Searches for rare B decays at Belle and Belle II

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on behalf of the Belle II collaboration

Moriond QCD & high energy interactions 2025
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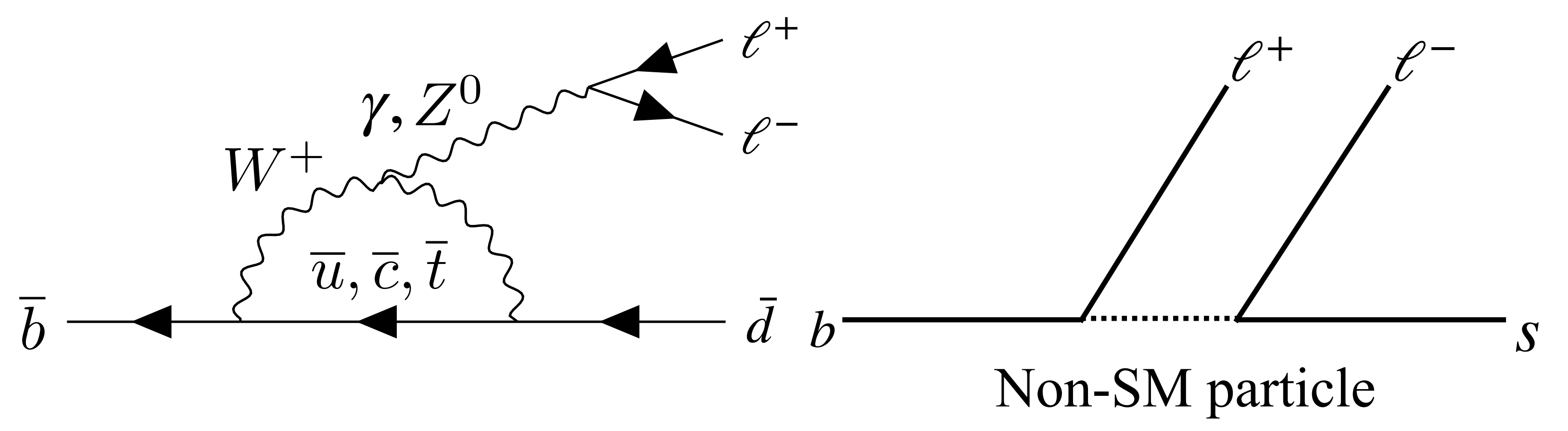
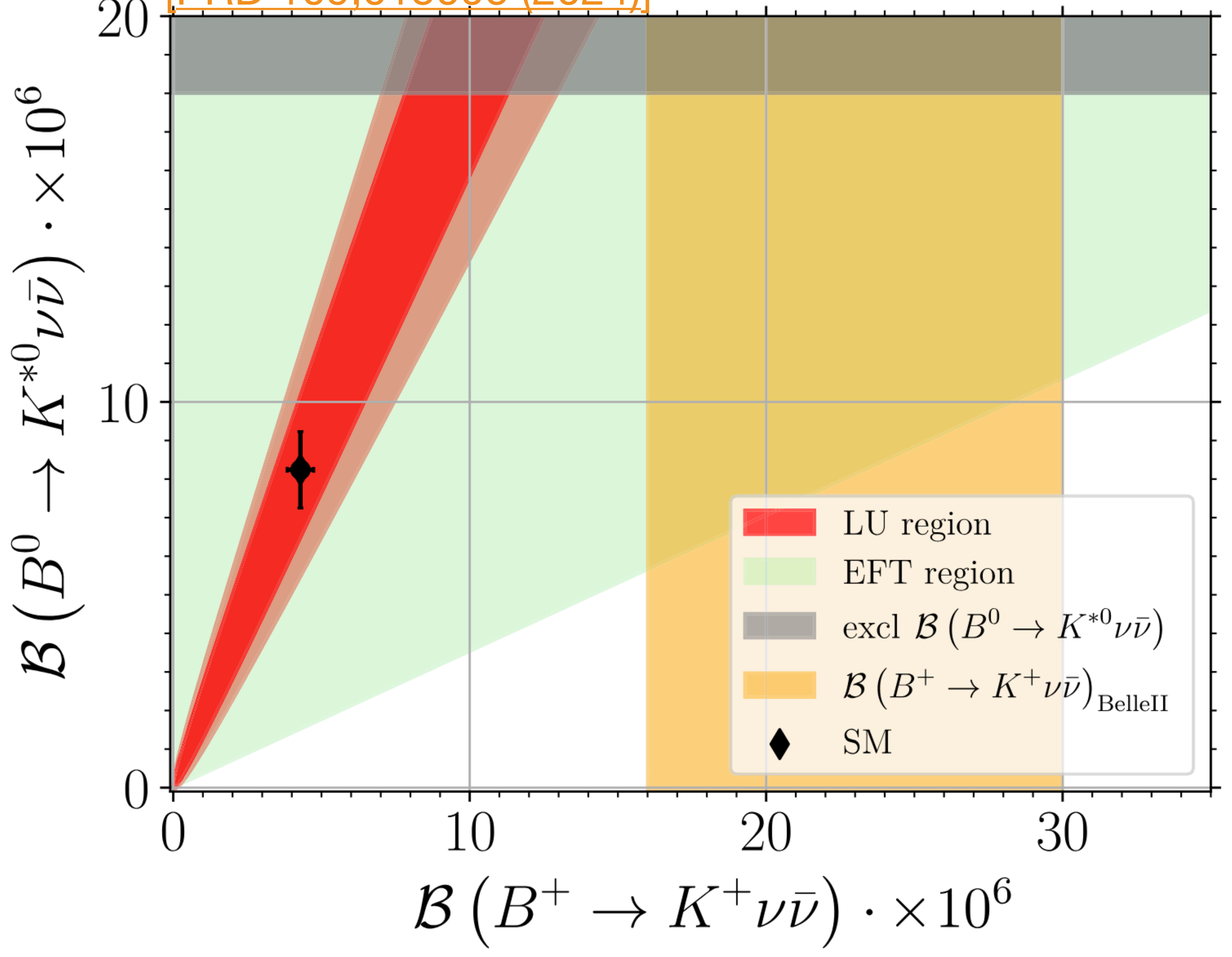
Physics

- Flavor changing neutral current processes are forbidden in SM at tree level. Non-SM particles could enhance decay amplitude as “loop” allows high-mass exchange:
  - new tree level interactions
  - reduce GIM cancellation in loop corrections
- Recent experimental anomalies in $b \to c\tau\nu$ and $b \to s\nu\bar{\nu}$ decays hint at non-SM particles coupling with third generation, τ [EPJC 83, 153 (2023)] [PLB 848, 138411 (2024)]
- Today’s topics: $B^0 \to K_S^0\tau^\pm\ell^\mp$, $B^0 \to K^{*0}\tau^\pm\ell^\mp$, $B^0 \to K^{*0}\tau^+\tau^-$
- Experimentally challenging due multiple undetected neutrinos in the final states



[PRD 109,015006 (2024)]

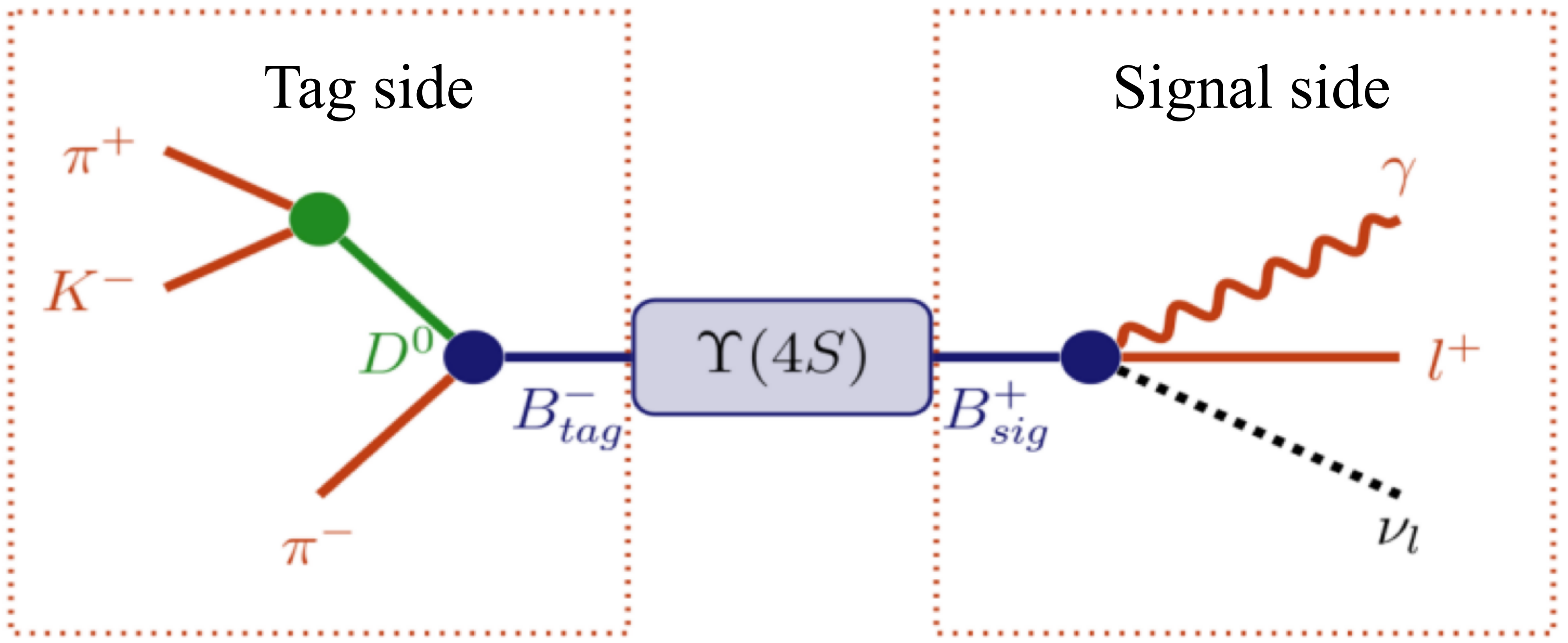


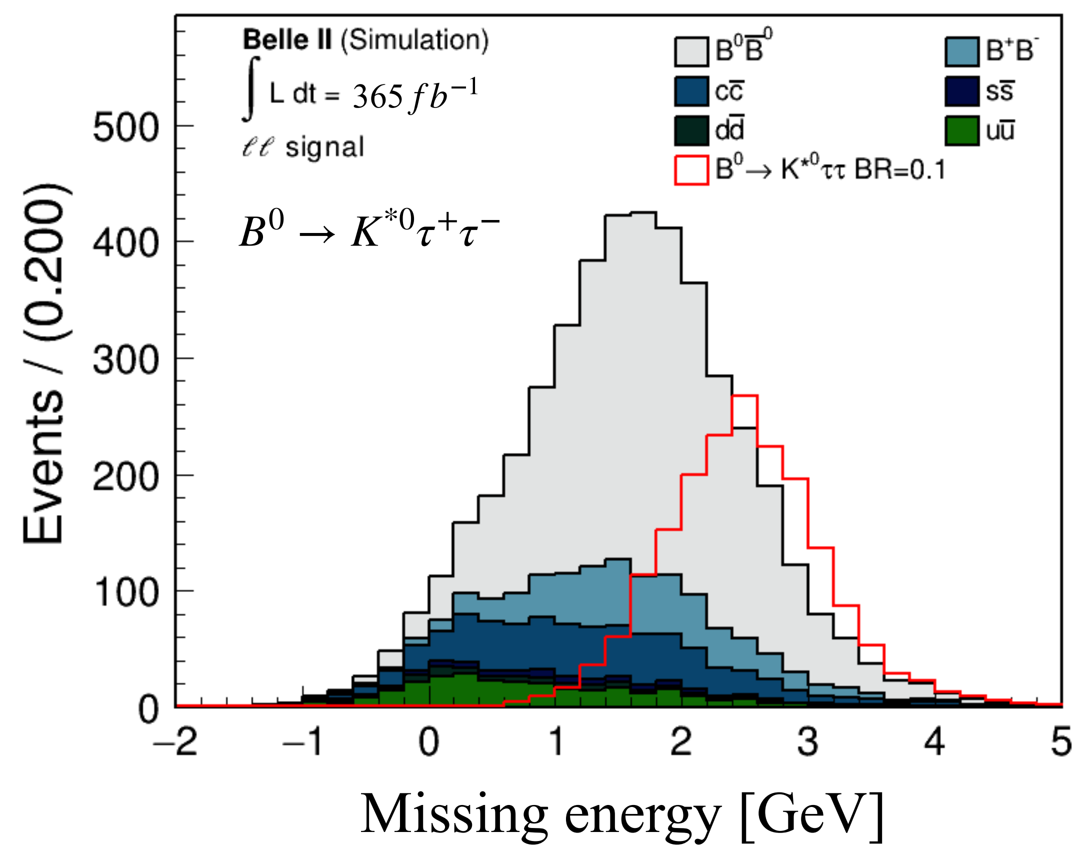
All results are new since last Moriond QCD

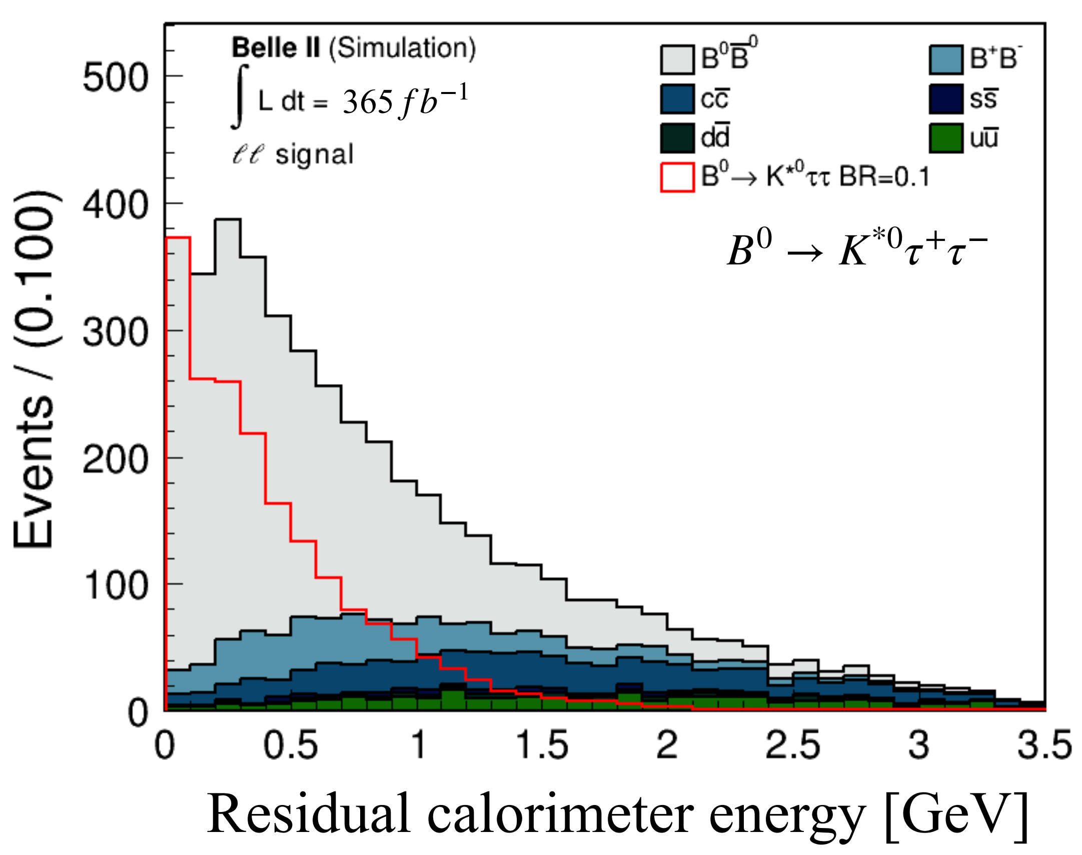
B factory advantage

Data set: 772 M (Belle) + 387 M (Belle II) $B\bar{B}$ pairs
See Bianca's slides for more details on detector

- e^+e^- collision near $B\bar{B}$ production threshold makes Belle (II) ideally suited: low background, precisely known collision energy
- Hermetic detector: full event reconstruction
- Hadronic tagging: full reconstruction of pair-produced B meson (B_{tag}) in hadronic final states allows to infer signal B kinematics; high purity $\mathcal{O}(10\%)$ but low efficiency $\mathcal{O}(1\%)$
- Advantageous for searches involving final states with multiple neutrinos
  - suppress significant background
  - provide powerful discriminators: missing energy, residual calorimeter energy left after $B\bar{B}$ reconstruction, etc.







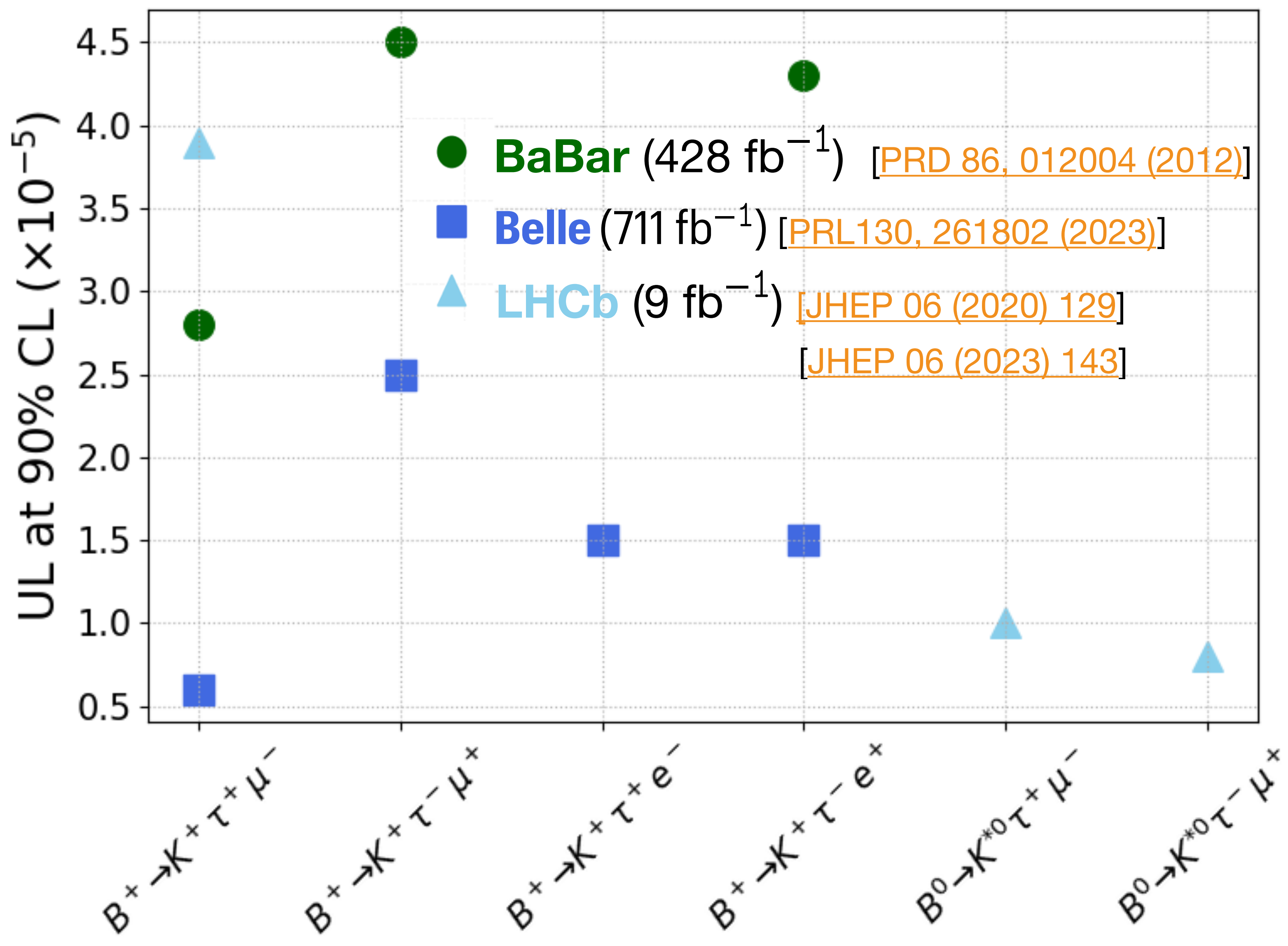
All results shown in this presentation involve hadronic tagging

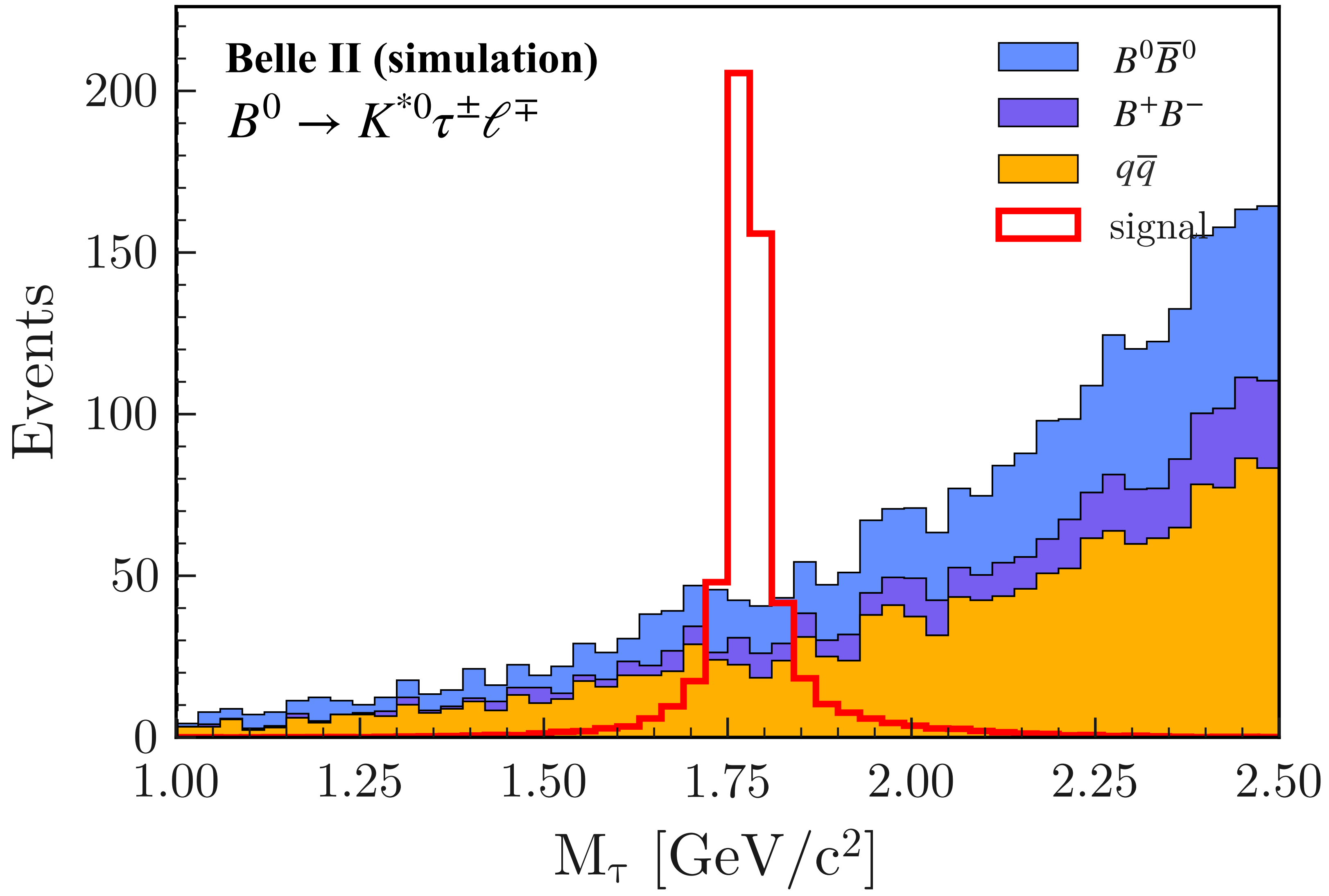
$$b \to s\tau^{\pm}\ell^{\mp}$$

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

- Forbidden decay. Non-SM particles, explaining recent anomalies, predict LFV with $\mathscr{B}(b \to s\tau\ell)$ at $\mathcal{O}(10^{-6})$. [EPJ C 76, 134 (2016)]
- Near current experimental limits at $\mathcal{O}(10^{-5})$
- Non-SM particle may couple differently between $b\tau$ and $b\ell$, or between $s\tau$ and $s\ell$, leading to asymmetric decay rate between $b \to s\tau^+\ell^-$ and $b \to s\tau^-\ell^+$
- Never searched for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ and $B^0 \to K^{*0} \tau^\pm e^\mp$
- Signal extraction observable: recoil τ mass after hadronic tagging,

$$M_\tau^2 = (p_{e^+e^-} - p_K - p_\ell - p_{B_{\text{tag}}})^2$$



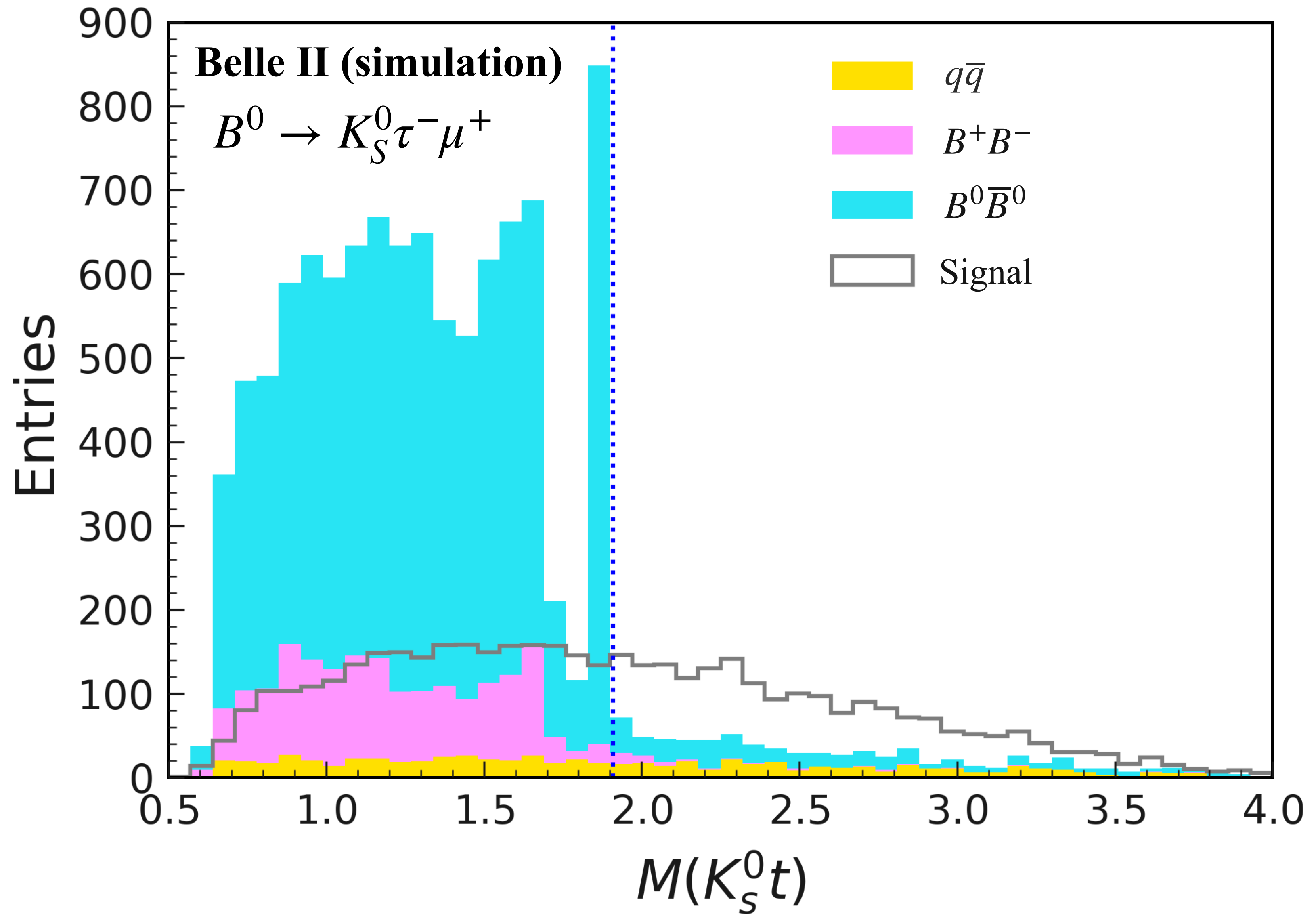


$b \to s\tau^{\pm}\ell^{\mp}$: strategy

Belle + Belle II
(711 + 365) fb^{-1}

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

- Search in 1-prong τ decays: $\tau^+ \to \ell^+\nu\bar{\nu}$, $\pi^+\nu$, $\rho^+\nu$; covers $\sim$70% of τ decay-width; first time use of $\tau \to \rho\nu$
- Restrict $m(K_S^0 t_\tau)$ to suppress dominant semileptonic $B \to D^{(*)}\ell X$ backgrounds; background rejection: 80-97%
- Suppress remaining background by 90% with classifier using $m(K_S^0\ell)$, residual calorimeter energy, lepton kinematics, etc.



$b \to s\tau^{\pm}\ell^{\mp}$: strategy

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

- Search in 1-prong τ decays: $\tau^+ \to \ell^+\nu\bar{\nu}$, $\pi^+\nu$, $\rho^+\nu$; covers ~70% of τ decay-width; first time use of $\tau \to \rho\nu$
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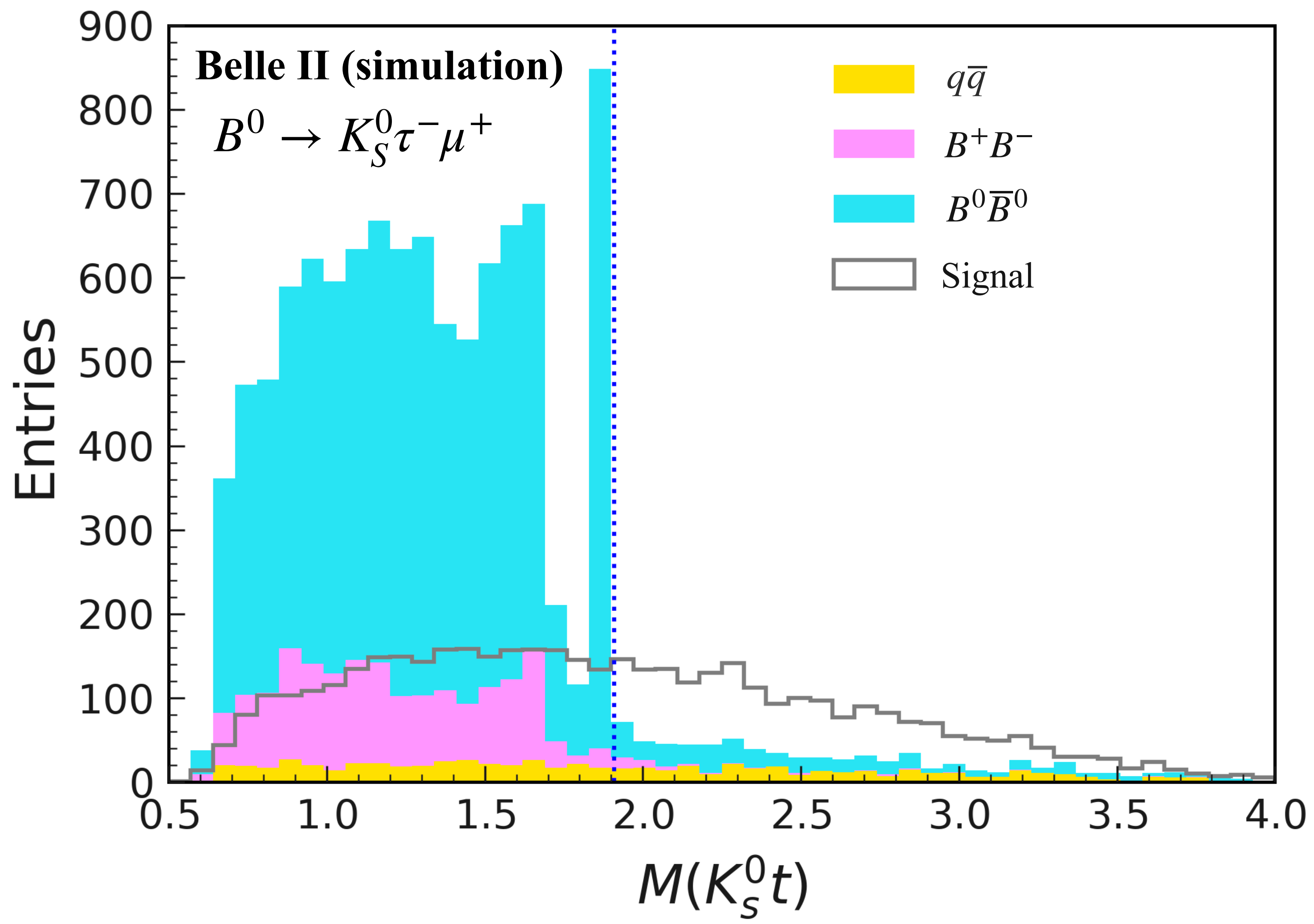
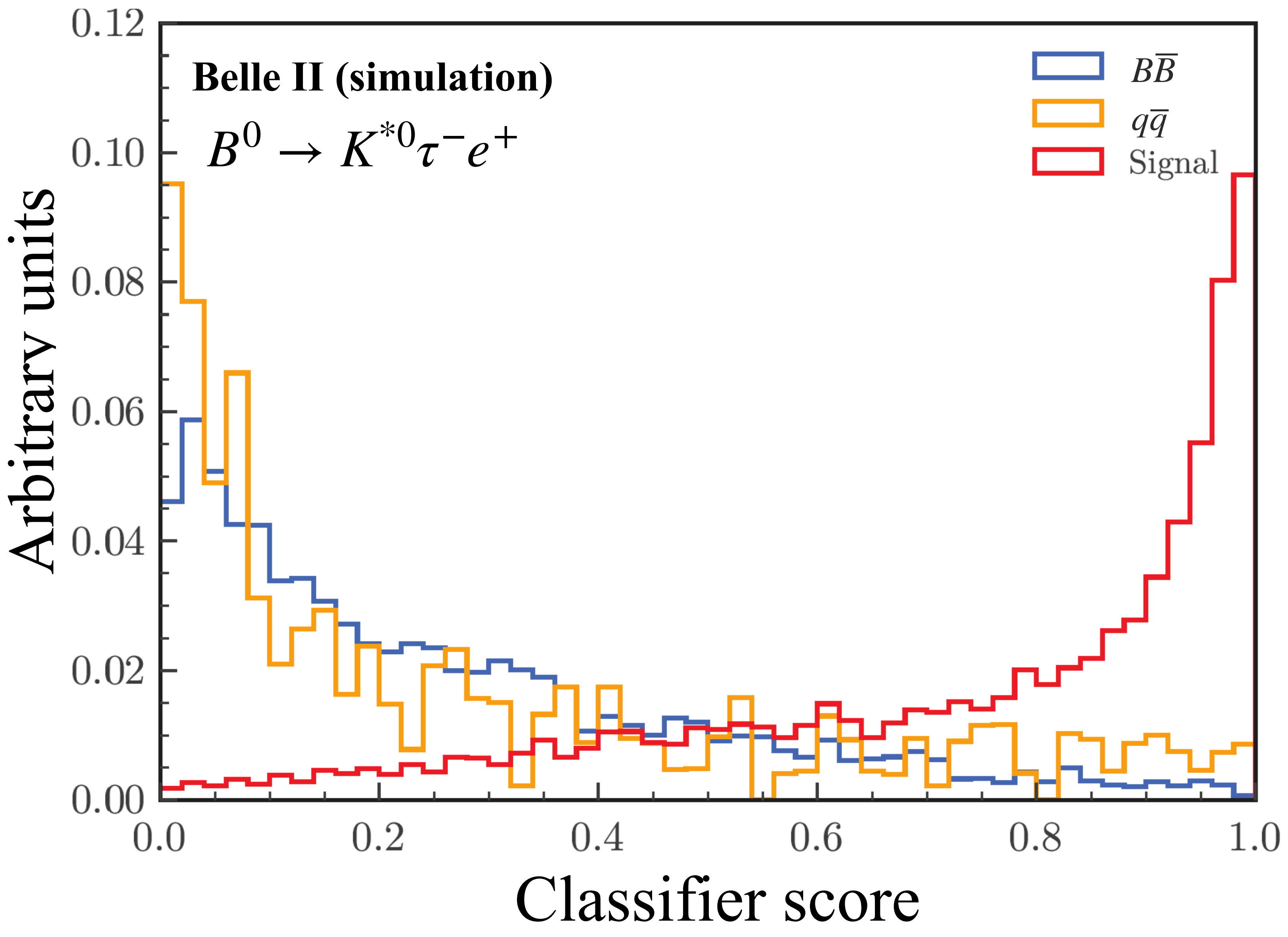


$B^0 \to K^{*0}\tau^{\pm}\ell^{\mp}$:

- Inclusive 1-prong τ reconstruction: one track from τ without any particle identification; covers ~ 80 % of τ decay-width
- Suppress background by 90 ~ 98 % with classifier using $m(K^{*0}\ell)$, $m(K^{*0}t_\tau)$, residual tracks and clusters properties, K^{*0} vertex information, event topology, etc.

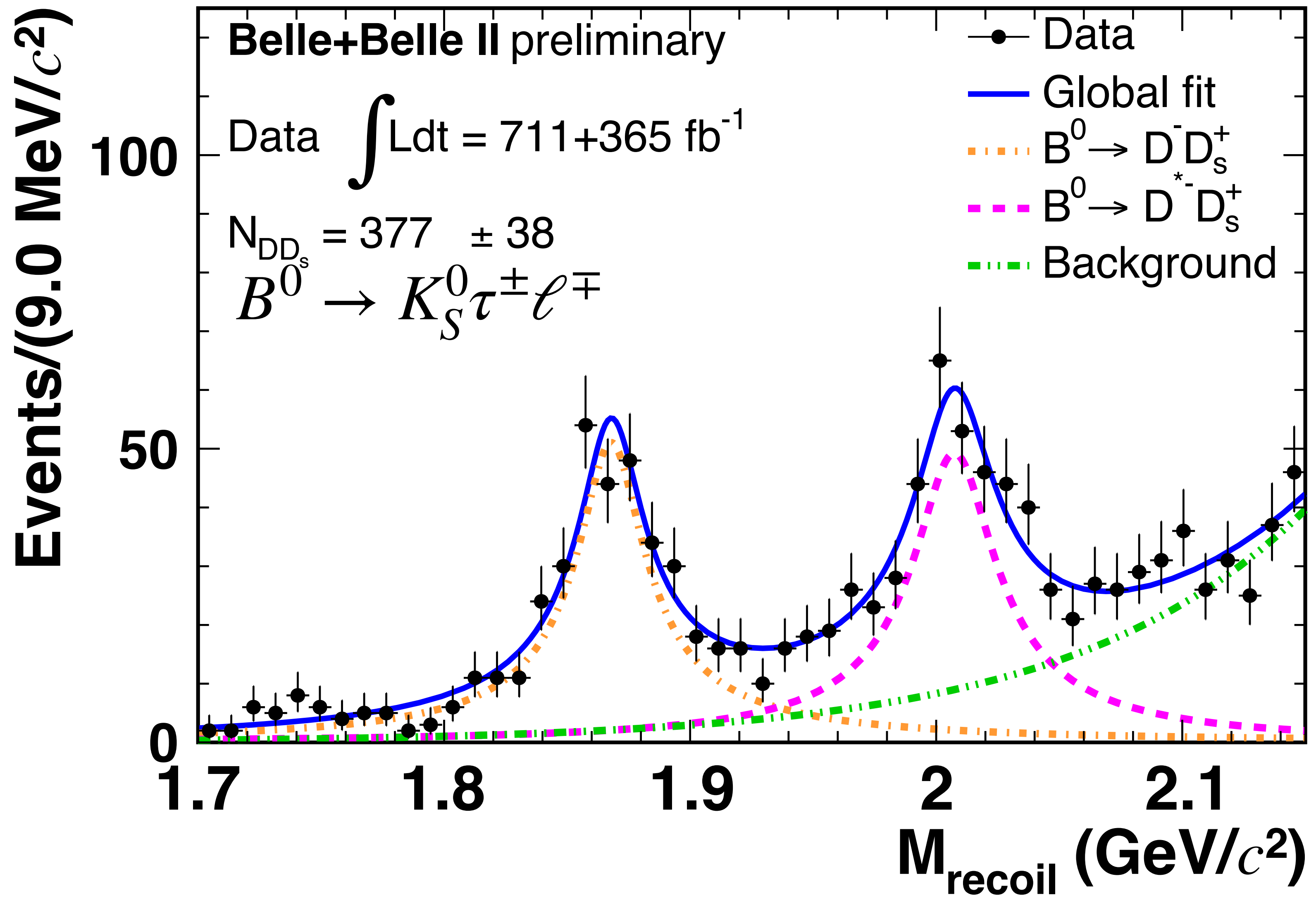


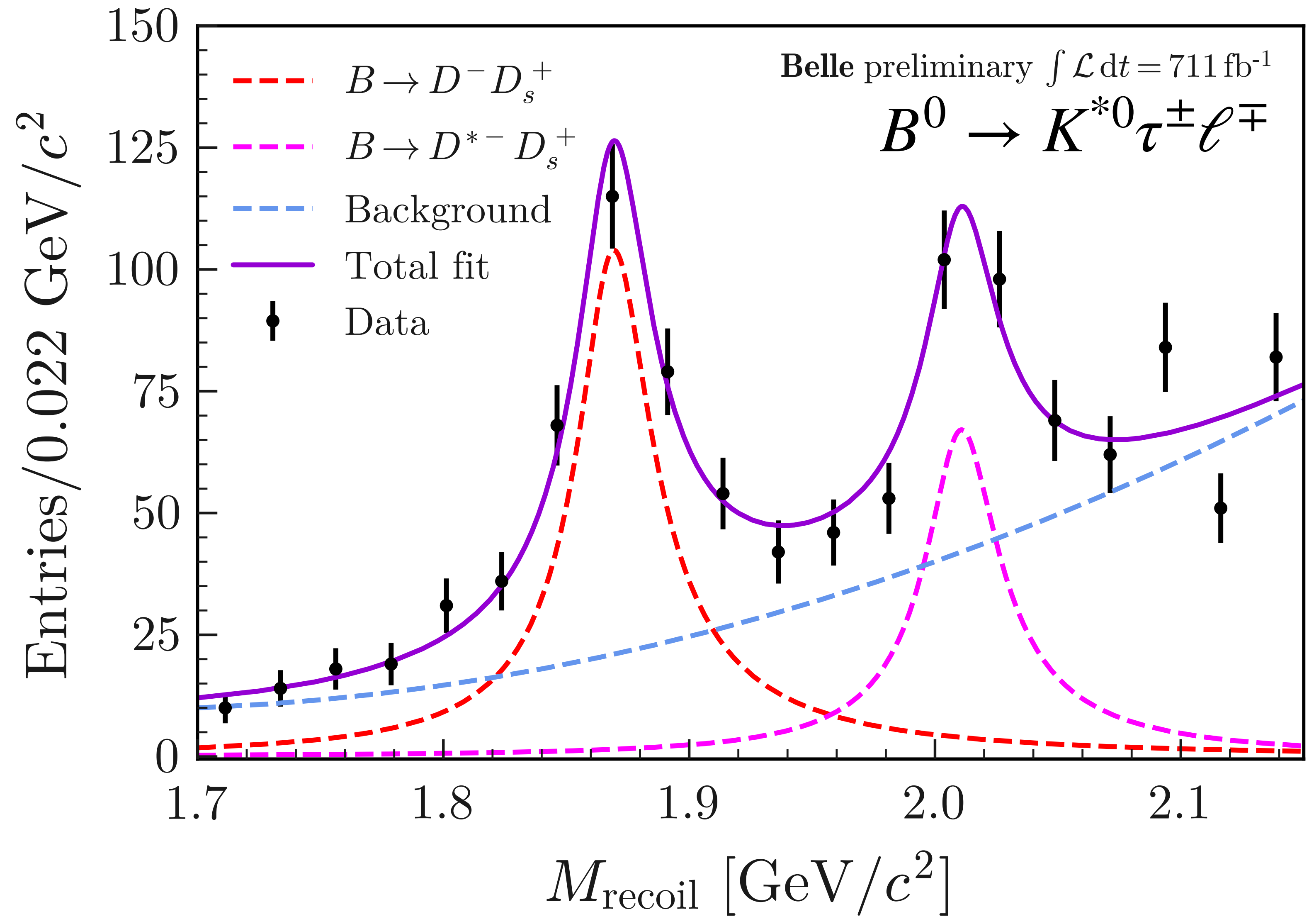
$b \to s\tau^{\pm}\ell^{\mp}$: validation

- Correct simulated B_{tag} efficiency using $B^0 \to D^-\pi^+$ and $B \to X_c\ell\nu$ control data.
- Correct signal shape and classifier selection efficiency by fitting recoil D mass in $B^0 \to D^-D_s^+$ where $D_s^+ \to \phi\pi^+$, $K_S^0K^+$ (for $B^0 \to K_S^0\tau^{\pm}\ell^{\mp}$), $K^{*0}K^+$ (for $B^0 \to K^{*0}\tau^{\pm}\ell^{\mp}$)

$$\mathrm{M}_D^2 = \mathrm{M}_{\text{recoil}}^2 = (p_{e^+e^-} - p_{D_s} - p_{B_{\text{tag}}})^2$$

- Dominant systematic uncertainties in terms of BF:
  - $B^0 \to K_S^0\tau^{\pm}\ell^{\mp}$: classifier efficiency correction (17 ~ 19 %) and signal shape (16%)
  - $B^0 \to K^{*0}\tau^{\pm}\ell^{\mp}$: classifier efficiency correction (18 ~ 34%) and background shape assumption $(0.1 \sim 0.3) \times 10^{-5}$ (absolute)





More details on systematic uncertainties in backup

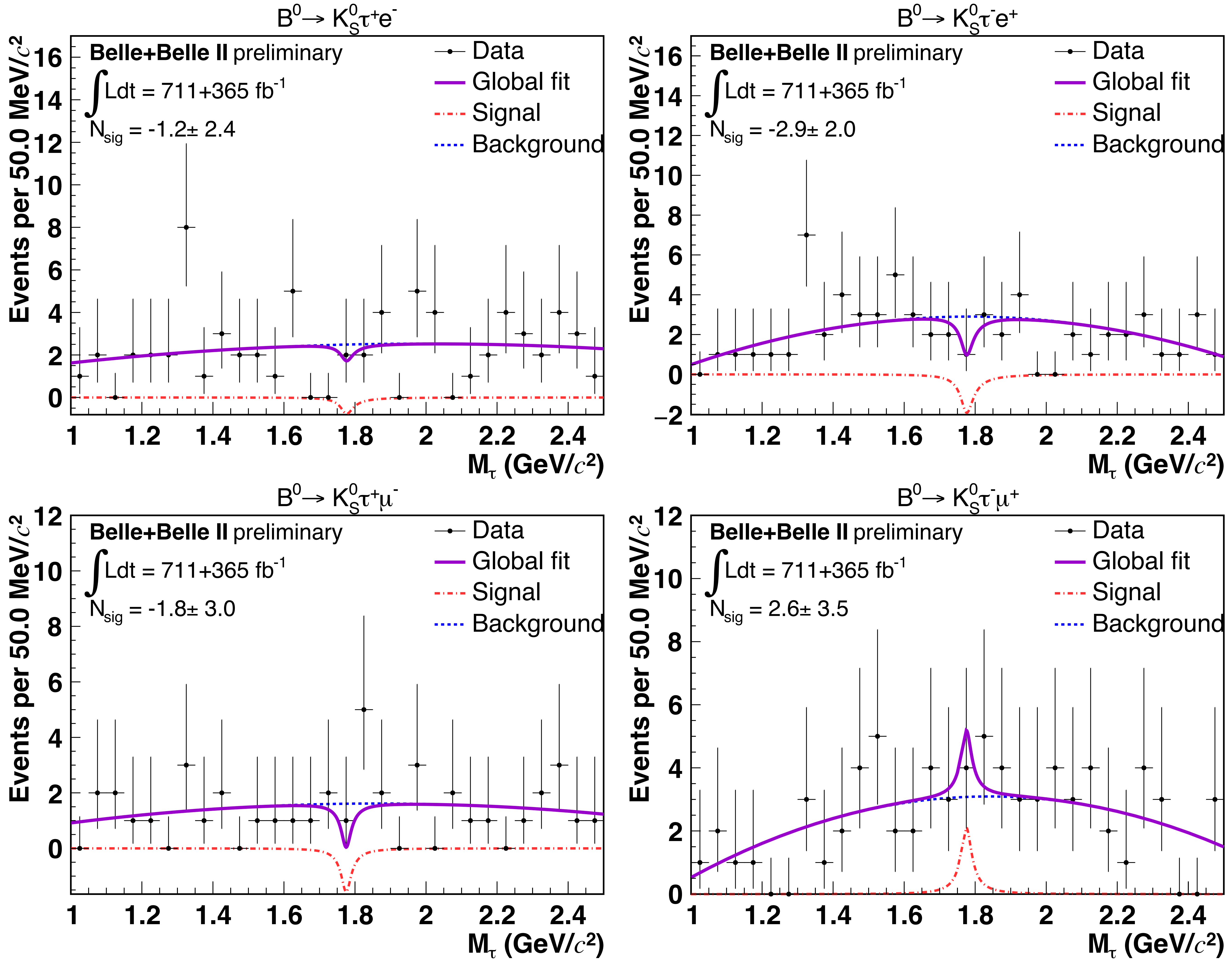
$B^0 \to K_S^0 \tau^\pm \ell^\mp$: result

Belle + Belle II
(711 + 365) fb^{-1}

Signal extraction: fit recoil τ mass (M_τ) in combined Belle + Belle II data set

	Efficiency (10^{-4})	$\mathcal{B}(10^{-5})$	$\mathcal{B}^{UL}(10^{-5})$ at 90% CL
$B^0 \to K_S^0 \tau^+ e^-$	2.0	$-0.5 \pm 1.1 \pm 0.1$	< 1.5
$B^0 \to K_S^0 \tau^- e^+$	2.1	$-1.2 \pm 0.9 \pm 0.3$	< 0.8
$B^0 \to K_S^0 \tau^+ \mu^-$	1.7	$-1.0 \pm 1.6 \pm 0.2$	< 1.1
$B^0 \to K_S^0 \tau^- \mu^+$	2.1	$1.1 \pm 1.6 \pm 0.3$	< 3.6

First search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ decays



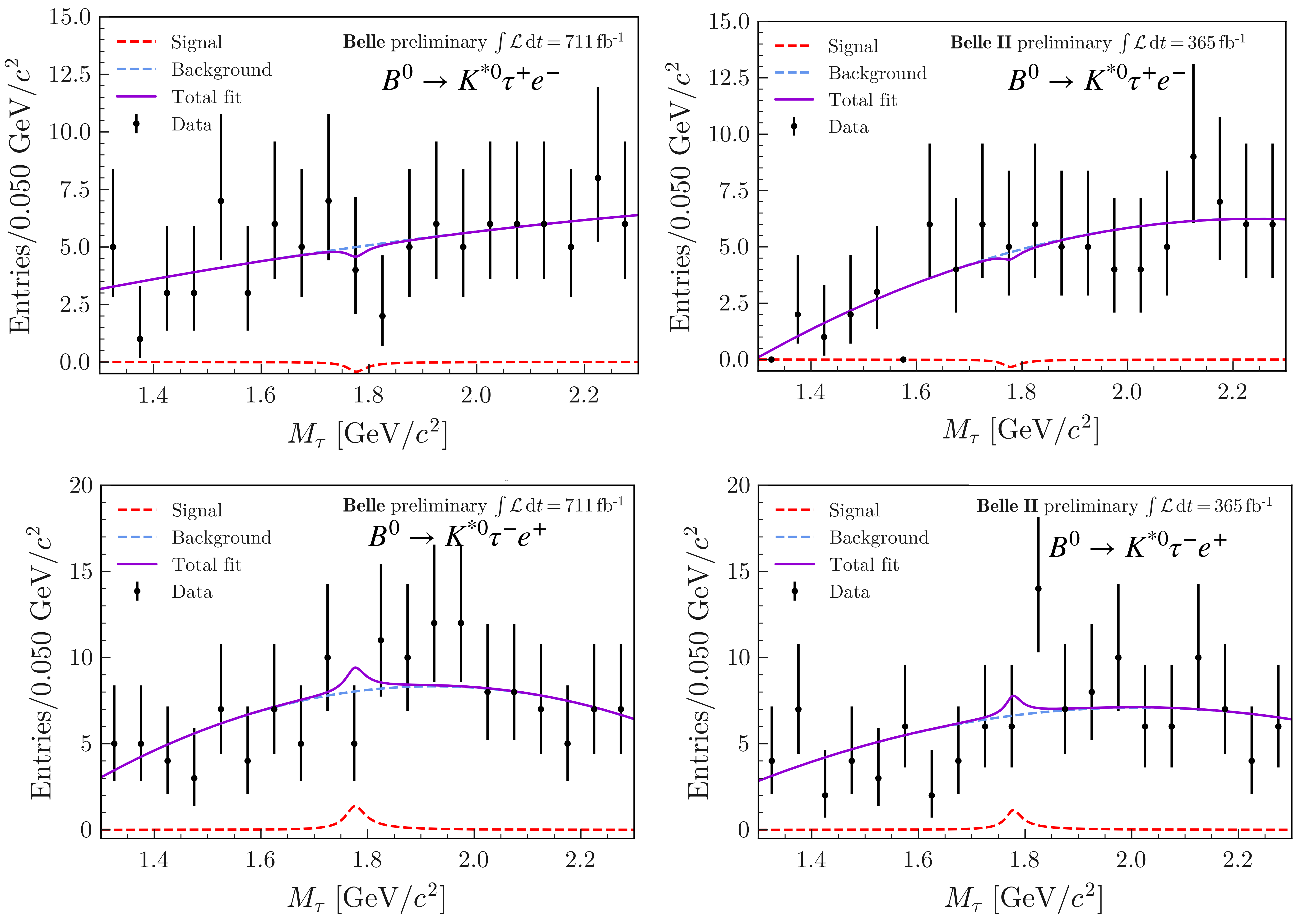
Submitted to PRL; arxiv 2412.16470

$B^0 \to K^{*0}\tau^\pm\ell^\mp$: result

Belle + Belle II (711 + 365) fb^{-1}

Signal extraction: simultaneous fit recoil τ mass (M_τ) in Belle and Belle II data sets

	Efficiency (10^{-4}) Belle	Efficiency (10^{-4}) Belle II	$\mathcal{B}(10^{-5})$	$\mathcal{B}^{UL}(10^{-5})$ at 90% CL
$B^0 \to K^{*0}\tau^+e^-$	4.6	7.5	-0.24 ± 1.44	< 2.7
$B^0 \to K^{*0}\tau^-e^+$	3.8	5.6	1.11 ± 2.65	< 5.6
$B^0 \to K^{*0}\tau^+\mu^-$	5.2	6.0	0.98 ± 1.74	< 3.9
$B^0 \to K^{*0}\tau^-\mu^+$	2.4	5.1	0.47 ± 2.59	< 5.1

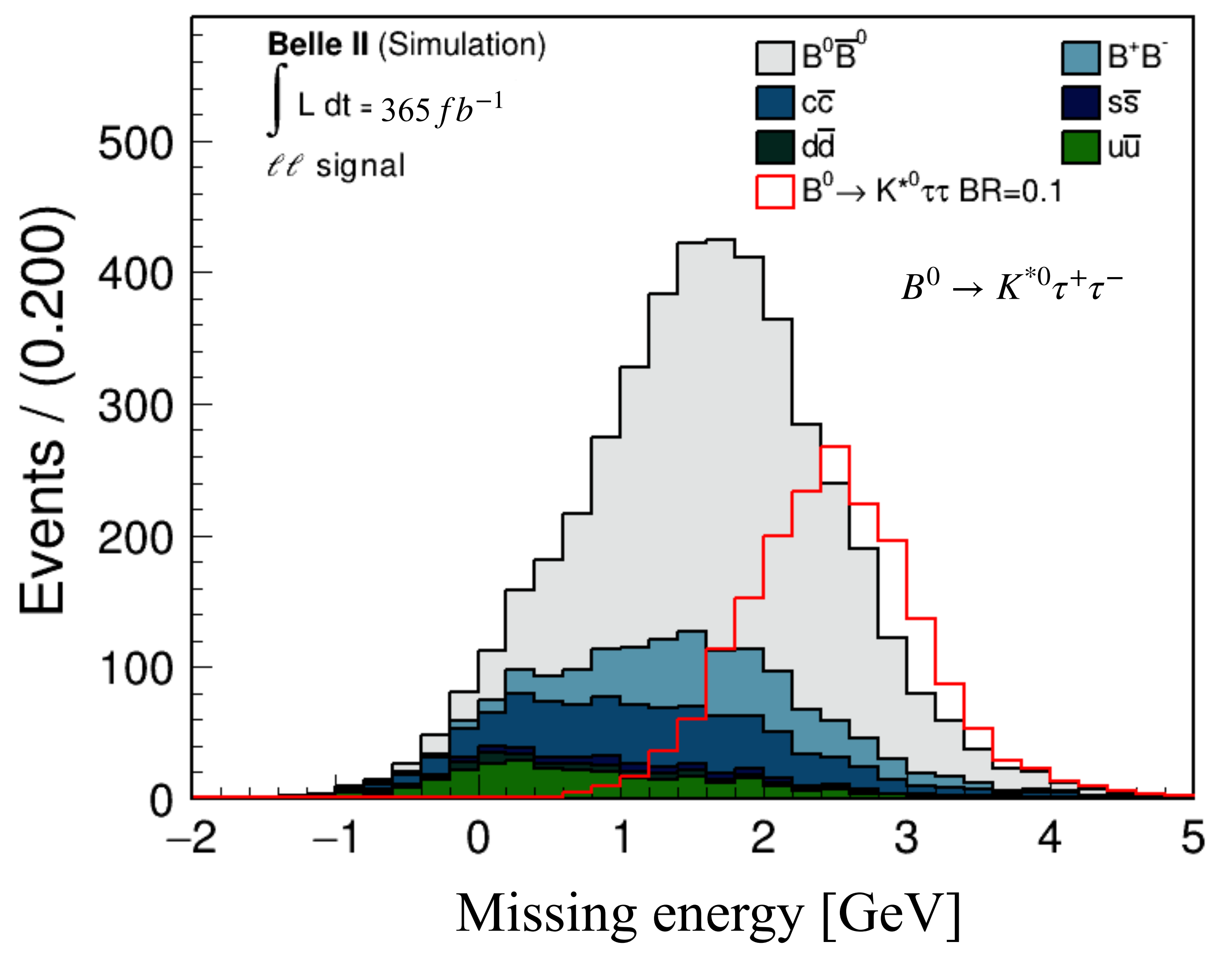


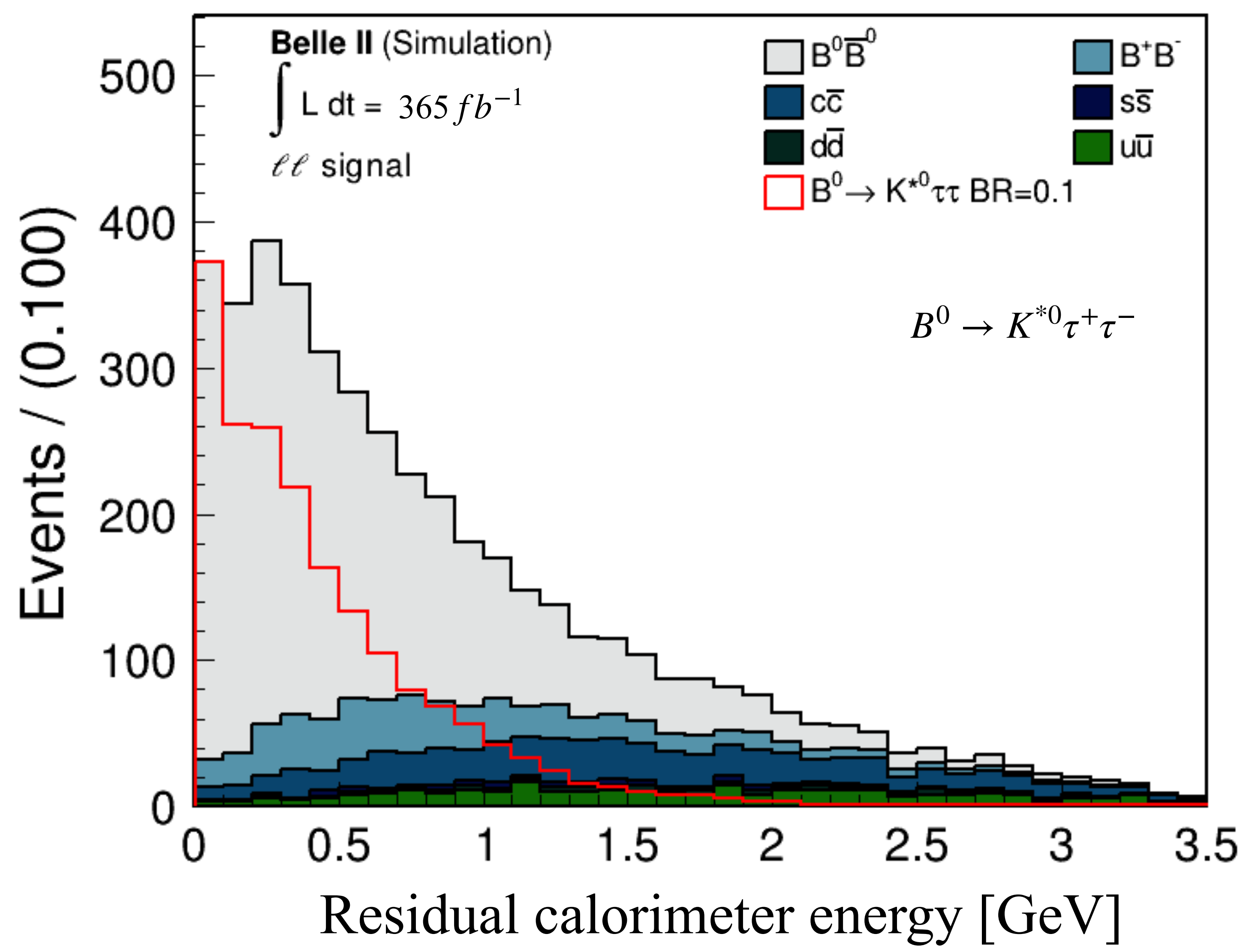
Not competitive with new LHCb results [Moriond EWP talk]

$$b \to s\tau^+\tau^-$$

Search for $B^0 \to K^{*0}\tau^+\tau^-$ Belle II (365 fb^{-1})

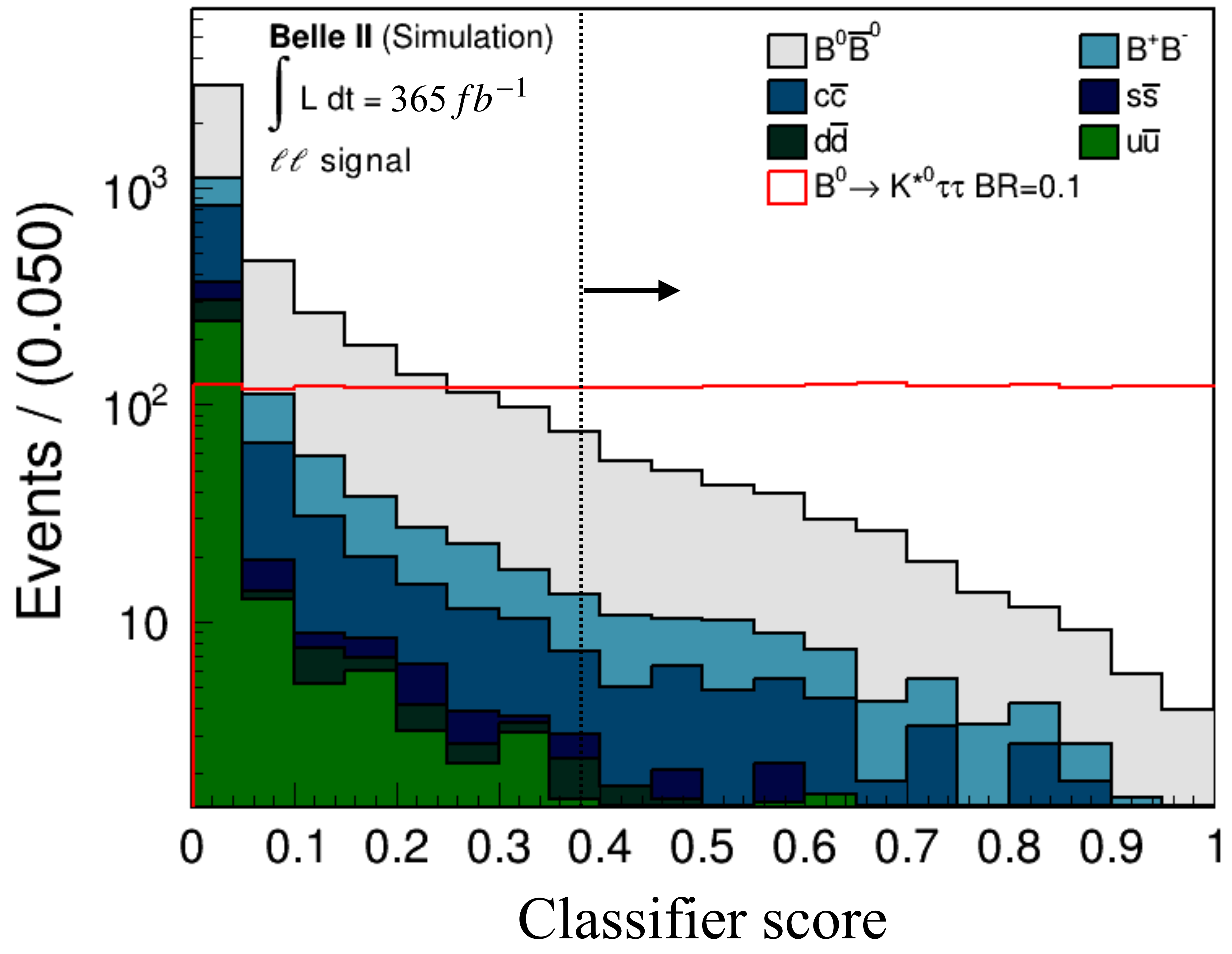
- $\mathscr{B}_{SM} = (0.98 \pm 0.10) \times 10^{-7}$
- Non-SM particles, explaining recent anomalies, would enhance BF up to $\mathcal{O}(10^3)$ due to presence of two τs [PRL 120, 181802 (2018)][EPJC 83, 153 (2023)]
- World-best result from Belle: UL at 3.1×10^{-3} (90% CL) Searched in 1-prong τ decays: $\tau^+ \to \ell^+\nu\bar{\nu}, \pi^+\nu$ [PRD 108, L011102 (2023)]
- Include $\tau^+ \to \rho^+(\to \pi^+\pi^0)\nu$ decays for the first time
- Main challenge: no signal peaking kinematic observable due to multiple undetected neutrinos
- Relies on missing energy information and residual calorimeter energy





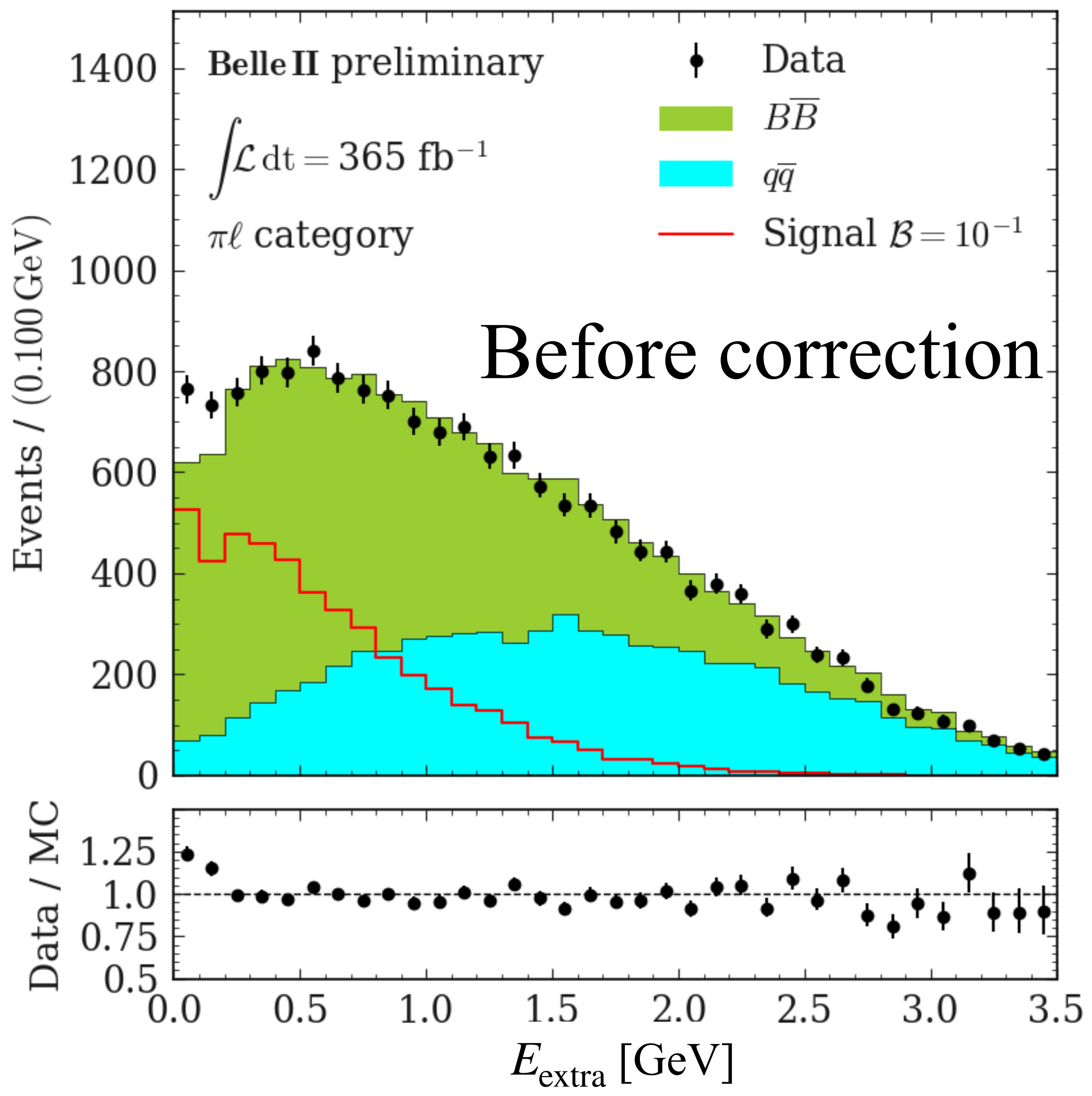
$B^0 \to K^{*0}\tau^+\tau^-$: strategy

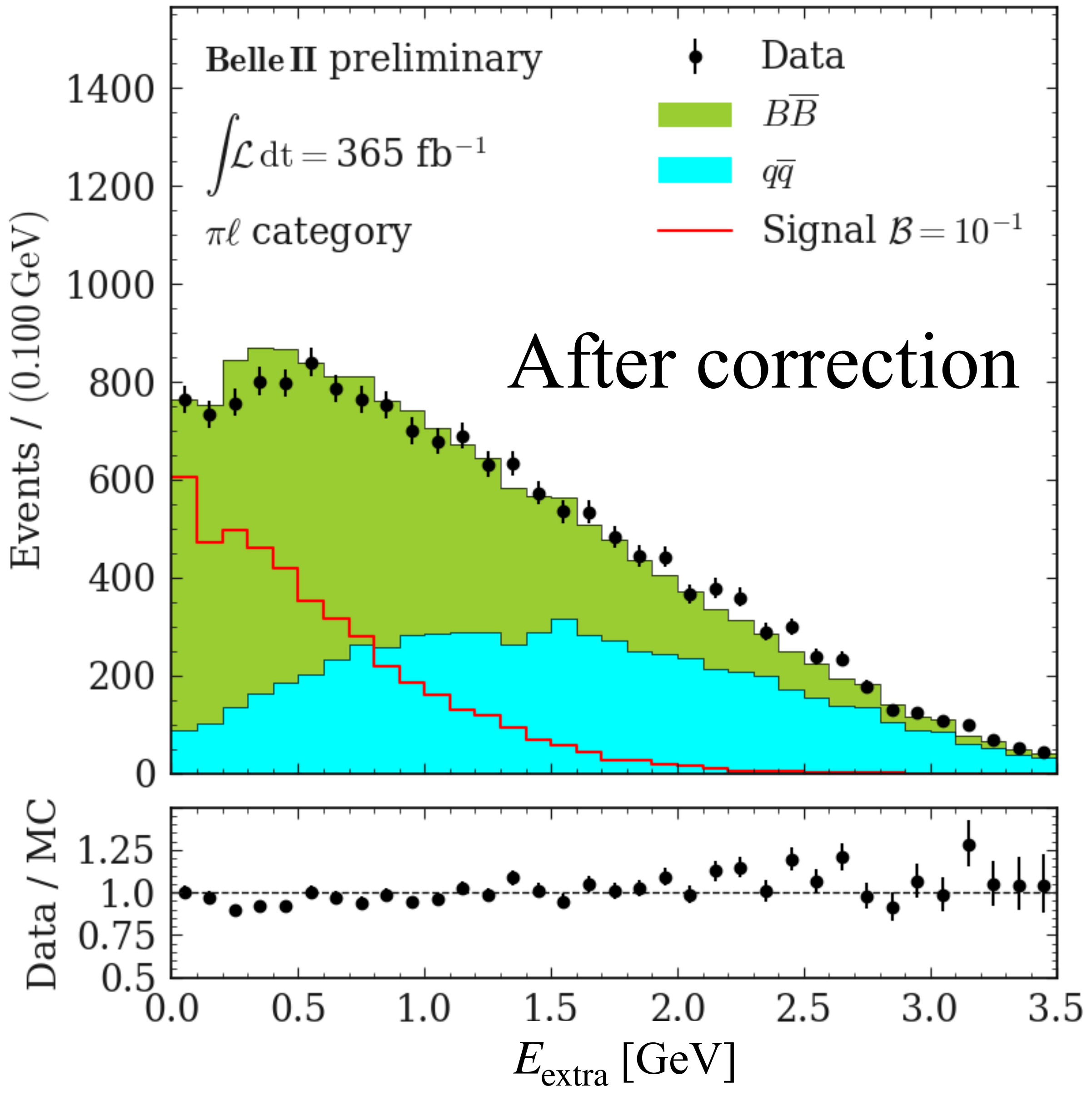
- Analyze separately four final-state categories from $\tau^+\tau^-$ pair: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX ($X = \ell, \pi, \rho$)
- Train classifier using missing energy, residual calorimeter energy, $m(K^{*0}t)$, event topology, etc.
- Choose signal region for fit at classifier score>0.4: Background rejection: 89~94%
- Remaining dominant background from semileptonic $B \to D^{(*)}\ell X$ decays



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

- Correct signal efficiency (×0.81) using $B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$ with modified kinematics to match signal.
  Signal efficiency: $(4 \sim 16) \times 10^{-5}$
- Correct background yield from same-flavor (BB, $\overline{B}\overline{B}$) control samples (×0.6~0.9) and off-resonance data (×0.7~0.8)
- Correct shape of residual calorimeter energy (E_{extra}), one of the most powerful discriminator, from same-flavor control sample
- Dominant systematic uncertainties in terms of BF ($\times 10^{-3}$):
  - poor knowledge of semileptonic $B \to D^{**}$ decays: 0.29
  - limited simulated sample size: 0.27





More details on systematic uncertainties in backup

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

Belle II (365 fb^{-1})

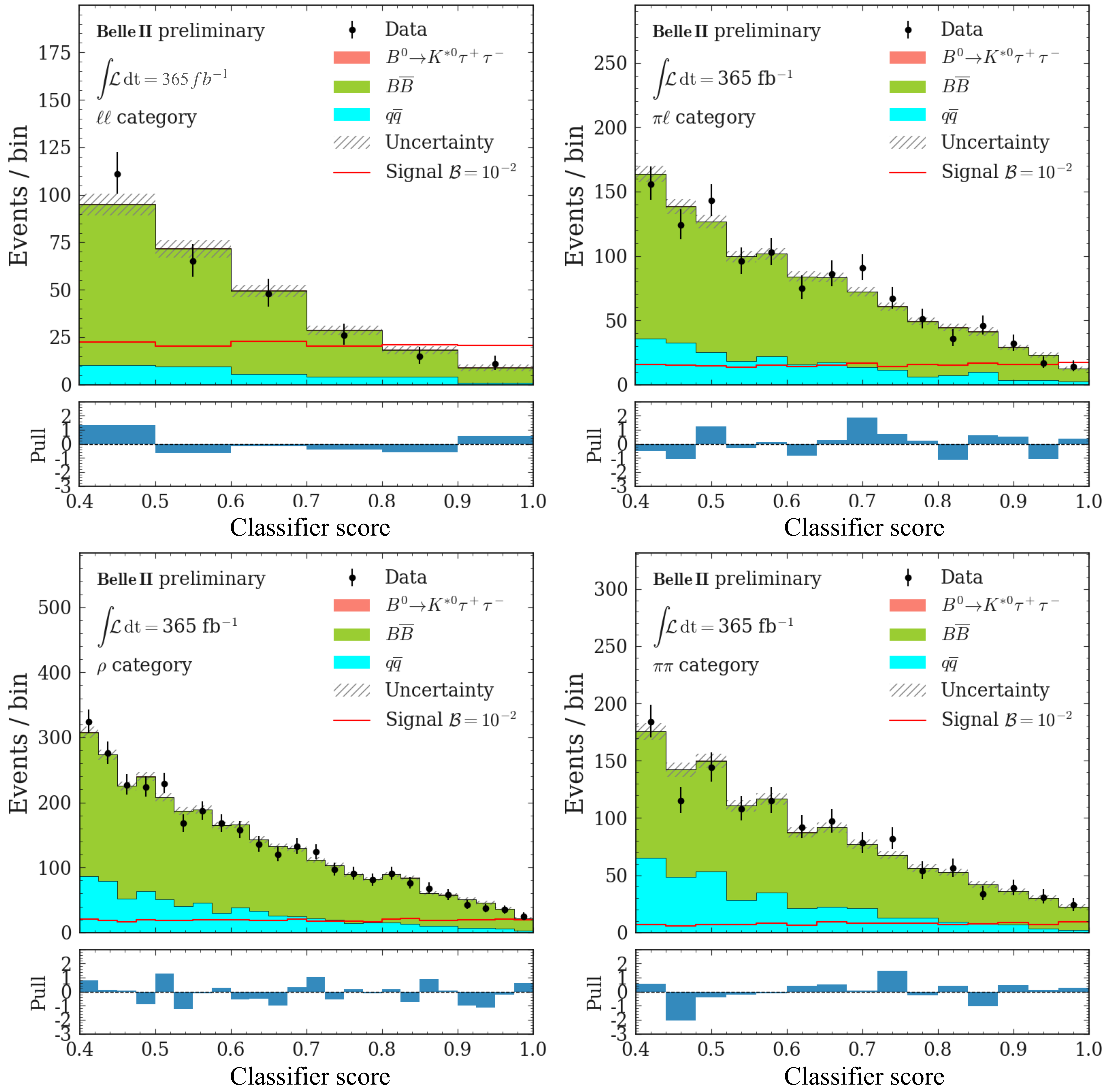
- Signal extraction: simultaneous fit classifier score above 0.4 of each category

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) = [-0.15 \pm 0.86 \pm 0.52] \times 10^{-3}$$

$$\mathcal{B}^{UL}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3} \text{ at } 90\% \text{ CL}$$

Twice better than current world best inspite of half sample size

Most stringent limit on $b \to s\tau\tau$ transition



Summary

- Flavor changing neutral current transitions are prime processes to probe non-SM particles
- Belle (II) offers unique abilities that are advantageous for these searches.
- New exciting Belle (II) results shown today, many of which world-best
  - $B^0 \to K_S^0 \tau^\pm \ell^\mp$: world best limits and new searches. [Submitted to PRL; arxiv 2412.16470]
  - $B^0 \to K^{*0} \tau^\pm \ell^\mp$: not competitive with new LHCb results
  - $B^0 \to K^{*0} \tau^+ \tau^-$: world best limits.

Reaching sensitivities of few 10^{-5} for $b \to s\tau\ell$ and few 10^{-3} for $b \to s\tau\tau$

Additional materials

$B^0 \to K_S^0 \tau^\pm \ell^\mp$: systematics

Belle + Belle II
(711 + 365 fb^{-1})

	Belle	Belle II	Combined Systematic U.
Lepton identification	0.3% for μ 0.4% for e	0.5% for μ 1.0% for e	0.24% for μ 0.43% for e
Pion identification	1.0%	1.0%	0.74%
Tag side efficiency	4.9%	5.2%	3.7%
$N_{\pi^0}^{ROE}$ veto	1.1%	2.8%	1.2%
π^0 reconstruction	0.5%	3.8%	1.3%
BDT selection	-	-	OS_μ:17.1%, SS_μ:17.5% OS_e:16.6%, SS_e:19.2%
Signal PDF shape	-	-	15.7%
Linearity	-	-	OS_μ:1.6%, SS_μ:1.4% OS_e:0.8%, SS_e:1.4%
Number of BB pairs	1.4%	1.6%	1.1%
Other sources	f^{+-}/f^{oo} (2.3 %)+ MC statistics (0.0004%)		

$B^0 \to K^{*0}\tau^\pm\ell^\mp$: systematics

Belle + Belle II
(711 + 365 fb^{-1})

Source	Belle				Belle II			
	OSe	SSe	$OS\mu$	$SS\mu$	OSe	SSe	$OS\mu$	$SS\mu$
FEI efficiency [%]	4.9	4.9	4.9	4.9	6.2	6.1	6.1	6.2
Lepton ID efficiency [%]	2.0	2.4	2.2	2.2	0.7	1.1	0.7	0.6
Hadron ID efficiency [%]	1.9	2.0	1.9	2.0	3.7	3.7	3.6	3.7
BDT efficiency [%]	27	21	18	23	29	31	34	31
Tracking efficiency [%]	1.4				1.1			
Total efficiency [%]	27.6	21.8	18.9	23.7	29.8	31.8	34.7	31.7
Signal PDF μ ($\times 10^{-5}$)	0.04	0.00	0.01	0.01	0.04	0.00	0.01	0.01
Signal PDF λ ($\times 10^{-5}$)	0.11	0.01	0.04	0.01	0.11	0.01	0.04	0.01
Background PDF ($\times 10^{-5}$)	0.11	0.28	0.09	0.02	0.11	0.28	0.09	0.02
$N_{\Upsilon(4S)}$ [%]	1.4				1.6			
f^{00} [%]	0.8							
$\mathcal{B}(K^{*0} \to K^+\pi^-)$ [%]	0.021							
Total impact on UL ($\times 10^{-5}$)	0.1	0.3	0.1	0.1	0.1	0.3	0.1	0.1

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

Belle II (365 fb^{-1})

Source	Impact on $\mathcal{B} \times 10^{-3}$
$B \to D^{**}\ell/\tau\nu$ branching fractions	0.29
Simulated sample size	0.27
$q\bar{q}$ normalization	0.18
ROE cluster multiplicity	0.17
π and K ID	0.14
B decay branching fraction	0.11
Combinatorial $B\overline{B}$ normalization	0.09
Signal and peaking $B^0\overline{B}^0$ normalization	0.07
Lepton ID	0.04
π^0 efficiency	0.03
f_{00}	0.01
$N_{\Upsilon(4S)}$	0.01
$D \to K_L$ decays	0.01
Signal form factors	0.01
Luminosity	< 0.01
Total systematics	0.52
Statistics	0.86