Search for $B \to X_s \nu\bar{\nu}$ decay in Belle II Experiment

30th ICEPP Symposium

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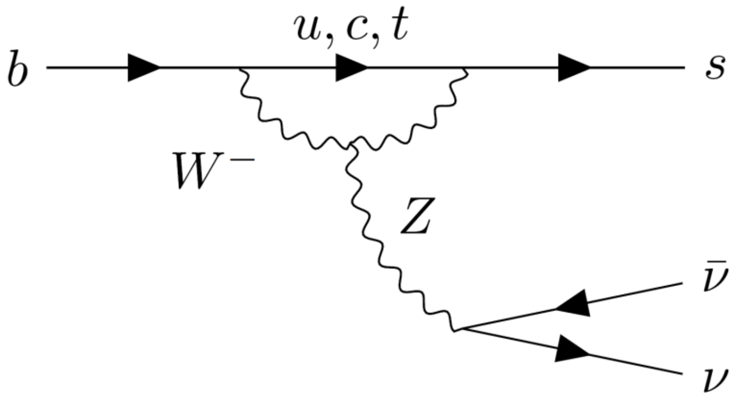
Motivation

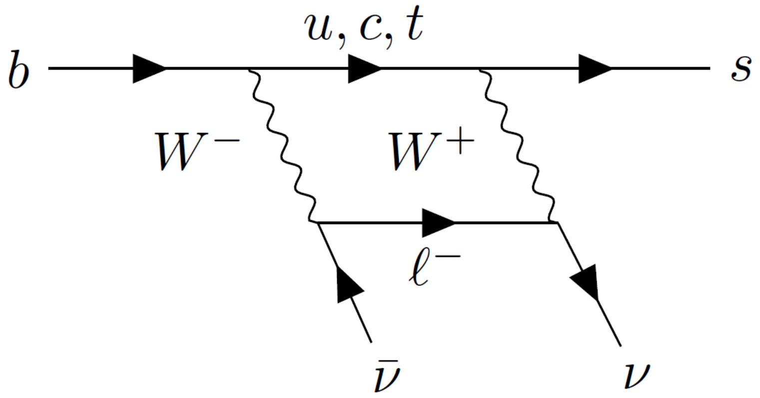
- $B \to X_s \nu\bar{\nu}$ decay is theoretically clean

- It is flavour changing neutral current (FCNC) process
  - $BR = (2.9 \pm 0.3) \times 10^{-5}$ by Standard Model [*Journal of High Energy Physics* 2015.2 (2015): 1-39.]
  - It can be enhanced by new physics, like Z' boson [*Journal of High Energy Physics* 2009.04 (2009): 022.]

- This decay mode have not been studied at Belle and Belle II

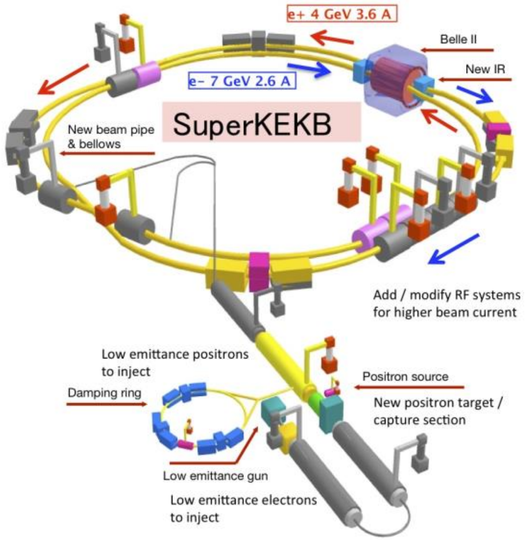
  $UL(b \to s\nu\bar{\nu}) = 6.4 \cdot 10^{-4}$ (90CL) by ALEPH [*The European Physical Journal C-Particles and Fields* 19.2 (2001): 213-227.]

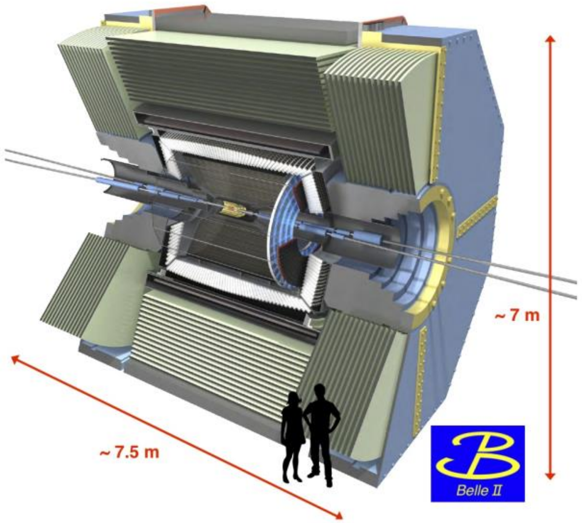


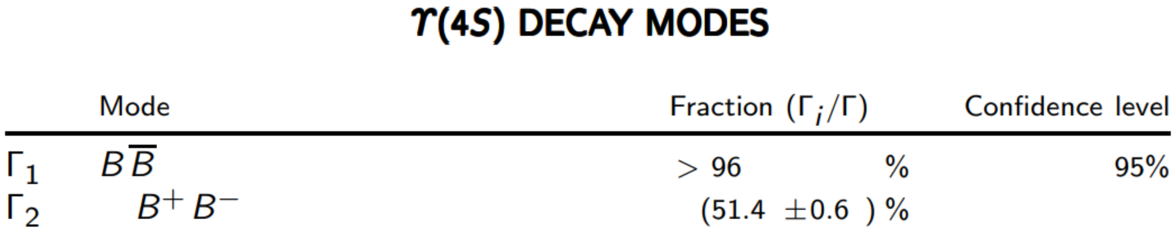


Belle II Experiment

- Electrons and positrons are accelerated up to 7 GeV and 4 GeV respectively by SuperKEKB
- Its energy correspond to the resonance of $\Upsilon(4S)$ which mainly decay into B meson pair
  - 10.58 GeV
- Belle II detector consists of several sub-detector components
  - pixelated silicon sensors (PXD), silicon strip sensors (SVD), central drift chamber (CDC), Aerogel Ring Imaging Cherenkov (ARICH), electromagnetic calorimeter (ECL), and K_L^0 and muon detector (KLM)







$\Upsilon(4S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$B\overline{B}$	> 96 %	95%
Γ_2	B^+B^-	(51.4 ± 0.6) %	

Event Generation

- For MC study, MC samples are produced
  - Particle decay and kinematics are simulated by `EvtGen`
  - Detector simulation is done by `Geant4`

- For background sample

  Official background samples are used. 6 types of samples are used:
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$)

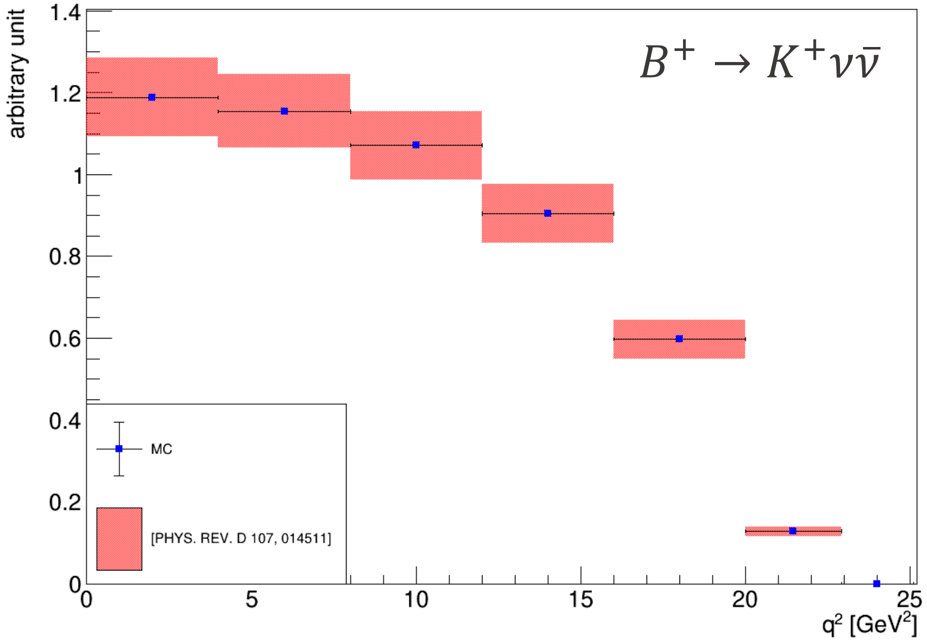
Event Generation

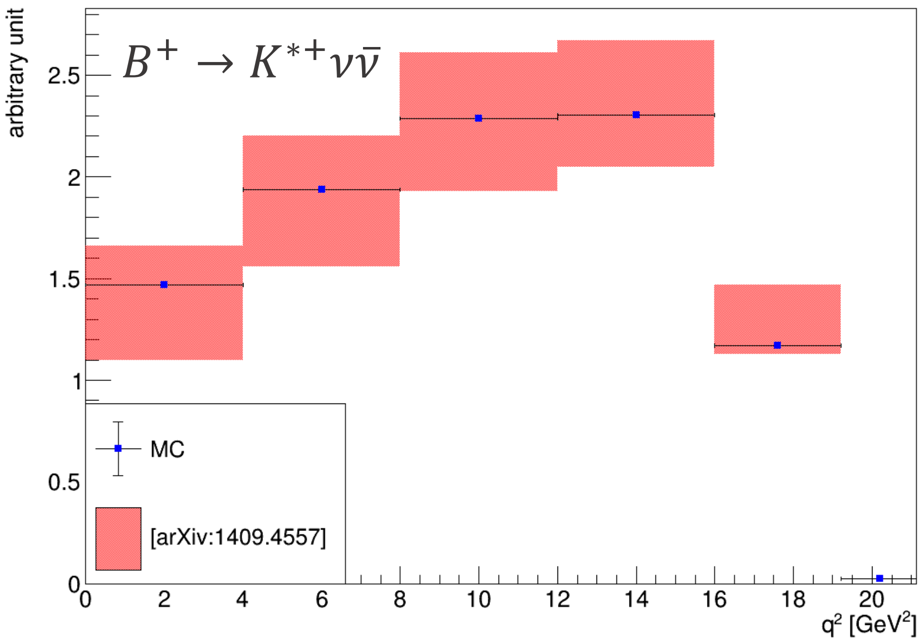
- $B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, and non-resonant $B \to X_s\nu\bar{\nu}$ MC samples are produced separately

$B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ samples are produced based on form factors [PhysRevD.107.014510] [JHEP08(2016)098]

$$\mathcal{M}(B \to K\nu\bar{\nu}) \propto f_+(q^2)\left\{(p_B + p)_\mu - \frac{m_B^2 - m_K^2}{s} q_\mu\right\}(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

$$\mathcal{M}(B \to K^*\nu\bar{\nu}) \propto T_\mu(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\text{, where } T_\mu = (m_B + m_{K^*})A_1(q^2)\epsilon_\mu^* - A_2(q^2)\frac{\epsilon^*\cdot q}{m_B+m_{K^*}}(p+p_{K^*})_\mu + i\frac{2V(q^2)}{m_B+m_{K^*}}\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho p_{K^*}^\sigma$$





※ $q^2 = (p_\nu + p_{\bar{\nu}})^2$

Event Generation

- For non-resonant $B \rightarrow X_s \nu\bar{\nu}$ MC samples, following distribution is used [JHEP04(2009)]

$$\frac{\mathrm{d}\Gamma}{dq^2} \propto \sqrt{\lambda(1, \hat{m}_s, s_b)}\left[3s_b\left(1 + \hat{m}_s^2 - s_b - 4\hat{m}_s + \lambda(1, \hat{m}_s, s_b)\right)\right]$$, where $\hat{m}_s = m_s/m_b$ and $s_b = q^2/m_b^2$

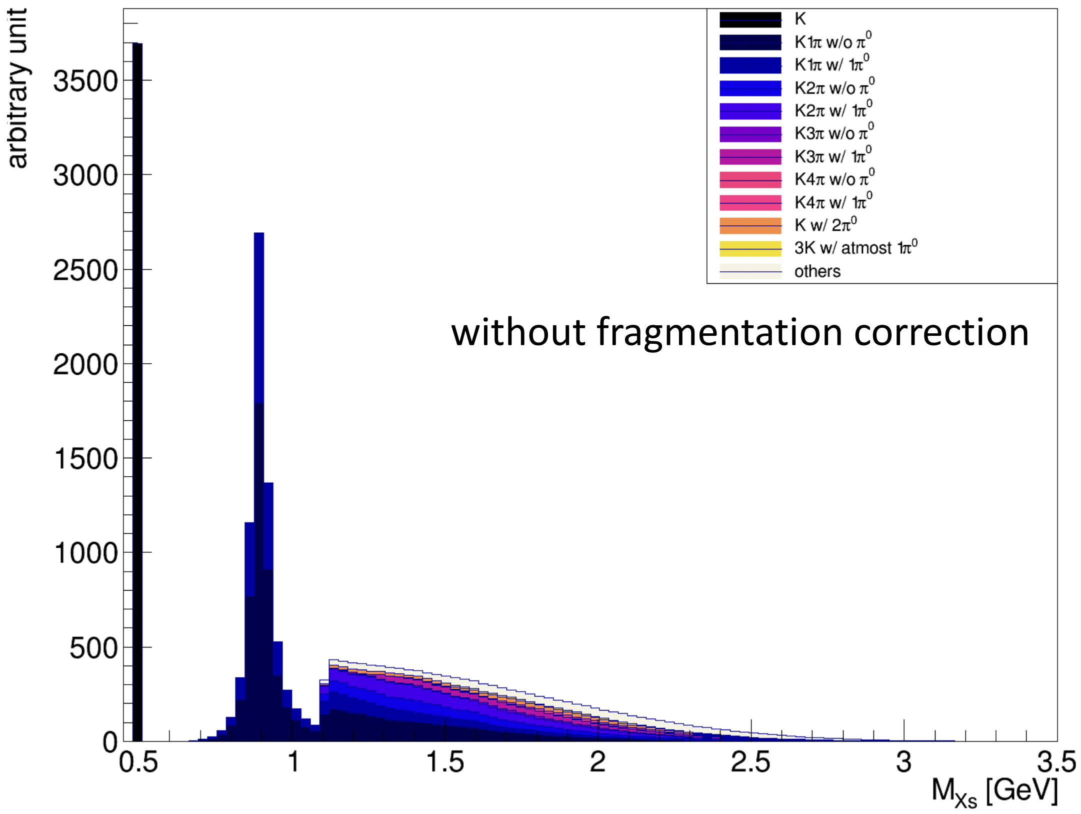
- To determine the mass of non-resonant X_s, Fermi motion model is used [PhysRevD.55.4105]

Inside B meson, b-quark are assumed to follow

$$\phi(p) = \frac{4}{\sqrt{\pi}p_F^3} \exp\left(\frac{-p^2}{p_F^2}\right)$$

as a momentum distribution

- Then non-resonant X_s decays by PYTHIA
  - ratio between decay modes (fragmetation) cannot be reliable
  - Fragmentation is corrected by $B \rightarrow X_s\gamma$ decay and uncertainty is estimated by $B \rightarrow X_s J/\psi$ decay



without fragmentation correction

Analysis Procedure

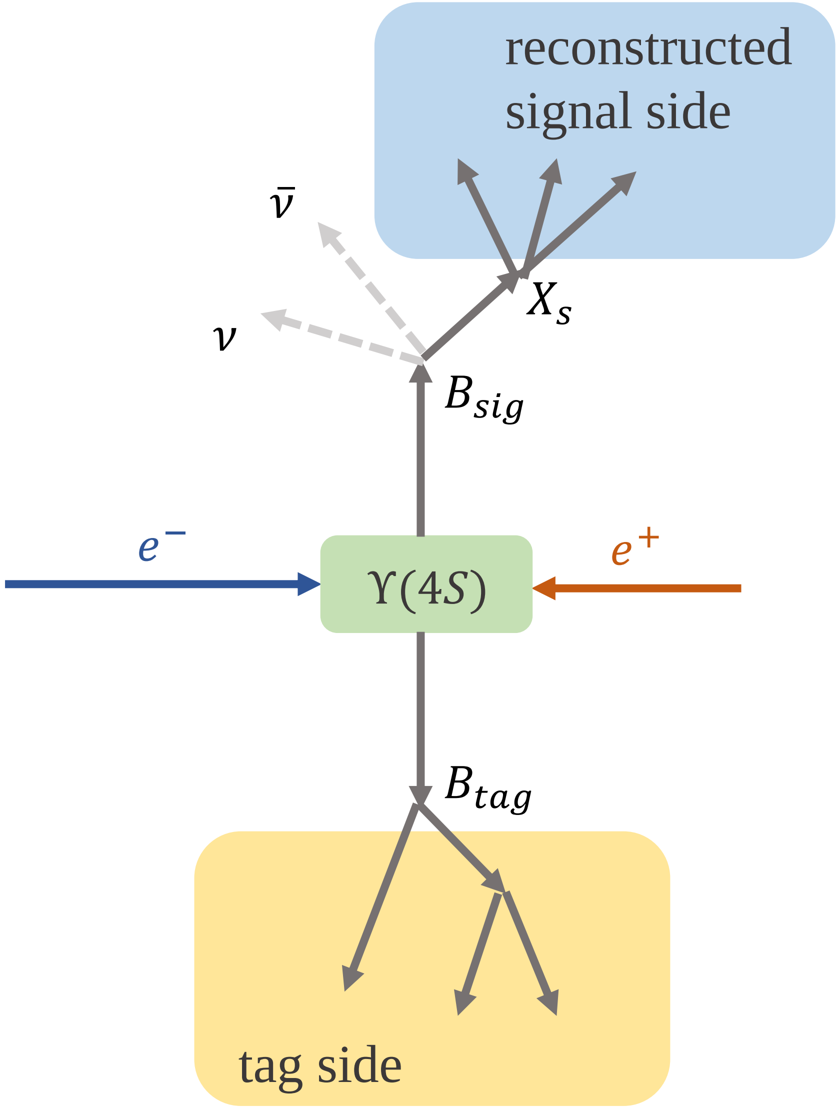
- In $B \rightarrow X_s \nu \bar{\nu}$ decay, there are two neutrinos, which leads to large amount of background

- One side of B meson (B_{tag}) is reconstructed by common decay modes
  - The tool FEI (full event interpretation) is used to reconstruct it automatically [s41781-019-0021-8]

- Information of B_{tag} can be used to remove background

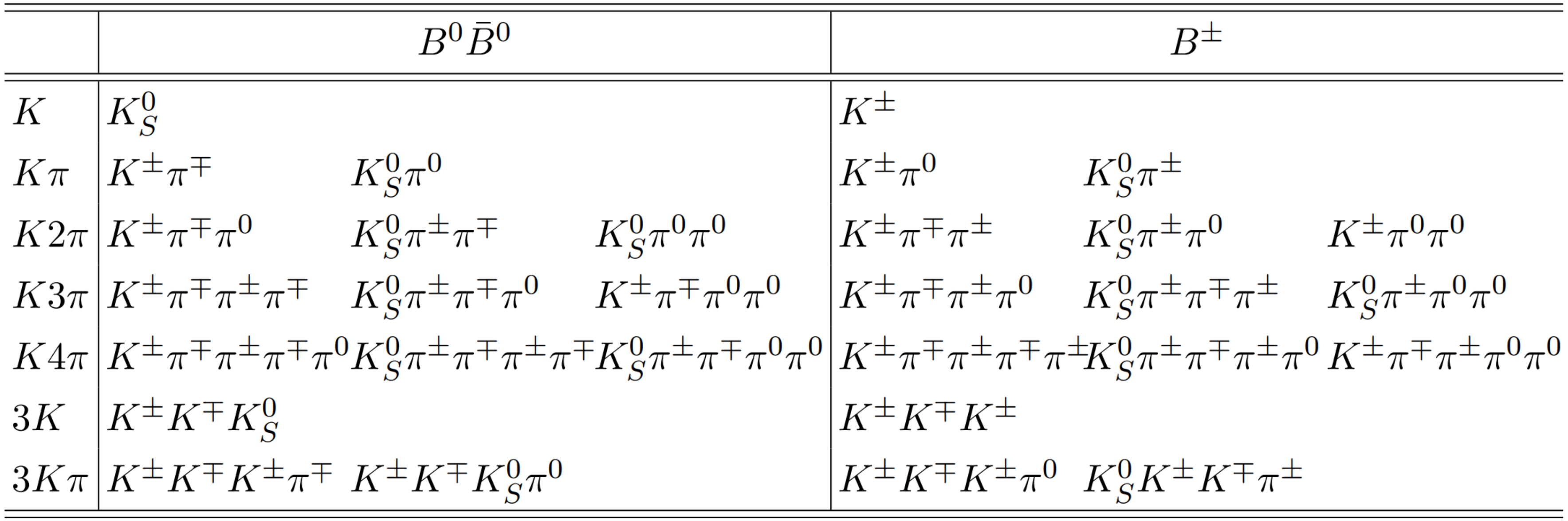
$M_{bc}^{tag} \equiv \sqrt{E_{beam}^2 - |p_B^2|}$ - generally B meson mass for signal

$\Delta E^{tag} \equiv E_B - E_{beam}$ - generally 0 for signal



Analysis Procedure

- 30 decay modes are reconstructed (sum of exclusive method)



	$B^0\bar{B}^0$			$B^\pm$		
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 ~83% of my non-resonant X_s sample
- $K\nu\bar{\nu}$ and $K^*\nu\bar{\nu}$ decays account for 16.8% and 33.0% of total $X_s\nu\bar{\nu}$ sample

Signal Selection

- Preselection

To reduce combinatorial backgrounds

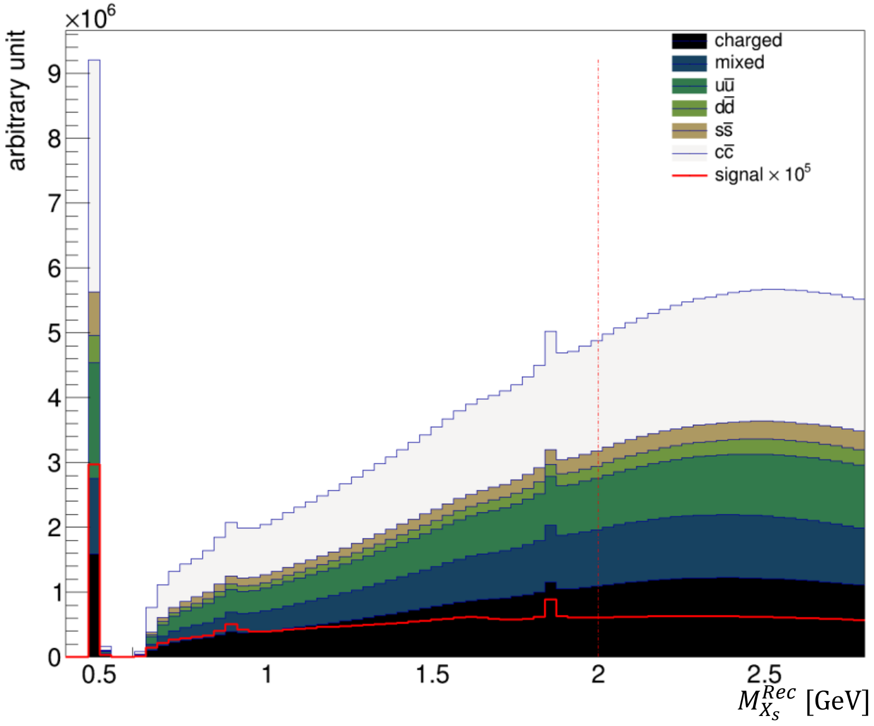
- $M_{X_s}^{Rec} < 2.0\ \mathrm{GeV/c^2}$
- Kinematic Fit converges for compatible X_s decay modes
- Kinematic Fit converges for B_{tag}

To reject backgrounds with additional tracks

- the number of remaining loose tracks † = 0

To reject backgrounds with additional particles

- the number of remaining π^0 = 0
- the number of remaining K_S^0 = 0



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† $dr < 2$ cm and $|dz| < 4$ cm

Signal Selection

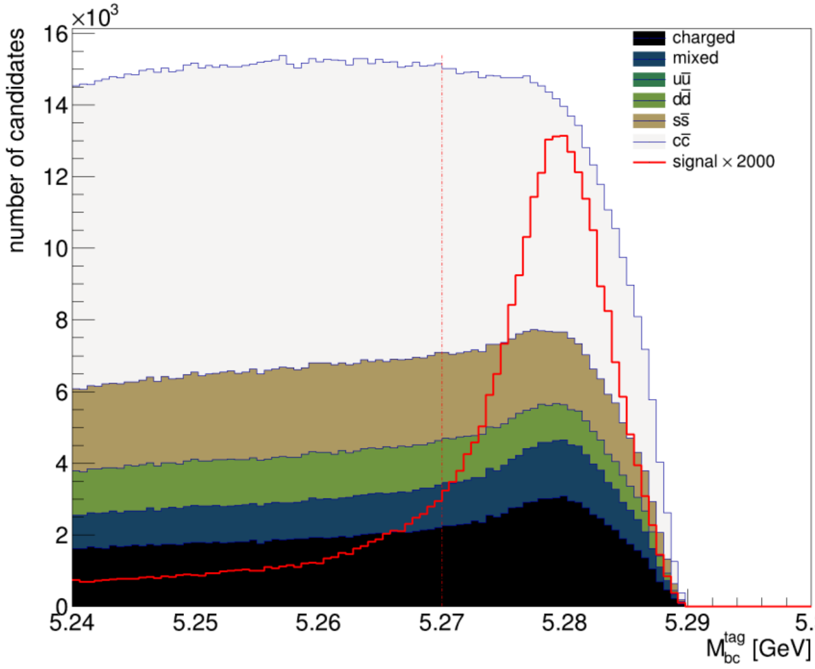
- Several selections are applied

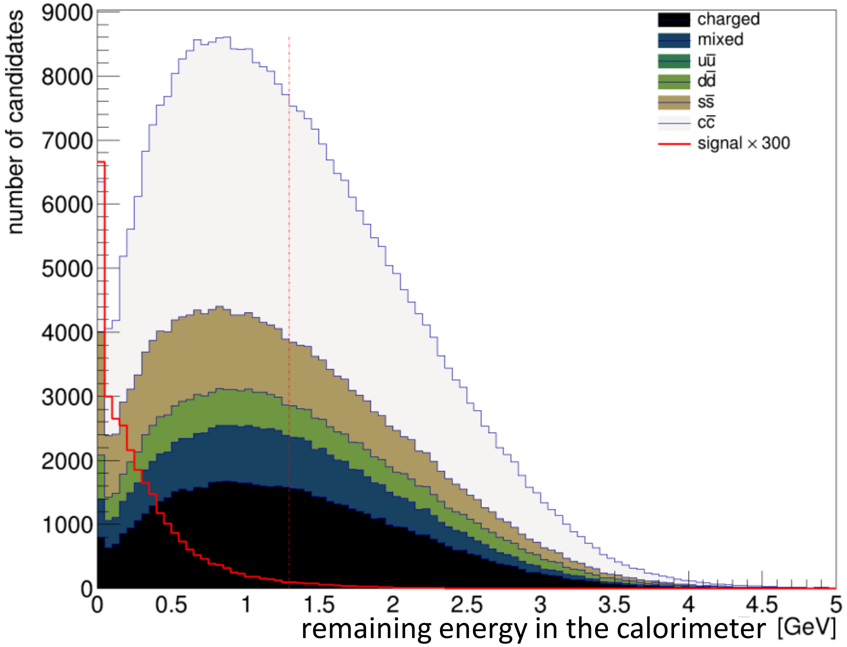
  loose selection is applied. Optimization is done at MVA stage

  - $M_{bc}^{tag} > 5.27$ GeV
  - $\left|\Delta E_{bc}^{tag}\right| < 0.2$ GeV
  - remaining energy in the calorimeter < 1.3 GeV
  - $0.297 < \theta_{\mathrm{missing}} < 2.618$ rad
  - $0.5 < p_{\mathrm{X_s}} < 2.96$ GeV
  - reject $1.84 < M_{Xs}^{Rec} < 1.89$ GeV

- There can be more than one candidates

  Best candidate selection is done by B_{tag} side information

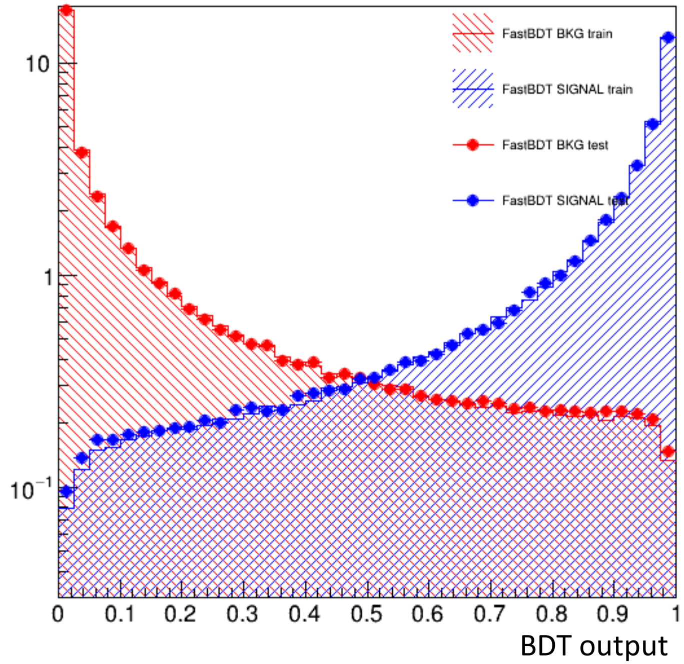


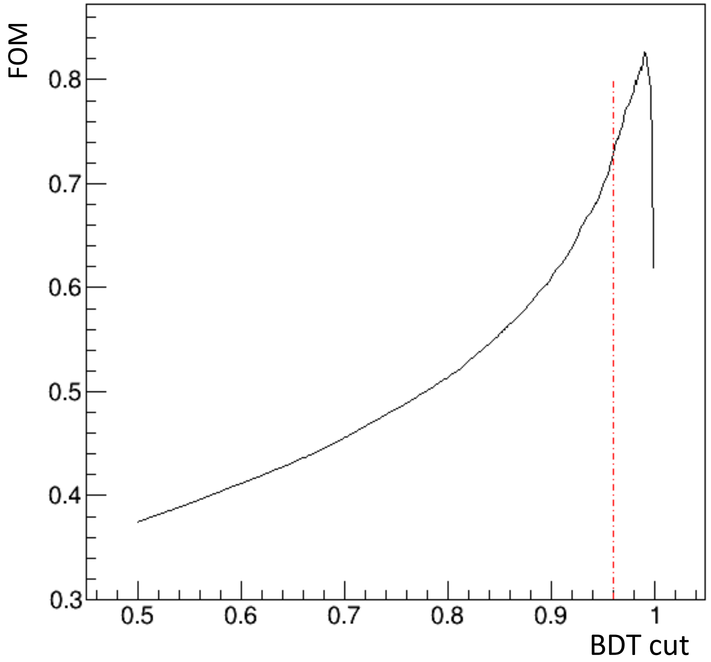


MVA

- BDT is used as a multi variate analysis (MVA)
  - 30 variables are used for BDT
  - Independent sample is used to check an overfitting
  - powerful variable: remaining energy in the calorimeter
  - These variables are selected based on discriminant power

- Figure of merit (FOM) is used to select BDT cut
  - $\mathrm{FOM} = \frac{S}{\sqrt{S+B}}$,
    where S and B are the number of signal and background, respectively
  - BDT output > 0.96 is applied: ensures good sensitivity and relatively high signal efficiency





Corrections

- Several corrections are applied

There can be difference between data and MC. We need to correct it!
Some examples:

PID correction

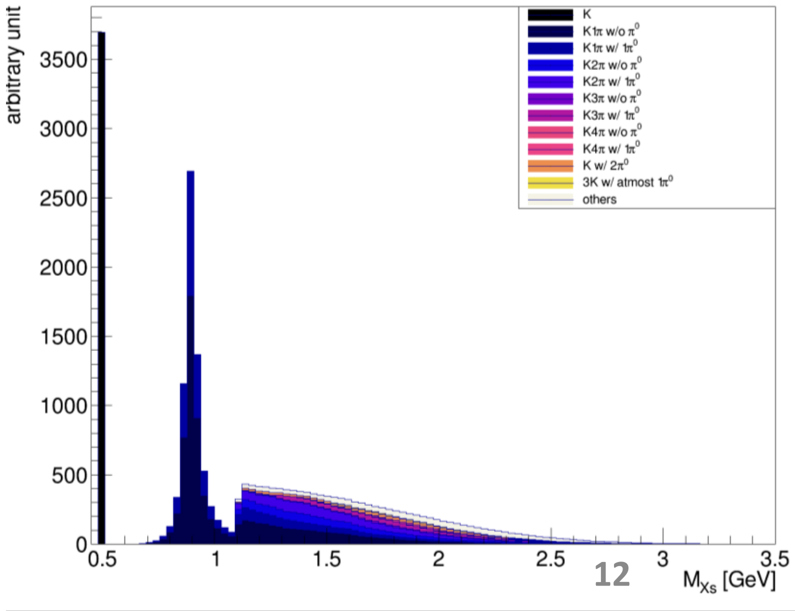
- official correction factors for particle identification are applied
- K and π efficiency, and K and π fake rate from leptons are corrected

π^0 efficiency correction

- official correction factors for π^0 reconstruction is applied

Fragmentation correction

- non-resonant $X_s\nu\bar{\nu}$ decay is produced by PYTHIA, which should be corrected
- use the result of $B \to X_s\gamma$ study



Corrections

- Several corrections are applied

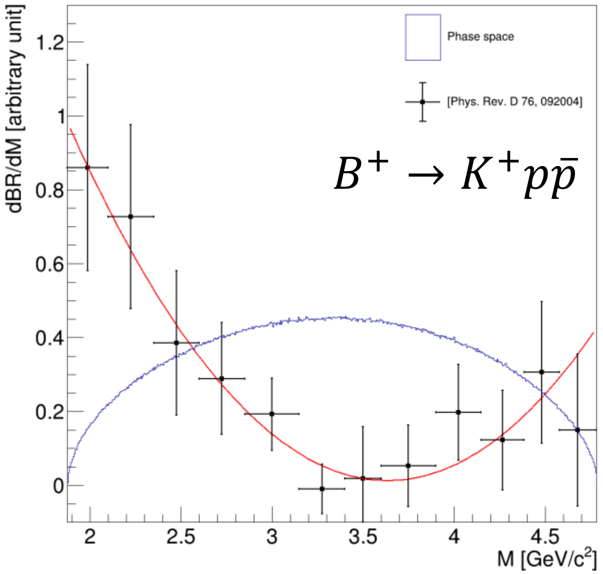
Some examples:

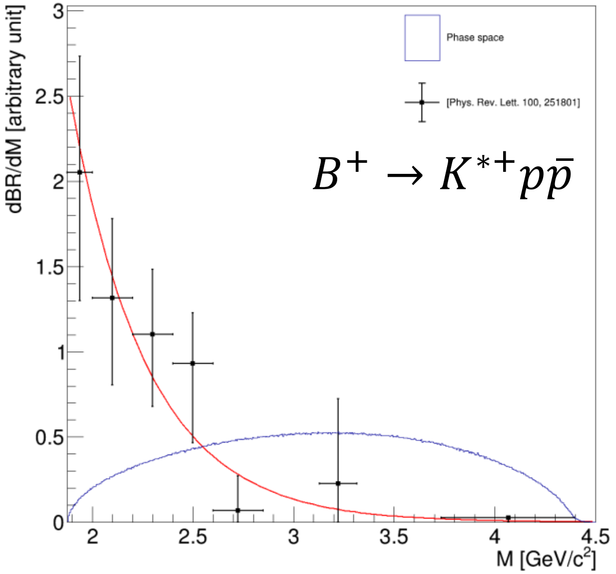
$B \to K^{(*)} n\bar{n}$ mismodeling correction

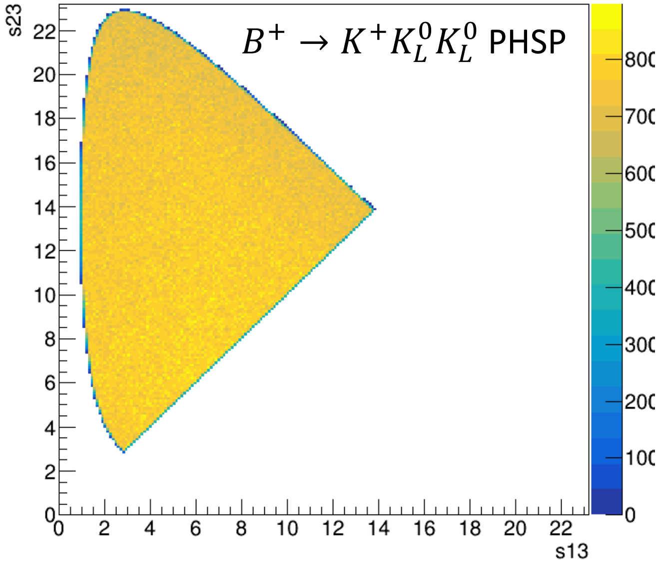
- MC sample is produced based on flat phase space
- it was found that there is a enhancement near a threshold
- use the result of $B \to K^{(*)} p\bar{p}$ study
[j.physletb.2007.11.063.] [PhysRevLett.100.251801] [PhysRevD.76.092004]
- $M_{n\bar{n}}$ distribution and BR are corrected

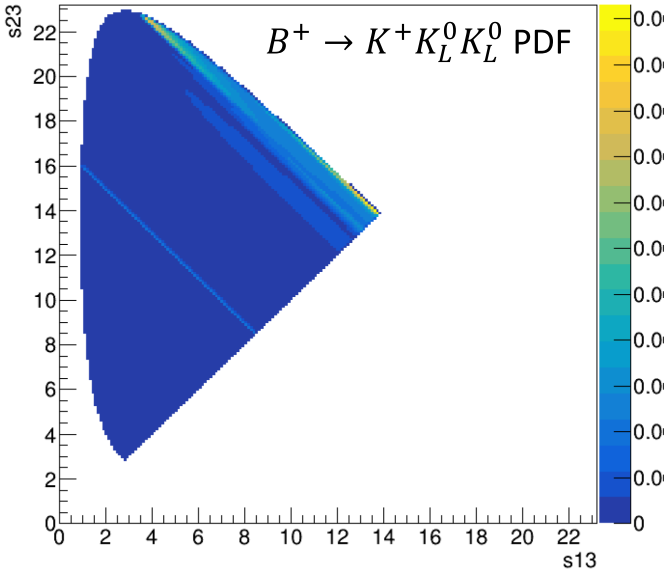
$B \to K K_L^0 K_L^0$ mismodeling correction

- MC sample does not agree with the experimental result
- use the result of $B \to K K_S^0 K_S^0$ study
[PhysRevD.85.112010] [PhysRevD.85.054023]
- Dalitz plots are reweighted





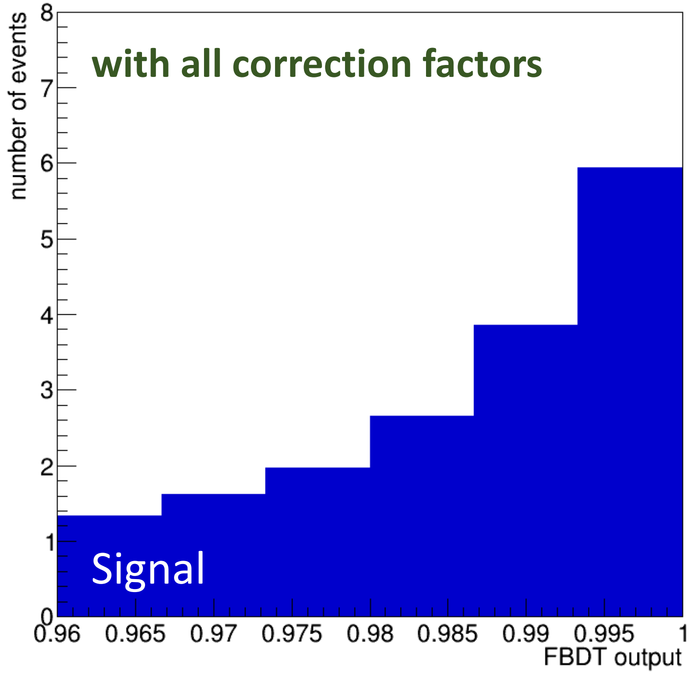


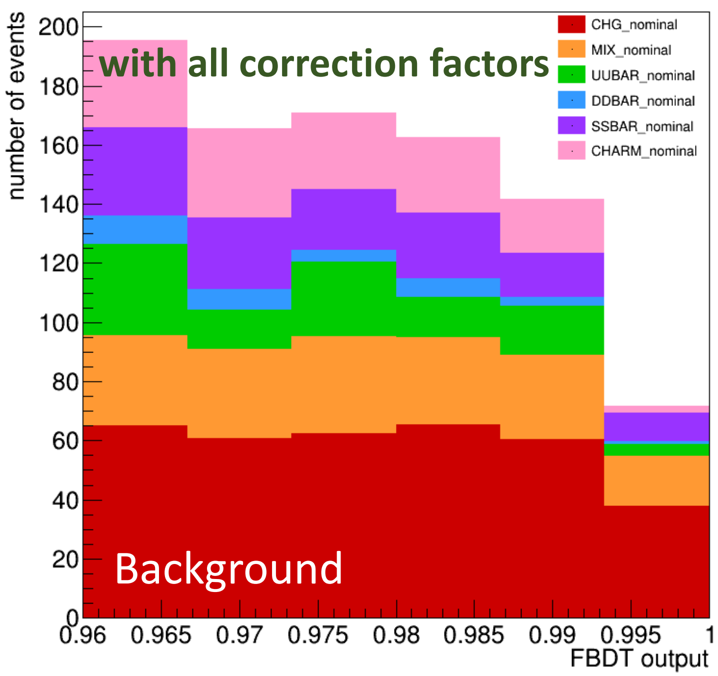


MC Result

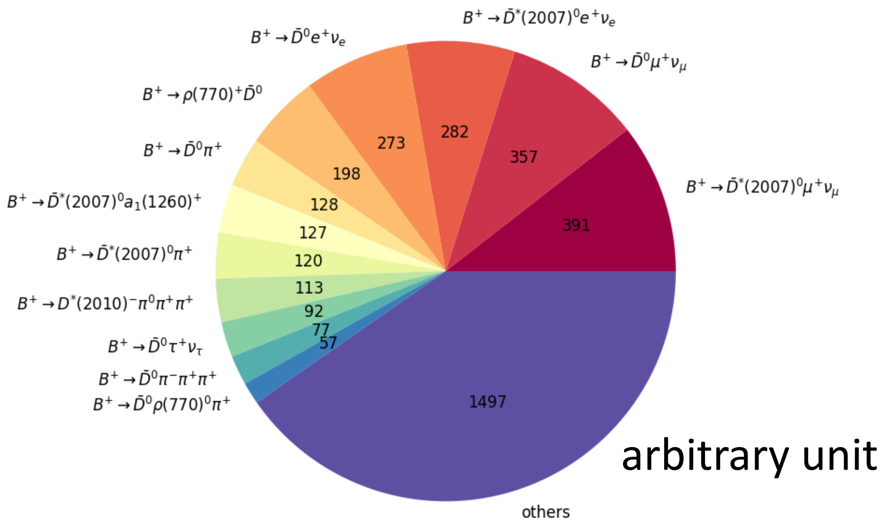
- The expected yields:

Signal: 16.9 events
Charged: 347.5 events
Mixed: 171.5 events
UUBAR: 73.1 events
DDBAR: 15.1 events
SSBAR: 99.1 events
CHARM: 97.5 events

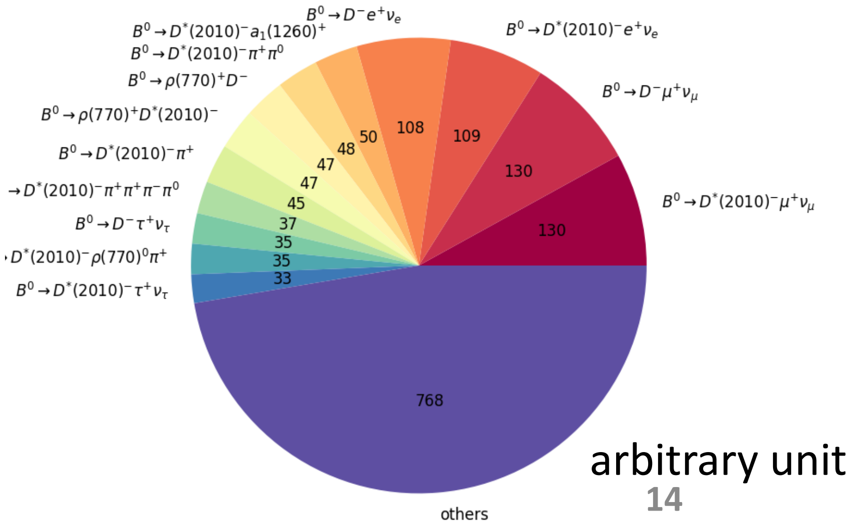




charged background



mixed background



Systematics

- Several systematics are estimated

some examples:

Background normalization

- The number of background may not agree with data
- conservatively apply $\pm 30\%$ uncertainties on each backgrounds
- motivated by the $B \to K\nu\bar{\nu}$ analysis [arXiv:2311.14647]

MC Statistics

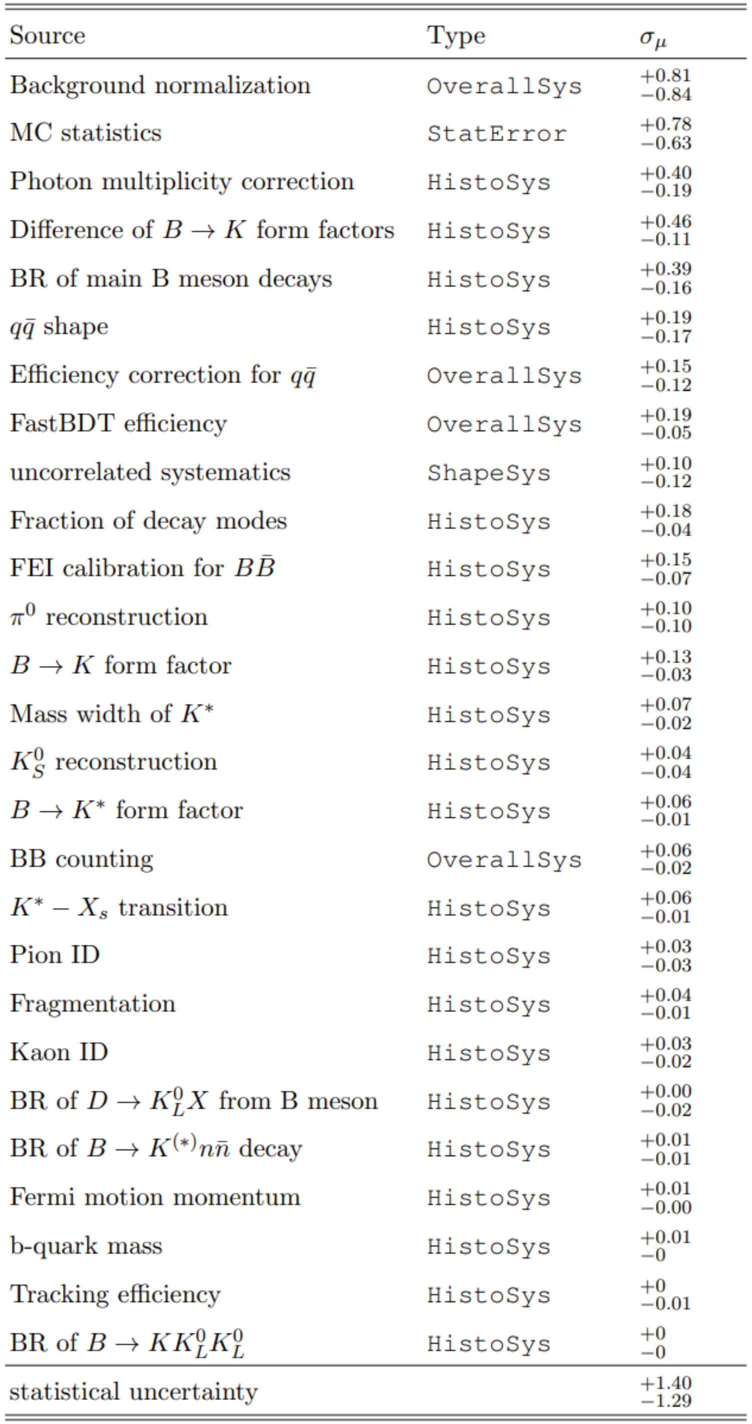
- comes from statistical uncertainty of MC sample

Difference of $B \to K$ form factors

- comes from two theoretical values [JHEP02(2015)184] [PhysRevD.107.014510]

BR of major B meson decays

- uncertainty of BR is obtained by PDG
- for major B decays, uncertainties are applied



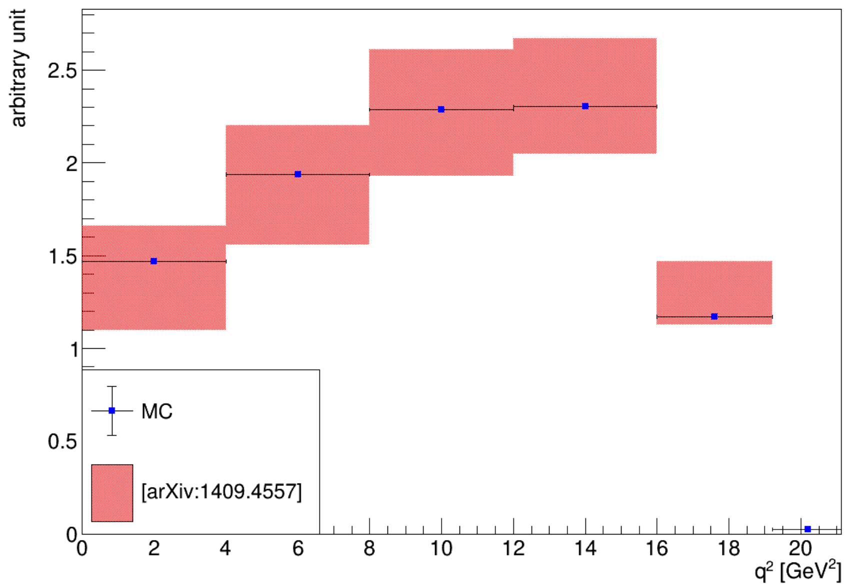
Source	Type	σ_μ
Background normalization	`OverallSys`	$^{+0.81}_{-0.84}$
MC statistics	`StatError`	$^{+0.78}_{-0.63}$
Photon multiplicity correction	`HistoSys`	$^{+0.40}_{-0.19}$
Difference of $B \to K$ form factors	`HistoSys`	$^{+0.46}_{-0.11}$
BR of main B meson decays	`HistoSys`	$^{+0.39}_{-0.16}$
$q\bar{q}$ shape	`HistoSys`	$^{+0.19}_{-0.17}$
Efficiency correction for $q\bar{q}$	`OverallSys`	$^{+0.15}_{-0.12}$
FastBDT efficiency	`OverallSys`	$^{+0.19}_{-0.05}$
uncorrelated systematics	`ShapeSys`	$^{+0.10}_{-0.12}$
Fraction of decay modes	`HistoSys`	$^{+0.18}_{-0.04}$
FEI calibration for $B\bar{B}$	`HistoSys`	$^{+0.15}_{-0.07}$
π^0 reconstruction	`HistoSys`	$^{+0.10}_{-0.10}$
$B \to K$ form factor	`HistoSys`	$^{+0.13}_{-0.03}$
Mass width of K^*	`HistoSys`	$^{+0.07}_{-0.02}$
K_S^0 reconstruction	`HistoSys`	$^{+0.04}_{-0.04}$
$B \to K^*$ form factor	`HistoSys`	$^{+0.06}_{-0.01}$
BB counting	`OverallSys`	$^{+0.06}_{-0.02}$
$K^* - X_s$ transition	`HistoSys`	$^{+0.06}_{-0.01}$
Pion ID	`HistoSys`	$^{+0.03}_{-0.03}$
Fragmentation	`HistoSys`	$^{+0.04}_{-0.01}$
Kaon ID	`HistoSys`	$^{+0.03}_{-0.02}$
BR of $D \to K_L^0 X$ from B meson	`HistoSys`	$^{+0.00}_{-0.02}$
BR of $B \to K^{(*)} n\bar{n}$ decay	`HistoSys`	$^{+0.01}_{-0.01}$
Fermi motion momentum	`HistoSys`	$^{+0.01}_{-0.00}$
b-quark mass	`HistoSys`	$^{+0.01}_{-0}$
Tracking efficiency	`HistoSys`	$^{+0}_{-0.01}$
BR of $B \to K K_L^0 K_L^0$	`HistoSys`	$^{+0}_{-0}$
statistical uncertainty		$^{+1.40}_{-1.29}$

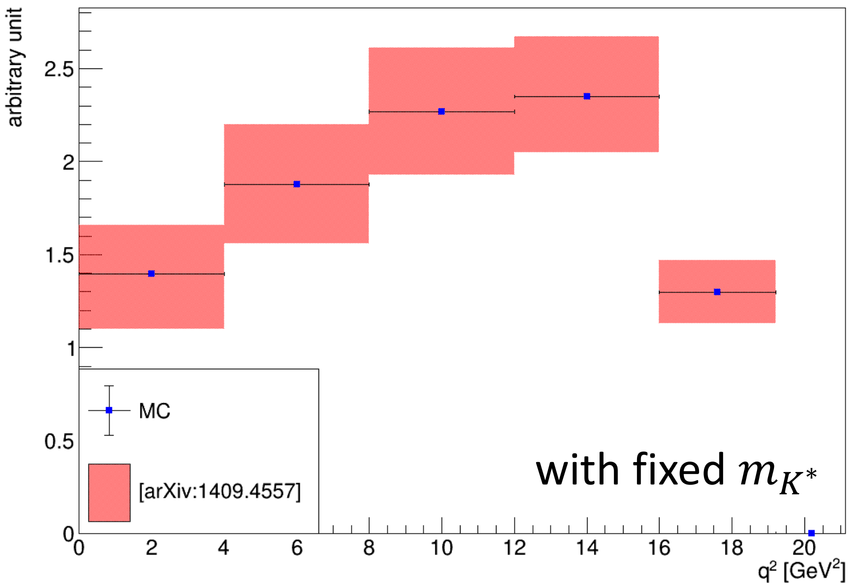
Systematics

- Several systematics are estimated

Mass width of K^*

- In theoretical calculation, the mass of K^* is fixed
- In MC generator, the mass of K^* has a finite width





※ $q^2 = (p_\nu + p_{\bar{\nu}})^2$

- The effect of it is estimated

Fitting and Limit Setting

- BDT output is used as a fitting variable
- PDF is constructed by HistFactory

$$\mathcal{P} = \underbrace{\prod_{b \in \text{bins}} \text{Pois}(n_b | \nu_b)}_{\text{Poisson distribution for each bin/channel}} \cdot \underbrace{\prod_{p} f_p(a_p | \alpha_p)}_{\text{Constraint term for systematic uncertainty (nuisance parameters)}}$$

※ $\mathrm{n_b}$: the number of observed event by data

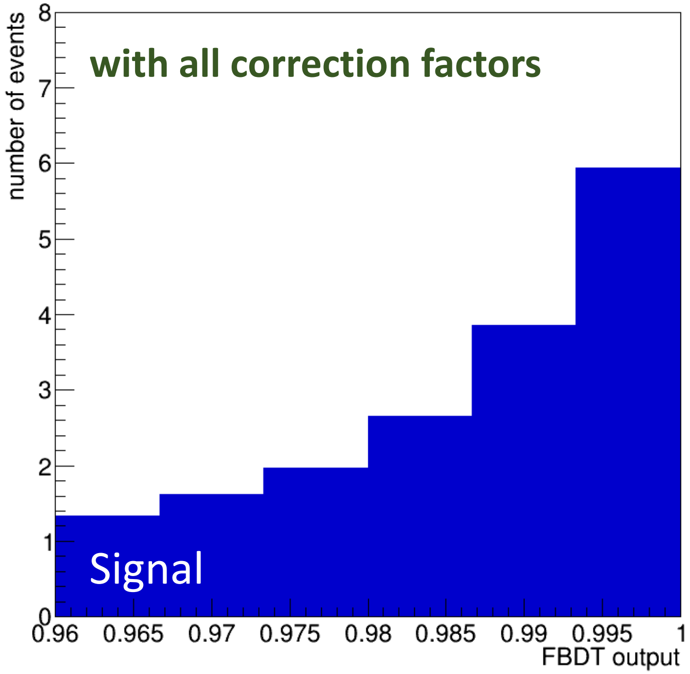
※ ν_{b}: the number of expected event by MC

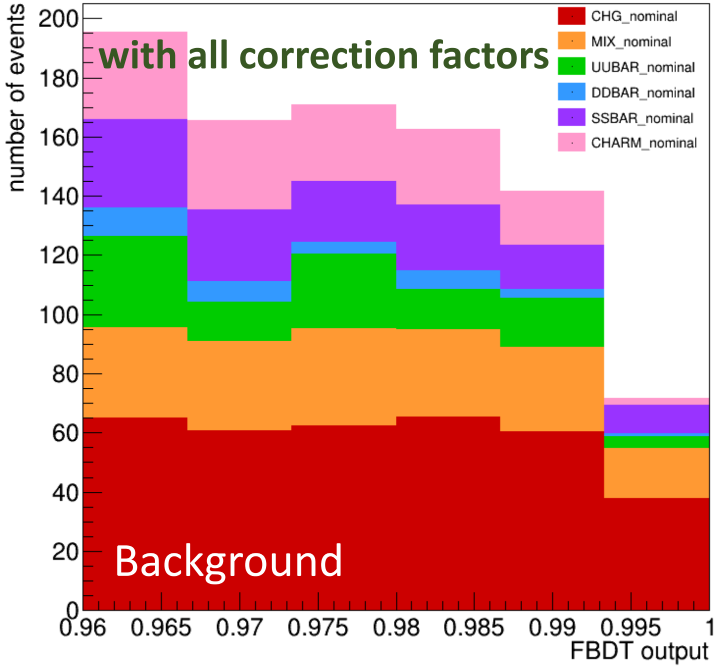
※ a_{p}: nominal value of nuisance parameter

※ α_{p}: nuisance parameter

Orange means the probability that we found n_b events
Blue means the probability that we found NP a_p

- Histogram template can easily describe variable shape



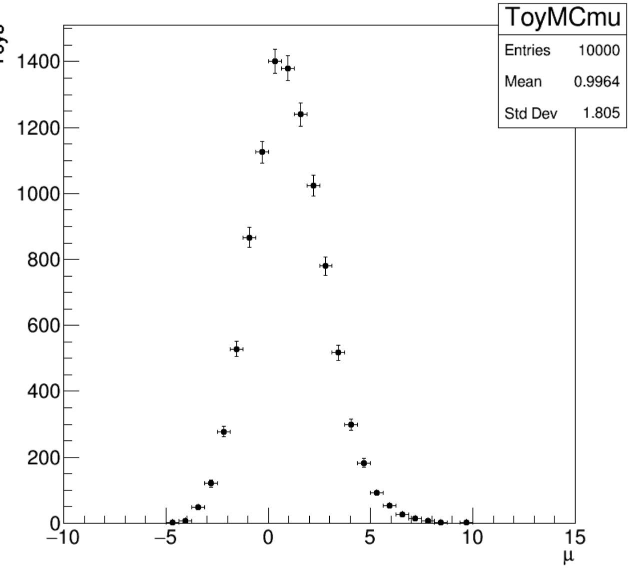


Toy MC study

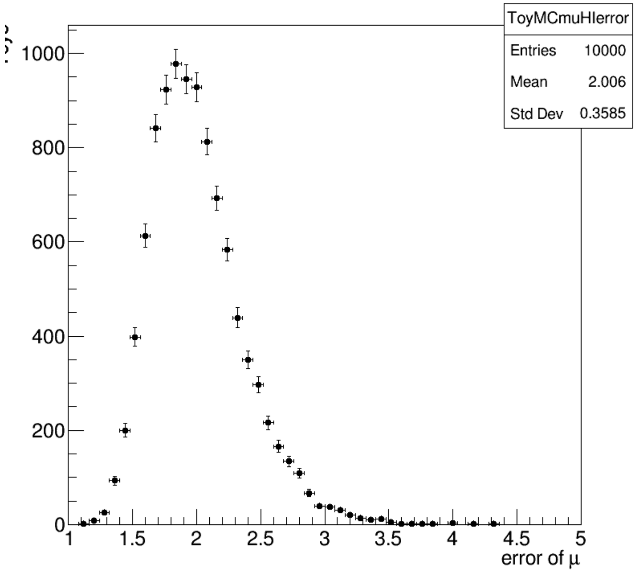
- Toy MC study is done
  - fluctuate nuisance parameters and produce toy MC
  - \`pull\` should follow normal distribution, if fitter works fine.
  - pull is calculated:

$$\text{pull} = \begin{cases} \dfrac{(\text{true value}) - (\text{fit result})}{(\text{positive MINOS error})} & \text{if } (\text{fit result}) \leq (\text{true value}) \\ \dfrac{(\text{fit result}) - (\text{true value})}{(\text{negative MINOS error})} & \text{otherwise,} \end{cases}$$

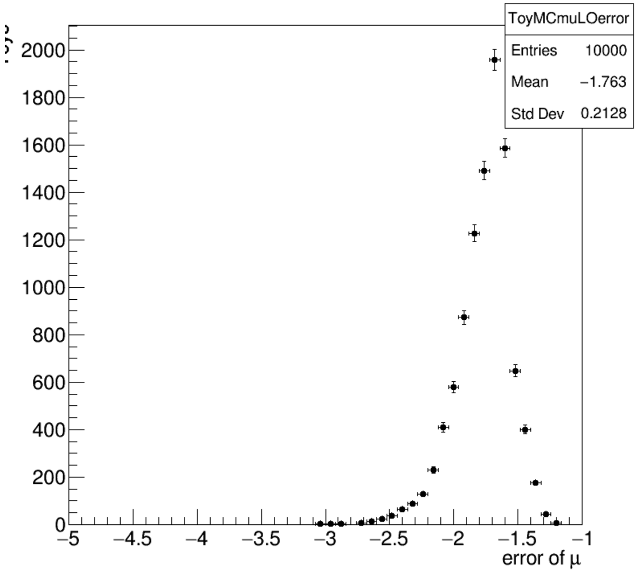
$\mu = 1$ corresponds to SM prediction ($\mathrm{BR} = 2.9 \times 10^{-5}$)



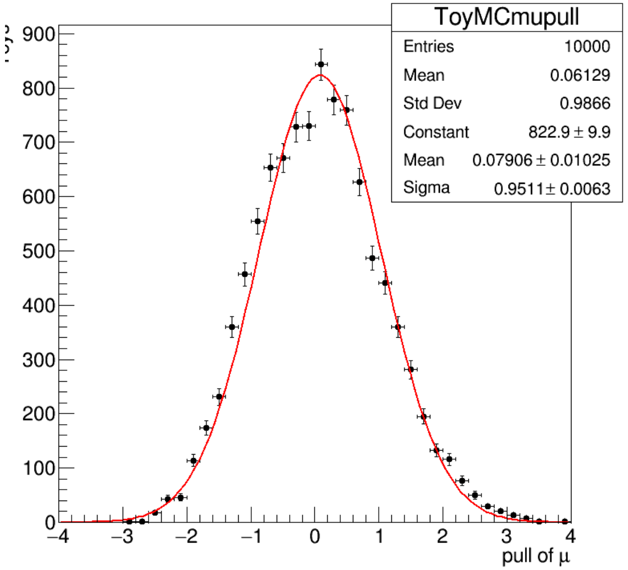
μ distribution



positive error of μ distribution



negative error of μ distribution

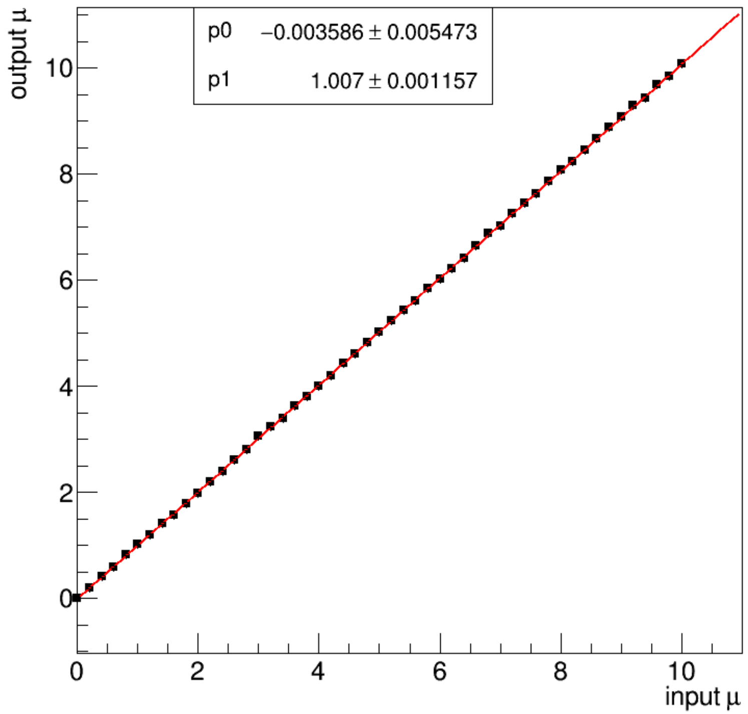


pull distribution

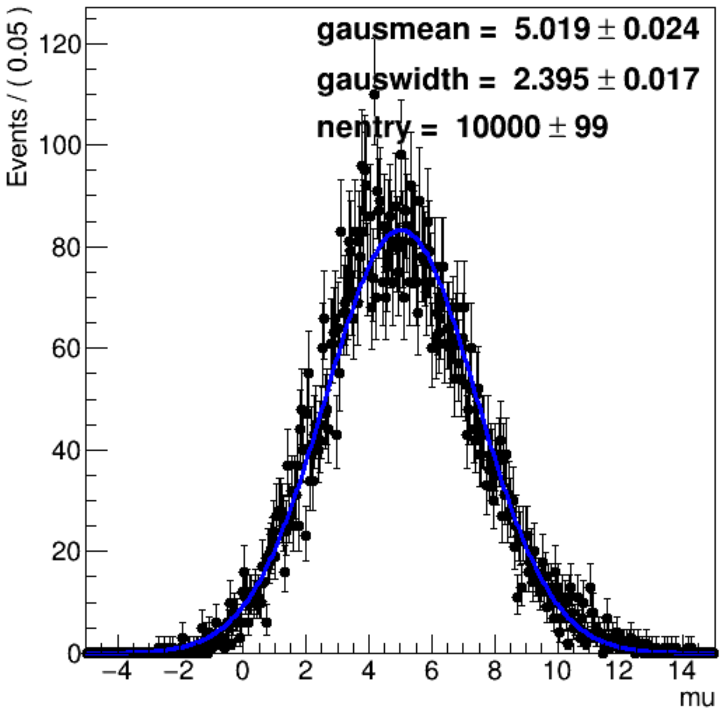
Linearity Test

- Linearity is done
  - do toy MC study for different μ values
  - check the μ distributions and fit them by Gaussian function
  - shows good linearity

$\mu = 1$ corresponds to SM prediction ($\mathrm{BR} = 2.9 \times 10^{-5}$)



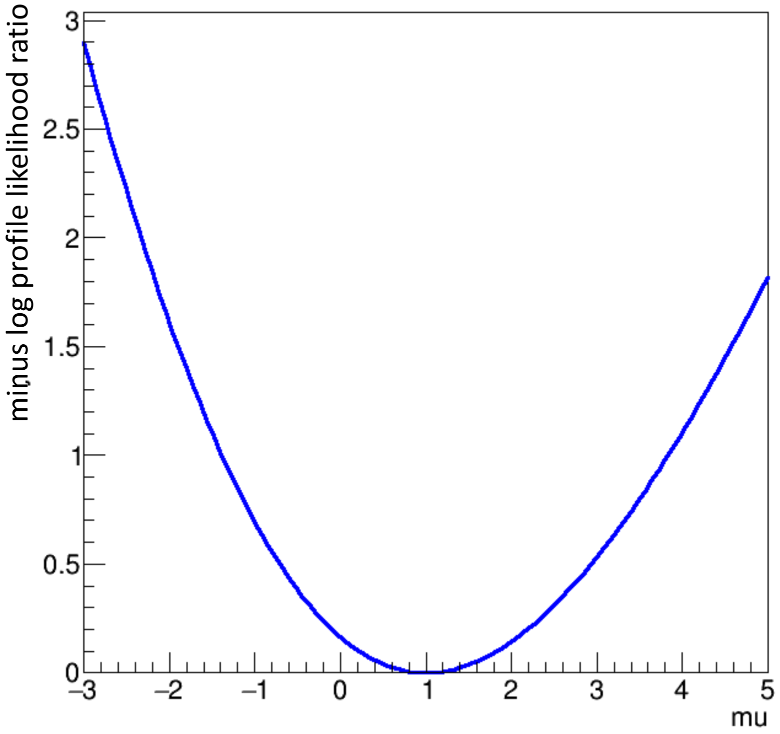
result of linearity test

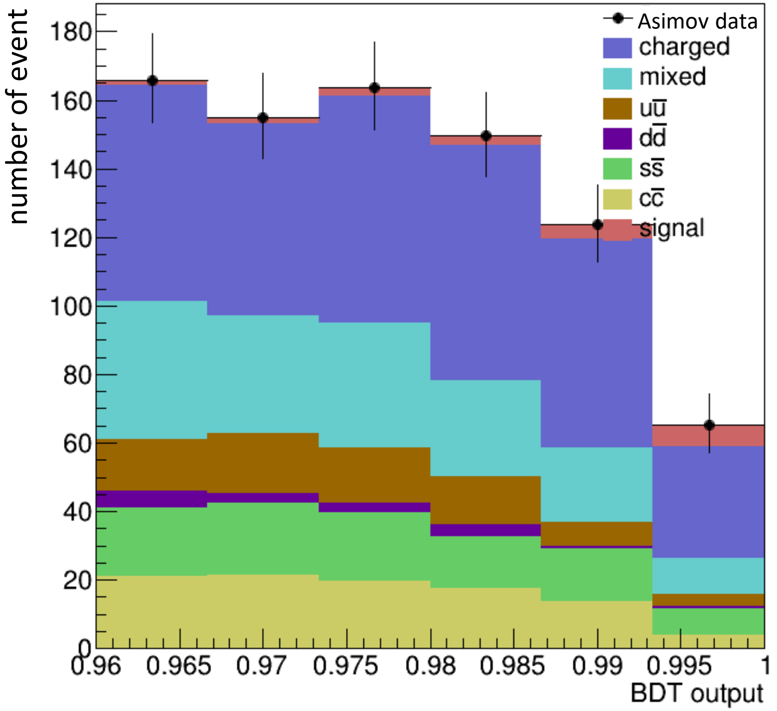


μ distribution when $\mu = 5$

Asimov Fit

- Fit is done with Asimov data †
  - To check the rough result
- No significant signal
  - Need to set an upper limit





$$\mu = 1.0^{+1.9}_{-1.7} = 1.0^{+1.4}_{-1.3}(\mathrm{stat})^{+1.3}_{-1.1}(\mathrm{syst})$$

† the sample which is exactly same with an expectation

Upper Limit

- Upper limit is calculated by CLs method

  calculated with 362 fb^{-1}

- Frequentist method

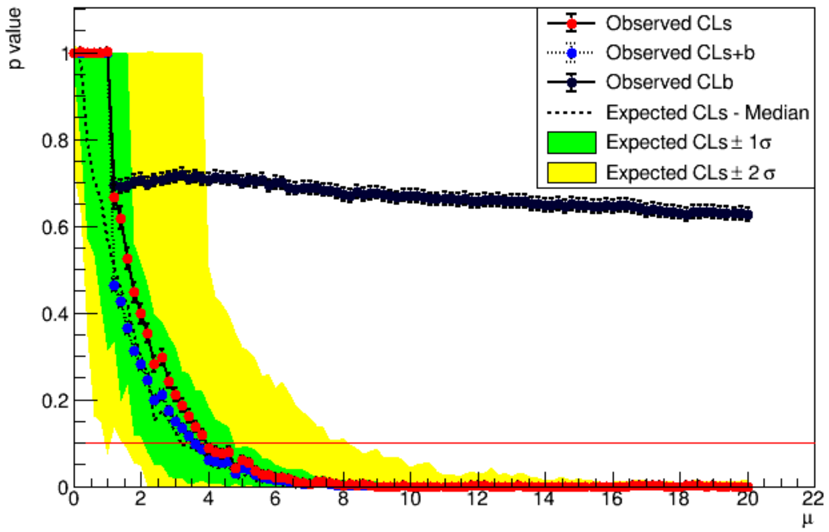
  null hypothesis ($\mu = 0$): $\mathrm{UL} = 9.17 \times 10^{-5}$ (90CL)
  Asimov data ($\mu = 1$): $\mathrm{UL} = 1.14 \times 10^{-4}$ (90CL)

- Hybrid method

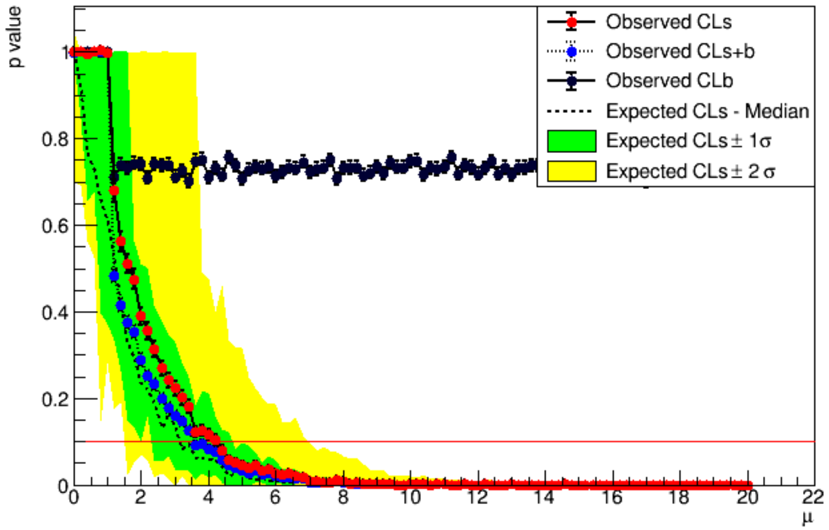
  null hypothesis ($\mu = 0$): $\mathrm{UL} = 9.72 \times 10^{-5}$ (90CL)
  Asimov data ($\mu = 1$): $\mathrm{UL} = 1.23 \times 10^{-4}$ (90CL)

  * ALEPH experiment: $\mathrm{UL} = 6.4 \times 10^{-4}$ (90CL)

  * $B^+ \to K^+\nu\bar{\nu}$ result: $BR = 2.3^{+0.5}_{-0.5}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst}) \times 10^{-5}$ [arXiv:2311.14647]



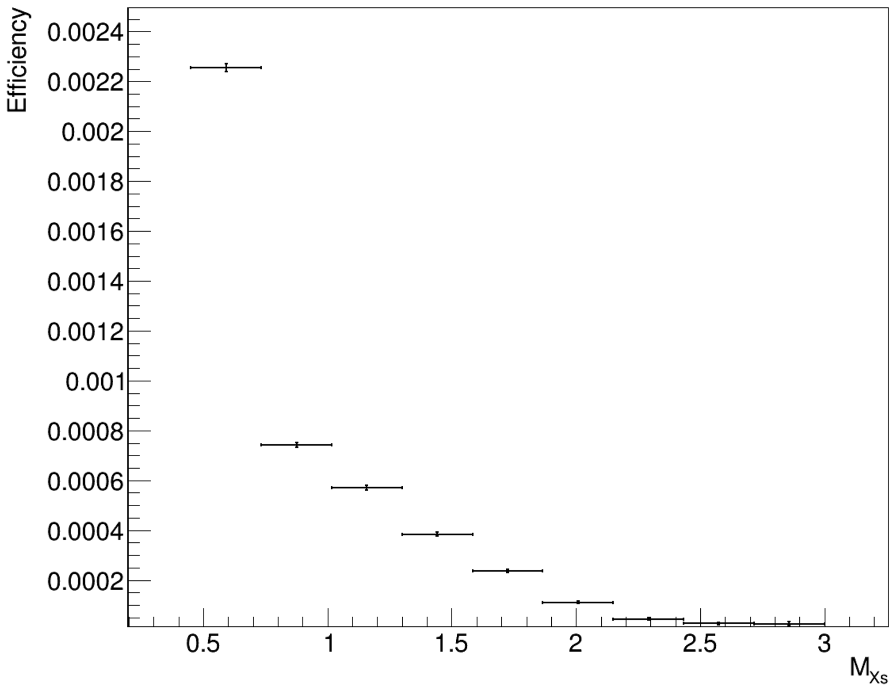
frequentist method



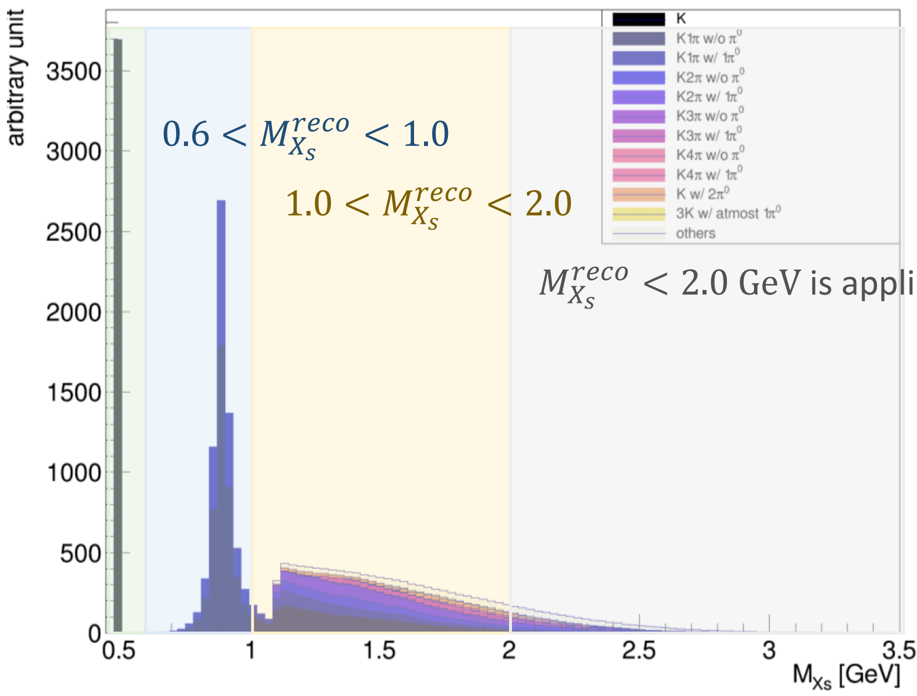
hybrid method

Action Item

- The signal efficiency is low at high multiplicity region
  - separate the candidate by M_{X_s}
  - result = $K + K^* + X_s$, which is better than just K



$0.0 < M_{X_s}^{reco} < 0.6$



$0.6 < M_{X_s}^{reco} < 1.0$

$1.0 < M_{X_s}^{reco} < 2.0$

$M_{X_s}^{reco} < 2.0$ GeV is applied

Summary

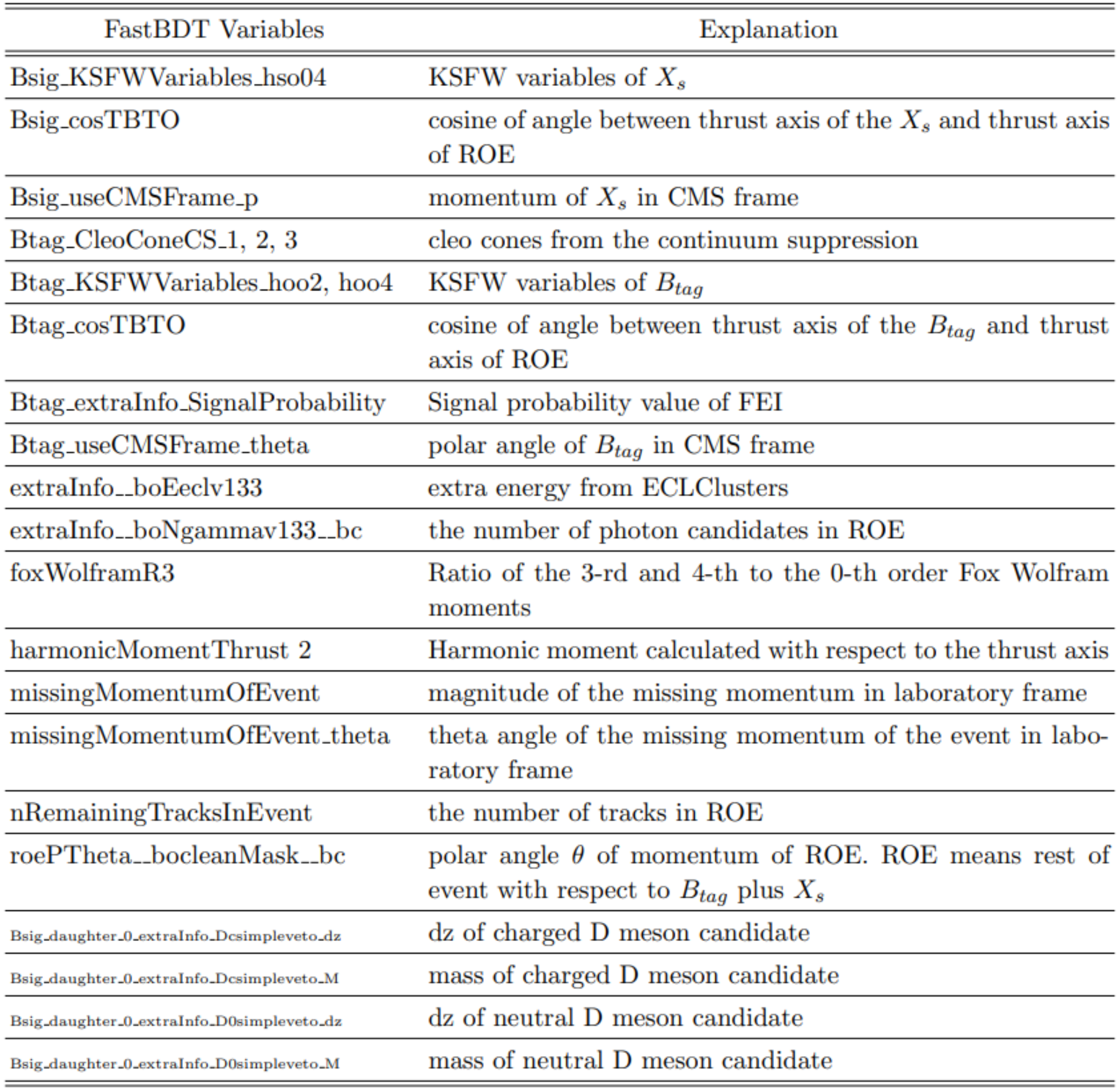
- Analysis procedure is established
- Several systematic uncertainties are estimated
- Upper limit is estimated

Plan

- New fitting method

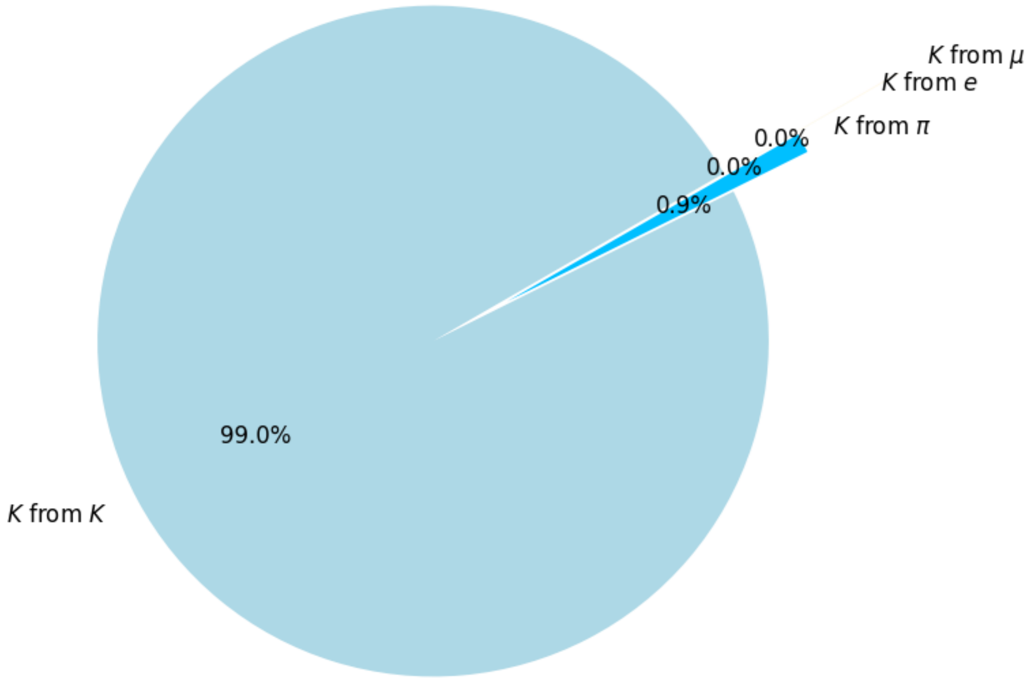
Backups

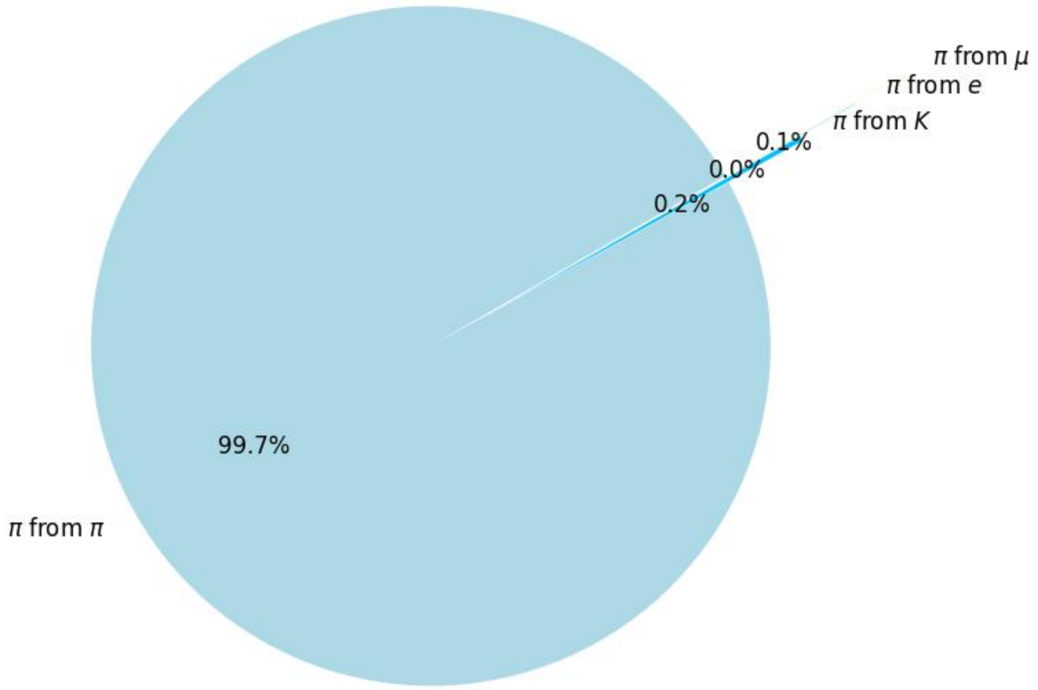
Backups



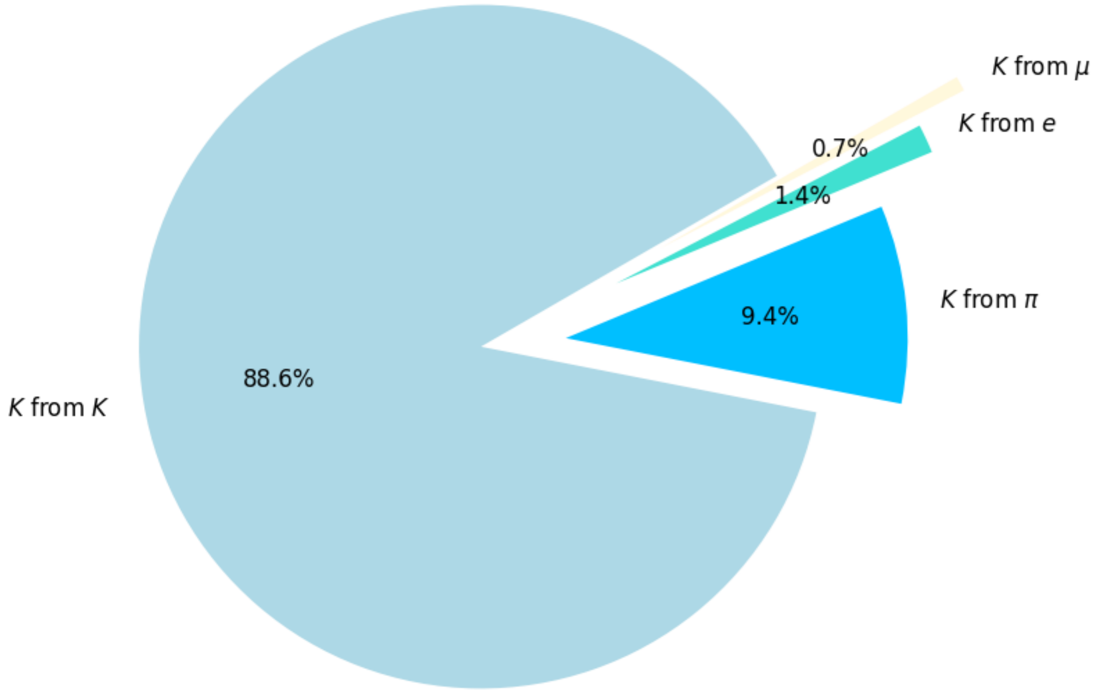
FastBDT Variables	Explanation
Bsig_KSFWVariables_hso04	KSFW variables of X_s
Bsig_cosTBTO	cosine of angle between thrust axis of the X_s and thrust axis of ROE
Bsig_useCMSFrame_p	momentum of X_s in CMS frame
Btag_CleoConeCS_1, 2, 3	cleo cones from the continuum suppression
Btag_KSFWVariables_hoo2, hoo4	KSFW variables of B_{tag}
Btag_cosTBTO	cosine of angle between thrust axis of the B_{tag} and thrust axis of ROE
Btag_extraInfo_SignalProbability	Signal probability value of FEI
Btag_useCMSFrame_theta	polar angle of B_{tag} in CMS frame
extraInfo__boEeclv133	extra energy from ECLClusters
extraInfo__boNgammav133__bc	the number of photon candidates in ROE
foxWolframR3	Ratio of the 3-rd and 4-th to the 0-th order Fox Wolfram moments
harmonicMomentThrust 2	Harmonic moment calculated with respect to the thrust axis
missingMomentumOfEvent	magnitude of the missing momentum in laboratory frame
missingMomentumOfEvent_theta	theta angle of the missing momentum of the event in laboratory frame
nRemainingTracksInEvent	the number of tracks in ROE
roePTheta__bocleanMask__bc	polar angle θ of momentum of ROE. ROE means rest of event with respect to B_{tag} plus X_s
Bsig_daughter_0_extraInfo_Dcsimpleveto_dz	dz of charged D meson candidate
Bsig_daughter_0_extraInfo_Dcsimpleveto_M	mass of charged D meson candidate
Bsig_daughter_0_extraInfo_D0simpleveto_dz	dz of neutral D meson candidate
Bsig_daughter_0_extraInfo_D0simpleveto_M	mass of neutral D meson candidate

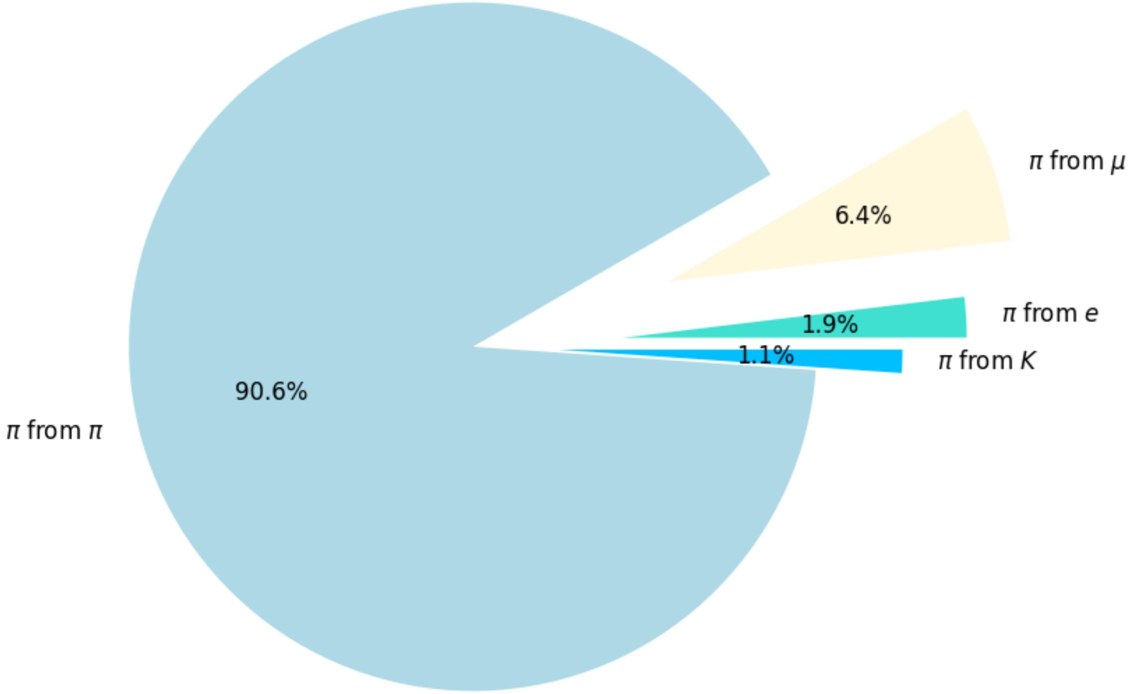
Fake hadron (signal)





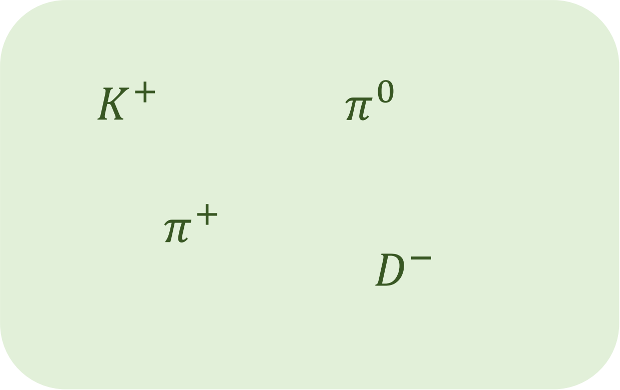
Fake hadron (background)





Reconstruction Precedure

- Reconstruction method



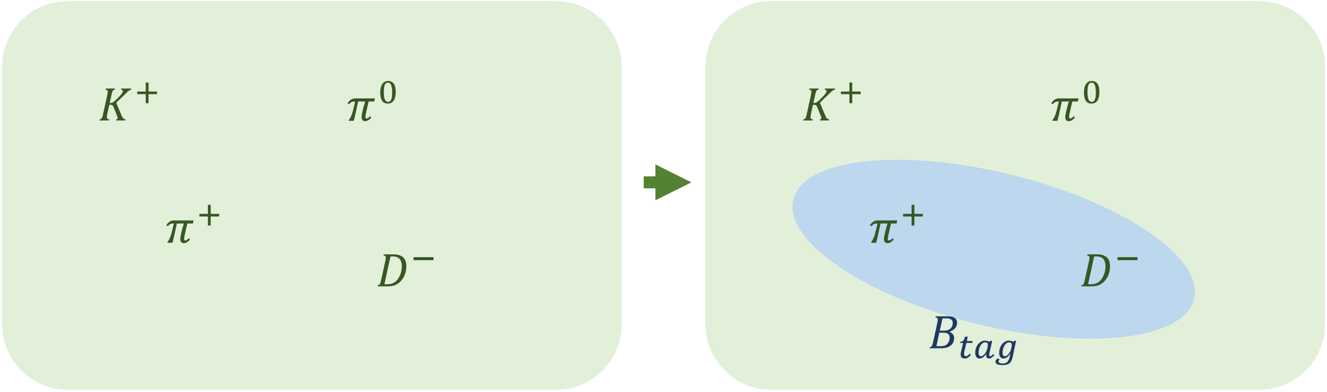
K^+ π^0

π^+

D^-

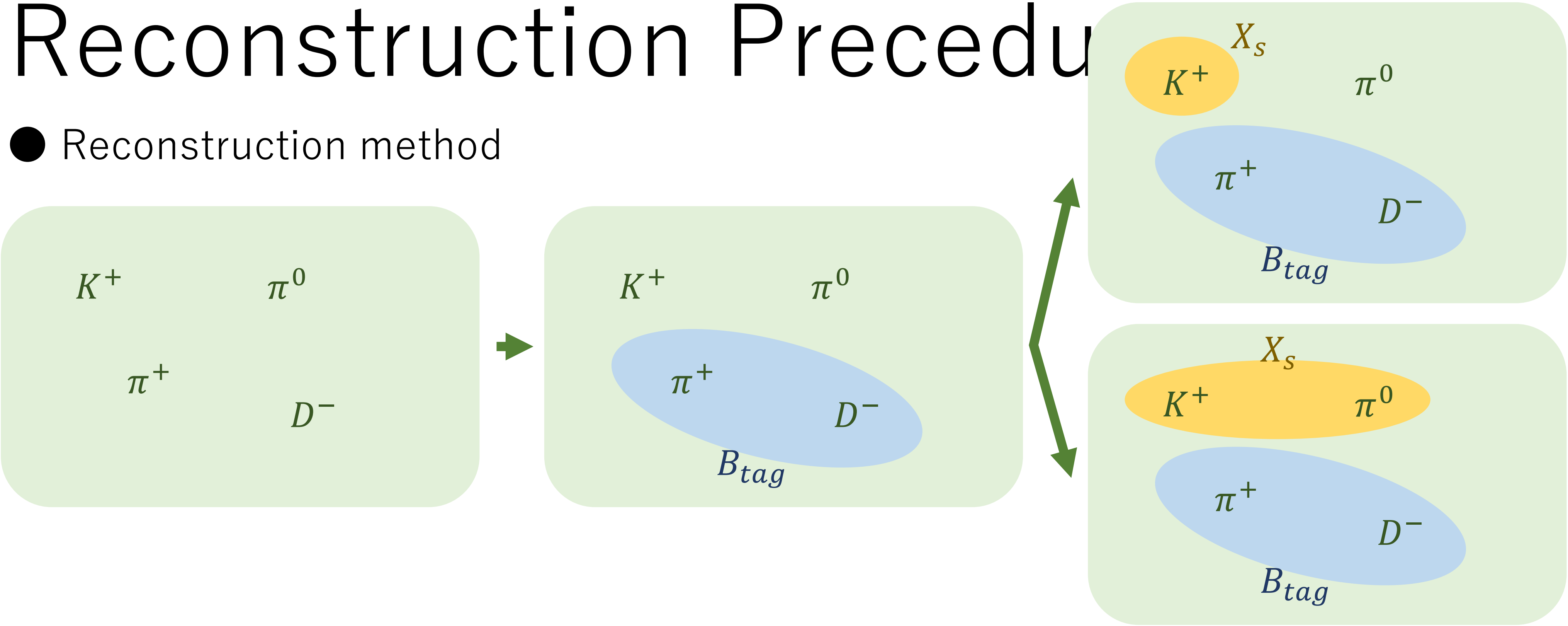
Reconstruction Precedure

- Reconstruction method



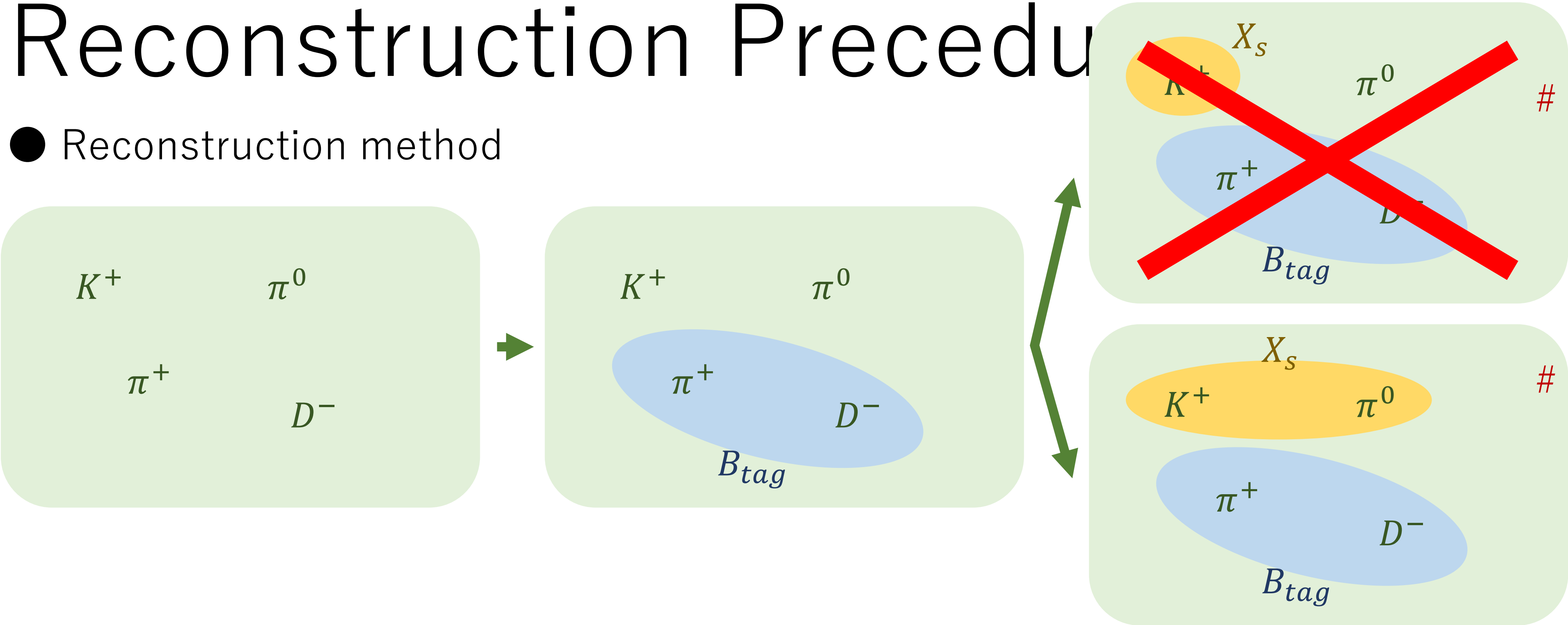
Reconstruction Precedu

- Reconstruction method



Reconstruction Procedu

- Reconstruction method

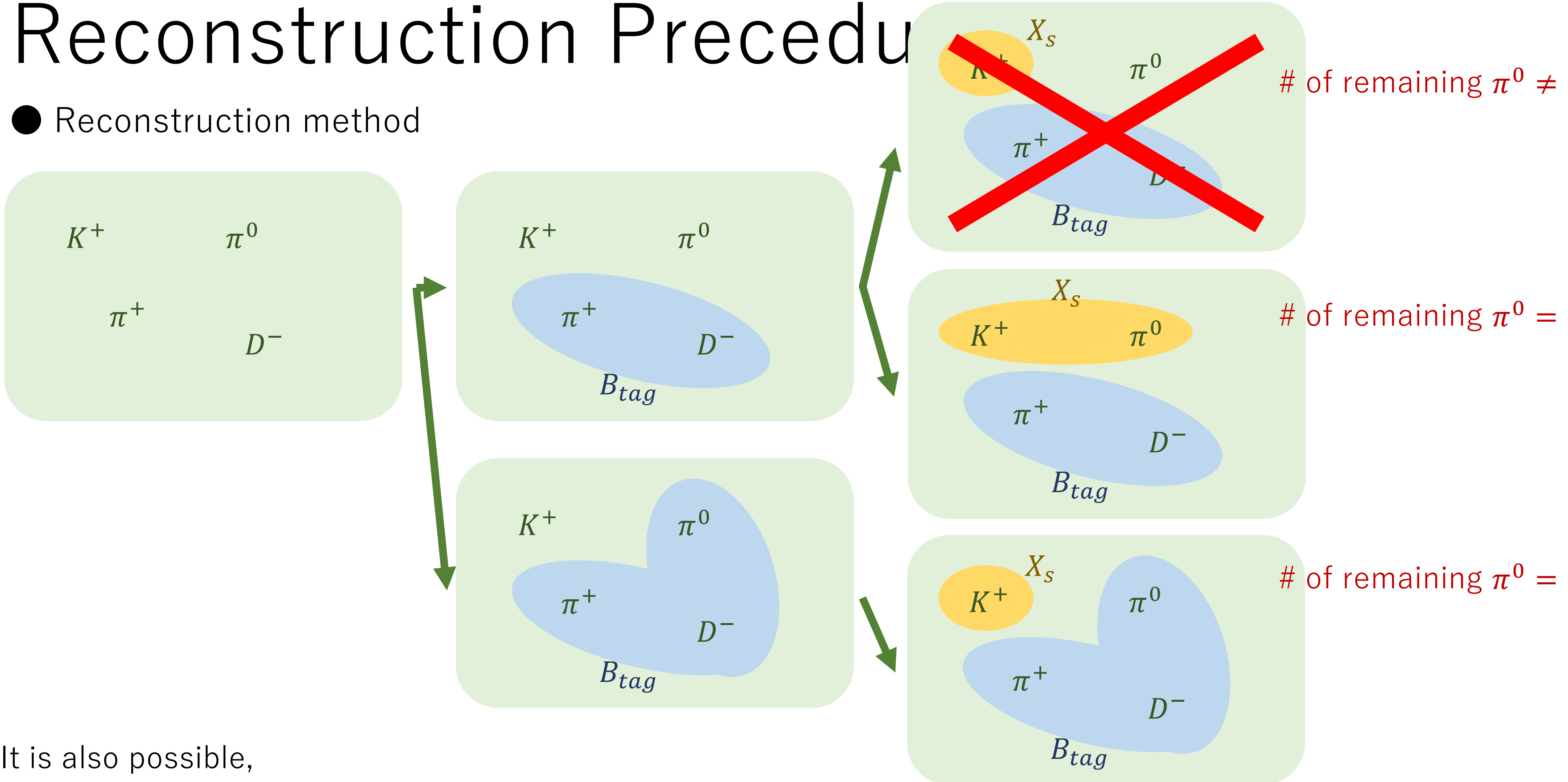


# of remaining $\pi^0 \neq$

# of remaining $\pi^0 =$

Reconstruction Precedu

- Reconstruction method



It is also possible,
if there are several Btag