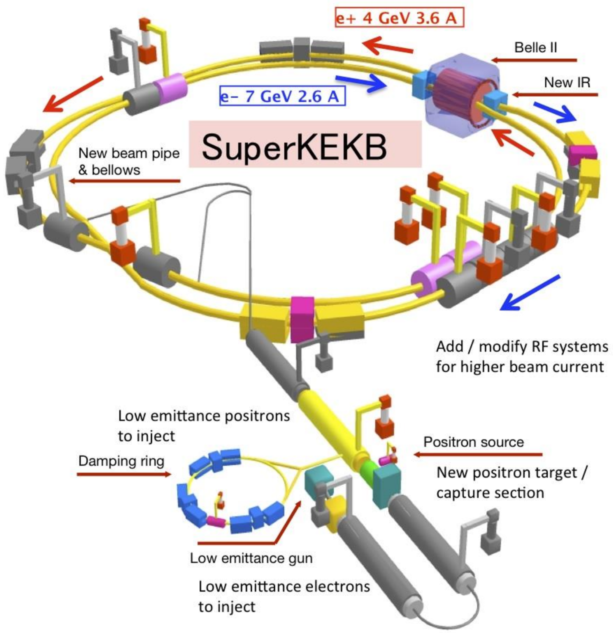
$B \to X_s \nu\bar{\nu}$ study at Belle II

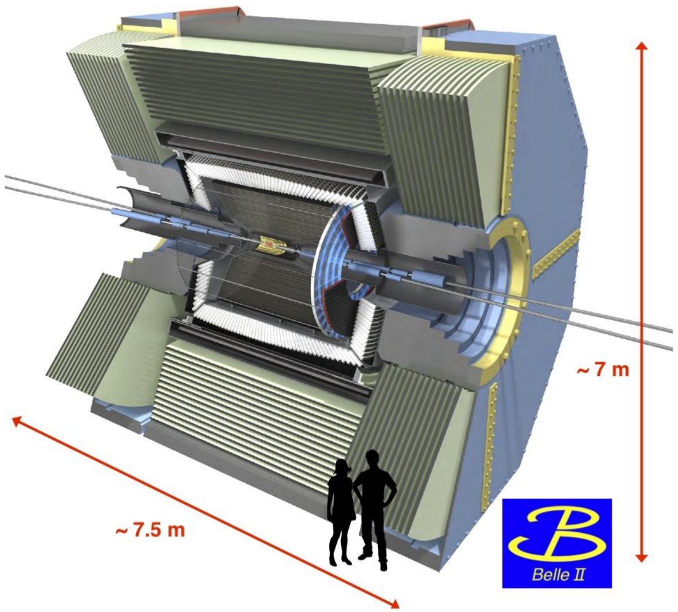
Junewoo Park
Yonsei University
2023.01.17

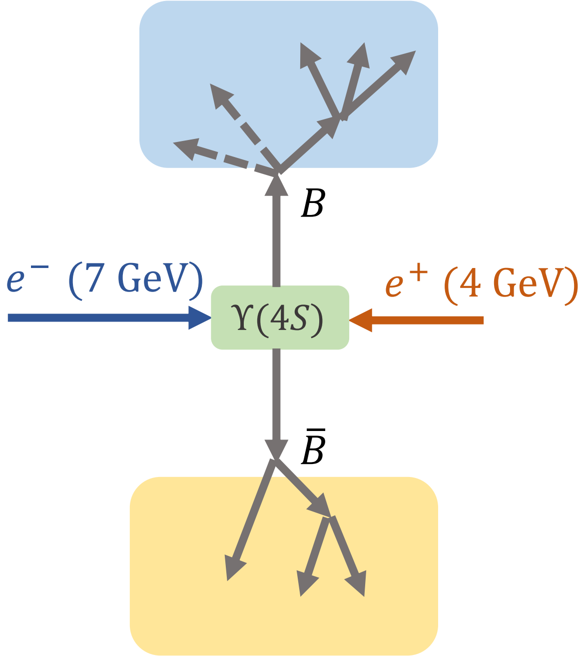
Contents

Belle II experiment

- Electrons and positrons are accelerated up to 7.007 GeV and 4.000 GeV respectively by SuperKEKB
- Its energy correspond to the resonance of $\Upsilon(4S)$ which mainly decay into B meson pair
- In my analysis, B meson pairs from $\Upsilon(4S)$ are used





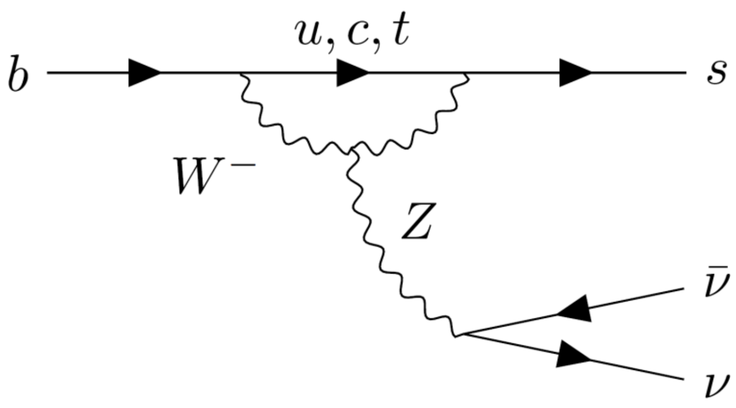


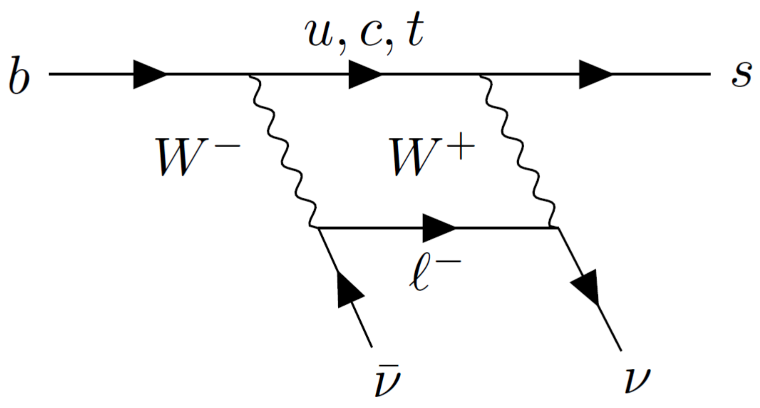
Motivation

- $B \to X_s \nu\bar{\nu}$ decay is theoretically cleaner than $B \to X_s ll$
- Branching ratio of $B \to X_s \nu\bar{\nu}$ does not depend on form factors

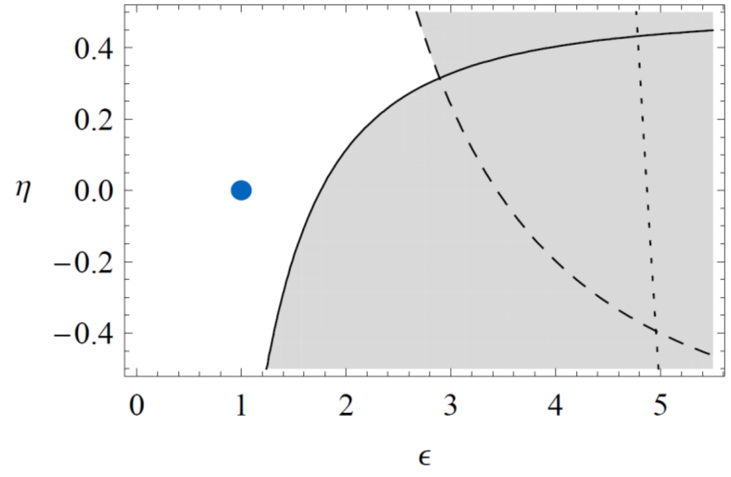
  cf. branching ratio of $B \to K^{(*)}\nu\bar{\nu}$ depends on form factors
- Its branching ratio depends on right-handed component

  New physics can enhance the decay





※ $\eta = -\frac{Re(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}, \quad \epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{SM}|}$



Wolfgang Altmannshofer *et al* JHEP04(2009)022

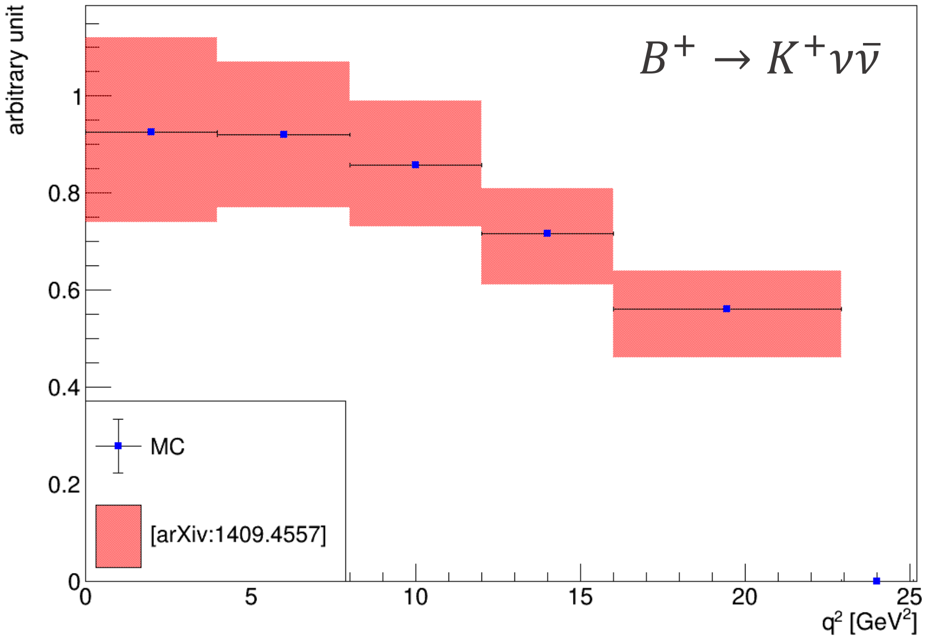
Event Generation

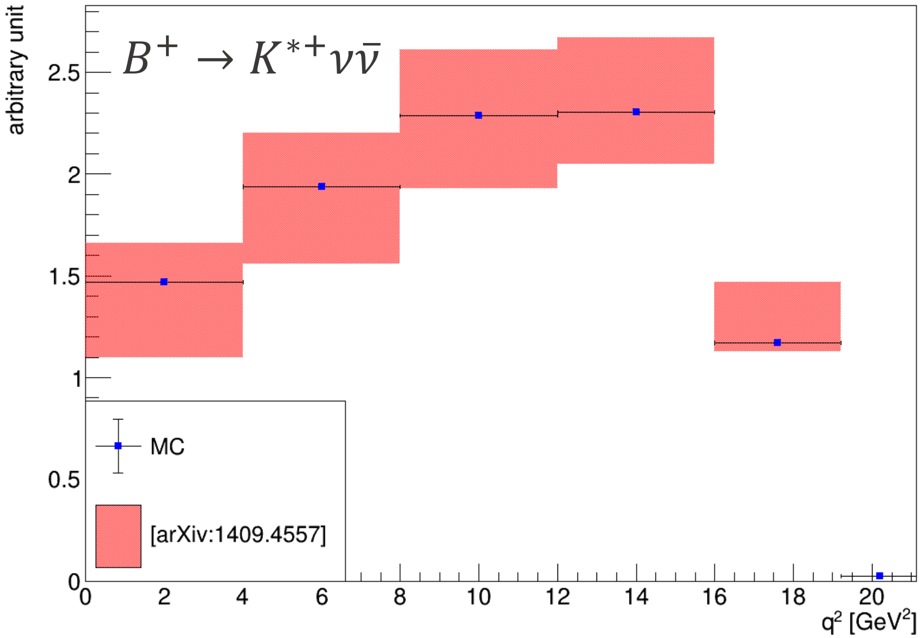
- $B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, and non-resonant $B \to X_s\nu\bar{\nu}$ MC samples are produced separately †‡

  $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ samples are produced based on form factors

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

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





※ $q^2 = (p_\nu + p_{\bar{\nu}})^2$

† Buras, Andrzej J., et al. " $B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond." Journal of High Energy Physics 2015.2 (2015): 1-39.

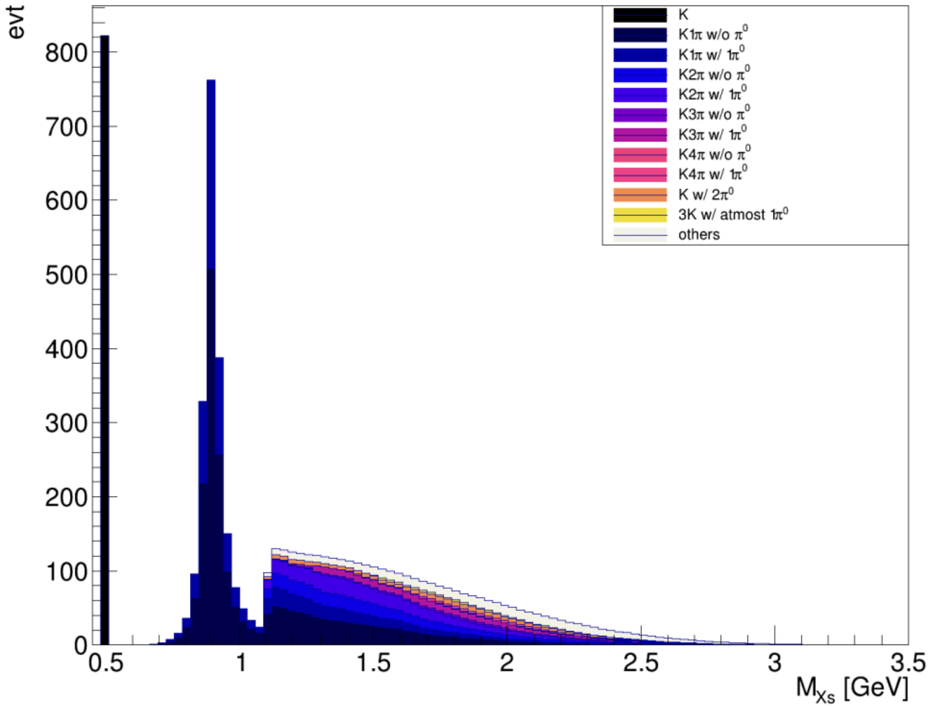
‡ Bharucha, Aoife, David M. Straub, and Roman Zwicky. " $B \to V\ell^+\ell^-$ in the Standard Model from light-cone sum rules." Journal of High Energy Physics 2016.8 (2016): 1-64.

Event Generation

- For non-resonant $B \to X_s \nu \bar{\nu}$ MC samples, following distribution is used †

$$\frac{d\Gamma}{dq^2} \propto \sqrt{\lambda(1, \hat{m}_s, s_b)}\left[3 s_b\left(1 + \hat{m}_s^2 - s_b - 4\hat{m}_s + \lambda(1, \hat{m}_s, s_b)\right)\right]$$, 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 ‡



† Altmannshofer, Wolfgang, et al. "New strategies for new physics search in B→ K* ν ν̄, B→ K ν ν̄ and B→ Xs ν ν̄ decays." *Journal of High Energy Physics* 2009.04 (2009): 022.

‡ Ali, Ahmed, et al. "Power corrections in the decay rate and distributions in B→ X s l+ l− in the standard model." *Physical Review D* 55.7 (1997): 4105.

Event Selection

- One side of B meson is reconstructed

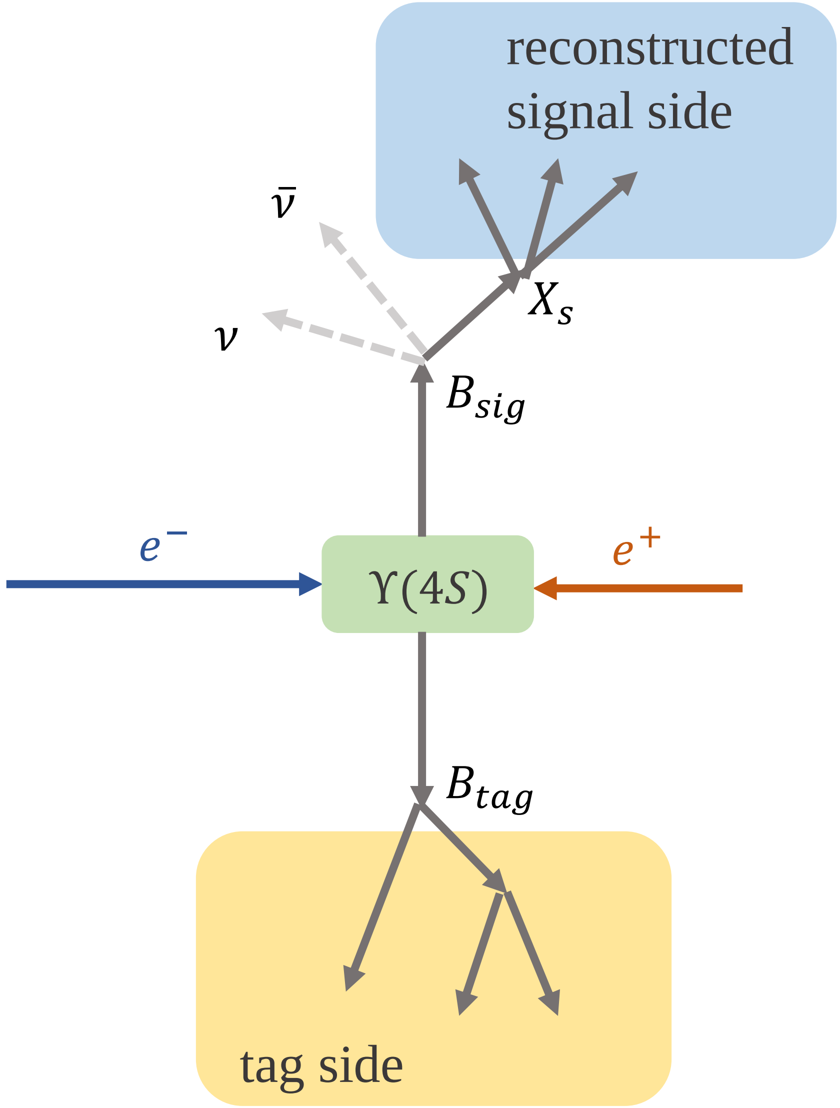
  hadronic decays are used for reconstruction

  this B meson is called B_{tag} (tag side B meson)

- Tag side B meson is used to suppress backgrounds

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

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



Event Selection

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

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

- It covers ~83% of my non-resonant X_s sample

- Pre-selections are based on
  - the number of remaining tracks
  - remaining energy deposited in the calorimeter
  - vertex fit information
  - mass of X_s candidate

Event Selection

Number of event

Selection	SIGNAL	CHG	MIX	UUBAR	DDBAR	SSBAR	CHARM
Generated	22946.1	$364.436\ fb^{-1}$					
Skim	761.7	$3.65 \cdot 10^7$	$2.81 \cdot 10^7$	$8.61 \cdot 10^7$	$2.07 \cdot 10^7$	$1.75 \cdot 10^7$	$9.80 \cdot 10^7$
Reconstruction & preselection	86.9	98380	58118	257768	61379	125023	430049
M_{bc}^{tag} > 5.27 GeV	61.7	27808	16007	51977	12613	26308	82031
$\|\Delta E^{tag}\|$ < 0.2 GeV	58.0	26917	15284	49152	11947	24805	77699
E_{ecl} < 1.5 GeV	56.4	12647	7678	19456	4859	12849	34144
0.297 < $\theta_{missing}$ < 2.618	53.1	11227	6760	16244	4087	11537	29495
0.5 < p_{X_s} < 2.96	51.3	10255	6100	14923	3772	10962	27334
D veto ($1.84 < M_{Xs} < 1.89$)	51.2	9945	5834	14735	3736	10858	26903
BCS	51.2	9945	5834	14735	3736	10858	26903
MVA	40.5	1461	791	365	109	366	552

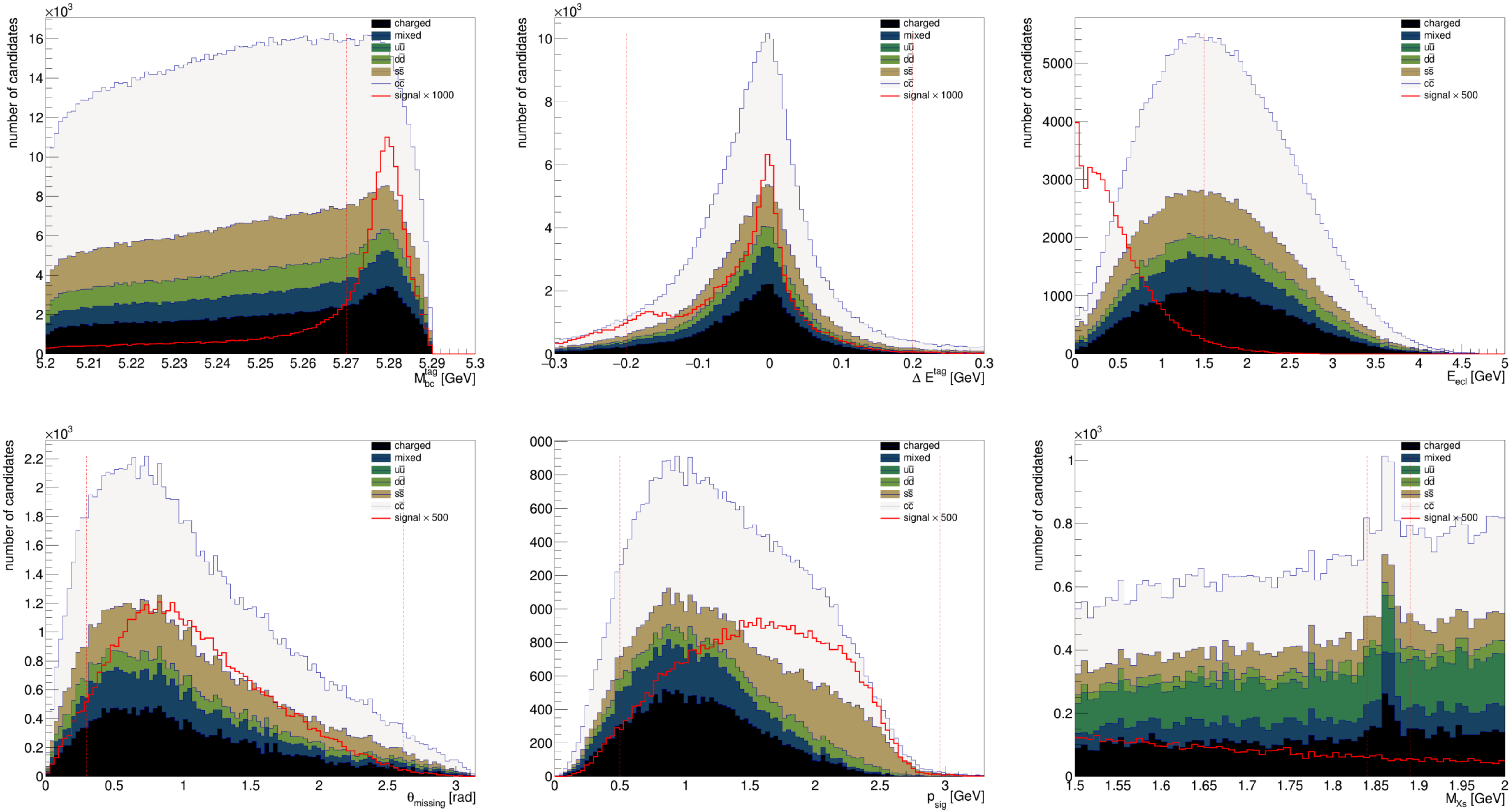
※ Signal and background samples are scaled by $364.436\ fb^{-1}$

※ Efficiency = $\frac{40.5}{22946.1} = 0.00177$

※ $M_{bc}^{tag} \equiv \sqrt{E_{beam}^2 - |p_B^2|}$

※ $\Delta E^{tag} \equiv E_B - E_{beam}$

※ E_{ecl}: remaining energy deposited in the calorimeter


×10³
number of candidates
charged
mixed
uū
dd̄
ss̄
cc̄
signal × 1000
M_{bc}^{tag} [GeV]
ΔE^{tag} [GeV]
signal × 500
E_{ecl} [GeV]
$\theta_{missing}$ [rad]
p_{sig} [GeV]
M_{Xs} [GeV]

Event Selection

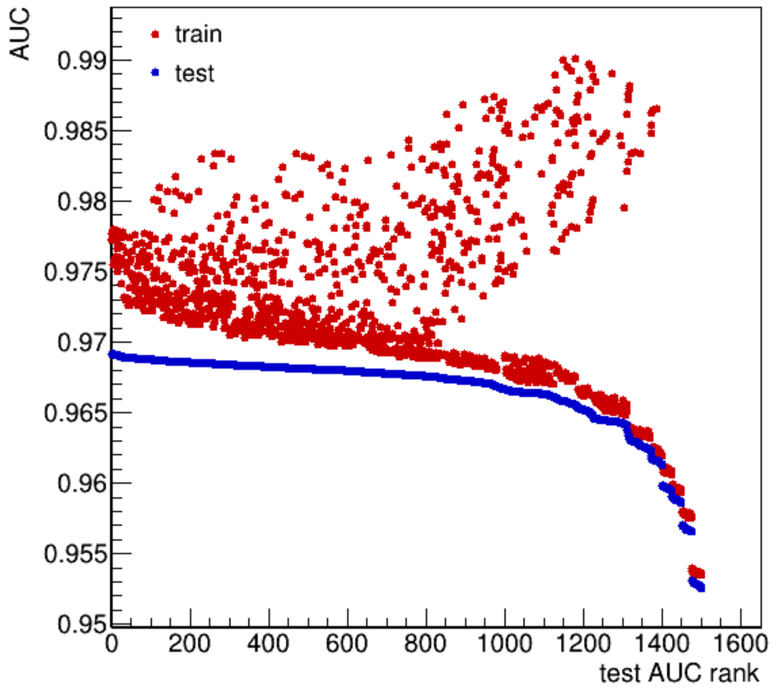
- BDT is used as MVA method
- 43 variables are used

  they are selected based on data

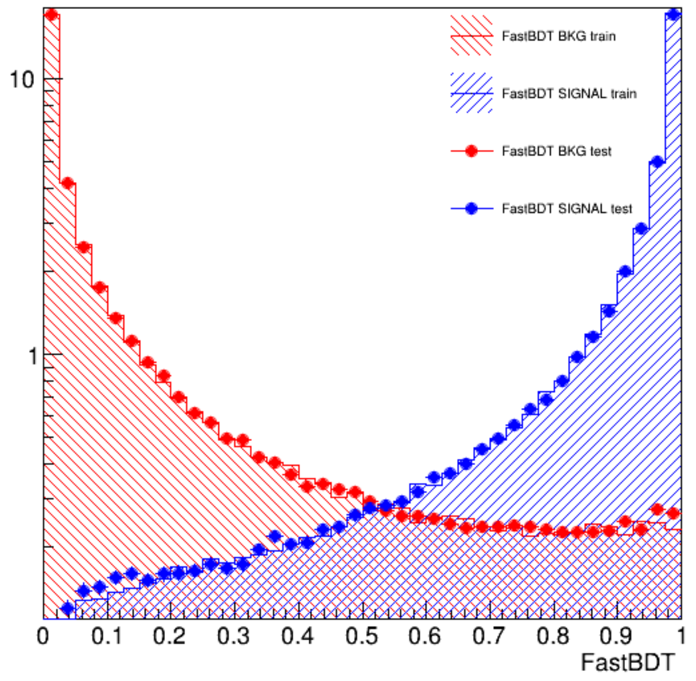
FastBDT Variables	Explanation
aplanarity	3/2 of the third sphericity eigenvalue.
Btag_chiProb	p-value of vertex fit from tag side
Btag_CleoConeCS_1, 2, 3, 4, 5	cleo cones from the continuum suppression
Btag_cosTBTO	cosine of angle between thrust axis of the B_{tag} and thrust axis of ROE
Btag_deltaE	ΔE of B_{tag}
Btag_KSFWVariables_hoo1, hoo2, hoo3, hoo4, hso1, hso03, hso04, hso10, hso12, hso20, hso22, hso24	KSFW variables of B_{tag}
Btag_useCMSFrame_theta	polar angle of B_{tag} in CMS frame
cleoConeThrust0, 1, 2, 3, 4, 5	Cleo cone calculated with respect to the thrust axis
foxWolframR1, 2, 3	Ratio of the i-th to the 0-th order Fox Wolfram moments.
harmonicMomentThrust1, 3, 4	Harmonic moment calculated with respect to the thrust axis
Btag_extraInfo_SignalProbability	Signal probability value of FEI
missingEnergyOfEventCMS	missing energy in center-of-mass frame
missingMomentumOfEvent	magnitude of the missing momentum in laboratory frame
missingMomentumOfEvent_theta	theta angle of the missing momentum of the event in laboratory frame
nParticlesInList__bomu__pl__clMuonFBDT_tight__bc	the number of muon candidates which satisfy $PID_{\mu} > 0.9$
roeEextra__bocleanMask__bc	extra energy from ECLClusters
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_M	mass of charged D meson candidate
Bsig_daughter_0_extraInfo_D0simpleveto_M	mass of neutral D meson candidate

Event Selection

- Gridsearch is used to optimize hyperparameters



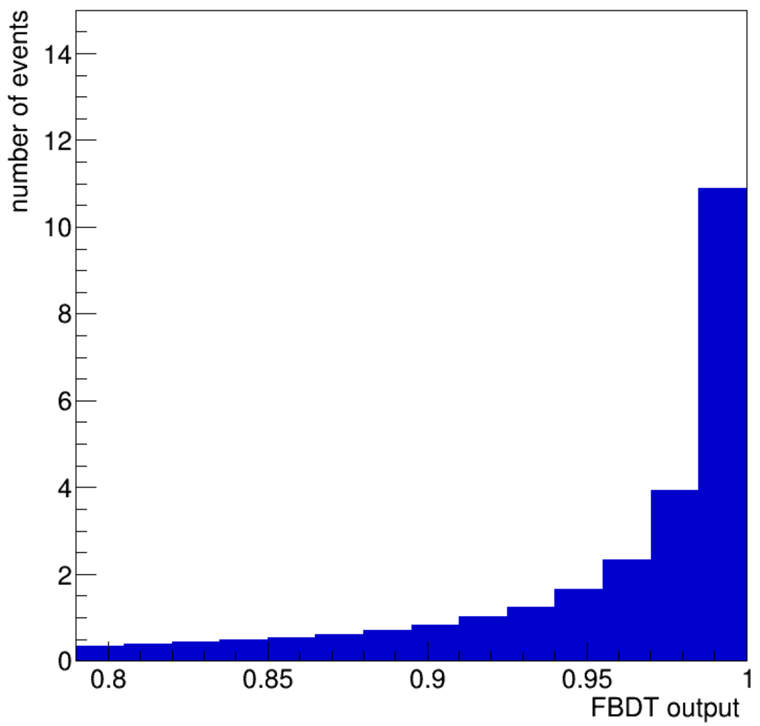
hyper parameter	tested values	selected value
nTrees	100, 500, 1000, 1500, 2000	1000
depth	2, 3, 4	2
shrinkage	0.05, 0.1, 0.15, 0.2	0.15
subsample	0.3, 0.4, 0.5, 0.6, 0.7	0.5
binning	6, 7, 8, 9	5



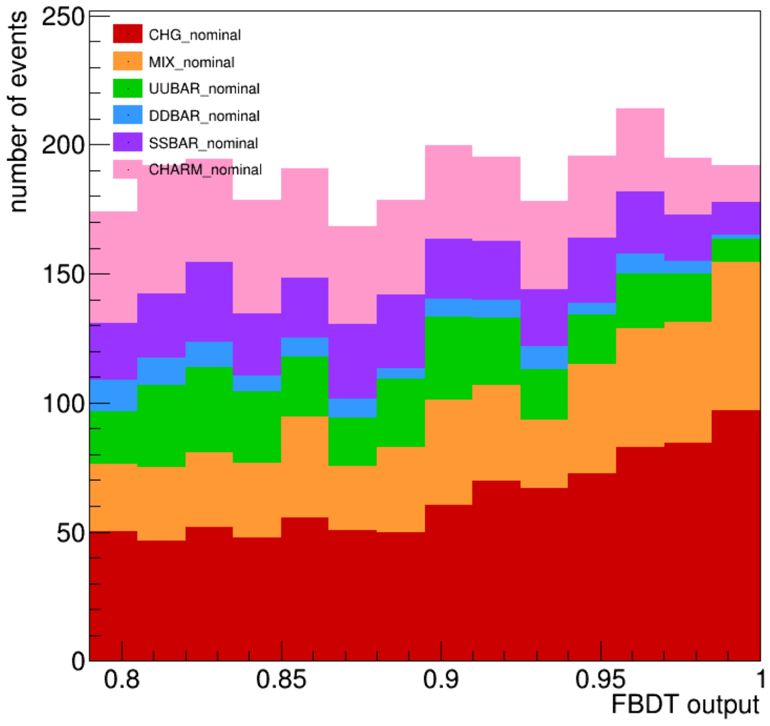
- Small overtraining can be found

However, it is acceptable amount

Event Selection



↑ signal



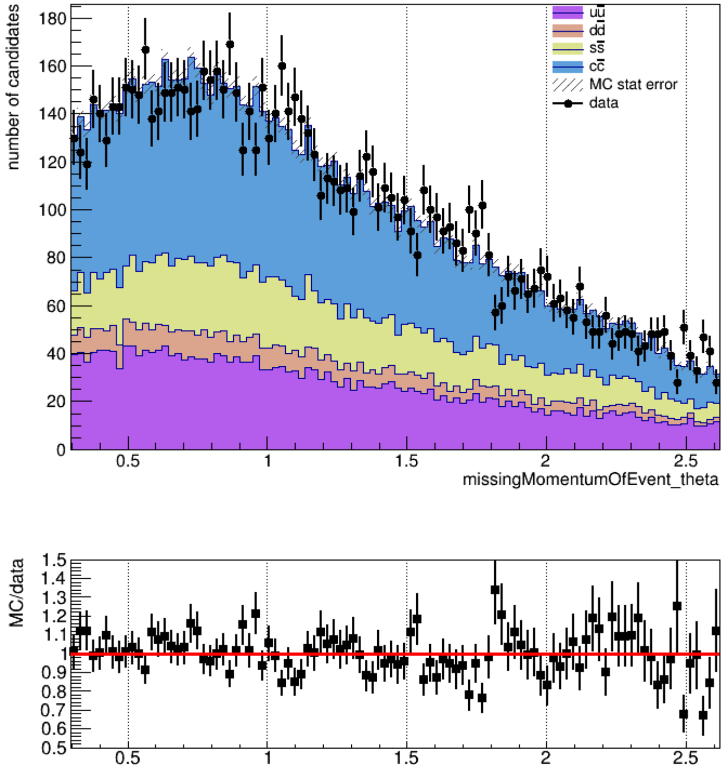
↑ background

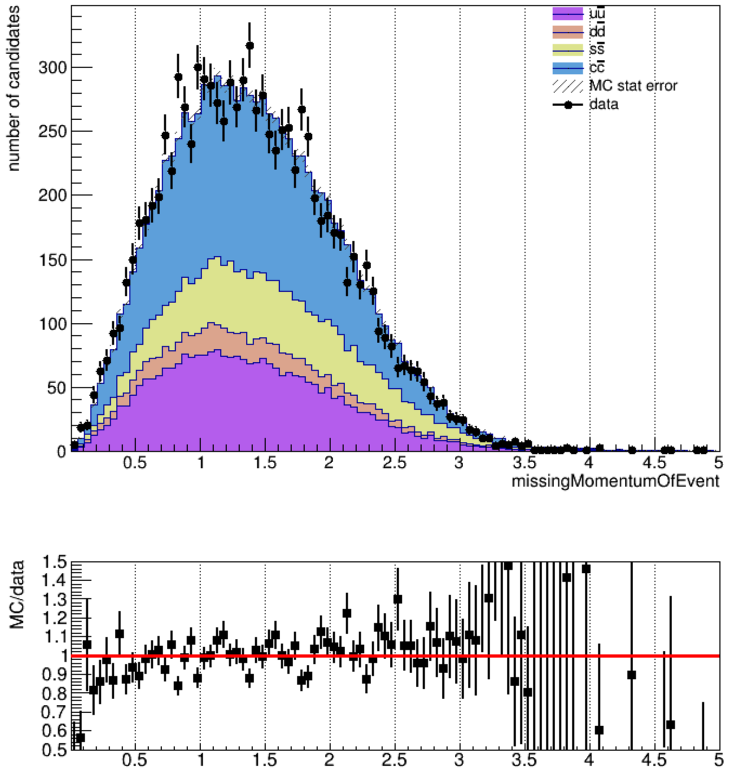
- MVA output value is also used for a fitting and limit setting

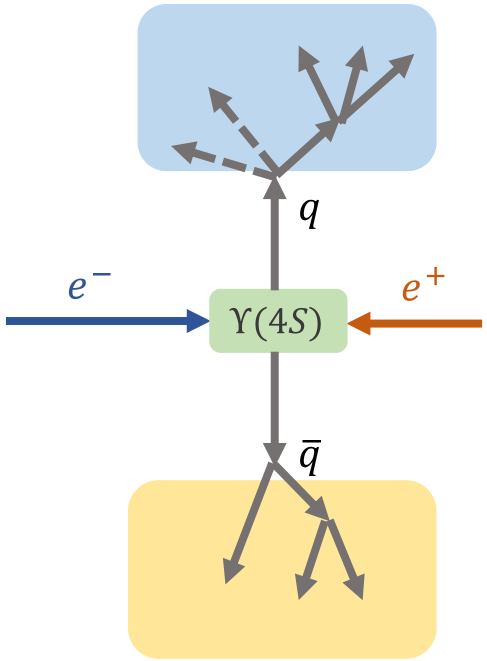
Validation

- Lower beam energy data is checked for a validation

  Because beam energy is lower, $\Upsilon(4S) \to B\bar{B}$ is not produced





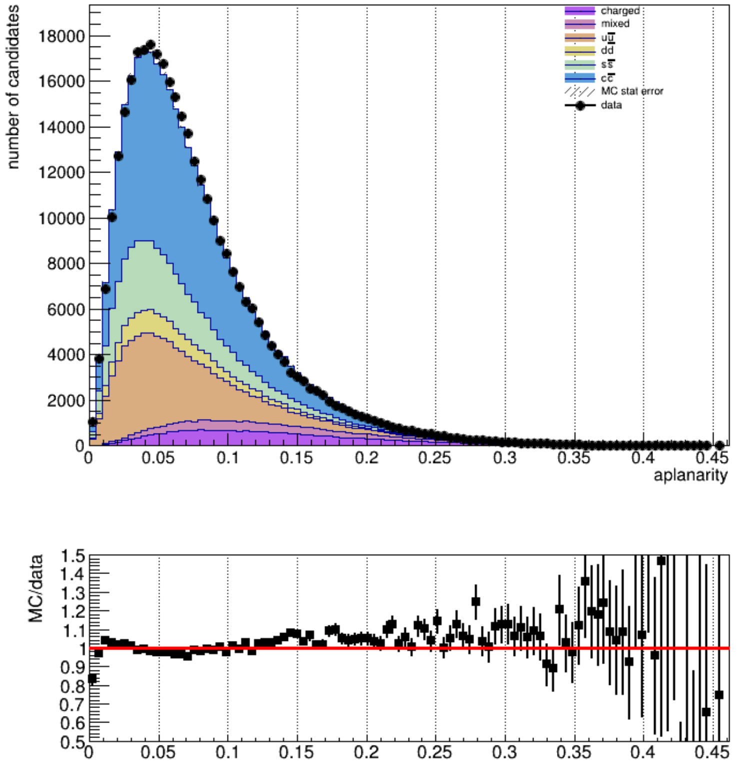


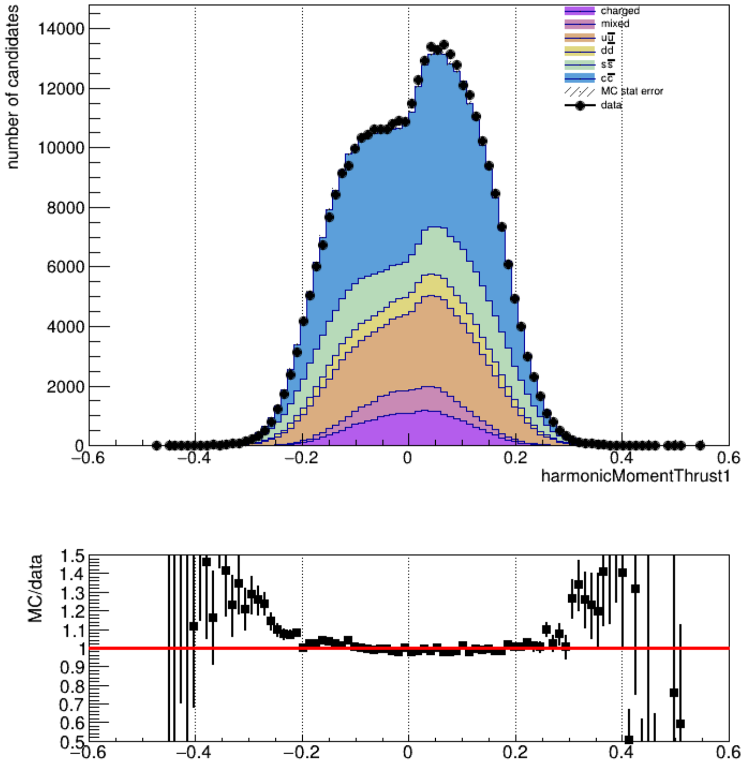
Validation

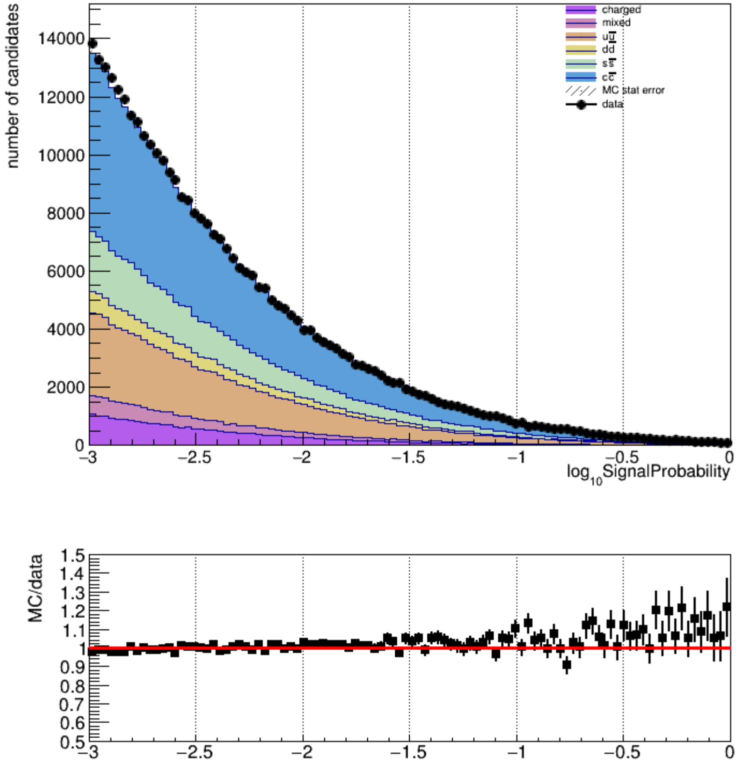
- Side band is checked for a validation

definition of sideband: $5.20 < M_{bc}^{tag} < 5.26\ \mathrm{GeV}$

※ $M_{bc}^{tag} \equiv \sqrt{E_{beam}^2 - |p_B^2|}$



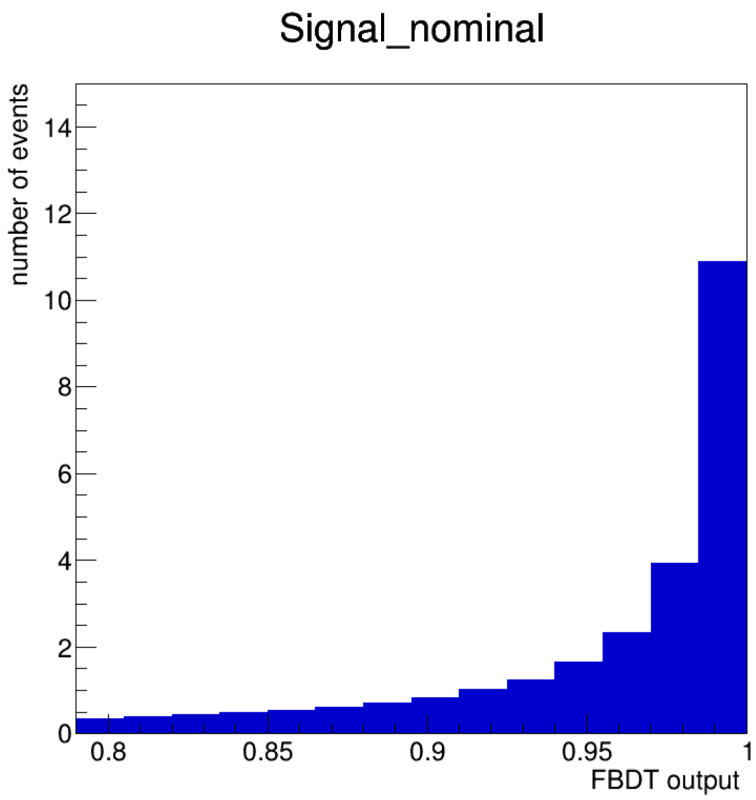


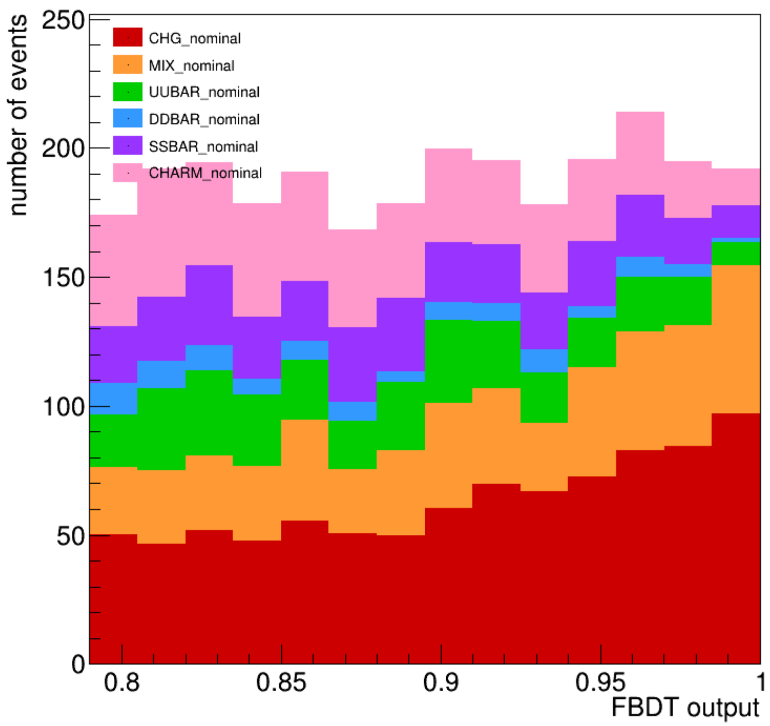


Fitting and Limit Setting

- BDT output value is used for a fitting and limit setting
- Histogram PDF is used

HistFactory is used as a tool





Fitting and Limit Setting

$$\mathcal{P}(n_{cb}, a_p \mid \phi_p, \alpha_p, \gamma_b) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb}|\nu_{cb}) \cdot G(L_0|\lambda, \Delta_L) \cdot \prod_{p \in \mathbb{S}+\Gamma} f_p(a_p|\alpha_p)$$

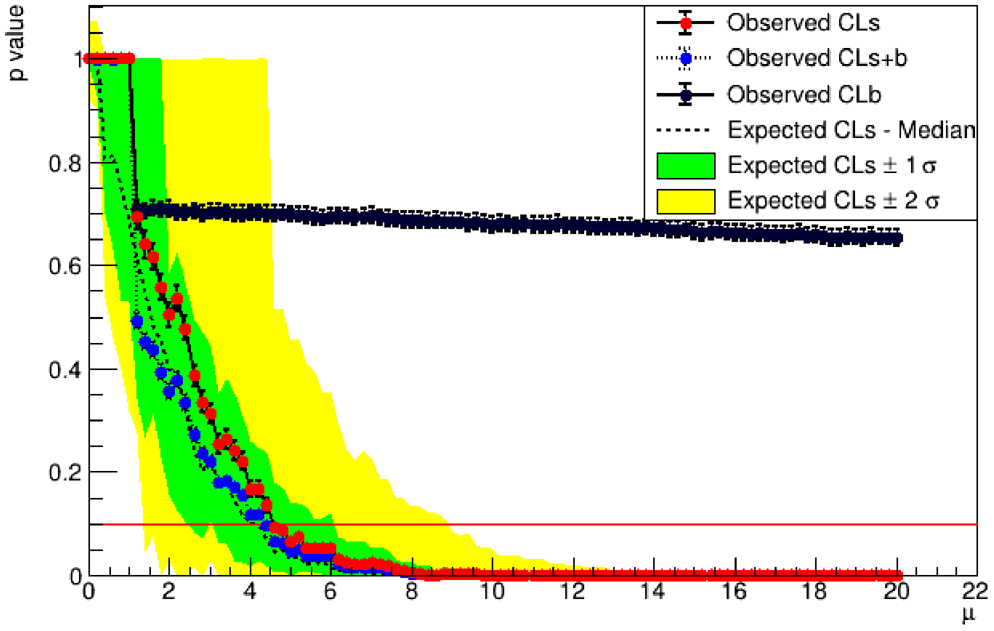
Poisson distribution for each bin/channel

Constraint term for systematic uncertainty (nuisance parameters)

- Probability density function is constructed by number of bin and constraint term

Fitting and Limit Setting

- Upper limit of branching ratio is calculated by CLs method



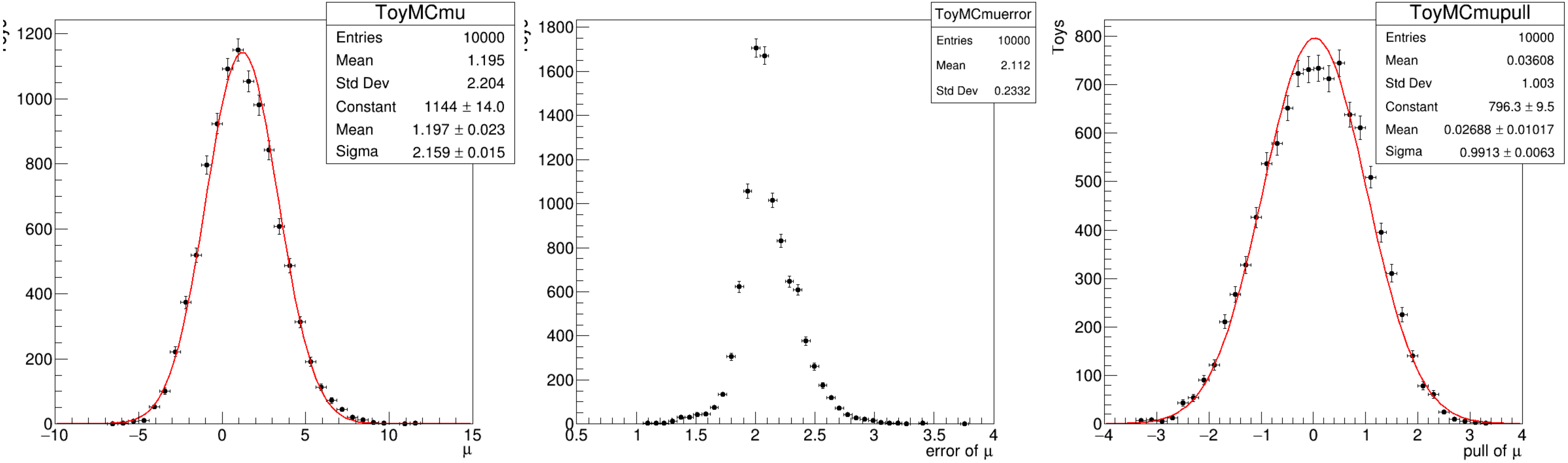
$UL(B \rightarrow X_s \nu\bar{\nu}) \sim 1.3 \times 10^{-4}$ (90CL)

※ SM prediction: $2.9 \cdot 10^{-5}$

Fitter Check

- Toy MC study is done to check a fitter quality

  All nuisance parameters are fluctuated for each toy ($\mu = 1$ when SM)

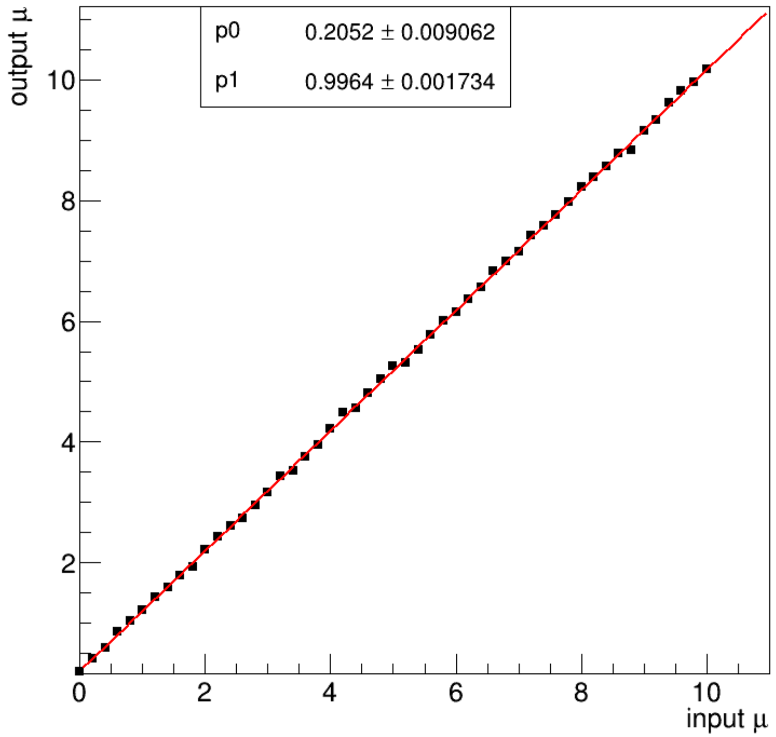


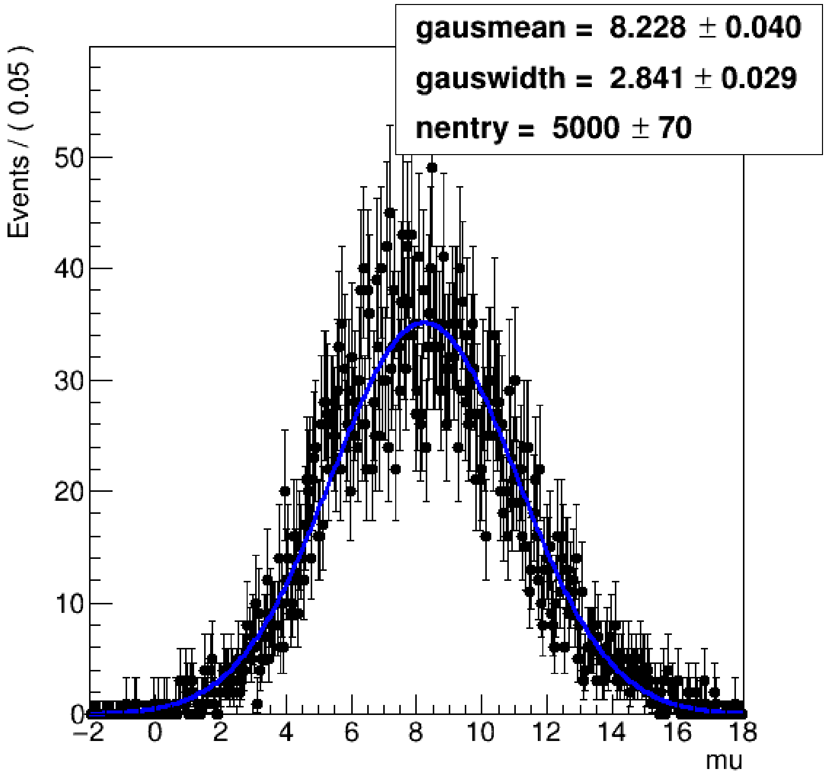
- Pull distribution seems to be fine

  $\mu = 0.027 \pm 0.010$

  $\sigma = 0.991 \pm 0.006$

Fitter Check





$\mu_{\text{injected}} = 8.0$

- Linearity test is done
- Linearity test show good linearity

$y = p_1 x + p_0$

$p_1 = 0.996 \pm 0.002$

$p_0 = 0.205 \pm 0.009$ (small bias)

Systematic Uncertainty

Source	Type
Tracking efficiency	HistoSys
Pion ID	Not yet
Kaon ID	HistoSys
K_S^0 reconstruction	HistoSys
π^0 reconstruction	HistoSys
FastBDT efficiency	Not yet
FEI calibration for $B\bar{B}$	HistoSys
Efficiency correction for $q\bar{q}$	OverallSys
$B \to K$ form factor	HistoSys
$B \to K^*$ form factor	HistoSys
Fermi motion momentum	HistoSys
$K^* - X_s$ transition	HistoSys
b-quark mass	HistoSys
Fraction of decay modes	HistoSys
MC statistics	StatError
Fragmentation	HistoSys
Mass width of K^*	HistoSys
Background normalization	OverallSys

- Systematic uncertainties are partially estimated

  remaining uncertainties will be estimated

Summary

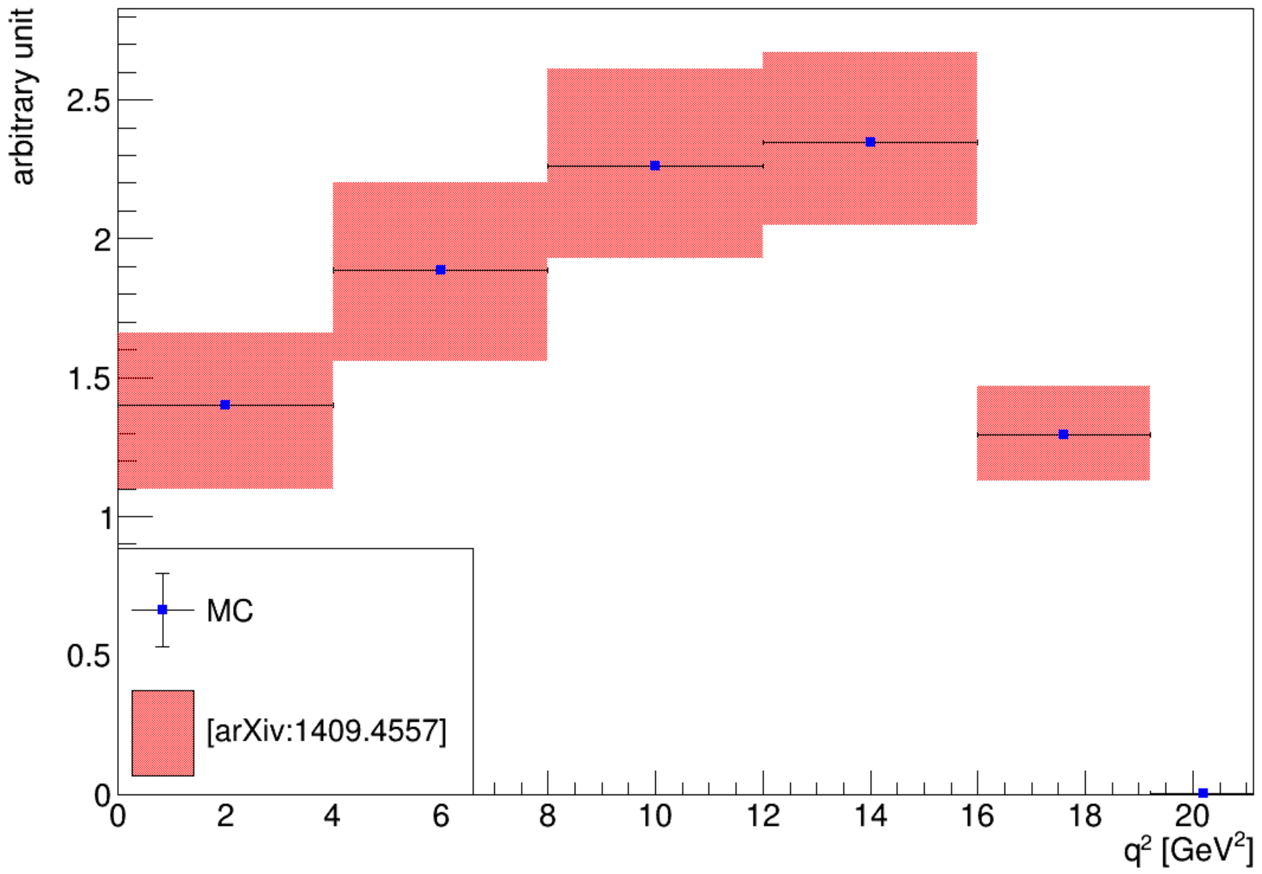
- $B \rightarrow X_s \nu \bar{\nu}$ analysis is theoretically clean
- Tagging method is used
- Some of systematic uncertainties are estimated
- Validations are done

Plan

- Control sample study ($B \rightarrow XJ/\psi$)

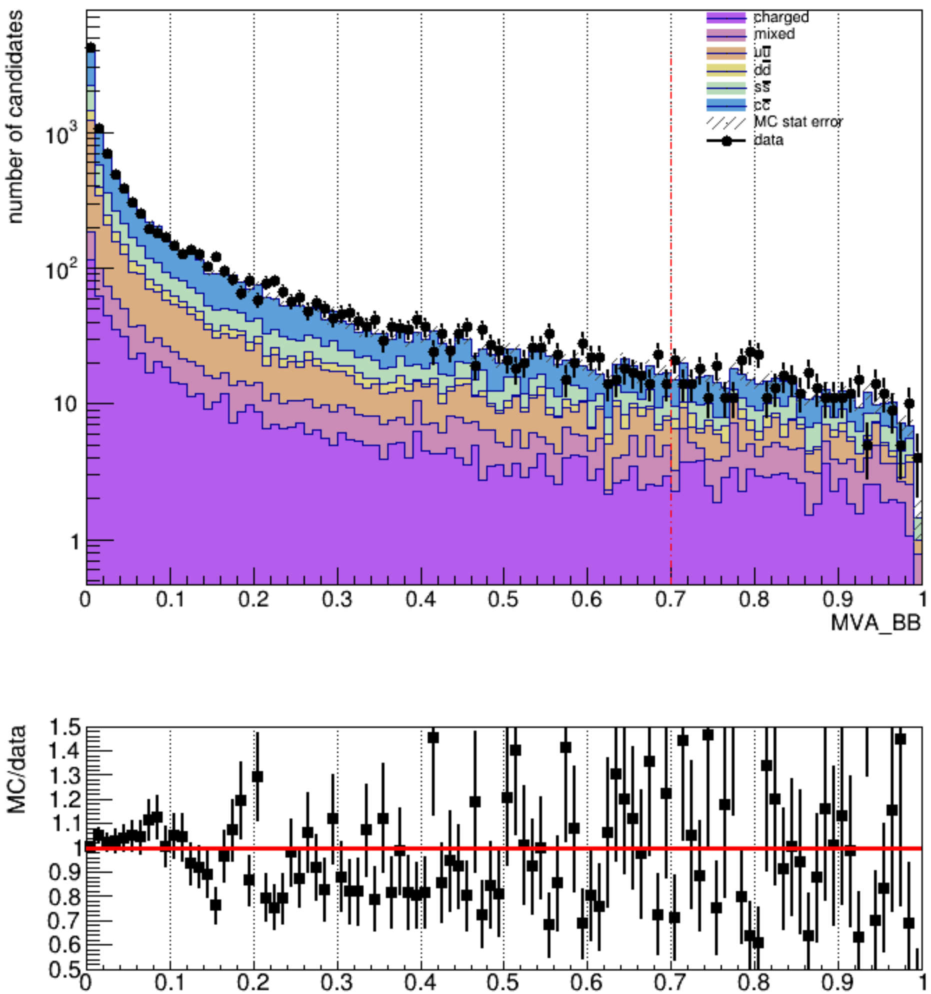
Back up

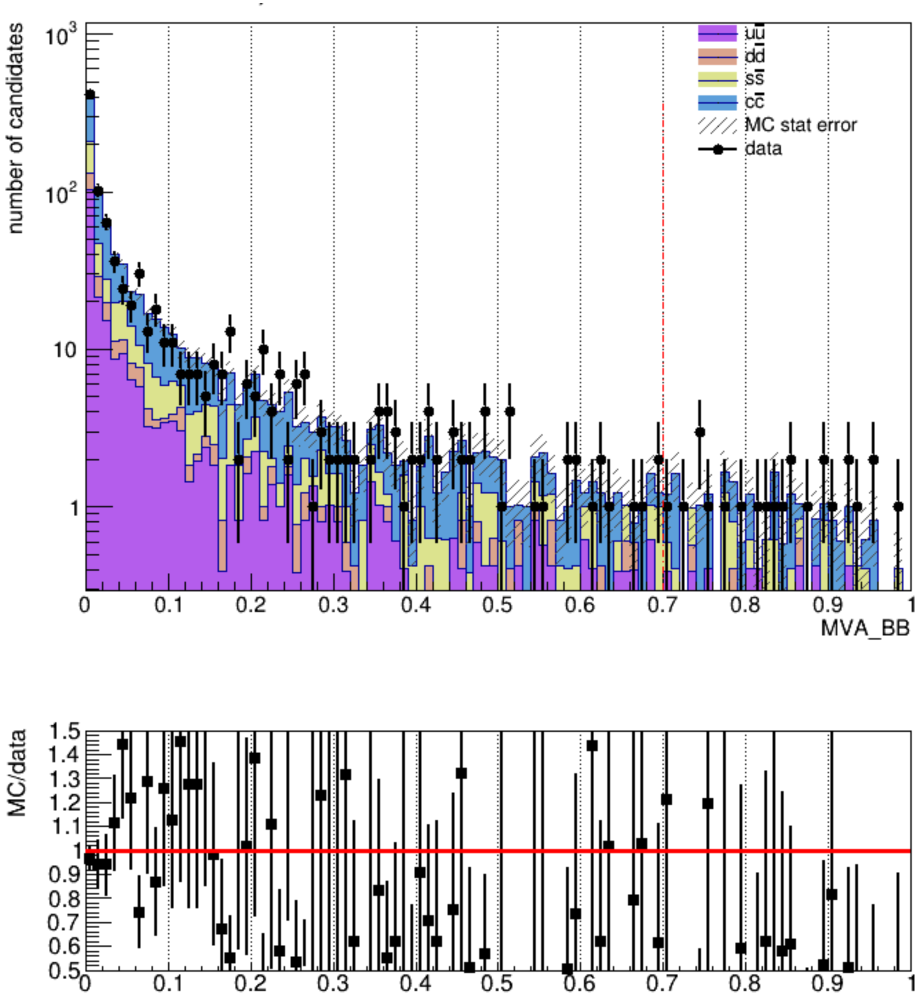
Back up

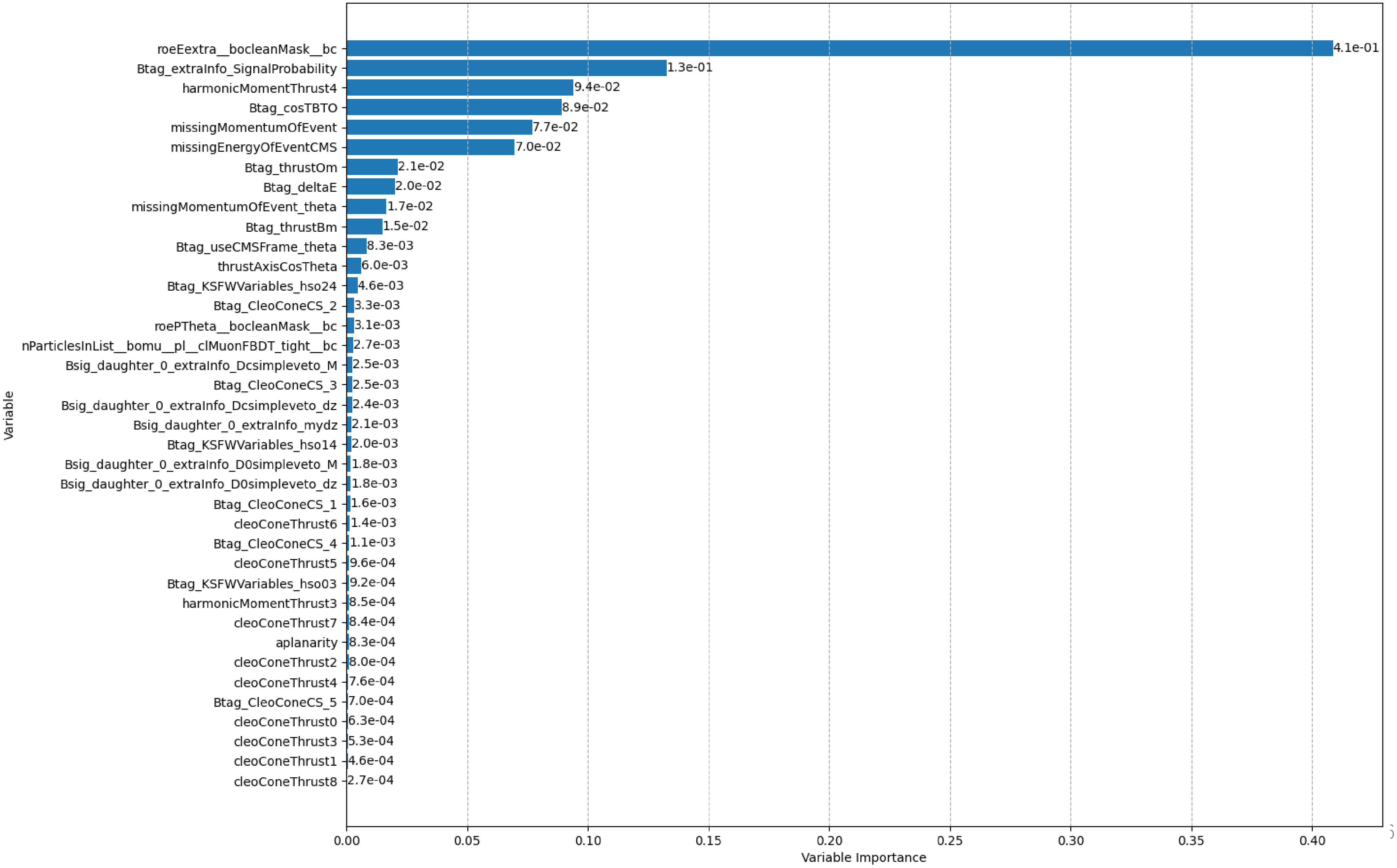


arbitrary unit
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
q² [GeV²]
MC
[arXiv:1409.4557]

Back up


charged
mixed
uū
dd̄
ss̄
cc̄
MC stat error
data
number of candidates
MVA_BB
MC/data


uū
dd̄
ss̄
cc̄
MC stat error
data
number of candidates
MVA_BB
MC/data


roeEextra__bocleanMask__bc
Btag_extraInfo_SignalProbability
harmonicMomentThrust4
Btag_cosTBTO
missingMomentumOfEvent
missingEnergyOfEventCMS
Btag_thrustOm
Btag_deltaE
missingMomentumOfEvent_theta
Btag_thrustBm
Btag_useCMSFrame_theta
thrustAxisCosTheta
Btag_KSFWVariables_hso24
Btag_CleoConeCS_2
roePTheta__bocleanMask__bc
nParticlesInList__bomu__pl__clMuonFBDT_tight__bc
Bsig_daughter_0_extraInfo_Dcsimpleveto_M
Btag_CleoConeCS_3
Bsig_daughter_0_extraInfo_Dcsimpleveto_dz
Bsig_daughter_0_extraInfo_mydz
Btag_KSFWVariables_hso14
Bsig_daughter_0_extraInfo_D0simpleveto_M
Bsig_daughter_0_extraInfo_D0simpleveto_dz
Btag_CleoConeCS_1
cleoConeThrust6
Btag_CleoConeCS_4
cleoConeThrust5
Btag_KSFWVariables_hso03
harmonicMomentThrust3
cleoConeThrust7
aplanarity
cleoConeThrust2
cleoConeThrust4
Btag_CleoConeCS_5
cleoConeThrust0
cleoConeThrust3
cleoConeThrust1
cleoConeThrust8
4.1e-01
1.3e-01
9.4e-02
8.9e-02
7.7e-02
7.0e-02
2.1e-02
2.0e-02
1.7e-02
1.5e-02
8.3e-03
6.0e-03
4.6e-03
3.3e-03
3.1e-03
2.7e-03
2.5e-03
2.5e-03
2.4e-03
2.1e-03
2.0e-03
1.8e-03
1.8e-03
1.6e-03
1.4e-03
1.1e-03
9.6e-04
9.2e-04
8.5e-04
8.4e-04
8.3e-04
8.0e-04
7.6e-04
7.0e-04
6.3e-04
5.3e-04
4.6e-04
2.7e-04
Variable
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Variable Importance