Result on $B^0 \to p\bar{\Lambda}D^{(*)-}$ at Belle

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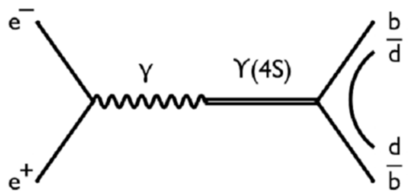
Outline

- Introduction to Belle experiment
- $B^0 \rightarrow p\overline{\Lambda}D^{(*)-}$ study (Phys. Rev. Lett. 115, 221803 (2015))
  - Physics motivation & Theoretical prediction
  - Selection criterion
  - Signal Monte Carlo(MC)
  - Continuum background suppression
  - Systematic uncertainty
  - Physics result
  - Conclusion
- Backup

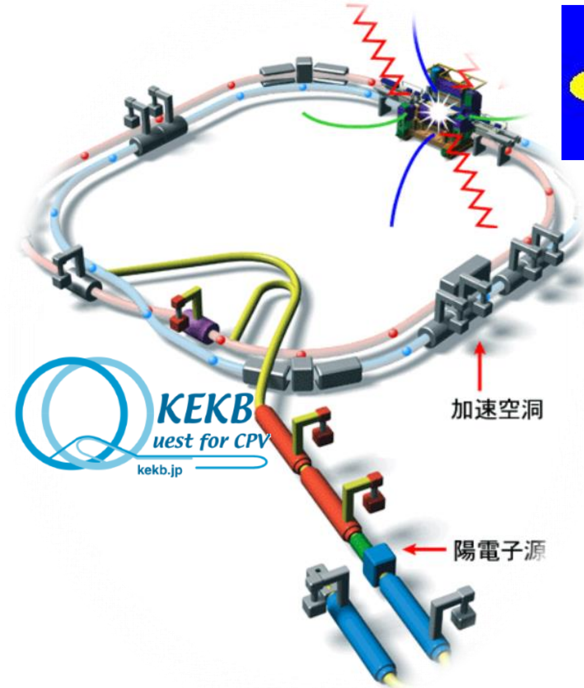
KEK B-factory and Belle experiment

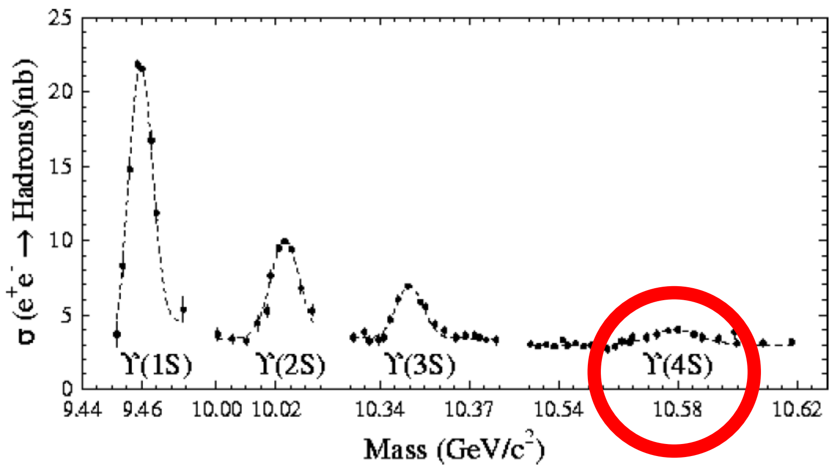
- An asymmetric energy e^+e^- collider at KEK.
- LER(e^+): 3.5 GeV
  HER(e^-): 8 GeV
  Crossing angle: ± 11 mrad



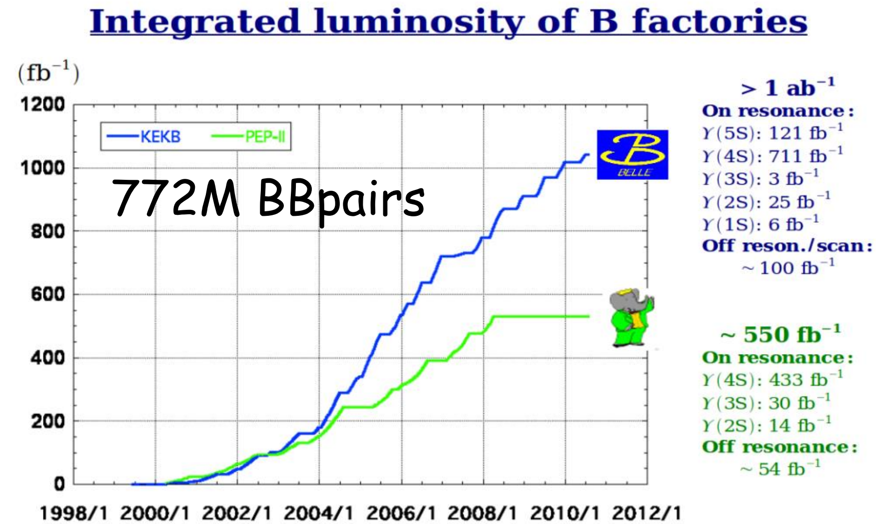
- Target: $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0\ (B^+B^-)$
- Main background: $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$ with approximately 3 times larger cross section.

- The CM energy of e^+e^- are set to be $\Upsilon(4S)$ resonance to produce B meson pairs.

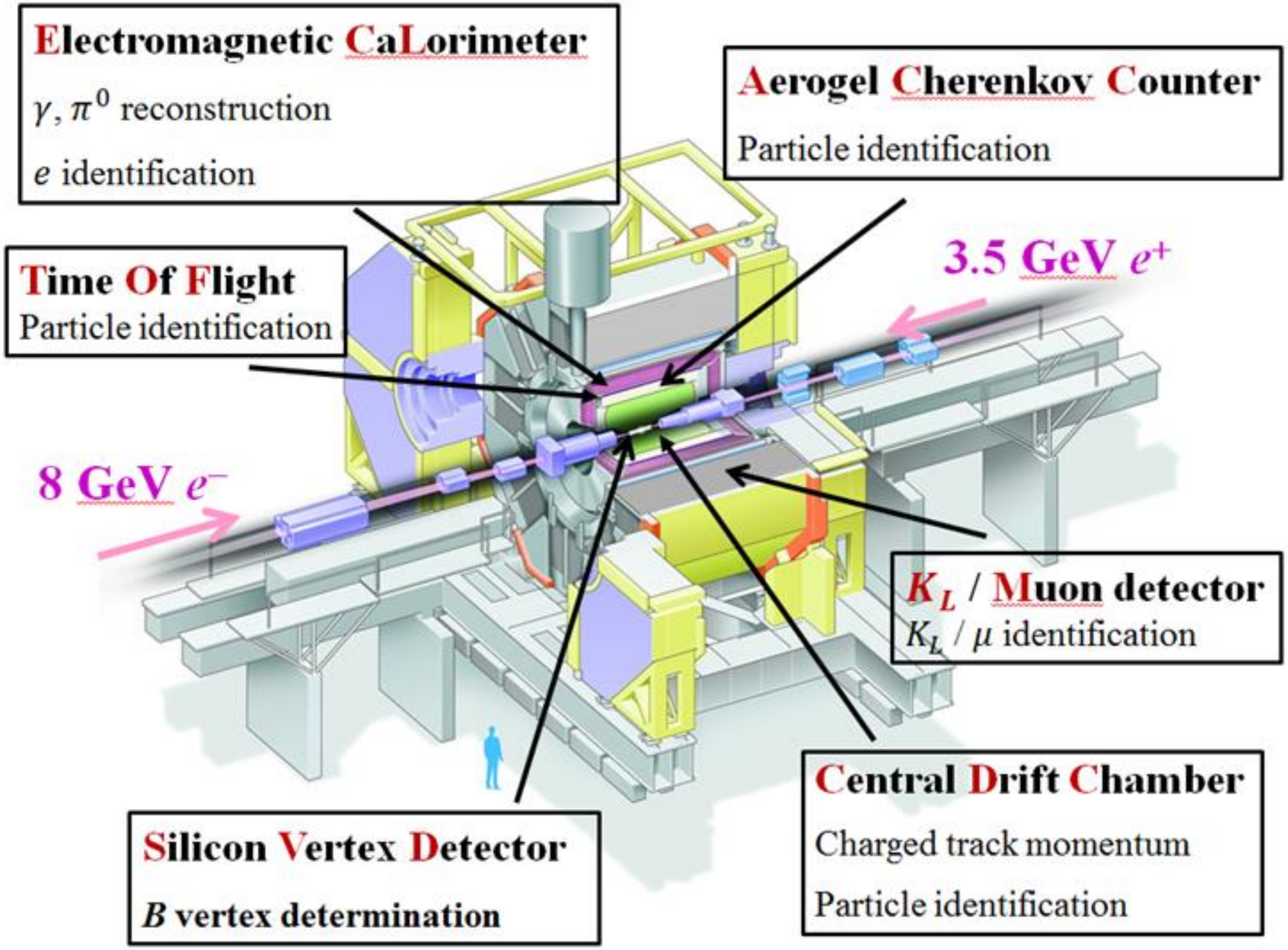




http://www.lns.cornell.edu/public/lab-info/upsilon.html

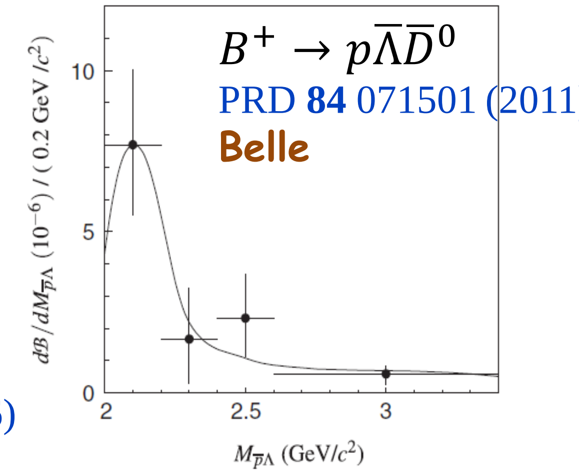


Belle Detector



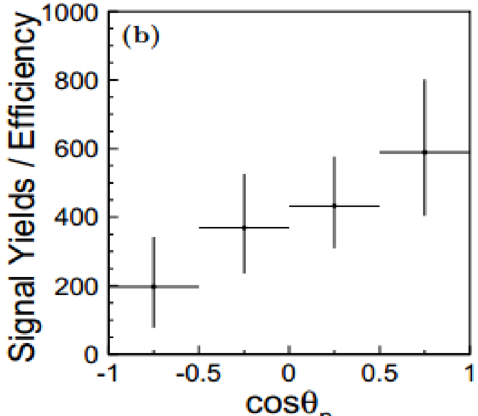
- **Generalized factorization**(GF) approach
  PRD 78 054016 (2008) C. Chen
- $B \to \mathbf{B}\bar{\mathbf{B}}M_{(c)}$ **threshold enhancement:**

B: B meson
B: baryon

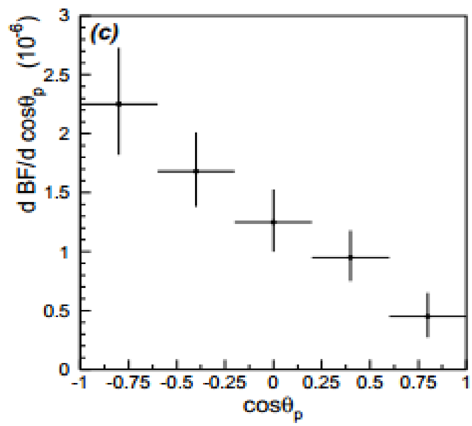


PRD **74** 094023 (2006)

- $pM_{(c)}$ **angular correlation** puzzle C. Q. Geng
  $(B^- \to p\bar{p}K^-, B^0 \to p\bar{\Lambda}\pi^-, \bar{B}^0 \to p\bar{p}D^0)$:
  - $A_\theta = \frac{\mathcal{B}_+ - \mathcal{B}_-}{\mathcal{B}_+ + \mathcal{B}_-}$, $A_\theta(\bar{B}^0 \to p\bar{p}D^0) > A_\theta(\bar{B}^0 \to p\bar{p}D^{*0}) > 0$ PRD **74** 051101 (2006) BABAR
  -



$B^- \to p\bar{p}K^-$
PRL **100** 251801 (2008) Belle



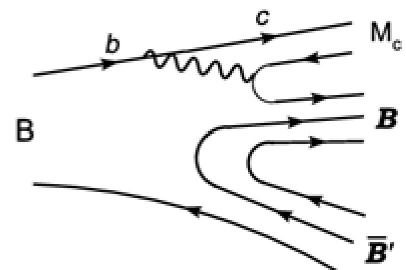
$B^0 \to p\bar{\Lambda}\pi^-$
PRD **76** 052004 (2007) Belle

$\theta_{(p)}$: angle between one baryon and the remaining meson in the di-baryon rest frame

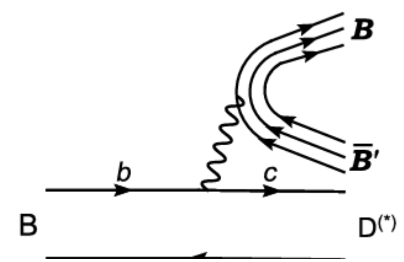
Theoretical prediction by Generalized Factorization

PRD 78 054016 (2008) C. Chen

- For 3-body charmful di-baryon B decay
- classified into 3 types
- interplay between weak interaction and fragmentation
- extract the relative phase and amplitude by experimental results



Transition type



Current type

Hybrid type (both diagrams)

- At the limit of $E_{\mathbf{B}/\mathbf{B}'} \sim M_{\mathbf{B}/\mathbf{B}'}$,
  - ❖ **$\mathcal{B}$(hybrid)/$\mathcal{B}$(current)** ~ 3
    →$\mathcal{B}(B^+ \to p\bar{\Lambda}\bar{D}^{*0})$/ $\mathcal{B}(B^0 \to p\bar{\Lambda}D^{*-})$ ~3
    →$\mathcal{B}(B^+ \to p\bar{\Lambda}\bar{D}^{0})$/ $\mathcal{B}(B^0 \to p\bar{\Lambda}D^{-})$ ~3
  - ❖ $\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}D^*)/\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}D) \gtrsim 3$(curr. and hybrid)
    →$\mathcal{B}(B^0 \to p\bar{\Lambda}D^{*-})/\mathcal{B}(B^0 \to p\bar{\Lambda}D^{-}) \gtrsim 3$

- $B^+ \to p\bar{\Lambda}\bar{D}^{(*)0}$ (PRD **84** 071501 (2011) **Belle**)
  - **hybrid type**
  - **measured and agrees with GF**
- $B^0 \to p\bar{\Lambda}D^{(*)-}$ **(this study)**:
  - **current type**

$\mathcal{B}(\times 10^6)$	GF	experimental
$B^+ \to p\bar{\Lambda}\bar{D}^0$	11.4±2.6	$14.3^{+2.8}_{-2.5} \pm 1.8$
$B^+ \to p\bar{\Lambda}\bar{D}^{*0}$	32.3±3.2	< 48 (90% C.L.)
$B^0 \to p\bar{\Lambda}D^-$	**3.4±0.2**	---
$B^0 \to p\bar{\Lambda}D^{*-}$	**11.9±0.5**	---

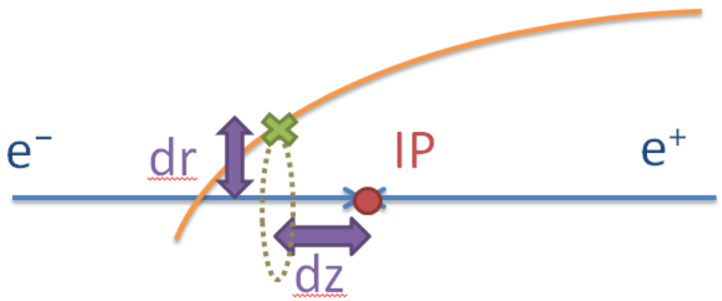
Selection Criterion

- MC samples are reconstructed with following sub-decays:

sub-decay	$\mathcal{B}$
$D^- \to K^+\pi^-\pi^-$	$(9.13 \pm 0.19)\%$
$D^{*-} \to \bar{D}^0\pi^-$	$(67.7 \pm 0.5)\%$
$\bar{D}^0 \to K^+\pi^-$	$(3.88 \pm 0.05)\%$
$\Lambda \to p\pi^-$	$(63.9 \pm 0.5)\%$

- Track: Momentum from CDC and user PID selection($\mathcal{L}_i$) to determine ID(energy).

- Track impact parameter: the shortest distance between a track and Interaction Point(IP):

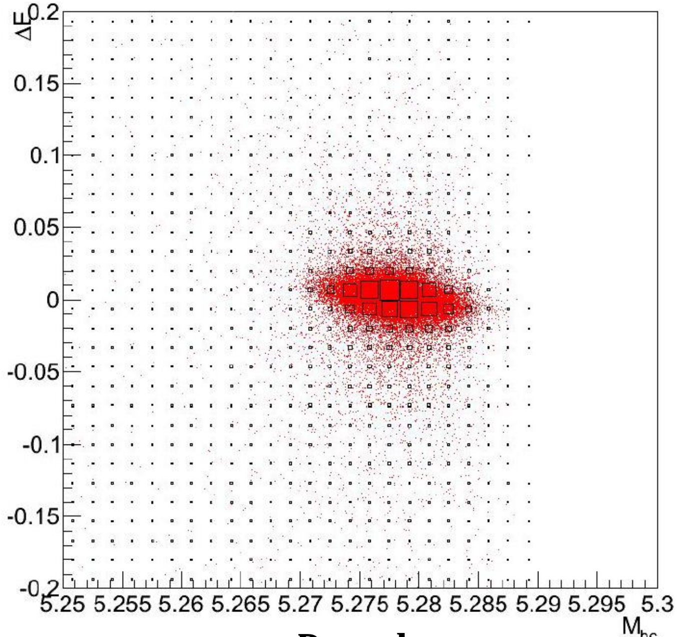


Item	Selection criteria	Item	Mass window(GeV/c^2)
Impact parameter	$\|dr\| < 0.3$ cm, $\|dz\| < 3$ cm	Λ	1.102 – 1.13
$\pi^\pm$	$\mathcal{L}_e < 0.95$, $\mathcal{L}_\mu < 0.95$, $\mathcal{L}_{K/\pi} < 0.4$	$D^\pm$	1.7 – 2.04
$K^\pm$	$\mathcal{L}_e < 0.95$, $\mathcal{L}_\mu < 0.95$, $\mathcal{L}_{K/\pi} > 0.6$	D^0	1.72 – 2.02
p	$\mathcal{L}_e < 0.95$, $\mathcal{L}_\mu < 0.95$, $\mathcal{L}_{p/K} > 0.6$, $\mathcal{L}_{p/\pi} > 0.6$	$D^{*\pm}$	1.86 – 2.16
		$D^{*\pm} - D^0$	0.136 – 0.156

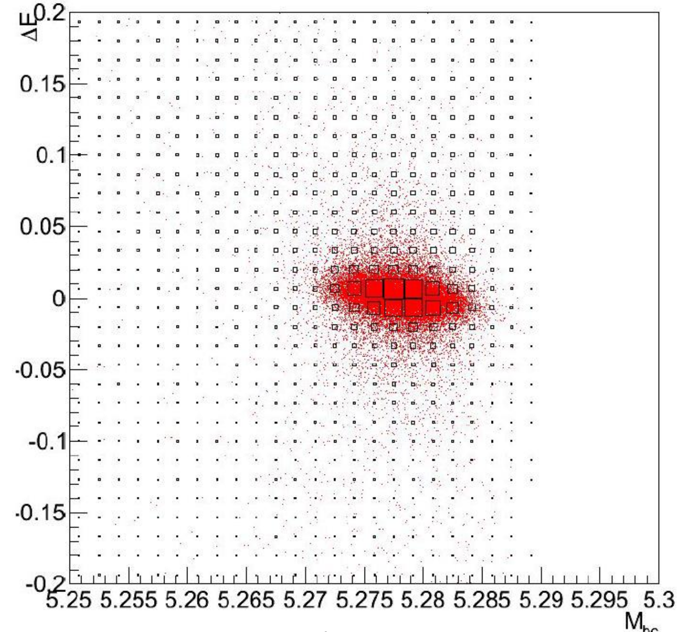
Signal MC

- **Beam-energy-constrained mass:**
  - $M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2 c^2}/c^2$
- **Energy difference:**
  - $\Delta E \equiv E_B - E_{beam}$

- Fitting templates to extract signal yield from data



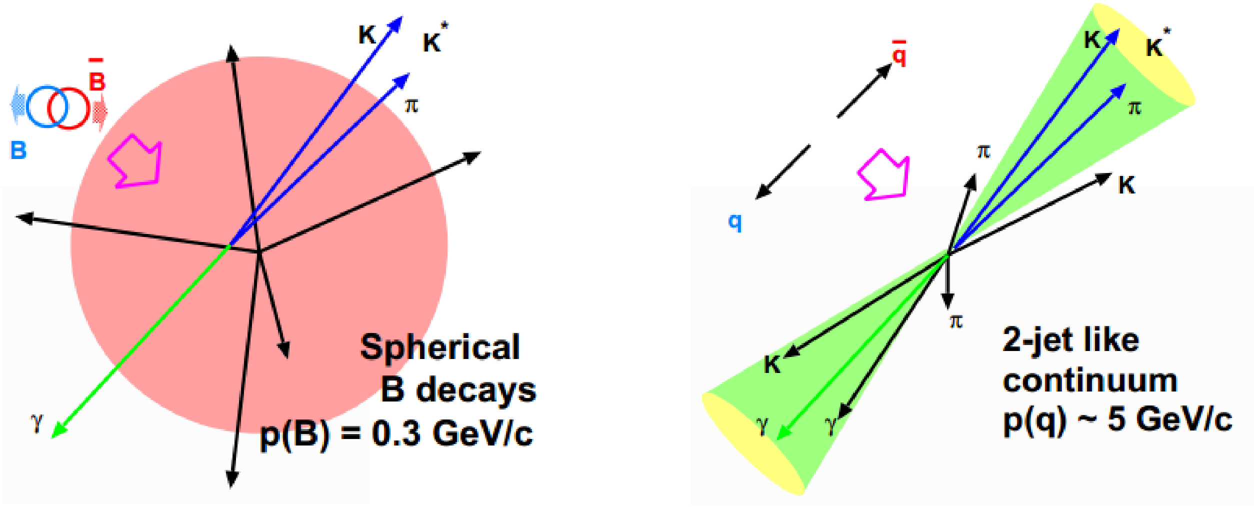
***D* mode**



D^* mode

- Main background:
  - Continuum background: $e^+e^- \to q\bar{q}$ $(q = u,\ d,\ s,\ c)$

- A main difference between B decay and continuum event: decay topology



- Continuum background suppression: we first use Fisher discriminant to combine event topology variables, then further construct a variable $\mathcal{L}$ with longitudinal deviation between IP and fitted B vertex(ΔZ), polar angle of B in CM frame(θ_B).

PRL **41** 1581 (1978) **G. C. Fox and S. Wolfram**
PRD **91** 261801 (2003) **Belle**
Ann. Eugenics **7**, 179 (1936) **R. A. Fisher**

Systematic uncertainty

- Modeling uncertainty is largely reduced by bin-by-bin correction, set by comparing bound-state/three-body MC.

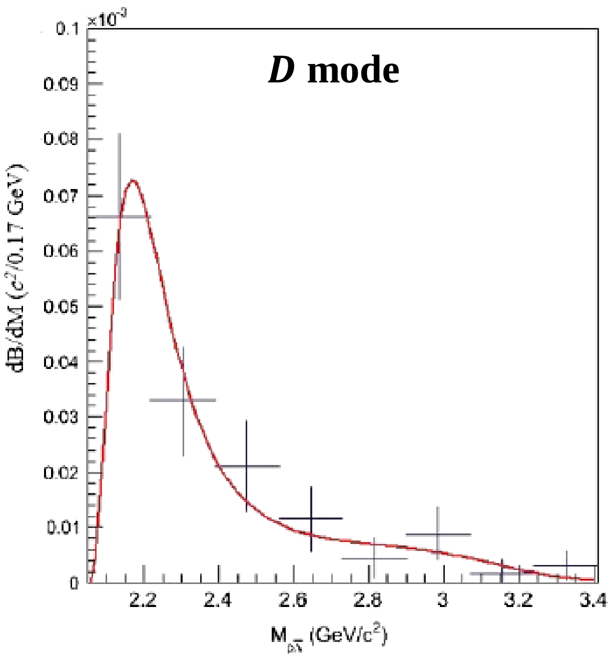
- We used high statistics $B^0 \to \pi K_S^0 D^{(*)-}$ to set uncertainties due to Continuum background suppression($\mathcal{L}$ selection).

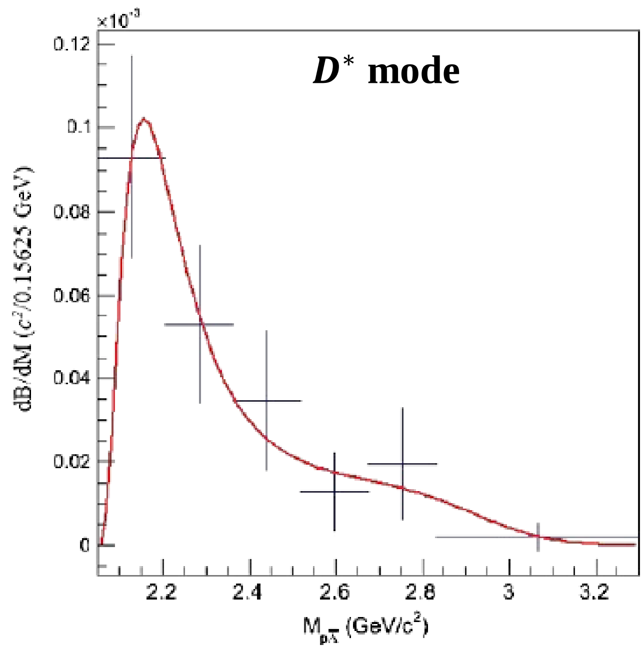
- We compared MC & data D mass widths to set D selection uncertainties.

	Systematic uncertainty (%)	
Item	D mode	D^* mode
Yield bias	Negligible	1.3 (0.5 event)
Modeling	≈3	≈2
Charged track	2.1	4.3
Charged-hadron identification	1.3	1.8
$\bar{\Lambda}$ identification	4.0	4.4
M_{D^-}, $M_{D^{*-}} - M_{\bar{D}^0}$ window	2.0	Negligible
$\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_B)$ requirement	11.5	11.0
PDF shape	Negligible	Negligible
$N_{B\bar{B}}$	1.4	1.4
Subdecay $\mathcal{B}$	2.2	1.7
Overall	13.9	13.1

Threshold enhancement: $M_{p\bar{\Lambda}}$

- Observed clear threshold enhancement with differential $\mathcal{B}$ measument on $M_{p\bar{\Lambda}}$.
- Fit by empirical threshold function: $\left(x - M_p - M_\Lambda\right)^a e^{bx+cx^2+dx^3}$ (a,b,c,d floated)
- The obtained branching fraction:
  - $\boldsymbol{\mathcal{B}\left(B^0 \to p\bar{\Lambda}D^-\right) = (25.1 \pm 2.6 \pm 3.5) \times 10^{-6},\ 19.8\sigma}$
  - $\boldsymbol{\mathcal{B}\left(B^0 \to p\bar{\Lambda}D^{*-}\right) = (33.6 \pm 6.3 \pm 4.4) \times 10^{-6},\ 10.8\sigma}$
  - Disagree with the GF's predictions:
    - $\mathcal{B}(B^0 \to p\bar{\Lambda}D^-) = (3.4 \pm 0.2) \times 10^{-6}$
    - $\mathcal{B}(B^0 \to p\bar{\Lambda}D^{*-}) = (11.9 \pm 0.5) \times 10^{-6}$

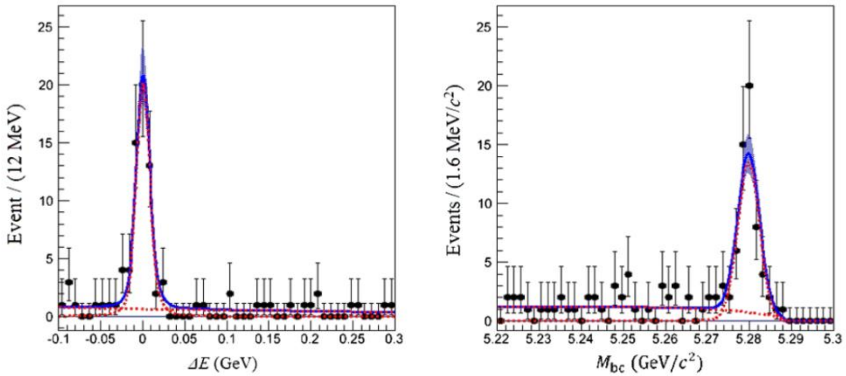




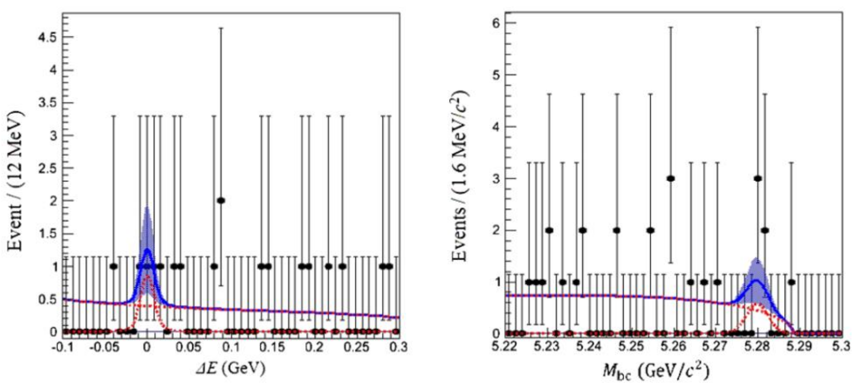
$M_{p\bar{\Lambda}}$ bin fit result

- Projections of $\Delta E - M_{bc}$ fits to data for events in the signal region of the orthogonal variable.
- Signal region:
  - ΔE: -0.05 - 0.05 (GeV)
  - M_{bc}: 5.27 – 5.29 (GeV/c^2)

Highest $M_{p\bar{\Lambda}}$ bin

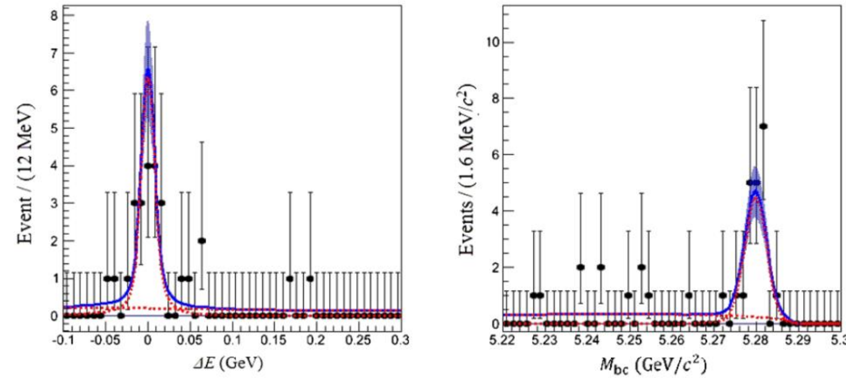


Lowest $M_{p\bar{\Lambda}}$ bin

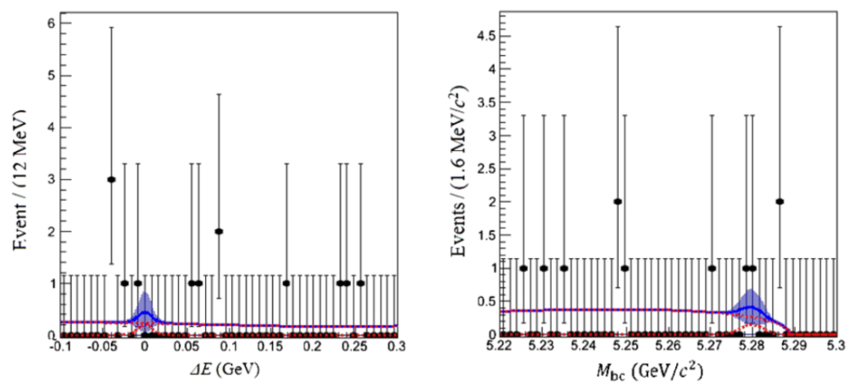


***D* mode**

Highest $M_{p\bar{\Lambda}}$ bin



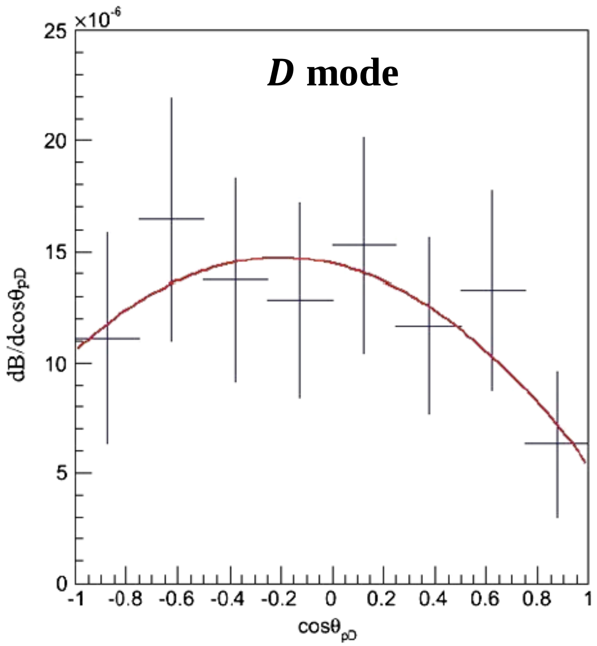
Lowest $M_{p\bar{\Lambda}}$ bin

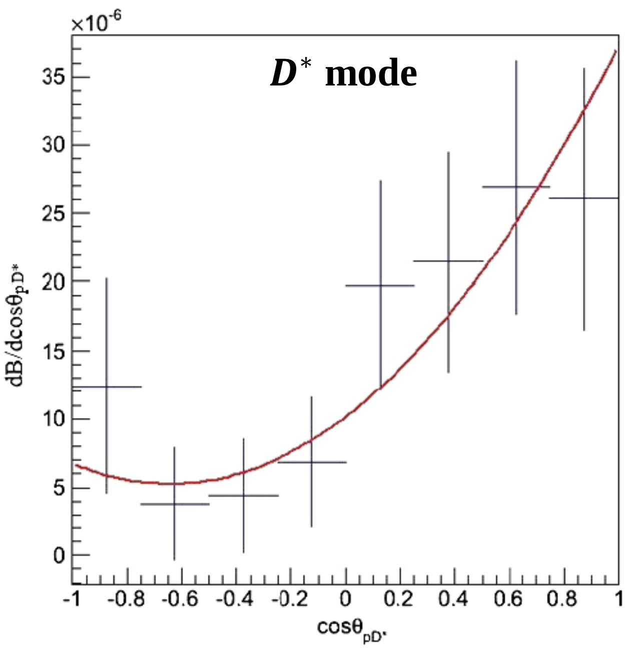


D^* mode

Angular distribution: $cos\theta_{pD^{(*)}}$

- Differential $\mathcal{B}$ measurement on $cos\theta_{pD^{(*)}}$.
  (Fit by 2nd-order polynomials) PRD **74** 094023 (2006) ***C. Q. Geng***
  - $\theta_{pD^{(*)}}$: angle between p & $D^{(*)}$ in the di-baryon rest frame
- Angular asymmetry $A_\theta = \frac{\mathcal{B}_+ - \mathcal{B}_-}{\mathcal{B}_+ + \mathcal{B}_-}$:
  - $\boldsymbol{A_\theta(B^0 \to p\bar{\Lambda}D^-) = -0.08 \pm 0.10}$
  - $\boldsymbol{A_\theta(B^0 \to p\bar{\Lambda}D^{*-}) = +0.55 \pm 0.17}$





Conclusion

- This study was motivated by generalized factorization, threshold enhancement, and $B \to \mathbf{B\overline{B}}M_{(c)}$ angular correlation puzzles.
  By comparing with the measured result of $B^+ \to p\overline{\Lambda}\overline{D}^{(*)0}$, quantitative prediction by GF can be checked.

- We have reported the first observation of the $B^0 \to p\overline{\Lambda}D^-$ and $B^0 \to p\overline{\Lambda}D^{*-}$ decays with branching fractions $(25.1 \pm 2.6 \pm 3.5) \times 10^{-6}(19.8\sigma)$ and $(33.6 \pm 6.3 \pm 4.4) \times 10^{-6}(10.8\sigma)$, which disagree with predictions based on the GF approach.

- The threshold enhancement effect is observed in $M_{p\overline{\Lambda}}$ and is consistent with some previous result on three-body baryonic B decays. With measurement on $\theta_{pD^{(*)}}$, we also find a hint of angular asymmetry in the $B^0 \to p\overline{\Lambda}D^{*-}$ but not in the $B^0 \to p\overline{\Lambda}D^-$ mode.

Backup

Particle Identification

Particle Identification:

Aerogel **C**erenkov **C**ounter: Silica aerogel

Time **of** **F**light: Plastic scintillator

Central **D**rift **C**hamber (dE/dx): Small cell + He/C_2H_6

Use $\mathcal{L}_i$ to define user PID in data analysis.

Cerenkov light detected by FM-PMT

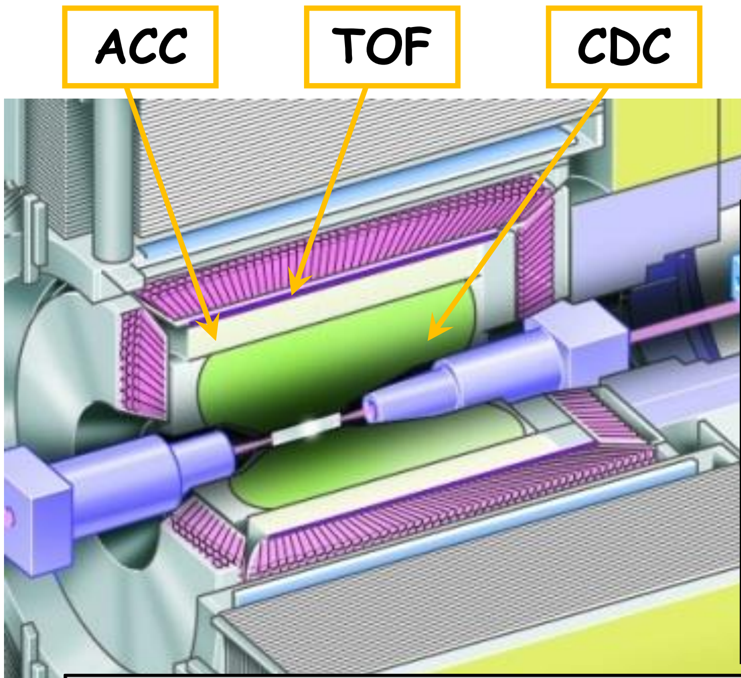
Timing resolution～100ps

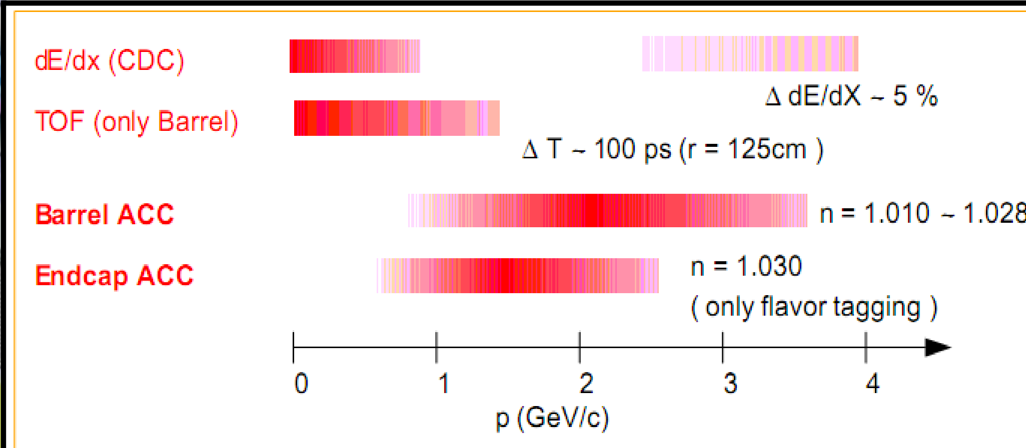
Momentum Measurement (CDC)

1. $P_{X\text{-}Y}$: Curvatures in the transverse plane

2. P_Z : Helical track information

dE/dx Information





$$\text{Likelihood: } \mathcal{L}_i = \mathcal{L}_i^{CDC} \times \mathcal{L}_i^{TOF} \times \mathcal{L}_i^{ACC}$$

$$(i = e, \mu, \pi, k, p)$$

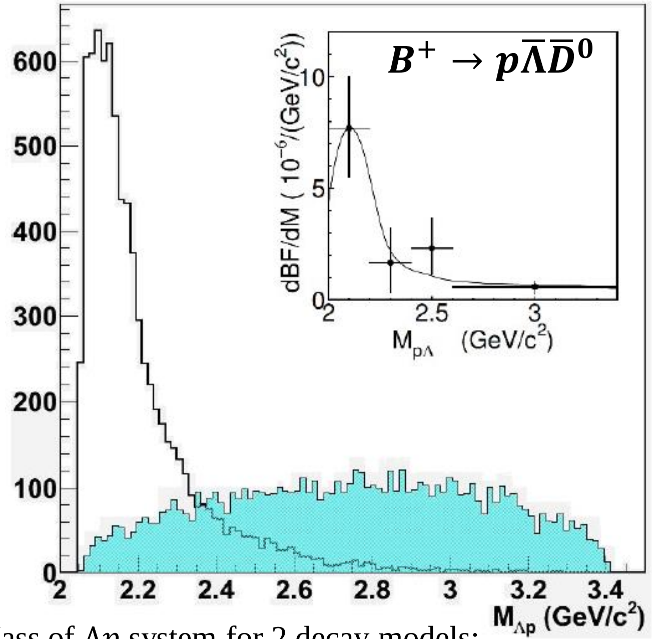
MC generation for signal study

- Tools: EvtGen generator and Geant3 detector simulation

  Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001)

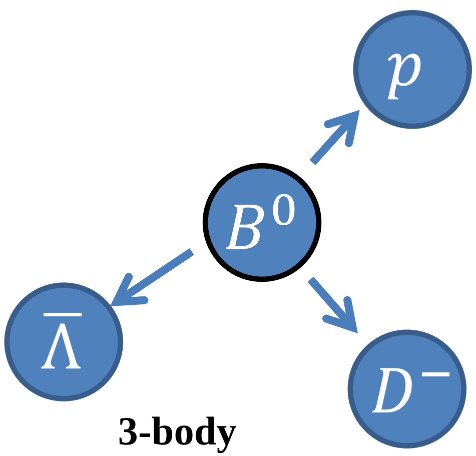
  D. J. Lange

- Threshold enhancement for baryonic decay is considered for signal MC:
  - In the decay chain, $(p\bar{\Lambda})$ is considered as a bound state(refer to $B^+ \to p\bar{\Lambda}\bar{D}^0$ result).
  - 3-body phase-space decay is also studied for systematic uncertainty due to modeling.

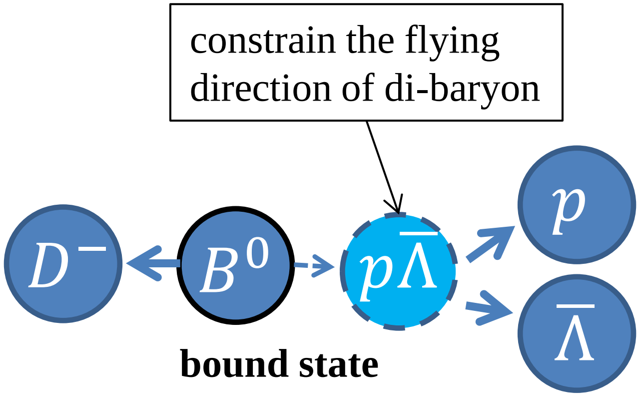


Mass of Λp system for 2 decay models:

- solid-line: bound state model
- blue-shadowed: 3-body phase-space



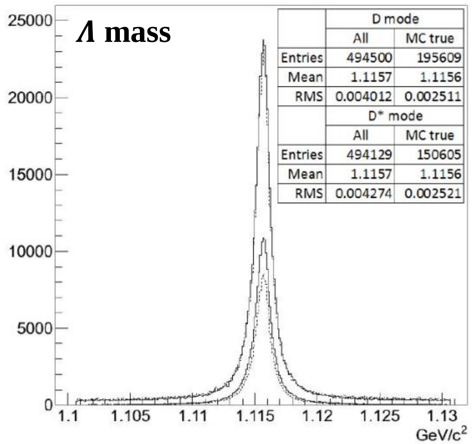
3-body phase space decay

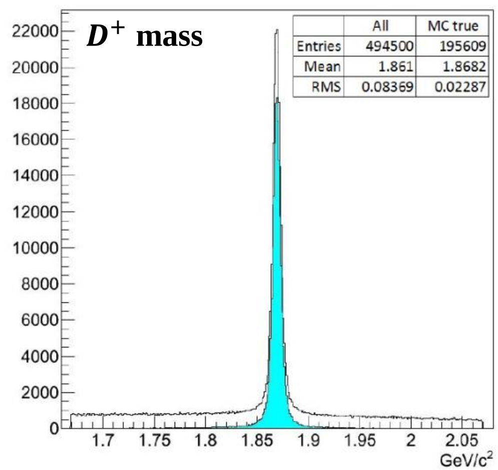


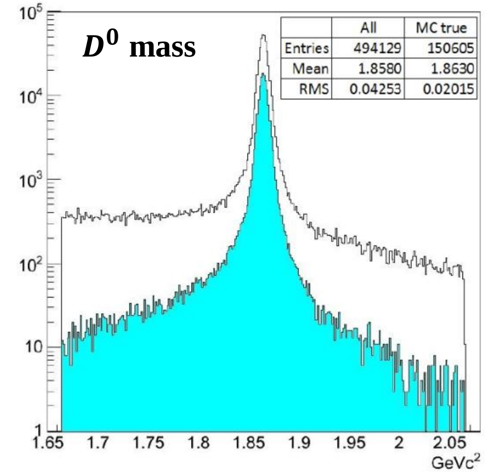
bound state decay model

Selection of the reconstructed immediate states

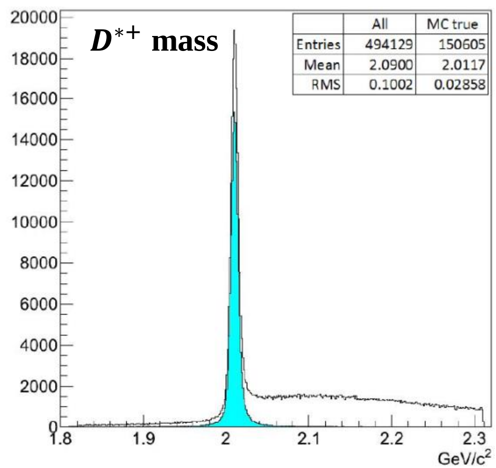
- Mass window of reconstructed immediate states

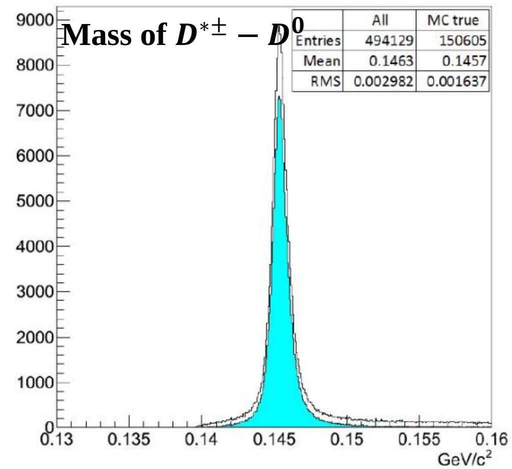






Item	Mass window(GeV/c^2)
Λ	1.102 – 1.13
$D^{\pm}$	1.7 – 2.04
D^{0}	1.72 – 2.02
$D^{*\pm}$	1.86 – 2.16
$D^{*\pm} - D^{0}$	0.136 – 0.156



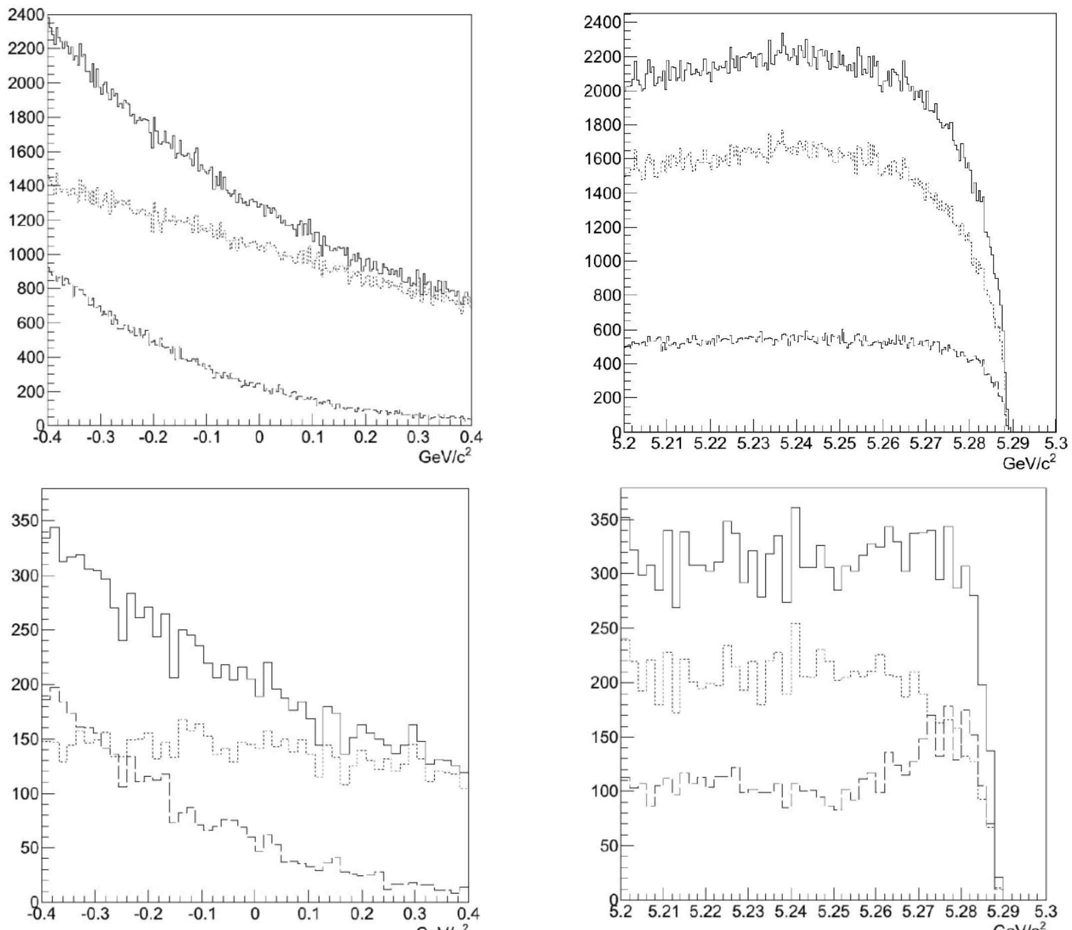


Background MC

- 2 main background MC are studied:
  - Continuum background: $e^+e^- \to q\bar{q}$ $(q = u,\ d,\ s,\ c)$
  - Generic B decay: $\Upsilon(4S) \to B\bar{B}, B$ decay with $b \to c$

***D* mode**

***D** mode**



ΔE **M_{bc}**

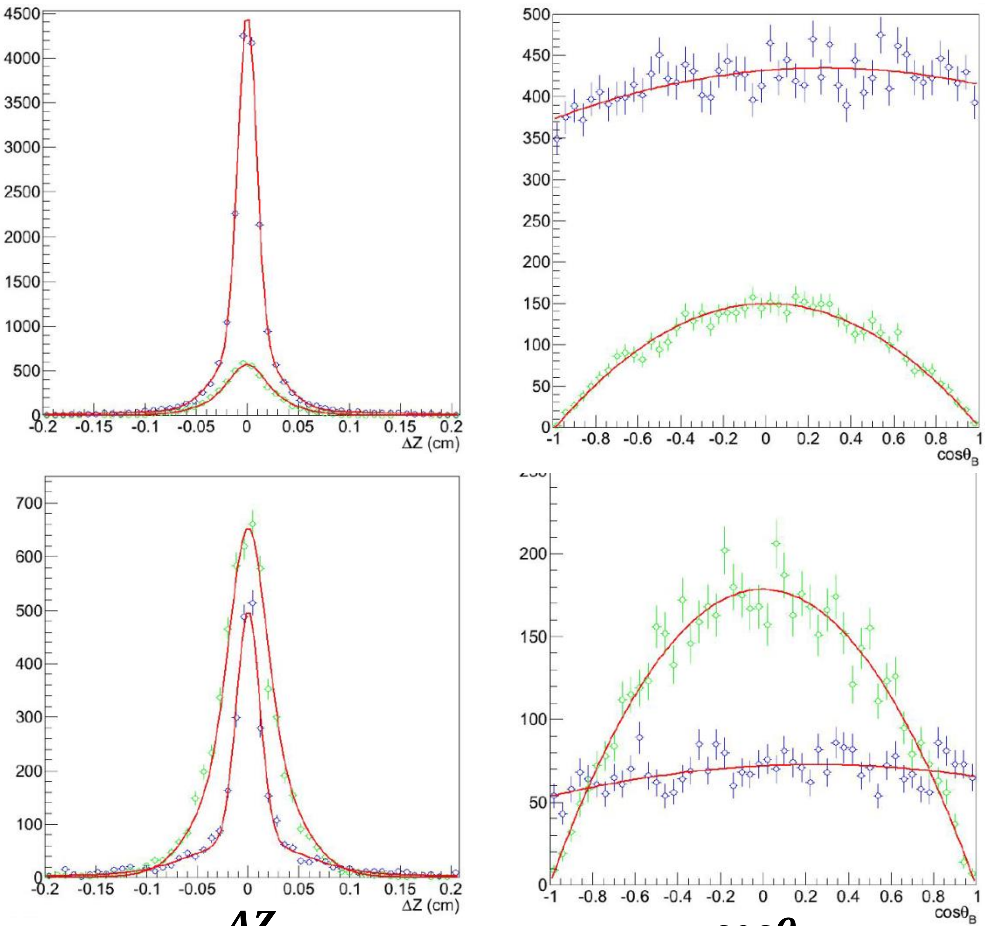
- solid: total
- short-dotted: Continuum
- long-dotted: Generic B

Background suppression

- ΔZ: deviation between IP and fitted B vertex at z direction
- θ_B: the angle between B momentum and the beam direction

D mode

D^* mode



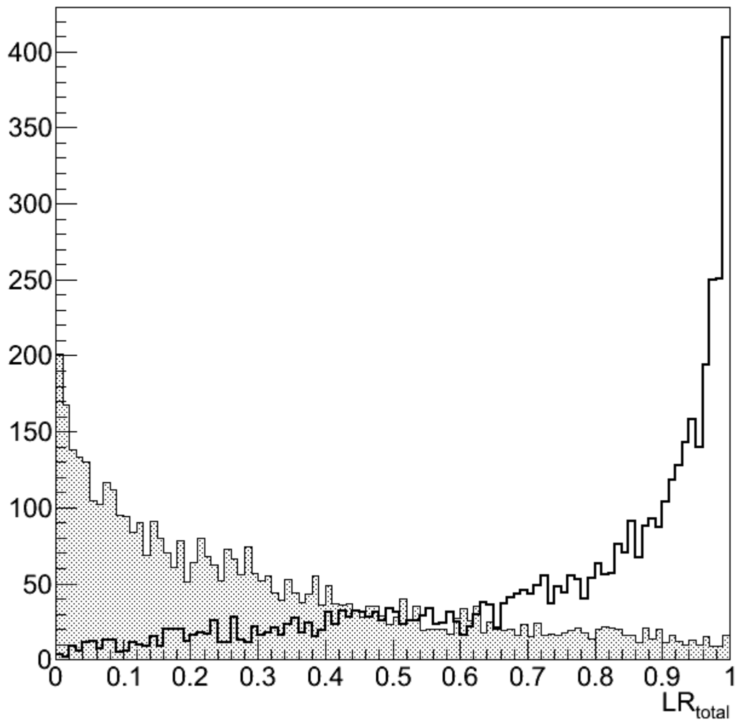
ΔZ $\cos\theta_B$

Background suppression(cont'd)

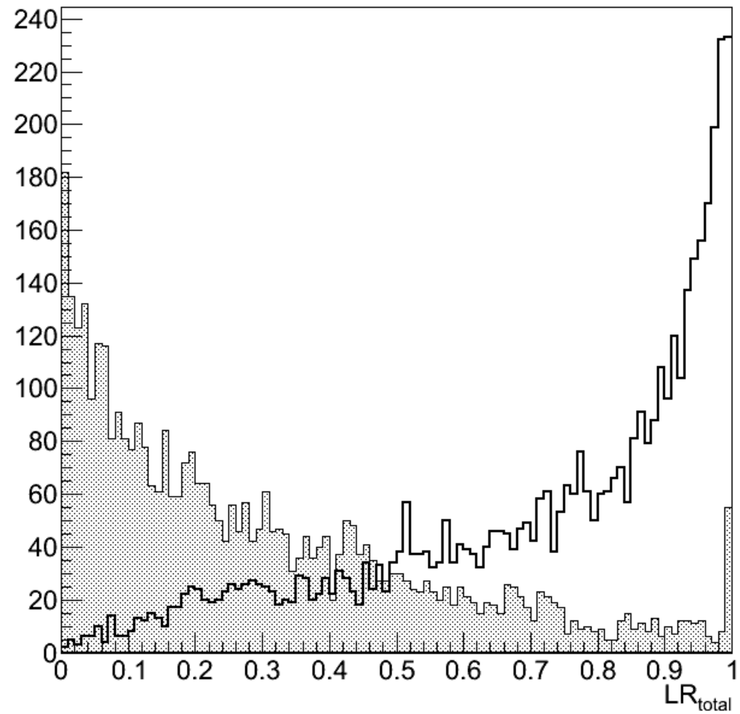
- $\mathcal{L} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B}, \mathcal{L}_{S(B)} = P(\mathcal{F})_{S(B)} \times P(\Delta Z)_{S(B)} \times P(\theta_B)_{S(B)}$
  $\mathcal{F}$: event topology variables

- $\mathcal{L}$ distribution:

- solid: signal
- shadowed: Continuum



D **mode**

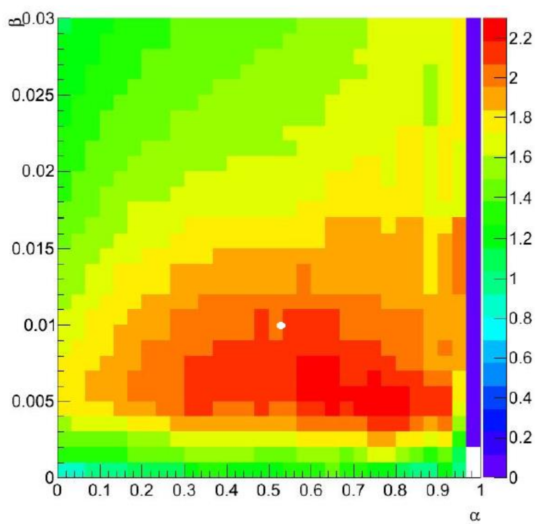


D^* mode

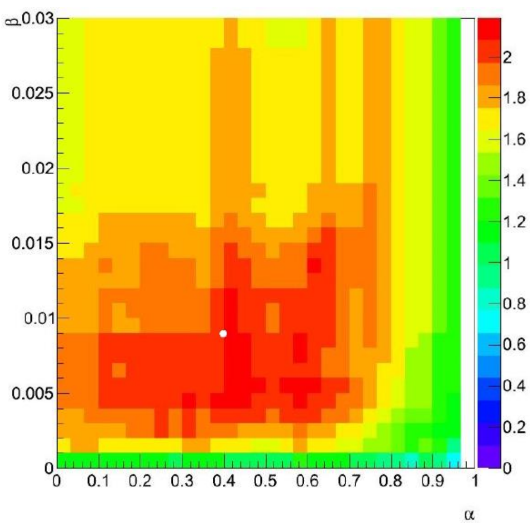
Optimization

- Scheme of optimization:
  - $\mathcal{L} > \alpha, 0.0 < \alpha < 1.0$
  - $|M_{D^\pm} - 1.87| < \beta\ (GeV/c^2)$ (for D mode)
  - $|M_{D^{*\pm}} - M_{D^0} - 0.145| < \beta\ (GeV/c^2)$ (for D^* mode)
- Optimize the α, β selection by Figure-of-Merit(F.O.M)
  - $F.O.M \equiv \frac{N_S}{\sqrt{N_S+N_B}}$, N_S: rescaled with GF's prediction, N_B:1X luminosity
- Events with multiple B candidate: use χ^2 from vertex fit to choose the best one
- Overall efficiency:

eff.	bound state	phase-space
***D* mode**	11.62%	10.31%
***D** mode**	11.04%	7.50%



***D* mode**



***D** mode**

Branching fraction measurement

- $\boldsymbol{\mathcal{B}} = \frac{N_{sig}}{N_{B\bar{B}} \times \epsilon_{MC} \times \epsilon_{cor} \times \mathcal{B}_{sub-decay}}$,
  $N_{B\bar{B}} = 771 \times 10^6$ for Belle's full data set
  - Signal yield(N_{sig}) is obtained by **2D fit of ΔE and M_{bc}.**

- Get $\boldsymbol{\epsilon_{MC}}$ and $\boldsymbol{N_{sig}}$ bin-by-bin for the variables($M_{p\bar{\Lambda}}$, $cos\theta_{pD^{(*)}}$) and calculate $\mathcal{B}$ in each bin → Differential $\mathcal{B}$ distribution.
  - Threshold enhancement pattern: $\boldsymbol{M_{p\bar{\Lambda}}}$ distribution
  - Angular correlation: $\boldsymbol{cos\theta_{pD^{(*)}}}$ distribution

Measurement result

- The fitted signal yield and efficiency in each $M_{p\bar{\Lambda}}$ bin:

	D mode			D* mode	
$M_{p\bar{\Lambda}}$ (GeV/c^2)	Yield	Efficiency (%)	$M_{p\bar{\Lambda}}$ (GeV/c^2)	Yield	Efficiency (%)
2.05–2.22	57 ± 8	12.2 ± 0.0	2.05–2.21	19 ± 5	12.2 ± 0.0
2.22–2.39	24 ± 5	10.5 ± 0.0	2.21–2.36	9 ± 3	10.2 ± 0.0
2.39–2.56	14 ± 4	9.5 ± 0.1	2.36–2.52	5 ± 3	8.7 ± 0.0
2.56–2.73	8 ± 3	9.8 ± 0.1	2.52–2.68	2 ± 1	8.4 ± 0.1
2.73–2.90	3 ± 2	10.4 ± 0.1	2.68–2.83	3 ± 2	7.6 ± 0.1
2.90–3.07	7 ± 3	10.9 ± 0.2	2.83–3.30	1 ± 1	6.3 ± 0.1
3.07–3.24	1 ± 2	10.8 ± 0.3			
3.24–3.41	2 ± 2	11.4 ± 0.7			
Total	117 ± 12			39 ± 7	

- The fitted signal yield and efficiency in each $cos\theta_{pD^{(*)}}$ bin:

	D mode		D* mode	
$\cos\theta_{pD^{(*)}}$	Yield	Efficiency (%)	Yield	Efficiency (%)
$-1.00 - -0.75$	10 ± 4	9.0	3 ± 2	8.6
$-0.75 - -0.50$	17 ± 5	10.5	1 ± 1	10.2
$-0.50 - -0.25$	16 ± 4	11.5	1 ± 1	11.3
$-0.25 - -0.00$	15 ± 4	12.2	2 ± 2	12.2
$+0.00 - +0.25$	19 ± 5	12.8	7 ± 3	12.7
$+0.25 - +0.50$	15 ± 4	13.0	7 ± 3	13.0
$+0.50 - +0.75$	16 ± 5	12.6	9 ± 3	12.8
$+0.75 - +1.00$	7 ± 3	11.5	8 ± 3	11.5