SUperSYmmetry search at LHC: The case for stop

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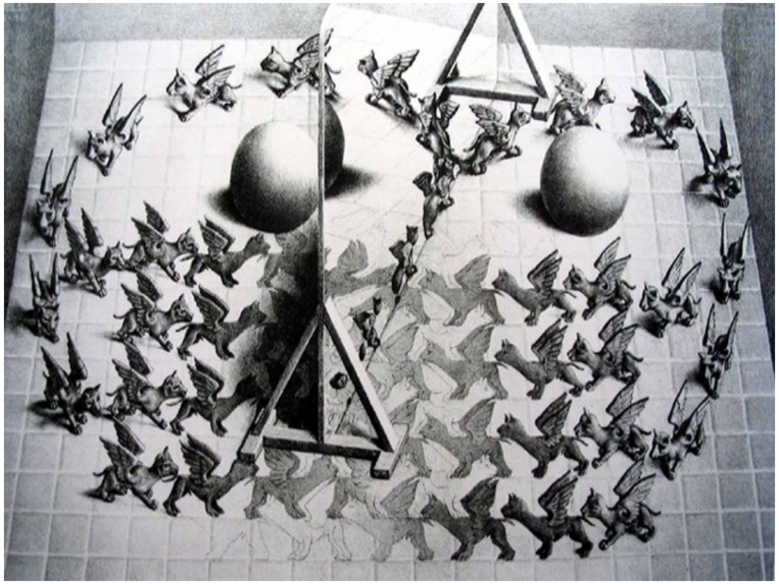
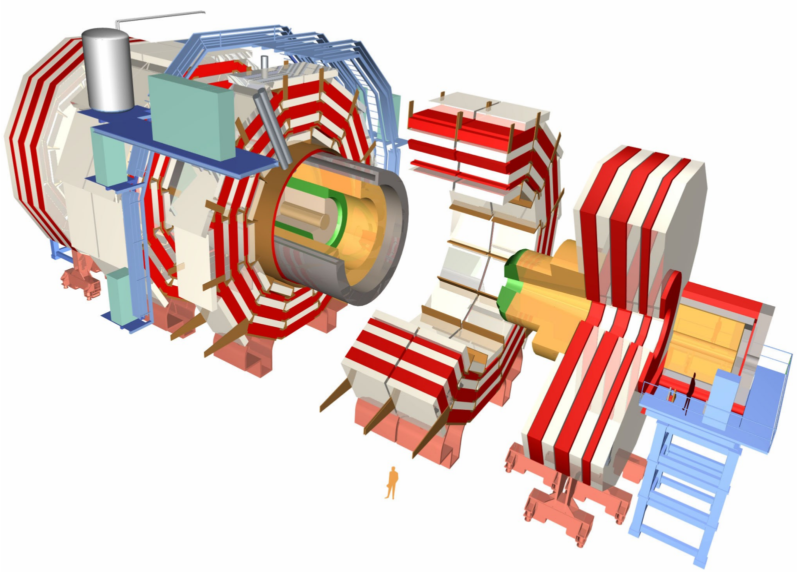
LIP



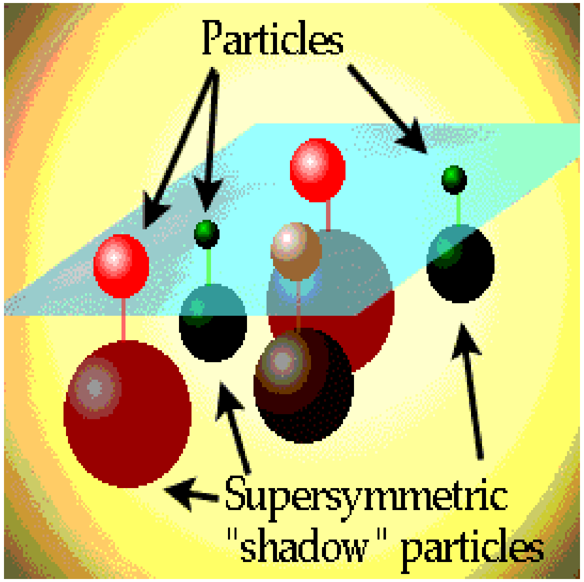


CEA 05/03/2012

Outline

- *SUperSYmmetry: Brief introduction*
- *The case for stop*
- *Types of search*
- *SUSY & stop perspectives: The project*
- *Conclusions*

SUperSYmmetry



“Generalize” the spin of known fields

SUperSYmmetry : spin particle ½ ↔ spin partner 0
spin particle 1 ↔ spin partner ½

Names		spin 0	spin 1/2
squarks, quarks (×3 families)	Q	$(\tilde{u}_L \ \ \tilde{d}_L)$	$(u_L \ \ d_L)$
	$\overline{u}$	$\tilde{u}^*_R$	$u^\dagger_R$
	$\overline{d}$	$\tilde{d}^*_R$	$d^\dagger_R$
sleptons, leptons (×3 families)	L	$(\tilde{\nu} \ \ \tilde{e}_L)$	$(\nu \ \ e_L)$
	$\overline{e}$	$\tilde{e}^*_R$	$e^\dagger_R$
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\tilde{H}^+_u \ \ \tilde{H}^0_u)$
	H_d	$(H^0_d \ \ H^-_d)$	$(\tilde{H}^0_d \ \ \tilde{H}^-_d)$

Names	spin 1/2	spin 1
gluino, gluon	$\tilde{g}$	g
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$
bino, B boson	$\tilde{B}^0$	B^0

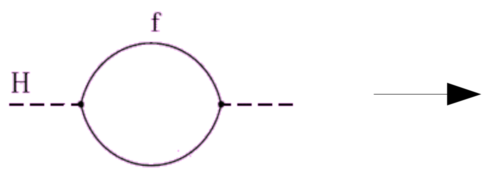
Observed SUSY particles with same mass than Standard-Model partners ? No !

SUSY : A broken symmetry !
Physical sParticles:
Mixture of super-partners

- Charginos ($\chi^\pm$) / Neutralinos (χ^0) : Bino/Wino ↔ Higgs (charged/neutral)
- Squarks, Sleptons : Mixture of $f_L \leftrightarrow f_R$

SUperSYmmetry: The *natural* cure of Hierarchy problem

- Admitting existence of a Higgs Boson
  - Considering Gauge boson scatterings at High-Energy
  - **Requiring Unitarity of scattering amplitudes**
    - **$m_H \sim O(100\ GeV/c^2)$**
- **Consider Higgs mass correction from fermionic loop:**



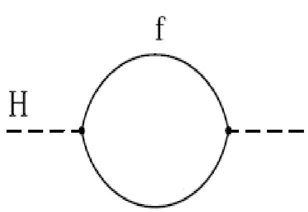
$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2} \cdot \left[-2\Lambda_{UV}^2 + ...\right]$$

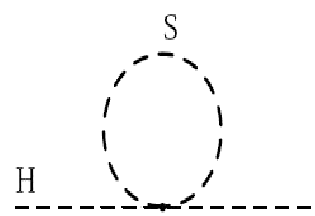
Λ_{UV}: Energy-scale at which new physics alters the Standard-Model (momentum cut-off regulating the loop-integral)

If $\Lambda_{UV} \sim M_P$ → $\Delta m^2_H \sim O(10^{30})$ larger than m_H !!!

And all Standard-Model masses indirectly sensitive to Λ_{UV} !!!

$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2} \cdot \left[-2\Lambda_{UV}^2 + ...\right]$$





$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \cdot \left[\Lambda_{UV}^2 - ...\right]$$

Δm^2_H quadratic divergence cancelled :

Hierarchy problem *naturally* solved !

Most general SUSY lagrangian allows interactions leading to Baryon- & Lepton-number violation !

Now if sParticles were to exist at TeV scale:
Such interactions seriously restricted by experimental observation !

In SUSY: $N_{B,L}$ conservation *can* be “protected” by new symmtery R_P:

- **Eigenvalue: $(-1)^{3(B-L)+s}$**
  - +1 / -1 for SM / SUSY particles
- **If R_P conserved: Lightest Supersymmetric Particle (LSP) is stable**
  In most SUSY scenarios, LSP is either:
  - The lightest neutralino $\tilde{\chi}^0$ (mixture of neutral Higgsinos / Bino / Wino)
  - Scalar neutrinos
- ...In all cases a weakly interacting neutral particle

SUSY *can* have a natural candidate for the observed Cold Dark Matter

SUSY breaking & consequences for the experimentalist

<u>How is it broken ?</u> We don't know... did not discover it (yet)...

How we *think* it's broken:

Models/Implications by/for the theorists/experimentalists

mSUGRA Spontaneous Super-Gravity breaking: More constrained → 5 parameters @ breaking scale -> RGEs → Our mass spectrum

- m_0: Scalar mass
- $m_{½}$: Fermion mass
- μ: Higgs parameter ($\mu H_1 H_2$)
- A: Tri-linear squark/slepton mixing term
- $\tan\beta = \langle H^0{}_2\rangle / \langle H^0{}_1\rangle$

MSSM Parametrizing our ignorance of SUSY breaking, i.e. no hypothesis: Un-constrained → 124 parameters

- $\tan\beta$ / μ / M_A (pseudoscalar Higgs boson mass)
- $M_{L1,2,3}$: Controls slepton masses
- $M_{Q1,2,3}$: Controls squark masses
- $M_{1,2}$: Controls neutralino/chargino sectors
- ...

The case for stop

Motivation for 3[rd] generation squarks

MSSM Lagrangian with soft breaking terms :

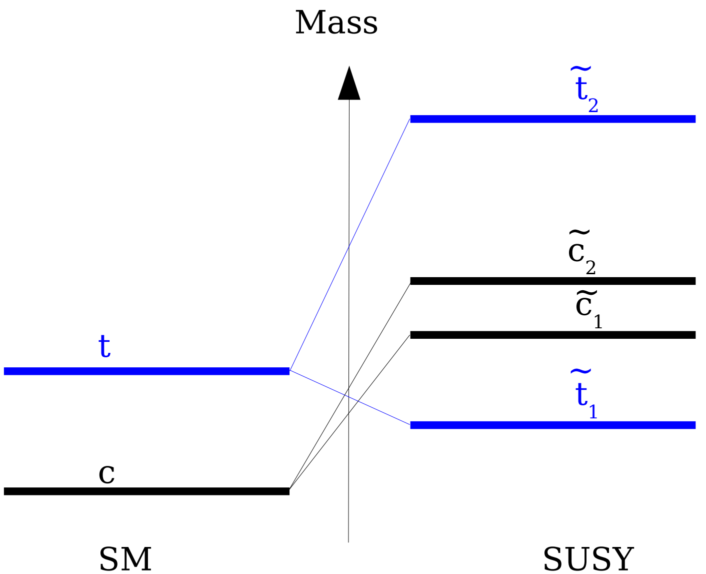
Quark left- & -right superpartners (scalars) can strongly mix to form mass eigenstates :

$$M_{\tilde{q}}^2 = \begin{pmatrix} \tilde{M}_Q^2 + M_Q^2 + M_Z^2\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\cos 2\beta & M_Q\left(A_T + \frac{\mu}{\tan\beta}\right) \\ M_Q\left(A_T + \frac{\mu}{\tan\beta}\right) & \tilde{M}_U^2 + M_Q^2 + \frac{2}{3}M_Z^2\sin^2\theta_W\cos 2\beta \end{pmatrix}$$

"Up" squarks

A_T : Tri-linear (stop) mixing term

M_Q = SM quark mass



Mass difference of quark superpartners:

Proportional to $M_Q = M_t$:

Strong mixing in the stops $\tilde{t}_{1,2}$ sector

→ $\tilde{t}_1$ might be the lightest squark

Lightest Neutralino $\tilde{\chi}^0_1$ stable: Natural candidate for Cold Dark Matter

$0.1 < \Omega_{CDM} h^2 < 1$: "Reproduced" in most of SUSY parameter space...

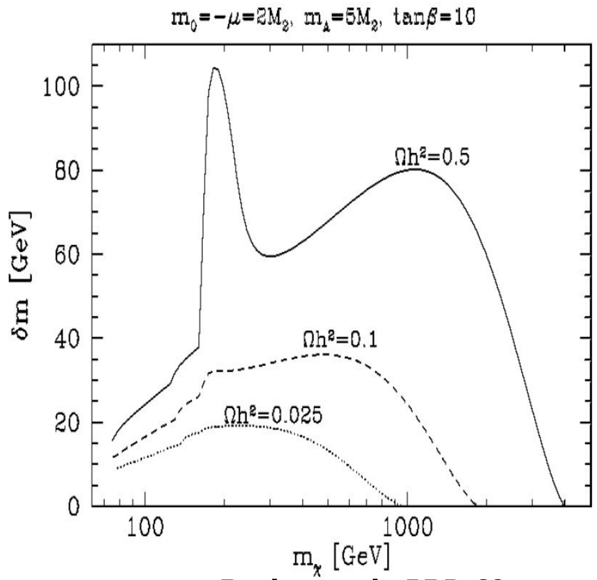
...**if $\tilde{\chi}^0_1 \tilde{\chi}^0_1$ annihilation** : Only process changing N(Superparticles)

IF : $\delta m = M(\tilde{P}) - M(\tilde{\chi}^0_1)$ small, co-annihilations dominates → $\Omega_{CDM} h^2 \approx 0.1$

- $\tilde{\chi}^0_1 \tilde{t}_1$ ---> tg, tH^0_i, bH^+
- $\tilde{t}_1 \tilde{t}^{(*)}_1$ ---> $t\bar{t}$, gg, $H^0_i H^0_j$, $H^- H^+$, $b\bar{b}$

$\Delta m = M(\tilde{t}_1) - M(\tilde{\chi}^0_1) \leq 50$ GeV/c^2 :

Compatible with **$\Omega_{CDM} h^2 = 0.11 \pm 0.01$ @ 95% CL** (WMAP)

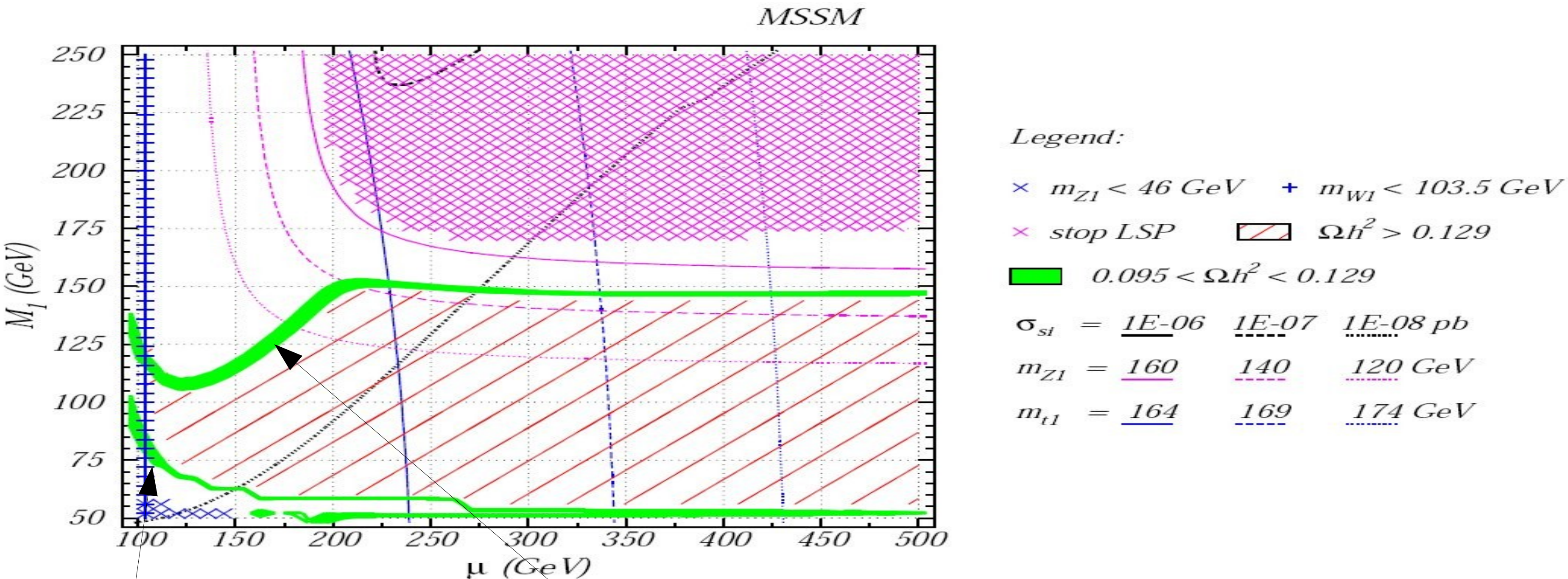


Boehm et al., PRD 62, 35012

Exciting times for SUSY searches in view of Cosmology Data:
Is stop degenerate with LSP ? NLSP ?

Motivation for the $\tilde{t}_1$: Constraints from cosmology data

$\Omega_{CDM} h^2 = 0.11 \pm 0.01$: Constraints the MSSM parameter space



Balazs et al. : hep-ph/0403224

$\tilde{\chi}^0_1 \tilde{\chi}^0_1$ --> h,H annihilations

- $\tilde{t}_1$ / $\tilde{\chi}^0_1$ **co-annihilation**
- Experimentally : Special interest for light $\tilde{t}_1$
- Data from cosmology: Shrinks the (μ, M_1) band

Exciting times for SUSY searches in view of Cosmology Data:

Stop/Higgs yukawa coupling

$\longrightarrow$ $M(h) = f\,[\,M(\tilde{q},\tilde{t}_{1,2})\,]$

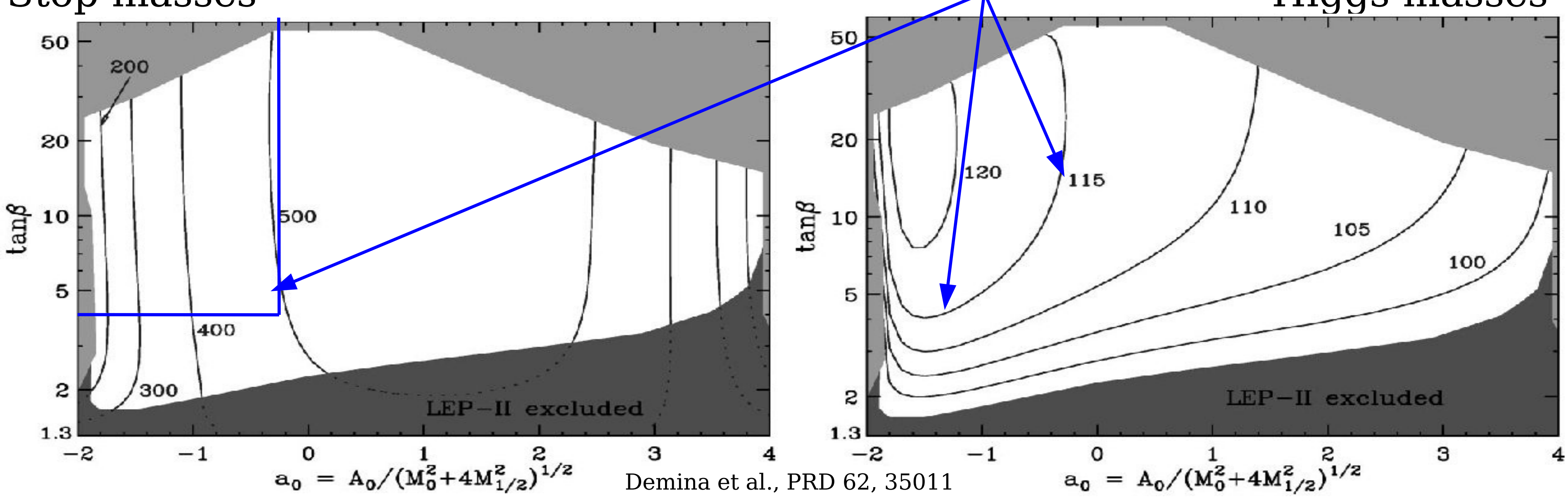
$$M^2_{h,H} = \frac{1}{2}\left\{M_A^2+M_Z^2+\frac{\epsilon_h}{\sin^2\beta}\pm\left[\left(M_A^2-M_Z^2\right)\cos 2\beta+\frac{\epsilon_h}{\sin^2\beta}\right)^2+\left(M_A^2+M_Z^2\right)^2\sin^2 2\beta\right]^{1/2}\right\}$$

$$\epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2}M_T^4\log\left(\frac{\tilde{m}^2}{M_T^2}\right)$$

Squark masses: Higgs mass particularly sensitive to $\sim t_{1,2}$ system

LHC: Higgs & stop searches can constraint each other

Stop masses | Higgs masses

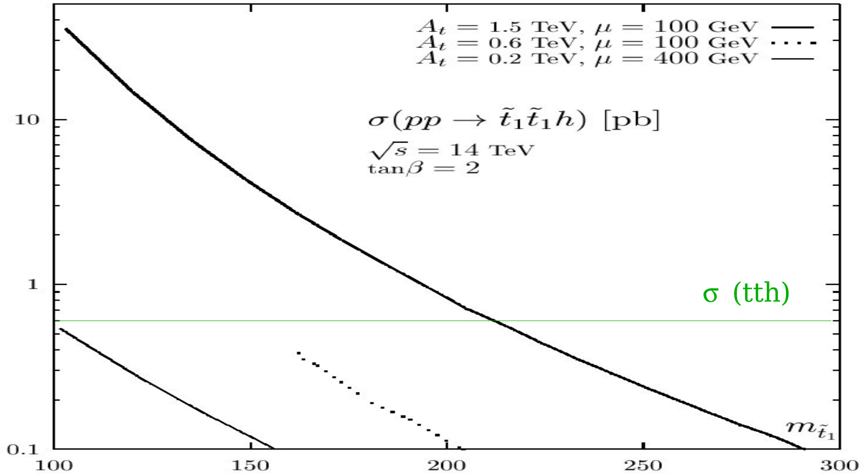


Demina et al., PRD 62, 35011

Motivation for the $\tilde{t}_1$: Special relations with Higgs

Decoupled regime: Light h "SM like": h -> γγ
{H, $H^\pm$, A} much heavier & degenerate

Coupling : $g_{h\tilde{t}\tilde{t}} = \ldots + [\ -m_{\tilde{t}}^2 + m_{\tilde{t}} \sin 2\theta_t (A_T + \mu/\tan\beta)/2] / M_Z^2$



Djouadi et al., PRL 80, 1830

- $A_T \sim 0$: σ $(\tilde{t}\,\tilde{t}\,h) = 2$ σ $(\tilde{t}_1\tilde{t}_1 h) \geq$ σ (tth)
- A_T intermediate : destructive interference
- A_T (very) large : σ $(\tilde{t}_1\tilde{t}_1 h) >$ σ (tth) for $M(\tilde{t}_1) < 220$ GeV/c^2

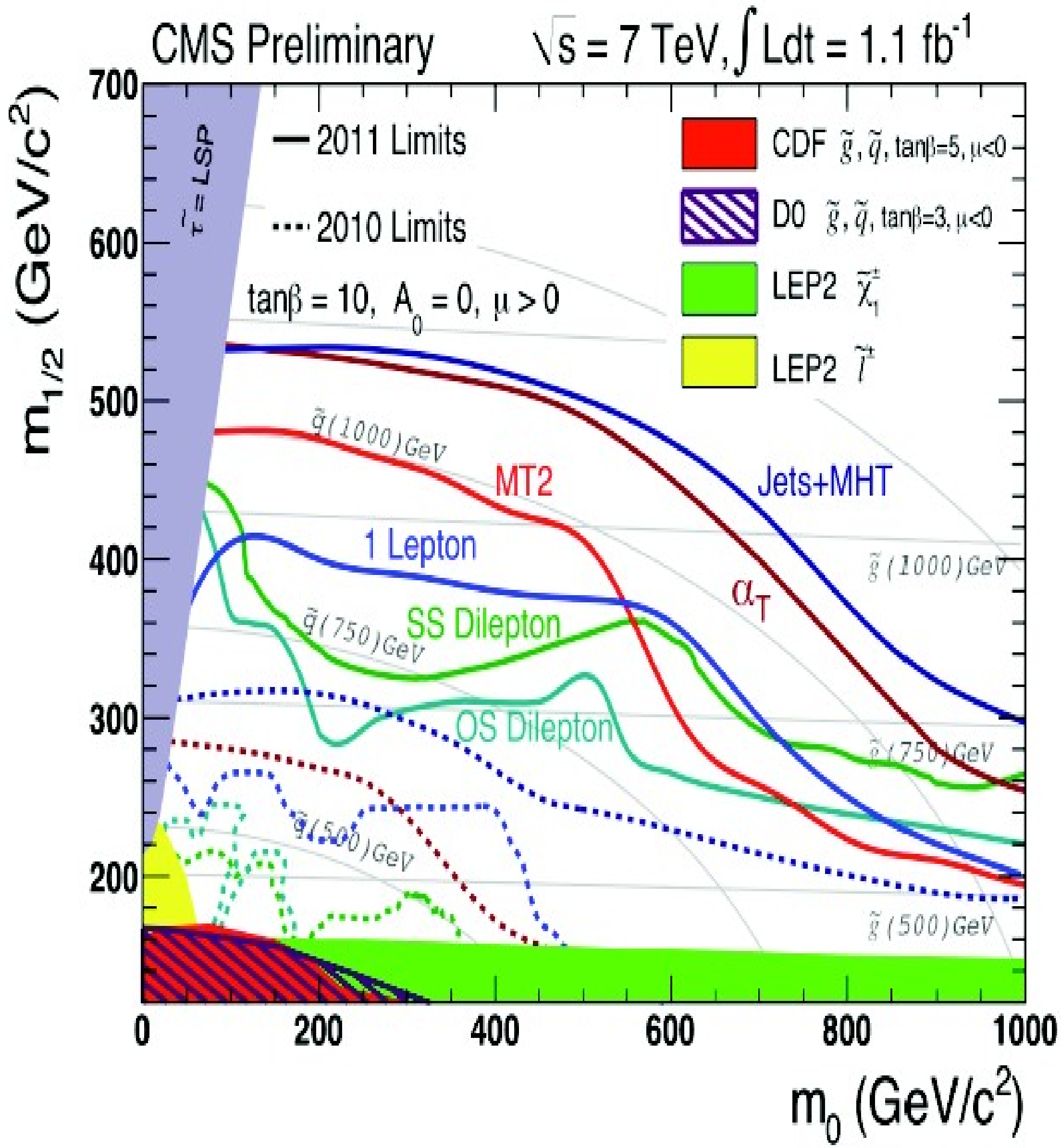
- For big part of SUSY parameter space : σ $(\tilde{t}_1\tilde{t}_1 h) >$ σ (tth)
- Even if σ $(\tilde{t}_1\tilde{t}_1 h) \sim$ σ (tth) : Γ(ll jj γγ) – Γ(tth) -> **$\tilde{t}_1\tilde{t}_1 h$ coupling** :
  - **Largest electroweak MSSM coupling**
  - Test of scalar potential (soft breaking of SUSY)

Summary of all CMS Susy searches, interpreted within mSUGRA

We can (very well) have the scenario where:
→ Squarks & gluino are so massive that out of reach of LHC
→ But $\tilde{t}_1$ is within reach: All these searches were quite/very general, not specifically looking for a given sParticle

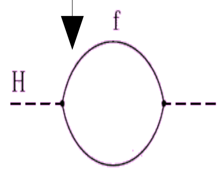
A lot of interest for $\tilde{t}_1$ **now**:

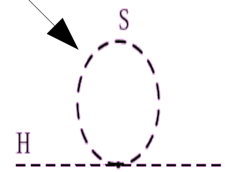
It's rather low σ
It's sometimes "sitting on" SM
But it might be the only sParticle reachable



In practice: The Δm^2_H quadratic divergence can be canceled @ TeV scale with <u>only stops</u>: Invoke only top & stop1 here

$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2} \cdot \left[-2\Lambda_{UV}^2 + \ldots\right]$$





$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \cdot \left[\Lambda_{UV}^2 - \ldots\right]$$

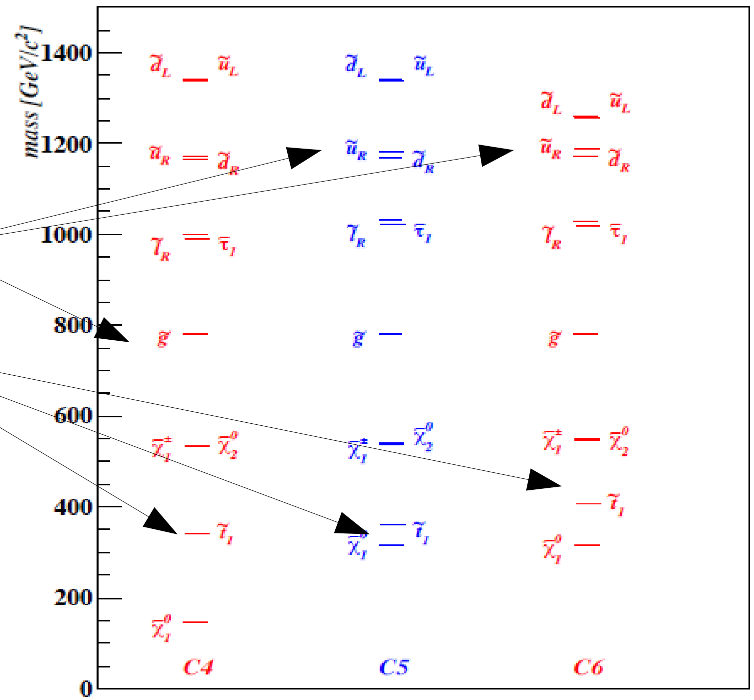
compressed SUSY with light stops

"Decoupled" SUSY:

1/ Squarks & Gluino can be (quite) heavy
2/ ~t1 can be (much) light(er)

→ We can still solve the Higgs hierarchy problem @ TeV scale :-)

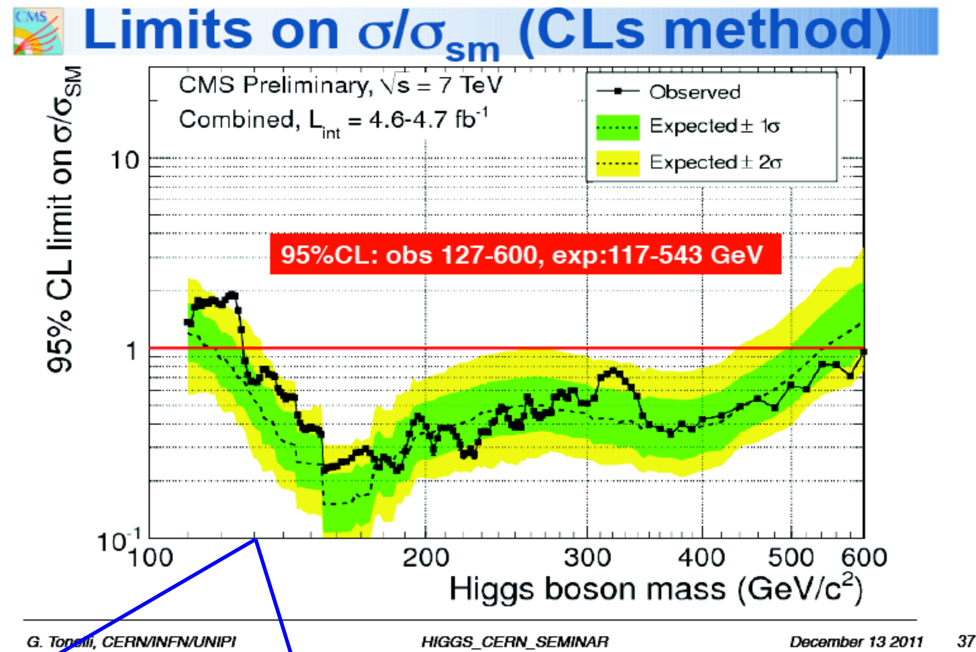
Remember what the Higgs sector tell us in this regard…



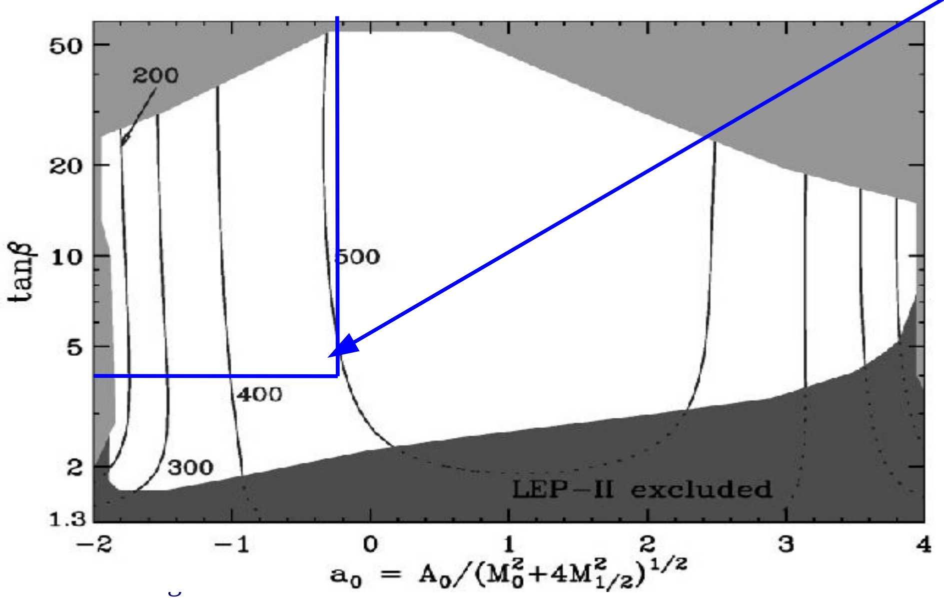
Where are we standing now: Higgs & stop picture

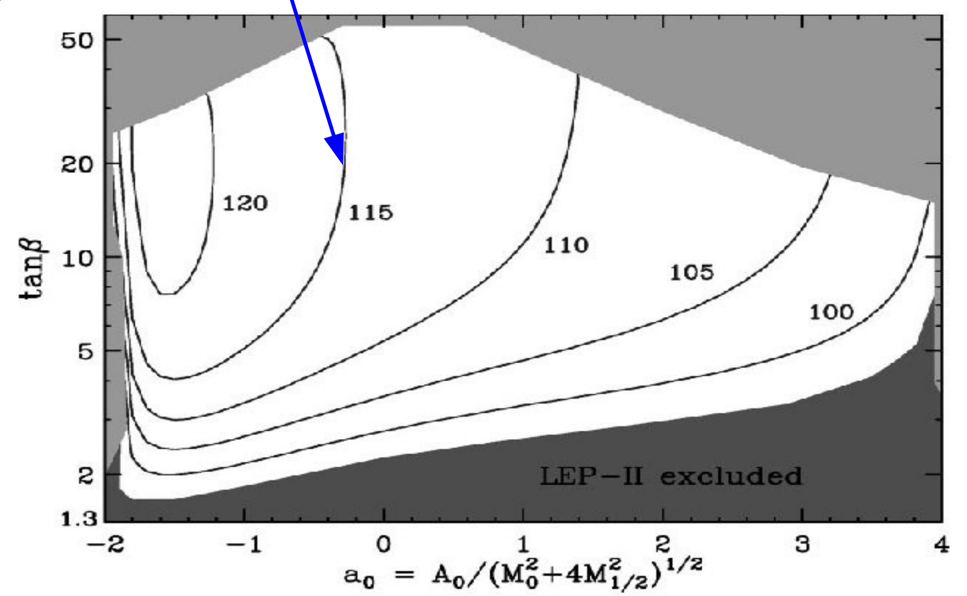
Higgs: **IF** there: It is "more & mor pushed towards" low-mass region

Implication for the $\sim t_{1,2}$ sector ?



Subsisting Higgs window "pushes" $\sim t_1$ towards M<500 GeV/c^2





Should ***stop not be the 1st sParticle to be discovered, it's really worth searching, hopefully discovering & studying***

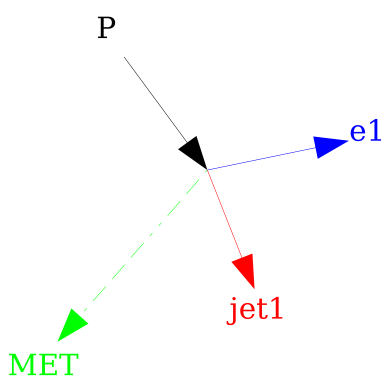
Types of searches

Type of search: All scenario-inclusive & per final-state

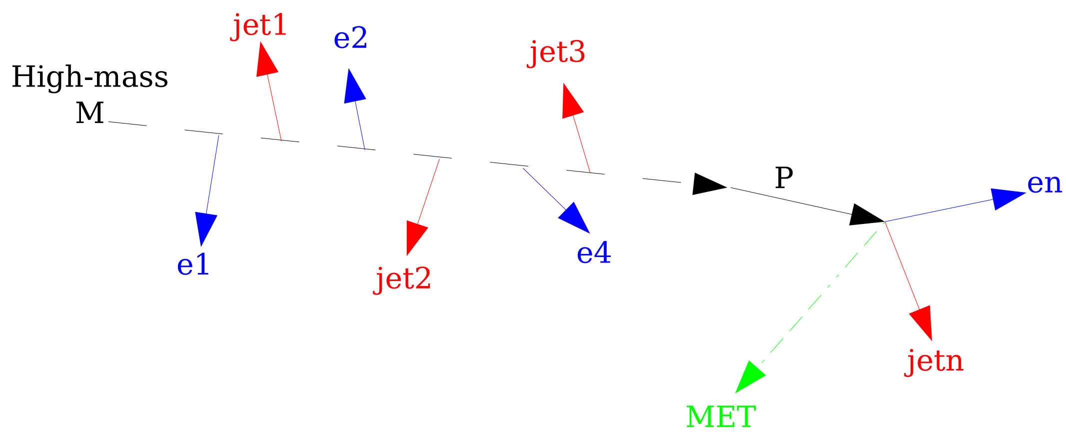
Look for a sparticle $\widetilde{P}$ in an all-scenario and per final-state approach:

- Analyze/Optimize with final objects (leptons, jets, MET, ...)
- Resolve different mass hierarchies with OSET

Now imagine we've tuned analysis with this...



...while we are getting this:



- Messes-up the whole p_T spectrum of all particles of final-state
- If we want to resolve this while being able to analyze/select: Per $[\widetilde{P},\widetilde{\chi}^0_1]$ signal-point, consider various upper-chain scenario with different kinematics !!!

Type of search: mSUGRA + OSET

- Constrained model: 5 keys (parameters) to predict sparticle mass spectra
  - Convenient for modeling different topologies (final-states)
- Physics PTDRs picked benchmark points to tune analysis
- Nice coverage of all possible SUSY topologies

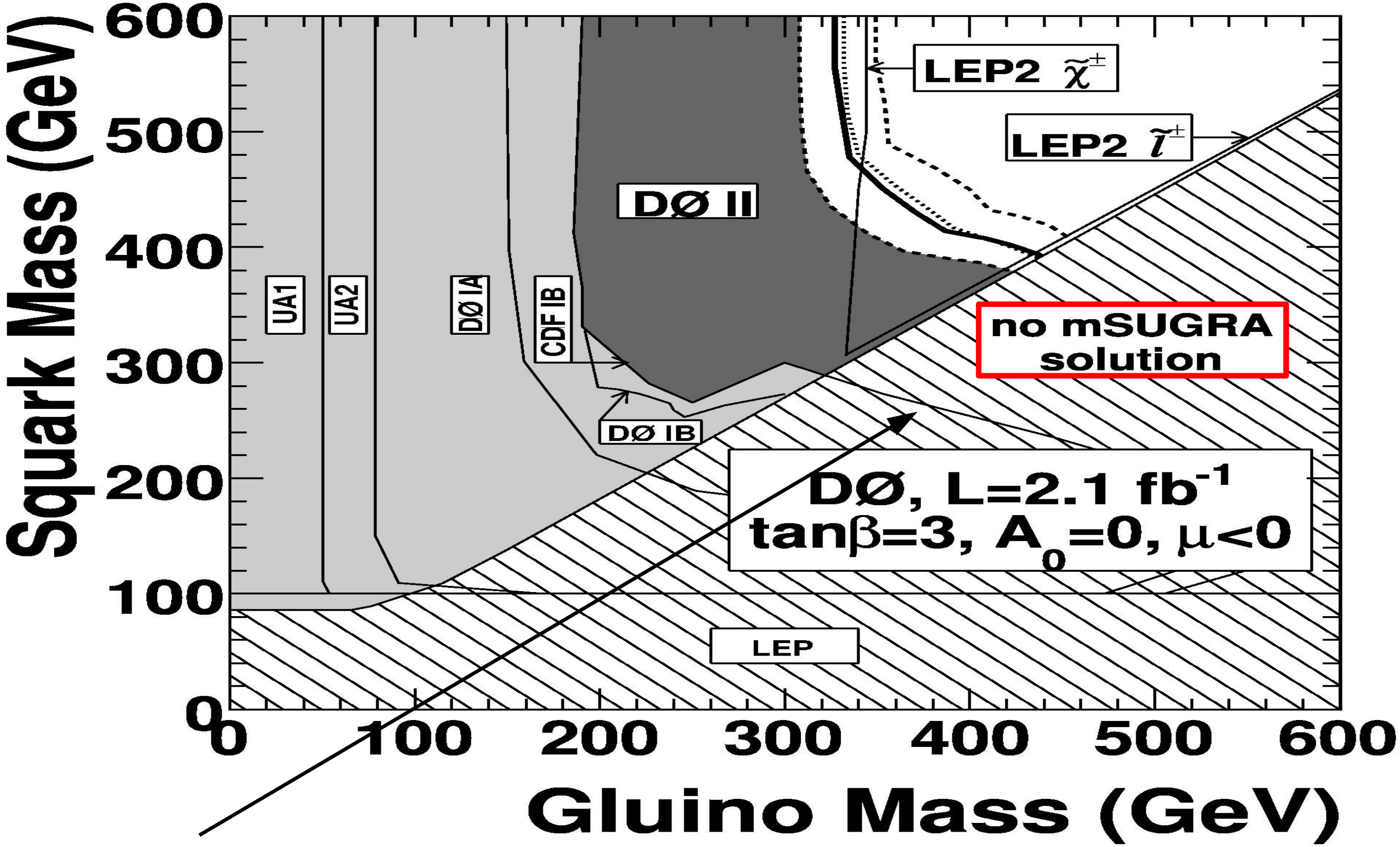
Should:

- An excess of events be observed in one of the looked-upon topologies...
- ...where mSUGRA would not have predicted the totally correct mass spectra for different sparticles

→ **On-Shell Effective Theories** (see back-up slides) should be capable of resolving the correct mass spectra, i.e. finding out the different actors of the decay chain

Type of search: mSUGRA & kinematics

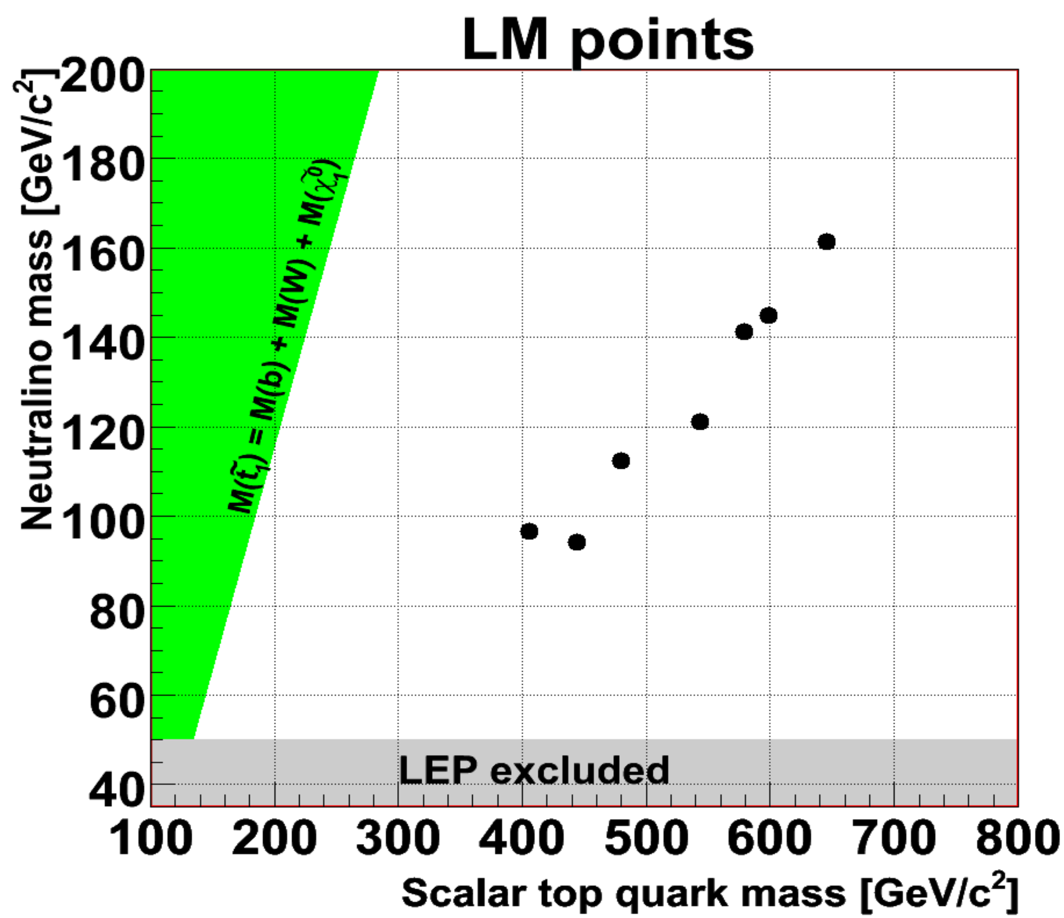
But mSUGRA has shortcomings in predicting all kinematic possibilities



What if SUSY is there ?

Kinematic shortcomings in a given case (decay): $\tilde{t}_1$ versus $\tilde{\chi}^0_1$

2 shortcomings...

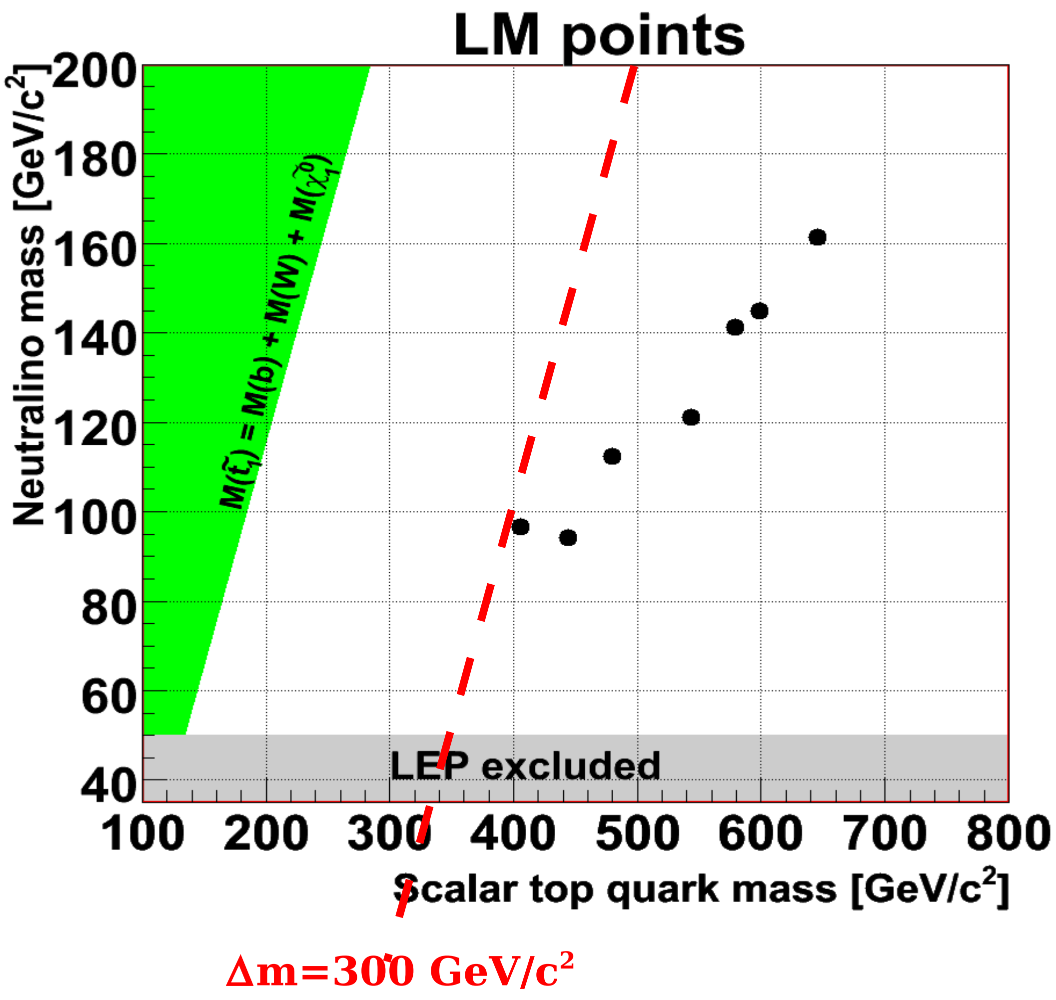


Type of search: mSUGRA & kinematics

Kinematic shortcomings in a given case (decay): $\tilde{t}_1$ versus $\tilde{\chi}^0_1$

2 shortcomings:

- A low $\Delta m \geq 300$ GeV/c^2 region totally unexplored while being preferred by cosmology data

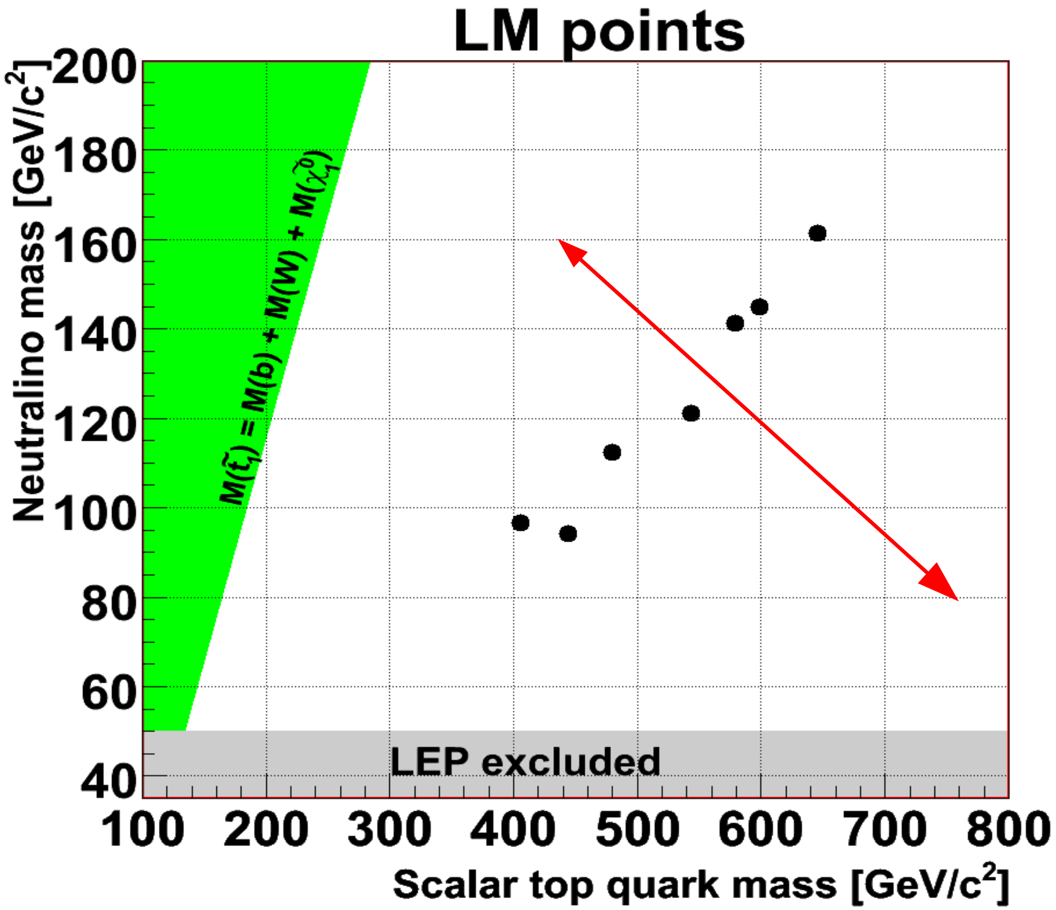


Type of search: mSUGRA & kinematics

Kinematic shortcomings in a given case (decay): $\tilde{t}_1$ versus $\tilde{\chi}^0_1$

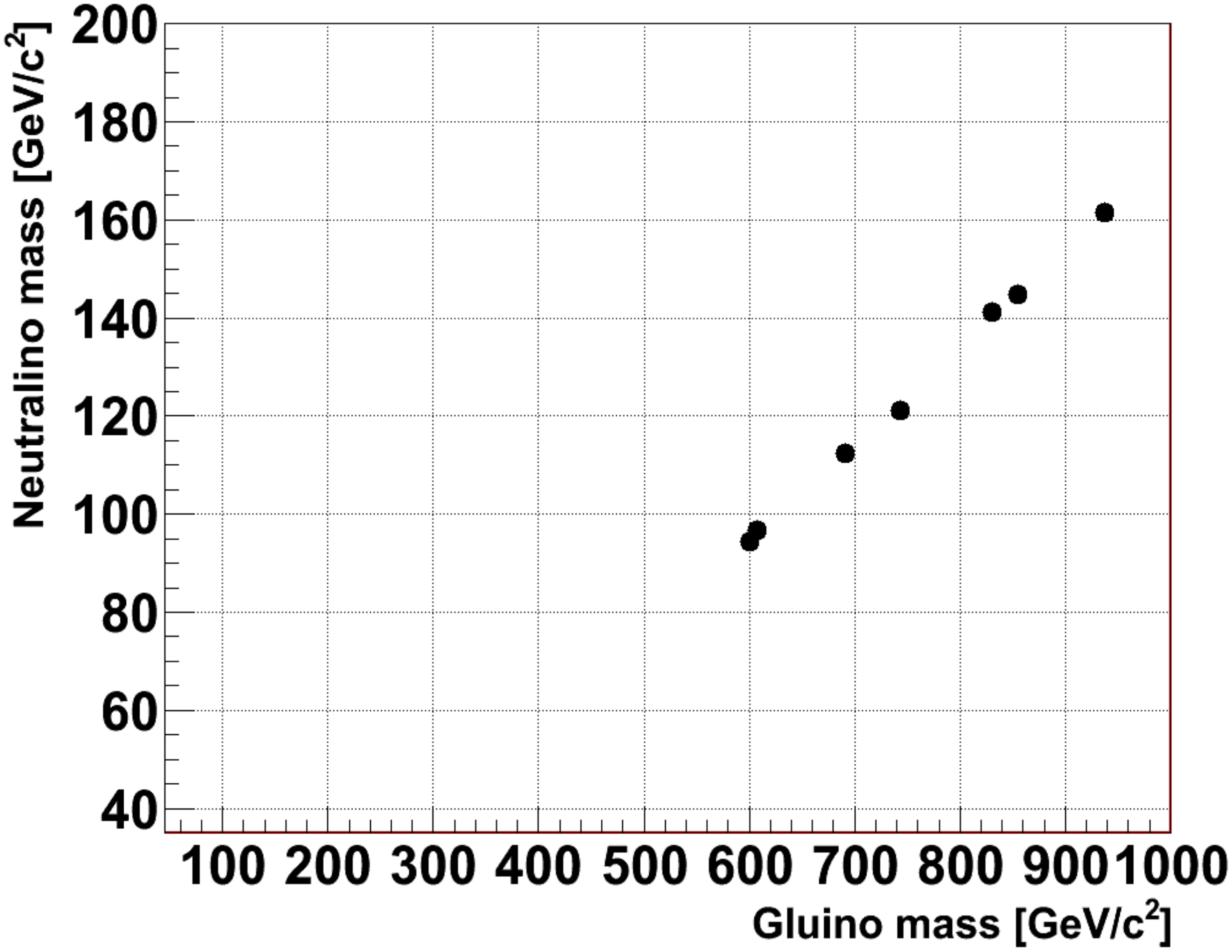
2 shortcomings:

- A low $\Delta m \geq 300$ GeV/c^2 totally unexplored while region preferred by cosmology data
- Different Δm kinematics not explored, i.e. wrong axis for exploring different kinematics



Type of search: mSUGRA & kinematics

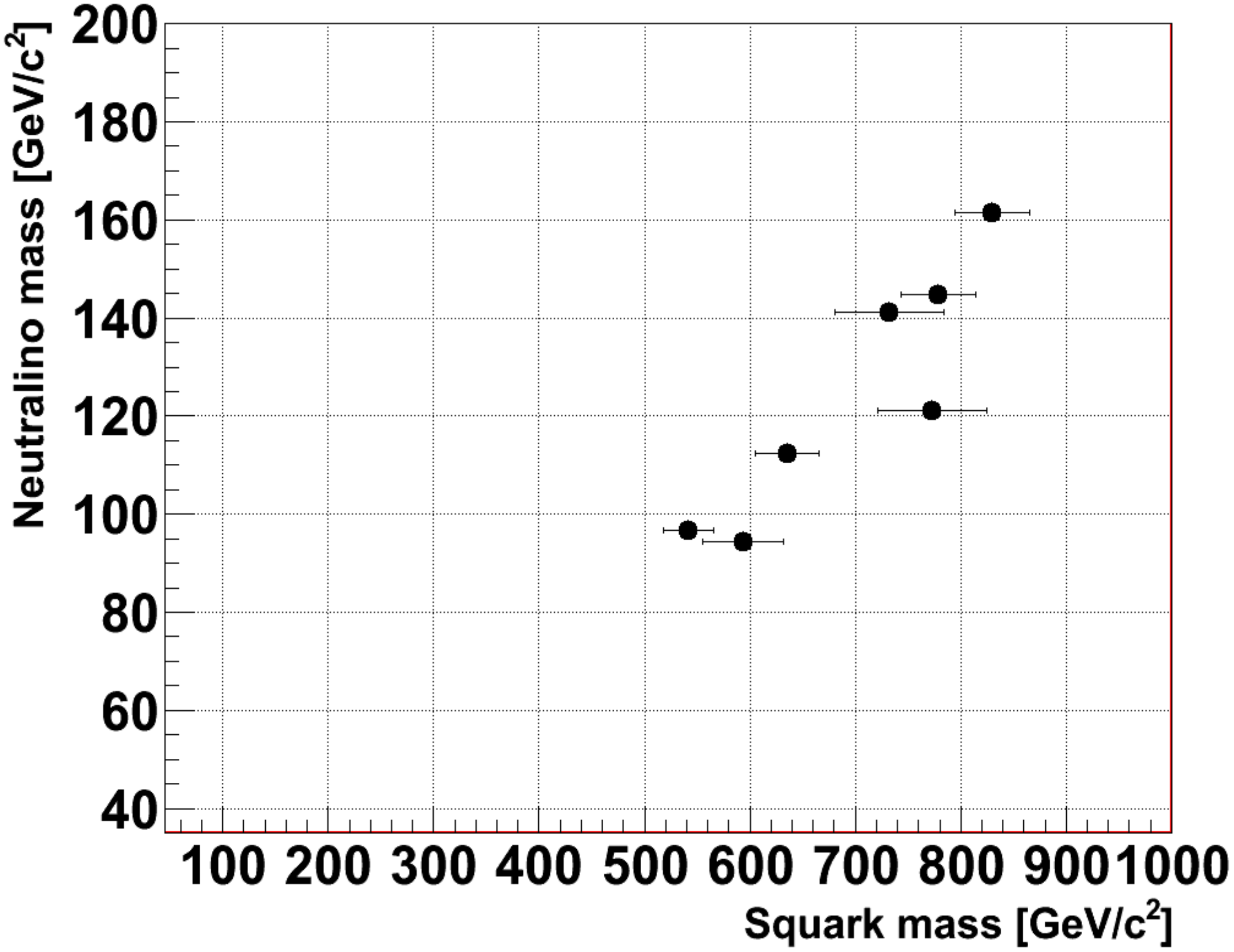
Kinematic shortcomings in another search/decay: $\tilde{g}$ versus $\tilde{\chi}^0_1$



Kinematic shortcomings in another search/decay: $\tilde{q}$ versus $\tilde{\chi}^0_1$

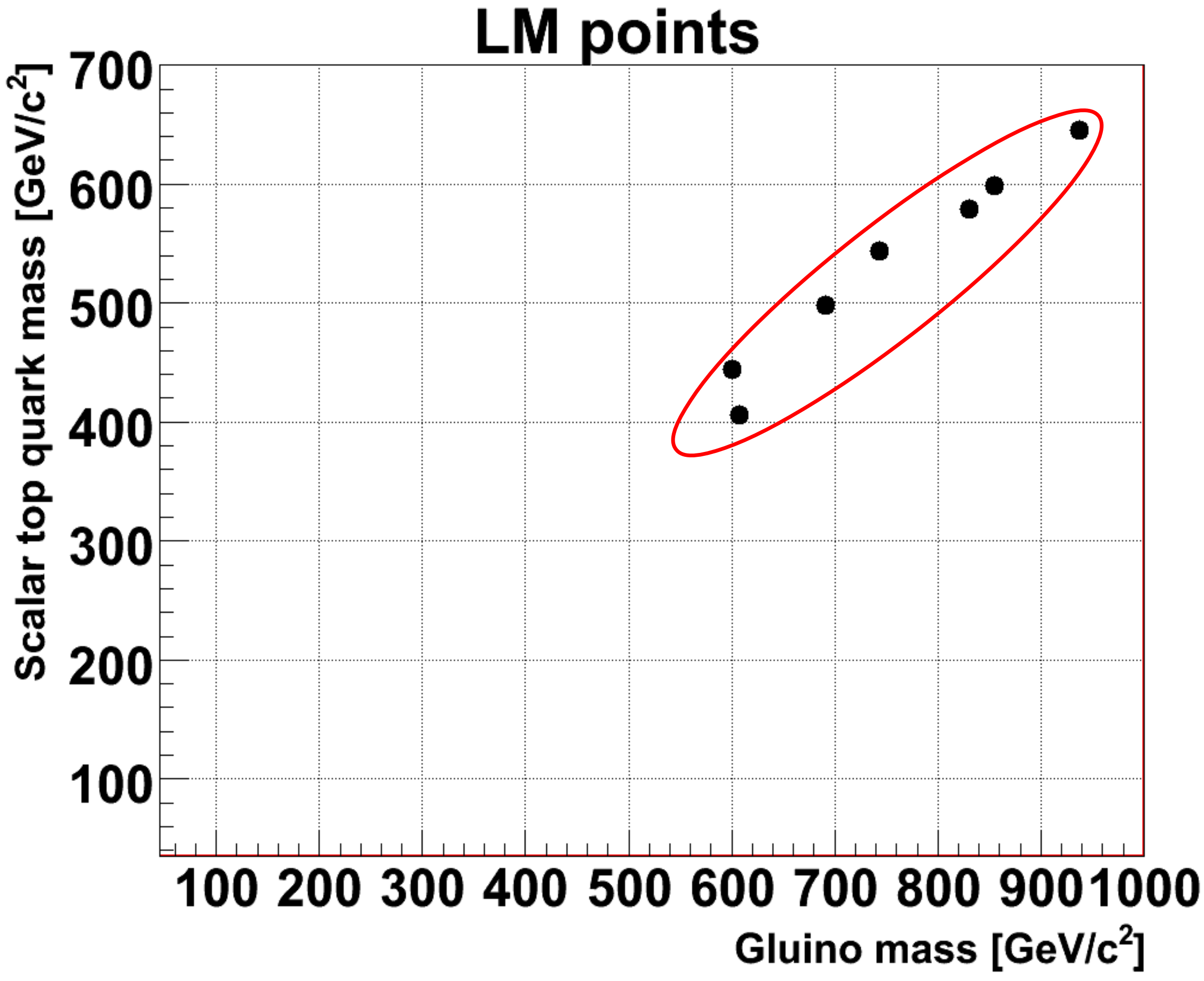
Bars on squark masses:

Spread of $\tilde{u}_{L,R} \rightarrow \tilde{b}_{1,2}$ squarks



Type of search: mSUGRA & kinematics

Kinematic shortcomings in another search/decay: $\tilde{g}$ versus $\tilde{t}_1$



Type of search: mSUGRA & kinematics

We might miss a signal despite correct topology, because looking (analysis cuts, **trigger**) in a wrong kinematic region

- Here: The hypothesis & scale on SUSY breaking dictate the kinematics. It results in narrow & rather high-mass kinematic windows
- **We want the opposite: We want to explore as much physical regions: <u>Mass regions</u>, discover SUSY**, THEN determine parameters... how SUSY is broken...

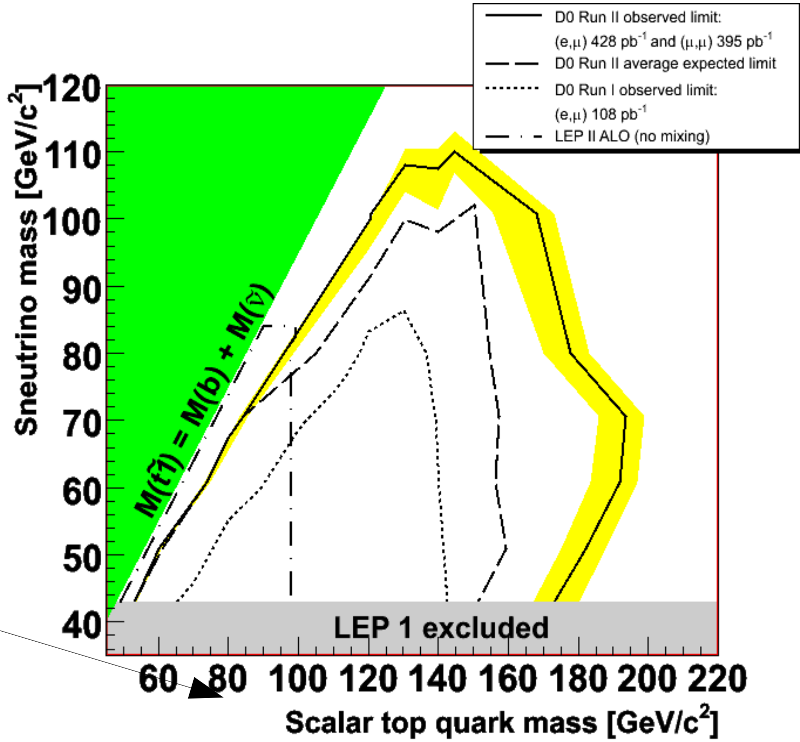
Type of search: MSSM + Mass-scanning / An example

*Be as **model-independent** as possible:*

Only assume SUSY, i.e. choose the less constrained SUSY framework: MSSM

***Focus on masses** dictating kinematics:*

Scan: Cover all experimental possibilities



Example: For $\tilde{t}_1 \to b\, l\, \tilde{\nu}$:

Framework: MSSM

$\tilde{\chi}^0_1$ = LSP

$\tan\beta = 20$, $\mu = +225$ GeV

$M_{\tilde{g}} = 500$ GeV/c^2

$M_A = 800$ GeV/c^2

- A_T, trilinear stop mixing : Controls $M_{\tilde{t}1}$
- $M_{L1,2}$, slepton masses : Controls $M_{\tilde{\nu}}$
- M_1, bino mass : Controls $M_{\tilde{\chi}0}$
- M_2, wino mass : Controls $M_{\tilde{\chi}+}$ (chargino virtual)

Playing only with 5 parameters → Cover a signal grid
Play with parameters only for covering different masses

Type of search: MSSM + Mass-scanning

*Be as **model-independent** as possible, while effectively & completely generating the signal*

As long as we are searching for SUSY in (rather) short decay chains:

- Possible to play with small number of parameters
- Simulate a whole grid of different mass signals
  - Kinematically "know" what we're hunting: Have a high-efficiency signal selection
  - While covering as much as possible various experimental possibilities: Towards being generic...

Stop search attractive: Probably/Hopefully around the bottom of the SUSY chain → Not too wrong to think that:

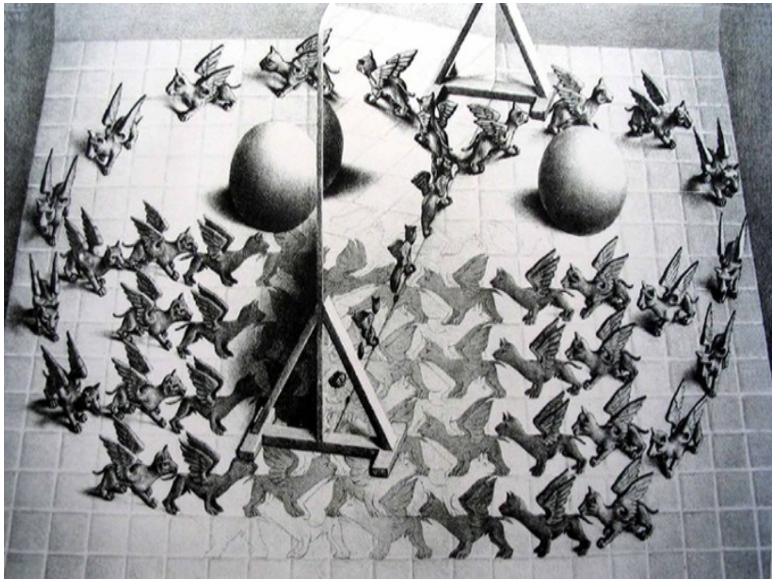
- Decays in rather short chains
- Most sParticles heavier: Reduce the number of different parameter hypothesis we should make in order to cover all mass configurations: Convenient

Type of search: MSSM + Mass-scanning

Why it is (so) important to scan through different masses, and not only/first through SUSY parameter space:

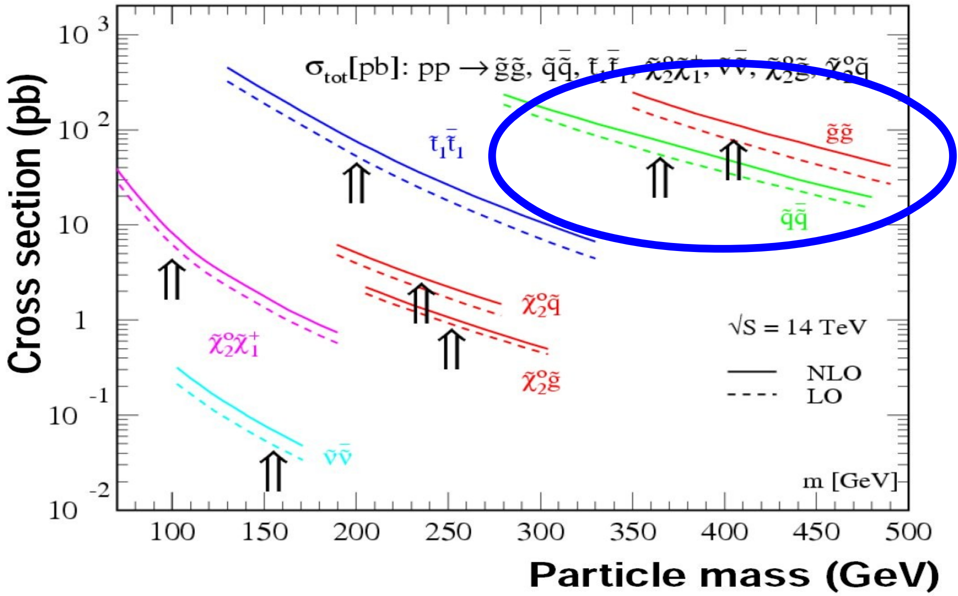
- Some SUSY models are phenomenologically too constrained, thus not covering all masses, i.e. physical possibilities
  - **1**st we find evidence for BSM, then spin/mass measurement
    - Spin measurement in short decay chains: Advantage (?)
  - **Then** do we determine parameters
- **In case of discovery:**
  - A mass scan can give a good idea of the mass of the new particles, say ($\tilde{P}$,$\tilde{\chi}^0_1$)
    - Guidance for parameter measurement
- **In case of non-discovery:**
  - Important to exclude mass regions to guide other searches. Lower limits on squarks / gluinos / charginos: Crucial inputs for other SUSY searches

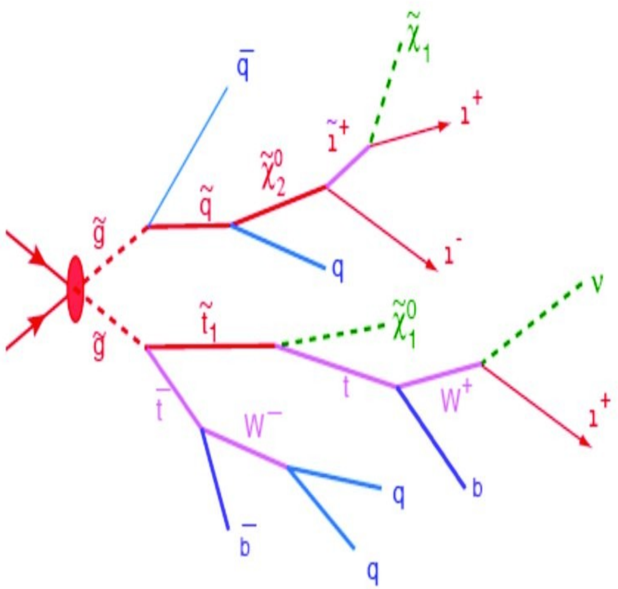
SUSY & Stop perspectives



Let's backup: LHC Susy landscape/challenges

- Most dominant processes: $\tilde{q}\tilde{q}$ / $\tilde{g}\tilde{g}$ / $\tilde{q}\tilde{g}$
- If:
  - Nature supersymmetric
  - Energy reach of the machine (7-14 TeV) high enough...
  - ... for objects at the top of mass-spectrum, say $\tilde{g}\tilde{g}$
- We might get:

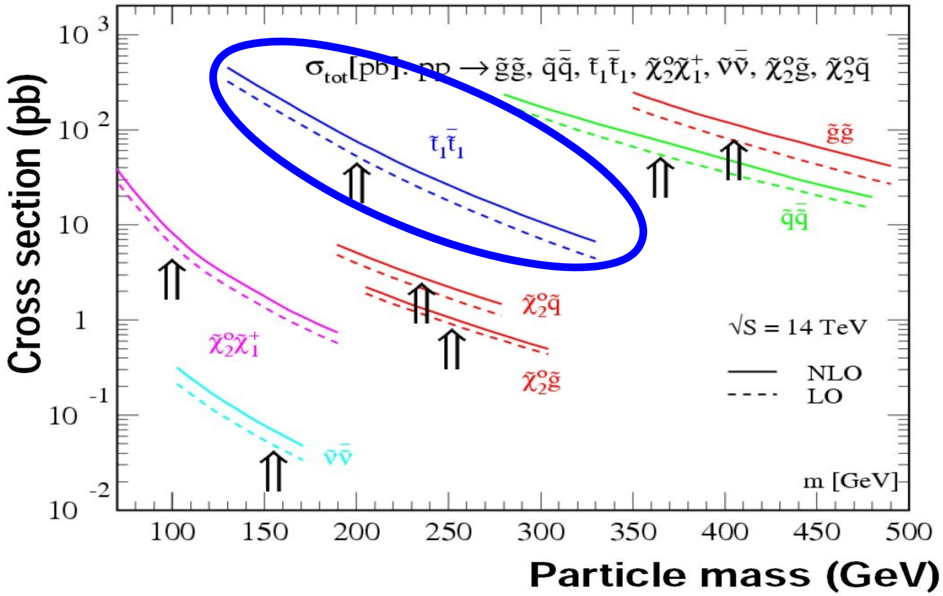




- Interesting/Challenging to analyze
  - Tools should (better) be tuned
- Very specific mass hierarchy:
  - Simulation: 7 unknown objects, play w how many parameters to vary masses ?
  - OSETs can resolve this, *provided* existing evidence of events beyond SM
- Who tells that all Susy particles within reach ?
- Why search for $\tilde{l}/\tilde{t}_1/\tilde{\chi}^{0\pm}_{1/2}$... in long decay chains ?...

An LHC Susy perspective: $\tilde{t}_1 \tilde{t}_1$-bar

Simpler approach:
Stop searches from low masses…



SUSY perspectives

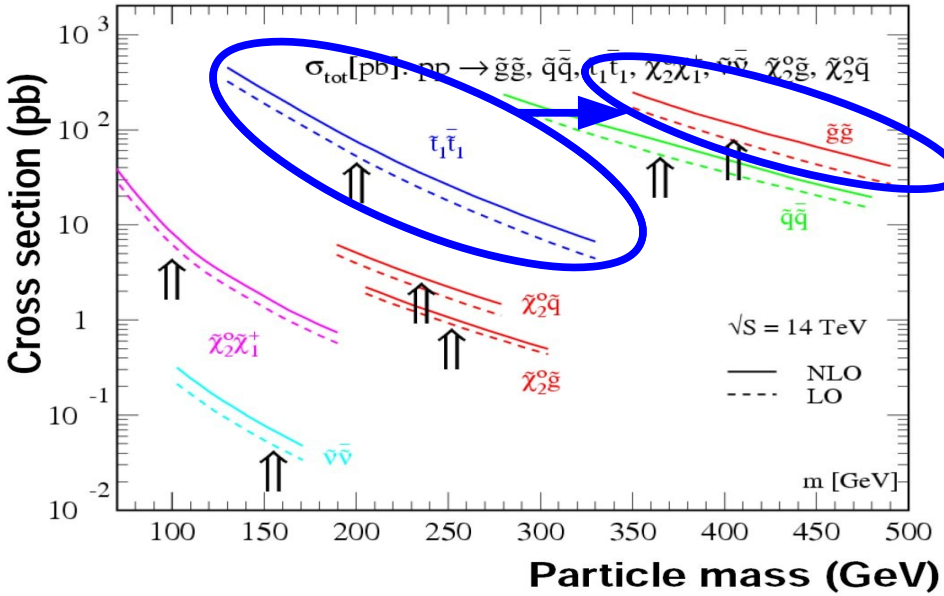
- One can perform a $[\tilde{t}_1, \tilde{\chi}^0_1]$ mass scan
- Decay products: More energetic than in long decay chains
- The Tevatron->LHC gap will be covered: No one is looking there now !
- $\tilde{t}_1 \to b\, W\, \tilde{\chi}^0_1$: Dominating most of SUSY space
  - No one has sensitivity for such stop decays
- **Among most generous SUSY sources…**
- **…with still simple topology & energetic kinematics**
- **Challenge:** ttbar is an irreducible background

Coherent approach:

Stop searches from low to higher masses: For higher stop masses:

When $[\sigma.\mathrm{Sel}](\tilde{t}_1\tilde{t}_1) \leq \sigma(\tilde{g}\tilde{g} \to tt\,\tilde{t}_1\tilde{t}_1)$:

Shift the gear to $\tilde{g}\tilde{g} \to tt\,\tilde{t}_1\tilde{t}_1$



SUSY perspectives

- σ: Next biggest source of stop
- Type of search: Next simplest: Still minimal hypothesis about Susy parameters
  - Generate the signal -> Tune analysis
- Kinematically: Decay objects still benefitting from larger phase-space than in long decay chains
- ttbar: Not irreducible background

Coherent/adiabatic search

An LHC perspective: $\tilde{g}\,\tilde{g} \rightarrow t\,t\,\tilde{t}_1\,\tilde{t}_1$

	4 l	2j + 3 l	4j + 2 l	6j + 1 l	8j + 0 l
	4e	2j 3e	4j 2e	6j 1e	8j
4b +	4μ	2j 3μ	4j 2μ	6j 1μ	
MET +	2e2μ	2j 2e1μ	4j eμ		
	1e3μ	2j 1e2μ			
	3e1μ				

Experimental perspectives

Should-we limit ourselves to electrons & muons:

- **Array of 4 x 14 different leptonic channels**
  - Gluino = Majorana particle -> 4 sign combinations
- In case of discovery: Array of different final states:
  - Branching-ratio cross-checks
  - Lepton-sign cross-checks

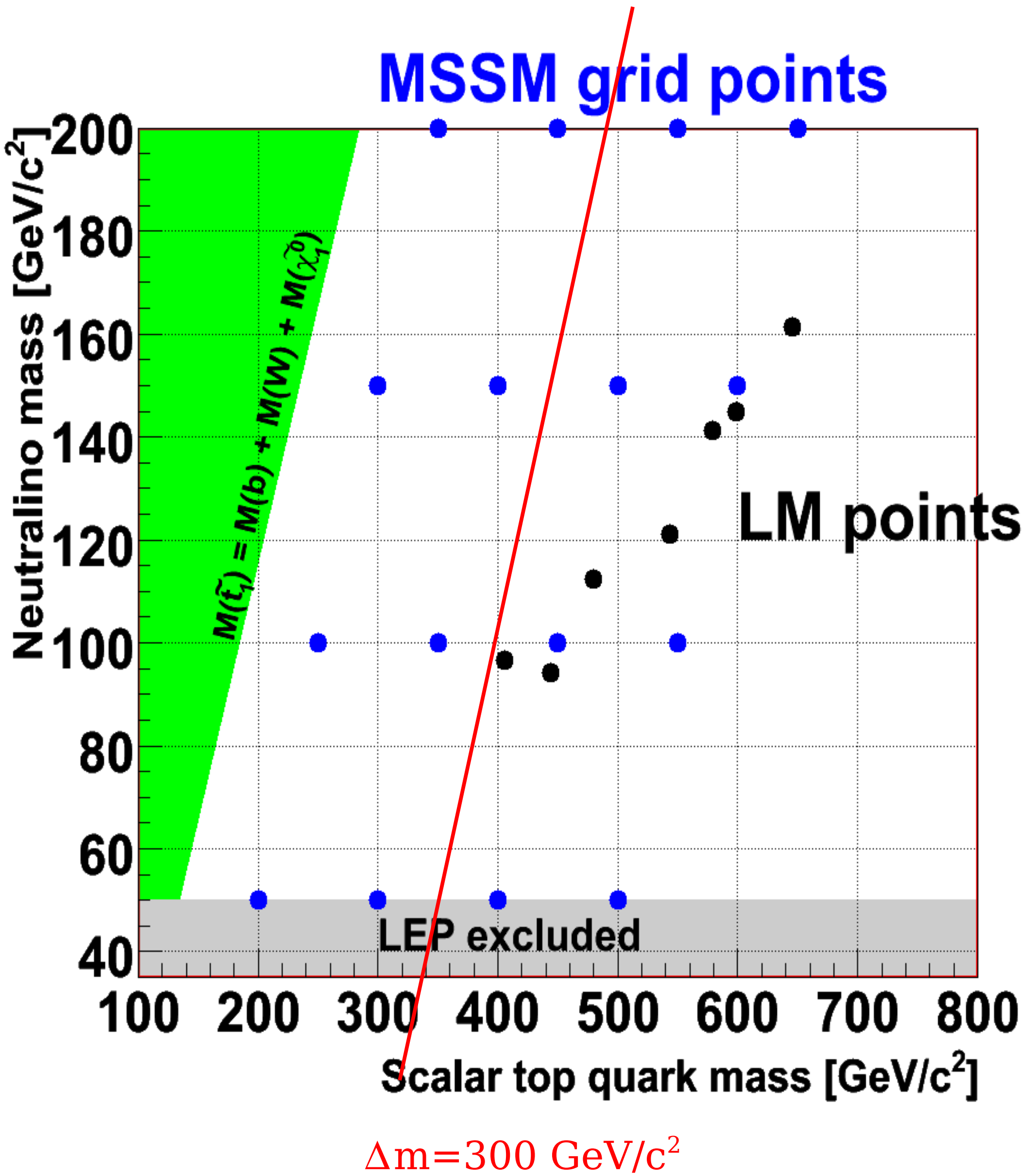
Grid of points

Consider these 2 production modes in a mass-grid

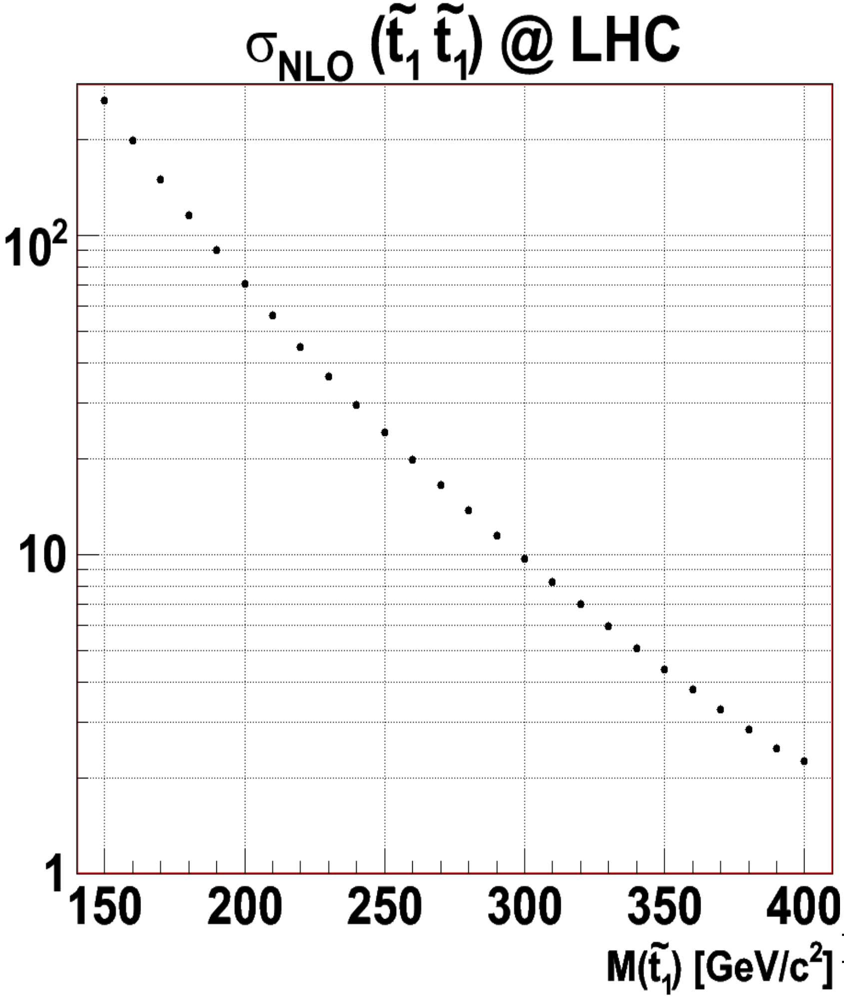
2 kinematic regions:

- $\Delta m < 300$: Soft-kinematic region
- $300 < \Delta m$: Hard-kinematic region: PTDR realm

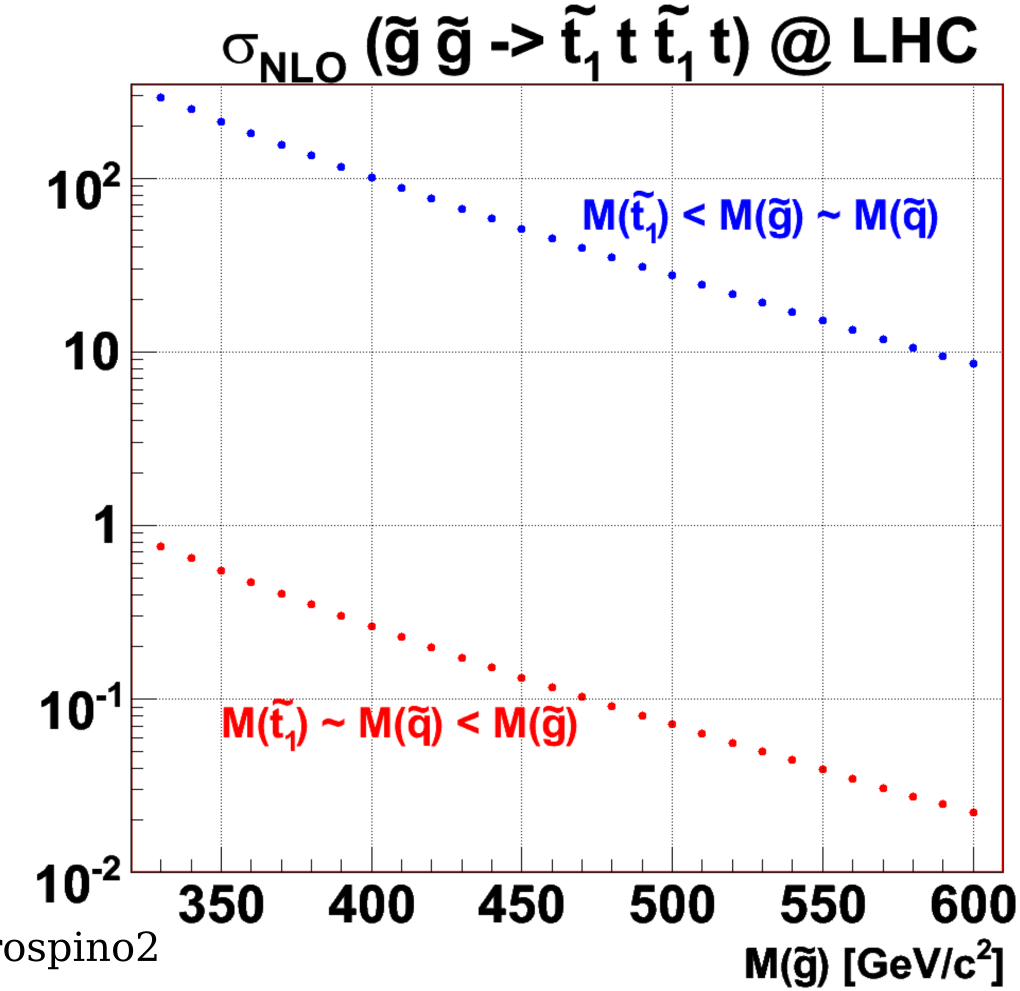
Consider new points, in all direction, as sensitivity will increase with integrated luminosity



Cross-sections: 14 TeV



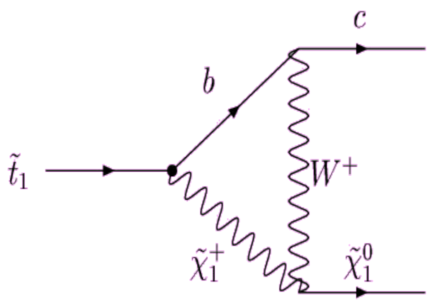
Prospino2



Scenarios:

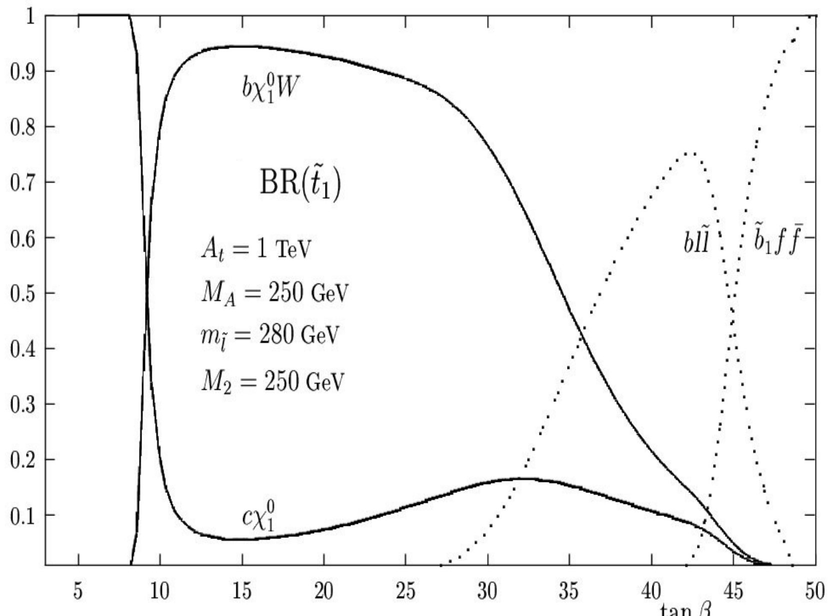
- Most favorable: $\tilde{g} \to \tilde{t}_1 t$ maximally opened: $Br(\tilde{g} \to q\tilde{q}) < 1$
- Less favorable: $Br(\tilde{g} \to \tilde{t}_1 t) \sim Br(\tilde{g} \to q\tilde{q})$

Is c $\tilde{\chi}^0_1$ the only / best window to search for stops ?

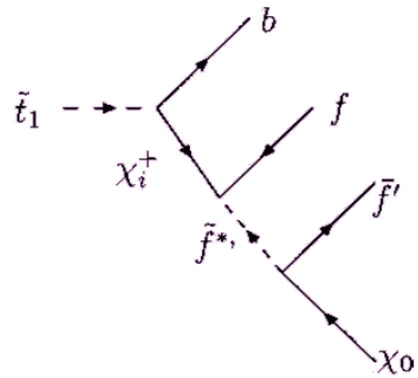


- Big contribution **if** $\log(\Lambda_{GUT}^2/M_W^2) \sim 65$: By choice !
  MSSM: Squark mass unification at low energy…
- $|V_{b\,c}| \sim 0.05$
- Preferred at low tanβ: Excluded by LEP Higgs searches

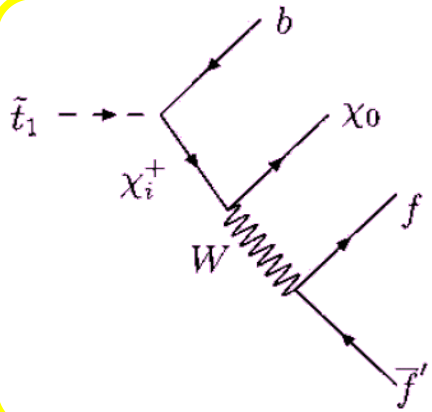
2/3-body decays



Djouadi et al. : PR D, Vol. 63, 115005



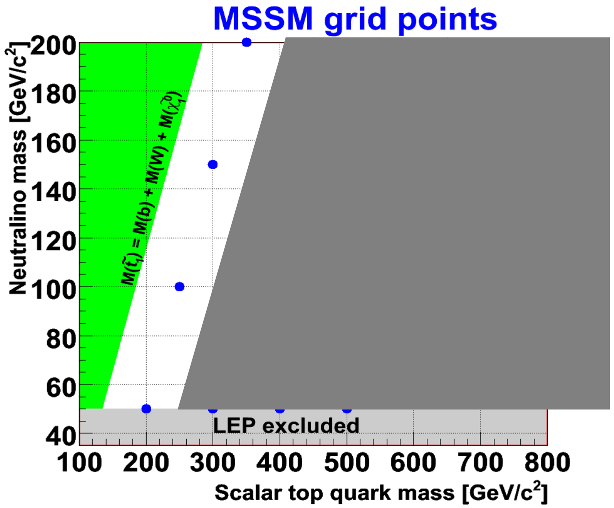
- f' = sneutrino
  f = lepton f̄' = neutrino
- Contributes more
  if M($\tilde{\nu}$) ~ 80 GeV/c²
- Br ($\tilde{\chi}^\pm$ -> $\tilde{\nu}$ lept) = 1/3



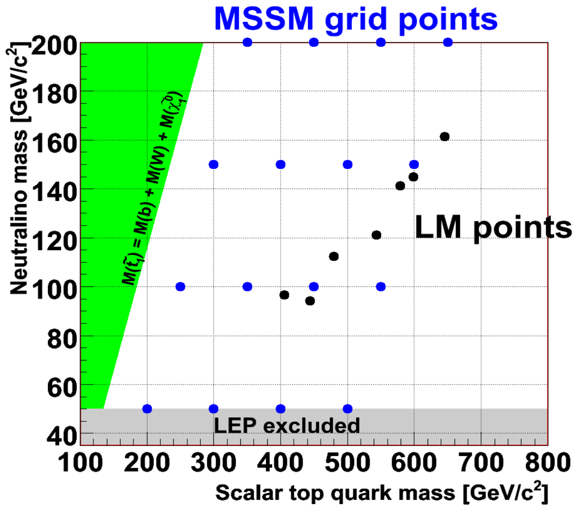
- **No hypothesis on M($\tilde{\nu}$)**
- **Dominating over a large parameter space**

Stop decays: Different diagrams for different domains

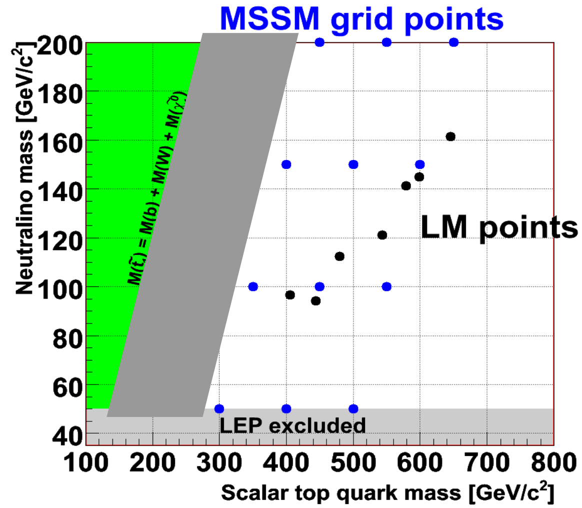
$\tilde{t}_1 \rightarrow b\, W^+ \tilde{\chi}_1^0$



$\tilde{t}_1 \rightarrow b\, \tilde{\chi}_1^+$



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



Conditions:

$b+W+\tilde{\chi}_1^0 < \tilde{t}_1$ | $b+W+\tilde{\chi}_1^0 < \tilde{t}_1$ | $t+\tilde{\chi}_1^0 < \tilde{t}_1$

$\tilde{t}_1 < t+\tilde{\chi}_1^0$: | $W+\tilde{\chi}_1^0 < \tilde{\chi}^+_1 < \tilde{t}_1 - b$

Close $\tilde{t}_1$ -> $t+\tilde{\chi}_1^0$ ← Not exclusive: Will co-exist →

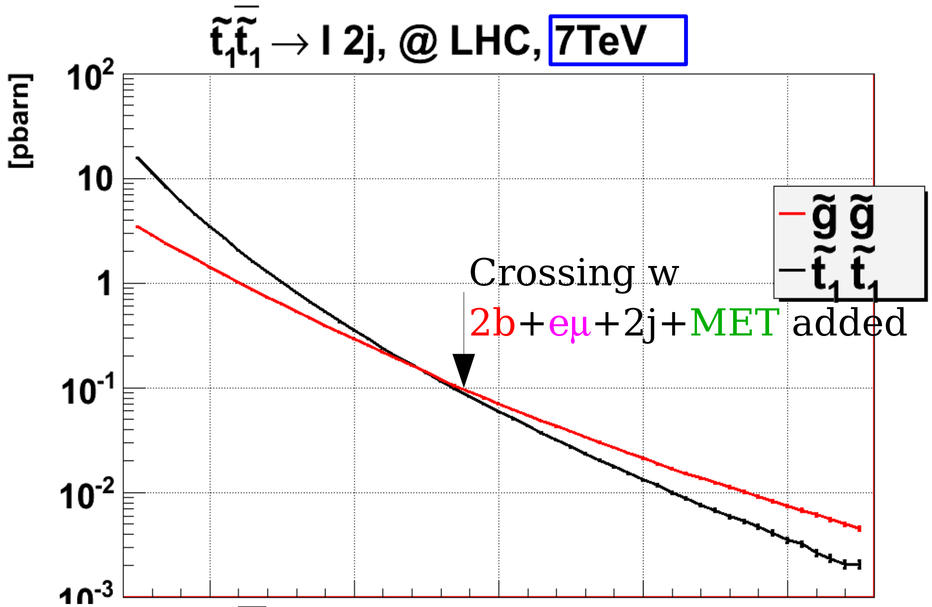
"Dominance" conditions:

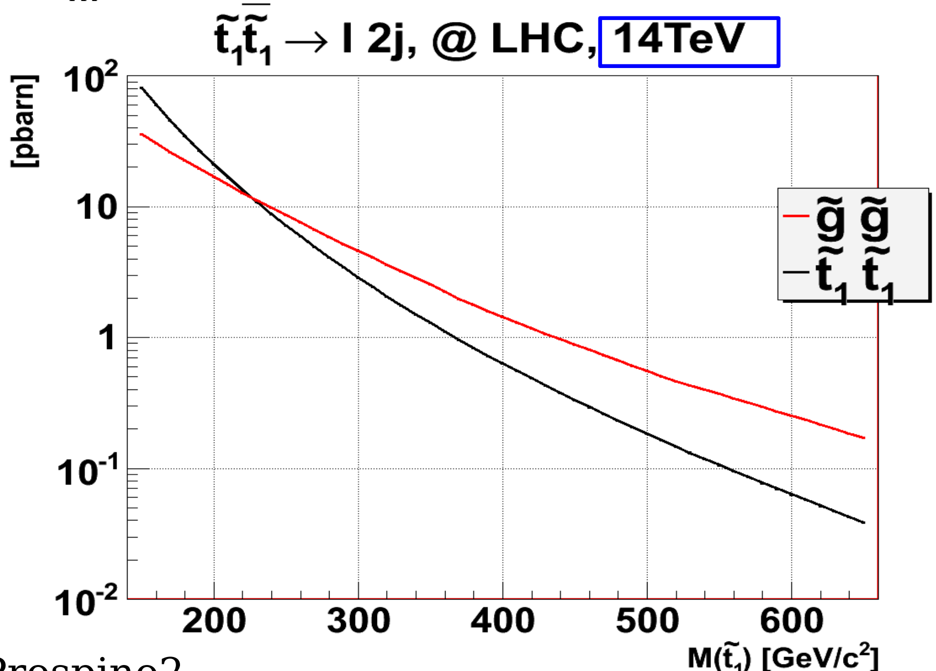
$\tilde{t}_1 < \tilde{\chi}^+_1 + b$: | $t+\tilde{\chi}_1^0 < \tilde{\chi}^+_1 + b$:

Make $\tilde{\chi}^+_1$ virtual | Privilege vs $b\, \tilde{\chi}_1^+$

1st the $\tilde{t}_1 \rightarrow b\, \tilde{\chi}_1^+$ decay-mode (covering largest mass range), then others

Cross-sections: "Final picture" @ 7 / 14 TeV





Prospino2

Let's 1st calculate total cross sections for $\tilde{t}_1\tilde{t}_1$ & $\tilde{g}\tilde{g}$:

$\tilde{t}_1\tilde{t}_1 \to$ 2b + e+μ+2j + MET

$\tilde{g}\tilde{g} \to$ 4l+3l+2l (just for exercise)

For given selection efficiency:
The $\tilde{g}\tilde{g}$ production mode dominates more at lower stop mass @ 14 TeV

→ 7-8 TeV runs: More $\tilde{t}_1\tilde{t}_1$ oriented

Needed data: Back-of-envelop calculations

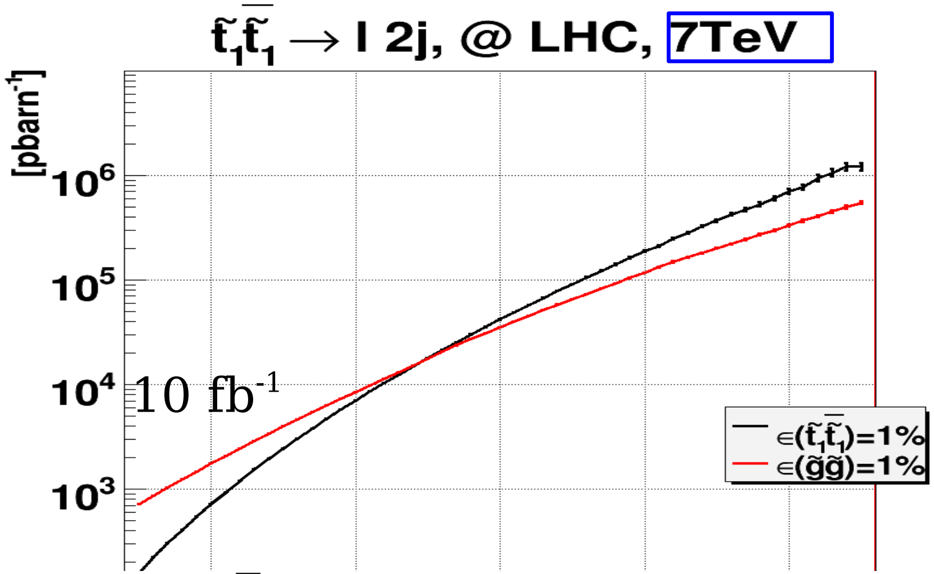
How much data needed for 5σ observation ? A couple of simplistic hypothesis:
→ 25/~0 signal/background events :-)
→ Signal efficiencies: 1%

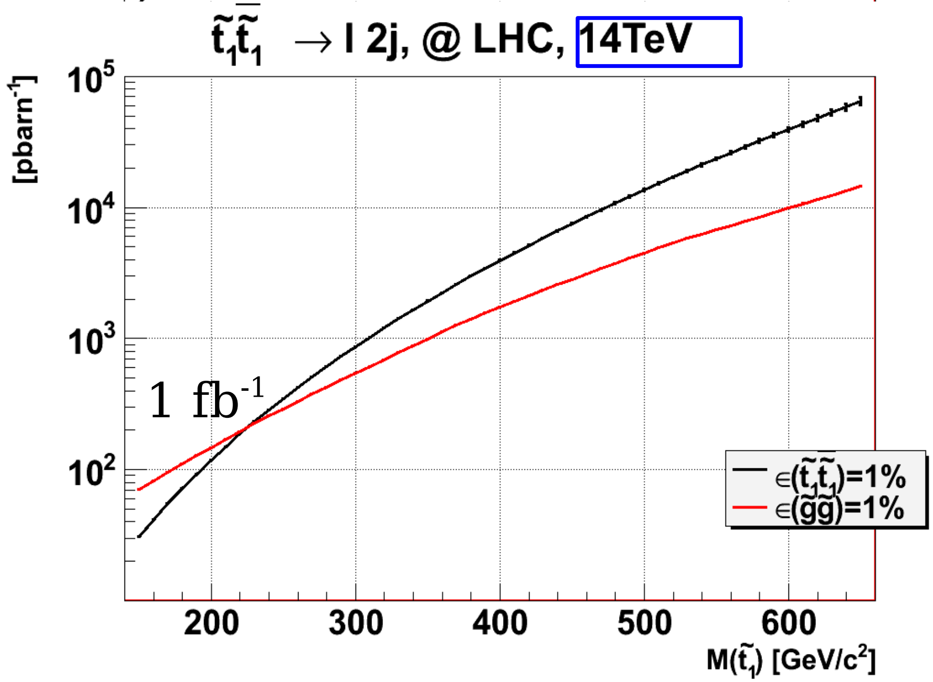
For low stop mass [150,300]GeV
$\tilde{t}_1\tilde{t}_1$: Get sensitivities w 1-10 fb^{-1}

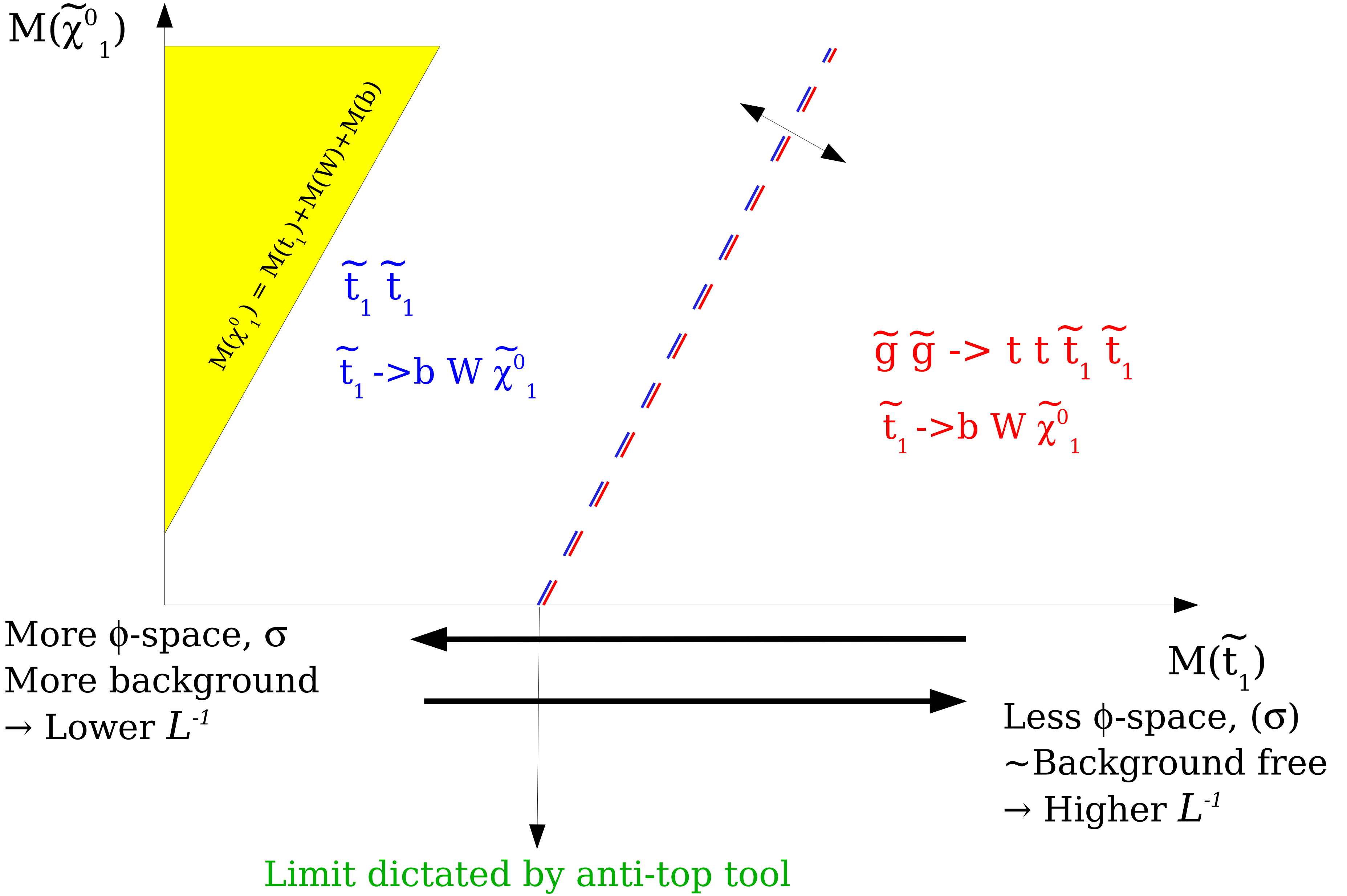
For higher stop mass:
→ Shift to $\tilde{g}\tilde{g}$
→ Even w $\tilde{g}\tilde{g}$: Need ~100 fb^{-1} @ 7TeV
→ **Waiting for 14 TeV**

→ **Have to have eff ~ O(10%)**

Even if the $\tilde{g}\tilde{g}$ production is more advantageous over some mass range: Who tells that $\tilde{g}$ will be produced ?
→ **Study the $\tilde{t}_1\tilde{t}_1$ mode anyway !**





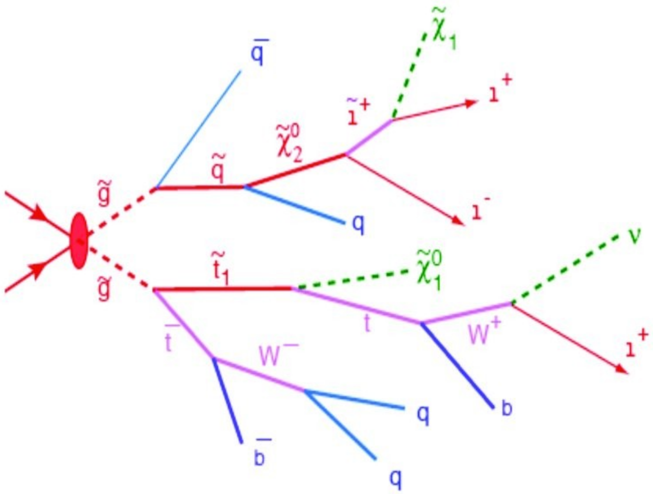

$M(\tilde{\chi}^0_1)$
$M(\chi^0_1) = M(t_1)+M(W)+M(b)$
$\tilde{t}_1\ \tilde{t}_1$
$\tilde{t}_1 \to b\ W\ \tilde{\chi}^0_1$
$\tilde{g}\ \tilde{g} \to t\ t\ \tilde{t}_1\ \tilde{t}_1$
$\tilde{t}_1 \to b\ W\ \tilde{\chi}^0_1$
More φ-space, σ
More background
→ Lower L^{-1}
$M(\tilde{t}_1)$
Less φ-space, (σ)
~Background free
→ Higher L^{-1}
Limit dictated by anti-top tool

Closing words…

SUSY is here to stay/discovered: Has to be explored !!!

Cures (so many) shortcomings of SM...
Around 1 TeV ?... and we have a ≥ 7 TeV microscope

Be realistic & prepared for the “worst” scenarios



... and only a few sParticles at the bottom of the SUSY mass-hierarchy might be produced

In these “worst” scenarios:
Bet on the one of the best “horses”: One of the probably lightest, thus most easily observable ones: Stop is among them...

Conclusion: Plan for stop search

- **Realistic**:
  - Based on SUSY particle <u>masses</u>
  - Pick up the 2 simplest production modes
- **Systematic / Coherent**:
  - Changing production- & decay-modes versus stop-mass, thus L^{-1}
- **As generic as possible**:
  - Only the spin hypothesis: MSSM
  - Try to cover as much possibilities as possible
- **In complementarity** with how we have started to look for SUSY:
  - Taking the benefit of already existing expertise per final state: Plugs well in already existing LHC searches
  - With increasing data: Time to use our *per-final-state* experience for searching *a given SUSY object in different final states*, kinematic regions

$\sim t_1$ as one of the only SUSY signatures might be there, even below 500 GeV/c^2, but in stealth mode: Rather low σ & "sitting on" SM. Requires new thinking, new tools, many-case-covering effort: A privileged axis of search for coming years

Many thanks to:

- *J. Lykken & A. De Roeck for their support*
- *All the MadGraph team for their great help & patience*

Backup slides

Generic tool: On-Shell Effective Theory (OSET)

Once there is evidence of data Beyond the Standard-Model, OSETs:

- Instead of describing the full Lagrangian..
- ...“characterizes hadron collider data in terms of masses, production cross sections, and decay modes of candidate new particles”
  - “allows efficient analysis of new-physics signals, especially when they arise from complicated production and decay topologies”

As such, it's a **generic interpretation-tool, not a generic searching-tool**

- It's a bottom → up, i.e. experiment → “phenomenology” tool
- “reconstructs the fundamental theory of the TeV scale from LHC data”
- “constrains the underlying new physics, and sharply motivates the construction of its Lagrangian”

Anti-ttbar tool

We are looking for in 2 x $\tilde{t}_1$ → 2 x (b W $\tilde{\chi}^0_1$)

Irreducible tt-bar background in:

- tt -> 2b 2l Met
- tt -> 2b l 2jets MET

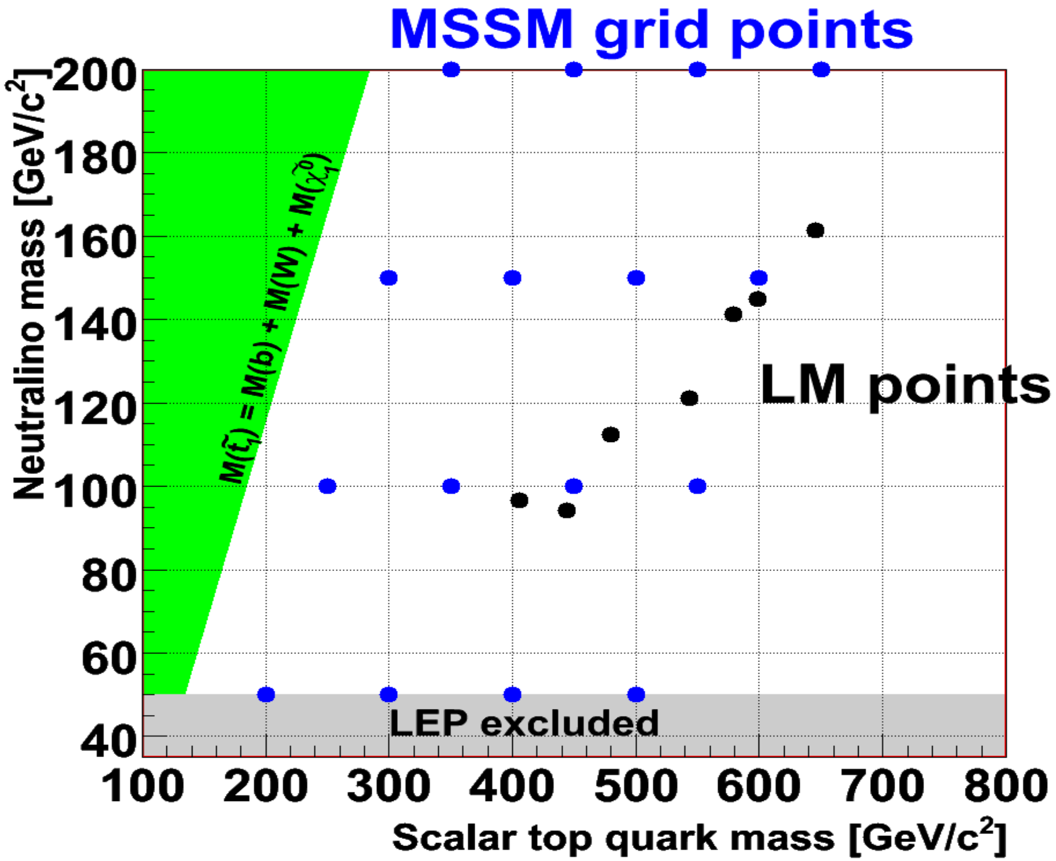
Way to go / Challenge:

- Reconstruct top mass in:
  - Dilepton (MET for 2 ν) / Semileptonic (Jet pairing: t->bjj)
  - In both cases: **Key = Top mass resolution**
- Separate top-peak from stop distribution
  - Reject as much/less as possible ttbar/$\tilde{t}_1\tilde{t}_1$
  - Stop $\tilde{t}_1\tilde{t}_1$ search as soon as [σ.Sel]($\tilde{t}_1\tilde{t}_1$) < σ(New $\tilde{t}_1$ production mode)

This is only the projection of the points in $\{M(\tilde{\chi}_1^0),M(\tilde{t}_1)\}$
Each of these MSSM, i.e.
$\mathbf{\{M(\tilde{\chi}_1^0),M(\tilde{t}_1),M(\tilde{q}),M(\tilde{g})\}}$
points, has to be used to generate:

- $\tilde{t}_1\ \tilde{t}_1$ production
- $\tilde{g}\ \tilde{g} \to \tilde{t}_1\ \tilde{t}_1\ t\ t$ production

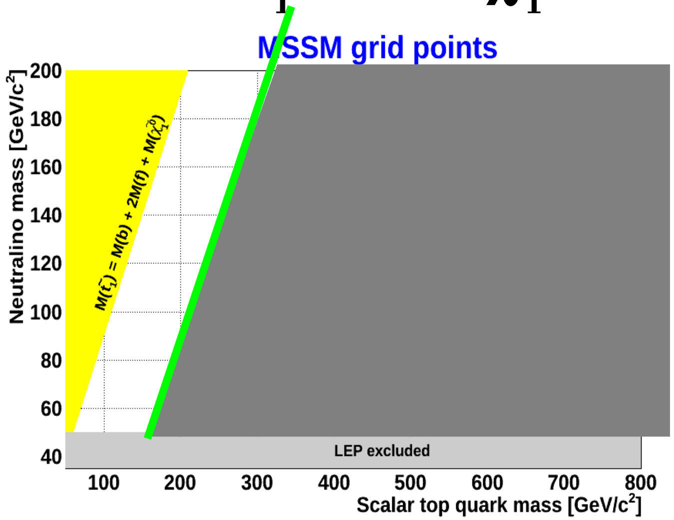
For each $\{M(\tilde{\chi}_1^0),M(\tilde{t}_1)\}$, we consider:



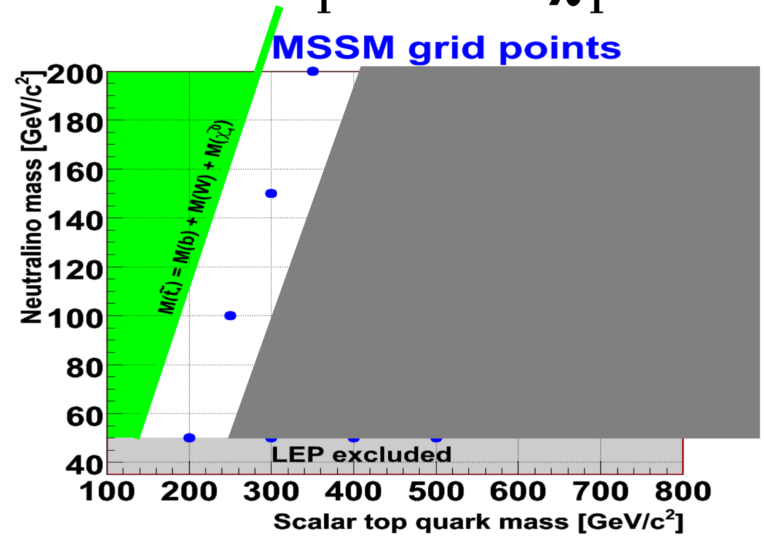
- **1 gluino mass**: $M(\tilde{g})=M(\tilde{t}_1)+M(t)+25$: Purposefully consider softest of gluino decays; also limits number of different hypothesis to be done
- **2 squark mass** hypothesis corresponding to 2 scenarios:
  - $M(\tilde{g})\sim M(\tilde{q})>M(\tilde{t}_1)$: $Br(\tilde{g} \to \tilde{t}_1\ t) \sim 50\%$
  - $M(\tilde{g})>M(\tilde{q})\sim M(\tilde{t}_1)$: $Br(\tilde{g} \to \tilde{t}_1\ t) \sim 1\text{-}2\%$

~t1 decays: Did-we cover all decay scenarios ? Not yet...

$\tilde{t}_1 \rightarrow b\, ff'\, \tilde{\chi}_1^0$



$\tilde{t}_1 \rightarrow b\, W^+\, \tilde{\chi}_1^0$



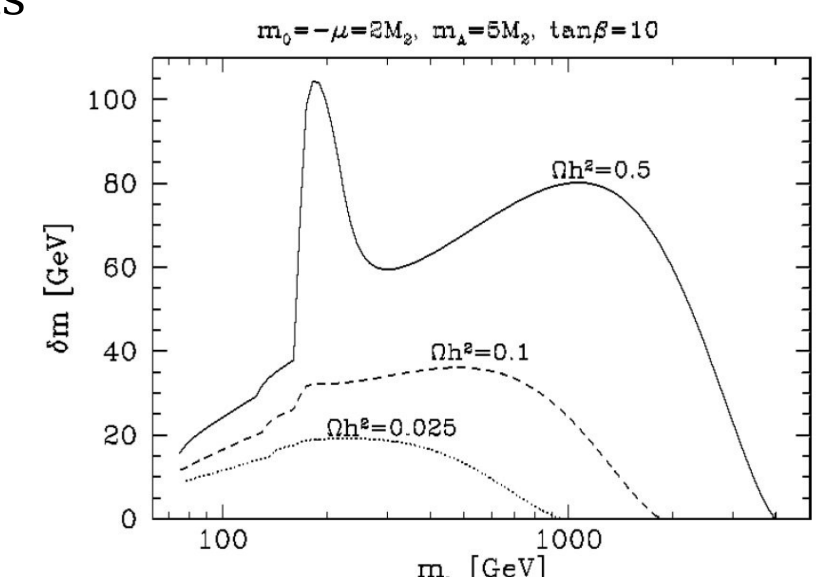
If $\delta m = M(\tilde{P}) - M(\tilde{\chi}^0_1)$ small, co-annihilations dominates → $\Omega_{CDM} h^2 \approx 0.1$

$\mathbf{\Omega_{CDM} h^2 = 0.11 \pm 0.01}$ @ 95% CL (WMAP) compatible with

$\Delta m = M(\tilde{t}_1) - M(\tilde{\chi}^0_1) \leq 50\ GeV/c^2$:

If SUSY: Cosmology seems to prefer very low Δm decays, here $\tilde{t}_1$ **4-body decays**:

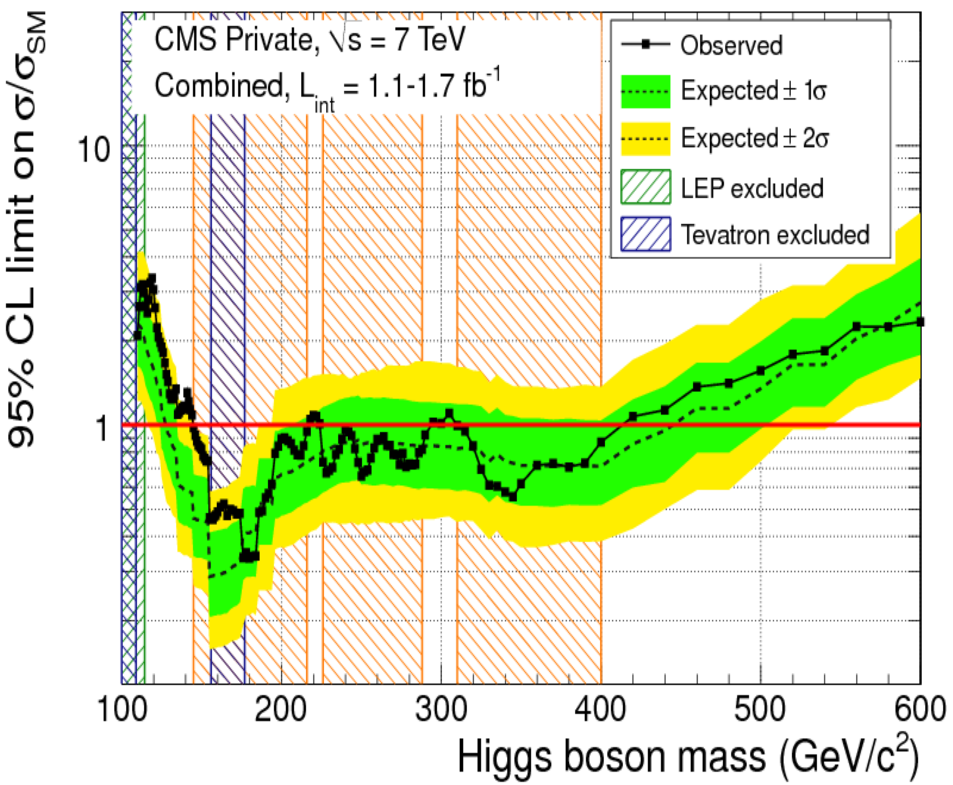
Very soft kinematics

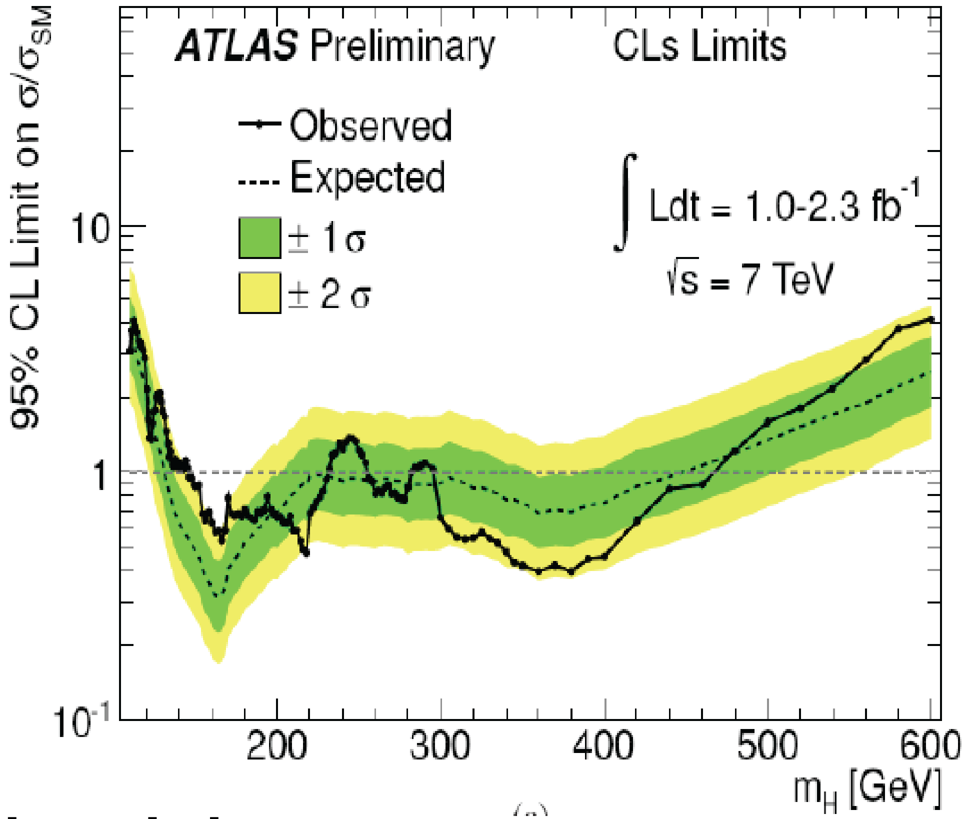


Boehm et al., PRD 62, 35012

Backup slides:
About Higgs ↔SUSY

Higgs: Where do we stand ?





- CMS+ATLAS combination: Probably exclude
  - High-mass: >145 GeV/c^2
  - SM type Higgs
- If we want to 95% CL-exclude SM Higgs over the whole mass range: Probably need 8-10 /fb
- Die-hard view on SM Higgs: With 30 /fb, able to 99% CL-exclusion up to 600 GeV/c^2

Questions

Typical (& legitimate) questions you hear in conference and physics-week coffee-breaks....

- Do present Higgs search limits exclude MSSM ?
- Does “no h -> 2γ” mean “end of SUSY” at all ?

Let's look at equations that theorists have in their minds & that experimentalists never mention...

Equations: Higgs in MSSM

2 Higgs complex doublets:

$$V_H = \left(|\mu|^2 + m_1^2\right)|H_1|^2 + \left(|\mu|^2 + m_2^2\right)|H_2|^2 - \mu B \epsilon_{ij}\left(H_1^i H_2^j + \text{h.c.}\right) + \frac{g^2 + g'^2}{8}\left(|H_1|^2 - |H_2|^2\right)^2 + \frac{1}{2} g^2 |H_1^* H_2|^2 \quad .$$

8 degrees of freedom – 3 (massive gauge bosons) = 5 physical Higgs fields:
h / H / H$^{\pm}$ / A (CP-odd)

2 VEVs:

$$\langle H_1^0 \rangle \equiv v_1$$
$$\langle H_2^0 \rangle \equiv v_2$$

→ Key MSSM parameter: $\tan\beta \equiv \frac{v_2}{v_1}$

3 parameters to describe the MSSM Higgs sector

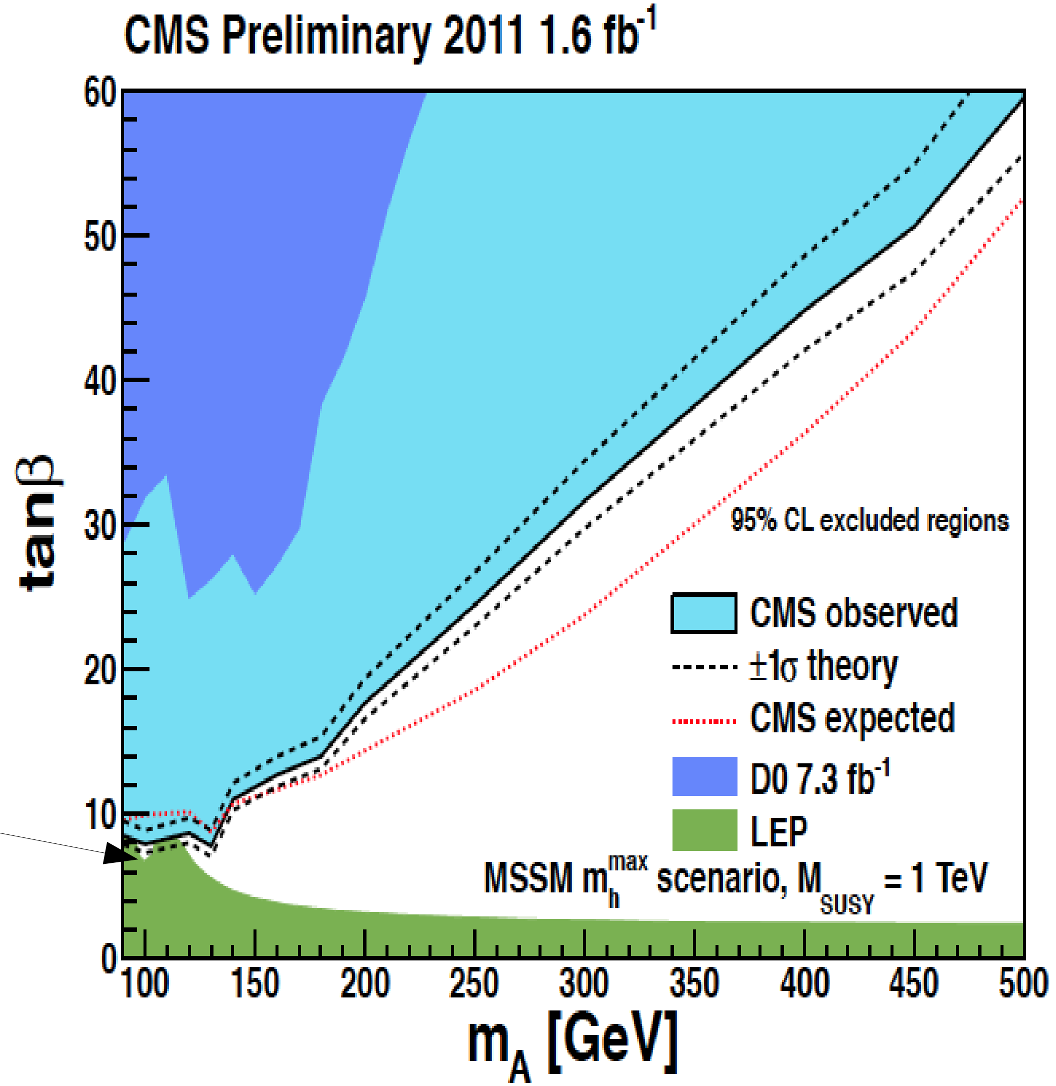
Once $v_{1,2}$ are fixed such that: $M_W^2 = \frac{g^2}{2}(v_1^2 + v_2^2)$

This whole sector is described by (only) 2 other parameters:
→ $\tan\beta$
→ M_A: $M_A^2 = \frac{2|\mu B|}{\sin 2\beta}$

Do present Higgs search limits exclude MSSM ?

Not really:

- M_A has no (dynamic) reason to be < 500, 700 GeV/c^2
  - High M_A region still quite open
- Be careful: Do not interpret this plot as a "probability density plot for something to exist": **IF** SUSY exists, it will be in 1 given spot
  - Could be here



The 1st M in MSSM means Minimal: We are dealing with 124 parameters here... "Not constrained at all" framework

{No h -> 2γ} = {End of SUSY} ?

Let's 1st look at places where MSSM looks like SM: **Decoupled regime**

1/ Light h "SM like":

→ Mass: Rather low

→ Br(h -> γγ) ~ Like in SM

2/ {H, H±, A} much heavier & degenerate

→ Couplings of lightest Higgs to fermions/γ/W/Z ~ Like in SM

→ Couplings of "additional" Higgs to fermions/γ/W/Z ~ 0

$$Z^\mu Z^\nu h: \quad \frac{igM_Z}{\cos\theta_W}\sin(\beta-\alpha)g^{\mu\nu}$$

$$Z^\mu Z^\nu H: \quad \frac{igM_Z}{\cos\theta_W}\cos(\beta-\alpha)g^{\mu\nu}$$

$$W^\mu W^\nu h: \quad igM_W\sin(\beta-\alpha)g^{\mu\nu}$$

SM couplings

$$\sin(\beta-\alpha) \to 1 \text{ for } M_A \to \infty$$
$$\cos(\beta-\alpha) \to 0 \quad .$$

Similar for coupling to γ & fermions

If SM Higgs, i.e. h → 2γ, not found over [115,...] GeV/c²:

→ No Higgs and/or MSSM at all

→ {There is an MSSM Higgs} & {couplings to 2γ are disfavored, i.e. we're not in a decoupled regime mode}

I doubt that LHC will have enough stat to mesure Higgs couplings...

More on Higgs <-> SUSY bounds

Equation governing lightest Higgs mass:

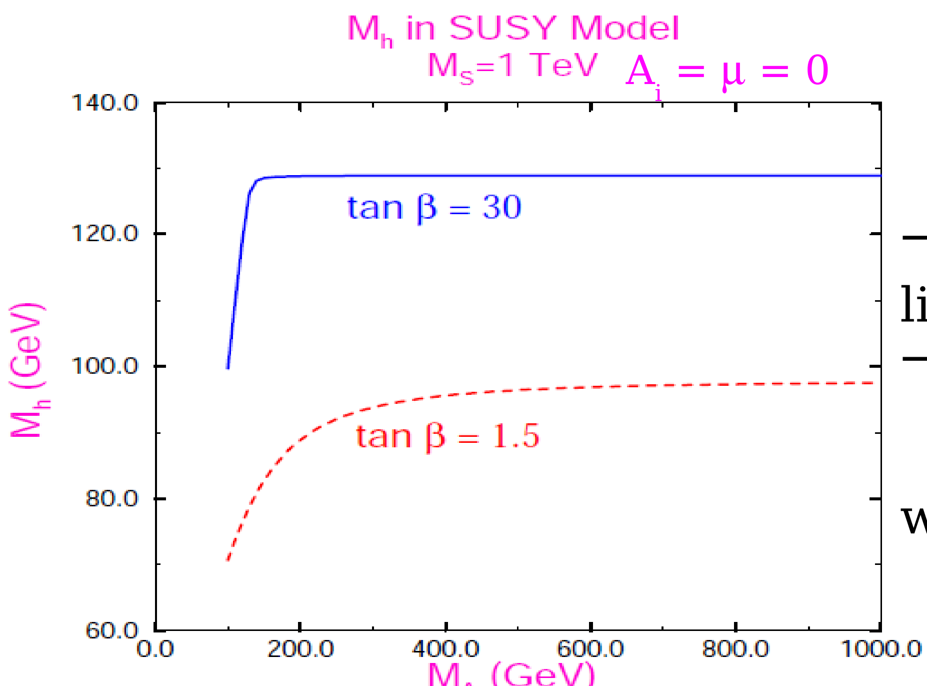
$$M^2_{h,H} = \frac{1}{2}\left\{M_A^2+M_Z^2+\frac{\epsilon_h}{\sin^2\beta} \pm \left[\left(\left(M_A^2-M_Z^2\right)\cos 2\beta+\frac{\epsilon_h}{\sin^2\beta}\right)^2+\left(M_A^2+M_Z^2\right)^2\sin^2 2\beta\right]^{1/2}\right\}$$

with: $\epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log\left(\frac{\tilde{m}^2}{M_T^2}\right)$

Contribution of 1-loop correction only !
Squark masses: Higgs mass particularly sensitive to $\sim t_{1,2}$ system

Upper bound:

$$M_h^2 < M_Z^2 \cos^2 2\beta + \epsilon_h$$



→ The "well-known" M_h < 135 GeV/c^2 limit for any-SUSY lightest Higgs
→ ...is dependent on
→ 2-loop calculations
→ Renormalization calculations
which can evolve...

Higgs/SUSY

- **Higgs/SUSY:**
  - Even though there is a rich Higgs <-> MSSM interconnection
    - Absence of SM-like Higgs doesn't exclude MSSM: It only brings down SM-favored couplings -> Have to look in MSSM-favored decays, which we do
      - We are only exploring lower M_A values: Still some room to look for SUSY-Higgs