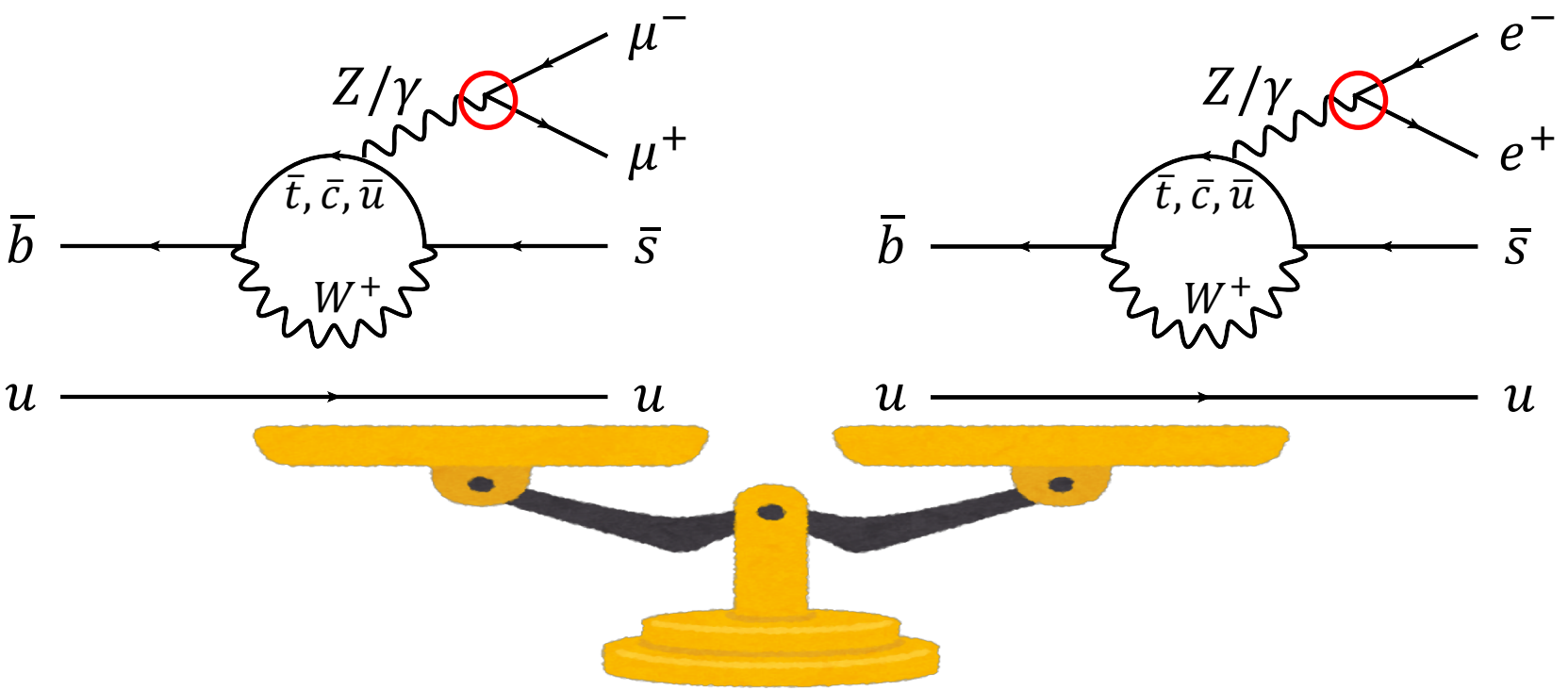
FPCP2021

Search of lepton flavor non-universality by R(K), R(K*) measurements and related studies

2021 7th June

Shun Watanuki
Yonsei University

Introduction (LFU)

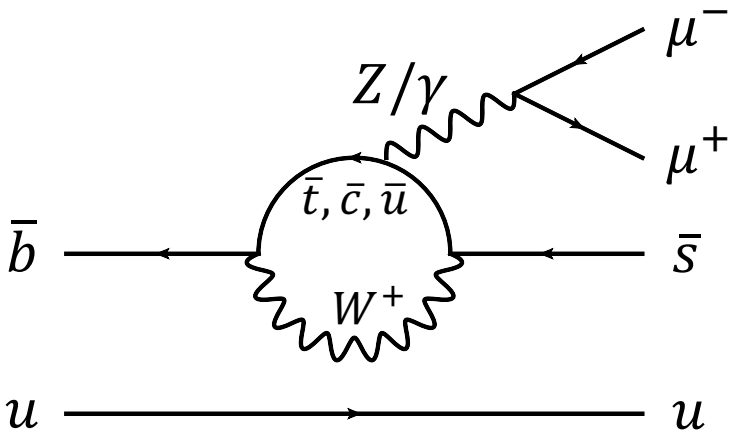


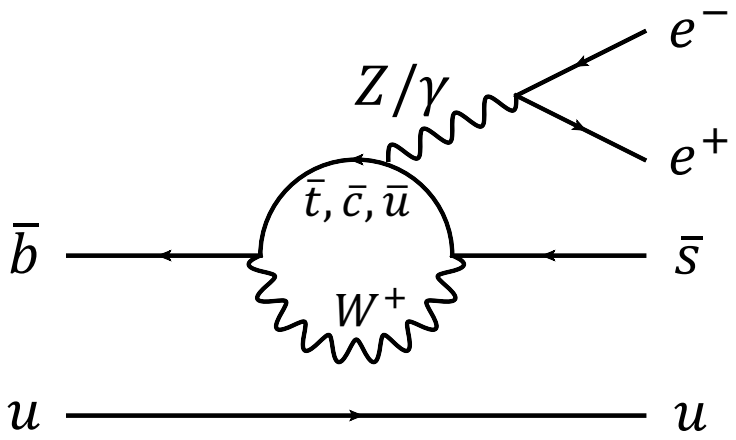
- In SM, the coupling constants of each generation leptons with Z/γ are identical.

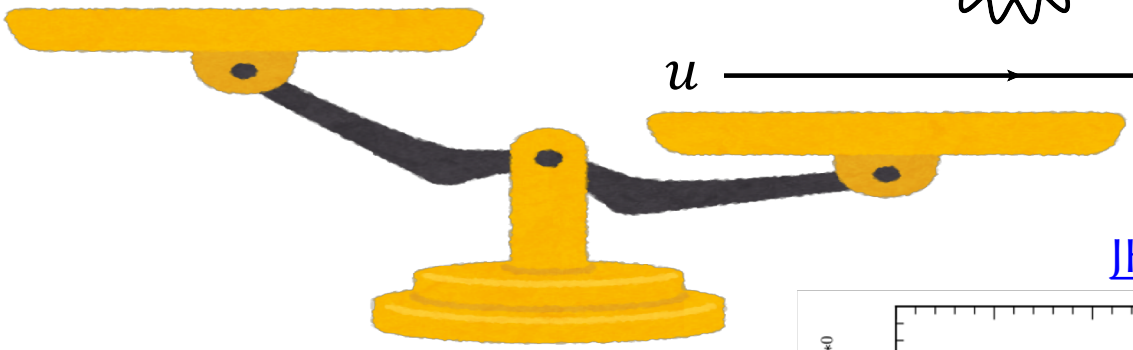
$$\rightarrow R_{K^{(*)}} \equiv \frac{\mathcal{B}\left(B \rightarrow K^{(*)} \mu^+ \mu^-\right)}{\mathcal{B}\left(B \rightarrow K^{(*)} e^+ e^-\right)} \approx 1(SM)$$ with very high accuracy.

※ $\mathcal{O}(1\%)$ QED correction in $M_{\ell\ell}^2 \equiv \boldsymbol{q^2} \in (1.1, 6.0) GeV^2/c^4$
10.1140/epjc/s10052-016-4274-7

Introduction (LFUV)

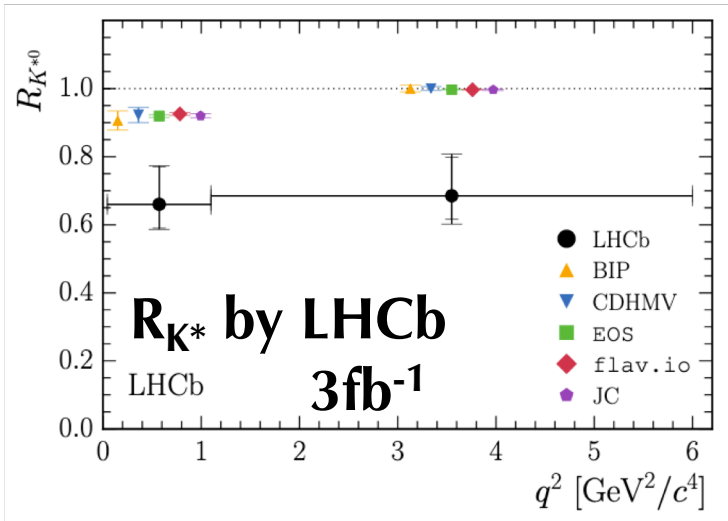




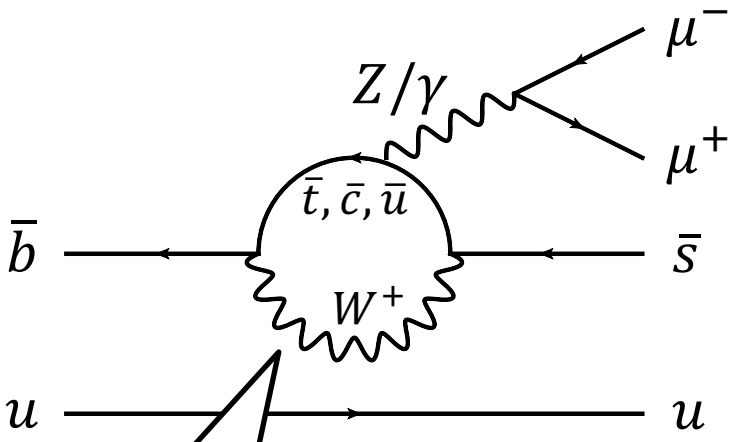


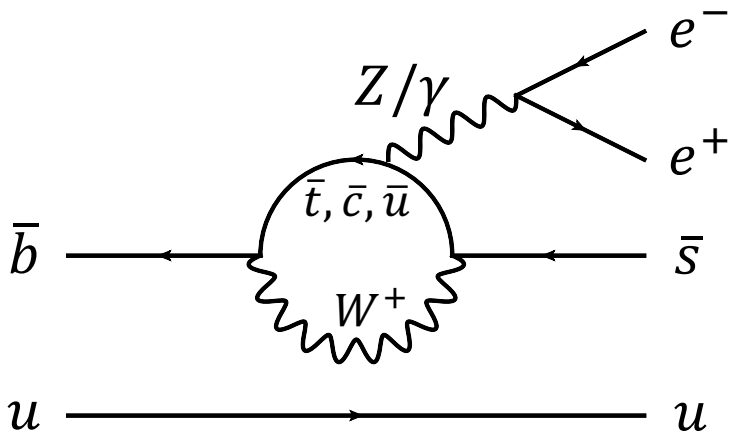
JHEP 08, 055(2017)

- As we might already know, LHCb reported a series of anomalies with several modes. ($\mathbf{B^0 \to K^{*0} \ell^+ \ell^-}$, $\mathbf{B^+ \to K^+ \ell^+ \ell^-}$, $\Lambda_b \to pK\ell^+\ell^-$)
- Angular analyses with $B \to K^* \mu^+ \mu^-$ also shows tensions, though the SM prediction suffers from the hadronic uncertainty.

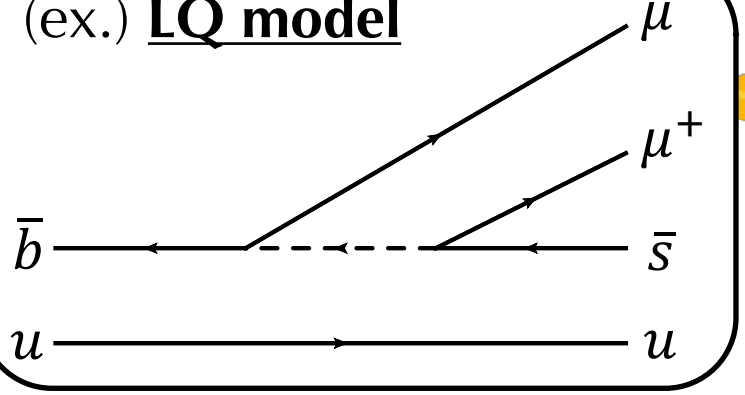


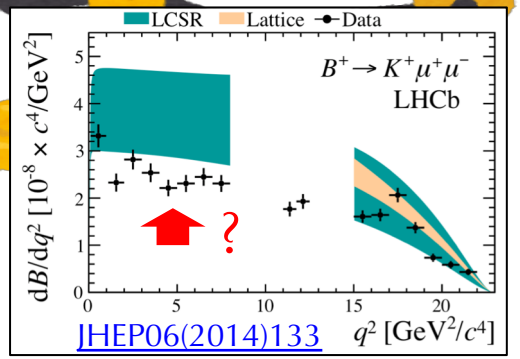
Introduction (LFUV)





(ex.) **LQ model**





A slightly lower tendency of $\mathcal{B}(B \to K\mu^+\mu^-)$.

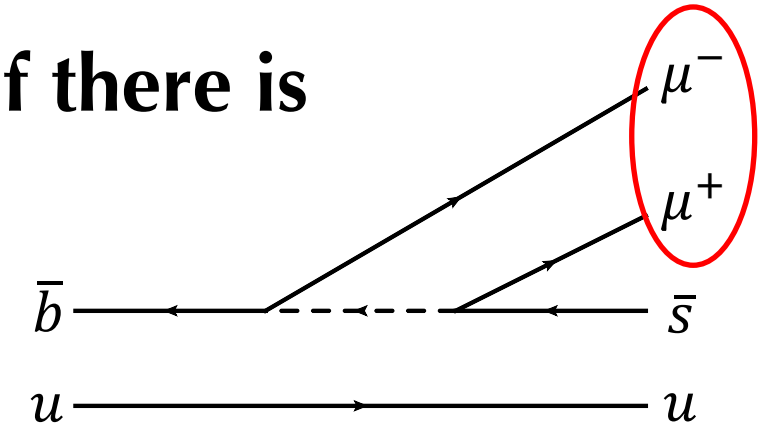
Kμμ receives NP effects more than Kee?

NP effects which violate the lepton universality? (***LFUV***)

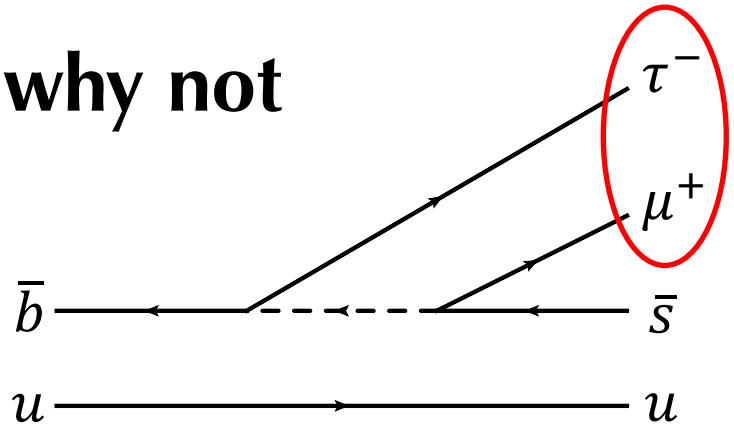
Introduction (LFV)

- Once LFU is violated, lepton flavor violation (LFV) is **no longer forbidden** in the model;

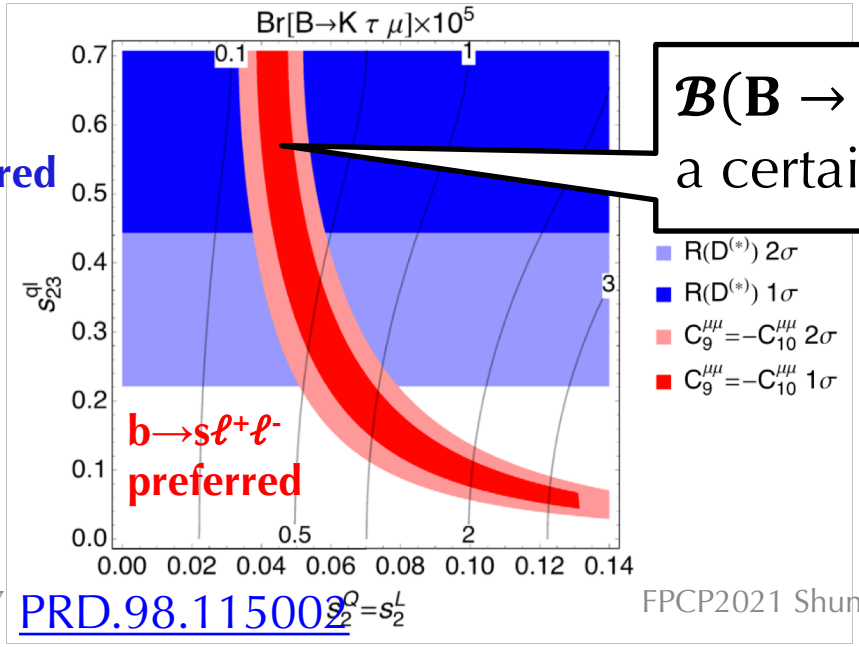
If there is



why not



R(D$^{(*)}$) preferred



PRD.98.115002

$\mathcal{B}(B \to K\tau\mu) \sim O(10^{-6})$ is preferred in a certain VLQ model, for example.

Searching LFV is also a fascinating topic!

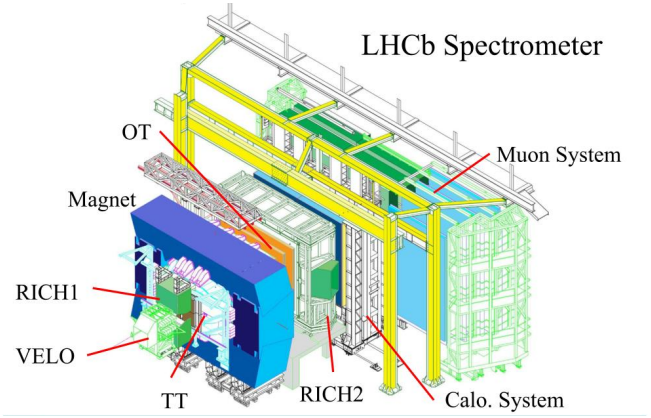
Today's contents

1. $R_{K^{(*)}}$ results by LHCb
2. $R_{K^{(*)}}$ results by Belle
3. Prospects at Belle II
4. LFV searches
5. $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

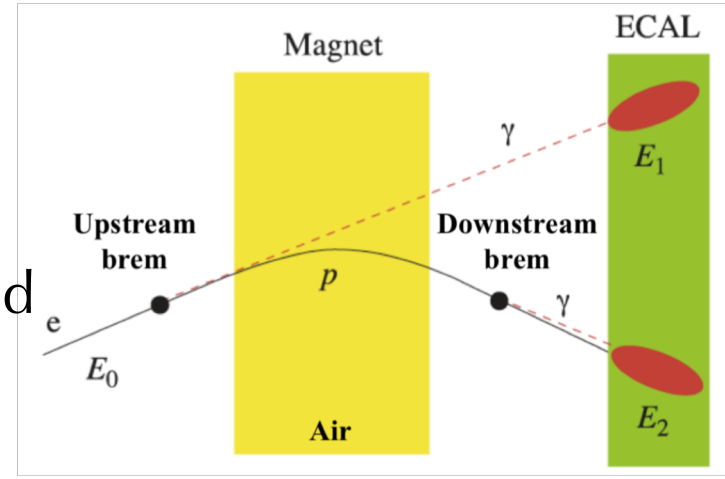
Tests of Lepton Flavor Universality by LHCb and Belle

R_{K^*} measurement @LHCb

- JHEP08(2017)055
- 3fb^{-1} proton-proton collision data at 7 and 8 TeV collected by LHCb detector
- Reconstruct $B^0 \to K^{*0}$ ($\to K^+\pi^-$) $\ell^+\ell^-$ mode
- q^2 bins are divided into:
  $[0.045, 1.1]$ (GeV^2/c^4) (low) and
  $[1.1, 6.0]$ (GeV^2/q^4) (central)



- **Bremsstrahlung recovery** in $\ell = e$
  - In case that e^- emitted bremsstrahlung in upstream of the magnet, the cluster of bremsstrahlung γ detected at ECAL should be found and recovered.



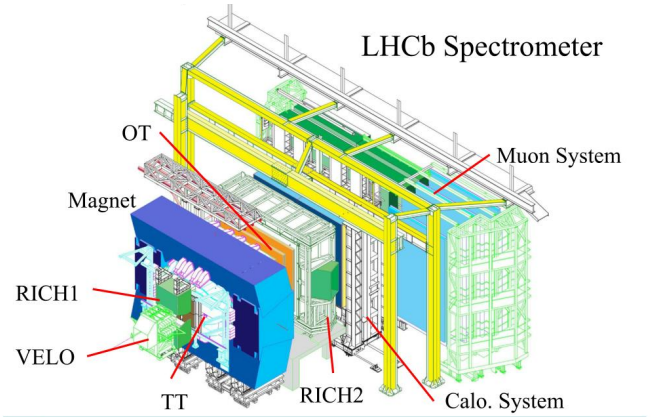
R_{K^*} measurement @LHCb

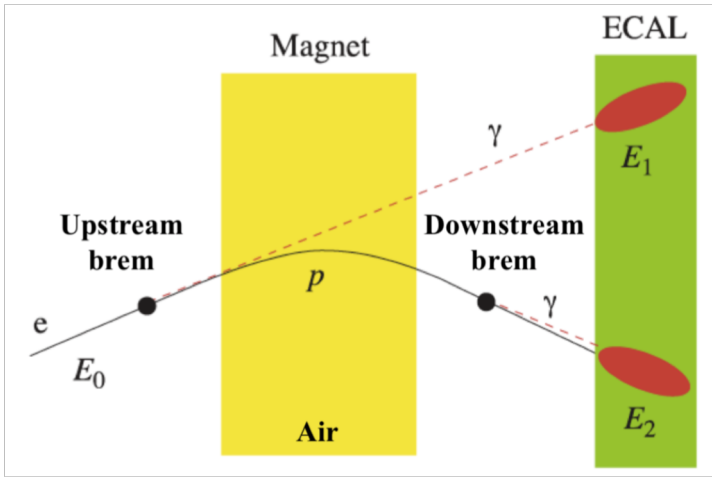
- **Double-ratio** with $K^{*0}J/\psi(\to \ell^+\ell^-)$ is taken to cancel systematics;

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

with $R_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))} = 1$

should be confirmed;
- True within $\pm 0.4\%$ (PDG)
- $R_{J/\psi} = 1.043 \pm 0.006 \pm 0.045$



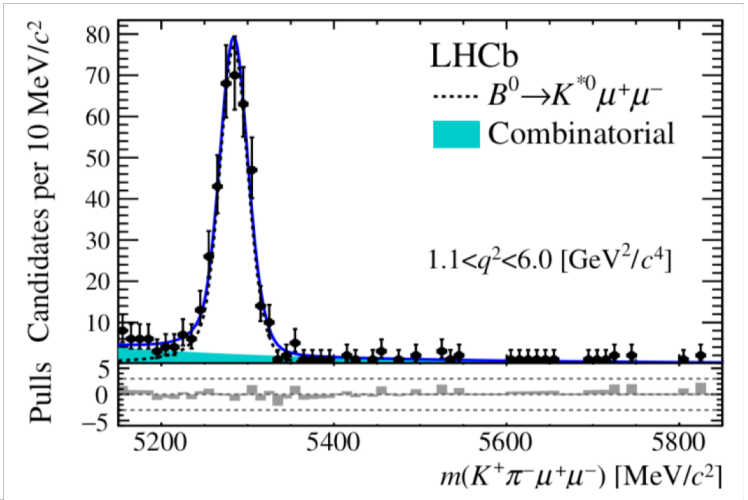


Note

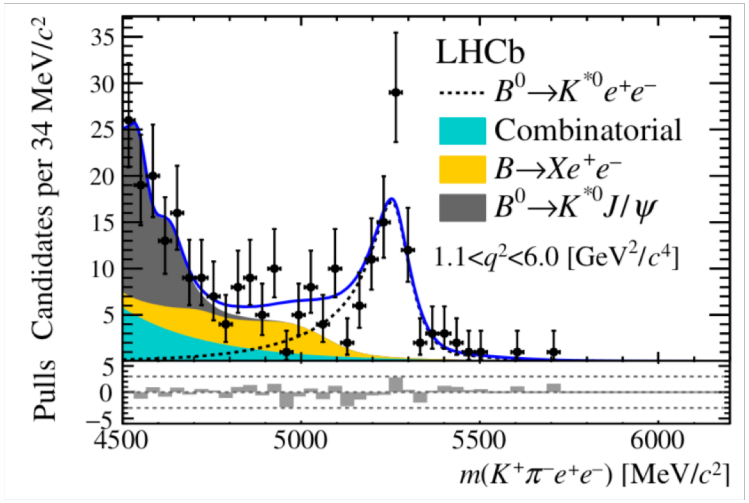
- This strategy is also adopted in R_K measurement at LHCb.

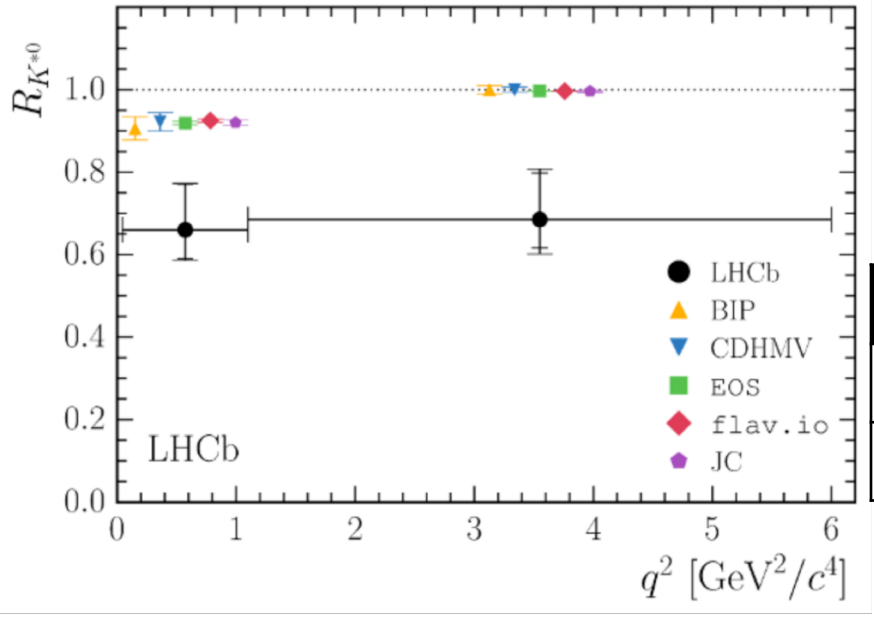
Result of R_{K^*} @LHCb

μ mode



e mode





- Consistent with the SM, but a slight tension can be seen.
- Statistical uncertainty dominant.

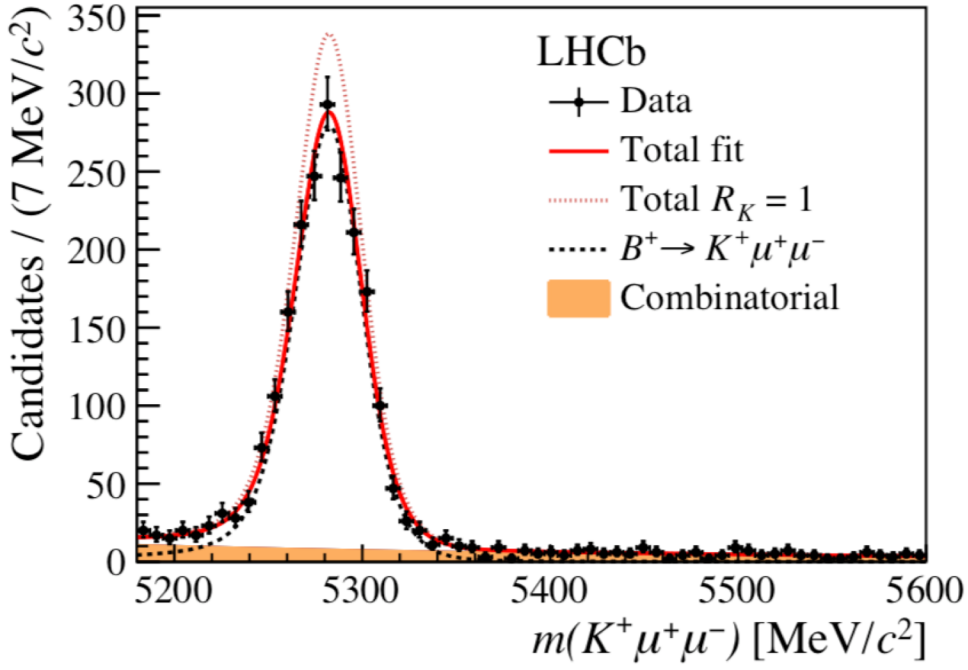
→ Study with **a larger size dataset** is important

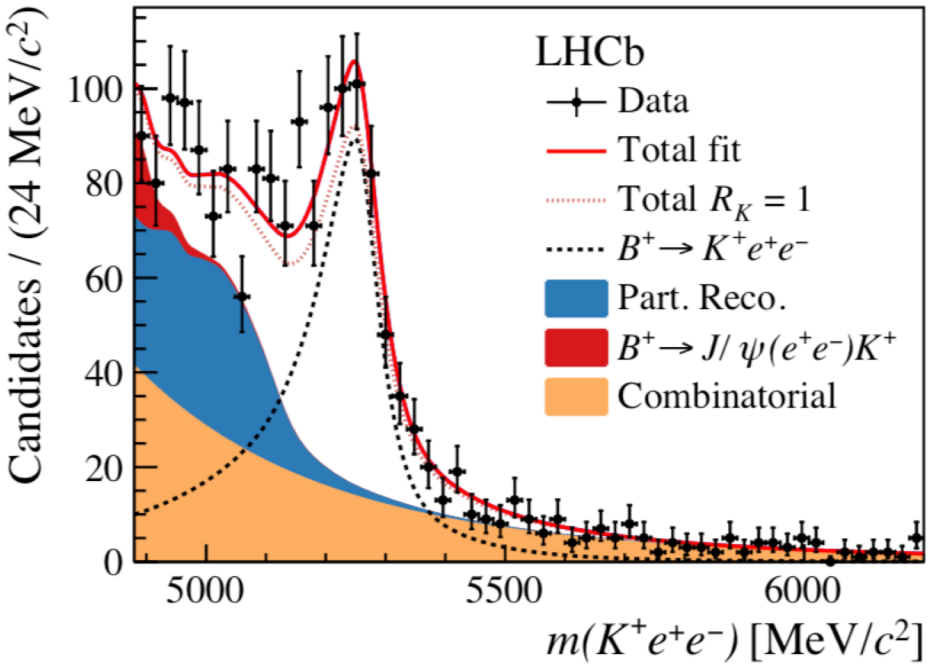
q^2 (GeV^2/c^4)	$R_{K^{*0}}$	SM Consistency
[0.045, 1.1]	$0.66^{+0.11}_{-0.07} \pm 0.03$	**2.1~2.3σ**
[1.1, 6]	$0.69^{+0.11}_{-0.07} \pm 0.05$	**2.4~2.5σ**

※ *depending on the theoretical predictions.*

R_K measurement @LHCb (2019)

- PRL122(2019)191801 (Run1+Run2, 5fb^{-1})
- $q^2 \in (1.1, 6.0)\ GeV^2/c^4$
- Analysis technique is similar as $K^*\ell^+\ell^-$ study.



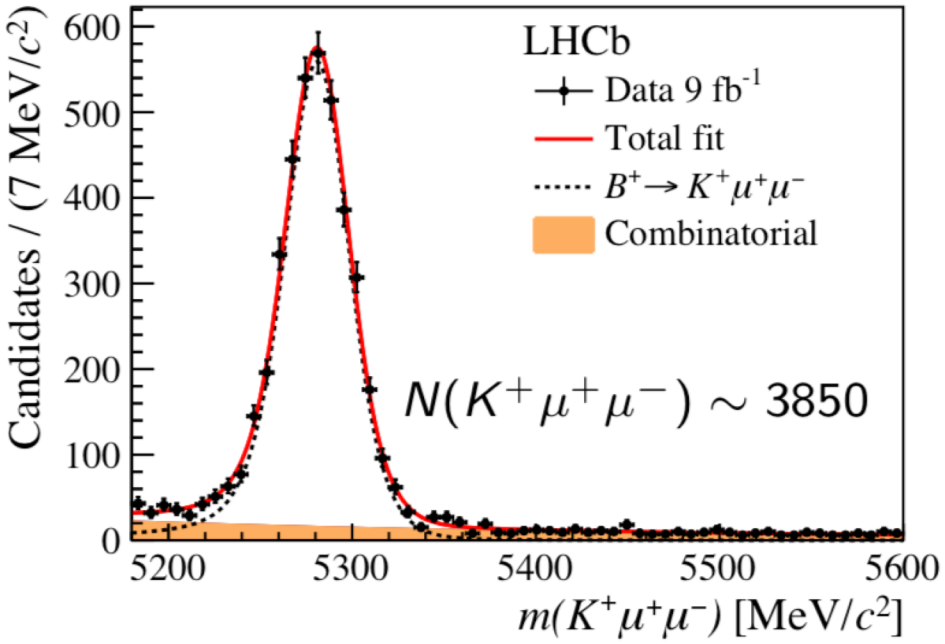


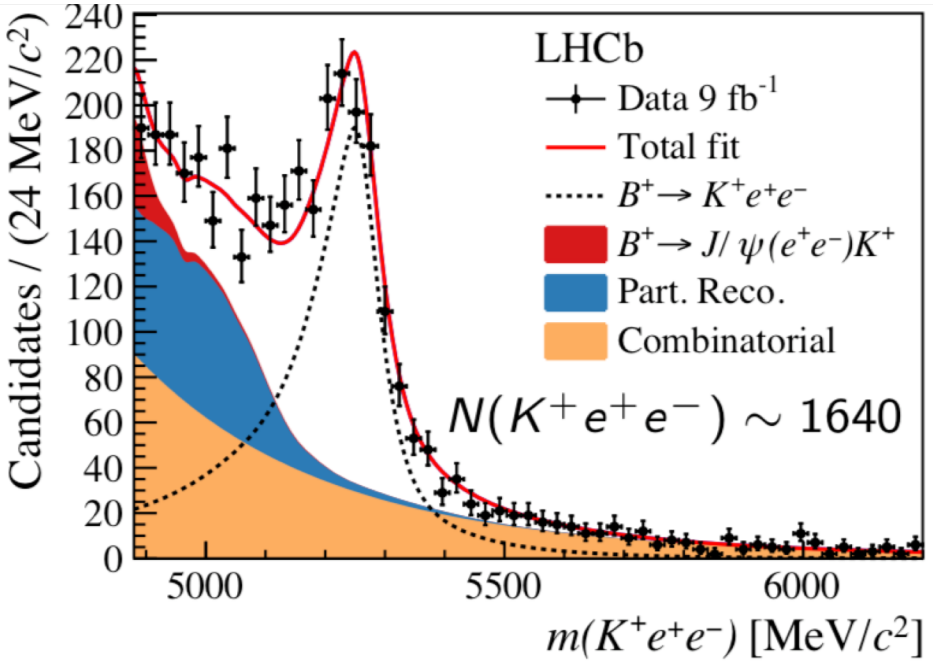
$$R_{K^+} = 0.864^{+0.060+0.016}_{-0.054-0.014}$$

← Compatible with the SM at 2.5σ level

R_K measurement @LHCb (2021)

- arXiv:2103.11769 (Run1+Run2, updated with 9fb^{-1})
- $q^2 \in (1.1, 6.0)\ GeV^2/c^4$
- Same analysis strategy is taken as their previous study with 5fb^{-1}.



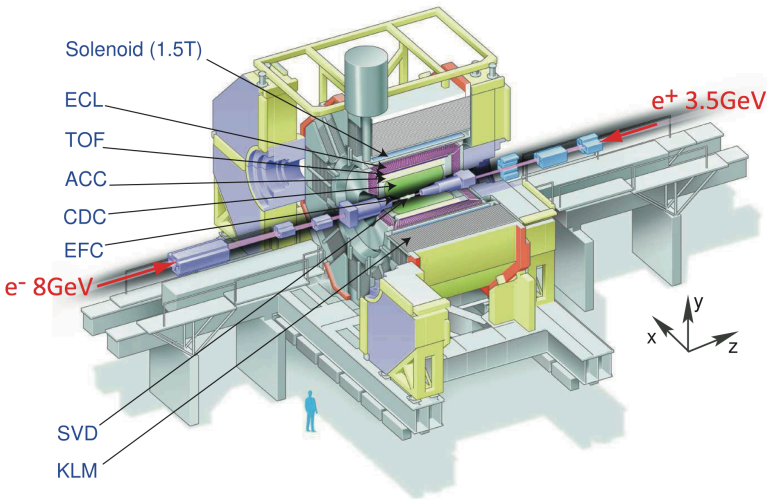


$$R_{K^+} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

← **Evidence** of LFUV at 3.1σ level

R_{K^*} measurements @Belle

- PRL.126.161801
- 711fb^{-1} (772x10^6 $B\bar{B}$) collected by Belle detector.
- Reconstruct 4 decay modes:
  - $B^+ \to K^{*+}(\to K^+\pi^0, K_S^0\pi^+)\ell^+\ell^-$
  - $B^0 \to K^{*0}(\to K^+\pi^-, K_S^0\pi^0)\ell^+\ell^-$
- Results in several q^2 bin options, including high q^2 region (up to 19 GeV^2/c^4).

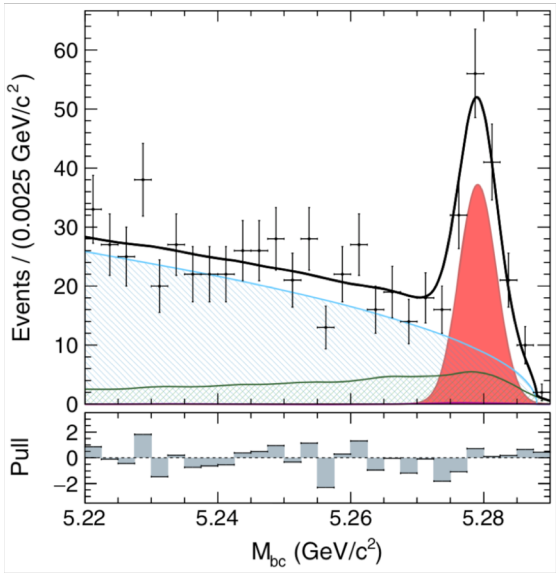


B factory observables

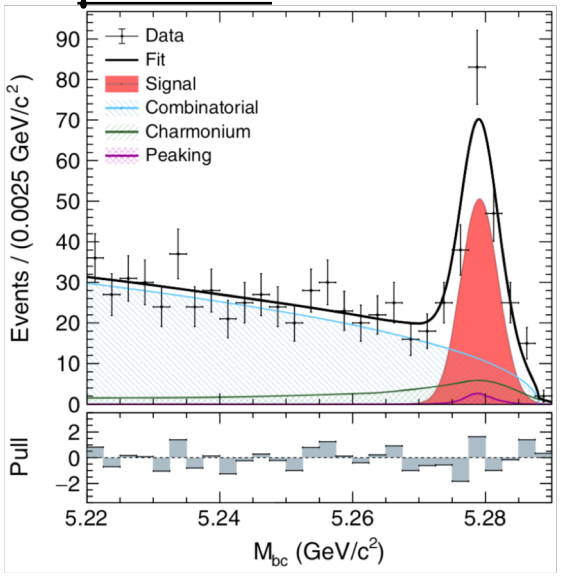
- $M_{bc} \equiv \sqrt{E_{beam}^2 - \left|\vec{p}_B\right|^2}$
- $\Delta E \equiv E_B - E_{beam}$

e mode can be measured as clean as μ mode.

e mode

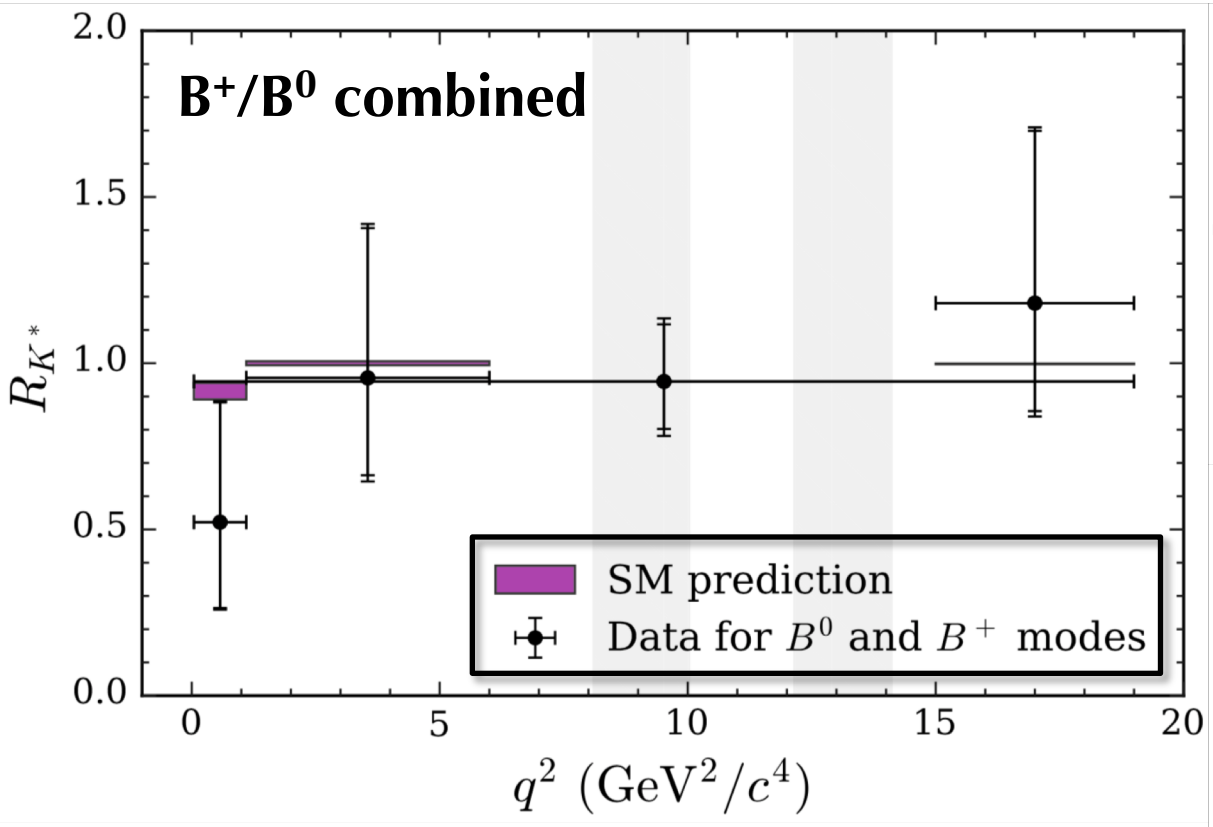


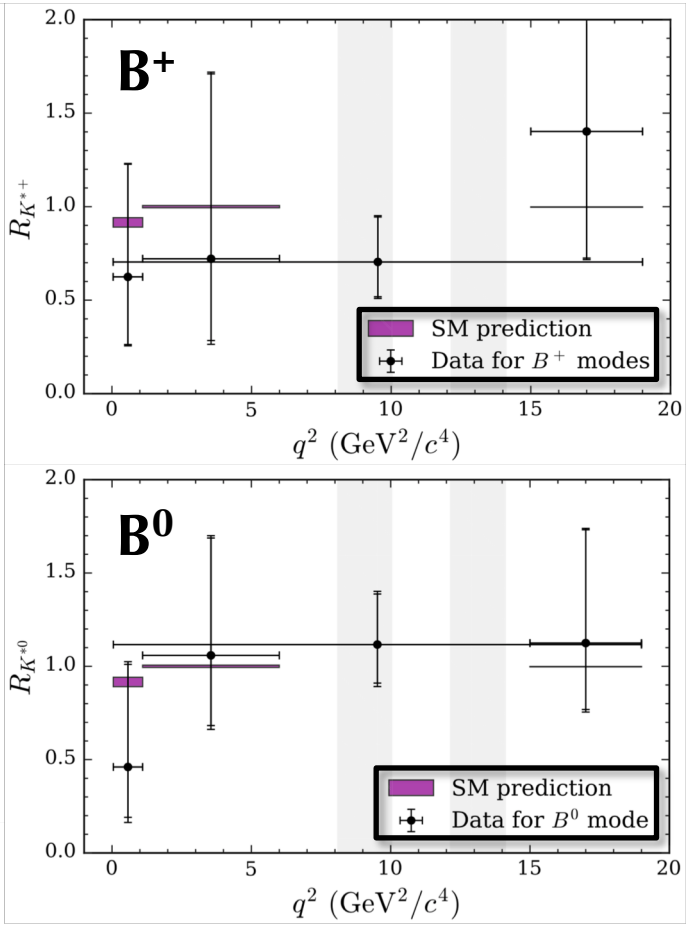
μ mode



B⁺/B⁰ combined

Results of R_{K^*} @Belle





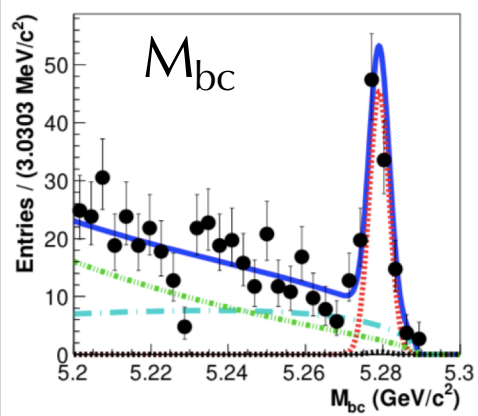
q^2 (GeV$^2/c^4$)	Comb. (B^0/B^+)
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$
[0.045, 19]	$\mathbf{0.94}^{+0.17}_{-0.14} \pm 0.08$

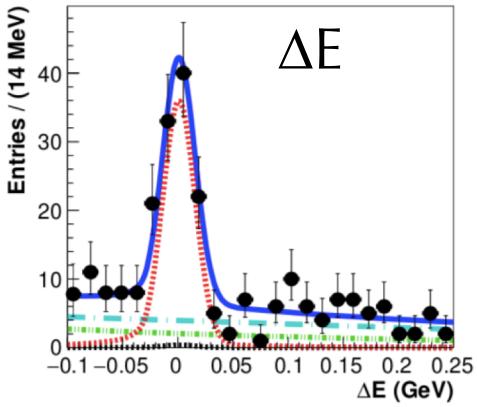
- R_{K^*} measured in Belle is **all consistent with SM**.
  - The largest deviation is in the lowest q^2 bin. (same as LHCb)
- This is the first result for $R_{K^{*+}}$ measurement.

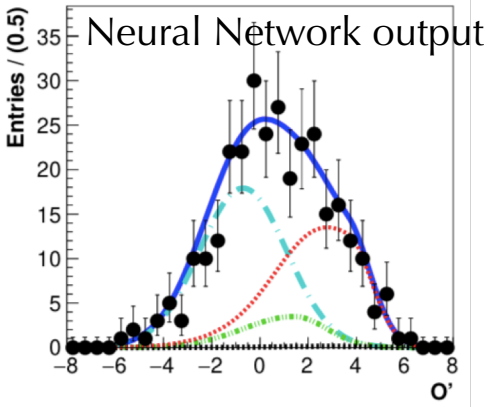
R_K measurements @Belle

Signal enhanced distributions

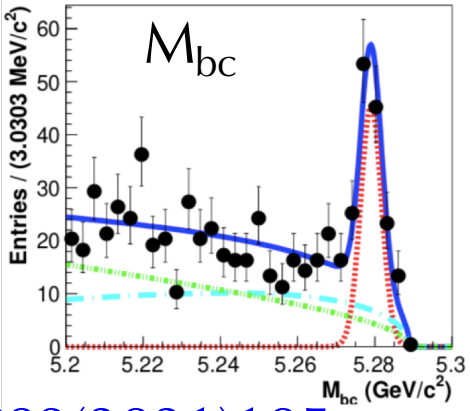
$K^+\mu^+\mu^-$

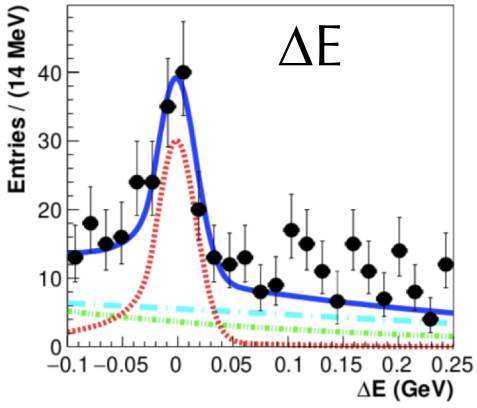


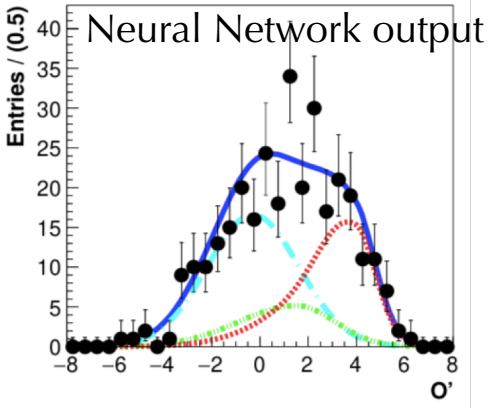




$K^+e^+e^-$

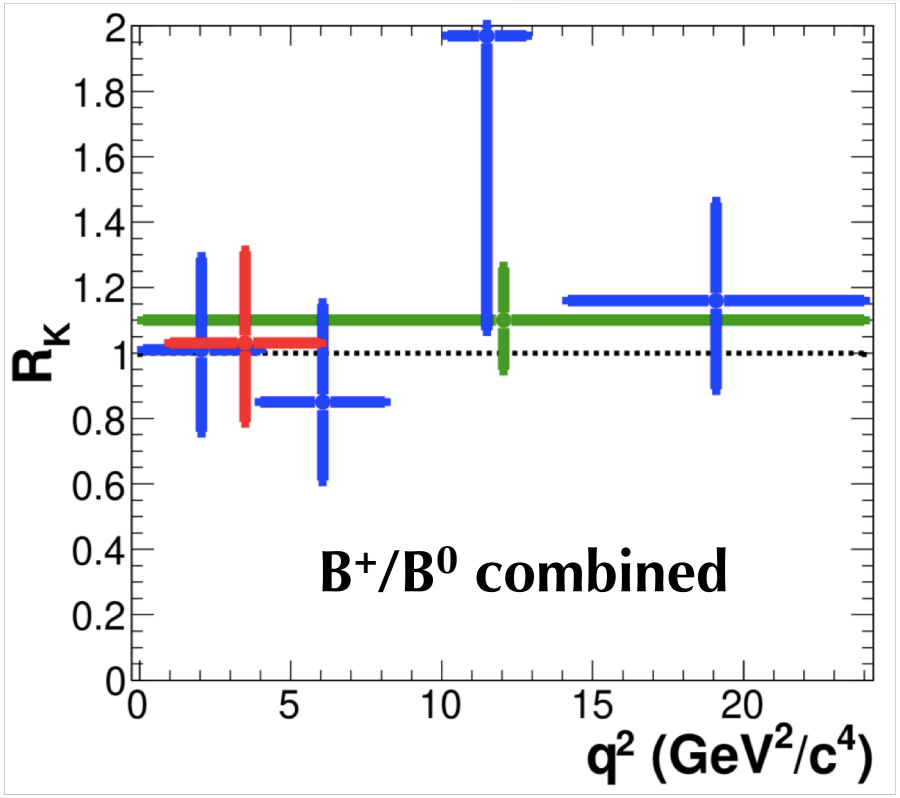


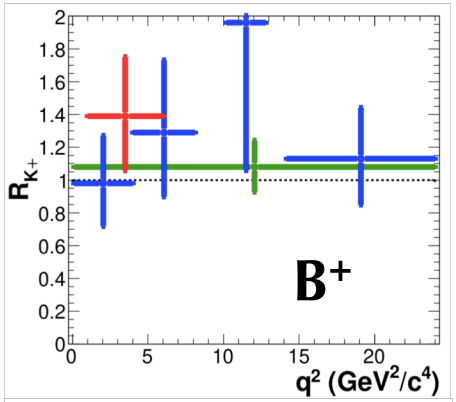


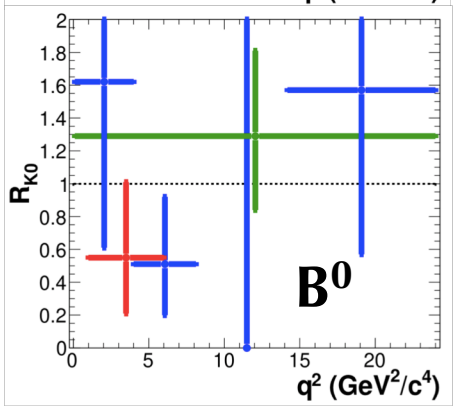


- JHEP03(2021)105
- 711fb^{-1} (772x10^6 $B\bar{B}$) collected by Belle detector.
- Both R_{K^+} and $R_{K^0_S}$ are measured.
- 3D fitting with M_{bc}, ΔE, and modified Neural Net output.

Results of R_K @Belle







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	$\mathbf{1.10^{+0.16}_{-0.15}} \pm 0.02$

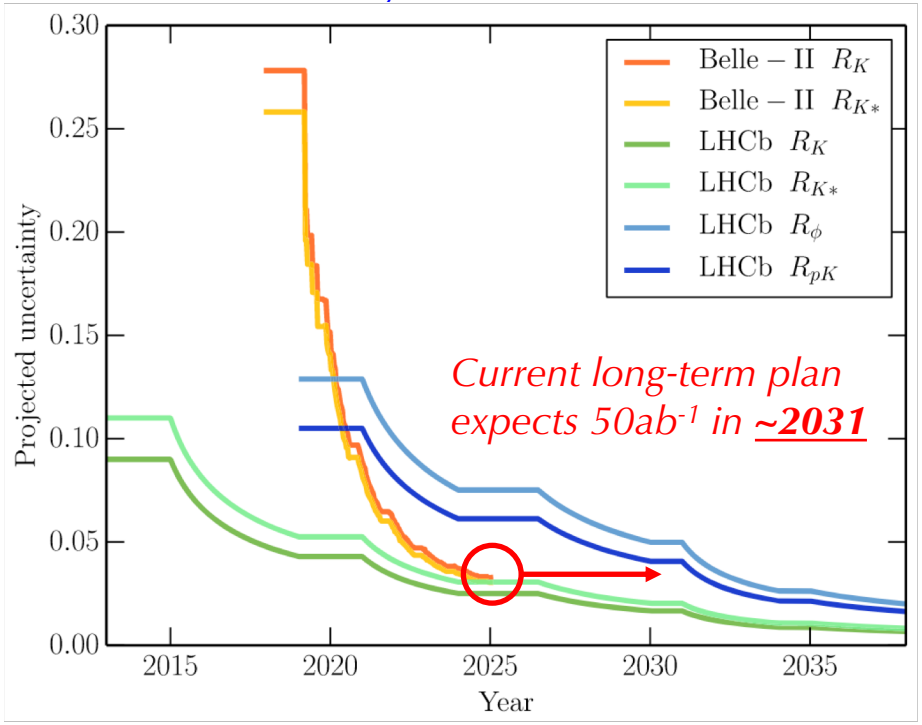
- R_K measured in Belle is **all consistent with SM**.
- The red bin is corresponding to the same range as the study at LHCb.

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 $B \to K^* e^+ e^-$**
  - Inclusive study ($X_s \ell^+ \ell^-$); **Measurement with small theoretical error**

Nucl. Part. Phys. **46** 023001



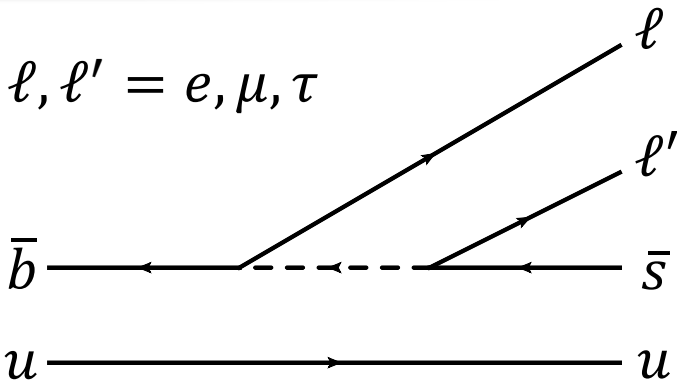
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ($[1.0, 6.0]$ GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]$ GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]$ GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%

PTEP 2019 (2019) 12, 123C01

Searches of Lepton Flavor Violation

Summary of LFV searches

Mode	BR U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	$<1.2\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu^-e^+$	$<1.6\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu e$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\mu^-e^+$	$<7.0\times10^{-9}$ (**LHCb**) $<3.0\times10^{-8}$ (**Belle**)
$B^+ \to K^+\mu^+e^-$	$<6.4\times10^{-9}$ (**LHCb**) $<8.5\times10^{-8}$ (**Belle**)
$B^0 \to K_s^0\mu^\pm e^\mp$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\tau\mu$	$<4.8\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau e$	$<3.0\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau^+\mu^-$	$<3.9\times10^{-5}$ (**LHCb**)



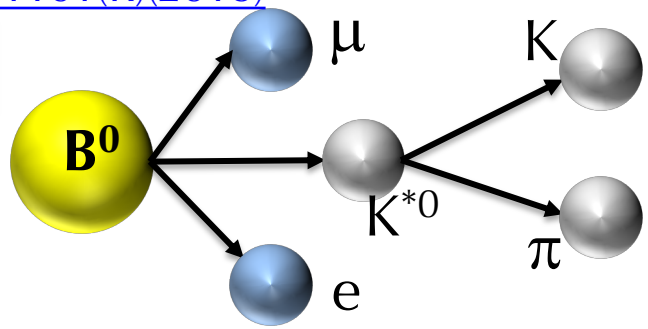
So far, no signals of LFV have been found...

$B \to K^{*0}\mu^{\pm}e^{\mp}$

Mode	BR U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	$<1.2\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu^-e^+$	$<1.6\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu e$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\mu^-e^+$	$<7.0\times10^{-9}$ (**LHCb**) $<3.0\times10^{-8}$ (**Belle**)
$B^+ \to K^+\mu^+e^-$	$<6.4\times10^{-9}$ (**LHCb**) $<8.5\times10^{-8}$ (**Belle**)
$B^0 \to K_s^0\mu^{\pm}e^{\mp}$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\tau\mu$	$<4.8\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau e$	$<3.0\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau^+\mu^-$	$<3.9\times10^{-5}$ (**LHCb**)

PRD98,071101(R)(2018)

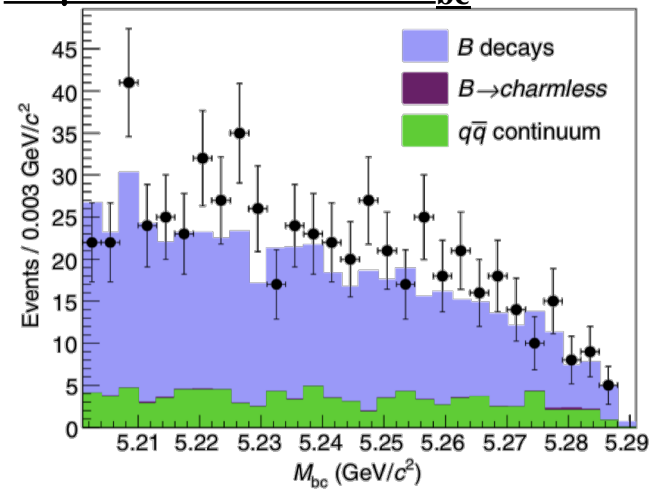
Signal



BG

- Both BB pair SL decay
- $B \to D^{(*)}Xl^+\nu$ followed by $D^{(*)} \to Xl^-\nu$
- Hadronic decay with mis-ID

$K\pi\mu^{\pm}e^{\mp}$ combined M_{bc}

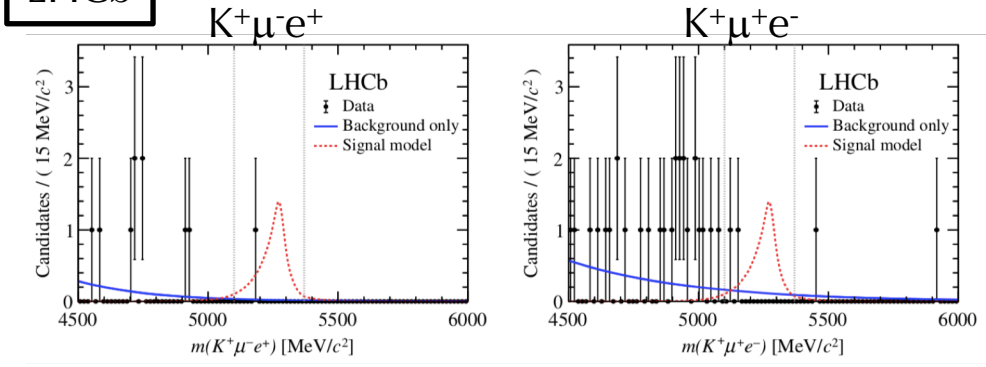


➢ Belle set the stringent U.L. $\mathcal{O}(10^{-7})$.

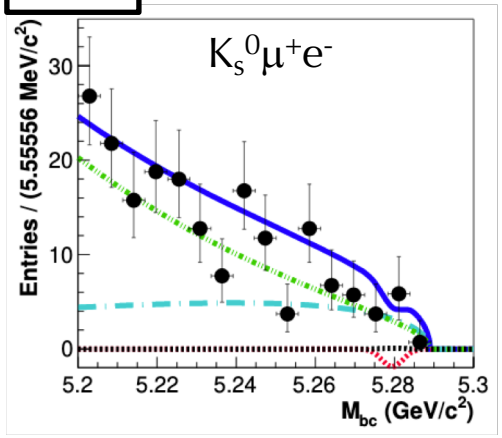
$B \to K\mu^{\pm}e^{\mp}$

Mode	BR U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	$<1.2\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu^-e^+$	$<1.6\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu e$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\mu^-e^+$	$<7.0\times10^{-9}$ (**LHCb**) $<3.0\times10^{-8}$ (**Belle**)
$B^+ \to K^+\mu^+e^-$	$<6.4\times10^{-9}$ (**LHCb**) $<8.5\times10^{-8}$ (**Belle**)
$B^0 \to K_s^0\mu^{\pm}e^{\mp}$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\tau\mu$	$<4.8\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau e$	$<3.0\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau^+\mu^-$	$<3.9\times10^{-5}$ (**LHCb**)

LHCb PRL123,241802(2019)



Belle arXiv:1908.01848v1

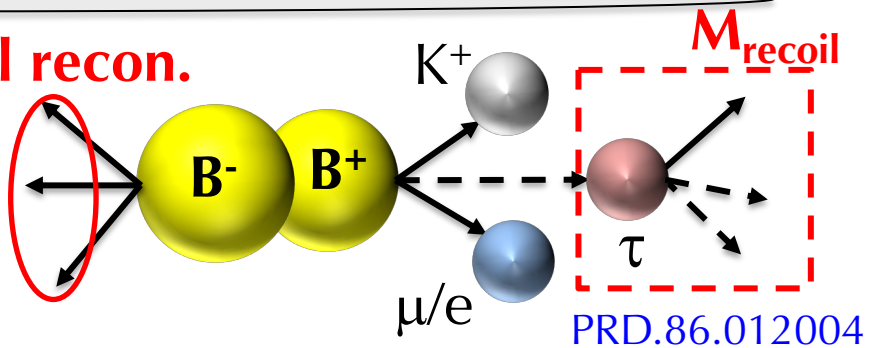


- LHCb set the stringent U.L. $\mathcal{O}(10^{-9})$.
- Belle succeeded to set the U.L. for $B^0 \to K_S^0\mu^{\pm}e^{\mp}$ as well ($\mathcal{O}(10^{-7})$).

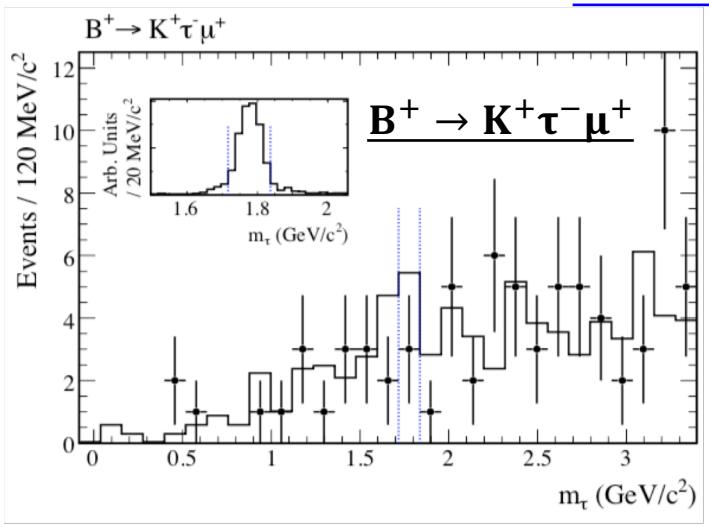
$B^+ \to K^+\tau^\pm\ell^\mp$

Mode	BR U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	$<1.2\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu^-e^+$	$<1.6\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu e$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\mu^-e^+$	$<7.0\times10^{-9}$ (**LHCb**) $<3.0\times10^{-8}$ (**Belle**)
$B^+ \to K^+\mu^+e^-$	$<6.4\times10^{-9}$ (**LHCb**) $<8.5\times10^{-8}$ (**Belle**)
$B^0 \to K_s^0\mu^\pm e^\mp$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\tau\mu$	$<4.8\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau e$	$<3.0\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau^+\mu^-$	$<3.9\times10^{-5}$ (**LHCb**)

Full recon.



PRD.86.012004

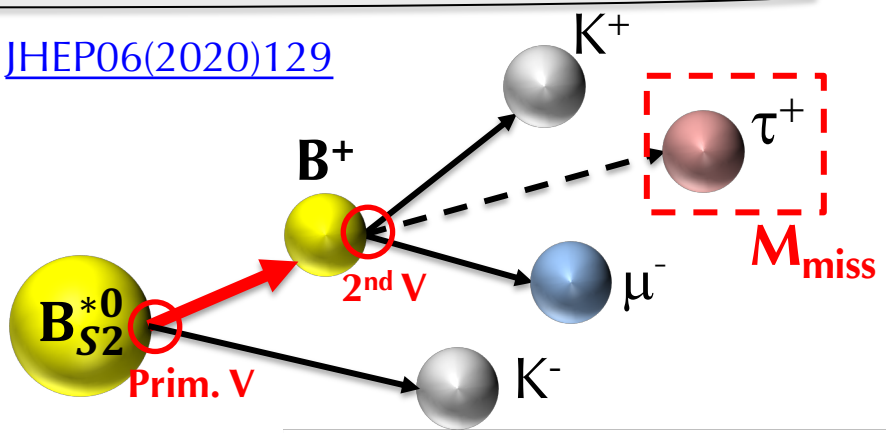


- $B \to K\tau\ell$ is more challenging modes for ν's in τ decay and more attractive for NP effects for its heavier mass.
  = (possibly) **stronger couplings with NP**
- BaBar succeeded to set the U.L. $\mathcal{O}(10^{-5})$ in both (ℓ=μ/e) channels.
- **Belle II 50ab^{-1}** is expected to set $< 3.3\times10^{-6}$.

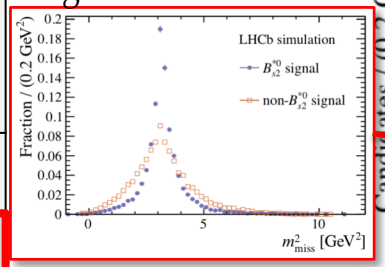
$B^+ \to K^+\tau^+\mu^-$

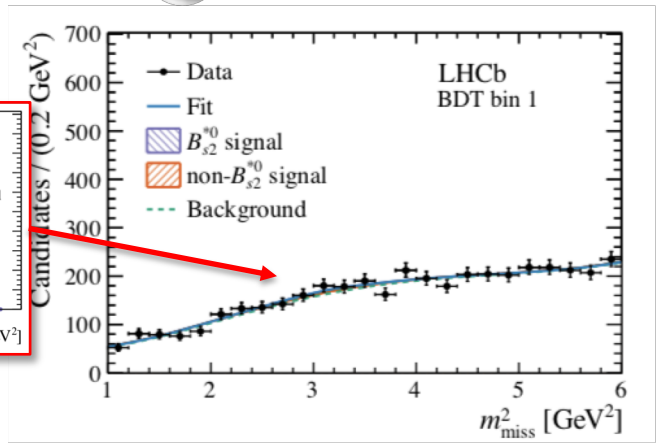
Mode	BR U.L. (90% CL)
$B^0 \to K^{*0}\mu^+e^-$	$<1.2\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu^-e^+$	$<1.6\times10^{-7}$ (**Belle**)
$B^+ \to K^{*0}\mu e$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\mu^-e^+$	$<7.0\times10^{-9}$ (**LHCb**) $<3.0\times10^{-8}$ (**Belle**)
$B^+ \to K^+\mu^+e^-$	$<6.4\times10^{-9}$ (**LHCb**) $<8.5\times10^{-8}$ (**Belle**)
$B^0 \to K_s{}^0\mu^{\pm}e^{\mp}$	$<1.8\times10^{-7}$ (**Belle**)
$B^+ \to K^+\tau\mu$	$<4.8\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau e$	$<3.0\times10^{-5}$ (**BaBar**)
$B^+ \to K^+\tau^+\mu^-$	$<3.9\times10^{-5}$ (**LHCb**)

JHEP06(2020)129



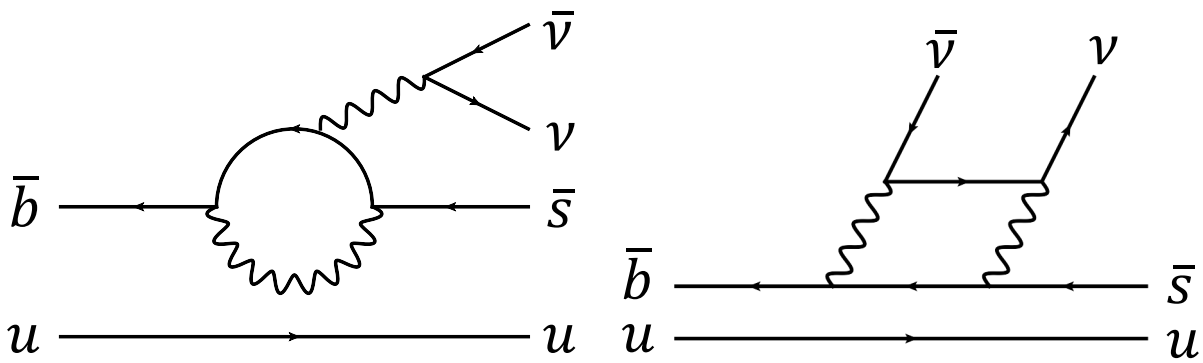
Signal distribution



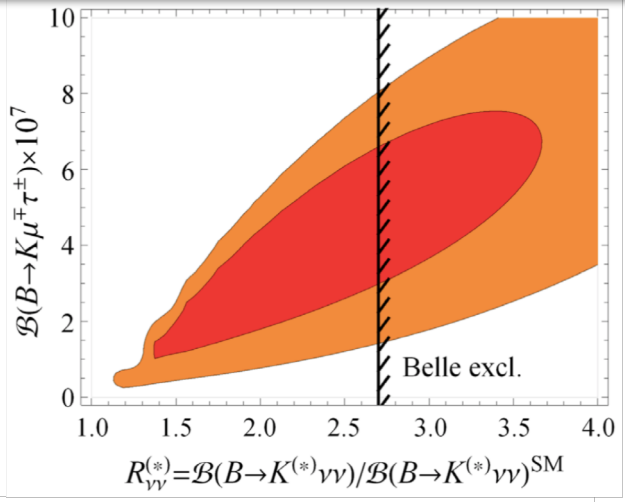


- LHCb also succeeded to set the U.L. $\mathcal{O}(10^{-5})$ in $K^+\tau^+\mu^-$ channel.
  - Primary and 2nd vertices are determined by high quality tracks.
  - Energy of B is calculated with kinematic information.
  - Direction of B can be known with vertices.

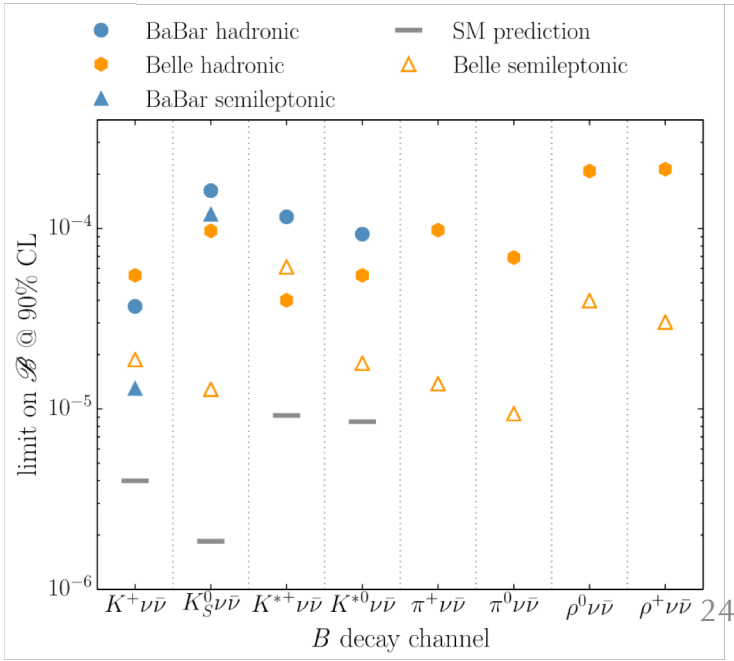
$B^+ \to K^+\nu\bar{\nu}$



The SLQ (PRD98,055003) predicts $\mathcal{B}(B \to K\tau\mu) \sim \mathcal{O}(10^{-7})$ against $R_{\nu\bar{\nu}}$

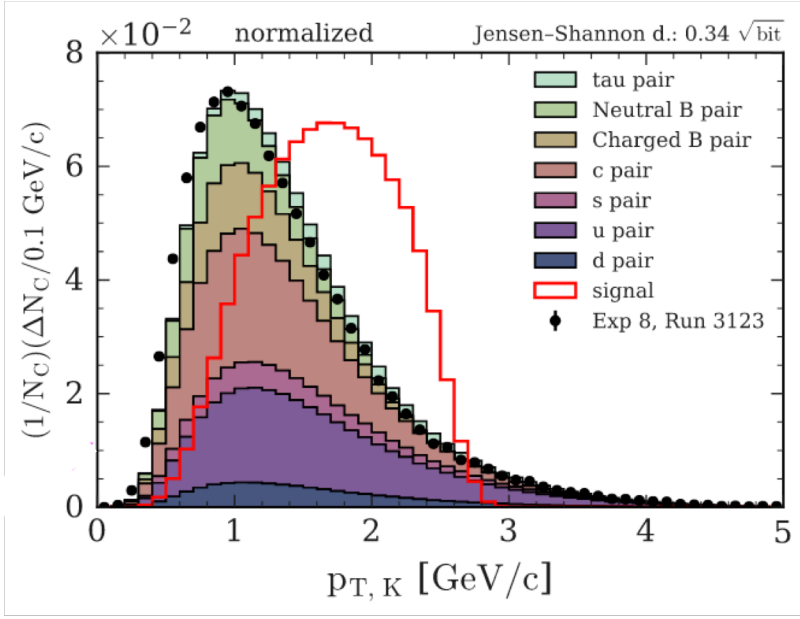


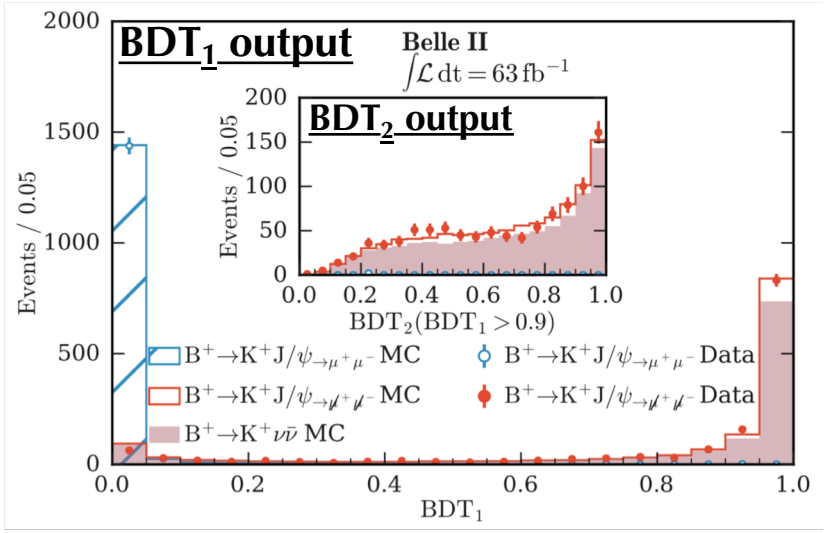
- A search of $B^+ \to K^+\nu\bar{\nu}$ is also very interesting topic for the complementary probe of NP.
  $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{SM} = (4.6 \pm 0.5)\times 10^{-6}$
- Current the U.L. of exclusive mode is
  $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{exp} < 1.6\times 10^{-5}$
  set by BaBar with hadronic tag
  - PhysRevD.87.112005
- Belle also performed the search both with semi-leptonic and hadronic tag and set the most stringent U.L. on other modes.
  - PhysRevD.96.091101

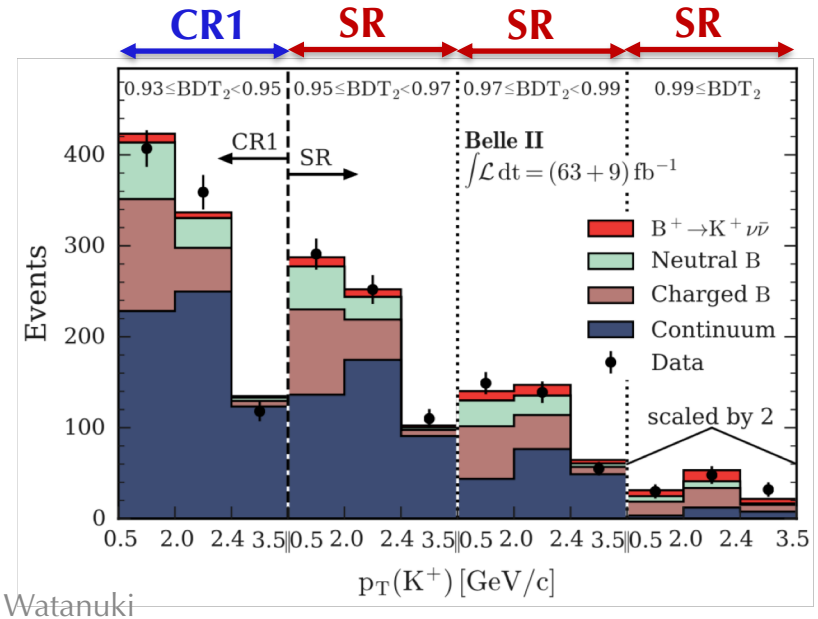


$B^+ \to K^+ \nu\bar{\nu}$

- arXiv:2104.12624v2
- Recently Belle II reported **inclusive tag method** with **63fb^{-1}**(on-resonance) and **9fb^{-1}**(off-resonance).
  $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) < 4.1 \times 10^{-5}$
- Extract signal yields from pT x BDT_2 histograms in signal region (SR) and 3 control regions (CR) by BDT_2.
- The method can provide the **competitive sensitivity** with the conventional full reconstruction method.
- Let's see the update in Belle II.







Summary

Lepton Flavor Universality

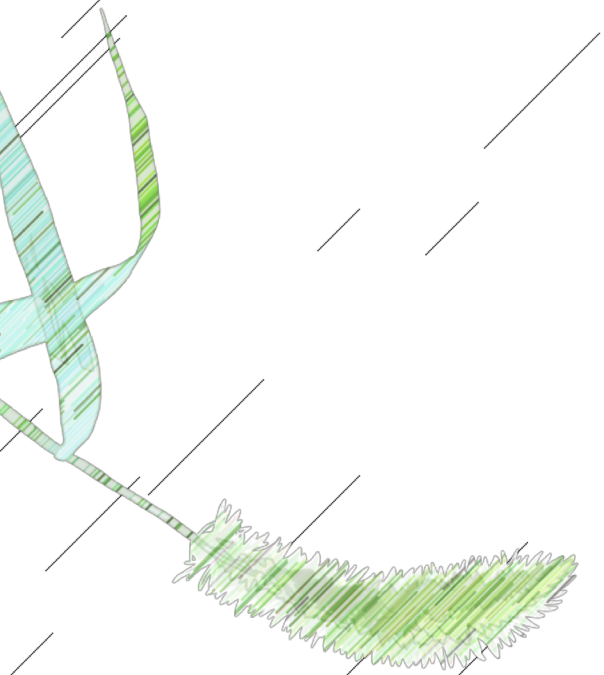
- LHCb updated the R_K measurement and reported $R_{K^+} = 0.846^{+0.042+0.013}_{-0.039-0.012}$ which deviates from the SM with 3.1σ.
- Belle reported the consistent results with the SM both in R_K and R_{K^*}.
- Complementary study at Belle II is also important as well as LHCb.

Lepton Flavor Violation

- LFV is possible once LFU is violated.
- LHCb, Belle and BaBar are looking for those modes, but no any signs of LFV have been found so far.
- Certain LQ models predict $\mathcal{B}(B \to K\tau\mu) \sim \mathcal{O}(10^{-6})$, and Belle II sensitivity with 50ab^{-1} will be around it.

Other related studies

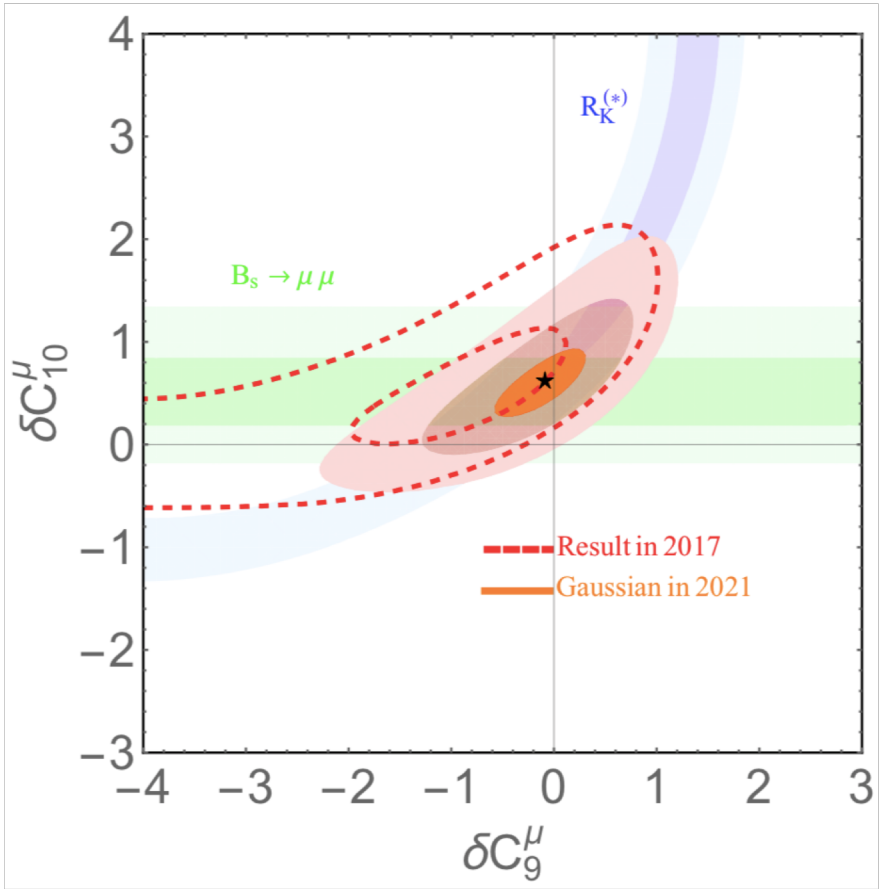
- Angular analyses of $B \to K^*\mu\mu$ at LHCb (and $B \to K^*ee$ at Belle II).
- Inclusive $B \to X_s\ell\ell$ study at Belle II.
- First report on $B^+ \to K^+\nu\bar{\nu}$ with inclusive tag method by Belle II.
- $B \to K\tau\tau$ will be also interesting since τ seems to receive NP effects, even though only Belle II can contribute to the mode significantly.



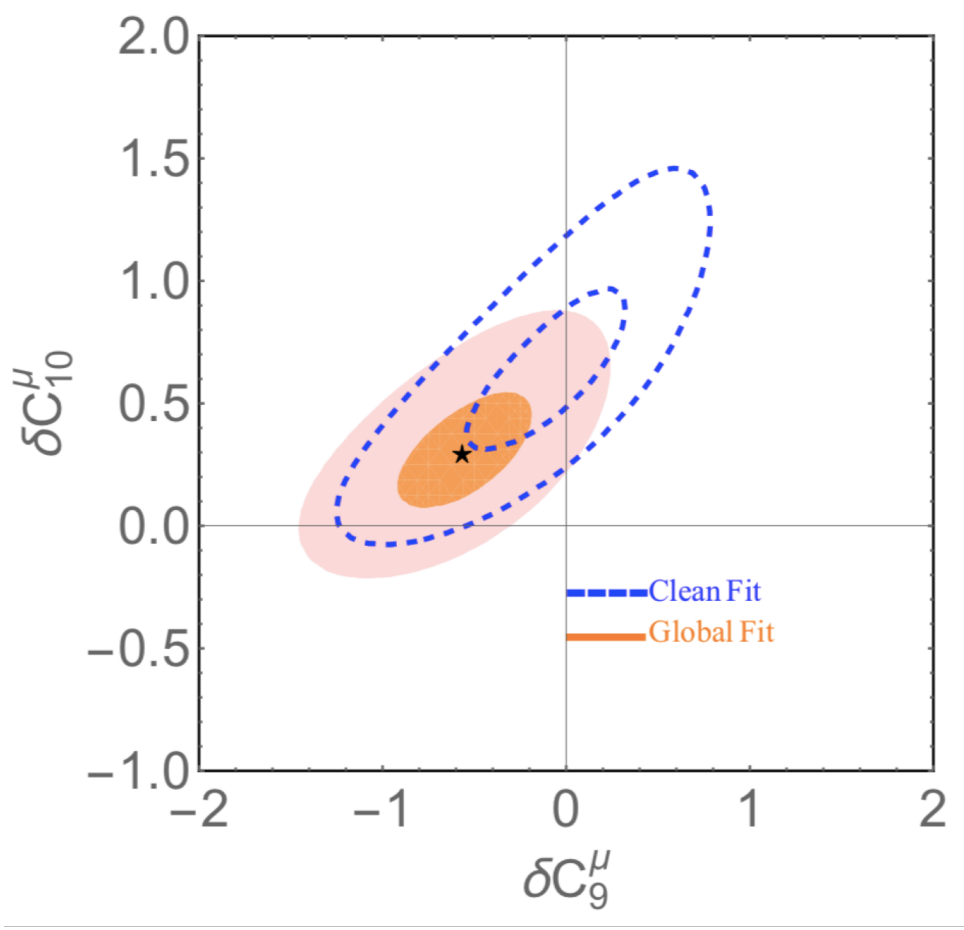
Backup

Global fits

Without angular analyses



With angular analyses

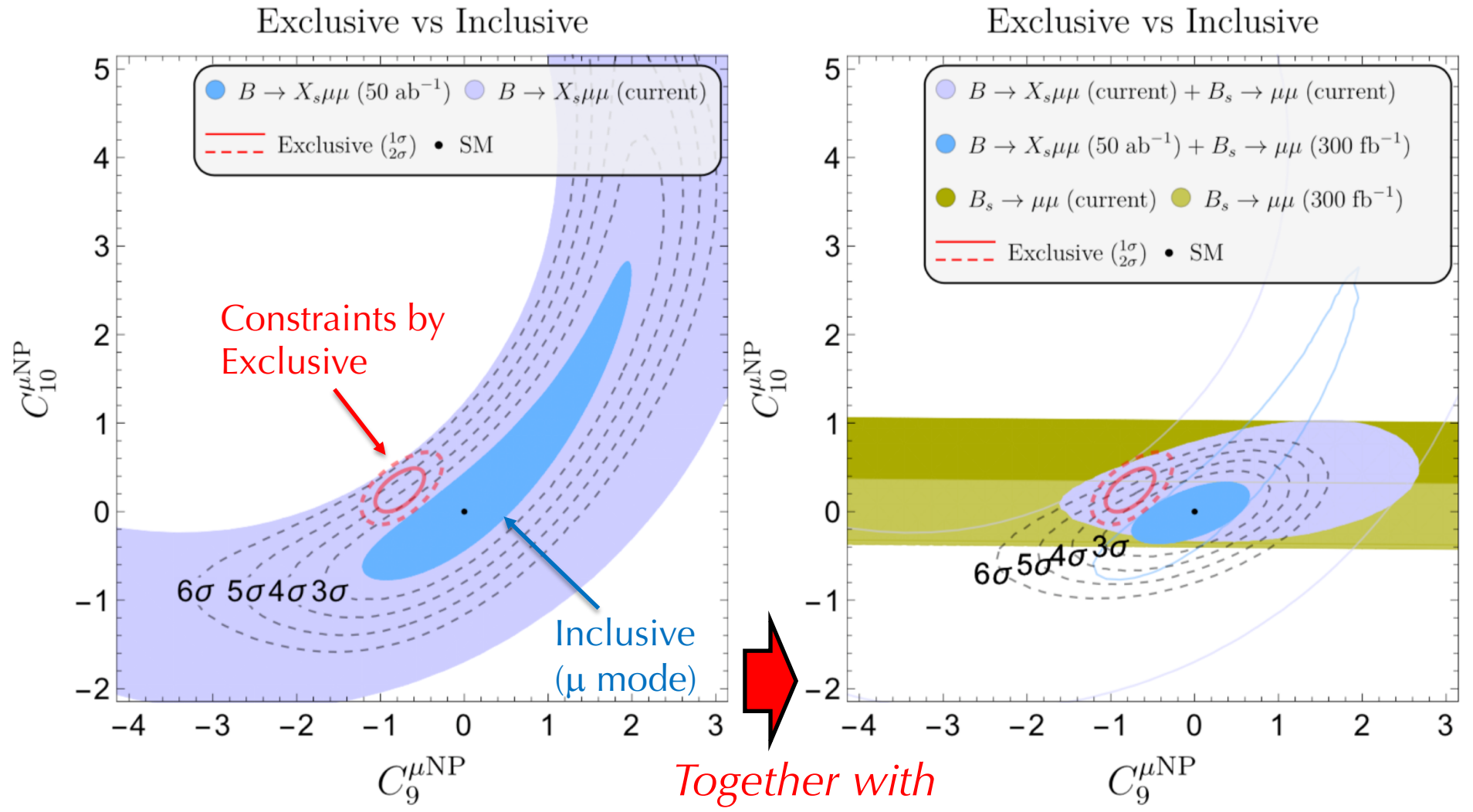


arXiv:2103.12738

Neural network output for R_K @Belle

- Modified Neural Net output; $\mathcal{O}' = \log\left[\frac{\mathcal{O}-\mathcal{O}_{min}}{\mathcal{O}_{max}-\mathcal{O}}\right]$
- Input parameters:
  - LR constructed from modified Fox-Wolfram moments
  - θ_B between the B flight direction and the z axis at CMS
  - θ_T between the Thrust axes
  - Flavor tag information
  - Confidence level of vertex fitting
  - The separation in z between signal and the other B′z
  - The separation between two leptons along z
  - Sum of ECL energy in signal side
  - CLEO cone thrust

$B \to X_s \ell\ell$ @Belle II

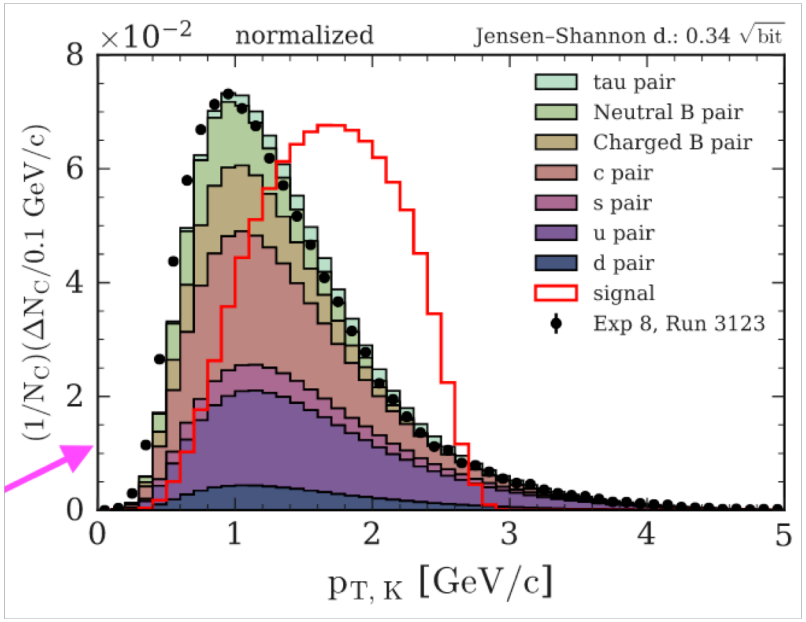


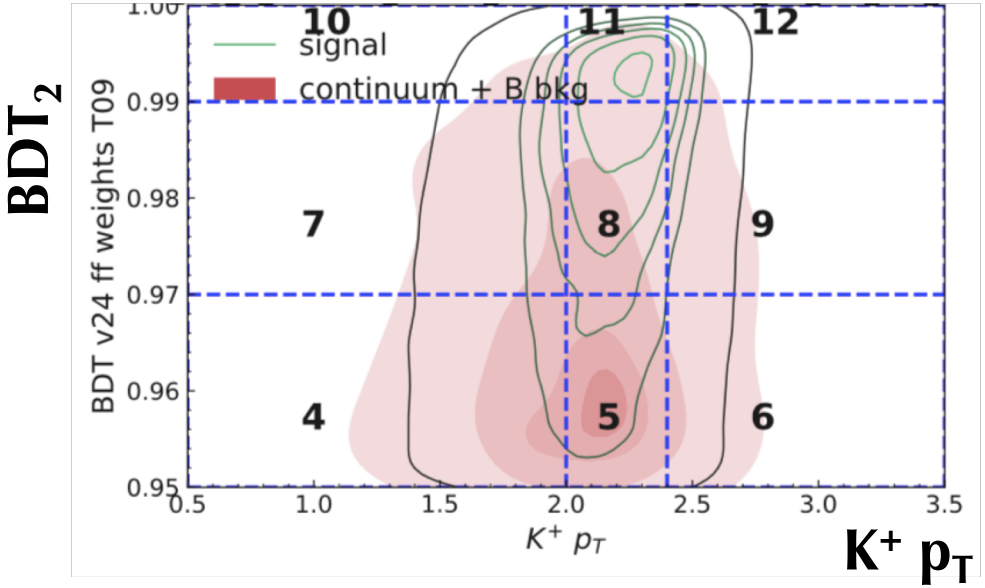
Together with $B_s \to \mu\mu$

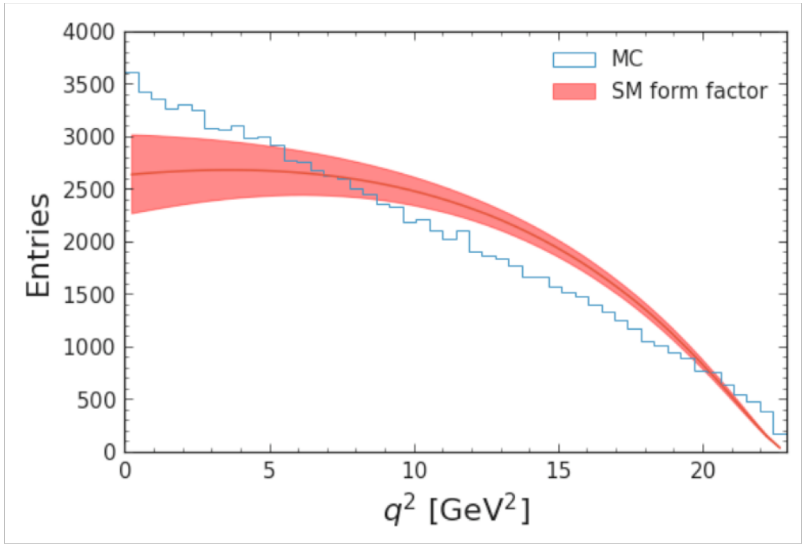
10.1007/JHEP10(2020)088

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

- Select the highest p_T kaon.
- Minimize the BG with event topology, missing energy and vertex separation.
- $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ ignoring dimuon is used to validate the method.
- Signal eff. ~ 3-4%
- Fit is performed in pT x BDT_2 with pyhf.
- Sensitivity depends on q^2;
  - ~10% eff. in q^2~0
  - little sensitive q^2>15 GeV^2

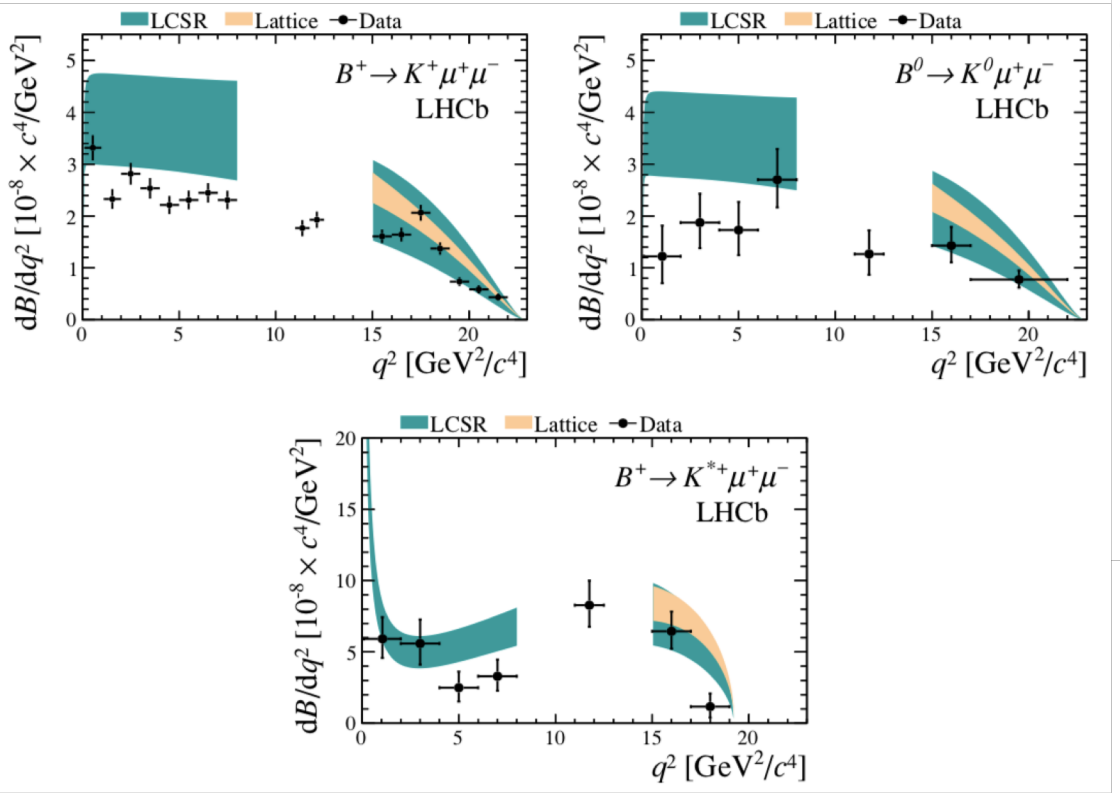






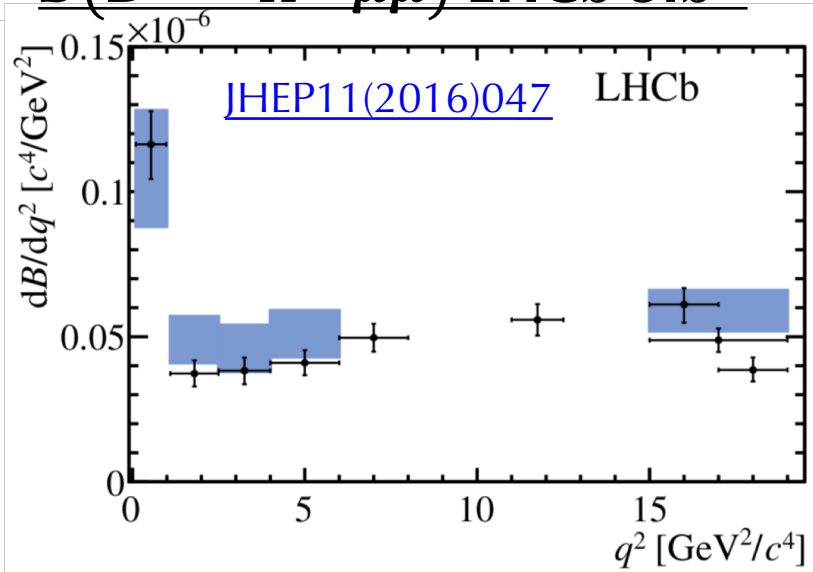
$\mathcal{B}(b \to s\mu\mu)$

$\mathcal{B}(B^+ \to K^+\mu\mu)$ LHCb 3fb^{-1}

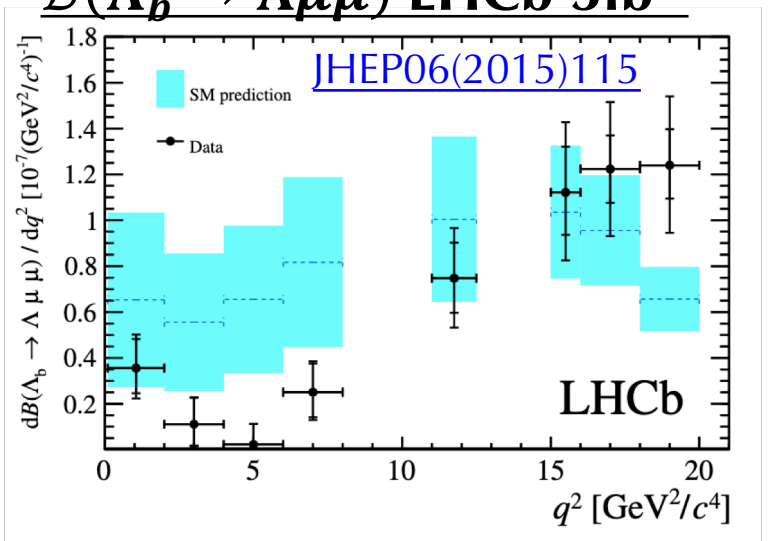


JHEP06(2014)133

$\mathcal{B}(B^0 \to K^{*0}\mu\mu)$ LHCb 3fb^{-1}



$\mathcal{B}(\Lambda_b \to \Lambda\mu\mu)$ LHCb 3fb^{-1}

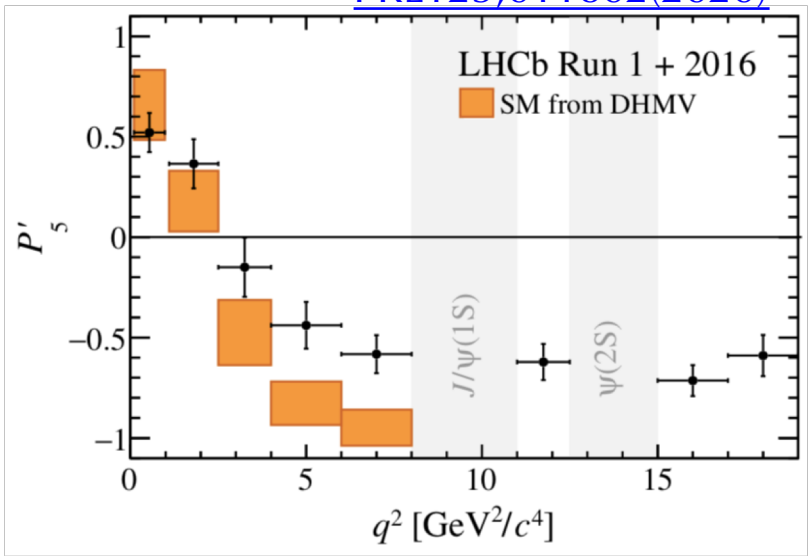


Angular analyses with $B^0 \to K^{*0}\ell^+\ell^-$

- Complementary observables with BF.
  - P_i' is defined to be free from form-factor uncertainty.
  - Non-zero $Q_i \equiv P_i^{\mu} - P_i^{e}$ would suggest NP (JHEP10,075(2016)).
- Consistency with SM:
  - **LHCb P'_5 ($K^{*0}\mu\mu$)**
    2.5σ in $q^2 \in (4.0,6.0) GeV^2/c^4$
    2.9σ in $q^2 \in (6.0,8.0) GeV^2/c^4$
  - **Belle P'_5 ($K^{*+}\ell\ell$)**
    2.6σ in $q^2 \in (4.0,8.0) GeV^2/c^4$, $\ell = \mu$

P'_5 ($K^{*0}\mu\mu$) at LHCb 4.7fb^{-1}

PRL125,011802(2020)



P'_5 and Q_5 ($K^*\ell\ell$) at Belle PRL118,111801(2017)