Constraining New Physics with Possible Dark Matter Signatures from the Study of Low Energy Processes

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Brief Outline

- Simplified Model
- Analysis and Result : Highmass Region
  - Constraints from flavor physics
  - Dark matter phenomenology
- Analysis and Result : Lowmass Region
  - Constraints from flavor physics
  - Dark matter phenomenology

Why BSM?

Standard Model prediction is validated to high precision, however

1. Matter-Anti matter asymmetry
   - $\eta = \frac{n_B - \bar{n}_B}{\gamma} \sim 10^{-9}$
2. Neutrino oscillation
   - Non-zero mass of neutron
3. Dark Matter
   - $\sim 25\%$ of total energy budget is dark matter
   - Observational Evidances: Galaxy Rotation Curve, Gravitational lensing, CMBR
   - WIMP, SIMP, FIMP ....
4. and many more.....

The Simplified Model

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \bar{\chi}(c_{s\chi} + i c_{p\chi}\gamma_5)\chi S - \bar{\psi}(c_{s\psi} + i c_{p\psi}\gamma_5)\psi S - V(S,H)$$

Where,

$V(S,H) = \mu_S^2 S^2 + \frac{\lambda_4}{4!}S^4 + \frac{\lambda_3}{3!}S^3 + \lambda_1 S H^\dagger H + \lambda_2 S^2 H^\dagger H$

Under $\mathcal{Z}_2 :: \chi \to -\chi$

High mass region :$M_S(\geq 100)$GeV

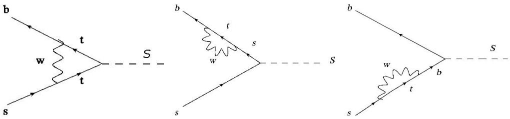
- Neutral meson mixing
- Anomalous magnetic moment
- $t \to bW_\mu$ decay
- Rare decays of mesons
- Global fit of $b \to s\ell\ell$ observables

Low mass region :$M_S(\leq 10)$GeV

- Neutral meson mixing
- $t \to bW_\mu$ decay
- Rare decay of mesons
- Invisible decay
- Fix Target Experiment

Contribution to FCNC vertex

- $b - s - S$ will be modified as:



- Yukawa coupling of **S-ψ-ψ** re-scaled as:

$$\begin{aligned} &\bar{\psi}(c_{s\psi} + i c_{p\psi}\gamma_5)\psi S \\ &= \bar{\psi}\left(\sqrt{2}m_\psi \frac{g_s}{v} + i\sqrt{2}m_\psi \frac{g_s}{v}\gamma_5\right)\psi S \\ &= m_\psi \bar{\psi}(\mathbf{c_s} + i\mathbf{c_p}\gamma_5)\psi S \end{aligned} \tag{1}$$

- Loop diagram contribution:

$$\mathcal{L}_{eff}^{bsS} = C_1[\bar{b}(m_b P_L + m_s P_R)s] + C_2[\bar{b}(m_b P_L - m_s P_R)s]$$

- Scalar and pseudoscalar operators
- $C_1, C_2 \Rightarrow$ loop function$\Rightarrow$ have **divergences** .

b-s-S vertex correction

- Divergences can be absorbed by RGE of coupling (in LLA):

$$C_1(\Lambda) = \frac{1}{2}(I_1 + I_2) + \frac{m_t^2}{m_w^2} 3c_s log \frac{\Lambda^2}{m_t^2}. \quad (2)$$

$$C_2(\Lambda) = \frac{1}{2}(I_1 - I_2) + \frac{m_t^2}{m_w^2} (-ic_p) log \frac{\Lambda^2}{m_t^2}. \quad (3)$$

$I_1, I_2 \rightarrow$ Finite part of loop integration.
$\Lambda \rightarrow$ cutoff scale.

- Studied for : $\Lambda = 2$ TeV and $\Lambda = 1$ TeV.
- We also have $b - d - S, s - d - S$ FCNC vertices in this model.

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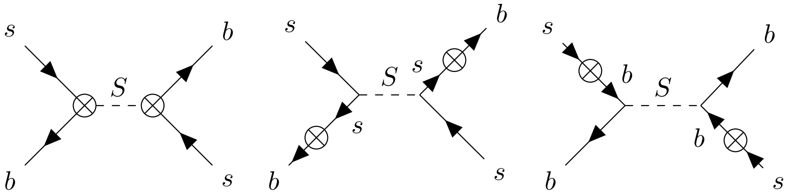
- High mass region of M_S.

Meson Mixing



Msss difference(in SM): hep-ex/0103016

$$\Delta M_d = \frac{|\mathcal{M}|}{m_B} = \frac{G_F^2}{6\pi^2} m_{B_d} f_{B_d}^2 B_{B_d} \eta_B m_w^2 |V_{td}^* V_{tb}|^2 f(\frac{m_t^2}{m_w^2})$$

$f_{B_d} \rightarrow$ decay constant, $B_{B_d} \rightarrow$ Bag parameter, $f(\frac{m_t^2}{m_w^2}) \rightarrow$ loop factor.

Mixing Observable:

$\Delta M_{tot} = \Delta M_{SM} + \Delta M_{NP}$

$$\mathbf{\Delta M_{tot} = \Delta M_{SM}(1+\Delta)}$$

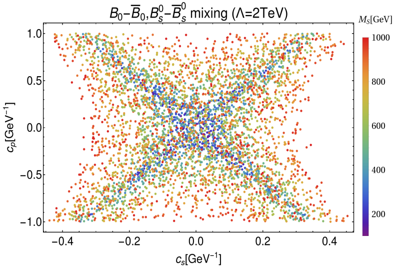
$B_s^0 - \bar{B}_s^0$ **Mixing:** JHEP12(2019)009

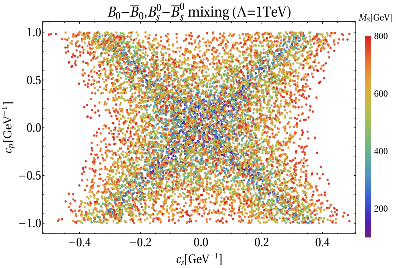
1σ error of parameters $\approx$ 7.5% NP contribution.

2σ error of parameters $\approx$ 15% NP contribution.

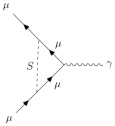
Meson Mixing

- Upto 10% of NP is allowed.
- $\Lambda = 2TeV$, $\Lambda = 1TeV$.





- Anomalous Magnetic Moment of Muon
- Anomalous Magnetic Moment of electron

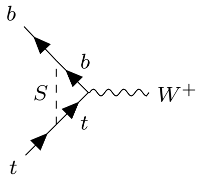


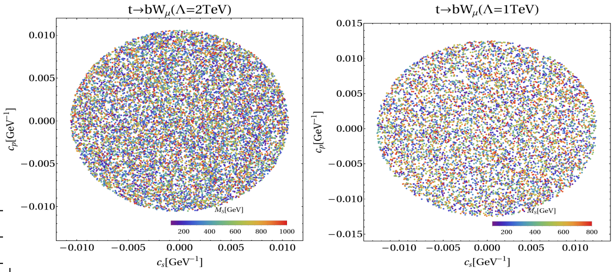
FCCC Process: $t \to bW$ decay

- The general Lagrangian for this decay can be given by :

$$\mathcal{L}_{tbW} = -\frac{g}{\sqrt{2}}\bar{b}\gamma_\mu(V_L P_L + V_R P_R)tW_\mu - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma_{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu + h.c$$

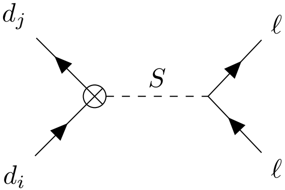
Phys.Rev.D 43 (1991) 3759-3762





95% CL interval	
Coupling	ATLAS
Re(V_R)	$[-0.17, 0.25]$
Re(g_L)	$[-0.11, 0.08]$
Re(g_R)	$[-0.03, 0.06]$
V_L(pdg)	0.995 ± 0.021

- No noticable corelation between c_s, c_p and M_S.

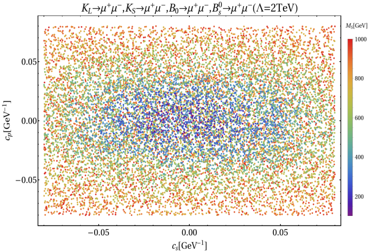


$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{d}_j P_R d_i)(\bar{\ell}\ell), \qquad \mathcal{O}'_S = \frac{e^2}{16\pi^2}(\bar{d}_j P_L d_i)(\bar{\ell}\ell),$$

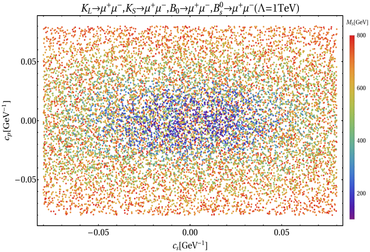
$$\mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{d}_j P_R d_i)(\bar{\ell}\gamma_5\ell), \qquad \mathcal{O}'_P = \frac{e^2}{16\pi^2}(\bar{d}_j P_L d_i)(\bar{\ell}\gamma_5\ell)$$

- $K_L \to \mu^+\mu^-$, $K_S \to \mu^+\mu^-$, $B_0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ decays are considered.

$\Lambda = 2$ **TeV**



$\Lambda = 1$ **TeV**



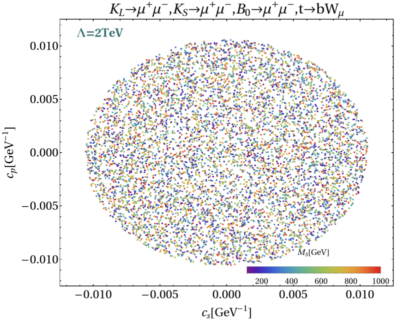
$b \to s\ell^+\ell^-$ from Global Fit

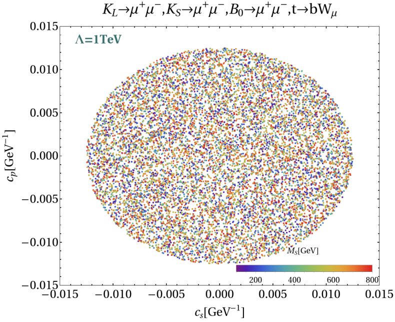
- Performed a global fit of the model parameters taking all the $b \to s\ell\ell$ observables into account.
- Branching Ratios, Isospin asymmetry, LFUV observables, Angular observables.

Λ[TeV]	M_S[GeV]	c_s[GeV^{-1}]	c_p[GeV^{-1}]
1	250	−0.00408±0.063692	−0.002321±0.477402
1	500	−0.225392±0.127408	0.004642±0.954786
1	800	−0.360628±0.203848	0.007428±1.52766
2	250	0.095424±0.0539296	−0.001965±0.404235
2	500	0.190849±0.107867	−0.003931±0.808468
2	1000	−0.381697±0.215758	0.007862±1.616922
P−value→5.19%			

Final Parameter Space : High Mass Region

- Taken all the constraints into account
  - Most constrained from $t \to bW_\mu$ decay

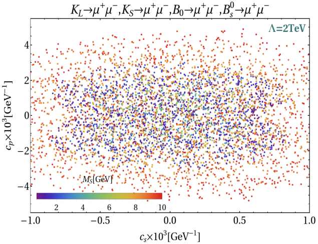




- Low mass region of M_S.

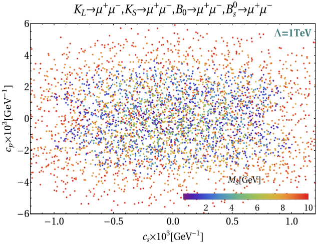
Rare Decay

$\Lambda = 2$ **TeV**



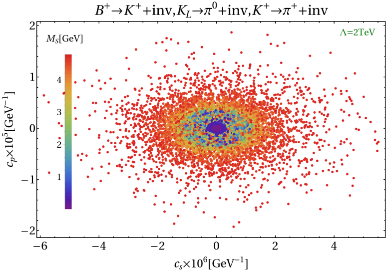
$$\mathcal{B}r[K_L \to \mu^+\mu^-]$$
$$\mathcal{B}r[K_S \to \mu^+\mu^-]$$
$$\mathcal{B}r[B_0 \to \mu^+\mu^-]$$
$$\mathcal{B}r[B_s^0 \to \mu^+\mu^-]$$

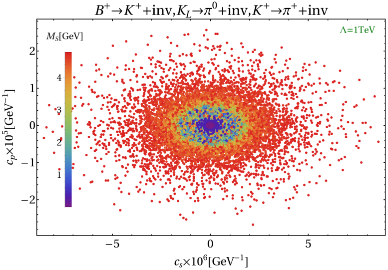
$\Lambda = 1$ **TeV**



Invisible Decay

- In SM : $B^+ \to K^+\nu\bar{\nu}$, $B_0 \to K_L\nu\bar{\nu}$, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
- If S doesnot decay to any invisible mode and its life-time is long enough that it will leave the detector without decaying at all.
- $B^+ \to K^+ + S$, $K^+ \to \pi^+ + S$, $K_L \to \pi^0 + S$
- $M_S \leq (M_B - M_K)$
- $M_S < 2m_\chi$

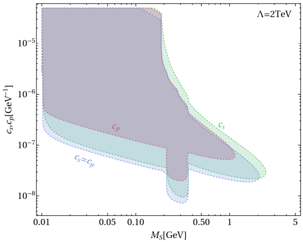




Fix Target Experiment

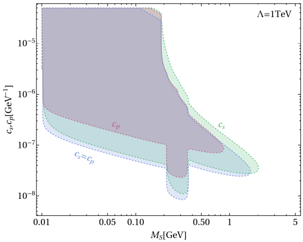
- Constraints are taken from CHARM experiment.
- Production cross. of $S \rightarrow$ number of S produced in the detector solid angle $\rightarrow$ number of decays of S in the detector region N_{det}.
- Constraint is taken as: $N_{det} < 2.3$ JHEP 03 (2015) 171
- Decays into $e^+e^-, \mu^+\mu^-$ and $\gamma\gamma$.

$\Lambda = 2$**TeV**



(a)

$\Lambda = 1$**TeV**



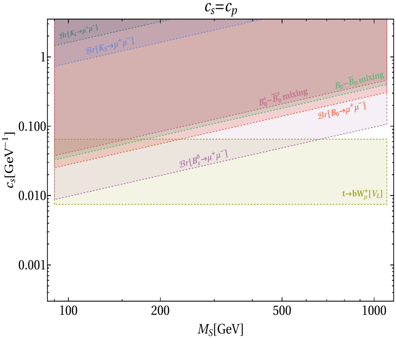
(b)

Figure: Excluded region for different combinations of c_s and c_p with choice of hard cutoff scale 2TeV (left) and 1TeV(right).

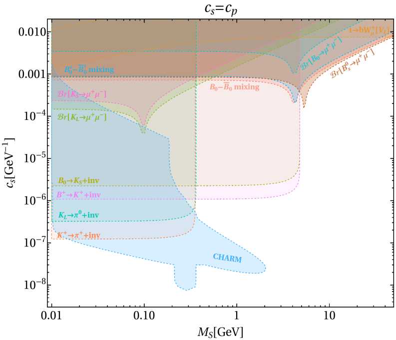
All Channels Combined

- All channels considered
- $c_s = c_p$
- Coloured region $\rightarrow$ excluded

Highmass



Lowmass

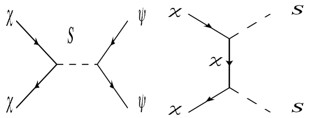


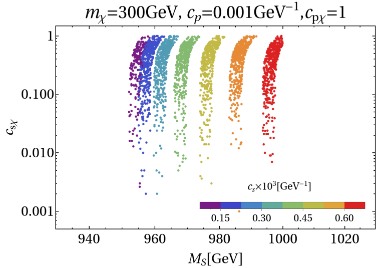
Dark Matter Phenomenology

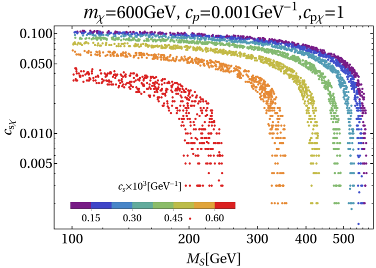
High mass region of M_S

- Observed relic satisfied
- Spin independent direct detection crossection (SIDD) bound satisfied[XENON1T]
- $c_{s\chi}, c_{p\chi} < \sqrt{4\pi}$
- $c_s, c_p \rightarrow$ allowed from flavor.

- **DM + DM $\rightarrow$** Annihilation channels:

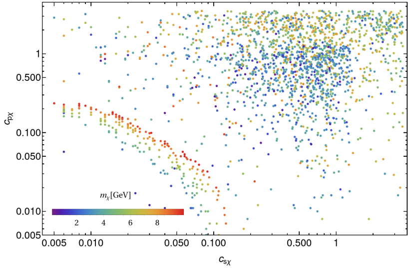






Low mass region of M_S

- Relic satisfied
- SIDD bound from XENON1T satisfied
- $c_{s\chi}, c_{p\chi} < \sqrt{4\pi}$
- $c_s, c_p \rightarrow$ allowed from flavor.



- For very small $c_{s\chi}, c_{p\chi}$, t-channel diagram will dominate.
- For higher c_s, c_p both diagrams will contribute.

Thank You