Non-τ LFV/LFU measurements at Belle and Belle II

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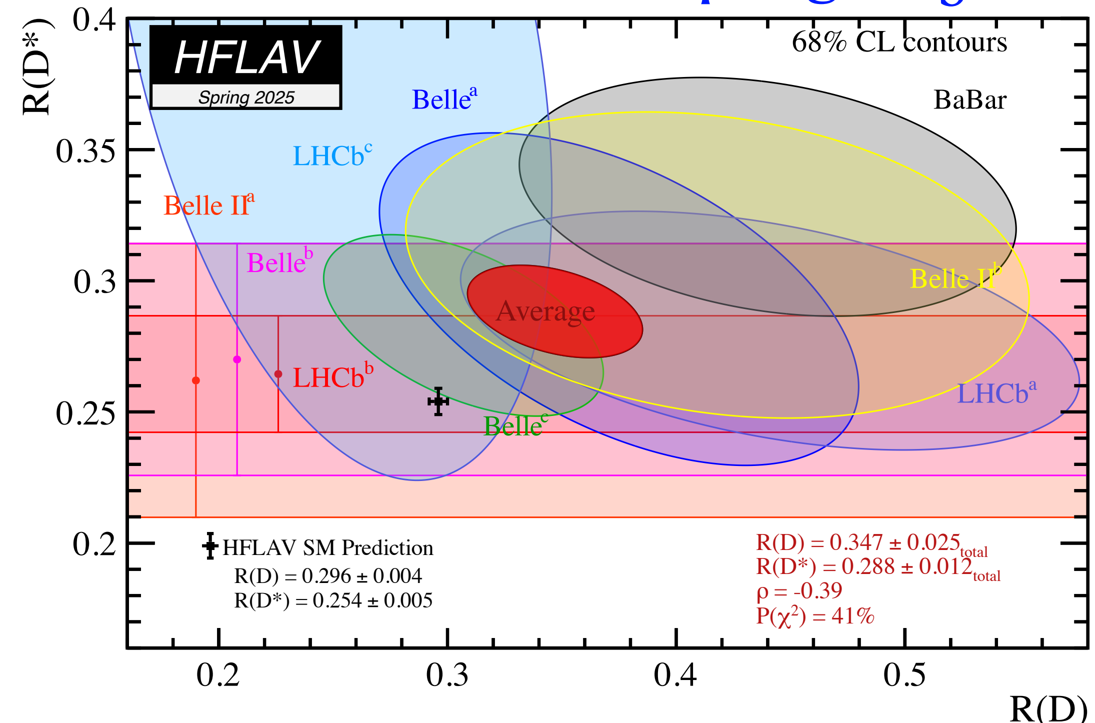
(On behalf of Belle II collaboration)

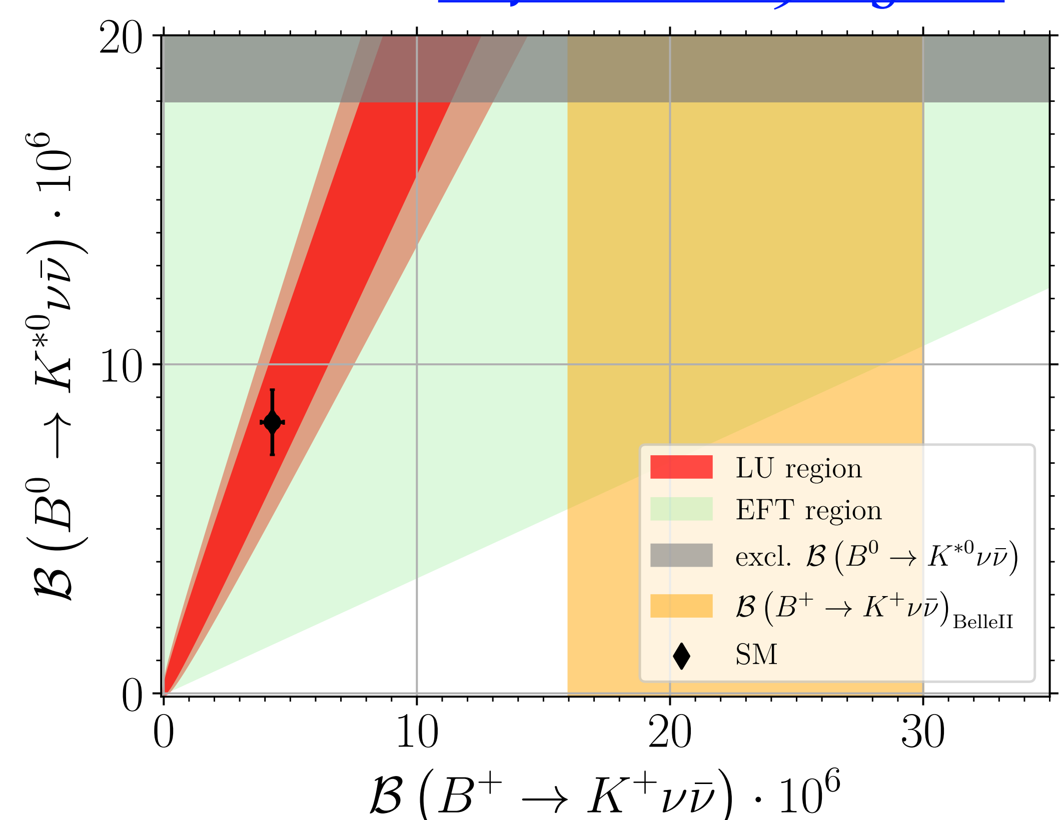
Why LFU and LFV?

- Deviation of $b \to c\ell\nu$ from SM predictions indicates the violations of lepton flavor universality (LFU).
- Recent evidence of $B^+ \to K^+\nu\bar{\nu}$ with a 2.7σ deviation from SM and the measurements of $b \to s\ell\ell$ processes enhence the possibility of physics beyound SM.
- Models describing LFU violations predict the enhancement of lepton flavor violation (LFV).
- LFV processes are deeply suppressed in the SM and give potential access to new physics beyond SM.

HFLAV, Spring 2025

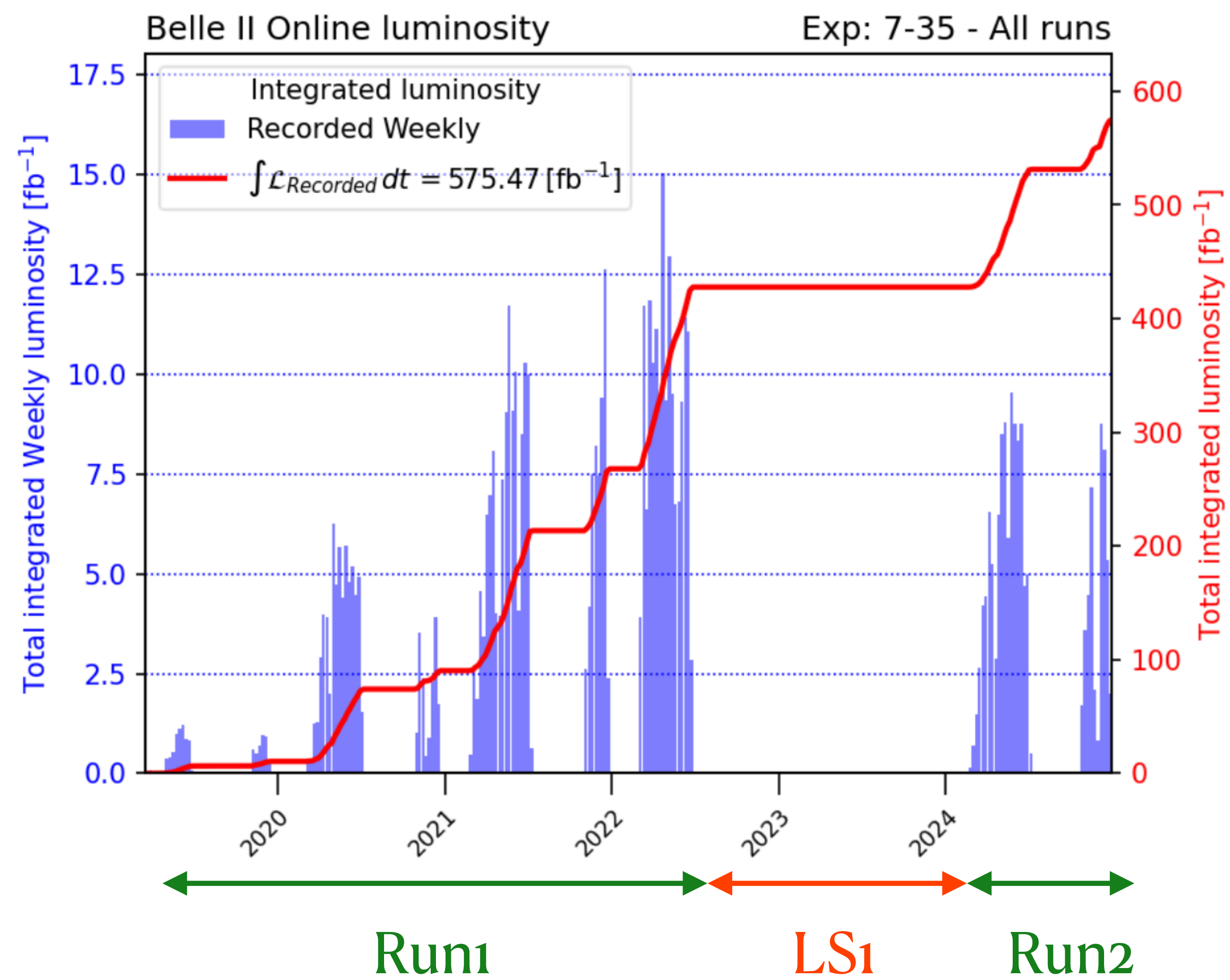


PhysRevD.109.015006



Belle and Belle II experiments

- Belle (1999 - 2010):
  - Integrated Luminosity ~ 1000 fb^{-1}
- Belle II Run1 (2019 - 2022):
  - Integrated Luminosity ~ 424 fb^{-1}
- Belle II Run1 (2024 - Ongoing):
  - Integrated Luminosity ~ 150 fb^{-1}
  - Peak luminosity $5.1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$



Belle Datasets

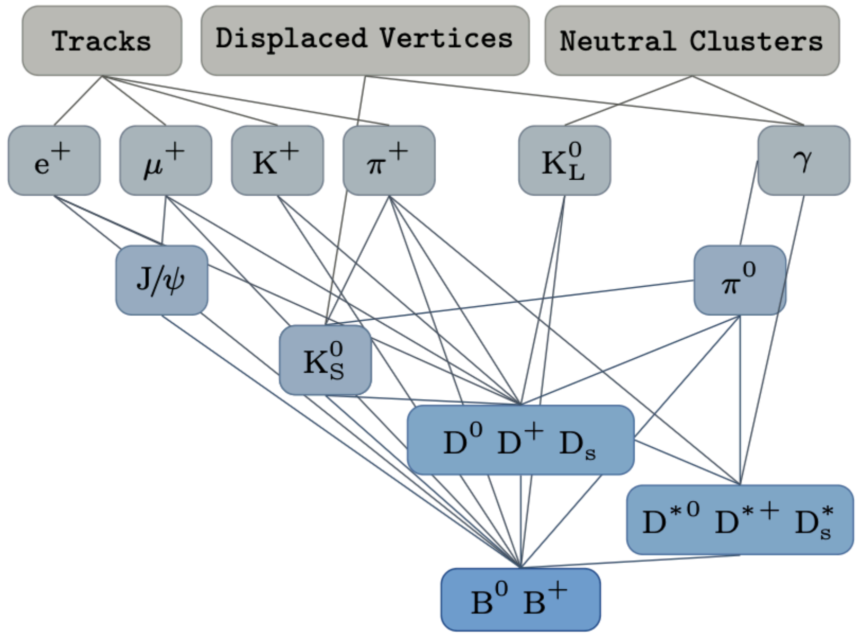
Resonance	Energy (GeV)			Luminosity (fb^{-1})
	HER	LER	$\sqrt{s}$	
$\Upsilon(1S)$	7.1511	3.1286	9.4603	6
$\Upsilon(2S)$	7.5750	3.3141	10.023	25
$\Upsilon(3S)$	7.8262	3.4240	10.355	3
$\Upsilon(4S)$	7.9988	3.4995	10.579	711
$\Upsilon(5S)$	8.2150	3.5941	10.860	121

$\Upsilon(4S)$	ON	OFF
Belle	711 fb^{-1}	90 fb^{-1}
Belle II	575 fb^{-1}	42 fb^{-1}

Study of LFV in Belle (II) experiment

- The Belle (II) experiment provides a clean environment for precision measurements.
- LFU/LFV searches often require missing energy techniques. Full event interpretation (FEI) algorithm provides the information of missing particles.
- Plenty of LFV searches are possible in decays of τ leptons, B mesons, B_S^0 mesons, quarkoniums, etc.
- Topics to cover in this talk:
  - Search for $B \to K^{*0}\tau^{\pm}\ell^{\mp}$ [arxiv:2505.08418]
  - Search for $B \to K_S^0\tau^{\pm}\ell^{\mp}$ [arxiv:2412.16470]
  - Search for $\chi_{bJ}(1P) \to \ell_1^{+}\ell_2^{-}$ [*New*]

- MVA-based tagging algorithm.
- Hierarchical approach to reconstruct thousands of decays.
- B tagging efficiency

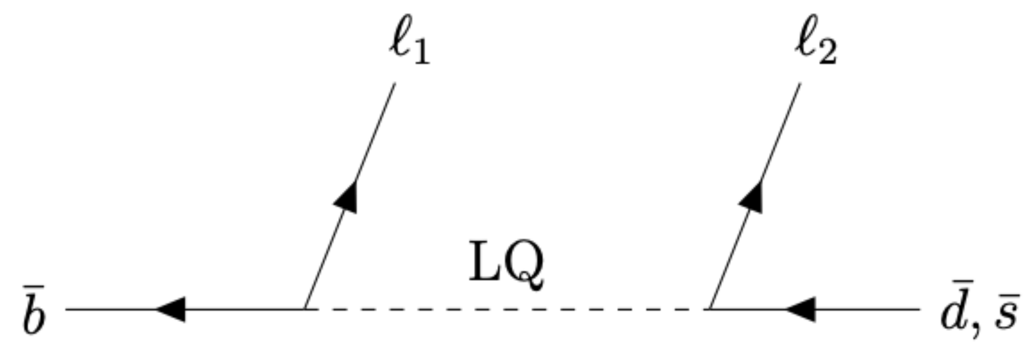


Search for $B \to K^{*0}\tau^{\pm}\ell^{\mp}$

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

JHEP08(2025)184

Motivation:



- Previously, LHCb experiment has reported results for $B^0 \to K^{*0}\tau^+\mu^-(\tau^-\mu^+) < 1.0(0.8) \times 10^{-5}$. JHEP06(2023)143

- There were no existing results from B-factories.

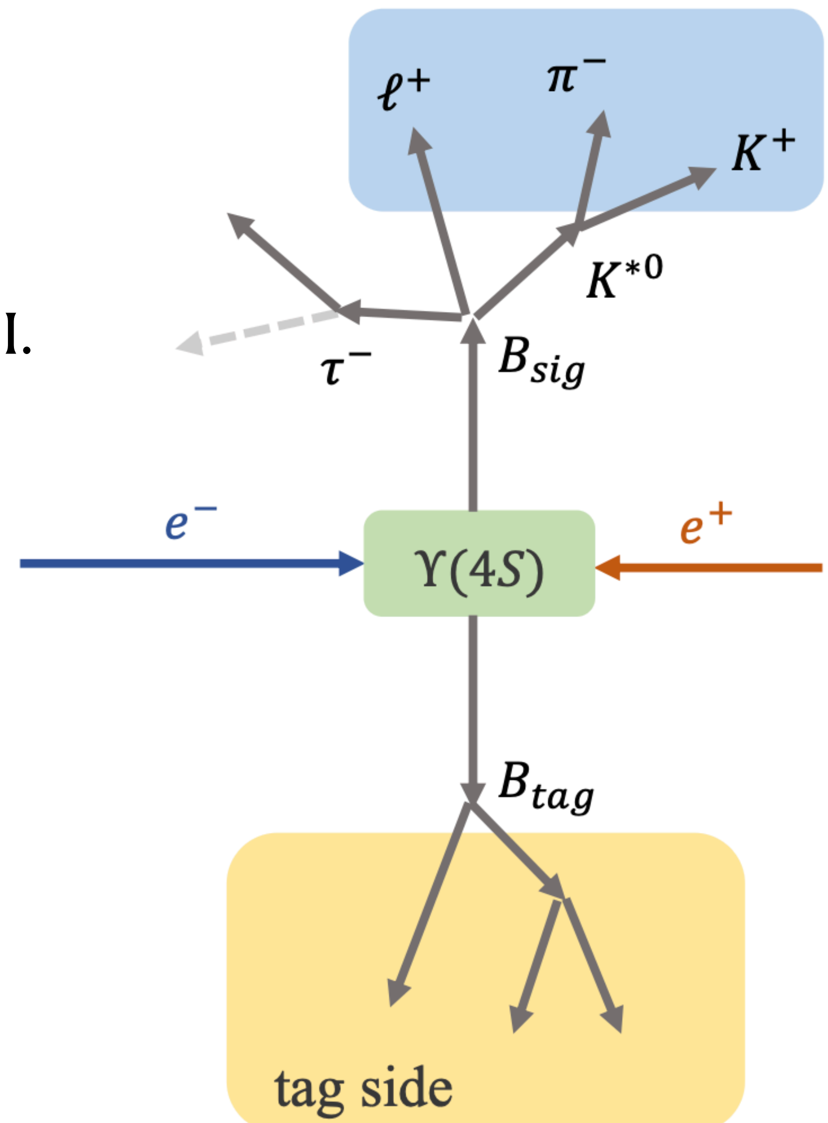
Analysis strategy:

- This analysis uses full Belle and Run1 data from Belle II.

- The tag side B meson is fully reconstructed using hadronic tagging method.

- The signal-side τ lepton is reconstructed inclusively, requiring 1-prong.

$$\vec{p}_\tau = -\vec{p}_{B_{\text{tag}}} - \vec{p}_{K^{*0}} - \vec{p}_\ell \qquad E_\tau = E_{\text{beam}} - E_{K^{*0}} - E_\ell\,.$$

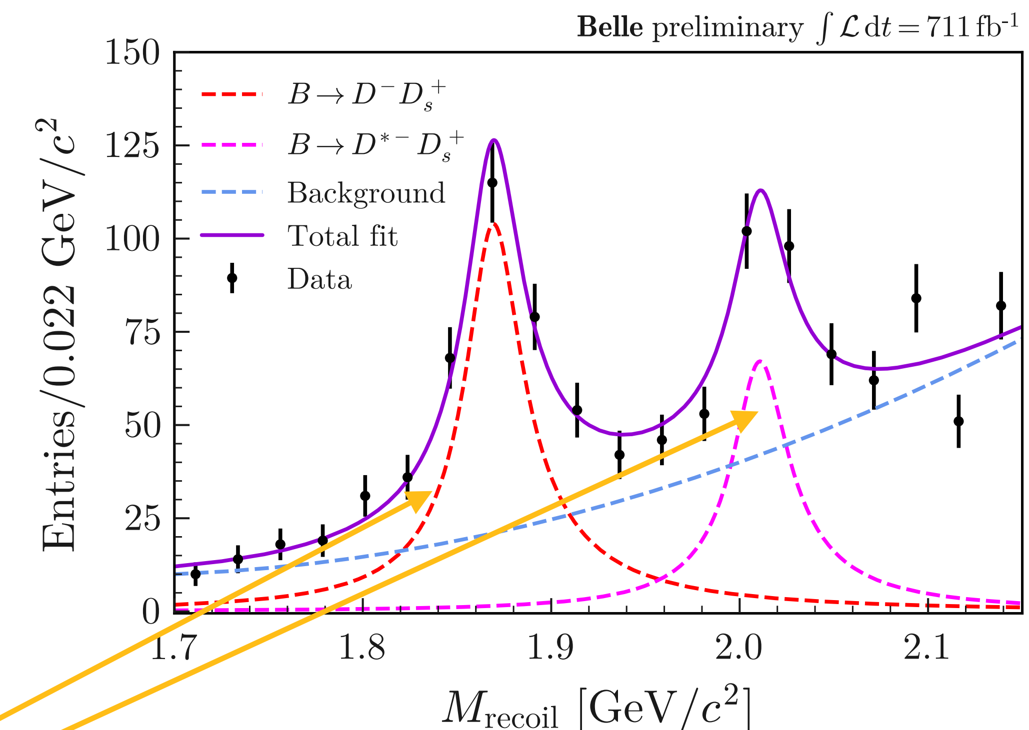


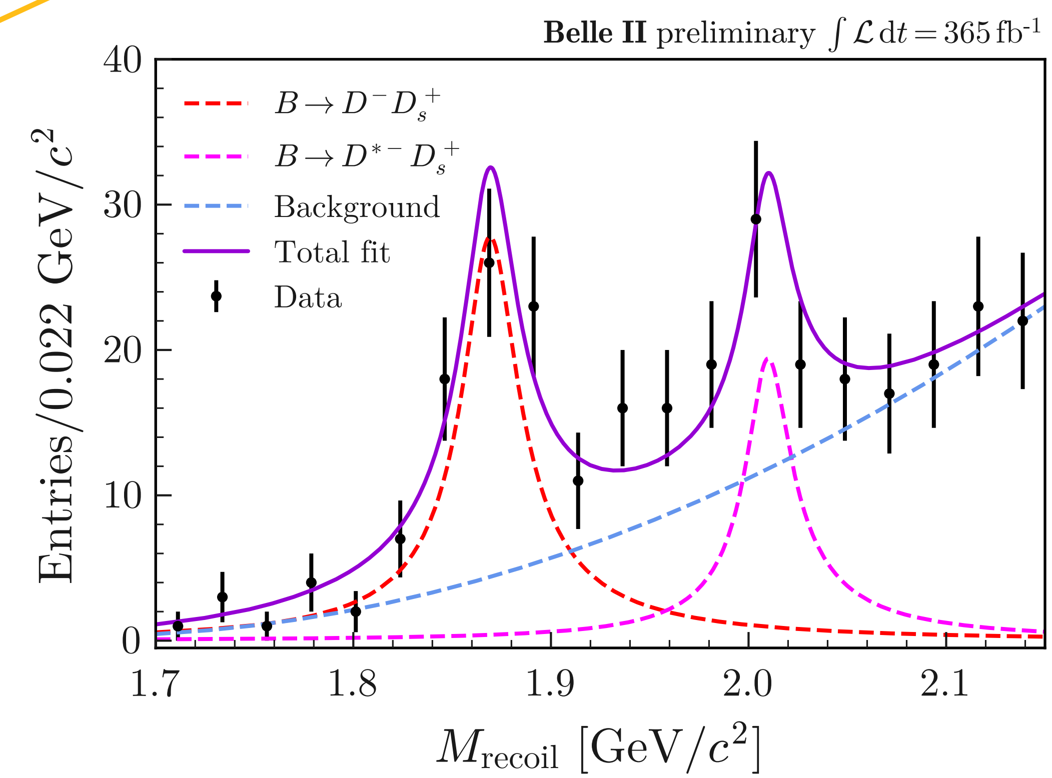
Search for $B \to K^{*0}\tau^{\pm}\ell^{\mp}$

JHEP08(2025)184

Belle + Belle II 1076fb^{-1}

- B_{tag} requires M_{bc} greater than 5.27 GeV/c^2.
- Dominant background:
  - for $K^{*0}\tau^-\ell^+$: $B \to D\ell\nu, D \to K\pi\pi$
  - for $K^{*0}\tau^+\ell^-$: $B \to DX, D \to K^{*0}\ell\nu$
- Boosted Decision Tree (BDT) is used to suppress the remaining background.
  - Variables used: $K^{*0}\ell$ vertex, Fox-Wolfram moments, rest of the events, other masses and momenta.
- Control modes: $B^0 \to D_s^+ D^{(*)-}, D_s^+ \to K^{*0}K^+/\phi\pi^+$
  - Used for validation and BDT correction.





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

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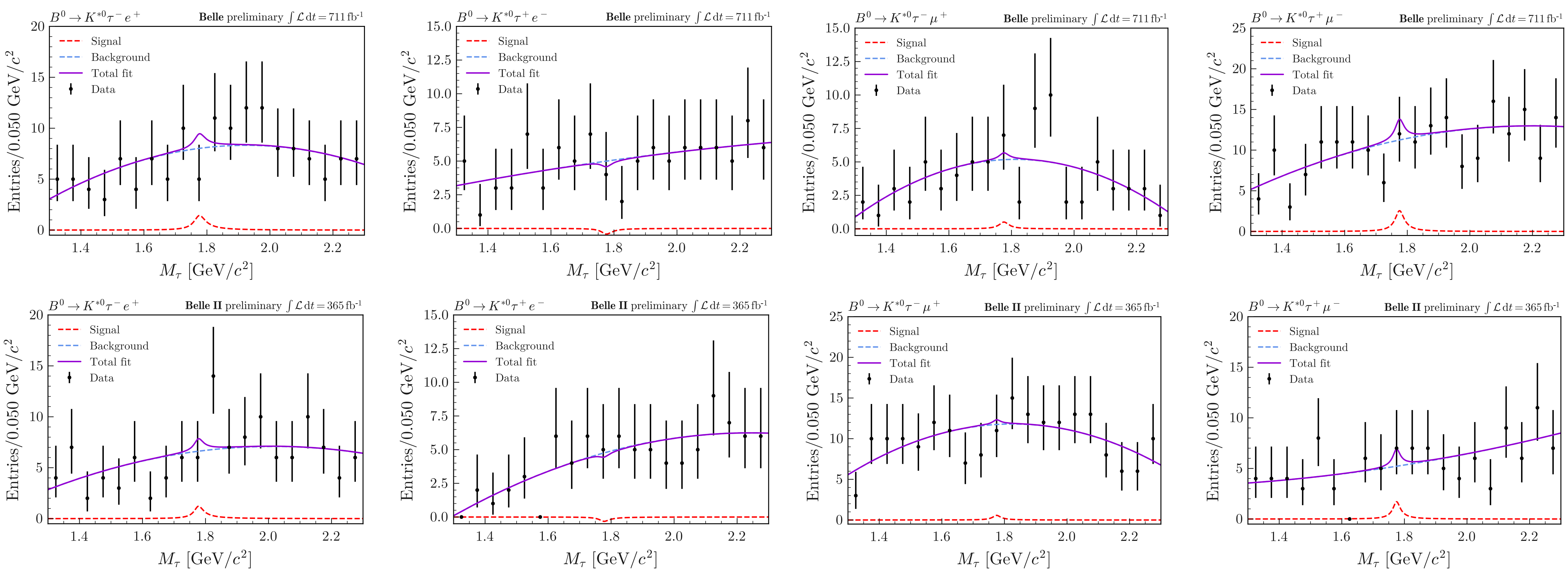
- We fit the Belle and Belle II datasets simultaneously. Belle + Belle II $1076 \mathrm{fb}^{-1}$



$$\mathcal{B}(B^0 \to K^{*0}\tau^+e^-) < 2.9 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-e^+) < 6.4 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 5.6 \times 10^{-5}$$

- In the absence of significant signal events, we provide upper limits at 90% CL.
- First reported ULs for $B \to K^{*0}\tau^{\pm}\ell^{\mp}$ in B-factories.

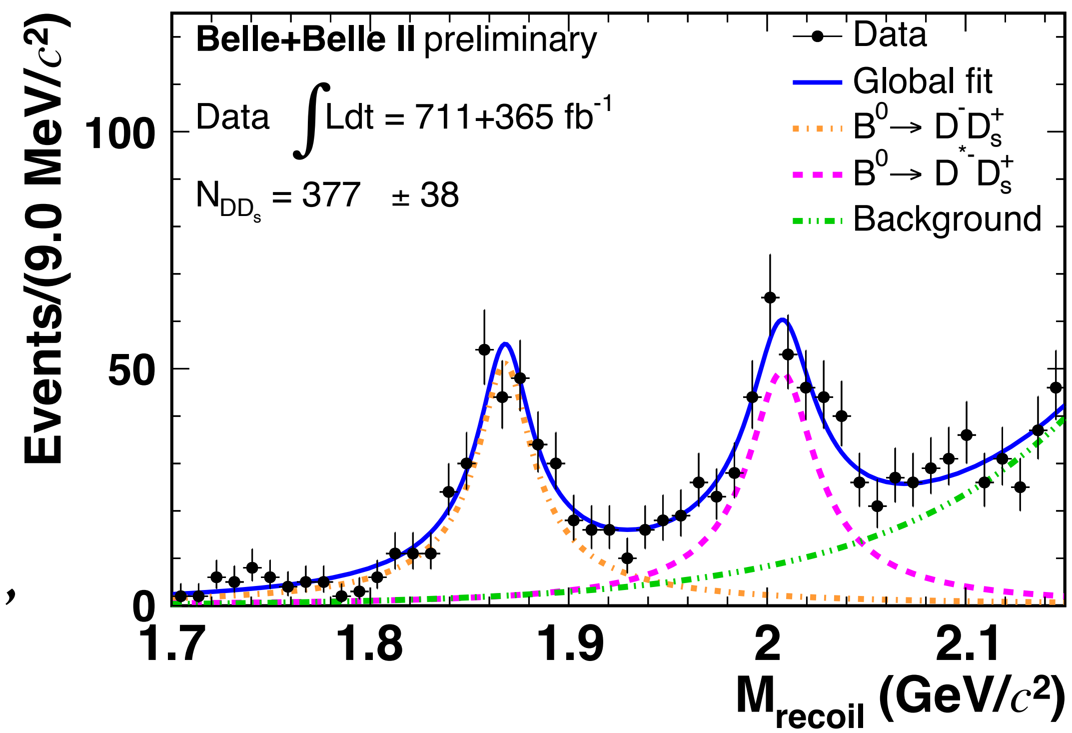
**Interesting LHCb preliminary result: arxiv:2506.15347

Search for $B \to K_S^0 \tau^{\pm} \ell^{\mp}$

Search for $B \to K_S^0 \tau^\pm \ell^\mp$

arxiv:2412.16470

- The analysis strategy is similar to $B \to K^{*0}\tau^\pm\ell^\mp$.
- The signal side τ is reconstructed in 1-prong decays.
- We use a specific veto for $B^0 \to J/\psi K_S^0$ background.
- Contron modes: $B^0 \to D_s^+ D^{(*)-}$, $D_s^- \to K_S^0 K^+/\phi\pi^-$, where D_s works as a dummy system for $K_S^0\ell$.
- Control modes used to validate of BDT and fit PDF.



$$M_{\rm recoil} = M_\tau = \left[m_B^2 + M_{K_S^0\ell}^2 - 2\left(E_{\rm beam}E_{K_S^0\ell} + |\vec{p}_{B_{\rm tag}}||\vec{p}_{K_S^0\ell}|\cos\theta\right)\right]^{\frac{1}{2}}$$

Search for $B \to K_S^0 \tau^\pm \ell^\mp$

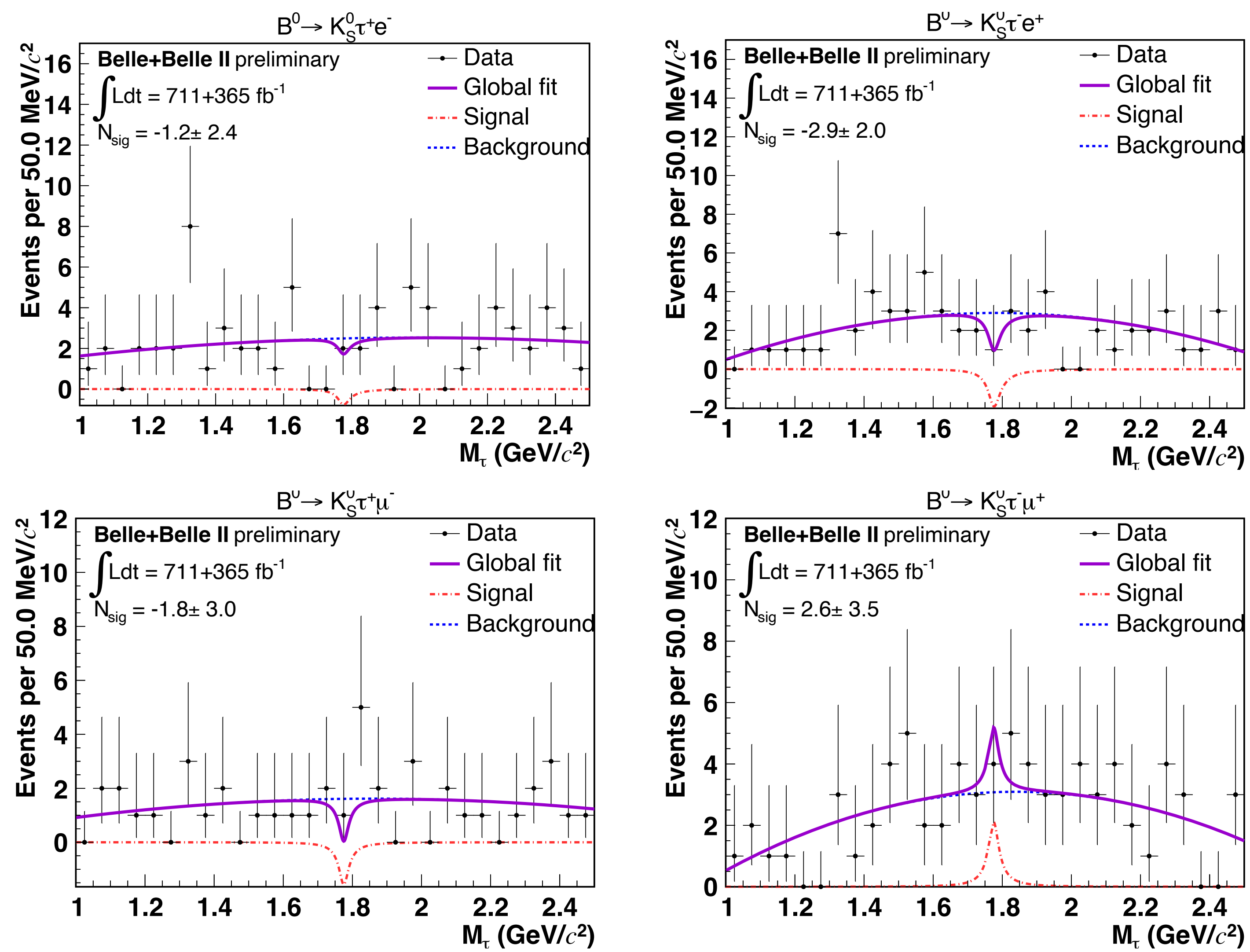
arxiv:2412.16470

- We fit M_τ the distribution from the combined Belle and Belle II datasets.

Belle + Belle II 1076fb^{-1}

- We obtain upper limits at 90% CL using an ensemble of pseudo-experiments.

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$



- We provide the first results on $B \to K_S^0 \tau^\pm \ell^\mp$ searches.

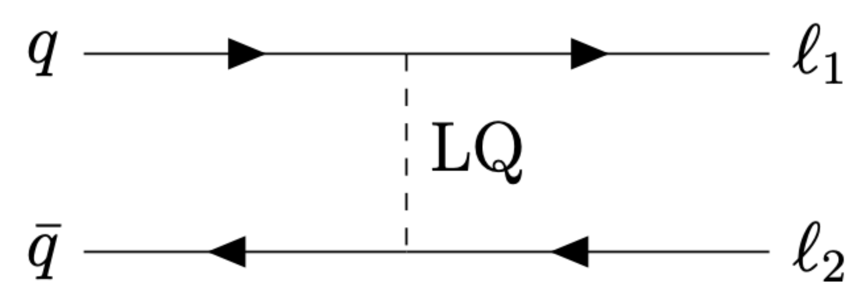
Search for $\chi_{bJ}(1P) \to \ell_1^+ \ell_2^+$

Search for $\chi_{bJ}(1P) \to \ell_1^+ \ell_2^-$

New

Motivation:

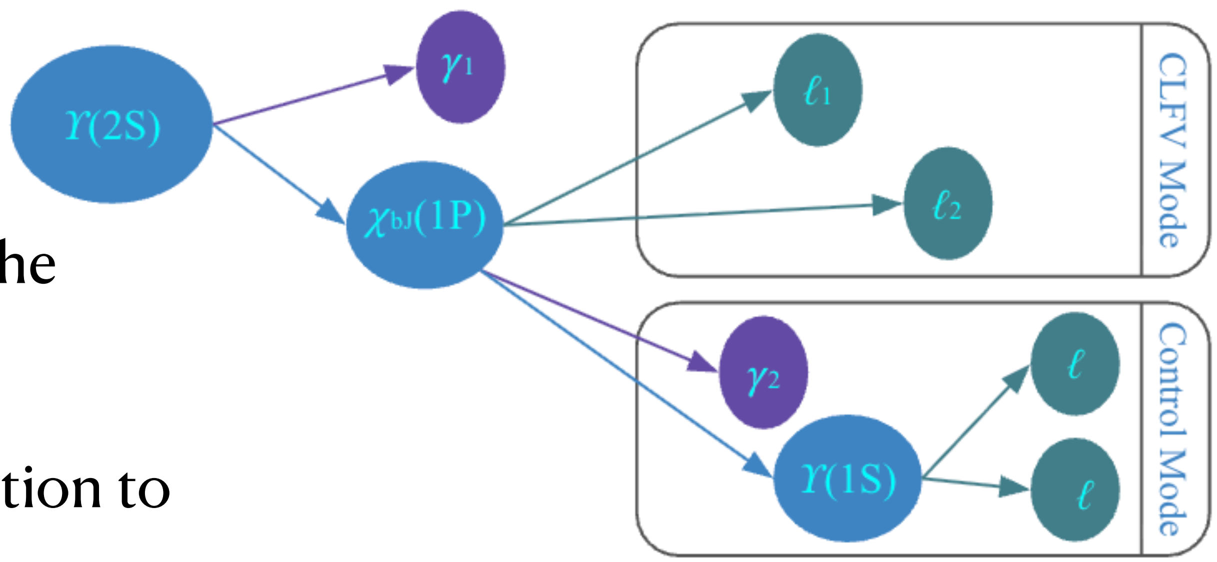
- Several results are available on vector and pseudo-scalar quarkonium decays. No results are available on scalar $q\bar{q}$ decays.



- Diepton decay of $\chi_{b0}(1P)$ is suppressed in the SM $\chi_{b0}(1P) \to \tau^+\tau^- \sim 1.2 \times 10^{-11}$. PhysRevD.93.055014

- But, LFV $\chi_{b0}(1P)$ decay can be significantly higher. PhysRevD.94.074023

Analysis strategy:



- For $\chi_{bJ}(1P) \to e\mu$ modes, fit $M^{\text{recoil}}_{\gamma_1}$ to extract the signal yields.

- For $\chi_{bJ}(1P) \to \ell_1\tau$ decays, we fit $M^{\text{recoil}}_{\gamma_1\ell_1}$ in addition to $M^{\text{recoil}}_{\gamma_1}$ for obtaining the signal yields.

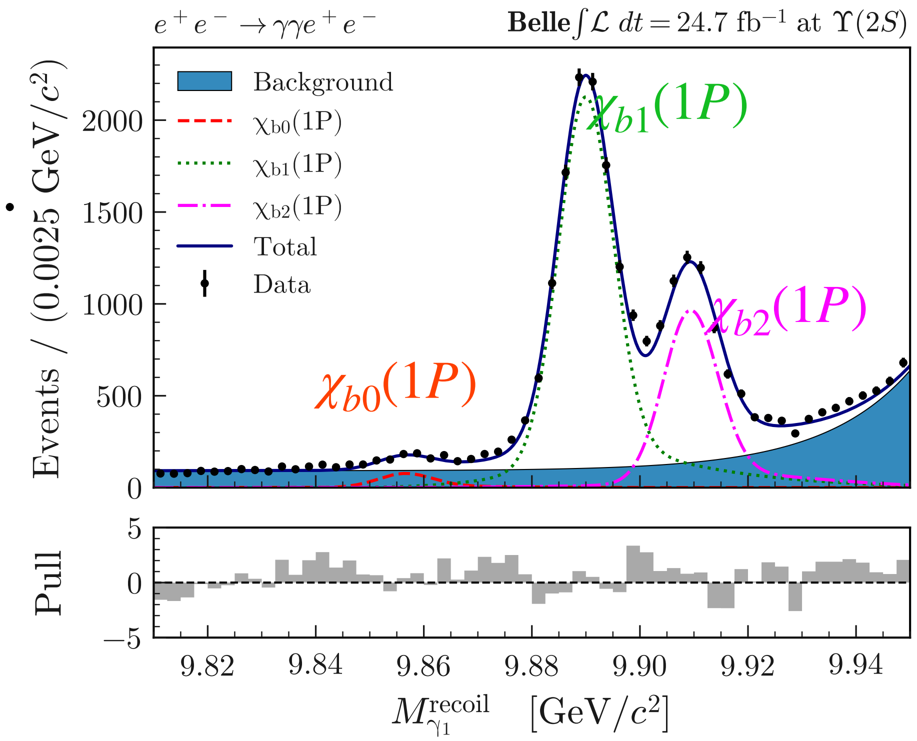
- Using 1.6×10^8 $\Upsilon(2S)$ decays.

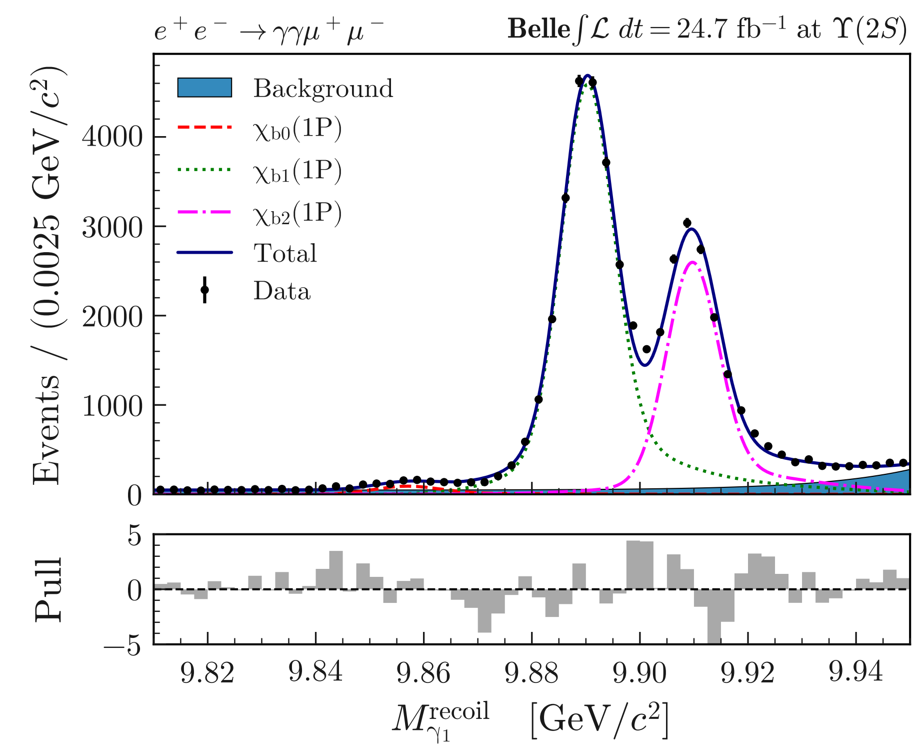
Study of $\chi_{bJ}(1P) \to \gamma \ell^+ \ell^-$

New

- Bhabha veto is simulated to correct the signal efficiency.
- We apply the 4C kinematic fit to improve the resolution.
- Signal yields are extracted from an unbinned fit to $M_{\gamma_1}^{\text{recoil}}$.
- Our results are more precise than the PDG values.

Belle $25\text{fb}^{-1}\Upsilon(2S)$





Decay Mode	Efficiency	Signal yield	Calculated BR (10^{-4})	PDG value (10^{-4})
$\chi_{b0}(1P)$	16.4%	452.8 ± 45.9	$0.175 \pm 0.018 \pm 0.008$	0.176 ± 0.035
$\chi_{b1}(1P)$	15.8%	12894.1 ± 140.5	$5.179 \pm 0.056 \pm 0.228$	5.805 ± 0.581
$\chi_{b2}(1P)$	12.8%	5654.8 ± 116.8	$2.799 \pm 0.058 \pm 0.129$	3.076 ± 0.308

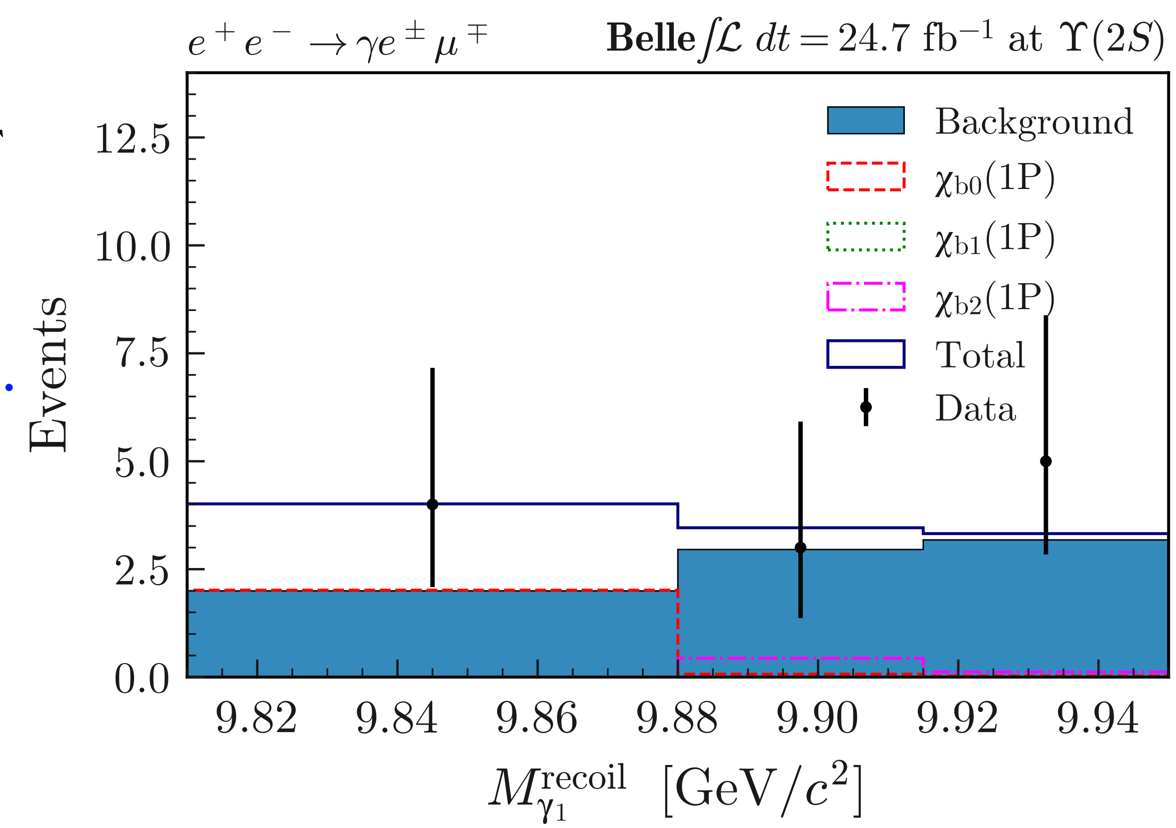
Decay Mode	Efficiency	Signal yield	Calculated BR (10^{-4})	PDG value (10^{-4})
$\chi_{b0}(1P)$	28.0%	648.7 ± 44.3	$0.147 \pm 0.01 \pm 0.006$	0.183 ± 0.037
$\chi_{b1}(1P)$	29.7%	27735.8 ± 194.3	$5.912 \pm 0.041 \pm 0.236$	6.023 ± 0.602
$\chi_{b2}(1P)$	29.0%	14971.6 ± 168.7	$3.267 \pm 0.037 \pm 0.137$	3.192 ± 0.319

Search for $\chi_{bJ}(1P) \to e^{\pm}\mu^{\mp}$

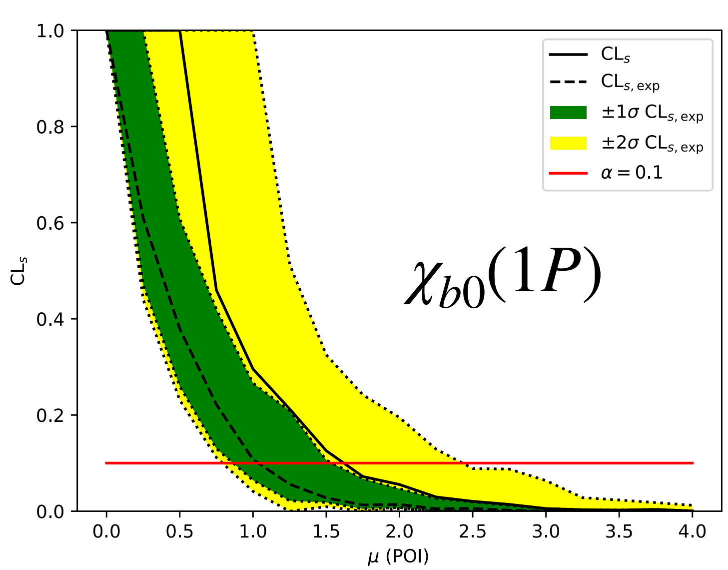
New

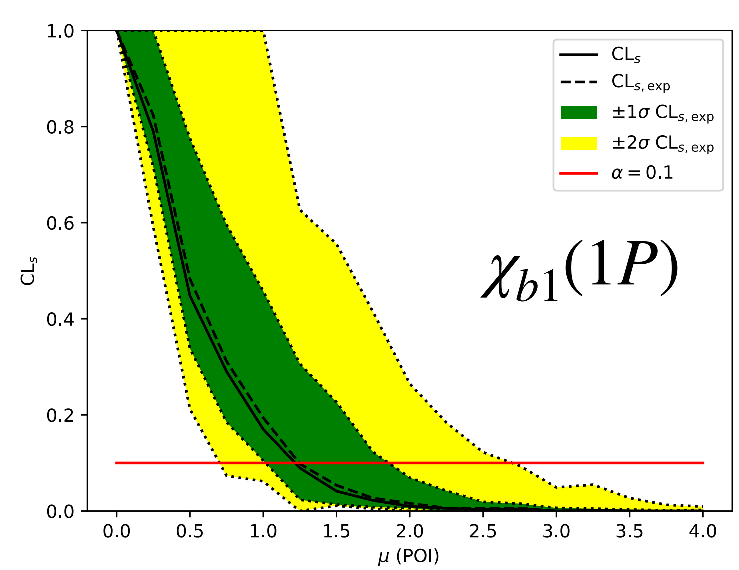
- Signal yields are extracted from a binned fit to $M_{\gamma_1}^{\rm recoil}$ for all three $\chi_{\rm bJ}(1P)$ simultaneously.
- ULs are obtained at 90% CL using pyhf with 5000 of pseudo-experiments.
- We provide the first ULs for $\chi_{bJ}(1P) \to e^{\pm}\mu^{\mp}$ decays.

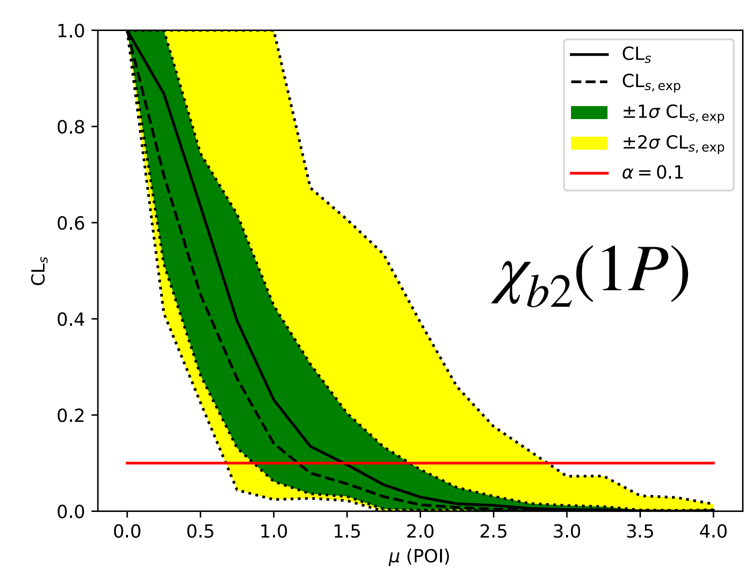
Belle $25 {\rm fb}^{-1} \Upsilon(2S)$



Resonance	$\chi_{bJ}(1P) \to e^{\pm}\mu^{\mp}$	
	Central value	UL at 90%CL
$\chi_{b0}(1P)$	$(1.2 \pm 1.3) \times 10^{-6}$	4.0×10^{-6}
$\chi_{b1}(1P)$	$(0.0 \pm 1.3) \times 10^{-6}$	1.5×10^{-6}
$\chi_{b2}(1P)$	$(0.2 \pm 0.8) \times 10^{-6}$	1.8×10^{-6}

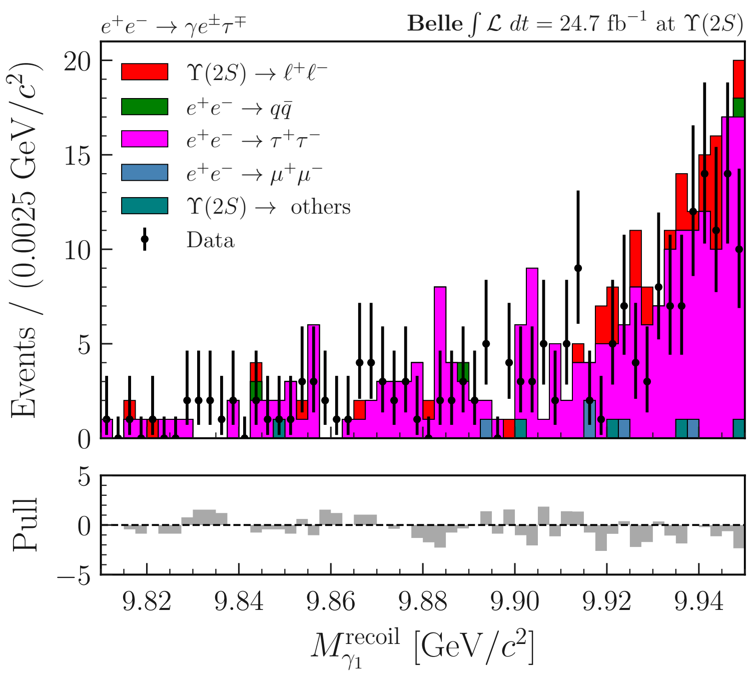


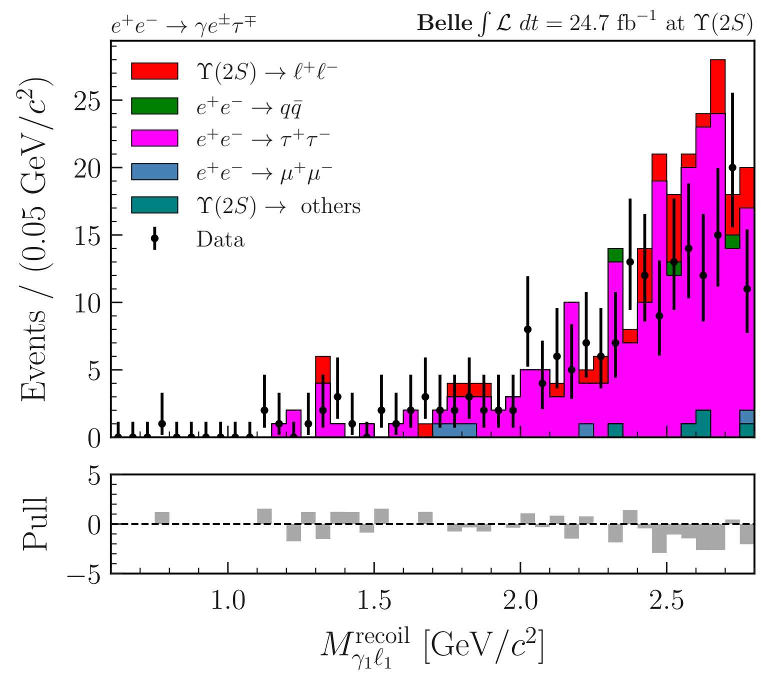




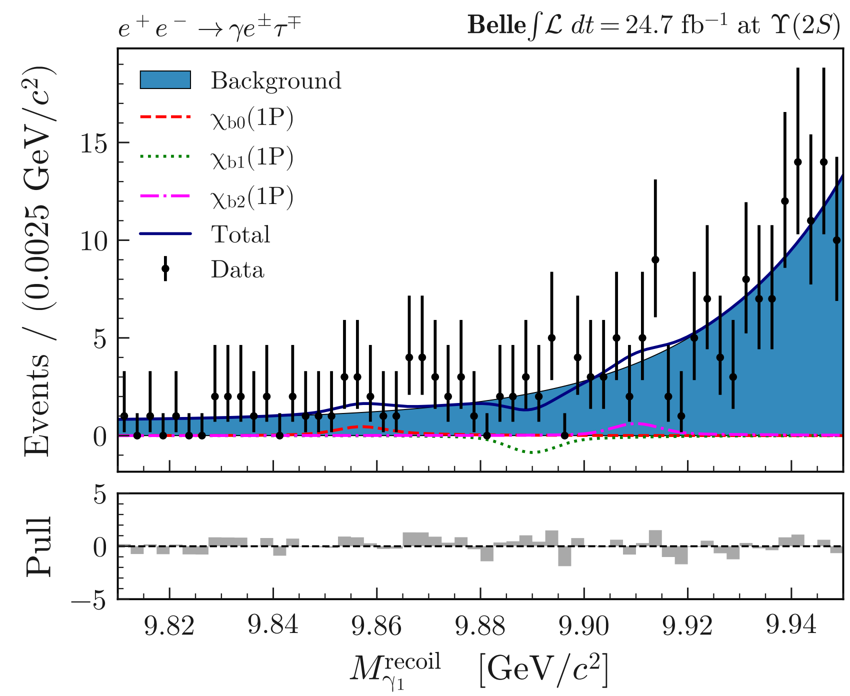
Search for $\chi_{bJ}(1P) \to e^{\pm}\tau^{\mp}$

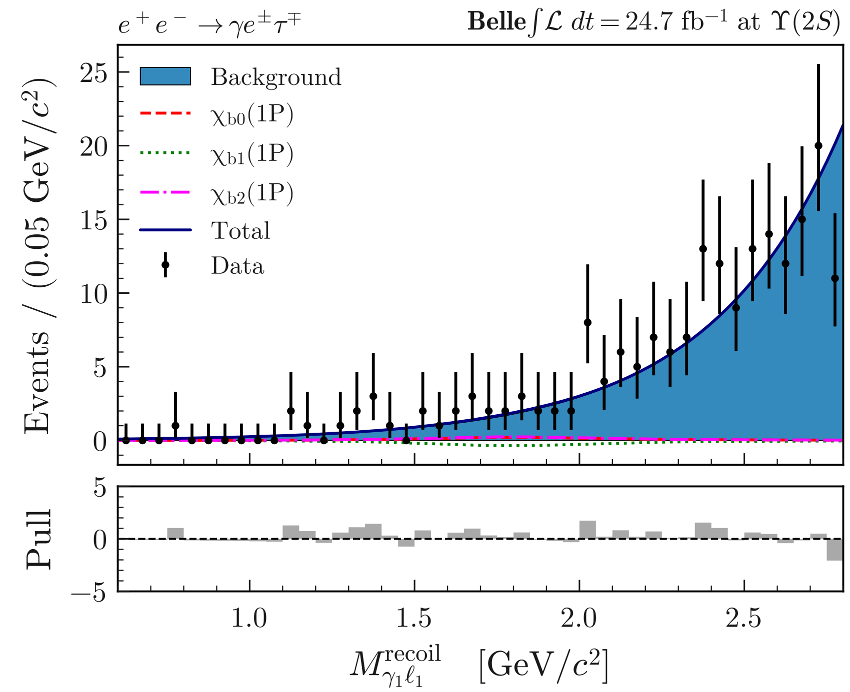
New





Belle $25\text{fb}^{-1}\Upsilon(2S)$



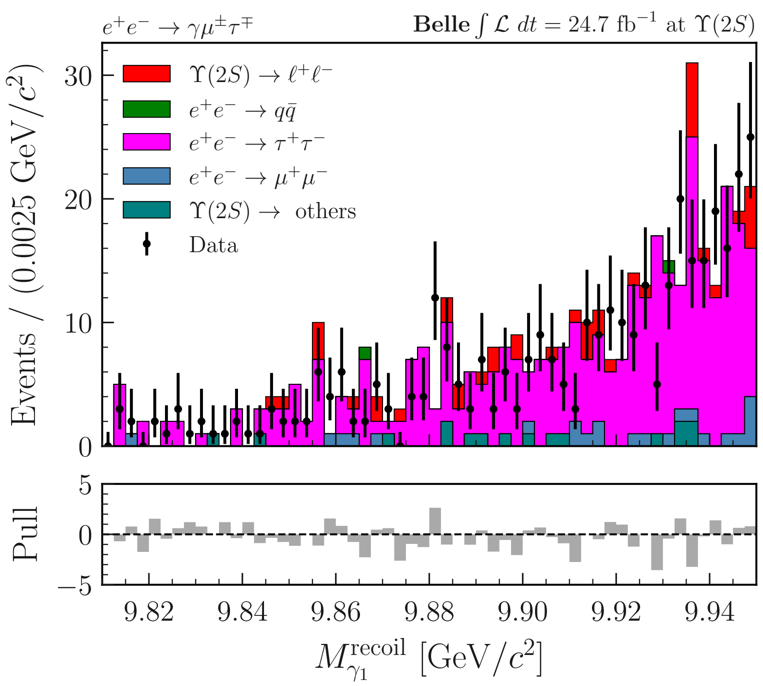


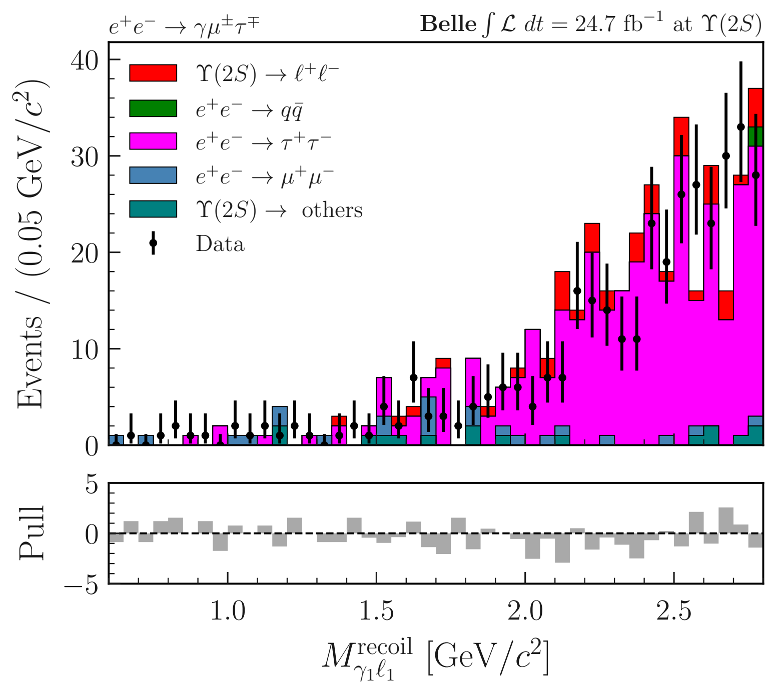
- Signal yields are extracted from an unbinned 2D fit to $M^{\text{recoil}}_{\gamma_1}$ and $M^{\text{recoil}}_{\gamma_1\ell_1}$ for all three $\chi_{\text{bJ}}(1P)$ simultaneously.
- We obtain the UL using a frequentist calculator with thousands of toys.

Resonance	$\chi_{bJ}(1P) \to e^{\pm}\tau^{\mp}$	
	Central value	UL at 90%CL
$\chi_{b0}(1P)$	$(1.4 \pm 1.8) \times 10^{-5}$	4.1×10^{-5}
$\chi_{b1}(1P)$	$(-1.3 \pm 0.8) \times 10^{-5}$	1.3×10^{-5}
$\chi_{b2}(1P)$	$(0.9 \pm 1.2) \times 10^{-5}$	2.6×10^{-5}

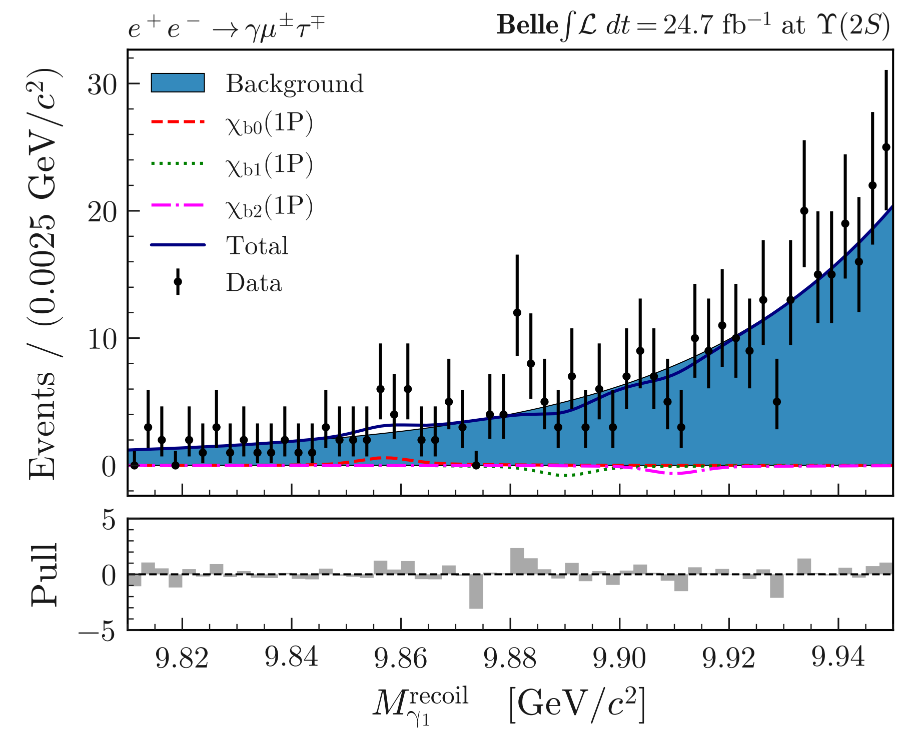
Search for $\chi_{bJ}(1P) \to \mu^\pm\tau^\mp$

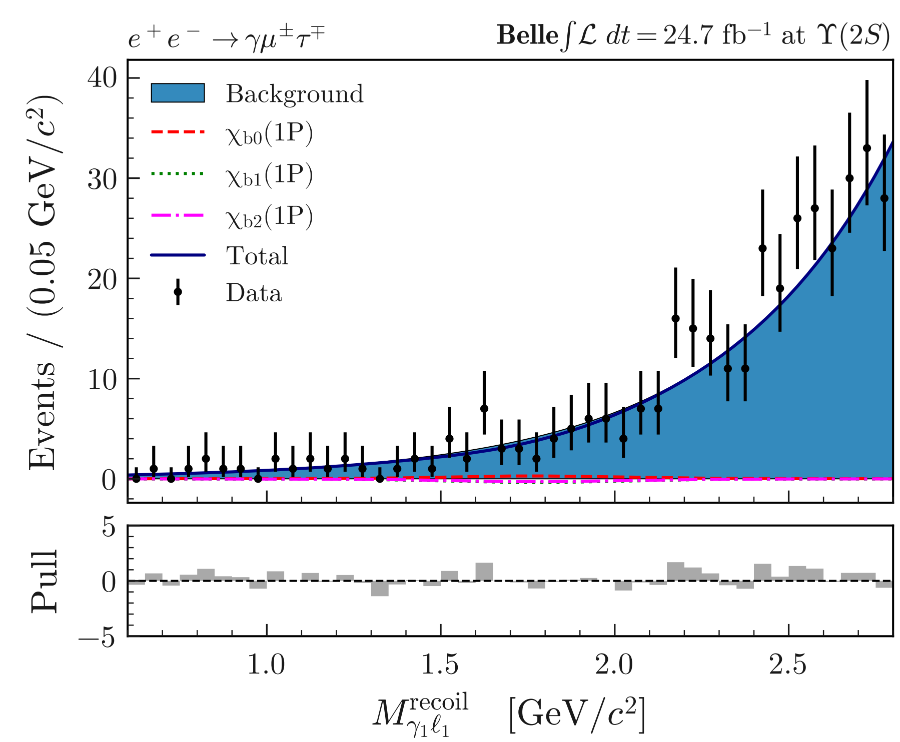
New





Belle $25\text{fb}^{-1}\Upsilon(2S)$





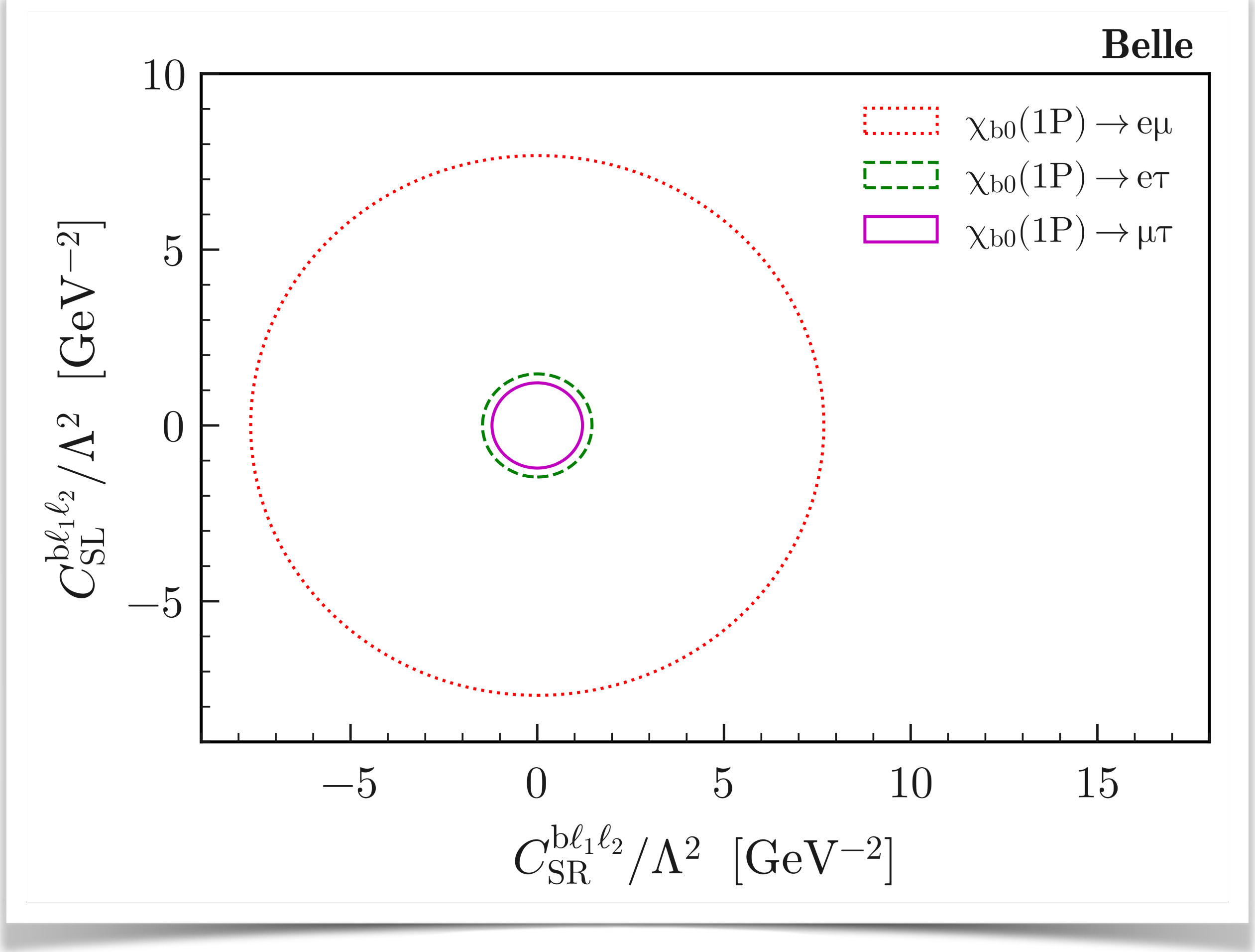
- We use an approach similar to $\chi_{bJ}(1P) \to e^\pm\tau^\mp$ study.
- We provide the first ULs for $\chi_{bJ}(1P) \to \mu^\pm\tau^\mp$ decays.

Resonance	$\chi_{bJ}(1P) \to \mu^\pm\tau^\mp$	
	Central value	UL at 90%CL
$\chi_{b0}(1P)$	$(1.1 \pm 1.0) \times 10^{-5}$	2.8×10^{-5}
$\chi_{b1}(1P)$	$(-0.8 \pm 0.5) \times 10^{-5}$	9.0×10^{-6}
$\chi_{b2}(1P)$	$(-0.6 \pm 0.5) \times 10^{-5}$	9.0×10^{-6}

Constraints on scalar Wilson coefficients

Resonance	$\chi_{bJ}(1P) \to e^{\pm}\mu^{\mp}$		$\chi_{bJ}(1P) \to e^{\pm}\tau^{\mp}$		$\chi_{bJ}(1P) \to \mu^{\pm}\tau^{\mp}$	
	Central value	UL at 90%CL	Central value	UL at 90%CL	Central value	UL at 90%CL
$\chi_{b0}(1P)$	$(1.2 \pm 1.3) \times 10^{-6}$	4.0×10^{-6}	$(1.4 \pm 1.8) \times 10^{-5}$	4.1×10^{-5}	$(1.1 \pm 1.0) \times 10^{-5}$	2.8×10^{-5}

$$\left(\frac{C_{\rm SL}^{{\rm q}\ell_1\ell_2}}{\Lambda^2}\right)^2 + \left(\frac{C_{\rm SR}^{{\rm q}\ell_1\ell_2}}{\Lambda^2}\right)^2 = \frac{16\pi m_\chi \Gamma_\chi \mathcal{B}(\chi \to \ell_1\ell_2)}{G_{\rm F}^2 f_\chi^2 m_{\rm b}^2 m_{\ell_2}^2 (m_\chi^2 - m_{\ell_2}^2)^2}$$



- All the modes are studied for the first time.
- Constraints on the Wilson coefficient of scalar operators are obtained.

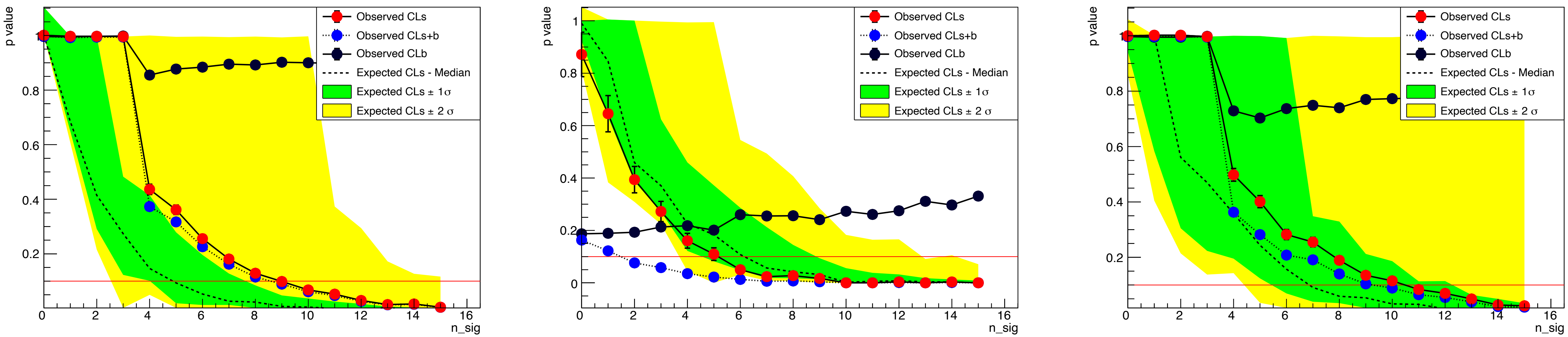
Summarry

- We have reported a few recent results on LFV searches in Belle and Belle II experiments.
- For $B \to K^{*0}\tau^{\pm}\ell^{\mp}$: We report the first results on $K^{*0}\tau^{\pm}e^{\mp}$ modes and first results from B-factories for $K^{*0}\tau^{\pm}\mu^{\mp}$ modes.
- For $B \to K_S^0\tau^{\pm}\ell^{\mp}$: We report the first results on these modes.
- For $\chi_{bJ}(1P) \to \ell_1^{+}\ell_2^{-}$: These are the reported for the first time.

Backup

Study of $\chi_{bJ}(1P) \to \ell_1^+ \ell_2^-$

$\chi_{bJ}(1P) \to e^{\pm}\tau^{\mp}$



$\chi_{bJ}(1P) \to \mu^{\pm}\tau^{\mp}$