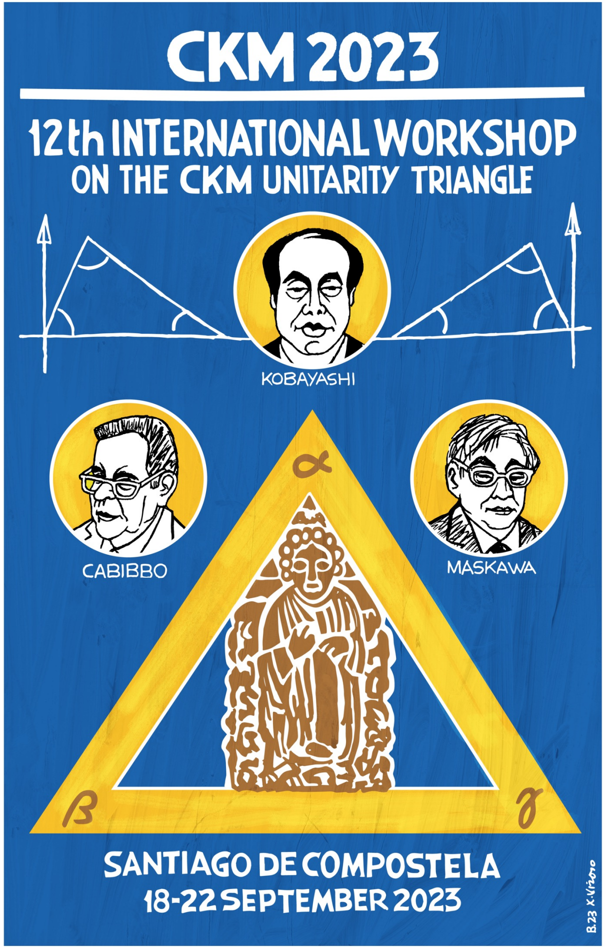


Lepton flavor violating *B* decays

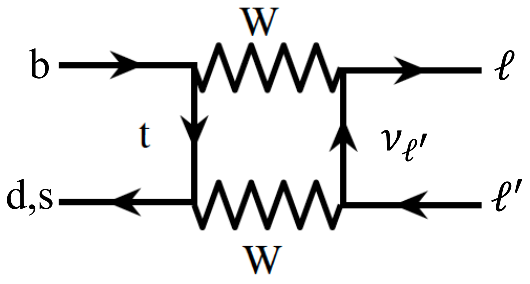
Gagan Mohanty

tifr

[Presented by Jim Libby]

Why worry?

- Lepton flavor violating (LFV) decays of B mesons
  - are forbidden at tree level in the standard model (SM)
  - can occur via neutrino mixing through loop or box diagrams
  - have very small rates, e.g. $\mathcal{B}(B_s^0 \to \ell\tau) \sim 10^{-9} \Rightarrow$ likely beyond our reach in foreseeable future



PRD 70, 113011 (2004)

- Motivation also comes from flavour anomalies $\Rightarrow$ lepton flavor universality violation necessarily leads to LFV processes with charged leptons in the final state

PRL 114, 091801 (2015)

- Observation of such decays would indicate physics beyond the SM (BSM)

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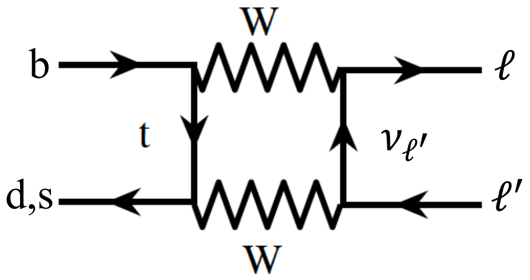

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  - ➢ are forbidden at tree level in the standard model (SM)
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- Observation of such decays would indicate physics beyond the SM (BSM)

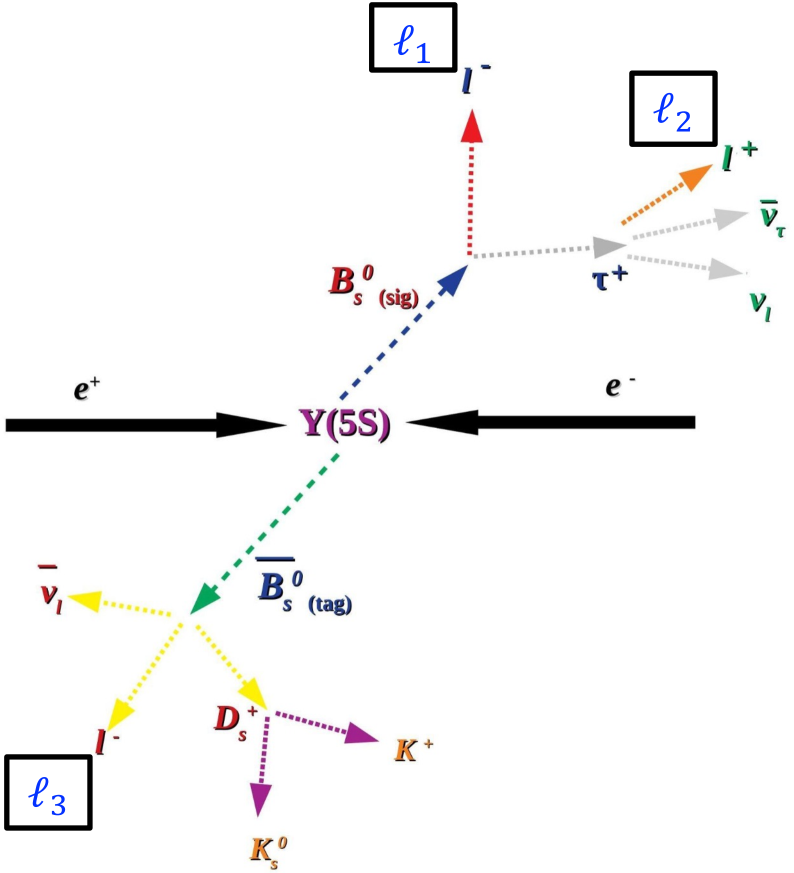
What will cover?

1) Search for $B_s^0 \to \ell\tau$ with the semi-leptonic tagging method at Belle JHEP 08, 178 (2023)
2) Search for the LFV decays $B^+ \to K^+\tau^\pm\ell^\mp$ at Belle PRL 130, 261802 (2023)
3) Search for the LFV decays $B^0 \to K^{*0}\tau^\pm\mu^\mp$ JHEP 06, 143 (2023)
4) Search for the LFV decays $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$ JHEP 06, 073 (2023)

Search for $B_s^0 \to \ell\tau$ ($\ell = e, \mu$)

JHEP 08, 178 (2023)

- BSM models such as Z' boson and leptoquark predict a decay rate $\mathcal{B}(B_s^0 \to \ell\tau) \sim 10^{-9} - 10^{-5}$
- For the latter, $\mathcal{B}(B_s^0 \to \ell\tau)$ can be as large as 10^{-5}
- Previous upper limits:
  - LHCb: $\mathcal{B}(B_s^0 \to \mu^{\mp}\tau^{\pm}) < 3.4\times10^{-5}$ at 90% CL
    PRL 130, 261802 (2023)
  - No experimental results for $B_s^0 \to e^{\mp}\tau^{\pm}$ as of yet



Key steps:

- Search for $B_s^0 \to \ell_1^-\tau^+(\to \ell_2^+\nu_\ell\bar{\nu}_\tau)$ with the recoiling $\bar{B}_s^0$ identified or tagged by its decay $\bar{B}_s^0 \to D_s^+\ell_3^-(X)\bar{\nu}_\ell$
- Reconstruct the D_s^+ meson in five decay channels: $\phi\pi^+$, $K^{*0}K^+$, $\phi\rho^0\pi^+$, $K_S^0K^+$, and $\phi\rho^+$
- Use the primary lepton's momentum calculated in the center-of-mass (c.m.) frame, p_1^*, as the final variable

Search for $B_s^0 \to \ell\tau$ ($\ell = e, \mu$)

Signal:

$e^+e^- \to \Upsilon(5S) \to B_s^{*0}\bar{B}_s^{*0}$ with $B_s^{*0} \to B_s^0\gamma$, $B_s^0 \to \ell\tau$

Background suppression:

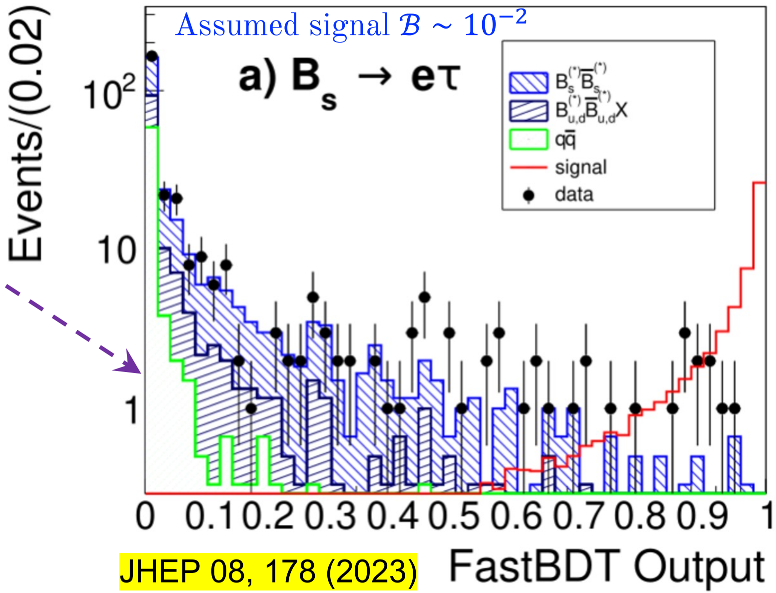
- A FastBDT classifier is trained for signal against the continuum and combinatorial backgrounds
- Key input variables: p_2^*, p_3^*, E_{extra}, E_{miss}, $M_{D_s^+}$
- The classifier output ranges from zero, where backgrounds peak, to one, where signal peaks
- 8–9% of events have multiple signal candidates where the ones with the highest FastBDT output value are retained
- Threshold on the classifier output is determined using the Punzi figure-of-merit physics/0308063

Background:

- ❑ $e^+e^- \to q\bar{q}$ (continuum)
- ❑ $B_s^{*0}B_s^{*0}X$ and $B_{u,d}^{*0}B_{u,d}^{*0}X$ (combinatorial)

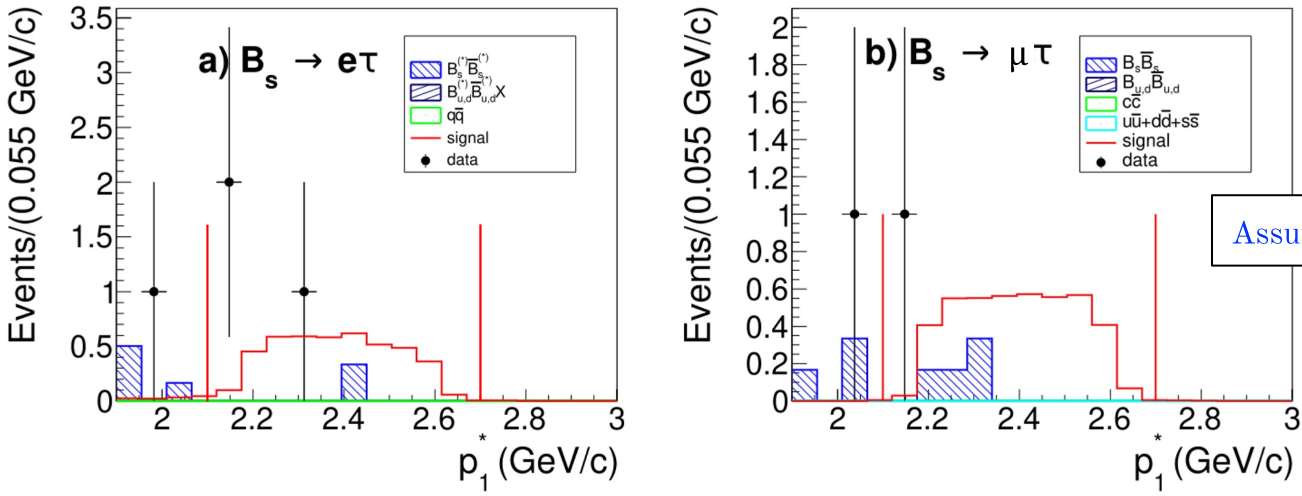
$121\ \text{fb}^{-1}$ data at $\Upsilon(5S) \Rightarrow 16.6\times10^6$ B_s^0 events

Assumed signal $\mathcal{B} \sim 10^{-2}$



JHEP 08, 178 (2023)

Search for $B_s^0 \to \ell\tau$ ($\ell = e, \mu$)



Assumed signal $\mathcal{B} \sim 10^{-3}$

JHEP 08, 178 (2023)

	ϵ (%)	$N_{\rm bkg}^{\rm exp}$	$N_{\rm obs}$	$\mathcal{B}$ ($\times 10^{-4}$)
$B_s \to e^-\tau^+$	0.031 ± 0.007	0.68 ± 0.69	3	< 14
$B_s \to \mu^-\tau^+$	0.030 ± 0.007	0.77 ± 0.78	1	< 7.3

LHCb: $< 3.4 \times 10^{-5}$
PRL 123, 211801 (2019)

- $N_{\rm obs}$ in the electron mode is larger but not inconsistent with $N_{\rm bkg}^{\rm exp}$ (p-value = 7.3%)
- Set upper limits at 90% CL ⇒ World's first limit on the $B_s^0 \to e^-\tau^+$ decay

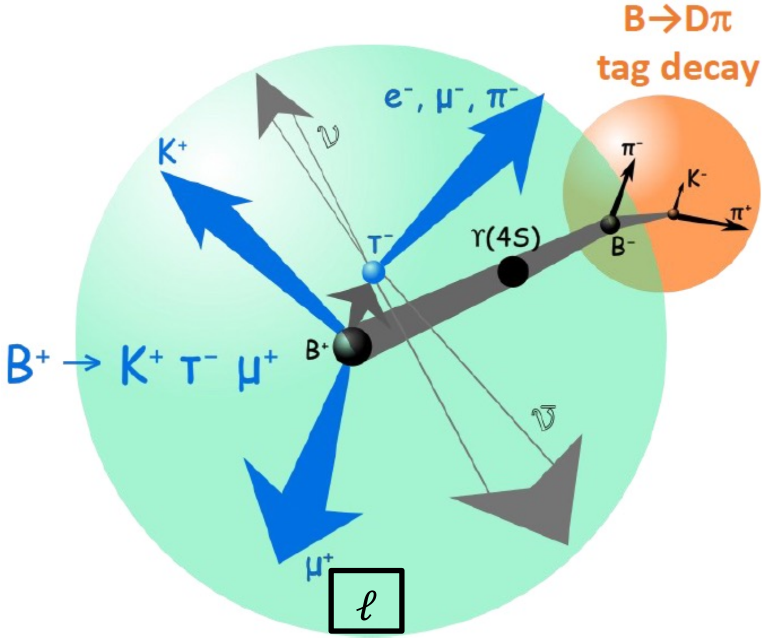
Search for $B^+ \to K^+\tau^\pm\ell^\mp$

PRL 130, 261802 (2023)

- BSM models with vector leptoquark (U_1) provide interesting lower bounds on the $b \to s\tau\mu$ transition with $\mathcal{B} \sim 10^{-7}$

- In the signal side, $B^+ \to K^+\tau^\pm\ell^\mp$ is reconstructed using $\tau \to e\nu_e\nu_\tau$, $\mu\nu_\mu\nu_\tau$, and $\pi\nu_\tau$ (no constraints on neutrals)
- The tag-side B meson is fully reconstructed in hadronic decay channels ⇒ hadronic tagging
- Used the full event interpretation algorithm, developed for B-tagged analyses at Belle (II) Comput. Software Big Sci. 1, 6 (2019)

- Extract the signal yield by fitting the recoil mass of the system containing the charged kaon and primary lepton, M_{recoil}, with no kinematic info from τ decay products
- Signal modes are categorised into:
  - $\text{OS}_{\mu/e}$, where $\ell(\mu/e)$ and kaon have the opposite charge
  - $\text{SS}_{\mu/e}$, where $\ell(\mu/e)$ and kaon have the same charge



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

PRL 130, 261802 (2023)

Dominant background sources:

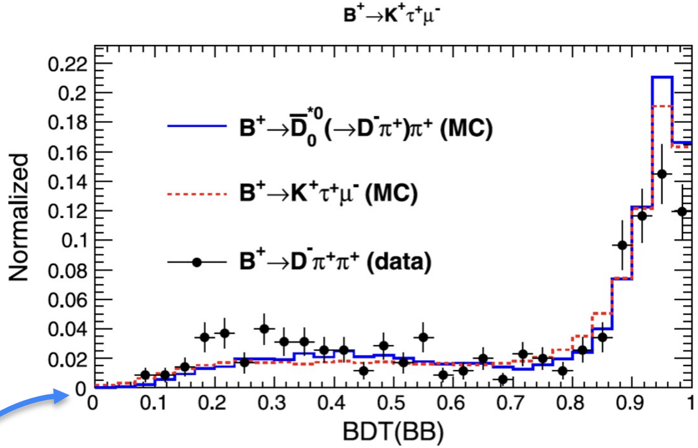
- $B \to D^0(K\ell\nu_\ell)X$ for $\mathrm{OS}_{\mu/e}$
- $B \to D^0(KX)X\ell\nu_\ell$ for $\mathrm{SS}_{\mu/e}$

Designed two separate BDT classifiers against:

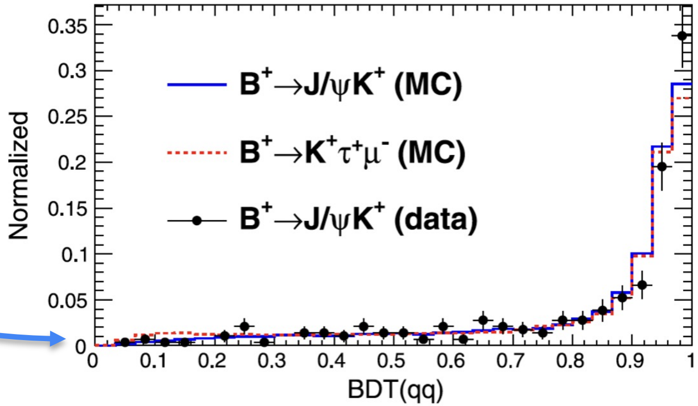
- ❑ $B\bar{B}$ background (kinematic info as well as topology of B_{sig} and info on extra clusters)
- ❑ Continuum $q\bar{q}$ (event-shape variables)

Control samples used for calibration:

- $B^+ \to D^-\pi^+\pi^+$ for $B\bar{B}$ suppression BDT
- $B^+ \to J/\psi K^+$ for $q\bar{q}$ suppression BDT



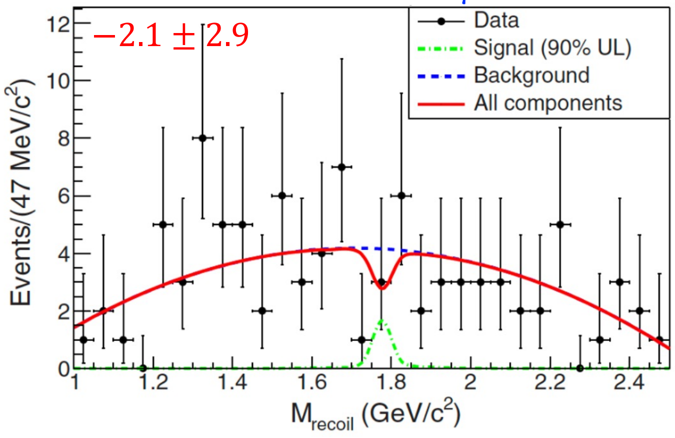
$711\ \mathrm{fb}^{-1}$ data at $\Upsilon(4S) \Rightarrow 772\times10^6 B\bar{B}$ events



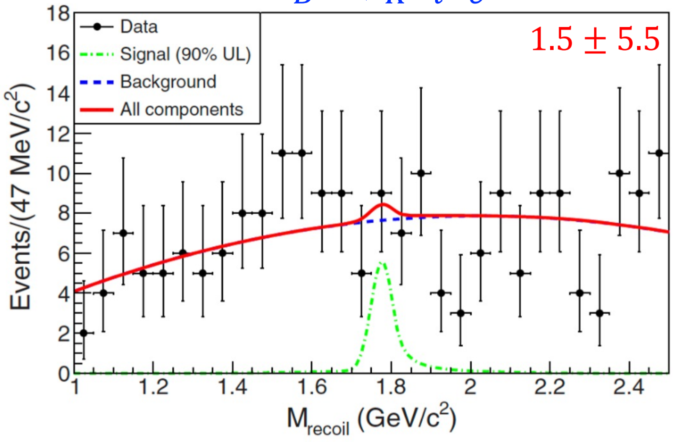
Search for $B^+ \to K^+\tau^\pm\ell^\mp$

PRL 130, 261802 (2023)

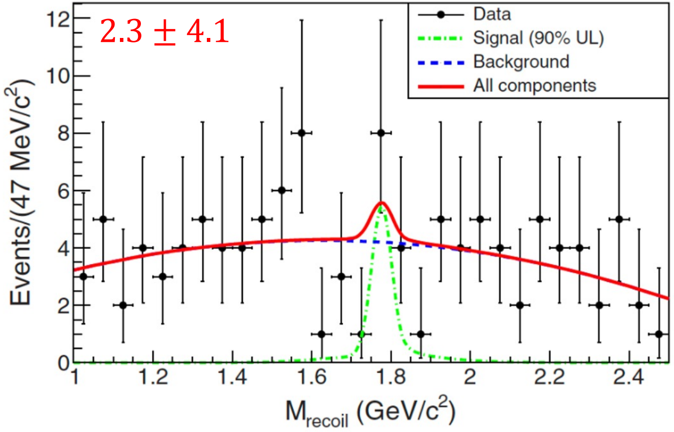
$B^+ \to K^+\tau^+\mu^-$



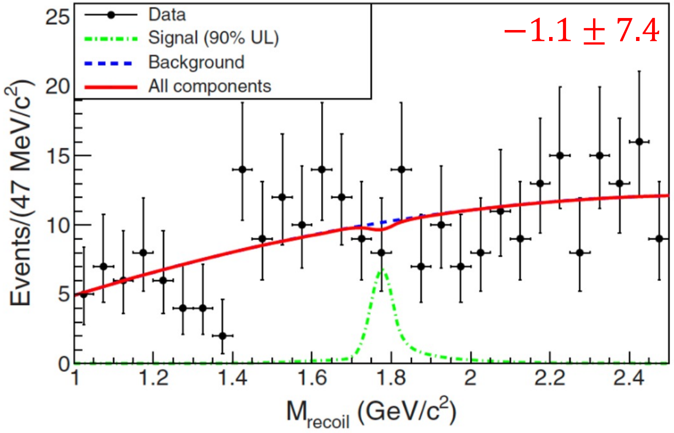
$B^+ \to K^+\tau^+e^-$



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



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



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

- In absence of any significant signals, upper limits are set with a frequentist method

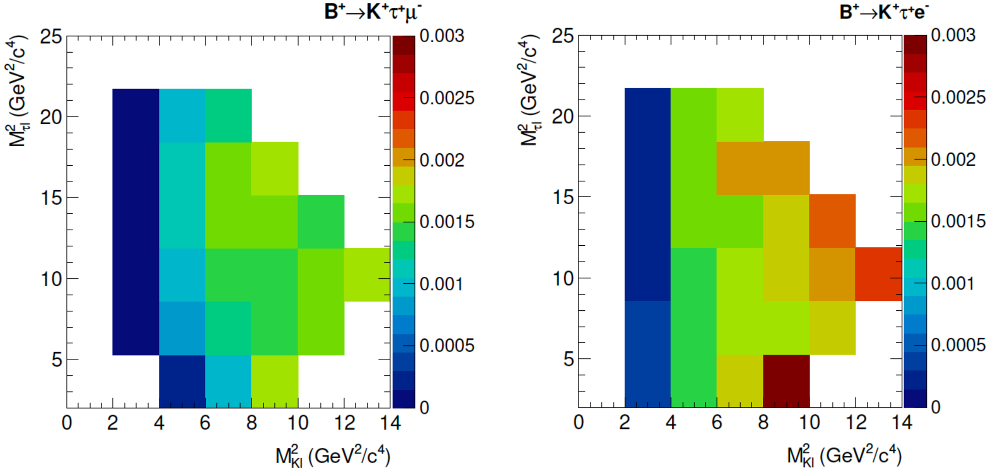
✓ Results obtained are the most stringent to date

❑ Presented the signal efficiency as function of Dalitz plot, which can be used to re-cast the results for various BSM models

PRD 86, 012004 (2012) JHEP 06, 129 (2020)

90% CL	BABAR ($\times 10^{-5}$)	LHCb ($\times 10^{-5}$)	Belle ($\times 10^{-5}$)
$B^+ \to K^+\tau^+e^-$	< 1.5		< 1.5
$B^+ \to K^+\tau^-e^+$	< 4.3		< 1.5
$B^+ \to K^+\tau^+\mu^-$	< 2.8	< 3.9	< 0.6
$B^+ \to K^+\tau^-\mu^+$	< 4.5		< 2.3

PRL 130, 261802 (2023)



JHEP 06, 143 (2023)

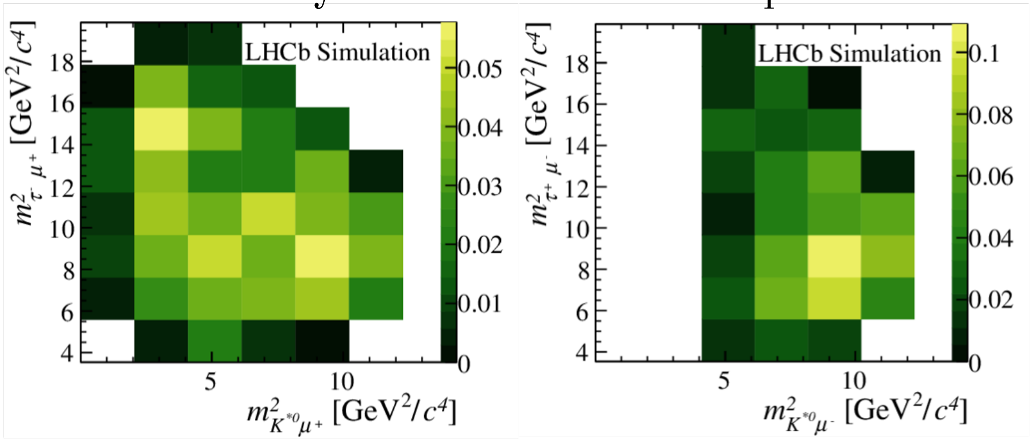
Search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$

- **First ever** search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$ with $K^{*0} \to K^+\pi^-$, $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ or $\pi^-\pi^+\pi^-\pi^0\nu_\tau$
- Signal modes are categorized into two categories:
  1) events with the charged kaon and tau having opposite charges
  2) events with the charged kaon and tau having the same charge

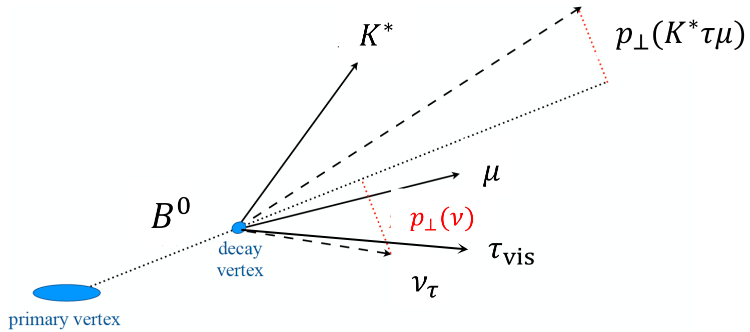
  as they could be affected differently by BSM contributions and by different background sources

- Signal yield is extracted by fitting the distributions of corrected mass: $m_{\text{corr}} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$

Efficiency as a function of Dalitz plot



$B^0 \to K^{*0}\tau^+\mu^-$ $B^0 \to K^{*0}\tau^-\mu^+$



- Used data collected at c.m. energies of 7 and 8 TeV in 2011-2012 (Run 1) and 13 TeV in 2015-2018 (Run 2) $\Rightarrow$ 9 fb^{-1}

Search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

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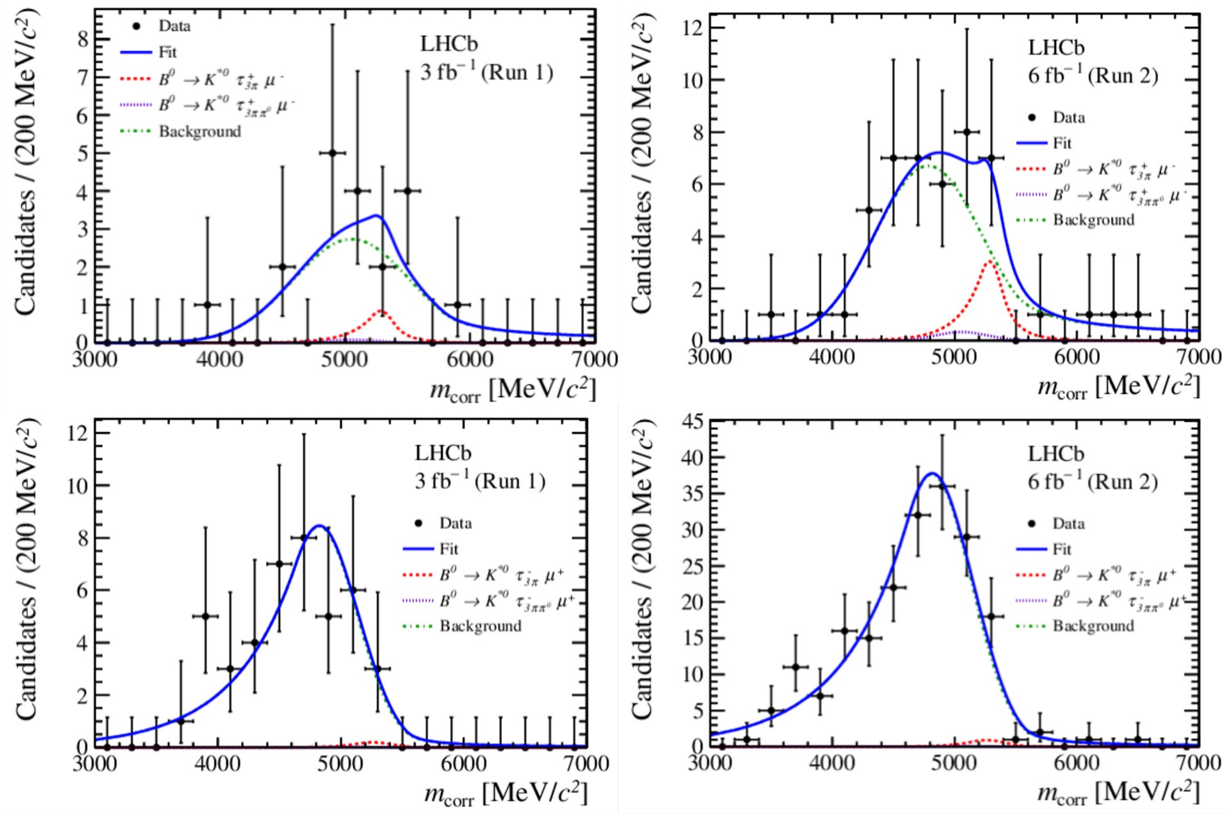
- For each mode, the m_{corr} distribution is described as a sum of three event components: signal ($K^{*0}\tau_{3\pi}\mu$ and $K^{*0}\tau_{3\pi\pi^0}\mu$) as well as background



Distributions of m_{corr} of selected $B^0 \to K^{*0}\tau^+\mu^-$ candidates in (left) Run 1 and (right) Run 2 data

Distributions of m_{corr} of selected $B^0 \to K^{*0}\tau^-\mu^+$ candidates in (left) Run 1 and (right) Run 2 data

Search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

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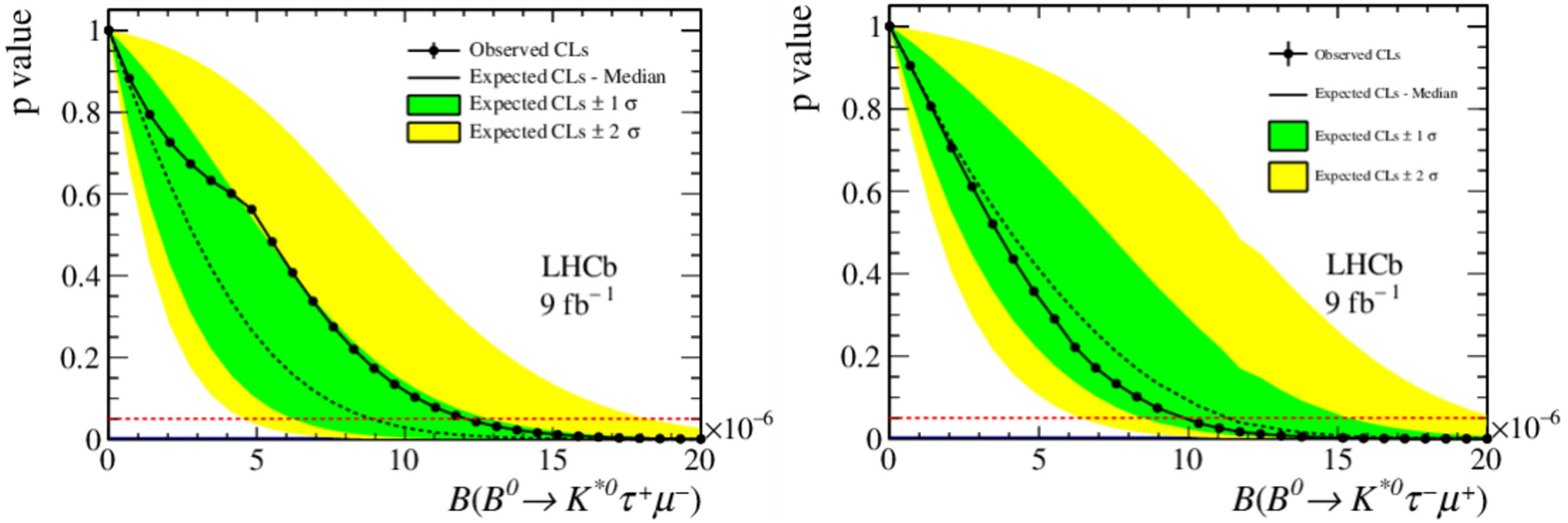


No significant signal is observed, and set the upper limits:

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\times10^{-5} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2\times10^{-6} \text{ at } 90\% \text{ CL}$$

☞ Worse than expected limit for the $B^0 \to K^{*0}\tau^+\mu^-$ mode due to upward fluctuations

Search for $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

- Generic Z' models could enhance $\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp)$ to as large as $\mathcal{O}(10^{-7})$ PRD 92, 054013 (2015)
- Reconstruct:
  - $B^0 \to K^{*0}\mu^\pm e^\mp$ with $K^{*0} \to K^+\pi^-$
  - $B_s^0 \to \phi\mu^\pm e^\mp$ with $\phi \to K^+K^-$

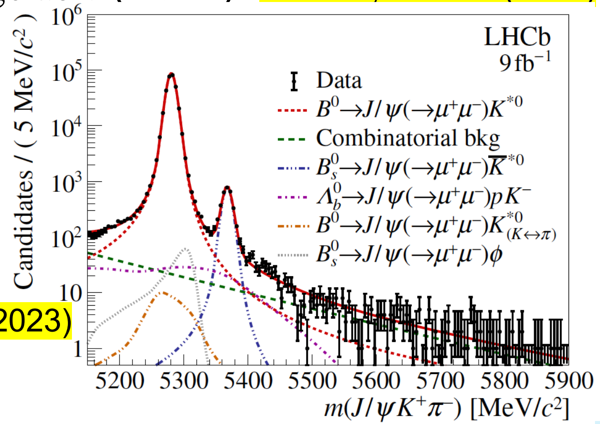
Peaking backgrounds:

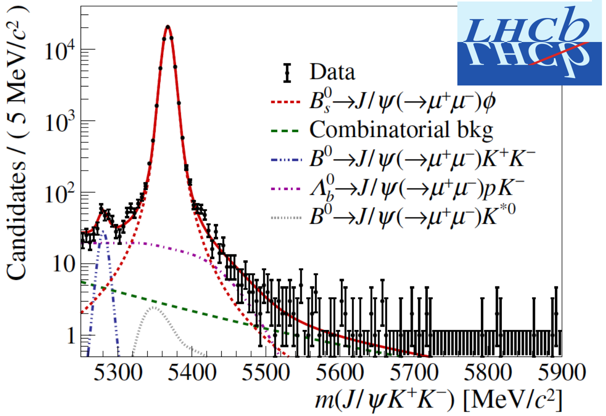
$B^0 \to J/\psi(\to \ell^+\ell^-)K^{*0}$ and $B^0 \to \psi(2S)(\to \ell^+\ell^-)K^{*0}$ JHEP 06, 073 (2023)

$B_s^0 \to J/\psi(\to \ell^+\ell^-)\phi$ and $B_s^0 \to \psi(2S)(\to \ell^+\ell^-)\phi$

Background suppression:

- Combinatorial background are suppressed using a BDT
- Features include p_T of $B^0_{(s)}$ candidate, its vertex fit quality and flight distance significance, the angle between the $B^0_{(s)}$ momentum and the vector connecting to the associated PV
- Signal efficiency is in the 55–80% range with greater than 99% background rejection depending on modes





Mass distributions of normalisation modes

Search for $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

- Signal yield is extracted by fitting the B^0 [B_s^0] mass distributions and translated to the signal branching fraction $\mathcal{B}_{\text{sig}}$ using the normalization mode $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}$ [$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$]:

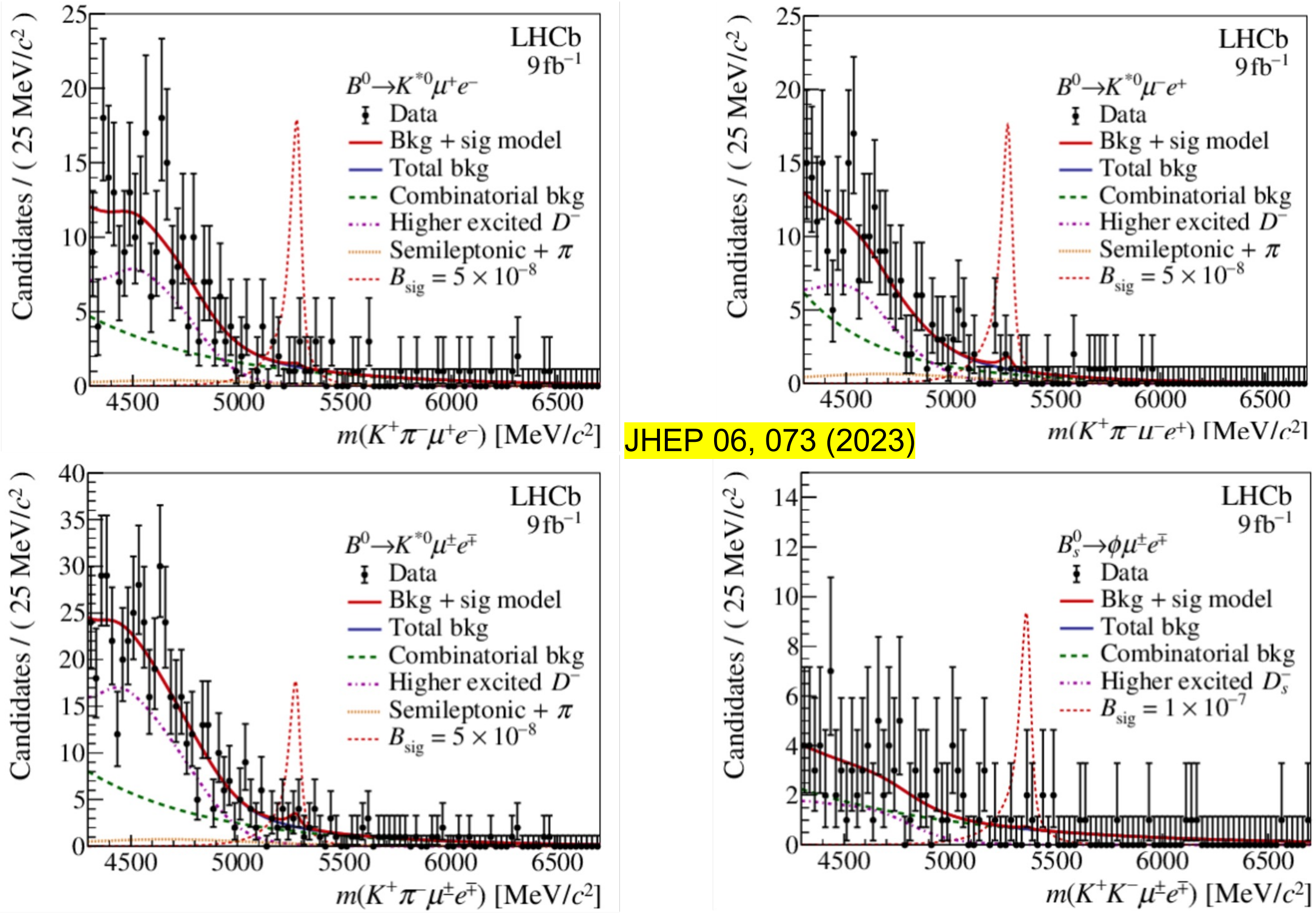
$$\mathcal{B}_{\text{sig}} = \underbrace{\frac{\mathcal{B}_{\text{norm}}}{N_{\text{norm}}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}}_{=\alpha} \times N_{\text{sig}}$$

JHEP 06, 073 (2023)

	$\alpha \pm (\sigma_{\text{stat}} \oplus \sigma_{\text{syst}})$ $[10^{-9}]$		
Mode	2011–2012	2015–2016	2017–2018
$B^0 \to K^{*0}\mu^+e^-$	2.47 ± 0.14	2.38 ± 0.16	1.49 ± 0.09
$B^0 \to K^{*0}\mu^-e^+$	2.50 ± 0.15	2.39 ± 0.16	1.49 ± 0.09
$B^0 \to K^{*0}\mu^\pm e^\mp$	2.48 ± 0.14	2.39 ± 0.16	1.49 ± 0.09
$B_s^0 \to \phi\mu^\pm e^\mp$	9.50 ± 0.70	9.68 ± 0.78	5.09 ± 0.39

- The year-to-year variation in α is due to different BDT criteria used against combinatorial background, tuned individually for each data-taking period and mode

Search for $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$



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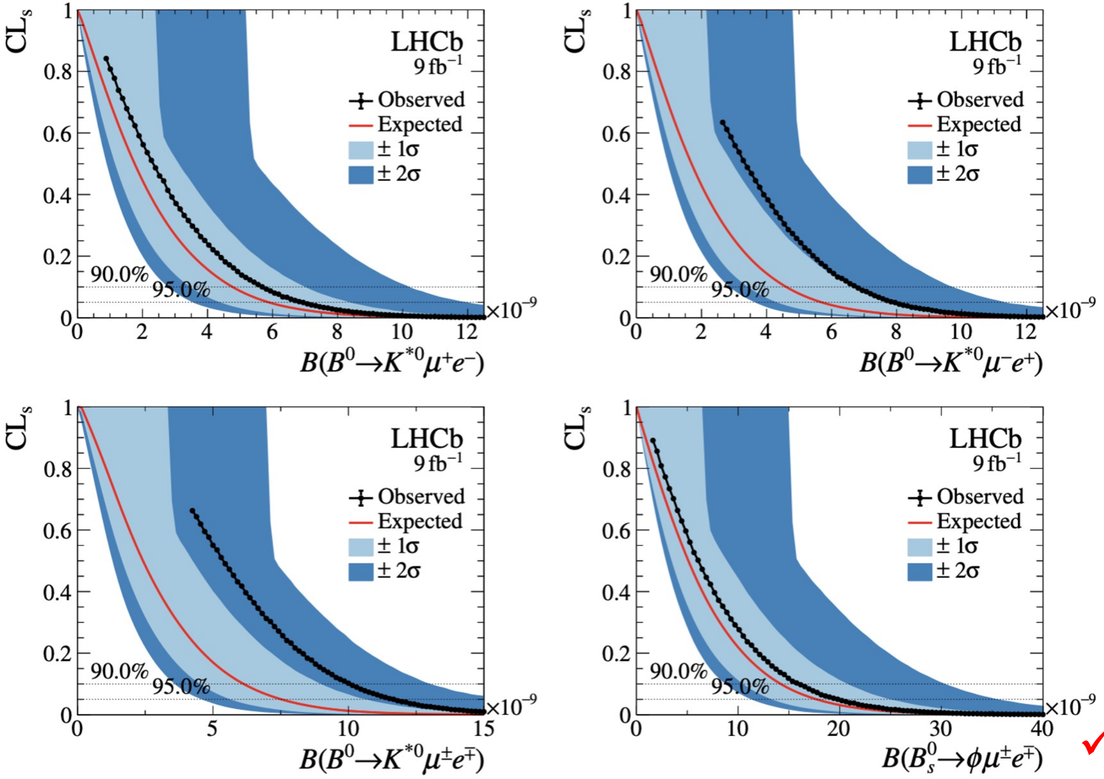
Search for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$



No significant signal is observed, upper limits are set at 90% (95%) CL

JHEP 06, 073 (2023)

The expected and observed upper limits [$\times10^{-9}$] at 90% (95%) CL are listed below:

Mode	Expected	Observed
$B^0 \to K^{*0}\mu^+e^-$	4.8 (5.9)	5.7 (6.9)
$B^0 \to K^{*0}\mu^-e^+$	4.6 (5.7)	6.8 (7.9)
$B^0 \to K^{*0}\mu^\pm e^\mp$	6.1 (7.5)	10.1 (11.7)
$B_s^0 \to \phi\mu^\pm e^\mp$	14.2 (17.7)	16.0 (19.8)

✓ World's most stringent limits with $B_s^0 \to \phi\mu^{\pm}e^{\mp}$ the first one to be set

Summary

- We have reported four new results, two each from Belle and LHCb; Belle II will soon be in the game
- In absence of significant signals, upper limits have been set in the range 10^{-4} to 10^{-5} for modes with taus and 10^{-9} for modes with electrons and muons
- These results being statistically limited, we expect tighter constraints once more data are collected with Belle II and LHCb