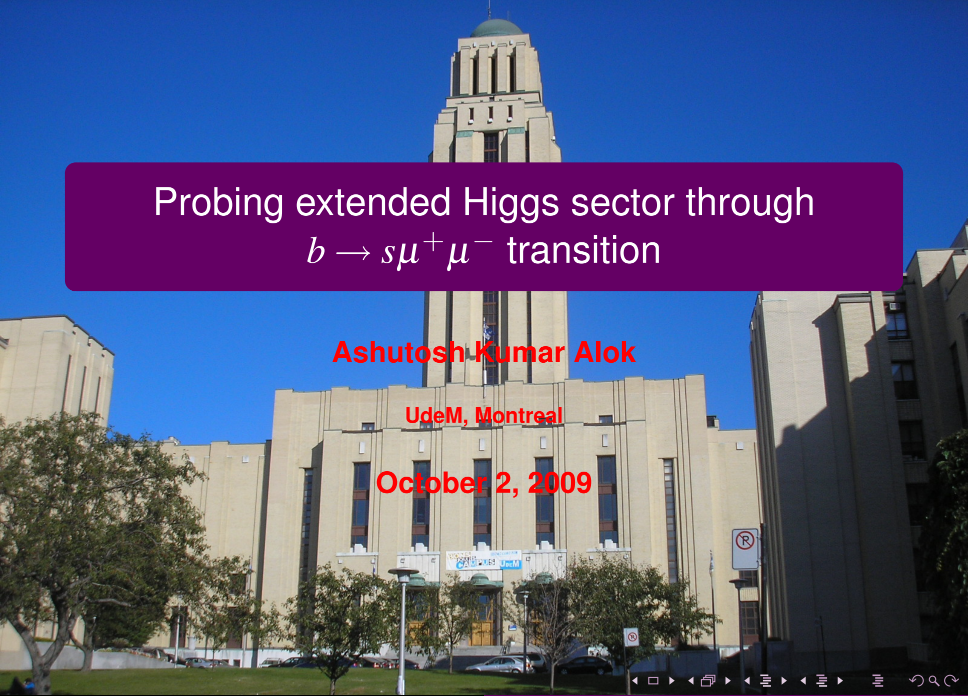

Probing extended Higgs sector through $b \to s\mu^+\mu^-$ transition

Ashutosh Kumar Alok

UdeM, Montreal

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Plan of talk

- $B_s \to \mu^+\mu^-$: Benchmark process for LHCb physics
- Possibility of invisibility of $B_s \to \mu^+\mu^-$ at the LHCb
- Correlation between $B(B_s \to \mu^+\mu^-)$ and $B(B \to K\mu^+\mu^-)$
- Forward-Backward asymmetry in $B \to K\mu^+\mu^-$
- Longitudinal Polarization asymmetry in $B_s \to \mu^+\mu^-$

In collaboration with Amol Dighe and S. Uma Sankar

[arXiv:0803.3511; PRD 78, 034020 (2008) & PRD 78, 114025 (2008)]

Importance of FCNC

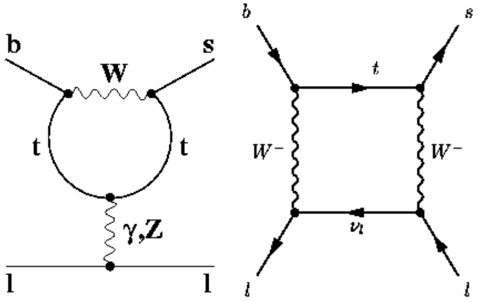
- The standard model (SM) of electroweak interaction is one of the most successful theory in particle physics.
- To date, almost all experimental tests of SM have agreed with its predictions.
- Still there are few sectors where this theory is to be verified completely.
- One such sector is the study of flavour changing neutral current (FCNC) decays.

Importance of FCNC

- Within the SM, FCNC decays are forbidden at tree level and can only occur at loop level, hence they are highly suppressed.
- Therefore FCNC can serve as an important probe to test SM at the loop level.
- A good way to search for new physics (physics beyond SM) is to look for process which are highly suppressed in the SM.
- Therefore FCNC process can also be useful in searching new physics (NP) and determining its Lorentz structure.

FCNC transition $\bar{b} \to \bar{s}\mu^+\mu^-$

- We consider the FCNC transition $\bar{b} \to \bar{s}\mu^+\mu^-$.
- The same quark level transition $\bar{b} \to \bar{s}\mu^+\mu^-$ is responsible for the purely leptonic decay $B_s \to \mu^+\mu^-$ and also for the semi-leptonic decays $B \to (K, K^*)\mu^+\mu^-$.



FCNC transition $\bar{b} \to \bar{s}\mu^+\mu^-$

- $B \to (K, K^*)\mu^+\mu^-$ have been observed at BaBar and Belle [HFAG, April 2008]:

$$B_{exp}(B \to K\mu^+\mu^-) = 0.42^{+0.09}_{-0.08} \times 10^{-6}$$

$$B_{exp}(B \to K^*\mu^+\mu^-) = 1.03^{+0.26}_{-0.23} \times 10^{-6}$$

- Within the error bars, the SM prediction and data are consistent with each other.
- Experimental errors are expected to reduce to 2% at the forthcoming SuperB factories.
- The uncertainty in the SM prediction is mainly due to the uncertainty in the form factors and the CKM matrix element $|V_{ts}|$.

FCNC transition $\bar{b} \to \bar{s}\mu^+\mu^-$

- $B_s \to \mu^+\mu^-$ is highly suppressed in the SM:

$$B_{SM}(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$$

- This decay is yet to be observed in the experiments.
- The present upper bound on $B(B_s \to \mu^+\mu^-)$ is 5.8×10^{-8} at 2σ which is still an order of magnitude away from its SM prediction. [CDF Collaboration, arxiv:0712.1708 (hep-ex)]
- $B_s \to \mu^+\mu^-$ can be observed at Tevatron only if $B(B_s \to \mu^+\mu^-) > 10^{-8}$.

$B_s \to \mu^+\mu^-$ at the LHCb

- $B_s \to \mu^+\mu^-$ is a benchmark process for the LHCb physics.
- LHCb will be the first experiment to be able to probe $B_s \to \mu^+\mu^-$ all the way down to its SM branching ratio.
- LHCb can reach SM sensitivity after one year of data collection.

Why is $B_s \to \mu^+\mu^-$ important?

- $B_s \to \mu^+\mu^-$ is highly suppressed within the SM, $B(B_s \to \mu^+\mu^-) \sim 10^{-9}$.
- Observation of $B_s \to \mu^+\mu^-$ with a branching ratio $\geq 10^{-8}$ will confirm the existence of NP.
- Look for NP which can provide an order of magnitude enhancement in $B(B_s \to \mu^+\mu^-)$.
- NP in the form of tensor operators do not contribute to $B_s \to \mu^+\mu^-$ as $\left\langle 0 \left| \bar{b}\sigma^{\mu\nu}s \right| B_s(p_B) \right\rangle = 0$.

Why is $B_s \to \mu^+\mu^-$ important?

- NP in the form of vector/axial-vector operators is constrained by the data on $B[B \to (K, K^*)\mu^+\mu^-]$ and cannot give rise to an order of magnitude enhancement in $B(B_s \to \mu^+\mu^-)$.
- However if NP is in the form of S-P operators then $B(B \to K^*\mu^+\mu^-)$ does not put any useful constraint on $B(B_s \to \mu^+\mu^-)$ and it can be as high as the present upper bound.
- Thus if $B(B_s \to \mu^+\mu^-) \geq 10^{-8}$ then it can only be due to S-P operators. [Ashutosh Kumar Alok and S. Uma Sankar, PLB 620, 61 (2005)]
- Hence $B_s \to \mu^+\mu^-$ is sensitive to NP models with extended Higgs sector like multi-Higgs doublet models, MSSM etc.

A legitimate question to ask at this stage is :

Does new physics scalar/pseudoscalar operators can only enhance $B(B_s \to \mu^+ \mu^-)$?

Effective $\bar{b} \to \bar{s}\mu^+\mu^-$ Lagrangian

- $$L(\bar{b} \to \bar{s}\mu^+\mu^-) = L_{SM} + L_{SP}$$
- $$L_{SM} = \frac{\alpha G_F}{2\sqrt{2}\pi} V_{tb} V_{ts}^{\star} \Big\{ C_9 \bar{b}\gamma_\mu (1-\gamma_5) s \, \bar{\mu}\gamma_\mu \mu$$
$$+ C_{10} \bar{b}\gamma_\mu (1-\gamma_5) s \, \bar{\mu}\gamma_\mu\gamma_5 \mu - 2\frac{C_7}{q^2} m_b \left(\bar{b} i \sigma_{\mu\nu} q^\nu s\right) \bar{\mu}\gamma_\mu \mu \Big\}$$
- $$L_{SP} = \frac{\alpha G_F}{2\sqrt{2}\pi} V_{tb} V_{ts}^{\star} \Big\{ R_S \bar{b}(1+\gamma_5) s \, \bar{\mu}\mu + R_P \bar{b}(1+\gamma_5) s \, \bar{\mu}\gamma_5 \mu \Big\}$$
- C_7, C_9 and C_{10} are SM Wilson coefficients. Their values are: $C_7 = -0.310$, $C_9 = +4.138$, $C_{10} = -4.221$. [A. J. Buras, M. Munj, PRD52, 186 (1995)]
- q is the sum of the μ^+ and μ^- momenta. R_S and R_P are the new physics couplings.

Branching ratio of $B_s \to \mu^+\mu^-$

- $$B(B_s \to \mu^+\mu^-) = a_s[(b_{SM} - b_P)^2 + b_S^2]$$

- $$b_{SM} = 2m_\mu |C_{10}|, \;\; b_P = m_{B_s} R_P, \;\; b_S = m_{B_s} R_S$$

- $$a_s \equiv \frac{G_F^2 \alpha^2}{64\pi^3} \left| V_{ts}^* V_{tb} \right|^2 \tau_{B_s} f_{B_s}^2 m_{B_s}$$

$B_s \to \mu^+\mu^-$ can be invisible at the LHC

- The interference between the S-P new physics and SM operators can decrease the branching ratio $B(B_s \to \mu^+\mu^-)$ far below its SM prediction.
- In fact it can even vanish, provided the following conditions are satisfied simultaneously:

$$R_S = 0, \;\; R_P = \frac{2m_\mu |C_{10}|}{m_{B_s}} \sim 0.17$$

- Hence it may also be possible that LHC fails to find $B_s \to \mu^+\mu^-$.
- Therefore the new physics S-P operators can not only lead to a large enhancement in $B(B_s \to \mu^+\mu^-)$ but can also cause a large suppression.

Correlations between $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

Correlations between $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- One good way to constrain new physics is to study the correlation between the observables which are sensitive to same type of new physics.
- Therefore it is natural to study the impact of large S-P couplings (that may provide an order of magnitude enhancement in $B(B_s \to \mu^+\mu^-)$) to the other related decays.
- We study the correlations between S-P new physics contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$.

Correlations between $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

The main motivation is to answer the following question:

Can an order of magnitude boost in $B(B_s \to \mu^+\mu^-)$ and the experimental data on $B(B \to K\mu^+\mu^-)$ can be explained simultaneously by S-P new physics?

$B_s \to \mu^+\mu^-$ branching ratio

- We assume that the S-P new physics will provide an order of magnitude increase in $B(B_s \to \mu^+\mu^-)$ so that it is of the order of 10^{-8}.
- In such a situation, the SM amplitude can be neglected in the calculation of branching ratio of $B_s \to \mu^+\mu^-$.

$B_s \to \mu^+\mu^-$ branching ratio

- $$B_{SP}(B_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2 m_{B_s}^3 \tau_{B_s}}{64\pi^3} |V_{tb}V_{ts}^*|^2 f_{B_s}^2 \times (R_S^2 + R_P^2)$$

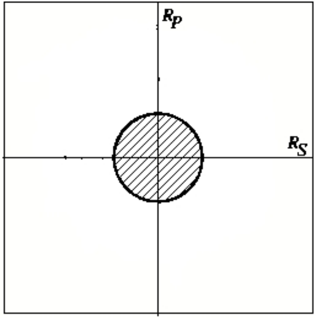
  $$f_{B_s} = (0.259 \pm 0.027)\ \mathrm{GeV};\ |V_{ts}| = (40.6 \pm 2.7) \times 10^{-3}$$

  $$B_{SP}(B_s \to \mu^+\mu^-) = (1.43 \pm 0.30) \times 10^{-7}\,(R_S^2 + R_P^2)$$

- Equating above expression to the present 2σ upper limit on $B(B_s \to \mu^+\mu^-)$, we get
  $$(R_S^2 + R_P^2) \le 0.70$$

Allowed R_S–R_P parameter space

- Thus, the allowed region in the R_S–R_P parameter space is the interior of the circle of radius 0.84 centered at the origin.



Matrix elements for $B \to K\mu^+\mu^-$

- We now consider $B \to K\mu^+\mu^-$. The necessary matrix elements are:

$$\left\langle K(p') \left| \bar{b}\gamma_\mu s \right| B(p) \right\rangle = (2p-q)_\mu f_+(z) + (\frac{1-k^2}{z})\, q_\mu [f_0(z) - f_+(z)]$$

$$\left\langle K(p') \left| \bar{b} i\sigma_{\mu\nu} q^\nu s \right| B(p) \right\rangle = -\left[(2p-q)_\mu q^2 - (m_B^2 - m_K^2) q_\mu\right] \frac{f_T(z)}{m_B + m_K}$$

$$\left\langle K(p') \left| \bar{b} s \right| B(p) \right\rangle = m_B(1-k^2) f_0(z)$$

- $q_\mu = (p-p')_\mu$ is the four-momentum transferred to the dilepton system. $k = m_K/m_B$ and $z = q^2/m_B^2$.

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

- $$B_{\rm tot} = \left[5.25 + 0.18(R_S^2 + R_P^2) - 0.13R_P\right] \times (1 \pm 0.20) \times 10^{-7}$$
- $B_{\rm tot} = (1+\varepsilon)B_{\rm SM}$.
- ε is the fractional change in the branching ratio due to S-P new physics.
- The maximum negative value that ε can take is -0.005.

$B(B \to K\mu^+\mu^-)$ cannot go below its SM prediction

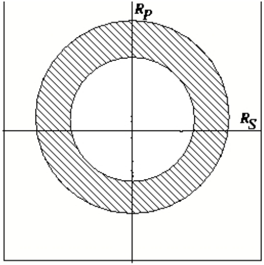
- S-P new physics cannot lower $B(B \to K\mu^+\mu^-)$ by more than 0.5% below its SM value.
- Thus, if future experiments were to find $B(B \to K\mu^+\mu^-)$ below its SM prediction, then it is almost guaranteed that this deficit is not due to S-P new physics.

Allowed R_S–R_P parameter space

- Equating the expression for $B \to K\mu^+\mu^-$ to its experimental value, we get

$$R_S^2 + (R_P - 0.36)^2 = \frac{B_{\exp}}{(0.18 \pm 0.036) \times 10^{-7}} - 29.04$$

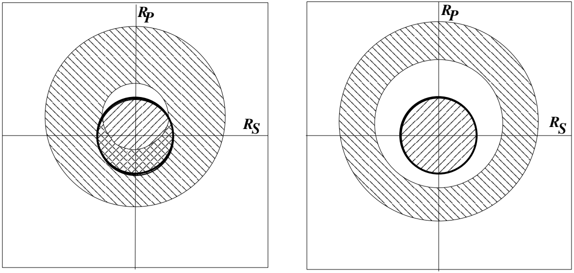
- The region in the R_S–R_P plane allowed by the measurement of $B(B_s \to K\mu^+\mu^-)$ is then an annulus centered at $(0, 0.36)$.



Conditions for Tension

- No tension if there is overlap between $B_s \to \mu^+\mu^-$ circle and $B \to K\mu^+\mu^-$ annulus.
- There is tension if there is no overlap.
- "No overlap" will occur if the inner radius of the $B \to K\mu^+\mu^-$ annulus is larger than the $B_s \to \mu^+\mu^-$ circle.

Tension between $B(B_s \to \mu^+\mu^-)$ and $B(B \to K\mu^+\mu^-)$ can be schematically understood with the following figure:



Tension between $B(B \to K\mu^+\mu^-)$ and $B(B_s \to \mu^+\mu^-)$

- If we represent the radius of the leptonic circle by r_ℓ and the inner radius of the semileptonic annulus by r_{in} , then
$$r_{in} - r_\ell > 0.36$$
would imply that the regions allowed by the two branching ratios do not overlap.
- Given the current value of $r_l = 0.84$, we require $0 < r_{in} < 1.2$ for an overlap.
- With present experimental and theoretical errors, $r_{in} = 0$.
- For the tension to be manifest in future experiments, the reduction of errors in $B_{\rm exp}$ and $B_{\rm SM}$ is the most crucial.

Tension between $B(B \to K\,\mu^+\,\mu^-)$ and $B(B_s \to \mu^+\,\mu^-)$

- The present upper bound on $B(B_s \to \mu^+\,\mu^-)$, restricts the maximum value of ε to be 0.025.
- Hence the S-P new physics cannot enhance $B(B \to K\,\mu^+\,\mu^-)$ by more than $\sim 3\%$ above its SM value.
- Thus the allowed values of $B(B \to K\,\mu^+\,\mu^-)$ are restricted within a narrow range around its SM prediction.

Forward-backward asymmetry in $B \to K\mu^+\mu^-$

FB asymmetry in $B \to K\mu^+\mu^-$

- Apart from the branching ratios of the purely leptonic and semi-leptonic decays, there are other observables which are sensitive to the S-P new physics contribution to $b \to s\mu^+\mu^-$ transitions.
- These are forward-backward (FB) asymmetry A_{FB} of muons in $B \to K\mu^+\mu^-$ and longitudinal polarization (LP) asymmetry A_{LP} of muons in $B_s \to \mu^+\mu^-$.
- Both these are predicted to be zero in the SM. Therefore, any nonzero measurement of one of these asymmetries is a signal for new physics.

FB asymmetry in $B \to K\mu^+\mu^-$

- The FB asymmetry is defined as

$$A_{FB}(z) = \frac{\int_0^1 dcos\theta \frac{d^2\Gamma}{dzdcos\theta} - \int_{-1}^0 dcos\theta \frac{d^2\Gamma}{dzdcos\theta}}{\int_0^1 dcos\theta \frac{d^2\Gamma}{dzdcos\theta} + \int_{-1}^0 dcos\theta \frac{d^2\Gamma}{dzd\cos\theta}} \, .$$

- $z = q^2/m_B^2$, q is the sum of μ^- & μ^+ momenta and θ is the angle between the momenta of K meson and μ^- in the dilepton center of mass frame.
- In the SM, FB asymmetry in $B \to K\mu^+\mu^-$ vanishes because the hadronic current for $B \to K$ transition does not have any axial vector contribution.
- This asymmetry can be nonzero in multi-Higgs doublet models and supersymmetric models due to the contributions from the extended Higgs sector.
- Therefore FB asymmetry in $B \to K\mu^+\mu^-$ is expected to serve as an important probe to test the existence of an extended Higgs sector.

FB asymmetry in $B \to K\mu^+\mu^-$

- The average (or integrated) FB asymmetry of muons in $B \to K\mu^+\mu^-$, which is denoted by $\langle A_{FB} \rangle$, has been measured by BaBar and Belle to be
$$\langle A_{FB} \rangle = (0.15^{+0.21}_{-0.23} \pm 0.08) \quad \text{(BaBar)}$$
$$\langle A_{FB} \rangle = (0.10 \pm 0.14 \pm 0.01) \quad \text{(Belle)}$$
- These measurements are consistent with zero. But on the other hand, they can be as high as $\sim 40\%$ within 2σ error bars.
- Our aim is to investigate what constraints the recently improved upper bound on $B(B_s \to \mu^+\mu^-)$ puts on the possible S-P new physics contribution to A_{FB} and A_{LP}.
- Do S-P operators enhance these observables to sufficiently large values to be measurable in future experiments?

FB asymmetry in $B \to K\mu^+\mu^-$

- The calculation of FB asymmetry gives

$$A_{FB}(z) = \frac{2\Gamma_0\, a_1(z)\, \phi\, \beta_\mu^2}{d\Gamma/dz} \left(\frac{m_\mu R_S}{m_B}\right) .$$

-

$$\begin{aligned} \Gamma_0 &= \frac{G_F^2 \alpha^2}{2^9 \pi^5} |V_{tb} V_{ts}^*|^2 m_B^5 , \\ a_1(z) &= \frac{1}{2}(1-k^2) C_9 f_0(z) f_+(z) \\ &\quad + (1-k) C_7 f_0(z) f_T(z) , \\ \phi &= 1 + k^4 + z^2 - 2(k^2 + k^2 z + z) , \\ \beta_\mu &= (1 - \frac{4\hat{m_\mu}^2}{z}) . \end{aligned} \tag{1}$$

- $d\Gamma/dz$ is the differential decay rate.

FB asymmetry in $B \to K\mu^+\mu^-$

- The average FB asymmetry is obtained by integrating the numerator and denominator separately over dilepton invariant mass, which leads to
$$\langle A_{FB}\rangle = \frac{5.25\times 10^{-9} R_S}{\left[5.25+0.18(R_S^2+R_P^2)-0.13R_P\right]\times 10^{-7}}(1\pm 0.3)$$
- With the present upper bound on $B(B_s \to \mu^+\mu^-)$, the maximum value of $\langle A_{FB}\rangle$ is 1.34% at 2σ.
- If $B(B_s \to \mu^+\mu^-)$ is bounded to 10^{-8}, the 2σ maximum value of $\langle A_{FB}\rangle$ will be only 0.56%.

FB asymmetry in $B \to K\mu^+\mu^-$

- The measurement of an asymmetry $\langle A_{FB} \rangle$ of a decay with the branching ratio $\mathscr{B}$ at $n\sigma$ C.L. with only statistical errors require
$$N \sim \frac{1}{\mathscr{B}} \left(\frac{n}{\langle A_{FB} \rangle} \right)^2$$
number of events.
- For $B \to K\mu^+\mu^-$, if $\langle A_{FB} \rangle$ is 1% at 2σ C.L., then the required number of events will be as high as 10^{11} !
- Therefore it is very difficult to observe such a low value of FB asymmetry in experiments. Hence FB asymmetry of muons in $B \to K\mu^+\mu^-$ will play no role in testing S-P new physics.

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

- The longitudinal polarization asymmetry of muons in $B_s \to \mu^+\mu^-$ is defined as

$$A_{LP} = \frac{N_R - N_L}{N_R + N_L}$$

$N_R\,(N_L)$ is the number of μ^- emerging with positive (negative) helicity

- The longitudinal polarization asymmetry of muons in $B_s \to \mu^+\mu^-$ is a clean observable that depends only on S-P new physics operators.
- It vanishes in the SM. It is nonzero if and only if the new physics contribution is in the form of S-P operator.
- Therefore any nonzero measurement of this observable A_{LP} will confirm the existence of an extended Higgs sector.

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

- $$A_{LP} = \frac{2b_S(b_{SM} - b_P)}{(b_{SM} - b_P)^2 + b_S^2}$$
- A_{LP} can be nonzero if and only if $b_S \neq 0$, i.e. for A_{LP} to be nonzero, we must have contribution from S-P operators.
- Within the SM, $b_S \simeq 0$ and hence $A_{LP} \simeq 0$.
- We will determine the allowed values of A_{LP} consistent with the present upper bound on $B(B_s \to \mu^+\mu^-)$, and explore the correlation between these two quantities.

Longitudinal polarization asymmetry in $B_s \to \mu^+\mu^-$

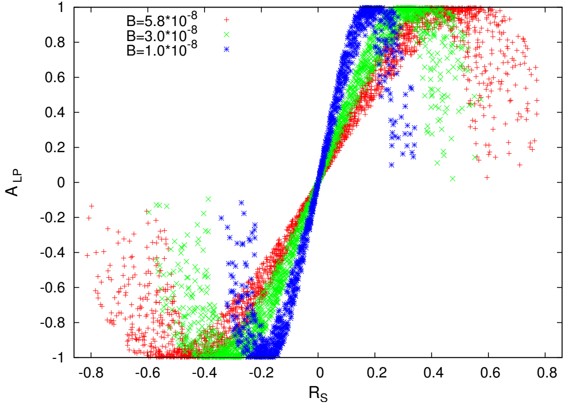


Figure: A_{LP} vs R_s plot for $B(B_s \to \mu^+\mu^-) = (5.8, 3.0, 1.0) \times 10^{-8}$

$(A_{LP})_{max}$ for present upper bound on $B(B_s \to \mu^+\mu^-)$ is 100%. $B(B_s \to \mu^+\mu^-)$ will be unable to put any constraint on A_{LP} even if it is as low as 10^{-8}.

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

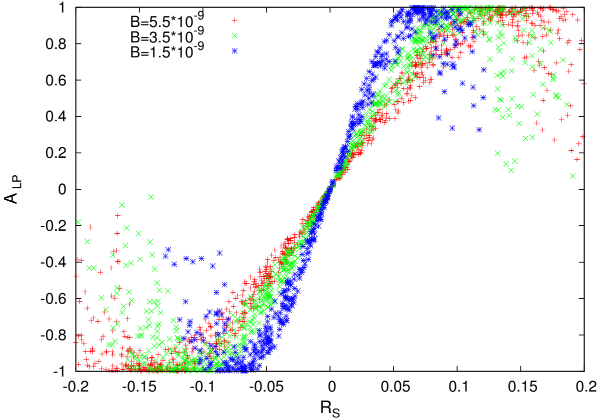


Figure: A_{LP} vs R_s plot for $B(B_s \to \mu^+\mu^-) = (5.5, 3.5, 1.5) \times 10^{-9}$

A_{LP} can be 100% even if $B(B_s \to \mu^+\mu^-)$ is close to its SM prediction !!

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

- The measurement of $B(B_s \to \mu^+\mu^-)$ will only give the allowed range for the values of the S-P couplings R_S and R_P.
- However the simultaneous determination of $B(B_s \to \mu^+\mu^-)$ and A_{LP} will allow the determination of new physics scalar coupling R_S and this in turn will enable us to determine the new physics pseudoscalar coupling R_P.

Longitudinal polarization asymmetry in $B_s \to \mu^+\mu^-$

- We now consider two exciting experimental possibilities, all of which can be accounted for with S-P new physics.
- $B(B_s \to \mu^+\mu^-)$ is consistent with SM but $A_{LP} \neq 0$.
- Both $B(B_s \to \mu^+\mu^-)$ and A_{LP} are consistent with the SM.

$B(B_s \to \mu^+\mu^-)$ is consistent with SM but $A_{LP} \neq 0$

- It is possible to have a non-zero value of A_{LP} even if $B(B_s \to \mu^+\mu^-)$ is equal to its SM prediction.
- $B_s \to \mu^+\mu^-$ branching ratio is
$$B(B_s \to \mu^+\mu^-) = a_s[(b_{SM} - b_P)^2 + b_S^2] \ .$$
- If $B(B_s \to \mu^+\mu^-)$ is equal to its SM prediction, then
$$a_s[(b_{SM} - b_P)^2 + b_S^2] = a_s b_{SM}^2 \ .$$

$B(B_s \to \mu^+ \mu^-)$ is consistent with SM but $A_{LP} \neq 0$

- This gives us a circle in $b_S - b_P$ plane with center at $(0, b_{SM})$:
$$(b_P - b_{SM})^2 + b_S^2 = b_{SM}^2$$
- This circle passes through the origin ($b_S = b_P = 0$), which corresponds to the SM.
- However, in general the points on the circle have nonzero b_S, and hence imply nonvanishing A_{LP}.
- Therefore it is possible to have a nonzero value of A_{LP} even if $B(B_s \to \mu^+\mu^-)$ is equal to its SM prediction.

Both $B(B_s \to \mu^+\mu^-)$ and A_{LP} are consistent with the SM

- Lepton polarization asymmetry vanishes when either $b_S = 0$ or $b_P = b_{SM}$.
- Thus there exists the interesting possibility of nontrivial S-P new physics even when both $B(B_s \to \mu^+\mu^-)$ and A_{LP} are consistent with the SM.
- This occurs when:
  $b_S = 0\ , b_P = 2\, b_{SM}\ .$
  $b_S = \pm b_{SM}\ , b_P = b_{SM}\ .$
- Therefore, the absence of S-P new physics is not guaranteed simply by the consistency of these observables with the SM; more channels need to be examined to rule out this possibility completely.

Conclusions

- We consider new physics in the form of S-P operators.
- We show that S-P new physics cannot decrease the branching ratio of $B \to K\mu^+\mu^-$ below its SM prediction.
- The S-P new physics operators are strongly constrained by the upper bound on $B(B_s \to \mu^+\mu^-)$, and in turn restrict the allowed values of $B(B \to K\mu^+\mu^-)$ to within a narrow range around its SM prediction.
- Future precise measurements of these two branching ratios may not only give an evidence for new physics, but also reveal the nature of its Lorentz structure.

Conclusions

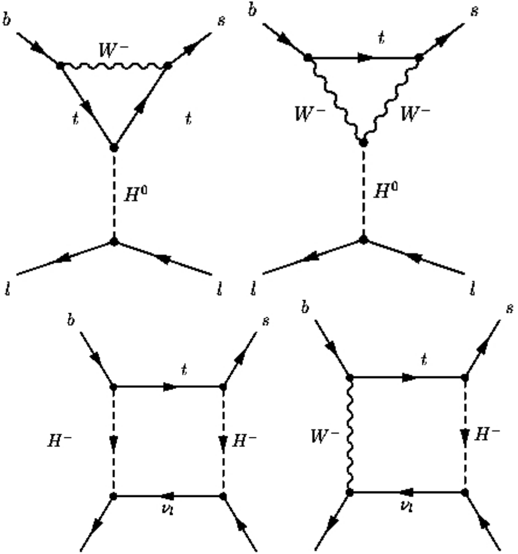
- Apart from $B(B_s \to \mu^+\mu^-)$ and $B(B \to K\mu^+\mu^-)$, observables such as FB asymmetry of muons in $B \to K\mu^+\mu^-$ and LP asymmetry of muons in $B_s \to \mu^+\mu^-$ are also sensitive to S-P operators.
- $B(B_s \to \mu^+\mu^-)$ puts very stringent constraint on S-P new physics contribution to $\langle A_{FB} \rangle$ and restricts its value to be less than $\sim 1\%$.
- Thus the present upper bound on $B(B_s \to \mu^+\mu^-)$ makes searching for S-P new physics through $\langle A_{FB} \rangle$ a futile exercise.

Conclusions

- A_{LP} is sensitive only to S-P operators and hence its nonzero value will give direct evidence for a non-standard Higgs sector.
- The present upper bound on $B(B_s \to \mu^+\mu^-)$ does not put any constraint on A_{LP}. Indeed, A_{LP} can be 100% even if $B(B_s \to \mu^+\mu^-)$ is close to its SM prediction.
- A simultaneous determination of $B(B_s \to \mu^+\mu^-)$ and A_{LP} will enable us to separate the new physics scalar and pseudoscalar contributions.
- Consistency of both $B(B_s \to \mu^+\mu^-)$ and A_{LP} with SM cannot rule out S-P new physics. However tension between $B(B_s \to \mu^+\mu^-)$ and $B(B \to K\mu^+\mu^-)$ will rule out new physics in the form of only S-P operators.


THANK
YOU!

Diagrams contributing to the $b \to s l^+ l^-$ in extended Higgs sector



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

The decay amplitude for $B(p) \to K(p')\mu^+(p_+)\mu^-(p_-)$ is given by

$$
\begin{aligned}
M\left(B \to K\mu^+\mu^-\right) &= \frac{\alpha G_F}{2\sqrt{2}\pi} V_{tb} V_{ts}^{\star} \times \\
& \Bigg[\left\langle K(p') \left| \bar{b}\gamma_\mu s \right| B(p) \right\rangle \times \\
& \left\{ C_9^{\rm eff} \bar{u}(p_-)\gamma_\mu v(p_+) + C_{10}\bar{u}(p_-)\gamma_\mu\gamma_5 v(p_+) \right\} \\
&- \frac{2C_7^{\rm eff} m_b}{q^2} \left\langle K(p') \left| \bar{b} i\sigma_{\mu\nu} q^\nu s \right| B(p) \right\rangle \bar{u}(p_-)\gamma_\mu v(p_+) \\
&+ \left\langle K(p') \left| \bar{b}s \right| B(p) \right\rangle \times \\
& \left\{ R_S \bar{u}(p_-) v(p_+) + R_P \bar{u}(p_-)\gamma_5 v(p_+) \right\} \Bigg], \qquad (2)
\end{aligned}
$$

where $q_\mu = (p - p')_\mu = (p_+ + p_-)_\mu$.

- The double differential decay width can be calculated as

$$\begin{aligned} \frac{d^2\Gamma}{dz dcos\theta} &= \frac{G_F^2\alpha^2}{2^9\pi^5}\,|V_{tb}V_{ts}^*|^2\, m_B^5\,\phi^{1/2}\,\beta_\mu \\ &\times \Bigg[\left(|A|^2\beta_\mu^2 + |B|^2\right)z \\ &\quad + \frac{1}{4}\phi\left(|C|^2 + |D|^2\right)(1-\beta_\mu^2\cos^2\theta) \\ &\quad + 2\hat{m}_\mu(1-k^2+z)Re(BC^*) + 4\hat{m}_\mu{}^2|C|^2 \\ &\quad + 2\hat{m}_\mu\,\phi^{\frac{1}{2}}\,\beta_\mu\,Re(AD^*)\cos\theta\Bigg] \end{aligned} \tag{3}$$

- The FB asymmetry arises from the $\cos\theta$ term in the above equation.

$B \to K\mu^+\mu^-$ double differential decay width

- The definitions used in the expression of double differential decay rate are:

$$
\begin{aligned}
A &\equiv \frac{1}{2}(1-k^2) f_0(z) R_S \,, \\
B &\equiv -\hat{m}_\mu C_{10} \left\{ f_+(z) - \frac{1-k^2}{z}\left(f_0(z) - f_+(z)\right) \right\} \\
&\quad + \frac{1}{2}(1-k^2) f_0(z) R_P \,, \\
C &\equiv C_{10} f_+(z) \,, \\
D &\equiv C_9^{eff} f_+(z) + 2\, C_7^{eff} \frac{f_T(z)}{1+k} \,, \\
\phi &\equiv 1 + k^4 + z^2 - 2(k^2 + k^2 z + z) \,, \\
\beta_\mu &\equiv \left(1 - \frac{4\hat{m}_\mu{}^2}{z}\right) .
\end{aligned} \tag{4}
$$

- $z = q^2/m_B^2$, $k = m_K/m_B$, $\hat{m}_\mu = m_\mu/m_B$ and θ is the angle between the momenta of K meson and μ^- in the dilepton

$B \to K\mu^+\mu^-$ double differential decay width

- The kinematical variables are bounded as

$$
\begin{aligned}
-1 \leq \cos\theta \leq 1 \,, \\
4\hat{m}_\mu^2 \leq z \leq (1-k)^2 \,.
\end{aligned}
$$

Form factors

The form factors $f_{+,0,T}$ can be calculated in the light cone QCD approach. Their q^2 dependence is given by

$$f(z) = f(0)\,\exp(c_1 z + c_2 z^2 + c_3 z^3)\ , \tag{5}$$

where the parameters $f(0), c_1$, c_2 and c_3 for each form factor are given below:

	$f(0)$	c_1	c_2	c_3
f_+	$0.319^{+0.052}_{-0.041}$	1.465	0.372	0.782
f_0	$0.319^{+0.052}_{-0.041}$	0.633	-0.095	0.591
f_T	$0.355^{+0.016}_{-0.055}$	1.478	0.373	0.700

Table: Form factors for the $B \to K$ transition.

$B_s \to \mu^+\mu^-$ decay amplitude

The decay amplitude for $B_s \to \mu^+\mu^-$ is given by

$$M\left(B_s \to \mu^+\mu^-\right) = \frac{\alpha G_F}{2\sqrt{2}\pi} V_{tb} V_{ts}^{\star} \langle 0 \left| \bar{s}\gamma_5 b \right| B_s \rangle \times \left[R_S \bar{u}(p_\mu) v(p_{\bar{\mu}}) + R_P \bar{u}(p_\mu) \gamma_5 v(p_{\bar{\mu}}) \right] .$$

On substituting

$\langle 0 \left| \bar{s}\gamma_5 b \right| B_s \rangle = -i \frac{f_{B_s} m_{B_s}^2}{m_b + m_s}$, we get

$$M\left(B_s \to \mu^+\mu^-\right) = -i \frac{\alpha G_F}{2\sqrt{2}\pi} V_{tb} V_{ts}^{\star} \frac{f_{B_s} m_{B_s}^2}{m_b + m_s} \times \left[R_S \bar{u}(p_\mu) v(p_{\bar{\mu}}) + R_P \bar{u}(p_\mu) \gamma_5 v(p_{\bar{\mu}}) \right] ,$$

where m_b and m_s are the masses of bottom and strange quark, respectively.

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

- In the rest frame of μ^+, we can define only one direction $\overrightarrow{p}_-$, the three momentum of μ^-.
- The unit longitudinal polarization 4-vectors along that direction are
$$\bar{s}^{\mu}_{\mu^\pm} = (0,\ \hat{e}_L^{\pm}) = \left(0,\ \pm\frac{\overrightarrow{p}_-}{|\overrightarrow{p}_-|}\right).$$
- Transformation of unit vectors from the rest frame of μ^+ to the center of mass frame of leptons (which is also the rest frame of B_s meson) can be accomplished by the Lorentz boost.
- After the boost, we get
$$s^{\mu}_{\mu^\pm} = \left(\frac{|\overrightarrow{p}_-|}{m_\mu},\ \pm\frac{E_\mu \overrightarrow{p}_-}{m_\mu |\overrightarrow{p}_-|}\right),$$ where E_μ is the muon energy.
- The longitudinal polarization asymmetry of muons in $B_s \to \mu^+\mu^-$ is defined as
$$A_{LP}^{\pm} = \frac{\Gamma(\hat{e}_L^{\pm}) - \Gamma(-\hat{e}_L^{\pm})}{\Gamma(\hat{e}_L^{\pm}) + \Gamma(-\hat{e}_L^{\pm})}.$$

Longitudinal polarization asymmetry in $B_s \to \mu^+\mu^-$

- Eliminating b_{SM} and b_P from A_{LP} using $B(B_s \to \mu^+\mu^-)$ expression, we get

$$A_{LP} = \pm \frac{2a_s b_S \sqrt{\frac{B(B_s \to \mu^+\mu^-)}{a_s} - b_S^2}}{B(B_s \to \mu^+\mu^-)}$$

- We now explore the correlation between A_{LP} and $B(B_s \to \mu^+\mu^-)$.

Longitudinal polarization asymmetry in $B_s \to \mu^+ \mu^-$

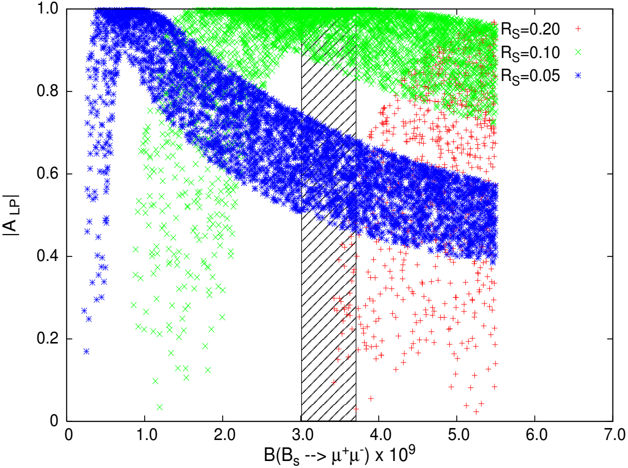


Figure: Plot between $|A_{LP}|$ and $B(B_s \to \mu^+\mu^-)$ for different R_S values, when $B(B_s \to \mu^+ \mu^-) \lesssim 10^{-8}$. The vertical shaded band corresponds to 1σ theoretical prediction within the SM.

$B \to K^*$ matrix elements

$$\langle K^*(p_{K^*})\left|\bar{s}\gamma_\mu b\right|B(p_B)\rangle = i\varepsilon_{\mu\vartheta\lambda\sigma}\varepsilon^\nu(p_{K^*})(p_B+p_{K^*})^\lambda$$
$$\times(p_B-p_{K^*})^\sigma V(q^2)\,,$$
$$\langle K^*(p_{K^*})\left|\bar{s}\gamma_5\gamma_\mu b\right|B(p_B)\rangle = \varepsilon_\mu(p_{K^*})(m_B^2-m_{K^*}^2)A_1(q^2)$$
$$- (\varepsilon.q)(p_B+p_{K^*})_\mu A_2(q^2)\,,$$
$$\langle K^*\left|\bar{s}\gamma_5 b\right|B\rangle = -i\left(\frac{2m_{K^*}}{m_b-m_s}\right)A_0(q^2)(q\cdot\varepsilon)\,.$$

where $q = p_{l^+}+p_{l^-}$.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- $$L_{SP} = \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^\star \left\{ \tilde{R}_S \,(\bar{b}\, P_R\, s)\, \bar{\mu}\,\mu + \tilde{R}_P\,(\bar{b}\, P_R\, s)\,\bar{\mu}\gamma_5\mu \right\}.$$
- $\tilde{R}_S$ and $\tilde{R}_P$ are the scalar and pseudoscalar new physics couplings respectively, which in general can be complex.
- $\tilde{R}_S \equiv R_S e^{i\delta_S}, \tilde{R}_P \equiv R_P e^{i\delta_P}$.
- Here the phases are restricted to be $0 \leq (\delta_S, \delta_P) < \pi$, whereas R_S and R_P can take positive as well as negative values.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- When $\tilde{R}_S$ and $\tilde{R}_P$ are complex, the constraint becomes:

$$R_S^2 + (R_P - 0.36\cos\delta_P)^2 = \frac{B_{\rm exp} \times 10^{-7}}{(0.18 \pm 0.036)} - 29.17 + (0.36\cos\delta_P)^2$$

- For nonzero δ_P, the center of the semileptonic annulus shifts along the R_P axis, while the radius of the annuli are almost unchanged.
- If the allowed regions do not overlap for $\delta_P = 0$, then they will not overlap for any value of δ_P.
- Hence the tension between $B(B_s \to \mu^+\mu^-)$ and $B(B \to K\mu^+\mu^-)$ persists, and gives rise to the same constraints on the semileptonic branching ratio even if the S-P NP couplings are complex.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- In writing the effective S-P new physics Lagrangian L_{SP}, we considered only the quark bilinear $\bar{b}P_R s$.
- Lorentz Invariance of the Lagrangian also allows the bilinear $\bar{b}P_L s$ in general.
- We take this generalization into account by replacing $\bar{b}P_R s$ by $\bar{b}(\alpha P_L + P_R)s$, where α is the strength of the $\bar{b}P_L s$ bilinear relative to that of $\bar{b}P_R s$.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- Thus the general expressions for the branching ratios of the two processes become:
  $B(B_s \to \mu^+\mu^-) = (1-\alpha)^2 (R_S^2 + R_P^2)\,(1.43 \pm 0.30) \times 10^{-7}$.
- $B(B \to K\mu^+\mu^-) = \left[5.25 + 0.18\,(1+\alpha)^2\,(R_S^2 + R_P^2) - 0.13\,(1+\alpha)R_P\right]\,(1 \pm 0.20) \times 10^{-7}$.
- For $\alpha = 0$, above equations reduce to the previous equations.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

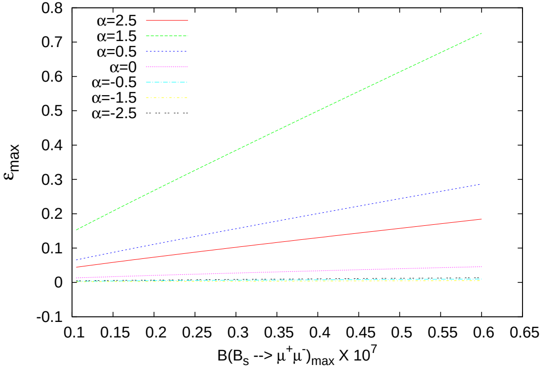


Figure shows $\varepsilon_{\rm max}$ (maximum fractional deviation of $B(B \to K\mu^+\mu^-)$ from SM value, as a function of 2σ upper bound on $B(B_s \to \mu^+\mu^-)$.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- The minimum allowed value of ε is almost independent of the value of α and the leptonic upper bound, and is approximately -0.005.
- For a class of models with multiple Higgs doublets, $\alpha = 0$, $\varepsilon_{\rm max}$ is restricted to $+0.025$, as seen earlier.
- With the additional freedom generated by the extra parameter α, this severe constraint is relaxed.
- For example, for the models with $\alpha \approx 1.5$, the value of ε may be as large as $+0.7$.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- When $\alpha < 0$, the expression for $B(B_s \to \mu^+\mu^-)$ indicates that the constraints on R_S and R_P should become more restrictive. As a result, ε is constrained to be even smaller.
- $\varepsilon_{\rm max}$ for negative α are very close to zero, and the corresponding $\varepsilon_{\rm max}$ curves are almost overlapping.
- This implies that for negative α, any significant deviation of $B(B \to K\mu^+\mu^-)$ from SM is impossible with S-P NP.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- For the measurements of $B(B_s \to \mu^+\mu^-)$ and $B(B \to K\mu^+\mu^-)$ to be compatible with S-P NP, the lower bound on $B(B \to K\mu^+\mu^-)$ should be less than $(1+\varepsilon_{\max})B_{\mathrm{SM}}$.
- Thus, the upper bound on $B(B_s \to \mu^+\mu^-)$ and the lower bound on $B(B \to K\mu^+\mu^-)$ allow us to constrain the value of α in a class of models that involve new physics scalar/pseudoscalar couplings.

Tension between S-P contribution to $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

- For the special case $\alpha = 1$, the new physics has no contribution to $B_s \to \mu^+\mu^-$ because the quark bilinear is pure scalar and the corresponding pseudoscalar meson to vacuum transition matrix element is zero.
- In such cases, $B(B_s \to \mu^+\mu^-)$ is entirely due to the SM, and provides no constraints on $B(B \to K\mu^+\mu^-)$.