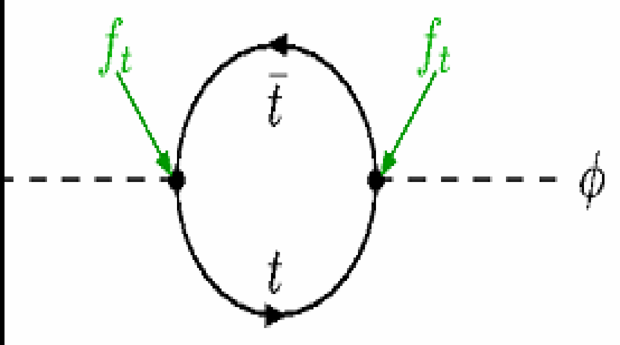
Search for SUSY with The ATLAS Detector at the LHC

- Motivation
- Phenomenology
- Model Driven
- Inclusive Searches
- Event Reconstruction
- RPV

Radiative Corrections to the Higgs Boson Mass

Corrections to the Higgs-boson mass diverge quadratically



$$\delta m^2_{\phi,t} = \frac{3f_t^2}{8\pi^2}\Lambda^2 + \mathcal{O}(\Lambda/m_\phi)$$

Where Λ is the momentum cutoff in the loop (GUT or Plank scale)

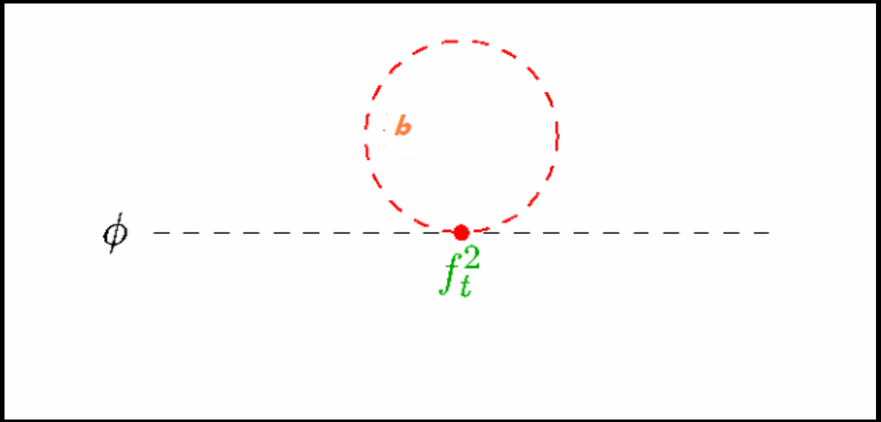
➔$M_H \sim 10^{16}$-10^{18}GeV

But the SM requires that $M_H \leq 1000$GeV

So we need fine tuning of $> 10^{30}$!!!!

Possible cancellation

A bosonic loop like:



$$\delta m^2_{\phi,\tilde{t}} = -\frac{3f_t^2}{8\pi^2}\Lambda^2 + \cdots$$

fermionic

$$\delta m^2_{\phi,t} = \frac{3f_t^2}{8\pi^2}\Lambda^2 + \mathcal{O}(\Lambda/m_\phi)$$

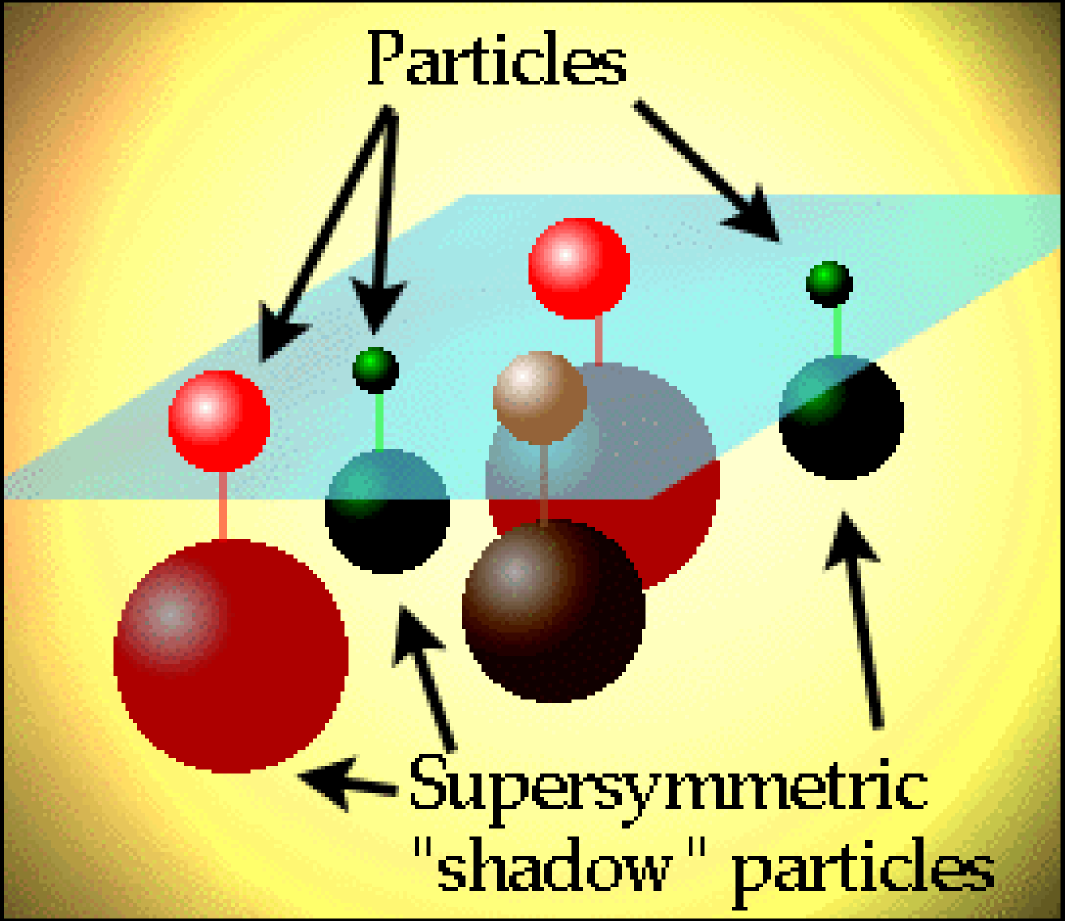
So bosonic and fermionic loops cancel each other

The Supersymmetric Solution

- Postulate symmetry between fermions-bosons

fermions ↔ bosons

- SUSY: “To every fermionic degree of freedom corresponds a bosonic degree of freedom”.
- So, a SM fermion acquires two super-partners
  - e.g. u-quark → s-tops: u_R & u_L
- One must have two Higgs doublets → 5 Higgs bosons (h,H,A,H^+,H^-)
- The Fermionic counterparts of the Higgs bosons and gauge bosons carry the same Quantum number and mix


Particles
Supersymmetric
"shadow" particles

The Fermionic SUSY sector

The supersymmetric partners of the 2 charged Higgs boson mix with those of the W^+ and W^- to give two charginos. Similarly , the supersymmetric partners of the Z, h,H,A and photon mix to give rise to four neutralinos.

H+
W+
H-
W-

$\chi_1^{\pm}$
$\chi_2^{\pm}$

Chargino

Z^0
h^0
H^0
A^0
γ

χ_1^0
χ_2^0
χ_3^0
χ_4^0

neutralino

SUSY Breaking

SUSY must be broken otherwise the supersymmetric particles would already be seen.

The breaking must be done in such a way that the cancellation of divergencies still works → supersymmetric particles must be relatively light O(1 TeV).

The breaking determines the phenomenology and the way SUSY will exhibit itself in future experiments

R or not

The most general SUSY lagrangian contains 3 terms:

$$+\frac{1}{2}\lambda_{ijk}LL\overline{E}+\lambda'_{ijk}LQ\overline{D}+\frac{1}{2}\lambda''_{ijk}\overline{U}\,\overline{D}\overline{D}+\kappa LH_u$$

Which are problematic and do not preserve the normal QN. Two of them can give rise to proton decay which is experimentally bounded very strongly. A way to avoid this problem is to introduce a new quantum number, R, which should be conserved:

$$\boxed{R\equiv(-1)^{3b+2s+L}=(-1)^{3(b-L)+2s}}$$

If indeed R is conserved: There is a lightest SUSY particle (LSP)

SUSY particles are produced in pairs

Other Motivations for SUSY

- Biggest possible symmetry of interacting QFTs
  - (Lorentz sym.) $\oplus$ (gauge sym.) $\oplus$ (SUSY)
- The only way known which allows unification of Gravity with the other interactions
- Provides a natural candidate for Dark Matter.

SUSY Breaking Models

The most general case has 105 free parameters.

Must make some simplifications in order to have a predictive theory: The easiest way – assume boundary conditions at the Planck scale, namely:

1. Common scalar mass m_0
2. Common gaugino mass $m_{1/2}$
3. Common trilinear scalar interaction A

These, together with the parameters of the Higgs sector:

4. Ratio of vevs of two Higgs fields $\tan\beta$
5. Sign of Higgs mass parameter μ

Define the whole model

Alternative Procedures

The mSugra, which was defined in the previous slide is not the only way. SUSY can be broken in a hidden sector somewhere in an intermediate scale (M) between the Planck and electroweak ones. The amount of SUSY breaking is a fundamental parameter (Λ), and the coupling of the LSP which is the gravitino in this model to the NLSP is another (κ). Thos together with the Higgs sector parameters ($tan\beta$ and μ) define the so called Gauge Mediated model (GMSB)

… and there are other models like AMSB, FMSB etc. and nobody knows if one of these models is right

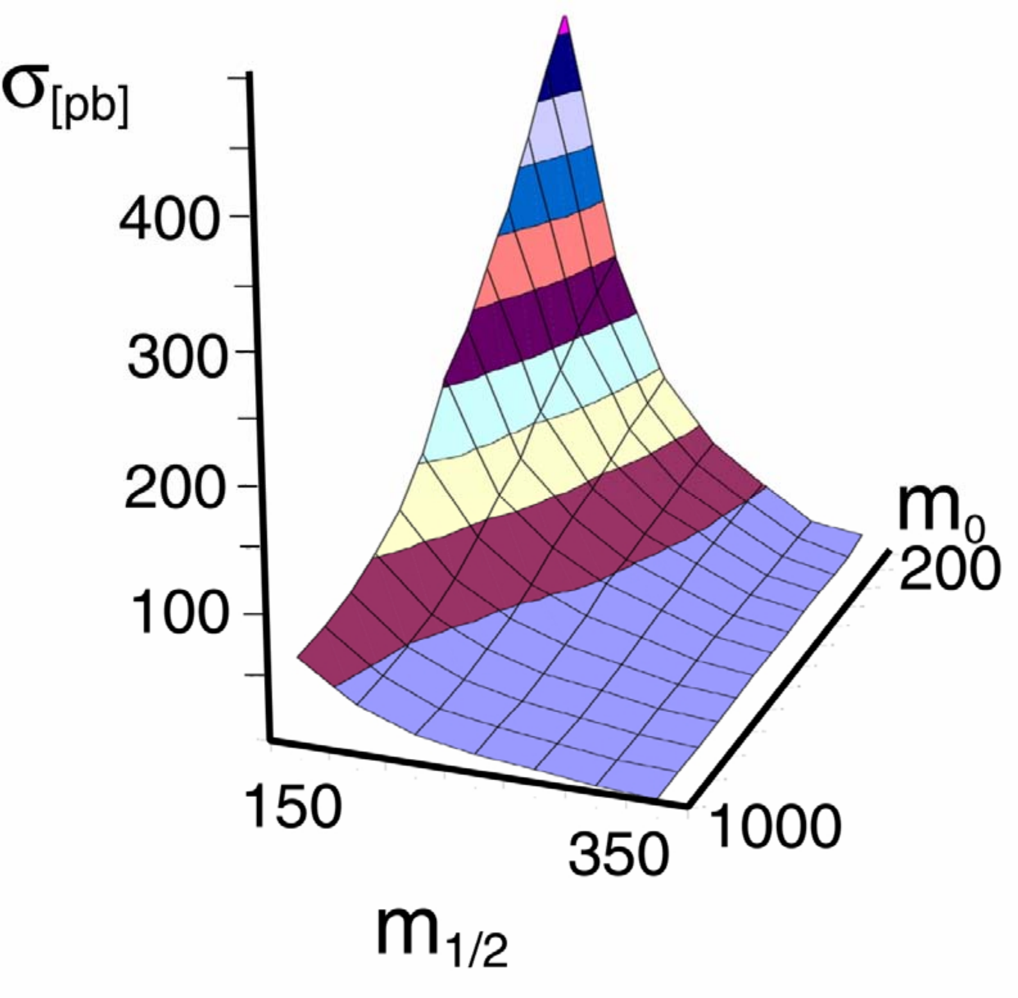
How will SUSY be seen?

There are many models. Each has many parameters. Each set of parameters in each of the models gives rise to a different mass spectrum. The mass spectrum defines how will the signal look.

Not knowing which is the right model and which are the values of the parameters implies that:

We do not know which signals will SUSY leave in our detectors !!!!

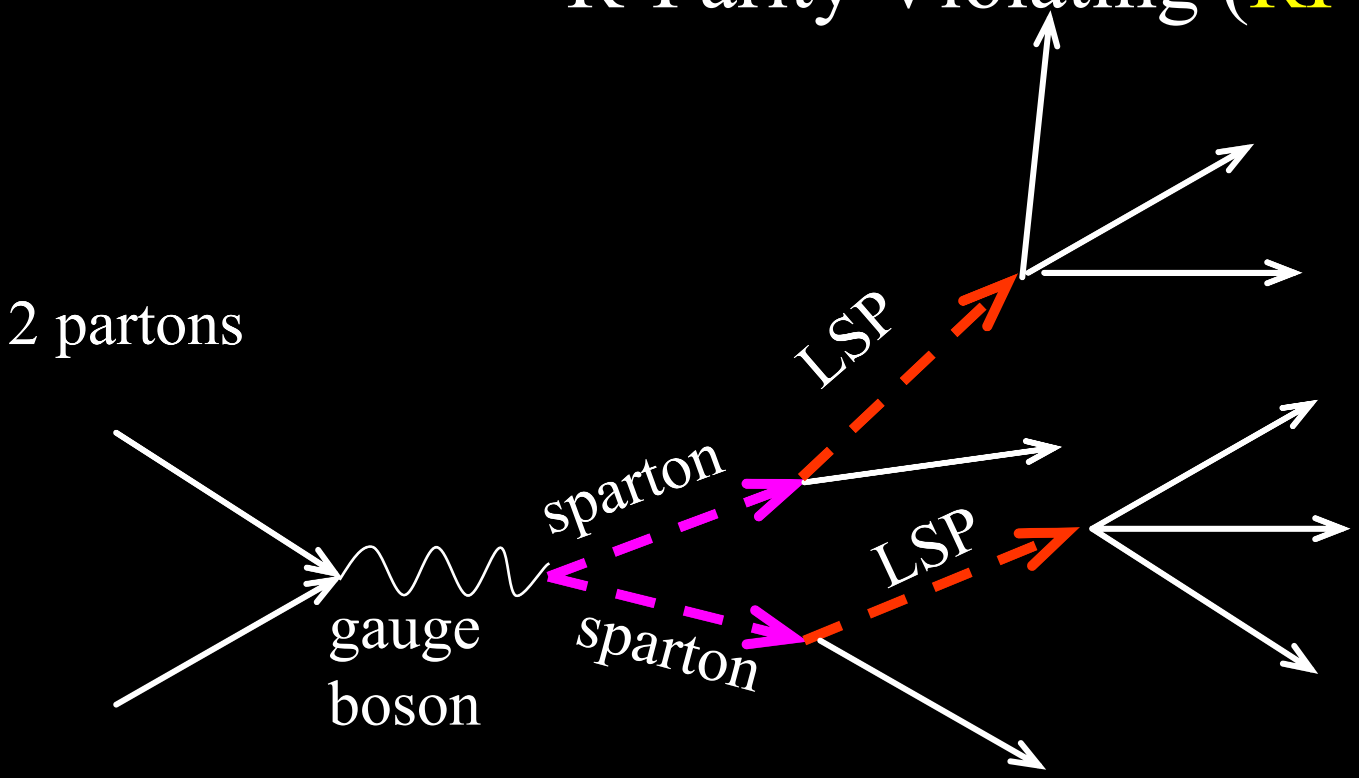
Potentially Huge Cross-Section



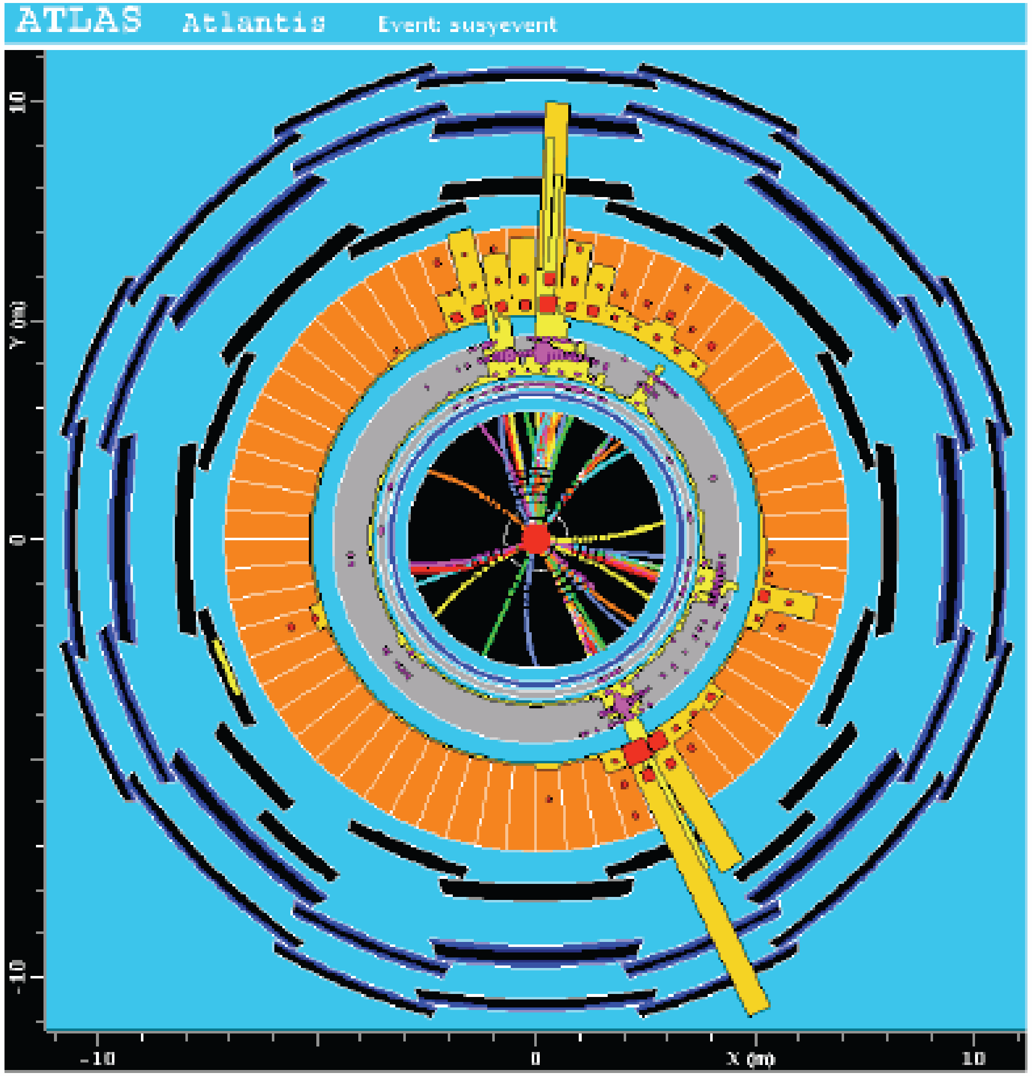
Search Strategies

Basic separation: R-Parity Conserving (RPC)

R-Parity Violating (RPV)

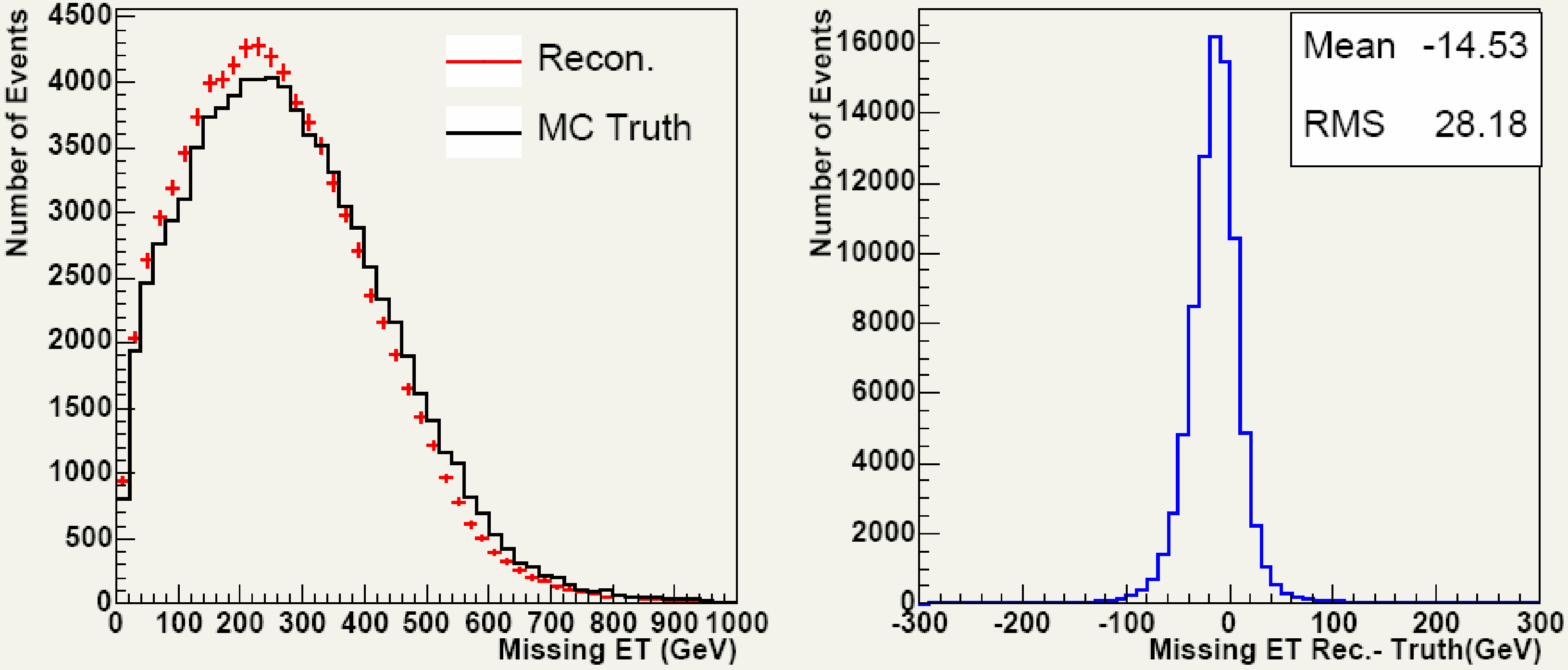


Simulated event



E_T^{miss} and high P_T jet are key for discovery of SUSY

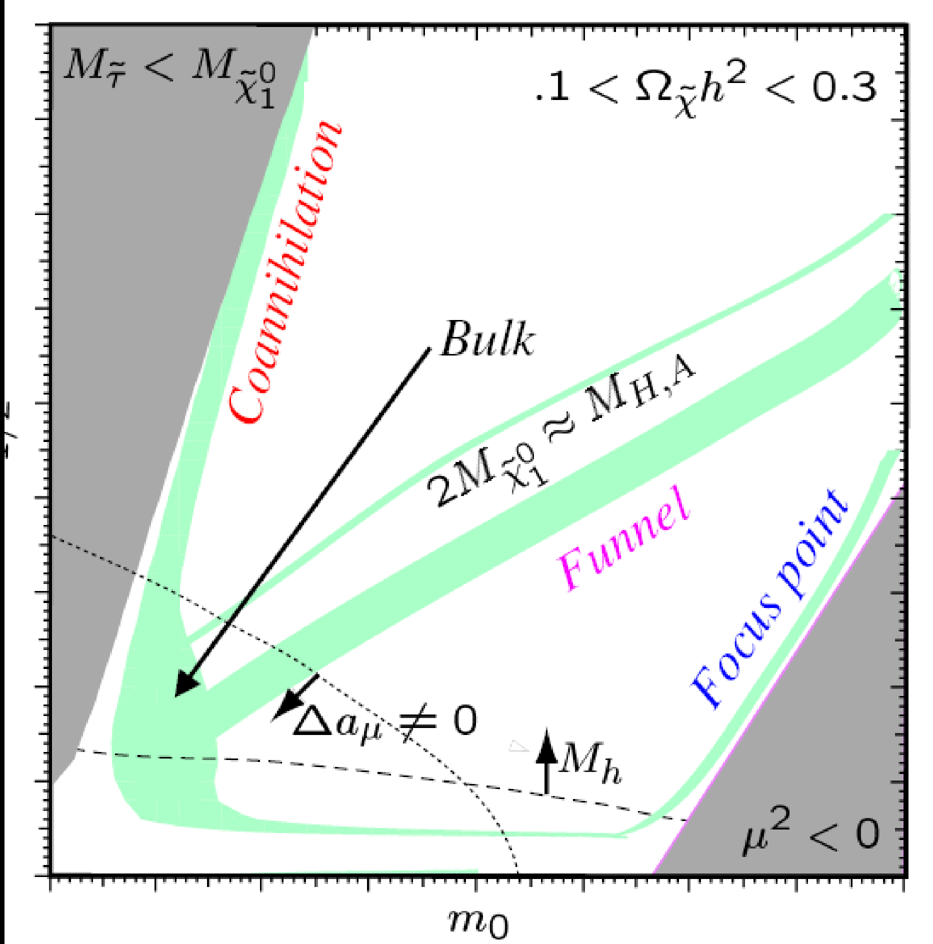
Missing ET reconstruction



10 ÷ 20 GeV Shift Observed in all the samples.

Model Driven: MSSM

Model driven analyses are relatively easy (you know what you are looking for). The most popular model is MSSM. Lots of physics input is injected in order to focus the work on ‘more likely’ regions



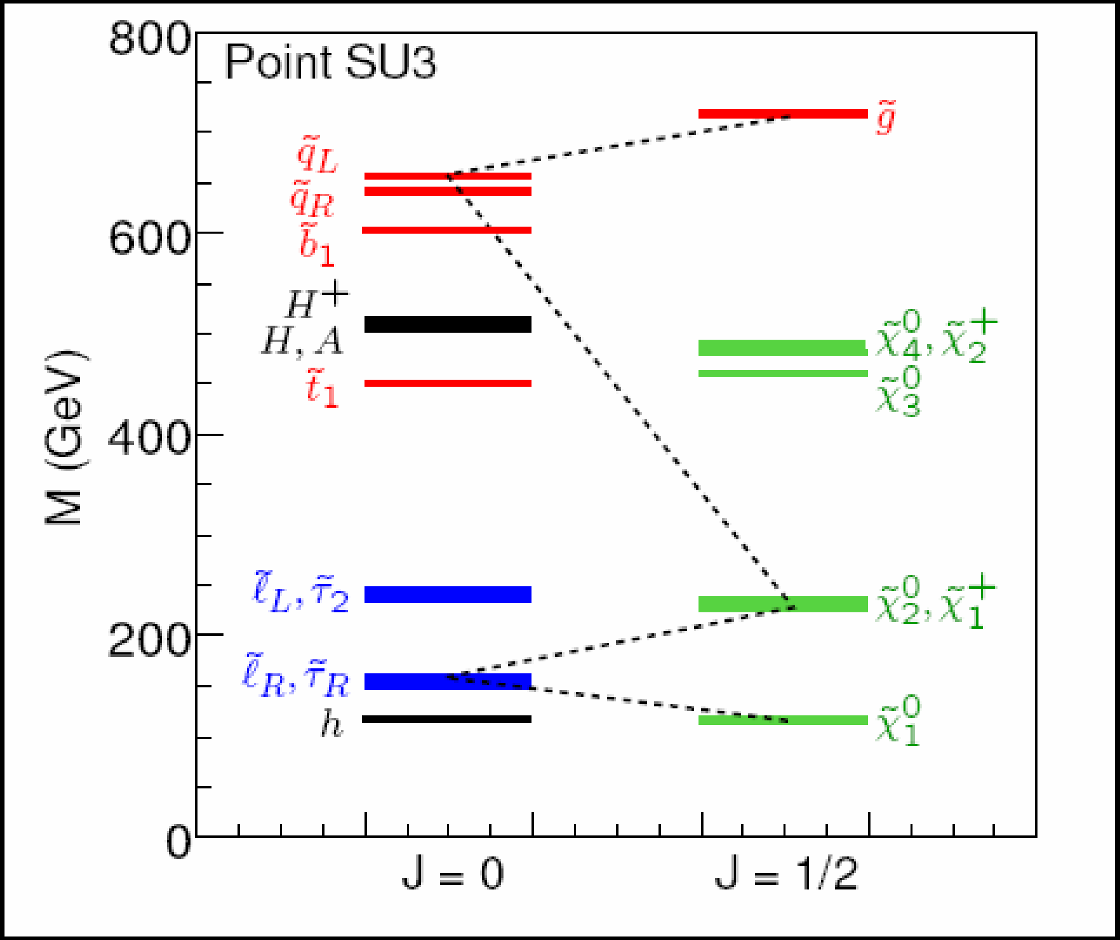
coannihilation

$\tilde{\chi}_1^0 \tilde{\tau}_1 \to \gamma\tau.$

Focus small μ higgsino anihilates.

Typical Mass Spectrum

MSSM



LSP is χ^0

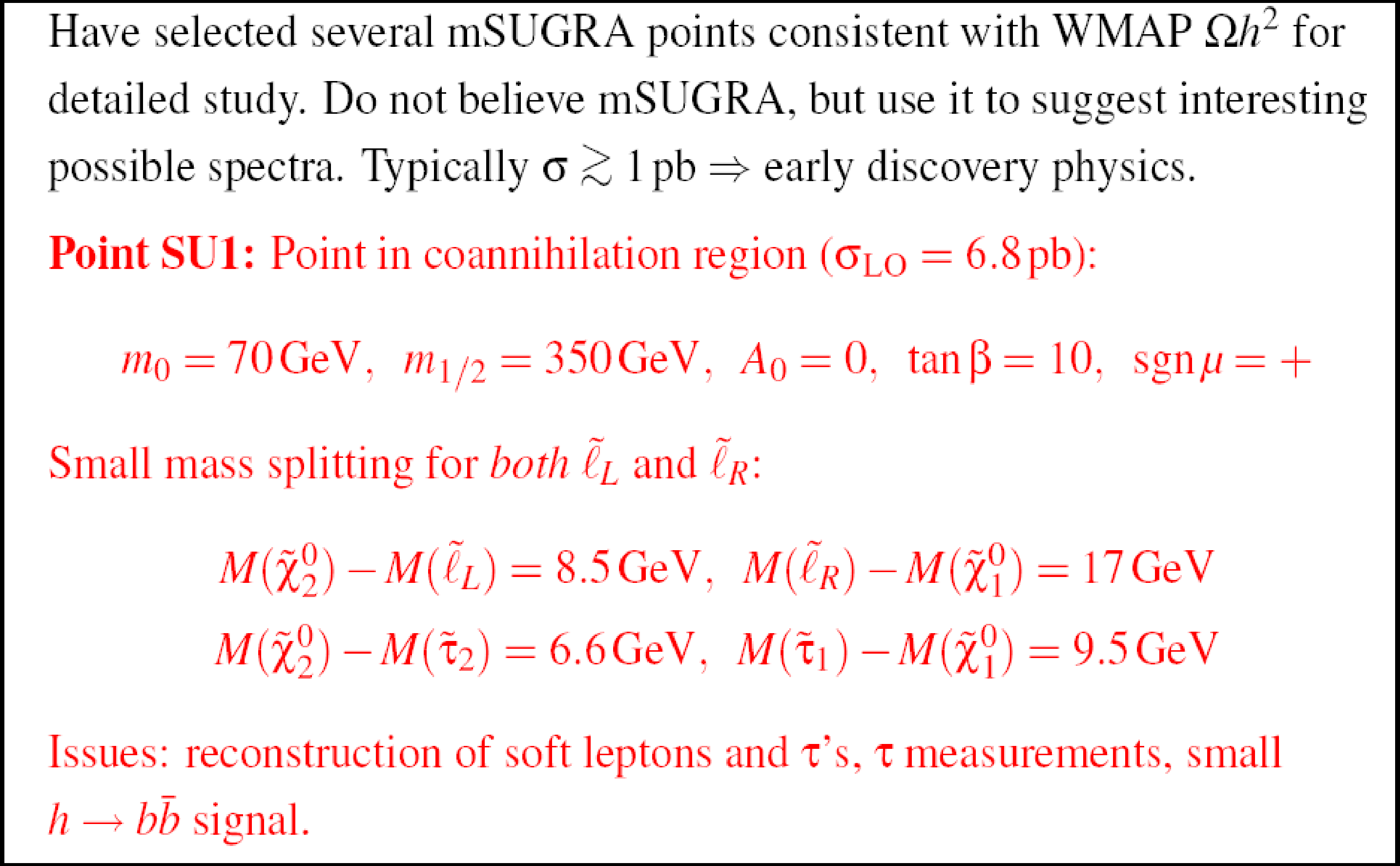
Mh<135 GeV

$q_L > q_R$

$$M_{\tau_1} < M_{\tau_2}$$

An example

Coannihilation point: light stau in equilibrium with the LSP χ leding to $\tilde{\chi}_1^0 \tilde{\tau}_1 \to \gamma\tau$.



Have selected several mSUGRA points consistent with WMAP Ωh^2 for detailed study. Do not believe mSUGRA, but use it to suggest interesting possible spectra. Typically $\sigma \gtrsim 1\,\mathrm{pb} \Rightarrow$ early discovery physics.

Point SU1: Point in coannihilation region ($\sigma_{\mathrm{LO}} = 6.8\,\mathrm{pb}$):

$$m_0 = 70\,\mathrm{GeV}, \ \ m_{1/2} = 350\,\mathrm{GeV}, \ \ A_0 = 0, \ \ \tan\beta = 10, \ \ \mathrm{sgn}\,\mu = +$$

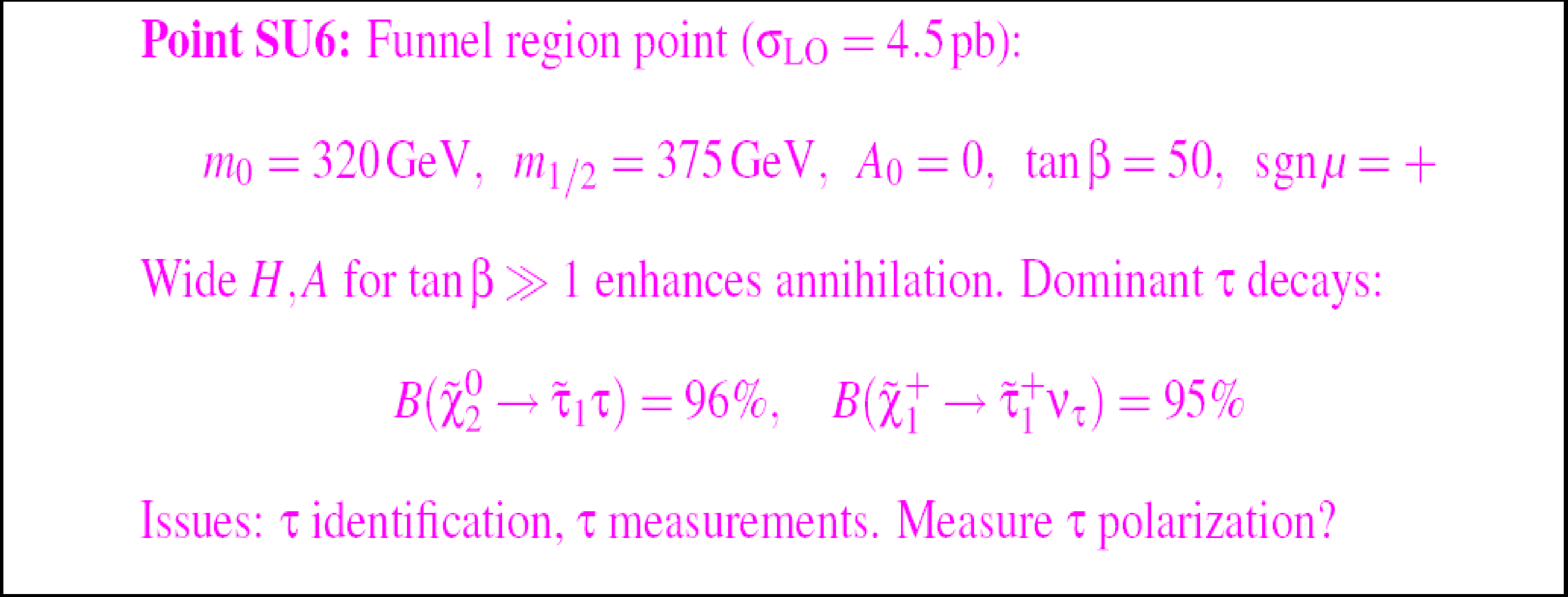
Small mass splitting for *both* $\tilde{\ell}_L$ and $\tilde{\ell}_R$:

$$M(\tilde{\chi}_2^0) - M(\tilde{\ell}_L) = 8.5\,\mathrm{GeV}, \ \ M(\tilde{\ell}_R) - M(\tilde{\chi}_1^0) = 17\,\mathrm{GeV}$$
$$M(\tilde{\chi}_2^0) - M(\tilde{\tau}_2) = 6.6\,\mathrm{GeV}, \ \ M(\tilde{\tau}_1) - M(\tilde{\chi}_1^0) = 9.5\,\mathrm{GeV}$$

Issues: reconstruction of soft leptons and τ's, τ measurements, small $h \to b\bar{b}$ signal.

Another Example

The ‘funnel’ where H and A poles enhance the annihilation for large tabβ $2M\chi=M_H$



Point SU6: Funnel region point ($\sigma_{LO} = 4.5\,\mathrm{pb}$):

$$m_0 = 320\,\mathrm{GeV},\ \ m_{1/2} = 375\,\mathrm{GeV},\ \ A_0 = 0,\ \ \tan\beta = 50,\ \ \mathrm{sgn}\,\mu = +$$

Wide H,A for $\tan\beta \gg 1$ enhances annihilation. Dominant τ decays:

$$B(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau) = 96\%, \quad B(\tilde{\chi}_1^+ \to \tilde{\tau}_1^+\nu_\tau) = 95\%$$

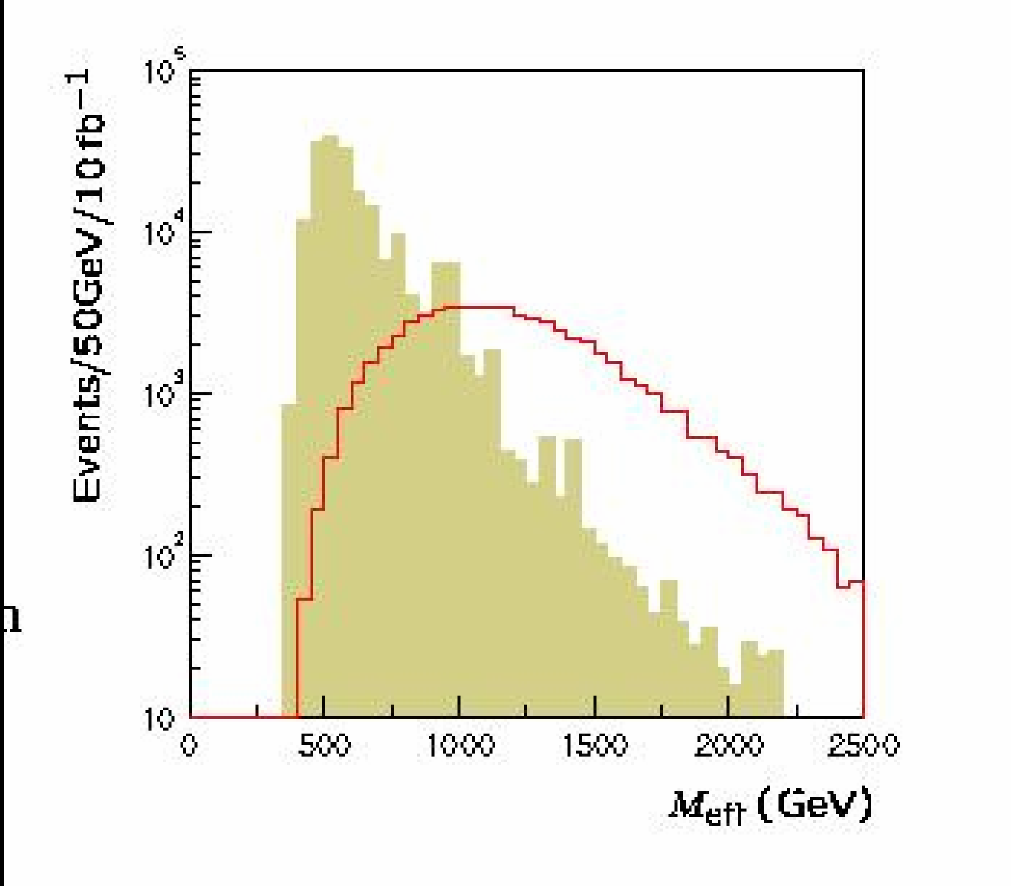
Issues: τ identification, τ measurements. Measure τ polarization?

Easy Selection

A common feature for almost all RPC points is large missing transverse momentum and large number of high PT jets. One can combine those in

$$M_{eff} = \not{E}_T + \sum_j E_{T,j}$$

n



Inclusive Searches

* Look for events in which heavy objects are pair produced.

* Look for events with high missing E_T

Characterize each event by:

- Missing E_T;
- P_t^{Jet1} – transverse momentum of 1st jet;
- P_t^{Jet2} – transverse momentum of 2ed jet;
- $\sum_{j=1}^{njet} E_T^{jet}$ - sum of the E_t of all jets;

The LSL Algorithm

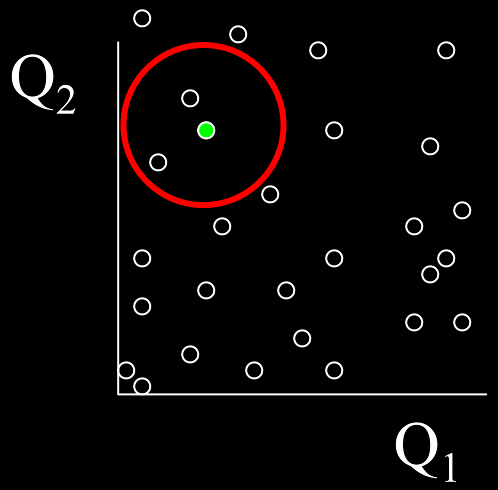
The Local Spherical Likelihood (LSL) algorithm is based on the k-neighborhood one.

Preparation:

- Select the relevant quantities, say N (separators);
- Normalize the separators to [0,1];
- Simulate all known SM (Background) processes;
- Construct a ‘*reference*’ n-dim space in which each b.g. event is represented by a point
- Repeat this procedure for data events and build the ‘*data*’ space in which each data event is represented by a point

How it Works *(simplified)*

data

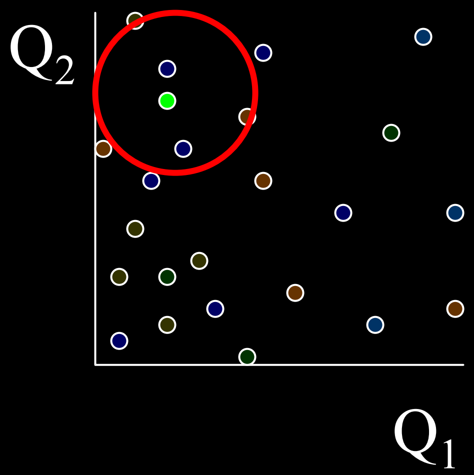


~2 events

ρ_{data}

Reference

(SM background)



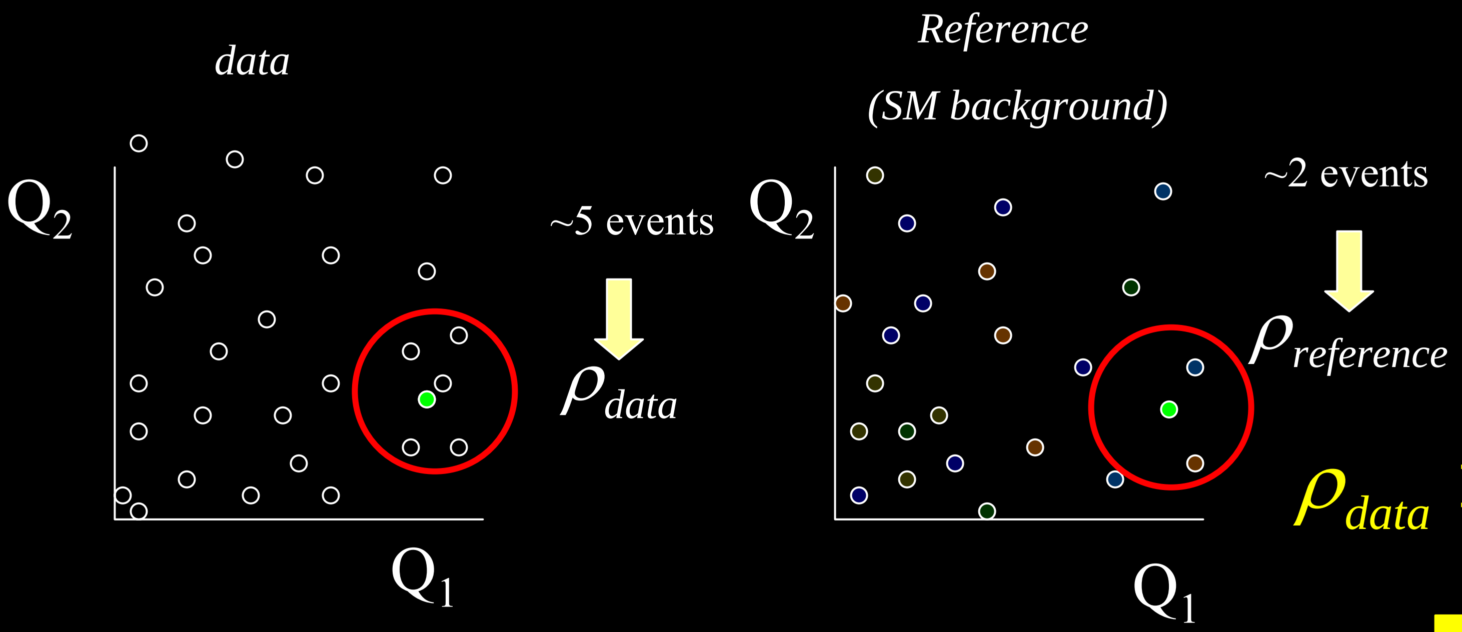
~2.5 events

$\rho_{reference}$

$\rho_{data} \approx \rho_{ref}$

No hint for a signal

How it Works *(simplified)*



$\rho_{data} >> \rho_{ref}$

A hint for a signal

The SLEUTH Algorithm

Same problem leads to similar solutions:

D0: SLEUTH: *A Quasi-model-independent search strategy for new physics*

Bruce Knuteson et al.

Beautiful and a bit

more complex

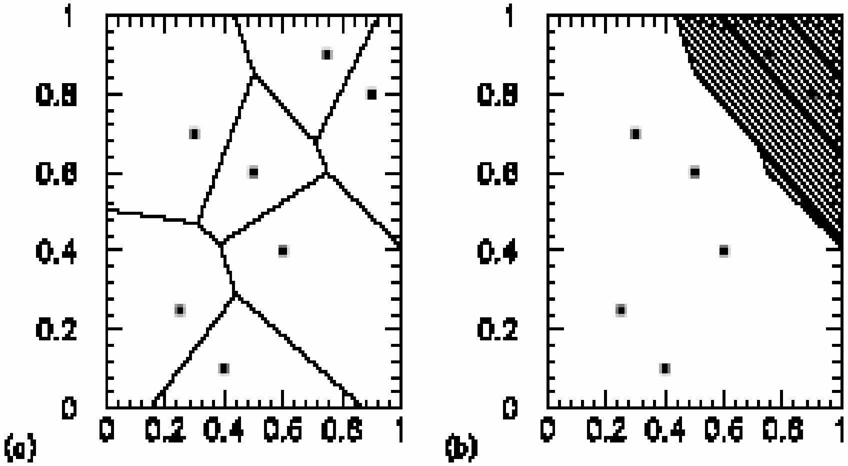
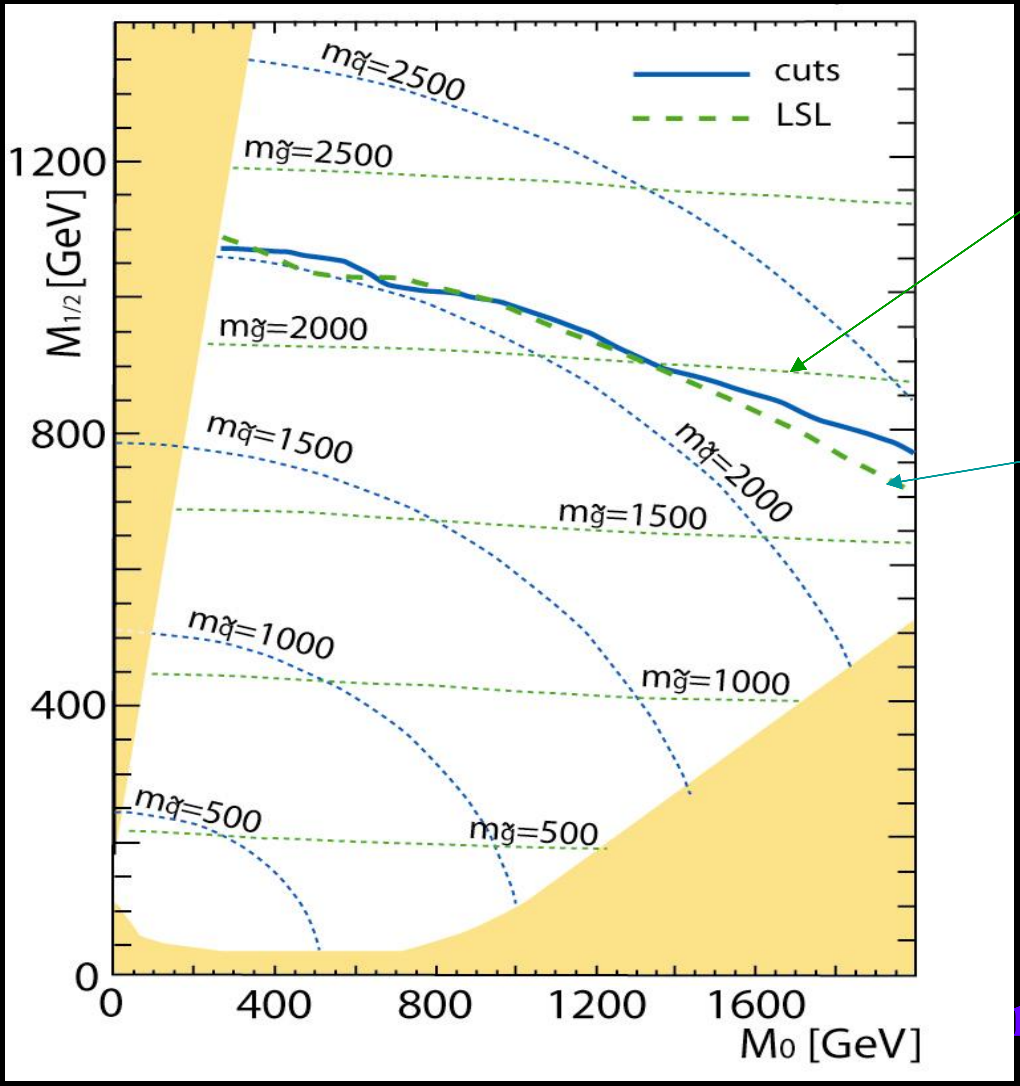


FIG. 2. A Voronoi diagram. (a) The seven data points are shown as black dots; the lines partition the space into seven regions, with one region belonging to each data point. (b) An example of a 2-region.

MSSM Results – Missing Energy



$M_{1/2}$

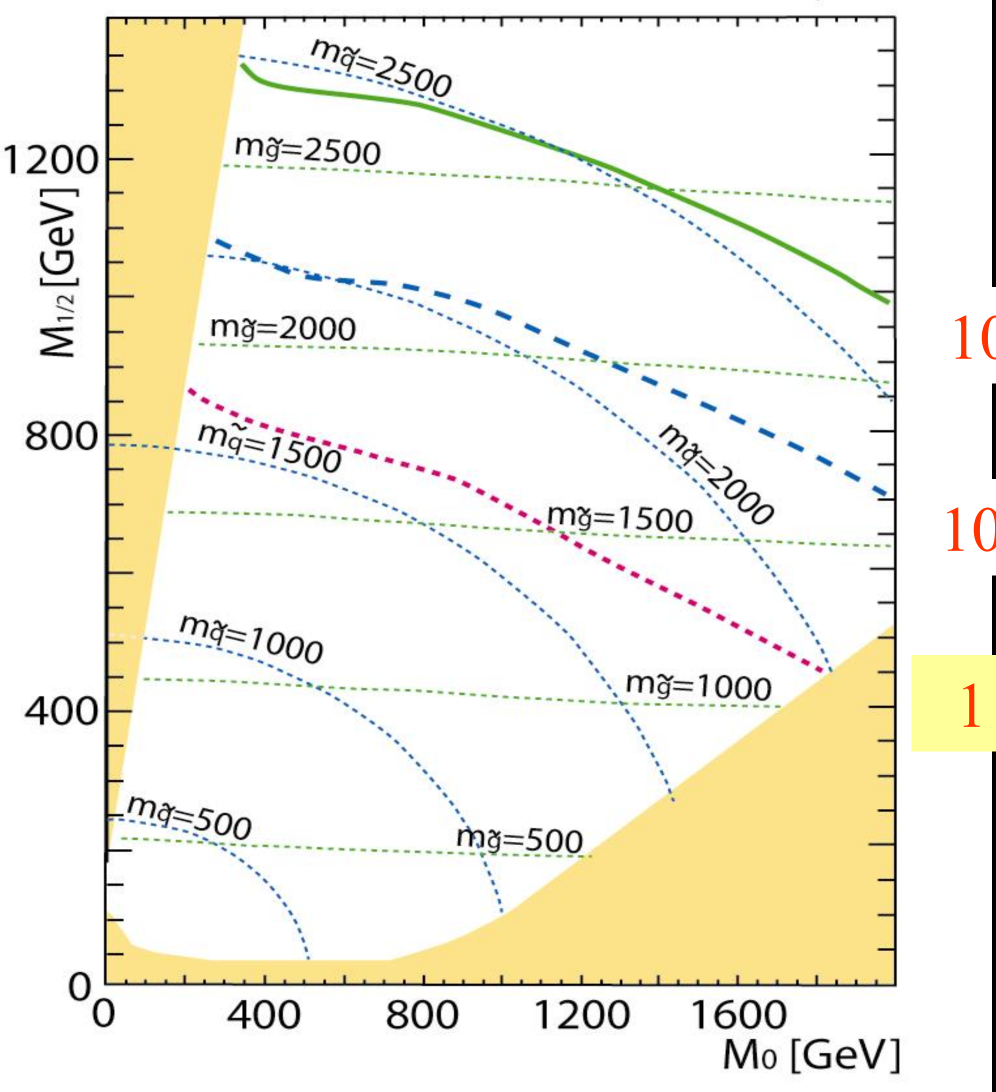
simplex results

LSL

m_0

MSSM Results – Sensitivity Evaluation

$M_{1/2}$



100 fb^{-1}

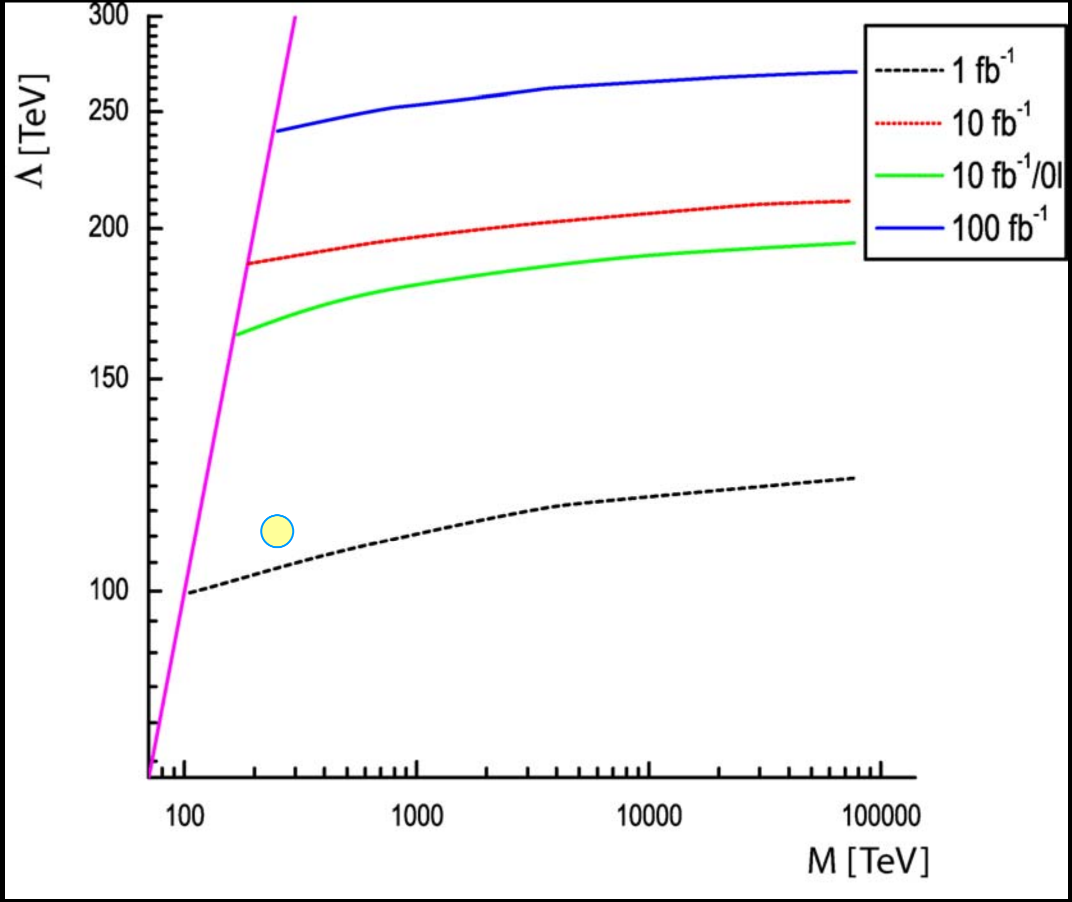
10 fb^{-1}

1 fb^{-1}

m_0

Results - GMSB

Λ



M

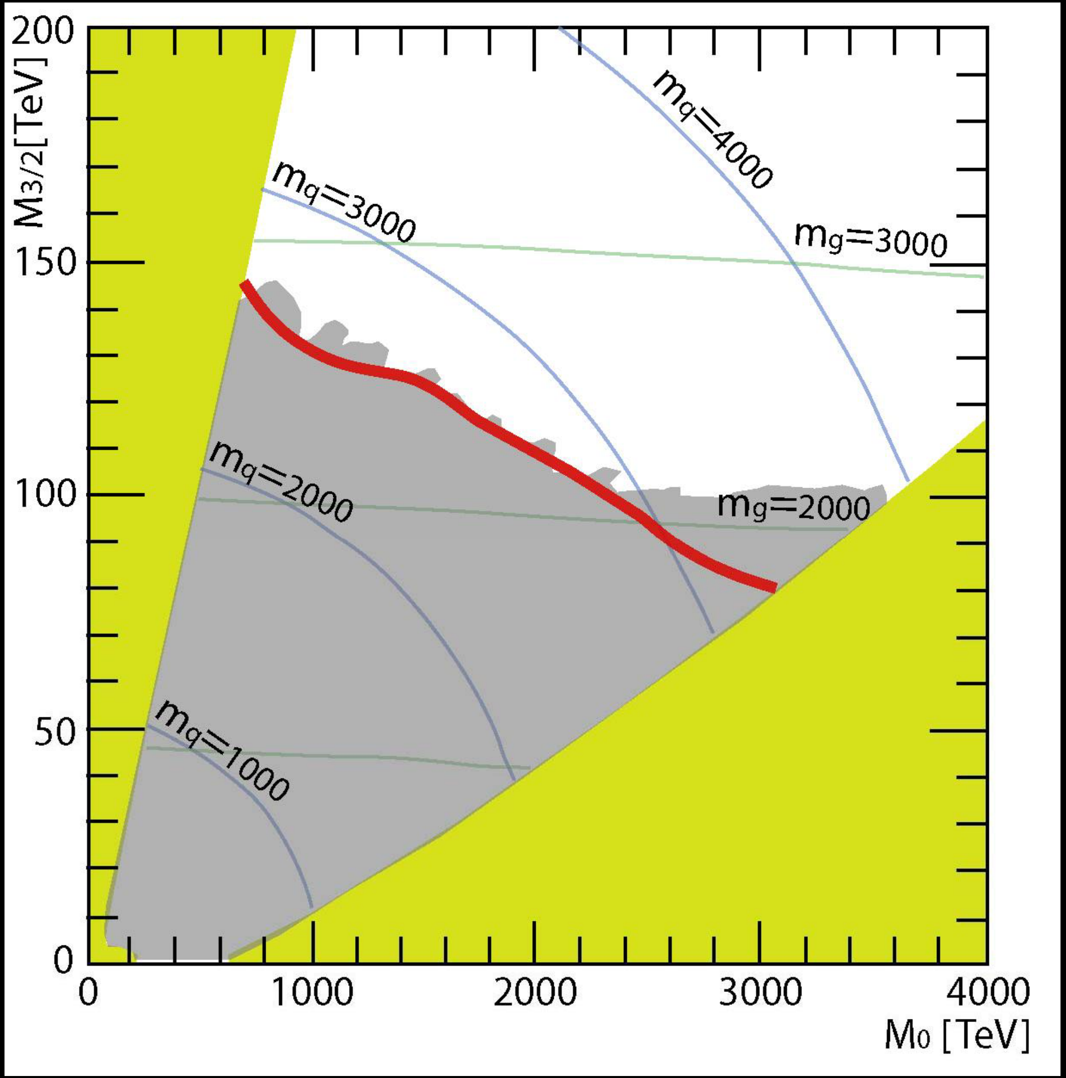
Sensitive
up to
Λ=120TeV

With lumi
of just 1fb^{-1}

Results - AMSB

$M_{3/2}$

[TeV]



M_0

[TeV]

Comparison with
A. J. Barr et al.

HEP-PH-0208214

Reconstruction of the mass Spectrum

Look for example on $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$

One can compute the di-lepton mass and it will attain a maximum when the χ^0_1 is at rest in the χ^0_2 frame. A typical M_{ll} distribution looks like

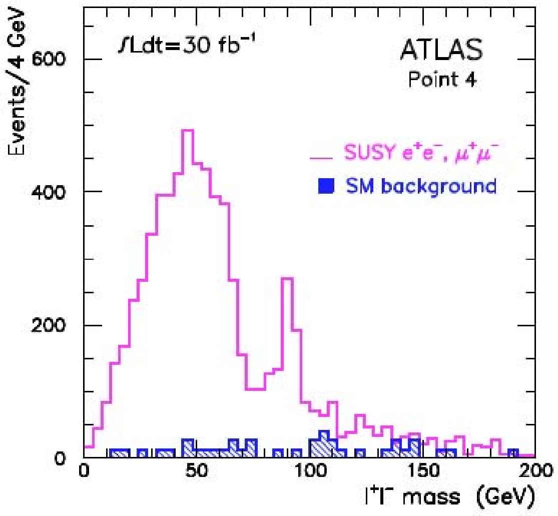


Figure 9: *Expected di-lepton invariant mass distributions for SUSY events containing opposite-sign same-flavour lepton pairs at Point 4 (full histogram) and for the* $t\bar{t}$ *background (dashed histogram), for an integrated luminosity of* $3 \cdot 10^4\ pb^{-1}$.

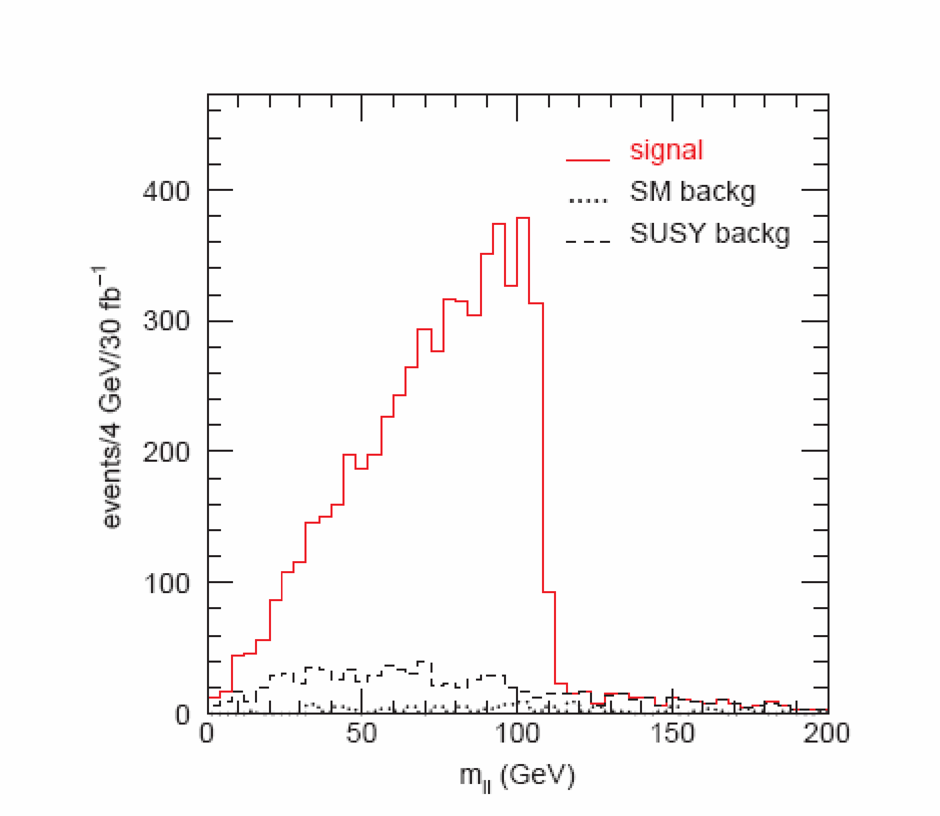
Next Step- Reconstruction

Look at ‘simple’ processes. $\chi_2^0 \to \tilde{l}_R l \to \chi_1^0 l^+ l^-$

One can reconstruct the invariant mass of the di-leptons which follows

$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$

And gives rise to a mass spectrum like:



Info from jet+lepton

Looking at the invariant mass of jets and leptons also can provide information

$$M_{llq}^{\max} = \left[\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2}\right]^{1/2}$$

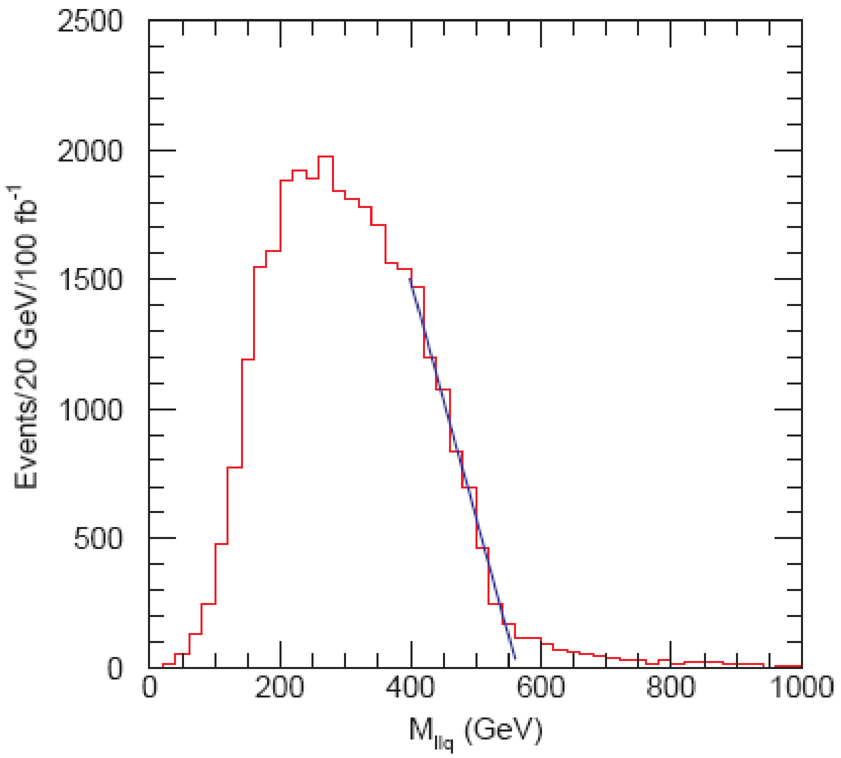


Figure 20-20 Smaller of the two l^+l^-q masses for the signal at Point 5.

Limitations of ‘end-point’ technique

- Use only small part of the data → large statistics
- Events are not fully reconstructed since the LSP is always missing
- Often signal comes from several cascades which leads to mix-up

Using ‘mass relation’

- The idea is to completely solve the kinematics of the SUSY cascade decay by using the assumption that the selected events satisfy the same mass shell conditions of the sparticles involved in the cascade decay.

$$\tilde{g} \to \tilde{b} b_2 \to \chi_2^0 b_1 b_2 \to \tilde{l} b_1 b_2 l_2 \to \chi_1^0 l_1 b_1 b_2 l_2$$

$$m^2_{\chi_1^0} = p^2_{\chi_1^0}$$

$$m^2_{\tilde{l}} = (p^2_{\chi_1^0} + p^2_{l_1})^2$$

$$m^2_{\chi_2^0} = (p^2_{\chi_1^0} + p^2_{l_1} + p^2_{l_2})^2$$

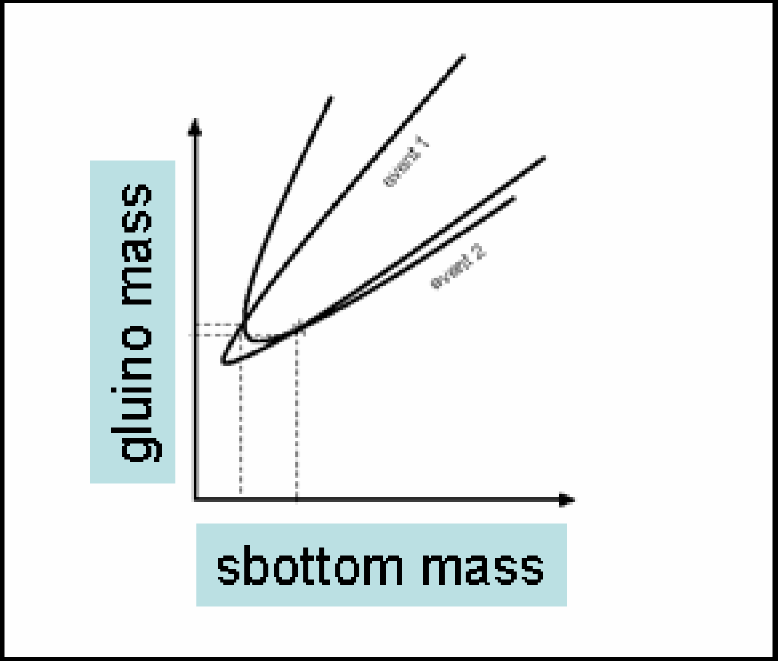
$$m^2_{\tilde{b}} = (p^2_{\chi_1^0} + p^2_{l_1} + p^2_{l_2} + p^2_{b_1})^2$$

$$m^2_{\tilde{g}} = (p^2_{\chi_1^0} + p^2_{l_1} + p^2_{l_2} + p^2_{b_1} + p^2_{b_2})^2$$

For a bbll event, the equations contain the 4 unknown degrees of freedom of the $\chi^0{}_1$ momentum. Each event therefore describes a 4-dimensional hyper-surface in a 5-dimensional mass parameter space, and the hyper-surface differs event by event. From the purely mathematical point of view 5 events would be enough to determine a discrete set of solutions for the masses of the involved sparticles,

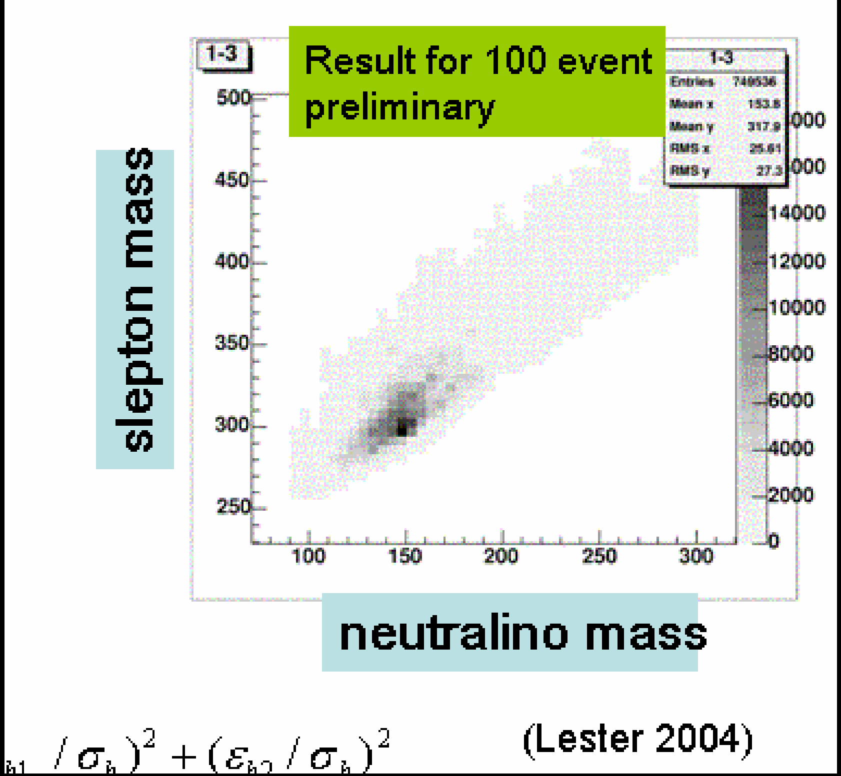
Mass Relation

Assuming the mass of slepton and two neutralino are known (after some time of running) one is left with two unknown: the mass of the gluino and bino and two events are, in principle, enough to solve the puzzle



(Due to error of measurement and uncertainties we will need many more)

Mass relation results



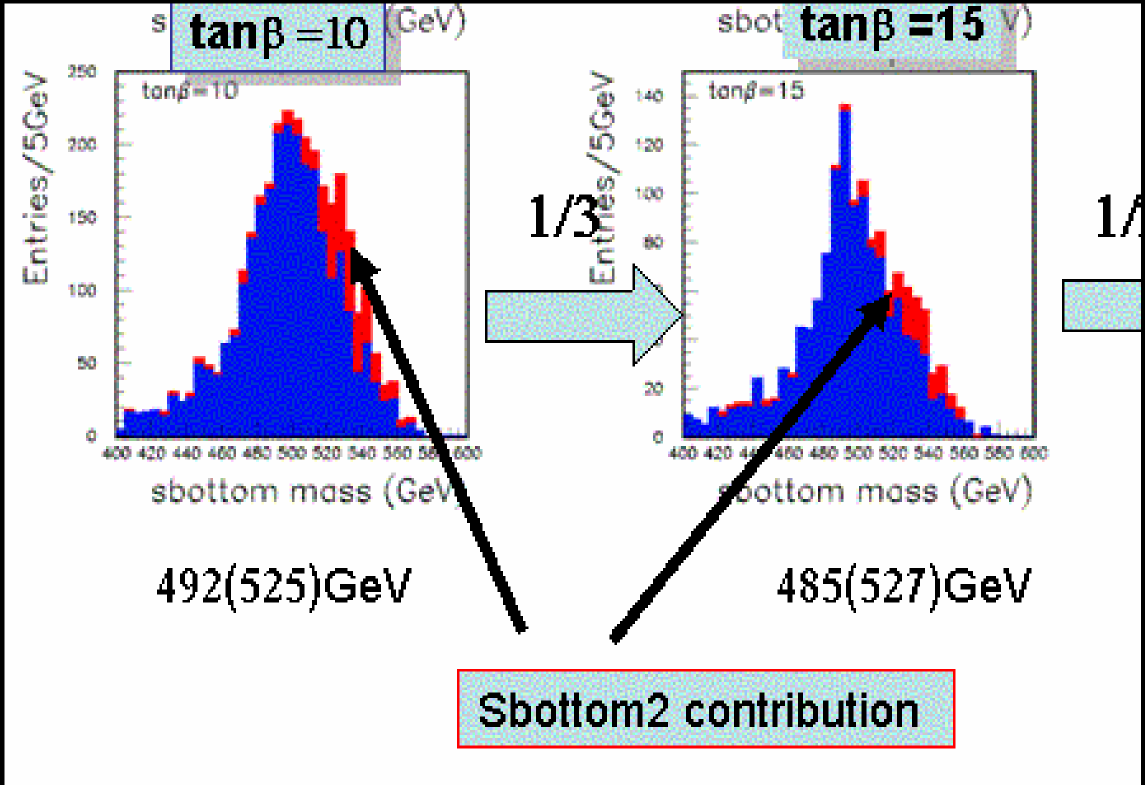
Result for 100 event preliminary

slepton mass

neutralino mass

$_{b1}/\sigma_b)^2 + (\varepsilon_{b2}/\sigma_b)^2$

(Lester 2004)



tanβ =10

tanβ =15

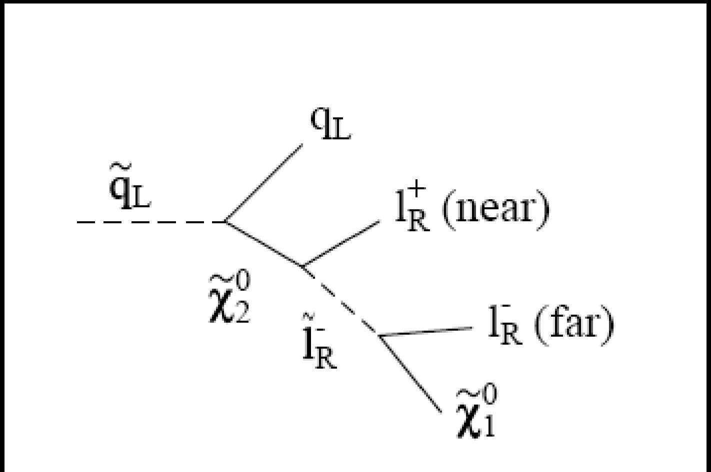
1/3

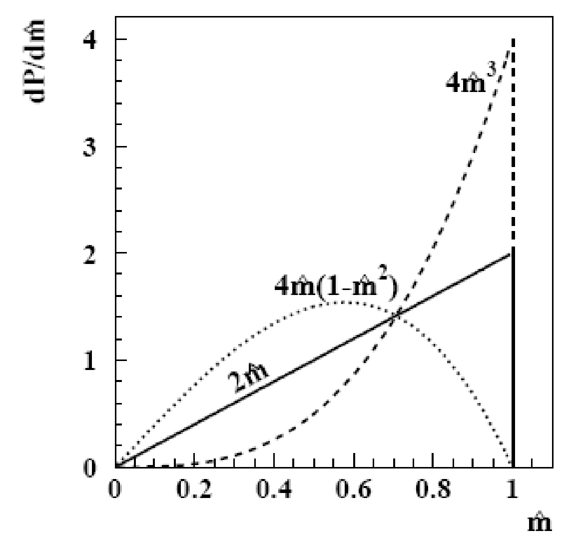
492(525)GeV

485(527)GeV

Sbottom2 contribution

Closer look

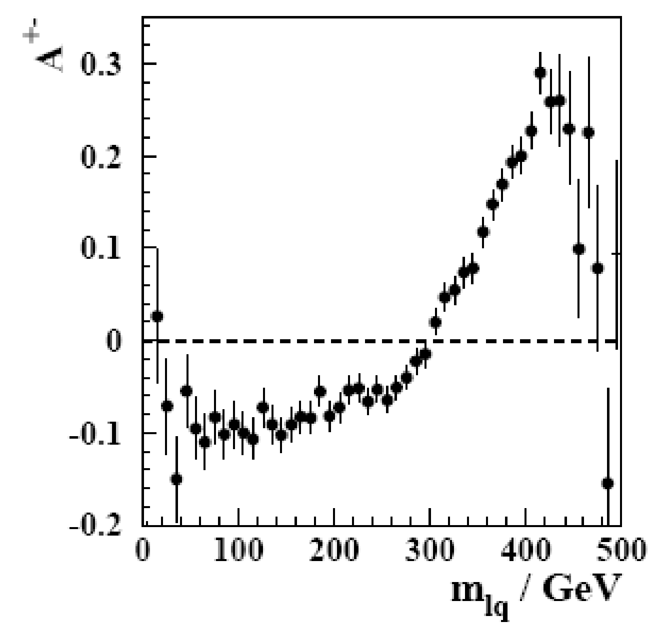




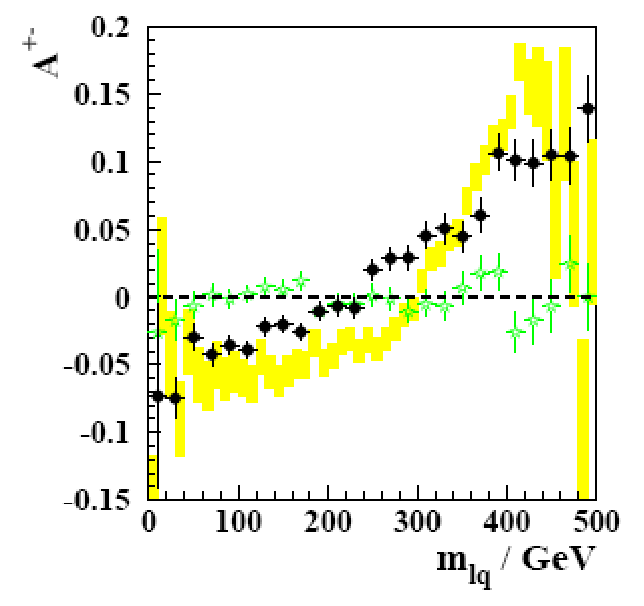
$$(m_{lq}^{near})^2 = (m_{\tilde{q}_L}^2 - m_{\chi_2^0}^2)(m_{\chi_2^0}^2 - m_{l_R}^2)/m_{\chi_2^0}^2 * \sin^2(\theta/2)$$

Spin- using charge Asymmetry

$$A^{+-} \equiv \frac{s^+ - s^-}{s^+ + s^-}, \quad \text{where} \quad s^\pm = \frac{d\sigma}{d(m_{l^\pm q})} .$$



Parton level



500 fb^{-1} simulation

R-Paruty Violating (RPV)

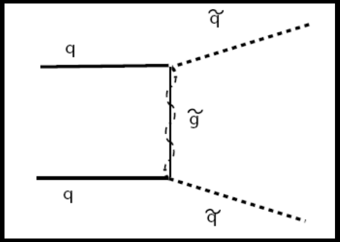
No LSP – all is seen and reconstructed

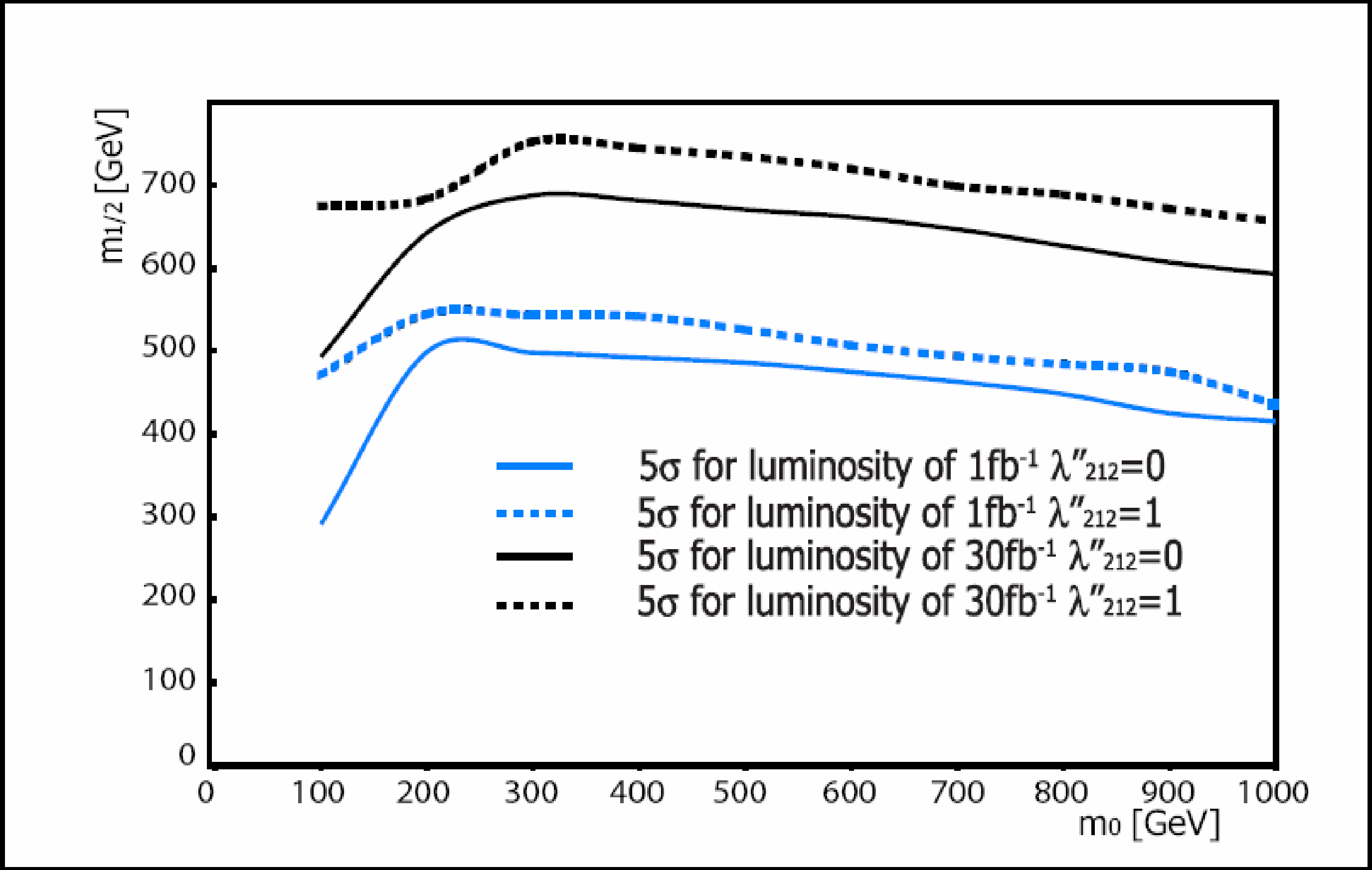
Large number of jets

Large total transverse energy (M_{eff})

To kill QCD usually require a lepton in the selection

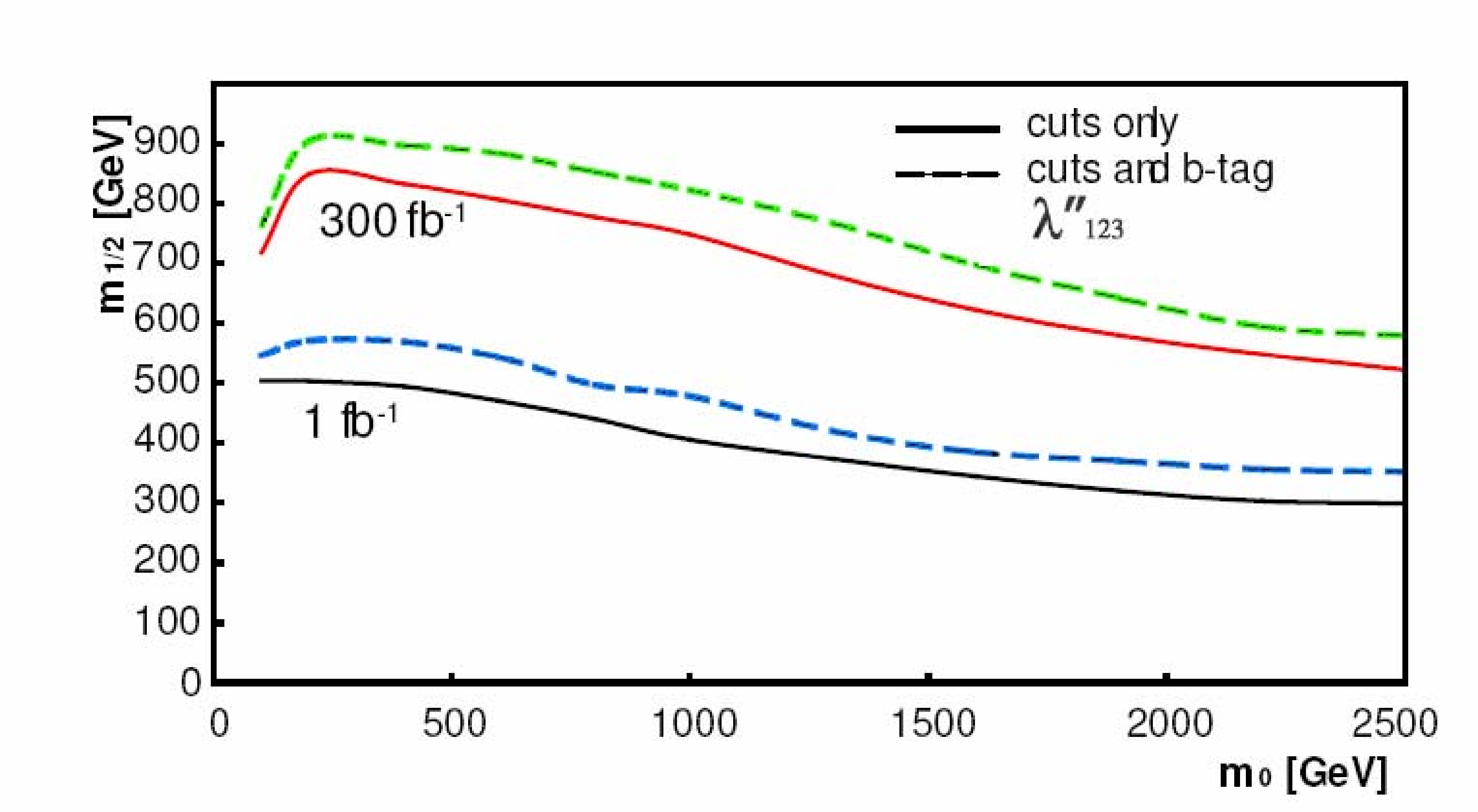
Purely Hadronic RPV





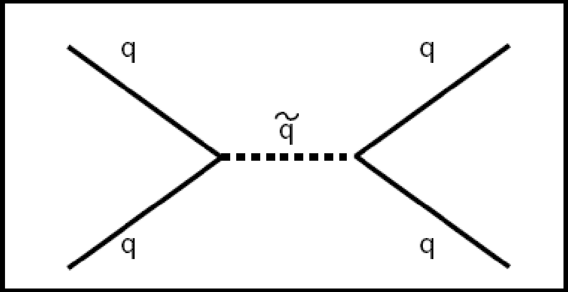
Include RPV coupling in RGE leads to a modification of the results

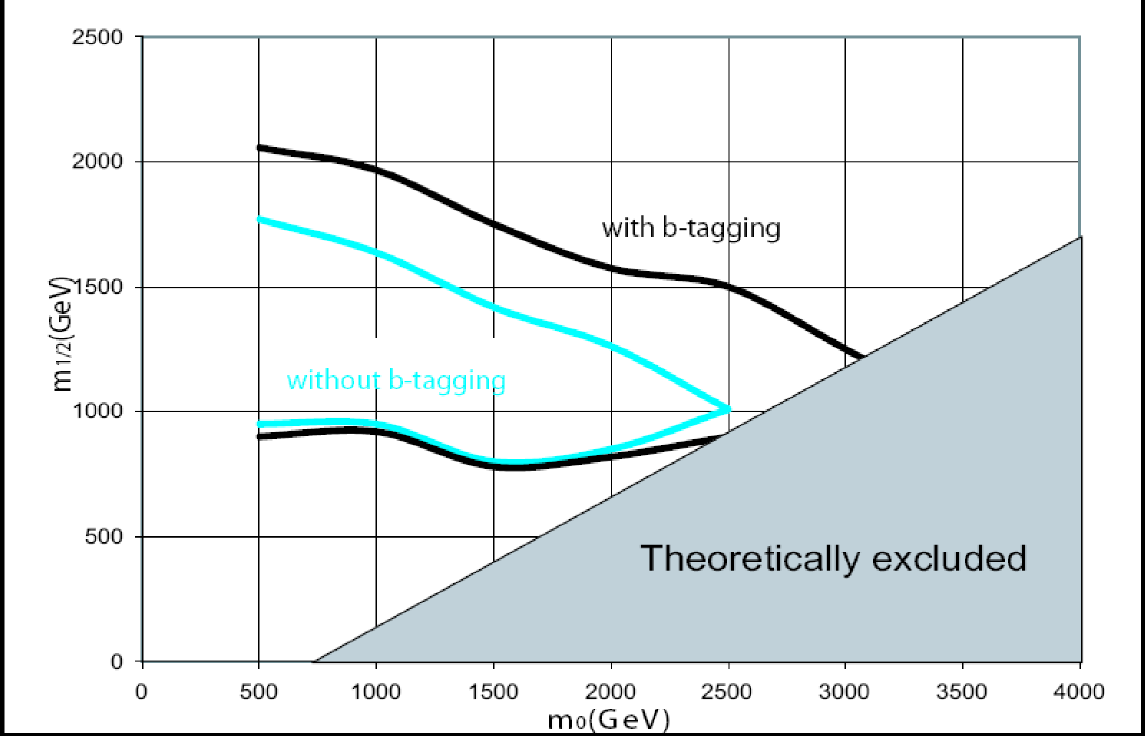
B-tag in RPV



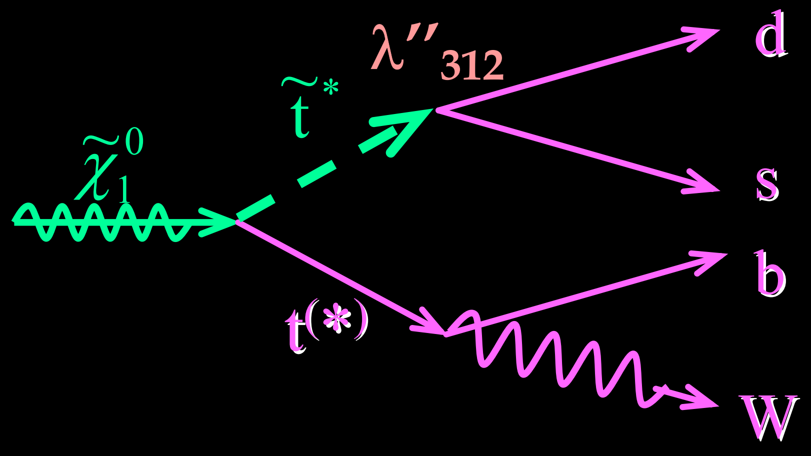
Inclusion if b-tag also improves the sensitivity in several cases

Resonance channel

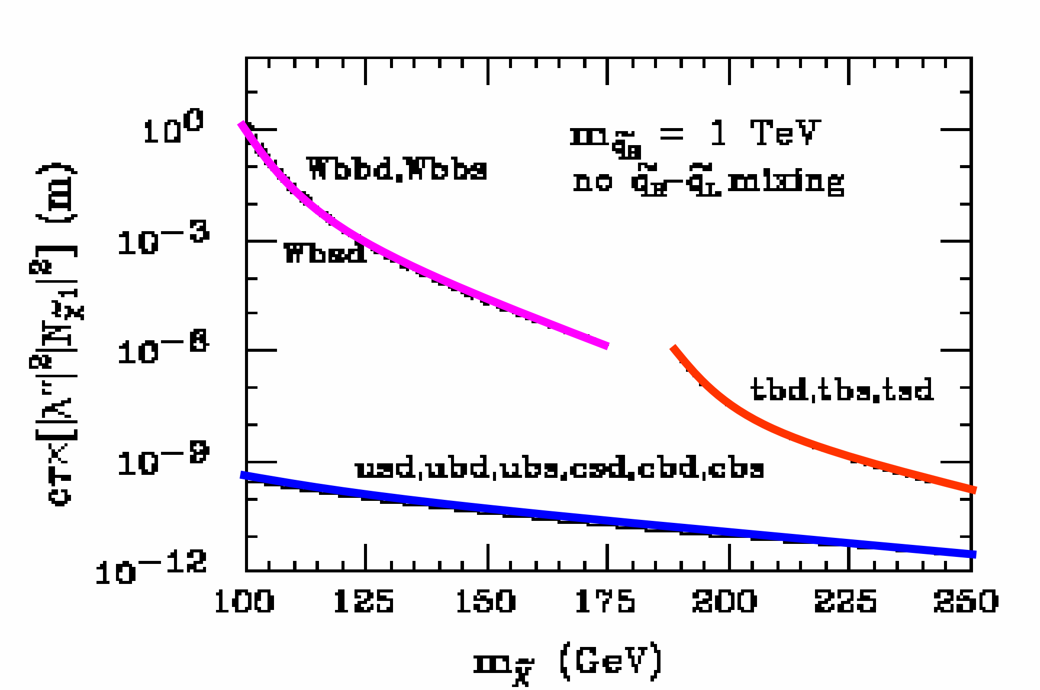




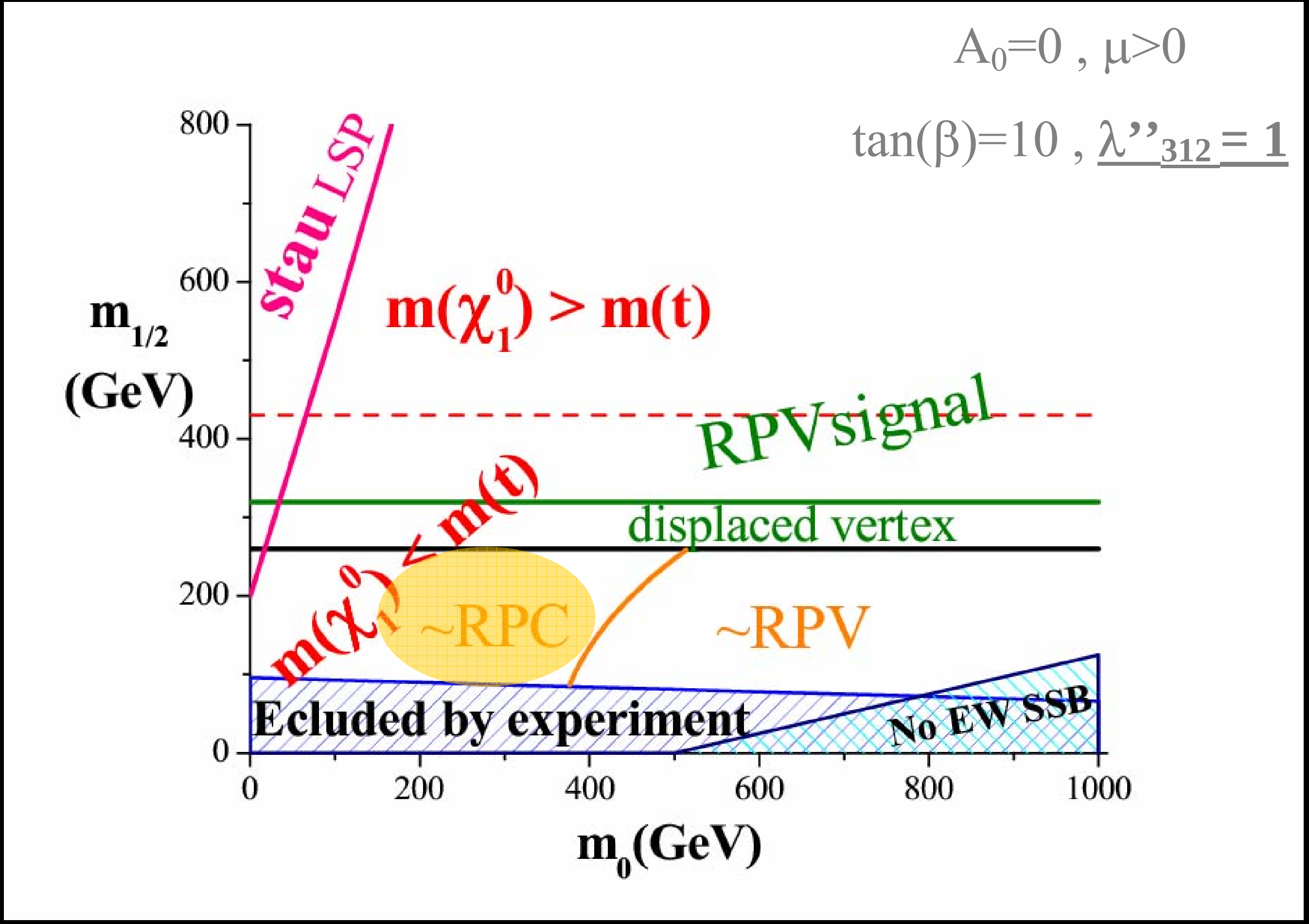
Is RPV always distinguishable from RPC



But if Mχ<Mt the decay is kinematically suppressed



The Relevant parameter space



Concluding Remarks

- The search for SUSY signals is probably the most challenging at LHC
- We do dot know what are we looking for
- Once we find candidate events a long struggle to verify their identity as SUSY events, to identify the underlying SUSY breaking mechanism, and to measure various properties like mass, spin and couplings will begin.
- I did cover a negligible part of the exciting topic…and probably ran overtime ☺