First measurement of time-dependent CP violation in $B^0 \to K^0_S \pi^0$ decays at Belle II

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tifr

Belle II

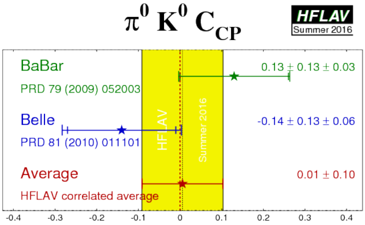
Motivation

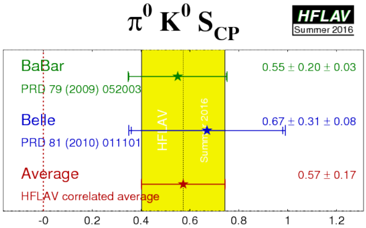
- The sum-rule relation proposed by Gronau for $B \to K\pi$ provides a stringent test of SM

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

- Predicted $\mathcal{A}_{K^0\pi^0} = -0.17 \pm 0.06$, Phys.Lett. B627 (2005) 82-8
- The limiting factor is $\mathcal{A}_{K^0\pi^0}$ precision. Need to push on this measurement, where Belle II is the key player.
- $B^0 \to K^0\pi^0$ is a golden mode at Belle II

Current Experimental status





B meson reconstruction

Selection criteria

$B^0 \to K_s^0(\to \pi^+\pi^-)\pi^0(\to \gamma\gamma)$

- π^0 reconstructed from a pair of photons
- K_S^0 reconstructed from two oppositely charged tracks, assummed to be pions

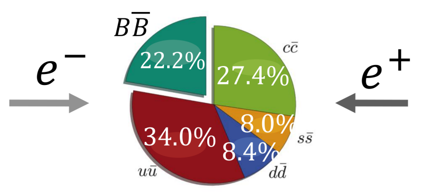
$B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0(\to \pi^+\pi^-)$ [control channel]

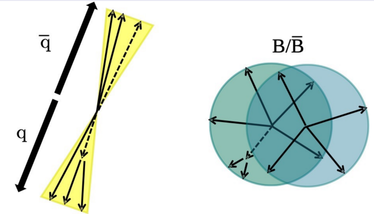
- K_S^0 selection criteria are same like the signal mode
- Only K_S^0 used for B^0 vertexing to mimic the signal decay
- J/ψ reconstructed from dimuons

- Following two kinematic variables used to select B meson
- $M_{bc} = \sqrt{E_{beam}^{*2} - \vec{p}_B^{*2}}$
- $\Delta E = E_{beam}^* - E_B^*$

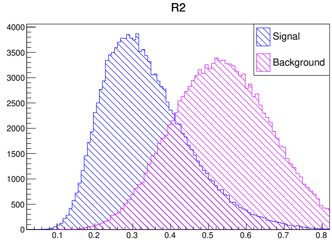
Background study

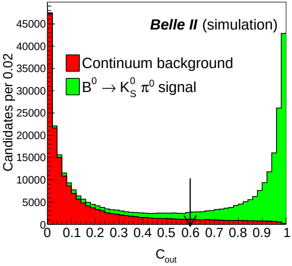
Continuum supression



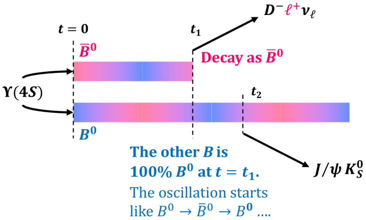


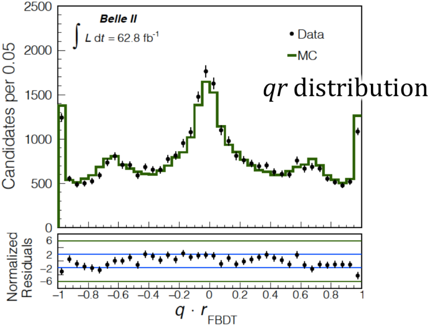
- Use a BDT to suppress the $e^+e^- \to q\bar{q}$ background
- An example input variable





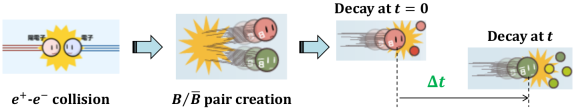
Flavor tagging



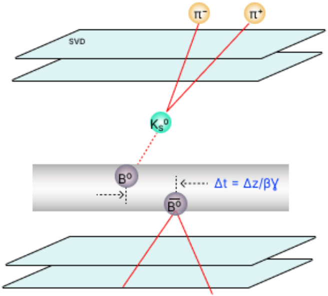


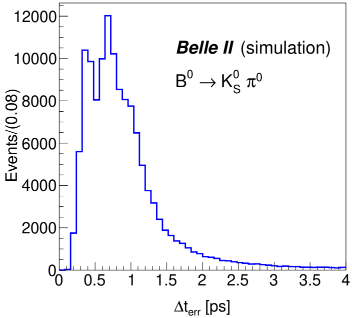
- $q = +1$ for B^0 and $q = -1$ for $\bar{B}^0$ tag
- $r = 0$ for no flavor information
- $r = 1$ for unambiguous flavor assignment
- Wrong tagging probability $w = \frac{1-r}{2}$

Going for time-dependent analysis



- Challenge: For $K_S^0\pi^0$, no primary charge track to help in vertexing, which leads to a poor decay time resolution
- B^0 vertex position is determined by projecting the K_S^0 trajectory to the interaction region





TDCPV fitter preparation

- Divide the dataset into 7 $q \cdot r$ bins for a simultaneous miaximun liklihood fit:

Compt.	Treatment during the fit
Signal	PDF shapes fixed from a $q \cdot r$ binned signal MC fit Floating parameters are the signal yield and $\mathcal{A}_{CP}$ Fix the $\mathcal{S}_{CP}$ value to the world-average of 0.57 [1]
$B\bar{B}$	PDF shapes are fixed from integrated $q \cdot r$ bin MC fit $B\bar{B}$ yield is floated with Gauss-constraint.
$q\bar{q}$	PDF shape parameters are floated over the $q \cdot r$ bin

- Signal and background modelled with an empirical PDF determined from MC
- Challenge: Perform a four-dimensional simultaneos fit in seven $q \cdot r$ bins
- Validate the framework with $B^0 \to J/\psi K_S^0$ control channel.

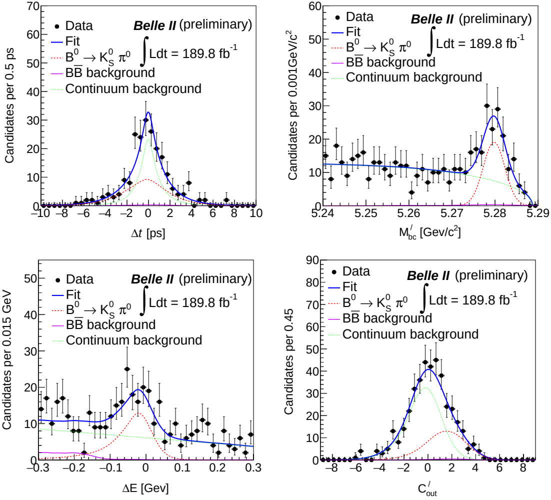
1] https://hflav-eos.web.cern.ch/hflav-eos/triangle/pdg2021

Projection of the fit result

- Signal enhanced region: $5.27 < M_{bc} < 5.29\ GeV/c^2$, $-0.15 < \Delta E < 0.1\ GeV$ and $C'_{out} > 0$

Shown fit projections are for the candidates with integrated $q \cdot r$ bin

Preliminary



Final results

Preliminary

Dominant systematic uncertainties

Source	$\delta\mathcal{B}$ (%)	δA_{CP}
π^0 reconstruction efficiency	7.5	–
Resolution function	–	0.050

Observable	Fitted value	World-average[1]
$\mathscr{B}(B^0 \to K^0\pi^0) \times 10^{-6}$	$11.0 \pm 1.2(stat) \pm 1.0(syst)$	9.9 ± 0.5
$\mathcal{A}_{CP}$	$-0.41^{+0.30}_{-0.32}(stat) \pm 0.09(syst)$	-0.01 ± 0.1

$$N_{\rm sig} = 135.0^{+16.0}_{-15.0}$$

- $\mathscr{B}$ and $\mathcal{A}_{CP}$ are consistent with PDG values within uncertainty

1] https://hflav-eos.web.cern.ch/hflav-eos/triangle/pdg2021

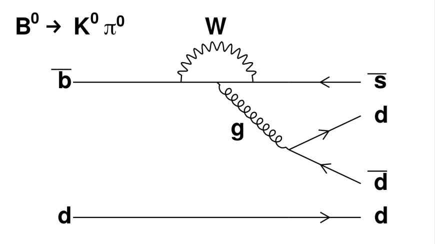
Summary and Plans

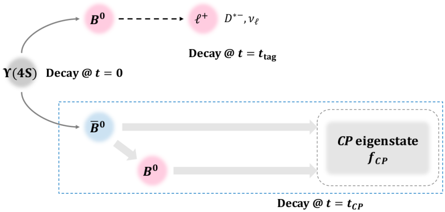
- Studied the $189.8\,\mathrm{fb}^{-1}$ data to measure $\mathscr{B}$ and $\mathcal{A}_{CP}$
- $\mathscr{B}$ and $\mathcal{A}_{CP}$ are consistent with PDG values within uncertainty
- The Belle II public result is available online: https://arxiv.org/abs/2206.07453
- Work underway to have a journal paper soon with $361.5\,\mathrm{fb}^{-1}$ dataset

Thank You

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.





- τ_{B^0} = lifetime of B^0, $\Delta m_d = B^0 - \bar{B}^0$ mixing frequency
- $\Delta t = t_{CP} - t_{tag}$ (decay time diff.)
- $A_{CP} = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} =$
- S_{CP} = mixing induced CPV
- In SM, $A_{CP} \approx 0$ & $S_{CP} = \sin 2\beta$

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}_{\mathcal{CP}} \cos(\Delta m_d \Delta t) + \mathcal{S}_{\mathcal{CP}} \sin(\Delta m_d \Delta t)\}]$$

Outline

- Motivation
- Development of time-dependent CPV fit
- Systematic uncertainties
- First measurement of $\mathcal{B}$ and A_{CP}
- Summary and Plans

Analysis overview

Selection

- baseline selection cut optimised on simulation followed by optimisation of continumm suppression cut.

Efficiencies and corrections

- efficiencies from simulation, validated on data

Signal extraction

- develop fit model from simulation, adjusted on control mode
- determine selection efficiencies for $\mathscr{B}$ calculation

Sytematic uncertainties

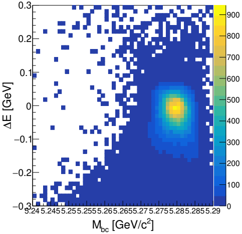
- toy studies and control mode analyses

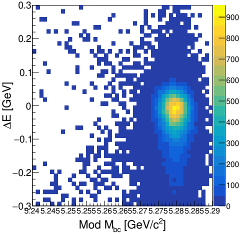
Validation & unblinding

- validate the full analysis on control on data
- apply full analysis to data

Modified M_{bc}

- π^0 in the final state causes correlation between ΔE and M_{bc}.
- $M_{bc} = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{B}}$
- $\vec{p}^{*}_{B} = \vec{p}^{*}_{K^0_S} + \vec{p}^{*}_{\pi^0}$
- $\vec{p}^{*}_{B} = \vec{p}^{*}_{K^0_S} + \frac{\vec{p}^{*}_{\pi^0}}{|\vec{p}^{*}_{\pi^0}|} \cdot \sqrt{(E^{*}_{beam} - E^{*}_{K^0_S})^2 - m^2_{\pi^0}}$



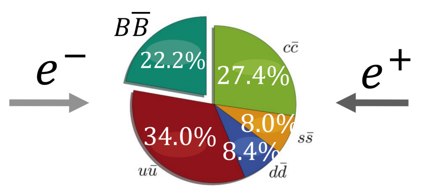


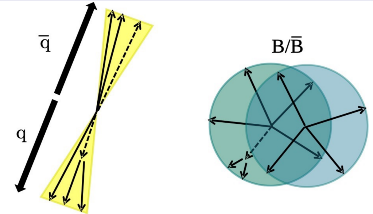
Comp.	Before	After
Signal	18.9%	−0.7%
$B\bar{B}$	−6.4%	4.4%
$q\bar{q}$	−0.4%	0.4%

Following M_{bc} reffered as modified M'_{bc}

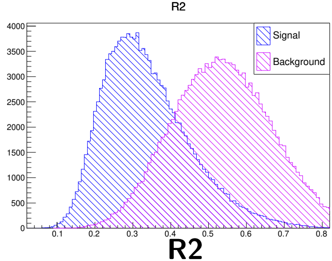
Background study

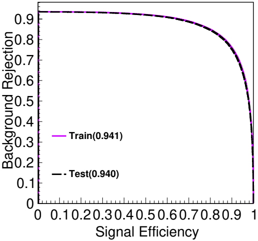
Continuum supression



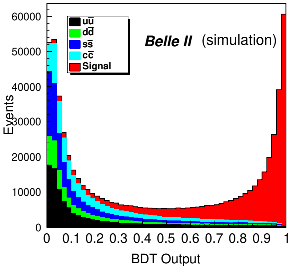


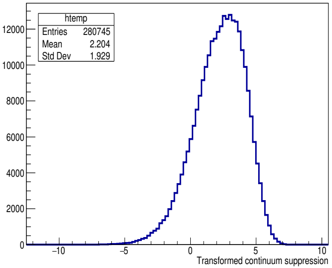
- $R_2 = \frac{H_2}{H_0} = \frac{\sum_i^N \sum_j^N [|\vec{p}_i||\vec{p}_j| \cdot (3\cos^2\theta_{ij} - 1)]}{2\sum_i^N \sum_j^N [|\vec{p}_i||\vec{p}_j|}$, for $q\bar{q}$ events $\cos\theta_{ij} \approx 1$





Log-transform of continuum output

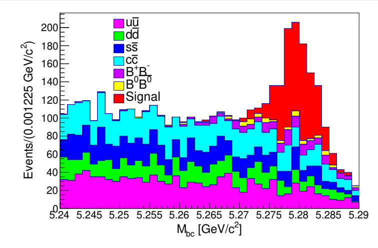




- We transform the BDT classifier output (C_{out}) to (C'_{out}) in order to parametrize using a simple PDF
- Transform continumm suppression variable is defined as

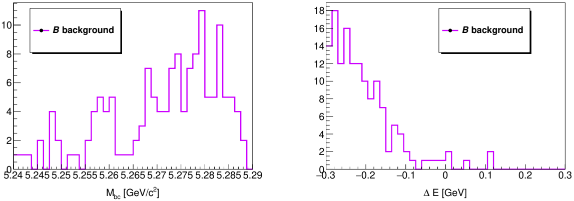
$$C'_{out} = log(\frac{C_{out} - C_{out_{min}}}{C_{out_{max}} - C_{out}}) \quad (1)$$

where $C_{out_{max}}$=0.99 and $C_{out_{min}}$=0.60



Background study continued

- We do not find any $B\bar{B}$ events peaking in the ΔE signal region.
- There is non-neglible $B\bar{B}$ combinatorial background present.

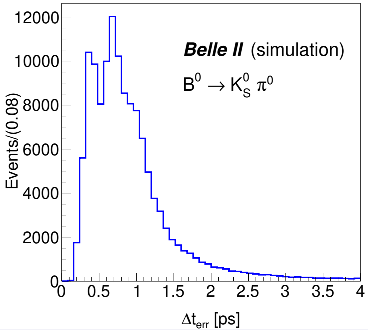


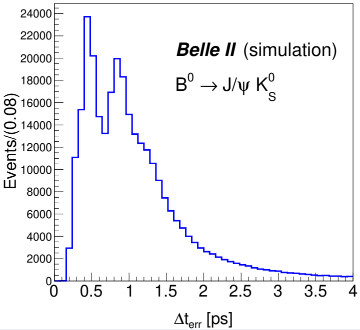
Correlation among fit variables

Category	ΔE–Δt	$M_{\rm bc}$–C'_{out}	$M_{\rm bc}$–Δt	ΔE–C'_{out}	Δt–C'_{out}
Signal	−0.01%	0.8%	0.7%	0.2%	0.3%
$B\bar{B}$	−0.1%	2.1%	−0.6%	−3.7%	−3.2%
$q\bar{q}$	−0.3%	−0.5%	0.5%	0.2%	0.6%

Decay-time uncertainty and time resolution

- Double peak observed in Δt_{err} distribution.
- Feature reproduced in the control channel.
- Considering contributions from both the peaks.
- Sum of two Gaussian use for the resolution function.





- Removing poor decay time resolution by applying $\sigma_{\Delta t_{err}} < 2.5$ ps.
- Signal efficiency $= 12.3\%$ ($N_{sig}^{expt} = 122$)

Validation results

- Check consistency with 1000 experiment
  → Pure toys: generate data from the PDFs and fit back.
  → GSIM toys: signal are sampling from simulated data, $B\bar{B}$ and $q\bar{q}$ are generated from PDFs

Pure toy

Parameter	Pull mean	Pull width	Fit value	Expected
Signal yield	0.06 ± 0.03	1.06 ± 0.03	124 ± 15	122
Continuum yield	0.02 ± 0.04	1.02 ± 0.03	2501 ± 53	2509
$B\bar{B}$ yield	gauss-cons.	gauss-cons.	43 ± 4	43
$\mathcal{A}_{CP}$	0.02 ± 0.04	1.08 ± 0.03	0.02 ± 0.33	0.0

GSIM toy

Parameter	Pull mean	Pull width	Fit value	Expected
Signal yield	0.03 ± 0.04	1.03 ± 0.03	123 ± 14	122
Continuum yield	-0.03 ± 0.04	1.02 ± 0.03	2506 ± 49	2509
$B\bar{B}$ yield	gauss-cons.	gauss-cons.	43 ± 4	43
$\mathcal{A}_{CP}$	-0.07 ± 0.04	0.98 ± 0.03	-0.01 ± 0.30	0.0

- There is no significant bias!

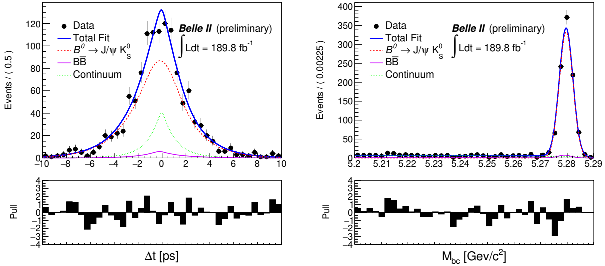
Control channel modelling

"Yesterday's discovery is today's calibration" – R.Feynman

- Want to perform the full analysis on the $B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0$ decay as a validation. Compare with known values, a measurement of
  $\to B^0$ lifetime, A_{CP} and S_{CP}
- Only K_S^0 used for B^0 vertexing
- First, develop the analysis on simulation, as done for the rare decay
- Simplified fit: since $B^0 \to J/\psi K_S^0$ is much cleaner, don't need CS. Fit M_{bc} and Δt only (details in backup).
- Same approach for flavour-tagging and time-dependent PDF:
  $\to 7\ q \cdot r$ bin fit. $\to$ cut a $\Delta t_{err} < 2.5$ ps, and resolution function (sum of two Gaussian)

B Lifetime fit(Data)

- $189.8\ fb^{-1}$ Data



Preliminary !

Parameter	Fitted value	WA[1] value
Lifetime (ps)	$1.59^{+0.09}_{-0.08}$	1.519 ± 0.004

- Lifetime is consistent within uncertainty.

1] https://hflav-eos.web.cern.ch/hflav-eos/triangle/pdg2021

Example of fit projection (Data)

Preliminary !

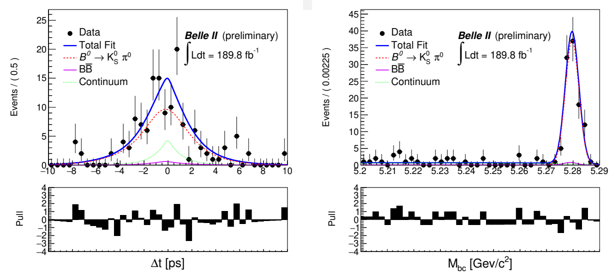


Figure: 4th-bin fit projection in Data

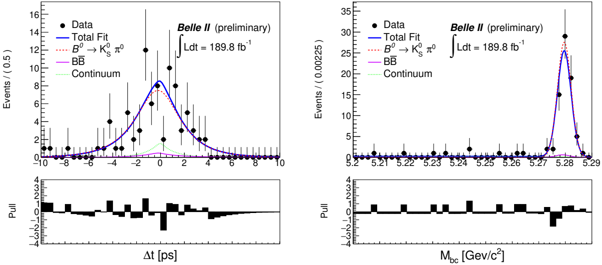


Figure: 5th-bin fit projection in Data

- Rest of the bin fit projection shown in backup slide

Results for $B^0 \to J/\psi K_S^0$

Preliminary !

- Sample size corresponding to 189.8 fb^{-1}

Parameter	Fitted value	WA[1]
$\mathcal{A}_{CP}$	$0.031^{+0.099}_{-0.098}$	0.000 ± 0.020
$\mathcal{S}_{CP}$	$0.818^{+0.156}_{-0.164}$	0.695 ± 0.019

- $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ are consistent within uncertainty.

1] https://hflav-eos.web.cern.ch/hflav-eos/triangle/pdg2021

Systematic uncertainty

Preliminary !

Table: List of systematic uncertainties contributing to the measured branching fraction.

Source	$\delta\mathcal{B}(\%)$
Tracking efficiency	0.6
K_S^0 reconstruction efficiency	4.2
π^0 reconstruction efficiency	7.5
Cont. supp. efficiency (see backup)	1.6
Number of $B\bar{B}$ events	3.2
Signal model	1.0
Continuum background model	0.9
Possible fit bias	2.0
Physics parameters	0.4
Total	9.6

Systematic uncertainty

Preliminary !

Table: List of systematic uncertainties contributing to $\mathcal{A}_{CP}$.

Source	$\delta\mathcal{A}_{CP}$
Flavor tagging	0.040
Resolution function	0.050
Physics parameter	0.021
B decay background asymmetry	0.002
Possible fit bias	0.010
Tag-side interference[1]	0.038
Background modeling	0.004
Signal modeling	0.015
Total	0.086

1] I. Adachi et al. (Belle Collaboration), Phys. Rev. Lett. **108**, 171802 (2012)

CKM Matrix

- The CKM matrix is a unitary matrix: $\begin{pmatrix} V_{ud} & V_{us} & \boldsymbol{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boldsymbol{V_{td}} & V_{ts} & V_{tb} \end{pmatrix}^\dagger \begin{pmatrix} V_{ud} & V_{us} & \boldsymbol{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boldsymbol{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

  From the unitarity condition, 6 equations are derived.

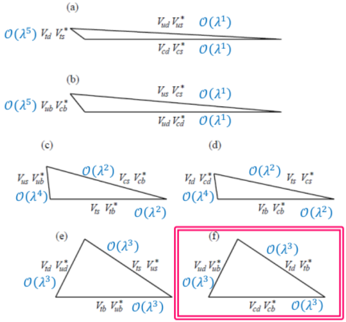
  (a) $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$
  (b) $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$
  (c) $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$
  (d) $V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$
  (e) $V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$
  (f) $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

- From physics discussion, the Wolfenstein parameterization is obtained:

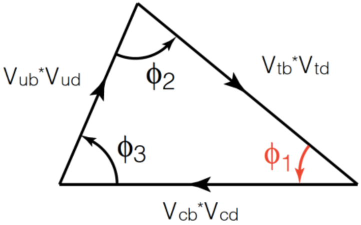
$$V_{\text{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

  - You need to remember that V_{td} and V_{ub} are complex.
  - You need to remember $\lambda \approx 0.2$ plus the order of λ for each element.
  - You need to remember $A \approx 0.8$.

CKM Triangle



- Each of the equation forms a triangle on the complex plane.
- The bottom right triangle, which is associated to the equation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ is moderately large.
- By assuming $V_{ud}V_{ub}^*$, $V_{cd}V_{cb}^*$, and $V_{td}V_{tb}^*$ are vectors, we can draw a triangle associated to the equation on the complex plane, which is called "CKM triangle".



Interior angle definition

$$\phi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = \pi - \arg(V_{td})$$

$$\phi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\phi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

If the KM theory is correct, $\phi_1 \neq 0, \pi$.

Mixing-Induced *CP* Violation

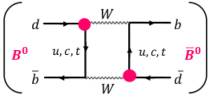
Phase difference from decay

B^0

$\bar{B}^0$

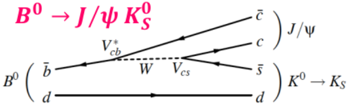
Phase difference from decay

***CP* eigenstate f_{CP}**

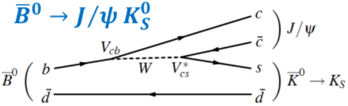
arg 

Phase difference from the mixing $\pm 2\phi_1$

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



$\bar{B}^0 \to J/\psi\, K_S^0$



$\arg\left(B^0 \to J/\psi\, K_S^0\right) = \arg(V_{cb}^* V_{cs}) = 0$

$\arg\left(\bar{B}^0 \to J/\psi\, K_S^0\right) = \arg(V_{cb} V_{cs}) = 0$

Remember only $\arg(V_{td})$ and $\arg(V_{ub})$ are non zero.

We can extract ϕ_1 by analyzing the $B \to J/\psi\, K^0$ and other $(c\bar{c})K^0$ modes.

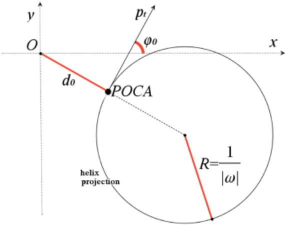
Determination of the *B*-Decay Position

- Charged particle trajectory in a magnetic field = **helix**

$$\text{helix parameter} \equiv (d_0, \phi_0, \omega, z_0, \tan\lambda)$$

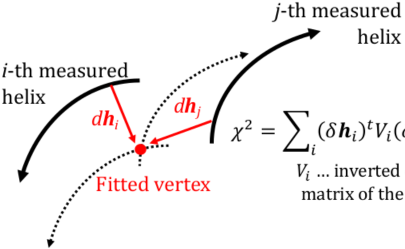
Belle II (BELLE2-NOTE-TE-2018-003)

$(x^P, y^P, z^P, p_x^P, p_y^P, p_z^P)$ at
POCA = Point of Closest Approach



$$x^P = d_0 \sin\phi_0 \qquad p_x^P = \cos\phi_0/\alpha\omega$$
$$y^P = -d_0 \cos\phi_0 \qquad p_y^P = \sin\phi_0/\alpha\omega$$
$$z^P = z_0 \qquad p_z^P = \tan\lambda/\alpha\omega$$

- The decay position (called vertex) is determined wit the χ^2-minimizing method.



$$\chi^2 = \sum_i (\delta \boldsymbol{h}_i)^t V_i (\delta \boldsymbol{h}_i)$$

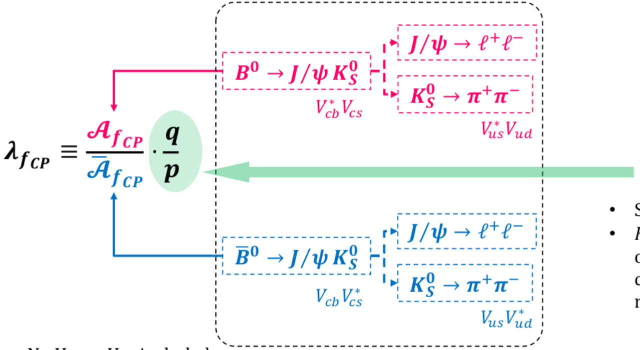
V_i ... inverted error matrix of the helix

The vertex that gives the minimum χ^2 is taken as the fitted vertex (KFit).
When the "IP constraint" is applied to KFit, $\chi^2 + \chi^2_{\mathrm{IP}}$ is minimized where χ^2_{IP} accounts for the IP spread.

Typical vertex resolution: $\delta z \approx$ **50 μm**

The Last Piece, $\lambda_{f_{CP}}$

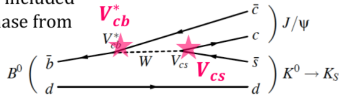
- Assume we use the golden mode for the test of the Kobayashi-Maskawa theory, where $B^0 \to J/\psi\, K_S^0$ and $\bar{B}^0 \to J/\psi\, K_S^0$.

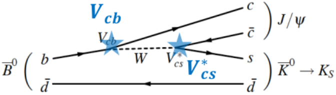


$$\frac{q}{p} \approx \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$

- Skipped derivation.
- K^0-$\bar{K}^0$ mixing is omitted for its small contribution to the B-meson system.

- No V_{td} or V_{ub} included → no CKM phase from the decay.





Application: CPV in B Decays at Belle (II)

- For $B^0(\bar{B}^0) \to J/\psi\, K_S^0$, $\lambda_{J/\psi K_S^0} \equiv \frac{\mathcal{A}_{f_{CP}}}{\bar{\mathcal{A}}_{f_{CP}}} \cdot \frac{q}{p} = \xi_{J/\psi K_S^0} \frac{V_{cb}^* V_{cs} V_{us}^* V_{ud}}{V_{cb} V_{cs}^* V_{us} V_{ud}^*} \cdot \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$

  Since only V_{td} and V_{ub} are complex, $\lambda_{J/\psi K_S^0} = \xi_{J/\psi K_S^0} \cdot e^{-2i\phi_1}$.

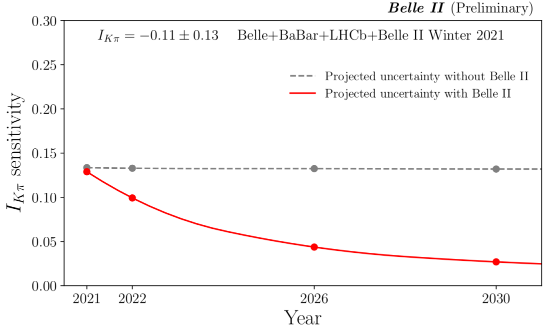
  $\mathcal{Im}\left(\lambda_{J/\psi K_S^0}\right) = -\xi_{J/\psi K_S^0} \sin 2\phi_1 = \sin 2\phi_1$.

$$\boldsymbol{P(t;\ell^\pm) = \frac{1}{2\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} (1 \pm \sin 2\phi_1 \sin \Delta m_d \Delta t)}$$

- $\mathcal{Im}(\lambda_{f_{CP}})$ depends on the $\mathcal{A}_{f_{CP}}$ and $\bar{\mathcal{A}}_{f_{CP}}$, which are determined by the chosen $B^0(\bar{B}^0) \to f_{CP}$ mode. For example, if one chooses $B^0(\bar{B}^0) \to \pi^+\pi^-$, he/she obtains the $P(t;\ell^\pm)$ equation with $\sin 2\phi_2$.

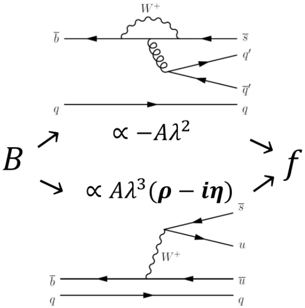
$\mathcal{B}[10^{-6}]$		
Mode	BaBar	Belle
$K^+\pi^-$	$19.1 \pm 0.6 \pm 0.6$ [16]	$20.00 \pm 0.34 \pm 0.60$ [17]
$K^+\pi^0$	$13.6 \pm 0.6 \pm 0.7$ [18]	$12.62 \pm 0.31 \pm 0.56$ [17]
$K^0\pi^+$	$23.9 \pm 1.1 \pm 1.0$ [19]	$23.97 \pm 0.53 \pm 0.71$ [17]
$K^0\pi^0$	$10.1 \pm 0.6 \pm 0.4$ [20]	$9.68 \pm 0.46 \pm 0.50$ [17]

$\mathcal{A}_{CP}$				
Mode	BaBar	Belle	LHCb	CDF
$K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$ [20]	$-0.069 \pm 0.014 \pm 0.007$ [17]	$-0.084 \pm 0.004 \pm 0.003$ [21]	$-0.083 \pm 0.013 \pm 0.004$ [22]
$K^+\pi^0$	$0.030 \pm 0.039 \pm 0.010$ [18]	$0.043 \pm 0.024 \pm 0.002$ [17]	$0.025 \pm 0.015 \pm 0.006 \pm 0.003$ [23]	
$K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$ [19]	$-0.011 \pm 0.021 \pm 0.006$ [17]	$-0.022 \pm 0.025 \pm 0.010$ [24]	
$K^0\pi^0$	$-0.13 \pm 0.13 \pm 0.03$ [25]	$0.14 \pm 0.13 \pm 0.06$ [26]		



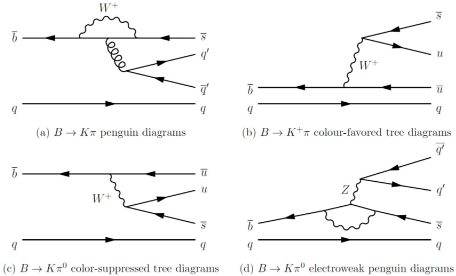
CP Violation

- Physical laws not invariant under charge conjugation + parity inversion (mirror flip)
- Consequence of interference when a physical process can proceed in different ways
- CP violation in mixing: $B^0 \to \overline{B^0} \neq \overline{B^0} \to B^0$
- Indirect CP violation: asymmetry due to interference between mixing and decay amplitudes
- **Direct CP violation:** $B \to f \neq \bar{B} \to \bar{f}$ due to interference in decay amplitudes
  - Requires non-zero relative weak and strong phase between amplitudes



The $B \to K\pi$ System

- $B^0 \to K^+\pi^-$, $B^0 \to K^0\pi^0$, $B^+ \to K^+\pi^0$, $B^+ \to K^0\pi^+$
- Dominated by QCD penguin diagrams
    - Suppressed by loop
    - Tree suppressed by V_{ub}
- Different $K\pi$ decays have contributions from different diagrams
- Potentially sensitive to new physics through massive virtual particles in loops



(a) $B \to K\pi$ penguin diagrams

(b) $B \to K^+\pi$ colour-favored tree diagrams

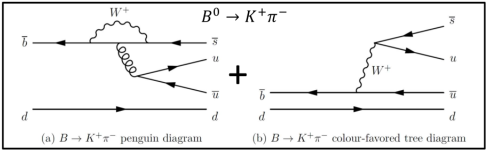
(c) $B \to K\pi^0$ color-suppressed tree diagrams

(d) $B \to K\pi^0$ electroweak penguin diagrams

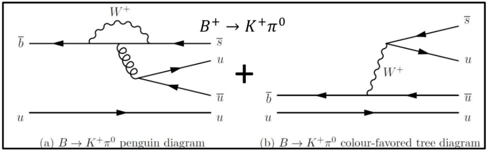
The $K\pi$ Puzzle

- CP asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ from interference between tree and penguin diagrams
- Expected to be equal from isospin arguments
- Differs by more than 5σ according to current measurements

$$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.124 \pm 0.021$$



(a) $B \to K^+\pi^-$ penguin diagram (b) $B \to K^+\pi^-$ colour-favored tree diagram



(a) $B \to K^+\pi^0$ penguin diagram (b) $B \to K^+\pi^0$ colour-favored tree diagram

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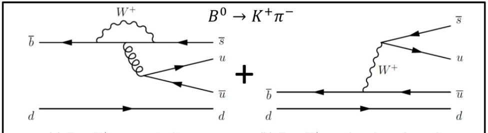
The $K\pi$ Puzzle

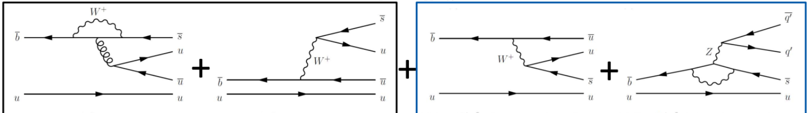
$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-)$
$= 0.124 \pm 0.021$

- Color-suppressed tree and electroweak penguin diagrams contribute to $K^+\pi^0$ but not $K^+\pi^-$



(a) $B \to K^+\pi^-$ penguin diagram (b) $B \to K^+\pi^-$ colour-favored tree diagram

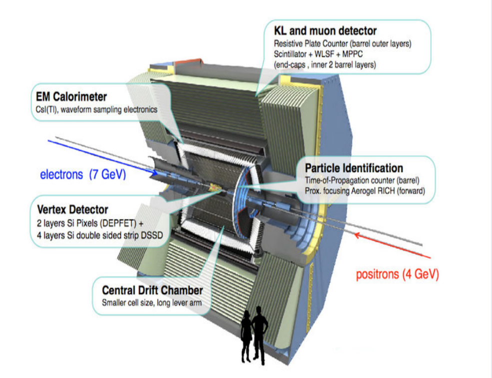
$B^+ \to K^+\pi^0$



(a) $B \to K^+\pi^0$ penguin diagram (b) $B \to K^+\pi^0$ colour-favored tree diagram (c) $B \to K^+\pi^0$ color-suppressed tree diagrams (d) $B \to K^+\pi^0$ electroweak penguin diagrams

SuperKEKB and Belle II Detector

- Asymmetric collider: e^- to 7 GeV and e^+ to 4 GeV
  → clean experimental environment
- World record peak luminosity: $3.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- New tracking system and improved vertexing
- Improved particle identification
- Better time resolution at calorimeter



Goal:

- Collect more than 50 ab^{-1} data ($5 \times 10^{10} B\bar{B}$ pairs)
- 700 $B\bar{B}$ pairs/second

Currently:

- 216 fb^{-1} data are collected. Today: results on $\approx 63\mathrm{fb}^{-1}$

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-2020-038.
- $dr < 0.5$ 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

Rare components investigation

2D (M_{bc}, ΔE) Extended Fit (Cont'd)

- Rare background contributing to the analysis region:

expected @ 62.8 fb^{-1}

		Mode	$\mathcal{B}[10^{-6}]$ (PDG2020 Avg. [3])	$\epsilon[\%]$	Yield
$N = \int \mathscr{L}dt \cdot \sigma \cdot f^{+-} \cdot 2 \cdot \mathscr{B} \cdot \epsilon$	B^+	$\rho^+ K^0$	$7.3^{+1.0}_{-1.2}$	1.05	5.5 ± 0.8
		$K^*(892)^+\pi^0$	6.8 ± 0.9	0.85	4.1 ± 0.5
		$X_{s,u}\gamma$	349 ± 19	<0.01	0.7 ± 0.0
		$a_1(1260)^+K^0$	35 ± 7	<0.01	0.1 ± 0.0
$N = \int \mathscr{L}dt \cdot \sigma \cdot f^{00} \cdot 2 \cdot \mathscr{B} \cdot \epsilon$	B^0	$f_2(1270)K^0$	$2.7^{+1.3}_{-1.2}$	0.52	1.0 ± 0.4
		$f_0(980)K^0$	4.1 ± 0.4	0.19	0.5 ± 0.1
		$X_{s,d}\gamma$	349 ± 19	<0.01	0.5 ± 0.0
		$K^0_S K^0_S$	0.61 ± 0.08	0.50	0.2 ± 0.0
		$K^0\eta'$	66 ± 4	<0.01	0.1 ± 0.0
Sum					12.7 ± 1.1

dominant processes
$B \to K^0\pi^+\pi^0$
(PDG; PRD)

- Finally assign a Gauss(μ=12.7, σ=1.1) constraint on the normalization of rare background

Thrust

- Thrust: For a colection of N momenta $\vec{p_i}$ (i=1, ... N), the thrust axis $\vec{T}$ is defined as the unit vector along which their total projection is maximal.
- $T = max \frac{\sum_i^N |\hat{T} \cdot \vec{p_i}|}{\sum_i^N |\vec{p_i}|}$

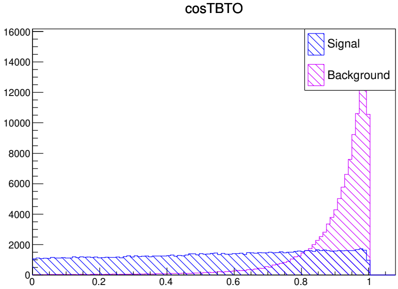
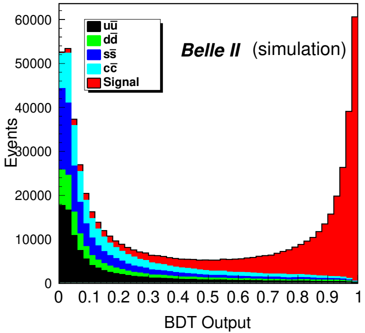


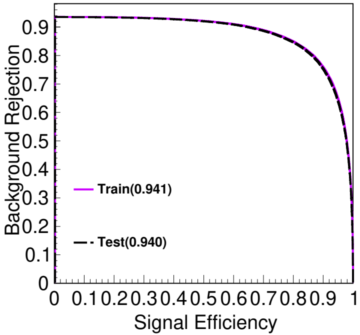
Figure: Cosine angle between signal B-meson and ROE (rest of the events)

Continuum suppression

- FatBDT as the multivariate classifier.
- Same number of signal and background events.
- 600 fb^{-1} for training and 400 fb^{-1} for testing.
- Same classifier input used(BELLE2-NOTE-PH-2020-046,BELLE2-NOTE-PH-2020-007).

Classifier Output





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

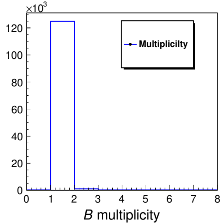
https://stash.desy.de/projects/B2B2C/repos/btohadronscripts/browse/BToCharmless_WithCorr_CSFBDT.root

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

Best candidate selection

- Found some events with more than one B candidate in an event.

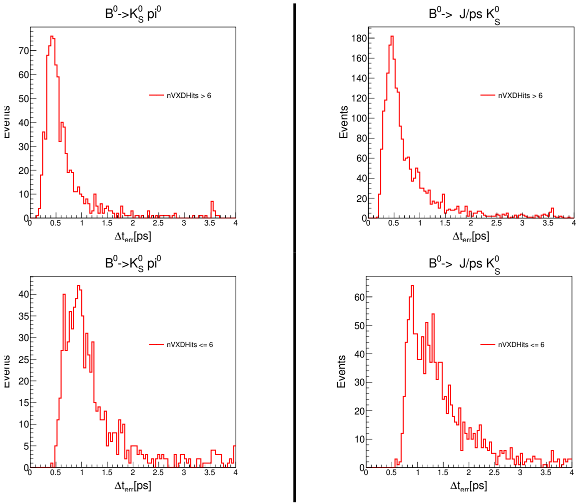


- Multiplicity=1.009
- π^0 multiplicity is severe than that of K_S^0.
  $\rightarrow$ First selection based fit π^0 chiProb (p-value) ($\epsilon = 73\%$)
  $\rightarrow$ If the candidate has the same chiProb (p-value) on π^0, then we do the K_S^0 chiProb (p-value) check ($\epsilon = 99\%$)

$$\epsilon_{\text{bcs}} = \frac{\text{No. of truth mathed events after BCS}}{\text{No. of truth matched events with multiplicity} > 1} = 74\% \qquad (2)$$

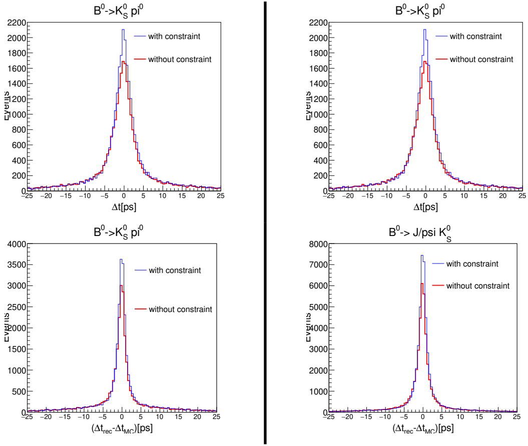
- Self-crossfeed fraction=1.5 %.
- Self-crossfeed component is taken into the signal PDF.

Δt_{err} double peak



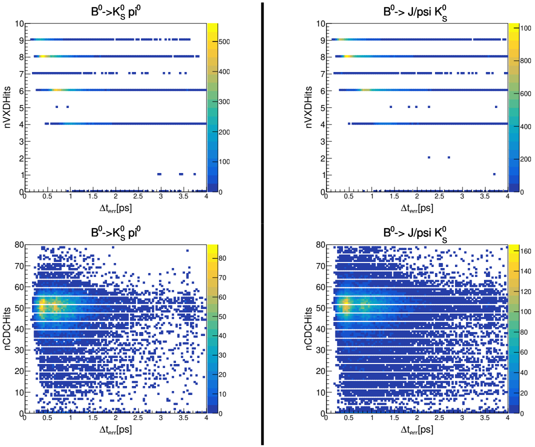
- We observe the decond peak due to fewer hits in VXD.

Effect of IP constraint



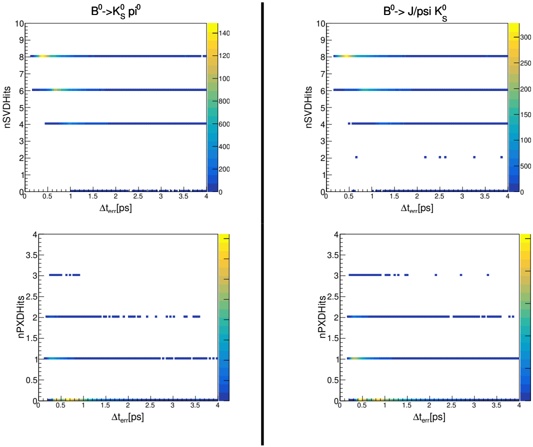
- After applying IP constraint in tag side Δt resolution improves.
- Similar trend is seen in the control channel .

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.

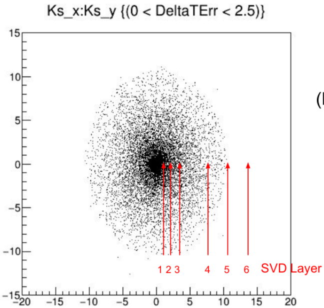
Δt_{err} vs. Hits



- 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)

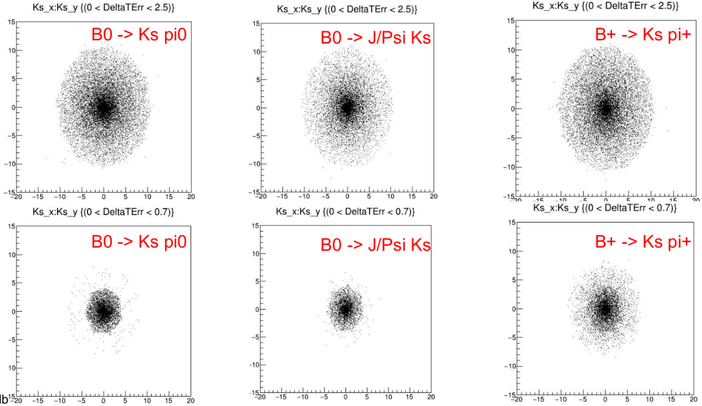
9

Tim Green, University of Melbourne

DeltaTErr and Ks Vertex Position

0 < DeltaTErr < 2.5

0 < DeltaTErr < 0.7
(First peak)



Tim Green, University of Melb

11

Signal mode

$\mathscr{B}$ calculation

The $\mathscr{B}$ is calculated as

$$\mathscr{B} = \frac{N_{sig}}{\epsilon \cdot f^{00} \cdot 2 \cdot \mathscr{B}_s \cdot N_{B\bar{B}}} \tag{3}$$

- $\mathscr{B}_s = 0.5$, 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=12.3 % (all selection + loose cont. supp. cut $+\sigma_{\Delta t}$)

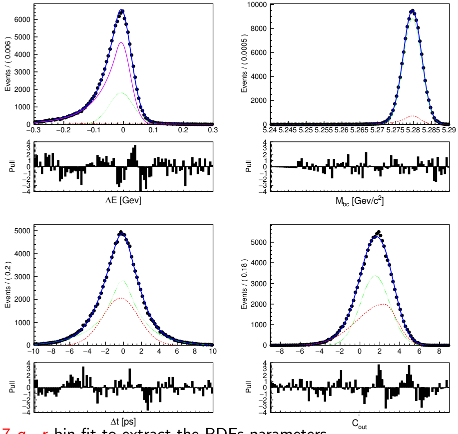
Signal Modeling

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

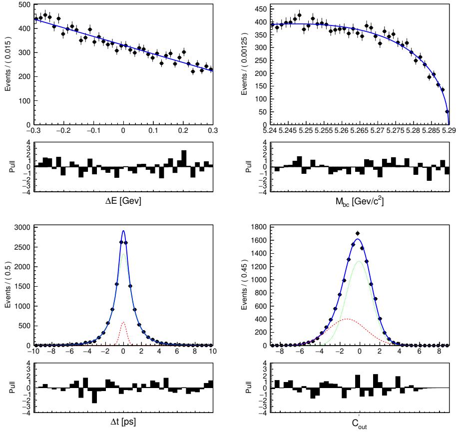
Example plot of integrated $q \cdot r$ bin



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

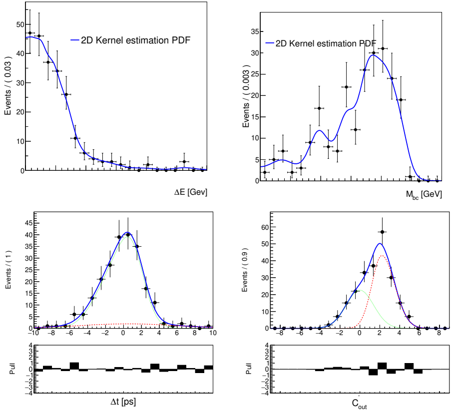
Continuum bkg modeling

- 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



M_{bc}–ΔE distribution between bad and good tag

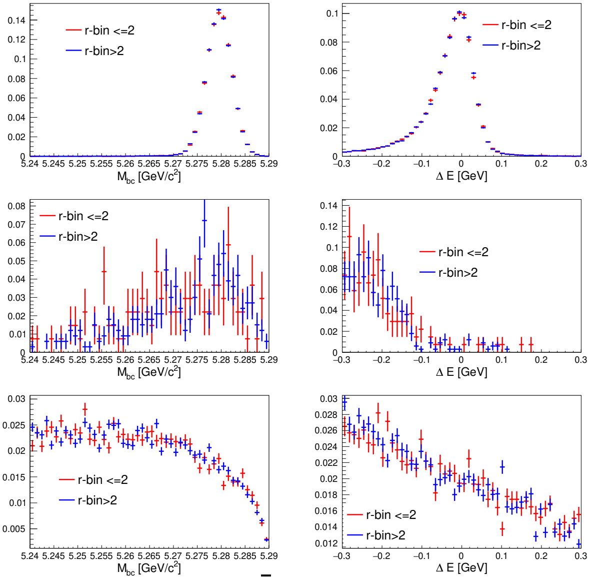


Figure: Signal (top), $B\bar{B}$ (middle) and $q\bar{q}$ (bottom)

$B\bar{B}$ normalisation sideband study

- Sideband region ($-0.3 < \Delta E < -0.2$)
- Optimsed CS$>$ 0.9 to reduce the continuum contribution.

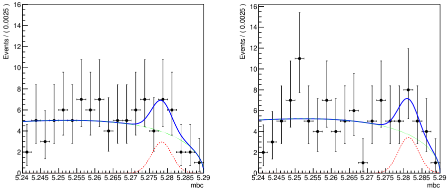


Figure: Sideband M_{bc} fit results in MC (left) and data (right) events.

Parameter	MC	Data
N_{peak}	8 ± 5	10 ± 5
N_{comb}	87 ± 10	90 ± 10

- We have confirmed this hypothesis in the case of MC events.
- Therefore, the uncertainty in the $B\bar{B}$ background yield is 5.

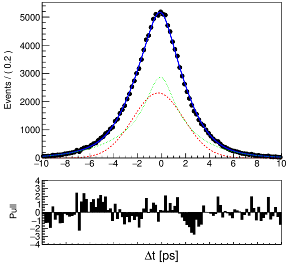
Control mode

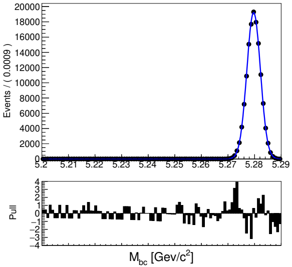
Signal Modeling

- Δt : RooBCPGenDecay PDF convolved with double Gaussian:

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

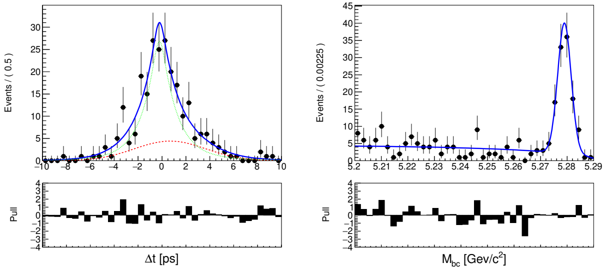
  Core and tail Gaussian
- M_{bc} : Crystal Ball function





$B\bar{B}$ 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



$q\bar{q}$ modeling

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