

New Physics in rare heavy flavour decays

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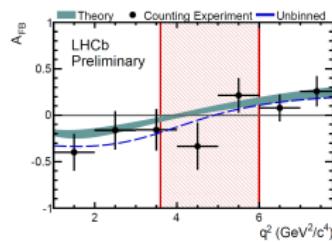
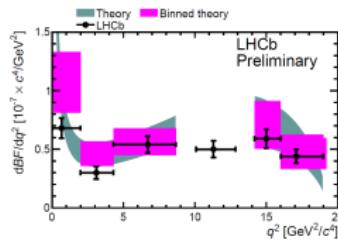
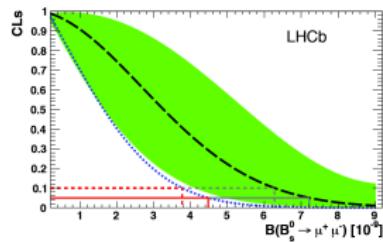
Motivations

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

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

LHCb has also a rich BSM program through indirect searches!

key rare processes: $B_s \rightarrow \mu^+ \mu^-$, $B \rightarrow K^* \mu^+ \mu^-$



→ Crucial to have a clear estimation of the SM predictions and errors!

A multi-scale problem

- new physics: $1/\Lambda_{\text{NP}}$
- electroweak interactions: $1/M_W$
- hadronic effects: $1/m_b$
- QCD interactions: $1/\Lambda_{\text{QCD}}$

⇒ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

- short distance: Wilson coefficients, computed perturbatively
- long distance: local operators

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1 \dots 10, S, P} (C_i(\mu) \mathcal{O}_i(\mu) + C'_i(\mu) \mathcal{O}'_i(\mu)) \right)$$

New physics:

- Corrections to the Wilson coefficients: $C_i \rightarrow C_i + \Delta C_i^{\text{NP}}$
- Additional operators: $\sum_j C_j^{\text{NP}} \mathcal{O}_j^{\text{NP}}$



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Many flavour observables sensitive to new physics

Key decays:



- LHCb golden channels
 - $B_s \rightarrow \mu^+ \mu^-$
 - $B \rightarrow K^* \mu^+ \mu^-$
- Inclusive penguins
 - $B \rightarrow X_s \gamma$
 - $B \rightarrow X_s \mu^+ \mu^-$
- Tree level neutrino modes
 - $B \rightarrow \tau \nu_\tau$
 - $B \rightarrow D \tau \nu_\tau$
 - $D_s \rightarrow \tau \nu_\tau$
 - $K \rightarrow \mu \nu_\mu$



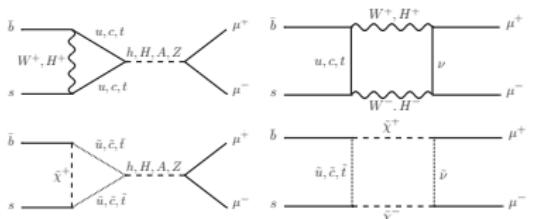
$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$$

Relevant operators:

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\ell)$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5\ell)$$



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

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

First experimental evidence:

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

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

Previous limit: $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-9}$ at 95% C.L.

ATLAS+CMS+LHCb combined value, LHCb-CONF-2012-017

- Measurement consistent with the SM prediction!
- Crucial to have a clear estimation of the uncertainties!



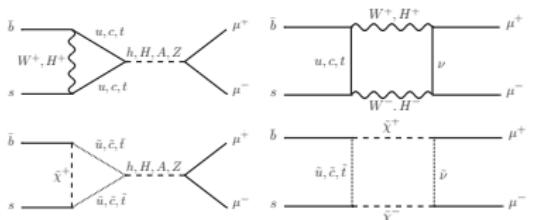
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Main source of uncertainty: f_{B_s}

- ETMC-11: 232 ± 10 MeV
 - HPQCD-12: 227 ± 10 MeV
HPQCD NR-09: 231 ± 15 MeV
HPQCD HISQ-11: 225 ± 4 MeV
 - Fermilab-MILC-11: 242 ± 9.5 MeV
- Our choice: 234 ± 10 MeV**

With the most up-to-date input parameters (PDG 2012), in particular $\tau_{B_s} = 1.497$ ps:

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

[FM, S. Neshatpour, J. Orloff, JHEP 1208 \(2012\) 092](#)

Most important sources of uncertainties:

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

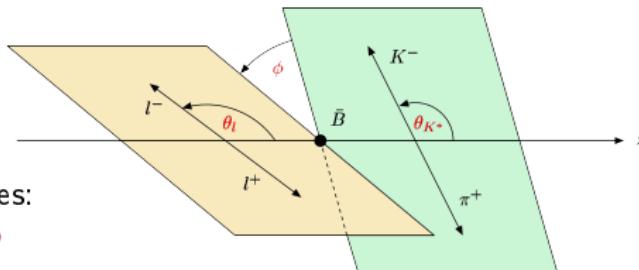
Using $f_{B_s} = 227$ MeV and $\tau_{B_s} = 1.466$ ps, one gets: $\text{BR}(B_s \rightarrow \mu^+ \mu^-) = 3.25 \times 10^{-9}$

[A. Buras et al. Eur.Phys.J. C72 \(2012\) 2172](#)



Angular distributions

The full angular distribution of the decay $\bar{B}^0 \rightarrow \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \rightarrow K^- \pi^+$) is completely described by four independent kinematic variables:
 q^2 (dilepton invariant mass squared), θ_ℓ , θ_{K^*} , ϕ



Differential decay distribution:

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_{K^*} d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

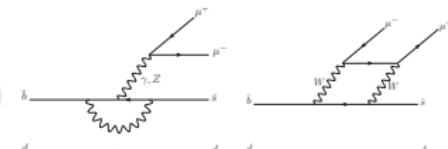
$J(q^2, \theta_\ell, \theta_{K^*}, \phi)$ are written in function of the angular coefficients $J_{1-9}^{s,c}$

J_{1-9} : functions of the spin amplitudes A_0 , A_\parallel , A_\perp , A_t , and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

$$\begin{aligned} \mathcal{O}_9 &= \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell), & \mathcal{O}_{10} &= \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell) \\ \mathcal{O}_S &= \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\ell), & \mathcal{O}_P &= \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5\ell) \end{aligned}$$

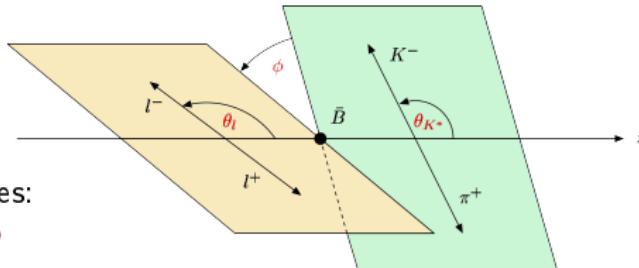


F. Kruger et al., Phys. Rev. D 61 (2000) 114028;

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

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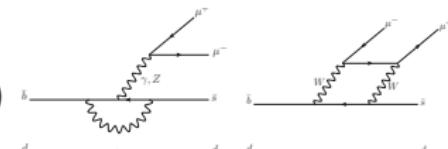
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$B \rightarrow K^* \mu^+ \mu^-$ – Observables

Dilepton invariant mass spectrum: $\frac{d\Gamma}{dq^2} = \frac{3}{4} \left(J_1 - \frac{J_2}{3} \right)$

Forward backward asymmetry:

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

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

→ fix the sign of C_9/C_7

Polarization fractions:

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}, \quad F_T(q^2) = 1 - F_L(q^2) = \frac{|A_{\perp}|^2 + |A_{||}|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}$$

Transverse asymmetries:

$$A_T^{(1)}(q^2) = \frac{-2\Re(A_{||} A_{\perp}^*)}{|A_{\perp}|^2 + |A_{||}|^2}$$

$$A_T^{(2)}(q^2) = \frac{|A_{\perp}|^2 - |A_{||}|^2}{|A_{\perp}|^2 + |A_{||}|^2}$$

$$A_T^{(3)}(q^2) = \frac{|A_{0L} A_{||L}^* + A_{0R}^* A_{||R}|}{\sqrt{|A_0|^2 |A_{\perp}|^2}}$$

$$A_T^{(4)}(q^2) = \frac{|A_{0L} A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L} A_{||L}^* + A_{0R}^* A_{||R}|}$$

→ Reduced form factor uncertainties



Main uncertainties from:

- form factors
- $1/m_b$ subleading corrections
- parametric uncertainties (m_b , m_c , m_t)
- CKM matrix elements
- scales

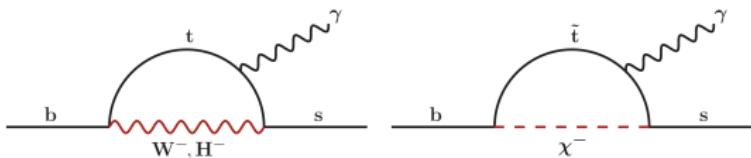
Observable	SM value	(FF)	(SL)	(QM)	(CKM)	(Scale)	Total
$10^7 \times BR(B \rightarrow K^* \mu^+ \mu^-)_{[1,6]}$	2.32	± 1.34	± 0.04	$+0.04$ -0.03	$+0.08$ -0.13	$+0.09$ -0.05	± 1.35
$\langle A_{FB}(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	-0.06	± 0.04	± 0.02	± 0.01	—	—	± 0.05
$\langle F_L(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	0.71	± 0.13	± 0.01	± 0.01	—	—	± 0.13
$q_0^2(B \rightarrow K^* \mu^+ \mu^-)/\text{GeV}^2$	4.26	± 0.30	± 0.15	$+0.14$ -0.04	—	$+0.02$ -0.04	± 0.35

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

$$B \rightarrow X_s \gamma$$

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

Contributing loops:



Main operator: \mathcal{O}_7

but higher order contributions from $\mathcal{O}_1, \dots, \mathcal{O}_8$.

NNLO calculations available for the SM

$$\mathcal{B}(\bar{B} \rightarrow X_s \gamma)_{E_\gamma > E_0} = \mathcal{B}(\bar{B} \rightarrow X_c e \bar{\nu})_{\text{exp}} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6 \alpha_{\text{em}}}{\pi C} [P(E_0) + N(E_0)]$$

$$\begin{aligned} P(E_0) &= P^{(0)}(\mu_b) + \alpha_s(\mu_b) \left[P_1^{(1)}(\mu_b) + P_2^{(1)}(E_0, \mu_b) \right] \\ &+ \alpha_s^2(\mu_b) \left[P_1^{(2)}(\mu_b) + P_2^{(2)}(E_0, \mu_b) + P_3^{(2)}(E_0, \mu_b) \right] + \mathcal{O}(\alpha_s^3(\mu_b)) \end{aligned}$$

$$\begin{cases} P^{(0)}(\mu_b) &= \left(C_7^{(0)\text{eff}}(\mu_b) \right)^2 \\ P_1^{(1)}(\mu_b) &= 2C_7^{(0)\text{eff}}(\mu_b) C_7^{(1)\text{eff}}(\mu_b) \\ P_1^{(2)}(\mu_b) &= \left(C_7^{(1)\text{eff}}(\mu_b) \right)^2 + 2C_7^{(0)\text{eff}}(\mu_b) C_7^{(2)\text{eff}}(\mu_b) \end{cases}$$



- SM contributions known to NNLO accuracy

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

- THDM contributions known to NNLO accuracy

T. Hermann, M. Misiak, M. Steinhauser, JHEP 1211 (2012) 036

- SUSY contributions known partially to NNLO accuracy

C. Greub et al., Nucl. Phys. B 853 (2011) 240

SM prediction: $\text{BR}(\bar{B} \rightarrow X_s \gamma) = (3.08 \pm 0.24) \times 10^{-4}$

SuperIso v3.4

Most important sources of uncertainties:

	parametric	higher order	m_c interpol.	non-perturb.	Overall
Uncertainty	3%	3%	3%	5%	8%

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

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



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

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

Large uncertainty from V_{ub} and f_B

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

Theoretical uncertainty on $\text{BR}(B \rightarrow \tau\nu)$: 25%

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

Experimental average (ICHEP 2012): $\text{BR}(B \rightarrow \tau\nu) = (1.14 \pm 0.23) \times 10^{-4}$

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



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Implications



Model independent constraints on New Physics

Minimal Flavour Violation (MFV): Flavour and CP symmetries are broken as in the SM
→ all flavour- and CP-violating interactions linked to the known structure of Yukawa couplings

Assuming MFV, what are the presently allowed ranges of the Wilson coefficients?

T. Hurth, FM, Nucl. Phys. B865 (2012) 461

Relevant Operators:

$$\mathcal{O}_7, \mathcal{O}_8, \mathcal{O}_9, \mathcal{O}_{10} \quad \text{and} \quad \mathcal{O}_{S-P} \propto (\bar{s}P_R b)(\bar{\mu}P_L \mu) \equiv \mathcal{O}_0^I$$

NP manifests itself in the shifts of the individual coefficients with respect to the SM values:

$$C_i(\mu) = C_i^{\text{SM}}(\mu) + \delta C_i$$

- Scans over the values of $\delta C_7, \delta C_8, \delta C_9, \delta C_{10}, \delta C_0^I$
- Calculation of flavour observables
- Comparison with experimental results
- Constraints on the Wilson coefficients C_i
- Prediction of flavour observables

Allows to test the MFV hypothesis!

see also: Hurth, Isidori, Kamenik, Mescia, Nucl.Phys. B808 (2009) 326



New Physics and Minimal Flavour Violation hypothesis

→ Global fits of the $\Delta F = 1$ observables obtained by minimization of

$$\chi^2 = \sum_i \frac{(O_i^{\text{exp}} - O_i^{\text{th}})^2}{(\sigma_i^{\text{exp}})^2 + (\sigma_i^{\text{th}})^2}$$

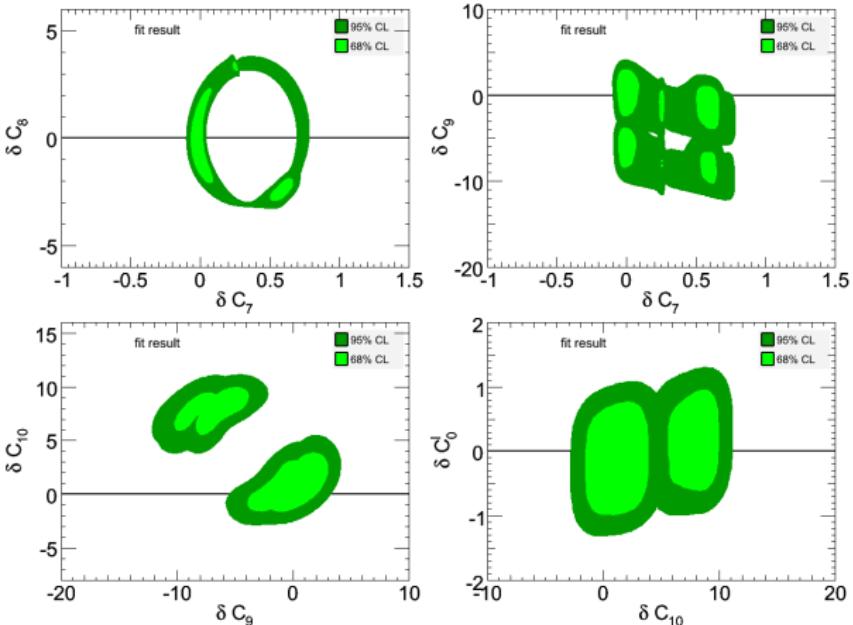
Observables:

- $\text{BR}(B \rightarrow X_s \gamma)$
- $\text{BR}(B \rightarrow X_d \gamma)$
- $\Delta_0(B \rightarrow K^* \gamma)$
- $\text{BR}^{\text{low}}(B \rightarrow X_s \mu^+ \mu^-)$
- $\text{BR}^{\text{high}}(B \rightarrow X_s \mu^+ \mu^-)$
- $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$
- $\text{BR}^{\text{low}}(B \rightarrow K^* \mu^+ \mu^-)$
- $\text{BR}^{\text{high}}(B \rightarrow K^* \mu^+ \mu^-)$
- $A_{FB}^{\text{low}}(B \rightarrow K^* \mu^+ \mu^-)$
- $A_{FB}^{\text{high}}(B \rightarrow K^* \mu^+ \mu^-)$
- $q_0^2(A_{FB}(B \rightarrow K^* \mu^+ \mu^-))$
- $F_L^{\text{low}}(B \rightarrow K^* \mu^+ \mu^-)$



New Physics and Minimal Flavour Violation hypothesis: fits

Before LHCb:



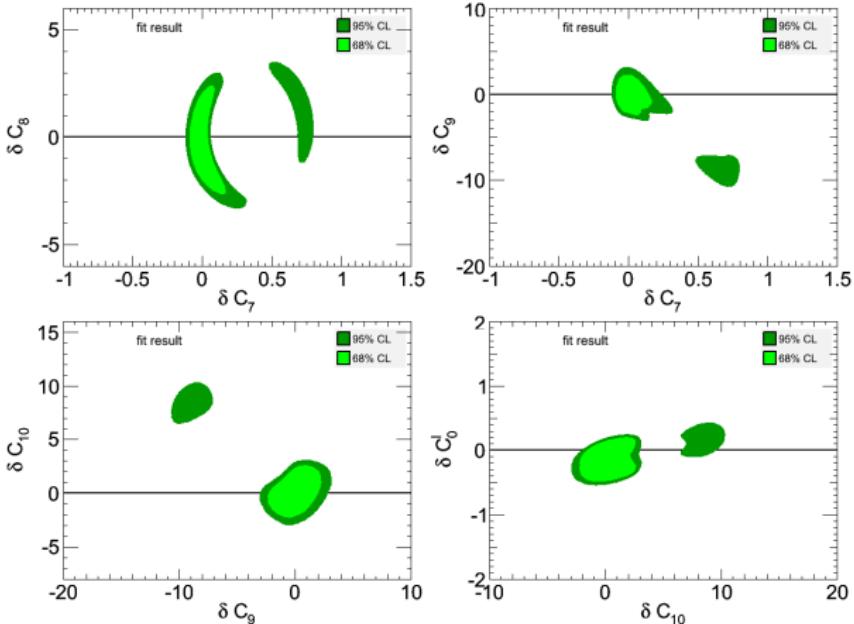
T. Hurth, FM, Nucl. Phys. B865 (2012) 461

Use these results to make predictions for new observables!
Check consistencies!



New Physics and Minimal Flavour Violation hypothesis: fits

After LHCb:



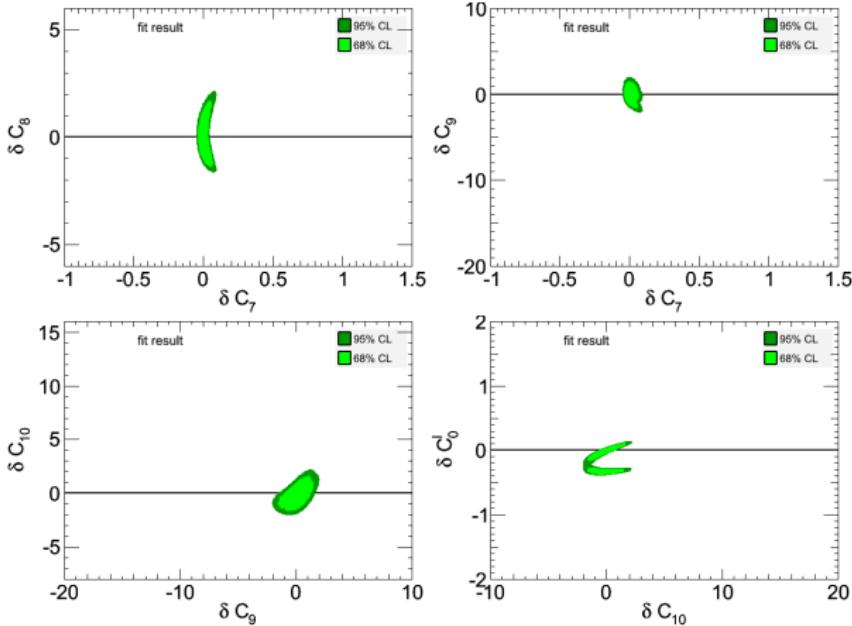
T. Hurth, FM, to appear in Rev. Mod. Phys.

Use these results to make predictions for new observables!
Check consistencies!



New Physics and Minimal Flavour Violation hypothesis: fits

Ultimate precision:



Use these results to make predictions for new observables!
Check consistencies!

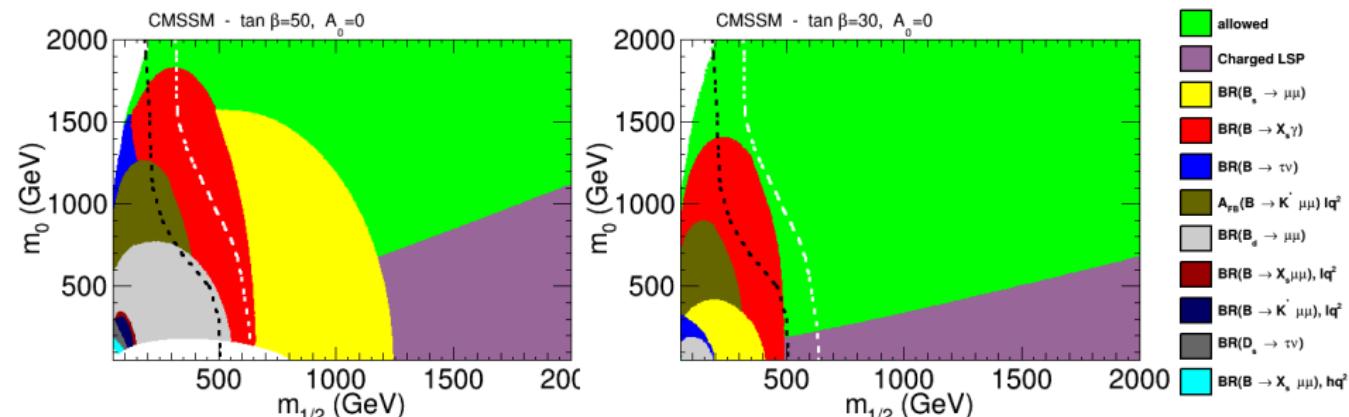


Constraints in CMSSM

Constrained MSSM (CMSSM): Universality assumptions at the GUT scale

Parameters: m_0 , $m_{1/2}$, A_0 , $\tan \beta$ and sign of μ

Present situation (using the latest results):



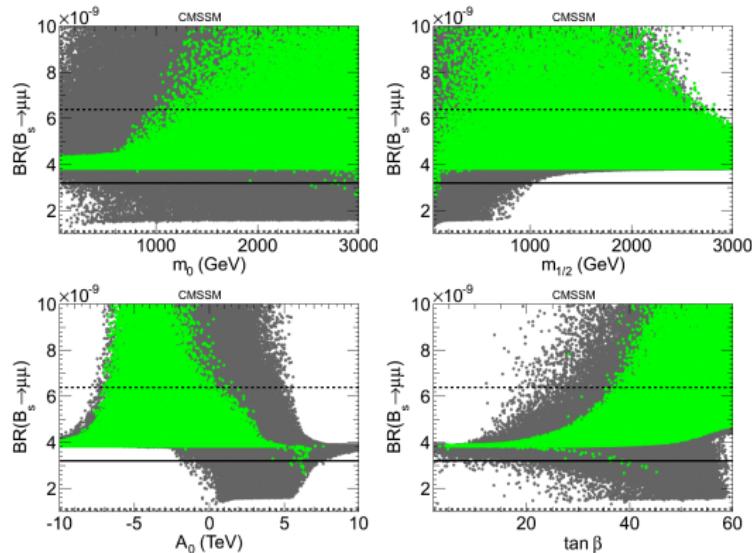
Dashed black line: CMS exclusion limit with 1.1 fb^{-1} data

Dashed white line: CMS exclusion limit with 4.4 fb^{-1} data



Constraints in CMSSM

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



A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D 87 (2013) 035026

Solid line: central value of the $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ measurement
Dashed lines: 2σ experimental deviations

Gray points: all valid points

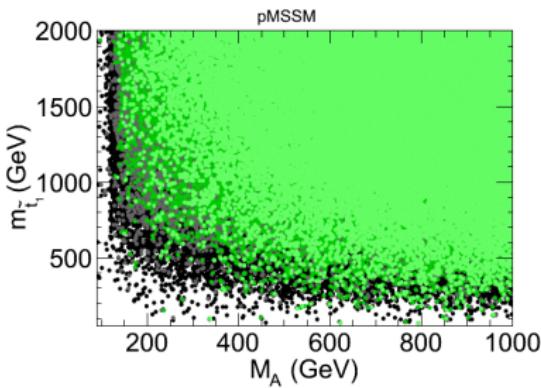
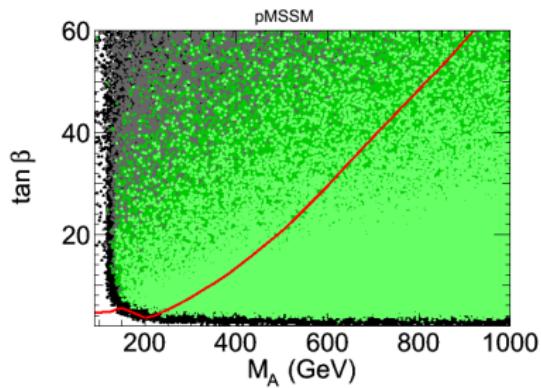
Green points: points in agreement with the Higgs mass constraint

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



Constraints in general MSSM

Phenomenological MSSM (pMSSM): No universality assumptions, 19 free parameters



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

Black points: all the valid pMSSM points

Gray points: $123 < M_h < 129$ GeV

Dark green points: in agreement with the latest $BR(B_s \rightarrow \mu^+ \mu^-)$

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

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



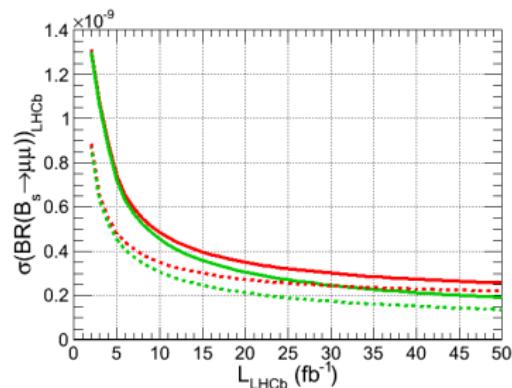
- Rare decays provide a convenient ground to test the fundamental theory assumptions (e.g. MFV)
- They give also extremely important and complementary information in the search for new physics
- Simplest NP scenarios already ruled out...
- NP should be subtle!
- Flavour physics can help guiding direct searches
- Theory uncertainties are well under control for most of the decays
- We are looking forward to more data!



Backup



Experimental expectations: uncertainty vs. luminosity



Red line: systematic uncertainty of 5% for LHCb

Green line: ultimate systematic uncertainty of 1% for LHCb

Dashed lines: LHC combinations

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

An ultimate uncertainty of $\sim 0.2 \times 10^{-9}$ can be expected after 50 fb^{-1} of data.



$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$$

Theory prediction: CP-averaged quantities, effect of $B_s - \bar{B}_s$ oscillations disregarded
 Experimental measurement: untagged branching fraction

K. De Bruyn et al., Phys. Rev. D 86, 014027; Phys. Rev. Lett. 109, 041801 (2012)

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

with

$$y_s \equiv \frac{1}{2} \tau_{B_s} \Delta\Gamma_s = 0.088 \pm 0.014$$

$$\mathcal{A}_{\Delta\Gamma} = \frac{|P|^2 \cos(2\varphi_P) - |S|^2 \cos(2\varphi_S)}{|P|^2 + |S|^2}$$

S and P are related to the Wilson coefficients by:

$$S = \sqrt{1 - 4 \frac{m_\mu^2}{M_{B_s}^2} \frac{M_{B_s}^2}{2m_\mu} \frac{1}{m_b + m_s} \frac{C_{Q_1} - C'_{Q_1}}{C_{10}^{SM}}}, \quad P = \frac{C_{10}}{C_{10}^{SM}} + \frac{M_{B_s}^2}{2m_\mu} \frac{1}{m_b + m_s} \frac{C_{Q_2} - C'_{Q_1}}{C_{10}^{SM}}$$

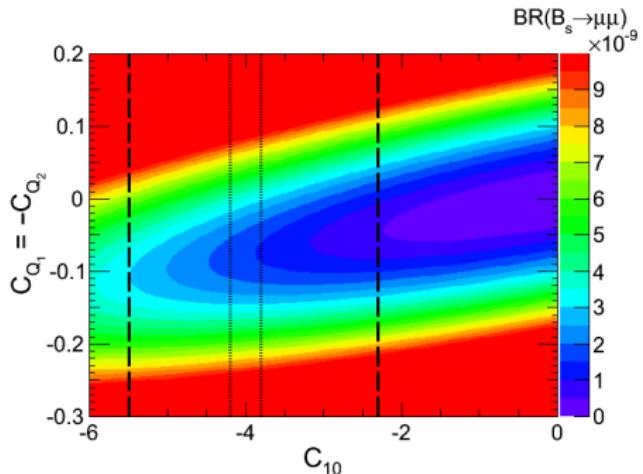
$$\varphi_S = \arg(S), \quad \varphi_P = \arg(P)$$

The SM expectation for this corrected branching fraction is:

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{untag}} = (3.87 \pm 0.46) \times 10^{-9}$$



Constraints on pMSSM



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

Dotted vertical lines: delimit the range of C_{10} in the CMSSM
Dashed lines: delimit the range of C_{10} in the pMSSM.

