Exploring resonance annihilation of Neutralino Dark Matter via muon signatures from Higgs bosons at the LHC

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Outline

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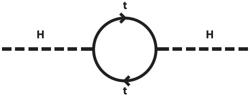
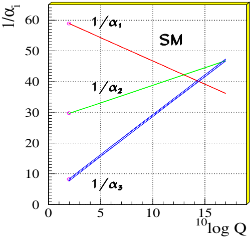
2. Supersymmetry and dark matter
   - SUSY features
   - The A-resonance annihilation region and large $\tan\beta$
3. Higgs production and decay to muons at the LHC
   - Signal and background analysis
   - Measuring m_A and Γ_A at the LHC
4. Conclusions

Motivation



We want a theory of physics beyond the Standard Model (SM) to

- solve the hierarchy problem
  - explain the Higgs mass
- support a Grand Unification Theory (GUT)
- provide Dark Matter (DM)



Supersymmetry

- Supersymmetry extends the Poincaré algebra with fermionic operators, implying a symmetry between fermions and bosons

$$\{Q, \bar{Q}\} = \sigma P, \qquad \{Q, Q\} = \{\bar{Q}, \bar{Q}\} = [P, Q] = [P, \bar{Q}] = 0$$

- The Minimal Supersymmetric Standard Model (MSSM) has the following matter content and superpotential

	$SU(3)$	$SU(2)$	$U(1)$
Q	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
$\bar{u}$	$\bar{\mathbf{3}}$	1	$-\frac{2}{3}$
$\bar{d}$	$\bar{\mathbf{3}}$	1	$\frac{1}{3}$
L	1	$\mathbf{2}$	$-\frac{1}{2}$
$\bar{e}$	1	1	1
H_u	1	$\mathbf{2}$	$\frac{1}{2}$
H_d	1	$\mathbf{2}$	$-\frac{1}{2}$

$$\begin{aligned} W =& y_u \bar{u} Q H_u + y_d \bar{d} Q H_d + y_e \bar{e} L H_d \\ &+ \mu H_u H_d \end{aligned}$$

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$$W = y_u\bar{u}QH_u + y_d\bar{d}QH_d + y_e\bar{e}LH_d + \mu H_u H_d$$

R-parity violating terms:

$$\lambda LL\bar{e}, \quad \lambda' LQ\bar{d}, \quad \lambda''\bar{u}\bar{d}\bar{d}, \quad \mu' LH_u$$

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R-parity violating terms:

$$\lambda L L \bar{e}, \quad \lambda' L Q \bar{d}, \quad \lambda'' \bar{u} \bar{d} \bar{d}, \quad \mu' L H_u$$

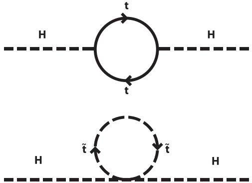
Note that **two Higgs fields** are needed to cancel anomalies and to keep the superpotential holomorphic in the chiral superfields.

Supersymmetry

	Spin 0	Spin 1/2
Q	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$
$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$
$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$
L	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$
H_u	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$
H_d	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$

Spin 1/2	Spin 1
$\tilde{g}$ $\tilde{W}^\pm, \tilde{W}^0$ $\tilde{B}$	g $W^\pm, W^0$ B

- Introduction of sfermions cancels quadratic divergences in Higgs mass loop corrections



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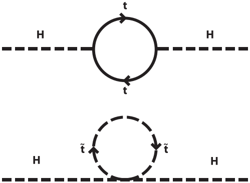
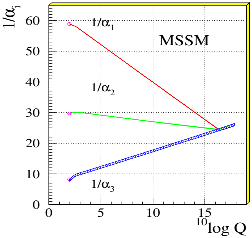
$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$
$\tilde{B}$	B

- Introduction of sfermions cancels quadratic divergences in Higgs mass loop corrections
- The added particle content makes the gauge couplings unify at the GUT scale





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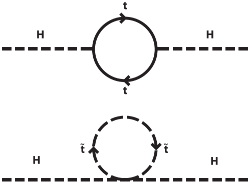
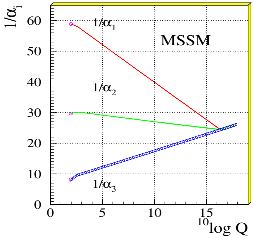
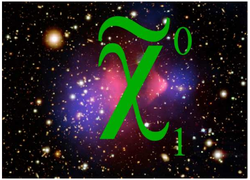
- Introduction of sfermions cancels quadratic divergences in Higgs mass loop corrections
- The added particle content makes the gauge couplings unify at the GUT scale
- Preventing proton decay suggests R-parity which implies that the LSP is stable





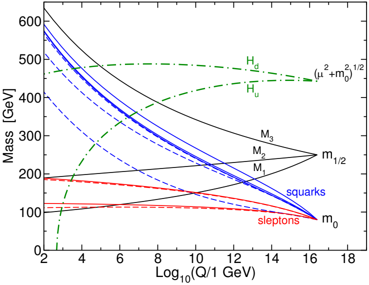


The mSUGRA framework

For general studies it is convenient to use minimal supergravity (mSUGRA) which has **five independent parameters**:

- m_0 - a common GUT scale scalar mass
- $m_{1/2}$ - a common GUT scale fermionic mass
- A_0 - a common GUT scale trilinear coupling
- $\tan\beta = \frac{v_u}{v_d}$ - the ratio of the two Higgs fields vacuum expectation values
- sign(μ) - the sign of the Higgs mass term parameter μ

The whole mass spectrum depends just on the five mSUGRA parameters and the energy scale

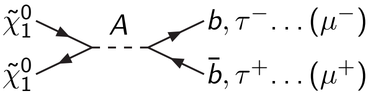


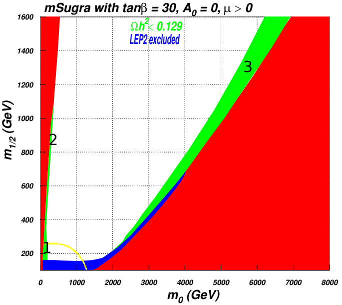
The parameter space of mSUGRA is largely excluded by

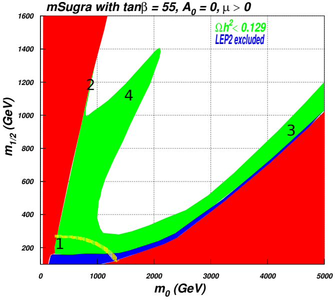
- Theory
- Dark Matter constraints
- Collider constraints

Only a few scenarios sets us in the **allowed regions**:

1. Bulk annihilation
2. $\tilde{\tau}$ co-annihilation
3. Hyperbolic branch/focus point
4. Annihilation through A-resonance



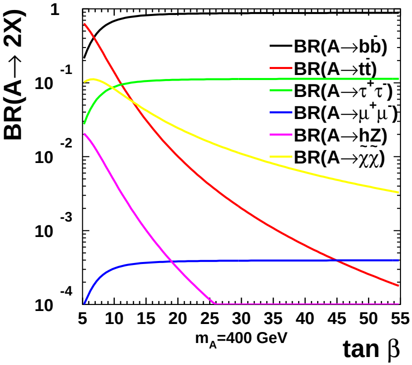


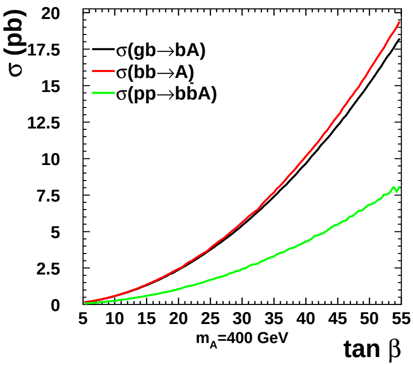


The tan β dependence

As $\tan\beta = \frac{v_u}{v_d}$ increases

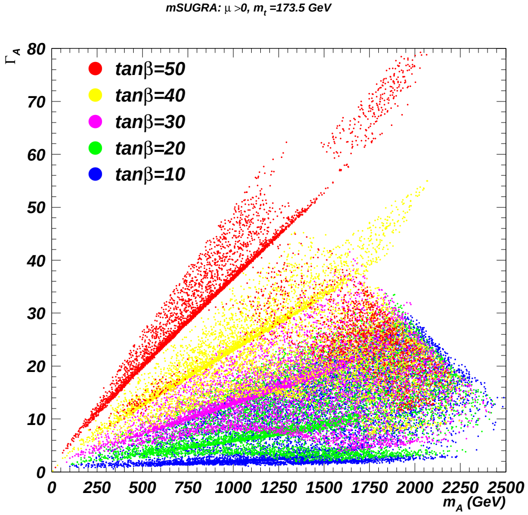
- The b-Yukawa coupling $f_b = \frac{m_b}{v\cos\beta}$ increases
- Partial widths $\Gamma(A \to b\bar{b})$ and $\Gamma(A \to \tau\bar{\tau})$ increase
- f_μ also increases and $\mathrm{BR}(A \to \mu^+\mu^-)$ remains at the 10^{-4} level
- Yukawa-induced Higgs production cross sections increase





The tan β dependence

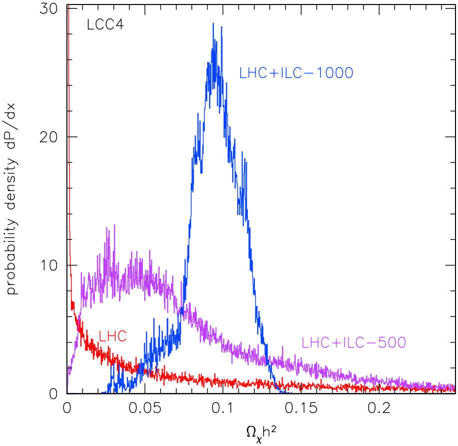
A scan over possible Γ_A and m_A in mSUGRA shows that measuring these quantities narrows down the possible values of tan β



Is it possible to measure Γ_A at LHC?

The LCC4 benchmark ($m_0 = 380, m_{1/2} = 420, \tan\beta = 53, A_0 = 0, \mu > 0$) has been studied and the importance of Γ_A for fitting SUSY parameters was noted. **LHC was considered incapable of measuring Γ_A.** [*Peskin et al. '06*]

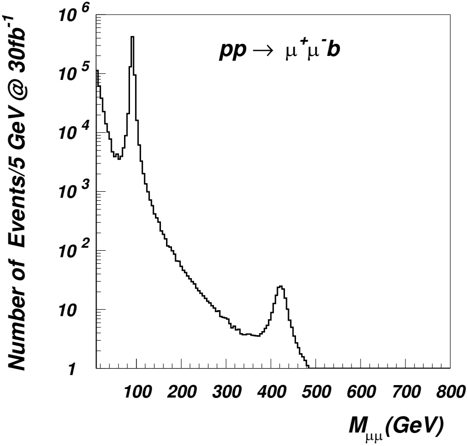
- Previous results: Only LHC + **International Linear Collider** (ILC) can reveal the SUSY/DM picture
- Our task: Can we do a better job just using LHC?

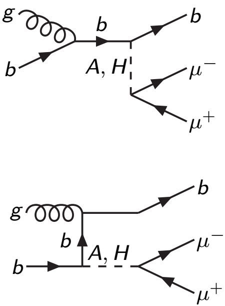


The Signal: $pp \to Ab \to \mu^+\mu^- b$

We choose to consider the $\mu^+\mu^- b$ final state with one tagged b-jet, which has been shown to have the best discovery potential for $A \to \mu^+\mu^-$ at the LHC as compared to 0 or 2 tagged b-jets [Dawson, Dicus, Kao, Malhotra '04]

The cross section after cuts can be as large as 10 fb for $m_A = 400$ GeV





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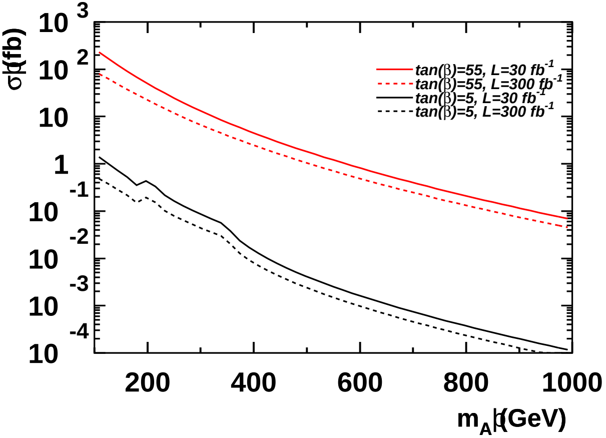
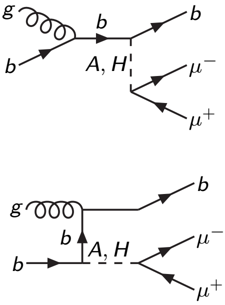
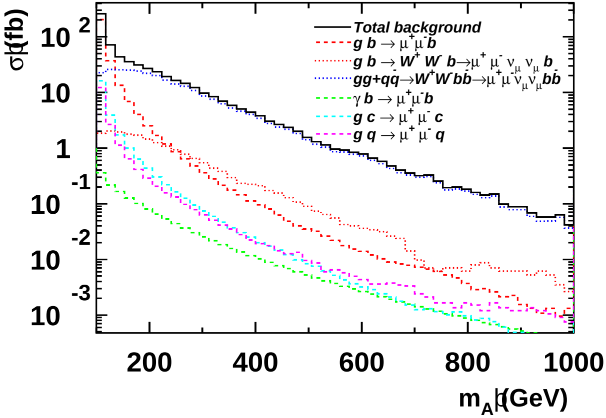
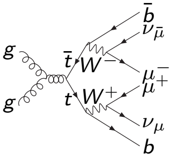
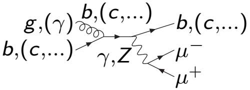




When calculating the backgrounds we take into account b-tagging efficiency including mistagging among different quarks. This makes it a large number of background subprocesses and diagrams to consider

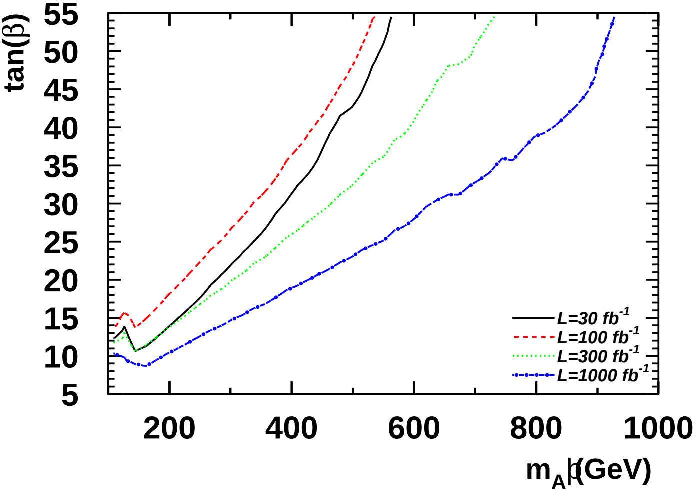






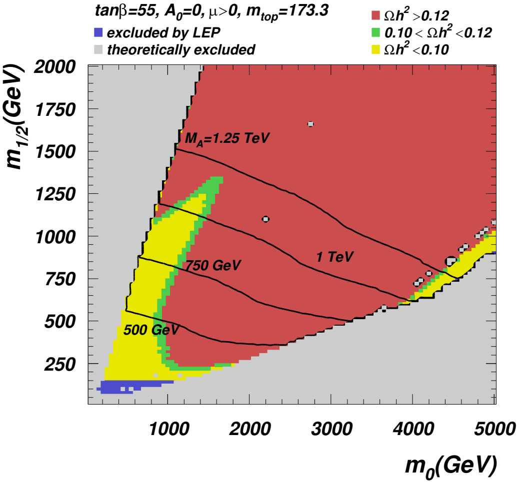
The LHC reach

Discovery is possible for $pp \to Ab \to \mu^+\mu^- b$ at LHC above these curves.



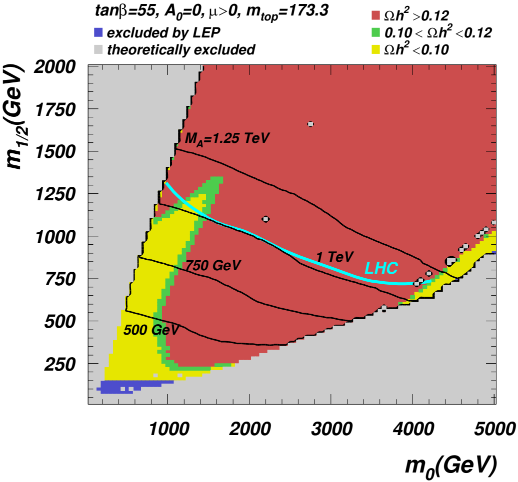
The limit for $L = 100$ fb^{-1} is worse than the $L = 30$ fb^{-1} because looser cuts on missing transverse momentum has been applied

The LHC reach and resolution



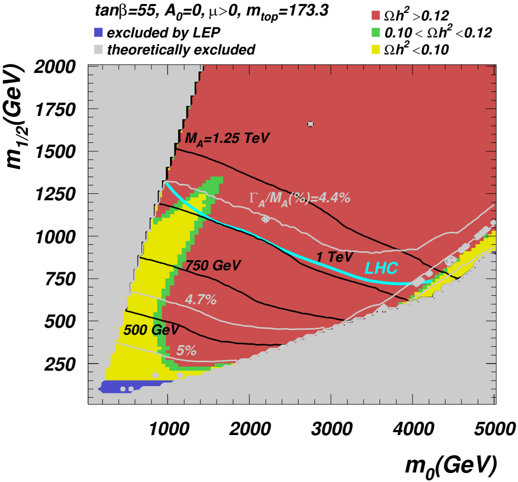
The A-funnel region is covered for $m_A \lesssim 1.25$ TeV

The LHC reach and resolution



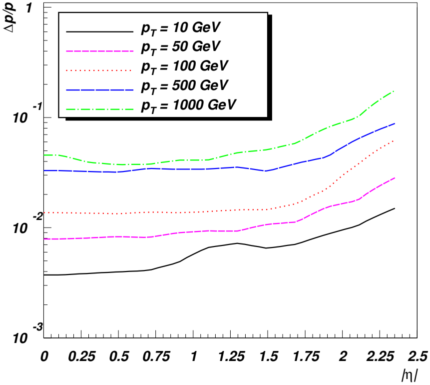
The LHC SUSY reach at 14 TeV and 100 fb^{-1} stretches over $m_A = 1$ TeV [*Baer, Balazs, Belyaev, Krupovnickas, Tata '03*]

The LHC reach and resolution



The decrease of Γ_A/m_A for larger mass makes the situation harder

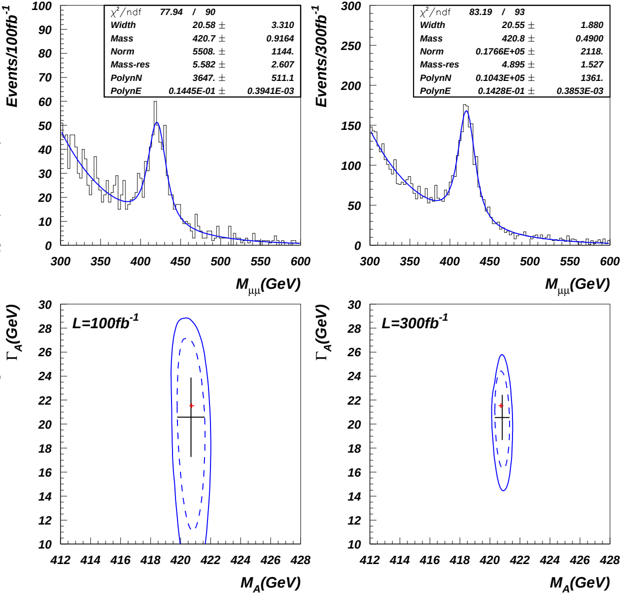
- The muon detector resolution gets worse for larger transverse momentum



Fitting Monte Carlo data

The dimuon invariant mass distribution is fitted taking into account the smearing from the muon detector

For large integrated luminosity it is possible to measure the width and mass precisely



Conclusions

- An detailed investigation of signal and background, including realistic cuts, mistagging and detector effects, has been made
- The process
$$pp \to A(H)b \to \mu^+\mu^- b$$
offers **a unique possibility to measure the Higgs boson mass and width** at the LHC
- The Higgs width is a key ingredient when fitting SUSY parameters like $\tan\beta$ and predicting neutralino relic density from colliders and LHC is not useless for this

The End