Electroweak penguin decays at Belle and Belle II

Renu
Carnegie Mellon University
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Why Electroweak Penguin (EWP) Decays?

Flavor-Changing Neutral Currents (FCNC)

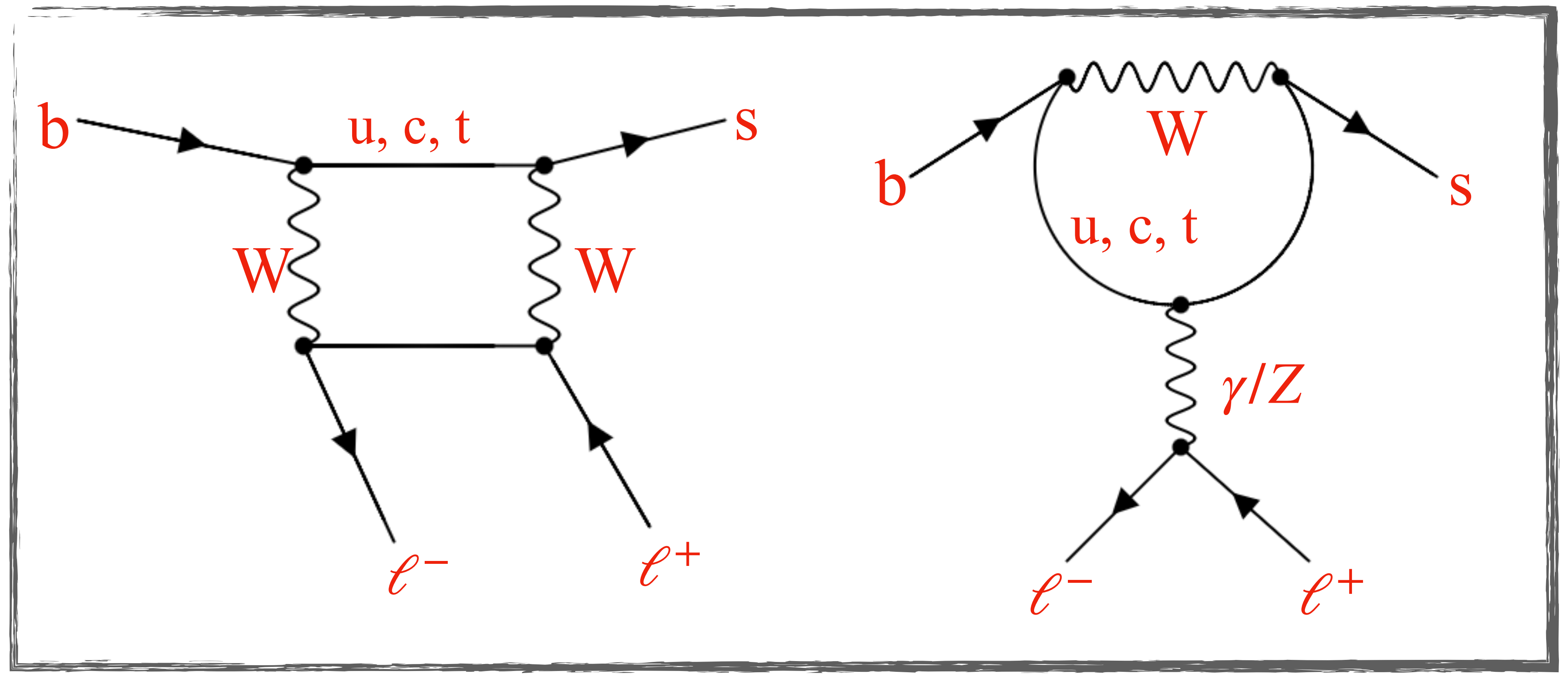
- Occur only via loop/box diagrams in SM → **naturally suppressed** (branching fraction:$10^{-5} - 10^{-10}$)

- **Highly sensitive to New Physics**
  - New heavy particles (e.g., $\boldsymbol{Z'}$, **leptoquarks**, etc.) can enter the diagram
  - Modify the variables like branching ratio, *CP* asymmetry, and angular observables arXiv:1512.09026

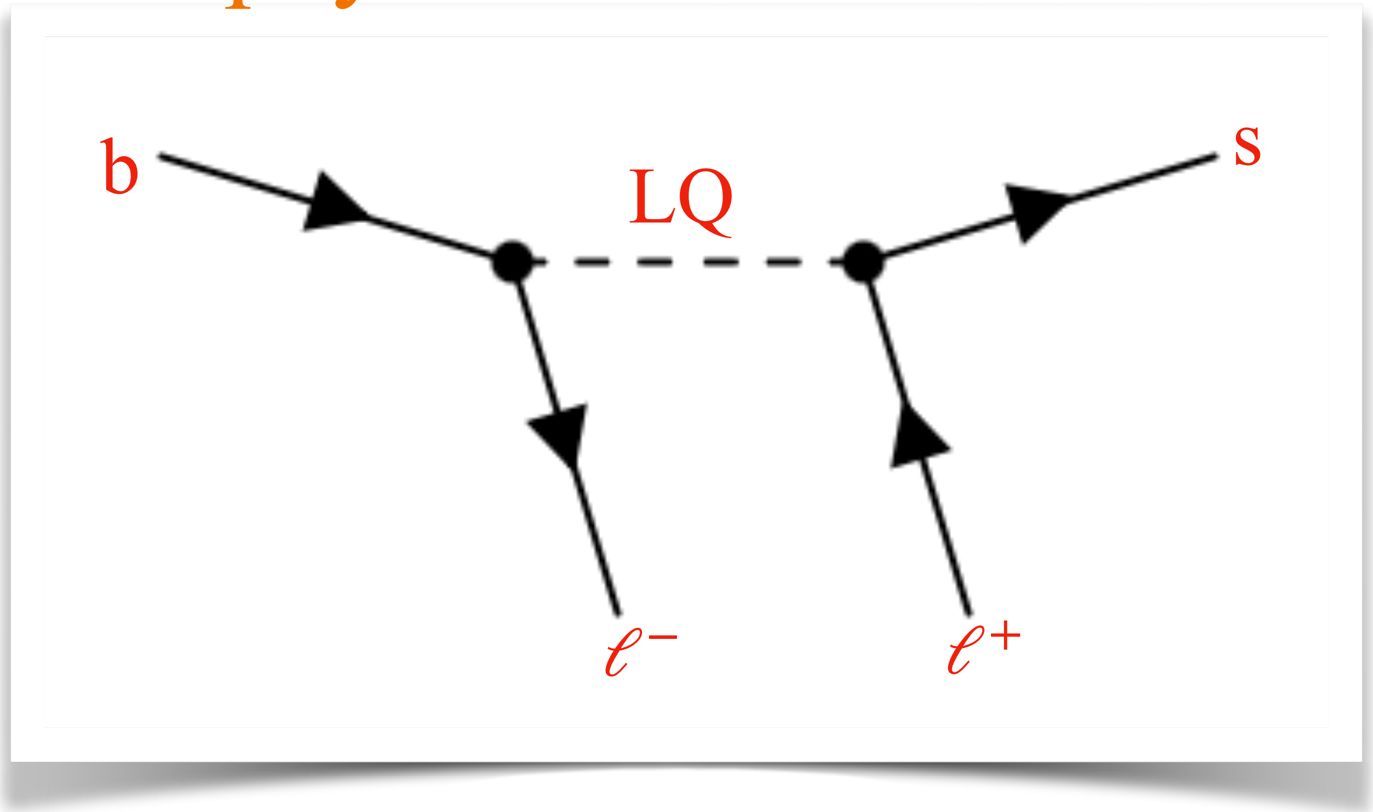
- **EWP** diagrams are a key class of FCNC processes

- **Taus Final States:**
  - Tau-involved decays (e.g., $B^0 \to K^{*0}\tau\tau$) are rare and largely unexplored
  - Heaviest lepton → stronger coupling to NP JHEP 04 (2022) 165
  - Less constrained experimentally → large discovery potential
  - Access complementary observables to $B \to K^{(*)}\mu\mu, ee$

SM



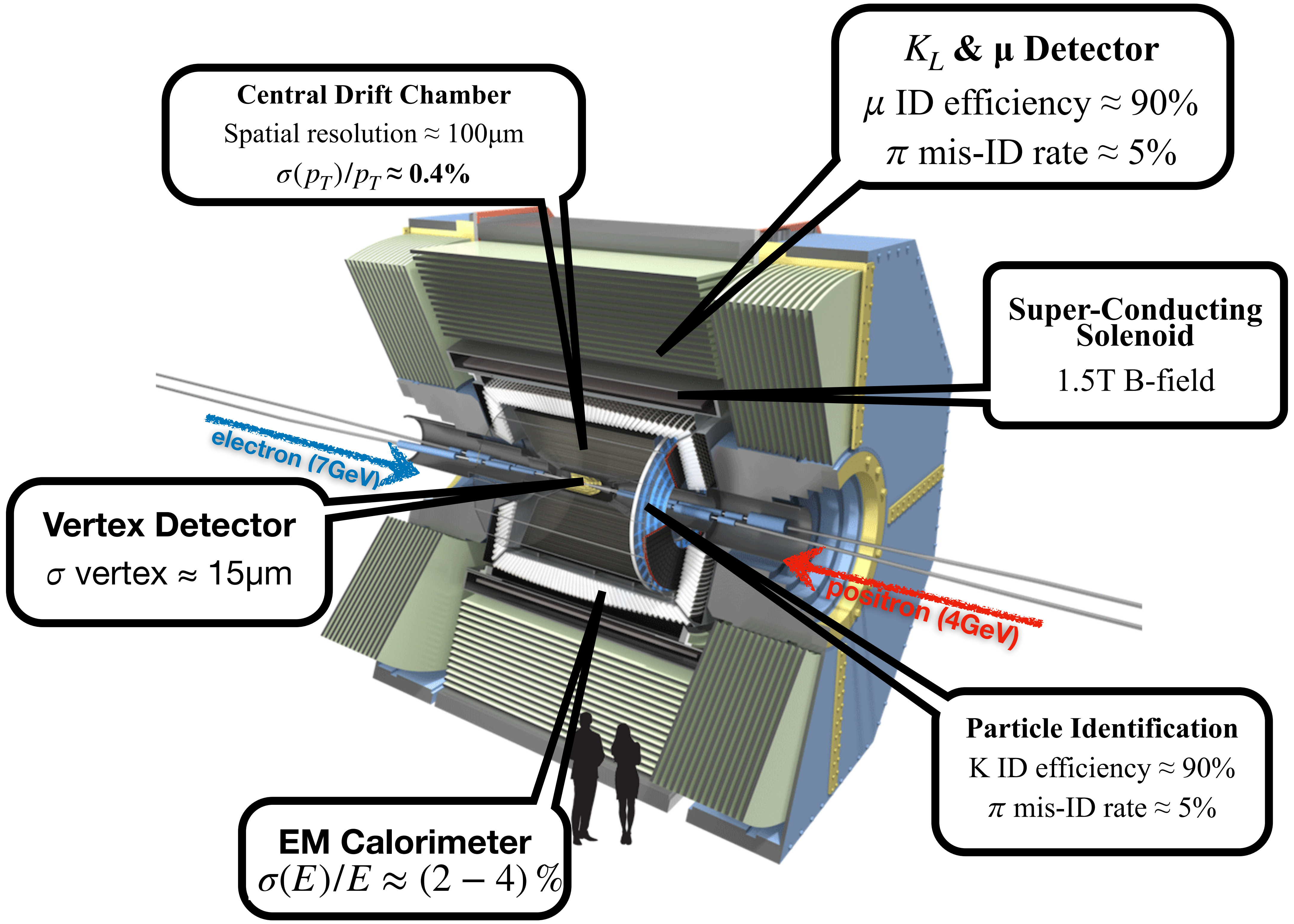
New physics



Today's topics: $B^0 \to K^{*0}\tau\tau$, $B^0 \to K^{*0}\tau^\pm\ell^\mp$, $B^0 \to K_S^0\tau^\pm\ell^\mp$

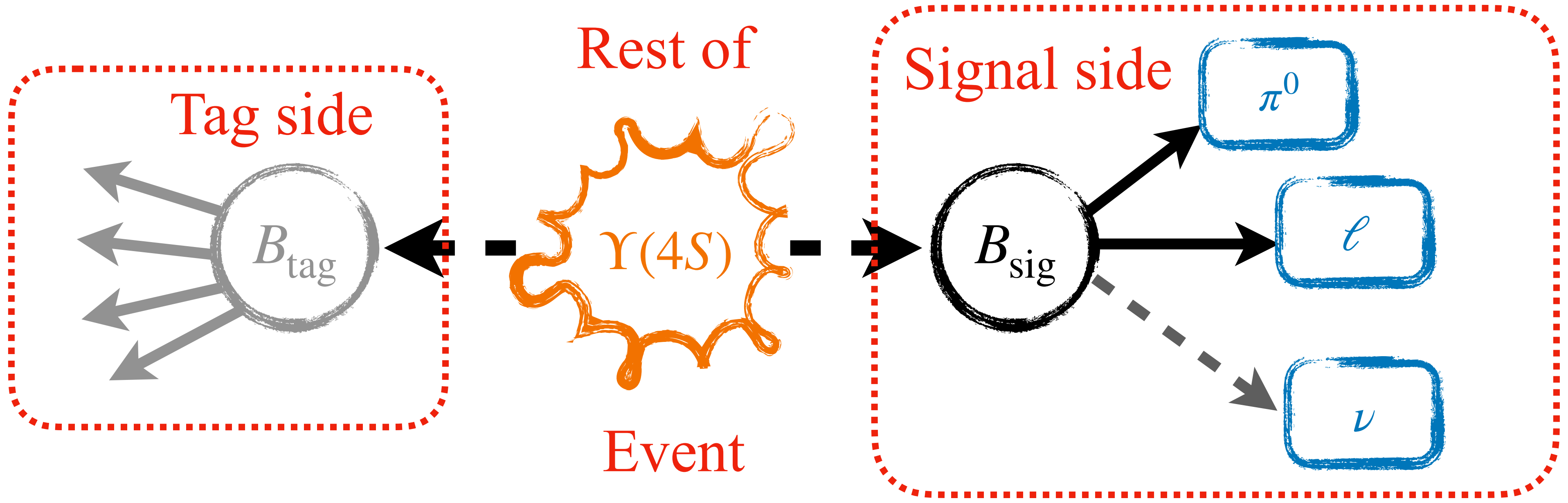
B factory: Ideal for Rare decays

- **Threshold $B\bar{B}$ production at $\Upsilon(4S)$**: Clean environment, low background, Known initial kinematics
- **Hermetic Detector**: Full event reconstruction with invisible particles
- **Clean Event Topology**: ~11 tracks/event, efficient detection of neutrals ($\gamma, \pi^0, n, \ldots$), low pile-up



Experimental techniques

- Full Event Interpretation (FEI) using **hadronic or semileptonic** tagging Comput. Softw. Big Sci. 3, 6 (2019)
- **Hadronic Tagging**: Full reconstruction of pair-produced B meson (B_{tag}) in hadronic final states enables precise determination of signal-side kinematics; high purity $\mathcal{O}(10\%)$ but low efficiency $\mathcal{O}(1\%)$
- **Powerful Discriminators**: Missing energy, residual calorimeter energy left after reconstruction, etc.

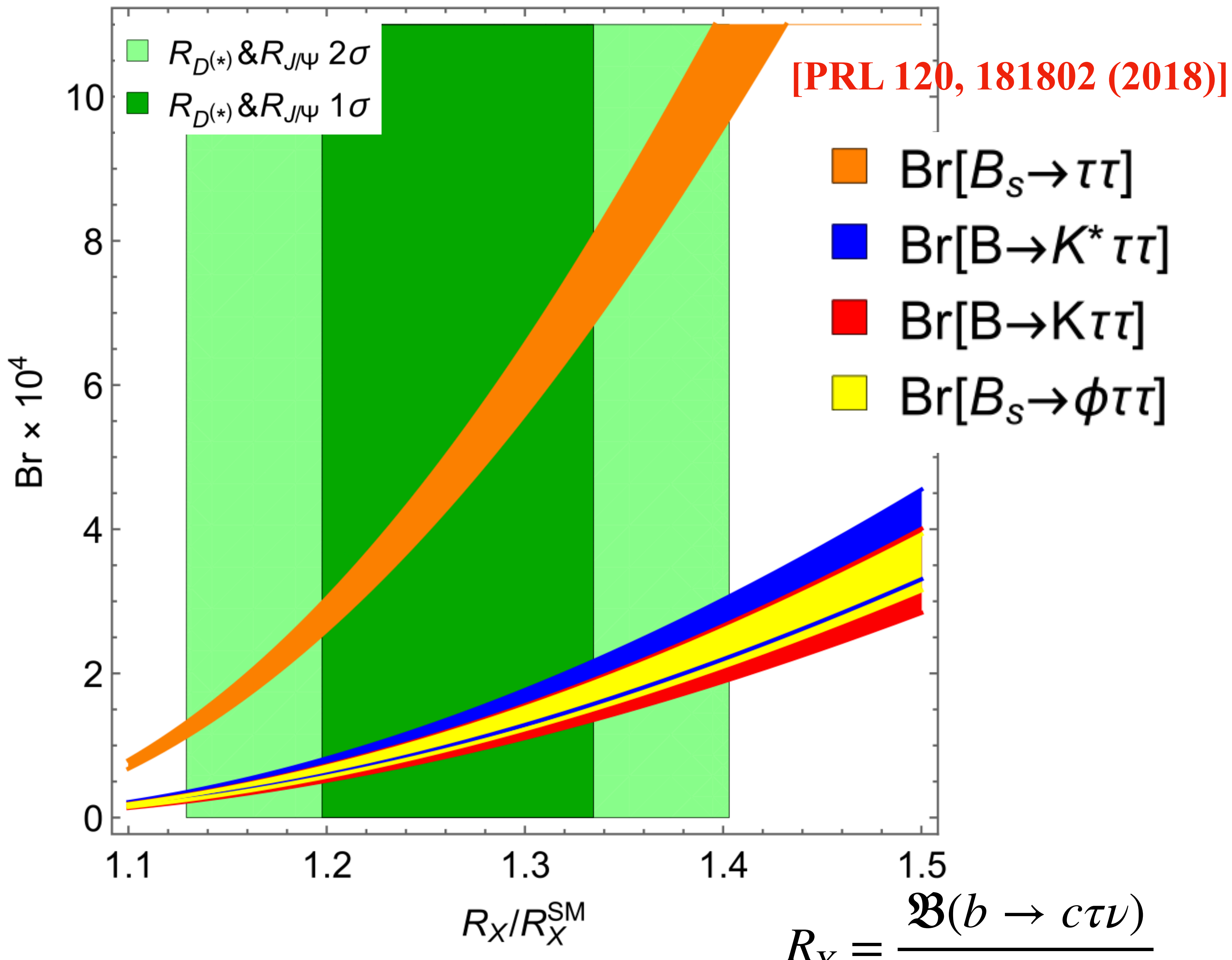


Search for $B^0 \to K^{*0}\tau\tau$ with Belle II

- FCNC - highly suppressed and sensitive to NP
- $\mathfrak{B}_{SM} = (0.98 \pm 0.10) \times 10^{-7}$
- Non-SM particles could enhance BF up to $\mathcal{O}(10^3)$ due to presence of two τ's PRL 120, 181802 (2018), EPJC 83, 153 (2023)
- World-best result from Belle: UL at 3.1×10^{-3} (90% C.L.)
  Searched in 1-prong τ decays: $\tau^+ \to \ell^+\nu\nu,\ \pi^+\nu\ (\ell = e, \mu)$
  [PRD 108, L011102 (2023)]

- Experimentally challenging:
  - Low efficiency
  - Large missing energy
  - No signal peaking kinematic observable due to multiple undetected neutrinos

Prediction of $\mathfrak{B}(b \to s\tau\tau)$ as a function of R_X/R_X^{SM}



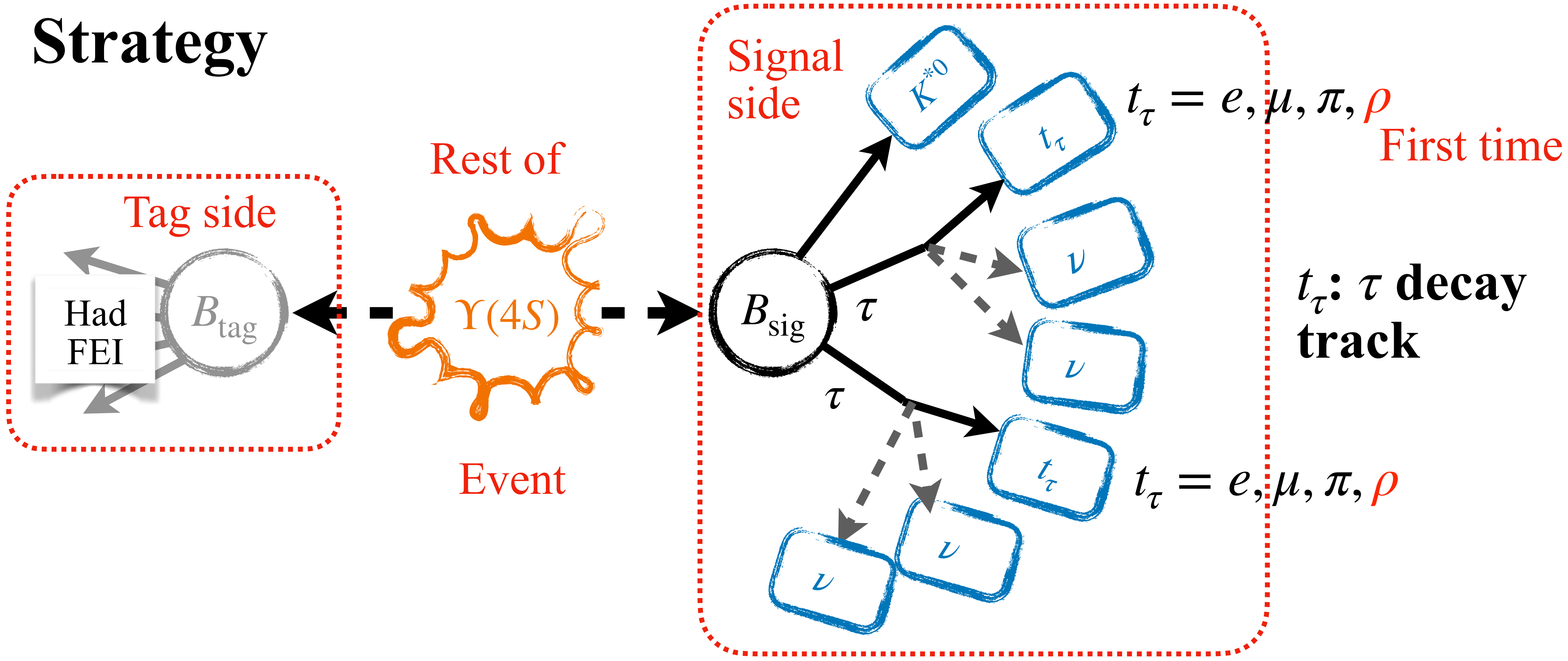
$$R_X = \frac{\mathfrak{B}(b \to c\tau\nu)}{\mathfrak{B}(b \to c\ell\nu)}$$

- **Revisited at Belle II**: Improved tagging method, included $\tau \to \rho\nu$ {BF: (25.52 ± 0.09) % } decays for the first time, Multivariate approach (MVA)
- **Data used:** 365/fb

Search for $B^0 \to K^{*0}\tau\tau$ with Belle II

- Analyzed four final state categories from $\tau\tau$ pair: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX $(X = \ell, \pi, \rho)$
- Train BDT classifier (14 variables) using missing energy, residual calorimeter energy, event topology, etc

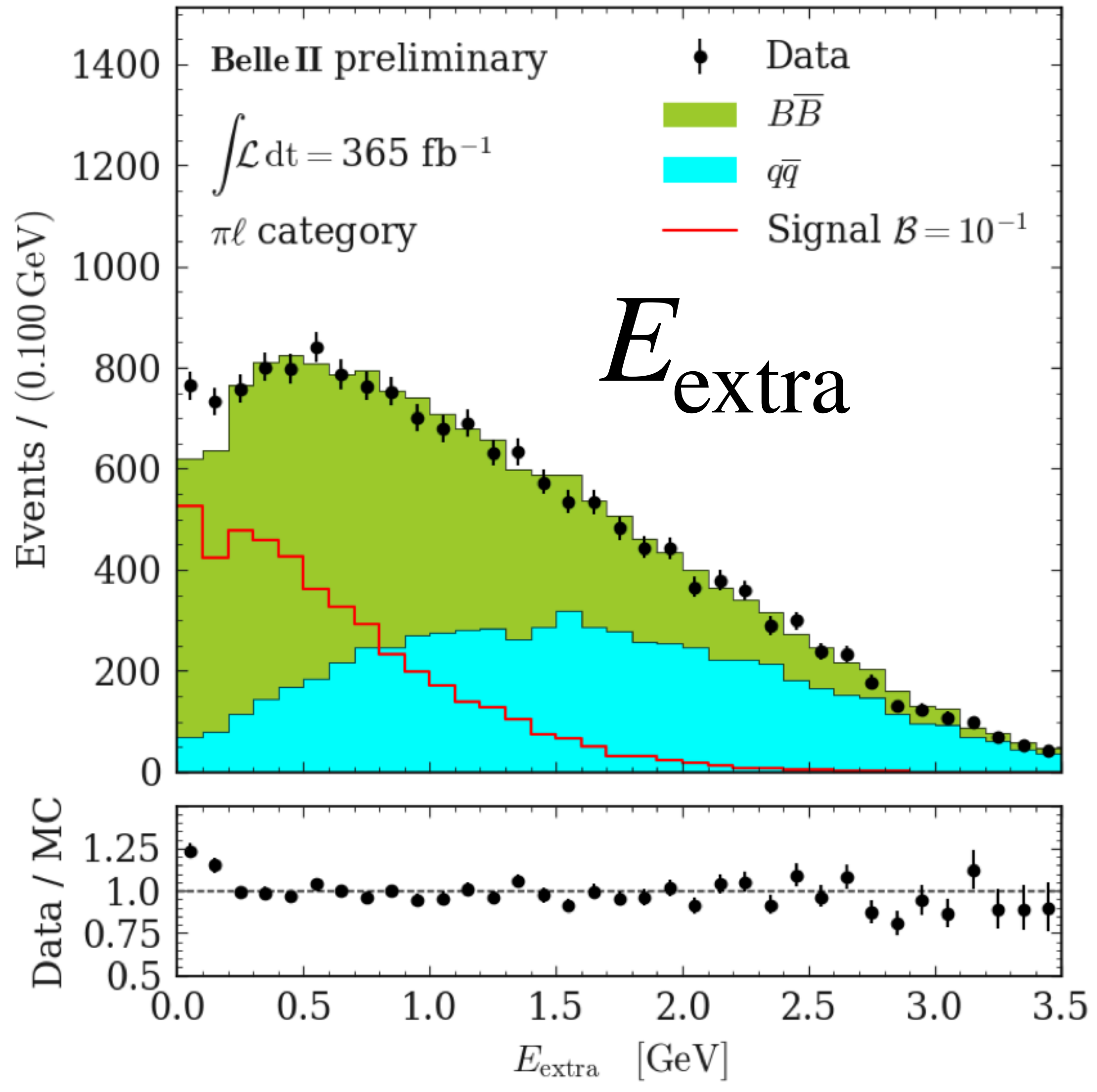
Strategy



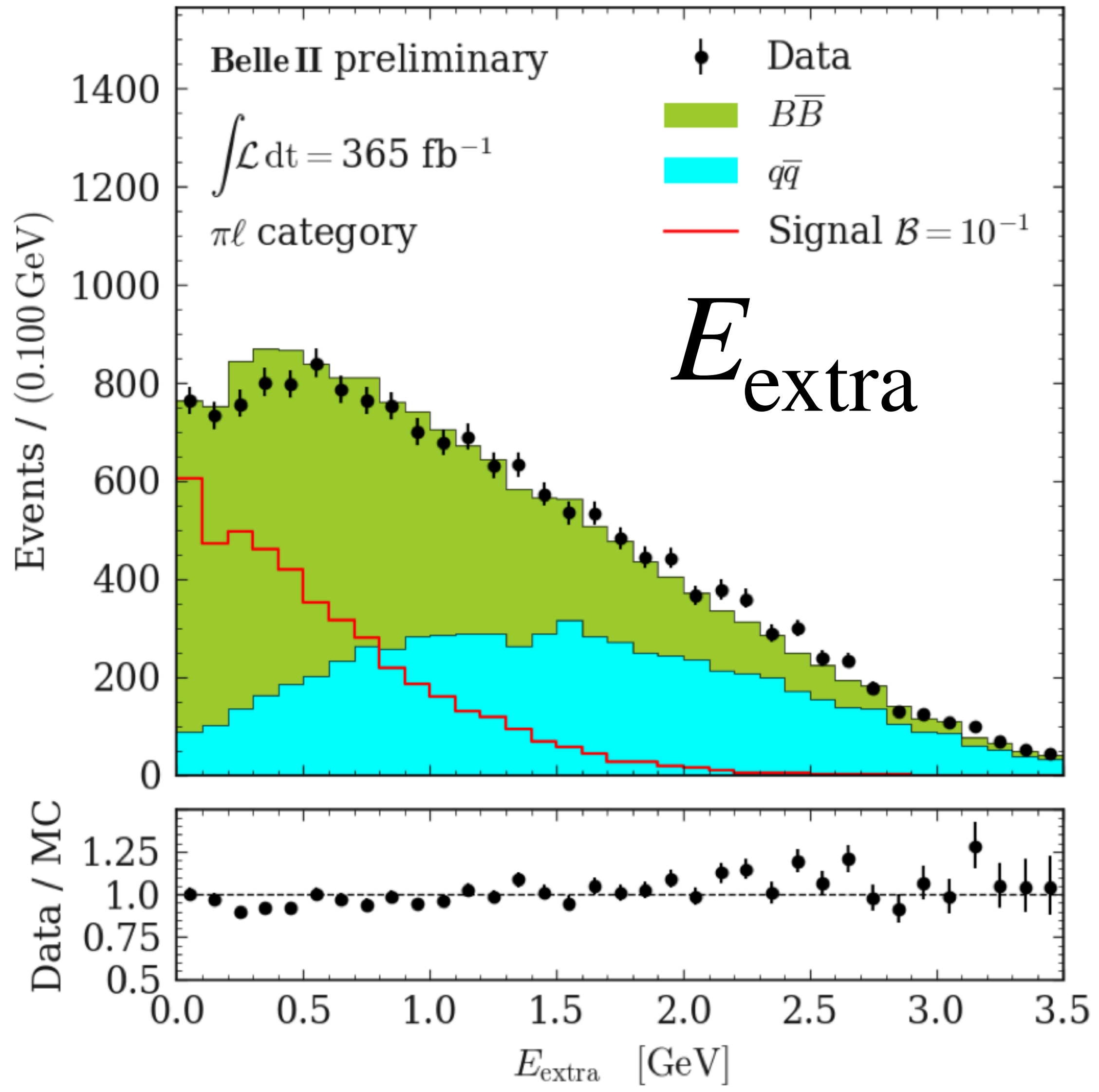
Correction

- Corrected efficiency from $B \to K^{*0} J/\psi(\mu\mu)$ with modified kinematics to match signal.
- Corrected background yield from same-flavor (BB, $\bar{B}\bar{B}$) control samples and off-resonance data.
- Corrected shape of residual calorimeter energy (E_{extra}), one of the most powerful discriminator, from same-flavor control sample.

Before correction



After correction



same-flavor: Mixed events which are not used to determine signal

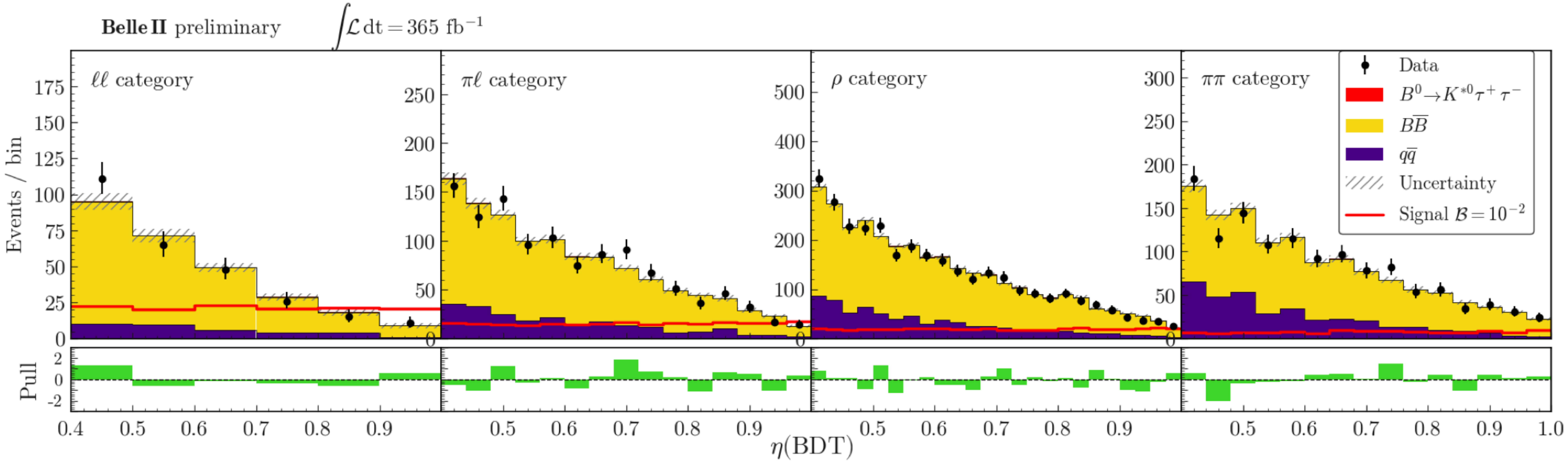
Search for $B^0 \to K^{*0}\tau\tau$ with Belle II

arxiv: 2504.10042

- **Signal extraction:** Simultaneously fit classifier scores above 0.4 of each category

$$\mathfrak{B}(B \to K^{*0}\tau\tau) < 1.8 \times 10^{-3} \ @90\,\%\,\text{CL}$$

- Dominant systematics in terms of BF ($\times 10^{-3}$): (Details in backup)
  - Poor knowledge of semi-leptonic $B \to D^{**}$ decays (0.29) and limited simulated sample size (0.27)

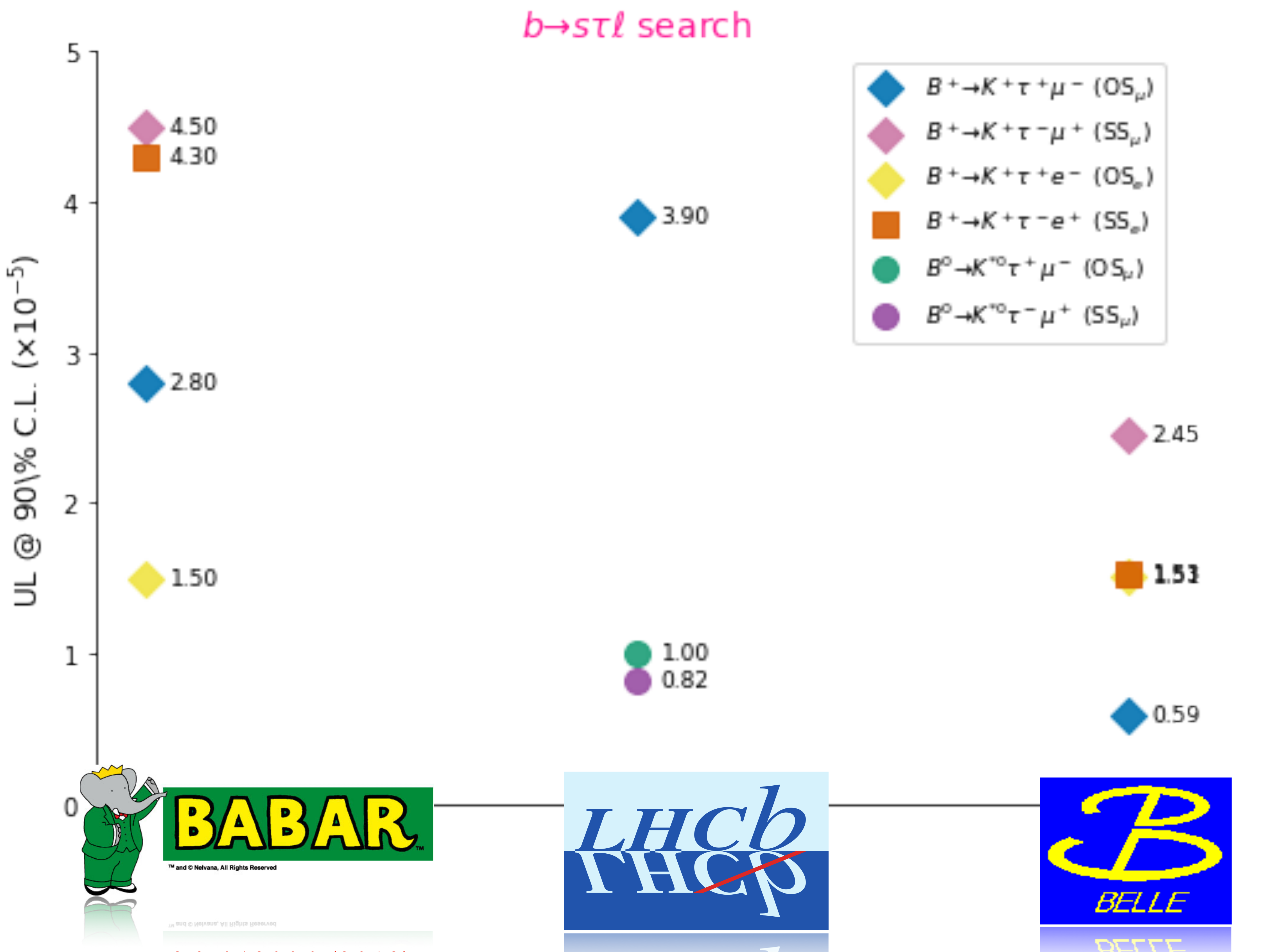


Twice better limit than Belle with half the statistics
Most stringent limit on $\boldsymbol{b \to s\tau\tau}$ transition

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

- FCNC with LFV, forbidden in SM
- Non-SM particles predicts LFV with Branching fraction $\mathcal{O}(10^{-6})$
- Non -SM particles 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 $b \to s\tau^{-}\ell^{+}$

- **Existing results**
  - $B^{+} \to K^{+}\tau^{\pm}\ell^{\mp}$ (BaBar, Belle, LHCb)
  - $B^{0} \to K^{*0}\tau^{\pm}\mu^{\mp}$ (LHCb)
- Never searched for $B^{0} \to K^{*0}\tau^{\pm}e^{\mp}$, $B^{0} \to K_{S}^{0}\tau^{\pm}\ell^{\mp}$



PRD 86, 012004 (2012)

JHEP 2020, 129 (2020)
JHEP 2023, 143 (2023)

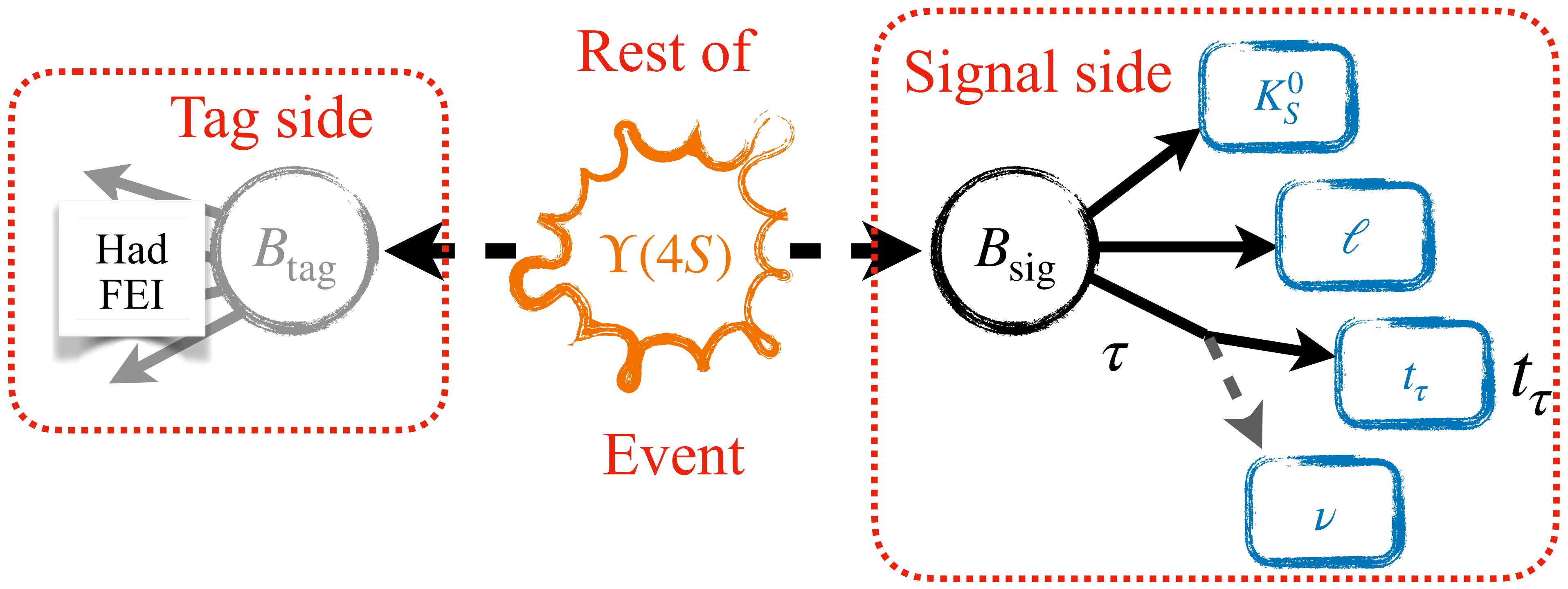
PRL 130, 261802 (2023)

OS (opposite sign), **SS** (same sign): lepton charge and b quark flavor

Searched for $B^{0} \to K^{*0}\tau^{\pm}\ell^{\mp}$, $B^{0} \to K_{S}^{0}\tau^{\pm}\ell^{\mp}$ using combined data of Belle and Belle II

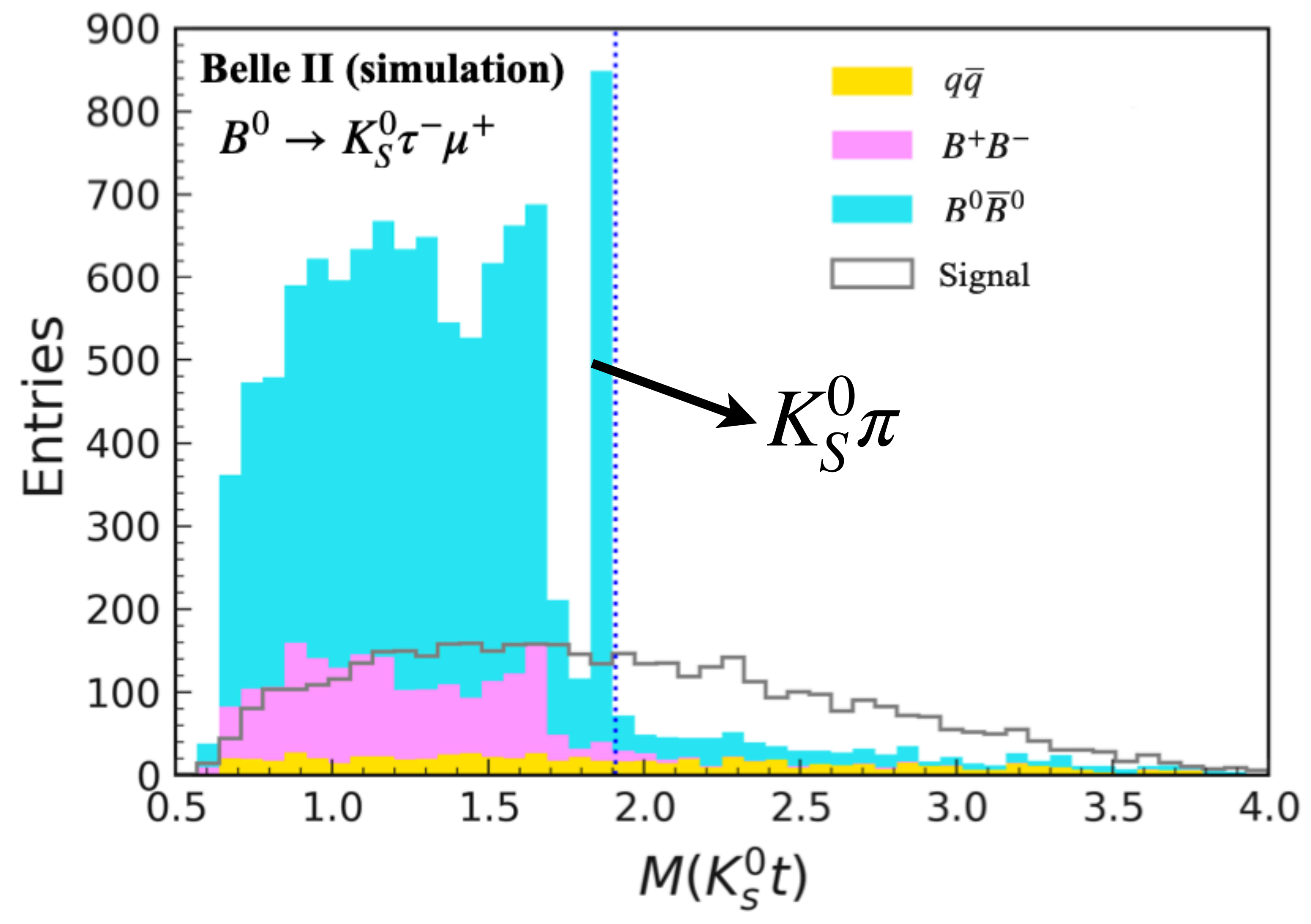
Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ with Belle + Belle II

Strategy



$t_\tau = e, \mu, \pi, \rho$

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



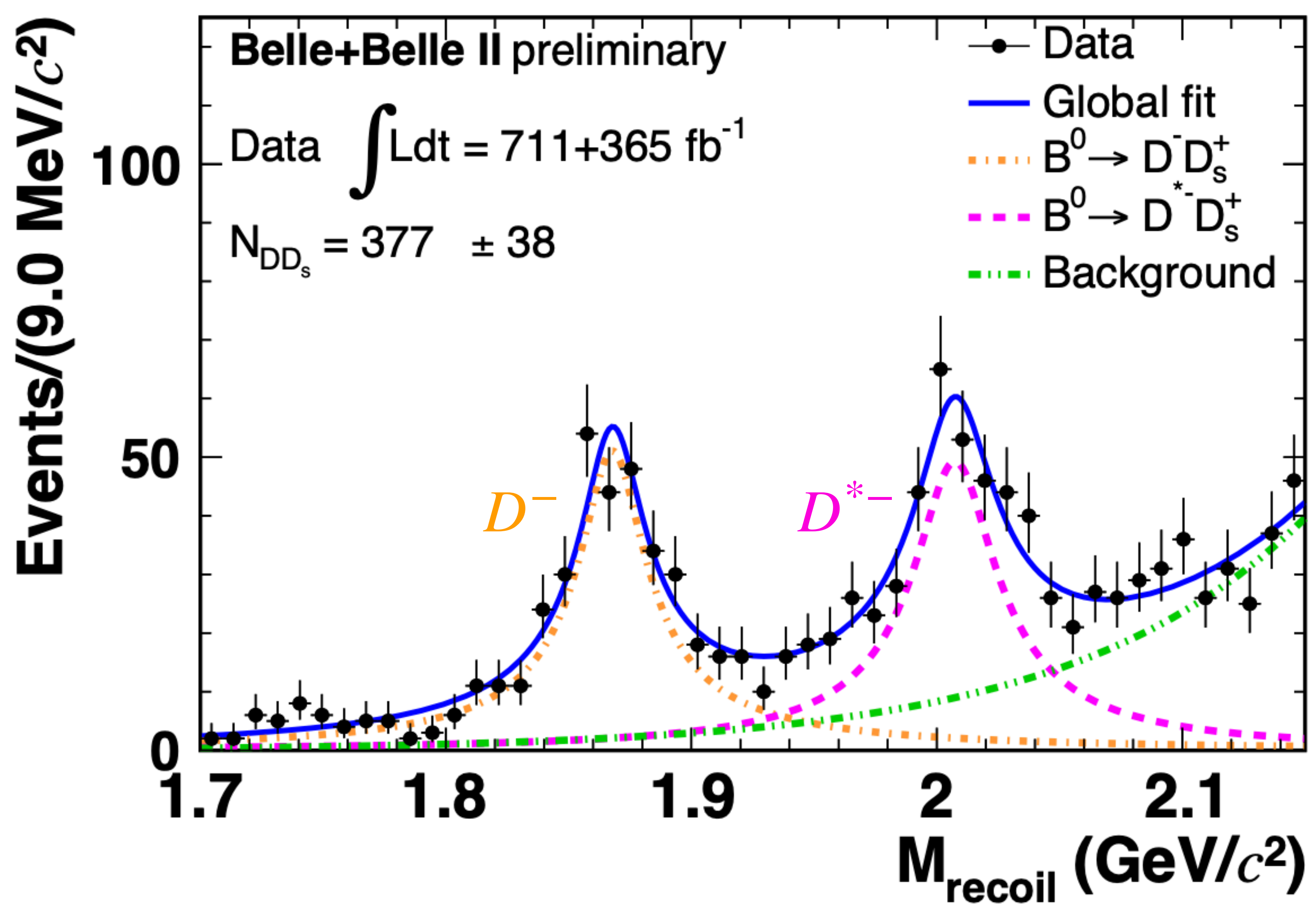
Background suppression

- Restrict $M(K_S^0 t_\tau)$ to suppress dominant $B \to D^{(*)}\ell X$ backgrounds; background rejection: (80-97)%
- Suppress remaining background by 90% with classifier (11 variables) using $M(K_S^0\ell)$, residual calorimeter energy, lepton kinematics, etc.

Calibration

- Calibrated simulated $B_{\rm tag}$ efficiency by fitting recoil D mass in $B^0 \to D^-\pi^+$ control data.
- Calibrated signal shape and classifier selection efficiency by fitting recoil $D^{(*)}$ mass in $B^0 \to D^- D_s^+$ where $D_s^+ \to \phi\pi^+, K_S^0 K^+$

$$M_D^2 = M_{\rm recoil}^2 = (p_{e^+e^-} - p_{D_s} - p_{B_{\rm tag}})^2$$



Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ with Belle + Belle II

[arxiv:2412.16470](https://arxiv.org/abs/2412.16470)

Signal extraction: recoil τ mass after hadronic tagging,

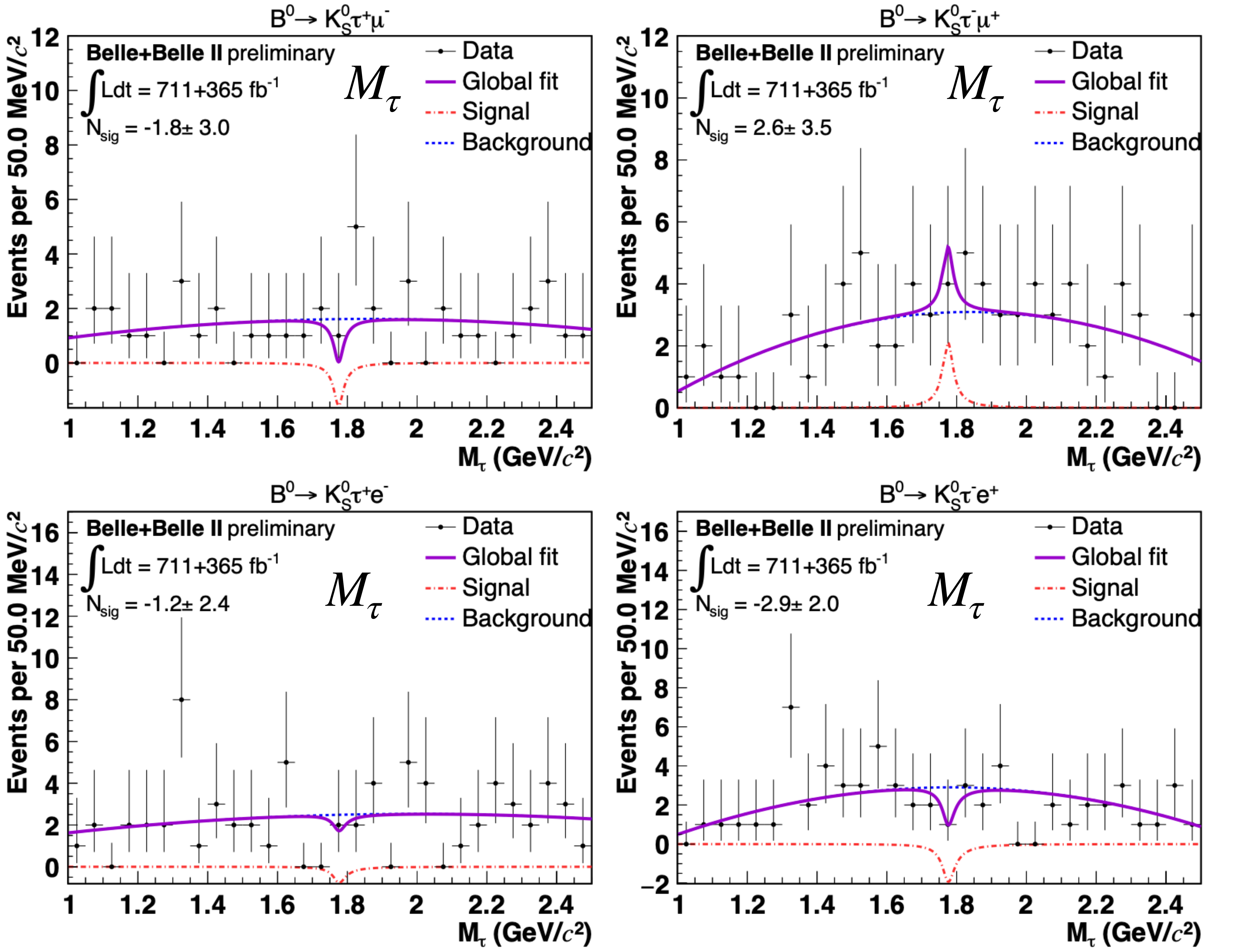
$$M_\tau^2 = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2$$

Upper limit on branching fractions

Decay	$\mathcal{B}$ $(\times 10^{-5})$	$\mathcal{B}^{\rm UL}$ $(\times 10^{-5})$
$B^0 \to K_S^0 \tau^+ e^-$	$-0.5 \pm 1.1 \pm 0.1$	1.5
$B^0 \to K_S^0 \tau^- e^+$	$-1.2 \pm 0.9 \pm 0.3$	0.8
$B^0 \to K_S^0 \tau^+ \mu^-$	$-1.0 \pm 1.6 \pm 0.2$	1.1
$B^0 \to K_S^0 \tau^- \mu^+$	$1.1 \pm 1.0 \pm 0.3$	3.6

Dominent Systematics: (Details in backup)

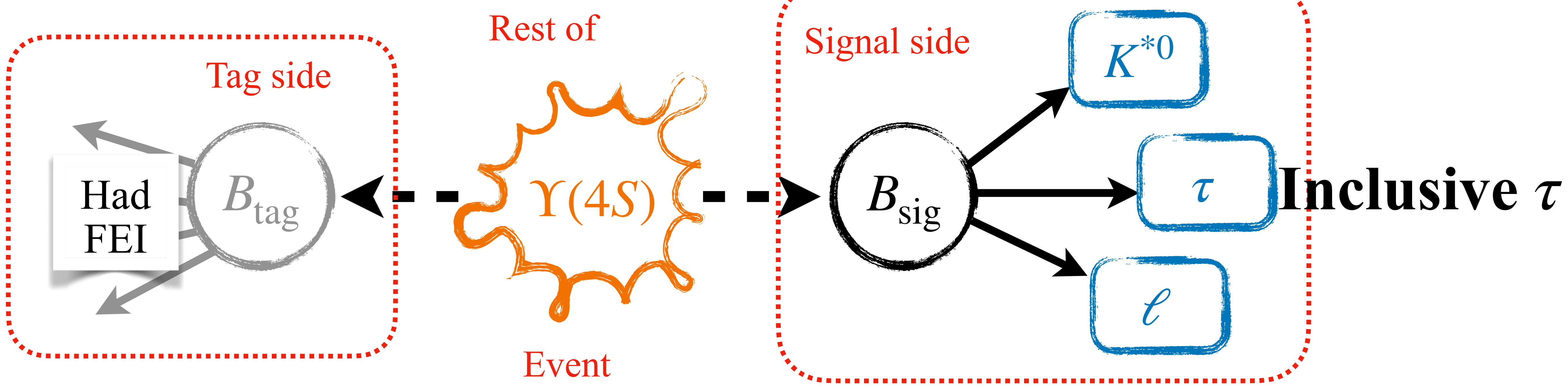
- Classifier efficiency correction (17 - 19%) and signal shape (16%)



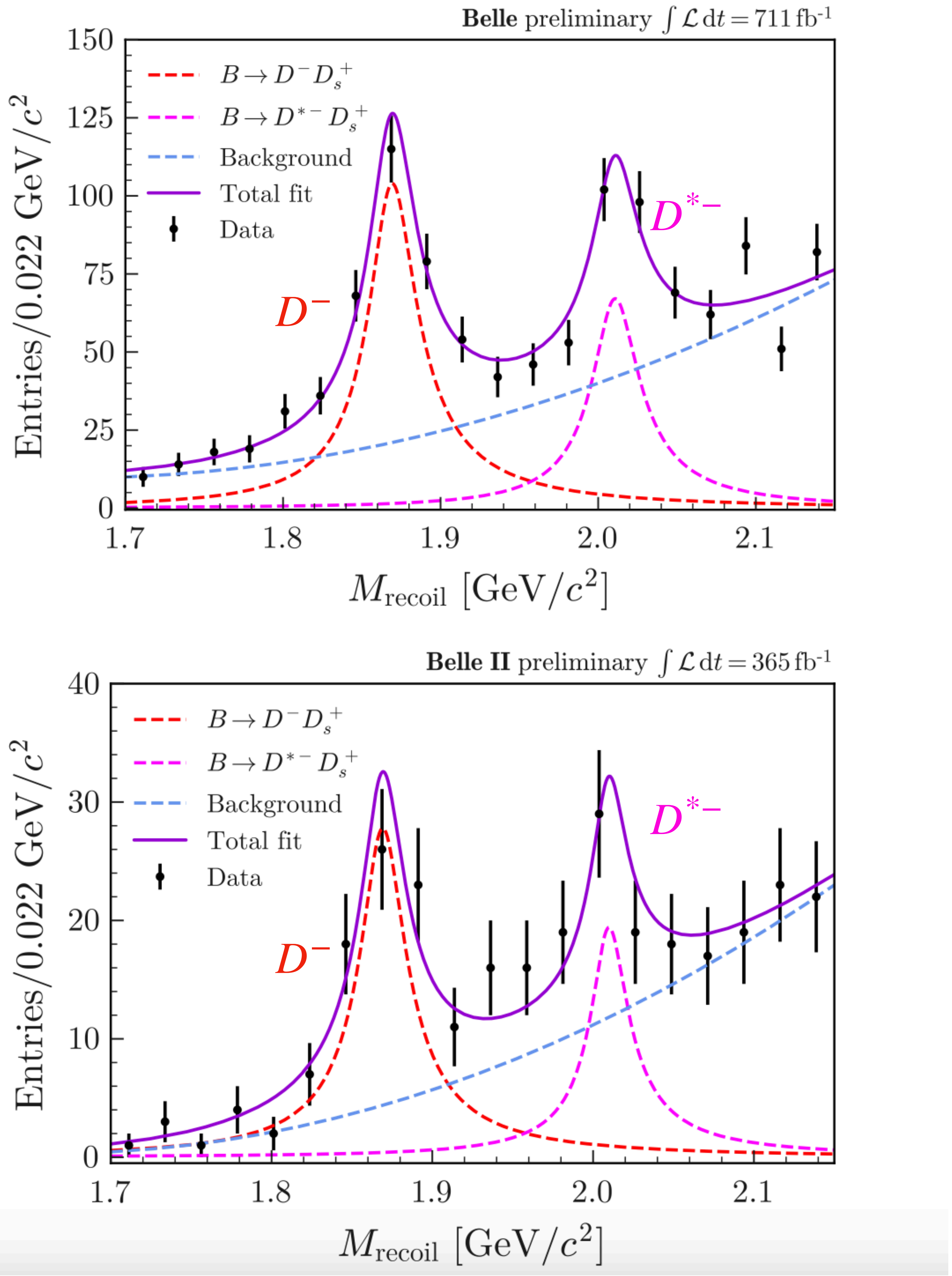
First search $B^0 \to K_S^0 \tau^\pm \ell^\mp$ for decays

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

Strategy



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



Background suppression

- Suppress background by (90 - 98) % with classifier (12-14 variables) using $M(K^{*0}\ell)$, $M(K^{*0}t_\tau)$, residual tracks and clusters properties, vertex information, event topology, etc.

Calibration

- Calibrated simulated B_{tag} efficiency from $B^0 \to D^-\pi^+$ and $B \to X_c\ell\nu$ control data.
- Calibrated signal shape and classifier selection efficiency by fitting recoils $D^{(*)}$ mass in $B^0 \to D^-D_s^+$ where $D_s^+ \to \phi\pi^+, K^{*0}K^+$

$$M_D^2 = M_{recoil}^2 = (p_{e^+e^-} - p_{D_s} - p_{B_{tag}})^2$$

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

arxiv:2505.08418

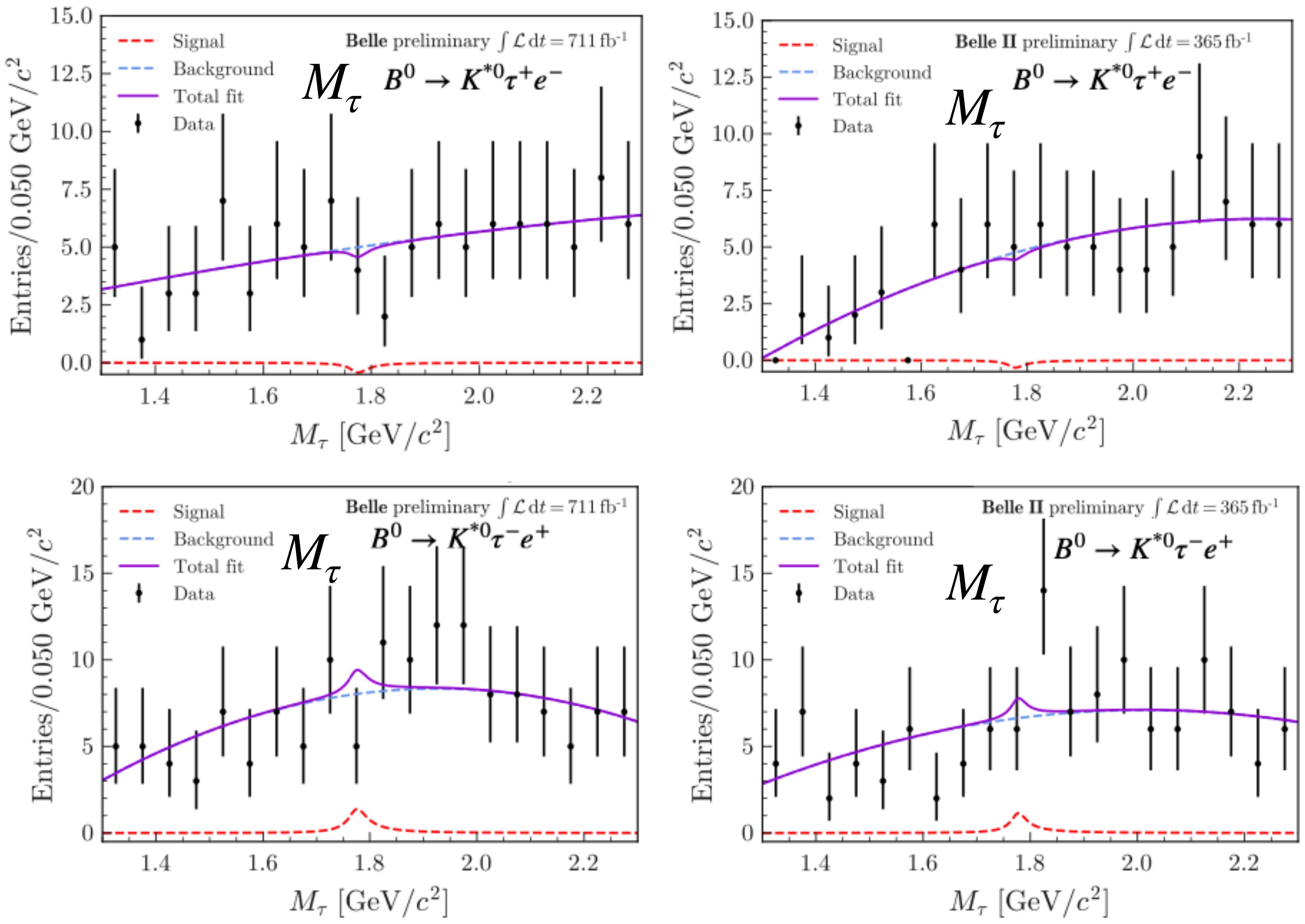
Signal extraction: Simultaneous fit to recoil τ mass of Belle and Belle II data

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

Upper limit on branching fractions

Decay	$\mathcal{B}$ $(\times 10^{-5})$	$\mathcal{B}^{\mathrm{UL}}$ $(\times 10^{-5})$
$B^0 \to K^{*0}\tau^+e^-$	-0.24 ± 1.46	2.9
$B^0 \to K^{*0}\tau^-e^+$	1.17 ± 2.77	6.4
$B^0 \to K^{*0}\tau^+\mu^-$	1.07 ± 1.80	4.2
$B^0 \to K^{*0}\tau^-\mu^+$	0.48 ± 2.61	5.6

M_τ distribution for $B^0 \to K^{*0}\tau^\pm e^\mp$ at Belle (left) and Belle II (right)



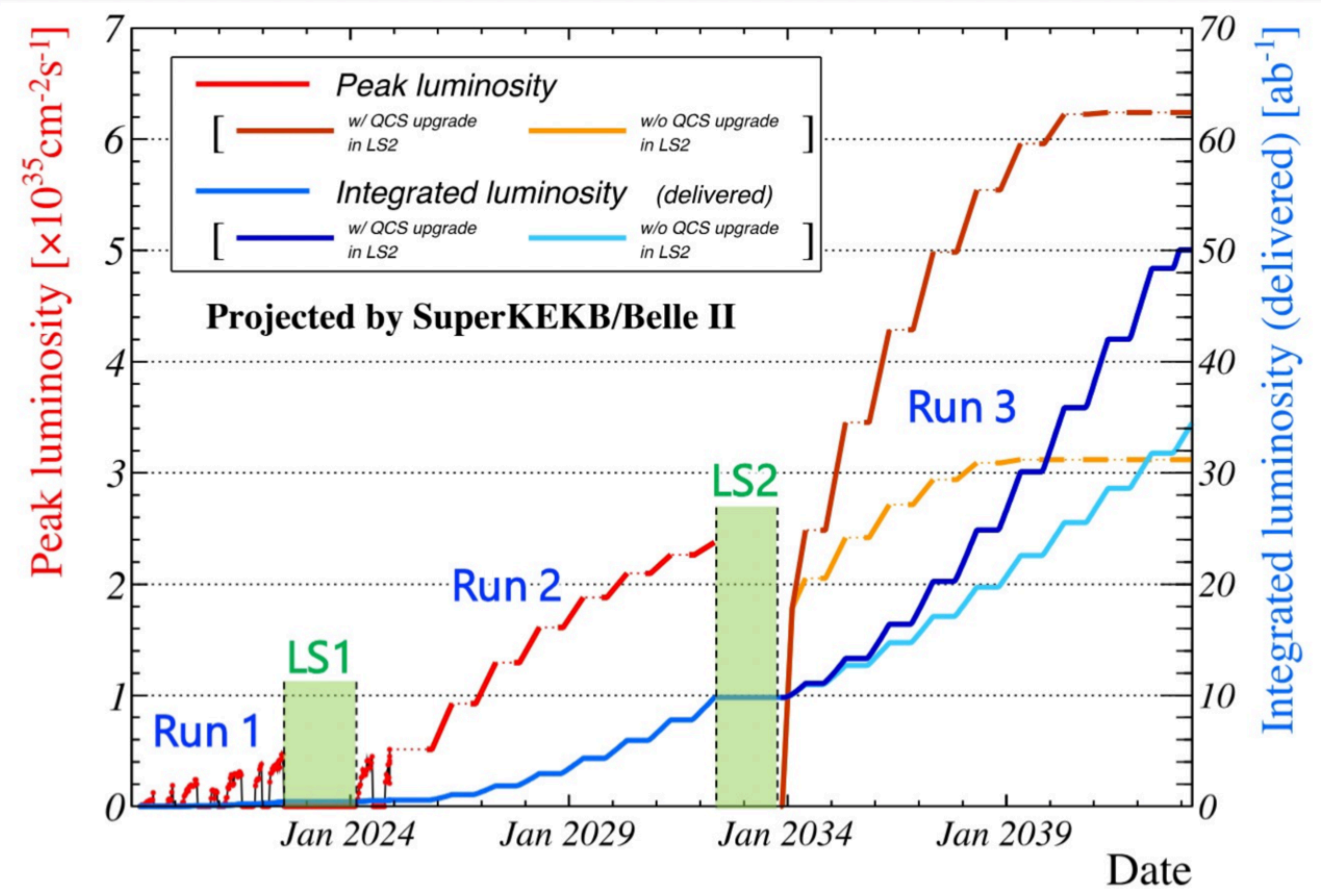
Dominent Systematics: (Details in backup)

- Classifier efficiency correction (18 - 34)% and background shape assumption (0.02 - 0.28) $\times 10^{-5}$

First search of $B^0 \to K^{*0}\tau^\pm e^\mp$ decays at B factories

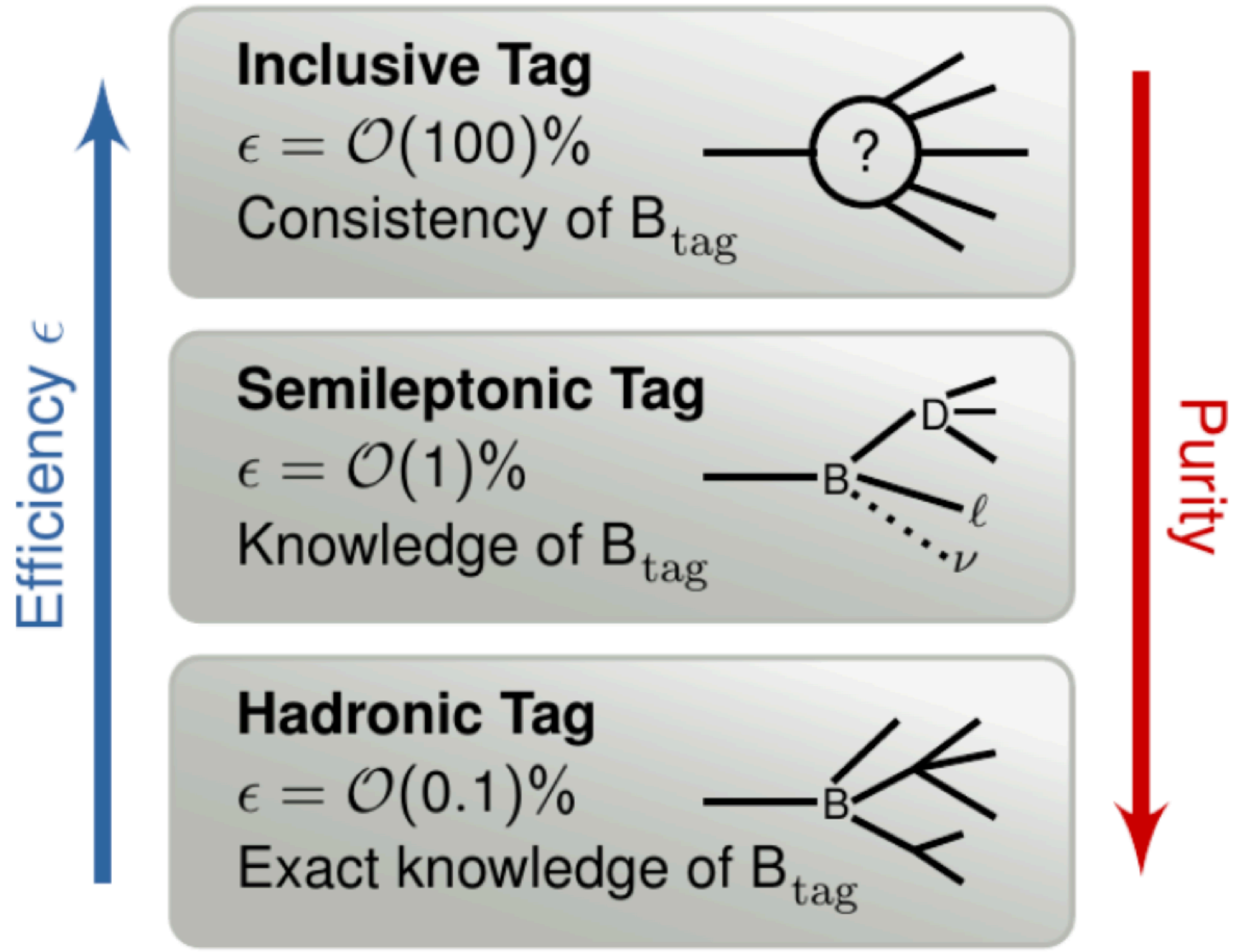
Closing remarks

- Flavor changing neutral current transitions are sensitive probes for new physics beyond the Standard Model
- Belle (II) provides unique abilities that are advantageous for these searches.
- New exciting Belle (II) results shown today, many of which world-best
    - $B^0 \to K^{*0}\tau\tau$: world best limits
    - $B^0 \to K^{*0}\tau^\pm\ell^\mp$: first search for $B^0 \to K^{*0}\tau^\pm e^\mp$ at B factories
    - $B^0 \to K_S^0\tau^\pm\ell^\mp$: world best limits
- Run 2 will resume later this year (currently in a short break), with the goal of collecting a large dataset over the next few years. Stay tuned for exciting results!



Backup

Tagging strategies



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

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
$D \to K^0_L$ 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	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

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 [%]	0.1				0.2			
Signal PDF λ [%]	21				59			
$N_{\Upsilon(4S)}$ [%]	1.4				1.6			
f^{00} [%]	0.8							
Background PDF ($\times 10^{-5}$)	0.11	0.28	0.09	0.02	0.11	0.28	0.09	0.02
Total impact on UL ($\times 10^{-5}$)	0.3	0.9	0.4	0.5	0.3	0.9	0.4	0.5

Cross sections at $\Upsilon(4S)$