Theory Review of $B_{s,d} \to \mu^+\mu^-$ Decays

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Fermilab

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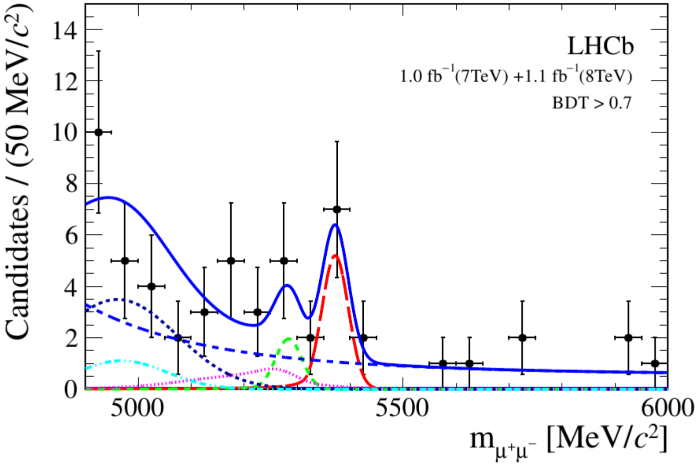
First Evidence for $B_s \to \mu^+\mu^-$

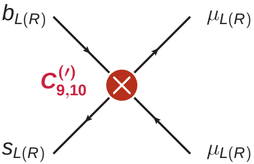


Observables and Standard Model Predictions

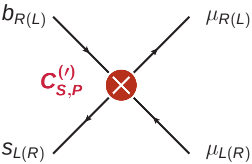
Effective Hamiltonian for $B_{s,d} \to \mu^+\mu^-$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

semileptonic operators



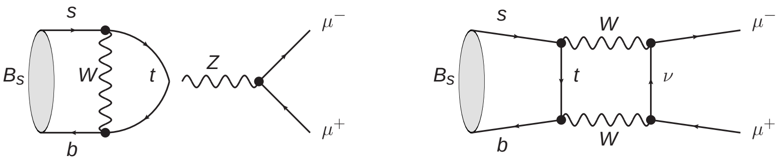
scalar operators



$$BR(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| (C_{10}^{\text{SM}} + C_{10}^{\text{NP}} - C_{10}') + \frac{m_{B_s}}{2m_\mu}(C_P - C_P') \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_S - C_S') \right|^2 \right)$$

1 Loop Contributions in the SM

- only relevant Wilson Coefficient in the SM: C_{10}
- induced by Boxes and Z penguins



$$C_{10} = \frac{1}{s_W^2} Y(x_t) = \frac{1}{s_W^2} \left(Y_0(x_t) + \frac{\alpha_s}{4\pi} Y_1(x_t) + \ldots \right)$$

- NLO QCD corrections are tiny $O(1\%)$ (Misiak, Urban '99; Buchalla, Buras '99)
- NLO electroweak corrections known in the large m_t limit (Buchalla, Buras '97)
- leftover electro-weak renormalization scheme dependence is $\sim 2\% - 3\%$

SM Predictions for the Branching Ratios

- main uncertainty in the SM prediction used to come from the *B* meson decay constants f_{B_s} and f_{B_d}
- remarkable progress on the lattice

$$f_{B_s} = (225 \pm 3)\text{MeV}$$ (HPQCD collaboration '13)

$$f_{B_d} = (186 \pm 4)\text{MeV}$$ (HPQCD collaboration '13)

- uncertainties at the % level!
  (looking forward to an independent confirmation)
- allows predictions for the branching ratios with very high precision

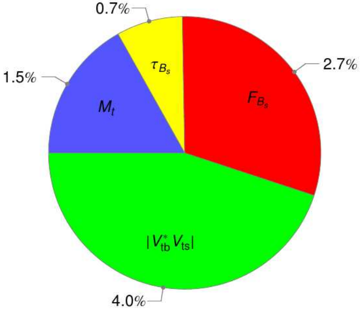
$$BR(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.25 \pm 0.17) \times 10^{-9}$$

$$BR(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.03 \pm 0.07) \times 10^{-10}$$

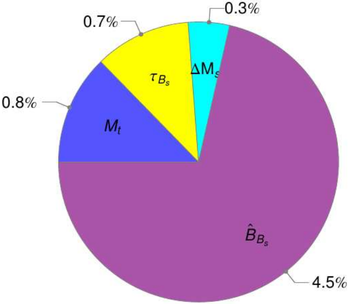
Buras, Fleischer, Girrbach, Knegjens '13 Buras, Girrbach, Guadagnoli, Isidori '12

Error Budgets for $B_s \to \mu^+\mu^-$

Buras, Fleischer, Girrbach, Knegjens '13



direct prediction



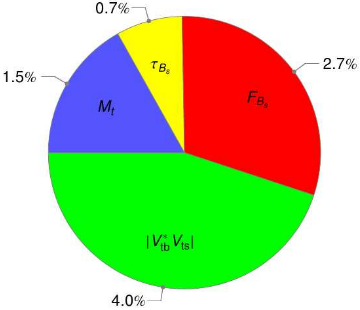
normalizing to ΔM_s

$BR(B_s \to \mu^+\mu^-)_{SM} = (3.25 \pm 0.17) \times 10^{-9}$, $BR(B_s \to \mu^+\mu^-)_{SM} = (3.38 \pm 0.17) \times 10^{-9}$

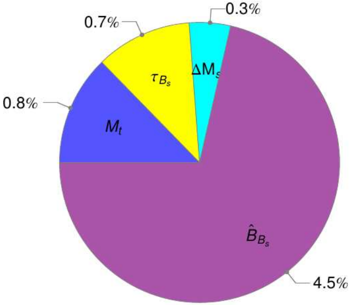
in addition: $\pm$ 5% electro-weak corrections

Error Budgets for $B_s \to \mu^+\mu^-$

Buras, Fleischer, Girrbach, Knegjens '13



direct prediction



normalizing to ΔM_s

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in addition: $\pm$ 5% electro-weak corrections

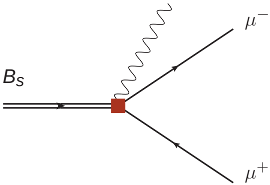
compare to experimental sensitivities: $\sim \pm 50\%$ now (with $(1 + 1.1)\text{fb}^{-1}$)
$\sim \pm 15\%$ expected (with $(1 + 1.5 + 4)\text{fb}^{-1}$)

Photon Radiation

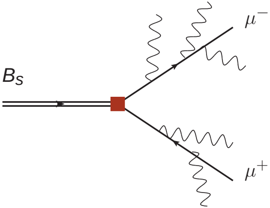
define "infrared-safe" observable

$$\text{BR}(B_s \to \mu^+\mu^- \quad + n\,\gamma)_{\sum E_\gamma < E_{\text{max}}} = \omega(E_{\text{max}}) \times \text{BR}(B_s \to \mu^+\mu^-)$$

direct emission



Bremsstrahlung



- for experimental cut $E_{\text{max}} = 60\text{MeV}$:
  direct emission contributions are well below 1%
  bremsstrahlung corrections lead to $\omega(60\text{MeV}) \simeq 0.89$

- $\text{BR}(B_s \to \mu^+\mu^-)$ corresponds to the branching ratio
  fully inclusive of bremsstrahlungs corrections

Isidori '07; Buras, Girrbach, Guadagnoli, Isidori '12; Aditya, Healey, Petrov '12

Effects of the Width Difference in the B_s System

- in the theory prediction, B_s mixing effects are "switched off"

$$BR(B_s \to \mu^+\mu^-)_{\text{theo}} = \frac{\tau_{B_s}}{2} \langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle_{t=0}$$

Effects of the Width Difference in the B_s System

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$$BR(B_s \to \mu^+\mu^-)_{\text{theo}} = \frac{\tau_{B_s}}{2} \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle_{t=0}$$

- sizable width difference in the B_s system has impact on the BR measurement

$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} = (8.8 \pm 1.4)\% \qquad \text{(LHCb-CONF-2012-002)}$$

- time dependent untagged rate is sum of two exponentials

$$\langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \propto e^{-\Gamma_s t} \times \left[\cosh(\Gamma_s y_s t) + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} \sinh(\Gamma_s y_s t)\right]$$

$$BR(B_s \to \mu^+\mu^-)_{\text{exp}} = \frac{1}{2}\int_0^\infty dt \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle$$

$$= \left(\frac{1 + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} y_s}{1 - y_s^2}\right) \times BR(B_s \to \mu^+\mu^-)_{\text{theo}}$$

- $-1 < \mathcal{A}^{\mu\mu}_{\Delta\Gamma} < +1$ is sensitive to NP and a function of the Wilson Coefficients

  in the SM, $\mathcal{A}^{\mu\mu}_{\Delta\Gamma} = +1$

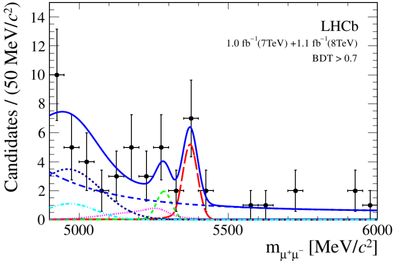
De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Tuning '12
De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Pellegrino, Tuning '12

Comparison with Experiment (I)

take into account the corrections from the large width difference in the B_s system

$\rightarrow$ in the SM enhancement by

$$\frac{1}{1-y_s} \simeq 110\%$$



$\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.56 \pm 0.18) \times 10^{-9}$

Buras, Fleischer, Girrbach, Knegjens ’13

$\text{BR}(B_s \to \mu^+\mu^-)_{\text{exp}} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

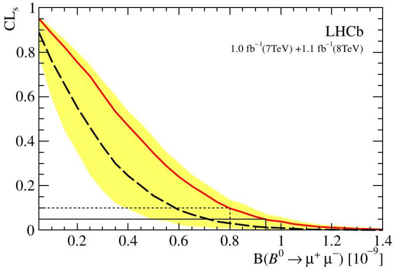
LHCb Collaboration, PRL 110 (2013) 021801

spot on! (unfortunately...)

Comparison with Experiment (II)

width difference in the B_d system is small

$\rightarrow$ negligible effect on the branching ratio extraction



$\text{BR}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.03 \pm 0.07) \times 10^{-10}$

Buras, Girrbach, Guadagnoli, Isidori ’12 (my update)

$\text{BR}(B_d \to \mu^+\mu^-)_{\text{exp}} < 9.4 \times 10^{-10}$ @ 95% C.L.

LHCb Collaboration, PRL 110 (2013) 021801

still factor $\sim$ 9 above the SM prediction

More Observables

- full time-dependent flavor tagged decay rate

$$\Gamma(B_s(t) \to \mu^+\mu^-) \propto e^{-\Gamma_s t} \times \Big(\pm S_{\mu\mu} \sin(\Delta M_s t) + \cosh(\Gamma_s y_s t) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \sinh(\Gamma_s y_s t) \Big)$$

- time-dependent tagged rate asymmetry

$$\frac{\Gamma(B_s(t) \to \mu^+\mu^-) - \Gamma(\bar{B}_s(t) \to \mu^+\mu^-)}{\Gamma(B_s(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s(t) \to \mu^+\mu^-)} = \frac{S_{\mu\mu} \sin(\Delta M_s t)}{\cosh(\Gamma_s y_s t) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \sinh(\Gamma_s y_s t)}$$

- $S_{\mu\mu}$ is sensitive to CP violation in B_s mixing and in the $B_s \to \mu^+\mu^-$ amplitude
- time dependent flavor tagged rates require reasonable statistics...

- effective lifetime measurement does not need tagging information

$$\tau_{\mu\mu} = \frac{\int_0^\infty dt\ t\ \langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle}{\int_0^\infty dt\ \langle \Gamma(B_s(t) \to \mu^+\mu^-) \rangle} = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2\mathcal{A}_{\Delta\Gamma}^{\mu\mu} y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} y_s} \right)$$

- can access $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$

De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Tuning ’12; De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Pellegrino, Tuning ’12; Buras, Fleischer, Girrbach, Knegjens, ’13

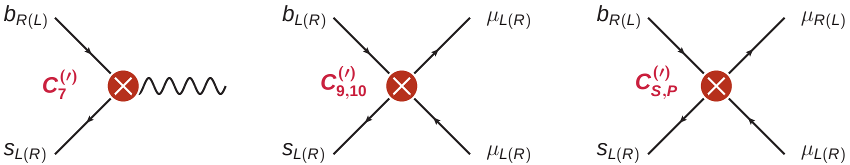
Implications for New Physics

Beaujean, Bobeth, van Dyk, Wacker '12; WA, Carena, Shah, Yu '12;
Arbey, Battaglia, Mahmoudi, Martinez Santos '12; Li, Lu, Gao '13; Buras, Girrbach, Ziegler '13;
Guadagnoli, Isidori '13; Straub '13; Kowalska, Roszkowski, Sessolo '13;
Buras, DeFazio, Girrbach, Knegjens, Nagai '13; Buras, Fleischer, Girrbach, Knegjens '13;
Lee '13; Crivellin, Kokulu, Greub '13; ...

Effective Hamiltonian for Rare B Decays

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators | semileptonic operators | scalar operators

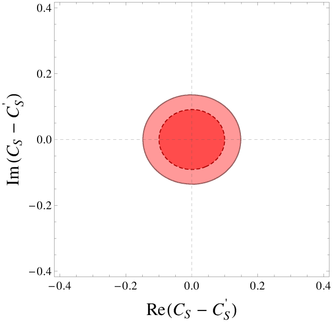


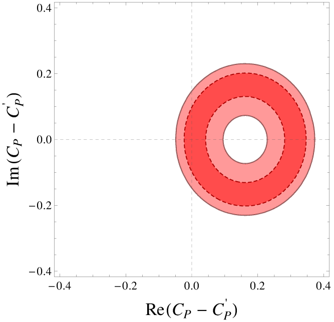
	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'	C_S, C_S', C_P, C_P'
$B \to (X_s, K^*)\,\gamma$	★			
$B \to (X_s, K, K^*)\,\ell^+\ell^-$	★	★	★	(★)
$B_s \to \mu^+\mu^-$			★	★

neglecting tensor operators

Model-Independent Constraints (I)

update from WA, Straub '12



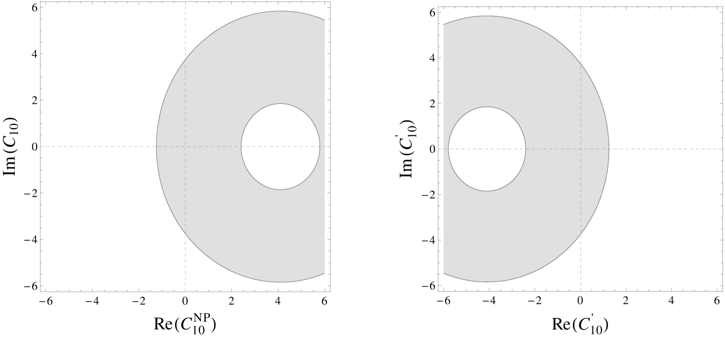


$$BR(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| (C_{10}^{SM} + C_{10}^{NP} - C'_{10}) + \frac{m_{B_s}}{2m_\mu}(C_P - C'_P) \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_S - C'_S) \right|^2 \right)$$

- $B_s \to \mu^+\mu^-$ only constrains the combinations $C_S - C'_S$ and $C_P - C'_P$
- complementary info on $C_S + C'_S$ and $C_P + C'_P$ can be obtained from $B \to K\mu^+\mu^-$ (Becirevic, Kosnik, Mescia, Schneider '12)

Model-Independent Constraints (II)

update from WA, Straub '12



$B_s \to \mu^+\mu^-$

(see also Beaujean, Bobeth, van Dyk, Wacker '12 and talk by Danny van Dyk)

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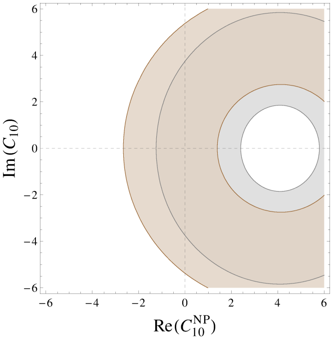

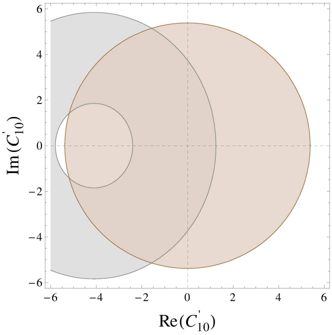

$B_s \to \mu^+\mu^-$

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

(see also Beaujean, Bobeth, van Dyk,
Wacker ’12 and talk by Danny van Dyk)

Model-Independent Constraints (II)

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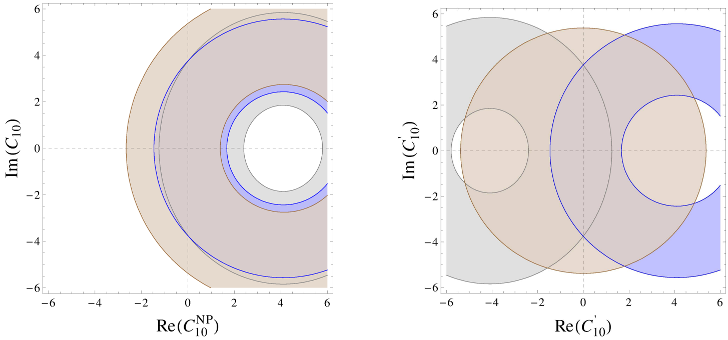

$B_s \to \mu^+\mu^-$

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

$B \to K\mu^+\mu^-$

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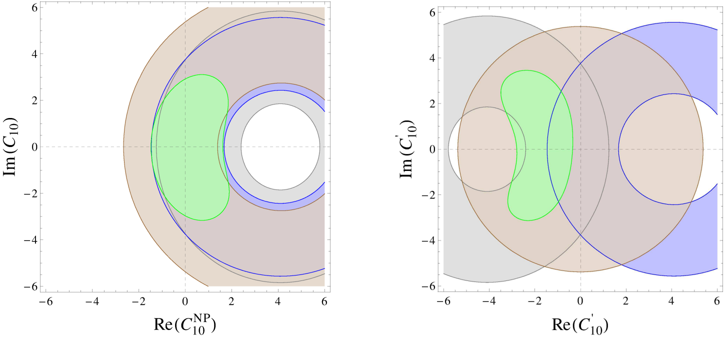

$B_s \to \mu^+\mu^-$

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

$B \to K\mu^+\mu^-$

$B \to K^*\mu^+\mu^-$

(see also Beaujean, Bobeth, van Dyk, Wacker '12 and talk by Danny van Dyk)

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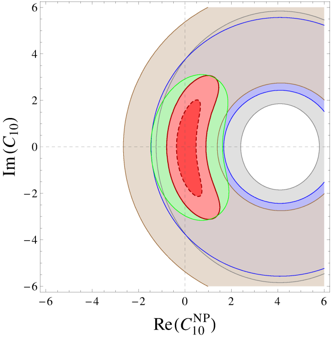
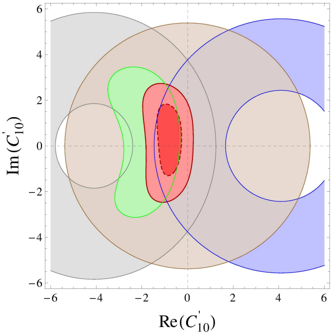




$B_s \to \mu^+\mu^-$

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

$B \to K\mu^+\mu^-$

$B \to K^*\mu^+\mu^-$

(see also Beaujean, Bobeth, van Dyk, Wacker '12 and talk by Danny van Dyk)

- Data shows reasonable agreement with SM: $\chi^2_{\text{SM}}/N_{\text{dof}} = 20.9/24$
- complementary information on RH currents from the different exclusive decays
- Imaginary parts are less constrained $\to$ need to measure T-odd CP asymmetries

Implications for the NP Scale

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \sum_i \left(\frac{c_i}{\Lambda_{\text{NP}}^2} \mathcal{O}_i + \frac{c_i'}{\Lambda_{\text{NP}}^2} \mathcal{O}_i' \right)$$

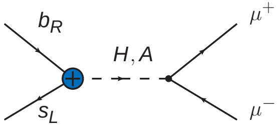
Operator		Λ_{NP} (TeV) for $\lvert c_i^{(\prime)} \rvert = 1$			
		$+$	$-$	$+i$	$-i$
$\mathcal{O}_{10} =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	39	37	22	22
$\mathcal{O}_{10}' =$	$(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	26	68	23	22
$\mathcal{O}_S - \mathcal{O}_S' =$	$\frac{m_b}{m_{B_s}}(\bar{s}\gamma_5 b)(\bar{\ell}\ell)$	91	91	95	95
$\mathcal{O}_P - \mathcal{O}_P' =$	$\frac{m_b}{m_{B_s}}(\bar{s}\gamma_5 b)(\bar{\ell}\gamma_5 \ell)$	113	57	91	91
$\mathcal{O}_S - \mathcal{O}_S' =$	$\frac{m_b}{m_{B_d}}(\bar{d}\gamma_5 b)(\bar{\ell}\ell)$	∼200	∼200	∼200	∼200
$\mathcal{O}_P - \mathcal{O}_P' =$	$\frac{m_b}{m_{B_d}}(\bar{d}\gamma_5 b)(\bar{\ell}\gamma_5 \ell)$	∼200	∼200	∼200	∼200

update from WA, Straub '12

The $C_S - C'_S = \pm(C_P - C'_P)$ Scenario

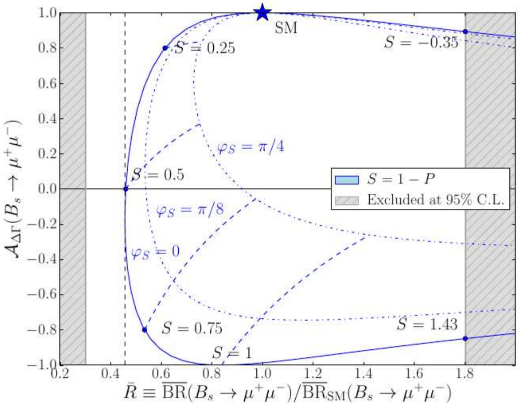
- realized e.g. in the decoupling limit of 2HDMs with MFV

$$C_S = -C_P$$



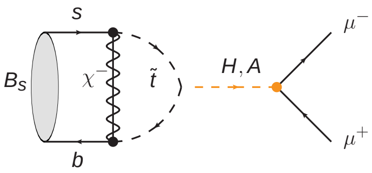
- leads to a lower bound on the branching ratio

$$\frac{BR(B_s \to \mu^+\mu^-)}{BR(B_s \to \mu^+\mu^-)_{\rm SM}} \geq \frac{1}{2}(1 - y_s)$$



Buras, Fleischer, Girrbach, Knegjens '13

- even for completely flavor blind soft terms, Higgsino stop loops can give huge contributions to $B_s \to \mu^+\mu^-$



$$C_S^{\tilde{H}} \simeq -C_P^{\tilde{H}} \propto \frac{y_t^2}{16\pi^2} \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{\tan\beta^3}{M_A^2} (V_{tb} V_{ts}^*)$$

- for large $\tan\beta$ huge enhancement possible (orders of magnitude)
  (Choudhury, Gaur ’98; Babu, Kolda ’99)
- decoupling with M_A and *not* with squark masses

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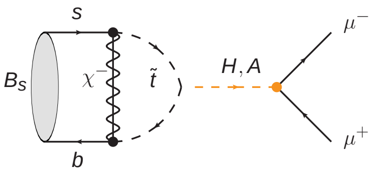

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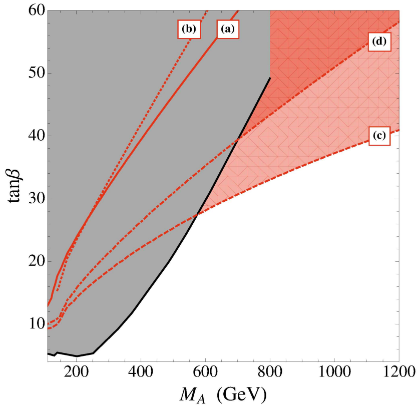
  (Choudhury, Gaur '98; Babu, Kolda '99)
- decoupling with M_A and *not* with squark masses

$$\frac{\text{BR}(B_s \to \mu^+\mu^-)}{\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}}} \geq \frac{1}{2}(1 - y_s)$$

$$1.1 \times 10^{-9} < BR_{\text{exp}} < 6.4 \times 10^{-9}$$

- experimental lower bound has no impact yet in the MSSM with MFV

WA, Carena, Shah, Yu ’12

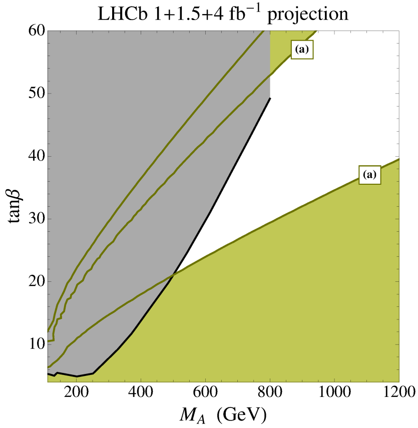


- in gray: region excluded by direct $H, A \to \tau\tau$ searches
- for $\mu A_t > 0$ *destructive interference* of Higgsino loop with SM amplitude
- for $\mu A_t < 0$ *constructive interference* of Higgsino loop with SM amplitude $\to$ currently stronger constraint

———	(a)	$\mu = 1\text{TeV}, A_t > 0$	- - - - - -	(c)	$\mu = -1.5\text{TeV}, A_t > 0$
· · · · · ·	(b)	$\mu = 4\text{TeV}, A_t > 0$	- · - · - ·	(d)	$\mu = 1\text{TeV}, A_t < 0$

all squarks degenerate $\tilde{m} = 2\text{TeV}$, $|A_t|$ such that $M_h = 125\text{GeV}$

WA, Carena, Shah, Yu '12



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- for $\mu A_t > 0$ *destructive interference* of Higgsino loop with SM amplitude
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- projected LHCb sensitivity $\delta\text{BR} \sim 0.5 \times 10^{-9}$

(a) $\mu = 1\text{TeV}, A_t > 0$ (c) $\mu = -1.5\text{TeV}, A_t > 0$
(b) $\mu = 4\text{TeV}, A_t > 0$ (d) $\mu = 1\text{TeV}, A_t < 0$

all squarks degenerate $\tilde{m} = 2\text{TeV}$, $|A_t|$ such that $M_h = 125\text{GeV}$

Constraints on Modified Z Couplings

- Modifications to the Z couplings can arise in many ways:

  loop induced (e.g. MSSM)
  tree level (e.g. models with partial compositness)

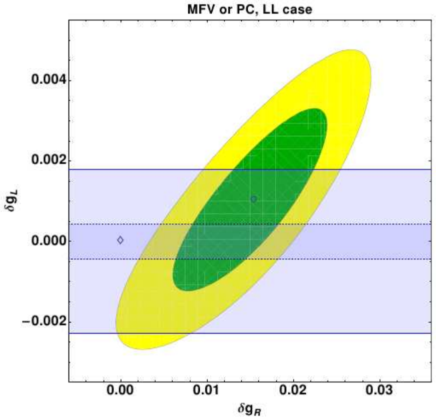
- in models with MFV the $Zb_L b_L$ and $Zb_L s_L$ couplings are related

- complementarity of $BR(B_s \to \mu^+\mu^-)$ and Z pole observables in constraining modified Z couplings

- with MFV, constraint from $BR(B_s \to \mu^+\mu^-)$ on the LH coupling starts to be stronger

- with MFV, no constraints from $BR(B_s \to \mu^+\mu^-)$ on RH coupling

Guadagnoli, Isidori '13



(for constraints on Zbb see e.g.
Baak et. al. '12; Batell, Gori, Wang '12)

"Golden" MFV Relation

(Buras '03; Hurth, Isidori, Kamenik, Mescia '08)

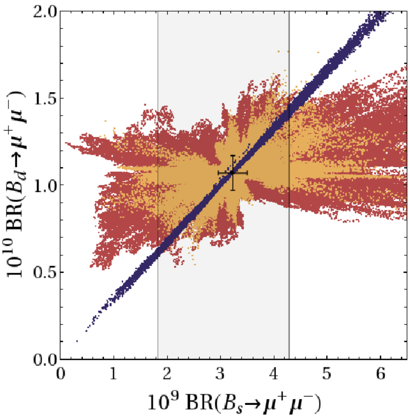
$$\frac{BR(B_s \to \mu^+\mu^-)}{BR(B_d \to \mu^+\mu^-)} \simeq \frac{f_{B_s}^2}{f_{B_d}^2} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} \simeq 32$$

- relation holds in the SM,
  models with MFV,
  and models with minimally broken
  $U(2)^3$ flavor symmetry

- experimental results on
  $B_s \to \mu^+\mu^-$ put
  upper and lower bounds on
  $BR(B_d \to \mu^+\mu^-)$

$$BR(B_d \to \mu^+\mu^-) \gtrsim 0.3 \times 10^{-10} \text{ @ } 95\% \text{ C.L.}$$
$$BR(B_d \to \mu^+\mu^-) \lesssim 1.8 \times 10^{-10} \text{ @ } 95\% \text{ C.L.}$$

- violation of these bounds implies
  sources of flavor violation
  beyond the CKM matrix



Straub '13:
analysis of several models
with partial compositness

Summary

- *It's not the End, it's the Beginning!*
- Spectacular effects in $B_s \to \mu^+\mu^-$ are excluded, but "natural" NP contributions of O(50%) are started to be probed only now
- $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ can be predicted with high accuracy in the SM

$\rightarrow$ even modest NP contributions can be clearly identified

- In the absence of any direct sign of NP at the LHC, indirect probes of NP are more important than ever