B physics and MSSM

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invisibles
neutrinos, dark matter & dark energy physics

A successful story...

Standard Model (SM)

- Based on SU(3)×SU(2)×U(1)
- **Fermions** can be grouped into 3 flavour families:

Up type quarks $(3)_{+2/3}$	u	c	t
Down type quarks $(3)_{-1/3}$	d	s	b
Charged leptons $(1)_{-1}$	e	μ	τ
Neutrinos $(1)_0$	ν_e	ν_μ	ν_τ

  Flavour physics describes interactions that distinguish between fermion generations
  Flavour mixings can be parametrized by the CKM matrix
  FCNC (Flavour changing neutral current): processes that involve either up- or down-type quarks but not both → highly suppressed in the SM
  MFV (Minimal Flavour Violation): Flavour and CP symmetries broken as in the SM → all flavour/CP violating interactions linked to SM structure of Yukawa couplings
- **Bosons**: Z and W bosons, photon, gluon and Higgs
- + anti-particles

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Beyond the SM

But many unanswered questions...

- Gravitation does not fit in the SM framework
- Dark matter, Dark energy
- Hierarchy problem
- Unification of the fundamental interactions
- ...

Going beyond the SM appears as a necessity!

Searches for New Physics

- direct detection of new physics particles
- nature of Dark Matter
- indirect evidence for new physics

The hope is that LHC will bring some answers!

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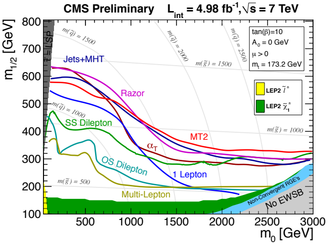
Direct searches for new particles

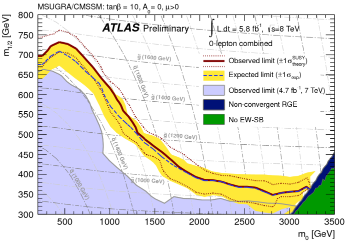
ATLAS and **CMS** main searches:

- Higgs bosons
- New Physics (NP)

most studied theoretically
most considered experimentally } Supersymmetry (SUSY)



CMS website (summary plot)



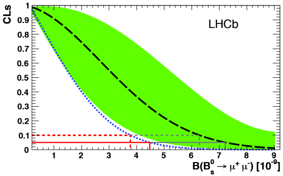
ATLAS-CONF-2012-109

Indirect searches using flavour data

LHCb

- LHCb has a very rich program to search for indirect signs of new physics!
- In the past, the B physics experiment objectives were focused on the tests of the CKM matrix for a long time, but this is now well established!
- Focus is now towards the new physics!

  And search for the indirect signs of new physics



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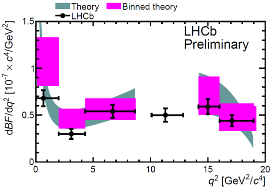

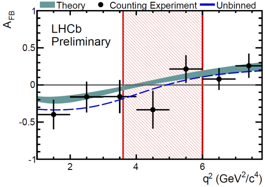

LHCB-CONF-2012-008

Interplay between direct and indirect searches

The combination of information from both sectors can help us to pin down the underlying NP scenario!

Let's consider Supersymmetry!

- Direct searches for SUSY particles: the limits on the masses are being pushed higher and higher.
- This is not enough!
- Interplay can play a crucial role

Also interesting non-LHC data on dark matter

Minimal Supersymmetric Model (MSSM)

Supersymmetry is based on an additional symmetry between fermions and bosons

SM particle	spin	Superpartner	spin
quarks	1/2	squarks	0
leptons	1/2	sleptons	0
gauge bosons	1	gauginos	1/2
Higgs bosons	0	higgsinos	1/2

gauginos + higgsinos mix to 2 charginos + 4 neutralinos

2 Higgs doublets $\rightarrow$ 5 physical Higgs bosons:

- neutral states: scalar h, H; pseudoscalar A
- charged states: H^+, H^-

Supersymmetry

- If SUSY were an exact symmetry, the SM particles and their supersymmetric partners would have the same masses.
- As this is not the case,
- Fortunately, how SUSY is broken is irrelevant for phenomenology
- This is the mediation mechanism and the associated scale of SUSY breaking which is important
- To keep δm_H^2 under control, the superparticles should have masses of about 1 TeV
- One can expect SUSY to be in the reach of LHC!

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Constrained MSSM scenarios

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Very difficult to perform systematic studies

A way out: Constrained MSSM scenarios

- Assume universality at GUT scale

  → Reduces the number of free parameters to a handful!

- Most well known scenario: CMSSM (or mSUGRA)

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

  → Very useful for phenomenology, benchmarking, model discrimination, ...

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Going beyond CMSSM...

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

Flavour Physics

Why is flavour physics interesting?

Flavour physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiments}$

Flavour physics can discover new physics or probe it before it is directly observed in experiments

CP violation is closely related to flavour physics

The only CP violating parameter in the SM is the CKM phase. However, we know from baryogenesis that new sources of CP violation is needed.

The Standard Model flavour puzzle:

Why are the flavour parameters small and hierarchical?

The New Physics flavour puzzle:

If there is NP at the TeV scale, why are flavour changing neutral current (FCNC) so small? If such NP has a generic flavour structure, it should contribute to FCNC processes

Flavour and New Physics

Assuming a generic flavour structure

Parametrisation of New Physics, with Higher Dimensional Operators:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}\mathcal{L}^{(5)} + \frac{1}{\Lambda_{\mathrm{NP}}^2}\mathcal{L}^{(6)} + \cdots$$

with

- Λ_{NP}: New Physics scale
- $\mathcal{L}^{(n)} : \sum_i C_i O_i^{(n)}$
- $O_i^{(n)}$: Local operators of dimension n

Example: B_s mixings, $O^{(6)} = (\bar{b}\gamma_\mu P_L s)(\bar{b}\gamma_\mu P_L s)$

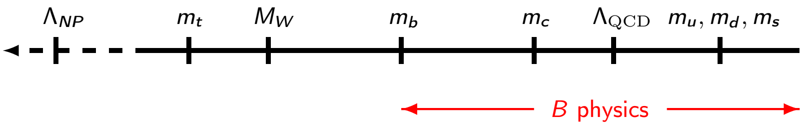
$$\rightarrow \Lambda_{\mathrm{NP}} \gtrsim 70 \text{ TeV}$$

$\rightarrow$ Any NP below the 1 TeV scale must have a non-generic flavour structure!

Why is it complicated?

Two different problems here due to mixture of strong/weak:

- Weak Lagrangian in terms of quarks, but hadronic final states
- Multi-scale problem M_W, m_b, $\Lambda_{\rm QCD}$, $m_{\rm light}$



Here scales of order m_b (or lower)!

So why not integrate out heavier degrees of freedom (t, W, Z)?

(with still b, c, s, d, u, g and γ as dynamical particles)

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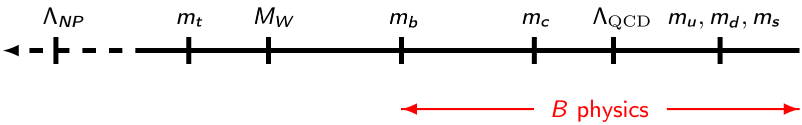

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Basic idea

Effective field theory approach:

separation between low and high energies using Operator Product Expansion

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

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1\cdots 10,S,P} C_i(\mu) \mathcal{O}_i(\mu) \right]$$

New physics:

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

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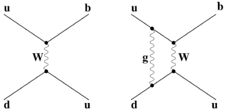

Current

$$O_3 = (\bar{s}\gamma_\mu P_L b)\sum_q(\bar{q}\gamma^\mu q)$$
$$O_4 = (\bar{s}\gamma_\mu T^a P_L b)\sum_q(\bar{q}\gamma^\mu T^a q)$$
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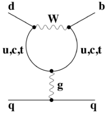
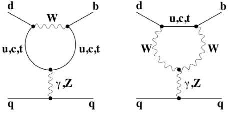
$$O_6 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} T^a P_L b)\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} T^a q)$$

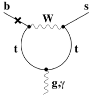


QCD penguins



Electroweak penguins

$$O_7 = \frac{e}{16\pi^2}\left[\bar{s}\sigma^{\mu\nu}(m_s P_L + m_b P_R)b\right]F_{\mu\nu}$$
$$O_8 = \frac{g_s}{16\pi^2}\left[\bar{s}\sigma^{\mu\nu}(m_s P_L + m_b P_R)T^a b\right]G^a_{\mu\nu}$$



Magnetic operators

$$O_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{l}\gamma_\mu l)$$
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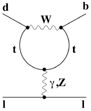

Semileptonic operators

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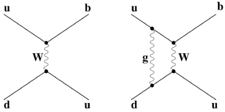

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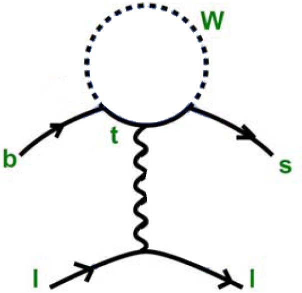

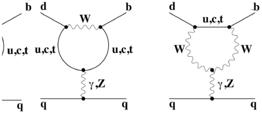

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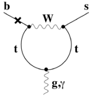

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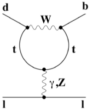

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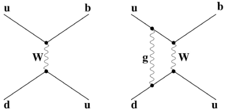

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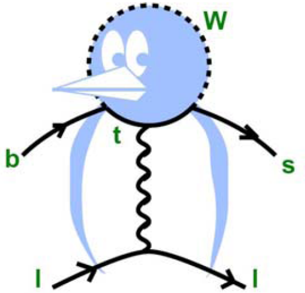

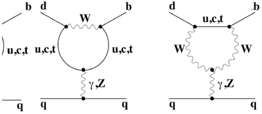

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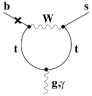

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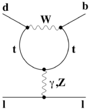

Semileptonic operators

Wilson coefficients

Two main steps:

- Calculating $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

- Evolving the $C_i^{eff}(\mu)$ to scale $\mu \sim m_b$ using the RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$:

$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \cdots$$

Form factors and decay constants

To compute the amplitudes:

$$\mathcal{A}(A \to B) = \langle B|\mathcal{H}_{\rm eff}|A\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu)\langle B|\mathcal{O}_i|A\rangle(\mu)$$

$\langle B|\mathcal{O}_i|A\rangle$: hadronic matrix element

How to compute matrix elements?

$\to$ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

$\to$ Describe hadronic matrix elements in terms of hadronic quantities

Two types of hadronic quantities:

- Decay constants: Probability amplitude of hadronizing quark pair into a given hadron
- Form factors: Transition from a meson to another through flavour change

Observables

Rare decays of interest for LHCb

- $B_s \to \mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$
  - Branching Ratio (BR)
  - Forward-Backward Asymmetry (A_{FB}, A_{FB_0})
  - Many angular observables (F_L, S_3, A_{Im}, ...)

Other important rare decays

- $B \to X_s\gamma$
- $B \to \tau\nu_\tau$ (and similarly $B \to D\tau\nu_\tau$, $D_s \to \tau\nu_\tau$, $K \to \mu\nu_\mu$, ...)

Observables

Rare decays of interest for LHCb

- $B_s \to \mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$
  - Branching Ratio (BR)
  - Forward-Backward Asymmetry (A_{FB}, A_{FB_0})
  - Many angular observables (F_L, S_3, A_{Im}, ...)

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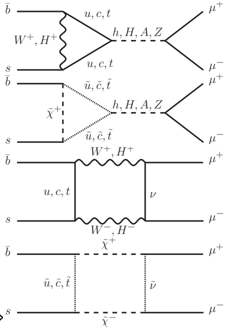
$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Relevant operators:

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

$$Q_1 = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$

$$Q_2 = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5\ell)$$



$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1-\frac{4m_\mu^2}{m_{B_s}^2}\right) \left|C_{Q_1} - C'_{Q_1}\right|^2 + \left|(C_{Q_2} - C'_{Q_2}) + 2\,(C_{10} - C'_{10})\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

Very sensitive to new physics, especially for large $\tan\beta$:

SUSY contributions can lead to an O(100) enhancement over the SM!

BR($B_s \to \mu^+\mu^-$)

First experimental evidence:

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

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

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

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

→ Consistent with the SM value!
→ Crucial to have a clear estimation of the SM prediction!

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

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$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Up-to-date input parameters (PDG 2012):

V_{ts}	V_{tb}	m_{B_s}	τ_{B_s}	m_t^{pole}
-0.0404	0.999146	5.3663 GeV	1.497 ps	173.5 GeV

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

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

Most important sources of uncertainties:

8% from f_{B_s}
2% from EW corrections
2% from scales

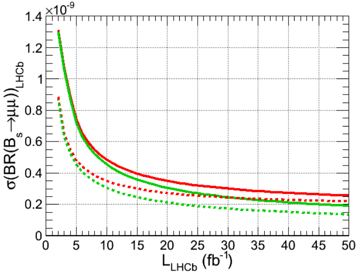
2% from B_s lifetime
5% from V_{ts}
1.3% from top mass

Overall TH uncertainty: $\sim$10%.

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

BR($B_s \to \mu^+\mu^-$)

Experimental expectations: uncertainty vs. luminosity

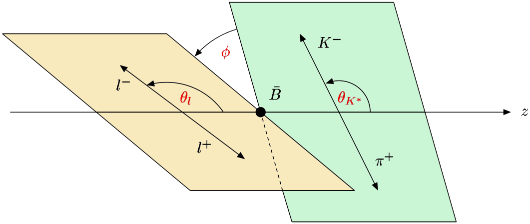


A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys. Rev. D87 (2013) 035026

Red line: systematic uncertainty of 5% for LHCb
Green line: ultimate systematic uncertainty of 1% for LHCb
Dashed lines: LHC combinations

$B \to K^* \mu^+ \mu^-$ – Angular distributions

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-$ with $\bar{K}^{*0} \to K^- \pi^+$ on the mass shell is completely described by four independent kinematic variables:

- q^2: dilepton invariant mass squared
- θ_ℓ: angle between ℓ^- and the $\bar{B}$ in the dilepton frame
- θ_{K^*}: angle between K^- and $\bar{B}$ in the $K^-\pi^+$ frame
- ϕ: angle between the normals of the $K^-\pi^+$ and the dilepton planes

$B \to K^* \mu^+ \mu^-$ – Differential decay distribution

Differential decay distribution:

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

Kinematics: $4m_\ell^2 \leqslant q^2 \leqslant (M_B - m_{K^*})^2$, $-1 \leqslant \cos\theta_\ell \leqslant 1$, $-1 \leqslant \cos\theta_{K^*} \leqslant 1$, $0 \leqslant \phi \leqslant 2\pi$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi)$ 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:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$

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

$$Q_1 = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$

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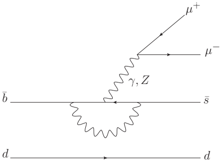
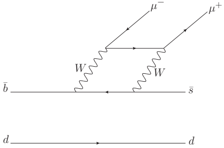




$B \to K^* \mu^+ \mu^-$ – Observables

Dilepton invariant mass spectrum

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

Forward backward asymmetry

Difference between the differential branching fractions in the forward and backward directions:

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

$\rightarrow$ Reduced theoretical uncertainty

Forward backward asymmetry zero-crossing

$\rightarrow$ Reduced form factor uncertainties

$$q_0^2 \simeq -2 m_b m_B \frac{C_9^{\rm eff}(q_0^2)}{C_7} + O(\alpha_s, \Lambda/m_b)$$

$\rightarrow$ fix the sign of C_9/C_7

$B \to K^* \mu^+ \mu^-$ – Polarization fractions and transverse asymmetries

Polarization fractions:

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

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

K^* **polarization parameter:**

$$\alpha_{K^*}(q^2) = \frac{2F_L}{F_T} - 1 = \frac{2|A_0|^2}{|A_\parallel|^2 + |A_\perp|^2} - 1$$

Transverse asymmetries:

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

$$A_T^{(3)}(q^2) = \frac{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2 |A_\perp|^2}} \qquad A_T^{(4)}(q^2) = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}$$

$$A_{Im}(q^2) = -2\,\mathrm{Im}\left(\frac{A_\parallel A_\perp^*}{|A_\perp|^2 + |A_\parallel|^2}\right) \qquad S_3(q^2) = \frac{1}{2}(1 - F_L(q^2))A_T^{(2)}(q^2)$$

$B \to K^* \mu^+ \mu^-$ – SM predictions

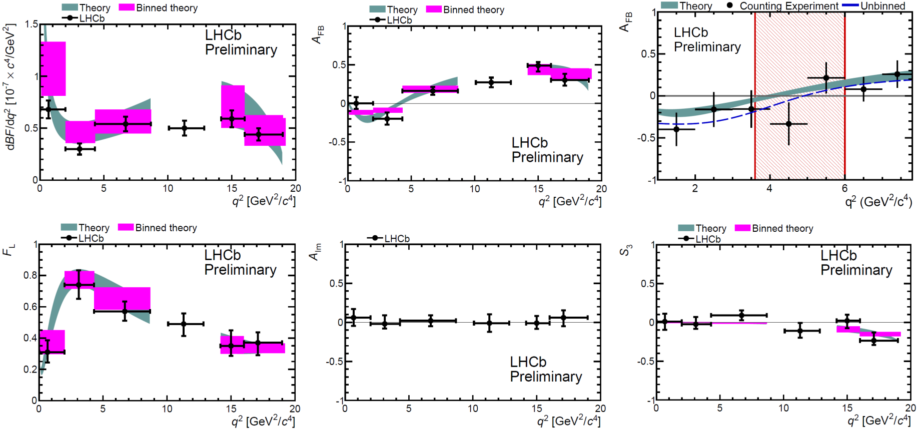
Observable	SM value	(FF)	(SL)	(QM)	(CKM)	(Scale)
$10^7 \times BR(B \to K^* \mu^+ \mu^-)_{[1,6]}$	2.32	± 1.34	± 0.04	$^{+0.04}_{-0.03}$	$^{+0.08}_{-0.13}$	$^{+0.09}_{-0.05}$
$\langle A_{FB}(B \to K^* \mu^+ \mu^-) \rangle_{[1,6]}$	-0.06	± 0.04	± 0.02	± 0.01	—	—
$\langle F_L(B \to K^* \mu^+ \mu^-) \rangle_{[1,6]}$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

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

Main uncertainties from:

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

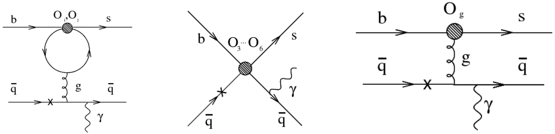
$B \to K^* \mu^+ \mu^-$ – Experimental results from LHCb



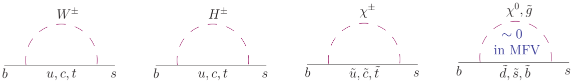
LHCB-CONF-2012-008

Other rare decays

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



Contributing loops:



First penguin ever observed!

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

SM prediction: $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.08 \pm 0.23) \times 10^{-4}$

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

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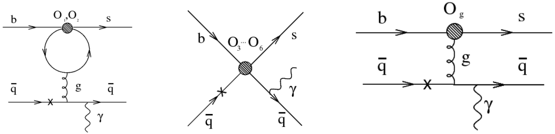

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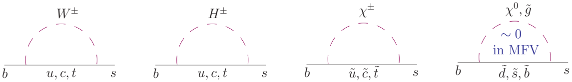

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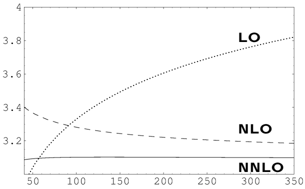
$B \to X_s \gamma$

NNLO calculations available for the SM

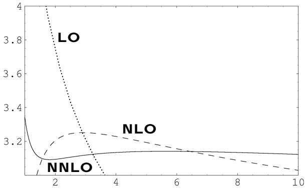
$$\mathrm{BR}(\bar{B} \to X_s \gamma)_{E_\gamma > E_0} = \mathrm{BR}(\bar{B} \to X_c e \bar{\nu})_{\mathrm{exp}} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6\alpha_{\mathrm{em}}}{\pi C} \left[P(E_0) + N(E_0) \right]$$

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

Reduced scale dependence:



μ_W-dependence

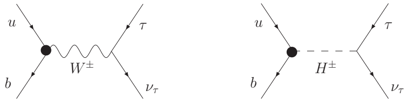


μ_b-dependence

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

$B \to \tau\nu$

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



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

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

⚠ Large uncertainty from V_{ub} and f_B

$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (1.15 \pm 0.29) \times 10^{-4}$
Theoretical uncertainty on $\mathrm{BR}(B \to \tau\nu)$: 25%

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

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

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

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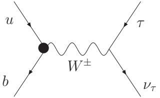

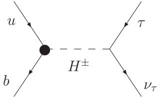

$$\mathrm{BR}(B \to \tau\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left|1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta}\right|^2$$

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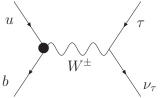

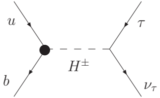

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Implications

CMSSM

CMSSM = MSSM with universality assumptions

→ 4 parameters + 1 sign

Two possible approaches:

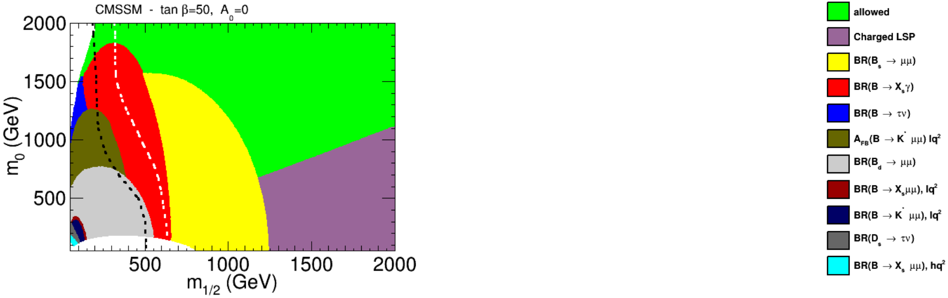
- Scans over 2 parameters, other parameters fixed
- Flat scans over all the parameters

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
m_0	[50, 3500]
$m_{1/2}$	[50, 3500]
A_0	[-10000, 10000]
$\text{sign}(\mu)$	± 1

Constraints on CMSSM

Constrained MSSM with m_0 and $m_{1/2}$ varied, $\mu > 0$, and A_0 and $\tan\beta$ fixed

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

FM, SuperIso v3.2

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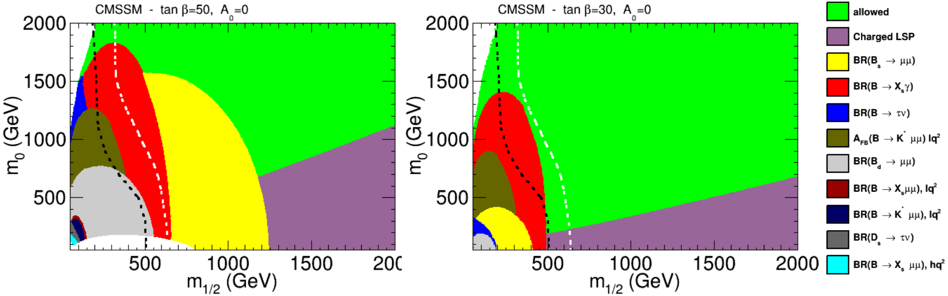

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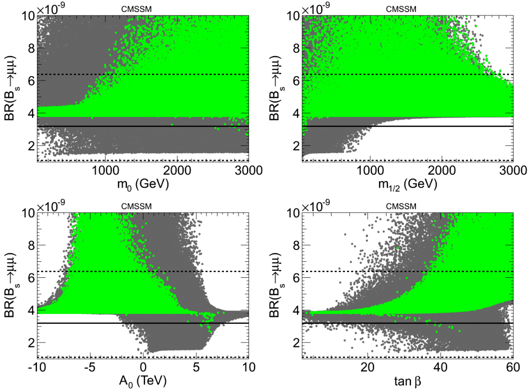
Constraints on CMSSM

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



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

Solid line: central value of the $BR(B_s \to \mu^+\mu^-)$ measurement

Dashed lines: 2σ experimental deviations

Gray points: all valid points

Green points: points in agreement with the Higgs mass constraint

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

pMSSM

MSSM with 19 parameters, CP and R-parity conservation

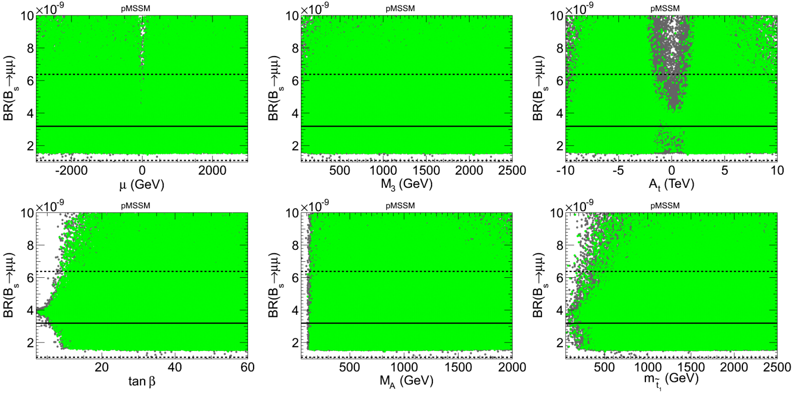
Parameter	Range (in GeV)
tan β	[1, 60]
M_A	[50, 2000]
M_1	[-2500, 2500]
M_2	[-2500, 2500]
M_3	[50, 2500]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[50, 2500]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[50, 2500]
$M_{\tilde{\tau}_L}$	[50, 2500]
$M_{\tilde{\tau}_R}$	[50, 2500]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[50, 2500]
$M_{\tilde{q}_{3L}}$	[50, 2500]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[50, 2500]
$M_{\tilde{t}_R}$	[50, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 2500]
$M_{\tilde{b}_R}$	[50, 2500]

Flat scans over the 19 parameters

$\sim$100M points generated with Softsusy

Flavour constraints with SuperIso

Constraints on pMSSM from BR($B_s \to \mu^+\mu^-$)



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

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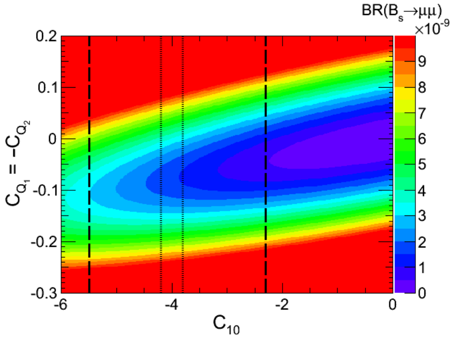
Constraints on pMSSM from BR($B_s \to \mu^+\mu^-$)

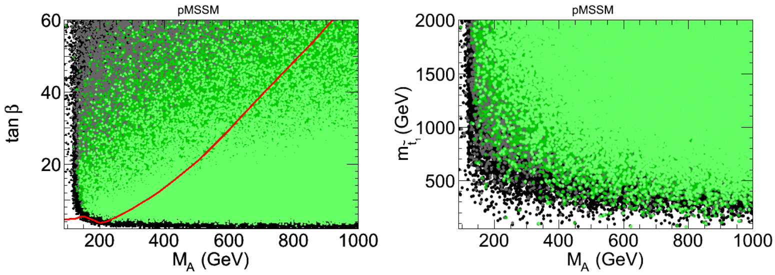


A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

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

Constraints on pMSSM from BR($B_s \to \mu^+\mu^-$)

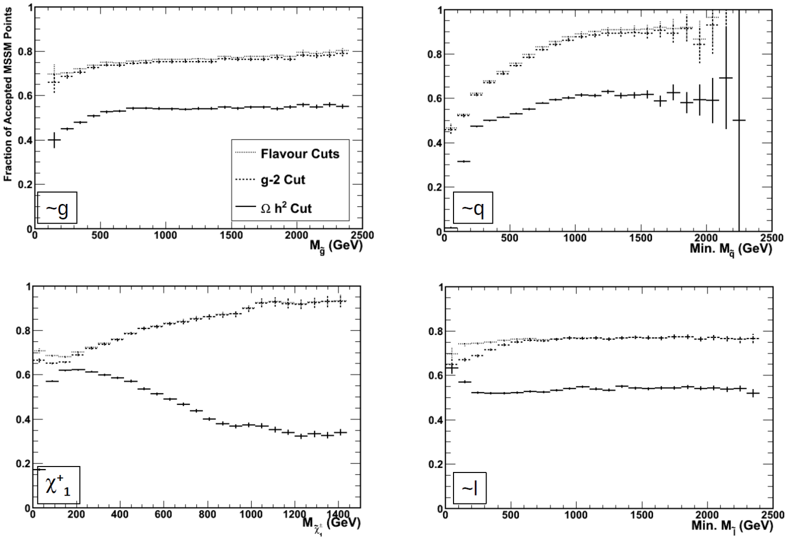
pMSSM



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($B_s \to \mu^+\mu^-$)
Light green points: in agreement with the ultimate LHCb BR($B_s \to \mu^+\mu^-$) measurement
Red line: excluded at 95% C.L. by the latest CMS $A/H \to \tau^+\tau^-$ searches

Constraints on pMSSM from flavour physics



A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1847

Conclusion

- Flavour physics plays a very important role in constraining BSM scenarios
- $B_s \to \mu^+\mu^-$ is a particularly sensive to the scalar contributions and the high $\tan\beta$ regime
- $B \to K^*\mu^+\mu^-$ offers multiple sensitive observables

  $\to$ complementary information!
- Theory uncertainties under control
- Regions with large $\tan\beta$ and small M_A disfavoured
- With more data constraints will tighten!
- Interesting interplay also with the Higgs and Dark Matter searches!

Flavour physics can guide direct searches!

Backup

Backup

$\mathrm{BR}(B_s \to \mu^+\mu^-)$

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. D86, 014027; Phys. Rev. Lett. 109, 041801 (2012)

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

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:

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

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

The SM expectation for this corrected branching fraction is:

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

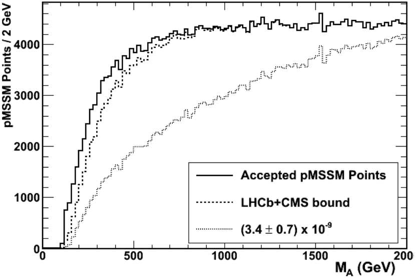
General MSSM – Sensitivity to M_A from $\mathrm{BR}(B_s \to \mu^+\mu^-)$

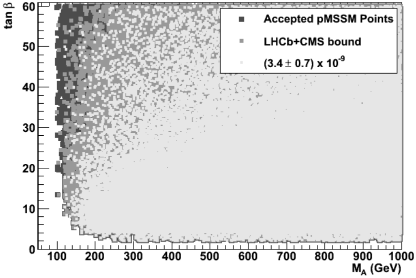
Considering 2 scenarios:

- 2011 bound from LHCb+CMS + estimated th syst:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$$

- SM like branching ratio with estimated 20% total uncertainty





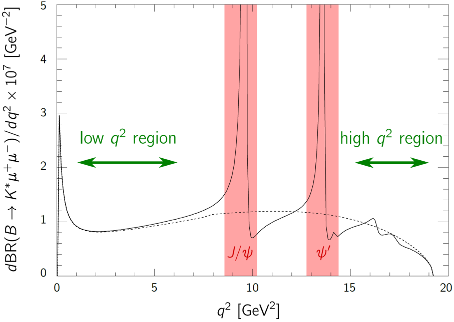
Light M_A strongly constrained!

A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1847
A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

$B \to K^* \mu^+ \mu^-$ – Low q^2 vs high q^2

Two regions of interest:

- Low q^2 $(1 - 6\ \text{GeV}^2)$
- High q^2 $(14.18 - 16\ \text{GeV}^2)$



$D_s \to \ell\nu$

Tree level process similar to $B \to \tau\nu$

$$\mathcal{B}(D_s \to \ell\nu) = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s}^2 m_\ell^2 M_{D_s} \tau_{D_s} \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right)^2$$
$$\times \left[1 + \left(\frac{1}{m_c + m_s}\right) \left(\frac{M_{D_s}}{m_{H^+}}\right)^2 \left(m_c - \frac{m_s \tan^2\beta}{1 + \epsilon_0 \tan\beta}\right)\right]^2 \quad \text{for } \ell = \mu, \tau$$

- Competitive with and complementary to analogous observables
- Dependence on only one lattice QCD quantity
- Interesting if lattice calculations eventually prefer $f_{D_s} < 250$ MeV
- Promising experimental situation (BES-III)

⚠ Sensitive to f_{D_s} and m_s/m_c

Double ratios

Example of double ratio of leptonic decays:

$$R = \left(\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_u \to \tau\nu)}\right) \Big/ \left(\frac{\mathrm{BR}(D_s \to \tau\nu)}{\mathrm{BR}(D \to \mu\nu)}\right)$$

From the form factor point of view:

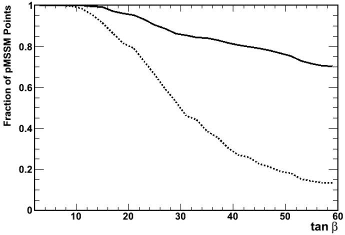
$$R \propto \left(\frac{f_{B_s}}{f_B}\right)^2 \Big/ \left(\frac{f_{D_s}}{f_D}\right)^2 \approx 1$$

R has no dependence on the form factors, contrary to each decay taken individually!

- No dependence on lattice quantities
- Interesting for V_{ub} determination
- Interesting for probing new physics
- Promising experimental situation

B. Grinstein, Phys. Rev. Lett. 71 (1993)
A.G. Akeroyd, FM, JHEP 1010 (2010)

Constraints on pMSSM

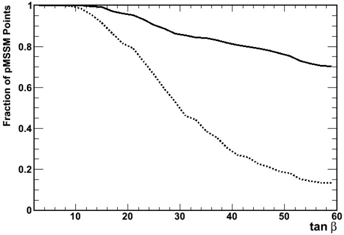


A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

Continuous line: in agreement with the latest BR($B_s \to \mu^+\mu^-$) measurement
Dotted line: in agreement with the ultimate LHCb BR($B_s \to \mu^+\mu^-$) measurement

Fraction of points	Current bounds	Projected bounds
All pMSSM points	95.3%	67.8%
Accepted pMSSM points	97.7%	78.1%
Points not excluded by LHC searches	95.1%	63.3%
Points compatible at 90% C.L. with Higgs results	97.2%	70.0%

Constraints on pMSSM



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

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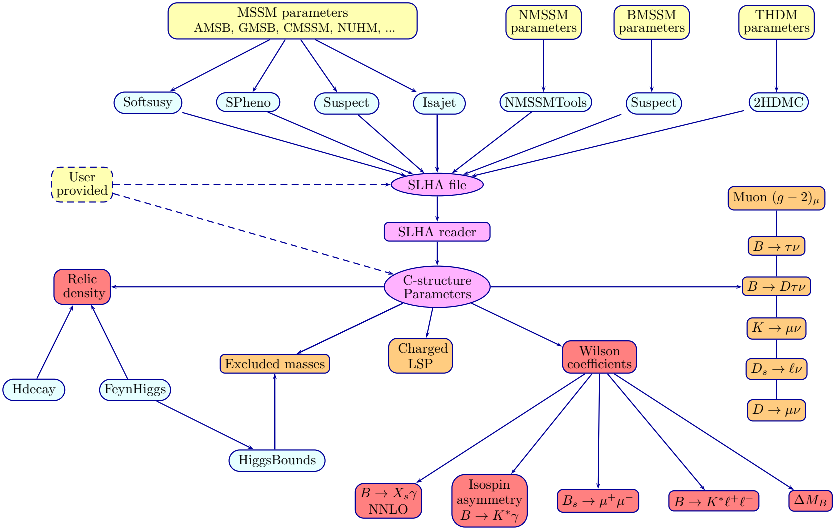
SuperIso

- public C program
- dedicated to the flavour physics observable calculations
- various models implemented
- interfaced to several spectrum calculators
- modular program with a well-defined structure
- complete reference manuals available

http://superiso.in2p3.fr

FM, Comput. Phys. Commun. 178 (2008) 745
FM, Comput. Phys. Commun. 180 (2009) 1579
FM, Comput. Phys. Commun. 180 (2009) 1718

SuperIso



MSSM parameters
AMSB, GMSB, CMSSM, NUHM, ...
NMSSM parameters
BMSSM parameters
THDM parameters
Softsusy
SPheno
Suspect
Isajet
NMSSMTools
Suspect
2HDMC
User provided
SLHA file
SLHA reader
C-structure Parameters
Relic density
Hdecay
FeynHiggs
HiggsBounds
Excluded masses
Charged LSP
Wilson coefficients
$B \to X_s\gamma$ NNLO
Isospin asymmetry $B \to K^*\gamma$
$B_s \to \mu^+\mu^-$
$B \to K^*\ell^+\ell^-$
ΔM_B
Muon $(g-2)_\mu$
$B \to \tau\nu$
$B \to D\tau\nu$
$K \to \mu\nu$
$D_s \to \ell\nu$
$D \to \mu\nu$