Rare B decays at Belle

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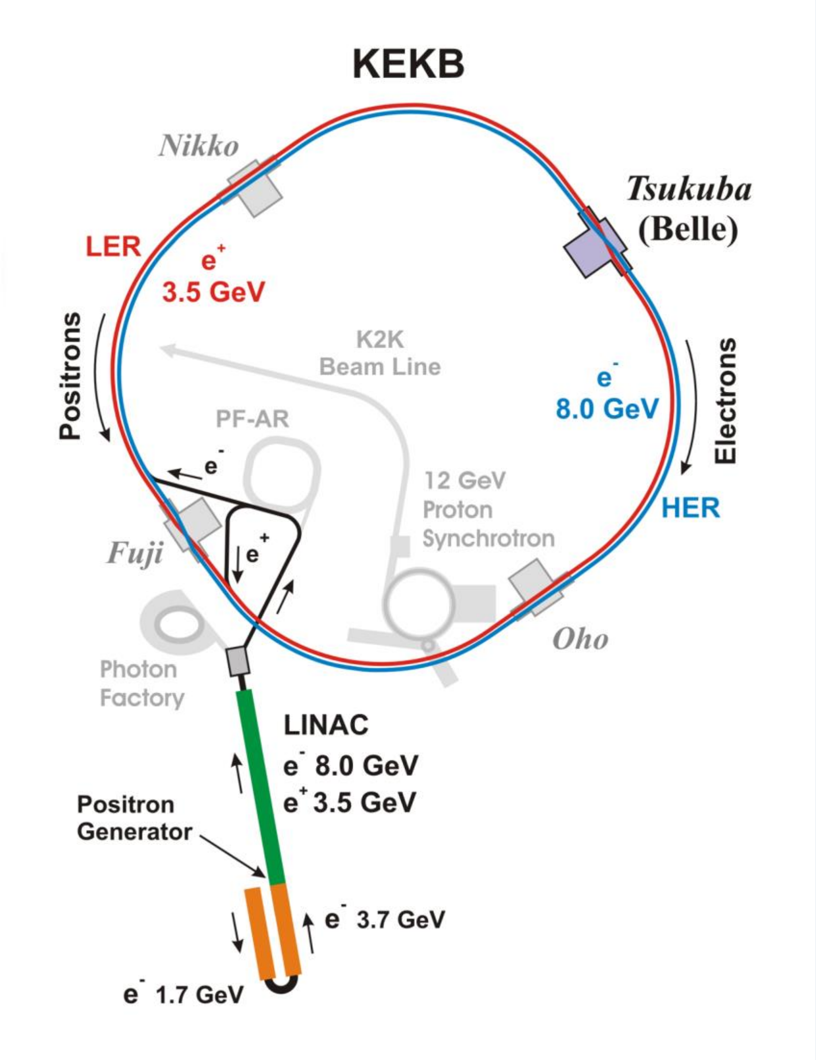
Rare B decays

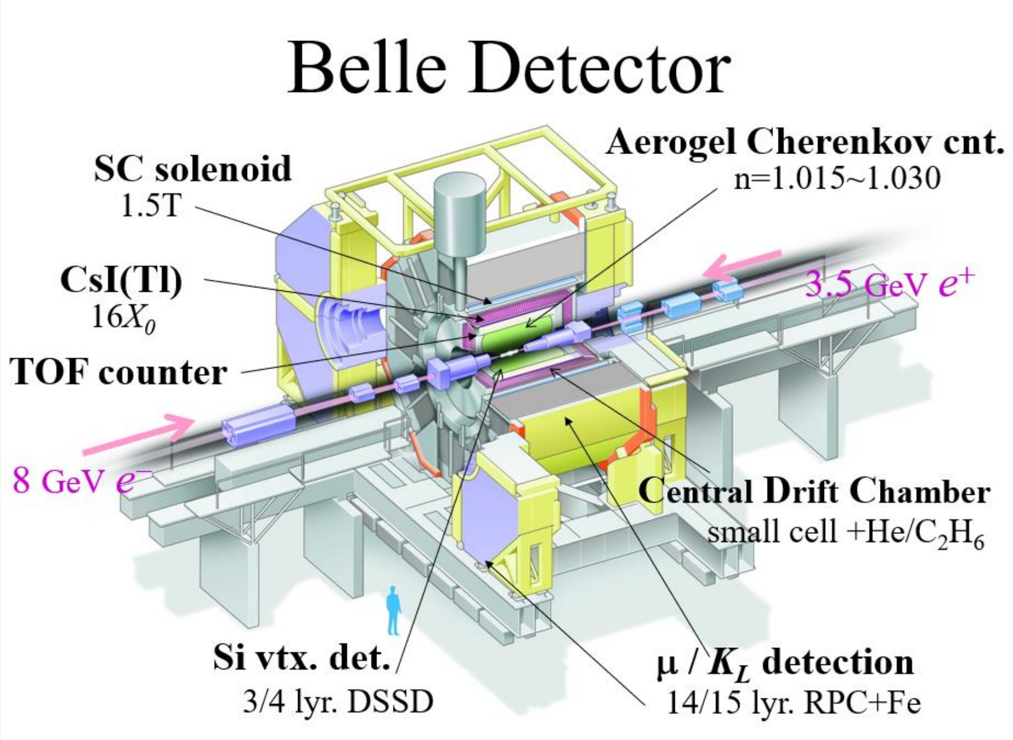
- In SM the coupling of gauge bosons to leptons is independent of lepton flavor – *Lepton Flavor Universality (LFU)*
- *LFU* is a good probe for New Physics (NP) – some models predict larger couplings for heavier leptons
- *LFU* can be also accompanied by *Lepton Flavor Violation (LFV)* ⇒ any signal observation could be an indication of *NP* contribution

This talk: recent Belle efforts to search for LFU in $b \to s$ transition and LFV

The Belle experiment



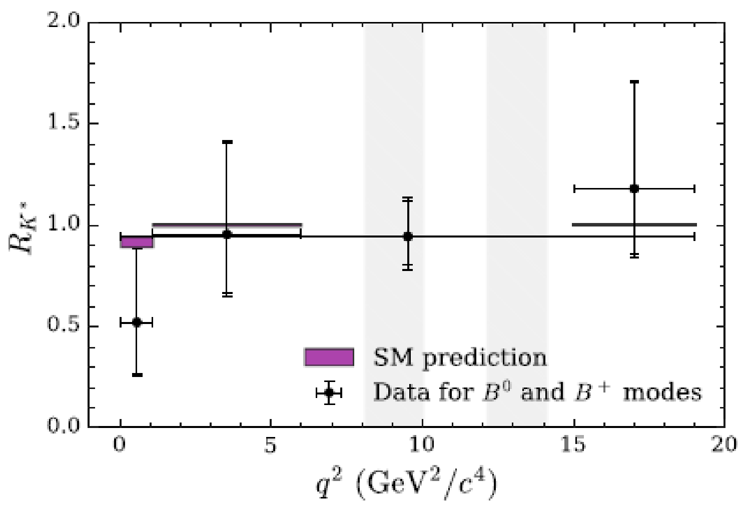
- KEKB asymmetric $e^+ e^-$ collider
- Operated from 1999 to 2010, followed by Belle II
- Collected data: $\Upsilon(4S)$ - 711 fb^{-1}, $\Upsilon(5S)$ - 121 fb^{-1}



LFU: $R(K^{(*)})$

- $R_{K^{(*)}} \equiv \frac{Br\,(B \to K^{(*)}\mu^+\mu^-)}{Br\,(B \to K^{(*)}e^+e^-)}$
- Multivariate analysis is used to suppress continuum background and select signal. Signal yields obtained from fit of M_{bc} in different q^2 bins
- Results consistent with SM
- The dominant systematic uncertainty coming from lepton identification - 5(10)%
- The same analysis $R(K)$ also searched for LFV $B \to K\mu e$. Upper limits at 90% CL obtained:

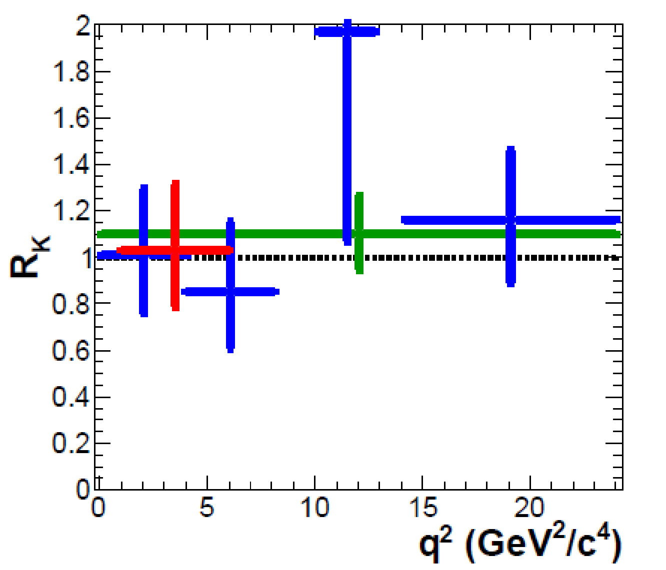
Channel	Babar $(\times 10^{-7})$	LHCb $(\times 10^{-9})$	**Belle** $(\times \mathbf{10^{-8}})$
$\mathcal{B}(B^+ \to K^+\mu^+e^-)$		6.4	**8.5**
$\mathcal{B}(B^+ \to K^+\mu^-e^+)$		7.0	**3.0**
$\mathcal{B}(B^+ \to K^0\mu^\pm e^\mp)$	2.7		**3.8**



Full data sample: $711\,fb^{-1}$

R_{K^*} in q^2 bins results compared to SM, dashed – charmonium veto

R_K in q^2 bins (green one – the whole region excluding charmonium resonances)



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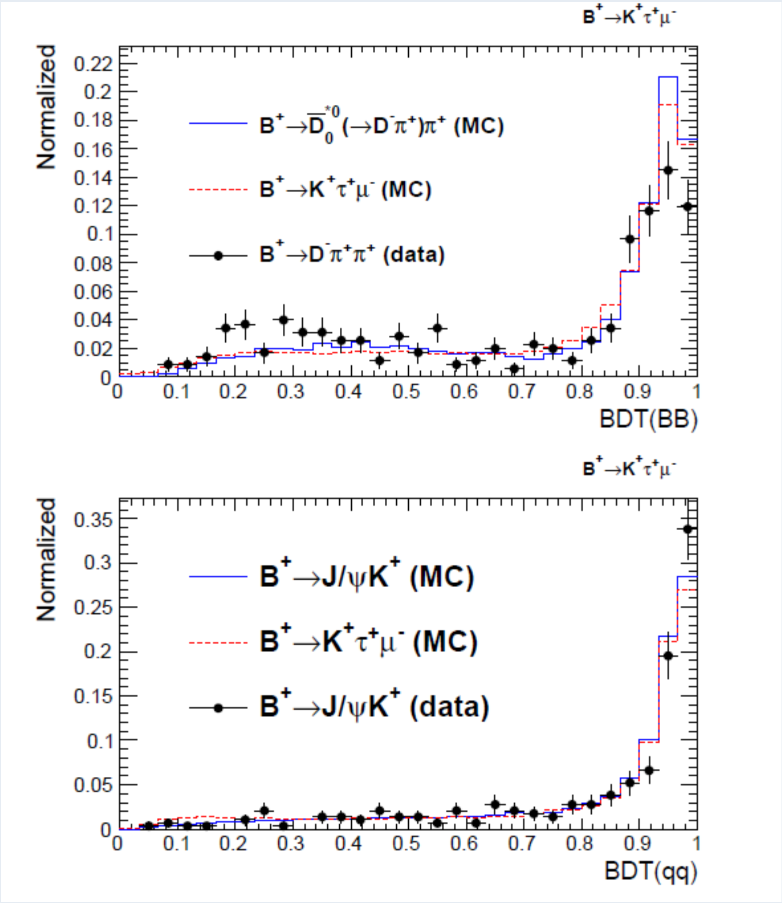
LFV: $B^+ \to K^+\tau^\pm l^\mp$

- Hadronic tagging with Full Event Interpretation
- FEI – reconstructs hierarchically exclusive B-meson channels ($\mathcal{O}(10^3)$ decays available)
- Signal B: 3 charged tracks originating from IP, not associated to B tag
- Consider τ decays $\tau \to e\nu\bar{\nu}, \tau \to \mu\nu\bar{\nu}, \tau \to \pi\nu$
- 2 BDTs trained for background suppression – $B\bar{B}$ and $q\bar{q}$. Systematic uncertainties are evaluated using the control samples: $B^+ \to \bar{D}^{**0} (\to D^-\pi^+)\pi^+$ (similar topology, D treated as τ); $B \to J/\psi K$ (for $q\bar{q}$ suppression evaluation – B_{sig} topology is not used)



BDT output distribution for signal MC, data, and control samples

Full data sample:
711 fb^{-1}

arXiv:2212.04128

LFV: $B^+ \to K^+\tau^\pm l^\mp$

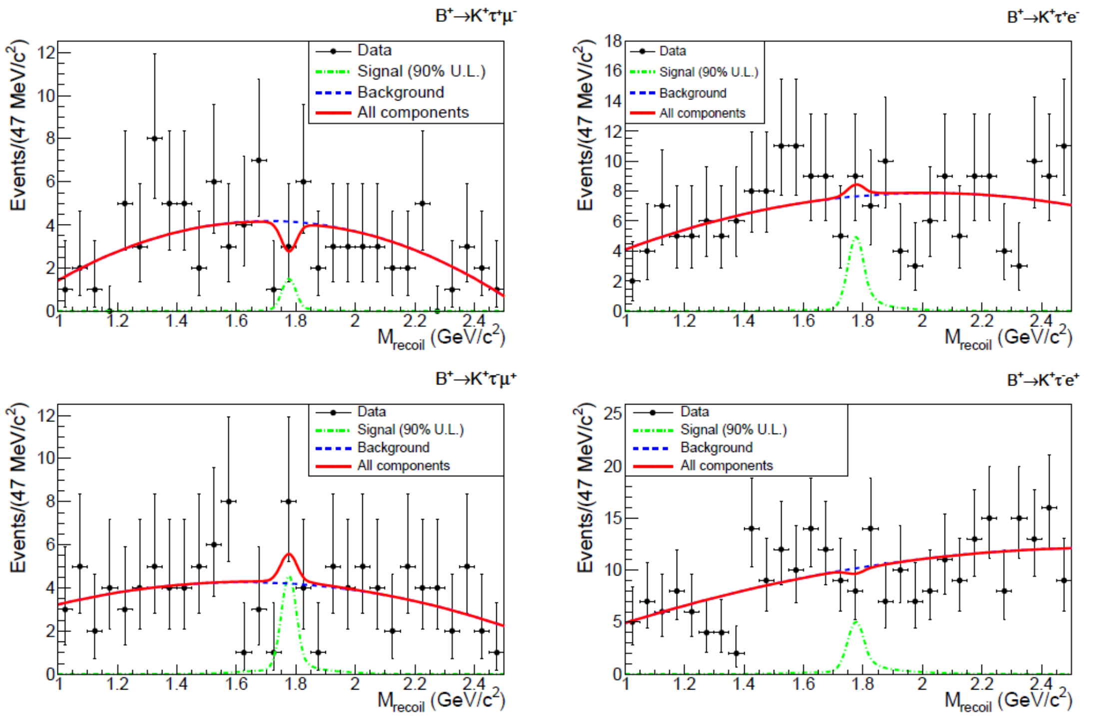
- Leading systematic uncertainties

$(B^+ \to K^+\tau^+\mu^-)$:

BDT selection $B\bar{B}$ - 10.6%, and $q\bar{q}$ – 10.8%, tag calibration – 5.9%

- The most stringent limits up-to-date:

Channel	Babar	LHCb ($\times 10^{-5}$)	**Belle** ($\times 10^{-5}$)
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-)$	2.8	3.9	**0.59**
$\mathcal{B}(B^+ \to K^+\tau^+e^-)$	1.5		**1.51**
$\mathcal{B}(B^+ \to K^+\tau^-\mu^+)$	4.5	3.9	**2.45**
$\mathcal{B}(B^+ \to K^+\tau^-e^+)$	4.3		**1.53**

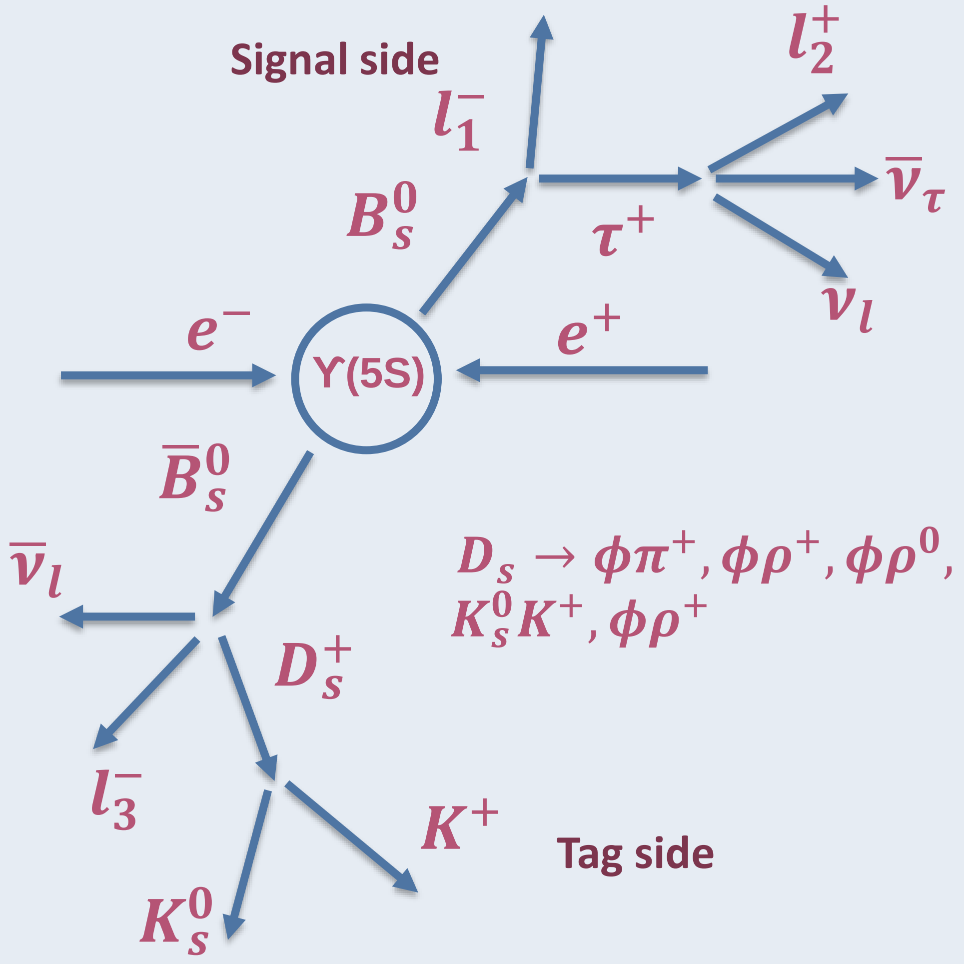


Recoil mass – used for fitting, should peak at mass of τ lepton

$$M^2_{\text{recoil}} = m^2_\tau = m^2_B + m^2_{K\ell} - 2(E^*_{\text{beam}} E^*_{K\ell}/c^4 + p^*_{B_{\text{tag}}} p^*_{K\ell} \cos\theta/c^2)$$

LFV: $B_s^0 \to l\tau$

- $e^+e^- \to \Upsilon(5S) \to B_s^{(*)0}\bar{B}_s^{(*)0}, B_s^{*0} \to B_s^0\gamma$, 100% mixing $B_s^0 \leftrightarrow \bar{B}_s^0$
- Semi-leptonic tag: $\bar{B}_s^0 \to D_s^+ l^-(X)\bar{\nu}_l$, select lepton from tag side with an opposite charge of primary lepton of signal-side
- FastBDT classifier to suppress continuum background (kinematics variables + Fox-Wolfram moments), optimized with Punzi FOM. Best candidate selection – based on FastBDT output



Schematic view of the process, signal and tag sides

Full data sample: $121\ fb^{-1}$

arXiv:2301.10989

LFV: $B_s^0 \to l\tau$

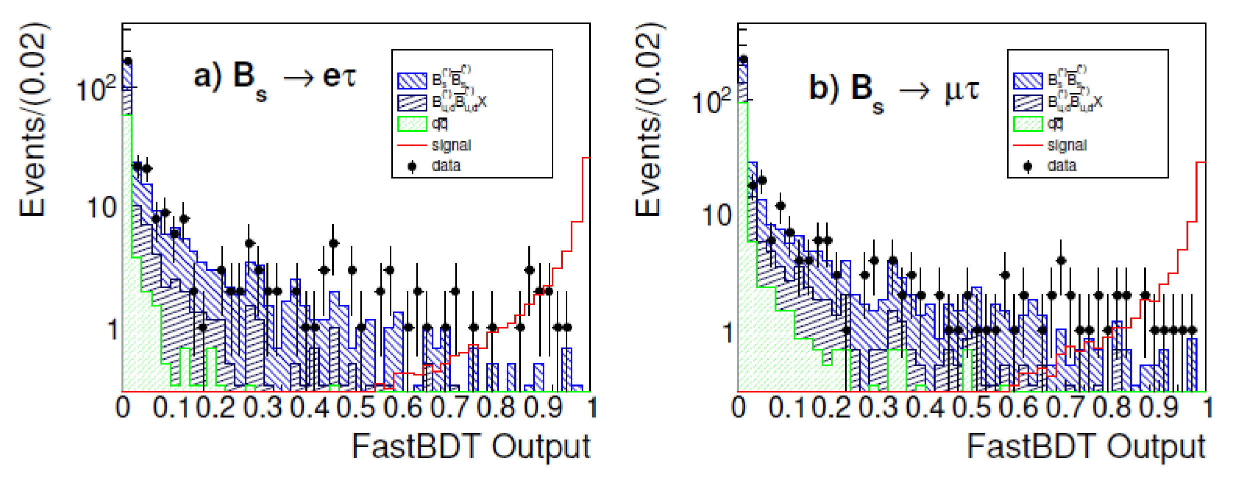
- Leading systematic uncertainties:

 SL tagging uncertainty – 15%, number of B_s – 16.1%, FBDT selection - 3.3(3.7)%

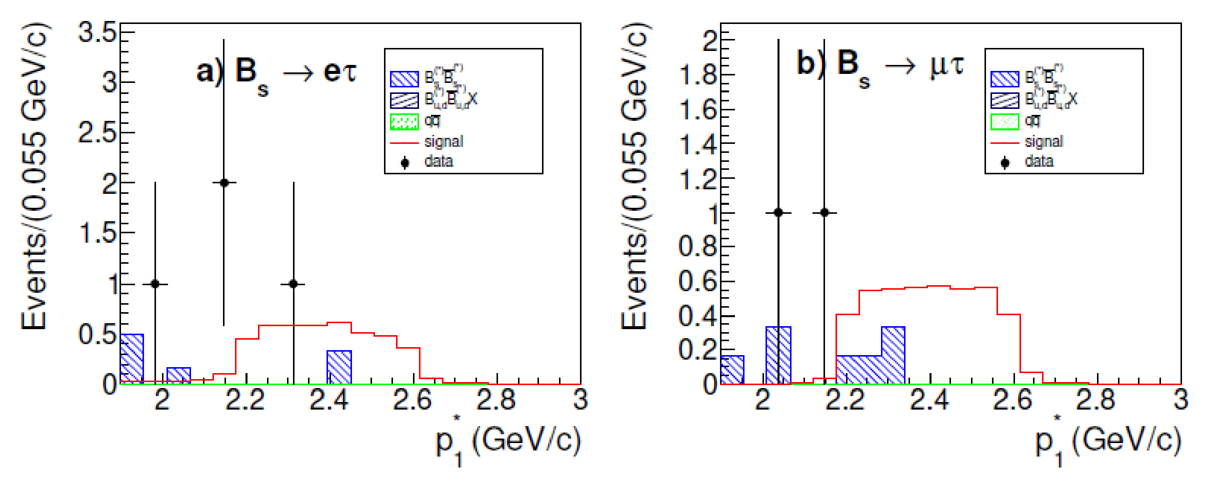
- Set up upper limits at 90% CL:

Channel	LHCb	**Belle**
$\mathcal{B}(B_s^0 \to e^\mp\tau^\pm)$	-	$\mathbf{14.1 \times 10^{-4}}$
$\mathcal{B}(B_s^0 \to \mu^\mp\tau^\pm)$	3.4×10^{-5}	$\mathbf{7.3 \times 10^{-4}}$

- Limit on electron channel is the first such limit reported!



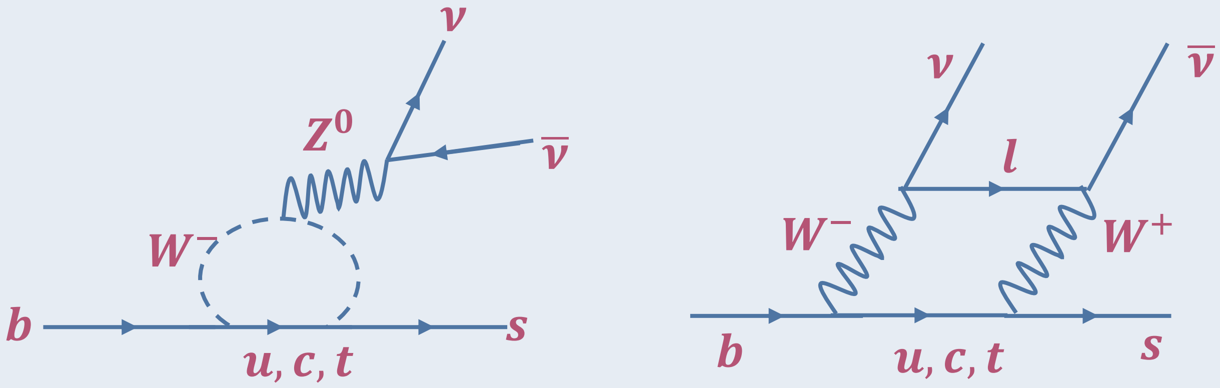
FBDT output distribution for signal MC, generic MC and data



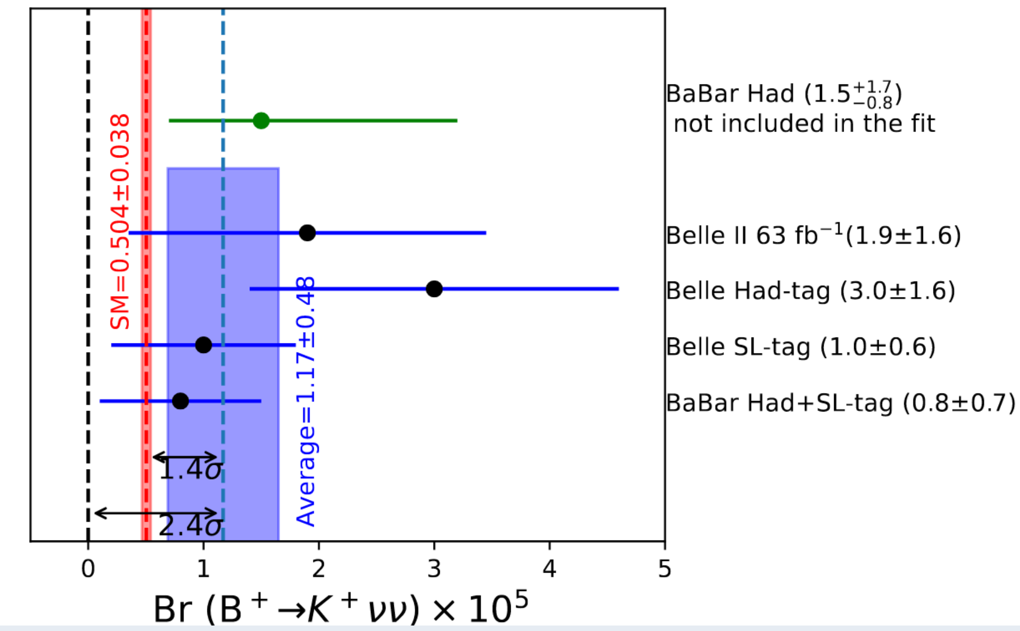
Final fit is performed on p_1^*

$B^+ \to K^+\nu\bar{\nu}$

- Has never been observed yet, the SM prediction is $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (5.04 \pm 0.38) \times 10^{-6}$ [substracting long-distance contribution]
- FCNC, clean theoretical prediction – exact factorization
- Sensitive to contributions of non-SM particles
- Possible scenarios: Z' (light/heavy), leptoquarks



Contributing Feynman diagrams: penguin and box



Experimental results from Belle (SL, had), BaBar (Had+SL), Belle II (inclusive)

- Challenging to detect: small branching fraction and large missing energy

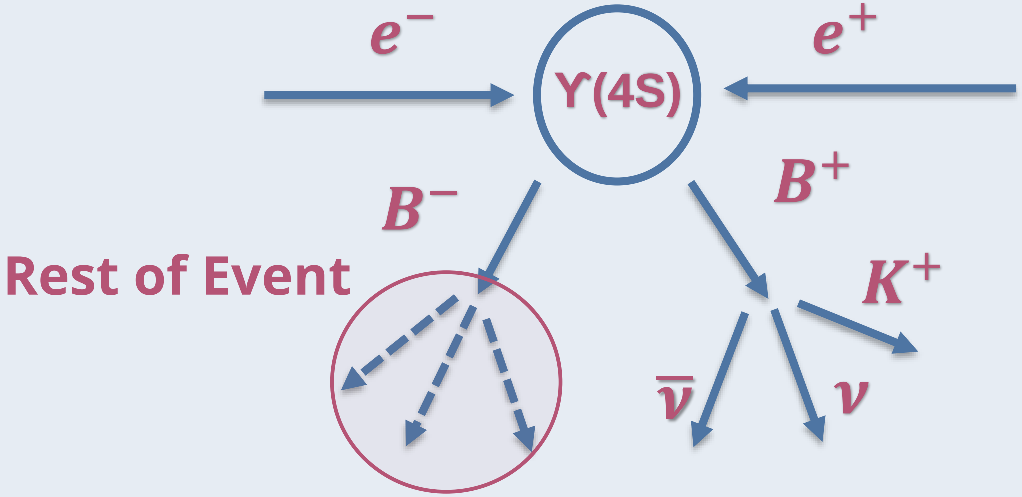
→ inclusive tagging method, used first in Belle II – intriguing result with relatively small dataset

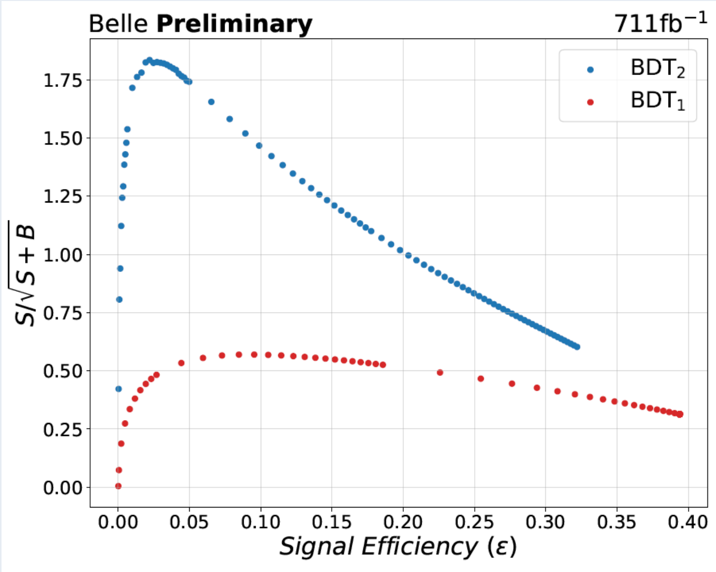
$B^+ \to K^+\nu\bar{\nu}$

Multivariate classification is used to suppress background and select signal:

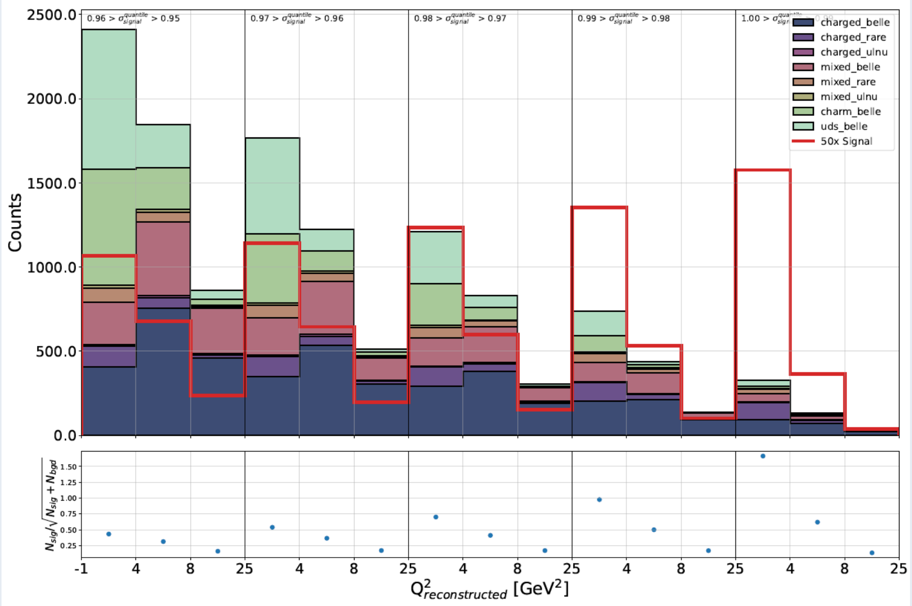
- BDT1: to reduce largely $B\bar{B}$ and $q\bar{q}$ background
- BDT2 or NN: to select signal. NN trained with decorrelation on q^2 variable to avoid biases
- Control sample: $B^+ \to K^+J/\psi \to K^+\mu^+\mu^-$, muons discarded

Not unblinded, preliminary MC results





FOM over signal efficiency dependence for BDT1 and BDT2



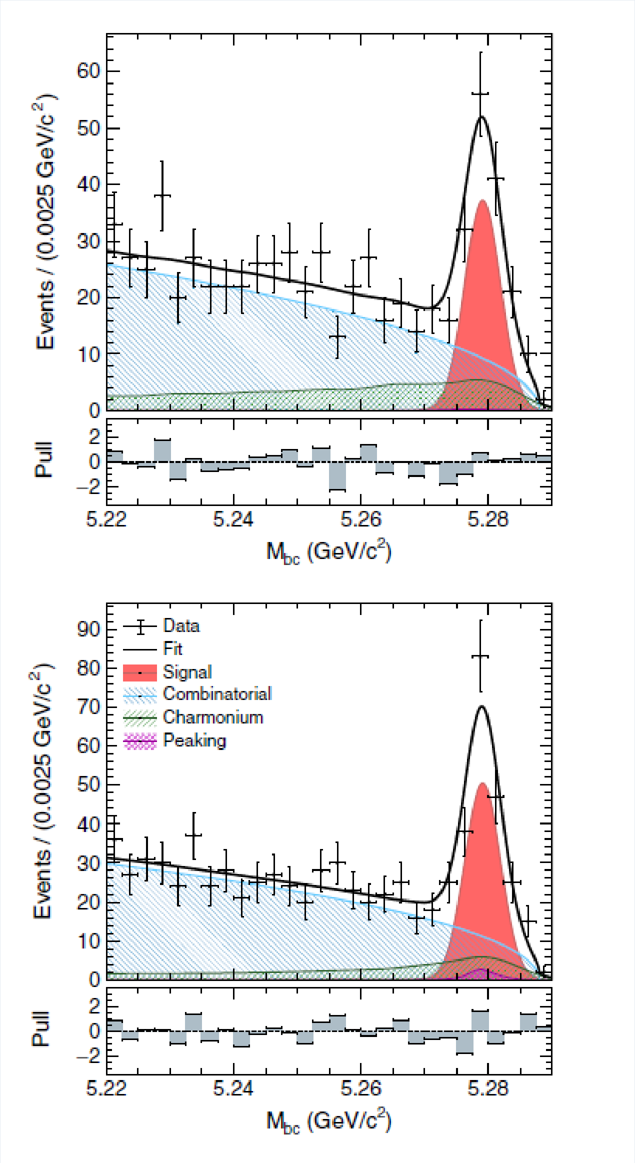
Distribution in $q^2 \times \sigma$ bins

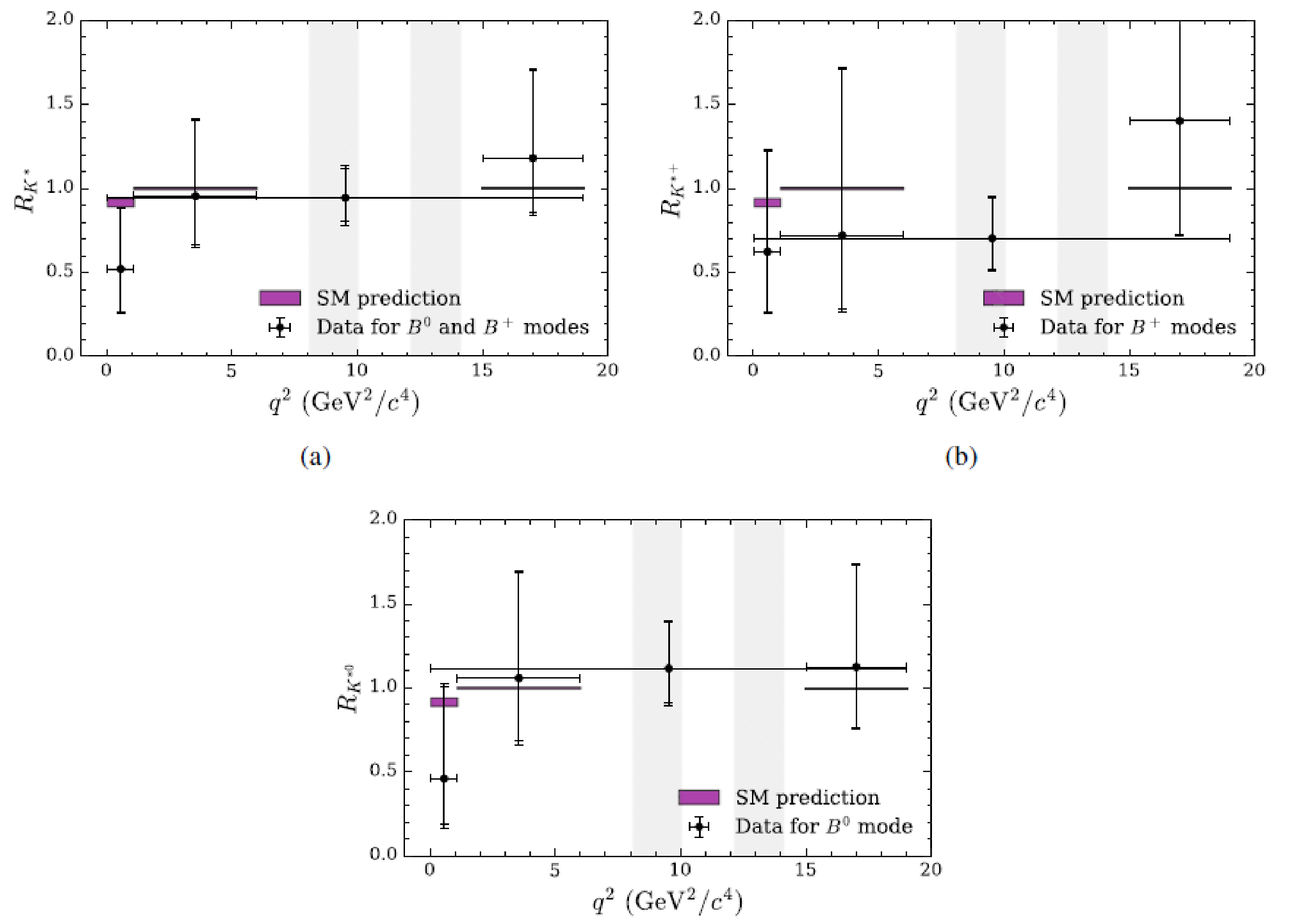
Summary

- New Physics could manifest itself in LFU and LFV
- $R(K^{(*)})$ – consistent with the SM
- $B_s^0 \to l\tau$ – the first upper limit estimation for the electron channel
- $B^+ \to K^+\tau^\pm l^\mp$ - the most stringent upper limits to-date
- $B^+ \to K^+\nu\bar{\nu}$ - inclusive tag analysis ongoing

Thank you for attention!

Backup $R(K^{(*)})$


Events / (0.0025 GeV/c²)
Pull
M_bc (GeV/c²)
Data
Fit
Signal
Combinatorial
Charmonium
Peaking


SM prediction
Data for B⁰ and B⁺ modes
Data for B⁺ modes
Data for B⁰ mode
q² (GeV²/c⁴)
(a)
(b)

Backup $R(K^{(*)})$

TABLE II. Results for R_{K^*}, $R_{K^{*0}}$, and $R_{K^{*+}}$. The first uncertainty is statistical and the second is systematic.

q^2 (GeV$^2/c^4$)	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.13$	$0.62^{+0.60}_{-0.36} \pm 0.07$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.14$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.09$	$0.96^{+0.56}_{-0.35} \pm 0.13$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045, 19]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.06$

TABLE III. Results for the branching fractions in $[10^{-7}]$ in the corresponding q^2 range in GeV$^2/c^4$. The first uncertainty is statistical and the second is systematic.

Mode	$q^2 \in [1.1, 6]$	$q^2 \in [0.1, 8]$	$q^2 \in [15, 19]$	$q^2 > 0.045$
$\mathcal{B}(B^0 \to K^{*0}e^+e^-)$	$1.8^{+0.6}_{-0.6} \pm 0.2$	$3.7^{+0.9}_{-0.9} \pm 0.4$	$2.0^{+0.6}_{-0.5} \pm 0.2$	$9.2^{+1.6}_{-1.6} \pm 0.8$
$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$	$1.9^{+0.6}_{-0.5} \pm 0.3$	$3.2^{+0.8}_{-0.8} \pm 0.4$	$2.2^{+0.5}_{-0.4} \pm 0.2$	$10.3^{+1.3}_{-1.3} \pm 1.1$
$\mathcal{B}(B^+ \to K^{*+}e^+e^-)$	$1.7^{+1.0}_{-1.0} \pm 0.2$	$4.6^{+1.6}_{-1.5} \pm 0.7$	$2.1^{+1.2}_{-1.0} \pm 0.2$	$14.1^{+3.1}_{-2.8} \pm 1.8$
$\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-)$	$1.2^{+0.9}_{-0.7} \pm 0.2$	$4.4^{+1.6}_{-1.4} \pm 0.5$	$2.9^{+1.0}_{-0.8} \pm 0.3$	$9.9^{+2.4}_{-2.3} \pm 1.1$

Backup $B^+ \to K^+\tau^\pm l^\mp$

TABLE II: Contributions to the systematic uncertainties of the measurements.

Source	$K^+\tau^+\mu^-$	$K^+\tau^+e^-$	$K^+\tau^-\mu^+$	$K^+\tau^-e^+$
Additive (events)				
PDF shape (mean)	0.09	0.01	0.08	0.08
PDF shape (width)	0.02	0.08	0.04	0.07
PDF shape (f_{sig})	0.28	0.16	0.11	0.16
Linearity	0.03	0.04	0.02	0.04
Total	0.30	0.18	0.14	0.20
Multiplicative (%)				
B_{tag} calibration	5.9	5.9	5.9	5.9
Track reconstruction	1.1	1.1	1.1	1.1
Kaon id.	1.3	1.4	1.3	1.3
Lepton id.	0.3	0.4	0.3	0.4
τ daughter id.	0.7	0.7	0.6	0.6
MC statistics	1.0	1.5	1.2	1.0
Number of $B\overline{B}$ pairs	1.4	1.4	1.4	1.4
BDT $B\overline{B}$ selection	10.6	10.0	12.7	12.6
BDT $q\overline{q}$ selection	8.8	8.6	9.2	6.6
f^{+-}	1.2	1.2	1.2	1.2
Total	15.3	14.8	17.0	15.7

Backup $B_s^0 \to l\tau$

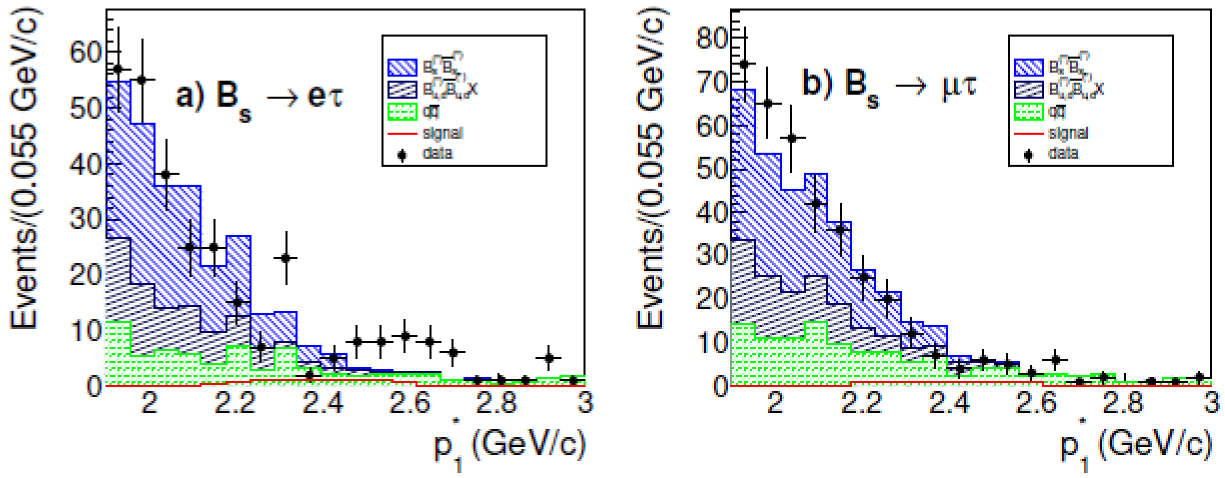


Figure 3: The p_1^* distribution of signal MC, generic MC and data in $B_s \to e^-\tau^+$ (a) and $B_s \to \mu^-\tau^+$ (b) modes. The different background components in generic MC are indicated by different colours as shown in the legend. The MC samples are normalized with respect to the data luminosity. The signal components correspond to $\mathcal{B} = 1 \times 10^{-3}$.

Backup $B^+ \to K^+\nu\bar{\nu}$

Decay	Fraction, %
$B^\pm \to \overline{D}^*(2007)^0\mu^\pm\nu_\mu$	7.880327
$B^\pm \to \overline{D}^*(2007)^0e^\pm\nu_e$	6.58383
$B^\pm \to \overline{D}^0\mu^\pm\nu_\mu$	6.08433
$B^\pm \to \overline{D}^0e^\pm\nu_e$	5.811197
$B^\pm \to \overline{D}^0\tau^\pm\nu_\tau$	1.048505
$B^\pm \to \overline{D}^*(2007)^0\tau^\pm\nu_\tau$	0.968968
$B^\pm \to D^0D_s^\pm$	0.757687
$B^\pm \to \overline{D}_0^*(2300)^0\mu^\pm\nu_\mu$	0.673378
$B^\pm \to \rho(770)^\pm D^0$	0.638757
$B^\pm \to \overline{D}_0^*(2300)^0e^\pm\nu_e$	0.640273
$B^\pm \to D_s^{*\pm}\overline{D}^*(2007)^0$	0.628755
$B^\pm \to \overline{D}^*(2007)^0e^\pm\nu_e\gamma$	0.603814
$B^\pm \to D^*(2007)^0\rho(770)^\pm$	0.5300025
$B^\pm \to D_1(2420)^0\mu^\pm\overline{\nu}_\mu$	0.518129
$B^\pm \to \overline{D}^0e^\pm\nu_e\gamma$	0.512394
$B^\pm \to \overline{D}_1(2430)^0\mu^\pm\nu_\mu$	0.51266
$B^\pm \to D^0\pi^\pm$	0.483492
$B^\pm \to \overline{D}^*(2007)^0K^\pm\overline{K}^0$	0.47301
$B^\pm \to \overline{D}_1(2420)^0e^\pm\nu_e$	0.465642
$B^\pm \to \overline{D}_1(2430)^0e^\pm\nu_e$	0.458707

Decay	Fraction, %
$B^0 \to D^*(2010)^\mp\mu^\pm\nu_\mu$	7.181017
$B^0 \to D^*(2010)^\mp e^\pm\nu_e$	5.938356
$B^0 \to D^\mp\mu^\pm\nu_\mu$	3.108249
$B^0 \to D^\mp e^\pm\nu_e$	2.915231
$B^0 \to D^-\overline{n}p$	0.788527
$B^0 \to D^*(2010)^\mp\tau^\pm\nu_\tau$	0.99131
$B^0 \to D_0^*(2300)^\mp\mu^\pm\overline{\nu}_\mu$	0.993152
$B^0 \to D_0^*(2300)^\mp e^\pm\nu_e$	0.93435
$B^0 \to D^*(2010)^\mp D_s^{*\pm}$	0.81219
$B^0 \to D^*(2010)^\mp K^\pm\overline{K}^0$	0.758093
$B^0 \to D_1(2420)^\mp\mu^\pm\nu_\mu$	0.66667
$B^0 \to D_1(H)^\mp\mu^\pm\nu_\mu$	0.646855
$B^0 \to D^*(2010)^\mp\overline{n}p$	0.483966
$B^0 \to D_1(2420)^\mp e^\pm\nu_e$	0.6095
$B^0 \to D_1(H)^\mp e^\pm\overline{\nu}_e$	0.588462
$B^0 \to D^\mp\tau^\pm\nu_\tau$	0.578569
$B^0 \to D^*(2010)^\mp e^\pm\nu_e\gamma$	0.56437
$B^0 \to D^*(2010)^\mp D_s^\pm$	0.503903
$B^0 \to D^\mp D_s^\pm$	0.492259
$B^0 \to D_s^{*\pm}D^\mp$	0.40087