

Interplay of direct and indirect searches

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and Experiments in Flavour Physics**

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Search for New Physics

Direct searches:

ATLAS and **CMS** main searches:

- Higgs bosons
- **New Physics (NP): SUSY** is the main focus of BSM searches

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

- Information on the properties of the DM candidate
→ Constraints on NP parameters



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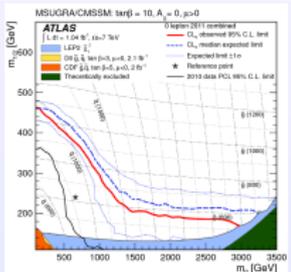
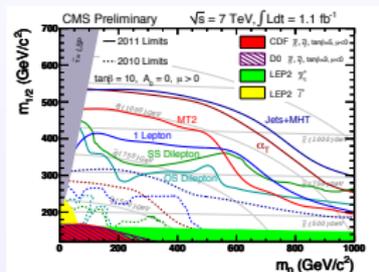
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SUSY searches

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

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



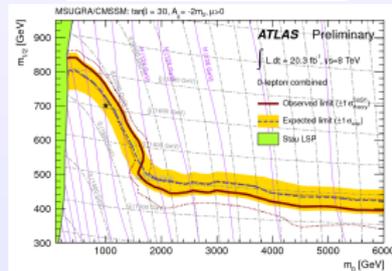
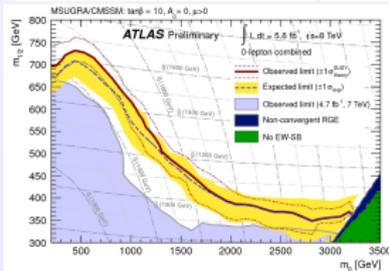
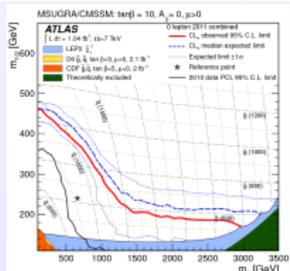
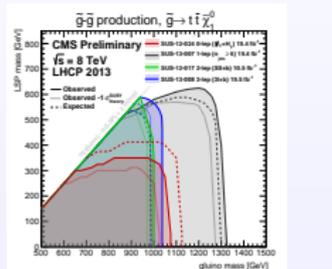
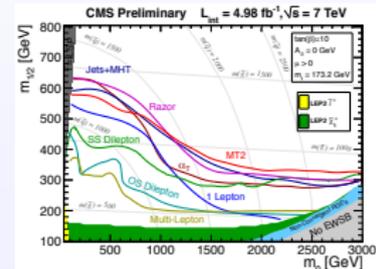
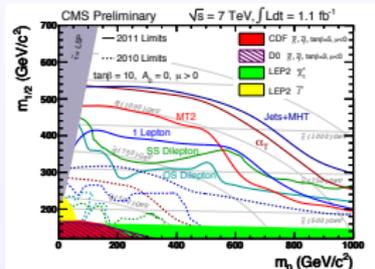
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Summer 2012
(with $\sim 5 \text{ fb}^{-1}$ of data
at 7 and 8 TeV)

Summer 2013
(with $\sim 25 \text{ fb}^{-1}$ of data
at 7 and 8 TeV)



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!

- Reinterpret the results in general MSSM with minimal theoretical assumptions
- 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: Direct DM search results



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Phenomenological MSSM (pMSSM)

- 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

→ 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, Higgs, 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]
$M_{\tilde{\tau}_R}$	[0, 3000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 3000]
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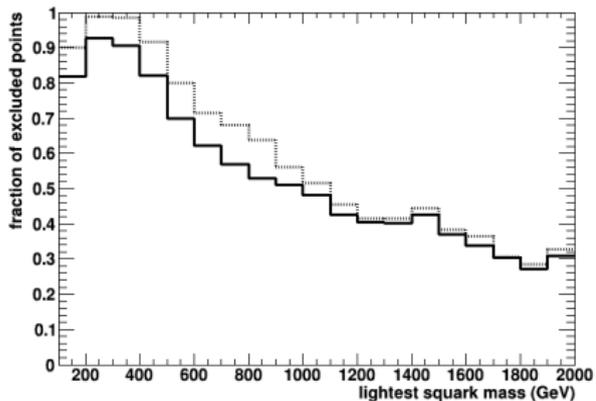
In collaboration with Alex Arbey and Marco Battaglia



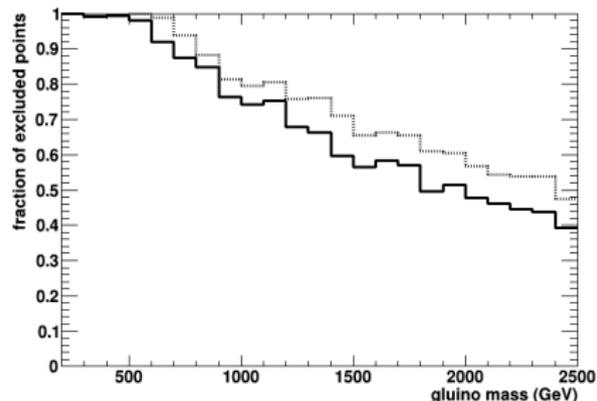
Monojets and direct SUSY searches in the pMSSM

Consequences on particle masses:

Lightest squark mass



Glino mass



Preliminary

Solid: jets/leptons+MET searches

Dotted: + monojet analyses

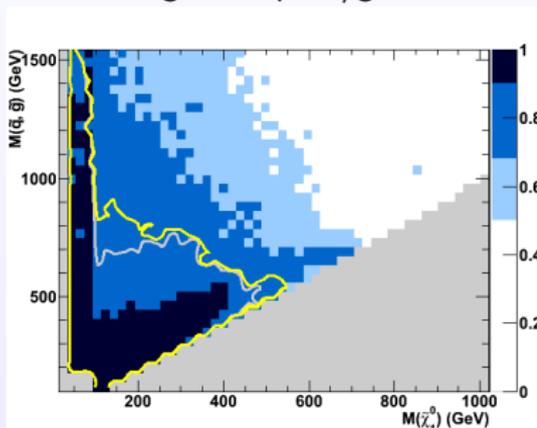
squark and gluino masses well below 1 TeV are still allowed!



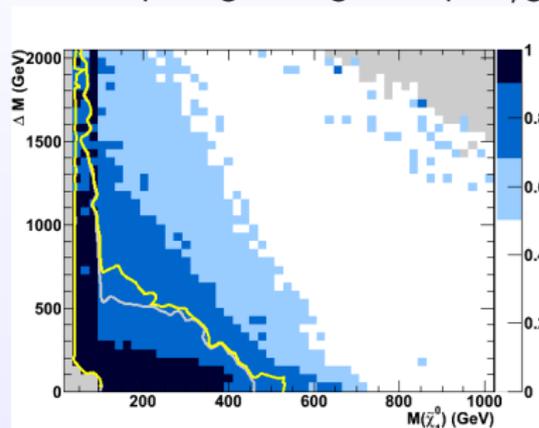
Monojets and direct SUSY searches in the pMSSM

Neutralino mass:

vs. lightest squark/gluino mass



vs. mass splitting with lightest squark/gluino



A. Arbey, M. Battaglia, FM, Phys.Rev. D89 (2014) 077701

Color scale: fraction of excluded points

Grey line: 68% C.L. exclusion by jets/leptons+MET searches

Yellow line: + monojet analyses



Higgs sector



Higgs decay rates

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

Signal strength is defined as:

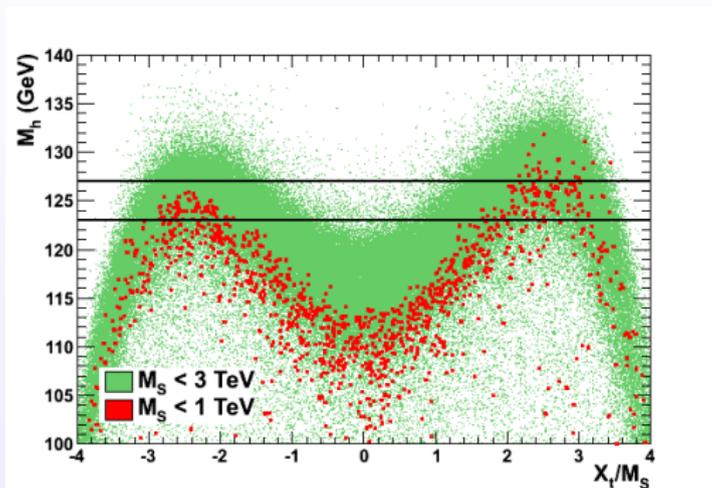
$$\mu_{XX} = \frac{\sigma(pp \rightarrow h) \text{BR}(h \rightarrow XX)}{\sigma(pp \rightarrow h)_{\text{SM}} \text{BR}(h \rightarrow XX)_{\text{SM}}}$$

→ compatible with the SM Higgs



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

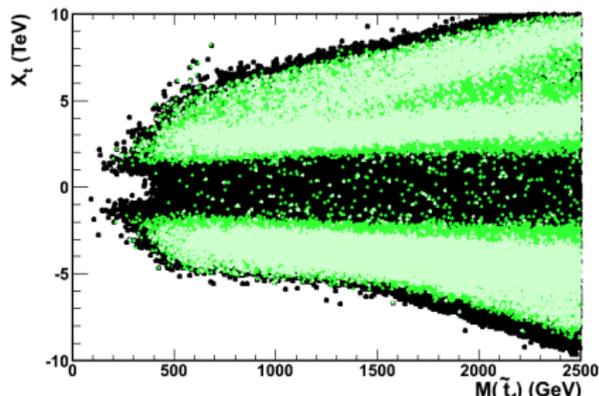
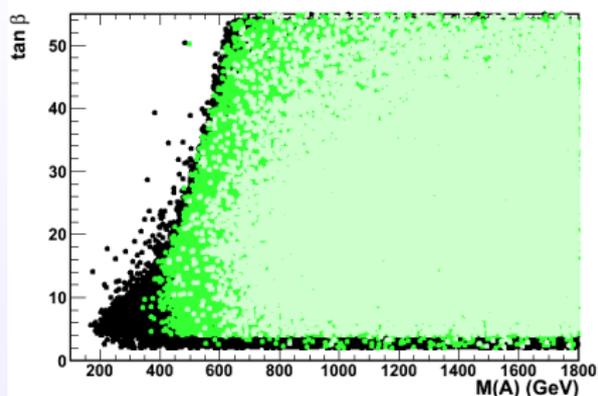
where:

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

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



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



Flavour sector



Indirect searches: Flavour sector

Flavour physics and rare decays in particular are excellent tools to probe New Physics!

- test quantum structure of the SM at loop level
- investigate the flavour and the CP symmetry of the model
 - test the Minimal Flavour Violation (MFV) hypothesis
- probe sectors inaccessible to direct searches
- constrain parameter spaces of new physics scenarios



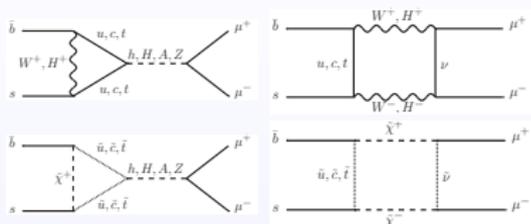
BR($B_s \rightarrow \mu^+ \mu^-$)

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

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

First experimental evidence:

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

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

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

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

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

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



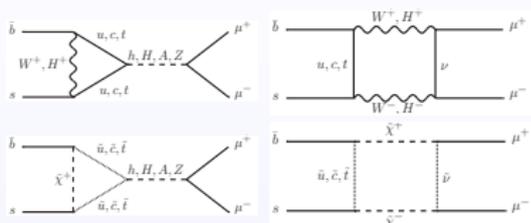
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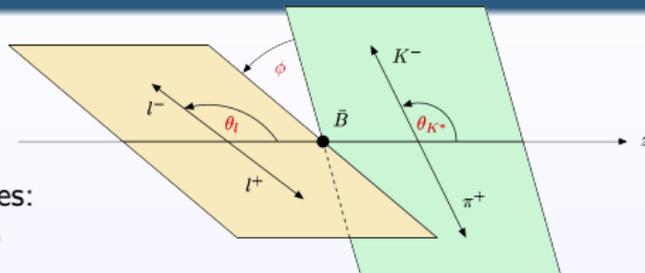
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$B \rightarrow K^* \mu^+ \mu^-$ – Angular distributions

Angular distributions

The full angular distribution of the decay $\bar{B}^0 \rightarrow \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \rightarrow K^- \pi^+$) 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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F. Kruger et al., Phys. Rev. D 61 (2000) 114028;

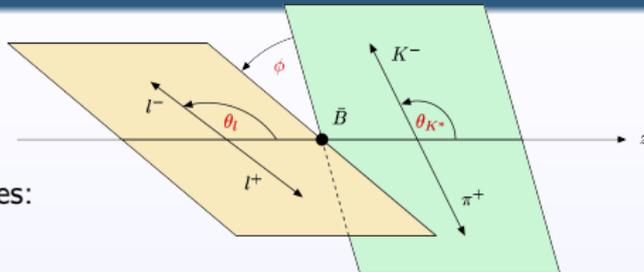
W. Altmannshofer et al., JHEP 0901 (2009) 019; U. Egede et al., JHEP 1010 (2010) 056



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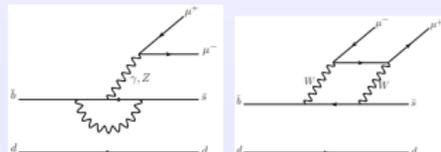
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$B \rightarrow K^* \mu^+ \mu^-$ – Optimised observables

Optimised: form factor uncertainties cancel at leading order

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

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

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

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

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

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

with

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

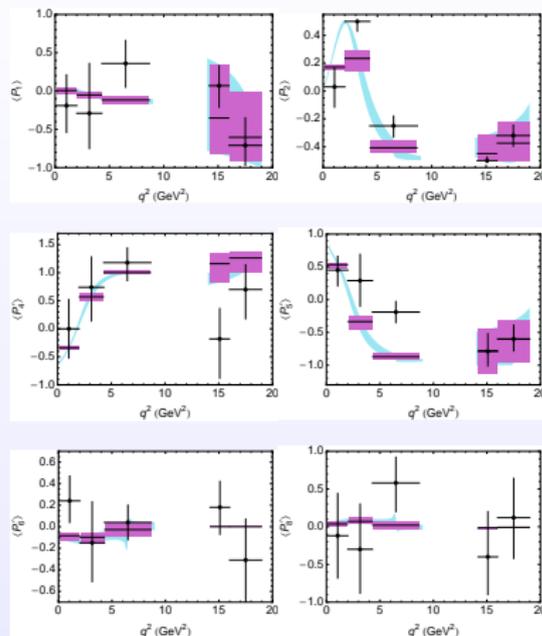
+ CP violating clean observables and other combinations

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

First measurements by LHCb:



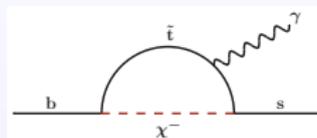
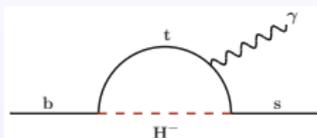
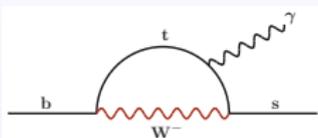
LHCb collaboration, Phys. Rev. Lett. 111 (2013), 191801

**3.7σ local discrepancy in the P'_5 ,
 $4.3 < q^2 < 8.68 \text{ GeV}^2$ bin**



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

Contributing loops:

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

- Charged Higgs loop always adds constructively to the SM penguin
- Chargino loops can add constructively or destructively
- Very precise theory prediction (at NNLO)

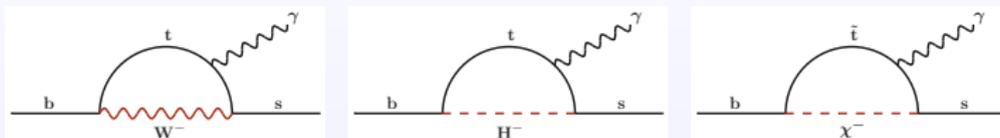
Experimental values (HFAG 2012): $\text{BR}(\bar{B} \rightarrow X_s \gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$ SM prediction: $\text{BR}(\bar{B} \rightarrow X_s \gamma) = (3.08 \pm 0.24) \times 10^{-4}$

M. Misiak et al., Phys.Rev.Lett. 98 (2007) 022002



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

Contributing loops:

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

- Charged Higgs loop always adds constructively to the SM penguin
- Chargino loops can add constructively or destructively
- Very precise theory prediction (at NNLO)

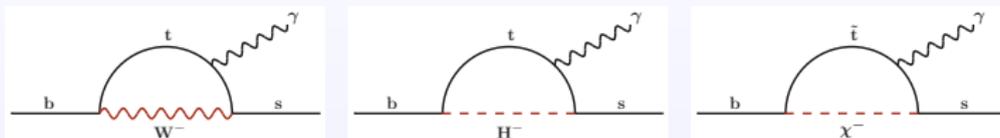
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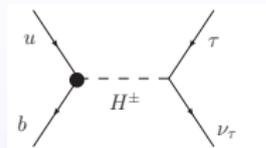
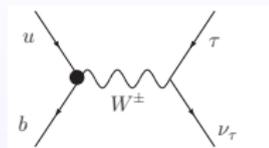
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$B \rightarrow \tau \nu$

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



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

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



Large uncertainty from V_{ub} and f_B

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

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

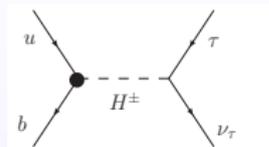
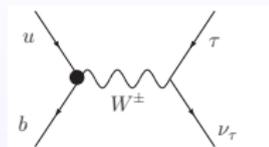
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Similar processes: $B \rightarrow D \tau \nu_\tau$, $D_s \rightarrow \ell \nu_\ell$, $D \rightarrow \mu \nu_\mu$, $K \rightarrow \mu \nu_\mu$, ...



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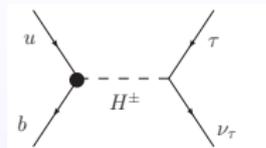
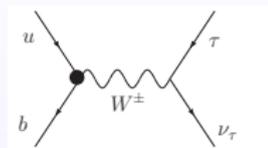
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Constrained MSSM (CMSSM)

CMSSM = MSSM with GUT scale universality assumptions
→ 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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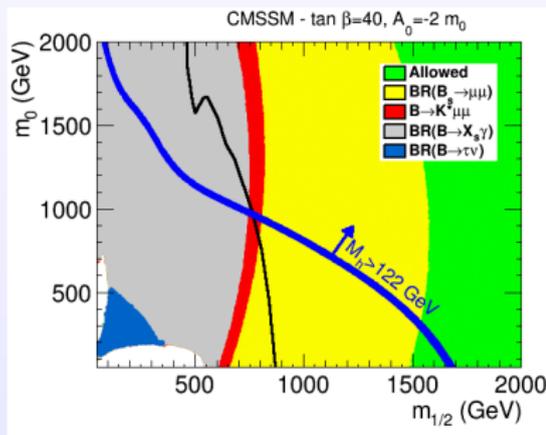
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FM, S. Neshatpour, J. Virto, arXiv:1401.2145

Black line: ATLAS exclusion limit with 20.3 fb^{-1} data

Blue line: Higgs mass exclusion limit ($M_h = 122 \text{ GeV}$)



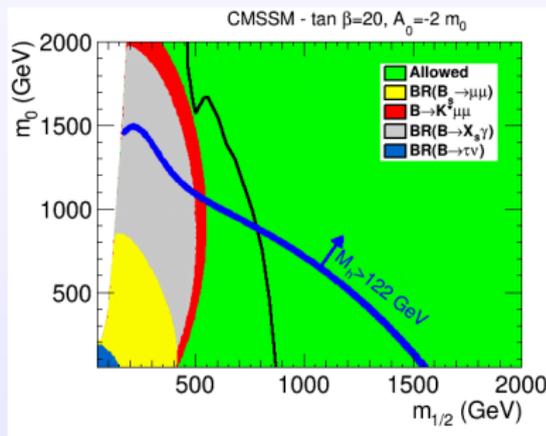
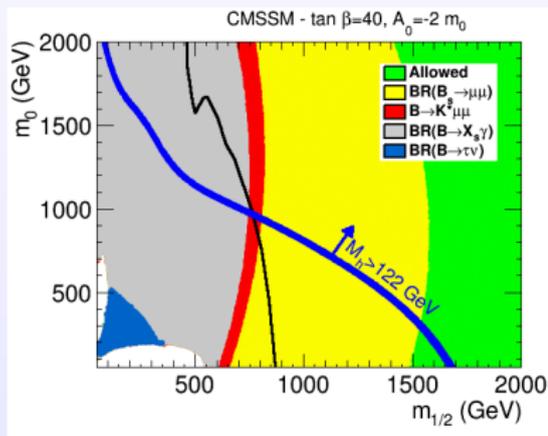
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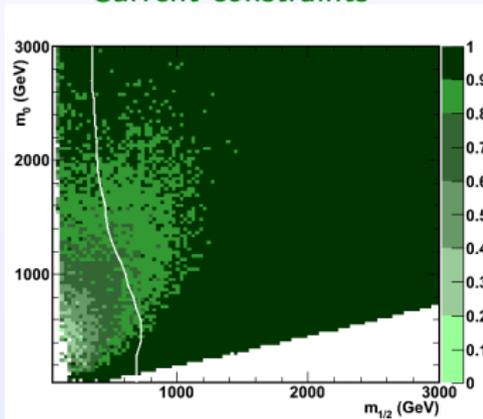


Constraints on CMSSM from $BR(B_s \rightarrow \mu^+ \mu^-)$

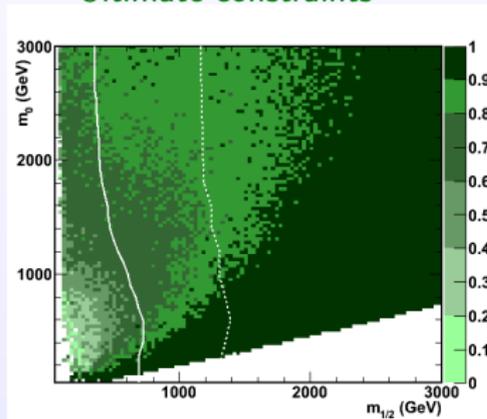
CMSSM with all parameters varied:

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

Current constraints



Ultimate constraints

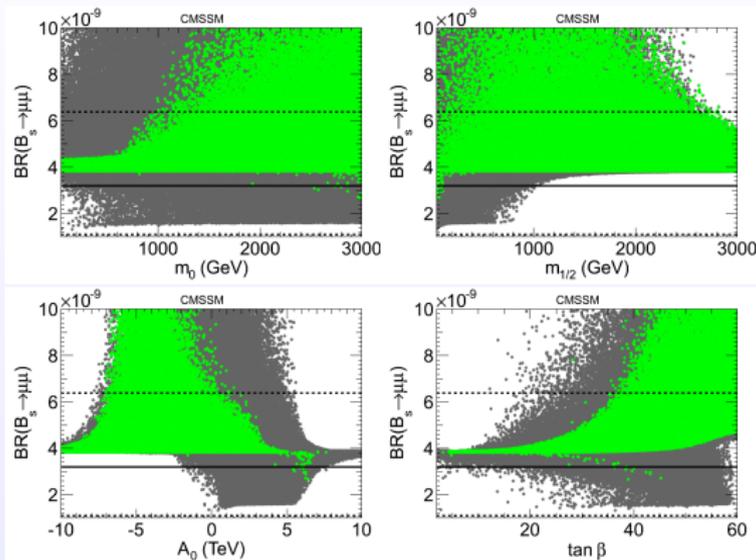


A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

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

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

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



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

Dashed lines: 2σ experimental deviations

Gray points: all valid points

Green points: points in agreement with the Higgs mass constraint

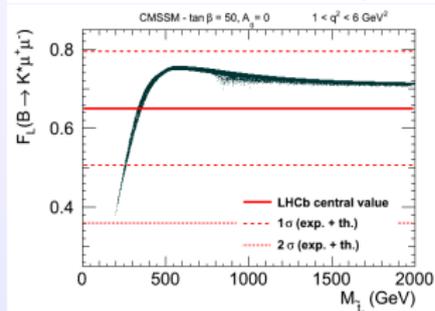
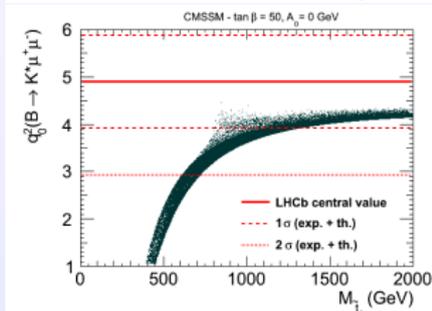
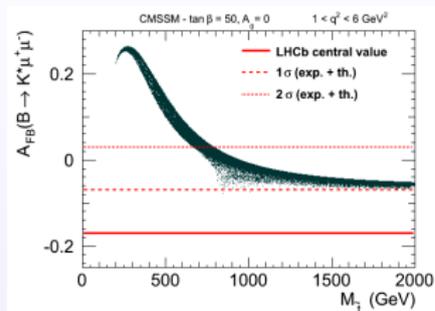
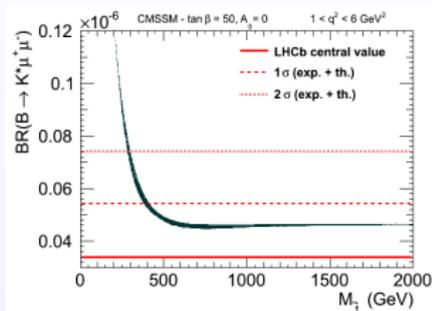
A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

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



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

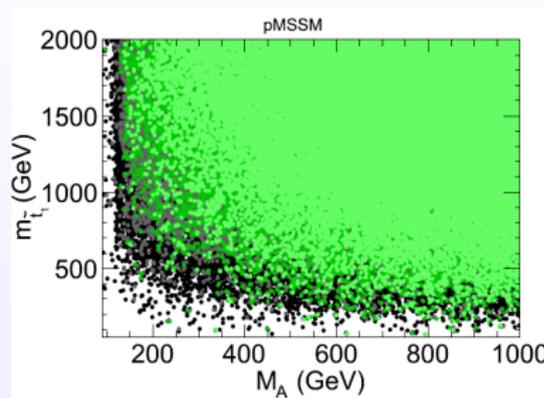
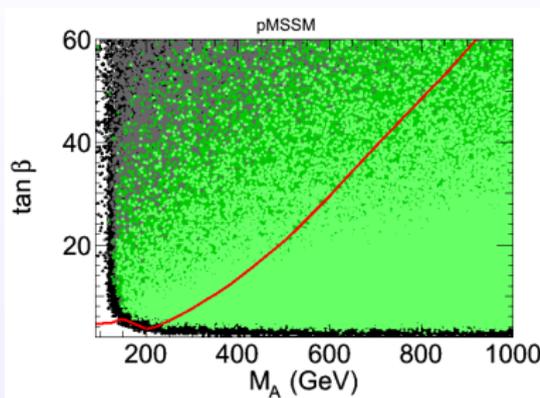
$B \rightarrow K^* \mu^+ \mu^-$ in the low q^2 region: CMSSM - $\tan \beta = 50$



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



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



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

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

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



Dark matter sector



Dark matter constraints

Dark matter constraints:

- **Relic density**
Sensitive to neutralino nature, Higgs resonances and co-annihilating particles
- **Direct detection**
Sensitive to the neutralino nature and scattering mediators, in particular heavy Higgs bosons
- **Indirect detection**
Sensitive to the neutralino nature and annihilation channels

For all these observables, large uncertainty from cosmology and astrophysics!



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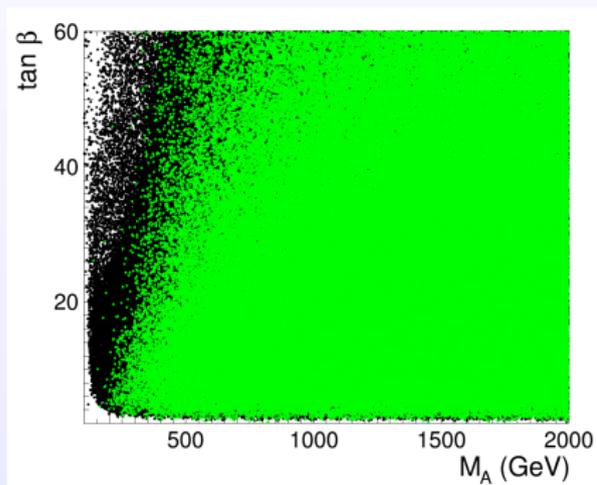
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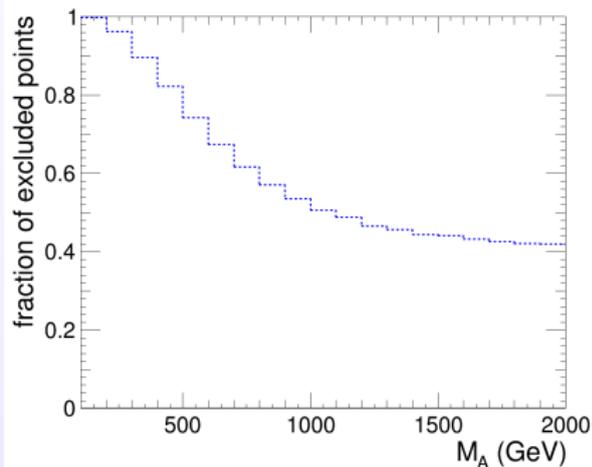


Dark matter direct detection

pMSSM points facing LUX limits



Preliminary

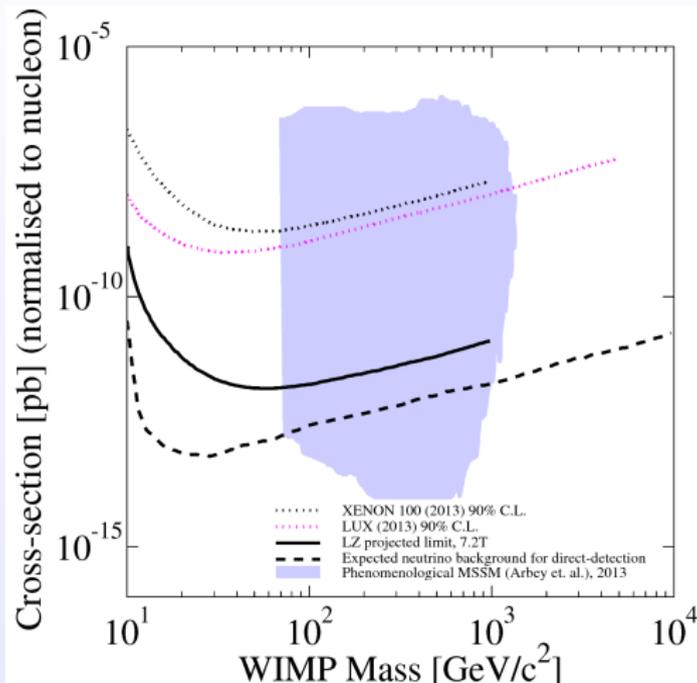


Results and sensitivity similar to those from $B_s \rightarrow \mu^+ \mu^-$ and $A/H \rightarrow \tau^+ \tau^-$, with different couplings/sectors probed.



Dark matter direct detection

Dark matter direct detection strongly probes the pMSSM parameter space

Filippini, Gaitskell, Speller, Wang, <http://cedar.berkeley.edu/plotter/>

Conclusions

After the first LHC run:

- Simplest NP scenarios already ruled out...
- NP should be subtle!
- Indirect information from Flavour physics and Dark matter can provide valuable information and help guiding direct searches!
 - we need to go beyond the simplest scenarios
 - pMSSM seems to be an adequate set-up
 - Low energy MSSM is still alive!

In the next run:

- Consistency checks and complementarity between different searches will be essential



Backup

Backup



Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from $\text{BR}(B \rightarrow X_s \gamma)$, $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$, $\text{BR}(B \rightarrow \tau \nu)$
- 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



Direct SUSY searches in the pMSSM

Direct SUSY searches used in our analysis:

squark and gluino direct searches (jets + \cancel{E}_T)

[ATLAS-CONF-2013-047](#)

stop and sbottom direct searches (b -jets + \cancel{E}_T)

[ATLAS-CONF-2013-053](#)

chargino and neutralino direct searches (2 or 3 leptons + \cancel{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 + \cancel{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: $pp \rightarrow \chi_1^0 + \chi_1^0 + j$,

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

→ Effective operator approach is not applicable in SUSY!

→ Re-analysis of the monojet search results in the context of the pMSSM

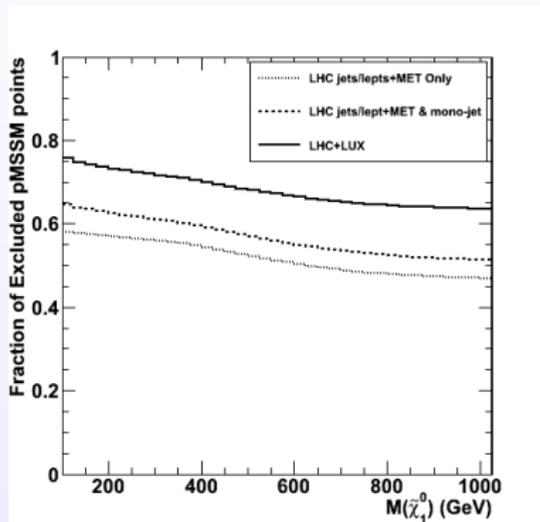
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- Event generation with MadEvent and PYTHIA
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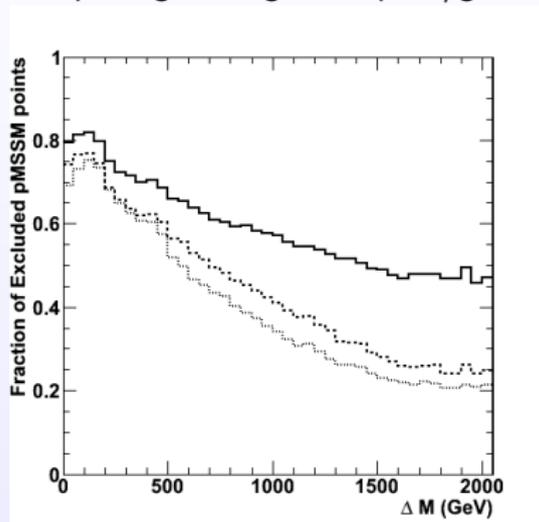


Monojets, direct SUSY searches and DM direct detection in the pMSSM

Neutralino mass



Mass splitting with lightest squark/gluino



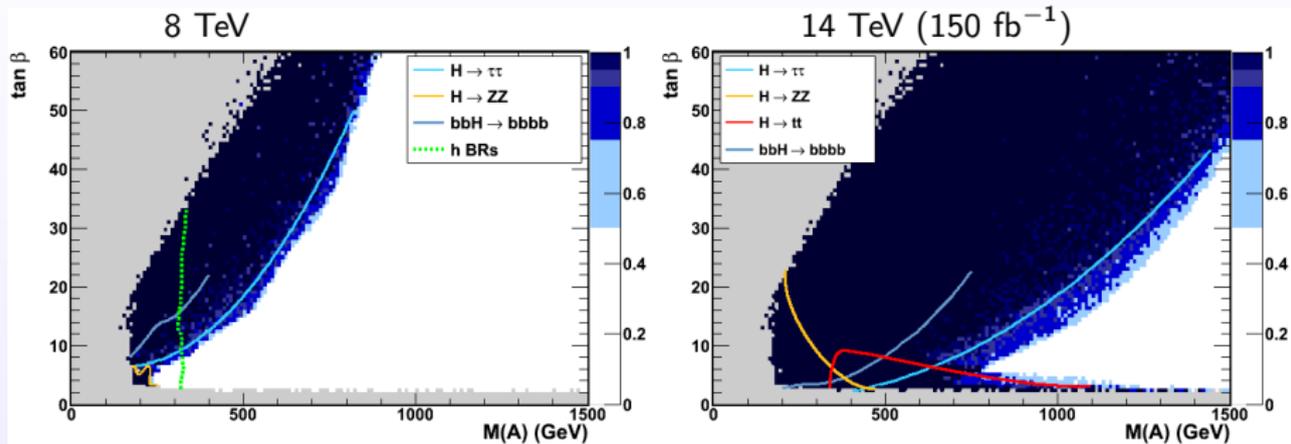
A. Arbey, M. Battaglia, FM, Phys.Rev. D89 (2014) 077701

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



Heavy Higgs search constraints

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



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

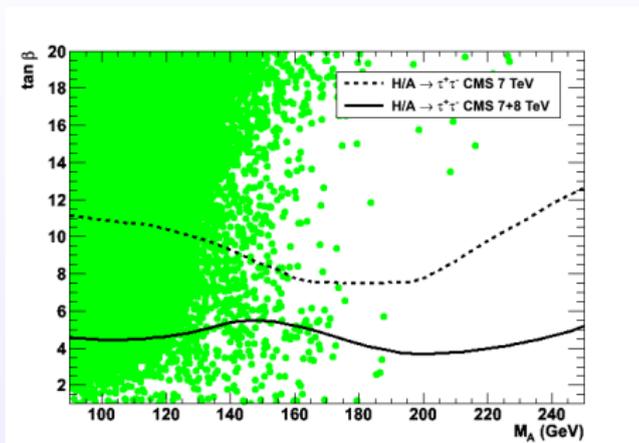
→ Some points inside the $H \rightarrow \tau\tau$ excluded region still survive

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



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 $\text{BR}(B \rightarrow X_s \gamma)$

Blue: + excluded by $\text{BR}(B \rightarrow \tau \nu)$

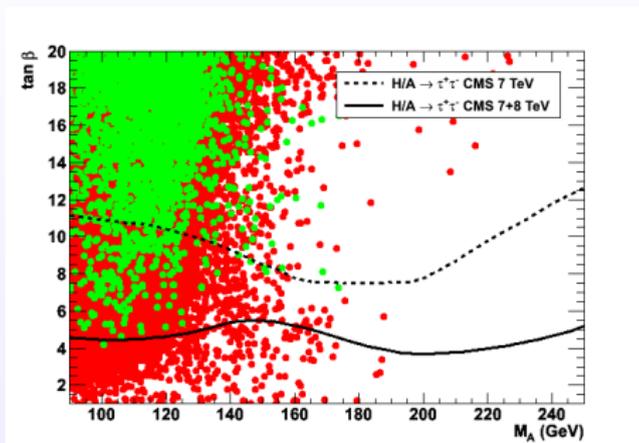
Yellow: + excluded by $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

→ 126 GeV heavy Higgs scenario excluded by flavour constraints



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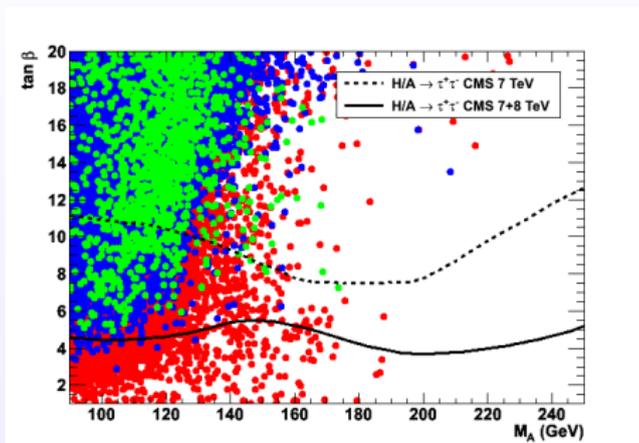
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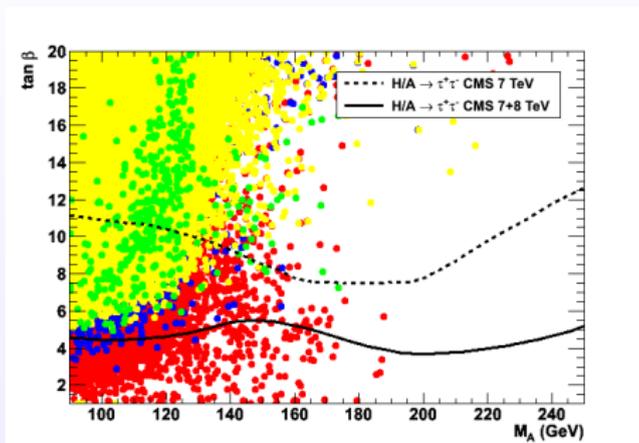
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BR($B_s \rightarrow \mu^+ \mu^-$)

Main source of uncertainty: f_{B_s}

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

Our choice: 234 ± 10 MeV

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

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

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

Most important sources of uncertainties:

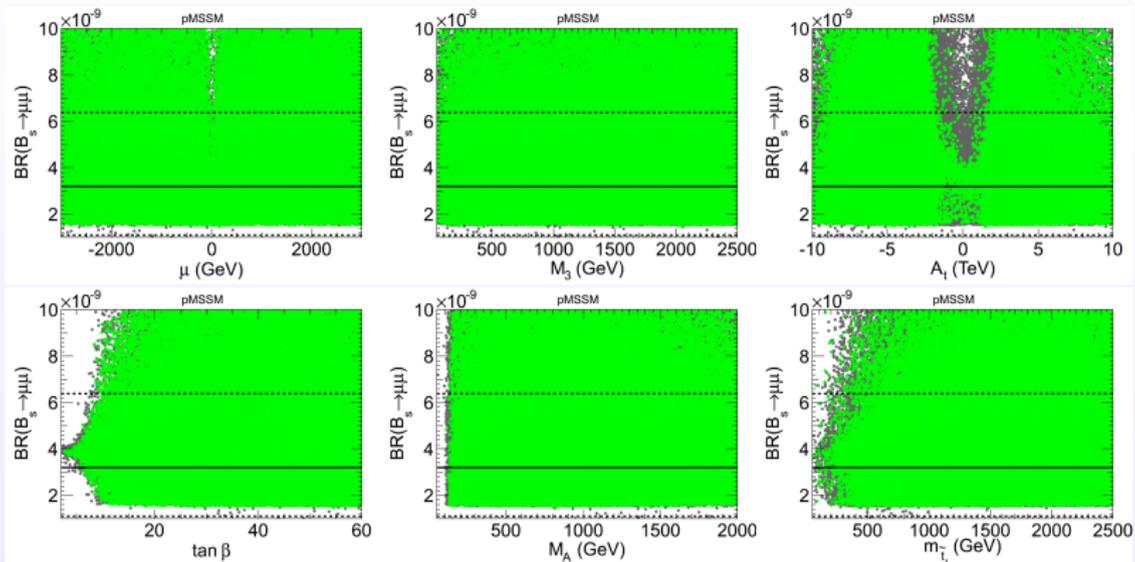
	f_{B_s}	EW cor.	scales	τ_{B_s}	V_{ts}	top mass	Overall
Uncertainty	8%	2%	2%	2%	5%	1.3%	$\sim 10\%$

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

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



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



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

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

Dashed lines: 2σ experimental deviations

Gray points: all valid points

Green points: points in agreement with the Higgs mass constraint



$B \rightarrow K^* \mu^+ \mu^-$ – “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:

$$A_{\text{FB}}(q^2) \equiv \left[\int_{-1}^0 - \int_0^1 \right] d \cos \theta_l \frac{d^2\Gamma}{dq^2 d \cos \theta_l} \Big/ \frac{d\Gamma}{dq^2} = \frac{3}{8} J_6 \Big/ \frac{d\Gamma}{dq^2}$$

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

→ 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

→ **Reduced form factor uncertainties**

