A Theoretical Perspective on Flavour Physics

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Prague

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THE UNIVERSITY of MISSISSIPPI
1848

Outline

- 50 years of Charm Discovery: Zoltan Ligeti's slides.
- Flavor Physics
  - Testing the flavor structure of the SM: UT Fits.
  - Beauty Decays. Status of Anomalies
  - Motivated by neutrino masses and mixing: Charged Lepton Flavor violating Decays.
  - Motivated by neutrino masses and mixing: Signatures of sterile neutrino in Effective Theory.
  - Dark Sector in rare decays to invisible states.
  - Conclusion

The J/Ψ discovery

"November revolution"?

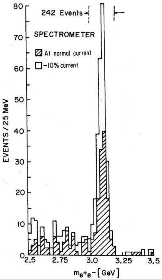
Why was it so surprising?

Usually learn things linearly

The real story is often confusing and much more complex

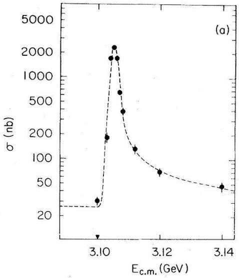
Experimental Observation of a Heavy Particle J

(Received 12 November 1974)



Discovery of a Narrow Resonance in e^+e^- Annihilation

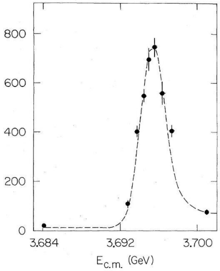
(Received 13 November 1974)



The Ψ': two weeks later — the D: two years later

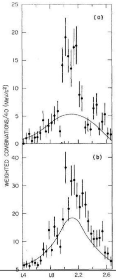
Discovery of a Second Narrow Resonance in e^+e^- Annihilation

(Received 25 November 1974)



Observation in e^+e^- Annihilation of a Narrow State at 1865 MeV/c^2 Decaying to $K\pi$ and $K\pi\pi\pi$ †

(Received 14 June 1975) → typo in PRL! preprint clearly June 1976



The state appears to be produced only in association with systems of comparable or higher mass.

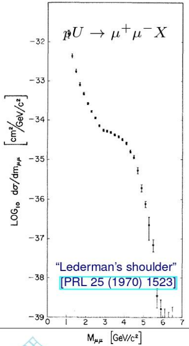
The $D^{\pm}$ discovered a month later [PRL 37 569]

Nearly a year after the τ discovery [PRL 35 1489] $(e^+e^- \to \mu^{\pm}e^{\mp} + E_{\text{miss}})$

NB: J/ψ has "charmness" $= 0$

Quantum numbers of J/ψ are same as vacuum, will play a role later in this talk

Several earlier hints of charm



"Lederman's shoulder"
[PRL 25 (1970) 1523]

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo
**Yokohama National University*

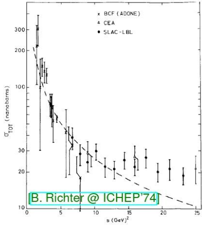
August 9, 1971

Among the secondary particles produced in a high energy jet shower and observed by emulsion chambers exposed to cosmic rays, a possible decay in flight of a new type particle was found.

One event reported as : $X \to \pi^+\pi^0$

$m_X \sim 1.78\ \mathrm{GeV},\ \tau_X \sim 2.2\times10^{-14}\,\mathrm{s}$

[There were other / earlier hints]



[B. Richter @ ICHEP'74]

$e^+e^- \to X$ total cross section

$c\bar{c}$ & $\tau^+\tau^-$ thresholds close to each other

Take 1: what's the big deal?

- GIM mechanism (1970)

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Take 1: what's the big deal?

- GIM mechanism (1970)
- Kobayashi-Maskawa 3-generation proposal (1973)

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Take 1: what's the big deal?

- GIM mechanism (1970)
- Kobayashi-Maskawa 3-generation proposal (1973)
- Constraints / predictions for m_c from Δm_K and $K_L \to \mu^+\mu^-$

Gaillard & Lee, March 1974

$\Delta m_K \quad \to \quad$ "Equation (2.8) is compatible ... with ... $m_u \ll m_c$ and $m_c \simeq 1.5\,\mathrm{GeV}$"

Vainshtein & Khriplovich, July 1973

$K_L \to \mu^+\mu^- \quad \to \quad m_c < 9\,\mathrm{GeV}$

$\Delta m_K \quad \to \quad m_c - m_u \sim 1\,\mathrm{GeV}$ ("less reliable")

(NB: vacuum insertion approximation works better for Δm_K than one could have expected)

Reading these papers, one might wonder when they haven't received the Nobel Prize?

Some lessons

- Seeds of the idea that if a quark is heavy (compared to $\Lambda_{\rm QCD}$), it does not matter how heavy it is in the papers
- Maybe surprising that Heavy Quark Symmetry came 15 years later, NRQCD even after

---

- Since 1970s, flavor has mostly been an input to model building, since the strong constraints on TeV-scale NP have been known

  All TeV-scale BSM models must contain some mechanism to avoid violating constraints
- For many models, Δm_K and ϵ_K can be the most constraining, since the SM suppressions are the strongest for kaons

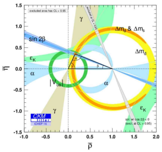
SM fits - UT triangles

Outline

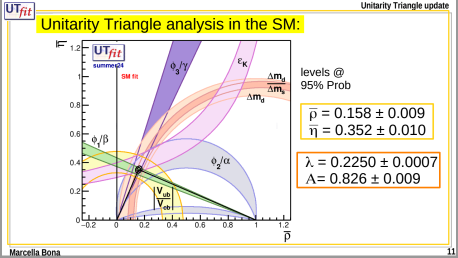
- Motivation: It is exceedingly important to determine UTs as precisely as possible….
- Briefly recall special role of lattice BK in confirmation of KM theory of CPV
- Progress in lattice eps'….implications for both UTs though crucial for KUT
- K UT
- B UT: esp gamma
- Summary

Use exptal data + lattice WME to test KM picture of CPV

http://ckmfitter.in2p3.fr
see also http://www.utfit.org



SM fits - UT triangles



What is the scale of new physics?

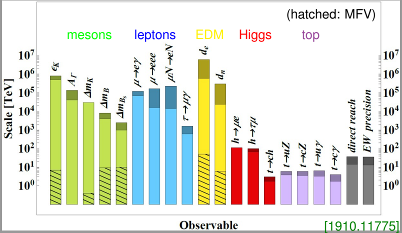
- Flavor, K, B, D: $\dfrac{(\bar{b}\,\Gamma d)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2 - 10^5\,\mathrm{TeV}$

  (Note special sensitivity of meson mixings)

- Electroweak: $\dfrac{(H^\dagger D_\mu H)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10\,\mathrm{TeV}$

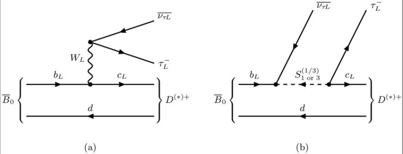
- Actual scales may be much less; e.g., in SM:

$$\frac{\Delta m_K}{m_K} \sim \frac{g_2^4}{16\pi^2}\,|V_{cs}V_{cd}|^2\,\frac{m_c^2}{m_W^4}\,f_K^2 \sim 7\times 10^{-15}$$



- Lack of NP in flavor tells us something; motivates tera-Z part of comprehensive search
- If NP is within any collider's reach, it must possess nontrivial structures (e.g., MFV-like)

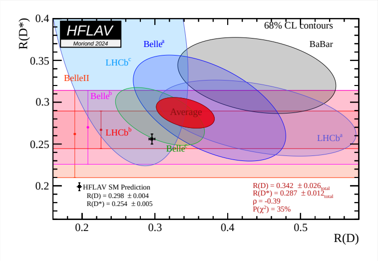
B anomalies: $R(D) - R(D^*)$ puzzle



$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\langle D^{(*)}(p') | \bar{c}\gamma^\mu (1-\gamma_5) b | \bar{B}(p) \rangle \right] \bar{\tau}\gamma_\mu (1-\gamma_5)\nu_\tau$$

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)} \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}.$$

Experiments: $R(D) - R(D^*)$ puzzle

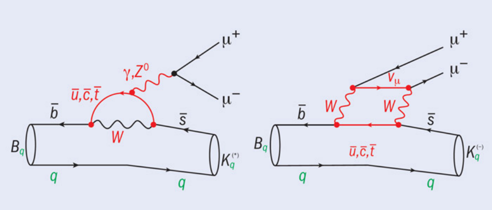


Including correlations, one finds that the deviation is at the level of 3.31σ from the SM prediction.

New developments in refining SM predictions for these decays. Severals talks in the conference.

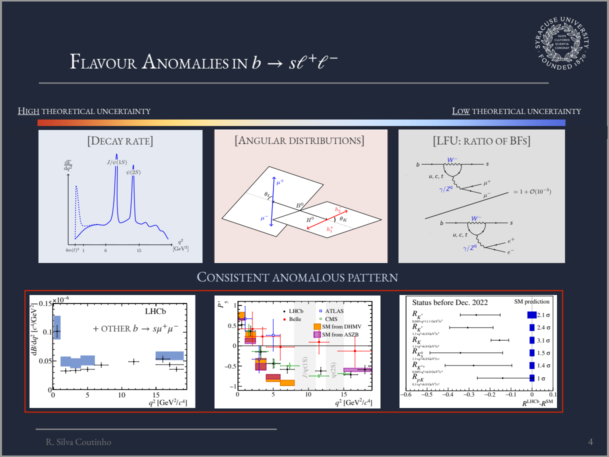
Analyze NP in model-indpendent way (see talk by Nicola Losacco) and in models(see talk on Leptoquarks by S. Fajfer)

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



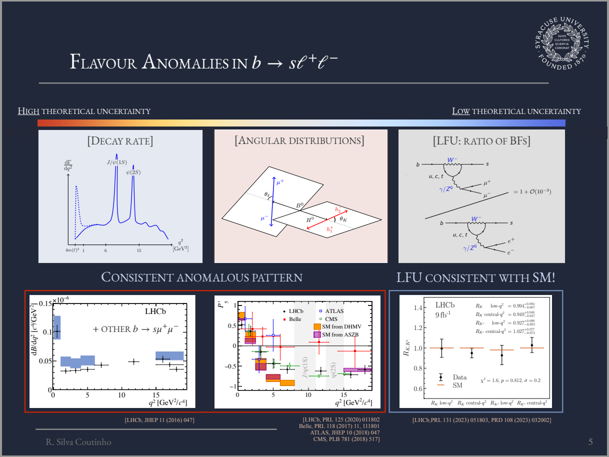
$$
\begin{aligned}
H_{\text{eff}}(b \to s\ell\bar{\ell}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[C_9 \left(\bar{s}_L \gamma^\mu b_L\right) \left(\bar{\ell}\gamma_\mu \ell\right) \right. \\
&\qquad \left. + \; C_{10} \left(\bar{s}_L \gamma^\mu b_L\right) \left(\bar{\ell}\gamma_\mu \gamma^5 \ell\right) \right] \;, \\
H_{\text{eff}}(b \to s\nu\bar{\nu}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \, C_L \left(\bar{s}_L \gamma^\mu b_L\right) \left(\bar{\nu}\gamma_\mu (1-\gamma^5)\nu\right) \;, \\
H_{\text{eff}}(b \to s\gamma^*) &= C_7 \, \frac{e}{16\pi^2} \left[\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b\right] F^{\mu\nu}
\end{aligned}
$$

$b \to s\ell^+\ell^-$: - Past



Lepton Non-Universal NP - cannot be faked by QCD.

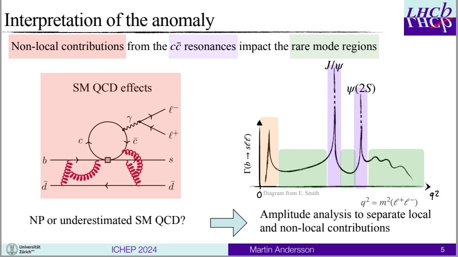
$b \to s\ell^+\ell^-$: - Current

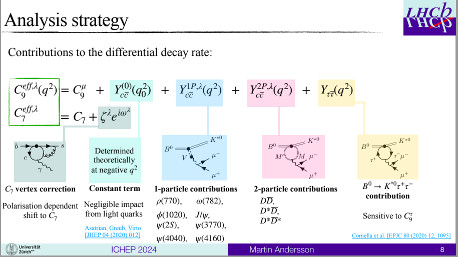


LUV anomalies have reduced significance: Lepton Universal NP or underestimated QCD effects.

$b \to s\ell^+\ell^-$: Long distance QCD effects

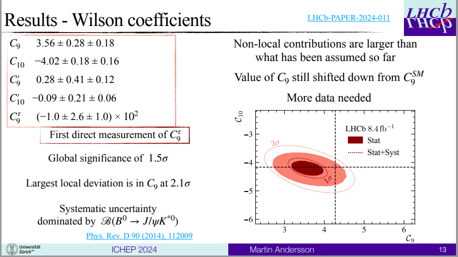
See also talk by Arianna Tinari

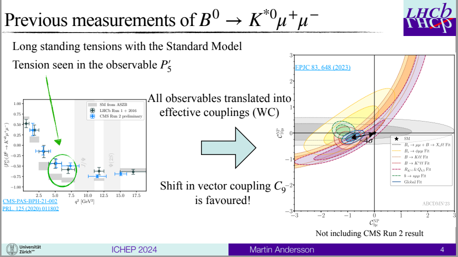




In fact NP in $bs\tau^+\tau^-$ is a possible source of a universal C_9 in SMEFT via RGE running.

$b \to s\ell^+\ell^-$: NP fits





With more data we can find out if QCD effects are behind the BR and angular observable deviations in $b \to s\ell^+\ell^-$ decays.

$b \to s\ell^+\ell^-$: NP SMEFT QQLL- Leptoquarks, Z'

operator & definition	chirality & flavour structure		
$Q_{\ell q}^{(1)}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_\ell)$	$(\bar{L}L)(\bar{L}L)$	3323
$Q_{\ell q}^{(3)}$	$(\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_\ell)$		3323
$Q_{\ell d}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_\ell)$	$(\bar{L}L)(\bar{R}R)$	3323
Q_{qe}	$(\bar{q}_i \gamma_\mu q_j)\ (\bar{e}_k \gamma^\mu e_\ell)$		2333
Q_{ed}	$(\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_\ell)$	$(\bar{R}R)(\bar{R}R)$	3323

Table: The list of semileptonic SMEFT operators that can potentially generate an LFU $\mathcal{O}_{9\ell}$ at scale m_b.

C_{SMEFT} (TeV^{-2})		C_9^{U}	C_{10}^{U}	$C_9'^{\mathrm{U}}$	$C_{10}'^{\mathrm{U}}$
$[C_{lq}^{(1)}]_{3323}$	-0.23 ± 0.04	$-1.20 - i0.022$	-0.004	0	0
$[C_{lq}^{(3)}]_{3323}$	-0.23 ± 0.04	$-1.17 - i0.022$	-0.021	0	0
$[C_{qe}]_{2333}$	-0.22 ± 0.03	$-1.16 - i0.022$	-0.005	0	0

Table: Fit prefers $C_9^{\mathrm{U}} = -1.18 \pm 0.19$

$b \to s\ell^+\ell^-$: NP SMEFT QQQQ: Diquarks, Z'

$C_{\rm SMEFT}$	ΔM_s $(\times 10^{11})$	κ_ε	ε'/ε $(\times 10^4)$	$S_{\psi\phi}$
$[C_{qq}^{(1)}]_{1123}$	(1.15 ± 0.06) $(\surd)$	-0.012 $(\surd)$	38.4 (?)	0.0369 ± 0.0019
$[C_{qq}^{(1)}]_{2223}$	(2.72 ± 0.10) $(\times)$	0.11 $(\surd)$	15.8 $(\surd)$	0.0265 ± 0.0008
$[C_{qq}^{(3)}]_{1123}$	(1.16 ± 0.06) $(\surd)$	-0.005 $(\surd)$	23.1 $(\surd)$	0.0369 ± 0.0019
$[C_{qq}^{(3)}]_{2223}$	(0.59 ± 0.05) $(\times)$	-0.04 $(\surd)$	17.8 $(\surd)$	0.0544 ± 0.0043
$[C_{qd}^{(1)}]_{2311}$	(1.16 ± 0.07) $(\surd)$	-0.75 $(\times)$	13.9 $(\surd)$	0.0369 ± 0.0019
$[C_{qd}^{(1)}]_{2322}$	(1.55 ± 0.07) $(\times)$	0.75 $(\times)$	13.9 $(\surd)$	0.0321 ± 0.0014
$[C_{qd}^{(1)}]_{2333}$	(0.76 ± 0.06) $(\times)$	0.0 $(\surd)$	13.9 $(\surd)$	0.0471 ± 0.0033
$[C_{qd}^{(8)}]_{2311}$	(1.16 ± 0.06) $(\surd)$	-15.0 $(\times)$	12.8 $(\surd)$	0.0368 ± 0.0018
$[C_{qd}^{(8)}]_{2322}$	(1.18 ± 0.05) $(\surd)$	14.3 $(\times)$	12.8 $(\surd)$	0.0128 ± 0.0002
$[C_{qd}^{(8)}]_{2333}$	(10.6 ± 0.5) $(\times)$	-0.001 $(\surd)$	12.8 $(\surd)$	-0.0061 ± 0.0003
$[C_{qu}^{(1)}]_{2311}$	(1.15 ± 0.06) $(\surd)$	0.0 $(\surd)$	13.9 $(\surd)$	0.0369 ± 0.0018
$[C_{qu}^{(1)}]_{2322}$	(1.16 ± 0.06) $(\surd)$	0.0 $(\surd)$	13.9 $(\surd)$	0.0369 ± 0.0019
$[C_{qu}^{(8)}]_{2311}$	(1.15 ± 0.06) $(\surd)$	0.0002 $(\surd)$	13.9 $(\surd)$	0.0369 ± 0.0019
$[C_{qu}^{(8)}]_{2322}$	(1.15 ± 0.06) $(\surd)$	-0.0003 $(\surd)$	13.9 $(\surd)$	0.0369 ± 0.0020

QQQQ operators can via gluonic RGE produce effects comparable to the SM in non leptonic decays and potentially resolve some of the hadronic puzzles : eg. $B \to \pi K$ Puzzle.

Lepton Flavor is conserved in SM

Neutrino Oscillation = LFV

May observe CLFV

One can use an effective Field theory description.

Various operator structures lead to different processes.

There can be cancellation between operators.

A model will have more than one operator

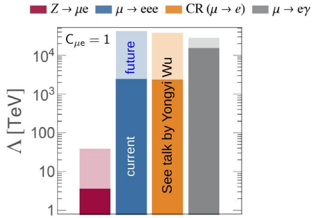
Standard Model Effective Field Theory

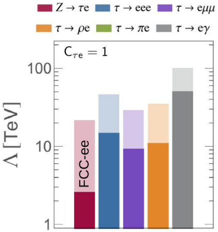
- 888 CLFV operators at d=6:

$$\frac{C_{ij}}{\Lambda^2}\ell_i^c\sigma_{\alpha\beta}\ell_j H F^{\alpha\beta}\,,\ \frac{C_{ij}}{\Lambda^2}\ell_i^c\gamma^\alpha\ell_j\, H^\dagger D_\alpha H\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j\ell_n^c\ell_m\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j q_n^c q_m$$

[Weinberg ‘79; Buchmüller & Wyler, ‘86; Grzadkowski++, ‘10; Fonseca, ‘17]

- Model-dependent coefficients; can get testable rates.





[Calibbi, Marcano, Roy, 2107.10273]

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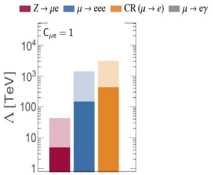

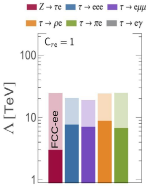

[Calibbi, Marcano, Roy, 2107.10273]

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[Weinberg '79; Buchmüller & Wyler, '86; Grzadkowski++, '10; Fonseca, '17]

- Model-dependent coefficients; can get testable rates.
  - $\ell_i \to \ell_j \ell_m \bar{\ell}_n$: $\mu \to ee\bar{e}$, $\tau \to ee\bar{e}, e\mu\bar{e}, \mu\mu\bar{e}, \ldots$
  - $\mu\mu\bar{e}\bar{e}$: $\Delta L_\mu = 2 \Rightarrow$ Muonium-antimuonium conversion

    [Conlin & Petrov, 2005.10276; Fukuyama, Mimura, Uesaka, 2108.10736; ...]

  - $\tau\tau\bar{\mu}\bar{\mu},\ldots$: $\Delta L_\tau = 2$, partly constrained by LFUV $\frac{\Gamma(\tau\to\mu\nu\nu)}{\Gamma(\tau\to e\nu\nu)}$

    but right-handed ones are tough:

    $\mathrm{BR}(Z \to \tau_R\tau_R\bar{\mu}_R\bar{\mu}_R) \simeq 4\times 10^{-11}\,(100\,\mathrm{GeV}/\Lambda)^4$

    [JH & Sokhashvili, 2401.09580]

Standard Model Effective Field Theory

- 888 CLFV operators at d=6:

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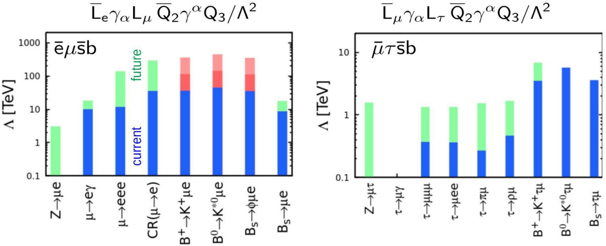


[Ali++, 2312.05071]

Effective Interactions of the sterile neutrino

- Sterile neutrinos might have new interactions via the exchange of light or heavy mediators(Higgs, Vector Bosons, Leptoquarks). Heavy mediators can be integrated out to get an effective theory: SMNEFT (νSMEFT).

- To lowest order in SMNEFT, the dimension-six B and L conserving SMNEFT Lagrangian is

$$L_{\mathsf{SMNEFT}} \supset L_{\rm SM} + \bar{n}\not{\partial} n + \sum_i \mathcal{C}_i \mathcal{O}_i \, ,$$

where $\mathcal{C}_i$ are the WCs with the scale of new physics absorbed in them, The 16 baryon and lepton number conserving ($\Delta B = \Delta L = 0$) operators involving the field n in SMNEFT are shown in next slide.

Effective Operators

Construct dim 6 operators with the sterile neutrino.

SMNEFT = SMEFT + N

16 new SMNEFT operators at dimension-six $\Delta B = \Delta L = 0$

$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
$\mathcal{O}_{nd}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qn}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{n}_s\gamma^\mu n_t)$	$\mathcal{O}_{\ell n\ell e}$	$(\bar{\ell}_p^j n_r)\epsilon_{jk}(\bar{\ell}_s^k e_t)$
$\mathcal{O}_{nu}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{\ell n}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{n}_s\gamma^\mu n_t)$	$\mathcal{O}_{\ell nqd}^{(1)}$	$(\bar{\ell}_p^j n_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$\mathcal{O}_{ne}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{e}_s\gamma^\mu e_t)$			$\mathcal{O}_{\ell nqd}^{(3)}$	$(\bar{\ell}_p^j \sigma_{\mu\nu} n_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} d_t)$
$\mathcal{O}_{nn}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{n}_s\gamma^\mu n_t)$			$\mathcal{O}_{\ell nuq}$	$(\bar{\ell}_p^j n_r)(\bar{u}_s q_t^j)$
$\mathcal{O}_{nedu}$	$(\bar{n}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu u_t)$				
$\psi^2\phi^3$		$\psi^2\phi^2 D$		$\psi^2 X\phi$	
$\mathcal{O}_{n\phi}$	$(\phi^\dagger\phi)(\bar{l}_p n_r\tilde{\phi})$	$\mathcal{O}_{\phi n}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{n}_p\gamma^\mu n_r)$	$\mathcal{O}_{nW}$	$(\bar{\ell}_p\sigma^{\mu\nu} n_r)\tau^I\tilde{\phi}W_{\mu\nu}^I$
		$\mathcal{O}_{\phi ne}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{n}_p\gamma^\mu e_r)$	$\mathcal{O}_{nB}$	$(\bar{\ell}_p\sigma^{\mu\nu} n_r)\tilde{\phi}B_{\mu\nu}$

CC Hadronic Decays Effective Operators

N production operator

- We assume N can talk to B quark and is at sub GeV scale
- N can be produced via B meson decay

$$-\mathcal{L}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\left(O^V_{LL} + \sum_{\substack{X=S,V,T\\ \alpha,\beta=L,R}} C^X_{\alpha\beta}\, O^X_{\alpha\beta}\right)$$

$$\begin{aligned} O^V_{\alpha\beta} &\equiv (\bar{c}\gamma^\mu P_\alpha b)(\bar{\ell}\gamma^\mu P_\beta \nu)\,,\\ O^S_{\alpha\beta} &\equiv (\bar{c}P_\alpha b)(\bar{\ell}P_\beta \nu)\,,\\ O^T_{\alpha\beta} &\equiv \delta_{\alpha\beta}(\bar{c}\sigma^{\mu\nu}P_\alpha b)(\bar{\ell}\sigma_{\mu\nu}P_\beta \nu)\,. \end{aligned}$$

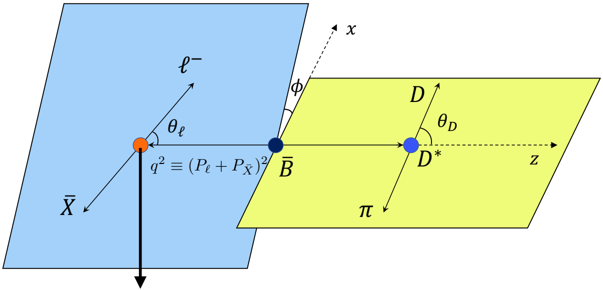
$$\begin{aligned} \mathcal{O}_{nedu} &\to O^V_{RR}\\ \mathcal{O}_{\ell nuq} &\to O^S_{LR}\\ \mathcal{O}^{(1)}_{\ell nqd} &\to O^S_{RR}\\ \mathcal{O}^{(3)}_{\ell nqd} &\to O^T_{RR} \end{aligned}$$

A sterile neutrino can solve the $R(D) - R(D^*)$ puzzle. (1211.0348, 1704.06659,1711.09525, 1804.04135,1804.04642, 1810.06597, 1811.04496 ....). The NP adds incoherently with SM and enhances rate.

CC B decays with Effective Operators

Even though no deviation in BR there can be striking signatures in angular distributions. Note large statistics in CC decays with a BR of a few percent.

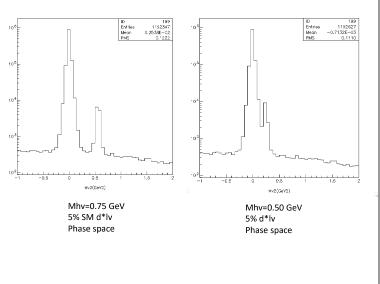
N production from B meson decay $\bar{B} \to D^{(*)} \ell \bar{X}$

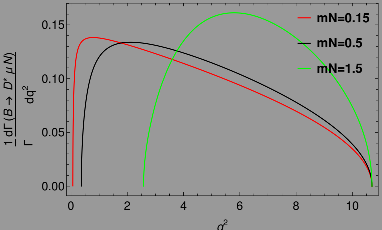


$\cdot\, L \equiv L\,(q^2, m_\ell, m_N, \theta_\ell, \phi)$

Signature of N in B decays at Belle 2

For $\bar{B} \to D^{*+}\ell^{-}\bar{\nu}_{\ell}$, N can be produced through mixing or effective operators. Mixing will alter just the SM operator.





Same processes in Collider Experiments

Dirac vs Majorana in SMNEFT

RHN Production

$$M^- \to \ell^- + \bar{N}$$
$$M^0 \to P^+ + \ell^- + \bar{N}$$
$$M^0 \to (P^+)^* + \ell^- + \bar{N}$$

$$\begin{pmatrix} M \in B, D, K\dots \\ P \in D, K, \pi\dots \\ \ell \in e, \mu, \tau \end{pmatrix}$$

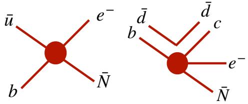
RHN decay

$$\bar{N}^- \to \ell^+ \ell^- \bar{\nu}$$

$$\mathcal{O}_{LNuQ} = (\bar{L}N)(\bar{u}Q)$$
$$\mathcal{O}_{Nedu} = (\bar{N}\gamma_\mu e)(\bar{d}\gamma^\mu u)$$
$$\mathcal{O}^{(3)}_{LNQd} = (\bar{L}^j \sigma_{\mu\nu} N)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} d)$$

$$\mathcal{O}_{LNLe} = (\bar{L}^j N)\epsilon_{jk}(\bar{L}^k e)$$
$$\mathcal{O}_{Ne} = (\bar{N}\gamma_\mu N)(\bar{e}\gamma^\mu e)$$
$$\mathcal{O}_{LN} = (\bar{N}\gamma_\mu N)(\bar{L}\gamma^\mu L)$$

LHC

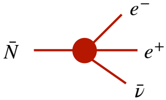


$$B^- \to e^- + \bar{N}$$
$$\bar{B}^0 \to D^+ + e^- + \bar{N}$$
$$\bar{B}^0 \to (D^+)^* + e^- + \bar{N}$$

FASER : 480m
FASER2 (FPF - Cavern) : 615m

Long lived RHN

FASER



$$\bar{N}^- \to e^+ e^- \bar{\nu}$$

Same processes in Collider Experiments

Dirac vs Majorana:
Opening angle distribution

SIMULATION:

RHN production & decay: Modified FORESEE

FASER Magnetic field simulation: HepJo

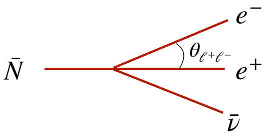
DETECTOR CONFIGURATION:

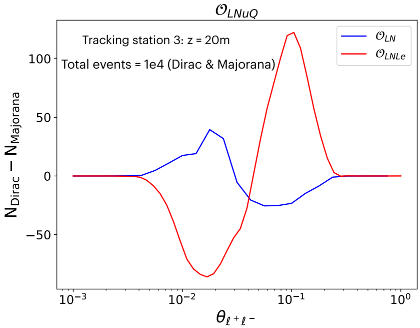
FASER 2 (FPF)

Cross section = 3x1 m Rectangle

Decay volume length = 10m

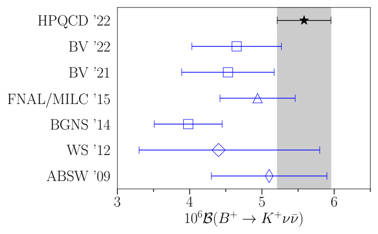
B = 1 T

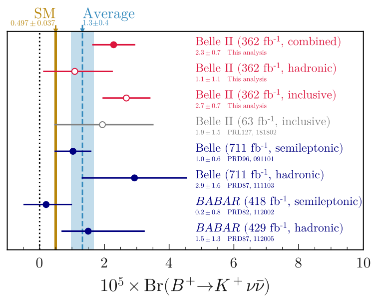




Dark sector in hadronic decays to invisible states: Eg. $B^+ \to K^+ + \text{inv}$, $K \to \pi\bar{\nu}\nu$

$B^+ \to K^+\nu\bar{\nu}$ Anomaly about 2.7 σ from SM: Belle II. Same Form Factors. From lattice:arXiv: 2207.13371, HPQCD





Dark sector in hadronic decays to invisible states: sterile neutrinos

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

- Vector :$(\bar{N}_p \gamma_\mu N_r)(\bar{d}_s \gamma^\mu d_t), (\bar{q}_p \gamma_\mu q_r)(\bar{N}_s \gamma^\mu N_t)$.
- Scalar-Tensor: $(\bar{\ell}^j_p \sigma_{\mu\nu} N_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} d_t), (\bar{\ell}^j_p N_r)\epsilon_{jk}(\bar{q}^k_s d_t)$.

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

- Within SMEFT for $B^+ \to K^+ + \mathrm{inv}$ see talk by O. Summensari. Generally, if one explains $b \to s\ell^+\ell^-$ by running of four Fermi operators $B^+ \to K^+ + \mathrm{inv}$ is difficult to explain.

Dark sector in decays to invisible states: Eg. General light states

Several suggestions to interpret $B^+ \to K^+ + \mathrm{inv}$ and $B \to KX$. See talk by Martin Novoa-Brunet

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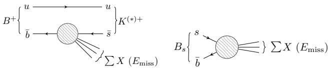
Theoretical Framework: Invisible Extended SMEFT



- Consider additional invisible final states ($\sum X$)
  - One or two particle final states (avoid phase space suppression)
- $X \in \{\phi, \psi, V_\mu, \Psi_\mu\}$ massive particles of spin $J = \{0, 1/2, 1, 3/2\}$

$$\sum X \in \{\phi, V, \phi\bar{\phi}, \psi\bar{\psi}, V\bar{V}, \Psi\bar{\Psi}\}$$

- Singlet under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ (can be charged under dark gauge or global symmetry)
  - Leads to only interactions involving gauge-invariant combinations of SM fields
- Interactions through renormalizable dim-4 operators (portals) or higher-dimensional effective operators (mediated by heavy NP)

$$\mathcal{L} = \underbrace{\mathcal{L}_{\mathsf{SM}+X}}_{\text{dim}=4} + \sum_i \underbrace{C_i^{(d)} \mathcal{O}_i^{(d)}}_{\text{dim}>4}$$

A specific example - Dark Higgs and sterile neutrino: arXiv: 2310.15136

Motivated by the recent excess observed by Belle 2 in $B \to K + \mathrm{inv.}$

A dark Higgs, S , mixes with a general extended unspecified Higgs sector (see: arXiv:1606.04943, 1908.08625, 2001.06522) and couples to a sterile neutrino state.

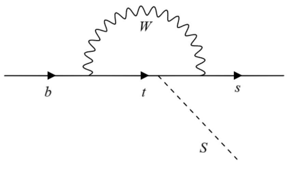
$$\mathcal{L}_S \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \eta_d \sum_{f=d,\ell} \frac{m_f}{v}\bar{f}fS - \sum_{f=u,c,t} \eta_f \frac{m_f}{v}\bar{f}fS - g_D S\bar{\nu}_D\nu_D - \frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu}\,, \quad (1)$$

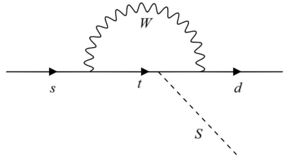
The sterile neutrino ν_D and the light neutrino mix and are taken to be Dirac fermion.

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

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

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





$$\mathcal{L}_{FCNC} = g_{bs}\bar{s}P_R bS + g_{sd}\bar{d}P_R sS,$$

$$g_{bs} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_b}{v}\eta_t V_{tb}V_{ts}^*$$

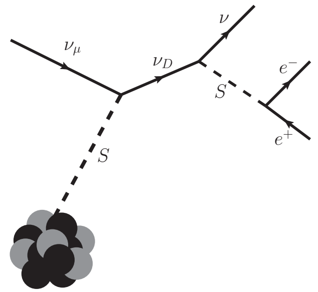
and

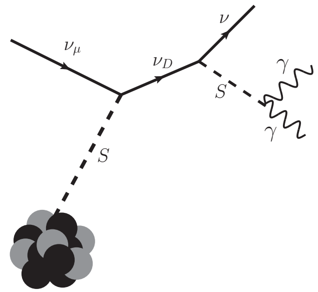
$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v}V_{ts}V_{td}^*\left(\eta_t + \eta_c\frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right)$$

- $\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*} \sim \lambda^{-4}$, λ is the Cabibbo angle..
- η_t can be fixed to accommodate the new measurement of $B \to K+\mathrm{inv}$.

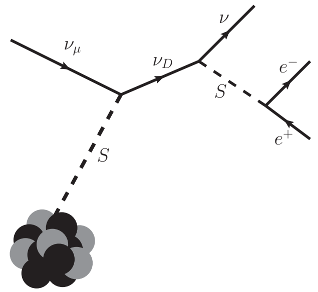
Neutrino NSI - MiniBooNE Electron like events

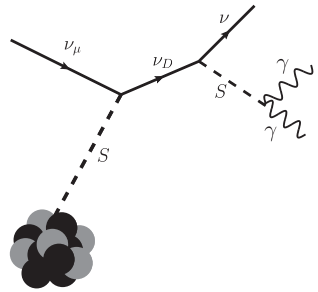
- Model predicts new effect in neutrino scattering $\nu_\mu + Z \to \nu_4 + Z$ and ν_4 decay, $\nu_4 \to \nu_\mu S \to \nu_\mu + (e^+e^-, \gamma\gamma, \bar{\nu_\mu}\nu_\mu)$.
- Consider as explanation for the MiniBooNE Electron like events. arXiv: 2308.02543(for review).





MiniBooNE - S model





$$\mathcal{L}_{SN} = C_N \bar{\psi}_N \psi_N S\,,$$
$$C_N = Z C_p + (A - Z) C_n\,.$$

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

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

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

- 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.

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.

Conclusions

- The SM continues to be tested in Flavor experiments with global fits.
- There are interesting anomalies: More data and theoretical improvement needed.
- Sensitivity to dark sectors like sterile neutrino, dark Higgs in Flavor observables.
- Future is exciting as increased statistics will improve sensitivity to BSM physics.