Searching new physics in rare B-meson decays into multiple muons

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(University of Granada)

Beyond the Flavour Anomalies II, April 2021

Searching new physics in rare B-meson decays into multiple muons

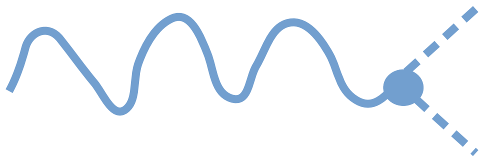
MC, Ulrik Egede and Michael Spannowsky

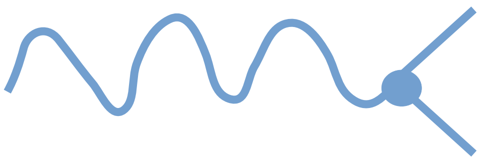
1902.10156

Novel B-decay signatures of light scalars at high energy facilities

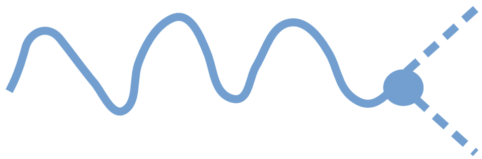
Andrew Blance, **MC**, Maria Ramos and Michael Spannowsky

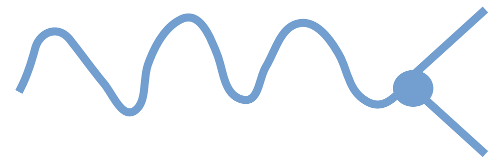
1907.13151





$$L \supset g_{12} V_\mu a_1 \overleftrightarrow{\partial^\mu} a_2 + g_{qq} V_\mu \overline{q_L} \gamma^\mu q_L$$
$$+ (g_1 a_1 + g_2 a_2) \bar{\ell} \ell$$





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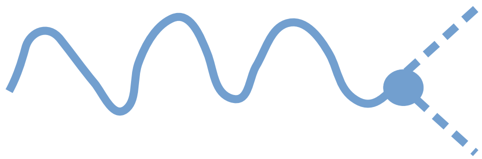
$a \to$ -a symmetry broken only in the lepton sector

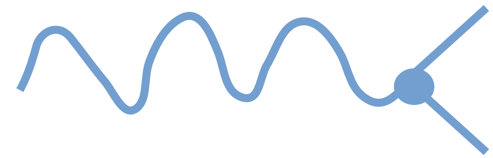
CHMs

V ~ TeV

SM ~ EW
a1, a2 [pNGBs]



B anomalies!



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muon
anomaly

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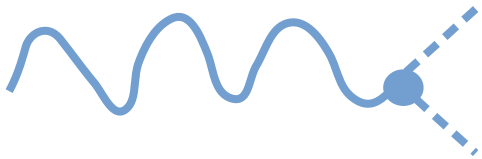

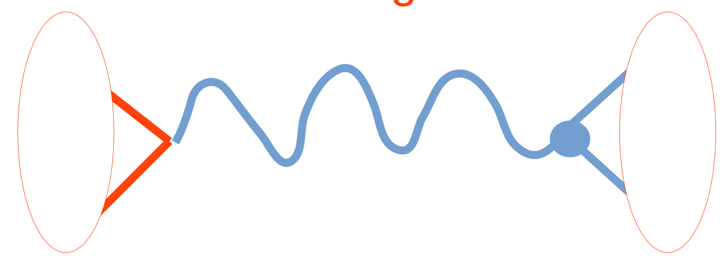

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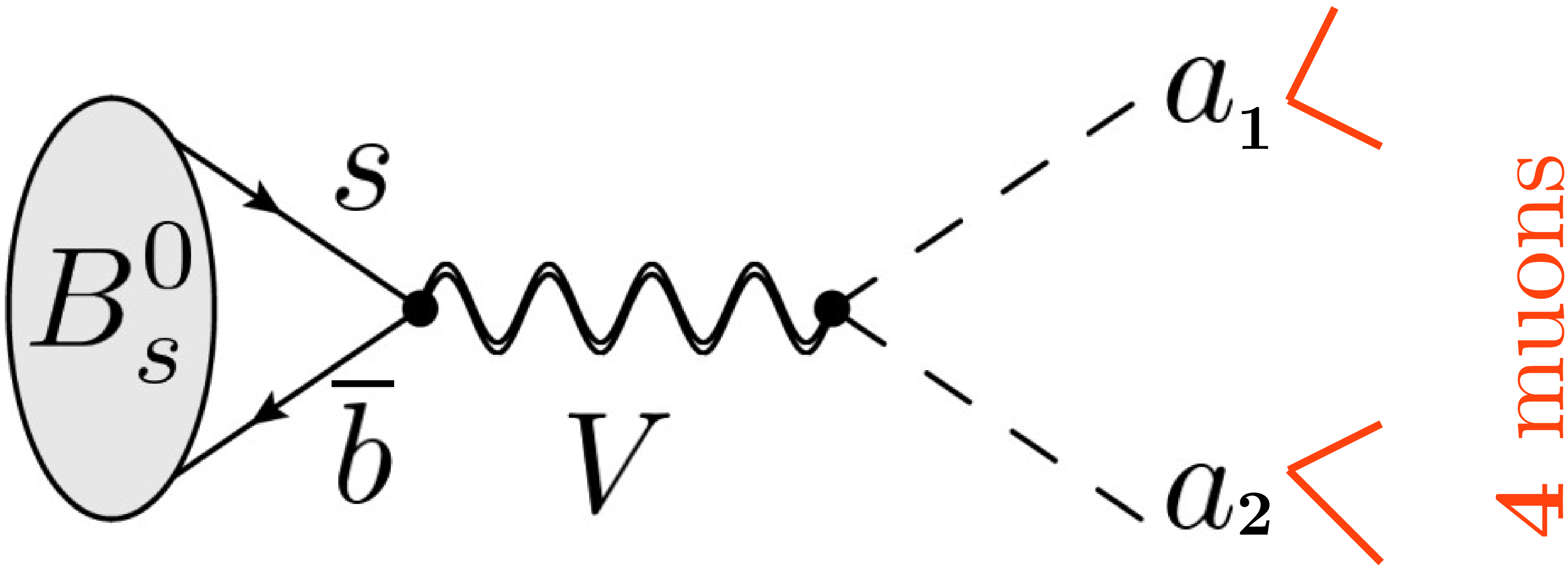
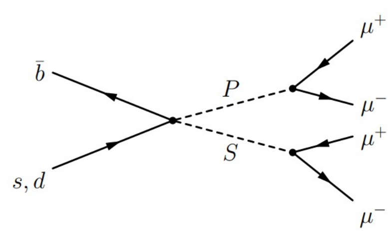
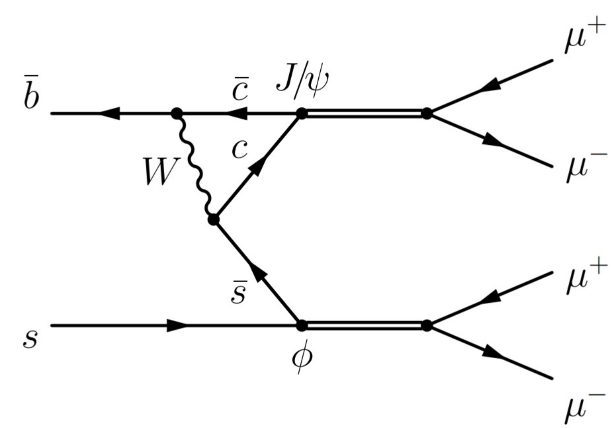
The most natural channel:



- This decay occurs naturally also in SUSY [Dermidov & Gorbunov, 1112.5230]



- Clean signal. Essentially background free:



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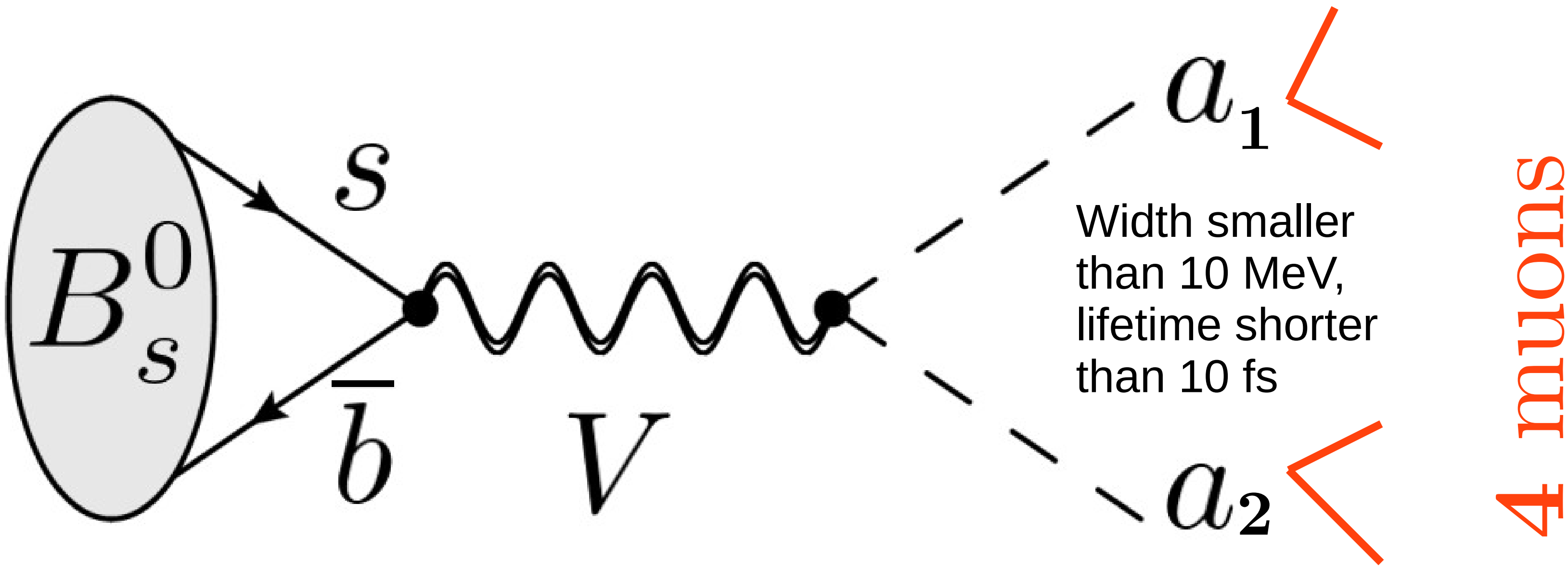

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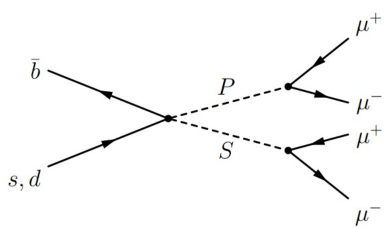

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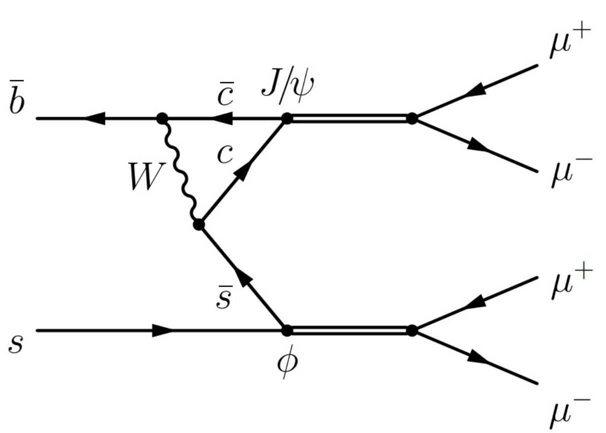

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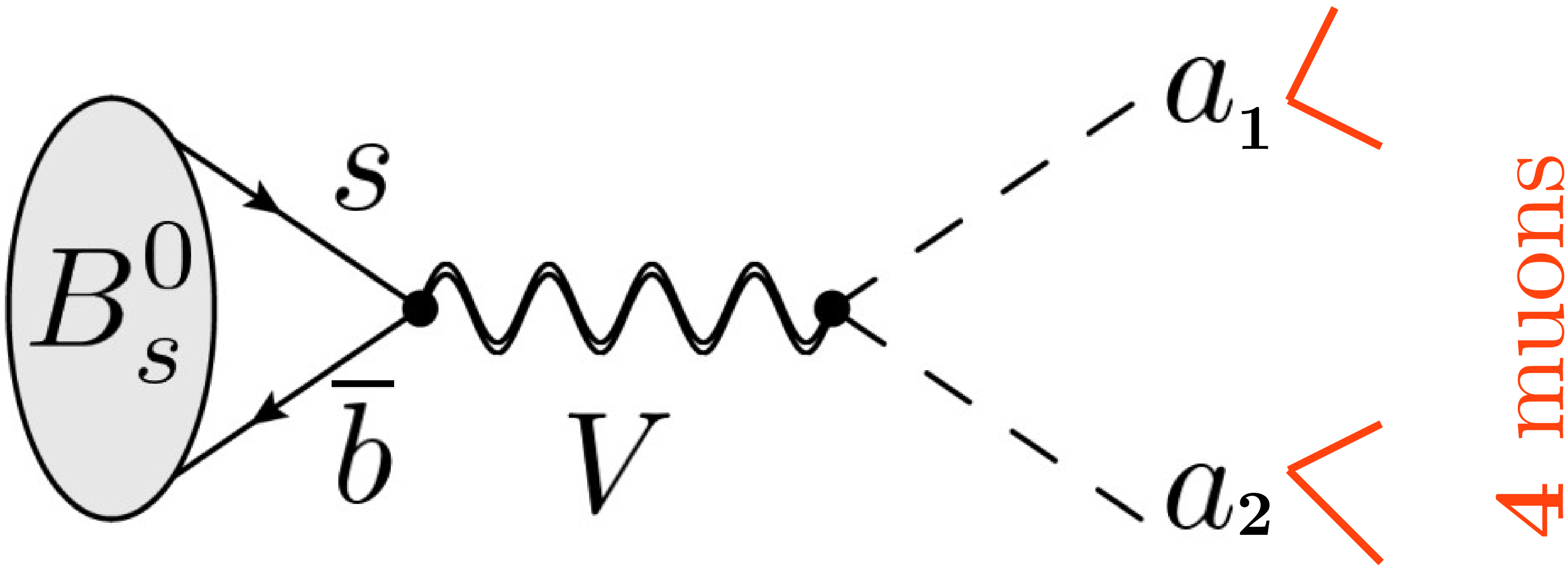
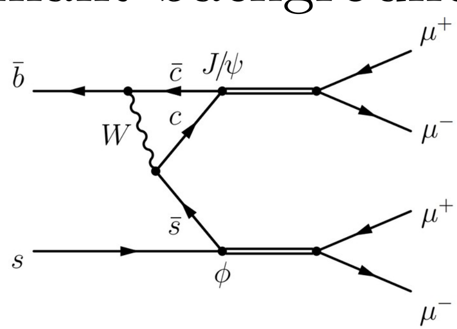
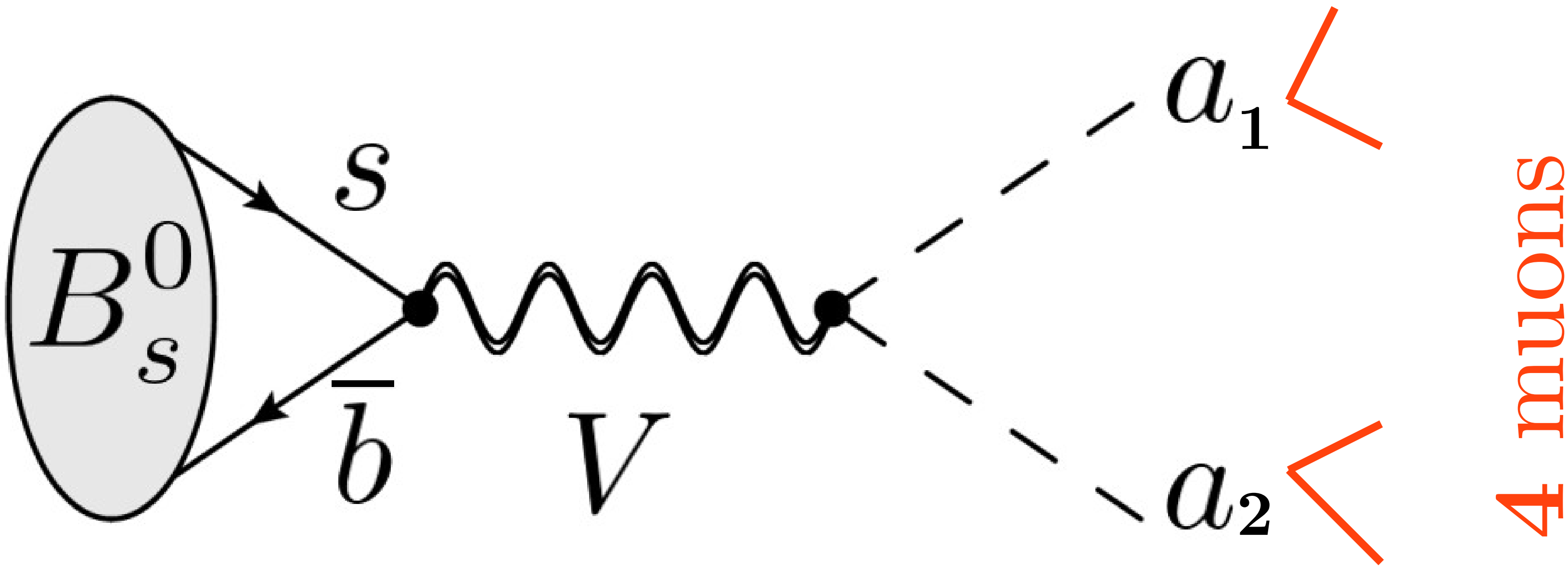


- Remove dominant background by vetoing a close in mass to φ or J/ψ



LHCb,
1611.07704

The most natural channel:



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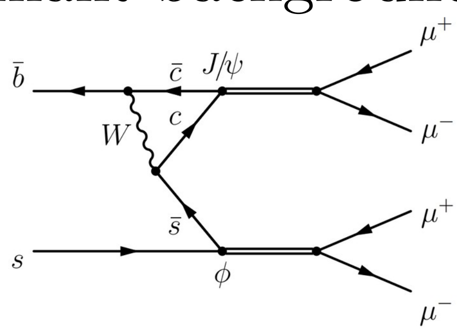
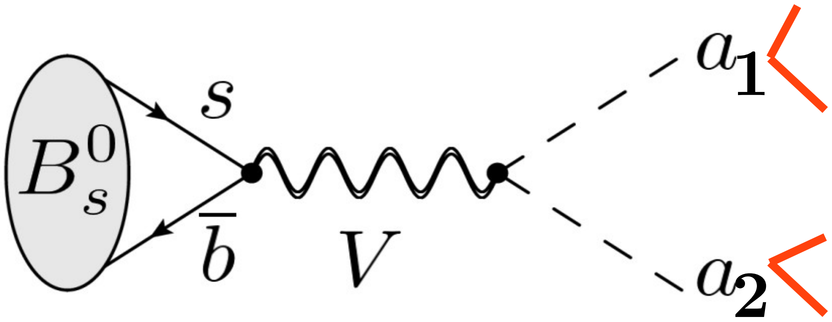
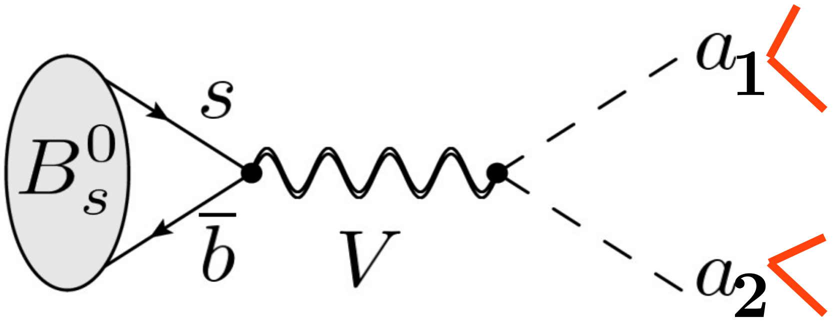


1611.07704

- The decay width vanishes in the limit of equal a masses



$$\Gamma = \frac{f_B^2}{16\pi m_V^4}\left(g_{sb}g_{12}\right)^2 \frac{\left(m_1^2 - m_2^2\right)^2}{m_B} \mathcal{K}\left(\frac{m_1}{m_B}, \frac{m_2}{m_B}\right)$$



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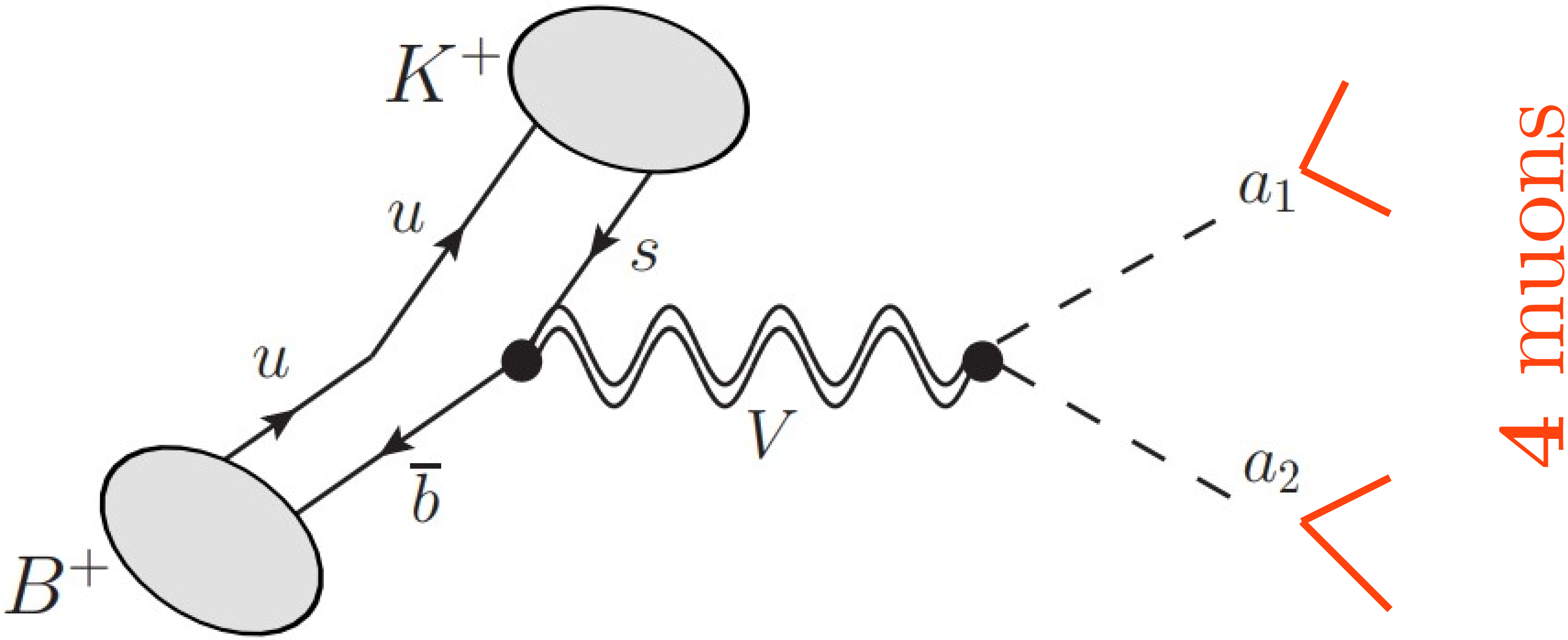
$$J_\mu = \phi^* \partial_\mu \phi - \partial_\mu \phi^* \phi$$

$$\sim (\partial_\mu B) J^\mu = -B\, \partial_\mu J^\mu = 0$$

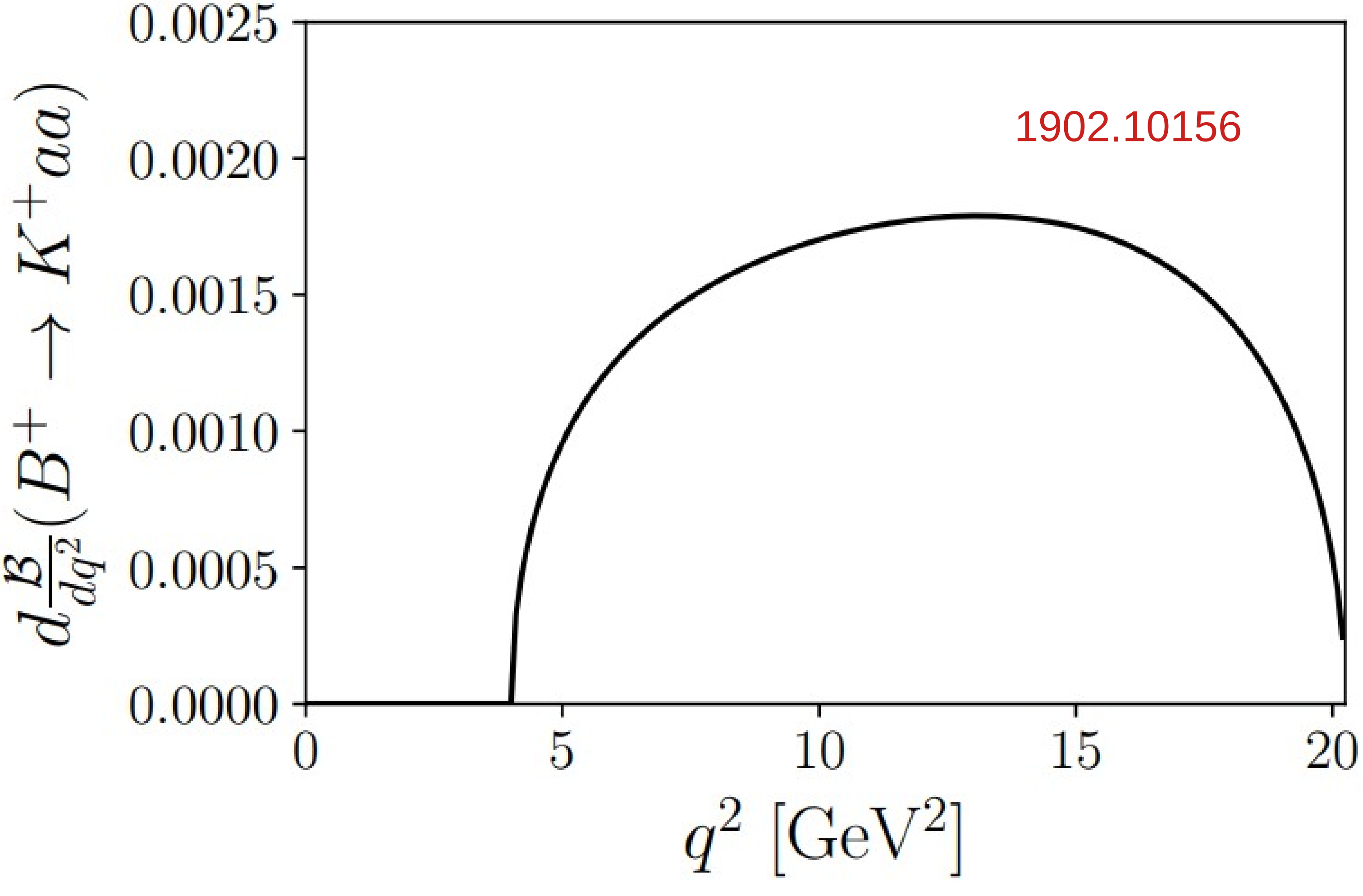
Alternative search



- This signal has not been studied experimentally

- The efficiency will be smaller, but this is compensated by the larger B^+ production cross section

$$\frac{d\Gamma}{dq^2} = \frac{(g_{sb}g_{12})^2}{768\pi^3 m_V^4 m_B^3} F(q^2)$$



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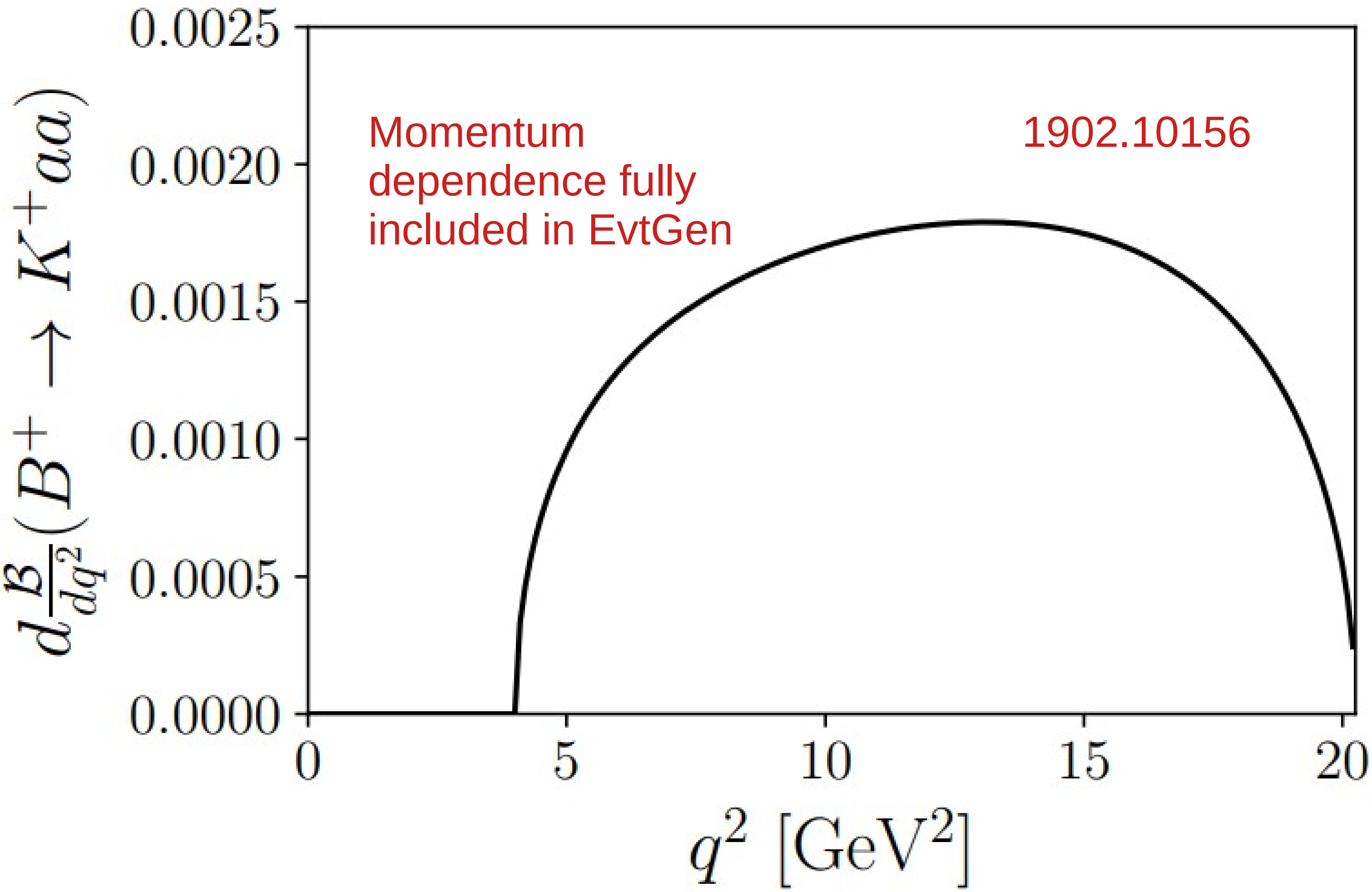
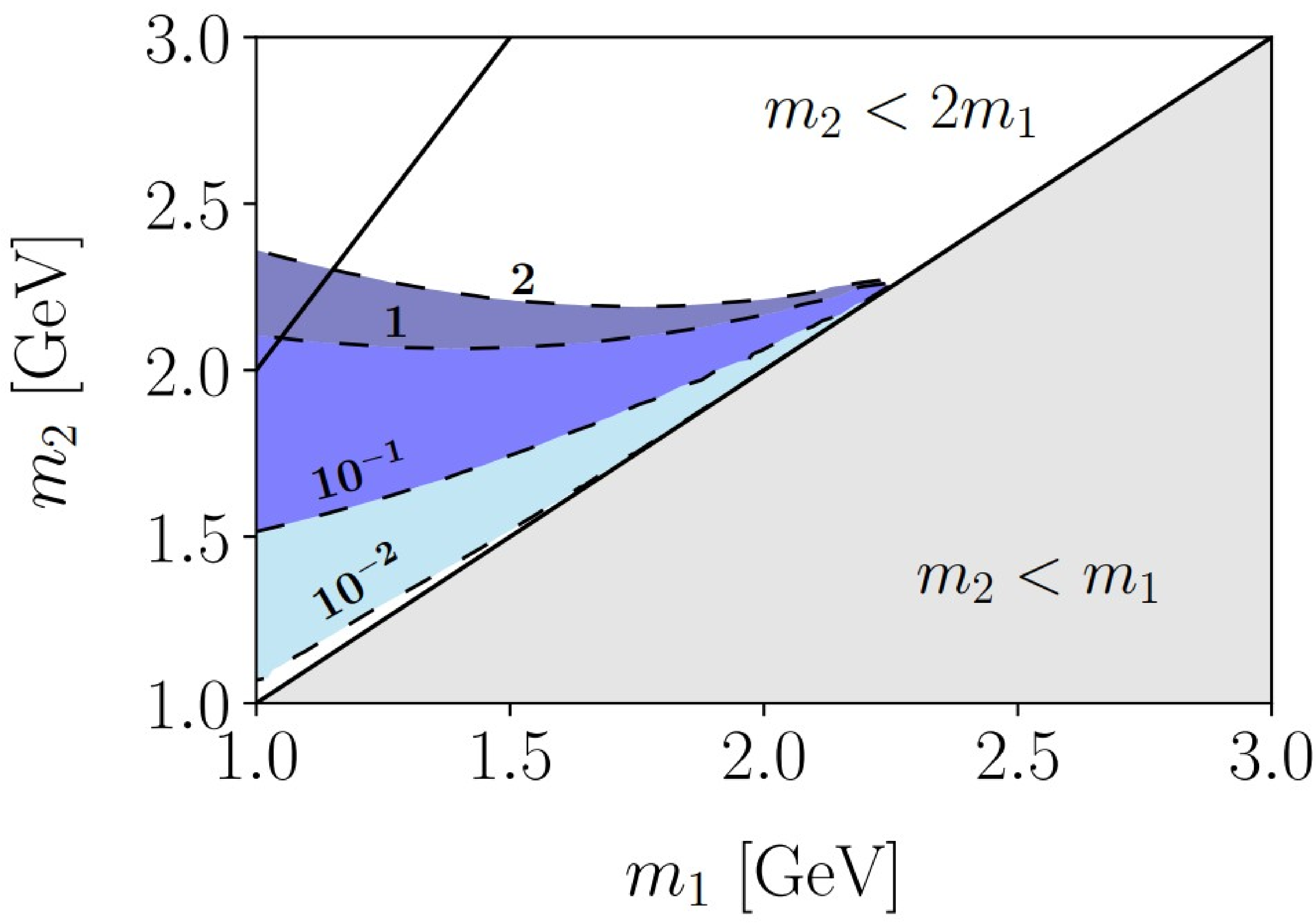


$$\Gamma\left(B_s^0 \to a_1 a_2\right) / \Gamma\left(B^+ \to K^+ a_1 a_2\right)$$



Analysis strategy/efficiency estimation

Inspired by 1611.07704

- [Trigger] At least one muon with PT $>$ 1.7 GeV

- Exactly four muons, with vanishing total charge

- All muon tracks with PT $>$ 0.5 GeV and within 2.5 $<$ ETA $<$ 5.0

- Each muon should have total momentum $>$ 2.5 GeV

- Veto muon pairs with mass in [0.95,1.09] U [3,3.2] GeV

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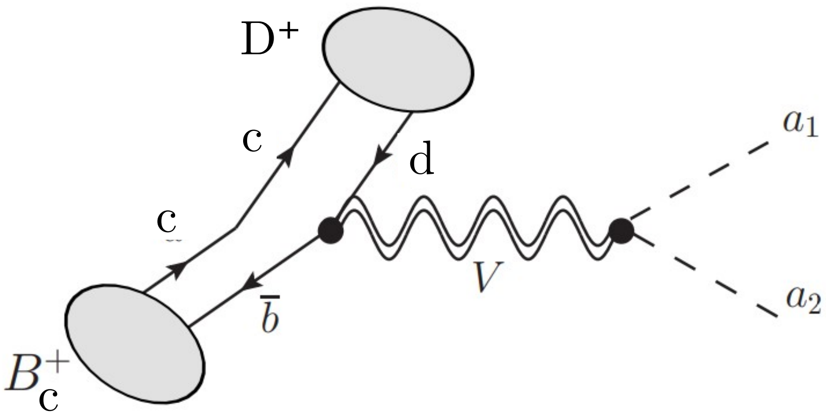
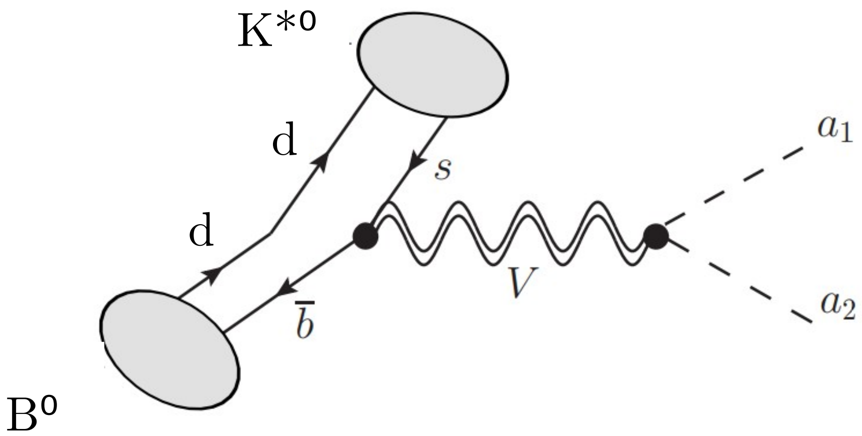
Other decay channels we considered:





Easy to reconstruct,
BR of about 9%

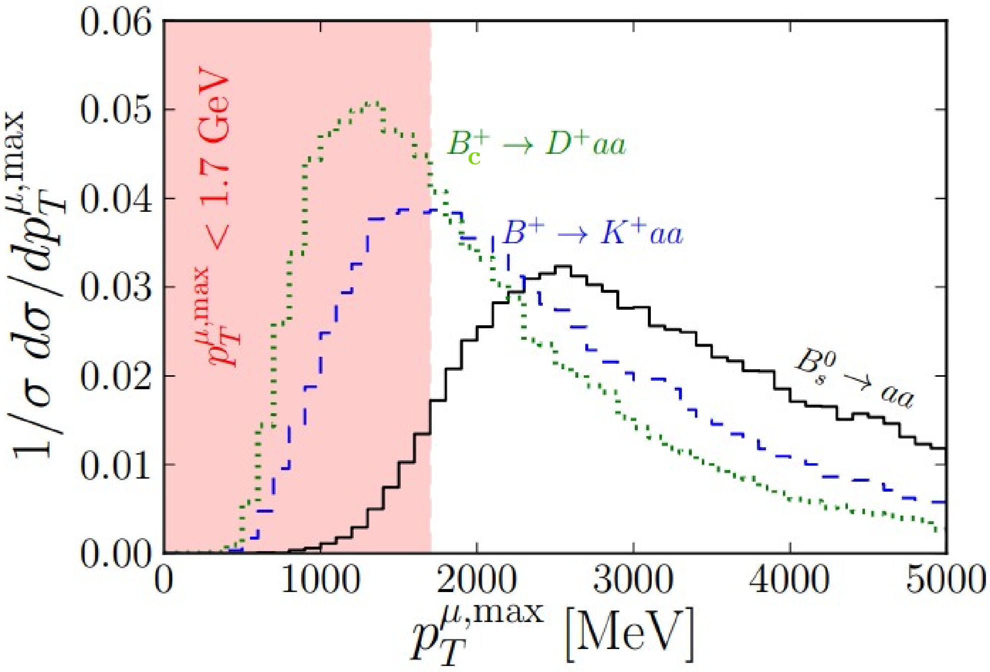
- $B_c^+ \rightarrow D^+ + $ 4muons, with $D^+ \rightarrow K^- \pi^+ \pi^+$

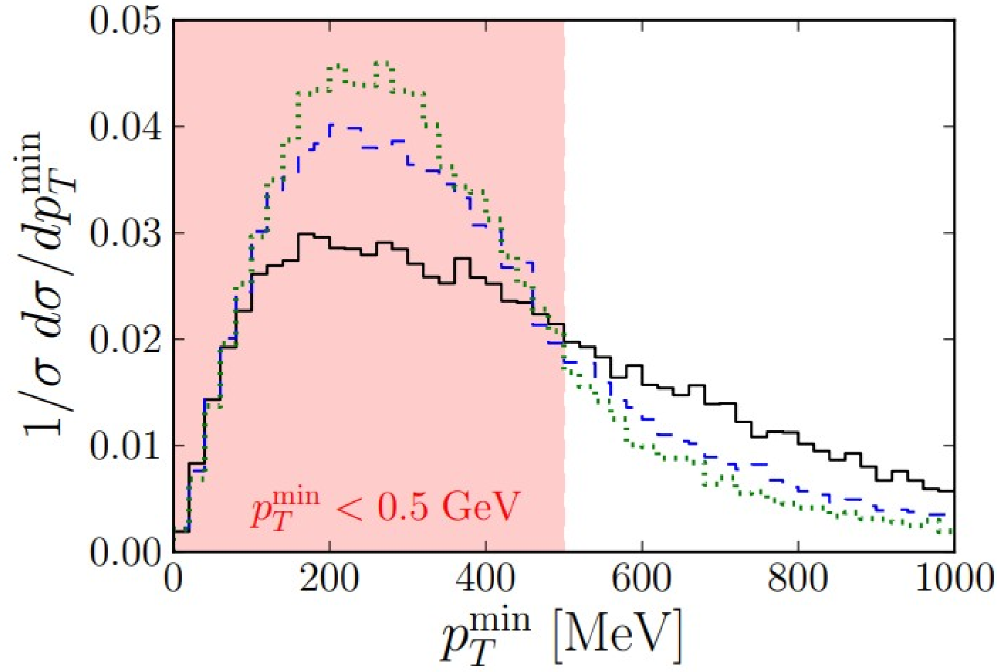
- $B^0 \rightarrow K^{*0} + $ 4muons, with $K^{*0} \rightarrow K^+ \pi^-$

BR ~ 67%

Effect of cuts:

larger final state multiplicity $\rightarrow$ smaller efficiency





Limit procedure:

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1.8 from 8 to 14 TeV

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$B^+ \sim B^0 \sim 3.7\ B_s^0$
[1111.2357]

- Scale upper limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu + \mu^-) < 2.5 \times 10^{-9}$ [from 1611.07704] accordingly:

$$\mathcal{B}_{max} \sim \frac{\mathcal{B}_{max}^{2\mu^+2\mu^-} \times \varepsilon_{2\mu^+2\mu^-}}{1.8 \times 3.7 \times \varepsilon} \times \frac{\mathcal{L}}{\mathcal{L}'}$$

Expected limits

Decay	LHCb	Upgrade I	Upgrade II
	9/fb	50/fb	300/fb
$B_s^0 \to \mu^+\mu^-\mu^+\mu^-$	60	9	1.4
$B^0 \to \mu^+\mu^-\mu^+\mu^-$	15	2.3	0.4
$B^+ \to K^+\mu^+\mu^-\mu^+\mu^-$	37	5	0.9
$B^0 \to K^{*0}\mu^+\mu^-\mu^+\mu^-$	100	16	2.7
$B_c^+ \to D^+\mu^+\mu^-\mu^+\mu^-$	1300	200	32

(BR in units of 10^{-11})

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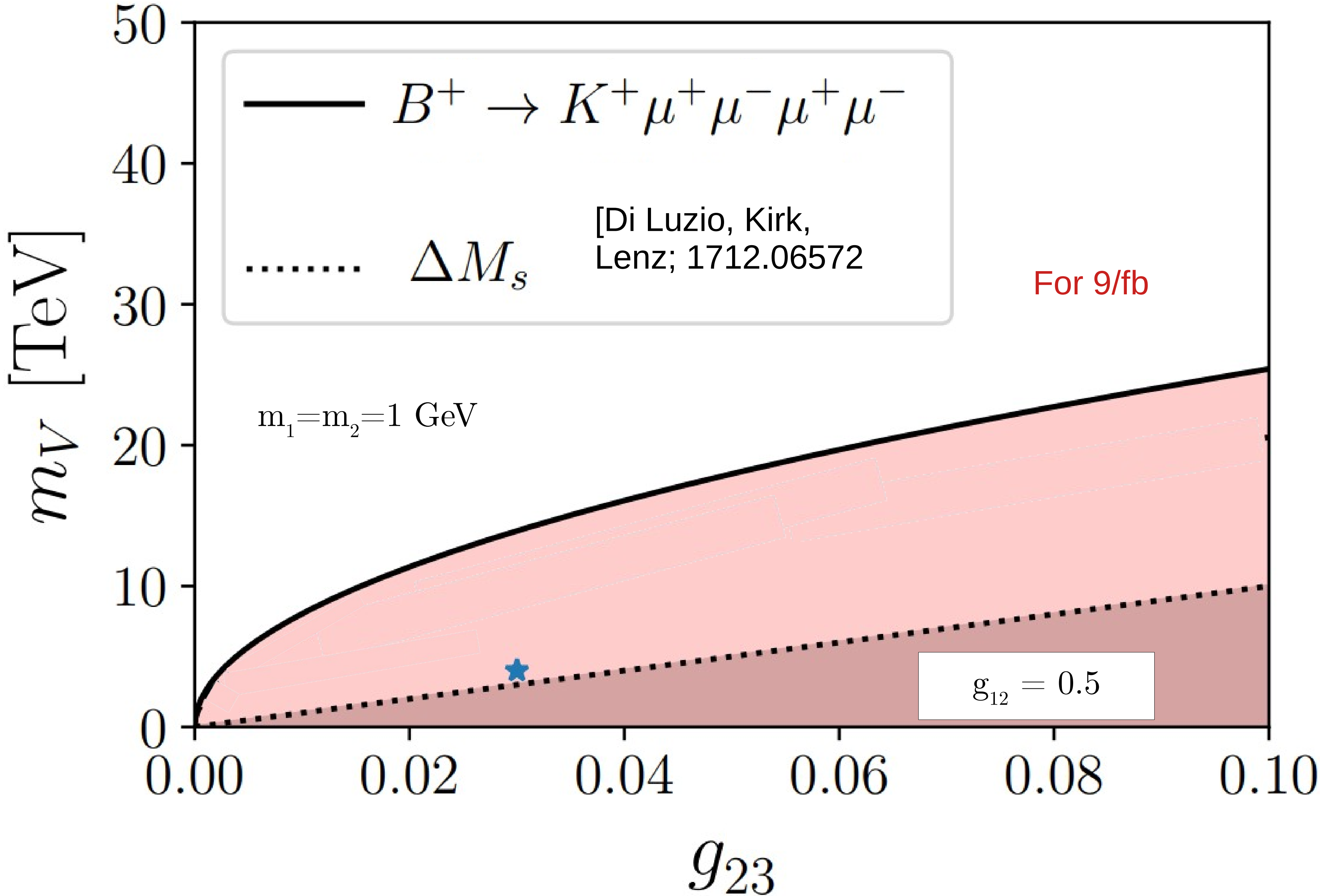
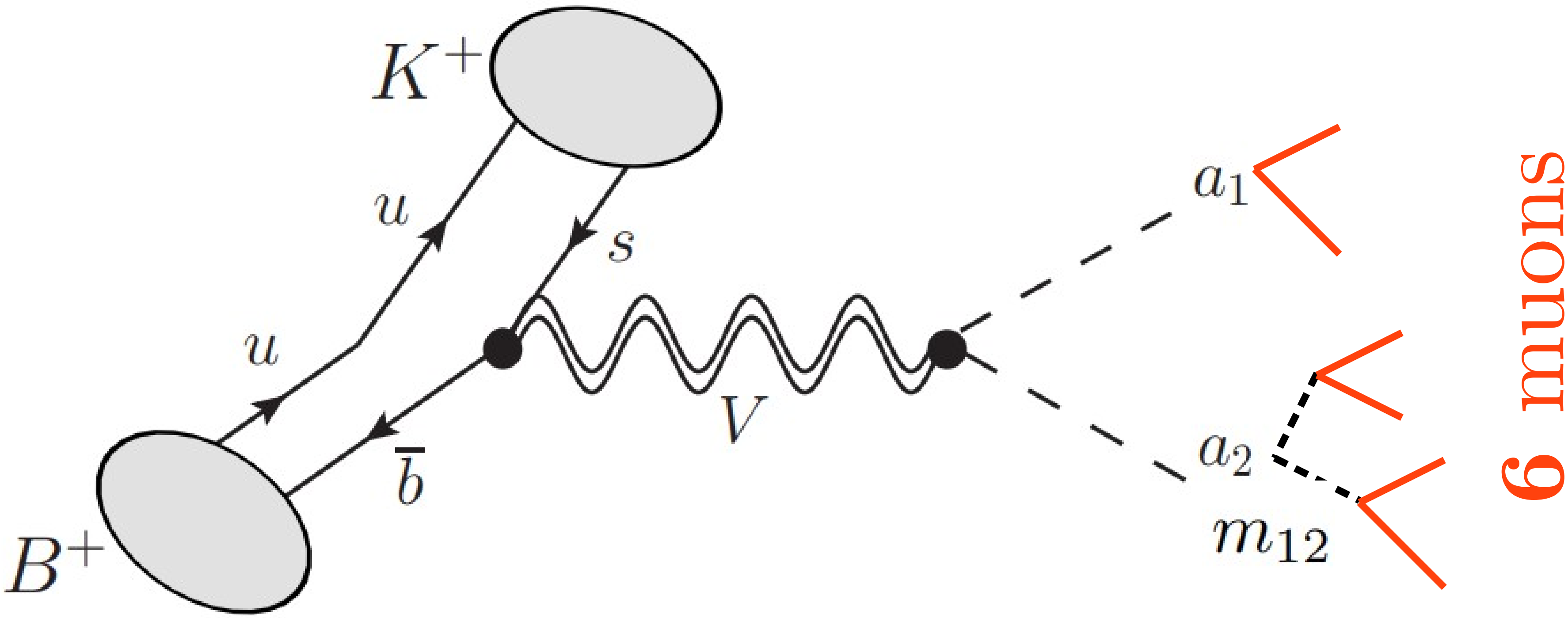
Comparison with other observables



One more search

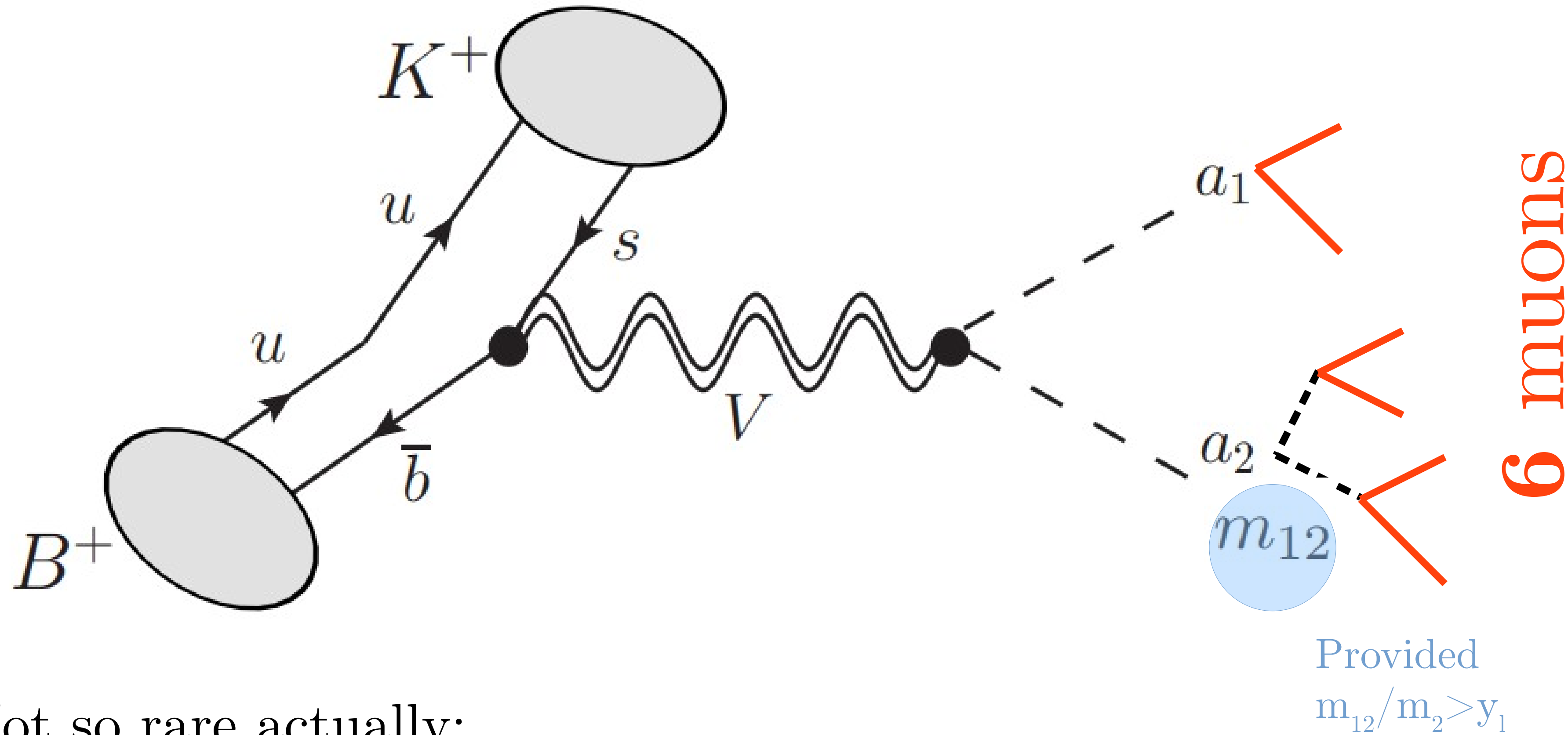


- Not so rare actually:

$$\Gamma(a_2 \to \ell^+\ell^-) = \frac{g_2^2 y_\ell^2}{8\pi}\left(1 - \frac{4m_\ell^2}{m_2^2}\right)^{3/2} m_2$$

$$\Gamma(a_2 \to a_1 a_1) = \frac{m_{12}^2}{8\pi m_2}\left(1 - \frac{4m_1^2}{m_2^2}\right)^{1/2}$$

One more search



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Efficiencies and limits:

	$m_X \geq m_1 + m_2$		$m_X < m_1 + m_2$
	$m_2 \geq 2m_1$	$m_2 < 2m_1$	$m_X \geq 3m_1$
$B_s^0 \to 3\mu^+ 3\mu^-$	[0.02,0.03]	[0.01,0.02]	[0.02,0.03]
limit ($\times 10^{-9}$)	[6.7, 11.6]	[7.9, 18.2]	[6.0, 11.9]
$B^+ \to K^+ 3\mu^+ 3\mu^-$	[0.007,0.009]	[0.003,0.009]	four-body
limit ($\times 10^{-9}$)	[5.9, 8.0]	[6.0, 16.6]	four-body

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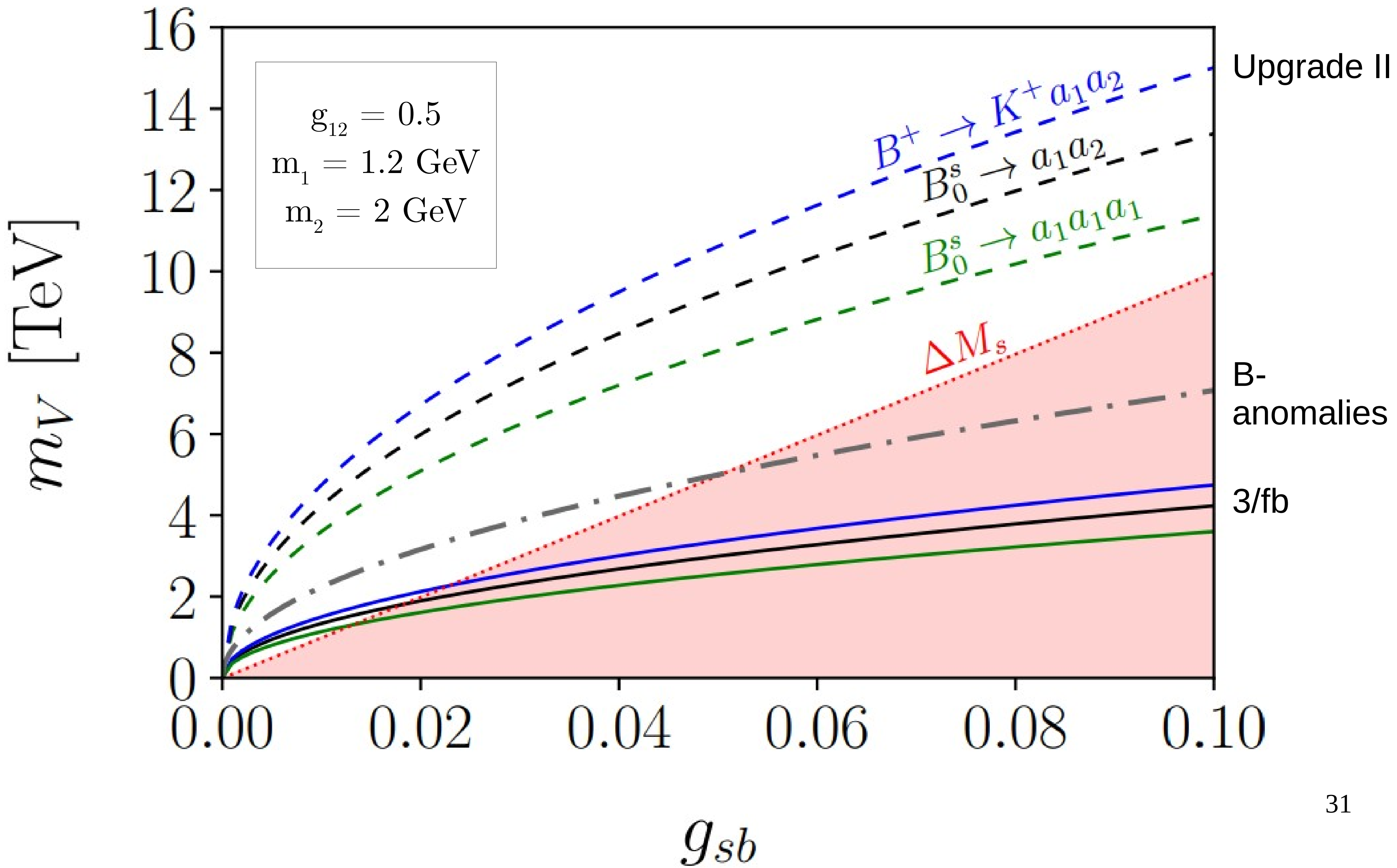
Comparison with other observables



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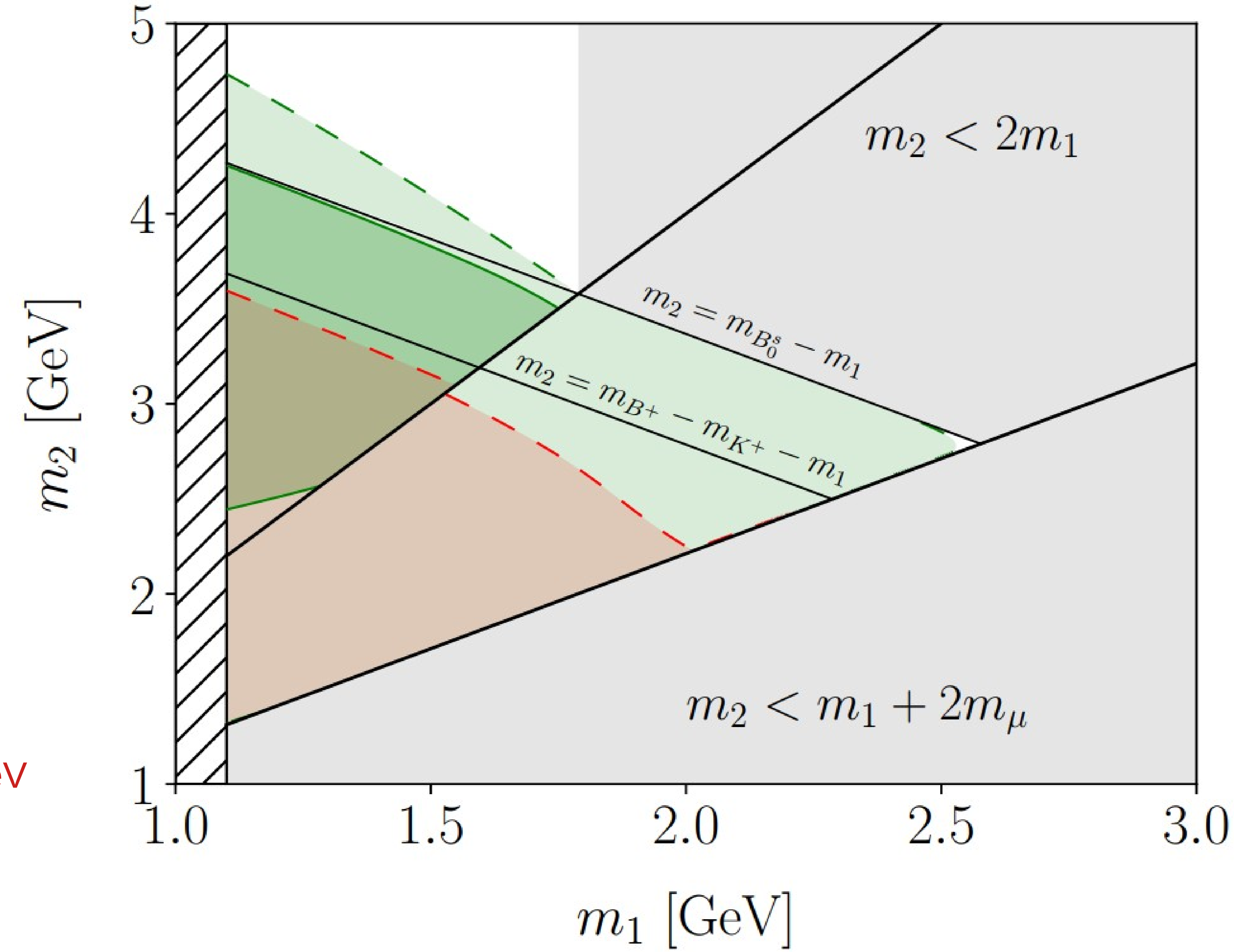


g_{sb}=0.04
g_{12} = 0.5
m_V = 5 TeV

Conclusions

- Heavy vector bosons and light scalars arise in a number of new physics models (CHMs, B anomalies, muon anomalies...)

- It can well be that their prime signature are B decay modes not yet explored, e.g.:

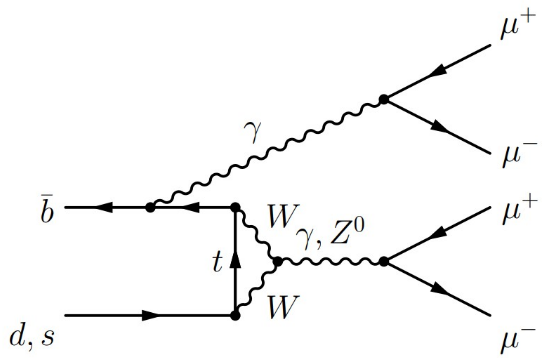
$$B^+ \to K^+(D^+)\mu^+\mu^-\mu^+\mu^-$$

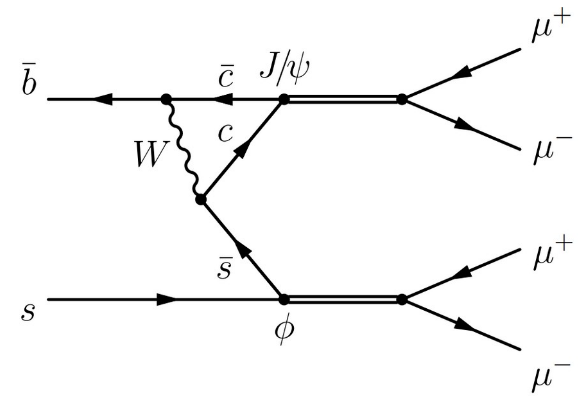
- The LHCb sensitivity to these Brs is of the order of 10^{-10}!

Thank you!

Backup

More about backgrounds





Irreducible backgrounds to the decay have to be considered. The decay $B_s^0 \to \varphi\varphi$ with $\varphi \to \mu^+\mu^-$ is one of these. Using the measured branching fractions [49, 50] we get $\mathcal{B}(B_s^0 \to (\varphi \to \mu^+\mu^-)(\varphi \to \mu^+\mu^-)) = 1.84 \times 10^{-5} \times (2.89 \times 10^{-4})^2 = 1.5 \times 10^{-12}$. As can be seen from the expected limits above, even at the end of LHCb Upgrade II, this is not relevant. For the equivalent decay mode of the B^0, the measured branching fraction limit for the $B^0 \to \varphi\varphi$ decay is three orders of magnitude below the B_s^0 mode and thus even less of a concern. The decay $B_s^0 \to \varphi\mu^+\mu^-$ has a measured differential rate of 2.6×10^{-8} GeV^{-2} in the region of the squared dimuon mass close to the φ mass [17]. Letting the φ decay to a muon pair and considering a mass region with width of around 20 MeV, corresponding to a realistic mass resolution, this will give a background at the 10^{-13} level and is thus not relevant.

$$B^+ \to K^+ a_1 a_2$$

$$\frac{d\Gamma}{dq^2} = \frac{\left(g_{sb} g_{12}\right)^2}{768\pi^3 m_V^4 m_B^3} F(q^2)$$

$$F(q^2) = \frac{1}{q^2}\left[\frac{(M_{BK}^2+q^2)^2}{q^4} - 4\frac{m_B^2}{q^2}\right]^{1/2}\left[\frac{(M_{12}^2+q^2)^2}{q^4} - 4\frac{m_2^2}{q^2}\right]^{1/2}$$
$$\times\left\{3M_{BK}^4 M_{12}^4 |f_0(q^2)|^2 + \left[q^4 + 2q^2\left(M_{BK}^2 - 2m_B^2\right) + M_{BK}^4\right]\left[q^4 + 2q^2\left(M_{12}^2 - 2m_2^2\right) + M_{12}^4\right]|f_+(q^2)|^2\right\}$$

$$\Gamma(a_2 \to a_1 \ell^+ \ell^-) \sim \frac{(g_1 y_\ell)^2}{64\pi^3 m_2^3} m_{12}^2 m_1^2 \left(1 + \frac{m_2}{m_1}\right)\left(\frac{m_2}{m_1} - 1\right)^5 . \quad (5)$$

This decay mode dominates if $g_1 \gtrsim 100 g_2$. We assume this hierarchy hereafter. Thus, for example for $g_1 = 3$ and $g_2 = 0.01$, a_2 decays always into four leptons mediated by a_1, which can be either on-shell or off-shell. Also, they both have widths smaller than 10 MeV and lifetime shorter than 10 fs. As a consequence, both $a_{1,2}$ would seem to have vanishing experimentally measurable widths and flight distances. Furthermore, note that the Yukawa suppression helps also avoiding bounds from BaBar and even the future Belle-II [22].

Reconstruction of masses

- Minimise $|m_{11}^{\text{rec}} - m_{12}^{\text{rec}}| + |m_{12}^{\text{rec}} - m_{13}^{\text{rec}}|$ Then a_2 is reconstructed from the two a_1 closer in DeltaR.

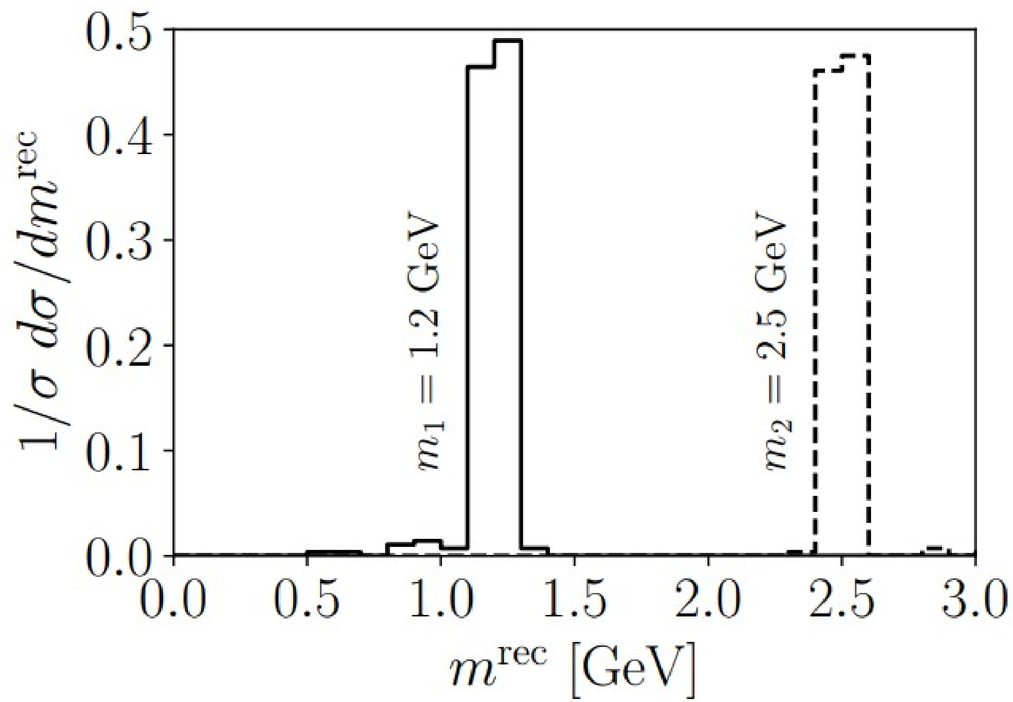


FIG. 9: *Normalized distribution of the reconstructed m_1 (solid) and m_2 (dashed) for $m_2 > 2m_1$.*