On the B-meson decay anomalies

Jonathan Kriewald

Laboratoire de Physique de Clermont-Ferrand

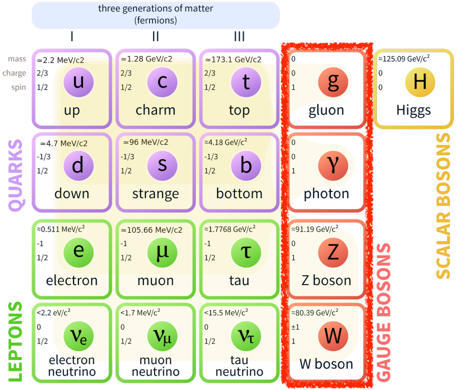
Based on: 2104.00015 with C. Hati, J. Orloff and A. M. Teixeira

22 October 2021

Flavour Physics

- In SM, force carriers

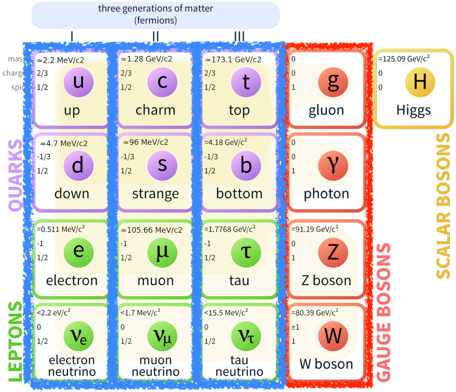
Standard Model of Elementary Particles



Flavour Physics

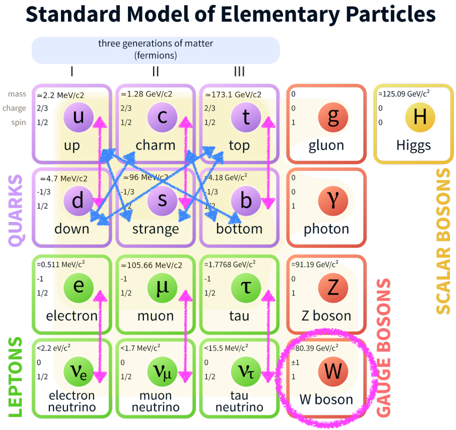
- In SM, force carriers and 3 generations of matter

Standard Model of Elementary Particles



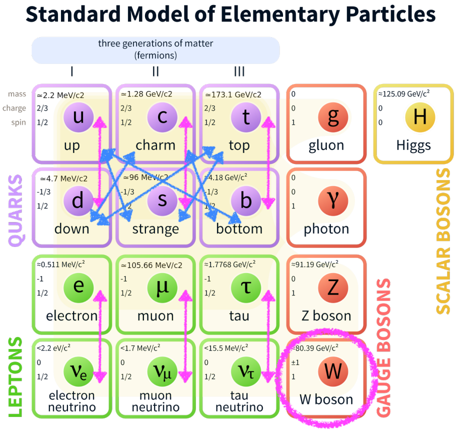
Flavour Physics

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



Flavour Physics

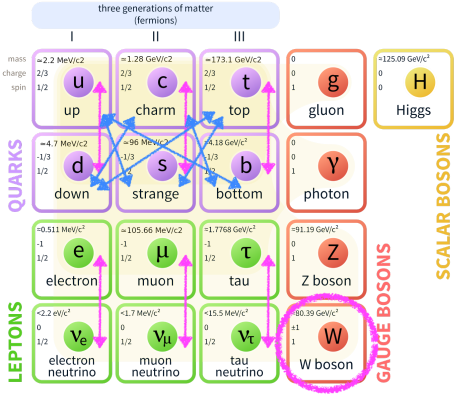
- In SM, force carriers and 3 generations of matter
- **Quark** sector: Higgs mechanism responsible for quark masses and **quark** flavour mixing
- Unitary **CKM** matrix ⇒ no flavour changing neutral current (**FCNC**) at *tree*-level



Flavour Physics

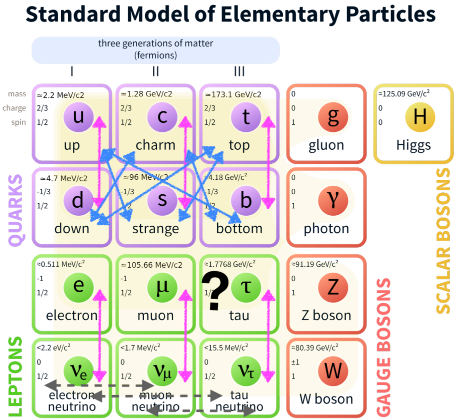
- In SM, force carriers and 3 generations of matter
- **Quark** sector: Higgs mechanism responsible for quark masses and **quark** flavour mixing
- Unitary **CKM** matrix ⇒ no flavour changing neutral current (**FCNC**) at *tree*-level
- **Lepton** sector: vanishing ν-masses ⇒ *accidental* lepton flavour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

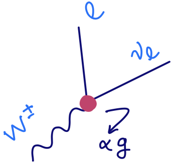


Lepton flavour universality

Only difference between leptons is their masses:

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

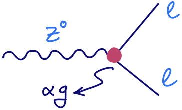
Accidental "symmetry" in the SM: couplings of electroweak gauge bosons are *"blind"* to lepton **flavour** ⇒ **Lepton Flavour Universality** (**LFU**)



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) %

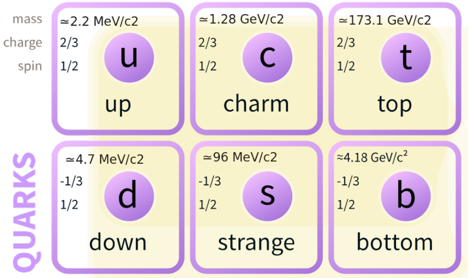
[PDG 2020]



⇒ **BUT:** current measurements in semi-leptonic B-meson decays and low energy precision observables appear to tell a different story!

Hadrons

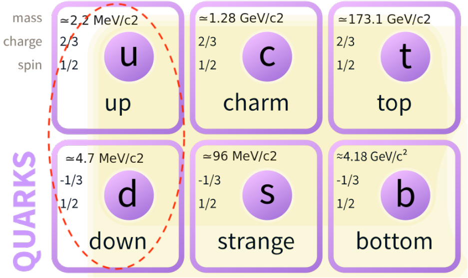
QCD bound states of quarks: Baryons $\sim$ 3 quarks, Mesons $\sim$ 1 quark, 1 anti-quark



Hadrons

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 $|\pi^0\rangle \sim \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}}$, $|\pi^+\rangle \sim |u\bar{d}\rangle$



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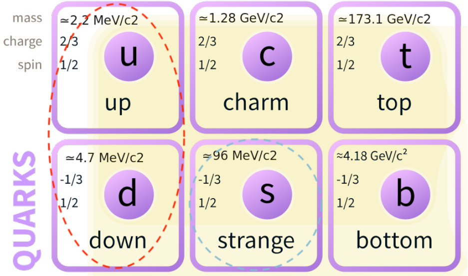
$\Rightarrow$ *K*aons: $|K^0\rangle \sim |\bar{s}d\rangle$, $|K^+\rangle \sim |\bar{s}u\rangle$



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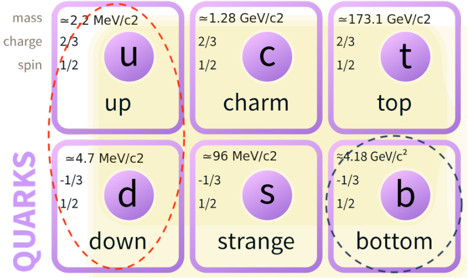
$\Rightarrow$ ***B*** mesons: $|B^0\rangle \sim |\bar{b}d\rangle$, $|B^+\rangle \sim |\bar{b}u\rangle$



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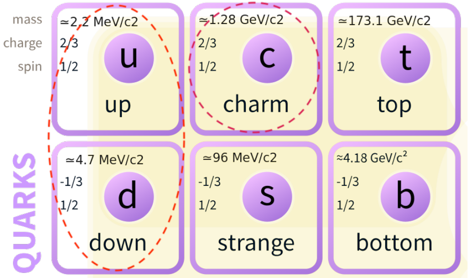
⇒ ***K***aons: $|K^0\rangle \sim |\bar{s}d\rangle$, $|K^+\rangle \sim |\bar{s}u\rangle$

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

⇒ ***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)



B-meson decays

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 (thanks to non-pert. QCD methods)
- **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 ($|V_{cb}|, |V_{ub}|, \gamma, \delta_{CP}$)
- 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

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- Theoretically "clean(... n theoretical approximations apply ... to non-pert. QCD methods)
- Experimentally acces ... design of LHCb), hundreds of decay ch ...
- Exciting **future progr** ...
- Charged current B-d ... $V_{cb}|, |V_{ub}|, \gamma, \delta_{CP}$)
- B and B_s-meson osc ... SM
- Due to extremely low ... ys 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) × 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) × 10^{-3}		2306
$\overline{D}^*_0(2420)^0\ell^+\nu_\ell$, $\overline{D}^{*0}_0 \to D^-\pi^+$		(2.5 ± 0.5) × 10^{-3}		–
$\overline{D}^*_2(2460)^0\ell^+\nu_\ell$, $\overline{D}^{*0}_2 \to D^-\pi^+$		(1.53 ± 0.16) × 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) × 10^{-3}		2254
$\overline{D}_1(2420)^0\ell^+\nu_\ell$, $\overline{D}^0_1 \to D^{*-}\pi^+$		(3.03 ± 0.20) × 10^{-3}		2084
$\overline{D}'_1(2430)^0\ell^+\nu_\ell$, $\overline{D}'^0_1 \to D^{*-}\pi^+$		(2.7 ± 0.6) × 10^{-3}		–
$\overline{D}^*_2(2460)^0\ell^+\nu_\ell$, $\overline{D}^{*0}_2 \to D^{*-}\pi^+$		(1.01 ± 0.24) × 10^{-3}	S=2.0	2065
$\overline{D}^0\pi^+\pi^-\ell^+\nu_\ell$		(1.7 ± 0.4) × 10^{-3}		2301
$\overline{D}^{*0}\pi^+\pi^-\ell^+\nu_\ell$		(8 ± 5) × 10^{-4}		2248
$D_s^{(*)-}K^+\ell^+\nu_\ell$		(6.1 ± 1.0) × 10^{-4}		–
$D_s^-K^+\ell^+\nu_\ell$		(3.0 $^{+1.4}_{-1.2}$) × 10^{-4}		2242

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B-meson decays

- B-mesons offer powerful ... cs:
- ... n theoretical
- ... to non-pert. QCD
- ... design of LHCb),
- ... $V_{cb}|, |V_{ub}|, \gamma, \delta_{CP})$
- ... SM
- ... ays are powerful

B^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$\ell^+ \nu_\ell X$	[///]	(10.99 ± 0.28) %		–
		(10.8 ± 0.4) %		–
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$D_s^{*-} K^+ \ell^+ \nu_\ell$		(2.9 ± 1.9) × 10^{-4}		2185
$\pi^0 \ell^+ \nu_\ell$		(7.80 ± 0.27) × 10^{-5}		2638
$\eta \ell^+ \nu_\ell$		(3.9 ± 0.5) × 10^{-5}		2611
$\eta' \ell^+ \nu_\ell$		(2.3 ± 0.8) × 10^{-5}		2553
$\omega \ell^+ \nu_\ell$	[///]	(1.19 ± 0.09) × 10^{-4}		2582
$\rho^0 \ell^+ \nu_\ell$	[///]	(1.58 ± 0.11) × 10^{-4}		2583
$p \overline{p} \ell^+ \nu_\ell$		(5.8 $^{+2.6}_{-2.3}$) × 10^{-6}		2467
$p \overline{p} \mu^+ \nu_\mu$		< 8.5 × 10^{-6}	CL=90%	2446
$p \overline{p} e^+ \nu_e$		(8.2 $^{+4.0}_{-3.3}$) × 10^{-6}		2467
$e^+ \nu_e$		< 9.8 × 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 ± 0.24) × 10^{-4}	S=1.2	2341
$\ell^+ \nu_\ell \gamma$		< 3.0 × 10^{-6}	CL=90%	2640
$e^+ \nu_e \gamma$		< 4.3 × 10^{-6}	CL=90%	2640
$\mu^+ \nu_\mu \gamma$		< 3.4 × 10^{-6}	CL=90%	2639
$\mu^+ \mu^- \mu^+ \nu_\mu$		< 1.6 × 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 $^{+1.1}_{-0.9}$) %		–
$\overline{c} X$		(97 ± 4) %		–

B-meson decays

B-mesons offer powerful … cs:

… n theoretical

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		(10.8 ± 0.4) %		–
		(9.7 ± 0.7) %		–
	[///]	(2.35 ± 0.09) %		2310

$D_s^{*-} K^+ \ell^+ \nu_\ell$		(2.9 ± 1.9) × 10^{-4}		2185
$\pi^0 \ell^+ \nu_\ell$		(7.80 ± 0.27) × 10^{-5}		2638
$\eta \ell^+ \nu_\ell$		(3.9 ± 0.5) × 10^{-5}		2611
$\eta' \ell^+ \nu_\ell$		(2.3 ± 0.8) × 10^{-5}		2553
$\omega \ell^+ \nu_\ell$	[///]	(1.19 ± 0.09) × 10^{-4}		2582
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$p \overline{p} \mu^+ \nu_\mu$		< 8.5 × 10^{-6}	CL=90%	2446
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$D_s^+ X$		(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 $^{+1.1}_{-0.9}$) %		–
$\overline{c} X$		(97 ± 4) %		–

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

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$p \overline{p} e^+ \nu_e$		(8.2		
$e^+ \nu_e$		< 9.8		
$\mu^+ \nu_\mu$		$2.90 \times 10^{-}$		
$\tau^+ \nu_\tau$		(1.09		
$\ell^+ \nu_\ell \gamma$		< 3.0		
$e^+ \nu_e \gamma$		< 4.3		
$\mu^+ \nu_\mu \gamma$		< 3.4		
$\mu^+ \mu^- \mu^+ \nu_\mu$		< 1.6		
Inclusive modes				
$D^0 X$		(8.6 ± 0.7) %		–
$\overline{D}^0 X$		(79 ± 4) %		–
$D^+ X$		(2.5 ± 0.5) %		–
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$D_s^+ X$		$(7.9 {}^{+1.4}_{-1.3})$ %		–
$D_s^- X$		$(1.10 {}^{+0.40}_{-0.32})$ %		–
$\Lambda_c^+ X$		$(2.1 {}^{+0.9}_{-0.6})$ %		–
$\overline{\Lambda}_c^- X$		$(2.8 {}^{+1.1}_{-0.9})$ %		–
$\overline{c} X$		(97 ± 4) %		–

$\pi^+ \ell^+ \ell^-$	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	[///]	$(4.51 \pm 0.23) \times 10^{-7}$	S=1.1	2617
$K^+ e^+ e^-$	B1		$(5.5 \pm 0.7) \times 10^{-7}$		2617
			$(4.41 \pm 0.22) \times 10^{-7}$	S=1.2	2612
			$(4.37 \pm 0.27) \times 10^{-7}$		2612
			$< 2.25 \times 10^{-3}$	CL=90%	1687
			$< 1.6 \times 10^{-5}$	CL=90%	2617
			$< 3.0 \times 10^{-5}$	CL=90%	2583
		]	$(1.01 \pm 0.11) \times 10^{-6}$	S=1.1	2564
			$(1.55 {}^{+0.40}_{-0.31}) \times 10^{-6}$		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

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

B-meson decays

B-mesons offer powerful … cs:

… n theoretical

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) %		–
		(10.8 ± 0.4) %		–
		(9.7 ± 0.7) %		–
	[lll]	(2.35 ± 0.09) %		2310

$D_s^{*-} K^+ \ell^+ \nu_\ell$		(2.9 ± 1.9) $\times 10^{-4}$		2185
$\pi^0 \ell^+ \nu_\ell$		(7.80 ± 0.27) $\times 10^{-5}$		2638
$\eta \ell^+ \nu_\ell$		(3.9 ± 0.5) $\times 10^{-5}$		2611
$\eta' \ell^+ \nu_\ell$		(2.3 ± 0.8) $\times 10^{-5}$		2553
$\omega \ell^+ \nu_\ell$	[lll]	(1.19 ± 0.09) $\times 10^{-4}$		2582
$\rho^0 \ell^+ \nu_\ell$	[lll]	(1.58 ± 0.11) $\times 10^{-4}$		2583
$p\bar{p}\ell^+ \nu_\ell$		(5.8 $^{+2.6}_{-2.3}$) $\times 10^{-6}$		2467
$p\bar{p}\mu^+ \nu_\mu$		< 8.5 $\times 10^{-6}$	CL=90%	2446
$p\bar{p}e^+ \nu_e$				
$e^+ \nu_e$				
$\mu^+ \nu_\mu$				
$\tau^+ \nu_\tau$				
$\ell^+ \nu_\ell \gamma$				
$e^+ \nu_e \gamma$				
$\mu^+ \nu_\mu \gamma$				
$\mu^+ \mu^- \mu^+ \nu_\mu$				
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 $^{+1.1}_{-0.9}$) %		–
$\bar{c} X$		(97 ± 4) %		–

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$K^+ e^+ e^-$	B1		(5.5 ± 0.7) $\times 10^{-7}$		2617
			… 2) $\times 10^{-7}$	S=1.2	2612
			… 7) $\times 10^{-7}$		2612
			$\times 10^{-3}$	CL=90%	1687
			$\times 10^{-5}$	CL=90%	2617
			$\times 10^{-5}$	CL=90%	2583
			… 1) $\times 10^{-6}$	S=1.1	2564
			…) $\times 10^{-6}$		2564
$K^*(892)^+ \mu^+ \mu^-$	B1		(9.6 ± 1.0) $\times 10^{-7}$		2560
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$\pi^+ \mu^+ \tau^-$	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

BUT: Significant **deviations from SM** observed in $B \to D^{(*)}\ell\nu$ and $B \to K^{(*)}\ell\ell$ decays!

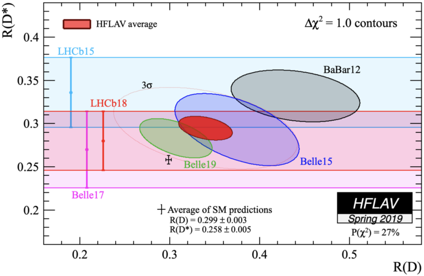
Observables in $b \to c\ell\nu$

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

- **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 $\sim \mathbf{3.1}\,\boldsymbol{\sigma}$!

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

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

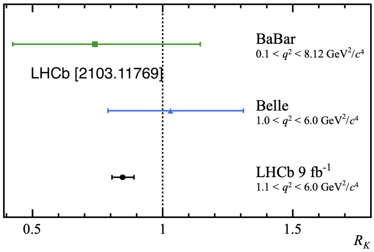
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$

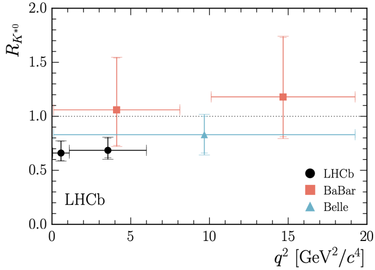
- **FCNC** *penguin* decay
- Theoretically clean: hadronic uncertainties cancel in the ratio
- **SM**: $\boldsymbol{R_K} = \boldsymbol{R_{K^*}} \simeq \mathbf{1}$
- **Exp.**: $\boldsymbol{R_K} = 0.846^{+0.044}_{-0.041}$ (NEW!)
  $\boldsymbol{R_{K^*}} = 0.69 \pm 0.12$

⇒ First **evidence** for violation of **LFU** @ $\mathbf{3.1}\,\boldsymbol{\sigma}$!

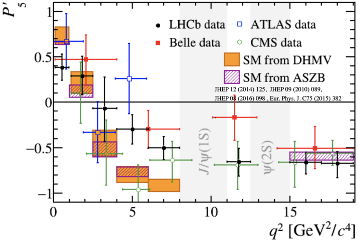
⇒ Strong hint on **new physics coupled** to $\boldsymbol{\mu}$! (and/or to $\boldsymbol{e}$)

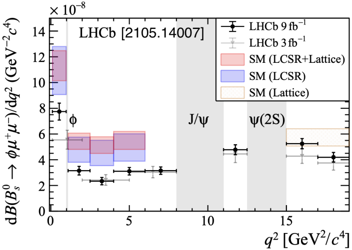
- (Recent measurements of $\boldsymbol{R_{K^0_S}}$ and $\boldsymbol{R_{K^{*+}}}$ corroborate the picture, but too low statistics)



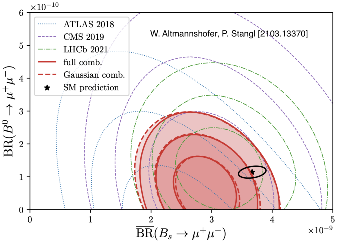


Observables in $b \to s\mu\mu$

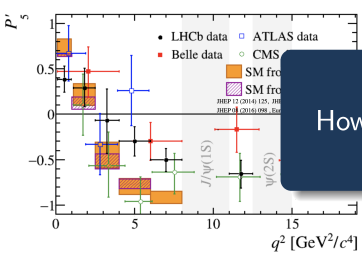


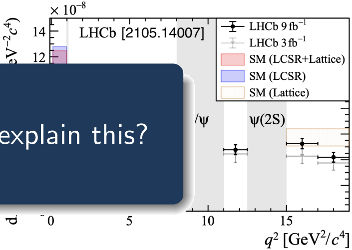


- Angular observables and BRs in $B^{+,0} \to K^*\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$, (local) deviations $2-3\,\sigma$!
- ATLAS, CMS and LHCb measurements of $\mathrm{BR}(B_{(s)} \to \mu^+\mu^-)$ consistent with SM



Observables in $b \to s\mu\mu$





How can we explain this?

- Angular observables and BRs in $B^{+,0} \to K^* \mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$, (local) deviations $2-3\,\sigma$!
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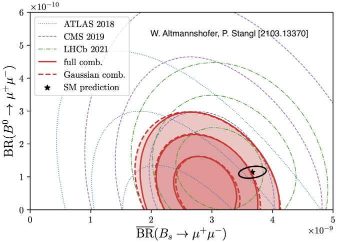
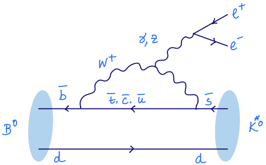
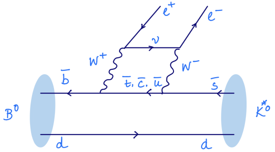


Electroweak penguins in $b \to s\ell\ell$

FCNC transitions in the SM are *"loop-suppressed"*: (e.g. $B^0 \to K^{0*}\ell^+\ell^-$)





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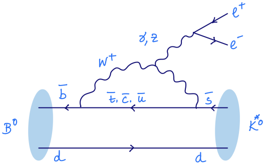
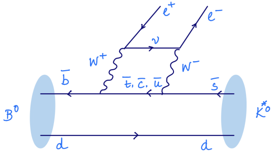
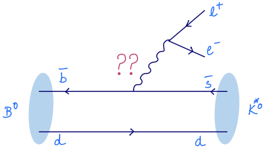
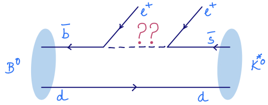




Heavy **BSM** contributions are *"mass suppressed"* $\Rightarrow$ If required to be large, must be present at *tree*-level:





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

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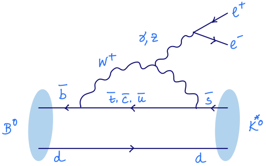

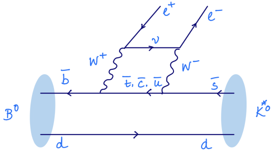

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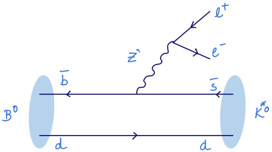

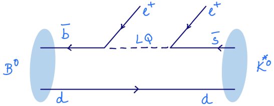

$\boldsymbol{Z'}$: BSM "cousin" of **SM** Z-boson

Leptoquarks: scalar or vector fields coupling **leptons** to **quarks**

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

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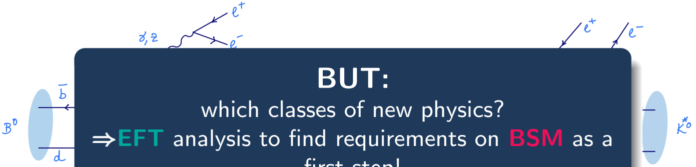
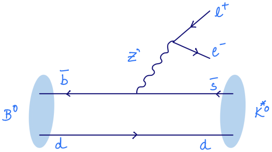
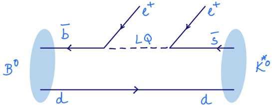


BUT:
which classes of new physics?
⇒**EFT** analysis to find requirements on **BSM** as a first step!

Heavy **BSM** contributions are *"mass suppressed"* ⇒ if required to be large, must be present at *tree*-level:





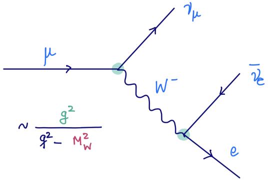
Z': BSM "cousin" of **SM** Z-boson

Leptoquarks: scalar or vector fields coupling **leptons** to **quarks**

EFT *intermezzo* I

Effective **F**ield **T**heory ≃ SM Lagrangian + non-renormalisable operators

Heavy fields are *"integrated out"*: only valid in certain energy regime



EFT *intermezzo* I

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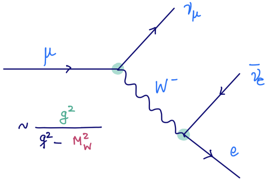
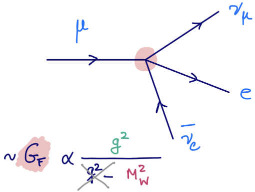


⇒

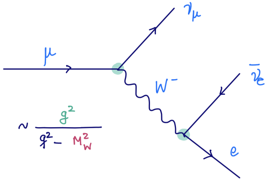


⇒**Fermi** constant G_F is an *effective* coupling constant

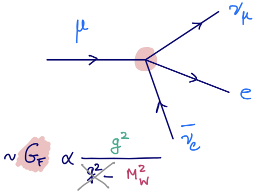
EFT *intermezzo* I

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

Heavy fields are *"integrated out"*: only valid in certain energy regime



⇒



⇒**Fermi** constant G_F is an *effective* coupling constant

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

- **Effective operators** $\mathcal{O}_k$ are accompanied by **effective coupling constants** 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

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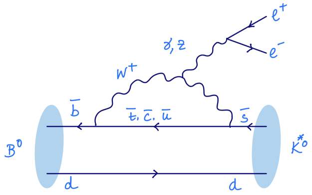

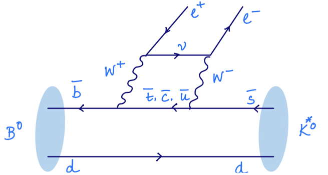

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$$\mathcal{O}_{10}^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, \gamma^\mu\, P_L d_j)(\bar{\ell}\, \gamma_\mu\, \gamma_5\, \ell')$$

$$\mathcal{O}_S^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \ell')\,,$$

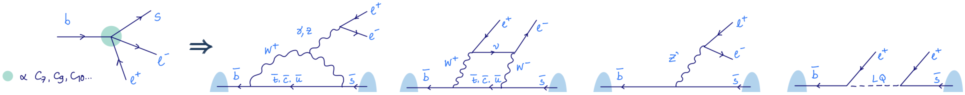
$$\mathcal{O}_P^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2}(\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \gamma_5\, \ell')\,,$$

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

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

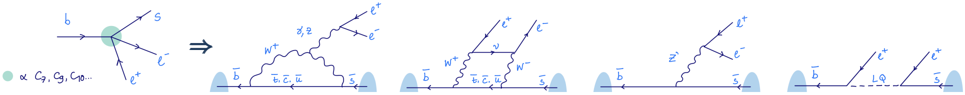
scale μ)

EFT *intermezzo* II



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

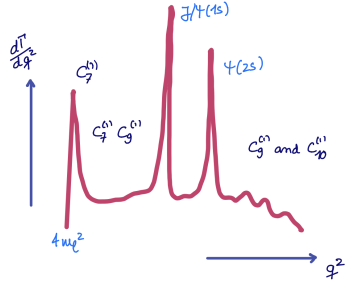
EFT *intermezzo* **II**



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

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

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

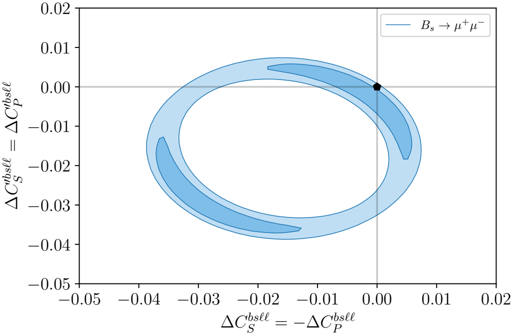


Constraints on (**pseudo-**) scalar operators

Weak effective theory fit @ $4.8\,\mathrm{GeV}$ for **all** $b \to s\ell\ell$ data:

$C_9^{bs\mu\mu}$	$C_{10}^{bs\mu\mu}$	$C_9^{\prime bs\mu\mu}$	$C_{10}^{\prime bs\mu\mu}$	C_7^{bs}
-1.17 ± 0.16	0.09 ± 0.14	0.41 ± 0.34	-0.19 ± 0.20	0.002 ± 0.014

$C_7^{\prime bs}$	$C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}$	$C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}$	Pull_{SM}	p-value
0.006 ± 0.017	-0.001 ± 0.025	-0.001 ± 0.025	5.8	49.7%

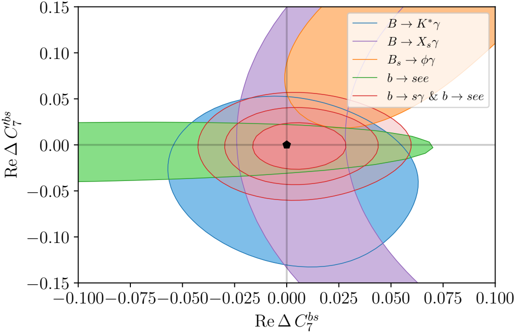


- Primed operators: **right-handed** quark current, vanishing in SM
- Scalar and pseudo-scalar operators tightly constrained by $\boldsymbol{B_s \to \mu^+\mu^-}$ and effective lifetime, consistent with 0

Constraints on dipoles

Weak effective theory fit @ $4.8\,\mathrm{GeV}$ for **all $b \to s\ell\ell$** data:

C_9	C_{10}	C'_9	C'_{10}	C_7	C'_7	$\mathrm{Pull}_{\mathrm{SM}}$
$1.18^{+0.17}_{-0.16}$	$0.11^{+0.15}_{-0.14}$	$0.34^{+0.33}_{-0.33}$	$-0.25^{+0.18}_{-0.17}$	$0.001^{+0.014}_{-0.014}$	$0.005^{+0.014}_{-0.014}$	**6.1**



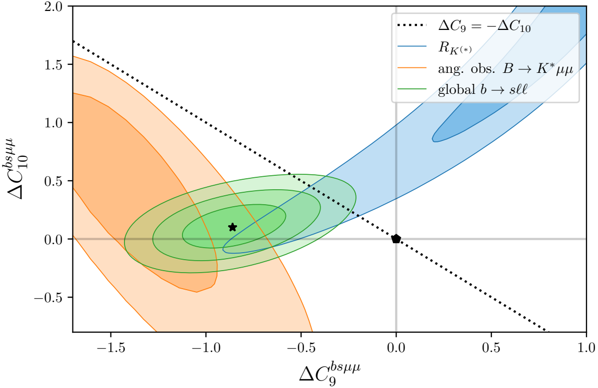
- Primed operators: **right-handed** quark current, vanishing in SM
- Dipole coefficients tightly constrained by $b \to s\gamma$ and $b \to see$, consistent with 0

DISCLAIMER: take pulls with a grain of salt, only a taste of how things are moving qualitatively...

C_9 vs C_{10}

Add **BSM** to **SM** contribution in LH V and A currents (SM: $C_9 \approx -C_{10} \rightsquigarrow V - A$)

$\Rightarrow$ best fit: $\Delta C_9^{bs\mu\mu} = \mathbf{-0.86}^{+0.18}_{-0.17}$, $\Delta C_{10}^{bs\mu\mu} = \mathbf{0.10}^{+0.12}_{-0.12}$, $\text{Pull}_{\text{SM}} = \mathbf{5.8}$



⬠: SM

★: best fit

small tension between R_K and R_{K^*} with ang. obs.

DISCLAIMER: take pulls with a grain of salt, only a taste of how things are moving qualitatively...

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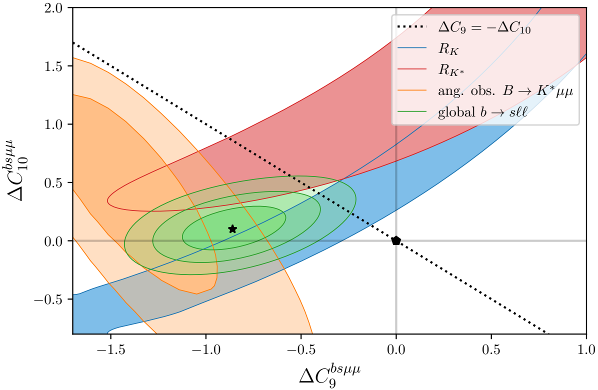


⬠: SM

★: best fit

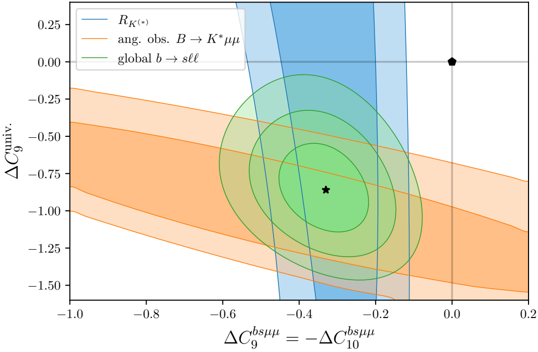
small tension between R_K and R_{K^*} with ang. obs.

DISCLAIMER: take pulls with a grain of salt, only a taste of how things are moving qualitatively...

$C_9 = -C_{10}$ vs $C_9^{\text{univ.}}$

First considered in Alguéro et.al. [1809.08447]: $C_9^{bsee} = \Delta C_9^{\text{univ.}}$, $C_9^{bs\mu\mu} = \Delta C_9^{bs\mu\mu} + \Delta C_9^{\text{univ.}}$

$\Rightarrow$ best fit: $\Delta C_9^{bs\mu\mu} = -\Delta C_{10}^{bs\mu\mu} = \mathbf{-0.33}^{+0.08}_{-0.08}$, $\Delta C_9^{\text{univ.}} = \mathbf{-0.86}^{+0.19}_{-0.17}$, $\text{Pull}_{\text{SM}} = \mathbf{6.4}$



⬠: SM

★: best fit

$C_9^{\text{univ.}}$ can be **RG running** induced (e.g. from large $C_9^{bs\tau\tau}$) $\rightsquigarrow R_{D^{(*)}}$?

Unknown $c\bar{c}$ corr. can mimic $C_9^{\text{univ.}}$ $\Rightarrow$ Lancierini et. al. [2104.05631]: $\mathbf{4.3\,\sigma}$ significance (with LEE)

DISCLAIMER: take pulls with a grain of salt, only a taste of how things are moving qualitatively...

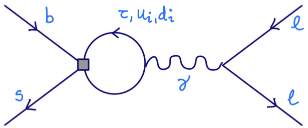
RG tales from the SMEFT

Consider Standard Model EFT (**SMEFT**) at $\Lambda_{\text{NP}} \sim \mathcal{O}(\text{TeV}) \gg \Lambda_{\text{EW}}$

Semileptonic operators:

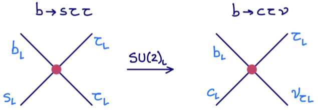
$SU(2)_L$-**singlet**: $(C_1)_{\ell q}^{ijmn} (\bar{L}_i \gamma_\mu L_j)(\bar{Q}_m \gamma^\mu Q_n)$

$SU(2)_L$-**triplet**: $(C_3)_{\ell q}^{ijmn} (\bar{L}_i \gamma_\mu \tau_a L_j)(\bar{Q}_m \gamma^\mu \tau_a Q_n)$



Tree-level matching SMEFT → WET:

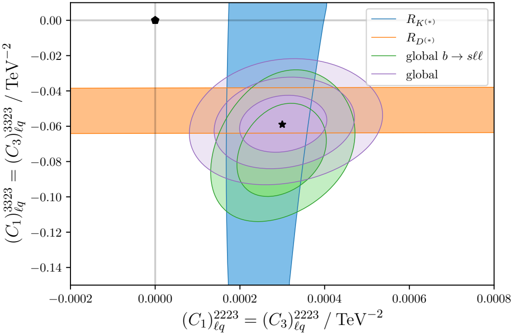
- $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} \propto (C_1)_{\ell q}^{2223} + (C_3)_{\ell q}^{2223}$
- $R_{D^{(*)}} \propto (C_3)_{\ell q}^{3323}$; also leads to $C_9^{bs\tau\tau} = -C_{10}^{bs\tau\tau}$ and under RG running to $C_9^{\text{univ.}}$
- Require $(C_1)_{\ell q}^{\ell\ell 23} = (C_3)_{\ell q}^{\ell\ell 23}$ to evade constraints from $B \to K^{(*)} \nu \bar{\nu}$!



SMEFT @ 2 TeV: $(C_1)^{2223}_{\ell q} = (C_3)^{2223}_{\ell q}$ vs $(C_1)^{3323}_{\ell q} = (C_3)^{3323}_{\ell q}$

$(C_1)^{3323}_{\ell q} = (C_3)^{3323}_{\ell q}$ $\Rightarrow$ large $C_9^{bs\tau\tau}$ via $SU(2)_L$ invariance $\Rightarrow$ RGE induced $C_9^{\text{univ.}}$

best fit: $(C_{1,3})^{2223}_{\ell q} = (\mathbf{3.0}^{+0.7}_{-0.6}) \times 10^{-4}\,\text{TeV}^{-2}$, $(C_{1,3})^{3323}_{\ell q} = -\mathbf{0.059}^{+0.01}_{-0.01}\,\text{TeV}^{-2}$, $\text{Pull}_{\text{SM}} = \mathbf{7.4}$



⬠: SM
★: best fit

Massive enhancement of $b \to s\tau\tau$ processes; for example: $\text{BR}(B_s \to \tau^+\tau^-)_{\text{SMEFT}} \simeq 10^3 \times \text{SM}$
Capdevila et. al. [1712.01919]

Candidate model: $V_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ vector **leptoquark** (e.g. Buttazzo et. al. [1706.07808])

Global likelihood now also contains $R_{D^{(*)}}$ and binned data for $\text{BR}(B \to D^{(*)}\ell\nu)$!

Requirements on (minimal) single-particle BSM explanations

- $b \to s\ell\ell$ requires **FCNC** at *tree*-level (competing with SM at 1-loop)
- $b \to c\ell\nu$ requires **charged** current at *tree*-level (competing with SM at *tree*-level)

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

⇒ Expect stringent constraints from **cLFV** observables (e.g. $B \to K\tau\mu$)

- 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, but heavily constrained from **cLFV**!

Extensive list of dedicated analyses, $\mathcal{O}(10^{23})$ relevant contributions...

Other approaches rely on more non-minimal field content (e.g. "4321"-models [EPJC 79(2019)4, 334], PS^3 [PLB 779(2018)317], RPV SUSY [PRD 102(2020)1, 015031] ...)

Conclusions and outlook

First **evidence** for **LFUV** in R_K!

- Waiting for R_{K^*} updates...
- Patterns of deviations in several $b \to s\mu\mu$ draw a more and more clear (and consistent) picture
- Slight tension between $R_{K^*} < R_K$ and $b \to s\mu\mu$ can be reduced by considering $C_9^{\text{univ.}}$

⇒ $C_9^{\text{univ.}}$ can be RG running induced; connection to $R_{D^{(*)}}$?

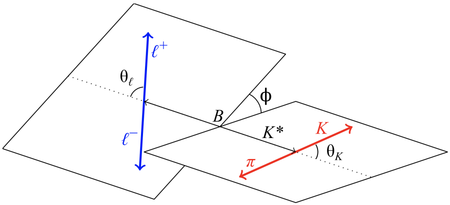
⇒ "Combined explanation" implies large $b \to s\tau\tau$

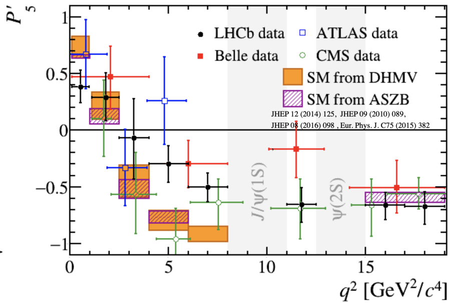
- SM extensions via V_1-leptoquark offer viable explanations for both B-decay anomalies
- Large region of the **parameter space** to be probed in the near **future!**

Thank you!!!

Bonus slides

Angular observables





Statistical setup

Likelihoods: $-2\Delta \log \mathcal{L} \approx \mathcal{O}^T (\mathcal{C}_{\text{exp}} + \mathcal{C}_{\text{theo}})^{-1} \mathcal{O}$ (see e.g. `smelli` [arXiv:1810.07698])
all observables (and their uncertainties) calculated with `flavio`

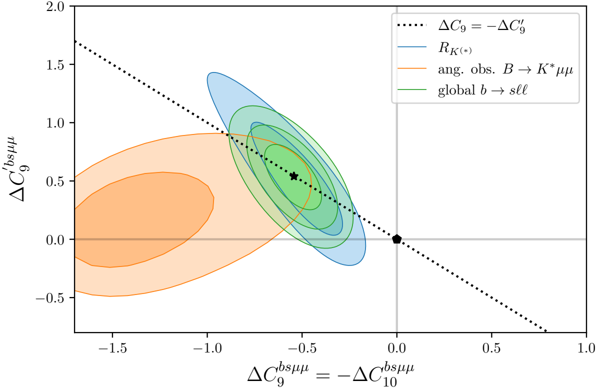
- **New**/**updated** **measurements**:
  - R_K, $q^2 \in [1.1, 6.0]\,\text{GeV}^2$
  - $\text{BR}(B^+ \to K^+ e^+ e^-)$, $q^2 \in [1.1, 6.0]\,\text{GeV}^2$
  - Updated measurement of $\text{BR}(B_{(s)} \to \mu^+ \mu^-)$
  - Angular data and binned BRs in $B_s \to \phi \mu^+ \mu^-$
- Other **observables** included:
  - $R_{K^{(*)}}$ measurements by LHCb, BaBar and Belle
  - Angular LFU Q_4, Q_5 measured by Belle
  - Angular data in $B^{+,0} \to K^* \mu^+ \mu^-$
  - Angular data in $B^0 \to K^* e^+ e^-$
  - (Binned) BR's of $B \to K^{(*)} \mu^+ \mu^-$
  - $\text{BR}(B \to K^* \gamma)$, $\text{BR}(B_s \to \phi \gamma)$, $\text{BR}(B \to X_s \gamma)$

DISCLAIMER: take absolute values of pulls with a grain of salt, only a taste of how things are moving qualitatively...

$C_9 = -C_{10}$ vs C_9'

Add **RH** (quark) V current C_9' to $C_9 = -C_{10}$

$\Rightarrow$ best fit: $\Delta C_9^{bs\mu\mu} = -\Delta C_{10}^{bs\mu\mu} = \mathbf{-0.54}^{+0.10}_{-0.10}$, $\Delta C_9'^{bs\mu\mu} = \mathbf{0.53}^{+0.18}_{-0.18}$, Pull$_{\text{SM}} = \mathbf{6.0}$



⬠: SM

★: best fit

Better, but ang. obs. vs. $R_{K^{(*)}}$ still not fully reconciled...

DISCLAIMER: take pulls with a grain of salt, only a taste of how things are moving qualitatively...

$C_9 = -C_{10}$ vs C_9'

Add **RH** (quark) ***V*** current C_9' to $C_9 = -C_{10}$

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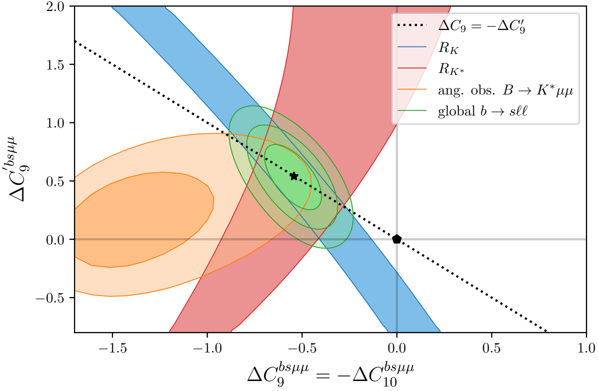


⬠: SM
★: best fit
Better, but ang. obs. vs. $R_{K^{(*)}}$ still not fully reconciled...

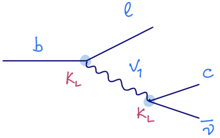
DISCLAIMER: take pulls with a grain of salt, only a taste of how things are moving qualitatively...

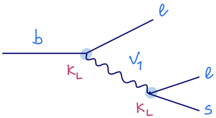
V_1 vector leptoquark

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

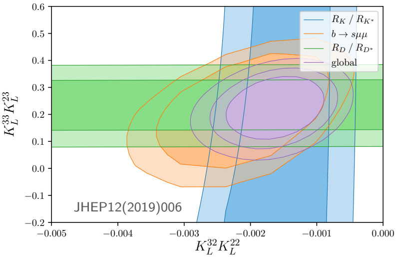
Leptoquark Lagrangian: $\mathcal{L} \supset V_1^\mu \left(\bar{d}_L^i \gamma_\mu \boldsymbol{K_L^{ik}} \ell_L^k + \bar{u}_L^j V_{ji}^\dagger \gamma_\mu \boldsymbol{K_L^{ik}} U_{kj}^{\mathsf{P}} \nu_L^j \right)$

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





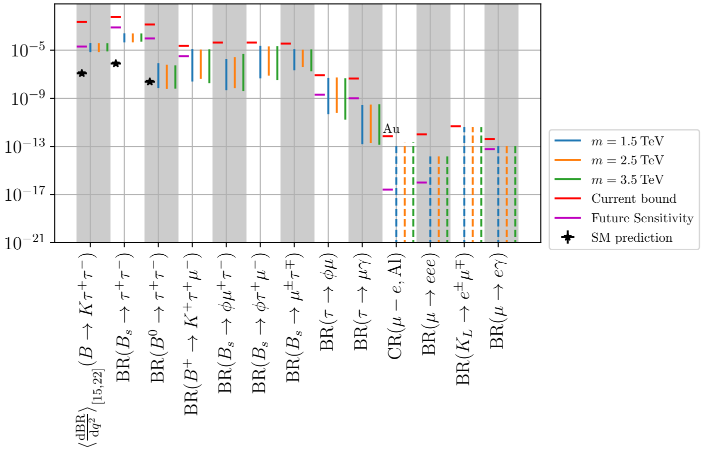
- $\boldsymbol{K_L^{23} K_L^{33}}$ contributes to $b \to c\tau\nu$ **and** $b \to s\tau\tau$
- (Large) $C_9^{bs\tau\tau}$ feeds universally into $C_9^{bs\mu\mu}$ and C_9^{bsee} (RG running) $\Rightarrow \Delta C_9^{\text{univ.}}$



LFV Prospects

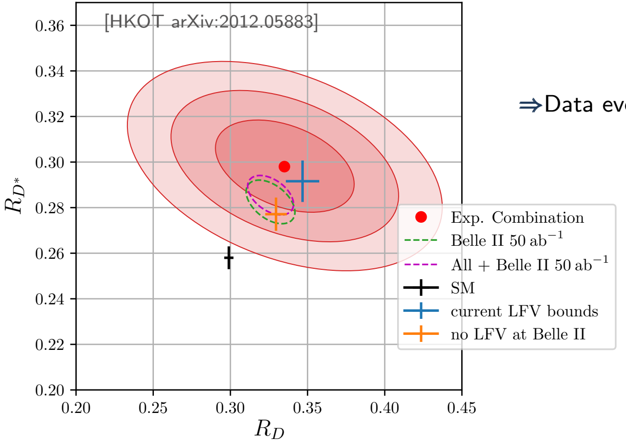
What does the future hold?

⇒ Fit of 9 **LQ** couplings ⇒ MCMC posterior distributions:



Prospects for $R_{D^{(*)}}$

BELLE II will improve sensitivities in several b and τ decay channels!
Fit of 9 **LQ** couplings:



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

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**

- Add n **vector-like** (VL) leptons mixing with (left-handed) SM leptons

effective LQ-q-ℓ couplings $K_L^{q\ell}$ 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**)

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

$\Rightarrow$ Required mixing pattern: 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...

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:

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