SuperIso: status and prospects

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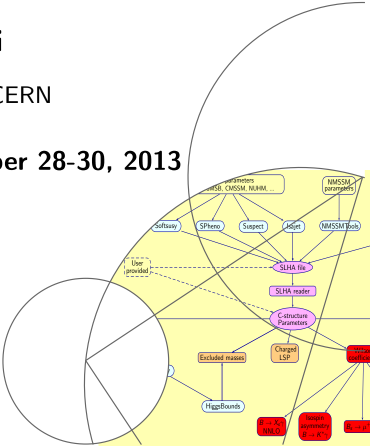

Outline

1. SuperIso
2. SuperIso Relic
3. Implications: $B \to K^* \mu^+ \mu^-$
4. Prospects
5. Conclusion

SuperIso

- public C program
- dedicated to the **flavour physics** observable calculations
- based on the most precise calculations publicly available
- various models implemented
- interfaced to several spectrum calculators
- modular program with a well-defined structure
- complete reference manual available ($\sim$ 150 pages)

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

A multi-scale problem

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

$\Rightarrow$ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

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

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

New physics:

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

The Calculation

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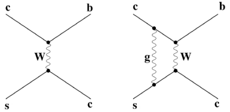
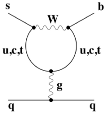
Operators

$$O_1 = (\bar{s}\gamma_\mu T^a P_L c)(\bar{c}\gamma^\mu T^a P_L b)$$
$$O_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b)$$

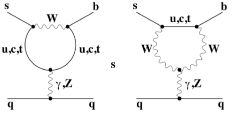


Current

$$O_3 = (\bar{s}\gamma_\mu P_L b)\sum_q(\bar{q}\gamma^\mu q)$$
$$O_4 = (\bar{s}\gamma_\mu T^a P_L b)\sum_q(\bar{q}\gamma^\mu T^a q)$$
$$O_5 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} P_L b)\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} q)$$
$$O_6 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} T^a P_L b)\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} T^a q)$$

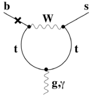


QCD penguins



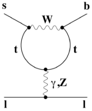
Electroweak penguins

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



Magnetic operators

$$O_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{l}\gamma_\mu l)$$
$$O_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{l}\gamma_\mu\gamma_5 l)$$



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 $\hat{\gamma}^{eff}(\mu)$:

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

Hadronic quantities

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?

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

$\rightarrow$ 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

I) Radiative penguin decays

- inclusive branching ratio of $B \to X_{s,d}\gamma$
- isospin asymmetry of $B \to K^*\gamma$

II) Electroweak penguin decays

- branching ratios of $B_{s,d} \to \mu^+\mu^-$
- observables related to $B \to X_s \ell^+\ell^-$: BR, A_{FB}, zero-crossing $q_0^2(A_{FB})$
- observables related to $B \to K^*\mu^+\mu^-$: BR, A_{FB}, $q_0^2(A_{FB})$, F_L, $A_T^{(i)}$, ...

III) Neutrino modes

- branching ratio of $B \to \tau\nu$
- branching ratio of $B \to D\tau\nu$
- branching ratios of $D_s \to \tau\nu/\mu\nu$
- branching ratios of $D \to \mu\nu$
- branching ratio of $K \to \mu\nu$

IV) Others

- Electroweak precision tests: oblique parameters (S, T, U), ρ, Γ_Z
- Muon anomalous moment a_μ
- Direct search limits
- Relic density

Models

Standard Model

General Two Higgs Doublet Model

automatic interface with 2HDMC for

- General 2HDM and Types I, II, III, IV

MSSM (with Minimal Flavour Violation)

automatic interfaces with Softsusy, Isajet, Spheno and Suspect available for

- CMSSM, NUHM, AMSB, HC-AMSB, MM-AMSB, GMSB, pMSSM

NMSSM

automatic interface with NMSSMTools available for

- CNMSSM, NNUHM, NGMSB

BMSSM

automatic interface with a modified version of Suspect

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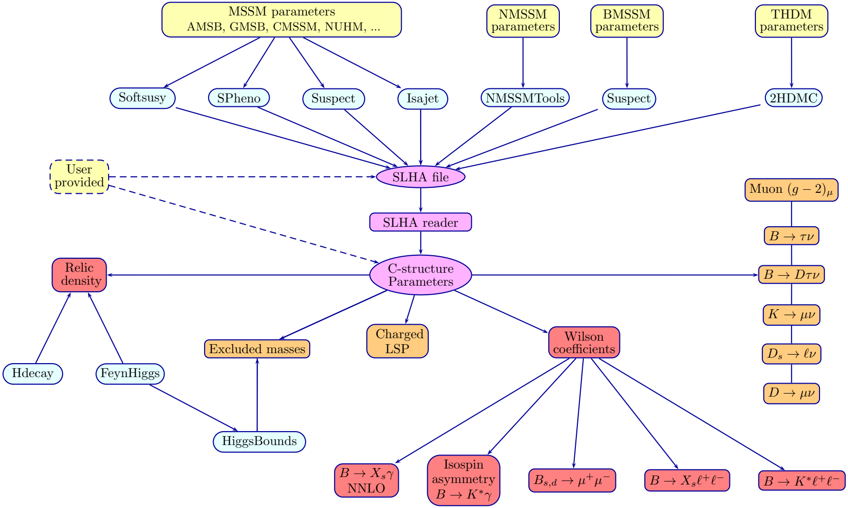
SuperIso v3.4



Download

http://superiso.in2p3.fr

SuperIso

By Farvah Nazila Mahmoudi

SuperIso
- Description
- Manual

SuperIso Relic
- Description
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AlterBBN
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Links

Calculation of flavour physics observables

SuperIso is a program for calculation of flavour physics observables in the Standard Model (SM), general two-Higgs-doublet model (2HDM), minimal supersymmetric Standard Model (MSSM) and next to minimal supersymmetric Standard Model (NMSSM). SuperIso, in addition to the isospin asymmetry of B -> K* gamma, which was the main purpose of the first version, incorporates other flavour observables such as the branching ratio of B -> Xs gamma at NNLO, the branching ratio of Bs -> mu+ mu-, the branching ratio of B -> tau nu, the branching ratio of B -> D tau nu, the branching ratio of K -> mu nu as well as the branching ratios of Ds -> tau nu and Ds -> mu nu, and many observables from the B -> Xs l+ l- and B -> K* mu+ mu- decays. It also computes the muon anomalous magnetic moment (g-2).

SuperIso uses a SUSY Les Houches Accord file (SLHA1 or SLHA2) as input, which can be either generated automatically by the program via a call to SOFTSUSY, ISAJET, SPHENO, SUSPECT, NMSSMTools or provided by the user. SuperIso can also use the LHA inspired format for the 2HDM generated by 2HDMC.

Since version 2.8, SuperIso is FLHA compliant, and generates automatically an output FLHA file. SuperIso v2.8 includes also an interface with HiggsBounds v2.

SuperIso is able to perform the calculations automatically in the SM, in the 2HDM (general 2HDM or types I-IV) and in different supersymmetric scenarios, such as CMSSM, NUHM, AMSB, and GMSB (for MSSM) and CNMSSM, NGMSB and NNUHM (for NMSSM).

For any comment, question or bug report please contact Nazila Mahmoudi.

Manual

NEW **The latest version of the manual can be found here (16 June 2012).**

For more information:

- F. Mahmoudi, **New constraints on supersymmetric models from b -> s gamma**
  arXiv:0710.3791 [hep-ph], JHEP 0712 (2007), 026

SuperIso Relic

SuperIso Relic = SuperIso (flavor physics calculator)
+ relic density calculation

Structure of the code

- Generation of a SLHA file with the SuperIso interfaces
- Generation of extra Higgs sector variables with Hdecay/FeynHiggs
- Calculation of W_{eff} and $\langle \sigma_{\text{eff}} v \rangle$
- Solving of the Boltzmann equation→ Relic density

Status

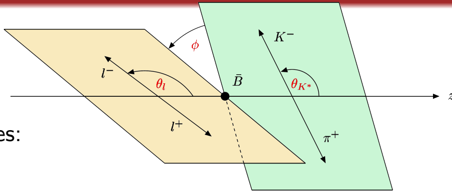
- Calculation of amplitudes within MSSM and NMSSM with MFV at tree level fully implemented (more than 7000 processes involved)
- Different cosmological models implemented
- BBN constraints to test the cosmological models available through an interface with AlterBBN v1.4 (by A. Arbey)

A. Arbey, FM, Comput. Phys. Commun. 181 (2010) 1277
A. Arbey, FM, Comput. Phys. Commun. 182 (2011) 1582

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

Angular distributions

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



Differential decay distribution:

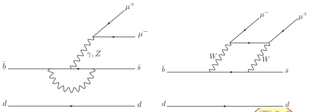
$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$
$J_i(q^2)$: angular coefficients $J^{s,c}_{1-9}$
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:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\gamma_5 \ell)$$



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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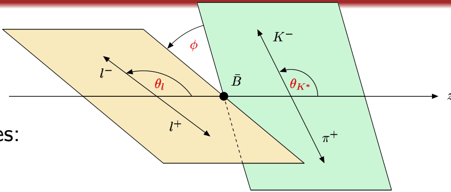

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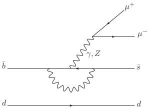

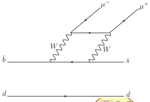

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W. Altmannshofer et al., JHEP 0901 (2009) 019; U. Egede et al., JHEP 1010 (2010) 056

$B \to K^* \mu^+ \mu^-$ – "Standard" Observables

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

Forward backward asymmetry:

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

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

$\rightarrow$ fix the sign of C_9/C_7

Polarization fractions:

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

Transverse asymmetries:

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

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

D. Becirevic, E. Schneider, Nucl. Phys. B854 (2012) 321

$\rightarrow$ **Reduced form factor uncertainties**

$B \to K^* \mu^+ \mu^-$ – Optimized observables

Optimized: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\rm bin} = \frac{1}{2} \frac{\int_{\rm bin} dq^2 [J_3 + \bar{J}_3]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\rm bin} = \frac{1}{8} \frac{\int_{\rm bin} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]}$$

$$\langle P'_4 \rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_4 + \bar{J}_4] \qquad \langle P'_5 \rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P'_6 \rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_7 + \bar{J}_7] \qquad \langle P'_8 \rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_8 + \bar{J}_8]$$

with

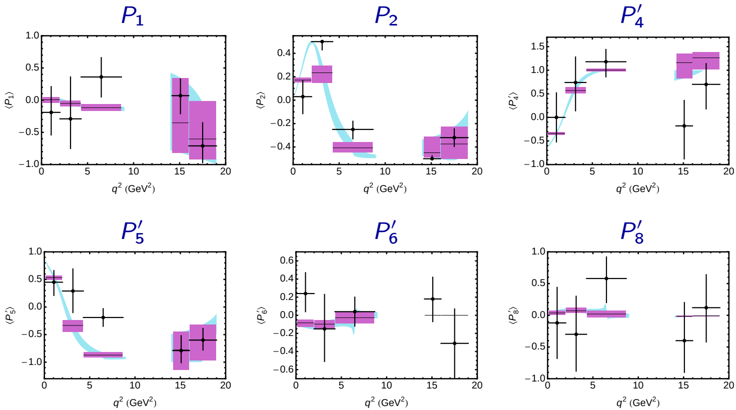
$$\mathcal{N}'_{\rm bin} = \sqrt{-\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}] \int_{\rm bin} dq^2 [J_{2c} + \bar{J}_{2c}]}$$

+ CP violating clean observables and other combinations

U. Egede et al., JHEP 0811 (2008) 032, JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

Experimental results

First observation by LHCb:

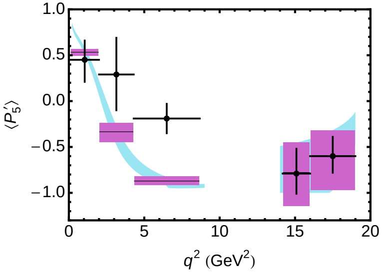


LHCb collaboration, arXiv:1308.1707 [hep-ex]

Anomaly...

3.7σ local discrepancy in one of the q^2 bins

$(P_5', 4.3 < q^2 < 8.68 \text{ GeV}^2)$



Possible explanations:

- Statistical fluctuations
- Underestimation of hadronic uncertainties
- New Physics!

S. Descotes-Genon, J. Matias, J. Virto, arXiv:1307.5683
W. Altmannshofer, D. M. Straub, arXiv:1308.1501
R. Gauld, F. Goertz, U. Haisch, arXiv:1308.1959, arXiv:1310.1082
F. Beaujean, C. Bobeth, D. van Dyk, arXiv:1310.2478

All these observables (and more!) now implemented in SuperIso

New Physics interpretation?

Global analysis of the latest LHCb data under the hypothesis of

Minimal Flavour Violation

→ need for new flavour structure?

Relevant $\mathcal{O}$perators:

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

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

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

→ Scans over the values of δC_7, δC_8, δC_9, δC_{10}, $\delta C'_0$

→ Calculation of flavour observables

→ Comparison with experimental results

→ Constraints on the Wilson coefficients C_i

→ Prediction for other flavour observables

Observables

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

$$\chi^2 = (\vec{O}^{\rm th} - \vec{O}^{\rm exp}) \cdot \Sigma^{-1} \cdot (\vec{O}^{\rm th} - \vec{O}^{\rm exp})$$

Σ^{-1} is the inverse correlation matrix.

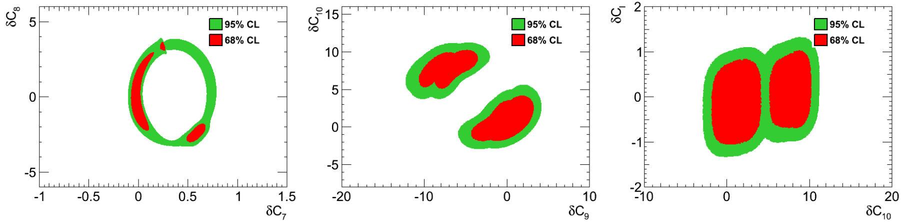
Observables:

- BR($B \to X_s \gamma$)
- BR($B \to X_d \gamma$)
- $\Delta_0(B \to K^* \gamma)$
- BR$^{\rm low}(B \to X_s \mu^+ \mu^-)$
- BR$^{\rm high}(B \to X_s \mu^+ \mu^-)$

- BR($B_s \to \mu^+ \mu^-$)
- BR($B_d \to \mu^+ \mu^-$)
- $B \to K^* \mu^+ \mu^-$
  P_1, P_2, P'_4, P'_5, P'_4, P'_8, BR, F_L
  in 5 bins of q^2:
  [0.1,2], [2,4.3], [4.3,8.68], [14.18,16], [16,19] GeV^2

Fit results

Before LHCb:

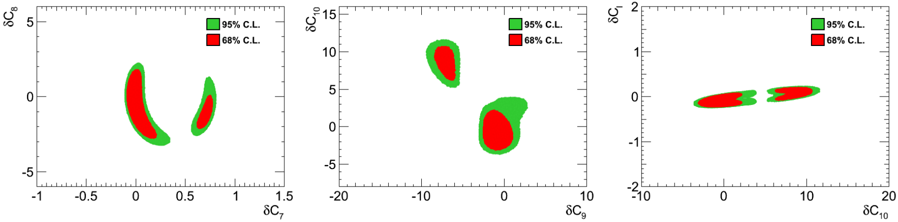


T. Hurth, FM, Nucl.Phys. B865 (2012) 461

- C_8 mostly constrained by $B \to X_{s,d}\gamma$
- C_7 constrained by the other observables as well
- $C_{9,10}$ constrained by $B \to X_s \mu^+\mu^-$ and $B \to K^* \mu^+\mu^-$
- C_l mostly constrained by $B_s \to \mu^+\mu^-$

Fit results

With the latest LHCb results



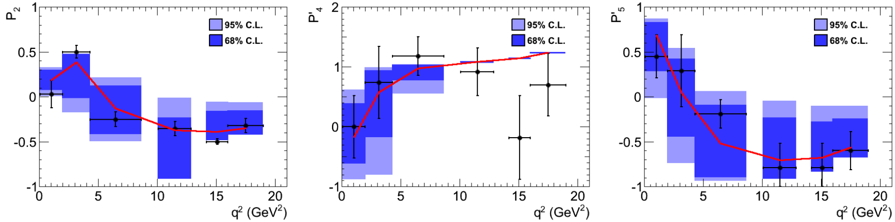
T. Hurth, FM, N. Serra, to appear

Strong impact from the new LHCb results on the fits!

MFV bounds

Global fit results for P_2, P_4' and P_5' in each q^2 bin:

Using all the observables:



T. Hurth, FM, N. Serra, to appear

The red line is *indicative* and shows the predictions for the best fit point

Less than 2σ agreement of the best fit point in all the bins!

Prospects

As usual, continuous effort in adding new observables and models

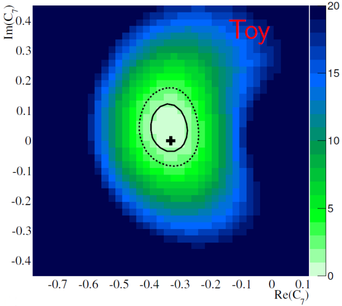
In addition, two new directions:

- In collaboration with LHCb members, using $B \to K^* \mu^+ \mu^-$ data:

  Direct fit of Wilson coefficients with an unbinned approach

  Global fit of the differential decay rate $\dfrac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi}$

  Use of toy datasets before using real data



Courtesy of C. Langenbruch

Prospects

- In collaboration with A. Arbey, B. Fuks, D. Tant: Extension to generic models

  Use of FeynRules to generate the Feynman rules

  - First step: Relic density

    SuperIso Relic currently uses amplitudes computed with FormCalc

    Two possibilities for the generic implementation:

    - FeynRules $\to$ FormCalc $\to$ SuperIso Relic

    - FeynRules $\to$ SuperIso Relic

  - Second step: Wilson coefficients

    Two possible approaches:

    - for each model, full amplitude calculation with FeynRules/Formcalc and matching with effective calculation

    - calculation of Wilson coefficients for generic diagrams, then mapping to the model

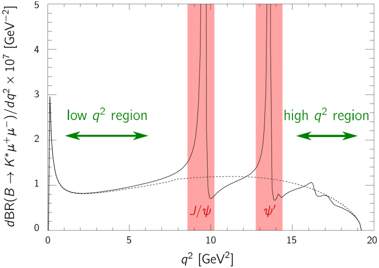
Conclusion

- Indirect constraints from flavour observables are essential to restrict new physics parameters
- Complementary to direct searches
- $B \to K^* \mu^+ \mu^-$ offers multiple sensitive observables
- SuperIso program provides the possibility to calculate many flavour observables in different models
- More than 50 observables already implemented in 2HDM and SUSY
- Generic implementation to go beyond SUSY is starting...

Backup

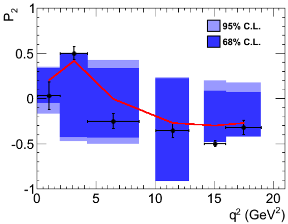
$B \to K^* \mu^+ \mu^-$ – Low q^2 vs high q^2

- Low q^2
  - small $1/m_b$ corrections
  - sensitivity to the interference of C_7 and C_9
  - high rate
  - long-distance effects not fully under control
  - non-negligible scale and m_c dependence
- High q^2
  - negligible scale and m_c dependence due to the strong sensitivity to C_{10}
  - negligible long-distance effects of the type $B \to J/\Psi X_s \to X_s + X' \ell^+ \ell^-$
  - sizable $1/m_b$ corrections
  - low rate

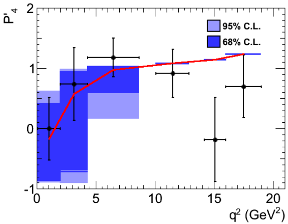


MFV predictions

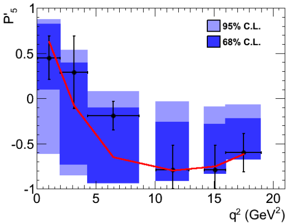
We can remove observables out of the fit, and make predictions for them



w/o P_2 in the fit



w/o P_4' in the fit



w/o P_5' in the fit

red line: predictions for the best fit point

Still no significant deviation from MFV predictions...