Study of $B^+ \to \pi^+\pi^0\pi^0$ at Belle

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BELLE

Outline

- Introduction.
- Study with Monte Carlo (MC):
  - Event selection and signal B reconstruction.
  - Background: continuum and $B\overline{B}$.
- Signal extraction and sPlot.
  - Fitter on sWeighted 2D $M_{\pi\pi}$ histogram: sub-decay and localized A_{CP}.
- Physics results.
- Summary

Introduction

- Charmless three-body B decays are useful to study the properties of the weak interaction in the quark sector.
  - Complicated structure of decay amplitudes, interference in between, and CP asymmetry localized in multi-body phase space.
  - Dalitz plot: search for intermediate resonances and localized A_{CP} in the three-body phase space.
  - Result is helpful to constrain magnitudes and phases of the CKM matrix elements. For instance, $B \to \rho\pi$ for $\phi_2(\alpha)$ and also $B^+ \to \chi_{c0}\pi^+$ for $\phi_3(\gamma)$.

PRD 79, 072006 (2009) PRD 101, 012006 (2020)

- Similar measurement on $B^+ \to \pi^+\pi^-\pi^+$ by BABAR and LHCb.
  - BF = $(15.2 \pm 0.6 \pm 1.2 \pm 0.4)\times10^{-6}$: Reference for our blinded analysis.
  - Full amplitude analysis.

- Upper limit of $B^+ \to \pi^+\pi^0\pi^0$ was reported: 8.9×10^{-4} at 90 C.L. by CLEO.

PLB 241 278-282 (1990)

- $B^+ \to \rho(770)^+\pi^0$: $(10.9 \pm 1.4) \times 10^{-6}$, by Belle and BABAR.

PRL 94 031801 (2005) PRD 75 091103 (2007)

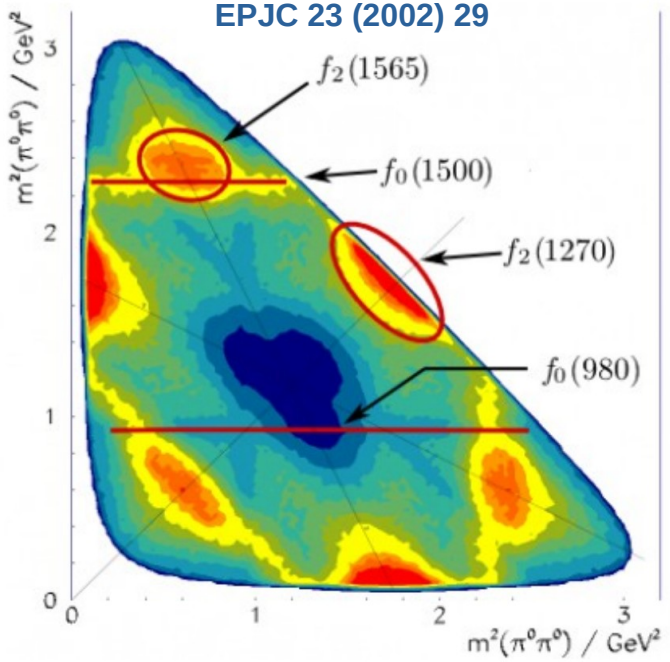
  - Majority of the $B^+ \to \pi^+\pi^0\pi^0$ decays.

Dalitz plot

- A method to unfold the three-body decay phase space visually.
  - Structure within this decay: amplitudes, spin, and inteference can be clearly seen.
- B → 1 , 2 , 3.
  - One of the representation: m^2_{12} vs m^2_{13} .

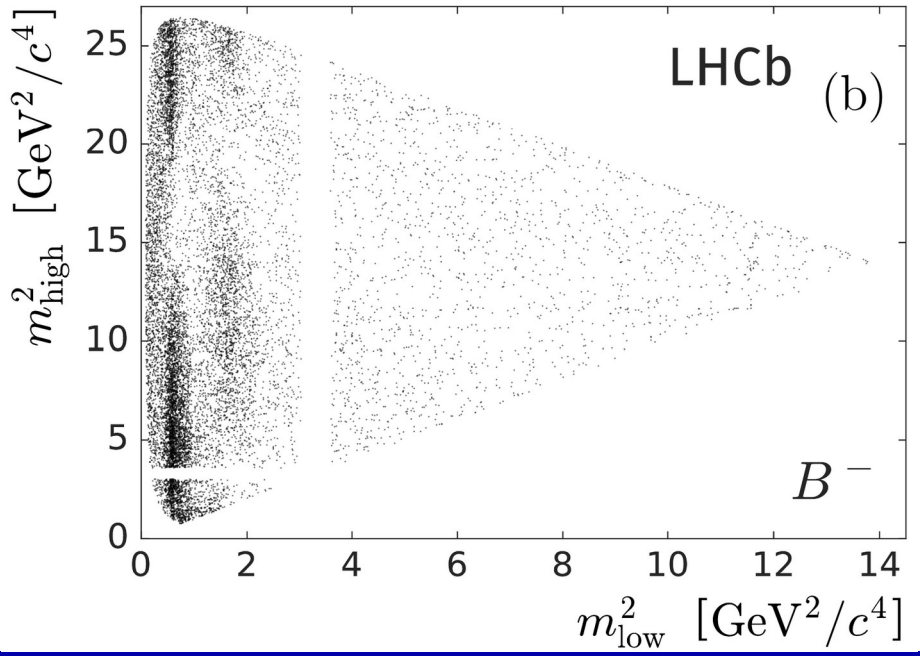
Dalitz plot of $p\bar{p} \to \pi^0\pi^0\pi^0$ by Crystal Ball

EPJC 23 (2002) 29



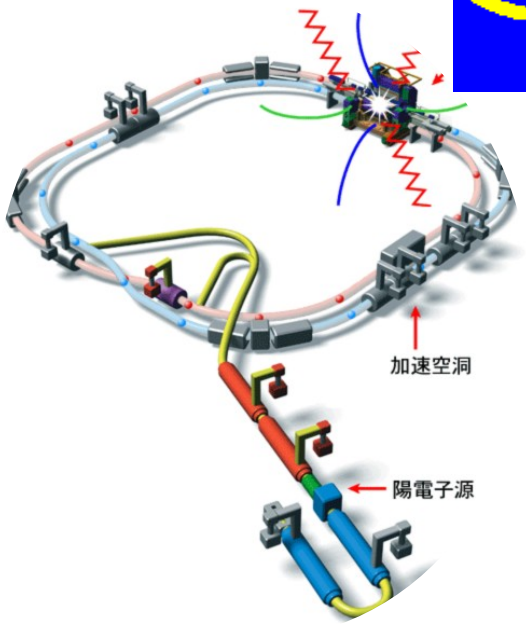
Dalitz plot of $B^- \to \pi^-\pi^+\pi^-$ by LHCb

PRD 101, 012006 (2020)

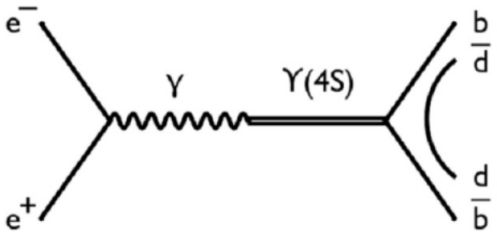


KEKB collider

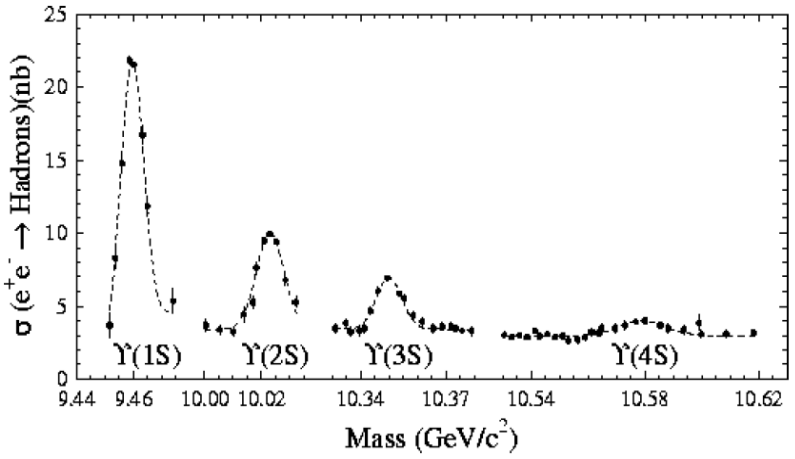
- An asymmetric energy e^+e^- collider at KEK.
  - LER(e^+) 3.5 GeV.
  - HER(e^-) 8 GeV.
  - Crossing angle: ±11 mrad.



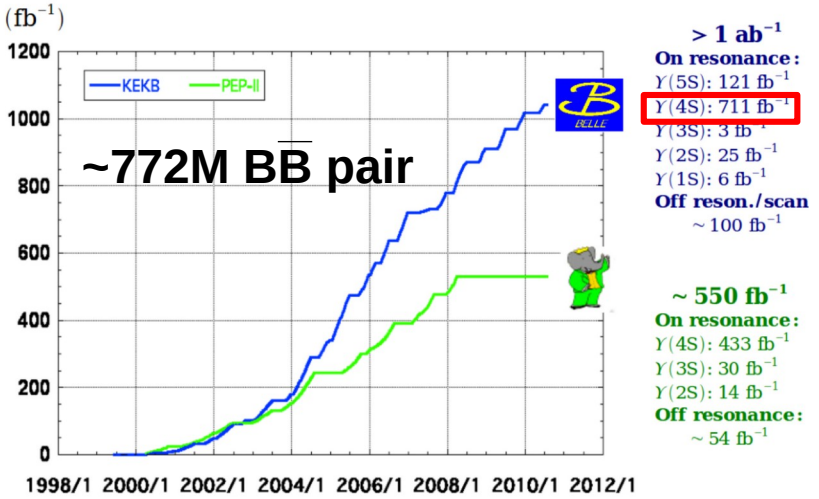
- Target: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for B physics.



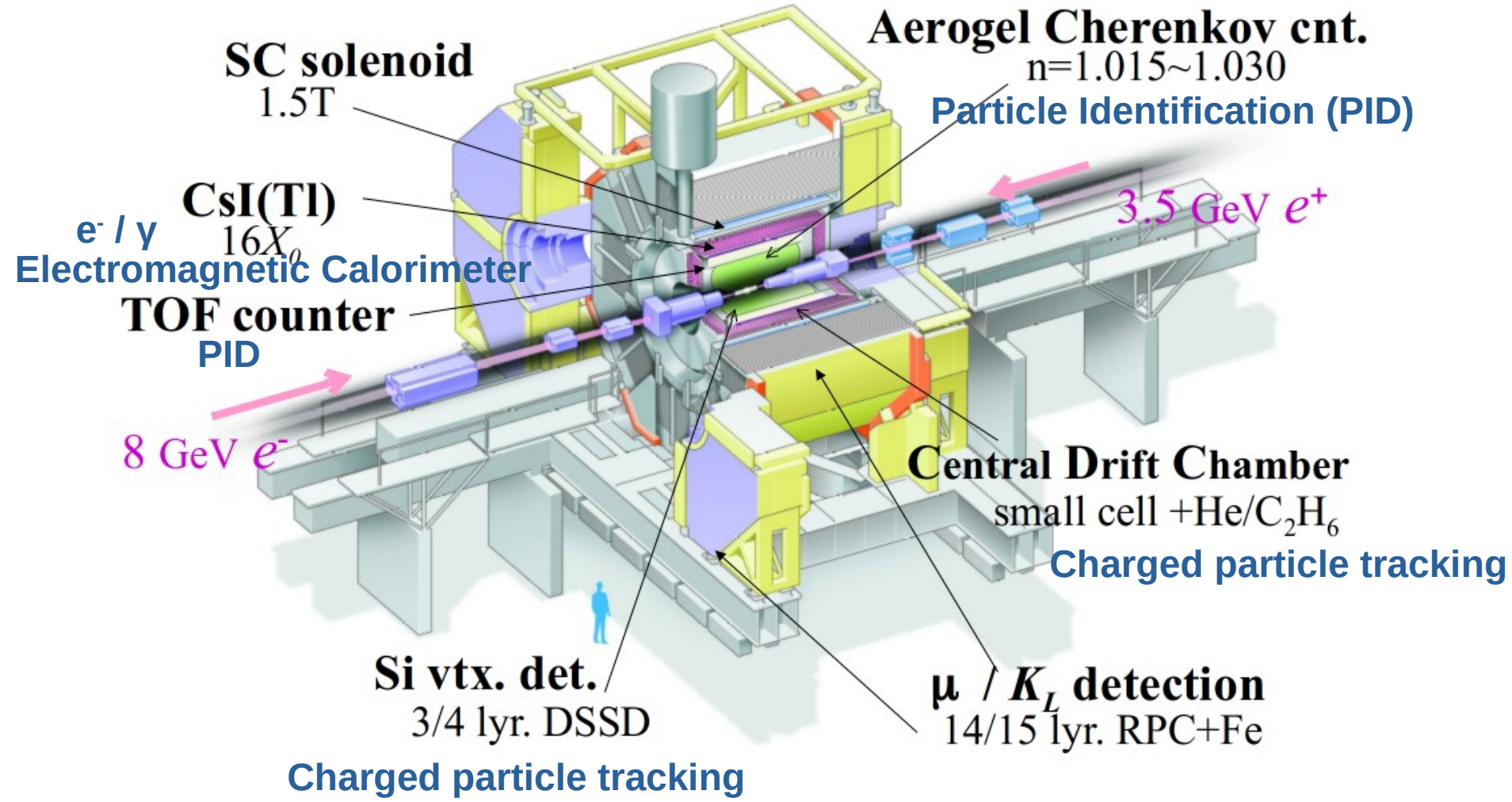
- Main background for B decay study:
  $e^+e^- \to q\bar{q}$, q=u,d,s,c with 3 times larger cross section.



http://www.lns.cornell.edu/public/lab-info/upsilon.html



Belle detector



Event sample with Monte Carlo

- Blinded analysis: Prestudy with Monte Carlo (MC) samples for signal and backgrounds.
  - Signal: assumed BF (1.5×10^{-5}), reconstruction efficiency by MC → Expected number of events in data.

- Event samples categories expected to be seen in data:

Signal	$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow$ $B \rightarrow \pi^+ \pi^0 \pi^0$, $\bar{B} \rightarrow$ randomly
Continuum background ($q\bar{q}$)	$e^+ e^- \rightarrow q\bar{q}$, $q = u, d, s, c$
$B\bar{B}$ background	$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow$ $B \rightarrow$ randomly, $\bar{B} \rightarrow$ randomly

Event sample with Monte Carlo (cont'd)

- In the signal reconstruction, there are truly reconstructed candidates ("true") and wrongly reconstructed candidates due to the decay of the other B:
  - Self-crossfeed (SCF).

- B decay backgrounds:
  - "Generic": $b \to c$. Larger BF. Well-measured.
  - "Rare": $b \to u,d,s$. Smaller BF (usually < 10^{-5}).

Signal	$e^+ e^- \to \Upsilon(4S) \to$ $B \to \pi^+ \pi^0 \pi^0$, $\overline{B} \to (b \to c)$
Continuum background ($q\overline{q}$)	$e^+ e^- \to q\overline{q}$, $q = u, d, s, c$
Generic $B\overline{B}$ background	$e^+ e^- \to \Upsilon(4S) \to$ $B \to (b \to c)$, $\overline{B} \to (b \to c)$
Rare $B\overline{B}$ background	$e^+ e^- \to \Upsilon(4S) \to$ $B \to (b \to u, d, s)$, $\overline{B} \to (b \to c)$

Within signal MC, there would be wrong reconstruction of $\pi^+ \pi^0 \pi^0$ candidates: **Self-crossfeed (SCF)**

Analysis overview

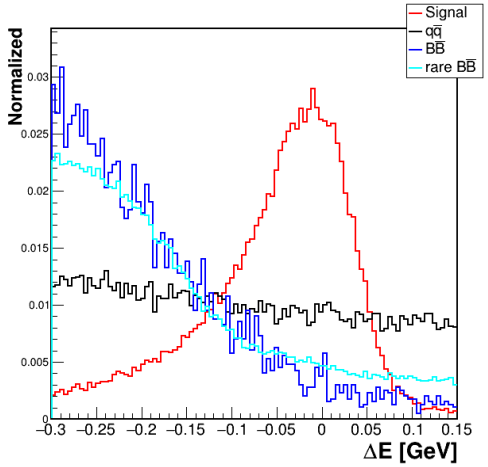
Blinded with Monte Carlo (MC)

Assume BF = 15×10^{-6}

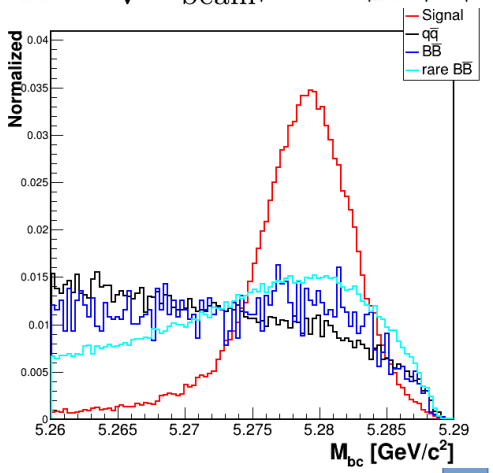
- **Signal $B^+ \to \pi^+\pi^0\pi^0$ reconstruction:**
  - π^+:Tracking&PID.
  - $\pi^0 \to \gamma\gamma$: Clusters in ECL (γ).
  - Details of signal study in Backup.
- **Background study:**
  - Continuum $e^+e^- \to q\bar{q}$.
    Suppression with multivariate tools.
  - $B\bar{B}$.

Major variables to identify signal B (in CM frame)

Energy difference $\Delta E \equiv E_B - E_{\rm beam}$

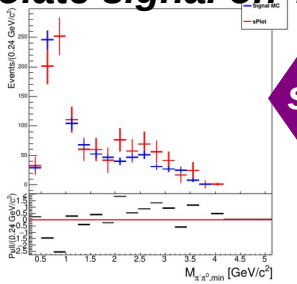


Beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_B/c|^2}$



- **sPlot technique** M. Pivk and F.R. Le Diberder, Nucl. Instrum. Methods Phys. Res., Sect. A 555, 356 (2005)
  - Use the sWeight from Laura++ to isolate signal in other dimensions.
  - Study Dalitz plot and $M_{\pi\pi}$.
- **2D fit on sWeights $M_{\pi\pi}$.**

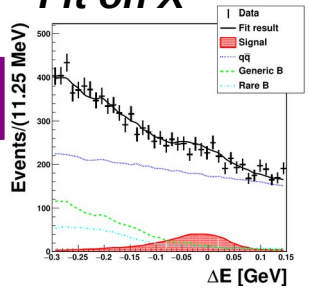
Isolate signal on Y



sPlot

- **Signal extraction by data fit**

Fit on X



  - 3D extended unbinned likelihood fit by Laura++.

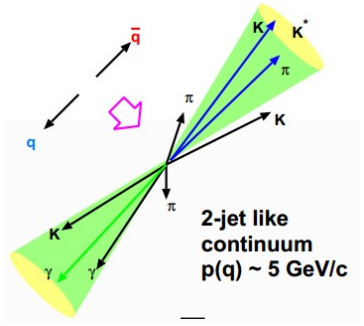
Sub-decays' BF & Localized A_{CP}

Total BF & Total A_{CP}

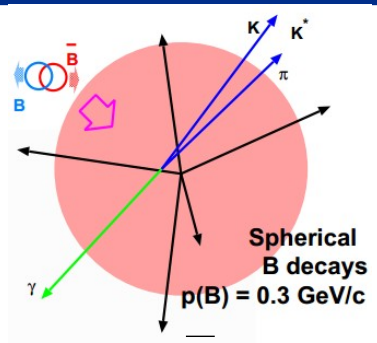
Continuum Background

- Continuum production: $e^+e^- \to q\bar{q}$, q=u,d,s,c.
  Dominant background.
  Decay shape difference between $B\bar{B}$ and $q\bar{q}$.

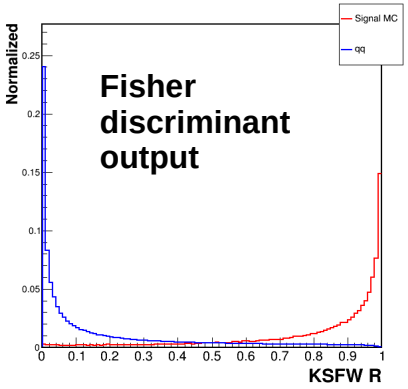
- Fisher discriminant with 17 event topology variables.
- Then combine with 3 more variables with Neuro-Network.

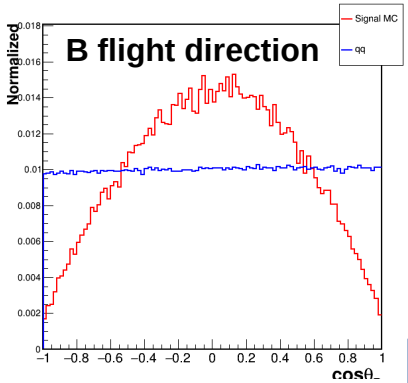


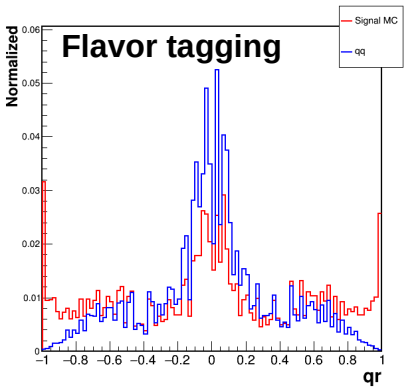
$q\bar{q}$

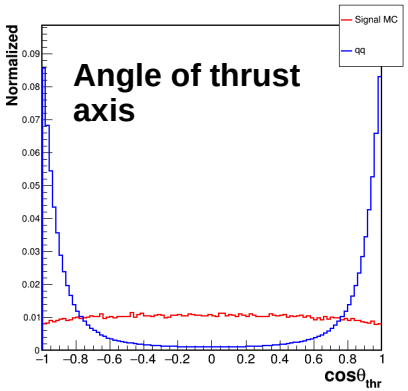


$B\bar{B}$

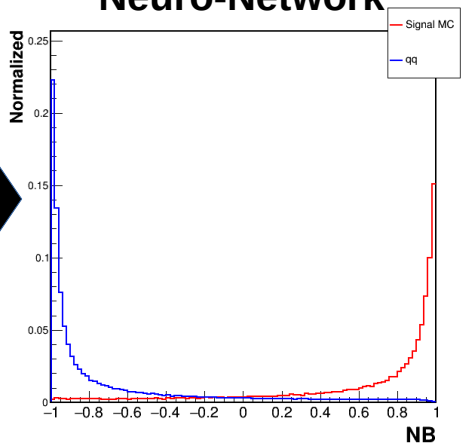








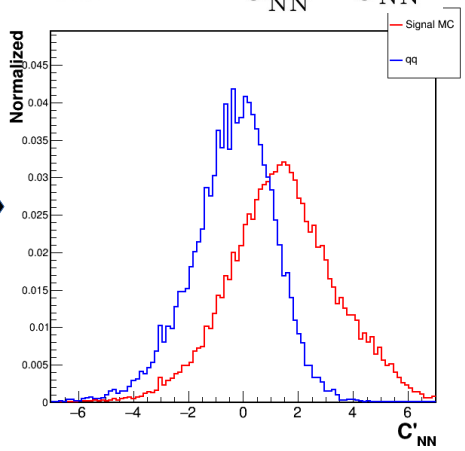
Output discriminant of Neuro-Network



Selection: NN > 0.75
Remove 98% of bkg while keeping 60% of signal.

Transformed output

$$C'_{\mathrm{NN}} \equiv \log\left(\frac{C_{\mathrm{NN}} - C_{\mathrm{NN}}^{\min}}{C_{\mathrm{NN}}^{\max} - C_{\mathrm{NN}}}\right)$$

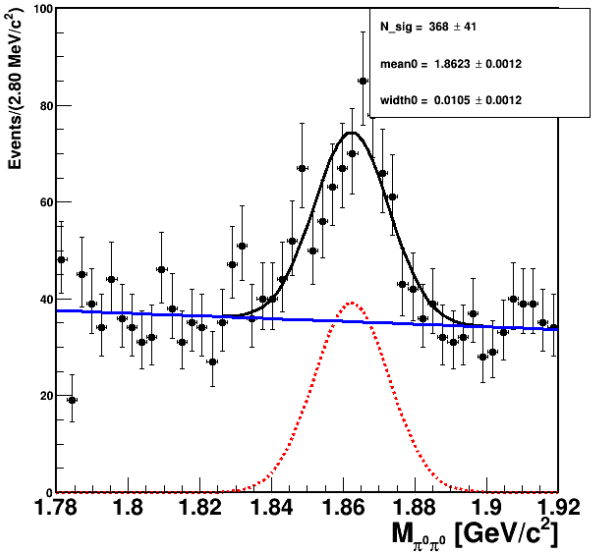


Gaussian-like shape.
Easier to model/fit.

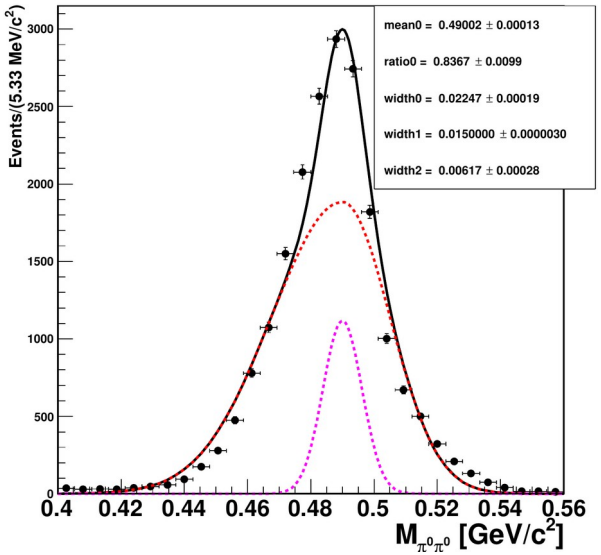
$B\bar{B}$ Background

- Backgrounds from $B\bar{B}$ events.
- Dedicated MC samples with two categories:
  - Generic $B\bar{B}$: $b \to c$.
  - Rare $B\bar{B}$: $b \to u,d,s$.
- Look for B decay modes causing peaks in ΔE and M_{bc}:
  reject the mass window (3σ of the resolution) around the nominal masses.

$D^0 \to \pi^0\pi^0$



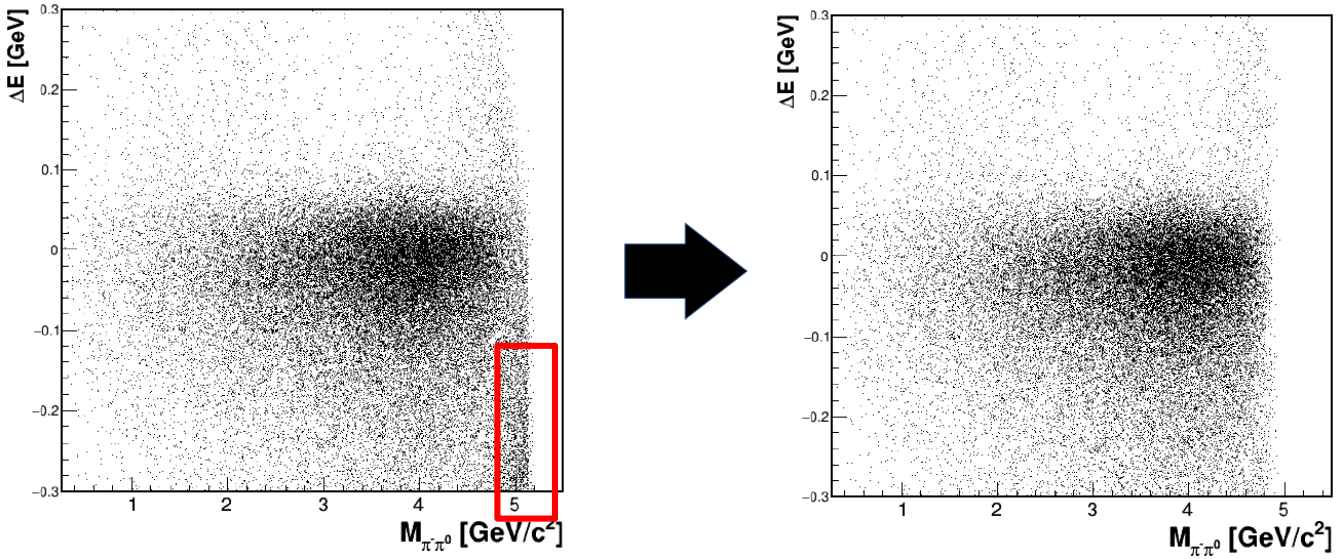
$K_s \to \pi^0\pi^0$



Soft-π^0 Background

- A structure in the ΔE v.s. $M_{\pi\pi}$ scattering plot due to soft-π^0.
  - Found in the self-crossfeed (SCF) and other background samples.
  - ΔE v.s. $M_{\pi\pi}$ correlation: Distorts the sWeighted $M_{\pi\pi}$ histogram.
- π^0 momentum > 0.5 GeV/c is required.
  - ~50% of the SCF is reduced.
  - Non-uniform efficiency over Dalitz plot.

Signal MC



Signal extraction: Extended unbinned likelihood fit

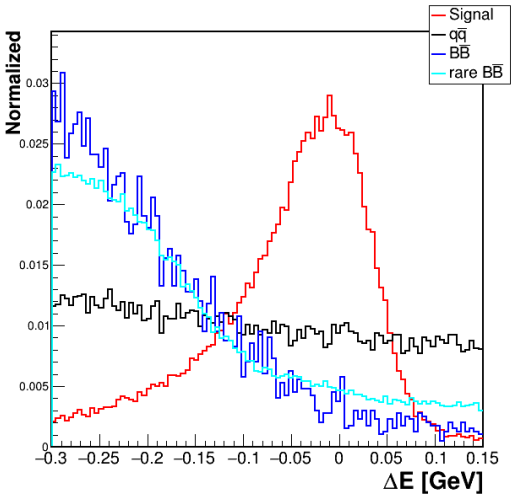
- MC study: Understand the behavior of signal and backgrounds, and their expected numbers in data.

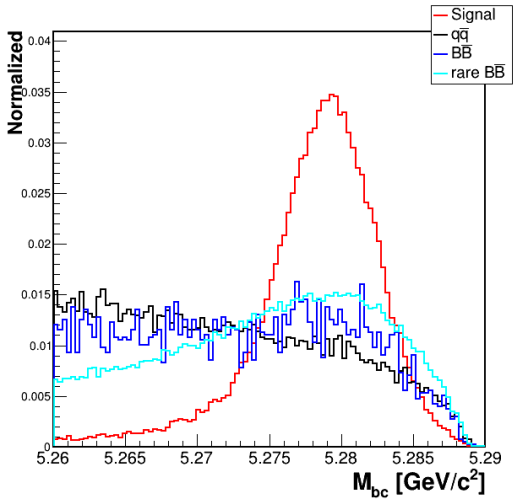
- Signal extraction: Extended unbinned likelihood fit.
  - Number of **signal yield** → **Inclusive BF**.
  - **A_{CP}**: signal yields of B^+ and B^-.

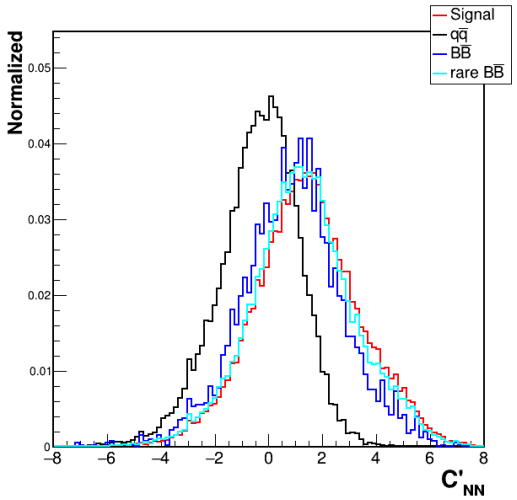
- **3D Fitter on ΔE, M_{bc}, C'_{NN}**:
  - The most distinctive variables.
  - Define each PDF based on MC distribution.

Fitted signal yield

$$\mathcal{B} = \frac{N_{\rm sig}}{\underbrace{\epsilon \times \eta}_{\text{Signal reconstruction eff. \& calibration.}} \times \underbrace{N_{B\overline{B}}}_{\text{Total number of B events in Belle.}}}$$







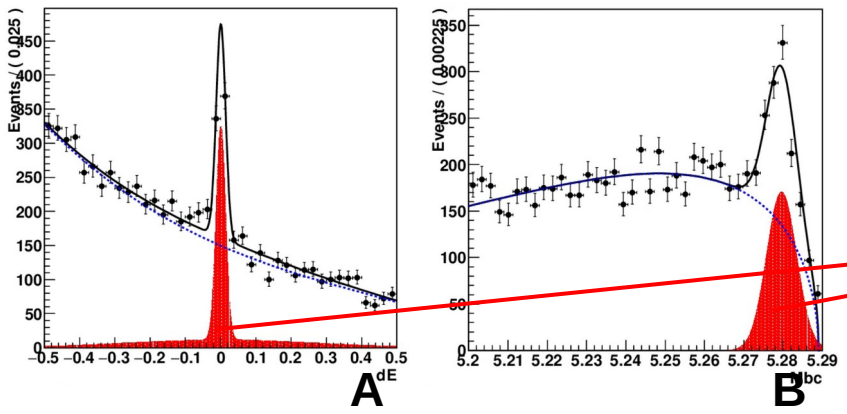
Signal extraction: Signal isolation by sPlot

- By the 3D unbinned fitter, we can obtain **the number of signal yield**.
  - To study the Dalitz plot, we need to further **isolate signal** within data: **sPlot** technique. M. Pivk and F.R. Le Diberder, Nucl. Instrum. Methods Phys. Res., Sect. A 555, 356 (2005)
  - Each event is assigned with a weight (**sWeight**) based on the likelihood.
  - Sum of sWeight = Fitted signal yield.
  - Sum of sWeight within other variables' binning: **Signal-isolated histogram** (sWeighted histogram).

- We use the sPlot to get the signal-isolated histogram of $M_{\pi\pi}$, Dalitz plot ($M^2_{\pi\pi}$ vs $M^2_{\pi\pi}$), helicity angles, etc.

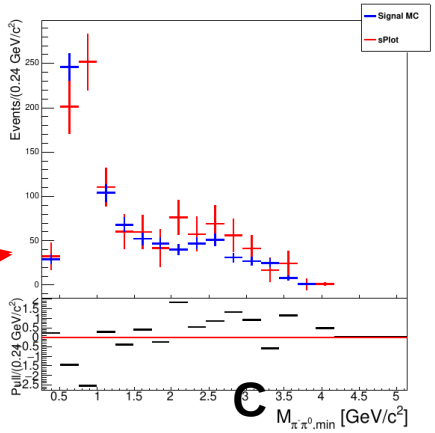
Illustration:

Unbinned fit on A & B



sPlot:
Event weight.

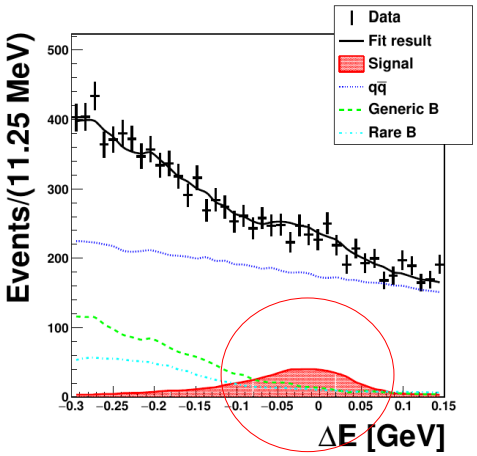
Isolate signal at C

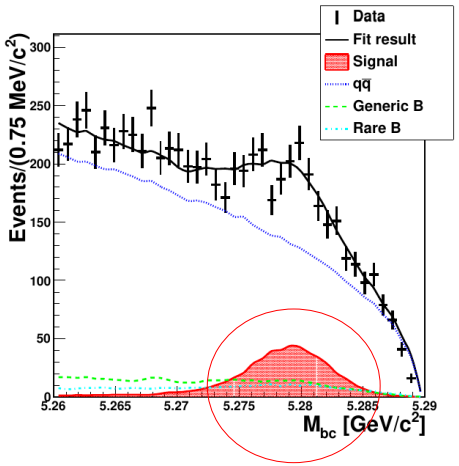


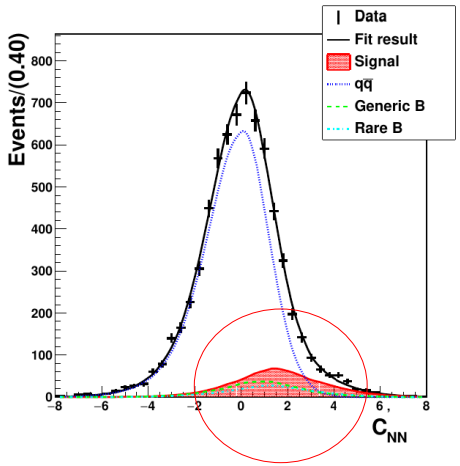
Signal extraction: Signal isolation by sPlot (cont'd)

- An example with MC cocktail sample.

Example:
27% PHSP (400 events)+
73% $\rho(770)^+\pi^0$ (700 events)

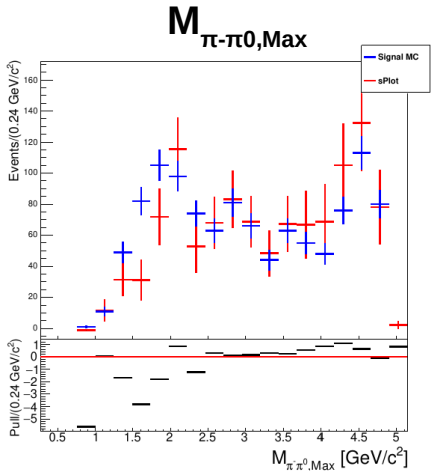


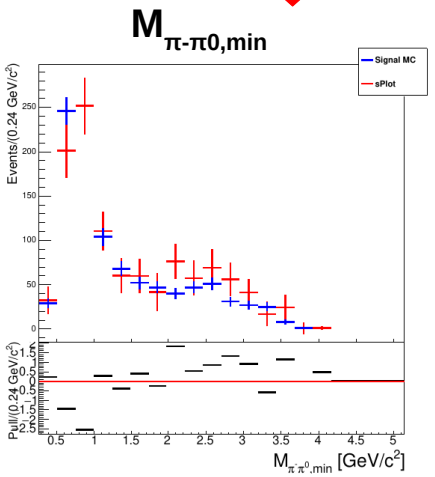


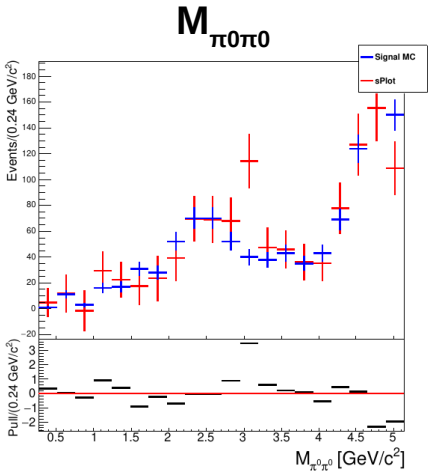


Fitted signal yield: ~1100.

Sum of sWeight after binning on $M_{\pi\pi}$.





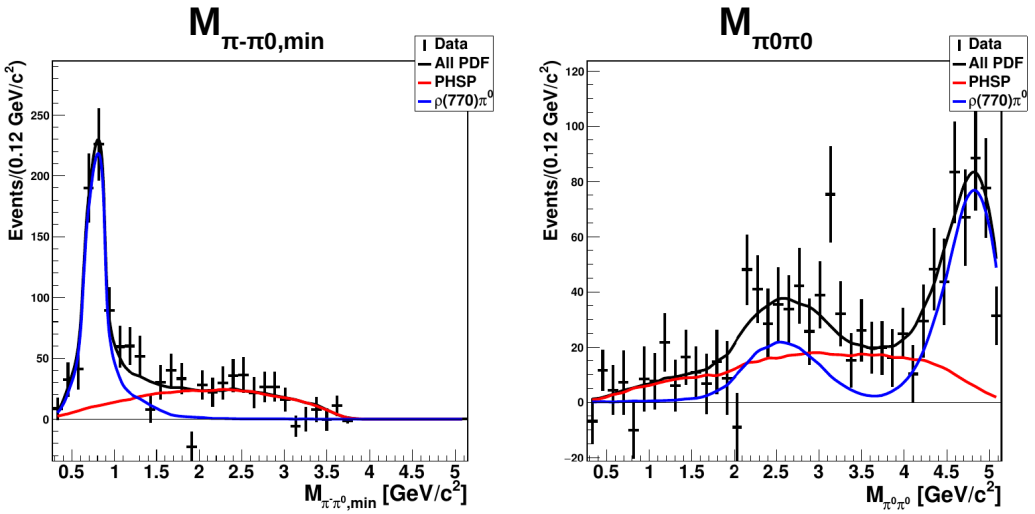


Entries of histogram: ~1100.

Signal extraction: 2D binned fit on signal-isolated $M_{\pi\pi}$

- After getting the signal-isolated histogram of $M_{\pi\pi}$ (Dalitz plot):
  - We perform a **2D binned fit** on it.
  - To get the signal decay structure: Fraction of each modes.
  - PDF: using MC samples as template.
  - Fitting on charge-separted histograms: Obtain localized A_{CP}.

Example:
27% PHSP (400 events)+
73% $\rho(770)^+\pi^0$ (700 events)



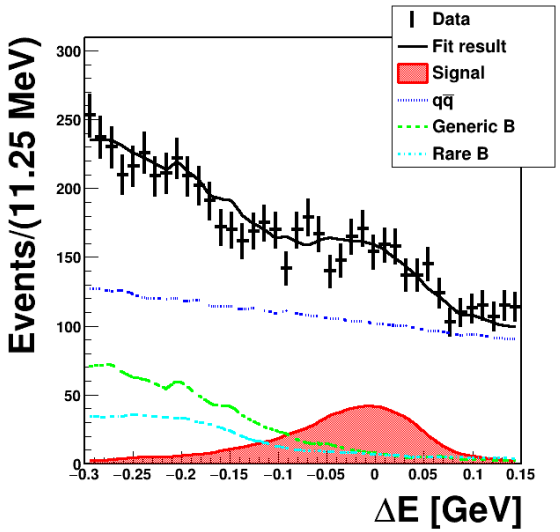
Decay modes considered in the 2D fit:

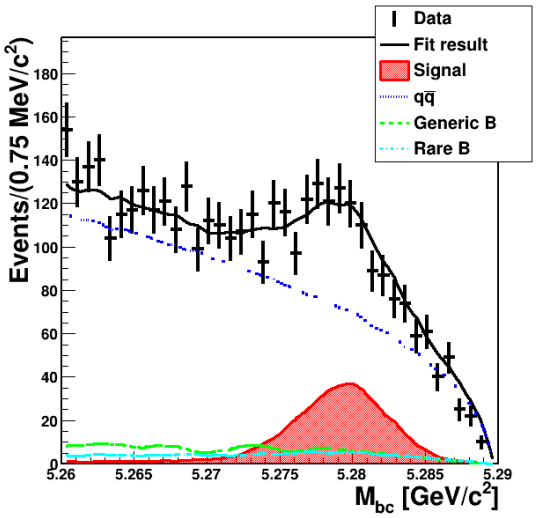
PHSP (nonresonant)
$\rho(770)^-\pi^0$
$\rho(1450)^-\pi^0$
$f_0(980)^0\pi^-$
$f_2(1270)^0\pi^-$
$f_0(600)^0\pi^-$
$f_0(1370)^0\pi^-$
$\chi_{c0}\pi^-$
$\chi_{c2}\pi^-$

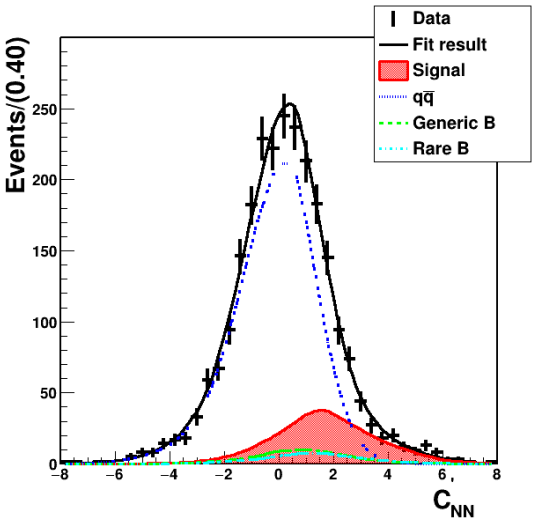
3D fit result on data

Preliminary

- Nsig = 1062.8 +86.8 -85.4.
  A_{CP} = 0.092 +0.068 -0.068.





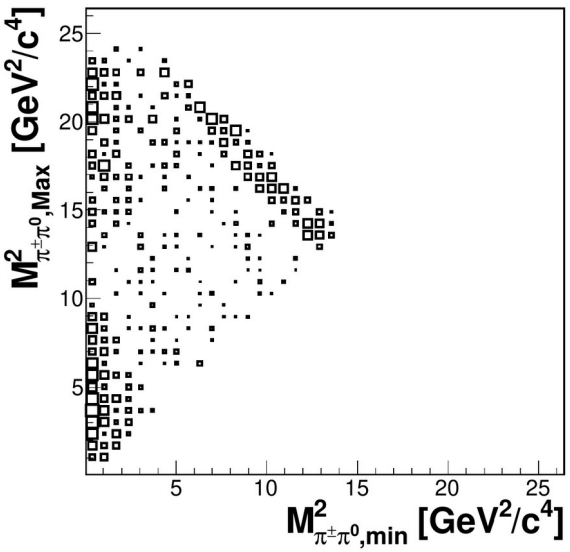


2D fit on sWeighted $M_{\pi\pi}$ histogram

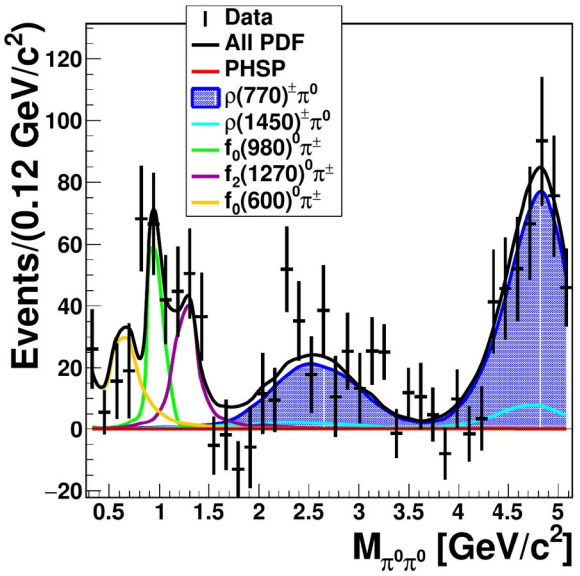
Preliminary

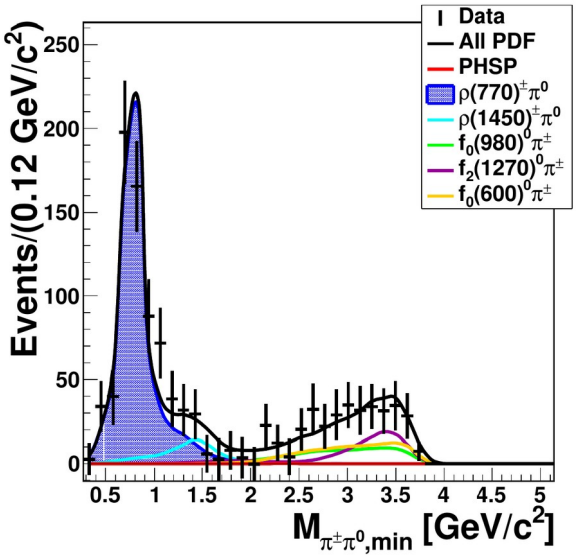
- Measured signal model: incoherent sum of 6 modes' PDF.
  - Interference is not considered in this study.
    (Different from the full amplitude analysis.)
  - $B^+ \to \rho(770)^+\pi^0$ with expected size and distribution.
  - Small contribution from non-resonant.
  - New structure found at low $M_{\pi^0\pi^0}$ region.
    Contribution from multiple resonances. → 9.2σ confirmed by 3D fit within selected region.
  - $f_0(1370)^0\pi^+$, $\chi_{c0}\pi^+$, $\chi_{c2}\pi^+$ not seen.

sWeighted Dalitz plot



2D fit result





Localized A_{CP}

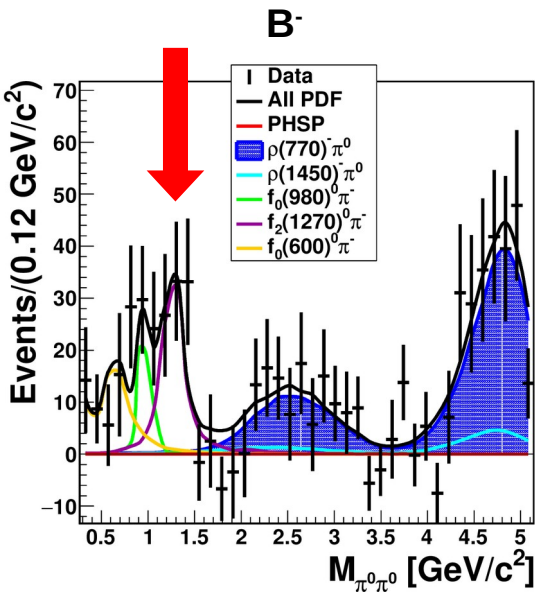
Preliminary

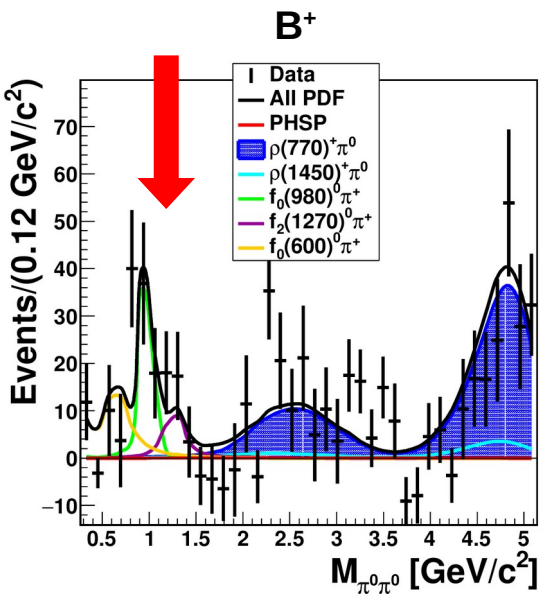
- 2D fit on the charge-separated $M_{\pi\pi}$ histograms.
- An asymmetry is found at $M_{\pi^0\pi^0} \sim 1.4$ GeV/c^2.
  - Corresponding to $f_2(1270)^0\pi^+$.
  - Also seen in $B^+ \to \pi^+\pi^-\pi^+$ by Babar and LHCb.

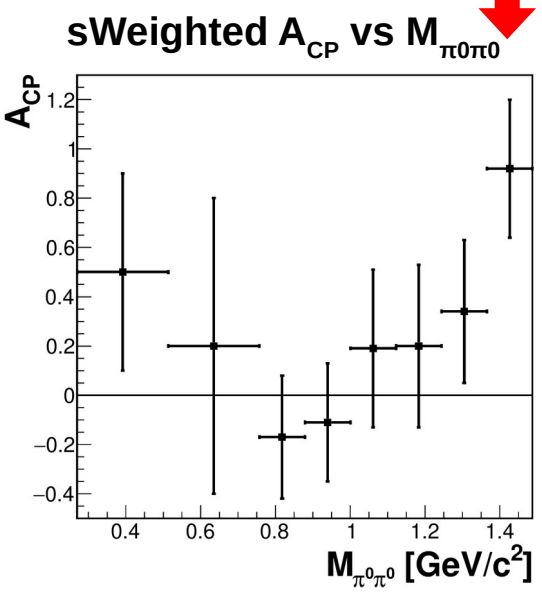
3.2σ confirmed by 3D fit within selected region.

PRD 79, 072006 (2009)

PRD 101, 012006 (2020)







Summary of measurement results

Preliminary

- Total BF: Efficiency is determined by the signal model from the last iteration
- BF($B^+ \to \rho(770)^+\pi^0$): We consider the interference effect with $B^+ \to \rho(1450)^+\pi^0$.
- BF of the $\pi^0\pi^0$ structure can't be reported separated due to lack of information: highly overlapping PDFs, large variations of masses and widths, interference.

Decay mode	Mass	Width	ϵ (%)	Fitted yield	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$ (%)
$\pi^+\pi^0\pi^0$ (total)			8.1	$1062.8^{+86.2}_{-85.4}$	$19.0 \pm 1.5 \pm 1.4$	$9.2 \pm 6.8 \pm 0.5$
Non-resonant			12.5	2.5 ± 13.5	$0.03 \pm 0.16^{+0.12}_{-0.15}$ (< 0.6)	-
$\rho(770)^+\pi^0$, $\rho(770)^+ \to \pi^+\pi^0$	775.5	150.3	8.5	636.5 ± 65.0	$11.2 \pm 1.1 \pm 0.9 \pm 1.4$	$8.0 \pm 15.0^{+2.2}_{-7.5}$
$\rho(1450)^+\pi^0$, $\rho(1450)^+ \to \pi^+\pi^0$	1465	400	9.9	79.7 ± 51.1	$1.2 \pm 0.6 \pm 0.2$ (< 2.5)	-
$f_0(980)^0\pi^+$, $f_0(980)^0 \to \pi^0\pi^0$	980	50	10.2	102.1 ± 30.0	-	$-27.0 \pm 30.0^{+44.8}_{-56.3}$
$f_2(1270)^0\pi^+$, $f_2(1270)^0 \to \pi^0\pi^0$	1275.4	185.1	6.6	119.3 ± 32.0	-	$57.0 \pm 23.0^{+11.4}_{-25.9}$
$f_0(600)^0\pi^+$, $f_0(600)^0 \to \pi^0\pi^0$	600	400	8.3	123.4 ± 37.4	-	$10 \pm 34^{+12.9}_{-22.6}$
$X\pi^+$, $X \to \pi^0\pi^0$	-	-	8.0	344.8 ± 47.5	$6.4 \pm 0.9 \pm 0.6$	-
$f_0(1370)^0\pi^+$, $f_0(1370)^0 \to \pi^0\pi^0$	1400	300	10.4	< 75.4	< 1.1	-
$\chi_{c0}\pi^+$, $\chi_{c0} \to \pi^0\pi^0$	3415.2	10.2	13.3	< 38.7	< 0.5	-
$\chi_{c2}\pi^+$, $\chi_{c2} \to \pi^0\pi^0$	3556.3	2.0	13.6	< 63.4	< 0.7	-

1st uncertainty: statistical.
2nd uncertainty: systematic.
3rd uncertainty (if any): interference effect.

Summary

- We perform the first measurement on the branching fraction and A_{CP} of the $B^+ \to \pi^+\pi^0\pi^0$ decay modes using the full data sample of 711 fb^{-1} collected by the Belle detector at the KEKB at Y(4S) resonance.
  - Inclusive BF = $(1.90 \pm 1.5 \pm 1.4)\times10^{-6}$.

- By using the sPlot technique, we study the structure in Dalitz plot, and measure the fraction and localized A_{CP} of sub-decay modes.
  - $BF(B^+ \to \rho(770)^+\pi^0) = (11.2 \pm 1.2 \pm 0.9 \pm 1.4)\times10^{-6}$.
  - New structure at low $M_{\pi0\pi0}$ region: $BF(B^+ \to X\pi^+) = (6.4 \pm 0.9 \pm 0.6)\times10^{-6}$.
  - An obvious asymmetry at $M_{\pi0\pi0} \sim 1.4$ GeV/c^2.

- Journal article is under preparation and will be published soon.

- In near future, larger data set from Belle2 with full amplitude analysis is helpful to further understand this decay.

Backup

Event selection and signal B reconstruction

- **MC sample for signal study**:
  - 3-body PHSP, $\rho(770)^+\pi^0$, $\rho(1450)^+\pi^0$, $f_0(980)^0\pi^+$, $f_2(1270)^0\pi^+$, $f_0(600)^0\pi^+$, etc.

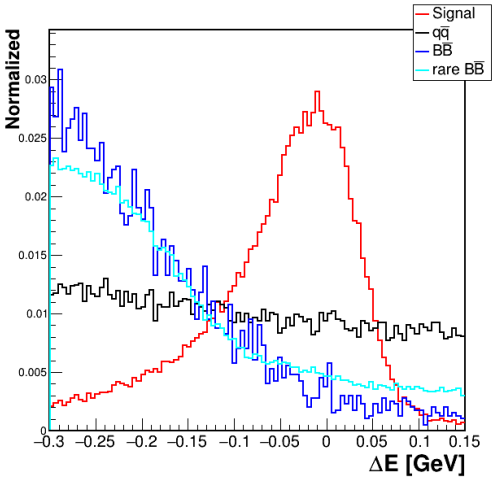
- **π^+ track**:
  - Tracking: SVD, CDC.
  - Impact parameter: $|dr| < 0.3$ cm, $|dz| < 5$cm.
  - $L(\pi)/(L(\pi) + L(K)) > 0.6$.

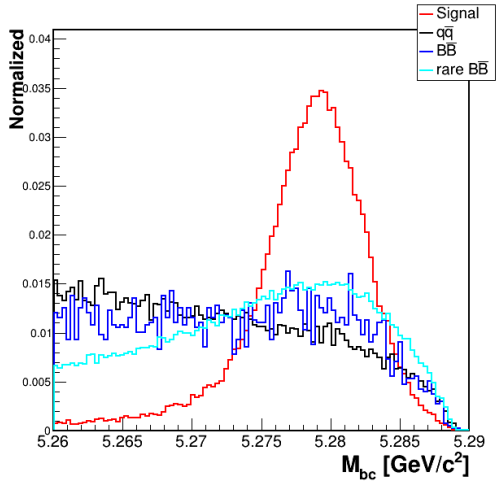
- **Mass-constrain on B candidate**:
  - Correct pion momenta for $M_{\pi\pi}$.

- **$\pi^0 \rightarrow \gamma\gamma$**:
  - Cluster on ECL crystal.
  - γ energy > 50 (100) MeV in barrel (endcap).
  - Mass-constrained fit on IP.
  - $115 < M_{\gamma\gamma} < 152$ MeV/c^2 (3σ)
  - Momentum > 0.5 GeV/c: Soft-π^0 background.

- **Multiple candidates in an event**:
  - Different π^0: smaller sum of χ^2.
  - Else: smaller $|dr|$.

- **B reconstruction**:
  Two kinematic variables in CM frame.
  For fitting purpose.
  - **Energy difference**:
    $$\Delta E \equiv E_B - E_{\rm beam}$$
  - **Beam-energy constrained mass**:
    $$M_{\rm bc} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_B/c|^2}$$

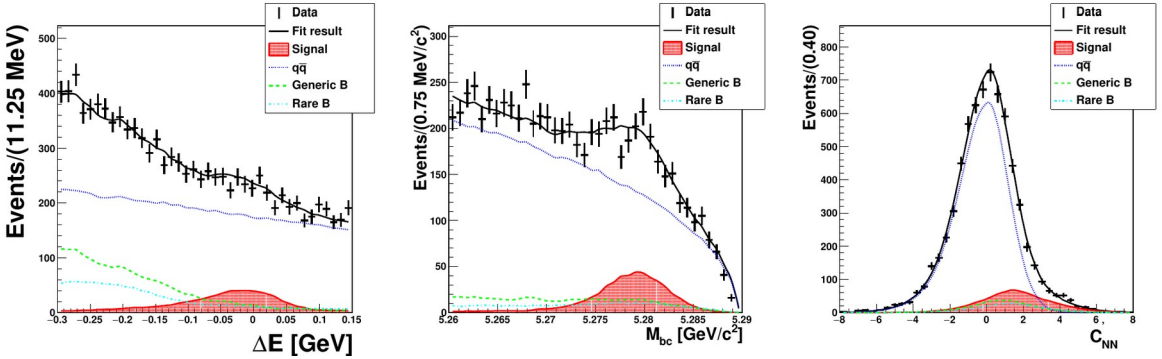




Signal extraction: Example with a MC cocktail sample

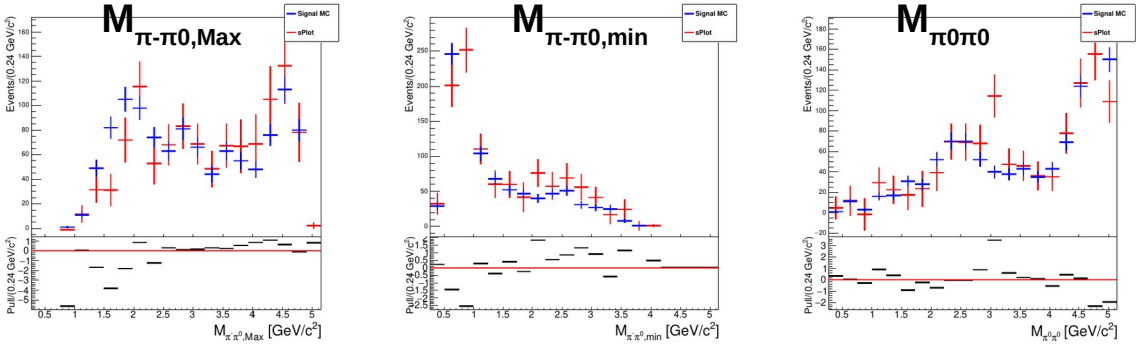
1. 3D (ΔE,M_{bc},C'_{NN}) extended unbinned maximum likelihood fit:

Based on Laura++ fitter.
Get total signal yield (BF) and total A_{CP}.



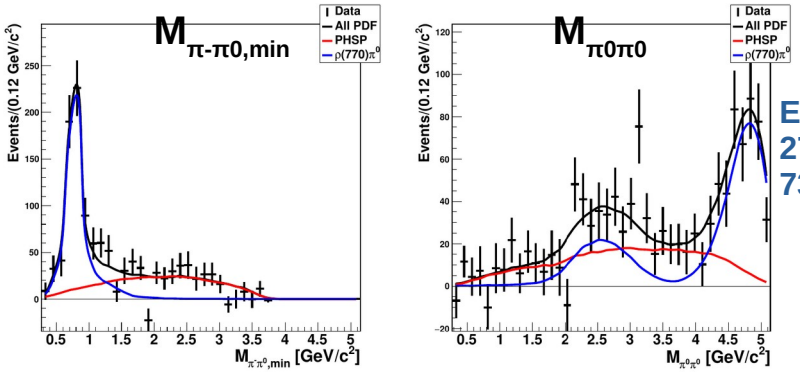
2. Background-subtraction with sPlot:

Get sWeighted Dalitz plot, $M_{\pi\pi}$ histograms.



3. 2D extended weighted binned likelihood fit on sWeighted $M_{\pi\pi}$ histograms:

Get fraction of each sub-decay mode and localized A_{CP}.



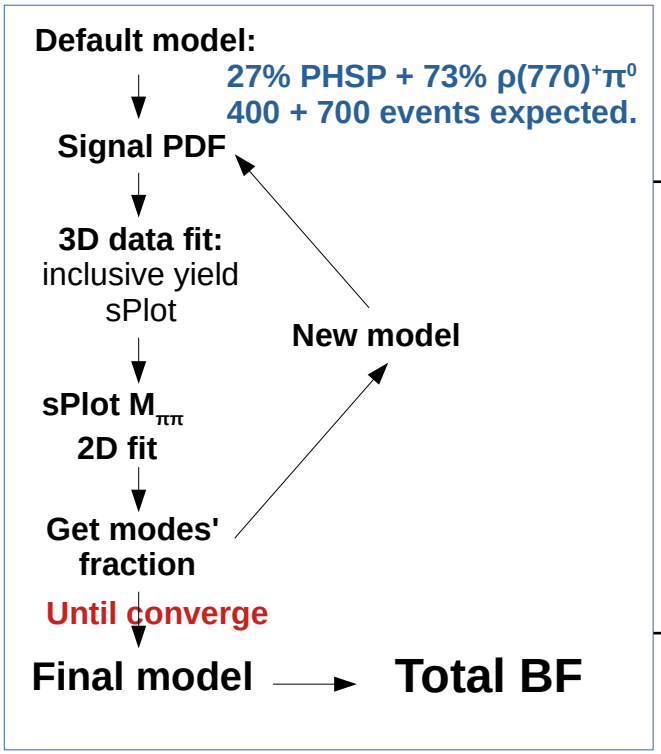
Example:
27% PHSP (400 events)+
73% $\rho(770)^+\pi^0$ (700 events)

Iteration on data measurement

- Signal model compositon matters for efficiency, SCF rate, PDF shape.
  It affects the measurement results.

- Iterate the procedure until converging.
  - The final model is close to the real one.

Work flow:



Signal modes to be considered:

Model	eff.(all) (%)	eff.(true) (%)	$\mathcal{F}_{SCF} \equiv \frac{N_{SCF}}{N_{True}+N_{SCF}}$ $(\frac{N_{SCF}}{N_{True}})$ (%)
PHSP	12.5	11.6	7.4 (8.0)
$\rho(770)^-\pi^0$	8.4	6.2	25.9 (34.9)
$\rho(1450)^-\pi^0$	9.7	7.3	24.6 (32.6)
$f_0(980)^0\pi^-$	4.5	4.1	10.2 (11.3)
$f_2(1270)^0\pi^-$	6.4	5.8	10.0 (11.1)
$f_0(600)^0\pi^-$	8.3	7.4	11.5 (13.0)
$f_0(1370)^0\pi^-$	10.6	9.5	10.1 (11.3)
$\chi_{c0}\pi^-$	13.3	12.8	3.4 (3.5)
$\chi_{c2}\pi^-$	13.7	12.3	3.2 (3.3)
Mixed (default)	9.5	7.7	19.2 (23.8)

Systematic uncertainty

*: Calculated as 10^{-6}.

BF, common for all modes

Sources common to all decay modes	%
$N_{B\overline{B}}$	1.4
Tracking	0.35
π^+ identification	0.9
π^0 identification	4.8
Continuum suppression	1.4
Limited MC statistics	0.02
Signal PDF	4.8
Background PDF	2.7
Iteration procedure	0.7

BF, depends on modes

Decay mode	Fit bias	${}_s\mathcal{P}lot$ bias	Resonance Shape	Dalitz model	Total
$\pi^+\pi^0\pi^0$ (total)	0.2	-	-	1.6	7.8
Non-resonant	$^{+0.0}_{-0.13}$ *	2.6	$^{+0.12}_{-0.08}$*	-	8.1 $^{+0.12}_{-0.15}$*
$\rho(770)^+\pi^0$	1.6	2.6	$^{+0.7}_{-0.9}$	-	8.3 ± 12.6
$\rho(1450)^+\pi^0$	5.6	2.6	$^{+10.9}_{-11.9}$	-	$^{+14.7}_{-15.4}$
$X\pi^+$	-	2.6	-	2.9	8.6
$f_0(1370)^0\pi^+$	$^{+0.0}_{-0.14}$ *	2.6	$^{+0.28}_{-0.42}$*	-	8.1, $^{+0.28}_{-0.44}$*
$\chi_{c0}\pi^+$	$^{+0.0}_{-0.08}$ *	2.6	$^{+0.003}_{-0.04}$*	-	8.1, $^{+0.003}_{-0.09}$*
$\chi_{c2}\pi^+$	$^{+0.0}_{-0.08}$ *	2.6	$^{+0.01}_{-0.03}$*	-	8.1, $^{+0.01}_{-0.09}$*

Total A_{CP}

Source for total $\mathcal{A}_{CP}$	%
Detector bias	0.3
Signal PDF	0.2
Background PDF	0.4
Total	0.5

Sub-decay A_{CP}

Source for sub-decays	mode	%
Resonance shape	$\rho(770)^+\pi^0$	$^{+2.2}_{-7.5}$
Resonance shape	$f_0(980)^0\pi^+$	$^{+44.8}_{-56.3}$
Resonance shape	$f_2(1270)^0\pi^+$	$^{+11.4}_{-25.9}$
Resonance shape	$f_0(600)^0\pi^+$	$^{+12.9}_{-22.6}$

- Resonance shape of each sub-decay: Large variation of mass and width from $\rho(1450)^+$, $f_0(980)^0$, $f_0(600)^0$.
- Fit bias: Using ensemble test with Toy MC samples. Separeted for 3D fit (total) and 2D fit (sub-decay).
- Interference between $\rho(770)^+\pi$ and $\rho(1450)^+\pi$: First time considered in BF of $\rho(770)^+\pi$ mode.