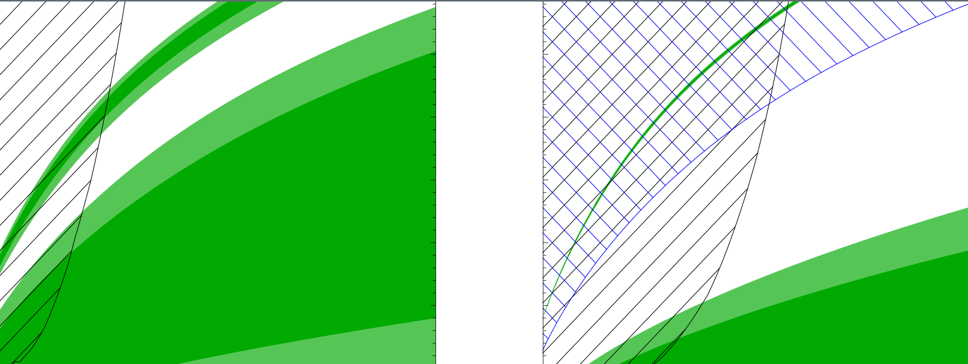
2017-12-18, Workshop “Impact of $B \to \mu\mu$ on New Physics Searches”, PSI

Impact of future $B_s \to \mu\mu$ measurements (on scalar new physics)

David M. Straub Universe Cluster/TUM, Munich



Advertisement (unrelated to this talk)

python-smeftrunner

- Python version of `DsixTools` for numerical evolution of SMEFT Wilson coefficients:
  - `https://github.com/DsixTools/python-smeftrunner`
  - By X. Pan & DS

WCxf

- New data exchange format for Wilson coefficients and complete, automatic (tree-level) SMEFT $\to$ WET matching
  - `https://wcxf.github.io`
  - Aebischer et al. 1712.05298

Credits (related to this talk)

Based on

"$B_s \to \mu^+\mu^-$ as current and future probe of new physics"

Wolfgang Altmannshofer, Christoph Niehoff & DS

arXiv:1702.05498

flavio

All the numerics was performed with the `flavio` open source code

- web site: `https://flav-io.github.io`
- repository with numerics from our paper: `https://github.com/DavidMStraub/paper-bsmumu-ans`

1 Introduction

2 New physics in scalar operators

B_s lifetime difference

Due to B_s-$\bar{B}_s$ mixing, there is a sizable lifetime difference between the two B_s mass eigenstates:

$$\tau_{B_s^L} = \Gamma_{B_s^L}^{-1} = 1.42\,\text{ps} \qquad \tau_{B_s^H} = \Gamma_{B_s^H}^{-1} = 1.61\,\text{ps}$$

$$\tau_{B_s} = \Gamma_{B_s}^{-1} = \left[\frac{1}{2}\left(\Gamma_{B_s^L} + \Gamma_{B_s^H}\right)\right]^{-1}$$

$B_s \to \mu^+\mu^-$: time dependence

Untagged time-dependent rate De Bruyn et al. 1204.1737

$$\Gamma(B_s(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s(t) \to \mu^+\mu^-) =$$
$$R_H\, e^{-t/\tau_{B_s^H}} + R_L\, e^{-t/\tau_{B_s^L}}$$
$$= (R_H + R_L)\left[\cosh\left(\frac{y_s t}{\tau_{B_s}}\right) + A_{\Delta\Gamma} \sinh\left(\frac{y_s t}{\tau_{B_s}}\right)\right] \times e^{-t/\tau_{B_s}}$$

$$\Delta\Gamma_s = \Gamma_{B_s^L} - \Gamma_{B_s^H} \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} = 0.065 \pm 0.005$$

$$A_{\Delta\Gamma}^{\mathrm{SM}} \equiv 1$$

NB: flavour tagging would give access to CP asymmetries Buras et al. 1303.3820, Fleischer et al. 1709.04735

Mass-eigenstate rate asymmetry

$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)}$$

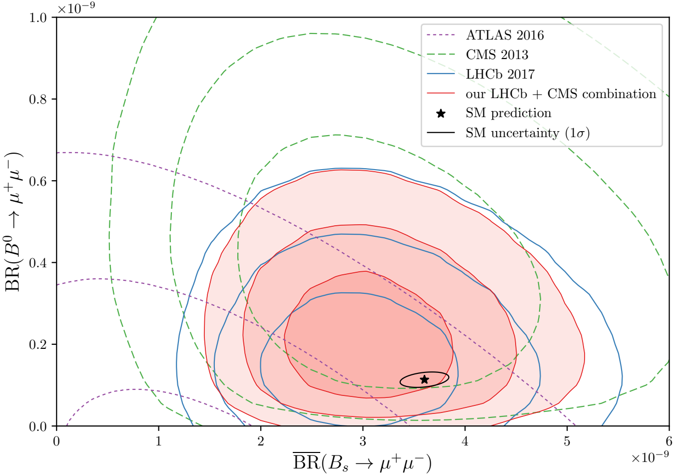
- 1:1 correspondence with *effective lifetime*

$$A_{\Delta\Gamma} = \frac{1}{y_s} \frac{(1-y_s^2)\tau_{\mu\mu} - (1+y_s^2)\tau_{B_s}}{2\tau_{B_s} - (1-y_s^2)\tau_{\mu\mu}}$$

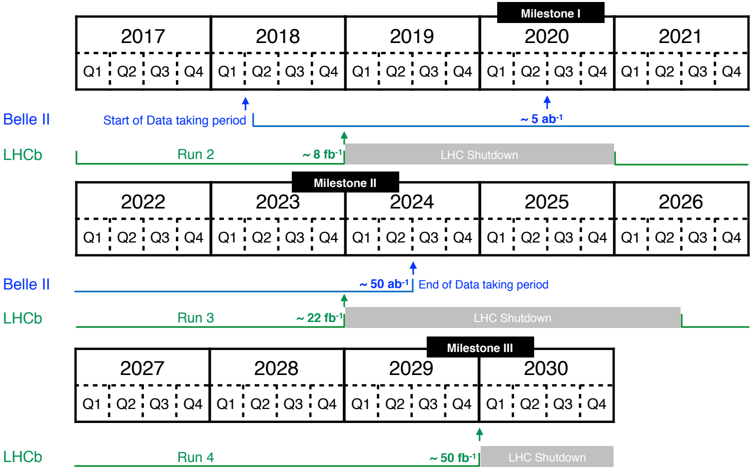
- First measurement of $\tau_{\mu\mu}$ by LHCb does not constrain $A_{\Delta\Gamma} \in [-1, 1]$ yet

$B_q \to \mu^+\mu^-$: experimental status

Unofficial world average



Future


Milestone I
2017
2018
2019
2020
2021
Q1 Q2 Q3 Q4
Belle II
Start of Data taking period
~ 5 ab-1
LHCb
Run 2
~ 8 fb-1
LHC Shutdown
Milestone II
2022
2023
2024
2025
2026
Belle II
~ 50 ab-1
End of Data taking period
LHCb
Run 3
~ 22 fb-1
LHC Shutdown
Milestone III
2027
2028
2029
2030
LHCb
Run 4
~ 50 fb-1
LHC Shutdown

Future scenarios

LHCb uncertainties

Naive theorists' scalings using some LHCb projections LHCb-PUB-2014-040

$$\sigma_{\rm exp}(B_s \to \mu^+\mu^-) = 0.19 \times 10^{-9} \qquad \sigma_{\rm exp}(A_{\Delta\Gamma}) = 0.8 \qquad \text{(Run 4)}$$
$$\sigma_{\rm exp}(B_s \to \mu^+\mu^-) = 0.08 \times 10^{-9} \qquad \sigma_{\rm exp}(A_{\Delta\Gamma}) = 0.3 \qquad \text{(Run 5)}$$

Theory uncertainties

Assuming $\sigma_{f_{B_s}} \sim 1$ MeV and sub-percent lattice computation of $B \to D$ form factors ($V_{cb} \sim -V_{ts}$)

$$\sigma_{\rm th}(B_s \to \mu^+\mu^-) = 0.06 \times 10^{-9} \qquad \sigma_{\rm th}(A_{\Delta\Gamma}) \approx 0$$

1. Introduction
2. New physics in scalar operators

Model-independent NP analysis

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{e^2}{16\pi^2} \sum_{i\in[10,S,P]} [C_i O_i + C_i' O_i' + \text{h.c.}] \,,$$

$$\begin{aligned} O_{10}^{(\prime)} &= (\bar{s}_{L(R)}\gamma_\rho b_{L(R)})(\bar{\mu}\gamma^\rho\mu) \\ O_S^{(\prime)} &= m_b(\bar{s}_{L(R)} b_{R(L)})(\bar{\mu}\mu) \\ O_P^{(\prime)} &= m_b(\bar{s}_{L(R)} b_{R(L)})(\bar{\mu}\gamma_5\mu) \end{aligned}$$

- Not all independent, since SMEFT dimension-6 relations imply
  Alonso et al. 1407.7044, Aebischer:2015fzz

$$C_S = -C_P = \frac{v^2}{4} C_{ledq}^{ji32*} \qquad C_S' = C_P' = \frac{v^2}{4} C_{ledq}^{ij23}$$

Modification of observables

$$\text{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2}{16\pi^3} \left|V_{ts}V_{tb}^*\right|^2 f_{B_s}^2 \tau_{B_s} m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \left|C_{10}^{\text{SM}}\right|^2 \left(|P|^2 + |S|^2\right)$$

$$A_{\Delta\Gamma} = \frac{|P|^2 \cos(2\varphi_P - \varphi_s^{\text{NP}}) - |S|^2 \cos(2\varphi_S - \varphi_s^{\text{NP}})}{|P|^2 + |S|^2}$$

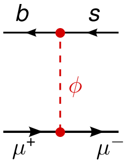
$$P = \frac{C_{10} - C'_{10}}{C_{10}^{\text{SM}}} + \frac{M_{B_s}^2}{2m_\mu} \frac{m_b}{m_b + m_s} \left(\frac{C_P - C'_P}{C_{10}^{\text{SM}}}\right)$$

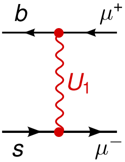
$$S = \sqrt{1 - 4\frac{m_\mu^2}{M_{B_s}^2}} \frac{M_{B_s}^2}{2m_\mu} \frac{m_b}{m_b + m_s} \left(\frac{C_S - C'_S}{C_{10}^{\text{SM}}}\right),$$

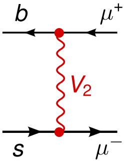
$A_{\Delta\Gamma}$ probes new physics in (pseudo-)scalar operators

How to generate large effects in $C_{S,P}^{(\prime)}$?

At tree level, 3 possibilities: neutral scalar; vector leptoquarks



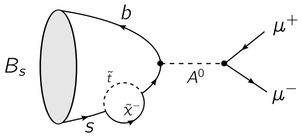




$\varphi \sim (1,2)_{1/2}$ $U_1 \sim (3,1)_{2/3}$ $V_2 \sim (\bar{3},2)_{5/6}$

MFV MSSM

- Contributions to $C_{S,P}$ are generated by H^0 and A^0 exchange



- Dominant contribution: chargino-stop loop

$$C_S \simeq -C_P \propto \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{m_{B_s} m_\mu}{m_A^2} \tan^3 \beta$$

- Present even for degenerate spectrum & flavour-blind SUSY breaking terms
- Potentially huge enhancement for large $\tan \beta$

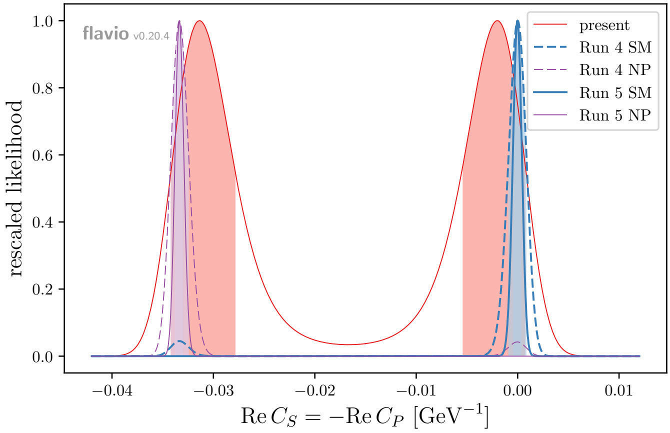
MFV MSSM: observables

$C_S = -C_P$. $S \simeq 1 - P \equiv A$

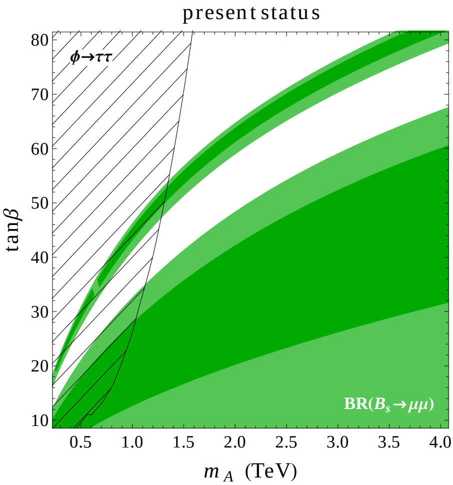
$$\begin{aligned} \frac{\overline{\text{BR}}(B_s \to \mu^+\mu^-)}{\overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{SM}}} &= (1-A)^2 + A^2 - \frac{y_s}{1+y_s} 2A^2 \geq \frac{1}{2} \\ A_{\Delta\Gamma} &= \frac{(1-A)^2 - A^2}{(1-A)^2 + A^2} \end{aligned}$$

- For $A = 1$, BR is unaffacted but $A_{\Delta\Gamma}$ changes sign!

Constraint on $C_S = -C_P$

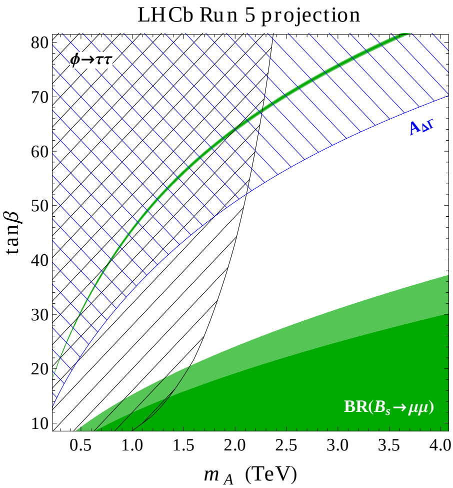


Complementarity with Higgs searches



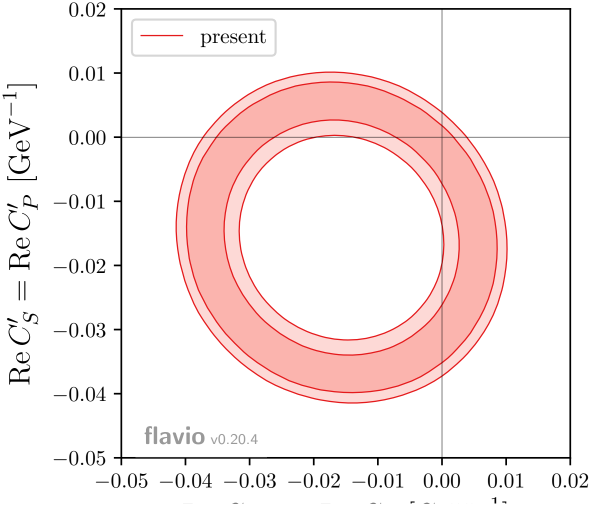
- $B_s \to \mu^+\mu^-$ is complementary to Higgs physics ($H/A \to \tau^+\tau^-$)
- Two disjoint solutions corresponding to different overall signs of the amplitude. How to disentangle?

Complementarity with Higgs searches



- $A_{\Delta\Gamma}$ can exclude (or confirm??) second solution

General constraint on real $C_{S,P}^{(\prime)}$



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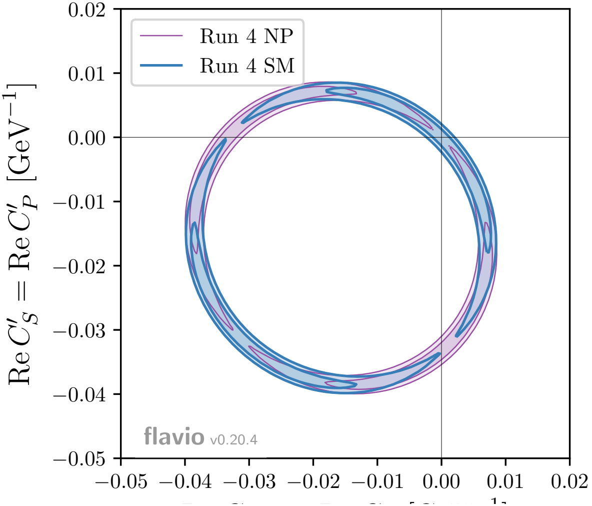
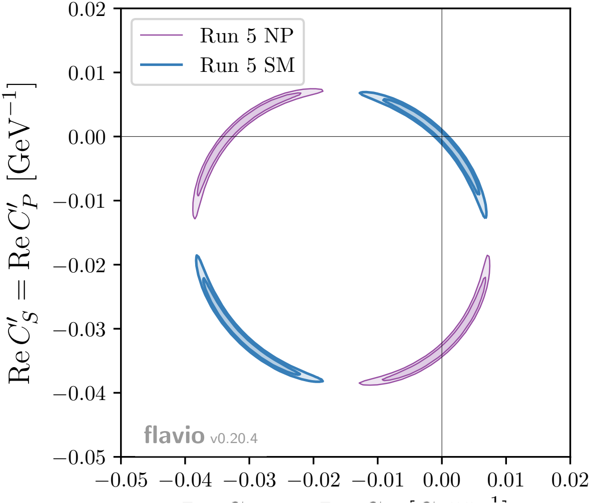
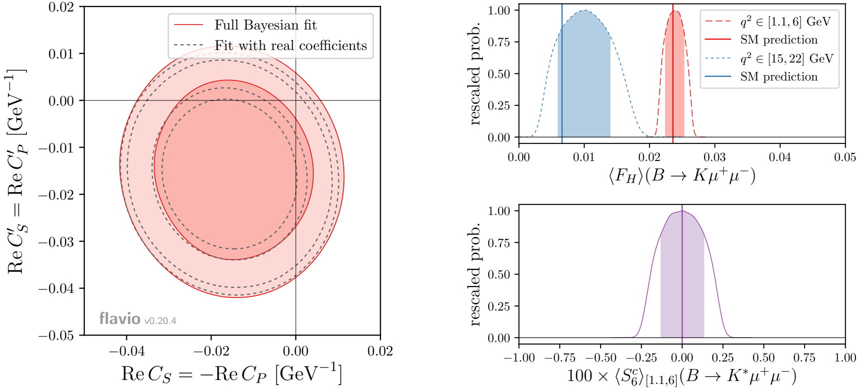


General constraint on real $C_{S,P}^{(\prime)}$

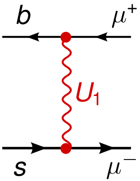


Bayesian fit of complex $C_{S,P}^{(\prime)}$



Leptoquarks: the U_1 example

$$\mathcal{L}_{U_1} = \hat{\lambda}_{\rm L}^{ij} \left(\bar{Q}_{\rm L}^i \gamma_\mu L_{\rm L}^j\right) U_1^\mu + \hat{\lambda}_{\rm R}^{ij} \left(\bar{d}_{\rm R}^i \gamma_\mu e_{\rm R}^j\right) U_1^\mu + \text{h.c.}$$



$C_9^{\rm NP}$	$-\frac{1}{2}\mathcal{N}\lambda_L^{s\mu}\lambda_L^{b\mu\,*}$
C_9'	$-\frac{1}{2}\mathcal{N}\lambda_R^{s\mu}\lambda_R^{b\mu\,*}$
$C_{10}^{\rm NP}$	$\frac{1}{2}\mathcal{N}\lambda_L^{s\mu}\lambda_L^{b\mu\,*}$
C_{10}'	$-\frac{1}{2}\mathcal{N}\lambda_R^{s\mu}\lambda_R^{b\mu\,*}$
$C_S = -C_P$	$\mathcal{N}\lambda_L^{s\mu}\lambda_R^{b\mu\,*}\,m_b^{-1}$
$C_S' = C_P'$	$\mathcal{N}\lambda_R^{s\mu}\lambda_L^{b\mu\,*}\,m_b^{-1}$

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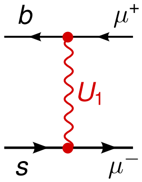
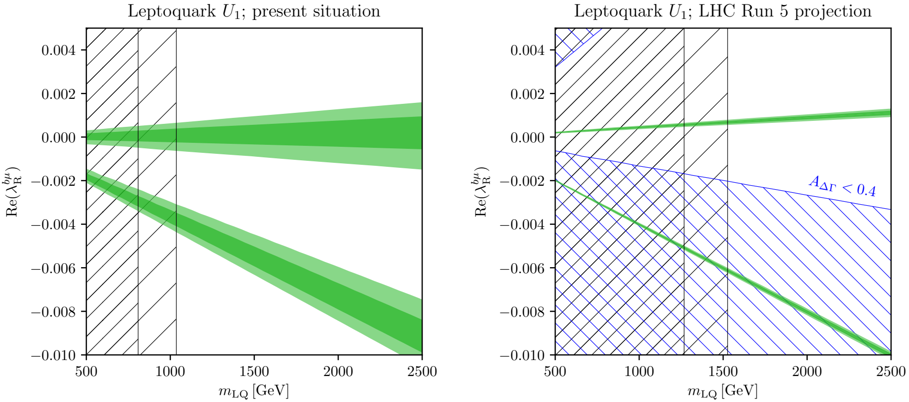


C_9^{NP}	$-\frac{1}{2}\mathcal{N}\lambda_L^{s\mu}\lambda_L^{b\mu\,*}$
C_9'	$-\frac{1}{2}\mathcal{N}\lambda_R^{s\mu}\lambda_R^{b\mu\,*}$
C_{10}^{NP}	$\frac{1}{2}\mathcal{N}\lambda_L^{s\mu}\lambda_L^{b\mu\,*}$
C_{10}'	$-\frac{1}{2}\mathcal{N}\lambda_R^{s\mu}\lambda_R^{b\mu\,*}$
$C_S = -C_P$	$\mathcal{N}\lambda_L^{s\mu}\lambda_R^{b\mu\,*}\, m_b^{-1}$
$C_S' = C_P'$	$\mathcal{N}\lambda_R^{s\mu}\lambda_L^{b\mu\,*}\, m_b^{-1}$

NB: λ_L employed in simultaneous explanation of $b \to s\mu\mu$ & $b \to c\tau\nu$ anomalies, see e.g. Barbieri et al. 1512.01560, Buttazzo et al. 1706.07808

Constraint on LQ parameter space

Scenario with $C'_S = C'_P = 0$, λ_L chosen to explain $b \to s\mu\mu$ anomalies



Conclusions

- BR($B_s \to \mu^+\mu^-$) is exceptionally sensitive to NP in scalar operators, but leaves an ambiguity
- $A_{\Delta\Gamma}$ can resolve this ambiguity and exclude scalar NP overcompensating the SM contribution
- Constraints are complementary to direct searches (e.g. $A \to \tau^+\tau^-$ in the MSSM)