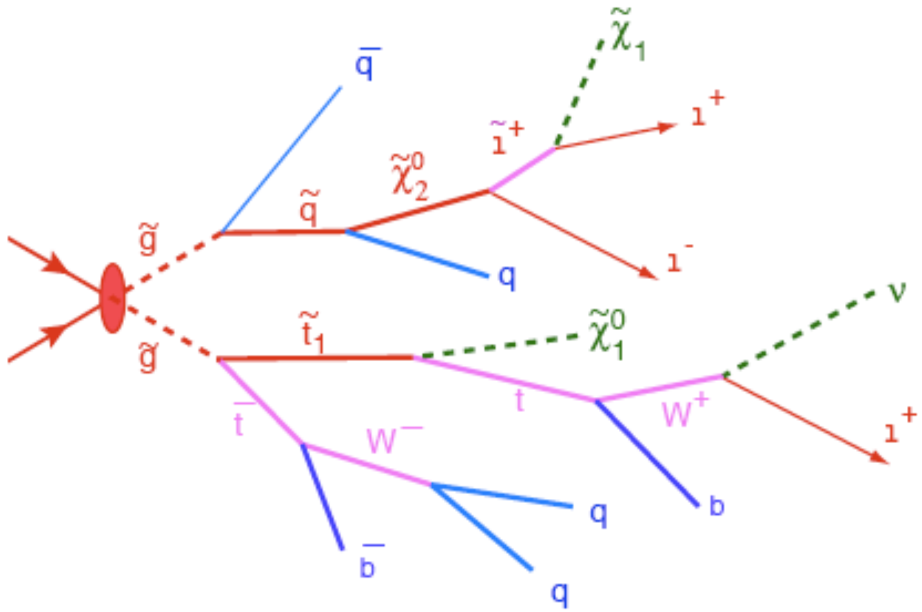
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

# What do we call a “SUSY search”?



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

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



***Missing Energy:***
- *from LSP*

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

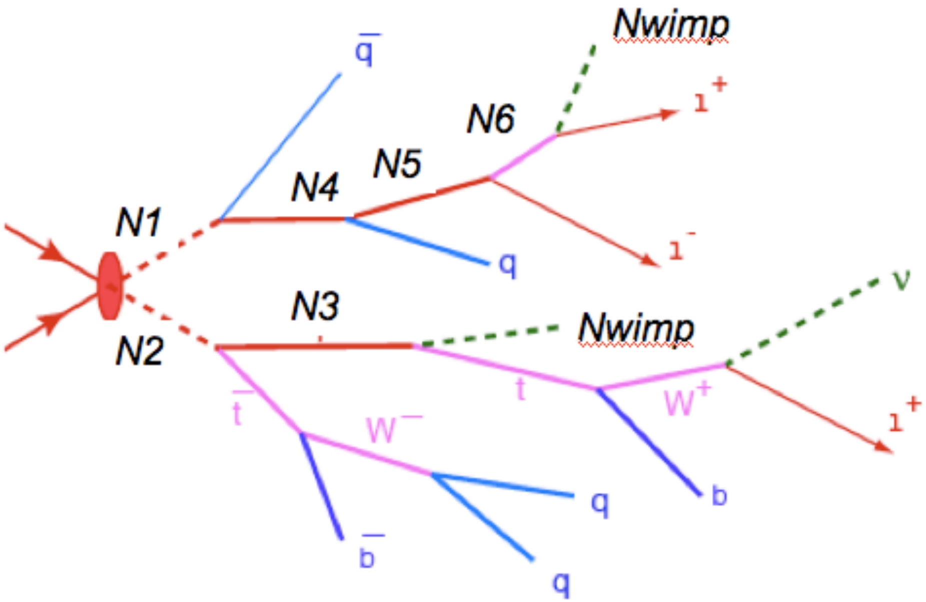
***Multi-Leptons:***
- *from decay of charginos/neutralios*

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

# What is its experimental signature?



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




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

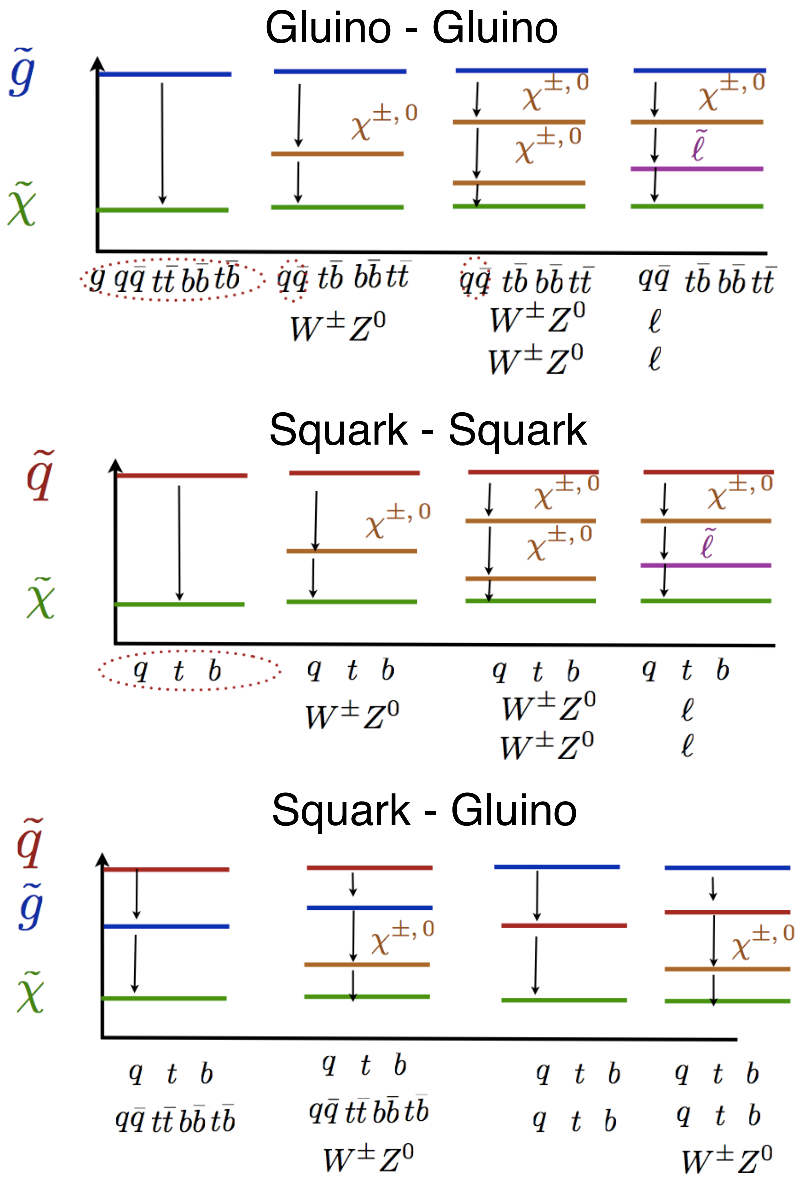
***Multi-Jet:***
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

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

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

# Early SUSY Search Strategy at the LHC






## Search Signatures

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

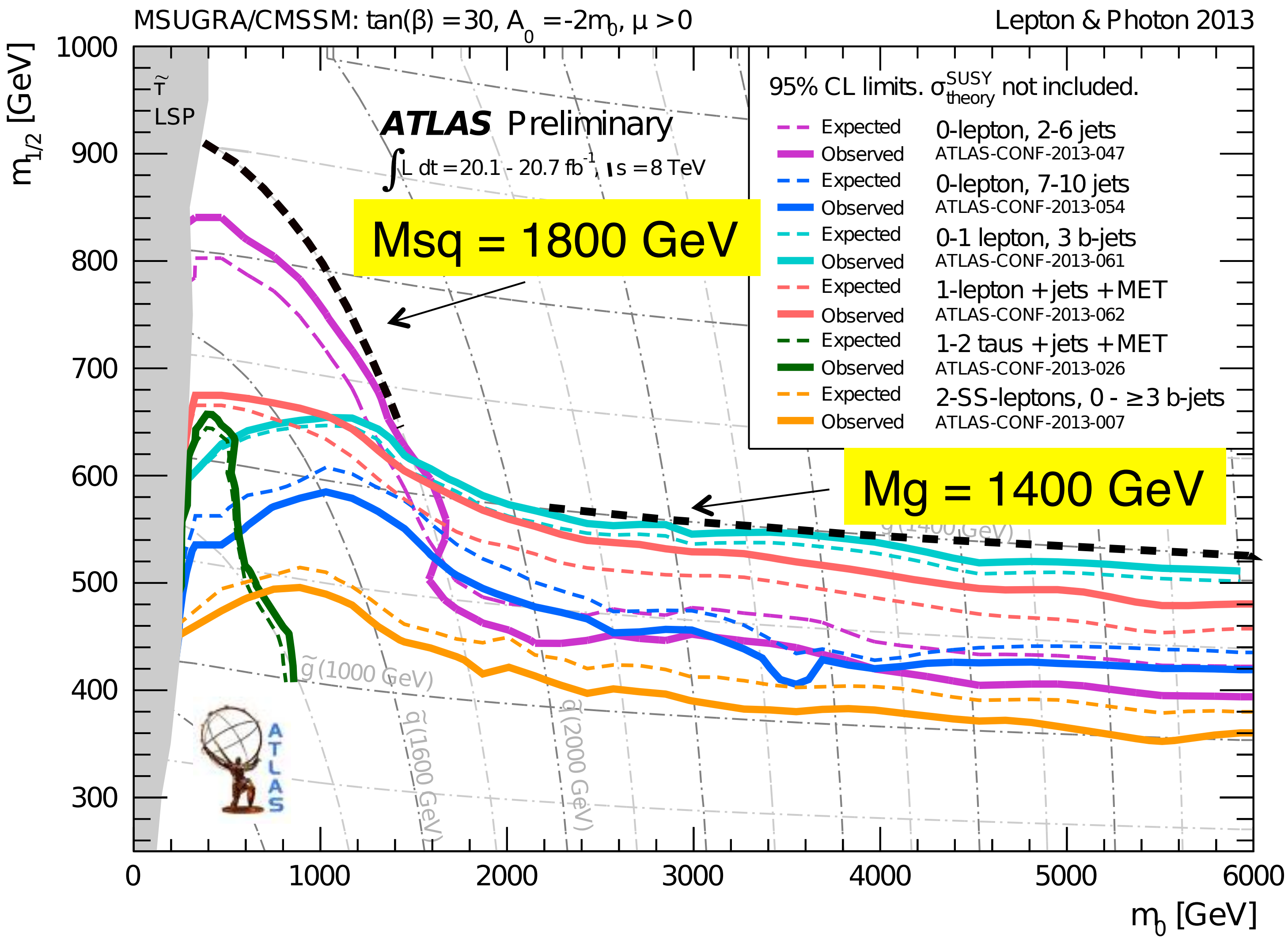
**References Analyses**

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

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

# Inclusive SUSY Searches in 2013





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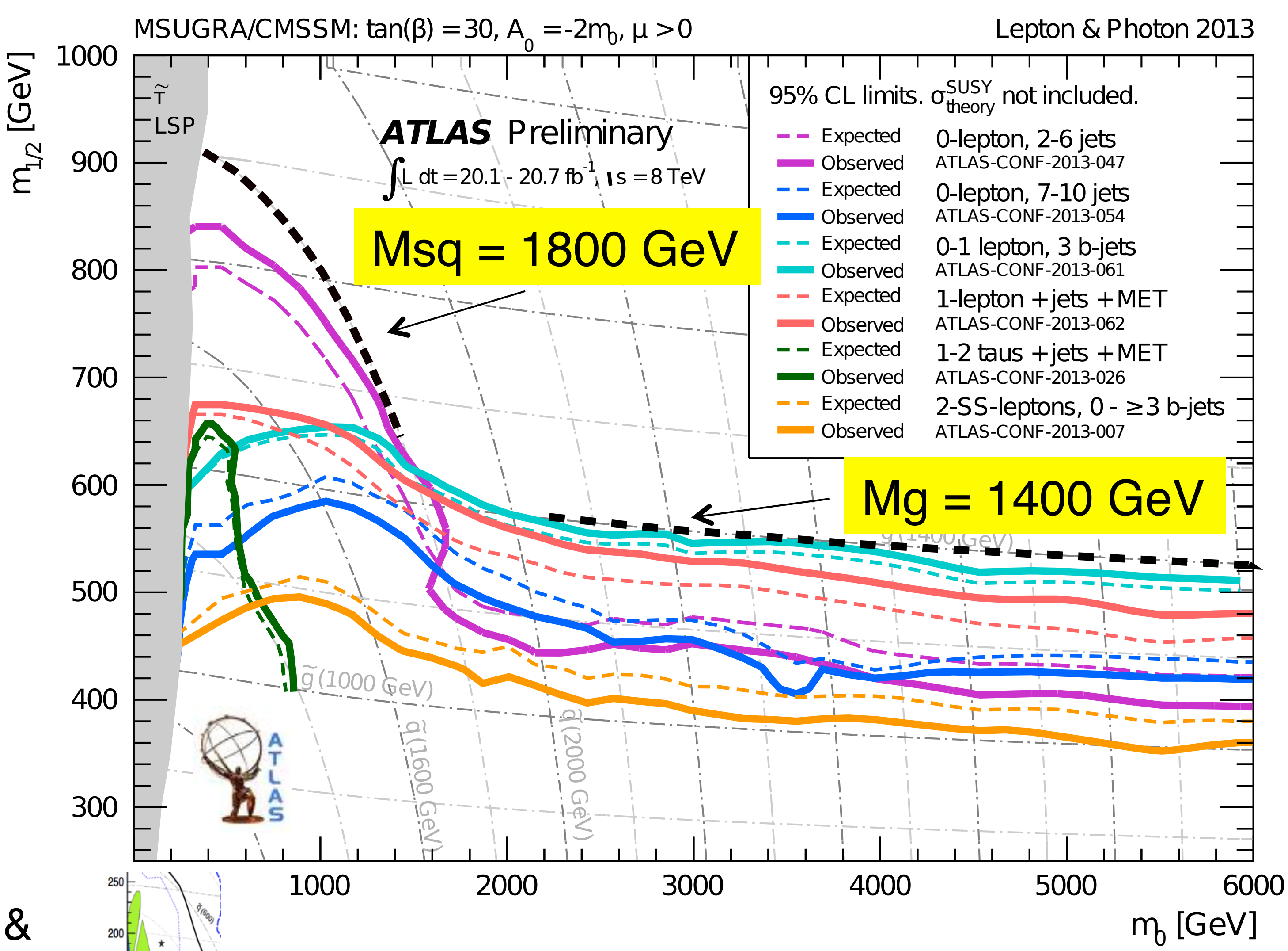
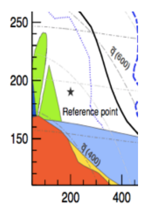


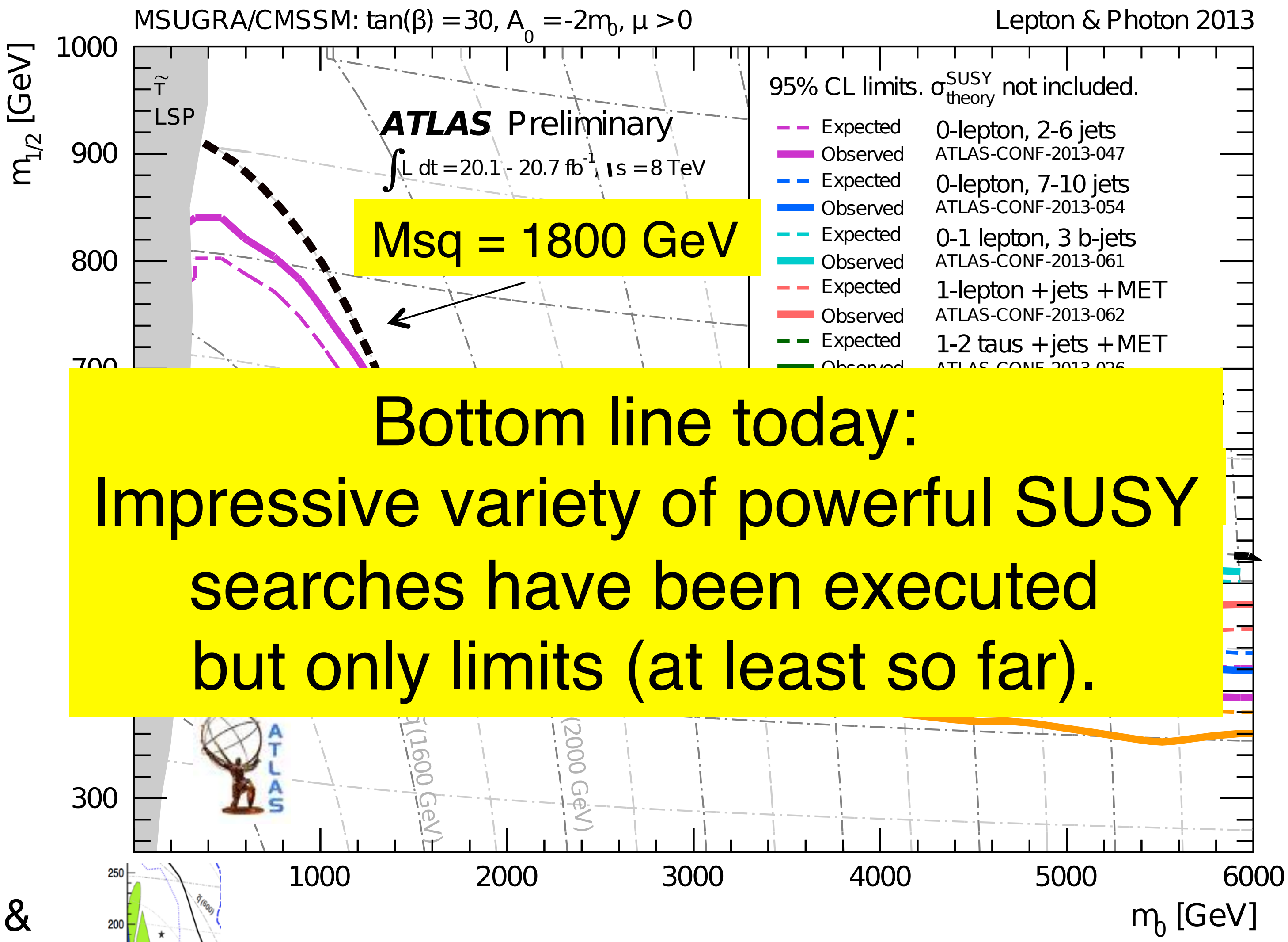

LEP & Tevatron




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

# Inclusive SUSY Searches in 2013

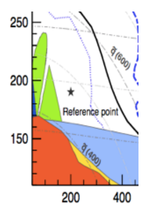





Msq = 1800 GeV

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

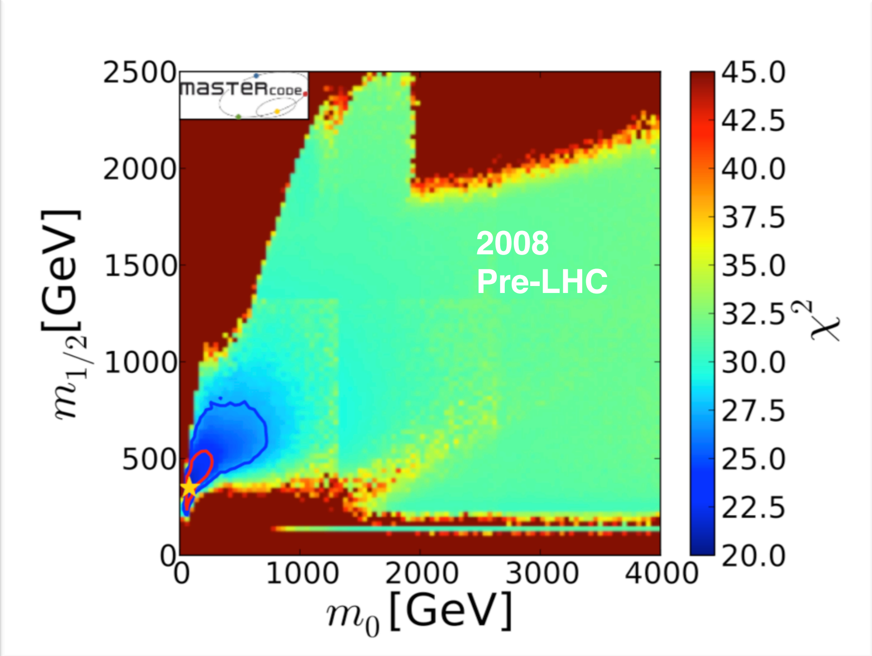
LEP & Tevatron



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

# CMSSM: Evolution with time






$X^2$ increase from
bluish to reddish

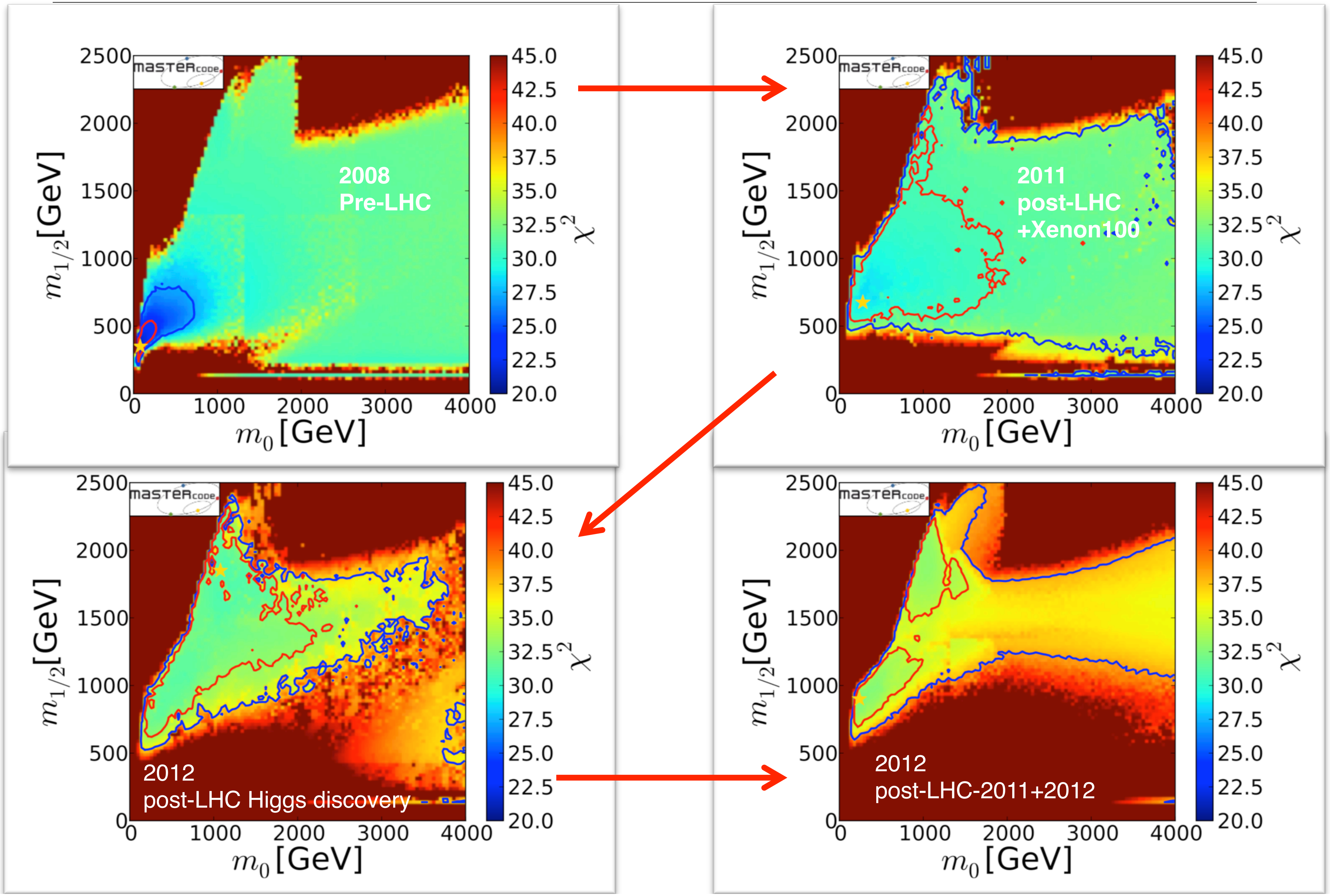
Source:
http://mastercode.web.cern.ch/mastercode/

| Observable | Source Th./Ex. | Constraint | $\Delta\chi^2$ (CMSSM) | $\Delta\chi^2$ (NUHM1) | $\Delta\chi^2$ ("SM") |
|---|---|---|---|---|---|
| $m_t$ [GeV] | [43] | $173.2 \pm 0.90$ | 0.05 | 0.06 | - |
| $\Delta\alpha_{had}^{(5)}(M_Z)$ | [42] | $0.02749 \pm 0.00010$ | 0.009 | 0.004 | - |
| $M_Z$ [GeV] | [44] | $91.1875 \pm 0.0021$ | $2.7\times10^{-5}$ | 0.26 | - |
| $\Gamma_Z$ [GeV] | [26] / [44] | $2.4952 \pm 0.0023 \pm 0.001_{SUSY}$ | 0.078 | 0.047 | 0.14 |
| $\sigma_{had}^0$ [nb] | [26] / [44] | $41.540 \pm 0.037$ | 2.50 | 2.57 | 2.54 |
| $R_l$ | [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 |
| $A_\ell(P_\tau)$ | [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 |
| $A_\ell$(SLD) | [26] / [44] | $0.1513 \pm 0.0021$ | 3.16 | 3.03 | 3.51 |
| $\sin^2\theta_w^\ell(Q_{fb})$ | [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] / [55,56] | $> 114.4[\pm1.5_{SUSY}]$ | 0.0 | 0.0 | 0.0 |
| $BR_{b\to s\gamma}^{EXP/SM}$ | [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 |
| $BR_{B\to\tau\nu}^{EXP/SM}$ | [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 |
| $BR_{B\to X_s\ell\ell}^{EXP/SM}$ | [47] / [46] | $0.99 \pm 0.32$ | 0.02 | $\ll 0.01$ | $\ll 0.01$ |
| $BR_{K\to\mu\nu}^{EXP/SM}$ | [29] / [48] | $1.008 \pm 0.014_{EXP+TH}$ | 0.39 | 0.42 | 0.33 |
| $BR_{K\to\pi\nu\bar\nu}^{EXP/SM}$ | [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 |
| $\frac{\Delta M_{B_s}^{EXP/SM}}{\Delta M_{B_d}^{EXP/SM}}$ | [29] / [46,51,52] | $1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$ | $\ll 0.01$ | 0.33 | $\ll 0.01$ |
| $\Delta\epsilon_K^{EXP/SM}$ | [49] / [51,52] | $1.08 \pm 0.14_{EXP+TH}$ | 0.27 | 0.37 | 0.33 |
| $\Omega_{CDM}h^2$ | [31] / [13] | $0.1120 \pm 0.0056 \pm 0.012_{SUSY}$ | $8.4\times10^{-4}$ | 0.1 | N/A |
| $\sigma_p^{SI}$ | [25] | $(m_{\chi_1^0}, \sigma_p^{SI})$ plane | 0.13 | 0.13 | N/A |
| jets + $\not{E}_T$ | [18,20] | $(m_0, m_{1/2})$ plane | 1.55 | 2.20 | N/A |
| $H/A, H^\pm$ | [21] | $(M_A, \tan\beta)$ plane | 0.0 | 0.0 | N/A |
| Total $\chi^2$/d.o.f. p-values | All | All | 28.8/22 15% | 27.3/21 16% | 32.7/23 (21.5/22) 9% (49%) |

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

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

# CMSSM: Evolution with time



# SUSY Status – post 7 TeV LHC data

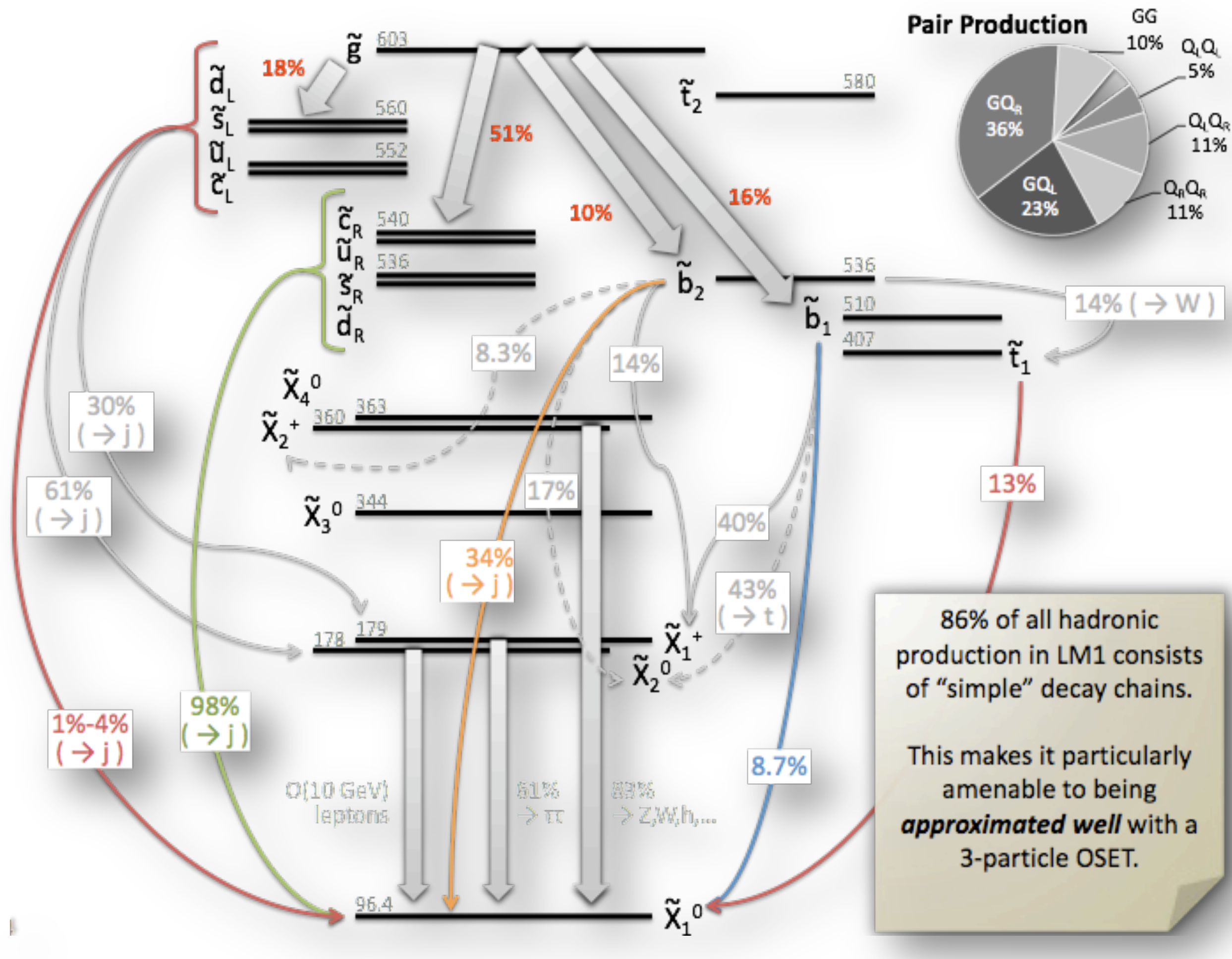


- Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!
- Experiments define new benchmarks and less complex SUSY models in order to present the interpretation of their searches.
- Aided by the discovery of a Higgs boson, the focus of the experimental search strategy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

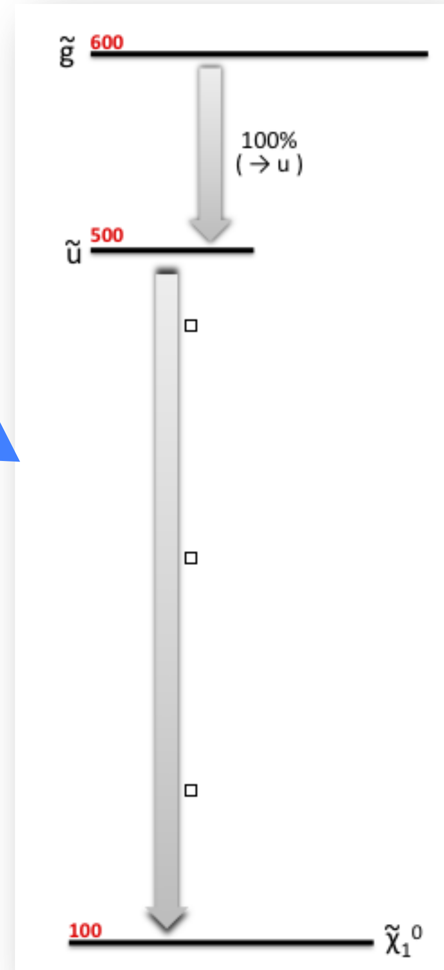
# Interpretation in Simplified Models



CMSSM




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

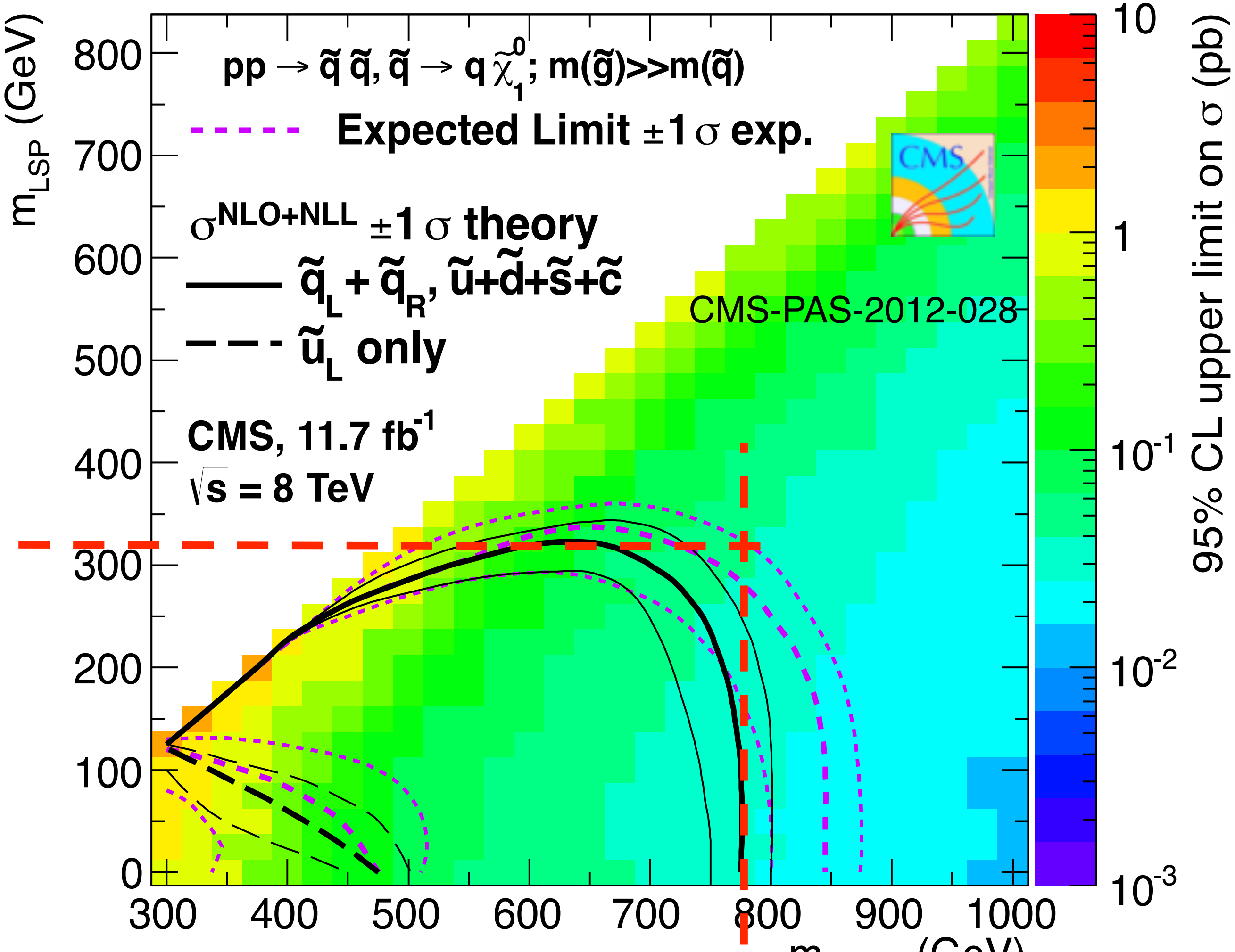


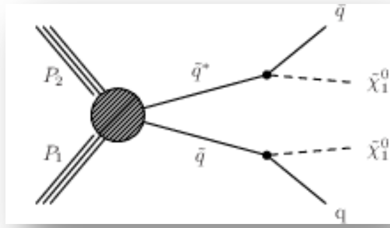

**Simplified model spectrum (SMS)**
with 3 particles, 2 decay modes

# SMS: a few interesting features



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



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

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

Assumes 100% BR for decay chain considered.

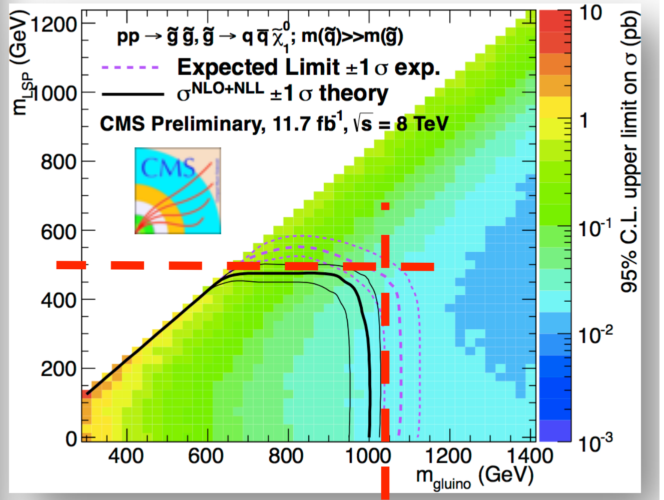
# How to summarize SMS limits?



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

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

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




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

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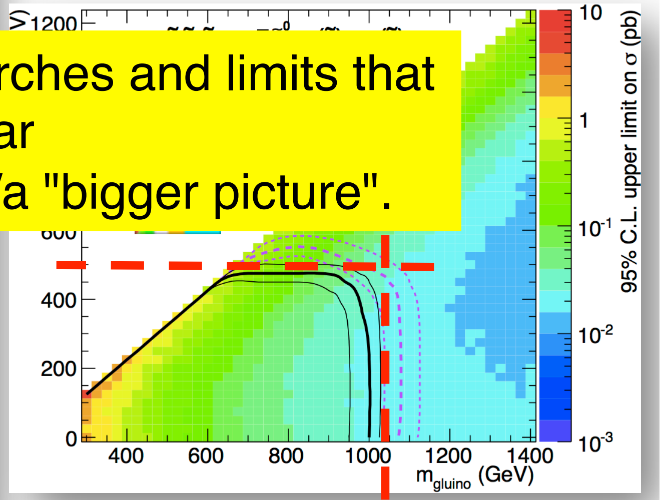
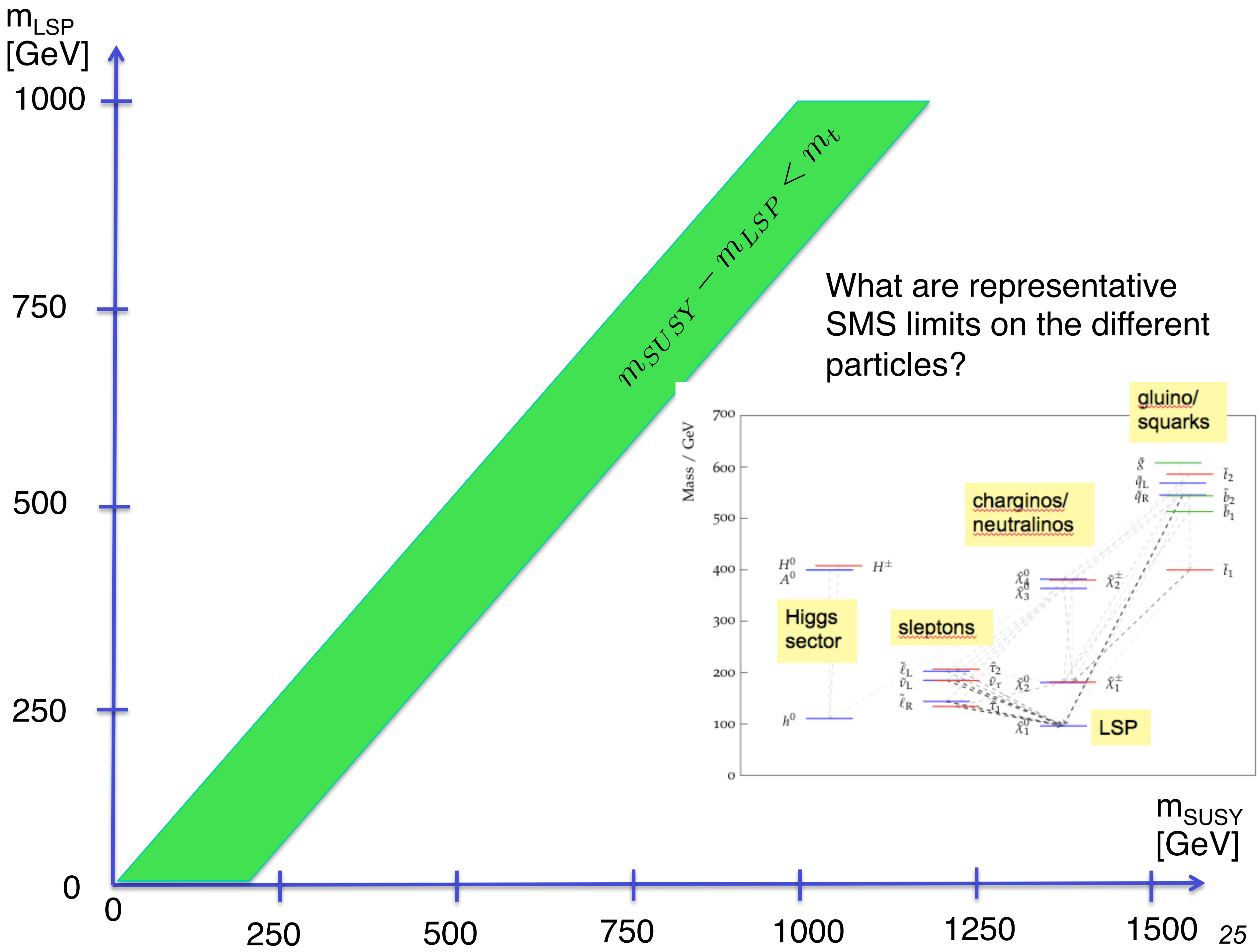
| Model | Assumption | $m_{\tilde{q}}$ | $m_{\tilde{g}}$ |
|---|---|---|---|
| | $m_{\tilde{q}} \approx m_{\tilde{g}}$ | 1400 | 1400 |
| CMSSM | all m… | | 800 |
| Simpli… | | | |
| Simplified model $\tilde{q}\bar{\tilde{q}}$ | $m_{\tilde{\chi}_1^0} = 0$ | 750 | - |
| | $m_{\tilde{\chi}_1^0} > 250$ |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

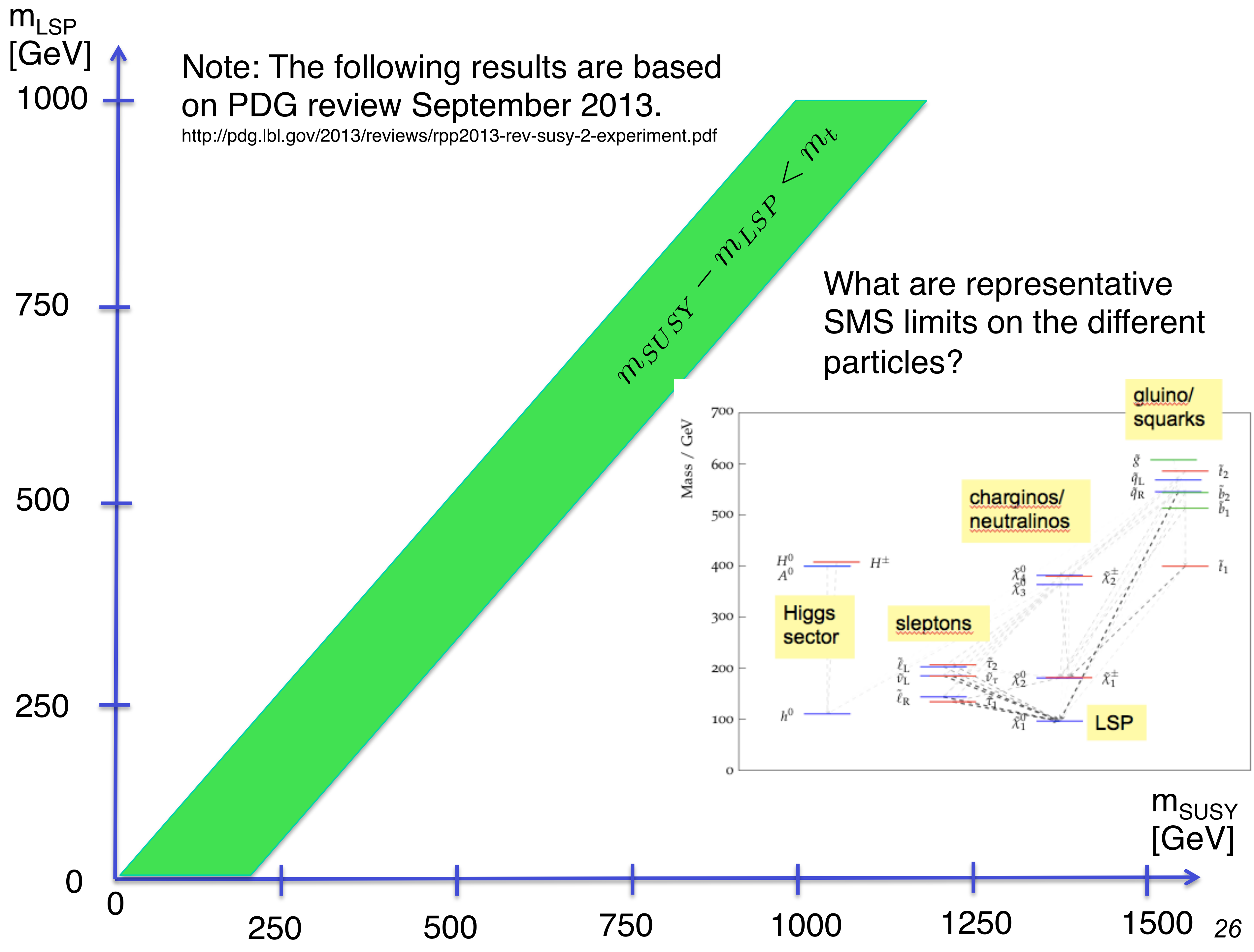



It is a challenge to do justice to the many searches and limits that have been established so far
- even more so to put it all together into the/a "bigger picture".

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



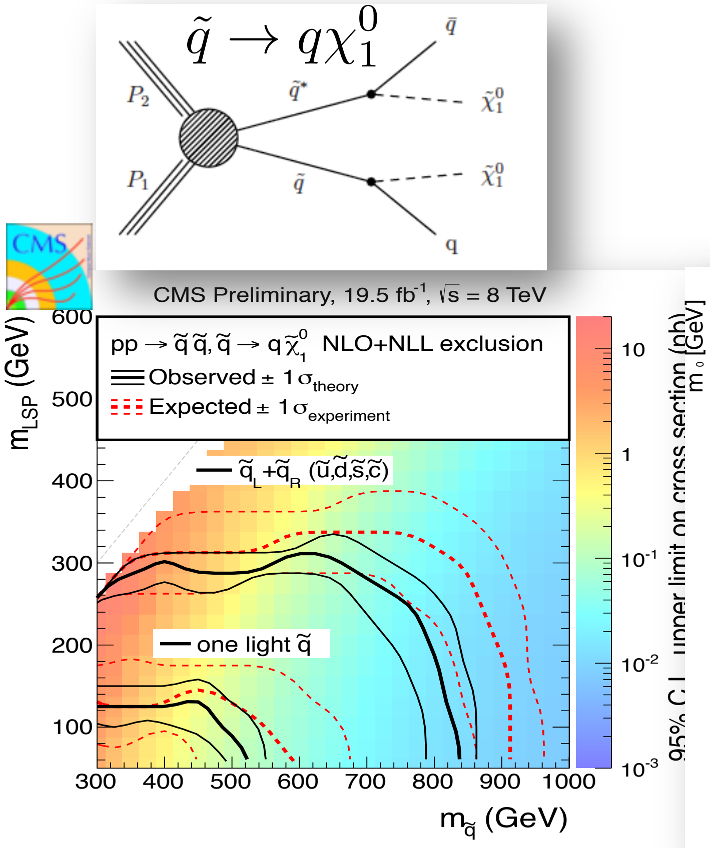

What are representative SMS limits on the different particles?

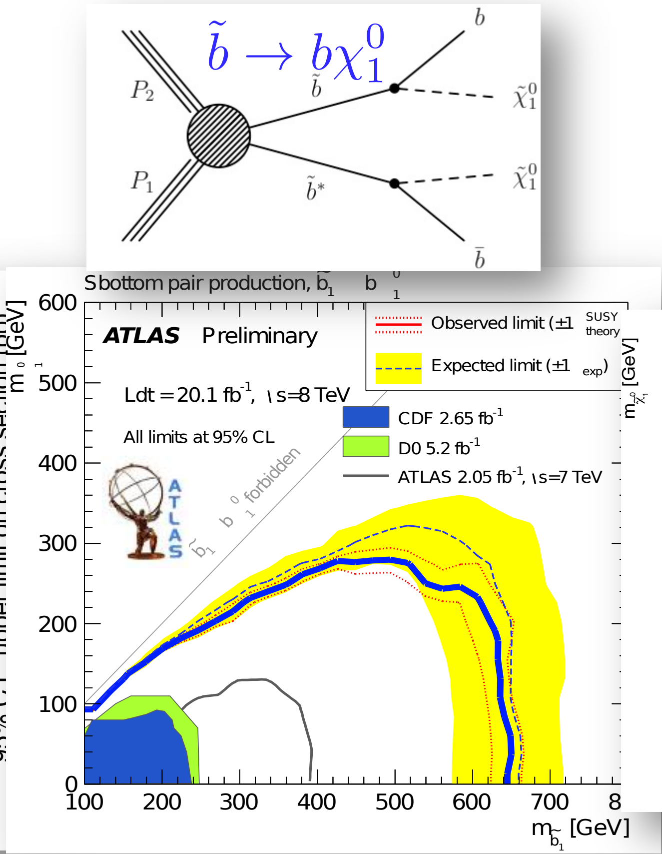


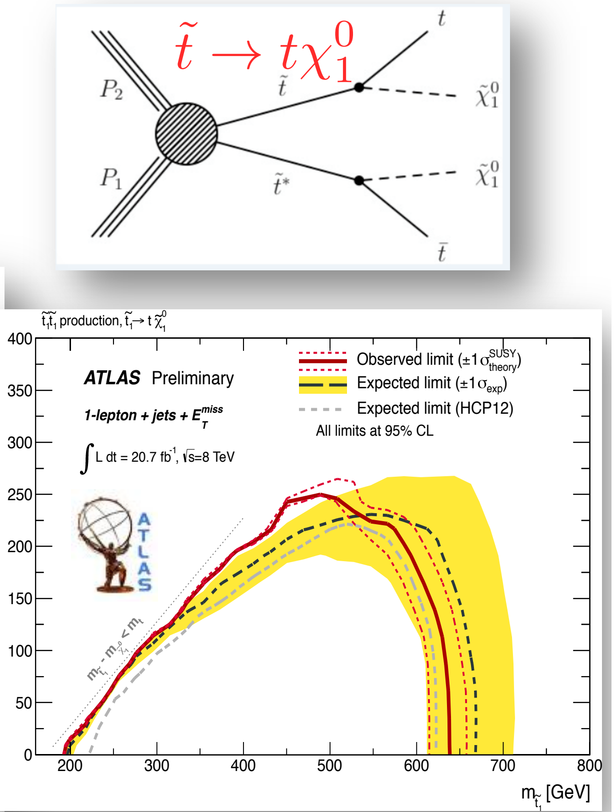
$m_{LSP}$ [GeV]
1000
750
500
250
0
Note: The following results are based on PDG review September 2013.
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
$m_{SUSY} - m_{LSP} < m_t$
What are representative SMS limits on the different particles?
Mass / GeV
700
600
500
400
300
200
100
0
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
$H^0$
$A^0$
$H^\pm$
$h^0$
$\tilde{\ell}_L$
$\tilde{\nu}_L$
$\tilde{\ell}_R$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{\tau}_1$
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
$\tilde{g}$
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{t}_2$
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{t}_1$
$m_{SUSY}$ [GeV]
0
250
500
750
1000
1250
1500

# Direct squark production – chosen limits





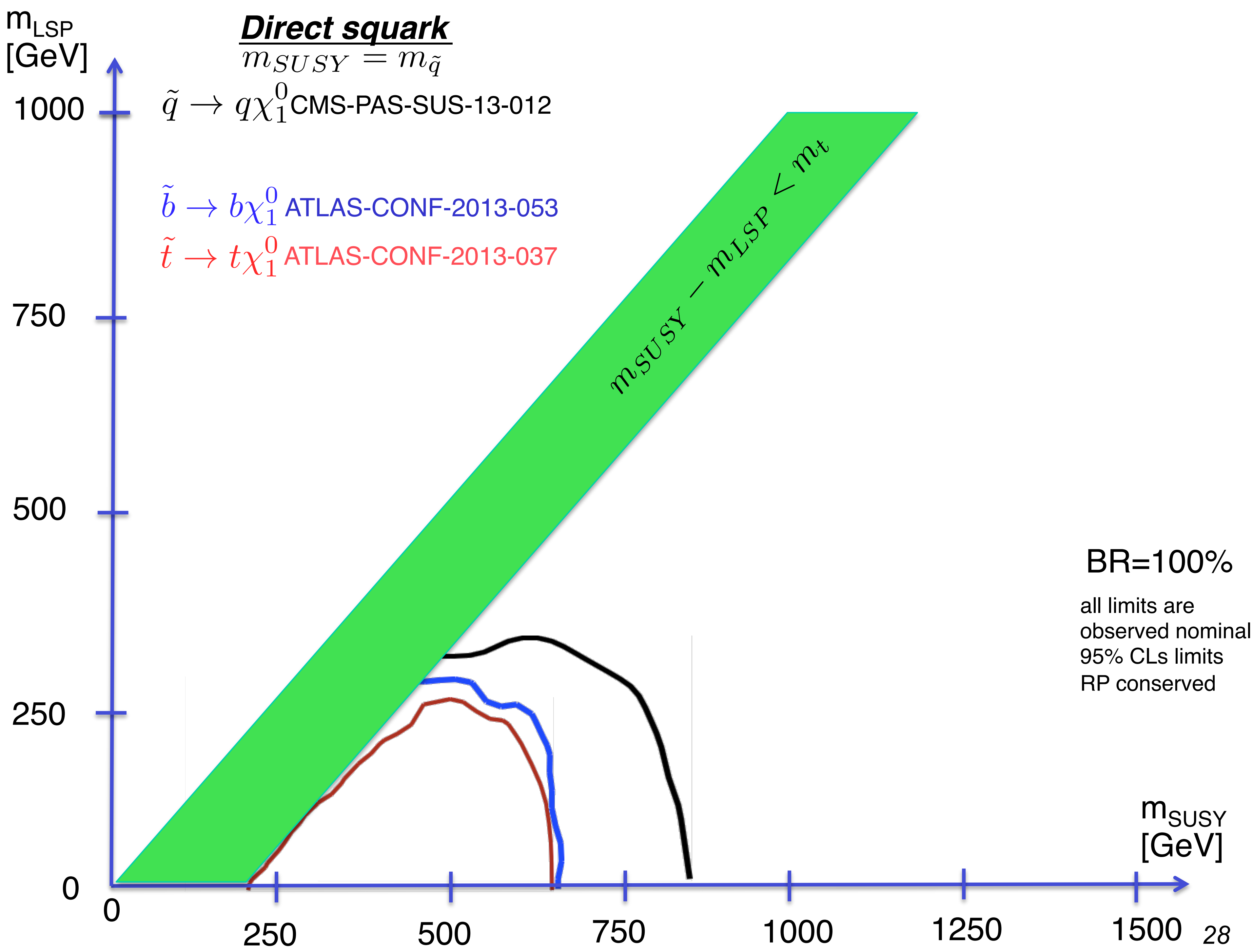



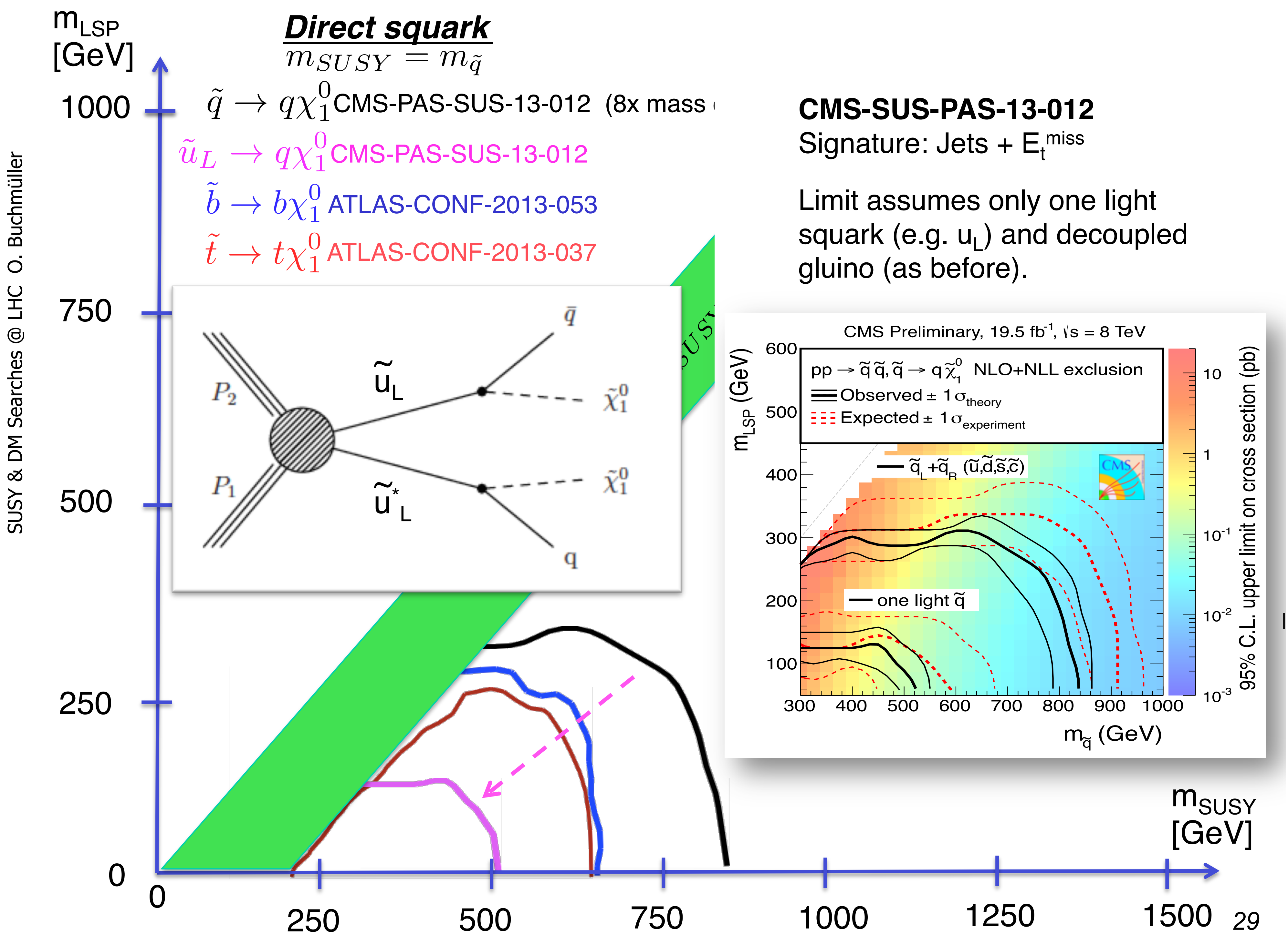




**CMS-SUS-PAS-13-012**
Signature: Jets + $E_t^{miss}$ + $H_T$
Limit assumes all 1st & 2nd gen squarks to be mass degenerate or only one light squark!

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

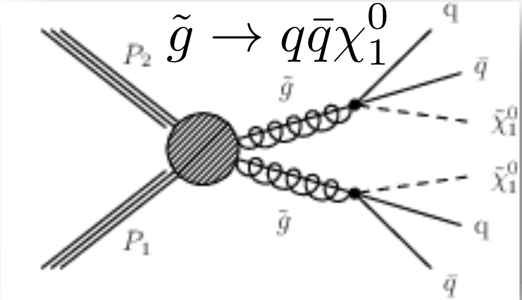
**ATLAS-CONF-2013-037**
Signature: 1Lepton + jets + $E_T^{mis}$

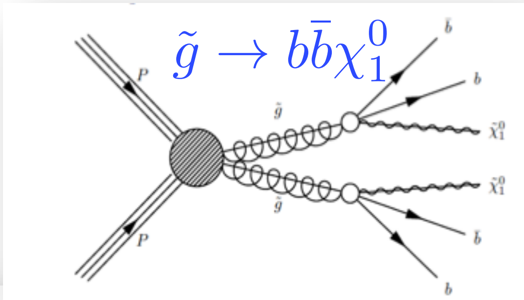

Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \rightarrow b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
$m_{SUSY} - m_{LSP} < m_t$
m_LSP [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_SUSY [GeV]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

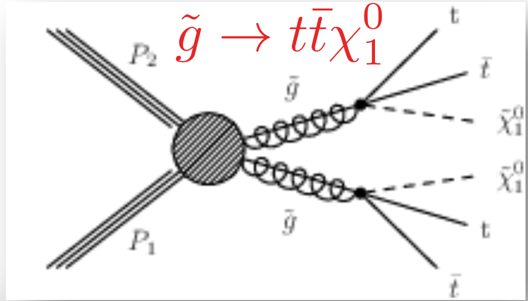

Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-13-012 (8x mass
$\tilde{u}_L \to q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
$m_{LSP}$ [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
$m_{SUSY}$ [GeV]
SUSY & DM Searches @ LHC O. Buchmüller
$P_2$
$P_1$
$\tilde{u}_L$
$\tilde{u}^*_L$
$\bar{q}$
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
$pp \to \tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}_1^0$ NLO+NLL exclusion
Observed ± 1 $\sigma_{theory}$
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)
CMS

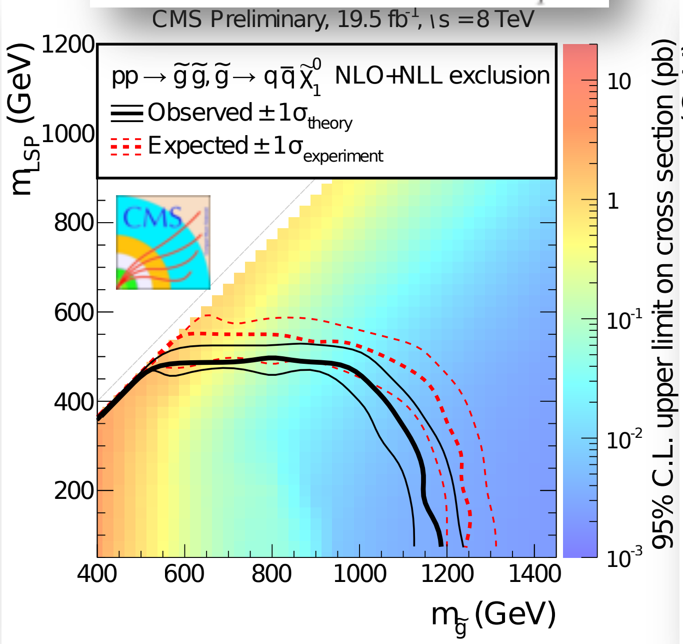
# Gluino mediated squark production – limits chosen

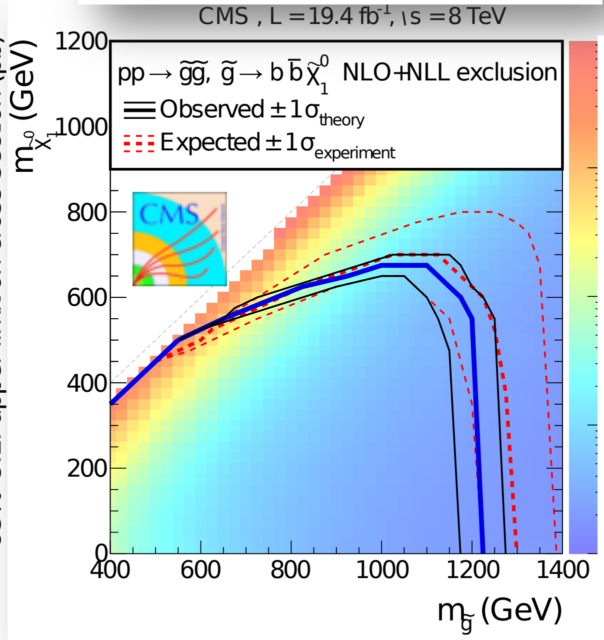


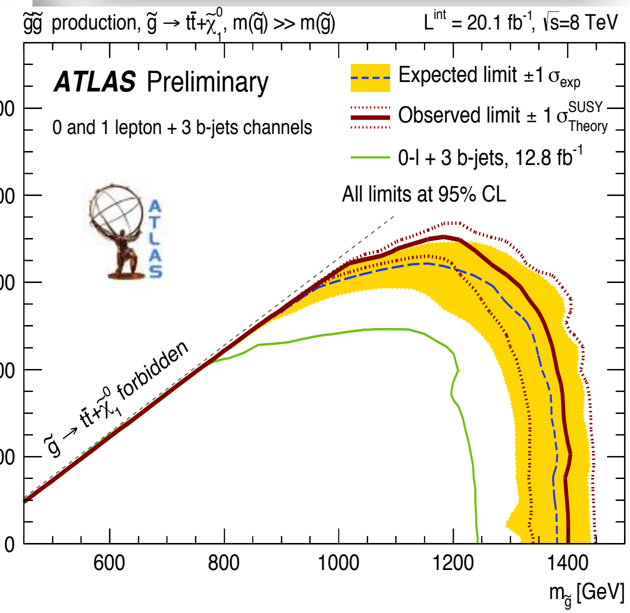


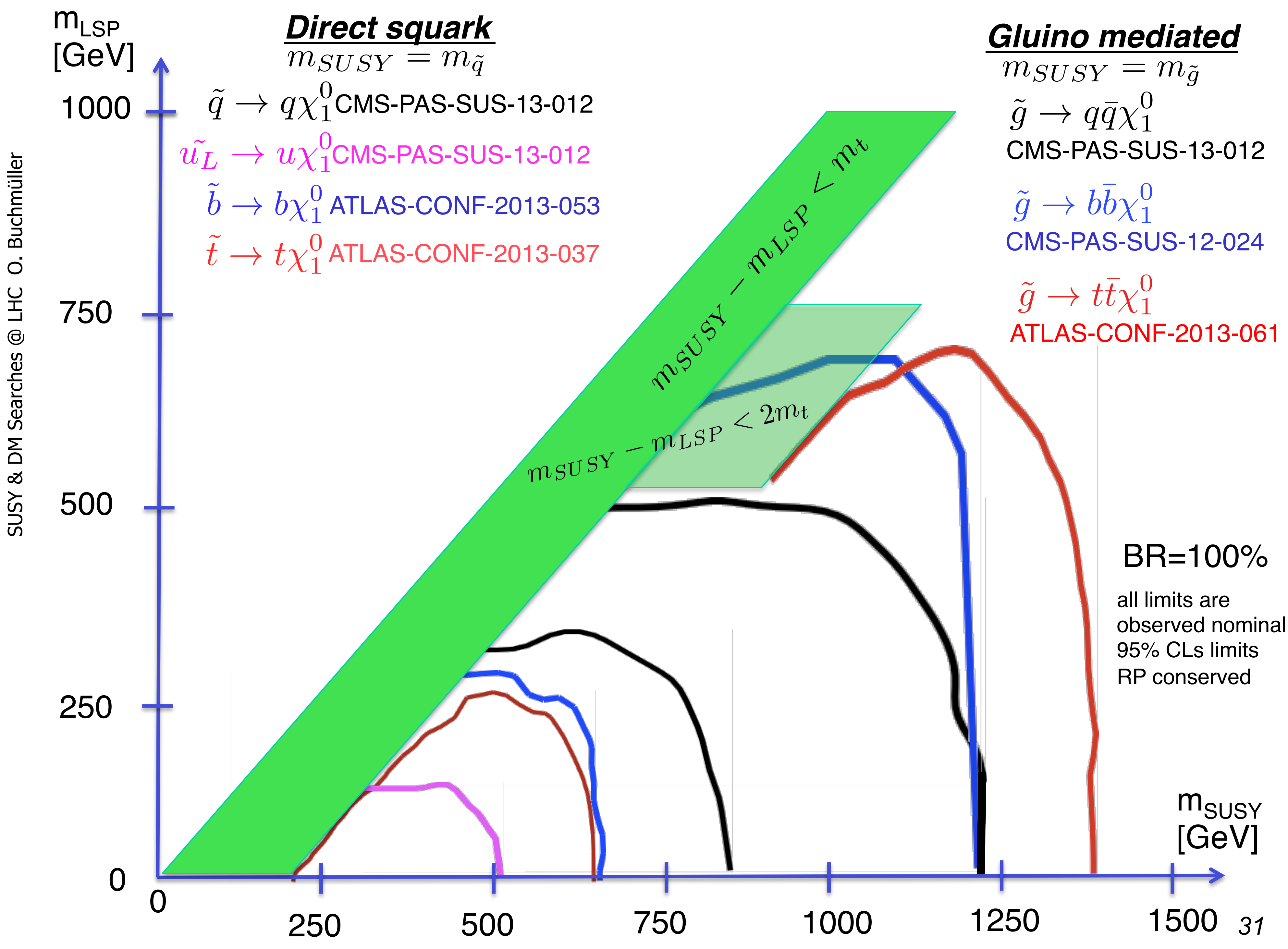




**CMS-SUS-PAS-13-012**
Signature: Jets + $H_T$ + $E_t^{miss}$

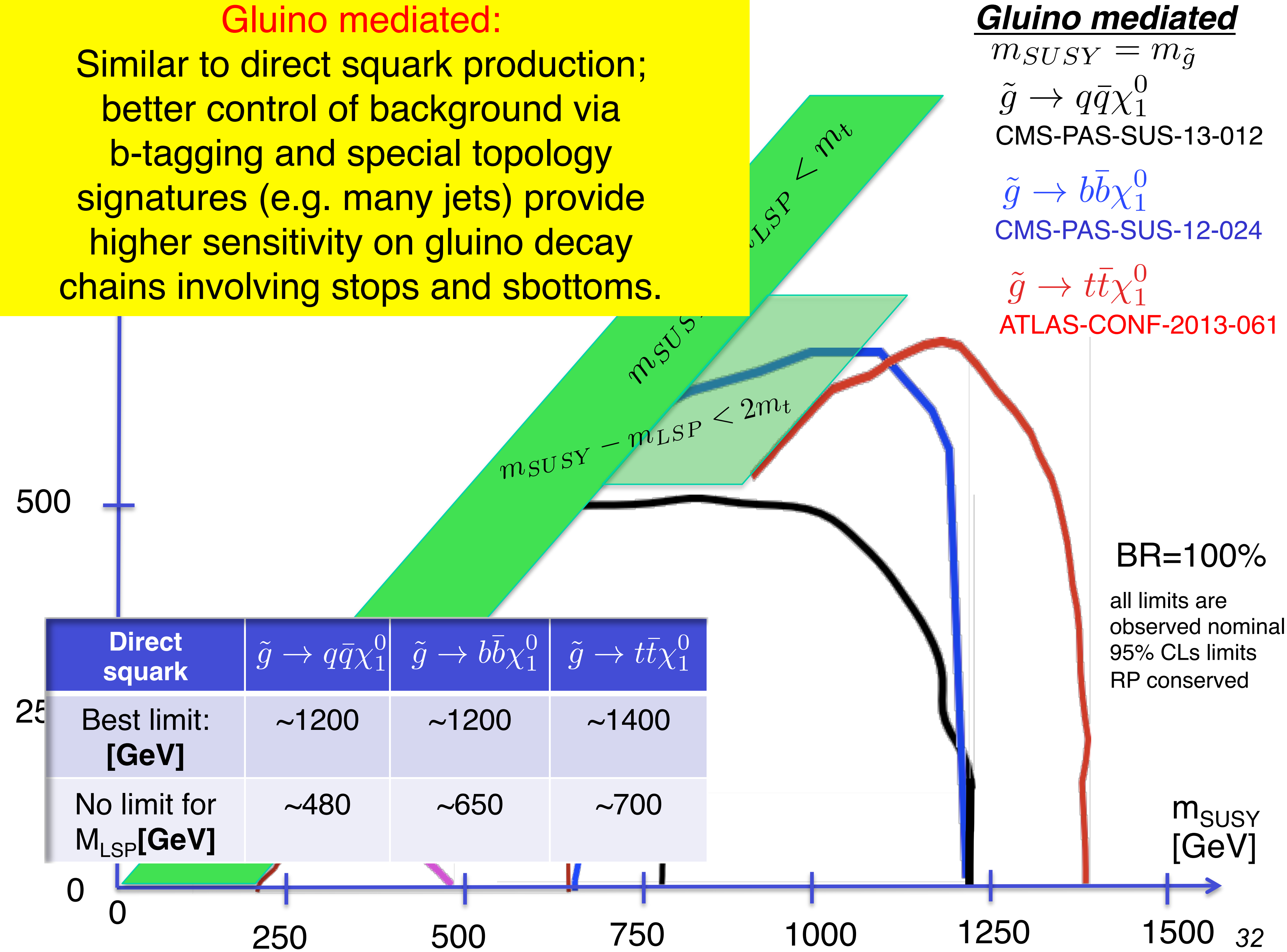
**CMS-SUS-PAS-12-024**
Signature: : Jets + b-tag + $E_t^{miss}$

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

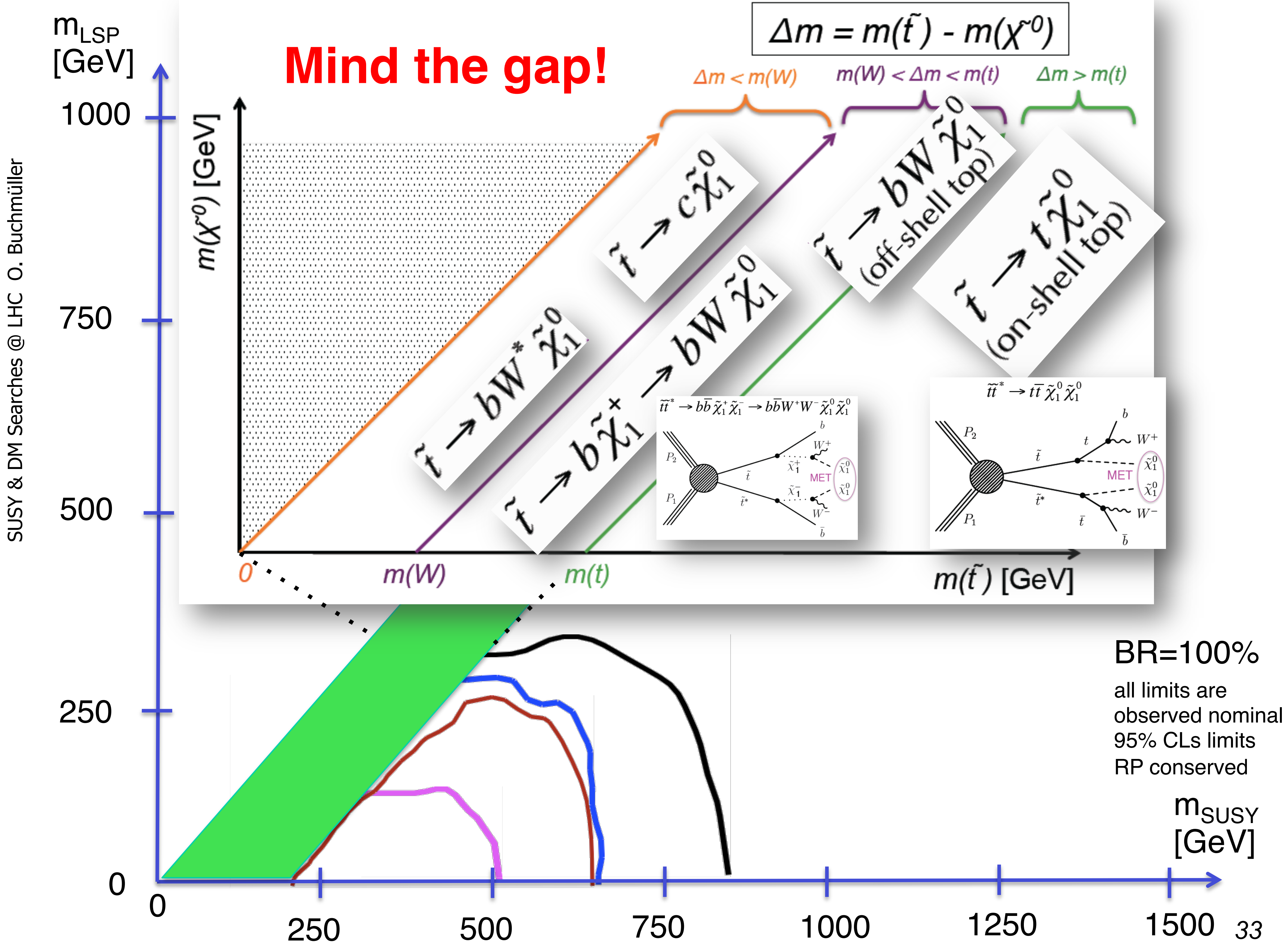


$m_{LSP}$ [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$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



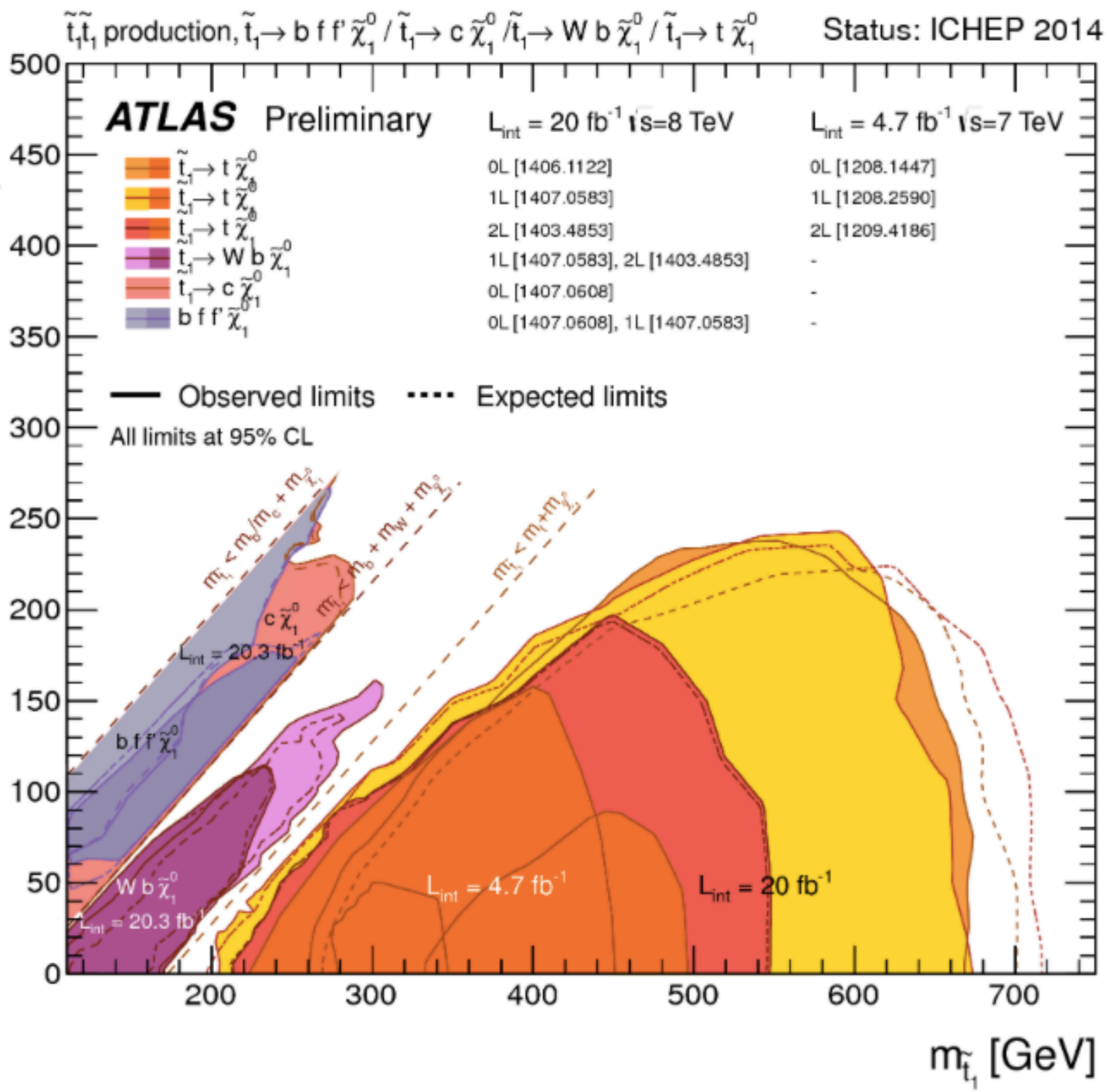

| Direct squark | $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ | $\tilde{g} \rightarrow b\bar{b}\chi_1^0$ | $\tilde{g} \rightarrow t\bar{t}\chi_1^0$ |
|---|---|---|---|
| Best limit: **[GeV]** | ~1200 | ~1200 | ~1400 |
| No limit for $M_{LSP}$**[GeV]** | ~480 | ~650 | ~700 |



SUSY & DM Searches @ LHC O. Buchmüller
Mind the gap!
mLSP [GeV]
1000
750
500
250
0
Δm = m(t̃) - m(χ̃0)
Δm < m(W)
m(W) < Δm < m(t)
Δm > m(t)
m(χ0) [GeV]
t̃ → bW* χ̃01
t̃ → cχ̃01
t̃ → bχ̃+1 → bW χ̃01
t̃ → bW χ̃01 (off-shell top)
t̃ → tχ̃01 (on-shell top)
0
m(W)
m(t)
m(t̃) [GeV]
MET
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
mSUSY [GeV]
0
250
500
750
1000
1250
1500

# Stop Searches Today

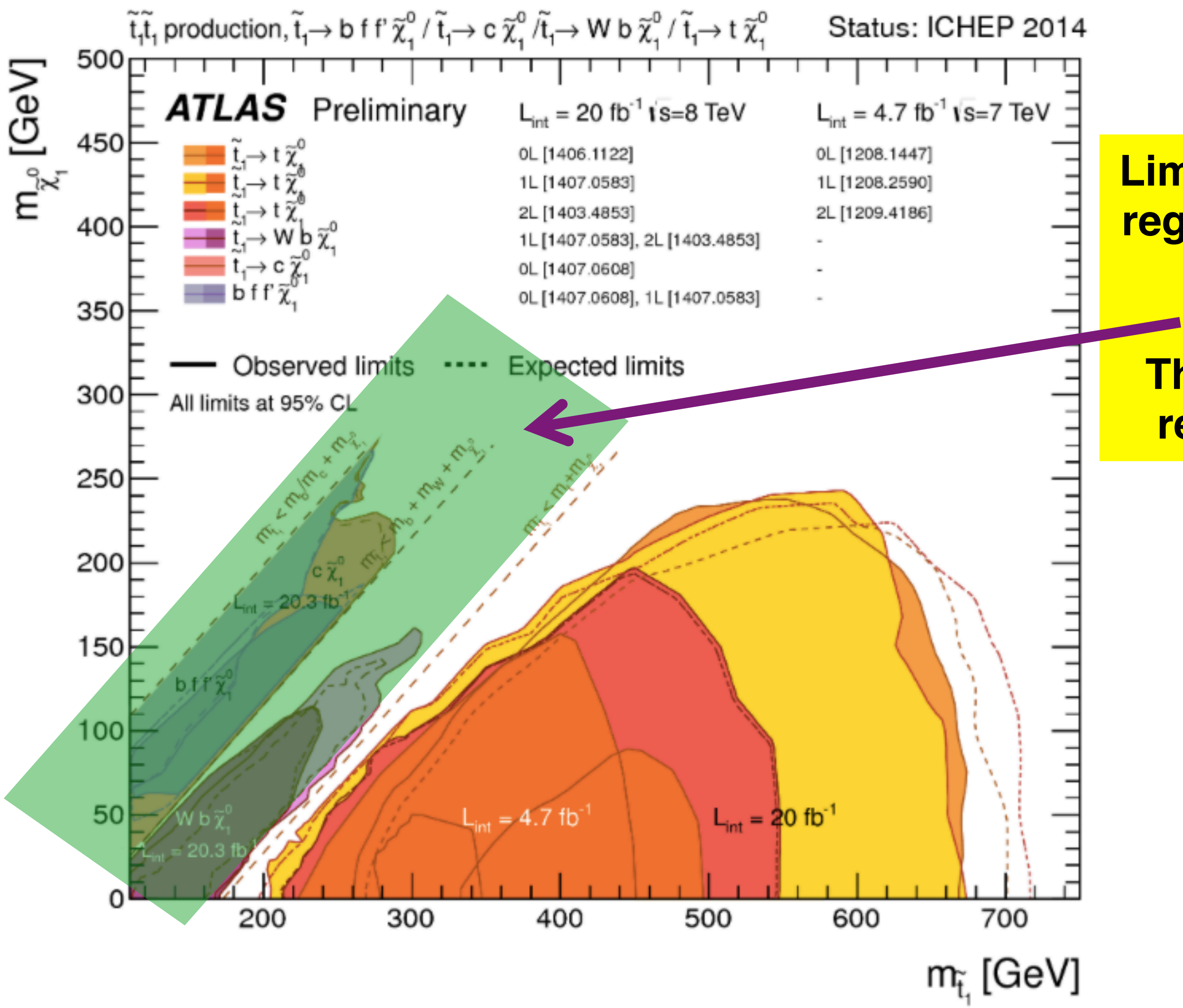





CMS similar!

# Add pMSSM here

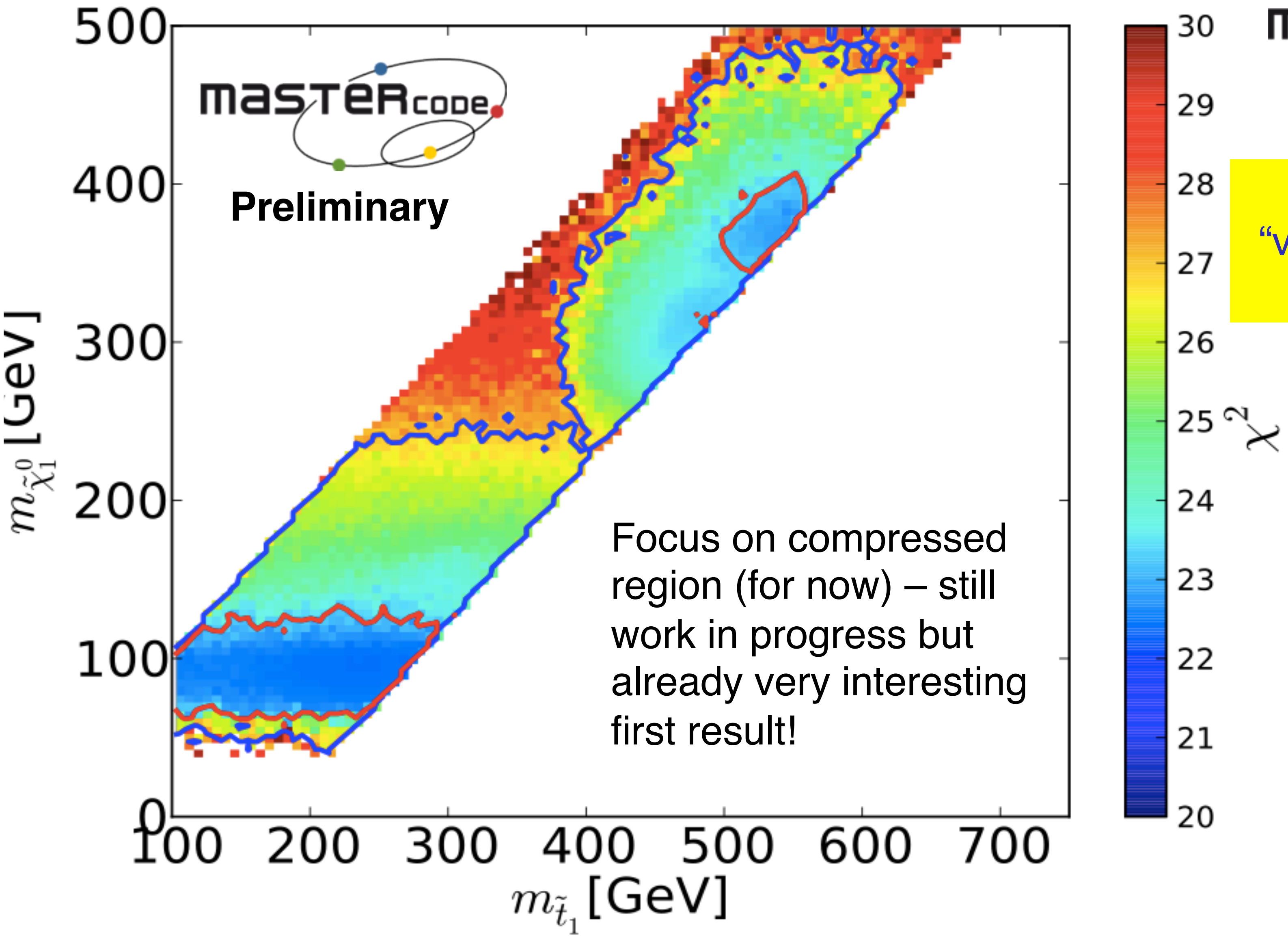





**Limits in the compressed region $m_{stop} - m_{LSP} < m_{top}$ are still very weak.**

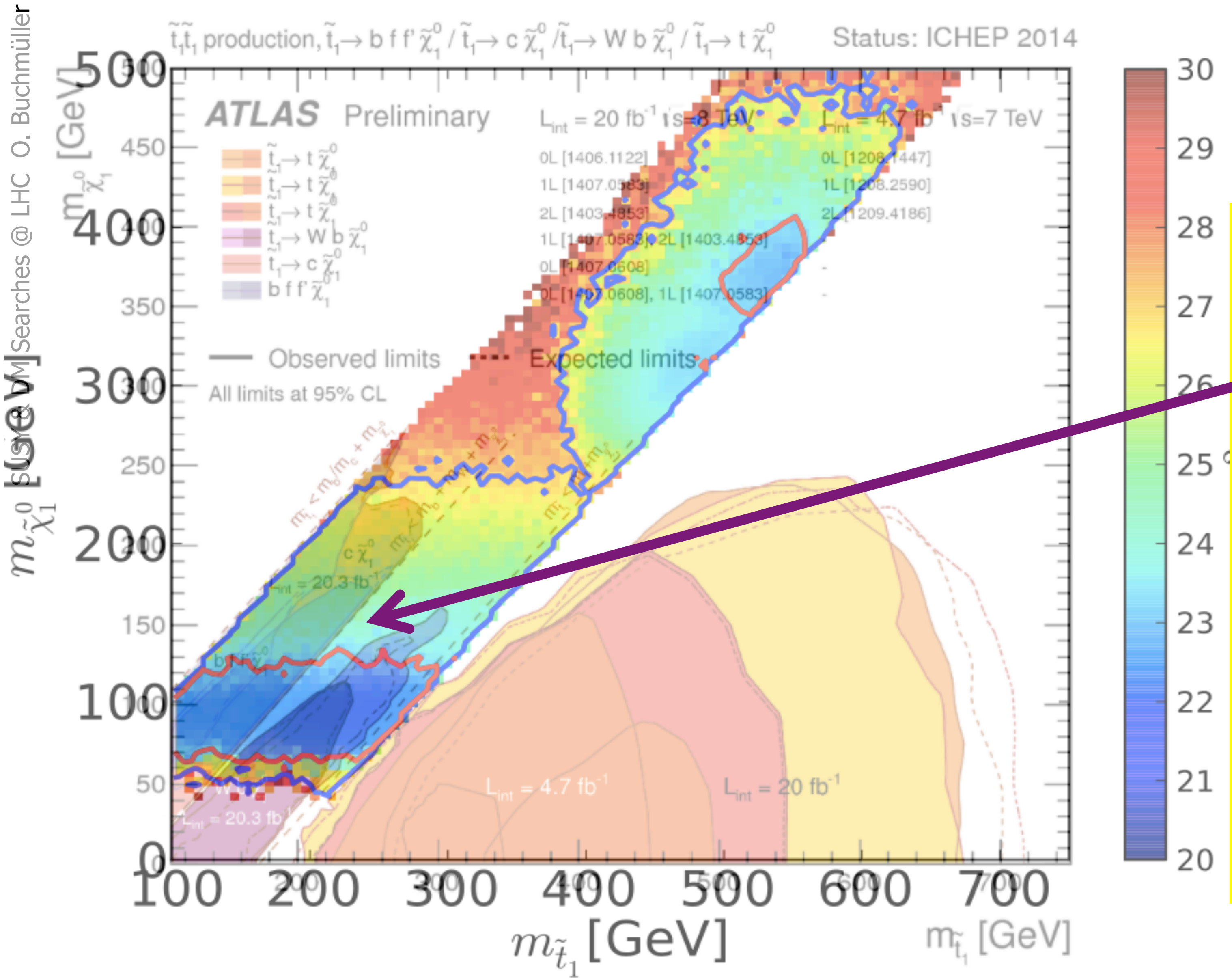
**This difficult kinematic region still has holes!**

# Add pMSSM here




**pMSSM study**
"very preliminary"

# pMSSM Prediction & Present limits

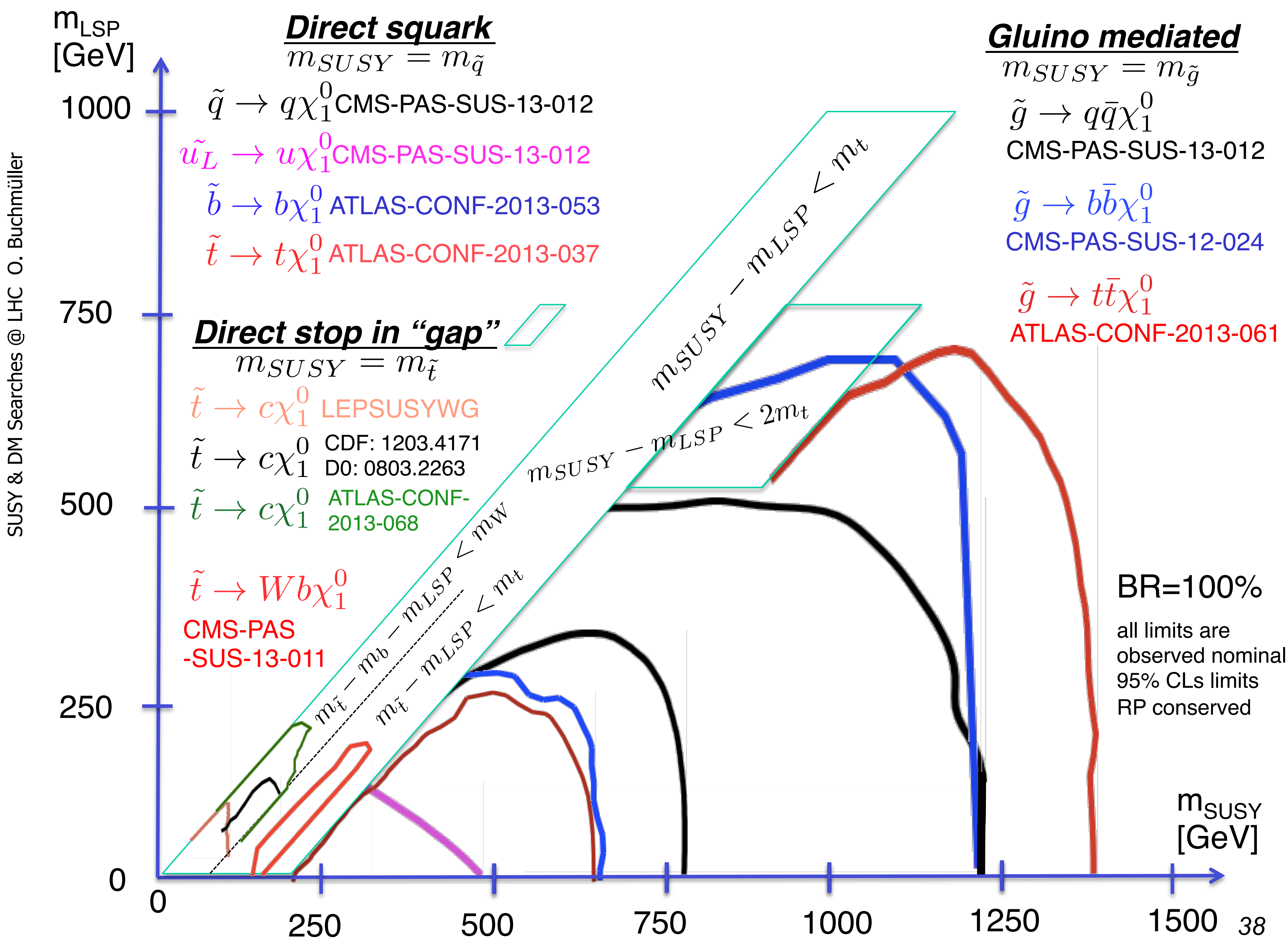





**pMSSM study**
"very preliminary"

Very interesting parameter space in "compressed region" even for very low $m_{stop}$!

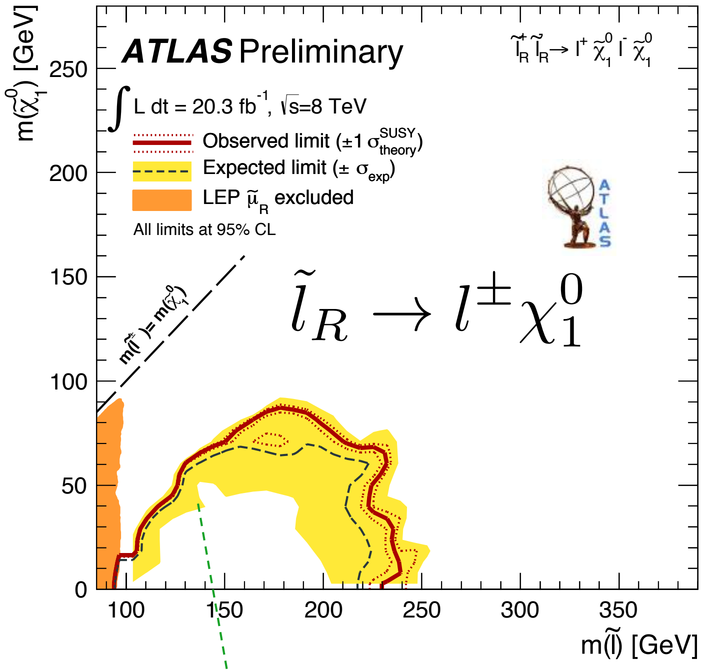
Fully compatible with all measurements and not ruled out by searches yet!

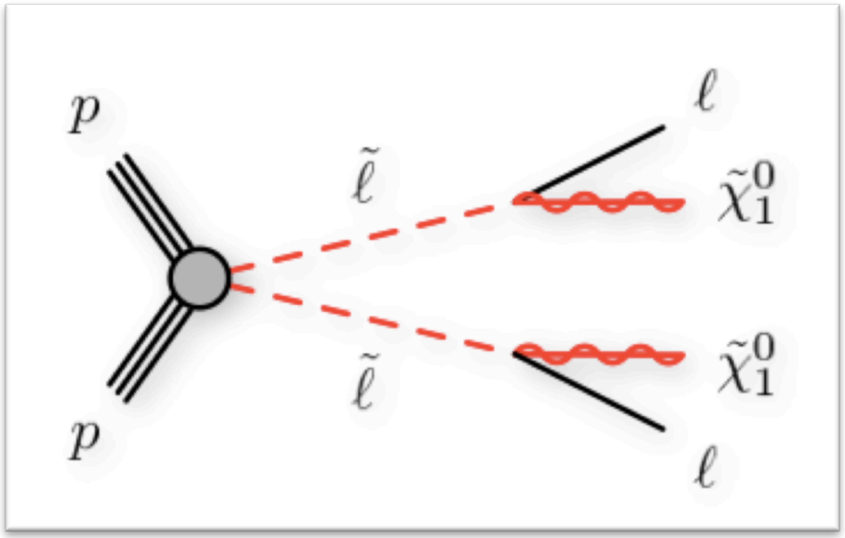


m_LSP [GeV]
1000
750
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{u}_L \rightarrow u\chi_1^0$ CMS-PAS-SUS-13-012
$\tilde{b} \rightarrow b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in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

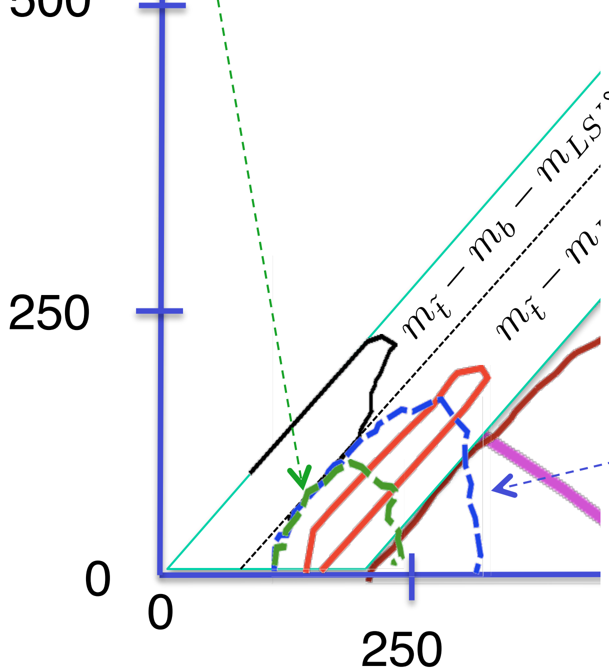
SUSY & DM Searches @ LHC O. Buchmüller

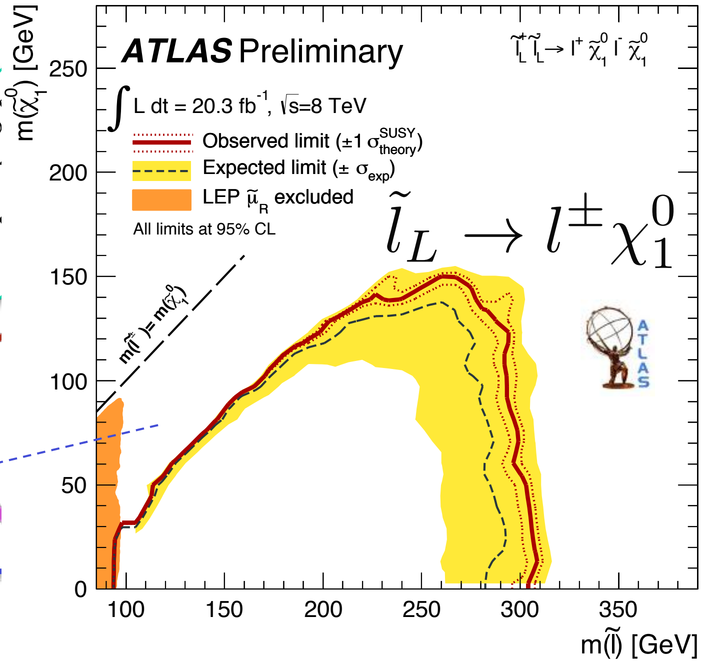
# Direct slepton production

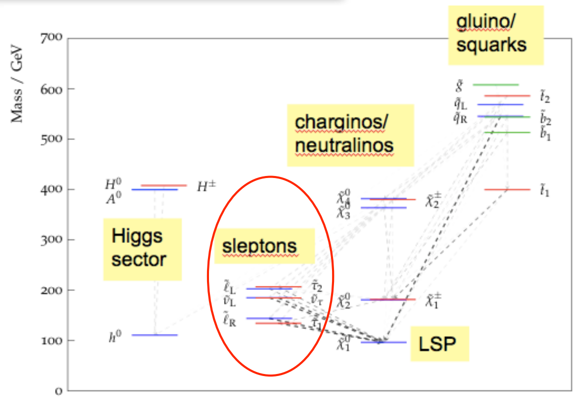



## Direct slepton



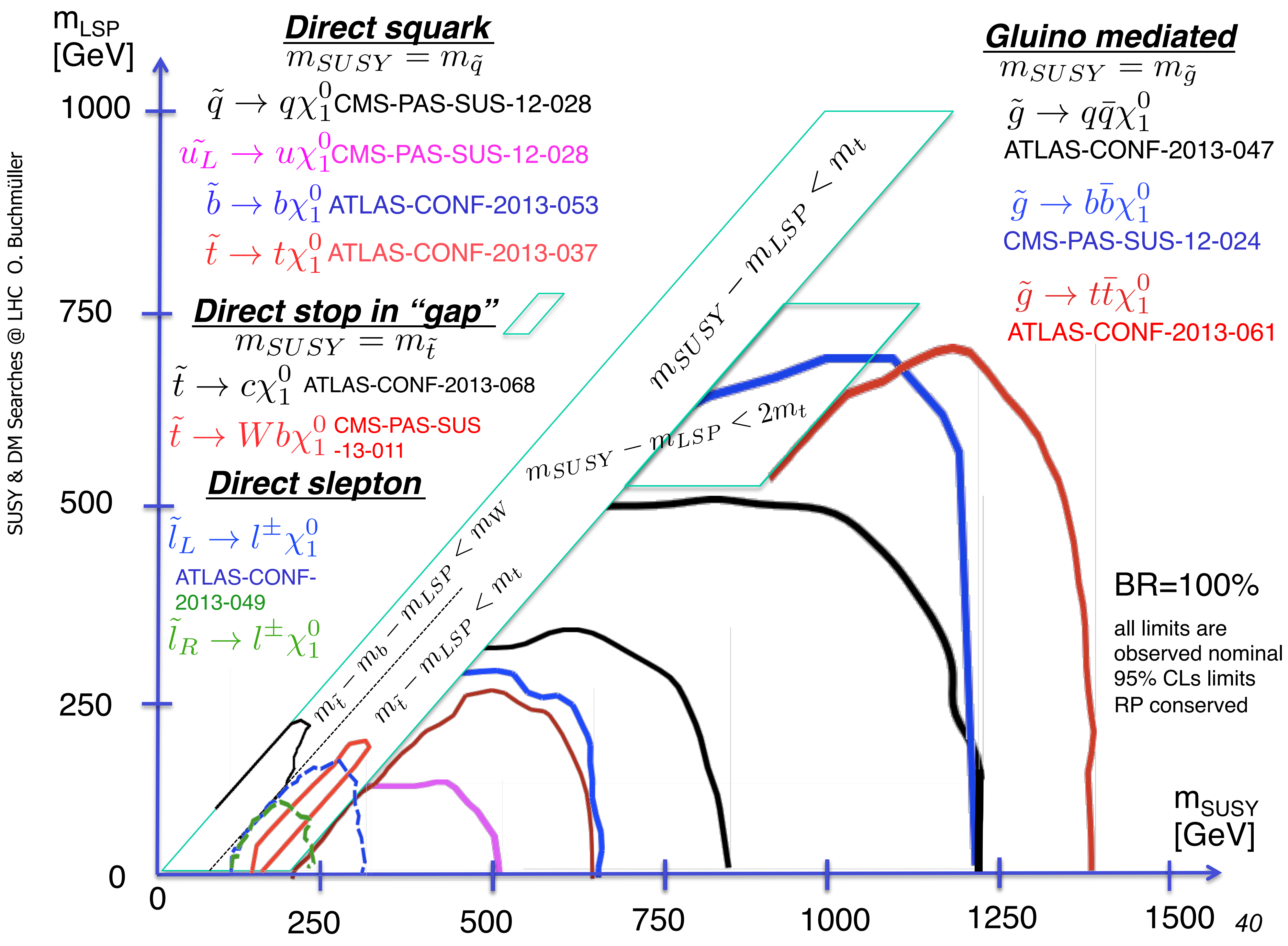




ATLAS-CONF-2013-049

Signature

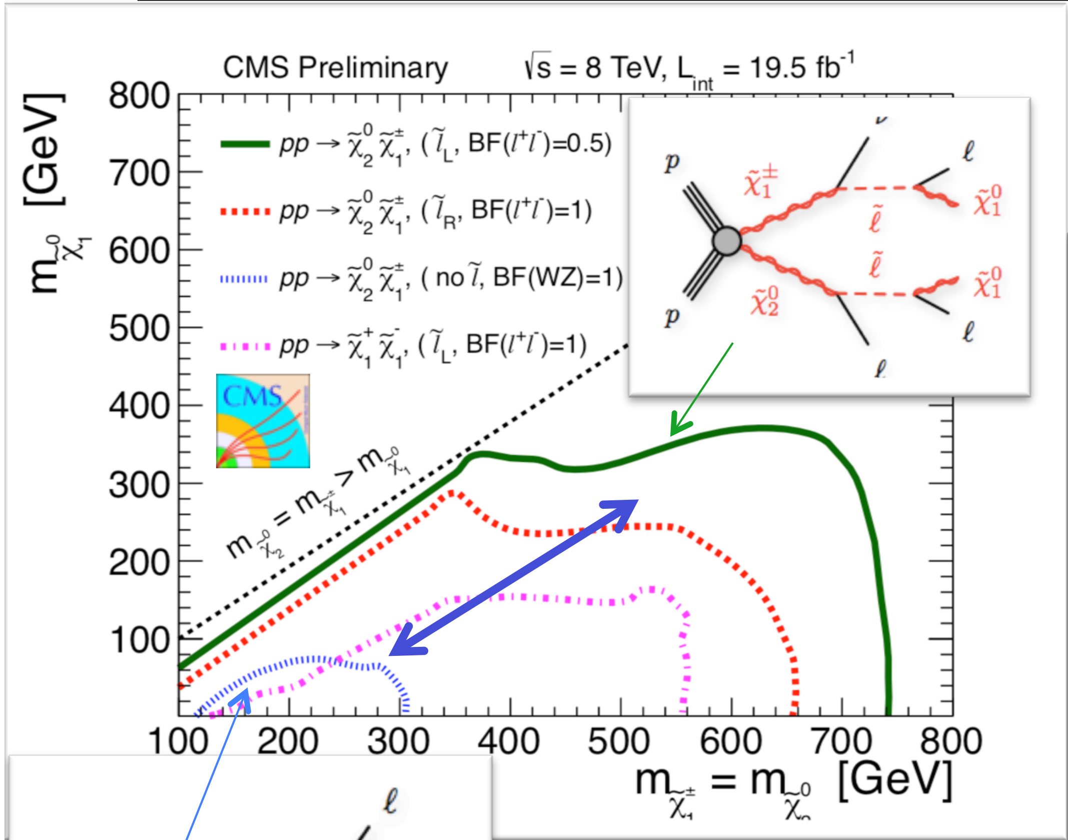
2 lepton + $E_T^{miss}$

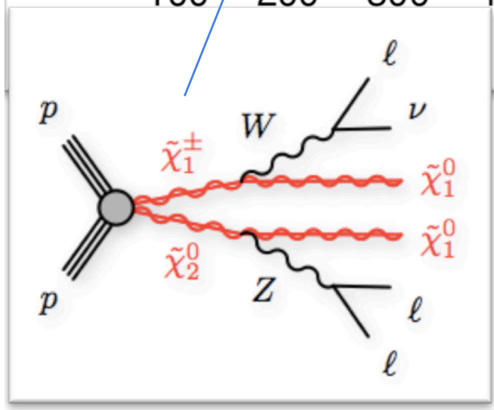


$m_{LSP}$ [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u}_L \to u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to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

Imperial College London

# Direct chargino/neutralino production



heavy slepton“hard(er)”

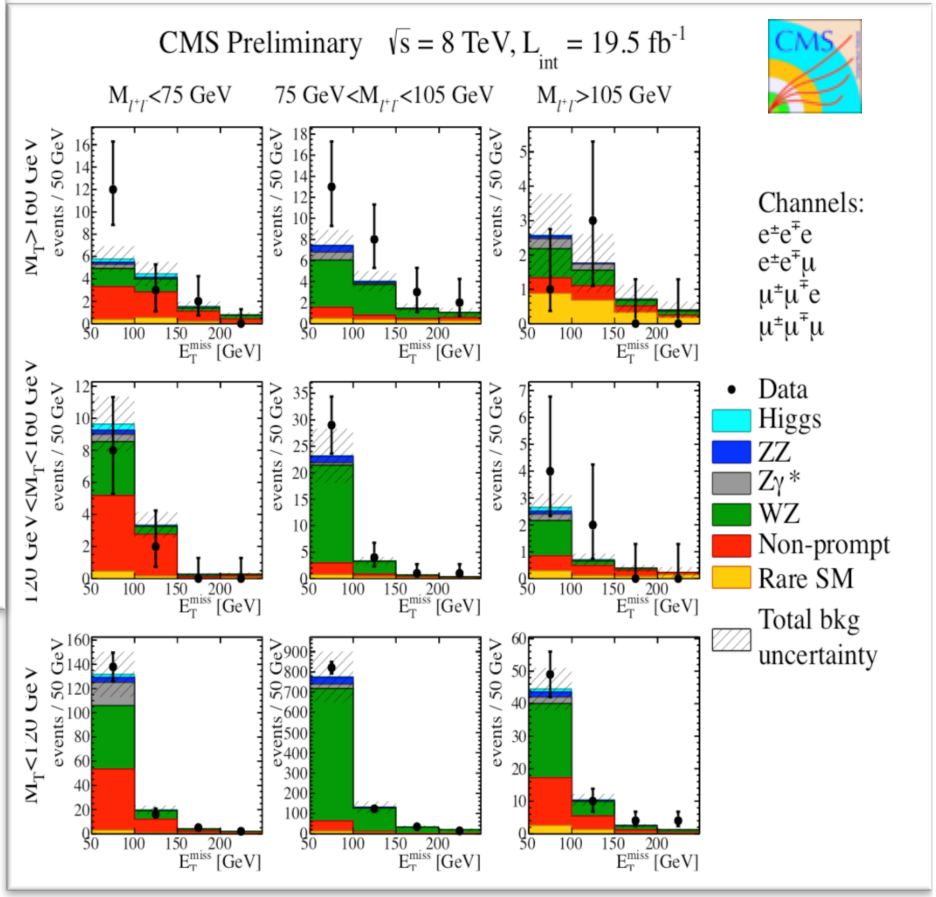
Add Z($l^+l^-$)+2jets topology in bins of $E_t^{miss}$ to increase sensitivity for “heavy” slepton case

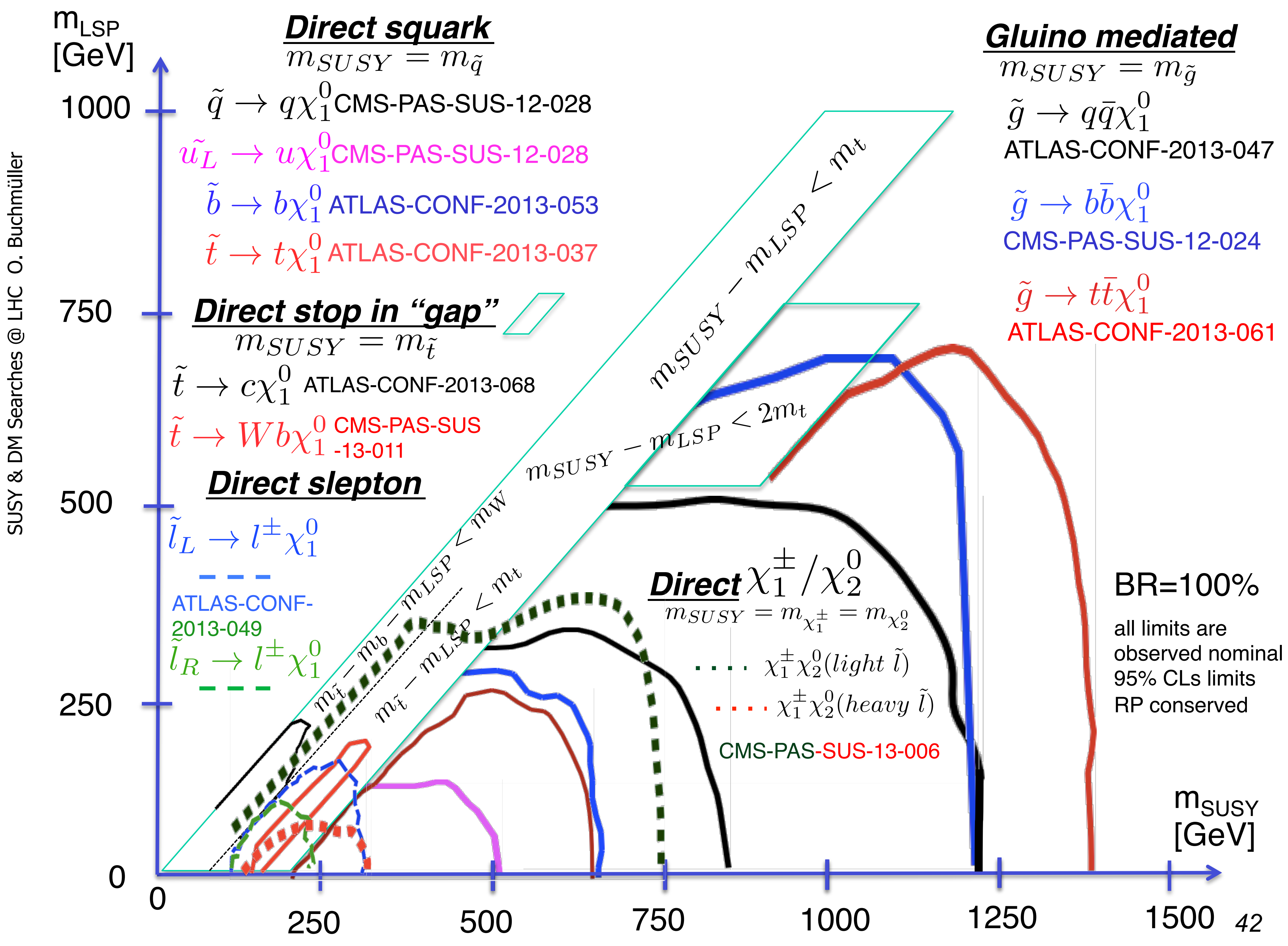
light slepton “easy”

CMS-PAS-SUS-13-006

NEW

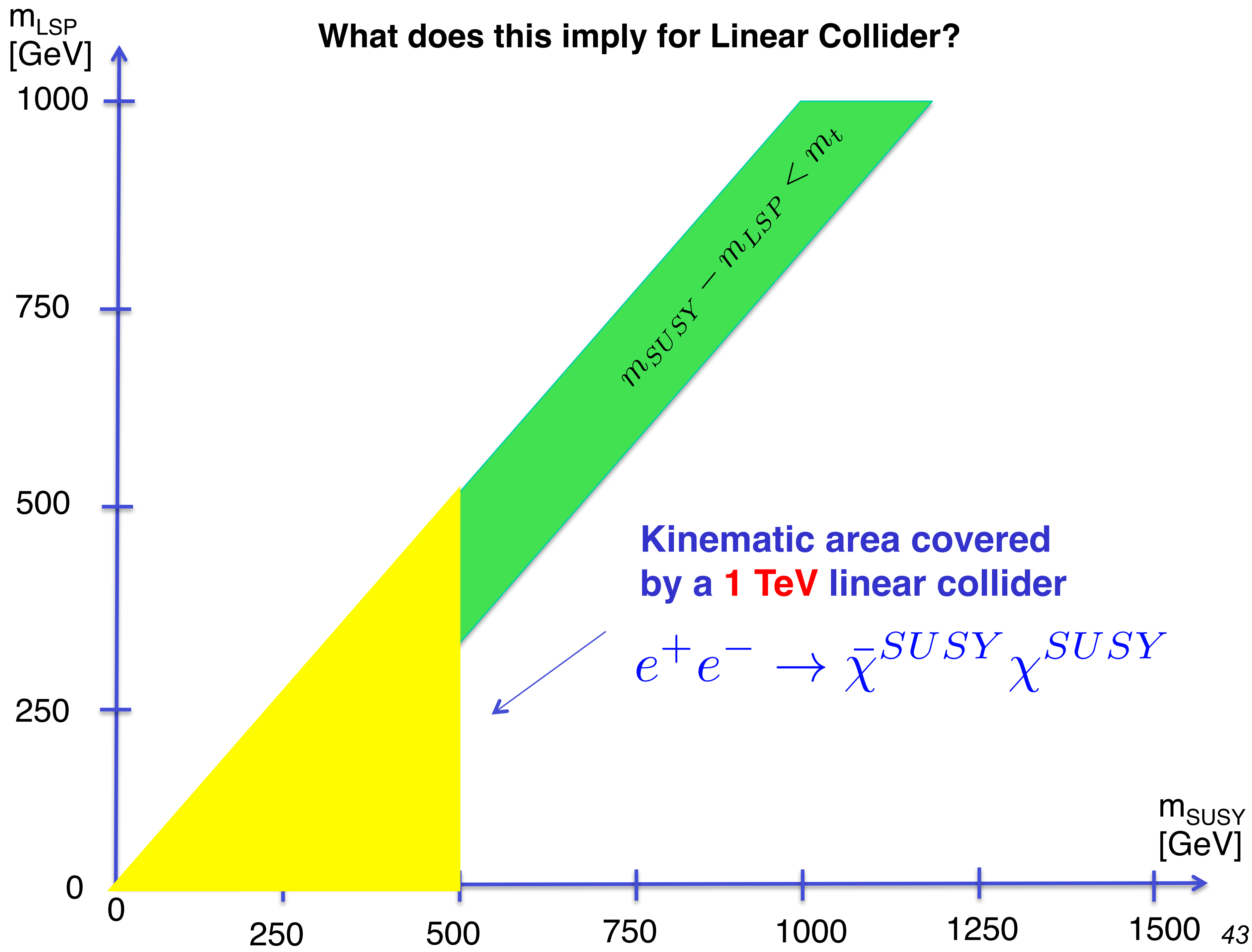
3l OSSF categorised in bins of $M_{ll}$, MT, and ETmis

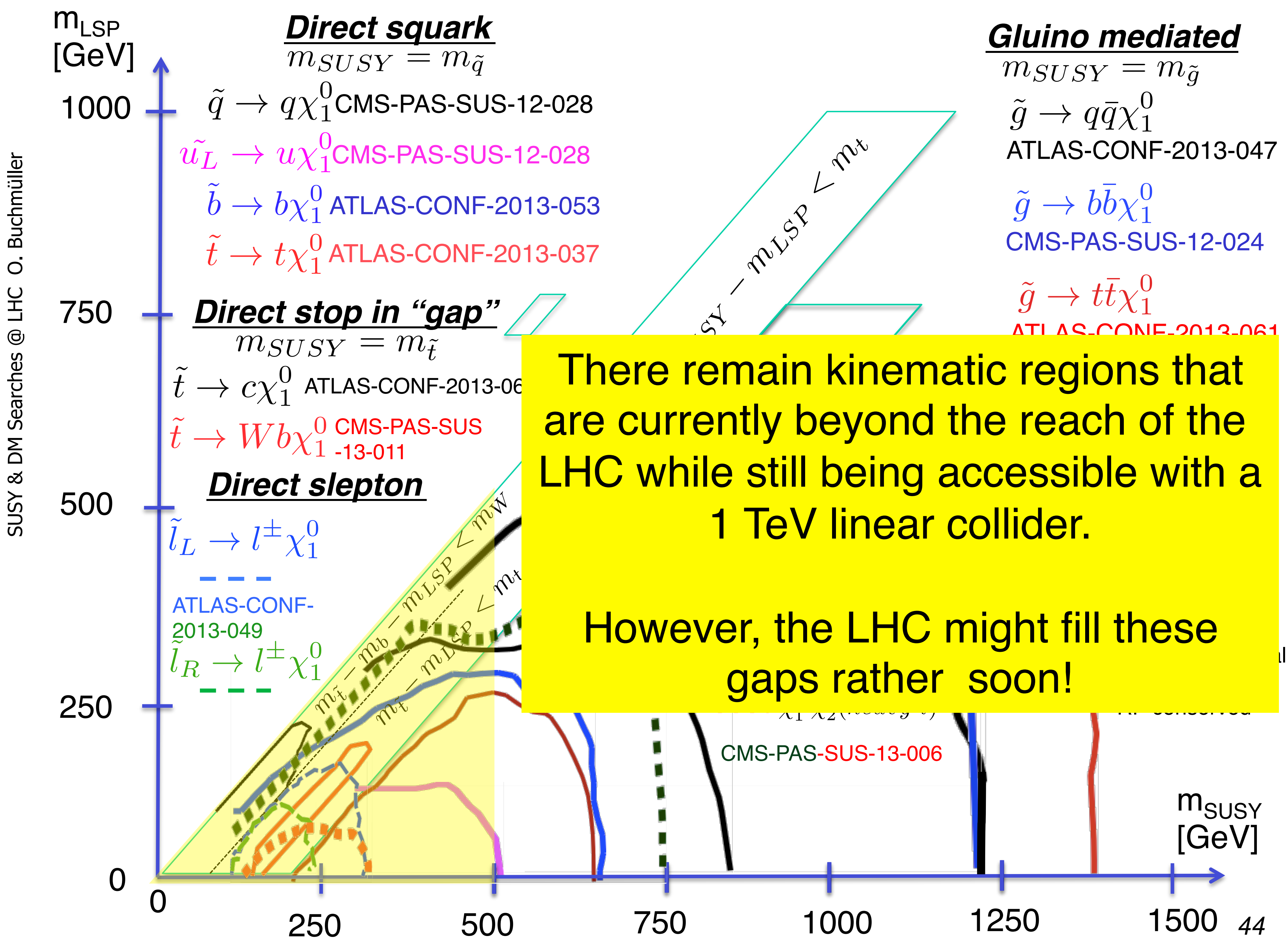




SUSY & DM Searches @ LHC O. Buchmüller
$m_{LSP}$ [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u}_L \rightarrow u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \rightarrow b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$ ATLAS-CONF-2013-068
$\tilde{t} \rightarrow Wb\chi_1^0$ CMS-PAS-SUS -13-011
Direct slepton
$\tilde{l}_L \rightarrow l^\pm\chi_1^0$
ATLAS-CONF-2013-049
$\tilde{l}_R \rightarrow l^\pm\chi_1^0$
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS-CONF-2013-047
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
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]
1000
750
500
250
0
0
250
500
750
1000
1250
1500

## What does this imply for Linear Collider?

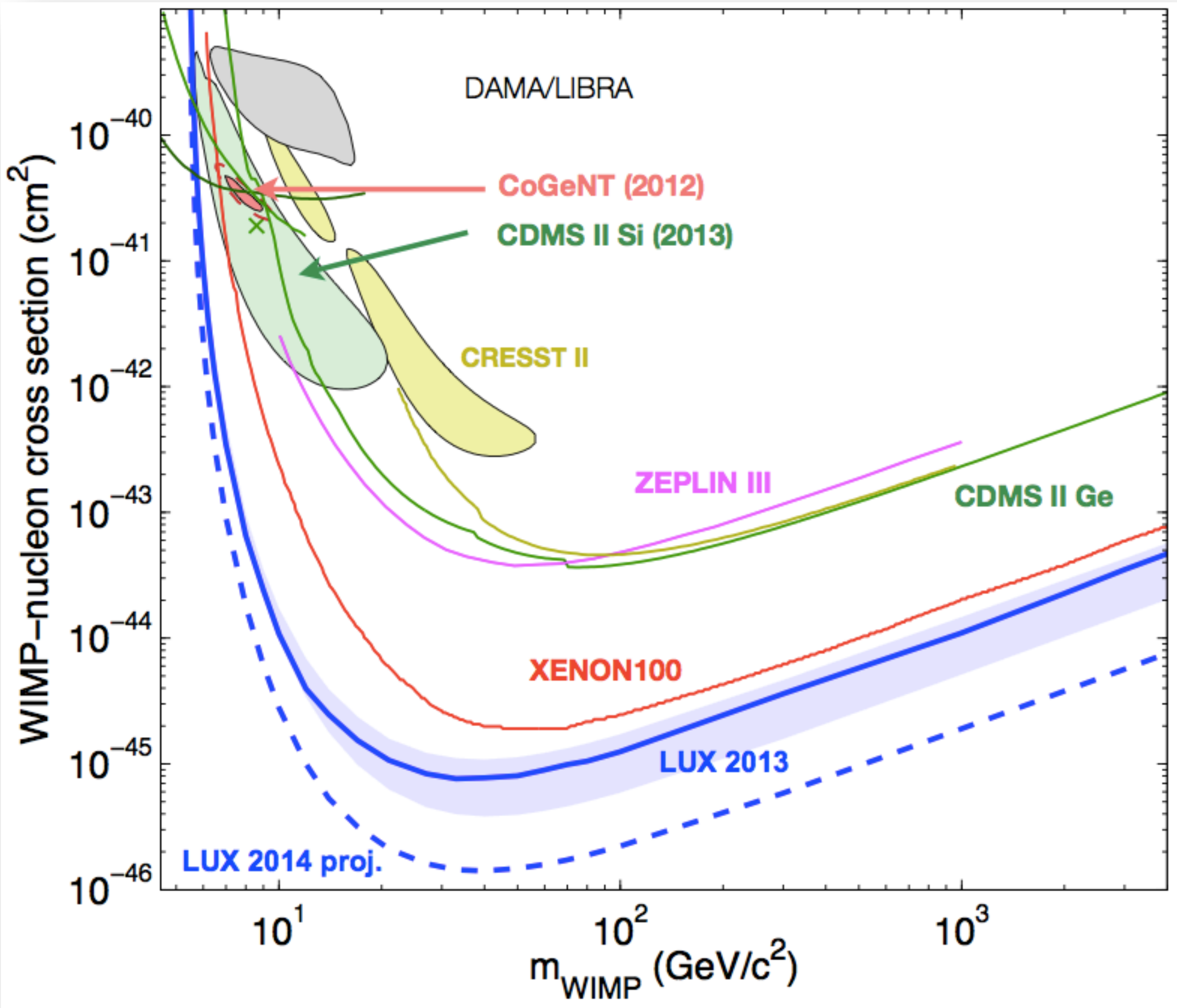




SUSY & DM Searches @ LHC O. Buchmüller
$m_{LSP}$ [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u_L} \to u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$ ATLAS-CONF-2013-06
$\tilde{t} \to Wb\chi_1^0$ 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
$\tilde{g} \to t\bar{t}\chi_1^0$
CMS-PAS-SUS-13-006
$m_{SUSY} - m_{LSP} < m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
$m_{SUSY}$ [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
There remain kinematic regions that are currently beyond the reach of the LHC while still being accessible with a 1 TeV linear collider.
However, the LHC might fill these gaps rather soon!

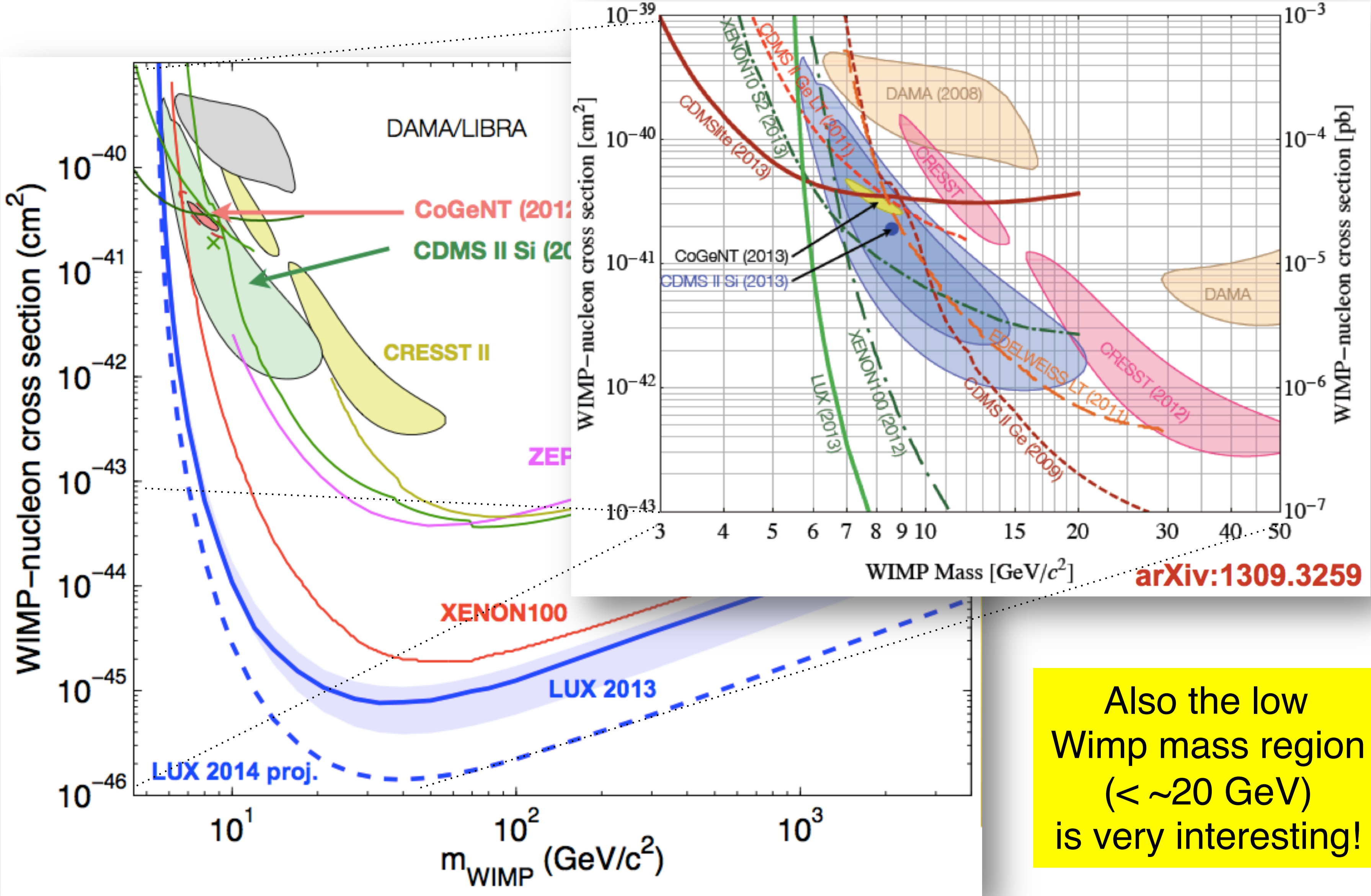
# Dark Matter Searches: Direct Detection Experiments





# Dark Matter Searches: Direct Detection Experiments






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

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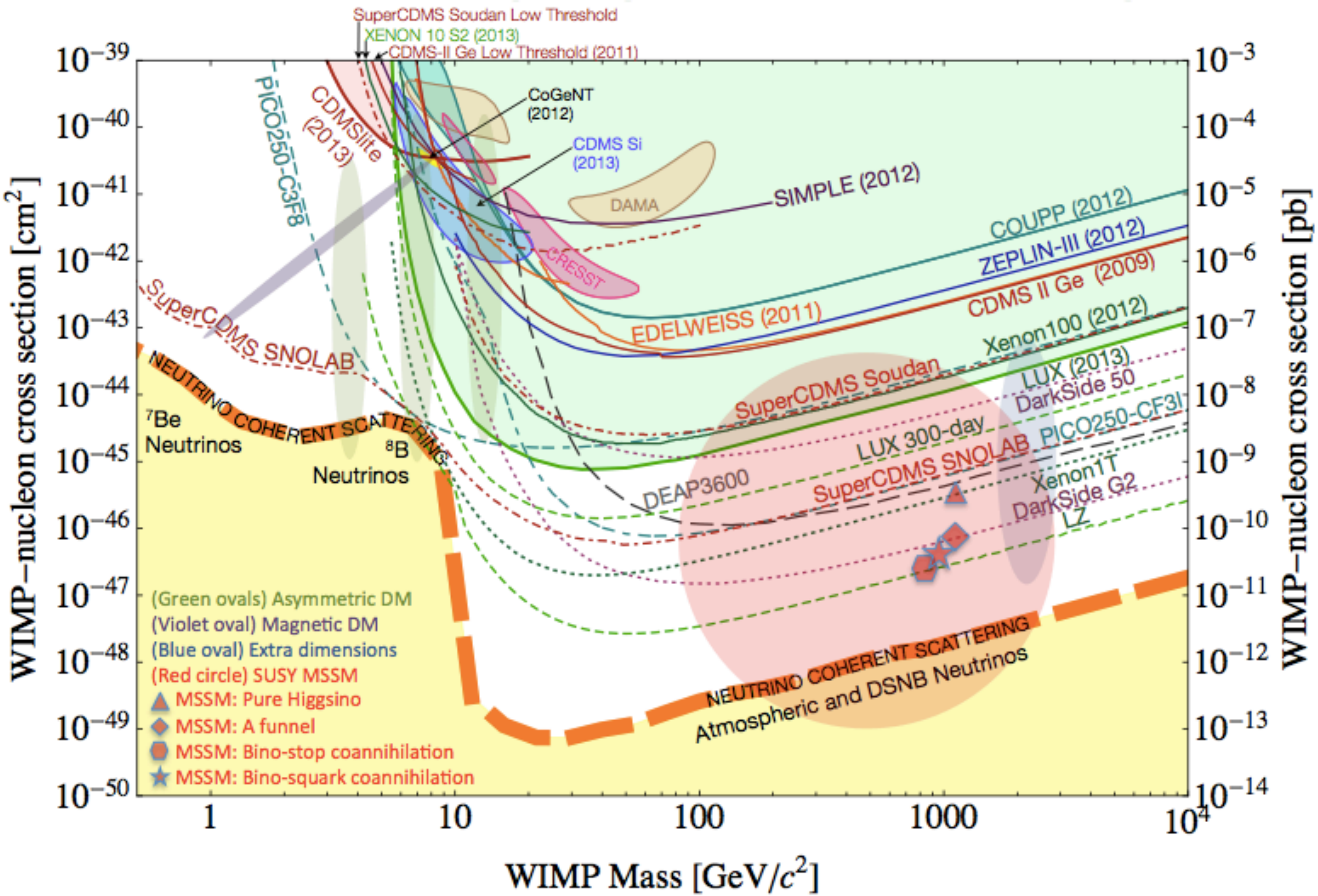
# Direct Detection Landscape in a nutshell!

SUSY & DM Searches @ LHC O. Buchmüller



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# Direct Detection Landscape in a nutshell!

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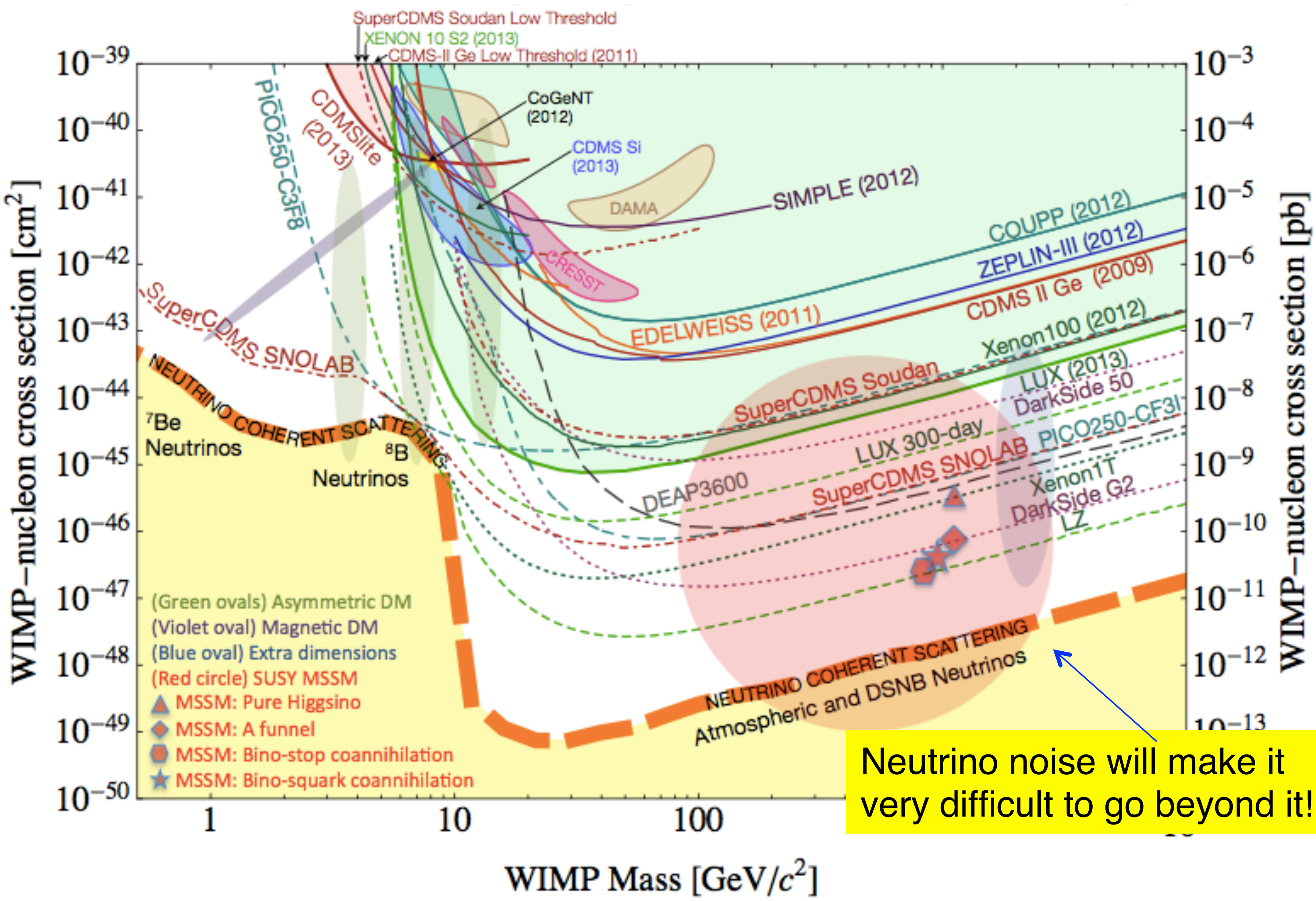
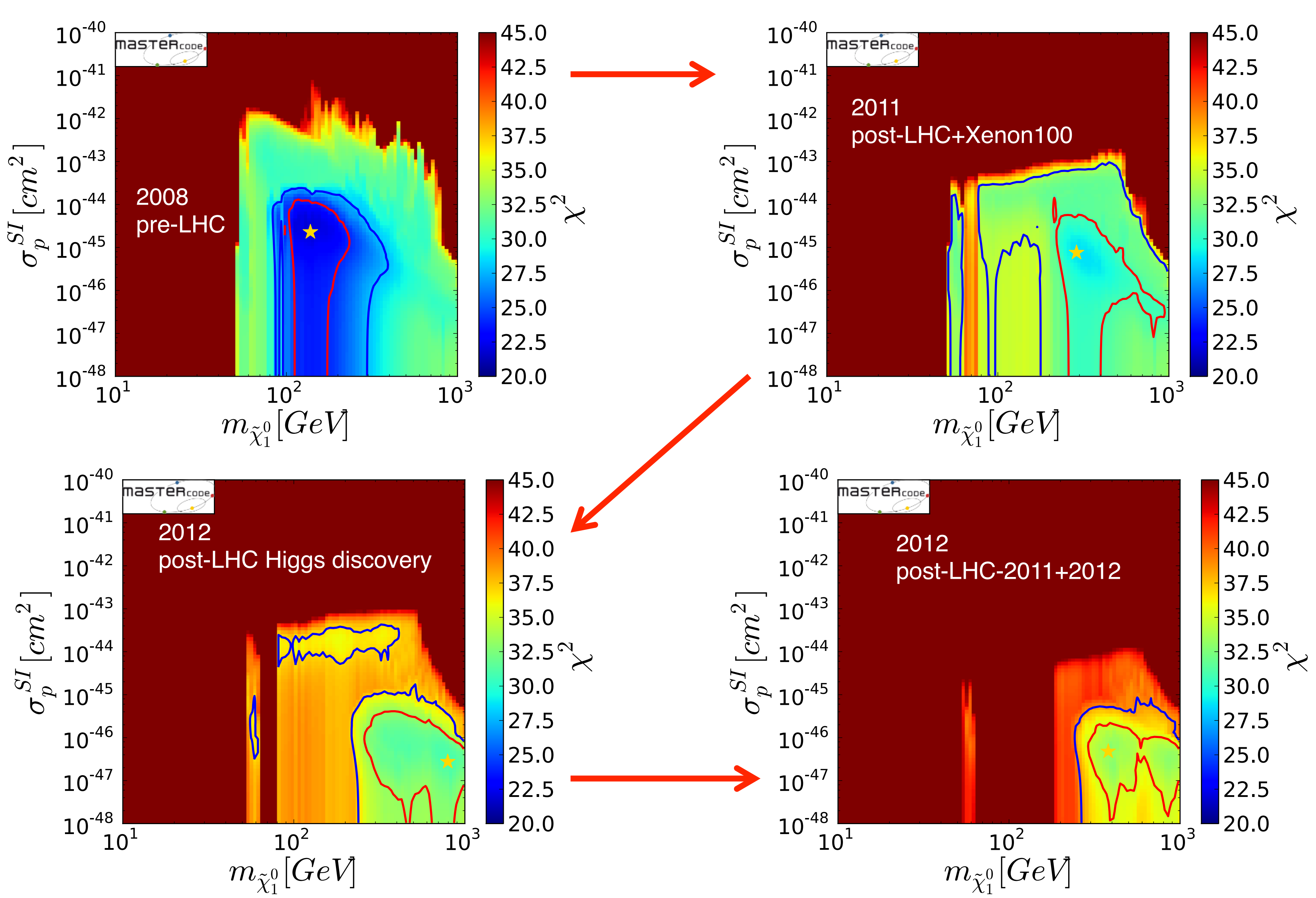



Neutrino noise will make it very difficult to go beyond it!

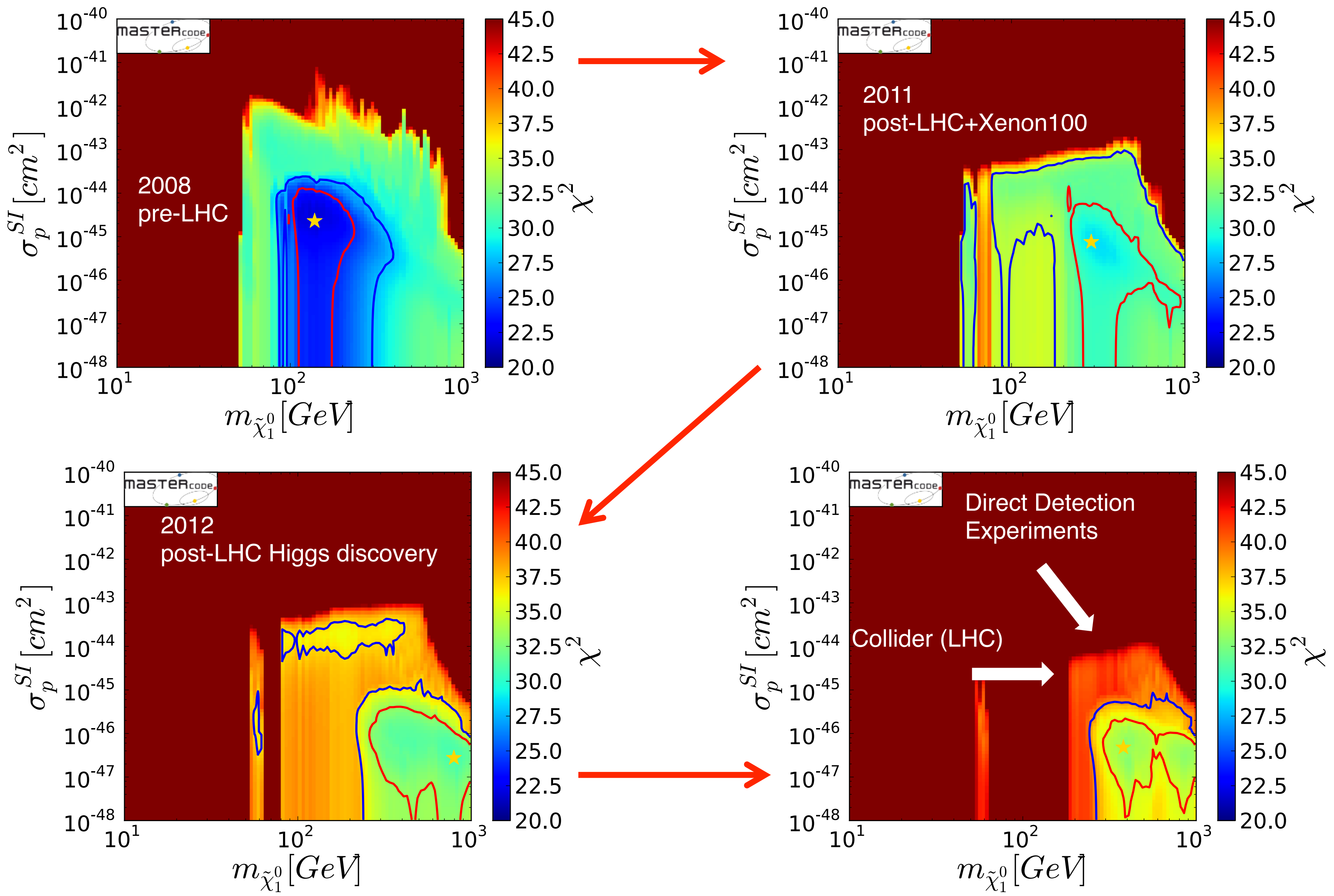
# SUSY & Dark Matter: Evolution with time





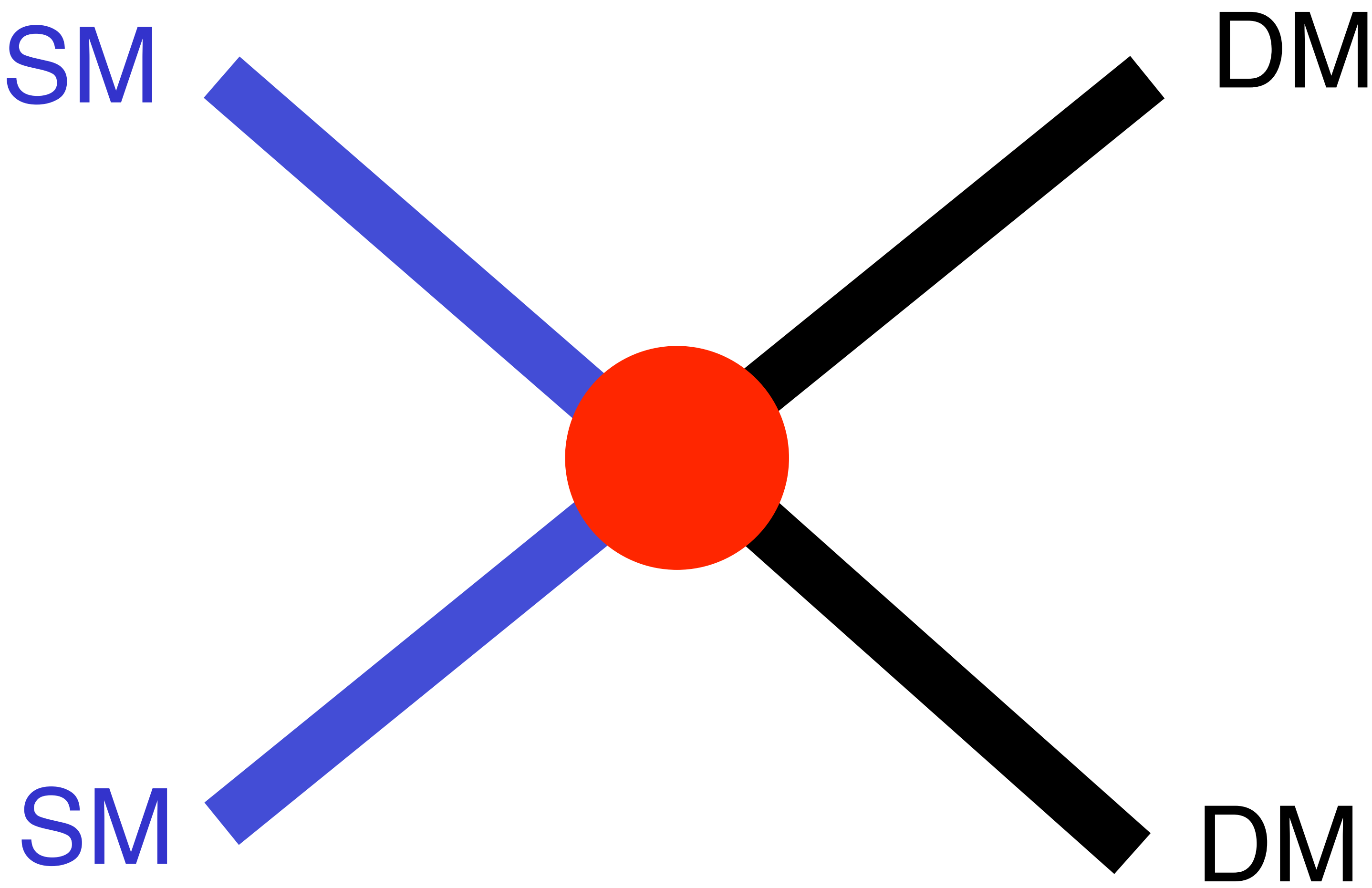
# SUSY & Dark Matter: Evolution with time

SUSY & DM Searches @ LHC O. Buchmüller



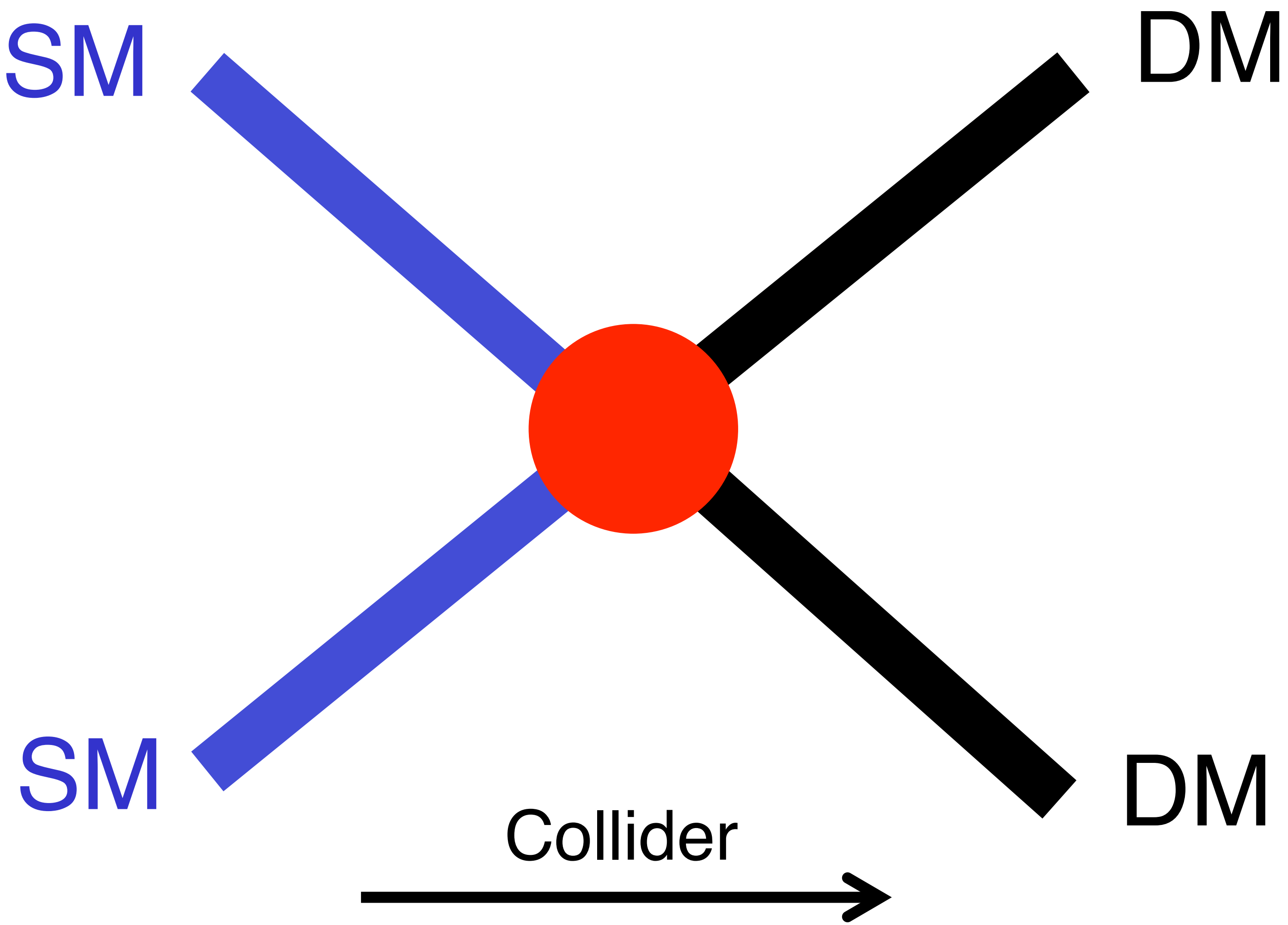
# Dark Matter Searches





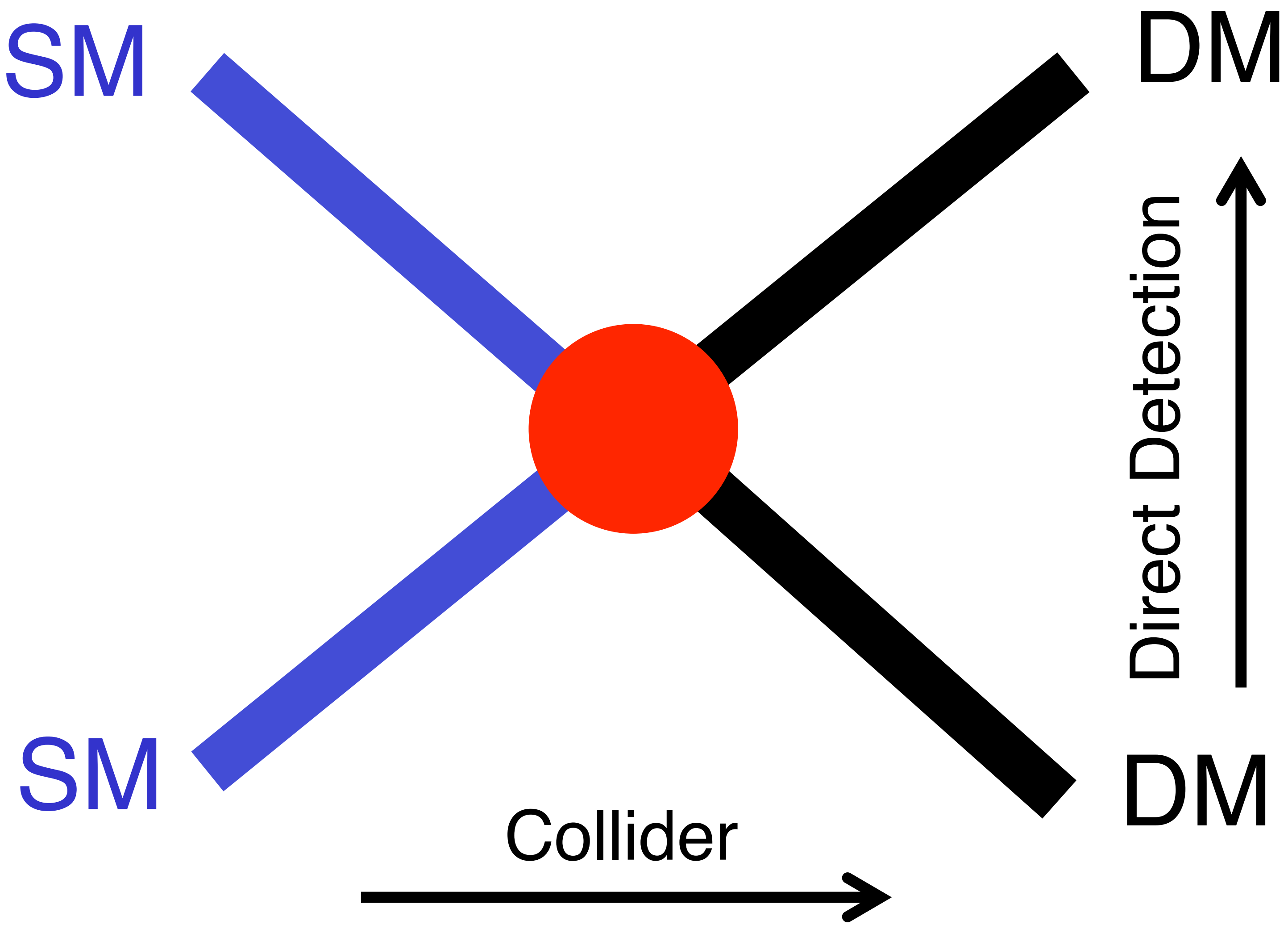
# Dark Matter Searches





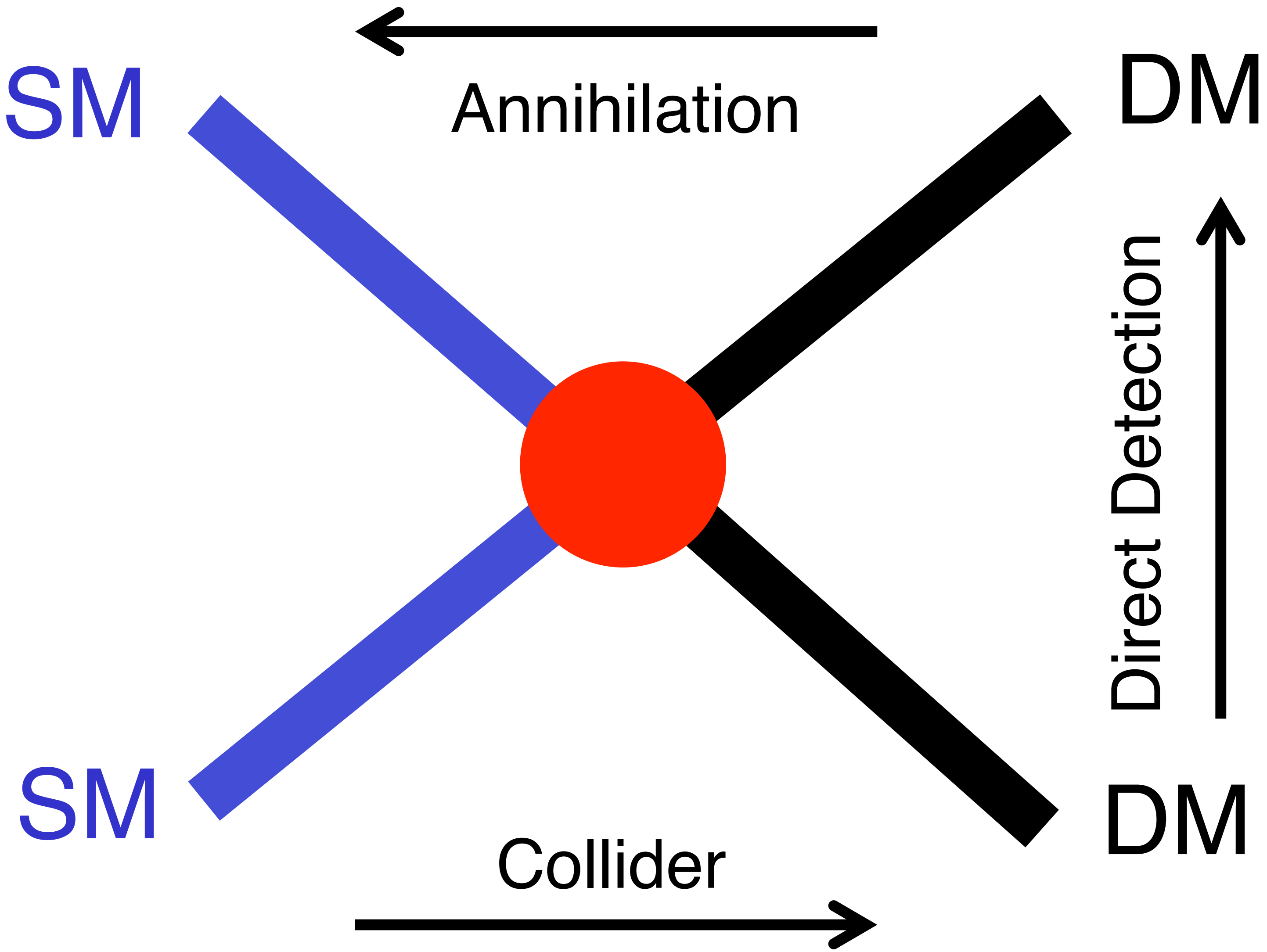
# Dark Matter Searches





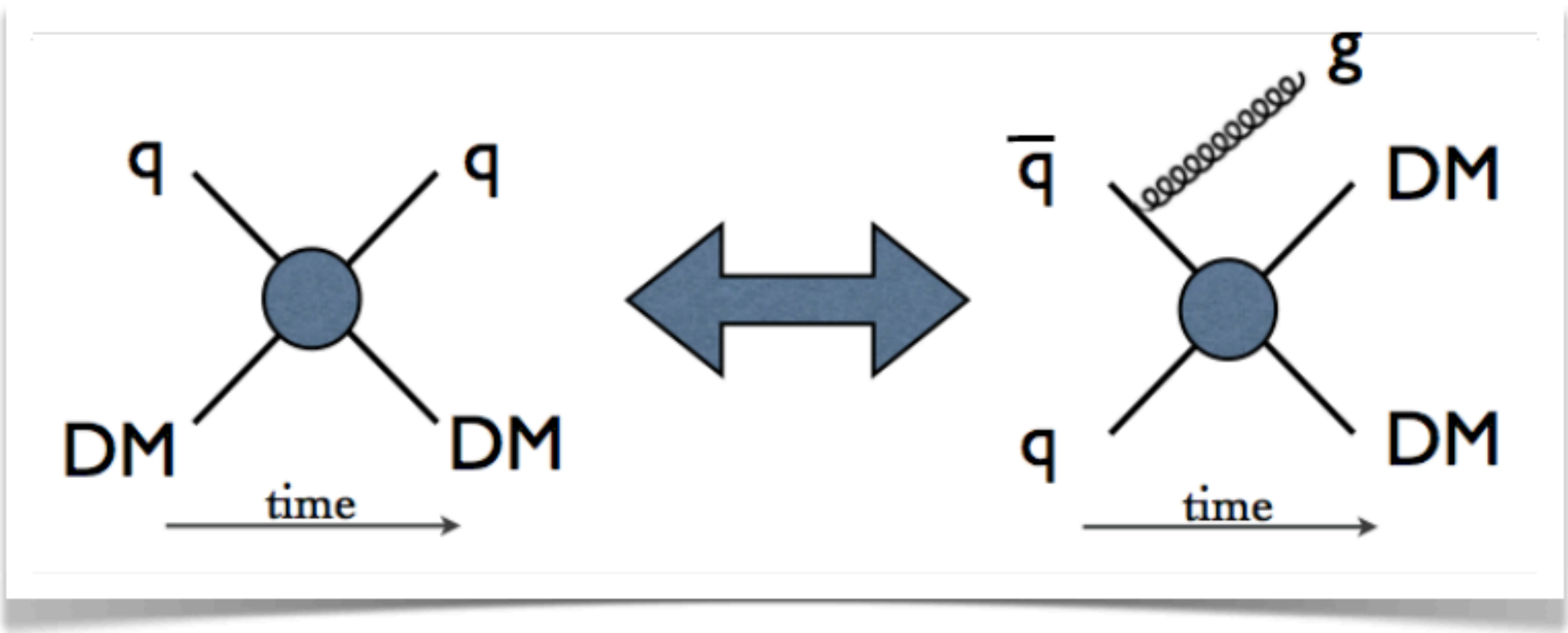
# Dark Matter Searches





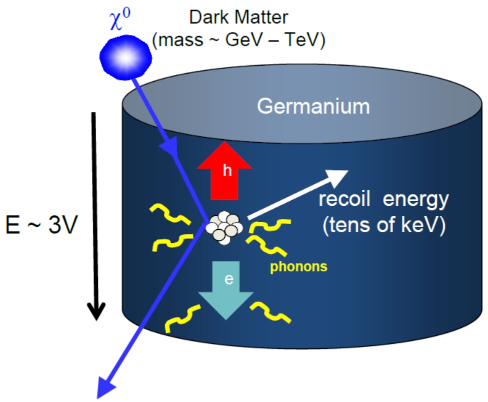
# Dark Matter Searches: Direct Detection vs Colliders





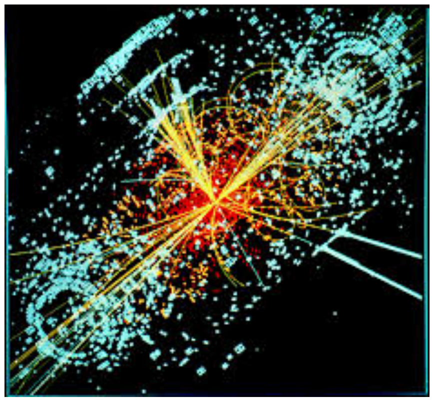

***Direct Detection Experiments***

- DM-nucleus scattering




***Collider Experiments***

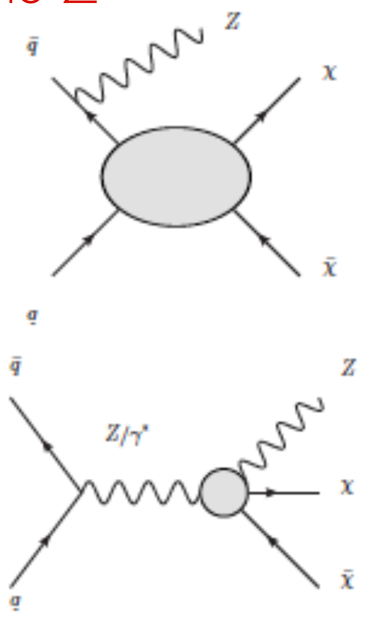
- Pair-production of DM
- missing energy signature



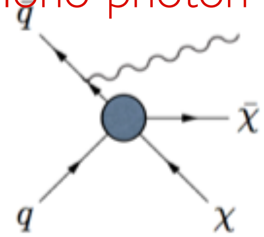
# Mono-Mania (at the LHC)



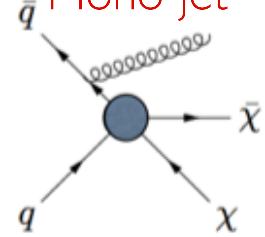
## Mono-Z



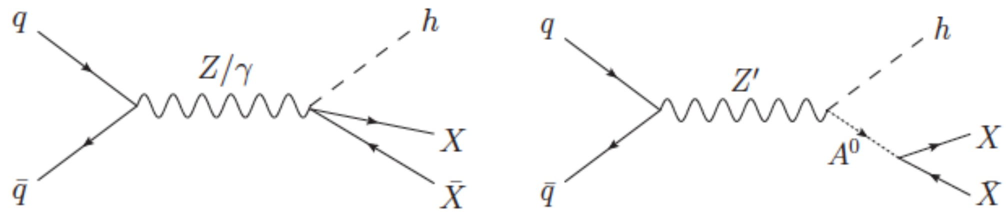
## Mono-photon



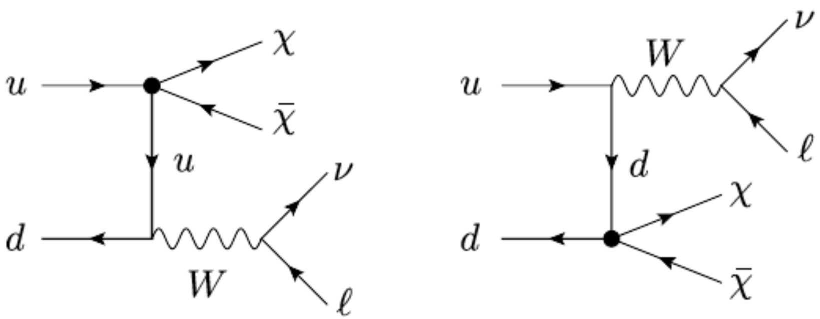

## Mono-jet



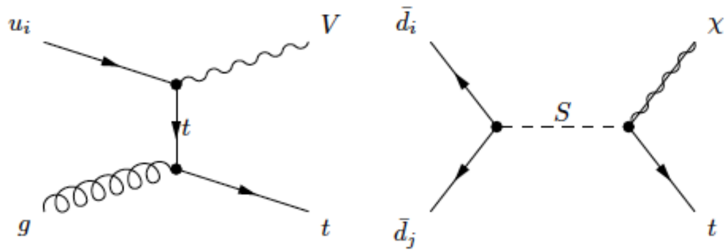

## Mono-Higgs




## Mono-W



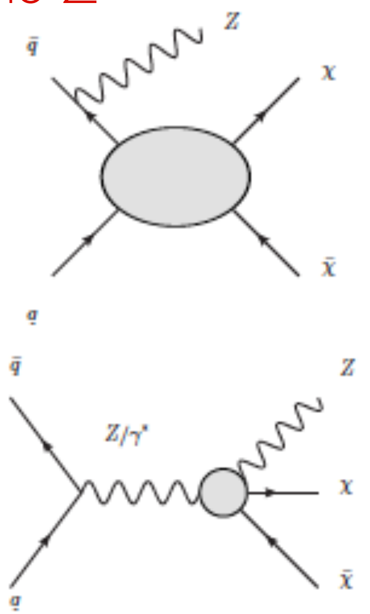

## Mono-top



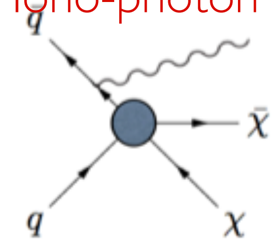
# Mono-Mania (at the LHC)



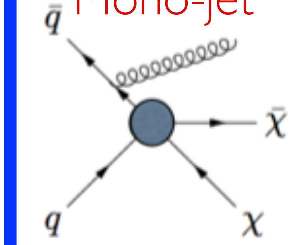
## Mono-Z



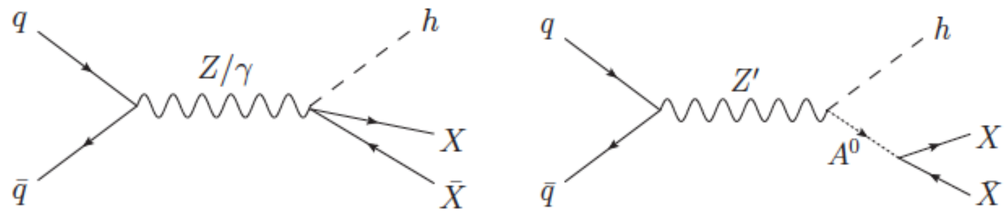

## Mono-photon



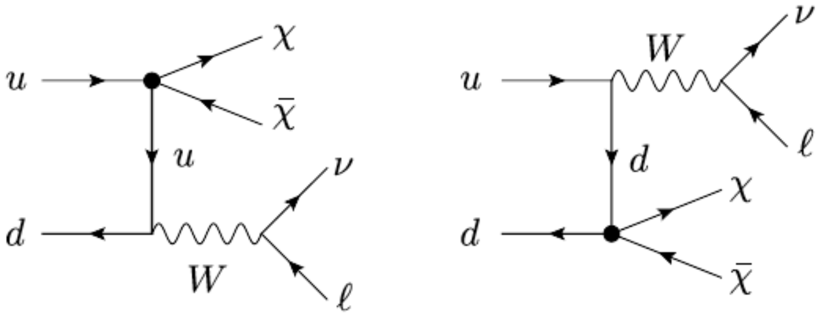

## Mono-jet



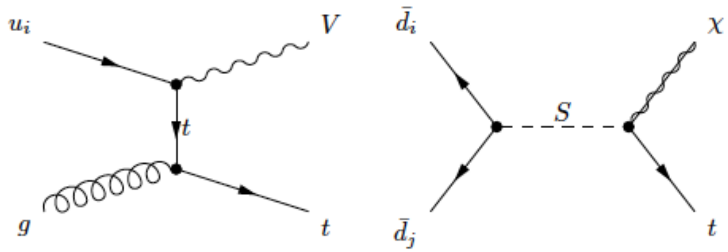

## Mono-Higgs




## Mono-W

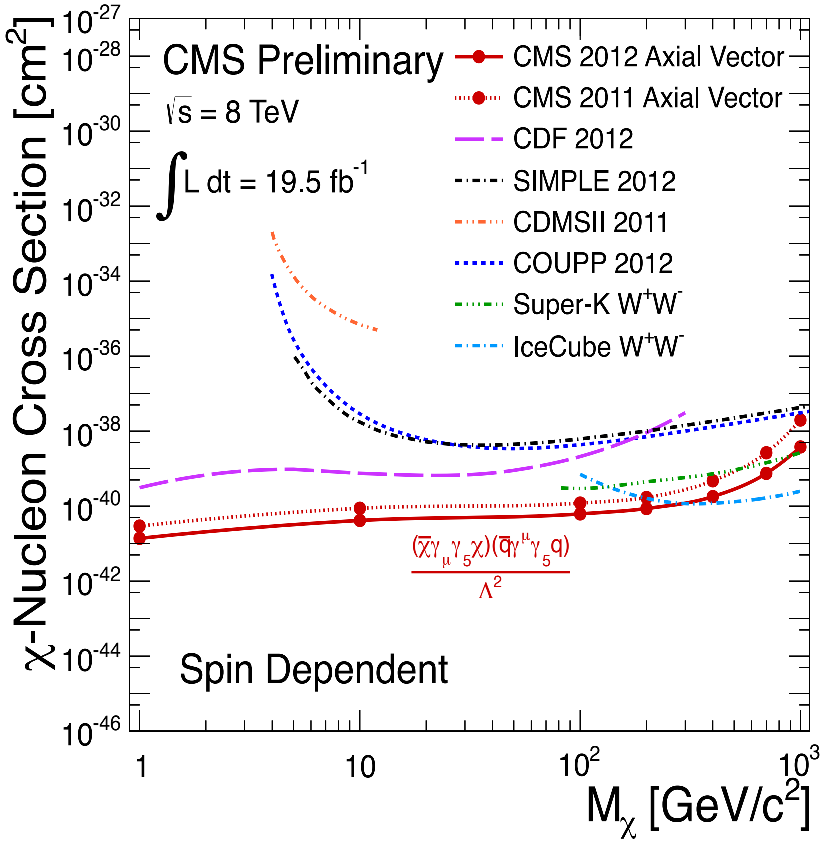


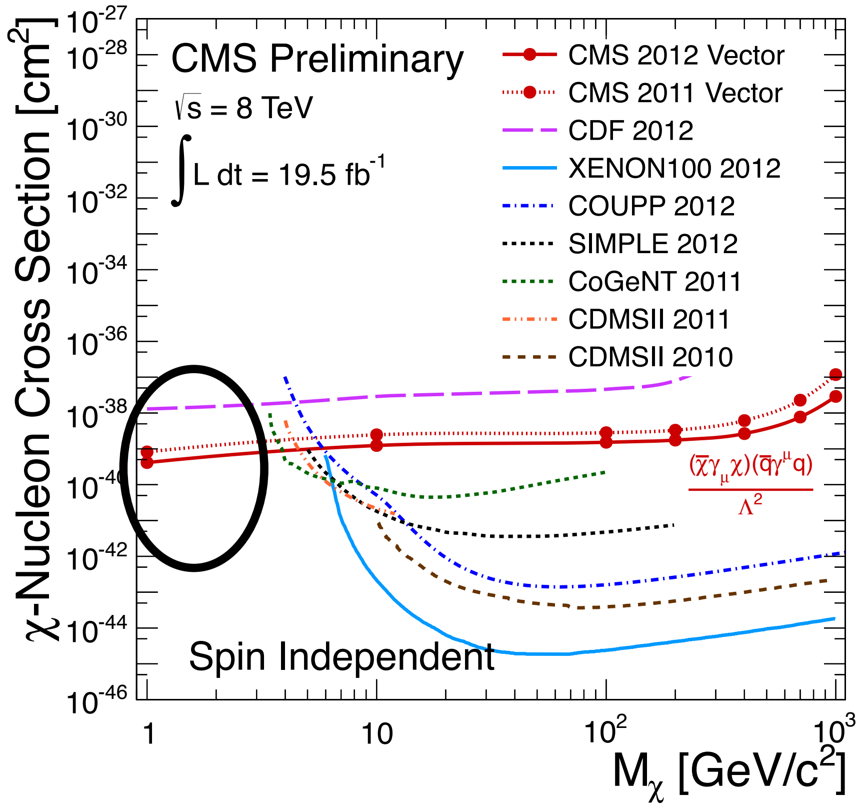

## Mono-top



# Monojet analyses better than direct detection?!






Claim [often made]:

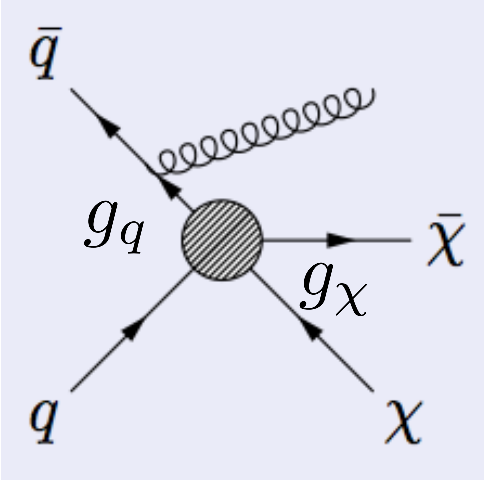
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

# Effective Field Theory (EFT) Interpretation



Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel




$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

**Assumption of EFT**

If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

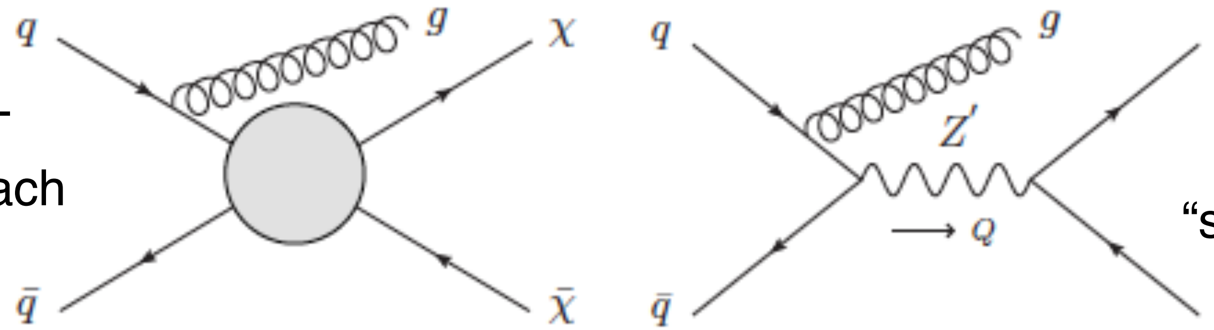
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

# Validity of Effective Field Theory Limits

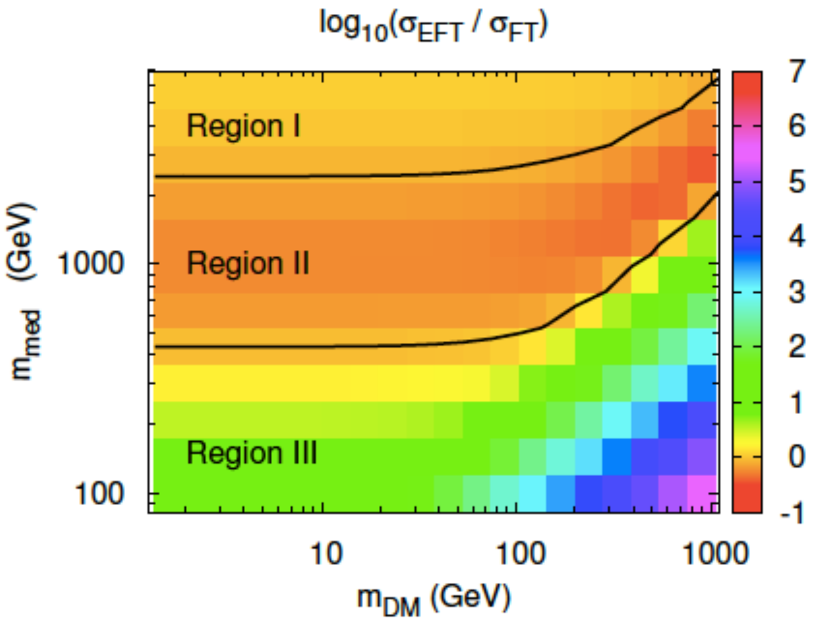


Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

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




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




Compare prediction of FT with EFT in $m_{med}$ – $m_{DM}$ plane. Three regions become visible:

Region I: EFT and FT agree better then 20%

- EFT is valid!

Region II: EFT yields significant weaker limits then FT

- EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT

- EFT limits are too aggressive!

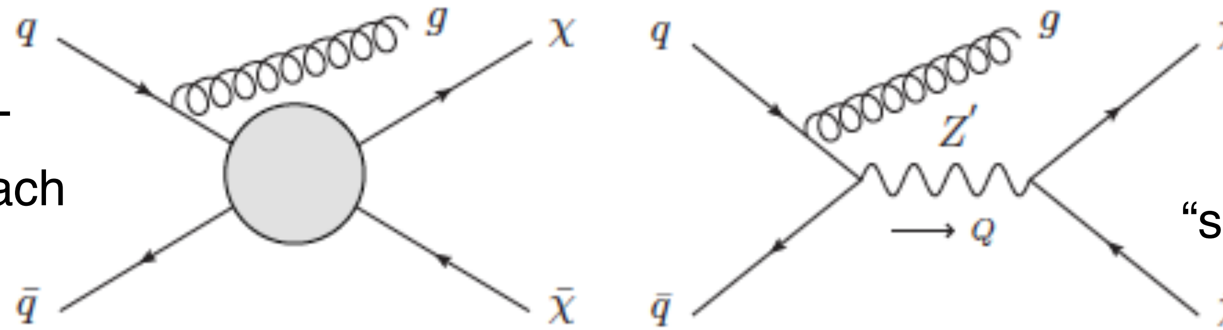
# Validity of Effective Field Theory Limits



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

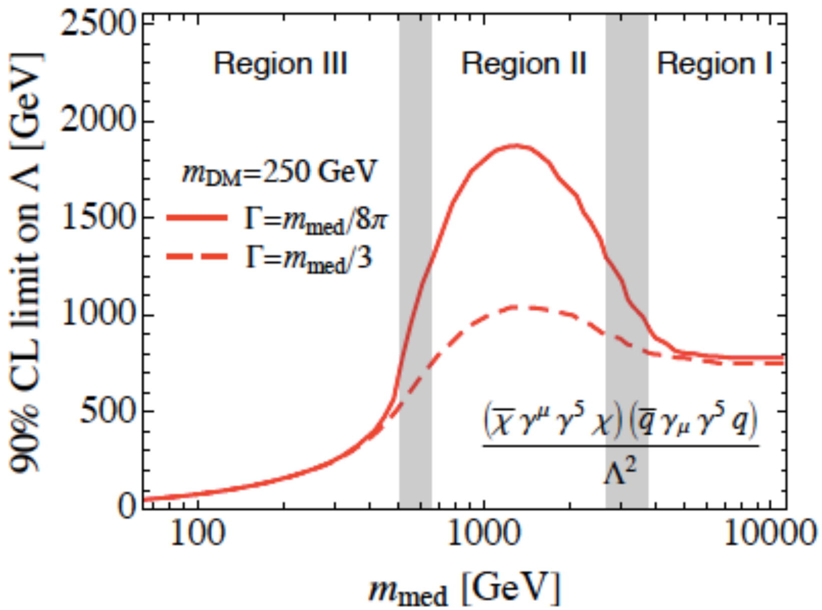
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach




FT one diagram "simplified model"

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




Three Regions as function of mediator mass:

Region I: Heavy $m_{med}$

- EFT is valid!

Region II: Medium $m_{med}$ – Resonant enhancement

- EFT limits are too conservative!

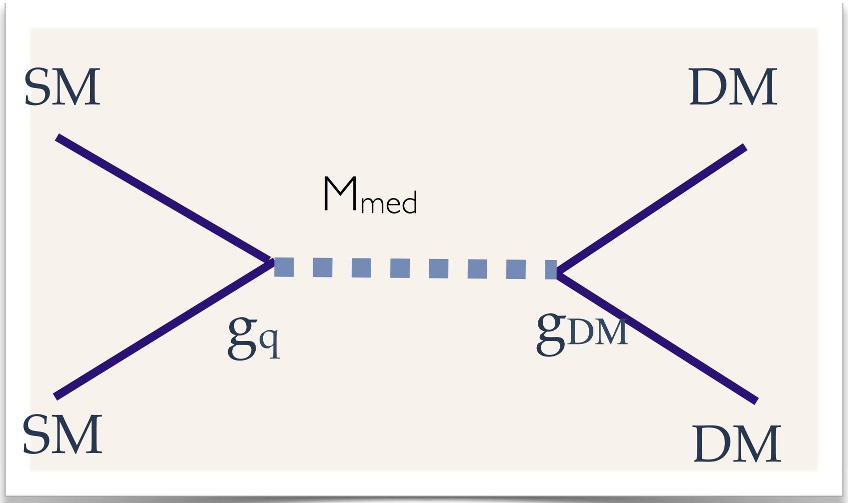
Region III: Low $m_{med}$

- EFT limits are too aggressive!

# Minimal Simplified Dark Matter Model



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




s-channel

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

| DM | |
|---|---|
| Dirac fermion | Scalar - real |
| Majorana fermion | Scalar - complex |

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

# MSDM: 4D Parameter Space



| | |
|---|---|
| $M_{DM}$ | $M_{med}$ |
| $g_q$ | $g_{DM}$ |

4-dimensional problem, projecting limits onto all 2-D plane:

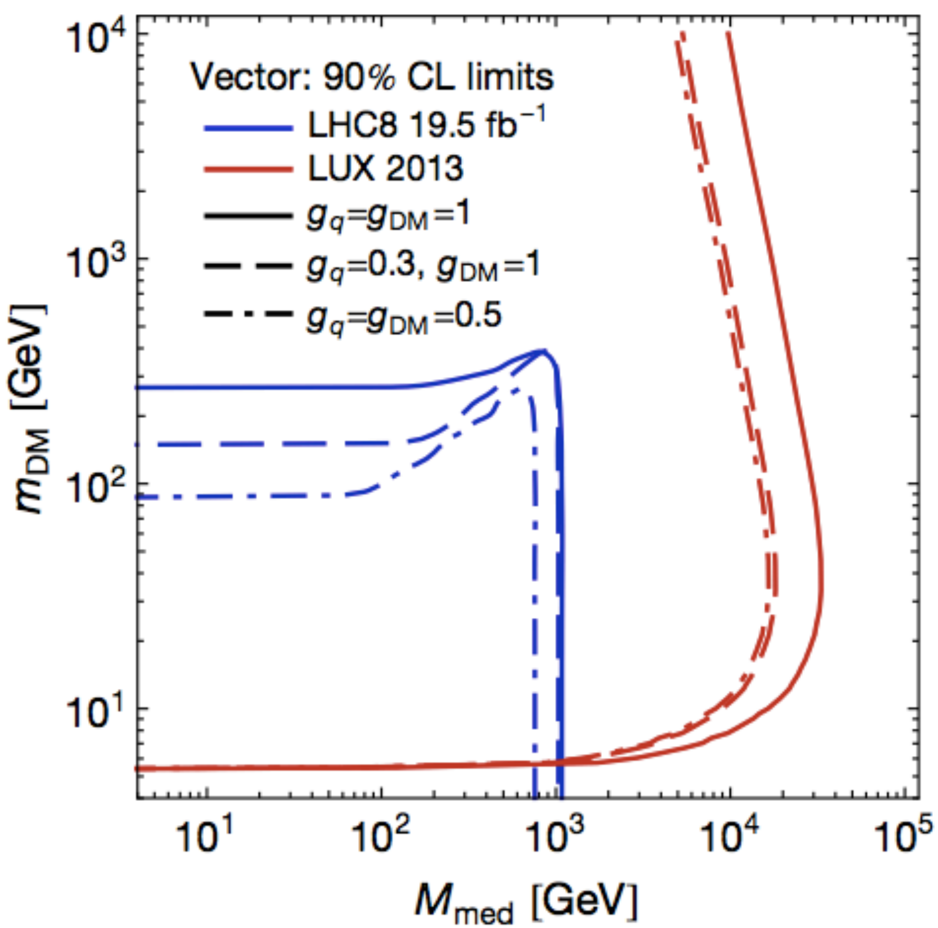
- $M_{DM}$ vs $M_{med}$ assuming $g_q = g_{DM}$ and $g_q \neq g_{DM}$
- $M_{med}$ vs $g_q, g_{DM}$ for fixed $M_{DM}$
- $M_{DM}$ vs $g_q, g_{DM}$ for fixed $M_{med}$
- $g_q$ vs $g_{DM}$ for fixed $M_{DM}$, $M_{med}$

# Collider vs Direct Detection

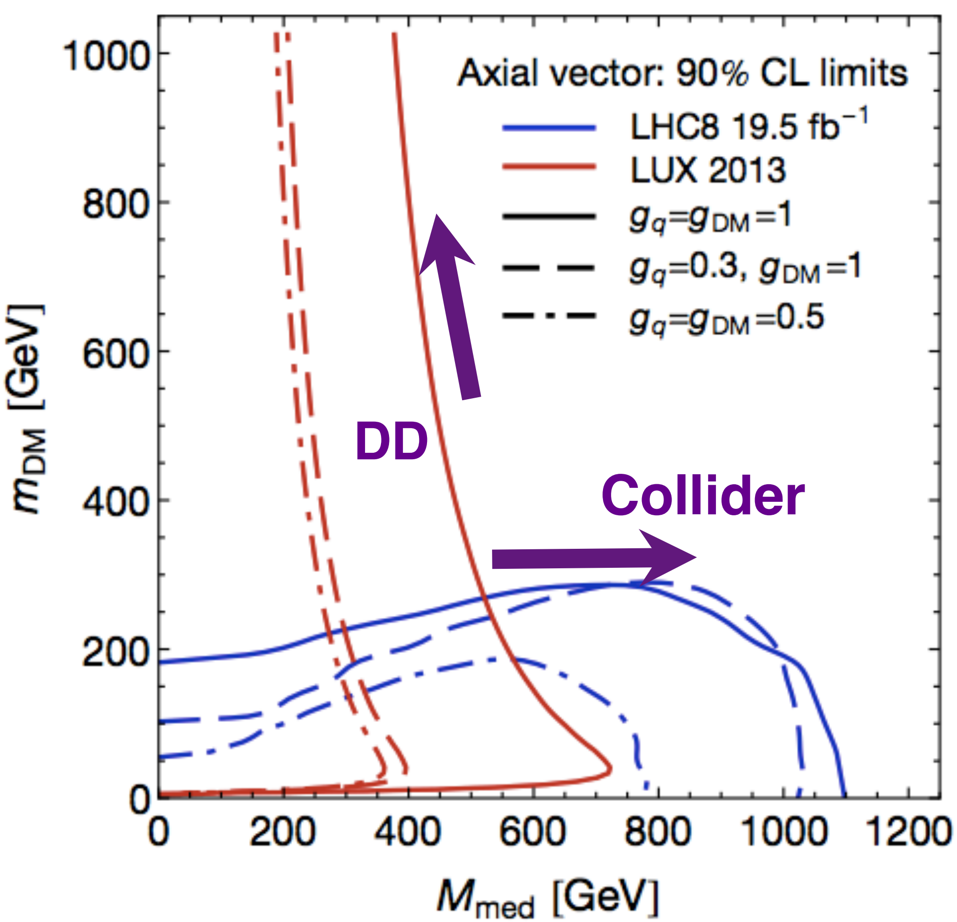
O. Buchmüller

| $M_{DM}$ | $M_{med}$ |
|---|---|
| $g_q$ | $g_{DM}$ |

**Vector**




**Axial vector**

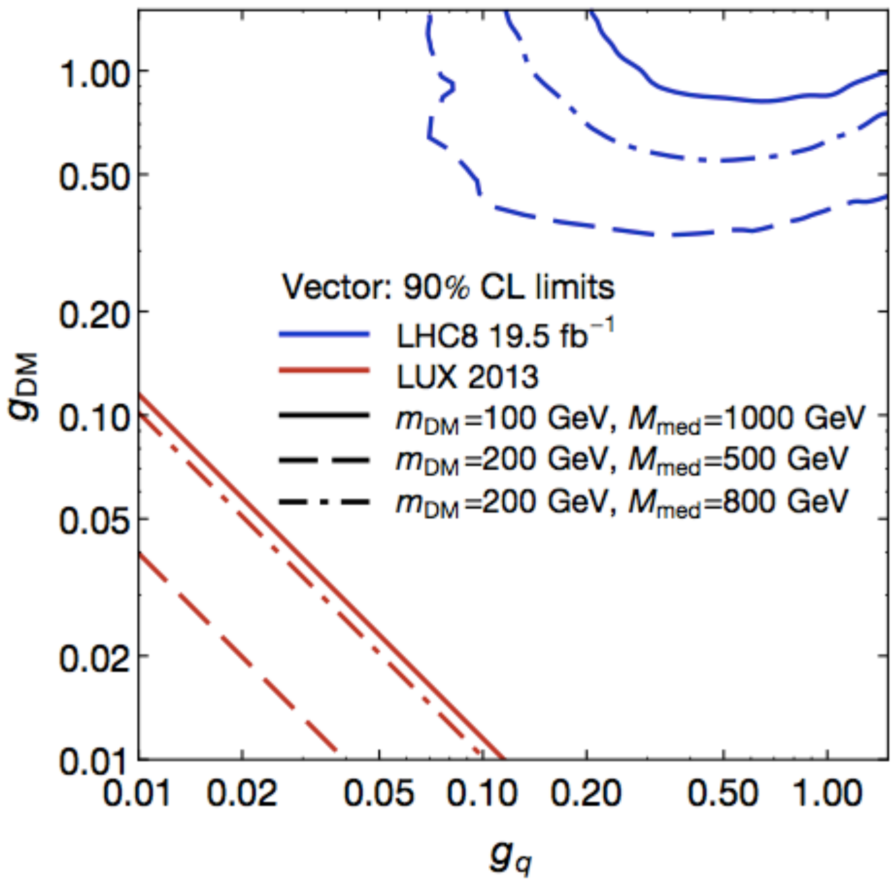


# Collider vs Direct Detection

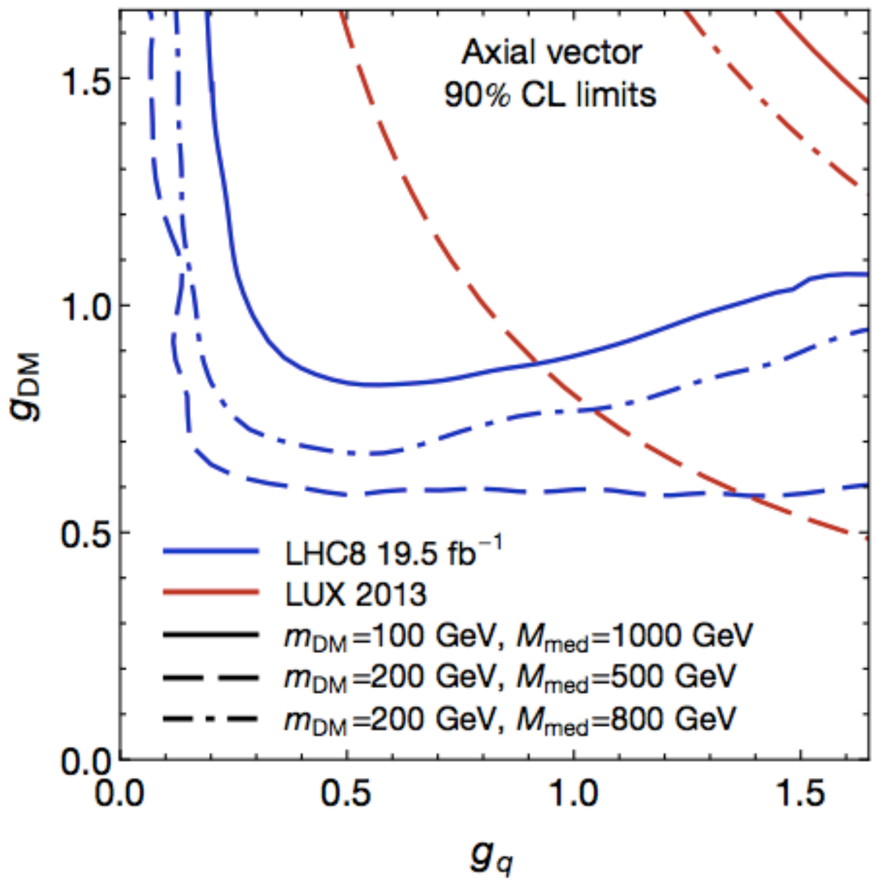


| $M_{DM}$ | $M_{med}$ |
| --- | --- |
| $g_q$ | $g_{DM}$ |

Vector




Axial vector



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



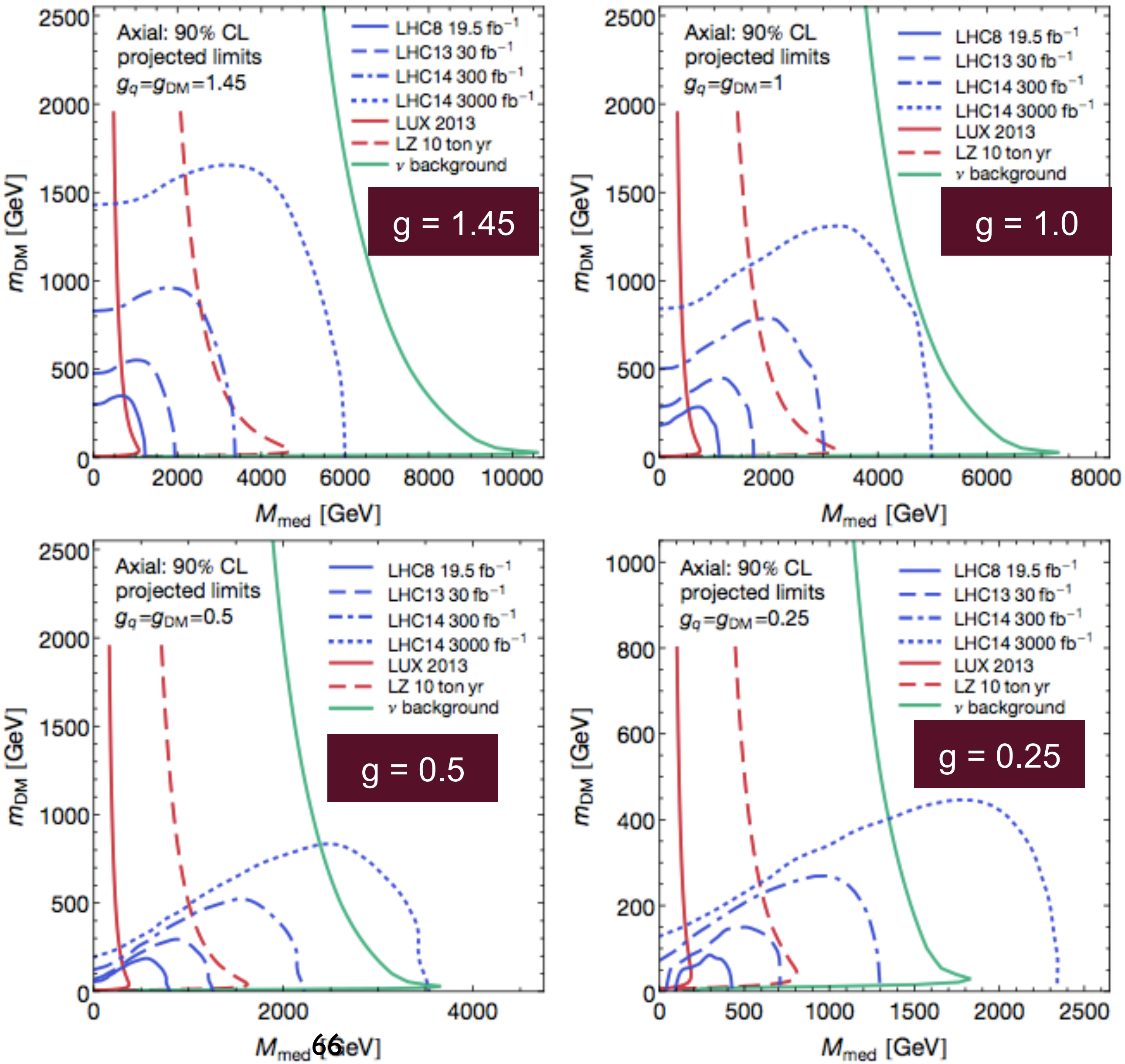
arXiv:1409.4075

Limits from 8 TeV monojet search and projected limits for 3 LHC scenarios:

- 13 TeV 30 $fb^{-1}$
- 14 TeV, 300 $fb^{-1}$
- 14 TeV, 3000 $fb^{-1}$

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

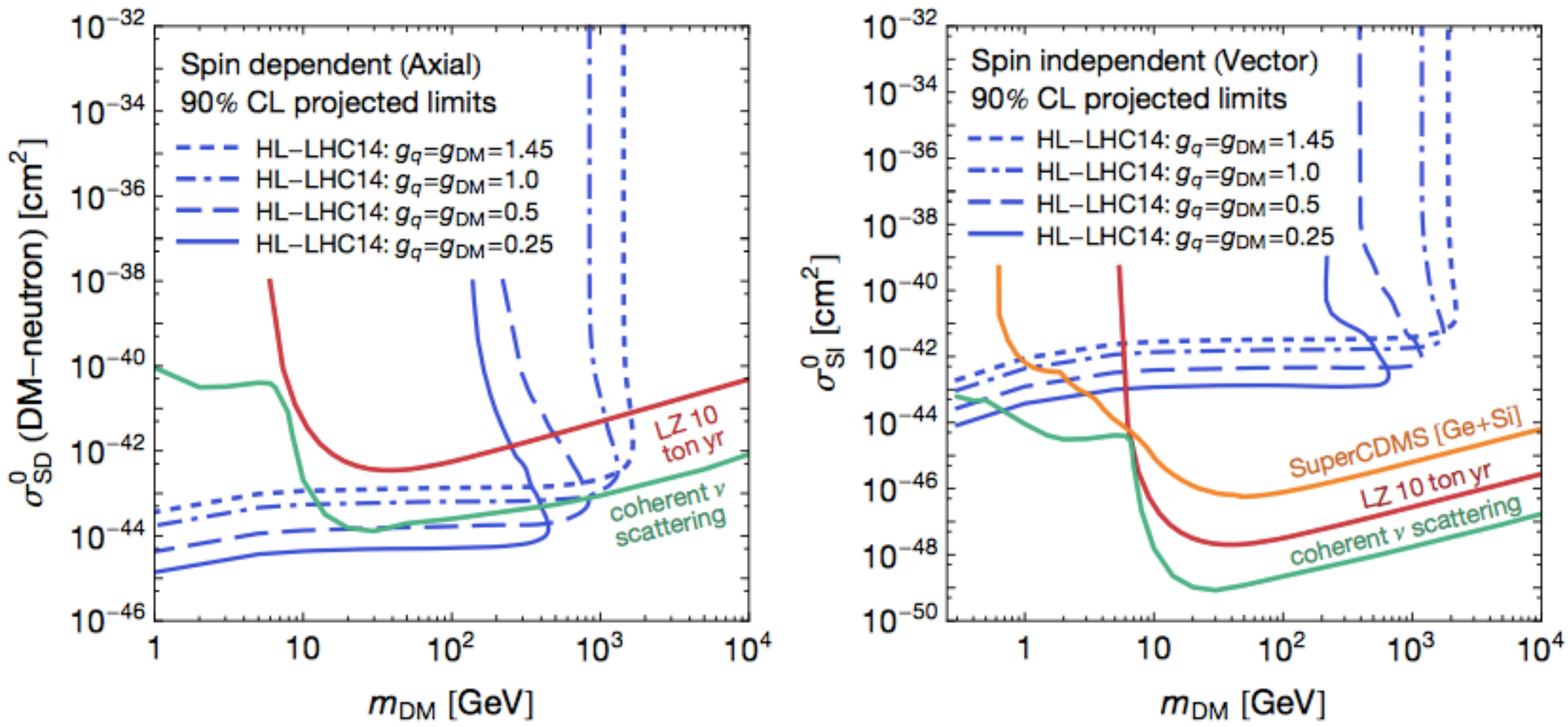
Discovery reach accounting for coherent neutrino scattering



# Projections for Future Experiments: $\sigma$ vs $M_{DM}$

iller

Can be also shown in the $\sigma$ vs $M_{DM}$ plane …




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

# Outlook: 8 TeV vs 14 TeV



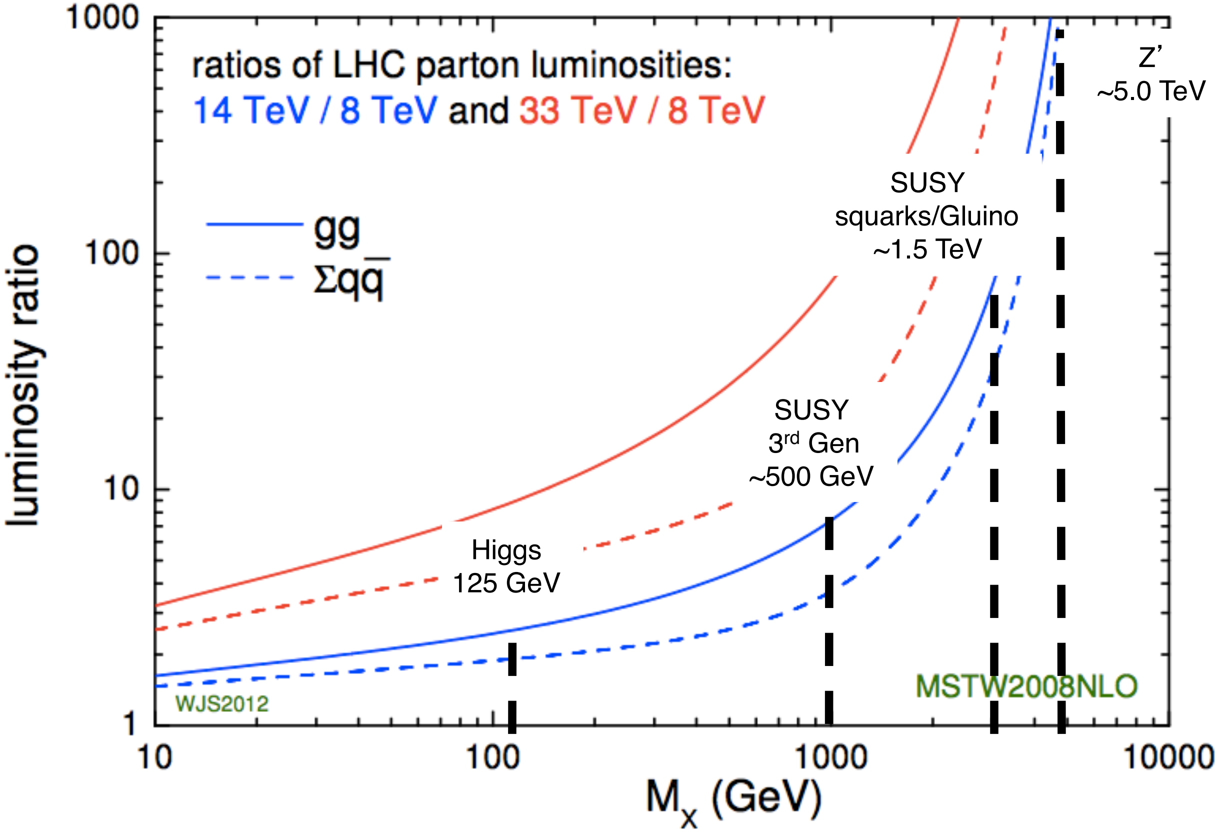
Use parton luminosities to illustrate the gain of 14 vs 8 TeV

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

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~3 to 6

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

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




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

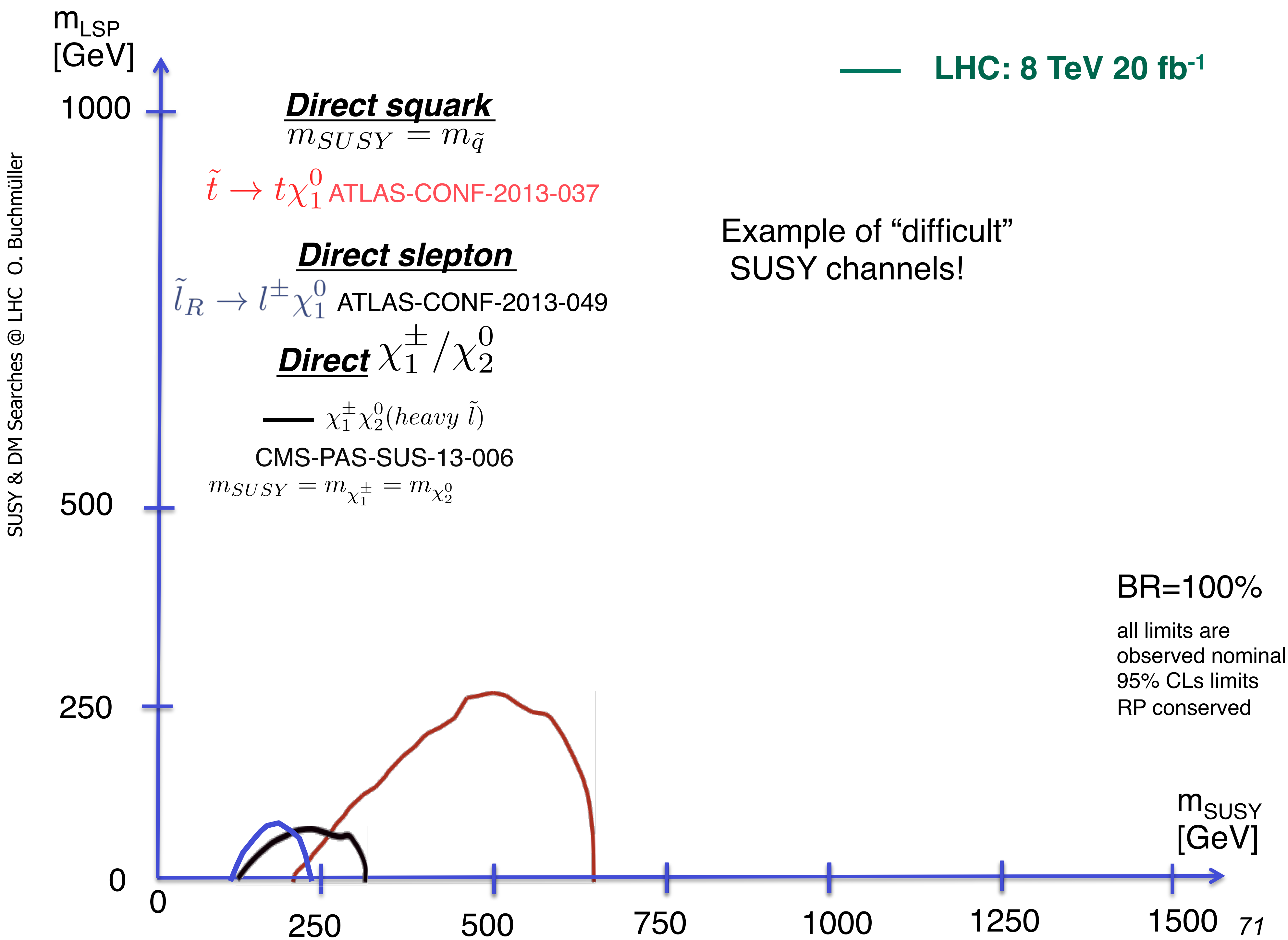
# Summary



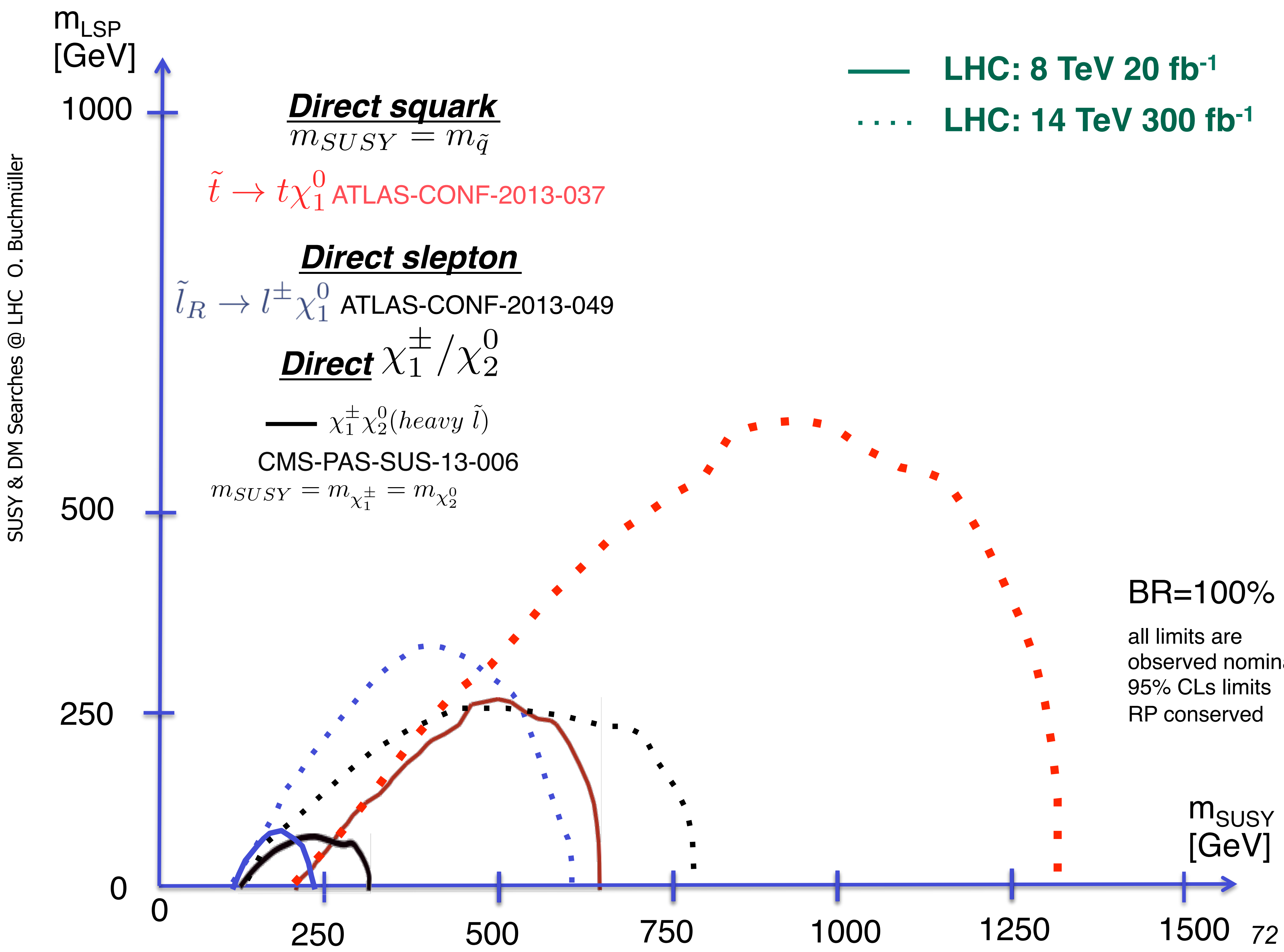
- So far New Physics has not revealed itself!
  - Even by 2010 the LHC has enter new territory for New Physics searches and since pushed e.g. the (coloured) SUSY mass scale to the ~1 TeV scale
  - We were well prepared for an early discovery but we also knew that it could take more time and ingenuity before we can claim a discovery (if NP exist)
- The LHC experiments have established an impressive variety of very powerful direct searches for many different final states!
  - Based on these results we need to establish the "big picture" in order to understand find out if/where our search strategy might have weak spots or even holes!
  - This requires appropriate interpretations of the searches and a MEANIGFUL comparison with other experiments – important example DM searches!
- The high energy running of the LHC starting 2015 will be our next very (as in VERY) real chance for discovery!

The story continues … stay tuned!

# BACKUP



SUSY & DM Searches @ LHC O. Buchmüller
$m_{LSP}$ [GeV]
1000
500
250
0
LHC: 8 TeV 20 fb$^{-1}$
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
Example of "difficult" SUSY channels!
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
$m_{SUSY}$ [GeV]
0
250
500
750
1000
1250
1500



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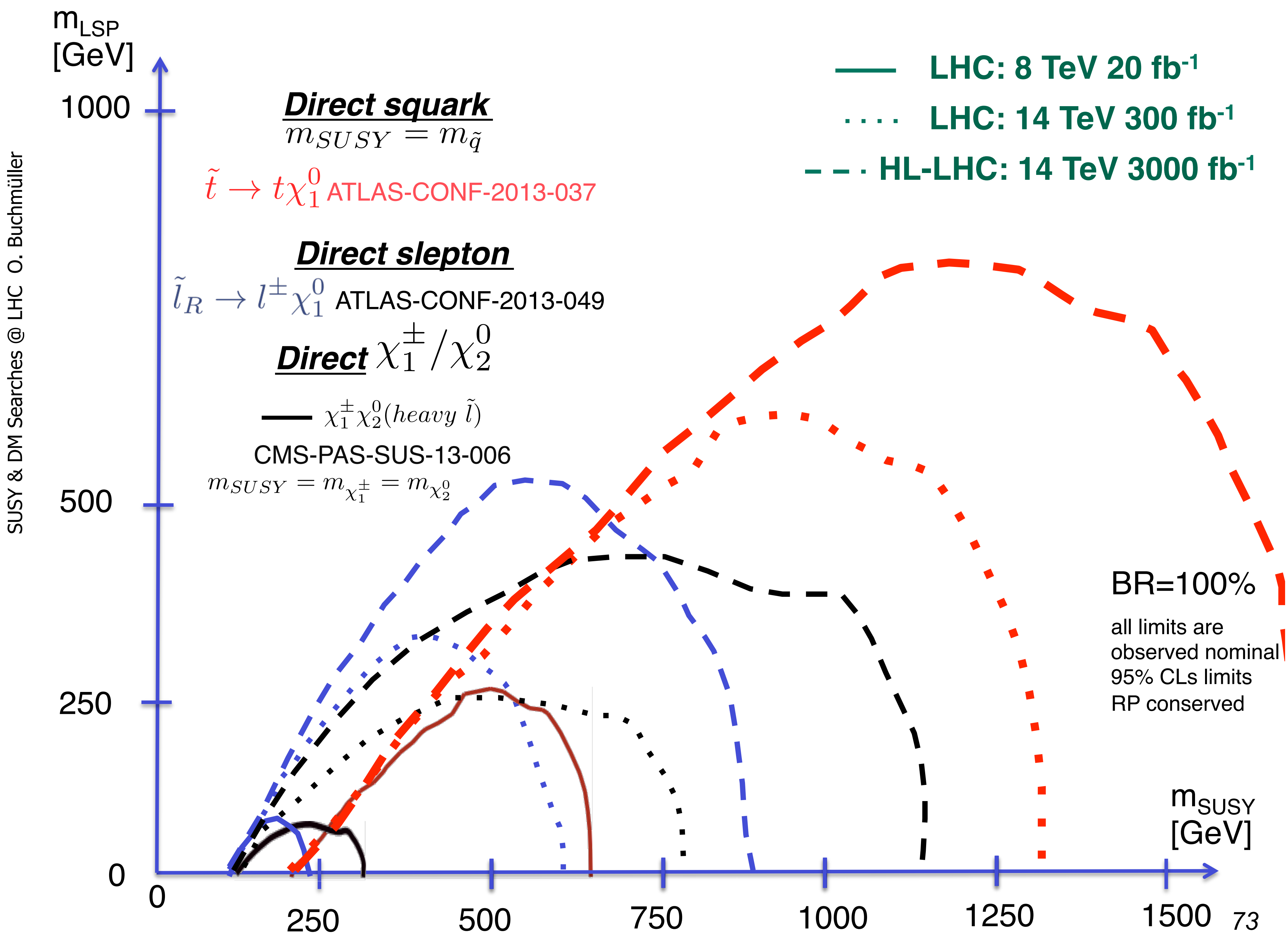
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SUSY & DM Searches @ LHC O. Buchmüller
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Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
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LHC: 14 TeV 300 fb-1
HL-LHC: 14 TeV 3000 fb-1
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all limits are
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RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
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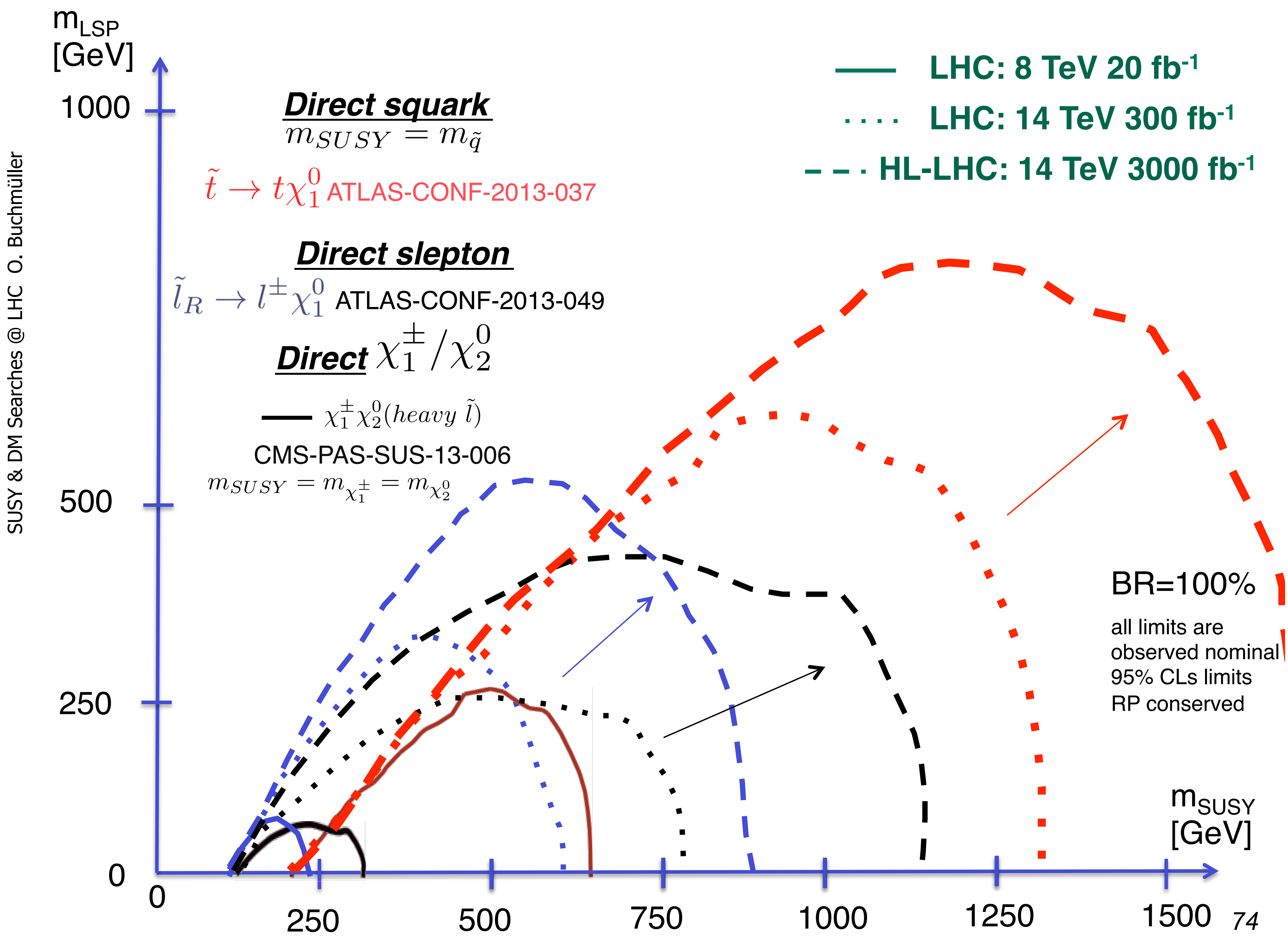

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1000
500
250
0
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Direct $\chi_1^{\pm}/\chi_2^0$
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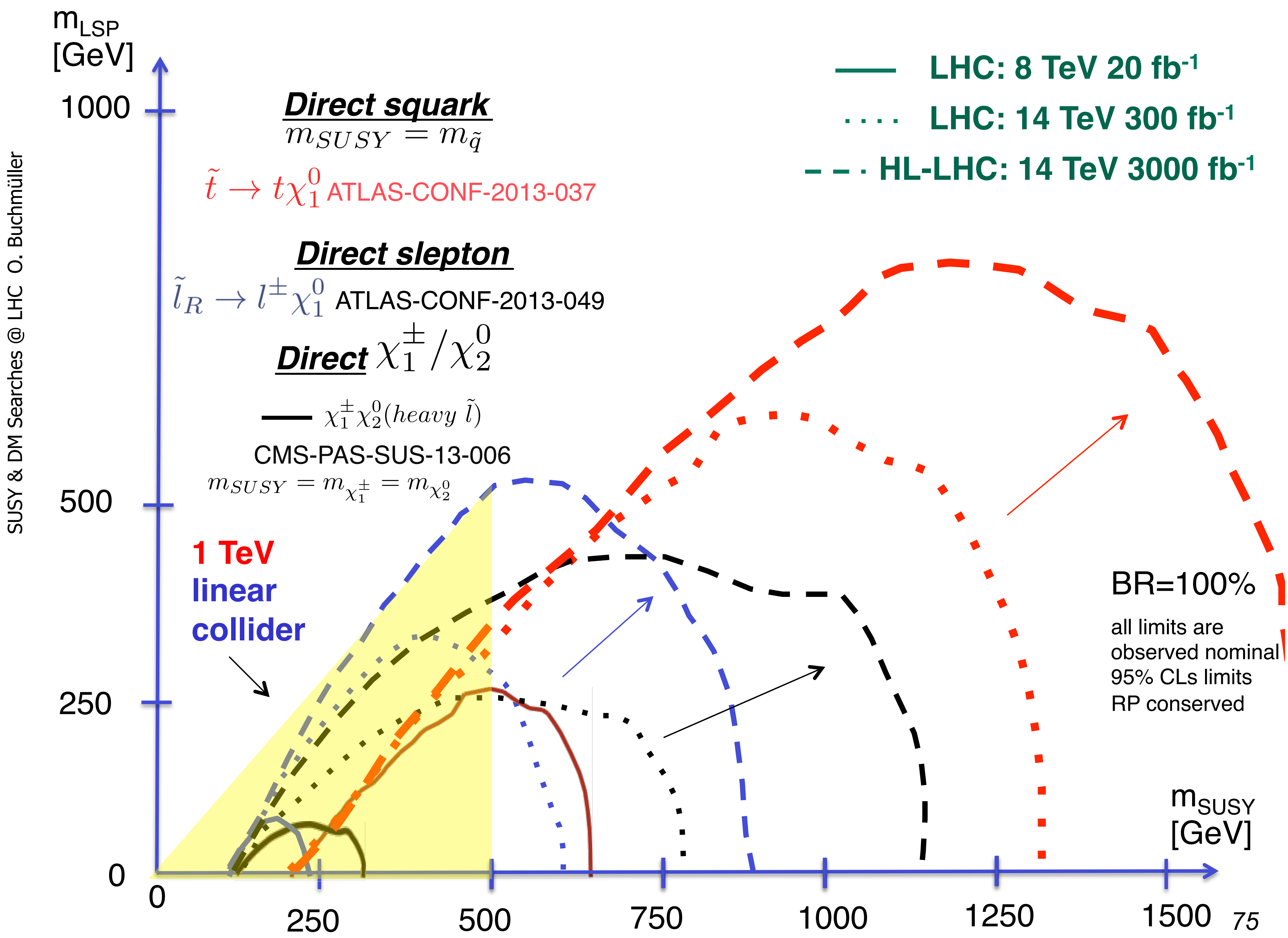
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb$^{-1}$
LHC: 14 TeV 300 fb$^{-1}$
HL-LHC: 14 TeV 3000 fb$^{-1}$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
SUSY & DM Searches @ LHC O. Buchmüller



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

# ATLAS & CMS public results



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

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

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

# ATLAS Summary



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

Status: EPS 2013

**ATLAS** Preliminary

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

| | Model | $e, \mu, \tau, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L} dt [fb^{-1}]$ | Mass limit | | Condition | 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 $e, \mu$ | 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 $e, \mu$ | 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 $e, \mu$ (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 $e, \mu$ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ | 1.24 TeV | $\tan\beta$<15 | 1208.4688 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ | 0-2 jets | Yes | 20.7 | $\tilde{g}$ | 1.4 TeV | $\tan\beta$ >18 | ATLAS-CONF-2013-026 |
| | GGM (bino NLSP) | 2 $\gamma$ | 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) | $\gamma$ | 1 $b$ | Yes | 4.8 | $\tilde{g}$ | 900 GeV | $m(\tilde{\chi}_1^0)$>220 GeV | 1211.1167 |
| | GGM (higgsino NLSP) | 2 $e, \mu$ ($Z$) | 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 $e, \mu$ | 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 $e, \mu$ | 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 $e, \mu$ (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 $e, \mu$ | 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 $e, \mu$ | 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 $e, \mu$ | 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 $e, \mu$ | 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 $e, \mu$ ($Z$) | 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 $e, \mu$ ($Z$) | 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 $e, \mu$ | 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 $e, \mu$ | 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 $\tau$ | 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 $e, \mu$ | 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 $e, \mu$ | 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 $\mu s<\tau(\tilde{g})$<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 $\mu$ | 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 $\gamma$ | 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 $\mu$ | 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 $e, \mu$ | 0 | - | 4.6 | $\tilde{\nu}_\tau$ | 1.61 TeV | $\lambda'_{311}$=0.10, $\lambda_{132}$=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 | $\lambda'_{311}$=0.10, $\lambda_{1(2)33}$=0.05 | 1212.1272 |
| | Bilinear RPV CMSSM | 1 $e, \mu$ | 7 jets | Yes | 4.7 | $\tilde{q}, \tilde{g}$ | 1.2 TeV | $m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<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 $e, \mu$ | 0 | Yes | 20.7 | $\tilde{\chi}_1^{\pm}$ | 760 GeV | $m(\tilde{\chi}_1^0)$>300 GeV, $\lambda_{121}$>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, $\lambda_{133}$>0 | ATLAS-CONF-2013-036 |
| | $\tilde{g}\to qqq$ | 0 | 6 jets | - | 4.6 | $\tilde{g}$ | 666 GeV | | 1210.4813 |
| | $\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ | 2 $e, \mu$ (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 $\chi$) | 0 | mono-jet | Yes | 10.5 | M* scale | 704 GeV | $m(\chi)$<80 GeV, limit of<687 GeV for D8 | ATLAS-CONF-2012-147 |

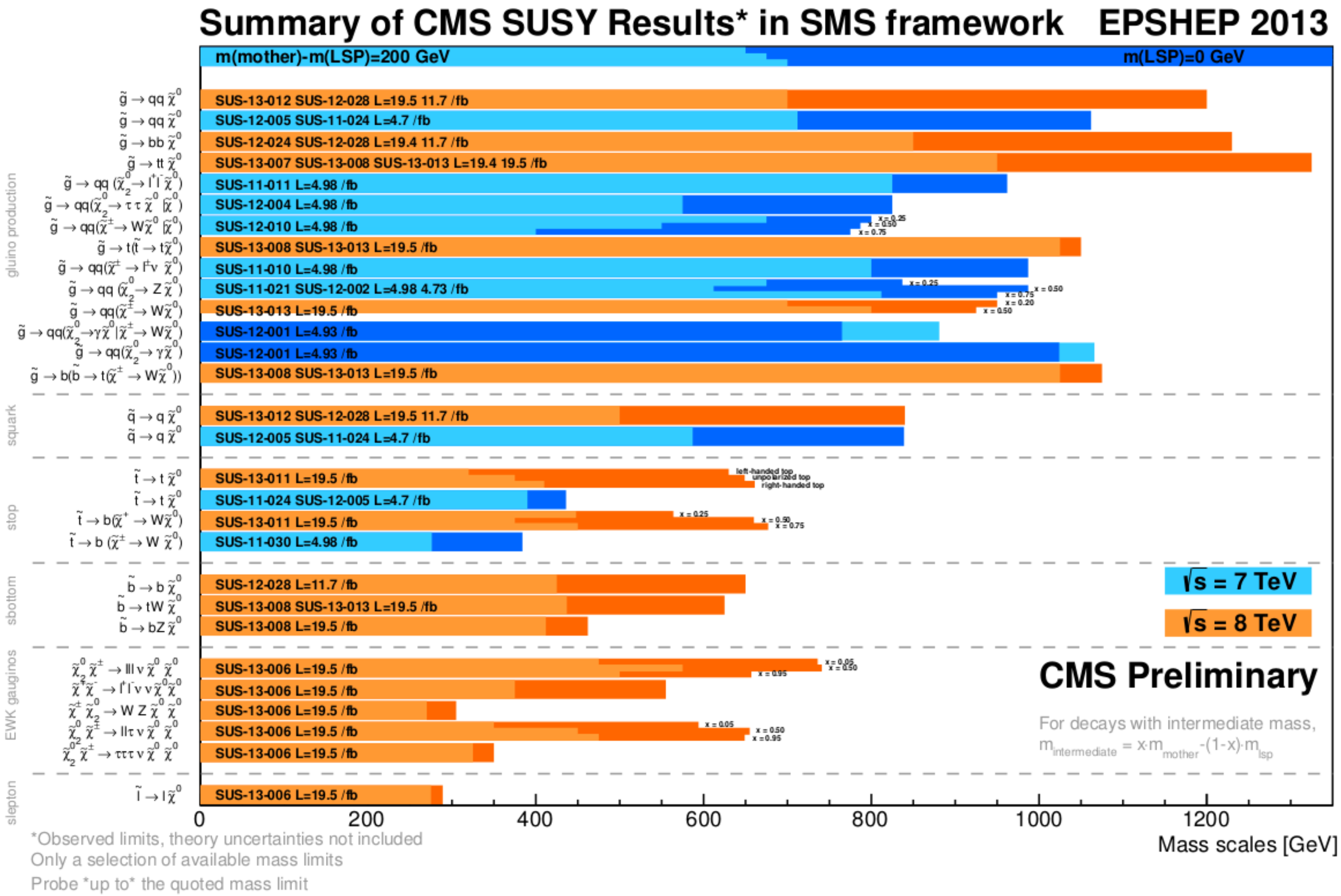
Mass scale [TeV] (axis: $10^{-1}$, 1)

Legend: $\sqrt{s}$ = 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 1$\sigma$ 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
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
squark
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
stop
SUS-13-011 L=19.5 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
sbottom
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother - (1-x)·m_lsp
0
200
400
600
800
1000
1200
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

# Summary

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

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

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

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



coloured sparticle production

| **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 |

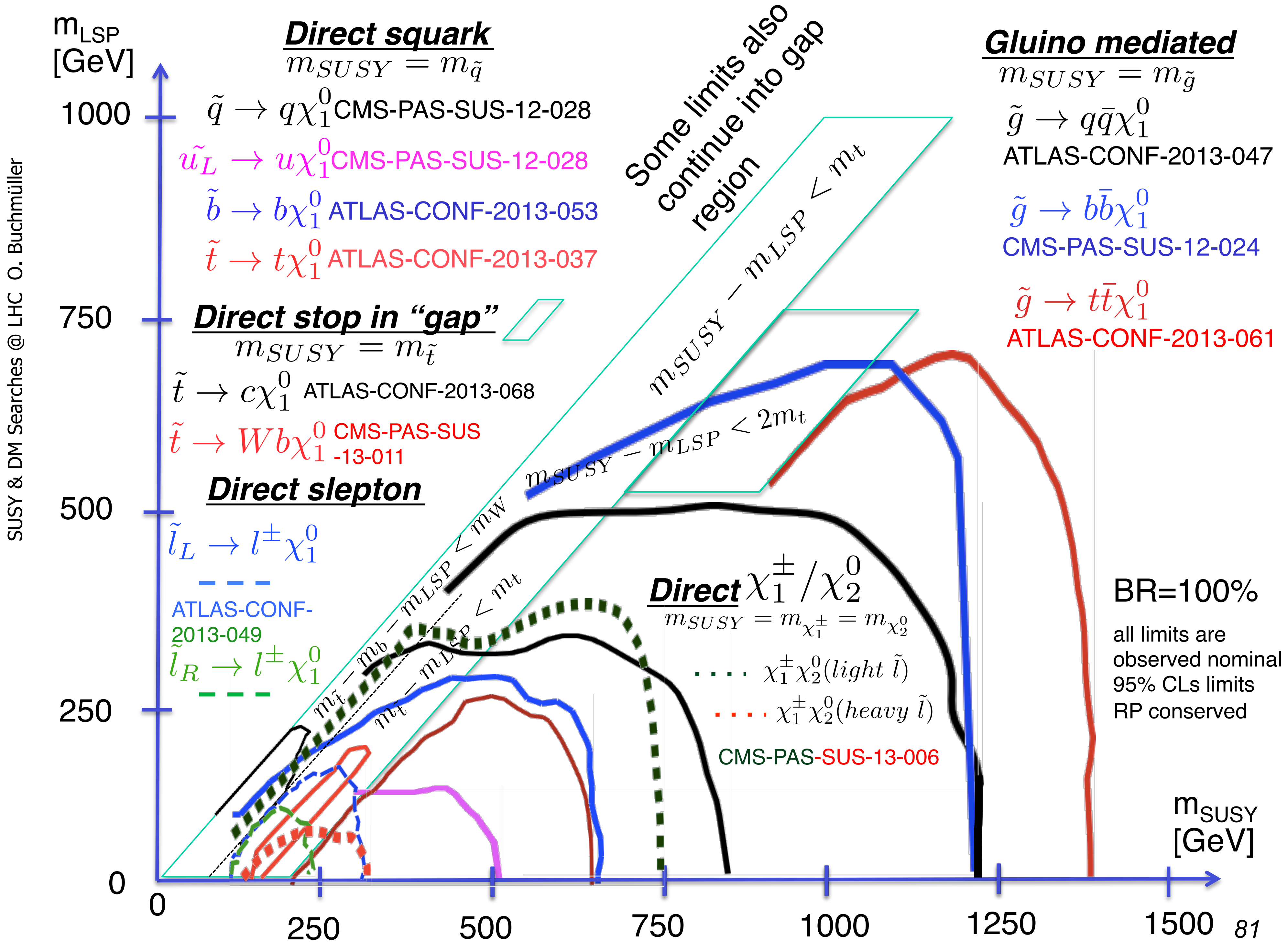
| **Direct squark** | $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ | $\tilde{g} \rightarrow b\bar{b}\chi_1^0$ | $\tilde{g} \rightarrow t\bar{t}\chi_1^0$ |
|---|---|---|---|
| Best limit: **[GeV]** | ~1200 | ~1200 | ~1400 |
| No limit for $M_{LSP}$**[GeV]** | ~480 | ~650 | ~700 |

| **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 |

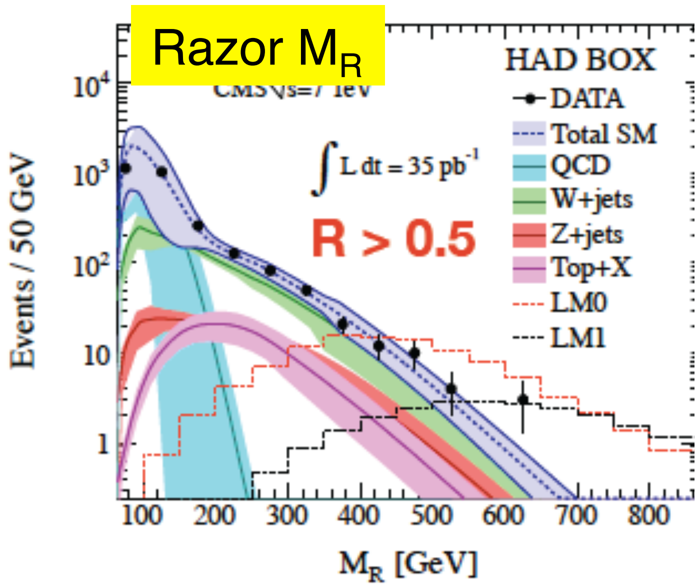
| $\chi_1^{\pm}\chi_2^0$ | $light\ \tilde{l}$ | $heavy\ \tilde{l}$ |
|---|---|---|
| Best limit: **[GeV]** | ~750 | ~300 |
| No limit for $M_{LSP}$**[GeV]** | ~350 | ~60 |

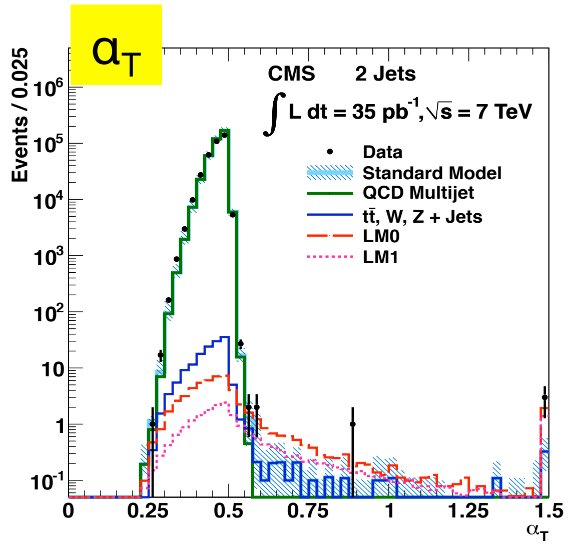


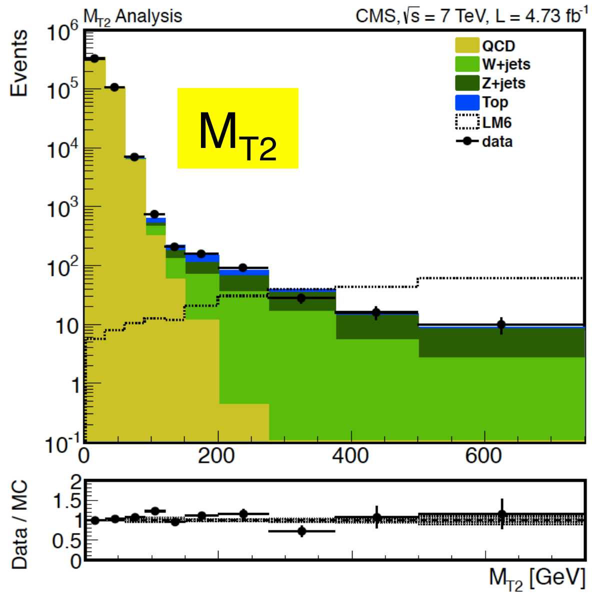
SUSY & DM Searches @ LHC O. Buchmüller
$m_{LSP}$ [GeV]
1000
750
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u_L} \to u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct 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
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_t - m_{LSP} < m_t$
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

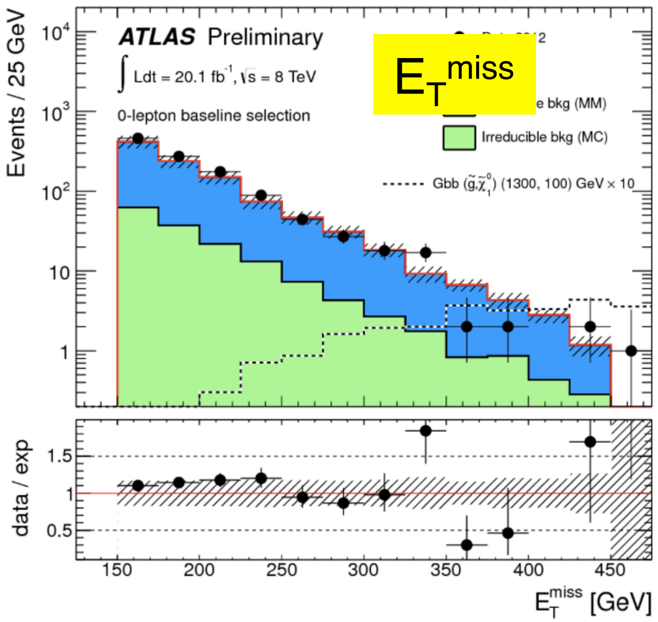
# Many Different Kinematic Variables

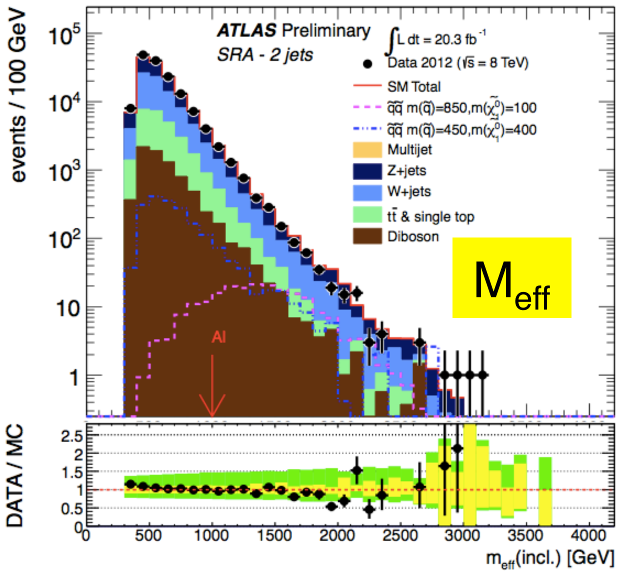


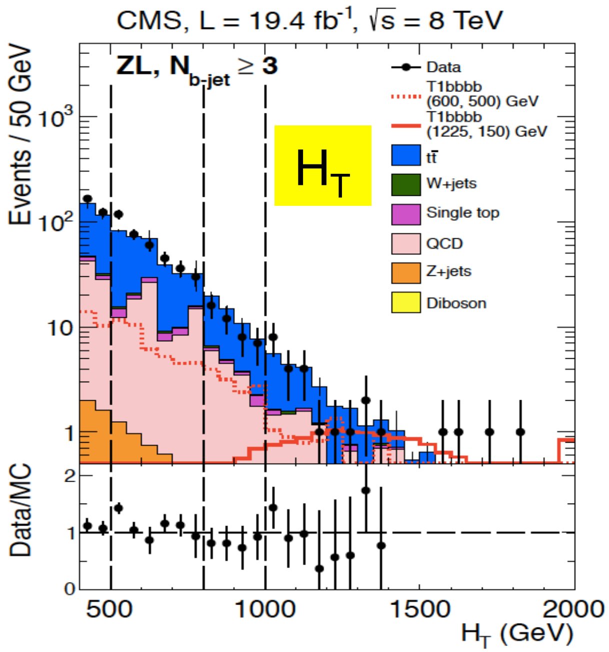


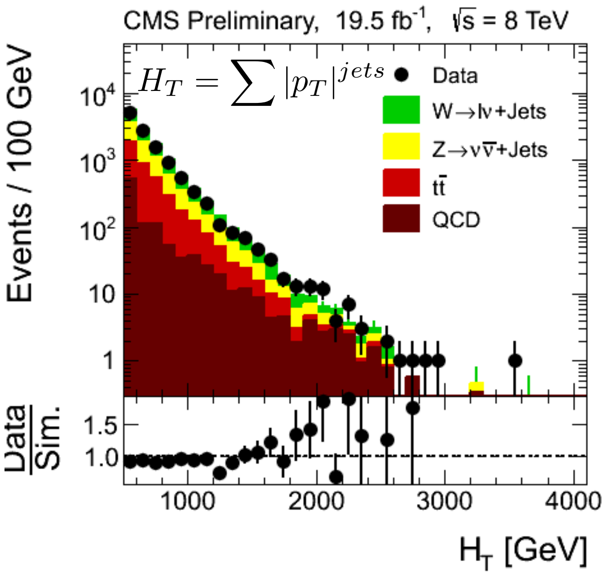



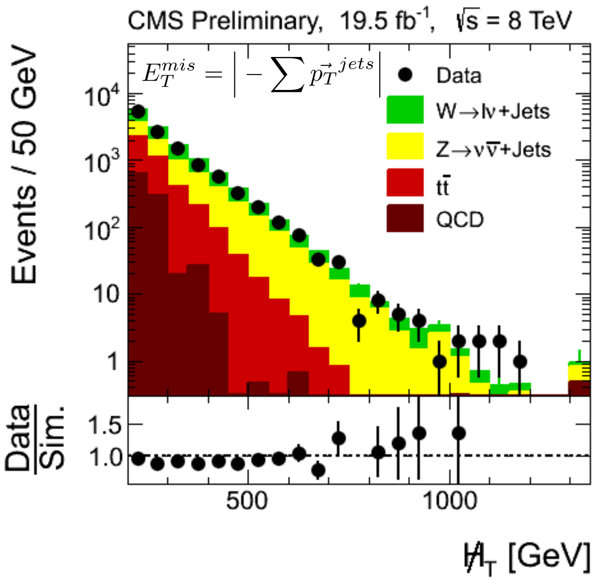



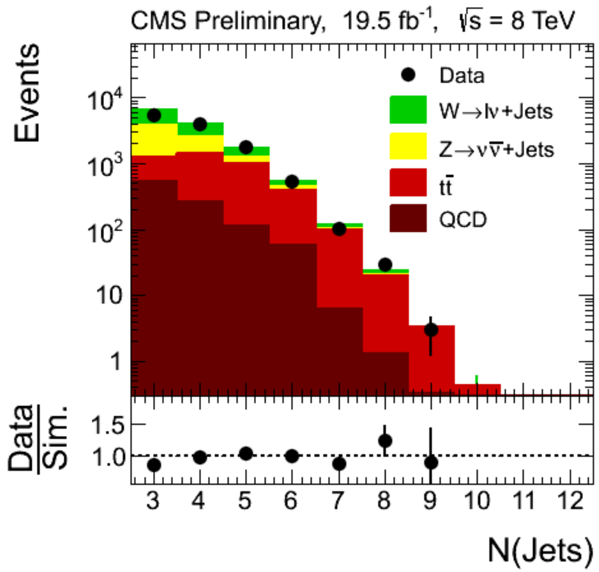



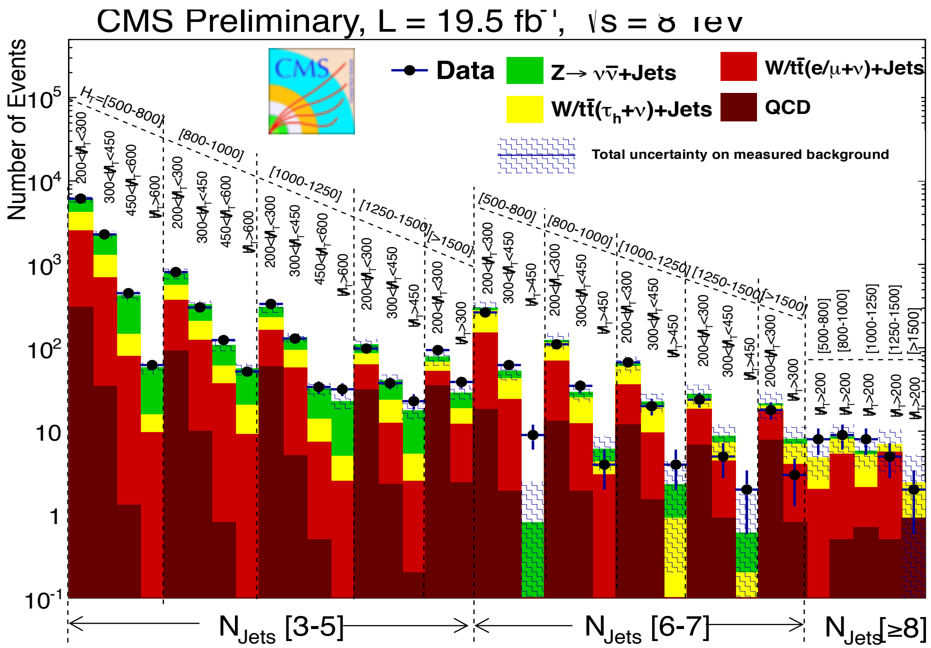



# Multijets & missing energy search



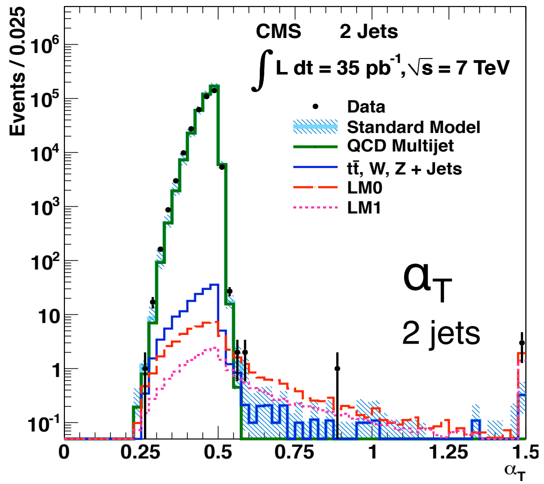

Traditional inclusive Jets + $E_t^{mis}$ search, which uses simple kinematic variables to categories the events.

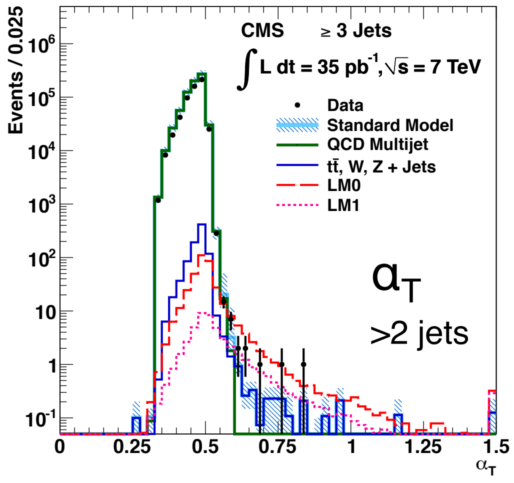
Main backgrounds QCD, W/Z+jet and ttbar are estimated using data-driven techniques.

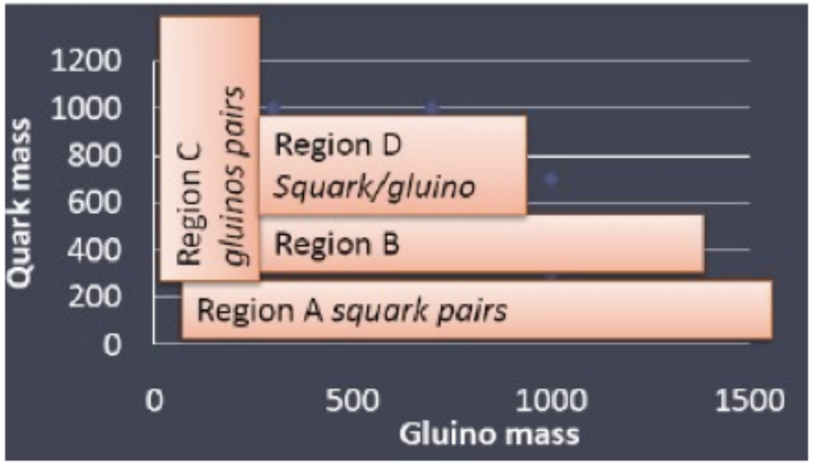
NEW

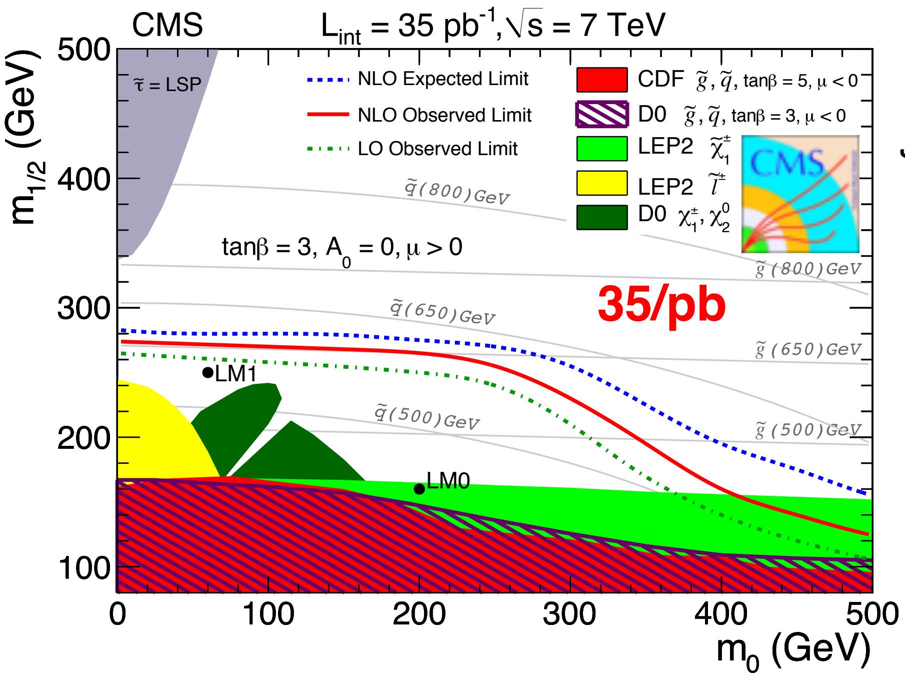
**CMS-SUS-PAS-13-012**
See parallel talk for details:
C. Autermann

# 2010: Entering New Territory at the LHC!

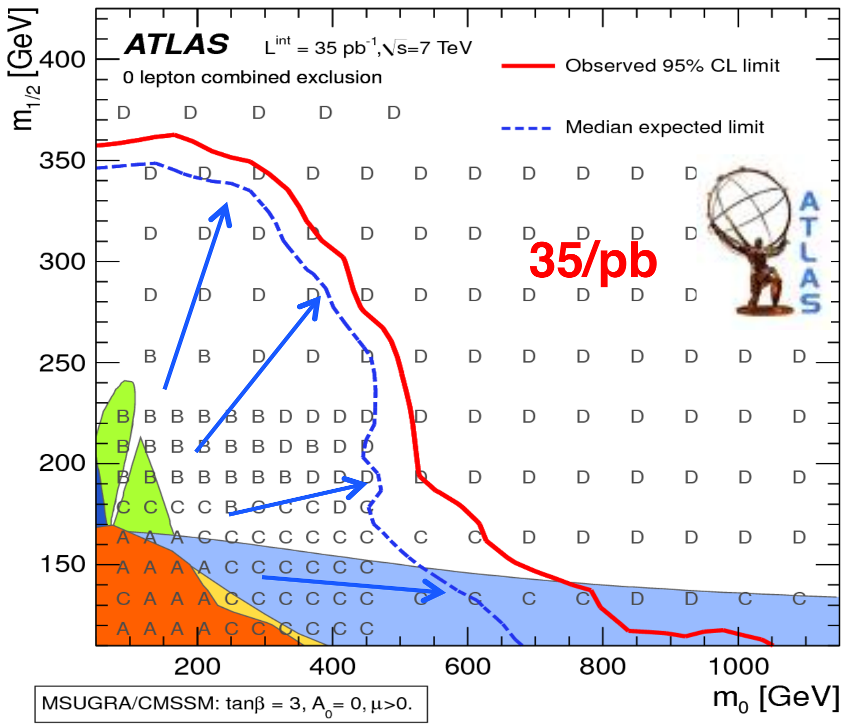


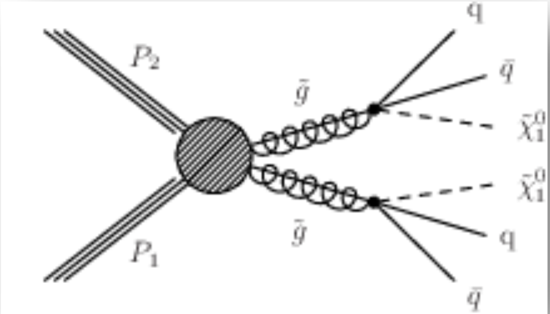

Phys. Lett. B698:196-218



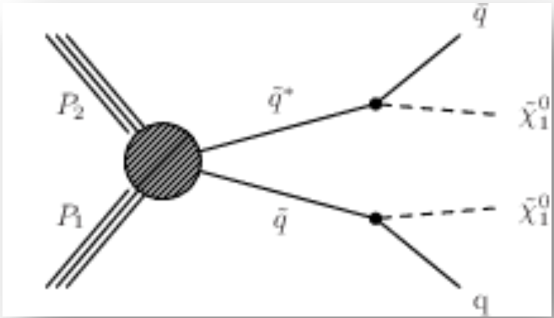

PLB 701 (2011) 186

# Simplified Model Spectra (SMS)

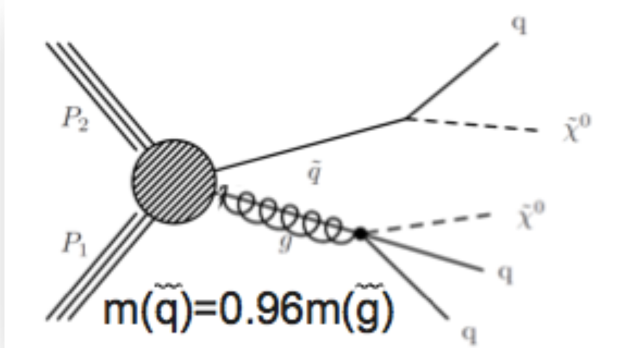




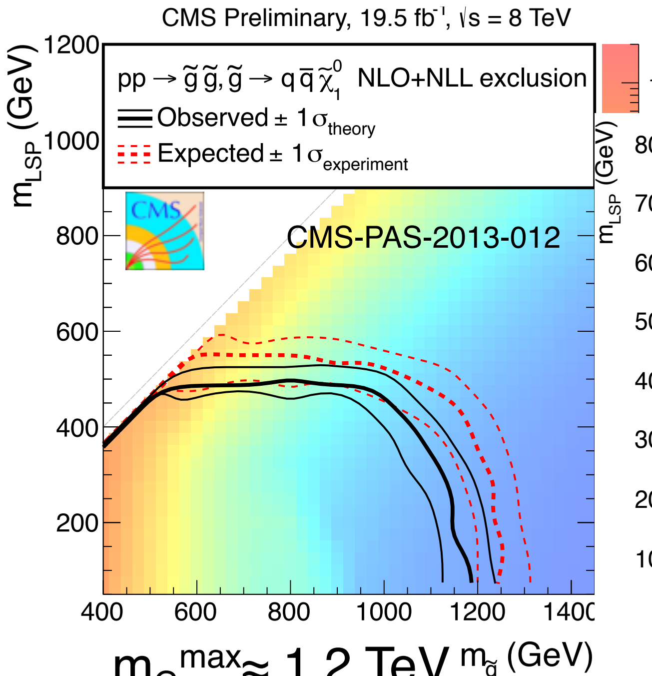
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$



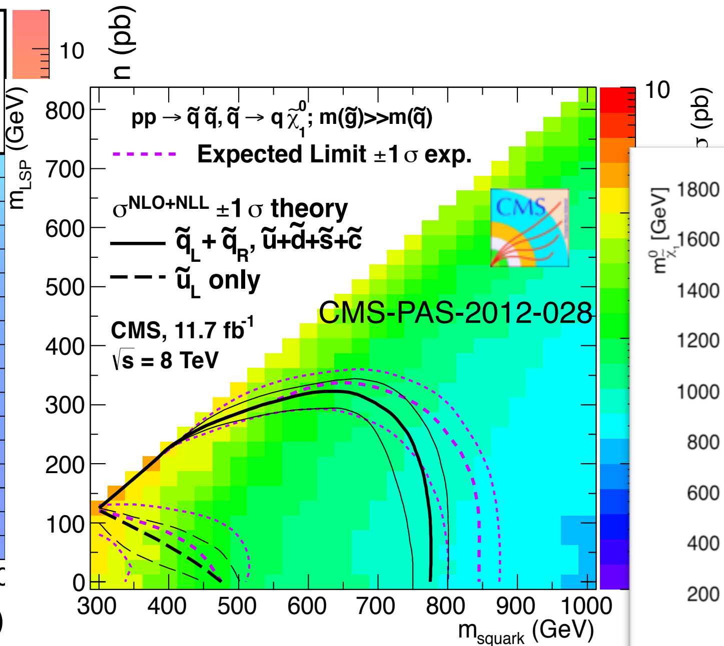
$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$




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

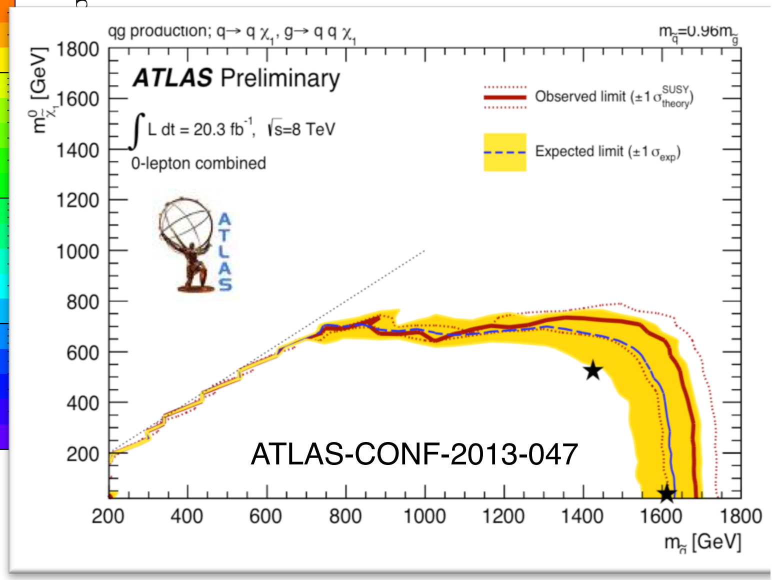



$m_G^{max} \approx 1.2$ TeV

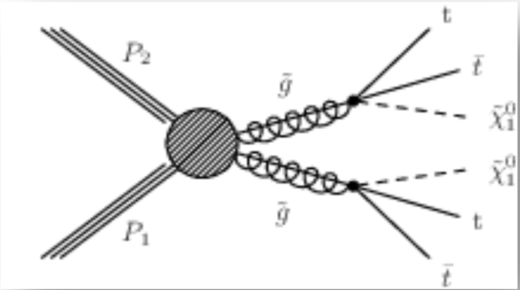



$m_{sq}^{max} \approx 0.8$ TeV

$m_G^{max} \approx 1.7$ TeV

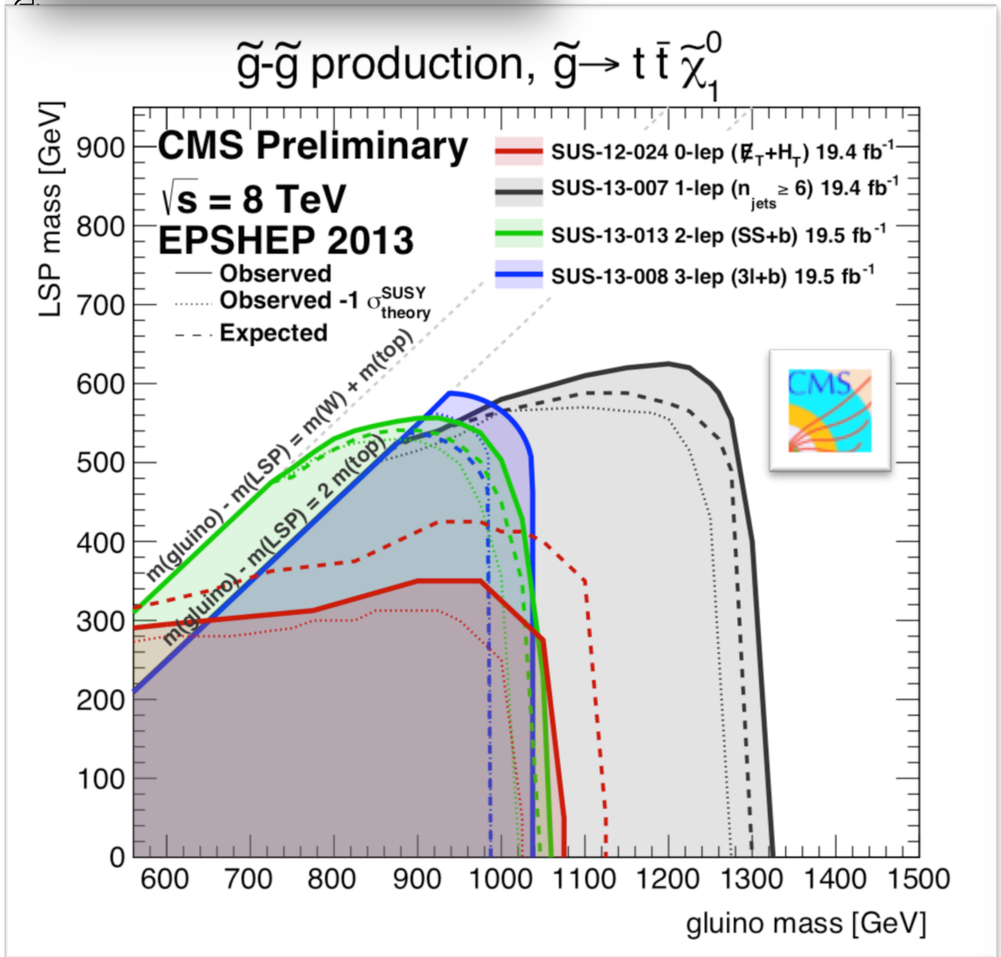


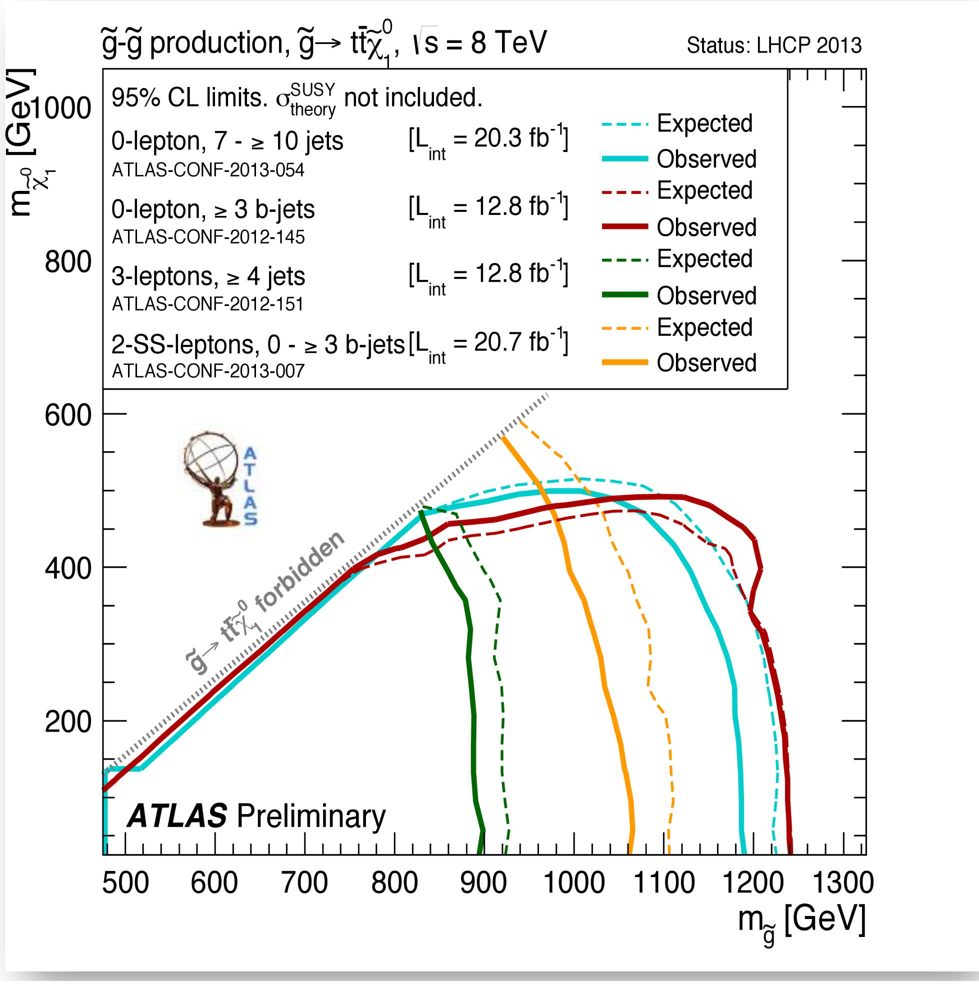
# Today: many more SMS and many more searches




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

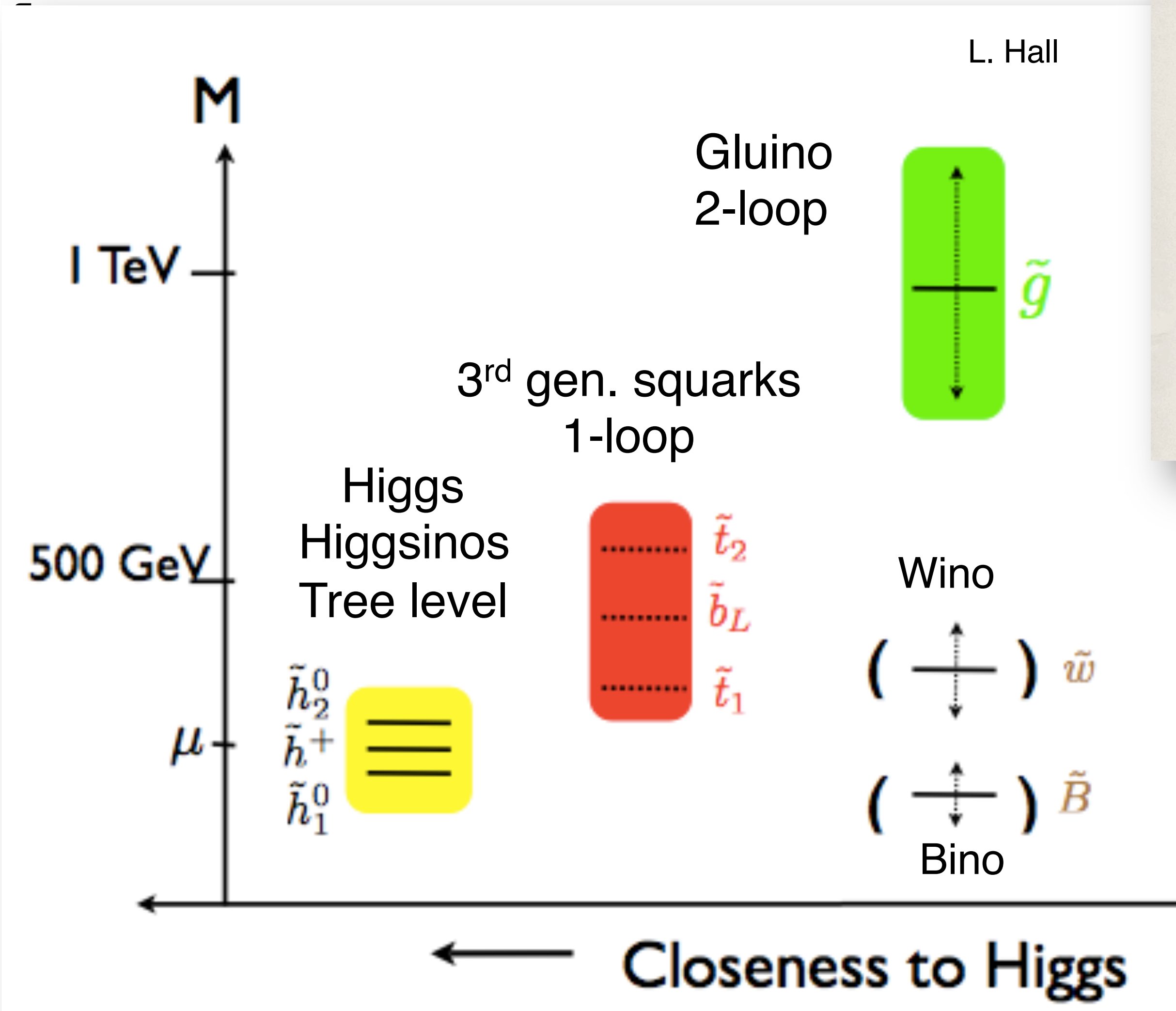
Several searches are interpret in this particular SMS!

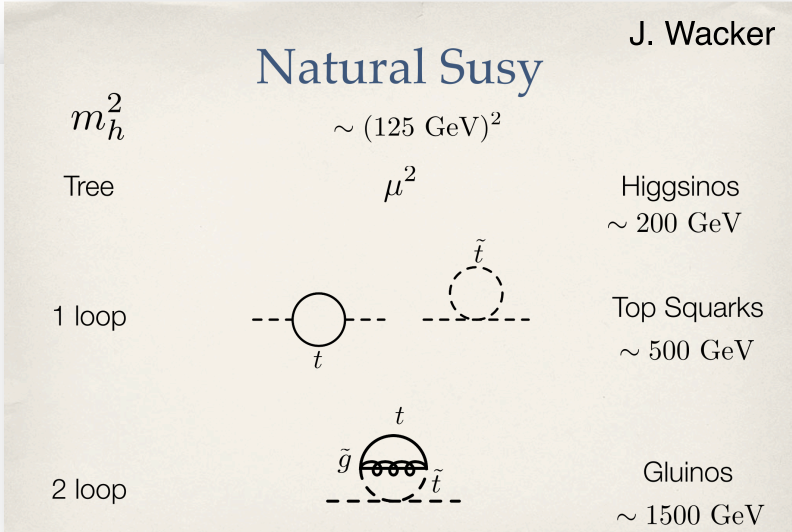


# (Minimal) Natural SUSY Spectrum

müller




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

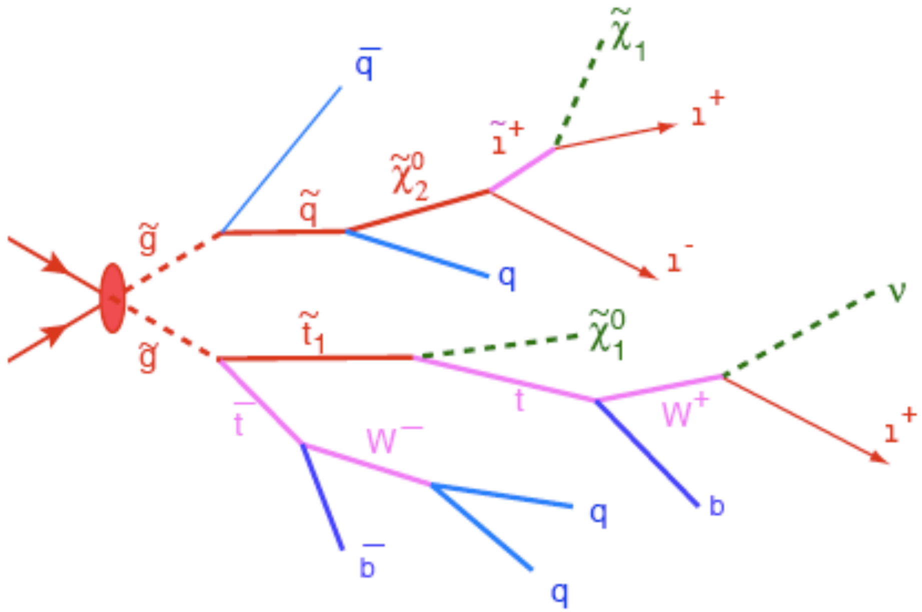
More in Gian Guidice talk!

# What do we call a “SUSY search”?



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

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



***Missing Energy:***

- *from LSP*

***Multi-Jet:***

- *from cascade decay (gaugino)*

***Multi-Leptons:***

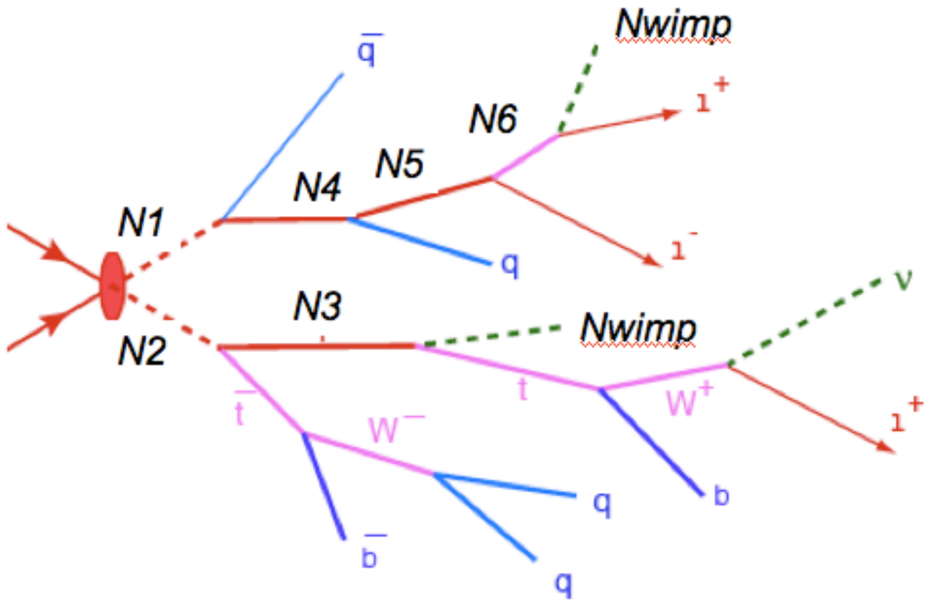
- *from decay of charginos/neutralios*

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

# What is its experimental signature?



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




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

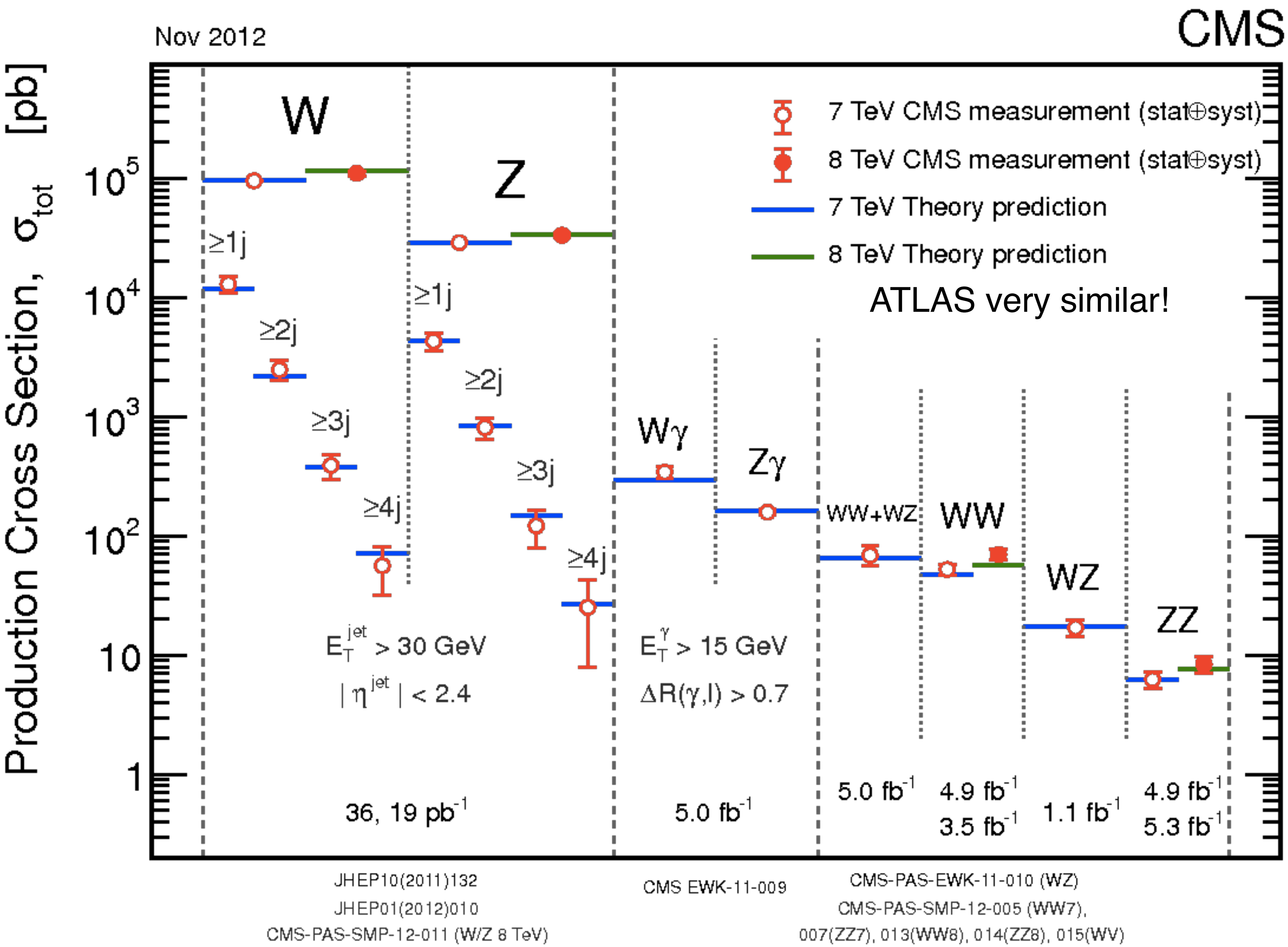
***Multi-Jet:***
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

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

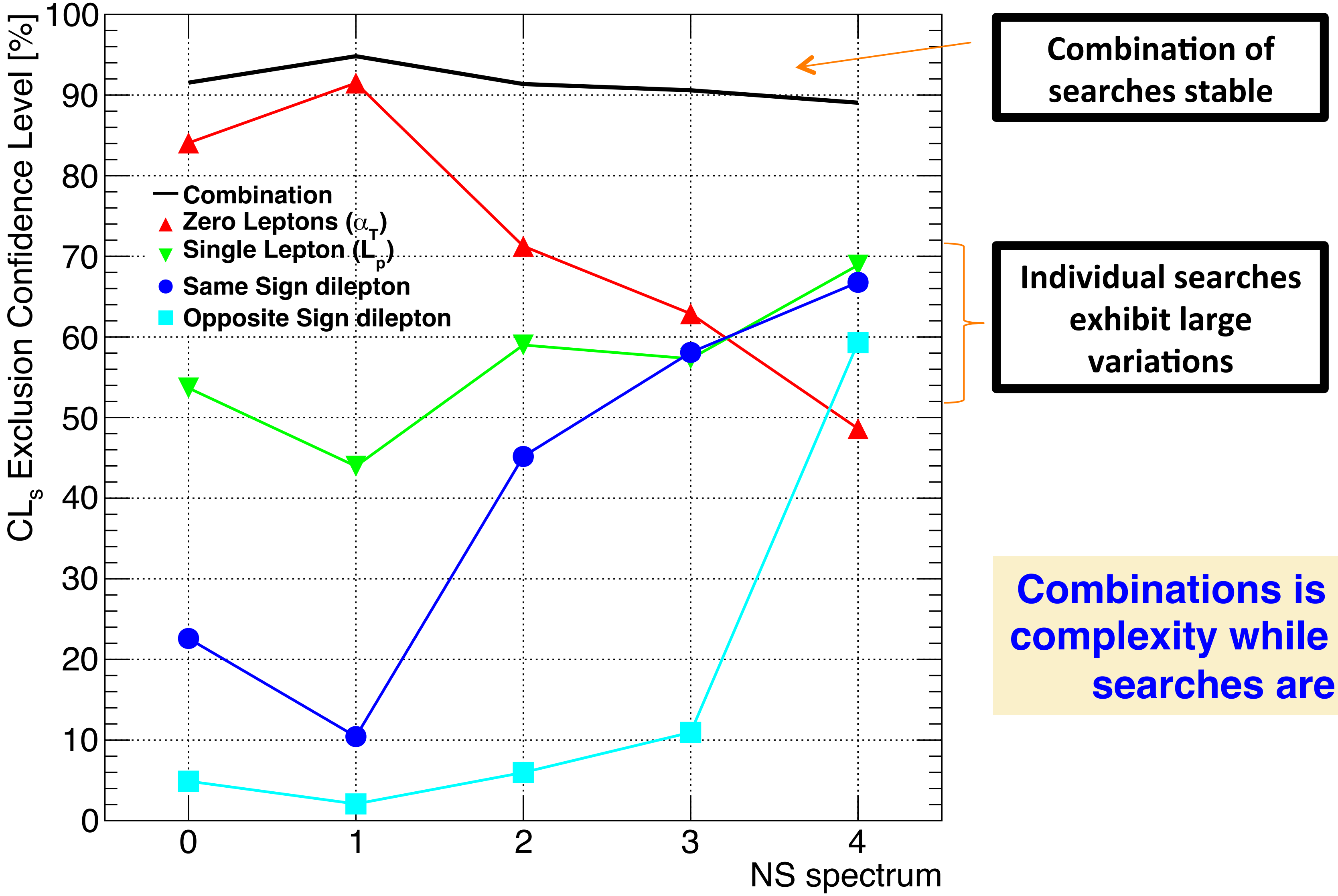
Model examples are Extra dimensions, Little Higgs, Technicolour, etc but a more generic definition for this signature is as follows.

# Rediscovery of the SM at a new energy frontier





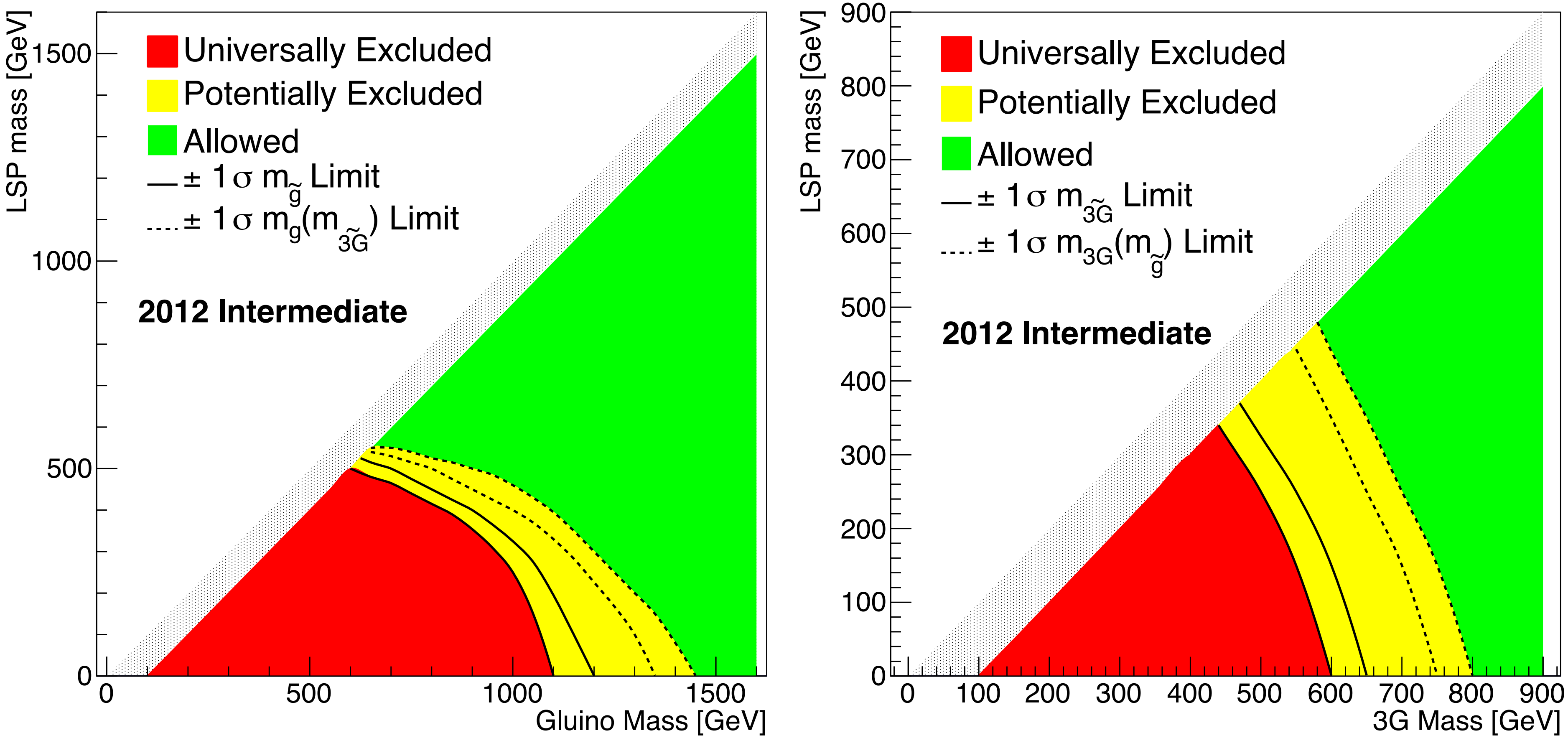
# Combination vs individual search




**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

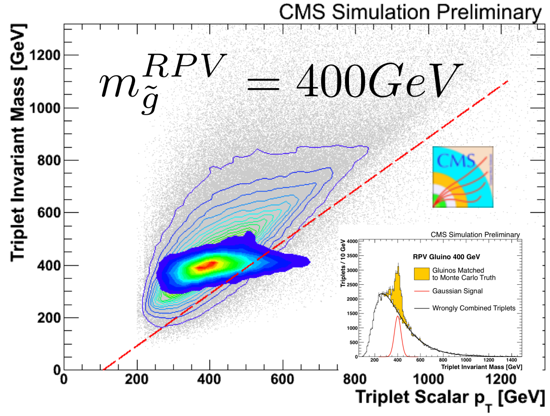
Searches @ LHC O. Buchmüller

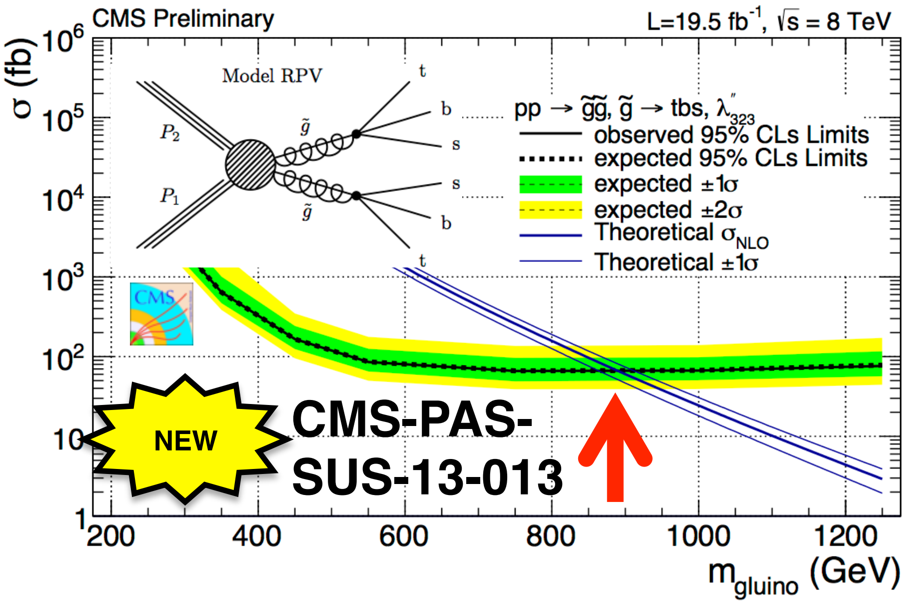
Generic same-sign di-lepton search with different signal regions

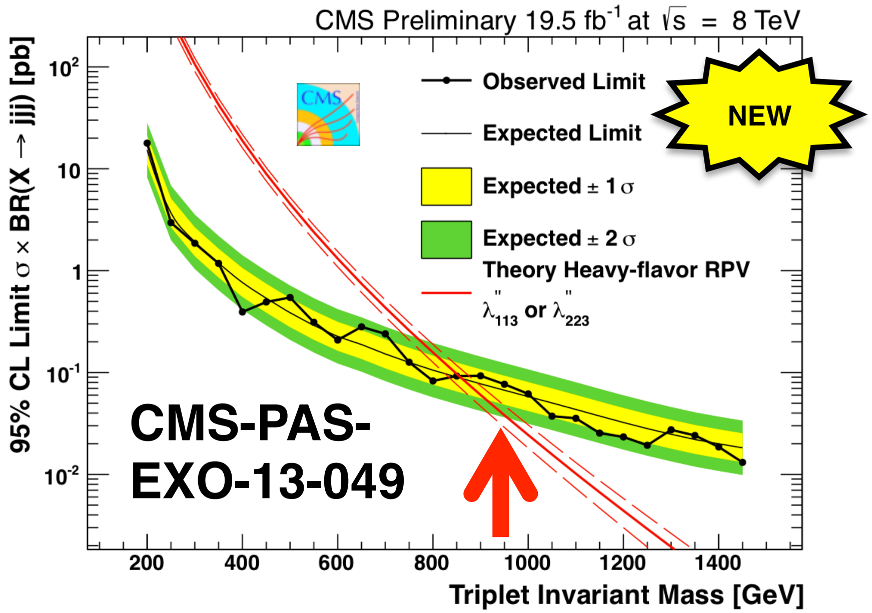
| SR | Expected | | | Observed |
|---|---|---|---|---|
| RPV0 | 38 | ± | 14 | 35 |
| RPV2 | 5.3 | ± | 2.1 | 5 |
| SStop1 | 160 | ± | 59 | 152 |
| SStop1++ | 90 | ± | 32 | 92 |
| SStop2 | 40 | ± | 13 | 52 |
| SStop2++ | 22 | ± | 8 | 25 |

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

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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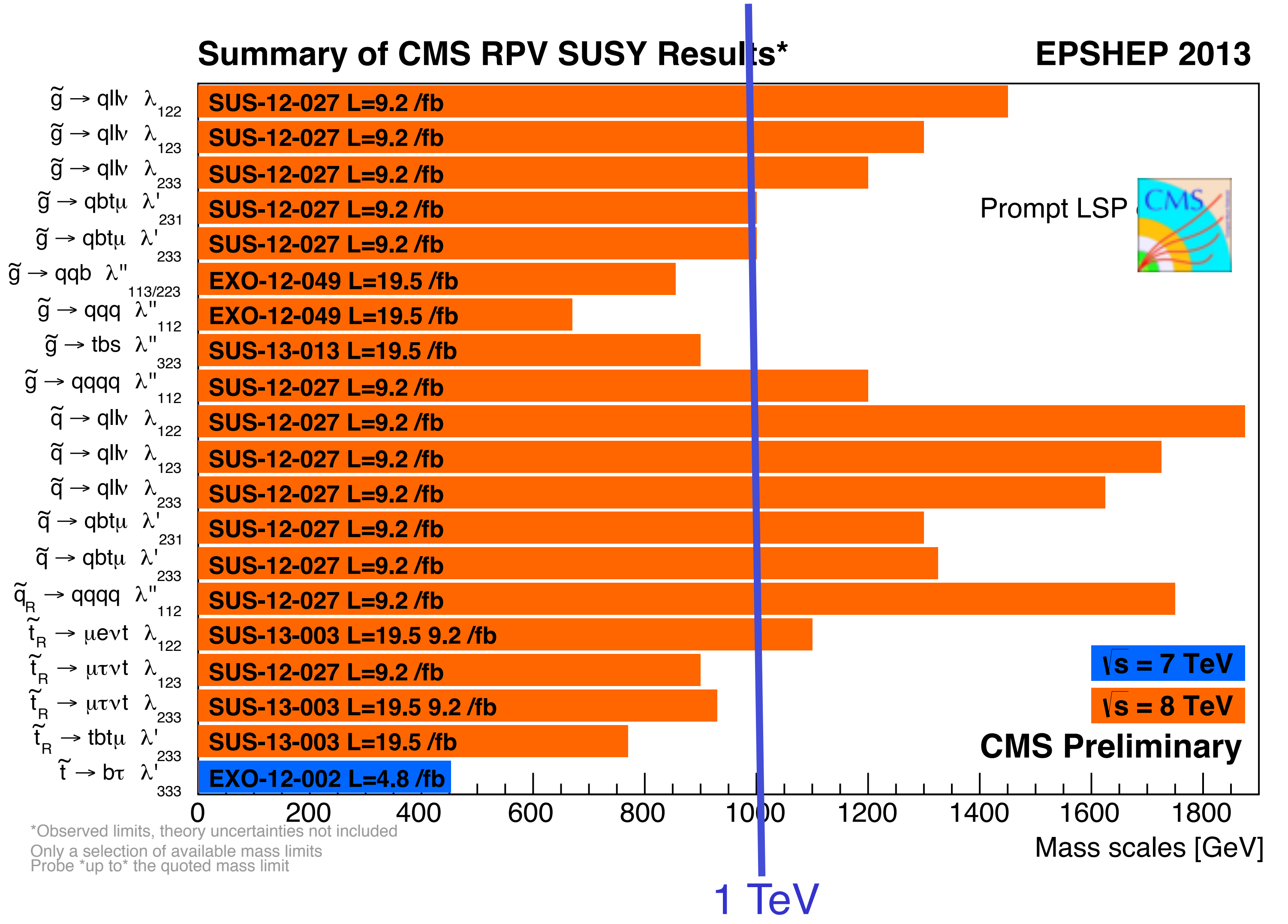
# RP violation searches: Summary

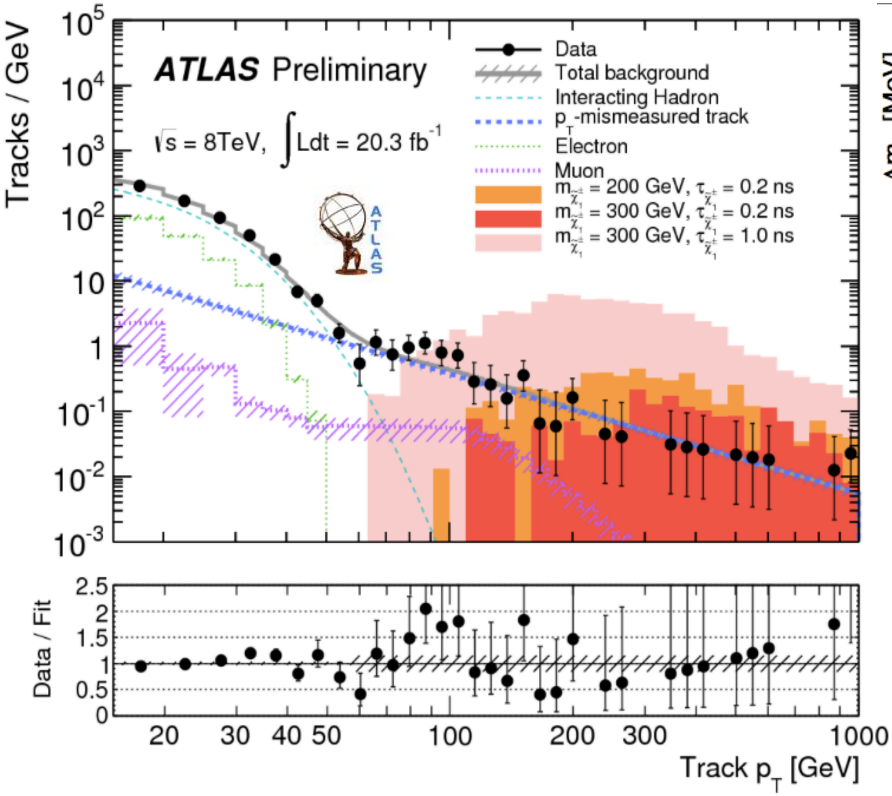


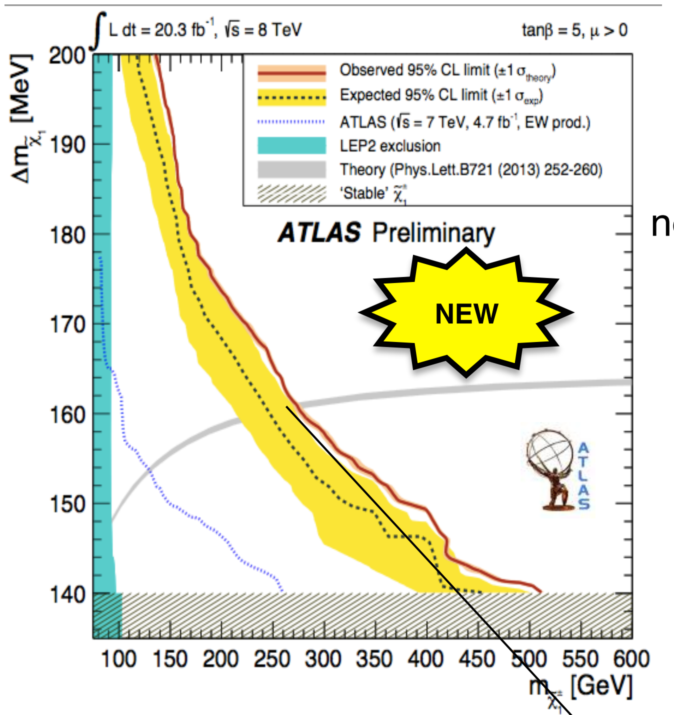



ATLAS similar

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

# Long-lived particle (SUSY) searches



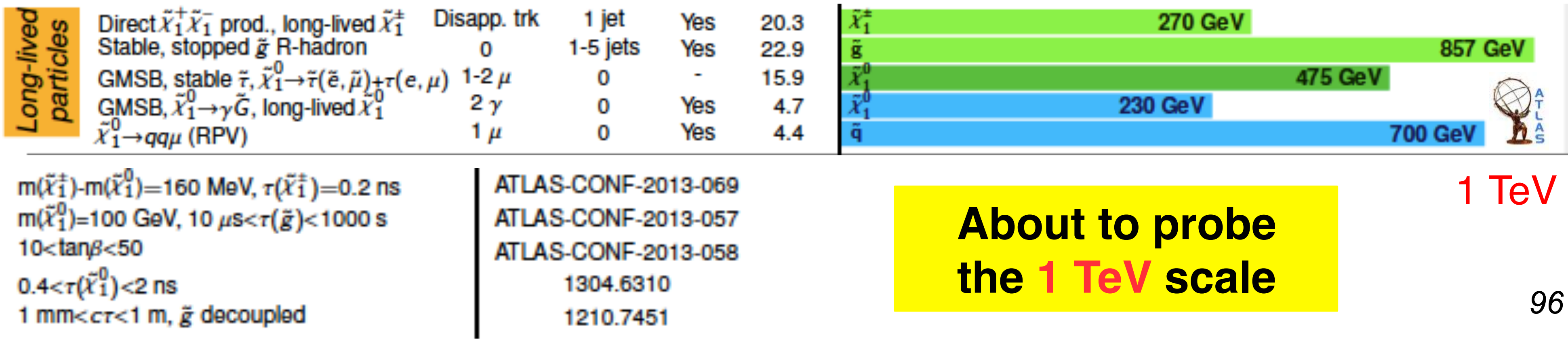

ATLAS-CONF -2013-069

nearly mass-degenerate

$\chi_1^\pm \chi_1^0$

search based on disappearing-track signature

CMS similar
See parallel talk from
L. Quertenmont




1 TeV

**About to probe the 1 TeV scale**

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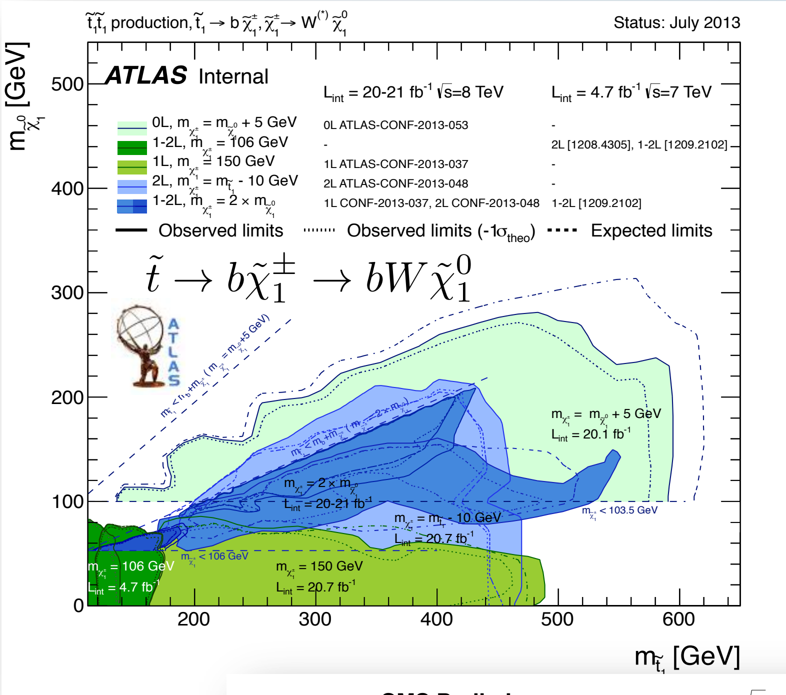
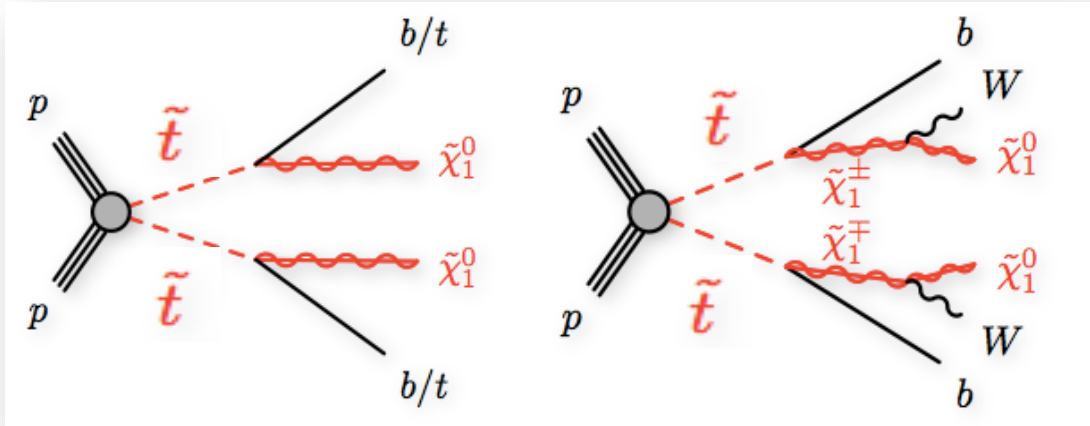
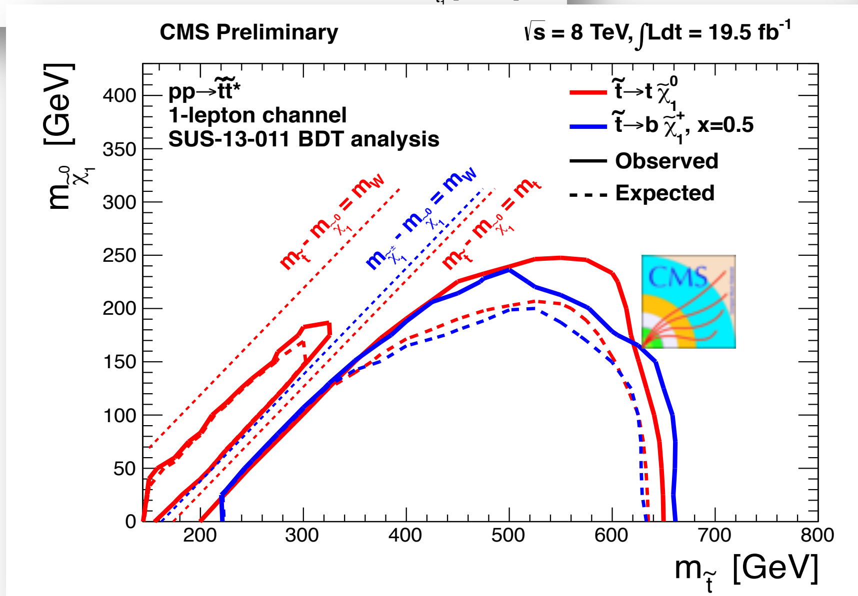
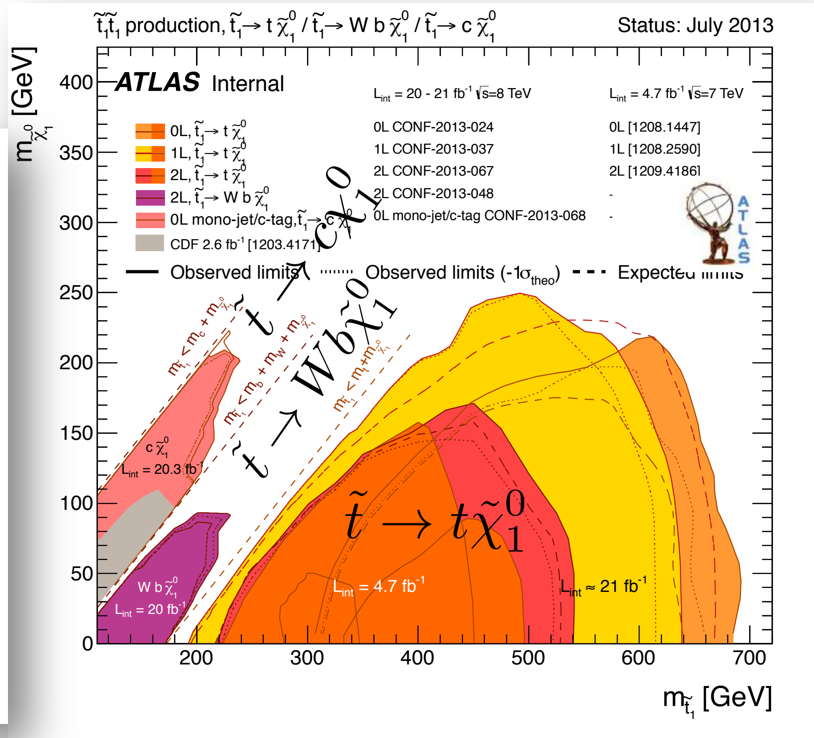
# Dedicated searches for direct stop-pair production

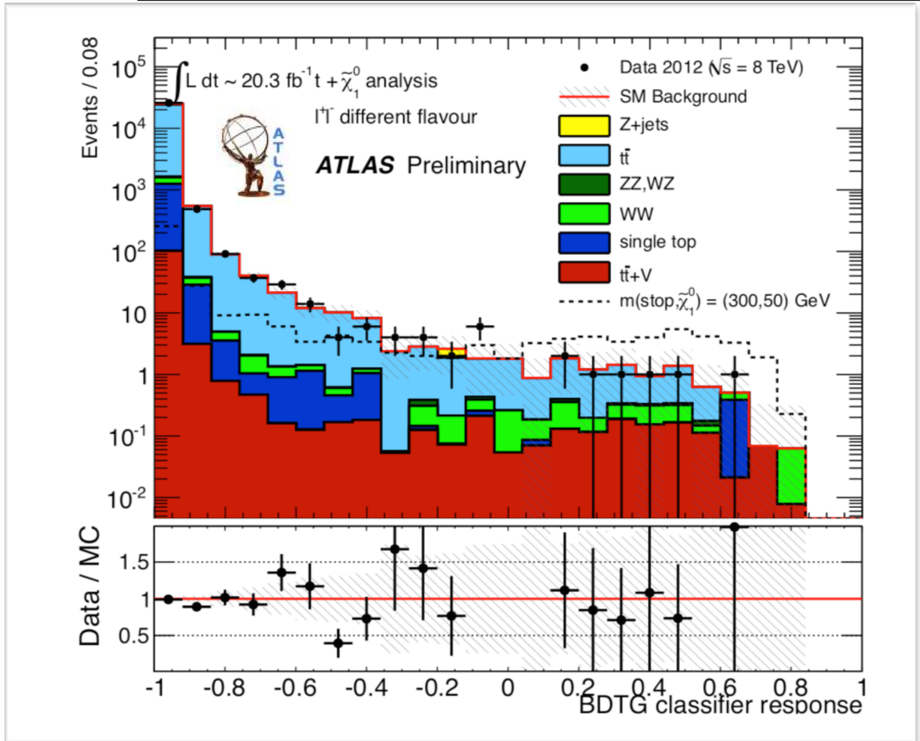


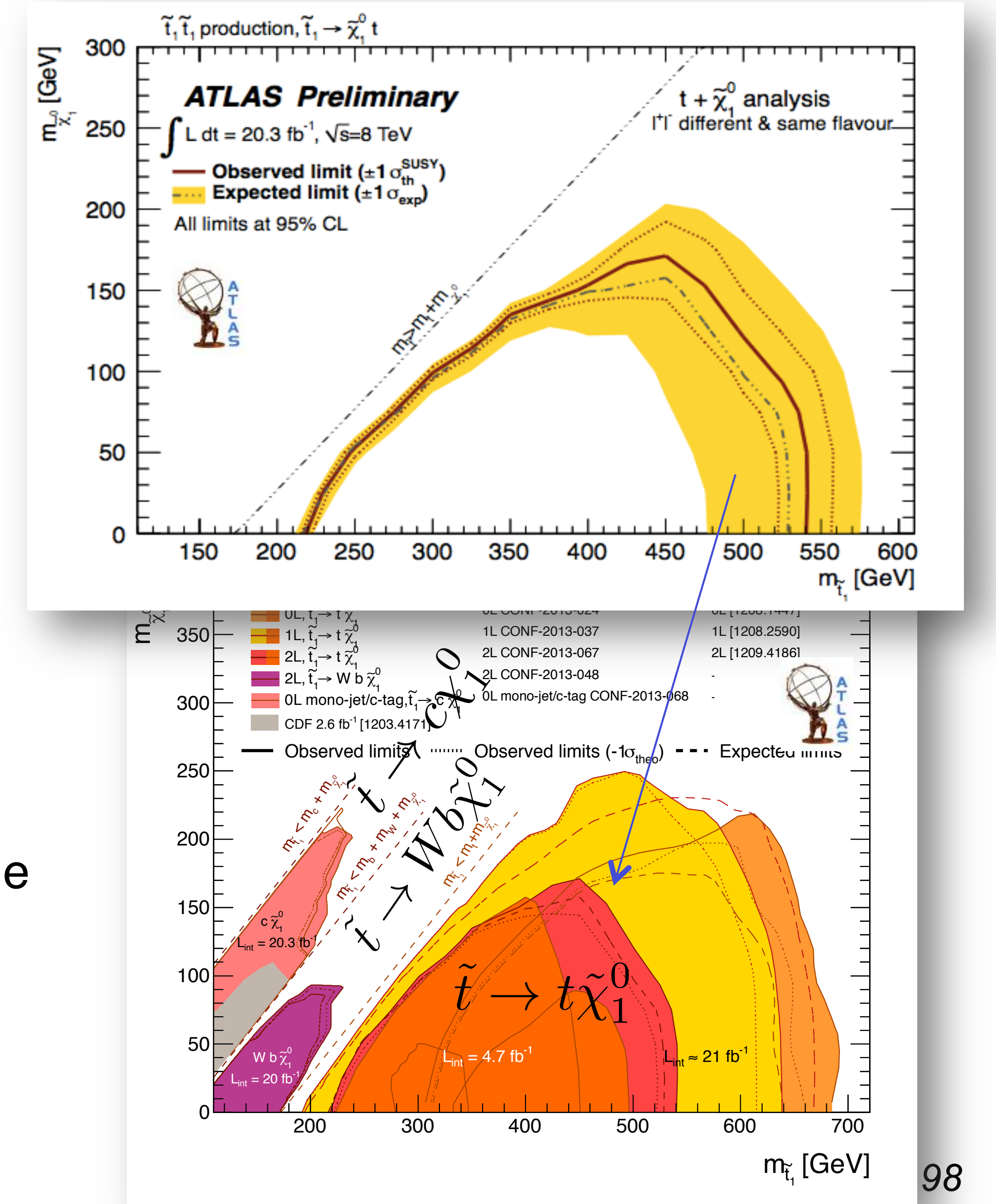



# Dedicated searches for direct stop-pair production



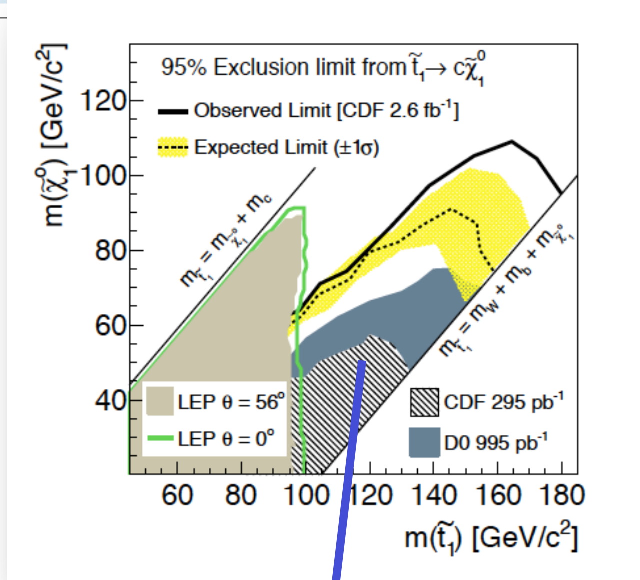




NEW

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

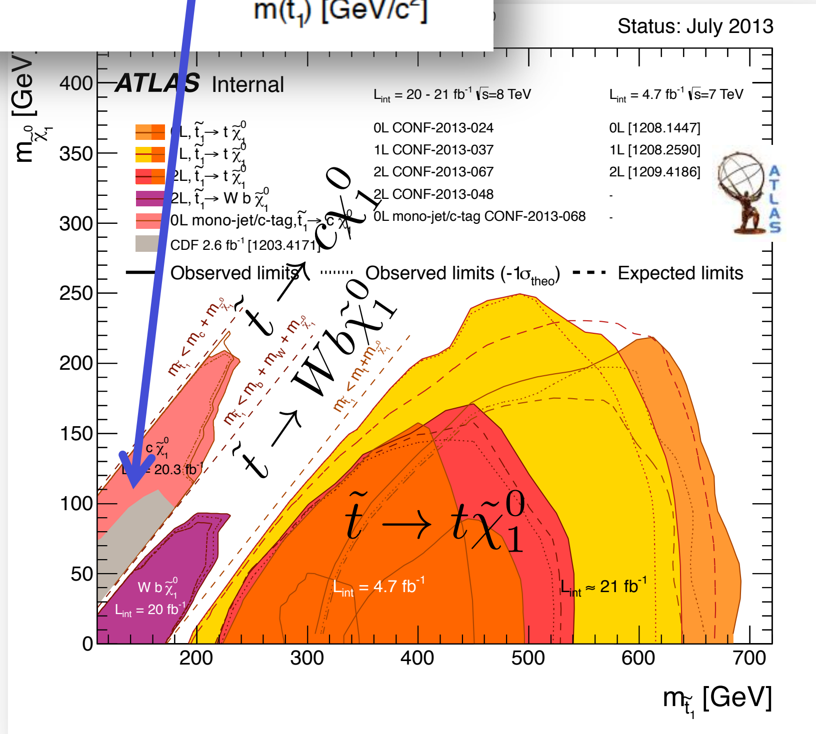
# Dedicated searches for direct stop-pair production

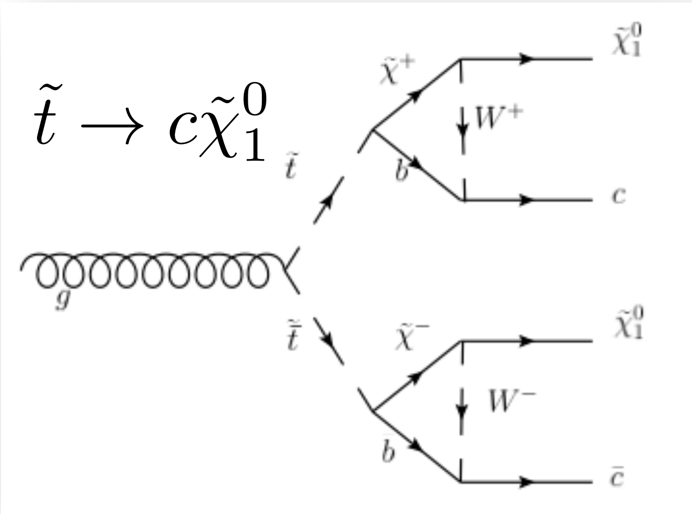





LEP:
LEPSUSY WG/04-01.1

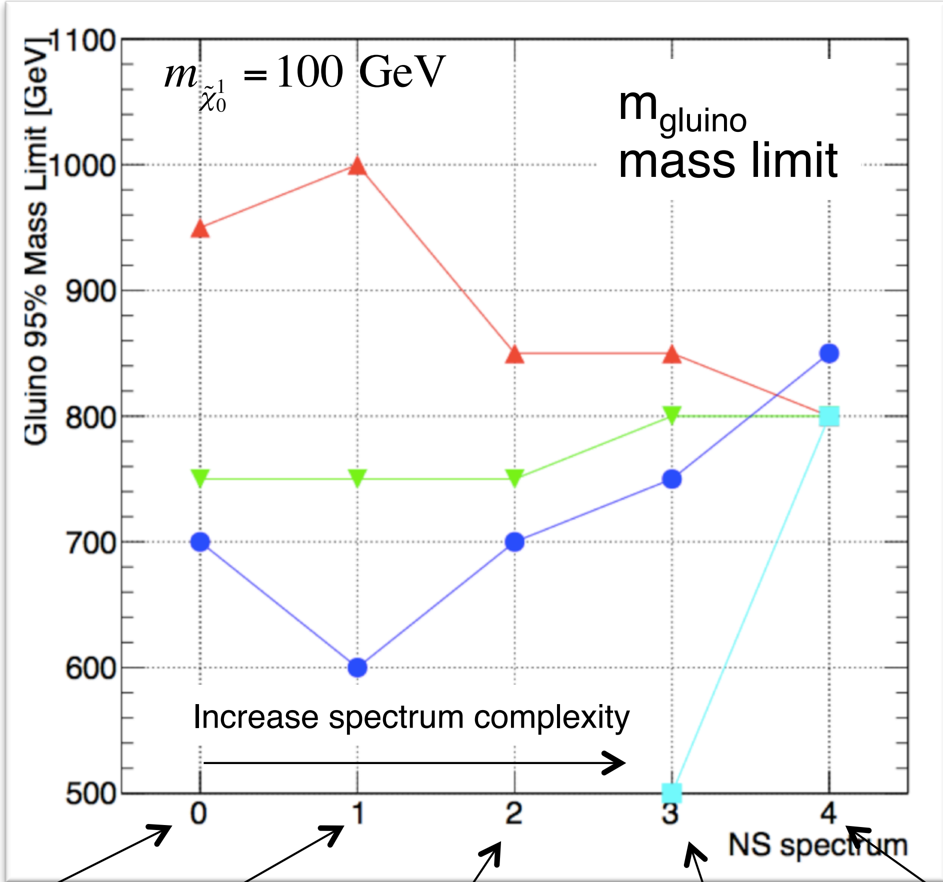
CDF:
1203.4171
D0:
0803.2263

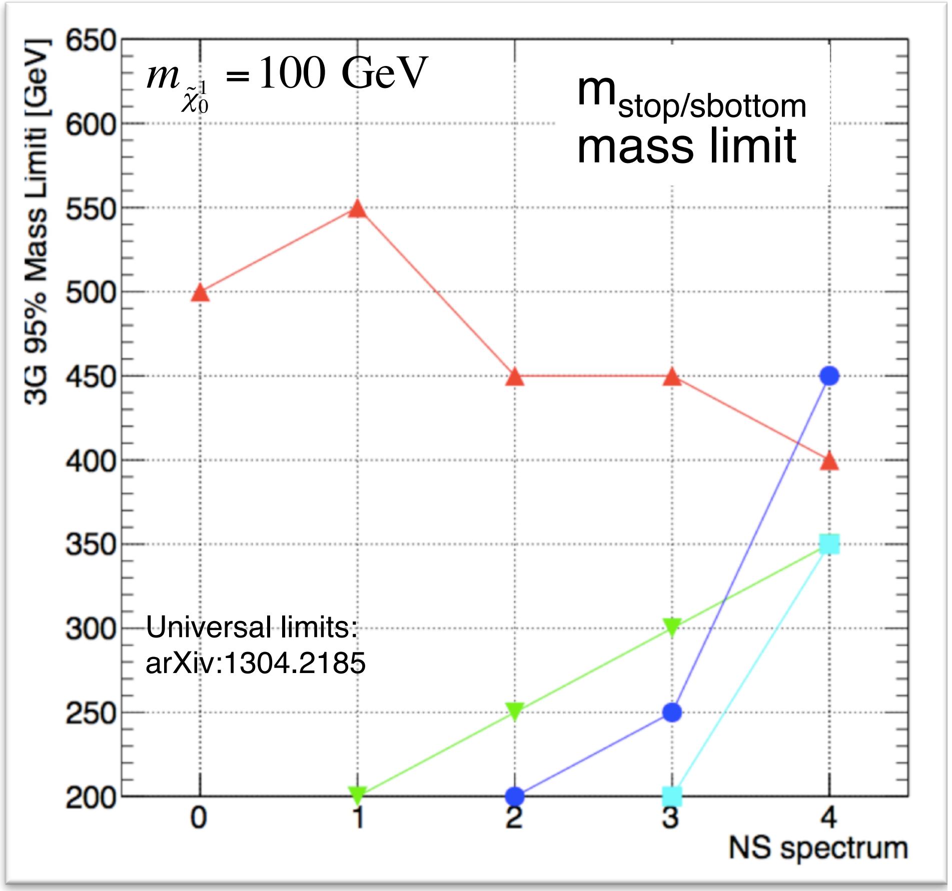


# SMS limits: A word of caution!





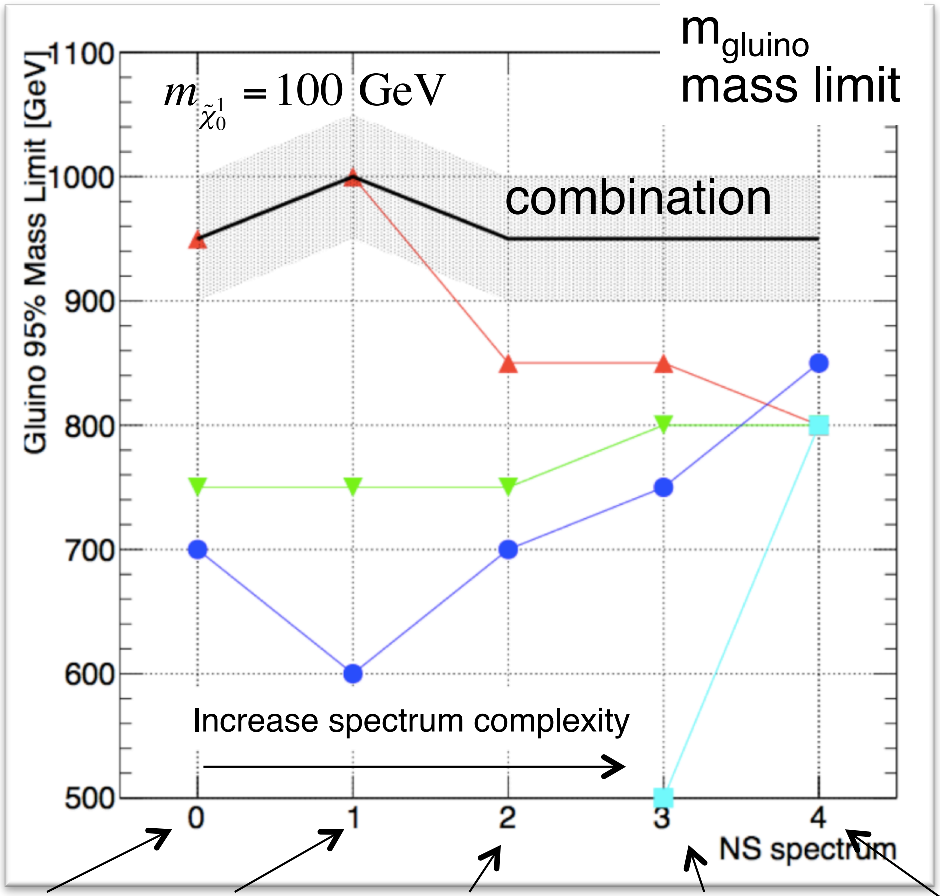



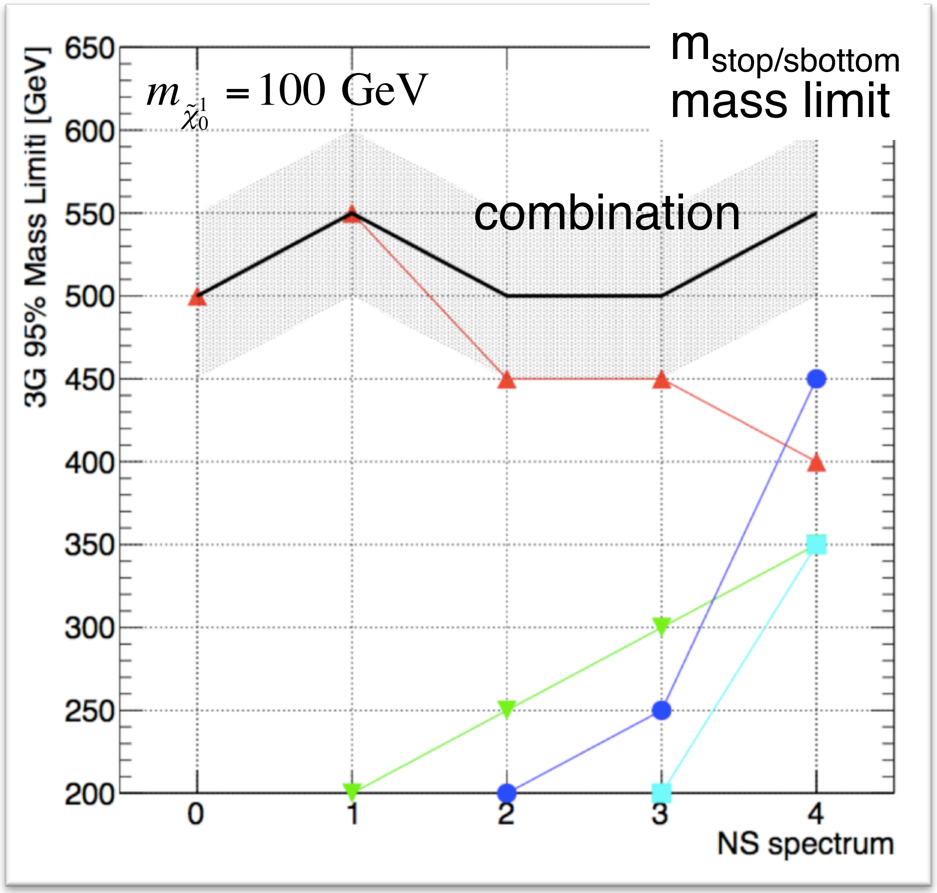

| NS0 | NS1 | NS2 | NS3 | NS4 |
|---|---|---|---|---|
| $\tilde{g}$ | $\tilde{g}$ | $\tilde{g}$ | $\tilde{g}$ | $\tilde{g}$ |
| $\tilde{t}_1, \tilde{t}_2$ | $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$ | $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$ | $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$ | $\tilde{t}_1,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

Used inclusive searches from 2011:

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

# Combining Searches = less model dependence




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

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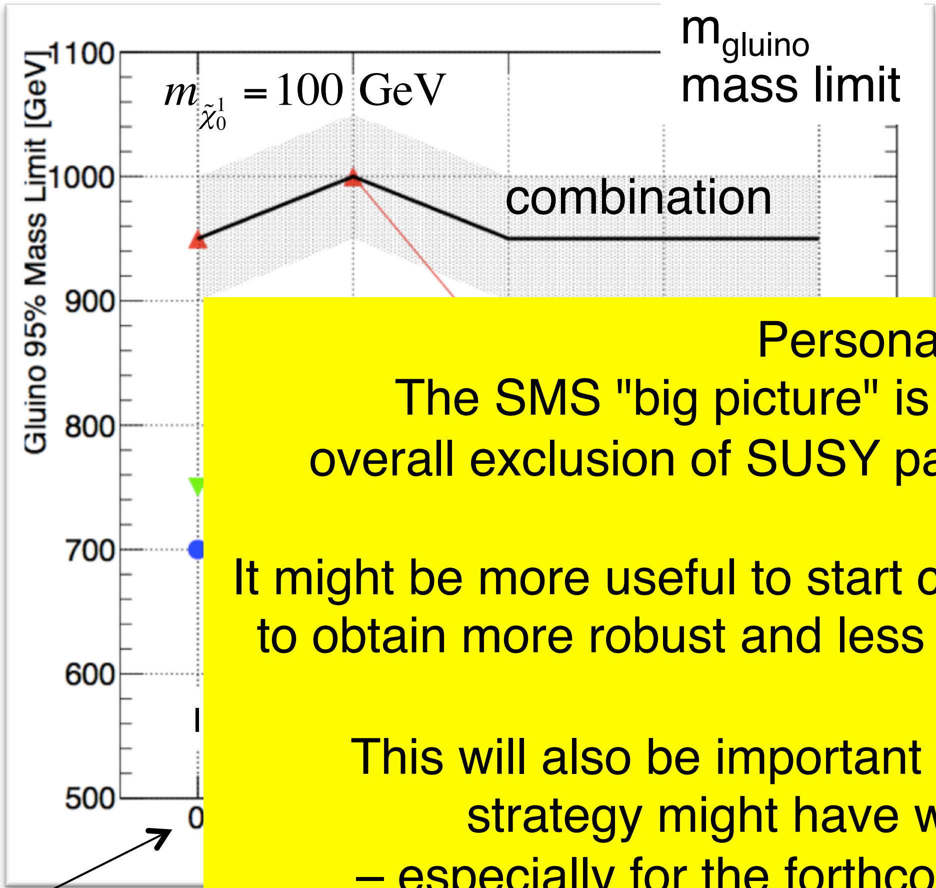
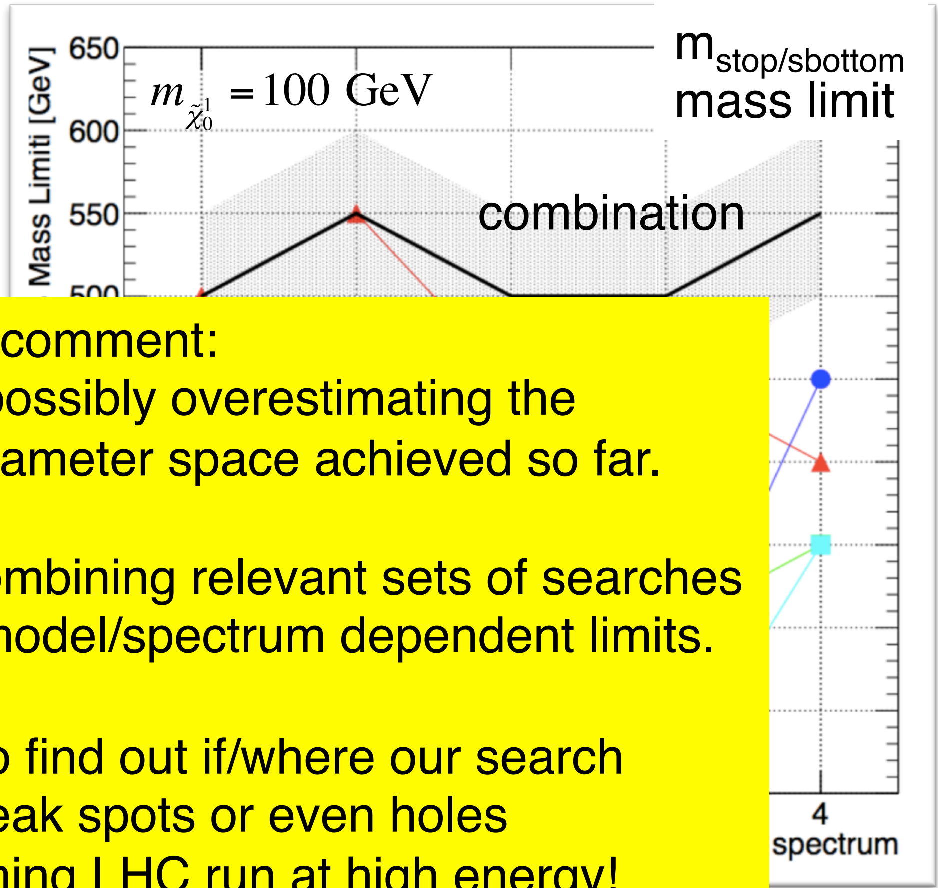
# Combining Searches = less model dependence




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

2011:

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

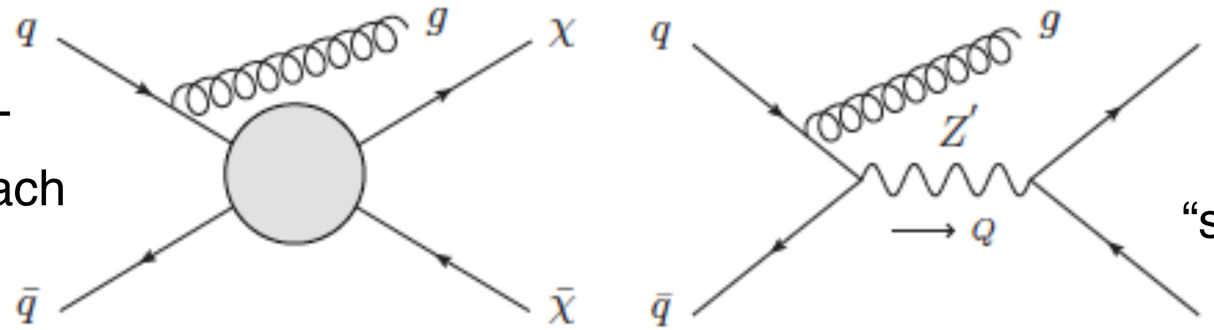
# Validity of Effective Field Theory Limits



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

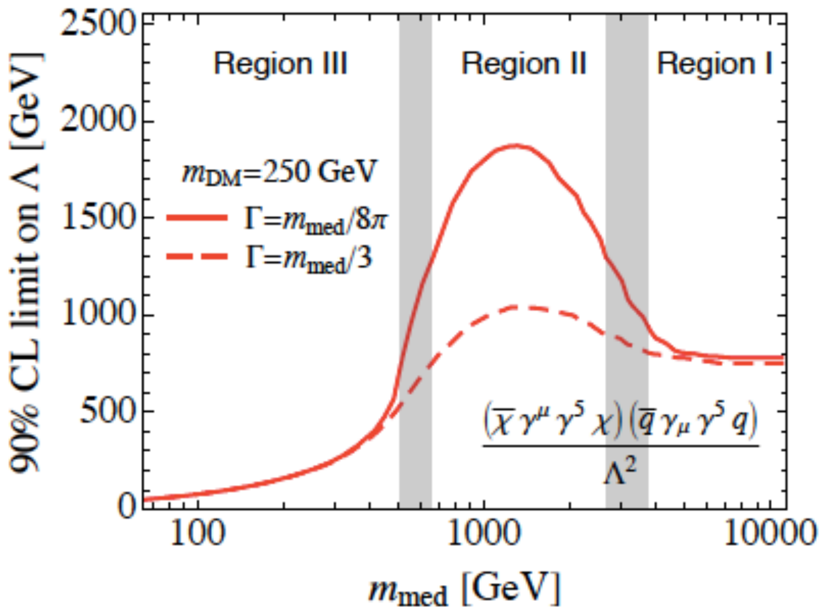
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT
approach




FT
one diagram
"simplified model"

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




Three Regions as function of mediator mass:

Region I: Heavy $m_{med}$

➢ EFT is valid!

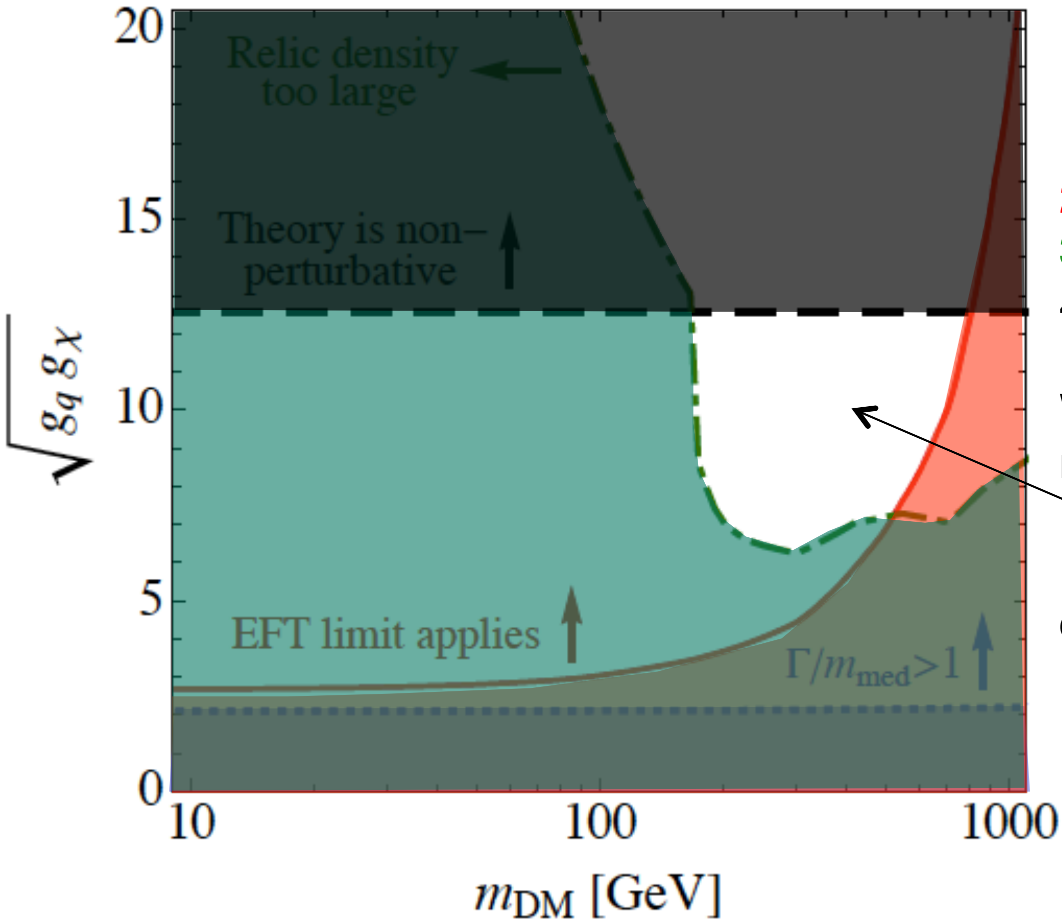
Region II: Medium $m_{med}$ – Resonant enhancement

➢ EFT limits are too conservative!

Region III: Low $m_{med}$

➢ EFT limits are too aggressive!

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




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

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

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

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

only a very small region is left!

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

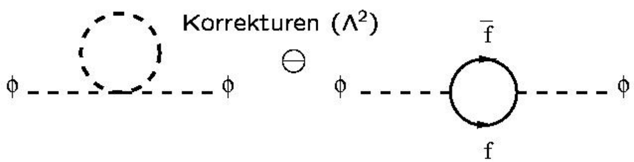
EFT limits of monojet searches are therefore highly model-depended!

# Why is SUSY so attractive?



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

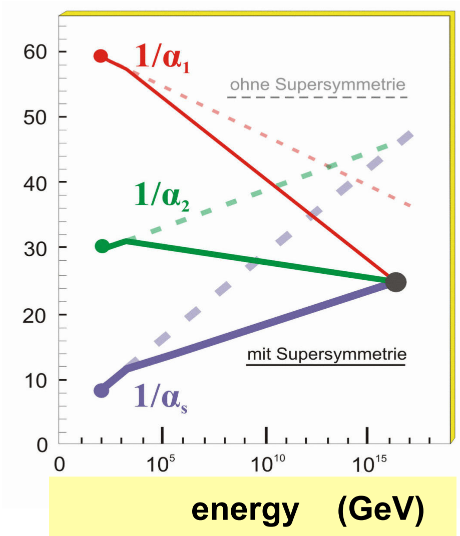
$$\Delta m_H = f(m_B^2 - m_f^2)$$




(Hierarchy or naturalness problem)

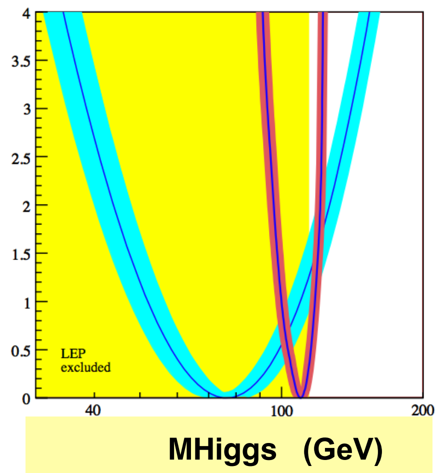
2. Unification of coupling constants of the three interactions seems possible

$m_{SUSY}$ ~ 1 TeV




3. SUSY provides a candidate for dark matter,

**The lightest SUSY particle (LSP)**




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

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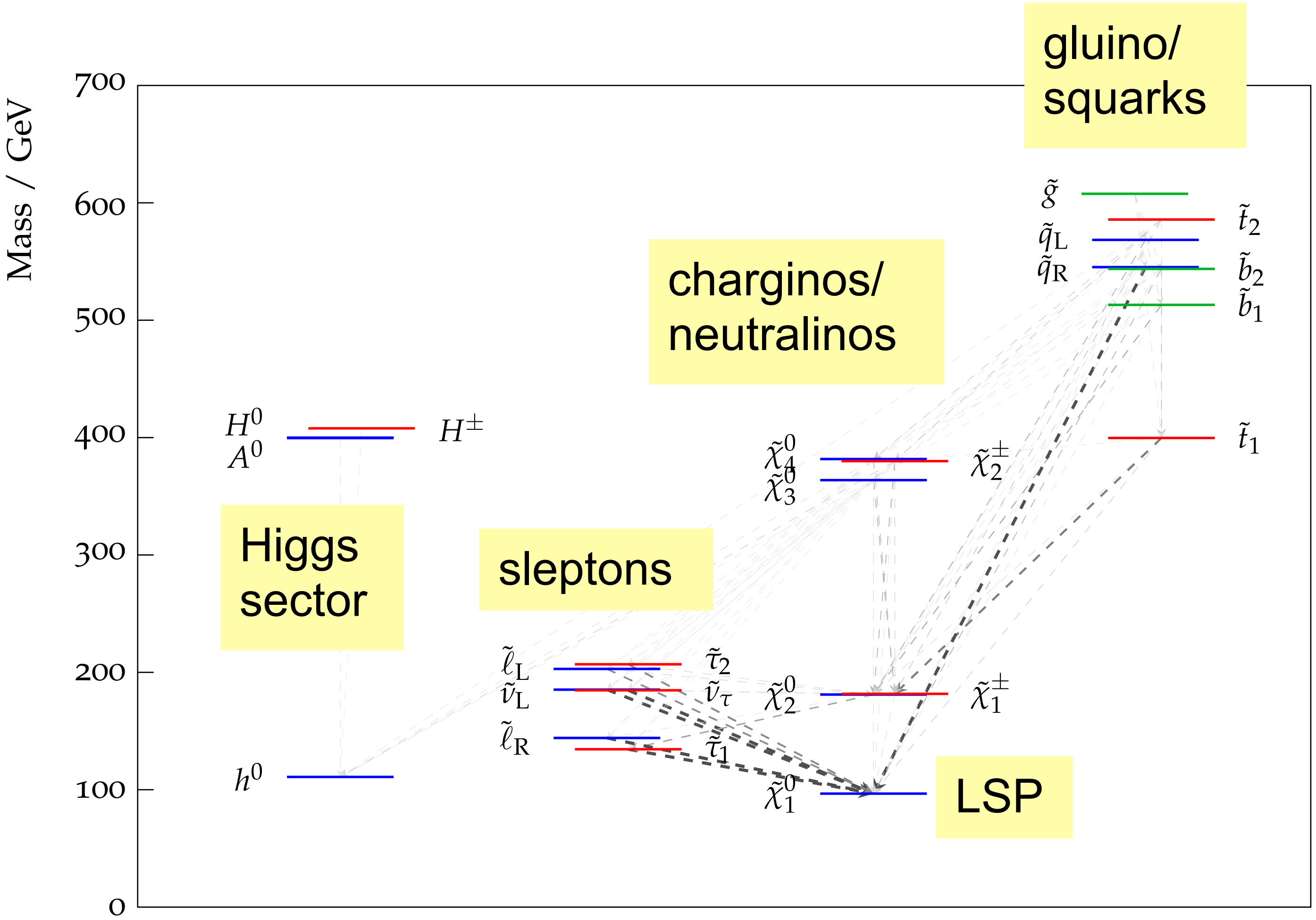
# A “typical” SUSY Spectrum

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

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



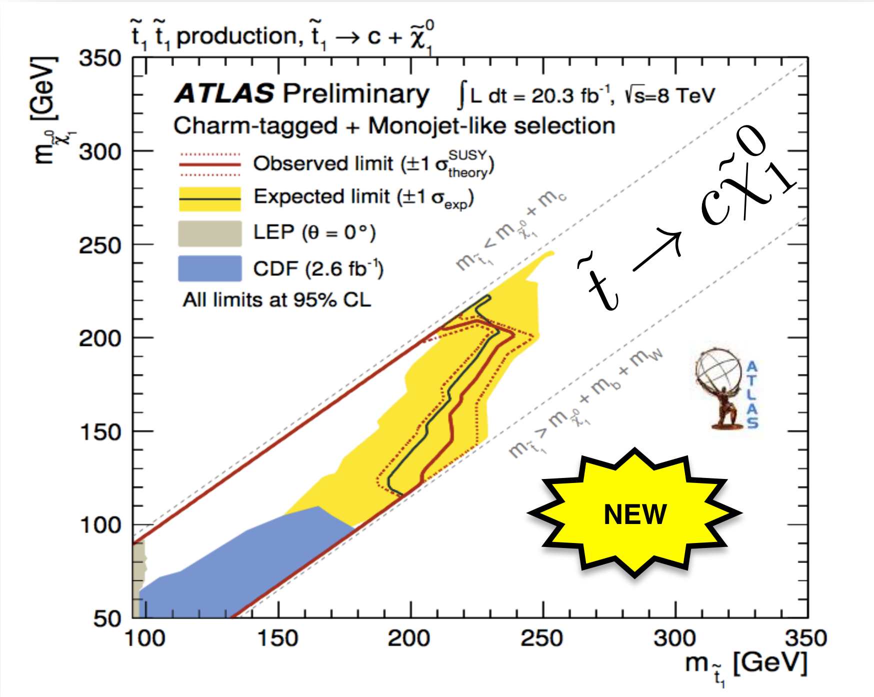

**Advantage:**

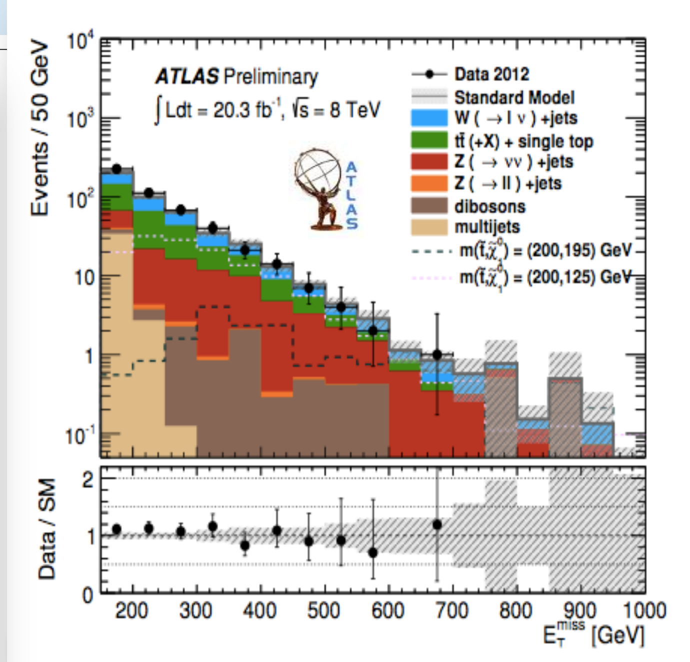
- Only four free parameters (when sign(μ) fixed)
- One of the most studied incarnations of the MSSM

**Disadvantage:**

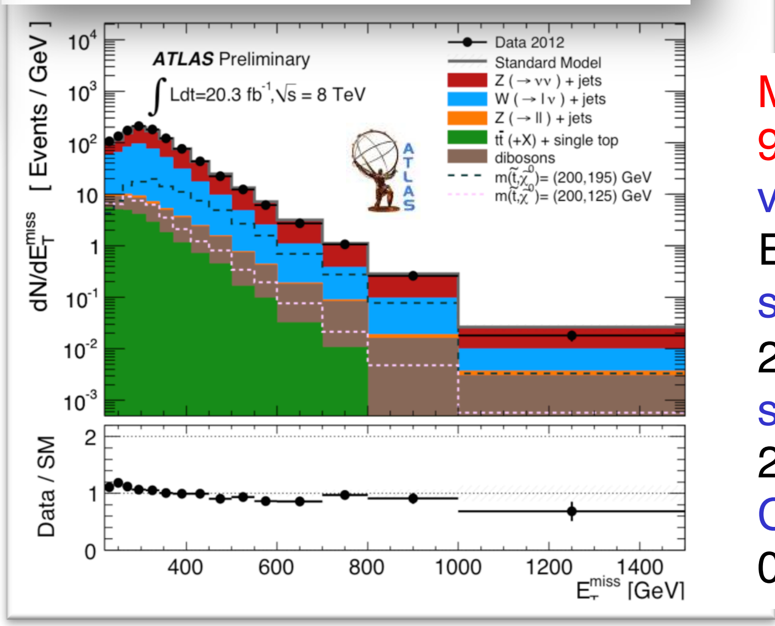
- Not generally representative of SUSY (e.g. fixed mass relation between $M_{gluion}$ and $M_{LSP}$)

# 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




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

ATLAS-CONF-2013-068:

Two different selections:

- ➢ Monojet-like selection

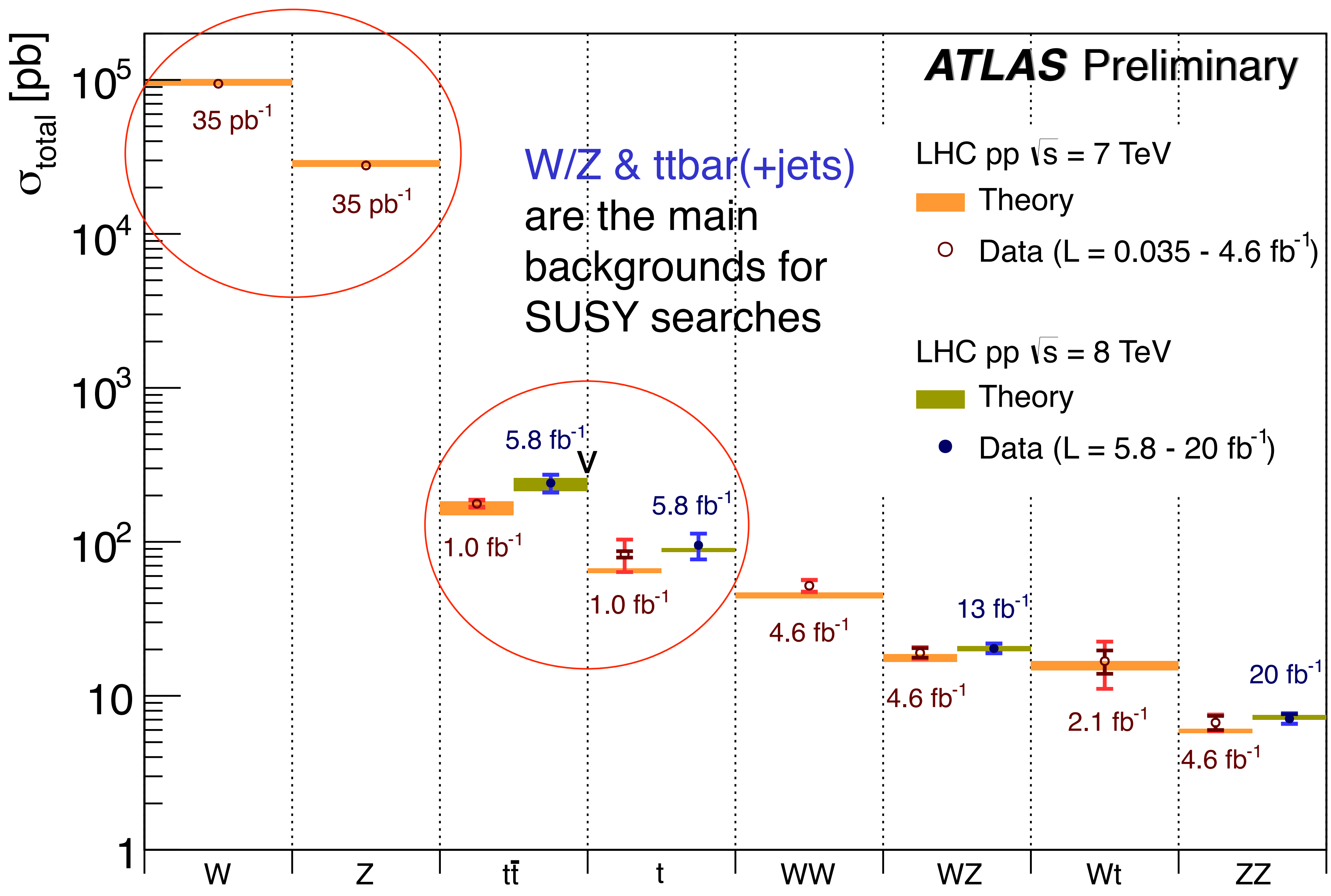
to cover region close to ‘diagonal”

- ➢ MVA based c-tag selection

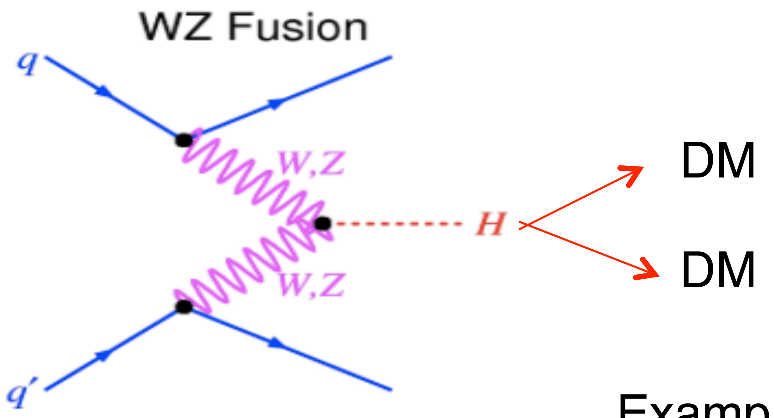
for remaining region

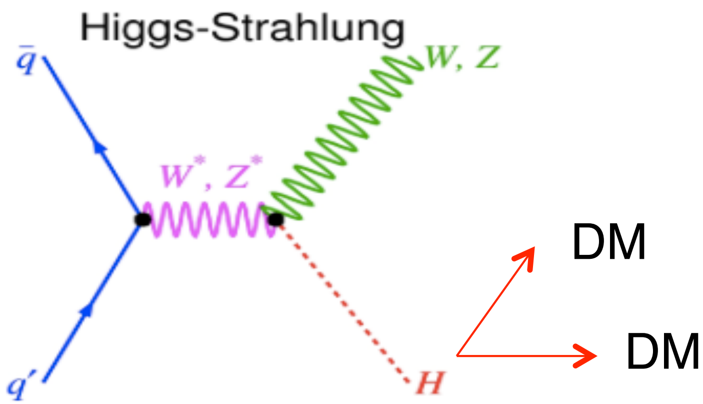
# Rediscovery of the SM at a new energy frontier



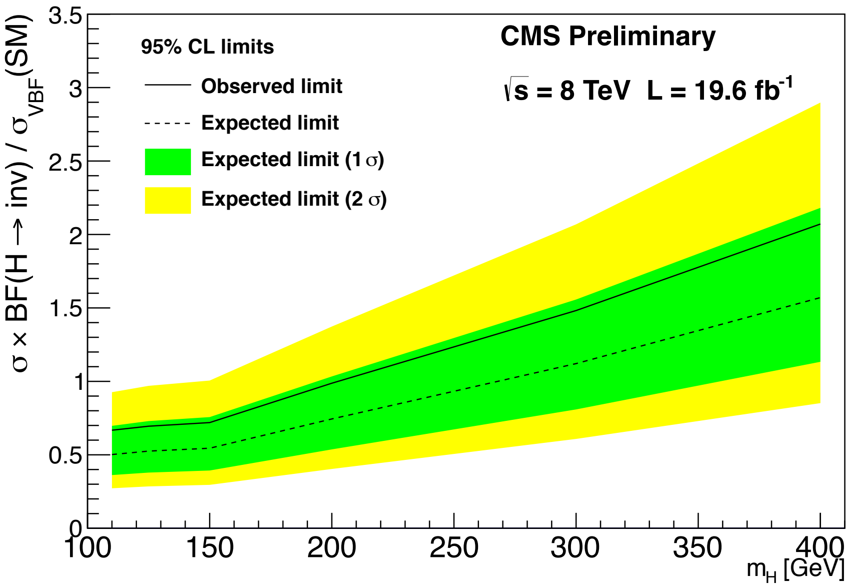


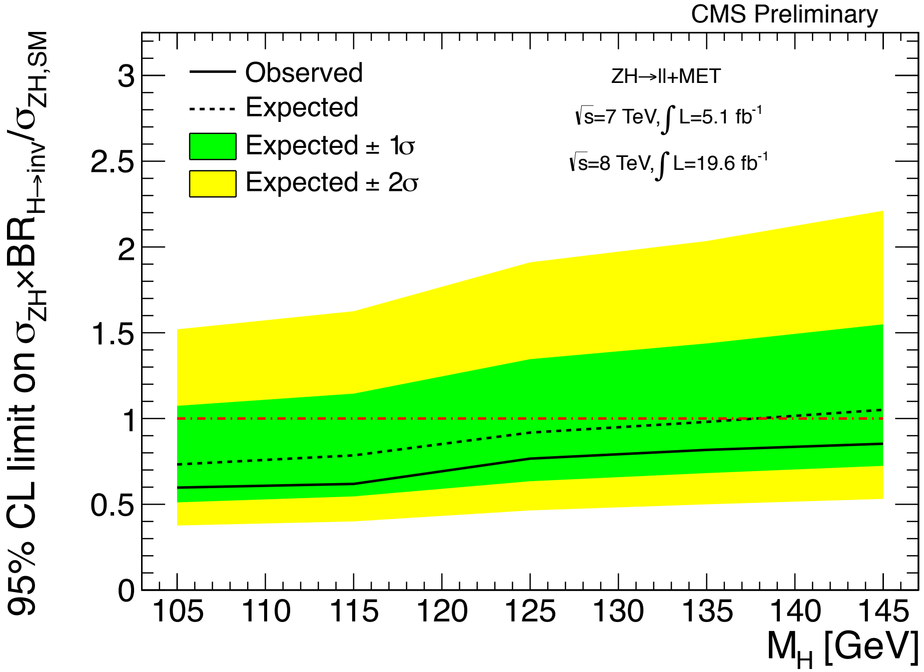
# Dark Matter from invisible Higgs searches




Example CMS




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

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

# Dark Matter from invisible Higgs searches



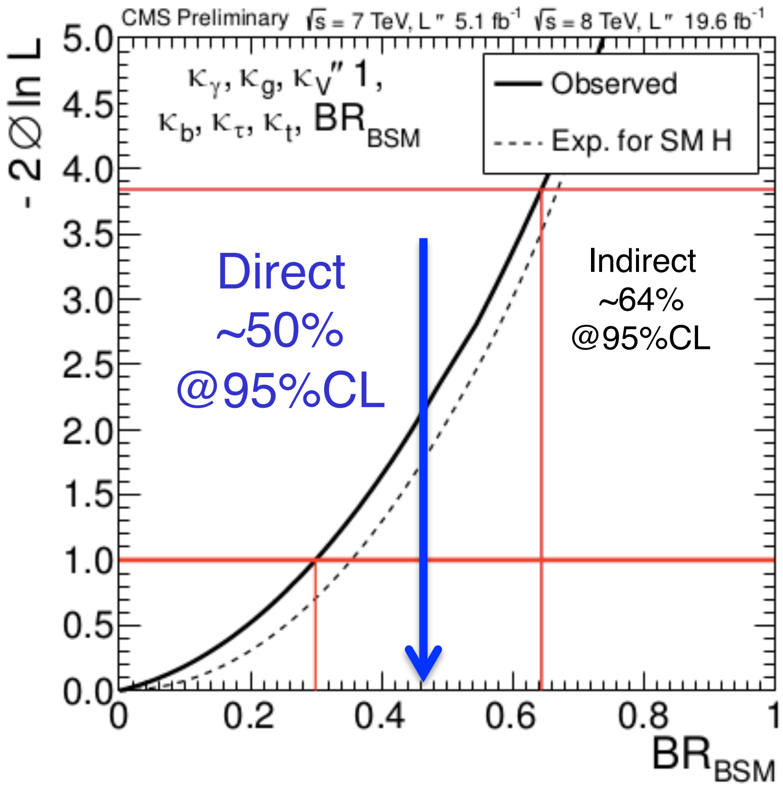
**Status 2012 CMS only:**

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

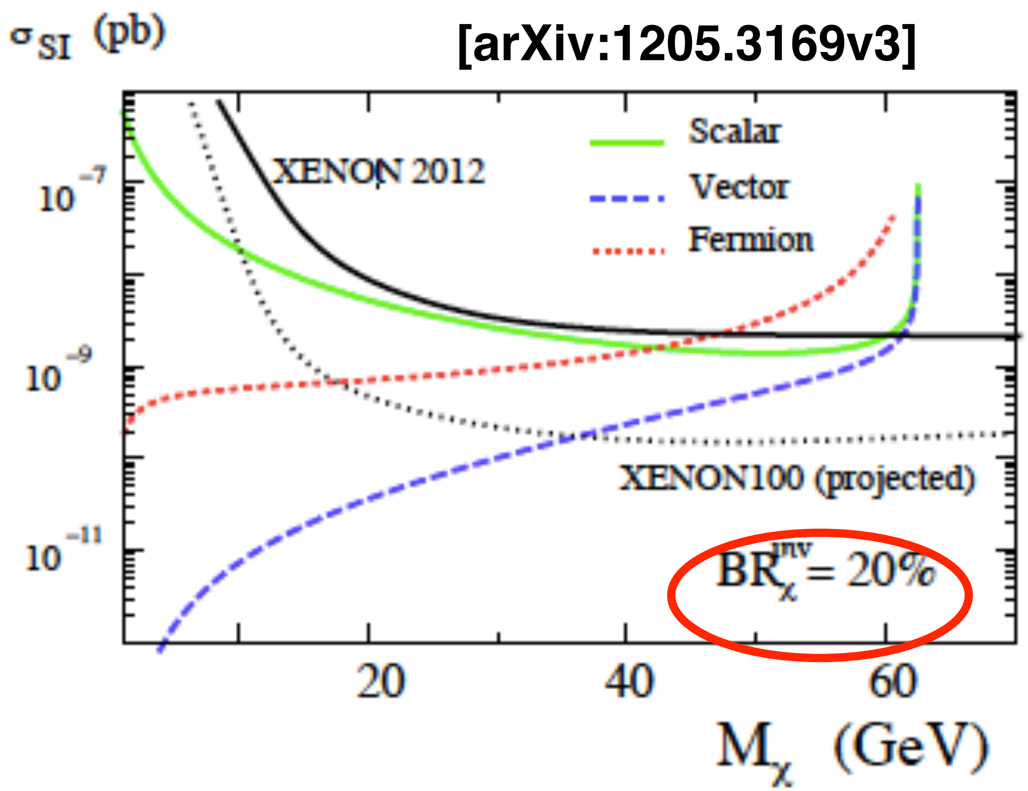
VH: $BR_{H\to invisible} < 75\%$ @ 95%CL

Naïve combination: ~ 50% @ 95% CL

$BR_{H\to invisible}$ Direct vs Indirect

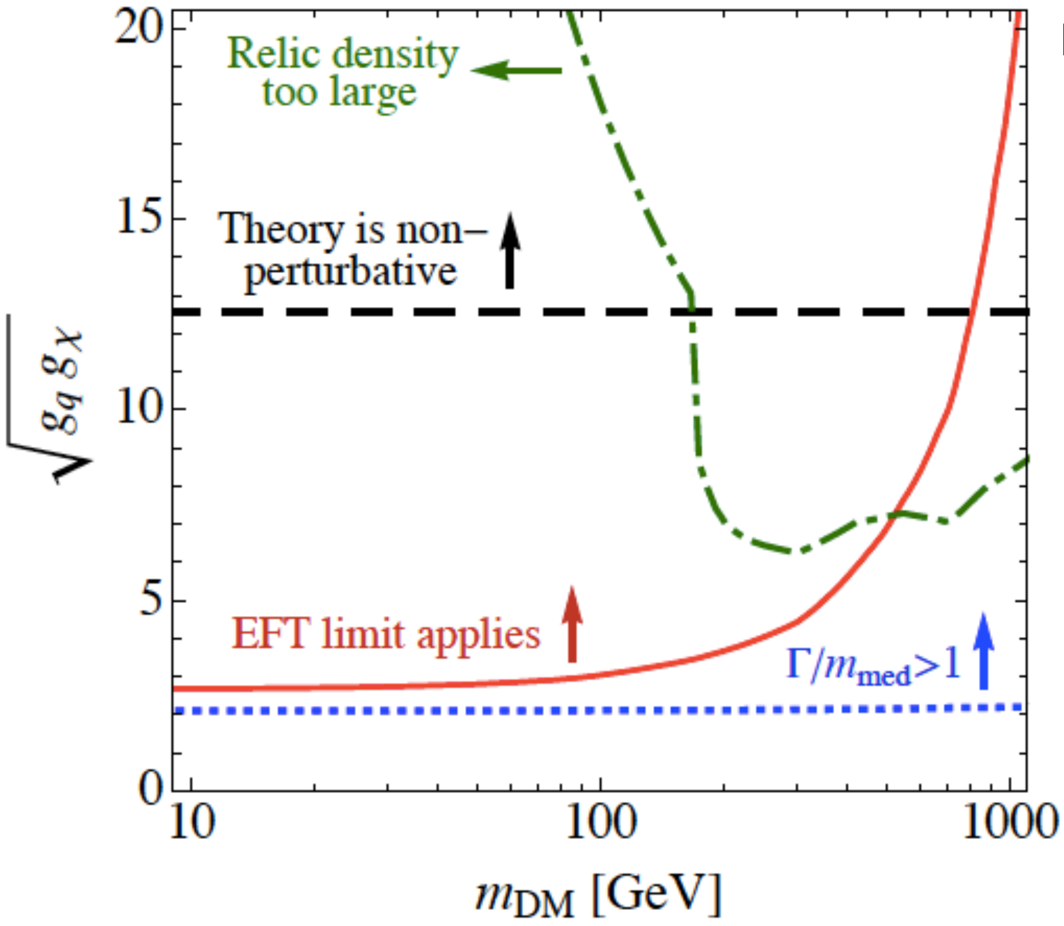



[arXiv:1205.3169v3]




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

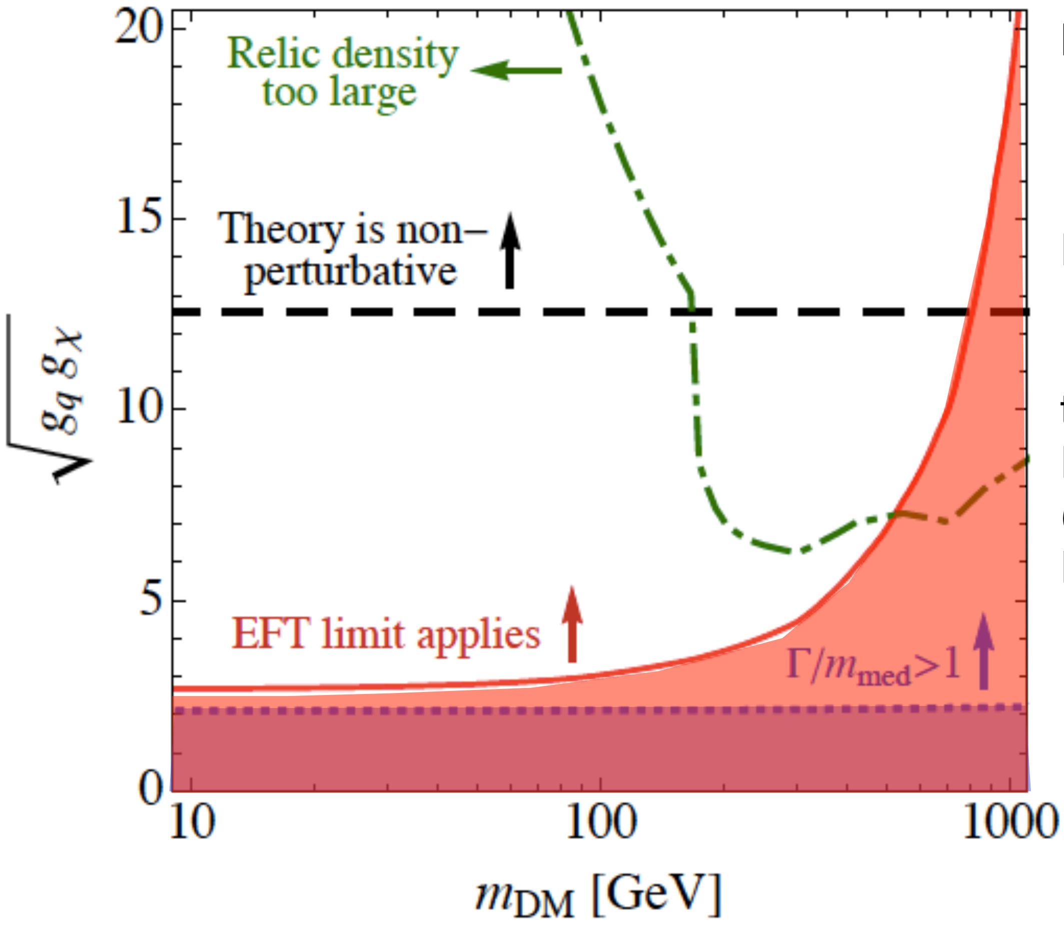
# What those this imply on model-dependences of EFT limits?




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

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

# Model-dependences of EFT limits




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

1. Region in which EFT is valid

For this we calculate the minimum coupling

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

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

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

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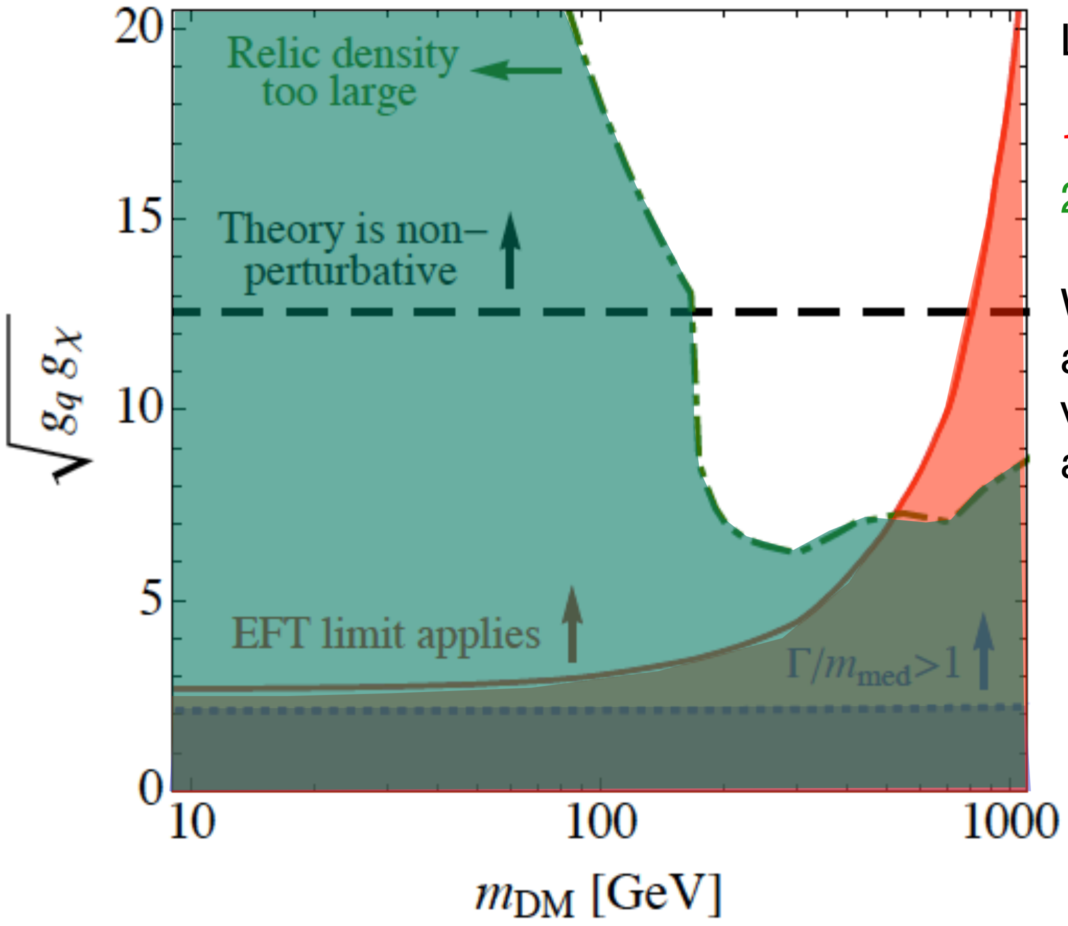
# Model-dependences of EFT limits



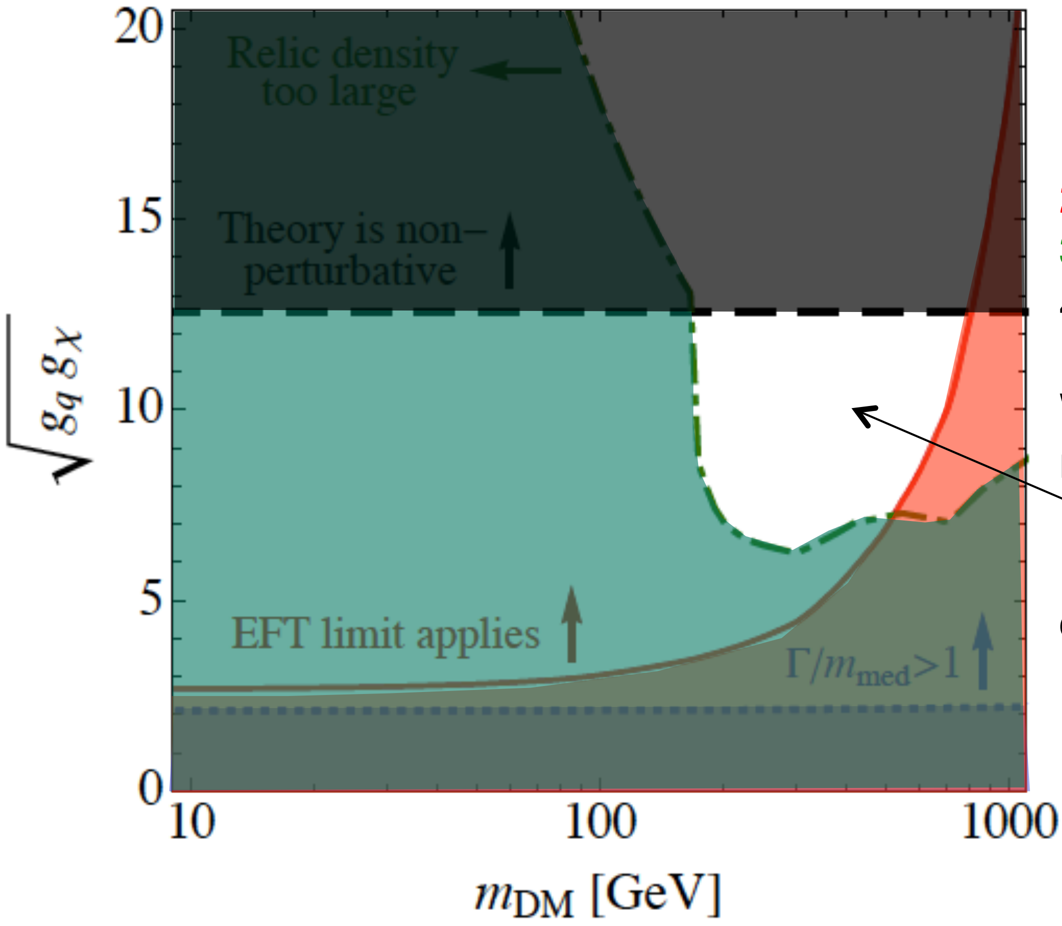

Look at EFT validity in $m_{DM}$ – coupling* plane!

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

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

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

# Model-dependences of EFT limits




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

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

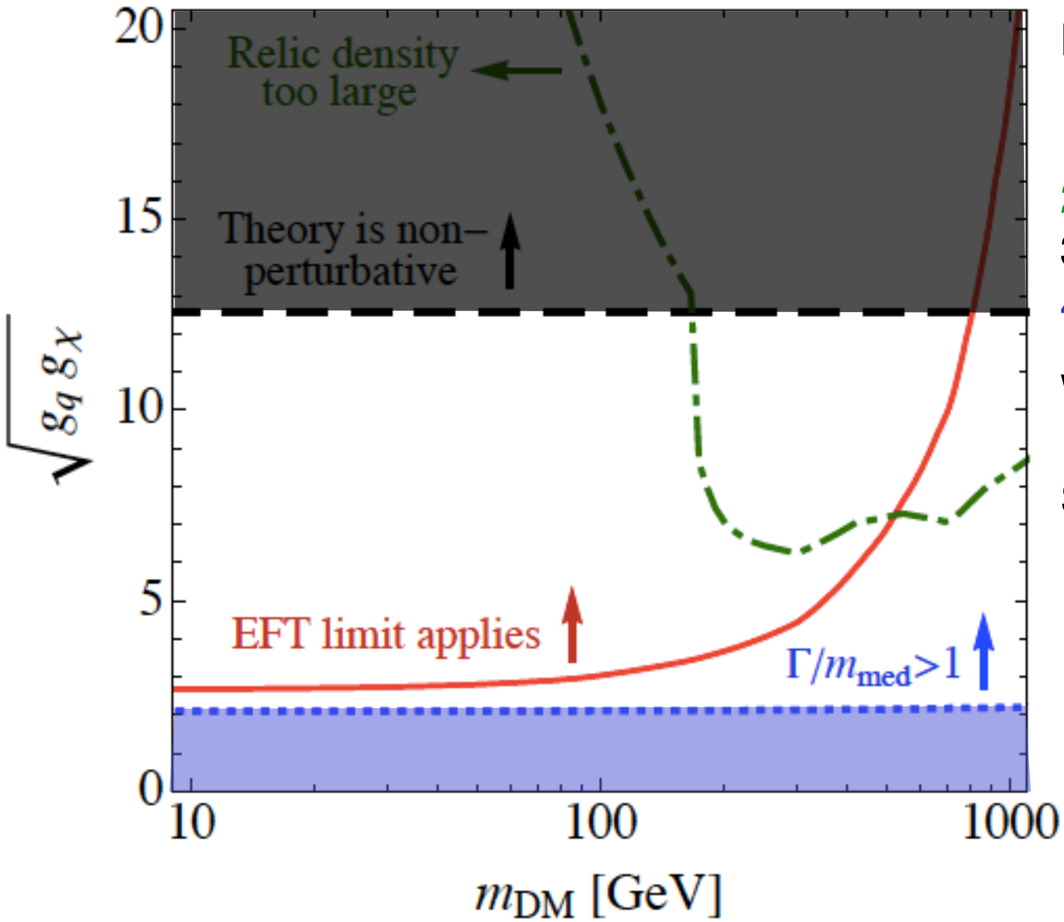
When we also require that the region/theory must be perturbative:

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

only a very small region is left!

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

# Model-dependences of EFT limits




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

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

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

In the reaming part of the plot:

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

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

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

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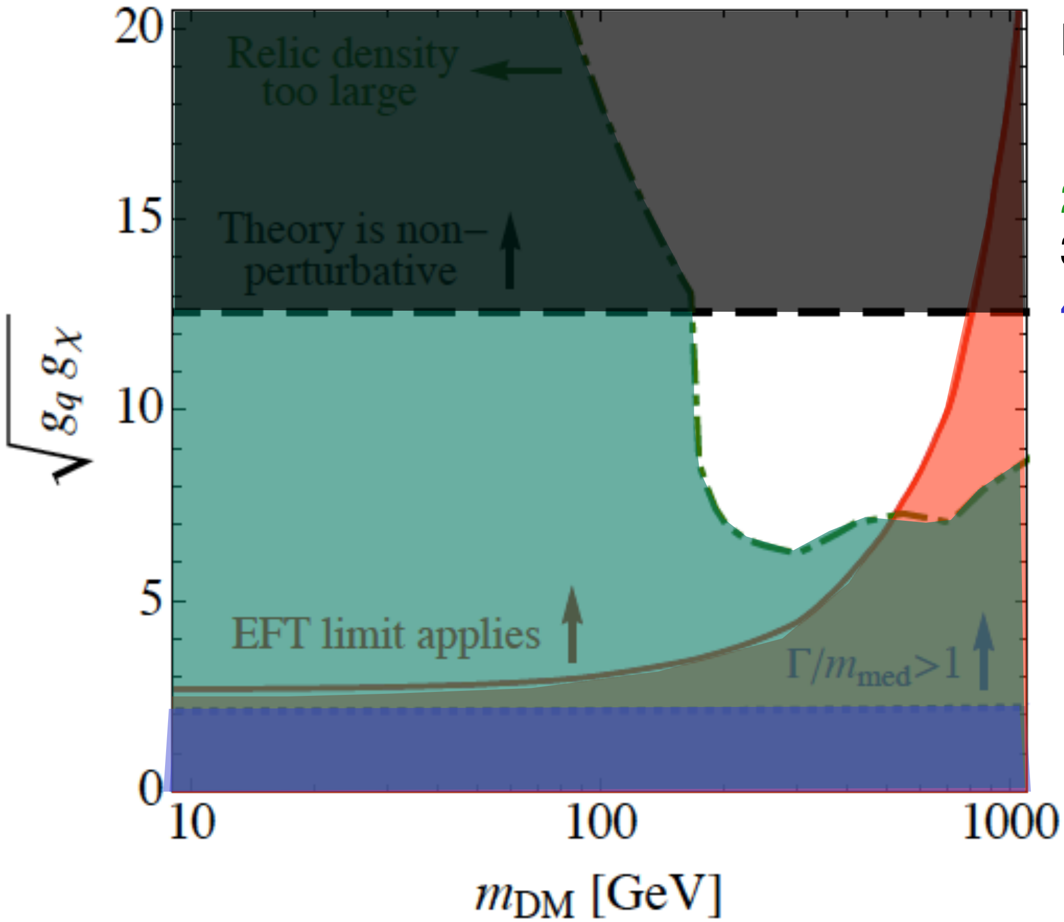
# What those this imply on model-dependences of EFT limits?




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

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

The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.
EFT limits of monojet searches are therefore highly model-depended!

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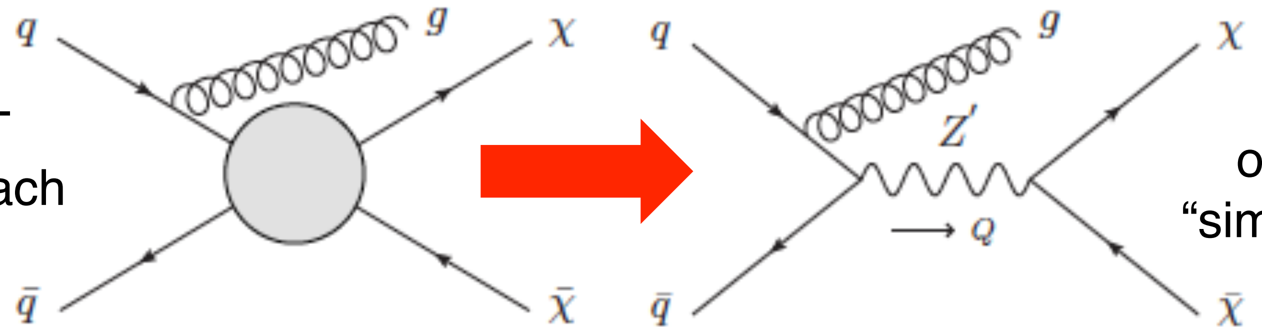
# Alternative Interpretation Ansatz: Simplified models



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

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

EFT approach

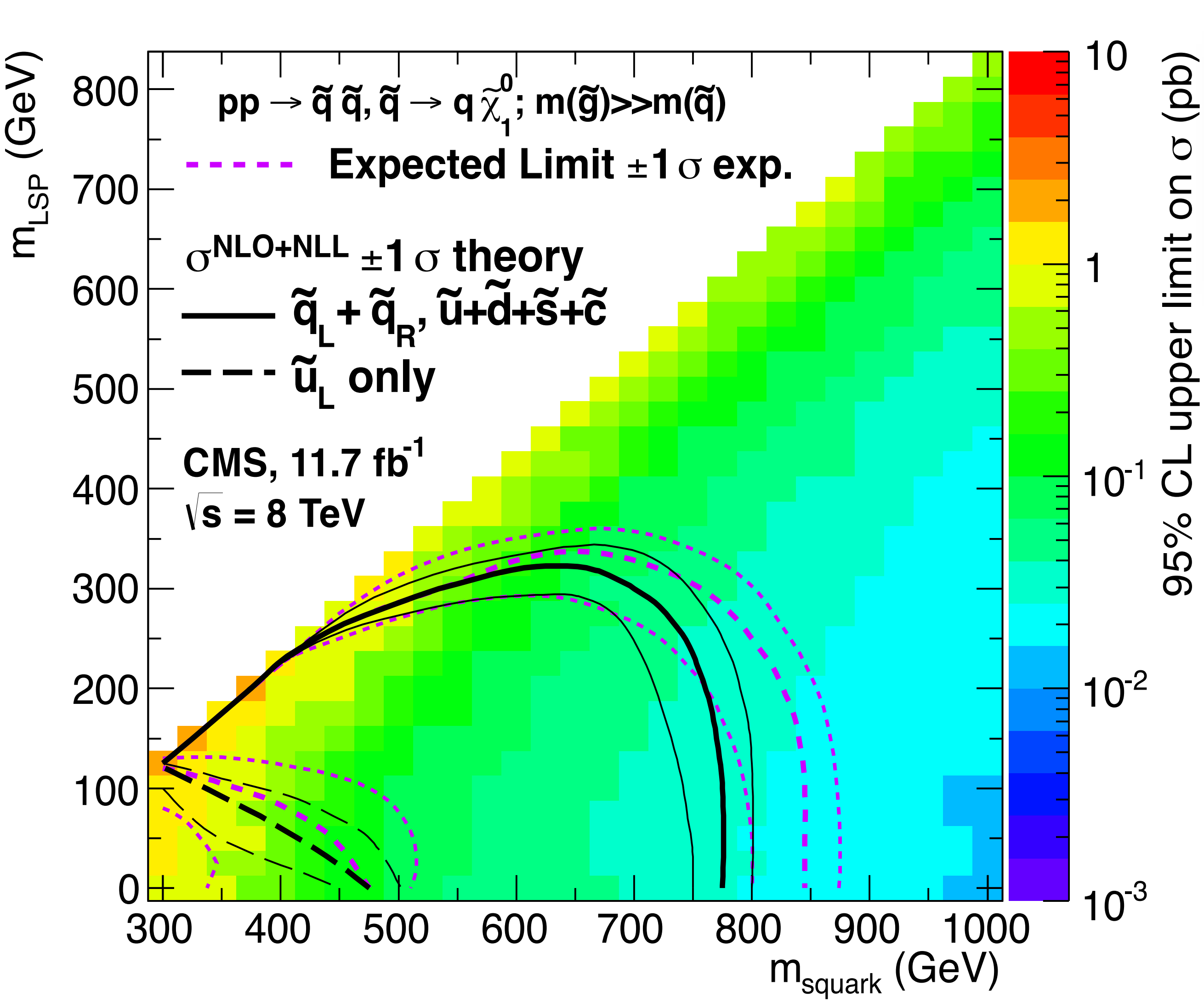


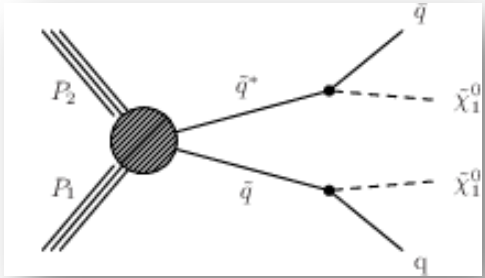

FT
one diagram
"simplified model"

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

# The proposal

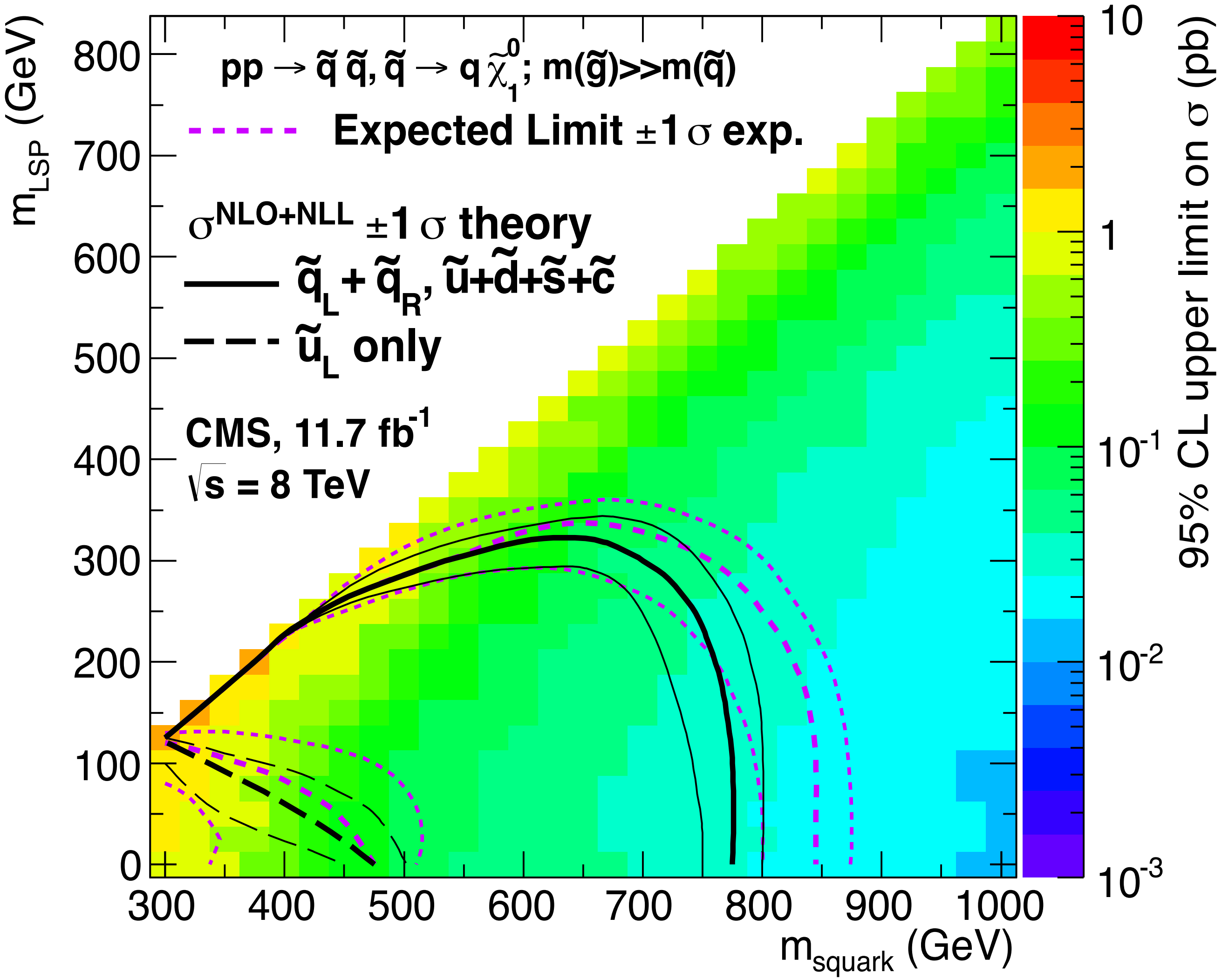


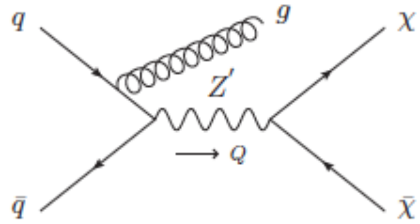


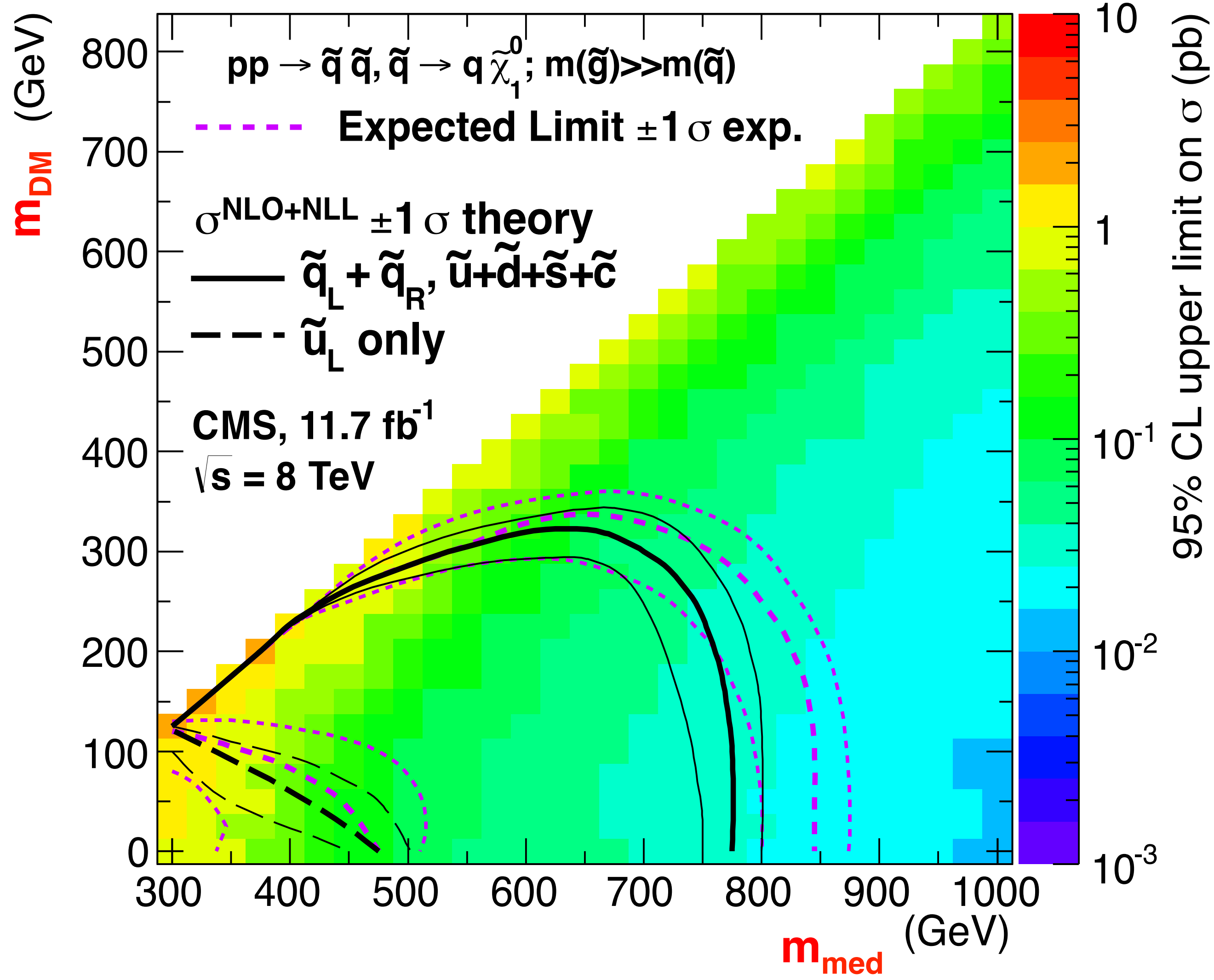
# The proposal

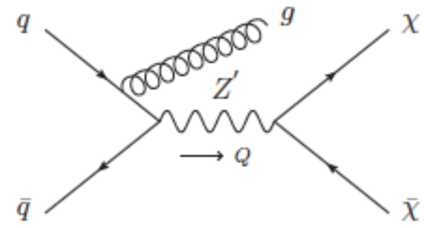




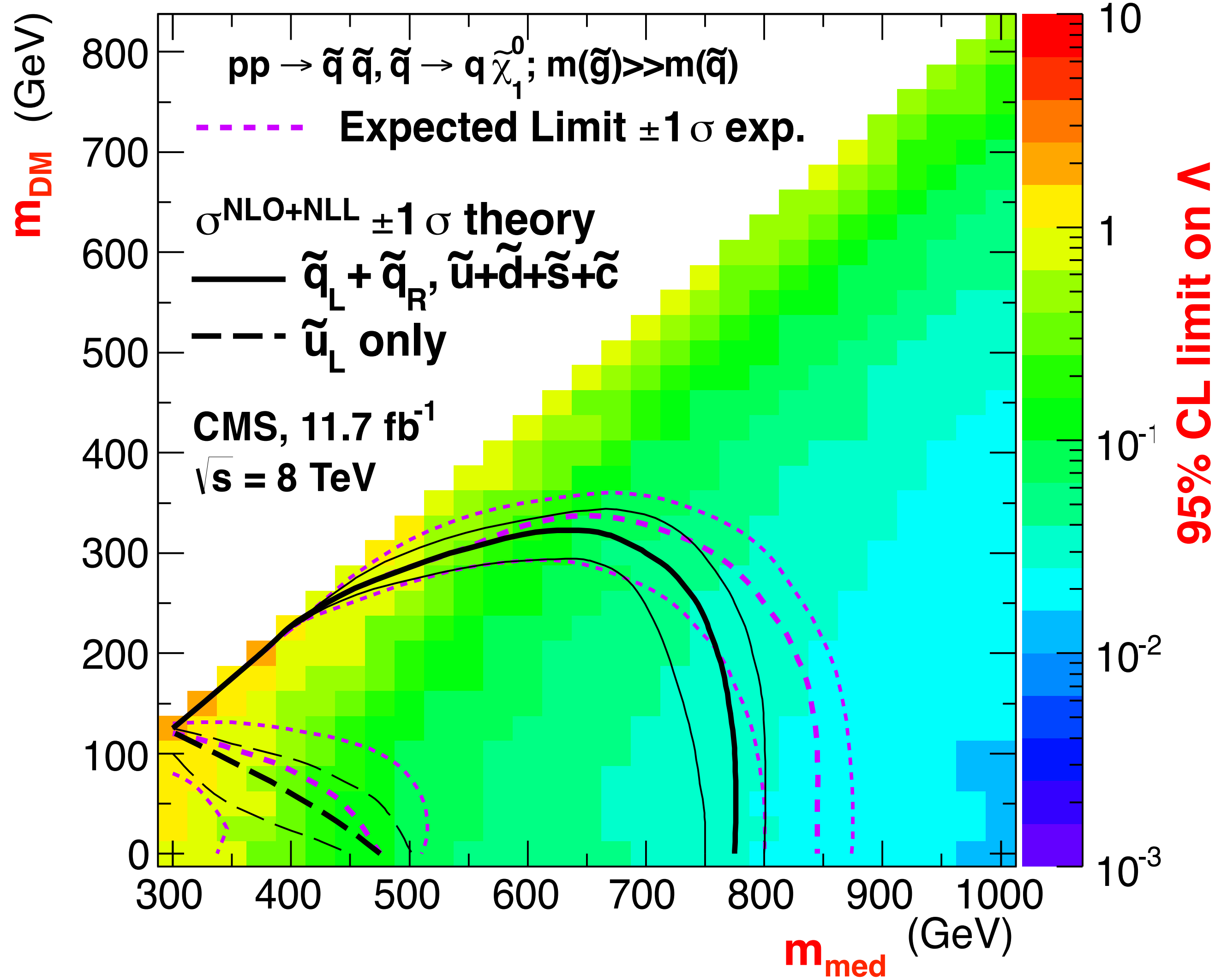
# The proposal

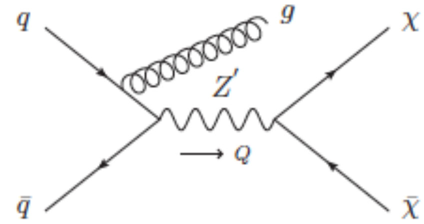


# The proposal



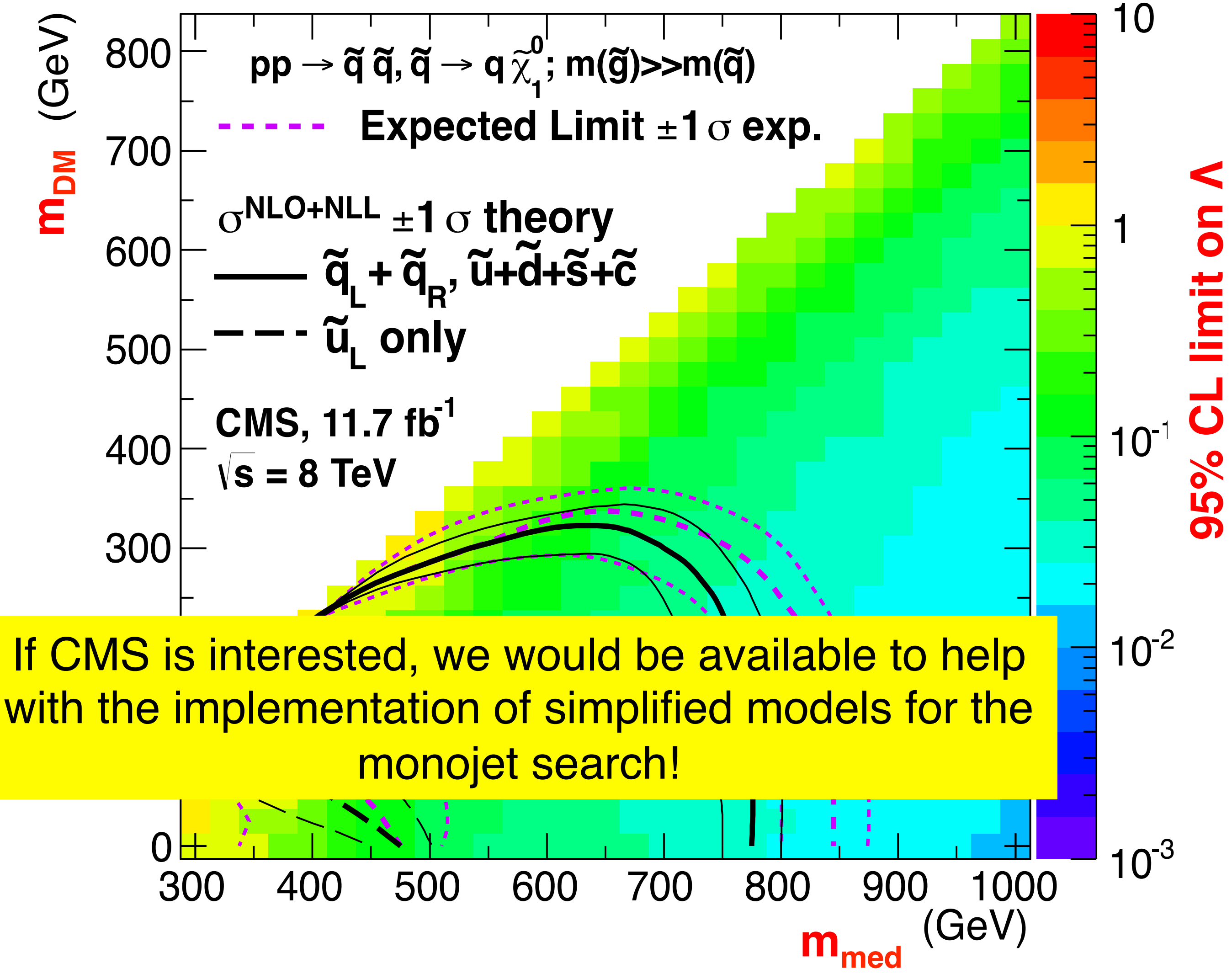


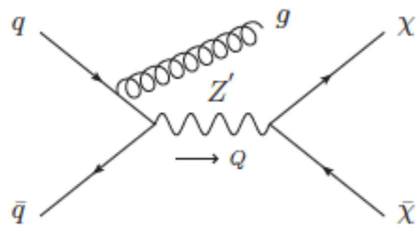
Very similar to limits in SUSY simplified models –
$m_{med}$, $m_{DM}$, $\Lambda$
and possibly some variation of $\Gamma_{med}$
will cover the full problem!

# The proposal






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

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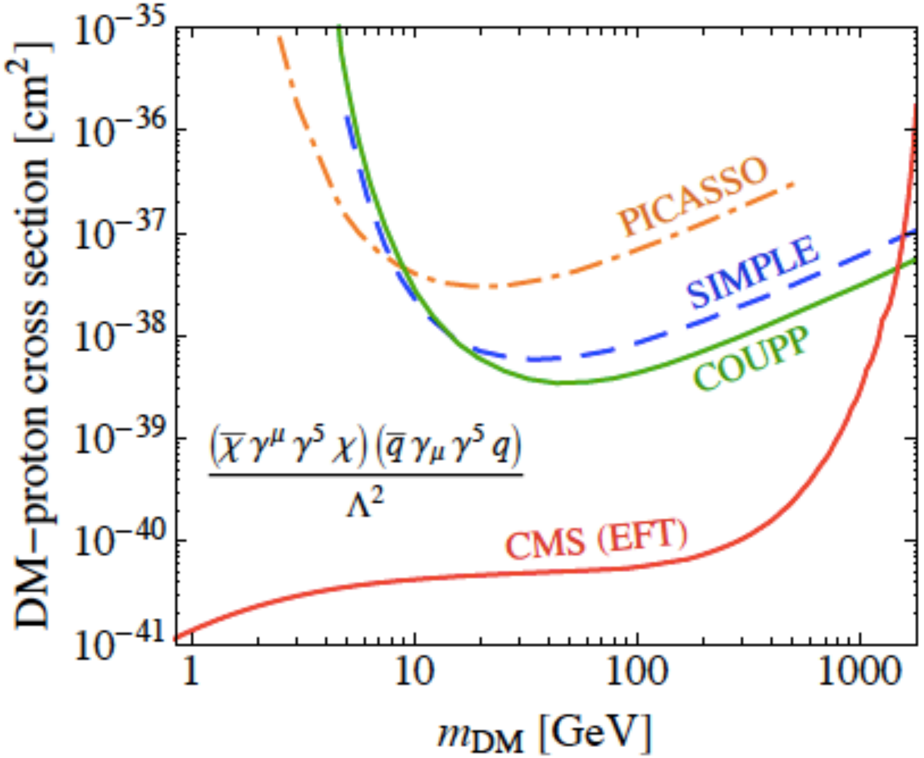
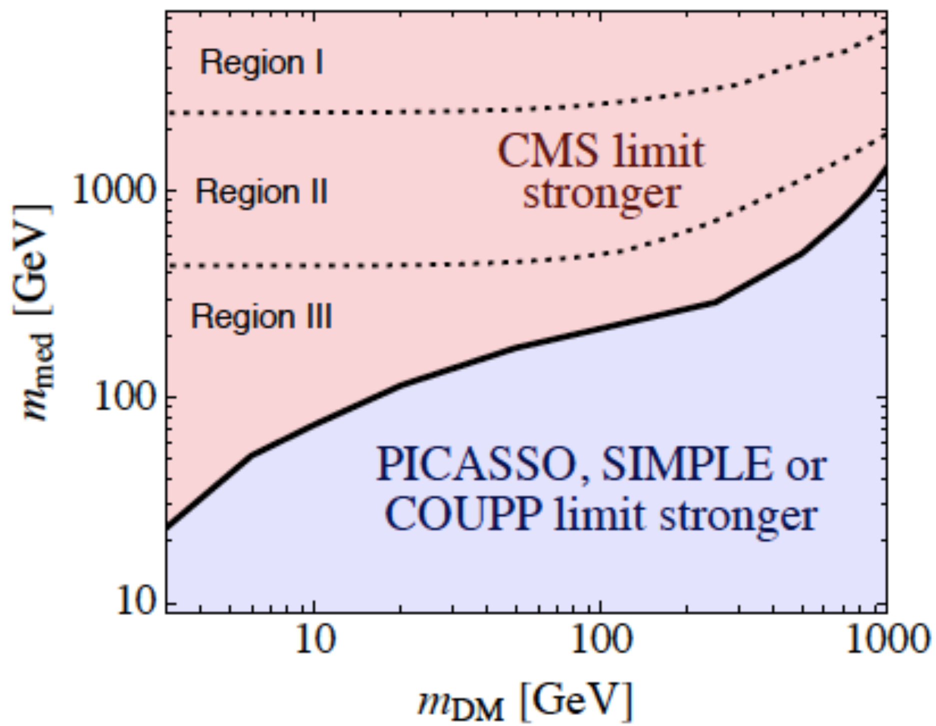
# Beyond EFT limits: Simplified models



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



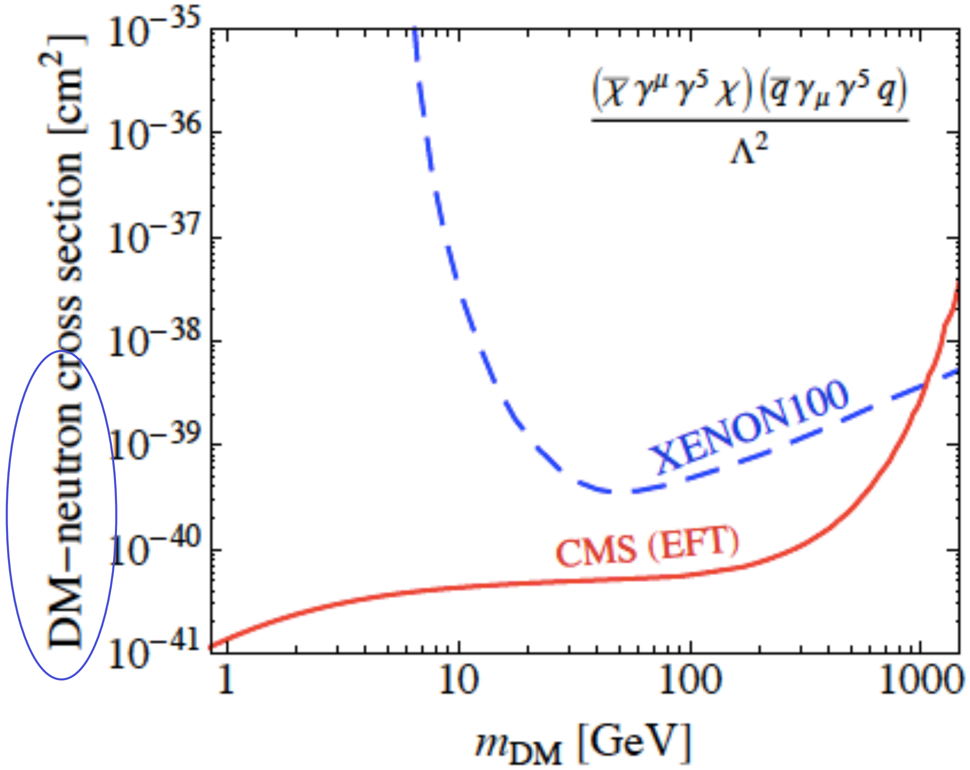

EFT limits give the impression that monsjet searches outperform direct detection BUT EFT only applies a VERY small class of DM models.

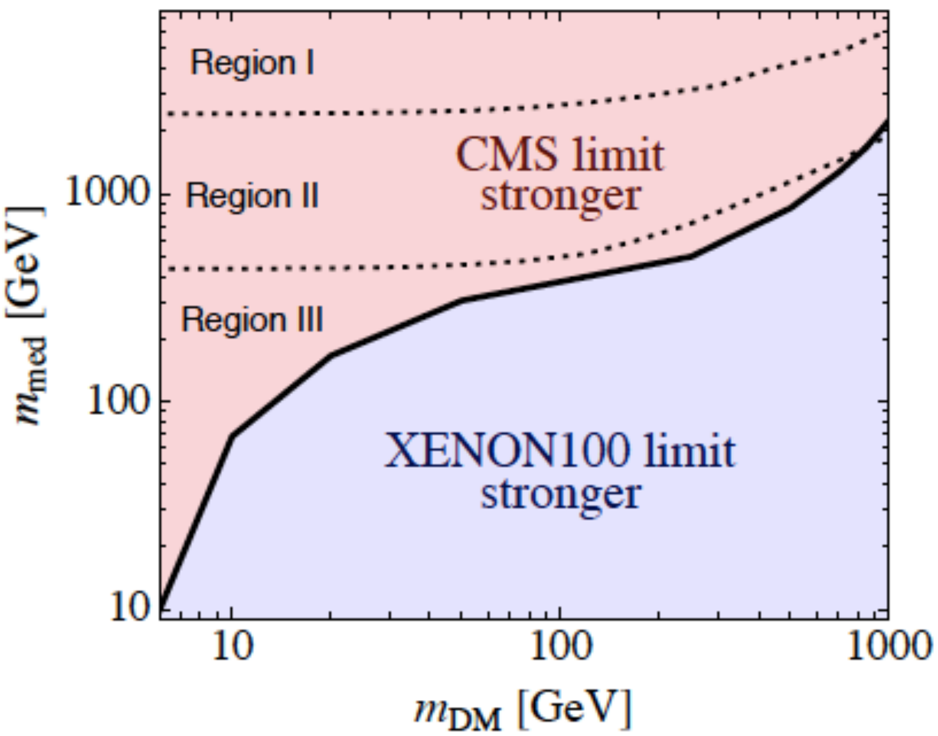
Simplified model limits give a much better Account of the REAL complementarity and thus seem superior for a comparison.

# Beyond EFT limits: Simplified models

Buchmüller

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

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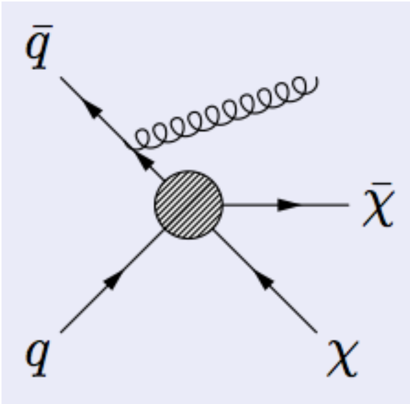
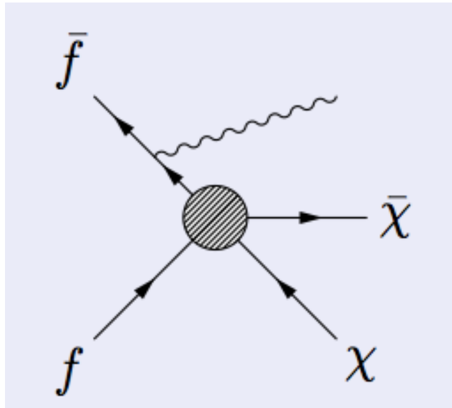
# Monojet and Monophoto (plus $E_T^{miss}$)



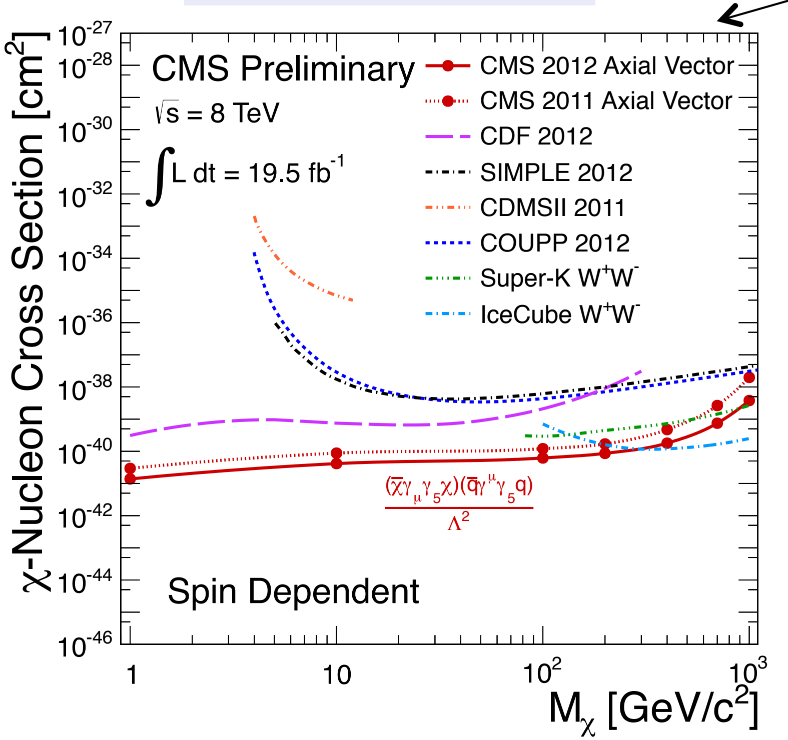
## Monojet: hard jet + $E_T^{miss}$

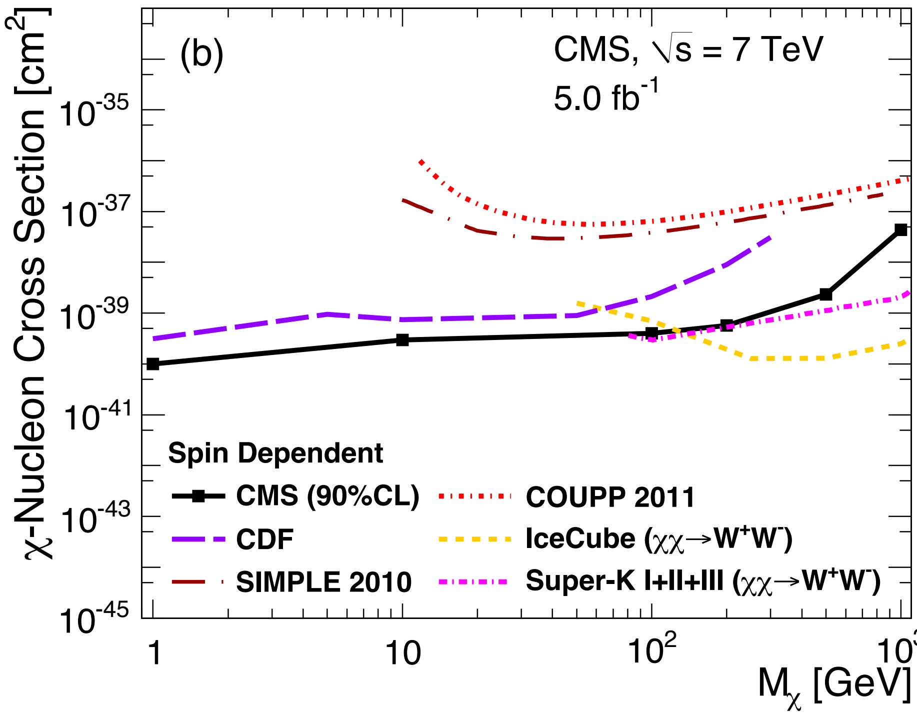


## Monphoton: hard photon + $E_T^{miss}$



Note different y scale



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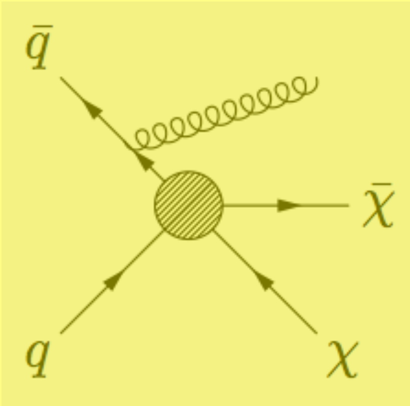

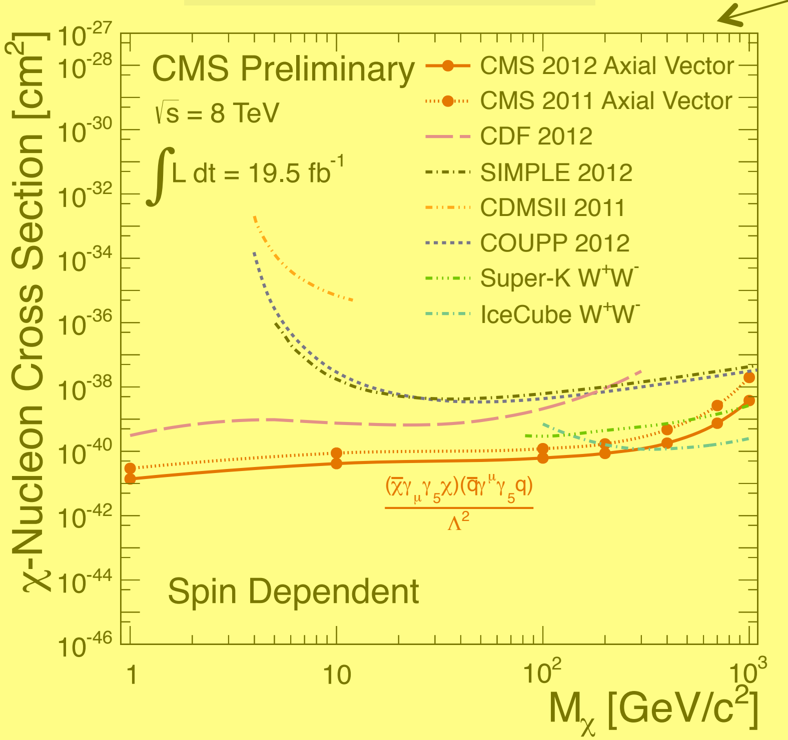


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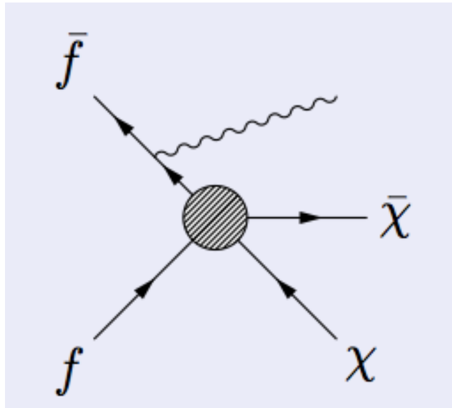

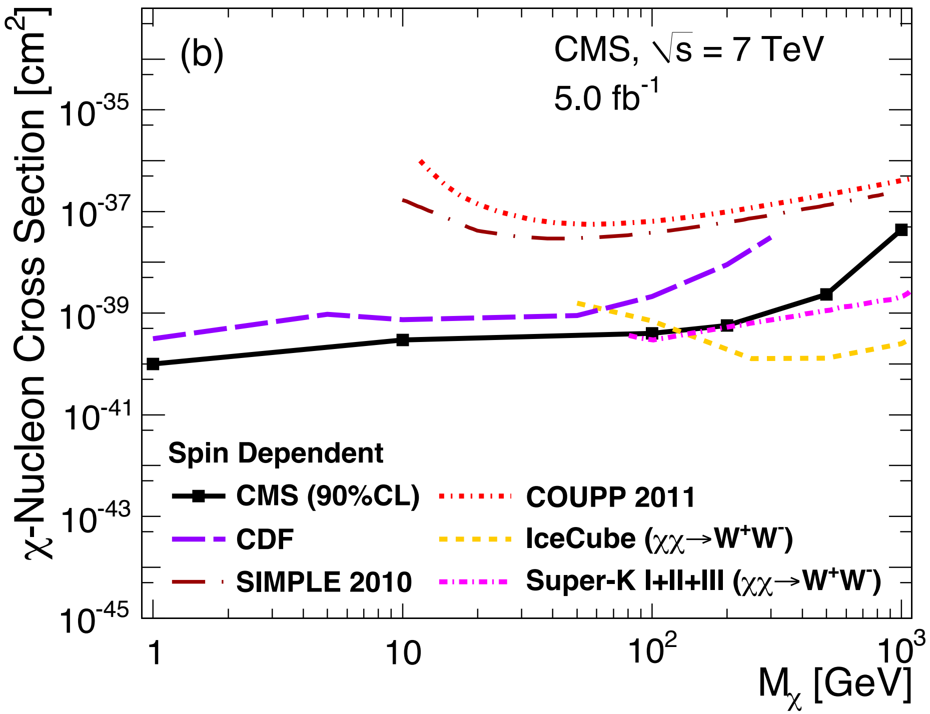

# Dedicated searches for direct stop-pair production