$B \to X_s \nu\bar{\nu}$

Junewoo Park

2026.09.04

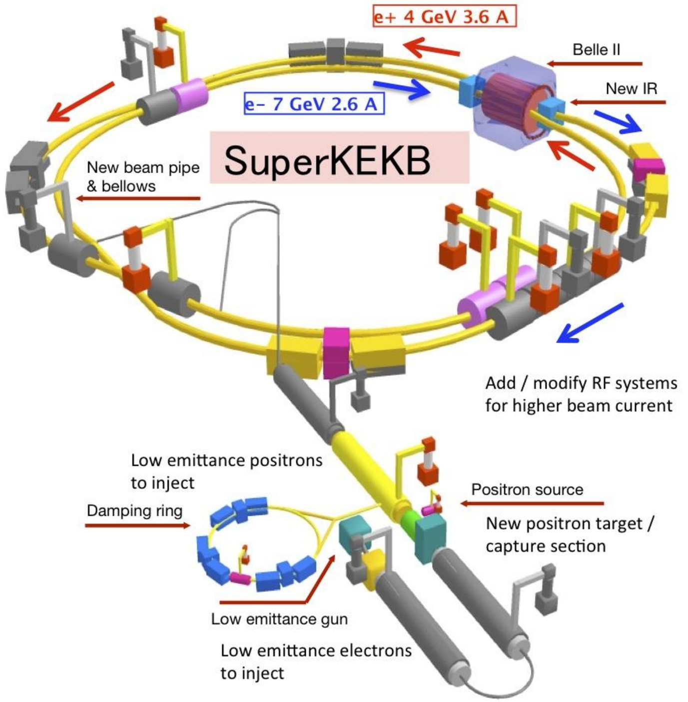
Flavor Frontier 2026

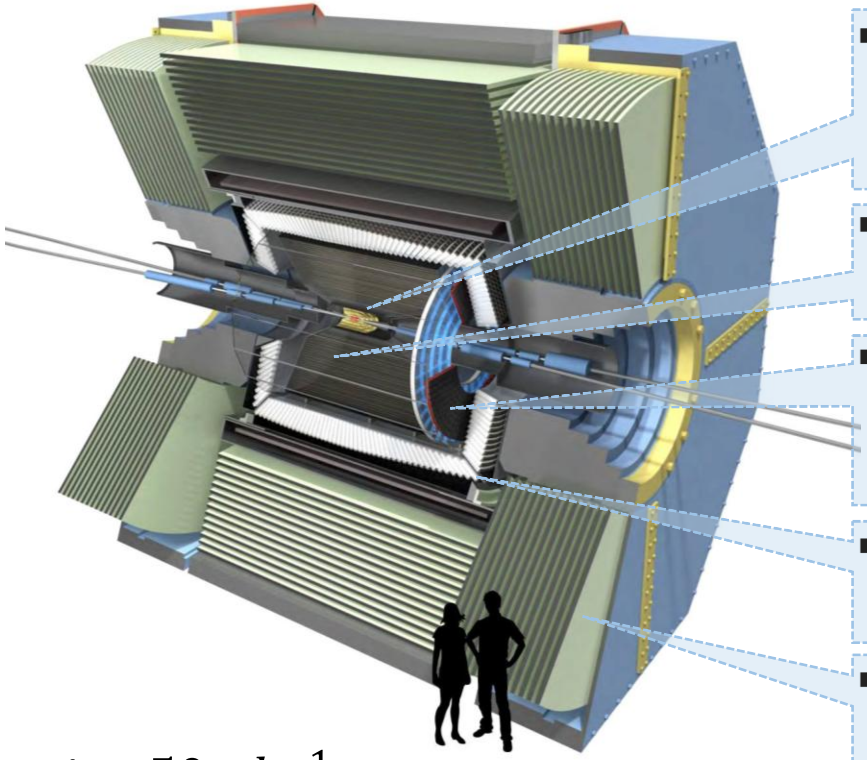
† covers $17° < \theta < 150°$

‡ covers $12.4° < \theta < 155.1°$

Belle II Experiment

- Electrons and positrons are accelerated up to $7\ \mathrm{GeV}$ and $4\ \mathrm{GeV}$ respectively by SuperKEKB accelerator
- Its energy correspond to the resonance of $\Upsilon(4S)$ which mainly decays into B meson pair
- Belle II detector consists of several sub-detector components

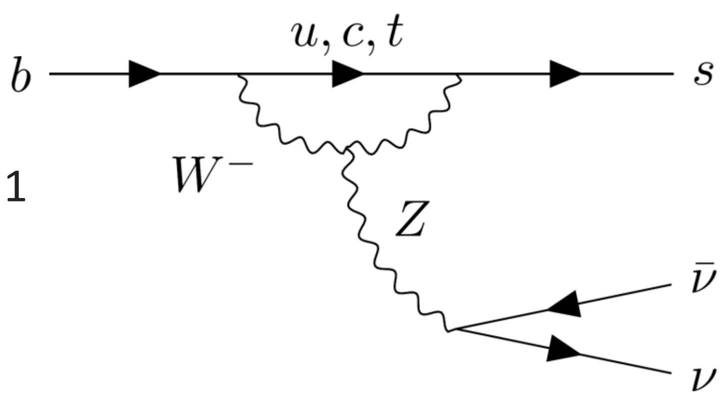


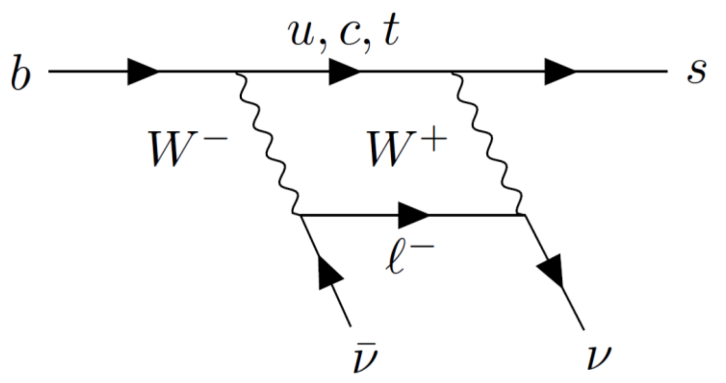


- For vertex detector
  - pixelated silicon sensors (PXD)
  - silicon strip sensors (SVD)
- For tracking
  - central drift chamber (CDC) †
- For particle identification
  - Aerogel Ring Imaging Cherenkov (ARICH)
  - Time of Propagation (TOP) Detector
- For electromagnetic shower energy detection
  - electromagnetic calorimeter (ECL) ‡
- For K_L^0 and μ detection
  - K_L^0 and muon detector (KLM)

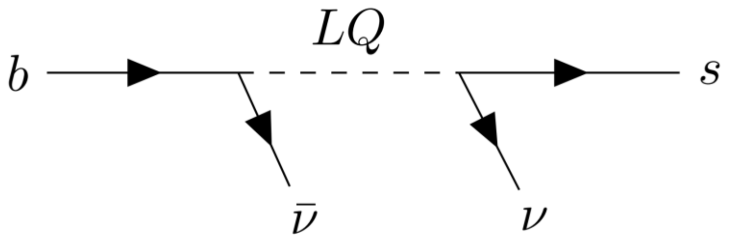
- The target integrated luminosity: $50\ ab^{-1}$
  - Currently, $914\ fb^{-1}$ data is recorded

Motivation





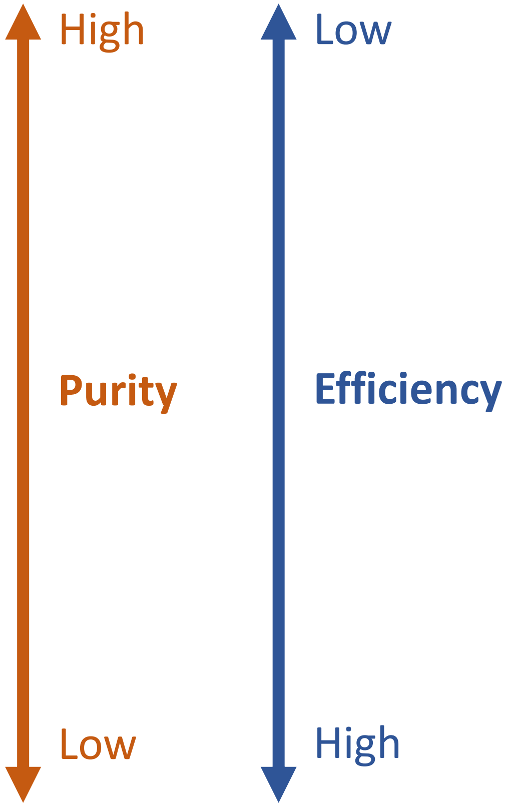
- What is X_s
  - Hadronic system with strangeness equal to 1
- $B \to X_s \nu\bar{\nu}$ decay
  - Flavour-changing neutral currents process
  - $\mathrm{BR} = (2.9 \pm 0.3) \times 10^{-5}$ in SM [JHEP02(2015)184]
- This decay can give a clue for the new physics
  - leptoquark [PhysRevD.95.035027]
  - invisible light scalar [Eur. Phys. J. C (2017) 77: 650]
  - fermion dark matter [arXiv:2405.06742]

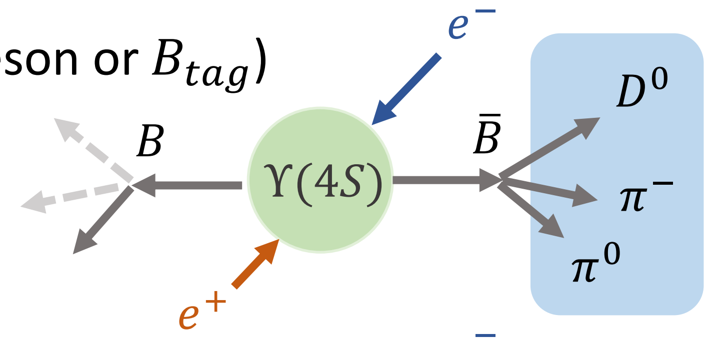


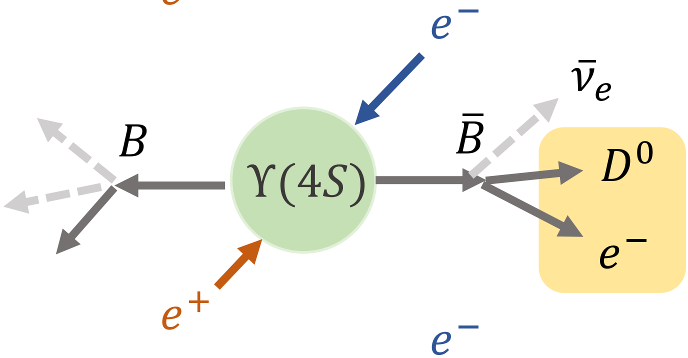
- Previous study
  - $UL(b \to s\nu\bar{\nu}) = 6.4 \times 10^{-4}$ (90% CL) by ALEPH [Eur.Phys.J.C 19 (2001) 213-227]
    - There is no $B \to X_s \nu\bar{\nu}$ results from Belle or Babar because $\nu\bar{\nu}$ makes it challenging
  - $BR(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$ by Belle II, which is 2.7σ deviation from SM [PhysRevD.109.112006]

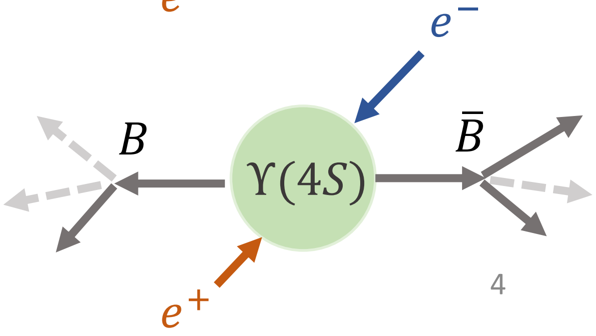
Analysis Strategy

- Neutrinos from $B \rightarrow X_s \nu\bar{\nu}$ makes this analysis challenging
- Entire information of initial states is known in Belle II experiment.
  → Non-signal side B meson can be used to suppress backgrounds
- There are three methods to deal with non-signal side B meson (tag side B meson or B_{tag})
  - Hadronic tagging
    - Reconstruct B_{tag} by hadronic decay modes
  - Semileptonic tagging
    - Reconstruct B_{tag} by semileptonic decay modes
  - Inclusive tagging
    - Use information about rest of event (ROE)

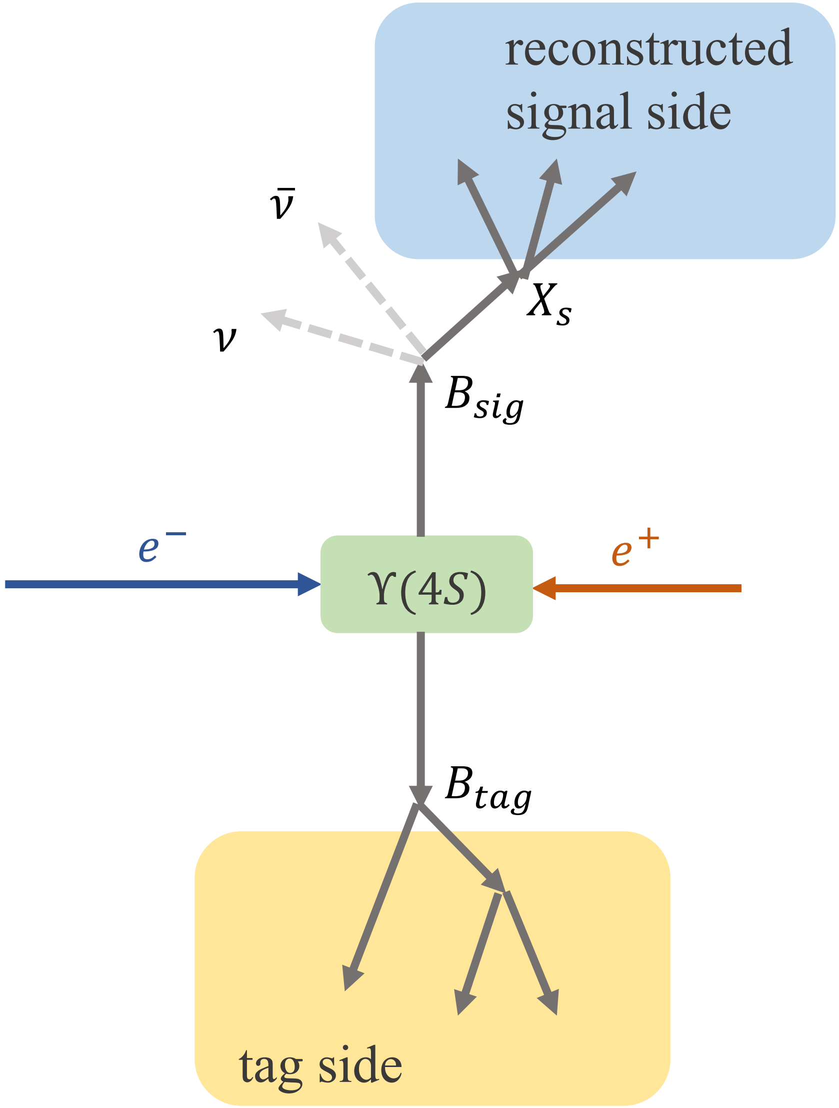








Analysis Strategy



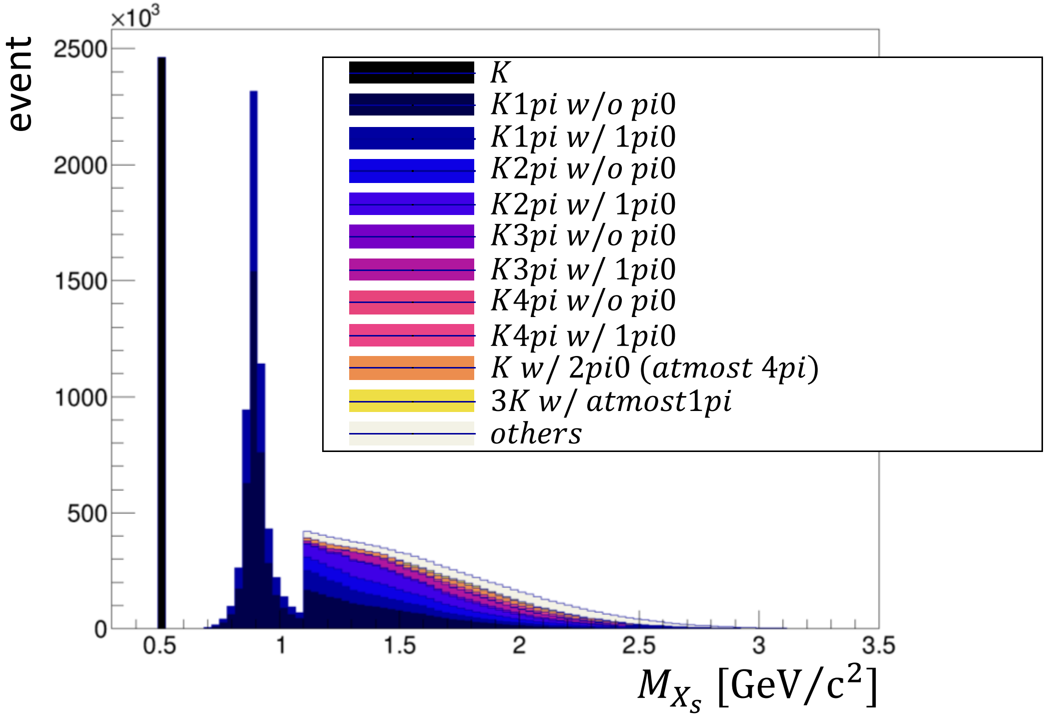
- The target sample: $365\ \mathrm{fb}^{-1}$ $\Upsilon(4S)$ on-resonance data
- One side of B meson is hadronically reconstructed [Comput Softw Big Sci 3, 6 (2019)]
  - Generally, this efficiency $\epsilon_{tag} \sim \mathcal{O}(0.1\%)$
- For signal side B meson, sum of exclusive method is used
  - 30 decay modes are reconstructed for X_s

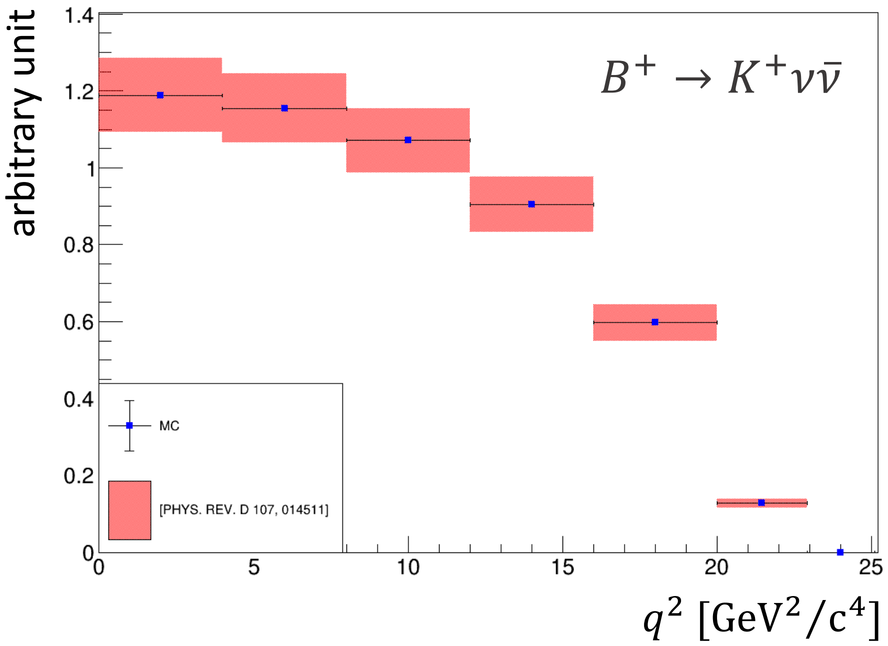
	B^0			$B^{\pm}$		
K	K_S^0			$K^{\pm}$		
$K\pi$	$K^{\pm}\pi^{\mp}$	$K_S^0\pi^0$		$K^{\pm}\pi^0$	$K_S^0\pi^{\pm}$	
$K2\pi$	$K^{\pm}\pi^{\mp}\pi^0$	$K_S^0\pi^{\pm}\pi^{\mp}$	$K_S^0\pi^0\pi^0$	$K^{\pm}\pi^{\mp}\pi^{\pm}$	$K_S^0\pi^{\pm}\pi^0$	$K^{\pm}\pi^0\pi^0$
$K3\pi$	$K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$	$K_S^0\pi^{\pm}\pi^{\mp}\pi^0$	$K^{\pm}\pi^{\mp}\pi^0\pi^0$	$K^{\pm}\pi^{\mp}\pi^{\pm}\pi^0$	$K_S^0\pi^{\pm}\pi^{\mp}\pi^{\pm}$	$K_S^0\pi^{\pm}\pi^0\pi^0$
$K4\pi$	$K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}\pi^0$	$K_S^0\pi^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$	$K_S^0\pi^{\pm}\pi^{\mp}\pi^0\pi^0$	$K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}\pi^{\pm}$	$K_S^0\pi^{\pm}\pi^{\mp}\pi^{\pm}\pi^0$	$K^{\pm}\pi^{\mp}\pi^{\pm}\pi^0\pi^0$
$3K$	$K^{\pm}K^{\mp}K_S^0$			$K^{\pm}K^{\mp}K^{\pm}$		
$3K\pi$	$K^{\pm}K^{\mp}K^{\pm}\pi^{\mp}$	$K^{\pm}K^{\mp}K_S^0\pi^0$		$K^{\pm}K^{\mp}K^{\pm}\pi^0$	$K_S^0K^{\pm}K^{\mp}\pi^{\pm}$	

  - It covers ~69% of entire X_s sample
  - With considering K^0 equally decays into K_S^0 or K_L^0, these decay modes cover ~93% of entire X_s sample

Event Generation

- We produce exclusive $B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, and the remaining $B \to X_s\nu\bar{\nu}$ MC sample separately
- For $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ Monte-Carlo (MC) samples, the SM form factors are used [Phys.Rev.D 107 (2023) 1, 014511] [JHEP02(2015)184] [JHEP02(2015)184]
- To produce the remaining $B \to X_s\nu\bar{\nu}$ MC sample, Fermi motion model is used
  - In Fermi motion model, quarks have some velocity inside B meson
  - Also, $M_{X_s} > 1.1\ \mathrm{GeV/c^2}$ is required for the remaining $X_s\nu\bar{\nu}$ MC sample
  - Hadronization is done by PYTHIA





※ $q^2 = (p_\nu + p_{\bar{\nu}})^2$

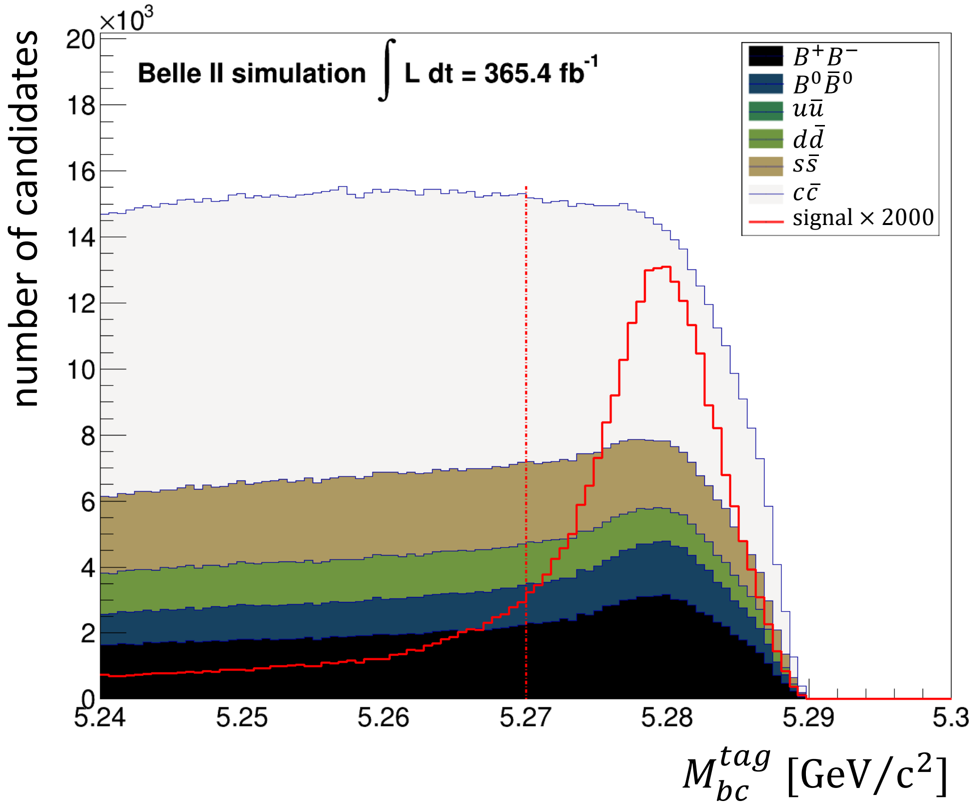
Selection on Signal and Tag Side

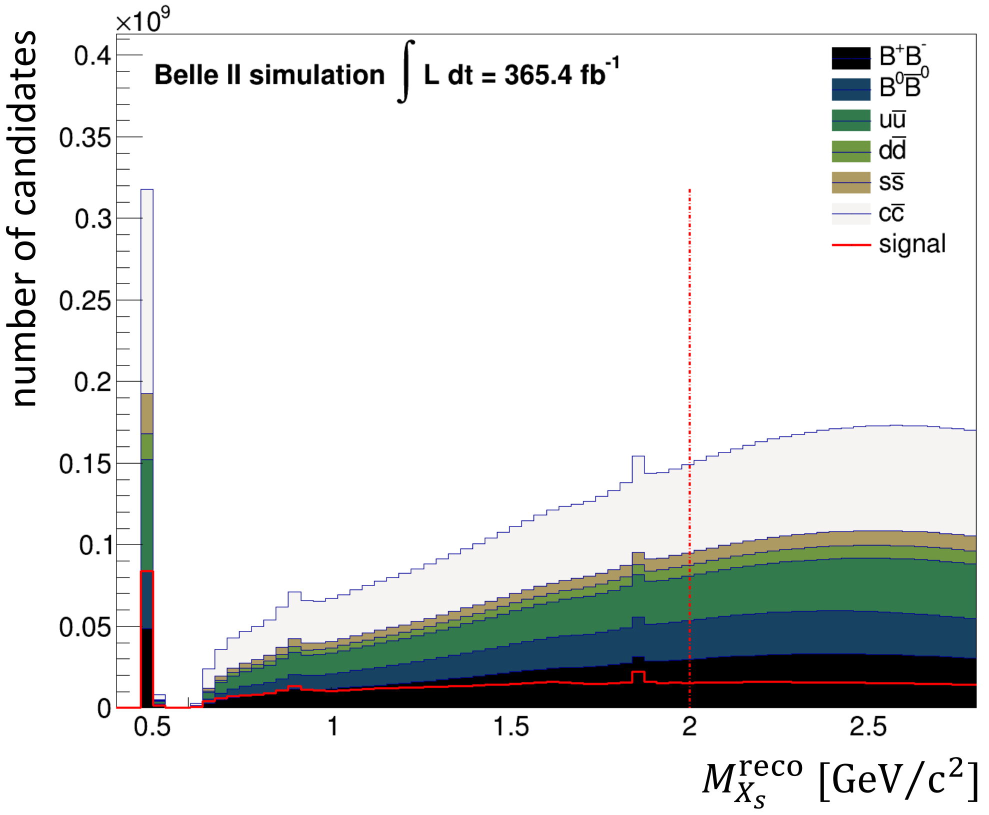
- Following conditions are applied for X_s and B_{tag}

To reduce combinatorial backgrounds

- $M_{\mathrm{bc}}^{\mathrm{tag}} > 5.27\ \mathrm{GeV/c^2}$
- reconstructed X_s mass, $M_{X_s}^{\mathrm{reco}} < 2.0\ \mathrm{GeV/c^2}$

※ $M_{\mathrm{bc}} \equiv \sqrt{(\sqrt{s}/2)^2 - |p_B^2 c|}$, where s is the center of mass energy





Selection on Signal and Tag Side

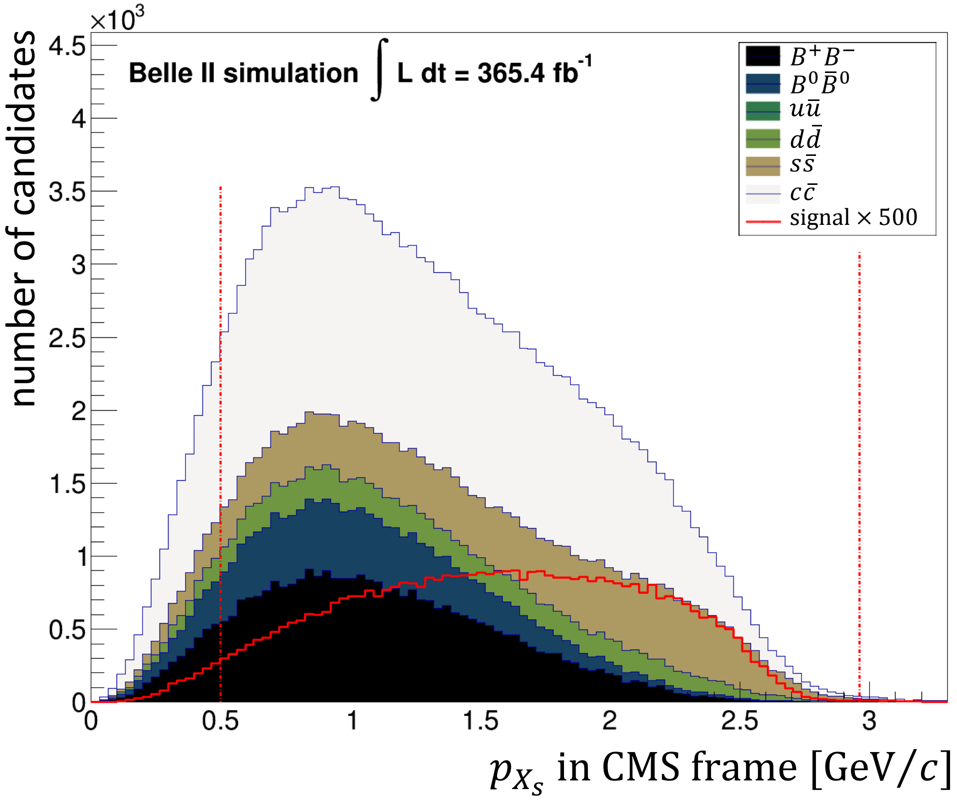
- Following conditions are applied for X_s and B_{tag}

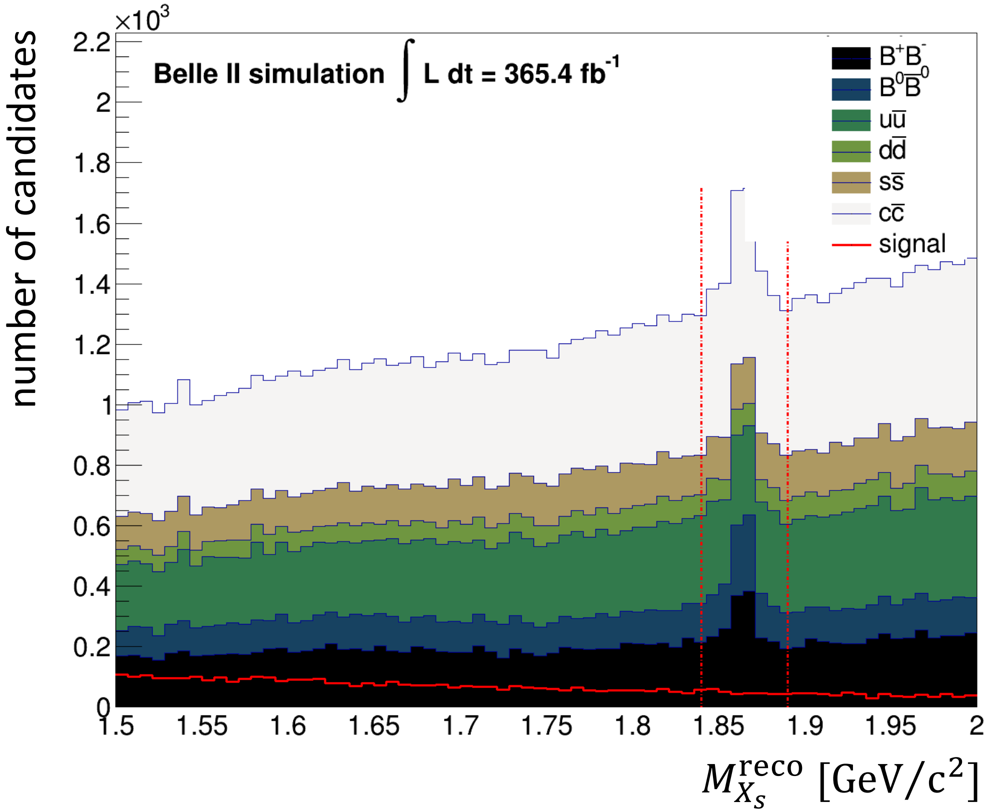
To reduce combinatorial backgrounds from B_{tag}

- $0.5 < p_{X_s} < 2.96$ GeV/c

To suppress backgrounds from D meson

- reject $1.84 < M_{X_s}^{\mathrm{reco}} < 1.89$ GeV/c^2





Selection on Rest of Event

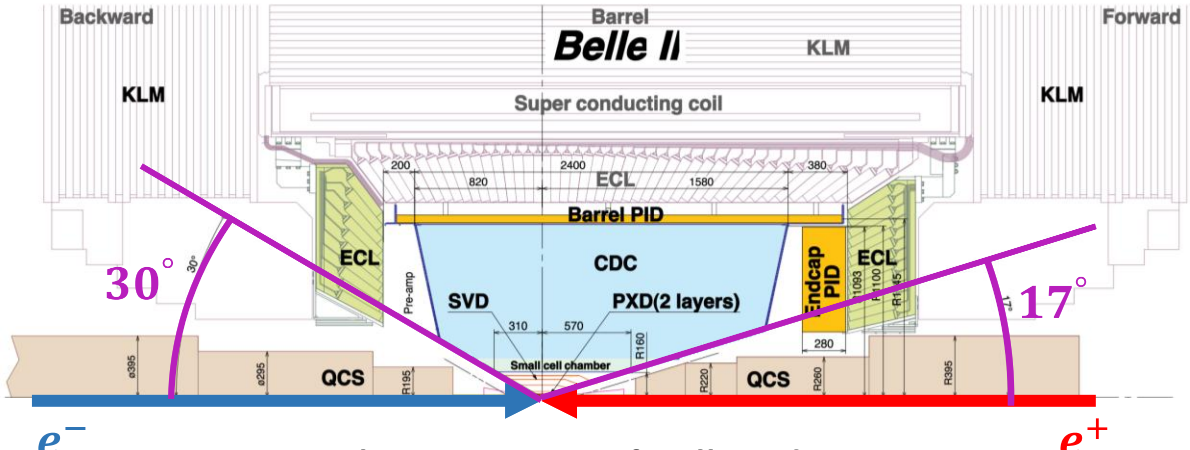
- Information from rest of event is used

To reject backgrounds with additional particles, outside of $B_{tag}X_s$ candidates

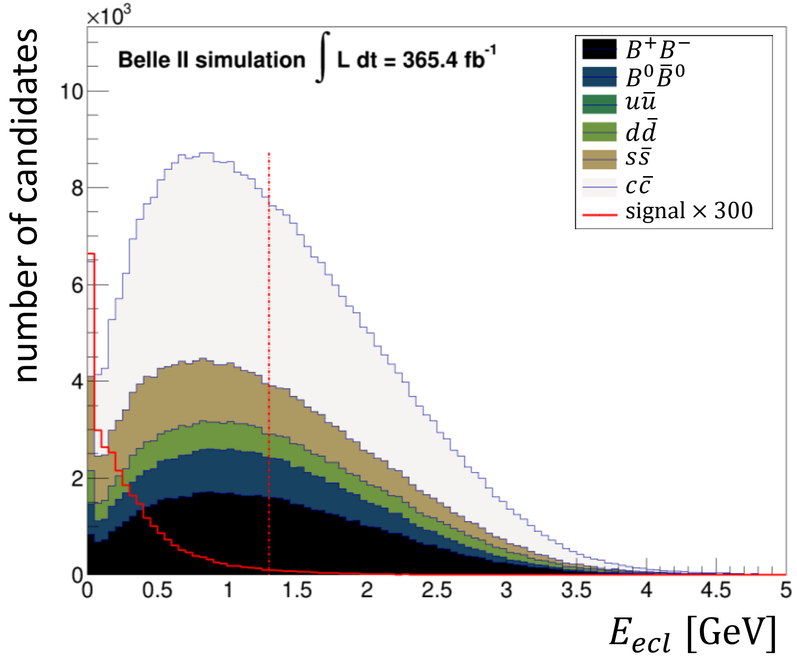
- the number of tracks = 0
- the number of π^0 candidates = 0
- the number of K_S^0 candidates = 0

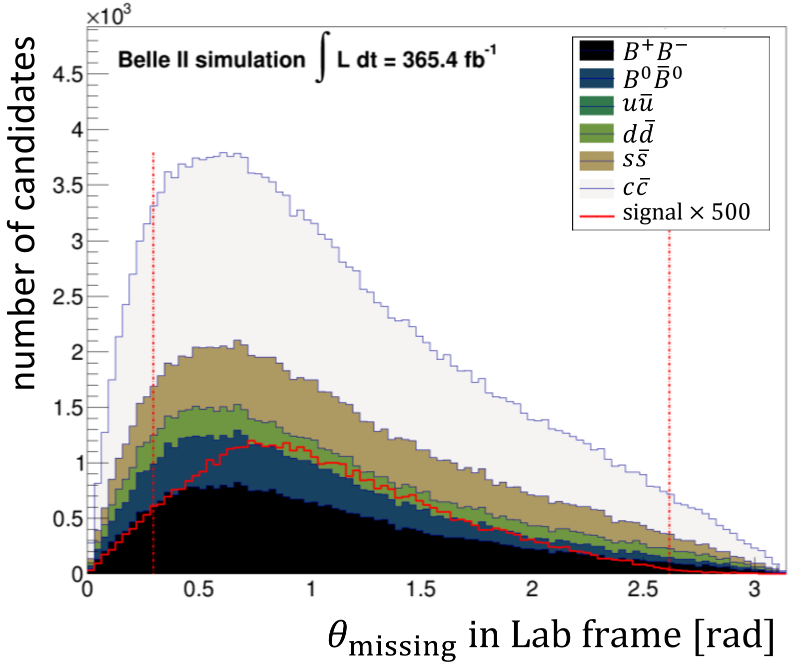
- $E_{ecl} < 1.3$ GeV
  - E_{ecl}: remaining energy deposited in the calorimeter

- $17^\circ < \theta_{\text{missing}} < 150^\circ$ **missing tracks can mimic $\nu\bar{\nu}$**



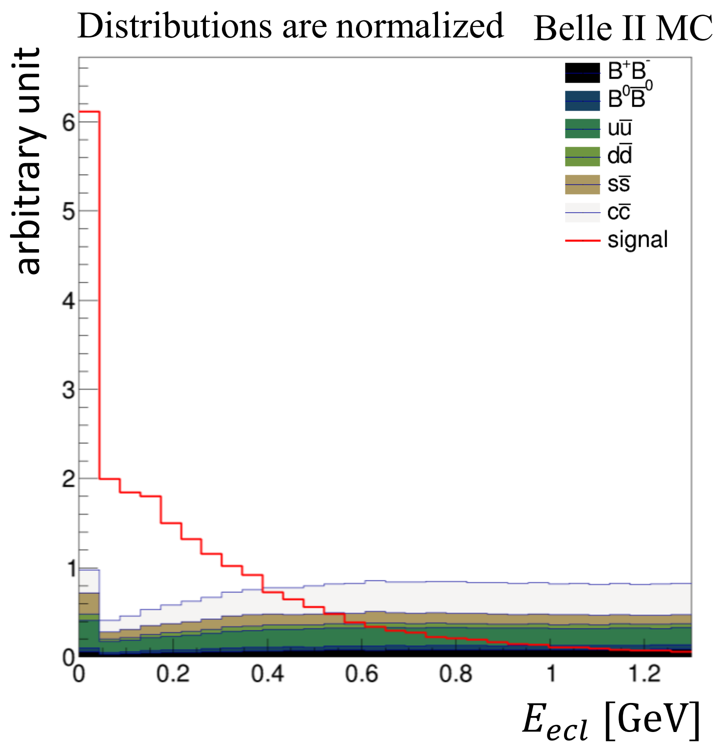
schematic view of Belle II detector





Background Suppression

- Boosted decision tree (BDT) is used as multivariate analysis (MVA) method
  - Dominant background component comes from $e^+e^- \rightarrow q\bar{q}$ process
- 32 variables are used
  - Variables are selected based on discriminant power and goodness of data/MC agreement on sideband
  - Example of powerful variables: E_{ecl} and event shape variable *[Nucl. Phys. B 149, 413 (1979)]*



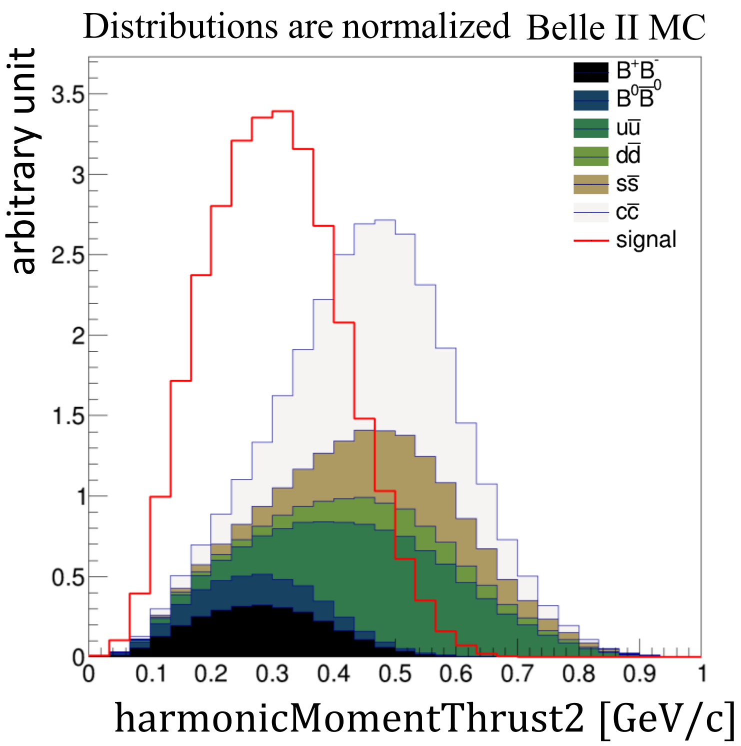
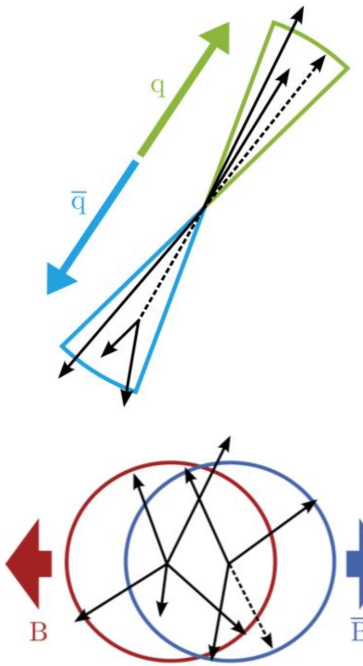


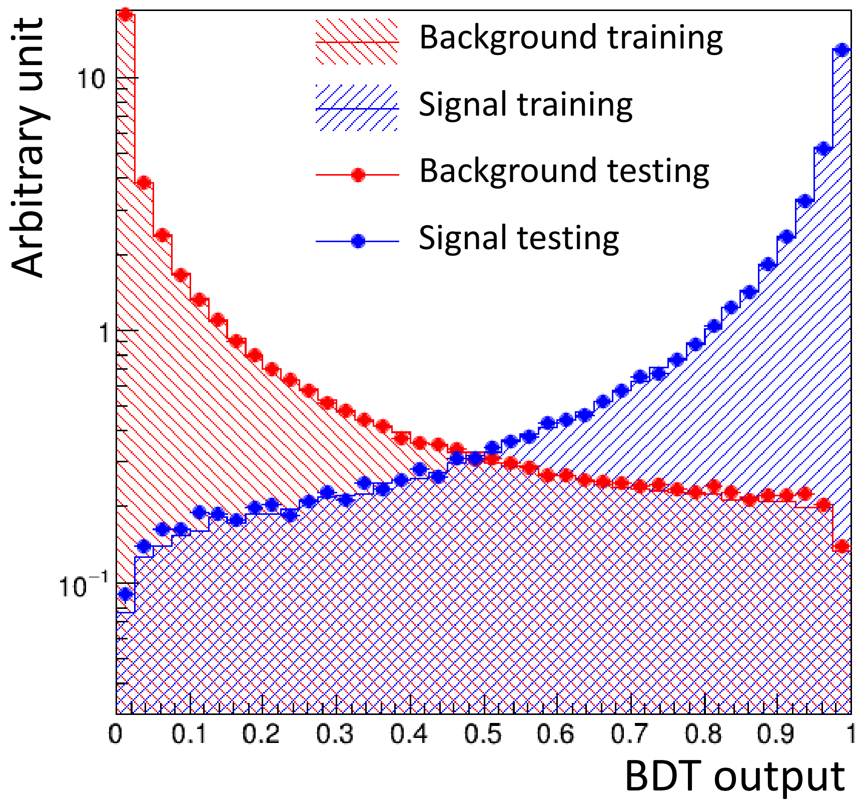
Figure by Dennis Weyland
[ETP-KA/2017-30]



Background Suppression

- BDT model has several hyperparameters
  - These parameters are optimized by the gridsearch method

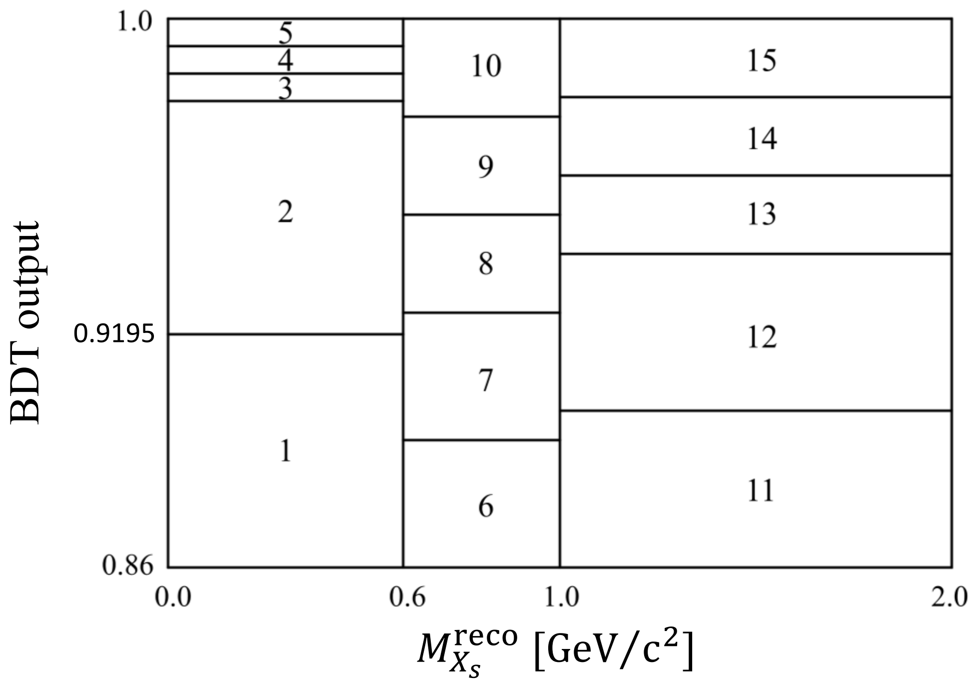
Hyperparameter	Tested values
Number of trees	100, 500, 1000, 1500, 2000
Maximum tree depth	2,3,4
Learning rate	0.05, 0.1, 0.15, 0.2
Sampling fraction	0.3, 0.4, 0.5, 0.6, 0.7
Number of binning levels	6, 7, 8, 9

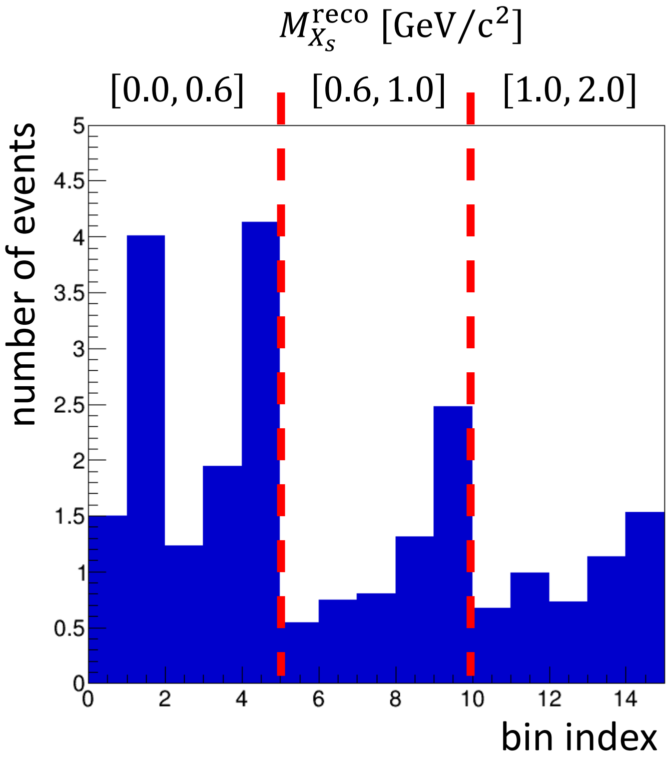


- Hyperparameter is selected with satisfying following conditions
  - Difference on performance (AUC value) for training and testing sample is smaller than 0.3%
  - Highest performance in testing sample

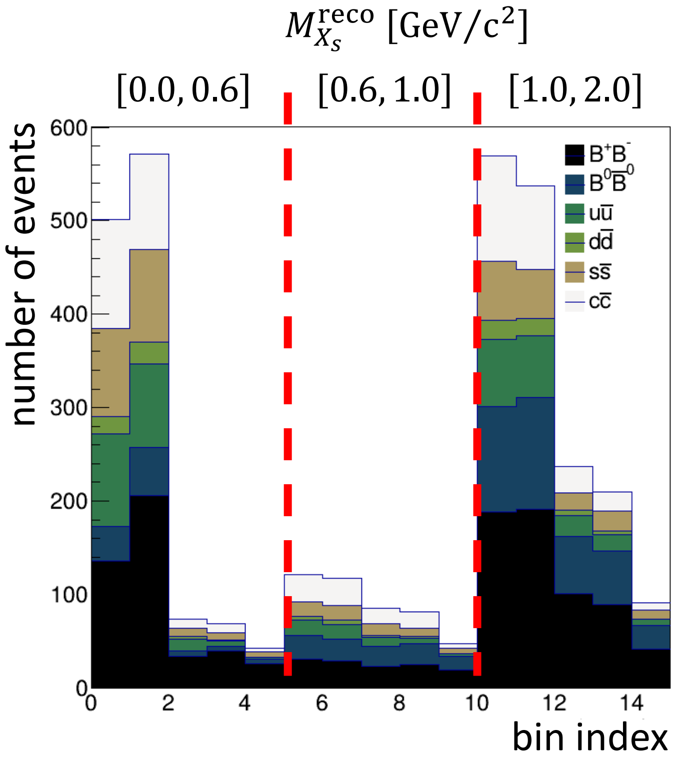
Binning and Fitting Range

- Signal extraction is done on 2 dimensional $M_{X_s}^{\mathrm{reco}} - (\mathrm{BDT\ output})$ plane
- For the convenience, this plane is mapped into “bin index” variable





Signal MC $(\int \mathcal{L}\, dt = 365\ \mathrm{fb}^{-1})$



Background MC $(\int \mathcal{L}\, dt = 365\ \mathrm{fb}^{-1})$

- Along $M_{X_s}^{\mathrm{reco}}$ axis, first and second bin is dominated by $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ resonances, respectively

Binning and Fitting Range

- Binned maximum likelihood fit is done to extract the signal yield
  - We want to maximize the following value:

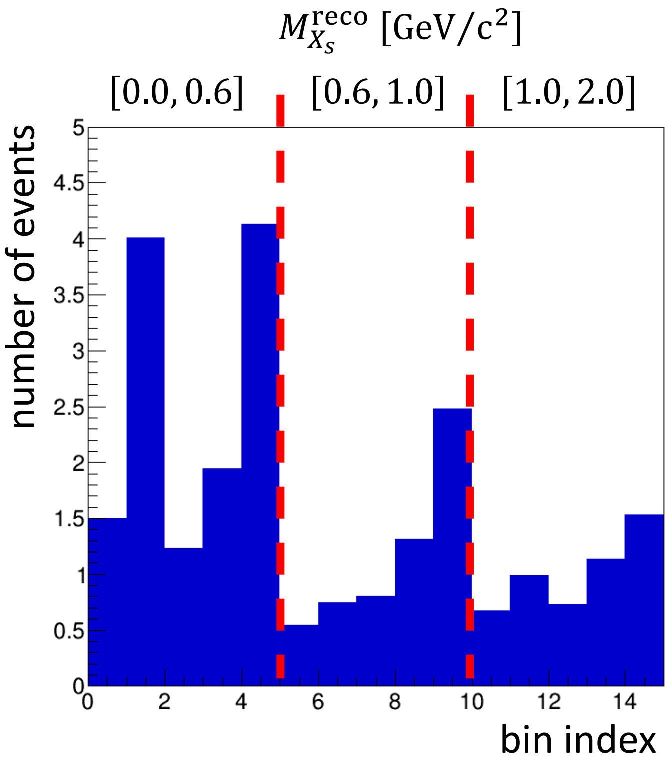
$$\mathcal{L} = \left[\prod_{i \in \text{bin}} \text{Pois}(n_i | s_i + b_i)\right] \cdot \prod_p f_p(a_p | \alpha_p)$$

The number of observed data

number of signal

The expected number of background

related with systematic uncertainty



Signal MC $\left(\int \mathcal{L}\, dt = 365\ \text{fb}^{-1}\right)$

- Free parameter μ (signal strength): a factor relative to the SM expectation

$$\text{Free parameters} \begin{cases} \mu_1 & \left(0.0 < M_{X_s}^{\text{true}} < 0.6\ \text{GeV}/c^2\right) \\ \mu_2 & \left(0.6 < M_{X_s}^{\text{true}} < 1.0\ \text{GeV}/c^2\right) \\ \mu_3 & \left(1.0 < M_{X_s}^{\text{true}} < M_{X_s}^{\max}\ \text{GeV}/c^2\right) \end{cases}$$

※ $M_{X_s}^{\text{true}}$: mass of X_s recorded by MC information

Corrections

- Several correction factors are estimated:
- $e^+e^- \to q\bar{q}$ efficiency
  - There can be difference on $e^+e^- \to q\bar{q}$ efficiency between data and MC
  - Off-resonance data is used to estimate the discrepancy
  - Off-resonance data has center of mass energy $60\ \mathrm{MeV}$ below the $\Upsilon(4S)$ resonance

    → There is no $\Upsilon(4S) \to B\bar{B}$

  - The same analysis procedure as for $B \to X_s \nu\bar{\nu}$ is followed, except for the additional M_{bc} correction :

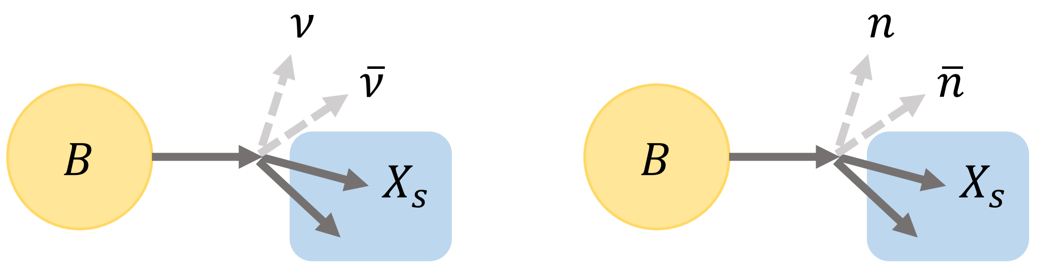
$$M_{\mathrm{bc,corrected}} \equiv \sqrt{\left(\sqrt{s^{\mathrm{off}}}/2\right)^2 - \left|p_B^2 c\right|} + (\sqrt{s^{\mathrm{on}}} - \sqrt{s^{\mathrm{off}}})/2$$

    - Correcting M_{bc} is needed because of shift by lower energy

  - Then, the ratio between MC and data is used as the correction factor

Corrections

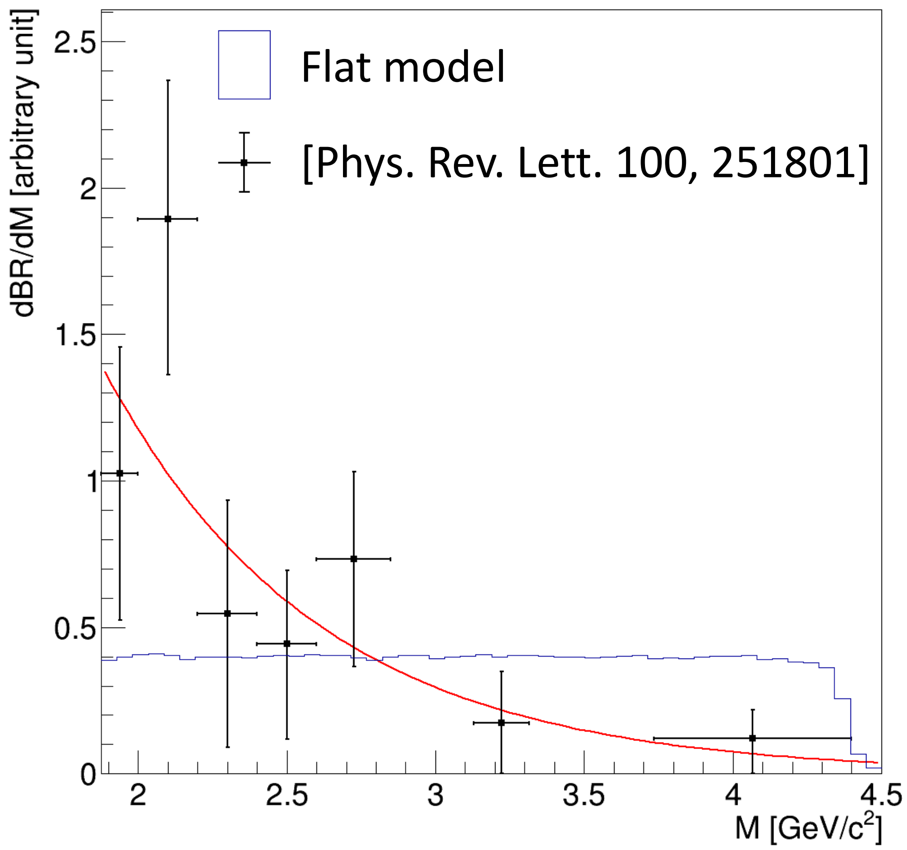
- $B \to X_s n\bar{n}$ modelling correction
  - $B \to X_s n\bar{n}$ is one of important background because its topology and detector response is similar to $B \to X_s \nu\bar{\nu}$



  - $M_{n\bar{n}}$ distribution of $B \to K^{(*)} n\bar{n}$ decay is corrected by $B \to K^{(*)} p\bar{p}$ study

[Physics Letters B, 659(1):80–86] [Phys. Rev. Lett., 100:251801] [Phys. Rev. D, 76:092004]

  - $B \to K^{(*)} n\bar{n}$ sample is produced with flat $M_{n\bar{n}}$ model
  - Then $B \to K^{(*)} n\bar{n}$ sample is weighted to get $M_{p\bar{p}}$ distribution from $B \to K^{(*)} p\bar{p}$ study
  - This $M_{p\bar{p}}$ distribution is modelled by exponential function or 2nd order polynomial

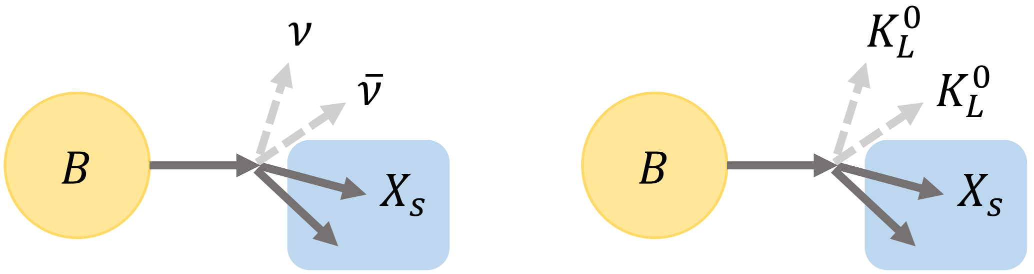


$M_{p\bar{p}}$ by Belle study and $M_{n\bar{n}}$ with flat mass model

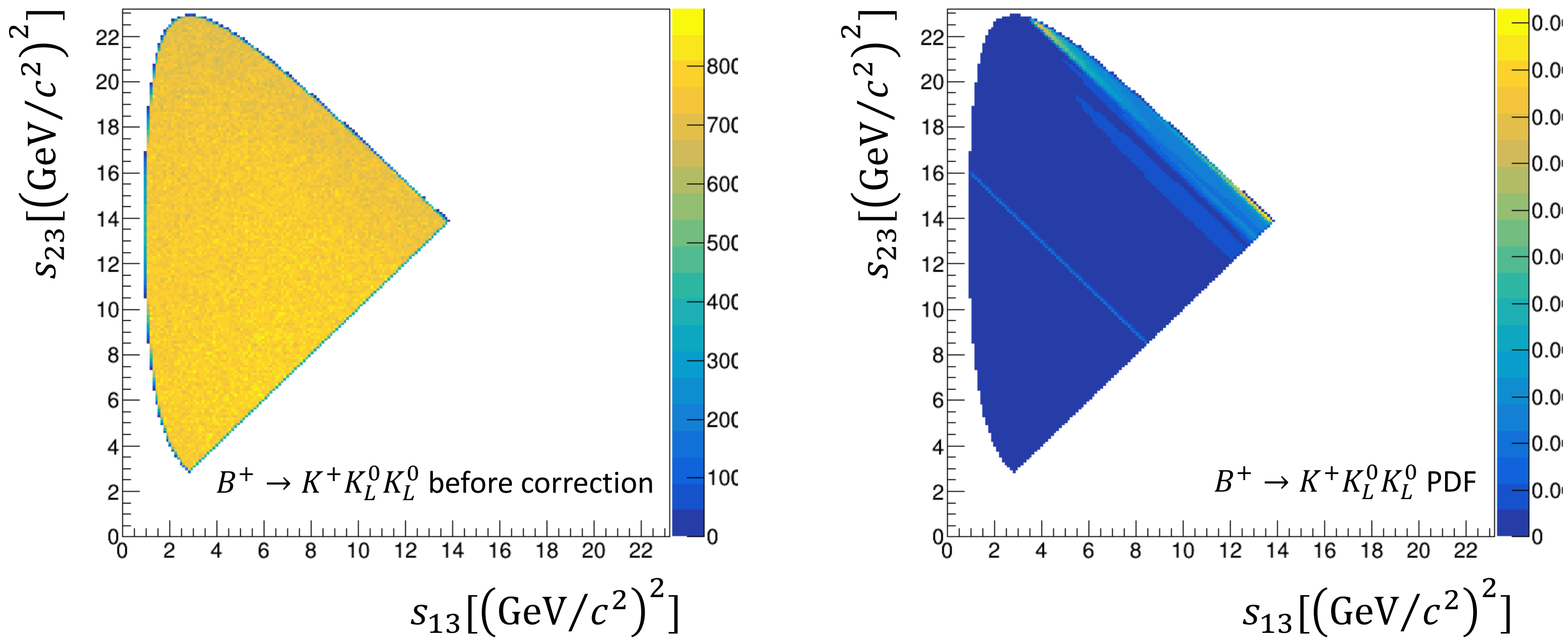
Corrections

- $B \to X_s n\bar{n}$ modelling correction
  - The remaining $B \to X_s p\bar{p}$ channels are reconstructed to correct $B \to X_s n\bar{n}$
  - The number of $B \to X_s p\bar{p}$ is obtained by fit on M_{bc}
  - The ratio between data and MC is adopted as the correction factor

Corrections



- $B \to X_s K_L^0 K_L^0$ modelling correction
  - $B \to X_s K_L^0 K_L^0$ is one of important background because its topology and detector response is similar to $B \to X_s \nu\bar{\nu}$
  - Dalitz plot of Belle II simulation is corrected by distribution obtained from $B \to K K_S^0 K_S^0$ study
    [Phys. Rev. D, 85:112010] [Phys. Rev. D, 85:054023]

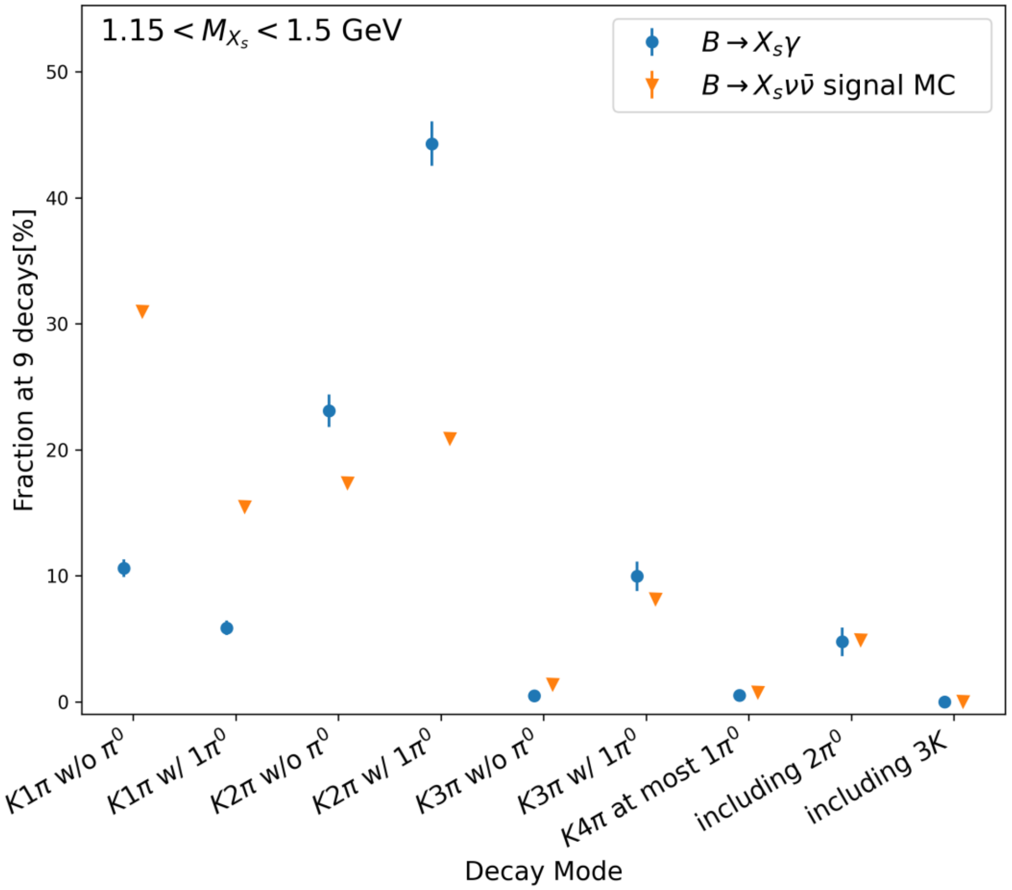


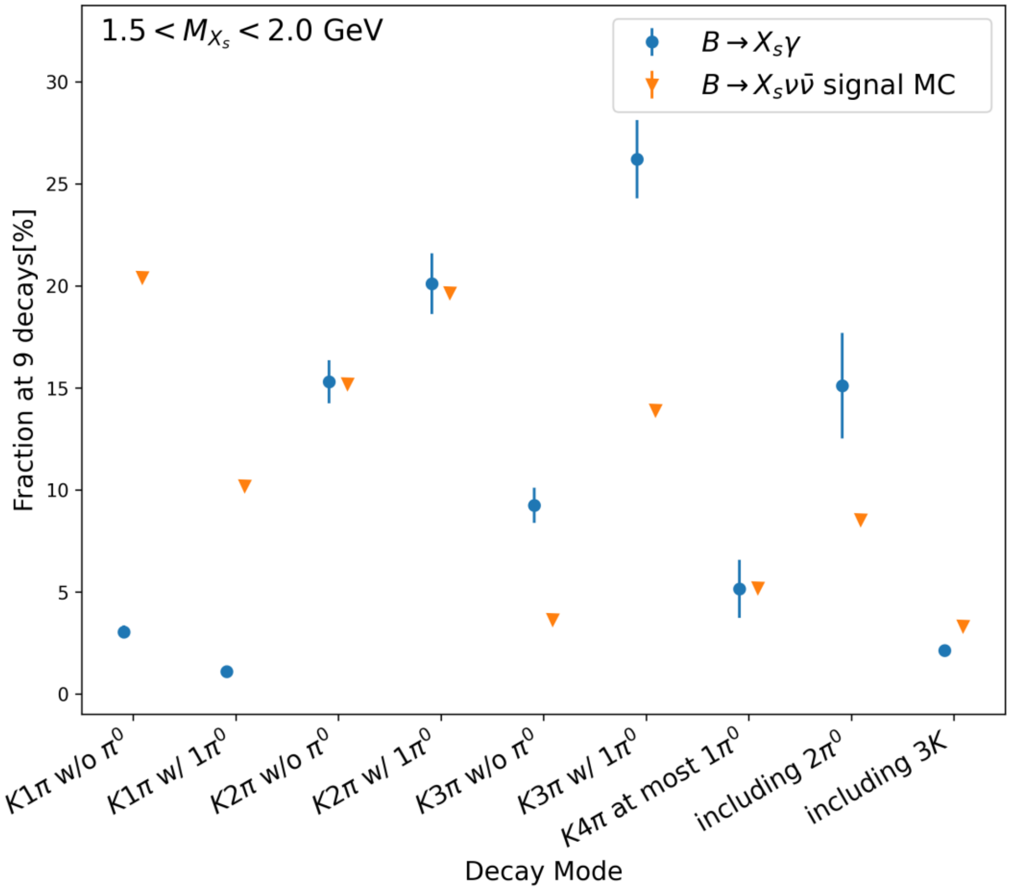
  - For the remaining $B \to X_s K_L^0 K_L^0$, $B \to X_s K_S^0 K_S^0$ is reconstructed and the result is used for the correction

Corrections

- X_s fragmentation correction
  - The hadronization of X_s is simulated by PYTHIA
  - The fragmentation of $B \to X_s\gamma$ is used to correct $B \to X_s\nu\bar{\nu}$

→ differences between them are adopted as the correction





Corrections

- Photon multiplicity correction
  - It is known that the simulation does not model the beam background perfectly
  - To address this issue, other analysis apply
    - An ECL energy-scale correction [Phys. Rev. D, 110(7):072020, 2024]
    - Photon-multiplicity correction [Phys. Rev. D, 109(11):112006, 2024]
  - In this analysis, photon multiplicity correction is applied
  - $X_s^0 B_{tag}^{\pm}$ is reconstructed for the photon multiplicity correction

Corrections

- Photon multiplicity correction
  - $X_s^0 B_{tag}^{\pm}$ is reconstructed for the photon multiplicity correction
  - The ratio between data and MC is adopted as correction factor in the number of photon candidates

  - $X_s^{\pm} B_{tag}^0$ is reconstructed to check the photon multiplicity correction

Systematics

- Several systematics are estimated
  - Impact on σ_{BR} at each $M_{X_s}^{\text{true}}$ region for major uncertainties:

	Impact on σ_{BR} $[10^{-5}]$			
Source	Full range	$[0, 0.6]$ GeV$/c^2$	$[0.6, 1.0]$ GeV$/c^2$	$[1.0, M_{X_s}^{\max}]$ GeV$/c^2$
MC statistics	6.0	0.4	1.5	6.3
Background normalization	5.7	0.6	2.0	6.6
BR of major B meson decay	2.3	0.1	0.6	2.0
Non-exclusive $X_s\nu\bar{\nu}$ generation point	2.1	0.0	0.0	2.2
BDT efficiency	2.1	0.0	0.4	2.3
Statistical uncertainty	8.3	0.8	2.6	9.0

- MC statistics
  - Statistical uncertainty of MC sample
  - Dominated by background sample

Systematics

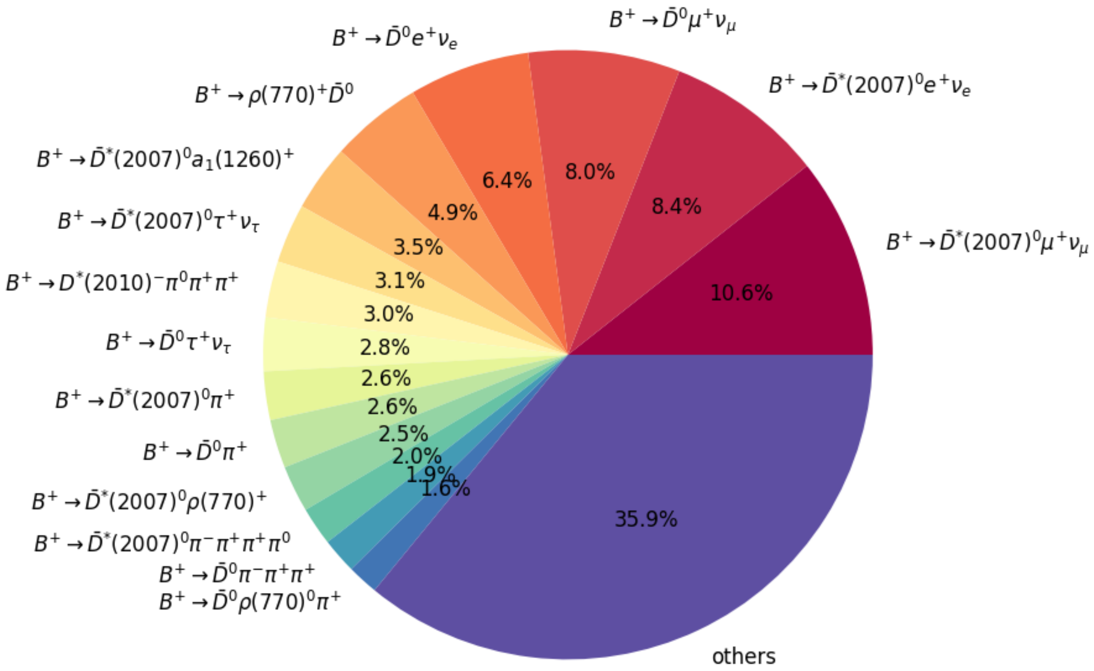
- Background normalization
  - Systematic uncertainty for the disagreement between data and MC
  - Two side bands are investigated:
    - M_{bc}^{tag} sideband: $5.235 < M_{bc}^{tag} < 5.26\ \mathrm{GeV/c^2}$
    - BDT sideband: 0.8 < BDT output < 0.86
  - We assign $\pm 20\%$ overall uncertainty
    - It covers the data-MC disagreement in the sidebands
    - This uncertainty is assigned at three $M_{X_s}^{\mathrm{reco}}$ regions:

$$\begin{cases} 0.0 < M_{X_s}^{\mathrm{reco}} < 0.6\,\mathrm{GeV}/c^2 \\ 0.6 < M_{X_s}^{\mathrm{reco}} < 1.0\,\mathrm{GeV}/c^2 \\ 1.0 < M_{X_s}^{\mathrm{reco}} < 2.0\,\mathrm{GeV}/c^2 \end{cases}$$

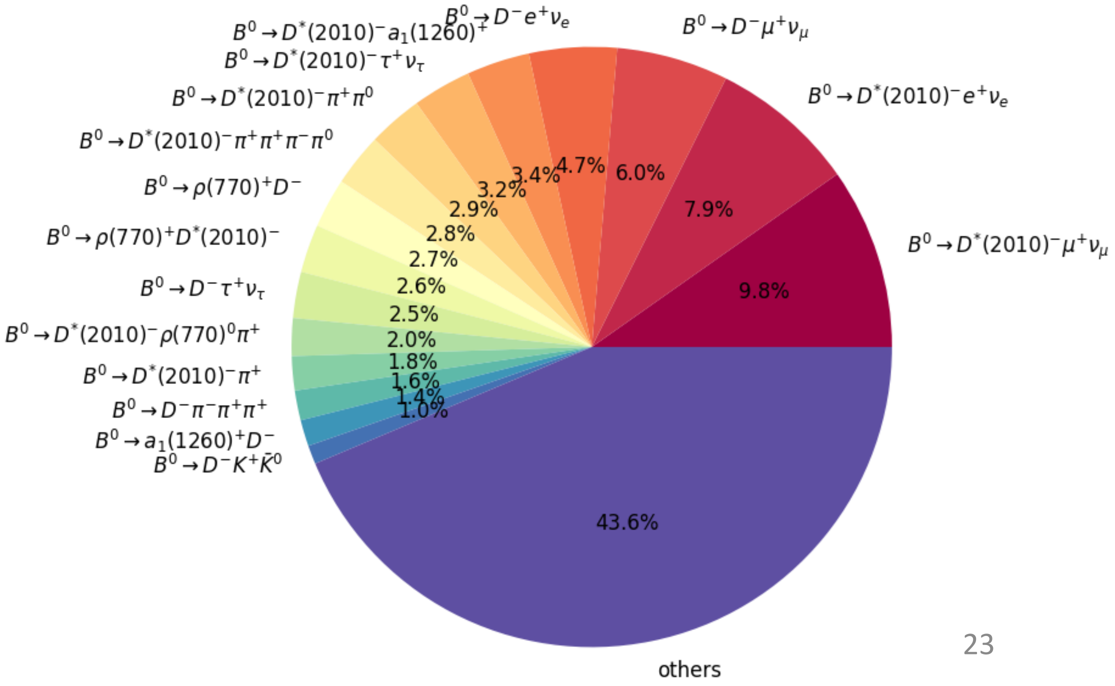
Systematics

- BR of major B meson decay
  - Background MC sample is based on PDG value
  - However, there is uncertainty on the branching ratio in PDG value
  - We fluctuate the branching ratio at several B meson decays
    - Because it is done manually, we only fluctuate 71% and 60% for B^+ and B^0 meson, respectively

B^+B^- background



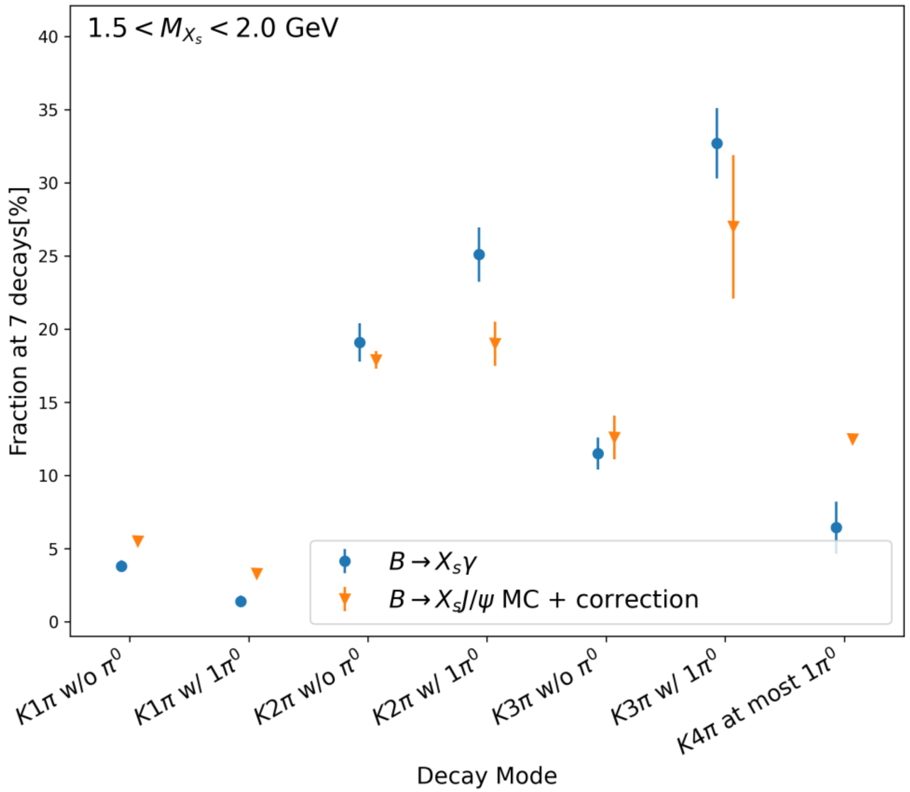
$B^0\overline{B}^0$ background

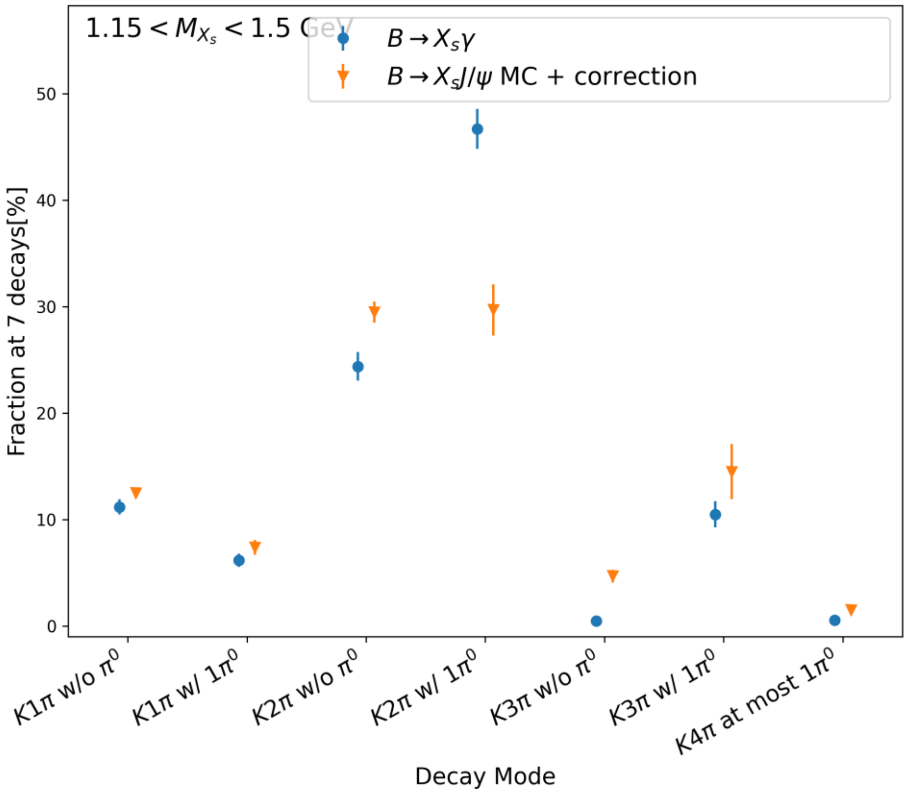


Systematics

- X_s fragmentation
  - Two methods are used:
    1. X_sJ/ψ vs $X_S\gamma$
       - The differences between them are adopted as systematic uncertainty

→ However, not all of M_{X_s} regions and decay channels are available



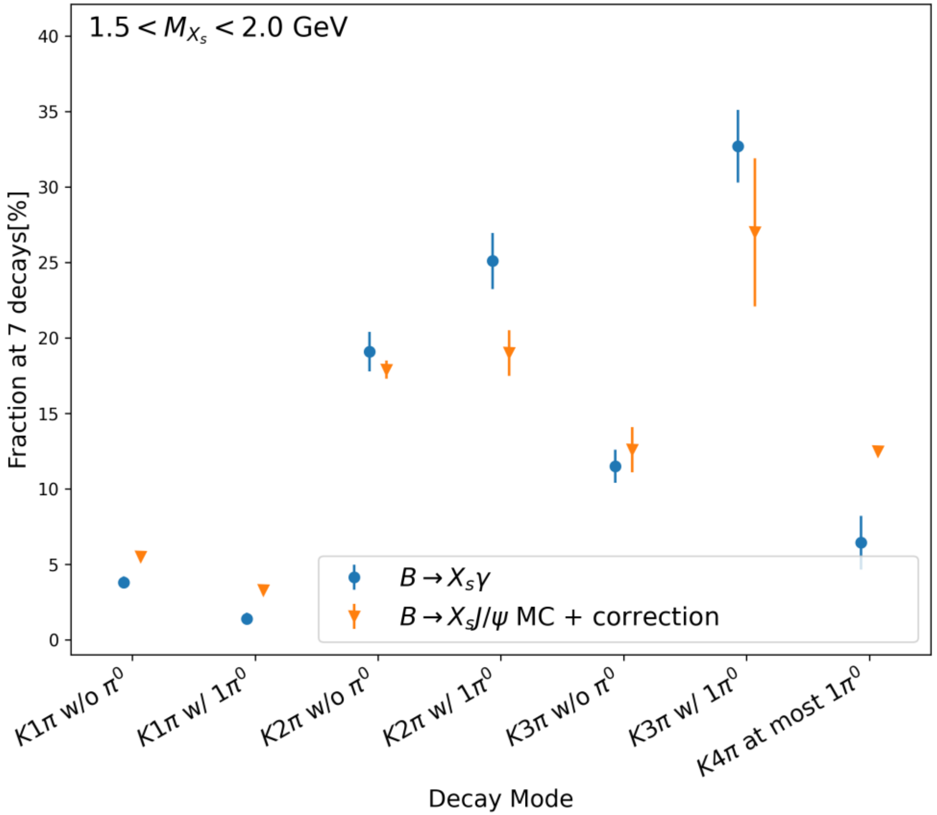


Systematics

- X_s fragmentation
  - Two methods are used:

    2. PYTHIA parameter fluctuation

       - We fluctuate PYTHIA parameters and select combinations whose fragmentation is within $B \to X_s\gamma$ and $B \to Xs\ J/\psi$
       - Then, the maximum deviation from nominal fragmentation is adopted as the systematic uncertainty
       - We assign the systematic uncertainty at several M_{X_S} regions and decay channels independently

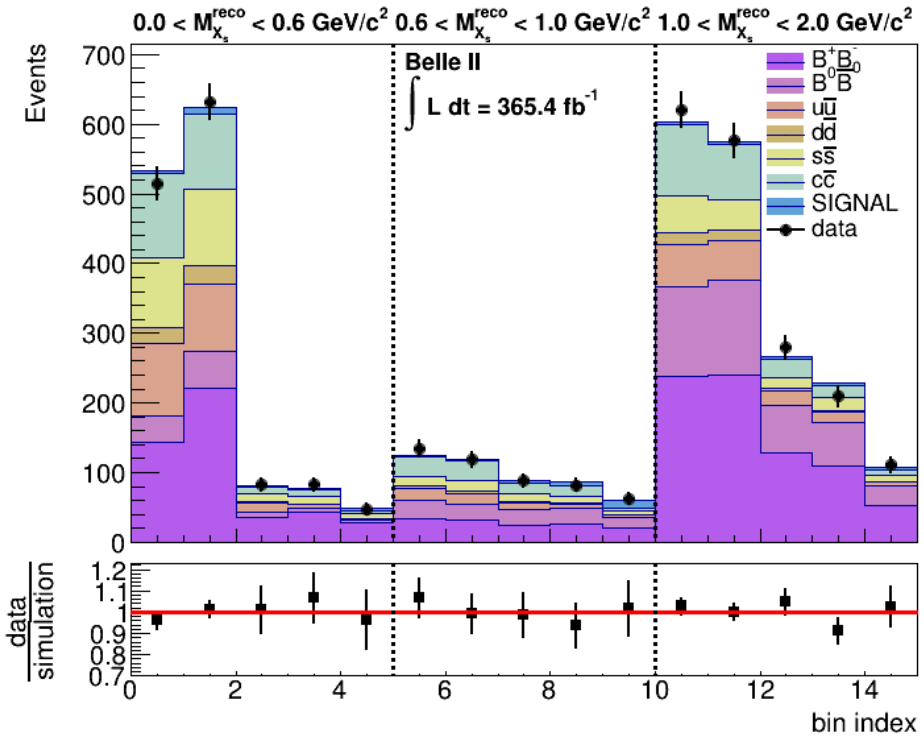


Systematics

- Photon multiplicity correction
  - $X_s^{\pm} B_{tag}^{0}$ is reconstructed to check the photon multiplicity correction
  - The remaining discrepancy is adopted as the systematic uncertainty

Result

- Central value from the fit:



$$BR(B \to X_s \nu\bar{\nu}) = \begin{cases} [0.3 \pm 0.8^{+0.8}_{-0.7}] \times 10^{-5} & (0.0 < M_{X_s}^{\mathrm{true}} < 0.6\,\mathrm{GeV}/c^2) \\ [3.5^{+2.7}_{-2.5}\,{}^{+3.1}_{-2.6}] \times 10^{-5} & (0.6 < M_{X_s}^{\mathrm{true}} < 1.0\,\mathrm{GeV}/c^2) \\ [5.1^{+9.2}_{-8.8}\,{}^{+12.9}_{-11.0}] \times 10^{-5} & (1.0\,\mathrm{GeV}/c^2 < M_{X_s}^{\mathrm{true}}) \end{cases}$$

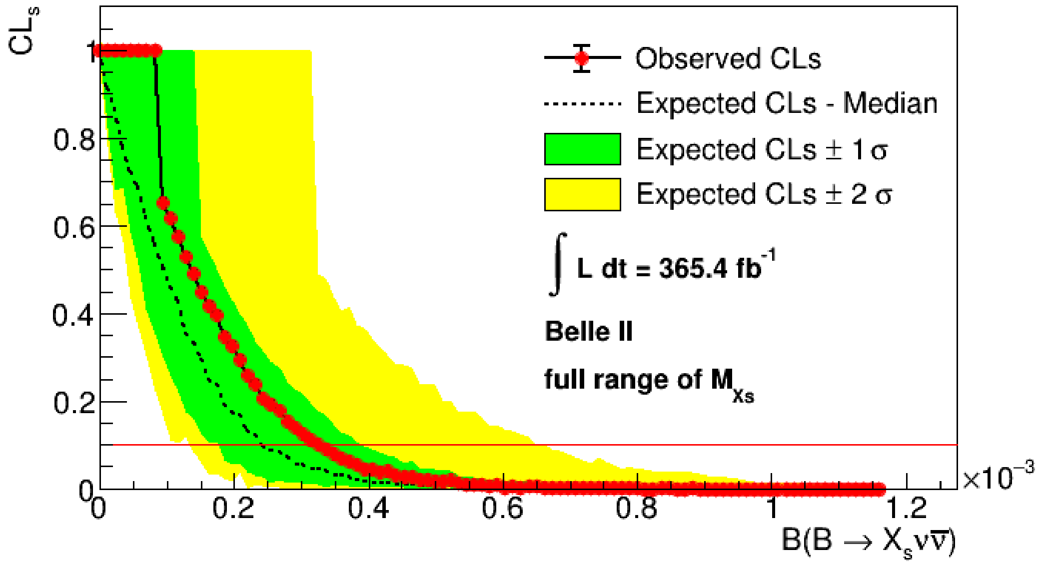
- If we combine the results:

$$BR(B \to X_s \nu\bar{\nu}) = \left[8.8^{+8.5}_{-8.2}\,{}^{+12.6}_{-10.7}\right] \times 10^{-5}$$

- The observed signal yield is not significant by the fit

Result

- Upper limits are calculated by CLs method:



$$UL(B \to X_s \nu\bar{\nu}) = \begin{cases} 2.2 \times 10^{-5} & (0.0 < M_{X_s}^{\text{true}} < 0.6\,\text{GeV}/c^2) \\ 9.3 \times 10^{-5} & (0.6 < M_{X_s}^{\text{true}} < 1.0\,\text{GeV}/c^2) \\ 30.9 \times 10^{-5} & (1.0\,\text{GeV}/c^2 < M_{X_s}^{\text{true}}) \end{cases}$$

at 90% confidence level

- If we combine the results:

$UL(B \to X_s \nu\bar{\nu}) = 32.7 \times 10^{-5}$ at 90% confidence level

[Phys. Rev. Lett. 136, 231801]

* $UL(b \to s\nu\bar{\nu}) = 64 \times 10^{-5}$ (90% CL) by ALEPH † [Eur.Phys.J.C 19 (2001) 213-227]

Summary

- $B \to X_s \nu \bar{\nu}$ is suppressed in Standard Model and can be enhanced by new physics
- Sum of exclusive method is used with 30 decay modes
- Several selections are applied to suppress backgrounds
- As the MVA technique, BDT is used
- Several corrections factors are considered, including $e^+e^- \to q\bar{q}$ efficiency correction
- Several systematic uncertainties are considered, including signal modeling
- The observed signal yield is not significant by the fit
- Upper limit is calculated by CLs method

Back up