Measurements of electroweak penguin and lepton-flavour violating B decays to final states with missing energy at Belle and Belle II

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on behalf of the Belle & Belle II collaborations

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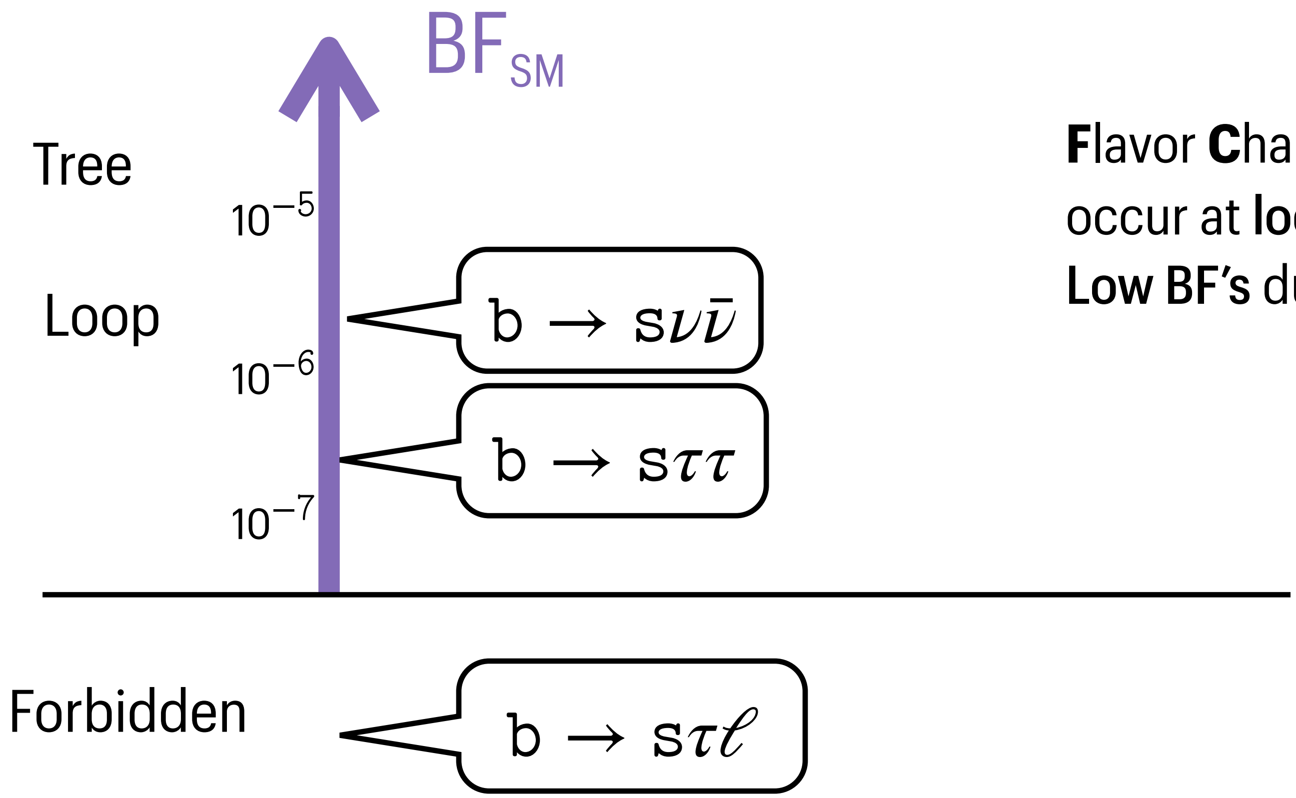
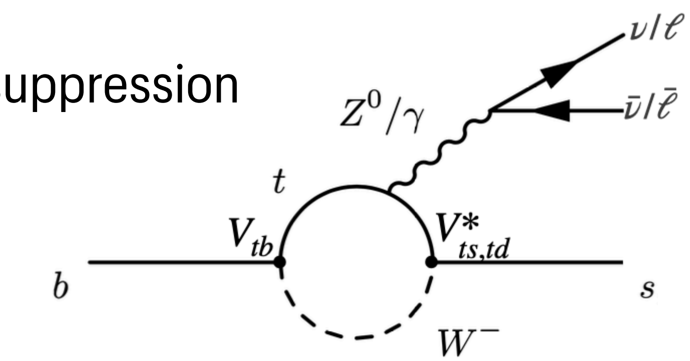
Electroweak Penguin and LFV @ Belle (II) experiment



Flavor **C**hanging **N**eutral **C**urrents (**FCNC**) $b \to s$ occur at **loop level** in the SM
Low BF's due to CKM and GIM suppression



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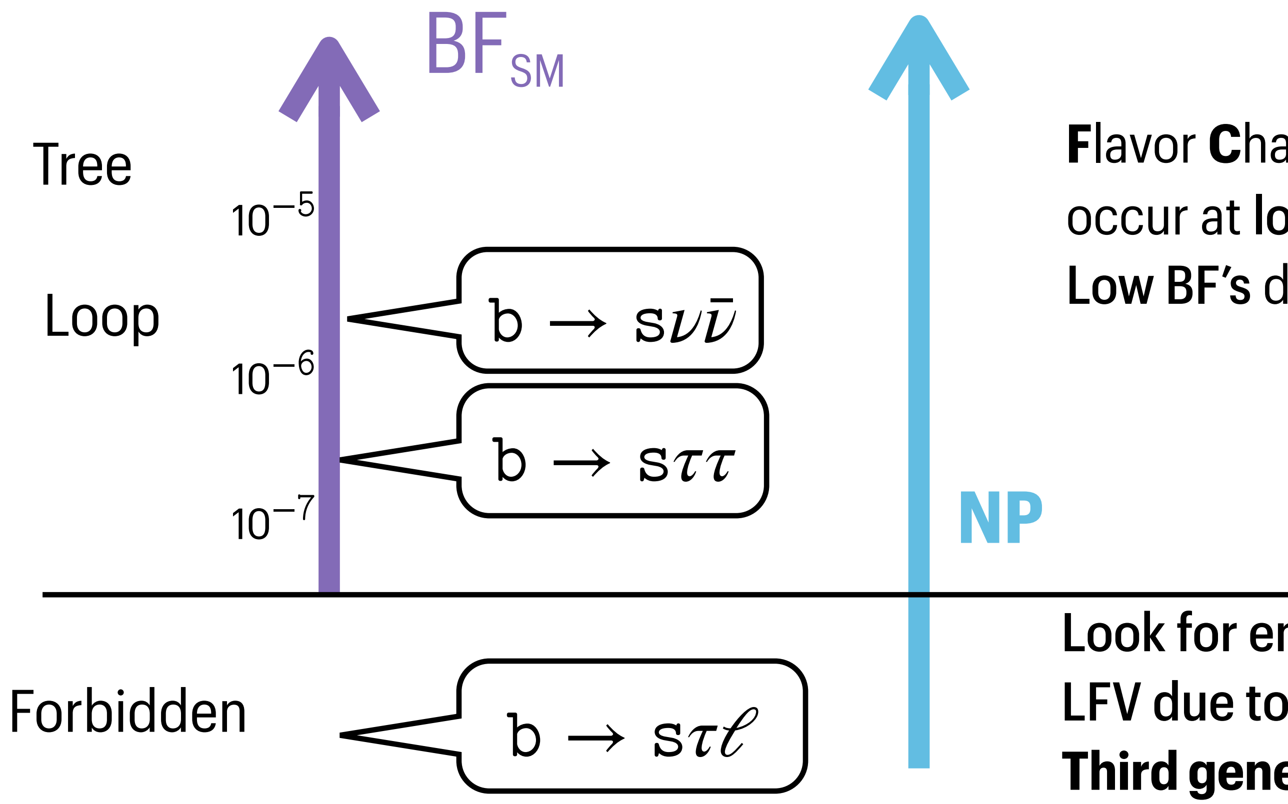

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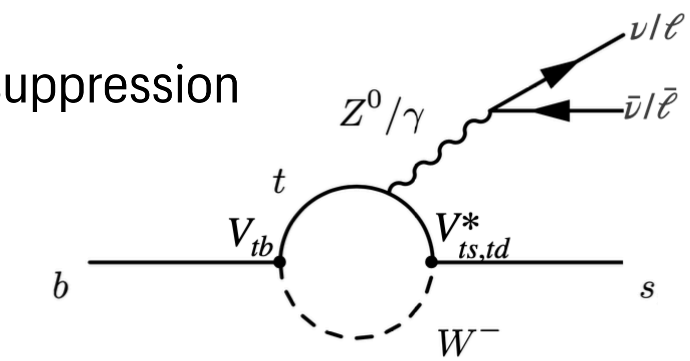
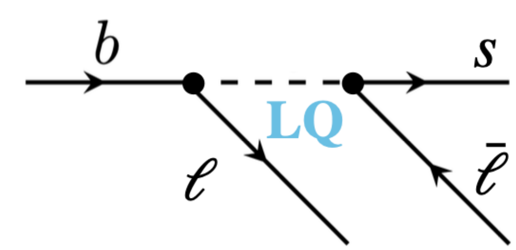
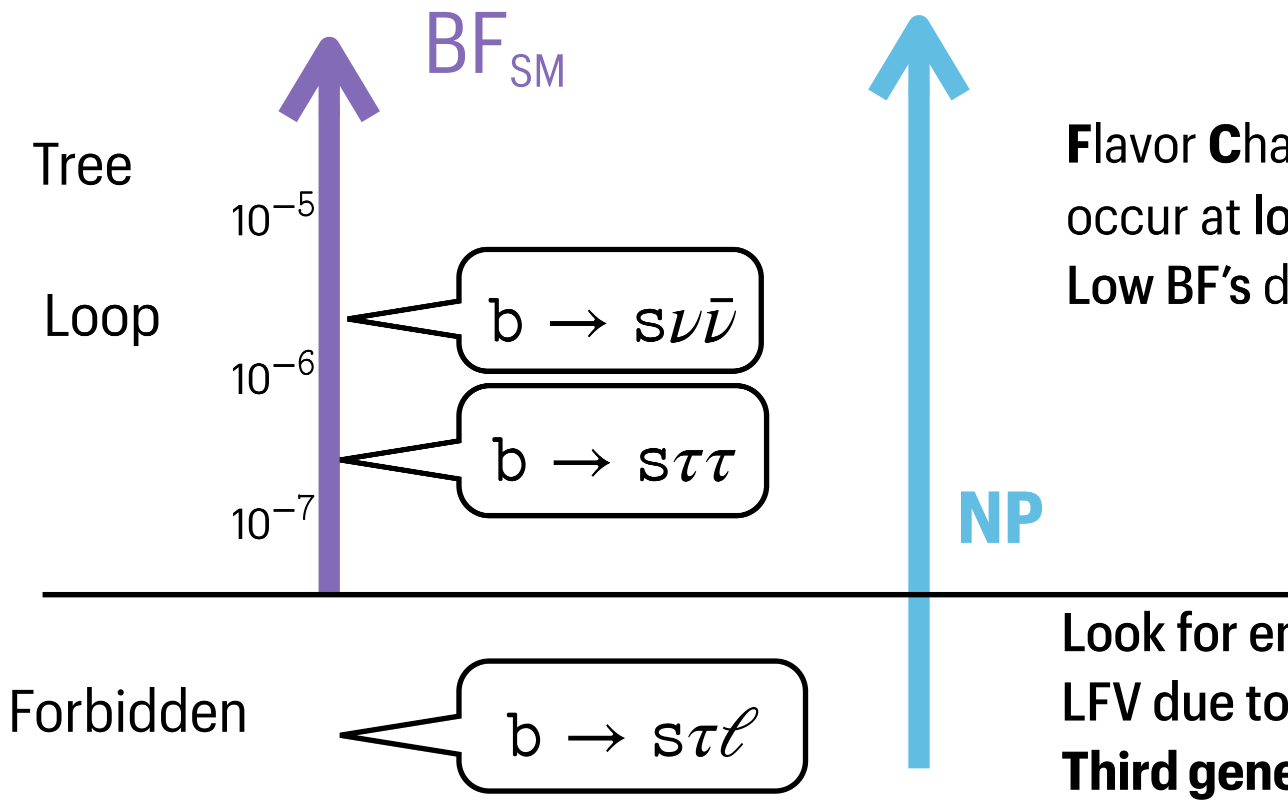


Look for enhancements in FCNC and
LFV due to NP contributions
Third generation coupling



Electroweak Penguin and LFV @ Belle (II) experiment



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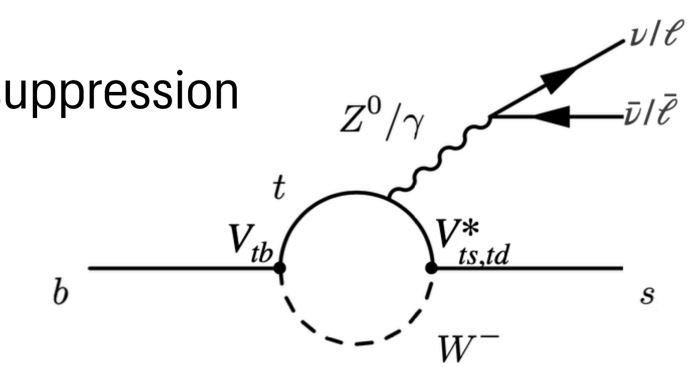

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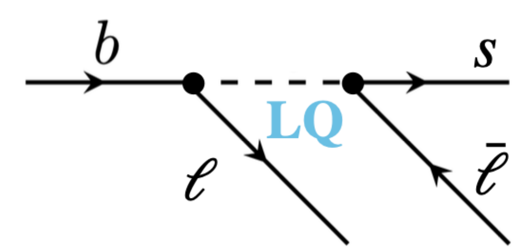
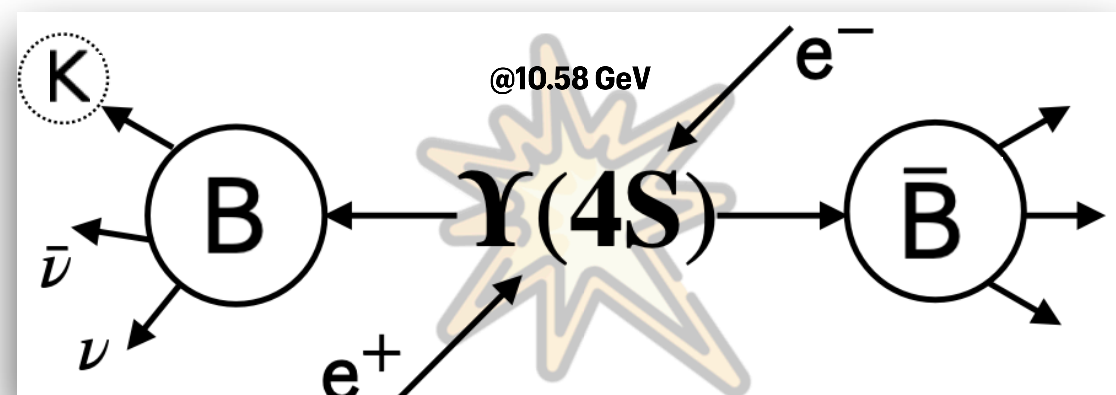




	ON	OFF
BELLE	711 fb^{-1}	90 fb^{-1}
Belle II	364 fb^{-1}	42 fb^{-1}

@ 60 MeV below $\Upsilon(4S)$

Known initial kinematics + 4π detector coverage
→ reconstruct final states with missing energy

$B\bar{B}$ **is produced at threshold**
→ relative low backgrounds

Today!

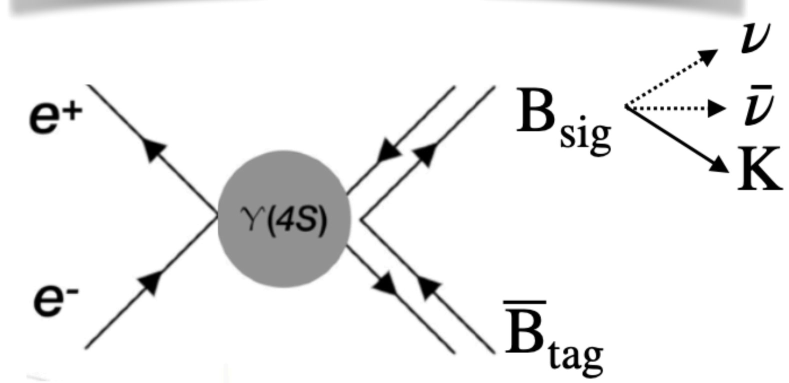
$B^+ \to K^+\nu\bar{\nu}$ [PRD 109 112006 (2024)]

$B^0 \to K^{*0}\tau^+\tau^-$
$B^0 \to K^0_S\tau^\pm\ell^\mp$
NEW! [paper in preparation]

B-tagging algorithm

Essential tool for decays with missing-energy

$$p_{e^+} + p_{e^-} = p_{B_{sig}} + p_{\bar{B}_{tag}}$$



Known initial 4-momentum beam energy transferred to $B\bar{B}$ pair:
Reconstruction of the tag-side allows to infer the properties of the signal-side with missing energy – (semi-)leptonic/penguin decays – and to have a handle on backgrounds

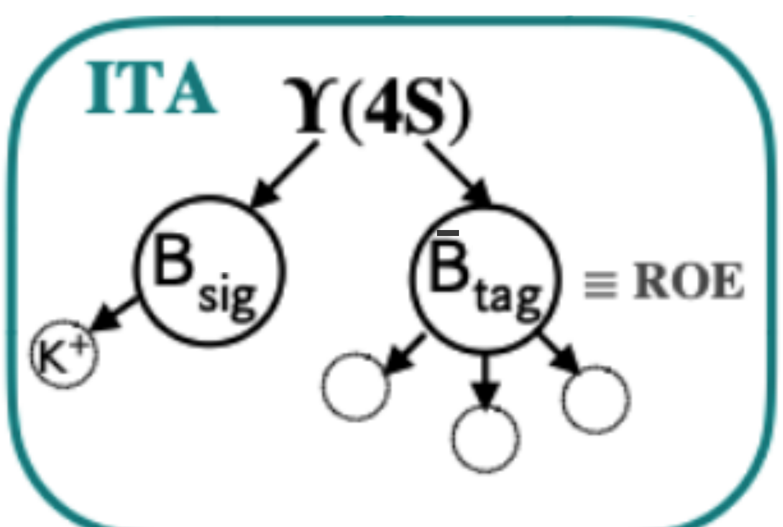
Different B-tagging strategies are possible

Efficiency ⟷ **Purity**

Inclusive Tag

X

$\epsilon = \mathcal{O}(10)\%$

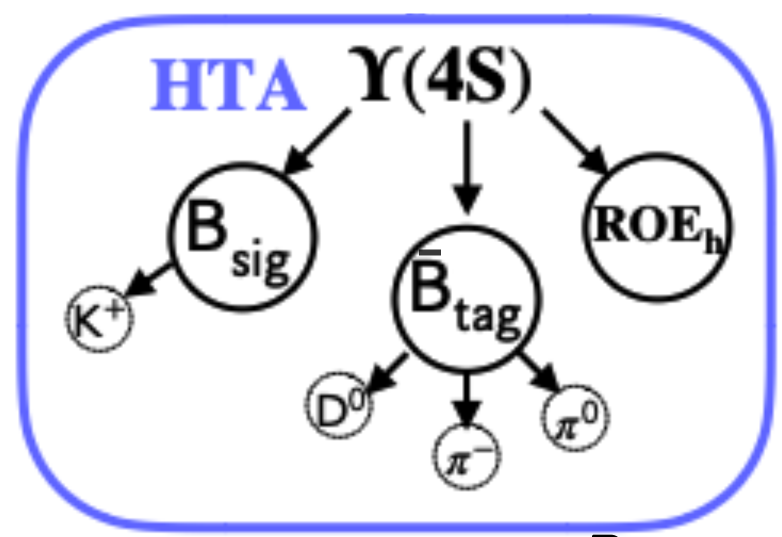


Inclusive properties of B_{tag}

Hadronic Tag

$D^{(*)}n\pi$, $J/\psi K^{(*)}$, $D^{(*)}D_s^{(*)}$....

$\epsilon = \mathcal{O}(0.1)\%$



Exact knowledge of B_{tag}

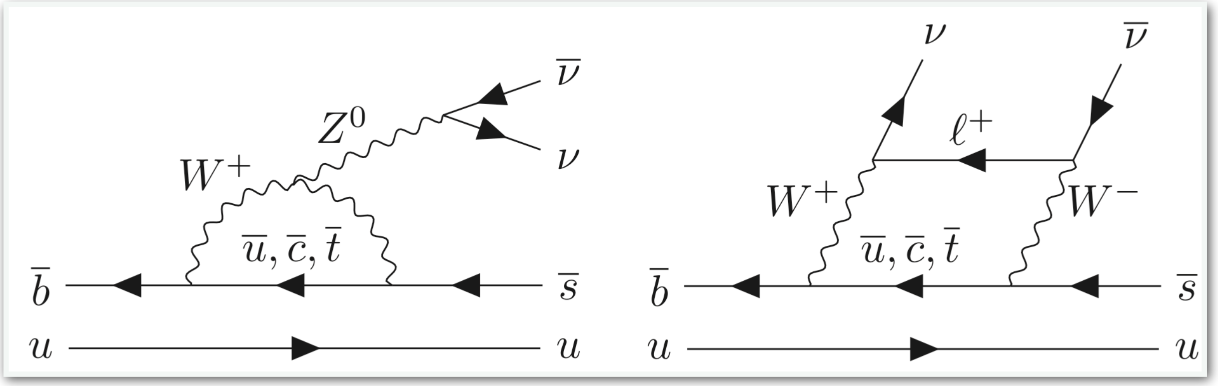
*__ROE:__ Rest Of Event (remaining charged and neutral particles)

$B^+ \to K^+ \nu \bar{\nu}$ [PRD 109 112006 2024]

Search for $B^+ \to K^+\nu\bar{\nu}$: Motivations

Belle II

- FCNC processes are suppressed in SM at tree level.
- Precise SM prediction — no hadronic uncertainties for charm annihilation like in $B \to K^{(*)}\ell^+\ell^-$



$$BF_{SM} = (5.6 \pm 0.4) \times 10^{-6}$$ [PRD 107 014511 (2023)]

Challenges

- Low BF
- No signal peaking kinematic observable
- Large backgrounds+one prompt track
- Missing energy from undetected neutrinos

Unique to experiments at e^+e^- machines

Exp	U.L. (90% CL)	Tag Method	Stat (fb^{-1})
BaBar	1.6×10^{-5}	SL+HAD	429
Belle	5.5×10^{-5}	HAD	711
Belle	1.9×10^{-5}	SL	711

TODAY

- **Inclusive Tag** leads the final sensitivity (total eff. ~8%, purity ~0.8%)
- Well-established **Hadronic Tag** is used for consistency check and provide 10% increasing in final combined result (total eff. ~0.4%, purity ~3.5%)

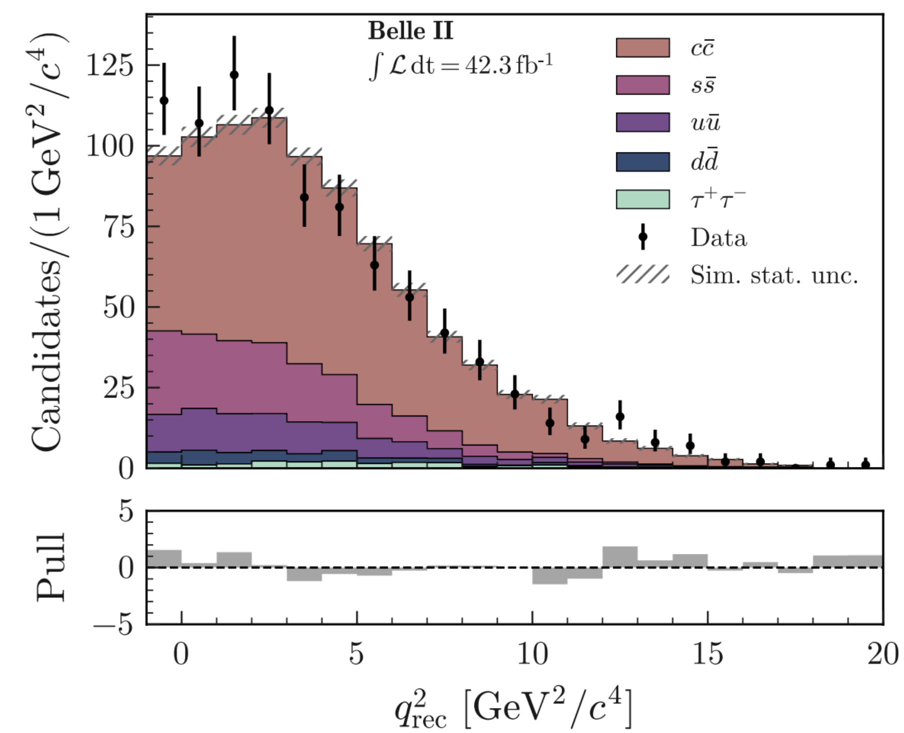
Search for $B^+ \to K^+\nu\bar{\nu}$: Strategy

Focus on Inclusive Tag: **Two consecutive classifiers** with signal kaon, event shape and ROE information

Final observables: q^2_{rec} in different second classifier (BDT) bins

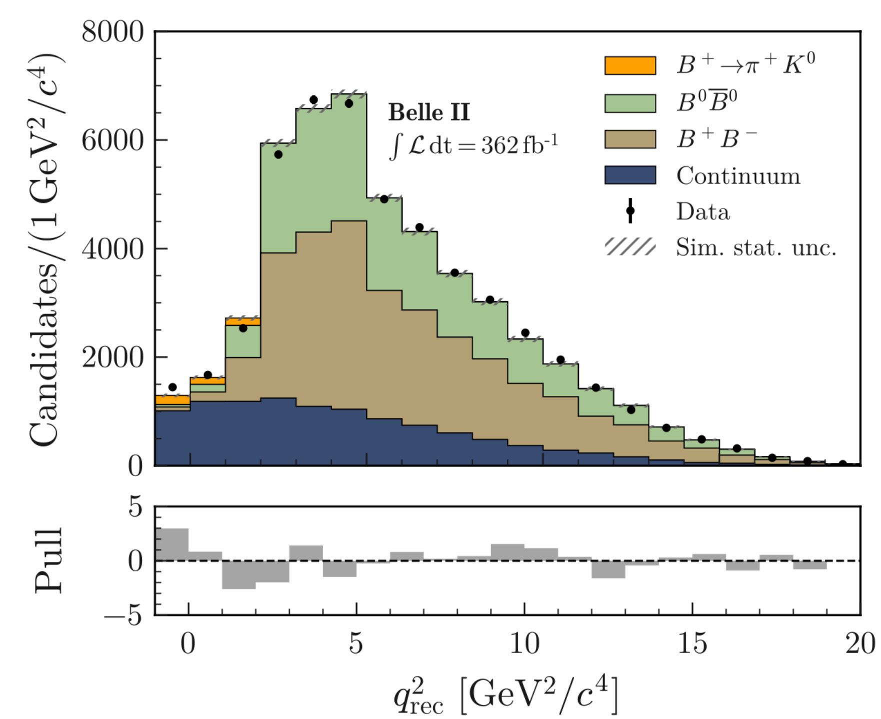
$$q^2_{rec} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c$$

Signal efficiency validation with $B^+ \to J/\psi K^+$ sample, remove J/ψ and correct K^+ kinematics to match $K^+\nu\bar{\nu}$ (1.00±0.03)



Background validation:

- $q\bar{q}$ background: Off-resonance data to correct for data/MC differences in normalisation and shape
- Undetected K^0_L in EM calorimeter can mimic neutrinos
  - K^0_L detection efficiency: $e^+e^- \to \gamma\phi(K^0_S K^0_L)$
  - $B \to K^+D^{(*)}(K^0_L X)$: corrected using pion-enriched sample
  - $B^+ \to K^+K^0_L K^0_L$ events: Model with BaBar [PRD85, 112010(2021)]
    $B^+ \to K^+K^0_S K^0_S$ measurement as input



Closure validation measuring:

$$\mathcal{B}(B^+ \to \pi^+K^0) = (2.5 \pm 0.5) \times 10^{-5}$$

Compatible with PDG $(2.38 \pm 0.08) \times 10^{-5}$

Evidence for $B^+ \to K^+ \nu\bar{\nu}$: Results

Belle II

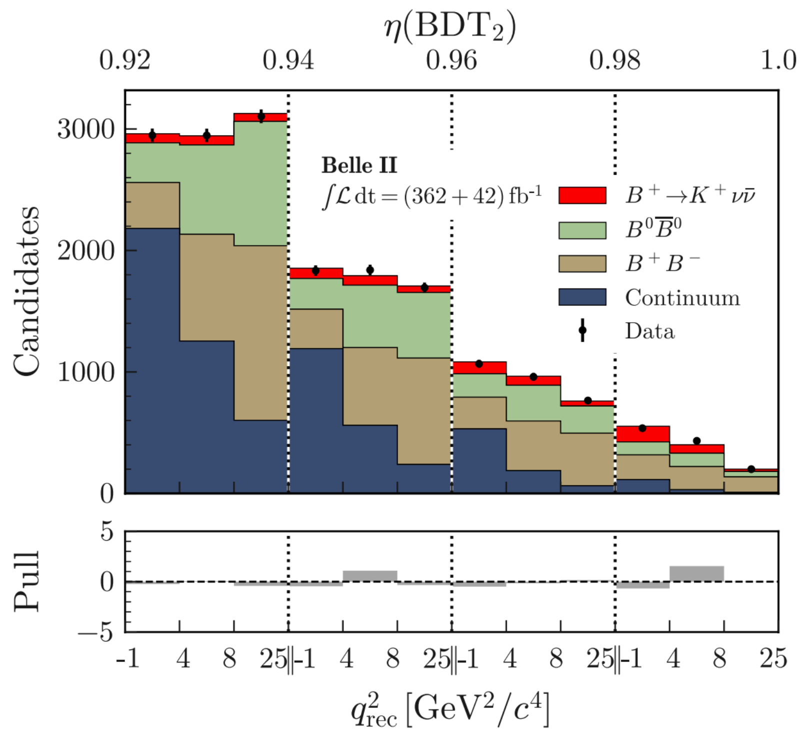
Consistent within 1.2σ

Inclusive Tag

$\mathcal{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

3.5σ significance

2.9σ deviation from SM

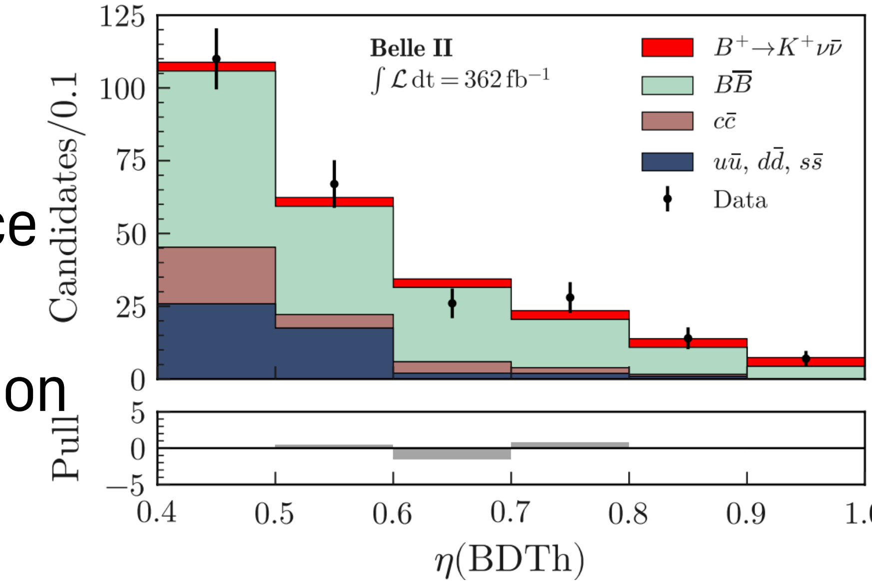


Hadronic Tag

$\mathcal{B} = (1.1 \ ^{+0.9}_{-0.8} \ ^{+0.8}_{-0.5}) \times 10^{-5}$

1.1σ significance

0.6σ deviation from SM



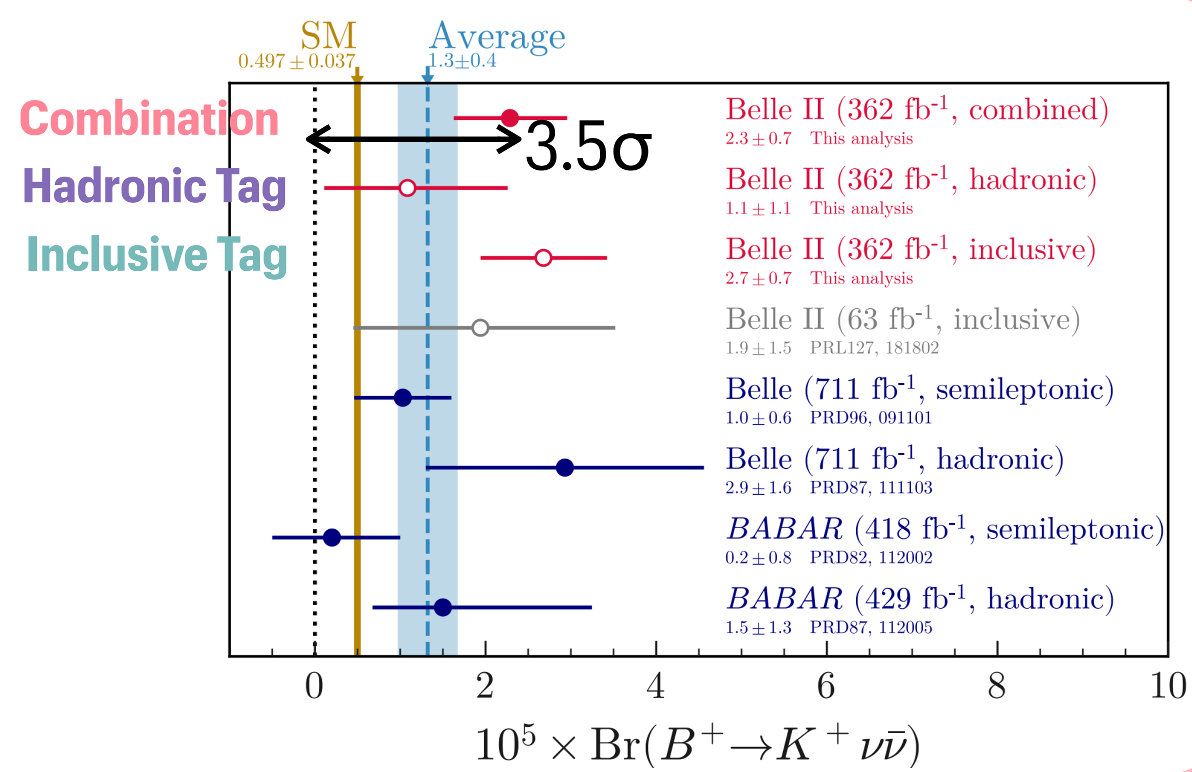
Combination

$\mathcal{B} = (2.3 \pm 0.5 \ ^{+0.5}_{-0.5}) \times 10^{-5}$

3.5σ significance

2.7σ deviation from SM

First evidence of $B^+ \to K^+ \nu\bar{\nu}$



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

New for ICHEP!

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

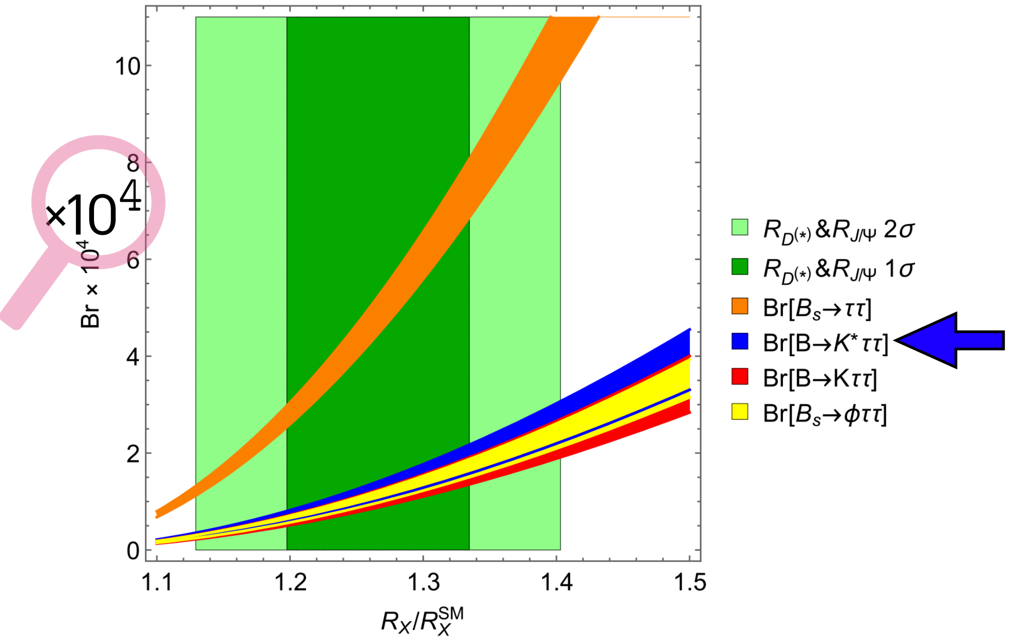
Belle II

- FCNC processes are suppressed in SM at tree level.

$$BF_{SM} = (0.98 \pm 0.10) \times 10^{-7}$$ [PRD 53, 4964 (1996)]

- NP models that accommodate the $b \to c\tau\ell$ anomalies predict an **enhancement of several orders of magnitude with $\tau\tau$ pair** in the final state.
- NP couplings are those involving the **third-fermion generation**.

[PRL 120 181802 (2018)]



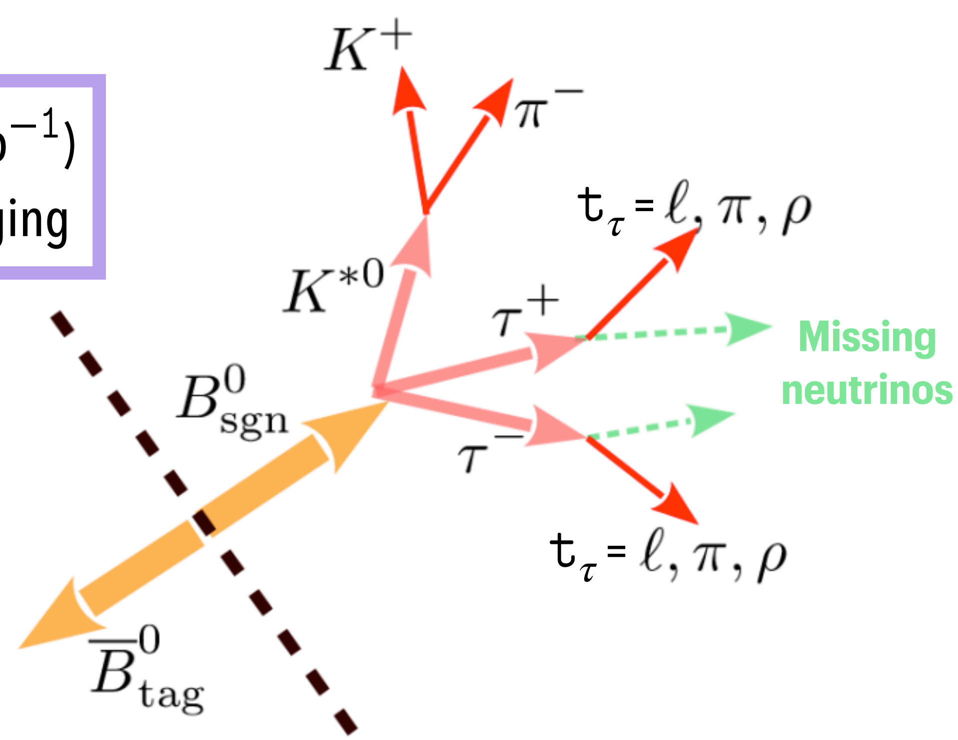
Belle (711 fb^{-1}) $\mathscr{B}^{UL}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ @ 90% CL [PRD 108 L011102 (2023)]

Challenges

Similar as $B^+ \to K^+\nu\bar{\nu}$

- Low BF
- No signal peaking kinematic observable
- Large backgrounds+more than 3 prompt track
- Up to **4 neutrinos** orignating from τ
- K^{*0} has **low momentum** due to the phase space

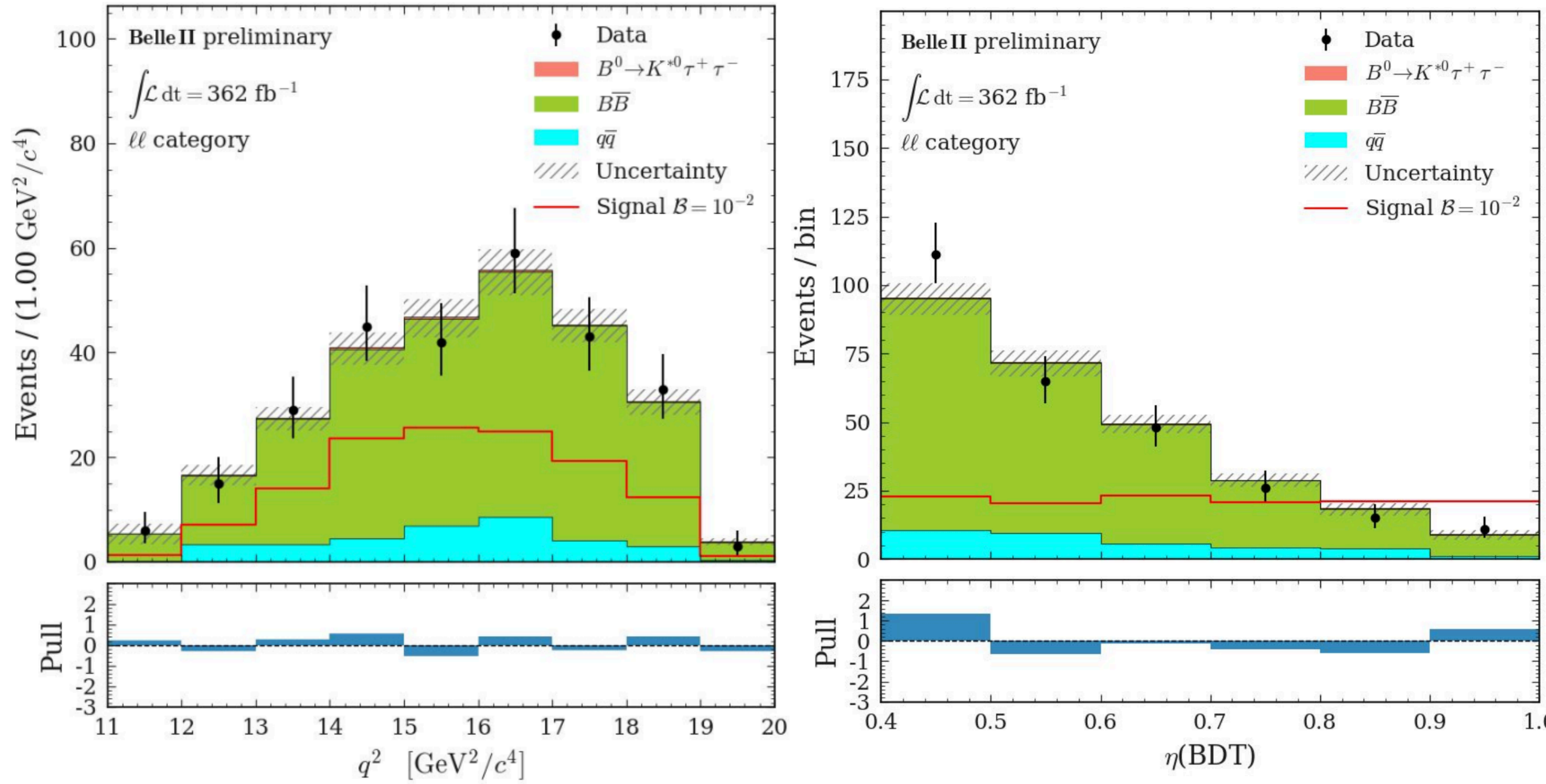
Belle II (364 fb^{-1})
hadronic B-tagging



Search for $B^0 \to K^{*0}\tau^+\tau^-$: Strategy and result

- Combinations of sub-track from τ lead to 4 categories: $\ell\ell, \ell\pi, \pi\pi, \rho X$
- **BDT** is trained using missing energy, extra cluster energy in EM calorimeter, $M(K^{*0}t_\tau)$, q^2, etc.
- BDT output η(BDT) is used to extract the signal yield with simultaneous fit to 4 categories

$\ell\ell$ as an example [best sensitivity]



Validation:

- Total efficiency and Peaking $B^0\bar{B}^0$: $B^0 \to K^{*0}J/\psi$ sample, replace $K^{*0}J/\psi$ with $K^{*0}\tau^+\tau^-$ (14% uncertainty)
- Non-peaking $B\bar{B}$: sample with B_{sig} and B_{tag} having same flavor
- $q\bar{q}$ background is scaled by off-resonance data

$$\mathcal{B}^{UL} = 1.8 \times 10^{-3} \text{ at 90\% CL}$$

Twice better with only half sample wrt Belle!
Better tagging + more categories + BDT classifer...

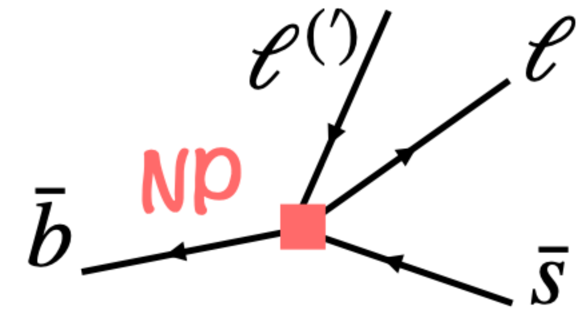
The most stringent limit on the $B^0 \to K^{*0}\tau^+\tau^-$ decay and in general on $b \to s\tau\tau$ transition!

$$B^0 \to K_S^0 \tau^{\pm} \ell^{\mp}, \ell = \{e, \mu\}$$

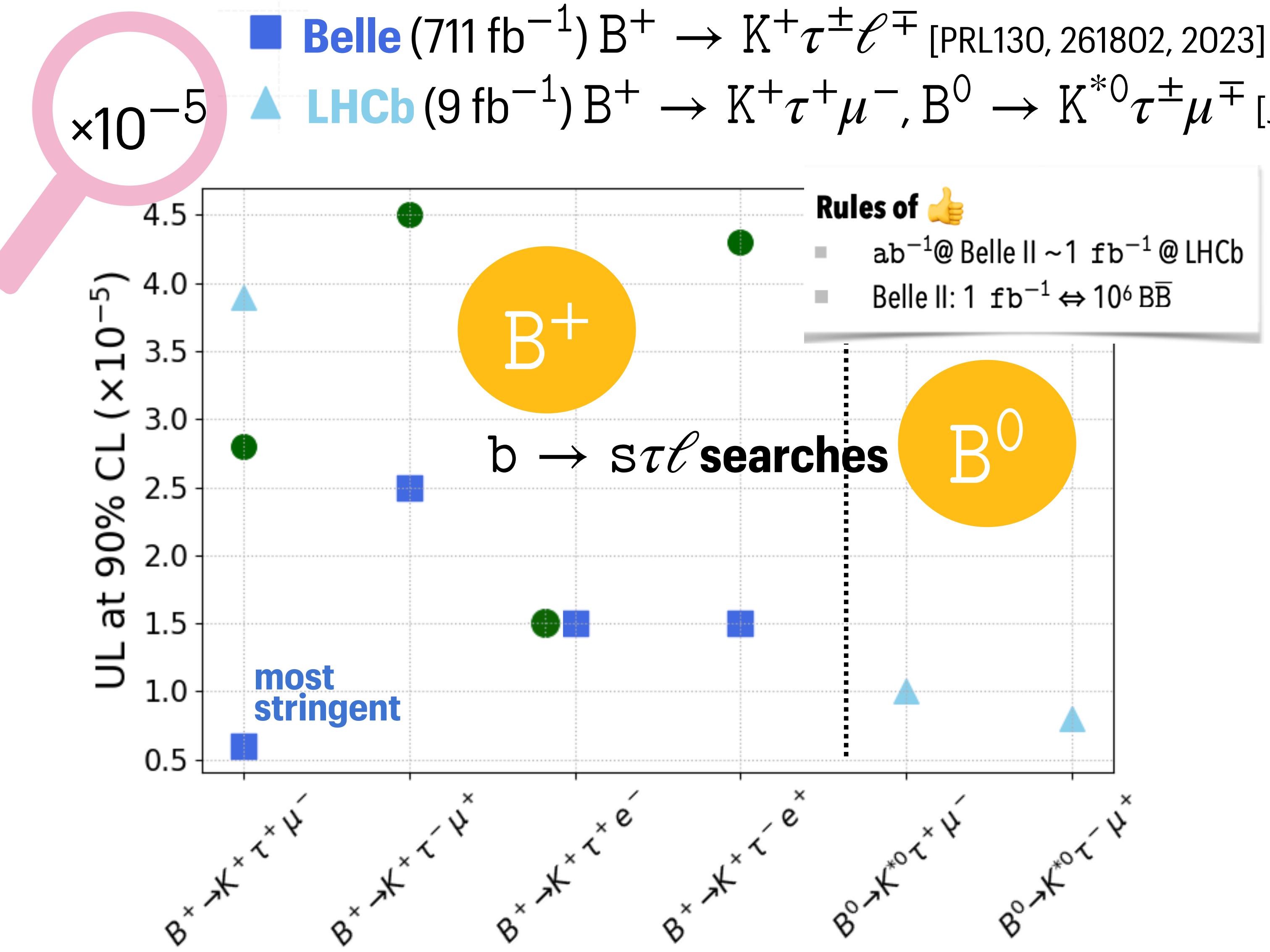
New for ICHEP!

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

- $\mathscr{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu})$ excess and $b \to c\tau\ell$ anomalies indicate the possibility of new heavy particles couple preferentially to second and third generation leptons.
- The BSM extensions predict that the decay rates for LFV $b \to s\tau\ell$ decays are close to current experimental sensitivity
- Third-generation couplings + τ lepton mass ->sensitivity to new physics

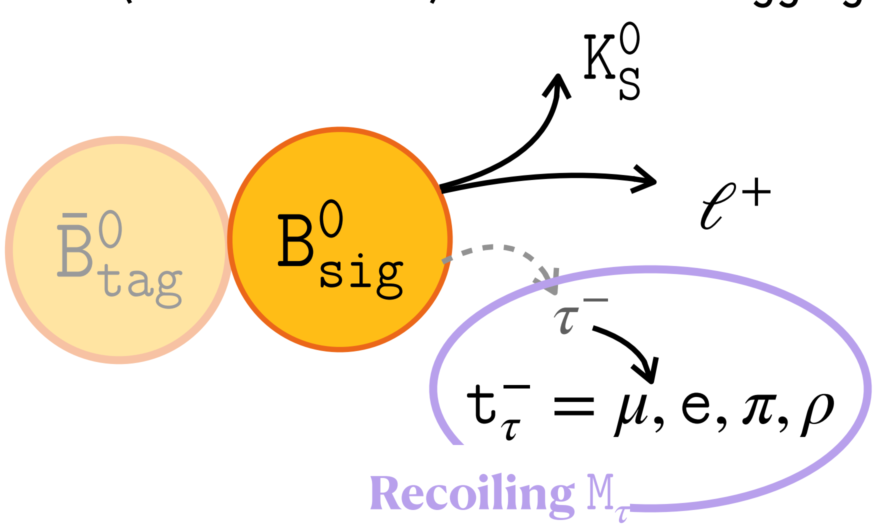


- **BaBar** (428 fb^{-1}) $B^+ \to K^+\tau^{\pm}\ell^{\mp}$ [PRD86, 012004, 2012]
- **Belle** (711 fb^{-1}) $B^+ \to K^+\tau^{\pm}\ell^{\mp}$ [PRL130, 261802, 2023]
- **LHCb** (9 fb^{-1}) $B^+ \to K^+\tau^+\mu^-$, $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ [JHEP06, 129, 2020] [JHEP06, 143, 2023]



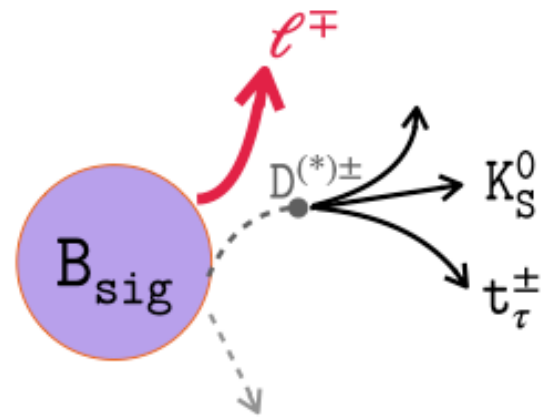
Today: first search in $B^0 \to K_S^0 \tau^{\pm} \ell^{\mp}$

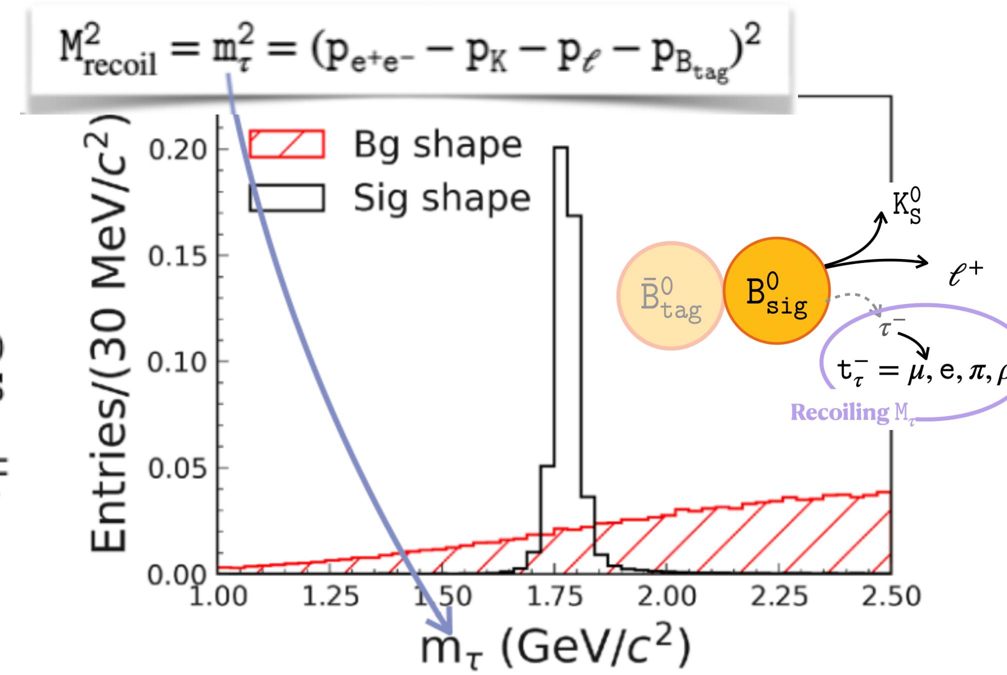
BELLE+Belle II (711+364 fb^{-1}) + hadronic B-tagging



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

- Has **neutrinos only from one τ** $\Leftrightarrow$ can compute recoiling mass of τ (unlike $B^+ \to K^+ \nu \bar{\nu}$, $B^0 \to K^{*0} \tau^+ \tau^-$ etc)
- K_S^0 purity is larger than 98%
- Reject dominant bkg: **B semi-leptonic decay**
- BDT for remaining bkg suppression



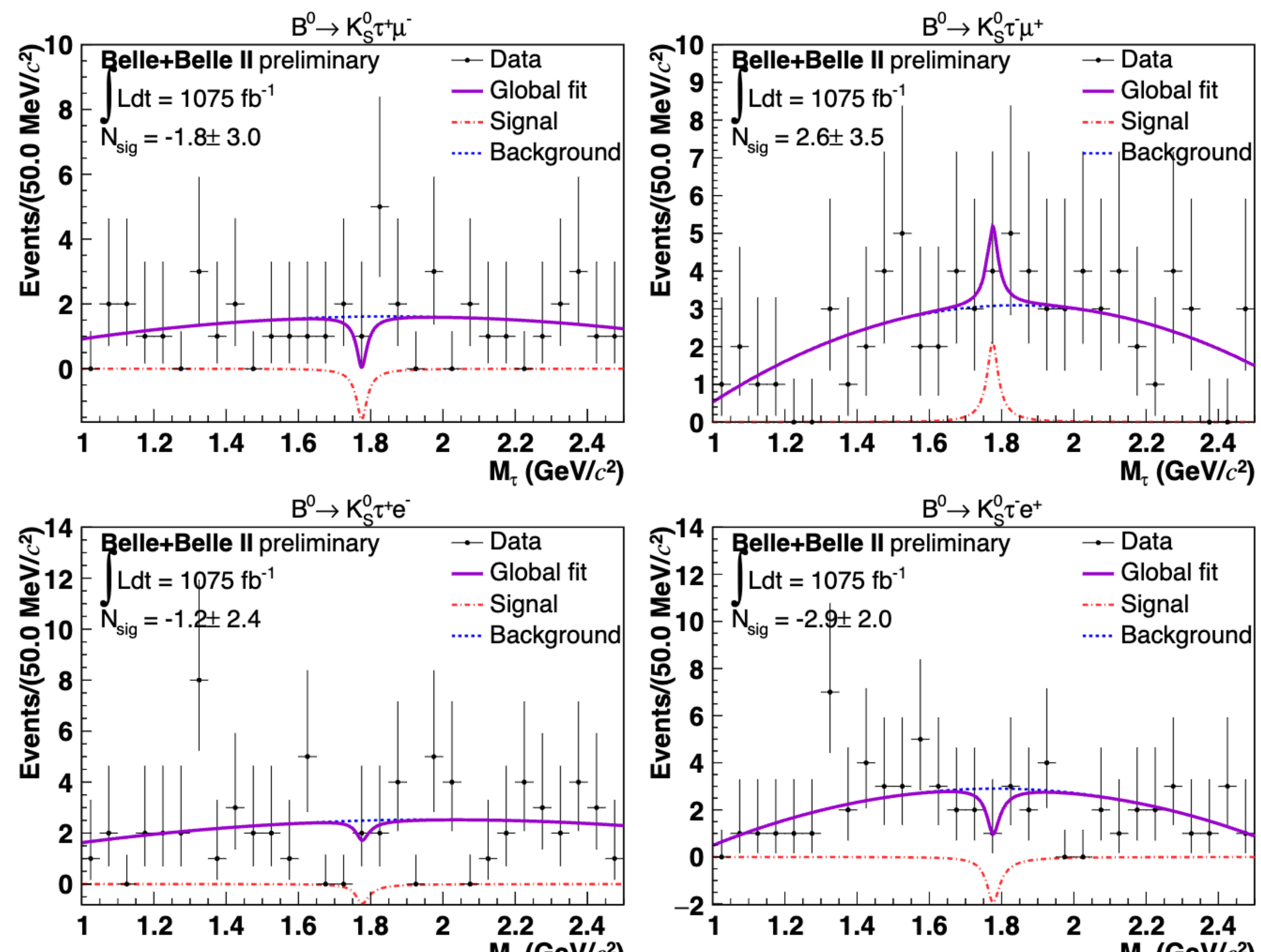


The first search in $B^0 \to K_S^0 \tau^\pm \ell^\mp$

90% CL upper limits are derived

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

The results are among the most stringent limit

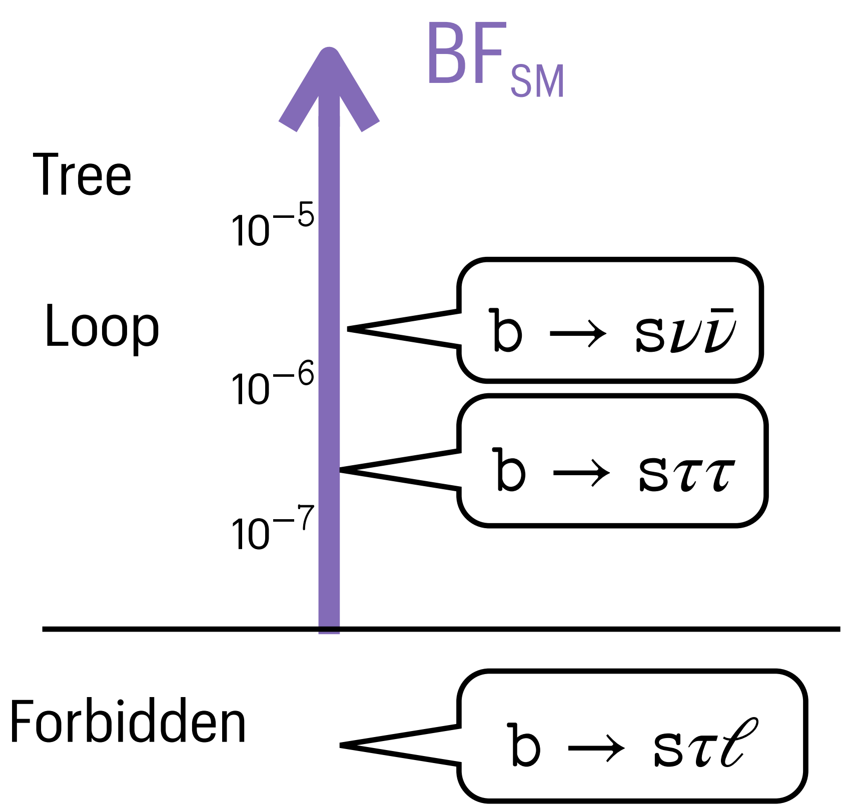


Summary

BELLE Belle II

Three new results since the last ICHEP:

First evidence on $B^+ \to K^+\nu\bar{\nu}$, searches on $B^0 \to K^{*0}\tau^+\tau^-$ and $B^0 \to K^0_S\tau^\pm\ell^\mp$



Inclusive *B*-tagging approach has proved to be the most sensitive to $B^+ \to K^+\nu\bar{\nu}$, tension wrt SM at 2.7σ for the combined (inclusive+hadronic) result.

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

The most stringent limit on the $B^0 \to K^{*0}\tau^+\tau^-$ decay and in general on $b \to s\tau\tau$ transition.

The first search on the $B^0 \to K^0_S\tau^\pm\ell^\mp$ decays;

The upper limits [0.8-3.6] $\times 10^{-5}$ at 90% CL are among the most stringent limits to date.

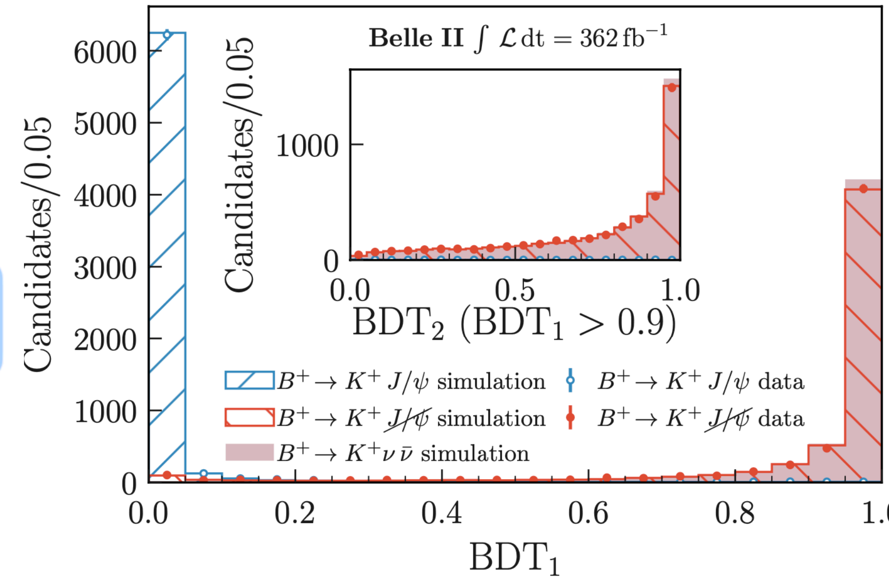
More results on these transitions will come soon!

Thank you for you attention

Backup

Evidence for $B^+ \to K^+\nu\bar{\nu}$: Signal Validation

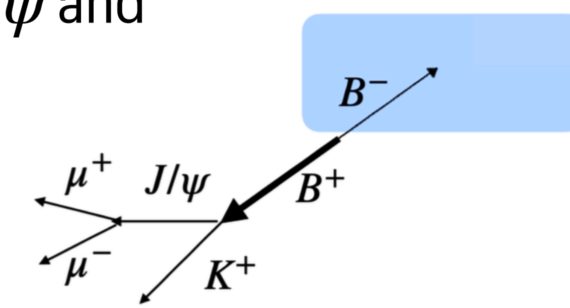
Belle II



<u>Total efficiency:</u>

with $B^+ \to J/\psi K^+$ sample, remove J/ψ and correct K^+ kinematics to match $K^+\nu\bar{\nu}$

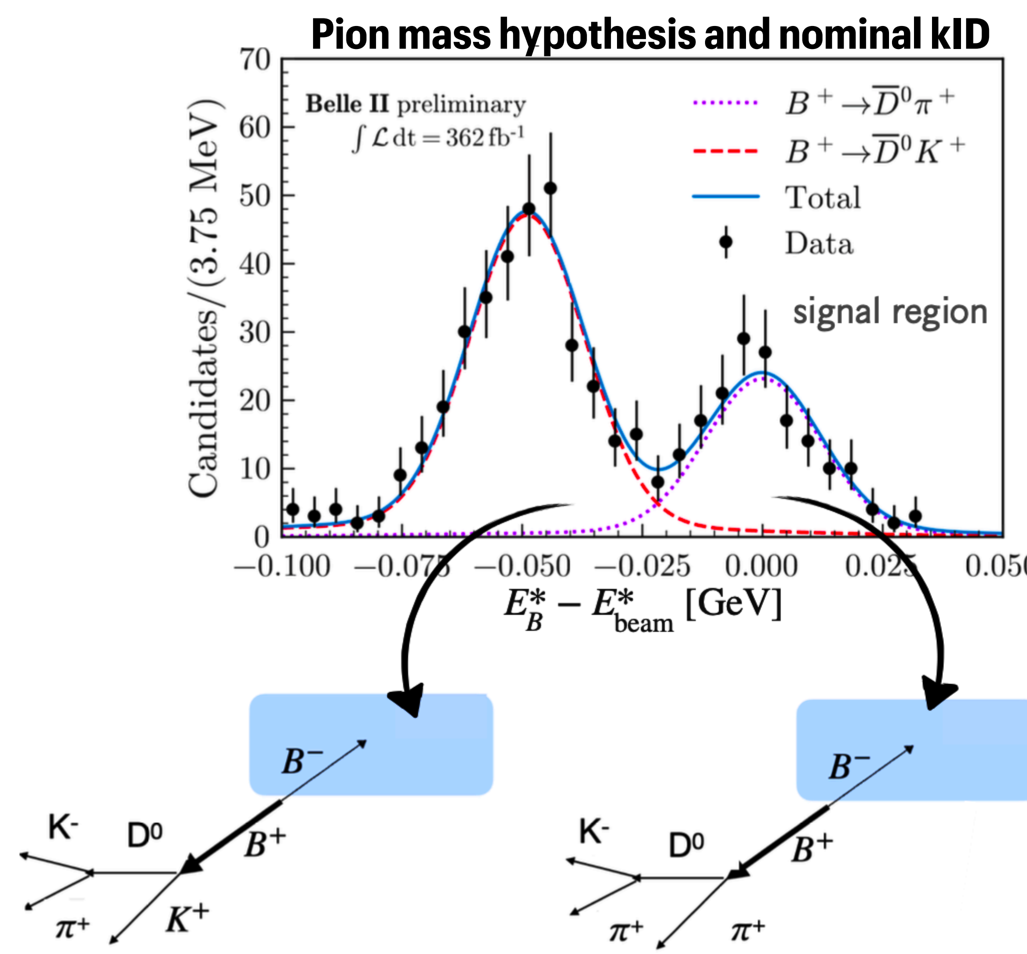
Data/MC efficiency ratio: 1.00 ± 0.03



<u>Kaon ID:</u>

validated with $B^+ \to \bar{D}^0 (\to K^+\pi^-) h^+, h = \{\pi, K\}$

Data/MC ratio of relative abundance of B→DK and B→Dπ: 1.03±0.09

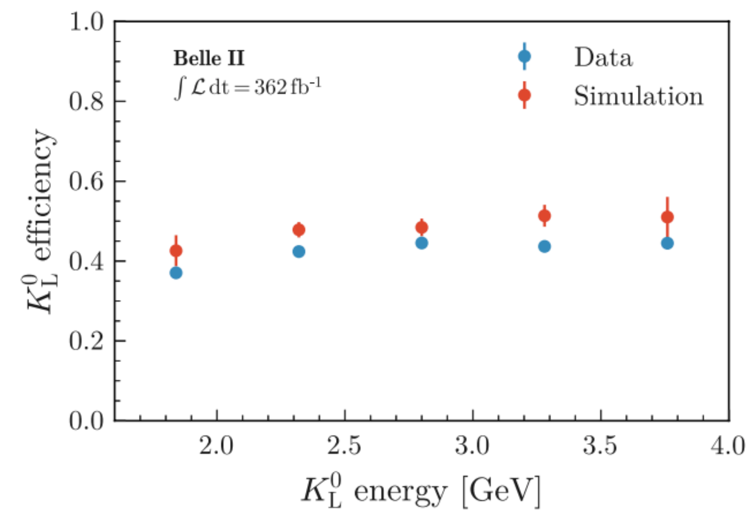


Evidence for $B^+ \to K^+\nu\bar{\nu}$: K_L^0-related Validation

Belle II

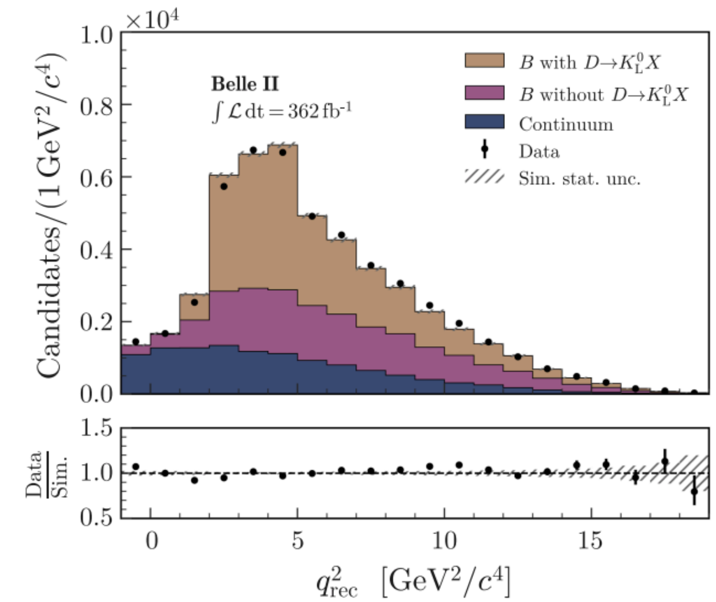
$\underline{B \to D^*K^+ \text{events:}}$

Modelling of K_L^0 detection efficiency in the calorimeter corrected using $e^+e^- \to \gamma\phi(K_S^0K_L^0)$ sample



$\underline{B \to X_c(K_L^0X) \text{ events:}}$

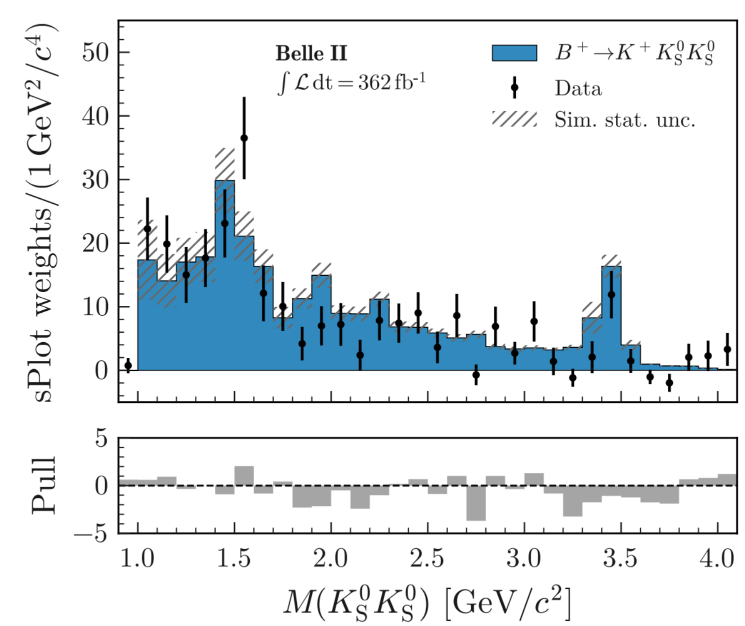
corrected using pion-enriched sideband



$\underline{B^+ \to K^+K_L^0K_L^0 \text{ events:}}$

Model with BaBar $B^+ \to K^+K_S^0K_S^0$ measurement as input

[PRD85, 112010(2021)]



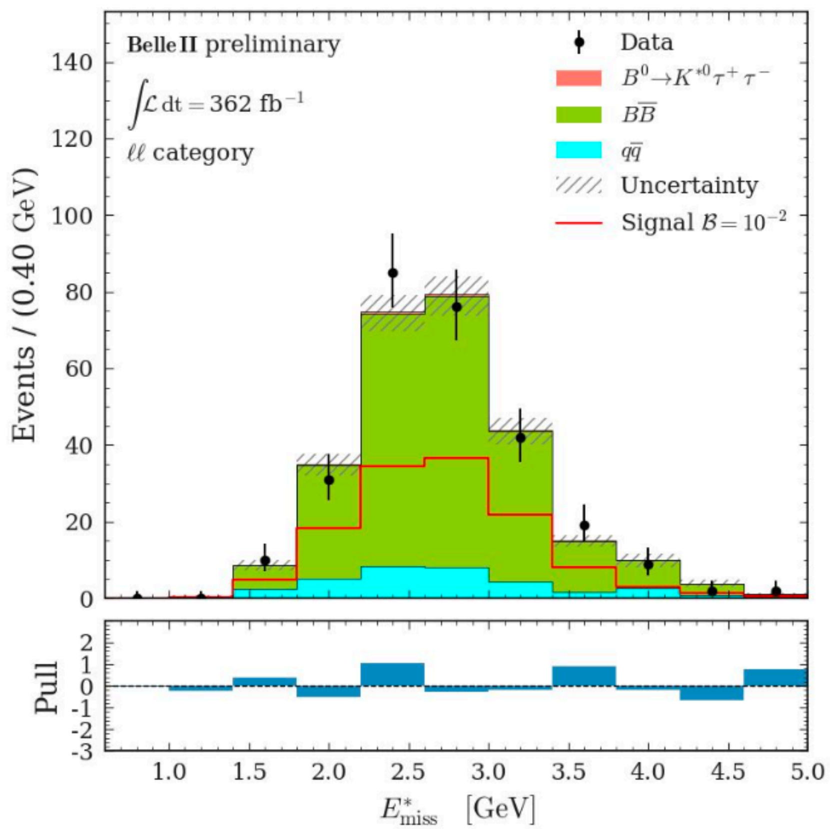
Evidence for $B^+ \to K^+ \nu\bar{\nu}$: systematic uncertainty

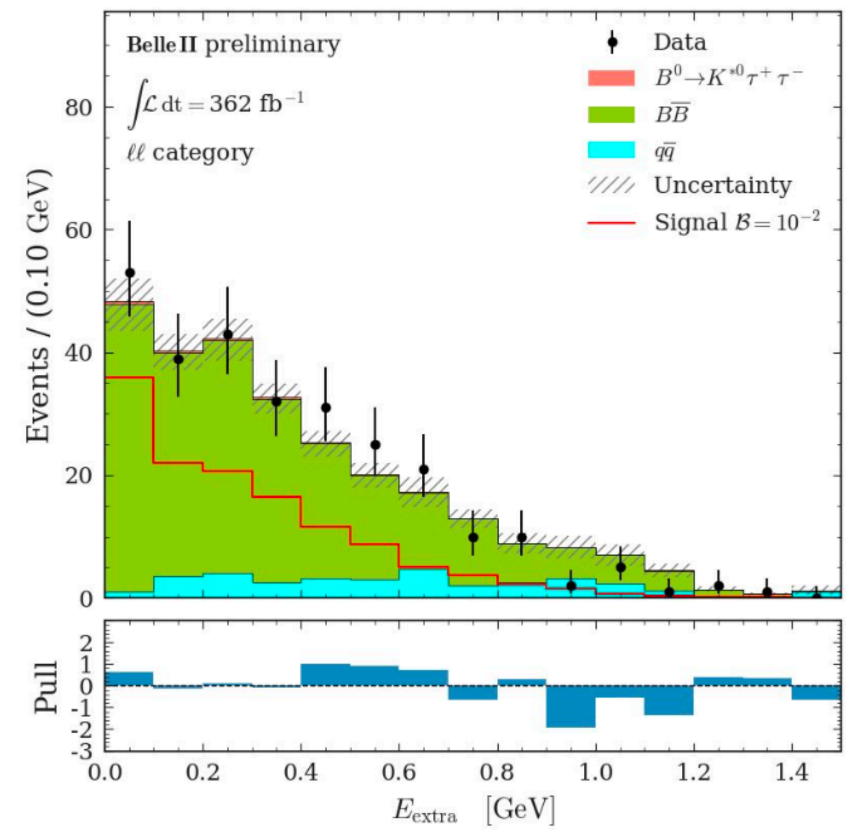
Belle II

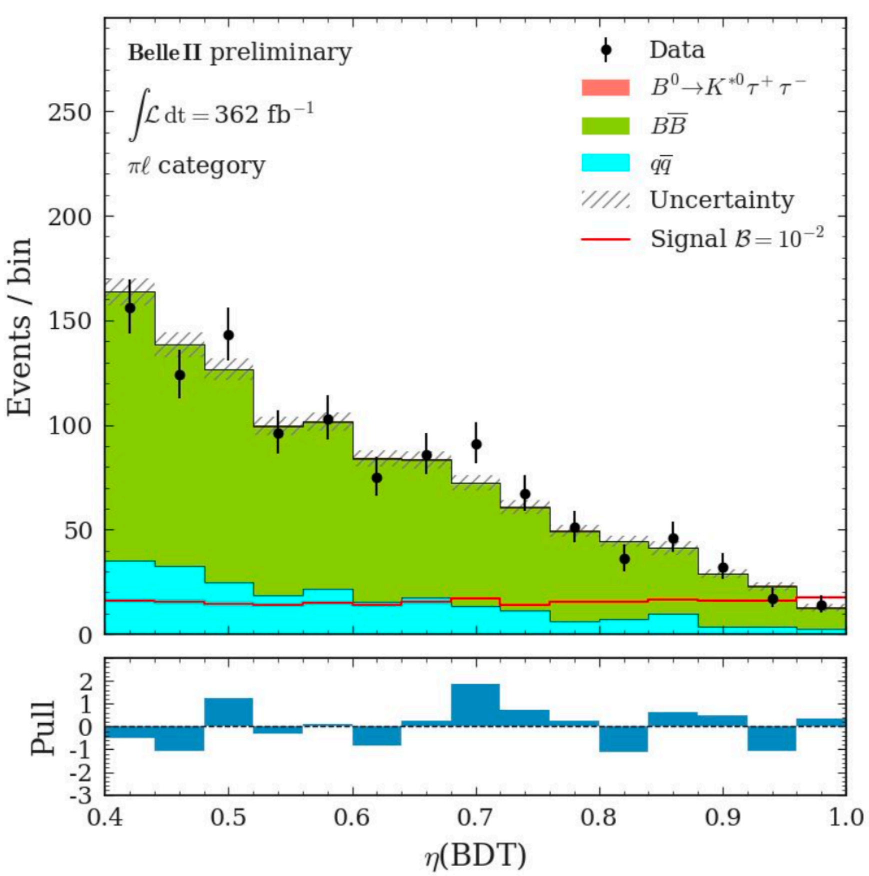
TABLE I. Sources of systematic uncertainty in the ITA, corresponding correction factors (if any), their treatment in the fit, their size, and their impact on the uncertainty of the signal strength μ. The uncertainty type can be "Global", corresponding to a global normalization factor common to all SR bins, or "Shape", corresponding to a bin-dependent uncertainty. Each source is described by one or more nuisance parameters (see the text for more details). The impact on the signal strength uncertainty σ_μ is estimated by excluding the source from the minimization and subtracting in quadrature the resulting uncertainty from the uncertainty of the nominal fit.

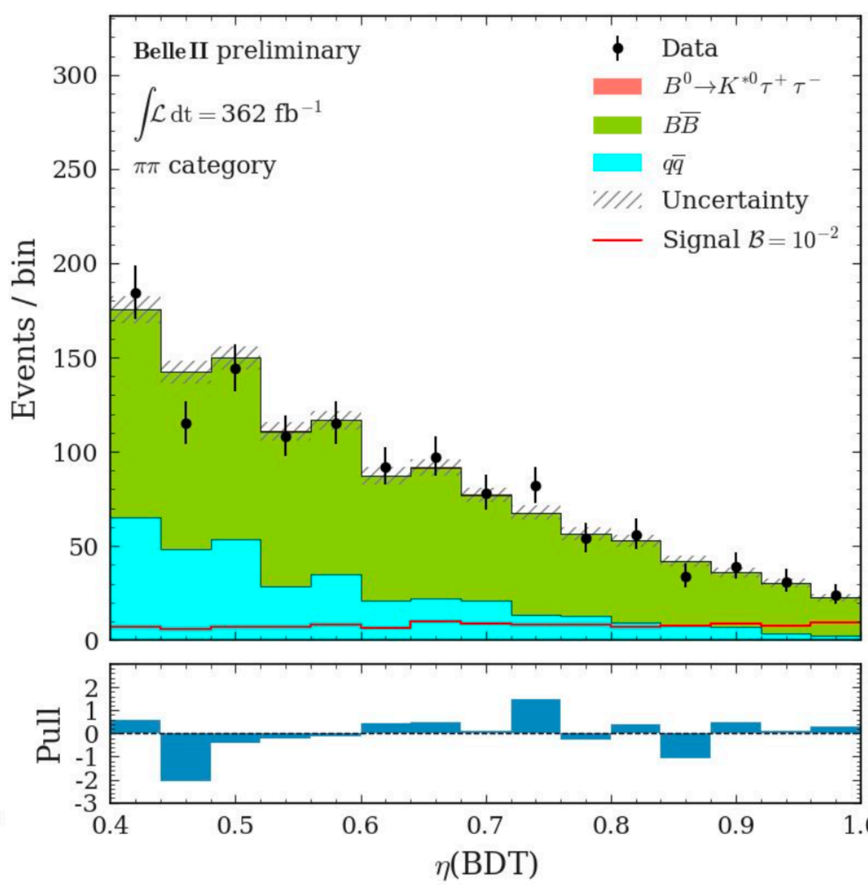
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background		Global, 2	50%	0.90
Normalization of continuum background		Global, 5	50%	0.10
Leading B-decay branching fractions		Shape, 6	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \to D^{**}$		Shape, 1	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity		Global, 1	1%	<0.01
Number of $B\bar{B}$		Global, 1	1.5%	0.02
Off-resonance sample normalization		Global, 1	5%	0.05
Track-finding efficiency		Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10–100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy		Shape, 1	0.5%	0.08
Hadronic energy	−10%	Shape, 1	10%	0.37
K^0_L efficiency in ECL	−17%	Shape, 1	8.5%	0.22
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency		Global, 1	3%	0.03
Simulated-sample size		Shape, 156	$O(1\%)$	0.52

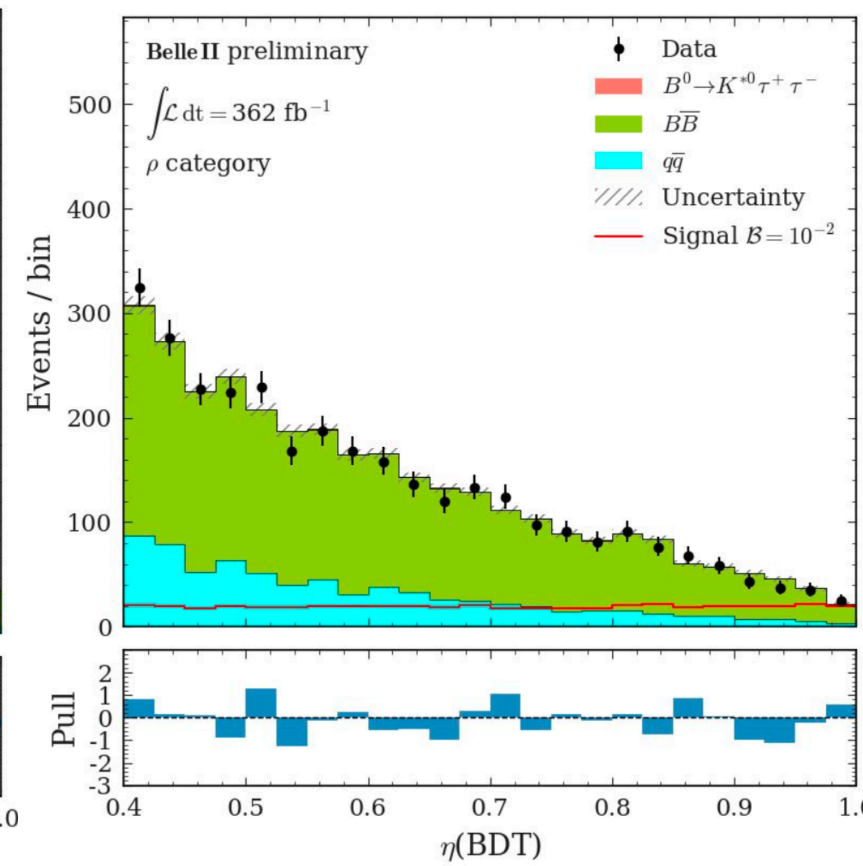
Search for $B^0 \to K^{*0}\tau^+\tau^-$: BDT features and output





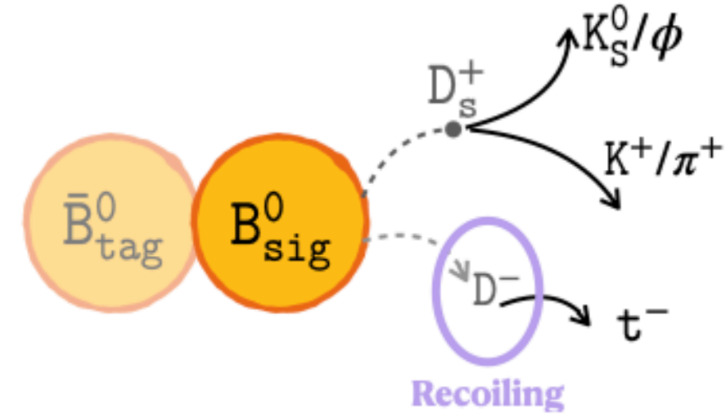


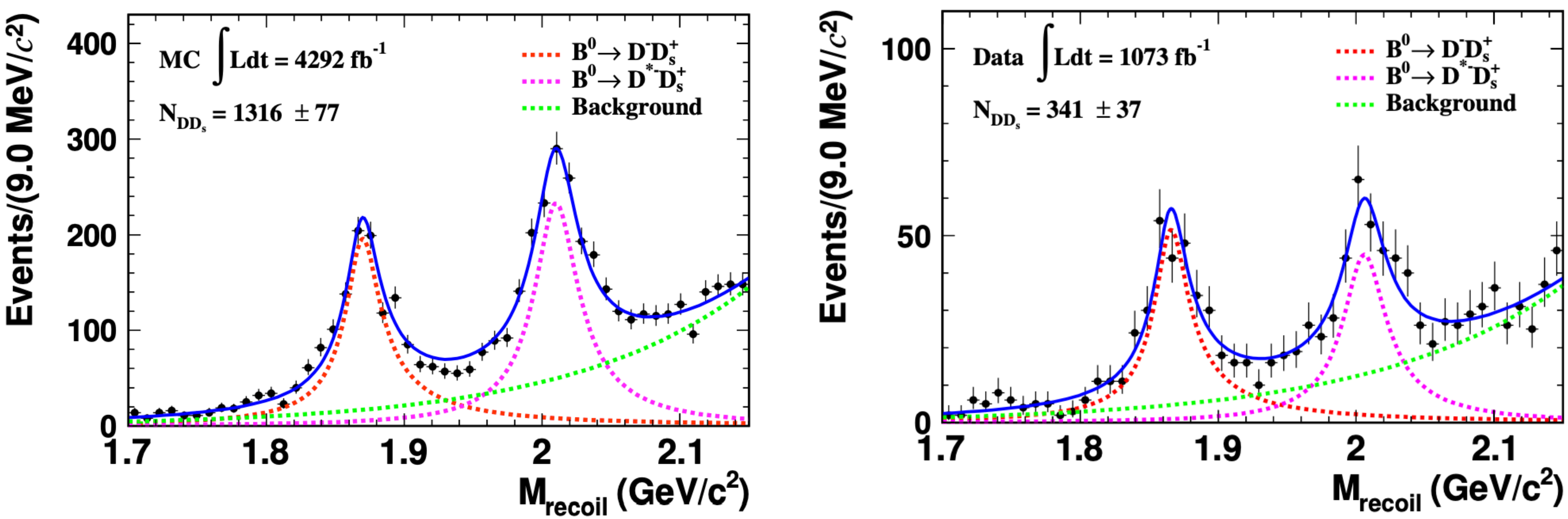




Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$: Validation

- Use $B^0 \to D_s^+ D^-$ to validate recoiling signal PDF and BDT training:
  - consistent resolutions in data/simulation
  - obtain BDT efficiency correction factor





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

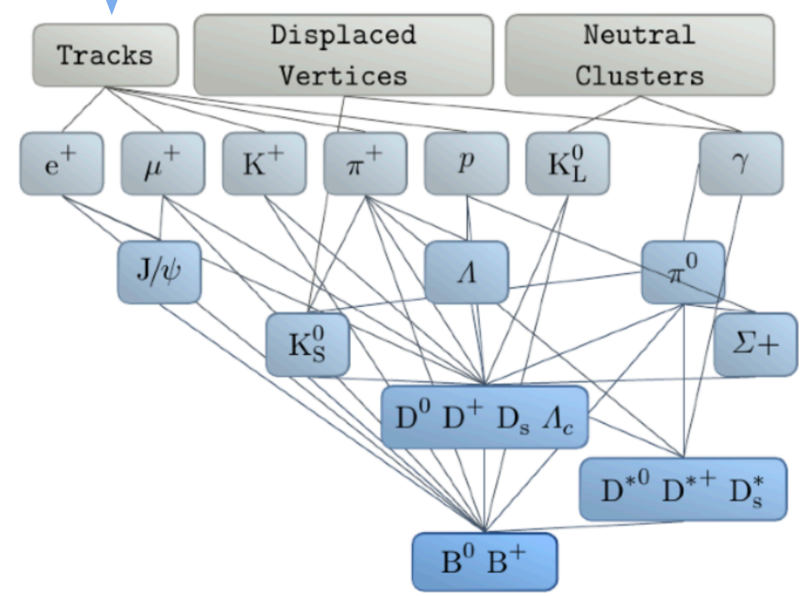
Belle II
BELLE

Source (%)	$K_S^0\tau^+\mu^-$	$K_S^0\tau^-\mu^+$	$K_S^0\tau^+e^-$	$K_S^0\tau^-e^+$
BDT selection	17.1	17.5	16.6	19.2
Signal PDF	15.7	15.7	15.7	15.7
B_{tag} calibration	3.7	3.7	3.7	3.7
Lepton identification	0.3	0.3	0.5	0.5
τ daughter reconstruction	5.3	6.5	6.1	6.4
Linearity	1.6	1.4	0.8	1.4
Number of $B\bar{B}$ pairs	1.1	1.1	1.1	1.1
f_{+-}/f_{00}	2.3	2.3	2.3	2.3
K_S^0, τ, ρ, π^0 branching fractions	0.7	0.7	0.7	0.7
Total	24	24	23	25

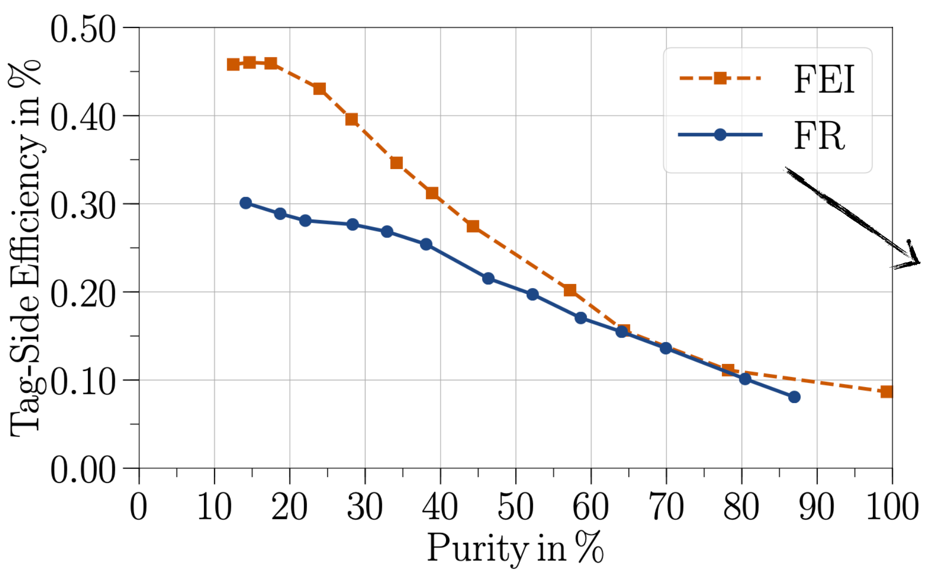
B-tagging: FEI algorithm

Efficiency ⟵⟶ Information Purity

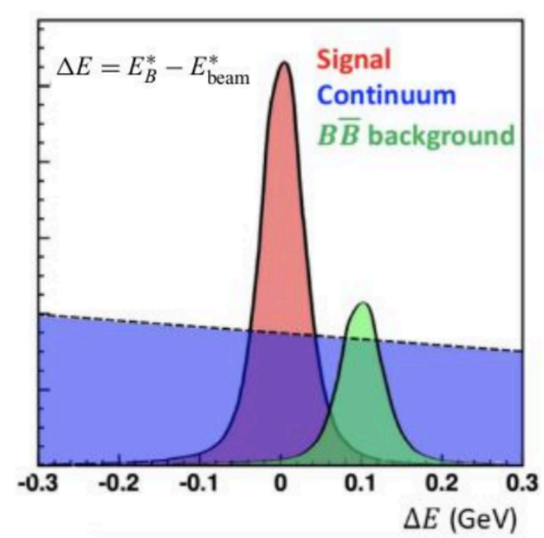
Inclusive	**Semileptonic**	**Hadronic**
X	$D^{(*)}\ell\nu$	$D^{(*)}n\pi$
$\epsilon = \mathcal{O}(100)\%$	$\epsilon = \mathcal{O}(1)\%$	$\epsilon = \mathcal{O}(0.1)\%$

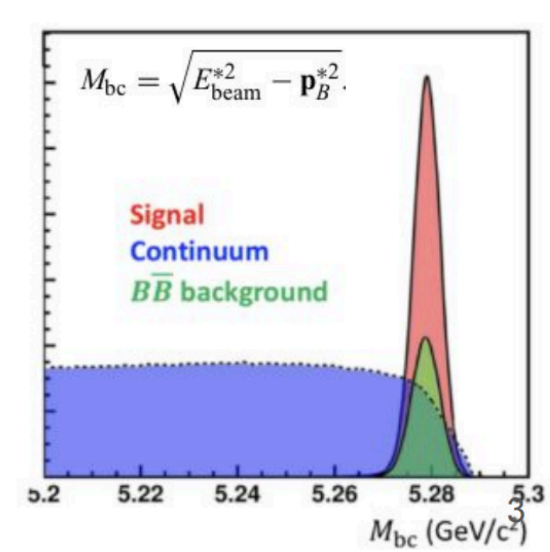


- The **F**ull **E**vent **I**nterpretation (FEI) is the algorithm for hadronic/semileptonic tag-side reconstruction at Belle II [Comput Softw Big Sci 3, 6 (2019)]
- Hierarchical approach
- Employs over 200 BDTs trained on simulated $\Upsilon(4S) \to B\bar{B}$ events to reconstruct *B*-decay chains



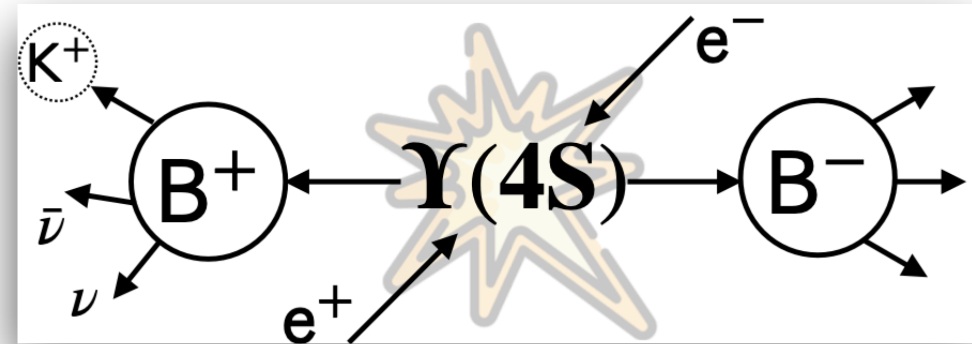
Full **R**econstruction hierarchical NeuroBayes-based Belle experiment





Belle II experiment

A pair of $B\bar{B}$ is produced at threshold → low backgrounds



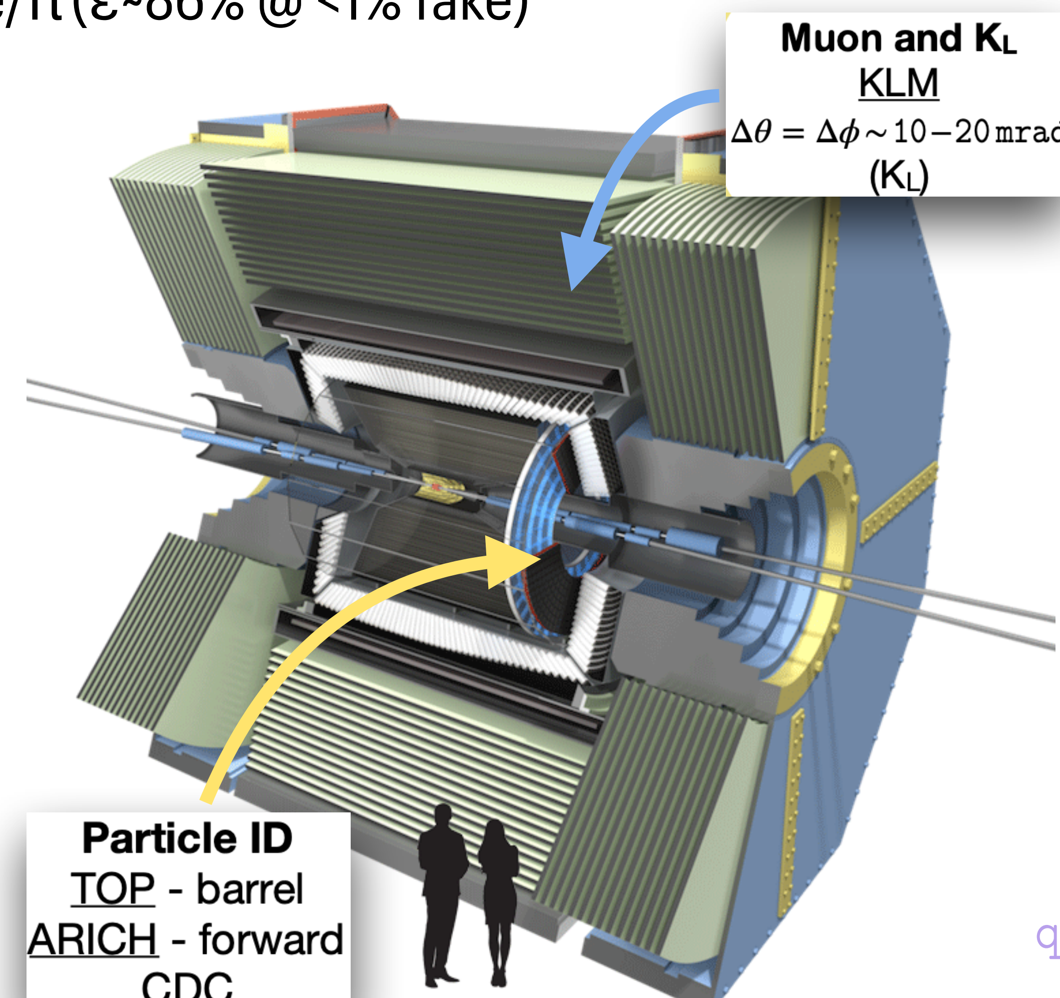
Hadron ID

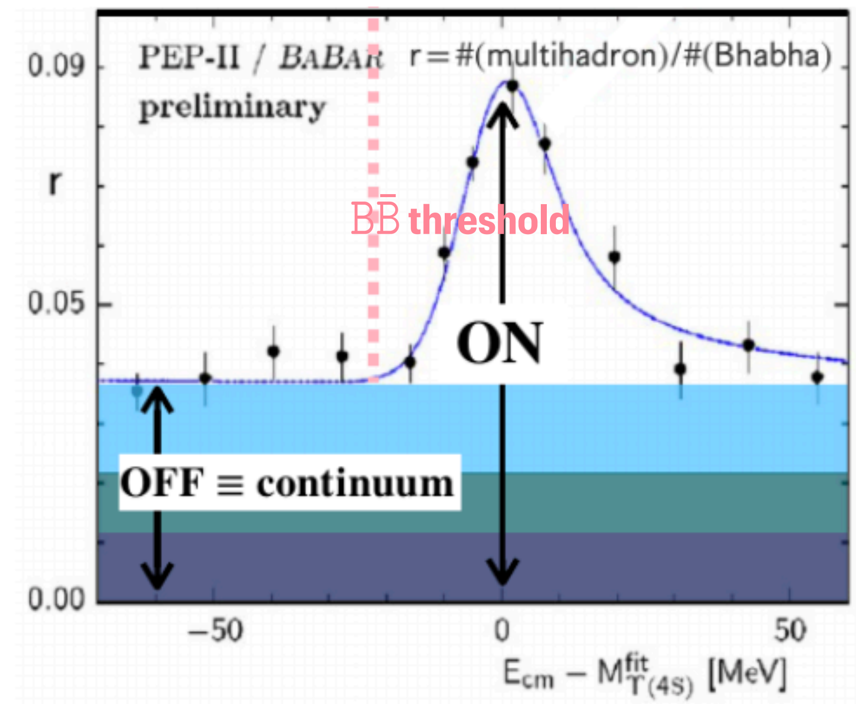
Good kaon identification in full momentum range ($\epsilon \sim 90\%$ @ K/π misID $\sim 6\%$)

lepton ID

μ/π (ε~90% @ 7% fake)

e/π (ε~86% @ <1% fake)





	ON	OFF
BELLE	711 fb^{-1}	90 fb^{-1}
Belle II	364 fb^{-1}	42 fb^{-1}

@ 60 MeV below $\Upsilon(4S)$