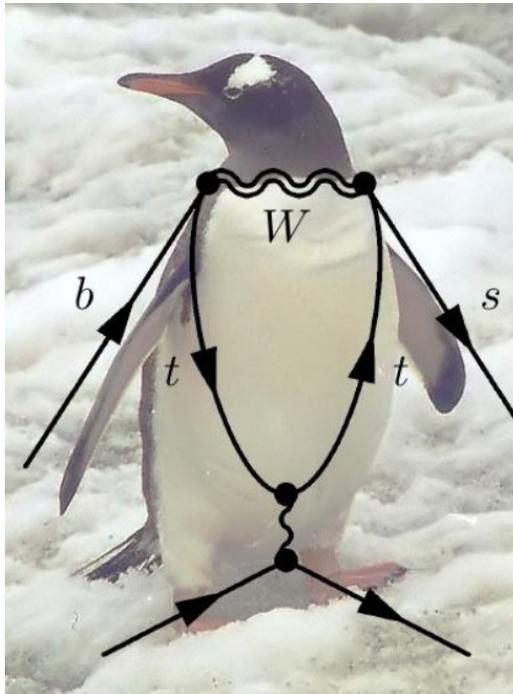


# Highlights on New Physics Searches in Heavy Flavor

## Decays



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2026/02/01



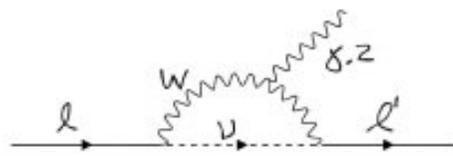
# Outline

- Introduction on (very) rare heavy hadron decays
- A heavily biased selection of recent results on
  - Rare B decays ( $b \rightarrow d\gamma$ ,  $b \rightarrow s\ell^+\ell^-$ ,  $b \rightarrow s\ell^+\ell'^-$ ,  $b \rightarrow sv\nu$ )
  - Rare charm decays into a pair of leptons
- Prospects & summary

# Rare decays and very rare decays

- Rare decays are processes mediated by flavor-changing neutral currents (FCNC)
- Very rare decays involve other highly suppressed processes that are usually out of reach experimentally

## NEUTRINO OSCILLATION



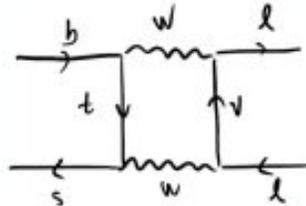
LFV

$\tau \rightarrow lll$   
 $\propto (10^{-55})$

$b \rightarrow sll'$   
 $\propto (10^{-50})$

$D^0 \rightarrow \mu\mu$   
 $O(10^{-13})$

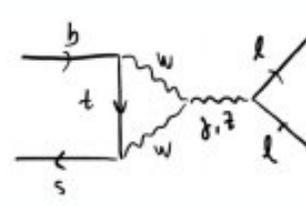
## LOOP-LEVEL



Helicity suppressed

$B_s \rightarrow \mu\mu$   
 $\propto (10^{-9})$

$\Sigma \rightarrow p\mu\mu$   
 $\propto (10^{-8})$



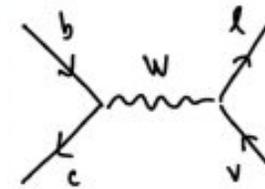
FCNC

$b \rightarrow s\tau\tau$   
 $\propto (10^{-7})$

$b \rightarrow sll$   
 $\propto (10^{-6})$

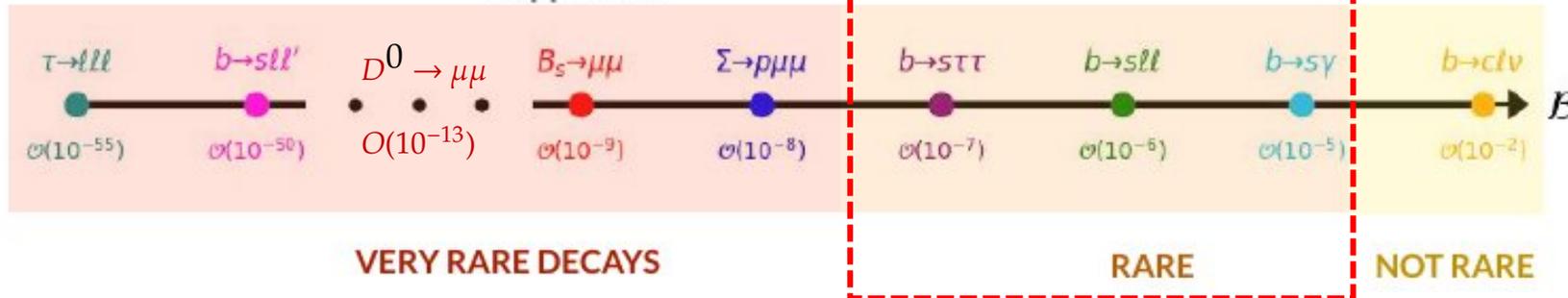
$b \rightarrow s\gamma$   
 $\propto (10^{-5})$

## TREE-LEVEL



FCCC

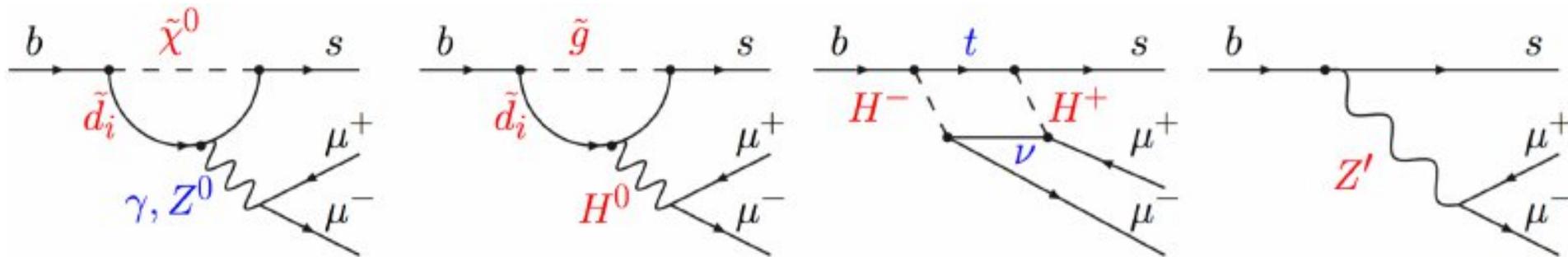
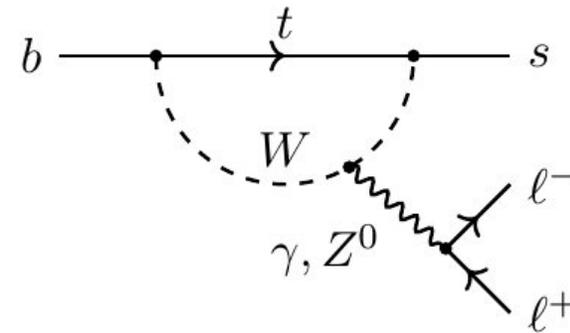
$b \rightarrow cl\nu$   
 $\propto (10^{-2})$



# Rare decays as a probe for New Physics

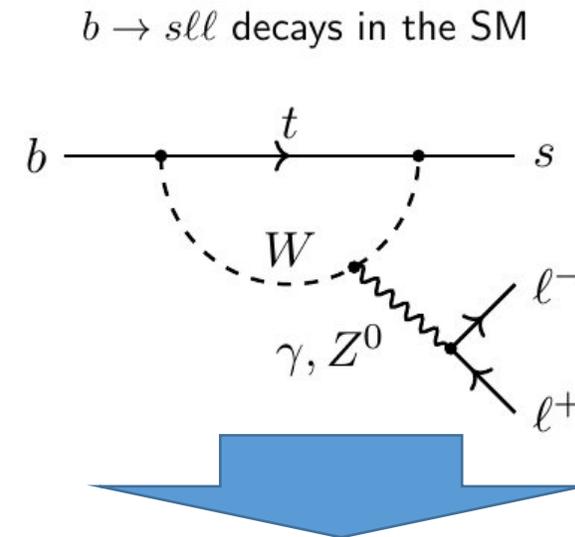
- FCNC processes suppressed in SM
- New physics particles with energy scale up to  $O(100)$  TeV could manifest in the loops

$b \rightarrow sll$  decays in the SM

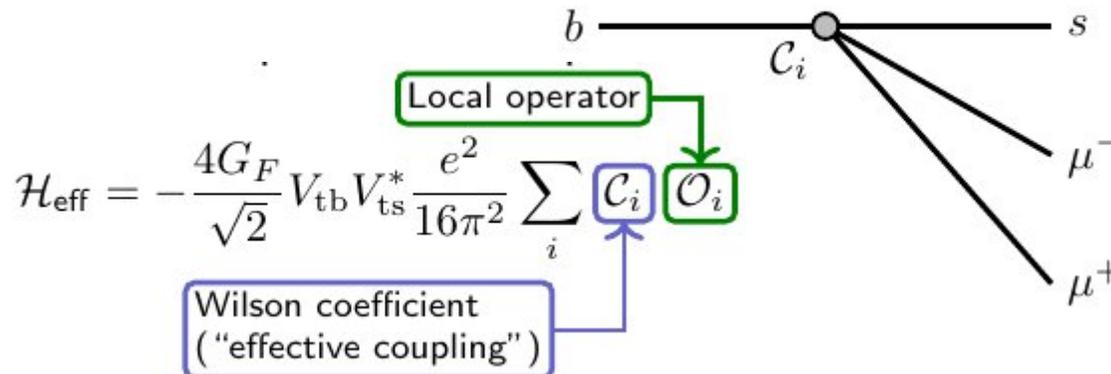


# Rare decays as a probe for New Physics

- FCNC processes suppressed in SM
- New physics particles with energy scale up to  $O(100)$  TeV could manifest in the loops
- This could cause deviation of Wilson coefficients from SM values



Effective description



Wilson coefficient	Operator
$\gamma$ -penguin <sup>1</sup>	$C_7^{(l)} \frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$C_9^{(l)} \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma^\mu l)$
	$C_{10}^{(l)} \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma^\mu \gamma_5 l)$
scalar	$C_S^{(l)} \frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{l} l)$
pseudoscalar	$C_P^{(l)} \frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{l} \gamma_5 l)$

$b \rightarrow s\gamma$   
 $b \rightarrow sll$   
 $B_s^0 \rightarrow \mu^+ \mu^-$

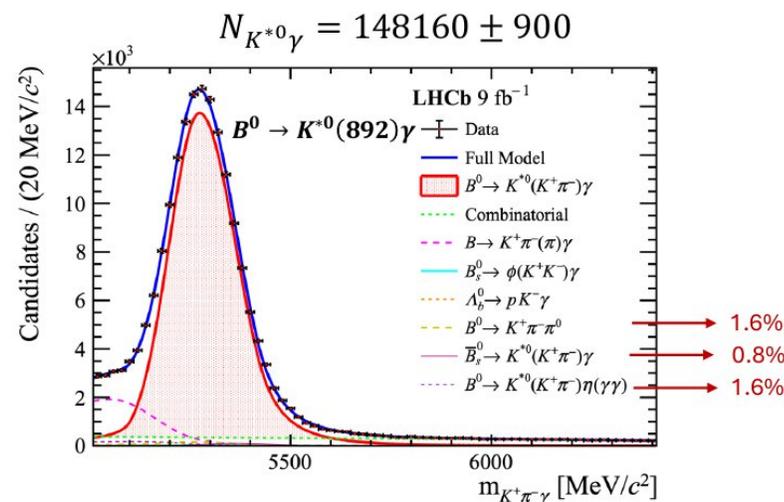
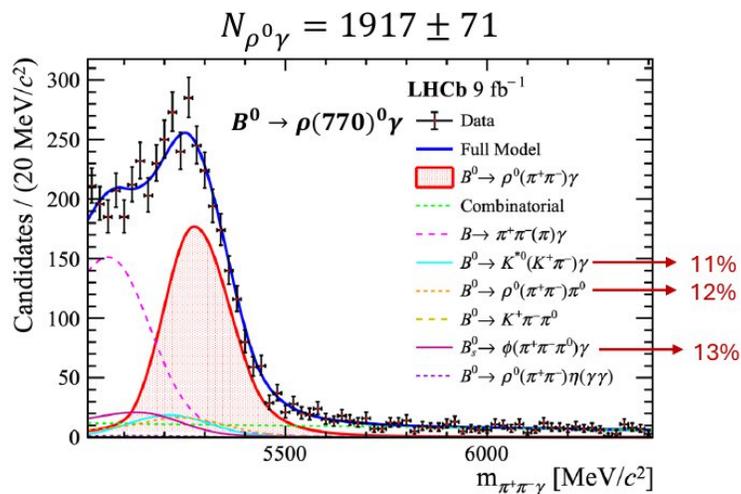
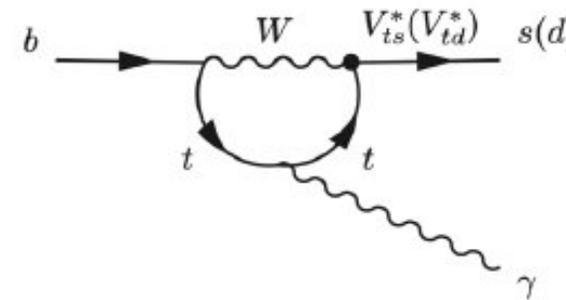
# Radiative $B^0 \rightarrow \rho^0(770)\gamma$ decays

- Using full  $9 \text{ fb}^{-1}$  Runs 1-2 data

- Normalization channel  $B^0 \rightarrow K^{*0}\gamma$

- Offering independent & direct constraint on  $|V_{td}/V_{ts}|$

$$\frac{\mathcal{B}(B^0 \rightarrow \rho^0(\pi^+\pi^-)\gamma)}{\mathcal{B}(B^0 \rightarrow K^{*0}(K^+\pi^-)\gamma)} \propto |V_{td}/V_{ts}|^2$$



$$\frac{\mathcal{B}(B^0 \rightarrow \rho(770)^0\gamma)}{\mathcal{B}(B^0 \rightarrow K^*(892)^0\gamma)} = 0.0189 \pm 0.0007 \pm 0.0005,$$

(stat.) (sys.)

$$\mathcal{B}(B^0 \rightarrow \rho^0\gamma) = (7.9 \pm 0.3 \pm 0.2 \pm 0.2) \times 10^{-7}$$

(stat.) (sys.) (BF norm.)

Most precise measurement to date

# First evidence of $B_s^0 \rightarrow K^- \pi^+ \gamma$

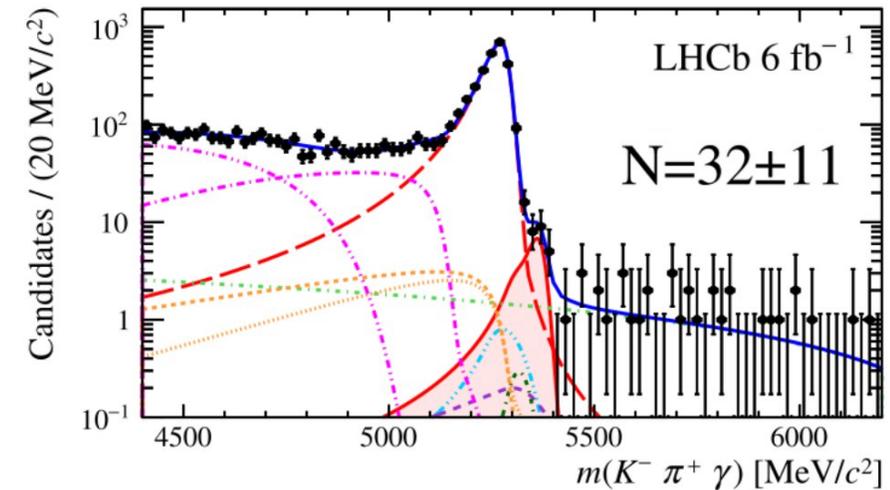
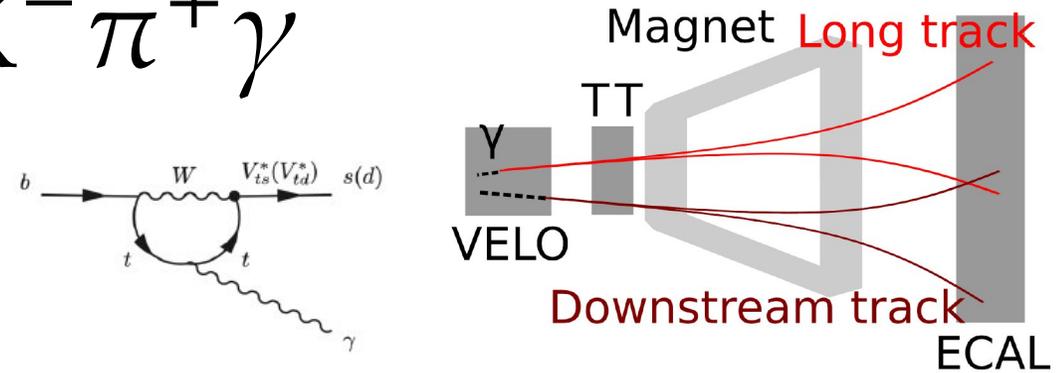
- Using full  $9 \text{ fb}^{-1}$  Runs 1-2 data
- Normalization channel  $B^0 \rightarrow K^{*0} \gamma$
- Using photons converting to  $e^+ e^-$ 
  - Long & downstream tracks
- Observing  $38 \pm 18$  signals with  $3.5\sigma$  significance
- BF results in good agreement with SM predictions:

$$\frac{\mathcal{B}(B_s^0 \rightarrow K^- \pi^+ \gamma)}{\mathcal{B}(\bar{B}^0 \rightarrow K^- \pi^+ \gamma)} = (3.7 \pm 1.2 \pm 0.4) \times 10^{-2} \quad (\text{stat., sys.})$$

for  $796 < m(K^- \pi^+) < 996 \text{ MeV}/c^2$

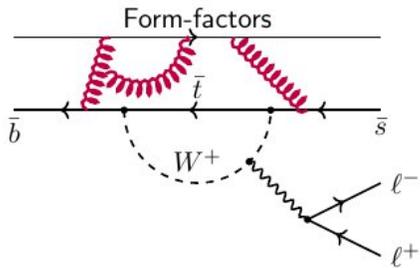
$$\frac{\mathcal{B}(B_s^0 \rightarrow K^- \pi^+ \gamma)}{\mathcal{B}(\bar{B}^0 \rightarrow K^- \pi^+ \gamma)} = (0.2 \pm 2.7 \pm 1.3) \times 10^{-2}$$

for  $996 < m(K^- \pi^+) < 1800 \text{ MeV}/c^2$



**Run2 Downstream low- $m(K\pi)$**   
 Better resolution due to less bremsstrahlung

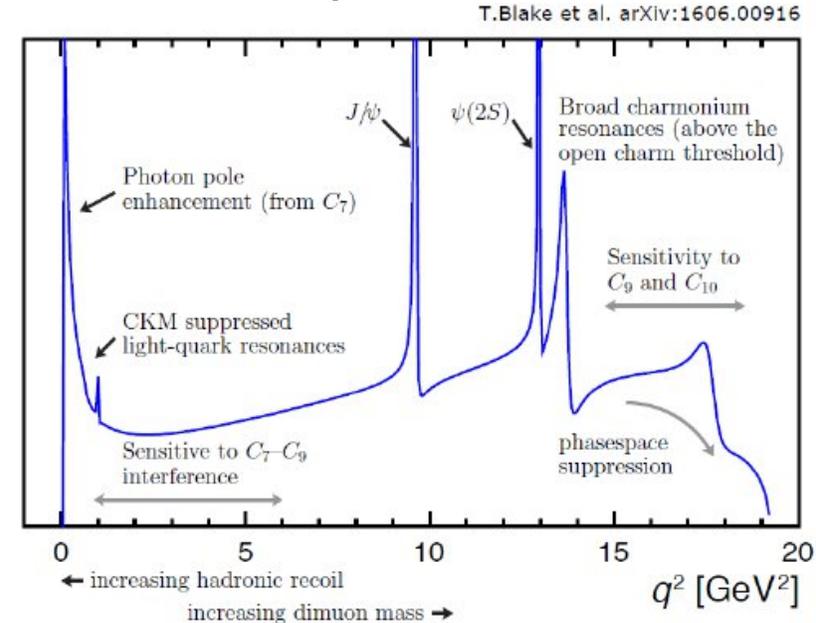
# Observables in FCNC $b \rightarrow s \ell \ell$ decays



Physics depends on  $q^2 = m_{\ell\ell}^2$  :

- Resonances (e.g.  $J/\psi$ ,  $\phi$ )
- Photon pole at low  $q^2$ :  $C_7$
- Vector or axial vector current:  $C_{9,10}$

$d\Gamma/dq^2$



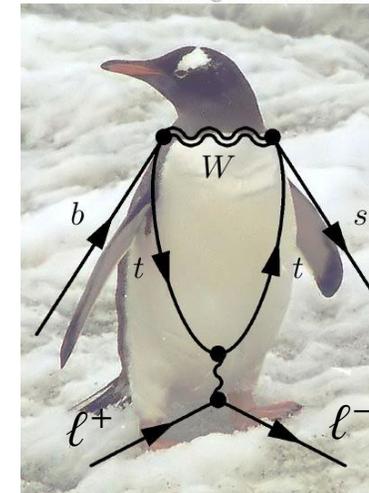
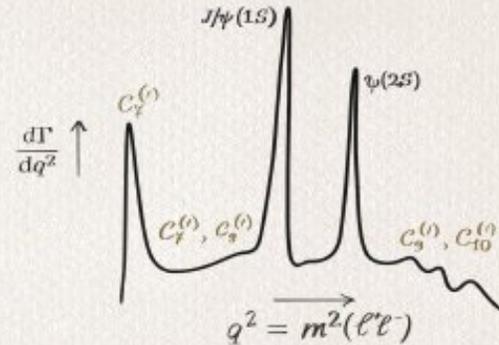
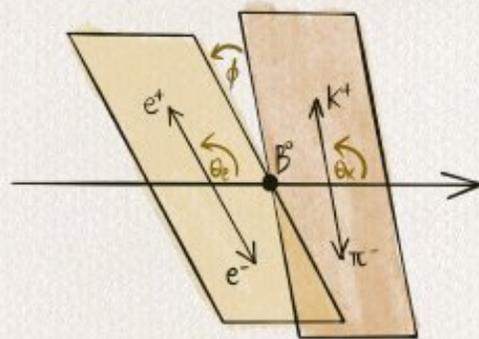
Theoretical uncertainties

Ratio of BFs  
Test of LFU

Angular Analyses

Differential  
branching fractions

$$R_H = \frac{\mathcal{B}(b \rightarrow s \mu \mu)}{\mathcal{B}(b \rightarrow s e e)}$$

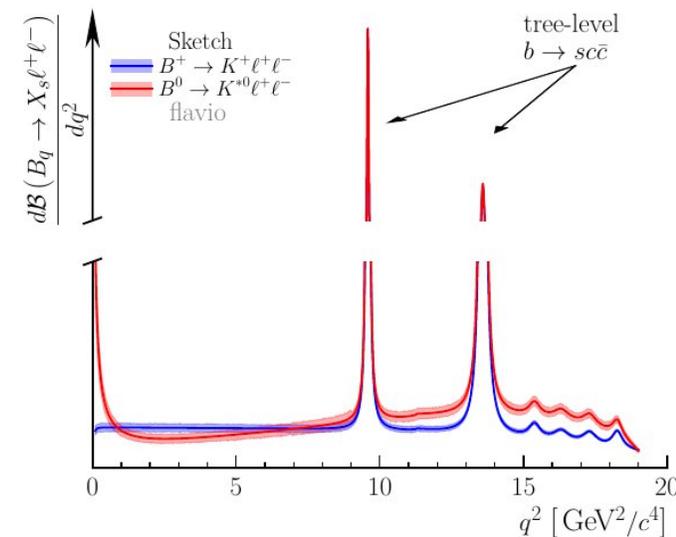
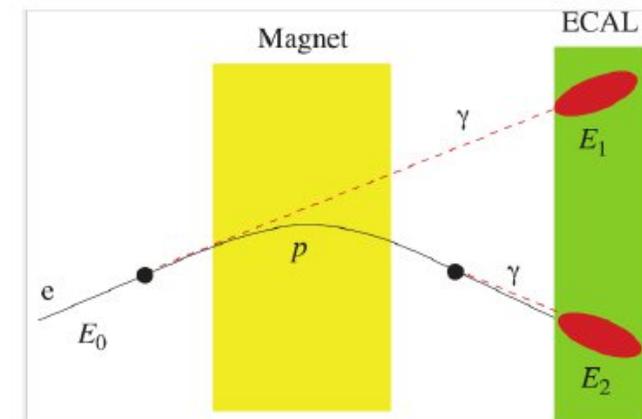
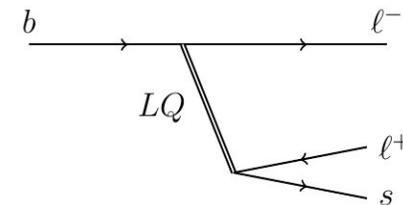


# R(K<sup>(\*)</sup>) measurements @ LHCb

- Electrons & muons behave quite differently in the LHCb detector
- Lower efficiencies & worse resolution (energy loss) for electrons
- Double-ratio of branching fractions:

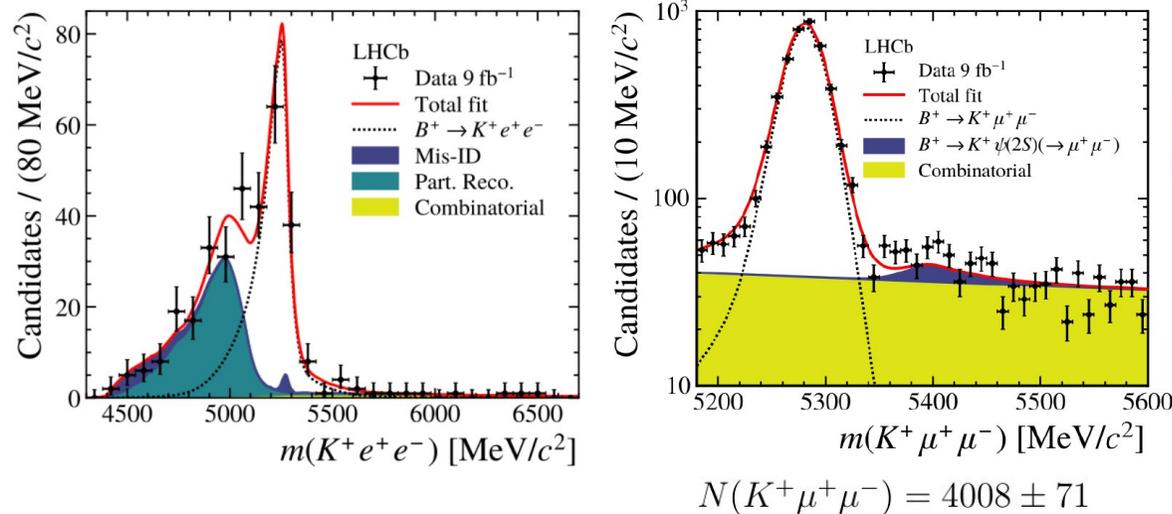
$$R_X = \frac{\mathcal{B}(B_q \rightarrow X_s \mu^+ \mu^-)}{\mathcal{B}(B_q \rightarrow X_s J/\psi(\mu^+ \mu^-))} \cdot \frac{\mathcal{B}(B_q \rightarrow X_s J/\psi(e^+ e^-))}{\mathcal{B}(B_q \rightarrow X_s e^+ e^-)}$$

- Most of systematic uncertainties cancel to 1st order
- LFU in  $J/\psi \rightarrow l^+ l^-$  well established at ‰ level [BESIII, PRD 88, 032007 (2013)]
- Validated in  $\psi(2S)$  mode



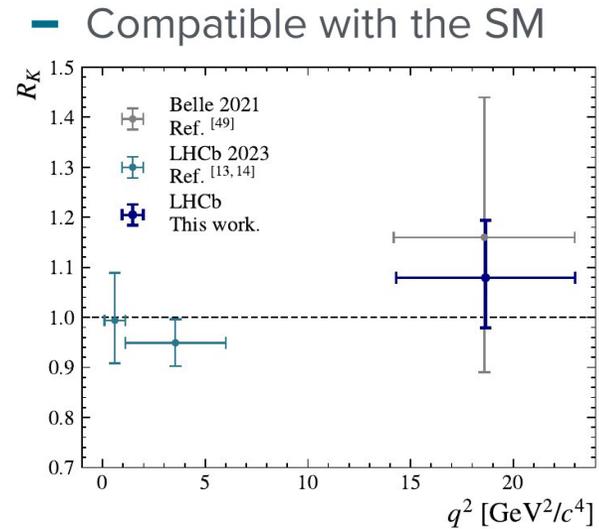
# R(K) result at high $q^2$

- First LHCb result at high  $q^2$  region above  $\psi(2S)$  ( $q^2 > 14.3 \text{ GeV}^2$ )
- Full Runs1-2 9 fb<sup>-1</sup> analysis



Most precise to date:

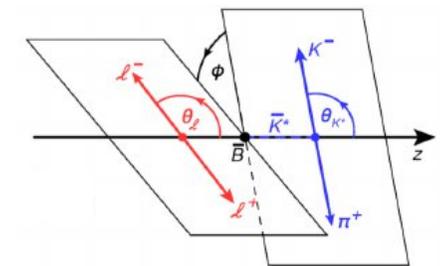
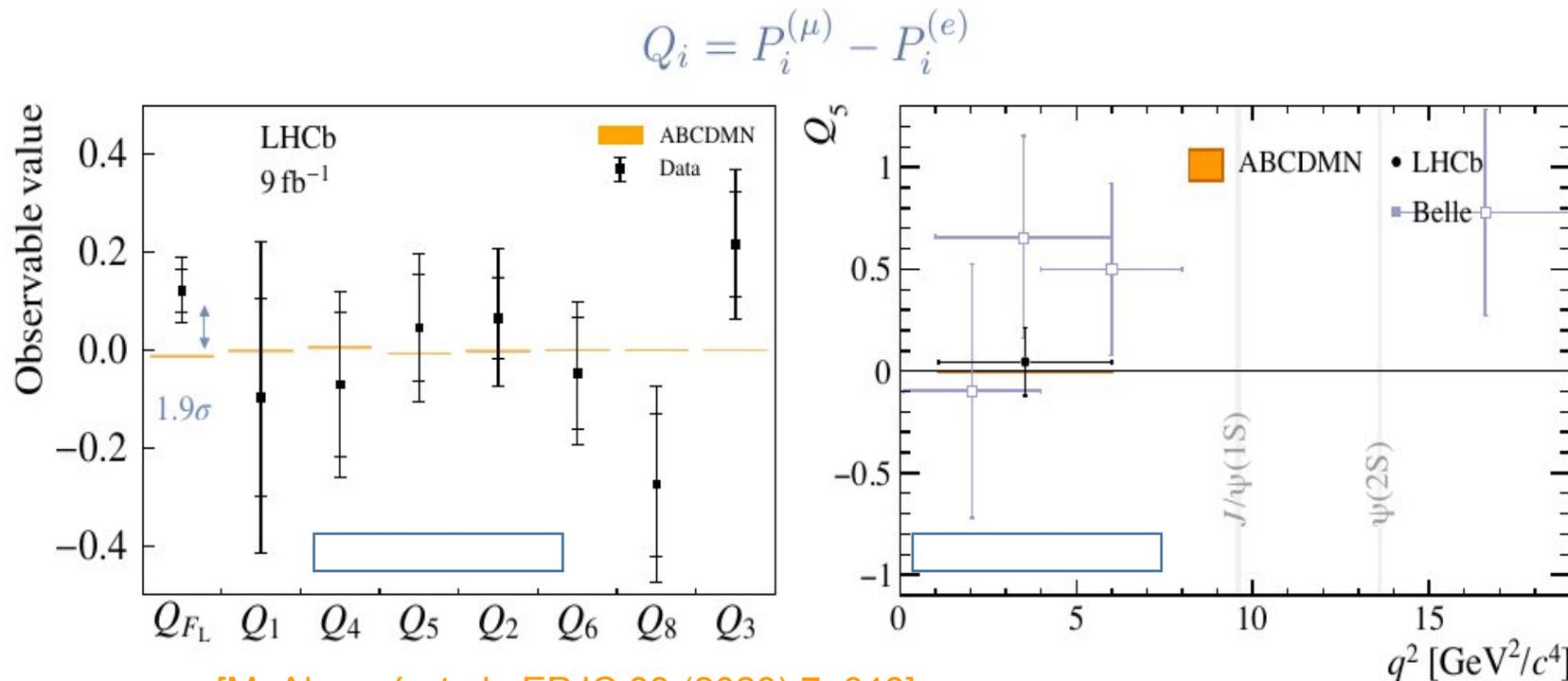
$R_K(q^2 > 14.3 \text{ GeV}^2/c^4) = 1.08^{+0.11}_{-0.09} {}^{+0.04}_{-0.04}$



$$R_K = \frac{N(K^+\mu^+\mu^-)}{N(K^+e^+e^-)} \cdot \frac{\epsilon(K^+e^+e^-)}{\epsilon(K^+\mu^+\mu^-)} \cdot \frac{1}{r_{J/\psi}}$$

# LFU in angular analysis of $B \rightarrow K^{*0} e^+ e^-$

- First angular analysis at central  $q^2$  region
- Full Runs1-2  $9 \text{ fb}^{-1}$  analysis with 5D unbinned weighted fit
- LFU quantities derived by comparing  $e^+ e^-$  to  $\mu^+ \mu^-$  results in [PRL 132 (2024) 131801]

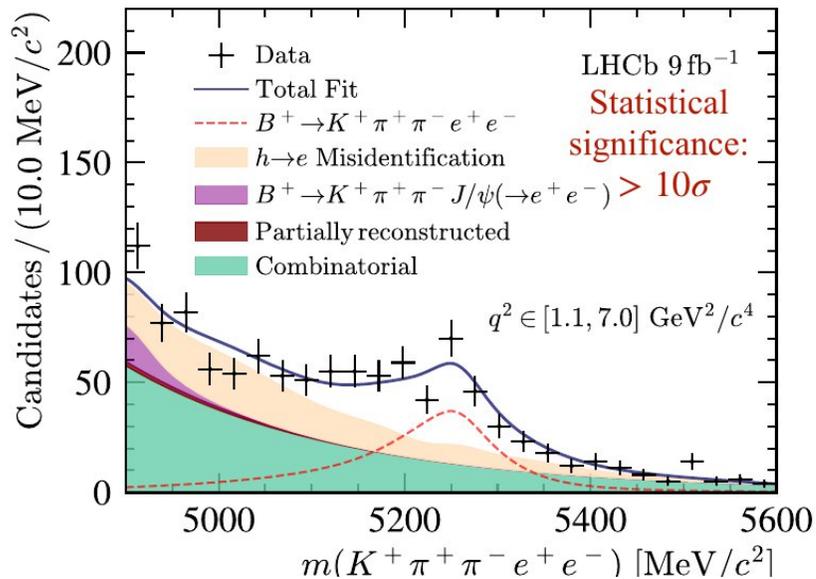


Results are all consistent with LFU conservation hypothesis

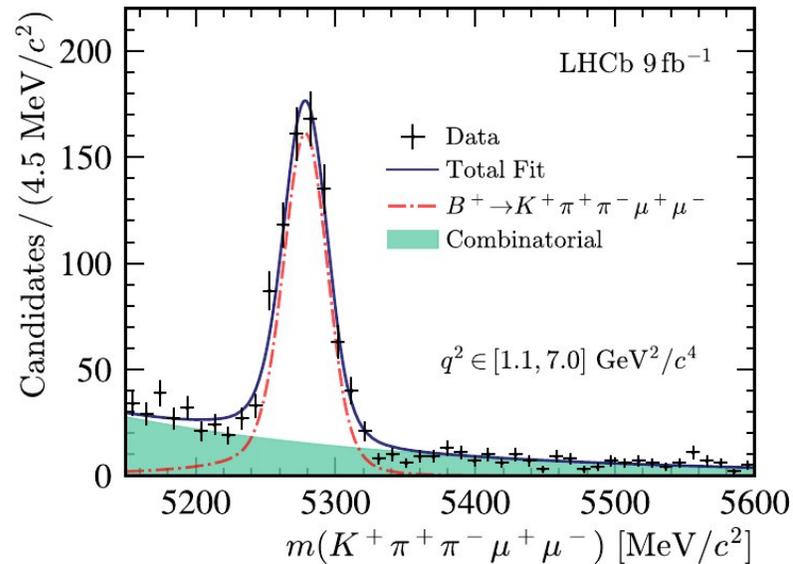
# R(Kππ): LFU in $B \rightarrow K\pi\pi l^+ l^-$

- First LFU test in this channel, inclusive  $K\pi\pi$  system
- In central  $q^2$  region:  $1.0 < q^2 < 7.0 \text{ GeV}^2$
- First observation of  $B^+ \rightarrow K^+ \pi^+ \pi^- e^+ e^-$
- Cross-checks:  $r_{J/\psi} = 1.033 \pm 0.017, R_{\psi(2S)} = 1.040 \pm 0.030$

$$R_{K\pi\pi}^{-1} \equiv \frac{\frac{\mathcal{N}}{\epsilon}(B^+ \rightarrow K^+ \pi^+ \pi^- e^+ e^-)}{\frac{\mathcal{N}}{\epsilon}[B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi (\rightarrow e^+ e^-)]} \bigg/ \frac{\frac{\mathcal{N}}{\epsilon}(B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-)}{\frac{\mathcal{N}}{\epsilon}[B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi (\rightarrow \mu^+ \mu^-)]}$$



$$\mathcal{N}(B^+ \rightarrow K^+ \pi^+ \pi^- e^+ e^-) = 264 \pm 21$$



$$\mathcal{N}(B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-) = 731 \pm 31$$

$$R_{K\pi\pi}^{-1} = 1.31_{-0.17}^{+0.18} \text{ (stat)} \quad +0.12_{-0.09} \text{ (syst)}$$

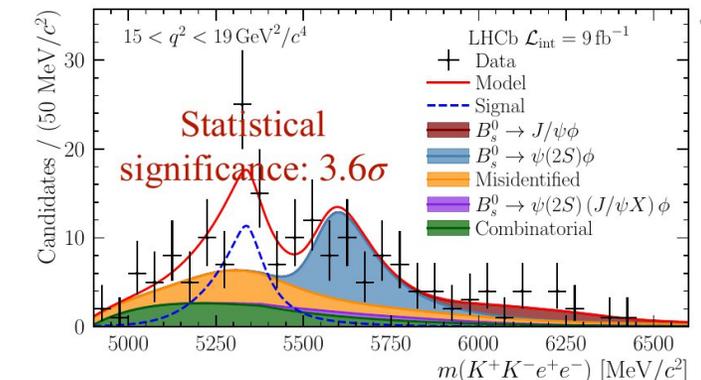
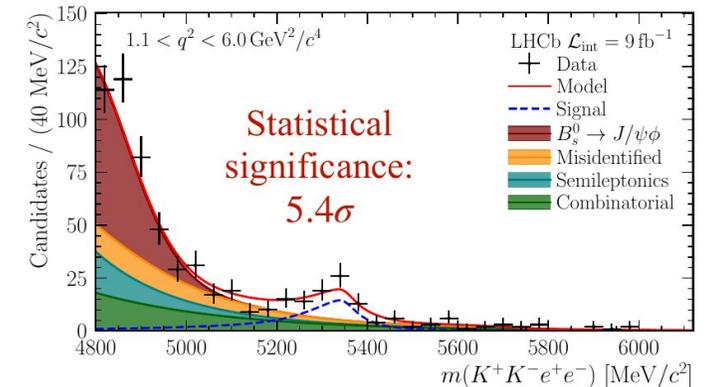
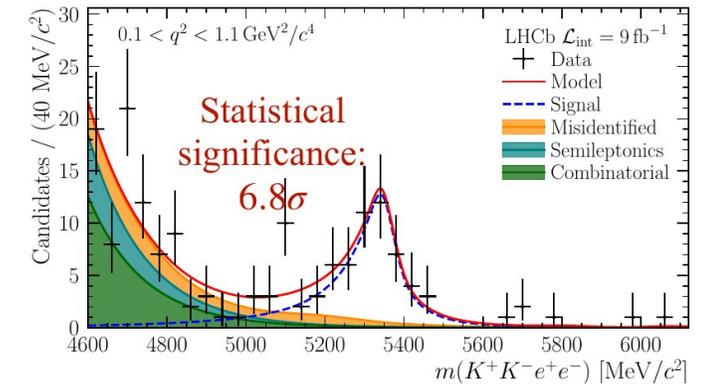
— Compatible with the SM

# $R(\phi)$ : LFU in $B_s^0 \rightarrow \phi l^+ l^-$

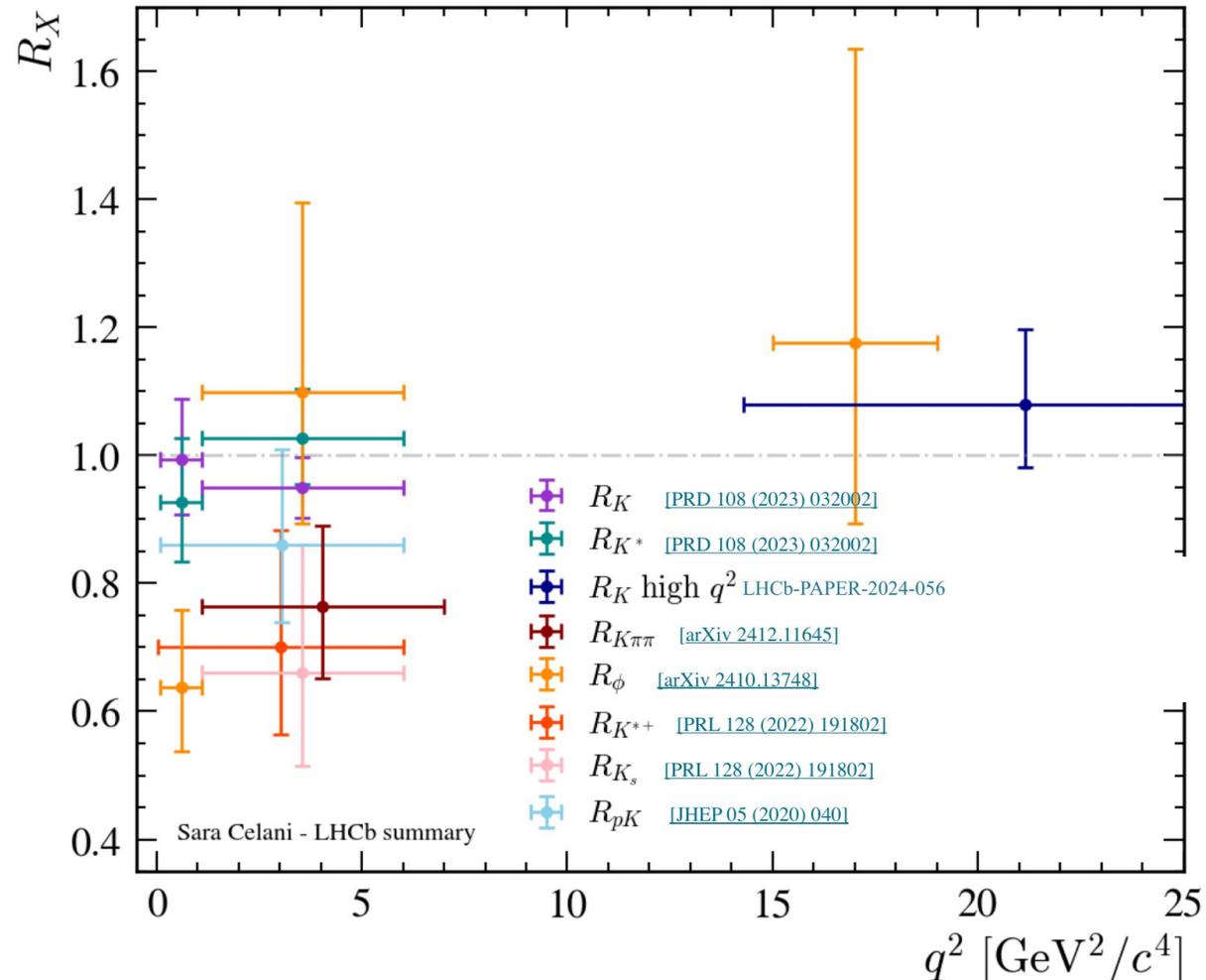
- First LFU test for  $B_s^0$  decays
- In three  $q^2$  regions:  $[0.1, 1.1]$ ,  $[1.1, 6.0]$ ,  $[15, 19]$   $\text{GeV}^2$
- Cross-checks:  $r_{J/\psi} = 0.997 \pm 0.013$ ,  $R_{\psi(2S)} = 1.010 \pm 0.026$
- Results in agreement with SM:

$q^2$ [ $\text{GeV}^2/c^4$ ]	$R_\phi^{-1}$
$0.1 < q^2 < 1.1$	$1.57^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85^{+0.24}_{-0.23} \pm 0.10$

$$R_\phi = \left( \frac{\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \phi)} \right) \bigg/ \left( \frac{\mathcal{B}(B_s^0 \rightarrow \phi e^+ e^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi(\rightarrow e^+ e^-) \phi)} \right)$$



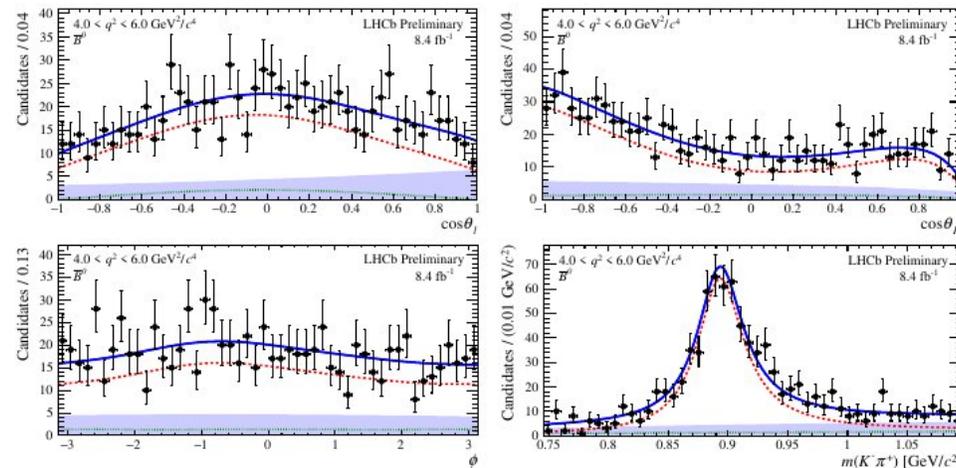
# Summary of LHCb FCNC LFU results



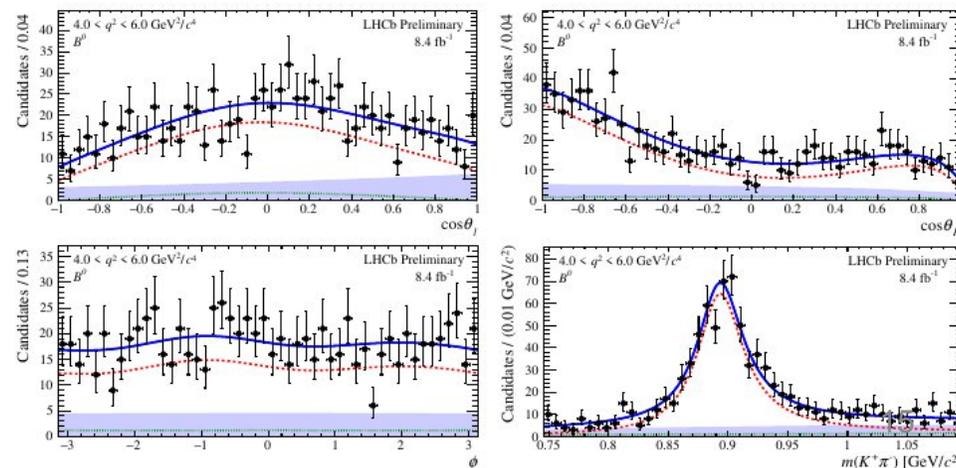
# Legacy Runs 1-2 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ measurement

- 5D (3 decay angles,  $m_B$ ,  $m_{K\pi}$ ) unbinned ML fit in bins of  $q^2$ 
  - Improved selection, more observables (CPV, dBF)
  - Finer  $q^2$  binning  $\sim 1 \text{ GeV}^2$
  - Lepton mass accounted for
  - Full suite of S-wave and P-/S-wave interference observables
  - 2x statistics:  $\sim 12\text{k}$  signals
  - Data split into  $B^0$  and  $\bar{B}^0$ , and fit simultaneously

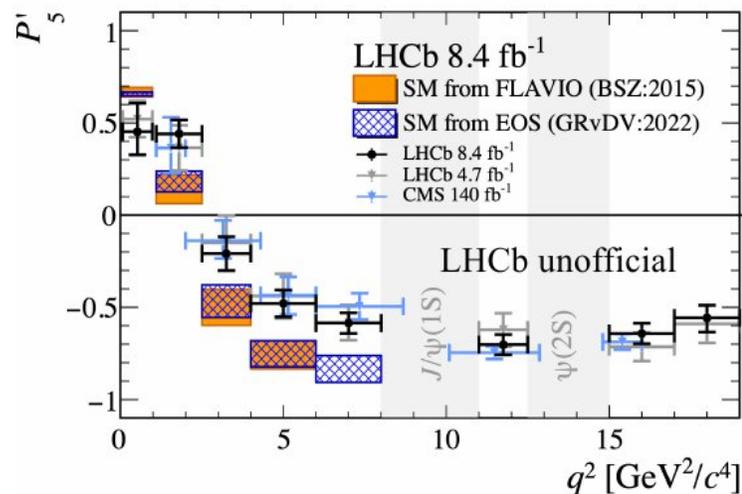
$\bar{B}^0$ :



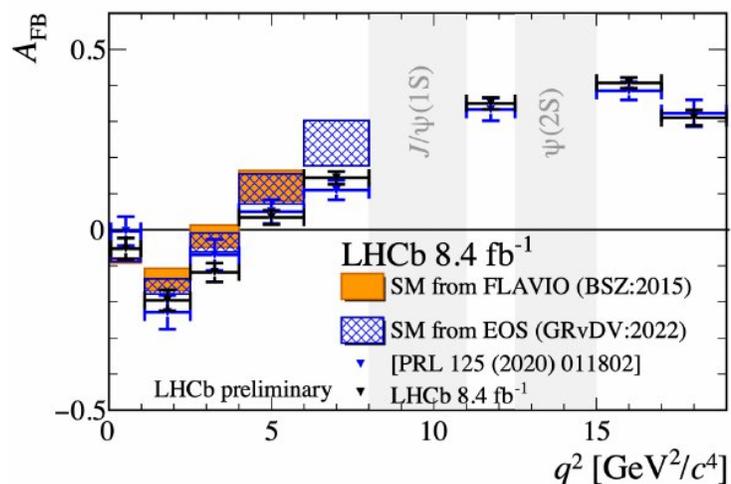
$B^0$ :



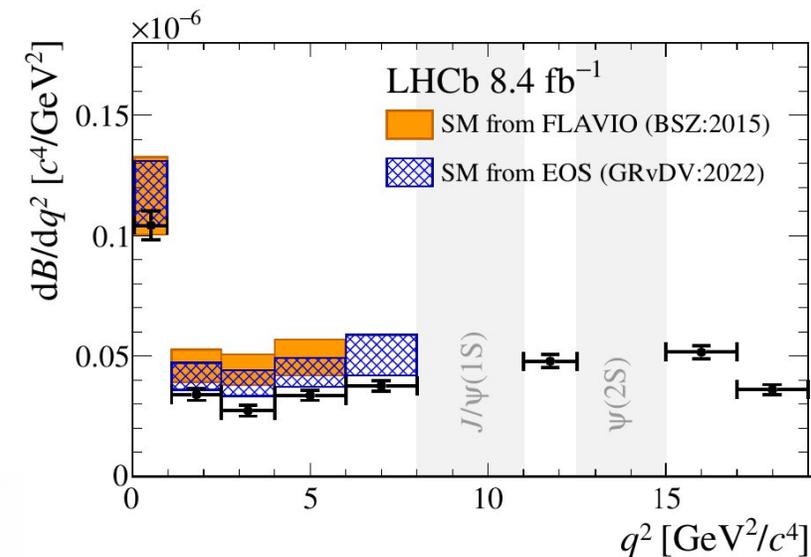
# Legacy Runs 1-2 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ measurement



- Results in  $P'_5$  excellent agreement with both CMS and previous LHCb
- Deviations of 2.6 and 2.7  $\sigma$  in 4-6 and 6-8 GeV<sup>2</sup> bins



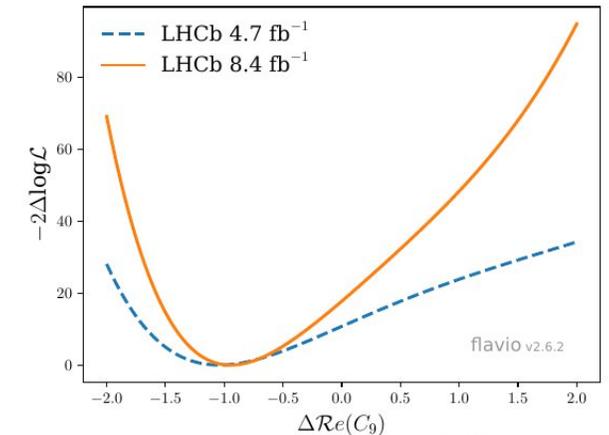
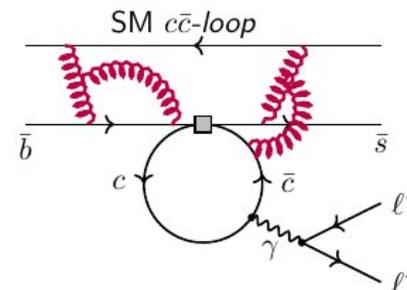
The forward-backward asymmetry,  $A_{FB}$ , also now shows marked disagreement with improved statistics



- The branching fraction is consistently below SM predictions

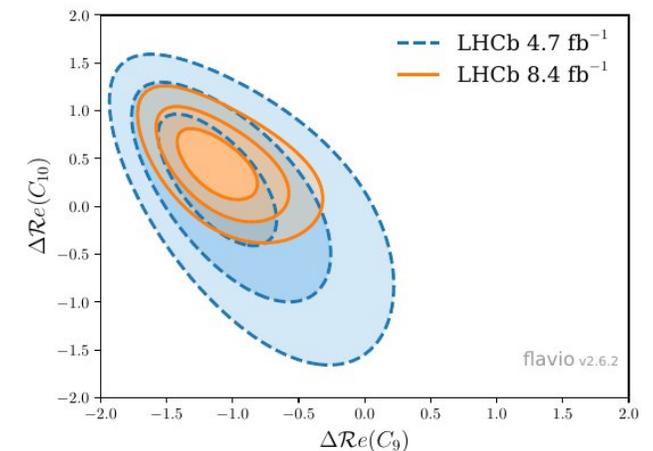
# Legacy Runs 1-2 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ measurement

- Interpretation in terms of Wilson coefficients, by combining angular observables and BFs up to  $8 \text{ GeV}^2$
- Alternative theory packages with different approaches on (non-local) FFs, with consistent results
- Tension most pronounced in  $\text{Re}(C_9)$ , with shifts consistent across  $q^2$  bins
- NP or underestimated hadronic (charm-loop) contributions?



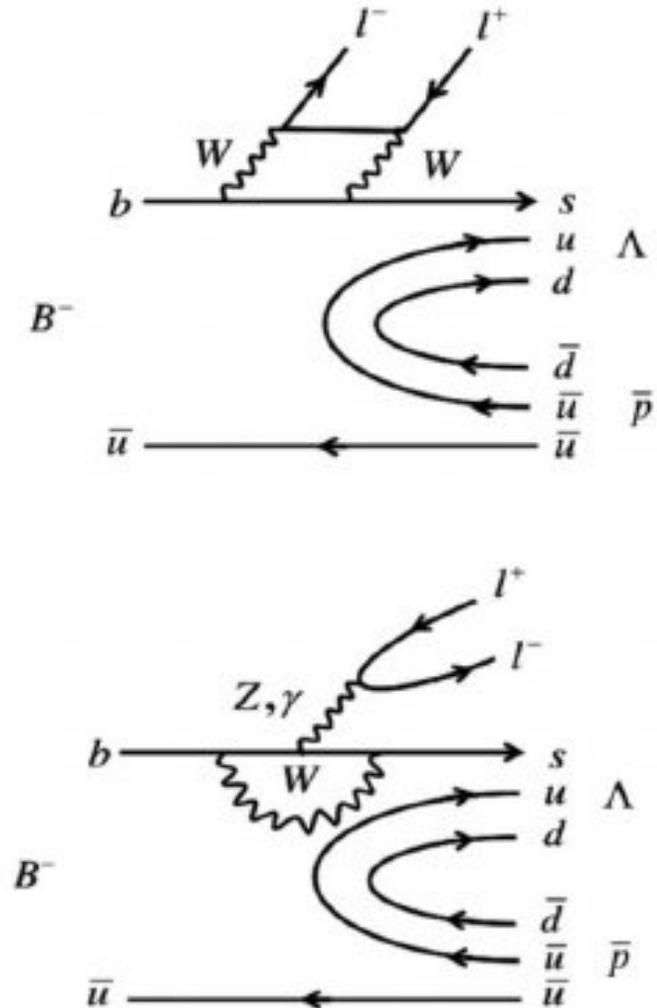
$$\Delta \text{Re} C_9 = -0.93^{+0.18}_{-0.16}$$

Significance  $4.1 \sigma$



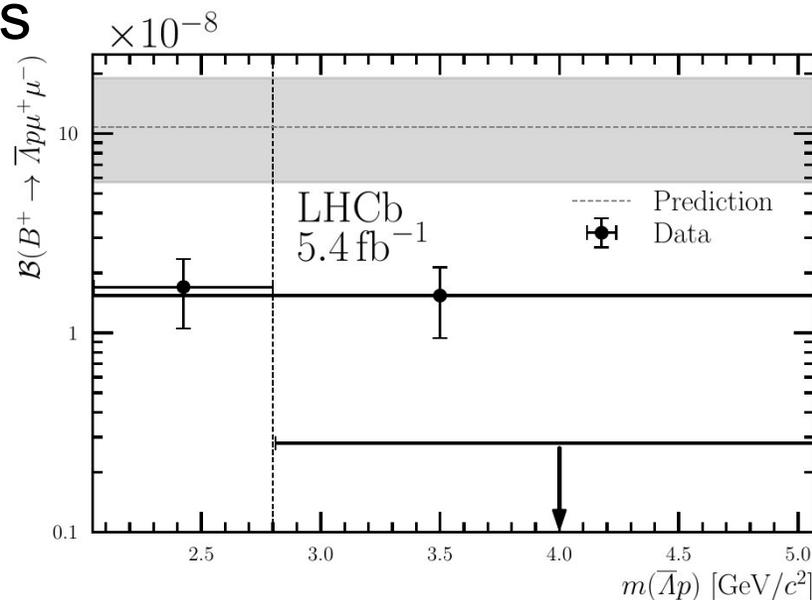
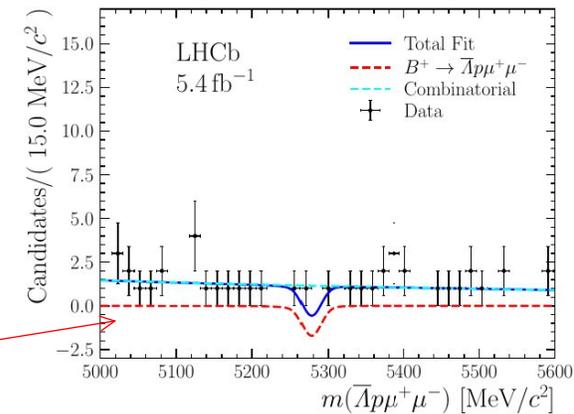
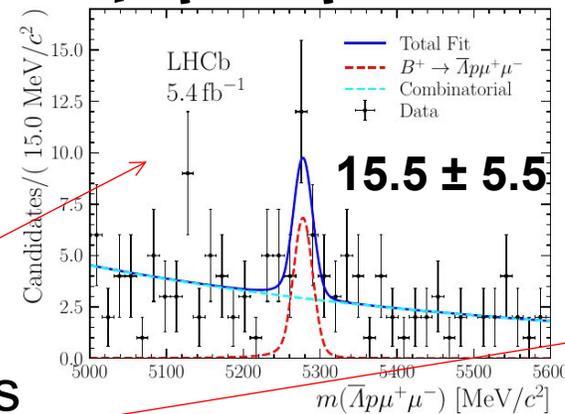
# First evidence of $B^+ \rightarrow \bar{\Lambda} p \mu^+ \mu^-$

- Mediated via  $b \rightarrow s \mu^+ \mu^-$ , baryonic final state less explored to mesonic counterparts
  - Phenomenology of hadronization
  - Rich dynamics in hadronic system
  - Clean access to exotic states such as [X\(2085\)](#)
- Threshold enhancement effects in  $\bar{\Lambda} p$  system observed in other multibody decays, e.g.  $B^+ \rightarrow \bar{\Lambda} p \pi^+ \pi^-$  [\[link\]](#) and  $B \rightarrow \bar{\Lambda} p K K$  [\[link\]](#)
- SM based BF prediction at  $\sim 1.08 \times 10^{-7}$  [\[link\]](#)
- Expecting significantly lower BF if FFs from a more recent paper [\[link\]](#) are used instead



# First evidence of $B^+ \rightarrow \bar{\Lambda} p \mu^+ \mu^-$

- Using  $5.4 \text{ fb}^{-1}$  Run2 data
- Normalization channel:  $B^+ \rightarrow J/\psi \bar{\Lambda} p$ 
  - Also used for signal shape calibration & correction for data/simulation differences
- Signal searched for in low & high  $m(\bar{\Lambda} p)$  regions



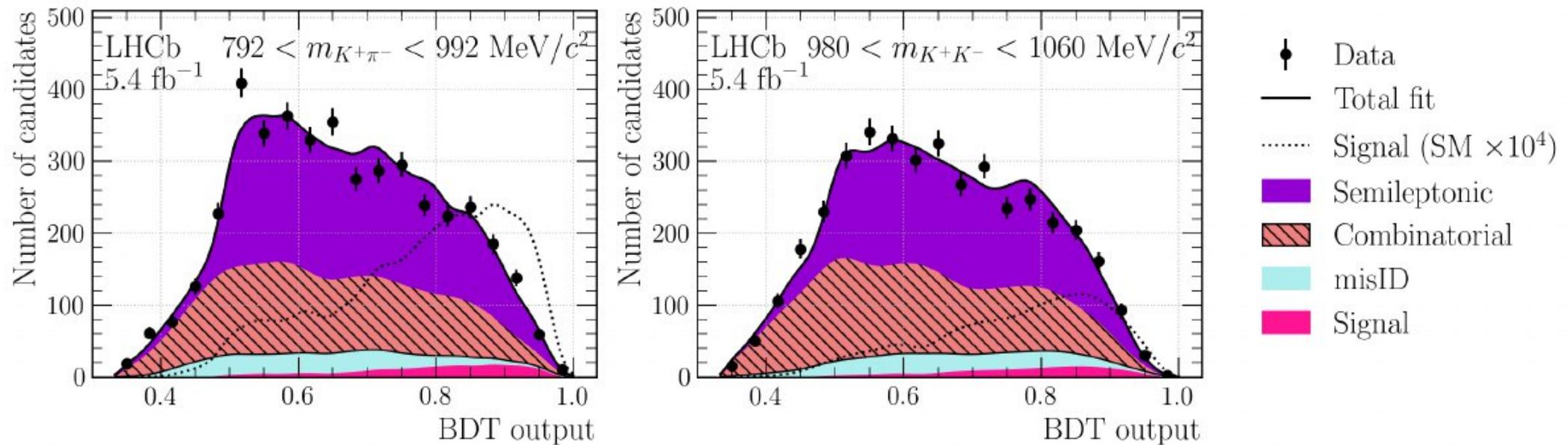
- Evidence for the decay found in the  $m(\bar{\Lambda} p) < 2.8 \text{ GeV}$  region with significance of  $3.5\sigma$
- The total branching fraction is measured:

$$\mathcal{B}(B^+ \rightarrow \bar{\Lambda} p \mu^+ \mu^-) = (1.54 \pm 0.65_{\text{stat}} \pm 0.18_{\text{sys}} \pm 0.13_{\text{ext}}) \times 10^{-8}$$

Work based on Run3 data has started

# Search for $B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-$ & $B_s^0 \rightarrow K^+ K^- \tau^+ \tau^-$

- Using Run2 5.4 fb<sup>-1</sup> data
- Reconstructing taus with muonic channel
- Decays are searched for in bins of dihadron masses



Searches in the lowest  $K\pi$  and  $KK$  bins

# Search for $B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-$ & $B_s^0 \rightarrow K^+ K^- \tau^+ \tau^-$

- Using Run2 5.4 fb<sup>-1</sup> data
- Reconstructing taus with muonic channel
- Decays are searched for in bins of dihadron masses
- No signal founds, upper limits are set:

$$\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \tau^-) < 2.8 \times 10^{-4} \quad (2.5 \times 10^{-4}) \text{ at 95\% (90\%) CL, } \text{One order of magnitude improvement than Belle!}$$

$$\mathcal{B}(B_s^0 \rightarrow \phi \tau^+ \tau^-) < 4.7 \times 10^{-4} \quad (4.1 \times 10^{-4}) \text{ at 95\% (90\%) CL. } \text{First search!}$$

Upper limit on the shift  $\Delta^2$  in the  $\mathcal{C}_{9(10)}^{\tau\tau}$  Wilson coefficient at 90% and 95% CL.

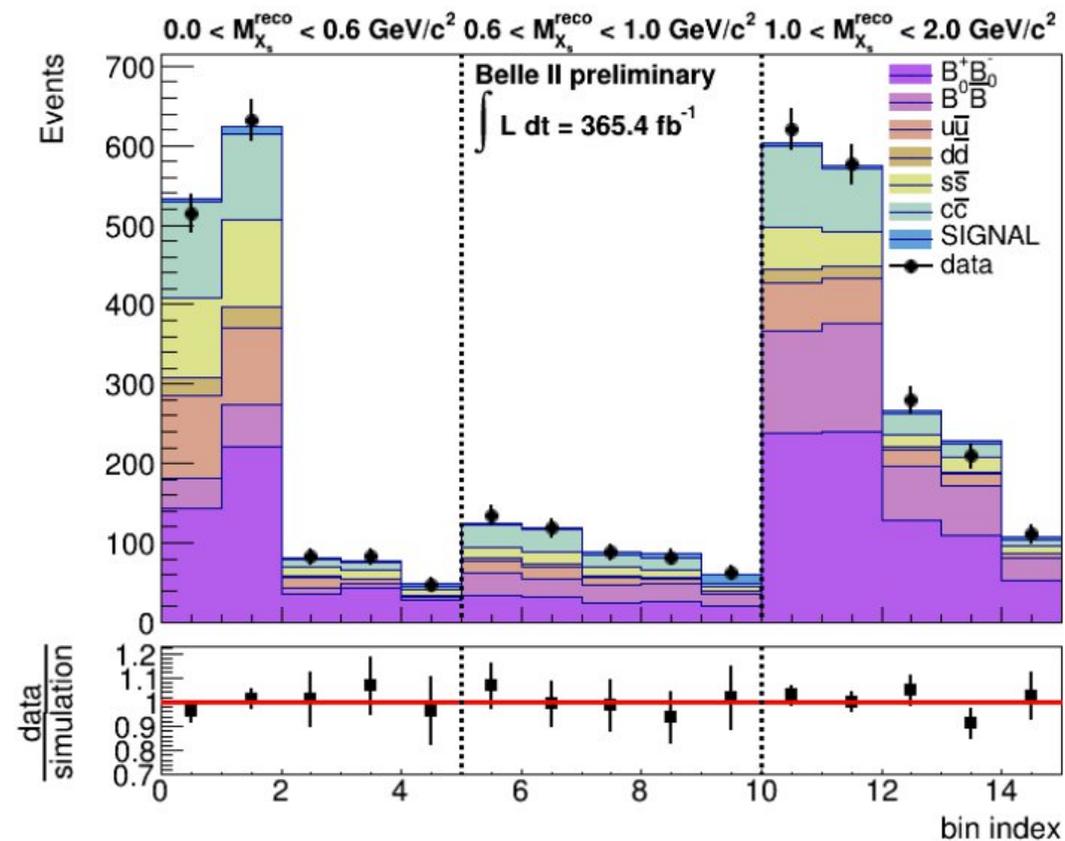
Confidence level	$B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-$	$B_s^0 \rightarrow K^+ K^- \tau^+ \tau^-$	$\mathcal{C}_{9(10)}^{\tau\tau} = \mathcal{C}_{9(10)}^{\text{NP}} - (+)\Delta$
90%	$2.5 \times 10^4$	$4.5 \times 10^4$	
95%	$2.9 \times 10^4$	$5.2 \times 10^4$	

# Search for $B \rightarrow X_s \nu \bar{\nu}$

- Using  $365 \text{ fb}^{-1}$  BELLE II data @  $\Upsilon(4S)$
- Machine-learning based hadronic B-tagging
- X candidates reco'ed in 30 modes of  $K\eta\pi$  +  $3K\eta\pi$
- BDT trained for background suppression
- **First upper limit @ 90% CL set:**

$$\mathcal{B}(B \rightarrow X_s \nu \bar{\nu}) < 3.2 \times 10^{-4}$$

$3 \times 5$  bins in  $M(X_s) \times O(\text{BDT})$  space



Approaching SM expectation of  $(2.9 \pm 0.3) \times 10^{-5}$

# Search for LFV decay $B^0 \rightarrow K^{*0} \tau^\pm e^\mp$

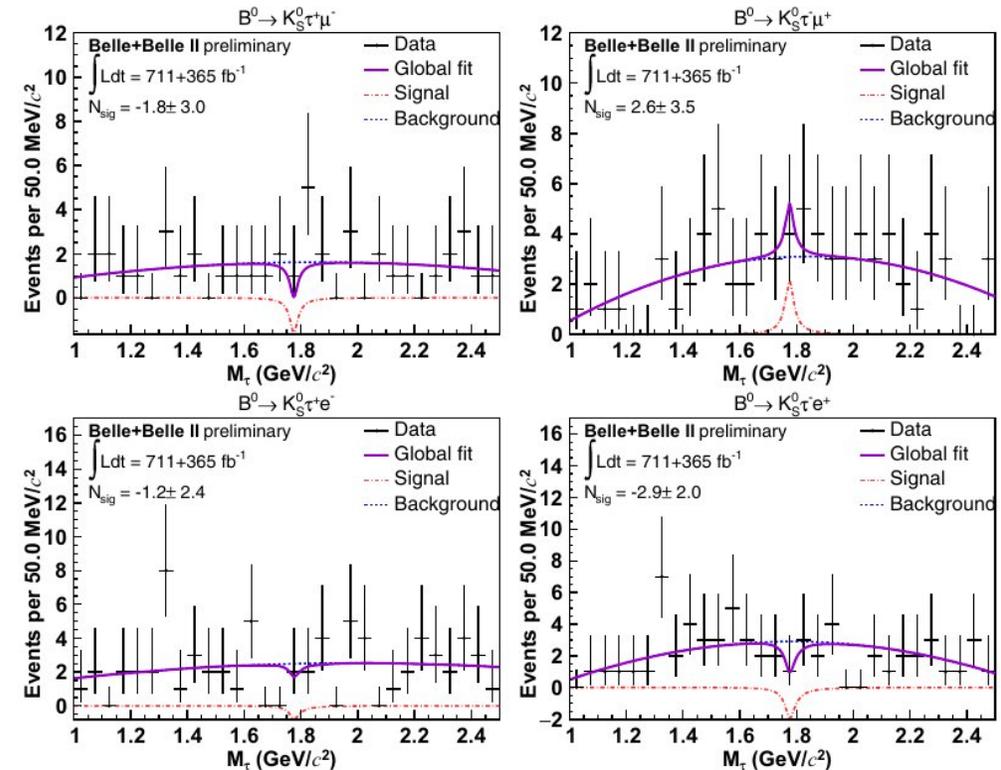
- Using  $711 \text{ fb}^{-1}$  BELLE +  $365 \text{ fb}^{-1}$  BELLE II data
- Machine-learning based hadronic B-tagging
- $\tau$  candidates reco'ed via  $e\nu\bar{\nu}, \mu\nu\bar{\nu}, \pi\nu, \rho(\pi\pi^0)\nu$  modes
- Among the best limits on  $b \rightarrow s\tau e(\mu)$ :

$$\mathcal{B}(B^0 \rightarrow K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$

$$\mathcal{B}(B^0 \rightarrow K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$

$$\mathcal{B}(B^0 \rightarrow K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$

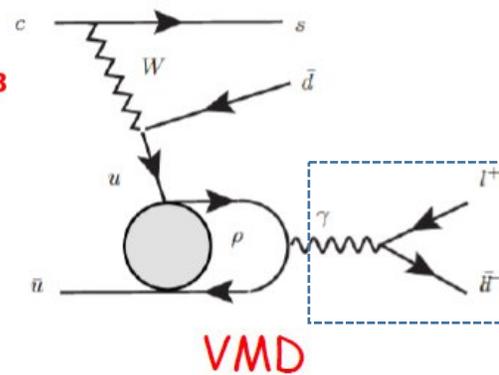
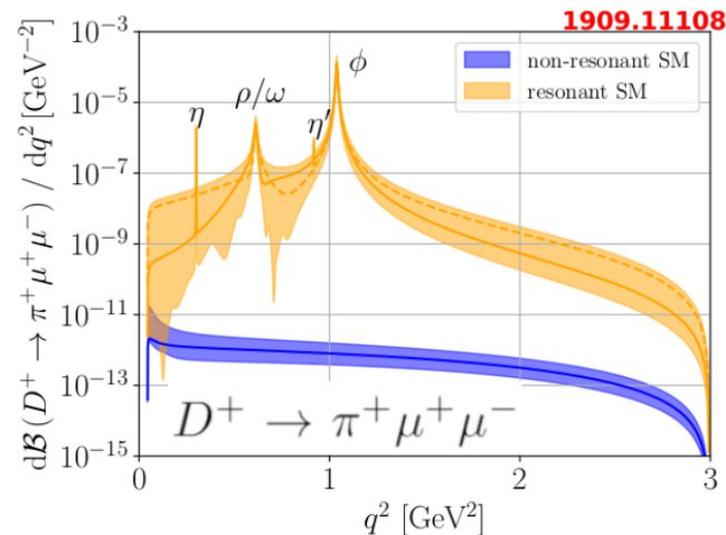
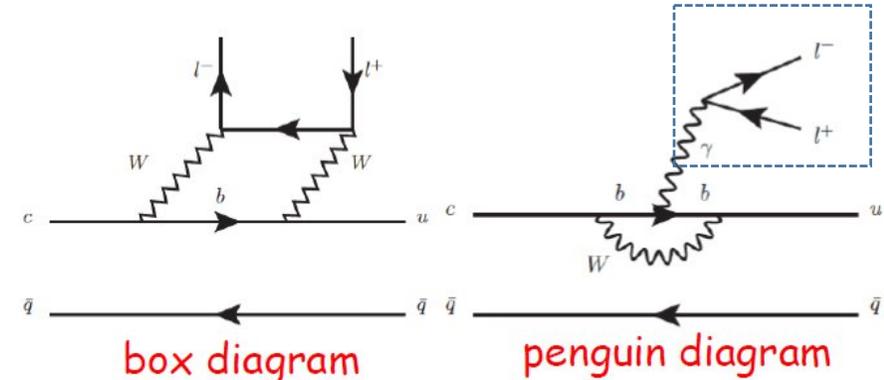
$$\mathcal{B}(B^0 \rightarrow K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$



Approaching possible BSM enhancement level of  $O(10^{-6})$

# Flavor Changing Neutral Currents in charm

- $c \rightarrow u\ell\ell$  processes forbidden at tree level in SM, only allowed in loop and box diagrams
  - Strongly suppressed due to GIM cancellation:
  - Expected SM BF  $\sim O(10^{-9})$
  - NP might manifest in the loops
- $D \rightarrow X\ell^+\ell^-$  dominated by Long-Distance contributions
  - Vector Meson Dominance (VMD)
  - BF  $\sim O(10^{-6})$  for  $D \rightarrow X\ell^+\ell^-$

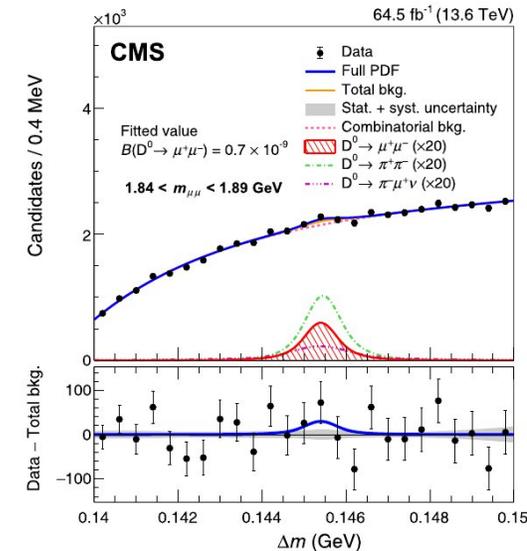
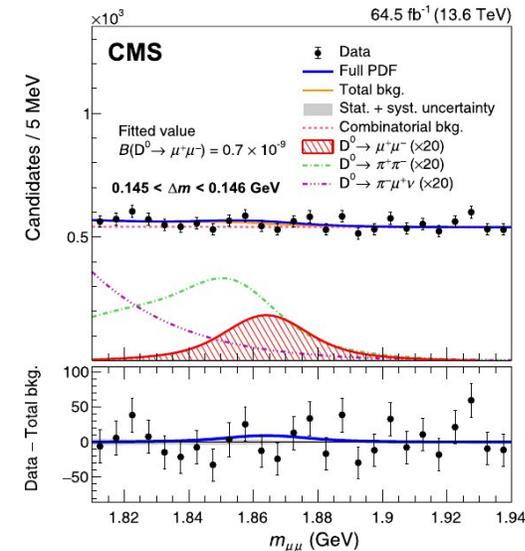


# Search for $D^0 \rightarrow \mu^+ \mu^-$

- Using  $64.5 \text{ fb}^{-1}$  data collected in 2022-2023
- Looking for  $D^0$  from  $D^{*+} \rightarrow D^0 \pi^+$
- Normalized to  $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+$
- Newly developed inclusive dimuon trigger for Run3
- Best upper limit:

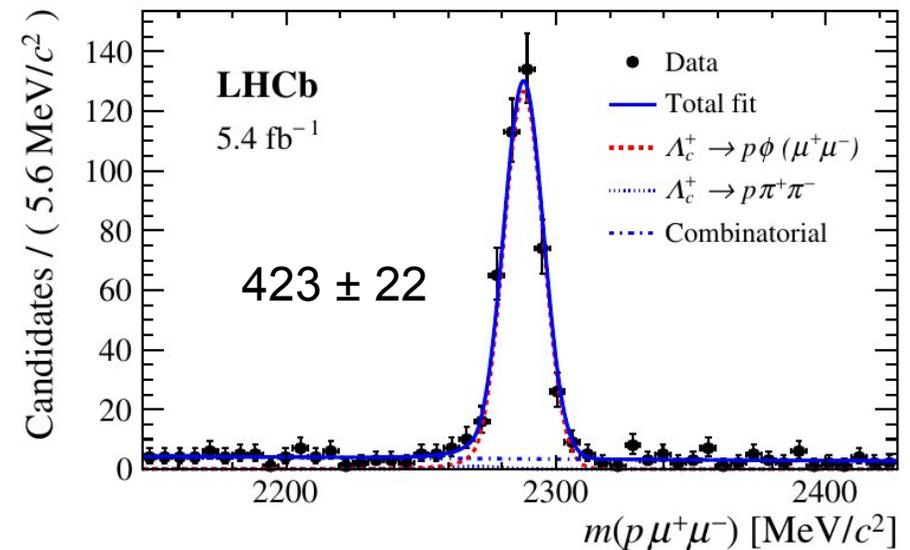
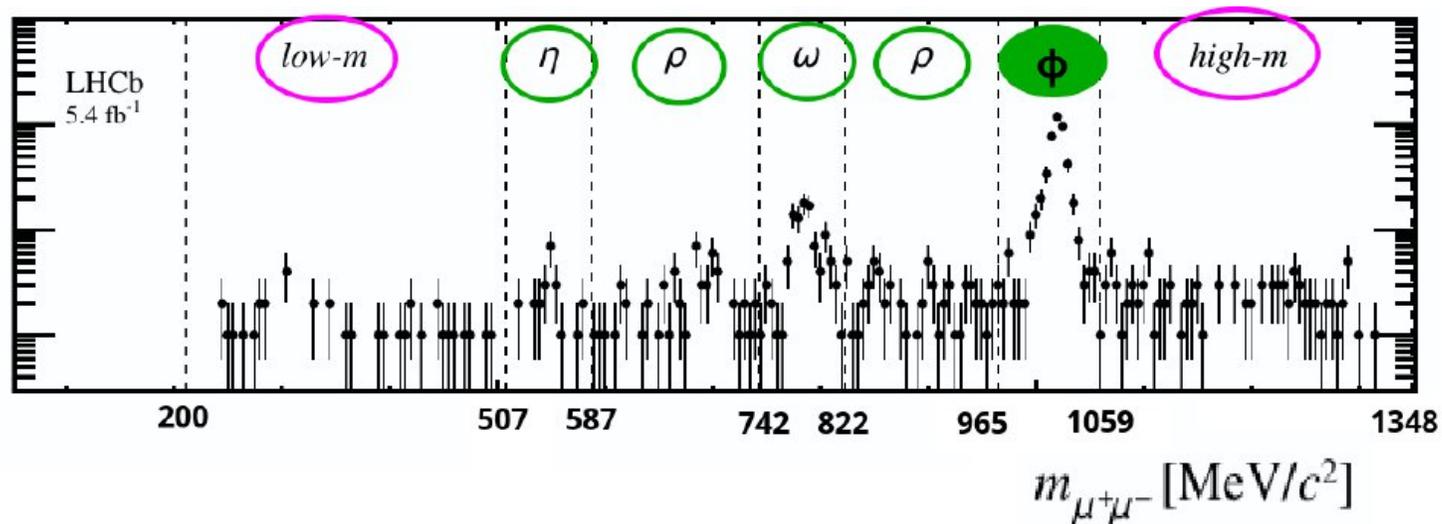
$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 2.1(2.4) \times 10^{-9} \text{ at } 90(95)\% \text{ CL.}$$

Most stringent constraint on FCNC transitions in charm sector



# Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

- Based on Run2 5.4 fb<sup>-1</sup> dataset
- Signals searched for in 6 dimuon mass regions
- Normalized to  $\phi$  resonant region



# Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

- BFs measured in different resonant regions:

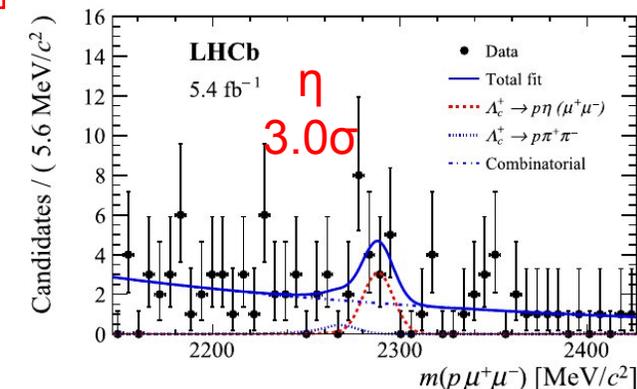
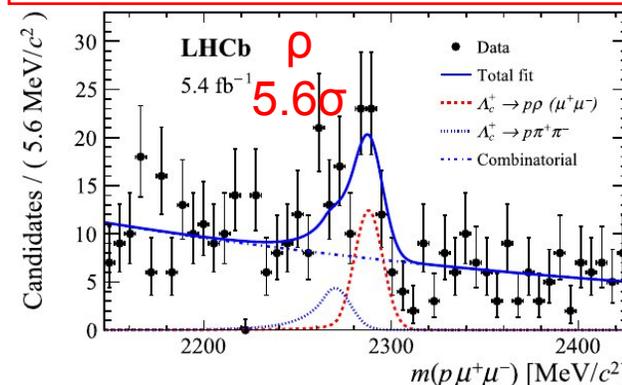
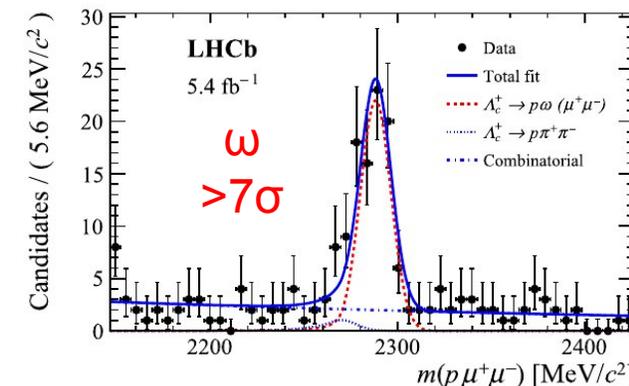
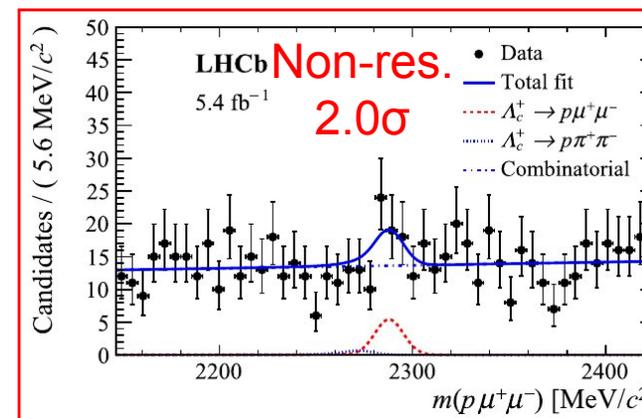
$$\mathcal{B}(\Lambda_c^+ \rightarrow p\omega) = (9.82 \pm 1.23(\text{stat}) \pm 0.73(\text{syst}) \pm 2.79(\text{ext})) \times 10^{-4}$$

$$\mathcal{B}(\Lambda_c^+ \rightarrow p\rho) = (1.52 \pm 0.34(\text{stat}) \pm 0.14(\text{syst}) \pm 0.24(\text{ext})) \times 10^{-3}$$

$$\mathcal{B}(\Lambda_c^+ \rightarrow p\eta) = (1.67 \pm 0.69(\text{stat}) \pm 0.23(\text{syst}) \pm 0.34(\text{ext})) \times 10^{-3}$$

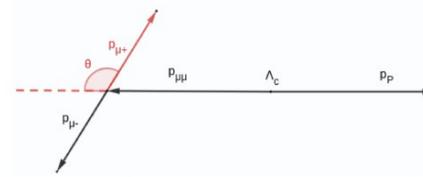
- Most stringent limit set on non-resonant BF:

$$\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 2.9 \text{ (3.2)} \times 10^{-8} \text{ at 90\% (95\%) CL.}$$



# $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ : CPV & angular asymmetries

- Asymmetries in  $\phi$  region compatible with SM prediction and conservation of P and CP symmetry



$$A_{FB} = \frac{\Gamma(\cos \theta_\mu > 0) - \Gamma(\cos \theta_\mu < 0)}{\Gamma(\cos \theta_\mu > 0) + \Gamma(\cos \theta_\mu < 0)}$$

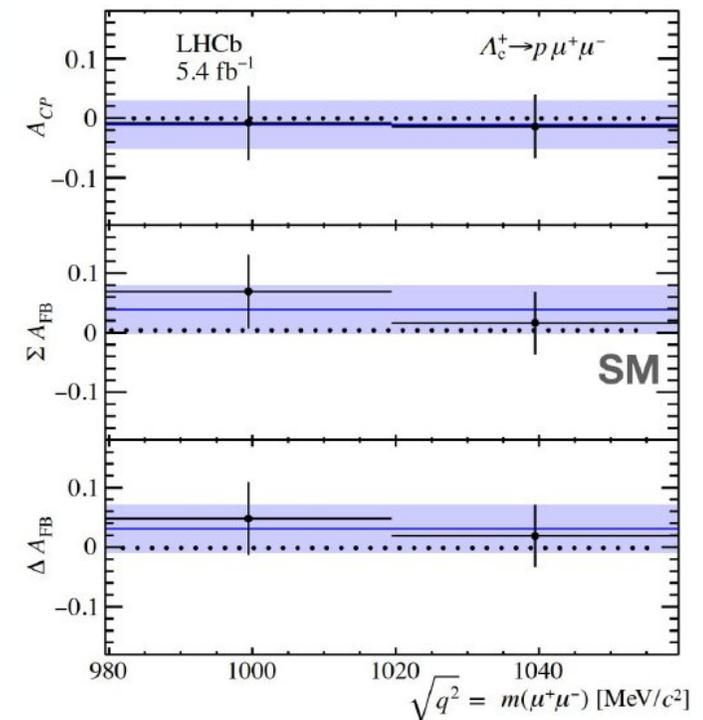
$$A_{CP} = \frac{\Gamma(\Lambda_c^+ \rightarrow p \mu^+ \mu^-) - \Gamma(\Lambda_c^- \rightarrow \bar{p} \mu^+ \mu^-)}{\Gamma(\Lambda_c^+ \rightarrow p \mu^+ \mu^-) + \Gamma(\Lambda_c^- \rightarrow \bar{p} \mu^+ \mu^-)}$$

$$\Sigma A_{FB}^{CP} \equiv 1/2 \cdot [A_{FB}^{\Lambda_c^+} + A_{FB}^{\Lambda_c^-}]$$

$$\Delta A_{FB}^{CP} \equiv 1/2 \cdot [A_{FB}^{\Lambda_c^+} - A_{FB}^{\Lambda_c^-}]$$

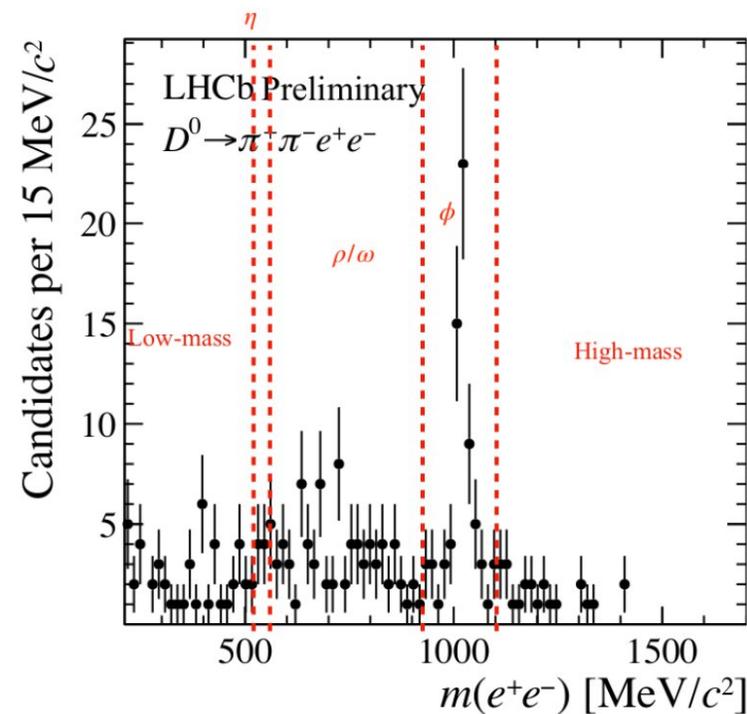
Dimuon-mass integrated

	Stat.	Sys.
$A_{CP}$	$-1.1 \pm 4.0$	$\pm 0.5$
$\Sigma A_{FB}$	$3.9 \pm 4.0$	$\pm 0.6$
$\Delta A_{FB}$	$3.1 \pm 4.0$	$\pm 0.4$



# Search for $D^0 \rightarrow h^+ h^- e^+ e^-$

- Based on Run2 5.4 fb<sup>-1</sup> dataset
- Signals searched for in different dielectron mass regions
- Normalized to  $D^0 \rightarrow K^- \pi^+ e^+ e^-$  in resonant region

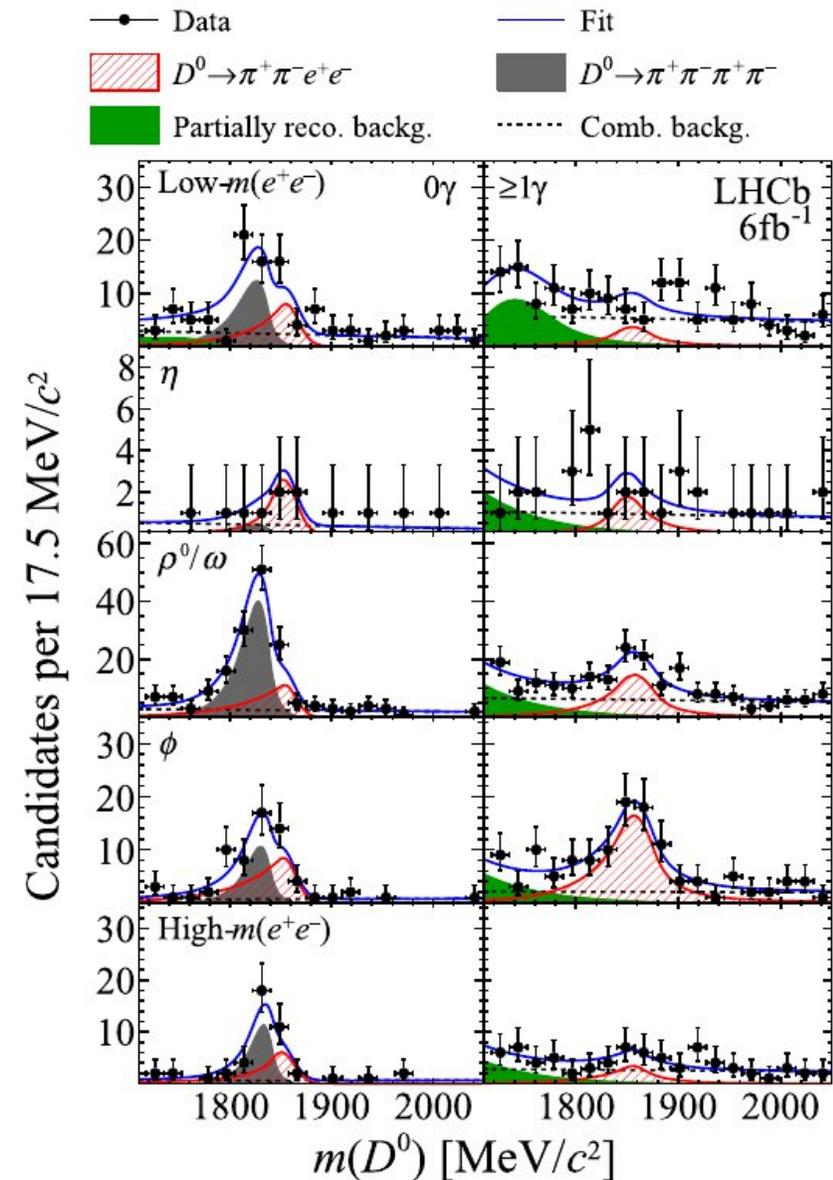


# Search for $D^0 \rightarrow \pi^+ \pi^- e^+ e^-$

- Based on Run2 6 fb<sup>-1</sup> dataset
- Signals searched for in 5 dielectron mass regions
- First observation in  $\rho/\omega$  &  $\phi$  regions

$m(e^+e^-)$ region	[MeV/c <sup>2</sup> ]	Yield	$S$
	$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$		
Low mass	$2m_\mu - 525$	$37 \pm 13$	$2.8\sigma$
$\eta$	525–565	$10 \pm 7$	$1.6\sigma$
$\rho^0/\omega$	565–950	$97 \pm 21$	$5.5\sigma$
$\phi$	950–1100	$100 \pm 18$	$8.1\sigma$
High mass	$> 1100$	$30 \pm 11$	$2.9\sigma$

- Total BF:  $\mathcal{B}(D^0 \rightarrow \pi^+ \pi^- [e^+ e^-]_{m(e^+e^-) > 2m_\mu})$   
 $= (13.3 \pm 1.7 \pm 1.7 \pm 1.8) \times 10^{-7}$



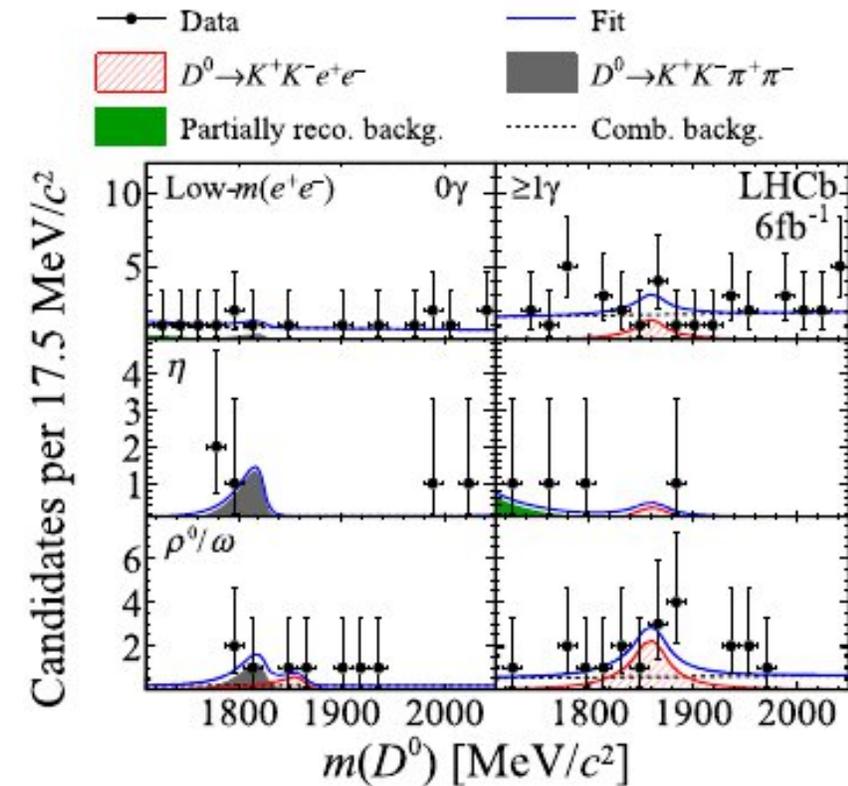
# Search for $D^0 \rightarrow K^+ K^- e^+ e^-$

- Based on Run2 6 fb<sup>-1</sup> dataset
- Signals searched for in 3 dielectron mass regions

$m(e^+e^-)$ region	[MeV/c <sup>2</sup> ]	Yield	$S$
	$D^0 \rightarrow K^+ K^- e^+ e^-$		
Low mass	$2m_\mu - 525$	$4 \pm 8$	$1.2\sigma$
$\eta$	525–565	$1 \pm 2$	$1.1\sigma$
$\rho^0/\omega$	$> 565$	$12 \pm 7$	$2.2\sigma$

- BF upper limits of  $O(10^{-7})$  are set in different regions

Similar study performed by BELLE(II) yielding less stringent limits  
[PRD 112 (2025) L071101]



# Search for $D_s^+ \rightarrow hh' ee$ decays

- First search for four-body  $D_s^+$  decays to an electron pair
- Using  $7.33 \text{ fb}^{-1}$  data @ 4.128-4.226 GeV
- $D_s^+$  mainly from  $e^+e^- \rightarrow D_s^{*\pm} D_s^\mp$ , with total number of  $N_{D_s^\pm D_s^\mp} = (64.7 \pm 0.3) \pm 10^5$
- Single-tag method, the BF for a given channel is given by:

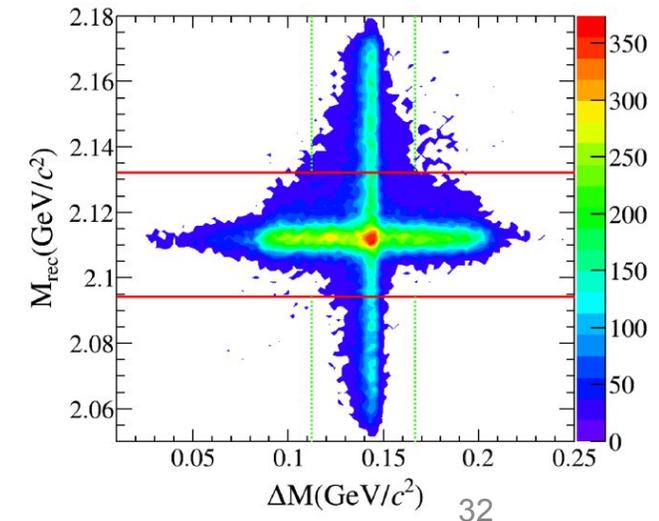
$$\mathcal{B}(D_s^+ \rightarrow h^+(h^0)e^+e^-) = \frac{N_{\text{sig}}}{2 \cdot N_{D_s^{*\pm} D_s^\mp} \cdot \epsilon \cdot \mathcal{B}_{\text{inter}}}$$

- 2D optimization of requirements on  $M_{\text{rec}}$  vs.  $\Delta M$

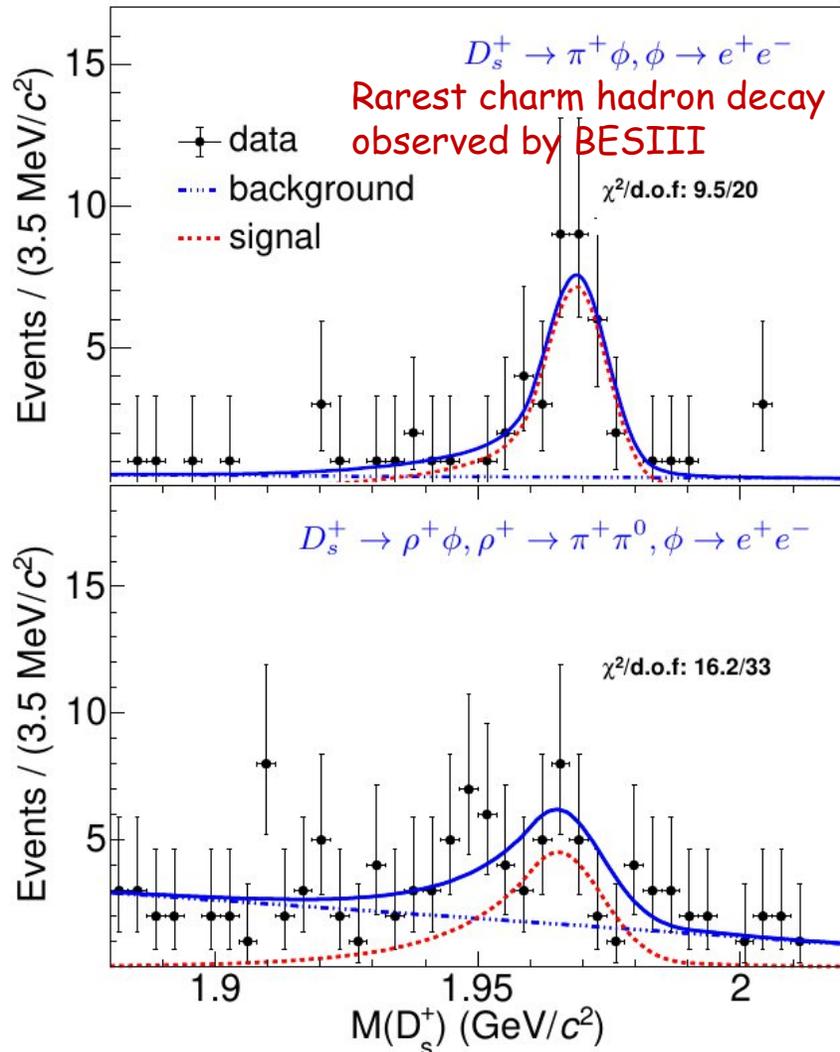
$$M_{\text{rec}} = \sqrt{\left(E_{\text{cm}} - \sqrt{|\vec{P}_{D_s^+}|^2 + m_{D_s^+}^2}\right)^2 - |P_{D_s^+}|^2},$$

$$\Delta M = M(D_s^+ \gamma) - M(D_s^+),$$

PRD 104, 012016 (2021)



# Results on $D_s^+ \rightarrow h(h^0)\phi(e^+e^-)$



- $M(e^+e^-) \in [0.98, 1.04] \text{ GeV}/c^2$
- $M(\pi^+\pi^0) \in [0.60, 0.95] \text{ GeV}/c^2$
- Unbinned maximum likelihood fits to the  $M(D_s^+)$  distributions

Decay	$N_{\text{sig}}$	$\epsilon$ (%)	$\mathcal{B} (\times 10^{-5})$
$D_s^+ \rightarrow \pi^+\phi, \phi \rightarrow e^+e^-$	$38.2_{-6.8}^{+7.8}$	25.1	$1.17_{-0.21}^{+0.23} \pm 0.03$
$D_s^+ \rightarrow \rho^+\phi, \phi \rightarrow e^+e^-$	$37.8_{-9.6}^{+10.3}$	12.1	$2.44_{-0.62}^{+0.67} \pm 0.16$

$7.8\sigma$  for  $D_s^+ \rightarrow \pi^+\phi, \phi \rightarrow e^+e^-$

improved by a factor of three

$4.4\sigma$  for  $D_s^+ \rightarrow \rho^+\phi, \phi \rightarrow e^+e^-$

first evidence

NB: Using  $D_{(s)}^+ \rightarrow \pi^+\phi$ , LHCb measured

$$R_{\phi\pi} = 1.022 \pm 0.012 \text{ (stat)} \pm 0.048 \text{ (syst)}$$

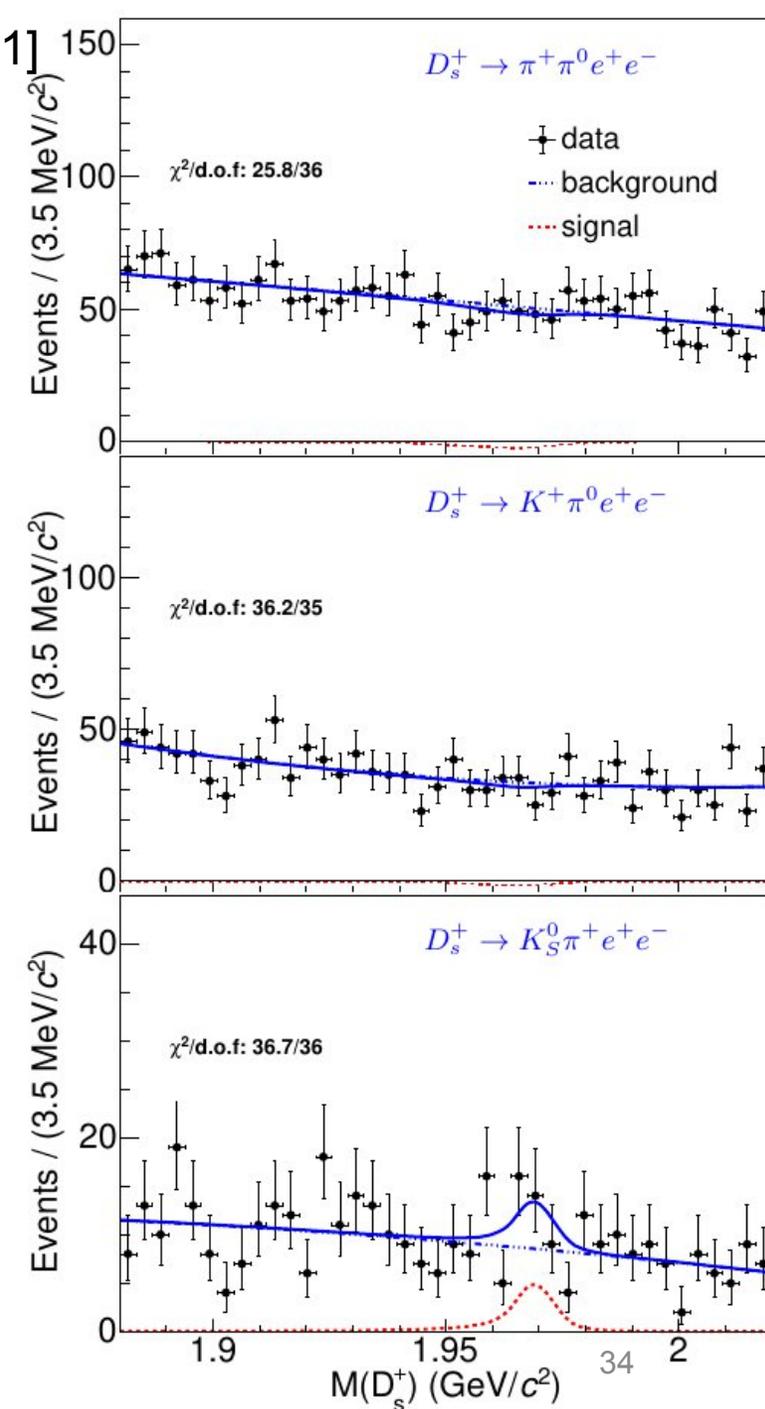
[JHEP 05 (2024) 293]

# Upper limits on $D_s^+ \rightarrow hh' e^+ e^-$

- FCNC  $c \rightarrow ue^+e^-$  process, highly suppressed in SM
- Exclusion of events with  $M(e^+e^-) \in [0.96, 1.05]$  GeV for mode  $\pi^+\pi^0e^+e^-$

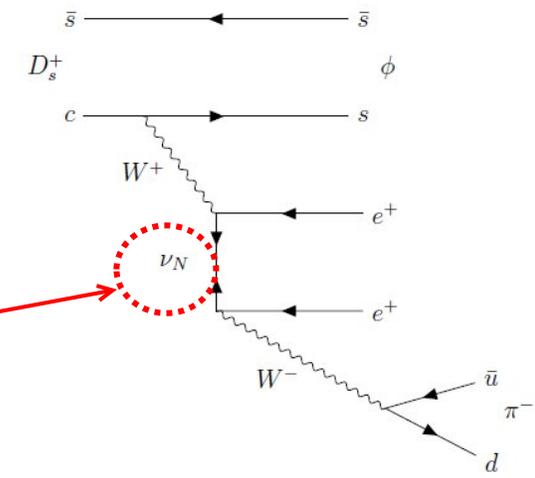
Decay	$N_{\text{sig}}$	$\epsilon$ (%)	$\mathcal{B}$ ( $\times 10^{-5}$ )
$D_s^+ \rightarrow \pi^+\pi^0e^+e^-$	...	7.4	$< 7.0$
$D_s^+ \rightarrow K^+\pi^0e^+e^-$	...	5.3	$< 7.1$
$D_s^+ \rightarrow K_S^0\pi^+e^+e^-$	...	6.7	$< 8.1$

All first upper limits!



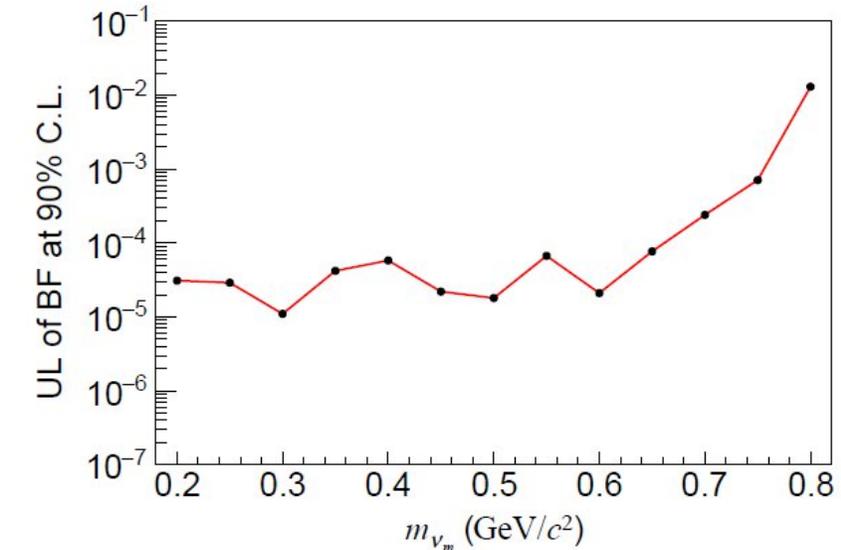
# Search for $D_s^+ \rightarrow h^- h^0 e^+ e^+$

- LNV ( $\Delta L = 2$ ) process could be mediated by a single Majorana neutrino
- First upper limits @ 90% CL:



$D_s^+ \rightarrow \phi \pi^- e^+ e^+$  (CF)

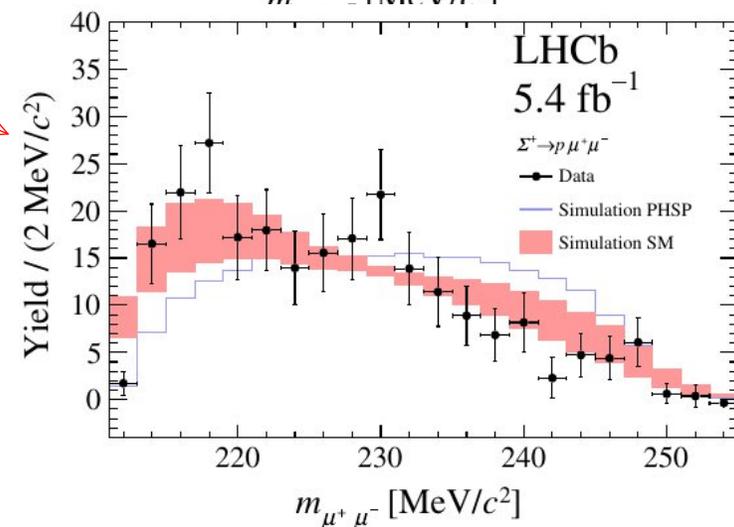
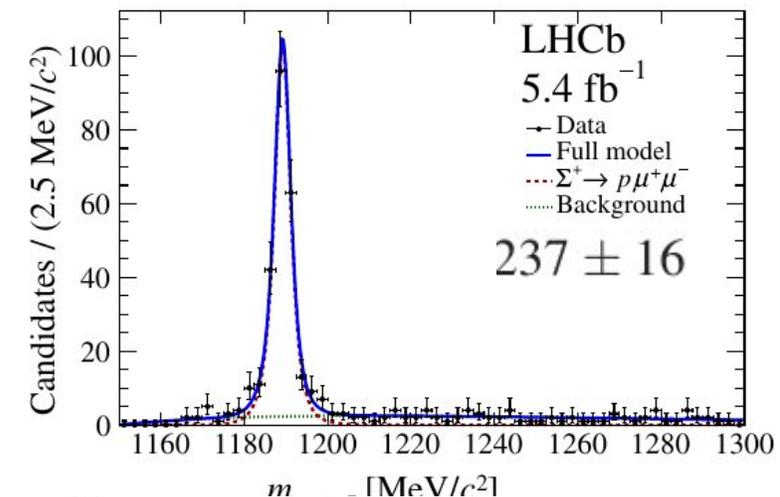
Decay channel	$\epsilon$ (%)	$\mathcal{B}_{UL}$ ( $\mathcal{B}_{UL}^{\text{expected}}$ )
$D_s^+ \rightarrow \phi \pi^- e^+ e^+$	$3.0 \pm 0.1$	$6.9$ ( $3.5$ ) $\times 10^{-5}$
$D_s^+ \rightarrow \phi K^- e^+ e^+$	$1.8 \pm 0.1$	$9.9$ ( $10.8$ ) $\times 10^{-5}$
$D_s^+ \rightarrow K_S^0 \pi^- e^+ e^+$	$6.4 \pm 0.1$	$1.3$ ( $2.4$ ) $\times 10^{-5}$
$D_s^+ \rightarrow K_S^0 K^- e^+ e^+$	$4.0 \pm 0.1$	$2.9$ ( $2.3$ ) $\times 10^{-5}$
$D_s^+ \rightarrow \pi^- \pi^0 e^+ e^+$	$6.4 \pm 0.1$	$2.9$ ( $2.7$ ) $\times 10^{-5}$
$D_s^+ \rightarrow K^- \pi^0 e^+ e^+$	$5.1 \pm 0.1$	$3.4$ ( $3.9$ ) $\times 10^{-5}$



First mass scan in a  $D \rightarrow V \ell \nu_m$  process

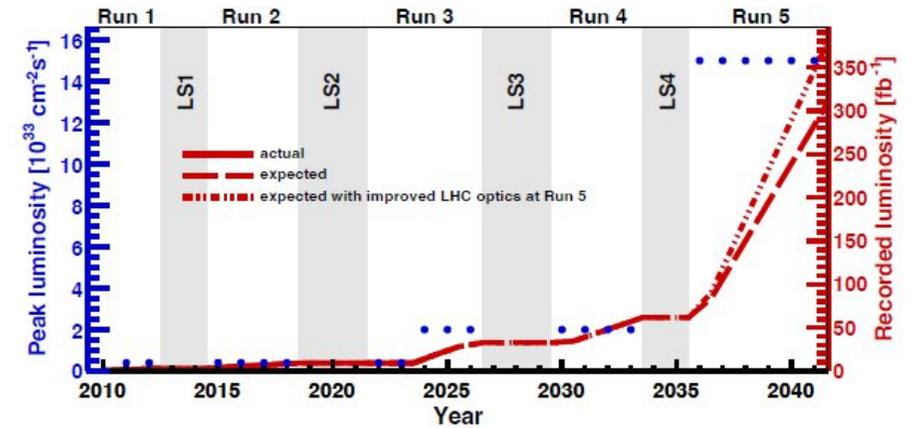
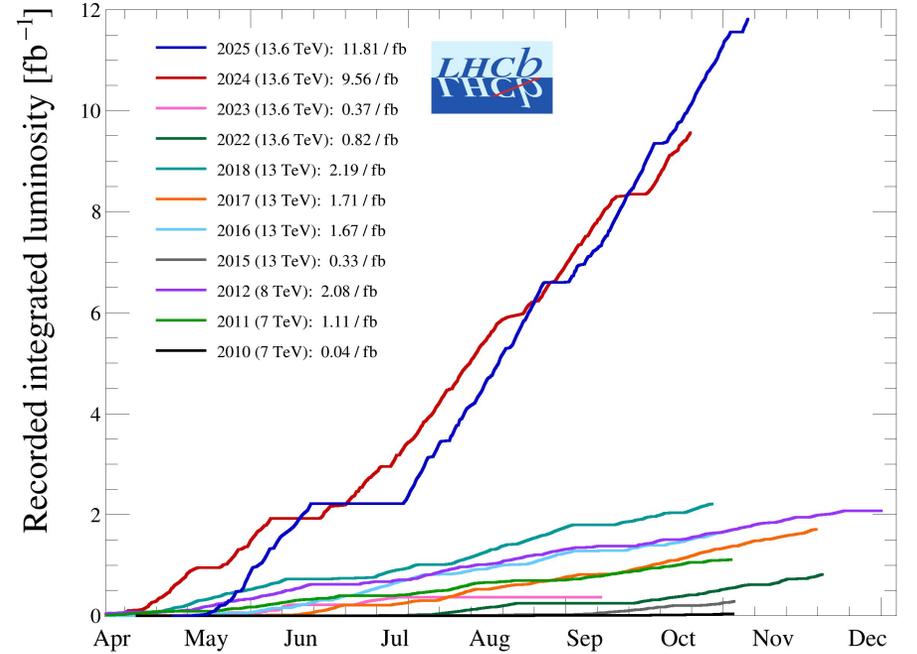
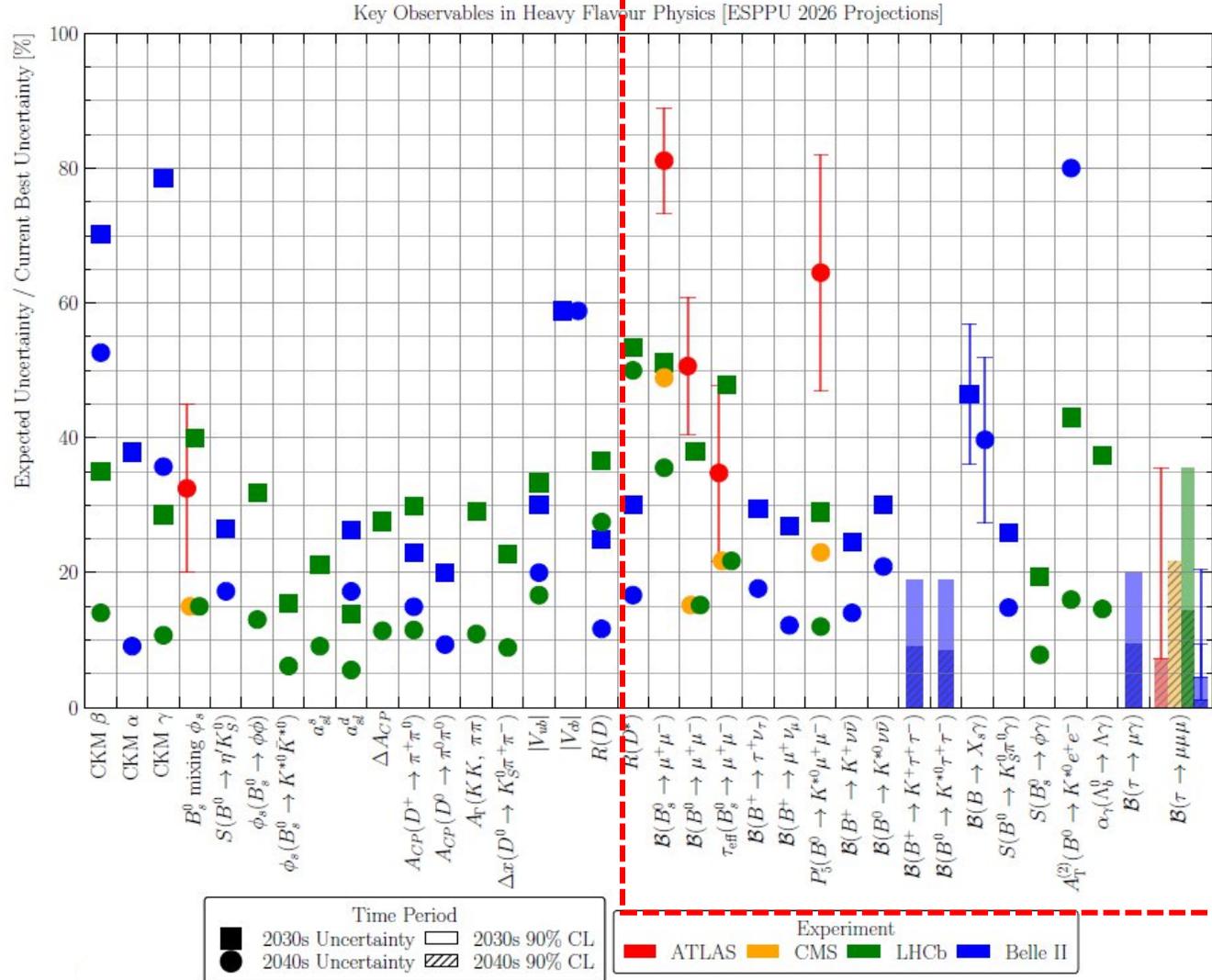
# Other rare decays: recent LHCb results

- First observation of  $\Sigma \rightarrow p\mu^+\mu^-$  [[PRL 135 \(2025\) 051801](#)]
  - $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (1.08 \pm 0.17) \times 10^{-8}$
  - Rarest baryon decay ever observed
  - No structure found in the dimuon mass spectrum, compatible with SM
- Search for  $K_{S(L)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$  [[arxiv:2511.02619](#)]
- Search for  $\eta^{(\prime)} \rightarrow (\pi^+\pi^-)\mu^+\mu^-$  [[LHCb-CONF-2025-002](#)]
- Search for  $\tau \rightarrow \mu\mu\mu$  [[arXiv:2601.20785](#)]



# LHCb prospects

Total recorded luminosity by year – pp

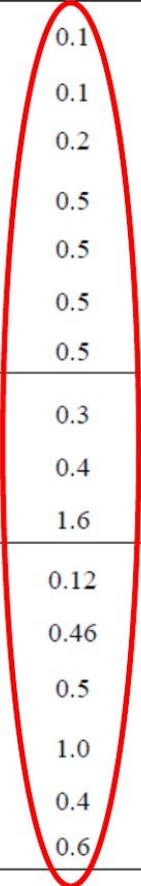


# BESIII prospects

	$10^{-6}$				$10^{-6}$
Decay	Upper limit	Experiment	Year	Ref.	BESIII Expected
$D^0 \rightarrow \pi^0 e^+ e^-$	0.4	BESIII	2018	[35]	0.1
$D^0 \rightarrow \eta e^+ e^-$	0.3	BESIII	2018	[35]	0.1
$D^0 \rightarrow \omega e^+ e^-$	0.6	BESIII	2018	[35]	0.2
$D^0 \rightarrow K_S^0 e^+ e^-$	1.2	BESIII	2018	[35]	0.5
$D^0 \rightarrow \rho e^+ e^-$	124.0	E791	2001	[36]	0.5
$D^0 \rightarrow \phi e^+ e^-$	59.0	E791	2001	[36]	0.5
$D^0 \rightarrow \bar{K}^{*0} e^+ e^-$	47.0	E791	2001		0.5
$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$	0.7	BESIII	2018		0.3
$D^0 \rightarrow K^+ K^- e^+ e^-$	1.1	BESIII	2018		0.4
$D^0 \rightarrow K^- \pi^+ e^+ e^-$	4.1	BESIII	2018	[35]	1.6
$D^+ \rightarrow \pi^+ e^+ e^-$	1.1	BaBar	2011	[37]	0.12
$D^+ \rightarrow K^+ e^+ e^-$	1.0	BaBar	2011	[37]	0.46
$D^+ \rightarrow \pi^+ \pi^0 e^+ e^-$	1.4	BESIII	2018	[35]	0.5
$D^+ \rightarrow \pi^+ K_S^0 e^+ e^-$	2.6	BESIII	2018	[35]	1.0
$D^+ \rightarrow K_S^0 K^+ e^+ e^-$	1.1	BESIII	2018	[35]	0.4
$D^+ \rightarrow K^+ \pi^0 e^+ e^-$	1.5	BESIII	2018	[35]	0.6
$D_s^+ \rightarrow \pi^+ e^+ e^-$	13.0	BaBar	2011		70.0
$D_s^+ \rightarrow K^+ e^+ e^-$	3.7	BaBar	2011		1.7

20 fb<sup>-1</sup>  
@ 3.773 GeV

6 fb<sup>-1</sup>@ 4.18 GeV



# Summary

- Rare heavy hadron decays offer unique opportunities for indirect NP searches
- Major players in the field for rare decays:
  - LHCb/CMS: Dominant role for heavy hadron decays to all-track final states due to overwhelming statistics
  - BESIII/BELLEII: Advantages in reconstruction of neutrals ( $\pi^0/\eta/K_S^0/\Lambda/\dots$ ) and invisible particles ( $\nu/K_L^0/n/DM/\dots$ )
- So far, no surprises, but tensions still persist ( $C_9$ ?)
- More results are on the way, stay tuned!
- A huge Run3 data sample available for analysis, while understanding of new LHCb detector ongoing [[arXiv:2511.16564](https://arxiv.org/abs/2511.16564)]
- And we will have Run4 and Upgrade-II!
  - $50 \text{ fb}^{-1}$  by 2033,  $> 300 \text{ fb}^{-1}$  by 2041 for LHCb