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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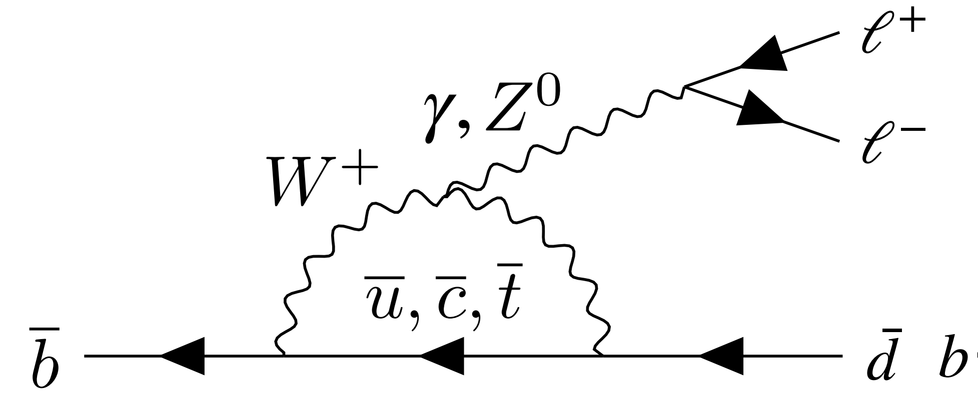
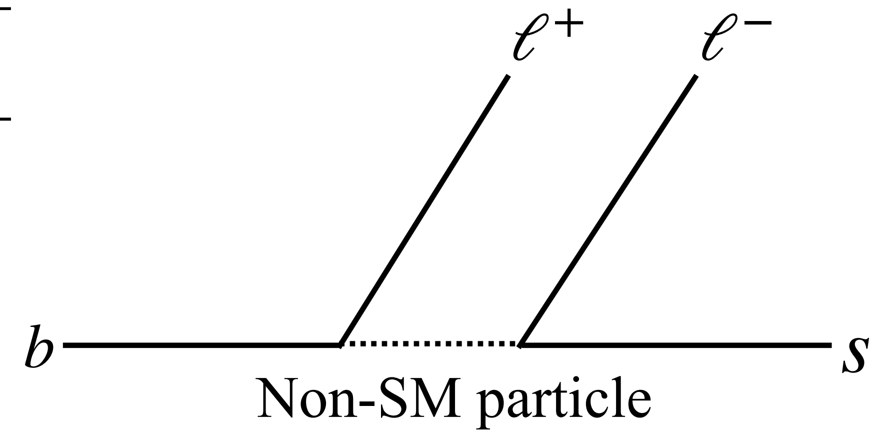
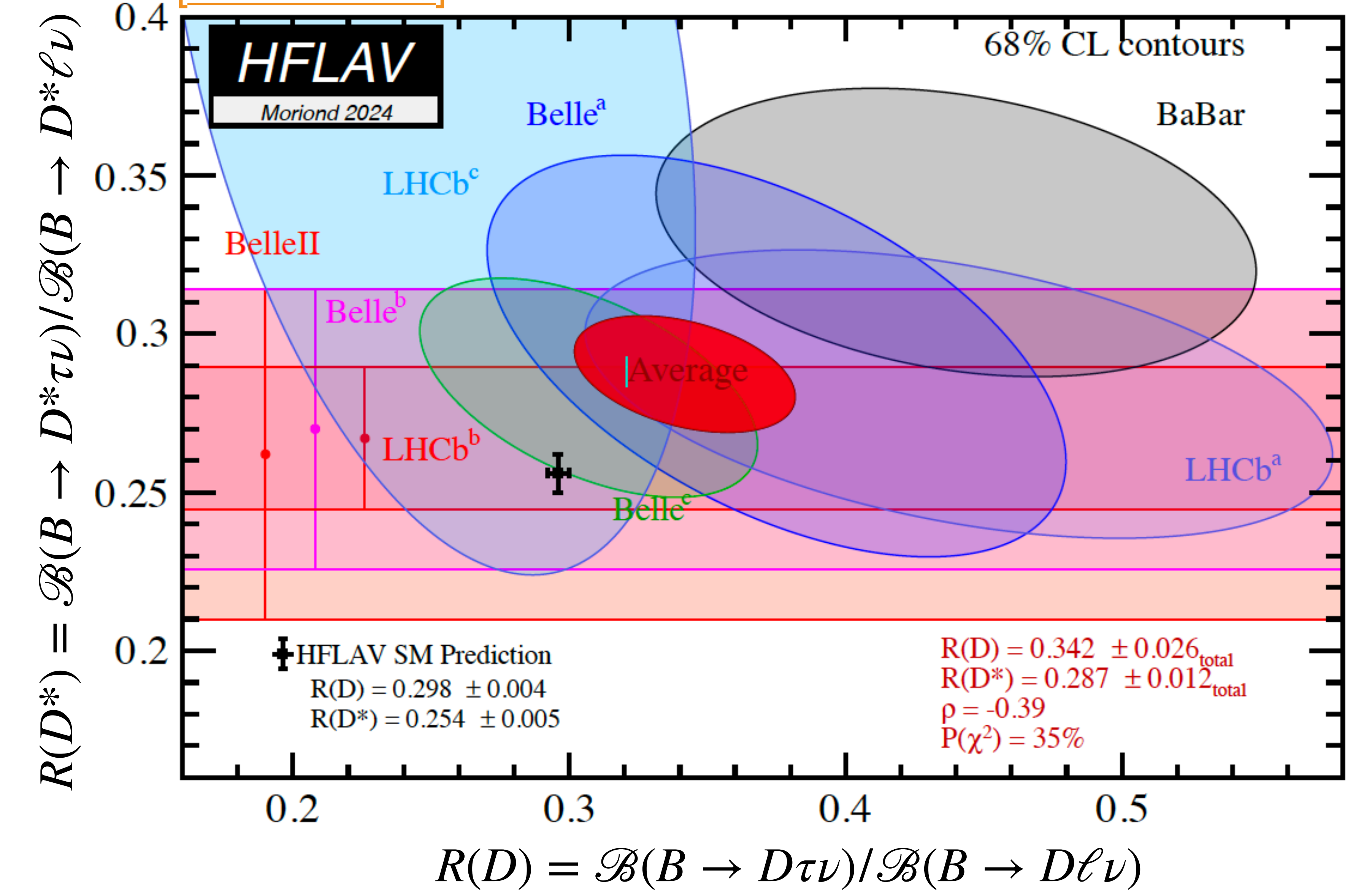
Physics

- 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 interaction
  - 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 and higher mass, τ [EPJC 83, 153 (2023)] [PLB 848, 138411 (2024)]
- Today's topics: $B^0 \to K_S^0\tau^\pm\ell^\mp$,$B^0 \to K^{*0}\tau^\pm\ell^\mp$, $B^0 \to K^{*0}\tau^+\tau^-$,
- Experimental challenge: undetected neutrinos in the final states from τs





[HFLAV 2023]

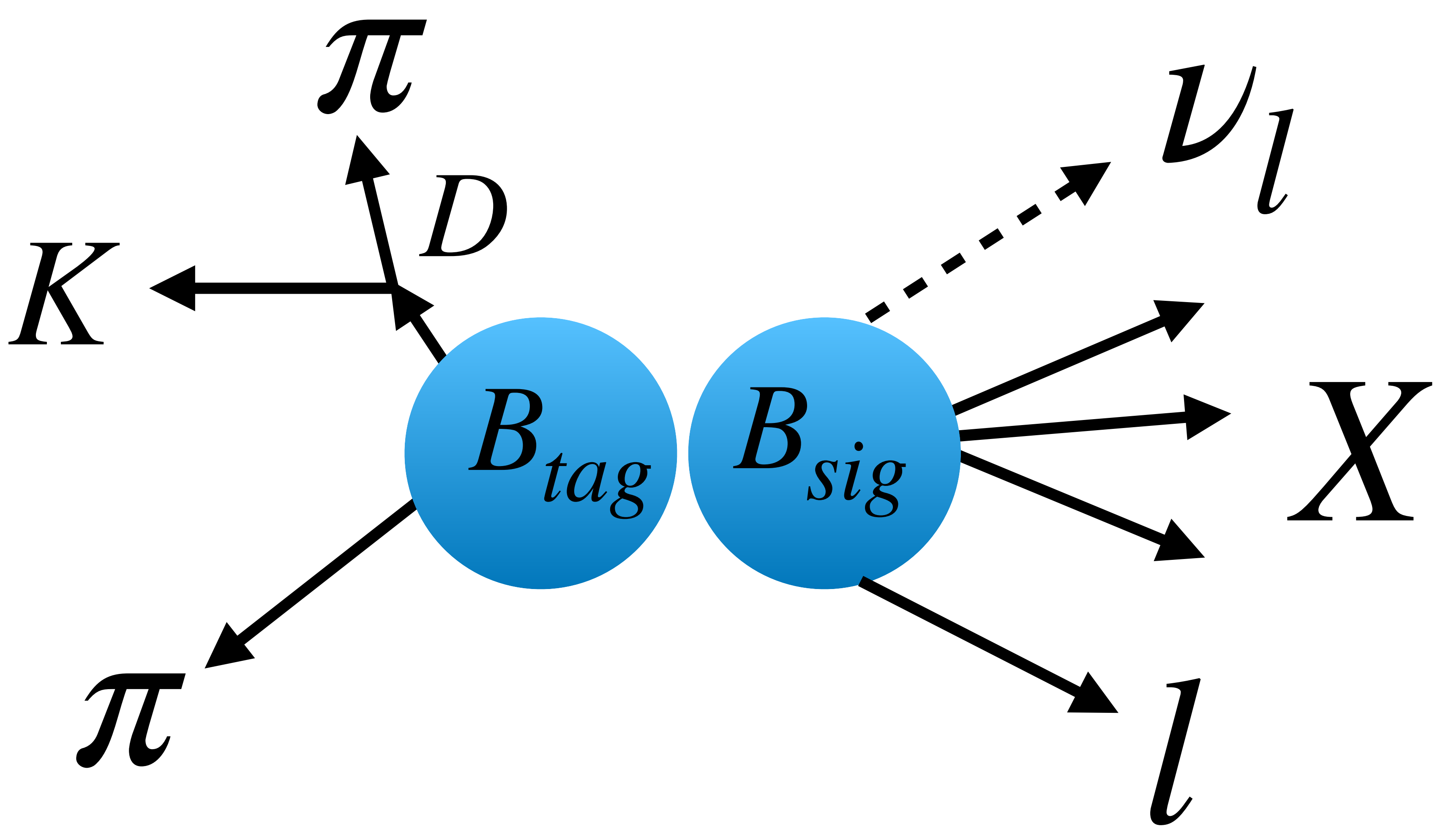


All new results since last Moriond QCD

Belle (II) advantage

See Bianca's slides for more details on detector

- e^+e^- collision near $B\overline{B}$ production threshold makes Belle (II) ideally suited: low background, precisely known collision energy
- Hermetic detector: full event reconstruction
- Kinematic well constrained with companion B meson reconstruction (tagging)
- Advantageous for searches involving final states with multiple neutrinos
- Dataset: 772 M (Belle) + 387 M (Belle II) $B\bar{B}$ pairs

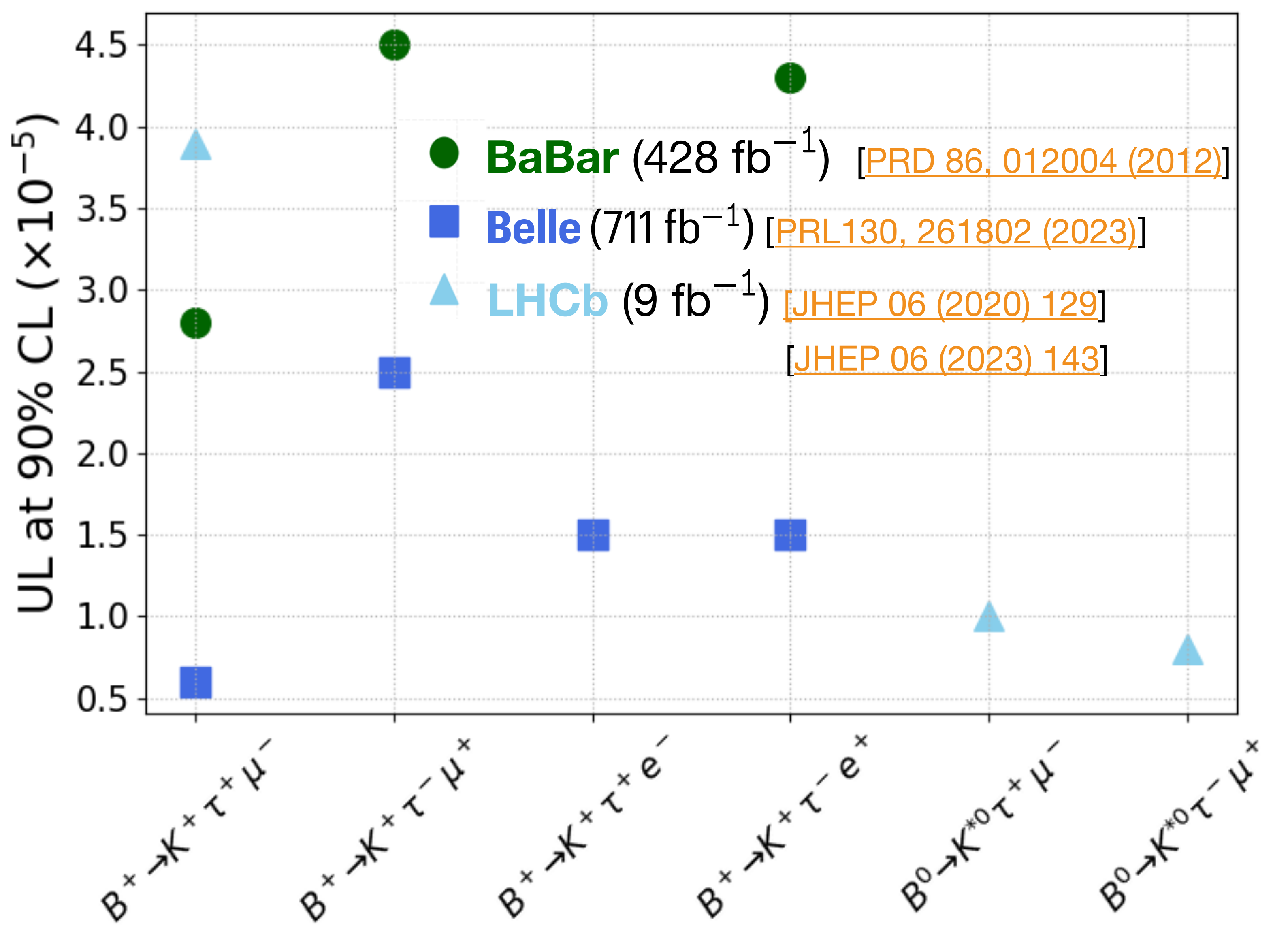


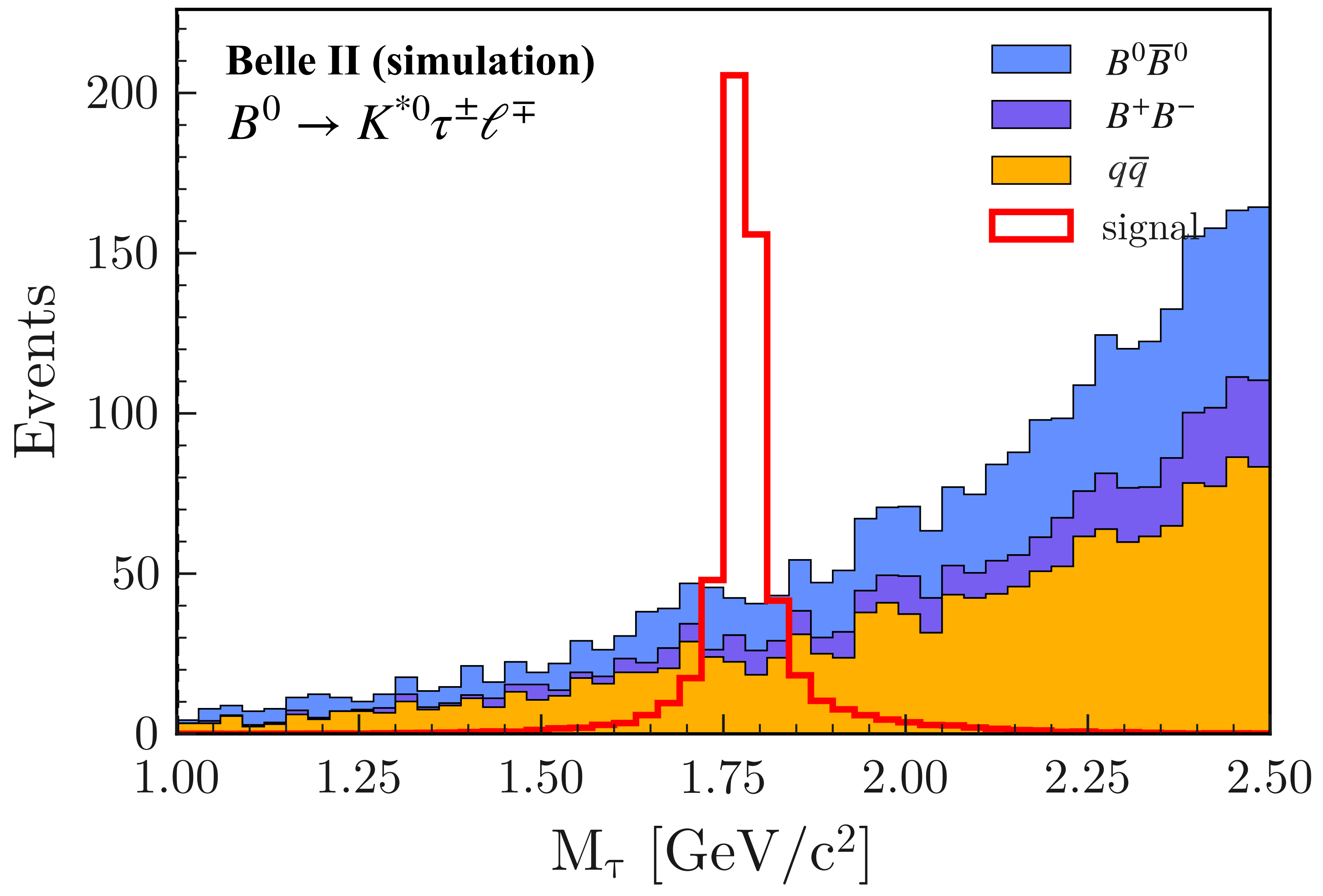
All results today involve hadronic tagging

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

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

- Forbidden decay. Non-SM particles, explaining recent anomalies, predict LFV with $\mathcal{B}(b \to s\tau\ell)$ at $\mathcal{O}(10^{-6})$ Near current experimental limits.
- World best limits from LHCb and Belle at $\mathcal{O}(10^{-5})$
- Advantage of one τ in the final state: restrict nonsignal B decays in fully hadronic states and compute recoil mass of τ, $M^2_{\text{recoil}} = M^2_\tau = (p_{e^+e^-} - p_K - p_\ell - p_{B_{\text{tag}}})^2$

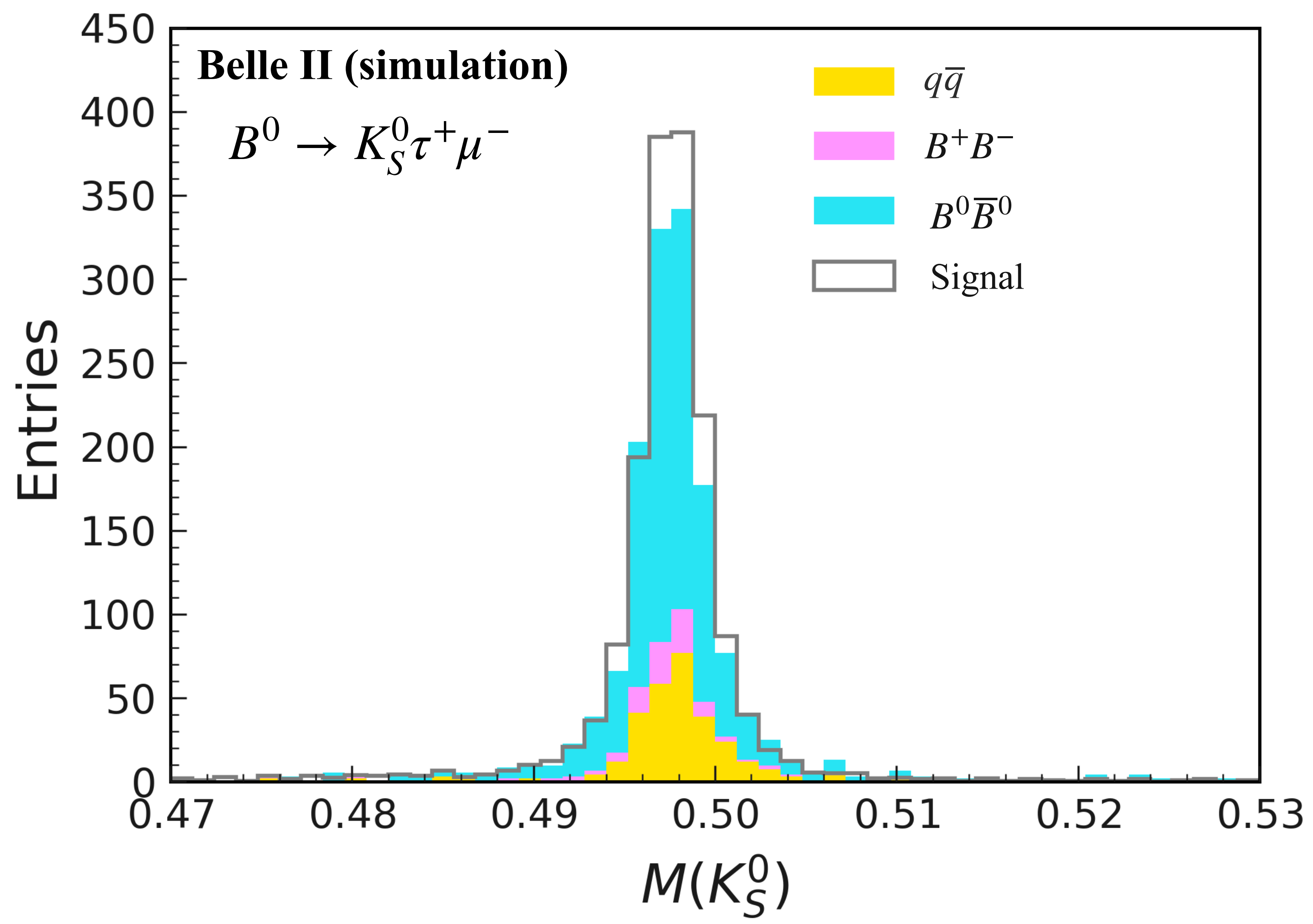


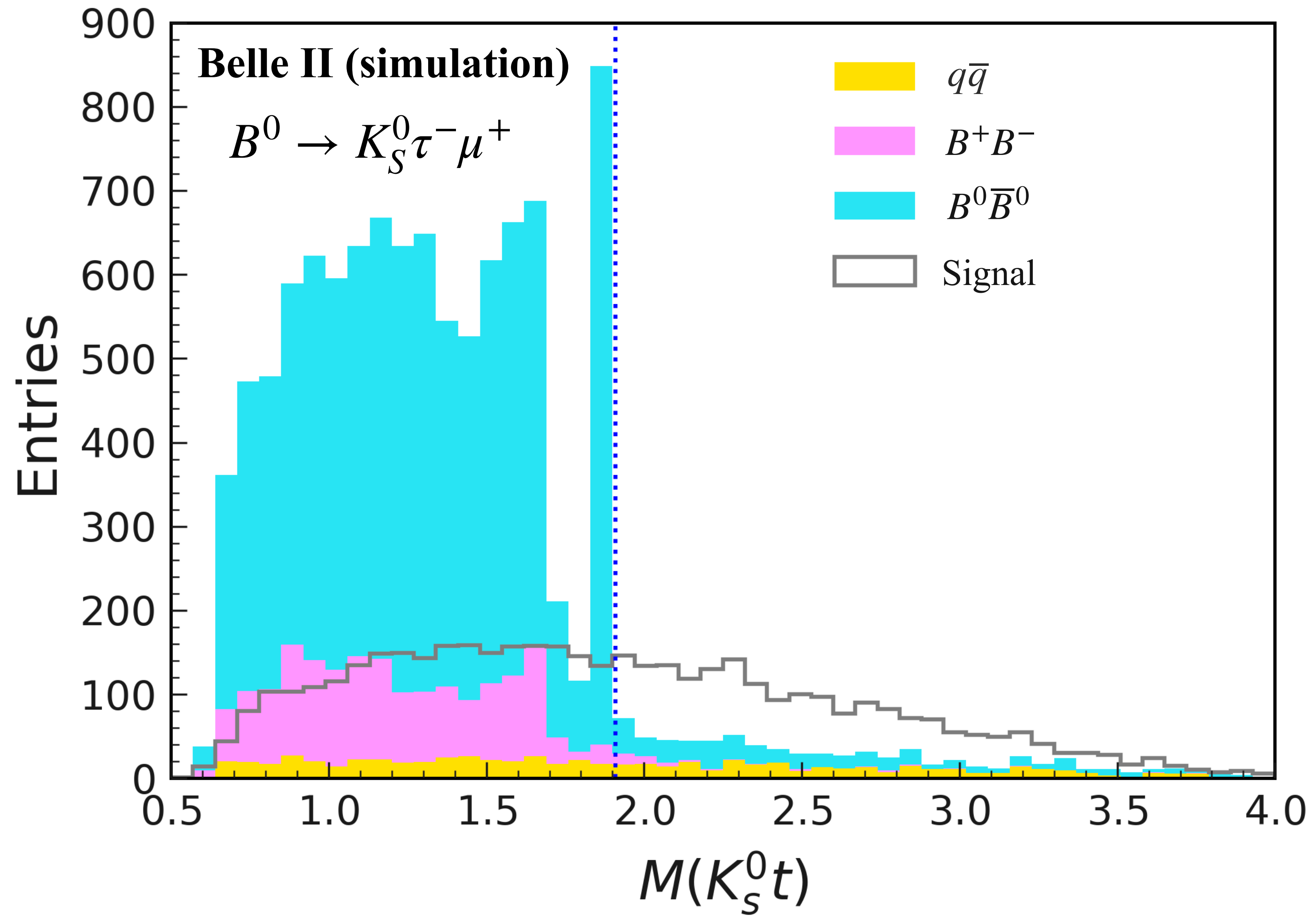


Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$

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

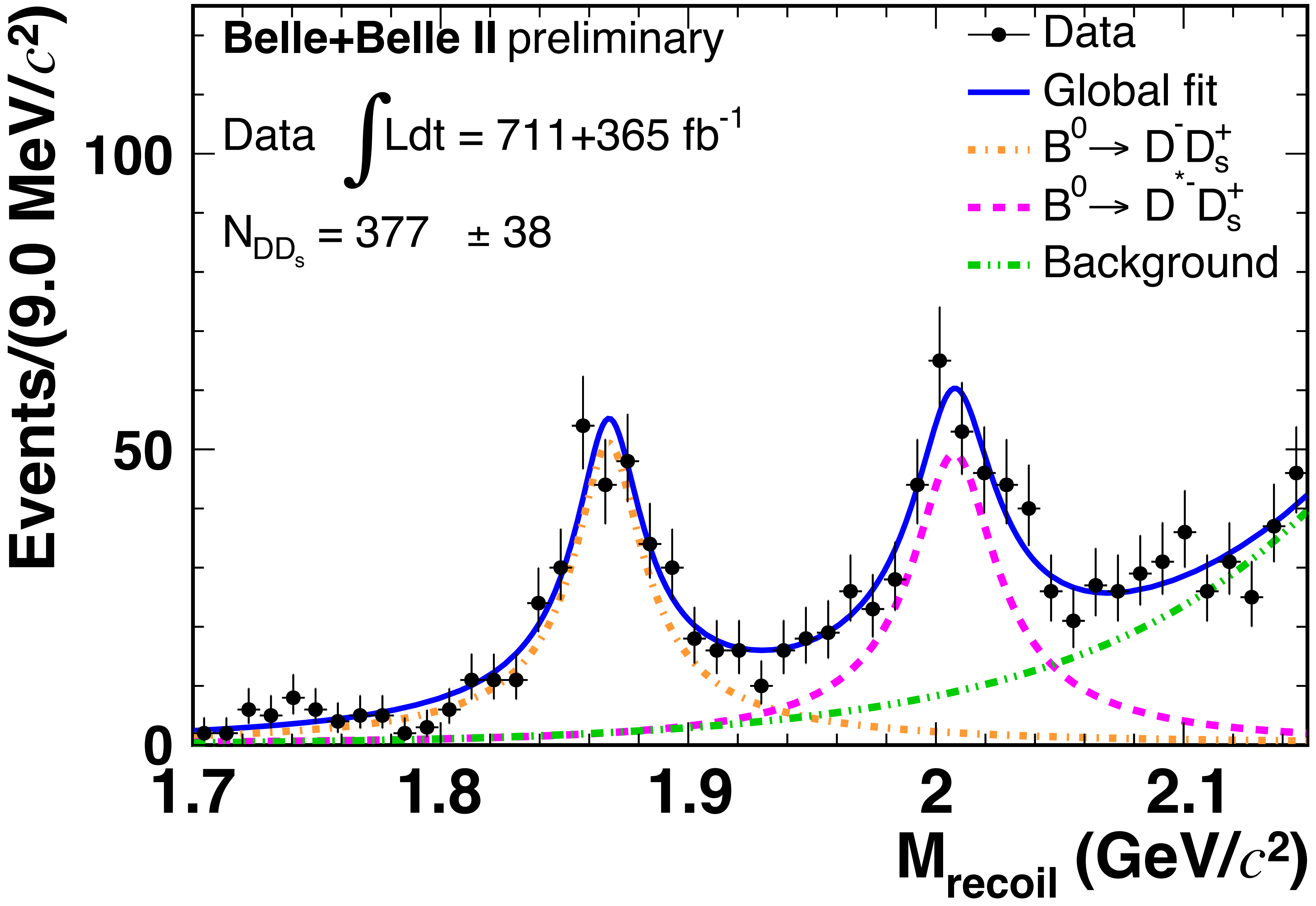
- Never searched for before
- High K_S^0 purity ($> 98\,\%$)
- Search in 1-prong τ decays: $\tau^+ \to \ell^+ \nu\bar{\nu}, \pi^+\nu, \rho^+\nu$. Use $\tau \to \rho\nu$ for the first time in $b \to s\tau^\pm\ell^\mp$ searches
- Restrict $m(K_S^0 t_\tau)$ to suppress dominant semileptonic $B \to D^{(*)}\ell X$ backgrounds
- Suppress remaining background with classifier using $m(K_S^0\ell)$, residual calorimeter energy, lepton kinematics and event topology
- Fit recoil τ mass (M_τ) for signal extraction in combined Belle + Belle II data set





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

- Correct simulated nonsignal B efficiency to match data from fits to recoil D mass in $B^+ \to \overline{D}^0 \pi^+$
- Validate signal shape and classifier selection efficiency from fits to recoil D mass in $B^0 \to D^- D_s^+ (\to \phi \pi^+, K_S^0 K^+)$
    - largest source of systematic uncertainty



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

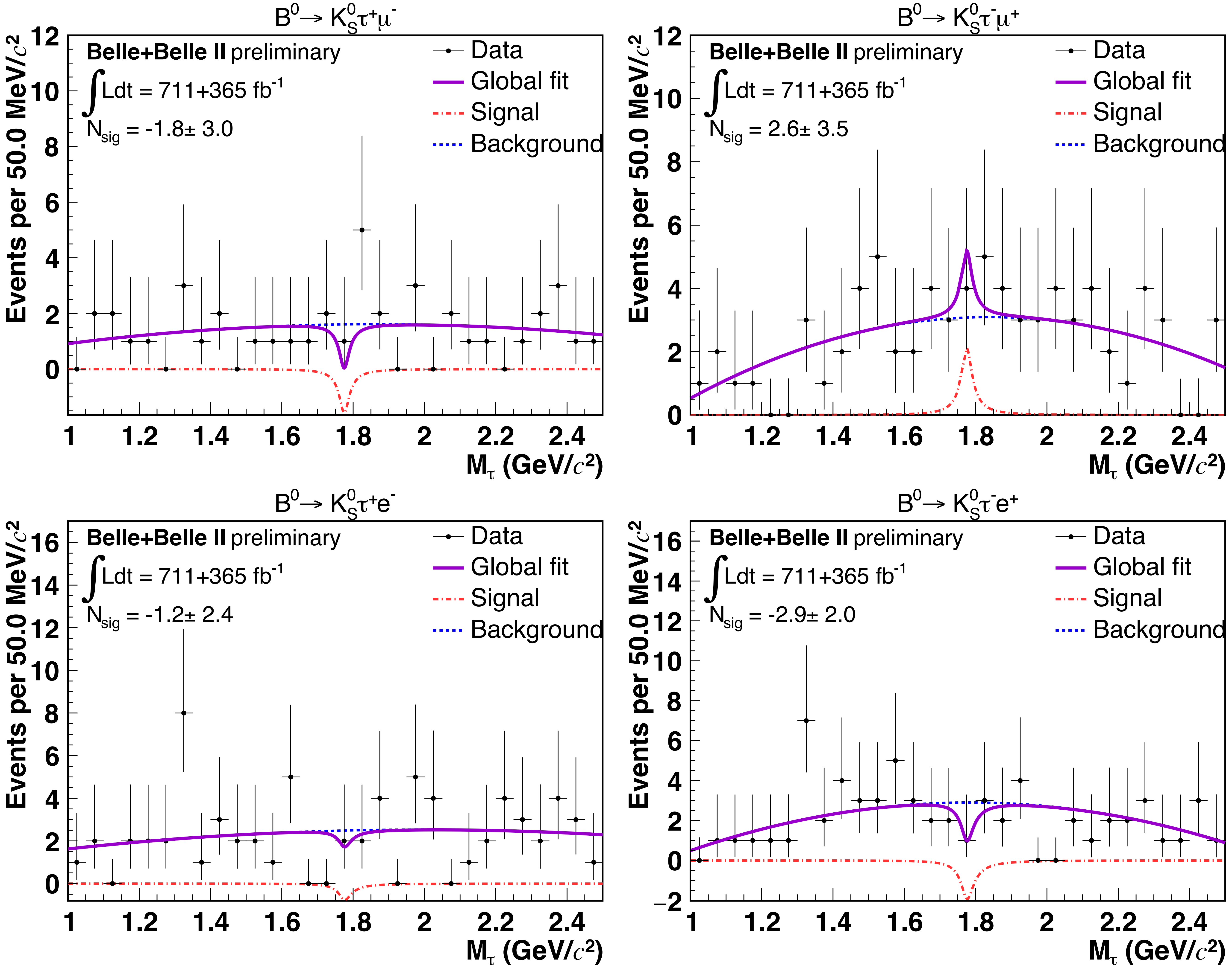
Belle + Belle II (711 + 365 fb^{-1})

- Signal extraction: fit recoil τ mass (M_τ)

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

at 90% CL

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

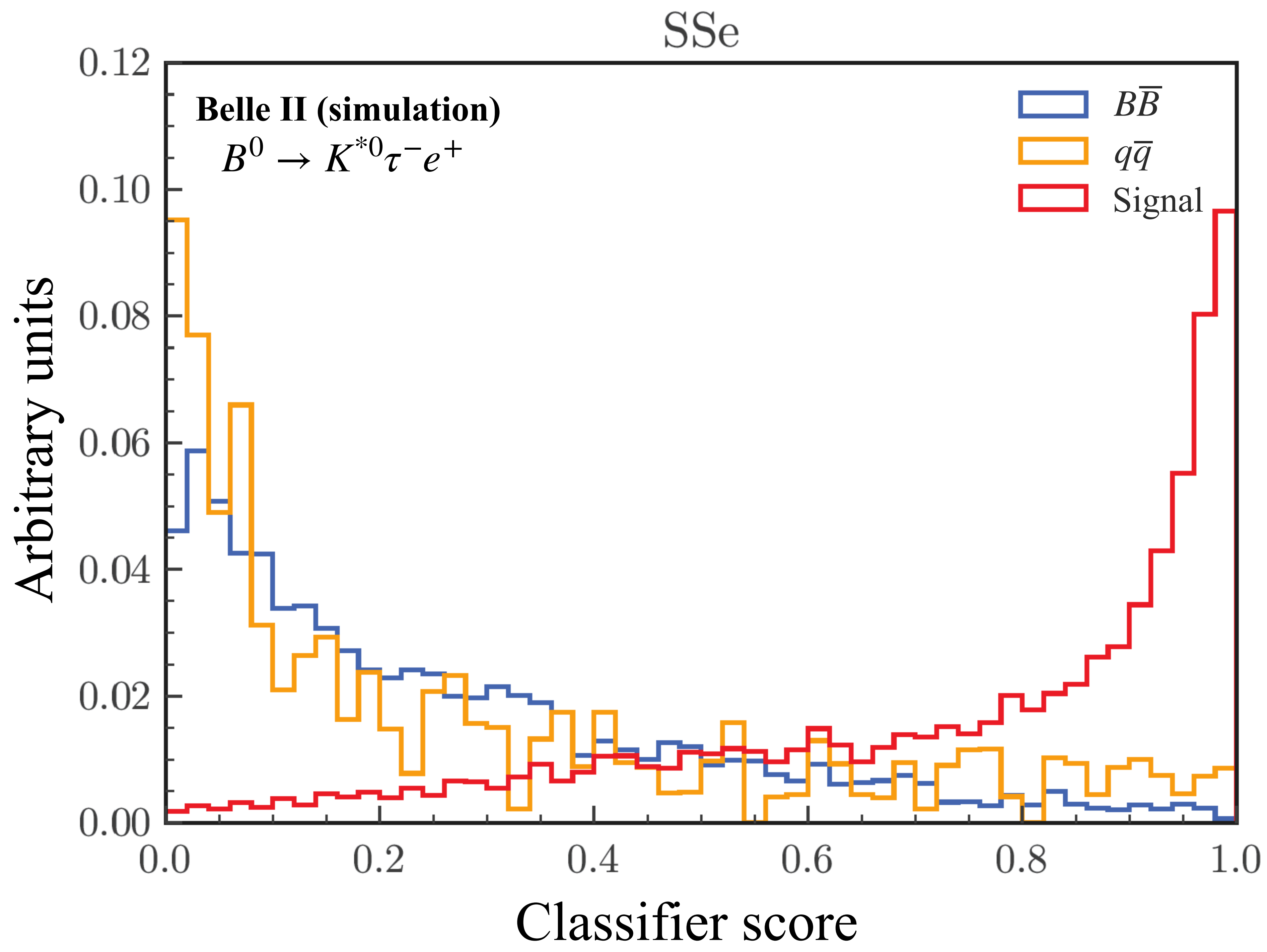


Submitted to PRL [arxiv 2412.16470]

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

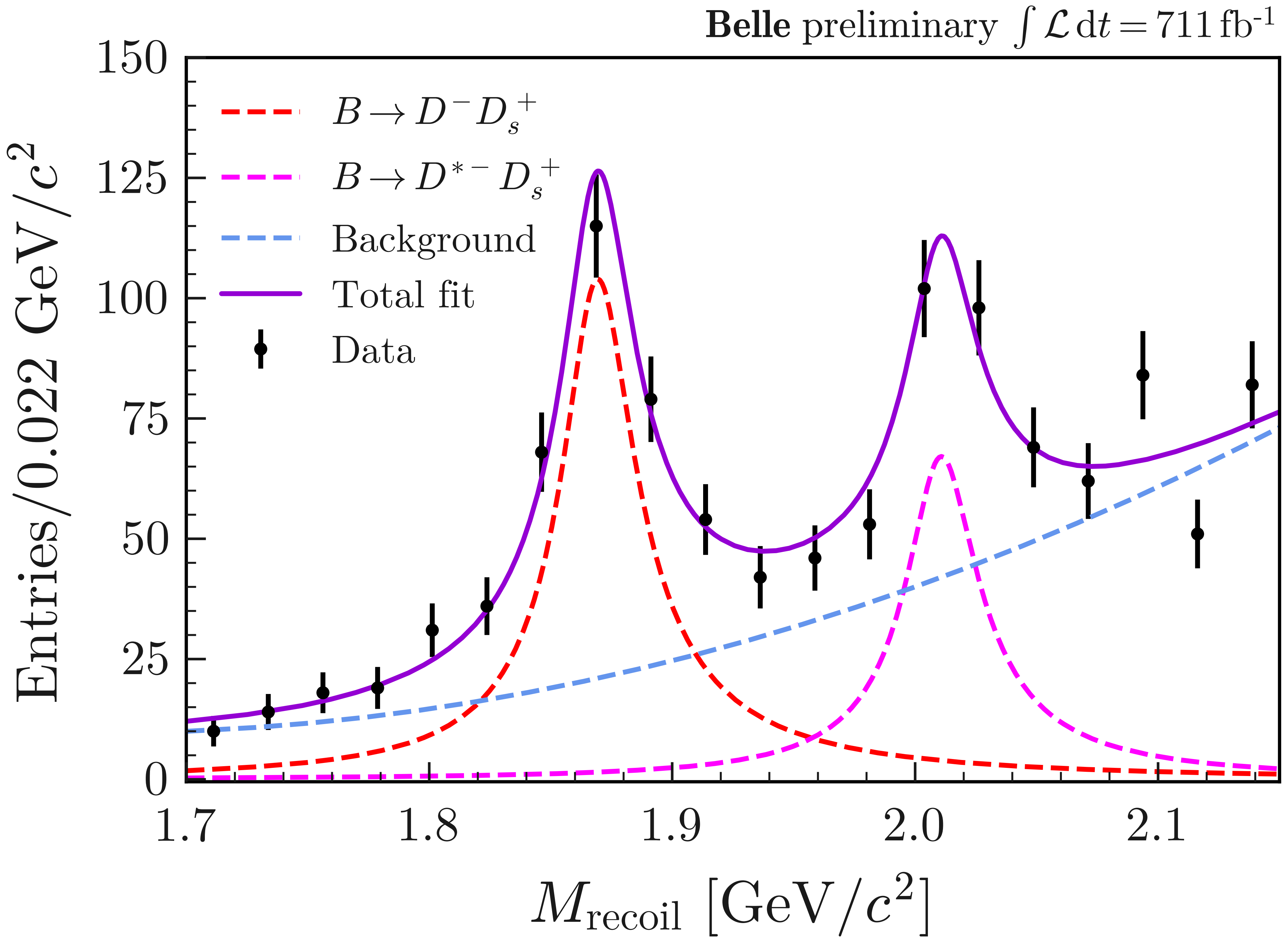
Belle + Belle II (711 + 365 fb^{-1})

- World best limit in $B^0 \to K^{*0}\tau^\pm\mu^\mp$ by LHCb:
  $\mathscr{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$;
  $\mathscr{B}(B^0 \to K^{*0}\tau^-\mu^+) < 0.8 \times 10^{-5}$
- No search for $B^0 \to K^{*0}\tau^\pm e^\mp$ yet
- Inclusive 1-prong τ reconstruction: $K^{*0}(\to K^+\pi^-)\ell$ + one track from τ — covers $\sim 80\,\%$ of τ decay-width
- Suppress background with classifier using $m(K^{*0}\ell)$, $m(K^{*0}t_\tau)$, residual tracks and clusters properties, K^{*0} vertex information, event topology, etc.
- Simultaneous fit recoil τ mass (M_τ) in Belle and Belle II data set



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

- Correct simulated nonsignal B efficiency using $B^0 \to D^-\pi^+$ and $B \to X_c\ell\nu$ control data
- Validate signal shape and classifier selection efficiency from fits to recoil D mass in $B^0 \to D^- D_s^+(\to \phi\pi^+, K^{*0}K^+)$
- Dominant systematic uncertainties from classifier selection efficiency and background shape assumption



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

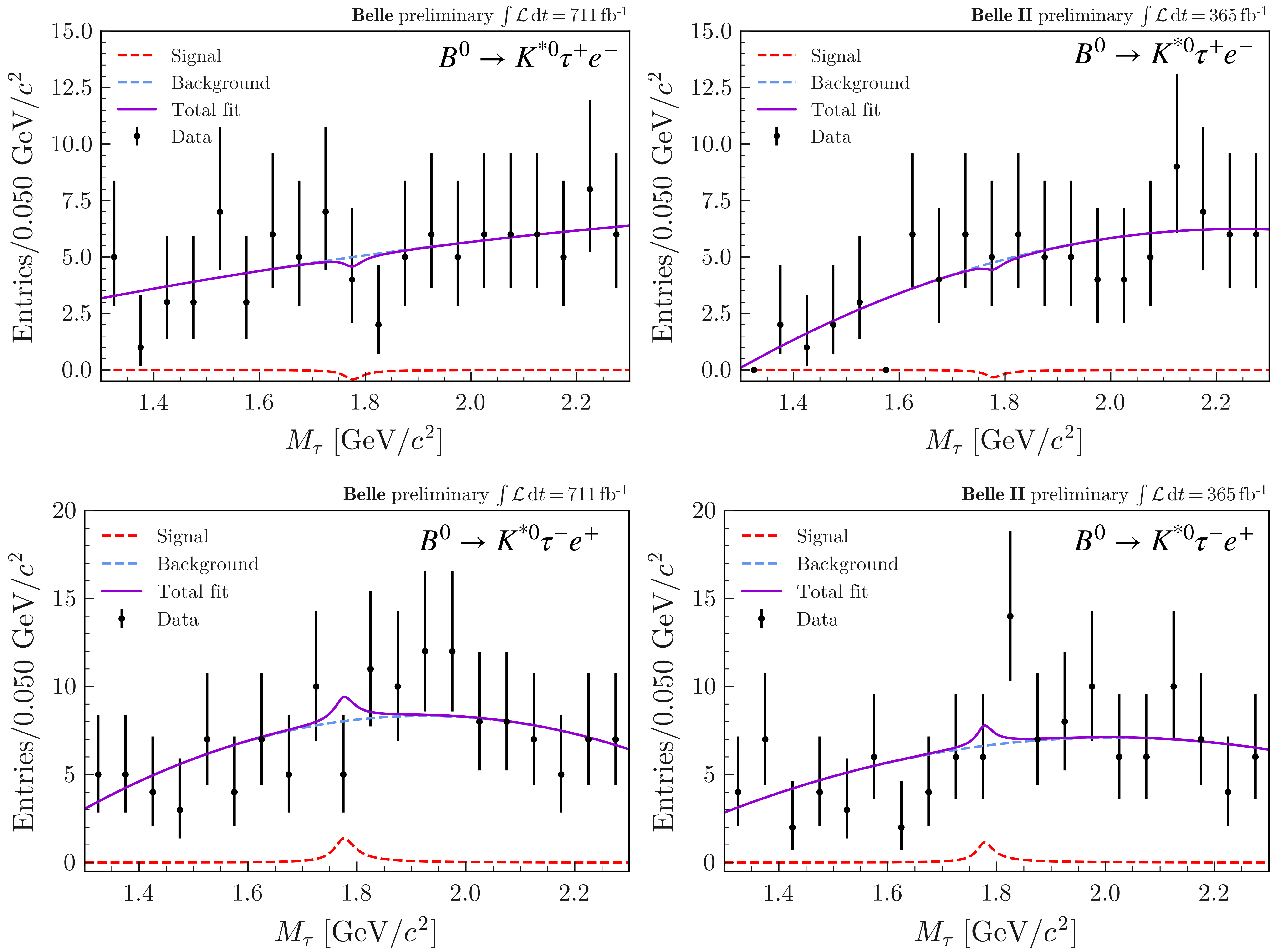
Belle + Belle II (711 + 365 fb^{-1})

- Signal extraction: fit recoil τ mass (M_τ)

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 3.9 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 5.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+e^-) < 2.7 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-e^+) < 5.6 \times 10^{-5}$$

at 90% CL

First results on electron modes

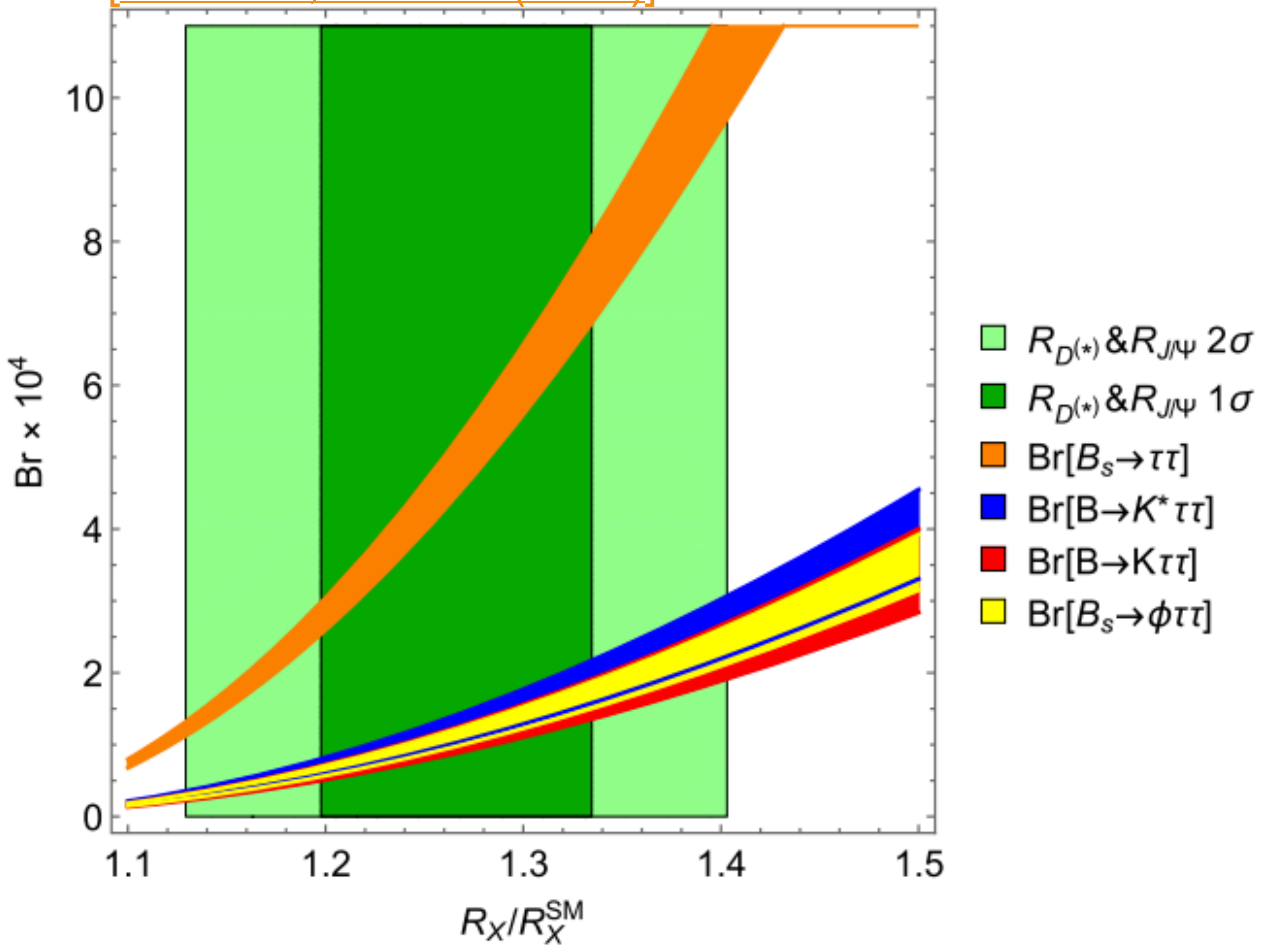


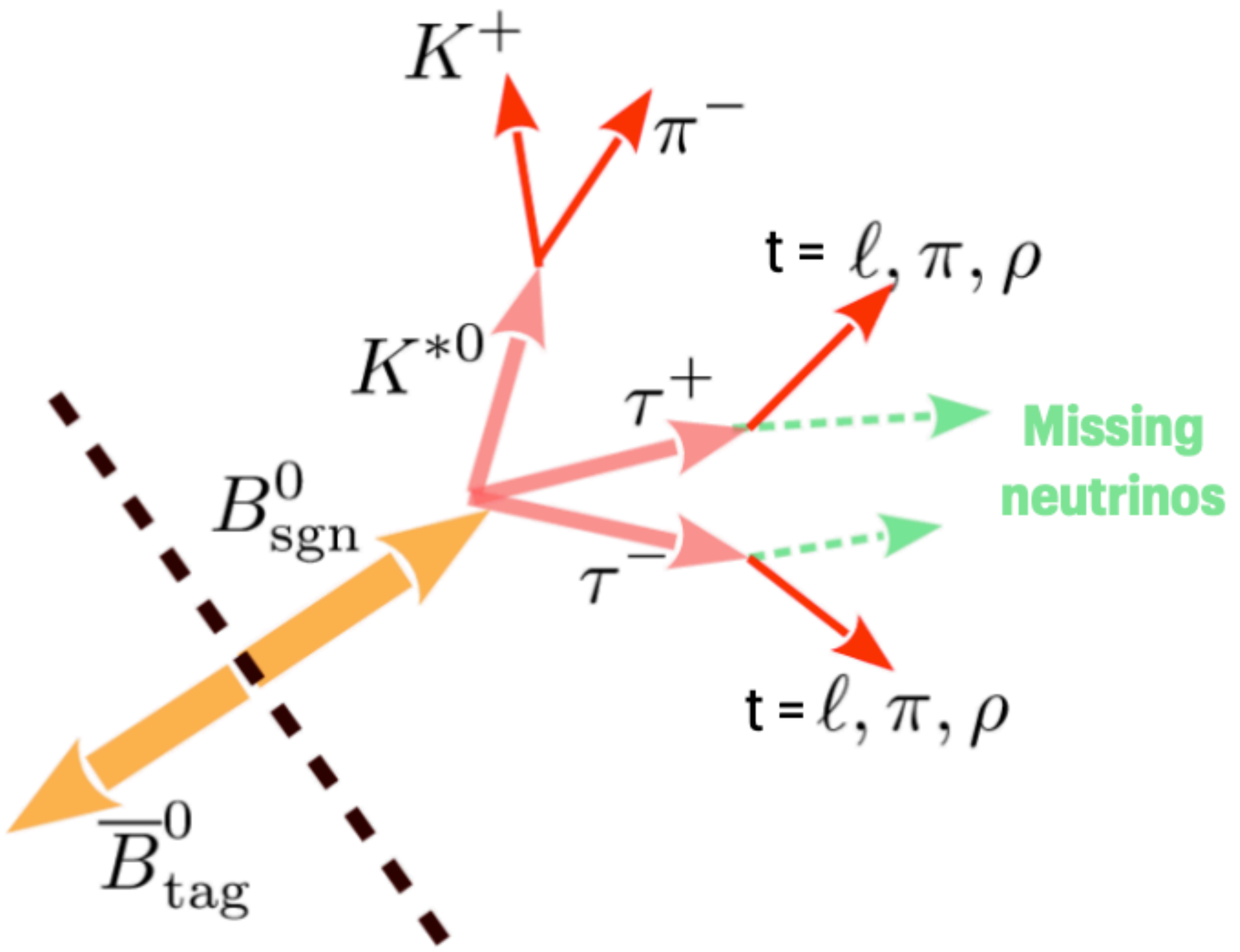
$$b \to s\tau^+\tau^-$$

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

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

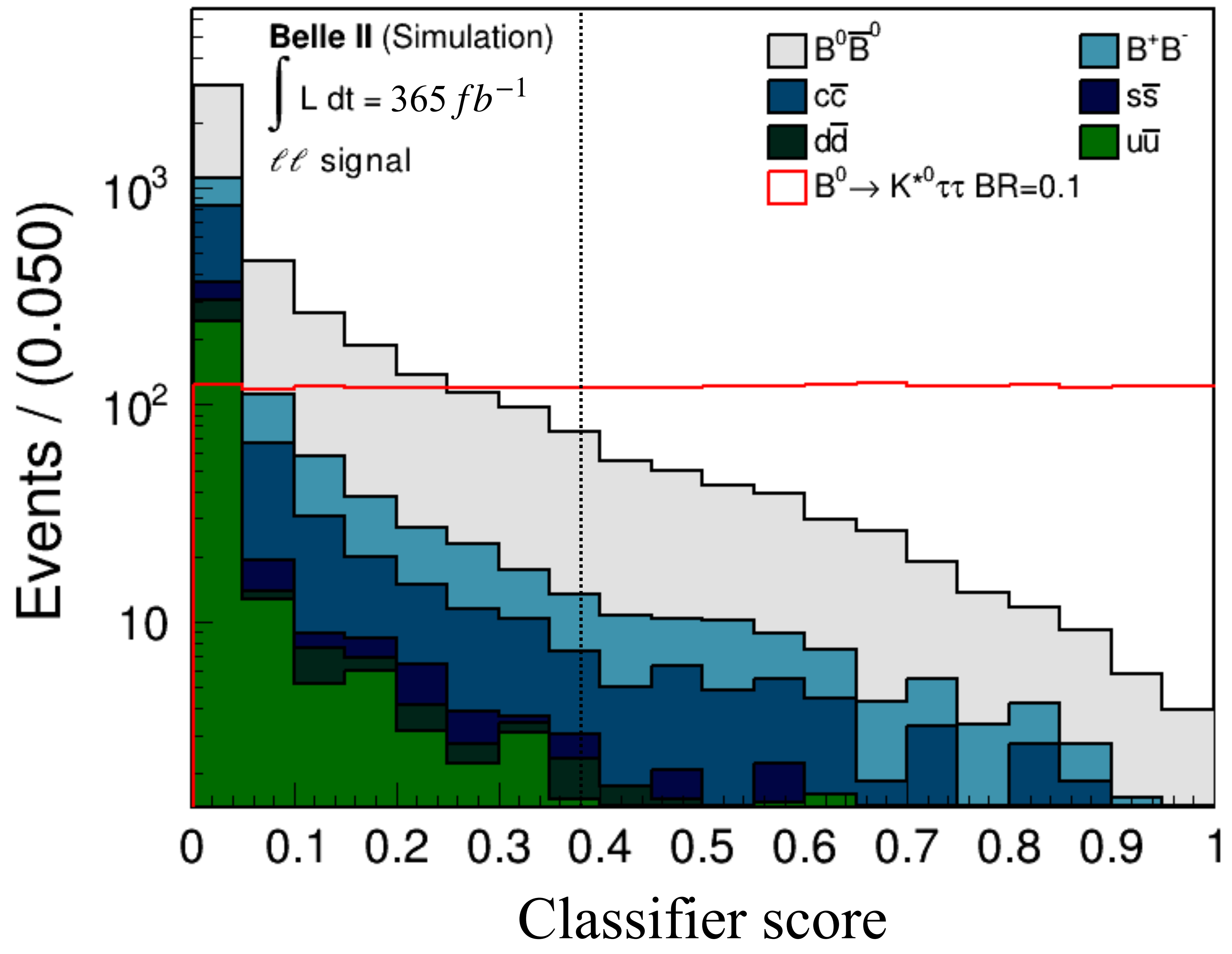
[PRL 120, 181802 (2018)]





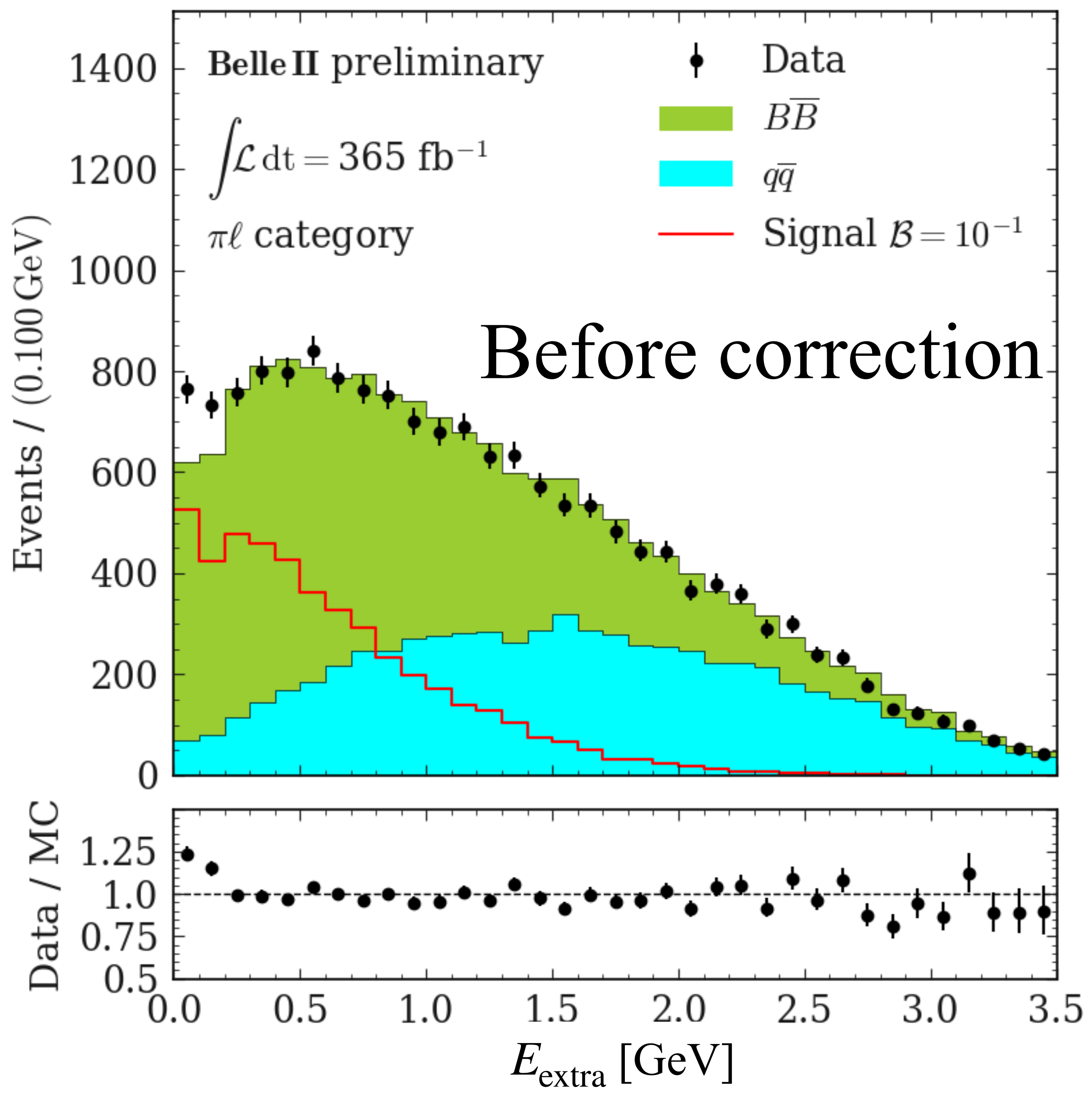
$B^0 \to K^{*0}\tau^+\tau^-$: strategy

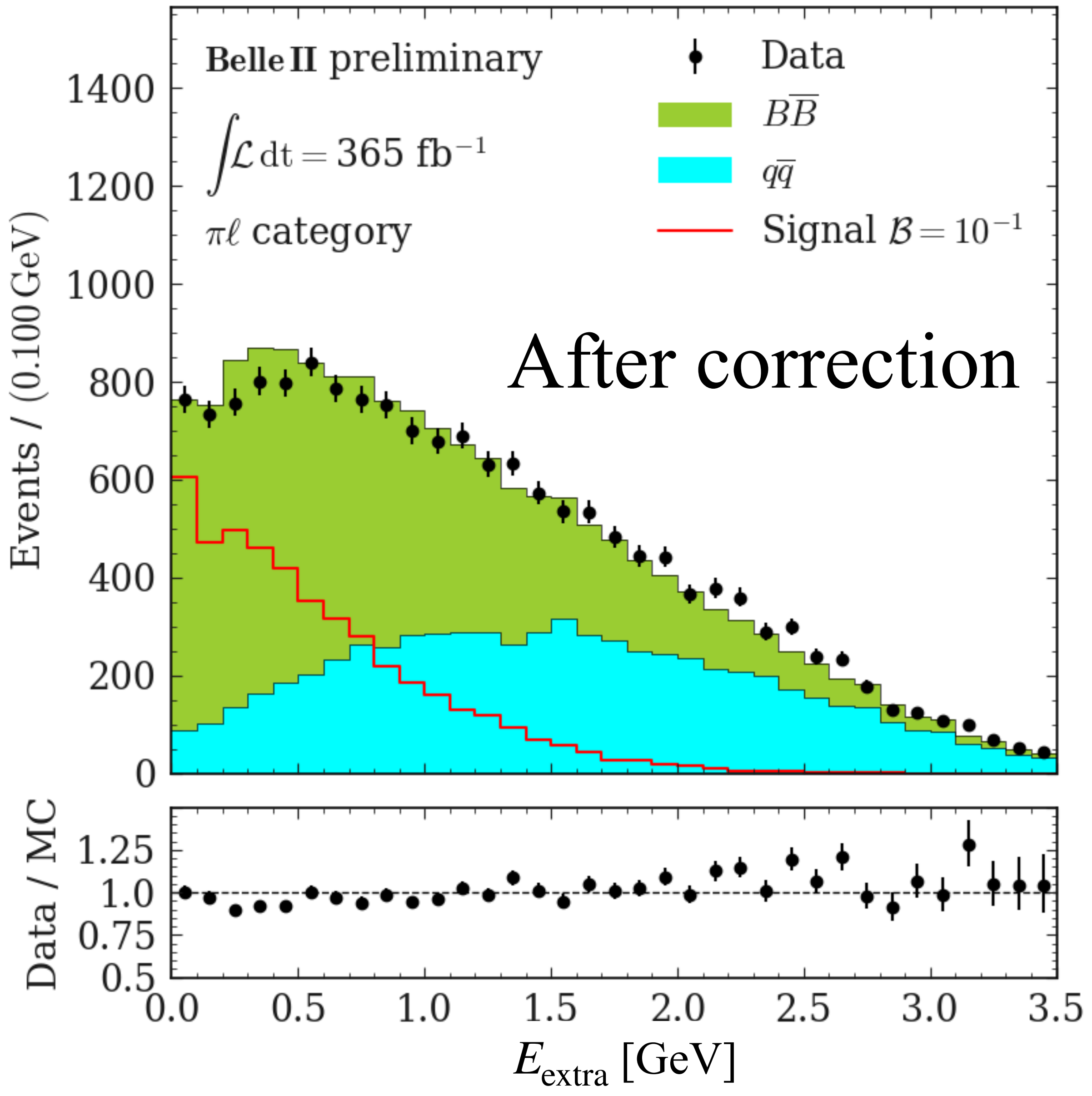
- Analyze separately in four final-state categories from $\tau^+\tau^-$ pair: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX ($X = \ell, \pi, \rho$)
- Train classifier using missing energy, residual calorimeter energy, $m(K^{*0}t)$, square ditau mass, etc.
- Simultaneous fit classifier score of each category for signal extraction



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

- Signal efficiency validation in $B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$ with modified kinematics to match signal
- Background yield correction from same-flavor (B^0B^0, $\overline{B}^0\overline{B}^0$) control samples and off-resonance data
- Correct shape of residual calorimeter energy (E_{extra}), most important discriminator, from same-flavor control sample
- Dominant systematics sources: poor knowledge of semileptonic $B \to D^{**}$ decays, limited simulated sample size, etc.





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

Belle II (365 fb^{-1})

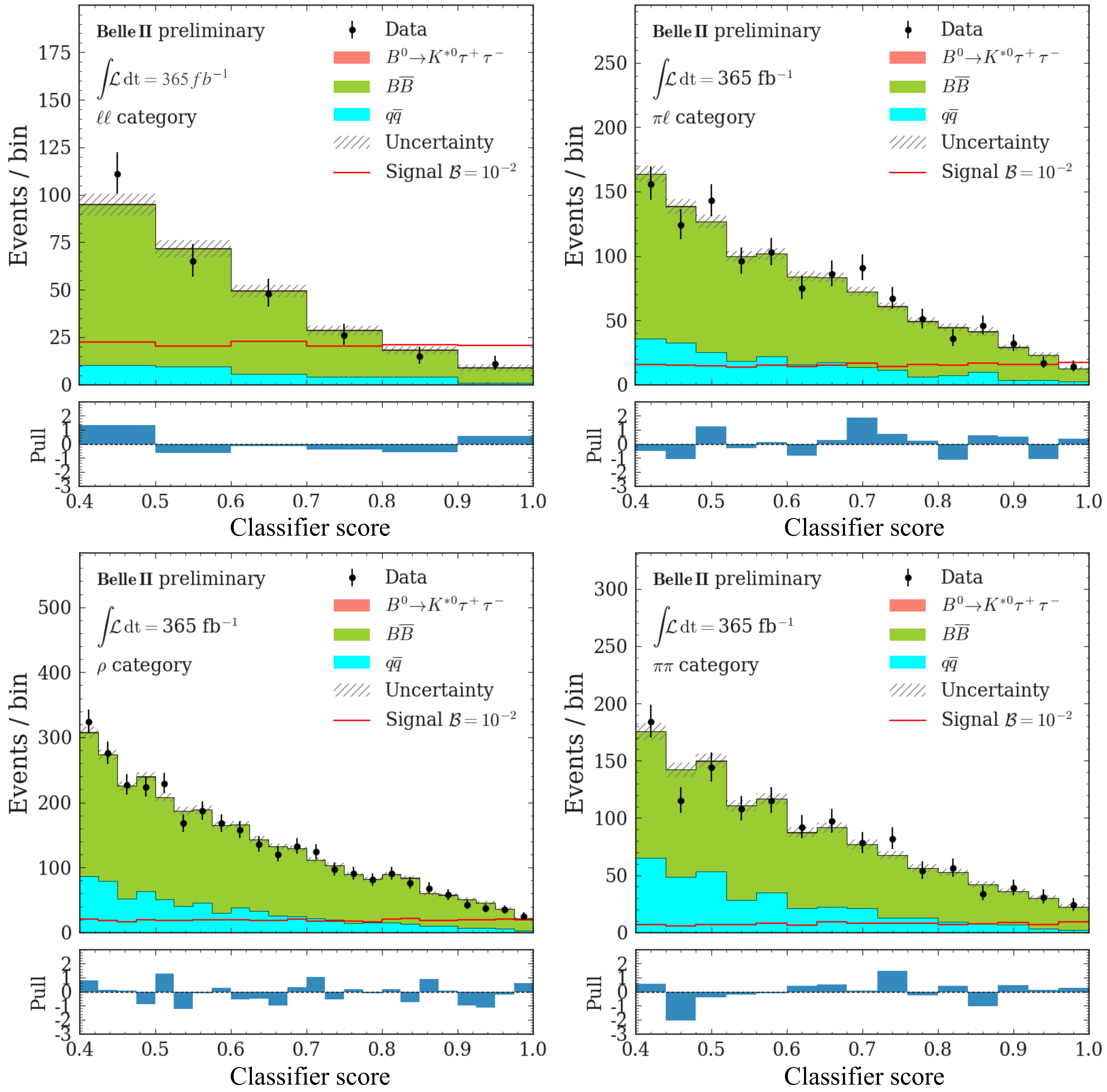
- Simultaneous fit classifier score of each category for signal extraction

$$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$$

at 90% C.L.

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 are shown today with many having world best results
  - $B^0 \to K_S^0 \tau^\pm \ell^\mp$: world best limits and new searches. [Submitted to PRL, arxiv 2412.16470]
  - $B^0 \to K^{*0} \tau^\pm \ell^\mp$: world best limits in electron modes and new searches.
  - $B^0 \to K^{*0} \tau^+ \tau^-$: world best limits.

Additional materials

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

$B^0 \to K_S^0 \tau^\pm \ell^\mp$: 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	0.11
$N_{\Upsilon(4S)}$ [%]	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