Scalar leptoquarks for $R_{D}(*)$ (and for $B \rightarrow K\nu\nu$)



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Motivation

Standard Model cannot address Dark Matter, BAU, Neutrino masses, ...

⇒ Need for **New Physics**: Direct searches at LHC - **Indirect searches** at low energy

Indirect searches - Test SM (accidental) symmetries

Flavour physics: test lepton flavour universality



W ⁺ DECAY MODES	CAY MODES Fraction (Γ_i/Γ)						
$\ell^+ u$		[<i>b</i>]	$(10.86\pm~0.09)~\%$				
$e^+ \nu$			$(10.71\pm~0.16)~\%$				
$\mu^+ \nu$			(10.63 ± 0.15) %				
$ au^+ u$			$(11.38\pm~0.21)~\%$				
hadrons			(67.41 \pm 0.27) %				
Z DECAY MODES		Frac	tion (Γ _i /Γ)				
e^+e^-	[<i>h</i>]	($3.3632 \pm 0.0042)$ %				
$\mu^+\mu^-$	[<i>h</i>]	($3.3662 \pm 0.0066)$ %				
$ au^+ au^-$	[<i>h</i>]	($3.3696 \pm 0.0083)$ %				
$\ell^+\ell^-$	[<i>b</i> , <i>h</i>]	($3.3658 \pm 0.0023)$ %				
	[PDG 2024]						





Motivation

Standard Model cannot address Dark Matter, BAU, Neutrino masses...

⇒ Need for New Physics: Direct searches at LHC - Indirect searches at low energy

Indirect searches - Test SM (accidental) symmetries

Flavour physics: test lepton flavour universality

BUT: current measurements of semi-leptonic *B*-meson decays appear to tell a different story!



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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 2024]						



B-meson decays

Powerful probes of New Physics

- Theoretically clean b-quark is heavy: HQET applies, precise predictions thanks to non-perturbative QCD possible
- **Experimentally accessible** at LHC mostly produced in forward region (design of LHCb), also dedicated "*B*-factories" (Belle II, BaBar)
- Scharged current decays used to measure CKM parameters ($|V_{cb}|, |V_{ub}|, \delta_{CP}, \gamma$)
- **During Long lifetime** measure B and B_s oscilations, insight on CP violation in the SM
- Hundreds of decay channels to explore

B-meson decays

	_	Scal	e factor/ p	
Powerf	B ⁺ DECAY MODES	Fraction (Γ_i/Γ) Confide	ence level(MeV/c)	
	Semilepto	nic and leptonic modes		
	$\ell^+ u_\ell X$	[///] (10.99 \pm 0.28) %	_	
▶The	$e^+ \nu_e X_c$	(10.8 \pm 0.4) %	_	ies, precise predictions thanks
	$\frac{D\ell^+}{D\ell^+} \nu_\ell X$	$($ 9.7 \pm 0.7 $)$ %	-	
to n	$\frac{D^0\ell^+\nu_\ell}{D^0\ell^+}$	[///] (2.35 \pm 0.09)%	2310	
	$\frac{D}{D} \tau^+ \nu_{\tau}$	$(7.7 \pm 2.5) \times 10^{-3}$	1911	
	$\frac{D^{*}(2007)^{\circ}\ell}{D^{*}(2007)^{\circ}\sigma^{+}}$	$[///] (5.66 \pm 0.22)\%$	2258	
≥Exp	$D^{-}(2007)^{*\gamma} \nu_{\tau}$	$(1.88 \pm 0.20)\%$ $(44 \pm 04) \times 10^{-3}$	1839	ed in forward region (design of
інс	$\overline{D}^*_{\ast}(2420)^0\ell^+\nu_{\ell}$ $\overline{D}^{*0}_{\ast}\rightarrow$	$(4.4 \pm 0.4) \times 10^{-3}$	- 2300	
LIIC	$D^{-}\pi^{+}$	(2.3 ± 0.3) × 10		/
	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell, \ \overline{D}_2^{*0} \rightarrow$	(1.53 \pm 0.16) $\times10^{-3}$	2065	
	$D^{+}\pi^{+}$			
▶Cha	$D^{(*)} n \pi \ell \nu_{\ell} (n \geq 1)$ $D^{*-} \pi^+ \ell^+ \mu_{\ell}$	$(1.88 \pm 0.25)\%$	-	fameters $(V_{ch} , V_{uh} , \delta_{CP}, \gamma)$
	$\overline{D}_{1}(2420)^{0}\ell^{+}\mu_{\ell}$ $\overline{D}_{2}^{0} \rightarrow$	$(0.0 \pm 0.4) \times 10^{-3}$	2254	
	$D_1(2+20) \sim \nu_\ell, D_1 = \ell$	$(3.03 \pm 0.20) \times 10$	2004	
▶Lon	$\overline{D}'_1(2430)^0 \ell^+ \nu_\ell, \ \overline{D}'^0_1 \rightarrow$	(2.7 \pm 0.6) $ imes$ 10 ⁻³	_	ht on <i>CP</i> violation in the SM
492*	$D^{*-}\pi^+$			
	$D_2^*(2460)^0 \ell^+ \nu_\ell$,	(1.01 \pm 0.24) $ imes$ 10 $^{-3}$	S=2.0 2065	
Mur	$\overline{D}_2^{*0} \rightarrow D^{*-}\pi^+$			
	$\frac{D^0}{2}\pi^+\pi^-\ell^+\nu_\ell$	$(1.7 \pm 0.4) imes 10^{-3}$	2301	
	$D^{*0}\pi^+\pi^-\ell^+\nu_\ell$	$(8 \pm 5) \times 10^{-4}$	2248	
	$D_{s}^{(*)-} K^+ \ell^+ u_{\ell}$	(6.1 \pm 1.0) $ imes$ 10 ⁻⁴	-	
	$D_s^- K^+ \ell^+ u_\ell$	$(3.0 \ + 1.4 \ - 1.2 \) imes 10^{-4}$	2242	
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neso	n decays		$D_{s}^{*-} K^{+} \ell^{+} \nu_{\ell} \\ \pi^{0} \ell^{+} \nu_{\ell} \\ \eta \ell^{+} \nu_{\ell} \\ \eta' \ell^{+} \nu_{\ell}$	$(2.9 \pm 1.9) \times 10^{-4}$ $(7.80 \pm 0.27) \times 10^{-5}$ $(3.9 \pm 0.5) \times 10^{-5}$ $(2.3 \pm 0.8) \times 10^{-5}$	2185 2638 2611 2553
Powerf	B+ DECAY MODES	S Fraction (Γ _i /Γ) Conf	$\omega \ell^+ \nu_\ell ho^0 \ell^+ \nu_\ell$	[///] (1.19 \pm 0.09) \times 10 ⁻⁴ [///] (1.58 \pm 0.11) \times 10 ⁻⁴	2582 2583
	Semilepton	ic and leptonic modes	$p \overline{p} \ell^+ \nu_\ell$	$(5.8 + 2.6 - 2.3) \times 10^{-6}$	2467
b - - 1	$\ell^+ \nu_\ell X$	$[///] (10.99 \pm 0.28)\%$	$p \overline{p} \mu^{ op} u_{\mu}$	$< 8.5 \times 10^{-0} \text{ CL}=90\%$	2446
Ine	$D\ell^+ \nu_{\ell} X$	$(10.8 \pm 0.4)\%$ $(9.7 \pm 0.7)\%$	ppe	$(8.2 - 3.3) \times 10^{-0}$	2467
to n	$\overline{D}^0 \ell^+ \nu_\ell$	[///] (2.35 \pm 0.09) %	$e^{+} \nu_{e}$ $\mu^{+} \nu$	$< 9.8 \times 10^{-7}$ CL=90% 2.00 $\times 10^{-07}$ to 1.07 $\times 10^{-06}$ CL=90%	2640 2630
	$\overline{D}^0 \tau^+ \nu_{\tau}$	$(7.7 \pm 2.5) \times 10^{-3}$		$(1.09 \pm 0.24) \times 10^{-4}$ S=1.2	2341
	$D^*(2007)^{\circ} \ell^+ \nu_{\ell}$ $\overline{D}^*(2007)^{\circ} -+ \nu_{\ell}$	$[///] (5.66 \pm 0.22) \% $	$\ell^+ \nu_\ell^{} \gamma$	$< 3.0 \times 10^{-6} \text{ CL}=90\%$	2640
≥Exp	$D^{-} \pi^{+} \ell^{+} \nu_{\ell}$	$(1.88 \pm 0.20)\%$ $(44 \pm 04) \times 10^{-3}$	$e^+_{\mu} u_e \gamma$	< 4.3 $\times 10^{-6}$ CL=90%	2640
LHC	$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell, \ \overline{D}_0^{*0} \rightarrow$	$(2.5 \pm 0.5) \times 10^{-3}$	$\mu^{ op} u_{\mu} \gamma$ $\mu^{+} \mu^{-} \mu^{+} \mu$	< 3.4 $\times 10^{-0}$ CL=90%	2639
	$ \frac{D^{-}\pi^{+}}{D_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}, \ \overline{D}_{2}^{*0} \rightarrow D^{-}\pi^{+}} $ $ D^{(*)}n\pi^{\ell^{+}}\nu_{\ell}(n > 1) $	$(1.53 \pm 0.16) \times 10^{-3}$	$\frac{D^{0}X}{D^{0}X}$	Inclusive modes (8.6 ± 0.7)% (79 ± 4)%	_
▶Cha	$D^{*-}\pi^{+}\ell^{+}\nu_{\ell}$ $\overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell}, \ \overline{D}_{1}^{0} \rightarrow D^{*-} +$	$(6.0 \pm 0.23) \times 10^{-3}$ $(3.03 \pm 0.20) \times 10^{-3}$	$D^+ X$ $D^- X$ $D^+ X$	(15 ± 10.5) (2.5 ± 0.5) % (9.9 ± 1.2) %	- -
▶Lon	$ \begin{array}{c} D^{*-}\pi^{+} \\ \overline{D}_{1}^{\prime}(2430)^{0}\ell^{+}\nu_{\ell}, \overline{D}_{1}^{\prime0} \\ D^{*-}\pi^{+} \\ \end{array} $	(2.7 \pm 0.6) $ imes$ 10 $^{-3}$	$D_s^+ X$ $D_s^- X$	(7.9 + 1.4 - 1.3)% (1.10 + 0.40 - 0.32)%	_
⊳Hur	$D_2^*(2460)^0 \ell^+ u_\ell,$ $\overline{D}_2^{*0} \to D^{*-} \pi^+$ $\overline{D}_2^{0} + - \ell^+$	$(1.01 \pm 0.24) \times 10^{-3}$	$\Lambda_c^+ X$ $\overline{\Lambda}^- X$	$\begin{pmatrix} 2.1 & + & 0.9 \\ - & 0.6 \end{pmatrix}$ % $\begin{pmatrix} 2.8 & + & 1.1 \end{pmatrix}$ %	_
-	$\frac{D^{\circ}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}}{D^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}}$	$(1.7 \pm 0.4) \times 10^{-3}$	\overline{c}	$(2.0 - 0.9)^{70}$	
	$D_{c}^{(*)-}K^{+}\ell^{+}\nu_{\ell}$	$(6.1 \pm 1.0) \times 10^{-4}$	-	(91 ± 4)70	_
	S^{s} $D_{c}^{-}K^{+}\ell^{+}\nu_{\ell}$	$(3.0 + 1.4) \times 10^{-4}$	4 2242		
	5 ~	- 1.2			

าeso	n decays				\mathcal{D} $\pi^{0}\ell$ $\eta\ell^{+}$	$\mathcal{D}_{s}^{*-} K^{+} \ell^{+} \nu_{\ell}$ $\mathcal{D}_{v_{\ell}}^{*-} \nu_{\ell}$	_		(2.9 (7.80 (3.9 (2.3	$egin{array}{ccc} \pm & 1.9 \ \pm & 0.27 \ \pm & 0.5 \ \pm & 0.8 \end{array}$) $\times 10^{-4}$) $\times 10^{-5}$) $\times 10^{-5}$) $\times 10^{-5}$		2185 2638 2611 2553
		$\pi^+ \ell^+ \ell^-$ $\pi^+ \circ^+ \circ^-$	B1	<	4.9 8 0	$\times 10^{-8}$	CL=90%	2638	` (1.19	± 0.09	$) \times 10^{-4}$		2582
Dowarf	B ⁺ DECAY MODES	$\pi^+ \mu^+ \mu^-$	BI R1	< (0.U	$\times 10^{-8}$ + 0.22) $\times 10^{-8}$	CL=90%	2038	(1.58	\pm 0.11) $\times 10^{-4}$		2583
UVVEII	c	$\pi^+ \nu \overline{\nu}$	B1	<	1.4	\pm 0.22) \times 10 \times 10 ⁻⁵	CL=90%	2638	(5.8	$+ 2.6 \\ - 2.3$	$) imes 10^{-6}$		2467
	$\rho + \nu_{\rho} X$	$K^+ \ell^+ \ell^-$	B1	[///] (4.51	\pm 0.23 $)\times 10^{-7}$	S=1.1	2617	8.5		imes 10 ⁻⁶	CL=90%	2446
▶ Tho	$e^+ \nu_e X_e$	$K^+ e^+ e^-$	B1	(5.5	\pm 0.7) $\times 10^{-7}$		2617	(82	+ 4.0) ~ 10-6		2467
P ine	$D\ell^+ \nu_\ell X$	$K^+ \mu^+ \mu^-$	B1	(4.41	\pm 0.22) \times 10 ⁻⁷	S=1.2	2612	0.2	- 3.3) × 10	e , e , (2407
to n	$\overline{D}^0 \ell^+ \overset{c}{\nu}_{\ell}$	${\it K^+\mu^+\mu^-}$ nonreso-	B1	(4.37	\pm 0.27) $ imes$ 10 ⁻⁷		2612	9.8	-07	$\times 10^{-7}$	CL=90%	2640
	$\overline{D}{}^0 au^+ \overset{\sim}{ u_ au}$	nant $\kappa^+ \tau^+ \tau^-$	R1	/	2.25	× 10 [−] 3	CI	1687	01×00	to I	1.07×10^{-4}	°CL=90%	2639
	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	$K^+ \overline{\nu} \nu$	B1 B1	<	2.25	$\times 10^{-5}$	CL = 90%	2617	(1.09	± 0.24	+) × 10 +	S=1.2	2341
≫Fyn	$\overline{D}^*(2007)^0 \tau^+ \nu_{\tau}$	$\rho^+ \nu \overline{\nu}$	B1	<	3.0	$\times 10^{-5}$	CL=90%	2583	3.0		× 10 °	CL = 90%	2040
	$D^-\pi^+\ell^+ u_\ell$	$K^*(892)^+ \ell^+ \ell^-$	B1	[///] (1.01	\pm 0.11) × 10 ⁻⁶	S=1.1	2564	4.5		$\times 10^{-6}$	CL = 90%	2040
LHC	$\overline{D}^*_0(2420)^0\ell^+ u_\ell$,	$K^{*}(892)^{+}e^{+}e^{-}$	B1	(1.55	$+ 0.40 \times 10^{-6}$		2564	1.6		$\times 10^{-8}$	CL = 95%	2634
	$D^{-}\pi^{+}$	$K^{*}(902) + \mu + \mu -$	D1	(0.6	-0.31 $/ \times 10^{-7}$		2560	1.0		× 10	CL=3370	2004
	$D_2^*(2460)^0 \ell^+ \nu_\ell$,	$K^{*}(892)^{+}\mu^{-}\mu^{-}$	BI R1	(9.0 4.0	± 1.0) × 10 $\times 10^{-5}$	CI 00%	2500	e mode	IS			
	$D^{(*)} = e^{-\pi^+}$	$K^{+}\pi^{+}\pi^{-}\mu^{+}\mu^{-}$	B1	(4.3	$(+ 0.4) \times 10^{-7}$	CL—9070	2593	(8.6	± 0.7)%		_
▶Cha	$D^{(\gamma)} \Pi \pi \ell^+ \nu_\ell (\Pi \geq 1)$ $D^{*-} \pi^+ \ell^+ \mu_\ell$	$\mathcal{A}\mathbf{K}^+ \mathcal{A}^+ \mathcal{A}^-$	D1	(7.0	$+ 2.1 \rightarrow 10^{-8}$		2400	(79)	± 4 ± 05)%		_
	$\frac{D}{D} (2420)^{0} \ell^{+} \mu_{\ell}$	$\varphi \kappa \cdot \mu \cdot \mu$	ы	(7.9	- 1.7) × 10 °		2490	$\begin{pmatrix} 2.5 \\ 0.0 \end{pmatrix}$	± 0.3 ± 1.2) %		_
	$D_1(2420) \ \ell \ \nu_{\ell}$	$\Lambda p \nu \overline{\nu}$		<	3.0	$\times 10^{-5}$	CL=90%	2430	(9.9	± 1.2 ± 1.4) /0		
l on	$\overline{D}'_{4}(2430)^{0}\ell^{+}\nu_{0}$	$\pi \cdot e \cdot \mu$ $\pi^+ e^- \mu^+$		<	6.4	$\times 10^{-3}$	CL=90%	2637	(7.9	-1.3)%		_
LOII	$D^{*-}\pi^+$	$\pi^+ e^{\pm} \mu^{\mp}$		< _	0.4 1 7	$\times 10^{-7}$	CL = 90%	2037	(1.10	+ 0.40	3)%		_
	$\overline{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}$	πe^{μ} $\pi^{+}e^{+}\tau^{-}$	LF	<	7.4	$\times 10^{-5}$	CL=90%	2338	(0.1	+ 0.9			
	$\overline{D}^{*0}_{2} \rightarrow D^{*-}$	$\pi^+ e^- \tau^+$	LF	<	2.0	$\times 10^{-5}$	CL=90%	2338	(2.1	- 0.6) %		-
PHU	$\overline{D}{}^0 \pi^+ \pi^- \ell^+ \nu_{\ell}$	$\pi^+ e^{\pm} au^{\mp}$	LF	<	7.5	imes 10 ⁻⁵	CL=90%	2338	(2.8	+ 1.1) %		_
	$\overline{D}^{*0}\pi^+\pi^-\ell^+\nu_\ell$	$\pi^+ \mu^+ au^-$	LF	<	6.2	imes 10 ⁻⁵	CL=90%	2333	(97	+ 4) %		_
	$D^{(*)-}K^+\ell^+\nu_{\ell}$	$\pi^+\mu^- au^+$	LF	<	4.5	$\times 10^{-5}$	CL=90%	2333	() //		
	$D_s = K + c + c$	$\pi^+ \mu^\pm \tau^\mp$	LF	<	7.2	$\times 10^{-5}$	CL=90%	2333					
	$D_s K^+ \ell^+ \nu_\ell$	$K^+ e^+ \mu^-$	LF	<	7.0	$\times 10^{-9}$	CL=90%	2615					
		K'e μ '	LF	<	6.4	× 10 ⁻⁹	CL=90%	2615					
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Powerf $ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	leso	n decays			D_s^{*-} $\pi^0 \ell^+ \nu_\ell$ $\eta \ell^+ \nu_\ell$	$K^+\ell^+\nu_\ell$		(2.9 ± 1.9) (7.80 ± 0.2) (3.9 ± 0.9) (2.3 ± 0.8)	$\begin{array}{l} 9 \\ 9 \end{array} \times 10^{-4} \\ 27 \end{array} \times 10^{-5} \\ 5 \\ 9 \times 10^{-5} \\ 8 \end{array} \times 10^{-5} \end{array}$	2185 2638 2611 2553
Powerfine $\frac{\pi^{+}\mu^{+}\mu^{-}}{\mu^{+}\nu_{k}}$ Bi $(175 \pm 0.22) \times 10^{-8}$ 2634 $\ell^{+}\nu_{k}X$ $e^{+}e^{+}e^{-}$ BI $(4.51 \pm 0.23) \times 10^{-7}$ 2617 $(4.31 \pm 0.22) \times 10^{-7}$ 2617 $(4.31 \pm 0.22) \times 10^{-7}$ 2617 $(109 \pm 0.24) \times 10^{-6}$ CL=90% $(109 \pm 0.24) \times 10^{-6}$ CL=90% $(100 \pm 0.24) \times 10^{-6}$		B+ DECAY MODES	$ \begin{array}{c} \pi^+ \ell^+ \ell^- \\ \pi^+ e^+ e^- \end{array} $	B1 B1	< 4.9 < 8.0	$\times 10^{-6}$ CL=90% $\times 10^{-8}$ CL=90%	2638 2638	(1.19 ± 0.0) (1.58 ± 0.1)	09) $ imes 10^{-4}$ 11) $ imes 10^{-4}$	2582 2583
$ \begin{aligned} & \text{Pring}_{t \to \mu_{x} X_{x}} \\ & e^{\pm} \nu_{\mu_{x} X_{x}} \\ & e^{\pm} \nu_{\mu_{x} X_{x}} \\ & D^{\pm} (2007)^{0} \ell^{\pm} \nu_{\mu_{x}} \\ & D^{\pm} \pi^{\pm} \ell^{+} \nu_{\mu_{x}} \\ & D^{\pm} 2(2400)^{0} \ell^{\pm} \nu_{\mu_{x}} \\ & D^{\pm} \pi^{\pm} \ell^{+} \mu^{-} \\ & D^{\pm} 2(2400)^{0} \ell^{\pm} \nu_{\mu} \\ & D^{\pm} 2(2400)^{0} \ell^{\pm}$	Powert	c	$\begin{array}{c} \pi^+ \mu^+ \mu^- \\ \pi^+ \nu \overline{\nu} \end{array}$	B1 B1	(1.75 ± < 1.4	0.22) $\times 10^{-8}$ $\times 10^{-5}$ CL=90%	2634 2638	(5.8 + 2.6)	$(53) \times 10^{-6}$	2467
$ \begin{aligned} & \text{The} \\ & e^{\pm}\nu_{e}X_{c} \\ & D^{\pm}\nu_{\mu}X_{c} \\ & D^{\pm}\nu_{\mu}X_{c} \\ & \overline{D^{0}}\ell^{+}\nu_{\mu}X_{c} \\ & \overline{D^{0}}\ell^{+}\nu^{+}\mu^{+}X_{c} \\ & \overline{D^{0}}\ell^{+}\nu^{+}\mu^{+}X_{c} \\ & \overline{D^{0}}\ell^{+}\mu^{+}\mu^{+}X_{c} \\ & \overline{D^{0}}\ell^{+}\mu^{+}\chi^{+}X_{c} \\ & \overline{D^{0}}\ell^{+}\mu^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}X_{c} \\ & \overline{D^{0}}\ell^{+}\mu^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}X_{c} \\ & \overline{D^{0}}\ell^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi^{+}\chi$		$\ell^+ \nu_{\ell} X$	$K^+\ell^+\ell^-$	B1 [///]	(4.51 \pm	0.23) $\times 10^{-7}$ S=1.1	2617	8.5	$\times 10^{-6}$ CL=90%	2446
to n $ \begin{array}{c} D_{1}^{2} \ell_{\nu} \ell_{\nu} \\ \overline{D}^{0} \ell_{\nu} \ell_{\nu} \\ \overline{D}^{0$	▶The	$e^+ \nu_e X_c$	$K^{+}e^{+}e^{-}$ $K^{+}u^{+}u^{-}$	B1 B1	$(5.5 \pm (4.41 \pm$	$(0.7) \times 10^{-7}$	2617 2612	(8.2 + 4.0)	$^{0}_{3}$) $ imes$ 10 ⁻⁶	2467
$ \begin{array}{c} \text{Lor} & D_{2}^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{0} (2007)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{+} (2007)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{+} (2007)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{+} (2007)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{-} \pi^{+} \ell^{+} \nu_{\ell} \\ \overline{D}^{-} \pi^{+} \ell^{+} \nu_{\ell} \\ \overline{D}^{-} \pi^{+} \ell^{+} \nu_{\ell} \\ \overline{D}^{-} (2420)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{-} (2420)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{-} (2420)^{0} \ell^{+} \nu_{\ell} \\ \overline{D}^{+} (2400)^{0} \ell^{+}$	+ o . o	$\frac{D\ell^+\nu_\ell X}{\overline{D}0} + $	$K^{+}\mu^{+}\mu^{-}$ nonreso-	B1 B1	(4.37 ±	$(0.22) \times 10^{-7}$	2612	9.8	$ imes 10^{-7}$ CL=90%	2640
$ \begin{aligned} & Exp \\ Exp \\ LHC \\ & D_{0}^{+}(2007)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{0}^{+}(2007)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{0}^{-}\pi^{+}\ell^{+}\nu_{\ell} \\ & \overline{D}_{1}^{-}(2420)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{2}^{-}(2460)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{2}^{$	ιο η	$\frac{D^{\circ} \ell + \nu_{\ell}}{D^{\circ} \sigma^{+} \mu}$	nant		(, , , , , , , , , , , , , , , , , , , ,		$90 imes 10^{-07}$ to	$1.07 \times 10^{-06} CL = 90\%$	2639
$ \begin{aligned} & \text{Exp} \\ \text{LHC} \\ & \overset{D}{D}_{0}^{+}(2007)^{0}\tau^{+}\nu_{\tau} \\ & \overset{D}{D}_{0}^{+}(2420)^{0}\ell^{+}\nu_{\ell}, \\ & \overset{D}{D}_{0}^{-}\tau^{+}\ell^{+}\nu_{\ell}, \\ & \overset{D}{D}_{0}^{-}\tau^{+}\ell^{+}\nu_{\ell}, \\ & \overset{D}{D}_{0}^{-}\tau^{+}\ell^{+}\nu_{\ell}, \\ & \overset{D}{D}_{0}^{-}\tau^{+}\ell^{+}\nu_{\ell}, \\ & \overset{D}{D}_{1}^{+}(2400)^{0}\ell^{+}\nu_{\ell}, \\ & \overset{T}{D}_{2}^{+}(2460)^{0}\ell^{+}\nu_{\ell}, \\ & \overset{T}{D}_{2}^{+}(2460)^{0}\ell^{+}\nu$		$\frac{D^* \gamma \cdot \nu_{\tau}}{D^* (2007)^0 \ell^+ \mu_{\ell}}$	$K^+ \tau^+ \tau^-$	R1	< 2.25	× 10 ⁻³ CI -90%	1687	(1.09 ± 0.2)	24) $\times 10^{-4}$ S=1.	2341
$ \begin{aligned} & Exp \\ LHC \\ & LHC \\ & D_{n}^{-\pi+\ell+\nu_{\ell}} \\ & D_{2}^{(2420)} D_{\ell+\nu_{\ell}}, \\ & D_{2}^{-\pi+\ell+\nu_{\ell}} \\ & D_{2}^{-\pi+\ell+\nu_{\ell}} \\ & D_{2}^{-\pi+\ell+\nu_{\ell}} \\ & D_{1}^{+n} A_{1}^{+\nu_{\ell}} In agreement with the SM \\ & All in agreement with the SM \\ & K^{*}(R) \\ & Lon \\ & D_{n}^{-\pi+\ell+\nu_{\ell}} \\ & D_{n}^{+n+\ell+\nu_{\ell}} \\ & D_{1}^{2(240)} D_{\ell+\nu_{\ell}}, \\ & D_{n}^{+n} D_{n+\ell+\nu_{\ell}}^{+n} \\ & D_{1}^{2(240)} D_{\ell+\nu_{\ell}}, \\ & D_{n}^{+n} D_{n+\ell+\nu_{\ell}}^{+n} \\ & D_{n}^{+n} D_{n+\ell+\nu}^{+n} \\ & D_{n+\ell+\nu}^{+n} \\ $		$\frac{D}{D^*}(2007)^0 \tau^+ \nu$	$K^+ \overline{\nu} \nu$	B1	< 1.6	$\times 10^{-5}$ CL=90%	2617	3.0	$\times 10^{-6}$ CL=90%	2640
LHC $ \begin{bmatrix} Triangle (2420)^{0} \ell^{+} \nu_{\ell}, \\ Triangle (2420)^{0} \ell^{+} \nu_{\ell}, \\ Triangle (2420)^{0} \ell^{+} \nu_{\ell}, \\ D^{-} \pi^{+} \ell^{+} \nu_{\ell}, \\ D^{+} n \pi^{+} \ell^{+} \mu^{-}, \\ D^{+} n \pi^{+} \ell^{+} \mu^{-}, \\ D^{+} n \pi^{+} \ell^{+} \ell^{+} \nu_{\ell}, \\ D^{+} n \pi^{+} \ell^{+} \nu_{\ell}, \\ D^{+} n \pi^{+} \ell^{+} \ell^{+} \ell^{+} \mu^{-}, \\ D^{+} n \pi^{+} \ell^{+} \ell^{+} \ell^{+} \mu^{-}, \\ D^{+} n \pi^{+} \ell^{+} \ell^{+} \ell^{+} \mu^{-}, \\ D^{+} n \pi^{+} \ell^{+} \ell^{+$	PEX P	$D^-\pi^+\ell^+\nu_\ell$	$\kappa^{+}(89) + \ell^{+} \ell^{-} Anc$	l hun	dred	s more	2583	4.3	$\times 10^{-6}$ CL=90%	2640
$\mathbb{E} \operatorname{Her} = \begin{bmatrix} D - \pi^{+} & D - \pi^{+} \\ \overline{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}, \\ D^{-}\pi^{+} & D^{-}\pi^{+} \\ D^{+}n\pi\ell^{+}\nu_{\ell}(n \geq 1) \\ D^{+}n\pi\ell^{+}\nu_{\ell}(n \geq 1) \\ D^{+}n\pi\ell^{+}\nu_{\ell}(n \geq 1) \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell}, \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell}, \\ \overline{D}_{1}(2430)^{0}\ell^{+}\nu_{\ell}, \\ \overline{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}, \\ \overline$	IHC	$\overline{D}_{0}^{*}(2420)^{0}\ell^{+}\nu_{\ell},$	$K^*(00)$			0.40 (-6)	2504	3.4	$\times 10^{-6}$ CL=90%	2639
$ \begin{split} & \widehat{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}, \\ & D_{-\pi^{+}}^{-}\ell^{+}\nu_{\ell}(n \geq 2) \\ D^{*}_{-\pi^{+}}\ell^{+}\nu_{\ell}(n \geq 2) \\ & \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{1}(2430)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{1}^{*}(2430)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell} \\ & \overline{D}_{2}^{*}(2460)^{0}\ell$		$D^-\pi^+$	All in a	greer	nent	with the S	SM	1.6	$\times 10^{-6}$ CL=95%	2634
$ \begin{aligned} & \sum_{n=1}^{\infty} C_{n} \\ & \sum_{n=1}^{\infty} C_{$		$\overline{D}_2^*(2460)^0 \ell^+ u_\ell$,	$K^{*}(92) \rightarrow \mu$		9.6 ¥	1.0^{-1} $\times 10^{-5}$ $ch = 00\%$	2560	modes		
$ \begin{aligned} & & \text{Cha} \\ & & \text{D}^{(s)} \pi \pi \ell^{s} \nu_{\ell} (n \geq D^{s} \pi^{s} \ell^{s} + \ell^{s} \nu_{\ell}} \\ & & & \frac{1}{D_{1}(2420)^{0}} \ell^{s} \nu_{\ell} \\ & & \frac{1}{D_{1}(2420)^{0}} \ell^{s} \nu_{\ell} \\ & & \frac{1}{D_{1}(2430)^{0}} \ell^{s} \nu_{\ell} \\ & & \frac{1}{D_{2}(2460)^{0}} \ell^{s} \nu_{\ell} \\ & & \frac{1}{D_{2}(2460)^{0}} \ell^{s} \nu_{\ell} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \\ & & \frac{1}{D_{2}^{0}(2^{s} \circ D^{s})} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{\pi^{s}} e^{-\pi} \ell^{s} \\ & & \frac{1}{D_{2}^{0} \circ D^{s}} \frac{1}{D_{2}^{0} \circ D^{s}}$		$D^-\pi^+$	$K^{+}(89) = 00$	BI R1	< 4.0	$\times 10^{\circ} \text{ CL}=90\%$	2504	8.6 ± 0.7	7)%	_
$ \begin{array}{c} \sum_{n=1}^{\infty} \sum_{n=1}^{\infty$	▶Cha	$D^{(*)}$ n $\pi \ell^+ \nu_\ell$ (n ≥ 1		DI	(4.3 ⊥	0.4 $\mathbf{J} \times 10$	2095	79 ± 4) %	_
$ \sum_{n=1}^{n} \sum_{j=1}^{n} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{$	dda.	n = - + n = -				2.1 $10-8$	0.400		-) 0/	
$ \begin{aligned} & \qquad \qquad$		$D^{*-}\pi^+\ell^+\nu_\ell$	$\phi K^+ \mu$	D1	(7 0 +	2.1 1.7 F	0.400	2.5 ± 0.5	5)%	-
		$D^{*-} \pi^{+} \ell^{+} \nu_{\ell} = \overline{D}_{1} (2420)^{0} \ell^{+} \nu_{\ell}$	$\phi K^{+} \mu$ $\overline{\Lambda} p \nu \overline{\nu}$ $+ + -$		< 3.0	$\times 10^{-5}$ CL=90%	2430	2.5 ± 0.5 (9.9 ± 1.2	5)% 2)%	_
$ \boxed{\begin{array}{c} \overline{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}} \\ \overline{D}_{2}^{*0} \rightarrow D^{*-} \\ $	⊳lon	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \end{array} $	$ \phi K^{+} \mu^{-} \\ \overline{\Lambda} p \nu \overline{\nu} \\ \pi^{+} e^{+} \mu^{-} \\ \pi^{+} e^{-} \mu^{+} $	LF	< 3.0 < 6.4	$\times 10^{-5}$ CL=90% $\times 10^{-3}$ CL=90% $\times 10^{-3}$ CL=90%	2430 2637 2627	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 3)%	_ _ _
$\blacksquare Hur = \begin{bmatrix} \overline{D}_{2}^{*0} \rightarrow D^{*} \\ \overline{D}_{2}^{0} + \pi^{-} \ell^{+} \nu_{\ell} \\ \overline{D}_{0}^{0} \pi^{+} \pi^{-} \ell^{+} \nu_{\ell} \\ \overline{D}_{s}^{*0} \pi^{+} \pi^{-} \ell^{+} \nu_{\ell} \\ \overline{D}_{s}^{*0} \pi^{+} \pi^{-} \ell^{+} \nu_{\ell} \\ D_{s}^{(*)-} K^{+} \ell^{+} \nu_{\ell} \\ D_{s}^{(*)-} K^{+} \ell^{+} \nu_{\ell} \\ D_{s}^{(*)-} K^{+} \ell^{+} \nu_{\ell} \\ HTTP: //PDG.LBL.GOV \\ Page 73 \\ \hline HTTP: //PDG.LBL.GOV \\ Page 73 \\ \hline LF < 2.0 \\ \times 10^{-5} CL = 90\% 2338 \\ \times 10^{-5} CL = 90\% 2338 \\ \times 10^{-5} CL = 90\% 2333 \\ \times 10^{-5} CL = 90\% 2333 \\ \times 10^{-5} CL = 90\% 2333 \\ K^{+} e^{+} \mu^{-} \pi^{+} \\ LF < 7.2 \\ \times 10^{-5} CL = 90\% 2333 \\ \times 10^{-9} CL = 90\% 2615 \\ K^{+} e^{-} \mu^{+} \\ LF < 6.4 \\ \times 10^{-9} CL = 90\% 2615 \\ \hline HTTP: //PDG.LBL.GOV \\ Page 73 \\ \hline HTTP: //PDG.LBL.GOV \\ $	▶Lon	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ D^{*-}\pi^{+} \end{array} $	$ \phi K^{+} \mu = \frac{1}{\sqrt{\rho}} $ $ \overline{\lambda} \rho \nu \overline{\nu} $ $ \pi^{+} e^{+} \mu^{-} $ $ \pi^{+} e^{-} \mu^{+} $ $ \pi^{+} e^{\pm} \mu^{\mp} $	LF LF LF	< 3.0	$ \begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \end{array} $	2430 2637 2637 2637	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 43)% 40)%	_ _ _
$\frac{\overline{D}^{0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}}{\overline{D}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}} \begin{bmatrix} \pi^{+}e^{\pm}\tau^{\mp} & LF < 7.5 & \times 10^{-5} \text{ CL}=90\% 2338 \\ \pi^{+}\mu^{+}\tau^{-} & LF < 6.2 & \times 10^{-5} \text{ CL}=90\% 2333 \\ \pi^{+}\mu^{-}\tau^{+} & LF < 4.5 & \times 10^{-5} \text{ CL}=90\% 2333 \\ \pi^{+}\mu^{\pm}\tau^{\mp} & LF < 7.2 & \times 10^{-5} \text{ CL}=90\% 2333 \\ \pi^{+}\mu^{\pm}\tau^{\mp} & LF < 7.2 & \times 10^{-5} \text{ CL}=90\% 2333 \\ K^{+}e^{+}\mu^{+}\tau^{-} & LF < 7.0 & \times 10^{-9} \text{ CL}=90\% 2615 \\ K^{+}e^{-}\mu^{+} & LF < 6.4 & \times 10^{-9} \text{ CL}=90\% 2615 \\ K^{+}e^{-}\mu^{+} & LF < 6.4 & \times 10^{-9} \text{ CL}=90\% 2615 \\ HTTP://PDG.LBL.GOV & Page 73 & Created: 8/28/2020 18:31 \end{bmatrix}$	▶Lon	$egin{array}{cccc} D^{*-}\pi^+\ell^+ u_\ell\ \overline{D}_1(2420)^0\ell^+ u_\ell\ D^{*-}\pi^+\ \overline{D}_1'(2430)^0\ell^+ u_\ell\ D^{*-}\pi^+\ \overline{D}_2^*(2460)^0\ell^+ u_\ell \end{array}$	$ \phi K^{+} \mu = \frac{1}{\sqrt{\rho}} $ $ \pi^{+} e^{+} \mu^{-} $ $ \pi^{+} e^{-} \mu^{+} $ $ \pi^{+} e^{\pm} \mu^{\mp} $ $ \pi^{+} e^{\pm} \tau^{-} $	LF LF LF LF	 < 3.0 < 6.4 < 6.4 < 1.7 < 7.4 	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \end{array}$	2430 2637 2637 2637 2637 2338	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 3)% 32)% 32)%	_ _ _
$\frac{\overline{D}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}}{D_{s}^{(*)-}K^{+}\ell^{+}\nu_{\ell}} \begin{bmatrix} \pi^{+}\mu^{+}\tau^{-} & LF < 6.2 & \times 10^{-5} \text{ CL}=90\% 2333 \\ \pi^{+}\mu^{-}\tau^{+} & LF < 4.5 & \times 10^{-5} \text{ CL}=90\% 2333 \\ \pi^{+}\mu^{\pm}\tau^{\mp} & LF < 7.2 & \times 10^{-5} \text{ CL}=90\% 2333 \\ K^{+}e^{+}\mu^{-} & LF < 7.0 & \times 10^{-9} \text{ CL}=90\% 2615 \\ K^{+}e^{-}\mu^{+} & LF < 6.4 & \times 10^{-9} \text{ CL}=90\% 2615 \end{bmatrix}$ $HTTP://PDG.LBL.GOV \qquad Page 73 \qquad Created: 8/28/2020 18:31$	▶Lon	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \phi K^{+} \mu = \frac{1}{\sqrt{\rho}} $ $ \pi^{+} e^{+} \mu^{-} $ $ \pi^{+} e^{-} \mu^{+} $ $ \pi^{+} e^{\pm} \mu^{\mp} $ $ \pi^{+} e^{\pm} \tau^{-} $ $ \pi^{+} e^{-} \tau^{+} $	LF LF LF LF LF	 3.0 6.4 6.4 1.7 7.4 2.0 	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \end{array}$	2430 2637 2637 2637 2338 2338	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 3)% 32)% 32)%	_ _ _ _
$D_{s}^{(*)-} \kappa^{+} \ell^{+} \nu_{\ell}$ $D_{s}^{-} \kappa^{+} \ell^{+} \nu_{\ell}$ $D_{s}^{-} \kappa^{+} \ell^{+} \nu_{\ell}$ $\frac{\pi^{+} \mu^{-} \tau^{+}}{\pi^{+} \mu^{\pm} \tau^{\mp}}$ $LF < 4.5 \times 10^{-5} \text{ CL}=90\% 2333$ $K^{+} \ell^{+} \mu^{\pm} \tau^{\mp}$ $LF < 7.2 \times 10^{-5} \text{ CL}=90\% 2615$ $K^{+} \ell^{-} \mu^{+}$ $LF < 6.4 \times 10^{-9} \text{ CL}=90\% 2615$ $K^{+} \ell^{-} \mu^{+}$ $LF < 6.4 \times 10^{-9} \text{ CL}=90\% 2615$ $K^{+} \ell^{-} \mu^{+}$ $LF < 6.4 \times 10^{-9} \text{ CL}=90\% 2615$ $K^{+} \ell^{-} \mu^{+}$ $LF < 6.4 \times 10^{-9} \text{ CL}=90\% 2615$	▶Lon ▶Hur	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{2}'(2460)^{0}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0} \rightarrow D^{*-} \\ \overline{D}^{0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \end{array} $	$\phi K^{+} \mu$ $\overline{\lambda} p \nu \overline{\nu}$ $\pi^{+} e^{+} \mu^{-}$ $\pi^{+} e^{-} \mu^{+}$ $\pi^{+} e^{\pm} \mu^{\mp}$ $\pi^{+} e^{\pm} \tau^{-}$ $\pi^{+} e^{-} \tau^{+}$ $\pi^{+} e^{\pm} \tau^{\mp}$	LF LF LF LF LF LF	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \end{array}$	2430 2637 2637 2637 2338 2338 2338	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 3)% 32)% 5)% 5)%	_ _ _ _
$D_{s}^{-}K^{+}\ell^{+}\nu_{\ell}$ $\frac{\pi^{+}\mu^{+}\tau^{+}}{K^{+}e^{+}\mu^{-}}$ $LF < 7.2 \times 10^{-9} \text{ CL}=90\% 2333$ $K^{+}e^{+}\mu^{-}$ $LF < 7.0 \times 10^{-9} \text{ CL}=90\% 2615$ $K^{+}e^{-}\mu^{+}$ $LF < 6.4 \times 10^{-9} \text{ CL}=90\% 2615$ $K^{+}e^{-}\mu^{+}$ $LF < 6.4 \times 10^{-9} \text{ CL}=90\% 2615$ $K^{+}e^{-}\mu^{+}$ $LF < 8/28/2020 18:31$	▶Lon ▶Hur	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{2}'(2460)^{0}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0} \rightarrow D^{*-} \\ \overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \end{array} $	$\phi K^{+} \mu$ $\overline{\Lambda} p \nu \overline{\nu}$ $\pi^{+} e^{+} \mu^{-}$ $\pi^{+} e^{-} \mu^{+}$ $\pi^{+} e^{\pm} \mu^{\mp}$ $\pi^{+} e^{\pm} \tau^{-}$ $\pi^{+} e^{-} \tau^{+}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$	LF LF LF LF LF LF LF	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \end{array}$	2430 2637 2637 2637 2338 2338 2338 2338	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 3)% 32)% 5)% 5)% 1)%)%	
$\frac{D_{s} R c}{K^{+} e^{-} \mu^{+}} = \frac{LF}{LF} < \frac{10}{6.4} \times \frac{10^{-9} CL}{90\%} = \frac{90\%}{2615}$ $\frac{10^{-9} CL}{90\%} = \frac{90\%}{2615}$ $\frac{10^{-9} CL}{90\%} = \frac{10^{-9} CL}{90\%} = $	►Lon	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{2}'(2460)^{0}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0} \rightarrow D^{*-} \\ \overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ D^{(*)-}\kappa^{+}\ell^{+}\nu_{\ell} \end{array} $	$\phi K^{+} \mu$ $\overline{\lambda} p \nu \overline{\nu}$ $\pi^{+} e^{+} \mu^{-}$ $\pi^{+} e^{-} \mu^{+}$ $\pi^{+} e^{\pm} \mu^{\mp}$ $\pi^{+} e^{\pm} \tau^{-}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} \mu^{+} \tau^{-}$ $\pi^{+} \mu^{-} \tau^{+}$ $+ + \pm$	LF LF LF LF LF LF LF	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\$	2430 2637 2637 2637 2338 2338 2338 2338 2333 2333	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 43)% 40)% 40)% 5)% 5)%	
HTTP://PDG.LBL.GOV Page 73 Created: 8/28/2020 18:31	►Lon	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{2}'(2460)^{0}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0} \rightarrow D^{*-} \\ \overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ \overline{D}_{3}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ D^{(*)-}\kappa^{+}\ell^{+}\nu_{\ell} \\ D^{-}\kappa^{+}\ell^{+}\nu_{\ell} \end{array} $	$ \begin{array}{c} \phi K^{+} \mu \\ \overline{\lambda} p \nu \overline{\nu} \\ \pi^{+} e^{+} \mu^{-} \\ \pi^{+} e^{-} \mu^{+} \\ \pi^{+} e^{\pm} \mu^{\mp} \\ \pi^{+} e^{\pm} \tau^{-} \\ \pi^{+} e^{\pm} \tau^{\mp} \\ \pi^{+} e^{\pm} \tau^{\mp} \\ \pi^{+} \mu^{+} \tau^{-} \\ \pi^{+} \mu^{\pm} \tau^{\mp} \\ \pi^{+} \mu^{\pm} \tau^{\mp} \\ \kappa^{+} e^{\pm} u^{-} \end{array} $	LF LF LF LF LF LF LF LF	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \end{array}$	2430 2637 2637 2637 2338 2338 2338 2333 2333 2333 2333	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 43)% 40)% 5)% 5)% 1)%	
HTTP://PDG.LBL.GOV Page 73 Created: 8/28/2020 18:31	Lon	$ \begin{array}{c} D^{*-}\pi^{+}\ell^{+}\nu_{\ell} \\ \overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell} \\ D^{*-}\pi^{+} \\ \overline{D}_{2}'(2460)^{0}\ell^{+}\nu_{\ell} \\ \overline{D}_{2}^{*0} \rightarrow D^{*-} \\ \overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ \overline{D}_{s}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell} \\ D^{(*)-}_{s}K^{+}\ell^{+}\nu_{\ell} \\ D^{-}_{s}K^{+}\ell^{+}\nu_{\ell} \end{array} $	$\phi K^{+} \mu$ $\overline{\lambda} p \nu \overline{\nu}$ $\pi^{+} e^{+} \mu^{-}$ $\pi^{+} e^{-} \mu^{+}$ $\pi^{+} e^{\pm} \mu^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} \mu^{+} \tau^{-}$ $\pi^{+} \mu^{-} \tau^{+}$ $\pi^{+} \mu^{\pm} \tau^{\mp}$ $K^{+} e^{+} \mu^{-}$ $K^{+} e^{-} \mu^{+}$	LF LF LF LF LF LF LF LF LF	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \times 10^{-9} \text{CL}=90\% \\ \times 10^{-9} \text{CL}=90\% \end{array}$	2430 2637 2637 2637 2338 2338 2338 2333 2333 2333 2333 23	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	5)% 2)% 43)% 432)% 5)% 5)% 1)%	
	Lon Hur	$D^{*-}\pi^{+}\ell^{+}\nu_{\ell}$ $\overline{D}_{1}(2420)^{0}\ell^{+}\nu_{\ell}$ $D^{*-}\pi^{+}$ $\overline{D}_{1}'(2430)^{0}\ell^{+}\nu_{\ell}$ $D^{*-}\pi^{+}$ $\overline{D}_{2}^{*}(2460)^{0}\ell^{+}\nu_{\ell}$ $\overline{D}_{2}^{*0} \rightarrow D^{*-}$ $\overline{D}_{2}^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}$ $D^{*0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}$ $D^{(*)-}_{s}K^{+}\ell^{+}\nu_{\ell}$ $D^{-}_{s}K^{+}\ell^{+}\nu_{\ell}$	$\phi K^{+} \mu$ $\overline{\lambda} p \nu \overline{\nu}$ $\pi^{+} e^{+} \mu^{-}$ $\pi^{+} e^{-} \mu^{+}$ $\pi^{+} e^{\pm} \mu^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} e^{\pm} \tau^{\mp}$ $\pi^{+} \mu^{\pm} \tau^{\mp}$ $\pi^{+} \mu^{\pm} \tau^{\mp}$ $K^{+} e^{+} \mu^{-}$ $K^{+} e^{-} \mu^{+}$	LF LF LF LF LF LF LF LF LF LF	$< 3.0 \\ < 6.4 \\ < 6.4 \\ < 1.7 \\ < 7.4 \\ < 2.0 \\ < 7.5 \\ < 6.2 \\ < 4.5 \\ < 7.2 \\ < 7.0 \\ < 6.4 $	$\begin{array}{c} \times 10^{-5} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-3} \text{CL}=90\% \\ \times 10^{-7} \text{CL}=90\% \\ \times 10^{-5} \text{CL}=90\% \\ \times 10^{-9} \text{CL}=90\% \\ \times 10^{-9} \text{CL}=90\% \end{array}$	2430 2637 2637 2637 2338 2338 2338 2333 2333 2333 2333 2615 2615	$\begin{array}{c} 2.5 \pm 0.9 \\ (9.9 \pm 1.2 \\ (7.9 \pm 1.4 \\ -1.3 \\ (1.10 \pm 0.3 \\ (1.10 \pm 0.3 \\ -0.3 \\ (2.1 \pm 0.4 \\ -0.6 \\ (2.8 \pm 1.1 \\ -0.9 \\ (97 \pm 4 \\ \end{array}$	5)% 2)% 43)% 432)% 5)% 5)%)%	



าeso	n decays				D $\pi^{0}\ell^{1}$ $\eta\ell^{+}$	$ \overset{s}{\overset{s}{\overset{s}{\overset{s}{\overset{s}{\overset{s}{\overset{s}{\overset{s}$			(2.9 (7.80 (3.9 (2.3	± 1.9 ± 0.27 ± 0.5 ± 0.8) $\times 10^{-4}$) $\times 10^{-5}$) $\times 10^{-5}$) $\times 10^{-5}$		2185 2638 2611 2553
		$\pi^{+}\ell^{+}\ell^{-}$ $\pi^{+}e^{+}e^{-}$	B1 B1	< <	4.9 8.0	$^{ imes}$ 10 ⁻⁸ $^{ imes}$ 10 ⁻⁸ $^{ imes}$	CL=90%	2638 2638	(1.19	\pm 0.09	$) \times 10^{-4}$		2582
Powerf	B ' DECAT MODES	$\pi^+ \mu^+ \mu^-$	B1	(1.75	\pm 0.22) \times 10 ⁻⁸	3	2634	(1.58 (E.9	\pm 0.11 + 2.6	$) \times 10^{-4}$	i i	2583
		$\begin{array}{c} \pi^+ \nu \overline{\nu} \\ \kappa^+ \ell^+ \ell^- \end{array}$	B1 B1	< [///] (1.4 4 51	$\times 10^{-5}$ + 0.23) $\times 10^{-7}$	CL=90%	2638 2617	(5.8 ° E	- 2.3	$) \times 10^{-6}$	CI	2407
	$\ell^+ \nu_\ell X$	$K^+ e^+ e^-$	B1 B1	[""] (4.51 5.5	\pm 0.23) × 10 \pm 0.7) × 10 ⁻⁷	, 5—1.1	2617	0.5	+ 4.0	× 10 °	CL=90%	2440
Pine	$D\ell^+ \nu_\ell X$	$K^+ \mu^+ \mu^-$	B1	(4.41	\pm 0.22) \times 10 ⁻⁷	S=1.2	2612	(8.2	- 3.3) × 10 °		2467
to n	$\overline{D}^0 \ell^+ \tilde{\nu}_\ell$	$K^+ \mu^+ \mu^-$ nonreso-	B1	(4.37	\pm 0.27) × 10 ⁻⁷		2612	9.8 90 × 10 ⁻	-07 _{to 1}	$\times 10^{-1}$	CL = 90%	2640 2639
	$\frac{D^0}{D^*} \tau^+ \nu_{\tau}$					~ 	<u> </u>	2001	T.09	= 0.24	$(10^{-4}) \times 10^{-4}$	S=1.2	2341
ь г	$\frac{D^{*}(2007)^{\circ}\ell^{-}\nu_{\ell}}{D^{*}(2007)^{\circ}\sigma^{+}\nu}$	$K^+ \overline{\nu} \nu$		<	1.6	× 10 ⁻⁵	C L =90%	2617	3.9		× 10 ⁻⁶	CL=90%	2640
≥Exp	$D^{-}(2007)^{-7} \nu_{\tau}$ $D^{-}\pi^{+}\ell^{+}\nu_{\ell}$	But: Signi		INK	ue	viation	I I I I I I I I I I		SIVI		$\times 10^{-6}$	CL=90%	2640
ІНС	$\overline{D}_{2}^{*}(2420)^{0}\ell^{+}\nu_{\ell}$	$(092)^{+}\ell^{+}\ell^{-}$	BI		1.01	$\pm 0.11 \times 10$	5=1.1	2504	3.4		× 10 ⁻⁰	CL=90%	2639
	$D^{-}\pi^{+}$	observed	1 in	R°	1.55	$D^{(r)}P$	v de	cav	/S ^{1.6}		× 10 ⁻⁰	CL=95%	2634
	$\overline{D}_2^*(2460)^0 \ell^+ u_\ell$,		BI		9.6	\pm 1.0) × 10 ⁻¹		2500	e mode				
	$D^{-}\pi^{+}$	$K^{+}(892) + \nu\nu$	B1		4.0	$\times 10^{-3}$		2564	(8.6	= 0.7) %		-
▶Cha	$D^{(*)}$ n $\pi \ell^+ \nu_\ell$ (n ≥ 1	$(\chi + \chi + \chi + \chi - \chi + \chi + \chi + \chi + \chi - \chi + \chi +$	DI		4.5	± 0.4) × 10 · · · + 2.1 · · · · · · · · · · · · · · · · · · ·		2095	(79	= 4)%		-
992	$D^{*} \pi^{+} \ell^{+} \nu_{\ell}$ $\overline{D}_{*} (2420)^{0} \ell^{+} \nu_{\ell}$					— 1. <i>1 ·</i>			(00	± 0.5 ± 1.2)%		_
	$D_1(2420) \ \ell \ \nu_{\ell}$	$\Lambda p \nu \overline{\nu}$		<	3.0	$\times 10^{-5}$	CL=90%	2430	(3.9	± 1.2 + 1.4) /0		
▶Lon	$\overline{D}'_{1}(2430)^{0}\ell^{+}\nu_{\ell}$	$\pi^+ e^- \mu^+$		< <	0.4 6.4	$\times 10^{-3}$	CL = 90%	2037 2637	(7.9	- 1.3) %		_
<i>w</i>	$D^{*-}\pi^+$	$\pi^+ e^\pm \mu^\mp$	LF	<	1.7	$\times 10^{-7}$	CL=90%	2637	(1.10	+ 0.40 - 0.32)%		-
	\overline{D}_2^* (2460) $^0\ell^+ u_\ell$	$\pi^+ e^+ \tau^-$	LF	<	7.4	imes 10 ⁻⁵	CL=90%	2338	(2.1	+ 0.9) %		_
Mur	$\overline{D}_2^{*0} \rightarrow D^{*-}$	$\pi^+ e^- \tau^+$	LF	<	2.0	$\times 10^{-5}$	CL=90%	2338	(- 0.6) / 0		
FIG	$\overline{D}{}^{0}\pi^{+}\pi^{-}\ell^{+}\nu_{\ell}$	$\pi^+ e^\pm \tau^+$	LF	<	7.5	$\times 10^{-5}$	CL=90%	2338	(2.8	$^+$ 0.9) %		-
	$D^{*0}\pi^+\pi^-\ell^+\nu_\ell$	$ \begin{array}{c} \pi \cdot \mu \cdot \tau \\ \pi^+ \mu^- \tau^+ \end{array} $		<	6.2 4 5	$\times 10^{-3}$	CL = 90%	2333	(97	± 4) %		-
	$D_{s}^{(+)-}K^{+}\ell^{+} u_{\ell}$	$ \begin{array}{c} \pi & \mu & \tau \\ \pi^+ \mu^{\pm} \tau^{\mp} \end{array} $	LF	<	4.5 7.2	$\times 10 \times 10^{-5}$	CL=90%	2333					
	$D_s^- K^+ \ell^+ \nu_\ell$	$K^+e^+\mu^-$	LF	<	7.0	$\times 10^{-9}$	CL=90%	2615					
		${\cal K}^+e^-\mu^+$	LF	<	6.4	× 10 ⁻⁹	CL=90%	2615					
	HTTP://PDG.LBL.GO	V Page 73	Crea	ted: 8/2	28/20	20 18:31							

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

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \tau \nu)}{\Gamma(B \to D^{(*)} \ell \nu)}, \quad \ell = e, \mu$$

▶ Test of lepton flavour universality

Theoretically clean; hadronic uncertainties cancel in the ratio

SM predictions significantly smaller than experiment, combined deviation: $\sim 3.3 \sigma$

 \Rightarrow Violation of LFU? **New Physics** coupled to b and τ ?





Observables in $b \rightarrow s\ell\ell$

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)} \mu \mu)}{\Gamma(B \to K^{(*)} e e)}$$

(Another) test of lepton flavour universality

Theoretically very clean

1810.08132 1605.07633

Combined deviation from the SM $\sim 4 \sigma$, until December 2022.

(now fully consistent with the SM)





EFT study -
$$\Lambda_{NP} \simeq m_{NP}/C_{NP} \sim \mathcal{O}(1-3)^{-1}$$

Possible NP solutions: W', neutrino interactions, ...

Or Leptoquarks!

		$\mathcal{L}_{\mathrm{b} ightarrow\mathrm{cr}}$	$-\nu = -2$	$2\sqrt{2}G_F V_{cb} \Big[\left(1+g_{V_L} ight) \left(\overline{a} ight) \Big]$	$ar{c}_L \gamma^\mu$	$b_L)\left(ar{ au}_L\gamma_\mu u_{ au L} ight)+g_{V_R}\left(ar{c}_R\gamma^\mu b_R ight)\left(ar{ au}_L\gamma_\mu u_{ au} ight)$
/	$C_{NP} \sim \mathcal{O}(1 \cdot$	- 3)	TeV	$+ g_{S_L} (ar{c}_R ar{c}_R)$	$b_L)($	$ar{ au}_R u_{ au L}) + g_T \left(ar{c}_R \sigma^{\mu u} b_L ight) \left(ar{ au}_R \sigma_{\mu u} u_{ au L} ight) ight]$
	Charged Higg	ses,	Exoti	C	_	
						τ
[$(\mathbf{CII}(2) \ \mathbf{CII}(2) \ \mathbf{II}(1))$	Spin	Sumbol	Tumo	F	
	$\frac{(SU(3), SU(2), U(1))}{(\overline{2} + 1/3)}$	Spin	Symbol Sol	$\frac{1 \text{ype}}{LL(S^L)}$		
	(3 , 2 , 7/6)	0	R_2	$RL(S_{1}^{L}), LR(S_{1}^{R})$	$\begin{bmatrix} -2\\ 0 \end{bmatrix}$	
	(3, 2, 1/6)	0	$ ilde{R}_2$	$\frac{1}{RL} (\tilde{S}_{1/2}^L), \frac{1}{LR} (\tilde{S}_{1/2}^L)$	0	
	$(\overline{3}, \underline{1}, 4/3)$	0	$ ilde{S}_1$	$RR(ilde{S}^R_0)$	-2	
	$(\overline{3}, 1, 1/3)$	0	S_1	$LL(S_0^L), RR(S_0^R), \overline{RR}(S_0^{\overline{R}})$	-2	ν
	$(\overline{3}, 1, -2/3)$	0	$ar{S}_1^-$	$\overline{RR}(ar{S}_0^{\overline{R}})$	-2	
	(3, 3, 2/3)	1	U_3	$LL(V_1^L)$	0	
	$(\overline{3}, 2, 5/6)$	1	V_2	$RL(V_{1/2}^{L}), LR(V_{1/2}^{R})$	-2	
	$(\overline{f 3},{f 2},-1/6)$	1	$ ilde{V}_2$	$RL(ilde{V}_{1/2}^{L}),\overline{LR}(ilde{V}_{1/2}^{\overline{R}})$	-2	
	(3 , 1 ,5/3)	1	$ ilde{U}_1$	$\stackrel{'}{RR}(ilde{V}^R_0)$	0	
	(3 , 1 ,2/3)	1	U_1	$LL\left(V_{0}^{L} ight),RR\left(V_{0}^{R} ight),\overline{RR}\left(V_{0}^{\overline{R}} ight)$	0	
	$({f 3},{f 1},-1/3)$	1	$ar{U}_1$	$\overline{RR}(ar{V}_0^{\overline{R}})$	0	

(1603.04993)



EFT study -
$$\Lambda_{NP} \simeq m_{NP}/C_{NP} \sim \mathcal{O}(1-3)^{-1}$$

Possible NP solutions: W', Charged Higgses, Exotic neutrino interactions

Or Leptoquarks

(SU(3), SU(2), U(1))	Spin	Symbo
$(\bar{3}, 3, 1/3)$	0	S_3
$({f 3},{f 2},7/6)$	0	R_2
$({f 3},{f 2},1/6)$	0	$ ilde{R}_2$
$(\overline{3},1,4/3)$	0	$ ilde{S}_1$
$(\overline{3},1,1/3)$	0	S_1
$(\overline{3},1,-2/3)$	0	$ar{S}_1$
(3, 3, 2/3)	1	U_3
$(\overline{3}, 2, 5/6)$	1	V_2
$(\overline{3}, 2, -1/6)$	1	$ ilde{V}_2$
$({f 3},{f 1},5/3)$	1	$ ilde{U}_1$
$({f 3},{f 1},2/3)$	1	U_1
(3 , 1 , -1/3)	1	$ar{U}_1$

(1603.04993)

$\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb} \Big[\left(1 + g_{V_L}\right) \left(\bar{c}_L \gamma^\mu b_L\right) \left(\bar{\tau}_L \gamma_\mu \nu_{\tau L}\right) + g_{V_R} \left(\bar{c}_R \gamma^\mu b_R\right) \left(\bar{\tau}_L \gamma_\mu \nu_{\tau L}\right) \Big]$ $+ g_{S_L} \left(\bar{c}_R b_L \right) \left(\bar{\tau}_R \nu_{\tau L} \right) + g_T \left(\bar{c}_R \sigma^{\mu\nu} b_L \right) \left(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \right) \Big]$ TeV





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[(SU(3), SU(2), U(1))]	Spin	Symbo
$(\bar{3}, 3, 1/3)$	0	S_3
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$({f 3},{f 2},1/6)$	0	$ ilde{R}_2$
$(\overline{3},1,4/3)$	0	$ ilde{S}_1$
$(\overline{3},1,1/3)$	0	S_1
$(\overline{f 3}, {f 1}, -2/3)$	0	$ar{S}_1$
$({\bf 3},{\bf 3},2/3)$	1	U_3
$(\overline{3}, 2, 5/6)$	1	V_2
$(\overline{3}, 2, -1/6)$	1	$ ilde{V}_2$
$({f 3},{f 1},5/3)$	1	$ ilde{U}_1$
(3, 1, 2/3)	1	U_1
$({f 3},{f 1},-1/3)$	1	$ar{U}_1$

(1603.04993)

$\mathcal{L}_{\mathrm{b}\to\mathrm{c}\tau\nu} = -2\sqrt{2}G_F V_{cb} \Big[\left(1 + g_{V_L}\right) \left(\bar{c}_L \gamma^{\mu} b_L\right) \left(\bar{\tau}_L \gamma_{\mu} \nu_{\tau L}\right) + g_{V_R} \left(\bar{c}_R \gamma^{\mu} b_R\right) \left(\bar{\tau}_L \gamma_{\mu} \nu_{\tau L}\right) \Big]$ $+ g_{S_L} \left(\bar{c}_R b_L \right) \left(\bar{\tau}_R \nu_{\tau L} \right) + g_T \left(\bar{c}_R \sigma^{\mu\nu} b_L \right) \left(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \right) \Big]$ TeV





EFT study -
$$\Lambda_{NP} \simeq m_{NP}/C_{NP} \sim \mathcal{O}(1-3)^{-1}$$

Possible NP solutions: W', Charged Higgses, Exotic neutrino interactions

Or Leptoquark	Ś
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(SU(3), SU(2), U(1))	Spin	Symbo
$(\bar{3}, 3, 1/3)$	0	S_3
$({f 3},{f 2},7/6)$	0	R_2
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$(\overline{3},1,1/3)$	0	S_1
$(\overline{f 3}, {f 1}, -2/3)$	0	$ar{S}_1$
(3, 3, 2/3)	1	U_3
$(\overline{f 3},{f 2},5/6)$	1	V_2
$({f \overline{3}},{f 2},-1/6)$	1	$ ilde{V}_2$
$({f 3},{f 1},5/3)$	1	$ ilde{U}_1$
$({f 3},{f 1},2/3)$	1	U_1
$({f 3},{f 1},-1/3)$	1	$ar{U}_1$

(1603.04993)

$\mathcal{L}_{\mathrm{b}\to\mathrm{c}\tau\nu} = -2\sqrt{2}G_F V_{cb} \Big[\left(1 + g_{V_L}\right) \left(\bar{c}_L \gamma^{\mu} b_L\right) \left(\bar{\tau}_L \gamma_{\mu} \nu_{\tau L}\right) + g_{V_R} \left(\bar{c}_R \gamma^{\mu} b_R\right) \left(\bar{\tau}_L \gamma_{\mu} \nu_{\tau L}\right) \Big]$ $+ g_{S_L} \left(\bar{c}_R b_L \right) \left(\bar{\tau}_R \nu_{\tau L} \right) + g_T \left(\bar{c}_R \sigma^{\mu\nu} b_L \right) \left(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \right) \Big]$ TeV





Constraints on LQ models - collider bounds

Direct searches $\Rightarrow M_{LO}^{\min} \sim 1 \text{ TeV} - 1.5 \text{ TeV}$

▶**High-** p_T tails in $pp \rightarrow \tau \tau, pp \rightarrow \tau \nu$

\Rightarrow Mathematica package High-pT



2207.10756 2207.10714 2112.14604 1801.07641





Constraints on LQ models - electroweak and flavour



 \mathbb{B} -physics observables: $B_s - \overline{B}_s$ mixing, $B \to K \nu \overline{\nu}, B_c \to \tau \nu, B_s \to \tau \tau$, $B \rightarrow K \tau \tau$, angular observables

Correlations between flavour observables are highly model dependent \Rightarrow i.e. dependent on the quantum numbers and "texture" of couplings



 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$\mathcal{L}_{R_2} = y_R^{ij} \bar{Q}_i^a e_j R_2^a + y_L^{ij} \bar{u}_{Ri} R_2^{T,a} \epsilon^{ab} L_j^b + \text{h.c.}$



 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$\frac{R_D}{R_D^{SM}} = 1 + 11.1 \operatorname{Re}(g_S) + 65.4 |g_S|^2$$
$$\frac{R_D^*}{R_D^{SM}} = 1 - 25.5 \operatorname{Re}(g_S) + 663 |g_S|^2$$
$$g_S = -0.59 \frac{y_R^{b\tau} y_L^{b\tau*}}{2}$$
After matching and running...





 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$\frac{R_D}{R_D^{\text{SM}}} = 1 + 11.1 \operatorname{Re}(g_S) + 65.4 |g_S|^2$$
$$\frac{R_D^*}{R_D^*} = 1 - 25.5 \operatorname{Re}(g_S) + 663 |g_S|^2$$

Fails to accommodate for the anomaly ... **Unless?**



 $\mathcal{L}_{R_2} = y_R^{ij} \bar{Q}_i^a e_j R_2^a + y_L^{ij} \bar{u}_{R_i} R_2^{T,a} \epsilon^{ab} L_j^b + \text{h.c.}$



 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$\frac{R_D}{R_D^{\rm SM}} = 1 + 11.1 \operatorname{Re}(g_S e^{-i\varphi}) + 65.4 |g_S e^{-i\varphi}|^2$$
$$\frac{R_D^*}{R_D^{\rm SM}} = 1 - 25.5 \operatorname{Re}(g_S e^{-i\varphi}) + 663 |g_S e^{-i\varphi}|^2$$

Fails to accommodate for the anomaly... Unless? ⇒ We allow couplings to have imaginary part!

1309.03012002.072721806.056892206.09717



 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

 $R_{D^{(*)}}$ can be accommodated :)



 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

 $R_{D^{(*)}}$ can be accommodated :)





 $R_2 = (3, 2, 7/6)$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

 $R_{D^{(*)}}$ can be accommodated :)

But: high- p_T - data and constraints from $Z \rightarrow \tau \tau$ decay exclude the viable parameter space :(



* 2σ allowed



 $\tilde{R}_2 = (3, 2, 1/6)$

The "opposite" of R_2 *wrt. to quantum numbers

$$\widetilde{y}_{L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \widetilde{y}_{L}^{b\tau} \end{pmatrix}, \qquad \widetilde{y}_{R} = \begin{pmatrix} 0 \\ \widetilde{y}_{R}^{sN} \\ 0 \end{pmatrix}$$

 $\mathcal{L} = -\widetilde{y}_L^{ij} \overline{d}^i \widetilde{R}_2^a \epsilon^{ab} L^{j,b} + \widetilde{y}_R^{iN} \overline{Q}^{i,a} \widetilde{R}_2^a N_R + \text{h.c.}$

 $R_2 = (3, 2, 1/6)$

The "opposite" of R_2 *wrt. to quantum numbers

 $\widetilde{y}_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \widetilde{y}_L^{b\tau} \end{pmatrix}, \qquad \widetilde{y}_R = \begin{pmatrix} 0 \\ \widetilde{y}_R^{sN} \\ 0 \end{pmatrix}$

Again, $R_{D^{(*)}}$ can be accommodated :) * if a **right-handed neutrino** is added!

But $B \rightarrow K \nu \nu$ is too severely affected **Modified** High- p_T with right-handed neutrinos









 $\mathcal{L}_{S_1} = y_L^{ij} \overline{Q_i^{C,a}} \epsilon^{ab} L_j^b S_1 + y_R^{ij} \overline{u_i^C} e_j S_1 + \tilde{y}_R^{iN} \overline{d_i^C} N_R S_1 + \text{h.c.}$





$S_1 = (\overline{3}, 1, 1/3)$

 $\mathcal{L}_{S_1} = y_L^{ij} \overline{Q_i^{C,a}} \epsilon^{ab} L_j^b S_1 + y_R^{ij} \overline{u_i^C} e_j S_1 + \tilde{y}_R^{iN} \overline{d_i^C} N_R S_1 + \text{h.c.}$

We will focus on three cases:

1. Only left-handed interactions



$S_1 = (\overline{3}, 1, 1/3)$

 $\mathcal{L}_{S_1} = y_L^{ij} \overline{Q_i^{C,a}} \epsilon^{ab} L_j^b S_1 + y_R^{ij} \overline{u_i^C} e_j S_1 + \tilde{y}_R^{iN} \overline{d_i^C} N_R S_1 + \text{h.c.}$

- **1.** Only left-handed interactions
- **2.** Left- and right-handed interactions



$S_1 = (\overline{3}, 1, 1/3)$

 $\mathcal{L}_{S_1} = y_L^{ij} \overline{Q_i^{C,a}} \epsilon^{ab} L_j^b S_1 + y_R^{ij} \overline{u_i^C} e_j S_1 + \tilde{y}_R^{iN} \overline{d_i^C} N_R S_1 + \text{h.c.}$

- **1.** Only left-handed interactions
- **2.** Left- and right-handed interactions
- **3.** Only right-handed interactions



$S_1 = (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$

 $\mathcal{L}_{S_1} = y_L^{ij} Q_i^{C,a} \epsilon^{ab} L_j^b S_1 + y_R^{ij} \overline{u_i^C} e_j S_1 + \tilde{y}_R^{iN} \overline{d_i^C} N_R S_1 + \text{h.c.}$

- **1.** Only left-handed interactions
- **2.** Left- and right-handed interactions
- **3.** Only right-handed interactions
 - \Rightarrow each of them will have specific correlations between flavour observables

"Left-handed" $S_1 = (\overline{3}, 1, 1/3)$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{s\tau} \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = 0$$

Solution Once again, $R_{D^{(*)}}$ can be accommodated

But this time the effect in $B_s - \overline{B}_s$ and $\tau \rightarrow \ell \nu \nu$ is slightly too large



"Left- and right-handed" $S_1 = (3, 1, 1/3)$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_R^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

▶Need right-handed interactions

 \Rightarrow evade $B_{s} - \overline{B}_{s}$ mixing constraint

Successfully accommodate $R_{D^{(*)}}$ and consistent with other observables :)

2008.09548





Predictions with "left- and right-handed" S_1

Explored 3 different minimal TeV-scale LQ models

Can be tested in $B \to D^{(*)} \tau \nu$ angular observables



- \Rightarrow Only S_1 with left and right-handed interactions **phenomenologically viable**







Predictions with "left- and right-handed" S_1

Tree level effect in $b \to c\tau \nu \Rightarrow \frac{\mathcal{B}(B_c \to B_c)}{\mathcal{B}(B_c \to B_c)}$

▶Loop effects in $b \rightarrow s\ell\ell$



$$\frac{(\tau - \tau \nu)^{S_1}}{(\tau - \tau \nu)^{SM}} \in [1.13, 1.48]$$

 $\frac{\mathcal{B}(B \to K^{(*)} \nu \nu)^{S_1}}{\mathcal{B}(B \to K^{(*)} \nu \nu)^{\text{SM}}} \in [1.001, 1.02]$



$B^+ \rightarrow K^+ \nu \nu \mu \text{ decay}$

Relatively clean theoretical prediction \Rightarrow No large uncertainties beyond the form factors

New Belle II measurement shows $\sim 2.7\sigma$ deviation from the SM prediction

 $\Rightarrow \begin{cases} \mathcal{B}(B^+ \to K^+ \nu \nu)^{\text{SM}} = 4.4(3) \times 10^{-6} \\ \mathcal{B}(B^+ \to K^+ \nu \nu)^{\text{exp.}} = 2.35(67) \times 10^{-5} \end{cases}$

The new neutral lepton of mass ~ 0.6 GeV fits the binned data best

2403.13887 2312.12507





Inert S₁ ("right-handed")

▶ Right-handed interactions

\Rightarrow no CKM mixing

 \Rightarrow evading a lot of constraints from flavour observables

Model with only right-handed interactions?

 $\rightarrow \mathcal{L}_{S_1} = y_{ij}^R \overline{u_i^C} e_j S_1 + \tilde{y}_{iN}^R \overline{d_i^C} N_R S_1$



Inert S₁ ("right-handed")

Right-handed couplings

\Rightarrow no CKM mixing

 \Rightarrow evading a lot of constraints from flavour observables

Model with only right-handed interactions?

 $\mathcal{L}_{S_1} = y_{c\tau}^R \overline{c^C} \tau S_1 + \tilde{y}_{bN}^R \overline{b^C} N_R S_1 + \tilde{y}_{sN}^R \overline{s^C} N_R S_1$

Create desired effect in $R_{D^{(*)}}$

Also allows an enhancing effect in $B \rightarrow K^{(*)}$ 'inv'



Inert S₁ ("right-handed")

 $R_{D^{(*)}}$ can be accommodated :)

 \Rightarrow up to masses of RHN up to $\sim 1 \text{ GeV}$

Only RH interactions

 \Rightarrow Evaded $B_s - \overline{B}_s$ mixing, also $Z \rightarrow \tau \tau$ and $\tau \rightarrow \ell \nu \nu$





Inert S₁ ("right-handed")

Excess in $\mathscr{B}(B^+ \to K^+ \text{ 'inv'})$ can also be accommodated :)



Besides $R_{D^{(*)}}$ and $B \rightarrow K^{(*)}$ inv', practically no other constraining observable



Inert S_1 ("right-handed") - predictions

For example: $B_c \rightarrow \tau$ 'inv', $B_c \rightarrow D_s$ 'inv', $B_c \rightarrow D_s$

▶Particularly interesting:

 $\Rightarrow D_{s} \rightarrow \text{'inv'}$ (branching fraction scal

 \Rightarrow Angular observables in $B \rightarrow D^{(*)} \tau \nu$ decays, example:

Quantity	\mathbf{SM}	$m_{N_R} = 0 \text{ GeV}$	0.6 C
$P_{\tau}^{D^*}$	-0.51(2)	-0.39(4)	-0.41
$F_L^{D^*}$	0.46(1)	0.46(1)	0.46

$$\rightarrow J/\psi \tau$$
 'inv' $(R_{J/\psi})$

les with the
$$m_{N_R}^2$$
)



Inert S_1 ("right-handed") - predictions

For example: $B_c \to \tau'$ inv', $B_c \to D_s'$ inv', $B_c \to J/\psi \tau'$ inv' $(R_{J/\psi})$

▶Particularly interesting:

 $\Rightarrow D_s \rightarrow \text{'inv'}$ (branching fraction sca

 \Rightarrow Angular observables in $B \rightarrow D^{(*)} \tau \nu$ decays, example:

Quantity	\mathbf{SM}	$m_{N_R} = 0 \text{ GeV}$	$0.6 { m ~GeV}$	$1 { m GeV}$
$P_{ au}^{D^*}$	-0.51(2)	-0.39(4)	-0.41(3)	-0.43(3)
$F_L^{D^*}$	0.46(1)	0.46(1)	0.46(1)	0.45(1)

 \Rightarrow Only some observables experimentally measured, poor accuracy

les with the
$$m_{\!N_R}^2$$
)

 \Rightarrow Improvements in Belle II?



Summary and conclusions

Hint for the New Physics in $b \to c \ell \nu$ transitions

- Explored 4 different minimal TeV-scale LQ models \Rightarrow Only two are viable:
 - $*S_1$ with left and right-handed interactions
 - \Rightarrow Plenty of observables affected; $R_{D^{(*)}}, Z \rightarrow \tau\tau, \nu\nu, \tau \rightarrow \ell\nu\nu$, High- p_T ,
 - FB asymmetry,...
 - $*S_1$ with only right-handed interactions, with the introduction of
 - **right-handed neutrino(s)**, enhances also $B \rightarrow K^{(*)}\nu\nu$

 - ⇒Few observables affected, **but has a specific signature in** angular observables in $B \rightarrow D^{(*)} \tau \nu$
 - \Rightarrow More specifically, the presence of **RHN can be inferred from** P_{τ}



Thank you for your attention!

