Interesting directions in Flavor Physics.

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Outline

- Focus on interesting results mostly from quark flavor physics.
- New effects in $\bar{b} \to \bar{s}$ transitions- $b \to s\ell^+\ell^-, b \to s\nu\bar{\nu}, b \to sq\bar{q}$.
- Review of the $b \to s\ell^+\ell^-, b \to s\nu\bar{\nu}$. New evidence of $B^+ \to K^+ + \mathrm{inv}$ - about 3σ away from SM prediction for $B^+ \to K^+ + \bar{\nu}\nu$.
- Review of the $b \to sq\bar{q}$. The $B \to K\pi$ puzzle.
- New physics may be heavy or light- Effective FieldTheory.
- Model with light NP that addresses $b \to s\nu\bar{\nu}$, the MiniBooNE anomaly, also muon $g-2$.

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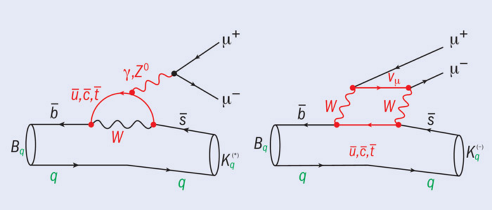
$b \to s\mu^+\mu^-$ and $b \to s\nu\bar{\nu}$ - SM



$$H_{\rm eff}(b \to s\ell\bar{\ell}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left[C_9\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\ell}\gamma_\mu\ell) + C_{10}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\ell}\gamma_\mu\gamma^5\ell)\right] ,$$

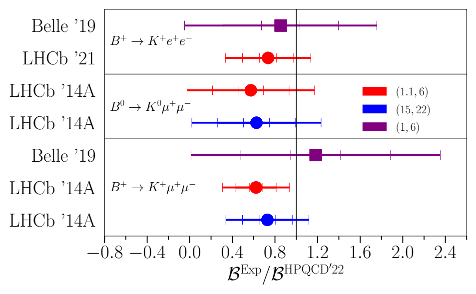
$$H_{\rm eff}(b \to s\nu\bar{\nu}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^*\, C_L\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\nu}\gamma_\mu(1-\gamma^5)\nu) ,$$

$$H_{\rm eff}(b \to s\gamma^*) = C_7\,\frac{e}{16\pi^2}\,[\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R)b]\,F^{\mu\nu}$$

$B \to K^{(*)}\ell\ell$ Anomaly ?

$$M_{\rm SM}(B \to K^{(*)}\ell\bar{\ell}) \;=\; -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \Big[C_9 \,\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle \bar{\ell}\gamma_\mu \ell\Big) + C_{10}\,\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle \bar{\ell}\gamma_\mu\gamma^5\ell \Big] \,,$$

Need Form Factors. From lattice:arXiv: 2207.13371, HPQCD

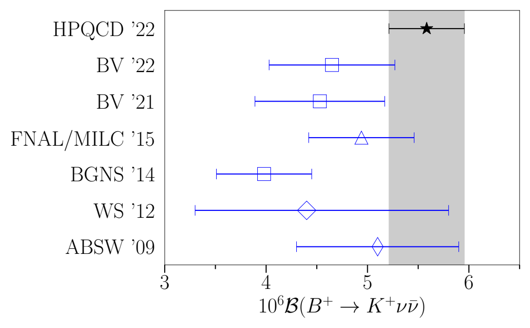


A universal ΔC_9 can explain the data.

$B \to K^{(*)}\nu\bar{\nu}$ Anomaly

$$M_{\rm SM}(B \to K^{(*)}\nu\bar{\nu}) \;=\; -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^{*}\, C_L \,\langle K^{(*)}|\bar{s}_L\gamma^{\mu} b_L|B\rangle \bar{\nu}\gamma_{\mu}(1-\gamma^5)\nu \;,$$

Same Form Factors. From lattice:arXiv: 2207.13371, HPQCD



Belle II (EPS-HEP2023, arXiv: 2311.14647) :
$\mathrm{BR}(B^+ \to K^+ + \mathrm{inv}) = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5} \sim 2.7\sigma$ from HPQCD22
SM prediction $(5.58 \pm 0.38) \times 10^{-6}$.

Hadronic Uncertainties: Charm Loop effects: arXiv: 1512.07157

$b \to s\ell^+\ell^-$ can also receive corrections from non-leptonic operators: tree level charged current operators

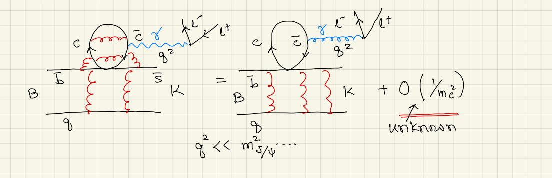
$$M = \left\langle K^* \ell^+ \ell^- \right| \bar{s} b \bar{q} q \left| B \right\rangle$$

$\bar{c}c \to \gamma^* \to \ell^+\ell^-$. Can generate a ΔC_9.

There can also be resonant contributions

$\bar{c}c \to J/\psi \to \ell^+\ell^-$.

Note the charm contamination cannot come to the rescue for $B^+ \to K^+\bar{\nu}\nu$: suppressed by $\leq \mathcal{O}(m_b^2/M_Z^2)$.



$B \to \pi K$ Puzzle

Decay	BR($\times 10^{-6}$)	A_{CP}	S_{CP}
$B^+ \to \pi^+ K^0$	23.79 ± 0.75	-0.017 ± 0.016	
$B^+ \to \pi^0 K^+$	12.94 ± 0.52	0.025 ± 0.016	
$B_d^0 \to \pi^- K^+$	19.57 ± 0.53	-0.084 ± 0.004	
$B_d^0 \to \pi^0 K^0$	9.93 ± 0.49	-0.01 ± 0.10	0.57 ± 0.17

Table: Branching ratios, direct CP asymmetries A_{CP}, and mixing-induced CP asymmetry S_{CP} (if applicable) for the four $B \to \pi K$ decay modes.

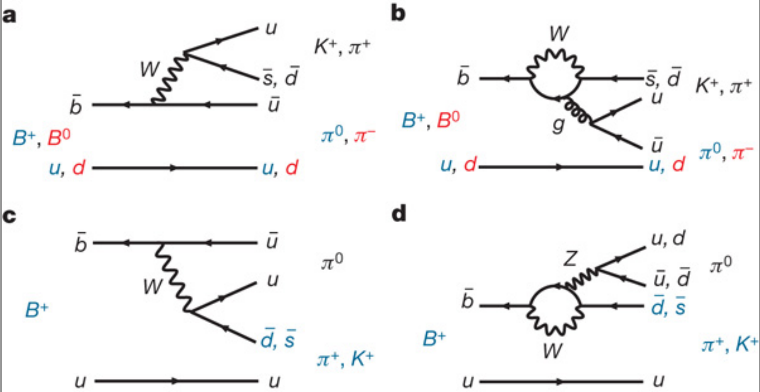
$$
\begin{aligned}
A(B \to f) &= A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} \ , \\
A(\bar{B} \to \bar{f}) &= A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} \ .
\end{aligned}
$$

Hence **direct** CP asymmetry:

$$
a_{dir}^{CP} \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = \frac{2A_1 A_2 \sin\Phi \sin\Delta}{A_1^2 + A_2^2 + 2A_1 A_2 \cos\Phi \cos\Delta} \ ,
$$

where $\Phi \equiv \phi_1 - \phi_2$ and $\Delta \equiv \delta_1 - \delta_2$.

$B \to \pi K$ simplified puzzle



$$P' > T' \sim P'_{EW} > C', P^C_{EW}$$

Topological Amplitudes, $b \to s$

We can describe all decays dominated by the $b \to s$ penguins by the following amplitudes: $T', C', P', P_{EW}, P_{EW}^C$.

$$\frac{|T'|}{|P'|} = \frac{|V_{ub}V_{us}|}{|V_{tb}V_{ts}|}\frac{C_1}{\frac{\alpha_s}{\pi}} \sim 0.15$$

$$\frac{|C'|}{|P'|} = \frac{|C_2|}{|C_1|} \times \frac{|T'|}{|P'|} \sim 0.03$$

$$\frac{|P'_{EW}|}{|P'|} = \frac{1.254\alpha}{\frac{\alpha_s}{\pi}} \sim 0.14$$

$$\frac{|P^C_{EW}|}{|P'|} = \frac{|C_7|}{|C_9|} \times \frac{|P'_{EW}|}{|P'|} \sim 0..014$$

The NP required to resolve the $B \to \pi K$ puzzle is $|A_{NP}| \sim |P'_{EW}|$.

Topological Amplitudes, $b \to d$

We can describe all decays dominated by the $b \to s$ penguins by the following amplitudes: $T, C, P, P_{EW}, P_{EW}^{C}$.

$$\begin{aligned}
\frac{|P|}{|T|} &= \frac{|V_{tb}V_{td}|}{|V_{ub}V_{ud}|}\frac{\frac{\alpha_s}{\pi}}{C_1} \sim 0.10 \\
\frac{|C|}{|T} &= \frac{|C_2|}{|C_1|} \sim 0.2 \\
\frac{|P_{EW}|}{|P|} &= \frac{1.254\alpha}{\frac{\alpha_s}{\pi}} \sim 0.14 \\
\frac{|P_{EW}^{C}|}{|P|} &= \frac{|C_7|}{|C_9|} \times \frac{|P_{EW}|}{|P|} \sim 0..014
\end{aligned}$$

The NP in $b \to d$ transition like $B \to \pi\pi$ is small.

$B \to \pi K$ simplified puzzle

For the $A^{ij} \equiv B \to \pi^i K^j$ amplitudes:

$$
\begin{aligned}
A^{+0} &= -P'_{tc} \ , \\
\sqrt{2}A^{0+} &= -T' e^{i\gamma} + P'_{tc} - P'_{EW} \ , \\
A^{-+} &= -T' e^{i\gamma} + P'_{tc} \ , \\
\sqrt{2}A^{00} &= -P'_{tc} - P'_{EW} \ .
\end{aligned}
$$

$$
P'_{EW} = \frac{3}{2}\frac{c_9}{c_1} R \, T' \quad ,
$$

where $R \equiv |(V^*_{tb} V_{ts})/(V^*_{ub} V_{us})| = 49.1 \pm 1.0$

- P'_{tc} and P'_{EW} have the same weak phase..
- T' and P'_{EW} have the same strong phase.
- So CPV is only from the $T' - P'_{tc}$ interference.

Tree and Electroweak

$$
\begin{aligned}
A^{+0} &= -P'_{tc} + P'_{uc} e^{i\gamma} - \frac{1}{3} P^{C}_{EW} \,, \\
\sqrt{2} A^{0+} &= -T' e^{i\gamma} - C' e^{i\gamma} + P'_{tc} - \ P'_{uc} e^{i\gamma} \\
&\quad - \ P'_{EW} - \frac{2}{3} P^{C}_{EW} \,, \\
A^{-+} &= -T' e^{i\gamma} + P'_{tc} - P'_{uc} e^{i\gamma} - \frac{2}{3} P^{C}_{EW} \,, \\
\sqrt{2} A^{00} &= -C' e^{i\gamma} - P'_{tc} + P'_{uc} e^{i\gamma} \\
&\quad - \ P'_{EW} - \frac{1}{3} P^{C}_{EW} \,.
\end{aligned}
$$

$$
\begin{aligned}
P'_{EW} &= \frac{3}{4} \frac{c_9 + c_{10}}{c_1 + c_2} R(T' + C') + \frac{3}{4} \frac{c_9 - c_{10}}{c_1 - c_2} R(T' - C') \,, \\
P^{C}_{EW} &= \frac{3}{4} \frac{c_9 + c_{10}}{c_1 + c_2} R(T' + C') - \frac{3}{4} \frac{c_9 - c_{10}}{c_1 - c_2} R(T' - C') \,,
\end{aligned}
$$

SM fits and "solutions"

χ^2/dof	3.18/2
Parameter	Fitted Value
$\lvert P'_{tc}\rvert$	50.7 ± 1.7
$\lvert T'\rvert$	5.5 ± 1.5
$\lvert C'\rvert$	3.8 ± 1.3
$\lvert P'_{uc}\rvert$	1.0 ± 9.1
$\delta_{P'_{tc}}$	-16.0 ± 7.3
$\delta_{C'}$	205 ± 20
$\delta_{P'_{uc}}$	8.0 ± 350

Table: All SM parameters, all data

- $|C'/T'| = 0.68$ is pretty large and generally inconsistent with observations of color suppressed decays.
- The default expectation $|C'/T'| \sim 0.2$ (see e.g. QCD factorization) which will worsen the fit.
- $ACP(00) = -0.11$. Hence precise measurement $\pi^0 K^0$ is crucial.

Default SM fits

χ^2/dof	40.2/6
Parameter	Fitted Value
$\lvert P'_{tc}\rvert$	50.19 ± 0.44
$\lvert T'\rvert$	7.3 ± 1.3
$\delta_{P'_{tc}}$	-15.4 ± 3.1

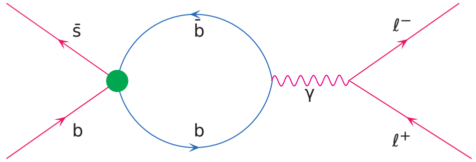
Table: Fit 1A: $P'_{uc} = 0, C' = 0$, all data

χ^2/dof	26.7/5
Parameter	Fitted Value
$\lvert P'_{tc}\rvert$	46.23 ± 0.50
$\lvert T'\rvert$	5.33 ± 0.72
$\delta_{P'_{tc}}$	-23.5 ± 3.9
$\delta_{C'}$	220 ± 16

Table: $P'_{uc} = 0, |C'/T'| = 0.2$, all data

Effective Operators: SMEFT

$Q_{qq}^{(1)}$	$(\bar{q}_i\gamma_\mu q_j)(\bar{q}_k\gamma^\mu q_\ell)$	$(\bar{L}L)(\bar{L}L)$	qq1_2333
$Q_{qq}^{(3)}$	$(\bar{q}_i\gamma_\mu\tau^I q_j)(\bar{q}_k\gamma^\mu\tau^I q_\ell)$		qq3_2333
$Q_{qd}^{(1)}$	$(\bar{q}_i\gamma_\mu q_j)(\bar{d}_k\gamma^\mu d_\ell)$	$(\bar{L}L)(\bar{R}R)$	qd1_2333
$Q_{qd}^{(8)}$	$(\bar{q}_i\gamma_\mu T^A q_i)\ (\bar{d}_k\gamma^\mu T^A d_\ell)$		qd8_2333
Q_{dd}	$(\bar{d}_i\gamma_\mu d_j)(\bar{d}_k\gamma^\mu d_\ell)$	$(\bar{R}R)(\bar{R}R)$	dd_2333



RGE effects can generate at the m_b scale $b \to s\ell^+\ell^-$ and $b \to sq\bar{q}$ operators.

Four quark operators: Datta, Ghosh, Duraisamy : arXiv:1310.1937

At the m_b scale

$$C^q_{V_{LL}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}_L\gamma_\mu b_L)(\bar{q}_L\gamma^\mu q_L), \quad C^q_{V_{LR}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}_L\gamma_\mu b_L)(\bar{q}_R\gamma^\mu q_R)$$

$$C^q_{V_{RL}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}_R\gamma_\mu b_R)(\bar{q}_L\gamma^\mu q_L), \quad C^q_{V_{RR}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}_R\gamma_\mu b_R)(\bar{q}_R\gamma^\mu q_R$$

$$C^{q,C}_{V_{LL}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}^\alpha_L\gamma_\mu b^\beta_L)(\bar{q}^\beta_L\gamma^\mu q^\alpha_L), \quad C^{q,C}_{V_{LR}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}^\alpha_L\gamma_\mu b^\beta_L)(\bar{q}^\beta_R\gamma^\mu q^\alpha_R$$

$$C^{q,C}_{V_{RL}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}^\alpha_R\gamma_\mu b^\beta_R)(\bar{q}^\beta_L\gamma^\mu q^\alpha_L), \quad C^{q,C}_{V_{RR}}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}(\bar{s}^\alpha_R\gamma_\mu b^\beta_R)(\bar{q}^\beta_R\gamma^\mu q^\alpha_R$$

$$C_9^{bs\ell\ell}\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}\frac{e^2}{16\pi^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$$

Four quarks SMEFT operators can potentially explain both the $b\to s\ell^+\ell^-$ and $b\to sq\bar{q}$ anomalies. Strong constraints come from B_s mixing.

$b \to s\nu\bar{\nu}$

- $b \to s\nu\bar{\nu}$ can potentially come from SMEFT operators discussed previously.

- Interesting possibilities for contribution to the $\mathrm{BR}(B^+ \to K^+ + \mathrm{inv})$: Dark matter, $B^+ \to K^+\phi\phi$ or $B^+ \to K^+\bar{\chi}\chi$ (arXiv:2309.12741) or sterile neutrinos (arXiv: 2309.02940)- uses effective theory and so less predictive.

- Another possibility is $B^+ \to K^+ + \mathrm{inv}$ is due to $B^+ \to K^+X$ where X is a vector or scalar that is either invisible or decays to invisible states. archive::2309.17191, 2310.15136, 2311.14629, 2312.00982

Light new physics: What can X be? arXiv: 2310.15136

- X has to be light enough to be produced on shell in B decays.
- X should be below the μ threshold so that it does not contribute to $b \to s\mu^+\mu^-$.
- Take m_X between $10 \lesssim m_X/\mathrm{MeV} \lesssim 150$ to be above the dielectron threshold.
- X is either invisible in the length scale of the experiment or couples to invisible states.
- X is scalar is preferred over vector avoid contributions from longitudinal polarizations $\sim \frac{E}{m_X}$. Causes problem to with B and K mixing, neutrino scattering at higher energies etc.

Phenomenology

- For $B^+ \to K^+ S$ to contribute to the Belle II signal $B^+ \to K^+\mathrm{inv}$, S has to be long lived and this is subject to beam dump constraint.
- Prefer to have S decay to invisible states (ν) and to visible states so that it is short lived.
- Introduce a massive sterile Dirac neutrino, ν_D, that couples to S. ν_D mixes with the active neutrino (ν_μ) with a mixing angle, U. This generates a coupling of S to light muon neutrino.
- The ν_D is short lived to avoid strong constraints on the mixing U.

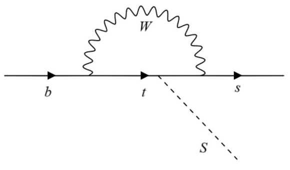
General Model- Effective Interaction

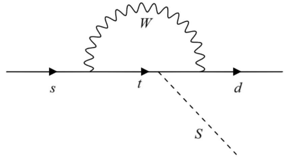
S mixes with a general extended unspecified Higgs sector and couples to a sterile neutrino state.

$$\mathcal{L}_S \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \eta_d \sum_{f=d,\ell} \frac{m_f}{v}\bar{f}fS - \sum_{f=u,c,t} \eta_f \frac{m_f}{v}\bar{f}fS - g_D S\bar{\nu}_D\nu_D - \frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu}\,, \quad (1)$$

- The mixing of S in the down sector is universal but not in the up sector.
- The production of S($B \to KS, K \to \pi S$) is decoupled from its decay ($S \to e^+e^-, \gamma\gamma, \bar{\nu}\nu$).
- The production of ν_D(from mixing with light neutrino) is decoupled from its decay ($\nu_D \to \nu_\mu S \to \nu_\mu e^+e^-, \nu_\mu\gamma\gamma, \nu_\mu\bar{\nu_\mu}\nu_\mu$).

$B \to KS$ and $K \to \pi S$





$$\mathcal{L}_{FCNC} = g_{bs}\bar{s}P_R bS + g_{sd}\bar{d}P_R sS,$$
$$g_{bs} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_b}{v}\eta_t V_{tb}V_{ts}^*$$

and

$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v}V_{ts}V_{td}^*\left(\eta_t + \eta_c\frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)$$

- $\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*} \sim \lambda^{-4}$, λ is the Cabibbo angle..
- η_t and η_c have to be adjusted to accommodate $B \to K + \mathrm{inv}$ and $K \to \pi + \mathrm{inv}$.

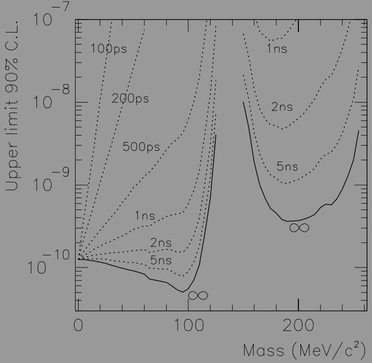
$K_L \to \pi^0 + \mathrm{inv}$ Bounds

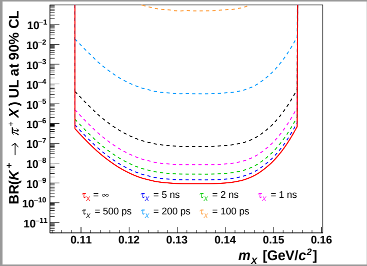
$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v} V_{ts}V_{td}^* \left(\eta_t + \eta_c \frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)$$

- If $\eta_t \sim \eta_c$ then predicted $K_L \to \pi^0 + \mathrm{inv}$ violates the KOTO bound (KOTO - arXiv: 2012.07571).
- $K_L \to \pi^0 S$ is CP conserving and so rate $\sim Re[V_{ts}V_{td}^* \left(\eta_t + \eta_c \frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)]$ and cancellation is possible to satisfy KOTO bound.
- We find $\eta_t \sim 0.005$ and $|\eta_c| \sim 0.1$ for $\mathcal{B}[S \to \bar{\nu}\nu] \sim 1$.

$K \to \pi + \text{inv}$ Bounds

$K^+ \to \pi^+ + \text{inv}$ interpreted as $K^+ \to \pi^+ X$





Various experiments like E979 (arXiv:0903.0030), NA62(arXiv: 2010.07644) put bounds on the $\mathcal{BR}[K^+ \to \pi^+ X]$ for different lifetimes. We avoid these bounds as we have shorter lifetime.

The sterile neutrino

The sterile neutrino ν_D and the light neutrino are taken to be Dirac fermion.

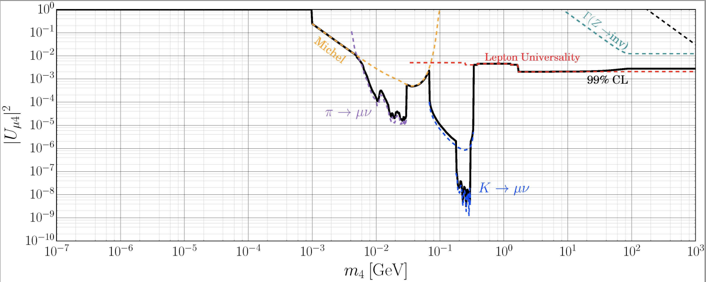
$$\nu_{\alpha(L,R)} = \sum_{i=1}^{4} U_{\alpha i}^{(L,R)} \nu_{i(L,R)} \ , \quad (\alpha = e, \mu, \tau, D) \, , \qquad (2)$$

$(U^L = U^R \equiv U)$. Here, we assume $U_{e4} \approx U_{\tau 4} \approx 0$

- Several experiments including PS191, NuTeV, BEBC , FMMF, CHARM II, NA62, T2K and MicroBooNE have placed limits on U for long lived HNL.
- We avoid these bounds because both S and ν_D are short lived with lifetime less than 0.1 ps.

Bounds on $U_{\mu 4}$

Decay independent bounds: arXiv:1511.00683



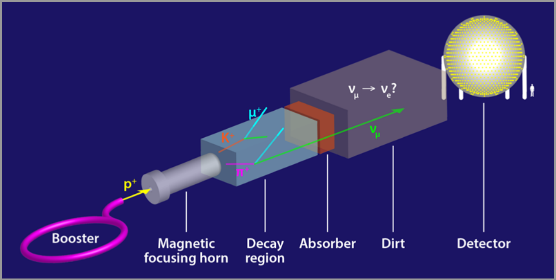
- arXiv:1802.02965(CMS) Upper limits at 95% limit for $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ from $W \to \ell\nu_4, \nu_4 \to \ell e^+ e^- \nu(100\%)$ between $1.2 \times 10^{-5} - 1.8$ for $m_{\nu 4}$ between 1 GeV- 1.2 TeV.
- Require m_{ν_4} around $400 - 500$ MeV with $U_{\mu 4} \sim 10^{-3}$ and so consistent with bounds.

Constraints

Observable	SM expectation	Measurement or constraint
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	$(5.58 \pm 0.38) \times 10^{-6}$	$(2.40 \pm 0.67) \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	$(9.2 \pm 1.0) \times 10^{-6}$	$< 1.8 \times 10^{-5}$
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$	$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu}) \frac{\tau_{B^+}}{\tau_{B^0}}$	$< 4 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)_{0.03-1 \text{ GeV}}$	$(2.43^{+0.66}_{-0.47}) \times 10^{-7}$	$(3.1^{+0.9+0.2}_{-0.8-0.3} \pm 0.2) \times 10^{-7}$
$\mathcal{B}(B_s \to \gamma\gamma)$	5×10^{-7}	$< 3.1 \times 10^{-6}$
$\mathcal{B}(B_s \to \mu^+ \mu^-)$	$(3.57 \pm 0.17) \times 10^{-9}$	$(3.52^{+0.32}_{-0.31}) \times 10^{-9}$
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	$(3.4 \pm 0.6) \times 10^{-11}$	$< 4.9 \times 10^{-9}$
$\mathcal{B}(K_L \to \pi^0 e^+ e^-)$	$(3.2^{+1.2}_{-0.8}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$
$\mathcal{B}(K_L \to \pi^0 \gamma\gamma)$	-	$(1.273 \pm 0.033) \times 10^{-6}$
$\mathcal{B}(K_S \to \pi^0 \gamma\gamma)$	-	$(4.9 \pm 1.8) \times 10^{-8}$
$\mathcal{B}(K^+ \to \pi^+ \gamma\gamma)$	-	$(1.01 \pm 0.06) \times 10^{-6}$
$\mathcal{B}(K^\pm \to \mu^\pm \nu_\mu e^+ e^-)_{m_{e^+e^-} \geq 140 \text{ MeV}}$	-	$(7.81 \pm 0.23) \times 10^{-8}$
ΔM_{B_s}	$(18.4^{+0.7}_{-1.2}) \text{ ps}^{-1}$	$(17.765 \pm 0.006) \text{ ps}^{-1}$
ΔM_K	$(47 \pm 18) \times 10^8 \text{ s}^{-1}$	$(52.93 \pm 0.09) \times 10^8 \text{ s}^{-1}$
a_μ	$116591810(43) \times 10^{-11}$	$116592059(22) \times 10^{-11}$

Implication for the MiniBooNE Anomaly

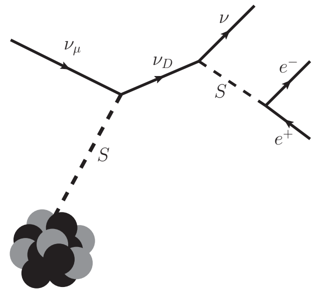
- Model predicts new effect in neutrino scattering $\nu_\mu + Z \to \nu_4 + Z$ and ν_4 decay, $\nu_4 \to \nu_\mu S \to \nu_\mu + (e^+, e^-, \gamma\gamma, \bar{\nu_\mu}\nu_\mu)$.
- Consider as explanation for the MiniBooNE Electron like events. arXiv: 2308.02543(for review).

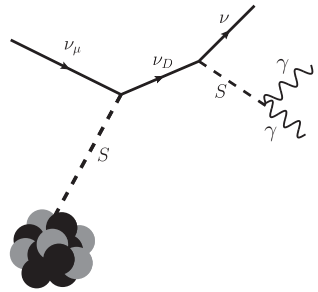


MiniBooNE Electron like events

- There is an apparent $\nu_\mu \to \nu_e$ conversion of neutrinos and antineutrinos at short baselines in the MiniBooNE experiment and the Liquid Scintillator Neutrino Detector (LSND).
- The MiniBooNE, excess is characterized by electron-like events in the energy region between 200 MeV and 600 MeV and is coincident in time with the $\langle E_\nu \rangle \sim 0.8$ GeV neutrino beam. Considered a 4.8 σ significance.
- Many solutions, oscillatory(3+1 oscillations) and non-oscillatory- like additional new physics sources of e^+e^- or $\gamma\gamma$ pairs and we focus on the later
- MicroBooNE rules out some of the solutions but many solutions still unconstrained.

MiniBooNE - S model: arXiv: 2310:15136





$$\mathcal{L}_{SN} = C_N \bar{\psi}_N \psi_N S\,,$$

$$C_N = Z C_p + (A - Z) C_n\,.$$

The proton and neutron couplings are related to the quark-scalar couplings by

$$C_p = \frac{m_p}{v}\left(\eta_c f_c^p + \eta_t f_t^p + \sum_d \eta_d f_d^p\right), \quad C_n = \frac{m_n}{v}\left(\eta_c f_c^n + \eta_t f_t^n + \sum_d \eta_d f_d^n\right)$$

MiniBooNE - S model

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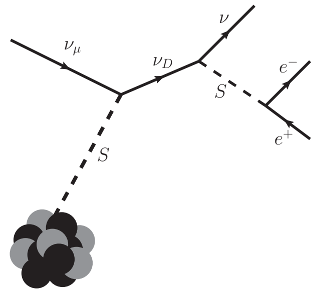
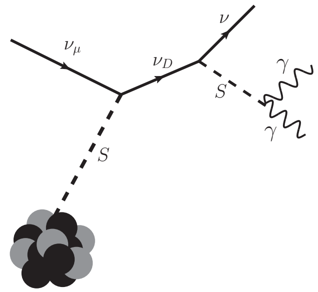
- η_t and η_c constrained from $B \to K + \mathrm{inv}$ and $K \to +\pi\mathrm{inv}$ decays.
- η_d determines coupling of S to electron pairs and so controls $B \to Ke^+e^-$ and $K \to \pi e^+e^-$.
- So all terms in the coherent neutrino scattering are constrained from rare B and K decays.

MiniBooNE - S model Signal



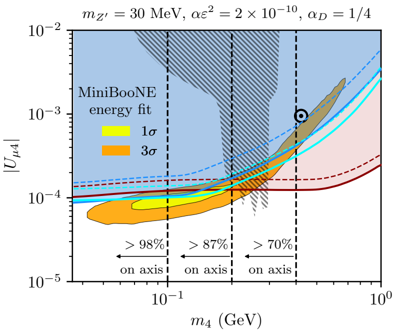


Signal with respect to the Z' model.

$$\mathcal{R} = \frac{\int \Phi \frac{d\sigma_S}{dT} dT dE_{\nu_\mu} \times (\mathcal{B}(S \to e^+e^-) + \mathcal{B}(S \to \gamma\gamma))}{\int \Phi \frac{d\sigma_{Z'}}{dT} dT dE_{\nu_\mu} \times \mathcal{B}(Z' \to e^+e^-)},$$

Denominator is evaluated at the benchmark point $m_{Z'} = 30$ MeV, $\alpha_{Z'} = 0.25$, $\alpha\epsilon^2 = 2 \times 10^{-10}$ to explain the MiniBooNE anomaly. The ν_μ flux at the Booster Neutrino Beam in the neutrino run is denoted by Φ.

MiniBooNE - S model Constraints



Can explain MiniBooNE and still be consistent with CHARM-II and MINERνA constraints as

$$\frac{\sigma_S \times (\mathcal{B}(S \to e^+e^-) + \mathcal{B}(S \to \gamma\gamma))}{\sigma_{Z'} \times \mathcal{B}(Z' \to e^+e^-)} < 1$$

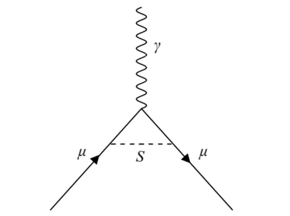
for $E_{\nu_\mu} = 20$ GeV where the denominator is evaluated for the parameter values with $|U_{\mu 4}| = 10^{-4}$.

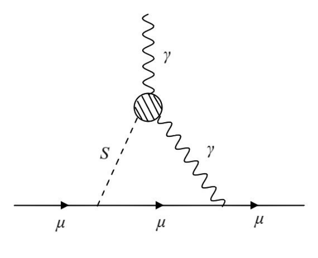
Predictions - S model

BP	$\mathcal{B}(S \to \gamma\gamma)$	$\mathcal{B}(S \to \nu\bar{\nu})$	$\mathcal{B}(S \to e^+e^-)$	$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$\mathcal{B}(B_s \to \nu\bar{\nu})$	$\mathcal{B}(B \to K^{(*)}\gamma\gamma)$
1	0.093	0.907	4.26×10^{-5}	1.71×10^{-9}	5.13×10^{-7}	1.3×10^{-6}
2	0.717	0.282	7.06×10^{-4}	3.61×10^{-11}	3.54×10^{-7}	3.7×10^{-5}
3	0.496	0.504	5.93×10^{-5}	9.02×10^{-10}	4.14×10^{-7}	1.7×10^{-5}
4	0.165	0.835	1.10×10^{-4}	1.73×10^{-9}	1.43×10^{-6}	2.65×10^{-6}
5	0.829	0.170	9.72×10^{-4}	2.04×10^{-10}	1.72×10^{-7}	6.8×10^{-5}
6	4.58×10^{-6}	0.999	7.10×10^{-4}	1.89×10^{-9}	1.01×10^{-6}	6.5×10^{-11}
7	3.95×10^{-4}	0.997	2.14×10^{-3}	2.84×10^{-9}	4.86×10^{-7}	7.6×10^{-9}

- $K_L \to \pi^0 + \mathrm{inv}$ can be close to the KOTO bound.
- Resonance in $B \to K^{(*)}\gamma\gamma$ is the main prediction.
- The branching ratio of S to electron-positron pair is tiny and so $b \to s\ell^+\ell^-(B \to K^{(*)}\ell^+\ell^-)$ decays mostly SM.

a_μ, a_e constraints/predictions





Because of small S coupling to leptons the Barr-Zee diagram dominates .

$$\delta(g-2)_\ell^{S\gamma\gamma} \approx \frac{\eta_d}{4\pi^2}\frac{\kappa m_\ell^2}{v}\ln\frac{\Lambda}{m_S}\,, \tag{3}$$

η_d and κ control the $S \to e^+e^-$ and $S \to \gamma\gamma$ rates.

ν_4 in Effective Theories- Heavy new physics

ν_4 neutrinos can be produced and decay through operators after integrating heavy fields like leptoquarks, new gauge bosons etc.

- For $d_i \to d_j + \mathrm{inv} \to d_j \bar{n} n$ - one can study in an effective field theory- ν SMEFT or SMNEFT:

$$(\bar{n}_p \gamma_\mu n_r)(\bar{d}_s \gamma^\mu d_t), (\bar{q}_p \gamma_\mu q_r)(\bar{n}_s \gamma^\mu n_t), (\bar{\ell}^j_p \sigma_{\mu\nu} n_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} d_t)$$

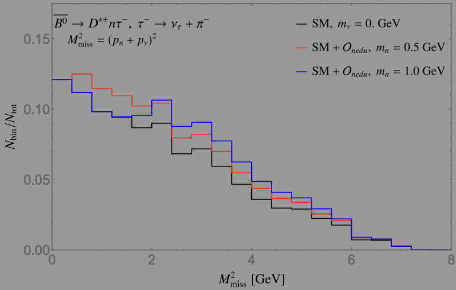
$$(\bar{\ell}^j_p n_r)\epsilon_{jk}(\bar{q}^k_s d_t)$$

- With the $B^+ \to K^+ + \mathrm{inv}$ measurement and other $B \to K^* + \mathrm{inv}$ bounds scalar operators are preferred (arXiv: 2309.02940).

- But no clear connection to other sectors but RGE effects can generate operators like $\bar{\nu}\sigma_{\mu\nu} n F^{\mu\nu}$ which can contribute to neutrino scattering.

ν_4 in Effective Theories.

- ν_4 do not have to be produced or decay through mixing. New sources of production and decay in Effective Theories. For example $\bar{n}n$ production from B, D decays.
- Allows one to explore ν_4 in Meson decays at facilities like Belle II, FASER, DUNE near detector etc.



$B \to D^* \tau X$ where $X = \nu, n$ with $\tau \to \pi \nu_\tau$.

Note presence of n might explain the $R^{\tau/\ell}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$ $(\ell = e, \mu)$

Summary

- Several puzzles in $\bar{b} \to \bar{s}$ transitions in semileptonic and nonleptonic B decays.
- Unified decscription may be possible in effective theory through RGE effects (SMEFT)
- New evidence for $B^+ \to K^+ + \mathrm{inv.}$ Interpreted as $B^+ \to K^+ + S$, where S is a short lived scalar that decays to neutrinos by coupling to a sterile neutrino ν_4, which mixes with the light neutrino.
- These effects may be the source of the MiniBooNE LEE events.
- $b \to s\nu\bar{\nu}$ may indicate heavy new physics with a sterile neutrino-*SMENFT*. This has interesting signatures in B decays.