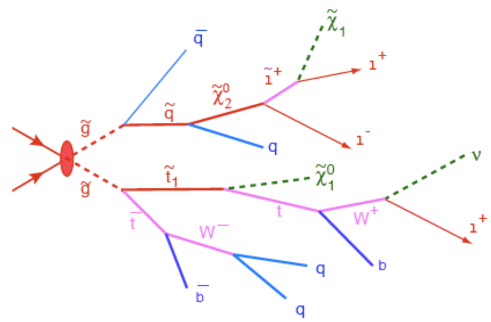
Search for Supersymmetry at the LHC
What have we learned so far?

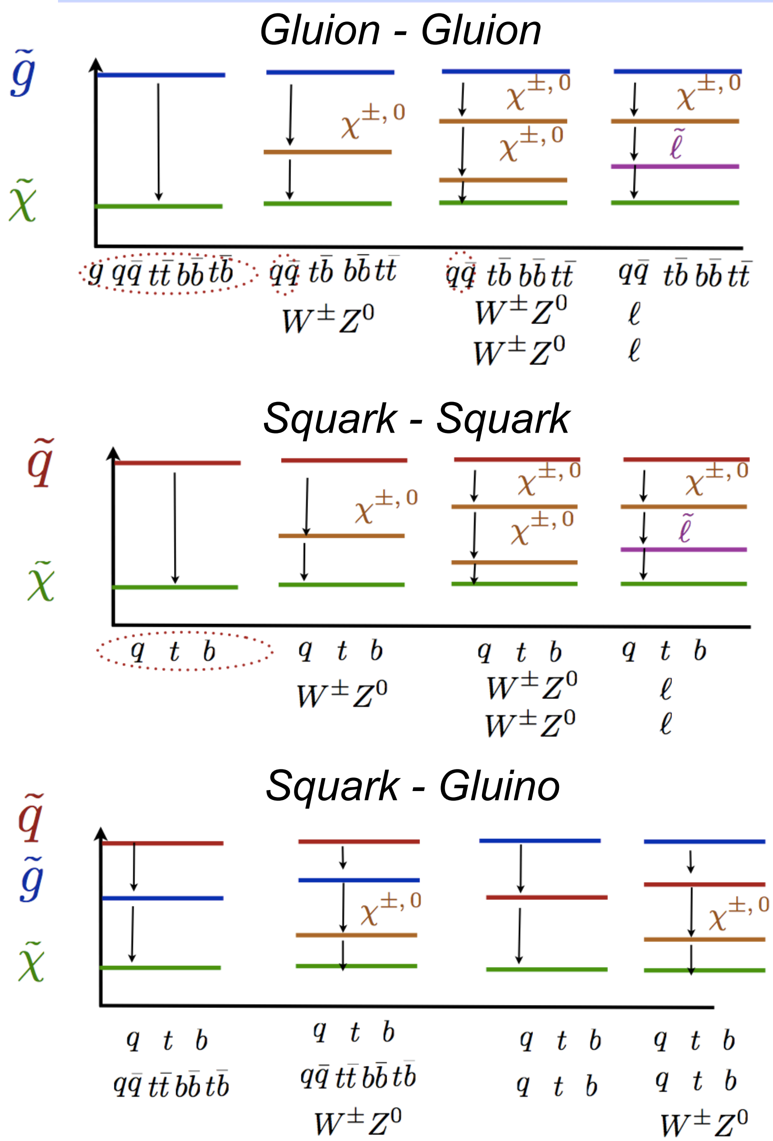
Oliver Buchmüller
(Imperial College London)



- *Search Strategy for SUSY at the LHC (so far)*
- *Where are we today?*
- *What have we learned?*

SUSY Searches at the LHC

SUSY Search Strategy in a Nutshell



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:

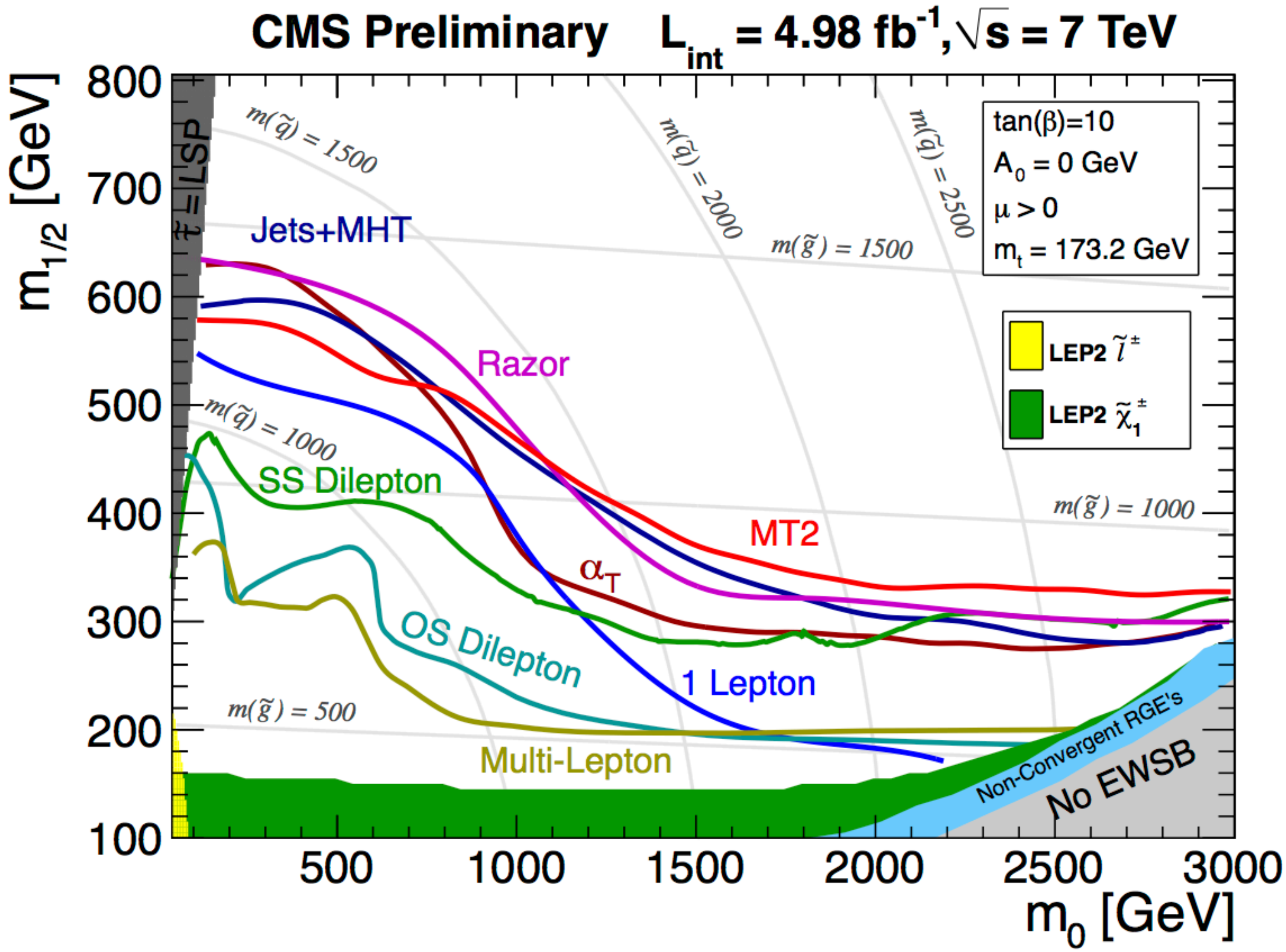
References Analyses

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 a full list of these core "SUSY References Analyses"!

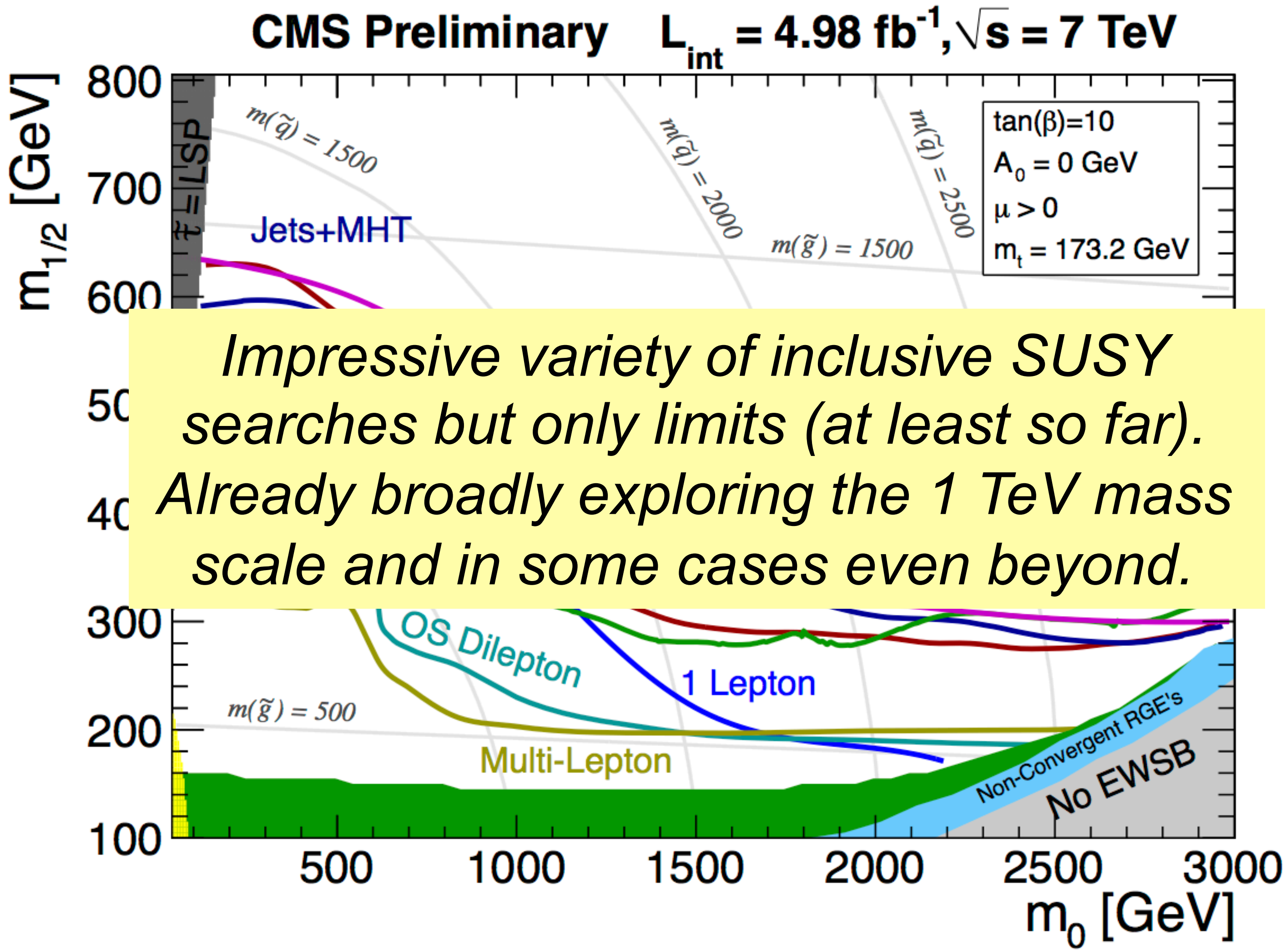
Inclusive SUSY Searches

Landscape Today: Example CMS



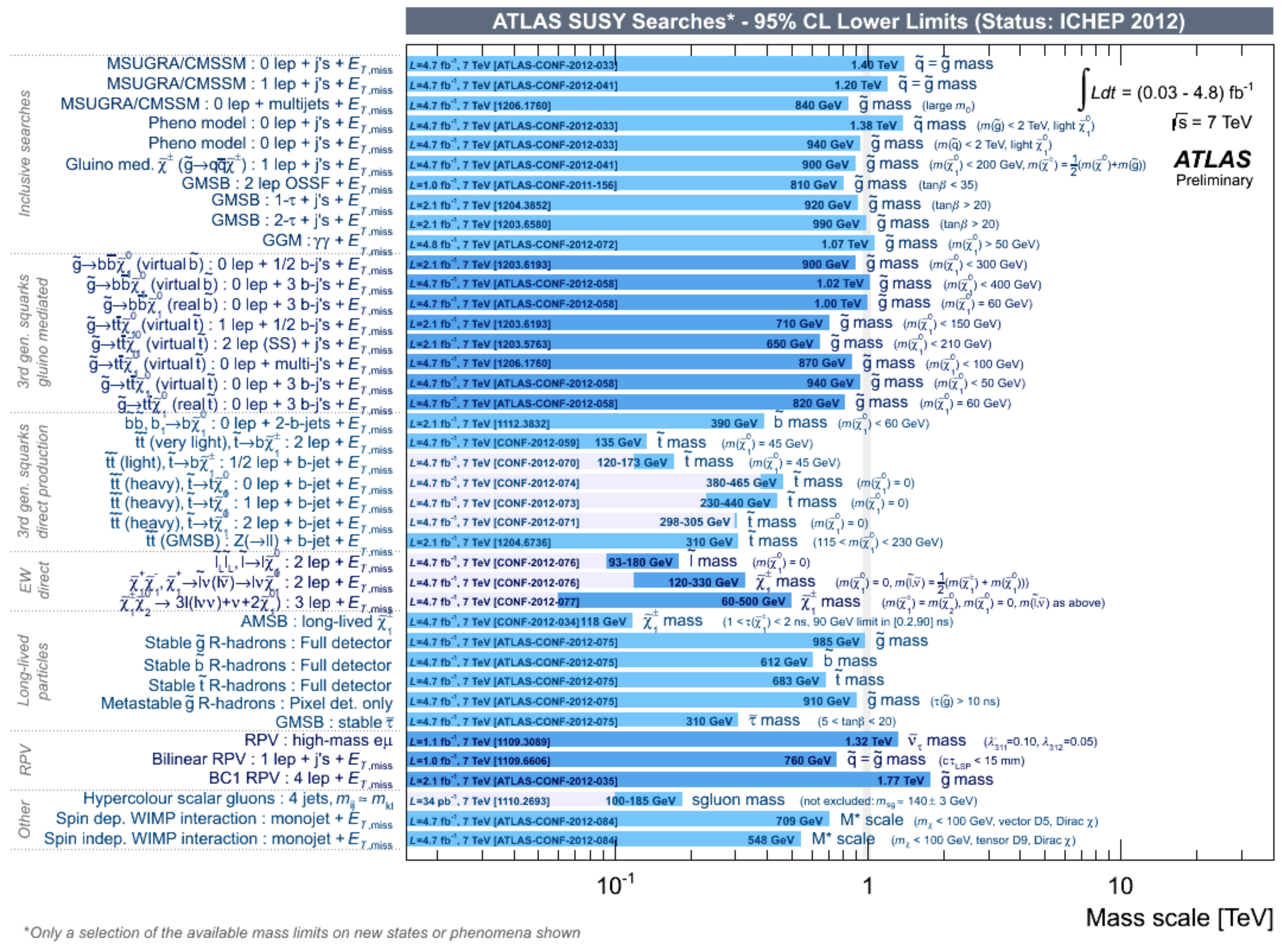
Inclusive SUSY Searches

Landscape Today: Example CMS



Impressive variety of inclusive SUSY searches but only limits (at least so far). Already broadly exploring the 1 TeV mass scale and in some cases even beyond.

SUSY Today – Only Limits!



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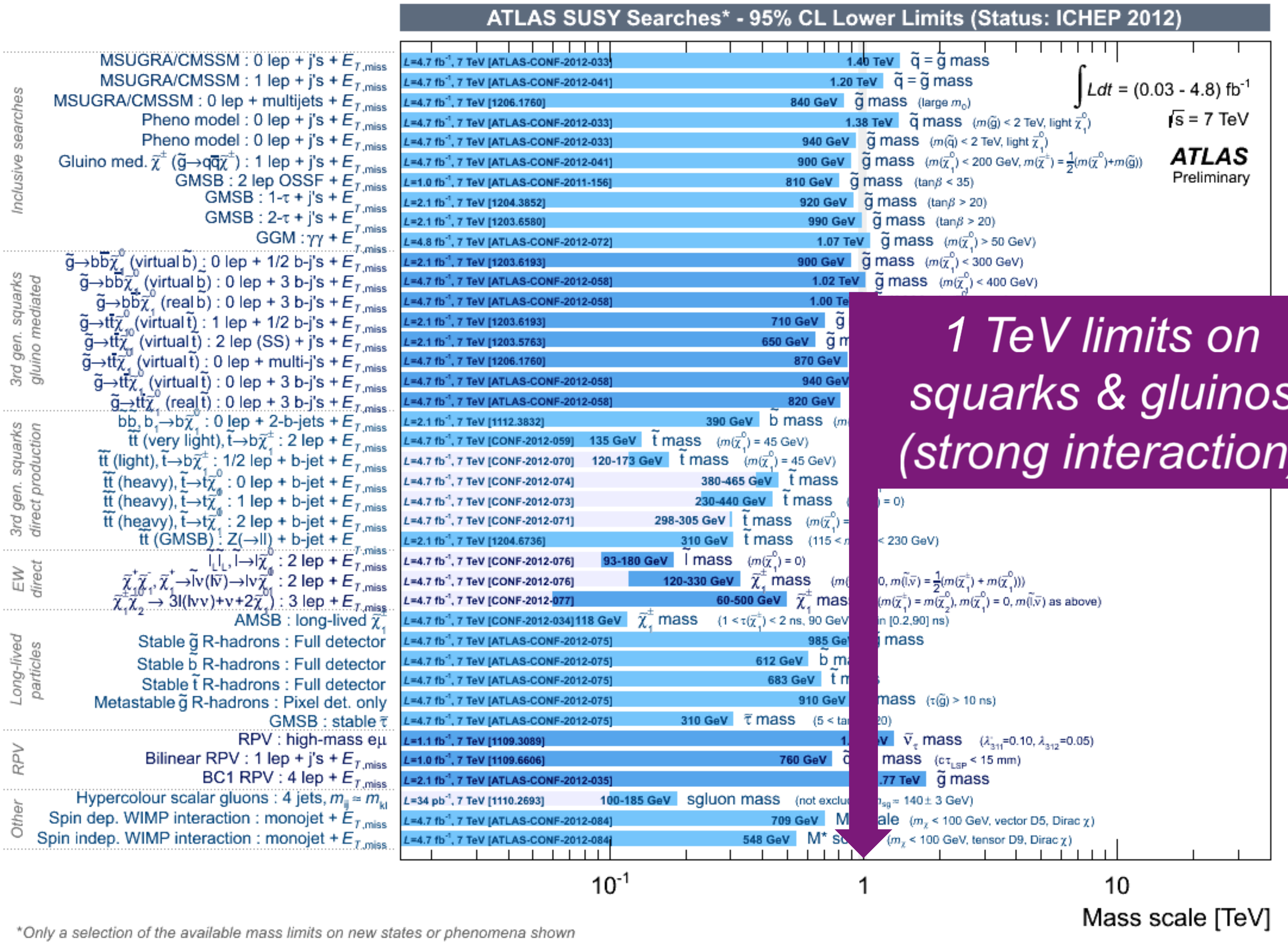
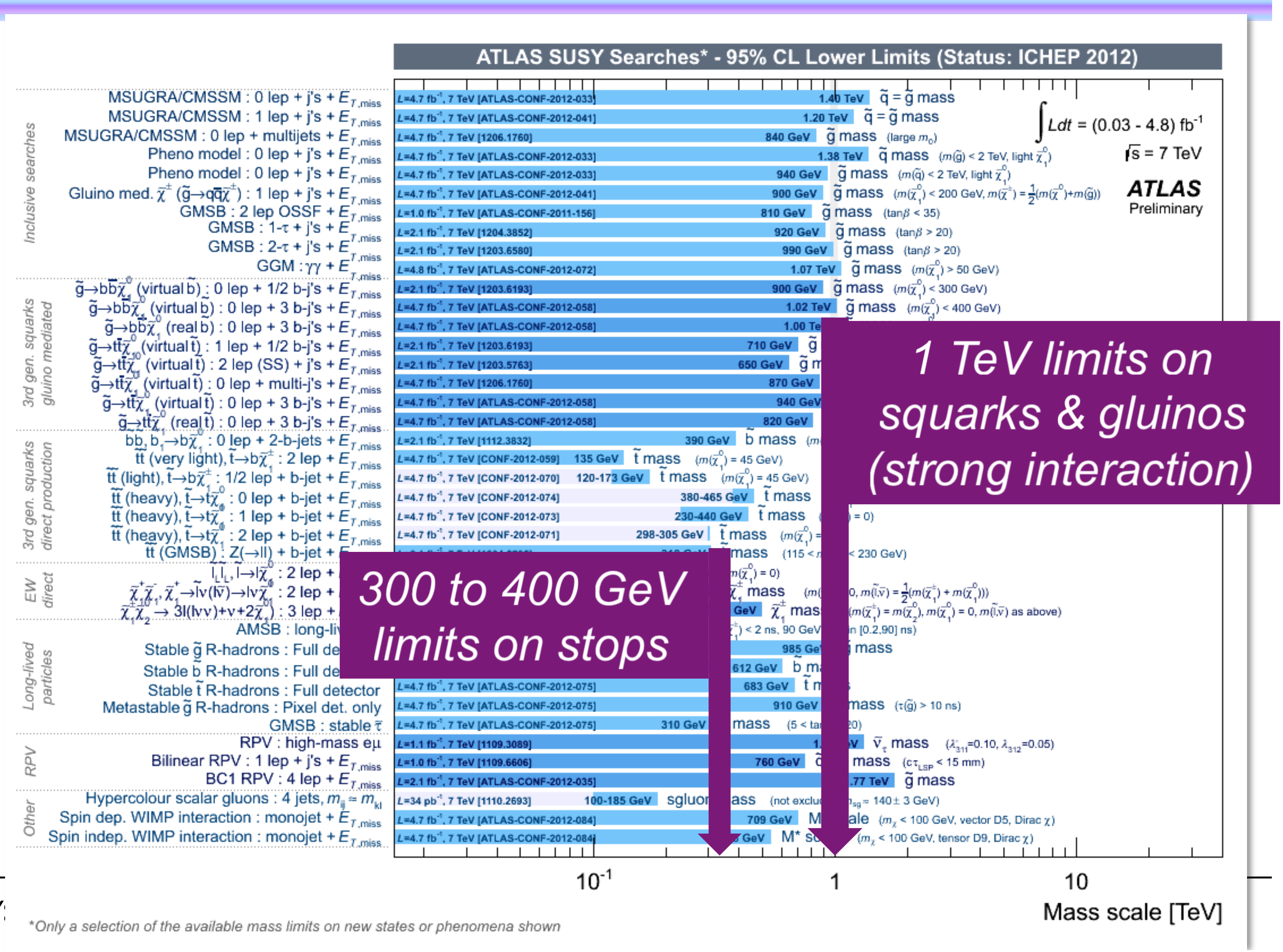


1 TeV limits on squarks & gluinos (strong interaction)

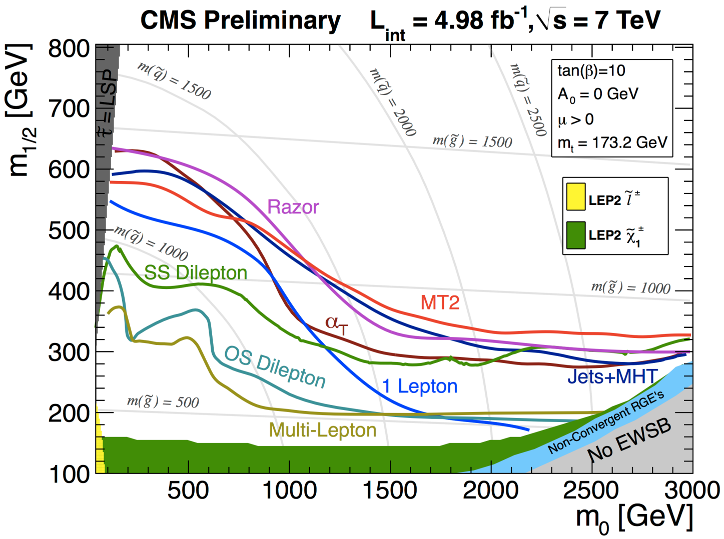
SUSY Today – Only Limits!



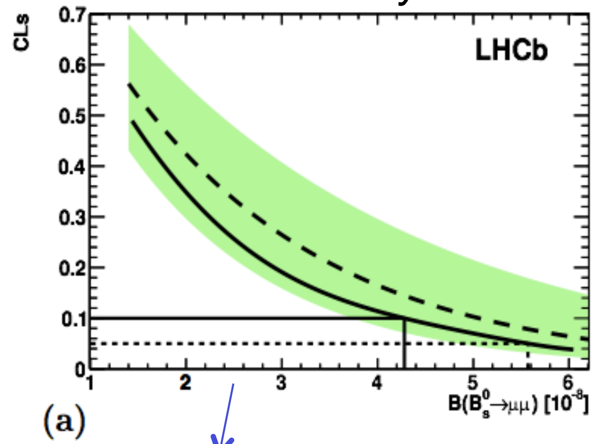
Lets make a short detour …

Putting it all Together – Where are Toady?

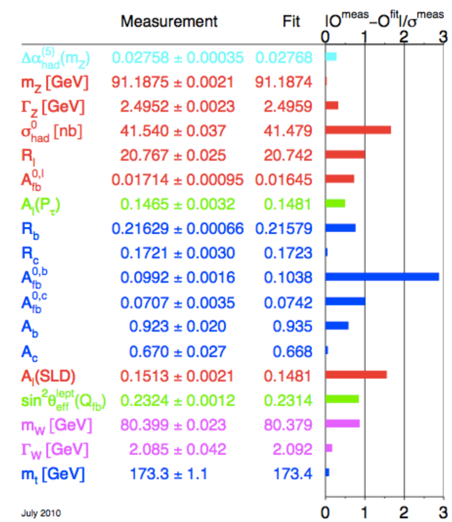
Direct Searches



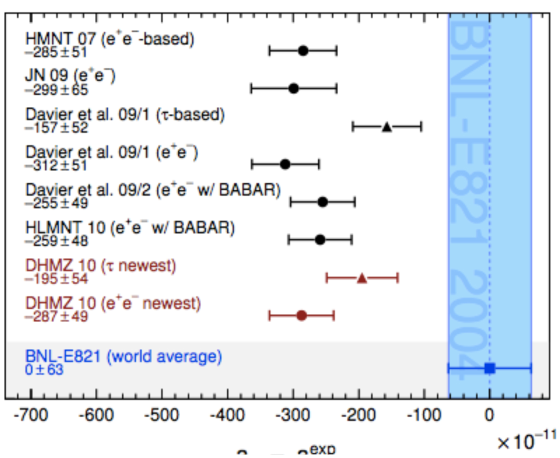
Flavour Physics

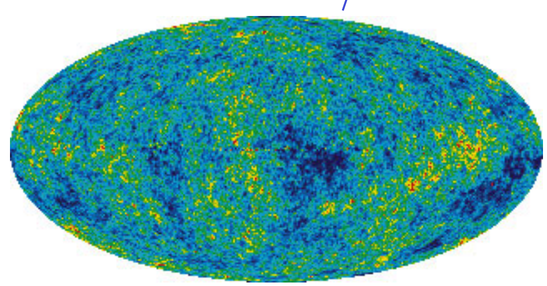


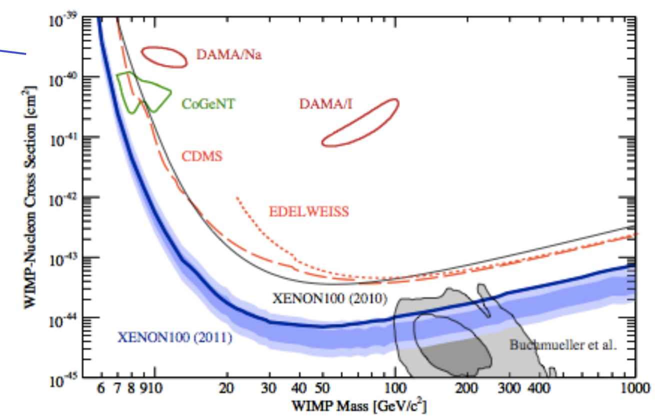
EWK results



SUSY







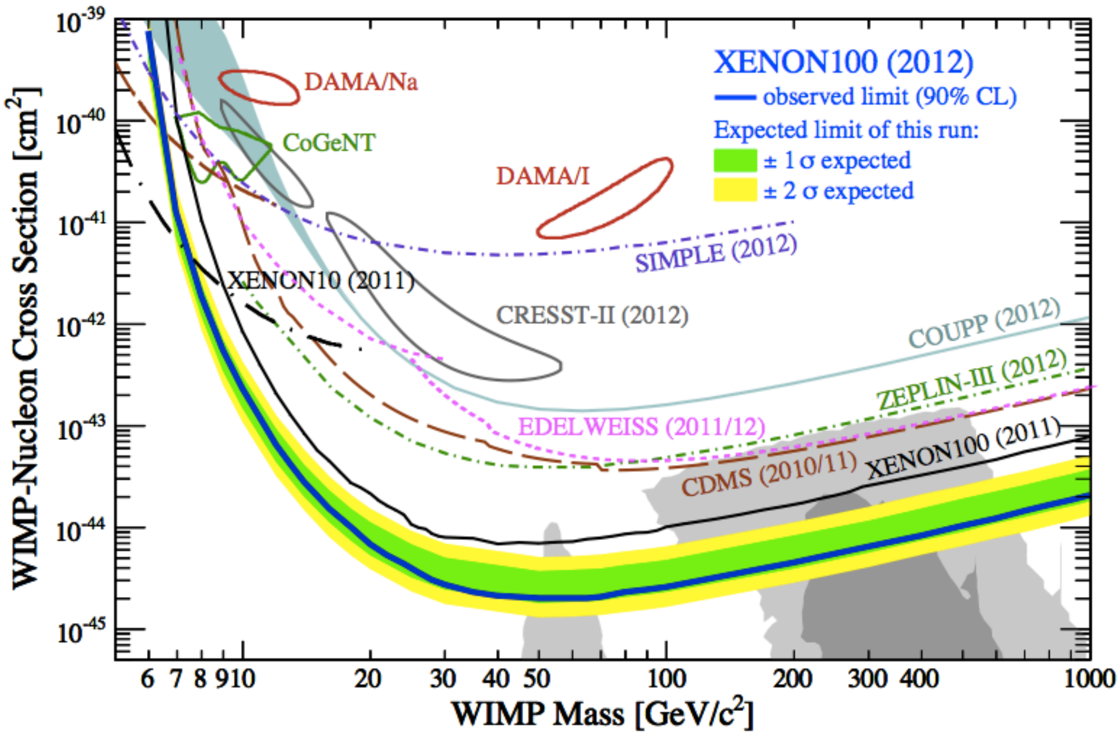
Low Energy Data e.g. g-2 *Dark Matter Searches*

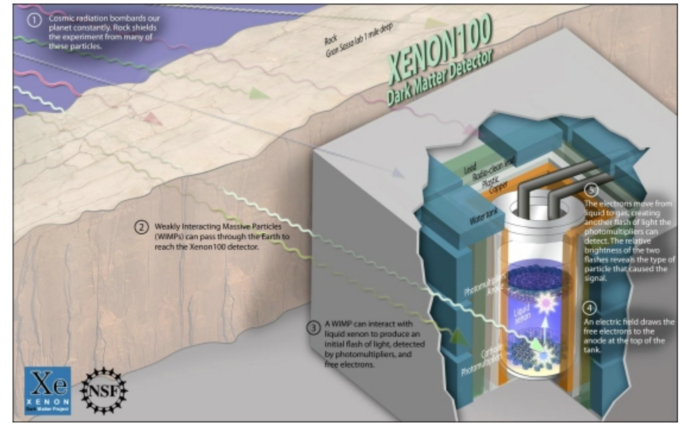
Cosmology

Direct Dark Matter Searches

Example: Xenon100

New result: arXiv:1207.5988v1





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

34 kg liquid Xenon target
225 days of data taking
1.0±0.2 events expected
2 events observed
⇒Exclude 2.0×10^{-45} cm²
for a M_{WIMP} = 55 GeV at 90% CL.

MasterCode Collaboration

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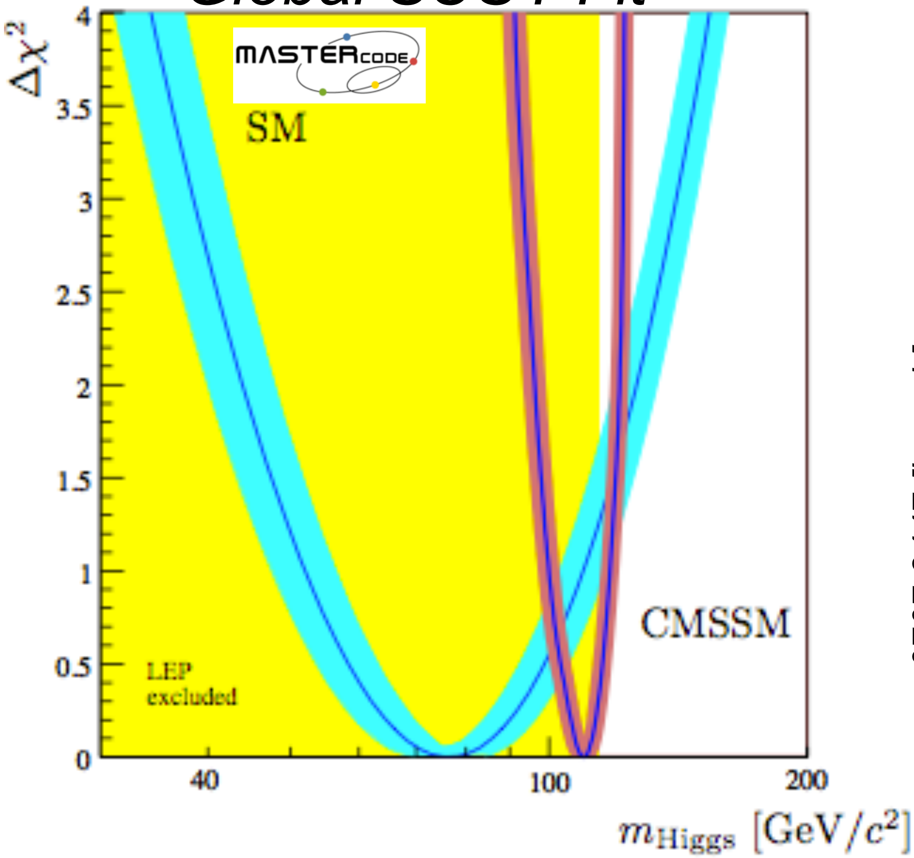
- *Collaboration of experimentalist and theorists was formed in 2007 to facilitate the interpretation of the LHC results in the context of particle physics and cosmology.*
- *The team consists of experts from different subjects (e.g. Higgs, SUSY, flavour physics, cosmology, etc.) and it operates on a truly international bases.*
- *Today the project resides under the London Centre for Terauniverse Studies (LCTS). It connects the three London universities: Imperial College, University College, and Kings College London as well as CERN.*

Higgs: SUSY vs. SM

Slide from 2007

Global SUSY Fit



Example: "redo" SM fit in SUSY predicting the lightest higgs boson mass in the Constraint Minimal Supersymmeteric Standard Model (CMSSM)

0707.3447 [hep-ph]

MasterCode Collaboration

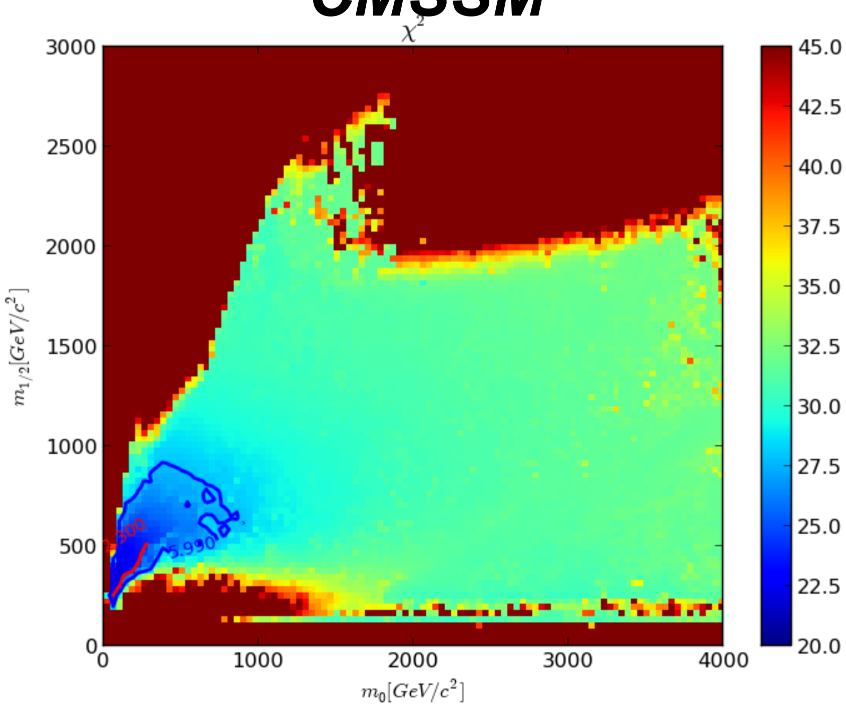
OB (Exp), R. Cavanaugh (Exp), A. De Roeck (Exp), J. Ellis (Theo), H. Flaecher (Exp), S. Heinemeyer (Theo), G. Isidori (Theo), K. Olive (Theo), P. Paradisi, (Theo), F. Ronga (Exp), G. Weiglein (Theo)

Pull for CMSSM fit

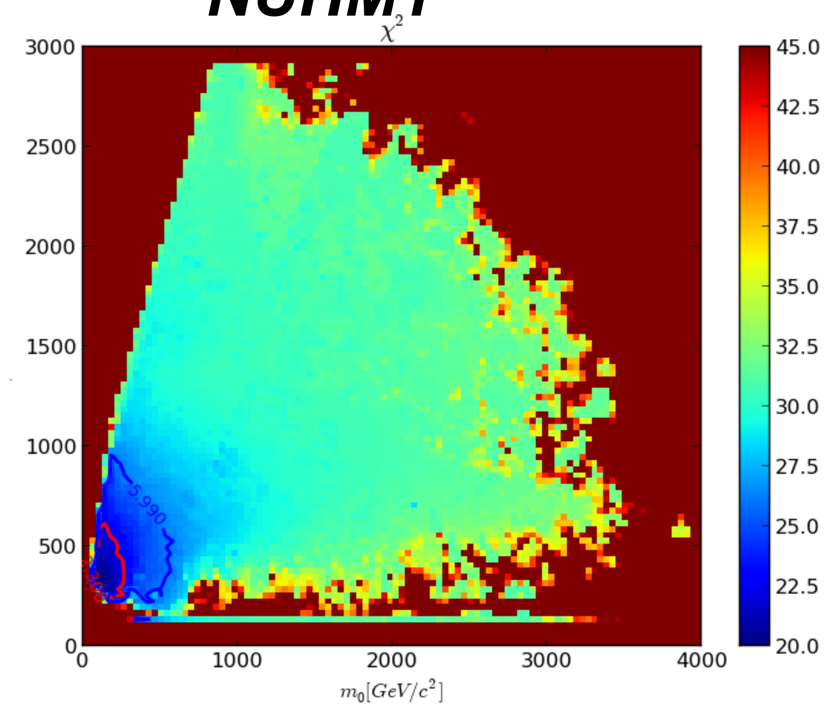
Variable	Measurement	Fit	$\vert O^{meas}-O^{fit}\vert/\sigma^{meas}$ (0 1 2 3)
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b\to s\gamma)$	1.13 ± 0.12	1.12	
$B_s\to\mu\mu$ [$\times10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

The pre-LHC era

CMSSM



NUHM1

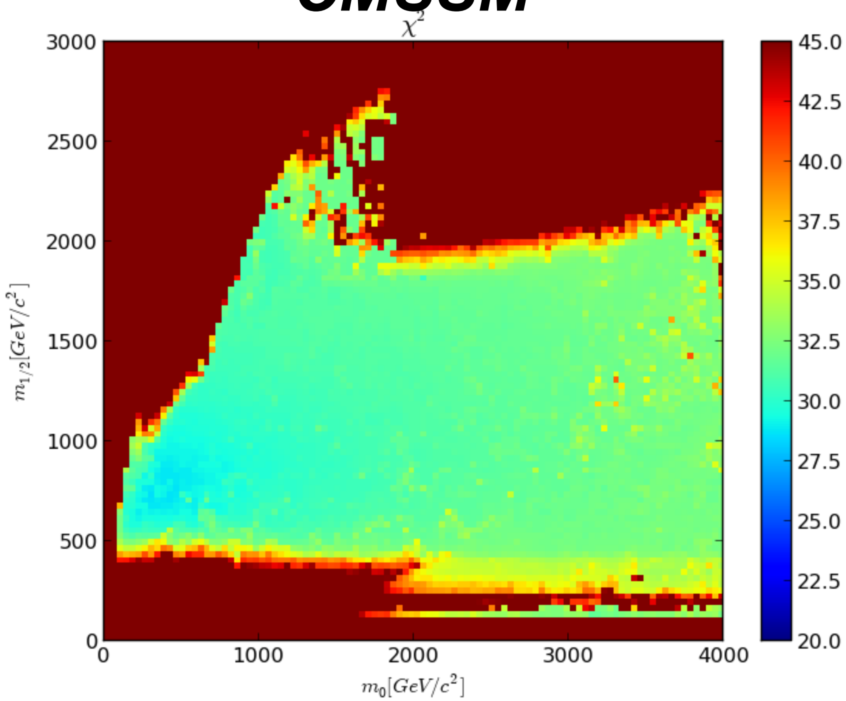


Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM	21.5	37%	360	90	400	15
NUHM1	20.8	29%	340	110	-520	13

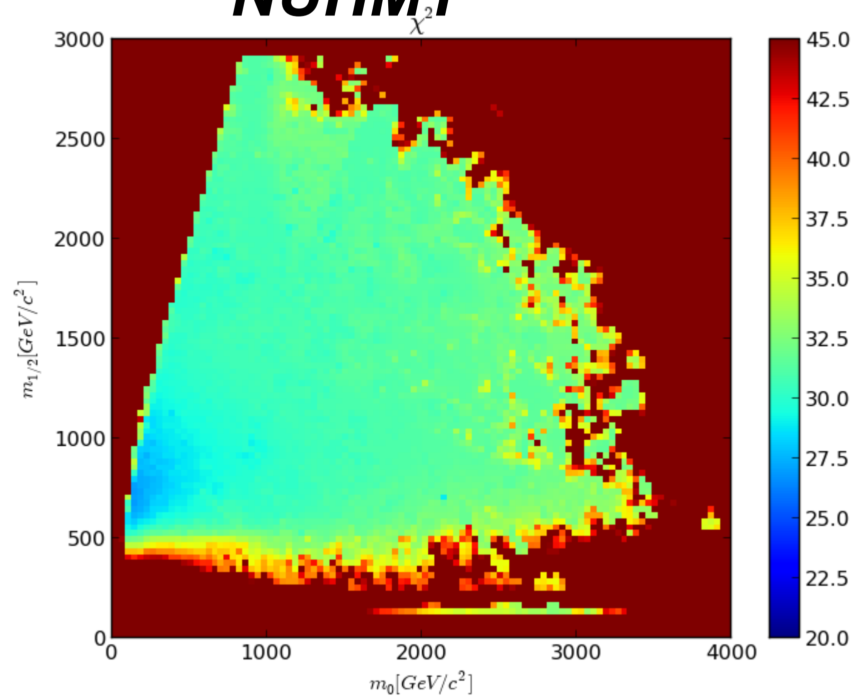
For references NDF ~ 22

The "post-LHC" era in 2011

CMSSM

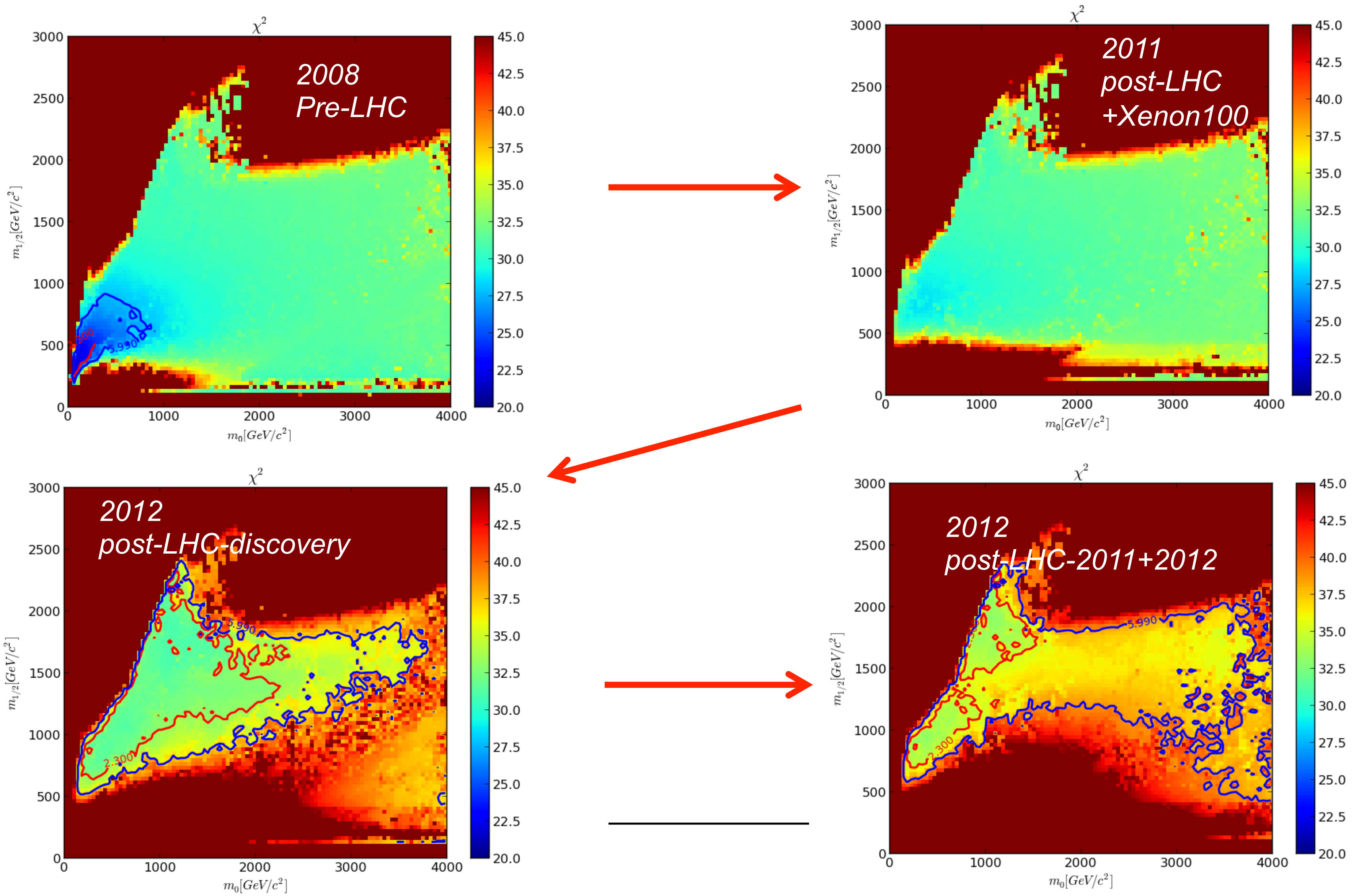


NUHM1



- Chi^2 increases
  - Shifting to higher masses, larger tan β
  - Plane relatively flat – no real preferred minima anymore

CMSSM: Evolution with time



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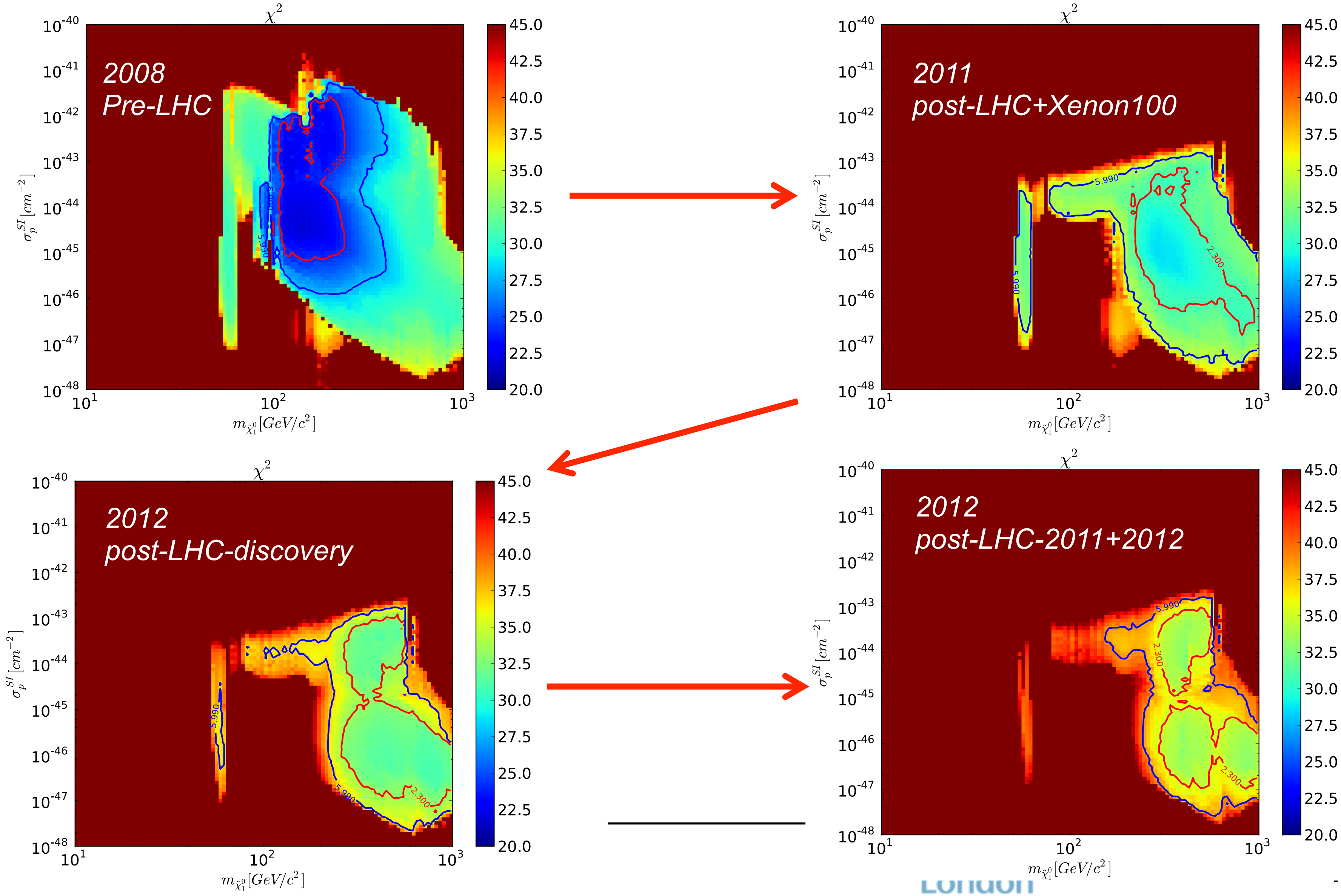

WHERE ARE WE TODAY?

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

- *Although even these “simple” SUSY models are not yet fully ruled out several people have asked the question:*

WHERE ARE WE TODAY?

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- *Although even these "simple" SUSY models are not yet fully ruled out several people have asked the question:*

Is Supersymmetry Dead?

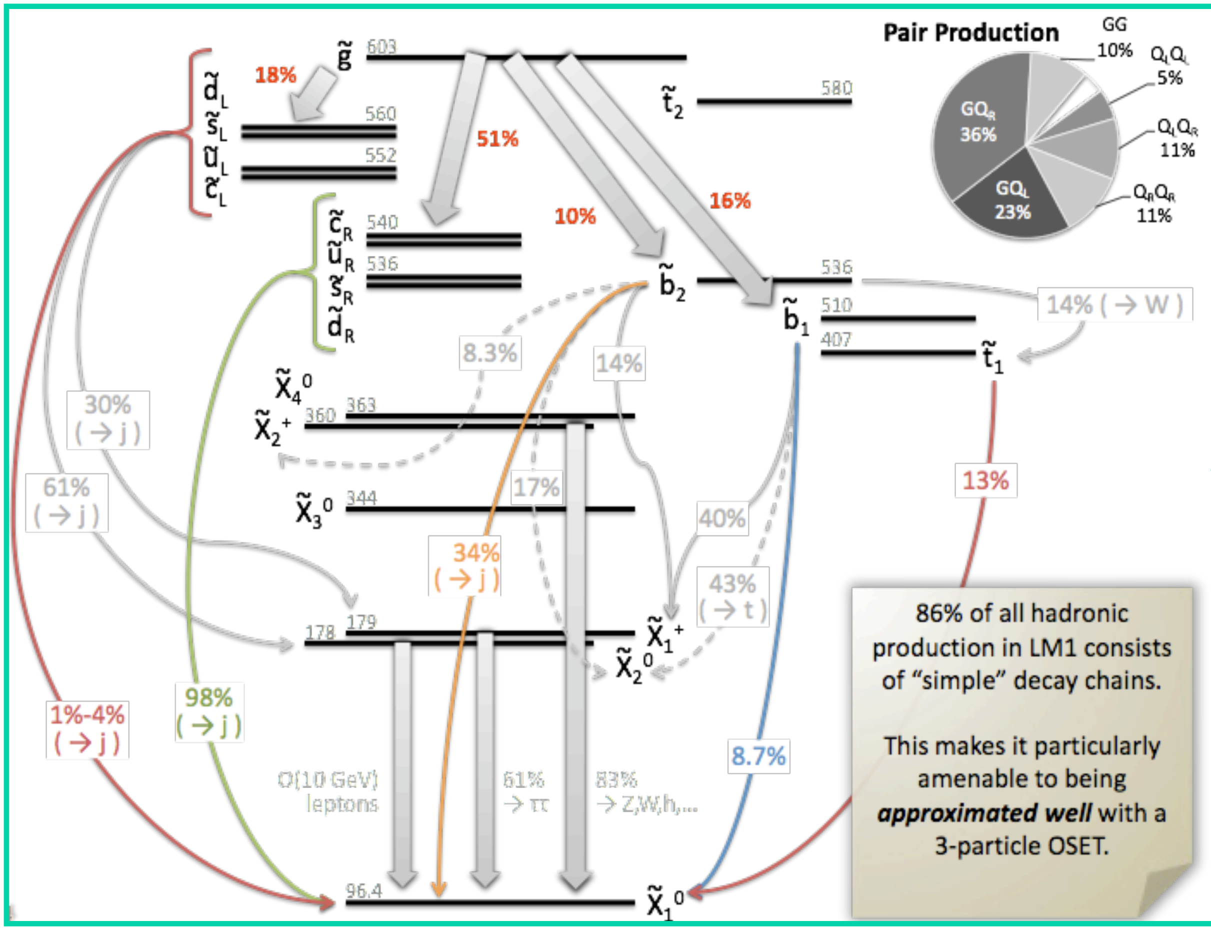
The grand scheme, a stepping-stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

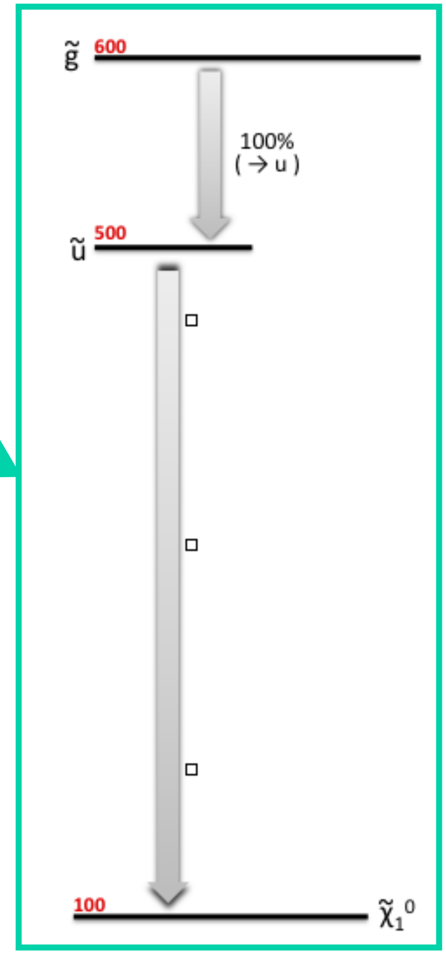
By Davide Castelvecchi

Additional Interpretation

CMSSM

What we see is much more simple…

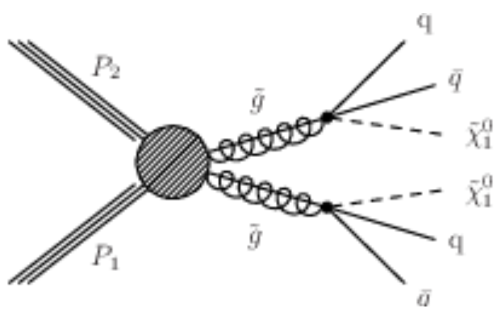




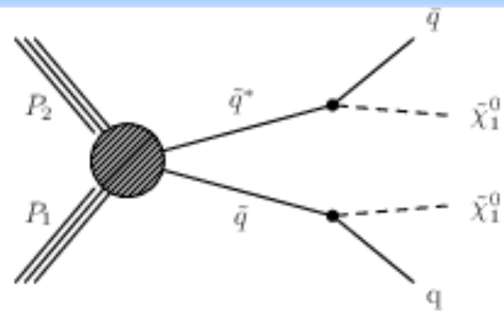
Simplified model spectrum or sms

with 3 particles, 2 decay modes

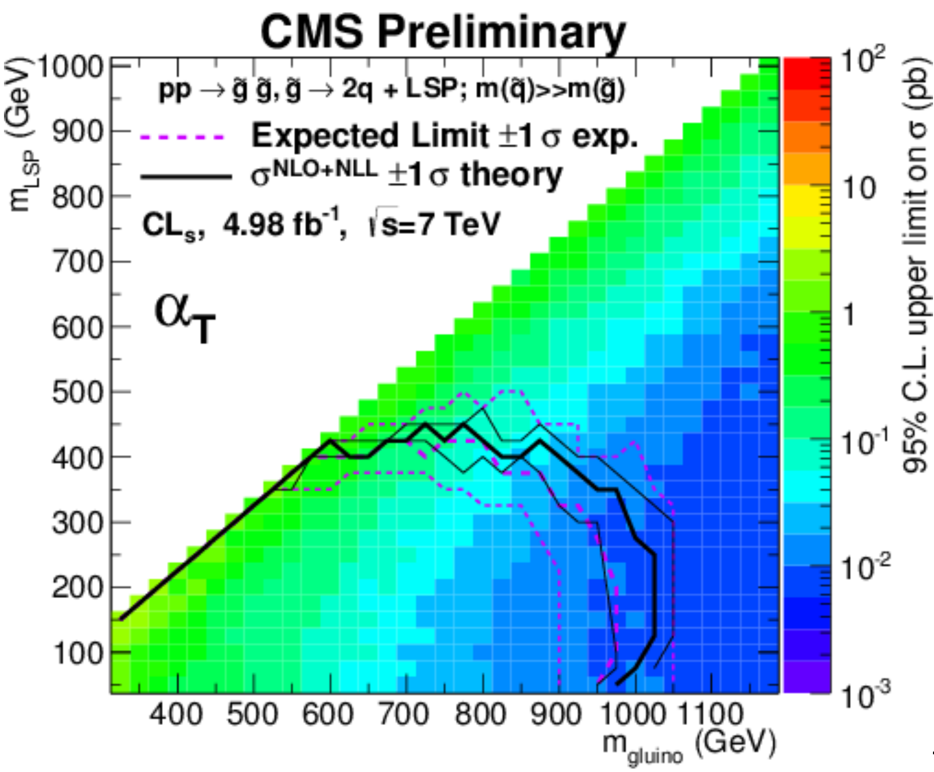
Simplified Model Spectra

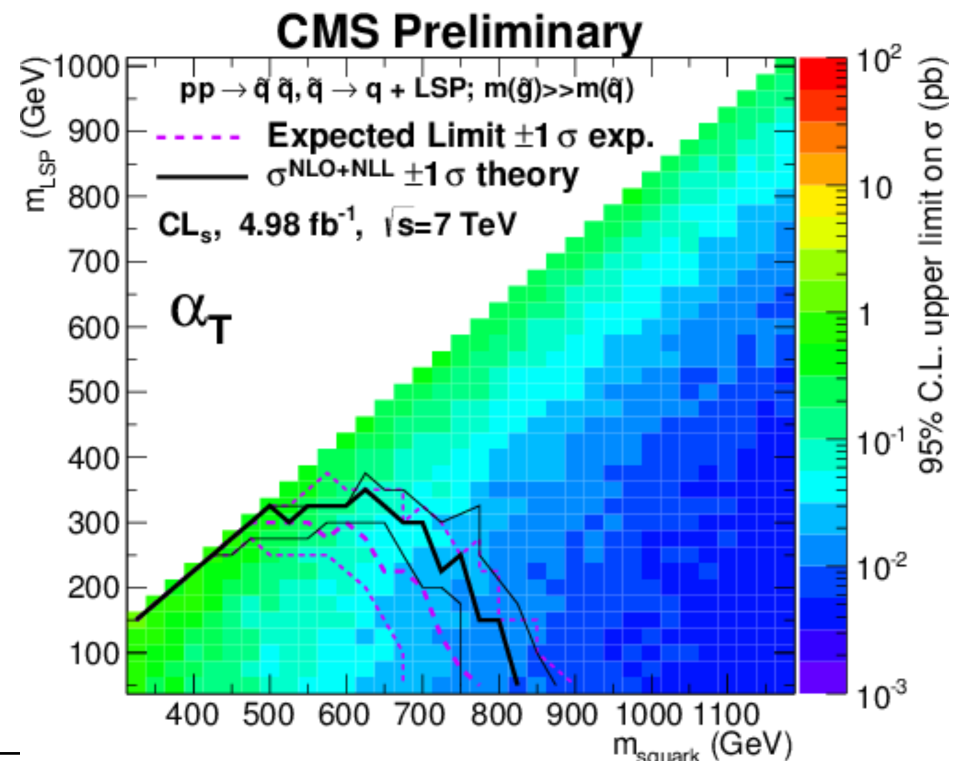


$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$



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



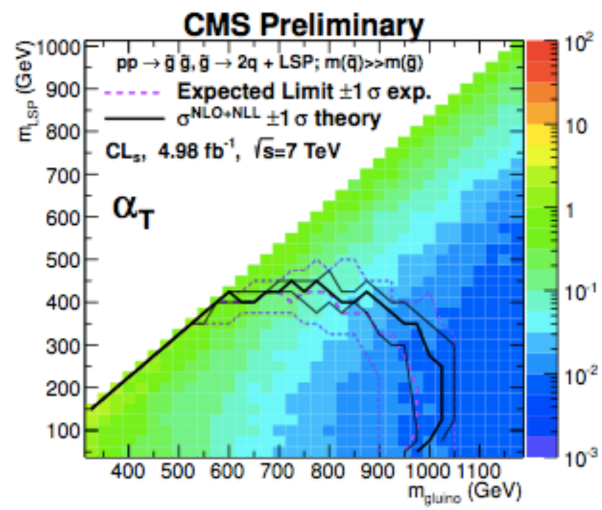


So, is SUSY now on life support?

The answer to this question is NO!

See 2012 Experimental SUSY PDG review [OB & Paul De Jong]:
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf

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



(a) $\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$ (Model *A*)

SUSY on life support?

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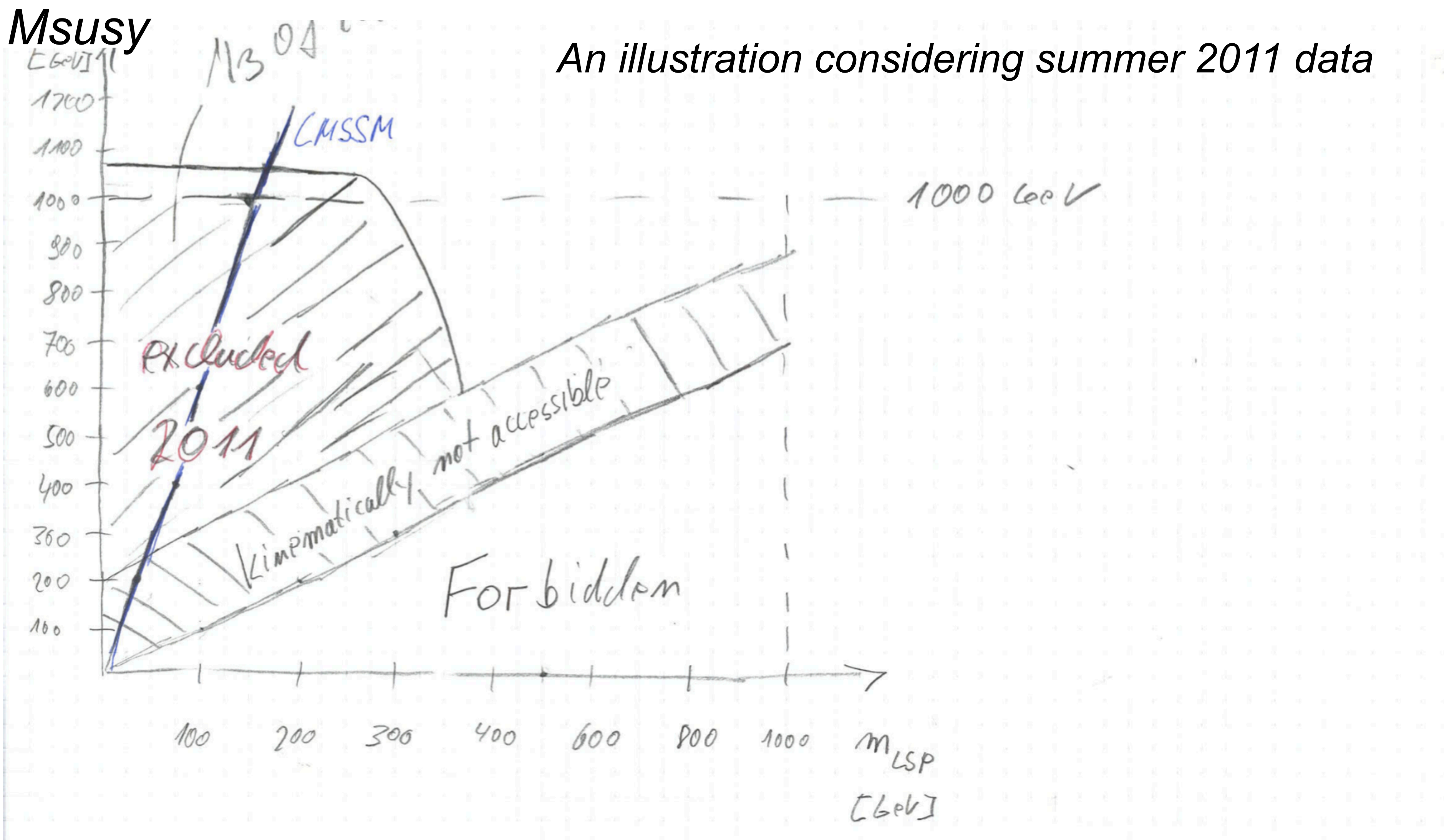
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900

In general, the LHC does not (yet) place limits on parameter space with M_{LSP} >~400 GeV
Leaving a very large Region of the MSSM, even at the mass scale below 1 TeV, unexplored!

SUSY Coverage

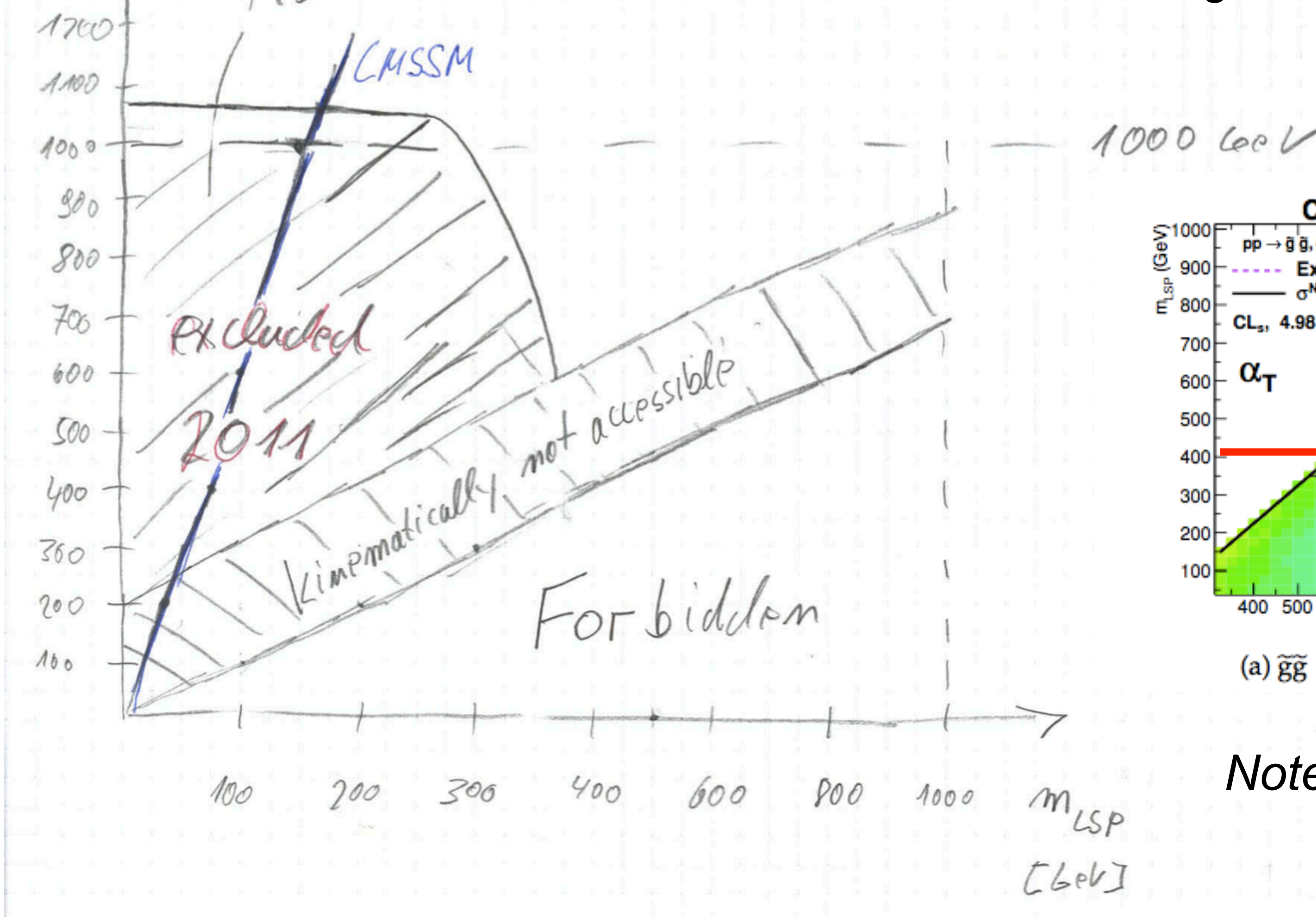
An illustration considering summer 2011 data

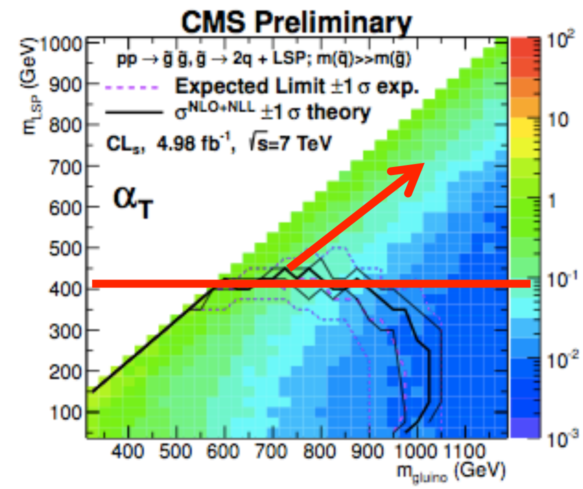


SUSY Coverage

Msusy

An illustration considering summer 2011 data





(a) $\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$ (Model A)

Note: access are flipped

SUSY Coverage

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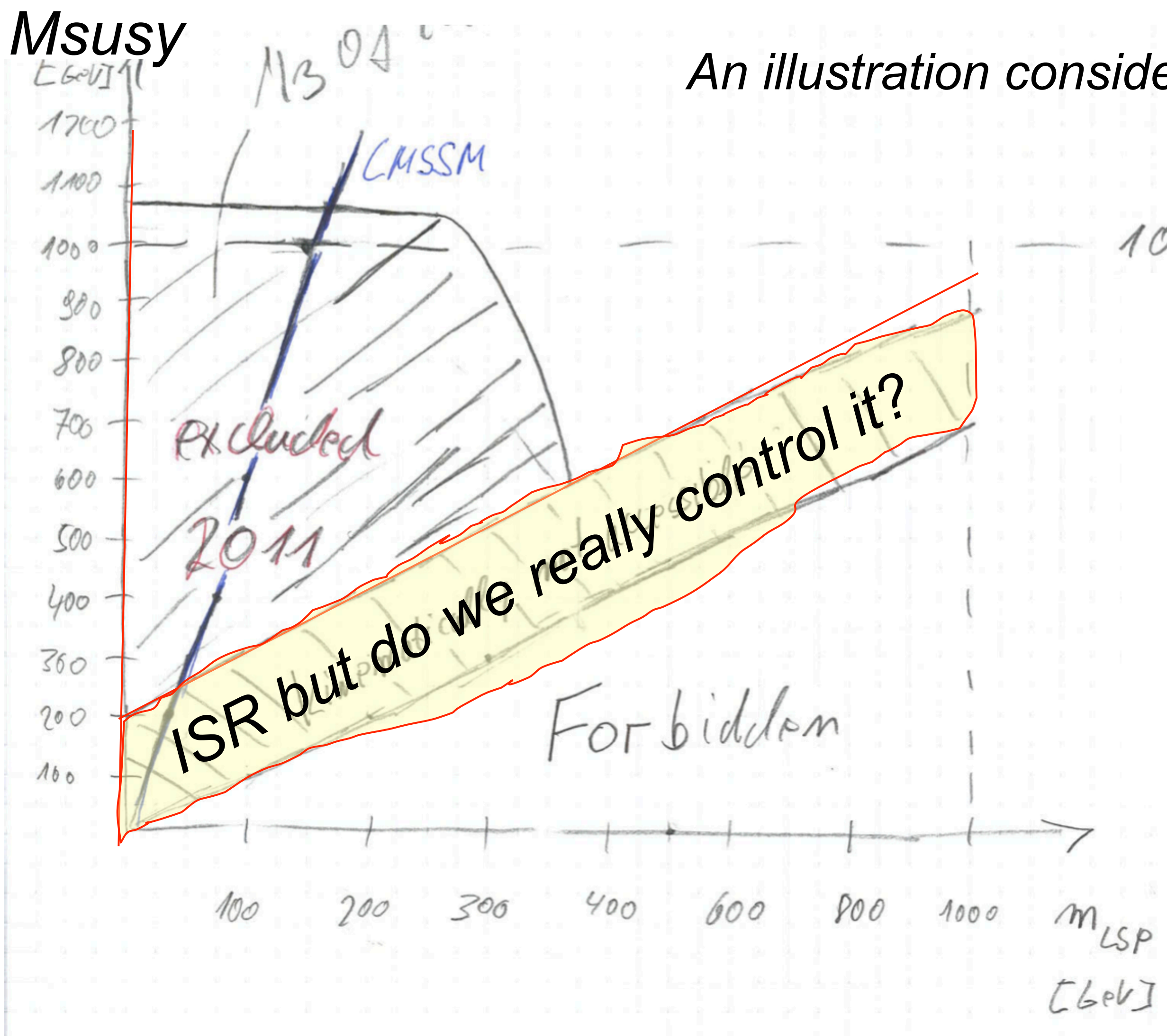
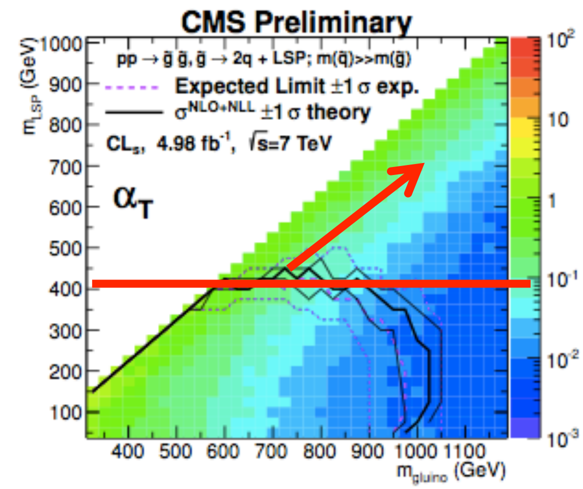




(a) $\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$ (Model A)

Note: access are flipped

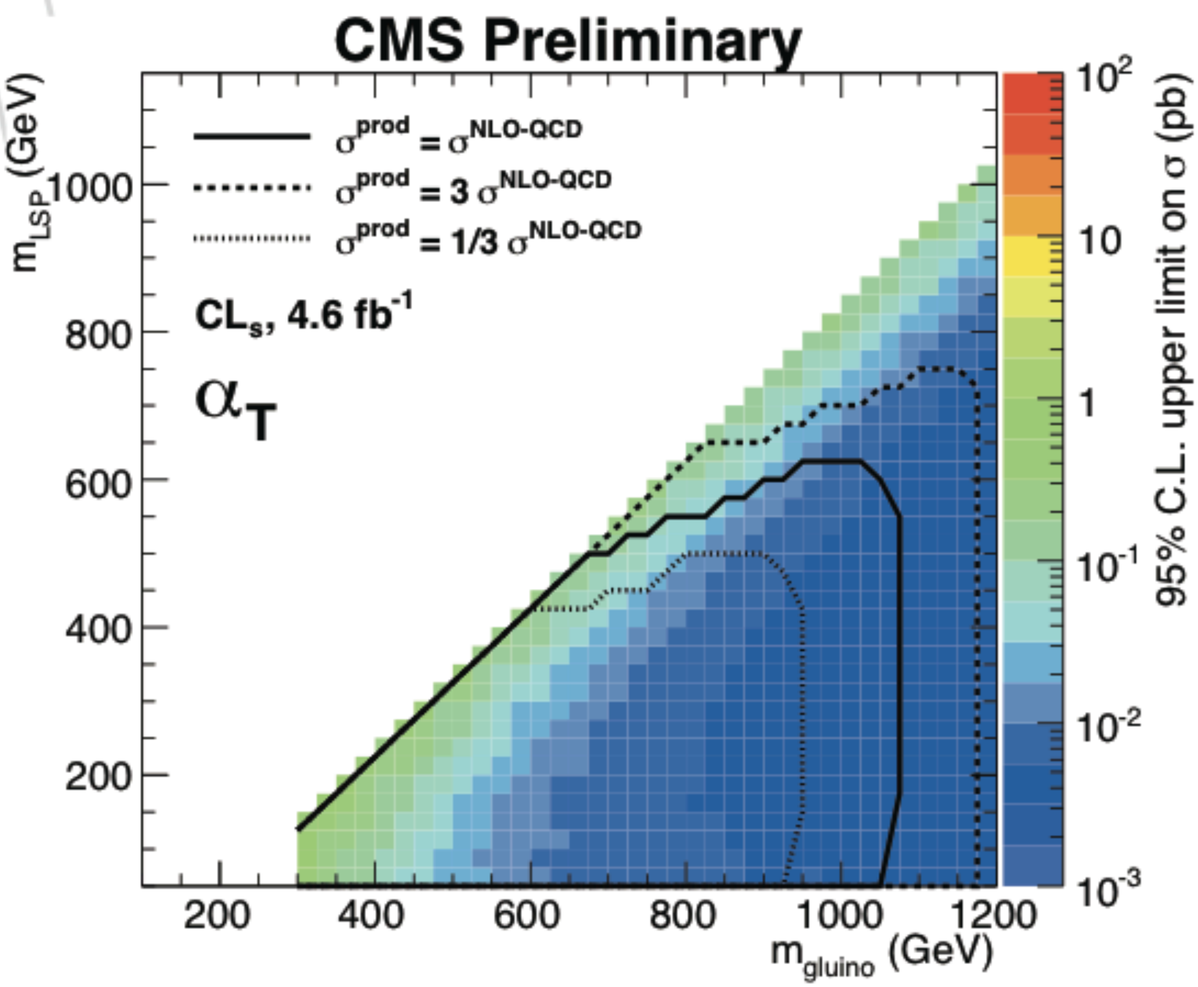
Yet, even this is still optimistic!

Example:
Gluion induced bb production.

Limit on M(gluino) is around 1.1 TeV and stems from an inclusive hadronic search (alpha_T)

Looks impressive!

Yet, what does this mean?



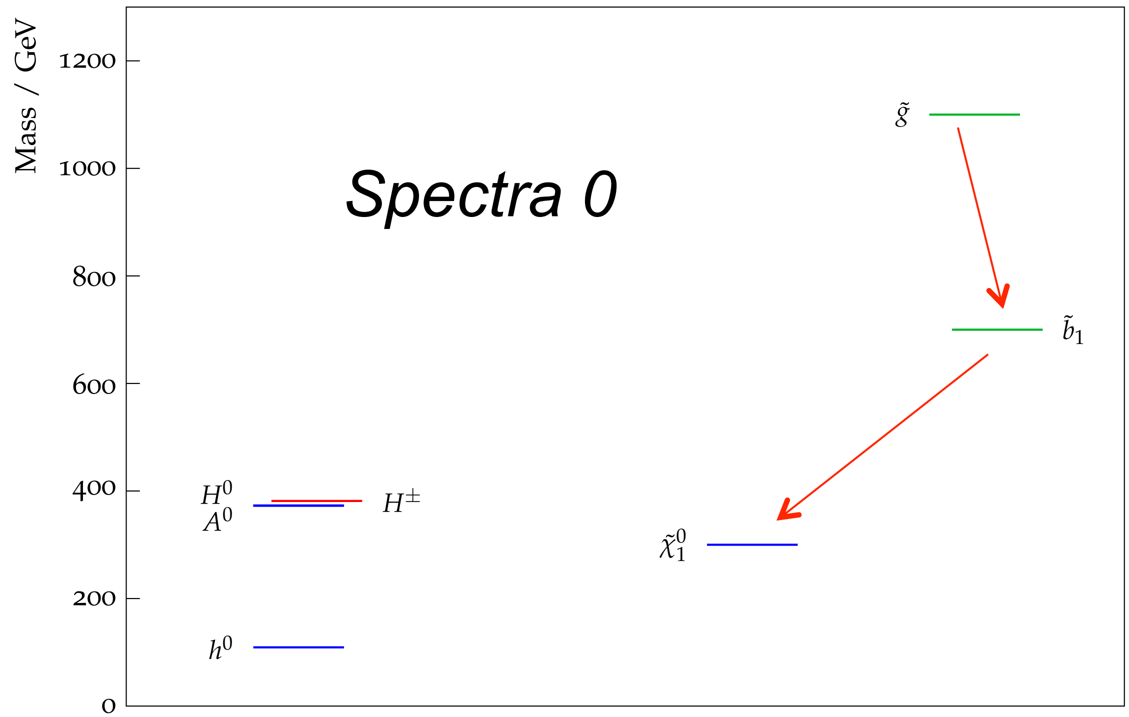
(f) $\tilde{g}\tilde{g} \to b\bar{b}\tilde{\chi}^0 b\bar{b}\tilde{\chi}^0$ (T1bbbb)

Limit on M(gluino) from T1bbbb

Lets do a little Gedankenexperiment:
Assume two topology searches:
a) all-hadronic (jets + MET)
b) OSSF (jets + MET + l^+l^-)

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

Also assume a SUSY spectrum:



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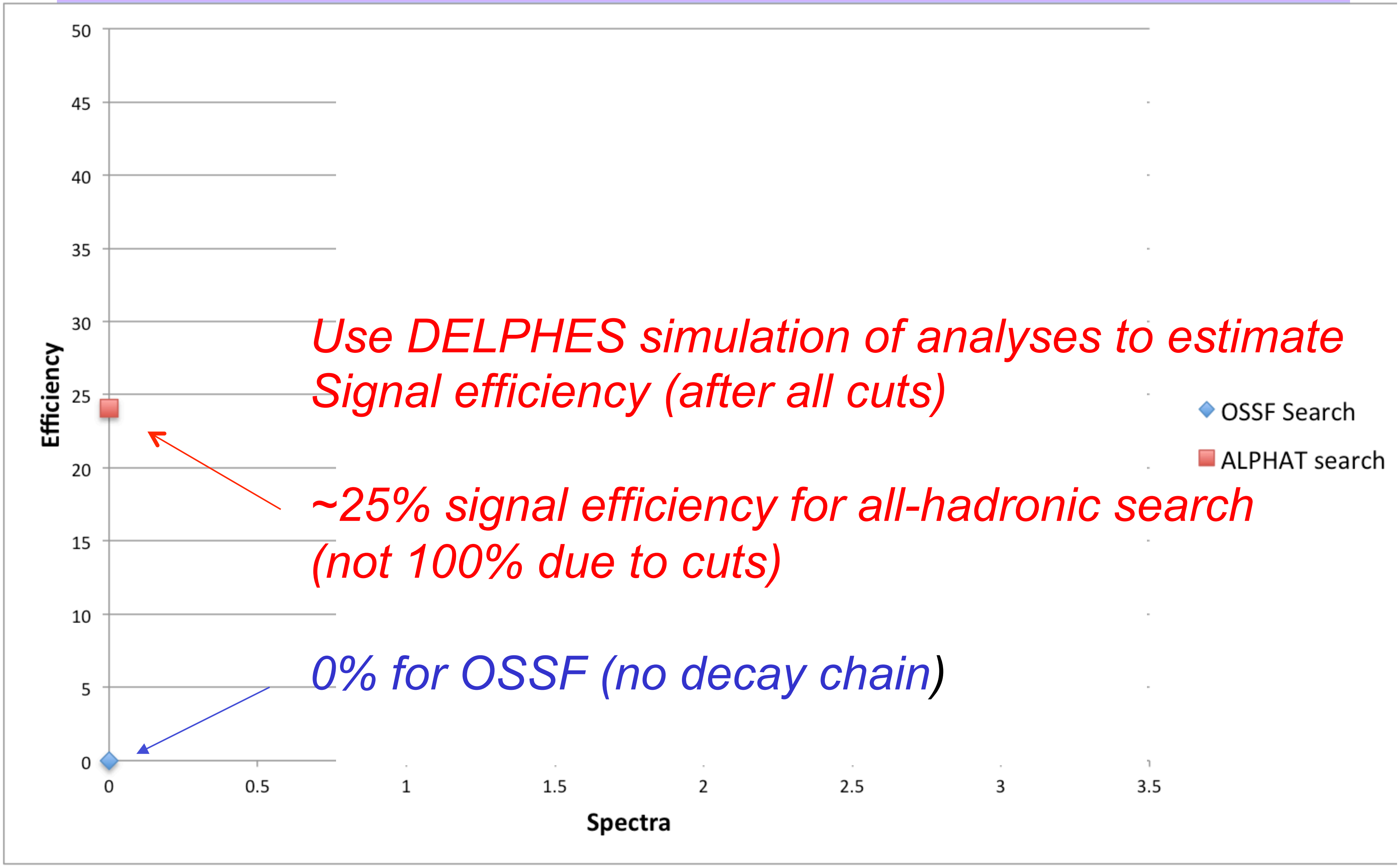
Signal Efficiency: Spectra 0



Use DELPHES simulation of analyses to estimate Signal efficiency (after all cuts)

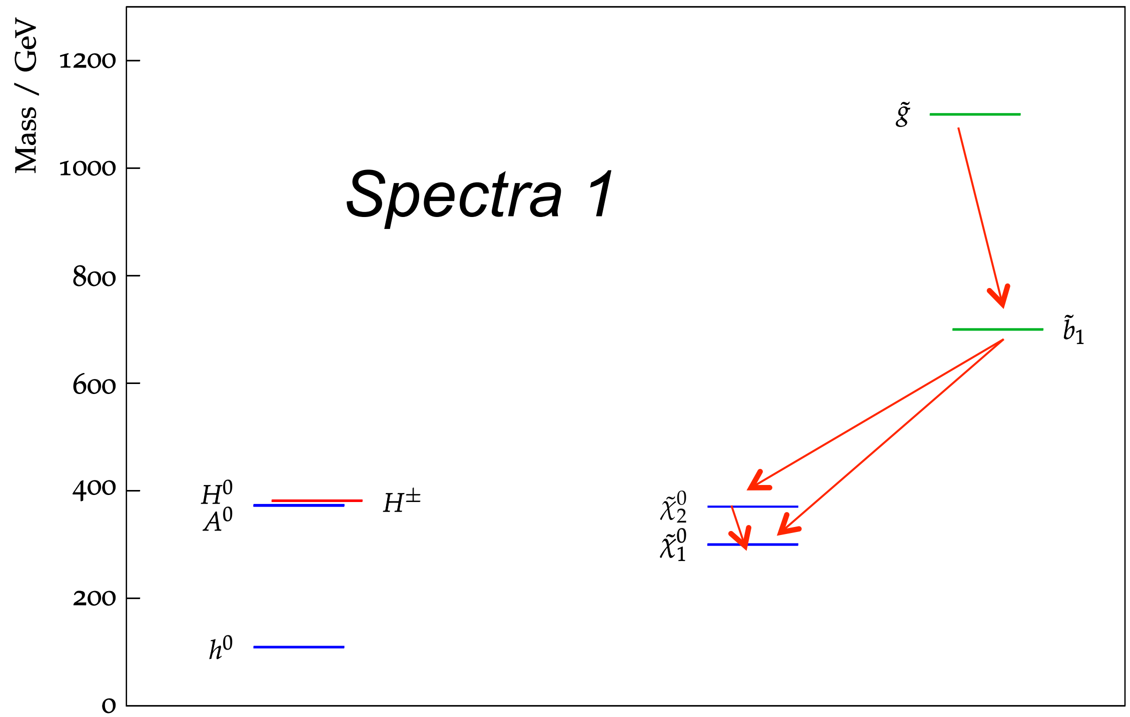
~25% signal efficiency for all-hadronic search (not 100% due to cuts)

0% for OSSF (no decay chain)

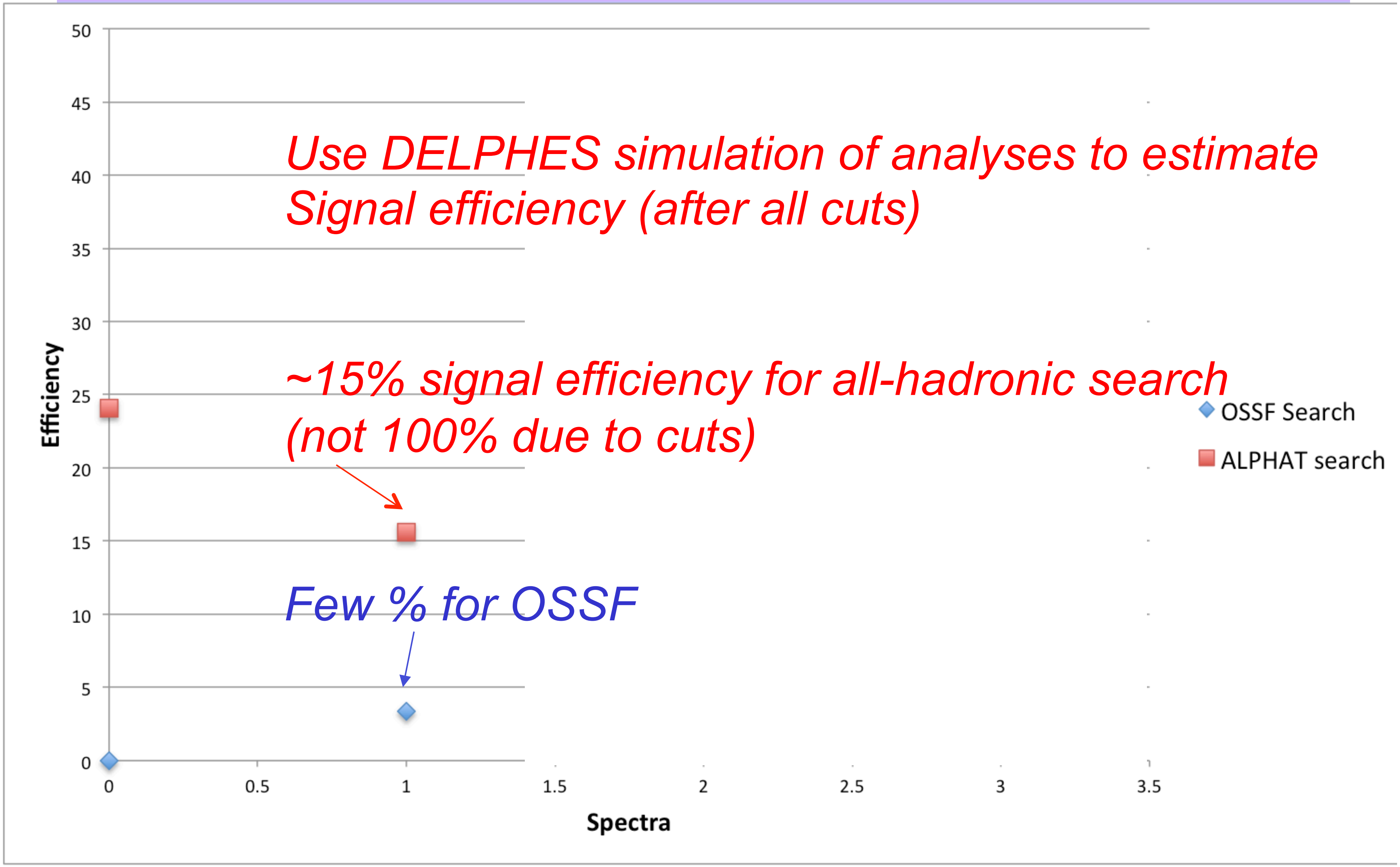
Limit on M(gluino) from T1bbbb

Lets do a little Gedankenexperiment:
Assume two topology searches:
a) all-hadronic (jets + MET)
b) OSSF (jets + MET + l^+l^-)

Also assume a SUSY spectrum
add chi_2^0



Signal Efficiency: Spectra 1



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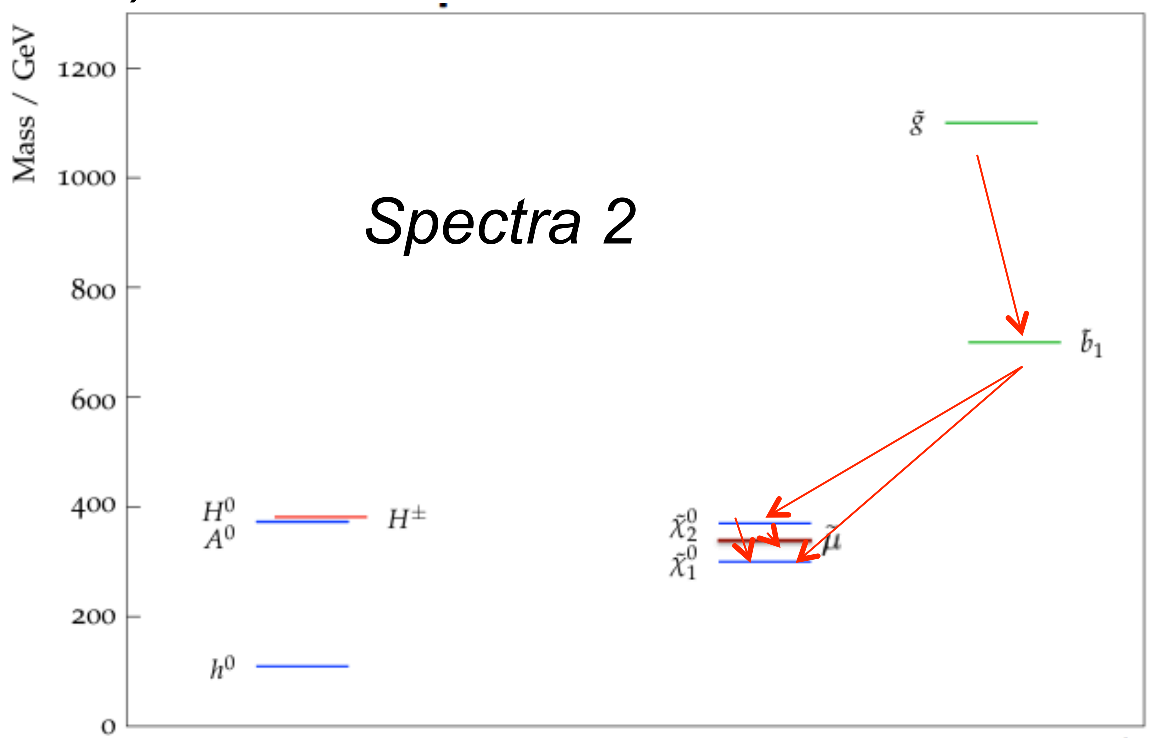
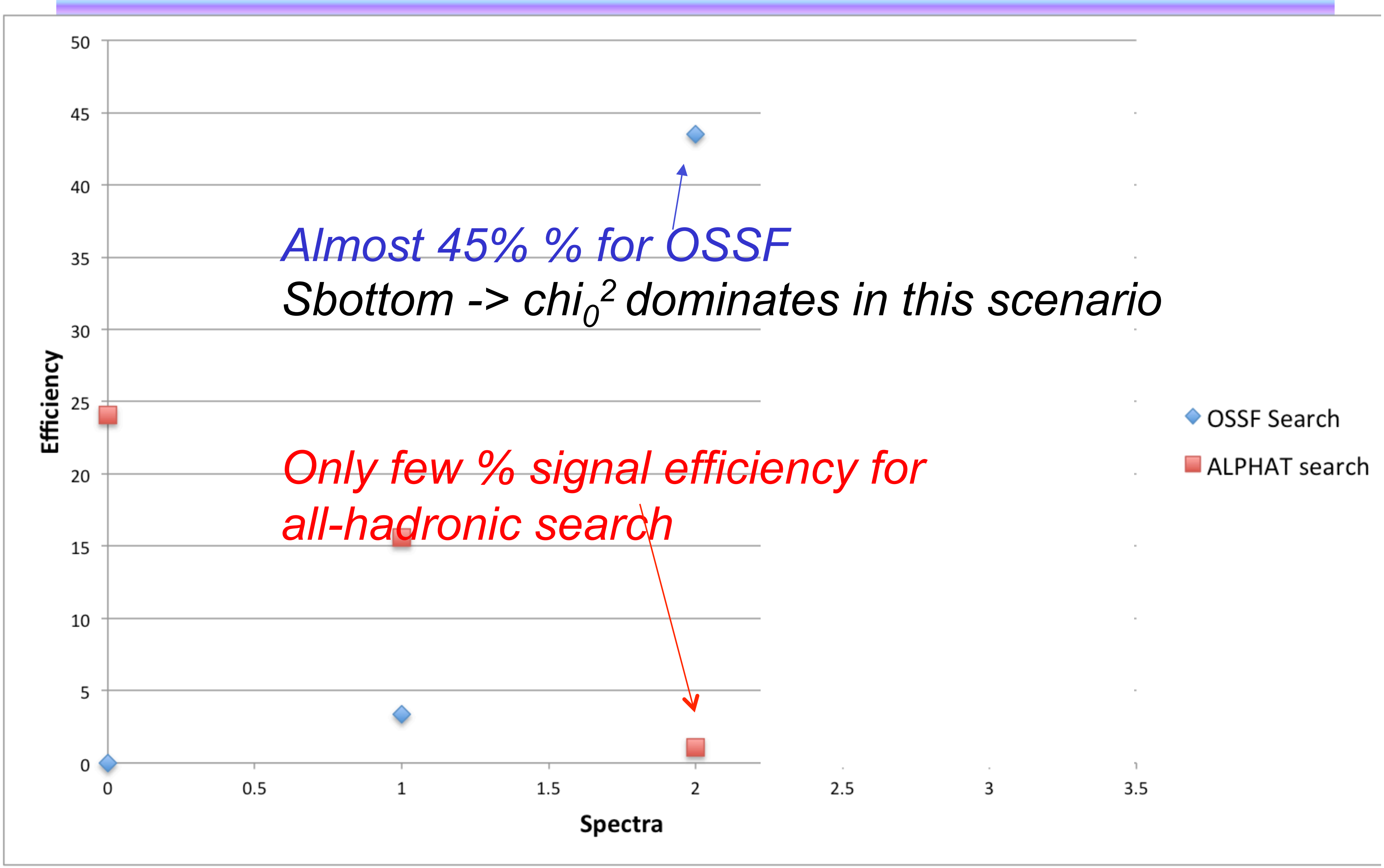
Limit on M(gluino) from T1bbbb

Lets do a little Gedankenexperiment:
Assume two topology searches:
a) all-hadronic (jets + MET)
b) OSSF (jets + MET + l^+l^-)

Also assume a SUSY spectrum
add chi$_2^0$
add smuon



Signal Efficiency: Spectra 2



Limit on M(gluino) from T1bbbb

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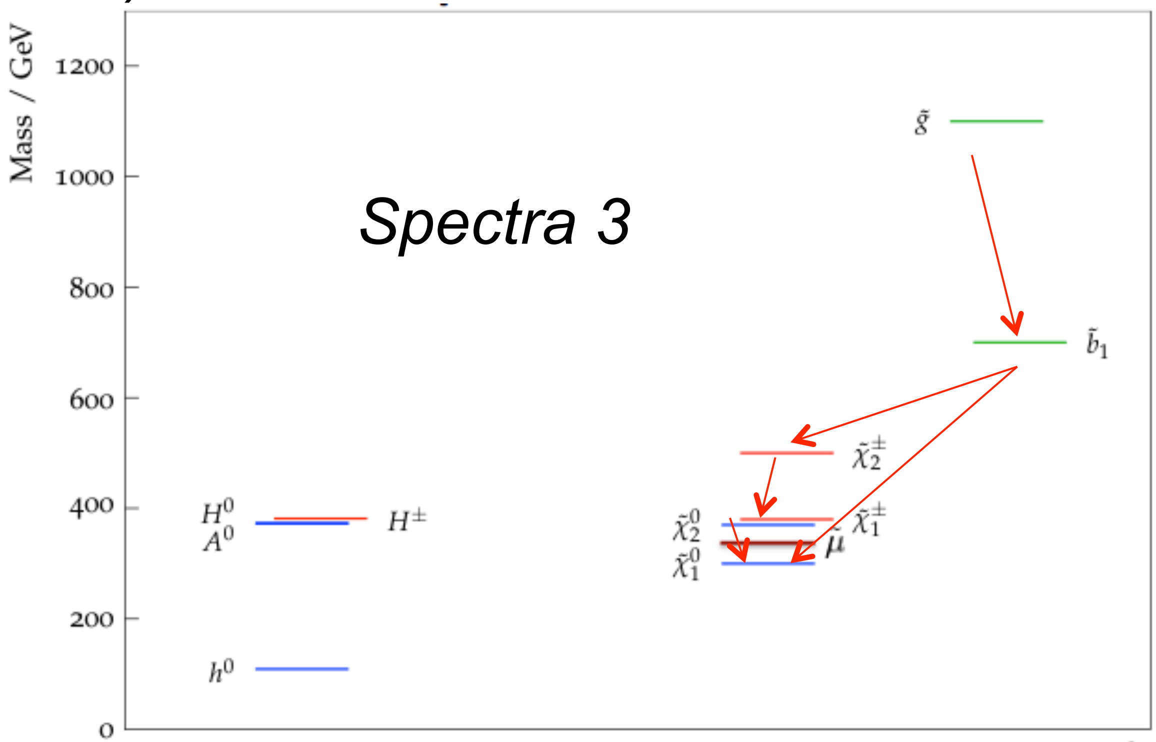
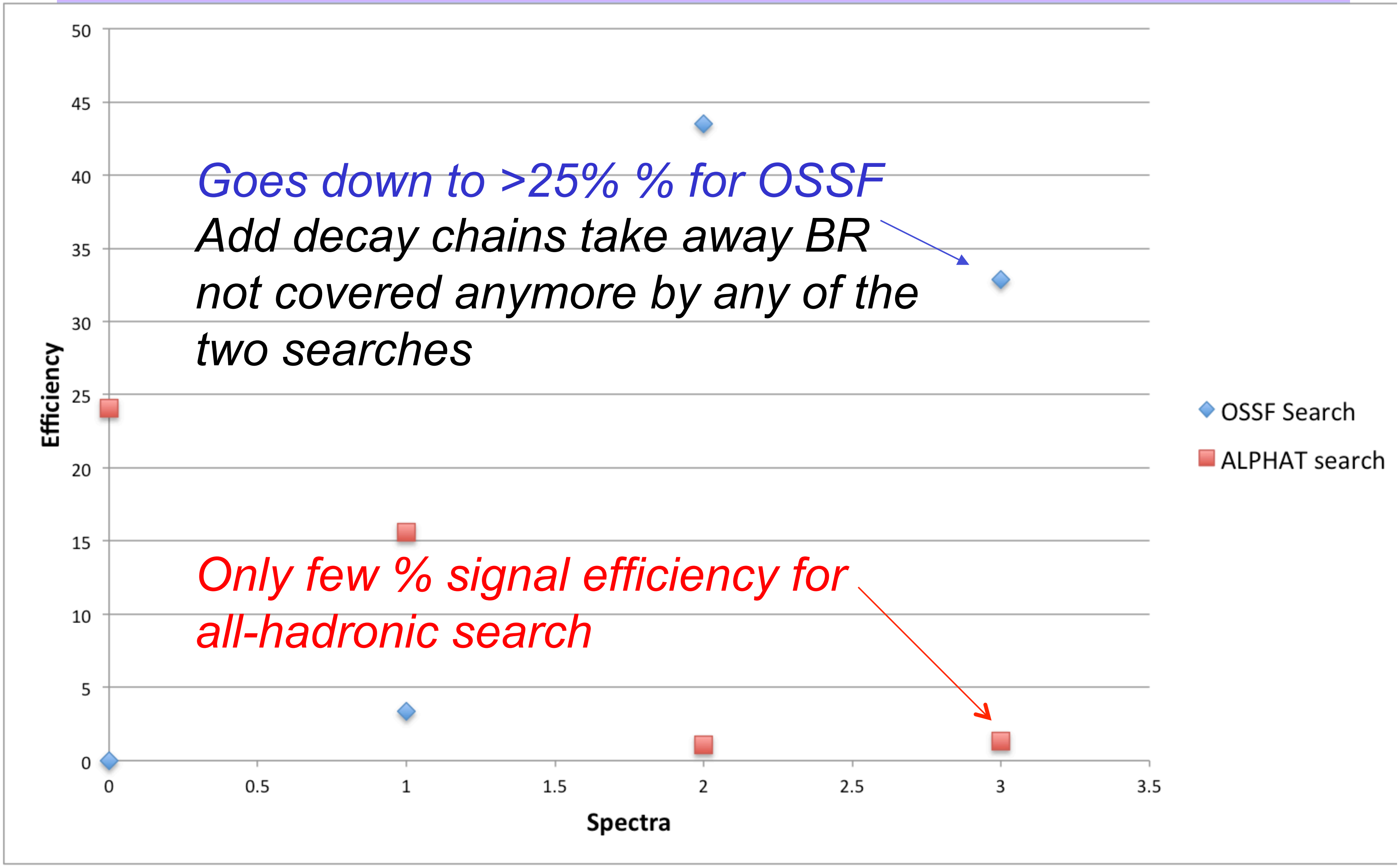
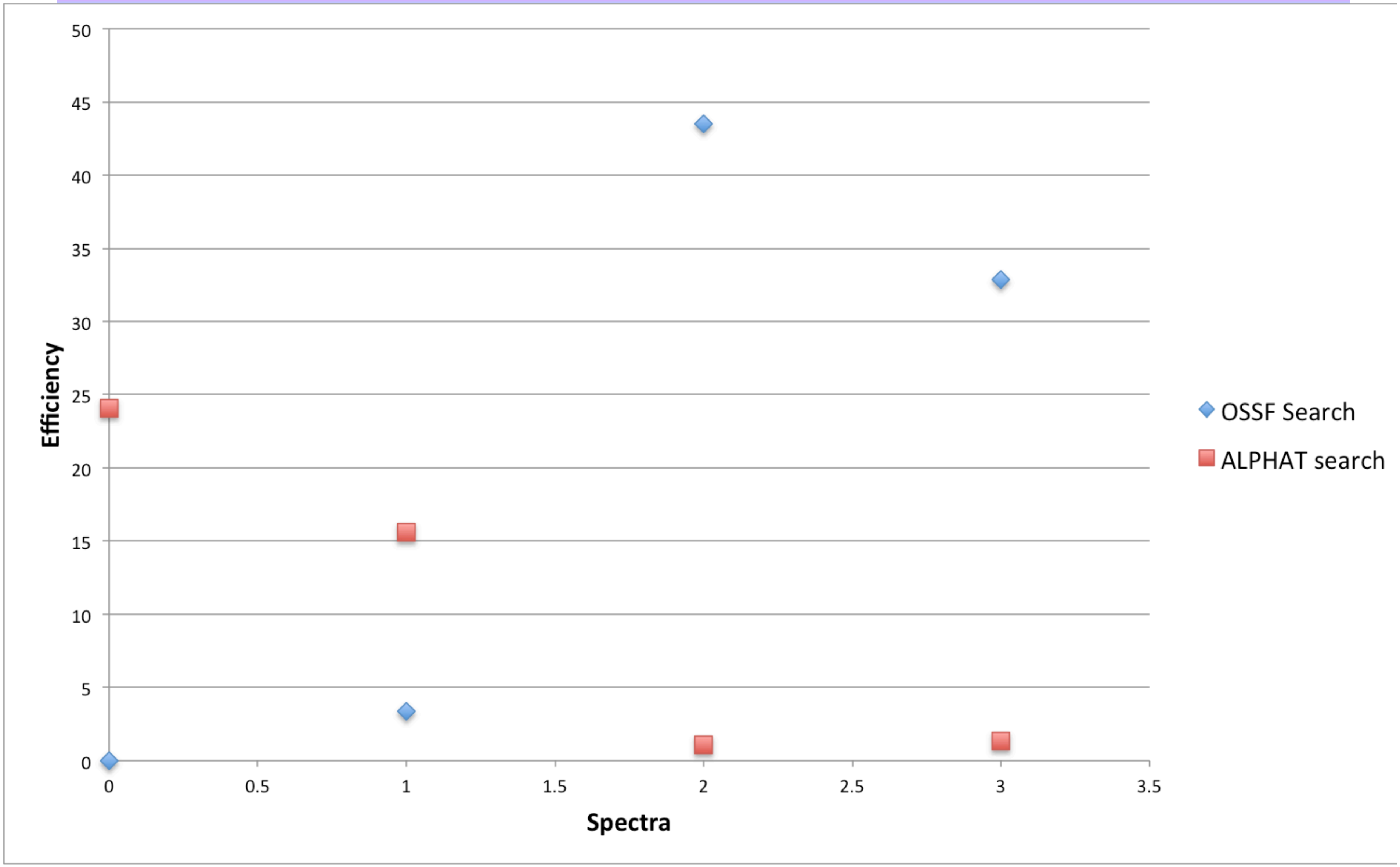
add chi_2^0
add smuon
Add chi_1^+ , chi_2^+



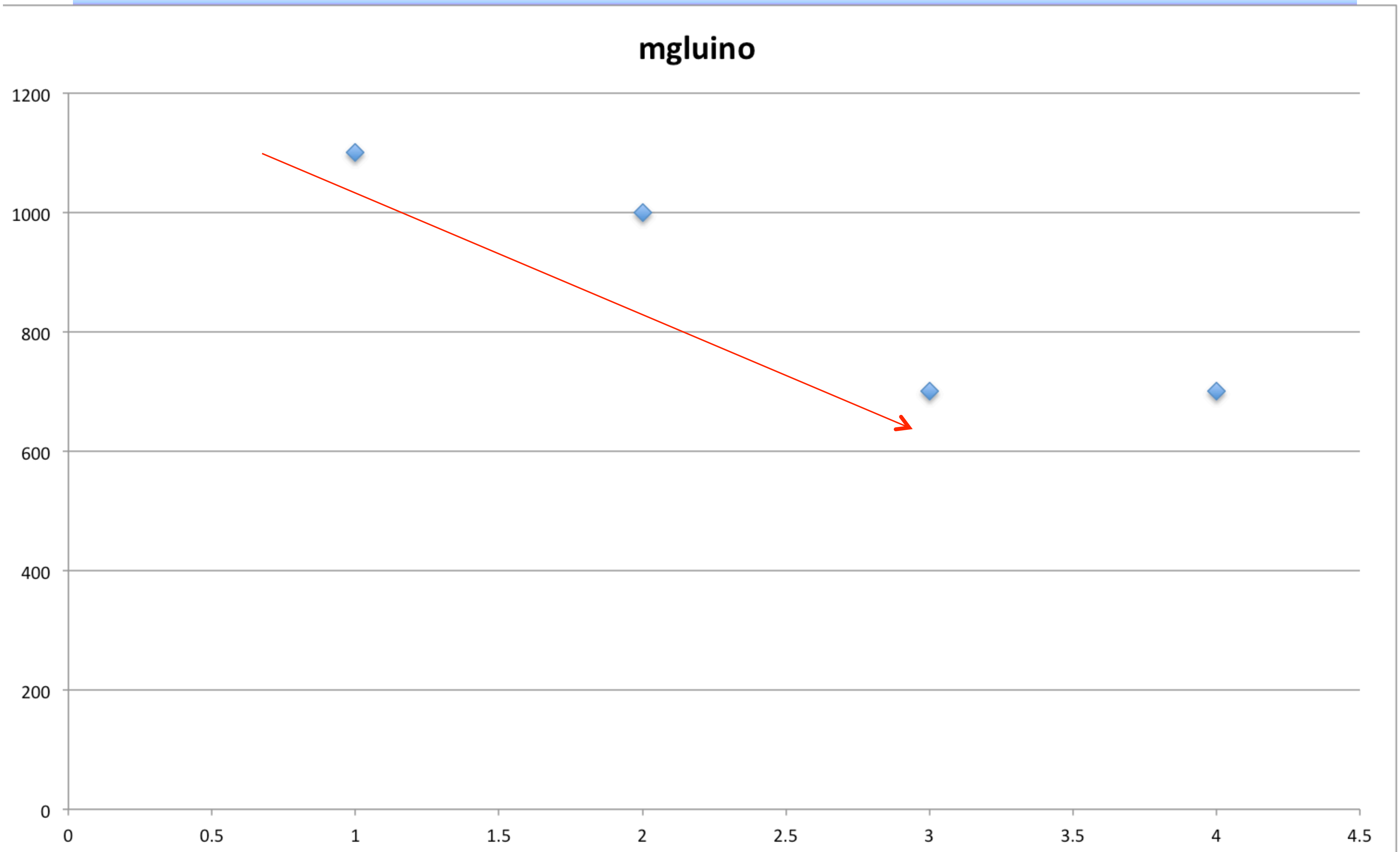
Signal Efficiency: Spectra 3



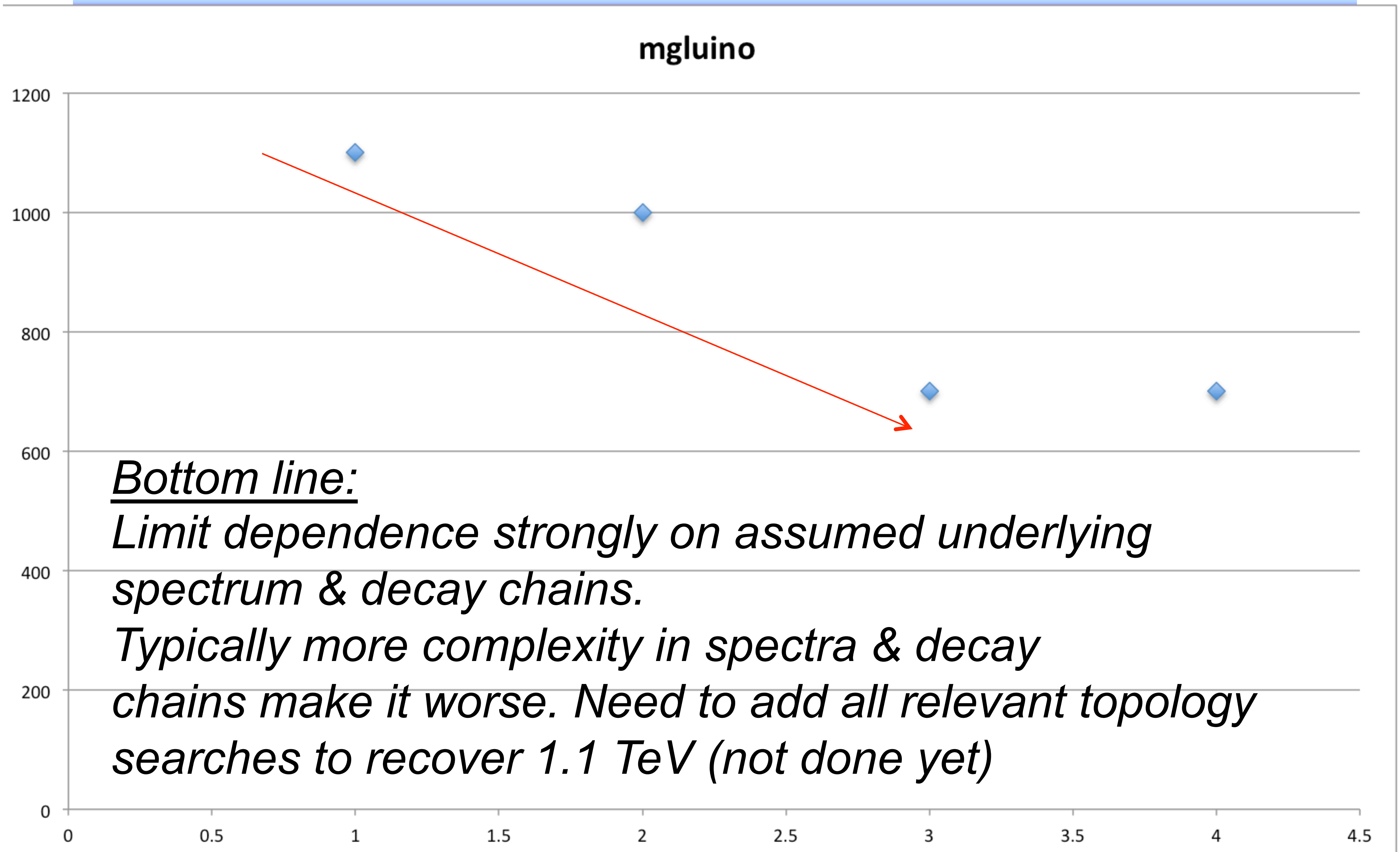
Signal Efficiency



M(gluino) Limit



M(gluino) Limit



Bottom line:

Limit dependence strongly on assumed underlying spectrum & decay chains.

Typically more complexity in spectra & decay chains make it worse. Need to add all relevant topology searches to recover 1.1 TeV (not done yet)

Refining SUSY Search Strategy

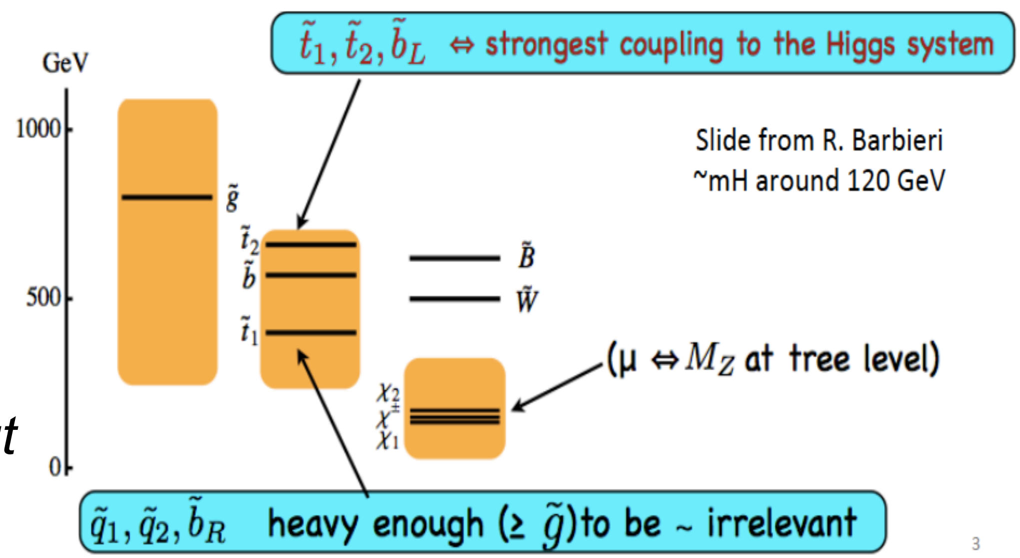
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Focus more on 3rd Generation squark searches
  - Both interpretation of inclusive searches as well as dedicated searches

Example: *"Natural SUSY"*

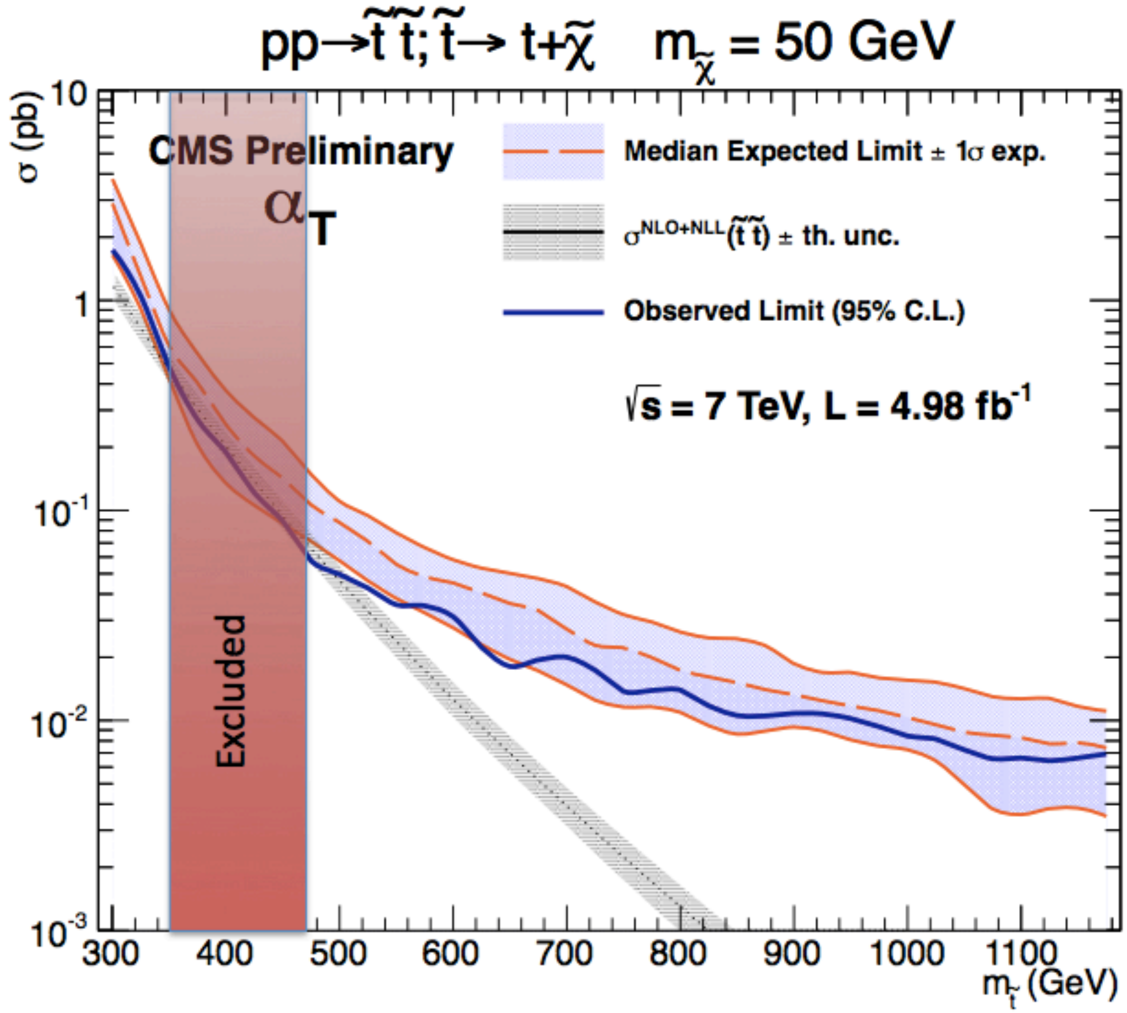
Use argument that light Higgs needs new physics to stabalise mass, which in turn motivates existences of a stop like particle.

Spectrum is model dependent but overall a good guideline for 3rd generation squark searches



Stop searches

- Mixture of dedicated signature searches as well as inclusive searches with b-tagging
  - Example CMS: add 0,1,2,>2 b-tag categories to inclusive α_T search

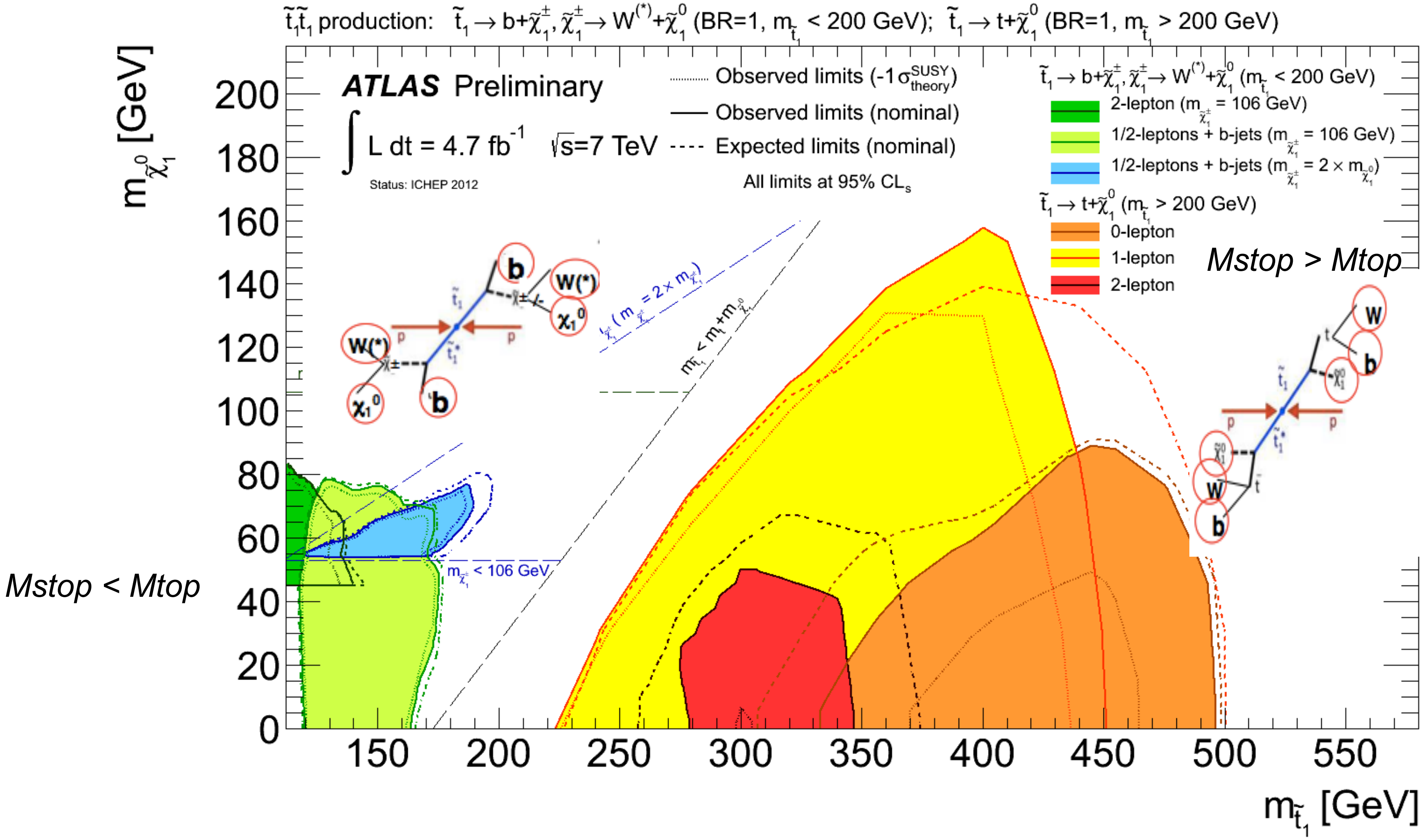


Just about to be sensitive to direct stop pair production.

Limits will improve rapidly with more data!

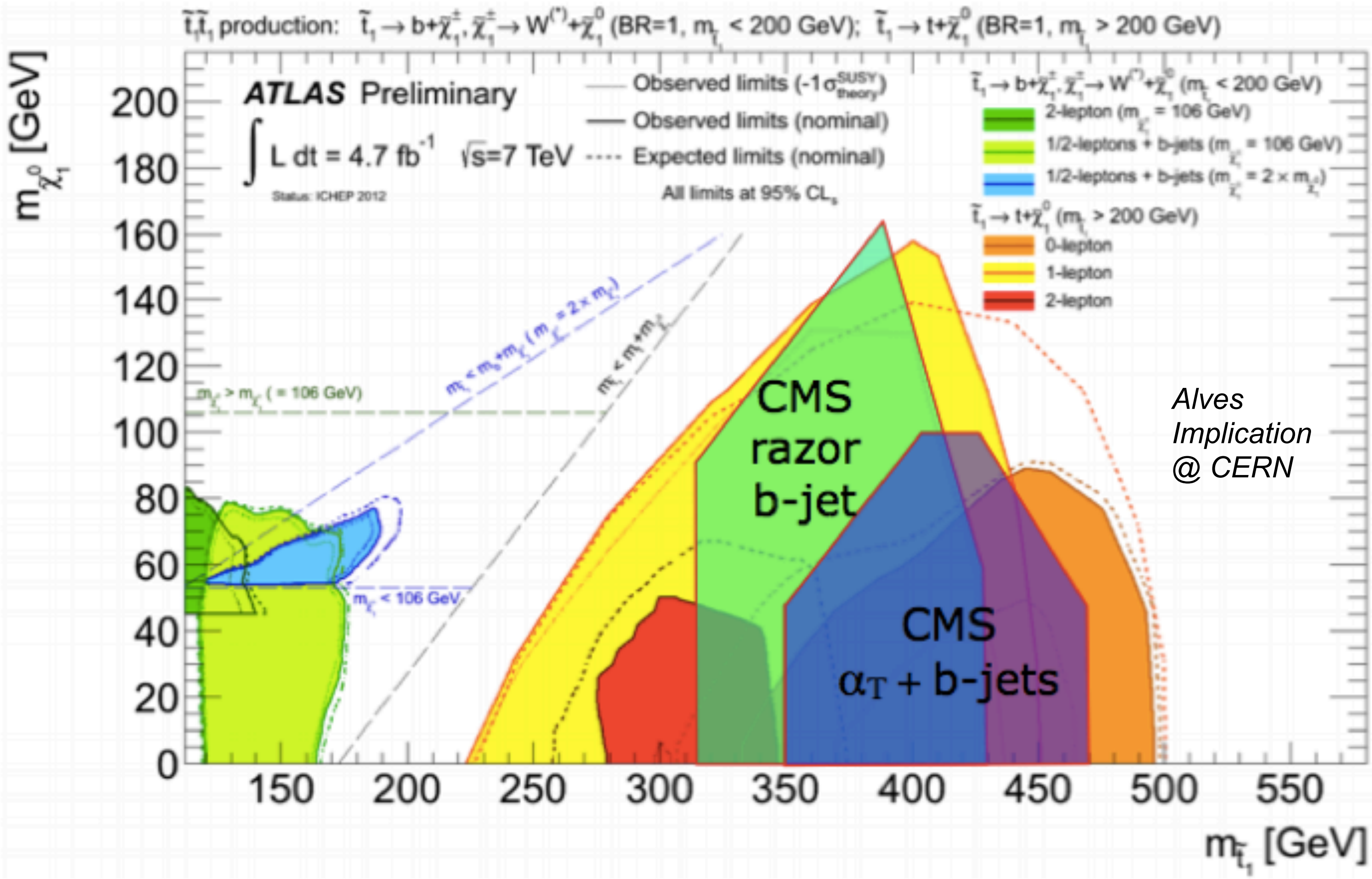
Direct Stop Searches Today

Nice summary plot from ATLAS …



… but keep in mind; no limits for m_{LSP} > 150 GeV (so far)

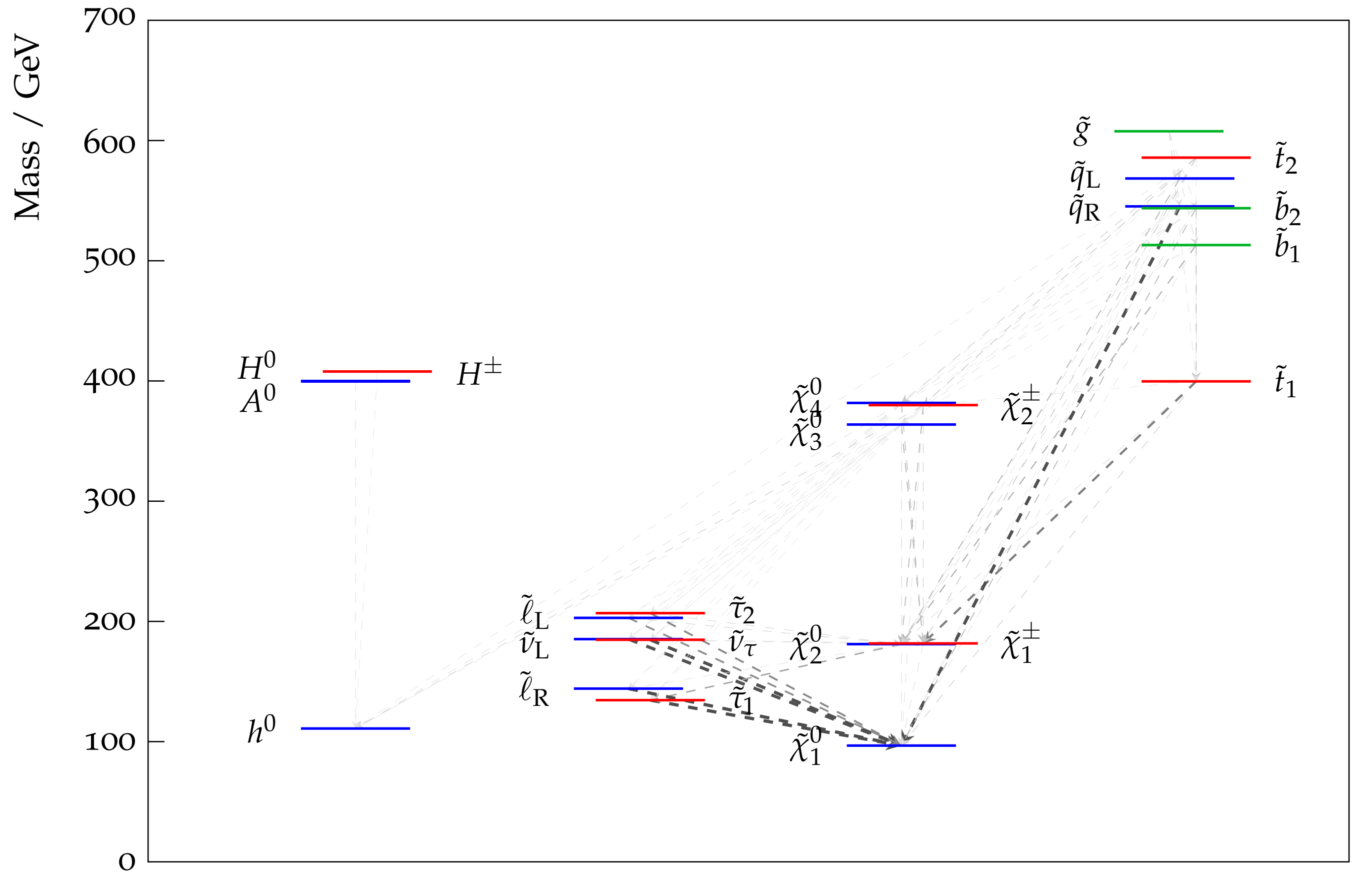
Direct Stop Searches Today



Direct searches not yet adding much over inclusive searches!
This needs more work!

What have we learned (so far)?

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



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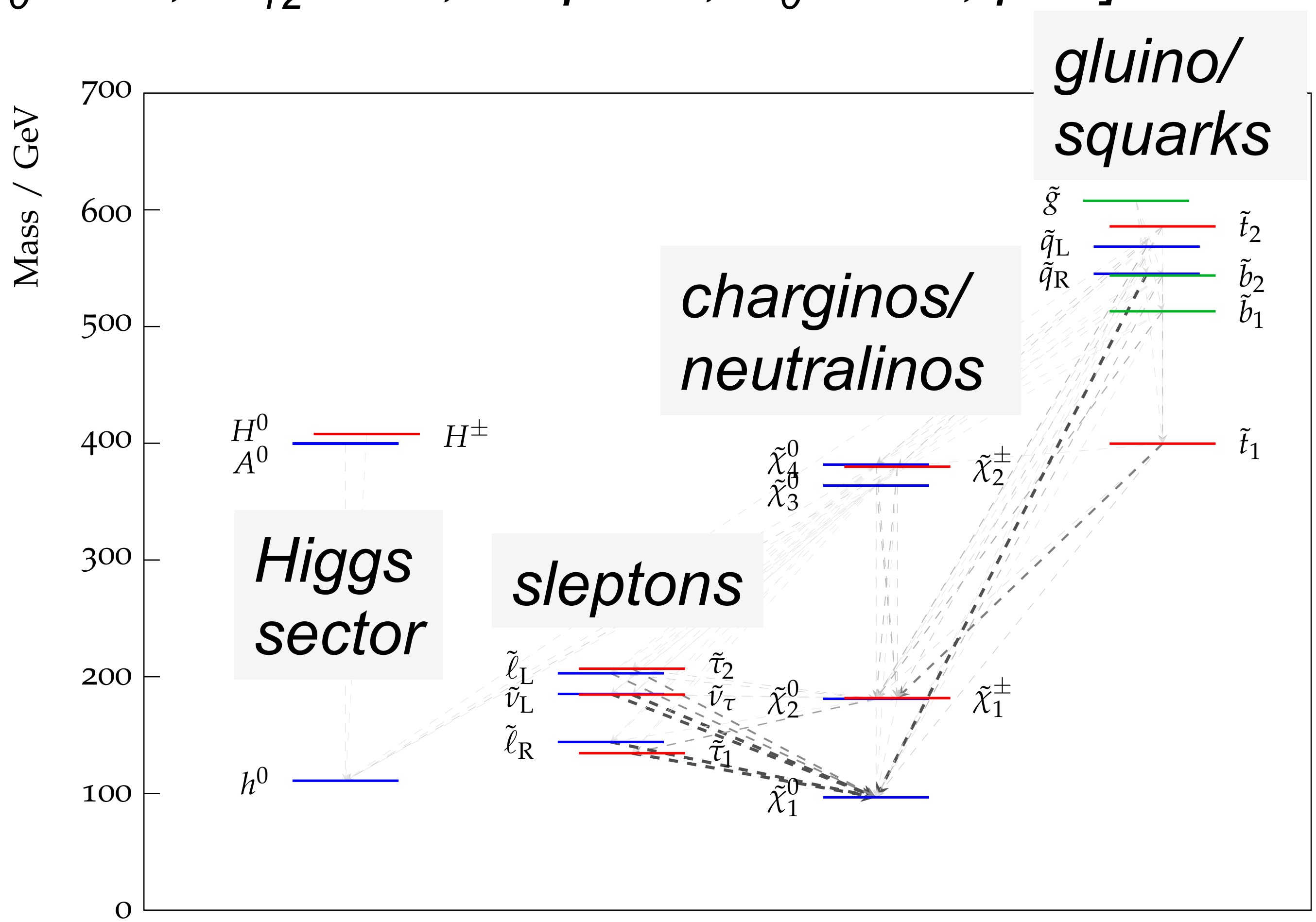

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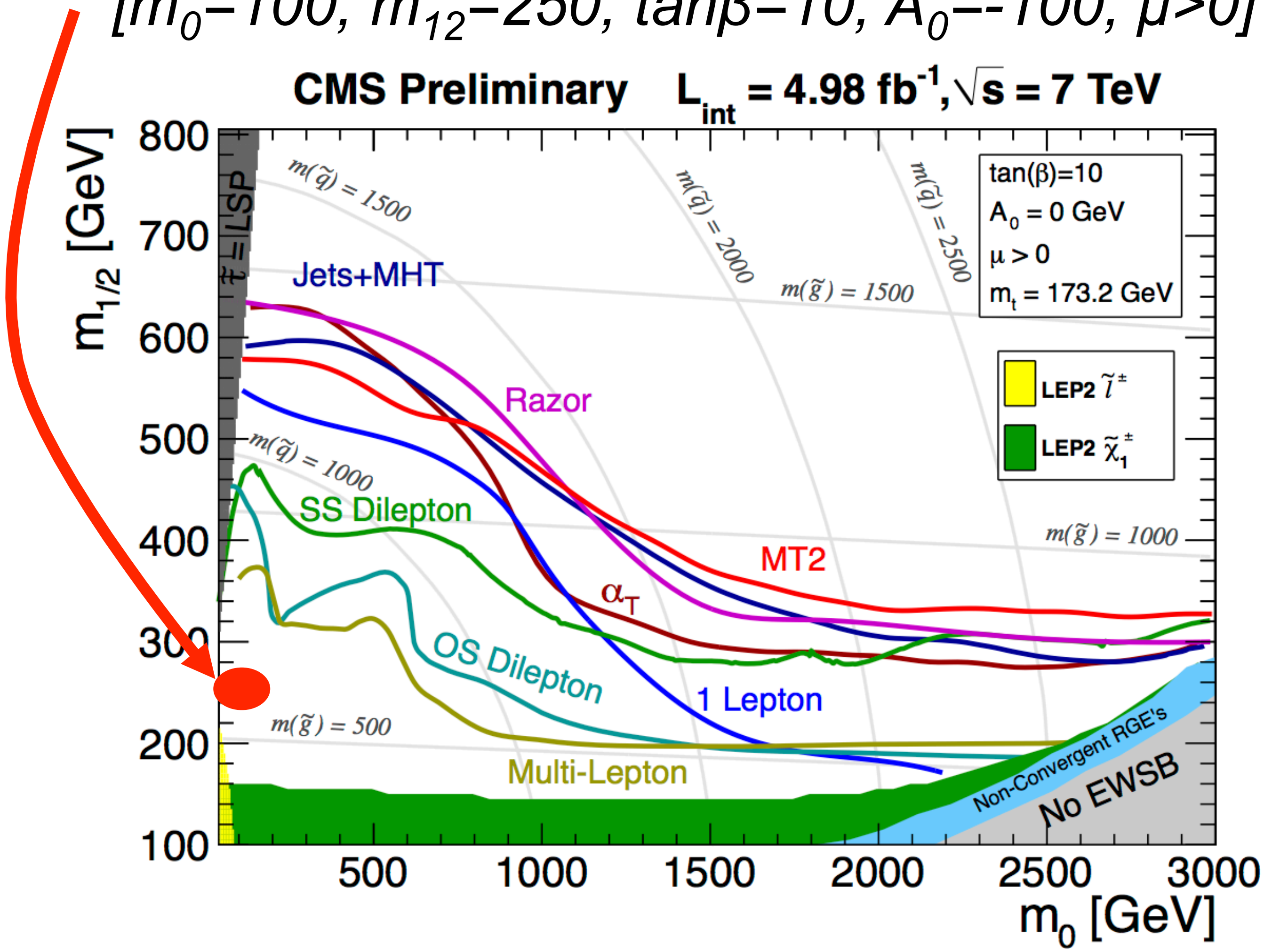
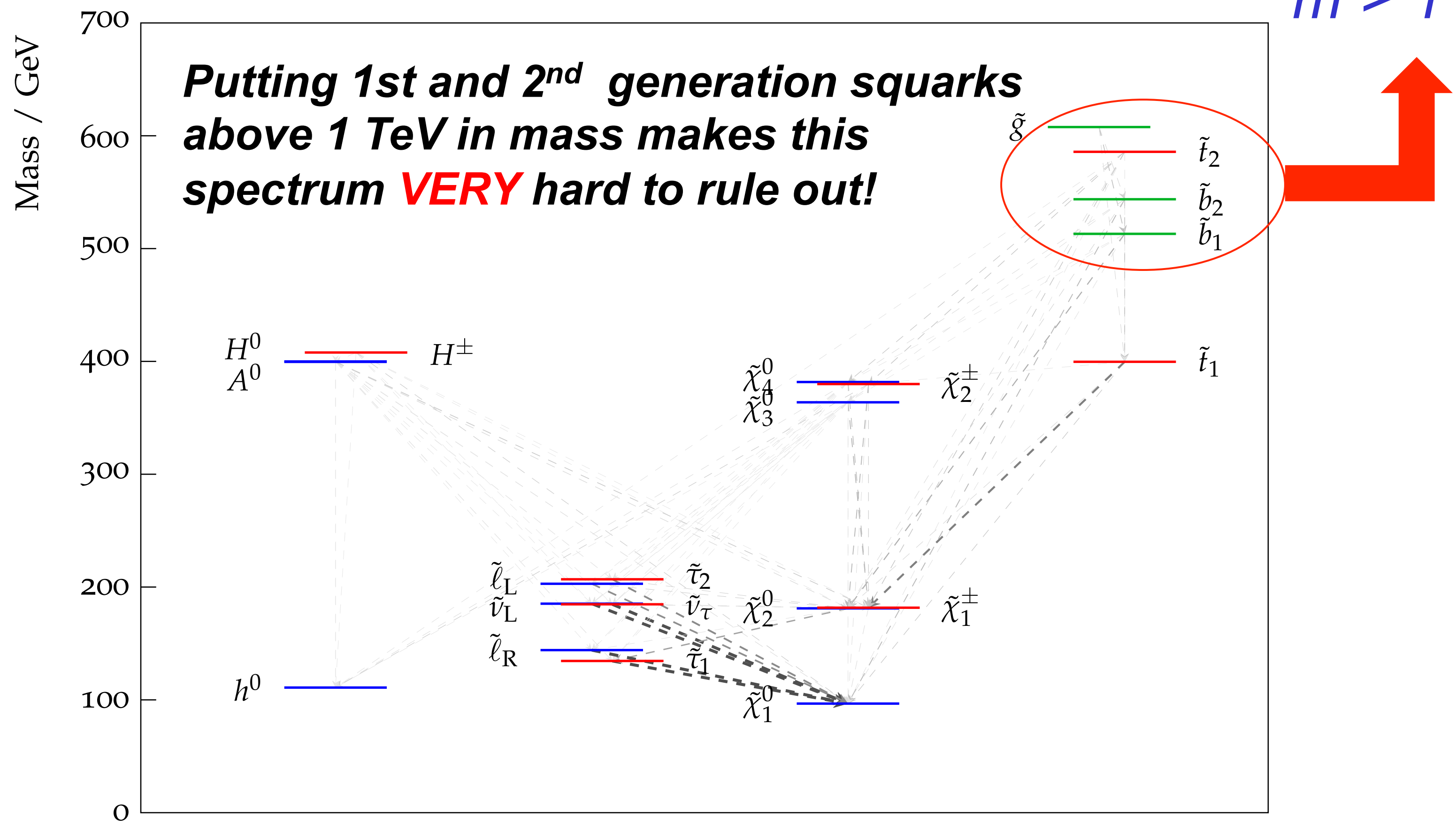


Point well ruled out already! But ….

What have we learned (so far)?

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

sq_l, sq_r
m > 1 TeV



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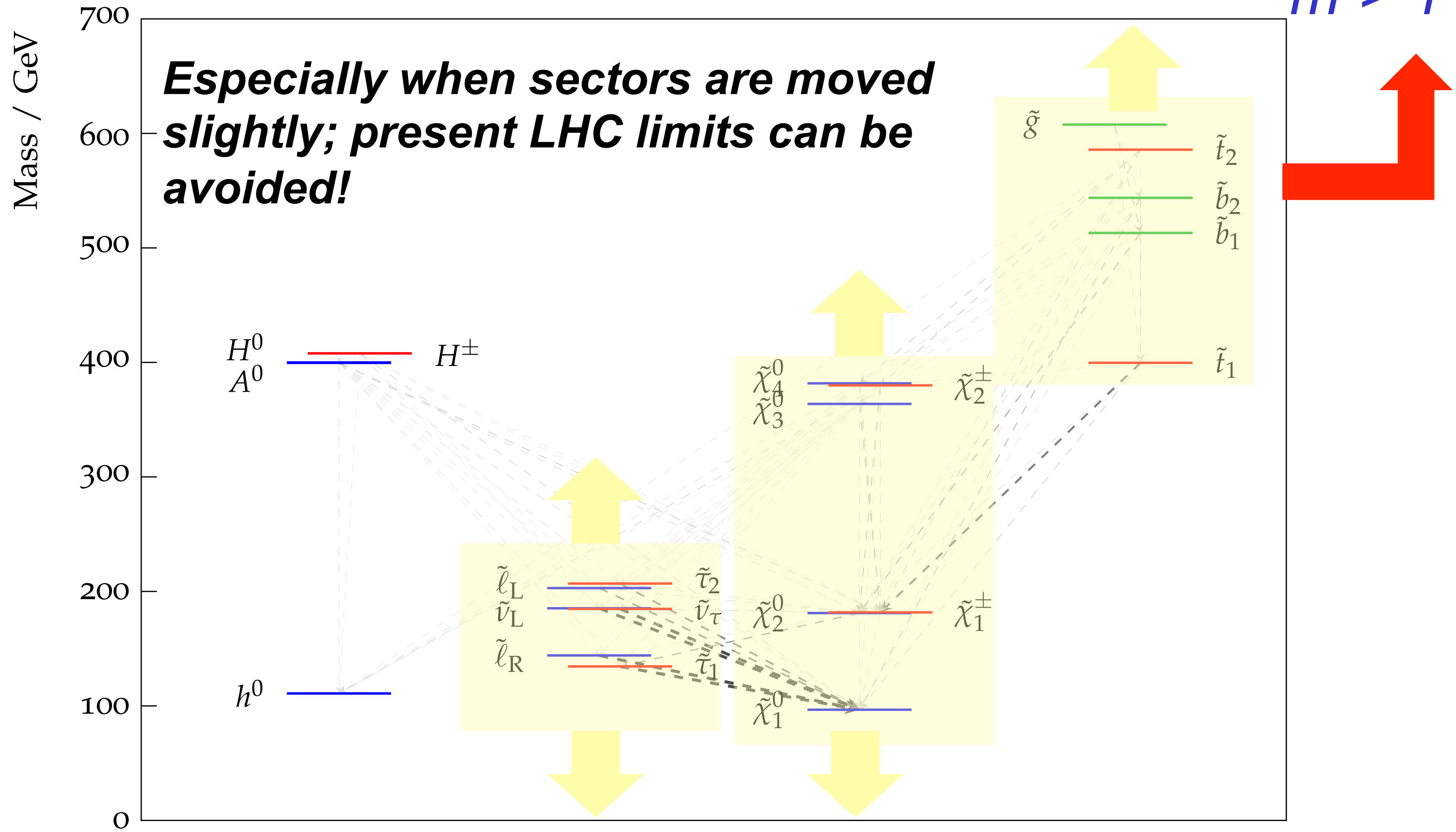
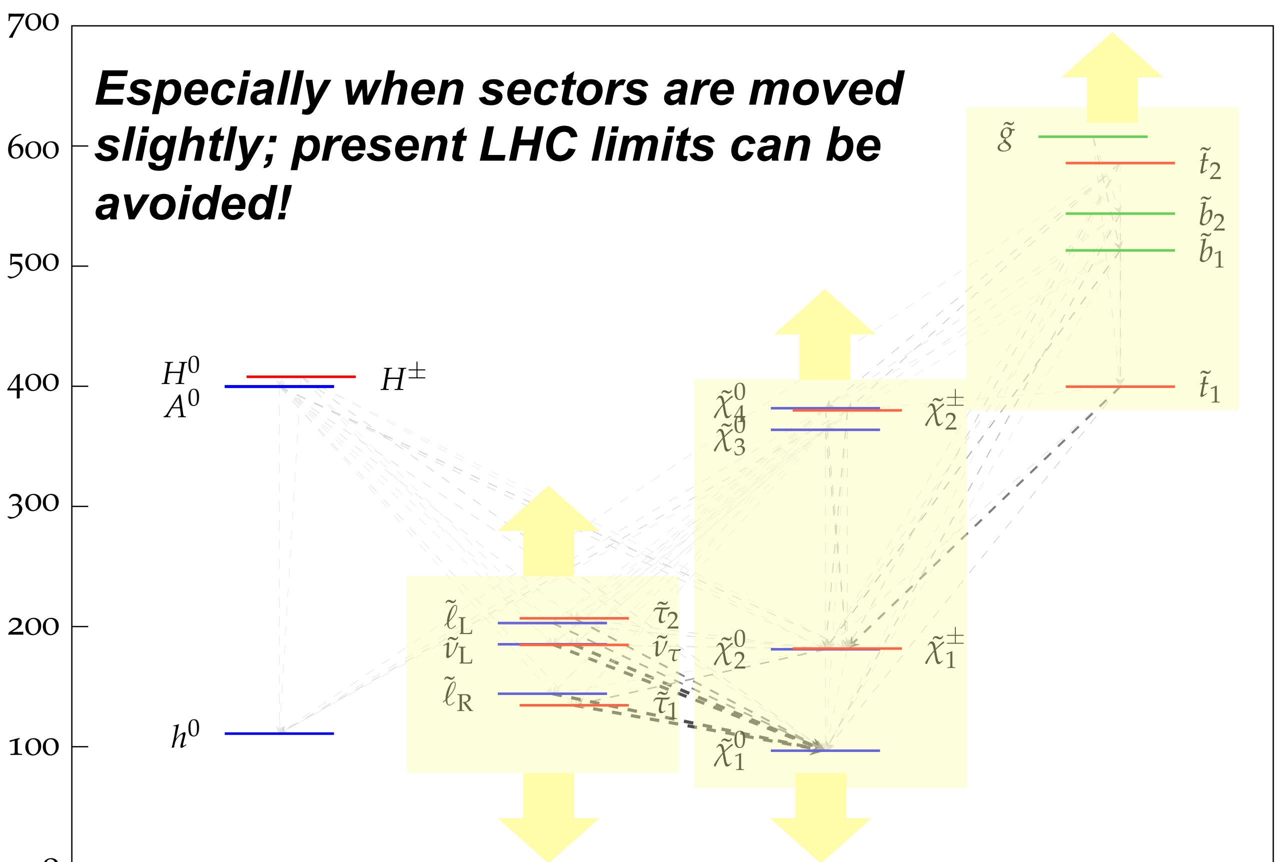
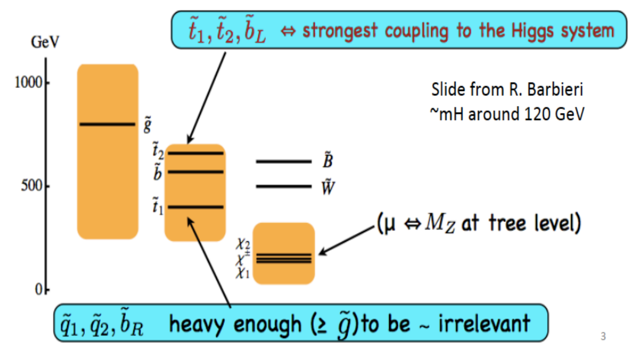


What have we learned (so far)?

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

Especially when sectors are moved slightly; present LHC limits can be avoided!





It is not a surprise that this looks very similar to what people call these days
"Natural SUSY" spectra

Summary

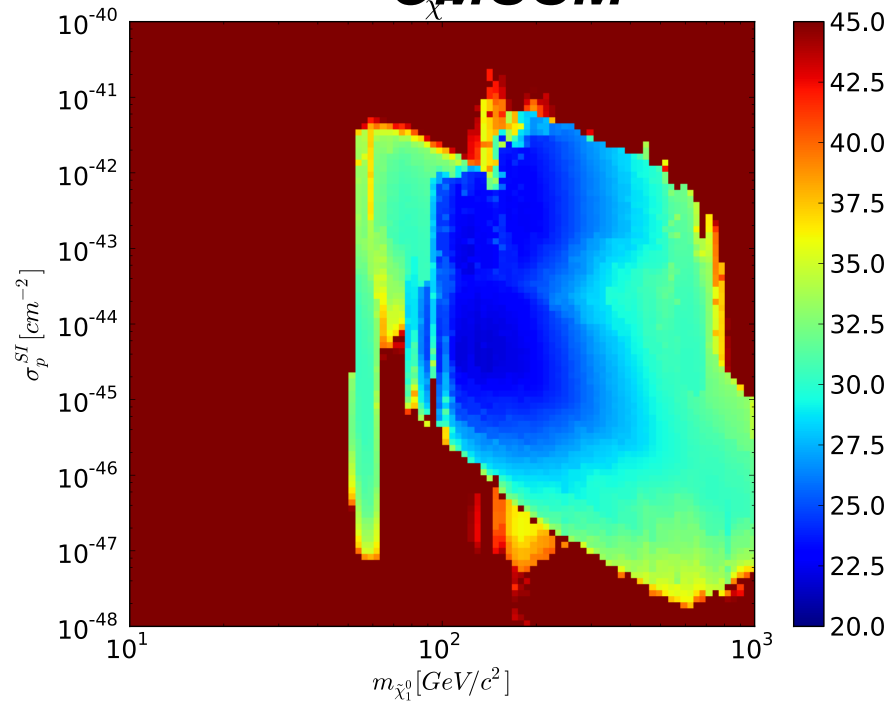
- What have we learned so far?
  - A lot! Yet, not as much as some people think.
  - We are just about to explore the 1 TeV scale and beyond and there are still major wholes in SUSY parameters space below the 1 TeV scale.
- So far SUSY has not revealed itself!
  - Yet, with many of the powerful direct searches continuing to push the limits, discovery of a SUSY-like signal could now happen almost every day!
  - It, however, might also take more time and ingenuity to claim a signal (or to rule out the most relevant parameter space).
- 13+ TeV operation in 2015 will be critical!

Backup Material

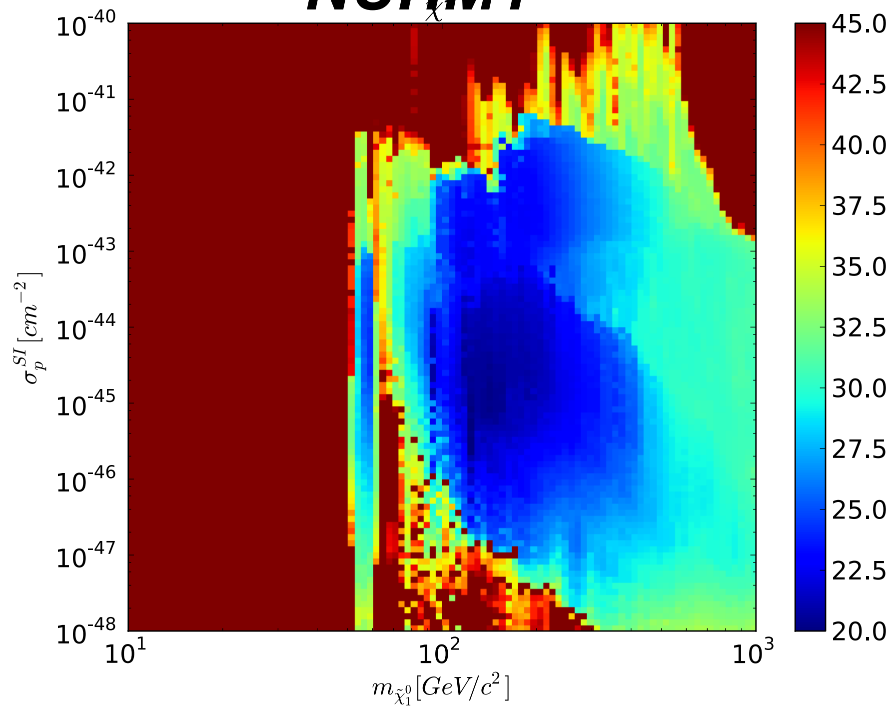
Spin Independent XS vs. M_{LSP}

Pre-LHC 2008

CMSSM



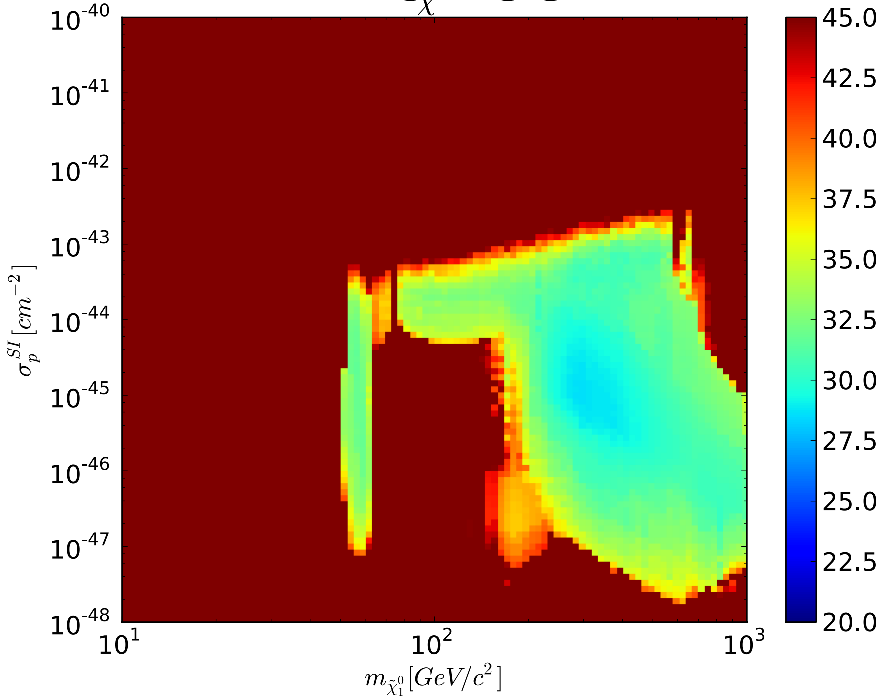
NUHM1



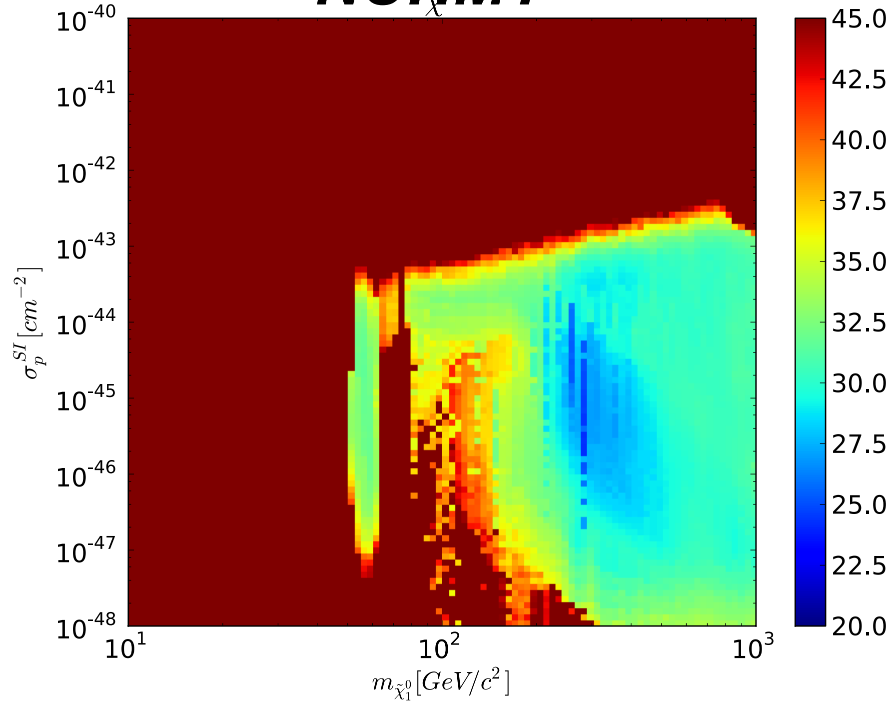
Spin Independent XS vs. M_{LSP}

Post-LHC (1/fb), Post-Xenon100 - 2011

CMSSM



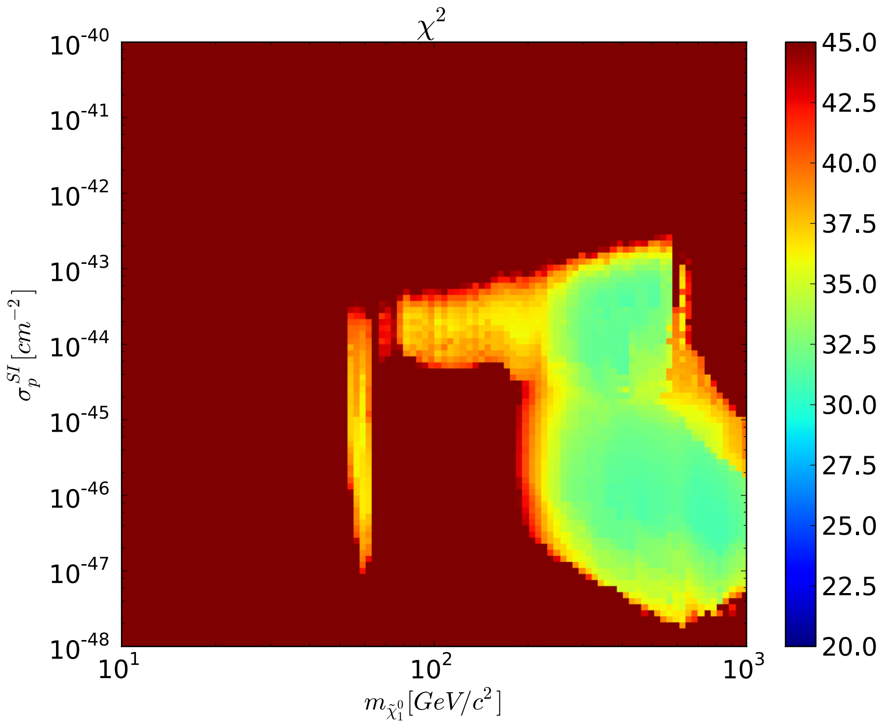
NUHM1



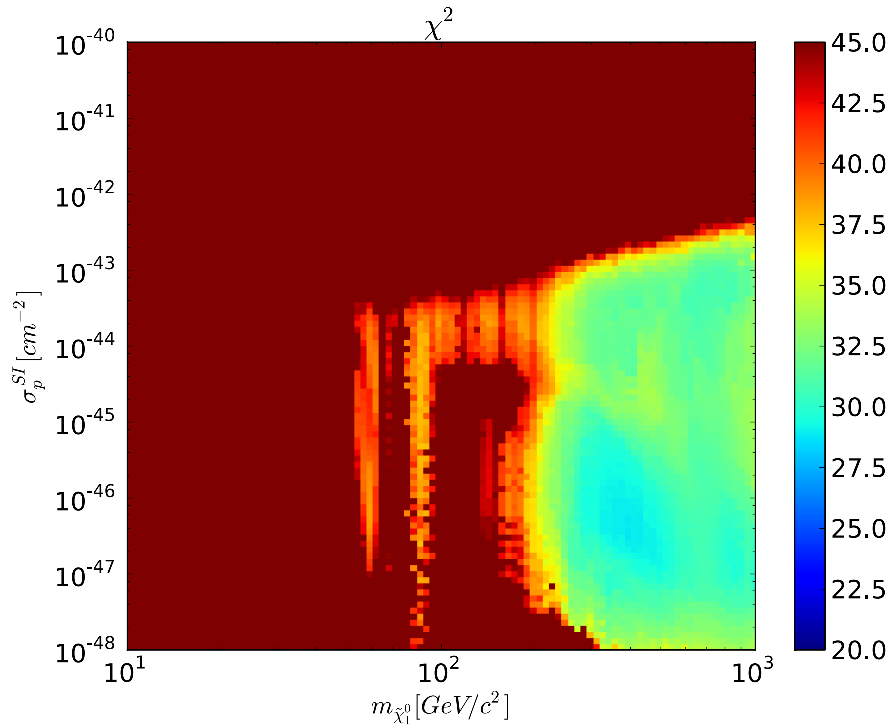
Spin Independent XS vs. M_{LSP}

Post Discovery!

assume m_H=125 +/- 1.5(theo) +/- 1.0 GeV



CMSSM

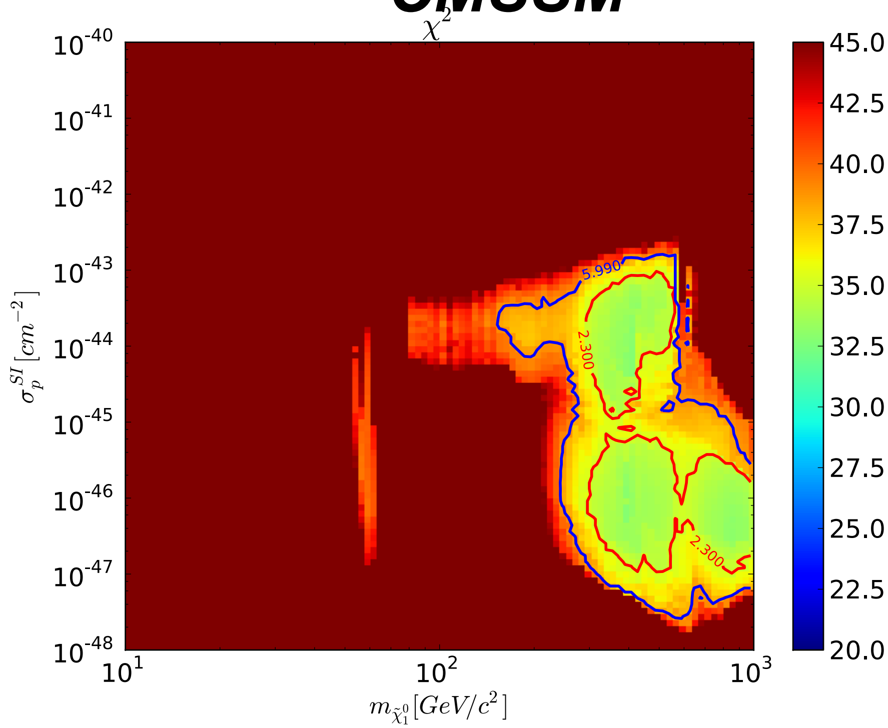


NUHM1

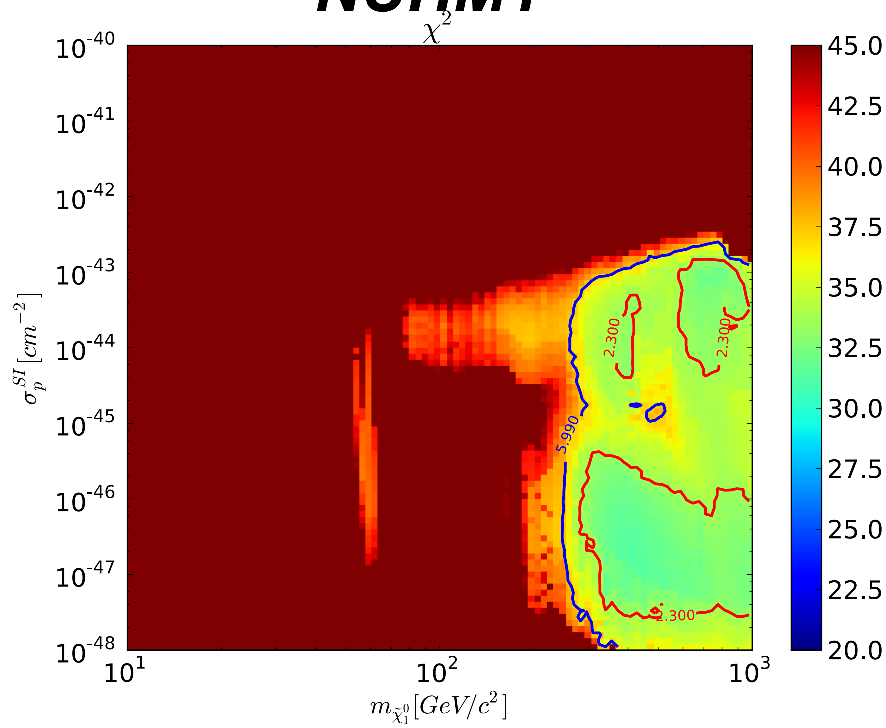
Spin Independent XS vs. M_{LSP}

Today

CMSSM

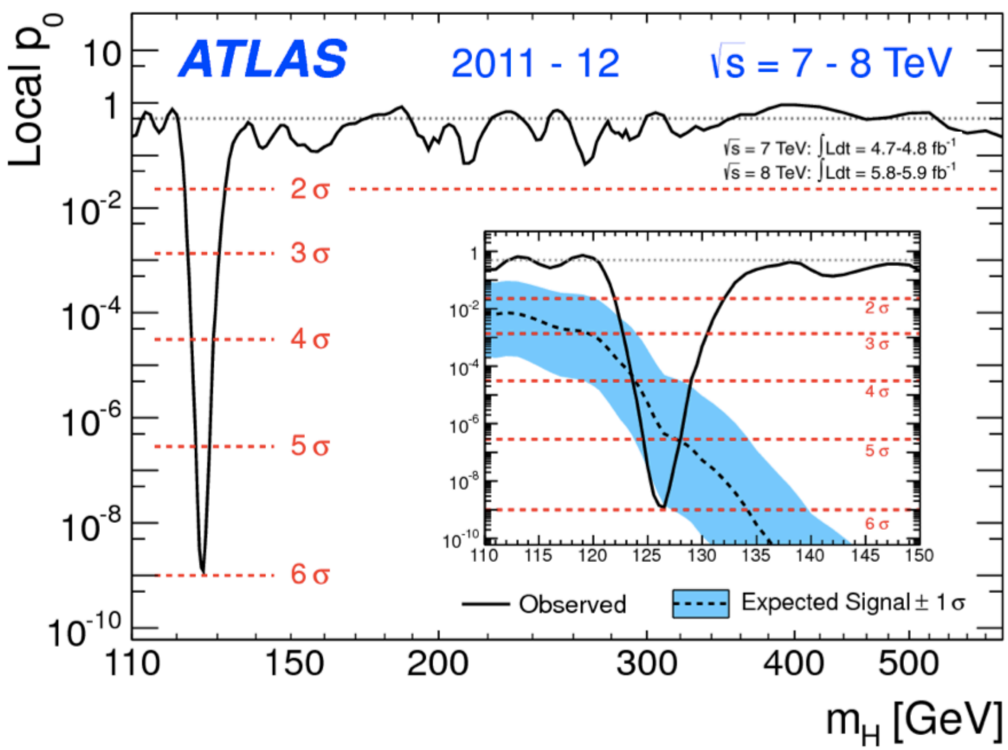


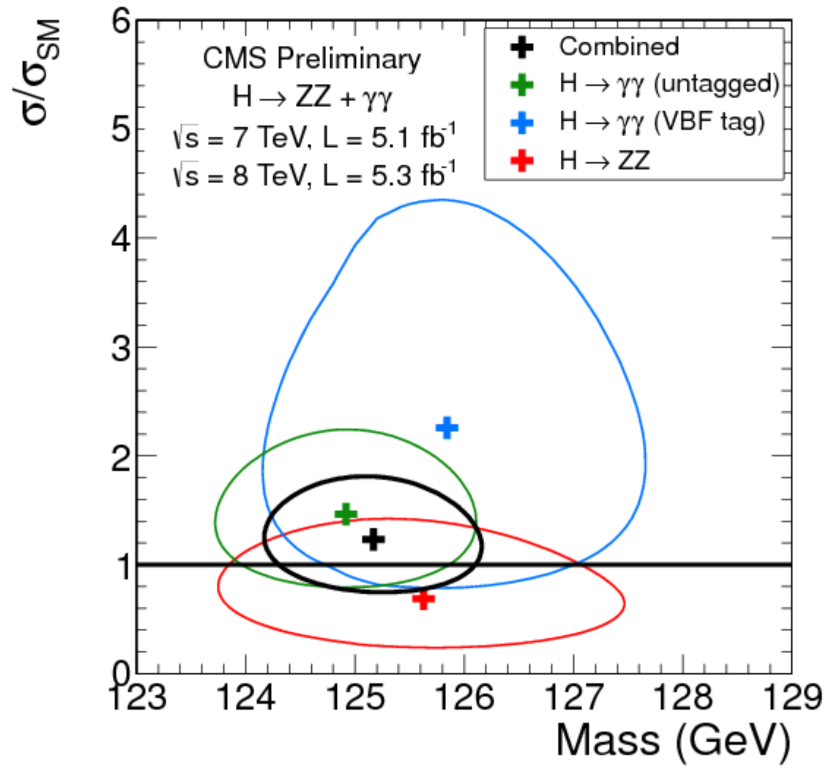
NUHM1



Discovery of a new Boson

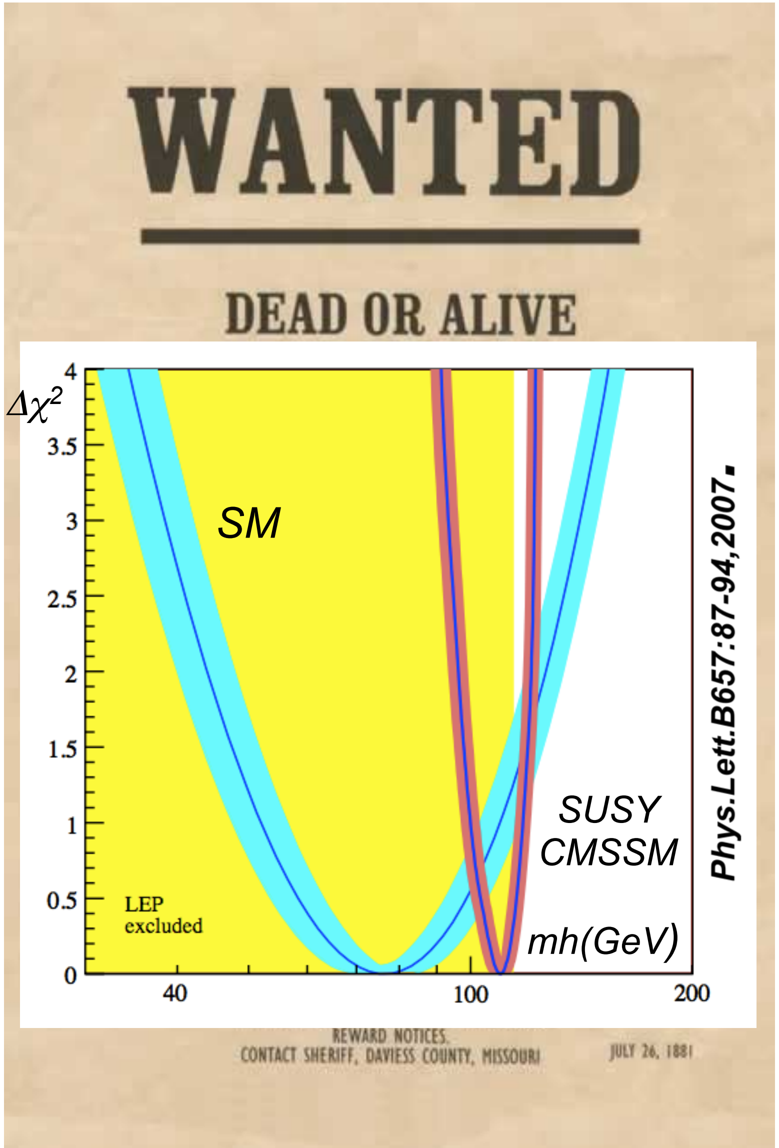
The summer's tale of 2012 (and beyond)





Discovery of a new Boson with SM-like Higgs properties at a mass around 125 GeV!

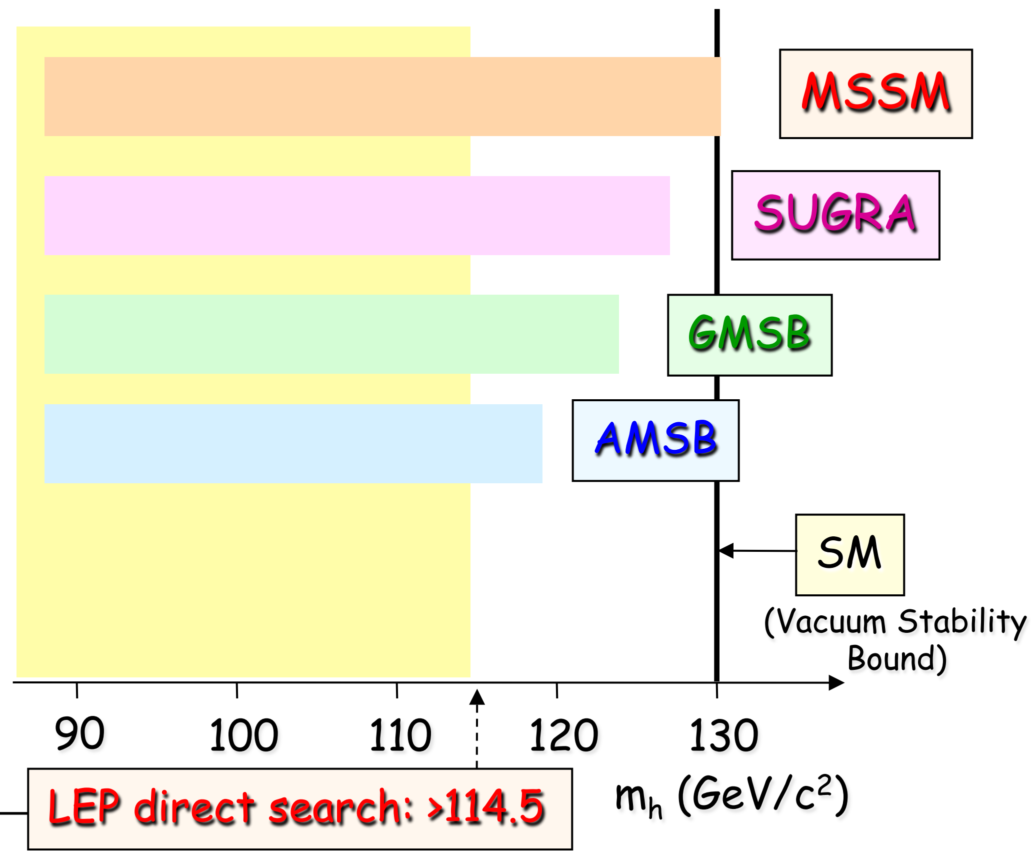
SM-like Higgs Boson



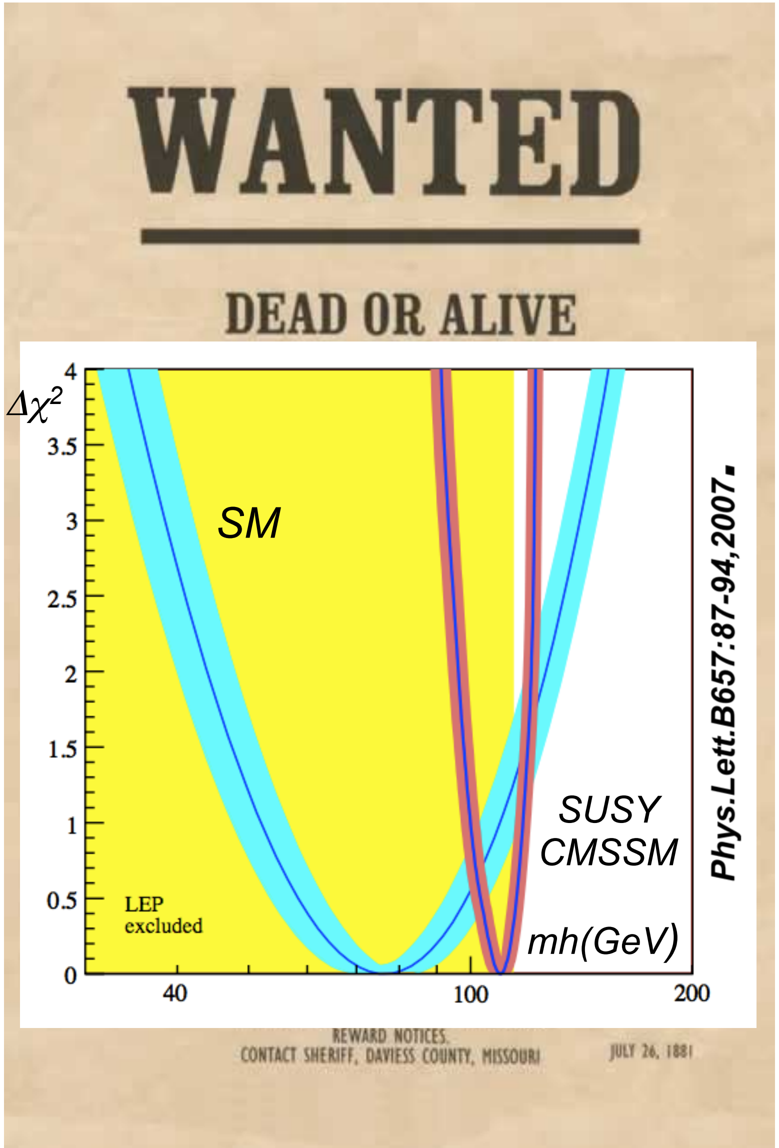
SM: Constrained Phase Space

mh(SM)<161 GeV @ 95% CL

SUSY: Accessible Phase Space



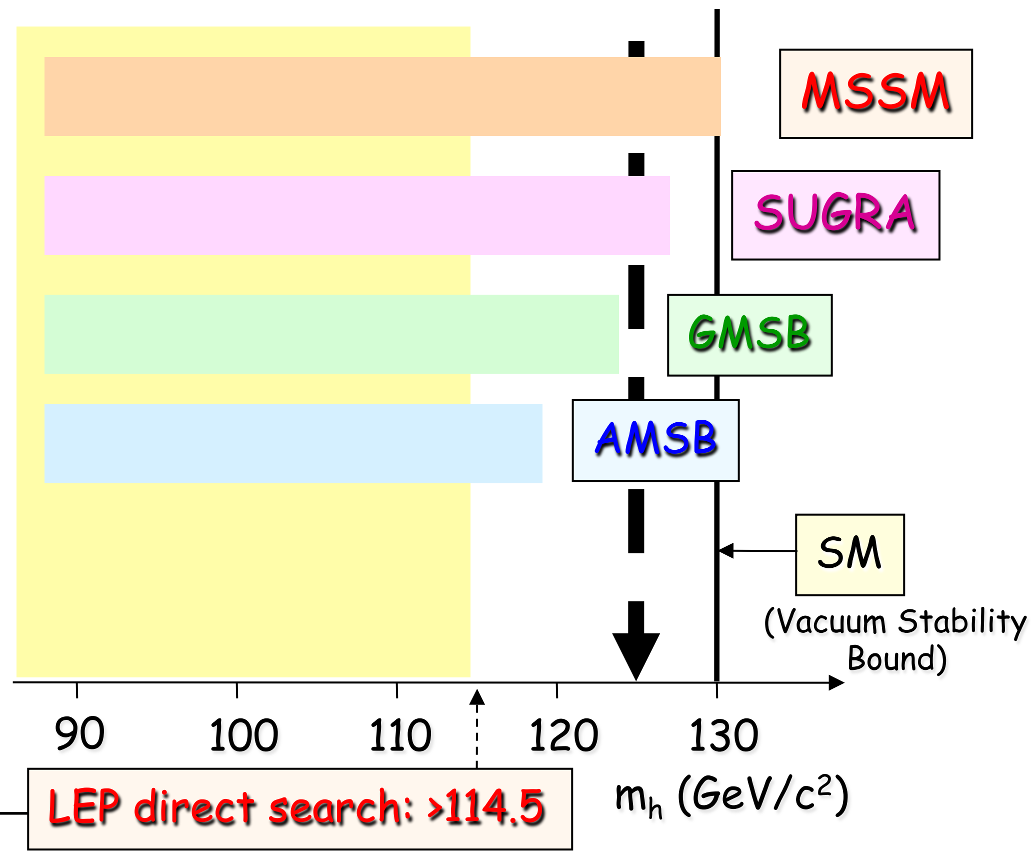
SM-like Higgs Boson



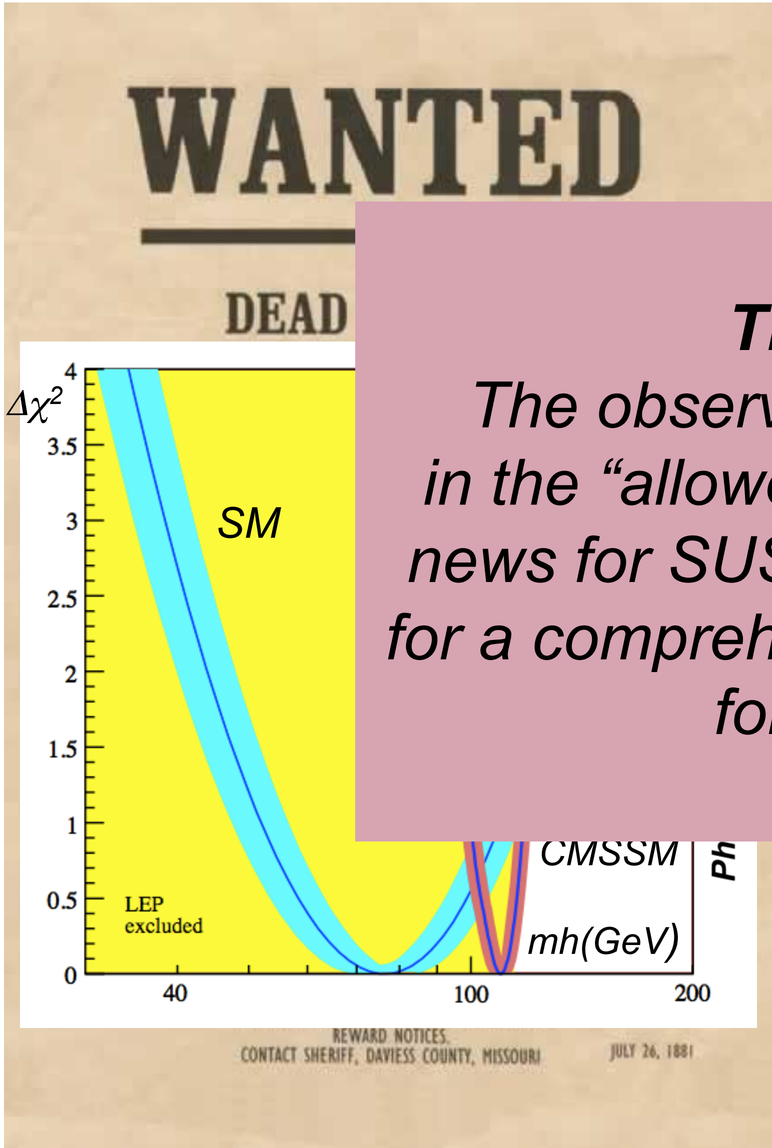
SM: Constrained Phase Space

mh(SM)<161 GeV @ 95% CL

SUSY: Accessible Phase Space



SM-like Higgs Boson

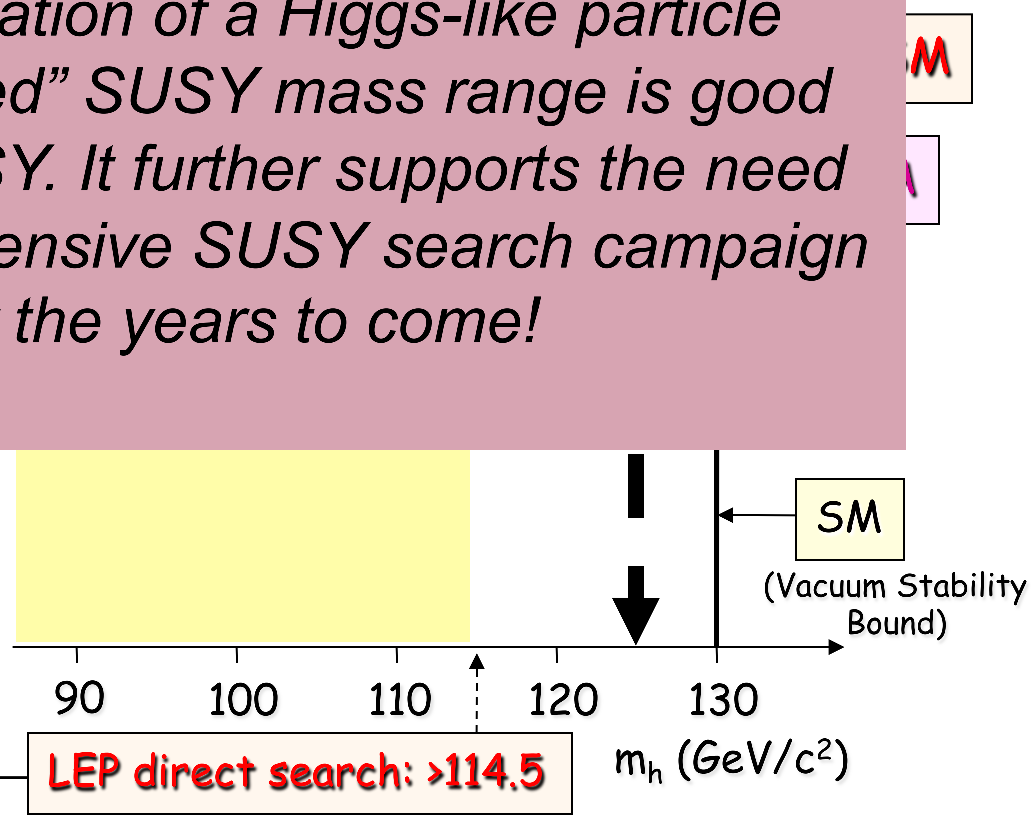


SM: Constrained Phase Space

mh(SM)<161 GeV @ 95% CL

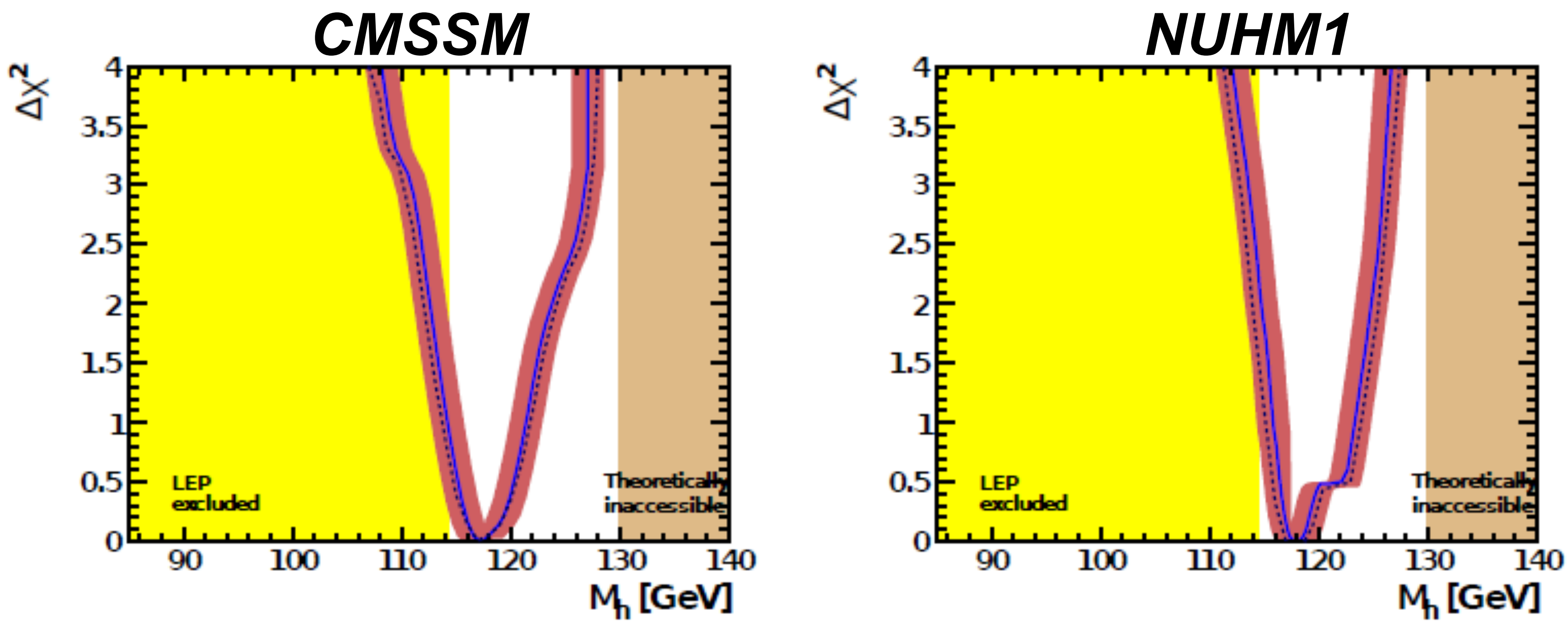
The way I look at it:

The observation of a Higgs-like particle in the "allowed" SUSY mass range is good news for SUSY. It further supports the need for a comprehensive SUSY search campaign for the years to come!



London

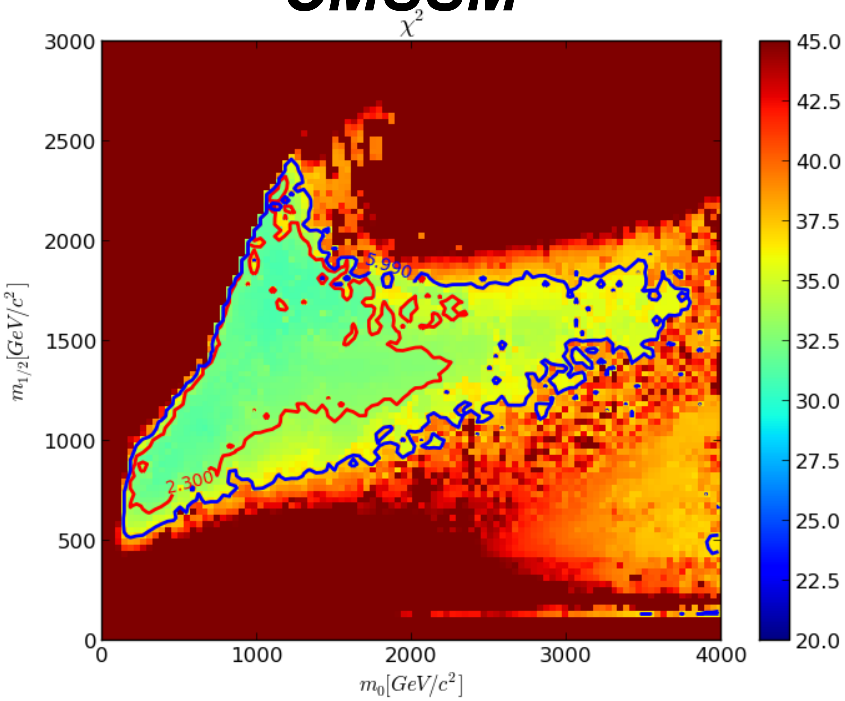
SUSY: Light Higgs Predictions



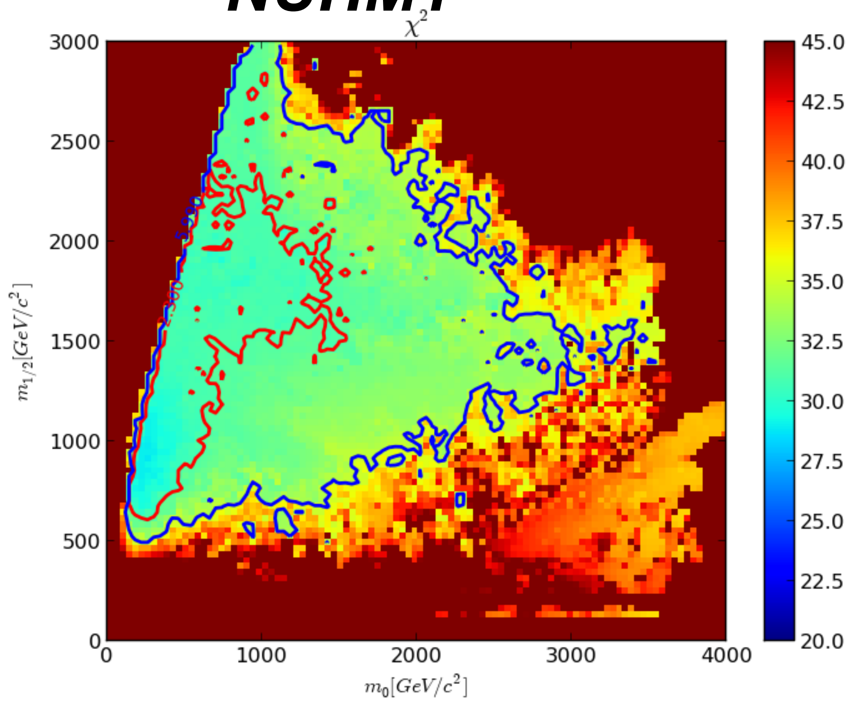
- Higgs important probe of SUSY
  - Predictions above produced based on analogous method to SM best-fit plots
    - → *No Higgs constraints imposed to make these plots!!*

The "post-Higgs" era

CMSSM



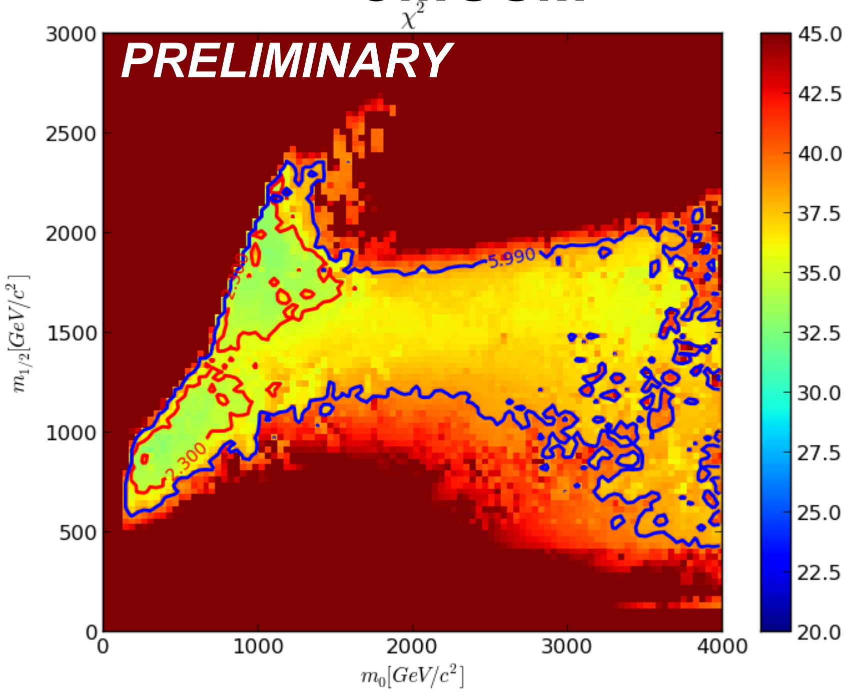
NUHM1



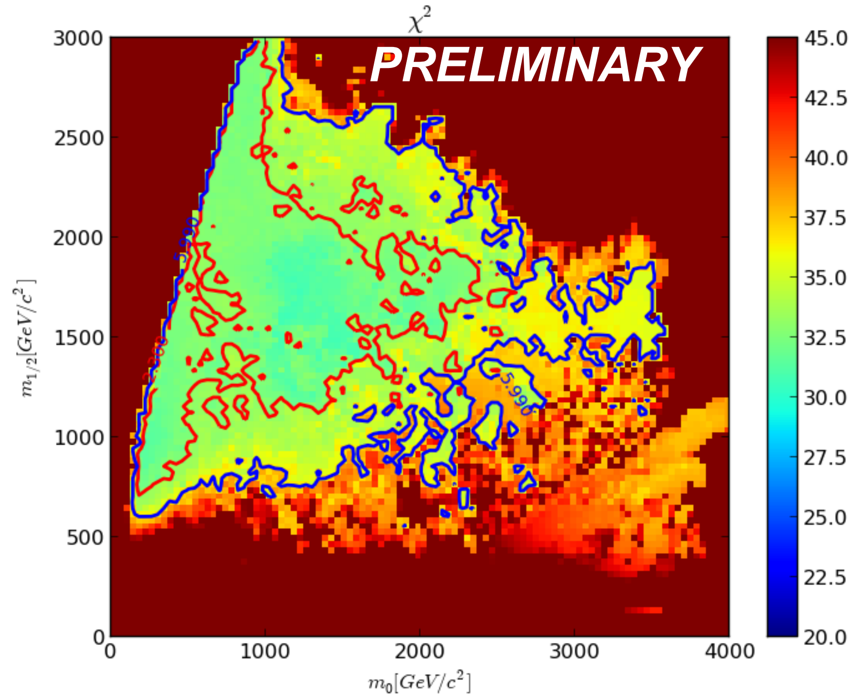
- Assume a putative measurement of m_H=125 +/- 1.5(theo) +/- 1.0 GeV
  - ➢ Further reduction in potential phase-space!

Post "LHC&Higgs" era in 2012

CMSSM



NUHM1



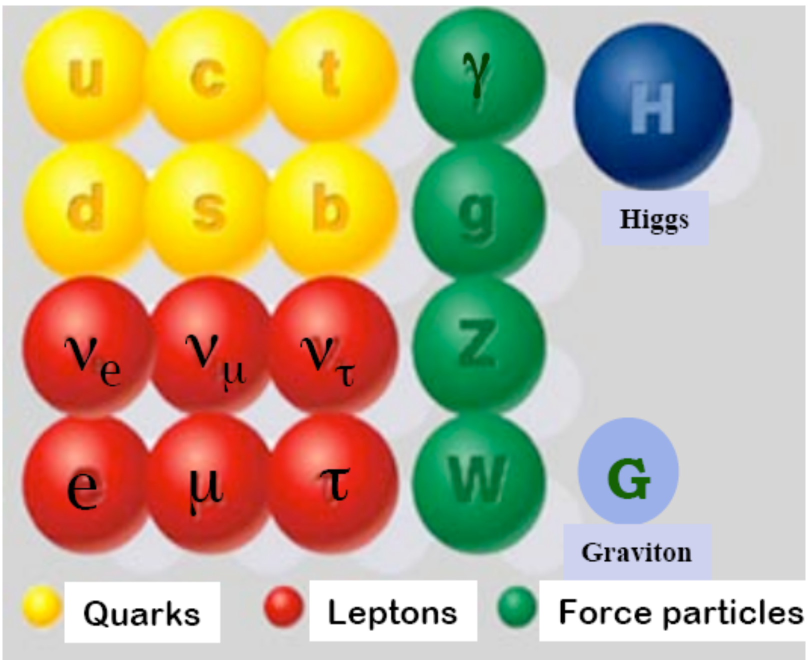
- Updated with
  - 5/fb direct search results
  - Updated BR(Bs-> $\mu\ \mu$) combination from the LHC (May 2012
- Prospects look bleak for constrained models
  - p-value ~10% (max)

Supersymmetry

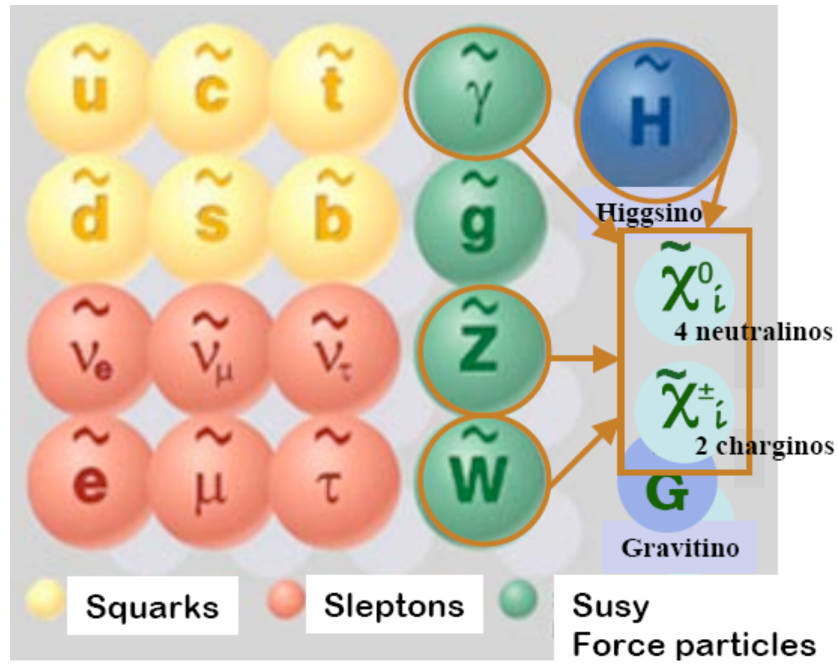
Extension of the Standard Model: Introduce a new symmetry

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*

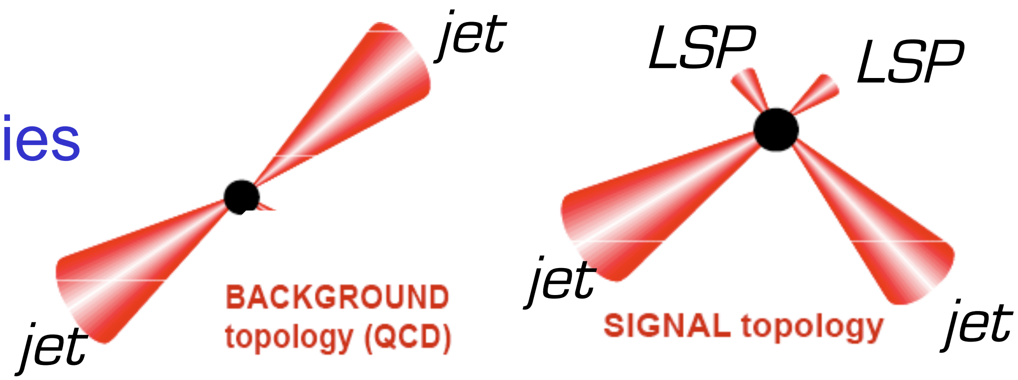
- 1 SUSY particles

R-parity conservation:

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

First SUSY Search: α_T

- Kinematic variable α_T
- Exploits QCD di-jet properties
  - jets are balanced in p_T
  - back-to-back in ϕ



Define: $H_T = \Sigma p_T(j_i)$, $MH_T = |- \Sigma p_T(j_i)|$, $\Delta H_T = E_T(pj_1) - E_T(pj_2)$

α_T for dijets:

$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}} \leq 0.5$$

Expectation for QCD: $\alpha_T = 0.5$
Jet mis-measurements: $\alpha_T < 0.5$

α_T for n jets:

$$\alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{M_T}$$

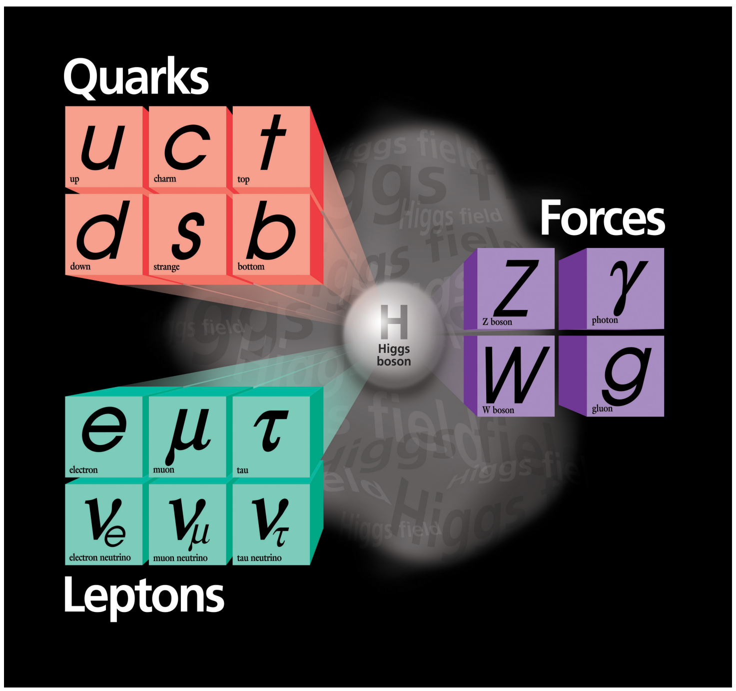
(form two pseudo-jets – defined by balance in "pseudo-jet" $H_T = \Sigma E_T$)

inspired by
L. Randall & D. Tucker-Smith,
Phys.Rev. Lett. 101 (2008) 221803

The Standard Model of Particle Physics

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics (SM).
The new (final?) "Periodic Table" of fundamental elements

Matter particles



Force particles

A crowning achievement of 20th Century Science

Yet, its most basic mechanism, that of granting mass to particles, is (was?) missing. Quantum of this field is the Spin Zero Higgs boson.

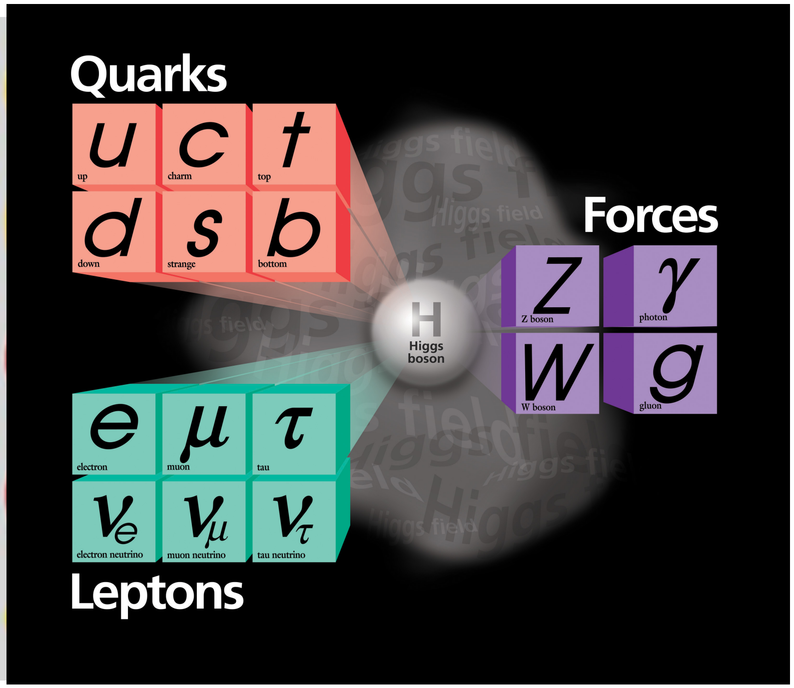
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry

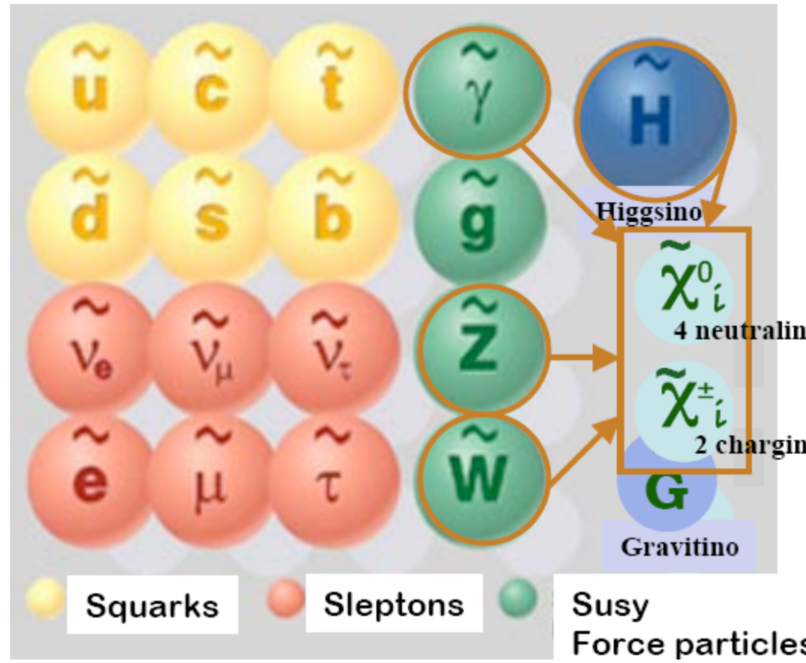
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles | *SUSY particles*

Matter particles



Force particles



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

- 1 SUSY particles

<u>R-parity conservation:</u>

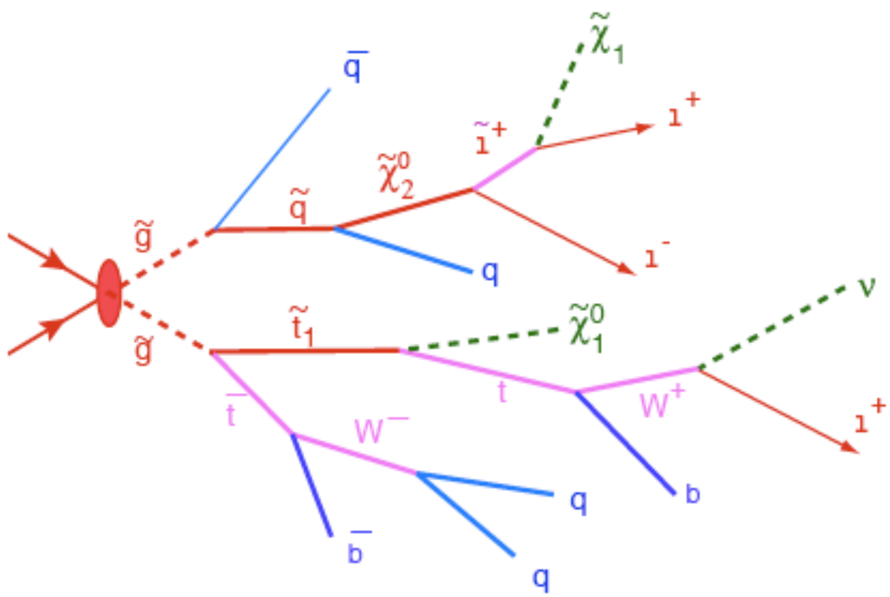
- *SUSY particles are produced in pairs*
- *The lightest SUSY particle (LSP) is stable*

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*

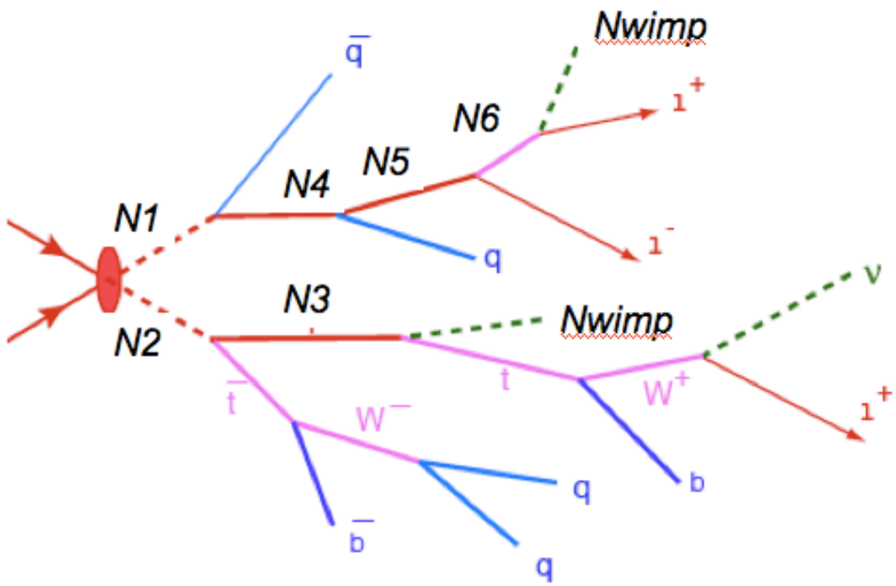
Multi-Jet:
- *from cascade decay (gaugino)*

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.