$B \to X_s \nu\bar{\nu}$ study at Belle2

Junewoo Park
Yonsei University
2022.01.28

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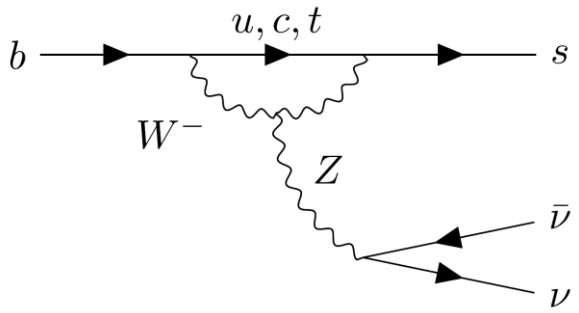
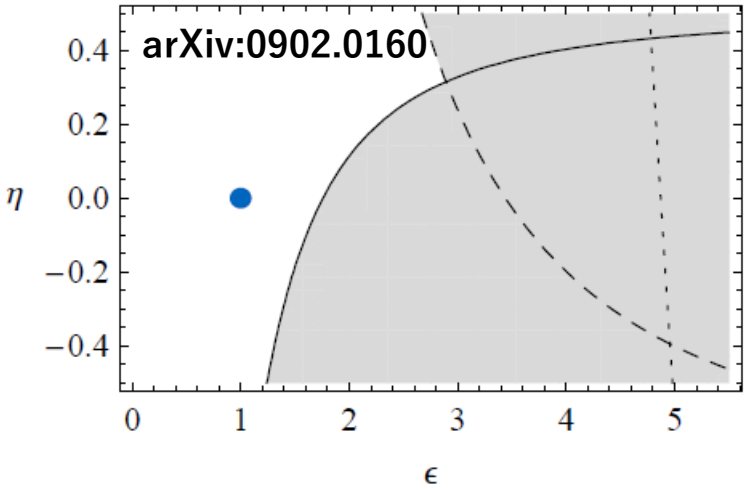
Introduction

- $B \to X_s \nu\bar{\nu}$ is theoretically clean and it can give constraints on Wilson coefficient





$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu\right) \;+\; \text{h.c.}$$

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

MC samples and setup

- MC samples

  Background MC sample: official background $1\ ab^{-1}(\Upsilon(4S) \to B^+B^-, B^0\overline{B^0}, u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c})$

  Signal sample: privately produced signal samples

  - $B^+ \to K^+\nu\bar{\nu}$: 10M
  - $B^+ \to K^{*+}\nu\bar{\nu}$: 10M
  - $B^+ \to X_s\nu\bar{\nu}$: 50M
  - $B^0 \to K^0\nu\bar{\nu}$: 10M
  - $B^0 \to K^{*0}\nu\bar{\nu}$: 10M
  - $B^0 \to X_s\nu\bar{\nu}$: 50M

- Skimming was based on FEI

  $M_{bc}^{tag} > 5.24\ \mathrm{GeV}$

  $|\Delta E^{tag}| < 0.2\ \mathrm{GeV}$

  signal probability > 0.001

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

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

MC samples and setup

- Signal MC samples were produced separately

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

  $B \to K^*\nu\bar{\nu}$

  $B \to X_s\nu\bar{\nu}$ $(M_{Xs} > 1.1\ \mathrm{GeV})$

  There ratio between modes was determined by theoretical value (reference is in the next slide)

- I used Fermi motion model to produce $B \to X_s\nu\bar{\nu}$ samples

  This model is also used in $B \to X_s ll$ model of evtgen

  In Fermi motion model, quarks inside B meson has velocity, which follows Gaussian distribution

  After producing X_s, hadronization is done by PYTHIA

- Decay was simulated by evtgen. Detector simulation was done by Geant4

MC samples and setup

- Form factor at $B \rightarrow K\,\nu\bar{\nu}$ [arXiv:1409.4557v2]
- Form factor at $B \rightarrow K^{*}\nu\bar{\nu}$ [arXiv:1503.05534v3]
- Decay distribution $B \rightarrow X_s\nu\bar{\nu}$ [arXiv:1509.06248v2]

$$\frac{d\Gamma}{ds_b} = m_b^5 \frac{\alpha^2 G_f^2}{128\pi^5} |V_{ts}^* V_{tb}|^2 \kappa(0)(|C_L^\nu|^2 + |C_R^\nu|^2)\lambda^{1/2}(1, \tilde{m}_s^2, s_b)$$
$$\times \left[3s_b(1 + \tilde{m}_s^2 - s_b - 4\tilde{m}_s \frac{Re(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}) + \lambda(1, \tilde{m}_s^2, s_b) \right] \quad ※ s_b = \frac{q^2}{{m_b}^2}$$

- Parameters for $B \rightarrow X_s\nu\bar{\nu}$ decay distribution ($m_b = 4.8$ GeV, $m_s = 0.2$ GeV)

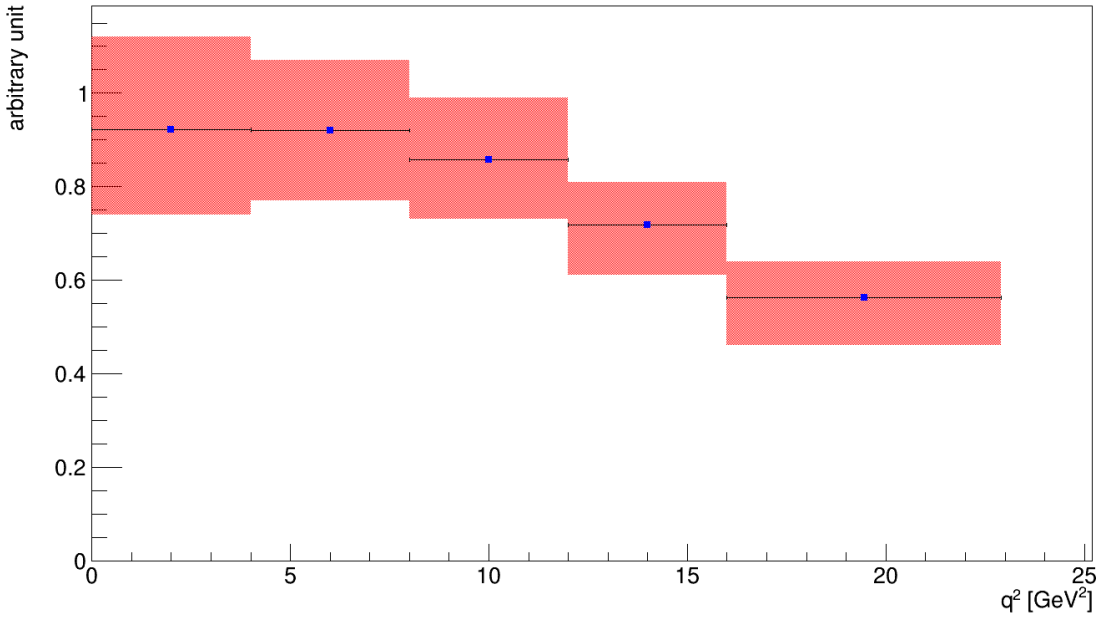
  Ali, Ahmed, et al. "Power corrections in the decay rate and distributions in B→ X s l+ l− in the standard model." *Physical Review D* 55.7 (1997): 4105.

- Fermi motion model for non-resonant $B \rightarrow X_s\nu\bar{\nu}$ decay

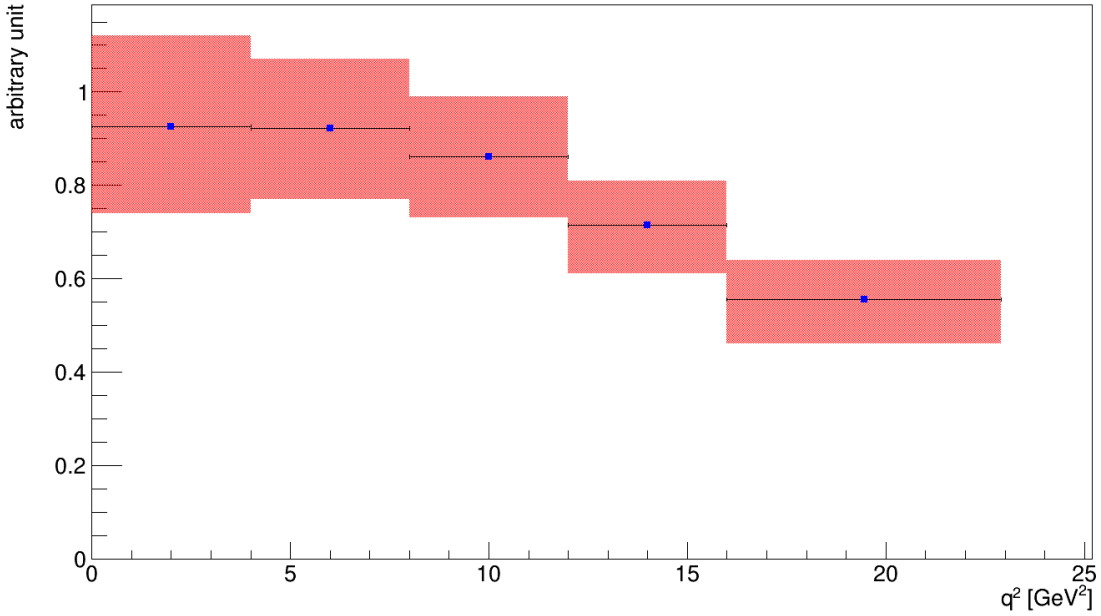
  Ali, Ahmed, et al. "Power corrections in the decay rate and distributions in B→ X s l+ l− in the standard model." *Physical Review D* 55.7 (1997): 4105.

- Parameter for fermi motion model ($p_F = 0.461$) [arXiv:1909.12524v3]
- Branching ration of $B \rightarrow K\,\nu\bar{\nu}$, $B \rightarrow K^{*}\nu\bar{\nu}$, and $B \rightarrow X_s\nu\bar{\nu}$ [arXiv:1409.4557v2]

MC samples and setup



$\uparrow B^+ \to K^+\nu\bar{\nu}$

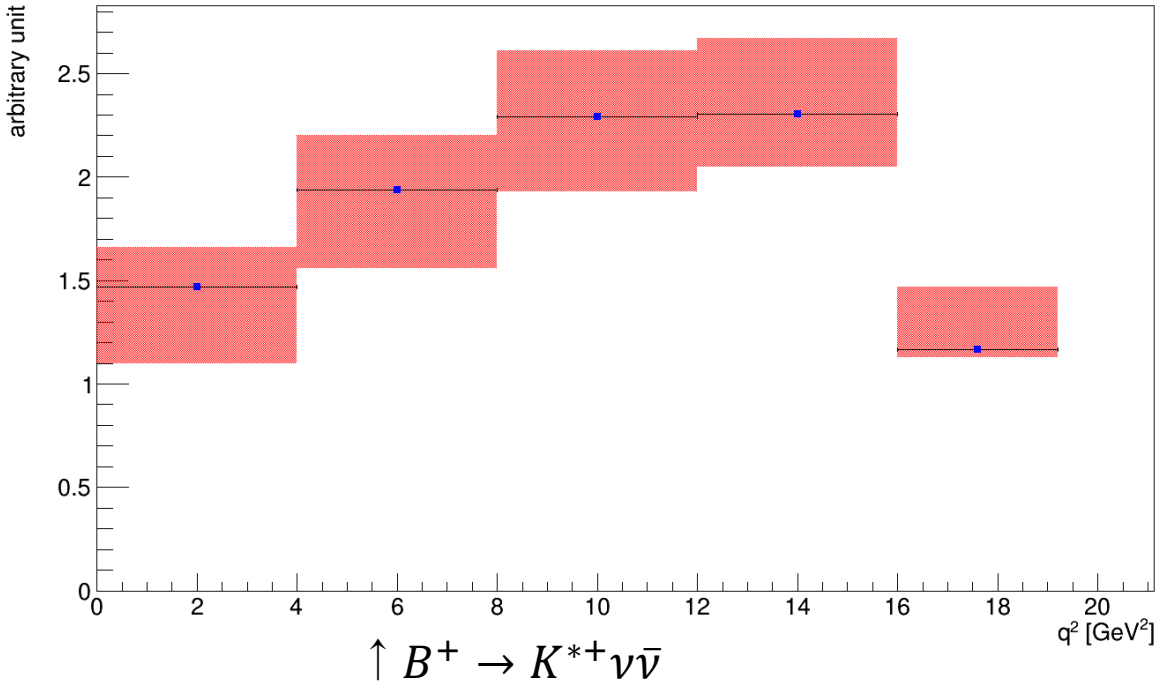


$\uparrow B^0 \to K^0\nu\bar{\nu}$

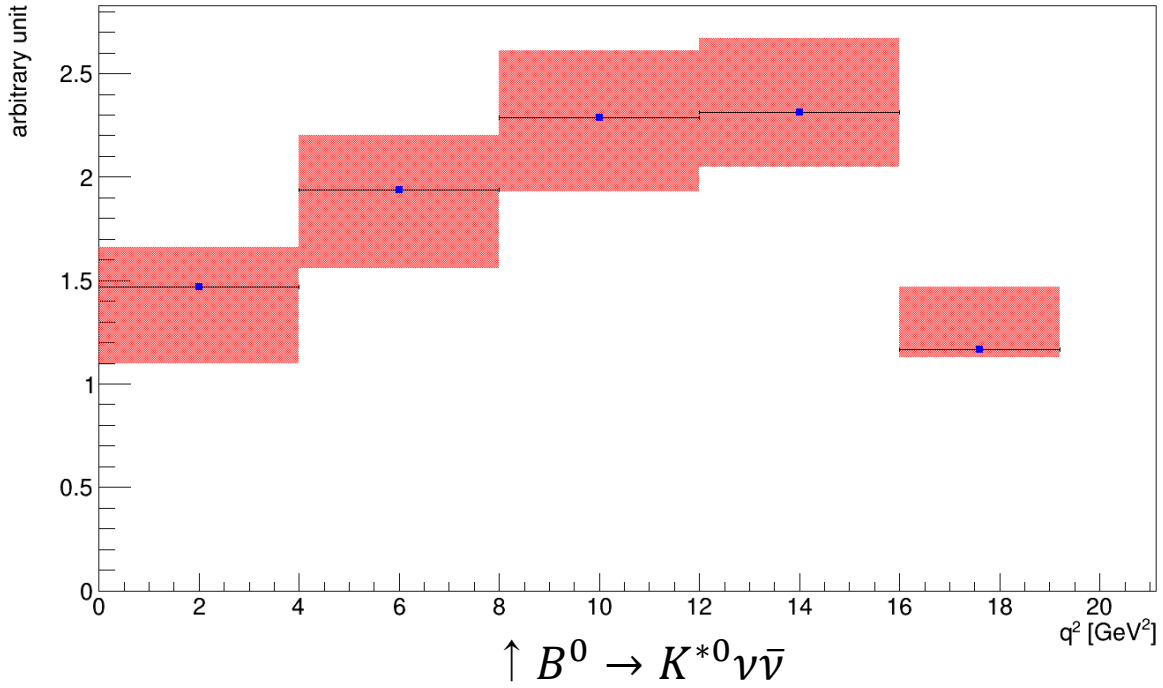
- Blue point: my MC sample (normalization: Sum of entry = 3.98)
- Red band: Theoretical calculation [arXiv:1409.4557]
  band indicates uncertainties from form factor and parameters

※ $q^2 = (p_\nu + p_{\bar{\nu}})^2$

MC samples and setup



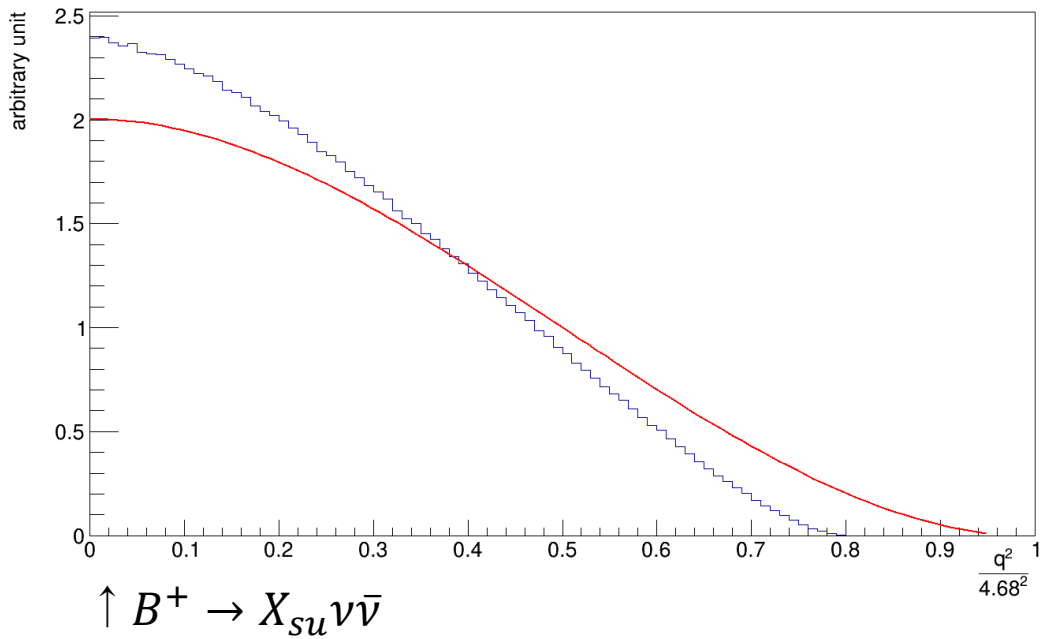
$\uparrow B^+ \to K^{*+}\nu\bar{\nu}$



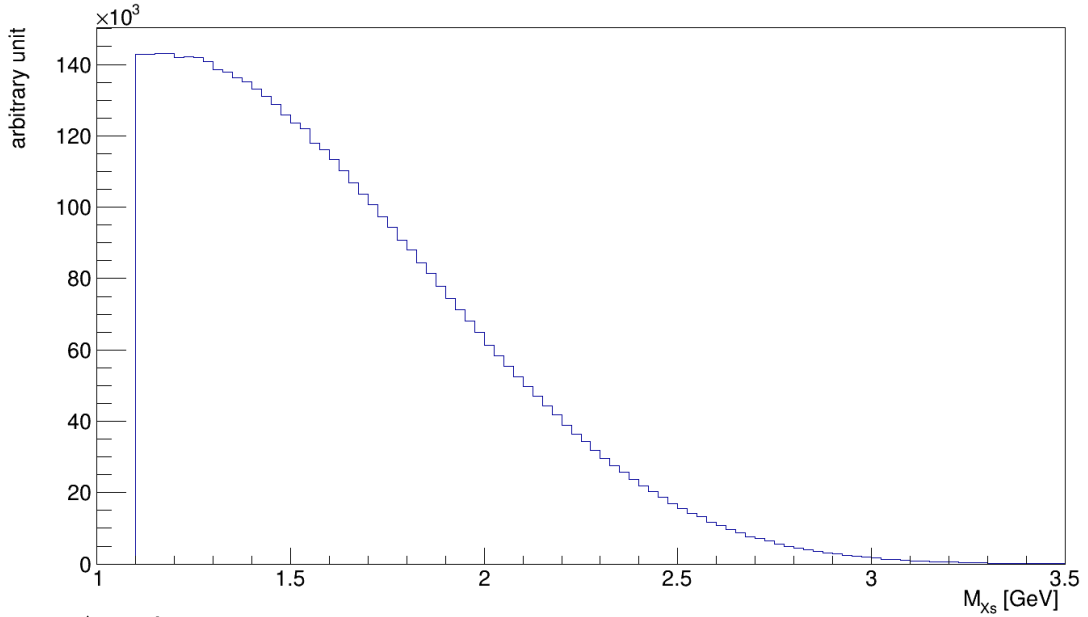
$\uparrow B^0 \to K^{*0}\nu\bar{\nu}$

- Blue point: my MC sample (normalization: Sum of entry = 9.19)
- Red band: Theoretical calculation [arXiv:1409.4557]
  band indicates uncertainties from form factor and parameters

MC samples and setup



↑ $B^+ \to X_{su}\nu\bar{\nu}$



↑ $B^+ \to X_{su}\nu\bar{\nu}$

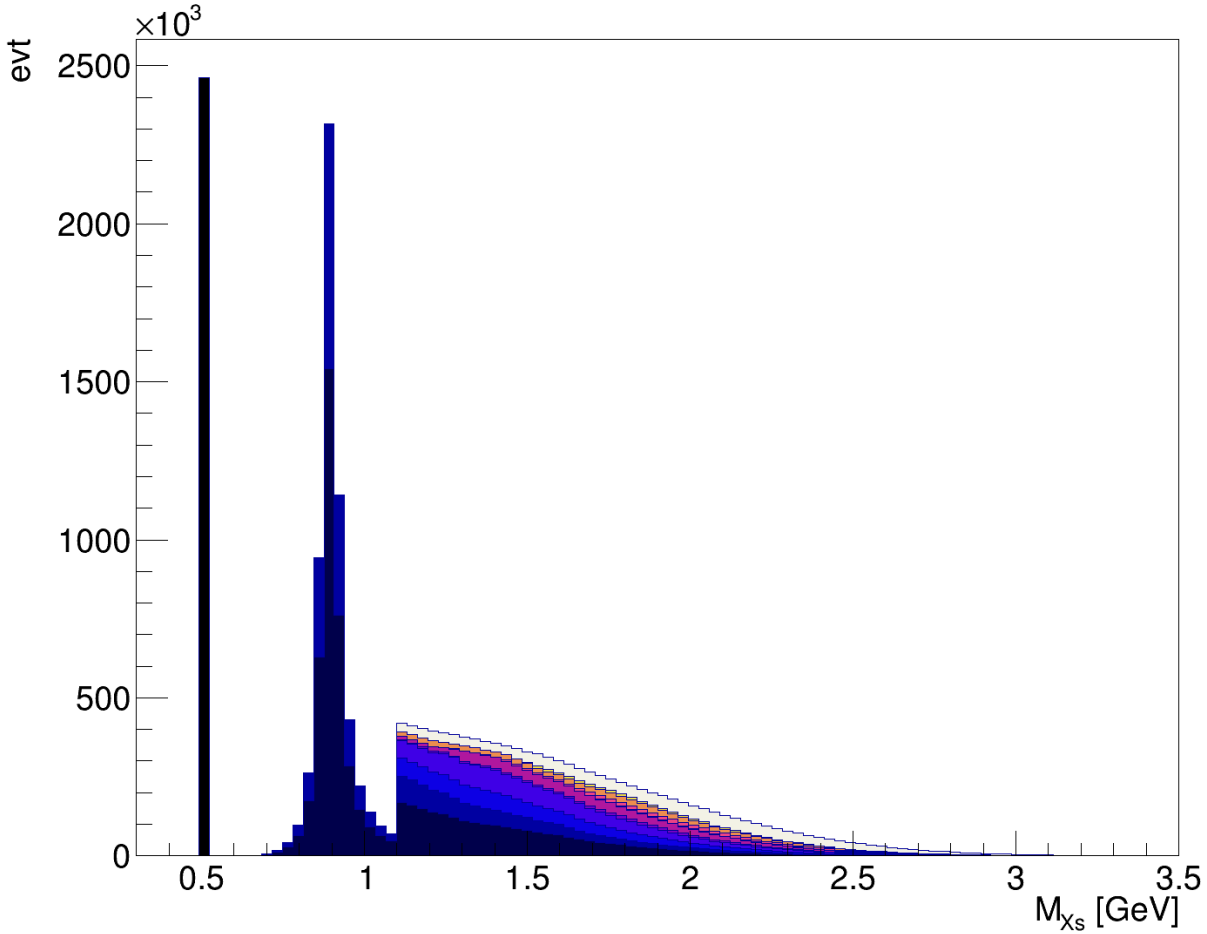
- Left histogram: my MC sample ($m_b = 4.8$ GeV, $m_s = 0.2$ GeV) ‡

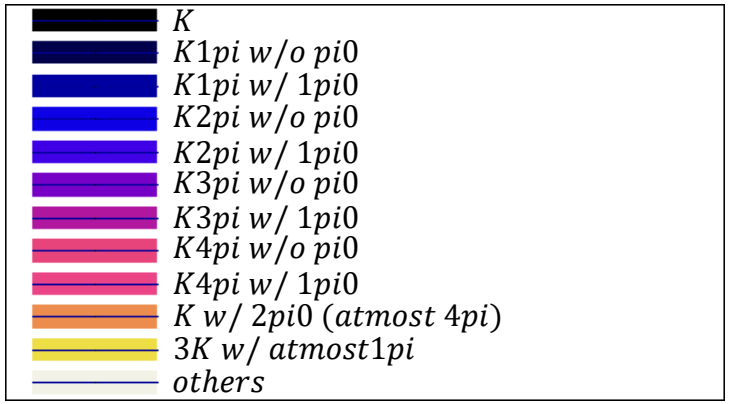
  Red line: theoretical calculation including resonant decay ($m_b = 4.68$ GeV, $m_s = 0.1$ GeV) [arXiv:1509.06248]

- Right histogram: Mass distribution of my MC sample

‡ 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.

MC samples and setup





- Hadronization of X_s was done by PYTHIA

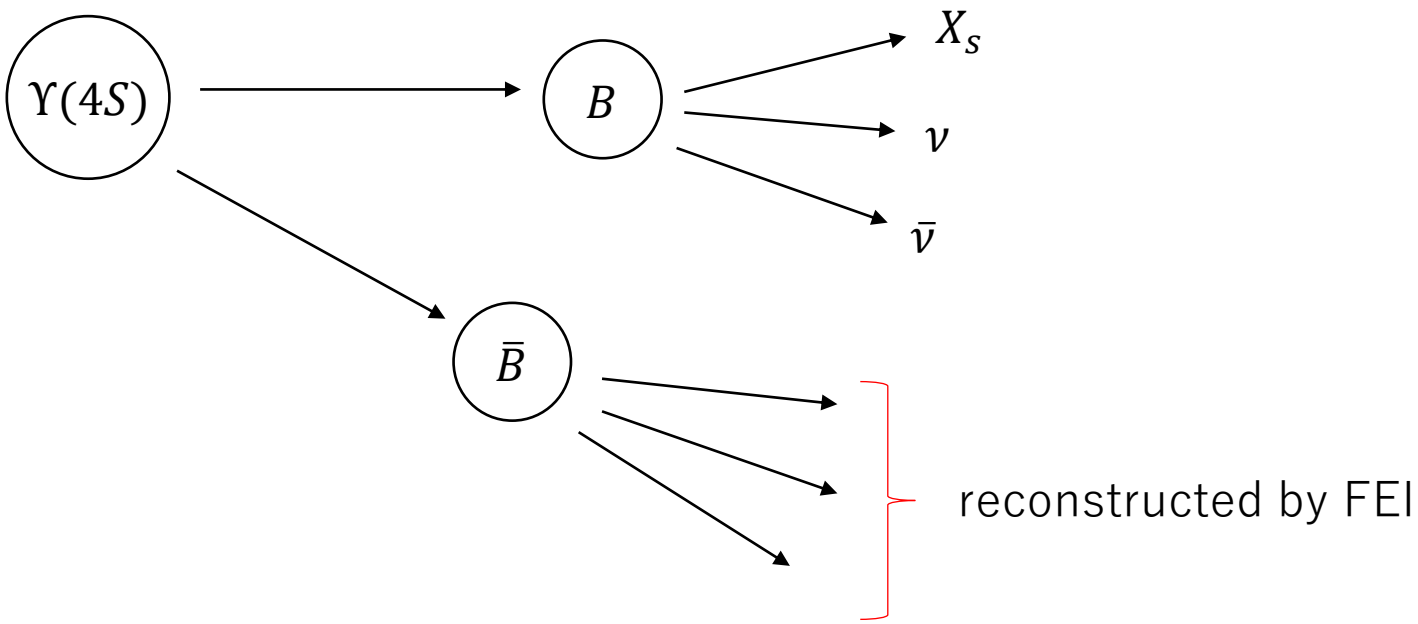
Particle selection criteria

Particle	Selection Criteria
Charged tracks	$dr < 0.5$ cm, $\lvert dz\rvert < 2$ cm
$K^{\pm}$	$PID_K > 0.6$, nCDCHits > 20
$\pi^{\pm}$	$PID_\pi > 0.6$, nCDCHits > 20
K_S^0	Reconstructed from two oppositely charged tracks with the vertex fit significanceOfDistance > 50, 0.4876 < M < 0.5076 GeV
γ	$17° < \theta_\gamma < 150°$, clusterNHits > 1.5 and [clusterReg == 1 and $E > 0.08$ GeV] or [clusterReg == 2 and $E > 0.03$ GeV] or [clusterReg == 3 and $E > 0.06$ GeV]
π^0	Reconstructed from two $\gamma's$ $0.12 < M_{\gamma\gamma} < 0.145$ GeV, $-1.5 < \Delta\phi_{\gamma\gamma} < 1.5$ rad, $p_{\pi^0} > 0.4$ GeV

Reconstruction and analysis

- Full event interpretation (FEI) was used to reconstruct tag side of B meson

  hadronic tag was used



- I reconstruct 20 decay modes of signal side (sum of exclusives method)

$B^+ \to K^+\nu\bar{\nu}$ $B^+ \to K^+\pi^0\nu\bar{\nu}$ $B^+ \to K_S^0\pi^0\nu\bar{\nu}$ $B^+ \to K_S^0\pi^+\pi^0\nu\bar{\nu}$ $B^+ \to K^+\pi^-\pi^+\pi^0\nu\bar{\nu}$

$B^+ \to K_S^0\pi^+\pi^-\pi^+\nu\bar{\nu}$ $B^+ \to K^+K^-K^+\nu\bar{\nu}$ $B^0 \to K_S^0\nu\bar{\nu}$ $B^0 \to K^+\pi^-\nu\bar{\nu}$ $B^0 \to K^0\pi^0\nu\bar{\nu}$

$B^0 \to K^+\pi^-\pi^0\nu\bar{\nu}$ $B^0 \to K_S^0\pi^+\pi^-\nu\bar{\nu}$ $B^0 \to K^+\pi^-\pi^+\pi^-\nu\bar{\nu}$ ⋯ and more⋯

Reconstruction and analysis

Number of event

Selection	SIGNAL	CHG	MIX	UUBAR	DDBAR	SSBAR	CHARM
Generated	18889	$0.3\ ab^{-1}$					
Skimed	240.21	$2.31 \cdot 10^7$	$1.74 \cdot 10^7$	$4.85 \cdot 10^7$	$1.17 \cdot 10^7$	$9.67 \cdot 10^6$	$5.59 \cdot 10^7$
Reconstructed & preselection	119.18	$4.33 \cdot 10^6$	$2.90 \cdot 10^6$	$5.84 \cdot 10^6$	$1.35 \cdot 10^6$	$2.11 \cdot 10^6$	$1.01 \cdot 10^7$
Number of remaining clean track	76.86	$2.01 \cdot 10^5$	$1.30 \cdot 10^5$	$3.89 \cdot 10^5$	94368	$2.04 \cdot 10^5$	$7.25 \cdot 10^5$
$0.297 < \theta_{missing} < 2.618$	72.16	$1.77 \cdot 10^5$	$1.15 \cdot 10^5$	$3.20 \cdot 10^5$	78253	$1.80 \cdot 10^5$	$6.23 \cdot 10^5$
$0.5 < p_{sig} < 2.96$	69.02	$1.62 \cdot 10^5$	$1.04 \cdot 10^5$	$3.00 \cdot 10^5$	73631	$1.72 \cdot 10^5$	$5.83 \cdot 10^5$
$M_{bc}^{tag} > 5.27$	55.39	70432	44147	$1.05 \cdot 10^5$	25522	60966	$1.99 \cdot 10^5$
D veto	55.17	67187	42039	$1.01 \cdot 10^5$	24611	59432	$1.93 \cdot 10^5$
MVA	4.65	70	25	5	2	1	6
BCS	4.65	70	25	5	2	1	6

※ Signal sample is scaled by $0.3\ ab^{-1}$

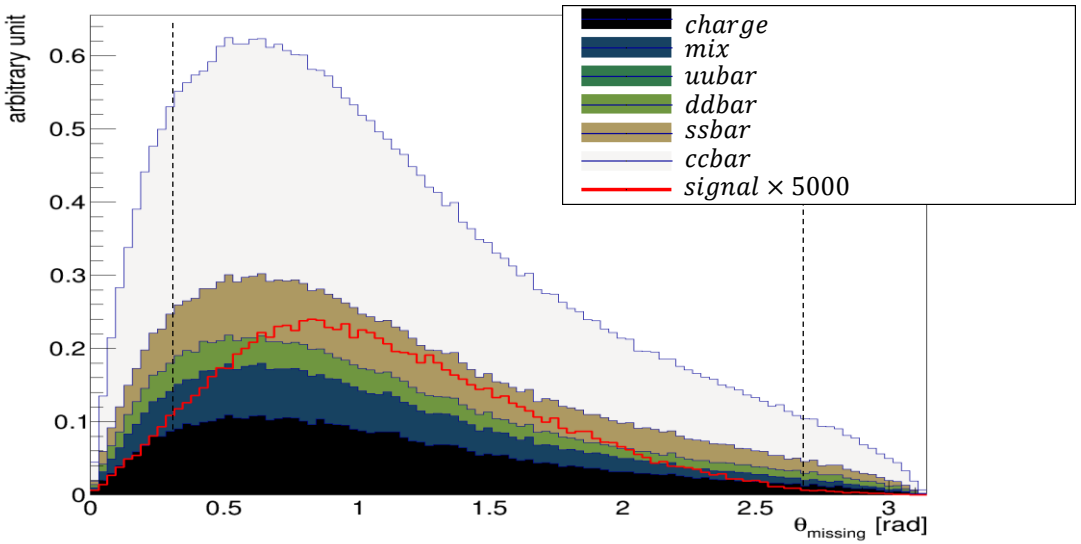
※ Clean track: $dr < 0.5$ cm, $|dz| < 2$ cm

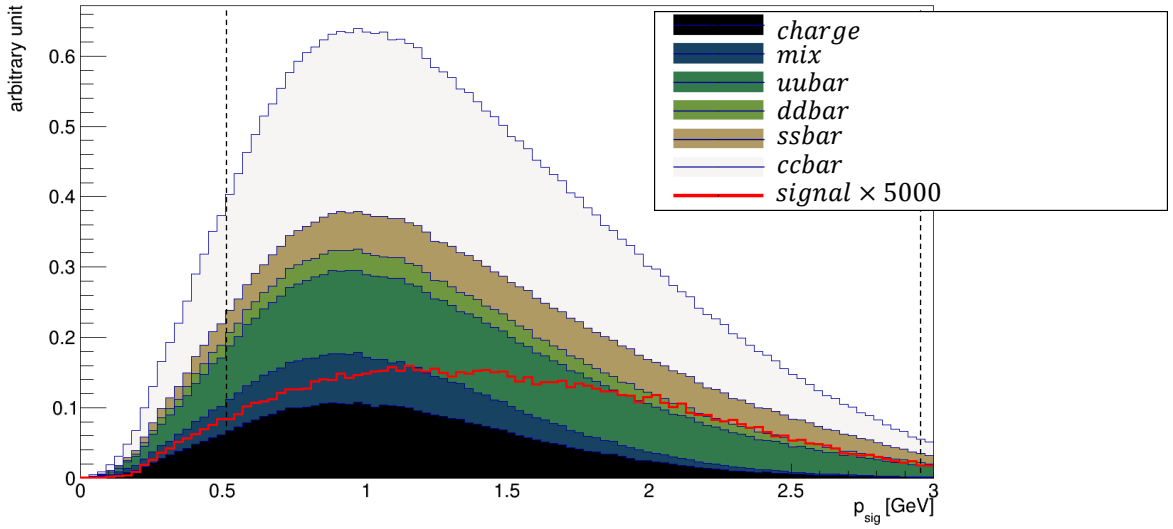
※ Best candidate selection was done by SignalProbability

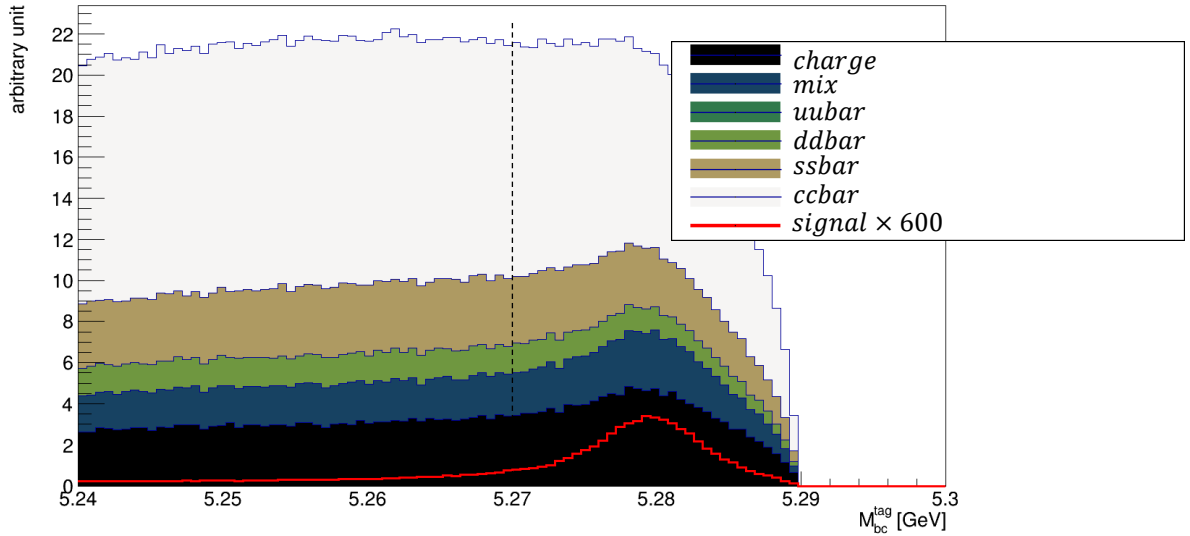
- D veto

Get mass from all combination of B_{sig} whose charge is 0 or ± 1.
And reject if the mass is in D meson mass window

Reconstruction and analysis







Reconstruction and analysis

- I used 15 variables for TMVA

Variables	Explanation
thrustBm	magnitude of the thrust axis
cosTBTO	cosine of angle between thrust axis of the B_{tag} and thrust axis of ROE
hso00, hso22, hso24, hoo1	KSFW variables
θ_{tag}	θ of B_{tag} in CMS frame
SignalProbability	Signal probability of B_{tag} from FEI
chiProb	χ^2 probability from vertex fit of B_{tag}
θ_{miss}	θ of missing momentum
nRemainingTracksInEvent	The number of remaining raw tracks
harmonicMomentThrust1	Harmonic moment of the 1st order calculated with respect to the thrust axis
cleoConeThrust0	0th Cleo cone calculated with respect to the thrust axis
MsquaredBsig_op1	$(p_{sig} + p_{miss})^2$ at CMS frame
ΔE^{tag}	ΔE of B_{tag}

I tried to select variables which had a low correlation with E_{ecl}

Reconstruction and analysis

- I trained 4 BDTs

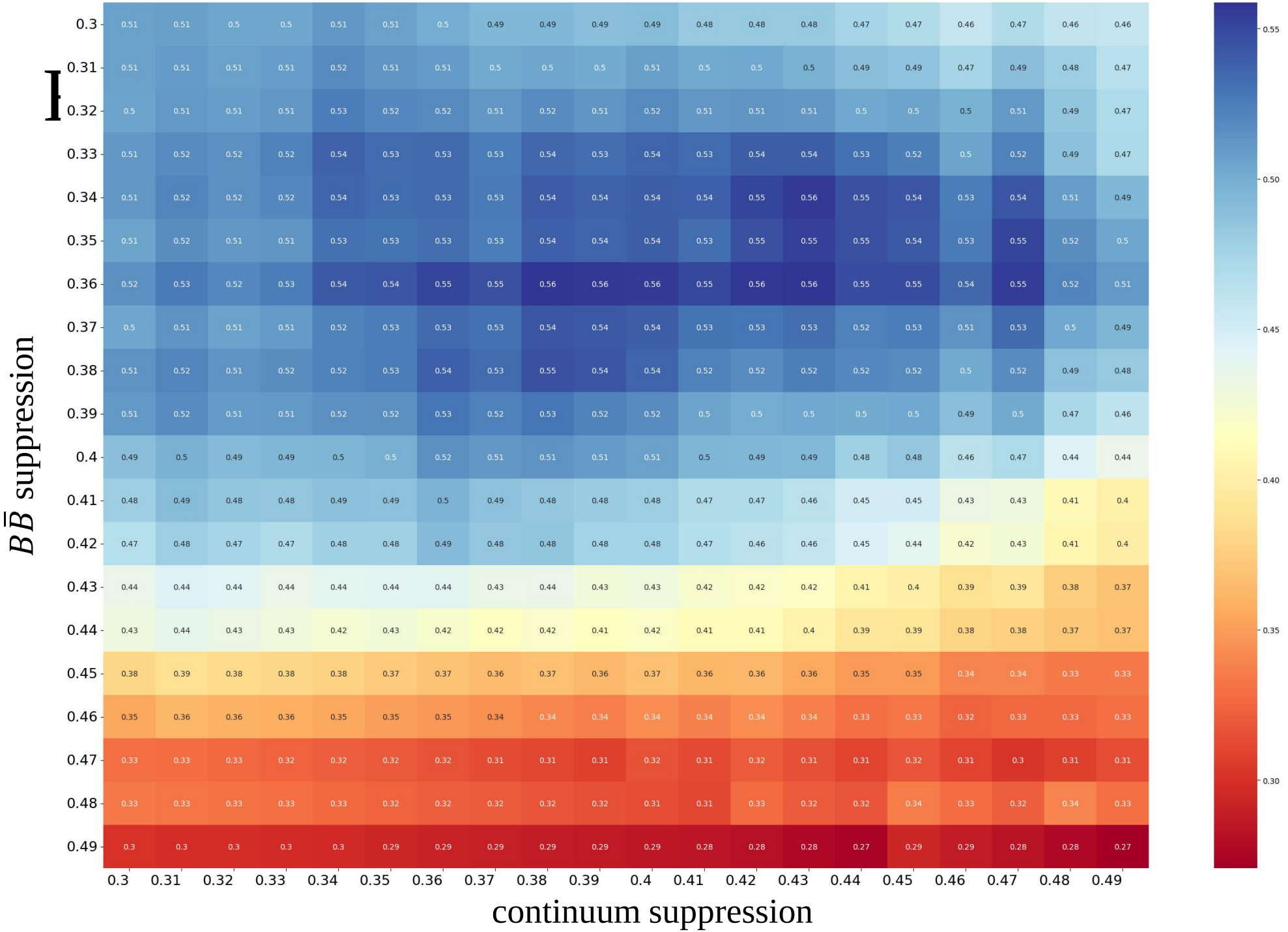
  signal VS continuum & $M_{Xs} < 1.1\ \mathrm{GeV}$

  signal VS $B\bar{B}$ & $M_{Xs} < 1.1\ \mathrm{GeV}$

  signal VS continuum & $M_{Xs} > 1.1\ \mathrm{GeV}$

  signal VS $B\bar{B}$ & $M_{Xs} > 1.1\ \mathrm{GeV}$

- Each signal candidate has two BDT outputs



← FOM plot for $M_{Xs} < 1.1\ \mathrm{GeV}$ and $E_{ecl} < 2\ \mathrm{GeV}$ region

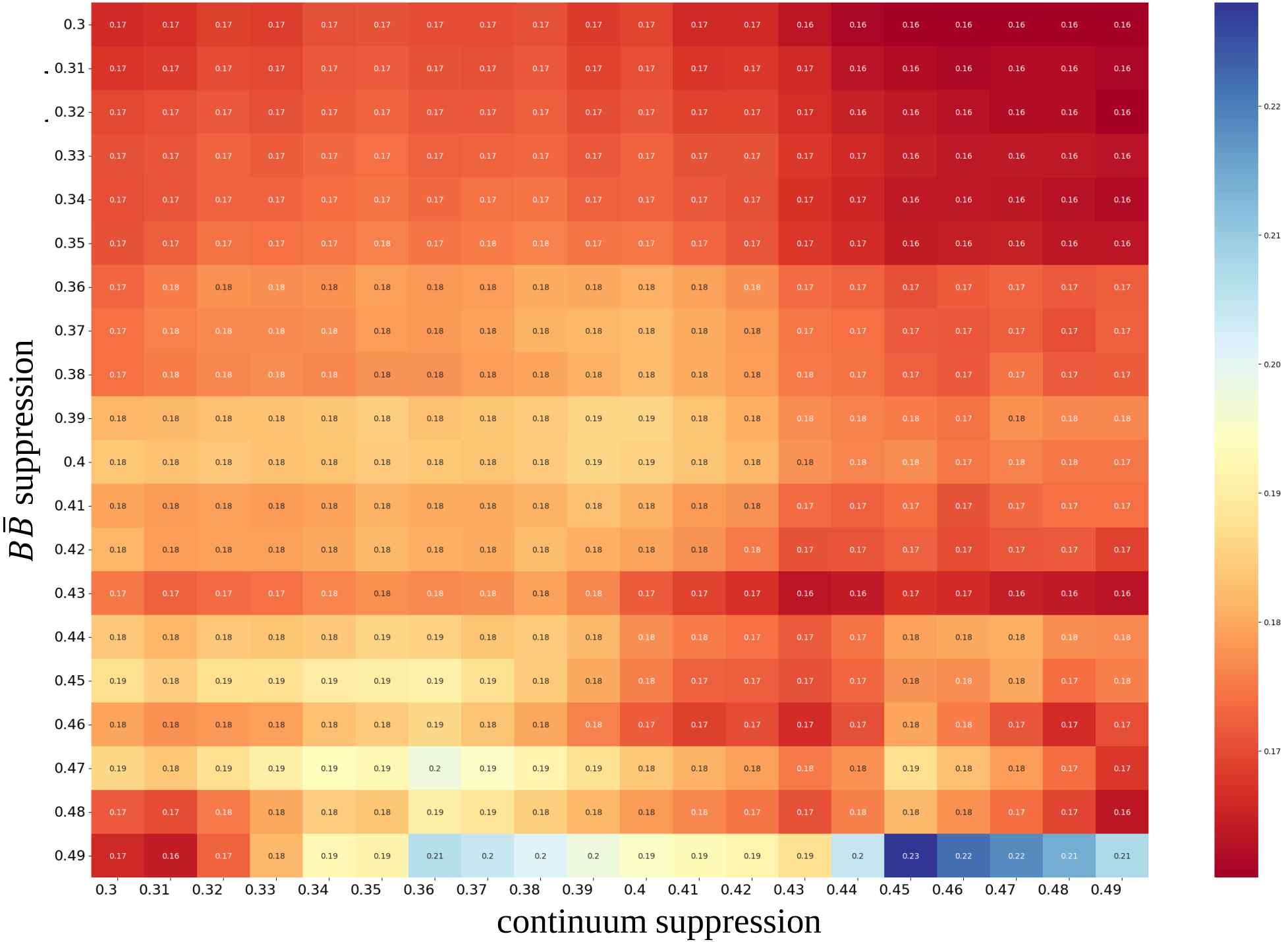
- FOM $\dfrac{S}{\sqrt{S+B}}$

  Signal is scaled by $0.3\ ab^{-1}$

- I select

  $\mathcal{O}_{B\bar{B}} > 0.35$

  $\mathcal{O}_{q\bar{q}} > 0.43$



← FOM plot for $M_{Xs} > 1.1\ \mathrm{GeV}$ and $E_{ecl} < 2\ \mathrm{GeV}$ region

- FOM $\dfrac{S}{\sqrt{S+B}}$

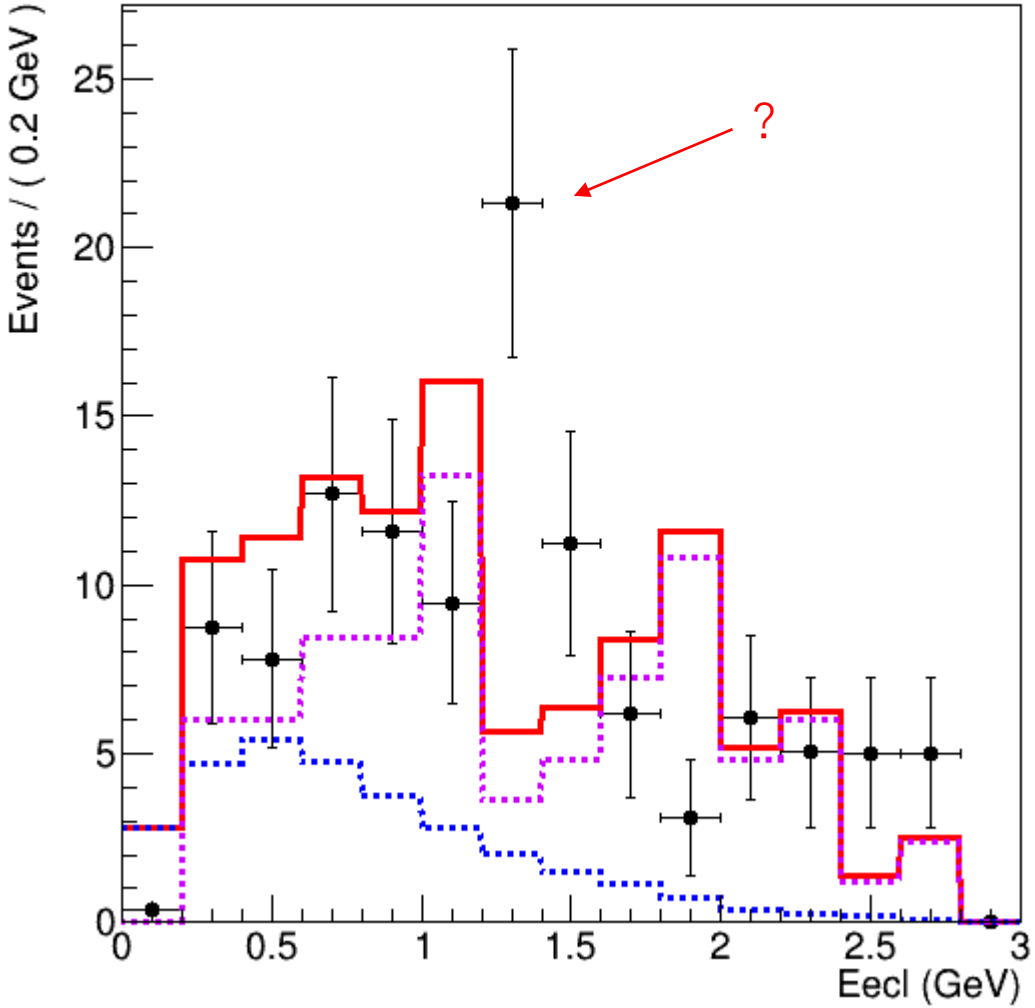
  Signal is scaled by $0.3\ ab^{-1}$

- I select

  $\mathcal{O}_{B\bar{B}} > 0.47$

  $\mathcal{O}_{q\bar{q}} > 0.44$

Reconstruction and analysis (Ongoing)



- I tried to do a fitting with a histogram PDF

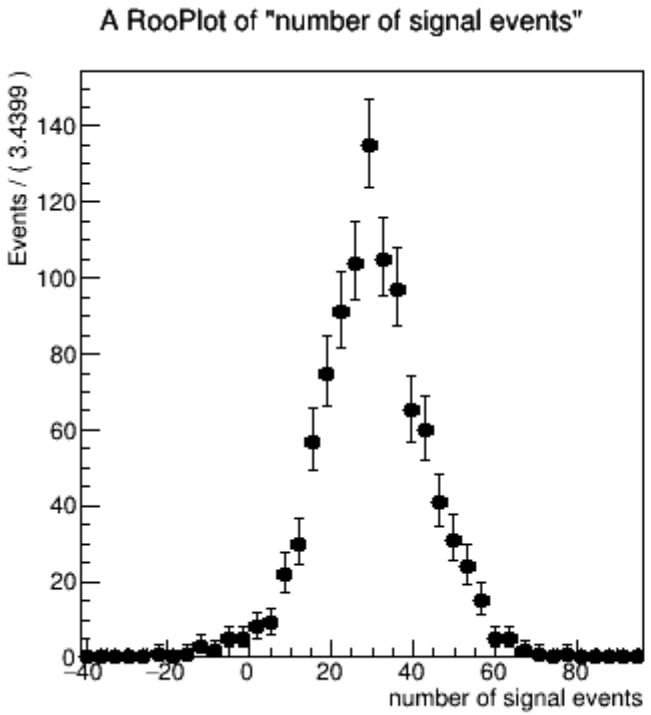
  It overestimate the number of signal

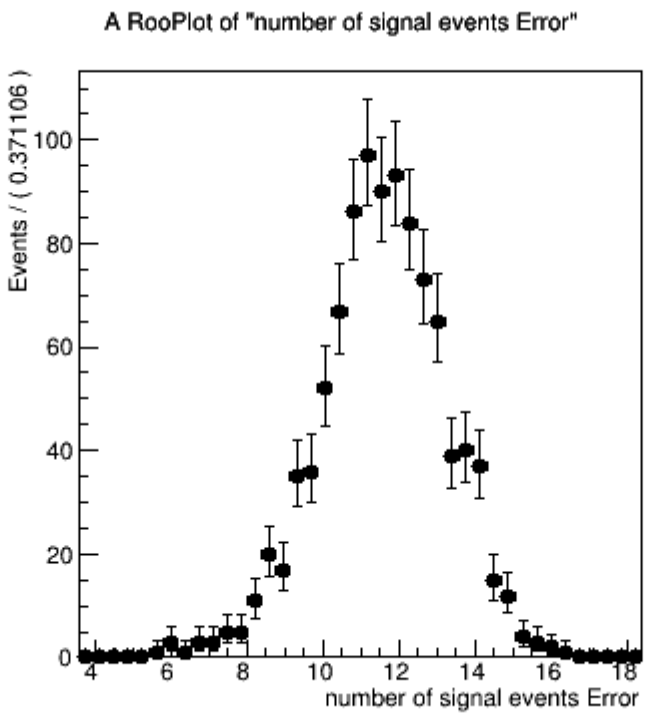
- 2D fit?

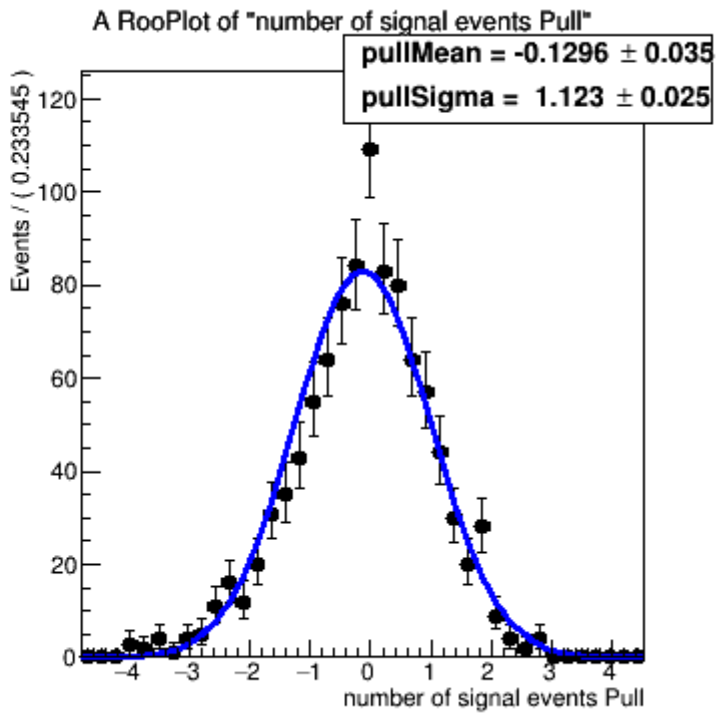
  small number of signal events are spread

  Also, there is no good variable which separate signal and background

Reconstruction and analysis (Ongoing)







- 1000 toy MC study

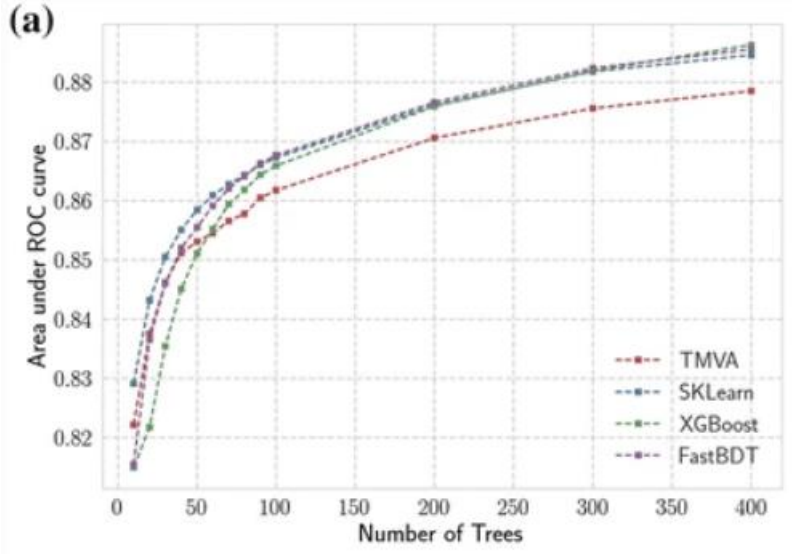
  pull distribution looks ok

Summary

- MC signal samples were produced and the validation was conducted
- FEI was used to reconstruct tag side B meson
- After MVA, there are still significant amount of background

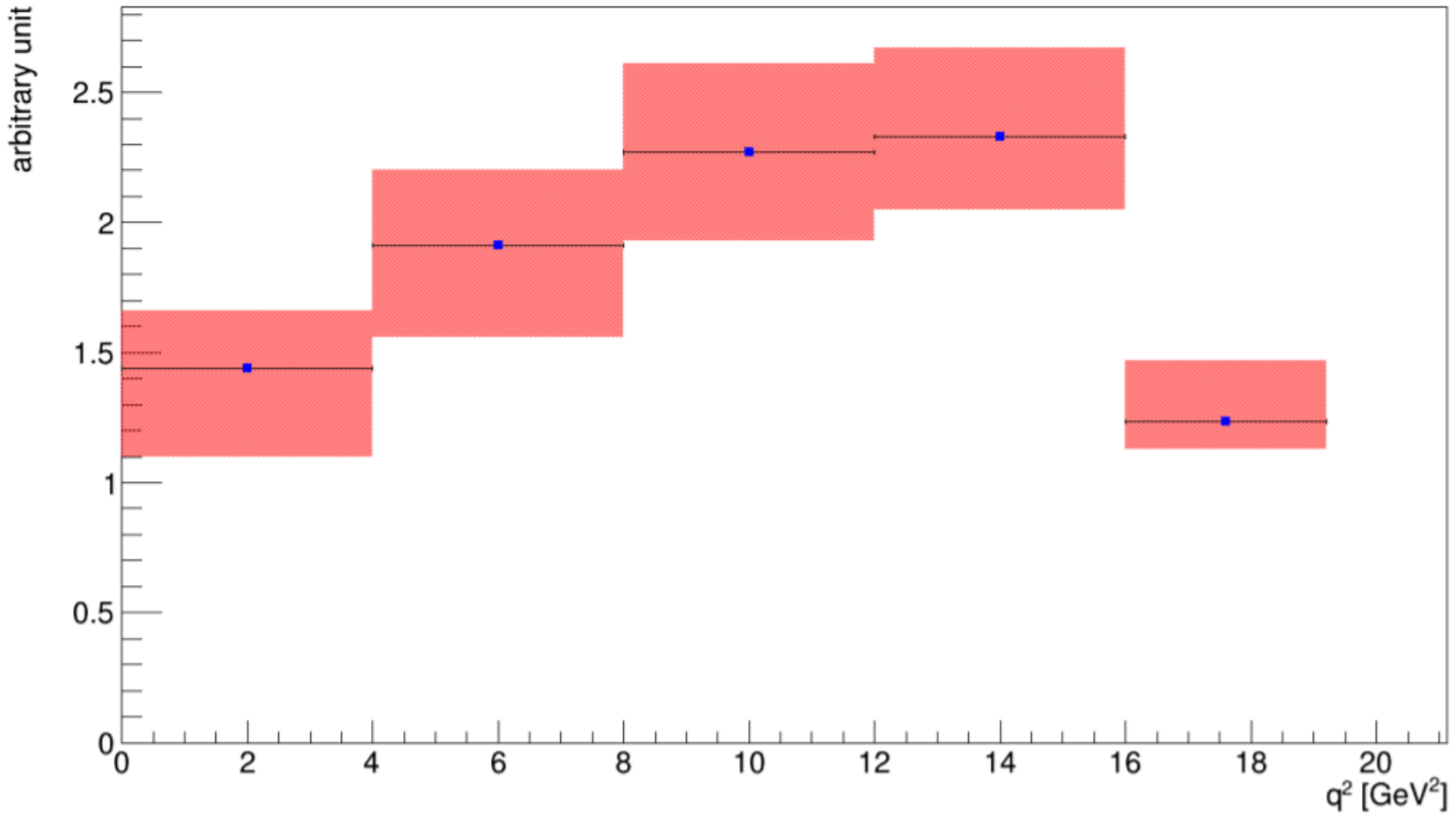
Plan

- Change from TMVA-BDT to fastBDT



Back up

Back up



↑ $B^+ \to K^{*+}\nu\bar{\nu}$ (set width of K^{*+} to be zero)