Theoretical Aspects of the Flavor Sector

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LHCP 2020,
8th annual conference on Large Hadron Collider Physics
May 25 - 30, 2020

$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$
$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ Y H \bar{\Psi} \Psi$$

Flavor in the Standard Model and Beyond

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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SM flavor puzzle

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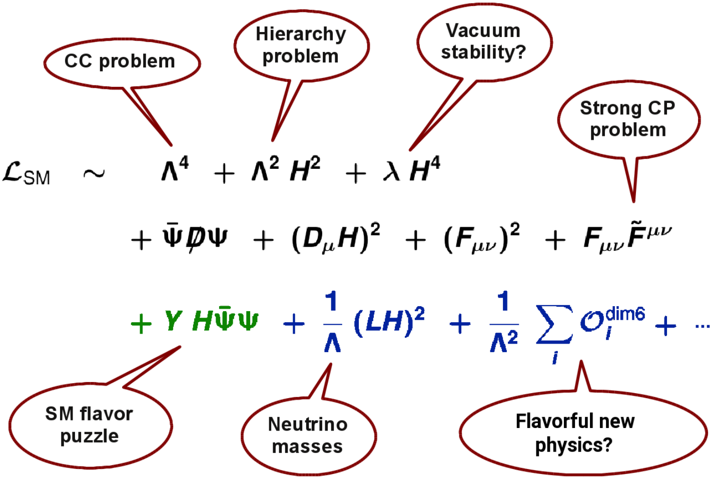
$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}} + \ldots$$

SM flavor puzzle

Neutrino masses

Flavorful new physics?

Flavor in the Standard Model and Beyond



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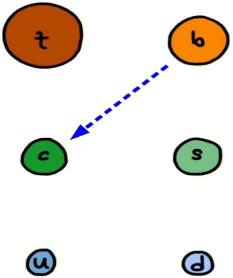
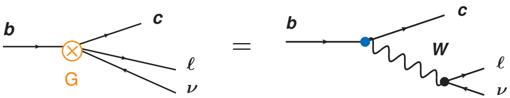
Q1: What is the origin of the hierarchies in the SM sources of flavor violation?

Q2: Are there other sources of flavor violation beyond the SM?

In the Standard Model, flavor changing charged currents arise at the tree level;
rates are suppressed by small CKM elements





$G \sim G_F V_{cb}$

Flavor Changing Processes in the SM

In the Standard Model, flavor changing charged currents arise at the tree level;
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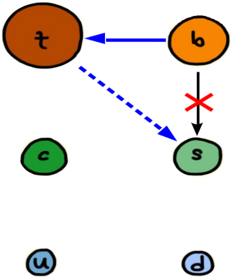
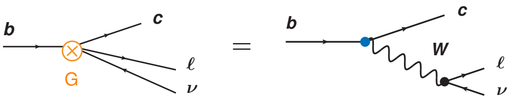
Flavor changing neutral currents can arise at the loop level; they are suppressed by loop factors and small CKM elements





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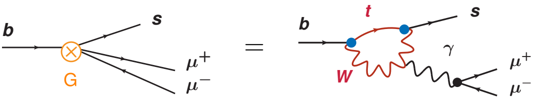
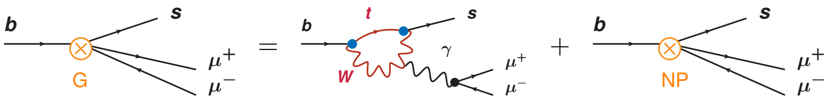


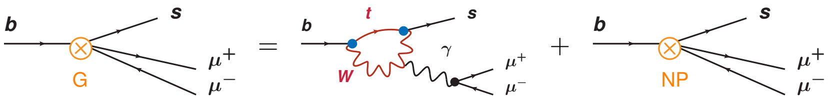
$$G \sim \frac{e^2}{16\pi^2} G_F \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^*$$

New Physics in Flavor Changing Processes



$$G \sim \frac{e^2}{16\pi^2} G_F \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely	**calculate precisely the SM contribution**	**get information on NP coupling and scale**



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"Anomalies" in flavor observales could establish
a new scale in particle physics

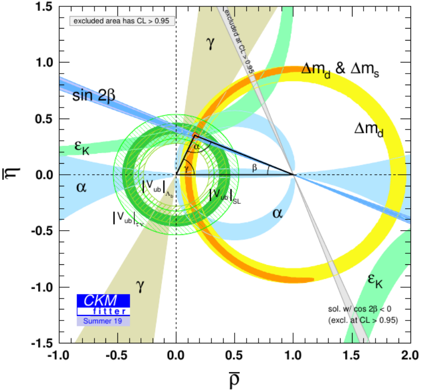
CKM Metrology

Wolfenstein parameterization

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{us}|^2 + |V_{ud}|^2}$$

$$A^2\lambda^2 = \frac{|V_{cb}|^2}{|V_{us}|^2 + |V_{ud}|^2}$$

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



ckmfitter.in2p3.fr (also utfit.org)

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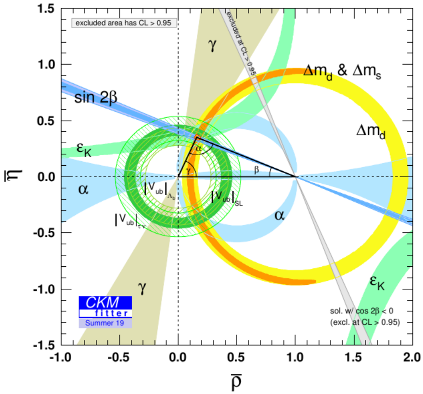
$$\lambda = 0.22484^{+0.00025}_{-0.00006}$$

$$A = 0.823^{+0.005}_{-0.014}$$

$$\bar\rho = 0.157^{+0.010}_{-0.006}$$

$$\bar\eta = 0.350^{+0.008}_{-0.007}$$



ckmfitter.in2p3.fr (also utfit.org)

Overall very good agreement among all measurements.

(Some tensions: $V_{cb}^{\text{excl.}}$ vs. $V_{cb}^{\text{incl.}}$, $V_{ub}^{\text{excl.}}$ vs. $V_{ub}^{\text{incl.}}$)

Recent Theory Improvement

CP violation in Kaon mixing (ϵ_K) is an important input to the CKM fits but is hard to predict precisely

Rearrangement of the perturbative series leads to a significant improvement (factor of 3!) of the perturbative uncertainty in ϵ_K

(Brod, Gorbahn, Stamou 1911.06822)

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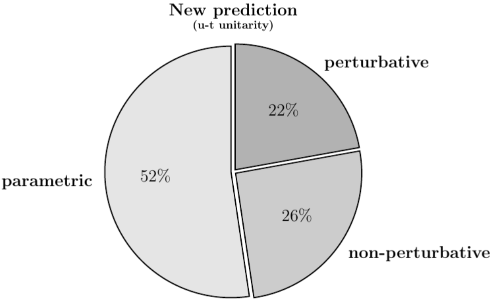
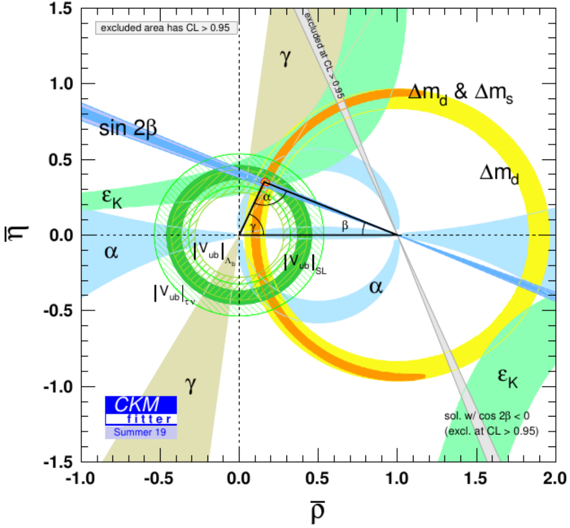


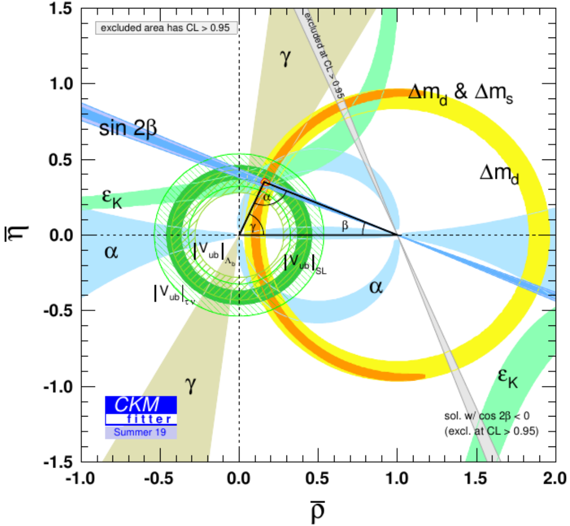
$$|\epsilon_K^{\text{SM}}| = 2.16(18) \times 10^{-3}$$

$$|\epsilon_K^{\text{exp.}}| = 2.228(11) \times 10^{-3}$$



old theory treatment

Impact on the CKM Fit



new theory treatment

visible improvement of the ϵ_K constraint

B Physics Anomalies

Theory Predictions for B Decays

SM predictions for b hadron decays require non-perturbative input

1. form factors ($\rightarrow$ lattice QCD, light-cone sum rules)
2. non-factorizable effects (sometimes only estimates exist)

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clever way to reduce/eliminate hadronic uncertainties:
lepton flavor universality (LFU) tests

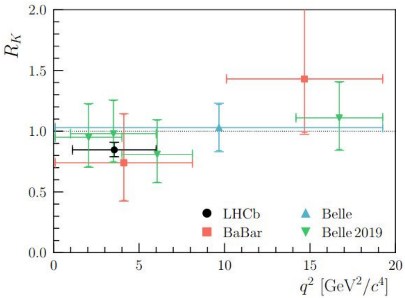
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

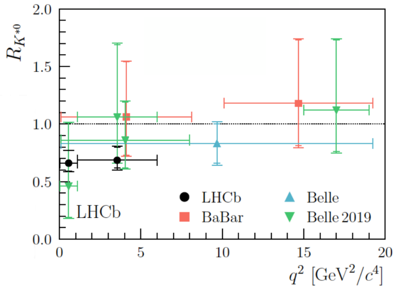
LFU ratios of
charged current decays

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

LFU ratios of
neutral current decays

R_K and R_{K^*}: Experimental Situation





$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

$$R_K^{[1,6]} = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

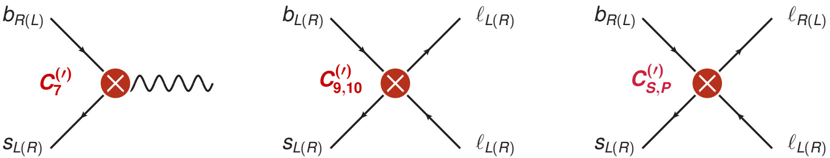
3 observables
deviating by $\sim 2\sigma - 2.5\sigma$
from the SM predictions $R \simeq 1$

also: $R_{pK}^{[0.1,6]} = 0.86^{+0.14}_{-0.11} \pm 0.05$

Model Independent New Physics Analysis

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators | semileptonic operators | scalar operators



$$C_7^{(\prime)} (\bar s \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar s \gamma_\mu P_{L(R)} b)(\bar\ell \gamma^\mu \ell) \quad , \quad C_S^{(\prime)} (\bar s P_{R(L)} b)(\bar\ell P_{L(R)} \ell)$$

$$C_{10}^{(\prime)} (\bar s \gamma_\mu P_{L(R)} b)(\bar\ell \gamma^\mu \gamma_5 \ell)$$

Fits to Wilson Coefficients

suppress the muon rate with $C_9^\mu < 0$ or $C_{10}^\mu > 0$
or enhance the electron rate with $C_9^e > 0$ or $C_{10}^e < 0$
(or linear combinations)

	LFUV		
1D Hyp.	$1\,\sigma$	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	$[-1.25, -0.61]$	3.3	60.7 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	$[-0.50, -0.28]$	3.7	75.3 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}$	$[-2.15, -1.05]$	3.1	53.1 %

(Sebastien Descotes-Genon @ Beyond the Flavour Anomalies workshop April 1, 2020)

many groups perform such fits:

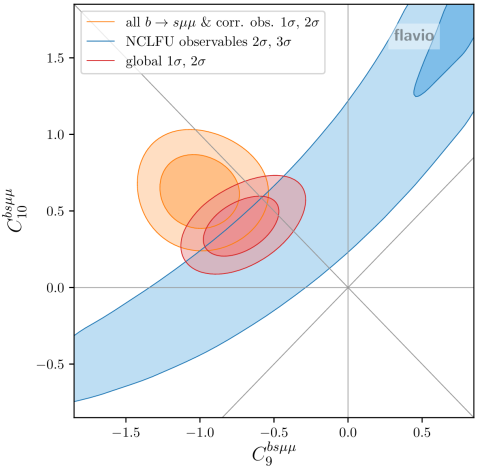
Aebischer, WA, Guadagnoli, Reboud, Stangl, Straub 1903.10434

Alguero et al. 1903.09578, Ciuchini et al., 1903.09632, Kowalska et al., 1903.10932,

Datta et al., 1903.10086, Arbey et al., 1904.08399

(+ many others, apologies for the omission...)

Compatibility with Other $b \to s\mu\mu$ Anomalies



(Peter Stangl @ Beyond the Flavour Anomalies workshop April 1, 2020; update of 1903.10434)

the LFU observables are fully compatible with other anomalies that are seen in $b \to s\mu\mu$ transitions ("P_5' and friends")

Sufficient to describe all $b \to s\ell\ell$ anomalies:

new physics in final states with muons

$$C_9^\mu (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

+SM-like final states with electrons

Implications for the New Physics Scale

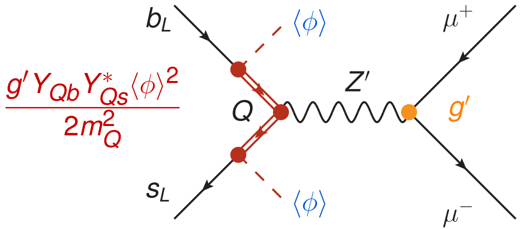
unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 120~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$

(MFV = Minimal Flavor Violation)

My Favorite Model

Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
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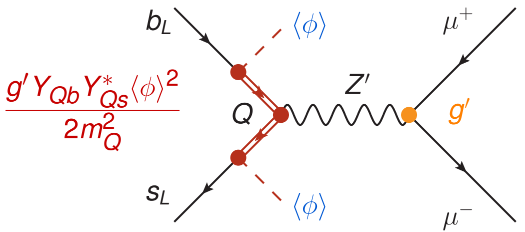

predicted Lepton Universality Violation!

predicts absence of Lepton Flavor Violation

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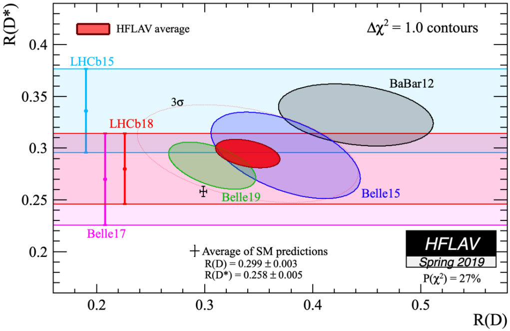
ϕ: scalar that breaks $L_\mu - L_\tau$

see also recent extension of the model that includes flavor universal axial vector currents

WA, Davighi, Nardecchia 1909.02021

R_D and R_{D^*}: Experimental Situation

world average from the heavy flavor averaging group



$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

$\ell = \mu, e$ (BaBar/Belle)

$\ell = \mu$ (LHCb)

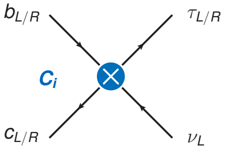
$$R_D^{\text{exp}} = 0.340 \pm 0.027 \pm 0.013 \ , \qquad R_{D^*}^{\text{exp}} = 0.295 \pm 0.011 \pm 0.008$$

$$R_D^{\text{SM}} = 0.299 \pm 0.003 \ , \qquad R_{D^*}^{\text{SM}} = 0.258 \pm 0.005$$

discrepancy with the SM by $\sim 3.1\sigma$

Model Independent New Physics Analysis

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i$$



$\mathcal{O}_i$ = contact interactions
with vector, scalar
or tensor currents

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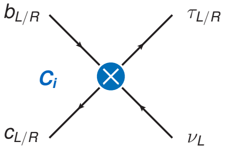
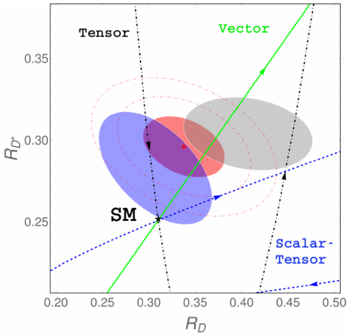


$\mathcal{O}_i$ = contact interactions with vector, scalar or tensor currents

rescaling of the SM vector operator fits the data best

combinations of operators are also possible

Shi et al. 1905.08498



(also Murgui et al. 1904.09311, Asadi, Shih 1905.03311, Cheung et al. 2002.07272, ...)

Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 8.4$ TeV
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 2.4$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{cb}\, (\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 0.5$ TeV

(MFV = Minimal Flavor Violation)

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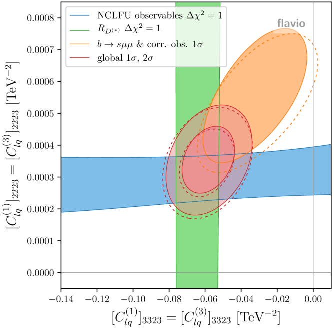
(MFV = Minimal Flavor Violation)

rather low scale $\rightarrow$ model building is non-trivial

(Peter Stangl; update of 1903.10434)



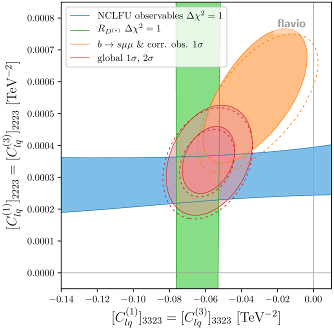
model independent EFT approach:

two new physics parameters describe consistently a dozen $(2-3)\sigma$ discrepancies

remarkable!

Combined Explanations of All B Anomalies

(Peter Stangl; update of 1903.10434)



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remarkable!

- operators point to leptoquarks with masses of few TeV (at most)
- could be the remnant of an extended gauge group: "4321 models", (Pati-Salam)^3 models Di Luzio et al. 1708.08450; Bordone et al. 1712.01368, ...

  (see talk by Admir Greljo in Tuesday's flavor parallel session)
- also attempts with RPV SUSY

  Deshpande, He, 1608.04817; WA, Dev, Soni 1704.06659; Earl, Gregoire 1806.01343; Trifinopoulos 1807.01638; WA, Dev, Soni, Sui 2002.12910; ...

Rare Kaon Decays

SM Predictions for $K \to \pi\nu\bar{\nu}$

- Rare Kaon decays can be predicted with high theoretical accuracy (uncertainties are almost entirely parametric)

$$\text{BR}(K^+ \to \pi^+\nu\bar{\nu})_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}$$

$$\text{BR}(K_L \to \pi^0\nu\bar{\nu})_{\text{SM}} = (3.4 \pm 0.6) \times 10^{-11}$$

(Brod, Gorbahn, Stamou 1009.0947; Buras et al. 1503.02693)

- Grossman-Nir bound (hep-ph/9701313)

$$\text{BR}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3 \times \text{BR}(K^+ \to \pi^+\nu\bar{\nu})$$

holds in the SM and scenarios with heavy new physics (isospin)

- decays are searched for at NA62 and at KOTO

K^+ @CERN

K_L @J-PARC

Experimental Situation

- few events seen at NA62

$$\text{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{exp.}} = \left(4.7^{+7.9}_{-4.7}\right) \times 10^{-11}$$

(preliminary NA62 result, Ruggiero @ Kaon 2019)

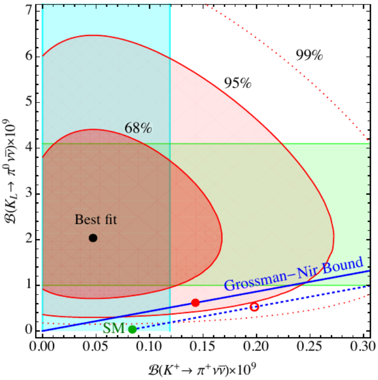
- In a preliminary analysis, KOTO saw events in the signal region
(Shinohara @ Kaon 2019)

$$\text{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\text{exp.}} = \left(210^{+200}_{-110}\right) \times 10^{-11}$$

(Not an official KOTO number! Theorist estimate from 1909.11111 interpreting 3 events as signal.)

Get the facts about KOTO from Augusto's talk

Kitahara et al. 1909.11111



in this interpretation $K_L \to \pi^0 \nu\bar{\nu}$ exceeds the SM rate by almost 2 orders of magnitude, and is incompatible with the Grossman-Nir bound ?!

A Sign of Light New Physics?

The Grossman-Nir bound can be violated in the presence of light new states (gives the possibility to play with kinematics)

simplest example:

(Fuyuto, Hou, Kohda 1412.4397)

introduce a light, very feebly interacting, long lived new physics particle X and look at $K \to \pi X$

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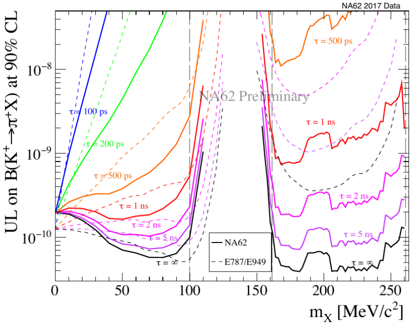
introduce a light, very feebly interacting, long lived new physics particle X and look at $K \to \pi X$

NA62 has a blind spot for $m_X \sim m_\pi$ but not KOTO



Roberta Volpe @ Pheno2020

Invites speculations about possible new physics origin of KOTO events

(Kitahara et al. 1909.11111; Egana-Ugrinovic et al. 1911.10203; Dev et al. 1911.12334
Jho et al. 2001.06572; Liu et al. 2001.06522; He et al. 2002.05467; Ziegler et al. 2005.00451
Liao et al. 2005.00753; Gori et al. 2005.05170; Hostert et al. 2005.07102; Datta et al. 2005.08920)

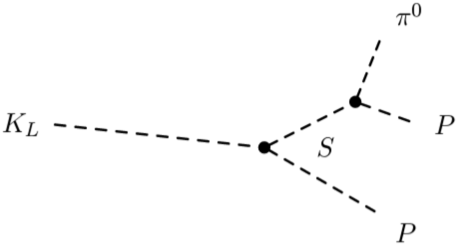
FIMPs at KOTO

Consider a model from Hostert, Kaneta, Pospelov 2005.07102

two light scalars, S and P, with masses of O(100 MeV) and couplings that lead to

$K_L \to SP$, $S \to \pi^0 P$

P is stable and leaves undetected



no corresponding decay chain exists for charged Kaons
$\to$ signal at KOTO but not at NA62

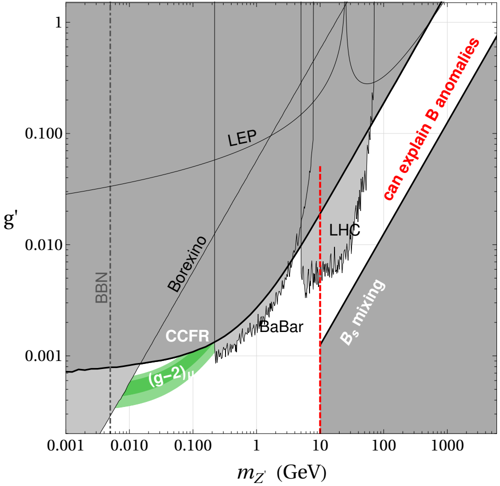
P is a natural dark matter candidate. Can be produced through freeze-in if the reheating temperature is low enough. WA, Lehmann, Profumo, in preparation

Summary

- Flavor Physics provides an indirect way to probe New Physics, complementary to direct searches.
- The B anomalies endure. If it is New Physics, it is not far above the TeV scale: Z' bosons? Leptoquarks?
- Rare Kaon decays can probe light dark sectors. First hints at KOTO?

Back Up

Viable Z' Parameter Space ($L_\mu - L_\tau$ Model)



Most important constraints from

$B_s - \bar{B}_s$ oscillations

neutrino tridents

WA, Gori, Pospelov, Yavin 1406.2332;

WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765

direct searches

CMS 1808.03684

$Z \to 2\mu Z' \to 4\mu$