$B_s \to \mu\mu$ within (mostly) the SM

Diego Guadagnoli
LAPTh Annecy

Outline

- ☑ **Why $B_s \to \mu\mu$**
- ☑ **$B_s \to \mu\mu$ in the SM:** structure and theory errors
- ☑ **$B_s \to \mu\mu$ beyond the SM:** possible directions

BR[$B_s \to \mu^+\mu^-$]: a hard probe of scalar-fermion interactions

Model-independent approach: effective operators

Beyond the SM,
a total of 6 operators can contribute:

(One may write also two tensor operators,
but their matrix elements vanish for this process.)

$$O_A \equiv \left(\bar{b}\,\gamma_L^\alpha\, s\right)\left(\bar{\mu}\,\gamma_\alpha\,\gamma_5\,\mu\right) \qquad O'_A \equiv \left(\bar{b}\,\gamma_R^\alpha\, s\right)\left(\bar{\mu}\,\gamma_\alpha\,\gamma_5\,\mu\right)$$

$$O_S \equiv \left(\bar{b}\,P_L\, s\right)\left(\bar{\mu}\,\mu\right) \qquad O'_S \equiv \left(\bar{b}\,P_R\, s\right)\left(\bar{\mu}\,\mu\right)$$

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Credits: Gino Isidori

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  the $B_s \to \mu\mu$ amplitude remains a well-defined object in the limit where gauge interactions go to zero ($g \to 0$).

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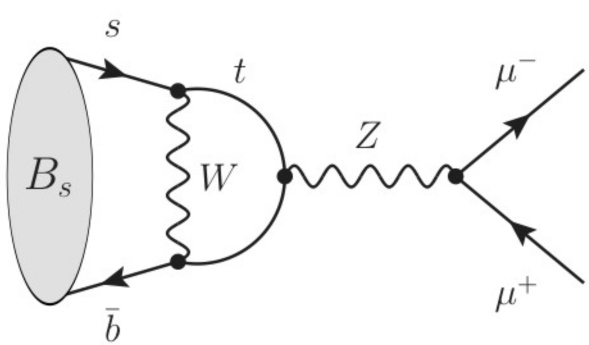

$$A_{B_s\to\mu\mu} \propto G_F \cdot \alpha_{e.m.} \cdot Y(M_t^2/M_W^2)$$

with $Y\left(\frac{M_t^2}{M_W^2}\right) \sim \frac{M_t^2}{M_W^2}$ because of GIM

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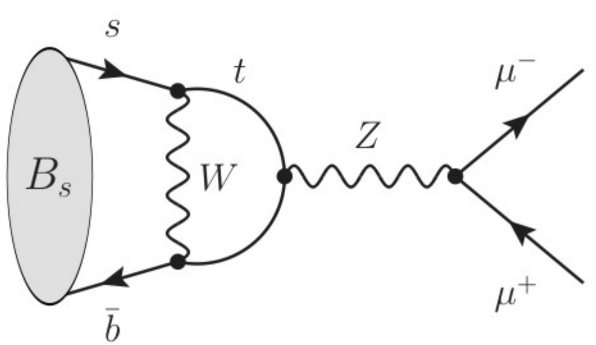

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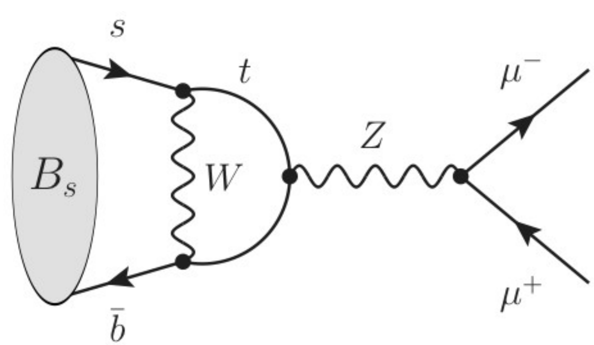

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- Hence the relevant proportionality is:

$$A_{B_s\to\mu\mu} \propto \frac{1}{v^2} \cdot g^2 \cdot \frac{M_t^2}{M_W^2} \propto \frac{y_t^2}{v^2}$$

the g² dependence cancels out

So this process is a genuine probe
of Yukawa interactions
i.e. of the scalar-fermion sector

$B_s \rightarrow \mu\mu$ within the SM

The $B_s \to \mu\mu$ decay within the SM: structure

See: Buchalla, Buras '93; Misiak, Urban '99

- **BR[$B_s \to \mu\mu$] has the following structure**

$$BR[B_s \to \mu^+ \mu^-] \simeq \frac{1}{\Gamma_s} \times \left(\frac{G_F^2 \alpha_{\text{e.m.}}^2}{16 \pi^3 s_W^4} \right) \cdot \left| V_{tb}^* V_{ts} \right|^2 \cdot f_{B_s}^2 \; m_{B_s} \cdot m_\mu^2 \cdot Y^2 (m_t^2 / M_W^2)$$

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Recall: the final state is purely leptonic

The only non-null matrix elem' is:

$$\langle 0|\bar{b}\gamma^\alpha\gamma_5 s|B_s(p)\rangle = -i f_{B_s} p^\alpha$$

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- f_{B_s} is among the simplest quantities for lattice QCD
- high-precision calculations possible, and in part already reality

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- Easy to understand:
  - take the B momentum p
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- Masses' & couplings' dependence of the BR = "usual" FCNC-related suppression $\times \boxed{\dfrac{m_\mu^2}{M_{B_s}^2}}$

Additional "chiral" suppression:
relative 4×10^{-4} factor

BR[$B_s \to \mu\mu$] error: parametric

- The main sources of error within the BR formula are:

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- Thus, one can write the following phenomenological expression for the BR

top "pole" mass here

$$BR[B_s \to \mu^+\mu^-] = 3.23 \cdot 10^{-9} \cdot \left(\frac{\tau_{B_s}}{1.466\,\text{ps}} \right) \cdot \left(\frac{\text{Re}\left(V_{tb}^* V_{ts}\right)}{4.05 \cdot 10^{-2}} \right)^2 \cdot \left(\frac{f_{B_s}}{227\,\text{MeV}} \right)^2 \cdot \left(\frac{M_t}{173.2\,\text{GeV}} \right)^{3.07}$$

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Input	$\tau_{B_s} = 1.466(31)\,\mathrm{ps}$	$\mathrm{Re}(V_{tb}^* V_{ts}) = 4.05(8) \cdot 10^{-2}$	$f_{B_s} = 227(8)\,\mathrm{MeV}$	$M_t = 173.2(0.9)\,\mathrm{GeV}$
Contribution to BR relative error	$2\,\%$	$4\,\%$	$7\,\%$	$1.6\,\%$

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Total relative error expected for BR[$B_s \to \mu\mu$]: **about 8.5%**

A qualification about the f_{Bs} error

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Input	$\tau_{B_s} = 1.466(31)\,\mathrm{ps}$	$\mathrm{Re}(V_{tb}^* V_{ts}) = 4.05(8)\cdot 10^{-2}$	$f_{B_s} = 227(8)\,\mathrm{MeV}$	$M_t = 173.2(0.9)\,\mathrm{GeV}$
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This issue is still debatable to some extent

(or at least it would be so in case of a SM vs. exp discrepancy)

BR[$B_s \to \mu\mu$] systematics: the initial state oscillates

Dunietz, Fleischer, Nierste, PRD 01;
Descotes, Matias, Virto, PRD 12;
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- The $B_s \to \mu\mu$ rate is measured as follows:

$b\,\bar{b}$ production

the b hadronizes into a $\bar{B}_s$
or
the $\bar{b}$ hadronizes into a B_s
at $t = 0$

the $\bar{B}_s(t)$
or
the $B_s(t)$
evolves with time and decays into $\mu\mu$

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☑ **How are BR_{th} and BR_{exp} connected**

$$\frac{\mathrm{BR}_{\mathrm{th}}}{1-y_s} = \mathrm{BR}_{\mathrm{exp}}$$

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$$\frac{\mathrm{BR}_{\mathrm{th}}}{1-y_s} = \mathrm{BR}_{\mathrm{exp}}$$

with $y_s = \Delta\Gamma_s/(2\Gamma_s) \simeq 0.088$

See:

- LHCb 1212.4140
- latest HFAG average: 1207.1158

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☑ **Intuitive picture of this correction**

Recall: $\mathrm{BR}_{\mathrm{th}} \propto \frac{1}{\Gamma_s}$

Then one finds: $\frac{1}{\Gamma_s} \times \frac{1}{1-\Delta\Gamma_s/(2\Gamma_s)} = \frac{1}{\Gamma_s}\,\frac{\Gamma_s}{\Gamma_{\mathrm{long}}}$

Namely the $1/(1-y_s)$ factor just "renormalizes" BR_{th} to the width of the long-lived B_s eigenstate

BR[$B_s \to \mu\mu$] error: systematics

Initial-state effect

- **Effect of $B_s - \overline{B}_s$ oscillations:**

  De Bruyn *et al.*, PRL 12 & PRD 12

$$BR_{\mathrm{exp}} = BR_{\mathrm{th}} \frac{1}{1 - \Delta\Gamma_s / 2\Gamma_s} = BR_{\mathrm{th}} \times 1.09$$

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EW final-state effect

- **Effect of soft undetected photons in the final state:**

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$$BR_{\text{exp}} = BR_{\text{th}} \times 0.89$$

Taken into account by exp

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- **Incomplete knowledge of NLO EW corrections:**

- *Implied systematic error comparable to f_{Bs} error*

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- *Final answer: full calculation*
  - ***NLO EW:** Bobeth et al., 1311.1348, PRD14*
  - ***SM pred.:** Bobeth et al., 1311.0903, PRL14*
  - *See also **NNLO QCD:** Hermann et al., 1311.1347, JHEP13*

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All in all, theory (SM) ready to match expected experimental accuracy

Some considerations on

$B_s \rightarrow \mu\mu$

beyond the SM

How to probe scalar operators and their phases thru $B_s \to \mu\mu$

See: De Bruyn *et al.*, PRL 12

Back to the initial-state systematic effect. For general new physics, the correction factor becomes

$$\mathrm{BR}_{\mathrm{th}} \cdot \left(\frac{1 + A_{\Delta\Gamma}\, y_s}{1 - y_s^2} \right) = \mathrm{BR}_{\mathrm{exp}}$$

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normalized Wilson coeff

for O_A (= SM operator)

and O_P (and primed counterparts)

$P_{SM} = 1$

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Therefore

- *in the SM* $A_{\Delta\Gamma} = 1$
- *if* $A_{\Delta\Gamma} \neq 1$*, it's new physics*
- *this NP could involve CPV or not*

Scalar operators and their phases thru $B_s \to \mu\mu$

Dunietz, Fleischer, Nierste, PRD 01;
De Bruyn *et al.*, PRL 12 & PRD 12

☑ The crucial point is that $A_{\Delta\Gamma}$ can be extracted from

$B_s \to \mu\mu$ effective lifetime

$$\tau_{\mu\mu} \equiv \frac{\int t\, dt \left(\Gamma(B_s(t) \to \mu\mu) + \Gamma(\bar{B}_s(t) \to \mu\mu) \right)}{\int dt \left(\Gamma(B_s(t) \to \mu\mu) + \Gamma(\bar{B}_s(t) \to \mu\mu) \right)}$$

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(After having measured $A_{\Delta\Gamma} \neq 1$)

- *To clarify whether it will be new CPV or not will call for measuring the time-dependent CP asymmetry*
- *This quantity requires tagging & time-dependence measurements in an ultra-rare decay*

Conclusions

☑ **$B_s \to \mu\mu$ SM prediction**

- *Systematics is under control – within below O(1%)*
- *Parametrics soon (or already?) dominated by CKM error*
- *Outlook: The SM error is, and will remain, negligible w.r.t. exp error*

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- *Exquisite probe of the Yukawa sector*

⇨ *Scalar operators $O_{S,P}^{(\prime)}$ and their phases*

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  ☞ *Constraining power superior to Z-peak observables measured at LEP (within reasonable flavor frameworks such as MFV or partial compositeness)*

DG, Isidori, PLB13