Status of SUSY after the 8 TeV LHC run

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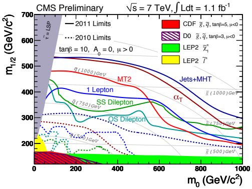
Hunting for SUSY at the LHC Miniworkshop

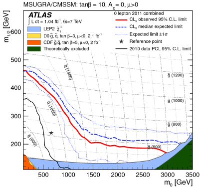
Laboratori Nazionali di Frascati, March 13th, 2014

SUSY searches

Search for SUSY is the main focus of BSM searches in both **ATLAS** and **CMS**

Summer 2011
(with $\sim$1 fb^{-1} of data
at 7 TeV)





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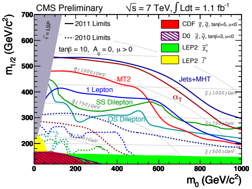

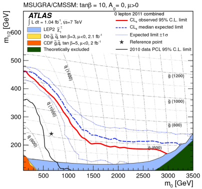

Summer 2012
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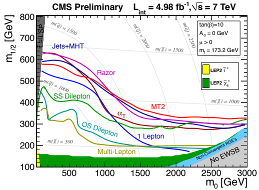

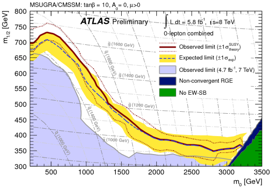

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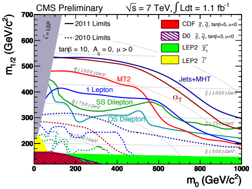

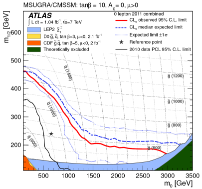

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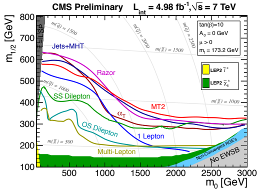

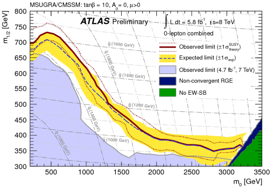

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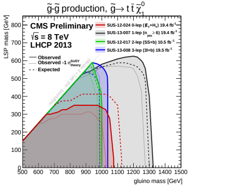

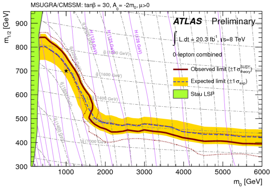

No signal yet...
SUSY masses pushed to larger and larger values!

Interpretation of the results

Two important points:

1. What do these limits mean exactly?

   Is low energy SUSY excluded??

   Most of the experimental limits are given for constrained or simplified MSSM scenarios

   Useful, but NOT representative of the whole MSSM!

$\rightarrow$ Reinterpret the results in general MSSM with minimal theoretical assumptions

$\rightarrow$ Phenomenological MSSM: an adequate set-up

Interpretation of the results

2. As a result of the current searches: the limits are pushed to larger masses

This does not provide any conclusive idea!

The only way to point to a specific SUSY scenario, or exclude SUSY would be to take advantage of **interplays** in particular:

- Direct searches
  - Information from the Higgs sector: Mass and couplings
  - Information from other than SUSY searches: Monojet searches
- Indirect searches
  - Flavour physics sector: Rare decays
  - Dark matter searches: Relic density and direct DM search results

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Phenomenological MSSM

Phenomenological MSSM (pMSSM)

- The most general CP/R parity-conserving MSSM
- 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: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$

3 gaugino masses: M_1, M_2, M_3

3 trilinear couplings: $A_d = A_s = A_b$, $A_u = A_c = A_t$, $A_e = A_\mu = A_\tau$

3 Higgs/Higgsino parameters: M_A, $\tan\beta$, μ

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

Pioneer study:

SUSY without prejudice, C.F. Berger, J.S. Gainer, J.L. Hewett, T.G. Rizzo, JHEP 0902 (2009) 023

pMSSM scans

Complete analysis in pMSSM:

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables (**SuperIso**)
- Computation of dark matter observables (**SuperIso Relic**, Micromegas)
- Determination of SUSY and Higgs mass limits (**SuperIso**, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, FeynHiggs, ...)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, MadGraph, Prospino)
- Determination of detectability with fast detector simulation (Delphes)

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 3000]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 3000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 3000]
$M_{\tilde{\tau}_L}$	[0, 3000]
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$M_{\tilde{t}_R}$	[0, 3000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 3000]
$M_{\tilde{b}_R}$	[0, 3000]

pMSSM scans

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s \gamma$), BR($B_s \to \mu^+ \mu^-$), BR($B \to \tau \nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density (neutralino LSP)
- Dark matter direct search limits
- Higgs mass limits
- Higgs production and decay rates
- LHC SUSY direct search limits
- LHC monojet limits

Statistics:

- more than 200M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.

Direct SUSY searches in the pMSSM

Direct SUSY searches used in our analysis:

squark and gluino direct searches (jets + $\not{E}_T$)

ATLAS-CONF-2013-047

stop and sbottom direct searches (b-jets + $\not{E}_T$)

ATLAS-CONF-2013-053

chargino and neutralino direct searches (2 or 3 leptons + $\not{E}_T$)

ATLAS-CONF-2013-049, ATLAS-CONF-2013-035

Method used for each pMSSM point:

- Event generation with PYTHIA
- NLO calculation with Prospino
- Detector simulation with Delphes

Monojet searches in the pMSSM

Monojet searches: search for 1 hard jet + $\not{E}_T$

ATLAS-CONF-2012-147, ATLAS-CONF-2013-068, CMS PAS EXO-12-048

Usually interpretation in terms of effective operators (WIMP-WIMP-q-$\bar{q}$ or -g-g)

In the MSSM: $pp \to \chi_1^0 + \chi_1^0 + j$,

but: $pp \to (\tilde{q}, \tilde{g}) + (\tilde{q}, \tilde{g}) + j$, where $(\tilde{q}, \tilde{g}) \to \chi_1^0 +$ soft jet, is often dominant!

$\to$ Effective operator approach is not applicable in SUSY!

$\to$ Re-analysis of the monojet search results in the context of the pMSSM

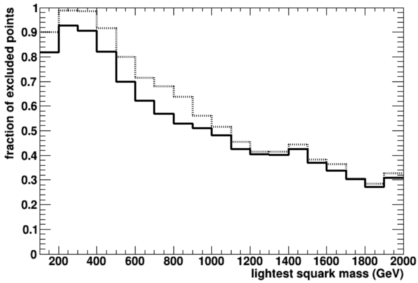
Method used for each pMSSM point:

- Amplitude generation with MadGraph
- Event generation with MadEvent and PYTHIA
- Detector simulation with Delphes

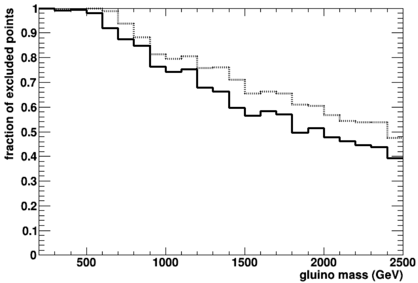
Monojets and direct SUSY searches in the pMSSM

Consequences on sparticle masses:

Lightest squark mass



Gluino mass



Preliminary

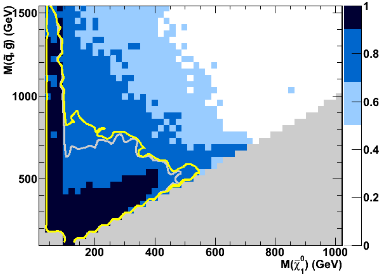
Solid: jets/leptons+MET searches
Dotted: + monojet analyses

squark and gluino masses well below 1 TeV are still allowed!

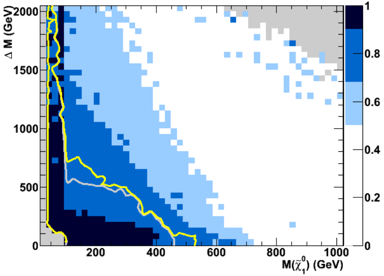
Monojets and direct SUSY searches in the pMSSM

Neutralino mass:

vs. lightest squark/gluino mass



vs. mass splitting with lightest squark/gluino



A. Arbey, M. Battaglia, FM, arXiv:1311.7641

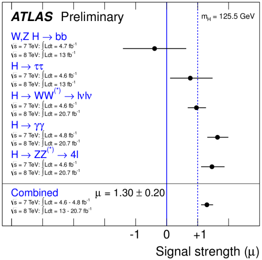
Color scale: fraction of excluded points
Grey line: 68% C.L. exclusion by jets/leptons+MET searches
Yellow line: + monojet analyses

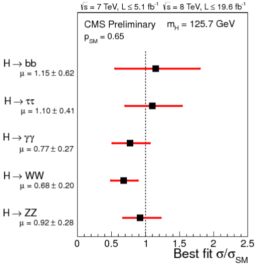
Higgs sector

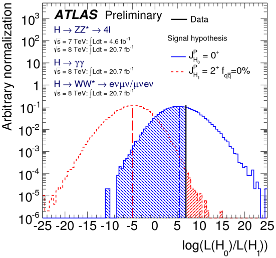
Higgs searches

Discovery of a Higgs boson announced in July 2012!

Compatible with the SM Higgs







Higgs decay rates

Signal strength is defined as:

$$\mu_{XX} = \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

LHC results:

Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 2.1	ATLAS+CMS
$\mu_{\gamma\gamma}$	1.20 ± 0.30	ATLAS+CMS
μ_{ZZ}	1.10 ± 0.22	ATLAS+CMS
μ_{WW}	0.77 ± 0.21	ATLAS+CMS
$\mu_{b\bar{b}}$	1.12 ± 0.45	ATLAS+CMS+(CDF+D0)
$\mu_{\tau\tau}$	0.94 ± 0.24	ATLAS+CMS

$\to$ diphoton decay mode $\Rightarrow$ massive neutral boson with spin $\neq 1$
$\to$ compatible with the SM Higgs

Implications of the Higgs mass determination

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle is bounded from above: $M_h^{max} \approx M_Z|\cos 2\beta| +$ radiative corrections $\lesssim 110 - 135$ GeV
- Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections

$$M_h^2 \approx M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2}\sin^2 2\beta\right] + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu/\tan\beta$
- M_h^{max} is obtained for:
  - a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$
  - large $\tan\beta$, *i.e.* $\tan\beta \gtrsim 10$
  - heavy stops, *i.e.* large M_S
  - maximal mixing scenario, *i.e.* $X_t \approx \sqrt{6} M_S$

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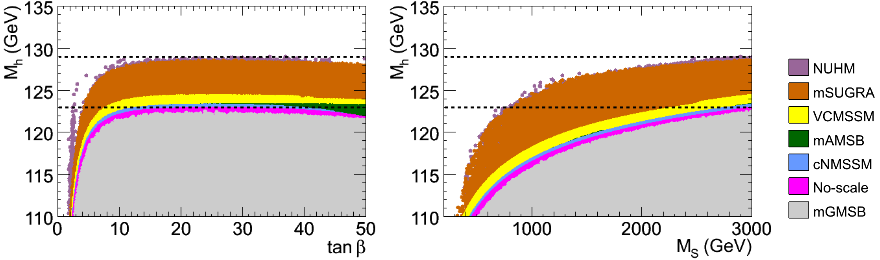
Implications of the Higgs mass determination

Maximal Higgs mass in constrained MSSM scenarios

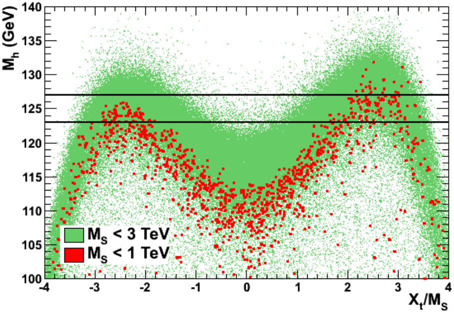


A. Arbey, M. Battaglia, A. Djouadi, F.M., JHEP 1209 (2012) 107

Several constrained models are excluded or about to be!

Implications of the Higgs mass determination

Implications in pMSSM:



A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

$M_h \sim 125$ GeV is easily satisfied in pMSSM

No mixing cases ($X_t \approx 0$) excluded for small M_S

Higgs couplings

Modified couplings with respect to the SM Higgs boson ($\rightarrow$ decoupling limit):

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha / \sin\beta \rightarrow 1$	$-\sin\alpha / \cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha / \sin\beta \rightarrow \cot\beta$	$\cos\alpha / \cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$\cot\beta$	$\tan\beta$	0

where:

$$\alpha = \frac{1}{2}\arctan\left(\tan(2\beta)\,\frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}\right)$$

Higher order corrections to the tree level couplings can be large for light SUSY particles

Also at tree level:

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

pMSSM regimes

Particular benchmark scenario: maximal mixing ($X_t \approx \sqrt{6} M_S$):

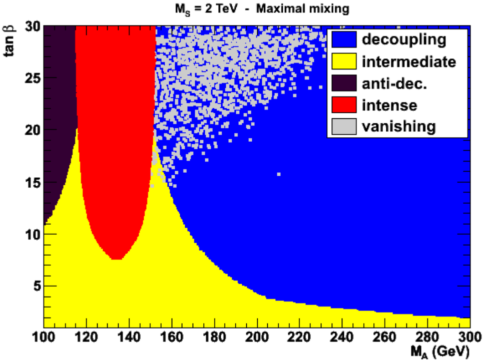
Decoupling regime:
large M_A, $\cos^2(\beta - \alpha) \leq 0.05$

Intermediate regime:
intermediate M_A

Anti-decoupling regime:
small M_A, $\cos^2(\beta - \alpha) \geq 0.95$

Intense coupling:
h, A, H rather close in mass,
g^2_{hbb} and $g^2_{Hbb} \geq 50$

Vanishing coupling:
g^2_{hbb} or $g^2_{hVV} \leq 0.05$



Green: LEP Higgs search limit

Solid black line: CMS $A/H \to \tau^+\tau^-$ search limit at 7+8 TeV with 17/fb

Dotted cyan line: ATLAS $t \to H^+ b$ search limit at 7 TeV with 4.6/fb

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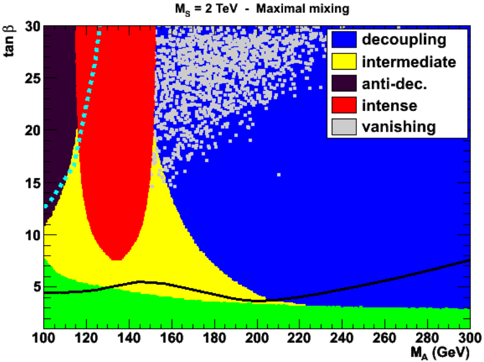

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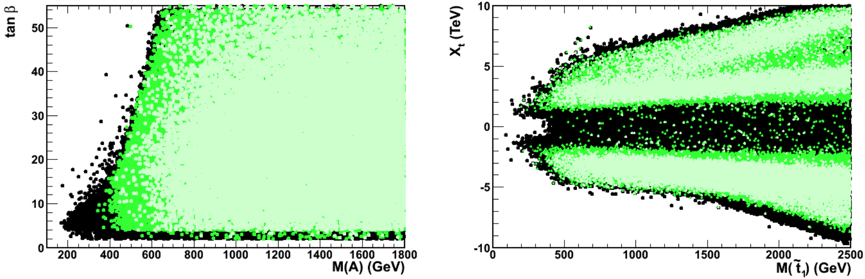
Consequences of the Higgs rate measurements in pMSSM



A. Arbey, M. Battaglia, A. Djouadi, FM, Phys. Lett. B720 (2013) 153

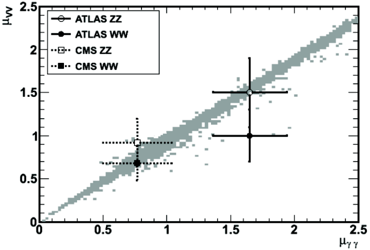
Black: all accepted points
Dark green: points compatible at 90% CL with the Higgs rates
Light green: points compatible at 68% CL with the Higgs rates

→ $M_A < 350$ GeV disfavoured by the Higgs signal strengths (→ decoupling regime)
→ Still possible to have $M_{\tilde{t}} < 500$ GeV!
→ $|X_t| < 1.5$ TeV strongly disfavoured by the Higgs data

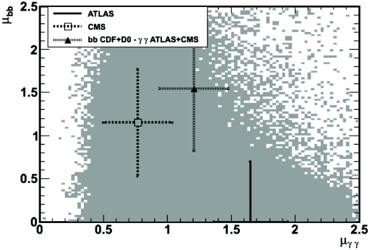
Consequences of the Higgs rate measurements in pMSSM

Correlations between the decay rates:

$\gamma\gamma - VV$



$\gamma\gamma - bb$



Interesting correlations!

Experimental values compatible with the bulk of the pMSSM points

Heavy Higgs searches

MSSM can be strongly constrained also by Heavy Higgs searches

$\rightarrow$ LHC experiments focussed mainly on $H/A \rightarrow \tau^+\tau^-$ so far

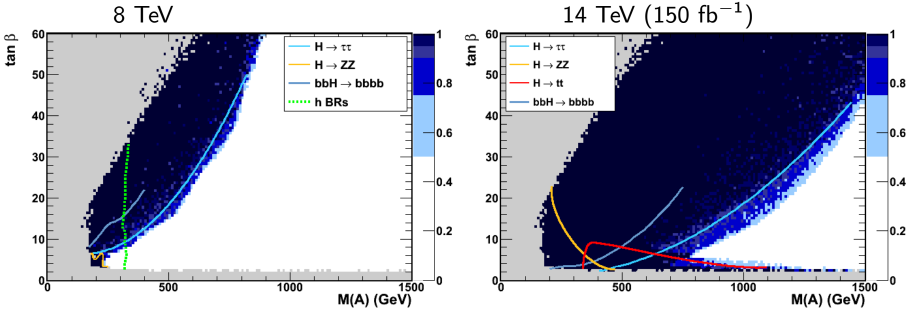
However:

- limits are given for the $M_h^{\max}$ scenario
- They can be falsified in case of light SUSY particles
  $\rightarrow$ Higgs decays to MSSM particles open (i.e. decays to light staus)
- Important to use several channels

$\rightarrow$ **Look for other channels, with the largest strengths**

Heavy Higgs search constraints

Complementary channels: $H \to ZZ, bb, tt, hZ, hh$



A. Arbey, M. Battaglia, FM, Phys.Rev. D88 (2013) 015007

lines: limits corresponding to an exclusion of 99.9% of the points
grey points: excluded by dark matter, flavour physics and Higgs mass constraints
colour (blue) scale: fraction of excluded points

→ Some points inside the $H \to \tau\tau$ excluded region still survive

→ Other channels ($H \to ZZ$, $H \to t\bar{t}$, ...) will help probing the small $\tan\beta$ region

Flavour sector

Indirect searches: Flavour sector

- **LHCb** has a very rich program to search for indirect signs of new physics!
  Main probes: CP Violating observables, Rare decays
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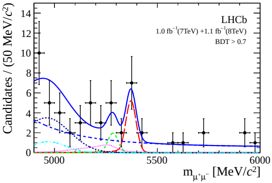
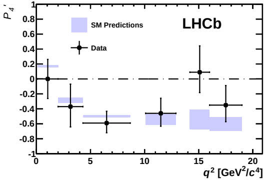
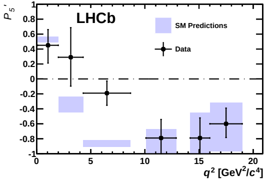


LHCb, Phys. Rev. Lett. 110 (2013) 021801





LHCb, Phys. Rev. Lett. 111 (2013), 191801

No clear hint for New physics yet, but very promising situation!

Combining results from direct and indirect searches provides valuable information

$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Relevant operators:

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

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$

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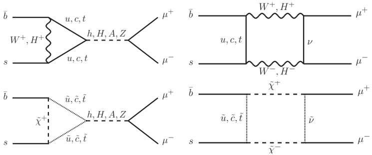

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Largest contributions in SM from a Z penguin top loop (75%) and a W box diagram (24%)

First experimental evidence:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.2^{+1.4}_{-1.2}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{syst})) \times 10^{-9}$$

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Combined LHCb/CMS result: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

CMS PAS BPH-13-007, LHCb-CONF-2013-012

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

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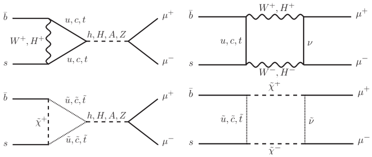

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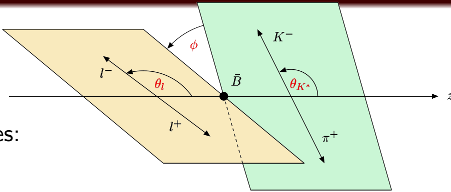
$B \to K^* \mu^+ \mu^-$ – Angular distributions

Angular distributions

The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \to K^- \pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ



Differential decay distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$

↘ angular coefficients J_{1-9}

↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$
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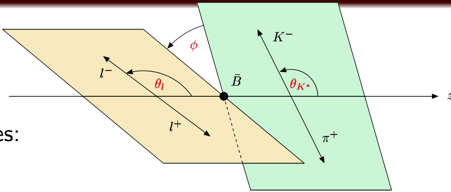

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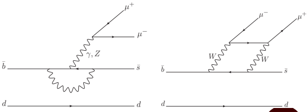

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$B \to K^* \mu^+ \mu^-$ – Optimised observables

Optimised: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\rm bin} = \frac{1}{2} \frac{\int_{\rm bin} dq^2 [J_3 + \bar{J}_3]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\rm bin} = \frac{1}{8} \frac{\int_{\rm bin} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]}$$

$$\langle P'_4 \rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_4 + \bar{J}_4] \qquad \langle P'_5 \rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P'_6 \rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_7 + \bar{J}_7] \qquad \langle P'_8 \rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_8 + \bar{J}_8]$$

with

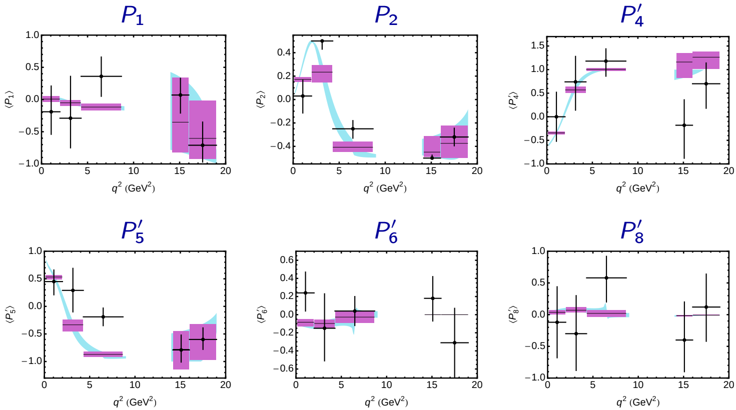
$$\mathcal{N}'_{\rm bin} = \sqrt{-\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}] \int_{\rm bin} dq^2 [J_{2c} + \bar{J}_{2c}]}$$

+ CP violating clean observables and other combinations

U. Egede et al., JHEP 0811 (2008) 032, JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

$B \to K^* \mu^+ \mu^-$ – Experimental results

First measurements by LHCb:



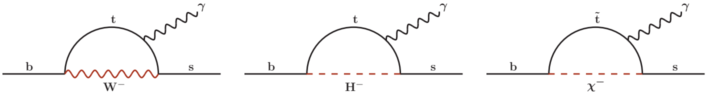
LHCb collaboration, Phys. Rev. Lett. 111 (2013), 191801

3.7σ local discrepancy in the P'_5, $4.3 < q^2 < 8.68$ GeV^2 bin

$B \to X_s\gamma$

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
- Very precise theory prediction (at NNLO)

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

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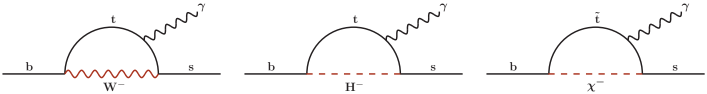

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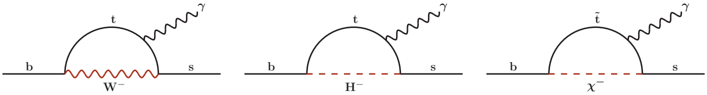

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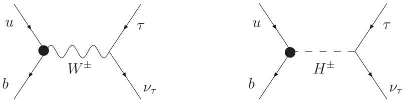
$B \to \tau\nu$

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



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

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⚠ Large uncertainty from V_{ub} and f_B

$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (1.15 \pm 0.29) \times 10^{-4}$

with $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ and $f_B = 194 \pm 10$ MeV

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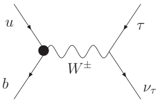

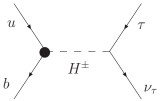

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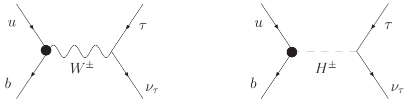

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Constrained MSSM (CMSSM)

CMSSM = MSSM with GUT scale universality assumptions
$\rightarrow$ 4 parameters + 1 sign

$\tan\beta \in [1, 60]$; $m_0 \in [50, 3500]$; $m_{1/2} \in [50, 3500]$; $A_0 \in [-10000, 10000]$

CMSSM with m_0 and $m_{1/2}$ varied, $\mu > 0$, $A_0 = -2\, m_0$ and $\tan\beta$ fixed:

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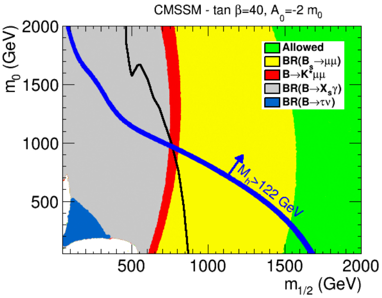

FM, S. Neshatpour, J. Virto, arXiv:1401.2145

Black line: ATLAS exclusion limit with 20.3 fb^{-1} data
Blue line: Higgs mass exclusion limit ($M_h = 122$ GeV)

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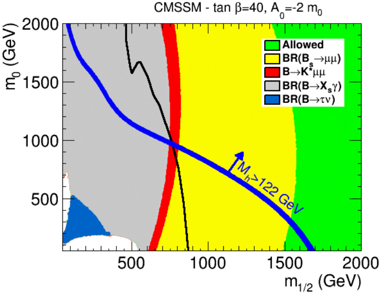

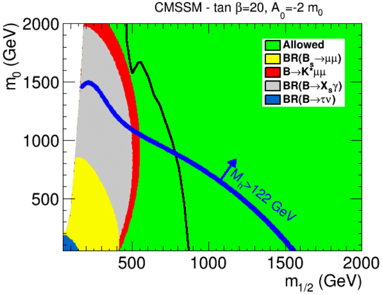

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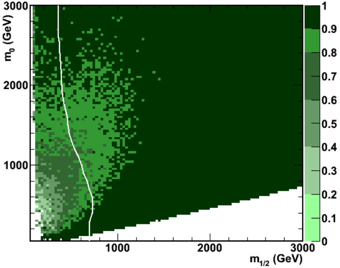
Constraints on CMSSM from BR($B_s \to \mu^+\mu^-$)

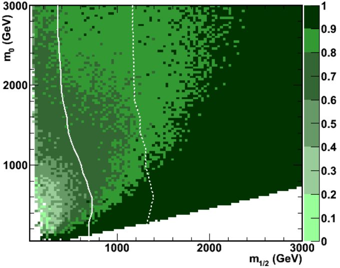
CMSSM with all parameters varied:

Fraction of CMSSM points compatible with BR($B_s \to \mu^+\mu^-$)

Current constraints



Ultimate constraints

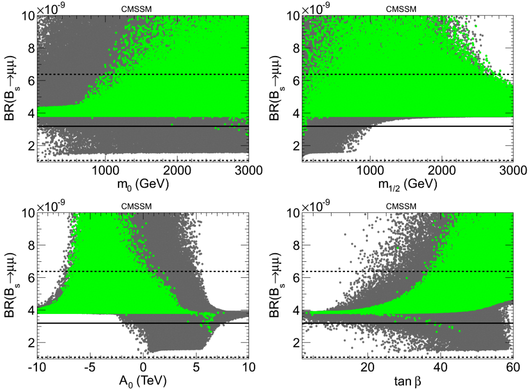


A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

Continuous line: ATLAS SUSY searches at 8 TeV with 5.8 fb^{-1} of data
Dotted line: reach estimated at 14 TeV with 300 fb^{-1}

Constraints on CMSSM from BR($B_s \to \mu^+\mu^-$)

Flat scans over the CMSSM parameters with $\mu > 0$



A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

Solid line: central value of the BR($B_s \to \mu^+\mu^-$) measurement

Dashed lines: 2σ experimental deviations

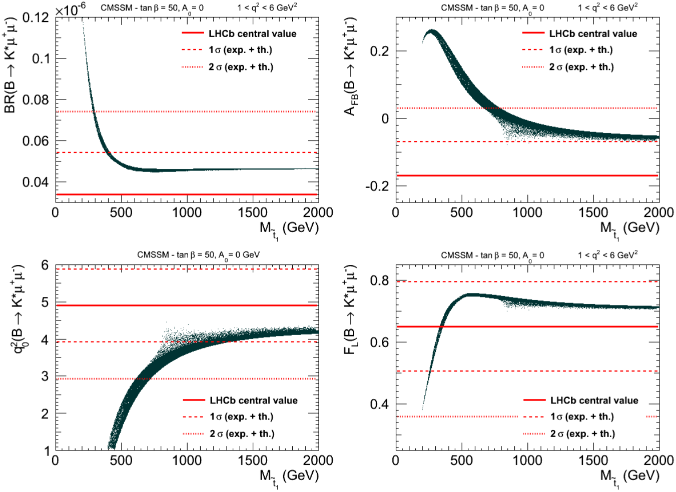
Gray points: all valid points

Green points: points in agreement with the Higgs mass constraint

BR($B_s \to \mu^+\mu^-$) smaller than SM and the Higgs mass constraint cannot be satisfied simultaneously!!

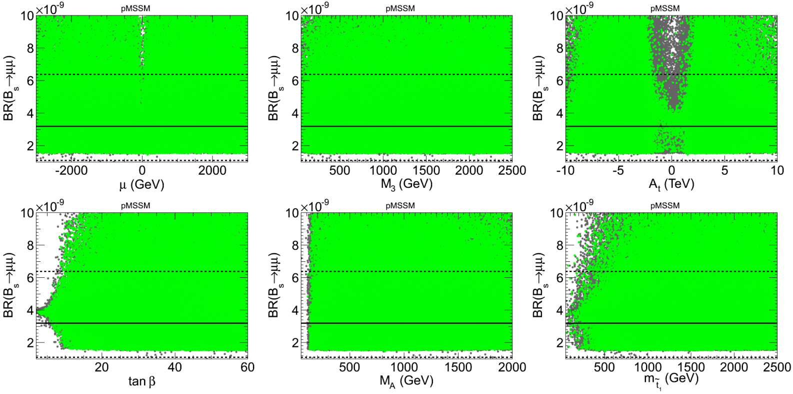
Constraints on CMSSM from $B \to K^* \mu^+ \mu^-$

$B \to K^* \mu^+ \mu^-$ in the low q^2 region: CMSSM - $\tan\beta = 50$



A_{FB} in the low q^2 region is especially interesting!

Constraints on pMSSM from BR($B_s \to \mu^+\mu^-$)



A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

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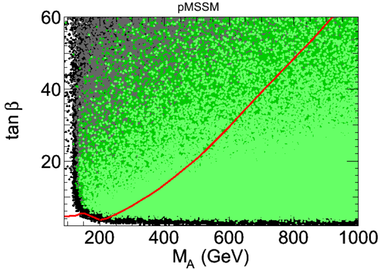
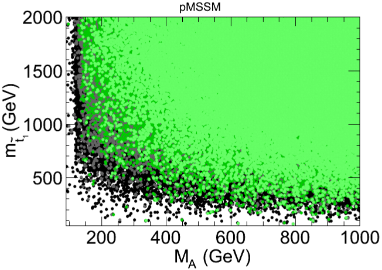




A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

Black points: all the valid pMSSM points

Gray points: $123 < M_h < 129$ GeV

Dark green points: in agreement with the latest BR($B_s \to \mu^+\mu^-$)

Light green points: in agreement with the ultimate LHCb BR($B_s \to \mu^+\mu^-$) measurement

Red line: excluded at 95% C.L. by the latest CMS $A/H \to \tau^+\tau^-$ searches

A closer look at the interplay with Higgs searches

- **Higgs mass**

  Large one-loop correction from stop loops:

$$(\Delta M_h^2)_{\tilde{t}} \approx \frac{3\sqrt{2}G_F}{2\pi^2}\, m_t^4 \left[-\log\left(\frac{m_t^2}{m_{\tilde{t}}^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

  with $X_t = A_t - \mu/\tan\beta$

  The maximal value can be reached for $X_t = \sqrt{6} m_{\tilde{t}}$ (maximal mixing).

- **Higgs decay rates**

  e.g. the diphoton channel receives contributions from stop, sbottom, stau, charged Higgs boson, and chargino loops:

$$\kappa_\gamma \equiv \frac{\Gamma(h \to \gamma\gamma)_{\rm MSSM}}{\Gamma(h \to \gamma\gamma)_{\rm SM}} \approx \frac{1}{F_W - \frac{4}{3}} \left[-\frac{4}{3}\kappa_{\tilde{t}} - \frac{1}{3}\kappa_{\tilde{b}} - \kappa_{\tilde{\tau}} + \kappa_{H^\pm} + \kappa_{\chi^\pm} \right]$$

  in particular

$$\kappa_{\tilde{\tau}} \approx -\frac{m_\tau^2 X_\tau^2}{4 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

  with where $X_\tau = A_\tau - \mu \tan\beta$.

Enhancement of $h \to \gamma\gamma$ in particular for small $m_{\tilde{\tau}}$, large μ and large $\tan\beta$

Interplay with Higgs searches

- $\mathrm{BR}(B \to X_s\gamma)$

$$\frac{\mathrm{BR}(B \to X_s\gamma)_{\mathrm{MSSM}}}{\mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}}} \approx 1 - 2.61\,\Delta C_7 + 1.66\,(\Delta C_7)^2$$

where $\Delta C_7^{H^\pm} \approx \frac{m_t^2}{3M_{H^\pm}{}^2}\left(\ln\frac{m_t^2}{M_{H^\pm}{}^2} + \frac{3}{4}\right)$, $\quad \Delta C_7^{\chi^\pm} \approx -\mu A_t \tan\beta \frac{m_t^2}{m_{\tilde{t}}{}^4}\, g(x_{\tilde{t}\mu})$

with $x_{\tilde{t}\mu} = m_{\tilde{t}}^2/\mu^2$ and $g(x) = -\frac{7x^2-13x^3}{12(1-x)^3} - \frac{2x^2-2x^3-3x^4}{6(1-x)^4}\ln x$

- $\mathrm{BR}(B_s \to \mu^+\mu^-)$

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{MSSM}}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1 - 13.2\; C_P + 43.6\,(C_S^2 + C_P^2)$$

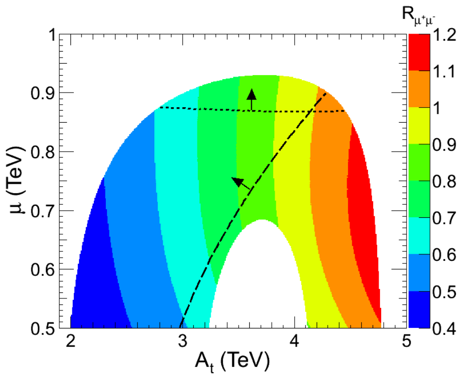
where $C_S \approx -C_P \approx -\mu A_t \frac{\tan^3\beta}{(1+\epsilon_b\tan\beta)^2}\frac{m_t^2}{m_{\tilde{t}}{}^2}\frac{m_b m_\mu}{4\sin^2\theta_W M_W^2 M_A{}^2} f(x_{\tilde{t}\mu})$

with $f(x) = -\frac{x}{1-x} - \frac{x}{(1-x)^2}\ln x$

Correlations with the Higgs sector through $m_{\tilde{t}}$, μ, A_t, $\tan\beta$, M_A

Interplay with Higgs searches

Consequences in a scenario with light staus



U. Haisch and FM, JHEP 1301 (2013) 061

In the region where the diphoton rate is enhanced, agreement with $\mathrm{BR}(\bar{B} \to X_s\gamma)$ imposes $\mathrm{BR}(B_s \to \mu^+\mu^-)$ to be smaller than SM!

Such correlations are testable at the LHC!

Dotted line: $R_{\gamma\gamma} > 1$
Dashed line: constraint from $\mathrm{BR}(\bar{B} \to X_s\gamma)$

Dark matter sector

Dark Matter Searches

Different types of dark matter searches:

- direct production of LSP's at the LHC
- DM annihilations: DM + DM → 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 → DM + matter

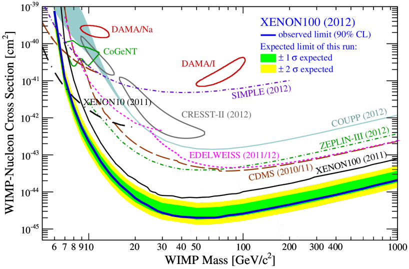
  → direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

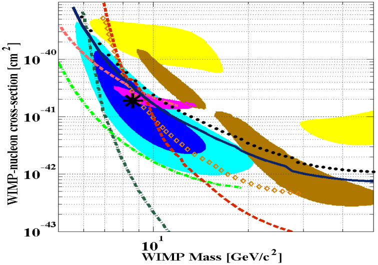
Dark matter direct detection experiments probe the Higgs sector of the MSSM!

Dark matter direct detection

Present situation:



XENON, arXiv:1207.5988



CDMS, arXiv:1304.4279

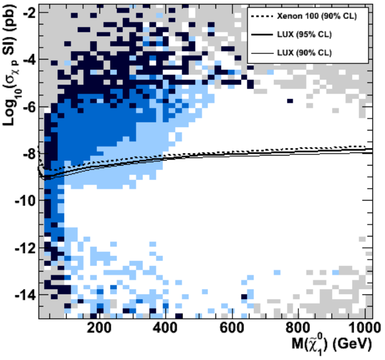
- DAMA, CoGeNT, CRESST and now CDMS claim for a possible WIMP discovery
- SIMPLE, COUPP, ZEPLIN, EDELWEISS and XENON (and LUX!) give exclusion limits

→ **Unclear situation, but the sensitivity is improving!**

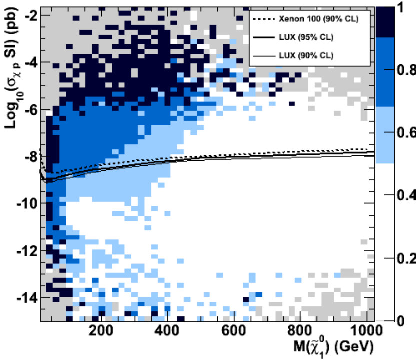
Monojets, direct SUSY searches and DM direct detection in the pMSSM

In the DM direct detection scattering cross section vs. neutralino mass plane:

jets/leptons+MET only



jets/leptons+MET searches and monojet



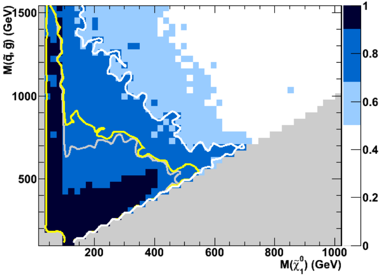
A. Arbey, M. Battaglia, FM, arXiv:1311.7641

Color scale: fraction of excluded points

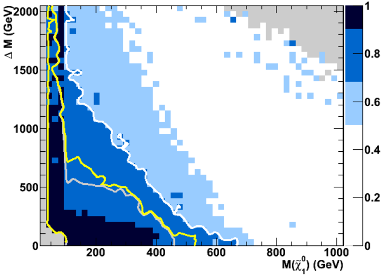
Monojets, direct SUSY searches and DM direct detection in the pMSSM

Neutralino mass:

vs. lightest squark/gluino mass



vs. mass splitting with lightest squark/gluino



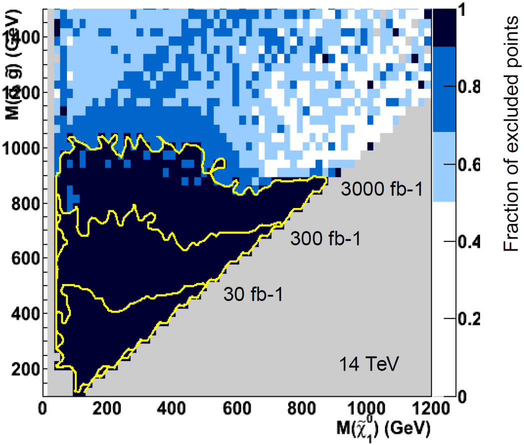
A. Arbey, M. Battaglia, FM, arXiv:1311.7641

Color scale: fraction of points excluded by jets/leptons+MET searches, monojet analyses and LUX direct DM search

Grey line: 68% C.L. exclusion by jets/leptons+MET searches
Yellow line: + monojet analyses
White line: + LUX direct DM search

Monojet searches at 14 TeV

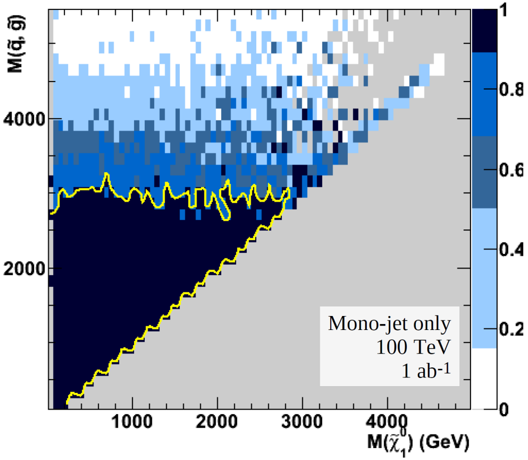
Neutralino mass vs. lightest squark/gluino mass



Preliminary

Monojet searches at 100 TeV

Neutralino mass vs. lightest squark/gluino mass, 1 ab^{-1}



Preliminary

Conclusions

After the first LHC run:

No signal for SUSY, but still many solutions survive!

– go beyond the lamp post scenario
– pMSSM seems to be an adequate set-up
– reinterpretations of the results in pMSSM are complex but doable!

$\rightarrow$ Low energy MSSM is still alive!

In the next run:

– if no signal, the only way to exclude SUSY would be through the interplay

- between different search channels
- between different sectors

– if new bumps show up

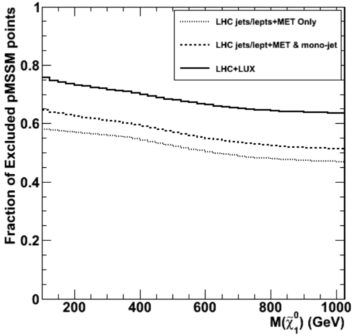
again the interplay would be extremely useful for model discrimination

Backup

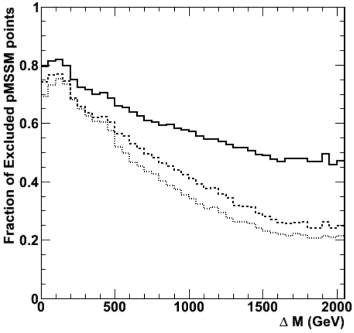
Backup

Monojets, direct SUSY searches and DM direct detection in the pMSSM

Neutralino mass



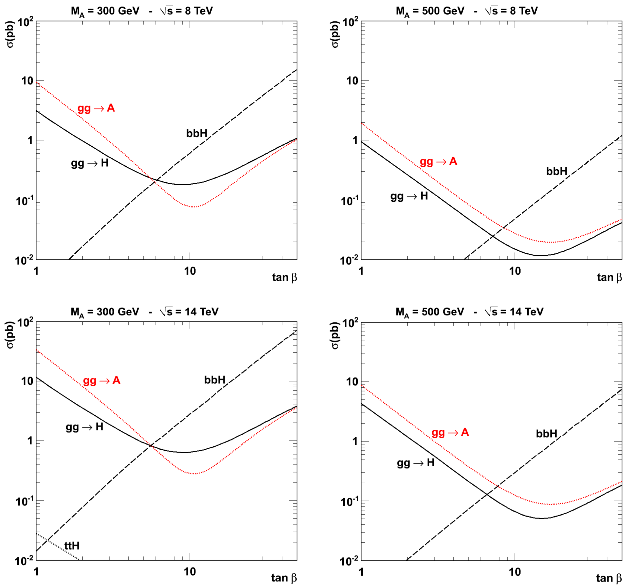
Mass splitting with lightest squark/gluino



A. Arbey, M. Battaglia, FM, arXiv:1311.7641

Dotted: jets/leptons+MET searches
Dashed: + monojet analyses
(Plain: + LUX direct DM search)

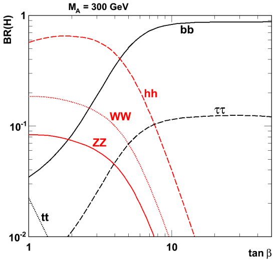
Heavy Higgs production

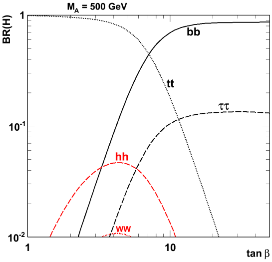


Heavy Higgs decays

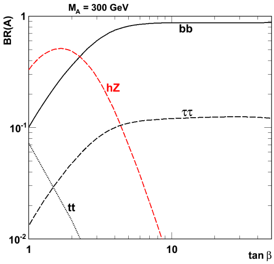
$M_A = 300$ GeV $\quad$ $M_A = 500$ GeV

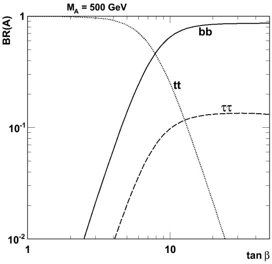
H decays





A decays

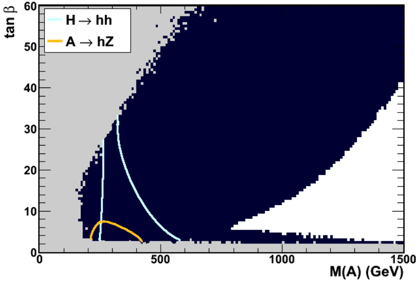




Heavy Higgs search constraints

Other future searches of interest: light Higgs production

14 TeV (150 fb^{-1})



lines: limits corresponding to an exclusion of 99.9% of the points
grey points: excluded by dark matter, flavour physics and Higgs mass constraints
dark blue points: excluded by the other heavy Higgs searches

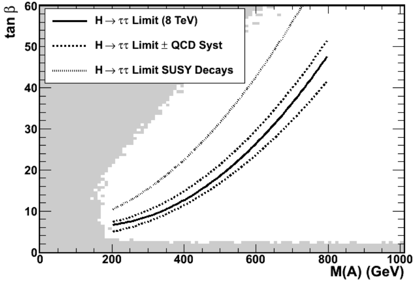
→ These channels will probe the small to intermediate $\tan\beta$ region

Heavy Higgs searches and uncertainties

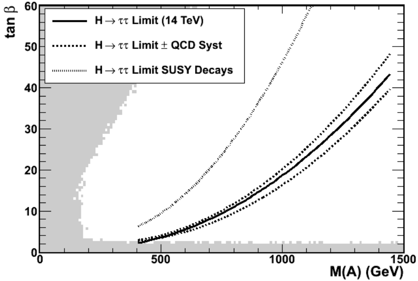
QCD uncertainties (PDF, α_s, m_t, ...) limiting factor for the $H/A \to \tau^+\tau^-$ constraints

Additional H to SUSY particle decays also limiting factor

8 TeV



14 TeV

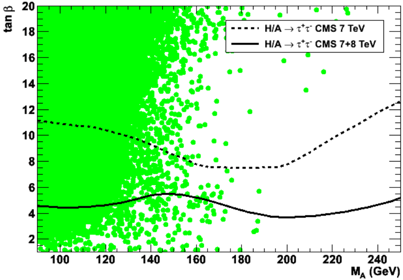


Existence of SUSY decays much more limiting than QCD uncertainties

→ **Exclusion limits should not be blindly applied**

SM-like heavy CP-even Higgs

Light or heavy Higgs at 126 GeV??



A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

Green: $122 < M_H < 129$ GeV

Red: + excluded by BR($B \to X_s \gamma$)

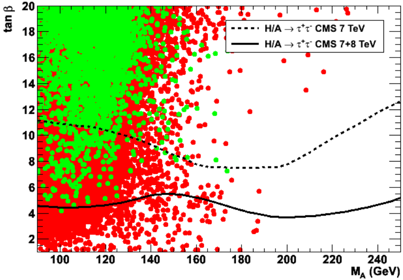
Blue: + excluded by BR($B \to \tau\nu$)

Yellow: + excluded by BR($B_s \to \mu^+\mu^-$)

→ **126 GeV heavy Higgs scenario excluded by flavour constraints**

SM-like heavy CP-even Higgs

Light or heavy Higgs at 126 GeV??



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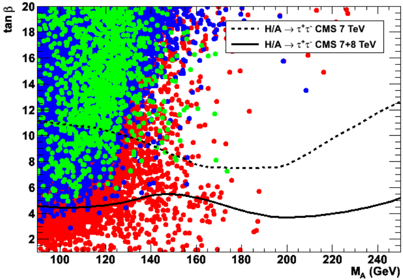

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$\rightarrow$ **126 GeV heavy Higgs scenario excluded by flavour constraints**

SM-like heavy CP-even Higgs

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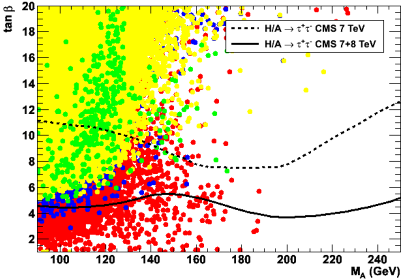

A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

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Yellow: + excluded by BR($B_s \to \mu^+\mu^-$)

→ **126 GeV heavy Higgs scenario excluded by flavour constraints**

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

Main source of uncertainty: f_{B_s}

- ETMC-11: **232** $\pm$ **10** MeV
- HPQCD-12: **227** $\pm$ **10** MeV
  HPQCD NR-09: 231 $\pm$ 15 MeV
  HPQCD HISQ-11: 225 $\pm$ 4 MeV
- Fermilab-MILC-11: **242** $\pm$ **9.5** MeV

Our choice: 234 $\pm$ 10 MeV

With the most up-to-date input parameters (PDG), in particular $\tau_{B_s} = 1.497$ ps:

SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.53 \pm 0.38) \times 10^{-9}$

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

Most important sources of uncertainties:

	f_{B_s}	EW cor.	scales	τ_{B_s}	V_{ts}	top mass	Overall
Uncertainty	8%	2%	2%	2%	5%	1.3%	$\sim$ **10%**

Using $f_{B_s} = 227$ MeV and $\tau_{B_s} = 1.466$ ps, one gets: $\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.25 \times 10^{-9}$

A. Buras et al. Eur.Phys.J. C72 (2012) 2172

$B \to K^* \mu^+ \mu^-$ – "Standard" Observables

Dilepton invariant mass spectrum: $\frac{d\Gamma}{dq^2} = \frac{3}{4}\left(J_1 - \frac{J_2}{3}\right)$

Forward backward asymmetry:

$$A_{\rm FB}(q^2) \equiv \left[\int_{-1}^{0} - \int_{0}^{1}\right] d\cos\theta_l \, \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} \Bigg/ \frac{d\Gamma}{dq^2} = \frac{3}{8} J_6 \Bigg/ \frac{d\Gamma}{dq^2}$$

Forward backward asymmetry zero-crossing: $q_0^2 \simeq -2 m_b m_B \frac{C_9^{\rm eff}(q_0^2)}{C_7} + O(\alpha_s, \Lambda/m_b)$

$\to$ fix the sign of C_9/C_7

Polarization fractions:

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}, \quad F_T(q^2) = 1 - F_L(q^2) = \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

Transverse asymmetries:

$$A_T^{(1)}(q^2) = \frac{-2\Re(A_\parallel A_\perp^*)}{|A_\perp|^2 + |A_\parallel|^2} \qquad A_T^{(2)}(q^2) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

$$A_T^{(3)}(q^2) = \frac{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2 |A_\perp|^2}} \qquad A_T^{(4)}(q^2) = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}$$

D. Becirevic, E. Schneider, Nucl. Phys. B854 (2012) 321

$\to$ **Reduced form factor uncertainties**

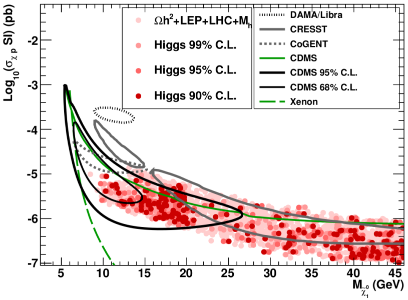
Low mass neutralino in pMSSM

Can pMSSM provide solutions compatible with CoGeNT/CRESST/DAMA/CDMS data?

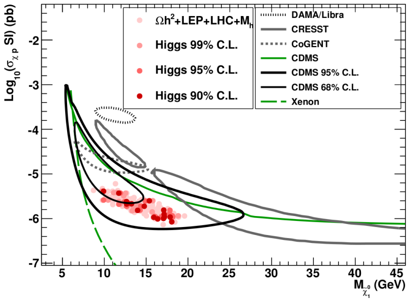
$\rightarrow$ **Low mass neutralino of mass ~ 10 GeV?**

Not possible in constrained MSSM...

Dedicated scans focusing on a region with $m_{\tilde{\chi}^0} < 50$ GeV



loose relic density constraint:
$10^{-4} < \Omega_\chi h^2 < 0.163$



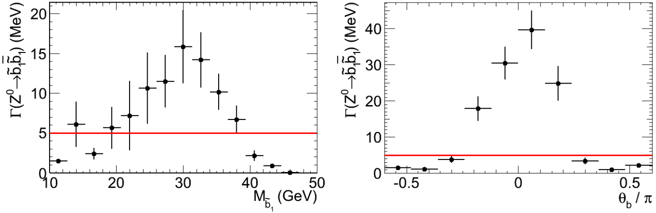
A. Arbey, M. Battaglia, FM, arXiv:1308.2153

tight relic density constraint:
$0.076 < \Omega_\chi h^2 < 0.163$

Light sbottom scenario

Two issues: $\Gamma(Z \to \tilde{q}\bar{\tilde{q}})$ is very large and $BR(h^0 \to \tilde{q}\bar{\tilde{q}})$ is the dominant Higgs BR... for the first and second generations!

Due to the sbottom mixing, $\Gamma(Z \to \tilde{b}_1\bar{\tilde{b}}_1)$ can be suppressed and pass the LEP constraint



Also, to pass the LEP $\Gamma(Z \to \text{invisible})$ constraint, $\Gamma(Z \to \tilde{\chi}_1\tilde{\chi}_1)$ needs to be suppressed

Main features:

- right-handed $\tilde{b}_1$ to respect $\Gamma(Z \to \tilde{b}_1\bar{\tilde{b}}_1)$ constraints
- bino-like $\tilde{\chi}_1$ to respect $\Gamma(Z \to \tilde{\chi}_1\tilde{\chi}_1)$ and other LEP constraints
- small mass splitting $(M_{\tilde{b}_1} - M_{\tilde{\chi}_1})$ to get an adequate relic density