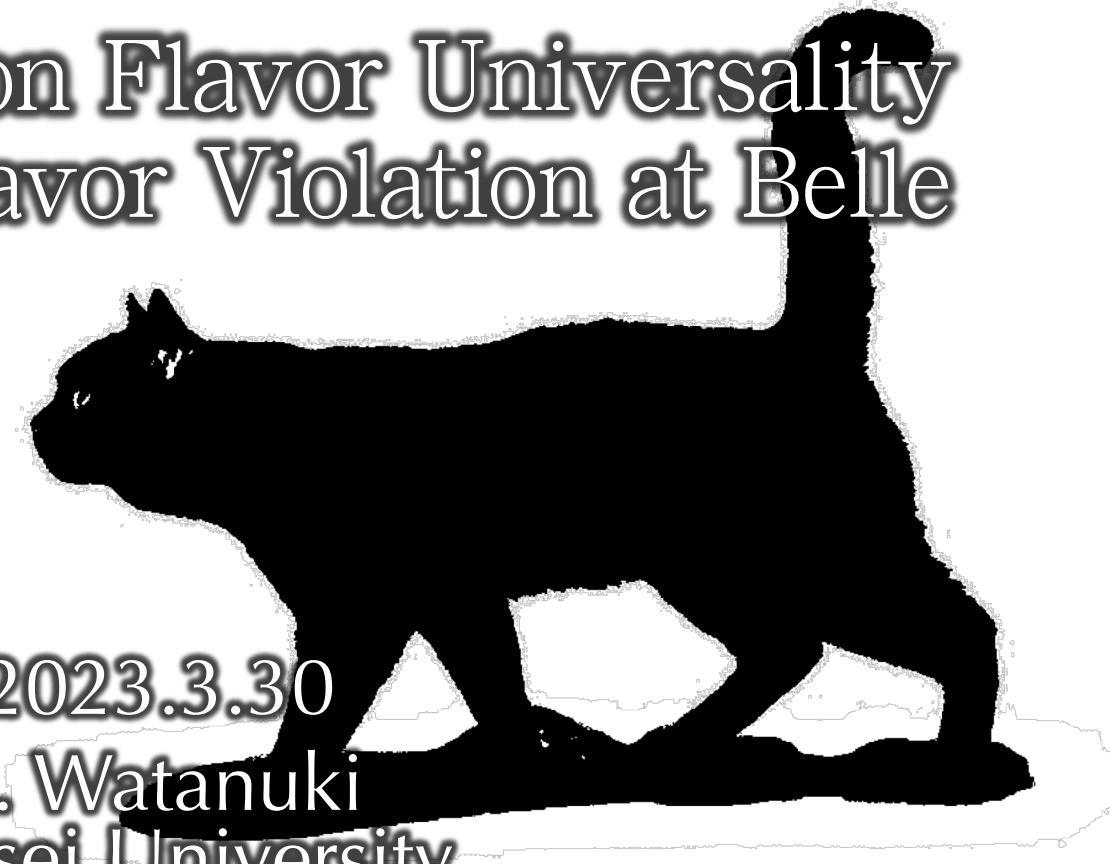


# Study of Lepton Flavor Universality and Lepton Flavor Violation at Belle



2023.3.30  
S. Watanuki  
Yonsei University

# Introduction

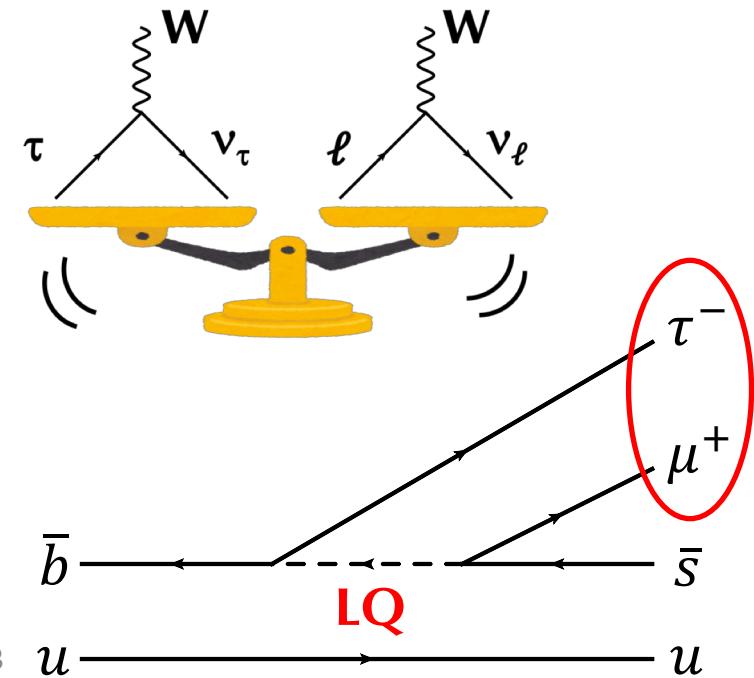
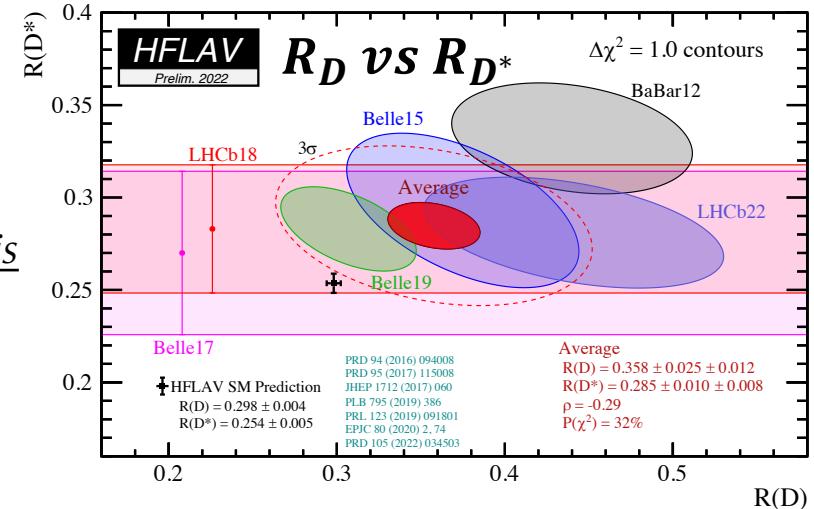
## Test of lepton flavor universality (LFU)

- We see anomalies in semi-leptonic B decays

- $R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu\mu)}{\mathcal{B}(B \rightarrow K^{(*)}ee)}$  (1-loop) Cross-check is still needed!!
- $R_{D^{(*)}} \equiv \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}$  (tree)

## Search for lepton flavor violation (LFV)

- If lepton flavor universality is violated, lepton flavor is no longer guaranteed
  - Leptoquark (LQ) model
  - Extended gauge sector
- B factory is also powerful to search the LFV modes:
  - $B^+ \rightarrow K^+\ell_1\ell_2$  Any combination
  - $B_{(s/d)}^0 \rightarrow \ell_1\ell_2$  using ( $e, \mu, \tau$ )



# Today's topics

## ➤ LFU tests at Belle

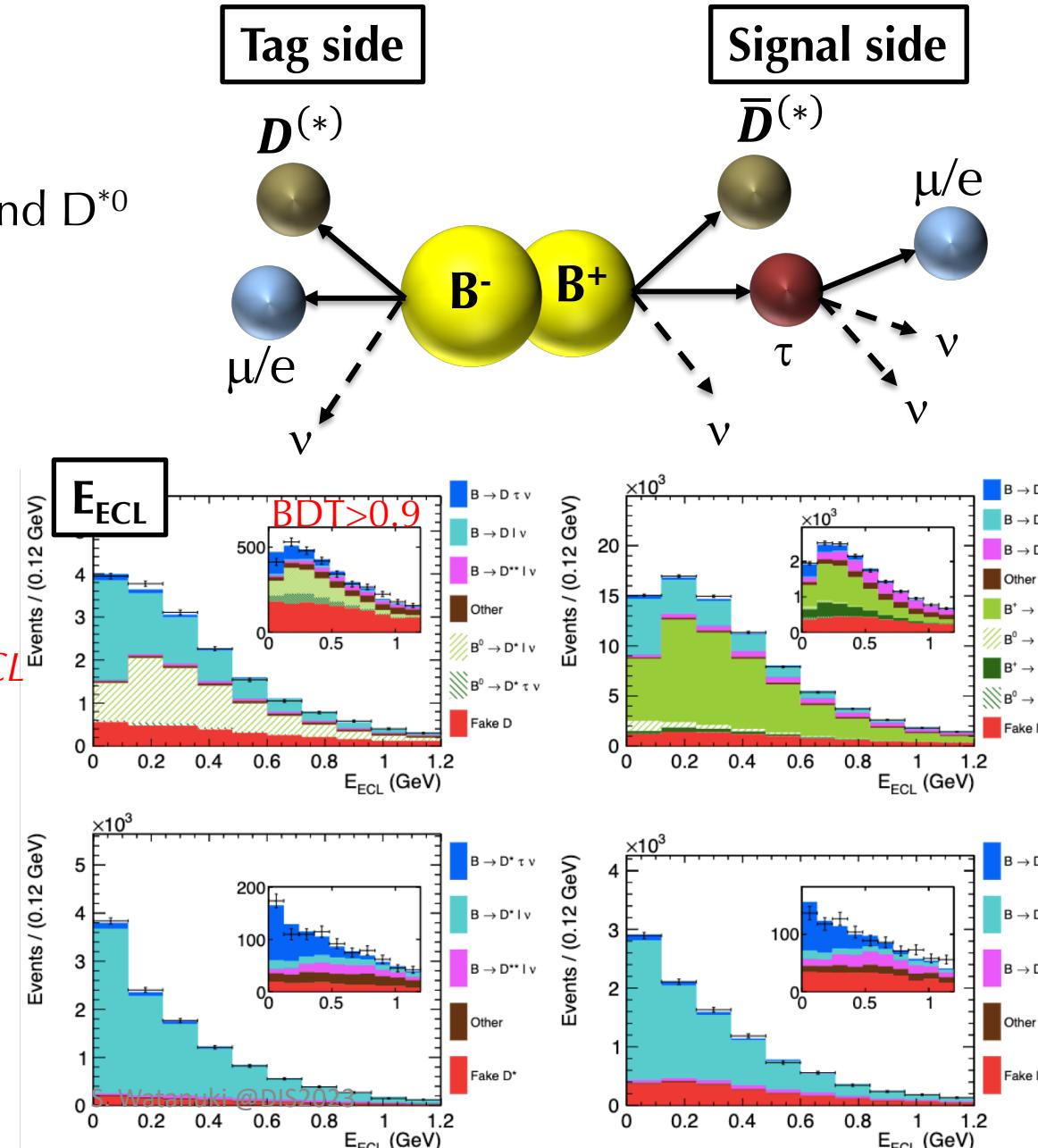
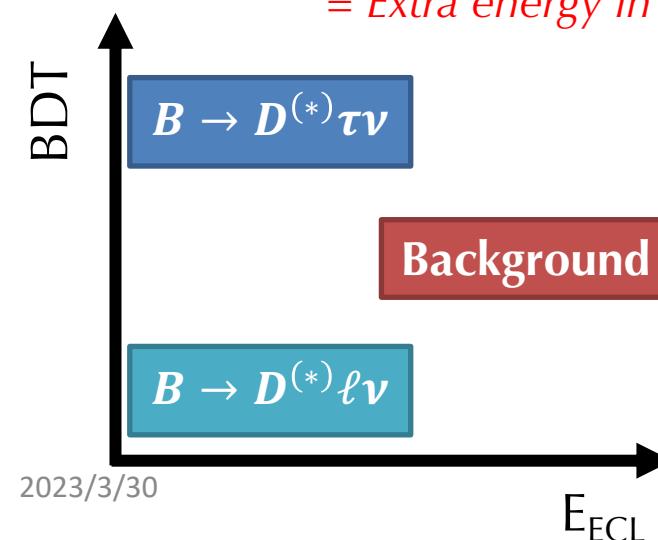
- $B \rightarrow D^{(*)}\tau\nu/D^{(*)}\ell\nu$  using semi-leptonic (SL) tag
- $B \rightarrow K^*\ell^+\ell^-$
- $B \rightarrow K\ell^+\ell^-$

## ➤ LFV searches at Belle

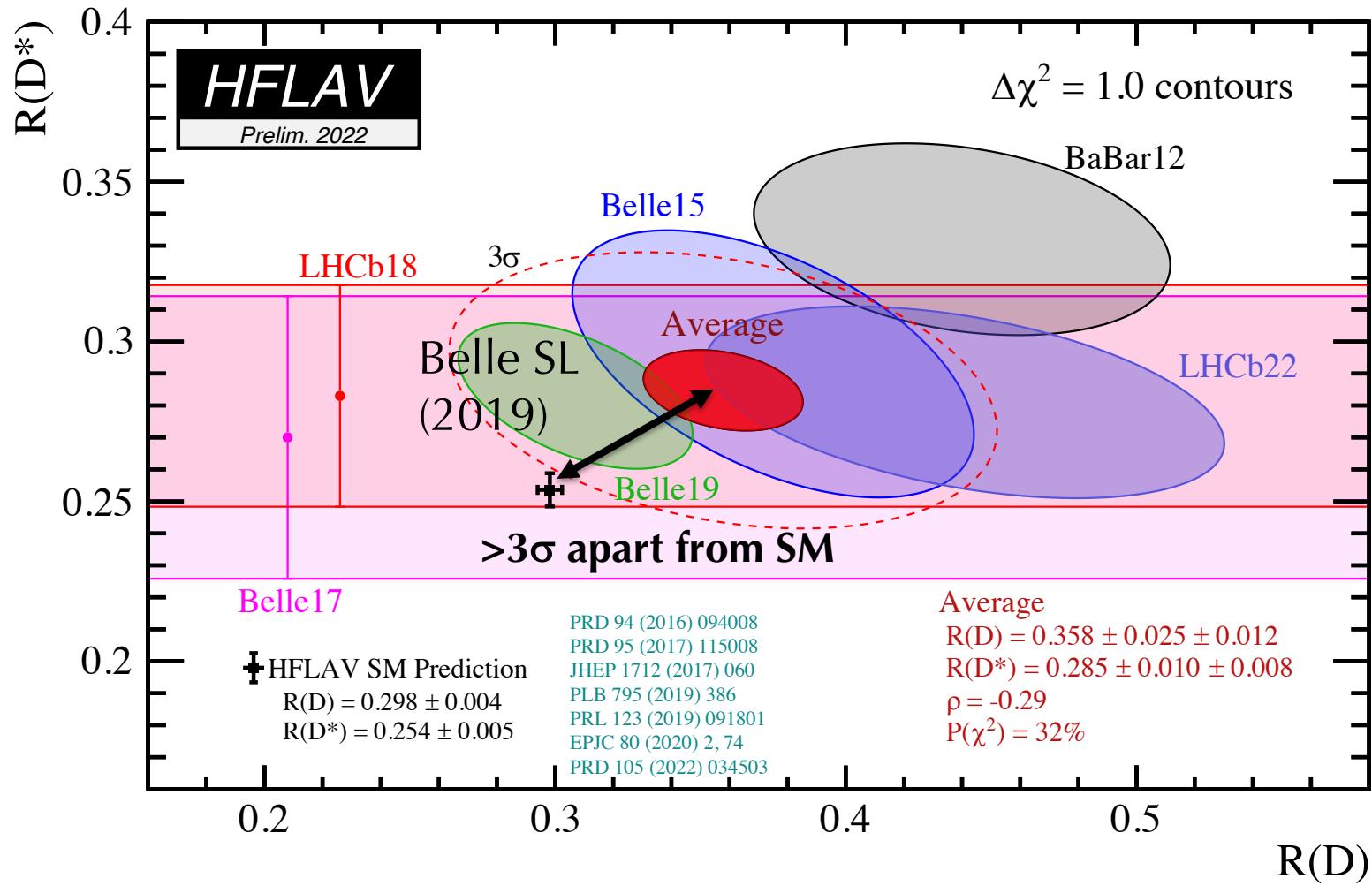
- $B_{(s/d)}^0 \rightarrow \tau\ell$  ( $\ell = \mu, e$ )
- $B^+ \rightarrow K^+\tau\ell$  ( $\ell = \mu, e$ ) using hadronic tag      ← New result!

# R(D) and R(D\*) at Belle

- PRL124, 161803 (2020)
- SL tag with  $\tau \rightarrow \ell \bar{\nu} \nu$  modes
- Measured by  $D^+$ ,  $D^0$ ,  $D^{*+}$  and  $D^{*0}$
- $D^{(*)}\tau\nu$  and  $D^{(*)}\ell\nu$  are distinguished by BDT
  - $m_{miss}^2$ , visible energy
  - $\cos \theta_{B,D^{(*)}\ell}$
- 2D fit on  $E_{ECL}$  vs BDT  
 $=$  Extra energy in ECL



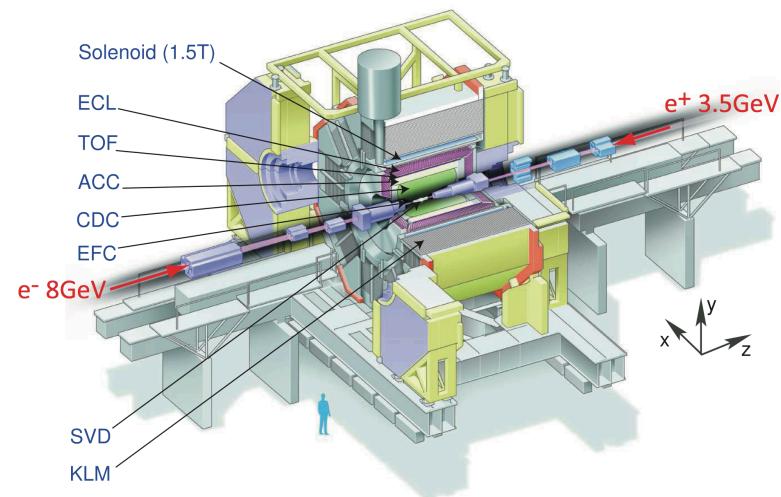
# Results of $R_D(*)$



***Looking forward the updates from Belle II***

# $R_{K^*}$ measurements at Belle

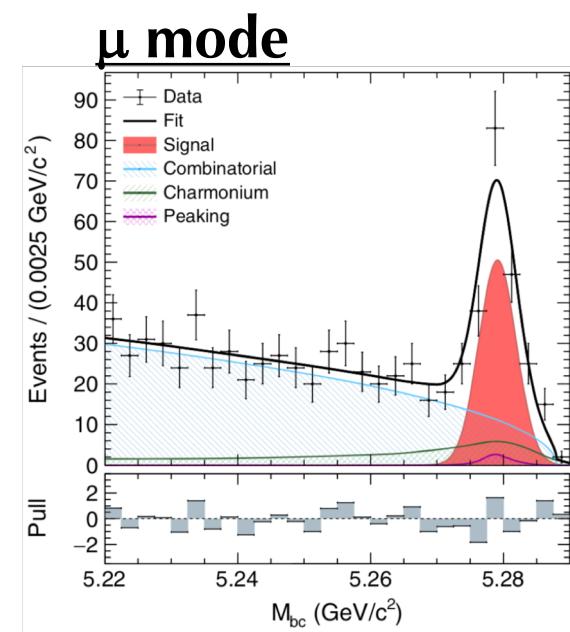
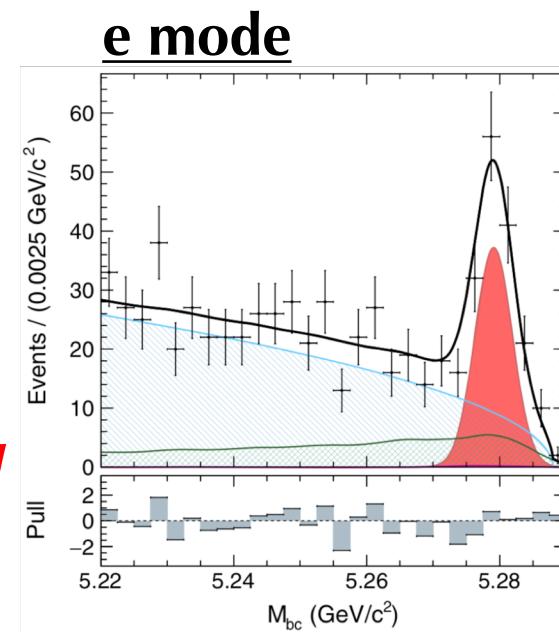
- [PRL.126.161801](#)
- $711\text{fb}^{-1}$  ( $772 \times 10^6 B\bar{B}$ ) collected by Belle detector.
- Reconstruct 4 decay modes:
  - $B^+ \rightarrow K^{*+} (\rightarrow K^+ \pi^0, K_S^0 \pi^+) \ell^+ \ell^-$
  - $B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-, K_S^0 \pi^0) \ell^+ \ell^-$
- Results in several  $q^2$  bin options, **including high  $q^2$  region** (up to  $19 \text{ GeV}^2/\text{c}^4$ ).



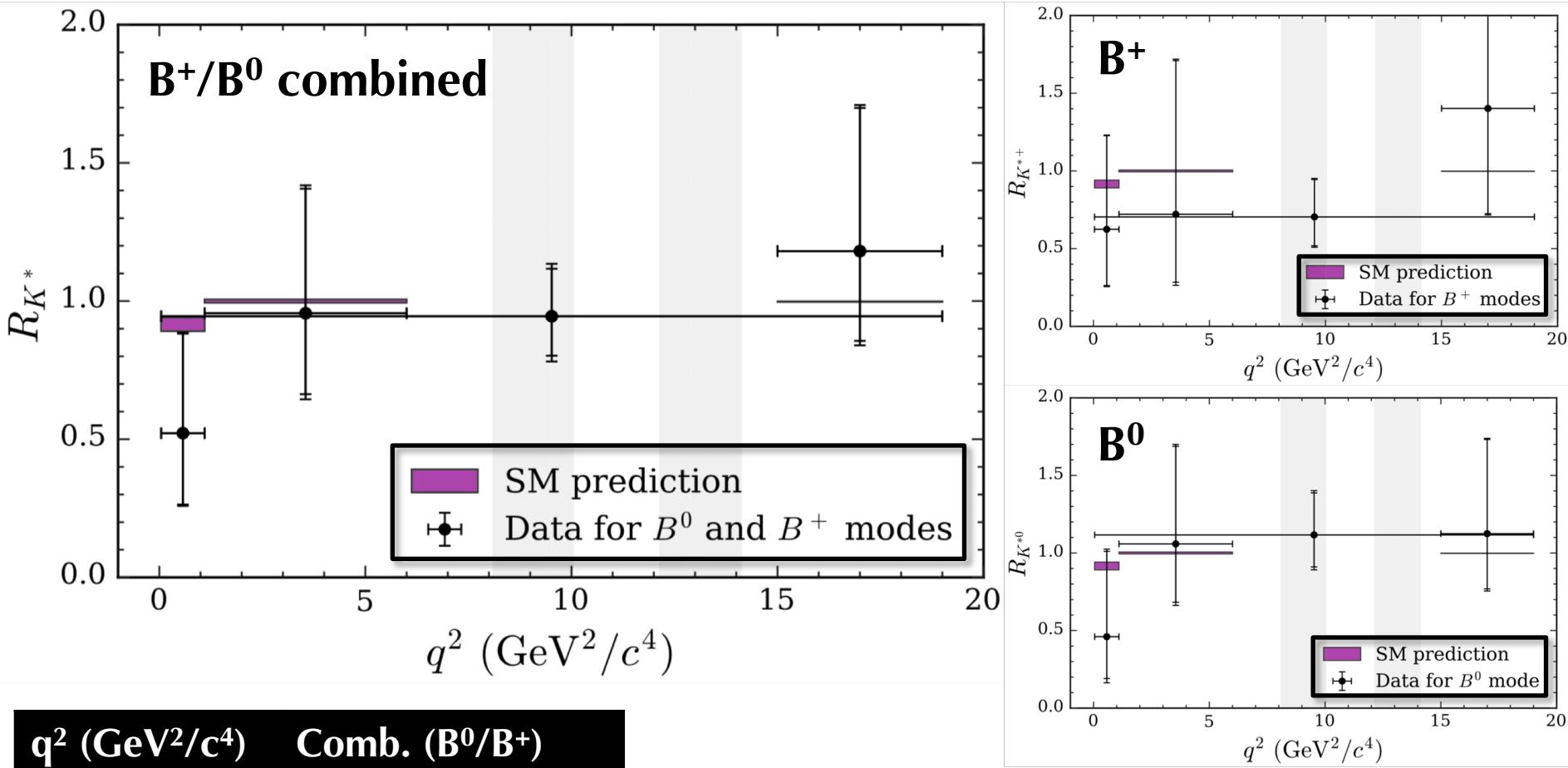
## B factory observables

- $M_{bc} \equiv \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$
- $\Delta E \equiv E_B - E_{beam}$

**e mode can be measured as clean as  $\mu$  mode.**



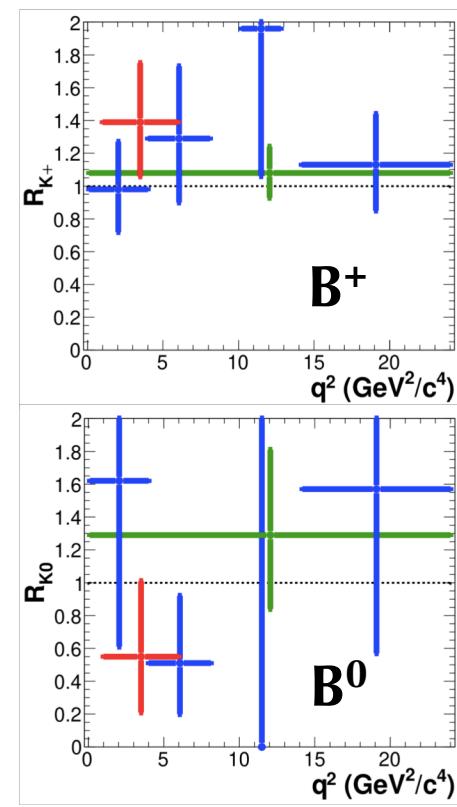
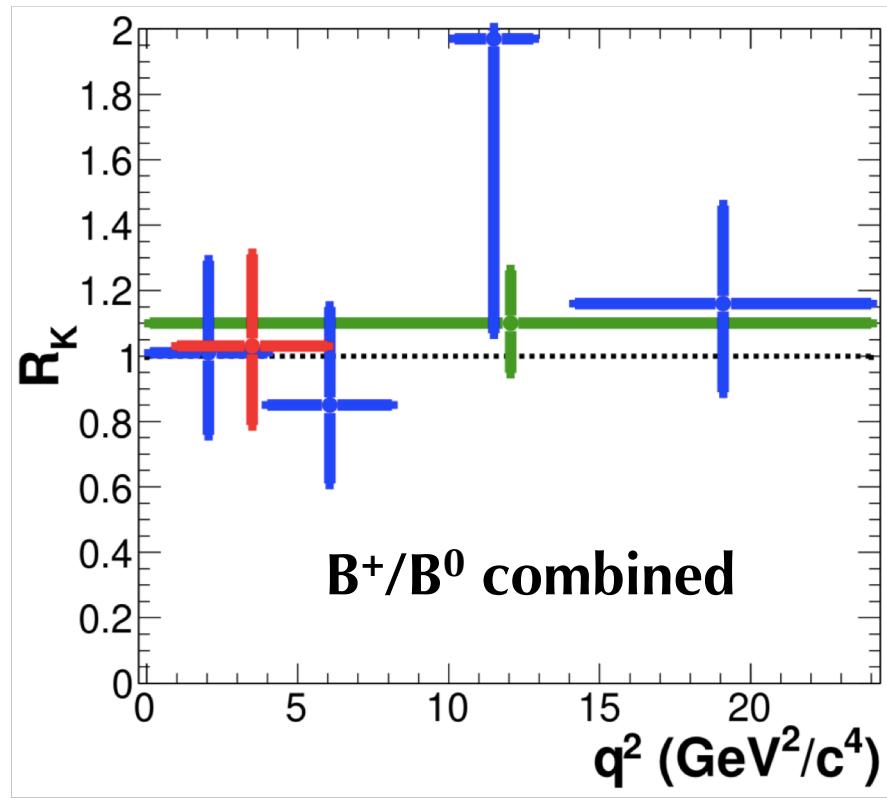
# Results of $R_{K^*}$



- $R_{K^*}$  measured in Belle is **all consistent with SM**.
- This is the first result for  $R_{K^{**}}$  measurement.

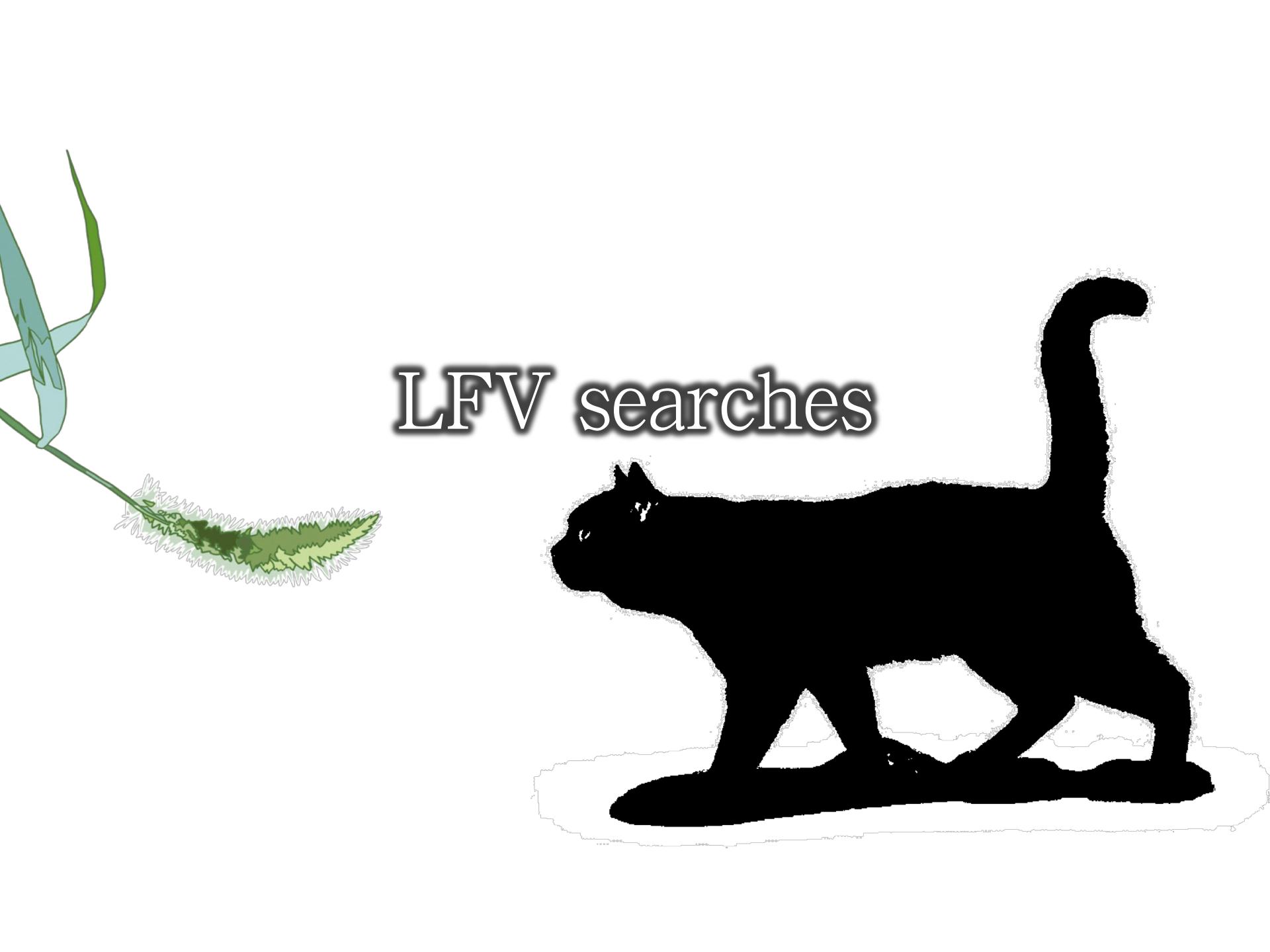
S. Watanuki @DIS2023

# Results of $R_{K^+}$ and $R_{K_S}$



$q^2$ (GeV $^2$ /c $^4$ )	Comb. ( $B^0/B^+$ )
[1.0, 6.0]	$1.03^{+0.28}_{-0.24} \pm 0.01$
whole $q^2$	$1.10^{+0.16}_{-0.15} \pm 0.02$

- [JHEP03\(2021\)105](#)
- 3D fitting with  $M_{bc}$ ,  $\Delta E$ , and modified Neural Net output.
- Results are **all consistent with SM**.



# LFV searches

# Search for $B_s^0 \rightarrow \tau^\pm \ell^\mp$

➤ arXiv:2301.10989

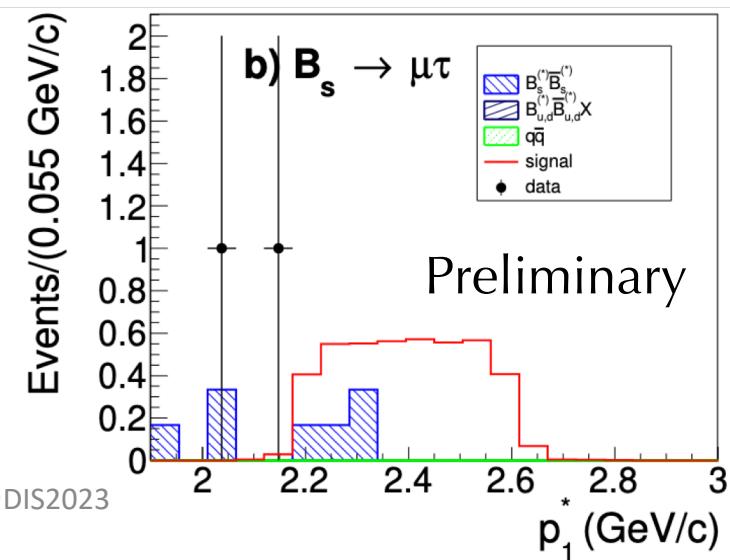
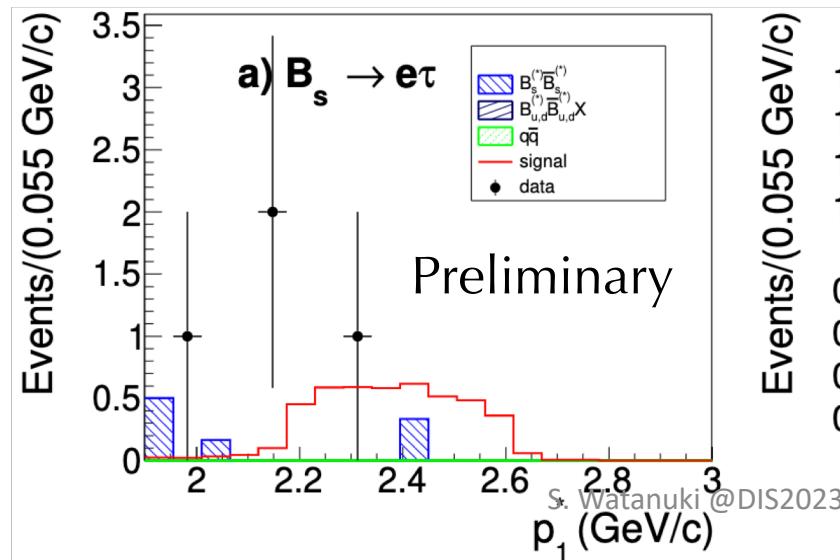
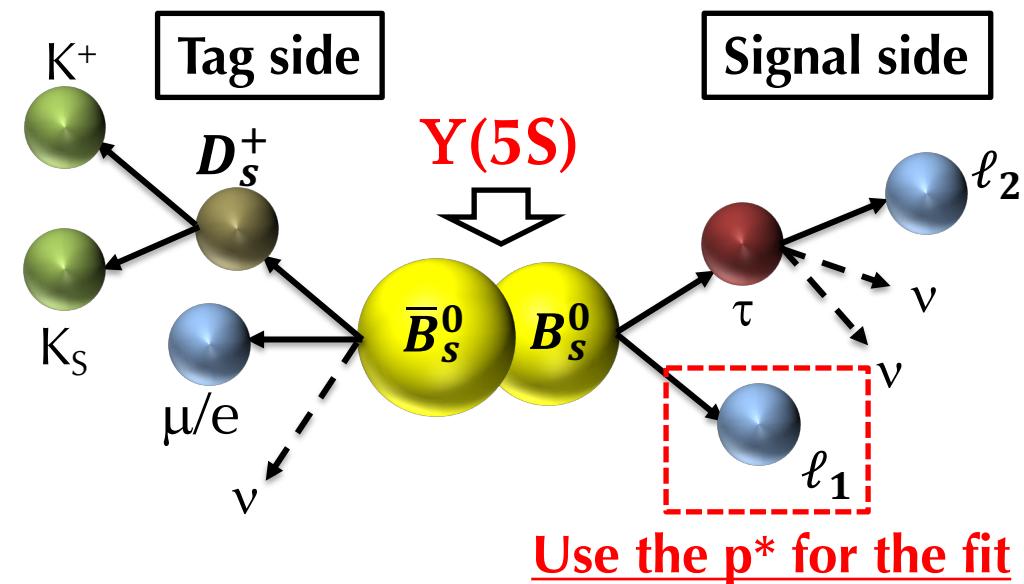
➤ Y(5S) resonance data (121/fb)  
at Belle, SL tag

➤ Fit the c.m. momentum ( $p^*$ ) of  
the primary lepton

➤  $\mathcal{B}(B_s^0 \rightarrow \tau^\pm e^\mp) < 14.1 \times 10^{-4}$

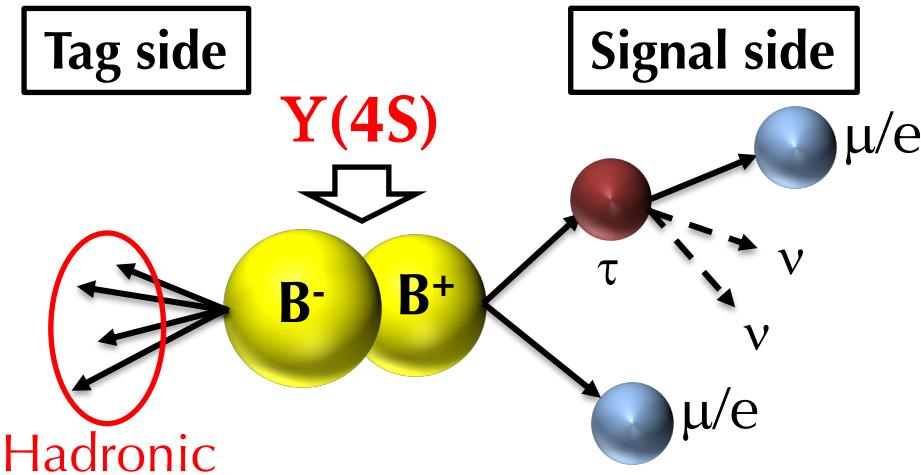
➤  $\mathcal{B}(B_s^0 \rightarrow \tau^\pm \mu^\mp) < 7.3 \times 10^{-4}$

LHCb ...  $\mathcal{B}(B_s^0 \rightarrow \tau^\pm \mu^\mp) < 3.4 \times 10^{-5}$   
[PRL123,211801 \(2019\)](#)

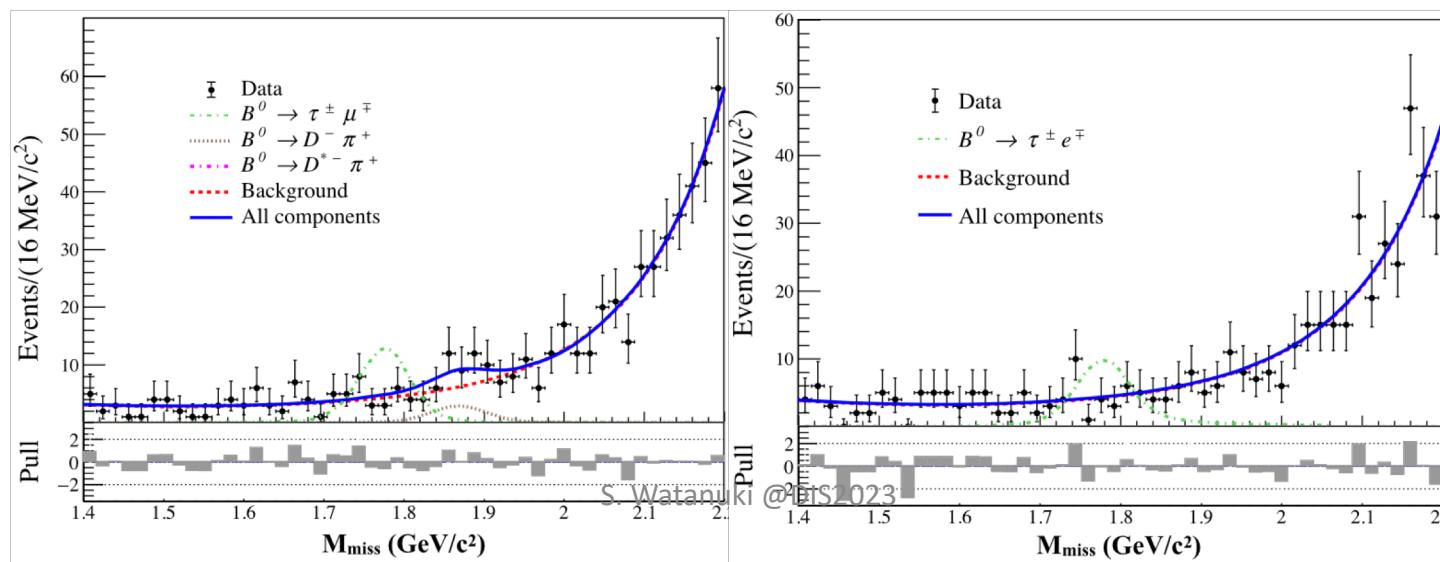


# Search for $B_d^0 \rightarrow \tau^\pm \ell^\mp$

- PRD 104, L091105 (2021)  
November 29)
- Y(4S) data (711/fb) with hadronic tag
  - Neural network package
- $\tau$  recoil mass for signal search
- $\mathcal{B}(B^0 \rightarrow \tau^\pm e^\mp) < 1.6 \times 10^{-5}$
- $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) < 1.5 \times 10^{-5}$

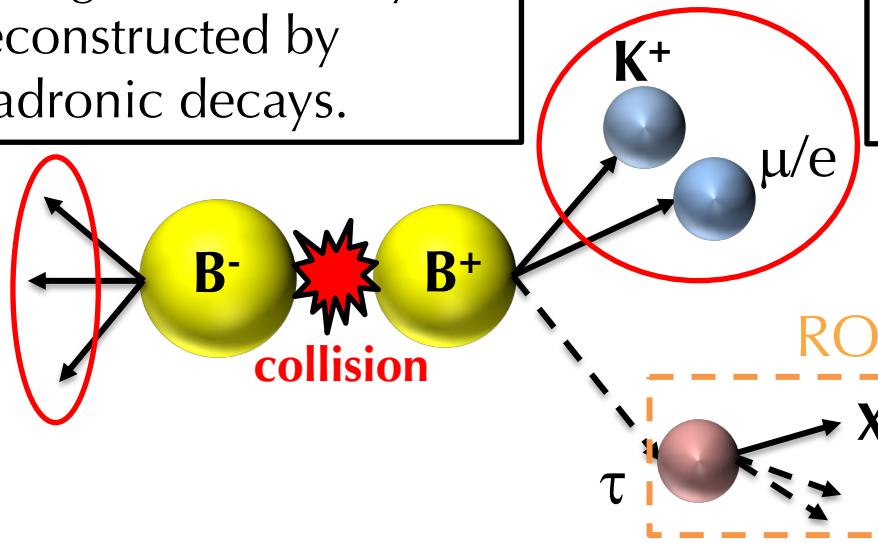


LHCb ...  $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) < 1.2 \times 10^{-5}$   
PRL123,211801 (2019)



# $B^+ \rightarrow K^+ \tau \ell$ hadronic tag at Belle

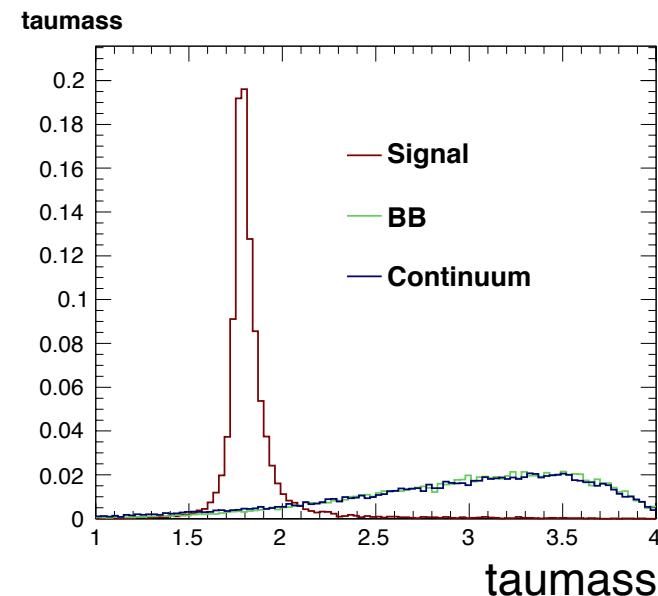
1. Tag side B is fully reconstructed by hadronic decays.



2. Primary charged tracks on signal side:  $K^+$  and lepton ( $\ell = \mu, e$ ) are selected.

3. (condition)  
Only 1 charged track ( $X = \mu, e, \pi$ ) with opposite sign to the primary lepton.

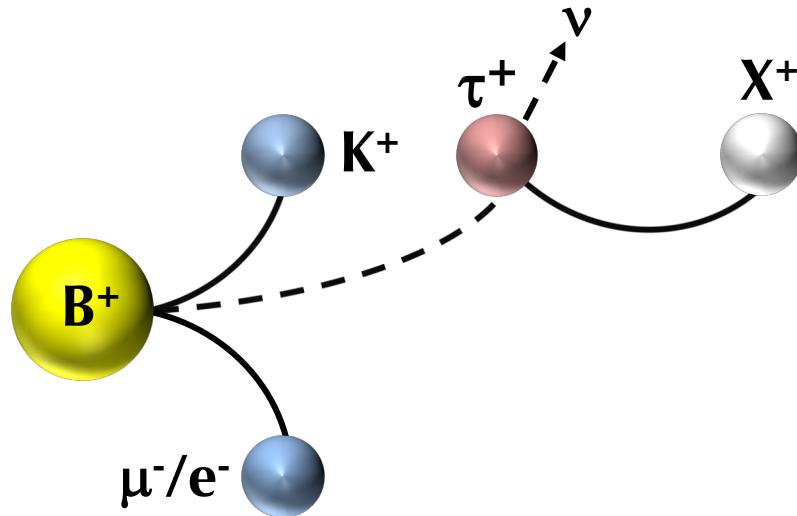
	Purity	Efficiency	Mass Reso.
<b>Hadronic (this study)</b>	High	Low	High
<b>Semi-Lep.</b>	Moderate	Moderate	Low
<b>Inclusive</b>	Low	High	Moderate?



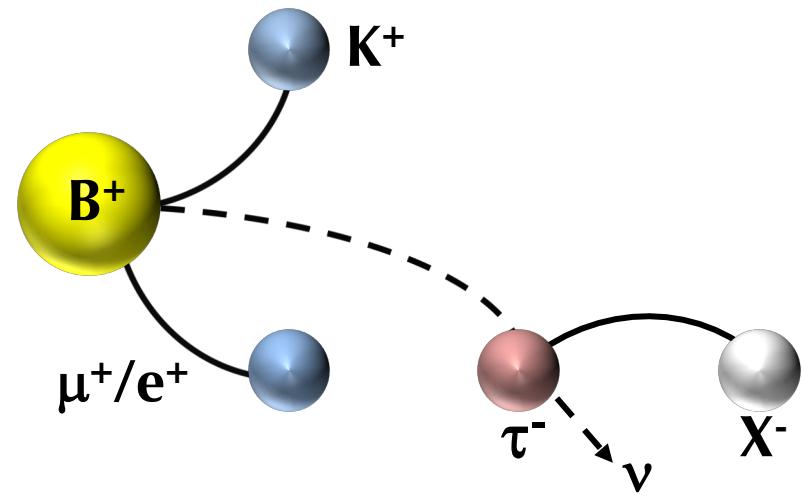
Hadronic FEI will provide a base line of sensitivity.

# 2 types of signal decay topology

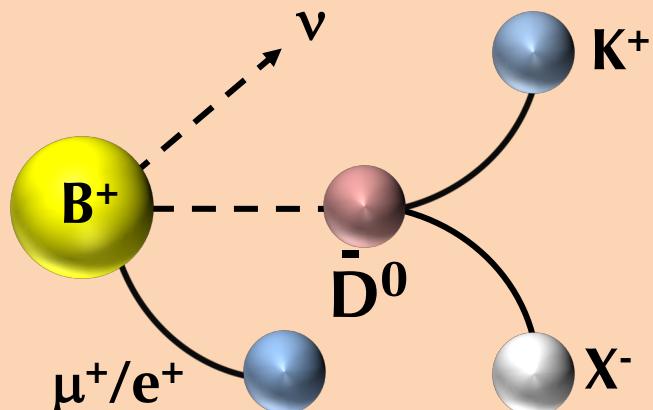
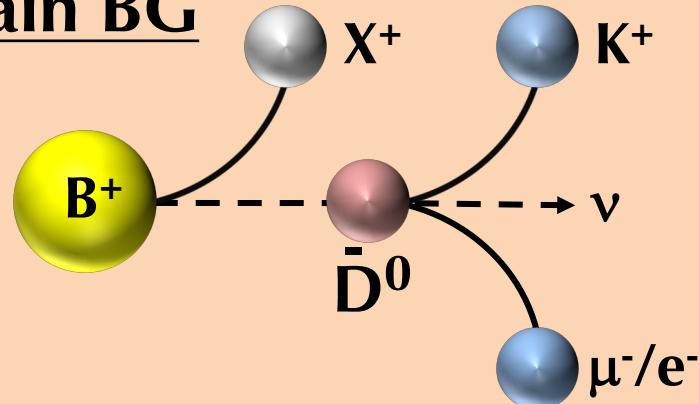
## Opposite Sign channel ( $\text{OS}_{\mu/e}$ )



## Same Sign channel ( $\text{SS}_{\mu/e}$ )



## Main BG



# Background suppression

## D veto

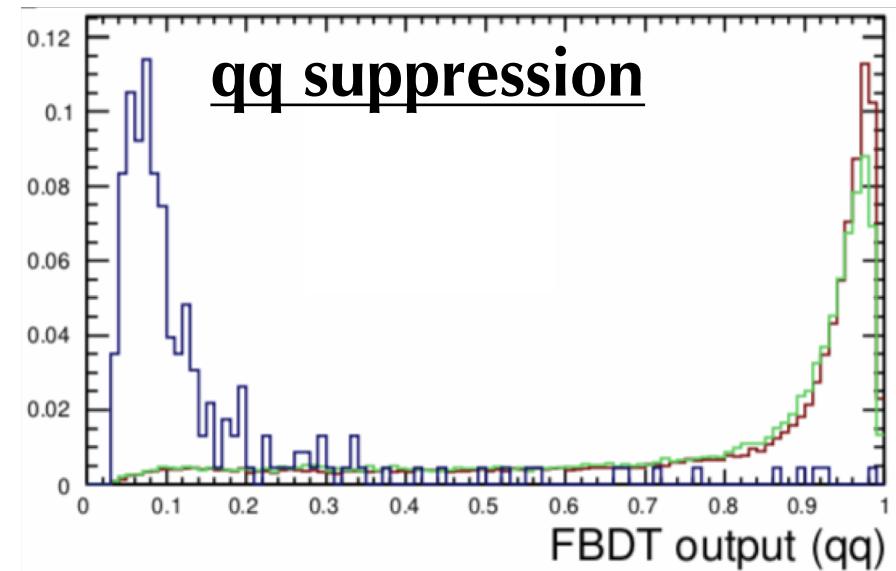
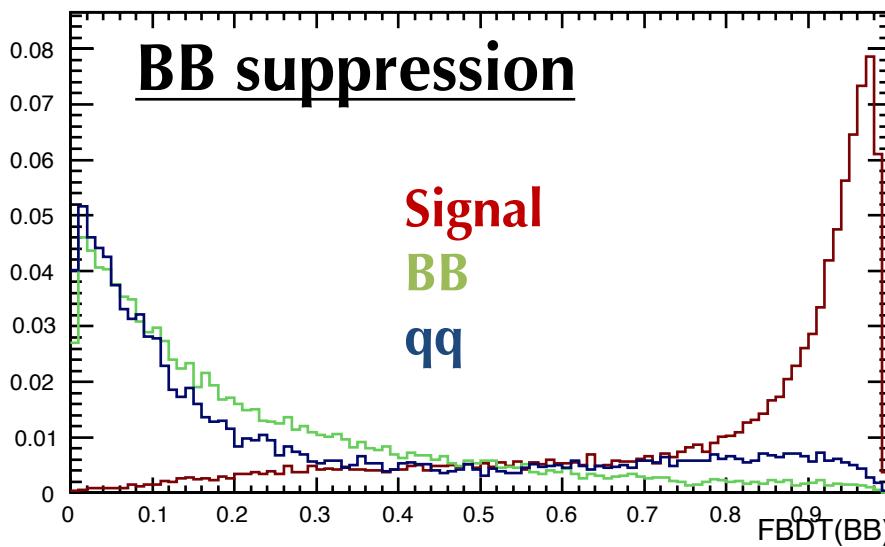
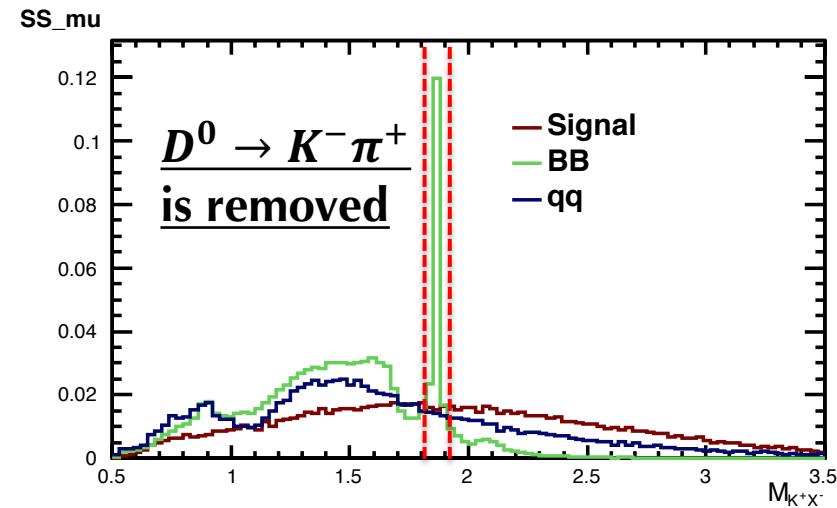
- $M(K^+X^-)$  for  $X=\pi$  (SS), or  
 $M(K^+\mu^-)$  for  $\mu/\pi$  miss-ID ( $OS_\mu$ ).

## BB suppression

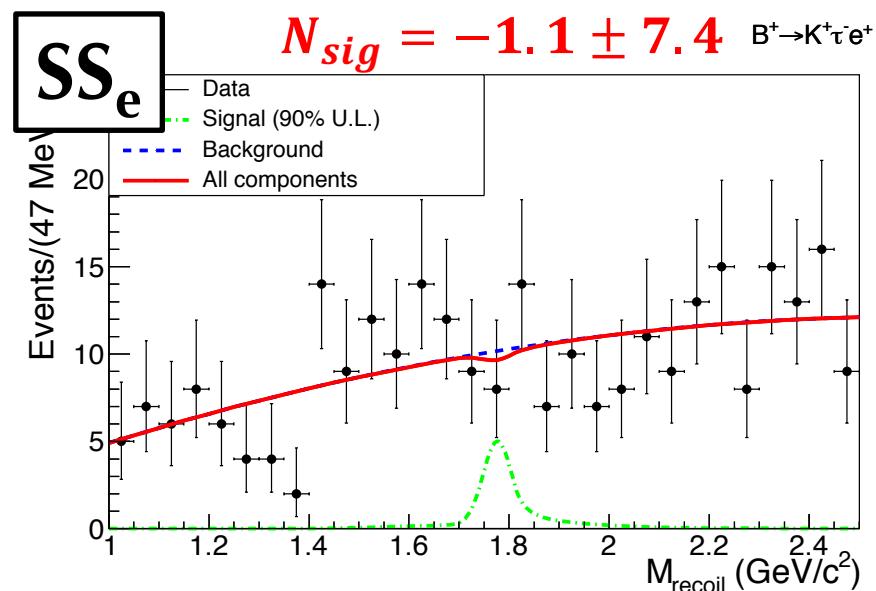
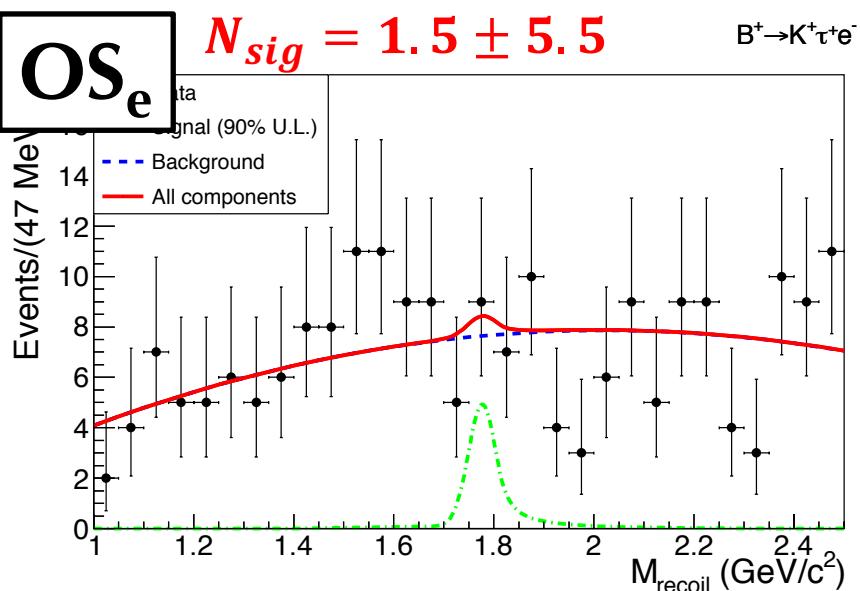
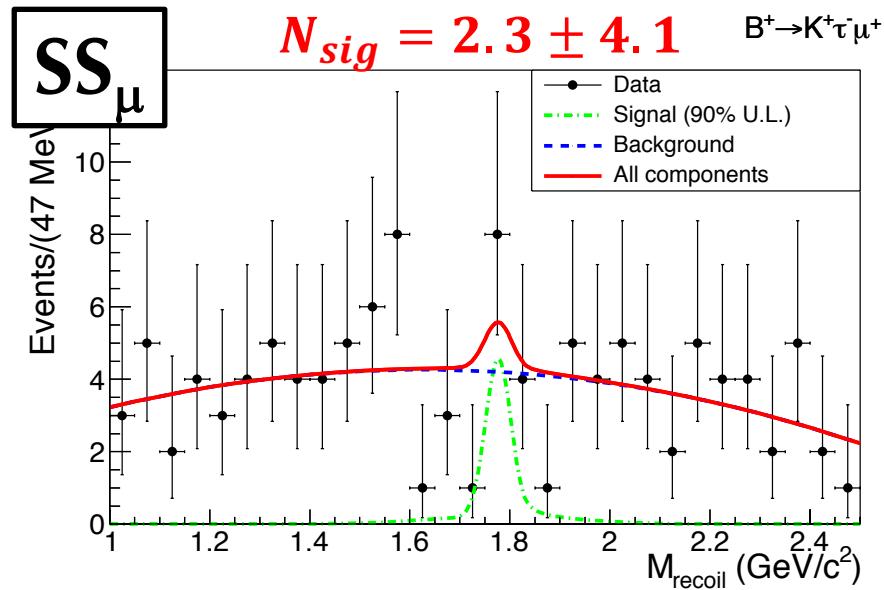
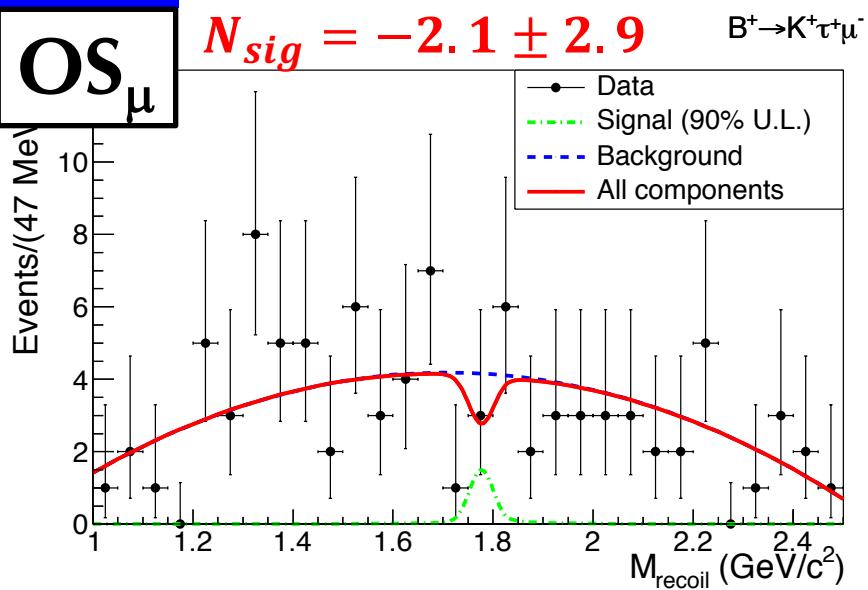
- BDT is trained using signal decay topology, neutral remnant, etc.

## qq suppression

- Another BDT is trained with tag side decay topology.



# Data unblinding (Belle 711/fb)



# Data unblinding (Belle 711/fb)

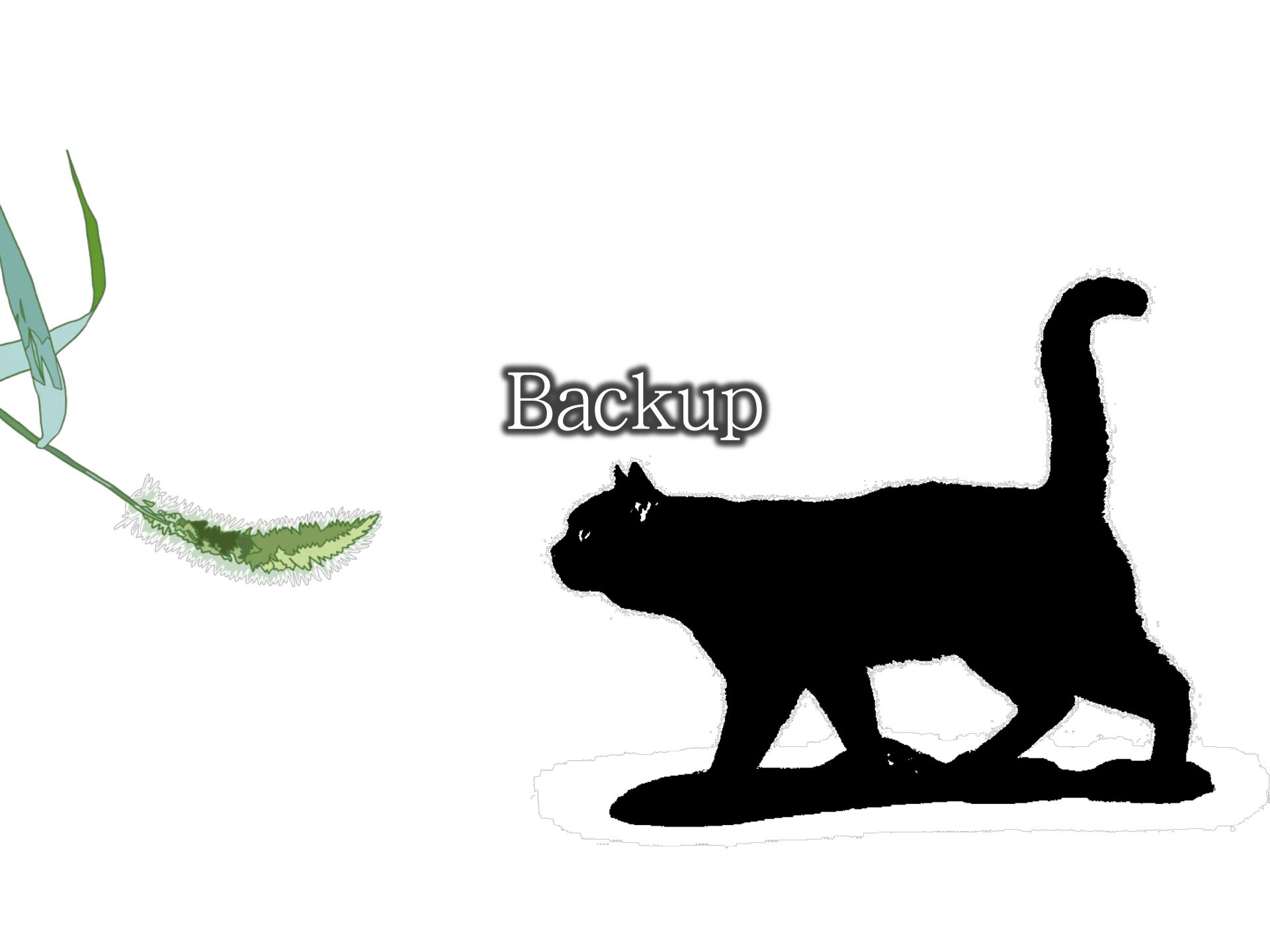
BR U.L. (90% CL)	$\mathcal{B}(K^+\tau^+\mu^-) \times 10^5$	$\mathcal{B}(K^+\tau^-\mu^+) \times 10^5$	$\mathcal{B}(K^+\tau^+e^-) \times 10^5$	$\mathcal{B}(K^+\tau^-e^+) \times 10^5$
Babar	<2.8	<4.5	<1.5	<4.3
LHCb	<3.9	-	-	-
Belle (Preliminary)	<b>&lt;0.59</b>	<b>&lt;2.45</b>	<b>&lt;1.51</b>	<b>&lt;1.53</b>

- [arXiv:2212.04128](https://arxiv.org/abs/2212.04128)
- $\tau$  recoil mass is fitted to search the  $B^+ \rightarrow K^+\tau^\pm\ell^\mp$ .
- Belle have provided **the most stringent upper limit on  $BR(B^+ \rightarrow K^+\tau\ell)$ .**
- Paper submitted to PRL.

BaBar ... [PRD86,012004\(2012\)](#)  
LHCb ... [JHEP06\(2020\)129](#)

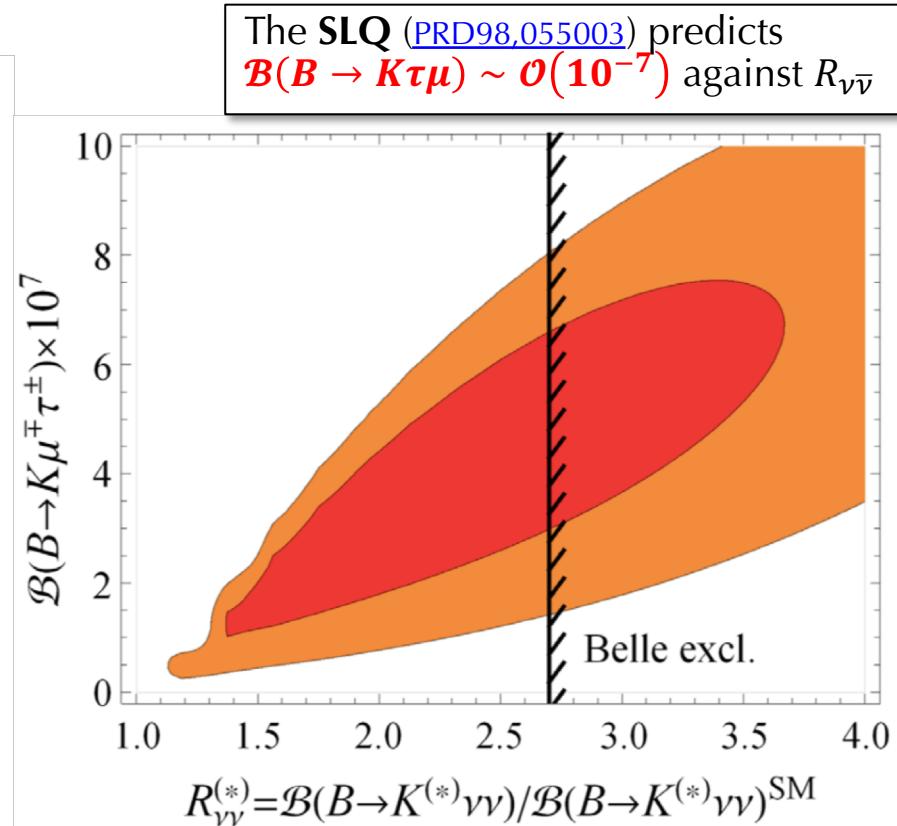
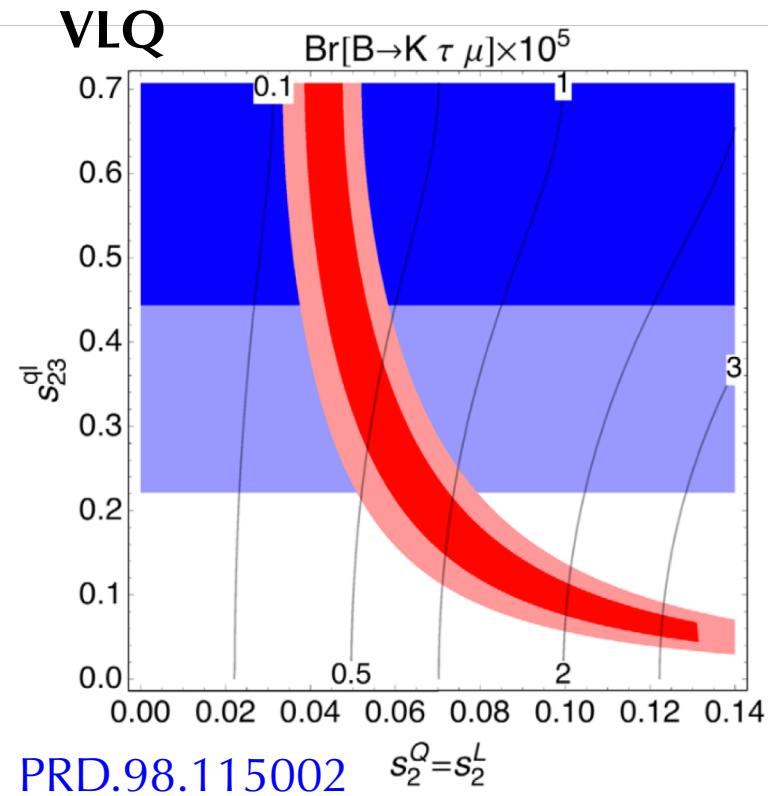
# Summary

- B semi-leptonic we are seeing sign of Lepton flavor universality violation
  - $R_{D^{(*)}}$  (tree) shows more than  $3\sigma$  anomaly from SM
  - $R_{K^{(*)}}$  (loop) is all consistent with SM
- LFUV allows LFV, and vice versa
  - So far, no significant peak have been found
  - For  $B_{s/d}^0 \rightarrow \tau^\pm \ell^\mp$ ,  $\ell = e$  channels are the first or the most stringent UL could be set
  - UL is early  $O(10^{-7})$  for  $K^* \mu e$  and  $K_S^0 \mu e$ ,  $O(10^{-9})$  for  $K^+ \mu e$  (LHCb)
  - Belle provided results of  $B^+ \rightarrow K^+ \tau \ell$ , one of which reaches  $O(10^{-6})$  level (world best limit)



Backup

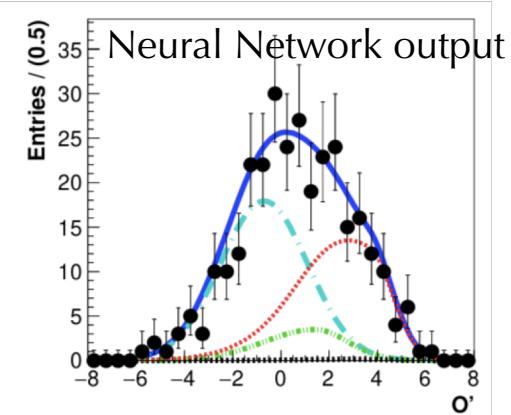
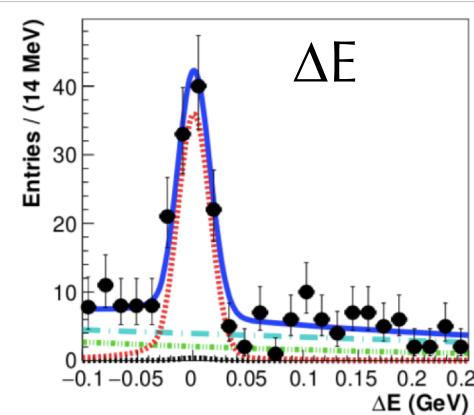
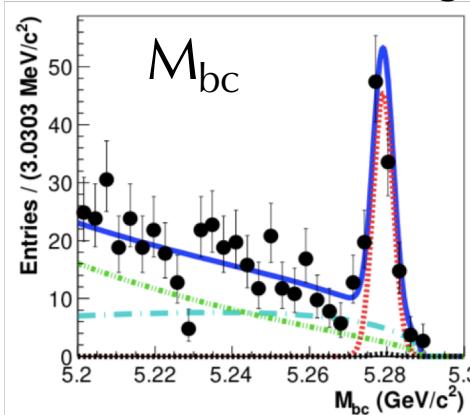
# Leptoquark & LFV $B \rightarrow K\tau\mu$



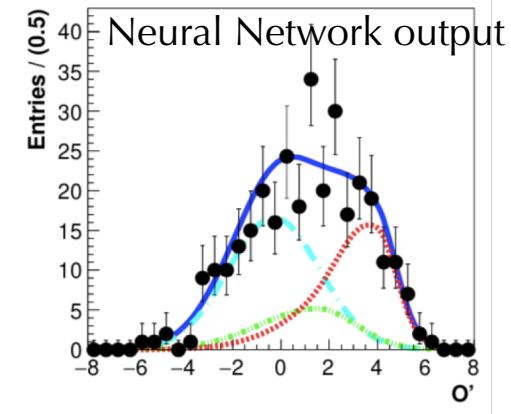
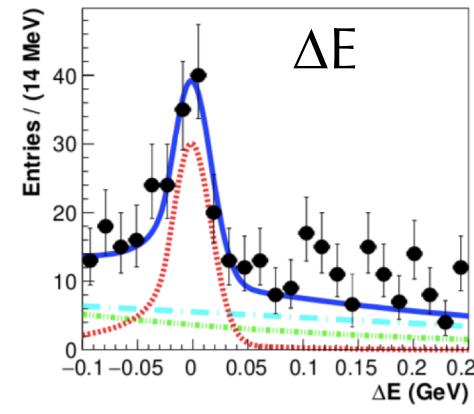
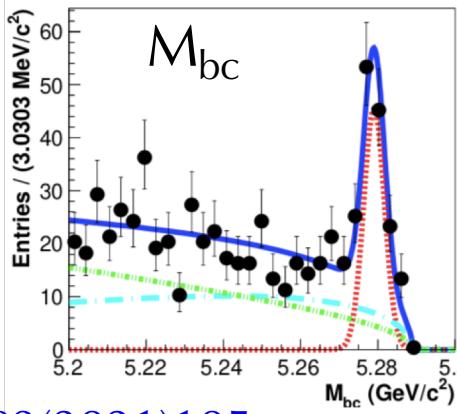
# $R_K$ measurements at Belle

*Signal enhanced distributions*

$K^+ \mu^+ \mu^-$

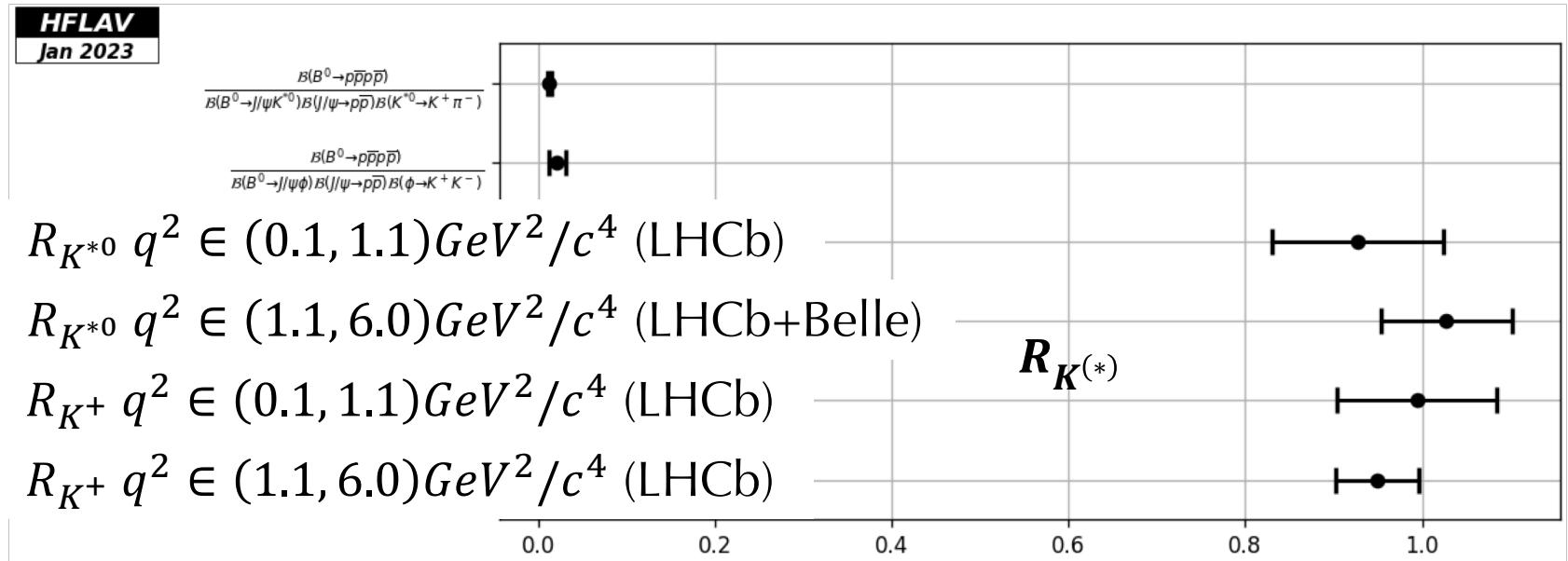


$K^+ e^+ e^-$



- [JHEP03\(2021\)105](#)
- $711\text{fb}^{-1}$  ( $772 \times 10^6 B\bar{B}$ ) collected by Belle detector.
- Both  $R_{K^+}$  and  $R_{K_S^0}$  are measured.
- 3D fitting with  $M_{bc}$ ,  $\Delta E$ , and modified Neural Net output.

# Test of lepton flavor universality



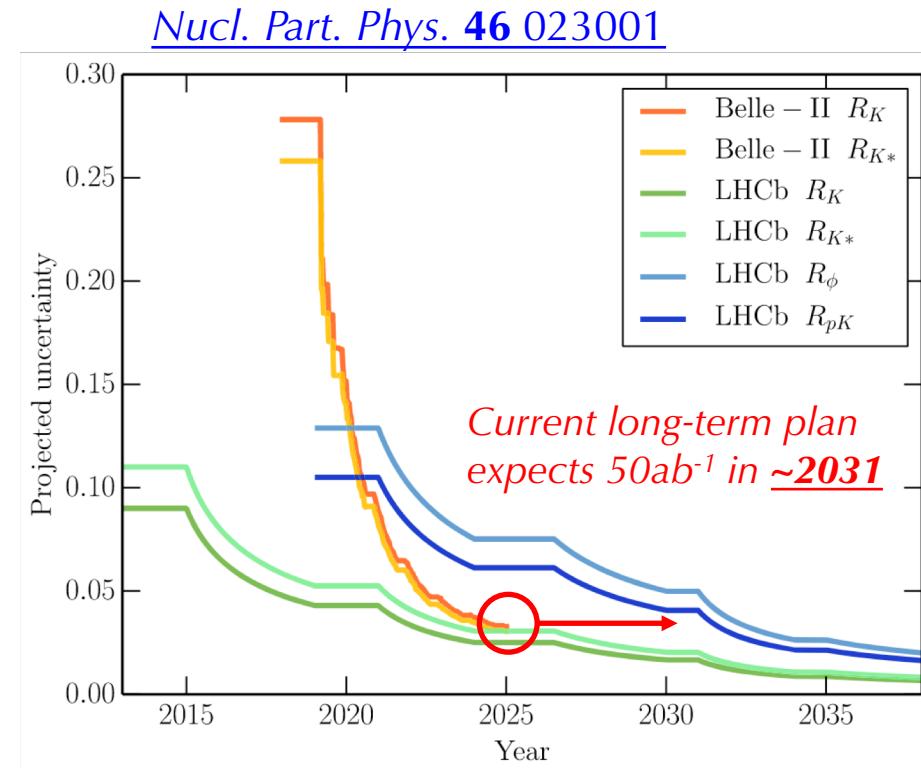
# Prospects @Belle II

- The uncertainty both stat. and syst. can be much reduced.

- A dominant source of systematics comes from imperfect lepton ID.
- After improve this,  $R_{K^{(*)}}$  become **statistical uncertainty dominated**.

- Complementary study with LHCb can be performed at Belle II:

- Clean study in electron channel;  
**Angular study for  $B \rightarrow K^* e^+ e^-$**
- Inclusive study ( $X_s \ell^+ \ell^-$ );  
**Measurement with small theoretical error**

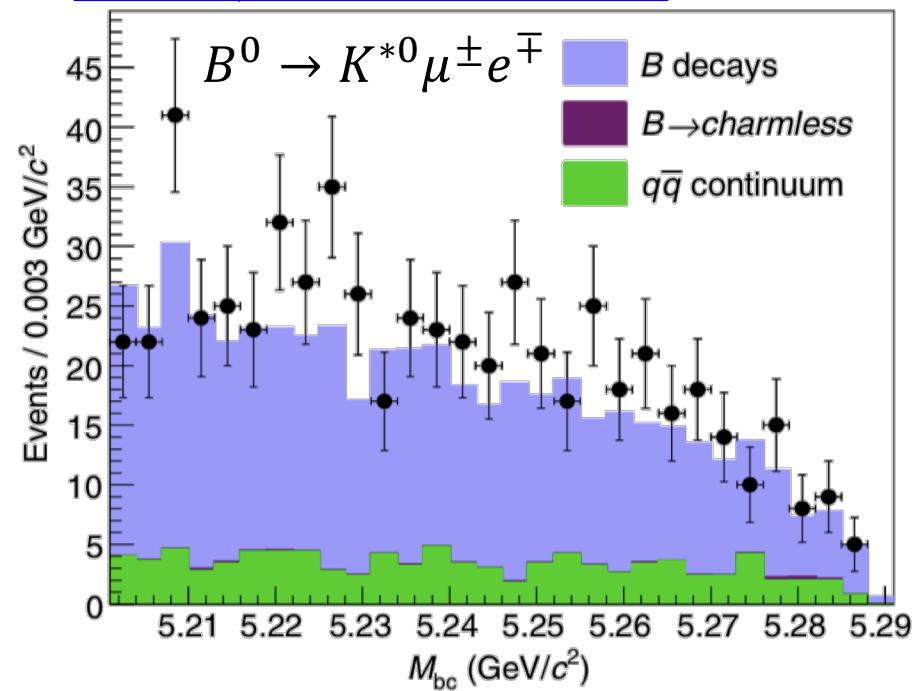


Observables	Belle $0.71 \text{ ab}^{-1}$	Belle II $5 \text{ ab}^{-1}$	Belle II $50 \text{ ab}^{-1}$
$R_K$ ( $[1.0, 6.0] \text{ GeV}^2$ )	28%	11%	3.6%
$R_K$ ( $> 14.4 \text{ GeV}^2$ )	30%	12%	3.6%
$R_{K^*}$ ( $[1.0, 6.0] \text{ GeV}^2$ )	26%	10%	3.2%
$R_{K^*}$ ( $> 14.4 \text{ GeV}^2$ )	24%	9.2%	2.8%
$R_{X_s}$ ( $[1.0, 6.0] \text{ GeV}^2$ )	32%	12%	4.0%
$R_{X_s}$ ( $> 14.4 \text{ GeV}^2$ )	28%	11%	3.4%

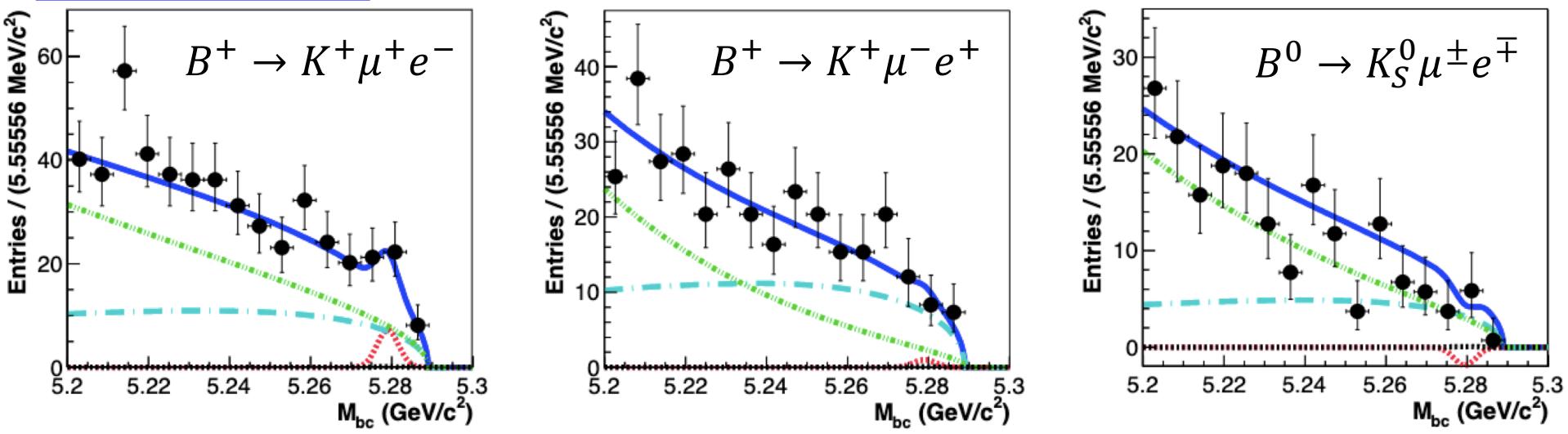
# Search for $B \rightarrow K^{(*)}\mu e$

Mode	BR U.L. (90% CL)
$B^0 \rightarrow K^{*0}\mu^+e^-$	$<1.2 \times 10^{-7}$ (Belle)
$B^0 \rightarrow K^{*0}\mu^-e^+$	$<1.6 \times 10^{-7}$ (Belle)
$B^0 \rightarrow K^{*0}\mu e$	$<1.8 \times 10^{-7}$ (Belle)
$B^+ \rightarrow K^+\mu^-e^+$	$<7.0 \times 10^{-9}$ (LHCb) $<3.0 \times 10^{-8}$ (Belle)
$B^+ \rightarrow K^+\mu^+e^-$	$<6.4 \times 10^{-9}$ (LHCb) $<8.5 \times 10^{-8}$ (Belle)
$B^0 \rightarrow K_s^0\mu^\pm e^\mp$	$<1.8 \times 10^{-7}$ (Belle)

[PRD98, 071101\(R\) \(2018\)](#)

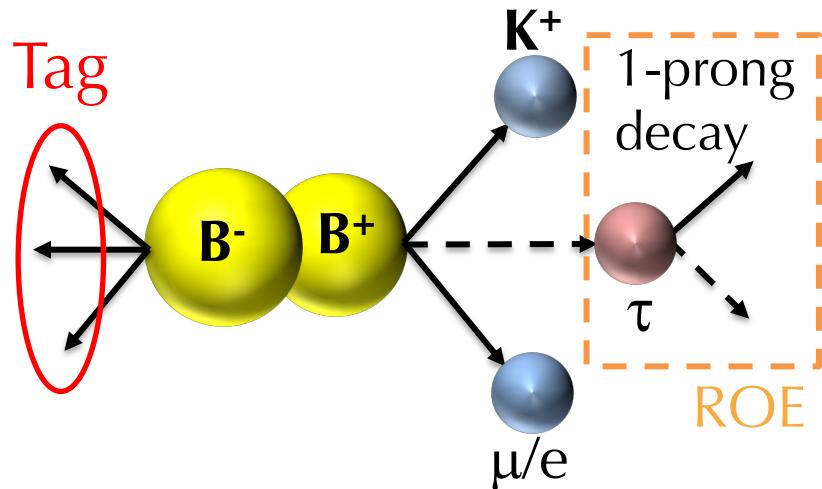


[JHEP03\(2021\)105](#)

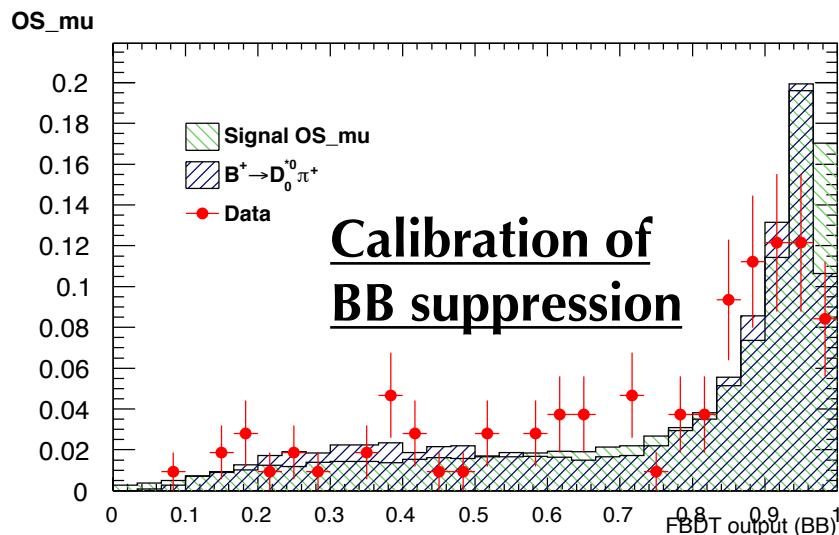
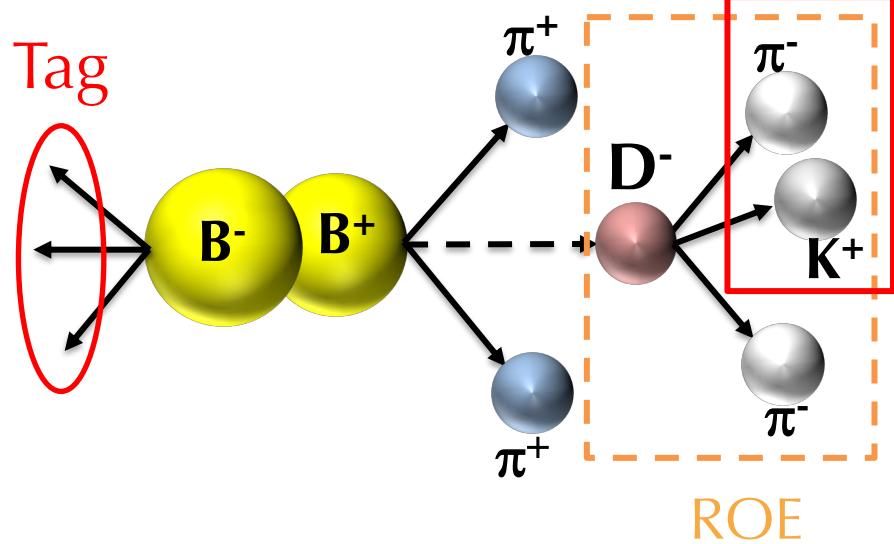


# Control sample study (BB sup.)

**Signal**



**Control**



$\bar{D}_0(2400)^{*0}\pi^+$  and  $\bar{D}_2(2460)^{*0}\pi^+$   
with fraction measured by BaBar  
Phys.Rev.D 79,112004(2009).

**Targets**

**BB sup. +  
D veto**

**PDF shape**

**qq sup.**

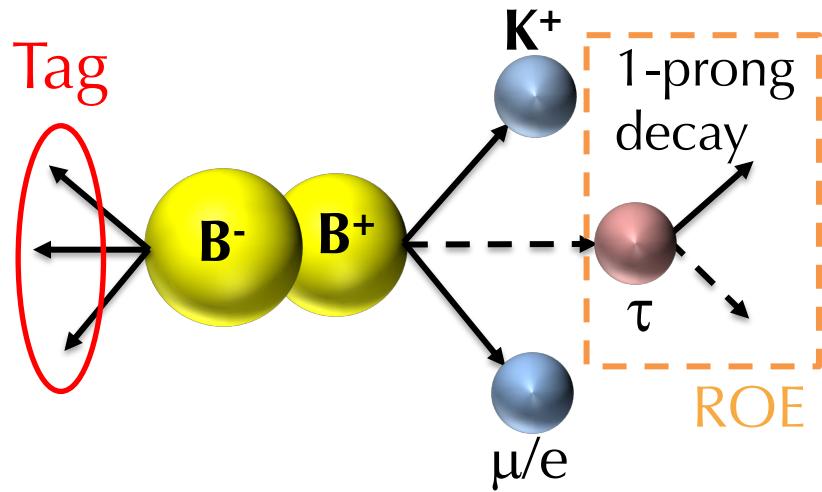
**Control channel**

$B^+ \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+ \pi^+$

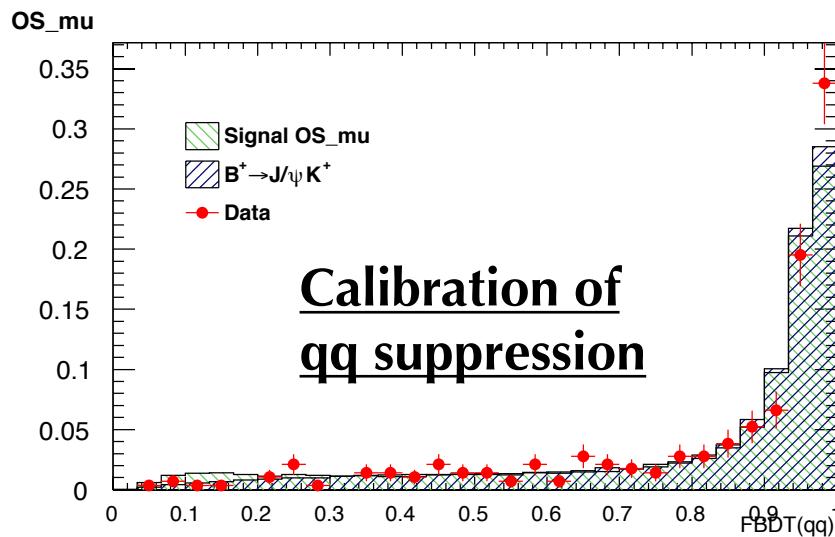
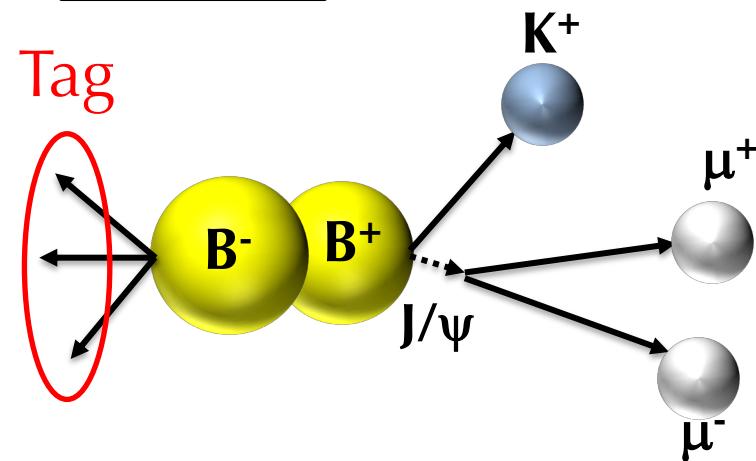
$B^+ \rightarrow J/\psi (\rightarrow \ell^+ \ell^-) K^+$

# Control sample study (qq sup.)

## Signal



## Control

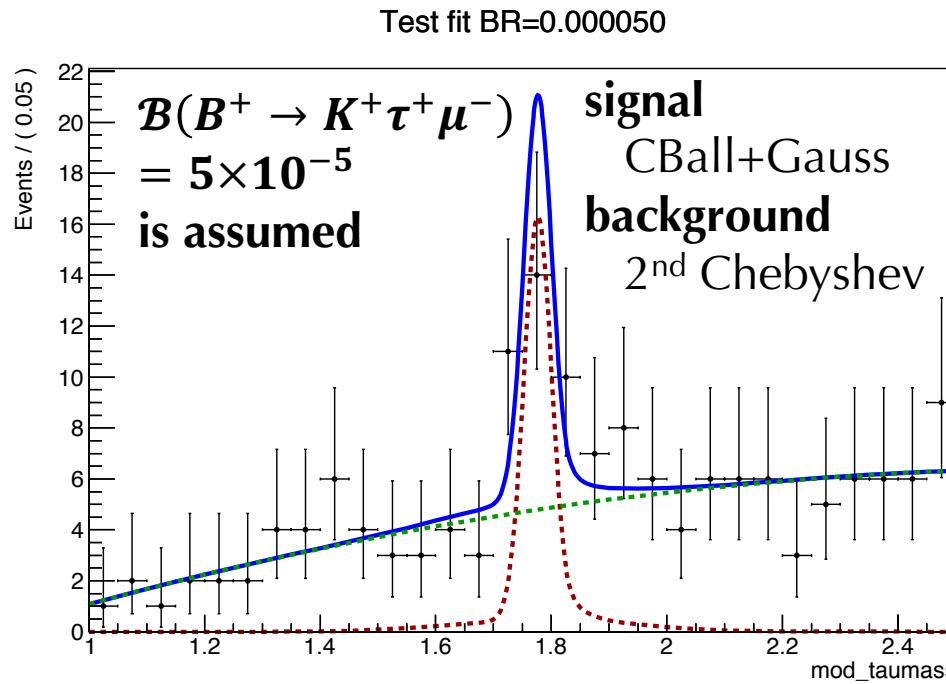


Advantage of more statistics  
than Dππ control sample

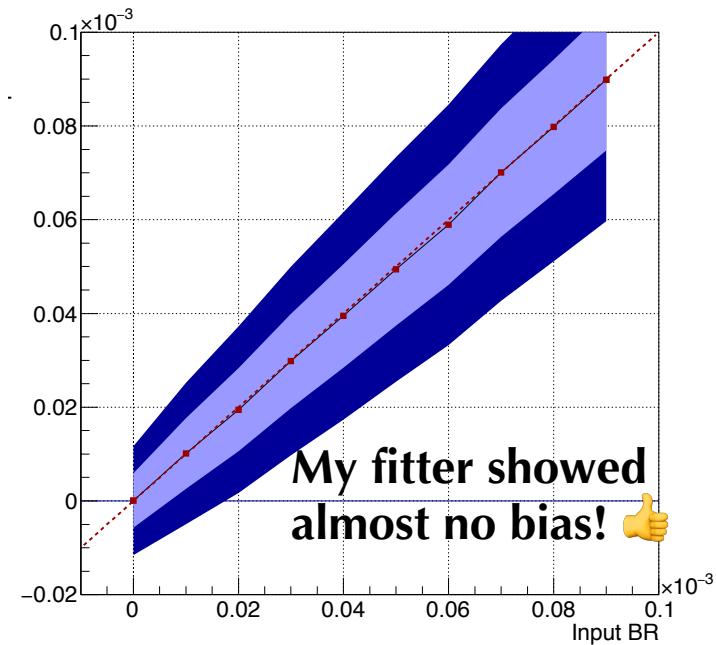
Targets	Control channel
BB sup. + D veto	$B^+ \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+ \pi^+$
PDF shape	
qq sup.	$B^+ \rightarrow J/\psi (\rightarrow \ell^+ \ell^-) K^+$

# Fitting and systematics

## + Fitting models



## + Linearity Check

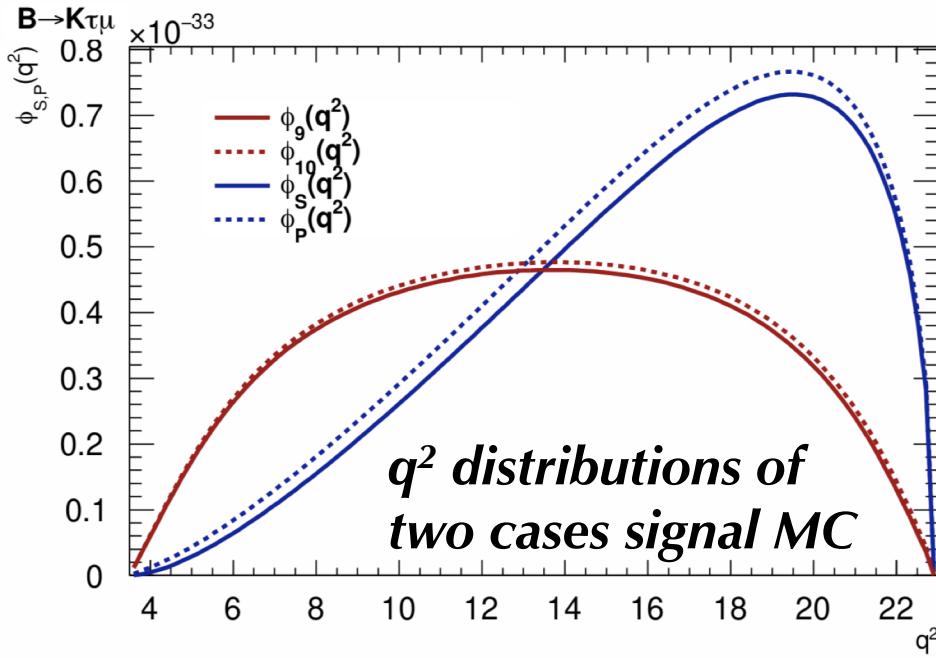


## + Systematics (by real data)

Additive (#evts)	OS <sub>μ</sub>	SS <sub>μ</sub>	OS <sub>e</sub>	SS <sub>e</sub>
PDF ( $f_{\text{sig}}$ )	0.28	0.11	0.16	0.16
...	...	...	...	...
<b>Total</b>	<b>0.30</b>	<b>0.14</b>	<b>0.18</b>	<b>0.20</b>

Multiplicative (%)	OS <sub>μ</sub>	SS <sub>μ</sub>	OS <sub>e</sub>	SS <sub>e</sub>
BB sup.	10.6	12.7	10.0	12.6
qq sup.	8.8	9.2	8.6	6.6
...	...	...	...	...
<b>Total</b>	<b>15.3</b>	<b>17.0</b>	<b>14.8</b>	<b>15.7</b>

# Model dependence



- The analysis was based on **PHSP signal MC**.
- We assumed an **extreme NP** operators (blue) and efficiencies are weighted.
  - See [arXiv:1602.00881](#) and [PRD71,014015\(2005\)](#) for detail.
- This would provide more conservative results.

	<i>PHSP</i>	<i>Extreme NP</i>	
Channels	Efficiency ( $O_9(10)$ )	Efficiency ( $O_{S(P)}$ )	Impact on $\mathcal{BR} \times 10^5$
$OS_\mu$	0.0615%	0.0553%	0.0749
$SS_\mu$	0.0481%	0.0399%	0.1956
$OS_e$	0.0680%	0.0588%	0.1213
$SS_e$	0.0750%	0.0546%	0.4064

# Model dependence

## PHSP

$$\varphi_{9(10)}(q^2) = \frac{1}{2}|f_0(q^2)|^2(m_1 \mp m_2)^2 \frac{(m_B^2 - m_K^2)^2}{q^2} \left[ 1 - \frac{(m_1 \pm m_2)^2}{q^2} \right] \\ + \frac{1}{2}|f_+(q^2)|^2 \lambda(m_B, m_K, \sqrt{q^2}) \left[ 1 - \frac{(m_1 \mp m_2)^2}{q^2} - \frac{\lambda(\sqrt{q^2}, m_1, m_2)}{3q^4} \right]$$

## Extreme NP

$$\varphi_{S(P)}(q^2) = \frac{q^2|f_0(q^2)|^2}{2(m_b - m_s)^2} (m_B^2 - m_K^2)^2 \left[ 1 - \frac{(m_1 \pm m_2)^2}{q^2} \right]$$

where Normalization factor is;

$$|\mathcal{N}_K(q^2)|^2 = \tau_{B_d} \frac{\alpha^2 G_F^2 |V_{tb} V_{ts}^*|^2}{512\pi^5 m_B^3} \frac{\lambda^{1/2}(\sqrt{q^2}, m_1, m_2)}{q^2} \lambda^{1/2}(\sqrt{q^2}, m_B, m_K)$$

- Wave function ... [1602.00881](https://arxiv.org/abs/1602.00881)
- Form factor ... [hep-ph/0406232](https://arxiv.org/abs/hep-ph/0406232)

# List of Systematics (toy-MC)

Source	$OS\mu \times 10^5$	$SS\mu \times 10^5$	$OSe \times 10^5$	$SSe \times 10^5$
FEI	0.0166	0.0243	0.0196	0.0243
Tracking	0.0071	0.0103	0.0083	0.0103
LID(prim. lep)	0.0188	0.0277	0.028	0.0351
LID(tau->mu)	0.0017	0.0034	0.0052	0.0081
LID(tau->e)	0.0064	0.0092	0.0037	0.0047
PID(prim. K)	0.0085	0.0127	0.0112	0.0124
PID(tau->pi)	0.0043	0.0053	0.0057	0.0059
BB sup. + D veto	0.0706	0.1227	0.0786	0.1156
qq sup.	0.0587	0.0882	0.067	0.0608
N_BB <b>dominant</b>	0.0092	0.0135	0.0108	0.0134
f+-/f00	0.0074	0.0108	0.0087	0.0108
MC stats.	0.0069	0.0113	0.0133	0.0091
Linearity	0.0377	0.0505	0.0258	0.0847
Signal PDF mean	0.0185	0.0074	0.0121	0.0376
Signal PDF width	0.0141	0.0294	0.0193	0.0744
tau mass (PDG)	0.0031	0.0074	0.0046	0.0224

Proportional  
to # of signal

(# of signal is  
assumed to be  
toy-MC  $1\sigma$ )

Independent  
on # of signal

# Belle II Plan

30

