Update for $B \to K^*\gamma$ analysis

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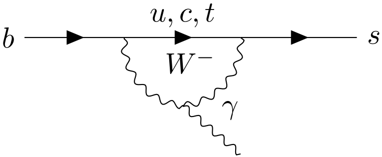
Outline

- Decay channel and dataset
- Preselection
- $M_{bc} - \Delta E$ correlations
- Background study
- Fit model and observables
- Control sample
- Summary

Motivation



- The decay of B meson to $K^*\gamma$ final state is forbidden at tree level in Standard model (SM).
- It proceeds dominantly through $b \to s\gamma$ electroweak loop diagram.
- Extensions of the SM predict new particles that can contribute to the loop and alter the branching fraction as well as other observables from their SM predictions.

Motivation

$$A_{CP} = \frac{\Gamma(\overline{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

- SM prediction of branching fraction suffers from large uncertainties due to form factors.
- Observables like CP (A_{cp}) and isospin (Δ_{+0}) assymetries are theoretically clean due to cancelation of these form factors.
- The latest measurement by Belle[1] observed evidence of isospin violation at significance of 3.1 standard deviations.

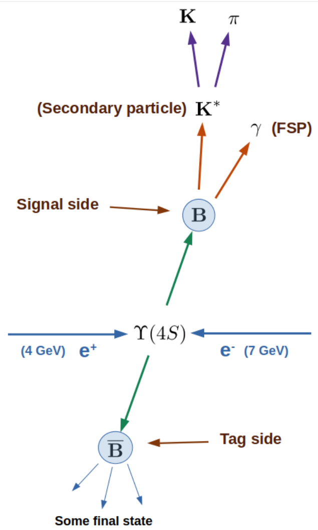
[1] T. Horiguchi et. al. Phys. Rev. Lett. 119 (2017) 19, 191802

Decay channel and dataset

- The decay channel of interest: $B \to K^*\gamma$, where the K^* is reconstructed in four modes namely $K^+\pi^-$, $K_S^0\pi^0$ for the neutral and $K^+\pi^0$ and $K_S^0\pi^+$ for the charged B candidates.
- MC sample:
  Signal: 2M signal events of SignalMC
  $q\overline{q} + B\overline{B}$ MC: $\int \mathcal{L} = 1$ ab^{-1} MC from MC15ri_b BGx1.

The analysis was performed with release **light-2203-zeus** of the BASF2 framework.

$B \to K^*\gamma$ event



Primary particles

Prompt photon selection

- `clusterReg` $!= 3$ (photons from barrel and forward end-cap).
- $|$`clusterTiming`$| < 200$ ns ($T_{event} - T_{\gamma}$) and `clusterTiming/clusterErrorTiming`>2. (standard timing selection)
- `clusterZernikeMVA` > 0.76 (reject neutral hadron clusters).
- `pi0Prob` < 0.68, `etaProb` < 0.84 (reject photons from π^0 and η^0)

Charged tracks

- Reconstruct tracks (except K_S^0 daughters) with impact parameter `dr`< 0.5, `dz` < 2 cm and `nCDCHits` > 20.
- `binary_PID_211_321` > 0.6 (< 0.6) to select π^+ (K^+).

Secondary particles

K_S^0 reconstruction

- Candidates from **mergedKshorts** list satisfying **GoodBelleKshort** flag.
- Mass window: $488 < M_{K_S^0} < 508$ MeV/c^2. ($\pm 3\sigma$)

π^0 reconstruction

- Combine two photons to get π^0, perform mass vertex fit.
- Append **pi0:eff20** selection cuts of May2020 recommendations.

K^* reconstruction

- Combine a kaon ($K^\pm$ or K_S^0) and pion ($\pi^\pm$ or π^0) to get K^*.
- Mass window: $817 < M_{K^*} < 967$ MeV/c^2 ($\pm 1.5\Gamma$, here Γ is the natural width of K^*).

B meson

B meson

- Reconstruct a B candidate using K^* and γ from the event.
- Vertex fit using `TreeFitter` with *ip constraint*. (`chiProb`>0.001)
- $5.2 < \sqrt{E^{*2}_{beam} - p^{*2}_B}$ ($\mathrm{M_{bc}}$) > 5.29 GeV/c^2.
- $-0.5 < E^*_B - E^*_{beam}$ (ΔE) < 0.3 GeV.

Signal region and figure of merit

- Signal region (around $\pm 3\sigma$):
  $5.27 < \mathrm{M_{bc}} < 5.29$ GeV/c^2 and $-0.15 < \Delta\mathrm{E} < 0.07$ GeV.
- Figure of Merit (FOM) = $\mathrm{S}/\sqrt{\mathrm{S+B}}$,
  S(B) $\Rightarrow$ number of Signal (background) events.
- Selection criteria are optimized using FOM inside signal region.

Fit variables and correlation

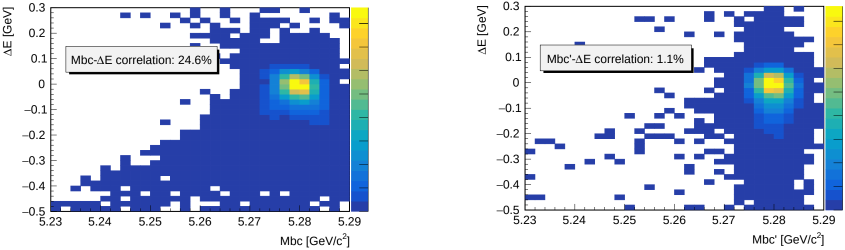
Correlation check

- Plan ⇒ Perform 2D fit to $M_{\rm bc}$ and ΔE variables.
- Checked the correlation between $M_{\rm bc}$ and ΔE for signal events.
- Obseved that $M_{\rm bc}$ and ΔE have significant correlation for the signal events. The culprit is high energy photon in the final state.
- Solution ⇒ Calculate $M'_{\rm bc}$ using the modified B momentum:

$$\vec{P}^*_B = \vec{P}^*_{K\pi} + \frac{\vec{P}^*_\gamma}{|\vec{P}^*_\gamma|} \times (E^*_{beam} - E_{K\pi})$$

The energy of the $K - \pi$ system is well measured compared to that of photon, which suffers due to ECL leakage. Hence, we replace the magnitude of photon momentum with $(E^*_{beam} - E_{K\pi})$.

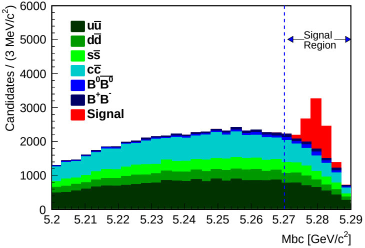
Correlations among fit variables



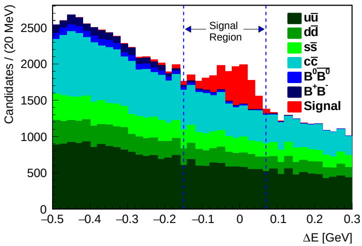
$M_{\rm bc} - \Delta E$ correlation: 24% $M^{'}_{\rm bc} - \Delta E$ correlation: 1.1%

- $M_{\rm bc} - \Delta E$ and $M^{'}_{\rm bc} - \Delta E$ correlation plots for signal events of $B^0 \to K^{*0}[K^+\pi^-]\gamma$ mode.
- Henceforth, in the remainder of this presentation $M^{'}_{\rm bc}$ will be referred to as $M_{\rm bc}$ and we will show results with $M^{'}_{\rm bc}$ variable.

Distribution of M_{bc} and ΔE after preselection



M_{bc}



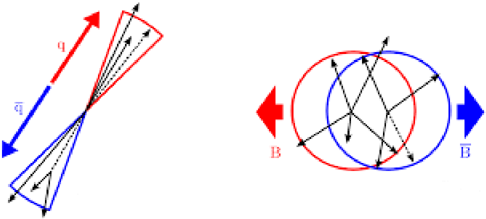
ΔE

- M_{bc} and ΔE for $B^0 \to K^{*0}[K^+\pi^-]\gamma$ mode.

Continuum suppression: MVA

Multivariate analyzer (MVA)

- Employed FastBDT (`BDT`) as the MVA method to supress background from light quark (u, d, s and c) events (denoted as $q\bar{q}$).
- Trained MVA with equal number of $q\bar{q}$ and signal events
- 600 fb^{-1} of generic MC to train and 400 fb^{-1} to test the MVA



Topology for decay products of $q\bar{q}$ (left) and $B\overline{B}$ (right) events

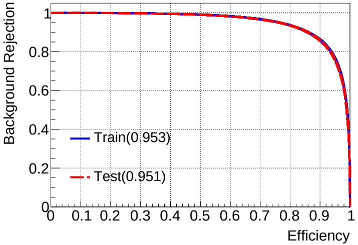
Continuum suppression : Training variables

Training variables

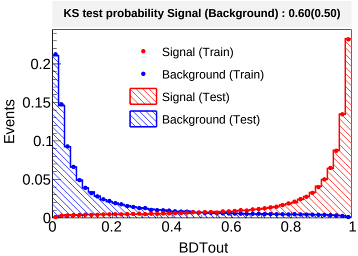
- Trained the MVA using feature variables exploiting the topological differences between signal and background events.
- These feature variables are known to show good separation between the signal and continuum events.
    - 14 KSFW moments, 8 CLEO cones.
    - Thrust for ROE (`thrustOm`), chi-square of vertex fit (`chiProb`).
    - Cosine of angle between ROE and beam axis (`cosTBTO`), between B meson and beam axis (`useCMSFrame(cosTheta)`).

- Variables with more than 5% correlation to M'_{bc} and ΔE (fit variables) were removed from the MVA to avoid sculpting.
- These correlated variables are: thrustBm, CleoCone(1), KSFW(hoo0) and KSFW(et).

Continuum supression: Overtraining check



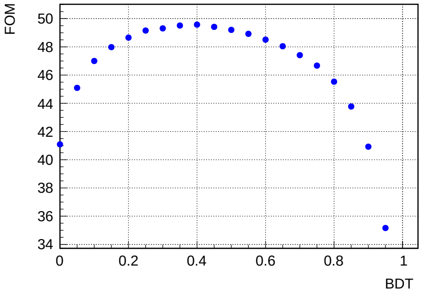
ROC



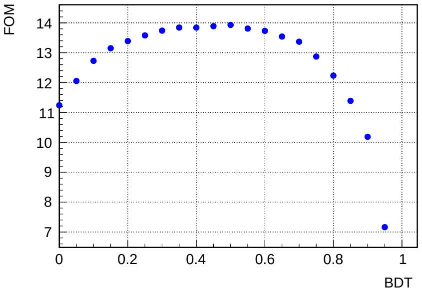
Kolmogorov-Smirnov (KS) test

- ROC and KS test results for $B^0 \to K^{*0}[K^+\pi^-]\gamma$ mode.
- Similar value of area under ROC for train and test samples.
- KS test probability greater than 0.05 for signal and background.
- We conclude that the MVA is not overtrained.

Continuum suppression: FOM



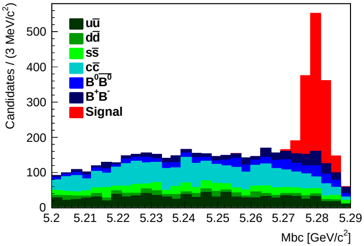
$B^0 \to K^{*0}[K^+\pi^-]\gamma$



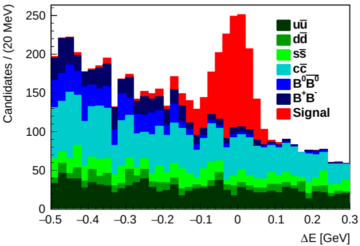
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$

- Optimal selection for BDT output determined using FOM.
- Selection : BDT $> 0.4 - 0.5$ depending on mode.
- The BDT selection rejects 72.2-84.5% of background with a signal loss of 8.7-16.9%

M_{bc} and ΔE



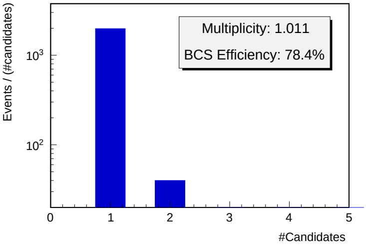
M'_{bc}



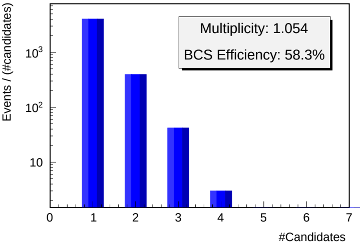
ΔE

- M_{bc} and ΔE for $B^+ \to K^{*+}[K_S^0\pi^+]\gamma$ mode after `BDT` selection.
- We now apply a selection of $M_{bc} > 5.23$ GeV$/c^2$ and $-0.3 < \Delta E$ GeV to further reject background events.

Multiple candidates



$B^0 \to K^{*0}[K^+\pi^-]\gamma$



$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$

- After application of all selection criteria we observe the presence of more than one B candidates in some of the events.
- Retain candidates with the highest value of `BDT` output.
- The candidate multiplicity is around 1.01-1.05% and the BCS efficiency is around 58.3-78.4% depending on the mode.

Overview of fit procedure

Fit procedure for flavour eigenstates

- Looking at the charge of final state π (or K depending on mode) we divide the dataset of flavour eigenstates into two subsamples of B and $\overline{B}$, respectively.
- Perform a simultaneous 2D $M_{bc} - \Delta E$ fit to B and $\overline{B}$ subsamples to obtain the branching fraction (BF) and charge-parity asymmetry (A_{CP}).

Fit procedure for $B^0 \to K^{*0}[K_S^0\pi^0]\gamma$ mode

- We perform a 2D fit to the $M_{bc} - \Delta E$ variables of $B^0 \to K^{*0}[K_S^0\pi^0]\gamma$ mode to extract the branching fraction.

Simultaneous fit

A_{CP} and BF

- The A_{CP} and BF are related to the number of signal events from B and $\overline{B}$ samples through the relations :

$$A_{CP} = \frac{N_{\overline{B}}/\epsilon_{\overline{B}} - N_B/\epsilon_B}{N_{\overline{B}}/\epsilon_{\overline{B}} + N_B/\epsilon_B}$$

$$BF = (N_{\overline{B}}/\epsilon_{\overline{B}} + N_B/\epsilon_B)/(2 \times N_{B\overline{B}}), \text{ where}$$

  - ϵ_B ($\epsilon_{\overline{B}}$)= Signal selection efficiency for B ($\overline{B}$) sample.
  - N_B ($N_{\overline{B}}$) = signal yield from B ($\overline{B}$) sample (obtained from fit).
  - $N_{B^0\overline{B^0}}$ ($N_{B^+B^-}$) = Number of neutral (charged) $B\overline{B}$ pairs.

Exploit these relations in the simultaneous fit to obtain A_{CP} and BF.

Fit model

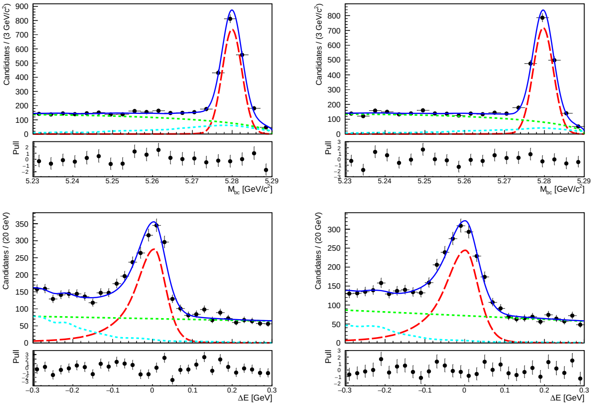
Maximum likelihood fit

- Perform an extended unbinned maximum likelihood fit to the $M_{bc} - \Delta E$ variables.
- Added fudge factors to mean and sigma of signal (to model possible data-MC differences). Other parameters are kept fixed.
- All shape parameters of continuum are floated in the fit.
- The yield of each component is determined from the fit.

Pdf model for different components

Component	M_{bc}	ΔE
Continuum	Argus	Chebychev
$B\overline{B}$	2D RooNDKeysPdf	
Signal	Crystal ball	RooCruijff + Gaussian

Simultaneous fit for $B^0 \to K^{*0}[K^+\pi^-]\gamma$



- Fit projections for the simultaneous fit. The plots on left (right) show projections for B^0 ($\overline{B^0}$).

Fit results

Mode	BF (fit)	BF (.dec)	$A_{\rm CP}$ (fit)	$A_{\rm CP}$ (.dec)
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	4.02 ± 0.08	4.18	0.00 ± 0.02	0.0
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	4.39 ± 0.33	4.18	–	–
$B^0 \to K^{*0}\gamma$	4.04 ± 0.08	4.18	0.00 ± 0.02	0.0
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	4.09 ± 0.16	3.92	-0.02 ± 0.04	0.0
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	3.99 ± 0.17	3.92	-0.02 ± 0.04	0.0
$B^+ \to K^{*+}\gamma$	4.04 ± 0.12	3.92	-0.02 ± 0.04	0.0
Mode	Δ_{0+} (fit)	Δ_{0+} (.dec)	$\Delta A_{\rm CP}$ (fit)	$\Delta A_{\rm CP}$ (.dec)
$B^{\to}K^*\gamma$	3.38 ± 1.76	6.86	-0.02 ± 0.04	0.0

- The results are consistent with the decay file.

Control Sample study

Motivation and plan

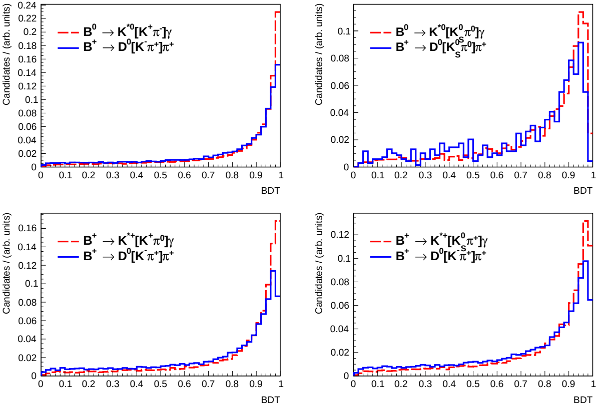
- To study the possible data vs simulation differences for the MVA, we use $B^+ \to D^0[K^-\pi^+]\pi^+$ control sample.
- The idea is to apply the MVA training on the control sample and calculate the data vs simulation double ratio ($R_{Data/MC}$).
- The propagated uncertainty and central value of the double ratio will be used to obtain the relevant systematic.

Control Sample study

Dataset and reconstruction

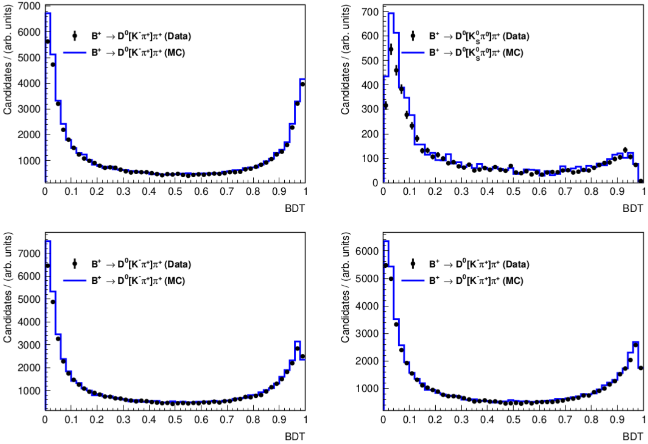
- MC data: 200 fb^{-1} Generic MC from MC15_b campaign BGx1
- Reconstruct charged particles with our nominal selection: `dr`$<$0.5 cm, `dz`$<$ 2 cm and `nCDCHits` $>$ 20.
- PID criteria `binary_PID_211_321`$> 0.6 (< 0.6)$ to select π (K).
- Combine $K^-\pi^+$ to get D^0, retain candidates where the mass of D^0 is $\pm$10 MeV around the nominal D^0 mass.
- Combine D^0 and π^+ to get B^+, retain candidates within $-0.1 < \Delta E < 0.2$ GeV and $M_{bc} > 5.2$ GeV/c^2 range.
- Apply the continuum suppression training to control sample.

Control Sample study: BDT comparison



- The shape of BDT variable for control sample and $B \to K^{*}\gamma$ modes are similar.

Control Sample study: BDT Data/MC agreement



- We observe good Data/MC agreement for the BDT output variable.

Control Sample study: Fit procedure

- Reconstruct $B^+ \to D^0[K^-\pi^+]\pi^+$ and $B^+ \to D^0[K_S^0\pi^0]\pi^+$ as control samples for flavor eigenstates and $B^0 \to K^{*0}[K_S^0\pi^0]\gamma$ mode respectively.
- Perform 2D unbinned maximum likelihood fit to obtain signal yield.
- $\epsilon = \frac{Yield_{BDT>x}}{Yield_{BDT>x}+Yield_{BDT<x}}$, here $x =$ BDT cut.
- $R_{Data/MC} = \epsilon_{Data}/\epsilon_{MC}$

Fit model for $B \to D\pi$ modes

Component	Shape ΔE	Shape $M_{\rm bc}$	Parameters	Yield
Continuum	Chebychev	ARGUS	Floated	Floated
$B\overline{B}$	Exponential	CB	Fixed	Fixed
$B \to D\pi$	Double sided CB	CB	Floated	Floated

Control Sample study: Results

$\mathcal{L}_{MC} = 200\ fb^{-1}$ sample of generic MC from KEKCC.
$\mathcal{L}_{Data} = 364\ fb^{-1}$ sample of Prco13 + prompt buckets data.

Mode	ϵ_{Data}	ϵ_{MC}	$R_{Data/MC}$
$K^{*0}[K^+\pi^-]\gamma$	0.8728 ± 0.0010	0.8735 ± 0.0031	0.9992 ± 0.0037
$K^{*0}[K^0_S\pi^0]\gamma$	0.7857 ± 0.0146	0.7970 ± 0.0209	0.9858 ± 0.0317
$K^{*+}[K^+\pi^0]\gamma$	0.8063 ± 0.0028	0.8056 ± 0.0036	1.0009 ± 0.0057
$K^{*+}[K^0_S\pi^+]\gamma$	0.8455 ± 0.0026	0.8528 ± 0.0033	0.9914 ± 0.0049

Results consistent between Data and MC with $R_{Data/MC} \approx 1$ within the statistical uncertainty.

Summary

- Presented a comprehensive update related to the study.
- Preparing Data/MC agreement plots for the signal sideband region and updating systematics section.
- Upload Belle II note once the remaining results are added.

Backup

Cut flow table : Neutral modes

$B^0 \to K^{*0}[K^+\pi^-]\gamma$

Cut	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$B^0\overline{B^0}$	B^+B^-	signal
Preselection	19351	5159	4943	16935	1878	2068	3692
BDT	3811	1034	1215	4769	1509	1674	3371
$M_{bc} - \Delta E$	1841	489	595	2121	916	967	3354
BCS	1825	486	591	2109	858	959	3340

$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$

Cut	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$B^0\overline{B^0}$	B^+B^-	signal
Preselection	2632	1390	1837	4558	352	443	366
BDT	329	193	302	829	245	325	304
$M_{bc} - \Delta E$	141	87	126	322	117	100	297
BCS	134	82	122	297	93	93	292

Cut flow table : Charged modes

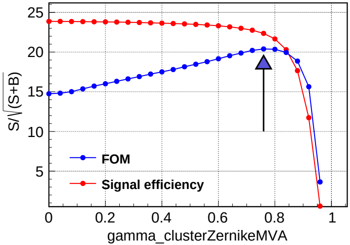
$B^+ \to K^{*+}[K^+\pi^0]\gamma$

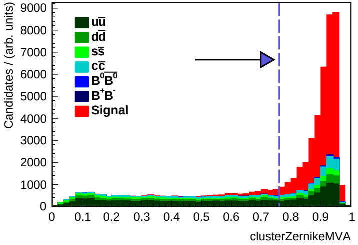
Cut	$u\overline{u}$	$d\overline{d}$	$s\overline{s}$	$c\overline{c}$	$B^0\overline{B^0}$	B^+B^-	signal
Preselection	24008	6034	6522	16611	1166	1156	1168
BDT	2464	545	751	3120	889	853	1038
$M_{bc} - \Delta E$	1047	214	308	1190	330	391	1016
BCS	990	205	298	1121	308	327	998

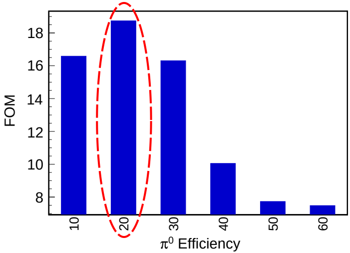
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$

Cut	$u\overline{u}$	$d\overline{d}$	$s\overline{s}$	$c\overline{c}$	$B^0\overline{B^0}$	B^+B^-	signal
Preselection	6856	2194	3735	7556	712	672	1062
BDT	1059	349	625	1851	538	538	945
$M_{bc} - \Delta E$	426	132	238	698	193	239	922
BCS	419	130	234	690	191	216	913

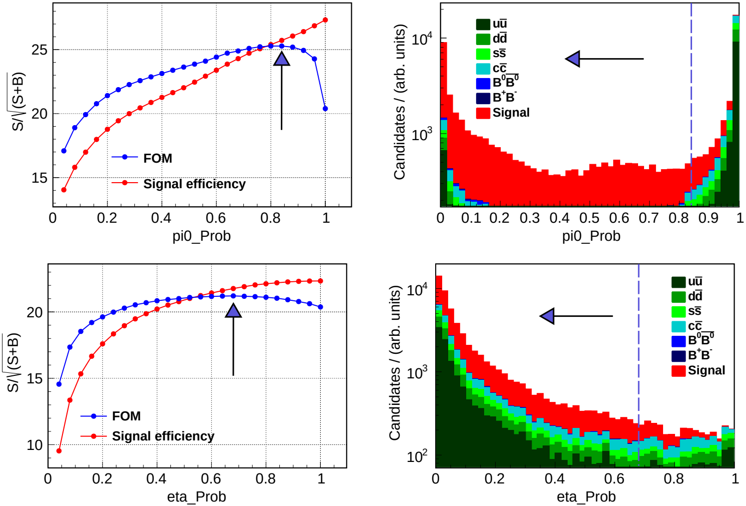
FOM plots for photon selection







FOM plots for photon selection



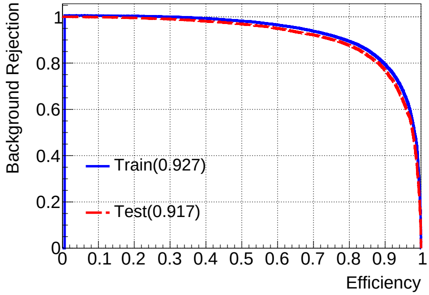
Variable importance

Variable	Score
cosTBTO	0.350327283
KSFWVariables(hso02)	0.166849986
KSFWVariables(hso12)	0.115673192
CleoConeCS(2)	0.0837808549
useCMSFrame(cosTheta)bc	0.0791520774
chiProb	0.0747683495
thrustOm	0.0235748738
KSFWVariables(hso04)	0.0199276898
CleoConeCS(3)bc	0.0186925791
KSFWVariables(hso22)	0.0120025929
KSFWVariables(hso10)	0.00959501974
KSFWVariables(mm2)	0.00730590755
CleoConeCS(4)	0.00719390716

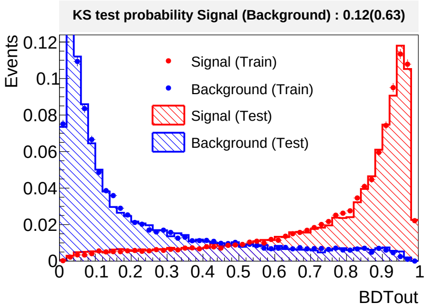
Variable importance

Variable	Score
KSFWVariables(hso24)	0.00562814809
CleoConeCS(5)	0.00544966012
KSFWVariables(hso00)	0.00428879261
KSFWVariables(hoo2)	0.0034612969
KSFWVariables(hso20)	0.00310488045
CleoConeCS(6)	0.00272009056
CleoConeCS(7)	0.00163650676
KSFWVariables(hso14)	0.00145011465
KSFWVariables(hoo1)	0.00129723153
KSFWVariables(hoo4)	0.000934657233
KSFWVariables(hoo3)	0.000466811151
CleoConeCS(9)	0.000390624889
CleoConeCS(8)	0.000326884881

Continuum supression overtraining check: $B^0 \to K^{*0}[K^0_S\pi^0]\gamma$



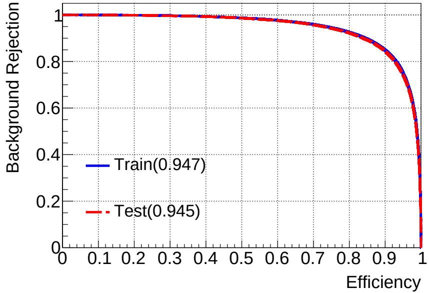
ROC



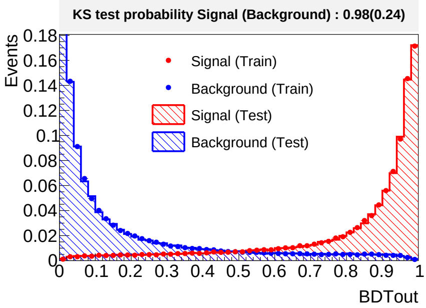
Kolmogorov-Smirnov test

- Results are ok, no overtraining.

Continuum supression overtraining check: $B^+ \to K^{*+}[K^+\pi^0]\gamma$



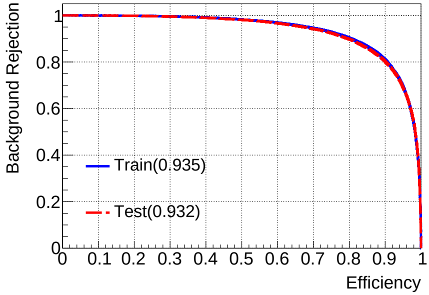
ROC



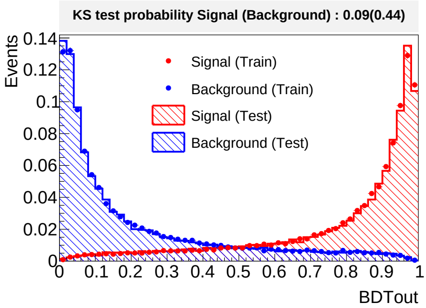
Kolmogorov-Smirnov test

- Results are ok, no overtraining.

Continuum supression overtraining check: $B^+ \to K^{*+}[K_S^0\pi^+]\gamma$



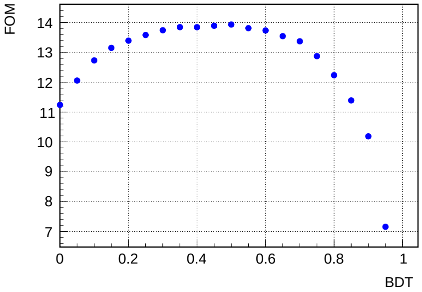
ROC



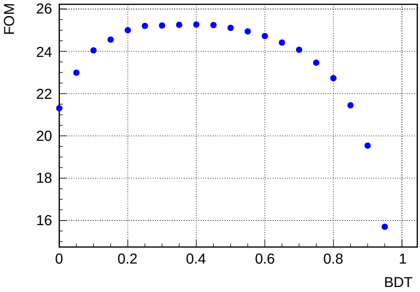
Kolmogorov-Smirnov test

- Results are ok, no overtraining.

Continuum suppression: FOM



$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$



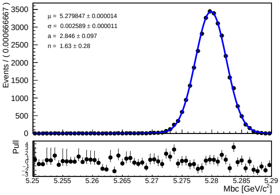
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$

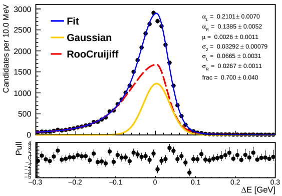
- Optimal selection for BDT output determined using FOM.
- Selection : BDT>0.3 (0.2) for $B^+ \to K^{*+}[K^+\pi^0]\gamma$ (other modes).

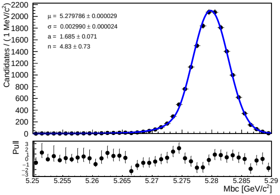
Candidate multiplicity and BCS efficiency

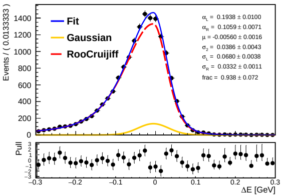
Mode	Candidate Multiplicity	BCS (BDT) efficiency (%)
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	1.01	78.4
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	1.10	60.6
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	1.05	58.3
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	1.04	67.7

Signal model: Neutral modes





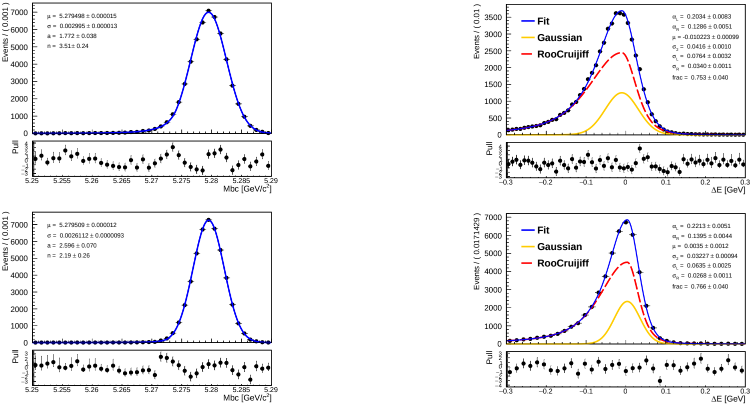




M'_{bc} ΔE

- Fit model for signal events of $B^0 \to K^{*0}[K^+\pi^-]\gamma$ (top) and $B^0 \to K^{*0}[K^0_S\pi^0]\gamma$ (bottom).

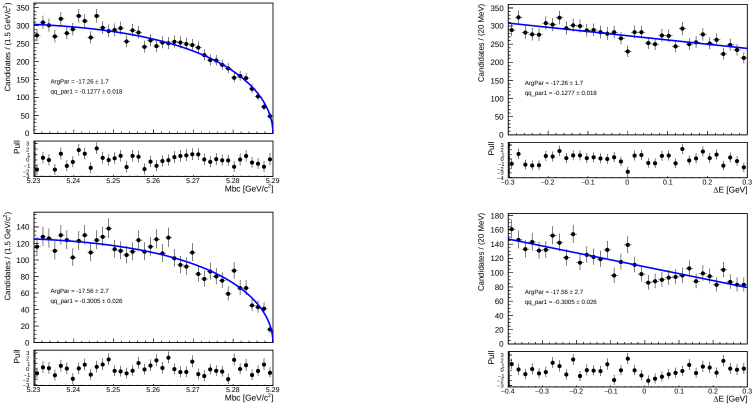
Signal model: Charged modes



M'_{bc} ΔE

- Fit model for signal events of $B^+ \to K^{*+}[K^+\pi^0]\gamma]$ (top) and $B^+ \to K^{*+}[K^0_S\pi^+]\gamma]$ (bottom).

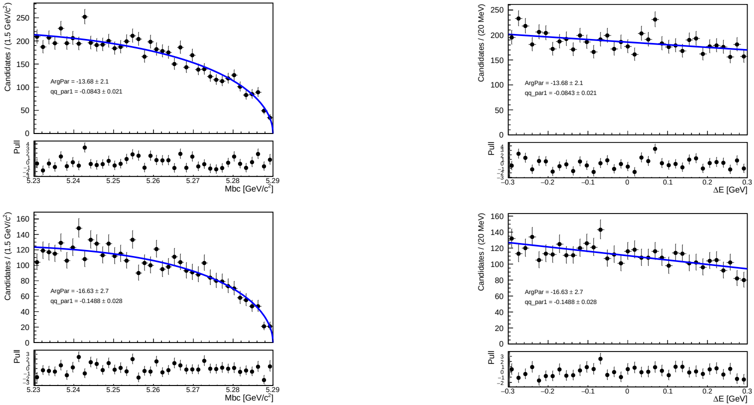
Continuum model: Neutral modes



M'_{bc} ΔE

- Fit model for continuum events of $B^0 \to K^{*0}[K^+\pi^-]\gamma]$ (top) and $B^0 \to K^{*0}[K^0_S\pi^0]\gamma]$ (bottom).

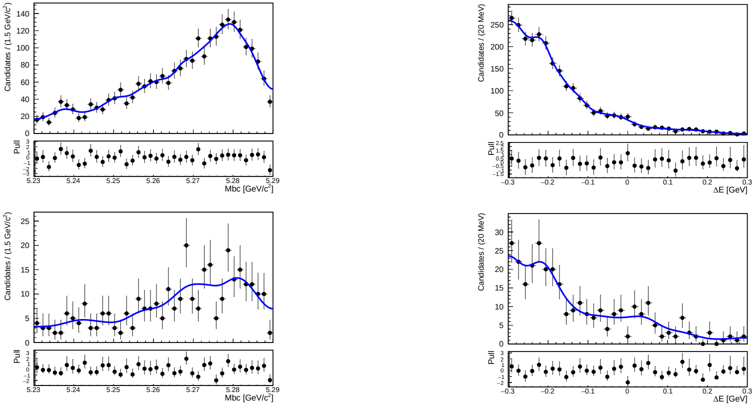
Continuum model: Charged modes



$M_{bc}^{'}$ ΔE

- Fit model for continuum events of $B^+ \to K^{*+}[K^+\pi^0]\gamma]$ (top) and $B^+ \to K^{*+}[K_S^0\pi^+]\gamma]$ (bottom).

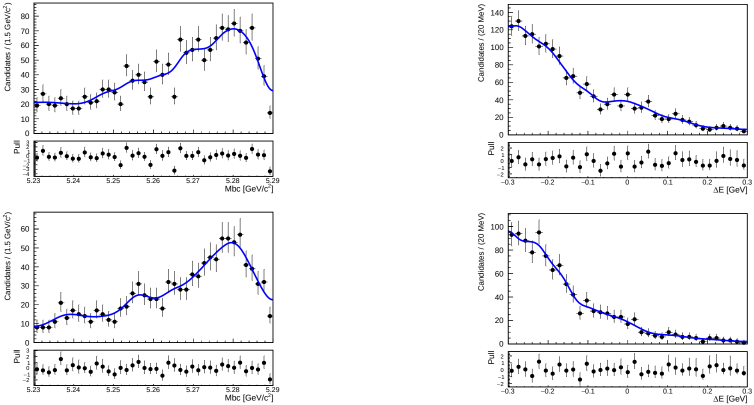
$B\overline{B}$ model: Neutral modes



M'_{bc} ΔE

- Fit model for $B\overline{B}$ events of $B^0 \to K^{*0}[K^+\pi^-]\gamma]$ (top) and $B^0 \to K^{*0}[K^0_S\pi^0]\gamma]$ (bottom).

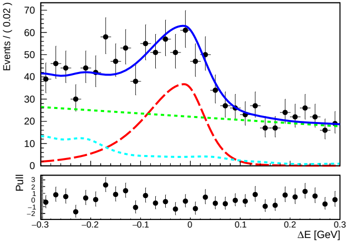
$B\overline{B}$ model: Charged modes



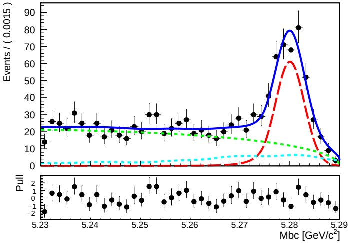
M'_{bc} ΔE

- Fit model for $B\overline{B}$ events of $B^+ \to K^{*+}[K^+\pi^0]\gamma]$ (top) and $B^+ \to K^{*+}[K^0_S\pi^+]\gamma]$ (bottom).

2D fit for $B^0 \to K^{*0}[K_S^0\pi^0]\gamma$



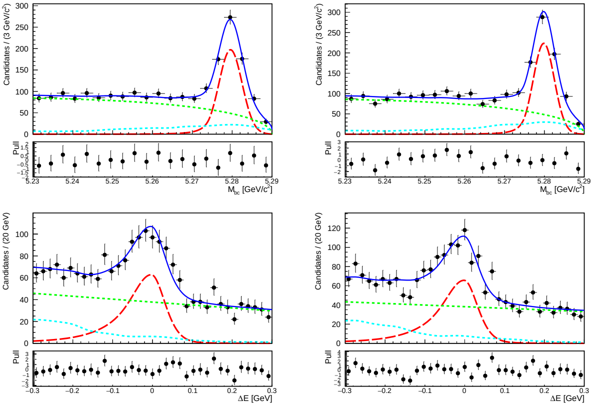
M'_{bc}



ΔE

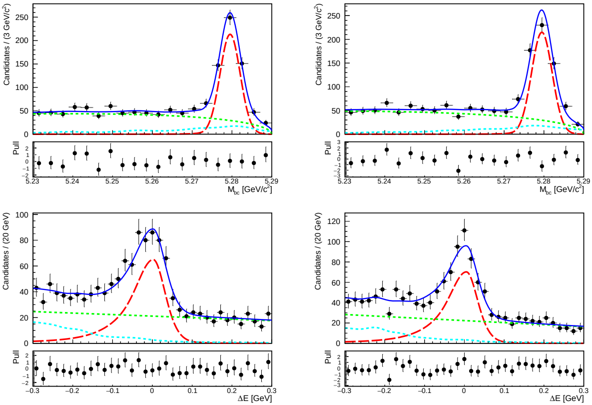
- Fit projections for the 2D fit.

Simultaneous fit for $B^+ \to K^{*+}[K^+\pi^0]\gamma$



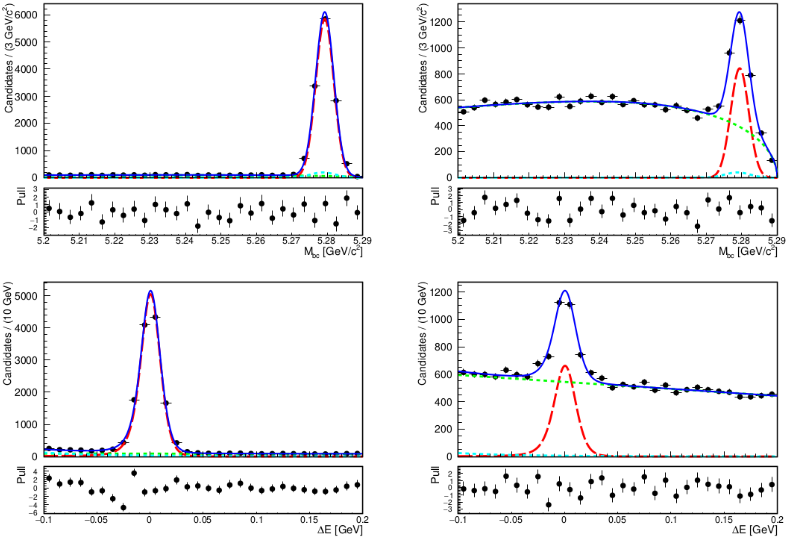
- Fit projections for the simultaneous fit. The plots on left (right) show projections for B^+ (B^-).

Simultaneous fit for $B^+ \to K^{*+}[K_S^0\pi^+]\gamma$

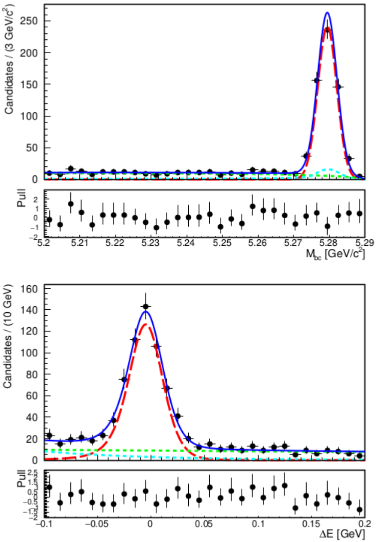


- Fit projections for the simultaneous fit. The plots on left (right) show projections for B^+ (B^-).

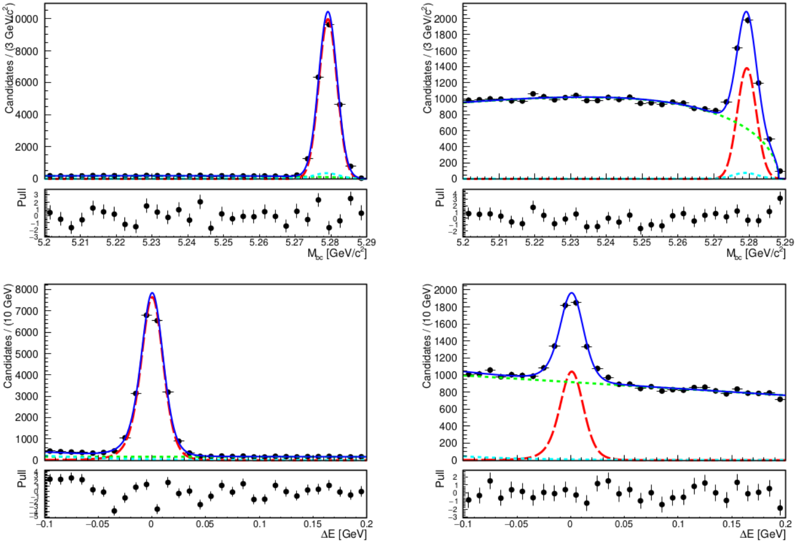
Fit to $B^+ \to D^0[K^-\pi^+]\pi^+$ MC



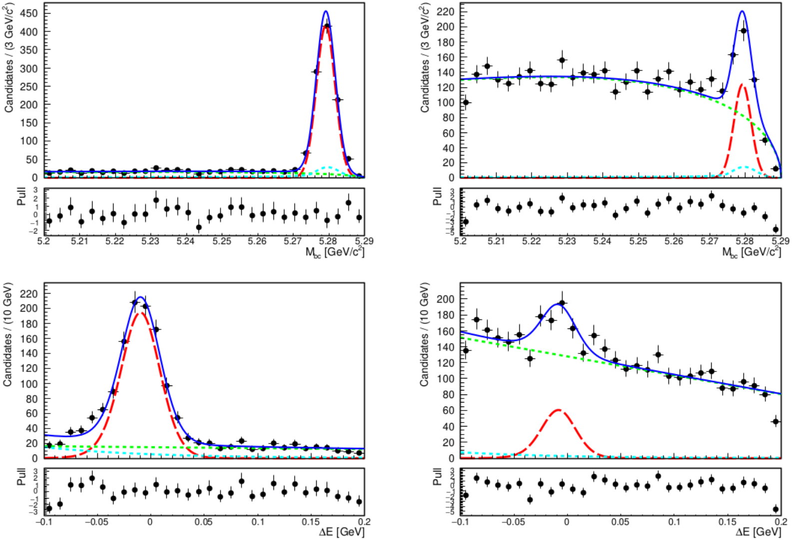
Fit to $B^+ \to D^0[K_S^0\pi^0]\pi^+$ MC



Fit to $B^+ \to D^0[K^-\pi^+]\pi^+$ Data



Fit to $B^+ \to D^0[K_S^0\pi^0]\pi^+$ Data



Data/MC agreement plots from off-resonance data and on-resonance MC for $B^0 \to K^{*0}[K^+\pi^-]\gamma$