





Understanding the first observation of $B \rightarrow K \nu \bar{\nu}$ by Belle-II

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Based on [2301.06990, 2309.02246], in collaboration with L. Allwicher, D. Becirevic, G. Piazza and S. Rosauro-Alcaraz

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Outline

- I. Introduction
- **II. SM description**
- **III. Belle-II results**

IV. What can we learn from $B \to K^{(*)} \nu \bar{\nu}$?

- Lessons within the SM
- EFT implications
- Probing hidden sectors?
- V. Summary and outlook

Flavor physics

- Gauge sector of the SM entirely **fixed by symmetry**:
 - \Rightarrow Only a handful of parameters.
 - \Rightarrow Theory renormalizable and verified at the loop level.
- Flavor sector **loose**:
 - \Rightarrow 13 free parameters (masses and quark mixing) fixed by data.

$$\mathcal{L}_{\text{Yuk}} = -\frac{Y_d^{ij}}{Q_i} \overline{Q_i} d_{Rj} H - \frac{Y_u^{ij}}{Q_i} \overline{Q_i} u_{Rj} \widetilde{H} - \frac{Y_\ell^{ij}}{L_i} \overline{L_i} e_{Rj} H + \text{h.c.}$$

 \Rightarrow These (many) parameters exhibit a hierarchical structure which we do not understand.

What is the origin of flavor?

• Striking hierarchy of fermion masses [does not look accidental...]



• Why three families? Why do quarks and leptons mix in different ways?

$$V_{\rm CKM} = \begin{pmatrix} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{pmatrix} \qquad V_{\rm PMNS} = \begin{pmatrix} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{pmatrix}$$

One of the roles of flavor physics is to unveil symmetries beyond those present in the SM.

What is experiment telling us?

No **direct evidence** for New Physics in LHC data (presence of a mass gap?).

$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Model	$l.\gamma$	Jets†	Emiss	(£ dt[fb	-1] Lim	nit	¢.		Reference
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	model	.,,		T	J~[· · · · · · · · · · · · · · · · · · ·				menerenee
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	ADD $G_{KK} + g/q$	0 e,μ	1 – 4 j	Yes	36.1	M _D		7.7 TeV	n = 2	1711.03301
ADD CBH $ 2 $ $ 3/2$ M_{m} $m_$	ADD non-resonant $\gamma\gamma$	2γ	_	-	36.7	Ms		8.6 TeV	n = 3 HLZ NLO	1707.04147
ADD BH might $p_{12}r_{11}$ $\geq 2 = \mu$ $\geq 2 = -3$ Ma Ball c_{11} $m_{12} = -3$ Ball $c_{11} = -3$ Ba	ADD QBH	-	2 j	-	37.0	M _{th}		8.9 TeV	n = 6	1703.09127
ADD BH multiple $ 23$ $ 36$ Max 525 TeV $n=0, M=35$ TeV	ADD BH high $\sum p_T \ge$	1 e,μ	≥ 2 j	-	3.2	M _{th}	1.00	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	ADD BH multijet	-	≥ 3 j	_	3.6	M _{th}		9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma \gamma$	2γ	-	-	36.7	G _{KK} mass	100 C	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Bulk RS $G_{KK} \rightarrow WW/ZZ$ mult	ti-channe	el		36.1	G _{KK} mass		2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell v q q$	1 e,µ	2j/1J	Yes	139	G _{KK} mass		2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
2 UED, RPP 1 e, $\mu \ge 2$ b, 2 i, yea 36.1 K (mass) 1 B TeV Ter (1, 1); (A(A ¹¹) \rightarrow (1) $=1$) (16) SSM Z' \rightarrow rr. 2 e, μ 36.1 Z (mass) 2.47 TeV (1, 1); (A(A ¹¹) \rightarrow (1) $=1$) (16) Lapophobic Z' \rightarrow b - 36.1 Z (mass) 2.47 TeV (1, 1); (A(A ¹¹) \rightarrow (1) $=1$) (16) (17) (17) (17) (17) (17) (17) (17) (17) (17) (17) (17) (17) (17) (18) (18) (17) (18) (17) (18) (18) (17) (18) (17) (18) (18) (18) (17)	Bulk RS $g_{KK} \rightarrow tt$	1e,µ 2	\geq 1 b, \geq 1J/	2j Yes	36.1	g _{KK} mass	1.1.1	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	2UED / RPP	1 e, µ	$\geq 2 \text{ b}, \geq 3$	j Yes	36.1	KK mass		1.8 TeV	Tier (1,1), $\mathcal{B}(\mathcal{A}^{(1,1)} \rightarrow tt) = 1$	1803.09678
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	SSM $Z' \to \ell \ell$	2 e, µ	-	-	139	Z' mass		5.1 TeV		1903.06248
Laptophobic $T \rightarrow bb$ -2 b-36.12 mas2.1 feV7 mas3.1 feV7 mas3.0 feVSSM $W' \rightarrow tr$ 1 e, μ -Yes139Y mass6.0 TeV6.0 TeV9.0 feV9.0 feV<	SSM $Z' \rightarrow \tau \tau$	2τ	-	_	36.1	Z' mass		2.42 TeV	2	1709.07242
Leptopholic $Z' \rightarrow tt$ $0 \ e_{\mu} \ \geq 1b \ \geq 2.4$ yes 139 $Z' mass$ $4.1 \ \text{FeV}$ $1/m = 1.2\%$ 200 SSM $W' \rightarrow tr'$ $1 \ e_{\mu} \ -$ Yes 36.1 W' mass $3.7 \ \text{FeV}$ V'' $V'' = 10^{10}$ $9'' = 3$ $9''' = 3$ <	Leptophobic $Z' \rightarrow bb$	-	2 b	-	36.1	Z' mass		2.1 TeV		1805.09299
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Leptophobic $Z' \rightarrow tt$	0 e, µ	≥ 1 b, ≥ 2 .	J Yes	139	Z' mass		4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	SSM $W' \rightarrow \ell v$	1 e, µ	-	Yes	139	W' mass	1.00	6.0 TeV		1906.05609
HYT W'' - WZ - h' og model B 10 W'' mass 4.3 TeV $k = 3$ Box B	SSM $W' \rightarrow \tau v$	1τ	-	Yes	36.1	W' mass		3.7 TeV		1801.06992
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	HVT $W' \rightarrow WZ \rightarrow \ell \nu q q$ model B	1 e,µ	2j/1J	Yes	139	W' mass	100 C	4.3 TeV	$g_V = 3$	2004.14636
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	HVT $V' \rightarrow WV \rightarrow qqqq$ model B	0 e, µ	2 J	-	139	V' mass		3.8 TeV	$g_V = 3$	1906.08589
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	HVT $V' \rightarrow WH/ZH$ model B mult	ti-channe	el		36.1	V' mass		2.93 TeV	$g_V = 3$	1712.06518
LHSM $W_R \to tb$ multi-channel 36.1 We mass 3.25 TeV $m(N_R) = 0.5 TeV, g_L = g_R$ 18 LHSM $W_R \to \mu W_R$ 2μ J J - 80 We mass 5.0 TeV $m(N_R) = 0.5 TeV, g_L = g_R$ 196 Cl qqq - 2 is μV_R 2 is $\mu \geq 1$ b ≥ 1 j We mass 5.0 TeV $m(N_R) = 0.5 TeV, g_L = g_R$ 197 Cl (tqq 2 e, μ - - 3.0 M 2.5 TeV $m(R_R) = 0.5 TeV, g_L = g_R$ 197 Cl (tqq 2 e, μ - - 3.0 M 2.57 TeV $[c_{trl} = 4\pi$ 181 Axial vector mediator (Dirac DM) 0 e, μ 1 - 4 i Yes 3.6 1 mem. 5 TeV $g_R = 0.0 m(\chi) = 1 0 eV$ $r_1 r_1 r_1 r_1 r_2 r_2 r_2 r_1 r_2 r_2 r_1 r_2 r_1 r_1 r_1 r_1 r_2 r_2 r_2 r_1 r_2 r_1 r_1 r_1 r_2 r_1 r_2 r_2 r_2 r_1 r_2 r_1 r_1 r_1 r_2 r_1 r_2 r_2 r_2 r_2 r_1 r_2 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_2 r_2 r_2 r_1 r_2 r_2 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_2 r_2 r_2 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_1 r_2 r_2 r_2 r_1 r_2 r_2 r_2 r_1 r_2 r_1 r_1 r_$	HVT $W' \rightarrow WH$ model B	0 e, µ	≥ 1 b, ≥ 2 .	J	139	W' mass		3.2 TeV	$g_V = 3$	CERN-EP-2020-0
LHSM $W_R \rightarrow \mu N_R$ 2μ 1 J - 80 We mass 5.0 TeV $m(N_r) = 0.5 W_{R}, r = gr 187 Cl qaqq - 2 - 37.0 A 21.8 TeV m_{L} 35.8 TeV m_{L} 157 167 158 m_{L} = gr 157 167 158 m_{L} = gr 157 167 168 158 168 158 168 158 168 $	LRSM $W_R \rightarrow tb$ mult	ti-channe	el		36.1	W _R mass		3.25 TeV		1807.10473
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	LRSM $W_R \rightarrow \mu N_R$	2μ	1 J	-	80	W _R mass		5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	CI qqqq	-	2 j	-	37.0	٨			21.8 TeV η _{LL}	1703.09127
Cittet $\geq 1 e, \mu$ $\geq 1 b \geq 1 j$ Yes 36.1 A 2.57 TeV $ f_{e_1} = 4\pi$ 187 Axial-vector mediator (Dirac DM) $0 e, \mu$ $1 - 4 j$ Yes 36.1 mead 5 TeV $g_{=0.25}, g_{=1.0}, m(\chi) = 1 GeV$ 177 Colored scalar mediator (Dirac DM) $0 e, \mu$ $1 J, s \downarrow j$ Yes 36.1 Mead 67 TeV $g_{=0.25}, g_{=1.0}, m(\chi) = 1 GeV$ 177 Scalar reson. $\phi = t\chi$ (Dirac DM) $0 = e, \mu$ $1 J, s \downarrow j$ Yes 36.1 LO mass 1 TeV $g_{=0.25}, g_{=0.1}, m(\chi) = 1 GeV$ 167 Scalar LO 2 ^{rdi} gen 1.2μ $\geq 2 j$ Yes 36.1 LO mass 1 TeV $\beta = 1$ 196 Scalar LO 3 ^{rdi} gen $0 - 1 e, \mu$ $2 b$ Yes 36.1 LO mass 1.3 TeV $\beta (LO_2^c \to tr) = 1$ 196 Scalar LO 3 ^{rdi} gen $0 - 1 e, \mu$ $2 b$ Yes 36.1 LO mass 1.3 TeV $\beta (LO_2^c \to tr) = 0$ 196 Scalar LO 3 ^{rdi} gen $0 - 1 e, \mu$ $2 b$ Yes 36.1 LO mass 1.3 TeV $\beta (LO_$	Cl llqq	2 e, µ	_	-	139	٨	100 C		35.8 TeV η _{LL}	CERN-EP-2020-0
Axial-vector mediator (Dirac DM)0e, μ 1-4 jYes36.1Mad55 TeV $g_{q}=0.25, g_{s}=1, n, n(x) = 1 \text{GeV}$ 177Colored scalar mediator (Dirac DM)0e, μ 1-4 jYes36.1Mad00 GeV π^{-1}	CI tttt	≥1 e,µ	≥1 b, ≥1 j	Yes	36.1	۸		2.57 TeV	$ C_{4t} = 4\pi$	1811.02305
Colored scalar mediator (Dirac DM) $0e, \mu$ $1-4j$ Yes 36.1 mess 67 TeV $g^{r+10}, m(x) = 1 \text{ GeV}$ $m(x) < 100 \text{ GeV}$	Axial-vector mediator (Dirac DM)	0 e,μ	1 – 4 j	Yes	36.1	m _{med}	1	55 TeV	g_q =0.25, g_χ =1.0, $m(\chi) = 1$ GeV	1711.03301
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Colored scalar mediator (Dirac DM)	0 e, µ	1 – 4 j	Yes	36.1	m _{med}		.67 TeV	$g=1.0, m(\chi) = 1 \text{ GeV}$	1711.03301
Scalar reson. $\phi \to t_{\chi}$ (Dirac DM) 0-1 e, μ 1 b, 0-1 J Yes 36.1 m_{μ} 3.4 TeV $y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$ 1 arr Scalar LO 1 st gen 1.2 e ≥ 2] Yes 36.1 LO mass 1 TeV $\beta = 1$ 196 Scalar LO 3 rd gen 2.7 2.b - 36.1 LO ⁿ mass 1.03 TeV $\beta (LQ_3^{-} \to r) = 1$ 196 Scalar LO 3 rd gen 0.1 e, μ 2.b Yes 36.1 LO ⁿ mass 1.03 TeV $\beta(LQ_3^{-} \to r) = 1$ 196 Scalar LO 3 rd gen 0.1 e, μ 2.b Yes 36.1 LO ⁿ mass 1.03 TeV $\beta(LQ_3^{-} \to r) = 1$ 196 VLO B T → Ht/Zt/Wb+X multi-channel 36.1 T mass 1.3 TeV SU(2) doublet 186 VLQ F 5/3 Ts/3 [Ts/3 → Wt + X 2(S)/23 e, $\mu \geq 1$ y Yes 36.1 Yes 36.1 </td <td>$VV_{\chi\chi}$ EFT (Dirac DM)</td> <td>0 e,μ</td> <td>$1 J_{i} \leq 1 j$</td> <td>Yes</td> <td>3.2</td> <td>M.</td> <td>700 GeV</td> <td></td> <td>$m(\chi) < 150 \text{ GeV}$</td> <td>1608.02372</td>	$VV_{\chi\chi}$ EFT (Dirac DM)	0 e,μ	$1 J_{i} \leq 1 j$	Yes	3.2	M.	700 GeV		$m(\chi) < 150 \text{ GeV}$	1608.02372
Scalar LQ 1 st gen 1,2 e $\geq 2j$ Yes 36.1 LQ mass 1 TeV $\beta = 1$ 190 Scalar LQ 2 st gen 2 r 2 b - 36.1 LQ mass 1 3 TeV $\beta = 1$ 190 Scalar LQ 3 st gen 2 r 2 b - 36.1 LQ mass 1 3 TeV $\beta = 1$ 190 Scalar LQ 3 st gen 2 r 2 b - 36.1 LQ mass 1 03 TeV $\beta (LQ'_1 \rightarrow r) = 1$ 190 Scalar LQ 3 st gen 0 - 1 e, μ 2 b Yes 36.1 LQ mass 970 GeV $\beta (LQ'_1 \rightarrow r) = 0$ 190 VLQ T/>LQ T// JT// HU// S// S(2 e, $\mu = 1 b, \geq 1$] Yes 36.1 T mass 1.3 TeV SU(2) doublet 180 VLQ T// JT// J 91 b, ≥ 1] Yes 36.1 Y mass 64 TeV $\beta (T_{513} \rightarrow W) = 1, c_r(T_{513}W) = 1$ 180 VLQ T// J/ Y = h / + L// 2 L) ≥ 1 Yes 36.1 Y mass 1.85 TeV $\beta (Y \rightarrow W) = 1, c_R(W) = 1$ 180 VLQ Q → WdWq 1 e, $\mu < 2$ Y Yes 20.3 R mass 690 GeV $\beta (T = V)$ $\beta (T$	Scalar reson. $\phi \to t\chi$ (Dirac DM) 0	-1 e,μ	1 b, 0-1 J	Yes	36.1	m _ø		3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$	1812.09743
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Scalar LQ 1 st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass	1.	TeV	$\beta = 1$	1902.00377
Scalar LQ 3'd gen 2τ $2b$ -36.1 LQ ^a mass 1.03 TeV $\mathcal{B}(LQ_{3}^{c} \rightarrow br) = 1$ 196 Scalar LQ 3'd gen $0.1 e, \mu$ $2b$ Yes 36.1 LCG ^a mass 1.03 TeV $\mathcal{B}(LQ_{3}^{c} \rightarrow br) = 1$ 196 VLQ T $\rightarrow Ht/Zt/Wb + X$ multi-channel 36.1 T mass 1.3 TeV $SU(2)$ doublet 196 VLQ T $\rightarrow Ht/Zt/Wb + X$ multi-channel 36.1 T mass 1.3 TeV $SU(2)$ doublet 196 VLQ T $\rightarrow Wt/Zb + X$ multi-channel 36.1 T mass 1.3 TeV $SU(2)$ doublet 196 VLQ T $373 T_{5/3} T_$	Scalar LQ 2 nd gen	1,2 µ	≥ 2 j	Yes	36.1	LQ mass	1	56 TeV	$\beta = 1$	1902.00377
Scalar LQ 3 rd gen 0-1 e, μ 2 b Yes 36.1 LQ ⁴ mass 970 GeV $\beta(LQ_{3}^{c} \to r) = 0$ 190 VLQ 7T \rightarrow Ht/Zt/Wb $+ X$ multi-channel 36.1 T mass 1.3 TeV SU(2) doublet 180 VLQ B \rightarrow Wt/Zb $+ X$ multi-channel 36.1 T mass 1.3 TeV SU(2) doublet 180 VLQ T ₅₁ /T ₅₁ /T ₅₀ \rightarrow Wt $+ X$ 2(S)/23 e, $\mu \ge 1$ b, ≥ 1 yes 36.1 T mass 1.34 TeV SU(2) doublet 180 VLQ T ₅₁ /T ₅₁ /T ₅₀ \rightarrow Wt $+ X$ 1 e, $\mu \ge 1$ b, ≥ 1 yes 36.1 T mass 1.85 TeV $\beta(T, \nabla_{51} \rightarrow Wt) = 1, c(T_{51} \rightarrow Wt) = 1$ 180 VLQ $Q \rightarrow Wdyq$ 1 e, $\mu \ge 1$ b, ≥ 1 yes 78.8 B mass 1.21 V V $\lambda = 0.5$ ATLAS-C VLQ $Q \rightarrow Wdyq$ 1 e, $\mu \ge 4$ y Yes 20.3 Q mass 690 GeV $\lambda = 0.5$ $\lambda = 0.5$ ATLAS-C Excited quark $a^{*} \rightarrow qg$ - 1 b, 1 j - 36.7 a^{*} mass 2.6 TeV $\lambda = 3.0$ TeV $\lambda = 3.0$ TeV 1192 Excited lepton t^{*} 3 e, μ, τ - 2.0	Scalar LQ 3rd gen	2τ	2 b	_	36.1	LQ ^u ₃ mass	1.03 TeV		$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
VLQ $TT \rightarrow Ht/Zt/Wb + X$ VLQ $BB \rightarrow Wt/Zb + X$ multi-channelmulti-channel36.1T mass1.3TeVSU(2) doublet180VLQ $BB \rightarrow Wt/Zb + X$ VLQ $P \rightarrow Wb + X$ 1 e, $\mu \ge 1$ b, ≥ 1 jYes36.1T mass1.34TeVSU(2) doublet180VLQ $Y \rightarrow Wb + X$ 1 e, $\mu \ge 1$ b, ≥ 1 jYes36.1Y mass64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 180VLQ $Y \rightarrow Wb + X$ 0 e, $\mu, 2 \gamma \ge 1$ b, ≥ 1 jYes36.1Y mass1.85 TeV $\mathcal{B}(T_{7/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 181VLQ $Q \rightarrow WqWq$ 1 e, $\mu \ge 4$ jYes20.3Q mass690 GeV1.85 TeV $\mathcal{B}(T_{7/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 185Excited quark $q^* \rightarrow qg$ -2 j-139q* mass1.21 TeV \mathcal{N} only u* and d*, $\Lambda = m(q^*)$ 197Excited quark $b^* \rightarrow bg$ -1 b, 1 j-36.1b* mass2.6 TeVonly u* and d*, $\Lambda = m(q^*)$ 197Excited lepton ℓ^* 3 e, μ, τ 20.3 ℓ^* mass3.0 TeV $\Lambda = 3.0$ TeV $\Lambda = 3.0$ TeV14Excited lepton ℓ^* 3 e, μ, τ 20.3 ℓ^* mass560 GeV M_{0} mass M_{0} mass3.2 TeV $m(W_R) = 4.1$ TeV, $g_L = g_R$ MtLS-CType III Seesaw1 e, $\mu \ge 2$ jYes79.8Ne mass560 GeV M_{0} mass M_{0} GeV $M(W_R) = 4.1$ TeV, $g_L = g_R$ MtLS-CHiggs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2.3, 4 e, μ (SS)3.6.1 <t< td=""><td>Scalar LQ 3rd gen 0</td><td>-1 e,μ</td><td>2 b</td><td>Yes</td><td>36.1</td><td>LQ³ mass</td><td>970 GeV</td><td></td><td>$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$</td><td>1902.08103</td></t<>	Scalar LQ 3 rd gen 0	-1 e,μ	2 b	Yes	36.1	LQ ³ mass	970 GeV		$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
VLQ $BB \rightarrow Wt/Zb + X$ NLQ $BB \rightarrow Wt/Zb + X$ multi-channel36.1 $T_{5/3}$ massB mass1.34 TeVSU(2) doublet $2(T_{5/3} \rightarrow Wt + X)$ 1000000000000000000000000000000000000	VLQ $TT \rightarrow Ht/Zt/Wb + X$ mult	i-channe	el l		36.1	T mass	1.3	TeV	SU(2) doublet	1808.02343
VLQ $T_{5/3}T_{5/3}T_{5/3} \to Wt + X$ $2(SS)/\geq 3 e, \mu \geq 1 b, \geq 1 j$ Yes 36.1 $T_{5/3}$ mass 64 TeV $\mathcal{B}(T_{5/3} \to Wt) = 1, c(T_{5/3}Wt) = 1$ 165 TeV VLQ $Y \to Wb + X$ $1 e, \mu \geq 1 b, \geq 1 j$ Yes 36.1 Y mass 1.85 TeV $\mathcal{B}(T_{5/3} \to Wt) = 1, c(T_{5/3}Wt) = 1$ 168 TeV VLQ $Q \to WdWq$ $1 e, \mu \geq 4 j$ Yes 20.3 Q mass 690 GeV \mathcal{V} $\mathcal{K}_{g=0.5}$ $\mathcal{H}(AS-C)$ Excited quark $q^* \to qg$ $ 2 j$ $ 36.1$ q^* mass 6.7 TeV only u* and d*, $\Lambda = m(q^*)$ 167 TeV Excited quark $s^* \to dg$ $ 1 b, 1 j$ $ 36.1$ \mathbf{V} mass 2.6 TeV only u* and d*, $\Lambda = m(q^*)$ 177 TeV Excited quark $s^* \to dg$ $ 1 b, 1 j$ $ 36.1$ t^* mass 2.6 TeV $\Lambda = 3.0 \text{ TeV}$ 167 TeV Excited quark $s^* \to dg$ $ 2 j$ Yes 79.8 N^0 mass 2.6 TeV $\Lambda = 3.0 \text{ TeV}$ 144 TeV Excited lepton t^* $3 e, \mu, \tau$ $ 20.3$ V^* mass 560 GeV $\Lambda = 3.0 \text{ TeV}$ 144 TeV Type III Seesaw $1 e, \mu \geq 2 j$ Yes 79.8 N^0 mass 560 GeV $M_0 mass$ 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 186 TeV Higgs triplet $H^{\pm\pm} \to \ell\ell$ $2,3,4 e, \mu(SS)$ $ 36.1$ $N_0 mass$ 300 GeV $M_0 M_0 H_0^{\pm\pm} \to \ell\tau$ 100 PV Higgs triplet $H^{\pm\pm} \to \ell\ell$ 2	$VLQ BB \rightarrow Wt/Zb + X$ mult	i-channe			36.1	B mass	1.34	TeV	SU(2) doublet	1808.02343
VLQ $Y \rightarrow Wb + X$ 1 $e, \mu \geq 1 b, \geq 1 j$ Yes36.1Y mass1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ $x_{g=} 0.5$ $x_{g=} $	VLQ $T_{5/3}T_{5/3} T_{5/3} \to Wt + X$ 2(S	S)/≥3 e,µ	u ≥1 b, ≥1 j	Yes	36.1	T _{5/3} mass		64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$	1807.11883
VLQ $B \rightarrow Hb + X$ VLQ $QQ \rightarrow WqWq$ $0 e,\mu, 2 \gamma \geq 1 b, \geq 1j$ YesYes79.8 Q massB mass1.21 T G mass $\kappa_B = 0.5$ ATLAS-C 150Excited quark $q^* \rightarrow qg$ $ 2j$ $-$ 139 q mass q^* mass 690 GeV only u^* and $d^*, \Lambda = m(q^*)$ 150 150Excited quark $q^* \rightarrow qg$ $ 2j$ $-$ 139 q mass q^* mass 690 GeV only u^* and $d^*, \Lambda = m(q^*)$ 199 170Excited quark $q^* \rightarrow qg$ $ 1 b, 1 j$ $ 36.7$ q mass q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$ 199 170Excited quark $b^* \rightarrow bg$ $ 1 b, 1 j$ $ 36.7$ q mass p^* mass 2.6 TeV $n = 0.5$ $\Lambda = 3.0 \text{ TeV}$ 160 160Excited lepton t^* $3 e, \mu, \tau$ $ 20.3$ t^* mass 560 GeV $\Lambda = 1.6 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$ 144 $\Lambda = 1.6 \text{ TeV}$ Type III Seesaw $1 e, \mu \geq 2j$ Yes 79.8 N^0 mass 560 GeV $N_0 mass$ 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ $M_1W_2 =$	$VLQ \ Y \to Wb + X$	1 e, µ	$\geq 1 \text{ b}, \geq 1 \text{ j}$	Yes	36.1	Y mass		1.85 TeV	$\mathcal{B}(Y \to Wb) = 1, c_R(Wb) = 1$	1812.07343
VLQ $QQ \rightarrow WqWq$ 1 $e, \mu \geq 4j$ Yes20.3Q mass690 GeV150Excited quark $q^* \rightarrow qq$ -2j-139 q^* mass690 GeV 6.7 TeV only u^* and $d^*, \Lambda = m(q^*)$ 197Excited quark $q^* \rightarrow qq$ 1 γ 1 j-36.7 q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$ 197Excited quark $b^* \rightarrow bg$ -1 b, 1 j-36.1 b^* mass 2.6 TeV only u^* and $d^*, \Lambda = m(q^*)$ 197Excited lepton ℓ^* $3 e, \mu$ 20.3 ℓ^* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$ 14Excited lepton v^* $3 e, \mu, \tau$ 20.3 ℓ^* mass 560 GeV $\Lambda = 1.6 \text{ TeV}$ 144Type III Seesaw $1 e, \mu \geq 2 j$ Yes79.8 N^0 mass 560 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 1160Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $2.3.4 e, \mu$ (SS) 36.1 $H^{\pm\pm}$ mass 870 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 1160Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ 20.3 $H^{\pm\pm}$ mass 400 GeV DY production $DY production$ $DY production, g(H_L^{\pm\pm} \rightarrow t, \tau) = 1$ 144Multi-charged particles 36.1 $multi-charged particle mass$ 1.22 eV $DY production, q = 5e$ 1160	$VLQ B \to Hb + X \qquad 0$	e,μ, 2 γ	$\geq 1 \text{ b}, \geq 1 \text{ j}$	Yes	79.8	B mass	1.21 1	V	κ _B = 0.5	ATLAS-CONF-2018
Excited quark $q^* \rightarrow qg$ -2 j-139 q^* mass6.7 TeVonly u^* and d^* , $\Lambda = m(q^*)$ 199Excited quark $q^* \rightarrow qg$ 1 γ 1 j-36.7 q^* mass5.3 TeVonly u^* and d^* , $\Lambda = m(q^*)$ 199Excited quark $b^* \rightarrow bg$ -1 b, 1 j-36.1 b^* mass2.6 TeVonly u^* and d^* , $\Lambda = m(q^*)$ 199Excited lepton ℓ^* $3 e, \mu$ 20.3 ℓ^* mass2.6 TeV $\Lambda = 3.0 \text{ TeV}$ 149Excited lepton v^* $3 e, \mu, \tau$ 20.3 ℓ^* mass3.0 TeV $\Lambda = 3.0 \text{ TeV}$ 149Type III Seesaw $1 e, \mu$ $\geq 2 j$ Yes79.8 N^0 mass560 GeV $\Lambda = 1.6 \text{ TeV}$ 140Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $2.3.4 e, \mu$ (SS)36.1 $N_{\rm mass}$ 32.7 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ 20.3 $H^{\pm\pm}$ mass870 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ 20.3 $H^{\pm\pm}$ mass870 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ 36.1 $H^{\pm\pm}$ mass870 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180Hulti-charged particles36.1 $H^{\pm\pm}$ mass870 GeV D^{\pm} production D^{\pm} production171Hulti-charged particles	VLQ $QQ \rightarrow WqWq$	1 e, µ	\geq 4 j	Yes	20.3	Q mass	690 GeV			1509.04261
Excited quark $q^* \rightarrow q\gamma$ 1γ $1j$ $ 36.7$ q^* mass 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ 177 Excited quark $b^* \rightarrow bg$ $ 1 b, 1 j$ $ 36.7$ q^* mass 2.6 TeV 180 Excited lepton ℓ^* $3 e, \mu$ $ 20.3$ ℓ^* mass 2.6 TeV $\Lambda = 3.0 \text{ TeV}$ 144 Excited lepton v^* $3 e, \mu, \tau$ $ 20.3$ ℓ^* mass 3.0 TeV $\Lambda = 1.6 \text{ TeV}$ 144 Type III Seesaw $1 e, \mu \ge 2j$ Yes 79.8 N^0 mass 560 GeV M_{mass} 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $2,3,4 e, \mu$ (SS) $ 36.1$ N_R mass 870 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $3 e, \mu, \tau$ $ 20.3$ $H^{\pm\pm}$ mass 870 GeV DY production 017 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ $ 20.3$ $H^{\pm\pm}$ mass 400 GeV DY production, $\beta(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ 144 Multi-charged particles $ 162$ 00 00 00 00 Momentaria $ 00$ 00 00 00 00 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ $ 00$ 00 00 00 00 <td< td=""><td>Excited quark $a^* \rightarrow ag$</td><td>-</td><td>2 i</td><td>-</td><td>139</td><td>q* mass</td><td></td><td>6.7 TeV</td><td>only u^* and d^*, $\Lambda = m(q^*)$</td><td>1910.08447</td></td<>	Excited quark $a^* \rightarrow ag$	-	2 i	-	139	q* mass		6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1910.08447
Excited quark $b^* \rightarrow bg$ -1 b, 1 j-36.1 b^* mass2.6 TeVA180Excited lepton ℓ^* $3 e, \mu, \tau$ 20.3 ℓ^* mass3.0 TeVA3.0 TeV14Excited lepton v^* $3 e, \mu, \tau$ 20.3 v^* mass6 TeVA1.6 TeV14Type III Seesaw1 e, μ $\geq 2 j$ Yes79.8N ⁰ mass560 GeVMemossA1.6 TeV14Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2.3,4 e, μ (SS)36.1N _R mass3.2 TeV $m(W_R) = 4.1$ TeV, $g_L = g_R$ 180Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ 3 e, μ, τ 20.3 $H^{\pm\pm}$ mass870 GeVDY production177Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ 3 e, μ, τ 20.3 $H^{\pm\pm}$ mass400 GeVDY production174Multi-charged particles36.1multi-charged particle mass1.22 eVDY production, $ q = 5e$ 186	Excited quark $q^* \rightarrow q\gamma$	1γ	11	-	36.7	q* mass		5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1709.10440
Excited lepton ℓ^* $3 e, \mu$ $ 20.3$ ℓ^* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$ 14 Excited lepton v^* $3 e, \mu, \tau$ $ 20.3$ v^* mass 16 TeV $\Lambda = 1.6 \text{ TeV}$ 14 Type III Seesaw $1 e, \mu \ge 2j$ Yes 79.8 N^0 mass 560 GeV M_{mass} 3.2 TeV $M(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 140 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $2.3.4 e, \mu$ (SS) $ 36.1$ N_R mass 370 GeV $M(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 140 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $3 e, \mu, \tau$ $ 20.3$ $H^{\pm\pm}$ mass 870 GeV DY production 177 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ $ 20.3$ $H^{\pm\pm}$ mass 400 GeV DY production DY productionMulti-charged particles $ 36.1$ $multi-charged particle mass$ 1.22 eV DY production, $ q = 5e$ 186	Excited quark $b^* \rightarrow bg$	_	1 b, 1 j	_	36.1	b* mass		2.6 TeV		1805.09299
Excited lepton v^* $3 e, \mu, \tau$ $ 20.3$ v^* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$ 14 Type III Seesaw $1 e, \mu$ $\geq 2 \text{ j}$ Yes 79.8 N^0 mass 560 GeV $M_{R}(w) = 0.1 \text{ TeV}$ $M_{R}($	Excited lepton ℓ^*	3 e,µ	_	_	20.3	l* mass		3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	1411.2921
Type III Seesaw1 $e, \mu \geq 2j$ Yes79.8N° mass560 GeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ ATLAS-CLRSM Majorana ν 2μ $2j$ $ 36.1$ N _R mass 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $2,3,4 e, \mu$ (SS) $ 36.1$ $H^{\pm\pm}$ mass 870 GeV DY productionHiggs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ $ 20.3$ $H^{\pm\pm}$ mass 400 GeV DY productionMulti-charged particles $ 36.1$ $H^{\pm\pm}$ mass 1.22 eV DY production $ q = 5e$ 180Mage triplet Holds $ -$ Multi-charged particles $ -$ Mage triplet approximation $ -$ Mage triplet approximation $ -$ <td>Excited lepton v[*] 3</td> <td>e, μ, τ</td> <td>-</td> <td>-</td> <td>20.3</td> <td>v* mass</td> <td></td> <td>.6 TeV</td> <td>$\Lambda = 1.6 \text{ TeV}$</td> <td>1411.2921</td>	Excited lepton v [*] 3	e, μ, τ	-	-	20.3	v* mass		.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
LRSM Majorana ν 2μ $2j$ $ 36.1$ NR mass 3.2 TeV $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 180.000 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ $2,3,4 e, \mu$ (SS) $ 36.1$ $H^{\pm\pm}$ mass 870 GeV DY production 177 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ $3 e, \mu, \tau$ $ 20.3$ $H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ 14 Multi-charged particles $ 36.1$ $M^{\pm\pm}$ mass 1.22 TeV DY production, $ q = 5e$ 180	Type III Seesaw	1 e.µ	≥ 2 i	Yes	79.8	N ⁰ mass 560	GeV			ATLAS-CONE-2018
Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2,3,4 e, μ (SS)36.1H^{\pm\pm} mass870 GeVDY productionDY productionHiggs triplet $H^{\pm\pm} \rightarrow \ell \tau$ 3 e, μ, τ 20.3H^{\pm\pm} mass400 GeVDY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ 14Multi-charged particles36.1multi-charged particle mass1.22 eVDY production, $ q = 5e$ 181Multi-charged particles36.1multi-charged particle mass1.22 eVDY production, $ q = 5e$ 181	LRSM Majorana v	2μ	2 j	-	36.1	N _R mass		3.2 TeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$	1809.11105
Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ 3 e, μ, τ 20.3 $H^{\pm\pm}$ mass400 GeVMulti-charged particles36.11.22 eVDY production, $ q = 5e$ 181Montrained particles36.11.22 eVDY production, $ q = 5e$ 181	Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2.3.4	e,μ (SS	S) –	-	36.1	H ^{±±} mass	870 GeV		DY production	1710.09748
Multi-charged particles – – – 36.1 multi-charged particle mass 1.22 eV	Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ 3	e, μ, τ	_	_	20.3	H ^{±±} mass 400 GeV			DY production, $\mathcal{B}(H_{\iota}^{\pm\pm} \rightarrow \ell \tau) = 1$	1411.2921
	Multi-charged particles	_	-	-	36.1	multi-charged particle mass	1.22	eV .	DY production, $ q = 5e$	1812.03673
Magnetic monopoles $ -$	Magnetic monopoles	-	-	-	34.4	monopole mass		2.37 TeV	DY production, $ g = 1g_D$, spin 1/2	1905.10130
			1-12			r r r r r r r				

Indirect searches of New Physics

Search deviations w.r.t. SM predictions:



$$\mathcal{O}_{exp} = \mathcal{O}_{SM} \left(1 + \delta_{NP}\right)$$

Both exp. and theory must be precise!

⇒ Complementary to the effort in the high-energy frontier!

Look for observables:

- (Highly) sensitive to contributions from New Physics
- Mildly sensitive to hadronic uncertainties
- Accessible in current and/or (near) future experiments.

NB. *Processes forbidden by accidental symmetries are very clean:*

 \Rightarrow BNV, LNV and LFV

⇒ **Rare** *B*-meson decays are a good example!

Flavor Changing Neutral Currents (FCNCs)

- FCNCs are absent at tree-level in the SM *i.e.*, couplings of neutral SM bosons to fermions are <u>flavor diagonal</u>.
- The only source of **flavor violation** in the SM is the **CKM matrix**:



• FCNC processes are <u>loop</u>- and <u>CKM-suppressed</u>:



- \Rightarrow <u>Rare</u> processes
- ⇒ <u>Sensitive</u> new physics probes!

• **<u>Reminder</u>**: GIM mechanism

$$\mathcal{M}(b \to s\ell\ell) \propto \sum_{k=u,c,t} V_{ks}^* V_{kb} \varphi\left(\frac{m_k^2}{m_W^2}\right) \approx \sum_{k=u,c,t} V_{ks}^* V_{kb} \frac{m_k^2}{m_W^2} \longrightarrow \text{Top-quark dominates!}$$
$$\varphi(x) = \operatorname{cte} + x + \mathcal{O}(x^2)$$

EFT description

• *B*-physics depends on many different scales ⇒ EFT approach!



- Low-energy coefficients can be precisely computed through matching + RGEs.
- O. Sumensari

FCNC B-meson decays

- $B \to K^{(*)}\ell\ell$:
- Sensitive to new physics effects.
- Experimentally clean (especially for $\ell = \mu$).
- Many observables (angular distribution).
- Theoretically challenging (non-factorizable contributions...)

• $B \to K^{(*)} \nu \bar{\nu}$:

X

- Sensitive to new physics effects.
- Exp. more challenging (missing energy).
- Fewer observables.
- Theoretically cleaner!
- Sensitive to operators with au-leptons. \checkmark





SM description

SM description

• Effective Hamiltonian within the SM:

see e.g. [Buras et al. '14]

$$\mathcal{L}_{\text{eff}}^{\mathrm{b}\to\mathrm{s}\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}} \frac{\alpha_{\text{em}}}{2\pi} \sum_i C_L^{\text{SM}} (\bar{s}_L \gamma_\mu b_L) (\bar{\nu}_{Li} \gamma^\mu \nu_{Li}) + \text{h.c.},$$
$$\lambda_t = V_{tb} V_{ts}^*$$

• Short-distance contributions known to good precision:

$$C_L^{\rm SM} = -X_t / \sin^2 \theta_W$$
$$= -6.32(7)$$

Including NLO QCD and two-loop EW contributions:

$$X_t = 1.462(17)(2)$$

[Buchala et al. '93, '99], [Misiak et al. '99], [Brod et al. '10]





SM description

• Effective Hamiltonian within the SM:

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[Buchala et al. '93, '99], [Misiak et al. '99], [Brod et al. '10]

Two main sources of uncertainties:



ii) CKM matrix:

From CKM unitarity:

$$V_{tb}V_{ts}^*| = |V_{cb}| \left(1 + \mathcal{O}(\lambda^2)\right)$$

Which value to take (incl. vs. excl.)?

I. Form-factors: $B \rightarrow K \nu \bar{\nu}$

• Lattice QCD data available at nonzero recoil $(q^2 \neq q_{\text{max}}^2)$ for all form-factors:

$$\langle K(k)|\bar{s}\gamma^{\mu}b|B(p)\rangle = \left[(p+k)^{\mu} - \frac{m_{B}^{2} - m_{K}^{2}}{q^{2}}q^{\mu}\right]f_{+}(q^{2}) + q^{\mu}\frac{m_{B}^{2} - m_{K}^{2}}{q^{2}}f_{0}(q^{2})$$

with $f_{+}(0) = f_{0}(0)$. Only form-factor needed for $B \to K\nu\bar{\nu}!$

• **[NEW]** We update the FLAG average by combining [HPQCD '22] results with [FNAL/MILC '16]:



I. Form-factors: $B \rightarrow K \nu \bar{\nu}$

*Annihilation contributions not included below (see next slides)!



$$\mathcal{B}(B \to K \nu \bar{\nu})^{\text{SM}} / |\lambda_t|^2 = \begin{cases} (1.33 \pm 0.04)_{K_S} \times 10^{-3} \\ (2.87 \pm 0.10)_{K^+} \times 10^{-3} \end{cases}$$

[Becirevic, Piazza, **OS**. 2301.06990]

I. Form-factors: $B \rightarrow K \nu \bar{\nu}$

*Annihilation contributions not included below (see next slides)!



[Intermezzo]: Cross-check of $f_+^{B \to K}(q^2)$

- SM predictions depend on the **extrapolation** of the LQCD **form-factors to low** q^2 values **parameterisation dependent?**
 - ⇒ How can we test the shape of the extrapolated LQCD form-factors?
- We propose to measure:

[Becirevic, Piazza, OS. 2301.06990]

$$r_{\rm low/high} = \frac{\mathcal{B}(B \to K \nu \bar{\nu})_{\rm low-q^2}}{\mathcal{B}(B \to K \nu \bar{\nu})_{\rm high-q^2}}$$

 $r_{\rm low/high} = 1.91 \pm 0.06$

 \Rightarrow <u>Independent</u> of λ_t and the form-factor normalisation, as well as of NP contributions.

NB. w/o ν_R

• Using the bins (0, $q_{\text{max}}^2/2$) vs. ($q_{\text{max}}^2/2$, q_{max}^2) :

e.g, using (old) FLAG average:

 $r_{\rm low/high} = 2.15 \pm 0.26$

I. Form-factors: $B \rightarrow K^* \nu \bar{\nu}$

• $B \rightarrow K^* \nu \bar{\nu}$ decays are **more challenging** for several reasons:

$$\begin{split} \bar{K}^{*}(k) |\bar{s}\gamma_{\mu}(1-\gamma_{5})b|\bar{B}(p)\rangle &= \varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^{\rho}k^{\sigma}\frac{2V(q^{2})}{m_{B}+m_{K^{*}}} \\ &-i\varepsilon_{\mu}^{*}(m_{B}+m_{K^{*}})A_{1}(q^{2}) \\ &+i(p+k)_{\mu}(\varepsilon^{*}\cdot q)\frac{A_{2}(q^{2})}{m_{B}+m_{K^{*}}} \\ &+iq_{\mu}(\varepsilon^{*}\cdot q)\frac{2m_{K^{*}}}{q^{2}}\left[A_{3}(q^{2})-A_{0}(q^{2})\right], \end{split}$$

• We use LCSR (+LQCD) results from [Bharucha et al. '15, Horgan et al. '13]:

$$\mathcal{B}(B \to K^* \nu \bar{\nu})^{\text{SM}} / |\lambda_t|^2 = \begin{cases} (5.9 \pm 0.8)_{K^{*0}} \times 10^{-3} \\ (6.4 \pm 0.9)_{K^{*+}} \times 10^{-3} \end{cases}$$

[$\approx 15\%$ uncertainty]

 \Rightarrow Relatively small uncertainties, **<u>but are they accurate</u>**?



 $q^2 \, [\text{GeV}^2]$

3.0

2.5

 $\stackrel{*}{\uparrow}$ 1.5

1.0

0.5

2

 $- A_0(q^2)$

 $- A_1(q^2)$

 $- A_2(q^2)$

2.0 – $V(q^2)$

O. Sumensari

II. Which CKM value?

• Using available $b \to c \ell \bar{\nu}$ data:

$$\begin{split} |\lambda_t| \times 10^3 &= \begin{cases} 41.4 \pm 0.8 \,, & (B \to X_c l \bar{\nu}) & \text{[HFLAV, '22]} \\ 39.3 \pm 1.0 \,, & (B \to D l \bar{\nu}) & \text{[FLAG, '21]} \\ 37.8 \pm 0.7 \,, & (B \to D^* l \bar{\nu}) & \text{[HFLAV, '22]} \end{cases} \end{split}$$

... to be compared to CKM global fits:

cf. also [Martinelli et al. '21]

$$|\lambda_t|_{\text{UTfit}} = (41.4 \pm 0.5) \times 10^{-2} \qquad |\lambda_t|_{\text{CKN}}$$

$$|\lambda_t|_{\text{CKMfitter}} = (40.5 \pm 0.3) \times 10^{-2}$$

• <u>Alternative strategy</u>: to use $\Delta m_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} |\lambda_t|^2$

[Buras, Venturini. '21, '22]

$$|\lambda_t| \times 10^3 = \begin{cases} 41.9 \pm 1.0 , & (N_f = 2 + 1 + 1) \\ 39.2 \pm 1.1 , & (N_f = 2 + 1) \end{cases} \qquad f_{B_s} \sqrt{\hat{B}_{B_s}} = 256 \pm 6 \text{ MeV} \qquad (N_f = 2 + 1 + 1) \\ \text{[HPQCD '19]} \\ f_{B_s} \sqrt{\hat{B}_{B_s}} = 274 \pm 8 \text{ MeV} \qquad (N_f = 2 + 1) \end{cases} \qquad (N_f = 2 + 1)$$

There is **not a clear answer** to this **ambiguity** so far.

Weak-annihilation contributions

• <u>To keep in mind</u>: decay modes with **charged mesons** are affected by **tree-level** weak **annihilation contributions**.



• Using *narrow-width* approximation:

$$\mathcal{B}(B^+ \to K^{(*)+} \nu \bar{\nu})$$

$$\simeq \mathcal{B}(B^+ \to \tau^+ \bar{\nu}) \,\mathcal{B}(\tau^+ \to K^{(*)+} \nu)$$

• Non-negligible contributions:

$$\frac{\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})_{\text{tree}}}{\mathcal{B}(B^+ \to K^+ \nu \bar{\nu}))_{\text{loop}}} \simeq 14 \%$$

 $\frac{\mathcal{B}(B^+ \to K^{*+} \nu \bar{\nu})_{\text{tree}}}{\mathcal{B}(B^+ \to K^{*+} \nu \bar{\nu}))_{\text{loop}}} \simeq 11 \%$

 $m_{K^{(*)+}} \le m_{\tau} \le m_B$

⇒ They cannot be removed by a simple kinematical cut...

<u>Belle-II</u>: These contributions are treated as a **background** thanks to the τ **lifetime**

Summary (circa '22)

[Belle 1303.3719, 1702.03224] [BaBar 1009.1529, 1303.7465]



Take-home:

- To remain **cautions** about **hadronic uncertainties** associated to the **form-factors** and the extraction of **CKM** matrix-elements *non-negligible given the projected Belle-II sensitivity.*
- Binned measurements at Belle-II would be a valuable piece of information to test the consistency the SM predictions.

Belle-II results

Belle-II strategy



• Belle-II (SuperKEKB) is an asymmetric e^+e^- collider operating at $\sqrt{s} \simeq m_{\Upsilon(4S)}$:



 $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

 $B_{\rm tag}\bar{B}_{\rm signal}$

 $m_{\Upsilon(4S)} \simeq 10.579 \text{ GeV}$

 $m_{B^+} \simeq m_{B^0} \simeq 5.279 \text{ GeV}$

• Different tagging methods:

	Hadronic	Semileptonic	Inclusive
	Fully reconstructed hadronic decay	$B_{\rm tag} o D^{(*)} \ell \nu$	Several channels
Efficiency	pprox 0.5~%	pprox 2%	pprox 8~%
Background	Small	Large	Large

NB. The inclusive-tagging method was not applied to BaBar and Belle data (yet)! O. Sumensari

[NEW] Belle-II results



- Only the incl. method shows an excess above background (and w.r.t. the SM predictions).
- The had. method is compatible with the SM (and with no observed signal).
- Semileptonic tagging (i.e., $B_{tag} \to X \ell \nu$) could be a useful cross-check, as well as the measurement of $B^0 \to K_S \nu \bar{\nu}$ decays.

⇒ More data is needed! Many possible cross-checks.

What can we learn from $B \to K^{(*)} \nu \bar{\nu}$?

- Remarks on $B \to K^{(*)} \nu \bar{\nu} / B \to K^{(*)} \mu \mu$
- Implications beyond the SM
- Hidden sectors?

[Intermezzo] Anomalies in $B \rightarrow K^{(*)}\mu\mu$ decays?

$$\mathcal{L}_{\text{eff}}^{b \to s\ell\ell} = \frac{4G_F}{\sqrt{2}} \lambda_t \sum_{\ell} \left[C_9^{\ell\ell} \left(\bar{s} \gamma^{\mu} P_L b \right) \left(\bar{\ell} \gamma_{\mu} \ell \right) + C_{10}^{\ell\ell} \left(\bar{s} \gamma^{\mu} P_L b \right) \left(\bar{\ell} \gamma_{\mu} \gamma_5 \ell \right) + \dots \right] + \text{h.c.}$$

• Angular $B \to K^{(*)}\mu\mu$ observables show a preference for $\delta C_{q}^{\mu\mu} < 0$:



New physics effects or underestimated hadronic uncertainties?

see e.g. Ciuchini et al'. '21



NB. LFU ratios $R_{K^{(*)}} = \mathscr{B}(B \to K^{(*)}\mu\mu)/\mathscr{B}(B \to K^{(*)}ee)$ do not depend on $C_9^{\ell\ell}$, but they are difficult to measure — cf. latest LHCb results, which now agree with the SM predictions.

Remarks on $B \rightarrow K^{(*)}\nu\nu/B \rightarrow K^{(*)}\mu\mu$

• $B \to K^{(*)}\nu\nu$ and $B \to K^{(*)}\mu\mu$ have a similar decay spectrum away from the narrow $c\bar{c}$ resonances: [Becirevic, Piazza, **OS**. 2301.06990] [Bartsch et al. '09]



• We can defined the **CKM-free ratio**:

*using 2-loop results for $c\bar{c}$ loops from [Asatryan et al. '09]

$$\mathcal{R}_{K^{(*)}}^{(\nu/l)}[q_0^2, q_1^2] \equiv \frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}ll)} \bigg|_{[q_0^2, q_1^2]} \qquad \qquad \text{Ratio of partial branching fractions integrated in the same } q^2\text{-bin.}$$

- \Rightarrow Form-factor uncertainties cancel out to a good extent for $q^2 \gg m_\ell^2$.
- \Rightarrow Neglecting NP contributions, this ratio can be used to extract $C_{0}^{\mu\mu}$!





• Predictions using perturbative calculation of $c\bar{c}$ loops:

 $\mathcal{R}_{K}^{(\nu/l)}[1.1,6]\Big|_{\mathrm{SM}} = 7.58 \pm 0.04$

with the following dependence on C_9^{eff} :

Precise measurements could help us to understand the various anomalies in $b \rightarrow s\mu\mu$ data.

[Becirevic, Piazza, **OS**. 2301.06990]

What can we learn from $B \to K^{(*)} \nu \bar{\nu}$?

- Remarks on $B \to K^{(*)} \nu \bar{\nu} / B \to K^{(*)} \mu \mu$
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EFT for $b \rightarrow s \nu \bar{\nu}$

• Low-energy EFT:

see e.g. [Buras et al. '14]

Exclusion from Belle/BaBar

$$\mathcal{L}_{\text{eff}}^{\text{b}\to\text{s}\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}} \frac{\alpha_{\text{em}}}{2\pi} \sum_{ij} \left[C_L^{\nu_i\nu_j} \left(\bar{s}_L \gamma_\mu b_L \right) \left(\bar{\nu}_{Li} \gamma^\mu \nu_{Lj} \right) + C_R^{\nu_i\nu_j} \left(\bar{s}_R \gamma_\mu b_R \right) \left(\bar{\nu}_{Li} \gamma^\mu \nu_{Lj} \right) \right] + \text{h.c.},$$

Complementarity of $B \to K \nu \bar{\nu}$ and $B \to K^* \nu \bar{\nu}$: lacksquare40 $[\delta C_L]$ $[\delta C_R]$ 35 $\frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\mathrm{SM}}} = 1 + \sum_{i} \frac{2\mathrm{Re}[C_{L}^{\mathrm{SM}}\left(\delta C_{L}^{\nu_{i}\nu_{i}} + \delta C_{R}^{\nu_{i}\nu_{i}}\right)]}{3|C_{L}^{\mathrm{SM}}|^{2}}$ 30 Belle (90% C.L.) $\mathcal{B} \left(B \to K^* \nu \overline{\nu} \right) \times 10^6$ 12 12 12 12 $+\sum_{i,j}rac{|\delta C_L^{
u_i
u_j}+\delta C_R^{
u_i
u_j}|^2}{3|C_L^{
m SM}|^2}$ $-\eta_{K^{(*)}}\sum_{i,j}\frac{\operatorname{Re}[\delta C_R^{\nu_i\nu_j}(C_L^{\mathrm{SM}}\delta_{ij}+\delta C_L^{\nu_i\nu_j})]}{3|C_L^{\mathrm{SM}}|^2},$ Belle II 10 $\eta_K = 0$ SM 5 $\eta_{K^*} = 3.5(1)$ Excluded (EFT) 0 25152030 0 355 10 40 [Becirevic, Piazza, **OS**. '22] $\mathcal{B}\left(B \to K \nu \overline{\nu}\right) \times 10^6$ Forbidden region in the EFT approach [Allwicher et al (**OS**). '23]

[Bause et al. '23]

EFT for $b \rightarrow s \nu \bar{\nu}$

• Another observable to measure is the K^* longitudinal-polarisation asymmetry:

$$F_L \equiv \frac{\Gamma_L(B \to K^* \nu \bar{\nu})}{\Gamma(B \to K^* \nu \bar{\nu})} \qquad \qquad F_L(B \to K^* \nu \bar{\nu})^{\rm SM} = 0.49(7) \qquad \qquad \mathcal{R}_{F_L} \equiv \frac{F_L}{F_L^{\rm SM}}$$

[Altmannshofer et al. '09]



The measurement of $\mathscr{B}(B \to K^* \nu \bar{\nu})$ and $F_L(B \to K^* \nu \bar{\nu})$ would be **model-independent tests** of Belle-II results.

SMEFT for $b \rightarrow s\nu\nu$ (and $b \rightarrow s\ell\ell$)

- **SMEFT** is formulated for $\Lambda \gg v_{ew}$ with $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant operators.
- Gauge invariance correlates $b \to s\nu\bar{\nu}$ with $b \to s\ell\ell$ since $L_i = (\nu_{Li}, \ell_{Li})^T$.
- Two types of d = 6 contributions at tree-level:

[Buchmuller & Wyler. '85, Gradkowski et al. '10]



SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

• ψ^4 operators invariant under $SU(2) \times U(1)_Y$:

$$\begin{split} \left[\mathcal{O}_{lq}^{(1)}\right]_{ijkl} &= \left(\overline{L}_{i}\gamma^{\mu}L_{j}\right)\left(\overline{Q}_{k}\gamma_{\mu}Q_{l}\right)\\ \left[\mathcal{O}_{lq}^{(3)}\right]_{ijkl} &= \left(\overline{L}_{i}\gamma^{\mu}\tau^{I}L_{j}\right)\left(\overline{Q}_{k}\tau^{I}\gamma_{\mu}Q_{l}\right)\\ \left[\mathcal{O}_{ld}\right]_{ijkl} &= \left(\overline{L}_{i}\gamma^{\mu}L_{j}\right)\left(\overline{d}_{k}\gamma_{\mu}d_{l}\right)\\ \left[\mathcal{O}_{eq}\right]_{ijkl} &= \left(\overline{e}_{i}\gamma^{\mu}e_{j}\right)\left(\overline{Q}_{k}\gamma_{\mu}Q_{l}\right)\\ \left[\mathcal{O}_{ed}\right]_{ijkl} &= \left(\overline{e}_{i}\gamma^{\mu}e_{j}\right)\left(\overline{d}_{k}\gamma_{\mu}d_{l}\right) \end{split}$$

• SMEFT \Leftrightarrow LEFT matching:

$$\delta C_L^{\nu_i \nu_j} \propto \frac{v^2}{\Lambda^2} \left(\mathcal{C}_{iq}^{(1)} - \mathcal{C}_{iq}^{(3)} \right)$$
$$\delta C_R^{\nu_i \nu_j} \propto \frac{v^2}{\Lambda^2} \mathcal{C}_{ij23}^{(1)}$$



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SMEFT for $b \rightarrow s\nu\nu$ (and $b \rightarrow s\ell\ell$)

• ψ^4 operators invariant under $SU(2) \times U(1)_Y$:

$$\begin{split} \left[\mathcal{O}_{lq}^{(1)}\right]_{ijkl} &= \left(\overline{L}_{i}\gamma^{\mu}L_{j}\right)\left(\overline{Q}_{k}\gamma_{\mu}Q_{l}\right)\\ \left[\mathcal{O}_{lq}^{(3)}\right]_{ijkl} &= \left(\overline{L}_{i}\gamma^{\mu}\tau^{I}L_{j}\right)\left(\overline{Q}_{k}\tau^{I}\gamma_{\mu}Q_{l}\right)\\ \left[\mathcal{O}_{ld}\right]_{ijkl} &= \left(\overline{L}_{i}\gamma^{\mu}L_{j}\right)\left(\overline{d}_{k}\gamma_{\mu}d_{l}\right)\\ \left[\mathcal{O}_{eq}\right]_{ijkl} &= \left(\overline{e}_{i}\gamma^{\mu}e_{j}\right)\left(\overline{Q}_{k}\gamma_{\mu}Q_{l}\right)\\ \left[\mathcal{O}_{ed}\right]_{ijkl} &= \left(\overline{e}_{i}\gamma^{\mu}e_{j}\right)\left(\overline{d}_{k}\gamma_{\mu}d_{l}\right) \end{split}$$

$$b \to s\ell\ell \qquad \qquad b \to s\nu\bar{\nu}$$

$$\left[\mathcal{O}_{lq}^{(1)} \right]_{ijkl} = \left(\overline{L}_i \gamma^{\mu} L_j \right) \left(\overline{Q}_k \gamma_{\mu} Q_l \right)$$

= $\left(\overline{\ell}_{Li} \gamma^{\mu} \ell_{Lj} \right) \left(\overline{d}_{Lk} \gamma_{\mu} d_{Ll} \right) + \left(\overline{\nu}_{Li} \gamma^{\mu} \nu_{Lj} \right) \left(\overline{d}_{Lk} \gamma_{\mu} d_{Ll} \right) + \dots$

$$\left[\mathcal{O}_{lq}^{(3)} \right]_{ijkl} = \left(\overline{L}_i \gamma^{\mu} \tau^I L_j \right) \left(\overline{Q}_k \gamma_{\mu} \tau^I Q_l \right)$$

=
$$\left(\overline{\ell}_{Li} \gamma^{\mu} \ell_{Lj} \right) \left(\overline{d}_{Lk} \gamma_{\mu} d_{Ll} \right) - \left(\overline{\nu}_{Li} \gamma^{\mu} \nu_{Lj} \right) \left(\overline{d}_{Lk} \gamma_{\mu} d_{Ll} \right) + \dots$$

$$\mathcal{O}_{ld}\big]_{ijkl} = \left(L_i\gamma^{\mu}L_j\right)\left(d_k\gamma_{\mu}d_l\right)$$
$$= \left(\overline{\ell}_{Li}\gamma^{\mu}\ell_{Lj}\right)\left(\overline{d}_{Rk}\gamma_{\mu}d_{Rl}\right) + \left(\overline{\nu}_{Li}\gamma^{\mu}\nu_{Lj}\right)\left(\overline{d}_{Rk}\gamma_{\mu}d_{Rl}\right)$$

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz OS. '23]

- i. Couplings to muons (... and electrons) are tightly constrained by $\mathscr{B}(B_s \to \mu\mu)$ (... and $R_{K^{(*)}}$).
- ii. LFV couplings are constrained by searches for $\mathscr{B}(B_s \to \ell_i \ell_j)$ and $\mathscr{B}(B \to K^{(*)} \ell_i \ell_j)$.

iii. The only viable option is coupling to τ 's (due to weak exp. limits on $b \to s\tau\tau$).

$$\Rightarrow \underline{\text{Predictions:}} \qquad \frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)^{\text{SM}}} \simeq \frac{\mathcal{B}(B \to K^{(*)}\tau\tau)}{\mathcal{B}(B \to K^{(*)}\tau\tau)^{\text{SM}}} \simeq 10$$

⇒ However, **experimentally challenging**...

O. Sumensari

Which flavor?

Which concrete model?

• More correlations between observables can arise in concrete models:



- $\mathcal{L}_{Z'} \supset g_{ij}^{\psi} \, (\bar{\psi}_i \gamma^{\mu} \psi_j) Z'_{\mu}$
- $\Delta F = 2$ imposes strict bounds :



 \Rightarrow Impossible to fit data with a perturbative coupling

 \Rightarrow Small coupling to quarks:

to τ 's for a heavy Z'.

 $\frac{|g_{sb}^R|}{m_{Z'}} \lesssim 2 \times 10^{-3} \text{ TeV}^{-1}$



$$\mathcal{L}_{\widetilde{R}_2} \supset y_{ij}^R \left(\bar{d}_{Ri} \widetilde{R}_2 i \tau_2 L_j \right) + \text{h.c.}$$



 \Rightarrow Upper bound on LQ mass:

 $m_{\rm LQ} \lesssim 3 {
m ~TeV}$

Difficult to accommodate such a large excess, but possible in certain models.

What can we learn from $B \to K^{(*)} \nu \bar{\nu}$?

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Hidden sectors?

- What if the excess is due to B → KX(→ inv), where X ~ (1, 1,0) is a light mediator produced on-shell (*i.e.*, with m_X < m_B)?
- The main difference would be a **peak** in the q^2 -distributions at $q^2 \simeq m_X^2$, smeared by the detector resolution.
- Good fit to Belle-II data too since the excess is mostly localised (within large uncertainties!):



 \Rightarrow To be checked by **dedicated searches**!

Summary & Outlook

Summary

- $B \to K^{(*)}\nu\bar{\nu}$ decays are cleaner than $B \to K^{(*)}\mu\mu$, but one should remain **cautious** about the **uncertainties** from the **form factors** and **CKM** matrix elements, in view of the **future Belle-II sensitivity**:
 - \Rightarrow Binned data can be used to test these predictions which are more reliable at high- q^2 .

 \Rightarrow We propose to measure the ratio $Br(B \to K \nu \bar{\nu})_{low}/Br(B \to K \nu \bar{\nu})_{high}$, which is sensitive to the q^2 -shape of the (extrapolated) vector form-factor.

 \Rightarrow The ambiguity in the CKM matrix-element determination is the dominant uncertainty for $B \rightarrow K \nu \bar{\nu}$ decays and it remains an open problem — which value to take?

- The ratio $B \to K^{(*)} \nu \bar{\nu} / B \to K^{(*)} \mu \mu$ is independent of the CKM and only mildly dependent on the form-factors **opportunity** to **extract** the $c\bar{c}$ -contributions to $C_{_{Q}}^{\mu\mu}$ (i.e., for $b \to s\mu\mu$).
- The latest Belle-II results show an excess that can be accommodated, e.g., by SMEFT operators with *τ*-flavor. Many cross-checks of these results are possible:
 - \Rightarrow Semileptonic tagging analysis.

$$\Rightarrow \operatorname{Br}(B^0 \to K_S \nu \overline{\nu}), \operatorname{Br}(B \to K^* \nu \overline{\nu}) \text{ and } F_L(B \to K^* \nu \overline{\nu}).$$

Thank you!

Many opportunities to learn more about physics (B)SM!

Back-up

Comparison from A. Lytle talk



[Intermezzo]: Warning!



 \Rightarrow Needs clarification to reliably extract $|V_{cb}|$ from $B \rightarrow D^* \ell \bar{\nu} \dots$

NB. Recent JLQCD agrees well with exp. data!

<u>Way out</u>: independent LQCD results + Belle-II data!









FIG. 1: Left: Combined fit to $Br[B \to KX]$ from Belle II and BaBar as a function of the mass of X. Right: Same for $Br[B \to K^*X]$ (only BaBar data available).

FIG. 5: Best fit and associated 1σ errors for $Br[B \to K^{(*)}X]$ as a function of m_X , for the fit to the BaBar distributions (green), the Belle II distribution (blue) and the combined fit to all data (red).