Batavia, sometime in 2006

Analysis of enhanced $\tan\beta$ effects in the MSSM from the GUT scale

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Fermilab

Based on:

E.L., O. Vives, W. Porod, in preparation

T. Huber, E.L., M. Misiak, D. Wyler, hep-ph/0512066

Outline

- Setting the scene up
- Results
- Aside on $b \to sll$
- Conclusions

Setting the scene up

- Introduction
- Higgs mediated FCNC's
- The models:
  - mSugra, Minimal Flavour Violation
- The observables:
  - $B_s \to \mu\mu,\ \Delta M_{B_s},\ B \to X_s\gamma,\ \delta a_\mu,\ \Omega h^2$

Introduction

- The MSSM is the simplest SUSY theory including the SM gauge group and matter content
- We do not know the mechanism of SUSY breaking and we parametrize it with soft breaking terms
  - this rises the number of parameters to about 124
- A truly fundamental theory would fix most of them
- From an effective theory point of view we can only use low-energy experimental results as constraints
- FCNC & CPV results point towards low energy new physics that is, at least approximatively, flavor blind

The MSSM

- We impose R-parity to avoid problems with proton decay and to have a dark matter candidate (LSP)

- The SUSY conserving part of the MSSM lagrangian depend on the same parameters as the SM
  - analyticity of the super-potential requires 2 Higgs doublets
  - the vev's can be chosen independently: $v_u/v_d = \tan\beta$
  - a mixing term is allowed: $\mu\, H_1 H_2$

superfields

- The soft-breaking terms introduce ~120 new parameters:

$$\mathcal{L}_{\text{soft}}^{squarks} = \tilde{Q}^\dagger M_Q^2 \tilde{Q} + \tilde{U}^\dagger M_U^2 \tilde{U} + \tilde{D}^\dagger M_D^2 \tilde{D} + \tilde{Q} Y_U^A H_u \tilde{U} + \tilde{Q} Y_D^A H_d \tilde{D}$$

$$\mathcal{L}_{\text{soft}}^{sleptons} = \tilde{L}^\dagger M_L^2 \tilde{L} + \tilde{E}^\dagger M_E^2 \tilde{E} + \tilde{L} Y_D^E H_d \tilde{E}$$

$$\mathcal{L}_{\text{soft}}^{gauginos} = \frac{1}{2}\left(M_1 \tilde{B} B + M_2 \tilde{W} W + M_3 \tilde{g} g\right)$$

$$\mathcal{L}_{\text{soft}}^{higgs} = \mu B H_1 H_2 + M_1^2 H_1^2 + M_2^2 H_2^2$$

scalar fields

Minimal Flavour Violation

- We adopt the definition of D'Ambrosio, Giudice, Isidori & Strumia: the only relevant information contained in the quark Yukawa's are the eigenvalues and the CKM

$$Y_U = D_L \, V_{\mathrm{CKM}}^{\dagger} \, \lambda_u^{diag} \, U_R \ , \ \ Y_D = D_L \, \lambda_d^{diag} \, D_R$$

- The structure of FCNC's follows the CKM pattern

- In large tanβ scenarios, integrating out the SUSY spectrum results in sizable corrections to dim≤4 operators as well as to the usual non-renormalizable dim 5 and 6 ones:
  - large (huge) effects on $B_s \to \mu\mu$ and ΔM_{B_s}

Minimal Flavour Violation

- Restore the flavour symmetry group of the SM:

$$SU(3)_q^3 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$$

- Assign transformation properties to the Yukawas:

$$Y_U \sim (3, \bar{3}, 1)_{SU(3)_q^3} \ , \ \ Y_D \sim (3, 1, \bar{3})_{SU(3)_q^3}$$

- Using the SU(3) symmetry we can rotate the background values of the auxiliary fields $Y_{U,D}$:

$$Y_U = V_{\mathrm{CKM}}^\dagger \, \lambda_u^{diag} \ , \ \ Y_D = \lambda_d^{diag}$$

- The three unitary matrices D_L, U_R, D_R are unphysical

our Minimal Flavour Violation

- Most analyses are done at the EW scale

- We want more “realistic” models and consider the Flavour Blind MSSM with GUT unification:
  - mSugra
  - most general model (referred from now on as MFV)

- At this time we do not include any new phase, but there is no impediment to do so, still remaining in a MFV framework.
  - Note that even in absence of new phases, the SUSY RGE’s propagate the CKM phase and in some parts of the parameter space the resulting EDM’s are too large. It is always possible to compensate for such large SUSY contributions by adding a small phase to the μ-parameter.

our Minimal Flavour Violation

- We introduce the soft-breaking terms are at the GUT scale we require *gauge coupling and gaugino mass* unification:

  $\tan\beta,\ \mathrm{sgn}(\mu),\ M_1 = M_2 = M_3 = M_{1/2}$

- The rest of the soft-breaking terms is defined as:

$$(M_Q^2)_{ij} = M_Q^2\ \delta_{ij}, \quad (M_U^2)_{ij} = M_U^2\ \delta_{ij}, \quad (M_D^2)_{ij} = M_D^2\ \delta_{ij},$$
$$(M_L^2)_{ij} = M_L^2\ \delta_{ij}, \quad (M_E^2)_{ij} = M_E^2\ \delta_{ij}, \quad M_{H_1}^2, \quad M_{H_2}^2,$$
$$(Y_U^A)_{ij} = A_U e^{i\phi_{A_U}} (Y_U)_{ij}, \quad (Y_D^A)_{ij} = A_D e^{i\phi_{A_D}} (Y_D)_{ij},$$
$$(Y_E^A)_{ij} = A_E e^{i\phi_{A_E}} (Y_E)_{ij},$$

- In the mSugra case we have:

  $M_{1/2},\ M_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$

our Minimal Flavour Violation

- We use Spheno *[Porod]* to run the 2-loop RGE's for the MSSM fully including generation mixing (most up-to-date machinery; not public yet)

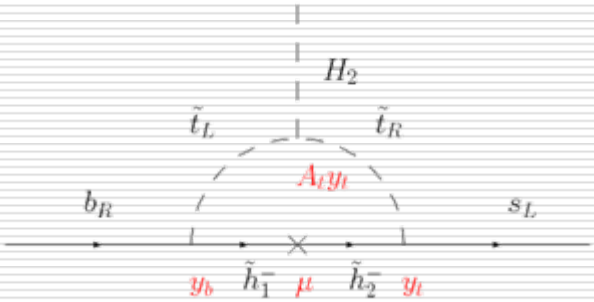
- Fix $|\mu|$ by requiring Radiative-EWSB

- At the low-scale we impose constraints from
  - direct searches
  - the ρ-parameter
  - neutral LSP
  - Ωh^2
  - perturbativity of the yukawas between the EW and GUT scales

Higgs-mediated FCNC

- The MSSM is a type-II 2HDM
- The μ-term in the superpotential induces non olomorphic higgs interactions and introduces tree level Higgs-mediated FCNC's:

$$\begin{aligned}\mathcal{L}_{\mathsf{Y}} &= -\bar{d}_{\mathsf{L}} Y^d d_{\mathsf{R}} H_1 + \bar{d}_{\mathsf{L}} \left(\Delta Y^d\right) d_{\mathsf{R}} H_2^* \\ &\quad + \bar{u}_{\mathsf{L}} Y^u u_{\mathsf{R}} H_2 + \bar{u}_{\mathsf{L}} \left(\Delta Y^u\right) u_{\mathsf{R}} H_1^*\end{aligned}$$



- After EWSB this lagrangian results in:

$$\mathcal{L}^d_{\mathsf{mass}} = \frac{v_1}{\sqrt{2}} \bar{d}_{\mathsf{L}_i} \left(Y^d_{ij} + \tan\beta \left(\Delta Y^d\right)_{ij}\right) d_{\mathsf{R}_j} + \mathsf{H.c.}$$

- In the *quark mass-eigenstate basis* we have (S=h,H,A):

$$\mathcal{L}_{S^0} = -\bar{d}_{\mathsf{L}_i} \left(\frac{\overline{m}_{d_j}}{v_1\ (1+\tilde{\epsilon}_j \tan\beta)}\ x_d^S\ \delta_{ij} + \left(\Delta Y^d\right)_{ij}\ x_u^S\right) d_{\mathsf{R}_j}\ S^0 + \mathsf{H.c.}$$

Resummation vs iteration

- We work in the quark mass eigenstate basis, extract the EW-scale yukawas from the measured mass matrices and run them up to the GUT-scale
- Introduce the soft-breaking terms and run everything down to the EW-scale
- The recalculated quark mass matrices are non-diagonal and do not reproduce the correct quark masses
- We adjust the tree-level yukawas to obtain the correct and diagonal quark mass matrices
- We *iterate* this process until the tree-level yukawas remain constant up to a given tollerance

$$M \propto Y + \Delta Y$$

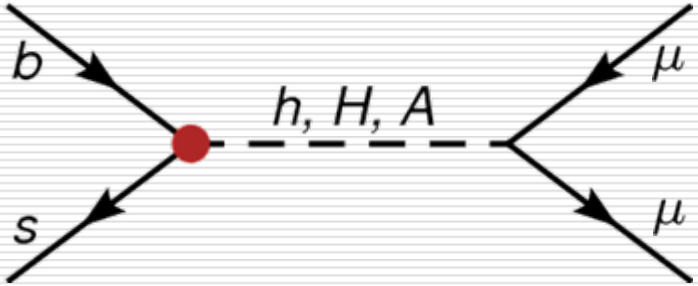
Physical masses diagonal

tree-level yukawas non-diagonal

SUSY contribution non-diagonal

- e.g.: $m_b \propto y_b(1+\varepsilon) \Rightarrow y_b \propto \begin{cases} m_b(1-\varepsilon) & \text{non resummed} \\ m_b/(1+\varepsilon) & \text{resummed} \end{cases}$

$B_s \to \mu\mu$



- The most important operators are:

$$\mathcal{H}_{\text{eff}} = -\frac{2G_F}{\sqrt{2}}\frac{\alpha V_{tb}^* V_{ts}}{2\pi \sin^2\theta_W}\left[C_S\, \overline{m}_b \left(\bar{b}_R s_L\right)\left(\bar{l}\, l\right) + C_P\, \overline{m}_b \left(\bar{b}_R s_L\right)\left(\bar{l}\, \gamma_5\, l\right)\right]$$

- They both receive similar contributions by tree-level exchange of heavy Higgses with one flavour changing Higgs insertion: $C_S \sim C_P \sim \tan^3\beta / M_A^2$

- The branching ratio is:

$$\text{BR}\left(B_s \to \mu^+\mu^-\right) \simeq 2.2 \times 10^{-6} \left[\frac{\tau_{B_s}}{1.5\ \text{ps}}\right]\left[\frac{F_{B_s}}{230\ \text{MeV}}\right]^2 \left[\frac{\overline{m}_t}{175\ \text{GeV}}\right]^4 \left[\frac{\tan\beta}{50}\right]^6 \left[\frac{350\ \text{GeV}}{M_A}\right]^4$$
$$\times \frac{A_t^2}{\mu^2}\ \frac{\left(H_2\left(m_{t_L}^2/\mu^2, m_{t_R}^2/\mu^2\right)\right)^2}{(1+\epsilon_0 \tan\beta)^2 (1+\tilde{\epsilon}_3 \tan\beta)^2}$$

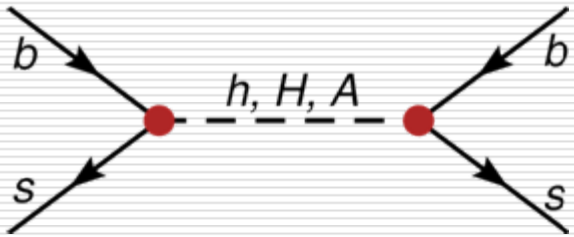
- The experimental bound and the SM theory predictions are:

$BR(B_s \to \mu\mu)_{\text{exp}} < 10^{-7}$ at 90% C.L. [CDF&D0]

$BR(B_s \to \mu\mu)_{\text{SM}} = (3.8 \pm 1.0) \times 10^{-9}$

$B_s - \bar{B}_s$ mixing

- The dominant contribution stems from double penguin diagrams:



- The B_s mass difference is given by:

$$\Delta M_{B_q} \propto |V_{tq}|^2 \left[S_0(m_t^2/M_W^2) - \frac{\sqrt{2}G_F}{\pi^2 M_W^2} \frac{m_b m_q m_t^4}{(1+\epsilon_0 \tan\beta)^2 (1+\tilde{\epsilon}_3 \tan\beta)^2} \frac{A_t^2 \tan^4\beta}{\mu^2 m_A^2} \times \left(H_2\left(m_{t_L}^2/\mu^2, m_{t_R}^2/\mu^2\right)\right)^2 \right]$$

- The double penguin contribution is always negative
- The experimental allowed limit is:

  $\Delta M_{B_s} > 14.5\ \mathrm{ps}^{-1}$ at $95\% C.L.$
- From the Universal Unitary Triangle analysis one gets:

  $\Delta M_{B_s} = (20.6 \pm 5.6)\ \mathrm{ps}^{-1}$

$B \to X_s\gamma$

- The dipole operators are:

$$H^{b\to s\gamma}_{\text{Dipole}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\left[C_7(\mu)\cdot\frac{em_b}{16\pi^2}\bar{s}_{\text{L}}\sigma_{\mu\nu}b_{\text{R}}F^{\mu\nu} \;+\; C_8(\mu)\cdot\frac{g_s m_b}{16\pi^2}\bar{s}_{\text{L}\alpha}T^a_{\alpha\beta}\sigma_{\mu\nu}b_{\text{R}\beta}G^{a\mu\nu}\right]$$

- Neutral Higgs penguin contributions are negligible (in the models under study $M_A \sim M_H$ over all the parameter space)

- W and charged Higgs contributions are both negative. The sign of the chargino one is given by $-\text{sign}(A_t\,\mu)$. Since A_t at the EW scale is dominanted by $-M_{1/2}$, we have destructive and constructive interference for $\mu>0$ and $\mu<0$, respectively

- The world average is:

$$BR(B\to X_s\gamma)_{\text{WA}} = (3.52 \pm 0.42)\times 10^{-4}$$

- The SM prediction is:

$$BR(B\to X_s\gamma)_{\text{SM}} = (3.61^{+0.37}_{-0.49})\times 10^{-4}$$

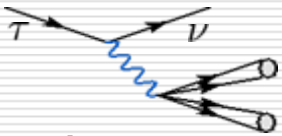
Muon g-2

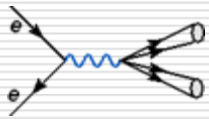
- The dominant contribution comes from the chargino-sneutrino diagram:

$$\delta a_{\mu^+}^{\chi\tilde{\nu}} \simeq \frac{g_2^2}{32\pi^2}\frac{m_\mu^2}{m_{\tilde{\nu}}^2}\frac{\mathrm{Re}(\mu)M_2\tan\beta}{m_{\tilde{\nu}}^2}$$

  - the sign of SUSY contribution is therefore, sign(μ)

- Complete theoretical predictions are complicated by non-perturbative QCD effects:
  - light by light scattering
  - hadronic contribution → can be extracted by data on ee and τ data (the latter up to isospin corr.)





- Experimental and theoretical results read:

$$a_\mu^{\mathrm{exp}} = 11\,659\,208\,(6)\times 10^{-10}$$
$$a_\mu^{\mathrm{SM}}(ee) = 11\,659\,181\,(8)\times 10^{-10} \longrightarrow 2.7\sigma$$
$$a_\mu^{\mathrm{SM}}(\tau) = 11\,659\,196\,(7)\times 10^{-10} \longrightarrow 1.4\sigma$$

(problematic)

Large $B_s \to \mu\mu$ & small $B \to X_s\gamma$?

- The behaviour of the two amplitudes is:

$$A(B_s \to \mu\mu) \sim \tan^3\beta/M_A^2$$
$$A(B \to X_s\gamma) \sim \tan\beta/M_{\tilde{t}}^2$$

- For $\mu < 0$
  - $C_{7\chi} < 0$: it is necessary to have a heavy stop
  - $(\delta a_\mu)_\chi < 0$: the whole scenario is disfavoured
  - large $B_s \to \mu\mu$ is difficult to achieve

- For $\mu > 0$
  - $C_{7\chi} > 0$: there is always a cancellation between chargino and charged Higgs.
  - $(\delta a_\mu)_\chi > 0$: it doesn't constrain much this scenario
  - large $B_s \to \mu\mu$ is possible and easy to achieve

Dark Matter

- In the MSSM with R-parity, the lightest neutralino is stable and provides an excellent dark matter candidate

- We use the program micrOmega to implement the calculation of the relic neutralino density

- Experimental results (WMAP data) are extremely good: $\Omega h^2 = 0.1121^{+0.0081}_{-0.0090}$

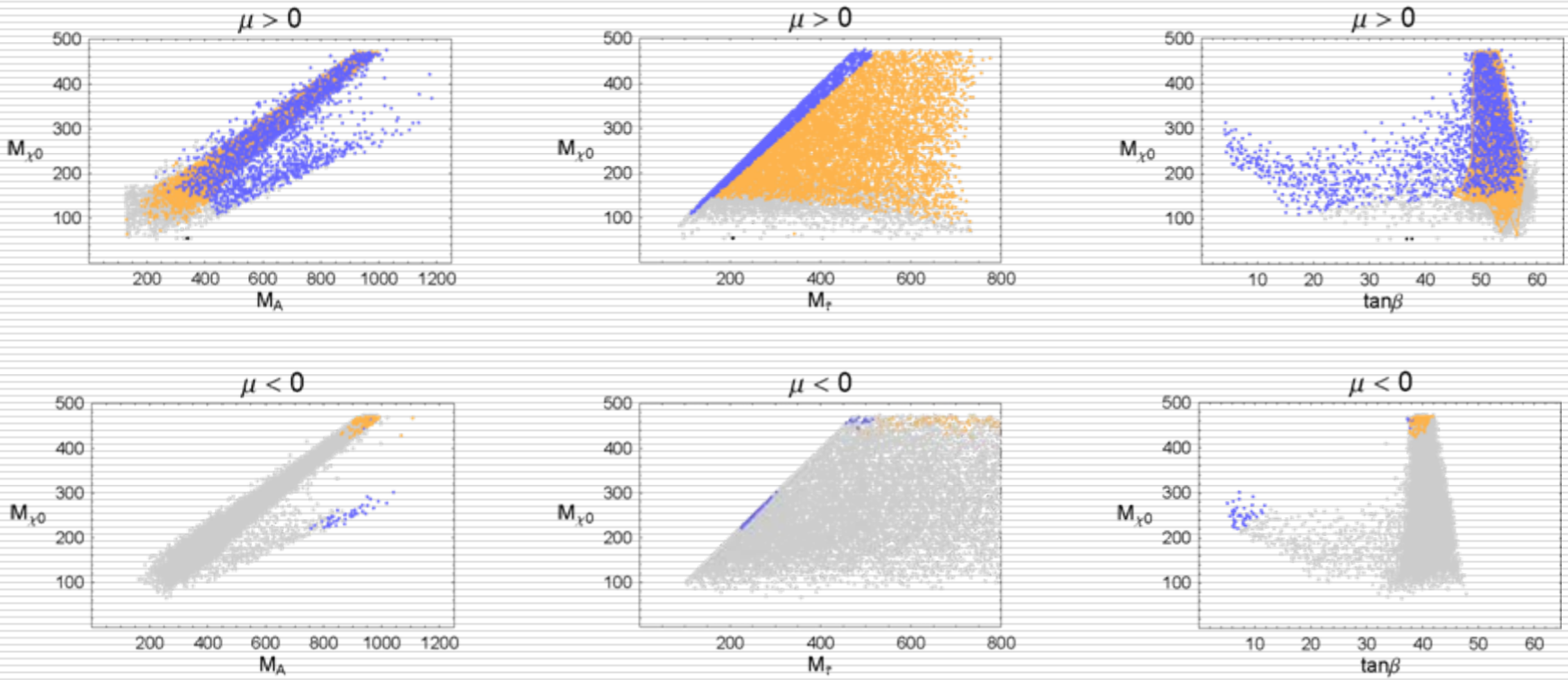
- Unfortunately the theoretical situation is much cloudier:
  - parametric errors (e.g. M_t) and uncertainties in the RGE running from the GUT to the EW scales (especially in the large $\tan\beta$ region) impact strongly the calculation of Ωh^2
  - Moreover, points for which Ωh^2 is too small can always be "saved" by some other dark matter candidate

- In view of these remarks, we take a conservative attitude and impose only a loose upper bound: $\Omega h^2 < 0.1369$ (99% C.L.)

Results

- mSugra vs MFV
- Dark matter scenarios
- impact of a large $B_s \to \mu\mu$

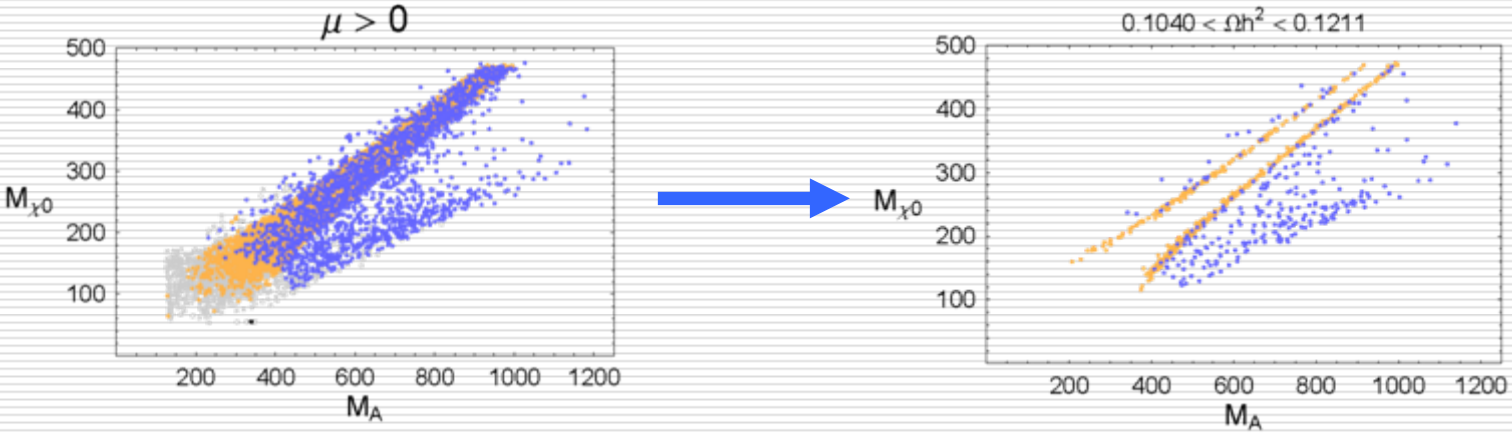
mSugra: impact of Ωh^2



- gray: no FCNC constraint is imposed
- blue: stau-coannihilation (we require $m_{\tilde{\tau}} - m_{\tilde{\chi}^0} < 10\%$)
- orange: A-pole region (funnel)

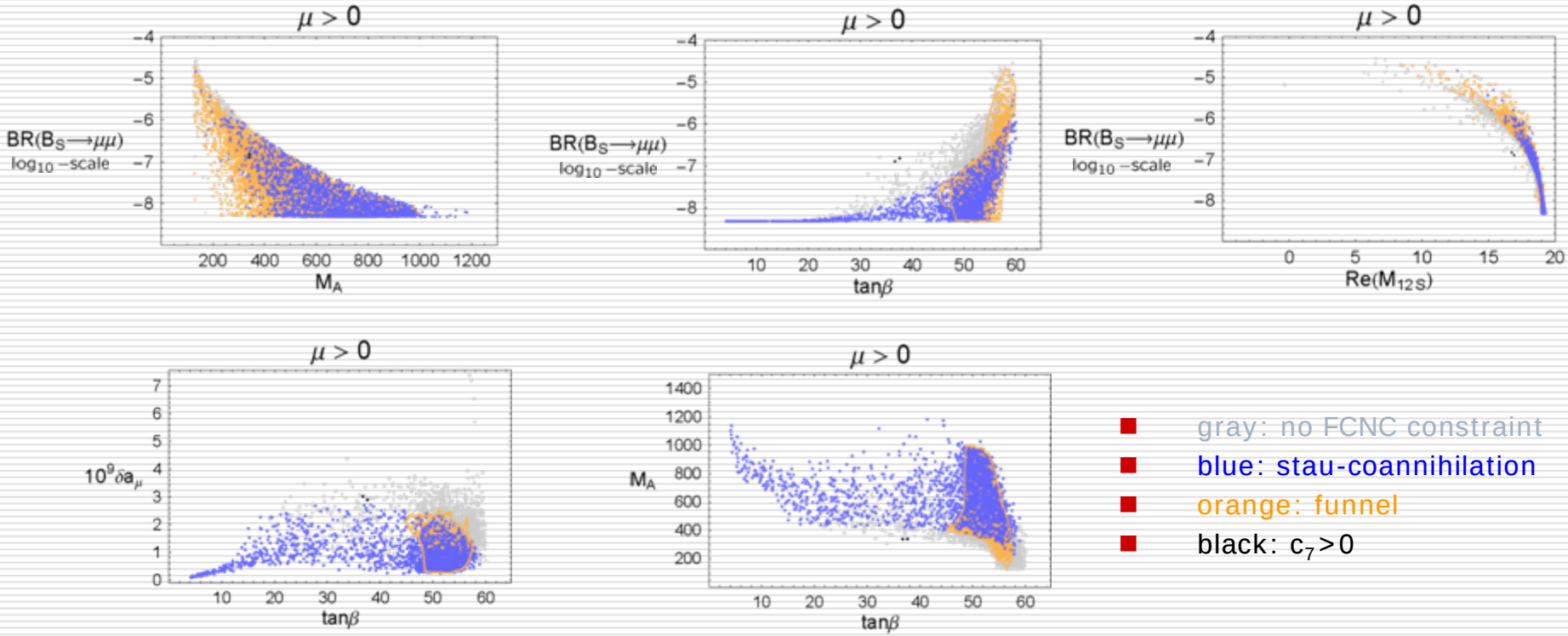
mSugra: impact of Ωh^2

- Using the 1-sigma bound one gets:



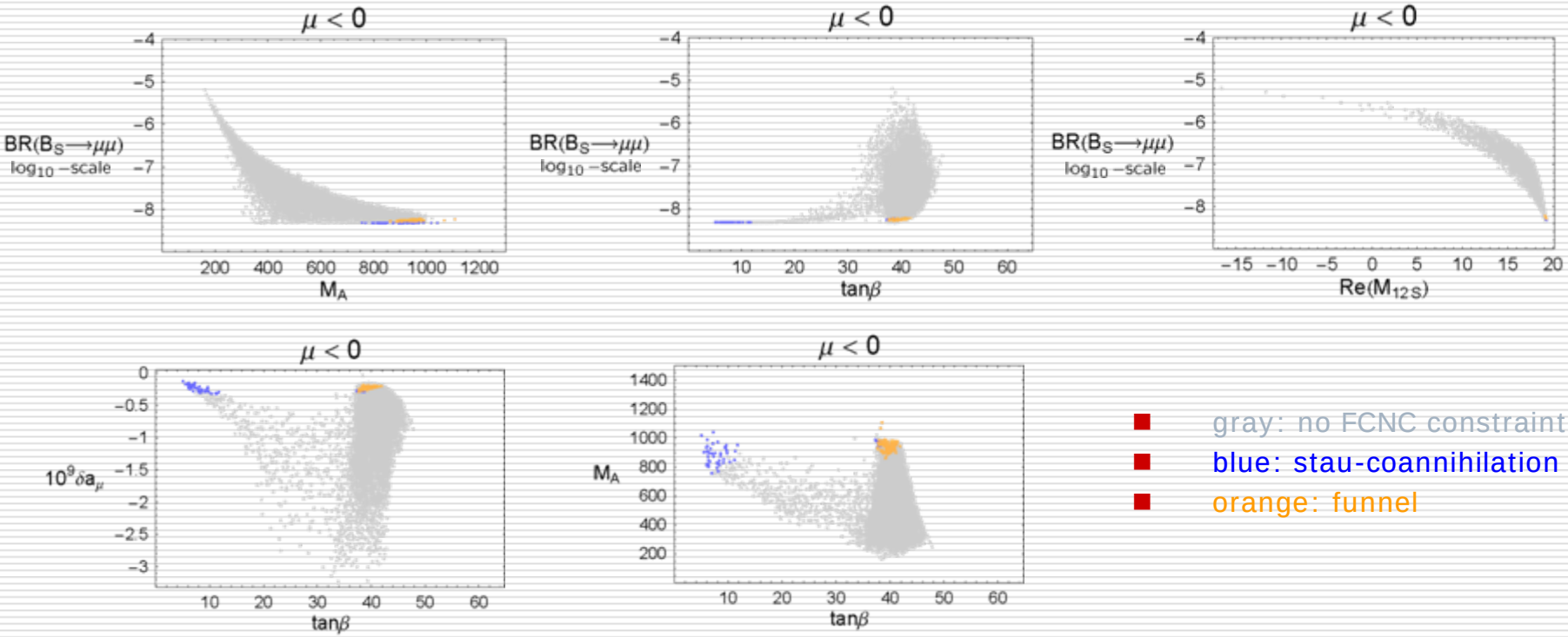
- In mSugra it is possible to evade the Ωh^2 constraint only with some fine tuning:
  - bulk region (low M_0, $M_{1/2}$): ecluded by direct searches
  - stau co-annhilation ($M_\chi \sim M_\tau$)
  - funnel ($M_\chi \sim M_A/2$)
  - focus point (large M_0, large $\tan\beta$)

mSugra: $\mu > 0$



- Very large effects are possible both on $B_s \to \mu\mu$ and ΔM_{B_s}
- The strongest constrain is b→sγ
- All regions shown satisfy the dark matter constraint

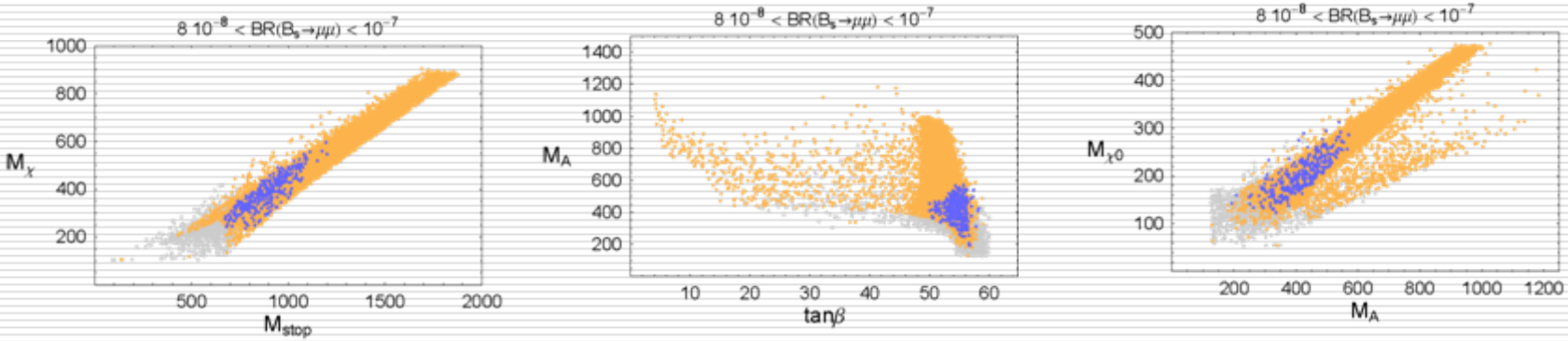
mSugra: $\mu < 0$



- No large effects are possible on $B_s \to \mu\mu$ or ΔM_{B_s}
- The strongest constrain is g-2
- All regions show satisfy the dark matter constraint

mSugra: impact of large $B_s \to \mu\mu$

- If we assume $8 \times 10^{-8} < BR(B_s \to \mu\mu) < 10^{-7}$

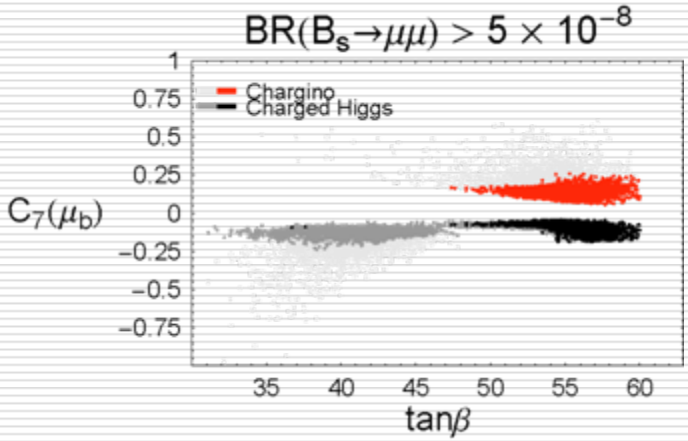


  - gray: no FCNC
  - orange: FCNC
  - blue: FCNC + large $B_s \to \mu\mu$

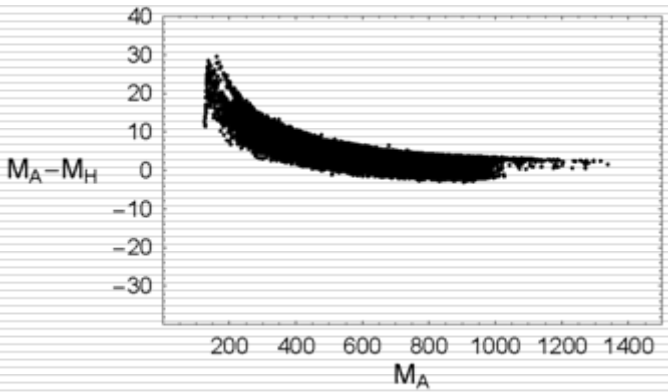
- Only $\mu > 0$
- tanβ is forced to be above 50
- The pseudoscalar Higgs has to be lighter than 600 GeV
- The stop mass is in the range [750 – 1200] GeV
- The b→sγ constraint requires a quite strong cancellation between chargino and charged Higgs

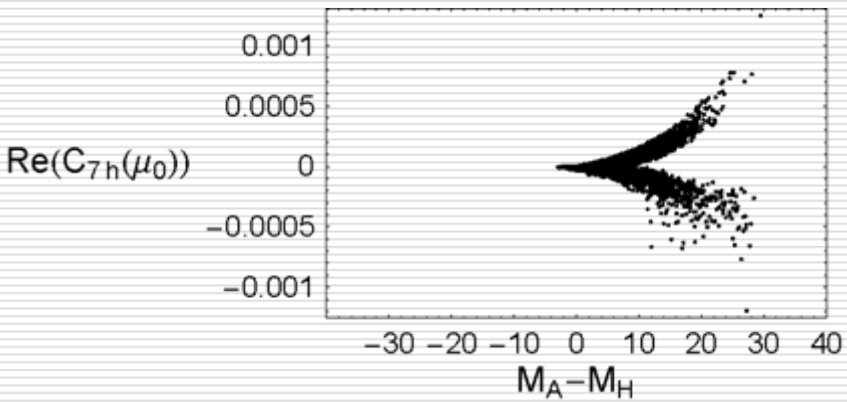
mSugra: analysis of C_7

- For mu positive we have indeed very precise cancellation between chargino and charged Higgs contributions:

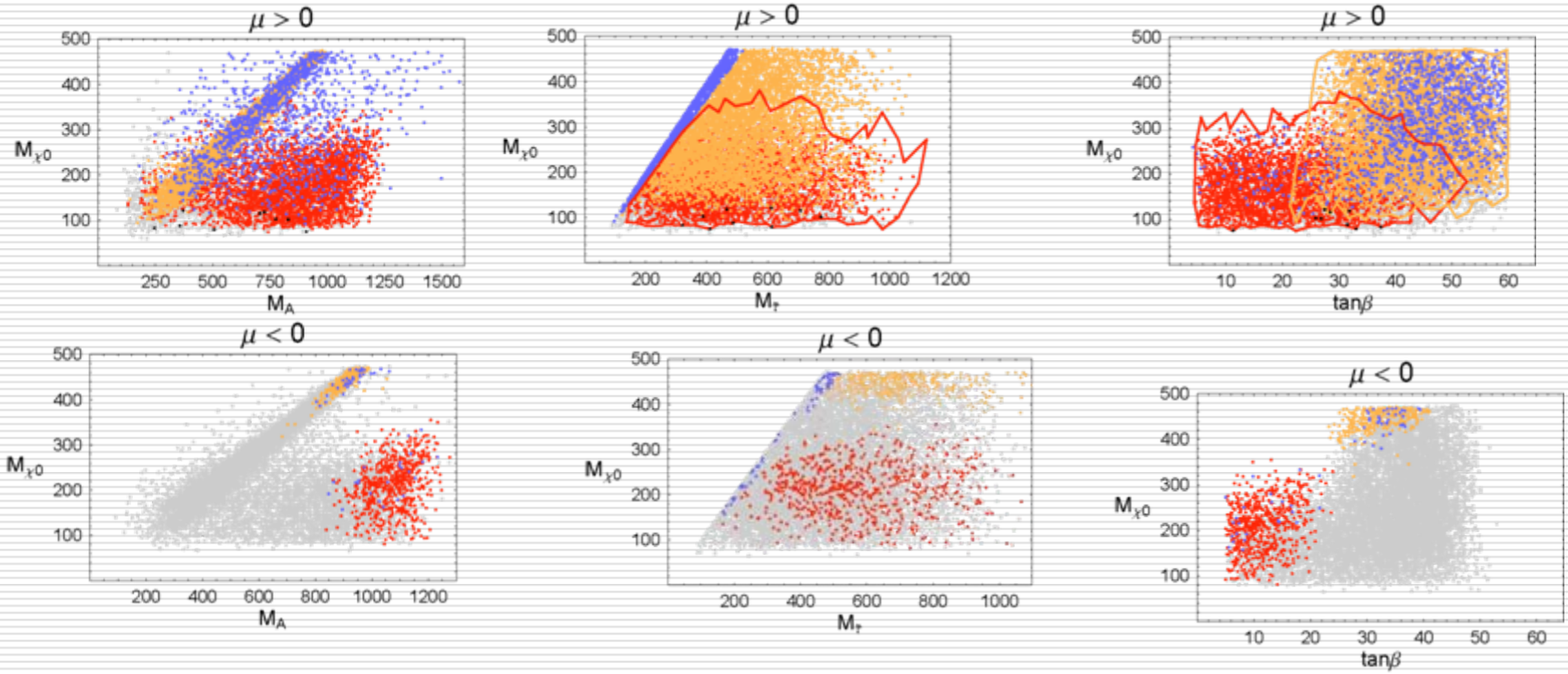


- Large neutral Higgs contributions are possible only if M_A and M_H are widely separated:





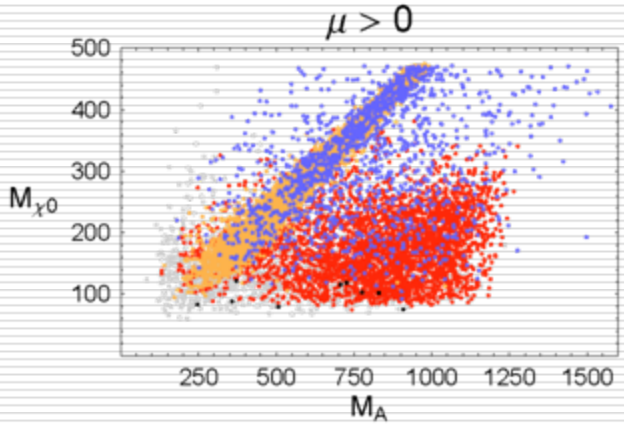
MFV: impact of Ωh^2

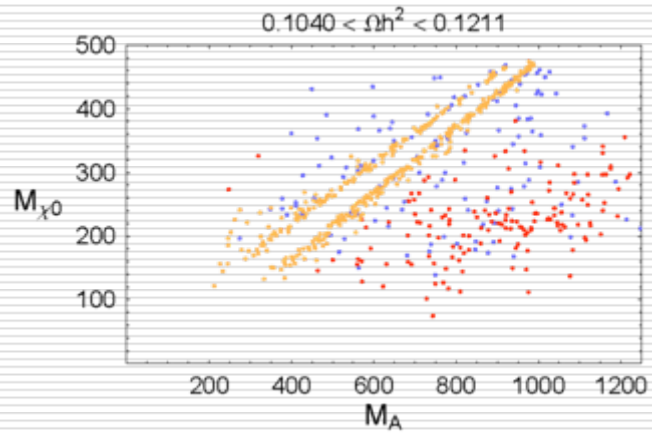


- gray: no FCNC constraint is imposed
- blue: stau-coannihilation (we require $m_{\tilde{\tau}} - m_{\tilde{\chi}^0} < 10\%$)
- orange: A-pole region (funnel)
- red: the neutralino is higgsino “dominated” (>5%)

MFV: impact of Ωh^2

- Using the 1-sigma bound one gets:





- Mechanisms to decrease the dark matter relic density:
  - bulk region (low M_0, $M_{1/2}$): ecluded by direct searches
  - stau co-annhilation ($M_\chi \sim M_\tau$)
  - funnel ($M_\chi \sim M_A/2$)
  - Higgsino-dominated neutralino

no fine tuning needed

MFV: impact of Ωh^2

- The neutralino mass matrix is:

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -g' v_d/2 & g' v_u \\ 0 & M_2 & g v_d/2 & -g v_u/2 \\ -g' v_d/2 & g v_d/2 & 0 & -\mu \\ g' v_u & -g v_u/2 & -\mu & 0 \end{pmatrix} \begin{matrix} \tilde{B} \\ \tilde{W}_3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{matrix}$$

$$\tilde{\chi}_1^0 = a_{\tilde{B}} \tilde{B} + a_{\tilde{W}} \tilde{W}_3 + a_{\tilde{H}_1} \tilde{H}_1^0 + a_{\tilde{H}_2} \tilde{H}_2^0$$

- The lightest neutralino is higgsino dominated if:

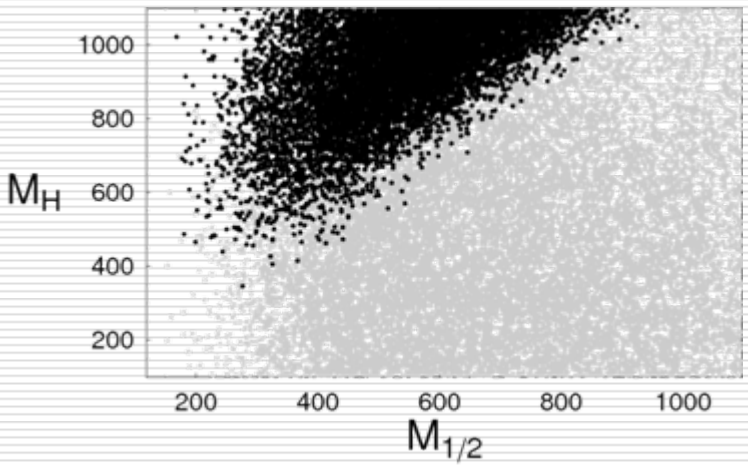
$$c_{\tilde{H}} = |a_{\tilde{H}_1}|^2 + |a_{\tilde{H}_2}|^2 > 5\% \Rightarrow |\mu| < M_{1,2}$$

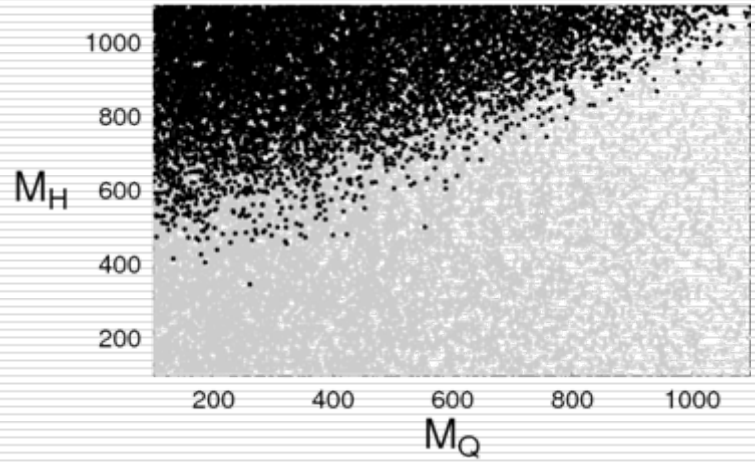
- In models with GU and REWSB we have:

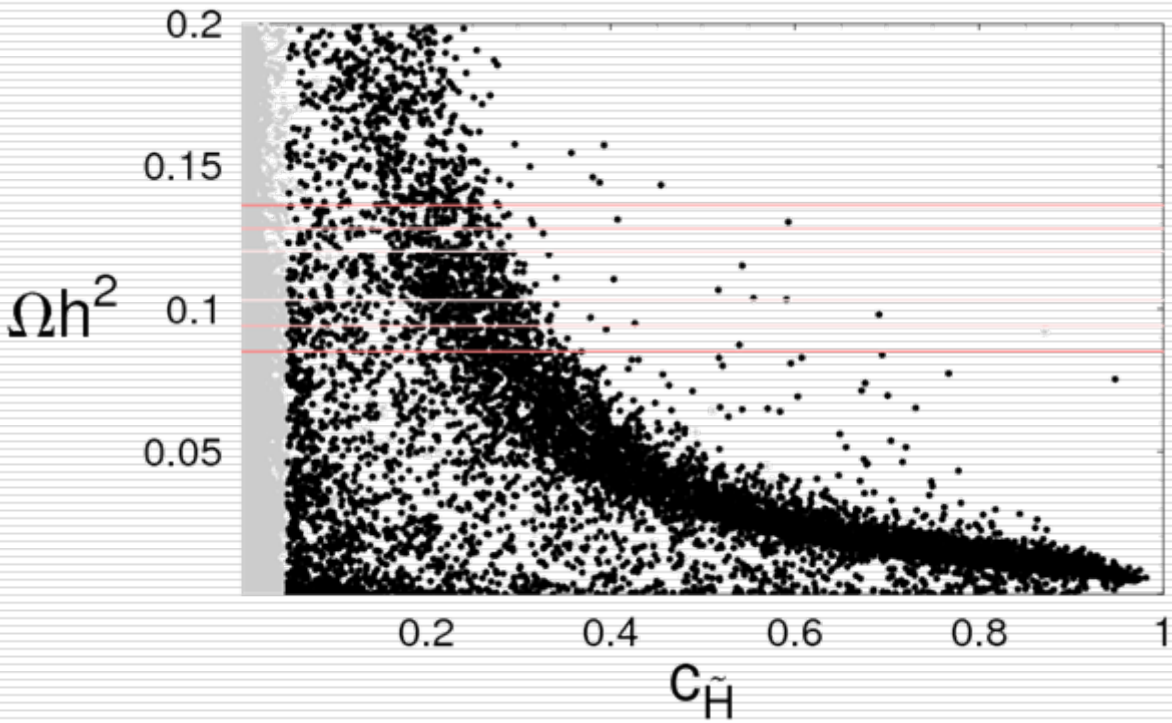
$$|\mu|^2 \sim +3\, M_{1/2}^2 + 0.75\, M_Q^2 - 0.63\, M_H^2 + \ldots$$

- So the LSP is higgsino dominated if $M_H \gg M_Q,\ M_{1/2}$

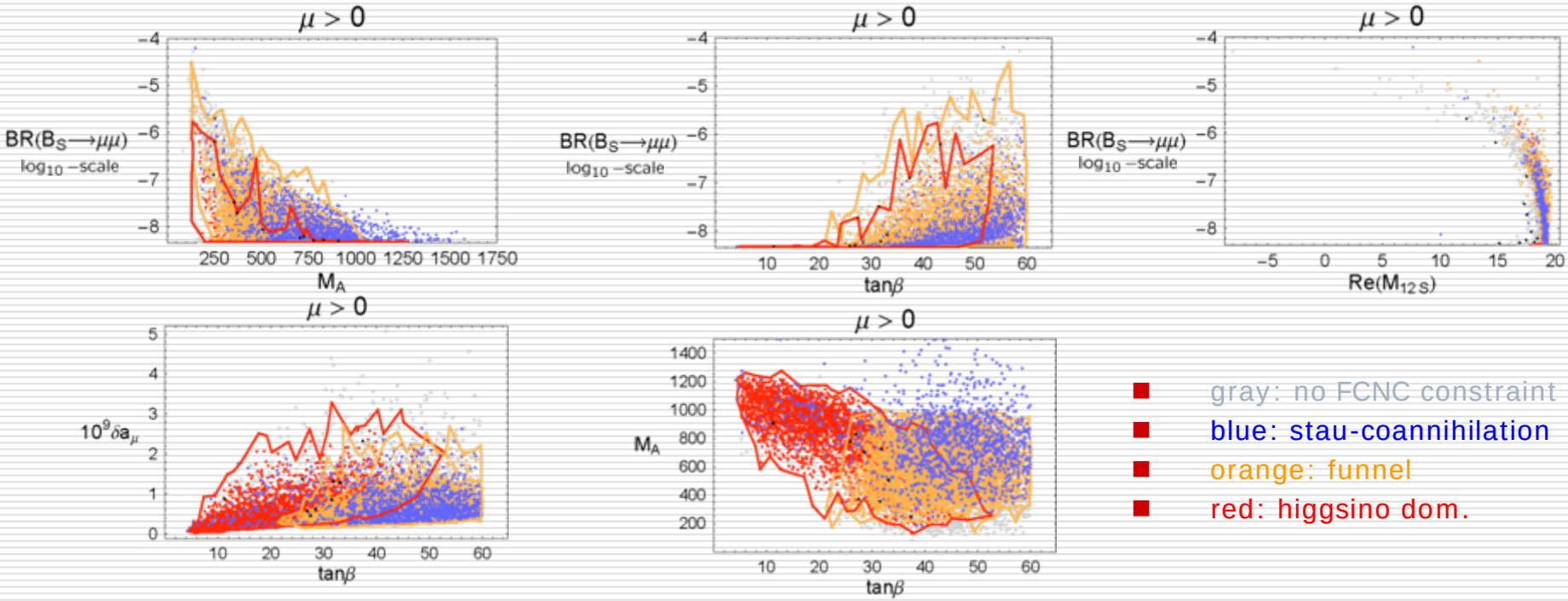
MFV: impact of Ωh^2





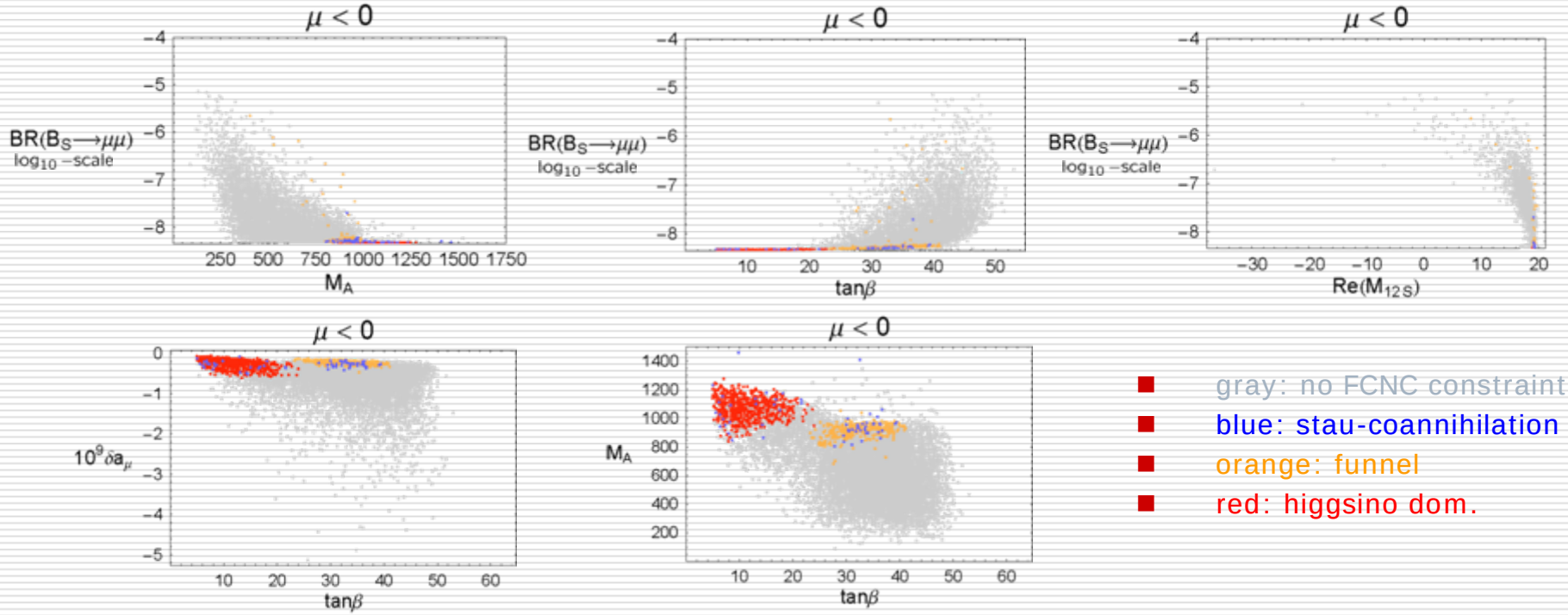


MFV: $\mu > 0$



- Very large effects are possible both on $B_s \to \mu\mu$ and ΔM_{B_s} for relatively small tanβ values
- The strongest constrain is b→sγ

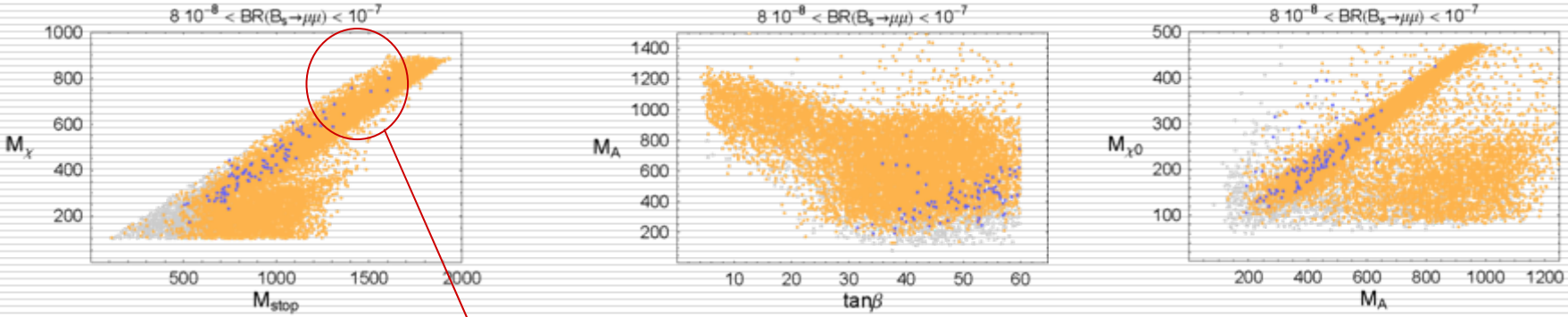
MFV: $\mu < 0$



- Contrary to the mSugra case, we find that large effects are possible on $B_s \to \mu\mu$, not much on ΔM_{B_s}
- The strongest constrain is again g-2
- In the MFV scenario the squark and Higgs sectors are more independent: we can have, at the same time, large stop and low pseudoscalar Higgs masses.

MFV: impact of large $B_s \to \mu\mu$

- If we assume $8 \times 10^{-8} < BR(B_s \to \mu\mu) < 10^{-7}$



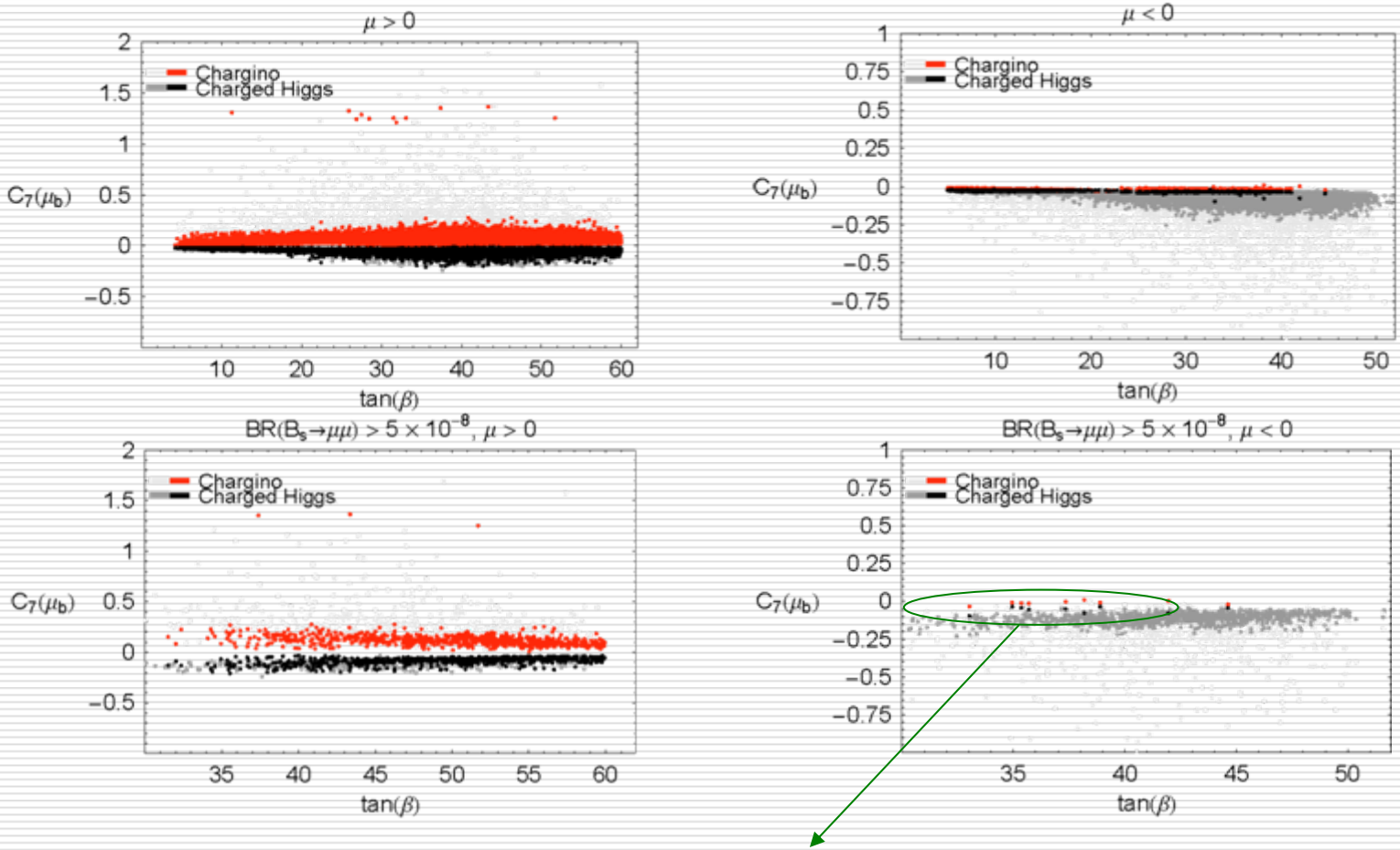
small b→sγ contributions

- gray: no FCNC
- orange: FCNC
- blue: FCNC + large $B_s \to \mu\mu$

- both μ positive and negative
- tanβ is forced to be above 30
- The pseudoscalar Higgs has to be lighter than 800 GeV
- The stop mass is in the range [750 – 1700] GeV

MFV: analysis of C_7

- The cancellation between chargino and charged Higgs contributions extends now to lower tanβ values



small $b \to s\gamma$ contributions

Aside on $B \to X_s \ell^+ \ell^-$

- Log-enhanced QED corrections
- Impact on C_7>0 scenarios

Short distance physics

- The effective Hamiltonian is:

$$H_{\text{eff}} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^*\Big[\sum_{i=1}^{10} C_iP_i + \underbrace{\sum_{i=3}^{6} C_{iQ}P_{iQ} + C_bP_b}_{\text{only for QED corrections}}\Big]$$

$$P_1 = (\bar{s}_L\gamma_\mu T^a c_L)(\bar{c}_L\gamma^\mu T^a b_L) \qquad P_7 = \frac{e}{16\pi^2}m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$$

$$P_2 = (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu b_L) \qquad P_8 = \frac{g}{16\pi^2}m_b(\bar{s}_L\sigma^{\mu\nu}T^a b_R)G^a_{\mu\nu}$$

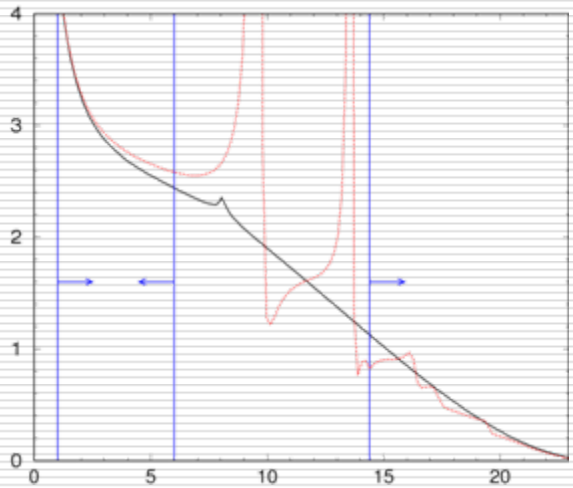
$$P_9 = (\bar{s}_L\gamma_\mu b_L)\sum_l(\bar{l}\gamma^\mu l)$$

$$P_{10} = (\bar{s}_L\gamma_\mu b_L)\sum_l(\bar{l}\gamma^\mu\gamma_5 l)$$

- We neglect terms proportional V_{ub} V_{us} (suppressed by $C_2V_{ub}V_{us}/(C_9V_{tb}V_{ts} \sim 0.5\%)$

Experimental cuts

- Presence of intermediate cc resonances is responsible for failure of quark-hadron duality and cuts on the di-lepton invariant mass are necessary ($s = (P_{\ell_1} + p_{\ell_2})^2$):
  - very low-s region (0.04 GeV^2 s < 1 GeV^2)
  - low-s region (1 GeV^2 < s < 6 GeV^2)
  - High-s region (s > 6 GeV^2)



- low-s region: + cc background
  + C_7-C_9 interference
  + more events
  - not optimal M_{Xs} cut

- Cuts on the hadronic invariant mass ($M_{X_s} < 0.1$ GeV) are necessary to eliminate the background from:

$$b \to e^- \nu c(\to s\nu e^+) = b \to s e^+ e^- + \text{missing energy}$$

Motivations for QED corrections

- The BR is proportional to $\alpha_{\rm em}^2(\mu)$; in absence of QED corrections the scale μ is undetermined and lead to an uncertainty of order 8%

- We need corrections of the type $\alpha_{\rm em}\log(M_W/m_b) = \alpha_{\rm em}L$; they can only appear in the matching.

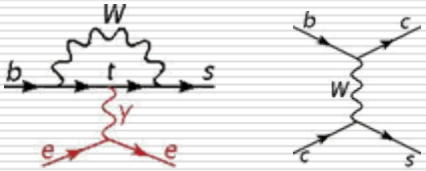
- The QCD RGE's resum all terms of the type $c_s=\alpha_s L$; hence the mixed QED & QCD RGE's lead naturally to an expansion in α_s and $\kappa=\alpha_{em}/\alpha_s$:
  - $\alpha_{em}\, L = c_s\, \alpha_{em}/\alpha_s \rightarrow f(c_s)\, \kappa$

- To obtain the whole log-enhanced corrections one has to calculate also 1-loop QED matrix elements of the various operators.
  - Surprisingly they contain terms enhanced by an explict $\log(m_\ell/m_b)$

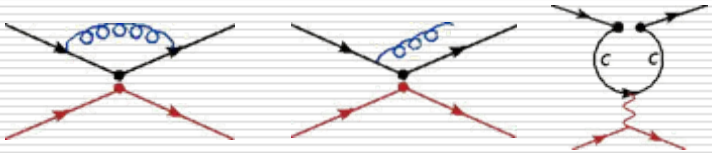
A short history of $B \to X_s \ell^+ \ell^-$

- QCD at NLO:

WC's:



ME's:



Misiak
Buras, Münz

- QCD at NNLO:

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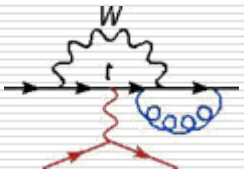
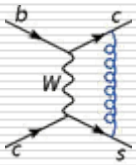
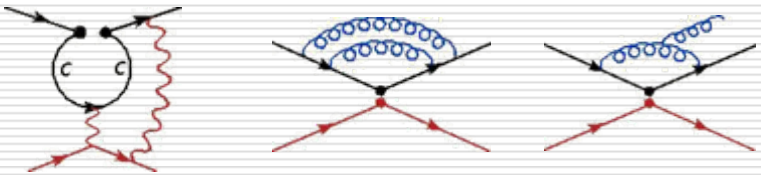




Bobeth,Misiak,Urban

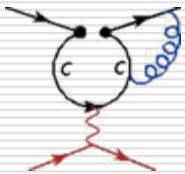
ME's:



Asatryan,Asatrian,Greub,Walker
Ghiculov,Hurth,Isidori,Yao
Bobeth,Gambino,Gorbahn,Haisch

- QED at NLO:

WC's:



Bobeth,Gambino,Gorbahn,Haisch
Huber,Lunghi,Misiak,Wyler

ME's:

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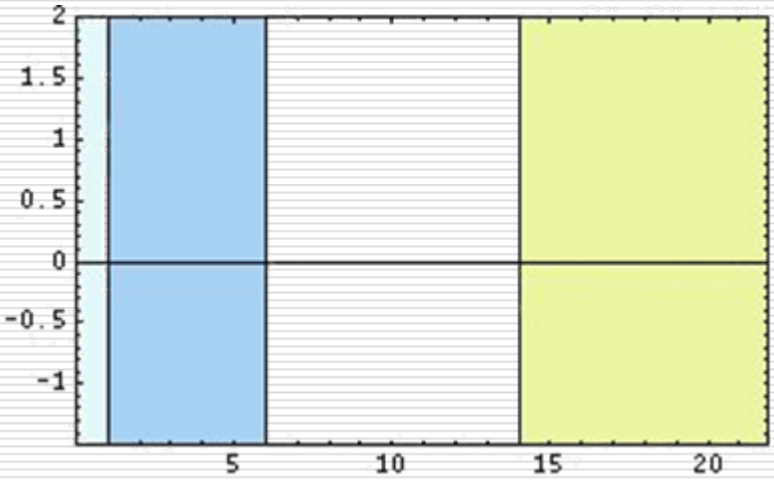
$\log(m_\ell/m_b)$-enhanced corrections

- The differential decay rate is not infrared safe with respect to collinear photon emission
  - the rate contains a collinear logarithm, $\log(m_\ell/m_b)$
  - the coefficient of the log vanishes when integrated over the whole dilepton spectrum



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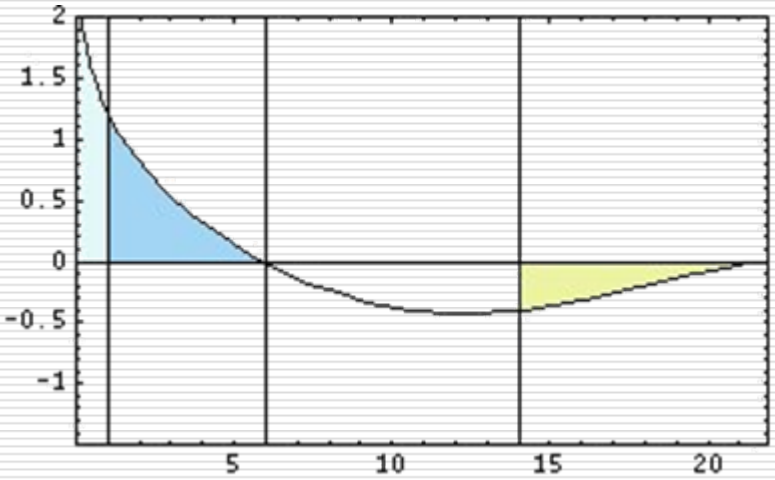


- This log appears as a residual $1/\varepsilon$ in NDR. Using the splitting function of the electron we were able to switch from NDR to mass regularization.

Are these corrections physical?

- The critical point is the lepton momentum reconstruction at Babar and Belle
- Muons are completely disentangled from collinear photons
- Electrons are more problematic: photon emitted at angles smaller than ~2° (θ < 0.035 mrad, ϕ<0.005) from the direction of either electrons are combined with the electron candidate to form a "recovered electron"
- The inclusion of photons emitted in a cone around the electron direction is equivalent to set an upper limit on the invariant mass of the photon-electron system:

$$\log\frac{m_b^2}{m_e^2} \rightarrow \log\frac{m_b^2}{\Lambda^2} \quad \text{with} \quad \Lambda < O(m_\mu)$$

- Rates for electron and muon channels are similar

Normalization and masses

- The $m_{b,pole}$ factors are removed by normalizing to the semileptonic $B \to X_u e \nu$ rate:

$$\frac{d\mathcal{B}(B \to X_s \ell\ell)}{ds} = BR^{exp}_{b->ce\nu} \left|\frac{V_{cb}}{V_{ub}}\right| \frac{1}{C} \frac{d\Gamma(B \to X_s \ell\ell)/ds}{\Gamma(B \to X_u e\nu)}$$

$$C = \left|\frac{V_{ub}}{V_{cb}}\right|^2 \frac{\Gamma(B \to X_c e\nu}{\Gamma(B \to X_u e\nu}$$

  - we adopt $C=0.58 \pm 0.01$ [Bauer,Ligeti,Luke,Manohar,Trott]
  - we assume 100% correlation between C and m_c

- Presence of renormalon ambiguities in the BR expressed in terms of $m_{b,pole}$: they are removed if the 1S or MSbar masses are adopted [Hoang,Ligeti,Manohar]

Numerics (low-s region)

- Most imporant parametric inputs:

$\mathcal{B}(B \to X_c e \bar{\nu}) = 0.1061 \pm 0.0017$ $\quad M_{t,pole}^{\text{WA}} = (173.1 \pm 3.5)$ GeV

$|V_{ts}V_{tb}/V_{cb}|^2 = 0.967 \pm 0.009$ $\quad m_b^{1S} = (4.69 \pm 0.03)$ GeV

$m_c(m_c) = (1.224 \pm 0.017 \pm 0.054)$ GeV

- Experimental results (e-μ average):

Belle: $(1.49 \pm 0.50^{+0.41}_{-0.32}) \times 10^{-6}$

Babar: $(1.8 \pm 0.7 \pm 0.5) \times 10^{-6}$

WA: $(1.60 \pm 0.51) \times 10^{-6}$

- Including QED corrections to the WC's only:

$\mathcal{B}(B \to X_s \ell\ell) = 1.56 \times 10^{-6}$

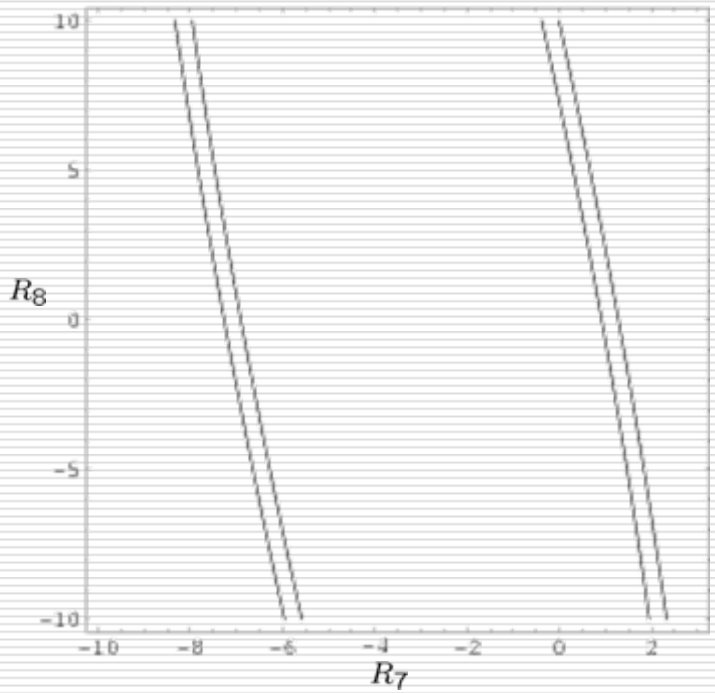
- Including all QED corrections:

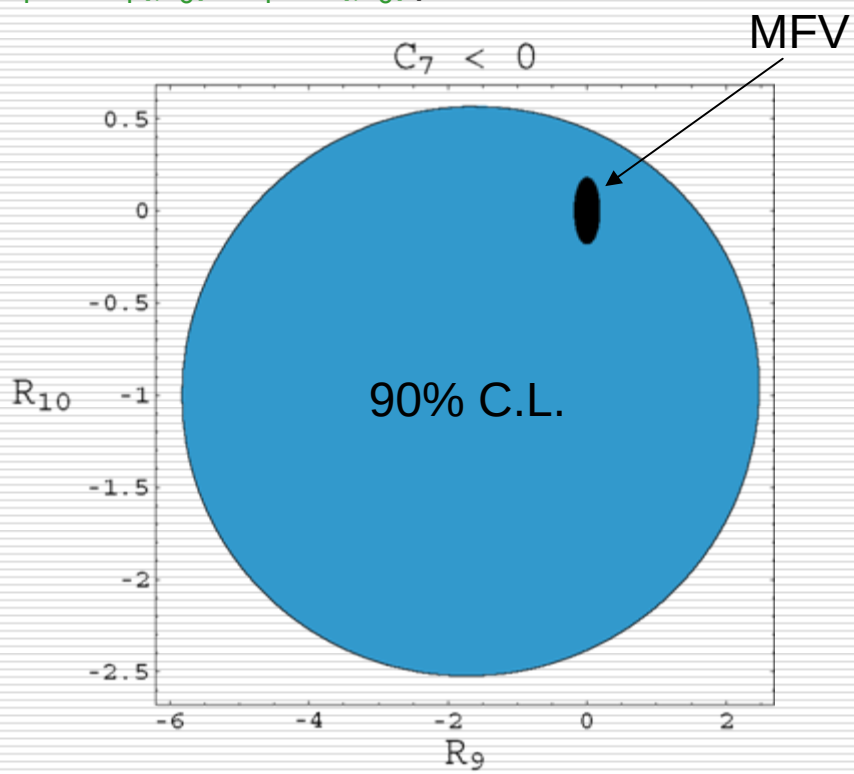
$$\begin{pmatrix} \mathcal{B}_{\mu\mu} \\ \mathcal{B}_{ee} \end{pmatrix} = \left[\begin{pmatrix} 1.59 \\ 1.64 \end{pmatrix} \pm 0.08_{\text{scale}} \pm 0.06_{m_t} \pm 0.024_{C,m_c} \pm 0.015_{m_b} \right.$$

$$\left. \pm 0.02_{\alpha_s(M_Z)} \pm 0.015_{\text{CKM}} \pm 0.026_{\text{BR}_{sl}} \right] \times 10^{-6} = \left[\begin{pmatrix} 1.59 \\ 1.64 \end{pmatrix} \pm 0.11 \right] \times 10^{-6}$$

Impact on $C_7>0$ scenarios

- We use $\mathcal{B}(B \to X_s\gamma) = (3.52 \pm 0.3) \times 10^{-4}$ to constrain the Wilson coefficients C_7 and C_8 ($R_i = C_i(\mu_0)/C_i^{SM}(\mu_0)$):





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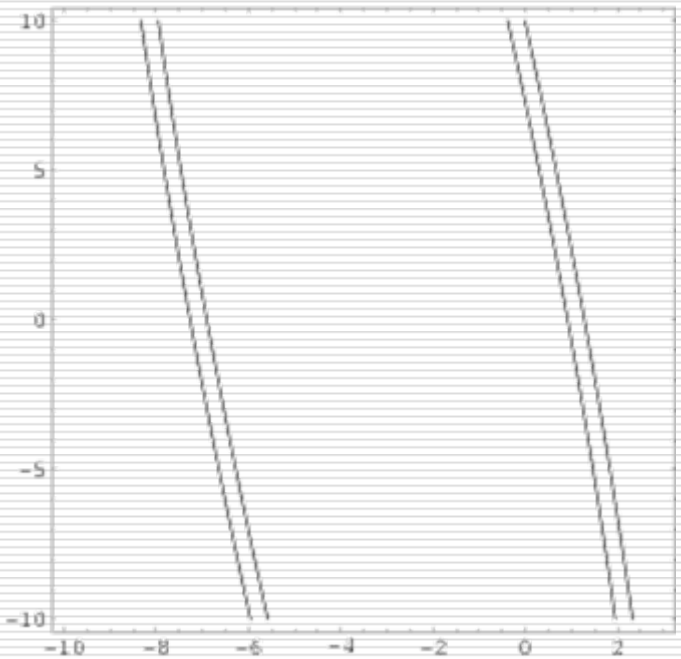

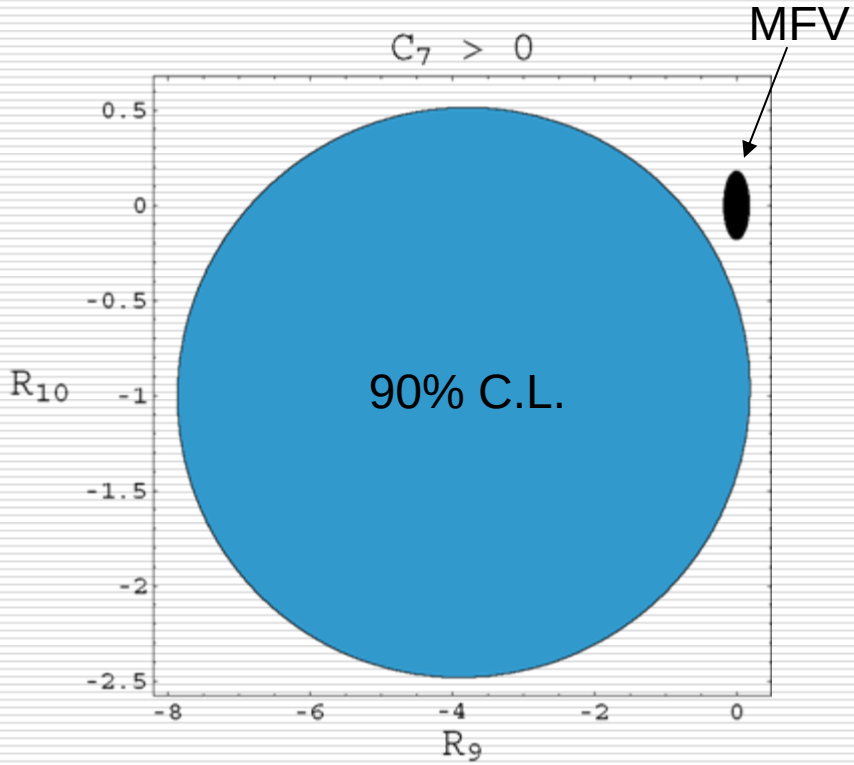

- Models with $C_7>0$ require sizable contributions to C_9 and C_{10}. This scenario is therefore excluded in MFV models

Summary

- Full scan of parameter space of MFV models with Grand Unification, using most up-to-date technical tools
- Dark matter scenarios (Higgsino dominated dm)
- Large tanβ phenomenology:
  - $B_s \to \mu\mu$
  - ΔM_{B_s}
  - $\mu > 0$ vs $\mu < 0$
- New results in
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  - impact on $C_7 > 0$ scenarios

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- Things look interesting..... if you believe in SUSY ☺