Dark Flavored Sector possible searches in Belle II
From Heidelberg Workshop

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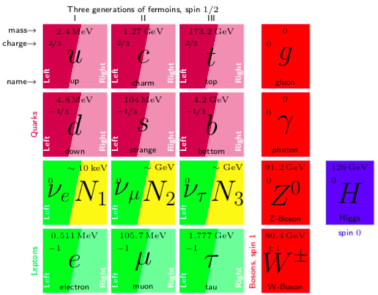
Many complex models trying to explain:

- Neutrino masses;
- Matter - antimatter asymmetry;
- Dark matter.

Particle contents of the νMSM



[T.Asaka, M.Shaposhnikov PLB 620 (2005) 17]

→ neutrino-minimal SM

- addition of **3 right-handed (i.e. sterile) massive neutrinos**
  - low LH ν masses generated via See-Saw mechanism:

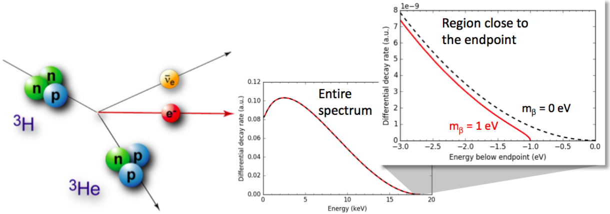
$$m_\nu \sim \frac{m_D^2}{M}$$

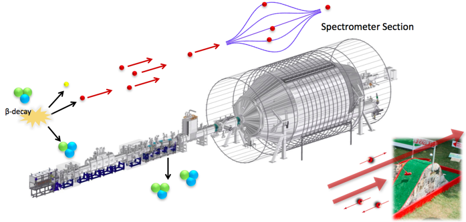
- **N_1** : keV mass range
  - long-lived
  - dark matter candidate
- **$N_{2,3}$** : GeV mass range
  - short-lived
  - nearly degenerate masses
  - baryon asymmetry via leptogenesis & sphalerons

Dominant N decay modes for $m_N < 500$ MeV:
$N \to \pi^0\nu$, $N \to \pi\mu$, $N \to \pi e^-$, $N \to \nu\nu\nu$.
Search for the heaviest new neutrino ($N_{2,3}$, aka "4th" neutrino):

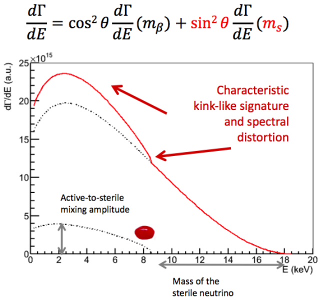
- $K \to lN$, $K \to \pi^0 lN$ ($l = \mu, e$).
  $\Gamma(K \to lN) = \Gamma(K \to l\nu_l) \cdot kinematic \cdot |U_{l4}|^2$
- HNL production + decay:
  - $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$, LNV (basically no SM bkg);
  - $K^\pm \to \pi^\pm\mu^+\mu^-$, LNC: di-muon resonance search.
    Main bkg: $K^\pm \to \pi^\pm\pi^-\pi^+$.
- HNL production:
  - $K^+ \to \mu^+ N$, looking to **missing mass** in $300 \div 375$ MeV;
  - $K^+ \to e^+ N$, looking to **missing mass** in $170 \div 448$ MeV.

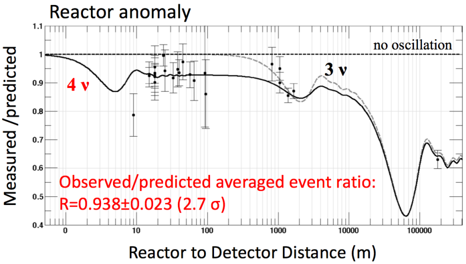
Katrin wants to directly measure neutrino mass through spectrum distortion in β decay (electric field acts as filter):





Flavor eigenstates $\neq$ mass eigenstates $\Rightarrow m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu_i}^2$. The existence of a 4th sterile neutrino could be deduced by further distortion in the spectrum: "automatic" if $m_{\nu_S} = O(\text{eV})$, otherwise a new dedicated detector is needed (Tristan).

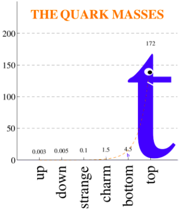




SOX would have been able to solve this doubt, but...

Axion, Axiflavon, ALP
Motivations

Hierarchies problem: quark and lepton masses are highly hierarchical; CKM too:



$$V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.23$$

Non-violation of CP by Strong Interaction seems to be a fine-tuning problem that can be solved introducing an ad hoc particle (Peccei-Quinn Axion):

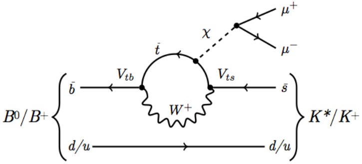
$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right) q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a \qquad \left(\tilde{G}_{\mu\nu}^a = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} G^{a,\rho\sigma}\right)$$

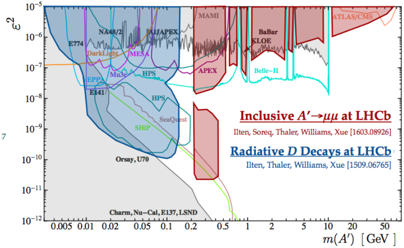
Axion, Axiflavon, ALP

Axion-Like Particles (ALP), 1/3

An ALP is any pseudoscalar neutral massive particle. Possible searches:

- $B \to KA$ (almost like my analysis: in my case $A \to \gamma\gamma$);
- $K \to \pi A$;
- $b \to sA$, $A \to \mu^+\mu^-$:



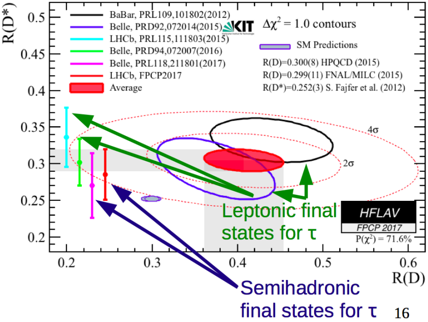


B decay mode with invisible particle(s) in final state:

- $B \to h^{(*)}X$, X invisible:
  - semileptonic tag-side and hadronic tag-side;
  - select $h^{(*)}$ in a certain momentum range, taking in account $B \to h^{(*)}\nu\nu$ expectation;
  - veto any additional track.
- $B^+ \to l^+\nu$, $l = \tau, \mu, e$:
  - due to helicity suppression, τ branching fraction is the highest;
  - on the other hand τ decays early in neutrinos, therefore imprecise momentum knowledge.
- $B \to D^*\tau\nu$:

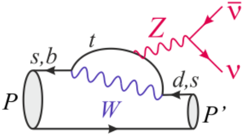
B decay mode with invisible particle(s) in final state:

- $B \to D^* \tau \nu$: 4σ discrepancy between world average and SM prediction:



At full luminosity we could be overwhelmed with bkg, so for this kind of low-multiplicity & tracking-vetoing analysis, Phase 2 data could be far more valuable than Phase 3's!

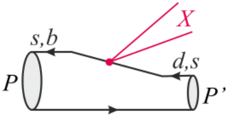
Some of the cleanest FCNC-induced decays produce neutrinos:



$P = B, K, \pi, \ldots$

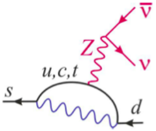
But neutrinos are undetected, only missing energy is reconstructed.

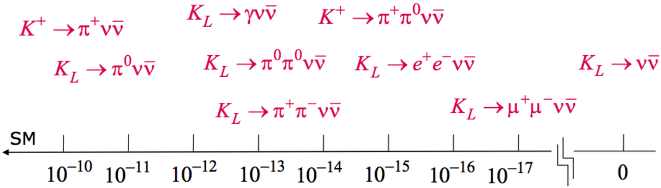
Could there be something else? Some new dark state X?

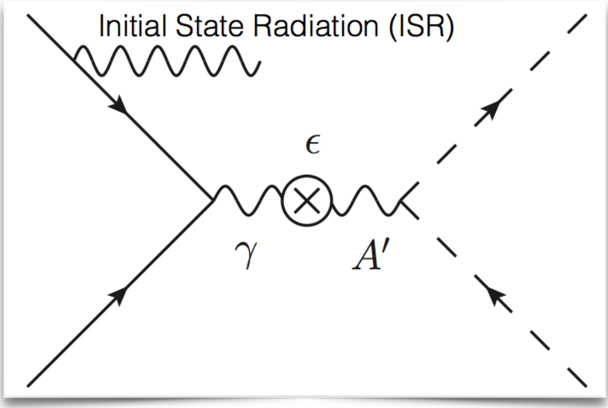


Dark Sector
FCNC, 2/2

	SM ($\times 10^{-11}$)	Experiment	
$K_L \to \pi^0 \nu\bar{\nu}$	$2.57^{+0.37}_{-0.37}$	$< 2.6 \cdot 10^{-8}$	E391a
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	$8.22^{+0.75}_{-0.75}$	$17.3^{+11.5}_{-10.5} \cdot 10^{-11}$	E787 E949

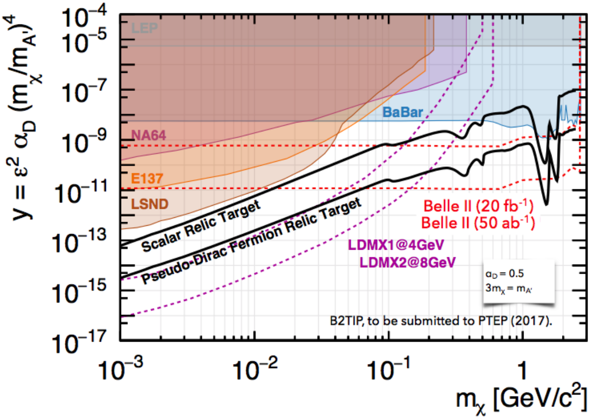






SM leptons
or
Dark Matter

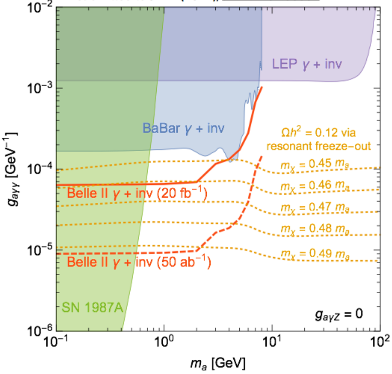
Belle II: Dark Photons to invisible (``Single photon search'')



Belle II: ALPs decaying into Dark Matter

- ALP decays can be invisible because the ALP decays outside of the detector or because the ALP decays into an invisible final state: Dark Matter.
- We re-interpreted BaBar's Dark Photon analysis in terms of ALPs decaying into Dark Matter.
- We studied the Belle II sensitivity for ALPs decaying into Dark Matter.

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP (2017), arXiv:1709.00009

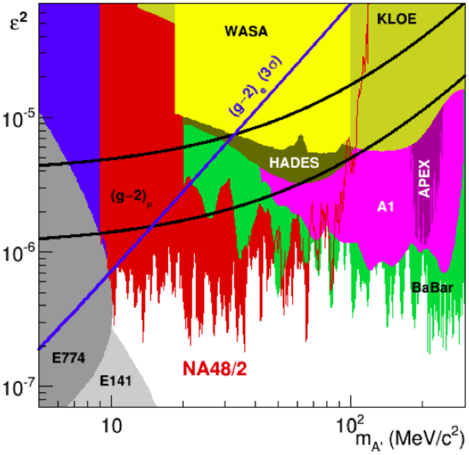


Belle II: Other planned Dark Sector and exotic searches

- Search for Dark Photons decaying into pseudo-Dirac DM: ***
  - $A' \to \chi_1 \chi_2$, $\chi_2 \to \chi_1 A'$, $A' \to e^+e^-$.
- Off-shell A′ decays. ***
- Long-lived neutral particle decays.
- Visible Dark Photon decays.
- Dark Scalar: $e^+e^- \to \tau^+\tau^- S$, $S \to \ell^+\ell^-$
- Magnetic monopoles with small magnetic charges. ***
- Invisible $\Upsilon(1S)$ decays via $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ (Requires beam energies at $\Upsilon(3S)$).
- Muonic Dark Force:
  - $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$
  - $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ Invisible ***
- Dark Higgs
- ...

*** Possible during Phase 2 (2018 data)

$$\pi^0 \to \gamma A',\ A' \to e^+ e^-$$



Flavor Violation

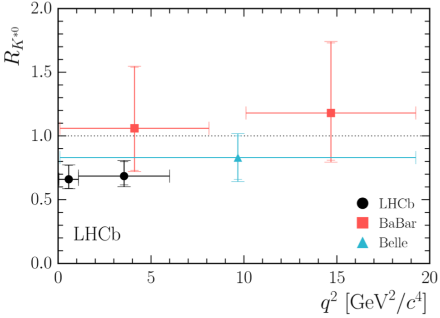
Possible investigated Lepton Flavor Violation processes:

- $\mu \to 3e$: Current limit: $BR(\mu \to 3e) < 1.0 \times 10^{-12} (90\% CL)$.
- $\mu \to e\gamma$: $BR(\mu \to e\gamma) \sim 10^{-54}$

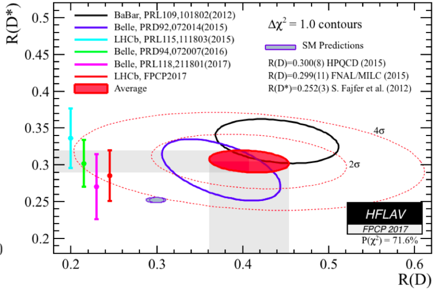
B anomalies

- From angular analysis of $B^0 \to K^{0^*} \mu\mu$ it comes out an anomaly in the P_5' form factor (seen by both LHCb and Belle);
- Differences in branching fractions for $b \to sll$ processes, particularly at low q^2;
- There are $2 \div 3\sigma$ differences between data and theory for the following ratios of branching fractions (where due to the ratio any hadronic uncertainties should rule out):
  - $R_{K^{+/0*}} = \frac{BR(B^{+/0} \to K^{+/0^*} \mu^+ \mu^-)}{BR(B^{+/0} \to K^{+/0^*} e^+ e^-)}$;
  - $R_{D^*} = \frac{BR(B^0 \to D^{+^*} \nu_\tau \tau^-)}{BR(B^0 \to D^{+^*} \nu_\mu \mu^-)}$.

B anomalies



$R_{K^{*0}}$
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
q^2 [GeV$^2/c^4$]
LHCb
LHCb
BaBar
Belle



R(D*)
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
$\Delta\chi^2$ = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
P(χ^2) = 71.6%