Constraints on the CP violating MSSM

Alexandre Arbey

Lyon U. & CERN TH

In collaboration with J. Ellis, N. Mahmoudi & R. Godbole

FPCapri2016, Anacapri – June 13th, 2016

Standard Model

CKM paradigm

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

unitary matrix, 1 phase

V_{ub}, V_{td} complex

CP violation observed in K and B mixings

Standard Model

CKM paradigm

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

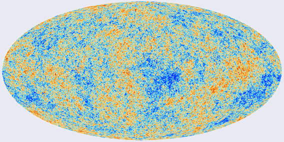
unitary matrix, 1 phase

V_{ub}, V_{td} complex

CP violation observed in K and B mixings

Baryon Asymmetry of the Universe

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



Sakharov conditions:
- baryon number violation
- C and CP violation
- departure from equilibrium

CP violation

Standard Model

CKM paradigm

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

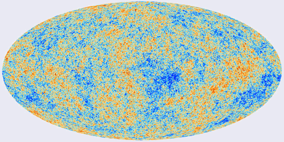
unitary matrix, 1 phase

V_{ub}, V_{td} complex

CP violation observed in K and B mixings

Baryon Asymmetry of the Universe

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



Sakharov conditions:
- baryon number violation
- C and CP violation
- departure from equilibrium

Electric dipole moments

EDM	Exp. (e.cm)
Tl	1.3×10^{-24}
Hg	3.5×10^{-29}
ThO	1.1×10^{-28}
n	4.7×10^{-26}
μ	1.9×10^{-19}

In atoms/molecules, EDMs combinations of electron and nucleon EDM

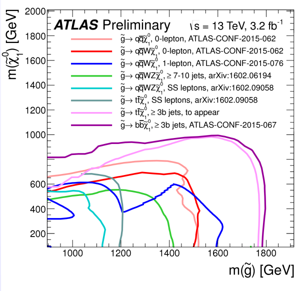
Limits orders of magnitude above the SM values

Yet very sensitive to CP violation and new physics

Typical values in MSSM for electron $\sim 10^{-26}$ e.cm

SUSY searches

Strong limits in the constrained and simplified SUSY scenarios by ATLAS and CMS



No New Physics signal so far (?)
SUSY masses pushed to higher values

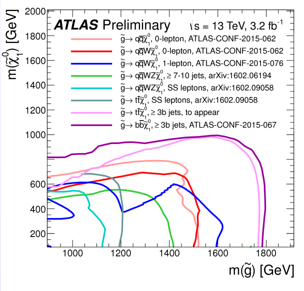
Higgs physics

Discovery of a Higgs boson

Strong constraints from the Higgs mass and rate measurements
Other Higgs searches

SUSY searches

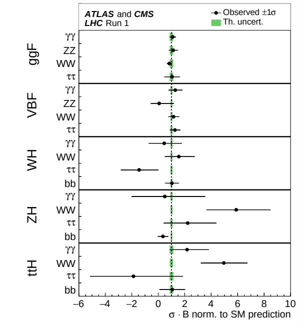
Strong limits in the constrained and simplified SUSY scenarios by ATLAS and CMS



No New Physics signal so far (?)
SUSY masses pushed to higher values

Higgs physics

Discovery of a Higgs boson

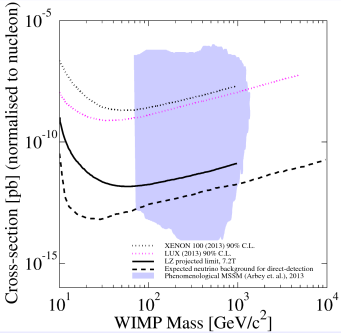


Strong constraints from the Higgs mass and rate measurements
Other Higgs searches

Dark matter

Constraints from dark matter searches

Direct detection...



... also constraints from AMS-2, FERMI, Planck, ...

Flavour physics

$B_s \to \mu^+\mu^-$ observed
No NP so far...

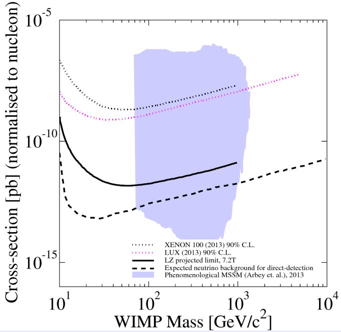
Unitarity triangle paradigm still fine

Tensions in $b \to s\ell\ell$ transitions

Dark matter

Constraints from dark matter searches

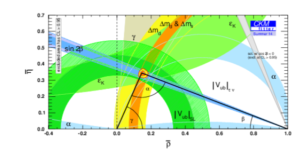
Direct detection...



... also constraints from AMS-2, FERMI, Planck, ...

Flavour physics

$B_s \to \mu^+\mu^-$ observed
No NP so far...



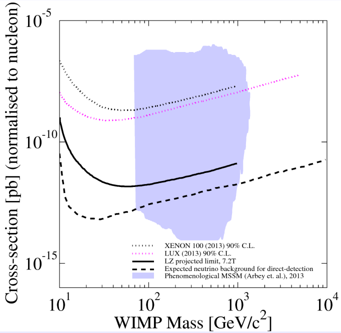
Unitarity triangle paradigm still fine

Tensions in $b \to s\ell\ell$ transitions

Dark matter

Constraints from dark matter searches

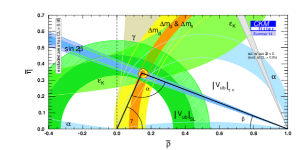
Direct detection...



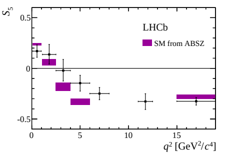
... also constraints from AMS-2, FERMI, Planck, ...

Flavour physics

$B_s \to \mu^+\mu^-$ observed
No NP so far...



Unitarity triangle paradigm still fine



Tensions in $b \to s\ell\ell$ transitions

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Very difficult to perform systematic studies
- Not every parameters relevant for every studies

Constrained MSSM scenarios

- Suppose a SUSY breaking mechanism

  $\rightarrow$ Strongly reduces the number of free parameters!

- Most studied scenario: CMSSM (or mSUGRA)

  GUT-universal parameters: scalar mass m_0, gaugino mass $m_{1/2}$, trilinear soft coupling A_0 and 2 Higgs(ino) parameters: sign of μ and $\tan\beta$

  $\rightarrow$ Useful for phenomenology, benchmarking, early testing, ...

  $\rightarrow$ But not representative of the full MSSM!

- Slightly more general: non-universal Higgs masses (NUHM2)

  CMSSM parameters + free μ and CP-odd Higgs mass

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Very difficult to perform systematic studies
- Not every parameters relevant for every studies

Constrained MSSM scenarios

- Suppose a SUSY breaking mechanism

  → Strongly reduces the number of free parameters!

- Most studied scenario: CMSSM (or mSUGRA)

  GUT-universal parameters: scalar mass m_0, gaugino mass $m_{1/2}$, trilinear soft coupling A_0 and 2 Higgs(ino) parameters: sign of μ and $\tan\beta$

  → Useful for phenomenology, benchmarking, early testing, ...

  → But not representative of the full MSSM!

- Slightly more general: non-universal Higgs masses (NUHM2)

  CMSSM parameters + free μ and CP-odd Higgs mass

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Very difficult to perform systematic studies
- Not every parameters relevant for every studies

Constrained MSSM scenarios

- Suppose a SUSY breaking mechanism

  $\rightarrow$ Strongly reduces the number of free parameters!

- Most studied scenario: CMSSM (or mSUGRA)

  GUT-universal parameters: scalar mass m_0, gaugino mass $m_{1/2}$, trilinear soft coupling A_0 and 2 Higgs(ino) parameters: sign of μ and $\tan\beta$

  $\rightarrow$ Useful for phenomenology, benchmarking, early testing, ...

  $\rightarrow$ But not representative of the full MSSM!

- Slightly more general: non-universal Higgs masses (NUHM2)

  CMSSM parameters + free μ and CP-odd Higgs mass

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

What about CP violation?

CP violating phenomenological MSSM (CPV-pMSSM)

$\rightarrow$ 19 pMSSM parameters + 6 phases = 25 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 gaugino phases: ϕ_1, ϕ_2, ϕ_3

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

+ 3 trilinear coupling phases for the third generation fermions: ϕ_b, ϕ_t, ϕ_τ

3 Higgs/Higgsino parameters: M_{H^+}, $\tan\beta$, μ

AA, J. Ellis, R. Godbole, F. Mahmoudi, Eur. Phys. J. C75 (2015), 85

$$M_\alpha = |M_\alpha| e^{i\phi_\alpha} \qquad\qquad A_\beta = |A_\beta| e^{i\phi_\beta}$$

The CP phases can take values between -180 and 180 degrees, and modify the mixing matrices and couplings

3 neutral Higgs bosons h_1, h_2, h_3 with scalar and pseudoscalar components

In the following, we consider only the case of neutralino LSP (= dark matter)

Definition of some constrained CPV-MSSM scenarios:

CPV-CMSSM: 10 parameters

GUT-universal parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$

+ 6 phases: ϕ_1, ϕ_2, ϕ_3, ϕ_b, ϕ_t, ϕ_τ

CPV-NUHM2: 12 parameters

GUT-universal parameters: m_0, $m_{1/2}$, A_0

+ Higgs/Higgsino non-universal parameters μ, m_{H^+}, $\tan\beta$

+ 6 phases: ϕ_1, ϕ_2, ϕ_3, ϕ_b, ϕ_t, ϕ_τ

CPX: 9 parameters

1 unified sfermion mass: M_S

with $\mu = 4M_S$, $|A_{U,D,\ell}| = 2M_S$, $|M_1| = |M_2| = 1$ TeV, $|M_3| = 3$ TeV

+ 2 Higgs parameters $\tan\beta$, m_{H^+}

+ 6 phases: ϕ_1, ϕ_2, ϕ_3, ϕ_b, ϕ_t, ϕ_τ

Methodology

Random scans in the CP violating MSSM scenarios described previously
(Codes involved: CPsuperH, SuperIso Relic, micrOMEGAs, ...)

AA, J. Ellis, R. Godbole, F. Mahmoudi, Eur. Phys. J. C75 (2015), 85

imposing many constraints:

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

Problem: the EDMs impose so strong constraints that only zero phases are allowed, apart in some very restricted regions of the parameter space!

Methodology

Random scans in the CP violating MSSM scenarios described previously
(Codes involved: CPsuperH, SuperIso Relic, micrOMEGAs, ...)

AA, J. Ellis, R. Godbole, F. Mahmoudi, Eur. Phys. J. C75 (2015), 85

imposing many constraints:

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

Problem: the EDMs impose so strong constraints that only zero phases are allowed, apart in some very restricted regions of the parameter space!

Methodology

Random scans in the CP violating MSSM scenarios described previously
(Codes involved: CPsuperH, SuperIso Relic, micrOMEGAs, ...)

AA, J. Ellis, R. Godbole, F. Mahmoudi, Eur. Phys. J. C75 (2015), 85

imposing many constraints:

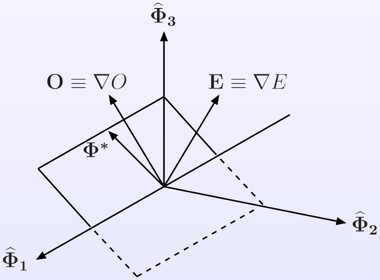
- LEP and Tevatron direct search limits
- Light Higgs mass range
- Flavour physics limits, in particular from BR($B \to X_s \gamma$), BR($B_s \to \mu^+ \mu^-$), BR($B \to \tau\nu$), ΔM_{B_s}
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density
- Dark matter direct search limits
- Heavy Higgs mass limits
- Higgs production and decay rates
- LHC SUSY direct search limits
- Electric dipole moments (EDMs): Thallium, Mercury, Neutron, Thorium monoxide

Problem: the EDMs impose so strong constraints that only zero phases are allowed, apart in some very restricted regions of the parameter space!

Method inspired by J. Ellis, J.S. Lee, A. Pilaftsis, JHEP 1010 (2010) 049

How to determine the direction in the phase parameter space minimizing the EDMs and maximizing other CP violation observables?

Let us consider a simple example: how to minimize the EDM E while maximizing the observable O in the 3 phases parameter space (ϕ_1, ϕ_2, ϕ_3)?



$\vec{\nabla} O$: direction corresponding to the maximal increase of $|O|$

$\vec{\nabla} E$: direction corresponding to the maximal increase of $|E|$

Optimal direction $\vec{\phi}^*$
= intersection of the plane perpendicular to $\vec{\nabla} E$ with the plane defined by $\vec{\nabla} O$ and $\vec{\nabla} E$
= direction minimizing $|E|$ and allowing for an increase in $|O|$

Works well in the limit of small phases...

In our study, we want to minimize the four strongest EDM constraints (E^i):

Thallium, Mercury, Neutron and Thorium monoxide

and maximize the CP asymmetry of $b \to s\gamma$ (O) over the six phases ϕ_i.

The optimal direction, computed for each choice of the 19 CP conserving pMSSM parameters, is given by:

$$\phi^*_\alpha = \epsilon_{\alpha\beta\gamma\delta\mu\eta}\,\epsilon_{\eta\nu\lambda\rho\sigma\tau}\,E^a_\beta\,E^b_\gamma\,E^c_\delta\,E^d_\mu\,O_\nu\,E^a_\lambda\,E^b_\rho\,E^c_\sigma\,E^d_\tau$$

with $\phi_\alpha = \phi_{1,2,3,t,b,\tau}$, $E^i_\alpha \equiv \partial E^i/\partial\phi_\alpha$ and $O_\alpha \equiv \partial O/\partial\phi_\alpha$

Iterative approach still necessary:

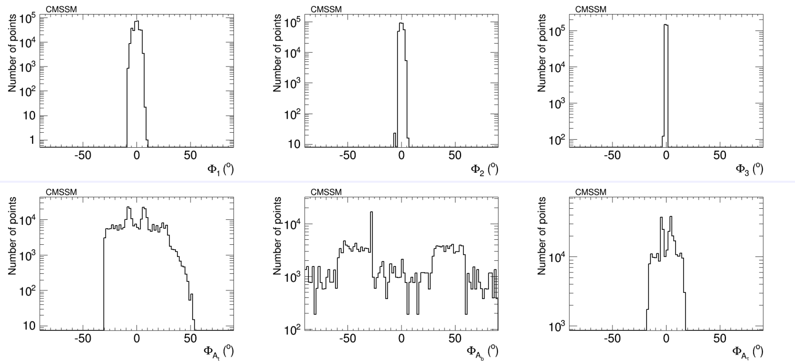
To go beyond the limit of small phases, we start with phases at 0, determine the optimal direction, move by at most 20 degrees, and iterate to determine the optimal direction at the new position.

We vary the phases for a CP conserving CMSSM best fit point (EPJC 74 (2014) 2922):

$$m_0 = 670 \text{ GeV}, \; m_{1/2} = 1040 \text{ GeV}, \; A_0 = 3440 \text{ GeV}, \; \tan\beta = 21$$

Initial statistics: 600000 points generated, then EDM constraints imposed

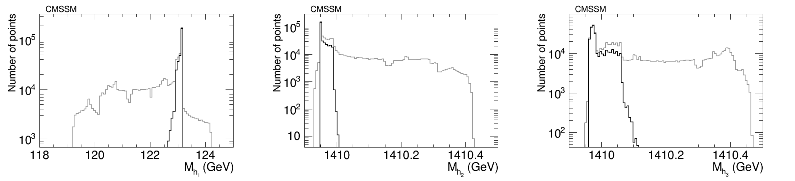
$\rightarrow$ without geometric approach, 10000 points / with geometric approach 300000 points



ϕ_1, ϕ_2, ϕ_3 very constrained

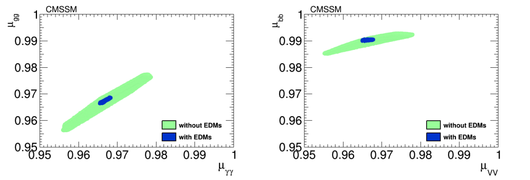
Constraints on the CMSSM: illustration of the EDM constraining power

Higgs masses:



gray: without EDMs　　black: with EDMs

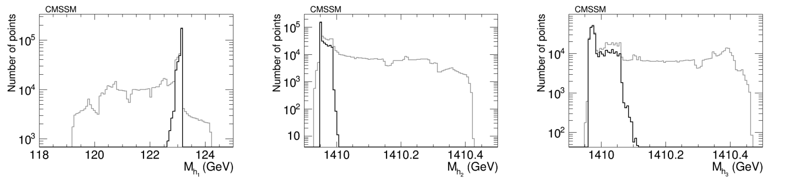
Higgs signal strengths:



EDMs limit CP violating MSSM to be very close to CP conserving MSSM

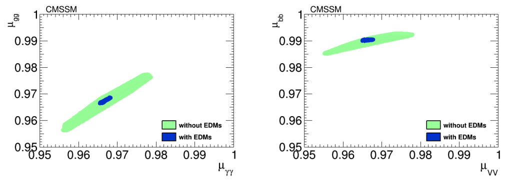
But attention, conclusion true only in the CMSSM!

Higgs masses:



gray: without EDMs black: with EDMs

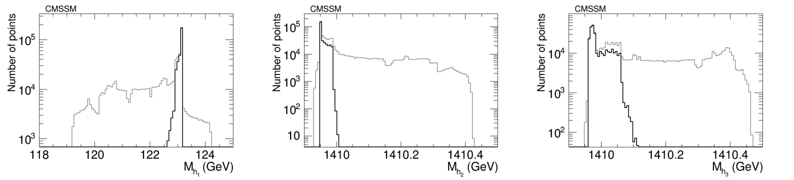
Higgs signal strengths:



EDMs limit CP violating MSSM to be very close to CP conserving MSSM

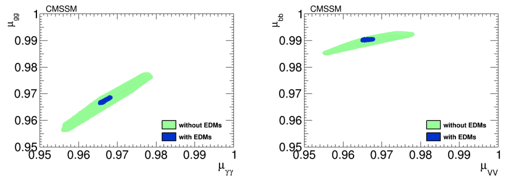
But attention, conclusion true only in the CMSSM!

Higgs masses:



gray: without EDMs black: with EDMs

Higgs signal strengths:

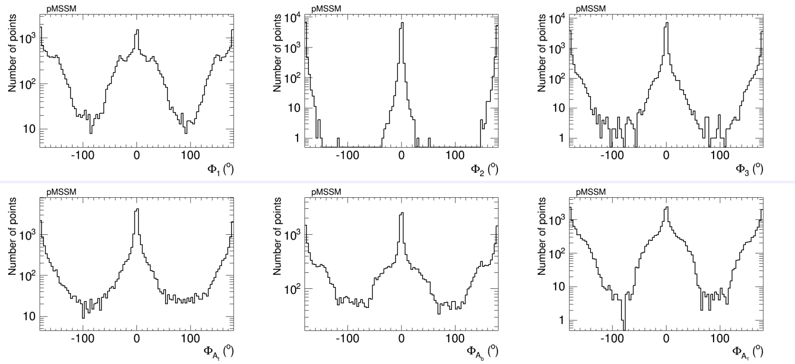


EDMs limit CP violating MSSM to be very close to CP conserving MSSM

But attention, conclusion true only in the CMSSM!

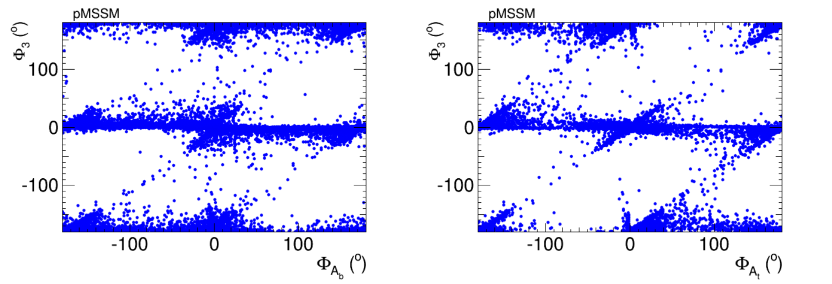
40 million CPV-pMSSM points with squark and gluino masses compatible with LHC,
1 million points with h_1 mass between 121 and 129 GeV and neutralino LSP
15000 points after the EDM constraints

After imposing the constraints:



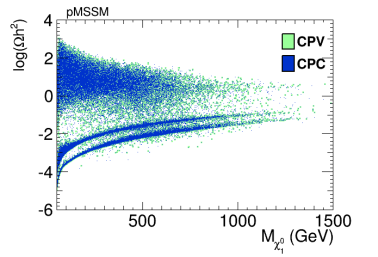
ϕ_2 very constrained, other phases can take any value

EDM constraints impose correlations between the phases



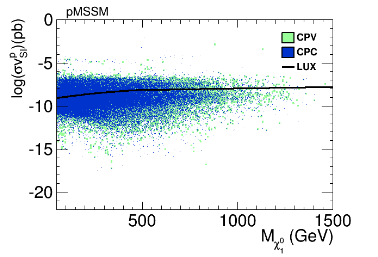
Relic density

Planck: $\Omega h^2 \sim 0.1$



Direct detection

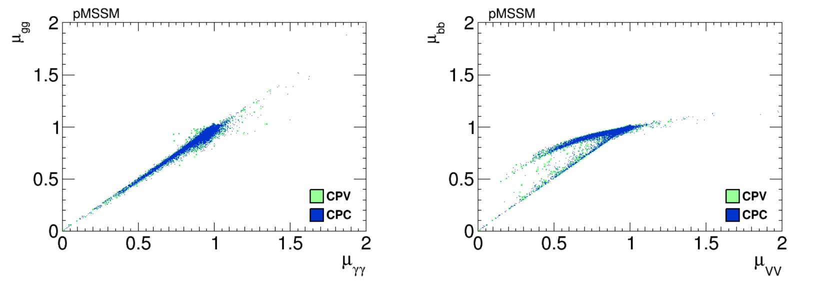
LUX upper limit



CP violation does not add much to the picture in the context of dark matter

h_1 associated to the observed Higgs boson, mass between 121 and 129 GeV

Higgs signal strengths (experimentally $\mu_{XX} \sim 1$):



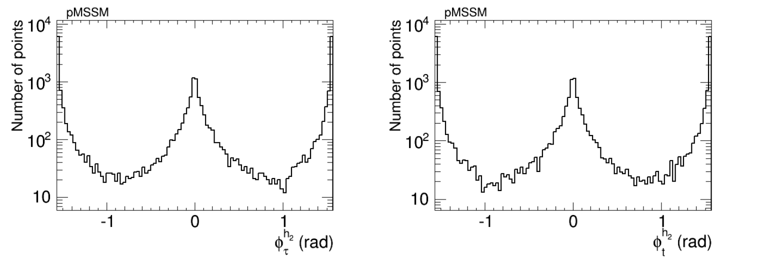
Again, CP violation does not add much in the context of Higgs rates

The Higgs bosons can be mixtures of scalar and pseudoscalar components

The constraints impose the h_1 to be a scalar with negligible pseudoscalar component

We define ($g_{S,P}^{h_i \bar{f} f}$: scalar,pseudoscalar coupling of h_i to $\bar{f} f$):

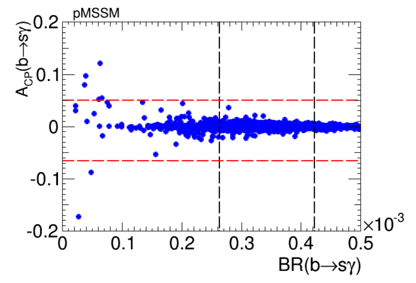
$$\tan \phi_\tau^{h_i} \equiv \frac{g_P^{h_i \tau\tau}}{g_S^{h_i \tau\tau}} , \quad \tan \phi_t^{h_i} \equiv \frac{g_P^{h_i \bar{t} t}}{g_S^{h_i \bar{t} t}}$$



Similar plots for h_3

A measurement of the $\tau\tau$ and $t\bar{t}$ spin correlations in $h_{2,3}$ decays may reveal the CP violating nature of the MSSM

CP asymmetry in $b \to s\gamma$



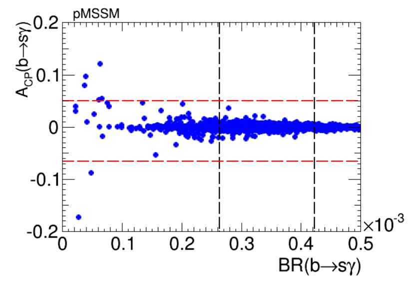
dashed lines: current limits

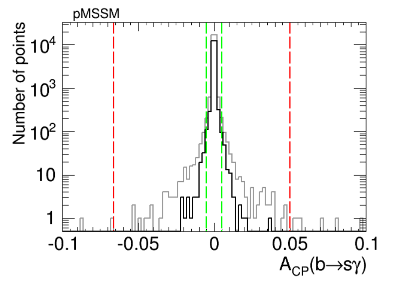
gray: without EDMs – black: with EDMs
red: current limits – green: prospective Belle-II

Current experiment limits superseded by EDM constraints

Good perspectives for the future

CP asymmetry in $b \to s\gamma$





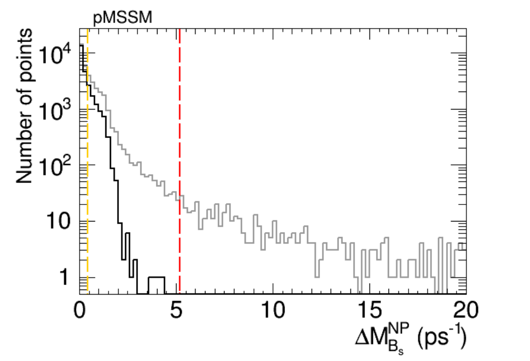
dashed lines: current limits

gray: without EDMs – black: with EDMs
red: current limits – green: prospective Belle-II

Current experiment limits superseded by EDM constraints

Good perspectives for the future

B_s meson mixing $\Delta M_{B_s}^{NP}$



gray: without EDMs – black: with EDMs
red: current limit – yellow: prospective limit

Constraints limited by the theoretical uncertainties

Good perpectives if order of magnitude improvement on theoretical uncertainties

Conclusions

- CP violating MSSM strongly constrained...
- ... but still a viable model
- Electric dipole moments very constraining...
- ... but large CP violating phases still possible
- Heavy Higgs decays are markers of CP violation in the MSSM
- Good perspectives to find evidence for CP violation through $b \to s\gamma$ and ΔM_{B_s}
- Still ample room for New Physics and CP violation!

- CP violating MSSM strongly constrained...
- ... but still a viable model
- Electric dipole moments very constraining...
- ... but large CP violating phases still possible
- Heavy Higgs decays are markers of CP violation in the MSSM
- Good perspectives to find evidence for CP violation through $b \to s\gamma$ and ΔM_{B_s}
- Still ample room for New Physics and CP violation!

- CP violating MSSM strongly constrained...
- ... but still a viable model
- Electric dipole moments very constraining...
- ... but large CP violating phases still possible
- Heavy Higgs decays are markers of CP violation in the MSSM
- Good perspectives to find evidence for CP violation through $b \to s\gamma$ and ΔM_{B_s}
- Still ample room for New Physics and CP violation!

Conclusions

- CP violating MSSM strongly constrained...
- ... but still a viable model
- Electric dipole moments very constraining...
- ... but large CP violating phases still possible
- Heavy Higgs decays are markers of CP violation in the MSSM
- Good perspectives to find evidence for CP violation through $b \to s\gamma$ and ΔM_{B_s}
- Still ample room for New Physics and CP violation!