Flavour physics 3

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Benasque, September 2015

Outline

Heavy quark effective theory

consider a heavy quark Q of mass m and momentum P interacting only softly with light quarks

e.g. heavy-light meson like $\overline{B}^0 = (b\,\bar{d})$, ...

$$P^\mu = m v^\mu + k^\mu \qquad \text{with} \qquad v^2 = 1, \qquad |k^\mu| \sim \Lambda_{\mathrm{QCD}} \ll m$$

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Propagator:

$$= \frac{i(\not{p} + m)}{p^2 - m^2} = i\,\frac{m(1+\not{v}) + \not{k}}{2m\,vk + k^2} = \frac{1+\not{v}}{2}\,\frac{i}{vk} + \mathcal{O}(k/m)$$

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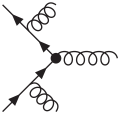
Gluon vertex:



$$\mu \quad \propto \quad \frac{1+\not{v}}{2}\gamma^\mu\frac{1+\not{v}}{2} = v^\mu\frac{1+\not{v}}{2}$$

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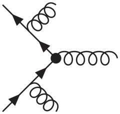

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Projectors: $P_{v+} = \frac{1+\not{v}}{2}, \qquad P_{v-} = \frac{1-\not{v}}{2}$

$$\Rightarrow \qquad P_{v+}^2 = P_{v-}^2 = 1, \qquad P_{v+}P_{v-} = 0, \qquad P_{v+} + P_{v-} = 1$$

Heavy quark effective theory

decompose heavy-quark field as

$$Q(x) = e^{-imvx}(H(x) + h(x))$$

with $\quad h(x) = e^{-imvx}\frac{1+\not{v}}{2}Q(x), \qquad H(x) = e^{-imvx}\frac{1-\not{v}}{2}Q(x)$

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HQET Lagrangian:

$$\mathcal{L}_{\text{QCD}} = \bar{Q}(i\slashed{D} - m)Q \quad \rightarrow \quad \mathcal{L}_{\text{HQET}} = \bar{h}\, i(Dv)h + \mathcal{O}(\Lambda_{\text{QCD}}/m)$$

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symmetries of HQET Lagrangian:

- flavour symmetry $b \leftrightarrow c$:
  $\mathcal{L}_{\text{HQET}}$ does not depend on quark mass
- spin symmetry $B \leftrightarrow B^*$, $D \leftrightarrow D^*$:
  $\mathcal{L}_{\text{HQET}}$ does not have a Dirac structure

Application

heavy-light form factors $B \to P$ (P: pseudo-scalar)

$$\langle P(p')|\bar{q}\,\gamma^\mu b|\bar{B}(p)\rangle = f_+(q^2)\left[p^\mu + p'^{\,\mu} - \frac{m_B^2 - m_P^2}{q^2}\,q^\mu\right] + f_0(q^2)\,\frac{m_B^2 - m_P^2}{q^2}\,q^\mu$$

$$\langle P(p')|\bar{q}\,\sigma^{\mu\nu} q_\nu b|\bar{B}(p)\rangle = \frac{i f_T(q^2)}{M + m_P}\left[q^2(p^\mu + p'^{\,\mu}) - (M^2 - m_P^2)\,q^\mu\right]$$

$\to$ parametrisation in terms of 3 scalar functions f_+, f_0, f_T

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$\to$ parametrisation in terms of 3 scalar functions $f_+,\ f_0,\ f_T$

- use HQET for b quark
- contruct effective theory for energetic light quark q:

$$p'^\mu = E n_-^\mu + k'^\mu \qquad \text{with} \qquad n_1^2 = 0, \qquad |k'^\mu| \sim \Lambda_{\text{QCD}} \ll m$$

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$\Rightarrow$ 3 scalar coefficient functions reduce to 1 soft form factor:

$$\langle P(p')|\bar{q}\,\gamma^\mu b|\bar{B}(p)\rangle = 2E\,\xi_P(E)\,n_-^\mu,$$
$$\langle P(p')|\bar{q}\,\sigma^{\mu\nu}q_\nu b|\bar{B}(p)\rangle = 2iE\,\xi_P(E)\,\big((m_B - E)\,n_-^\mu - M v^\mu\big)$$

Soft FF decomposition

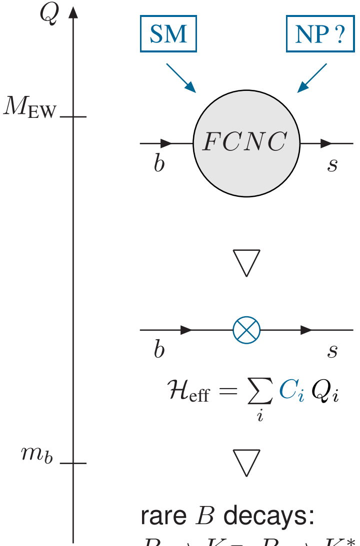
$$
\begin{aligned}
f_+(q^2) &= \xi_P(E) + \Delta f_+^{\alpha_s}(q^2) + \Delta f_+^{\Lambda}(q^2) \\
f_0(q^2) &= \frac{2E}{m_B}\,\xi_P(q^2) + \Delta f_0^{\alpha_s}(q^2) + \Delta f_0^{\Lambda}(q^2) \\
f_T(q^2) &= \frac{m_B + m_P}{E}\,\xi_P(q^2) + \Delta f_T^{\alpha_s}(q^2) + \Delta f_T^{\Lambda}(q^2)
\end{aligned}
$$

- decomposition into soft FF and PC not unique: redefinition of ξ_P allows to reshuffle the two parts
- choice of scheme allows to partly absorb PC into soft FF's $\Rightarrow$ impact of PC depends on input scheme
- $\mathcal{O}(\alpha_s)$ via QCD factorization
- For $B \to V$ form factors:
  Set of FF reduces to two independent soft form factors

$$\{V, A_0, A_1, A_2, T_1, T_2, T_3\} \to \{\xi_\perp, \xi_\parallel\}$$

Outline

Exploring New Physics in FCNCs



$$\mathcal{H}_{\text{eff}} = \sum_i C_i\, Q_i$$

rare B decays:
$B \to K\pi$, $B \to K^* \mu\mu$,
$B \to X_s\gamma$, $B_s \to \mu\mu$, ...

2

Which NP model
can account for this pattern?

↑

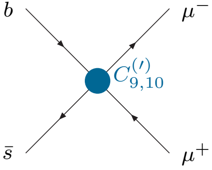
fit effective coefficients
NP in certain C_i

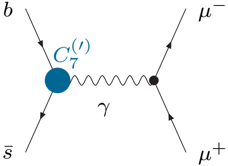
↑

tensions in
rare B decay data

The EW penguin sector

SM and NP particles induce an effective $b\bar{s}\mu^+\mu^-$ coupling





$$\mathcal{O}_9^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\mu}\gamma_\mu \mu]$$

$$\mathcal{O}_{10}^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\mu}\gamma_\mu \gamma_5 \mu]$$

$$\mathcal{O}_7^{(\prime)} = \frac{\alpha}{4\pi} m_b [\bar{s}\sigma_{\mu\nu} P_{R(L)} b] F^{\mu\nu}$$

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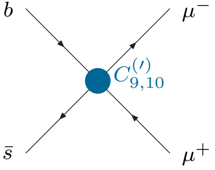

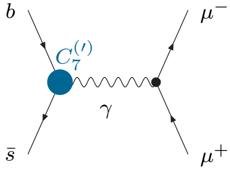

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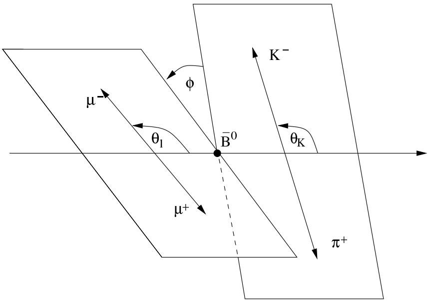
The decay $B \to K^* \mu^+\mu^-$ with angular observables $P_i^{(\prime)}$ is a good place to investigate the EW penguin sector

Wilson coefficients	Observables	SM values
$\mathbf{C_7^{eff}(\mu_b)}$	$\mathcal{B}(\bar{B} \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, A_{FB}, F_L, P_2, P'_{4,5}$	-0.292
$\mathbf{C_9(\mu_b)}$	$\mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L, P_2, P'_{4,5}$	4.075
$\mathbf{C_{10}(\mu_b)}$	$\mathcal{B}(B_s \to \mu^+\mu^-), \mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L, P'_4$	-4.308
$\mathbf{C'_7(\mu_b)}$	$\mathcal{B}(\bar{B} \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, A_{FB}, F_L, P_1$	-0.006
$\mathbf{C'_9(\mu_b)}$	$\mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L, P_1$	0
$\mathbf{C'_{10}(\mu_b)}$	$\mathcal{B}(B_s \to \mu^+\mu^-), A_{FB}, F_L, P_1, P'_4$	0

$B \to K^* \mu^+ \mu^-$

4-body decay $\bar{B}_d \to \bar{K}^{*0}(\to K^- \pi^+) l^+ l^-$ with on-shell K^{*0}



invariant mass of lepton-pair q^2

angles $\theta_\ell, \theta_K, \phi$

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$

- observables $S_i, P_i^{(\prime)}$ as ratios of J_i
- most interesting region: small $q^2 \lesssim 9\,\mathrm{GeV}$

Form factors

- Theory predictions for $B \to K^* \mu^+ \mu^-$ depend on seven hadronic form factors $V, A_0, A_1, A_2, T_1, T_2, T_3$
  - calculations of FFs have large errors
  - Correlations of FF errors not public
  - model dependence: systematics for different calculational methods (QCD sum rules, LCSR, Dyson-Schwinger)

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  - Correlations of FF errors not public
  - model dependence: systematics for different calculational methods (QCD sum rules, LCSR, Dyson-Schwinger)
- For small q^2 and at LO in α_s and Λ/m_b:
  Set of FFs reduces to two independent FFs (soft FFs)

$$\{V, A_0, A_1, A_2, T_1, T_2, T_3\}$$
$$\Downarrow$$
$$\{V, A_0\} \text{ or } \{V, a_1 A_1 + a_2 A_2\} \text{ or } \{T_1, A_0\} \text{ or } \ldots$$

  + Dominant correlations automatically taken into account
  + $\mathcal{O}(\alpha_s)$ via QCD factorization
  ? factorizable power corrections of $\mathcal{O}(\Lambda/m_b)$?

Clean observables

- reduction $7 \to 2$ FFs implies relations at LO, e.g.

$$\frac{m_B(m_B + m_{K^*})A_1 - 2E(m_B - m_{K^*})A_2}{m_B^2 T_2 - 2E m_B T_3} = 1 + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

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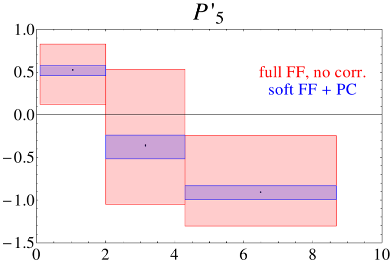
the observable P_5'



FFs from Khodjamirian et al.

- no reliable prediction from full FF without correlations of errors

- $P_i^{(\prime)}$ clean when calculated in soft-FF approach
  (or including correlations of full FFs)

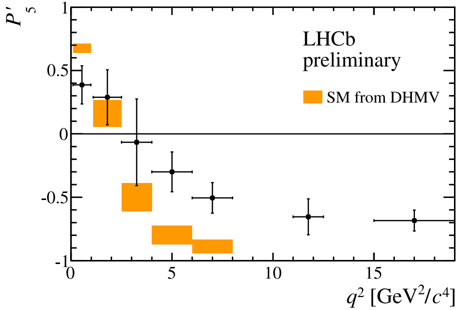
The $B \to K^* \mu^+ \mu^-$ anomaly

2013: evaluation of $1\,\text{fb}^{-1}$ data

$3.7\,\sigma$ tension in $[4, 8.3]\,\text{GeV}^2$ bin of observable P_5'

2015: evaluation of $3\,\text{fb}^{-1}$ data:

[LHCb-CONF-2015-002]



2.9 σ in $[4, 6]\,\text{GeV}^2$

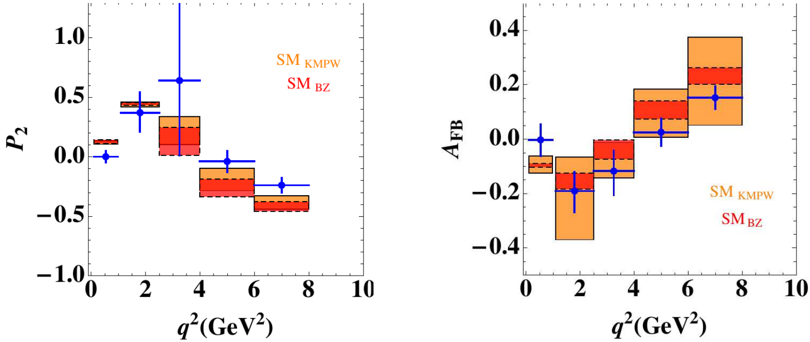
2.9 σ in $[6, 8]\,\text{GeV}^2$

naive combination:
(negl. theory correlations)

$3.7\,\sigma$ tension

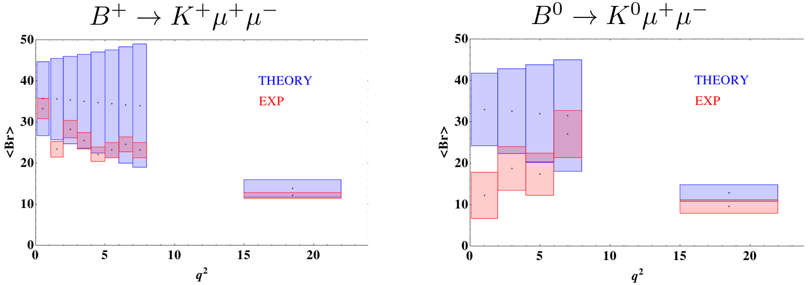
tension in P_5' confirmed

An isolated anomaly?



- reasonable agreement with SM prediction for P_2, $A_{\rm FB}$
- but: systematic pull of curves to larger q^2
  - pull of zero of P_2 ($=$ zero of $A_{\rm FB}$) to larger q^2
- consistent with P_5' anomaly [Matias,Serra; LH,Matias]

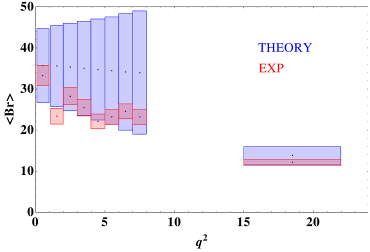
$B \to K\mu^+\mu^-$ and R_K



- Agreement between theory and experiment at $\sim 1\,\sigma$ ($\sim 2\,\sigma$ in the first bin of $B^0 \to K^0\mu^+\mu^-$)
- but: experiment systematically lower than theory prediction (for all available FF parametrizations: LCSR FFs from KMPW and BZ as well as lattice QCD)

$B \to K\mu^+\mu^-$ and R_K

$B^+ \to K^+\mu^+\mu^-$



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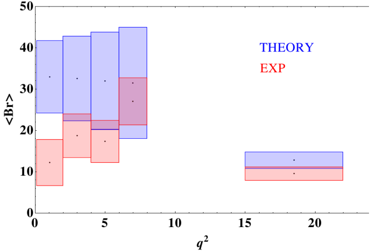

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- but: experiment systematically lower than theory prediction (for all available FF parametrizations: LCSR FFs from KMPW and BZ as well as lattice QCD)
- $R(K) = \mathrm{Br}(B \to K\mu^+\mu-)/\mathrm{Br}(B \to Ke^+e^-)$
  2.6 sigma deviation from clean SM prediction $R(K) = 1$

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- statistical fluctuation of data
  $\rightarrow$ perform consistence checks [Matias,Serra]

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- new physics (Z'-models, lepto-quarks)
  $+$ can explain tension in R_K if coupled only to muons

New physics fits

- fit to $B \to K^* \mu^+ \mu^-$ data gives: [Descotes-Genon,Matias,Virto]
  (including $B \to K^* \gamma$, $B \to X_s \gamma$, $B \to X_s \mu^+ \mu^-$, $B_s \to \mu^+ \mu^-$)

$$C_9^{\rm NP} \in [-1.6, -0.9], \qquad C_7^{\rm NP} \in [-0.05, -0.01], \qquad C_{10}^{\rm NP} \in [-0.4, 1.0],$$
$$C_9'^{\rm NP} \in [-0.2, 0.8], \qquad C_7'^{\rm NP} \in [-0.04, 0.02], \qquad C_{10}'^{\rm NP} \in [-0.4, 0.4]$$

- same pattern consistent with $B \to K \mu^+ \mu^-$ data
  and with R_K (if NP couples only to muons)
  [Gosh,Nardecchia,Renner; Hurth,Mahmoudi,Neshatpour; Altmannshofer,Straub]

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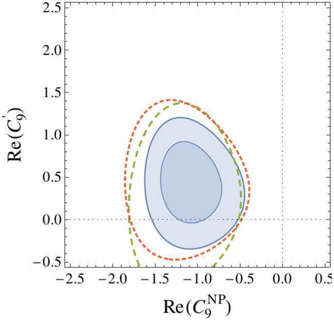
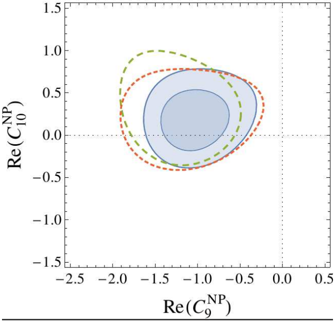
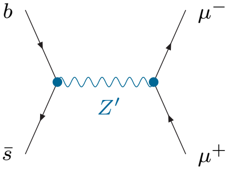




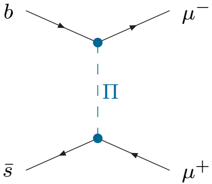
fits from [Altmannshofer,Straub 2015]

New physics in $C_{9,10}^{(\prime)}$

- tree-level new-physics contributions to $C_{9,10}^{(\prime)}$



Z' models
Buras et al;
Altmannshofer,Gori,Pospelov,Yavin;
Crivellin,D'Ambrosio,Heeck; ...

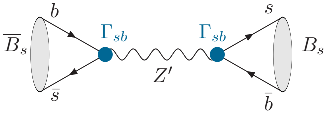


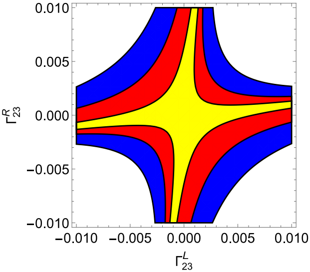
lepto-quarks
Hiller,Schmaltz;
Gripaios,Nardecchia,Renner; ...

- loop-induced NP contributions (SUSY, extra-dimensions, ...)
  $\rightarrow$ constraints from other FCNC processes exclude large effects

- in the following: Z' boson with generic couplings

$B_s - \overline{B}_s$ mixing





- contributions from left- and righthanded Z' couplings:

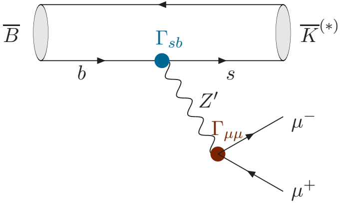
$$(\Gamma^L_{sb})^2, \qquad (\Gamma^R_{sb})^2, \qquad -\Gamma^L_{sb}\Gamma^R_{sb}$$

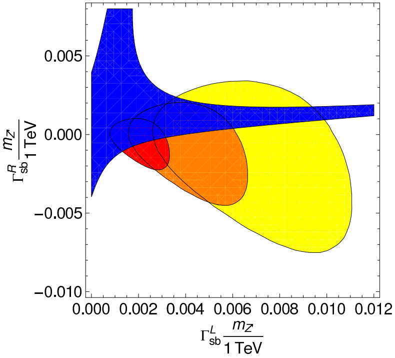
- solution of $B \to K^*\mu^+\mu^-$ anomaly requires non-zero Γ^L_{sb}

- constraint from $B_s - \overline{B}_s$ mixing can be softened by same-size coupling Γ^R_{sb} with $\Gamma^R_{sb} \ll \Gamma^L_{sb}$:

  $\to$ destructive interference of $(\Gamma^L_{sb})^2$ and $\Gamma^L_{sb}\Gamma^R_{sb}$ terms

Z' coupling to muons



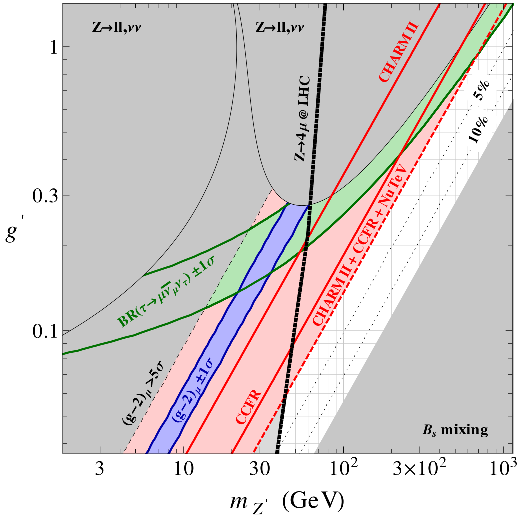


$\Gamma_{\mu\mu} = 1.0$, $\Gamma_{\mu\mu} = 0.5$, $\Gamma_{\mu\mu} = 0.3$

- $C_9^{\rm NP} \sim \Gamma^L_{sb}\Gamma_{\mu\mu}$, $C_9'^{\rm NP} \sim \Gamma^R_{sb}\Gamma_{\mu\mu}$
- fulfill $B_s - \overline{B}_s$ mixing constraint without unnatural fine-tuning between Γ^L_{sb} and Γ^R_{sb}

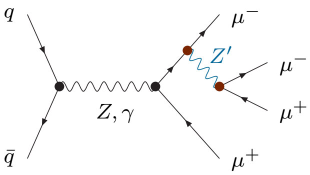
sizable coupling $\Gamma_{\mu\mu}$ required

constraints on generic $Z'\mu^+\mu^-$ coupling

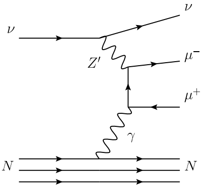


[Altmannshofer,Gori,Pospelov,Yavin arXiv:1403.1269]

Atlas signature:



Neutrino tridents



$L_\mu - L_\tau$ gauge models

Lepton charges: $Q_L = (0, 1, -1) \to$ gauged $L_\tau - L_\mu$

- no coupling to electrons
  - allows to solve R_K
  - avoids LEP bounds
- good symmetry for PMNS matrix
- anomaly free

Atlas signature:

- allowed final states:
  4μ, 4τ, $2\mu 2\tau$, $2\mu + E_{T,\text{miss}}$, $2\tau + E_{T,\text{miss}}$
- non-allowed final states:
  $4e$, $2e2\mu$, $2e2\tau$, $2e + E_{T,\text{miss}}$

LFV Z' coupling?

- solve $B \to K^* \mu^+ \mu^-$ anomaly and R_K tension simultaneously

  $\Rightarrow$ Z' couples to muons but not electrons

- Z' model violates lepton universality

  $\Rightarrow$ natural to assume also presence of LFV $Z'\tau\mu$ coupling

- search for LFV decays $B_s \to \tau\mu$, $B \to K^{(*)}\tau\mu$

  [Glashow,Guadagnoli,Kane]

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- study most general framework: arbitrary couplings

$$Z'sb : \Gamma_{sb}, \qquad Z'\mu\mu : \Gamma_{\mu\mu}, \qquad Z'\tau\mu : \Gamma_{\tau\mu}$$

Constraints in lepton sector

- $\tau \to 3\mu$: $\Gamma^2_{\mu\tau}\Gamma^2_{\mu\mu}$

  Belle + BarBar (90% conf. lev.): $\mathrm{Br}(\tau \to 3\mu) < 1.2 \times 10^{-8}$

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- $\tau \to \mu\nu\bar{\nu}$: $\Gamma^2_{\mu\tau}$ (at loop-level $\Gamma_{\mu\mu}\Gamma_{\tau\tau}$)

  $\mathrm{Br}_{\mathrm{exp}} = (17.41 \pm 0.04)\%$, $\mathrm{Br}_{\mathrm{SM}} = (17.29 \pm 0.03)\%$ [Pich]

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- loop corrections to $Z \to \ell\ell'$: $\Gamma_{\mu\tau}^2$, $\Gamma_{\mu\mu}^2$, $\Gamma_{\mu\tau}\Gamma_{\mu\mu}$

  LEP: $\mathrm{Br}(\mu^+\mu^-) = (3.366 \pm 0.007)\%$, $\mathrm{Br}(\tau^\pm\mu^\mp) < 1.2 \times 10^{-5}$

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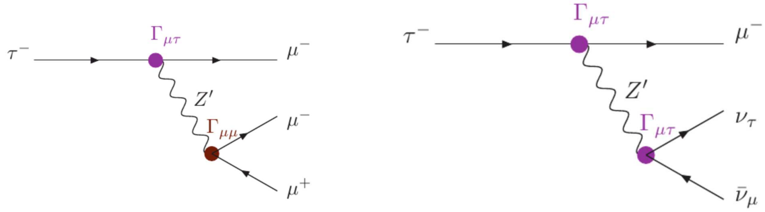
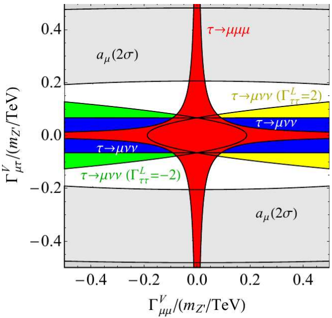
- neutrino tridents $\nu_\mu N \to \nu_\ell N \mu^+ \mu^+$: $\Gamma_{\mu\mu}^2$, $\Gamma_{\mu\tau}^2 \Gamma_{\mu\mu}^2$
  [Altmannshofer,Pospelov,Gori,Yavin]

  combined bound from CHARM-II/CCFR/NuTeV:
  $\sigma_{\text{exp}}/\sigma_{\text{SM}} = 0.83 \pm 0.18$

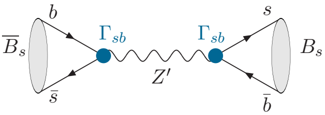
Lepton couplings





vectorial $Z'\ell\ell'$ coupling

Strategy of our analysis



1 Constrain Γ_{sb}
from $B_s - \overline{B}_s$ mixing

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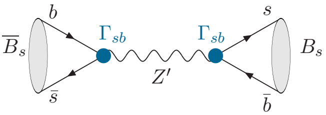

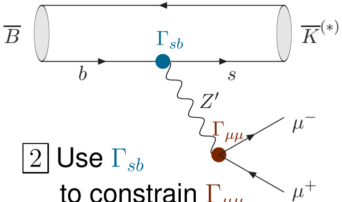

$\boxed{1}$ Constrain Γ_{sb}

from $B_s - \overline{B}_s$ mixing

$\boxed{2}$ Use Γ_{sb}

to constrain $\Gamma_{\mu\mu}$

from $B \to K^{(*)}\mu^+\mu^-$

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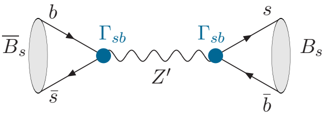

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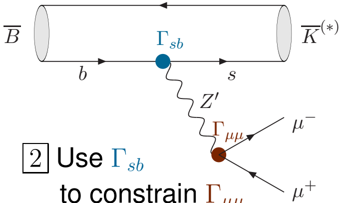

2 Use Γ_{sb}

to constrain $\Gamma_{\mu\mu}$

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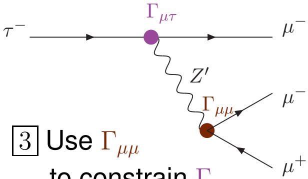

3 Use $\Gamma_{\mu\mu}$

to constrain $\Gamma_{\mu\tau}$

from $\tau^- \to \mu^-\mu^+\mu^-$

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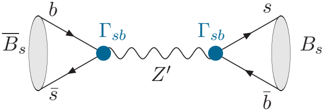

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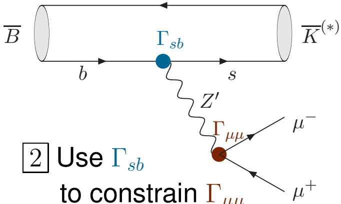

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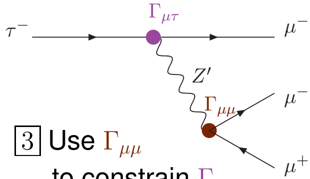

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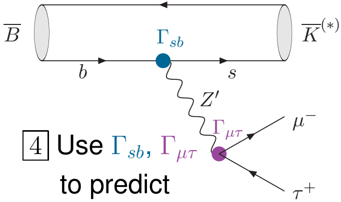
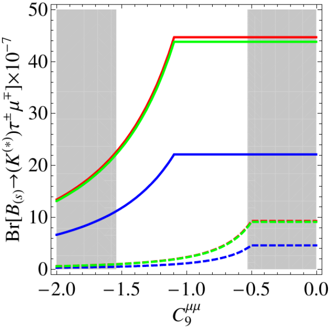


4 Use Γ_{sb}, $\Gamma_{\mu\tau}$
to predict
$B \to K^{(*)}\tau^+\mu^-$
$\Rightarrow$ Large effects possible?

$B_s \to \tau\mu$ and $B \to K^{(*)}\tau\mu$

Max. branching ratio of $B_s \to \tau\mu$, $B \to K^*\tau\mu$, $B \to K\tau\mu$ tuning B_s mixing to $X_{B_s} = 100$ (solid), $X_{B_s} = 20$ (dashed)



constraints from

- $\tau \to 3\mu$: $\propto \; (1 + X_{B_s})^2/|C_9^{\mu\mu}|^2$
- $\tau \to \mu\nu\bar{\nu}$: $\propto \; (1 + X_{B_s})$