Review of prospects for H^+ in SUSY models

in view of flavour and dark matter results

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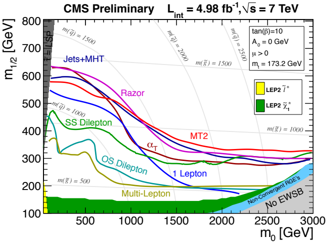
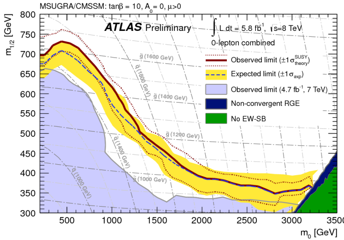
cH$^{\pm}$arged 2012
Uppsala, October 8-11, 2012

- Direct searches

- Search for SUSY is the main focus of BSM searches in both **ATLAS** and **CMS**
- Strong limits in the constrained SUSY scenarios
- No signal so far...



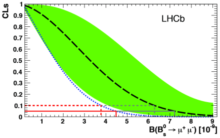
CMS website (summary plot)

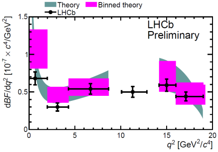


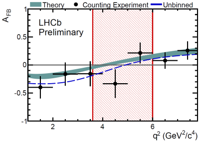
ATLAS-CONF-2012-109

- Indirect searches: flavour sector

- Precision flavour physics is sensitive to the presence of new particles in the virtual states.
- Probes sectors inaccessible to the direct searches!

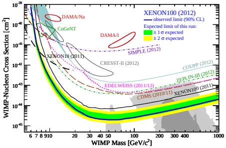






- Indirect searches: dark matter sector

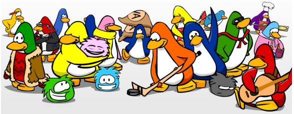
- Valuable information on the properties of the DM candidate
- Constraints on the SUSY parameters



While direct searches are only pushing the limits higher, indirect searches can add to the picture substantially!

Exciting time for flavour physics!

- Soon the discovery of $B_s \to \mu^+\mu^-$
- Many new observables are now in the game!



- However, a correct estimate of the theory predictions and uncertainties is crucial!

Exciting time also for dark matter!

- Planck cosmological results to be released next year
- Increasing sensitivity for the dark matter direct detection experiments
- Results from DAMA, CRESST and CoGeNT!

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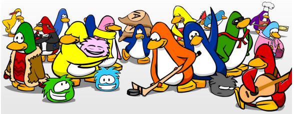

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Flavour Sector

A multi-scale problem

- new physics: $1/\Lambda_{\rm NP}$
- electroweak interactions: $1/M_W$
- hadronic effects: $1/m_b$
- QCD interactions: $1/\Lambda_{\rm QCD}$

$\Rightarrow$ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

- short distance: Wilson coefficients, computed perturbatively
- long distance: local operators

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big(\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \big) \Big)$$

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i + \Delta C_i^{NP}$
- Additional operators: $\sum_j C_j^{NP} \mathcal{O}_j^{NP}$

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$\mathcal{O}$perators

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \qquad \mathcal{O}'_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a} \qquad \mathcal{O}'_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_L b) G^{\mu\nu\, a}$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}'_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu) \qquad \mathcal{O}'_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\mu) \qquad \mathcal{O}'_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\mu)$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\gamma_5 \mu) \qquad \mathcal{O}'_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\gamma_5 \mu)$$

Primed operators: opposite chirality to the unprimed ones,
vanish or highly suppressed in the SM

Two main steps:

- Calculating $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

- Evolving the $C_i^{eff}(\mu)$ to scale $\mu \sim m_b$ using the RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

  driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$:

$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \cdots$$

Knowing the Wilson coefficients we can go ahead and calculate the observables.

To compute the amplitudes:

$$\mathcal{A}(A \to B) = \langle B|\mathcal{H}_{\rm eff}|A\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu)\langle B|\mathcal{O}_i|A\rangle(\mu)$$

$\langle B|\mathcal{O}_i|A\rangle$: hadronic matrix element

How to compute matrix elements?

$\rightarrow$ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

$\rightarrow$ Describe hadronic matrix elements in terms of hadronic quantities

Two types of hadronic quantities:

- Decay constants: Probability amplitude of hadronizing quark pair into a given hadron
- Form factors: Transition from meson to another through flavour change

Many flavour observables sensitive to SUSY particles through loop effects or exchange of charged Higgs at tree level

Key observables:

- BR($B_s \to \mu^+\mu^-$)
- BR($B \to X_s\gamma$)
- BR($B \to \tau\nu_\tau$)

Other interesting decays:

- $B \to K^*\mu^+\mu^-$
- $B \to K^*\gamma$
- $B \to D\tau\nu_\tau$
- $D_s \to \tau\nu_\tau$
- $K \to \mu\nu_\mu$

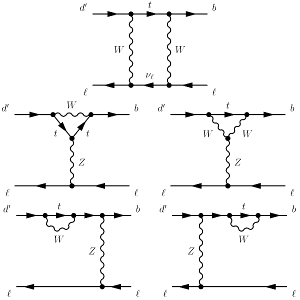
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \big) \Big]$$

Relevant operators:

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} (\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\,\ell)$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} (\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\gamma_5\ell)$$



$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left|C_S - C'_S\right|^2 + \left|(C_P - C'_P) + 2\,(C_{10} - C'_{10})\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

Very sensitive to new physics, especially for large $\tan\beta$:

SUSY contributions can lead to an O(100) enhancement over the SM!

BR($B_s \to \mu^+\mu^-$)

Experimental limit: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.2 \times 10^{-9}$ at 95% C.L.

ATLAS+CMS+LHCb combined value, LHCb-CONF-2012-017

→ Approaching dangerously the SM value!
→ Crucial to have a clear estimation of the SM prediction!

Most up-to-date key input parameters:

f_{B_s}	V_{ts}	V_{tb}	M_{B_s}	τ_{B_s}
234 MeV	-0.0403	0.999152	5.3663 GeV	1.472 ps

SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.58 \pm 0.36) \times 10^{-9}$

FM, S. Neshatpour, J. Orloff, JHEP 1208 (2012) 092

Most important sources of uncertainties:

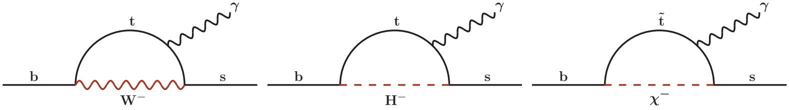
8% from f_{B_s}
2% from EW corrections
1% from matching scale
2% from μ_b scale

2% from B_s lifetime
5% from V_{ts}
1.3% from top mass

Overall TH uncertainty: 10%.

Inclusive branching ratio of $B \to X_s\gamma$

Contributing loops:

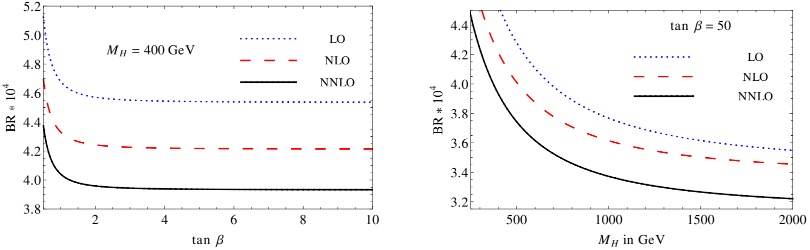


Main operator: $\mathcal{O}_7$
but higher order contributions from $\mathcal{O}_1$, ..., $\mathcal{O}_8$.

- Charged Higgs loop always adds constructively to the SM penguin
- Chargino loops can add constructively or destructively

$\to$ Cancellation possible in SUSY but not in the THDM 2!

- SM contributions known to NNLO accuracy
- THDM contributions known to NNLO accuracy
- SUSY contributions known partially to NNLO accuracy

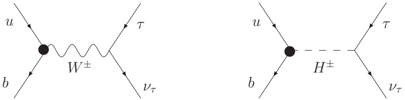


T. Hermann, M. Misiak, M. Steinhauser, arXiv:1208.2788

Experimental values (HFAG 2012): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$

SM prediction: $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.08 \pm 0.24) \times 10^{-4}$

Tree level process, mediated by W^+ and H^+, higher order corrections from sparticles



$$\mathrm{BR}(B \to \tau\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left|1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta}\right|^2$$

$$\epsilon_0 = -\frac{2\alpha_s}{3\pi} \frac{\mu}{m_{\tilde{g}}} H_2\left(\frac{m_Q^2}{m_{\tilde{g}}{}^2}, \frac{m_D^2}{m_{\tilde{g}}{}^2}\right) , \quad H_2(x,y) = \frac{x \ln x}{(1-x)(x-y)} + \frac{y \ln y}{(1-y)(y-x)}$$

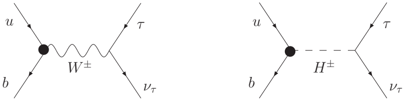
⚠ Large uncertainty from V_{ub} and f_B

Also used:

$$R_{\tau\nu_\tau}^{\mathrm{MSSM}} = \frac{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{MSSM}}}{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{SM}}} = \left[1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta}\right]^2$$

Similar processes: $B \to D\tau\nu_\tau$, $D_s \to \ell\nu_\ell$, $D \to \mu\nu_\mu$, $K \to \mu\nu_\mu$, ...

Tree level process, mediated by W^+ and H^+, higher order corrections from sparticles



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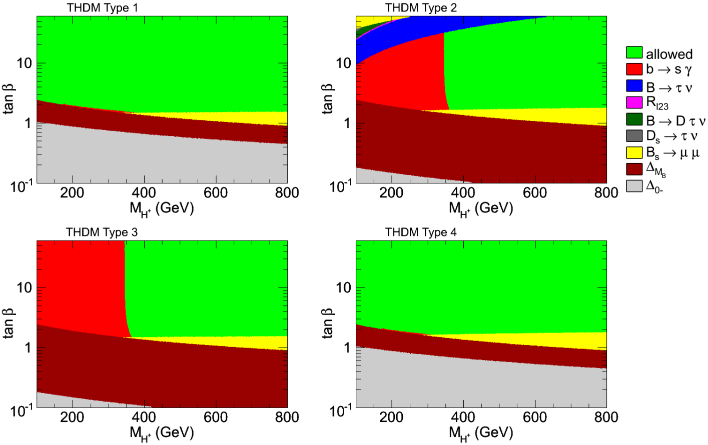
Definitions:

THDM types I–IV

- Type I: one Higgs doublet provides masses to all quarks (up and down type quarks) and charged leptons ($\sim$ SM)
- Type II: one Higgs doublet provides masses to up type quarks and the other to down-type quarks and charged leptons ($\sim$ MSSM)
- Type III: one Higgs doublet provides masses to up type quarks and charged leptons and the other to down-type quarks
- Type IV: one Higgs doublet provides masses to all quarks (up and down type quarks) and the other to charged leptons

Type	λ_U	λ_D	λ_L
I	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
III	$\cot\beta$	$-\tan\beta$	$\cot\beta$
IV	$\cot\beta$	$\cot\beta$	$-\tan\beta$

Strong constraints from $b \to s\gamma$ in THDM in particular for Types 2 and 3

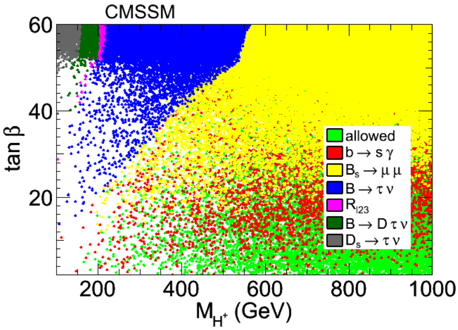


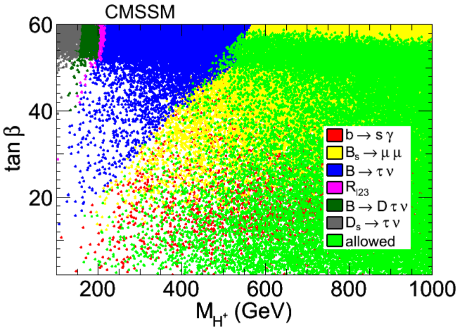
F.M., O. Stål, to appear

SuperIso v3.4

- $M_{H^\pm} < 340$ GeV is excluded at 95% C.L. in Types 2 and 3 for any $\tan\beta$.
- $\tan\beta < 2$ is excluded by several observables: $b \to s\gamma$, $\Delta_0(B \to K^*\gamma)$, ΔM_{B_d} and now even $B_s \to \mu^+\mu^-$!

Strong constraints from $b \to s\gamma$, $B \to \tau\nu$ and $B_s \to \mu^+\mu^-$ in the CMSSM





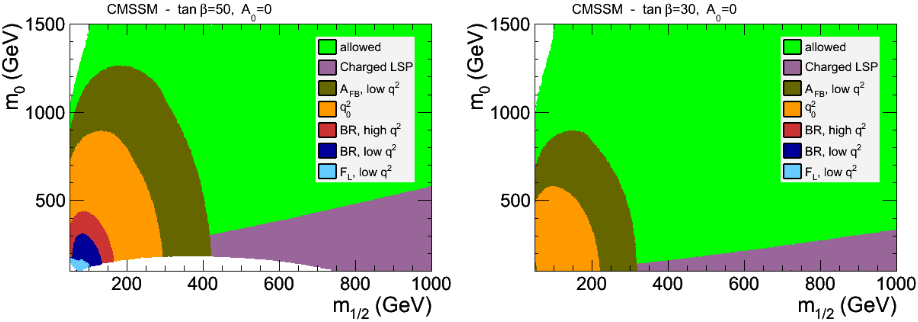
F.M., O. Stål, to appear

SuperIso v3.4

Light charged Higgs still allowed at small $\tan\beta$

... ruled out however by the neutral Higgs searches

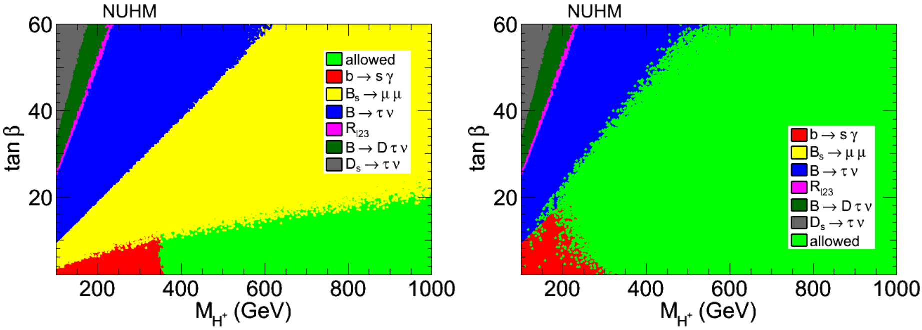
Strong constraints also from $B \to K^* \mu^+ \mu^-$ in specific CMSSM cases



FM, S. Neshatpour, J. Orloff, JHEP 1208 (2012) 092

Forward-backward asymmetry is particularly constraining!

Strong constraints from $b \to s\gamma$, $B \to \tau\nu$ and $B_s \to \mu^+\mu^-$ also in NUHM



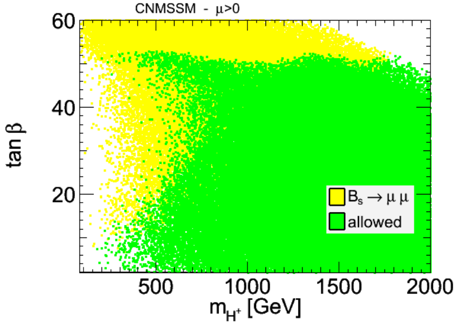
F.M., O. Stål, to appear

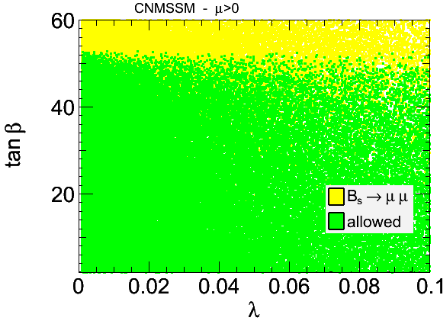
SuperIso v3.4

Light charged Higgs still allowed at small $\tan\beta$

$B_s \to \mu^+\mu^-$ more sensitive to the SUSY parameters than $b \to s\gamma$ and $B \to \tau\nu$

Constraints from $B_s \to \mu^+\mu^-$ in the CNMSSM (all parameters varied)





A.G. Akeroyd, F.M., D. Martinez Santos, JHEP 1112 (2011) 088
SuperIso v3.2

Very strong constraint for tan $\beta \gtrsim 50$

Going beyond constrained scenarios

- Constrained MSSM: useful for benchmarking, model discrimination,...
- However the mass patterns could be more complicated

Phenomenological MSSM (pMSSM)

- Flat scans over the pMSSM 19 parameters
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters

10 sfermion masses, 3 gaugino masses, 3 trilinear couplings, 3 Higgs/Higgsino

A. Djouadi et al., hep-ph/9901246

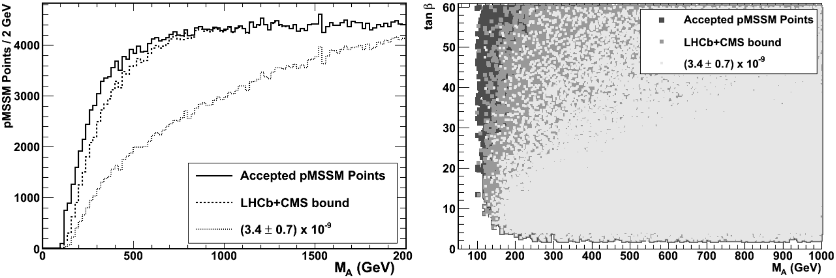
$\rightarrow$ **Interplay between low energy observables and high p_T results**

Considering 2 scenarios:

- 2011 bound from LHCb+CMS + estimated th syst:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$$

- SM like branching ratio with estimated 20% total uncertainty

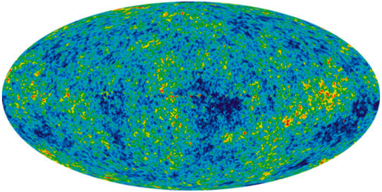


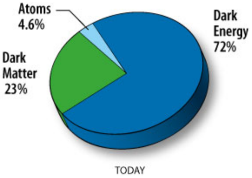
Light M_A strongly constrained!

A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1847
A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1906

Dark Matter Sector

- A cosmological and astrophysical problem...





- Most of dark matter is cold $\rightarrow$ WIMP hypothesis
- in the MSSM with R-parity conservation, the LSP is a stable WIMP
  $\rightarrow$ dark matter candidate!
- light neutralino is often the LSP

In the following, we consider the pMSSM with neutralino LSP

Dark matter searches:

- direct production of LSP's at the LHC
- DM annihilations: DM + DM $\rightarrow$ SM + SM + ...
  - indirect detection: protons, gammas, anti-protons, positrons, ...
  - dark matter relic density

  Possible enhancements of the annihilation cross-sections through Higgs resonances

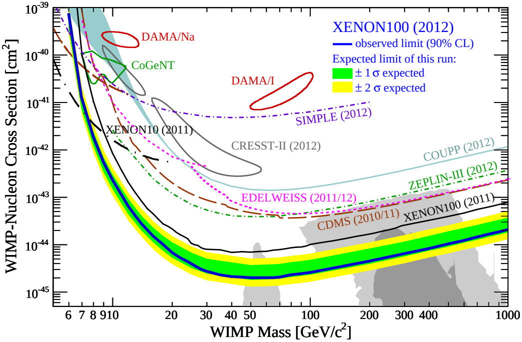
- DM scattering with matter: DM + matter $\rightarrow$ DM + matter

  $\rightarrow$ direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

Dark matter direct detection experiments probe the Higgs sector of the MSSM!

Present situation:

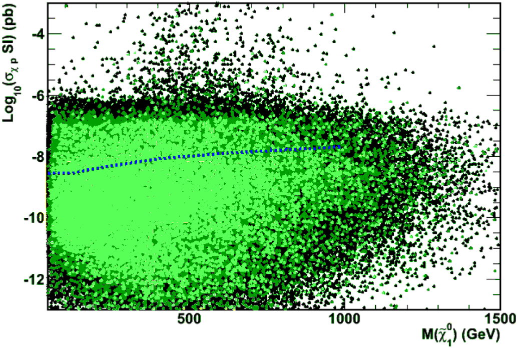


XENON, arXiv:1207.5988

- DAMA, CoGeNT, CRESST claim for a possible WIMP discovery
- SIMPLE, COUPP, ZEPLIN, CDMS, EDELWEISS and XENON give exclusion limits

$\rightarrow$ **Unclear situation, but the sensitivity is improving!**

pMSSM points and XENON dark matter exclusion limit

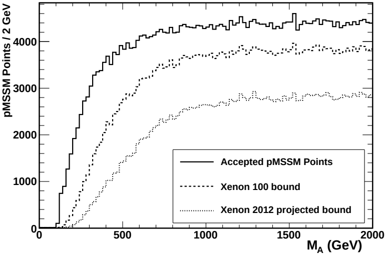


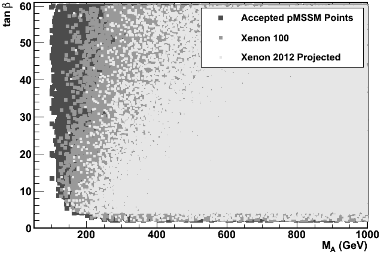
A. Arbey, M. Battaglia, A. Djouadi, FM, to appear

Black: all valid points
Dark green: points compatible at 90% C.L. with the LHC Higgs search results
Light green: points compatible at 68% C.L. with the LHC Higgs search results

Dotted blue line: 2012 XENON-100 limit at 95% C.L.

28% of the valid points are excluded by XENON-100 pMSSM points and XENON dark matter exclusion limit



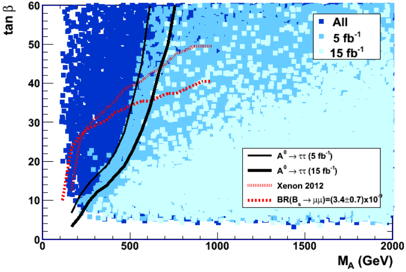


A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

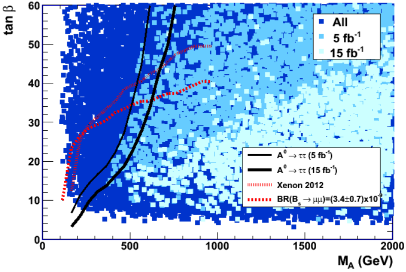
Results and sensitivity similar to those from $B_s \to \mu^+\mu^-$ and $A/H \to \tau^+\tau^-$, with different couplings/sectors probed.

Constraints from flavour physics, dark matter direct detection, SUSY and Higgs searches

Without Higgs decay rate constraints



With Higgs decay rate constraints



A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

Once putting everything together the allowed region is really squeezed!

News from SuperIso

- Full THDM NNLO corrections to $b \to s\gamma$
- Untagged BR($B_s \to \mu^+\mu^-$)
- Addition of many observables related to $B \to K^*\mu^+\mu^-$:
  - Differential branching fractions
  - Forward-Backward asymmetry and zero-crossing
  - Isospin asymmetry and zero-crossing
  - F_L, F_T, α_{K^*}
  - $A_T^{(1)}$, ..., $A_T^{(5)}$, A_{im}
  - $H_T^{(1)}$, $H_T^{(2)}$, $H_T^{(3)}$
  - P_1, P_2, P_3
- Addition of observables related to $B \to X_s\ell^+\ell^-$:
  - Differential branching fractions
  - Forward-Backward asymmetry and zero-crossing

FM, Comput. Phys. Commun. 178 (2008) 745
FM, Comput. Phys. Commun. 180 (2009) 1579
FM, Comput. Phys. Commun. 180 (2009) 1718

http://superiso.in2p3.fr

- Interplay between direct and indirect searches is very important and plays a crucial role for constraining SUSY
- Many interesting flavour observables available
- Dark matter direct detection probes the same parameter regions as flavour physics
- The constrained SUSY scenarios are highly constrained
- General MSSM: A lot of viable model points survive, but flavour, dark matter and Higgs searches can squeeze the parameter space

Backup

Muon anomalous magnetic moment