Analysis of the decay channel $B^0 \to \psi(2S)\pi^0$ with Belle

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- Physics Motivation
- Study of the decay $B^0 \to \psi(2S)\pi^0$
- Summary and outlook

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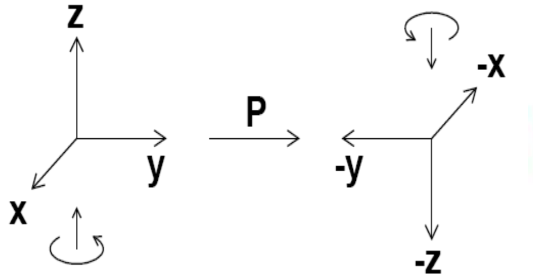
Physics Motivation

Matter-antimatter Asymmetry – **CP** Violation

CP is a product of two symmetries

C (charge conjugation) and

P (parity)



CP violation in the Standard Model ⇒ Cabibbo-Kobayashi-Maskawa (CKM)mechanism ⇒ relation between the weak and the mass eigenstates

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

V_{ij} : quark flavor transition couplings

CP Violation in the Standard Model

Wolfenstein parametrization

$\lambda = \sin\theta_C \approx 0.22 (Cabibbo \quad angle)$

4 free parameters:

- 3 real parameters
- 1 complex phase

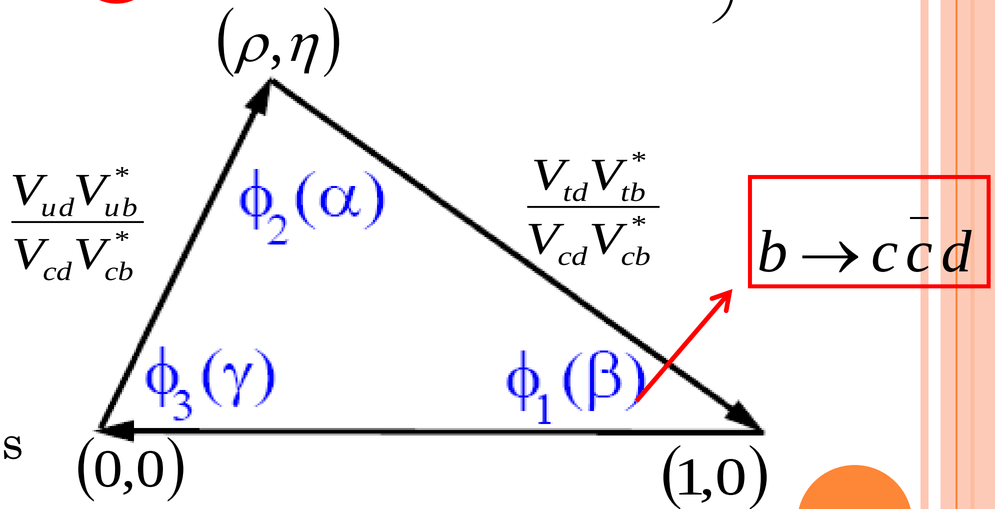
$$V^{CKM} = \begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & -A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

CKM matrix is unitary

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

$O(\lambda^3)$ $O(\lambda^3)$ $O(\lambda^3)$

relevant for the B meson system

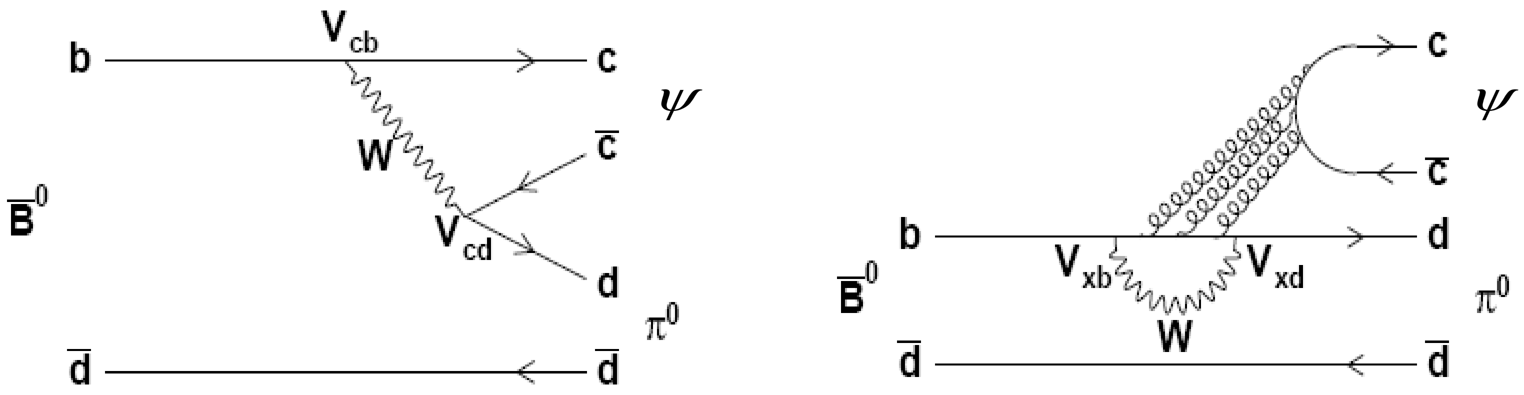


Sides with similar size ⟶ large angles

5 observables (2 sides, 3 angels)

Confirm SM or hint for New Physics

$B^0 \to \psi(2S)\pi^0 \; (b \to (c\bar{c})d)$



$$M_{tree} \propto V_{cb} * V_{cd}^{*} \propto \lambda^2 * \lambda \propto \lambda^3 \qquad M_{penguin} \propto V_{tb} * V_{td}^{*} \propto \lambda^3 * 1 \propto \lambda^3$$

Matrix elements

Additional motivation to study charmonium $b \to (c\bar{c})d$

Using the result from $B^0 \to \psi(2S)\pi^0$ and SU(3) symmetry the penguin pollution to $B^0 \to \psi(2S)K_S^0$ can be estimated

For the tree amplitude

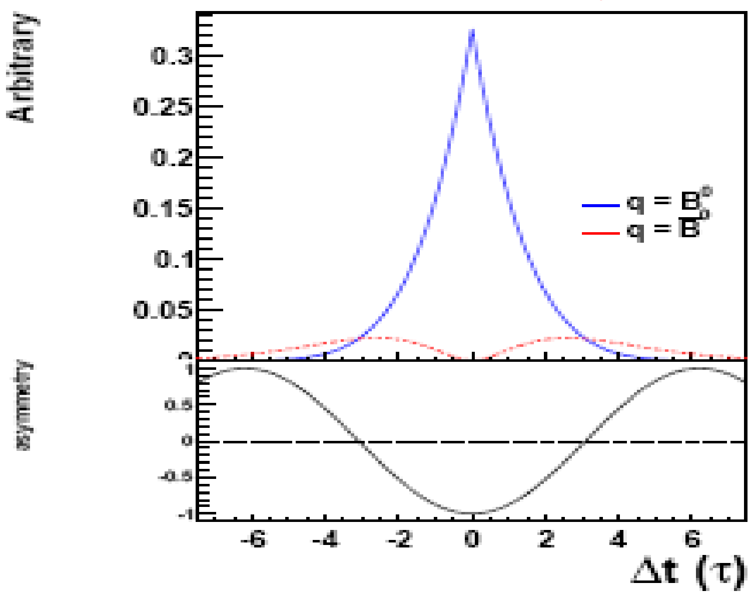
- $A_{CP} = 0$
- $S_{CP} = \sin 2\phi_1$

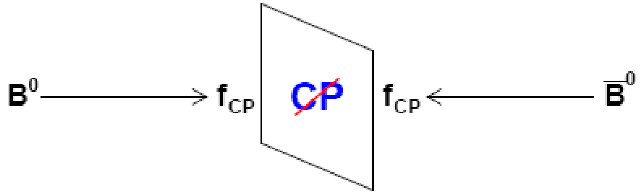
CP Violation in the B meson system

Time-dependent CP asymmetry

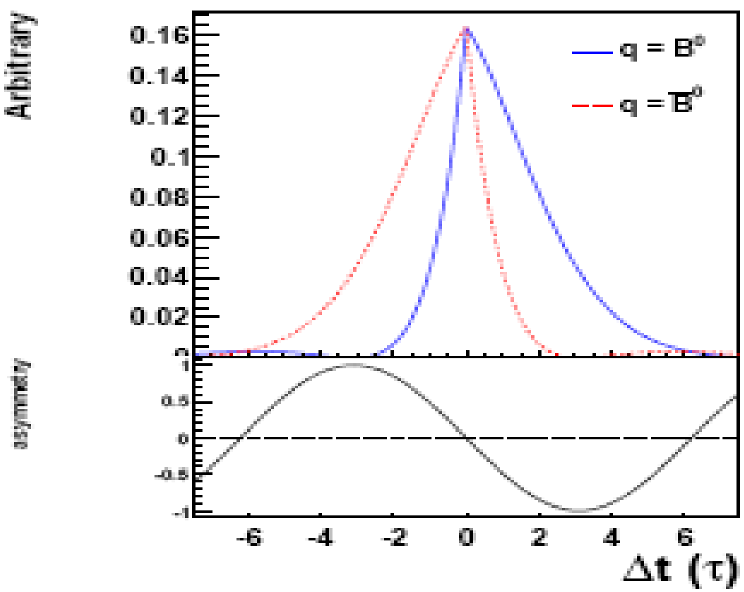
$$a_{CP}(\Delta t, f_{CP}) = \frac{N_{\bar{B}^0}(\Delta t, f_{CP}) - N_{B^0}(\Delta t, f_{CP})}{N_{\bar{B}^0}(\Delta t, f_{CP}) + N_{B^0}(\Delta t, f_{CP})} = A_{CP}\cos(\Delta m \Delta t) + S_{CP}\sin(\Delta m \Delta t)$$

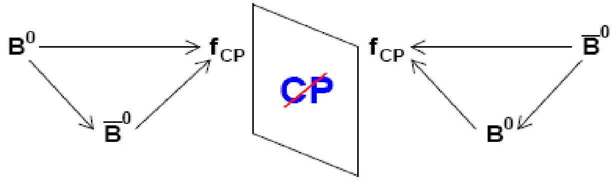
A_{CP} ➡ **direct** CP violation
different decay rates





S_{CP} ➡ **indirect** CP violation
different time evolution





B Meson Production

Υ(4S) resonance decays ➡ into $B\bar{B}$ pair

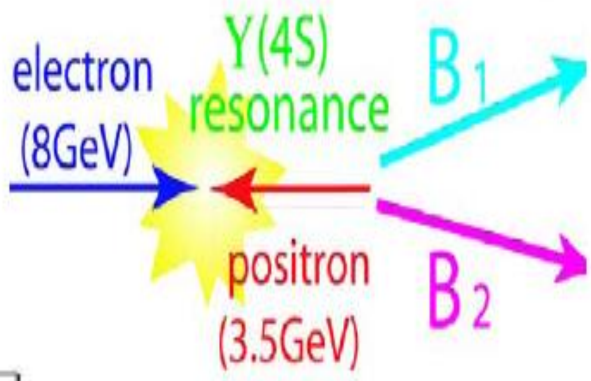
Υ(4S): $J^{PC} = 1^{--}$

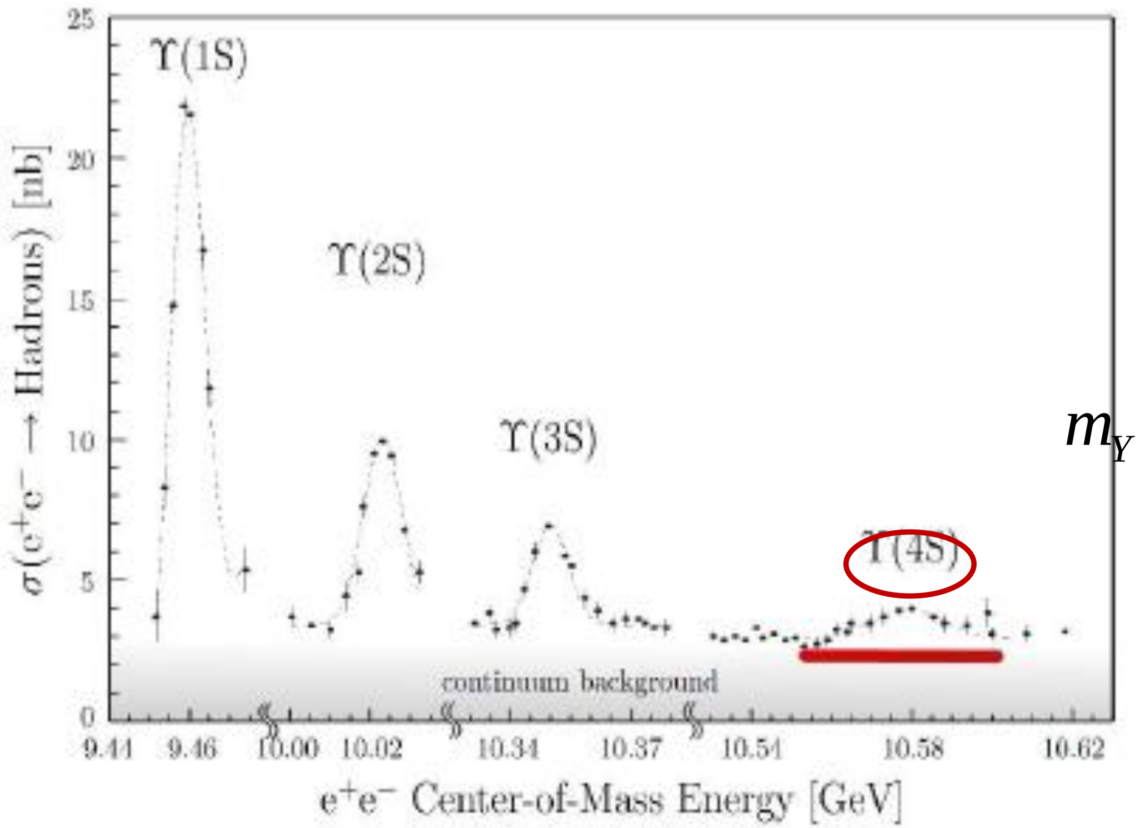
B: $J^{P} = 0^{-}$

➡ B meson pair in a p-wave

Asymmetric wave function

➡ B mesons have opposite flavor



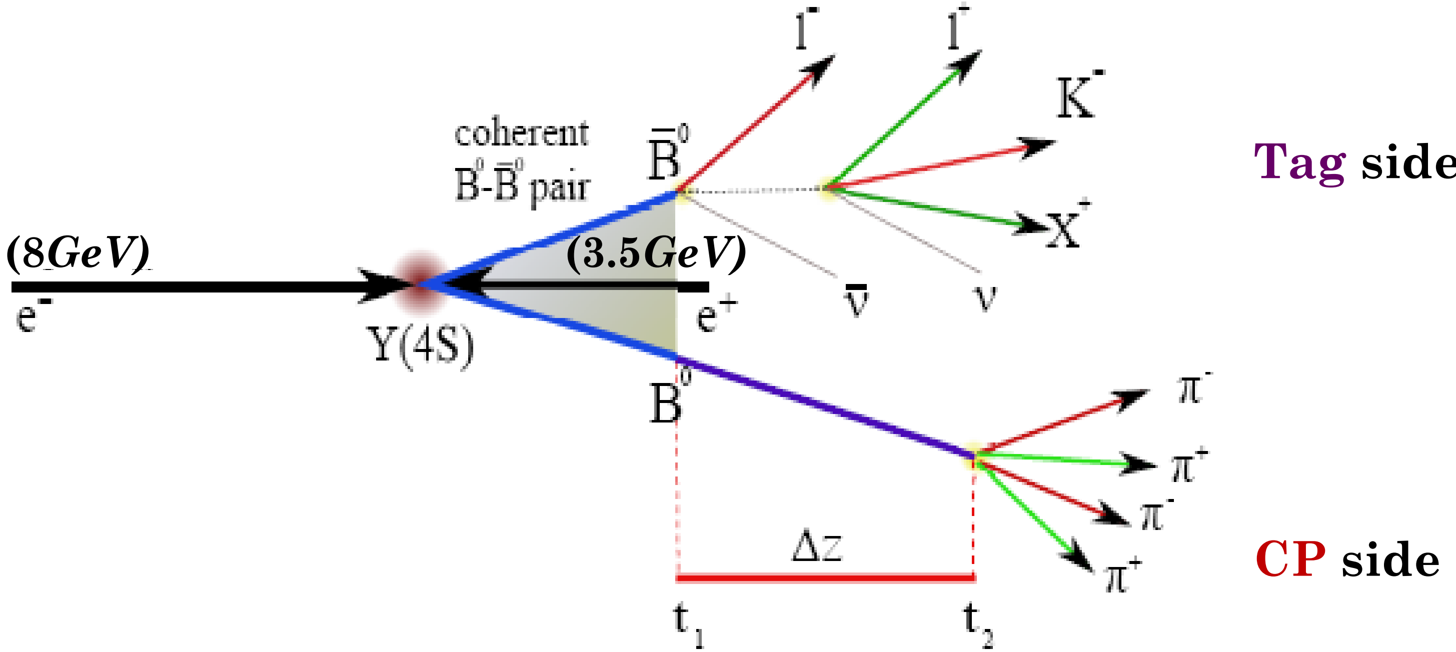


B meson pair in an entangled state

$$m_{Y(4S)} = 10.58 GeV/c^2 \approx 2 \times m_B$$

$$m_B = 5.28 GeV/c^2$$

CP Violation Measurement Principle



How to distinguish between B^0 **and** $\bar{B}^0$ **?**

- if l^- ⟹ $\bar{B}^0$ on the Tag side
  ⟹ B^0 on the CP side
- if l^+ ⟹ $\underline{B}^0$ on the Tag side
  ⟹ B^0 on the CP side

Measurement of the time difference

$\Delta z \sim 100\mu m \Rightarrow \Delta t \sim ps$

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

Reconstruction of $B^0 \to \psi(2S)\pi^0$

$B^0 \to \psi(2S)\pi^0$

$\psi(2S) \to e^+e^-, \mu^+\mu^-, J/\psi\pi^+\pi^-$

$\pi^0 \to \gamma\gamma$

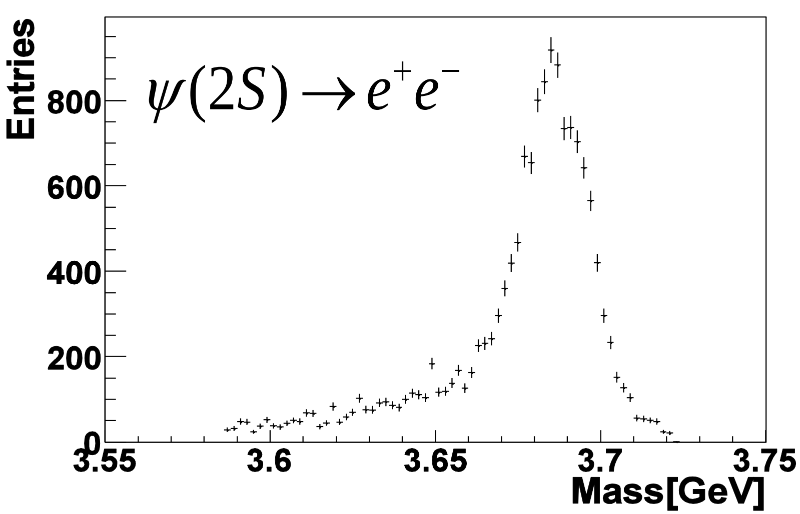
$J/\psi \to e^+e^-, \mu^+\mu^-$

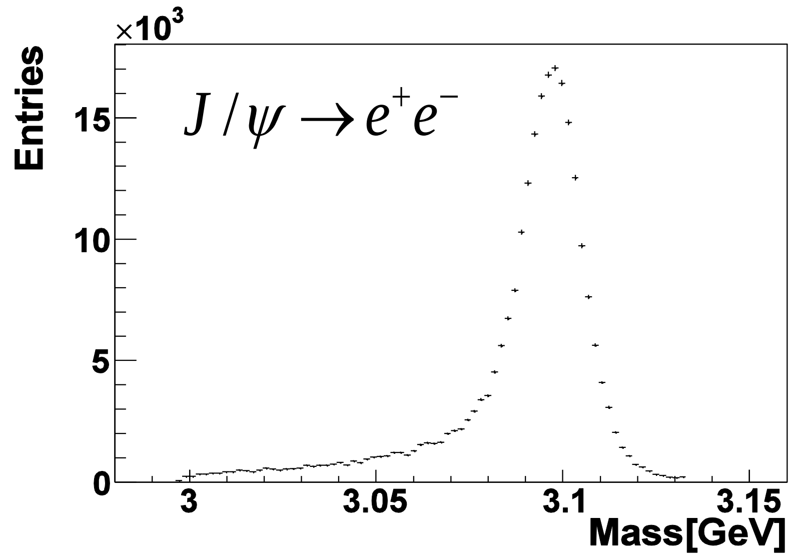
Selection criteria for the data sample:

- $|dz| < 5cm$
- $|dr| < 1.5cm$
- $R_2 < 0.5$ to suppress continuum background

For the e^+e^- decay mode:

$$-150 \leq M_{e^+e^-} - M_{\psi(2S)(J/\psi)} \leq 36 MeV/c^2$$

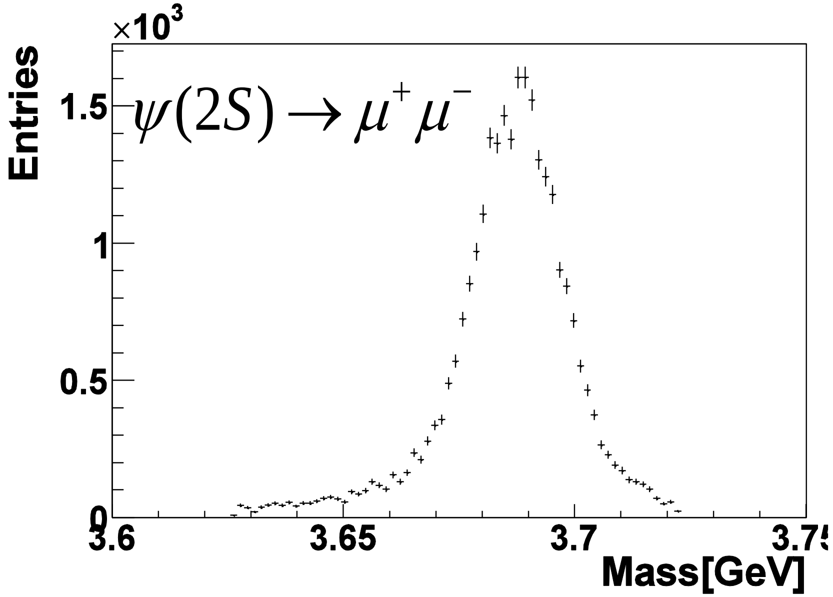


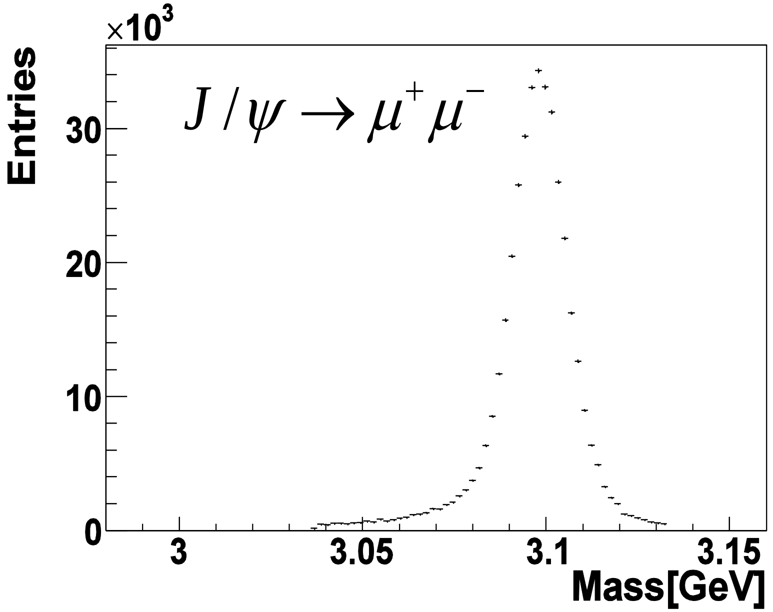


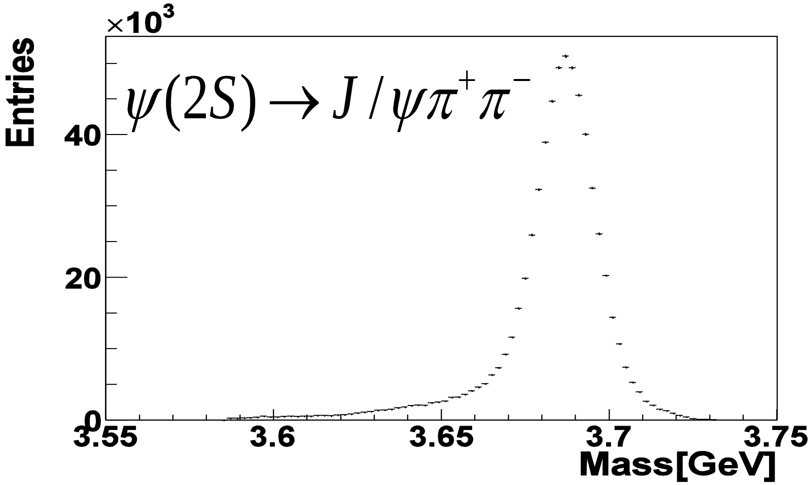
Reconstruction of $B^0 \to \psi(2S)\pi^0$

For the $\mu^+\mu^-$ decay mode:

$$-60 \le M_{\mu^+\mu^-} - M_{\psi(2S)(J/\psi)} \le 36 MeV/c^2$$



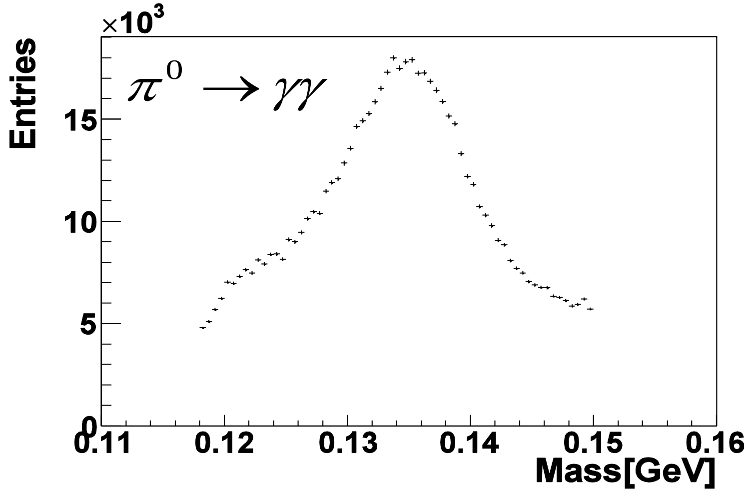




Reconstruction of $B^0 \to \psi(2S)\pi^0$

For the π^0 selection:

$E_\gamma > 0.05 GeV \quad (Barrel)$
$E_\gamma > 0.10 GeV \quad (Endcap)$
$\cos\theta < 0.95$
$0.115 GeV/c^2 < m_{\gamma\gamma} < 0.152 GeV/c^2$



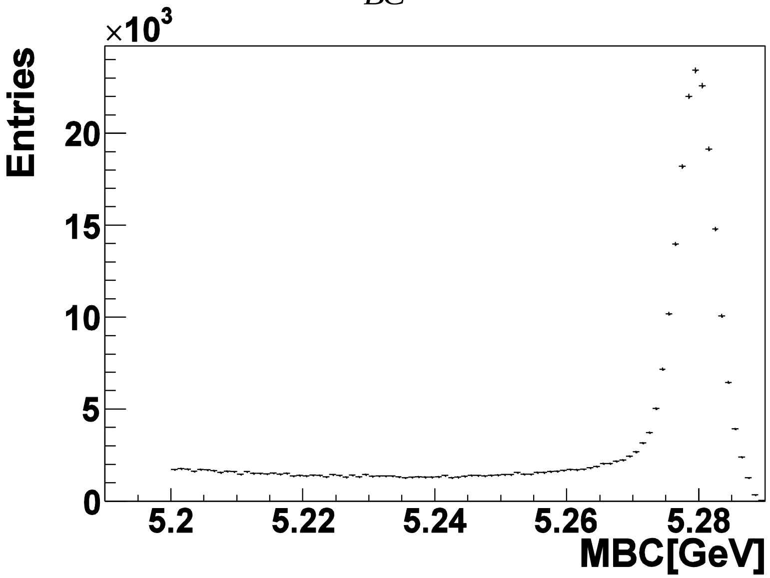
Reconstruction of the B mesons:

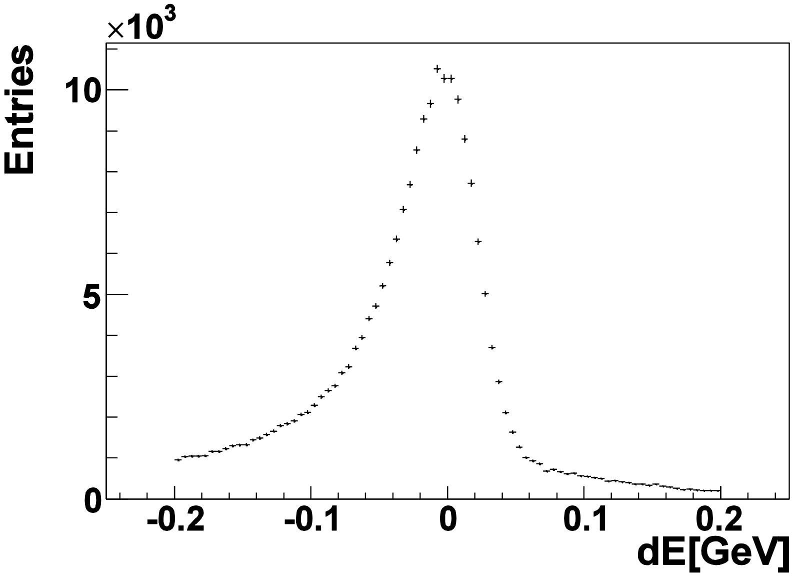
$$M_{BC} = \sqrt{(E_{beam}^{CMS})^2 - (p_B^{CMS})^2}$$

$5.2 GeV/c^2 < M_{BC} < 5.3 GeV/c^2$

$$\Delta E = E_B^{CMS} - E_{beam}^{CMS}$$

$-0.2 GeV < \Delta E < 0.2 GeV$





Summary and outlook

- $B^0 \to \psi(2S)\pi^0$ is one of the "golden" modes due to its clean experimental signature and relatively small background
- $b \to (c\bar{c})d$ transition is sensitive to ϕ_1
- Reconstruction procedure completed
- Measure the branching fraction
- World's first measurement