Is the CMSSM already ruled out?

...by $(g-2)_\mu$...

Leszek Roszkowski

Astro–Particle Theory and Cosmology Group

Sheffield, England

with R. Ruiz de Austri and R. Trotta

hep-ph/0602028 $\longrightarrow$ JHEP06, hep-ph/0611173$\longrightarrow$ JHEP07

and arXiv:0705.2012$\longrightarrow$ JHEP07

Outline

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- the Constrained MSSM (CMSSM)

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- summary

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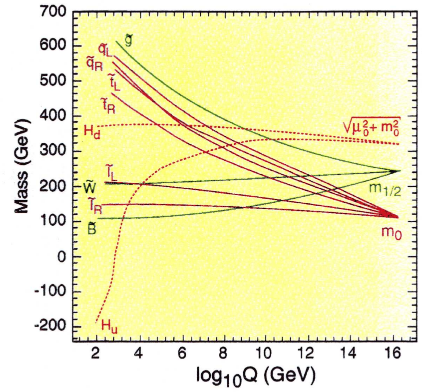
- gauginos $M_1 = M_2 = m_{\widetilde{g}} = m_{1/2}$ (c.f. MSSM)
- scalars $m^2_{\widetilde{q}_i} = m^2_{\widetilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m^2_0$
- 3–linear soft terms $A_b = A_t = A_0$



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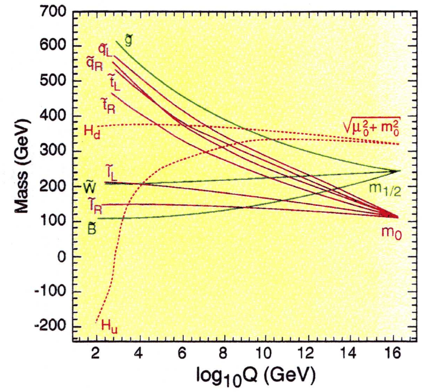

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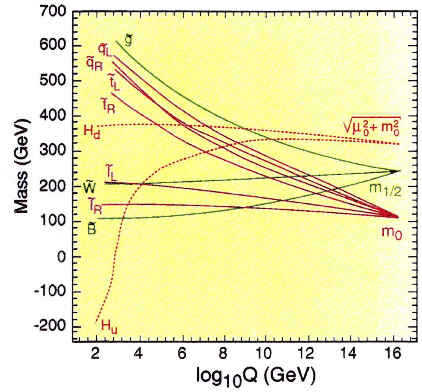

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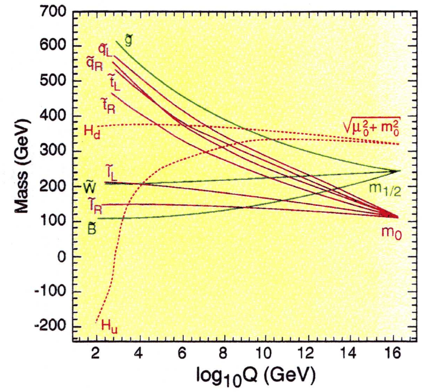

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- five independent parameters: $\tan\beta,\ m_{1/2},\ m_0,\ A_0,\ {\rm sgn}(\mu)$
- mass spectra at m_Z: run RGEs, 2–loop for g.c. and Y.c, 1-loop for masses
- some important quantities $(\mu, m_A, \ldots)$ very sensitive to procedure of computing EWSB & minimizing V_H

we use SoftSusy and FeynHiggs

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Roszkowski, Ruiz, Nihei ('02)

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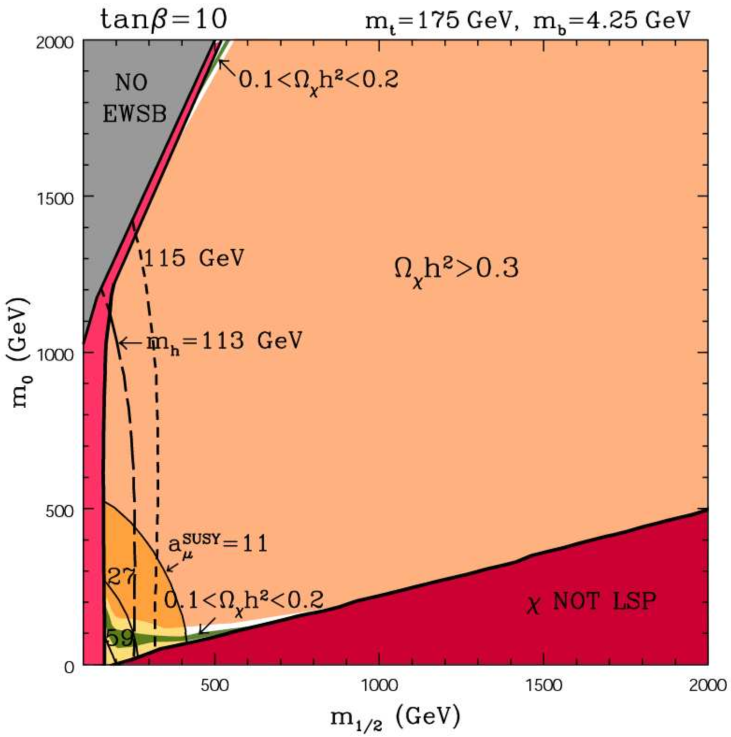

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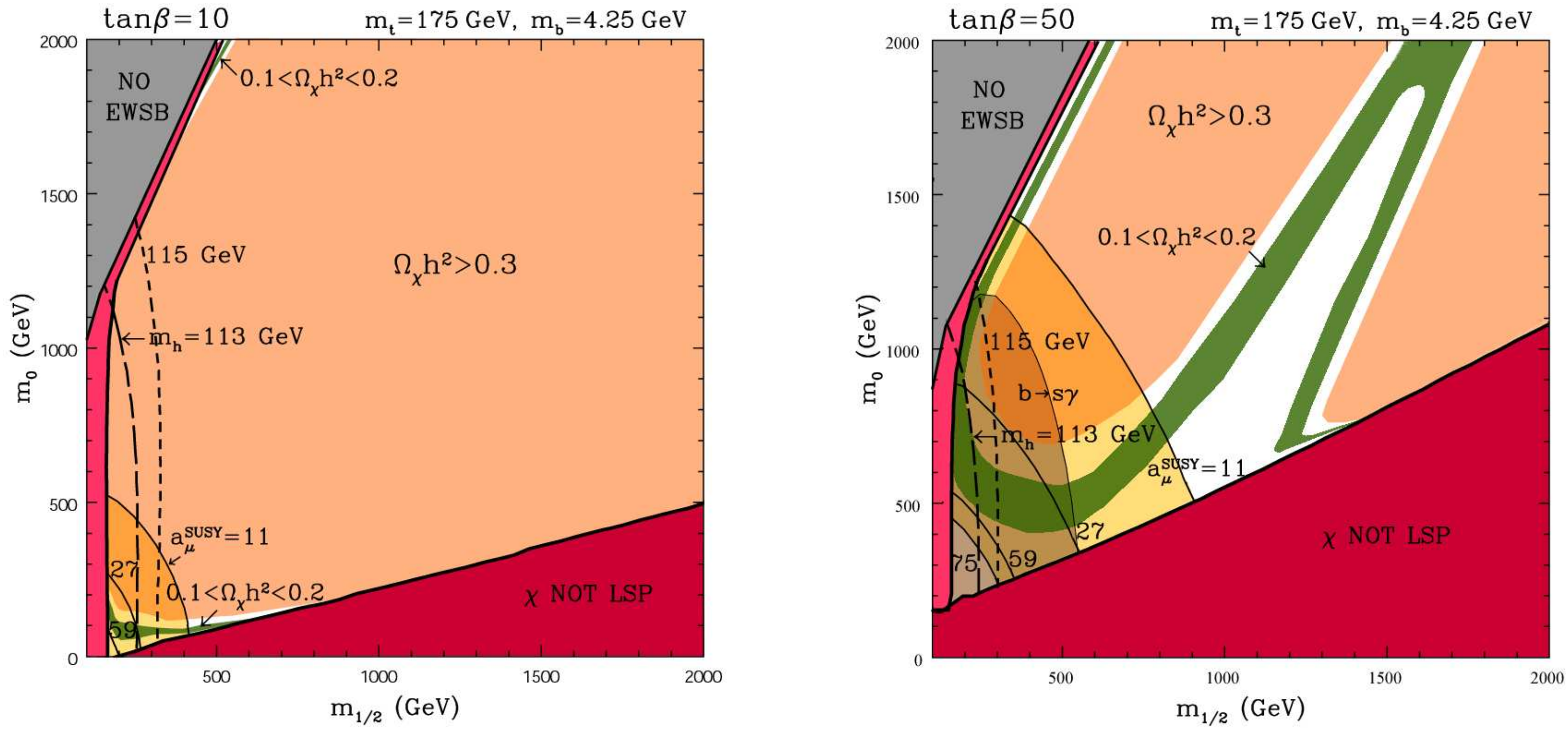

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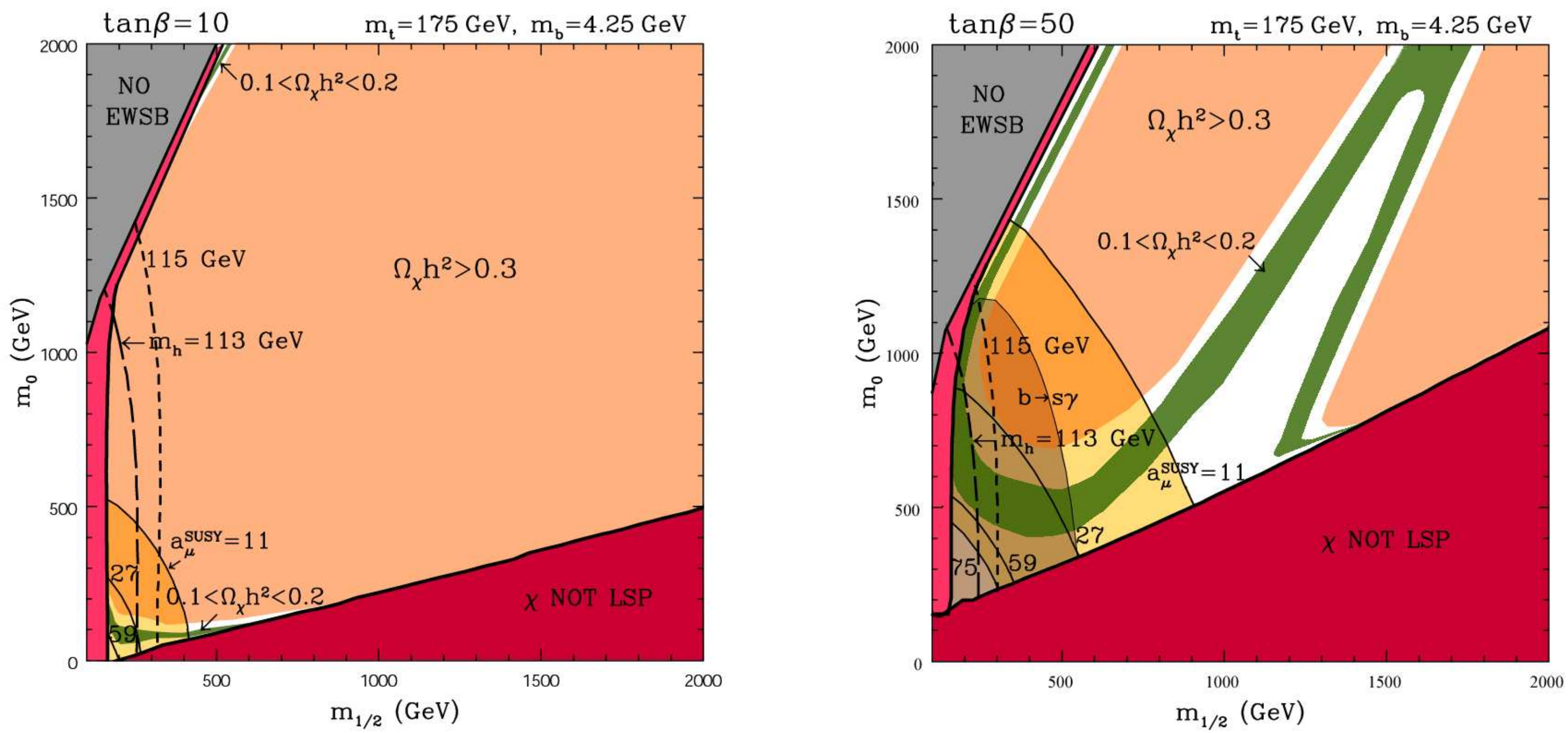

- fixed-grid scans, assuming rigid 1σ or 2σ exp'tal ranges
- green: consistent with conservative $\Omega_\chi h^2$
- most points excluded by LEP, $\mathrm{BR}(\bar{B} \to X_s \gamma)$, $\Omega_\chi h^2$, EWSB, charged LSP,...
- hard to compare relative impact of various constraints, include TH errors, etc.
- proper way: employ statistical analysis

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Powerful method of exploring multi–parameter models;

allows one to make global statements, expose correlations, etc.

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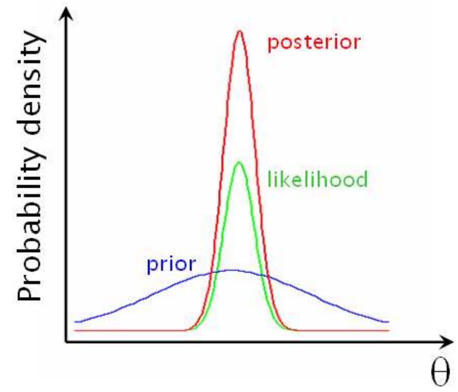

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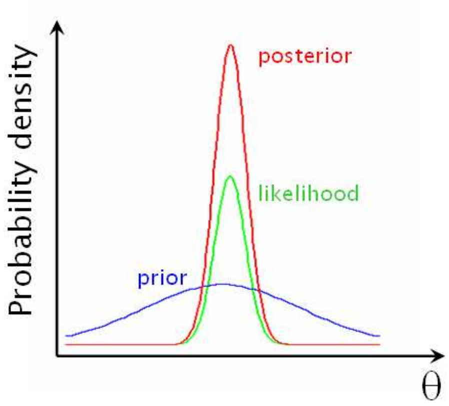

- Bayes' theorem: posterior pdf

$$p(\theta, \psi | d) = \frac{p(d|\xi)\pi(\theta,\psi)}{p(d)}$$

- $p(d|\xi)$: likelihood
- $\pi(\theta, \psi)$: prior pdf
- $p(d)$: evidence (normalization factor)

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalization factor}}$$

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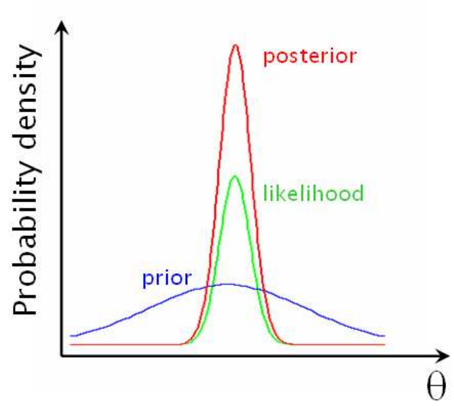

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- $p(d|\xi)$: likelihood
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- usually marginalize over SM (nuisance) parameters $\psi \;\Rightarrow\; p(\theta|d)$

Bayesian Analysis of the CMSSM

- $\theta = (m_0, m_{1/2}, A_0, \tan\beta)$: CMSSM parameters
- $\psi = (M_t, m_b(m_b)^{\overline{MS}}, \alpha_{em}(M_Z)^{\overline{MS}}, \alpha_s^{\overline{MS}})$: SM (nuisance) parameters
- priors – assume flat distributions and ranges as:

CMSSM parameters θ
$50\,\mathrm{GeV} < m_0 < 4\,\mathrm{TeV}$
$50\,\mathrm{GeV} < m_{1/2} < 4\,\mathrm{TeV}$
$\lvert A_0 \rvert < 7\,\mathrm{TeV}$
$2 < \tan\beta < 62$

flat priors: SM (nuisance) parameters ψ
$160\,\mathrm{GeV} < M_t < 190\,\mathrm{GeV}$
$4\,\mathrm{GeV} < m_b(m_b)^{\overline{MS}} < 5\,\mathrm{GeV}$
$0.10 < \alpha_s^{\overline{MS}} < 0.13$
$127.5 < 1/\alpha_{em}(M_Z)^{\overline{MS}} < 128.5$

- vary all 8 (CMSSM+SM) parameters simultaneously, apply MCMC
- include all relevant theoretical and experimental errors

Experimental Measurements

(assume Gaussian distributions)

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SM (nuisance) parameter	Mean μ	Error σ (expt)
M_t	171.4 GeV	2.1 GeV
$m_b(m_b)^{\overline{MS}}$	4.20 GeV	0.07 GeV
α_s	0.1176	0.002
$1/\alpha_{\rm em}(M_Z)$	127.918	0.018

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new $M_W = 80.413 \pm 0.048\,\mathrm{GeV}$ (Jan 07, not yet included)

new $M_t = 170.9 \pm 1.8\,\mathrm{GeV}$ (Mar 07, not yet included)

$\mathrm{BR}(\bar{B} \to X_s\gamma) \times 10^4$: new SM: 3.15 ± 0.23 (Misiak & Steinhauser, Sept 06) used here

Derived observable	Mean μ	Errors σ (expt)	τ (th)
M_W	$80.392\,\mathrm{GeV}$	$29\,\mathrm{MeV}$	$15\,\mathrm{MeV}$
$\sin^2\theta_{\mathrm{eff}}$	0.23153	16×10^{-5}	15×10^{-5}
$\delta a_\mu^{\mathrm{SUSY}} \times 10^{10}$	28	8.1	1
$\mathrm{BR}(\bar{B} \to X_s\gamma) \times 10^4$	3.55	0.26	0.21
ΔM_{B_s}	17.33	0.12	4.8
$\Omega_\chi h^2$	0.119	0.009	$0.1\,\Omega_\chi h^2$

take as precisely known: $M_Z = 91.1876(21)\,\mathrm{GeV}$, $G_F = 1.16637(1) \times 10^{-5}\,\mathrm{GeV}^{-2}$

Experimental Limits

Derived observable	upper/lower limit	Constraints $\xi_{\rm lim}$	τ (theor.)
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	UL	1.5×10^{-7}	14%
m_h	LL	$114.4\,\mathrm{GeV}$ ($91.0\,\mathrm{GeV}$)	$3\,\mathrm{GeV}$
$\zeta_h^2 \equiv g_{ZZh}^2/g_{ZZH_{\rm SM}}^2$	UL	$f(m_h)$	3%
m_χ	LL	$50\,\mathrm{GeV}$	5%
$m_{\chi_1^\pm}$	LL	$103.5\,\mathrm{GeV}$ ($92.4\,\mathrm{GeV}$)	5%
$m_{\tilde{e}_R}$	LL	$100\,\mathrm{GeV}$ ($73\,\mathrm{GeV}$)	5%
$m_{\tilde{\mu}_R}$	LL	$95\,\mathrm{GeV}$ ($73\,\mathrm{GeV}$)	5%
$m_{\tilde{\tau}_1}$	LL	$87\,\mathrm{GeV}$ ($73\,\mathrm{GeV}$)	5%
$m_{\tilde{\nu}}$	LL	$94\,\mathrm{GeV}$ ($43\,\mathrm{GeV}$)	5%
$m_{\tilde{t}_1}$	LL	$95\,\mathrm{GeV}$ ($65\,\mathrm{GeV}$)	5%
$m_{\tilde{b}_1}$	LL	$95\,\mathrm{GeV}$ ($59\,\mathrm{GeV}$)	5%
$m_{\tilde{q}}$	LL	$318\,\mathrm{GeV}$	5%
$m_{\tilde{g}}$	LL	$233\,\mathrm{GeV}$	5%
(σ_p^{SI}	UL	WIMP mass dependent	$\sim 100\%$)

Note: DM direct detection σ_p^{SI} not applied due to astroph'l uncertainties (eg, local DM density)

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- for several uncorrelated observables (assumed Gaussian):

$$\mathcal{L} = \exp\left[-\sum_i \frac{\chi_i^2}{2}\right]$$

Probability maps of the CMSSM

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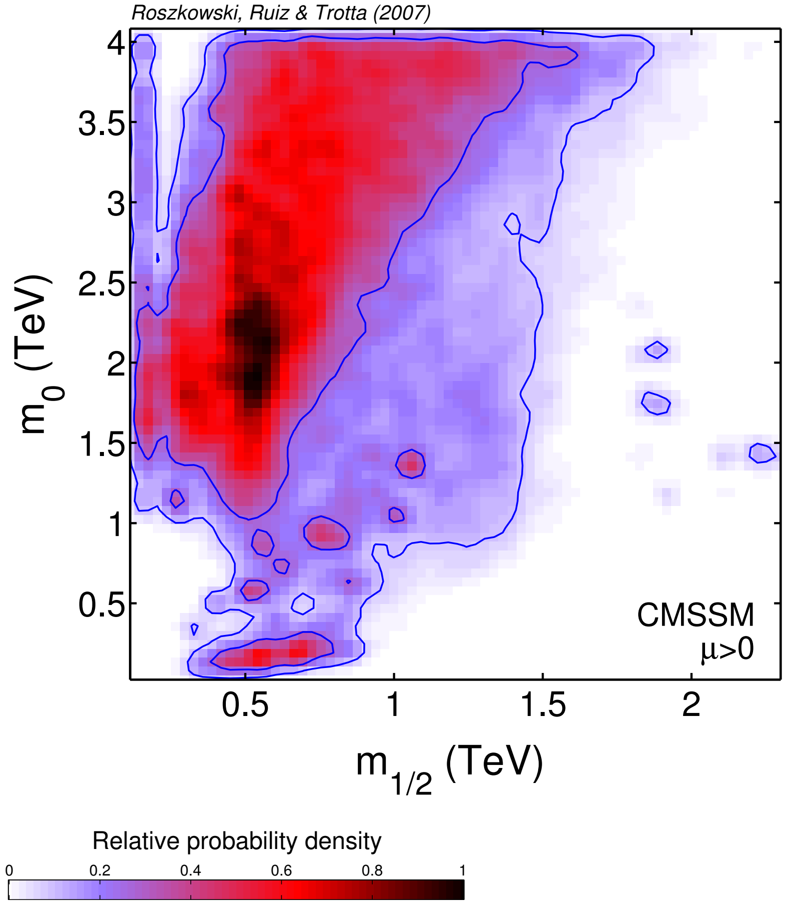
arXiv:0705.2012



- MCMC scan
- Bayesian analysis
- relative probability density fn
- flat priors
- 68% total prob. – inner contours
- 95% total prob. – outer contours
- 2-dim pdf $p(m_0, m_{1/2}|d)$
- favored: $m_0 \gg m_{1/2}$ (FP region)

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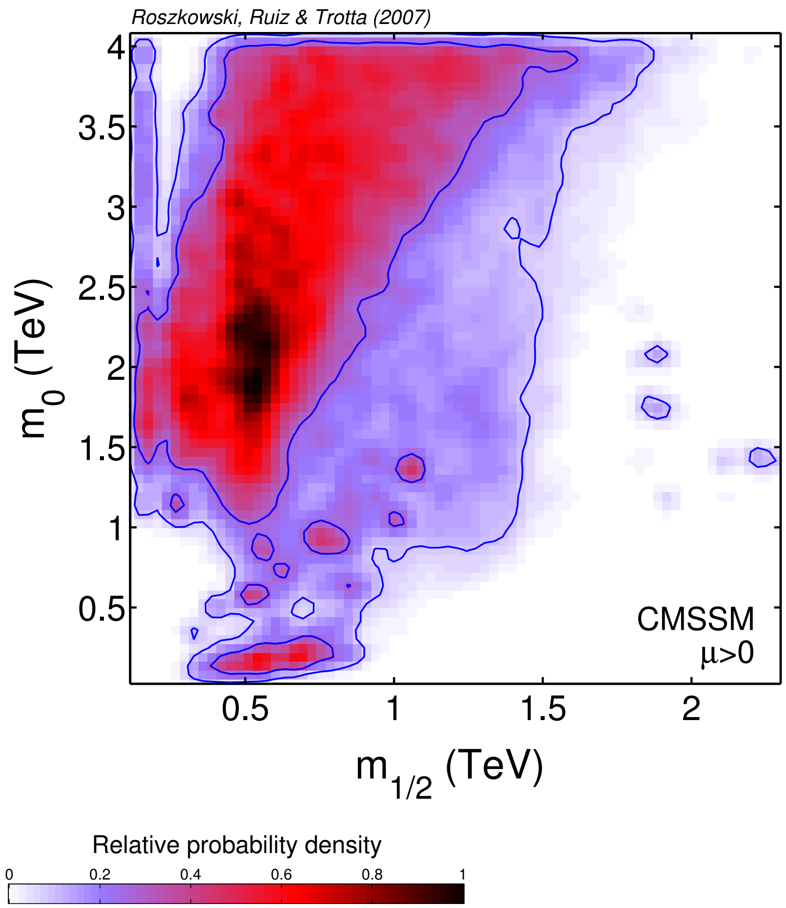

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similar study by Allanach+Lester(+Weber) (but no mean qof),
see also, Ellis et al (EHOW, χ^2 approach, no MCMC, fixed SM parameters)

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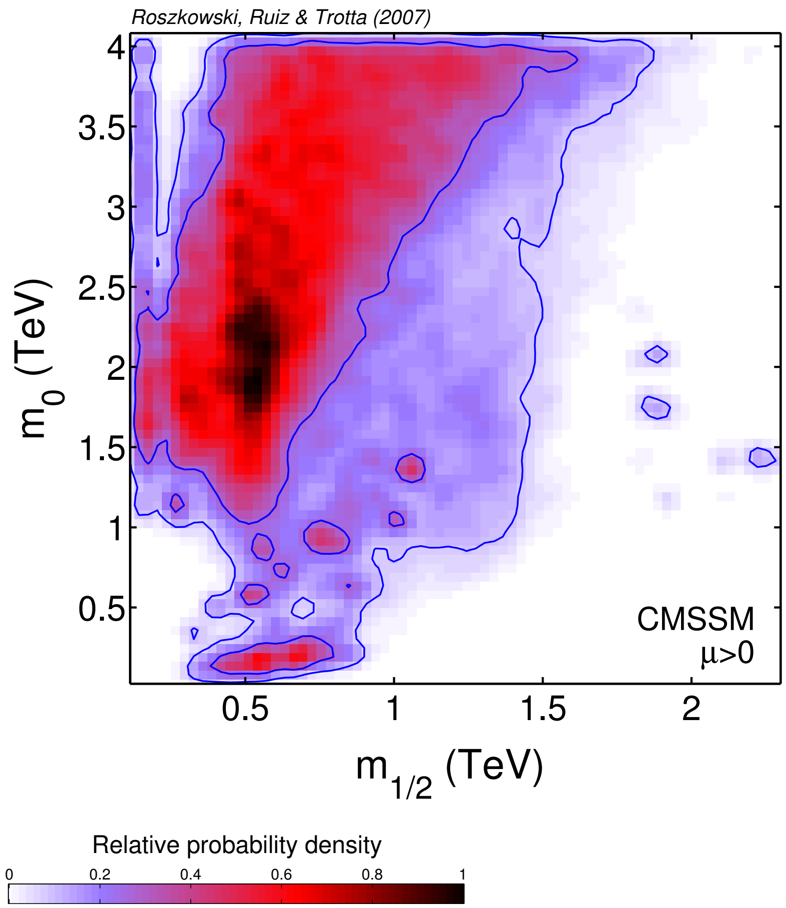

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unlike others (except for A+L), we vary also SM parameters

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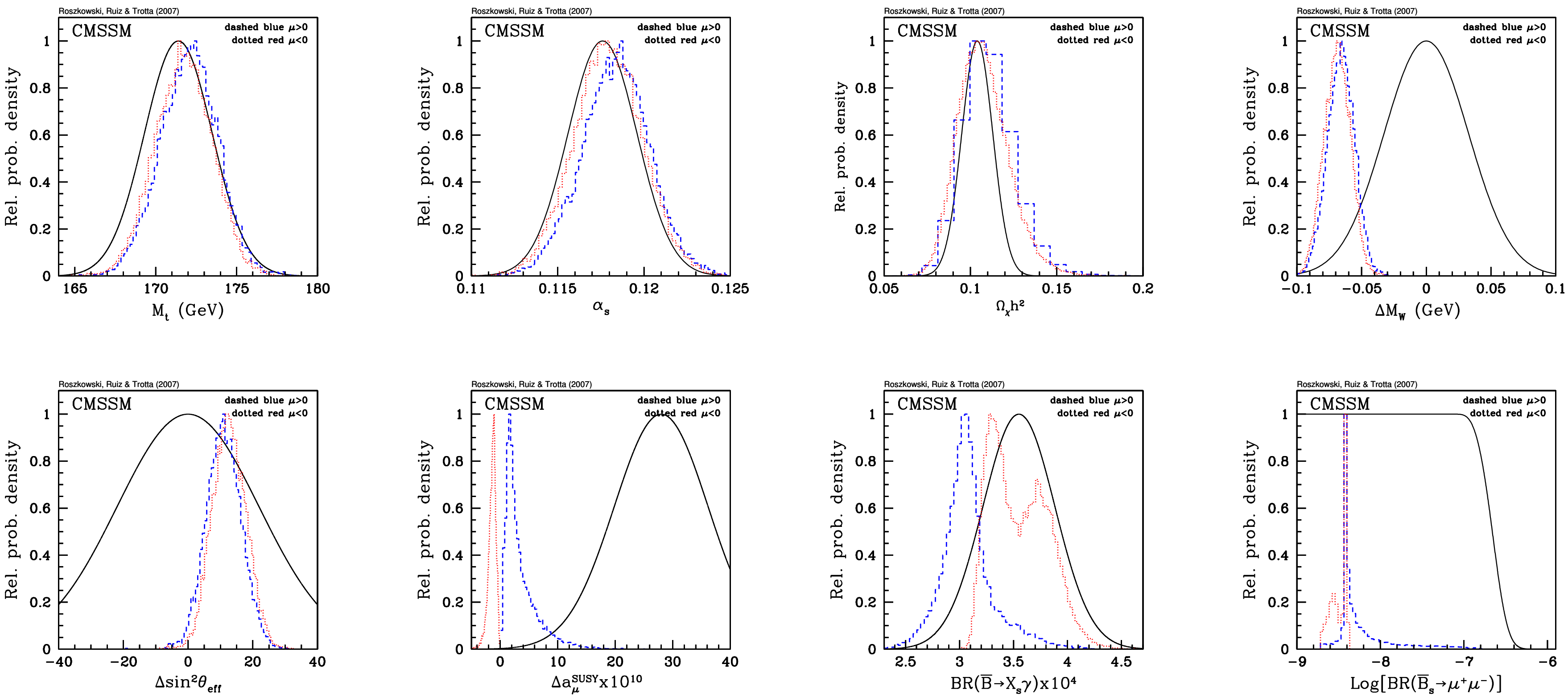

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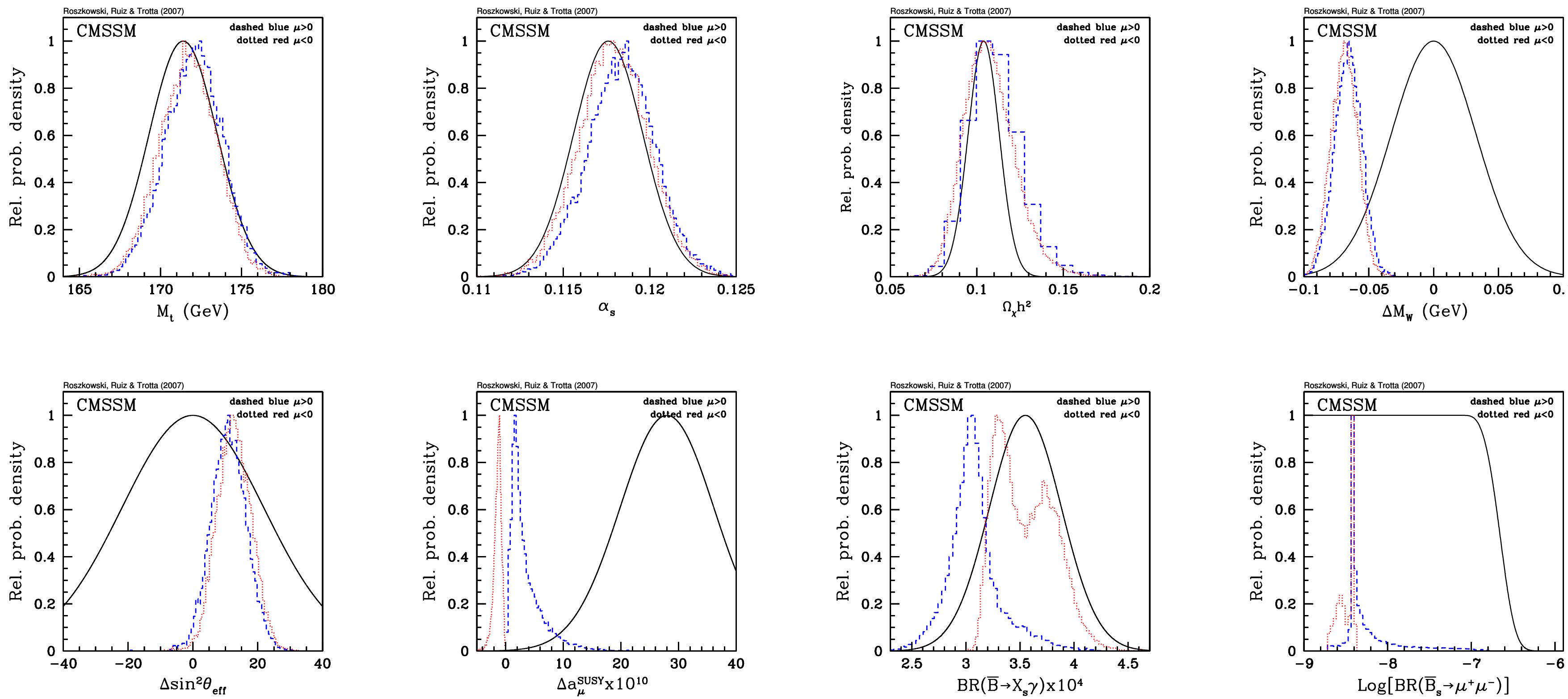

- good fits: M_t, α_s, $\Omega_\chi h^2$, $\mathrm{BR}(\bar{B} \to X_s\gamma)$ (for $\mu < 0$!)
- not so good: M_W, $\sin^2\theta_{\mathrm{eff}}$, $\mathrm{BR}(\bar{B} \to X_s\gamma)$ (for $\mu > 0$!)
- bad: $\delta a_\mu^{\mathrm{SUSY}}$ (for both signs of μ!)

Impact of new SM $b \to s\gamma$

recall $$BR(B \to X_s\gamma) = B(W^-/t) + B(H^-/t) - \mathrm{sgn}(\mu)\, B(\chi^-/\widetilde{t})$$

SM: full NLO + NNLO of m_c (from M. Misiak);

SUSY: dominant NLO terms $\propto \tan\beta, \log(M_S/m_W)$

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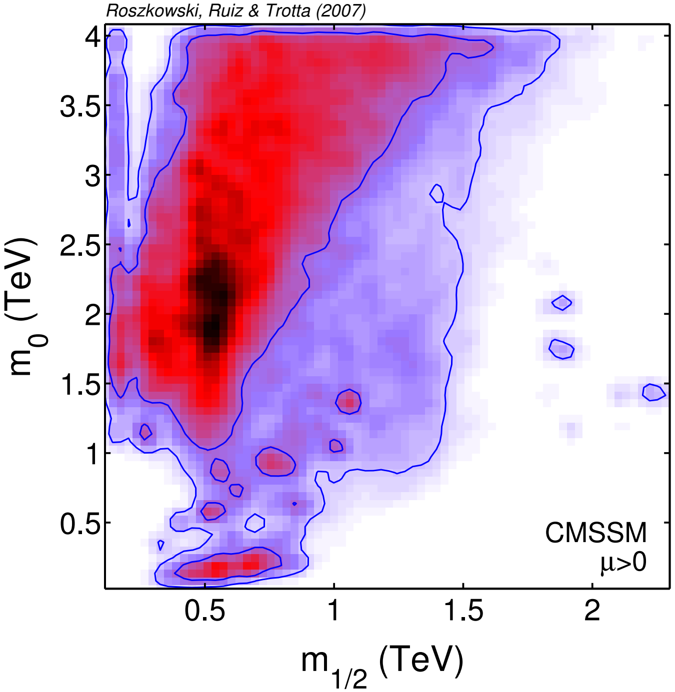
NEW: $BR(B \to X_s\gamma) \times 10^4$

EXPT: 3.55 ± 0.26, SM: 3.11 ± 0.21

(with our inputs), (May 07)



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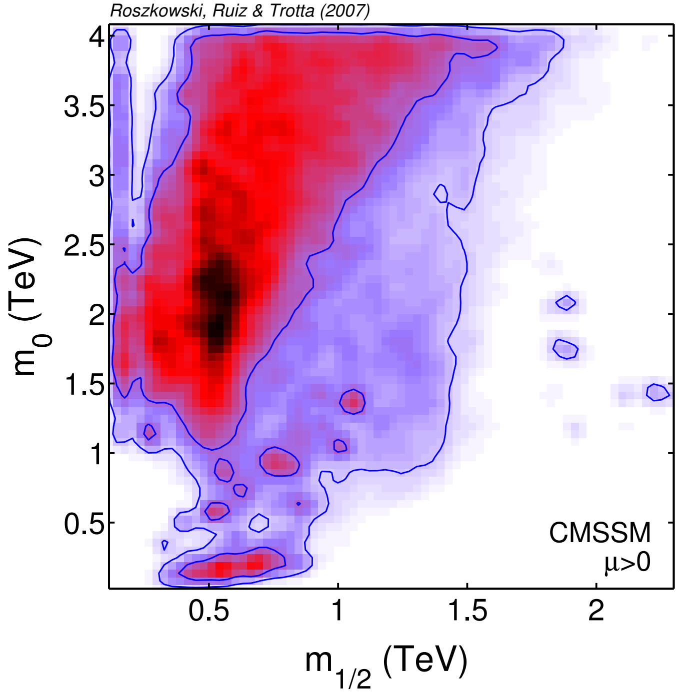
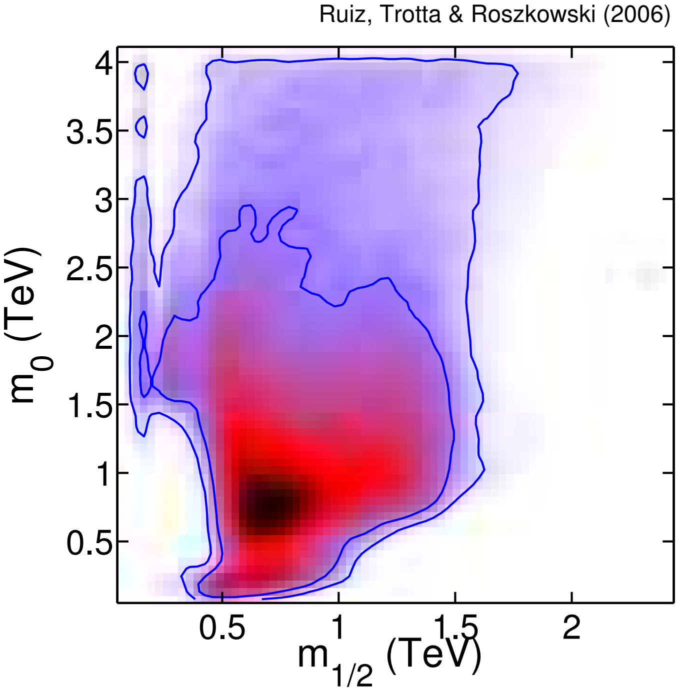
SUSY: dominant NLO terms $\propto \tan\beta, \log(M_S/m_W)$

NEW: $BR(B \to X_s\gamma) \times 10^4$
EXPT: 3.55 ± 0.26, SM: 3.11 ± 0.21
(with our inputs), (May 07)

OLD: $BR(B \to X_s\gamma) \times 10^4$
EXPT: 3.39 ± 0.68, SM: 3.70 ± 0.30
(Feb 2006)





$\Rightarrow$ big shift towards large m_0 (focus point region!)

Tension between $\delta a_\mu^{\rm SUSY}$ and $b \to s\gamma$?

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$\delta a_\mu^{\rm SUSY}$:

D. Stockinger ('07)

$$\delta a_\mu^{\rm SUSY} \simeq 13 \times 10^{-10} \left(\frac{100\,{\rm GeV}}{\widetilde{m}_{\rm EW}}\right)^2 \tan\beta \,{\rm sgn}(\mu)$$

$\widetilde{m}_{\rm EW}$ - average EW spartner mass, LO approx'n

$$\delta a_\mu^{\rm SUSY} = (g-2)_\mu^{\rm expt} - (g-2)_\mu^{\rm SM} = (28 \pm 8.1 \pm 1) \times 10^{-10}$$

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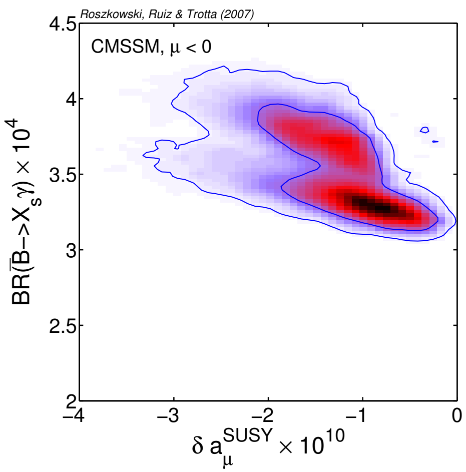

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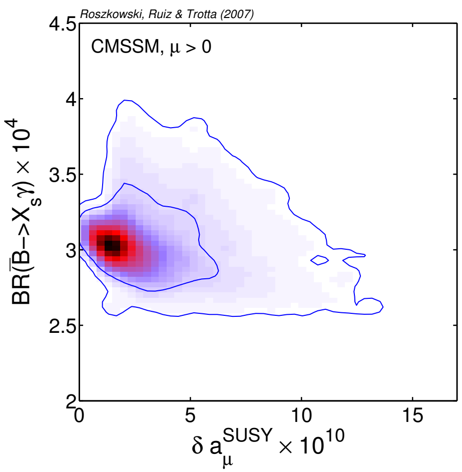

- flat priors
- 68% total prob. – inner contours
- 95% total prob. – outer contours

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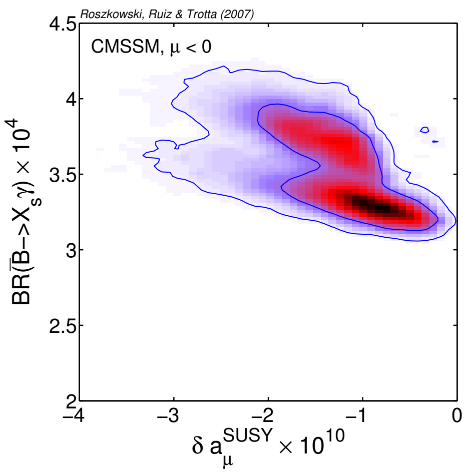

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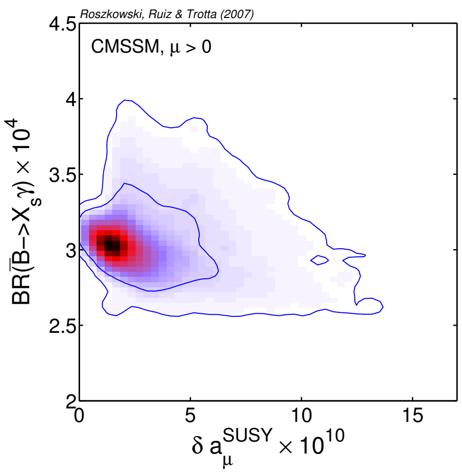

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$\Rightarrow$ in CMSSM: strong tension between $(g-2)_\mu$ and $b \to s\gamma$

Tension between $\delta a_{\mu}^{\rm SUSY}$ and $b \to s\gamma$?

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$\widetilde{m}_{\mathrm{EW}}$ - average EW spartner mass, LO approx'n

$\delta a_\mu^{\mathrm{SUSY}} \Rightarrow$ need fairly light $\tilde{\nu}_\mu$ and $\chi^\pm$, and/or $\tilde{\mu}$ and χ^0 (and $\mu > 0$)

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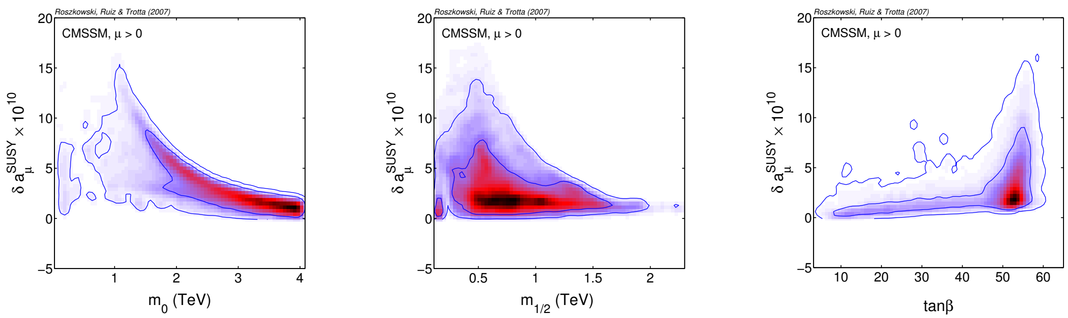

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- and large $\tan\beta$

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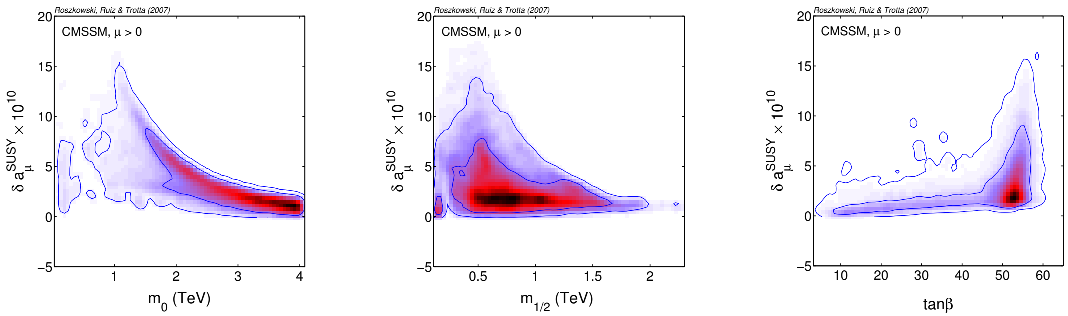

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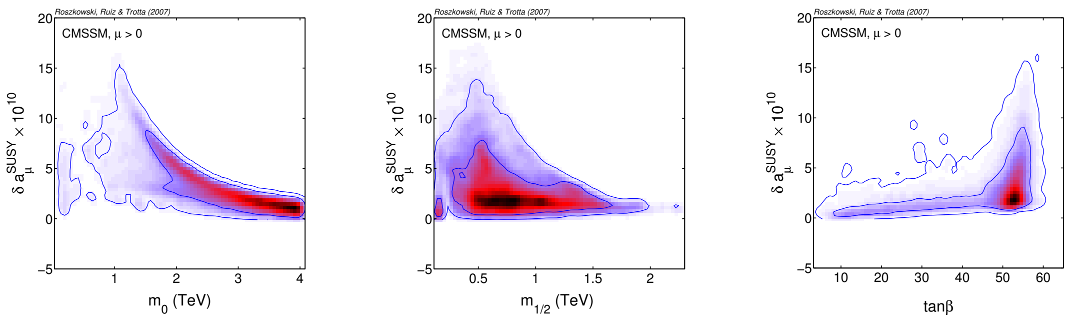

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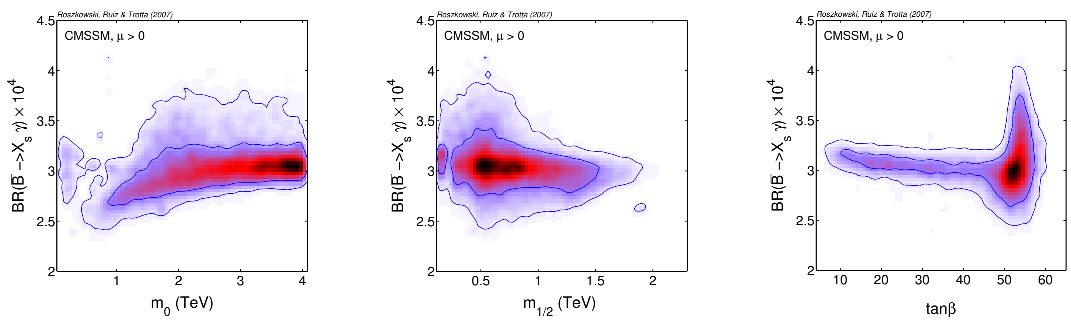

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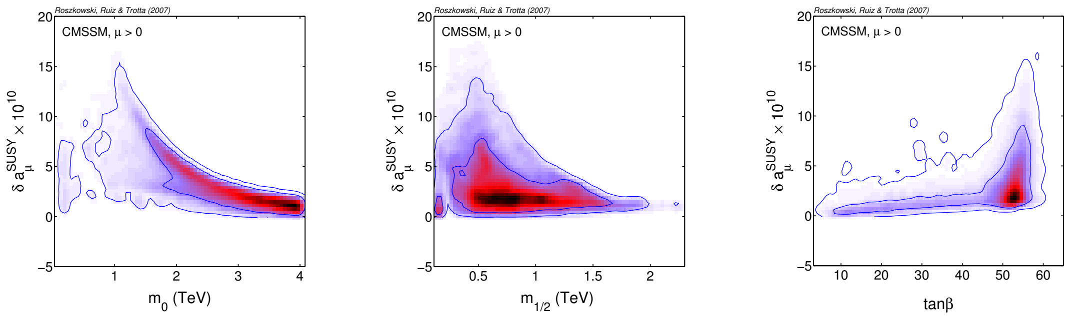

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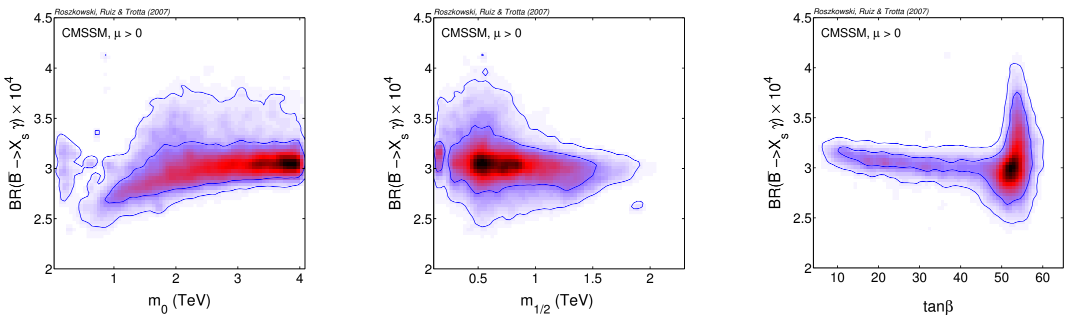

- new SM $b \to s\gamma$ favors large m_0
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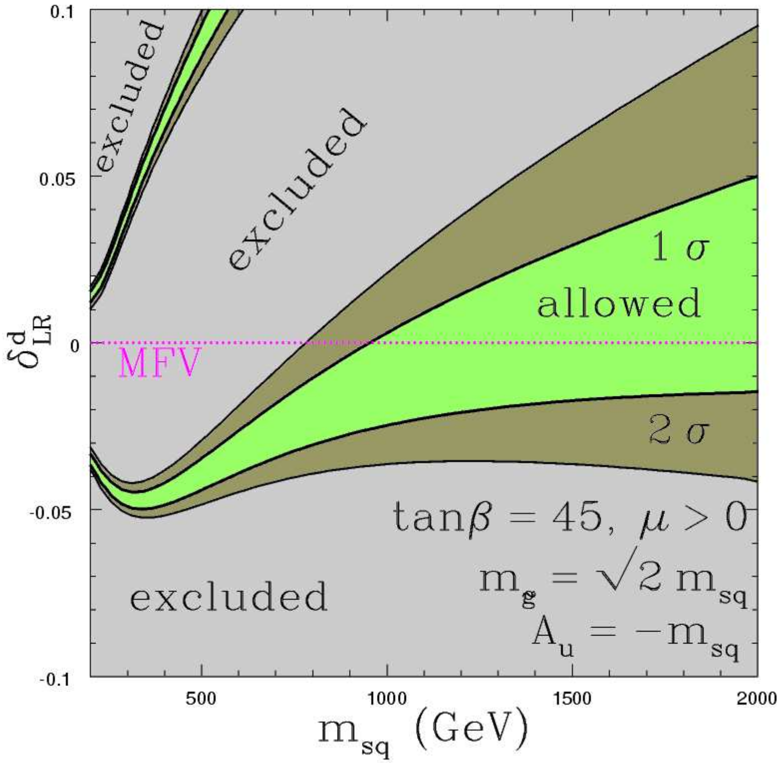
- $\Rightarrow$ split slepton and squark soft masses, and/or
- $\Rightarrow$ invoke non-minimal flavor violation (at least in the squark sector): $b \to s\gamma$ can be very sensitive to it

$b \longrightarrow s\gamma$ and GFM

GFM: general flavor mixing

MFV: minimal flavor violation

Okumura+Roszkowski, PRL'04



include dominant NLO–level contributions

enhanced at large $\tan\beta$

$$(\delta^d_{LL}) = \left(m^2_{d,LL}\right)_{23} / \sqrt{\left(m^2_{d,LL}\right)_{22}\left(m^2_{d,LL}\right)_{33}}$$

MFV: $\delta^d_{\cdot\cdot} = 0$

bounds highly unstable against small perturbations of MFV

Dark matter detection: σ_p^{SI}

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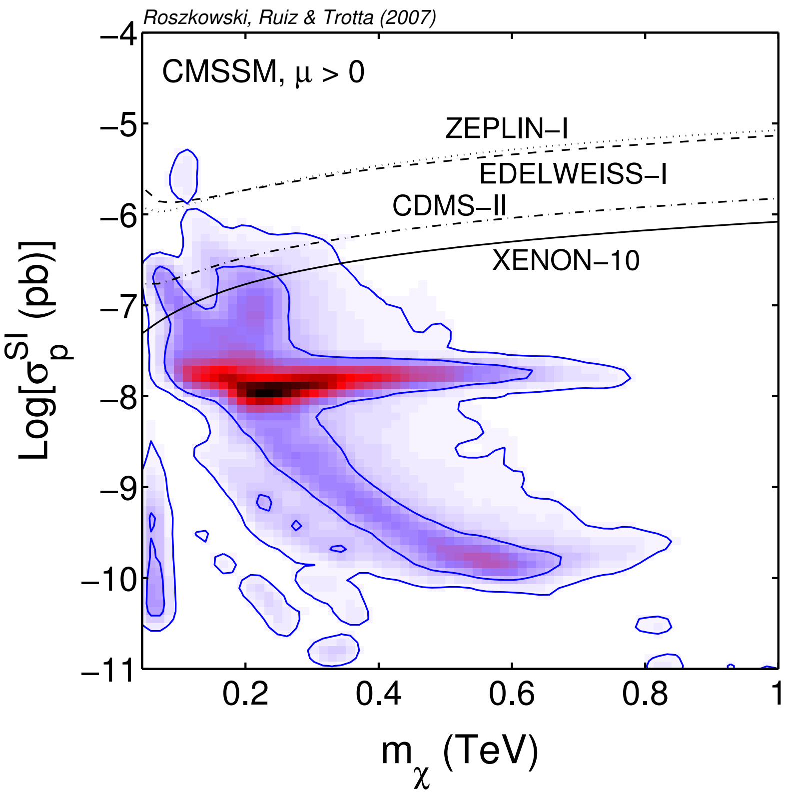
MCMC+Bayesian analysis



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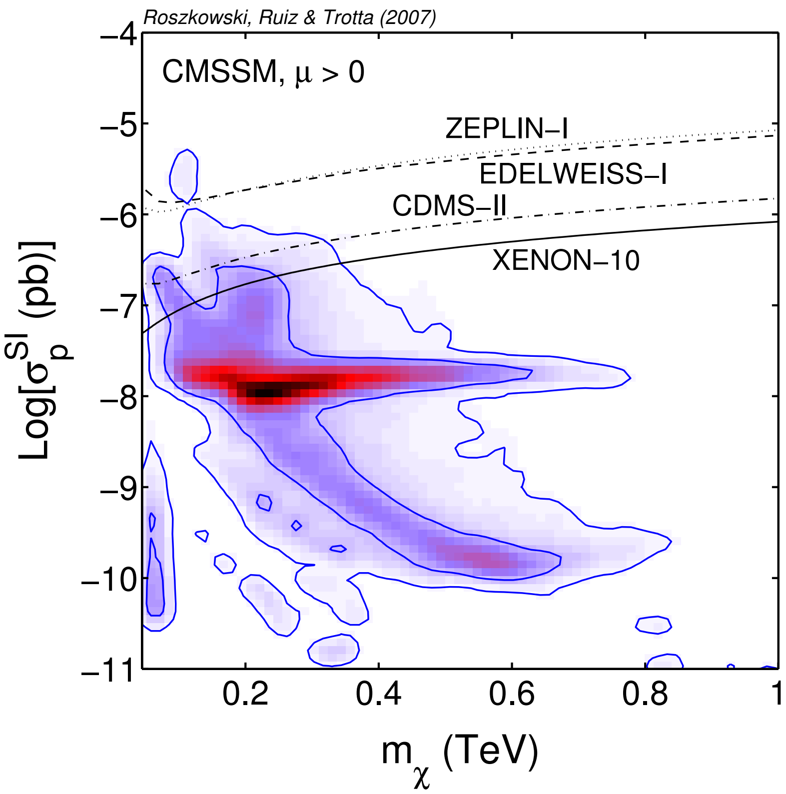
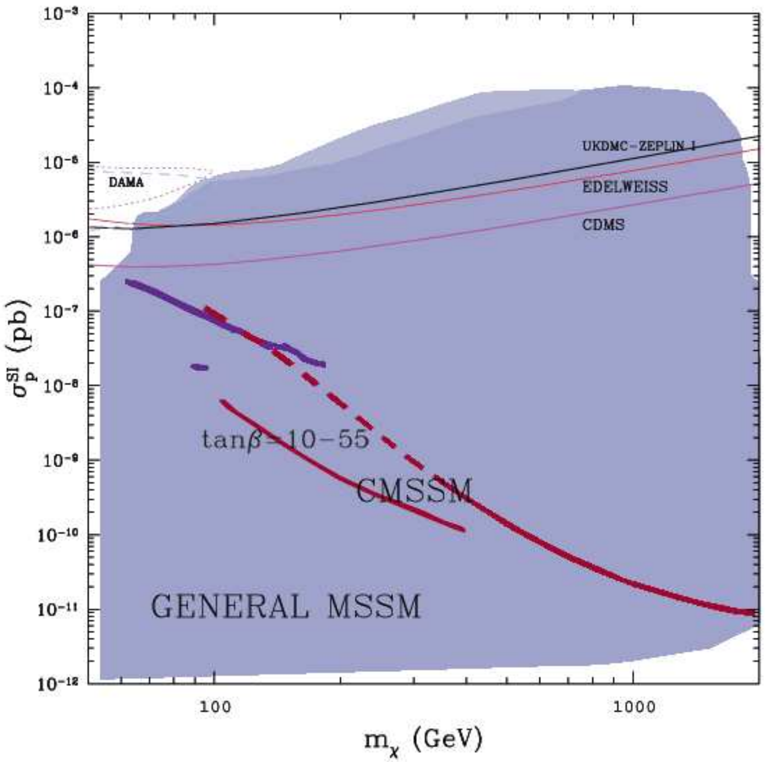


compare: fixed grid scan



Dark matter vs. $\delta a_\mu^{\rm SUSY}$

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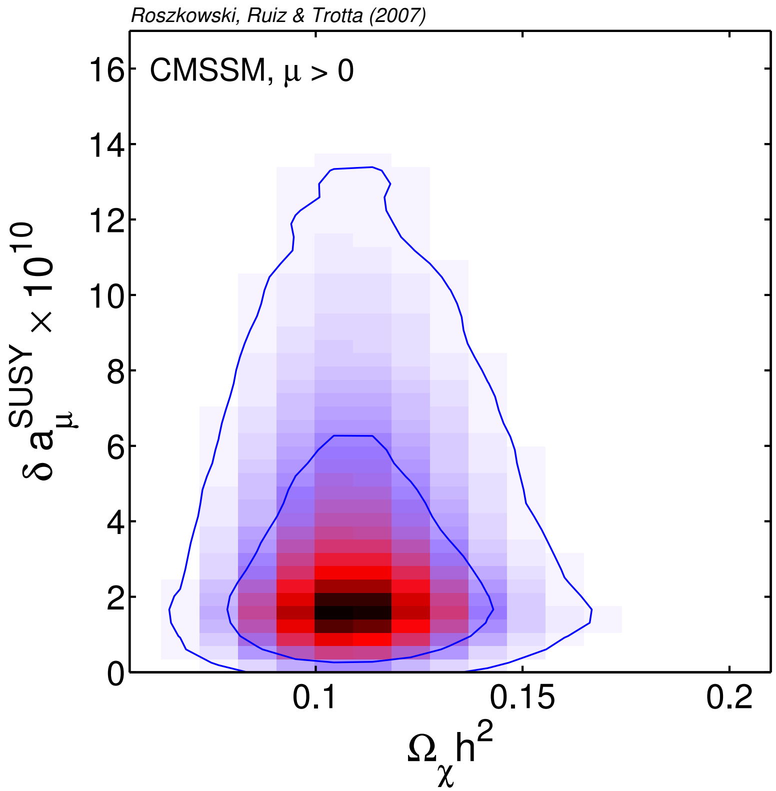

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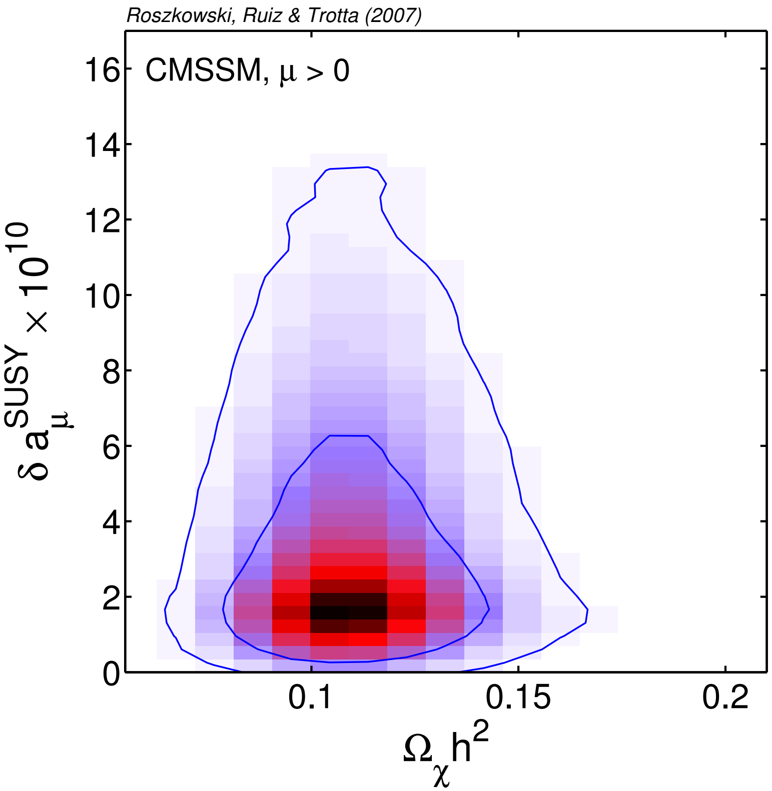

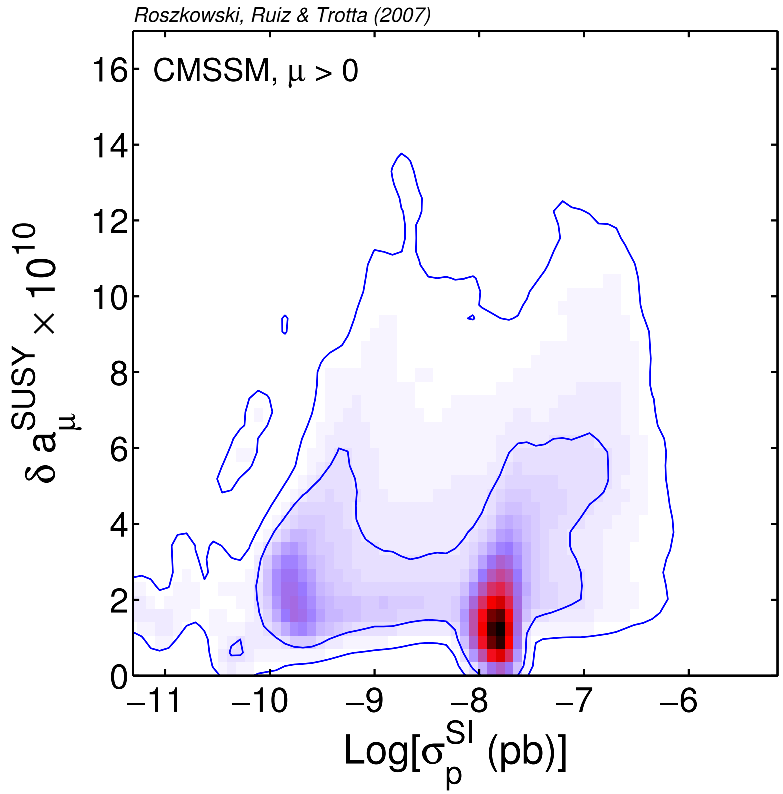

- $\Rightarrow$ not much correlation

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- improved error on $(g-2)_\mu^{\rm expt} - (g-2)_\mu^{\rm SM}$ will be most helpful in guiding model building

Backup...

$b \to s\gamma$ vs. $\delta a_\mu^{\rm SUSY}$

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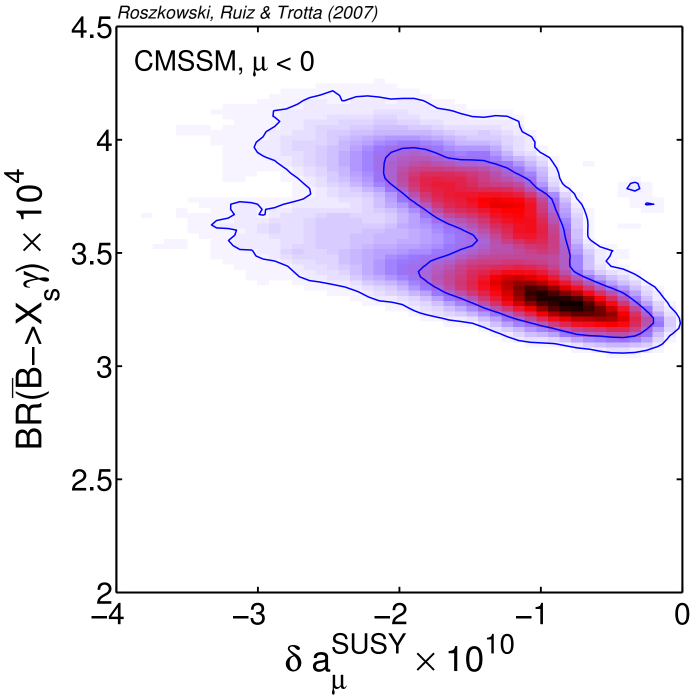

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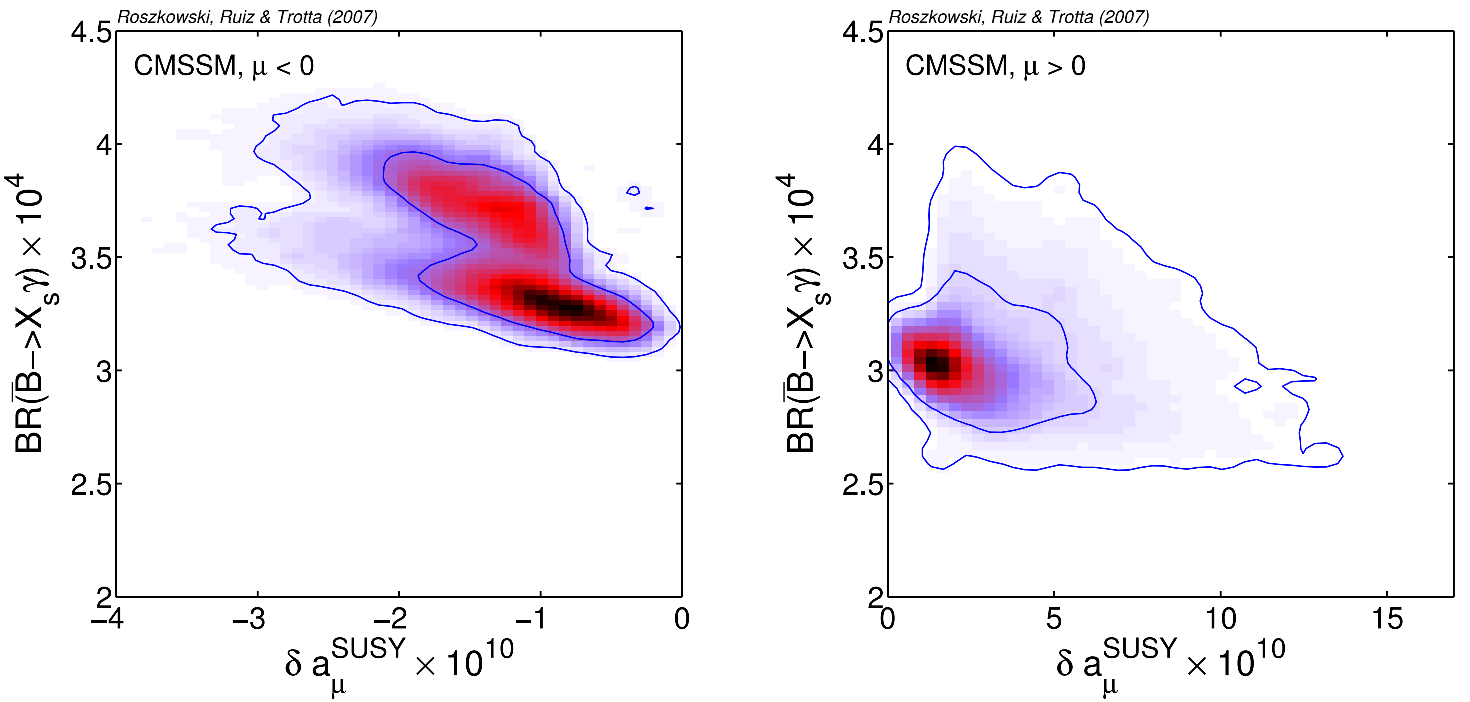

- $\Rightarrow$ not much correlation
- $\mu > 0$: $BR(B \rightarrow X_s\gamma) \simeq$ SM-value
- $\mu < 0$: $BR(B \rightarrow X_s\gamma) \gtrsim$ SM-value