Effects of fourth generation on various observables in $b \to s\ell^+\ell^-$ Decay

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Outline

Fourth Generation

Abstract

In this study a systematical analysis of various polarization asymmetries in inclusive $b \to s\ell^+\ell^-$ decay in the standard model (SM) with four generation of quarks is carried out. It is obtained that the various asymmetries are sensitive to the new mixing and quark masses for both of the μ and τ channels. Sizeable deviations from the SM values are obtained. Hence, $b \to s\ell^+\ell^-$ decay is a valuable tool for searching physics beyond the SM, especially in the indirect searches for the fourth-generation of quarks (t', b').

Outline

- Standard Model has some well-known theoretical shortcomings. There are also few experimental puzzles: a) Measurement of direct CP -asymmetry of $B \longrightarrow K\pi$ decays [1] and b) the nonvanished CP phase measured in $b \longrightarrow s$ transition by CDF [2] and D [3]

- Perhaps the simplest extension of the standard model is to allow for a chiral fourth generation.

- A lower bound on the number of families comes from LEP data ($N \geq 3$), and upper bound is 8 from asymptotic freedom. But, the fifth family is excluded at more than 5σ level by precision electroweak data, where in the case of five SM families four "light" neutrinos are expected[4].
- Recent fits of electroweak precision data to the Standard Model (SM) with a 4th sequential family (SM4) point to a possible "three-prong composite solution": (1) the Higgs mass is at the TeV-scale, (2) the masses of the 4th family quarks t0, b0 are of $O(500)$ GeV and (3) the mixing angle between the 4th and 3rd generation quarks is of the order of the Cabibbo angle, $\theta_{34} \sim O(0.1)$[5].

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- Such extension can include extra weak phases in quark mixing matrix which can introduce better solutions to the baryon anti-baryon asymmetry of universe. SM4 can also explain the direct CP-asymmetry of $B \to K\pi$ decays [1].

Outline

- $b \rightarrow s(d)$ transitions.

Outline

Dipole moments of fundamental particles like μ and ....

- The QCD corrected effective Hamiltonian for the $b \to s\ell^+\ell^-$ transitions leads to the following matrix element:

$$M = \frac{G_F V_{tb} V_{ts}^*}{\sqrt{2}\pi}\alpha_{em}\Big[\quad C_9^{tot}(\bar{s}\gamma_\mu P_L b)\bar{\ell}\gamma_\mu\ell + C_{10}^{tot}(\bar{s}\gamma_\mu P_L b)\bar{\ell}\gamma_\mu\gamma^5\ell$$
$$-2C_7^{tot}\bar{s}i\sigma_{\mu\nu}\frac{q^\nu}{q^2}(m_b P_R + m_s P_L)b\bar{\ell}\gamma_\mu\ell\Big], \quad (1)$$

- New physics effects can come through the modification of Wilson coefficients(C_i), new operator structures or modification of CKM elements.
- The effects of consequential 4th family come through the modification of Wilson coefficients(C_i) and make change of CKM elements via unitarity.
- New operators don't contribute.

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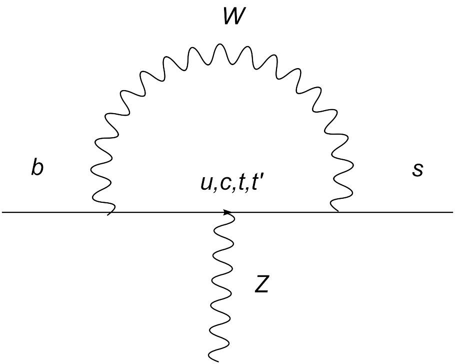


Figure:

The Wilson coefficients are modified as follows:

$$\lambda_t C_i \to \lambda_t C_i^{SM} + \lambda_{t'} C_i^{new} \ , \qquad (2)$$

where $\lambda_f = V_{fb}^* V_{fs}$. The unitarity of the 4×4 CKM matrix leads to

$$\lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0. \qquad (3)$$

One can neglect $\lambda_u = V_{ub}^* V_{us}$ in Eq. 2 which is very small in strength compared to the others ($|\lambda_u| \sim 10^{-3}$). Then, $\lambda_t \approx -\lambda_c - \lambda_{t'}$.

Now, we can re-write Eq. 1 as:

$$\lambda_t C_i^{SM} + \lambda_{t'} C_i^{new} = -\lambda_c C_i^{SM} + \lambda_{t'} (C_i^{new} - C_i^{SM}). \qquad (4)$$

It is clear that when $m_{t'} \to m_t$ or $\lambda_{t'} \to 0$, $\lambda_{t'}(C_i^{new} - C_i^{SM})$ vanishes, as is required by the GIM mechanism.

- Branching ratio, CP asymmetry, Forward-backward Asymmetry, Lepton polarization Asymmetry ..

Outline

The existence of direct CPA(A_{CP}) requires: firstly at least two different terms in decay amplitude. Secondly, These terms must depend on two types of phases named weak(δ) and strong(ϕ) phases. The A_{CP} depends on the interference of different amplitude and is proportional to the phases. i.e.,

$$A_{CP} \propto \sin(\delta)\sin(\phi) \tag{5}$$

The sizable value of A_{CP} can be obtained if both phases are non-zero and large.

In the SM3 there isn't weak phase, but there is a strong phase embedded in C_9^{eff}. A new weak phase come through $\lambda_{t'}$ in the SM4. Therefore, unlike SM3, the possibility of CPA in the SM4 can be studied.

The spin directions first can be defined in the rest frame of leptons as a the 4-vector $s^{\mu}_{\ell^-}$, after the Lorentz boost from its rest frame can be obtain as [2]:

$$s^{\mu}_{\ell-} = \left\{ \frac{|p^-|}{m_\ell} s_z^-, s_x^-, s_y^-, \frac{E}{m_\ell} s_z^- \right\} \quad , \quad s^{\mu}_{\ell+} = \left\{ \frac{|p^+|}{m_\ell} s_z^+, s_x^+, s_y^+, \frac{E}{m_\ell} s_z^+ \right\} , \tag{6}$$

where $\mathbf{s}^{\pm}$ and $p^{\pm}$ are the unit vectors and three-momenta of leptons in the $\ell^{\pm}$ rest frames, respectively.

The double–lepton polarization asymmetries $\mathcal{P}_{ij}$ are defined as [3]

$$\mathcal{P}_{ij} = \frac{\left[\frac{d\Gamma(\mathbf{s}^+=\hat{i},\mathbf{s}^-=\hat{j})}{d\hat{s}} - \frac{d\Gamma(\mathbf{s}^+=\hat{i},\mathbf{s}^-=-\hat{j})}{d\hat{s}}\right] - \left[\frac{d\Gamma(\mathbf{s}^+=-\hat{i},\mathbf{s}^-=\hat{j})}{d\hat{s}} - \frac{d\Gamma(\mathbf{s}^+=-\hat{i},\mathbf{s}^-=}{d\hat{s}}\right.}{\left[\frac{d\Gamma(\mathbf{s}^+=\hat{i},\mathbf{s}^-=\hat{j})}{d\hat{s}} + \frac{d\Gamma(\mathbf{s}^+=\hat{i},\mathbf{s}^-=-\hat{j})}{d\hat{s}}\right] + \left[\frac{d\Gamma(\mathbf{s}^+=-\hat{i},\mathbf{s}^-=\hat{j})}{d\hat{s}} + \frac{d\Gamma(\mathbf{s}^+=-\hat{i},\mathbf{s}^-=}{d\hat{s}}\right.} \quad (7)$$

where $\hat{i}$ and $\hat{j}$ are unit vectors. Considering the single and double lepton polarizations one may define 12 physical observables as follows:

$\mathcal{P}_x, \mathcal{P}_y, \mathcal{P}_z, \mathcal{P}_{xx}, \mathcal{P}_{xy}, \mathcal{P}_{xz}, \mathcal{P}_{yy}, \mathcal{P}_{yx}, \mathcal{P}_{yz}, \mathcal{P}_{zz}, \mathcal{P}_{zx}, \mathcal{P}_{zy}$

Equipped with the definition of the spin directions in the CM frame of leptons, we can evaluate the forward-backward asymmetries corresponding to various polarization components of the ℓ^- and/or ℓ^+ spin by writing [2]:

$$
\begin{aligned}
A_{FB}(\mathbf{s}^+,\mathbf{s}^-,\hat{s}) &= A_{FB}(\hat{s}) \\
&+ \Big[\mathcal{A}_x^- s_x^- + \mathcal{A}_y^- s_y^- \\
&+ \mathcal{A}_z^- s_z^- + \mathcal{A}_x^+ s_x^+ + \mathcal{A}_y^+ s_y^+ + \mathcal{A}_z^+ s_z^+ \\
&\quad + \mathcal{A}_{xx} s_x^+ s_x^- + \mathcal{A}_{xy} s_x^+ s_y^- + \mathcal{A}_{xz} s_x^+ s_z^- \\
&\quad + \mathcal{A}_{yx} s_y^+ s_x^- + \mathcal{A}_{yy} s_y^+ s_y^- + \mathcal{A}_{yz} s_y^+ s_z^- \\
&\quad + \mathcal{A}_{zx} s_z^+ s_x^- + \mathcal{A}_{zy} s_z^+ s_y^- + \mathcal{A}_{zz} s_z^+ s_z^- \Big]\,. \qquad (8)
\end{aligned}
$$

The different polarized forward-backward asymmetries are then calculated as follows:

$$\mathcal{A}_x^+ = 0, \tag{9}$$

$$\mathcal{A}_y^+ = \frac{2}{\Delta}\mathrm{Re}(C_9^{tot} C_{10}^{tot*})\,\frac{(1-\hat{s})\,\hat{m}_\ell}{\sqrt{\hat{s}}}\sqrt{1-\frac{4\,\hat{m}_\ell^2}{\hat{s}}}, \tag{10}$$

$$\begin{aligned}\mathcal{A}_z^+ = \frac{1}{\Delta}\Bigg\{ & 6\,\mathrm{Re}(C_7^{tot} C_9^{tot*}) - \frac{6\,|C_7^{tot}|^2}{\hat{s}} - 3\,(\,|C_9^{tot}|^2 - |C_{10}^{tot}|^2)\,\hat{m}_\ell^2 \\ & -12\,\mathrm{Re}(C_7^{tot} C_{10}^{tot*})\,\frac{\hat{m}_\ell^2}{\hat{s}} - 6\,\mathrm{Re}(C_9^{tot} C_{10}^{tot*})\,\frac{\hat{m}_\ell^2}{\hat{s}} \\ & - \frac{3}{2}\,(\,|C_9^{tot}|^2 + |C_{10}^{tot}|^2)\,\hat{s}\,(1-\frac{2\,\hat{m}_\ell^2}{\hat{s}})\Bigg\},\end{aligned} \tag{11}$$

$$
\begin{aligned}
\mathcal{A}_x^- &= 0, && (12)\\
\mathcal{A}_y^- &= \mathcal{A}_y^+, && (13)\\
\mathcal{A}_z^- &= \frac{1}{\Delta}\Bigg\{ -6\,\mathrm{Re}(C_7^{tot} C_9^{tot*}) - \frac{6\,|C_7^{tot}|^2}{\hat{s}} - 3\,(\,|C_9^{tot}|^2 - |C_{10}^{tot}|^2)\,\hat{m}_\ell^2 \\
&\quad + 12\,\mathrm{Re}(C_7^{tot} C_{10}^{tot*})\,\frac{\hat{m}_\ell^2}{\hat{s}} + 6\,\mathrm{Re}(C_9^{tot} C_{10}^{tot*})\,\frac{\hat{m}_\ell^2}{\hat{s}} \\
&\quad - \frac{3}{2}\,(\,|C_9^{tot}|^2 + |C_{10}^{tot}|^2)\,\hat{s}\,(1 - \frac{2\,\hat{m}_\ell^2}{\hat{s}})\Bigg\}, && (14)\\
\mathcal{A}_{xx} &= 0, && (15)\\
\mathcal{A}_{xy} &= \frac{-6}{\Delta}\,(2\,\mathrm{Im}(C_7^{tot}\,C_{10}^{tot*}) + \mathrm{Im}(C_9^{tot}\,C_{10}^{tot*}))\,\frac{\hat{m}_\ell^2}{\hat{s}}, && (16)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{A}_{yx} &= -\mathcal{A}_{xy}\,, && (18)\\
\mathcal{A}_{yy} &= 0, && (19)\\
\mathcal{A}_{yz} &= \left(2|C_9^{tot}|^2 - \frac{8\,|C_7^{tot}|^2}{\hat{s}}\right)\frac{(1-\hat{s})\,\hat{m}_\ell}{\Delta\sqrt{\hat{s}}}, && (20)\\
\mathcal{A}_{zx} &= \mathcal{A}_{xz}\,, && (21)\\
\mathcal{A}_{zy} &= \mathcal{A}_{yz}\,, && (22)\\
\mathcal{A}_{zz} &= \frac{-3}{\Delta}\left(2\,\mathrm{Re}(C_7^{tot}\,C_{10}^{tot^*}) + \mathrm{Re}(C_9^{tot}\,C_{10}^{tot^*})\,\hat{s}\right)\sqrt{1-\frac{4\,\hat{m}_\ell^2}{\hat{s}}} && (23)
\end{aligned}
$$

The free parameters are quark mass ($m_{t'}$) and $V^*_{t'b}V_{t's} = r_{sb}e^{i\phi_{sb}}$.
The SM parameters used in this analysis are shown in Table 1:

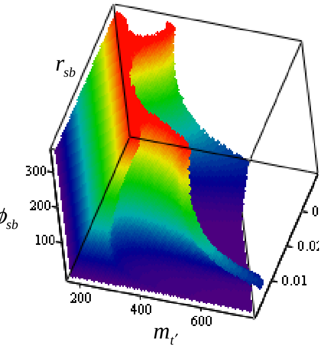
Parameter	Value
α_{em}	$1/129$ (GeV)
m_u	2.3 (MeV)
m_d	4.6 (MeV)
m_c	1.25 (GeV)
m_b	4.8 (GeV)
m_μ	0.106 (GeV)
m_τ	1.780 (GeV)

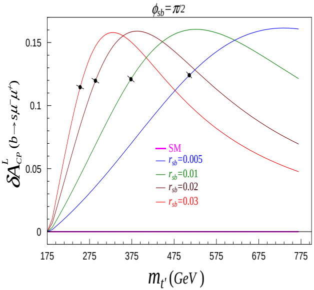
Table: The values of the input parameters used in the numerical calculations.

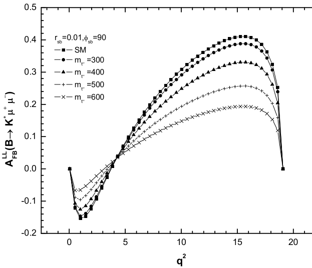
Using the experimental values of $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$, the bound on $r_{sb} \sim \{0.01 - 0.03\}$ has been obtained [4, 6] for $\phi_{sb} \sim \{0 - 2\pi\}$ and $m_{t'} \sim \{200, 600\}$ (GeV)(see table 2). Also considering Δm_{B_s}, ϕ_{sb} receives a strong restriction ($\phi_{sb} \sim \pi/2$) [5].

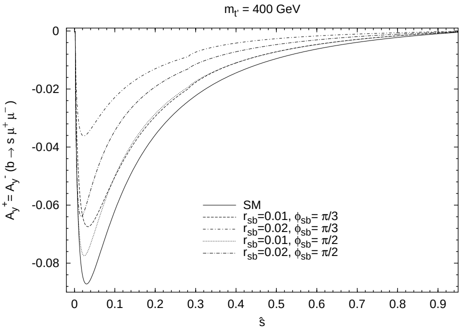
r_{sb}	0.01	0.02
$m_{t'}(GeV)$	373	289

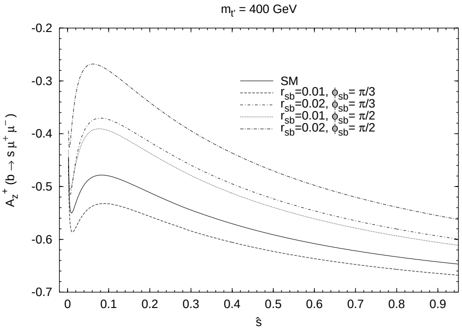
Table: The experimental limit of $m_{t'}$ for $\phi_{sb} = \pi/2$[6]

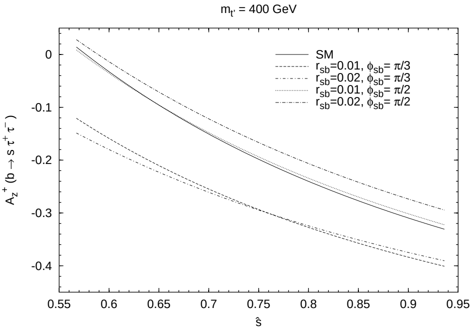

r_{sb}
ϕ_{sb}
$m_{t'}$
300
200
100
200
400
600
0
0.01

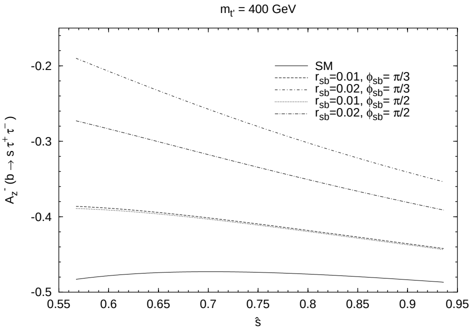

$\phi_{sb}=\pi/2$
$\delta A^{L}_{CP}(b \to s\mu^-\mu^+)$
$m_{t'}(GeV)$
SM
r_{sb}=0.005
r_{sb}=0.01
r_{sb}=0.02
r_{sb}=0.03
0.15
0.1
0.05
0
175
275
375
475
575
675
775

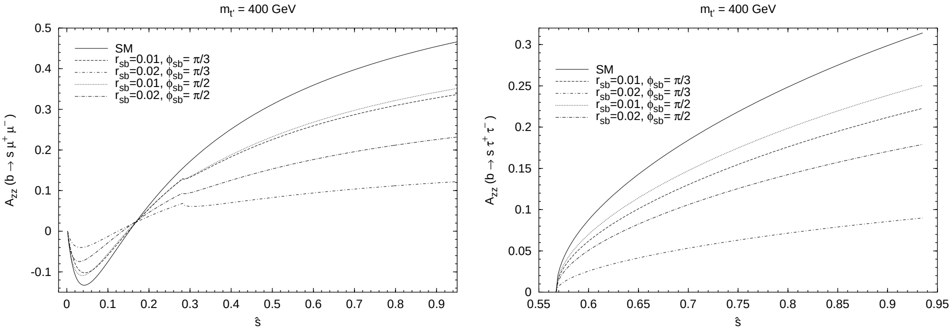

r_{sb}=0.01,ϕ_{sb}=90
SM
$m_{t'}$ =300
$m_{t'}$ =400
$m_{t'}$ =500
$m_{t'}$ =600
$A^{LL}_{FB}(B \to K^* \mu^+ \mu^-)$
q^2
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
0
5
10
15
20

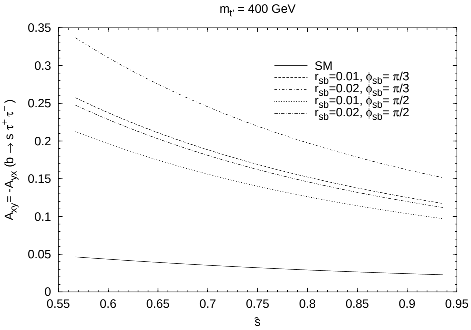

$m_{t'}$ = 400 GeV
$A_y^+ = A_y^-$ ($b \to s\,\mu^+\mu^-$)
ŝ
SM
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$

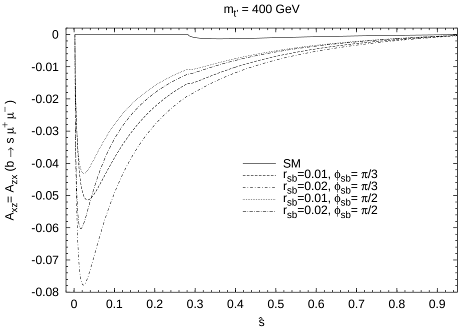

$m_{t'}$ = 400 GeV
A_z^+ ($b \to s\,\mu^+\mu^-$)
ŝ
SM
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$

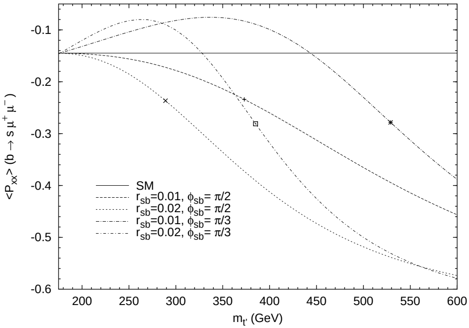

$m_{t'}$ = 400 GeV
$A_z^+(b \to s\tau^+\tau^-)$
$\hat{s}$
SM
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$
0
-0.1
-0.2
-0.3
-0.4
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95

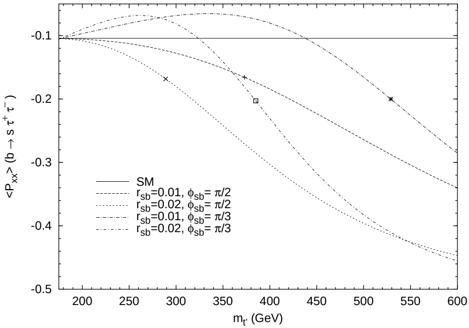

$m_{t'}$ = 400 GeV
$A_z^-(b \to s\tau^+\tau^-)$
$\hat{s}$
SM
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$
-0.2
-0.3
-0.4
-0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95

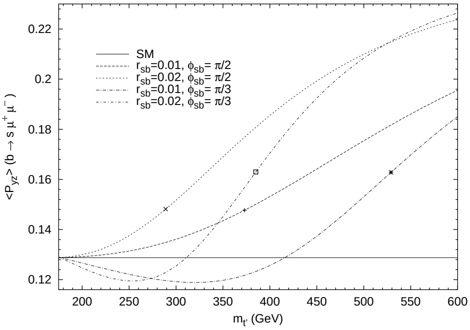

m_t' = 400 GeV
SM
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
A_zz (b → s μ+ μ−)
ŝ
m_t' = 400 GeV
SM
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
A_zz (b → s τ+ τ−)
ŝ

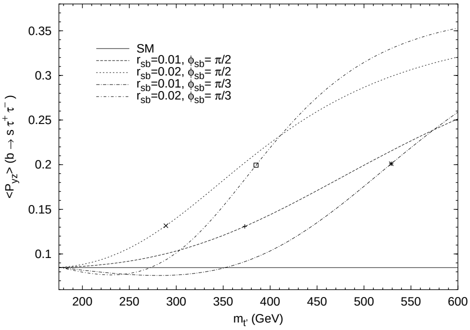

m_t' = 400 GeV
A_xy = -A_yx (b → s τ+ τ−)
ŝ
SM
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95

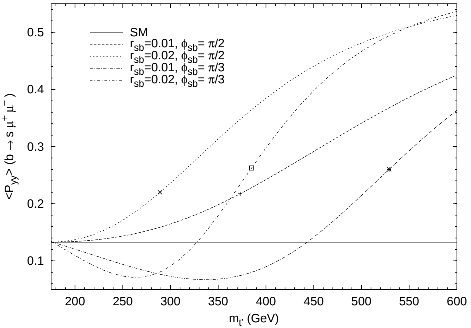

m_t' = 400 GeV
A_xz = A_zx (b → s μ+ μ−)
ŝ
SM
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

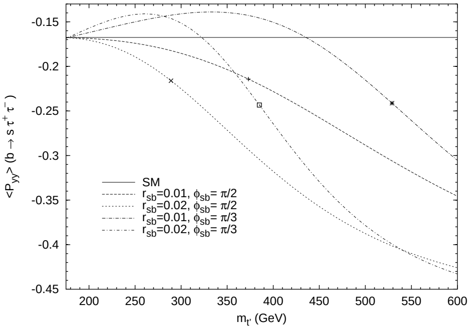

-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
200
250
300
350
400
450
500
550
600
$m_{t'}$ (GeV)
$<P_{xx}> (b \to s\,\mu^+\,\mu^-)$
SM
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$

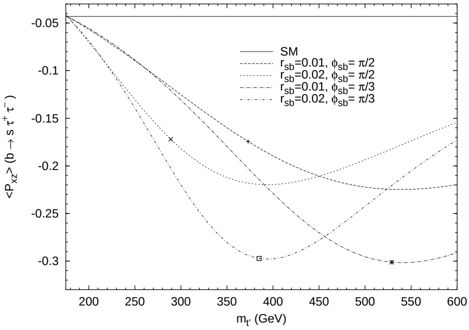

-0.1
-0.2
-0.3
-0.4
-0.5
200
250
300
350
400
450
500
550
600
$m_{t'}$ (GeV)
$<P_{xx}> (b \to s\,\tau^+\,\tau^-)$
SM
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$

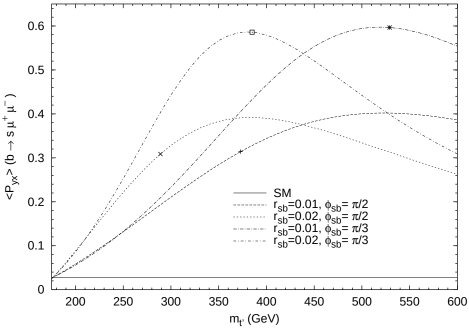

SM
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$
$<P_{yz}> (b \to s\,\mu^+\mu^-)$
$m_{t'}$ (GeV)
0.12
0.14
0.16
0.18
0.2
0.22
200
250
300
350
400
450
500
550
600


SM
r_{sb}=0.01, ϕ_{sb}= $\pi/2$
r_{sb}=0.02, ϕ_{sb}= $\pi/2$
r_{sb}=0.01, ϕ_{sb}= $\pi/3$
r_{sb}=0.02, ϕ_{sb}= $\pi/3$
$<P_{yz}> (b \to s\,\tau^+\tau^-)$
$m_{t'}$ (GeV)
0.1
0.15
0.2
0.25
0.3
0.35
200
250
300
350
400
450
500
550
600


SM
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
<P_yy> (b → s μ+ μ−)
m_t' (GeV)
0.1
0.2
0.3
0.4
0.5
200
250
300
350
400
450
500
550
600


SM
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
<P_yy> (b → s τ+ τ−)
m_t' (GeV)
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
200
250
300
350
400
450
500
550
600


SM
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
<P_xz> (b → s τ+ τ−)
m_t' (GeV)
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
200 250 300 350 400 450 500 550 600


SM
r_sb=0.01, φ_sb= π/2
r_sb=0.02, φ_sb= π/2
r_sb=0.01, φ_sb= π/3
r_sb=0.02, φ_sb= π/3
<P_yx> (b → s μ+ μ−)
m_t' (GeV)
0 0.1 0.2 0.3 0.4 0.5 0.6
200 250 300 350 400 450 500 550 600

To sum up, we present the various asymmetries in inclusive $b \to s\ell^+\ell^-$ transition using the SM with the 4^{th} generation of quarks. The results are:

- The zero point position of the polarized single or double lepton polarization FB asymmetry coincide with each other in the SM3 and SM4. Furthermore, there are sizable discrepancies, specially, in the non–resonance region between the result of the SM3 and SM4.
- Some of the double–lepton polarization and polarized double or single lepton polarization Forward–Backward asymmetries which are already accessible at LHC depict the strong dependency on the 4^{th} generation quark mass and product of quark mixing.

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- Some of the double–lepton polarization and polarized double or single lepton polarization Forward–Backward asymmetries which are already accessible at LHC depict the strong dependency on the 4^{th} generation quark mass and product of quark mixing.

- While the magnitude of asymmetries, which is proportional to the real part of the product of Wilson coefficients, is generally suppressed by the 4^{th} generation parameters. The situation for the asymmetries proportional to the imaginary part of the product of Wilson coefficients is enhanced
  Thus, the study of such strong dependent asymmetries can serve as good test for the predictions of the SM3 and indirect search for the 4th generation up type quarks t'.

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