Measurements of branching fraction and time-dependent *CP* asymmetries for $B^0 \to J/\Psi\pi^0$ decays at Belle

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Particle Physics Seminar at BNL

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Some part of this work is done at

Belle experiment at KEK

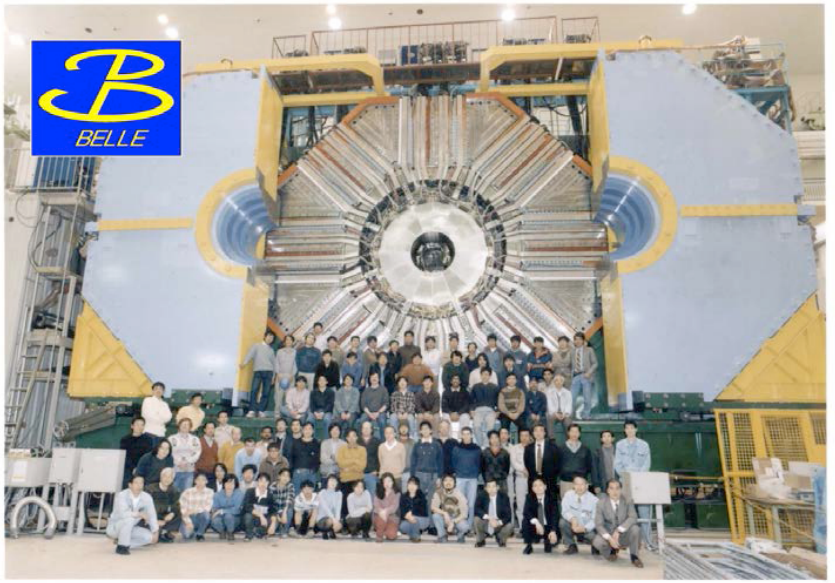
- Asymmetric energy $e^+ e^-$ collider.
- 8 GeV e^- beam and 3.5 GeV e^+ beam
- Peak achieved luminosity 2.1 x 10^{34} cm^{-2} s^{-1}, 2 times higher than the design luminosity
- Integrated luminosity ~ 1 ab^{-1}

The Belle experiment confirmed CPV in *B* decays and is part of a board-based search for New Physics in the Intensity frontier

- Leads to 2008 Nobel Prize in Physics

Please accept our deepest respect for the B-factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize.

Belle detector (already disassembled)



High resolution, multipurpose, good PID separation, 4π spectrometer

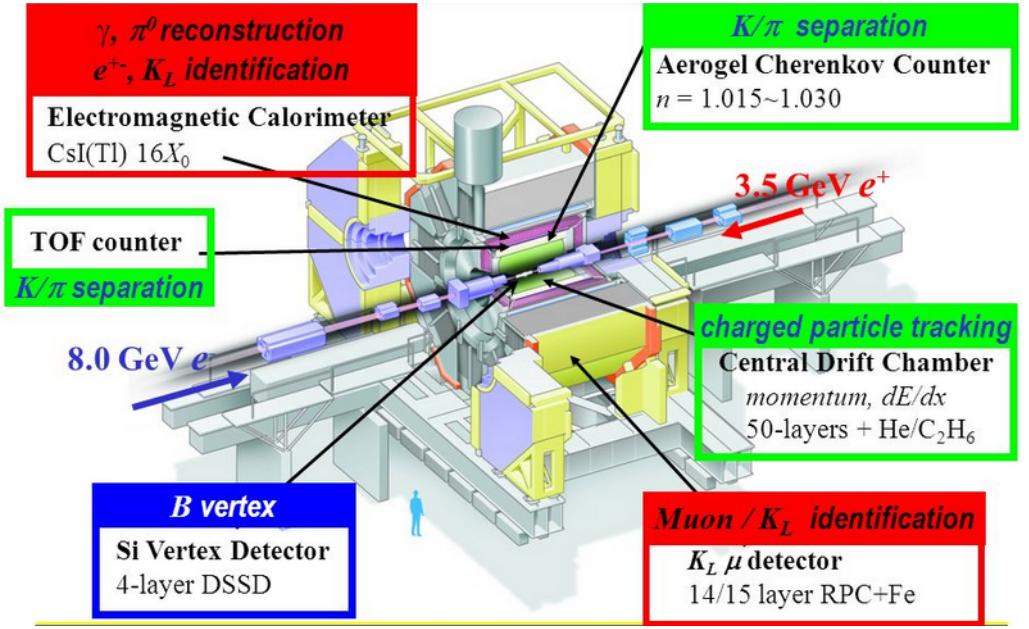


Table 1. Summary of the luminosity integrated by Belle, broken down by CM energy.

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of resonances
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$ SVD1	140.0	15.6	152×10^6 $B\bar{B}$
$\Upsilon(4S)$ SVD2	571.0	73.8	620×10^6 $B\bar{B}$
$\Upsilon(5S)$	121.4	1.7	7.1×10^6 $B_s\bar{B}_s$
Scan		27.6	

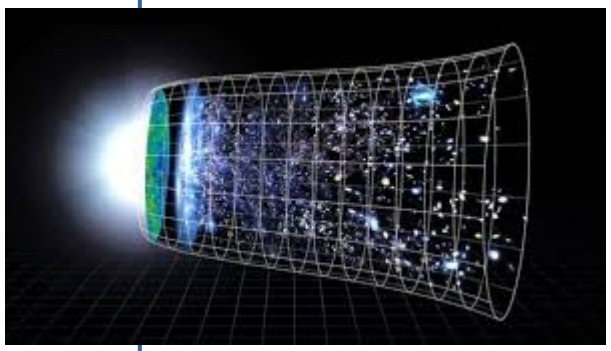
Data used for $B^0 \to J/\psi\pi^0$ analysis

Belle completed data taking on June 2010 to prepare for next generation B-factory Belle II

CP violation?

Difference between particle and its anti-particle
(matter and anti-matter)

Big Bang → N (matter) = N (anti-matter)



Universe today:
almost matter
(no anti-matter)

JETP Lett. 5, 24 (1967)

In 1967, A. Sakharov identified 3 conditions for an initially symmetric universe to subsequently develop a matter-antimatter asymmetry (baryogenesis):

- There must be processes that change the net matter-antimatter balance (Baryon number violation)
- Some corresponding mirror (matter ◄► antimatter) processes must proceed at different rates (~~C~~, ~~CP~~)
- These processes must occur in a phase when there was no thermal equilibrium

A brief history of CP violation

- 1963: Cabibbo introduced his angle for the quark mixing with two families
- 1964: Christensen, Cronin, Fitch and Turlay discover CP violation in the K^0 system
- 1967: Sakharov conditions
- 1973: Kobayashi and Maskawa propose three generations
- 1980: Nobel Prize to Cronin and Fitch
- 1981: Bigi and Sanda propose measuring CP violation in $B^0 \rightarrow J/\Psi K^0$ decays
- 1987: P. Oddone realizes how to measure CP violation: convert the PEP ring into an asymmetric energy e+e- collider
- 1999: BaBar and Belle start to take data.
- 2001: CP violation has ben established and confirmed by measuring $\sin(2\Phi_1) \neq 0$ in $B^0 \rightarrow J/\Psi K^0$ decays.
- 2008: Nobel Prize to Kobayashi and Maskawa

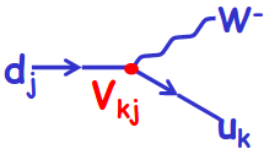
CKM matrix

CPV: due to **a complex phase** in the quark mixing matrix

CKM matrix

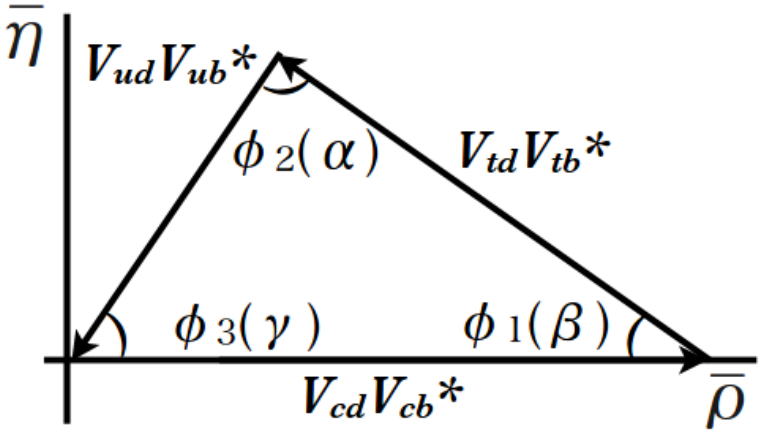
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix connects quark mass eigenstates to weak interaction eigenstates and thus describes coupling strength of quarks to charged current weak interaction



Unitarity requires

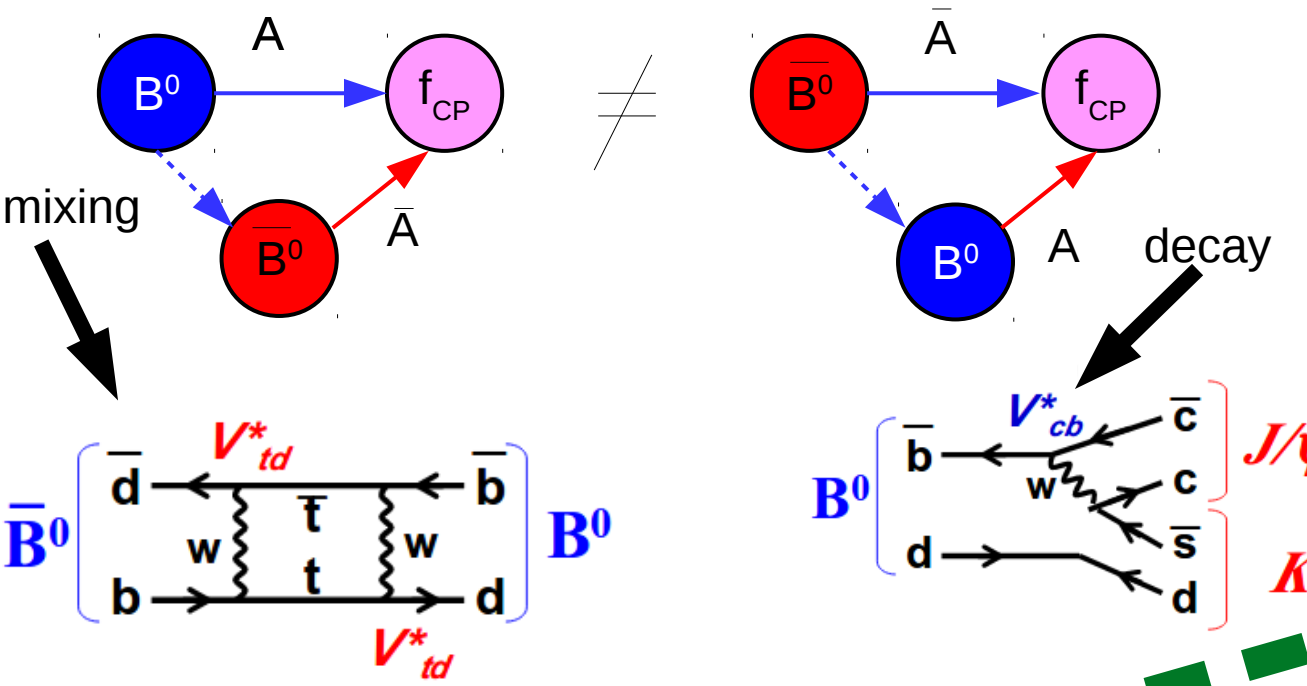
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Wolfenstein representation

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CPV in B^0 decays



- CPV in decays
- CPV in mixing
- CPV in interference bet^n a decay with and without mixing

Time-dependent CP violation

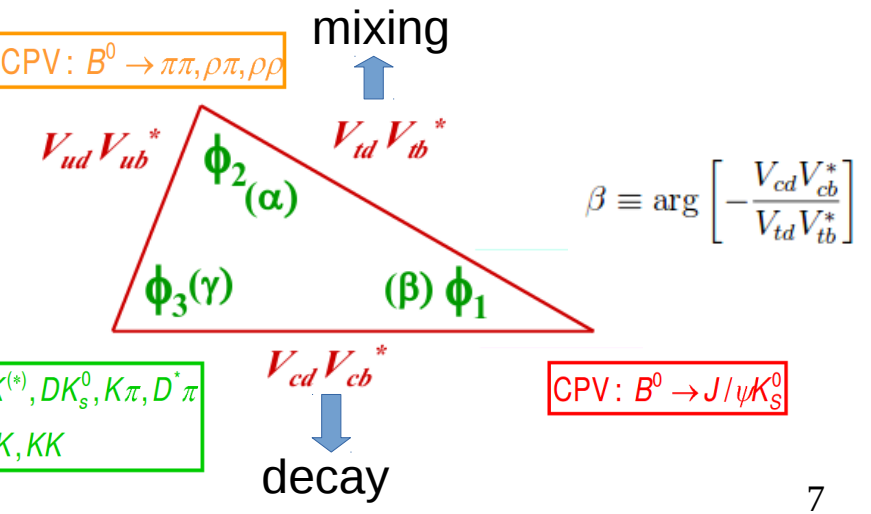
$$A_{CP} \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP}\,;\,\Delta t) - \Gamma(B^0 \to f_{CP}\,;\,\Delta t)}{\Gamma(\overline{B}^0 \to f_{CP}\,;\,\Delta t) + \Gamma(B^0 \to f_{CP}\,;\,\Delta t)}$$

$$= S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)$$

Mixing-induced CPV

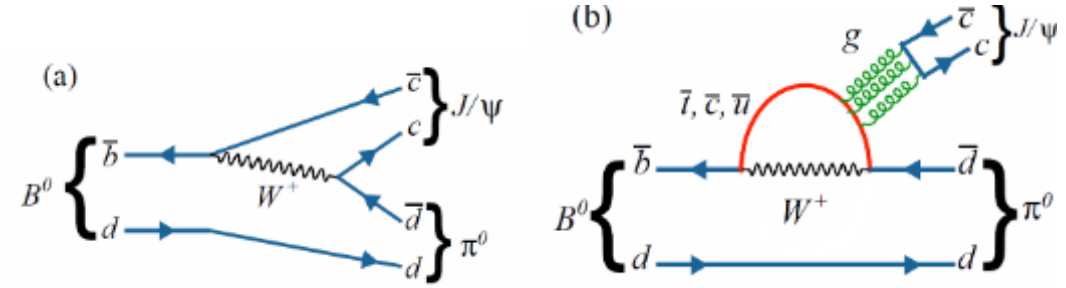
Direct CPV

Directly related to CKM angles



[1] A. B. Carter and A. I. Sanda, PRD 23, 1567 (1981)
[2] I. I. Bigi and A. I. Sanda, NPB 193, 85 (1981)

$B^0 \to J/\Psi\pi^0$: analysis motivation

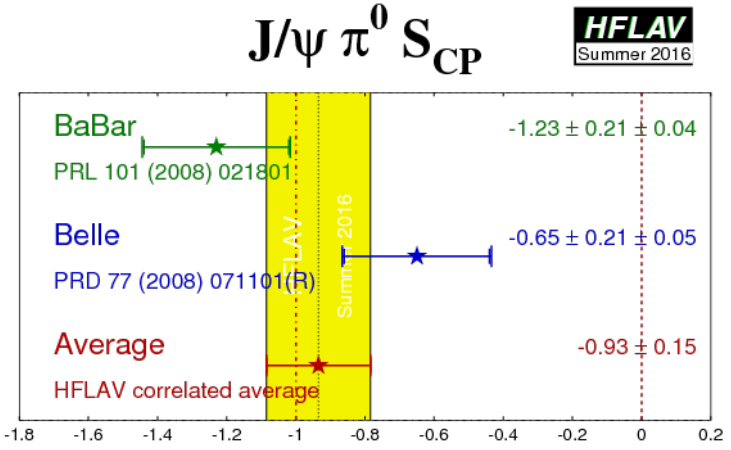


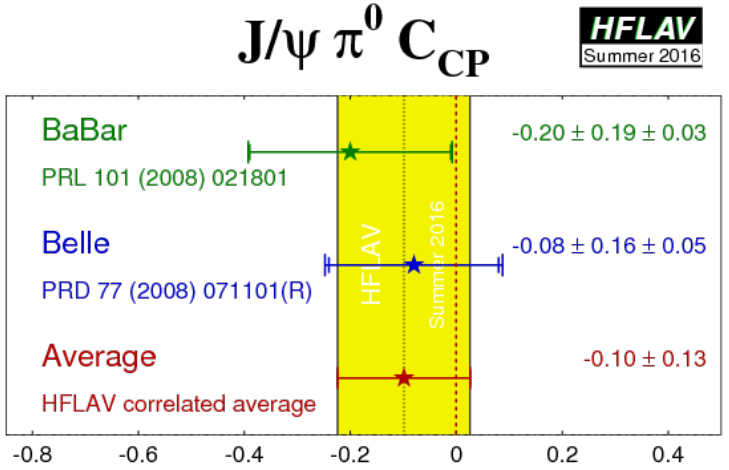
- These decays are sensitive to the *CP* violating angle $\Phi_1(\beta)$ of the unitarity triangle
- In the absence of the penguin amplitude, the direct *CP* asymmetry $A = 0$ and the mixing-induced *CP* asymmetry $S = -\sin(2\Phi_1)$
- Penguin and/or any new physics (NP) process will shift *A* and *S* from these values. Thus, experimental measurement of these parameters provide a way to search for NP.
- The values of *A* and *S* in this decay are useful to constrain the penguin pollution in the golden mode $B^0 \to J/\psi\, K_S$ decays [1,2,3,4,5]

Same motivations also hold for similar decay modes, i.e., $B^0 \to \psi(2S)\pi^0$, $B^0 \to J/\psi\eta^{(\prime)}$. These decays modes are currently statistically limited in Belle, but good for Belle II.

1) M. Ciuchini et al, PRL 95, 221804 (2005)
2) S. Faller et al, PRD 79, 014030 (2009)
3) M. Jung, PRD 86, 053008 (2012)
4) Z. Ligeti and D. Robinson, PRL 115, 251801 (2015)
5) P. Frings et al, PRL 115, 061802 (2015)

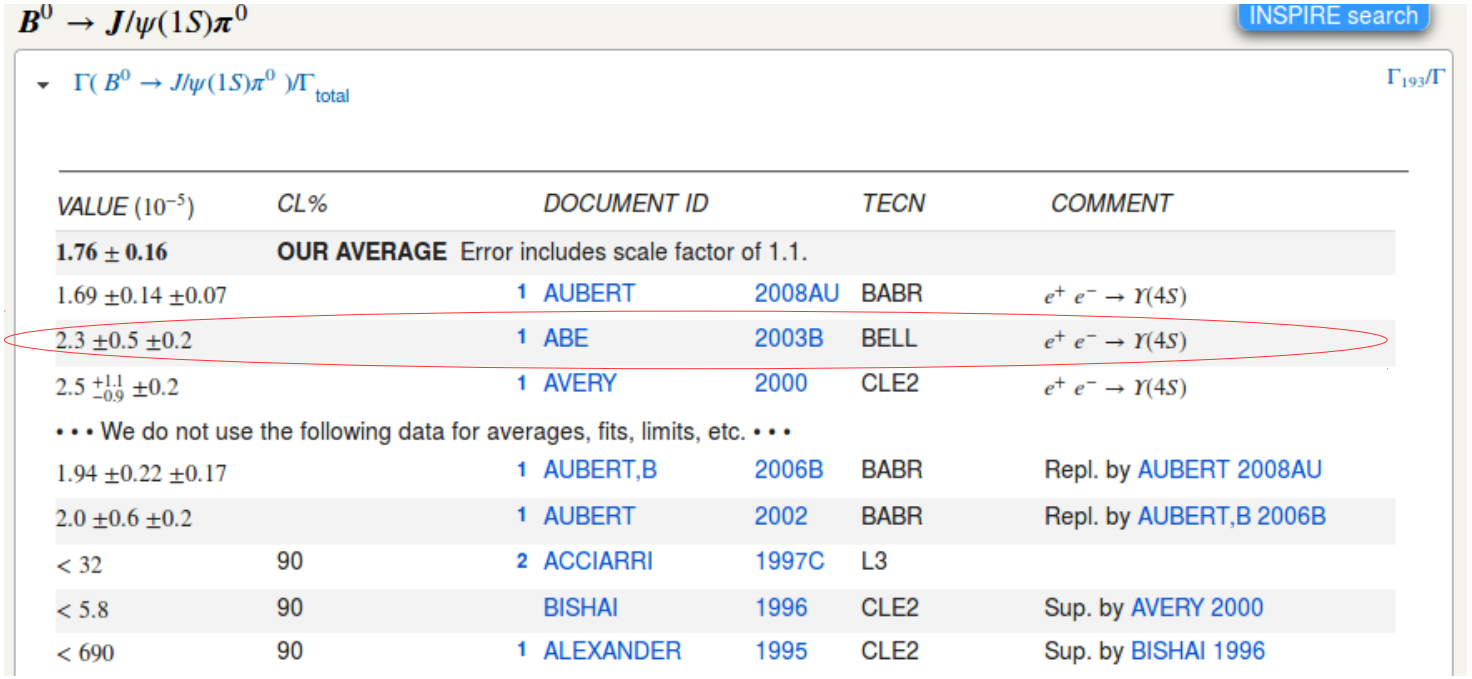
$B^0 \to J/\Psi\pi^0$: analysis motivation





- Previous measurements of mixing induced CP asymmetries from BaBar and Belle experiments are not in good agreement and BaBar result lies outside the physically allowed region (although the error is large)
- A more precise measurement can clarify this unsatisfactory situation
- Previous Belle measurement is based on 535M BB pairs.
- We expect improvement with final Belle data set, which corresponds to 772M BB pairs.

$B^0 \to J/\Psi\pi^0$: analysis motivation



$B^0 \to J/\psi(1S)\pi^0$ INSPIRE search

$\Gamma(B^0 \to J/\psi(1S)\pi^0)/\Gamma_{total}$ Γ_{193}/Γ

VALUE (10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
1.76 ± 0.16	**OUR AVERAGE**	Error includes scale factor of 1.1.			
1.69 ±0.14 ±0.07		1 AUBERT	2008AU	BABR	$e^+ e^- \to \Upsilon(4S)$
2.3 ±0.5 ±0.2		1 ABE	2003B	BELL	$e^+ e^- \to \Upsilon(4S)$
$2.5\ ^{+1.1}_{-0.9}$ ±0.2		1 AVERY	2000	CLE2	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.94 ±0.22 ±0.17		1 AUBERT,B	2006B	BABR	Repl. by AUBERT 2008AU
2.0 ±0.6 ±0.2		1 AUBERT	2002	BABR	Repl. by AUBERT,B 2006B
< 32	90	2 ACCIARRI	1997C	L3	
< 5.8	90	BISHAI	1996	CLE2	Sup. by AVERY 2000
< 690	90	1 ALEXANDER	1995	CLE2	Sup. by BISHAI 1996

Previous Belle measurement of the branching fraction was only with 30/fb. With the final data set, we expect huge improvement

Pre-selection requirements

Variable	Requirement
e^+, e^-, μ^+, μ^-	
Information from ECL and CDC is used for e+/e- identification. KLM information is used for muon identification.	
π^0	MDST_π^0
	Mass-constraint fit by default
χ^2 (mass-constraint fit)	< 30
E_γ	> 100 MeV in ECL endcap region
	> 50 MeV in ECL barrel region
$\lvert M_{\gamma\gamma} - M_{\pi^0}\rvert$	< 0.020 GeV/c^2
J/ψ	Vertex- and mass-constraint fit
Mass window	-0.150 GeV/c^2 $< M_{ee(\gamma)} - M_{J/\psi} <$ +0.036 GeV/c^2
	-0.060 GeV/c^2 $< M_{\mu\mu} - M_{J/\psi} <$ +0.036 GeV/c^2
B^0	
$M_{\rm bc}$	> 5.24 GeV/c^2
ΔE	$-0.20 < \Delta E < 0.10$ GeV

$M_{\rm bc} = \sqrt{E^2_{\rm beam} - |\vec{p}_B|^2 c^2}/c^2$

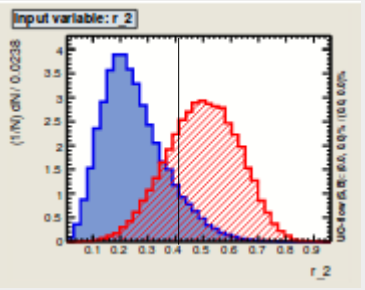
$\Delta E = E_B - E_{\rm beam}$

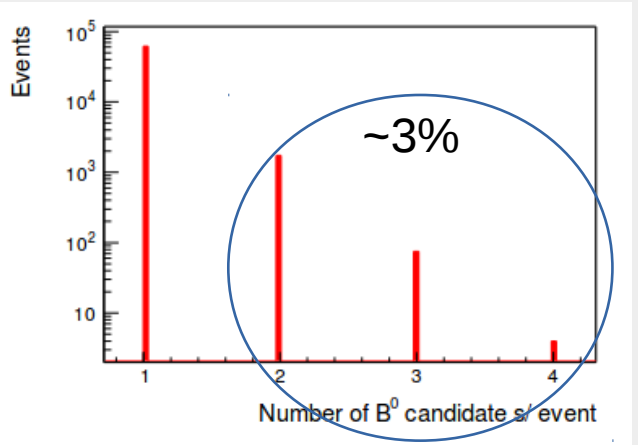
- In order to take into account the radiative energy loss in J/Ψ → e^+e^-, we include up to two bremsstrahlung photons, that lie within 50 mrad of reconstructed electron/positron tracks.

Pre-selection requirements are similar to that used in the previous Belle publication [PRD 77, 071101 (2008)]

In B-factory, one of the common background is the continuum background, arises from light quark production (e+e- → qq_bar, q = u, d, s, c).

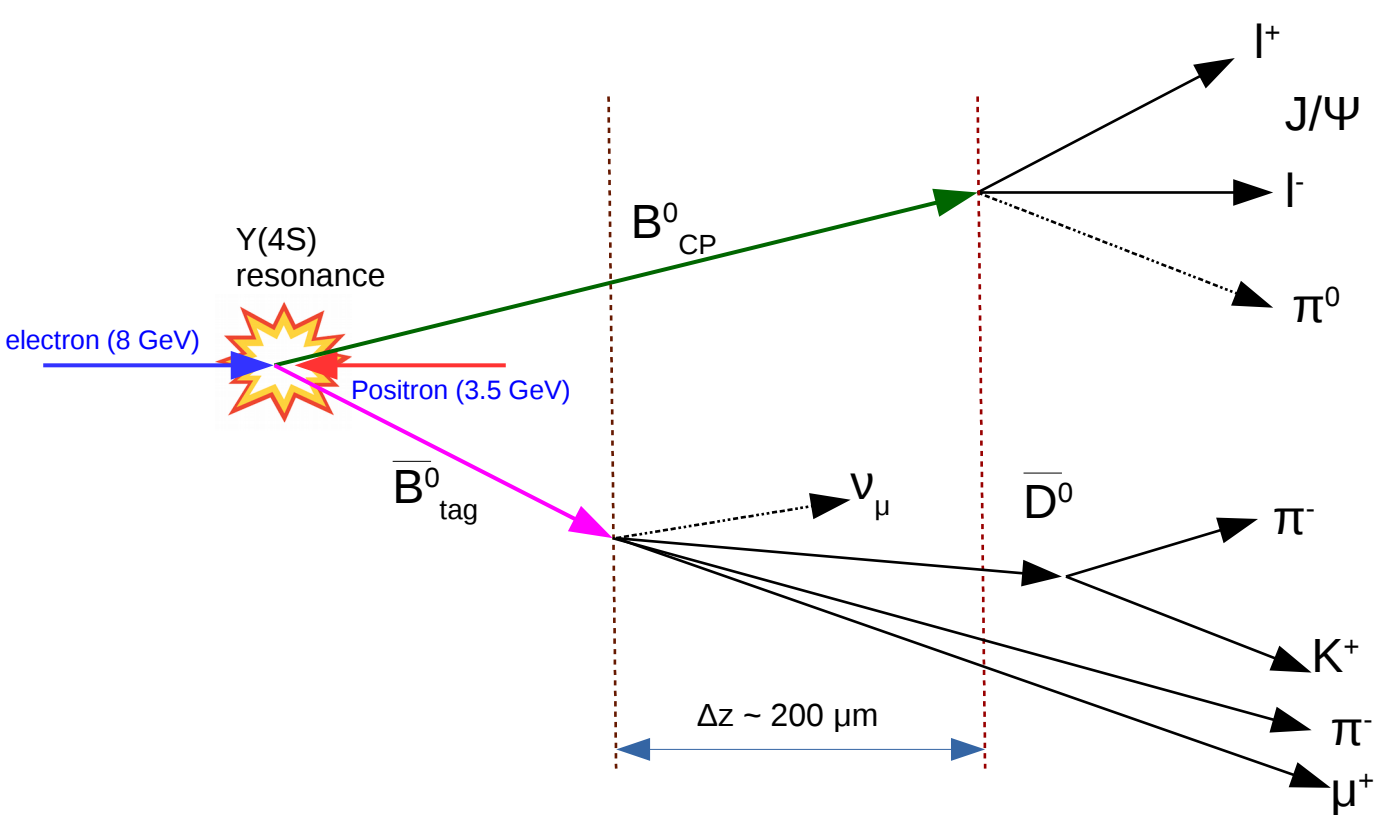
Ratio of 2nd to 0th Fox-Wolfram moment to suppress continuum events.





- Lowest ($X^2_{\pi 0\ \text{mass const}} + X^2_{J/\Psi\ \text{mass const}} + X^2_{J/\Psi\ \text{vertex const}}$) is used to select the best candidate.
- This criterion chooses the correct candidate in 74% multiple candidate events.

Vertex reconstruction



We fully reconstruct one *B* meson which decays to *CP* eigenstate $J/\Psi\pi^0$ for this case.

Since there are no other particles in the event beside the two *B* mesons, all tracks that are not associated to B_{CP} are used to reconstruct the B_{tag} vertex. [H. Tajima et al, NIM A 533, 370 (2004)]

Proper time (Δt) is measured from decay-vertex difference Δz:
$\Delta t \approx \Delta z/\beta\gamma c$, $\beta\gamma = 0.425$ is the boost factor

Event with poorly reconstructed vertices are rejected by applying cut on the vertex χ^2 and error on the vertex z-coordinate.

Flavor-tagging

- The purpose of the flavor tagging is to classify the B_{tag} either as a B^0 or B^0-*bar*.
- The flavor of B_{tag} can be determined from the charge of

(1) high-momentum leptons from $B^0 \to X\ell^+\nu$ decays,
(2) kaons, since the majority of them originate from $B^0 \to K^+X$ decays through the cascade transition $\bar{b} \to \bar{c} \to \bar{s}$,
(3) intermediate momentum leptons from $\bar{b} \to \bar{c} \to \bar{s}\ell^-\bar{\nu}$ decays,
(4) high momentum pions coming from $B^0 \to D^{(*)}\pi^+X$ decays,
(5) slow pions from $B^0 \to D^{*-}X, D^{*-} \to \overline{D}^0\pi^-$ decays, and
(6) $\overline{\Lambda}$ baryons from the cascade decay $\bar{b} \to \bar{c} \to \bar{s}$.

All available information obtained by the considered six categories are combined by multi-dimensional likelihood method and flavor charge q=+1 or -1 and flavor tagging quality r are returned by the flavor tagging routine.

The details of the Belle's flavor tagging is described in H. Kakuno et al, NIM A 533, 516 (2004)

- For various reason, this categorization is not perfect. There is a finite probability to incorrectly tag an event and thus dilute measurements that rely on this information.

Time dependent PDF: $S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)$

$-\Delta w + r[S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)]$

$r = 1 - 2w$ (*r = dilution factor*)
$w = (w_B + w_{\bar{B}})/2$
$\Delta w = w_B - w_{\bar{B}}$
w_B = *mistag probability of* B^0

Flavor-tagging

$r = 1 - 2w$ *(r = dilution factor)*

$w = (w_B + w_{\bar{B}})/2$

$\Delta w = w_B - w_{\bar{B}}$

w_B = *mistag probability of* B^0

Dilution factor = 0 for no flavor discrimination
and 1 for unambiguously determined flavor.

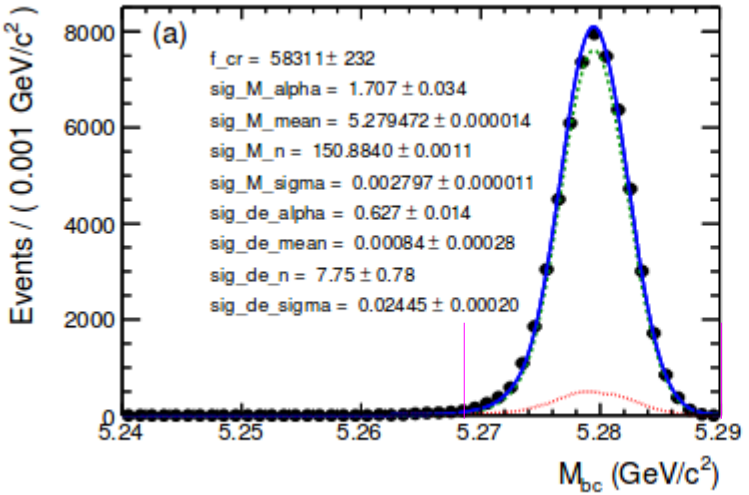
Mistag probabilities and their differences in different r bins are measured from semileptonic and hadronic b→ c decays.

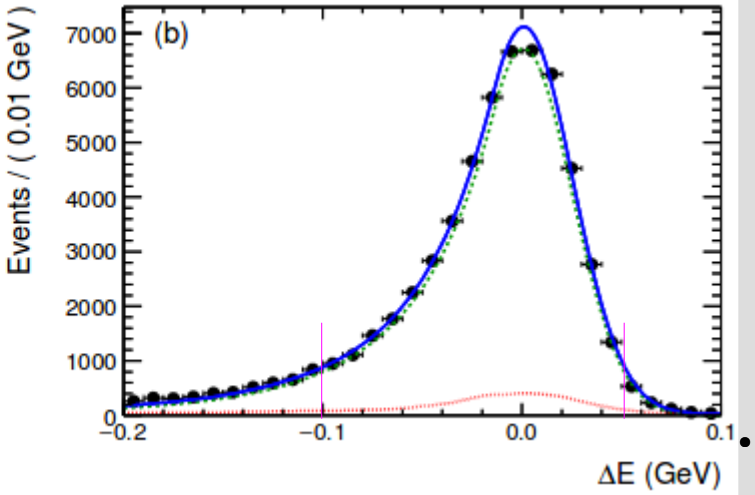
		SVD1		SVD2	
l	r interval	ω	$\Delta\omega$	ω	$\Delta\omega$
0	0.000-0.100	0.500	0.000	0.500	0.000
1	0.100-0.250	0.419	0.057	0.419	-0.009
2	0.250-0.500	0.330	0.013	0.319	0.010
3	0.500-0.625.	0.234	-0.015	0.223	-0.011
4	0.625-0.750	0.171	-0.001	0.163	-0.019
5	0.750-0.875	0.100	0.009	0.104	0.002
6	0.875-1.000	0.023	0.005	0.025	-0.004

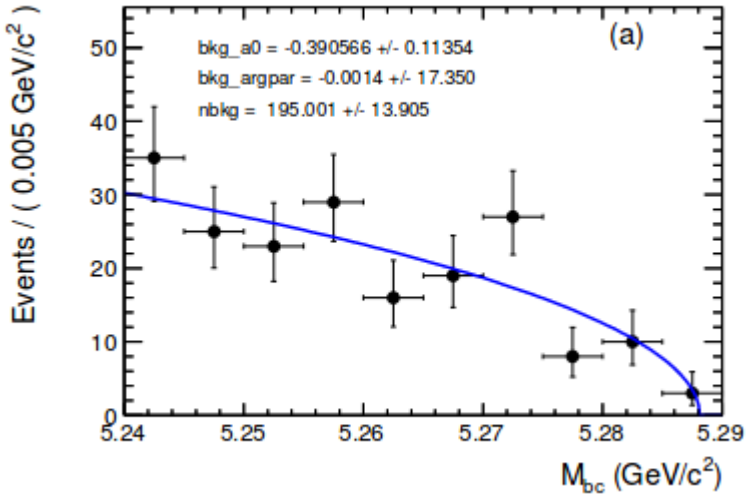
This table is generated centrally to be used in all time-dependent analyses at Belle.

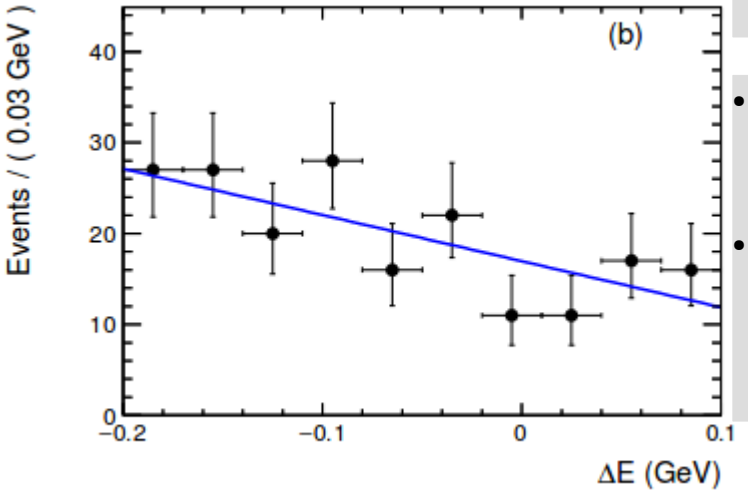
M_{bc}- ΔE shapes

$$\mathcal{P}_{\rm sig}(M_{\rm bc},\Delta E) = f_{\rm CR}\mathcal{P}_{\rm CR}(M_{\rm bc},\Delta E) + (1-f_{\rm CR})\mathcal{P}_{\rm IR}(M_{\rm bc},\Delta E)$$







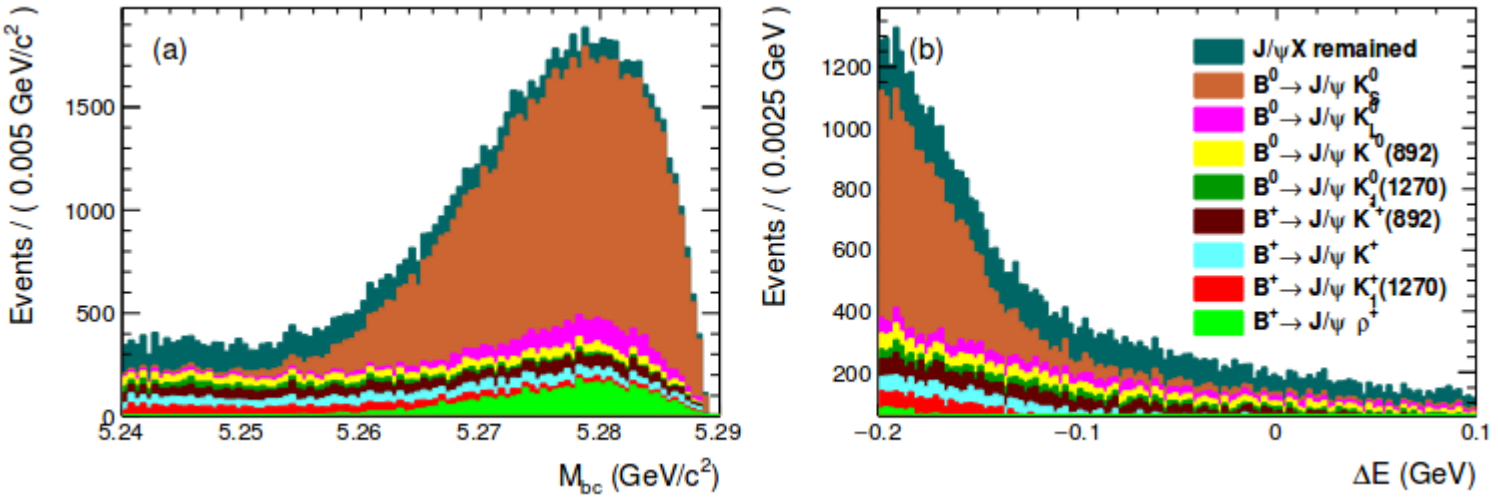


- Signal shapes are studied from signal MC. Two parts: one for candidates that are correctly reconstructed (CR) and the other for those where at least one daughter originates from the tag side. The fraction of incorrectly reconstructed (IR) candidates are fixed in the fit to real data.
- Crystal Ball functions are used for CR M_{bc} and ΔE
- 2D non-parametric function is used for IR events.

- Centrally generated MC is used to study the continuum and other background.
- Fixed end-point Argus function for M_{bc} and 1st order polynomial function for ΔE.

M_{bc} - ΔE shapes

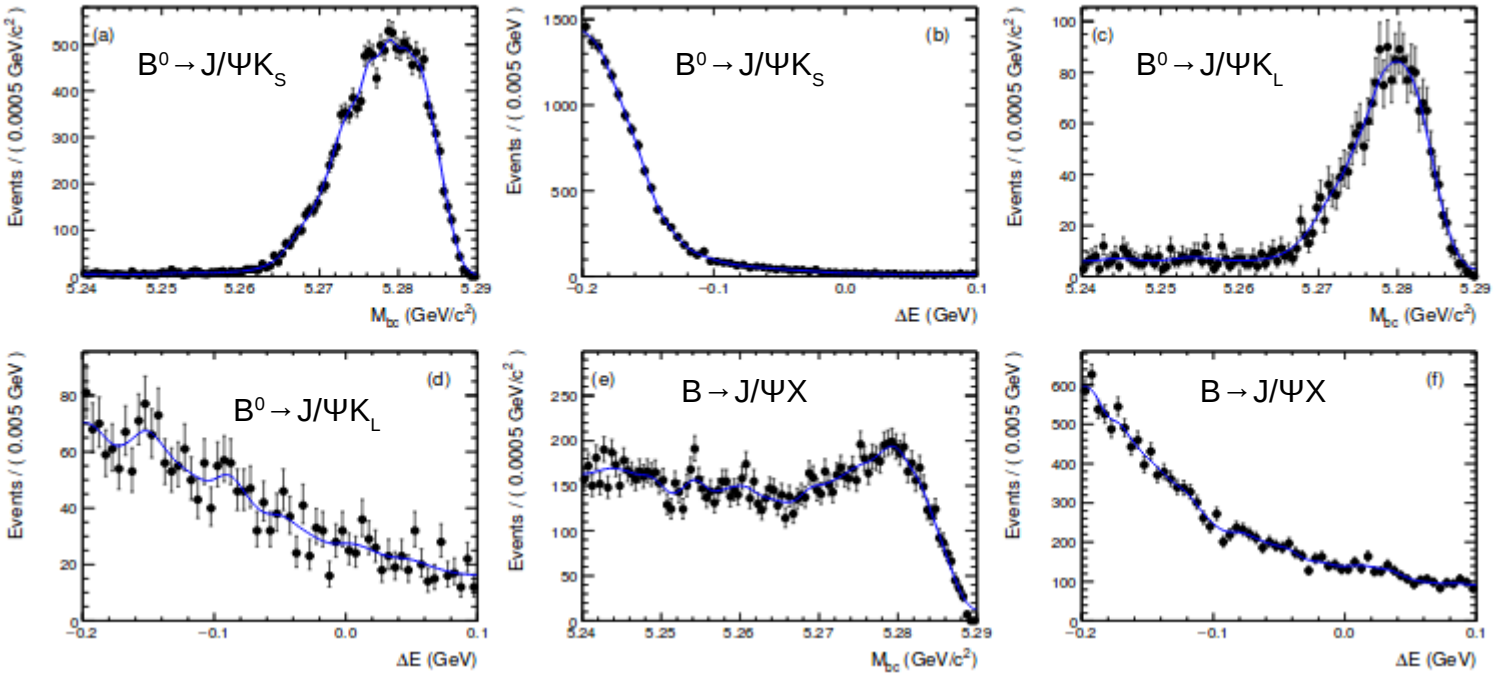
Dominant background is B→ J/ΨX, studied from MC samples equivalent to 100x the data.



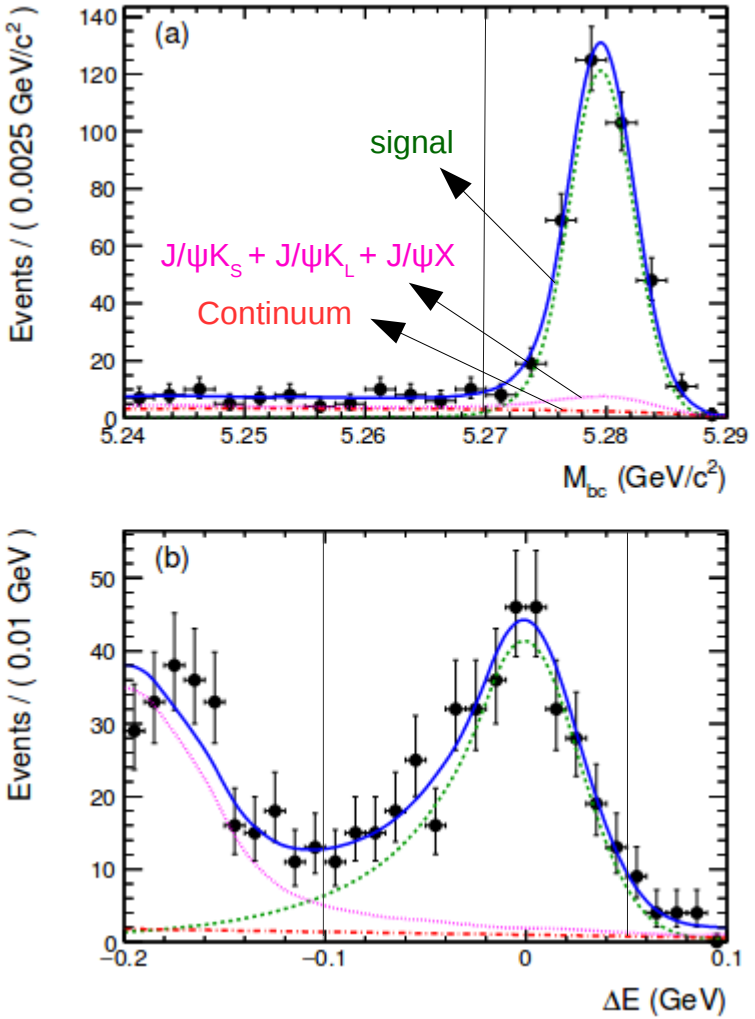
Two dominant contribution comes from CP violating decays $B^0 \to J/\Psi K_S$ (CP even) and $B^0 \to J/\Psi K_L$ (CP odd). They are treated separately in our analysis.

- 2D non-parametric PDFs are used.
- We fix the yields of these three categories in the fit to the data, which are
  - 10.8 $J/\Psi K_S$
  - 10.0 $J/\Psi K_L$
  - 17.5 $J/\Psi X$

  in the signal region



Branching fraction measurement



Signal = 330 ± 22

Continuum bkg = 16 ± 4

$$\mathcal{B}(B^0 \to J/\psi\pi^0) = \frac{Y_{\rm sig}}{\varepsilon \times N_{B\bar{B}} \times \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

$$\mathcal{B}(B^0 \to J/\psi\pi^0) = (1.62 \pm 0.11 \pm 0.07) \times 10^{-5},$$

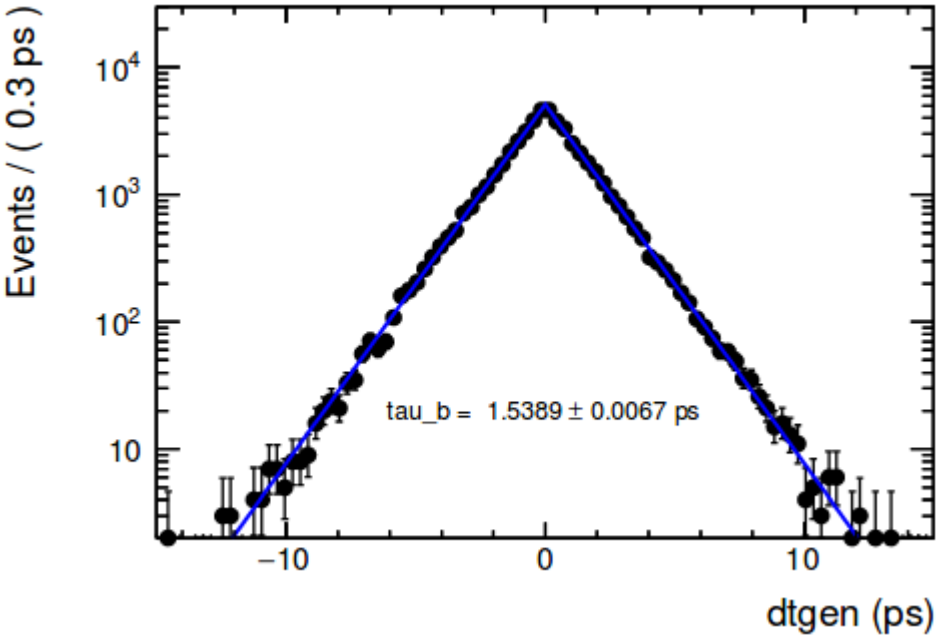
TABLE I. Systematic uncertainties for $\mathcal{B}(B^0 \to J/\psi\pi^0)$.

Source	Uncertainty (%)
PDF parametrization	0.1
π^0 reconstruction	1.5
Tracking	0.7
Lepton-ID selection	2.1
Incorrectly reconstructed signal events	1.8
$B \to J/\psi\,(K^0_S, K^0_L, X)$ background	$^{+1.8}_{-2.0}$
MC statistics	0.4
$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	0.8
Number of $B\bar{B}$ pairs	1.4
Total	$^{+4.0}_{-4.2}$

Our measurement is consistent with the WA and more precise than any previous measurement!

VALUE (10^{-5})	*CL%*	*DOCUMENT ID*		*TECN*
1.76 ± 0.16	**OUR AVERAGE**	Error includes scale factor of 1.1.		
1.69 ±0.14 ±0.07		1 AUBERT	2008AU	BABR
2.3 ±0.5 ±0.2		1 ABE	2003B	BELL
2.5 $^{+1.1}_{-0.9}$ ±0.2		1 AVERY	2000	CLE2

Time-dependent study: fit to generated level Δt



Signal MC generated with τ = 1.5344 ps

$$\mathcal{P}_{\rm gen}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}$$

This study shows no evidence of reconstruction bias!

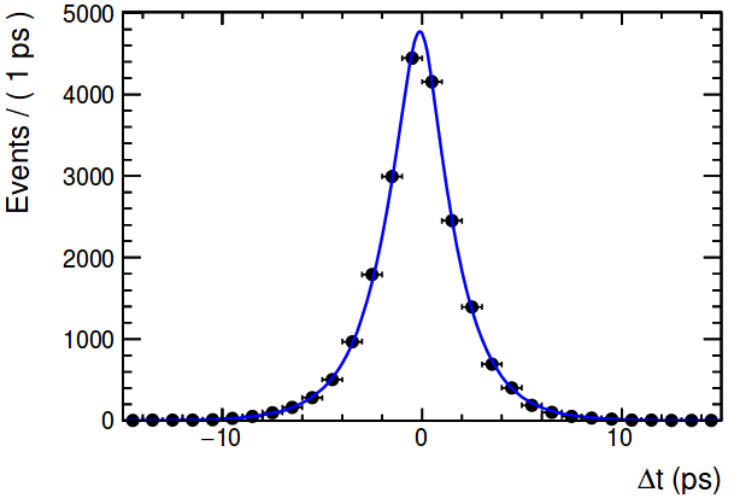
Time-dependent study: Resolution function and lifetime fit

To account for the finite decay time resolution the PDF for the TD study is convolved with a resolution function

- To the first order the resolution function is a Gaussian function function with zero mean and width corresponding to the average resolution.
- The Belle resolution function [H. Tajima et al, NIM A 533, 370 (2004)] is itself a convolution of four components:
  - B_{CP} vertex resolution
  - B_{tag} vertex resolution
  - Shift of the B_{tag} vertex position due to secondary tracks from charmed particle decay
  - The kinematic approximation that the B mesons are at rest in the CM frame.

Resolution function is checked by performing a lifetime fit using reconstructed signal MC:

$$\mathcal{P}_{\text{lifetime}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \otimes R_{\text{sig}}(\Delta t)$$

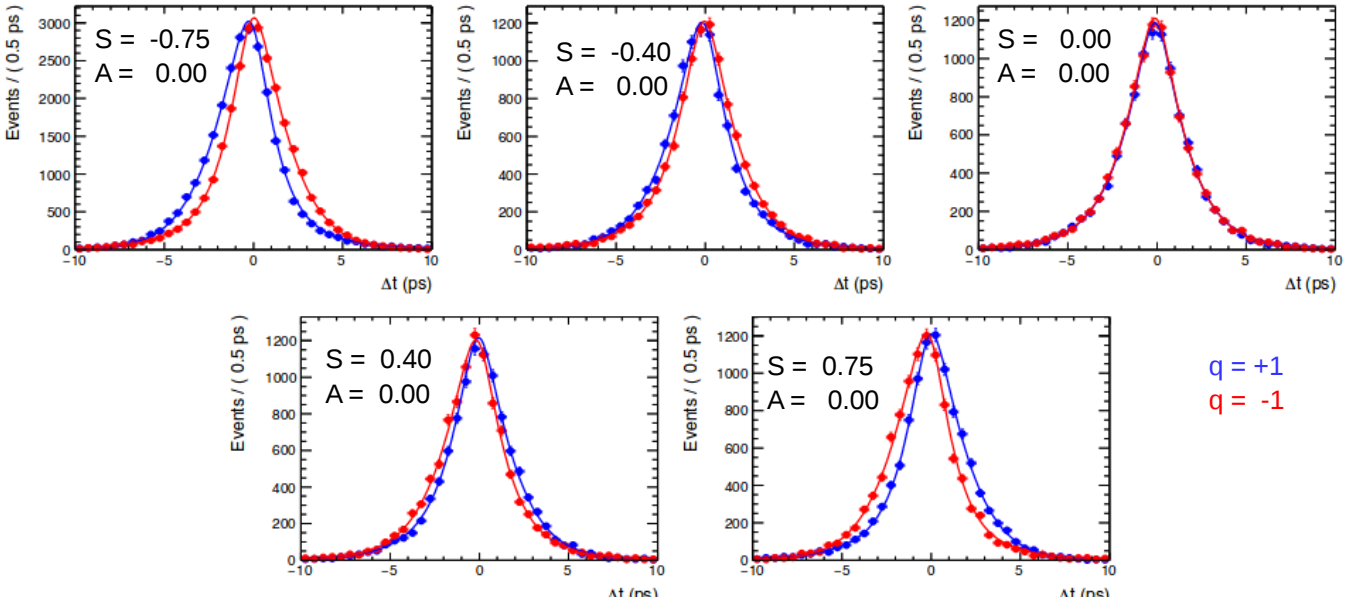


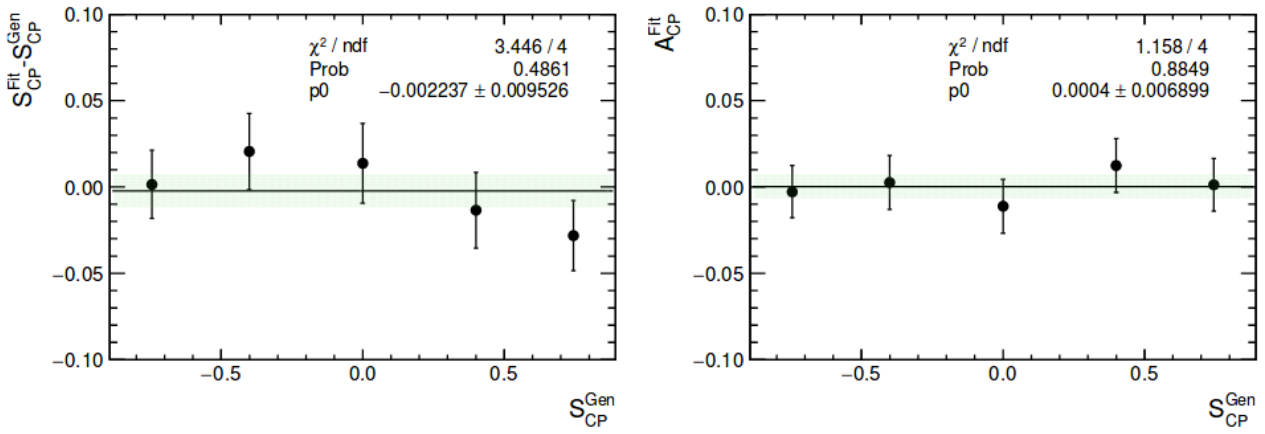
Generated τ = 1.5344 ps
Fitted τ = 1.5373 ± 0.0122 ps

TD PDF: Signal MC

$$\mathcal{P}_{\rm sig}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \Big[1 - q\Delta w_l + q(1-2w_l)\Big(\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\Big)\Big] \otimes R_{\rm sig}(\Delta t)$$

Fixed to WA values





TD PDF: J/ψ background

For $B^0 \to J/\Psi K_S$ and $B^0 \to J/\Psi K_L$, the PDF is similar to signal PDF, but S and A are fixed to [PRL 108, 171802 (2012)]

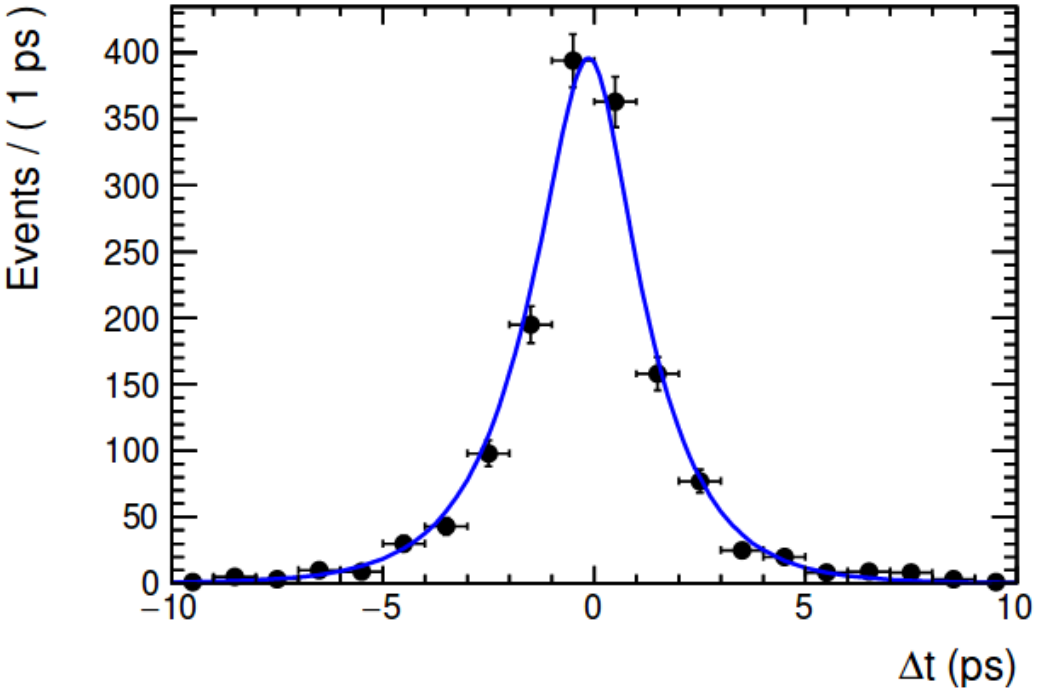
$$\mathcal{S}_{J/\psi K^0_S} = +0.670 \pm 0.029 \pm 0.013$$
$$\mathcal{S}_{J/\psi K^0_L} = -0.642 \pm 0.047 \pm 0.021,$$
$$\mathcal{A}_{J/\psi K^0_S} = -0.015 \pm 0.021^{+0.045}_{-0.023},$$
$$\mathcal{A}_{J/\psi K^0_L} = +0.019 \pm 0.026^{+0.017}_{-0.041},$$

For $B^0 \to J/\Psi X$ we also use the same PDF but with A = 0, S = 0 and B lifetime is replaced with effective lifetime. Effective lifetime is measured from MC (100x the data) and fixed in the fit to data.

$$\mathcal{P}_{J/\psi X}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{J/\psi X}}}{4\tau_{J/\psi X}}\Big[1 - q\Delta w_l\Big] \otimes R_{\rm sig}(\Delta t)$$

$T_{effective}$ = 1.200 ± 0.104 (SVD1)

$T_{effective}$ = 1.186 ± 0.041 (SVD2)

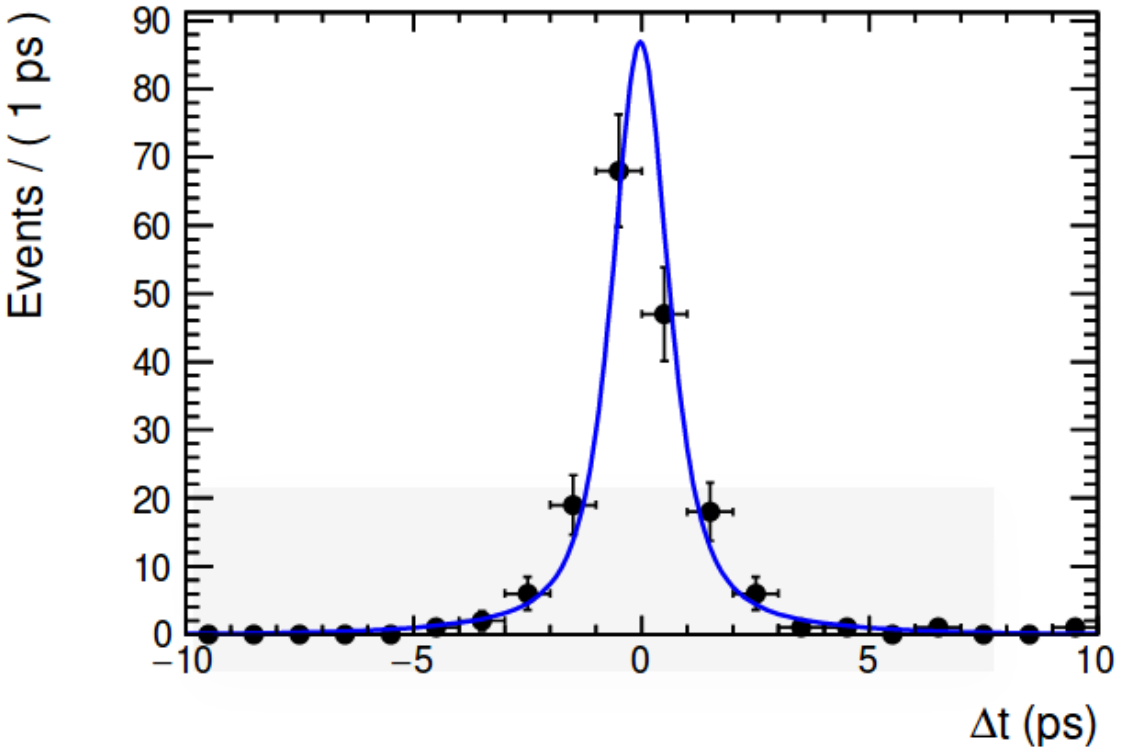


TD PDF: continuum background

Sideband data is used to study this background.

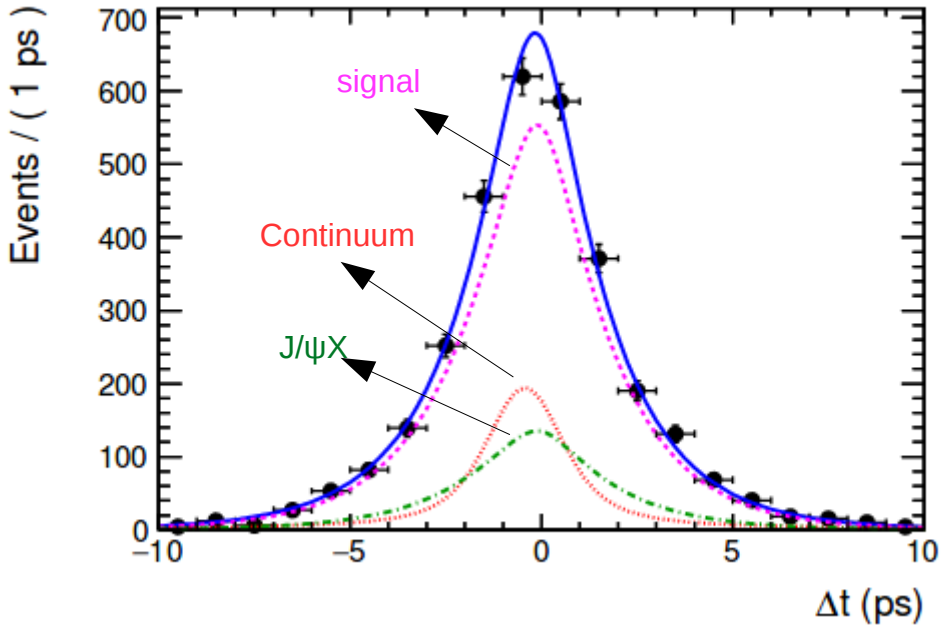
$$M_{\rm bc} < 5.26\ {\rm GeV}/c^2 \text{ and } 0.5\ {\rm GeV} < \Delta E < 1.0\ {\rm GeV}$$

$$\mathcal{P}_{\rm bkg}(\Delta t) = 2G(\Delta t; \mu, \sigma_1, \sigma_2, f_2)$$



Lifetime fit

- Before combining all these components, we perform a lifetime fit using a control sample.
- Our control sample is $B^+ \to J/\Psi K^{*+}, K^{*+} \to K^+\pi^0$ (signal yield ~ 3000)
- Fitted lifetime = 1.644 ± 0.043 ps
- World average = 1.638 ± 0.004 ps

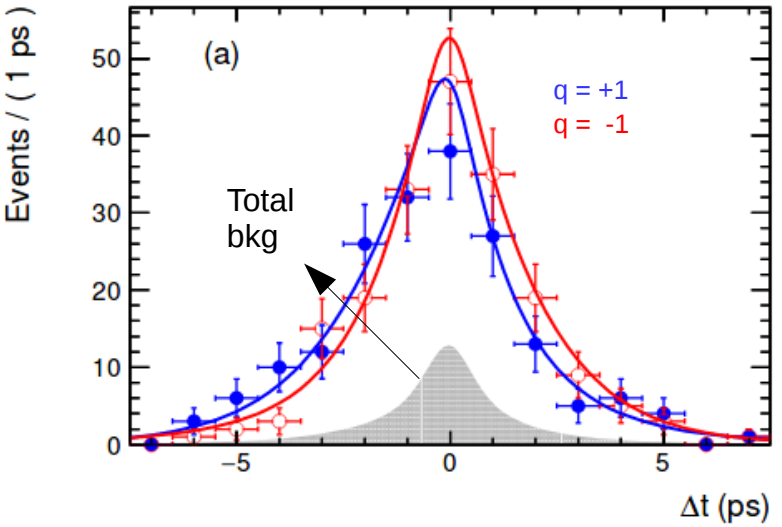


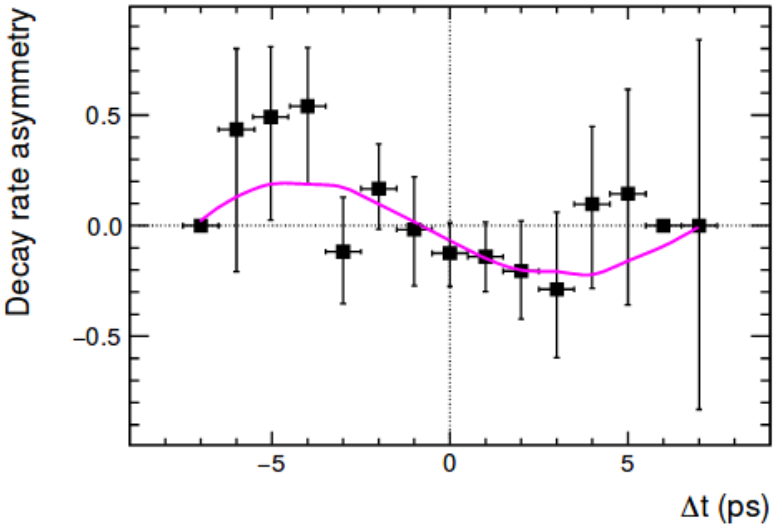
Measurements of S and A

$$\begin{aligned}\mathcal{P}_i(\Delta t) &= (1-f_{\rm ol})\int d(\Delta t')\Big[R_{\rm sig}(\Delta t_i-\Delta t')\times \\ &\Big(f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t')+f_{J/\psi K^0_S}\mathcal{P}_{J/\psi K^0_S}(\Delta t') \\ &+ f_{J/\psi K^0_L}\mathcal{P}_{J/\psi K^0_L}(\Delta t')+f_{J/\psi X}\mathcal{P}_{J/\psi X}(\Delta t')\Big) \\ &+ f_{q\bar{q}}\mathcal{P}_{q\bar{q}}(\Delta t_i)\Big]+f_{\rm ol}\mathcal{P}_{\rm ol}(\Delta t_i)\,, \qquad (3\end{aligned}$$

Outlier component described by a board Gaussian with small fraction.

$$\begin{aligned}\mathcal{S} &= -0.59\pm0.19\pm0.03 \\ \mathcal{A} &= -0.15\pm0.14\,^{+0.04}_{-0.03}\,,\end{aligned}$$

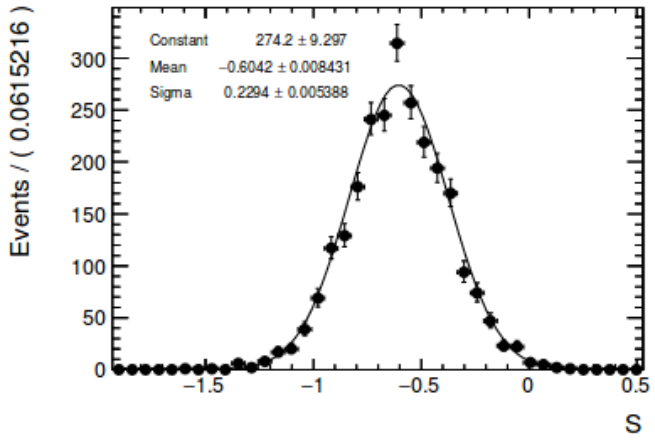


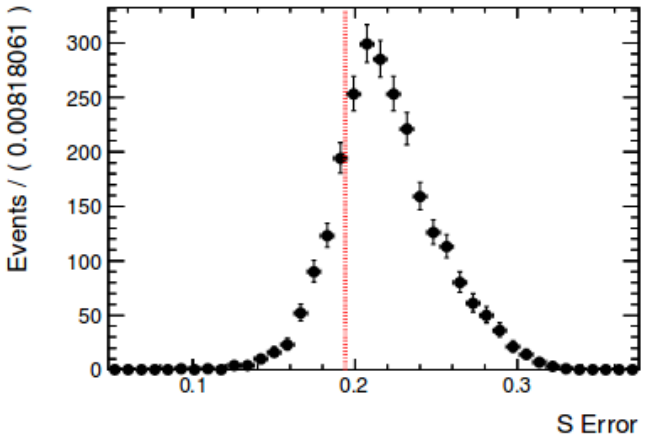


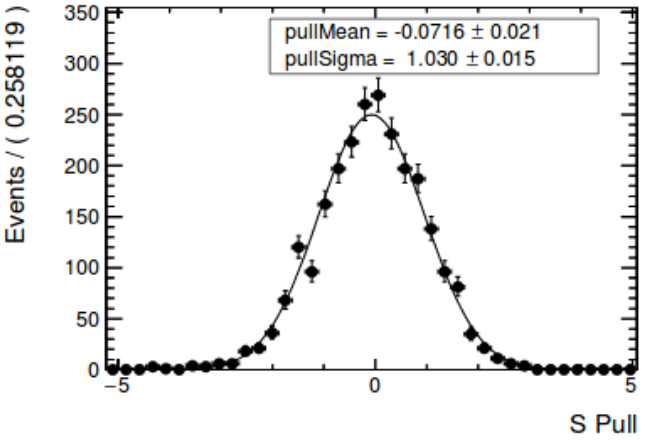
$$(Y_{\rm sig}^{(q=+1)}-Y_{\rm sig}^{(q=-1)})/(Y_{\rm sig}^{(q=+1)}+Y_{\rm sig}^{(q=-1)})$$

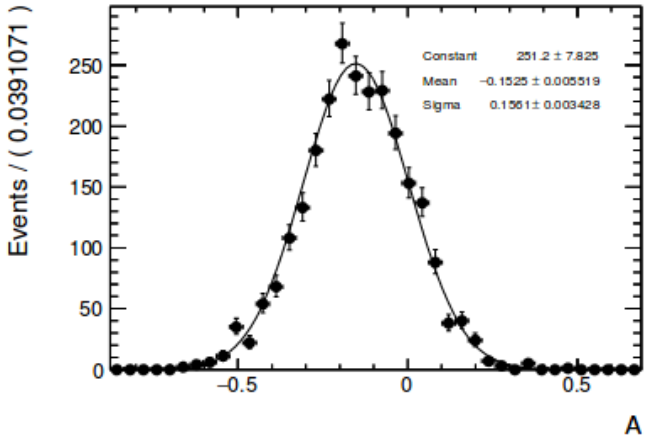
Toy simulations

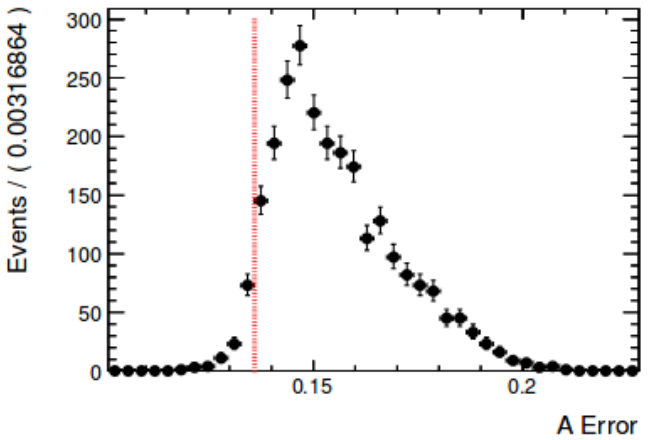
Toy simulations with 2500 pseudo-experiments

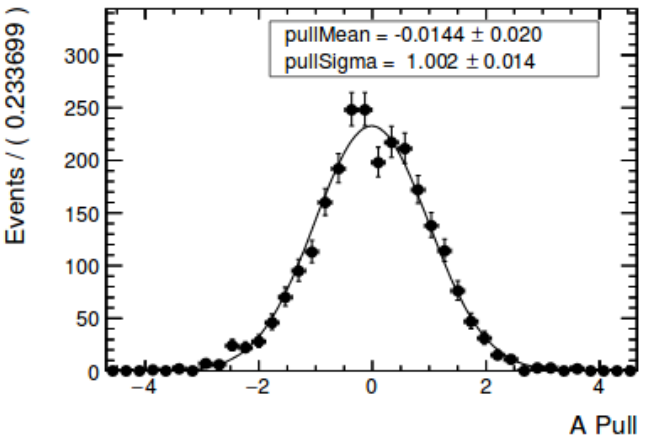












Systematic uncertainties

$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$
$$\mathcal{A} = -0.15 \pm 0.14 \,^{+0.04}_{-0.03},$$

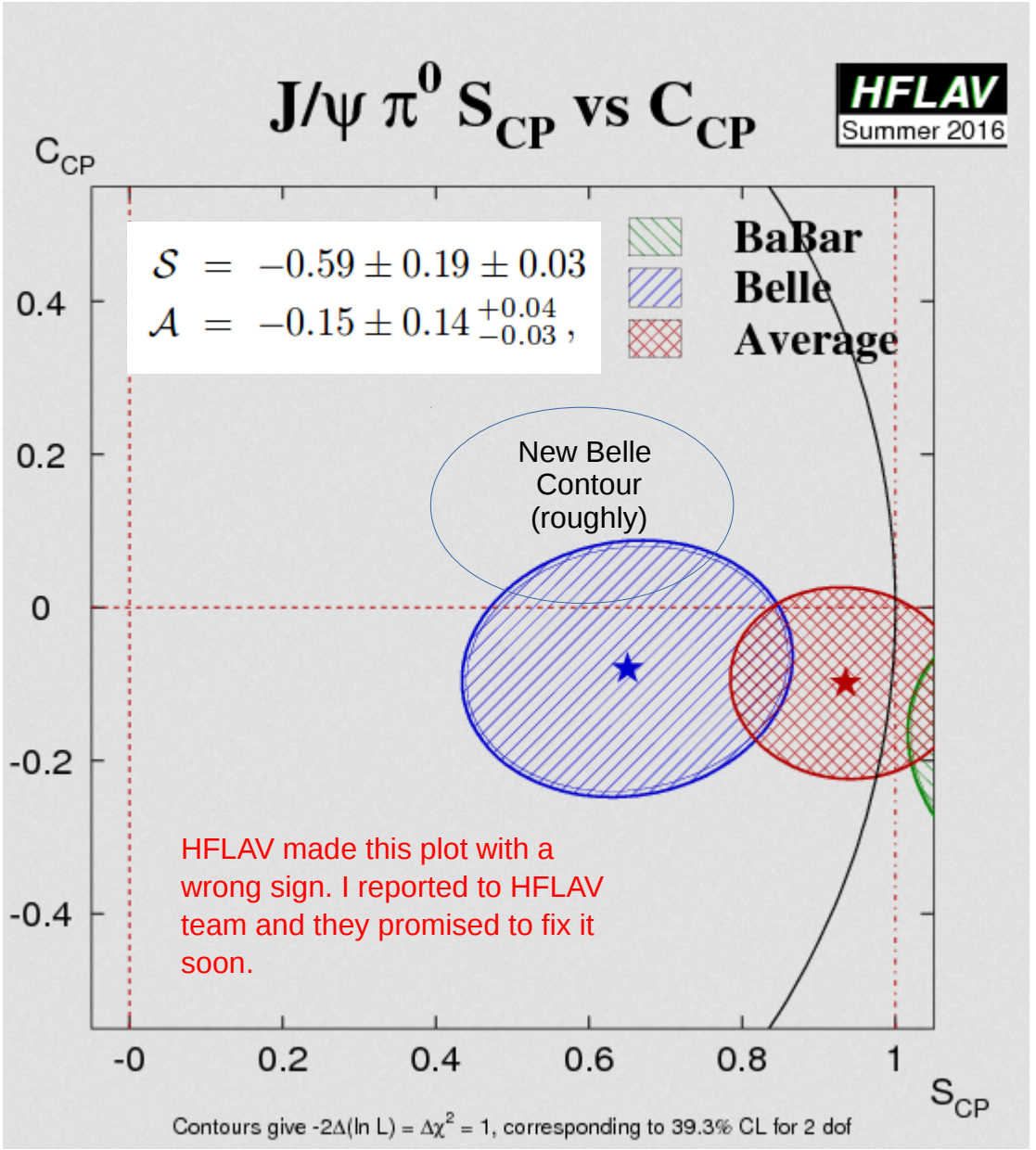
TABLE II. Absolute systematic uncertainties for $\mathcal{S}$ and $\mathcal{A}$.

Source	$\sigma_{\mathcal{S}}$ (%)	$\sigma_{\mathcal{A}}$ (%)
Vertex reconstruction	$^{+2.36}_{-1.75}$	$^{+1.40}_{-2.22}$
Resolution function	$^{+1.43}_{-2.37}$	$^{+1.00}_{-0.91}$
Physics parameters	$^{+0.04}_{-0.03}$	± 0.04
Fit bias	± 0.68	± 0.27
Wrong tag fraction	$^{+0.41}_{-0.20}$	$^{+0.43}_{-0.17}$
$M_{\rm bc} - \Delta E$ shape	$^{+0.52}_{-0.45}$	$^{+0.50}_{-0.48}$
Signal and background fraction	$^{+0.71}_{-0.62}$	$^{+0.49}_{-0.72}$
Background Δt shape	$^{+0.20}_{-0.12}$	± 0.10
Tag side interference	± 0.20	$^{+3.80}_{-0.00}$
Total	$^{+3.02}_{-3.14}$	$^{+4.26}_{-2.57}$

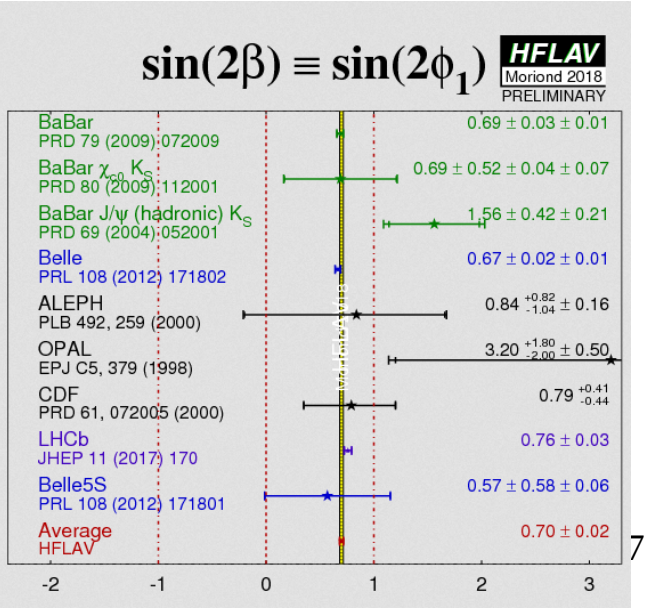
Results from previous Belle analysis, PRD 77, 071101 (2008) (R)

$$\mathcal{S}_{J/\psi\,\pi^0} = -0.65 \pm 0.21(\text{stat}) \pm 0.05(\text{syst}) \text{ and}$$
$$\mathcal{A}_{J/\psi\,\pi^0} = +0.08 \pm 0.16(\text{stat}) \pm 0.05(\text{syst}),$$

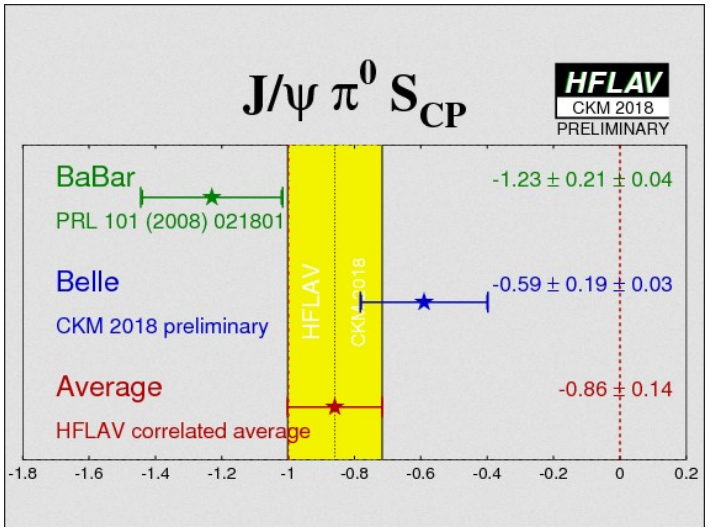
Measurements of S and A: discussions

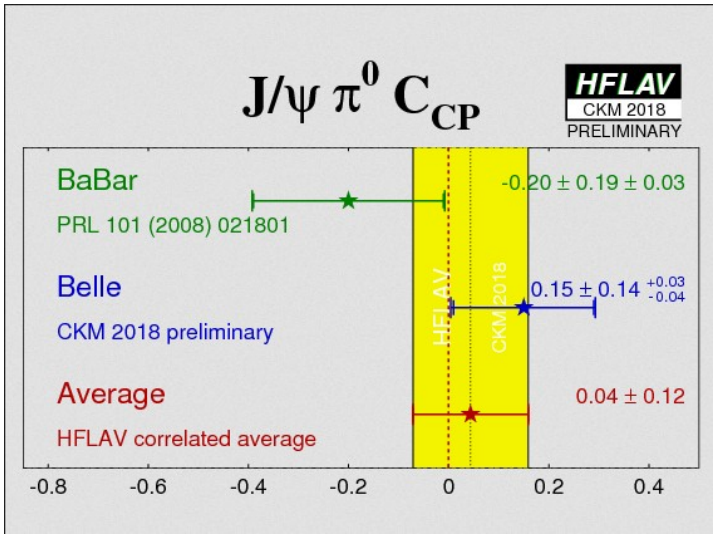


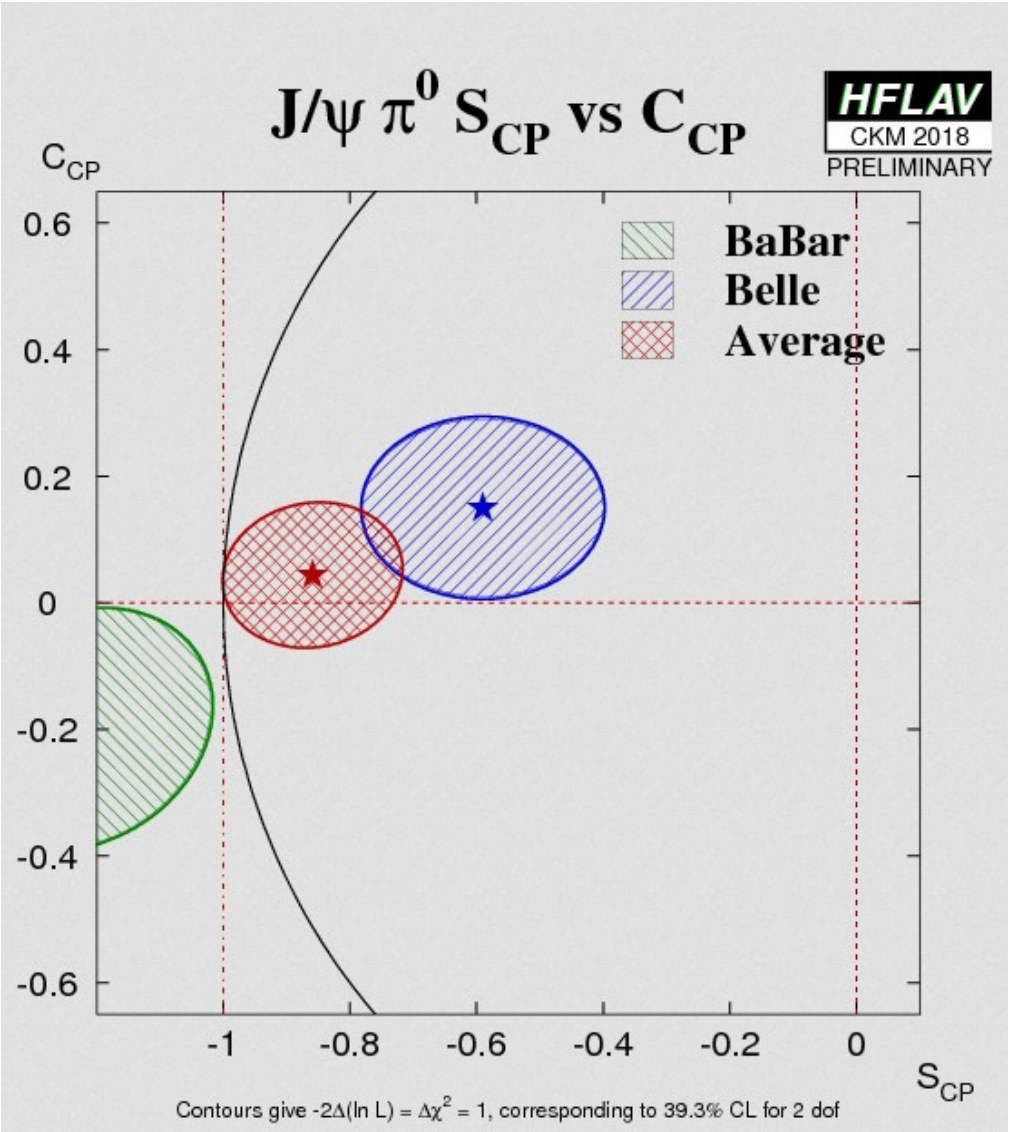
- Our measured CP asymmetries are consistent with and supersede our previous measurements.
- S differs from zero by 3.0 standard deviations
  - We also differ from BaBar by 3.2 standard deviations
- Our measured value is consistent with the measurements from $b \to ccs$ channels



Measurements of S and A: discussions







Post CKM2018 Update; updated yesterday

What next?

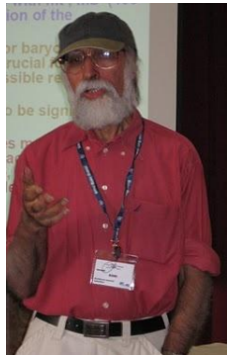
- Uncertainties are still large to resolve the disagreement between two experiments
  - Need more precise measurements
    - The Belle II is expected to reach a sensitivity to $\delta S \sim 0.027$ [The Belle II Physics Book, arXiv:1808.10567[hep-ex]]
      - Sensitivity of this order is sufficient for controlling the penguin pollution in the golden channel $B^0 \to J/\psi\, K_S$

  - Need measurements from other $b \to$ ccd transitions
    - Potential decay modes are
      - $B^0 \to \psi(2S)\pi^0$
      - $B^0 \to J/\psi\eta^{(\prime)}$
      - $B^0 \to \chi_{c1}\pi^0$
  - Most of these decay modes are difficult in LHCb [neutral pion in the final state]

The need for more precision

"Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

- A. Soni at SuperKEKB Proto - collaboration meeting (2008)



Flashback: A lesson from history

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \to \pi^+\pi^-$ event among 600 decays into charged particle (Anikira et al, JETP 1962). At that stage the search was terminated by the administration of the Lab. The groupo was unlucky.

Approximately at the level 1/1350 the effect was discovered by J. Christensen, J. Cronin, V. Fitch and R. Turlay at Brookhaven in 1964 in an Experiment the main goal of which was $K_L - K_S$ regeneration in matter."

- Lev Okun, arXiv:hep-ph/011203

A failure of imagination? Lack of patience?

Summary

- Recent measurements of branching fraction and time-dependent CP asymmetries of the decay $B^0 \to J/\psi\pi^0$ using full set of Belle data are discussed
  - The branching fraction is measured to be [1.62 ± 0.11 ± 0.07] x 10^{-5}; to date this is the most precise measurement and is consistent with all previous measurements
  - The measured CP asymmetries are

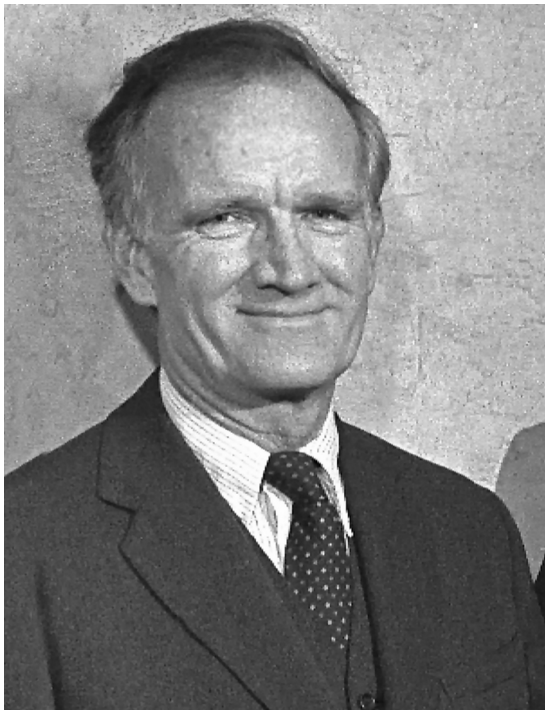
$$\begin{aligned} \mathcal{S} &= -0.59 \pm 0.19 \pm 0.03 \\ \mathcal{A} &= -0.15 \pm 0.14 \,^{+0.04}_{-0.03}\,, \end{aligned}$$

    They are consistent with and supersede our previous results. Mixing-induced CP asymmetry S differs from BaBar result by 3.2 sigma.
  - We need more precise measurements to resolve this discrepancy; measurements from high luminosity Belle II experiments will hopefully clarify this unsatisfactory situation.

Wise words from one of the discoverers of CP violation

At any one time there is a natural tendency among physicists to believe that we already know the essential ingredients of a comprehensive theory. But each time a new frontier of observation is broached we inevitably discover new phenomena which force us to modify substantially our previous conceptions. I believe this process to be unending, that the delights and challenges of unexpected discovery will continue always.

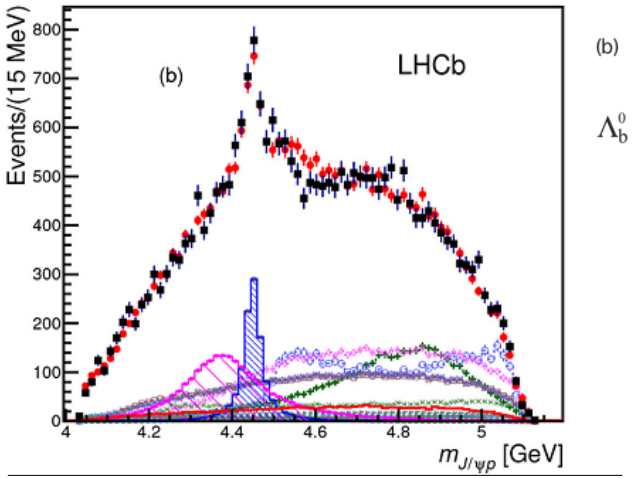
- Val Fitch, Nobel Prize Speech 1980

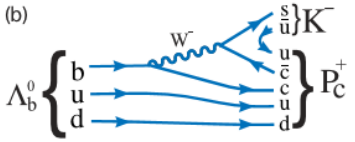


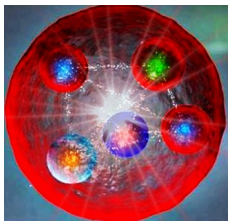
Val Fitch, who shared the 1980 Nobel Prize in Physics for a discovery made at Brookhaven Lab's Alternating Gradient Synchrotron (AGS)


EXTRA!
EXTRA!

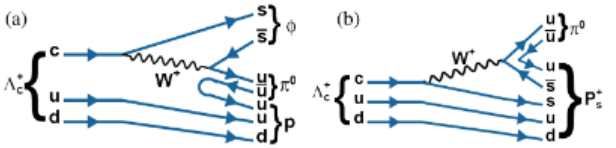
In 2015 LHCb reported the existence of two hidden-charm pentaquarks in the P_c → $J/\Psi p$ intermediate state of $\Lambda_b \to J/\Psi p K^-$ decays. [PRL, 115, 072001 (2015)]

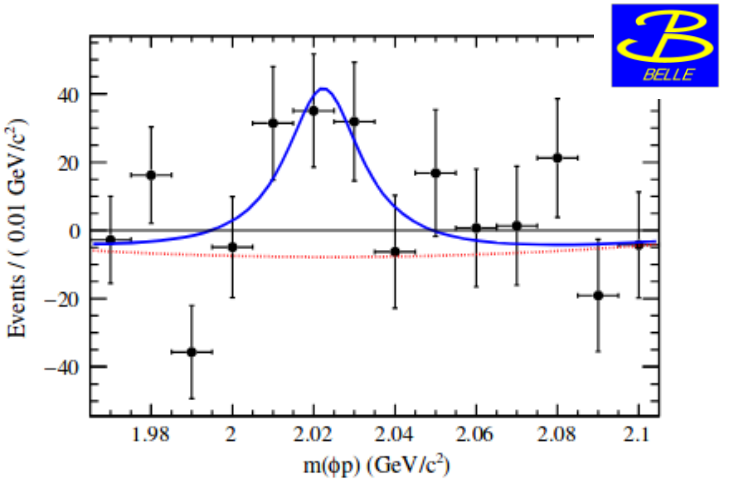






This triggered us to search for hidden-strangeness siblings of P_c in the Φp intermediate state of $\Lambda_c \to \Phi p \pi^0$

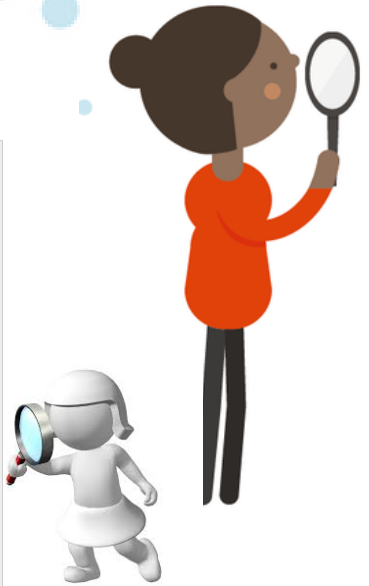




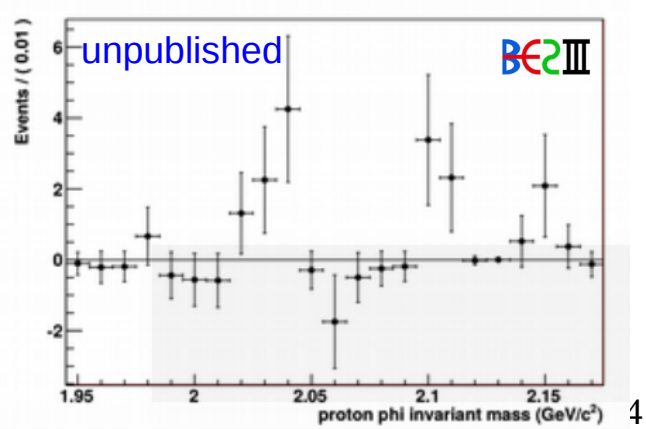
Significance ~2.2 standard deviations.
[PRD, 96, 051102(2017) (R)]

There are many suggested channels for LHCb, one of them is $\Lambda_b \to \Lambda_c D^0 K^-$.

G. Cowan and T. Gershon, Tetaquarks and Pentaquarks



- Recently a BNL Fall intern student started working on $\Lambda_c \to \Lambda K^- \pi^0$, this is similar to $\Lambda_b \to \Lambda_c D^0 K^-$
- This decay has not been studied yet theoretically or experimentally
- We expect to see this decay at Belle and search for the intermediate structures
- In any case, if no intermediate structure is found, we learn something about Λ_c decays.
- Gronau, Rosner [arXiv:1808.03720] suggested for more studies in Λ_c



https://agenda.infn.it/getFile.py/access?contribId=7&sessionId=0&resId=0&materialId=slides&confId=14612

$B^0 \to p\bar{p}\pi^0$

- Only few baryonic B decays are observed so far
  - Observed charmless baryonic B decays are even fewer
    - These decays proceed via $b \to u$ tree or $b \to d/s$ penguin transition (rare in SM)
  - Except for $B^+ \to p\Lambda\pi^0$, $p\Lambda\gamma$ all the channels are entirely reconstructed from charged particles in the final state
    - studying more channels with neutral particles in the final state will help us to understand the dynamics of the decays
- No experimental/theoretical study yet for $B^0 \to pp\pi^0$

- Using the known branching fractions of similar decays we estimate the branching of this decays: $B(B^0 \to p\bar{p}\pi^0) \sim 1 \times 10^{-6}$

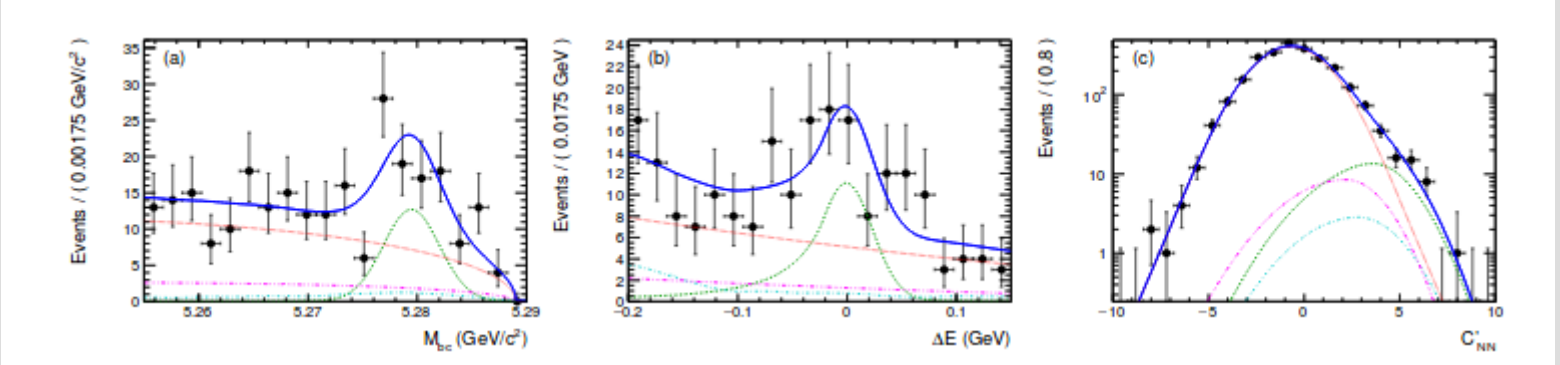
$$\begin{aligned}\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0) &= \mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^0)\left|\frac{V_{ub}}{V_{cb}}\right|^2 \times f_{\rm dyn} \\ &\approx (1.56 \times 10^{-6}) \times f_{\rm dyn}.\end{aligned}$$

$$\begin{aligned}\mathcal{B}(B^- \to p\bar{p}\pi^-) &= \mathcal{B}(B^- \to \Lambda_c^+ \bar{p}\pi^-)\left|\frac{V_{ub}}{V_{cb}}\right|^2 \times f_{\rm dyn} \\ \Rightarrow f_{\rm dyn} &\approx 0.72.\end{aligned}$$

- Branching fraction of this order is accessible at Belle
- Measurement of DCPV is one of the interest. But with this estimated Branching fraction, we expect <100 events. (Not good for DCPV, not a self tagging decay)

$B^0 \to p\bar{p}\pi^0$

- Only few baryonic B decays are observed so far
- Using the known branching fractions of
- This analysis is in review process with the internal Belle referees, fit to the data is not shown yet to referees, so I am not allowed to show them here. Following are the fit to simulated data normalized to expected signal and background components.



- No experimental/theoretical study yet for $B^0 \to p\bar{p}\pi^0$

for DCPV, not a self tagging decay)