Status and plan of $B^0 \to K^0\pi^0$ Time-dependent study

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Outline

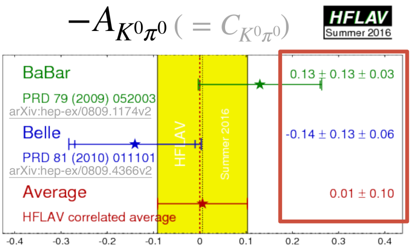
- Motivation & Status at Belle II
- Goal and current development
- 4D $(\Delta E, M_{bc}, \Delta t, C^{'}_{out})$ PDFs modeling
- A_{CP} & S_{CP} measurement
- $B^0 \to J/\psi K^0_S$ control sample study
- B Lifetime, A_{CP} & S_{CP} measurement
- Summary and Plans

Motivation

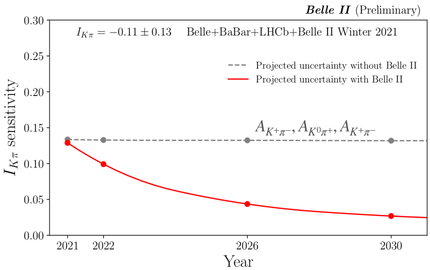
- In the SM, the decay $B^0 \to K^0\pi^0$ proceeds via $b \to s$ loop diagrams.
- Such FCNC transitions are highly suppressed in the SM and sensitive to non-SM particles appearing in the loops.
- Sum rule relation for $B \to K\pi$ decays

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B0}}{\tau_{B+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B0}}{\tau_{B+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

Predicting $A_{K^0\pi^0} = -0.17 \pm 0.06$ (Phys.Lett. B627 (2005) 82-8)



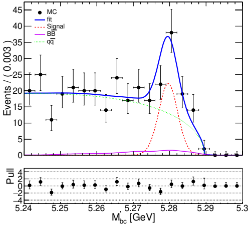
BELLE2-NOTE-PH-2020-046

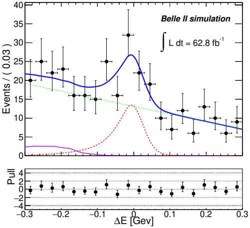


Status at Belle II

- Measurement of $\mathscr{B}$ and A_{CP} shown on Moriond using 62.8 fb^{-1}

Validation study





Parameter	62.8 fb^{-1} MC cocktail
B.F.($\times 10^{-6}$)	$9.08^{+1.57}_{-1.50}$
N_{qq}	$262.1^{+17.2}_{-16.9}$ (exp.=254)
N_{bb}	$12.7^{+1.0}_{-1.0}$ (exp.=13)
$q\bar{q}\Delta E$ slope	$-1.5442^{+0.3271}_{-0.3182}$

BELLE2-NOTE-PH-2020-046

Parameter	62.8 fb^{-1} MC cocktail
$\mathcal{B}$ [$\times 10^{-6}$]	$9.13^{+1.73}_{-1.59}$
N_{qq}	$241.3^{+17.1}_{-16.4}$
N_{rare}	$12.7^{+1.1}_{-1.1}$
$q\bar{q}$ ΔE slope	$-1.1181^{+0.3888}_{-0.3721}$
ΔE mean-shift [MeV]	-

Current development

- Aim is to do time-dependent analysis
- Adding the Δt in the fitter
- To improve the precision on A_{CP} & S_{CP} measurement, include the log transform continuum suppression (C'_{out}) variable
- **4D ($\Delta E, M_{bc}, \Delta t, C'_{out}$)**
- Targeting LEPTON-PHOTON to use 200 fb^{-1}

Selection criteria

$B^0 \to K_s^0 \pi^0$ selection

- $120 < m_{\pi^0} < 145$ MeV and $|\cos\theta_H| < 0.98$
- Barrel $E_\gamma > 30$, Backward $E_\gamma > 60$ and Forward $E_\gamma > 80$ MeV
- $482 < m_{K_S^0} < 513$ MeV
- $5.24 < M_{bc} < 5.3$ GeV and $-0.3 < \Delta E < 0.3$ GeV

$B^0 \to J/\psi K_S^0$ selection

- Criterias are taken from `BELLE2-NOTE-PH-202`.
- $dr < 0.5$ cm, $|dz| < 3$ cm, for muon tracks.
- muonID(μ^+) or muonID(μ^+) > 0.2
- $2.80 < M_{J/\psi} < 3.40$ GeV and $482 < M_{K_S^0} < 513$ MeV
- $5.2 < M_{bc} < 5.3$ GeV and $|\Delta E| < 0.05$ GeV

- For CP-side: IP constraint and only K_S^0 vertexing
- For tag-side : IP constraint
- $\sigma_{\Delta t} < 2.5$ ps

4D $(\Delta E, M_{bc}, \Delta t, C^{'}_{out})$

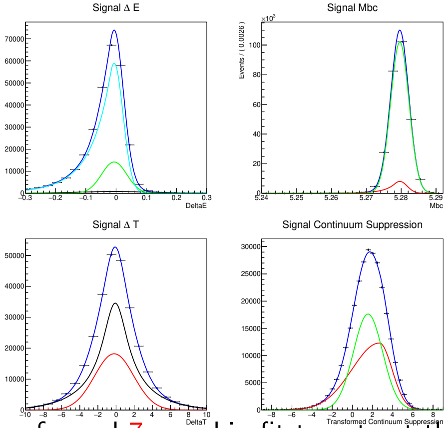
Signal Modeling

- Δt : RooBCPGenDecay PDF PDF convolved with double Gaussian:

  $P_{sig}(\Delta t, q) = \frac{\exp^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}([1 - q\Delta w + q\mu_i(1-2w)] + [q(1-2w) + \mu_i(1-q\Delta w)](A_{CP}\cos(\Delta m_d \Delta t) - S_{CP}\cos(\Delta m_d \Delta t)))$

  Core and tail Gaussian, $\tau_{B^0} = 1.520$ ps and $\Delta m_d = 0.507/$ps
- ΔE : Crystal Ball + double Gaussian with common mean
- M_{bc} : Crystal Ball + Gaussian, C'_{out} : Bifurcated + Gaussian

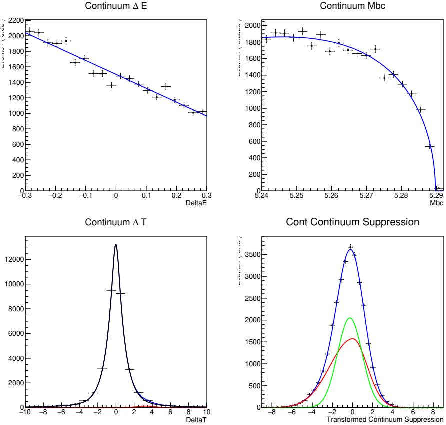
Example plot of integrated $q \cdot r$ bin



- In same way performed $7\ q \cdot r$ bin fit to extract the PDFs parameters

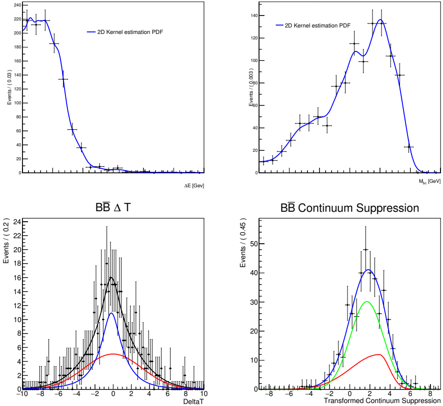
Continuum bkg modeling

- Δt : RooDecay PDF convolved with double Gaussian : $e^{-|t|/\tau}$
  Core and tail Gaussian
- ΔE : Linear function
- M_{bc} : ARGUS function, C'_{out} : Bifurcated + Gaussian



$B\bar{B}$ bkg Modeling

- Δt : RooDecay PDF convolved with double Gaussian : $e^{-|t|/\tau}$ Core and tail Gaussian
- 2D Kernel estimation PDF used for $\Delta E - M_{bc}$ modeling
- C'_{out} : Bifurcated + Gaussian

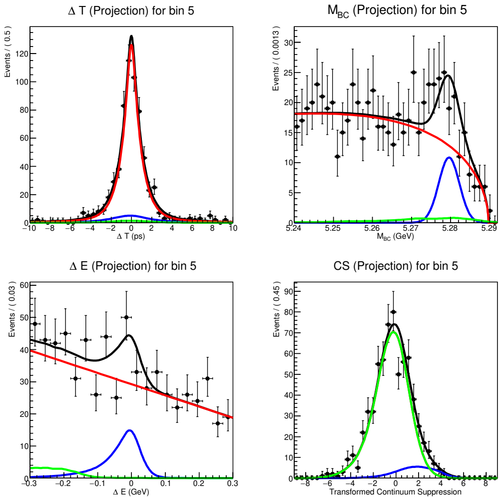


TDCPV binned model

- Divide the signal, continumm and $B\bar{B}$ bkg dataset in $7\ q \cdot r$ bins
- Use the same PDFs (signal, continuum and $B\bar{B}$) for all the bin
- Signal PDFs shape parameters are taken from each bin fit
- Continuum and $B\bar{B}$ BKG PDFs shape parameters are same for all the bin and taken from integrated $q \cdot r$ bin fit
- All the PDFs shape parameters are fixed except A_{CP}, S_{CP} and Yield for simultaneous fit
- $500\ fb^{-1}$ cocktail of signal, continuum and $B\bar{B}$ used

7-bin fit projection

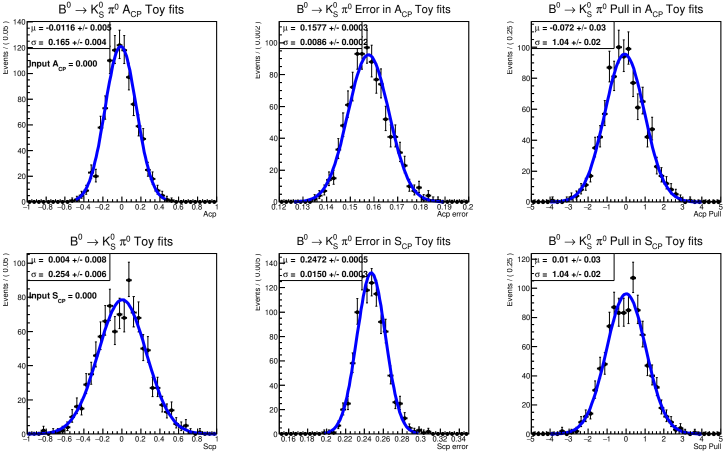
Example plot of single bin



- Rest of the bin fit projection shown in backup slide

Pure toy test

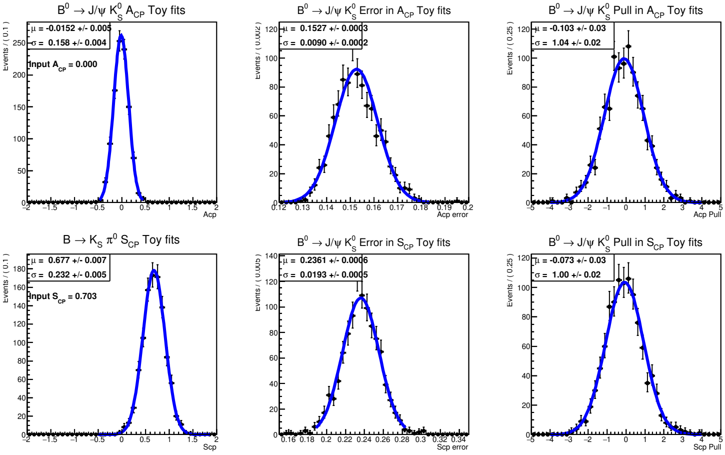
- To validate the fitter, 1000 toy experiments performed
- Signal, continuum and $B\bar{B}$ dataset are generated
- Expected A_{CP}: 0.0 and S_{CP}: 0.0



- There is no significant bias !

GSIM Toy test

- Signal dataset are used from the corresponding MC sample
- Continuum and $B\bar{B}$ dataset are generated using the PDF shape
- $\sin(2\beta) = sin(2\phi_1) = S_{CP} = 0.7032$, where $\beta = 0.39$ rad
- Expected A_{CP}: 0.0 and S_{CP}: 0.7032



- There is no significant bias !

Toy results

- Signal efficiency=0.140 (all selection + loose cont. supp. cut $+\sigma_{\Delta t}$)

Pure toy

Parameter	Fitted value	Expected value
Signal Yield	364 ± 24	353
Continuum Yield	7654 ± 92	7683
A_{CP}	-0.011 ± 0.157	0.0
S_{CP}	0.004 ± 0.247	0.0

GSIM toy

Parameter	Fitted value	Expected value
Signal Yield	356 ± 24	353
Continuum Yield	7639 ± 88	7683
A_{CP}	-0.0152 ± 0.152	0.0
S_{CP}	0.677 ± 0.236	0.703

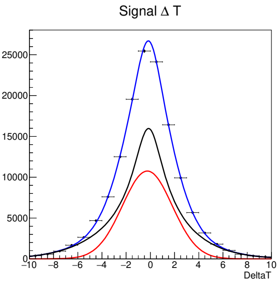
Control Sample study $B^0 \to J/\psi K_S^0$

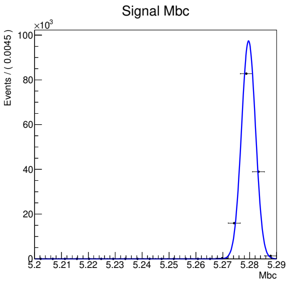
B Lifetime

A_{CP} **&** S_{CP}

Signal Modeling

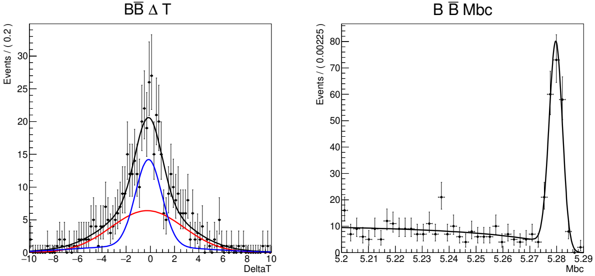
- Δt : RooBCPGenDecay PDF convolved with double Gaussian:
  $P_{sig}(\Delta t, q) = \frac{\exp^{-|\Delta t|/\tau_{B0}}}{4\tau_{B0}}([1 - q\Delta w + q\mu_i(1-2w)] + [q(1-2w) + \mu_i(1 - q\Delta w)](A_{CP}\cos(\Delta m_d \Delta t) - S_{CP}\cos(\Delta m_d \Delta t)))$
  Core and tail Gaussian
- M_{bc} : Crystal Ball function



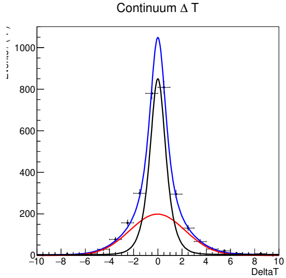


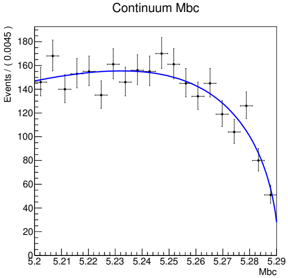
$B\bar{B}$ modeling

- Peaking compoment peaking at the true B mass ($2-3\%$ of signal events)
- Δt : RooDecay PDF convolved with double Gaussian : $e^{-|t|/\tau}$
  Core and tail Gaussian
- M_{bc} : ARGUS + Gaussian function



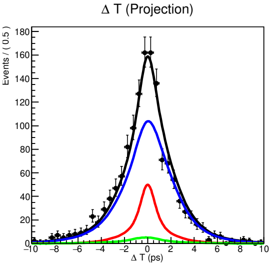
- Δt : RooDecay PDF convolved with double Gaussian : $e^{-|t|/\tau}$
  Core and tail Gaussian
- M_{bc} : ARGUS function

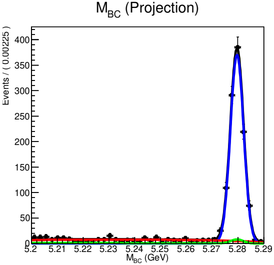


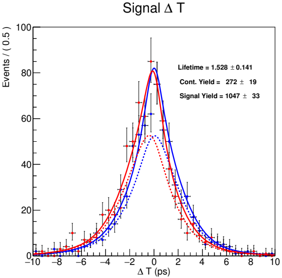


B Lifetime fit

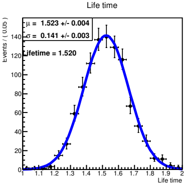
- $200\ fb^{-1}$ cocktail of signal, background are generated from PDFs.
- All shape parameters are fixed

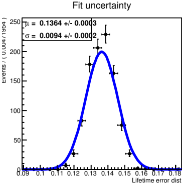


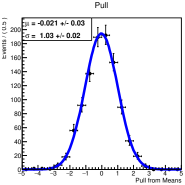




GSIM toy



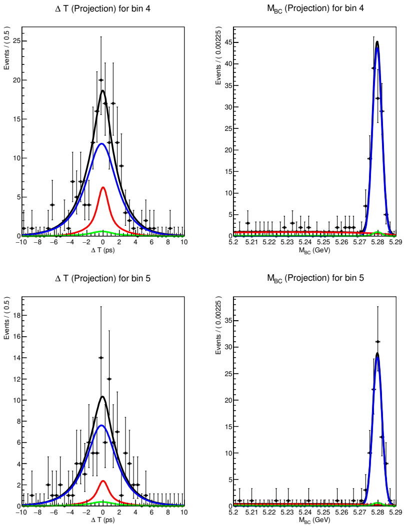




Parameter	Fitted value	Expected value
Signal Yield	1045 ± 33	1044
Background Yield	275 ± 18	275
Lifetime (ps)	1.523 ± 0.136	1.52

Validation of TDCPV fitter

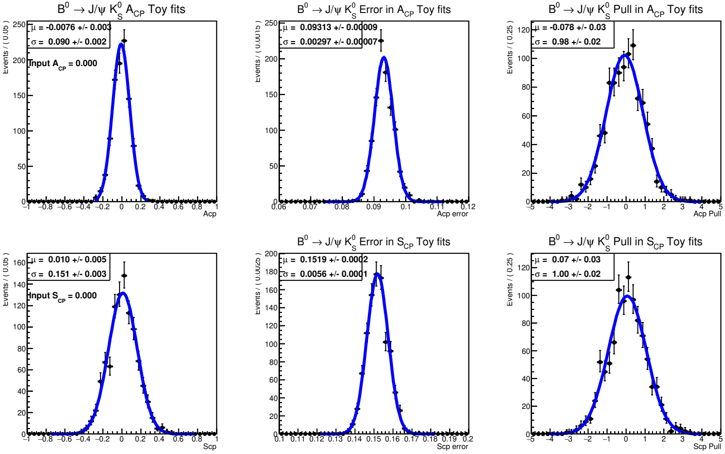
Example plot of few bin



- Rest of the bin fit projection shown in backup slide

Pure toy test

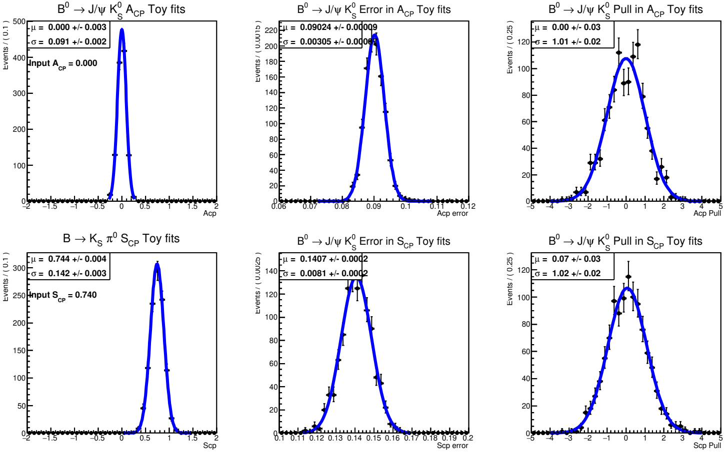
- To validate the fitter, 1000 toy experiments performed
- Signal, continuum and $B\bar{B}$ dataset are generated using the shape
- Expected A_{CP}: 0.0 and S_{CP}: 0.0



- There is no significant bias !

GSIM Toy test

- Signal dataset are used from the corresponding MC sample
- Continuum and $B\bar{B}$ dataset are generated using the PDF shape
- Expected A_{CP}: 0.0 and S_{CP}: 0.74



- There is no significant bias !

Toy results

- Expected signal yield= 1044 (200 fb^{-1})

Pure toy

Parameter	Fitted value	Expected value
Signal Yield	1043 ± 33	1044
Continuum Yield	275 ± 18	275
A_{CP}	-0.007 ± 0.093	0.0
S_{CP}	0.010 ± 0.151	0.0

GSIM toy

Parameter	Fitted value	Expected value
Signal Yield	1044 ± 33	1044
Continuum Yield	274 ± 18	275
A_{CP}	0.0 ± 0.09	0.0
S_{CP}	0.744 ± 0.140	0.74

- $S_{CP} = 0.749 \pm 0.055$ ($500 fb^{-1}$) BELLE2-NOTE-PH-202.

Summary and plans

- A_{CP} & S_{CP} measurement
- B lifetime, A_{CP} & S_{CP} measurement measurement in control sample
- Validate with toy study

- B Lifetime, A_{CP} & S_{CP} measurement in data
- Full phase analysis report will be ready by Oct. end

- Two groups are working on $B^0 \to K_s^0\pi^0$ time-dependent analysis
- Expect to have preliminary result in next winter conference.

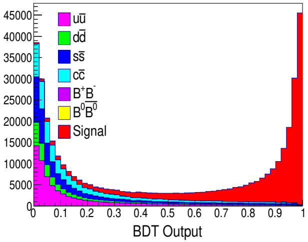
Thank You

Continuum suppression validation

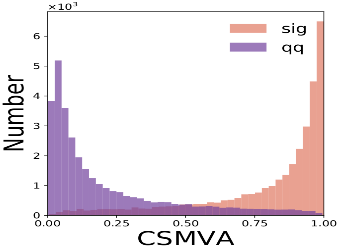
- FatBDT as the multivariate classifier.
- Same number of signal and background events.
- 800 fb^{-1} for training and 400 fb^{-1} for testing.
- Use only continuum (u, d, s, c) background instead of generic$(u, d, s, c, B\bar{B})$ background.
- Same classifier input used(BELLE2-NOTE-PH-2020-046).

Classifier Output

Our study



BELLE2-NOTE-PH-2020-046



Background rejection comparison

Using our CS weight file

1) generic BKG to train CS

Cut	BKG rej.	$\#u\bar{u}$	$\#d\bar{d}$	$\#s\bar{s}$	$\#c\bar{c}$	$\#B^0\bar{B}^0$	$\#B^+B^-$	# signal
0.0		5434	2287	4180	4280	109	22	98
0.9	98.33 %	80	46	52	90	58	11	53

2) Continuum BKG to train CS

Cut	BKG rej.	$\#u\bar{u}$	$\#d\bar{d}$	$\#s\bar{s}$	$\#c\bar{c}$	$\#B^0\bar{B}^0$	$\#B^+B^-$	# signal
0.0		5434	2287	4180	4280	109	22	98
0.9	98.25 %	90	49	58	84	54	9	48

Using BELLE2-NOTE-PH-2020-046 CS weight file

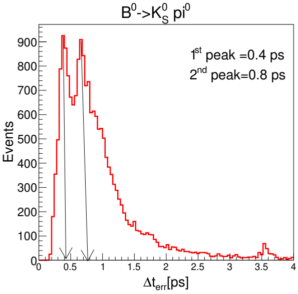
https://stash.desy.de/projects/B2B2C/repos/btohadronscripts/browse/BToCharmless_WithCorr_CSFBDT.root

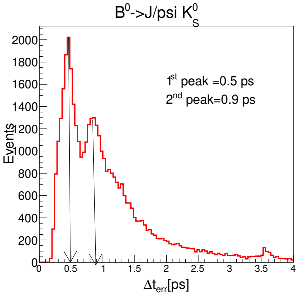
Cut	BKG rej.	$\#u\bar{u}$	$\#d\bar{d}$	$\#s\bar{s}$	$\#c\bar{c}$	$\#B^0\bar{B}^0$	$\#B^+B^-$	# signal
0.0		5434	2287	4180	4280	109	22	98
0.9	98.39 %	74	45	52	88	54	11	48

- Now we use the common BToCharmless weight file for CS

Δt_{err} distribution

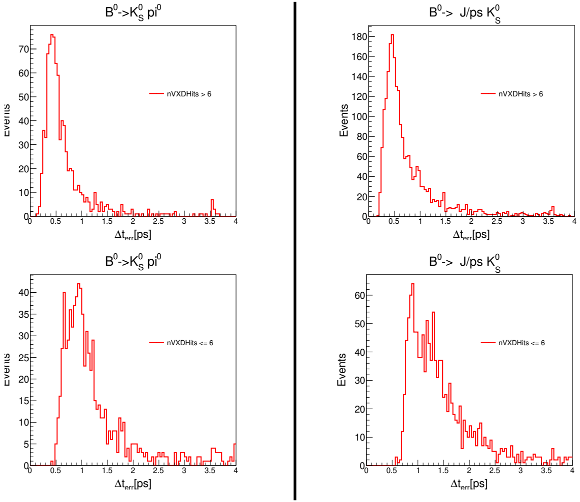
only K_S^0 vertexing





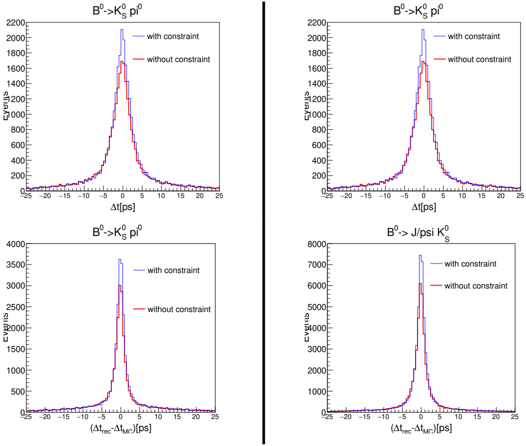
- After including only K_S^0 in the vertexing we get double peak in both cases.

Δt_{err} double peak



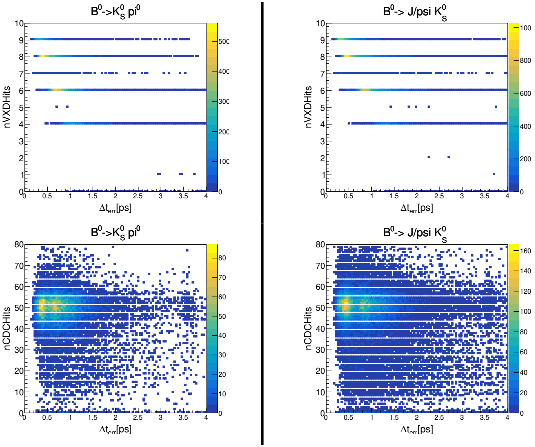
- We observe the decond peak due to fewer hits in VXD.

Effect of IP constraint



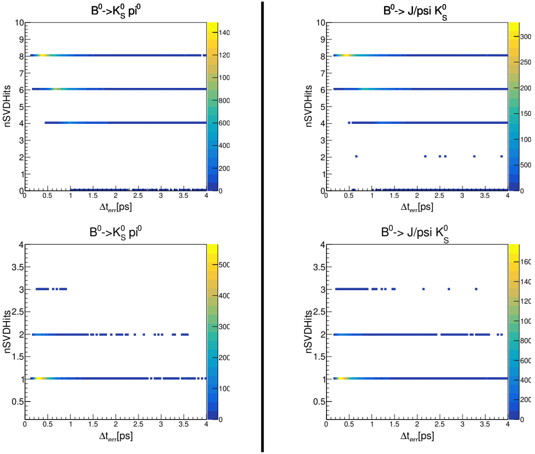
- After applying IP constraint in tag side Δt resolution improves.
- Similar trend is seen in the control channel .

Δt_{err} vs. Hits



- We plots number of hits in VXD and CDC to find out the double peak structure in the Δt_{err} distribution.

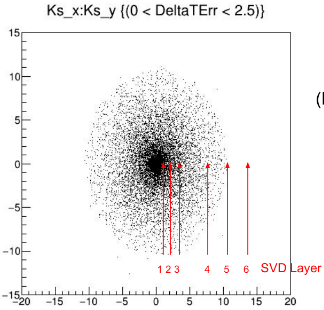
Δt_{err} vs. Hits



- We plots number of hits in VXD and CDC to find out the double peak structure in the Δt_{err} distribution.

DeltaTErr and Ks Vertex Position

- Location of Ks vertex on x-y plane
- Cut of 2.5 on DeltaTErr corresponds to the 5th layer of the SVD
- This means the cut requires two hits in the SVD

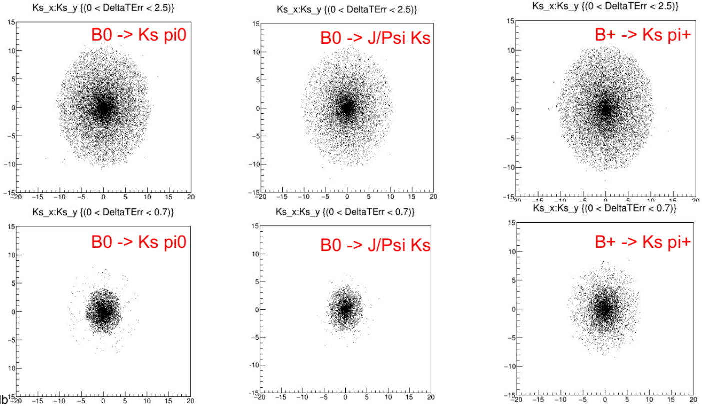


(B -> J/Psi Ks)

DeltaTErr and Ks Vertex Position

0 < DeltaTErr < 2.5

0 < DeltaTErr < 0.7
(First peak)



Tim Green, University of Melb

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Signal mode

Signal yield calculation

The expected signal yield is calculated as

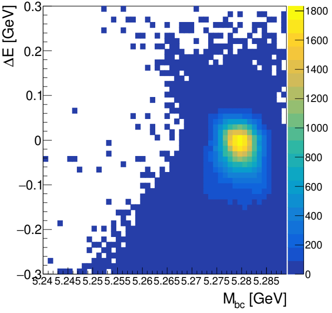
$$N_{sig}^{expected} = \mathscr{B} \cdot \epsilon \cdot \mathscr{B}_s \cdot 2 \cdot N_{B^0\bar{B}^0} \quad (1)$$

- $N_{B^0\bar{B}^0} = \int \mathcal{L} \cdot \sigma \cdot f^{00}$, where $\sigma = 1.110$ and $f^{00} = 0.487$
- $\mathscr{B}_s = 0.5$, probability of $K^0 \to K_S^0/K_L^0$
- $\mathscr{B}(B^0 \to K^0\pi^0) = 9.93 \times 10^{-6}$ (PDG value 2020)
- Signal efficiency=0.140 (all selection + loose cont. supp. cut $+\sigma_{\Delta t}$)
- N_{sig}^{expt}=353 (500 fb^{-1})

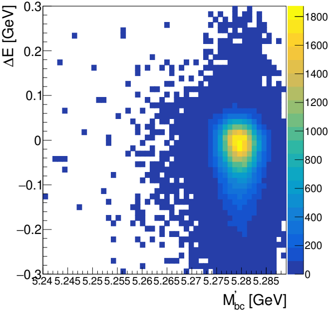
Modified M_{bc}

- $M_{bc} = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{B}}$
- $\vec{p}^{*}_{B} = \vec{p}^{*}_{K^0_S} + \vec{p}^{*}_{\pi^0}$
- $\vec{p}^{*}_{B} = \vec{p}^{*}_{K^0_S} + \frac{\vec{p_{\pi^0}}^{*}}{|\vec{p_{\pi^0}}^{*}|}(\sqrt{(E^{*}_{beam} - E^{*}_{K^0_S})^2 - m^2_{\pi^0}}$

cor=0.143(signal)



cor=-0.03(signal)

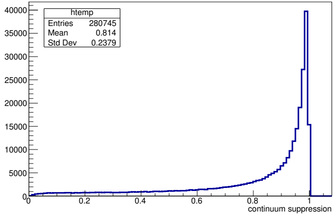


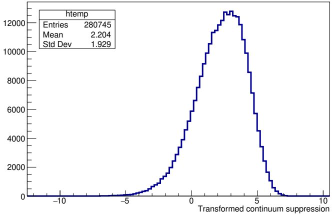
Adding extra dimension to the fitter

- We transform the BDT classifier output (C_{out}) to (C'_{out}) in order to parametrize using a simple PDF
- Transform continumm suppression variable is defined as

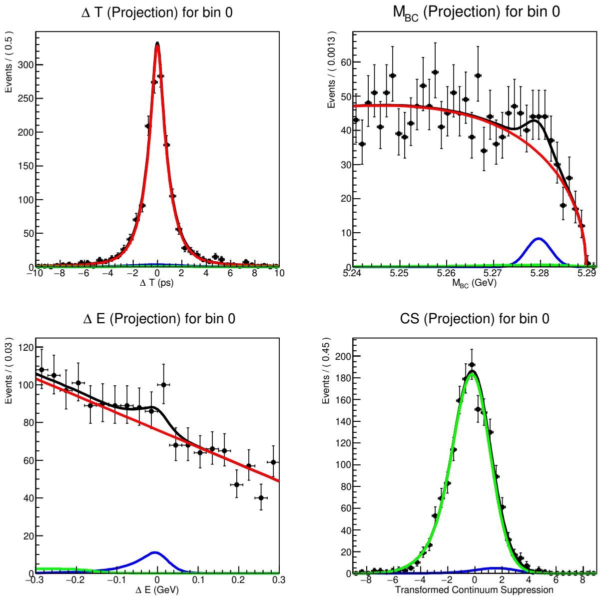
$$C'_{out} = log(\frac{C_{out} - C_{out_{min}}}{C_{out_{max}} - C_{out}}) \tag{2}$$

where $C_{out_{max}}$=0.999339 and $C_{out_{min}}$=0.6

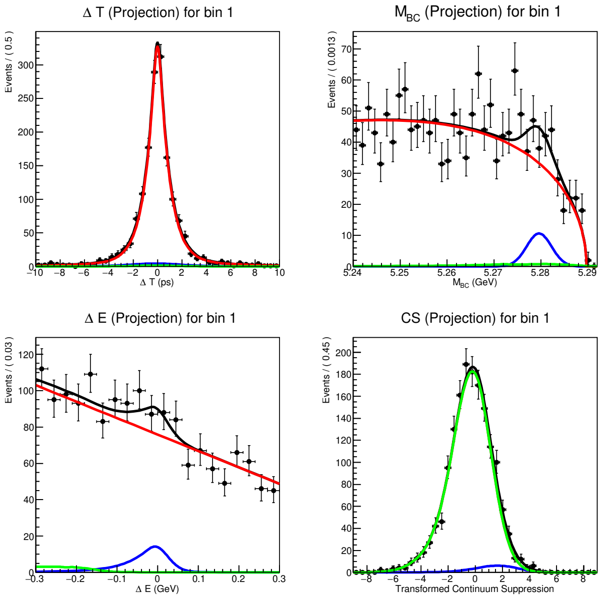




7-bin fit projection



7-bin fit projection



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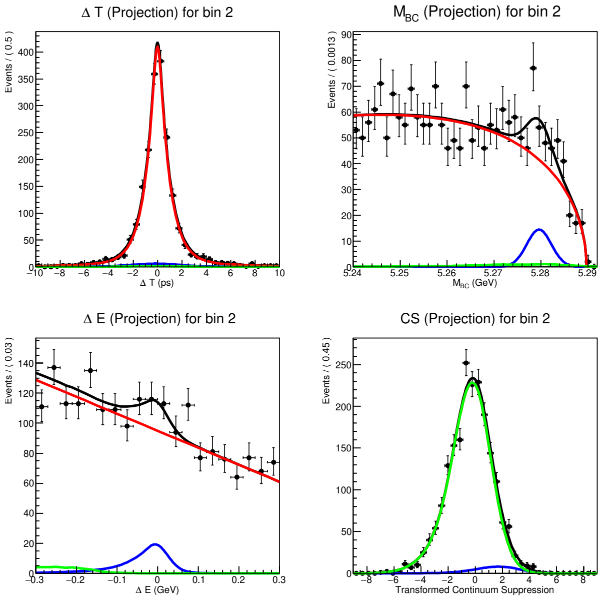
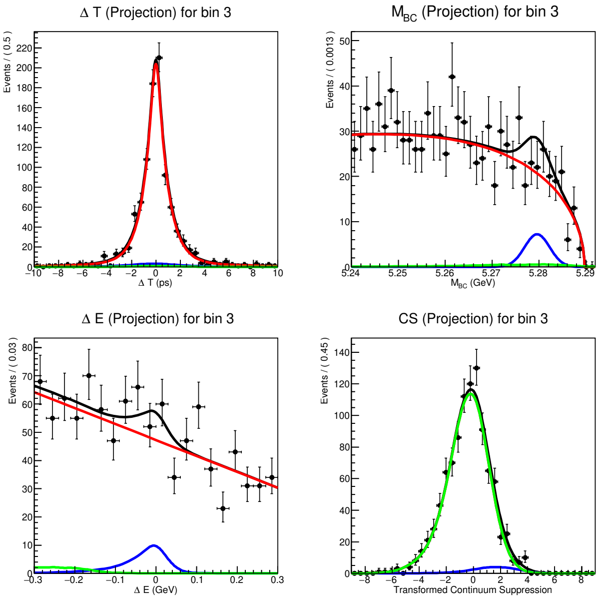
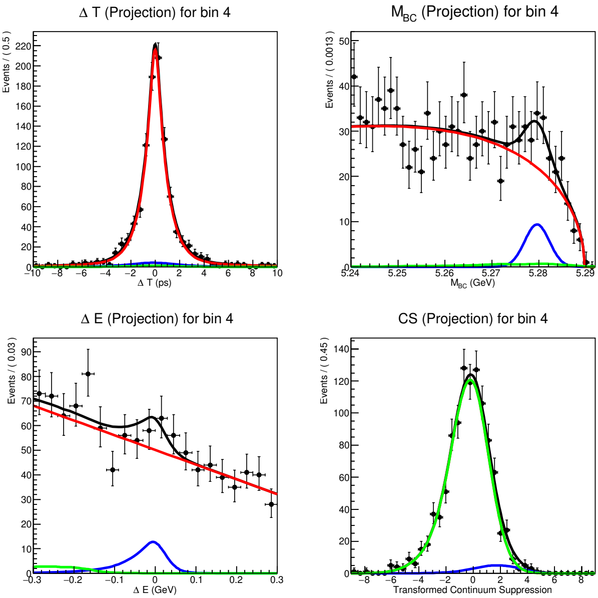


7-bin fit projection

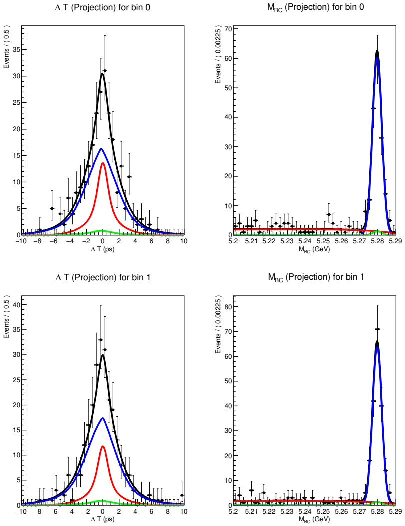


7-bin fit projection

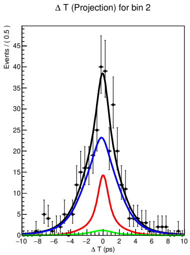


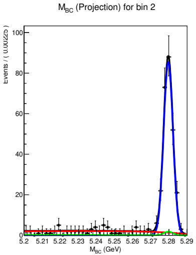
Control mode

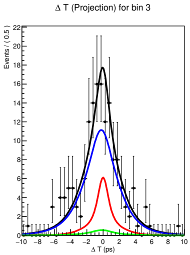
7-bin fit projection

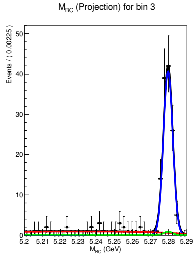


7-bin fit projection

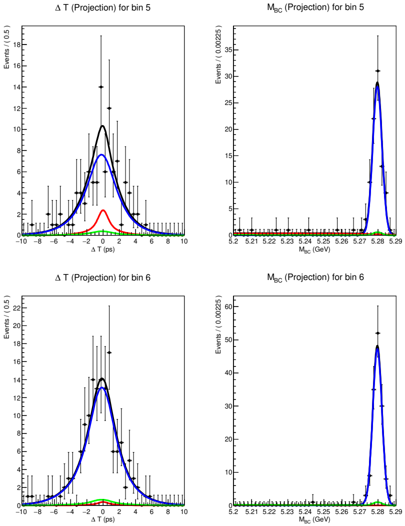








7-bin fit projection



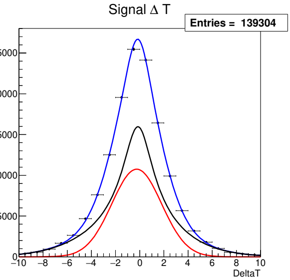
Lifetime fit on Signal MC

- Δt : RooBCPGenDecay PDF convolved with double Gaussian:

$$P_{sig}(\Delta t, q) = \frac{\exp^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}([1 - q\Delta w + q\mu_i(1-2w)] + [q(1-2w) + \mu_i(1-q\Delta w)](A_{CP}\cos(\Delta m_d \Delta t) - S_{CP}\cos(\Delta m_d \Delta t)))$$

Core and tail Gaussian

$B^0 \to J/\psi K^0_S$



Lifetime (ps)	1.521 ± 0.011	1.52