Collider probes of SUSY

Where do we go now with SUSY searches?

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Happening at the Pre SUSY school at SUSY 2014, Manchester.

- Introductory remarks.
- The particle spectrum and the final states
- Current LHC results on SUSY searches. How to read the simplified models results?
- What is the future for 13/13.5 TeV searches?

SUSY: One of the most attractive BSM idea.

Lot of theoretical and experimental effort has gone in!

Stubbornly refuses to show up!

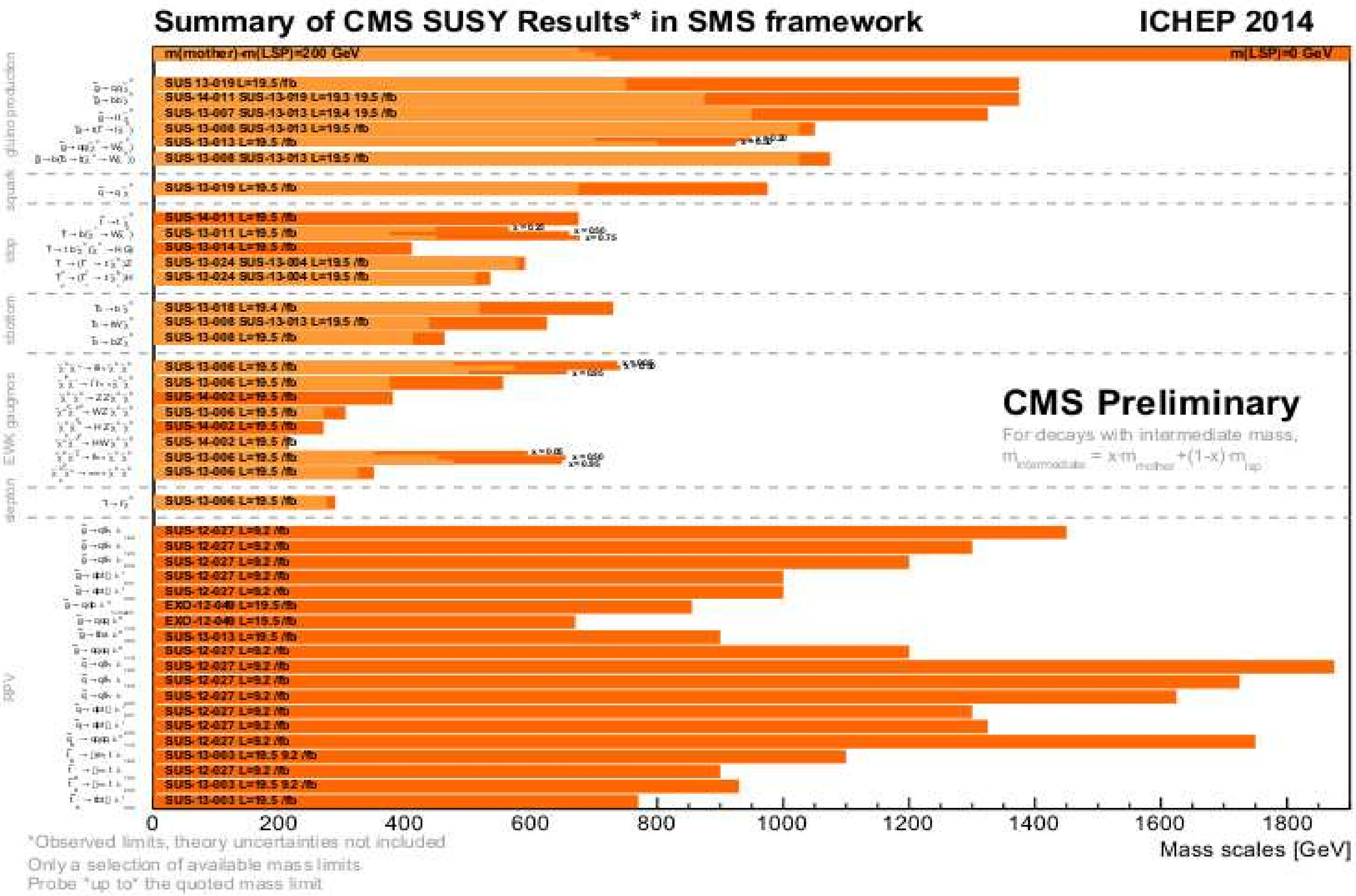
Is it in danger of extinction?

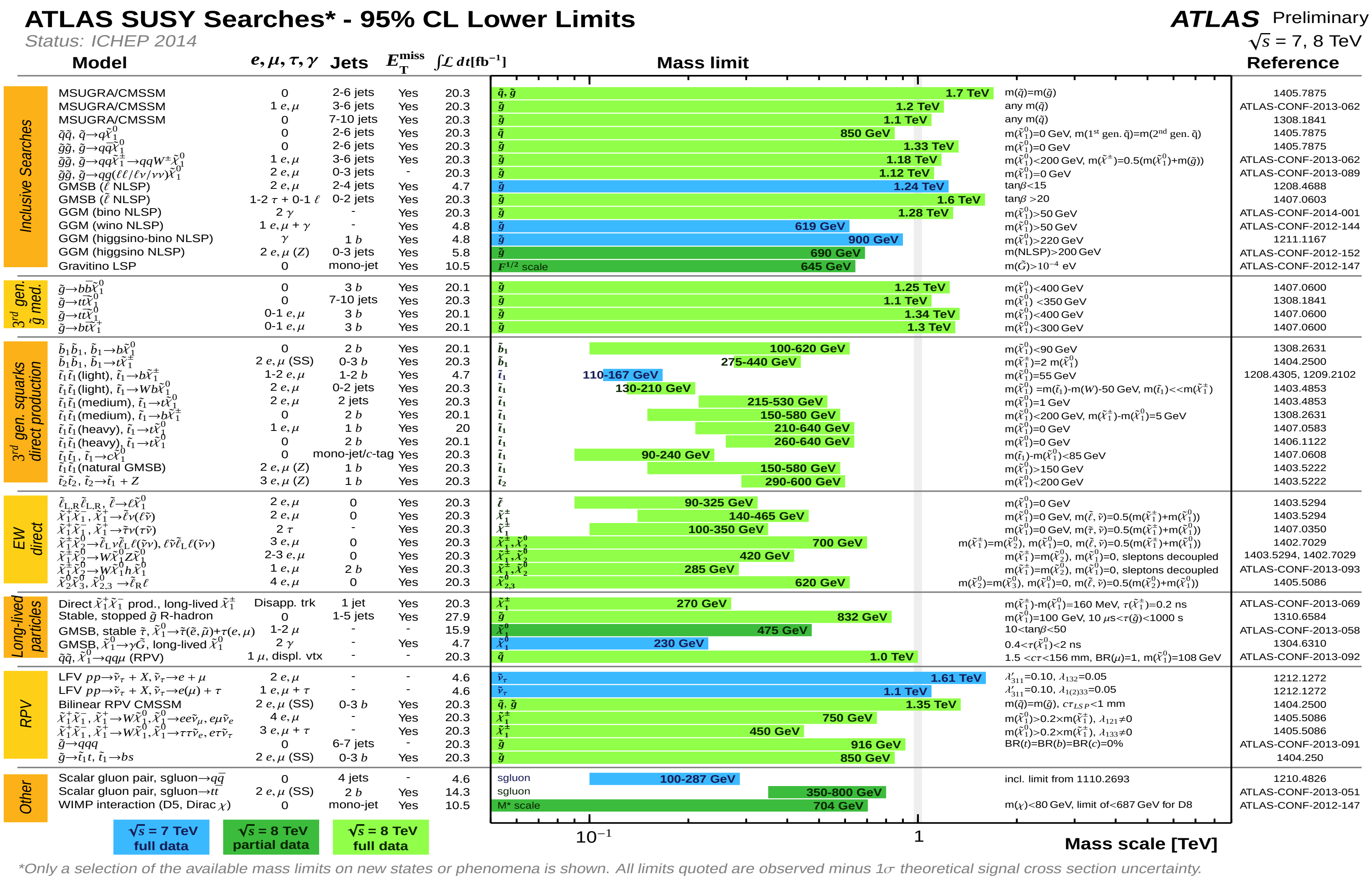
At least a very major part of the natural parameter space is excluded!

How do we look into cracks?

(for experimental slides I have freely borrowed from presentations from G. Polesello, without always giving credit)

Sfermions		Gauginos and higgsinos	
Name	Symbol	Name	Symbol
(left, right) selectron	$\tilde{e}_{L,R}$	gluinos	$\tilde{g}^a$
(left, right) smuon	$\tilde{\mu}_{L,R}$		
(left, right) stau	$\tilde{\tau}_{L,R}$	lighter charginos	$\tilde{\chi}_1^{\pm}$
e-sneutrino	$\tilde{\nu}_e$		
μ-sneutrino	$\tilde{\nu}_\mu$	heavier charginos	$\tilde{\chi}_2^{\pm}$
τ-sneutrino	$\tilde{\nu}_\tau$		
(left, right) u-squark	$\tilde{u}_{L,R}$	lightest neutralino	$\tilde{\chi}_1^0$
(left, right) d-squark	$\tilde{d}_{L,R}$		
(left, right) c-squark	$\tilde{c}_{L,R}$	next-to-lightest neutralino	$\tilde{\chi}_2^0$
(left, right) s-squark	$\tilde{s}_{L,R}$		
(left, right) stop	$\tilde{t}_{L,R}$	next-to-heaviest neutralino	$\tilde{\chi}_3^0$
(left, right) sbottom	$\tilde{b}_{L,R}$	heaviest neutralino	$\tilde{\chi}_4^0$

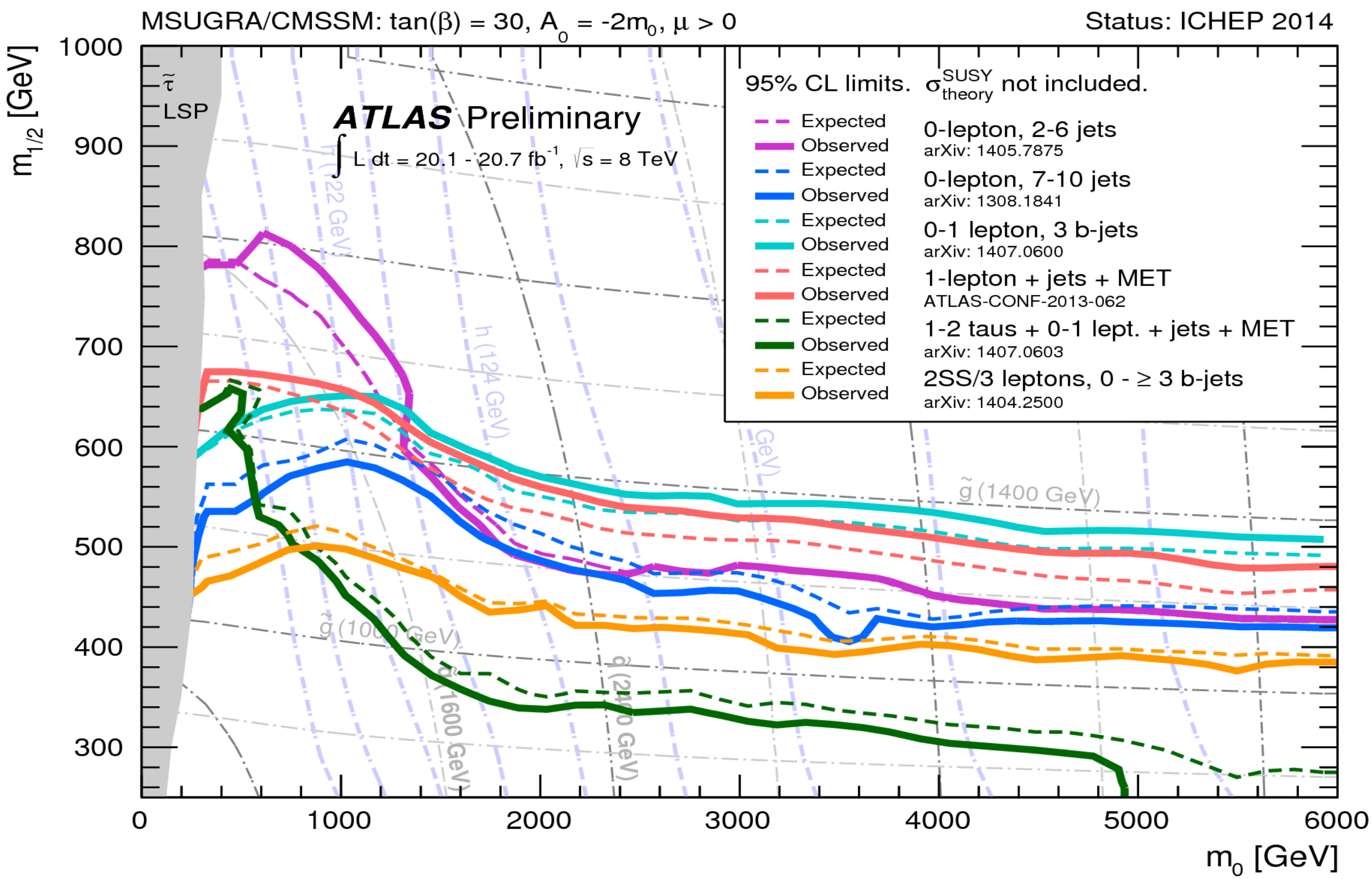

Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} + (1-x) \cdot m_{lsp}$
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: ICHEP 2014
ATLAS Preliminary
√s = 7, 8 TeV
Model | e, μ, τ, γ | Jets | E_T^miss | ∫L dt[fb^-1] | Mass limit | Reference
Inclusive Searches
MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | q̃, g̃ 1.7 TeV | m(q̃)=m(g̃) | 1405.7875
MSUGRA/CMSSM | 1 e, μ | 3-6 jets | Yes | 20.3 | g̃ 1.2 TeV | any m(q̃) | ATLAS-CONF-2013-062
MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | g̃ 1.1 TeV | any m(q̃) | 1308.1841
q̃q̃, q̃→qχ̃₁⁰ | 0 | 2-6 jets | Yes | 20.3 | q̃ 850 GeV | m(χ̃₁⁰)=0 GeV, m(1st gen. q̃)=m(2nd gen. q̃) | 1405.7875
g̃g̃, g̃→qq̄χ̃₁⁰ | 0 | 2-6 jets | Yes | 20.3 | g̃ 1.33 TeV | m(χ̃₁⁰)=0 GeV | 1405.7875
g̃g̃, g̃→qqχ̃₁±→qqW±χ̃₁⁰ | 1 e, μ | 3-6 jets | Yes | 20.3 | g̃ 1.18 TeV | m(χ̃₁⁰)<200 GeV, m(χ̃±)=0.5(m(χ̃₁⁰)+m(g̃)) | ATLAS-CONF-2013-062
g̃g̃, g̃→qq(ℓℓ/ℓν/νν)χ̃₁⁰ | 2 e, μ | 0-3 jets | - | 20.3 | g̃ 1.12 TeV | m(χ̃₁⁰)=0 GeV | ATLAS-CONF-2013-089
GMSB (ℓ̃ NLSP) | 2 e, μ | 2-4 jets | Yes | 4.7 | g̃ 1.24 TeV | tanβ<15 | 1208.4688
GMSB (ℓ̃ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 20.3 | g̃ 1.6 TeV | tanβ >20 | 1407.0603
GGM (bino NLSP) | 2 γ | - | Yes | 20.3 | g̃ 1.28 TeV | m(χ̃₁⁰)>50 GeV | ATLAS-CONF-2014-001
GGM (wino NLSP) | 1 e, μ + γ | - | Yes | 4.8 | g̃ 619 GeV | m(χ̃₁⁰)>50 GeV | ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | g̃ 900 GeV | m(χ̃₁⁰)>220 GeV | 1211.1167
GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | g̃ 690 GeV | m(NLSP)>200 GeV | ATLAS-CONF-2012-152
Gravitino LSP | 0 | mono-jet | Yes | 10.5 | F^1/2 scale 645 GeV | m(G̃)>10⁻⁴ eV | ATLAS-CONF-2012-147
3rd gen. g̃ med.
g̃→bb̄χ̃₁⁰ | 0 | 3 b | Yes | 20.1 | g̃ 1.25 TeV | m(χ̃₁⁰)<400 GeV | 1407.0600
g̃→tt̄χ̃₁⁰ | 0 | 7-10 jets | Yes | 20.3 | g̃ 1.1 TeV | m(χ̃₁⁰) <350 GeV | 1308.1841
g̃→tt̄χ̃₁⁰ | 0-1 e, μ | 3 b | Yes | 20.1 | g̃ 1.34 TeV | m(χ̃₁⁰)<400 GeV | 1407.0600
g̃→bt̄χ̃₁⁺ | 0-1 e, μ | 3 b | Yes | 20.1 | g̃ 1.3 TeV | m(χ̃₁⁰)<300 GeV | 1407.0600
3rd gen. squarks direct production
b̃₁b̃₁, b̃₁→bχ̃₁⁰ | 0 | 2 b | Yes | 20.1 | b̃₁ 100-620 GeV | m(χ̃₁⁰)<90 GeV | 1308.2631
b̃₁b̃₁, b̃₁→tχ̃₁± | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | b̃₁ 275-440 GeV | m(χ̃₁±)=2 m(χ̃₁⁰) | 1404.2500
t̃₁t̃₁(light), t̃₁→bχ̃₁± | 1-2 e, μ | 1-2 b | Yes | 4.7 | t̃₁ 110-167 GeV | m(χ̃₁⁰)=55 GeV | 1208.4305, 1209.2102
t̃₁t̃₁(light), t̃₁→Wbχ̃₁⁰ | 2 e, μ | 0-2 jets | Yes | 20.3 | t̃₁ 130-210 GeV | m(χ̃₁⁰) =m(t̃₁)-m(W)-50 GeV, m(t̃₁)<<m(χ̃₁±) | 1403.4853
t̃₁t̃₁(medium), t̃₁→tχ̃₁⁰ | 2 e, μ | 2 jets | Yes | 20.3 | t̃₁ 215-530 GeV | m(χ̃₁⁰)=1 GeV | 1403.4853
t̃₁t̃₁(medium), t̃₁→bχ̃₁± | 0 | 2 b | Yes | 20.1 | t̃₁ 150-580 GeV | m(χ̃₁⁰)<200 GeV, m(χ̃₁±)-m(χ̃₁⁰)=5 GeV | 1308.2631
t̃₁t̃₁(heavy), t̃₁→tχ̃₁⁰ | 1 e, μ | 1 b | Yes | 20 | t̃₁ 210-640 GeV | m(χ̃₁⁰)=0 GeV | 1407.0583
t̃₁t̃₁(heavy), t̃₁→tχ̃₁⁰ | 0 | 2 b | Yes | 20.1 | t̃₁ 260-640 GeV | m(χ̃₁⁰)=0 GeV | 1406.1122
t̃₁t̃₁, t̃₁→cχ̃₁⁰ | 0 | mono-jet/c-tag | Yes | 20.3 | t̃₁ 90-240 GeV | m(t̃₁)-m(χ̃₁⁰)<85 GeV | 1407.0608
t̃₁t̃₁(natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.3 | t̃₁ 150-580 GeV | m(χ̃₁⁰)>150 GeV | 1403.5222
t̃₂t̃₂, t̃₂→t̃₁ + Z | 3 e, μ (Z) | 1 b | Yes | 20.3 | t̃₂ 290-600 GeV | m(χ̃₁⁰)<200 GeV | 1403.5222
EW direct
ℓ̃L,Rℓ̃L,R, ℓ̃→ℓχ̃₁⁰ | 2 e, μ | 0 | Yes | 20.3 | ℓ̃ 90-325 GeV | m(χ̃₁⁰)=0 GeV | 1403.5294
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→ℓ̃ν(ℓν̃) | 2 e, μ | 0 | Yes | 20.3 | χ̃₁± 140-465 GeV | m(χ̃₁⁰)=0 GeV, m(ℓ̃, ν̃)=0.5(m(χ̃₁±)+m(χ̃₁⁰)) | 1403.5294
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→τ̃ν(τν̃) | 2 τ | - | Yes | 20.3 | χ̃₁± 100-350 GeV | m(χ̃₁⁰)=0 GeV, m(τ̃, ν̃)=0.5(m(χ̃₁±)+m(χ̃₁⁰)) | 1407.0350
χ̃₁±χ̃₂⁰→ℓ̃Lνℓ̃Lℓ(ν̃ν), ℓν̃ℓ̃Lℓ(ν̃ν) | 3 e, μ | 0 | Yes | 20.3 | χ̃₁±, χ̃₂⁰ 700 GeV | m(χ̃₁±)=m(χ̃₂⁰), m(χ̃₁⁰)=0, m(ℓ̃, ν̃)=0.5(m(χ̃₁±)+m(χ̃₁⁰)) | 1402.7029
χ̃₁±χ̃₂⁰→Wχ̃₁⁰Zχ̃₁⁰ | 2-3 e, μ | 0 | Yes | 20.3 | χ̃₁±, χ̃₂⁰ 420 GeV | m(χ̃₁±)=m(χ̃₂⁰), m(χ̃₁⁰)=0, sleptons decoupled | 1403.5294, 1402.7029
χ̃₁±χ̃₂⁰→Wχ̃₁⁰hχ̃₁⁰ | 1 e, μ | 2 b | Yes | 20.3 | χ̃₁±, χ̃₂⁰ 285 GeV | m(χ̃₁±)=m(χ̃₂⁰), m(χ̃₁⁰)=0, sleptons decoupled | ATLAS-CONF-2013-093
χ̃₂⁰χ̃₃⁰, χ̃₂,₃⁰→ℓ̃Rℓ | 4 e, μ | 0 | Yes | 20.3 | χ̃₂,₃⁰ 620 GeV | m(χ̃₂⁰)=m(χ̃₃⁰), m(χ̃₁⁰)=0, m(ℓ̃, ν̃)=0.5(m(χ̃₂⁰)+m(χ̃₁⁰)) | 1405.5086
Long-lived particles
Direct χ̃₁⁺χ̃₁⁻ prod., long-lived χ̃₁± | Disapp. trk | 1 jet | Yes | 20.3 | χ̃₁± 270 GeV | m(χ̃₁±)-m(χ̃₁⁰)=160 MeV, τ(χ̃₁±)=0.2 ns | ATLAS-CONF-2013-069
Stable, stopped g̃ R-hadron | 0 | 1-5 jets | Yes | 27.9 | g̃ 832 GeV | m(χ̃₁⁰)=100 GeV, 10 μs<τ(g̃)<1000 s | 1310.6584
GMSB, stable τ̃, χ̃₁⁰→τ̃(ẽ, μ̃)+τ(e, μ) | 1-2 μ | - | - | 15.9 | χ̃₁⁰ 475 GeV | 10<tanβ<50 | ATLAS-CONF-2013-058
GMSB, χ̃₁⁰→γG̃, long-lived χ̃₁⁰ | 2 γ | - | Yes | 4.7 | χ̃₁⁰ 230 GeV | 0.4<τ(χ̃₁⁰)<2 ns | 1304.6310
q̃q̃, χ̃₁⁰→qqμ (RPV) | 1 μ, displ. vtx | - | - | 20.3 | q̃ 1.0 TeV | 1.5 <cτ<156 mm, BR(μ)=1, m(χ̃₁⁰)=108 GeV | ATLAS-CONF-2013-092
RPV
LFV pp→ν̃τ + X, ν̃τ→e + μ | 2 e, μ | - | - | 4.6 | ν̃τ 1.61 TeV | λ′311=0.10, λ132=0.05 | 1212.1272
LFV pp→ν̃τ + X, ν̃τ→e(μ) + τ | 1 e, μ + τ | - | - | 4.6 | ν̃τ 1.1 TeV | λ′311=0.10, λ1(2)33=0.05 | 1212.1272
Bilinear RPV CMSSM | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | q̃, g̃ 1.35 TeV | m(q̃)=m(g̃), cτLSP<1 mm | 1404.2500
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→Wχ̃₁⁰, χ̃₁⁰→eeν̃μ, eμν̃e | 4 e, μ | - | Yes | 20.3 | χ̃₁± 750 GeV | m(χ̃₁⁰)>0.2×m(χ̃₁±), λ121≠0 | 1405.5086
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→Wχ̃₁⁰, χ̃₁⁰→ττν̃e, eτν̃τ | 3 e, μ + τ | - | Yes | 20.3 | χ̃₁± 450 GeV | m(χ̃₁⁰)>0.2×m(χ̃₁±), λ133≠0 | 1405.5086
g̃→qqq | 0 | 6-7 jets | - | 20.3 | g̃ 916 GeV | BR(t)=BR(b)=BR(c)=0% | ATLAS-CONF-2013-091
g̃→t̃₁t, t̃₁→bs | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | g̃ 850 GeV | | 1404.250
Other
Scalar gluon pair, sgluon→qq̄ | 0 | 4 jets | - | 4.6 | sgluon 100-287 GeV | incl. limit from 1110.2693 | 1210.4826
Scalar gluon pair, sgluon→tt̄ | 2 e, μ (SS) | 2 b | Yes | 14.3 | sgluon 350-800 GeV | | ATLAS-CONF-2013-051
WIMP interaction (D5, Dirac χ) | 0 | mono-jet | Yes | 10.5 | M* scale 704 GeV | m(χ)<80 GeV, limit of<687 GeV for D8 | ATLAS-CONF-2012-147
√s = 7 TeV full data
√s = 8 TeV partial data
√s = 8 TeV full data
10⁻¹
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Interpretation of these exclusions needs a model framework.

A model is essentially decided by the SUSY breaking mechanism!

CMSSM, PMSSM, NMSSM, GMSB,AMSB.....


MSUGRA/CMSSM: tan(β) = 30, A0 = -2m0, μ > 0
Status: ICHEP 2014
ATLAS Preliminary
∫L dt = 20.1 - 20.7 fb-1, √s = 8 TeV
τ̃ LSP
95% CL limits. σ SUSY theory not included.
Expected
Observed
0-lepton, 2-6 jets
arXiv: 1405.7875
0-lepton, 7-10 jets
arXiv: 1308.1841
0-1 lepton, 3 b-jets
arXiv: 1407.0600
1-lepton + jets + MET
ATLAS-CONF-2013-062
1-2 taus + 0-1 lept. + jets + MET
arXiv: 1407.0603
2SS/3 leptons, 0 - ≥ 3 b-jets
arXiv: 1404.2500
g̃ (1400 GeV)
g̃ (1000 GeV)
q̃ (1600 GeV)
q̃ (2400 GeV)
h (124 GeV)
h (122 GeV)
m1/2 [GeV]
m0 [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000

A few remarks:

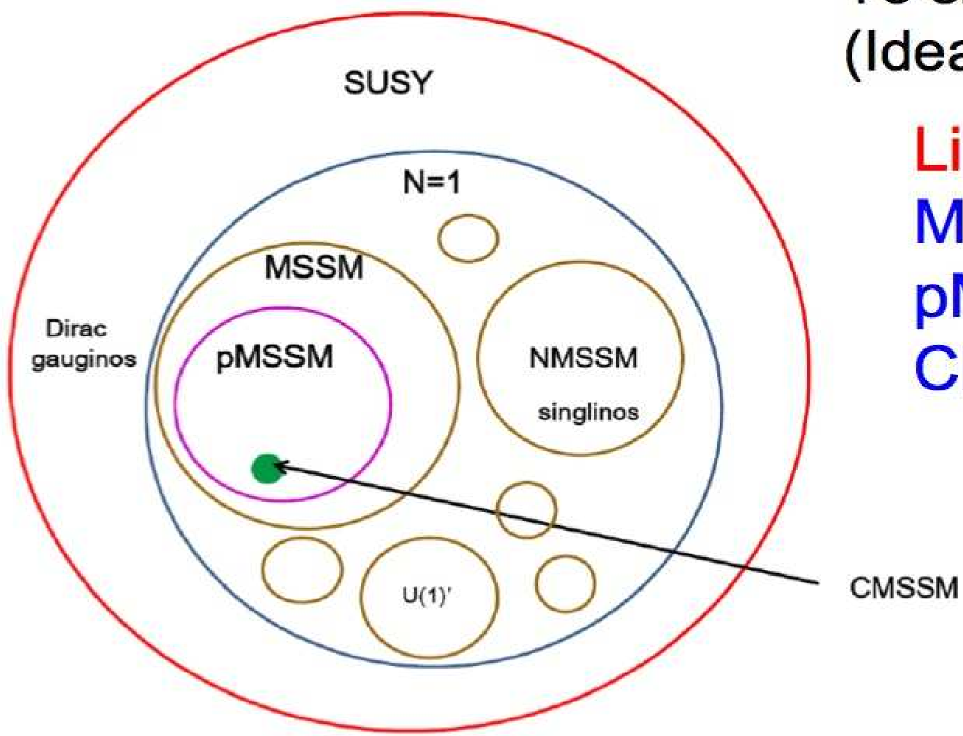
In the framework of the model, a given value of $m_0, m_{1/2}$ and $\tan\beta, \mu, A$ the particle spectra and branching ratios are completely determined. As we will see later the missing E_T searches are reasonably insensitive by the last three parameters.

For a given final state various processes contribute.

The reach in large $m_{1/2}$ at large m_0 comes from the final states containing leptons as shown by the cyan line.

So in this framework one can identify which subprocesses give the best reach in a particular search!

SUSY theory space



For interpretations need to reduce
To small parameter dimensionality
(Ideally 2)

Limiting to MSSM:
MSSM: ~109 parameters
pMSSM: 19 parameters
CMSSM: 4 parameters

The smaller the number
Of parameters, the smaller
The fraction of SUSY space
explored

(G. Polesello)

$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{SOFT}}$

The particle spectra controlled by $\mathcal{L}_{\text{SOFT}}$.

Ignorance of SUSY breaking is encoded in these!

$$\begin{aligned}
-\mathcal{L}_{\text{SOFT}} &= \tilde{q}^{\star}_{iL}(\mathcal{M}^2_{\tilde{q}})_{ij}\tilde{q}_{jL} + \tilde{u}^{\star}_{iR}(\mathcal{M}^2_{\tilde{u}})_{ij}\tilde{u}_{jR} + \tilde{d}^{\star}_{iR}(\mathcal{M}^2_{\tilde{d}})_{ij}\tilde{d}_{jR} + \tilde{\ell}^{\star}_{iL}(\mathcal{M}^2_{\tilde{\ell}})_{ij}\tilde{\ell}_{jL} \\
&+ \tilde{e}^{\star}_{iR}(\mathcal{M}^2_{\tilde{e}})_{ij}\tilde{e}_{jR} + [h_1\cdot\tilde{\ell}_{iL}(f^e A^e)_{ij}\tilde{e}^{\star}_{jR} + h_1\cdot\tilde{q}_{iL}(f^d A^d)_{ij}\tilde{d}^{\star}_{jR} \\
&+ \tilde{q}_{iL}\cdot h_2(f^u A^u)_{ij}\tilde{u}^{\star}_{jR} + \text{h.c.}] + m_1^2|h_1|^2 + m_2^2|h_2|^2 + (B\mu h_1\cdot h_2 + \text{h.c.}) \\
&+ \frac{1}{2}(M_1\bar{\tilde{\lambda}}_0 P_L\tilde{\lambda}_0 + M_1^{\star}\bar{\tilde{\lambda}}_0 P_R\tilde{\lambda}_0) + \frac{1}{2}(M_2\bar{\tilde{\vec{\lambda}}} P_L\tilde{\vec{\lambda}} + M_2^{\star}\bar{\tilde{\vec{\lambda}}} P_R\tilde{\vec{\lambda}}) \\
&+ \frac{1}{2}(M_3\bar{\tilde{g}}^a P_L\tilde{g}^a + M_3^{\star}\bar{\tilde{g}}^a P_R\tilde{g}^a) \\
&\equiv V_{\text{SOFT}} + \text{gaugino mass terms.}
\end{aligned}$$

$\overline{\tilde{e}_L}$ for the right spositron. The antisfermionic fields denoted by conjugation of the sfermionic fields.

Assumes $R_p = (-1)^{(3(B-L)+2S)} = (-1)^{(3B-L+2S)}$ is conserved.

The μ term from the $\mathcal{L}_{SUSY}$ plays an important role as well.

Mass eigenstates are not interaction eigenstates.

Just EW breaking, **even without SUSY breaking**, will cause mixing between the charged EW gauginos $(\tilde{\lambda}_1, \tilde{\lambda}_2)$ and the charged higgsinos $(\tilde{h}_1^-, \tilde{h}_2^+)$, to produce the mass eigenstates $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$.

EW and SUSY breaking $\Rightarrow \tilde{\lambda}_0, \tilde{\lambda}_3, \tilde{h}_1^0, \tilde{h}_2^0$ mix $\Rightarrow \tilde{\chi}_i^0, i = 1, 4$.

The mixing in this sector depends on $\mu, M_i, i = 1, 2, \tan\beta$**.**

The SUSY breaking terms induce mixing in the sfermion sector too!

$\tilde{f}_R - \tilde{f}_L$ mixing decided by $A, \mu, \tan\beta$ **and** m_f.

Sfermion generation mixing: mainly controlled by soft parameters.

These mixings decide the interactions of the mass eigenstates and hence their decay patterns.

They also affect the indirect effects caused in the loops.

The parameters $\mu, \tan\beta, M_1, M_2$ and A for the third generations affect the search strategies and determination of the mixing can be used to get information on the Lagrangian parameters as well.

• 124 total parameters and 105 are new :-)! Complex Gaugino masses: 6, sfermion mass matrices: 45, trilinear couplings : 54, bilinears: 4, Higgs sector: 2

111 - 6 (constraints from Higgs sector) = 105!

• Luckily most processes, at tree level, depend only on a few of these 105 parameters.

• But severe phenomenological problems for 'generic' values of these parameters! FCNC, unacceptable CP violation (large electric dipole moments for neutron (for example)). In radiatively driven EW symmetry breaking one gets colour/charge breaking vacua! Impossible to get right values of M_Z..!

- Discussions of the SUSY phenomenology tractable only in **Constrained** MSSM (CMSSM) where assumptions are made to reduce the parameters drastically!

- The assumptions guided by SUSY breaking scenarios.

- 44 of these are phases and they can NOT be rotated away by field redefinition. In most discussions these are put to zero by hand, as the constraints from low energy phenomenology are quite severe. $\not{C}\not{P}$ MSSM discussions USED to be interesting.

Phenomenologically motivated choices which have been used in the analyses by default:

- All new $\not{C}\not{P}$ phases to be zero. **With the newer data on EDM's scope for non zero CP violation is reduced drastically**.
- Masses and trilinear coupling diagonal in flavour basis. **NO FCNC. Flavour models and correlations between SUSY searches with mainly leptonic flavor violation is quite an active area of investigations now!**
- Universal first and second generation squarks. I.e no problems with K_0–$\bar{K}_0$ mixing!

Now number of parameters: Three gaugino masses: M_1, M_2 and M_3 : 3, Higgs mass parameters: m_1^2, m_2^2 : 2, First two generation sfermion masses: $m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R} m_{\tilde{e}_R}, m_{\tilde{l}}$,: 5 parameters; three trilinear couplings A_u, A_d, A_e: 3, Third generation masses and Trilinear parameters: 8

Usually collider phenomenology insensitive to A_u, A_d, A_e (which play an important role in neutron edm, $(g-2)_\mu$ etc.)

Main ideas discussed here: Gravity meditation (mSUGRA), modulii mediation, GMSB and AMSB. 10 TeV $< \Lambda_s \leq M_M \leq M_{Pl}$ and $M_M \simeq \Lambda_s^2/M_s$

Mediation mechanism	Model	Gravitino mass $m_{3/2}$	Gaugino mass M_α	Sfermion mass squared m_i^2
Gravity mediated	mSUGRA	$\leq \mathcal{O}$ (TeV)	$(g_\alpha/g_2)^2 M_2$	$m_0^2 + G_i M_{1/2}^2 +$ D-terms
	$\tilde{\text{C}}$MSSM	$\leq \mathcal{O}$ (TeV)	$(g_\alpha/g_2)^2 M_2$	$\tilde{q}_\ell$: $m_{\tilde{q}_L}^2 + G_{\tilde{q}_L} M_{1/2}^2 +$ D-terms $\tilde{l}_L$: $m_{\tilde{\ell}}^2 + G_{\tilde{\ell}} M_{1/2}^2 +$ D-terms $\tilde{e}_R$: $m_{\tilde{e}_R}^2 + G_{\tilde{e}_R} M_{1/2}^2 +$ D-term $\tilde{u}_R$: $m_{\tilde{u}_R}^2 + G_{\tilde{u}_R} M_{1/2}^2 +$ D-term $\tilde{d}_R$: $m_{\tilde{d}_R}^2 + G_{\tilde{d}_R} M_{1/2}^2 +$ D-term
	AMSB	20–100 TeV	$(g_\alpha b_\alpha/g_2 b_2)^2 M_2$	$m_0^2 + C_i (16\pi^2)^{-2} m_{3/2}^2$
Gauge mediated	mGMSB	10^{-5} eV – 1 keV	$(g_\alpha/g_2)^2 M_2$	$\tilde{q}_L$: $M_3^2\ G'_{\tilde{q}_L} +$ D-terms $\tilde{l}_L$: $M_2^2\ G'^2_{\tilde{\ell}_L} +$ D-terms $\tilde{e}_R$: $M_2^2\ G'_{\tilde{e}_R} +$ D-terms $\tilde{u}_R$: $M_3^2\ G'_{\tilde{u}_R} +$ D-terms $\tilde{d}_R$: $M_3^2\ \tilde{G}'_{\tilde{d}_R} +$ D-terms

mSUGRA $M_1 : M_2 : M_3 \simeq 1 : 2.8 : 7$, $m_0, M_{1/2}, A, \tan\beta, sgn(\mu)$

mGMSB : similar, subject to some corrections depending on couplings of the messenger fields. $M_M, \Lambda_s, sgn(\mu), \tan\beta, n_q, n_l$ and $m_{3/2}$.

AMSB: $M_1 : M_2 : M_3 \simeq 2.8 : 1 : 8.3$, $m_0, M_{3/2}, \tan\beta, sgn(\mu)$.

mSUGRA: LSP is $\tilde{\chi}_1^0$.

mGMSB Gravitino is LSP, NLSP: $\tilde{\chi}_1^0, \tau_1, \tilde{e}_R$. NLSP can be long lived and quasi stable! Cosmological constraints on $m_{3/2}$ and hence on scale of SUSY breaking.

NUGMSSM,.... Non universal Gaugino masses, with extended Higgs sector. $\tilde{\chi}_1^0$ LSP, Singlino LSP, Small mass differences $\Delta m\ldots$

Dirac Gaugino: recently persued by a few groups.

mSUGRA,mGMSB: Once LEP constraints are imposed, $\tilde{\chi}_1^0$ is an almost pure $U(1)$ gaugino and $\tilde{\chi}_2^0 \sim$ pure $SU(2)$ gaugino. $(|M_1| < |\mu|)$.

Note : These things have important implications for viability of the LSP as the DM. Higgsinos annihilate too efficiently and can be a good DM candidate only if heavier than $\sim$ TeV.

AMSB: Both $\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0$ are pure $SU(2)$ gauginos and degenerate. Loop effects need to be included to lift the degeneracy.

Some of these special features of the spectra in GMSB and AMSB pushed developments of strategies which involve detection of long lived charged particle (e.g. $\tilde{\tau}_R$ in GMSB) OR compressed spectra and hence NO missing energy , which are today assuming special significance!

Most of the constraints come in the form of inequalities.

The first two generation squarks can not be much lighter than the gluinos.

$\left(m_{\tilde{q}}/m_{\tilde{l}}\right)|_{GMSB} > \left(m_{\tilde{q}}/m_{\tilde{l}}\right)|_{mSUGRA}$;

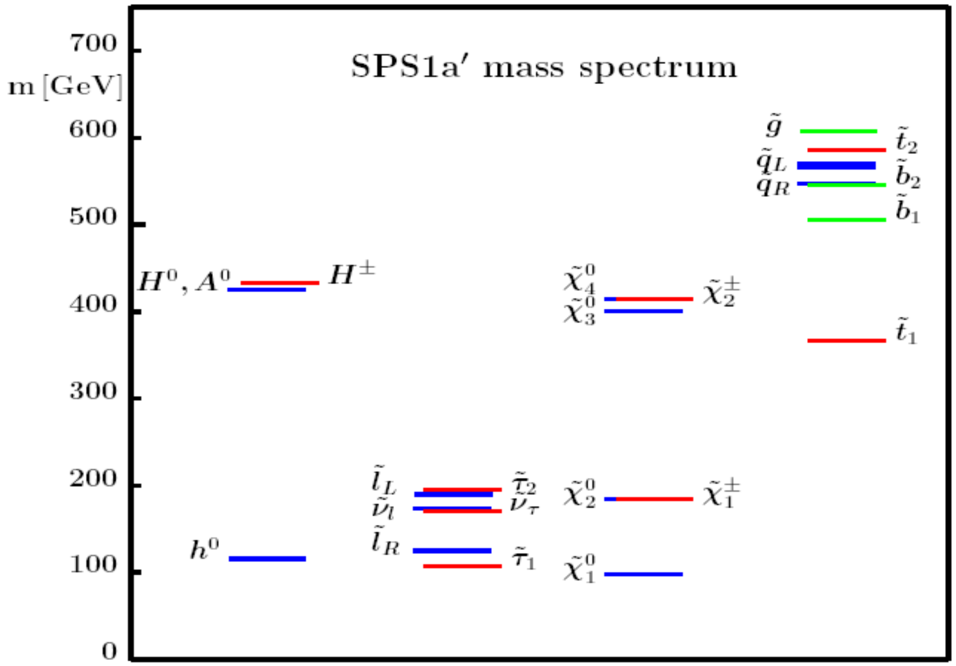
$m_{\tilde{e}} < m_{\tilde{q}}$ for mSUGRA;

$m_{\tilde{e}_L} \simeq m_{\tilde{e}_R}$ for GMSB;

$m_{\tilde{e}_R} < m_{\tilde{e}_L}$ for mSUGRA.

Third generation sfermions are lighter than the other two due to the larger Yukawa coupling contribution to the running. In that the $\tilde{f}_R$ will be lightest.! Due to larger hyper charge!

A representative spectrum. One of the benchmark points for LHC analyses. Used in early SUSY searches!



What did we expect colliders to do for SUSY?

• **Discovery of sparticles** and determination of their quantum numbers.

• Quantitative verification of coupling equalities implied by supersymmetry.

• **Measurement of the masses of scalars (including Higgs) as well as gauginos.**

• Determination of the gaugino-higgsino mixing parameters.

• Study of the properties of third generation sfermions including L-R mixing.

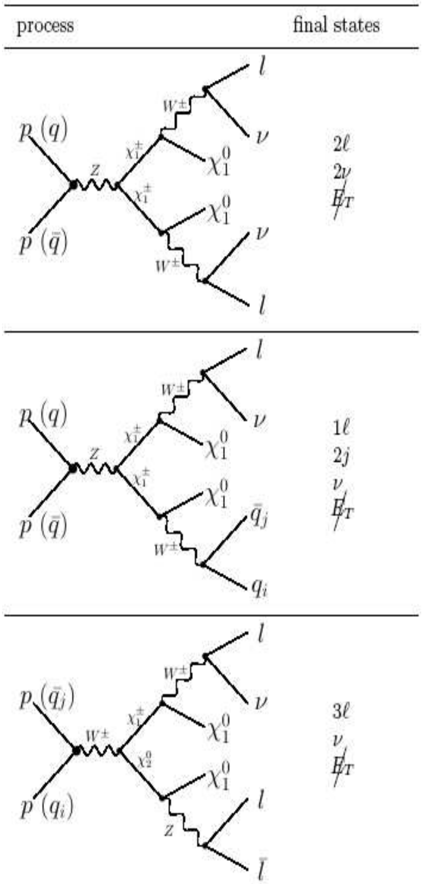
Over the years many variables, methods developed for measurements!

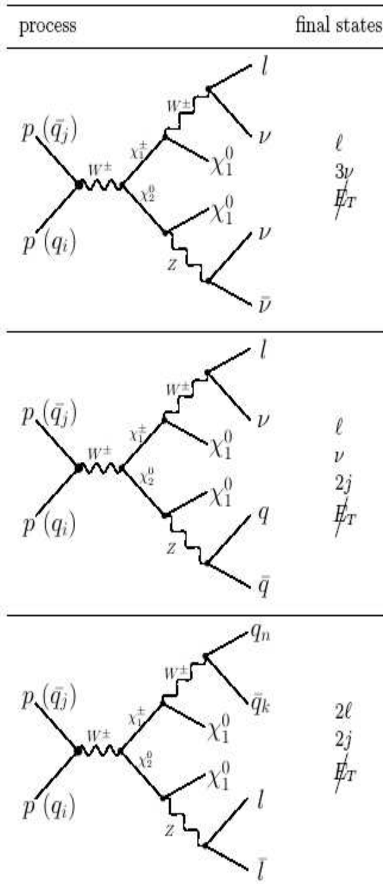
Right now they are playing a very important role in looking into specific regions of parameter space!

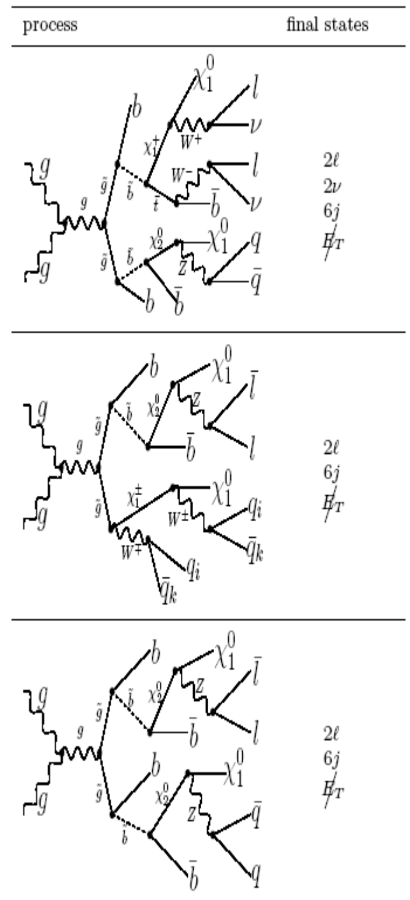
General lesssons:

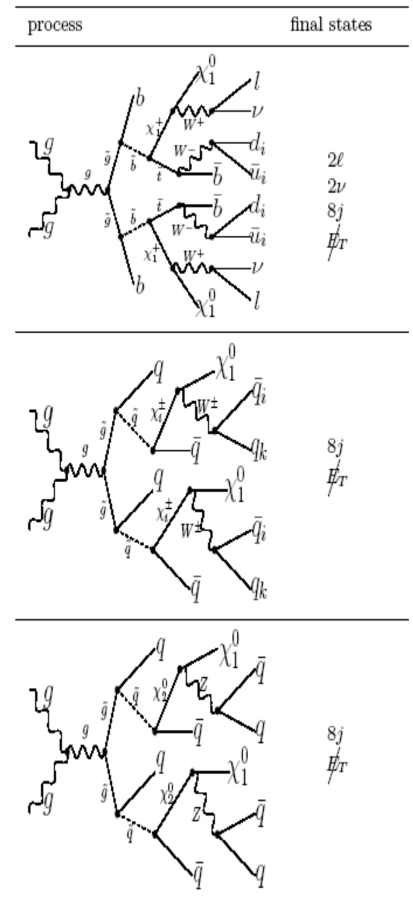
Limits depend on Δm: mass difference between the particle and the LSP.

I will come back in the end to the theory ideas which lower the current limits and how to explore those windows!


process
final states
2ℓ 2ν E̸T
1ℓ 2j ν E̸T
3ℓ ν E̸T


process
final states
ℓ 3ν E̸T
ℓ ν 2j E̸T
2ℓ 2j E̸T


process
final states
2ℓ 2ν 6j E̸T
2ℓ 6j E̸T
2ℓ 6j E̸T


process
final states
2ℓ 2ν 8j E̸T
8j E̸T
8j E̸T

- Missing transverse energy signature: $\not{E}_T$ Because of R_p conservation sparticles are produced in pairs and will contain LSP which is **neutral and stable**.

- Decay patterns of $\tilde{\chi}_i^0/\tilde{\chi}_j^{\pm}$ very important.

- Generically m jets, n leptons and $\not{E}_T$.

- In case of GMSB: hard photons which come from decays of the NLSP $\tilde{\chi}_1^0 \to \gamma\tilde{G}$. Large life times of the NLSP can give rise to pointing photons. So all the above + photons! If $\tilde{\tau}_1$ is the NLSP, heavy long lived charged particle tracks is the signature.

- AMSB : difficult. $165 MeV < \Delta M(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}) < 1$ GeV and $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \pi$. Stopping track in the vertex detector or the soft pion is to be detected. **Associated production techniques with ISR/FSR: now the flavor of the day!**

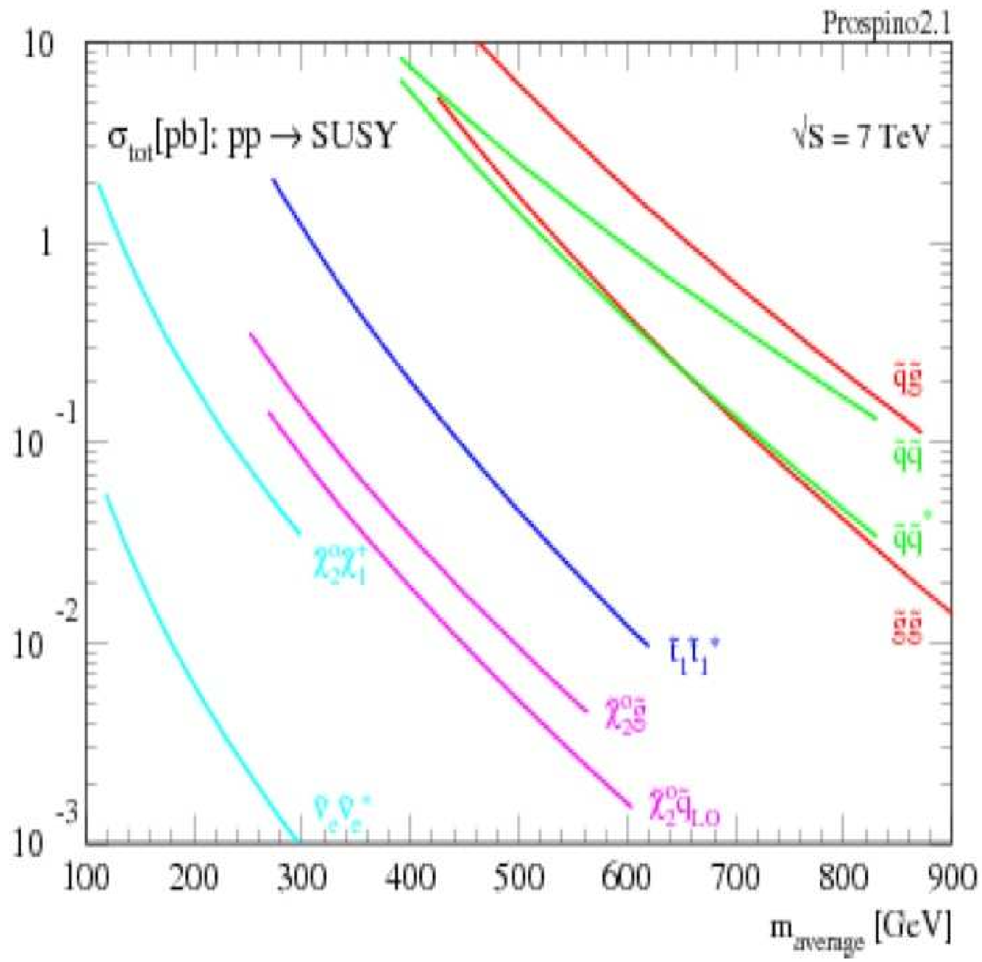
- $R\!\!\!/_p$: Even then due to very energetic neutrinos missing ET signal is not gone + large number of jets and leptons. Of course specific signals containing **jets** using Boosted jet substructure techniques now are the new tools for exploring these.

Squarks and gluinos highest cross-section

Cross section only depends on squark-gluino masses ? highly model-independent

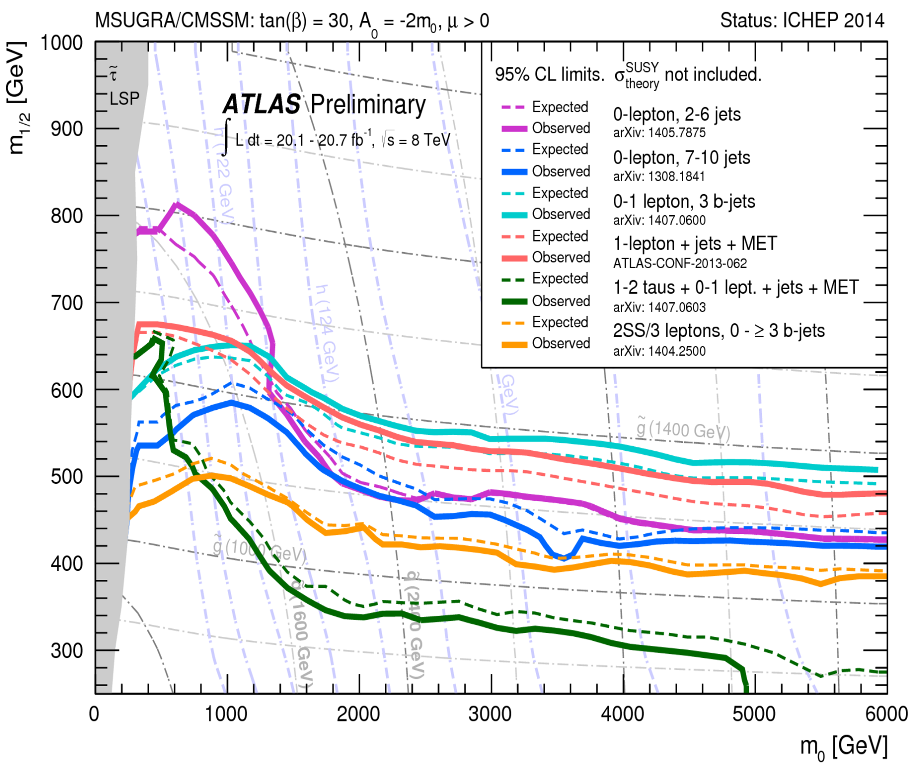
Highest priority in early searches for the production of gluinos and squarks of the first two generations

Looking under the lamppost

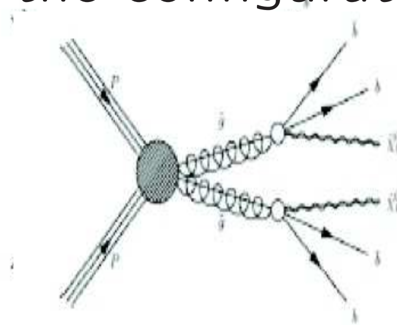


1) Strong limits. How to interpret in your favorite model? One road towards this is the 'Simplified Model Spectra: SMS'.

Fine print in ATLAS plots are the assumptions about the spectra!



One can identify the final state that gives the best reach in a particular region of choices of parameters. Dominant reach in high mass regain for gluino comes from the configuration:



Which searches best?

Higgs mass + exclusions implies different things for different people

Naturalness a'la L. Hall: 'light' third generation sparticles...

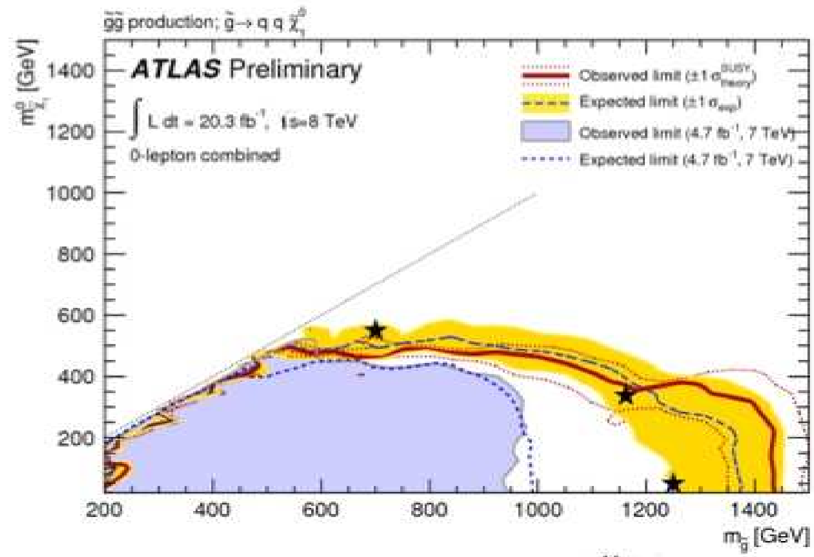
Naturalness $\Rightarrow$: Non universal gaugino masses, Additional Higgs singlets... (Lectures G. Ross)

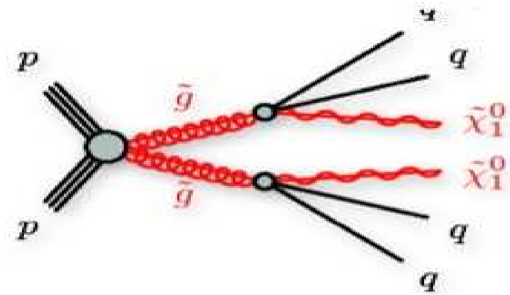
Naturalness a'la Baer, Tata: Small μ, Higgsino LSP and heavier squarks, including stops!

Squarks heavy, stops and bottoms light, gluino light.

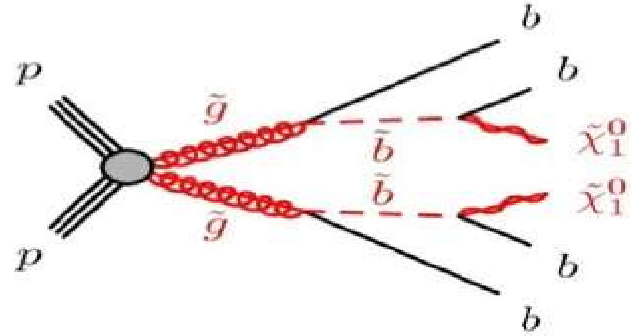
Look for $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

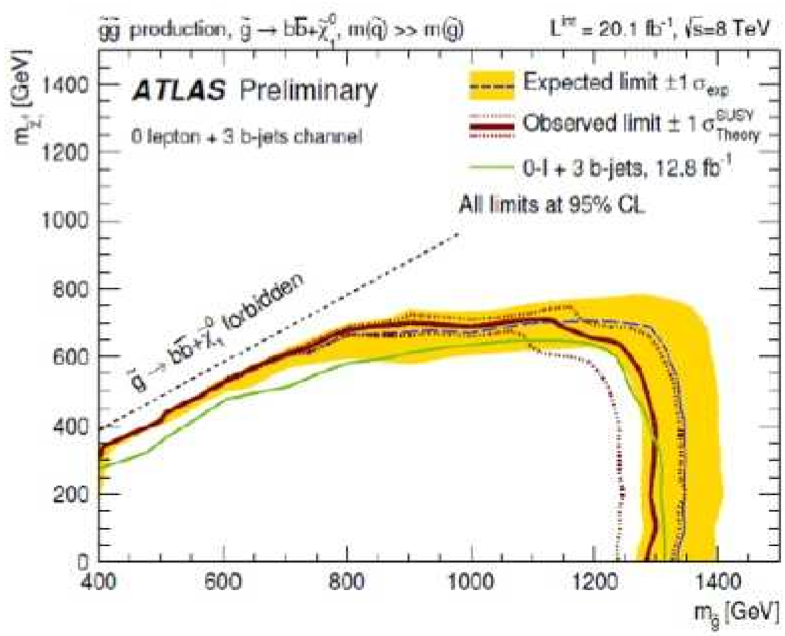
Simplified models as a tool for analysis optimisation and display:
Generate events with given decay chain on both legs
Assume 100% BR in both legs and the SUSY production cross-section
Express reach in the plane determined by the involved masses
No statement on theory but very clear Representation of the potential of experiments for a specific kinematics. Also one uses the observables most efficient for that particular kinematics!

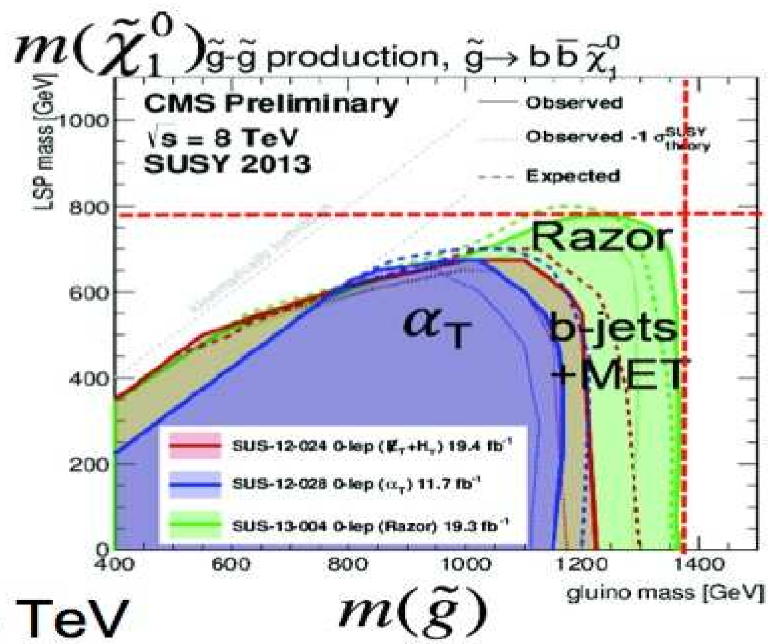




Results







Exclude gluinos up to 1.3-1.4 TeV

❑ Exclusion limits : a new standard ATLAS/CMS procedure (>June 2012)

- Ease the life of theorist by separating the signal theoritical and experimental systematics

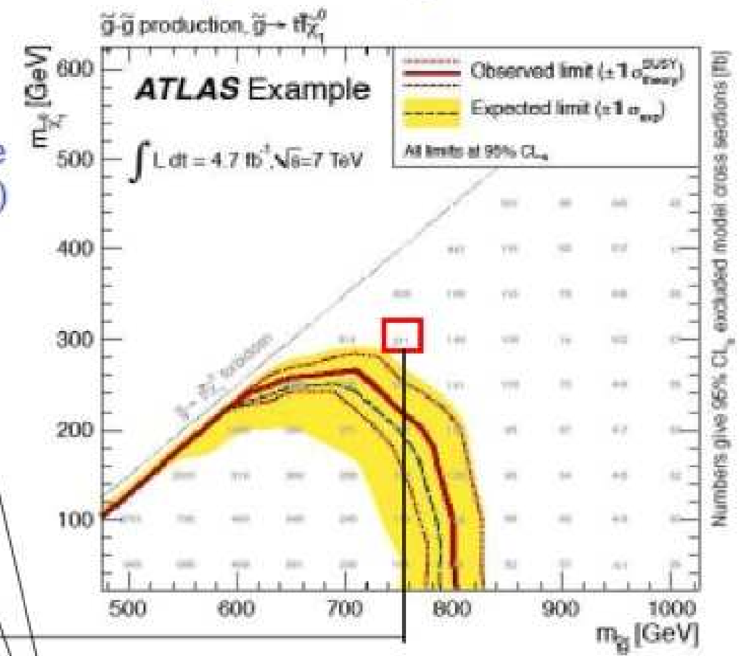
Expected limit:

- **Central value:** all uncertainties included in the fit as nuisance parameters, except theoretical signal uncertainties (PDF, scales)
- **±1σ band** : ±1σ results of the fit

Observed limit:

- **Central value**: Idem as for expected limit
- **±1σ band** : re-run and increase/decrease the signal cross section by the theoretical signal uncertainties (PDF, scales)

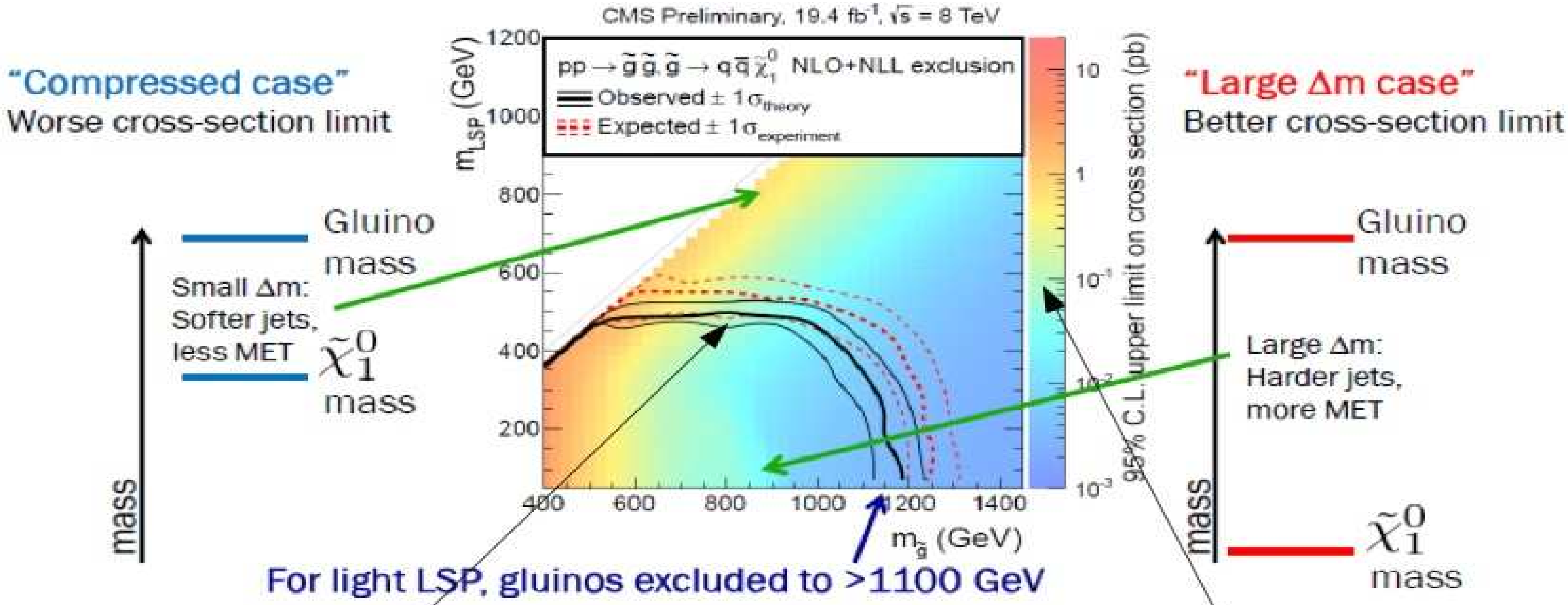
Excluded Model Cross section (SMS)



→ Number quoted in paper correspond to observed -1 σ observed (conservative)

ATLAS CMS

How to read a simplified model plot



Lines are model dependent, assume
•Production cross-section for initial state
•Branching fraction for decay

Color of plot is important:
It gives excluded cross section
In model-indipendent way,
Can be used to exclude different
Model with same topology

25

2)Tools to interpret in your favorite model now available.

a)SModelS: takes the spectrum of your model, decomposes the signal into the SMS topologies, simulates the signal and compares with the upper limits provided by both ATLAS and CMS for 50 analyses.

b)FASTLIM: Reconstructs the visible cross-section using precalculated efficiencies for simplified event topologies, for 11 ATLAS analyses, mainly involving stop and sbottom.

c)CheckMate: Uses results from few ATLAS and CMS analyses and confronts any BSM with these using a fast simulation. In particular also SUSY

d)ATOM: Automated Testing of Models.

These different tools are all in different stages of development! Follow it on their web pages.

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e)MadAnaylsis 5: Public Data Base for LHC searches (1407.3278)

Which searches best?

Higgs mass + exclusions implies different things for different people

Naturalness a'la L. Hall: 'light' third generation sparticles...

Naturalness ⇒ : Non universal gaugino masses, Additional Higgs singlets... (Lectures G. Ross)

Naturalness a'la Baer, Tata: Small μ, Higgsino LSP and heavier squarks, including stops!

1) Third generations squarks and stau: stop:

a)Regions where $m_{\tilde{t}} \simeq m_t + m_{\tilde{\chi}_1^0}$.

b)$m_{\tilde{t}} \simeq m_{\tilde{\chi}_1^0} + m_c$

a,b : cases of small δm

c) $m_t \simeq m_{\tilde{t}}$:

The $t\bar{t}$ background can not be discriminated against. Cross-section for scalars of the same mass smaller than the fermions.

2)Compressed spectra in general due to non universal gaugino masses (nice paper : Martin + Compte)

• Strong constraints on the masses of the first two generation of squarks.

• Those do not apply directly to the third generation squarks due to differences in processes contributing to the production and different final states..

• For stops the final states containing top quarks accessible only for heavy stops and *further* need not always have the largest branching ratio.

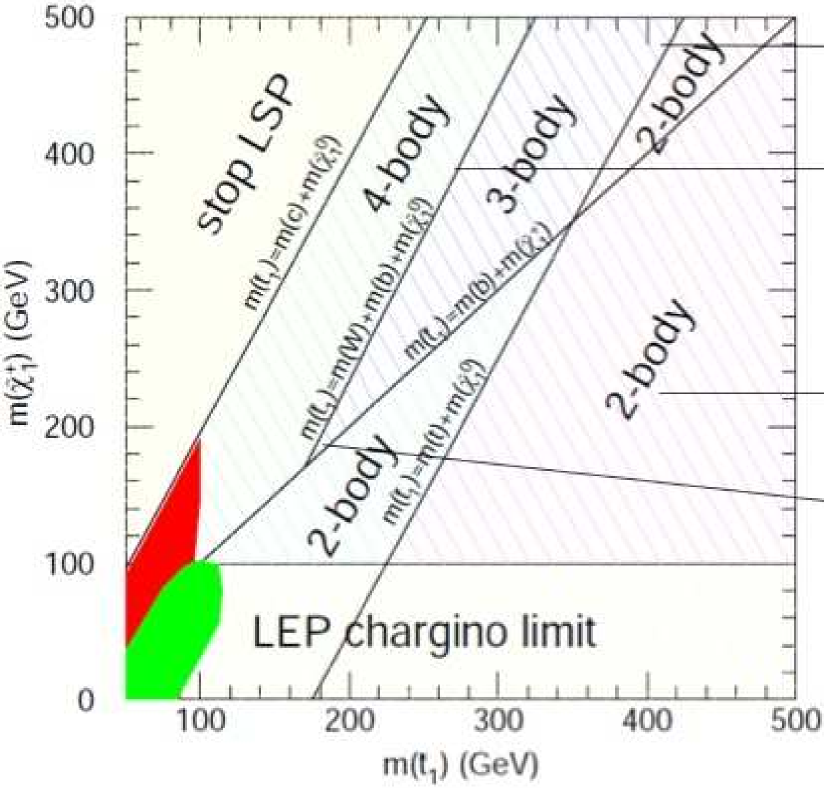
- Separate, dedicated search strategies for third generation squarks needed.

- Both $\tilde{t}/\tilde{b}$ CAN have a top quark in the final state.

- The final states $\tilde{b}, \tilde{t}$ decays are b–quark rich, lepton rich!

- Both the features used to look effectively for these.

Depends on three parameters: m(stop), m(chargino), m(neutralino1)
Show 2d-plane assuming m(chargino)=2m(neutralino1)



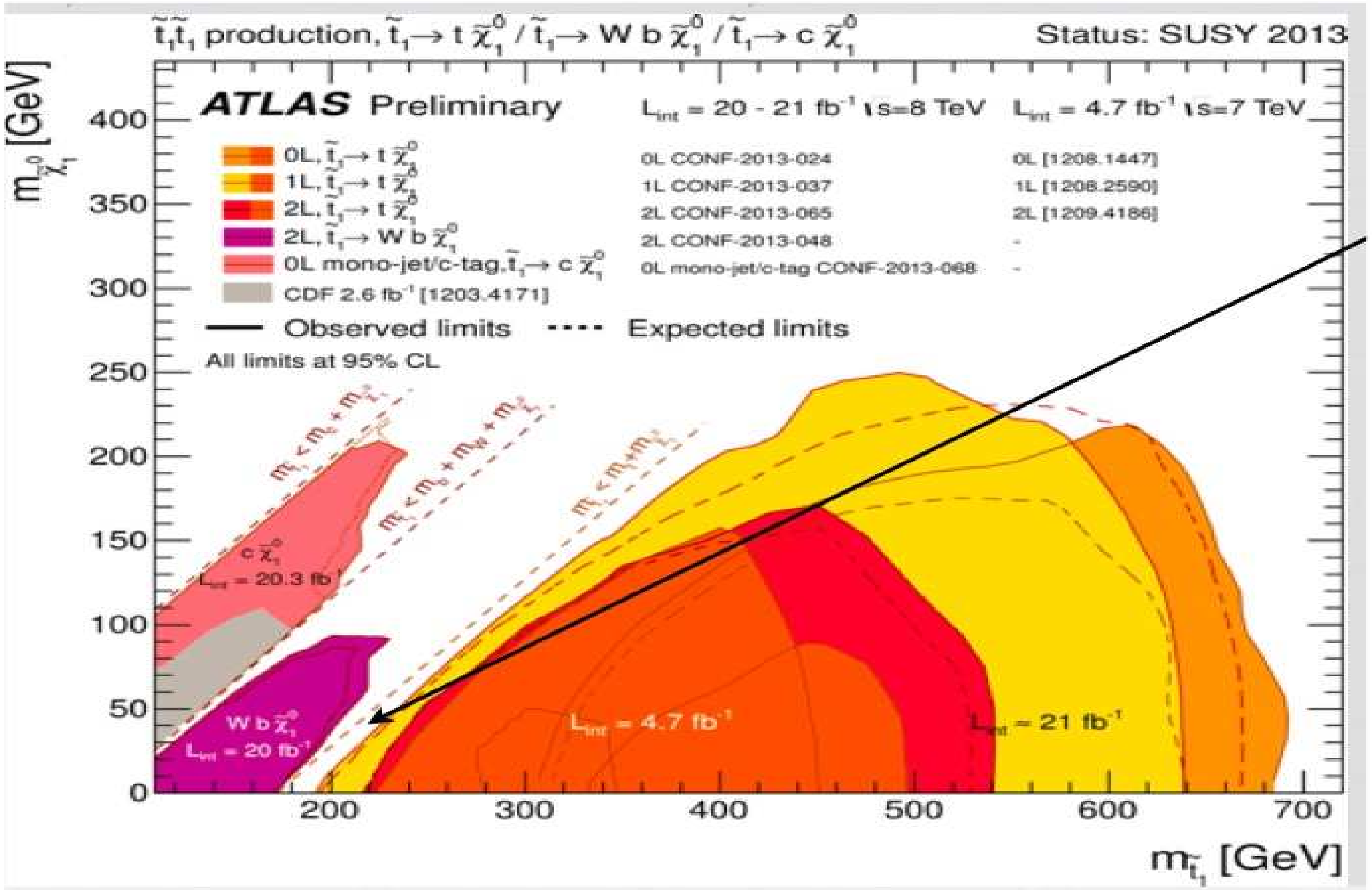
Only $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

$\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$
Or multibody

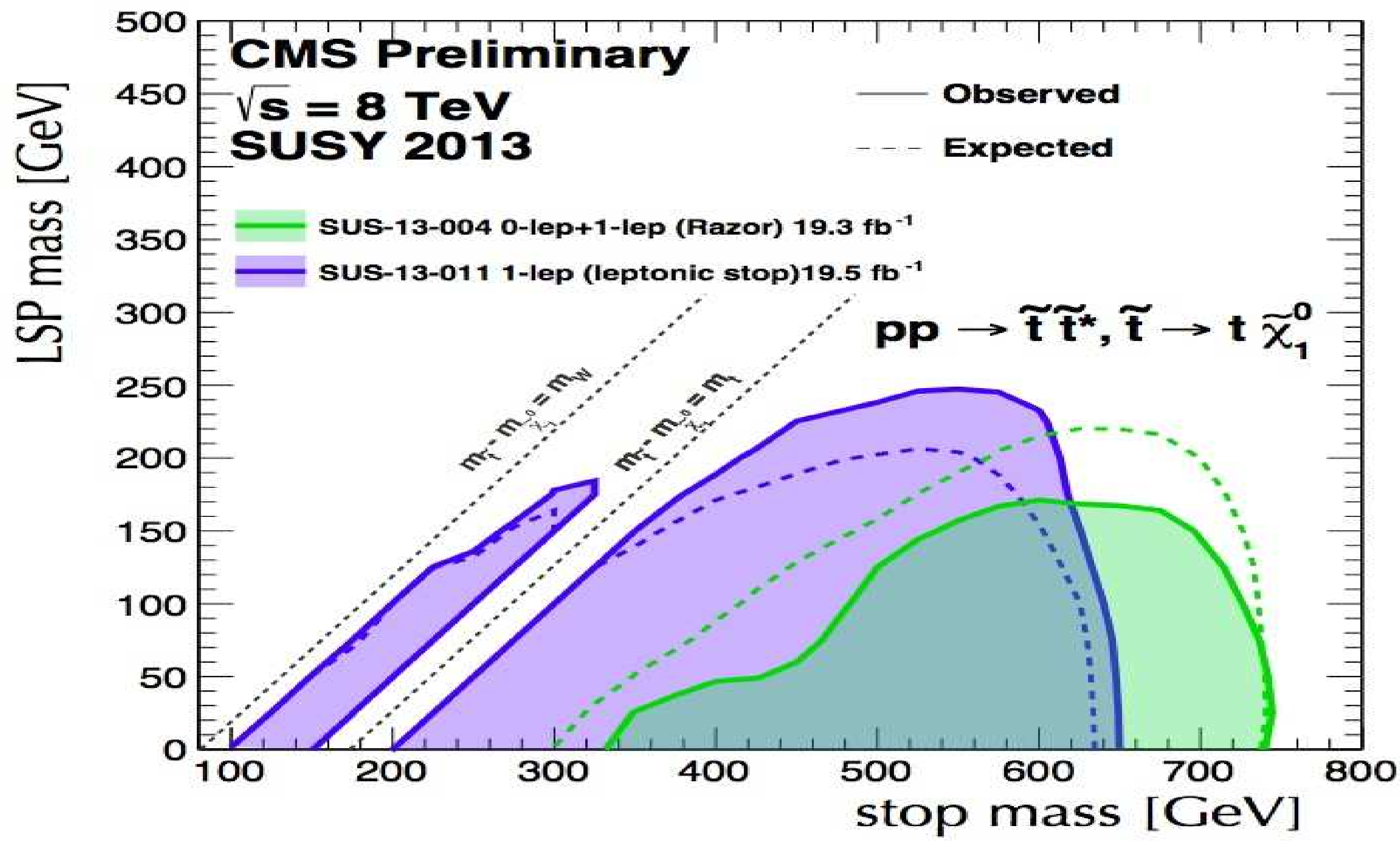
$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$ and $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

Only $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$

Both two and three body decays studied


t̃₁t̃₁ production, t̃₁→ t χ̃₁⁰ / t̃₁→ W b χ̃₁⁰ / t̃₁→ c χ̃₁⁰
Status: SUSY 2013
ATLAS Preliminary
L_int = 20 - 21 fb⁻¹ √s=8 TeV
L_int = 4.7 fb⁻¹ √s=7 TeV
0L, t̃₁→ t χ̃₁⁰
1L, t̃₁→ t χ̃₁⁰
2L, t̃₁→ t χ̃₁⁰
2L, t̃₁→ W b χ̃₁⁰
0L mono-jet/c-tag, t̃₁→ c χ̃₁⁰
CDF 2.6 fb⁻¹ [1203.4171]
0L CONF-2013-024
1L CONF-2013-037
2L CONF-2013-065
2L CONF-2013-048
0L mono-jet/c-tag CONF-2013-068
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
Observed limits
Expected limits
All limits at 95% CL
c χ̃₁⁰
L_int = 20.3 fb⁻¹
W b χ̃₁⁰
L_int = 20 fb⁻¹
L_int = 4.7 fb⁻¹
L_int = 21 fb⁻¹
m_χ̃₁⁰ [GeV]
m_t̃₁ [GeV]

EPS-result.



Talk by J. Boyd at SUSY 2013.

Region where: $\tilde{t} \to c\tilde{\chi}_1^0$

can be probed with $pp \to Jet + MET$: **MONOJET**

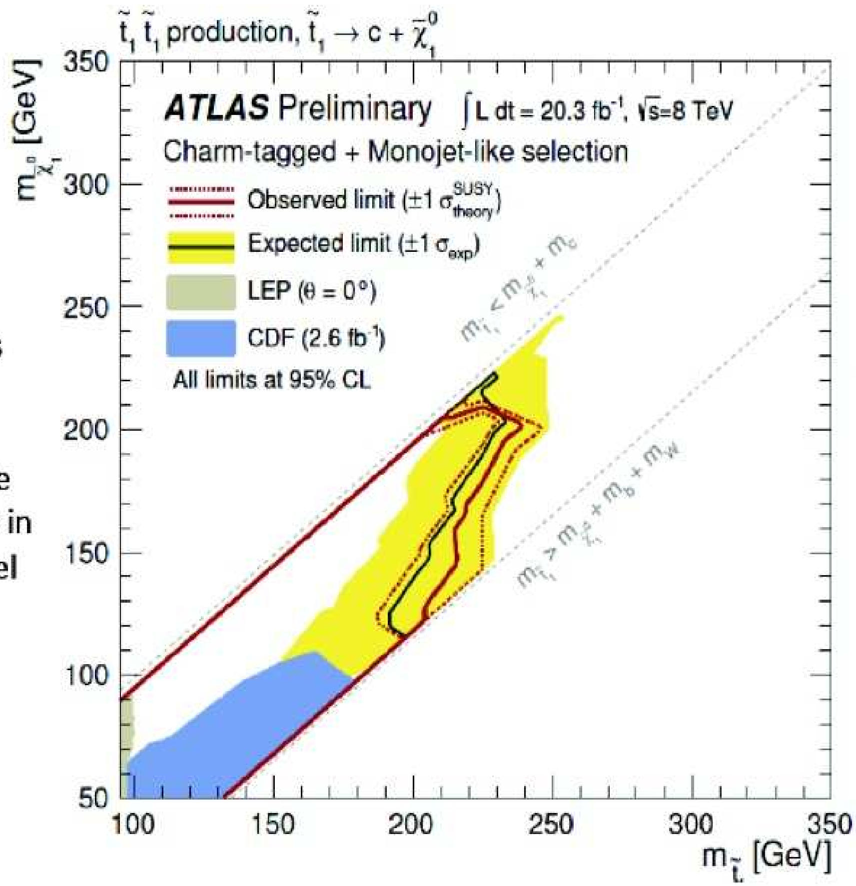
The jet is due an ISR radiation. This way of probing very important for compressed spectra

Mono-jet, mono-Z, mono-photon.

Dependency of the limits on Monte Carlo parameters: M. Kraemer, H. Dreiner (will show a plot if time remains)

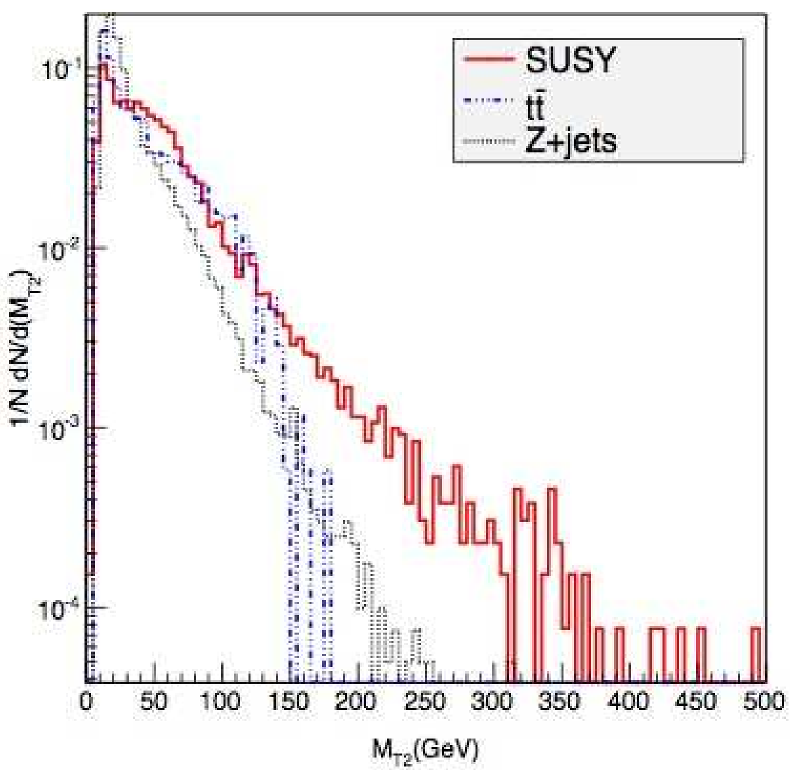
$\tilde{t}_1$ -> c $\tilde{\chi}^0_1$: exclusions

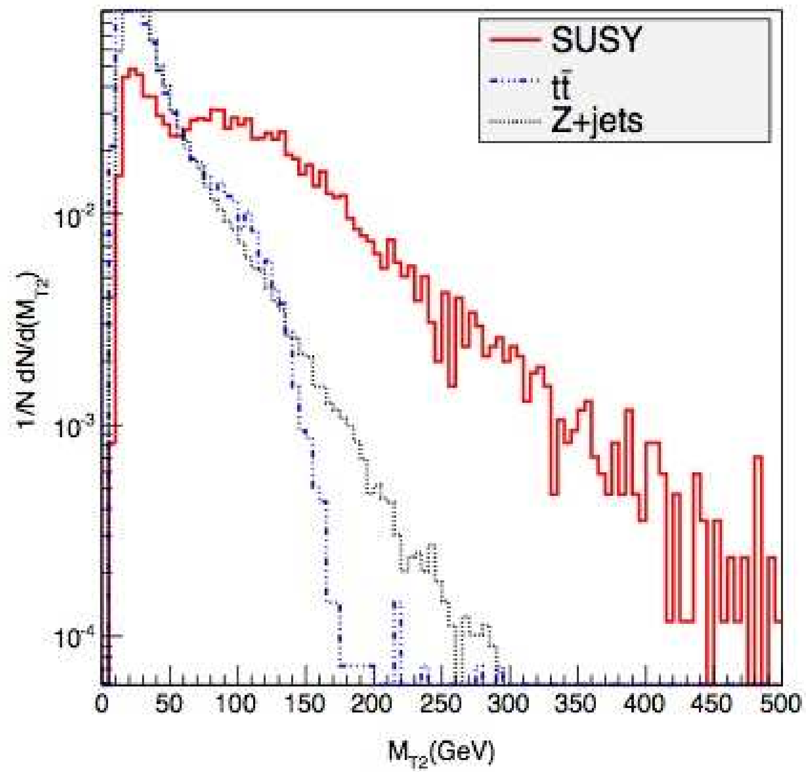
monojet-like selection helps extend reach along the diagonal where the charm-jets in the $c\chi^0_1$ channel are too soft



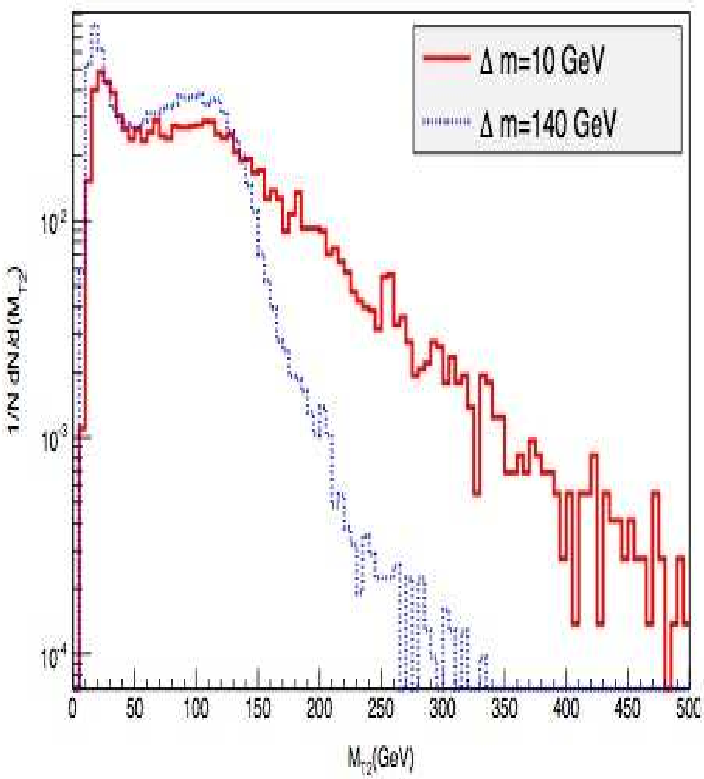
Charm-tagged search extends reach where other decay modes are excluded

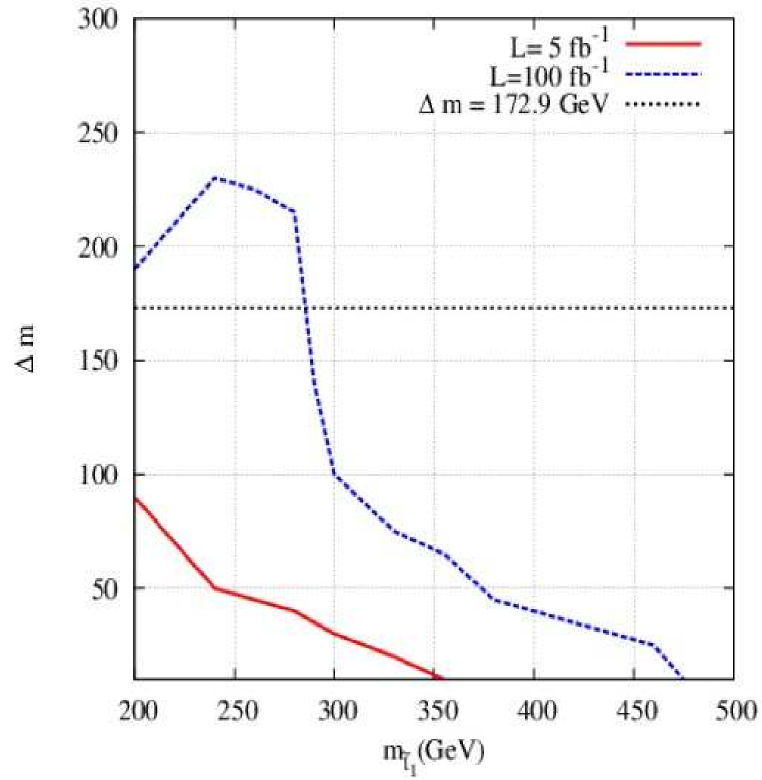
Use now m_{T2} variable as discriminator (from 1306.6484) G. Belanger, RG, Guchait, Sengupta,Ghosh





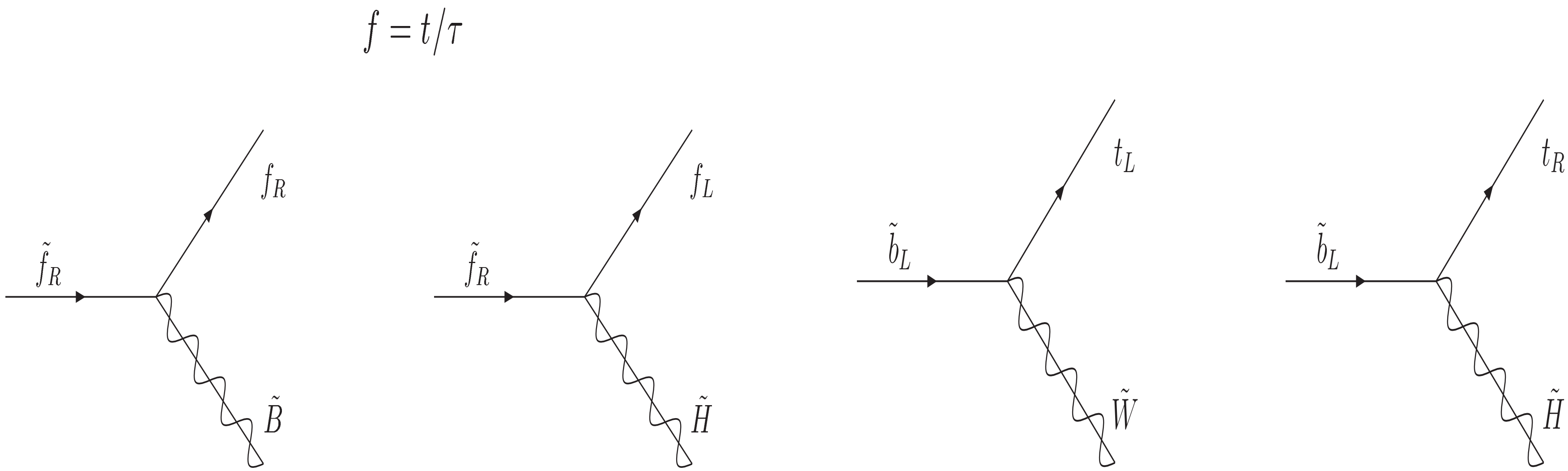
Even better: it becomes better for smaller Δm





Works well over a wide values of $\tilde{\chi}_1^0$ mass.

$\tau(t)$ produced in stau/stop decay. M. Nojiri, PRD **51** (1995) 6281 [hep-ph/9412374]



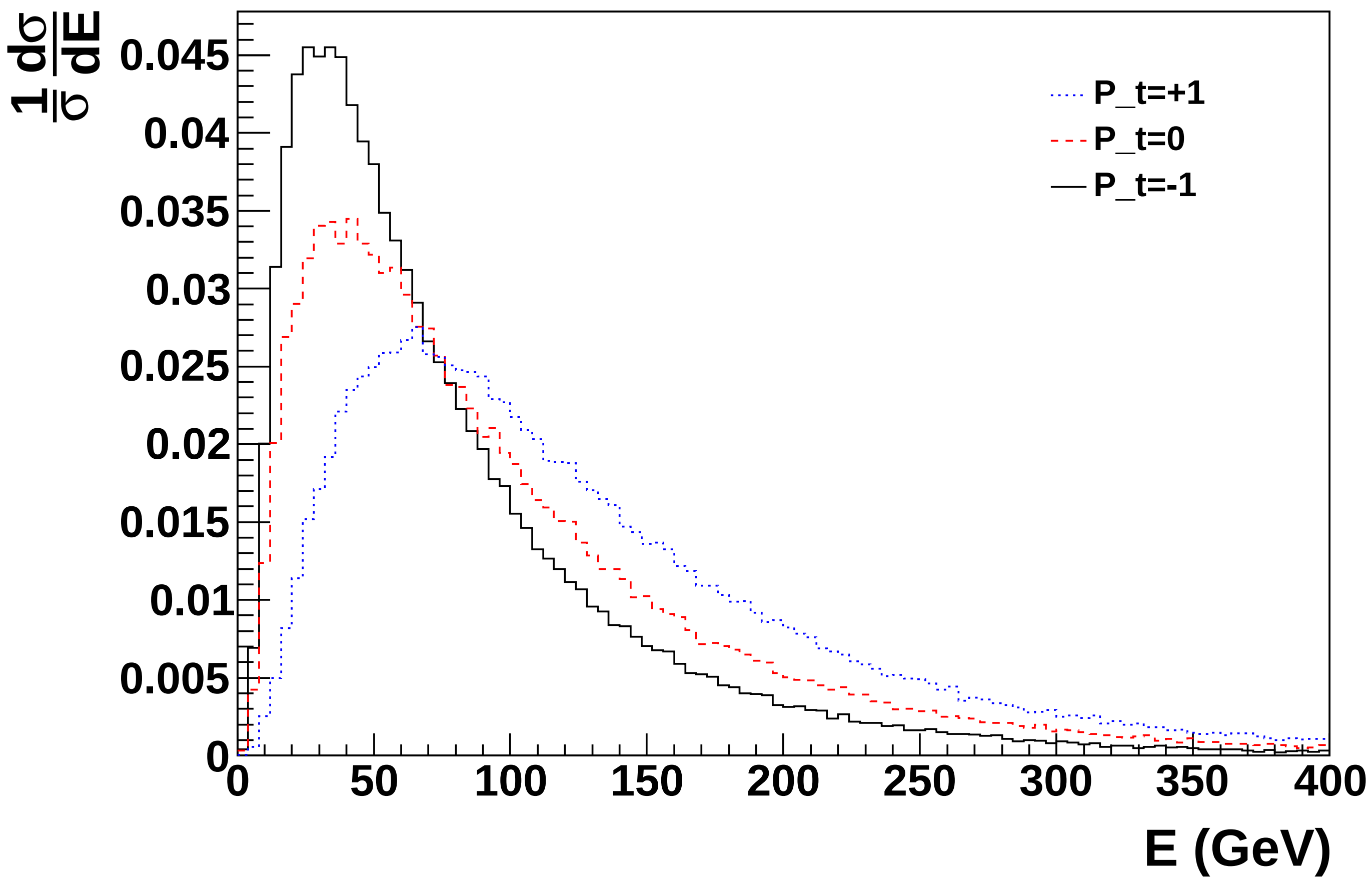
□ In MSSM mass eigenstates of $\tilde{f}$ (sleptons/squarks) $\tilde{f}_1, \tilde{f}_2$, are mixtures of $\tilde{f}_L$ and $\tilde{f}_R$, $f = t, \tau$.

□ The $\tilde{\chi}_j^{\pm}, j = 1, 2$, $\tilde{\chi}_j^0, j = 1, 4$ are mixtures of higgsinos and gauginos.

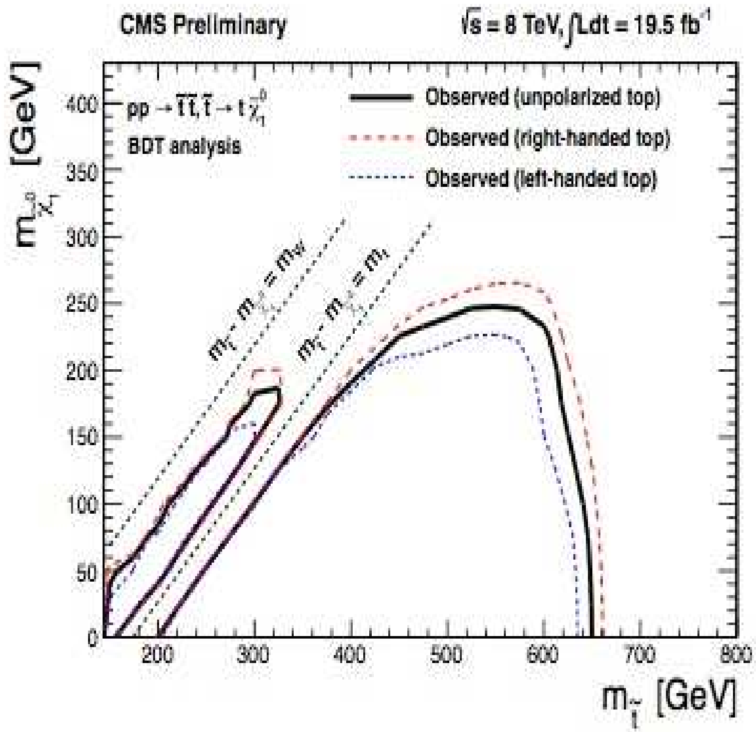
□ Couplings of sfermions with higgsinos flip chirality whereas those with gauginos do not.

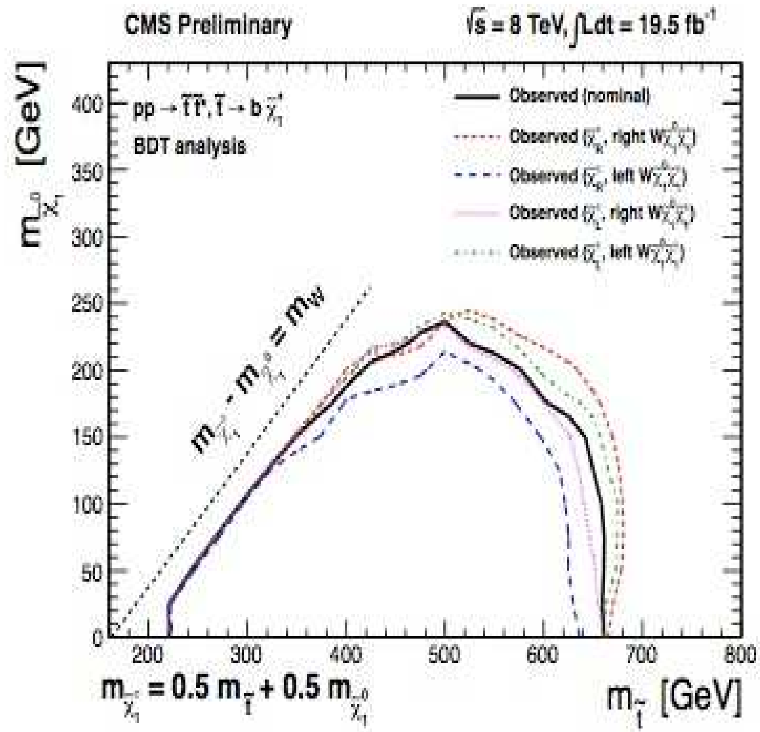
• **The helicity of the fermion produced in the decay of the sfermion decided by the character of the sfermions as well as the neutralino/chargino**.

□ Net helicity of produced f in the decay $\tilde{f}_i \to \tilde{\chi}_j^0 f$ AND $\tilde{f}_i \to \tilde{\chi}_j^{\pm} f'$ depends on the L–R mixing in the sfermion sector and on the gaugino-higgsino mixing.



For the negatively polarised top distributions peak at lower values of energy 1212.3526, G. Belanger et al





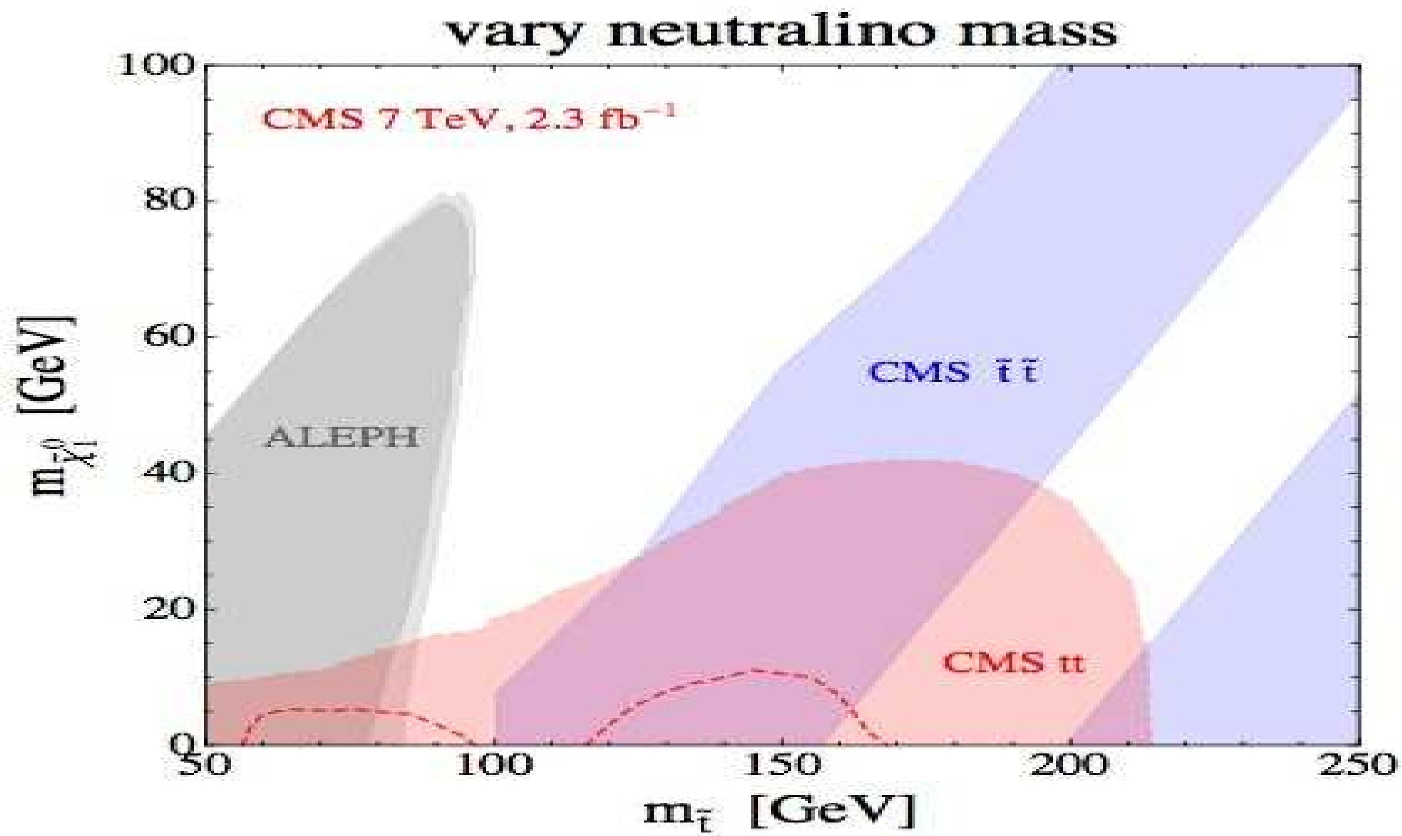
In the leptonic channel the limits could depend on the assumed polarisation of top quark produced in the stop decay. (CMS PAS note: SUSY-13-011-PAS)

One of the possible direction for exploration :

Can one use the fact that top from stop is polarised in handling the background from the top?

Either the top polarization or spin-spin correlations?

I have taken a plot from Weiler, Papucci et al: 1407.1043



Use the topology of two forward backward jet in gauge boson fusion digram:

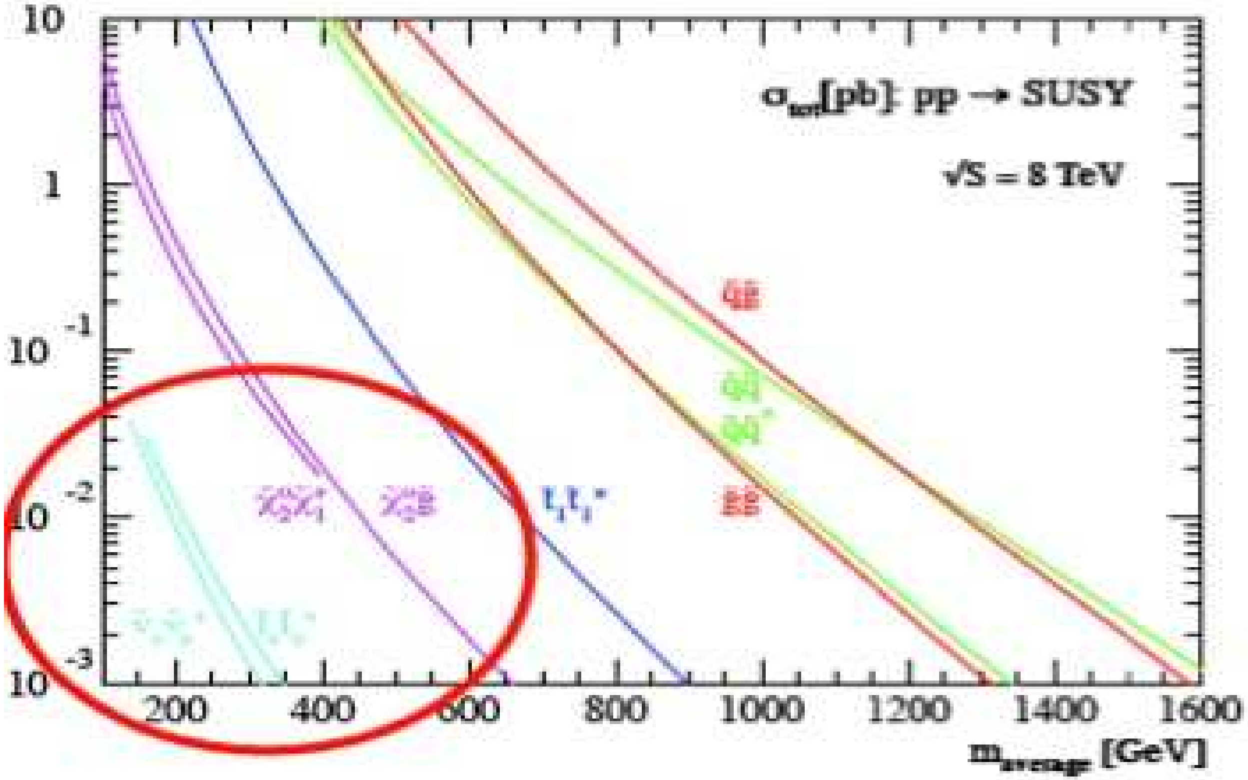
1)$pp \to \tilde{t}\tilde{\bar{t}} + 2$jets

(Plehn et al):

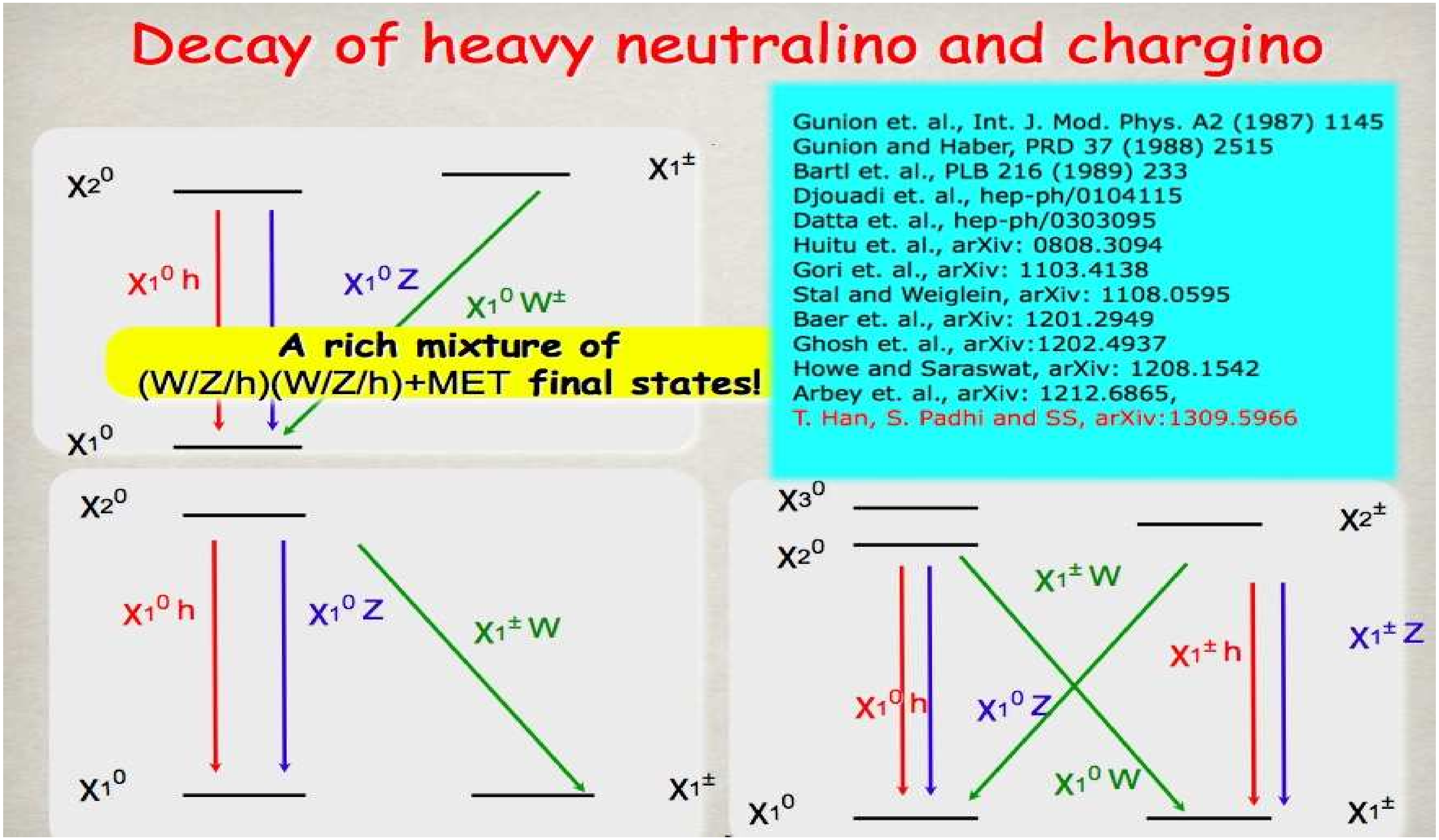
Difference between the top and the stop case

2) Use WW fusion production of $\tilde{\chi}_1^0 \chi_2^0$ etc. Use the kinematics (rapidity gaps) to increase S/B.

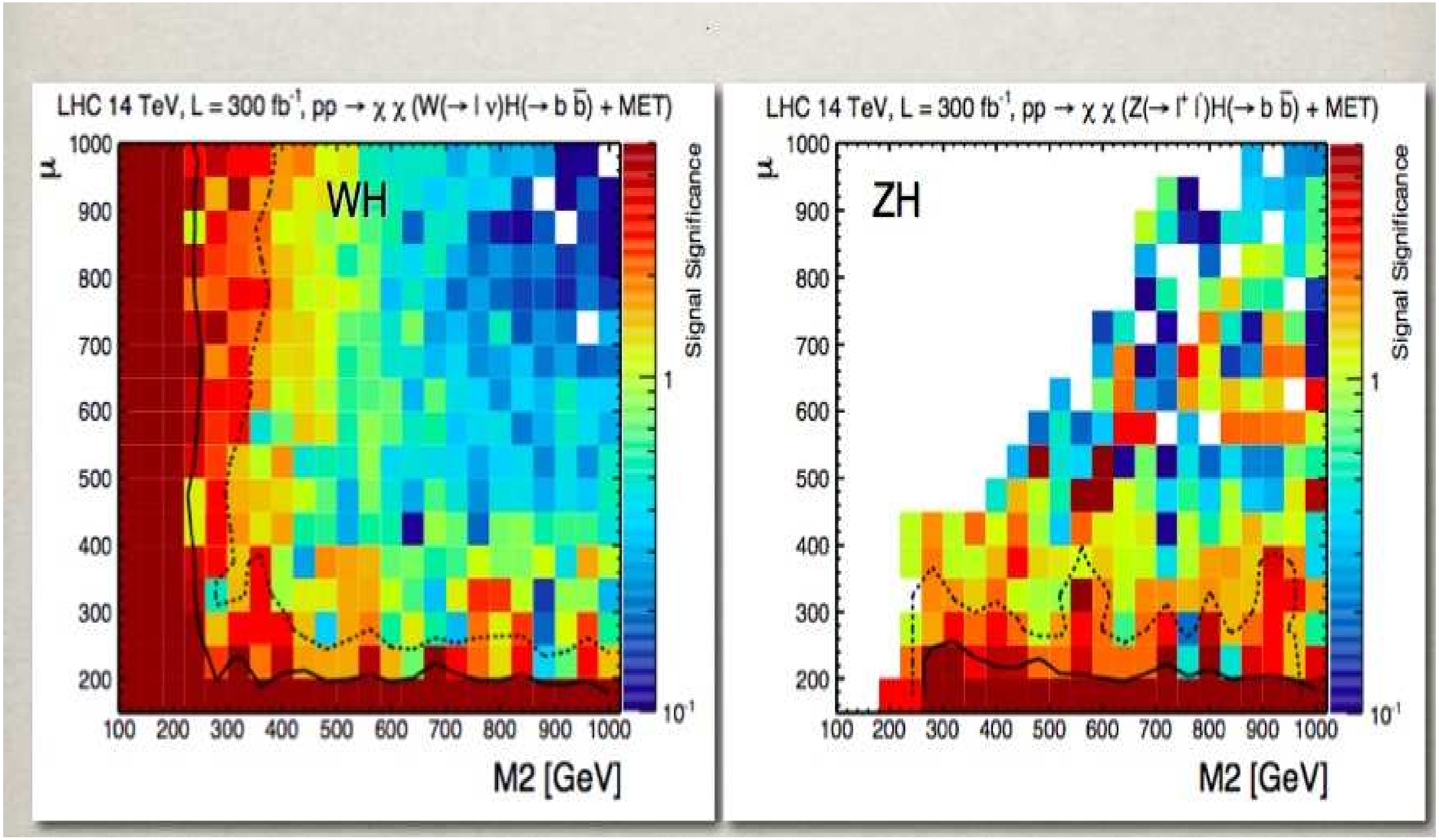
(Bhaskar Dutta et al)



σtot[pb]: pp → SUSY
√S = 8 TeV
m_average [GeV]
10
1
10^-1
10^-2
10^-3
200
400
600
800
1000
1200
1400
1600



From a talk by Tao Han at Fermilab meeting in November 2013.



From a talk by Tao Han at Fermilab meeting in November 2013.

1)Use tags: ISR/FSR (Mono)photon, jet, Z (compressed spectra)

2)use h as a tag (to paint the needle bright and blue)

In both 1,2 use jet substructure techniques

3)Vector boson fusion kinematics

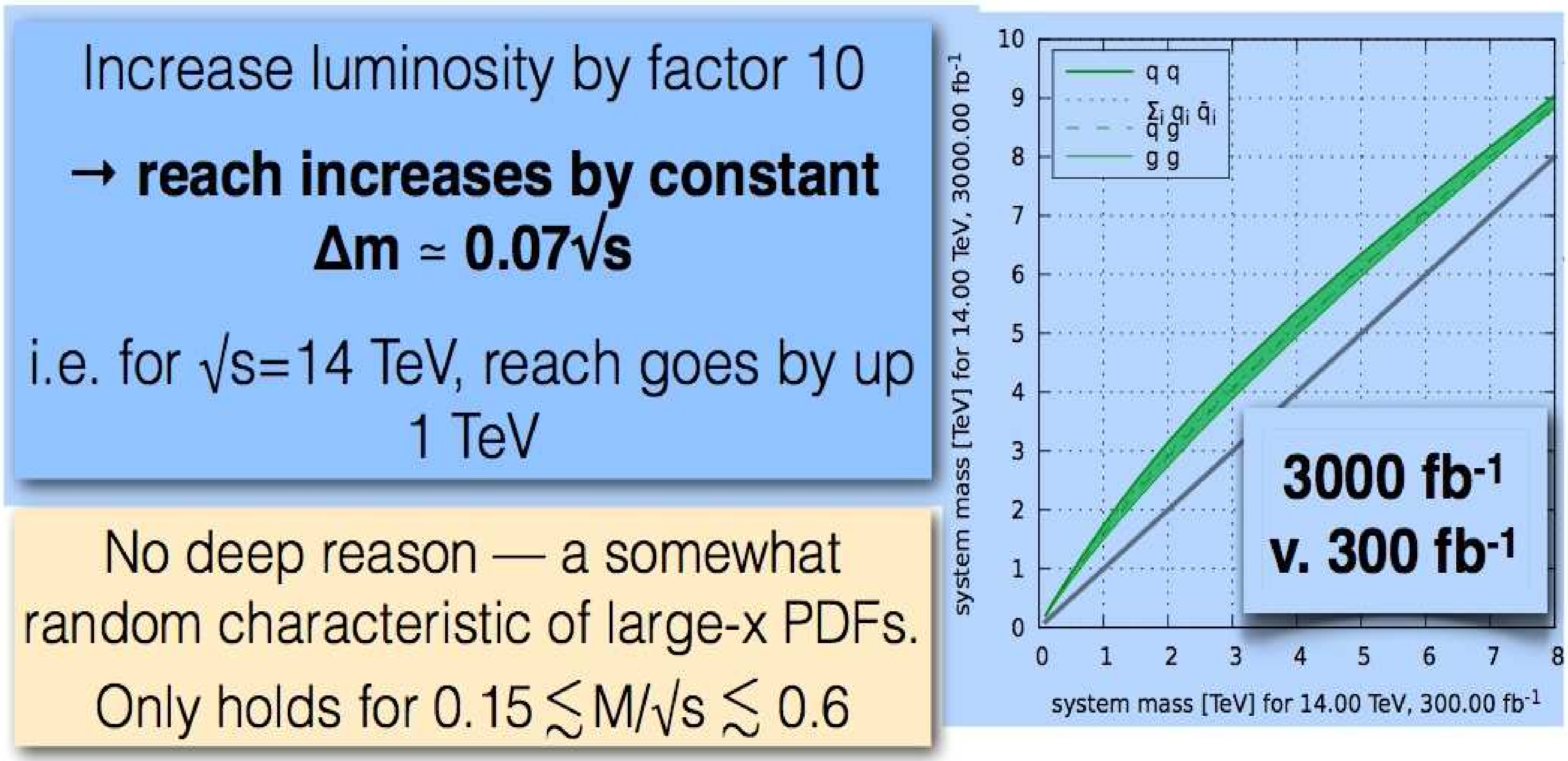
4)Use of effect of t polarisation

5)Higgs physics!

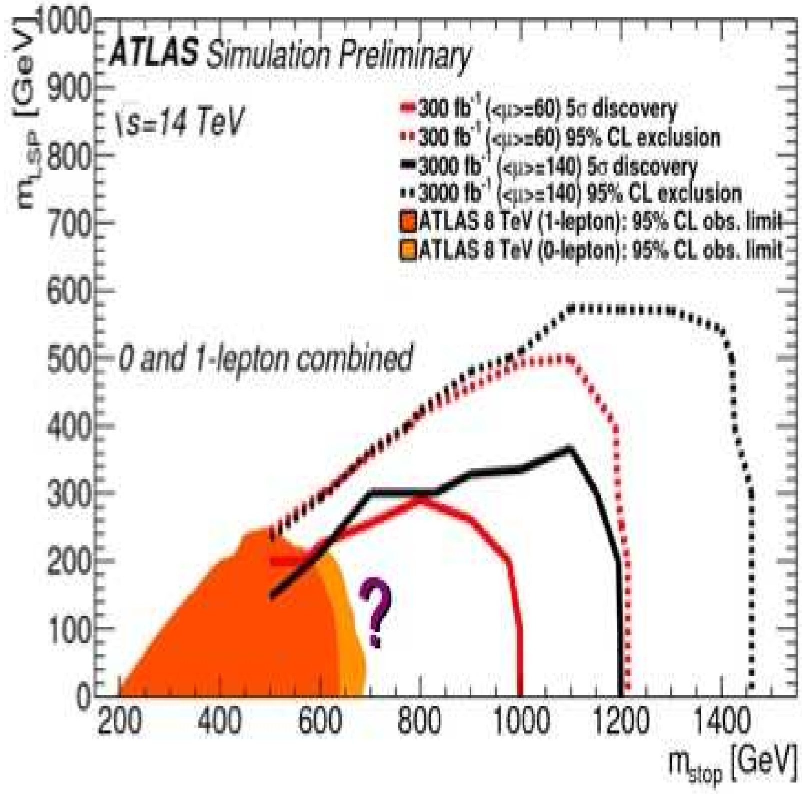
Increase the energy by a factor 2 and luminosity by a factor 4, reach in M by a factor 2.

How about reach in δM access?

At a given energy increase luminosity by a factor 10, reach seems to go up by $\Delta m = 0.07\sqrt{s}$



From a slide from G. Salam for a FCC workshop


ATLAS Simulation Preliminary
√s=14 TeV
300 fb⁻¹ (<μ>=60) 5σ discovery
300 fb⁻¹ (<μ>=60) 95% CL exclusion
3000 fb⁻¹ (<μ>=140) 5σ discovery
3000 fb⁻¹ (<μ>=140) 95% CL exclusion
ATLAS 8 TeV (1-lepton): 95% CL obs. limit
ATLAS 8 TeV (0-lepton): 95% CL obs. limit
0 and 1-lepton combined
?
m_LSP [GeV]
m_stop [GeV]

Wait and watch! May be in two years we will all have forgotten that we were agonizing over this non observation!