Just a taste: hints of new physics in **flavour** observables

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LPC Seminar

Based on: JHEP 12 (2019) 006, JHEP 07 (2020) 235 and arXiv:2012.05883 with C. Hati, J. Orloff and A. M. Teixeira

26 February 2021

1. Introduction
2. Heavy flavours: tales from the terascale
3. Flavour (de)*light*: anomalous magnetic moments
4. Summary

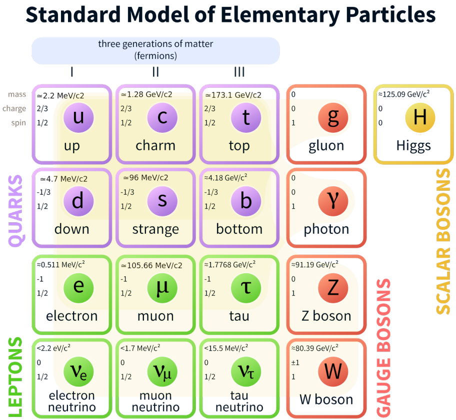
Introduction

Introduction

- Highly successful theory describing fundamental particles and their interactions
- Based on gauge symmetries:

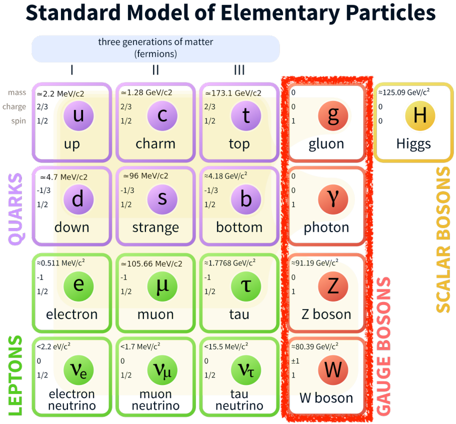
$$\mathcal{G}_{\text{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Completed by the discovery of the Higgs-boson in 2012



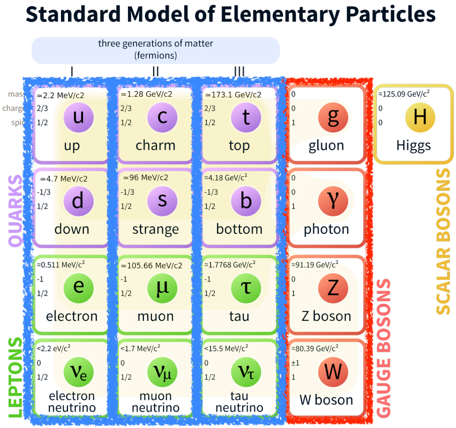
Flavour Physics

- In SM, force carriers



Flavour Physics

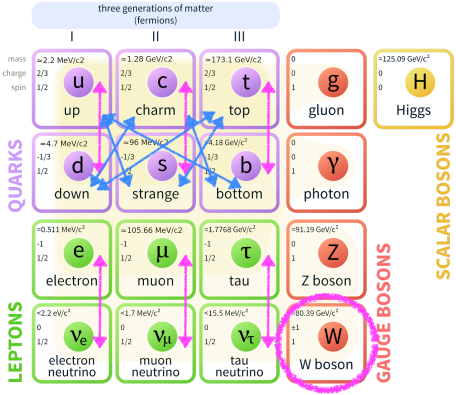
- In SM, force carriers and 3 generations of matter



Flavour Physics

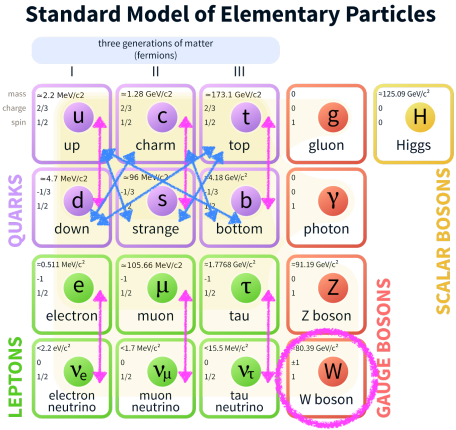
- In SM, force carriers and 3 generations of matter
- **Quark** sector: Higgs mechanism responsible for quark masses and **quark** flavour mixing

Standard Model of Elementary Particles



Flavour Physics

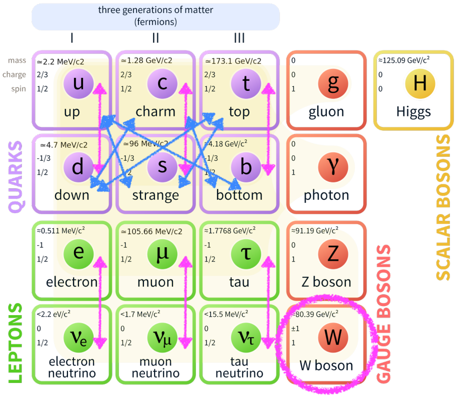
- In SM, force carriers and 3 generations of matter
- **Quark** sector: Higgs mechanism responsible for quark masses and **quark** flavour mixing
- Unitary **CKM** matrix $\Rightarrow$ no flavour changing neutral current (**FCNC**) at *tree*-level



Flavour Physics

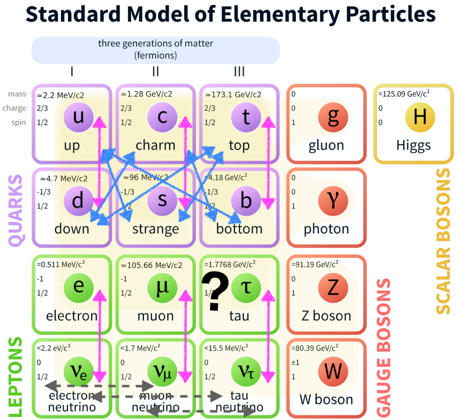
- In SM, force carriers and 3 generations of matter
- **Quark** sector: Higgs mechanism responsible for quark masses and **quark** flavour mixing
- Unitary **CKM** matrix ⇒ no flavour changing neutral current (**FCNC**) at *tree*-level
- **Lepton** sector: vanishing ν-masses ⇒ *accidental* lepton flavour conservation

Standard Model of Elementary Particles



Flavour Physics

- In SM, force carriers and 3 generations of matter
- **Quark** sector: Higgs mechanism responsible for quark masses and **quark** flavour mixing
- Unitary **CKM** matrix $\Rightarrow$ no flavour changing neutral current (**FCNC**) at *tree*-level
- **Lepton** sector: vanishing $\boldsymbol{\nu}$-masses $\Rightarrow$ *accidental* lepton flavour conservation
- **BUT:** ν oscillate, thus have (*tiny*) masses $\Rightarrow$ explaining ν oscillations opens the door to lepton flavour violation (**LFV**)!

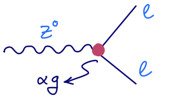


Lepton flavour universality

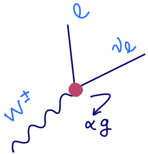
Only difference between leptons is their masses:

$$m_e \sim 511\,\text{keV}, \quad m_\mu \sim 105\,\text{MeV}, \quad m_\tau \sim 1.7\,\text{GeV}$$

Accidental "symmetry" in the SM: couplings of electroweak gauge bosons are *"blind"* to lepton **flavour** $\Rightarrow$ **Lepton Flavour Universality** (**LFU**)



W^+ **DECAY MODES**		Fraction (Γ_i/Γ)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %
$e^+\nu$		(10.71 ± 0.16) %
$\mu^+\nu$		(10.63 ± 0.15) %
$\tau^+\nu$		(11.38 ± 0.21) %
hadrons		(67.41 ± 0.27) %
Z **DECAY MODES**		Fraction (Γ_i/Γ)
e^+e^-	[h]	(3.3632 ± 0.0042) %
$\mu^+\mu^-$	[h]	(3.3662 ± 0.0066) %
$\tau^+\tau^-$	[h]	(3.3696 ± 0.0083) %
$\ell^+\ell^-$	[b,h]	(3.3658 ± 0.0023) %

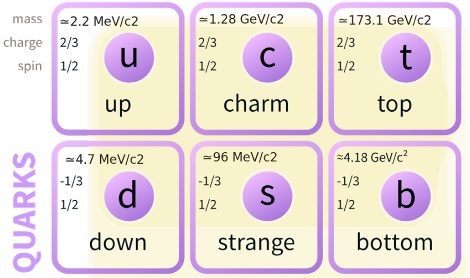


[PDG 2020]

$\Rightarrow$ **BUT:** current measurements in semi-leptonic $\boldsymbol{B}$-meson decays and low energy precision observables appear to tell a different story!

Hadrons

QCD bound states of quarks: Baryons $\sim$ 3 quarks, Mesons $\sim$ 1 quark, 1 anti-quark



Hadrons

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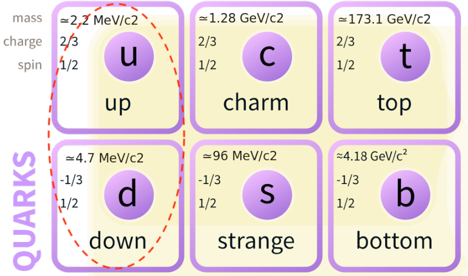
- Proton $|p\rangle \sim |uud\rangle$,
  neutron $|n\rangle \sim |udd\rangle$,
  pions $|\pi^0\rangle \sim \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}}$, $|\pi^+\rangle \sim |u\bar{d}\rangle$



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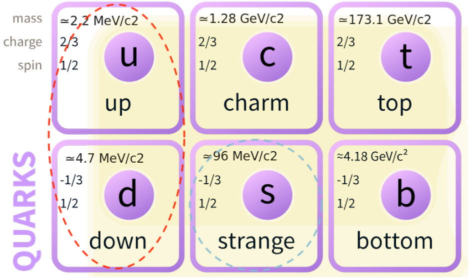
$\Rightarrow$ *K*aons: $|K^0\rangle \sim |\bar{s}d\rangle$, $|K^+\rangle \sim |\bar{s}u\rangle$



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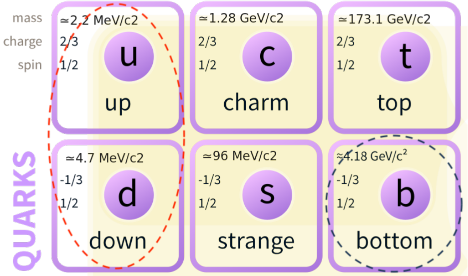
$\Rightarrow$ ***K*** aons: $|K^0\rangle \sim |\bar{s}d\rangle$, $|K^+\rangle \sim |\bar{s}u\rangle$

$\Rightarrow$ ***B*** mesons: $|B^0\rangle \sim |\bar{b}d\rangle$, $|B^+\rangle \sim |\bar{b}u\rangle$



Hadrons

QCD bound states of quarks: Baryons $\sim$ 3 quarks, Mesons $\sim$ 1 quark, 1 anti-quark

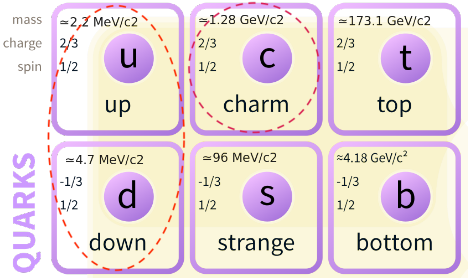
- Proton $|p\rangle \sim |uud\rangle$, neutron $|n\rangle \sim |udd\rangle$, pions $|\pi^0\rangle \sim \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}}$, $|\pi^+\rangle \sim |u\bar{d}\rangle$

$\Rightarrow$ ***K***aons: $|K^0\rangle \sim |\bar{s}d\rangle$, $|K^+\rangle \sim |\bar{s}u\rangle$

$\Rightarrow$ ***B*** mesons: $|B^0\rangle \sim |\bar{b}d\rangle$, $|B^+\rangle \sim |\bar{b}u\rangle$

$\Rightarrow$ ***D*** mesons: $|D^0\rangle \sim |\bar{c}u\rangle$, $|D^-\rangle \sim |\bar{c}d\rangle$

- Heavy flavours: hadrons involving ***b*** or ***c*** quarks
- (**top** quark does not hadronise, it decays before a bound state can be formed)



Heavy flavours: tales from the terascale

B-meson decays I

B-mesons offer powerful **probes of the SM** and hints of **new physics**:

- **Theoretically** "clean(ish)" - due to large mass of b-quark, certain theoretical approximations apply and precise predictions are possible
- **Experimentally** accessible - mostly produced in forward region (design of LHCb), hundreds of decay channels to explore
- Exciting **future programme** (LHCb, Belle II, ...)
- **Charged** current B-decays used to measure **CKM** parameters (e.g. $|V_{cb}|, |V_{ub}|, \gamma$)
- B and B_s-meson oscillations offer insight on CP violation in the SM
- Due to extremely low SM background, rare **FCNC** B-meson decays are powerful **probes of new physics**

B-meson decays I

B-mesons offer powerful … cs:

- **Theoretically** "clean(… n theoretical approximations apply …
- **Experimentally** acce… design of LHCb), hundreds of decay ch…
- Exciting **future progr**…
- **Charged** current B-d… .g. $|V_{cb}|, |V_{ub}|, \gamma$)
- B and B_s-meson osc… SM
- Due to extremely low … ays are powerful **probes of new physi**…

B^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$\ell^+ \nu_\ell X$	[lll]	(10.99 ± 0.28) %		–
$e^+ \nu_e X_c$		(10.8 ± 0.4) %		–
$D \ell^+ \nu_\ell X$		(9.7 ± 0.7) %		–
$\overline{D}^0 \ell^+ \nu_\ell$	[lll]	(2.35 ± 0.09) %		2310
$\overline{D}^0 \tau^+ \nu_\tau$		(7.7 ± 2.5) $\times 10^{-3}$		1911
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[lll]	(5.66 ± 0.22) %		2258
$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		(1.88 ± 0.20) %		1839
$D^- \pi^+ \ell^+ \nu_\ell$		(4.4 ± 0.4) $\times 10^{-3}$		2306
$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_0^{*0} \to D^- \pi^+$		(2.5 ± 0.5) $\times 10^{-3}$		–
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^- \pi^+$		(1.53 ± 0.16) $\times 10^{-3}$		2065
$D^{(*)} n\pi \ell^+ \nu_\ell (n \geq 1)$		(1.88 ± 0.25) %		–
$D^{*-} \pi^+ \ell^+ \nu_\ell$		(6.0 ± 0.4) $\times 10^{-3}$		2254
$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_1^0 \to D^{*-} \pi^+$		(3.03 ± 0.20) $\times 10^{-3}$		2084
$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell$, $\overline{D}_1'^0 \to D^{*-} \pi^+$		(2.7 ± 0.6) $\times 10^{-3}$		–
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^{*-} \pi^+$		(1.01 ± 0.24) $\times 10^{-3}$	S=2.0	2065
$\overline{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$		(1.7 ± 0.4) $\times 10^{-3}$		2301
$\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$		(8 ± 5) $\times 10^{-4}$		2248
$D_s^{(*)-} K^+ \ell^+ \nu_\ell$		(6.1 ± 1.0) $\times 10^{-4}$		–
$D_s^- K^+ \ell^+ \nu_\ell$		(3.0 $^{+1.4}_{-1.2}$) $\times 10^{-4}$		2242

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B-meson decays I

B-mesons offer powerful … cs:

… n theoretical

… design of LHCb),

… .g. $|V_{cb}|, |V_{ub}|, \gamma$)

… SM

… ays are powerful

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		$(8 \pm 5) \times 10^{-4}$		2248
		$(6.1 \pm 1.0) \times 10^{-4}$		–
		$(3.0 ^{+1.4}_{-1.2}) \times 10^{-4}$		2242

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$D_s^{*-} K^+ \ell^+ \nu_\ell$		$(2.9 \pm 1.9) \times 10^{-4}$		2185
$\pi^0 \ell^+ \nu_\ell$		$(7.80 \pm 0.27) \times 10^{-5}$		2638
$\eta \ell^+ \nu_\ell$		$(3.9 \pm 0.5) \times 10^{-5}$		2611
$\eta' \ell^+ \nu_\ell$		$(2.3 \pm 0.8) \times 10^{-5}$		2553
$\omega \ell^+ \nu_\ell$	[///]	$(1.19 \pm 0.09) \times 10^{-4}$		2582
$\rho^0 \ell^+ \nu_\ell$	[///]	$(1.58 \pm 0.11) \times 10^{-4}$		2583
$p \overline{p} \ell^+ \nu_\ell$		$(5.8 ^{+2.6}_{-2.3}) \times 10^{-6}$		2467
$p \overline{p} \mu^+ \nu_\mu$		$< 8.5 \times 10^{-6}$	CL=90%	2446
$p \overline{p} e^+ \nu_e$		$(8.2 ^{+4.0}_{-3.3}) \times 10^{-6}$		2467
$e^+ \nu_e$		$< 9.8 \times 10^{-7}$	CL=90%	2640
$\mu^+ \nu_\mu$		2.90×10^{-07} to 1.07×10^{-06}	CL=90%	2639
$\tau^+ \nu_\tau$		$(1.09 \pm 0.24) \times 10^{-4}$	S=1.2	2341
$\ell^+ \nu_\ell \gamma$		$< 3.0 \times 10^{-6}$	CL=90%	2640
$e^+ \nu_e \gamma$		$< 4.3 \times 10^{-6}$	CL=90%	2640
$\mu^+ \nu_\mu \gamma$		$< 3.4 \times 10^{-6}$	CL=90%	2639
$\mu^+ \mu^- \mu^+ \nu_\mu$		$< 1.6 \times 10^{-8}$	CL=95%	2634
Inclusive modes				
$D^0 X$		(8.6 ± 0.7) %		–
$\overline{D}^0 X$		(79 ± 4) %		–
$D^+ X$		(2.5 ± 0.5) %		–
$D^- X$		(9.9 ± 1.2) %		–
$D_s^+ X$		$(7.9 ^{+1.4}_{-1.3})$ %		–
$D_s^- X$		$(1.10 ^{+0.40}_{-0.32})$ %		–
$\Lambda_c^+ X$		$(2.1 ^{+0.9}_{-0.6})$ %		–
$\overline{\Lambda}_c^- X$		$(2.8 ^{+1.1}_{-0.9})$ %		–

B-meson decays I

B-mesons offer powerful

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Semileptonic and leptonic modes				
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$e^+ \nu_e X_c$		(10.8 ± 0.4) %		–
$D \ell^+ \nu_\ell X$		(9.7 ± 0.7) %		–
$\overline{D}^0 \ell^+ \nu_\ell$		[illegible]		[illegible]
$\overline{D}^0 \tau^+ \nu$		[illegible]		[illegible]

$D_s^{*-} K^+ \ell^+ \nu_\ell$		$(2.9 \pm 1.9) \times 10^{-4}$		2185
$\pi^0 \ell^+ \nu_\ell$		$(7.80 \pm 0.27) \times 10^{-5}$		2638
$\eta \ell^+ \nu_\ell$		$(3.9 \pm 0.5) \times 10^{-5}$		2611
$\eta' \ell^+ \nu_\ell$		$(2.3 \pm 0.8) \times 10^{-5}$		2553
$\omega \ell^+ \nu_\ell$	[lll]	$(1.19 \pm 0.09) \times 10^{-4}$		2582
$\rho^0 \ell^+ \nu_\ell$	[lll]	$(1.58 \pm 0.11) \times 10^{-4}$		2583
$p \overline{p} \ell^+ \nu_\ell$		$(5.8 \,^{+2.6}_{-2.3}) \times 10^{-6}$		2467
$p \overline{p} \mu^+ \nu_\mu$		$< 8.5 \times 10^{-6}$	CL=90%	2446
$p \overline{p} e^+ \nu_e$		$(8.2 \,^{+4.0}_{-3.3}) \times 10^{-6}$		2467
$e^+ \nu_e$		$< 9.8 \times 10^{-7}$	CL=90%	2640
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$\tau^+ \nu_\tau$		$(1.09 \pm 0.24) \times 10^{-4}$	S=1.2	2341
$\ell^+ \nu_\ell \gamma$		$< 3.0 \times 10^{-6}$	CL=90%	2640
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$\mu^+ \mu^- \mu^+ \nu_\mu$		$< 1.6 \times 10^{-8}$	CL=95%	2634
Inclusive modes				
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$\overline{D}^0 X$		(79 ± 4) %		–
$D^+ X$		(2.5 ± 0.5) %		–
$D^- X$		(9.9 ± 1.2) %		–
$D_s^+ X$		$(7.9 \,^{+1.4}_{-1.3})$ %		–
$D_s^- X$		$(1.10 \,^{+0.40}_{-0.32})$ %		–
$\Lambda_c^+ X$		$(2.1 \,^{+0.9}_{-0.6})$ %		–
$\overline{\Lambda}_c^- X$		$(2.8 \,^{+1.1}_{-0.9})$ %		–

$\pi^+ \ell^+ \ell^-$	B1		$< 4.9 \times 10^{-8}$	CL=90%	2638
$\pi^+ e^+ e^-$	B1		$< 8.0 \times 10^{-8}$	CL=90%	2638
$\pi^+ \mu^+ \mu^-$	B1		$(1.75 \pm 0.22) \times 10^{-8}$		2634
$\pi^+ \nu \overline{\nu}$	B1		$< 1.4 \times 10^{-5}$	CL=90%	2638
$K^+ \ell^+ \ell^-$	B1	[lll]	$(4.51 \pm 0.23) \times 10^{-7}$	S=1.1	2617
$K^+ e^+ e^-$	B1		$(5.5 \pm 0.7) \times 10^{-7}$		2617
$K^+ \mu^+ \mu^-$	B1		$(4.41 \pm 0.22) \times 10^{-7}$	S=1.2	2612
$K^+ \mu^+ \mu^-$ nonresonant	B1		$(4.37 \pm 0.27) \times 10^{-7}$		2612
$K^+ \tau^+ \tau^-$	B1		$< 2.25 \times 10^{-3}$	CL=90%	1687
$K^+ \overline{\nu} \nu$	B1		$< 1.6 \times 10^{-5}$	CL=90%	2617
$\rho^+ \nu \overline{\nu}$	B1		$< 3.0 \times 10^{-5}$	CL=90%	2583
$K^*(892)^+ \ell^+ \ell^-$	B1	[lll]	$(1.01 \pm 0.11) \times 10^{-6}$	S=1.1	2564
$K^*(892)^+ e^+ e^-$	B1		$(1.55 \,^{+0.40}_{-0.31}) \times 10^{-6}$		2564
$K^*(892)^+ \mu^+ \mu^-$	B1		$(9.6 \pm 1.0) \times 10^{-7}$		2560
$K^*(892)^+ \nu \overline{\nu}$	B1		$< 4.0 \times 10^{-5}$	CL=90%	2564
$K^+ \pi^+ \pi^- \mu^+ \mu^-$	B1		$(4.3 \pm 0.4) \times 10^{-7}$		2593
$\phi K^+ \mu^+ \mu^-$	B1		$(7.9 \,^{+2.1}_{-1.7}) \times 10^{-8}$		2490
$\overline{\Lambda} p \nu \overline{\nu}$			$< 3.0 \times 10^{-5}$	CL=90%	2430
$\pi^+ e^+ \mu^-$	LF		$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+ e^- \mu^+$	LF		$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+ e^\pm \mu^\mp$	LF		$< 1.7 \times 10^{-7}$	CL=90%	2637
$\pi^+ e^+ \tau^-$	LF		$< 7.4 \times 10^{-5}$	CL=90%	2338
$\pi^+ e^- \tau^+$	LF		$< 2.0 \times 10^{-5}$	CL=90%	2338
$\pi^+ e^\pm \tau^\mp$	LF		$< 7.5 \times 10^{-5}$	CL=90%	2338
$\pi^+ \mu^+ \tau^-$	LF		$< 6.2 \times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^- \tau^+$	LF		$< 4.5 \times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^\pm \tau^\mp$	LF		$< 7.2 \times 10^{-5}$	CL=90%	2333
$K^+ e^+ \mu^-$	LF		$< 7.0 \times 10^{-9}$	CL=90%	2615
$K^+ e^- \mu^+$	LF		$< 6.4 \times 10^{-9}$	CL=90%	2615

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Semileptonic and leptonic modes				
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$e^+ \nu_e X_c$		(10.8 ± 0.4) %		–
$D \ell^+ \nu_\ell X$		(9.7 ± 0.7) %		–
$\overline{D}^0 \ell^+ \nu_\ell$		[illegible]		
$\overline{D}^0 \tau^+ \nu_\tau$		[illegible]		

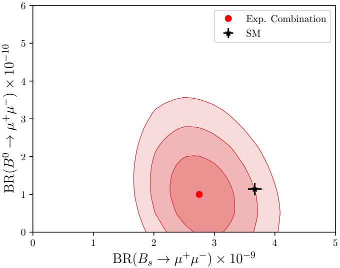
$D_s^{*-} K^+ \ell^+ \nu_\ell$		(2.9 ± 1.9) $\times 10^{-4}$		2185
$\pi^0 \ell^+ \nu_\ell$		(7.80 [illegible]		
$\eta \ell^+ \nu_\ell$		(3.9 [illegible]		
$\eta' \ell^+ \nu_\ell$		(2.3 [illegible]		
$\omega \ell^+ \nu_\ell$	[lll]	(1.19 [illegible]		
$\rho^0 \ell^+ \nu_\ell$	[lll]	(1.58 [illegible]		
$p \overline{p} \ell^+ \nu_\ell$		(5.8 [illegible]		
$p \overline{p} \mu^+ \nu_\mu$		< 8.5 [illegible]		
$p \overline{p} e^+ \nu_e$		(8.2 [illegible]		
$e^+ \nu_e$		< 9.8 $\times 10^{-[illegible]}$	CL=90%	2640
$\mu^+ \nu_\mu$		2.90×10^{-07} to 1.07×10^{-06}	CL=90%	2639
$\tau^+ \nu_\tau$		(1.09 ± 0.24) $\times 10^{-4}$	S=1.2	2341
$\ell^+ \nu_\ell \gamma$		< 3.0 $\times 10^{-6}$	CL=90%	2640
$e^+ \nu_e \gamma$		< 4.3 $\times 10^{-6}$	CL=90%	2640
$\mu^+ \nu_\mu \gamma$		< 3.4 $\times 10^{-6}$	CL=90%	2639
$\mu^+ \mu^- \mu^+ \nu_\mu$		< 1.6 $\times 10^{-8}$	CL=95%	2634
Inclusive modes				
$D^0 X$		(8.6 ± 0.7) %		–
$\overline{D}^0 X$		(79 ± 4) %		–
$D^+ X$		(2.5 ± 0.5) %		–
$D^- X$		(9.9 ± 1.2) %		–
$D_s^+ X$		(7.9 $^{+1.4}_{-1.3}$) %		–
$D_s^- X$		(1.10 $^{+0.40}_{-0.32}$) %		–
$\Lambda_c^+ X$		(2.1 $^{+0.9}_{-0.6}$) %		–
$\overline{\Lambda}_c^- X$		(2.8 $^{+1.1}_{-0.9}$) %		–

$\pi^+ \ell^+ \ell^-$	B1	< 4.9 $\times 10^{-8}$	CL=90%	2638
$\pi^+ e^+ e^-$	B1	< 8.0 $\times 10^{-8}$	CL=90%	2638
$\pi^+ \mu^+ \mu^-$	B1	(1.75 ± 0.22) $\times 10^{-8}$		2634
$\pi^+ \nu \overline{\nu}$	B1	< 1.4 $\times 10^{-5}$	CL=90%	2638
[illegible]	[illegible]	(4.51 ± 0.23) $\times 10^{-7}$	S=1.1	2617
[illegible]		(5.5 ± 0.7) $\times 10^{-7}$		2617
[illegible]		(4.41 ± 0.22) $\times 10^{-7}$	S=1.2	2612
[illegible]		(4.37 ± 0.27) $\times 10^{-7}$		2612
[illegible]		< 2.25 $\times 10^{-3}$	CL=90%	1687
[illegible]		< 1.6 $\times 10^{-5}$	CL=90%	2617
[illegible]		< 3.0 $\times 10^{-5}$	CL=90%	2583
[illegible]	[illegible]	(1.01 ± 0.11) $\times 10^{-6}$	S=1.1	2564
$K^*(892)^+ e^+ e^-$	B1	(1.55 $^{+0.40}_{-0.31}$) $\times 10^{-6}$		2564
$K^*(892)^+ \mu^+ \mu^-$	B1	(9.6 ± 1.0) $\times 10^{-7}$		2560
$K^*(892)^+ \nu \overline{\nu}$	B1	< 4.0 $\times 10^{-5}$	CL=90%	2564
$K^+ \pi^+ \pi^- \mu^+ \mu^-$	B1	(4.3 ± 0.4) $\times 10^{-7}$		2593
$\phi K^+ \mu^+ \mu^-$	B1	(7.9 $^{+2.1}_{-1.7}$) $\times 10^{-8}$		2490
$\overline{\Lambda} p \nu \overline{\nu}$		< 3.0 $\times 10^{-5}$	CL=90%	2430
$\pi^+ e^+ \mu^-$	LF	< 6.4 $\times 10^{-3}$	CL=90%	2637
$\pi^+ e^- \mu^+$	LF	< 6.4 $\times 10^{-3}$	CL=90%	2637
$\pi^+ e^\pm \mu^\mp$	LF	< 1.7 $\times 10^{-7}$	CL=90%	2637
$\pi^+ e^+ \tau^-$	LF	< 7.4 $\times 10^{-5}$	CL=90%	2338
$\pi^+ e^- \tau^+$	LF	< 2.0 $\times 10^{-5}$	CL=90%	2338
$\pi^+ e^\pm \tau^\mp$	LF	< 7.5 $\times 10^{-5}$	CL=90%	2338
$\pi^+ \mu^+ \tau^-$	LF	< 6.2 $\times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^- \tau^+$	LF	< 4.5 $\times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^\pm \tau^\mp$	LF	< 7.2 $\times 10^{-5}$	CL=90%	2333
$K^+ e^+ \mu^-$	LF	< 7.0 $\times 10^{-9}$	CL=90%	2615
$K^+ e^- \mu^+$	LF	< 6.4 $\times 10^{-9}$	CL=90%	2615

… and hundreds more, most in excellent agreement with SM!

B-meson decays II

For example $B_{(s)} \to \mu^+\mu^-$
Rare **FCNC** decays recently measured, in excellent agreement with SM predictions



Strongly constrains many (flavour changing) **BSM** constructions (e.g. SUSY)

If new physics contributes to flavour (violating) processes:

$\Rightarrow$No new flavour violating couplings (forcing it to higher order)

$\Rightarrow$New physics at large scales

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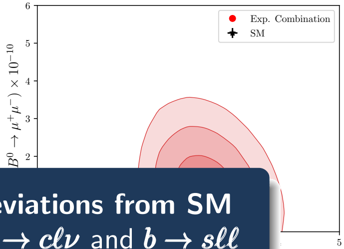


BUT: Significant **deviations from SM** observed in certain $b \to c l \nu$ and $b \to s l l$ decays!

Strongly cons … SUSY)

If new physics contributes to flavour (violating) processes:

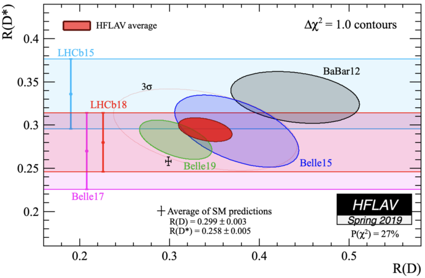
⇒No new flavour violating couplings (forcing it to higher order)

⇒New physics at large scales

Observables in $b \to c\ell\nu$

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

- **Charged current** *tree*-level decay
- Theoretically clean: hadronic uncertainties cancel in the ratio
- **SM**: $R_D = 0.299 \pm 0.003$, $R_{D^*} = 0.258 \pm 0.005$
- **Exp.**: $R_D = 0.340 \pm 0.030$, $R_{D^*} = 0.295 \pm 0.014$



⇒**SM** predictions are **significantly smaller** than experimental results, (combined) deviation from SM $\sim 3.1\,\sigma$!

⇒Violation of **LFU**? New physics coupled to τ?

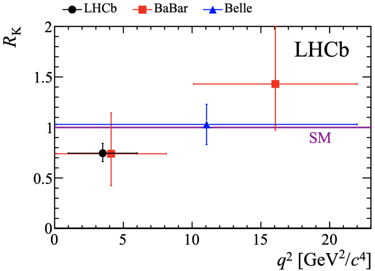
Observables in $b \to s\ell\ell$

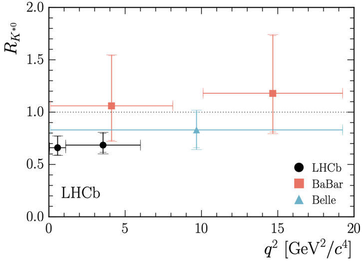
$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

- **FCNC** *penguin* decay
- Theoretically clean: hadronic uncertainties cancel in the ratio
- **SM**: $R_K = R_{K^*} \simeq 1$
- **Exp.**: $R_K = 0.845 \pm 0.06, R_{K^*} = 0.69 \pm 0.12$
- Other deviations in **angular observables**
- (Local) deviations from **SM $\sim 2 - 3\sigma$**!

⇒ 2nd system with violation of **LFU**?

⇒ Strong hint on **new physics coupled** to μ!





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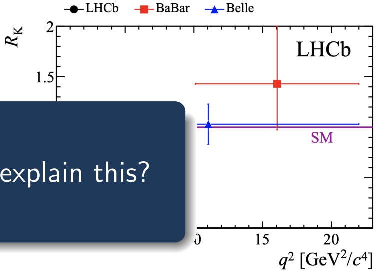
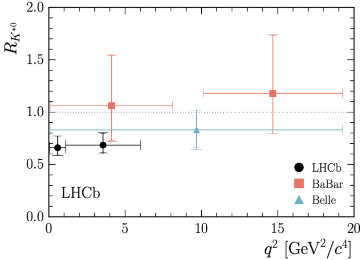
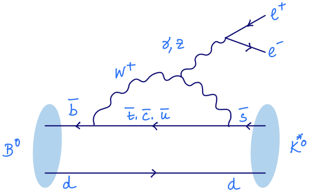
How can we explain this?

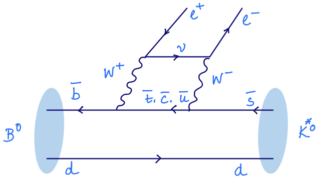




Electroweak penguins in $b \to s\ell\ell$

FCNC transitions in the SM are *"loop-suppressed"*:





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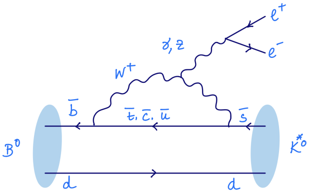
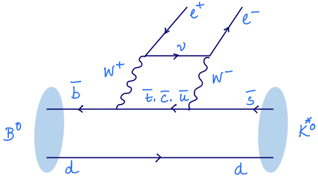
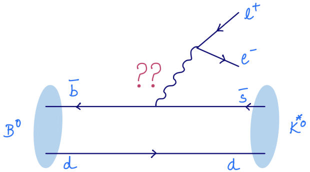
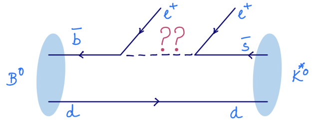




Heavy **BSM** contributions are *"mass suppressed"* $\Rightarrow$ If expected to be large, should contribute at *tree*-level:





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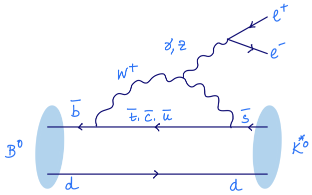

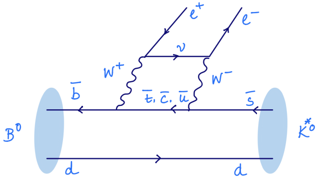

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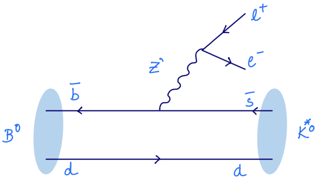

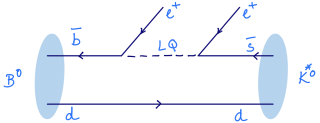

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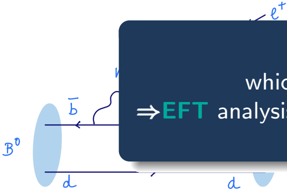

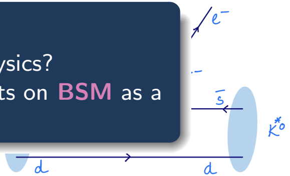

BUT:

which classes of new physics?

⇒**EFT** analysis to find requirements on **BSM** as a first step!

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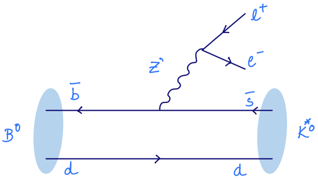
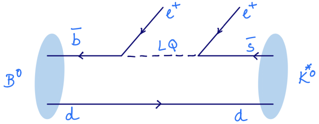
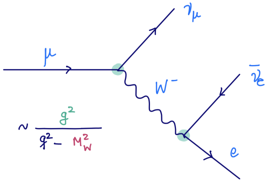




EFT *intermezzo* **I**

Effective **F**ield **T**heory $\simeq$ SM lagrangian + non-renormalisable operators

Only valid in certain energy regime: heavy fields are *"integrated out"*



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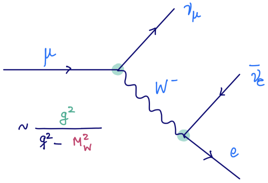
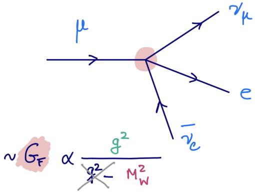


$\Rightarrow$



$\Rightarrow$**Fermi** constant G_F is an *effective* coupling constant

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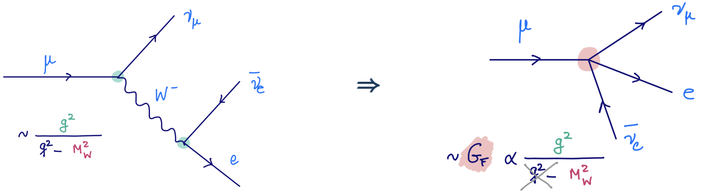


⇒**Fermi** constant $\boldsymbol{G_F}$ is an *effective* coupling constant

EFT Lagrangian for $\boldsymbol{b \to s\ell\ell}$: $\mathcal{L}_{\text{eff}} \propto \frac{4G_F}{\sqrt{2}} \sum_k \boldsymbol{C_k}(\mu)\boldsymbol{\mathcal{O}_k}(\mu)$

- **Effective operators** $\boldsymbol{\mathcal{O}_k}$ are accompanied by **effective coupling constants** $\boldsymbol{C_k}$ (**Wilson** coefficients)
- Couplings run! (depend on energy scale μ)

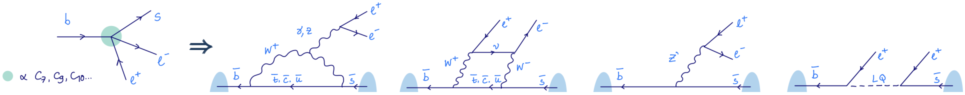
$$\mathcal{O}_7^{ij} = \frac{e\, m_{d_j}}{(4\pi)^2}(\bar{d}_i\, \sigma_{\mu\nu}\, P_R\, d_j)\, F^{\mu\nu}\,, \qquad \mathcal{O}_9^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, \gamma^\mu\, P_L\, d_j)(\bar{\ell}\, \gamma_\mu\, \ell')\,,$$

$$\mathcal{O}_{10}^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, \gamma^\mu\, P_L d_j)(\bar{\ell}\, \gamma_\mu\, \gamma_5\, \ell')\,, \quad \mathcal{O}_S^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \ell')\,,$$

$$\mathcal{O}_P^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \gamma_5\, \ell')\,, \qquad \mathcal{O}_T^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i \sigma_{\mu\nu}\, d_j)(\bar{\ell}\sigma^{\mu\nu}\, \ell')\,,$$

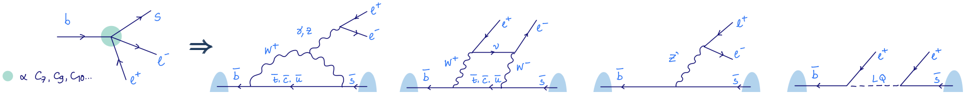
$$\mathcal{O}_{T5}^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i \sigma_{\mu\nu}\, d_j)(\bar{\ell}\sigma^{\mu\nu}\, \gamma_5\, \ell')\,,$$

EFT *intermezzo* II



⇒All diagrams contribute to the **Wilson** coefficients!

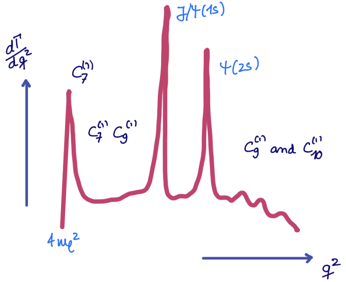
EFT *intermezzo* II



⇒All diagrams contribute to the **Wilson** coefficients!

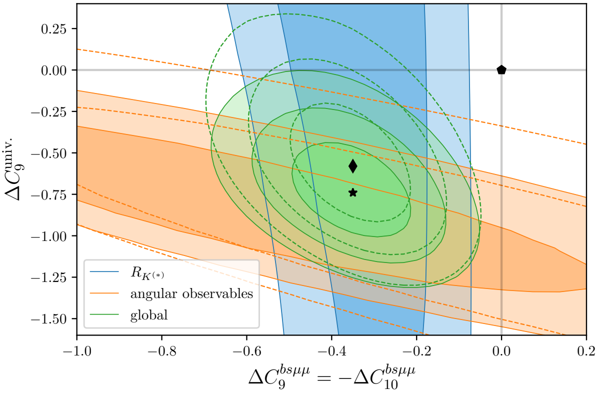
- Different energy bins are sensitive on different **Wilson** coefficients

⇒ Fit Wilson coefficients on **data** to **discriminate** between new physics scenarios!



Status of the global fit

New LHCb analyses of angular observables in $B \to K^* \mu\mu$ [PRL 125 (2020) 011802, arXiv:2012.13241]



- - -: old data
⬠: SM
◊: former best fit (B.F.)
★: new B.F.

[C. Hati, **JK**, J. Orloff, A. M. Teixeira: arXiv:2012.05883]

RG running-induced **universal** contribution (from large τ couplings) $\rightsquigarrow$ $R_{D^{(*)}}$

Requirements on (minimal) single-particle BSM explanations

- New physics **scale** in $\boldsymbol{b \to s\ell\ell}$: $\Lambda_{\text{NP}} \simeq m_{\text{NP}}/C_{\text{NP}} \sim \mathcal{O}(10 - 30\,\text{TeV})$
- New physics **scale** in $\boldsymbol{b \to c\ell\nu}$: $\Lambda_{\text{NP}} \sim \mathcal{O}(1 - 3\,\text{TeV})$

⇒ Single particle explanations need very different couplings, for $b \to c\ell\nu$ a low mass is required $\mathcal{O}(\text{TeV})$

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- Scalar $SU(2)_L$-triplet leptoquark S_3: **only** $b \to s\ell\ell$
- Vector $SU(2)_L$-triplet leptoquark V_3: ruled out by $B \to K\nu\bar{\nu}$

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- Heavy Z' can explain **only** $b \to s\ell\ell$, most models ruled out by $B_s - \bar{B}_s$ mixing
- Scalar $SU(2)_L$-singlet leptoquark S_1: **only** $b \to c\ell\nu$
- Scalar $SU(2)_L$-triplet leptoquark S_3: **only** $b \to s\ell\ell$
- Vector $SU(2)_L$-triplet leptoquark V_3: ruled out by $B \to K\nu\bar{\nu}$

⇒ **Vector $SU(2)_L$-singlet leptoquark** V_1: explains **both** anomalies, heavily constrained from **cLFV**!

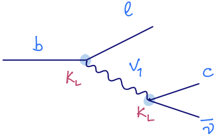
Other approaches rely on more non-minimal field content

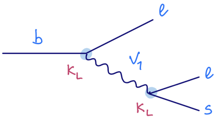
V_1 vector leptoquark

Leptoquarks: scalar or vector fields coupling **leptons** to **quarks** (typically arise in GUTs)

Leptoquark Lagrangian: $\mathcal{L} \supset V_1^\mu \left(\bar{d}_L^i \gamma_\mu \boldsymbol{K_L^{ik}} \ell_L^k + \bar{u}_L^j V_{ji}^\dagger \gamma_\mu \boldsymbol{K_L^{ik}} U_{kj}^{\mathsf{P}} \nu_L^j \right)$

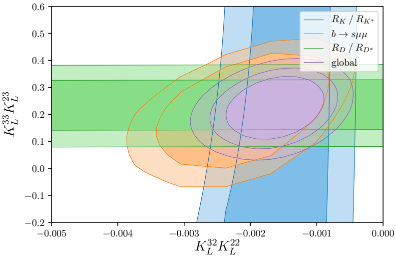
Both $b \to c\ell\nu$ and $b \to s\ell\ell$ at *tree*-level:





- $\boldsymbol{K_L^{23} K_L^{33}}$ contributes to $b \to c\tau\nu$ **and** $b \to s\tau\tau$

⇒ (Large) $C_9^{bs\tau\tau}$ feeds universally into $C_9^{bs\mu\mu}$ and C_9^{bsee} (RG running) $\Rightarrow \Delta C_9^{\text{univ.}}$



Non-universality from universal gauge interactions

Gauge couplings are strictly universal; how to explain **LFU Violation?**

- Add $\boldsymbol{n}$ **vector-like** (VL) leptons mixing with (left-handed) SM leptons

effective LQ-q-ℓ couplings $\boldsymbol{K_L^{q\ell}}$ parametrised via **non-unitary matrix** (from mixing with heavy states)

$\Rightarrow$ Induce **LFUV structure** in $C_{9,10}^{ij;\ell\ell'}$ **Wilson coefficients** (*tree*-level)

$$\boldsymbol{C_{9,10}^{ij;\ell\ell'} = \mp \frac{\pi}{\sqrt{2}G_F\, \alpha\, V_{3j}\, V_{3i}^*} \frac{1}{m_{V_1}^2} K_L^{i\ell'}\, K_L^{j\ell *}}$$

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⇒ Required mixing pattern could induce non-universal $Z \to \ell\ell^{(\prime)}$ (at *tree*-level)

⇝ VL leptons have to be $SU(2)_L$**-doublets!!**

⇒ $R_{K^{(*)}}$ and $R_{D^{(*)}}$ can be explained, tight constraints from **cLFV**, **EWPO**, colliders...

Results: V_1 leptoquark & non-unitary mixing from VL leptons

Observables taken into account:

cLFV: $(\mu - e)$-conversion, $\ell \to \ell'\gamma$, $\ell \to \ell'\ell'\ell'$, $\tau \to (\rho, \phi)\ell$

LFV: $B_{d,s} \to \ell^\pm \ell'^\mp$, $K_L \to \mu^\pm e^\mp$, $B \to (K, K^*, \pi)\ell^\pm \ell'^\mp$, $K \to \pi \ell^\pm \ell'^\mp$, $(B \to K\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu})$

EWPO: g_V^ℓ, g_A^ℓ, Γ_Z^ℓ, $Z \to \ell\ell^{(\prime)}$

LFC: $B_{d,s} \to \mu\mu$, $B_s \to \phi\mu\mu$, $B \to K^{(*)}\mu\mu$, $B \to K^{(*)}ee$, $B \to D^{(*)}\tau\nu$

LFU: $R_{K^{(*)}}$, $R_{D^{(*)}}$, angular observables and asymmetries in $b \to s\ell\ell$ à la P_5'

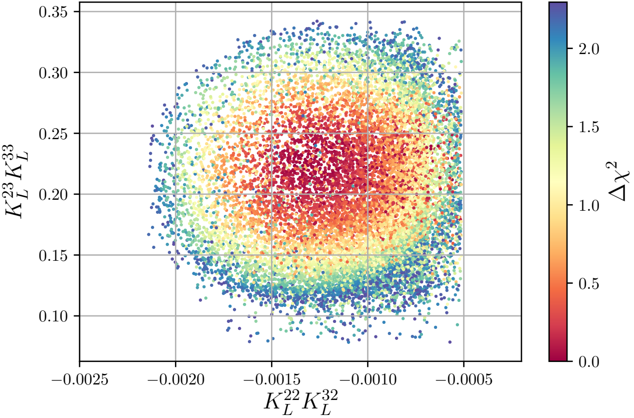
Direct searches (colliders): $m_{V_1} \gtrsim 1.5\,\mathrm{TeV}$

Results: V_1 leptoquark & non-unitary mixing from VL leptons

Random scan, taking all SM-(q,ℓ)-couplings of V_1 into account, complying with all constraints:

$m_{V_1} \sim 1.5\,\mathrm{TeV}$ & $n = 3$ generations of **VL leptons**

[C. Hati, **JK**, J. Orloff, A. M. Teixeira JHEP12(2019)006]



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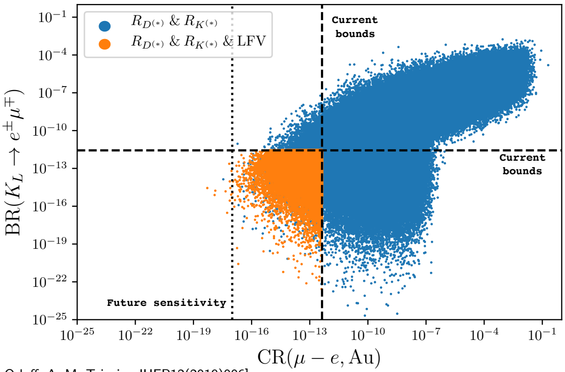
Confrontation with the most constraining observables (**cLFV decays**)



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Future limits: $\mathrm{CR}(\mu - e, \mathrm{Al}) \lesssim \mathcal{O}(10^{-17})$ (Mu2e, COMET)

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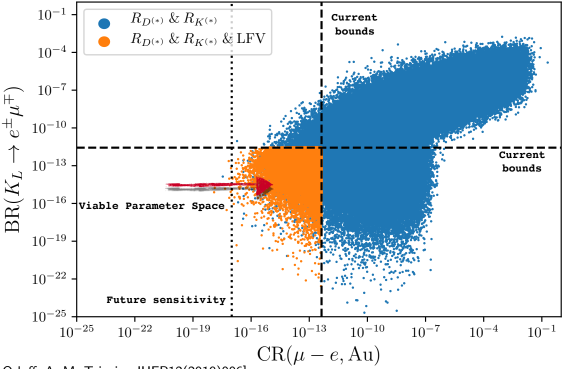

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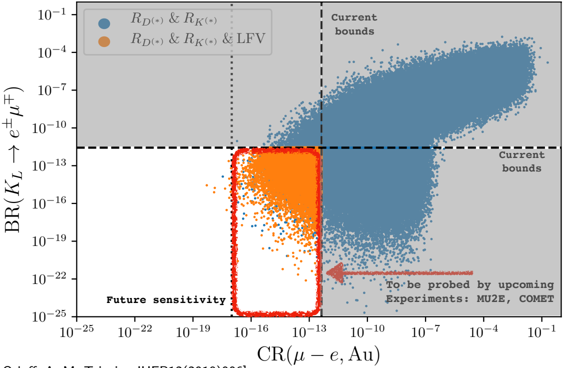


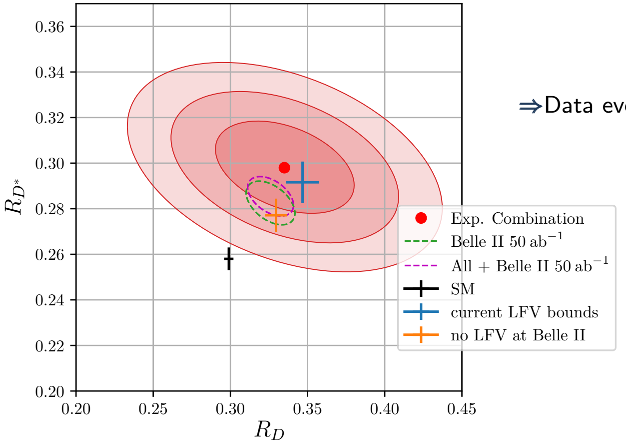
[C. Hati, **JK**, J. Orloff, A. M. Teixeira JHEP12(2019)006]

Future limits: $\mathrm{CR}(\mu - e, \mathrm{Al}) \lesssim \mathcal{O}(10^{-17})$ (MU2E, COMET)

Prospects

BELLE II will improve sensitivities in several b and τ decay channels!

Fit of 9 **LQ** couplings: [C. Hati, **JK**, J. Orloff, A. M. Teixeira: arXiv:2012.05883]



⇒Data evolution of $R_{D^{(*)}}$ is crucial!

B anomalies

Although most flavour observables are in excellent agreement with the SM, some show very peculiar deviations hinting on **LFUV** ($R_{D^{(*)}}, R_{K^{(*)}}$)...

- SM extensions via V_1-leptoquark offer viable explanations for both B-decay anomalies
- **Non-unitary** coupling matrix needed:
  - $\Rightarrow$ Add 3 generations of **VL leptons** (amongst other possibilities)
  - $\Rightarrow$ Strong constraints from LFV meson decays & **cLFV** observables
- Large region of the **parameter space** to be probed in the near **future!**

Flavour (de)*light*: anomalous magnetic moments

$(g-2)_\ell$: anomalous magnetic moments in the SM I

Electromagnetic (lepton) currents can be parametrised via:

$$\mathcal{J}_\mu = \bar{\ell}(p') \left[\boldsymbol{F_1}(k^2)\gamma_\mu + \frac{i}{2m_\ell}\boldsymbol{F_2}(k^2)\sigma_{\mu\nu}k^\nu - \boldsymbol{F_3}(k^2)\gamma_5\sigma_{\mu\nu}k^\nu + \boldsymbol{F_4}(k^2)(k^2\gamma_\mu - 2m_\ell k_\mu)\gamma_5 \right] \ell(p)$$

Magnetic dipole moment defined as $\mu_\ell = g_\ell \frac{e}{4m_\ell}$

From Dirac equation: Landé factor g_ℓ given by:

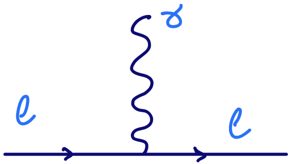
$$g_\ell = 2(\boldsymbol{F_1}(0) + \boldsymbol{F_2}(0))$$

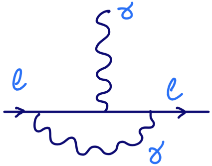
At *tree*-level: $\boldsymbol{F_1}(0) = 1,\ \boldsymbol{F_2}(0) = 0 \quad \Rightarrow g_\ell = 2\ (\equiv g_\ell^{\text{Dirac}})$

Contributions to $\boldsymbol{F_2}$ are generated at *loop*-level

$\Rightarrow$ define *anomalous* **magnetic moment**: $\boldsymbol{a_\ell} \equiv \frac{g_\ell - g_\ell^{\text{Dirac}}}{g_\ell^{\text{Dirac}}}\ (= \boldsymbol{F_2}(0))$

First leading correction to $a_\ell = F_2(0) = \frac{\alpha}{2\pi}$ calculated in 1948



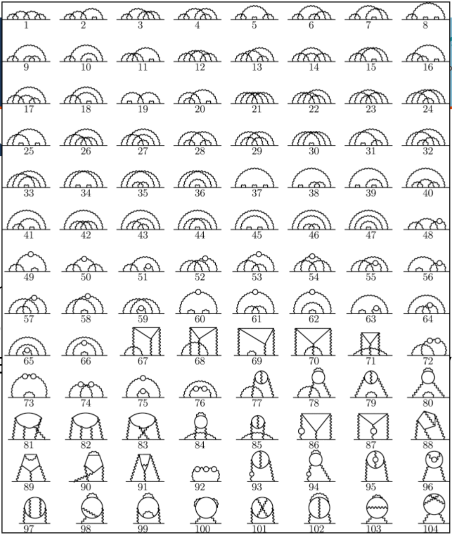


$(g-2)_\mu$: anomalous magnetic moments in the SM II

First leading correction to $a_\ell = F_2(0) = \frac{\alpha}{2\pi}$ calculated in 1948

Since then: $a_\ell = a_\ell^{\text{QED}} + a_\ell^{\text{had}} + a_\ell^{\text{EW}}$
with QED at 5-loop, EW contributions at 2-loop + LQCD for HVP and HLxL

$(g-2)_\mu$: anomalous m



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First leading correction

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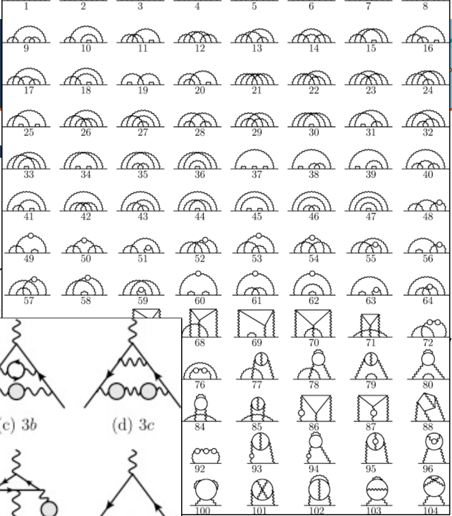
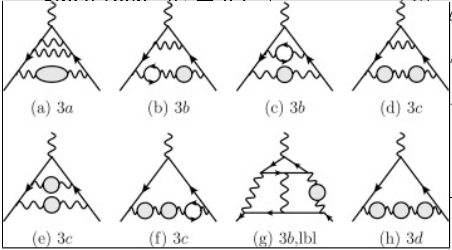
P and HLxL





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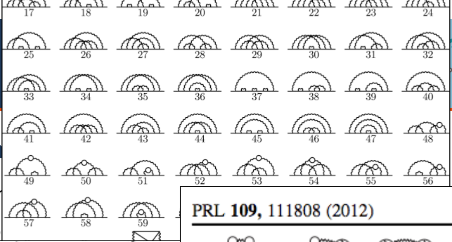

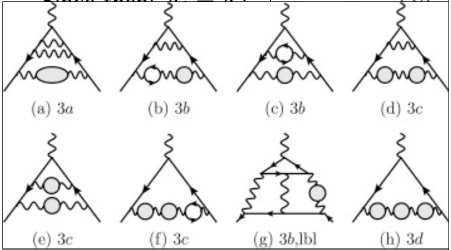

PRL **109,** 111808 (2012) PHYSICAL REV

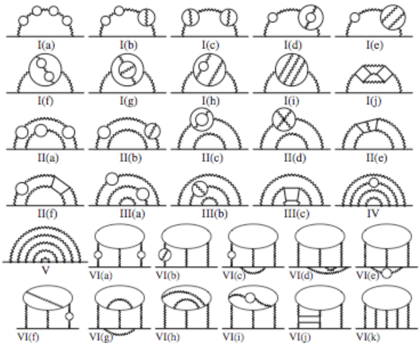

FIG. 2. Self-energy-like diagrams representing 32 gauge-invariant subsets contributing to the lepton $g-2$ at the tenth order. Solid lines represent lepton lines propagating in a weak magnetic field.

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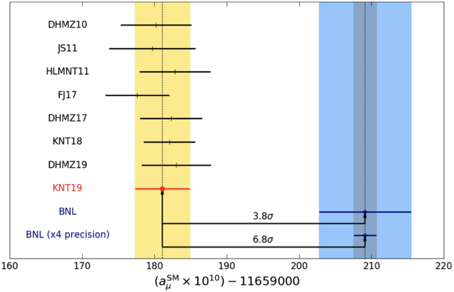
Since then: $a_\ell = a_\ell^{\text{QED}} + a_\ell^{\text{had}} + a_\ell^{\text{EW}}$

For the muon magnetic moment a_μ:

- QED makes up $\gtrsim 99.99\%$ of contributions, mostly m_{ℓ_i} and α_e only input parameters
- Extremely **high precision calculation**
- Extremely **high precision measurement**

⇒ Experimental uncertainties on par with theoretical uncertainties (numerical & Lattice)



[From PRD 101, 014029]

Today: $\boldsymbol{\Delta a_\mu} \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \sim (2.7 \pm 0.7) \times 10^{-9}$ ⇒ $\mathbf{3.7\,\sigma}$ discrepancy

α_e and $(g-2)_{e,\mu}$

$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \sim (2.7 \pm 0.7) \times 10^{-9} \;\Rightarrow$ **$3.7\,\sigma$** discrepancy [2006.04822]

NP Expectation for Δa_e:
- scaling of eff. dipole ops.: $\frac{\Delta a_e}{\Delta a_\mu} \sim \frac{m_e}{m_\mu} \sim 5 \times 10^{-3}$
- minimal flavour violation: $\frac{\Delta a_e}{\Delta a_\mu} \sim \frac{m_e^2}{m_\mu^2} \sim 2.5 \times 10^{-5}$

Recently improved measurement of α_e with Cs atoms (at $0.2\,\mathrm{ppb}$):

$\Rightarrow$ **Δa_e** $\sim (-0.88 \pm 0.36) \times 10^{-12}$ vs **Δa_μ** $\sim (2.7 \pm 0.7) \times 10^{-9} \Rightarrow \frac{\Delta a_e}{\Delta a_\mu} \sim -3 \times 10^{-4}$

- **$2.5\,\sigma$** tension in electron has "*wrong*" sign **and** order of magnitude!

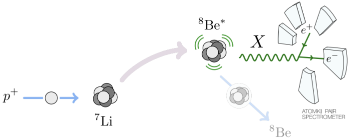
  $\Rightarrow$**Another** strong hint towards **LFUV** new physics?

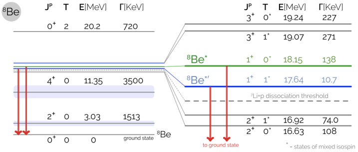
Most attempts to explain both $\Delta a_{\mu,e}$ require **light new physics** à la dark photon, axion, Z'...

Atomki experiment: a new light resonance?

In 2015, the ATOMKI collaboration claimed a $6.8\,\sigma$ excess in $^8\mathrm{Be}^* \to {}^8\mathrm{Be}\gamma(\to e^+e^-)$ transitions, compatible with a **resonance** [PRL 116 4, 042501]

- Create excited $^8\mathrm{Be}^*$ from a p-beam on $^7\mathrm{Li}$
- Nucleus de-excites emitting a γ
- Measure angular distribution of e^+e^- form internal pair creation





Figures from [1608.03591]

Atomki result: a new light resonance $m_X \sim 17\,\mathrm{MeV}$

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The result in particular:

- Measurement of **I**nternal **P**air **C**reation **C**orrelation
- Open circles "*control region*": asymmetric energy distribution
- Closed circles "*signal region*": symmetric energy distribution

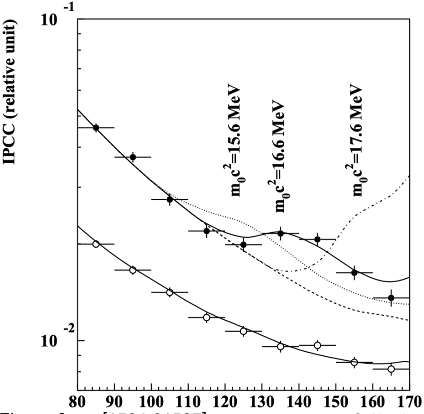

Figure from [1504.01527]

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⇒ Signal consistent with the **creation** and subsequent **decay** of a *bosonic* **resonance** $m \sim 17\,\mathrm{MeV}$

$\rightsquigarrow X_{17}$

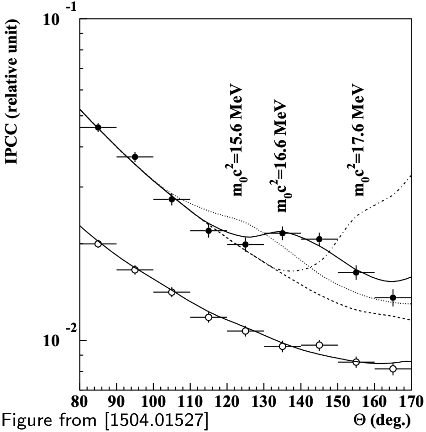

Figure from [1504.01527]

Requirements on X_{17}: nature & couplings to matter (I)

Possible Nuclear transitions in detail:

$$^{8}\text{Be}^{*\prime}(j^{\pi}=1^{+},T=1^{*})\rightarrow {}^{8}\text{Be}^{0}(j^{\pi}=0^{+},T=0),\;\; E=17.64\,\text{MeV}$$
$$^{8}\text{Be}^{*}\,(j^{\pi}=1^{+},T=0^{*})\rightarrow {}^{8}\text{Be}^{0}(j^{\pi}=0^{+},T=0),\;\; E=18.15\,\text{MeV}\quad \Leftarrow$$

Resonance observed in iso-spin **conserving** transition but absent in iso-spin violating one!

Possible candidates for $\boldsymbol{X_{17}}$:

- **Light scalar** resonance ⇒ would violate angular momentum conservation in $1^{+}\rightarrow 0^{+}$ transition ✗
- **Light pseudo-scalar**: ok with angular momentum ✓, but minimal models for ALP already excluded in the required coupling range ✗ [1609.01669]
- **Light vector**: ok with angular momentum ✓, severe constraints on couplings (more details on next slides)
- **Light axial vector**: ok with angular momentum ✓, explored e.g. in [1612.01525]

Other exotic possibilities have been explored from open string QED mesons to "4 bare quarks" interpretations

Requirements on (vector) X_{17}: nature & couplings to matter (II)

Parametrise Z' neutral currents via effective couplings to fermions (ψ):

$$J^\mu_{Z'} = e\bar{\psi}_i\gamma^\mu(\varepsilon^V_{ij} + \gamma^5\varepsilon^A_{ij})\psi_j$$

Immediate constraint: on-shell $\boldsymbol{X_{17}} \equiv Z'$ must **decay inside detector** $\mathcal{O}(\mathrm{cm})$:

$$\Rightarrow |\varepsilon^V_{ee}| \gtrsim 1.3\times 10^{-5}\sqrt{\mathrm{BR}(Z' \to e^+e^-)}$$

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A fit of the ATOMKI data results in:

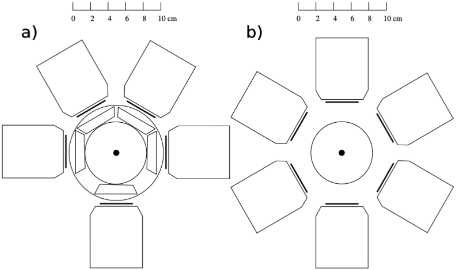
$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq (6 \pm 1) \times 10^{-6} \quad \text{for} \quad m_{Z'} \simeq 17.01 \pm 0.16\,\mathrm{MeV}$$

Conservative range: $|\varepsilon^V_n + \varepsilon^V_p| \simeq (2 - 15) \times 10^{-3}\sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$

Cross-checks of the $^8\mathrm{Be}$ anomaly

Only the ATOMKI collaboration published results on such nuclear transitions...

- Original result 2015; since then new detector to re-investigate $^8\mathrm{Be}$ transition



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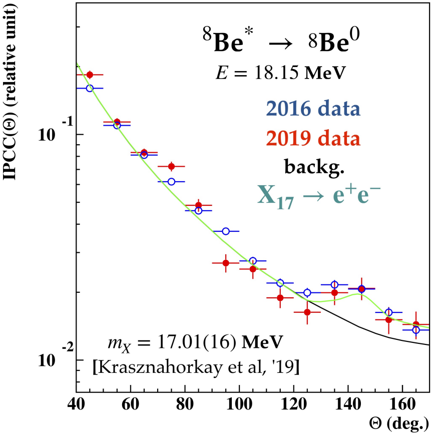

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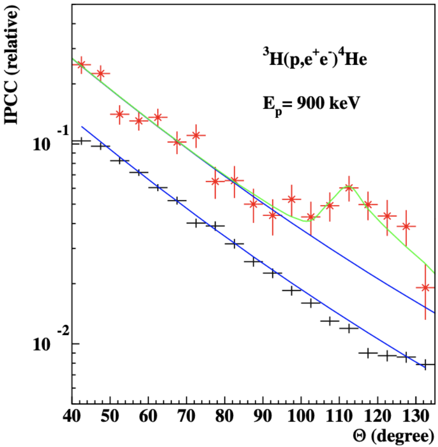

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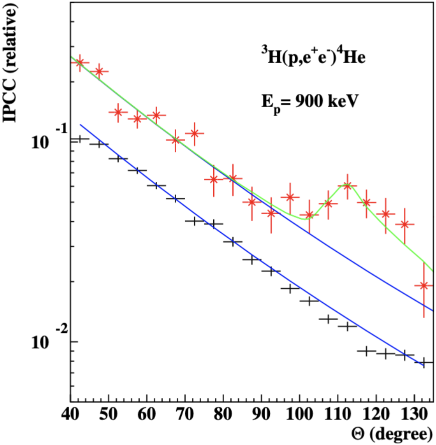
- New study by Feng et. al. [2006.01151] suggests **both** are **highly consistent** with the **same** new **vector**!



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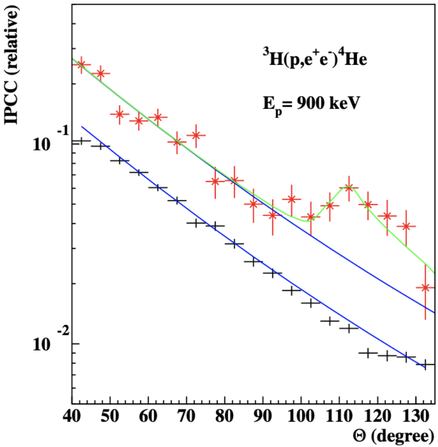
⇒ Has a **fifth force** been discovered?

- Plans to study similar transitions in ^{12}C for *conclusive* confirmation



Model independent constraints on (vector) $X_{17} \Rightarrow Z'$

New light vector from $U(1)$ extension of the SM with $J^{\mu}_{Z'} = e\bar{\psi}_i \gamma^{\mu}(\varepsilon^V_{ij} + \gamma^5 \varepsilon^A_{ij})\psi_j$

Recall from $^8\mathrm{Be}$ anomaly: $|\varepsilon^V_n + \varepsilon^V_p| \simeq (2-15) \times 10^{-3}, \; |\varepsilon^V_{ee}| \gtrsim 1.3 \times 10^{-5}$

Other **constraints**:

- KLOE-2 bound for $e^+e^- \to \gamma Z'(\to e^+e^-)$ leads to $\sqrt{\varepsilon^{V2}_{ee} + \varepsilon^{A2}_{ee}} \lesssim 2 \times 10^{-3}$
- NA48/2 bound for $\pi^0 \to \gamma Z'$ leads to $|\varepsilon^V_p| \lesssim 1.2 \times 10^{-3}$
- NA64 **electron beam dump**: $\sqrt{|\varepsilon^V_{ee}|^2 + |\varepsilon^A_{ee}|^2} \gtrsim 6.8 \times 10^{-4} \sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$
- **Neutrino scattering** (TEXONO & CHARM-II): $|\varepsilon^A_{\nu_e\nu_e}| \lesssim 1.2 \times 10^{-5}$ & $|\varepsilon^A_{\nu_\mu\nu_\mu}| \lesssim 12.2 \times 10^{-5}$
- **Atomic parity violation** (effective weak charge of Cs): $|\varepsilon^A_{ee}| \lesssim 2.6 \times 10^{-9}$

Model independent constraints on (vector) $X_{17} \Rightarrow Z'$

New light vector from $U(1)$ extension of the SM with $J^{\mu}_{Z'} = e\bar{\psi}_i\gamma^{\mu}(\varepsilon^V_{ij} + \gamma^5\varepsilon^A_{ij})\psi_j$

Recall from $^8\mathrm{Be}$ anomaly: $|\varepsilon^V_n + \varepsilon^V_p| \simeq (2-15)\times 10^{-3}$, $|\varepsilon^V_{ee}| \gtrsim 1.3\times 10^{-5}$

Other **constraints**:

- KLOE-2 ... $^{2} \lesssim 2\times 10^{-3}$
- NA48/2
- NA64 **ele**... $\mathrm{BR}(Z' \to e^+e^-)\Big)^{-1}$
- **Neutrin**... $^{-5}$ & $|\varepsilon^A_{\nu_\mu\nu_\mu}| \lesssim 12.2\times 10^{-5}$
- **Atomic parity violation** (effective weak charge of Cs): $|\varepsilon^A_{ee}| \lesssim 2.6\times 10^{-9}$

$\Rightarrow$ Can we explain the $g-2$ anomalies (hinting at **LFUV**) with this light Z'?

A $U(1)_{B-L}$ model

- Extend SM by $U(1)_{B-L}$: Z' coupled to baryons and leptons
- New scalar singlet h_X: spontaneously breaks $U(1)_{B-L}$ below EW-scale

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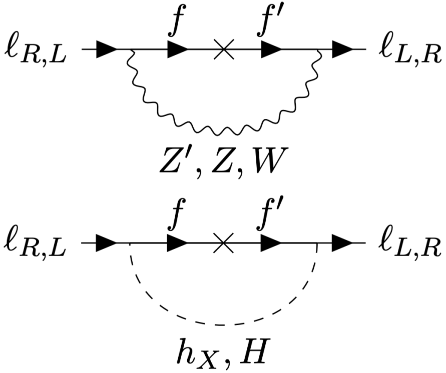
$$- \lambda_E^{ij} h_X \bar{E}_L^i e_R^j - M_E^{ij} \bar{E}_L^i E_R^j - h^{ij} h_{\text{SM}} \bar{L}_L^i E_R^j + k^{ij} \tilde{h}_{\text{SM}} \bar{E}_L^i L_R^j$$

- Right-handed neutrinos N_R^j for anomaly cancellation $\Rightarrow$ **type-I seesaw** for free
- 3 vector-like doublet leptons $L_{L,R}$ to suppress $Z' - \nu\nu$ couplings
- 3 vector-like singlet leptons $E_{L,R}$ to suppress axial $Z' - \ell\ell$ couplings

New physics contributions to $g-2$

2 types of new contributions:

- Dominant contributions by Z' and h_X
- Since $m_{Z'} \simeq 17\,\mathrm{MeV}$, Z' contributions are too large



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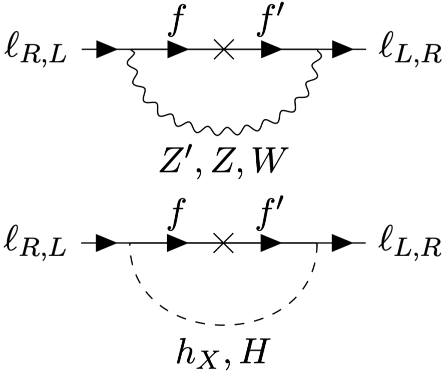

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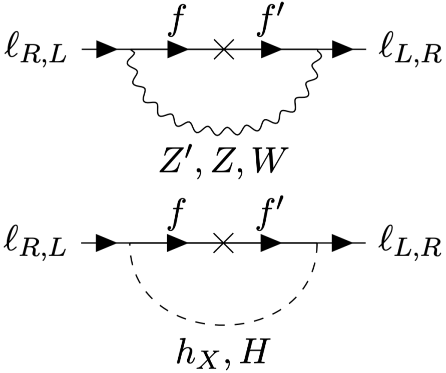

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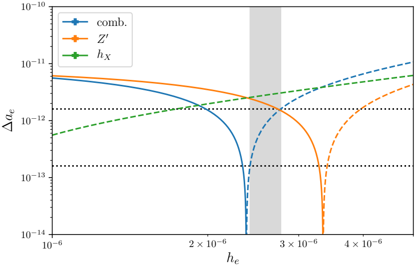
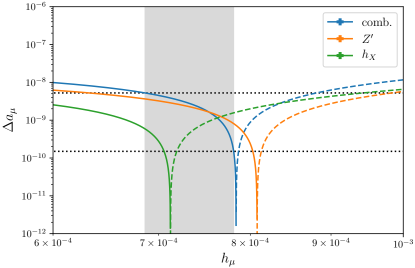
$\Rightarrow$ **Partial cancellation** from axial and pseudo-scalar contributions

Cancellation of scalar/vector contributions leading to Δa_e, Δa_μ





- $M_E = M_L \simeq 90\,\text{GeV}$, $\lambda_L = \lambda_E = M_L/v_X (\simeq 6.4)$, $m_{h_X} \simeq 70\,\text{GeV}$, $\varepsilon_{B-L} = 2\times10^{-3}$, $\varepsilon = -8\times10^{-4}$, $k_e = k_\mu = 10^{-7}$
- Dashed lines: change of sign when pseudo-scalar contribution larger than scalar and/or axial larger than vector

⇒ **Accommodate both Δa_e & Δa_μ!**

$g-2$ and the hungarian fifth force

- Exciting hints towards **LFUV** new physics in $(g-2)_{\mu,e}$
- Exciting hints of a **fifth force** discovered by `ATOMKI`

⇒ Parameter space to be probed soon (completely) by `NA64`

⇒ All 4 *anomalies* are explained in a single and very predictive model

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- `Atomki` anomaly: has a fifth force been discovered?

$\Rightarrow$ Vector interpretation of `Atomki` explains $(g-2)_{e,\mu}$!

Lepton **flavour** observables provide crucial tests of the SM (**LFUV**) and beyond (**cLFV**)!

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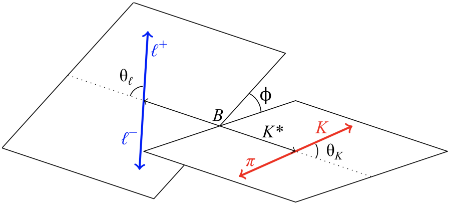
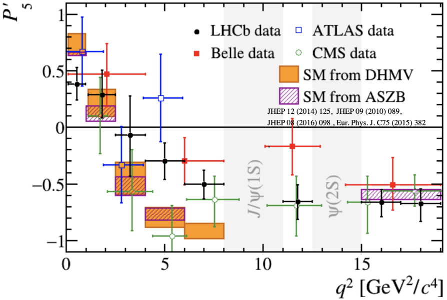
Lepton **flavour** observables provide crucial tests of the SM (**LFUV**) and beyond (**cLFV**)! A bright and exciting experimental future lies ahead and we will leave no stone unturned: **charm** physics precision programmes just started!

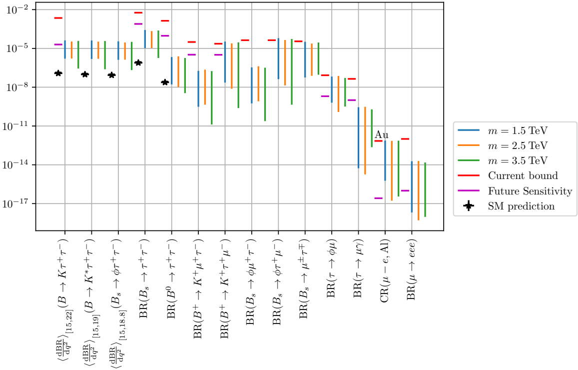
Thank you!!!

Angular observables





LFV Prospects



Non-universality from universal gauge interactions

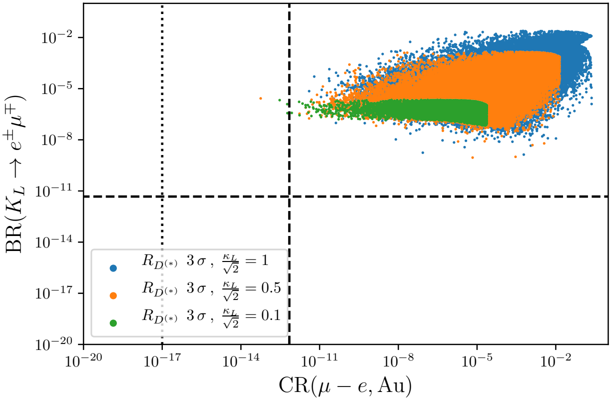
Gauge couplings are strictly universal; how to explain **LFU Violation?**

$\Rightarrow$ Only unitary $q\ell$ mass missalignment is ruled out by **LFV**

Non-universality from universal gauge interactions

Gauge couplings are strictly universal; how to explain **LFU Violation?**

$\Rightarrow$ Using unitary quark lepton mass misalignment:



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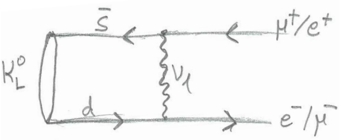
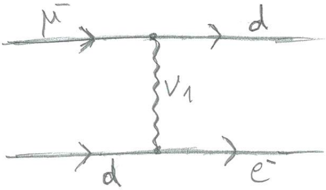
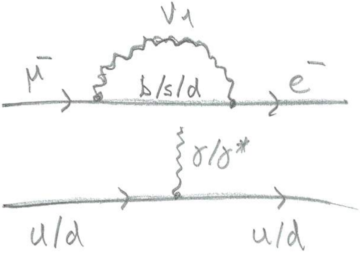
Gauge couplings are strictly universal; how to explain **LFU Violation?**

Why are the LFV constraints so severe?

$\Rightarrow$ Contributions are on **tree** level:







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- Add $\boldsymbol{n}$ **vector-like** (VL) leptons mixing with (left-handed) SM leptons

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effective LQ-q-ℓ couplings $\boldsymbol{K_L^{q\ell}}$ parametrised via **non-unitary matrix** (from mixing with heavy states)

⇒ Induce **LFUV structure** in $C_{9,10}^{ij;\ell\ell'}$ **Wilson coefficients** (tree-level)

$$\boldsymbol{C_{9,10}^{ij;\ell\ell'} = \mp \frac{\pi}{\sqrt{2}G_F\,\alpha\,V_{3j}\,V_{3i}^*}\,\frac{1}{m_{V_1}^2} K_L^{i\ell'}\,K_L^{j\ell *}}$$

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$\Rightarrow$ Required mixing pattern could induce non-universal $Z \to \ell\ell^{(\prime)}$ (at tree-level)

$\rightsquigarrow$ VL leptons have to be $SU(2)_L$-**doublets!!**

$\Rightarrow$ $R_{K^{(*)}}$ and $R_{D^{(*)}}$ can be explained, tight constraints from **cLFV**, **EWPO**, colliders...

Unitary Quark-Lepton mass misalignment

Non-unitary parametrisation

In analogy to neutrino physics, the mixing matrices get enlargened:

$$U_L^\ell = \begin{pmatrix} A & R \\ B & S \end{pmatrix} \begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

In case of $\boldsymbol{n = 3}$ generations:

$$\begin{pmatrix} A & R \\ B & S \end{pmatrix} = \mathcal{R}_{56}\mathcal{R}_{46}\mathcal{R}_{36}\mathcal{R}_{26}\mathcal{R}_{16}\mathcal{R}_{45}\mathcal{R}_{35}\mathcal{R}_{25}\mathcal{R}_{15}\mathcal{R}_{34}\mathcal{R}_{24}\mathcal{R}_{14}$$

$$\begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix} = \mathcal{R}_{23}\mathcal{R}_{13}\mathcal{R}_{12}$$

Defining **semi-unitary** rectangular matrix:

$$\boldsymbol{K_L^{q\ell}} \; = \; (K_1, K_2) \; = \; \frac{\kappa_L}{\sqrt{2}}(A\,V_0, R)$$

Backup: Requirements on (vector) X_{17}: Nucleus & electron couplings I

Neutral current of fermions ψ_i can be parametrised with effective couplings:

$$J^{\mu}_{Z'} = e\bar{\psi}_i\gamma^{\mu}(\varepsilon^V_{ij} + \gamma^5\varepsilon^A_{ij})\psi_j$$

Most obvious constraint: on-shell $\boldsymbol{X_{17}} \equiv Z'$ has to decay inside detector $\mathcal{O}(\mathrm{cm})$:

$$\Gamma(Z' \to e^+e^-) = (|\varepsilon^V_{ee}|^2 + |\varepsilon^A_{ee}|^2)\frac{\lambda^{\frac{1}{2}}(m_{Z'}, m_e, m_e)}{24\pi m_{Z'}}$$

... leading to $|\varepsilon^V_{ee}| \gtrsim 1.3 \times 10^{-5}\sqrt{\mathrm{BR}(Z' \to e^+e^-)}$

A fit of the `ATOMKI` data results in:

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq (6 \pm 1) \times 10^{-6} \quad \text{for} \quad m_{Z'} \simeq 17.01 \pm 0.16\,\mathrm{MeV}$$

Backup: Requirements on (vector) X_{17}: Nucleus & electron couplings II

With a vector resonance Z' the nuclear matrix elements cancel:

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq (\varepsilon_p^V + \varepsilon_n^V)^2 \left[1 - \left(\frac{m_{Z'}}{18.15\,\mathrm{MeV}}\right)^2\right]^{\frac{3}{2}}$$

... leading to $|\varepsilon_p^V + \varepsilon_n^V| \simeq 1.2 \times 10^{-2} \sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$

Including iso-spin mixing effects:

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq |0.05(\varepsilon_p^V + \varepsilon_n^V) + 0.95(\varepsilon_p^V - \varepsilon_n^V)|^2 \left[1 - \left(\frac{m_{Z'}}{18.15\,\mathrm{MeV}}\right)^2\right]^{\frac{3}{2}}$$

... leads to $\sim 15\%$ modification and a heavier Z' leads to smaller width $\frac{\Gamma_{Z'}}{\Gamma_\gamma} \sim 0.5 \times 10^{-6}$

Conservative range: $|\varepsilon_n^V + \varepsilon_p^V| \simeq (2 - 15) \times 10^{-3} \sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$

Model independent constraints on (vector) X_{17}

Backup: Minimal model ingredients

- New vector coming from gauge extension of SM – new $\boldsymbol{U(1)}$-gauge group
- We need a new scalar breaking $\boldsymbol{U(1)}$ and giving a mass around $\sim \mathbf{17}\,\mathrm{MeV}$
- We need couplings to **nucleons** (hadrons) and **electrons**

⇒ Could be a dark photon $\boldsymbol{A'}$?

"*Pure*" $\boldsymbol{A'}$-couplings due to kinetic mixing with photon: $\varepsilon_n^V = \varepsilon_\nu^V = 0\,, \quad \varepsilon_p^V = -\varepsilon_{ee}^V$

Recall from $^8\mathrm{Be}$ anomaly: $|\varepsilon_n^V + \varepsilon_p^V| \simeq (2-15)\times 10^{-3}\,,\ |\varepsilon_{ee}^V| \gtrsim 1.3\times 10^{-5}$

⇒ KLOE-2 bound for $e^+e^- \to \gamma \boldsymbol{A'}(\to e^+e^-)$ leads to $\sqrt{\varepsilon_{ee}^{V2} + \varepsilon_{ee}^{A2}} \lesssim 2\times 10^{-3}$ ✗

Furthermore NA48/2 bound for $\pi^0 \to \gamma \boldsymbol{A'}$ leads to $|\varepsilon_p^V| \lesssim 1.2\times 10^{-3}$ ✗✗

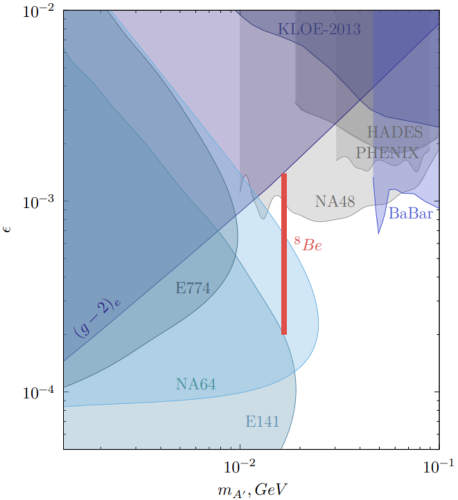
Protophobic scenario: proton couplings smaller than neutron, **dark photon** excluded!

Backup: Constraints: direct searches

Also NA64 (electron beam dump) is looking for light neutral vectors:

- Very recent result [1912.11389]
- Either $\varepsilon_{ee}^{V2} + \varepsilon_{ee}^{A2} < 1.1 \times 10^{-16}$ (negligible production)
- Or $\sqrt{|\varepsilon_{ee}^{V}|^2 + |\varepsilon_{ee}^{A}|^2} \gtrsim \frac{6.8\times 10^{-4}}{\sqrt{\mathrm{BR}(Z' \to e^+ e^-)}}$ (decay inside beam dump)

⇒ Globally allowed range:
$\sqrt{|\varepsilon_{ee}^{V}|^2 + |\varepsilon_{ee}^{A}|^2} \sim \frac{(0.68-2)\times 10^{-3}}{\sqrt{\mathrm{BR}(Z' \to e^+ e^-)}}$
(NA48/2 does not directly apply in *protophobic* case)



Backup: Constraints: (atomic) parity violation

Search for **parity** violating Møller scattering at `SLAC E158` yields a bound

$$|\varepsilon^V_{ee}\varepsilon^A_{ee}| \lesssim 1.1 \times 10^{-7}$$

Much more severe is *atomic* parity violation (effective weak charge) in Cs:

$$|\Delta Q_w| = |\frac{2\sqrt{2}}{G_F} 4\pi\alpha\varepsilon^A_{ee}[\varepsilon^V_{uu}(2Z+N) + \varepsilon^V_{dd}(Z+2N)]\frac{\mathcal{K}(m_{Z'})}{m^2_{Z'}}| \lesssim 0.71$$

At low energy, the nucleon couplings are $\varepsilon^V_p \simeq 2\,\varepsilon^V_{uu} + \varepsilon^V_{dd}$ and $\varepsilon^V_n \simeq \varepsilon^V_{uu} + 2\,\varepsilon^V_{dd}$

⇒ For $^8\mathrm{Be}$ nucleon couplings and $m_{Z'} \simeq 17\,\mathrm{MeV}$: upper bound $|\varepsilon^A_{ee}| \lesssim 2.6 \times 10^{-9}$

Backup: Constraints: neutrino-electron scattering

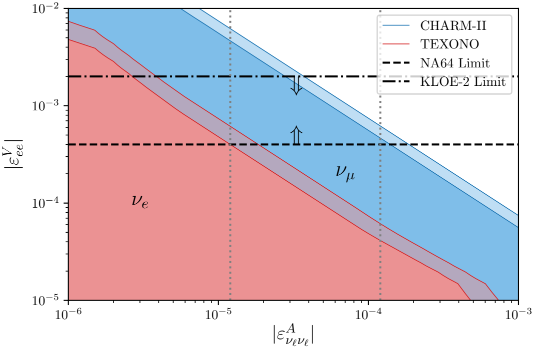
Neutrino-electron scattering provides very stringent constraints:

For **LFU** couplings and **Dirac ν**: $\sqrt{|\varepsilon^V_{ee}\varepsilon^V_{\nu_\ell\nu_\ell}|} < 7 \times 10^{-5}$ c.f. [1608.03591] and TEXONO data

For **Majorana ν** the vector coupling vanishes! ⇒ new (**LFUV**) fit with **Majorana ν**:

- CHARM-II: SPS experiment $\nu_\mu - e$ scattering
- TEXONO: Reactor experiment $\nu_e - e$ scattering

⇒ Bound for lowest allowed $\varepsilon^V_{ee} \simeq 6.8 \times 10^{-4}$:
$|\varepsilon^A_{\nu_e\nu_e}| \lesssim 1.2 \times 10^{-5}$ &
$|\varepsilon^A_{\nu_\mu\nu_\mu}| \lesssim 12.2 \times 10^{-5}$



Model recipe

- Extend SM by $\boldsymbol{U(1)_{B-L}}$: Z' coupled to baryons and leptons
- New scalar singlet $\boldsymbol{h_X}$: spontaneously breaks $\boldsymbol{U(1)_{B-L}}$ somewhere below EW-scale

$\Rightarrow$ triangular gauge anomalies

$$\mathcal{A}\left[\boldsymbol{U(1)_{B-L}}(SU(2)_L)^2\right], \mathcal{A}\left[(\boldsymbol{U(1)_{B-L}})^3\right], \mathcal{A}\left[\boldsymbol{U(1)_{B-L}}(U(1)_Y)^2\right], \mathcal{A}\left[\mathrm{G.}^2 \times \boldsymbol{U(1)_{B-L}}\right]$$

... remaining $B-L=3 \Rightarrow$ add 3 gens of sterile Majorana $\boldsymbol{N_R}$ with $\boldsymbol{Q^{B-L}}=-1$

$\Rightarrow$ with $\boldsymbol{Q^{B-L}}=+2$ for $\boldsymbol{h_X}$: dynamical type-I **seesaw** neutrino masses "for free"!

$$\mathcal{L}_{\text{Yuk.}} \supseteq -y_\ell^{ij} h_{\text{SM}} \bar{\ell}_L^i e_R^j + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}_L^i \boldsymbol{N_R^j} - \frac{1}{2} y_M^{ij} \boldsymbol{h_X} \boldsymbol{\bar{N}_R^{i\,c}} \boldsymbol{N_R^j}$$

Coupling to nucleons now determined by photon kinetic mixing and $B-L$-current:

$$\varepsilon_n^V \propto g_{B-L}\,,\;\; m_{Z'}^2 \propto g_{B-L}^2 v_X^2 \Rightarrow \text{fixing vev of } \boldsymbol{h_X} \text{ to } v_X \simeq 14\,\text{GeV}$$

Gauge boson mixing

$U(1)_{B-L}$ is **kinetically** mixed with the $U(1)_Y$:

$$\mathcal{L}_{\text{kin}}^{\text{gauge}} \supseteq -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{\epsilon_k}{2}\tilde{F}_{\mu\nu}\tilde{F}'^{\mu\nu}$$

⇝ consequently **mass mixing** between $U(1)_{B-L}$-boson and W^3 with $\tan 2\theta' \simeq -2\frac{\epsilon_k}{\sqrt{1-\epsilon_k^2}}\sin\theta_w$

Diagonalising **kinetic** and **mass mixing** gives physical (gauge) couplings (at leading order):

$$D_\mu \simeq \partial_\mu + \ldots + i\frac{g}{\cos\theta_w}(T_{3\,f} - \sin^2\theta_w \boldsymbol{Q_f})Z_\mu + ie\boldsymbol{Q_f}A_\mu + ie(\varepsilon\boldsymbol{Q_f} + \varepsilon_{B-L}\boldsymbol{Q_f^{B-L}})Z'_\mu$$

with $\varepsilon = \frac{\epsilon_k\cos\theta_w}{\sqrt{1-\epsilon_k^2}}$ and $\varepsilon_{B-L} = \frac{g_{B-L}}{e\sqrt{1-\epsilon_k^2}}$

⇒ Nucleon couplings and mass: $\varepsilon_p^V = \varepsilon_{B-L} - \varepsilon\,,\ \varepsilon_n^V = \varepsilon_{B-L}\,,\ m_{Z'}^2 \simeq 4\varepsilon_{B-L}^2 v_X^2$

⇒ But also: $\varepsilon_{\nu\nu}^A = -\varepsilon_n^V$ neutrino coupling 10^2 too large! ✗✗✗

Vector-like leptons: Neutrino cancellation

Solution: Add 3 gens. of **vector-like lepton** *doublets* $L_{L,R} = \begin{pmatrix} L^0 \\ L^- \end{pmatrix}$ with $Q^{B-L} = +1$

- **VL**-fermions do not add further gauge anomalies
- Choice of charge to not spoil **LFU** SM-boson couplings

⇒ Mass mixing of ${L^0}_L$ with SM ν_ℓ will modify Z'-couplings

$$\mathcal{L}_{\text{Yuk.}} \supseteq -y_\ell^{ij} h_{\text{SM}} \bar{\ell}_L^i e_R^j + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}_L^i N_R^j - \frac{1}{2} y_M^{ij} h_X \bar{N}_R^{i\,c} N_R^j - \lambda_L^{ij} h_X \bar{\ell}_L^i {L^j}_R - M_L^{ij} {\bar{L}^i}_L {L^j}_R$$

- λ_L^{ij} needs to be (almost) diagonal to comply with **LFV** bounds: $\lambda_L^{ij} \to \lambda_{L\,\alpha}$
- M_L^{ij} can be chosen to be diagonal; **collider bounds:** mass scale $\sim 100\,\text{GeV}$

⇒ Z'-$\nu\nu$-couplings get modified: $\varepsilon_{\nu_\alpha \nu_\alpha} \simeq \varepsilon_{B-L} \left(1 - \frac{\lambda_{L\,\alpha}^2 v_X^2}{M_{L\,\alpha}^2}\right)$

⇒ $\lambda_{L\,\alpha}^2 v_X^2 \simeq M_{L\,\alpha}^2$ is fixed for each lepton generation α !

Vector-like leptons: atomic parity violation

The *charged* component of L_L mixes with the **left-handed** SM leptons

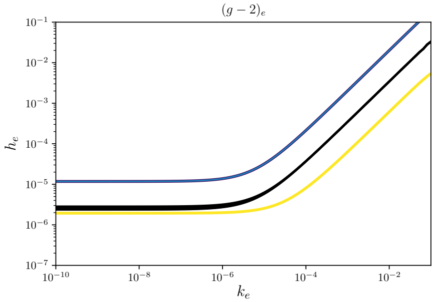
$\Rightarrow g^{\ell_\alpha \ell_\alpha}_{Z', L} \simeq -\varepsilon + \left(\frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}} - 1\right) \varepsilon_{B-L}$, but **right-handed** couplings unmodified

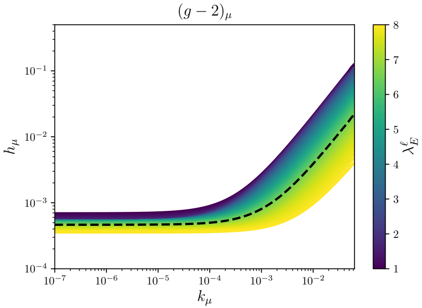
Solution: Add 3 gens. of charged **vector-like lepton** *singlets* $E_{L,R}$ with $Q^{B-L} = +1$

$$\mathcal{L}_{\text{Yuk.}} \supseteq - y_\ell^{ij} h_{\text{SM}} \bar{\ell}^i_L e^j_R + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}^i_L N^j_R - \frac{1}{2} y_M^{ij} h_X \bar{N}^{i\,c}_R N^j_R - \lambda_L^{ij} h_X \bar{\ell}^i_L L^j{}_R - M_L^{ij} \bar{L}^i{}_L L^j{}_R$$
$$- \lambda_E^{ij} h_X \bar{E}^i{}_L e^j_R - M_E^{ij} \bar{E}^i{}_L E^j{}_R - h^{ij} h_{\text{SM}} \bar{L}^i{}_L E^j{}_R + k^{ij} \tilde{h}_{\text{SM}} \bar{E}^i{}_L L^j{}_R$$

- $\Rightarrow \varepsilon^A_{\ell_\alpha \ell_\alpha} \simeq \frac{1}{2}\left(\frac{\lambda^2_{E\,\alpha} v_X^2}{M^2_{E\,\alpha}} - \frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}}\right) \varepsilon_{B-L} \Rightarrow \lambda_{E\,\alpha}$ is fixed for the 1. gen!
- $\Rightarrow \varepsilon^V_{\ell_\alpha \ell_\alpha} \simeq -\varepsilon + \frac{1}{2}\left(\frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}} + \frac{\lambda^2_{E\,\alpha} v_X^2}{M^2_{E\,\alpha}} - 2\right) \varepsilon_{B-L} \Rightarrow$ fixes $\varepsilon \simeq -(8-20) \times 10^{-4}$
- $\Rightarrow$ 2 new Yuk. matrices h^{ij} and k^{ij} (assumed to be diagonal): if different, their asymmetry will generate axial and pseudo-scalar couplings in $Z' - \ell L$ and $h_X - \ell L$ interactions

Remaining parameter space: impact from Δa_e, Δa_μ





- Black line: $(g-2)_e$ explained ✓ coloured region: $(g-2)_\mu$ explained ✓✓
- λ_E^μ is still mostly free
- Curious hierarchy between h_ℓ & k_ℓ ($\Rightarrow$ could hint on residual Z_n-symmetry?)

Backup: Gauge boson mixing

$$\begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^{\,\mu} \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w \cos\theta' & \cos\theta_w \cos\theta' & \sin\theta' \\ \sin\theta_w \sin\theta' & -\cos\theta_w \sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} B^\mu \\ W_3^\mu \\ B'^{\,\mu} \end{pmatrix}$$

$$\tan 2\theta' = \frac{2\,\varepsilon'\,g'\,\sqrt{g^2+g'^2}}{\varepsilon'^2\,g'^2 + 4\,m_{B'}^2/v^2 - g^2 - g'^2}$$

$$M_A = 0\,, \qquad M_{Z,\,Z'} = \frac{g}{\cos\theta_w}\,\frac{v}{2}\left[\frac{1}{2}\left(\frac{\varepsilon'^2 + 4\,m_{B'}^2/v^2}{g^2+g'^2} + 1\right) \mp \frac{g'\,\cos\theta_w\,\varepsilon'}{g\,\sin 2\theta'}\right]^{\frac{1}{2}}$$

Backup: Charged lepton masses

$$\mathcal{L}^{\ell}_{\text{mass}} = \begin{pmatrix} \bar{e}_L & \bar{L}^-_L & \bar{E}_L \end{pmatrix} \begin{pmatrix} y\frac{v}{\sqrt{2}} & \lambda_L \frac{v_X}{\sqrt{2}} & 0 \\ 0 & M_L & h\frac{v}{\sqrt{2}} \\ \lambda_E \frac{v_X}{\sqrt{2}} & k\frac{v}{\sqrt{2}} & M_E \end{pmatrix} \begin{pmatrix} e_R \\ L^-_R \\ E_R \end{pmatrix}$$

$$U_L = \begin{pmatrix} 1 - \frac{\lambda_L^2 v_X^2}{4M_L^2} & \frac{\lambda_L v_X}{\sqrt{2}M_L} - \frac{\lambda_L^3 v_X^3}{4\sqrt{2}M_L^3} & \frac{(k\lambda_L M_E + h\lambda_L M_L + \lambda_E M_E y) v v_X}{2M_E^3} \\ \frac{\lambda_L^3 v_X^3}{4\sqrt{2}M_L^3} - \frac{\lambda_L v_X}{\sqrt{2}M_L} & 1 - \frac{\lambda_L^2 v_X^2}{4M_L^2} & \frac{(kM_E M_L + h(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} \\ \frac{(h\lambda_L M_E - \lambda_E M_L y) v v_X}{4M_E^3} & -\frac{(kM_E M_L + h(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} & 1 \end{pmatrix}$$

$$_R = \begin{pmatrix} 1 - \frac{\lambda_E^2 v_X^2}{4M_E^2} & \frac{\lambda_L v v_X}{2M_L^2} - \frac{\lambda_E (kM_E M_L + h(M_E^2 + M_L^2)) v v_X}{2M_E^3 M_L} & \frac{\lambda_E v_X}{\sqrt{2}M_E} - \frac{\lambda_E^3 v_X^3}{4\sqrt{2}M_E^3} \\ \frac{(h\lambda_E M_L - \lambda_L M_E y) v v_X}{2M_E M_L^2} & 1 & \frac{(hM_E M_L + k(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} \\ \frac{\lambda_E^3 v_X^3}{4\sqrt{2}M_E^3} - \frac{\lambda_E v_X}{\sqrt{2}M_E} & -\frac{(hM_E M_L + k(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} & 1 - \frac{\lambda_E^2 v_X^2}{4M_E^2} \end{pmatrix}$$

Backup: Neutrino masses

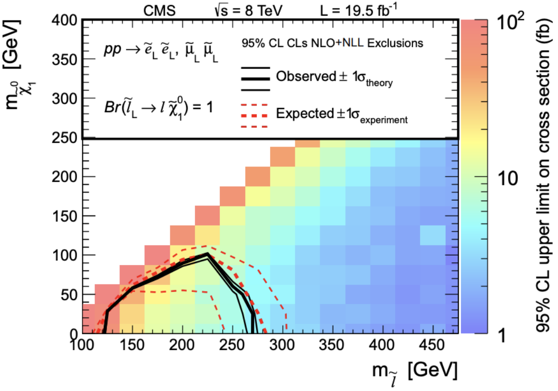
$$\mathcal{L}^{\nu}_{\text{mass}} = \begin{pmatrix}\nu^T & N^{c\,T} & L^{0\,T} & L^{0\,c\,T}\end{pmatrix}_L C^{-1} \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{v_X}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{v_X}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{v_X}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix} \begin{pmatrix} \nu \\ N^c \\ L^0 \\ L^{0c} \end{pmatrix}_L$$

$$\tilde{U}_\nu = \begin{pmatrix} 1 - \frac{\lambda_L^2 v_X^2}{4M_L^2} - \frac{v^2 y_\nu^2}{2v_X^2 y_M^2} & \frac{v y_\nu}{v_X y_M} & \frac{\lambda_L v_X}{2M_L} & \frac{\lambda_L v_X}{2M_L} \\ -\frac{v y_\nu}{v_X y_M} & 1 - \frac{v^2 y_\nu^2}{2v_X^2 y_M^2} & 0 & 0 \\ -\frac{\lambda_L v_X}{\sqrt{2} M_L} & -\frac{\lambda_L v y_\nu}{\sqrt{2} M_L y_M} & \frac{1}{\sqrt{2}} - \frac{\lambda_L^2 v_X^2}{4\sqrt{2} M_L^2} & \frac{1}{\sqrt{2}} - \frac{\lambda_L^2 v_X^2}{4\sqrt{2} M_L^2} \\ 0 & 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$m_\nu \simeq -\frac{y_\nu^2 v^2}{v_X y_M}\,, \quad U_\nu = \tilde{U}_\nu\, \text{diag}(U_P, 1, 1, 1)$$

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\,\mu,\,\tau} \sum_{i=1}^{9} \sum_{j=1}^{12} \bar{\ell}_i \,(U_L^\dagger)_{i\,\alpha}\, \gamma^\mu\, P_L\, (U_\nu)_{\alpha\, j}\, \nu_j + \text{H.c.}\,,$$

Backup: Collider bounds



Recast searches for slepton/neutralino pair production: $\boldsymbol{h_X} \to \tilde{\chi}^0$, $\boldsymbol{E, L} \to \tilde{l}$

$\Rightarrow$ $m_{h_X} \gtrsim 50\,\mathrm{GeV}$ and **physical vector-like lepton** mass $\gtrsim 120\,\mathrm{GeV}$