

CP Violation Sensitivity Study of $B^0 \rightarrow \pi^0 \pi^0$ at the Belle II Experiment

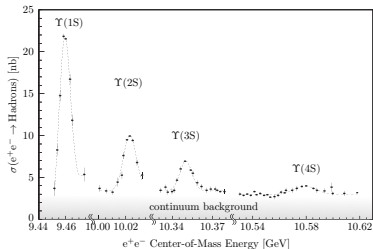
Fernando Abudinén

21. April, 2017

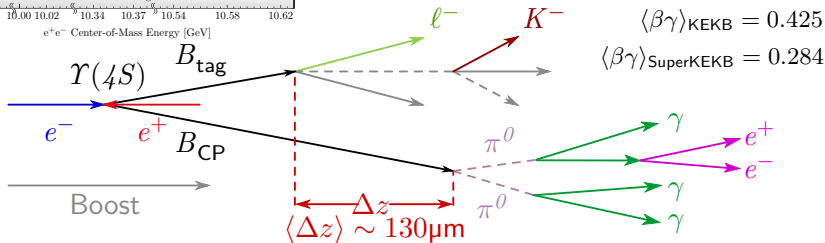
- 1 Time-dep. CP-Analysis
- 2 B^0 Selection and Efficiency
- 3 Toy MC Results
- 4 Extraction of ϕ_2 from $B \rightarrow \pi\pi$
- 5 Summary and Outlook



Max-Planck-Institut
für Physik



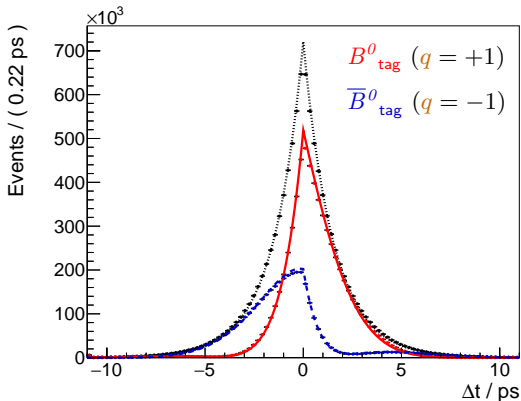
- $\Upsilon(4S)$ above $B\bar{B}$ prod. threshold
- ⇒ B-Factory
- $\sim 51\%$ are B^+B^-
- $\sim 49\%$ are $B^0\bar{B}^0$



- $B^0\bar{B}^0$ at rest in CMS $\Delta t = \frac{\Delta z}{\langle \beta \gamma \rangle c} \Rightarrow$

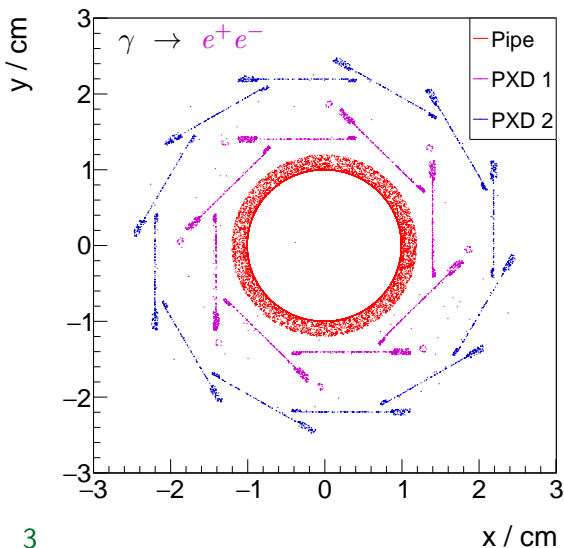
$$\mathcal{P}^{\text{Sig}}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q(\mathcal{A}_{CP} \cos(\Delta m \Delta t) + \mathcal{S}_{CP} \sin(\Delta m \Delta t))]$$

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



- $\mathcal{A}_{CP}^{\pi^0\pi^0} = 0.44$ (PDG)

- $\mathcal{S}_{CP}^{\pi^0\pi^0} = \sqrt{1 - \mathcal{A}_{CP}^2} \sin 2 \cdot (\alpha - \Delta\alpha^*) \approx 0.78$



- $\Upsilon(4S) \rightarrow B^0_1 B^0_2 \rightarrow B_1 \rightarrow \text{generic} B_2 \rightarrow \pi^0 \pi^0$
- $\pi^0_{\gamma\gamma} \rightarrow \gamma\gamma$ ($\mathcal{B} = 98.82\%$)
- $\pi^0_{\text{dal}} \rightarrow e^+ e^- \gamma$ ($\mathcal{B} = 1.17\%$)
- $N_{\text{Belle II}} =$
 - $\mathcal{L}_{\text{Belle II}} \cdot \mathcal{B}(\Upsilon(4S) \rightarrow B^0 \bar{B}^0)$
 - $\cdot 2 \cdot \mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) \sim$
 - $50 \text{ab}^{-1} \cdot 1.1 \text{nb} \cdot 0.49$
 - $\cdot 2 \cdot 1.91 \cdot 10^{-6}$

$\sim 100\text{k}$ events.
- Accept.: $\theta \in [17, 150]^\circ$
- ECL: $\theta \in [12.4, 155.1]^\circ$

$$1 \quad B^0 \rightarrow \pi^0 \gamma \pi^0 \gamma \pi^0 \gamma \gamma$$

$$2 \quad B^0 \rightarrow \pi^0_{\text{dal}} (\rightarrow e^+ e^- \gamma) \pi^0 \gamma \gamma$$

$$3 \quad B^0 \rightarrow \pi^0_{\gamma_c \gamma} (\rightarrow \gamma (\rightarrow e^+ e^-) \gamma) \pi^0 \gamma \gamma$$

Reconstruction of π^0 s:

- γ Selection: $E_\gamma > 50$ MeV (Barrel)
 $E_\gamma > 100$ MeV (Front)
 $E_\gamma > 150$ MeV (Back)

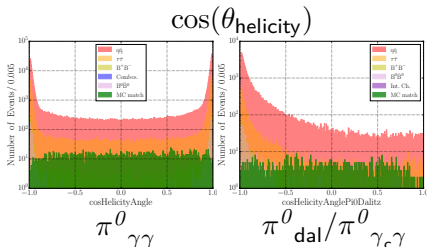
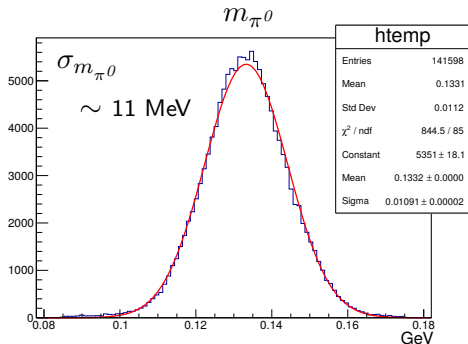
- e^\pm Selection: $d_0 < 0.25$ cm

- At least one PXD hit (e^+ or e^-)

- $m_{\pi^0} \in [105, 165]$ MeV $\sim \pm 2.5 \cdot \sigma_{m_{\pi^0}}$

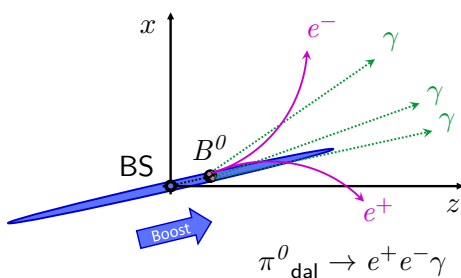
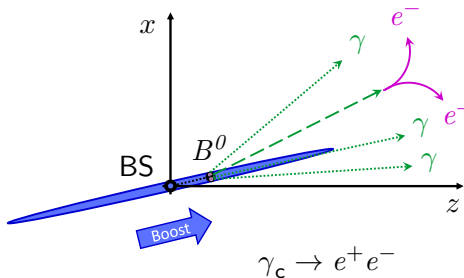
- $|\cos(\theta_{\text{helicity}})| < 0.95$

4

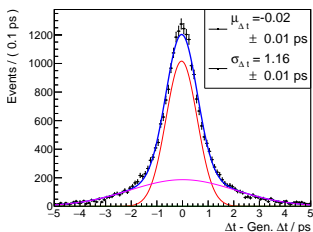


- Vertex Reconstruction with **iptube** constrain.
 - If conversion in beam pipe and e^\pm with PXD hits
- $\Rightarrow \pi_c^0$ and π_{dal}^0 kinematically indistinguishable.

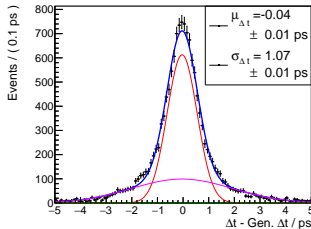
- $\tau_{\pi^0} \sim 0.9$ as $\cong 0.1$ nm
- $\Rightarrow \pi^0$ Vertex $\hat{=}$ B^0 Vertex.
- Check with MC truth.



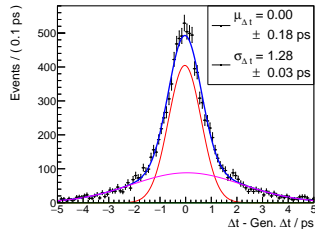
Reconstructed as $B^0_{\text{dal}} \rightarrow \pi^0 \gamma \pi^0_{\text{dal}}$
 $\hookrightarrow e^+ e^- \gamma$



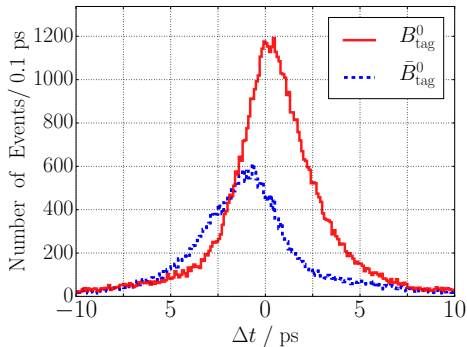
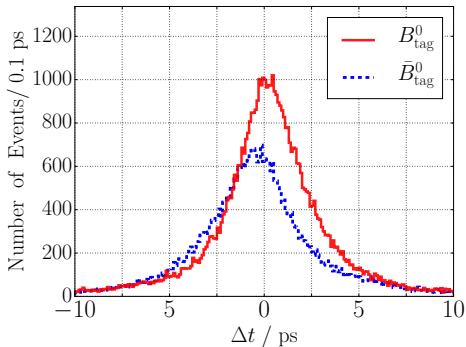
Dalitz and
Conversion case



Only Dalitz
(58% of Events)



Only Conversion
(42% of Events)



$q \cdot r$

$\epsilon_{\text{Eff}}(\text{Belle II}) = 35\%$

$\epsilon_{\text{Eff}}(\text{Belle}) = 29\%$

MC Flavor

- $m_{bc} = \sqrt{E_{\text{beam}}^*{}^2 - \mathbf{p}_{B^0}^2}$
 $> 5.26 \text{ GeV}/c^2$

- $\Delta E = E_{\text{beam}}^* - E_{B^0}$
 $\in [-0.3, 0.2] \text{ GeV}$

- Continuum Suppr.
 $y_{\text{FBDT}} > 0.976$

⇒ Maximizes $\frac{n_{\text{sig}}}{\sqrt{n_{\text{sig}} + n_{\text{bkg}}}}$

- Flavor Dilution
 $r > 0.1$

- Multiplicity $\lesssim 1.01$

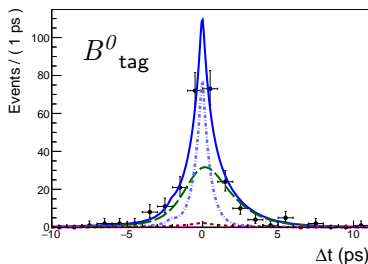
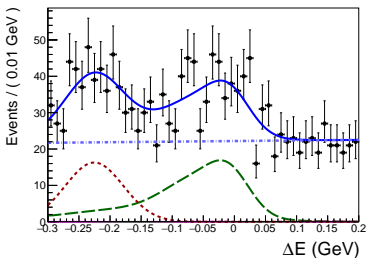
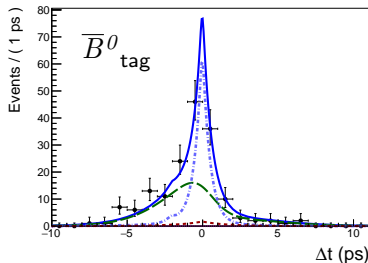
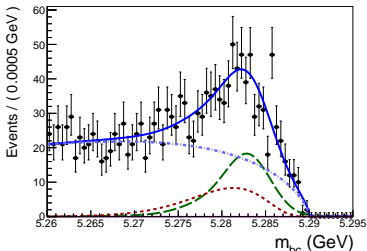
⇒ Ranking according to Dilution

Decay. Channel	$\frac{n_{\text{acc}}}{n_{\text{gen}}}$ [%]	$\frac{n_{\text{rec}}}{n_{\text{acc}}}$ [%]	$\frac{n_{\text{rec}}^{\text{FS}}}{n_{\text{acc}}}$ [%]
$B^0 \rightarrow \pi^0_{\text{dal}} \pi^0_{\gamma\gamma}$	2.0	52.0	7.0
$B^0 \rightarrow \pi^0_{\gamma\gamma} \pi^0_{\gamma\gamma}$	3.0	48.8	4.0
Dal + Conv	5.0	50.1	5.2
$B^0 \rightarrow \pi^0_{\gamma\gamma} \pi^0_{\gamma\gamma}$	76.2	86.0	19.2

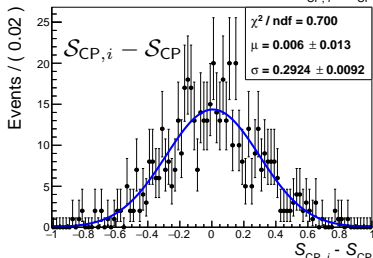
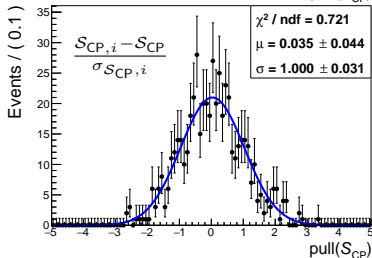
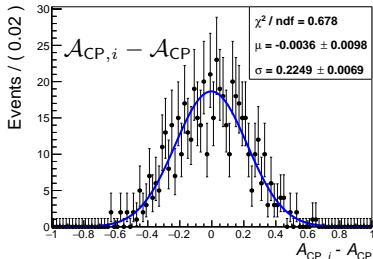
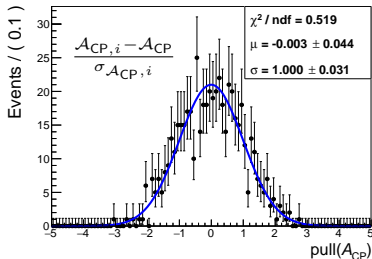
Decay. Channel	Purity [%]	$\frac{n_{\text{combin}}}{n_{\text{sig}} + n_{\text{comb}}}$ [%]
Dal + Conv	17.7	0.8
$B^0 \rightarrow \pi^0_{\gamma\gamma} \pi^0_{\gamma\gamma}$	15.8	1.0

$$\text{Purity} = \frac{n_{\text{sig}}}{n_{\text{sig}} + n_{\text{combin}} + n_{\text{cont}} + n_{B\bar{B}}}$$

$$B^0 \rightarrow \pi^0(\rightarrow e^+e^-\gamma)\pi^0(\rightarrow \gamma\gamma)$$

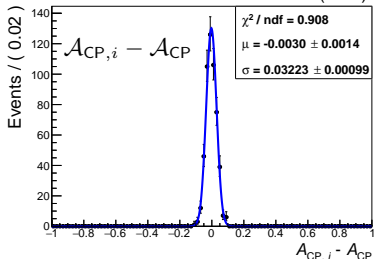
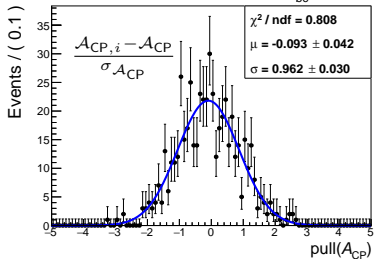
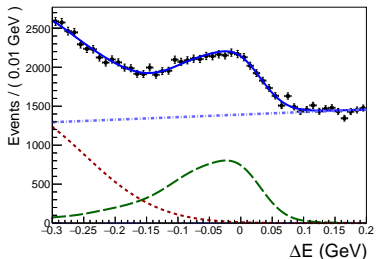
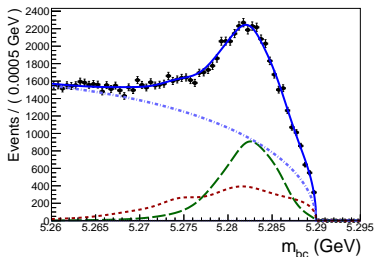


$$B^0 \rightarrow \pi^0 (\rightarrow e^+ e^- \gamma) \pi^0 (\rightarrow \gamma \gamma)$$

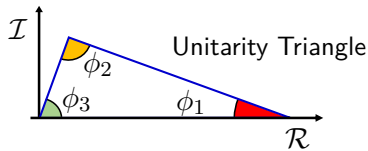


$$\Rightarrow \Delta \mathcal{S}_{CP}(\text{stat}) = 0.29$$

$$B^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow \gamma\gamma)$$



$$\Rightarrow \Delta \mathcal{A}_{CP}(\text{stat}) = 0.03$$



■ $\phi_2 = \phi_2^{\text{poll}} - \Delta\phi_2$

⇒ Extr. $\Delta\phi_2$ through isospin analysis:

$$A^{+-} = A(B \rightarrow \pi^+\pi^-)$$

1 $\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$

2 $\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$

■ Isospin analysis input:

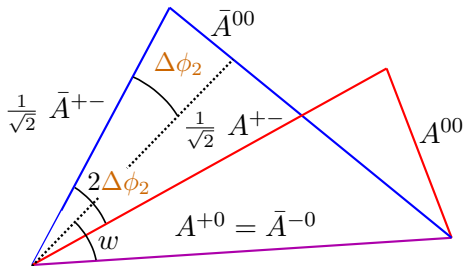
$$\mathcal{B}(B^0 \rightarrow \pi^+\pi^-), \mathcal{B}(B^0 \rightarrow \pi^0\pi^0), \mathcal{B}(B^+ \rightarrow \pi^+\pi^0)$$

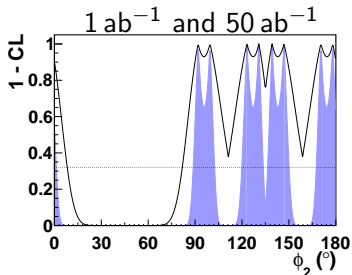
$$\mathcal{A}_{\text{CP}}(B^0 \rightarrow \pi^+\pi^-), \mathcal{S}_{\text{CP}}(B^0 \rightarrow \pi^+\pi^-),$$

$$\mathcal{A}_{\text{CP}}(B^0 \rightarrow \pi^0\pi^0), [\mathcal{S}_{\text{CP}}(B^0 \rightarrow \pi^0\pi^0)]$$

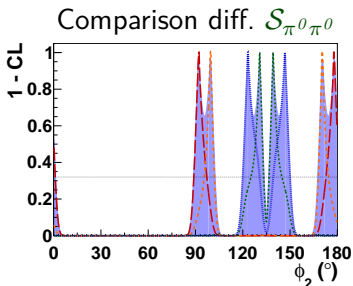
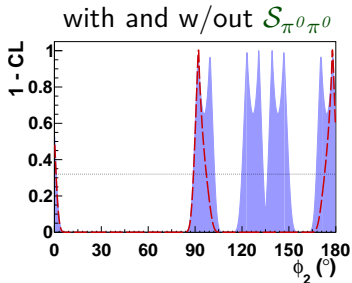
PhysRevLett. 65. 3381

hep-ph/0406263





	Value	0.8 ab^{-1}	50 ab^{-1}
$^a \mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm 0.21 \pm 0.18$	$\pm 0.03 \pm 0.08$
$^b \mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.31	$\pm 0.19 \pm 0.18$	$\pm 0.04 \pm 0.04$
$^a \mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm 0.26 \pm 0.38$	$\pm 0.03 \pm 0.09$
$^c \mathcal{A}_{\pi^+\pi^-}$	0.33	$\pm 0.06 \pm 0.03$	$\pm 0.01 \pm 0.03$
$^c \mathcal{S}_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$	$\pm 0.01 \pm 0.01$
$^b \mathcal{A}_{\pi^0\pi^0}$	0.14	$\pm 0.36 \pm 0.12$	$\pm 0.05 \pm 0.01$
$\mathcal{S}_{\pi^0\pi^0}$	0.81		$\pm 0.29 \pm 0.03$



- a PRD 87 031103
- b Belle Draft
- c PRD 88 092003

- Statistical Uncertainties from Toy MC:

$$\Delta \mathcal{S}_{\pi^0 \pi^0} = \pm 0.29,$$

$$\Delta \mathcal{A}_{\pi^0 \pi^0} = \pm 0.03,$$

$$\Delta \mathcal{B}_{\pi^0 \pi^0} = \pm 0.04 \cdot 10^{-6}$$

- Projection of Systematical Uncertainties:

$$\Delta \mathcal{S}_{\pi^0 \pi^0} = \pm 0.03,$$

$$\Delta \mathcal{A}_{\pi^0 \pi^0} = \pm 0.02,$$

$$\Delta \mathcal{B}_{\pi^0 \pi^0} = \pm 0.04 \cdot 10^{-6}$$

- Sensitivity on ϕ_2 : $\mathcal{S}_{\pi^0 \pi^0}$ will help to reduce ambiguities by factor 4.

⇒ Expected $\Delta \phi_2 \approx 4^\circ$.

Time of Propagation counter
with 20 mm quartz bars
MCP-PMT readout

K_L^0/μ Detector (outside)
RPC Plates and plastic
scintillators with SiPM readout

Superconducting Magnet
homogeneous field of 1.5 T

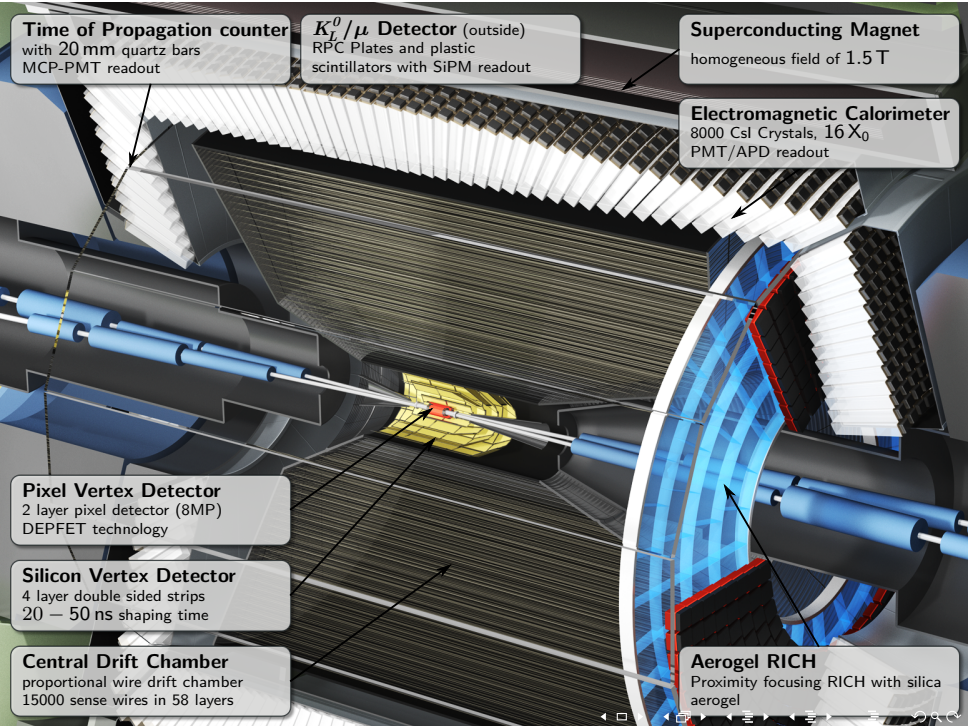
Electromagnetic Calorimeter
8000 CsI Crystals, $16 X_0$
PMT/APD readout

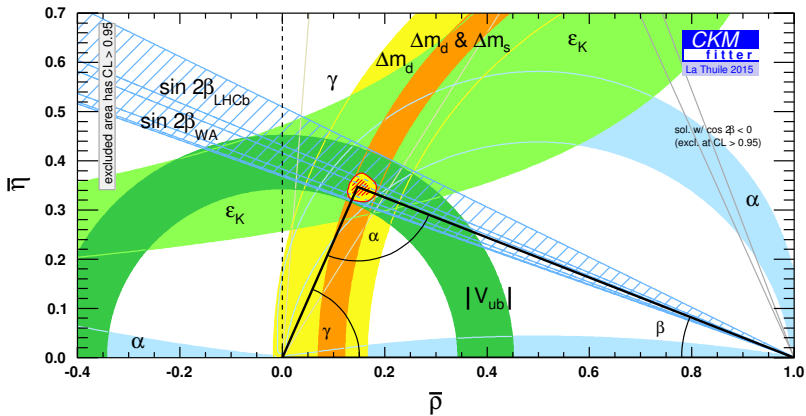
Pixel Vertex Detector
2 layer pixel detector (8MP)
DEPFET technology

Silicon Vertex Detector
4 layer double sided strips
20 – 50 ns shaping time

Central Drift Chamber
proportional wire drift chamber
15000 sense wires in 58 layers

Aerogel RICH
Proximity focusing RICH with silica
aerogel

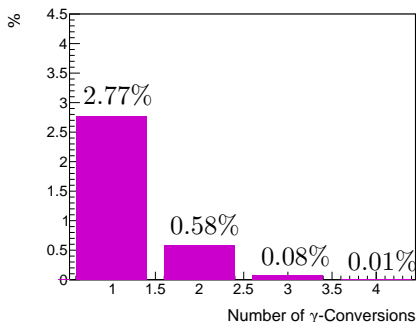




$$\bar{\rho} = \left(1 - \frac{\lambda^2}{2}\right) \rho \quad \bar{\eta} = \left(1 - \frac{\lambda^2}{2}\right) \eta$$

a) If there is an event with γ -conversions

⇒ How Many?



b) How many Events have at least one γ -conversion?

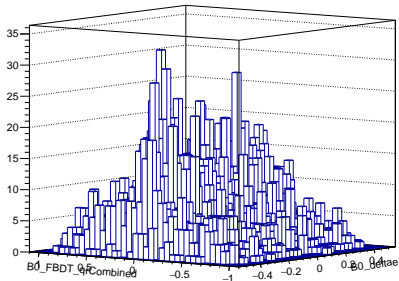
Vertex in	Events %
Beam Pipe	2.00 %
1st. PXD Layer	0.60 %
2nd. PXD Layer	0.50 %
Total inside PXD	3.10 %

c) ... and at least one γ -conversion or one $\pi^0 \rightarrow e^+e^-\gamma$ decay?

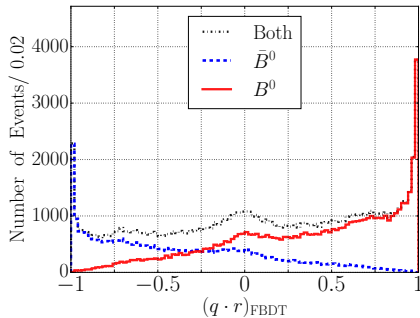
$\pi^0 \rightarrow e^+e^-\gamma$	2.00 %
Total $\pi^0 \cup \gamma$	5.05 %

Requirement: All converted γ in accept. and not converted in ECL

B0_FBDT_qrCombined:B0_deltae



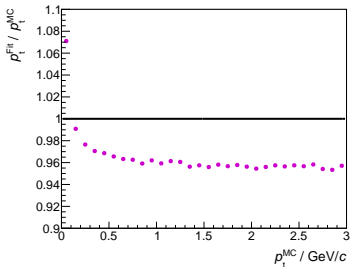
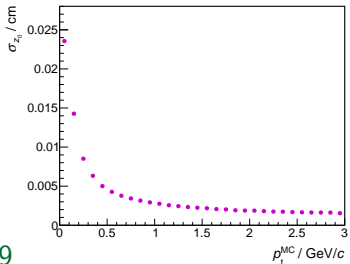
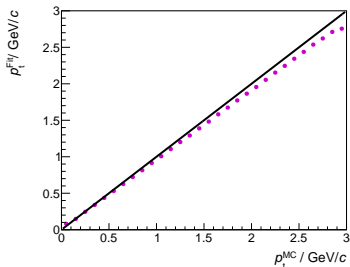
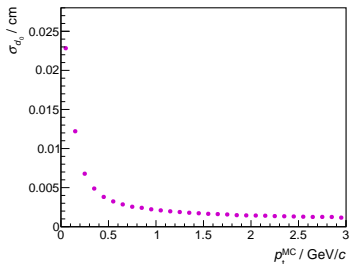
Distribution of Continuum



Distribution on signal

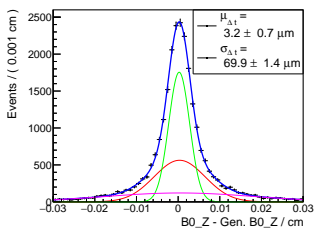
$$B^0 \rightarrow \pi^0 \pi^0_{\text{dal}}$$

■ e^+ , e^-

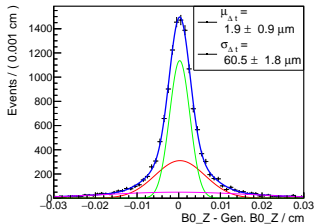


Reconstructed as $B^0_{dal} \rightarrow \pi^0_{\gamma\gamma} \pi^0_{dal}$

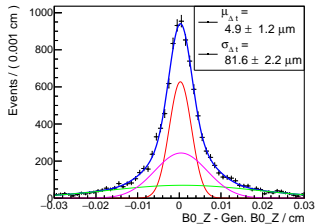
$\hookrightarrow e^+ e^- \gamma$



Dalitz and
Conversion case



Only Dalitz
(58% of Events)

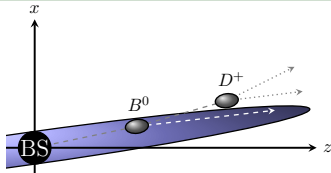


Only Conversion
(42% of Events)

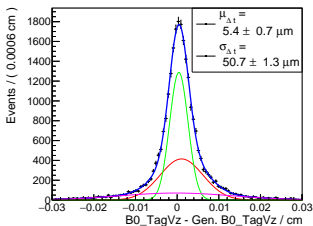
Tag Side: Tracks which remain from reco. side. B_{CP}

Algorithm: RAVE's Adaptive Vertex Fit

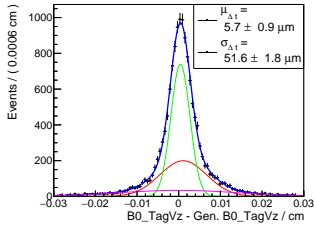
- Track weighting according to proximity to other tracks and spatial constraint.
- Various instances.



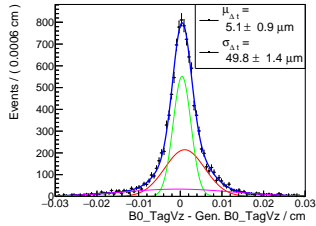
- Class. acc. mother: $B\checkmark, D\checkmark, K_S^0 \times$



Dalitz and
Conversion case

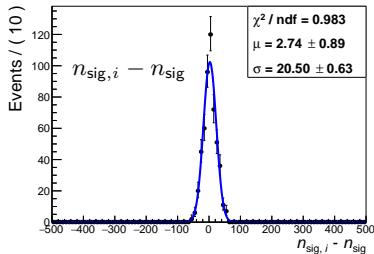
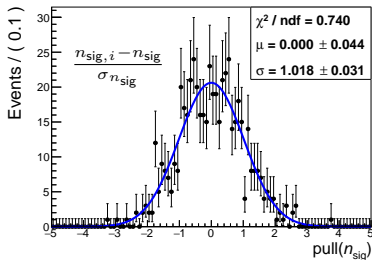


Only Dalitz
(58% of Events)

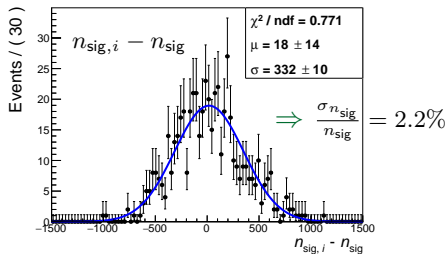
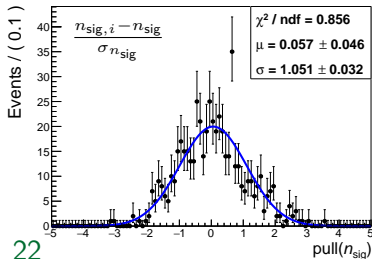


Only Conversion
(42% of Events)

$$B^0 \rightarrow \pi^0(\rightarrow e^+e^-\gamma)\pi^0(\rightarrow \gamma\gamma)$$



$$B^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow \gamma\gamma)$$



$$\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0)$$

$$\mathcal{A}_{\text{CP}}(B^0 \rightarrow \pi^0 \pi^0)$$

Source	Belle ^a	50 $\frac{1}{\text{ab}}$ [%]
Flavor Tagging ^b	0.034	0.0034
$B\bar{B}$ Bkg. Param.	0.06	0.008
Cont. Bkg. Param	0.08	0.010
Fit Bias	0.02	0.003
Total	0.12	0.01

^a Belle Draft M. Seviar

^b BaBar PRD 87 052009

Source	Belle ^a [%]	50 $\frac{1}{\text{ab}}$ [%]
Signal Sel.	1.5	0.19
Cont. Bkg. Param	11.0	1.39
Off-res Cont. Bkg.	3.0	0.38
ΔE and m_{bc}	4.0	0.51
π^0 det. eff.	4.4	0.56
$B\bar{B}$ Bkg. Param.	5	0.60
Luminosity	1.4	1.40
Rec. Conv. Ph.	1.0	0
Timing Cut	0.5	0.06
Fit Bias	1.0	0.13
Total	14.0	2.25

$$\mathcal{B}(B^0 \rightarrow \pi^+ \pi^-)$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \pi^0)$$

Source	Belle ^a [%]	50 _{ab} ¹ [%]
Signal PDF	0.50	0.06
$B\bar{B}$ Bkg. Param.	1.77	0.22
Tracking	0.70	0.09
Luminosity	1.37	1.37
Kpi PID	1.72	0.22
Ratio Cut	0.24	0.03
MC Statistics	0.15	0.02
Feed-across	1.50	0.19
PHOTOS	0.80	0.80
Total	3.42	1.63

Source	Belle ^a [%]	50 _{ab} ¹ [%]
Signal PDF	0.73	0.09
$B\bar{B}$ Bkg. Param.	4.53	0.57
Tracking	0.70	0.09
Luminosity	1.37	1.37
Kpi PID	0.86	0.11
Ratio Cut	0.92	0.12
MC Statistics	0.17	0.02
Feed-across	1.19	0.15
π^0 det. eff.	4.00	0.51
Total	6.52	1.59

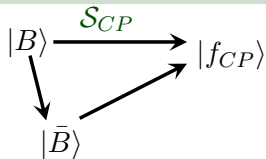
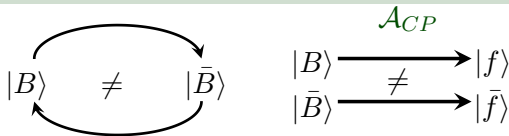
^a Belle PRD 87 031103

$$A_{CP}(B^0 \rightarrow \pi^+\pi^-)$$

Source	Belle ^a [10 ⁻²]	50 _{ab} [%]
Track Helix	0	0
Δt Sel.	0.01	0.001
Missalign.	0.40	0.051
Δz Bias	0.50	0.063
IP Profile	0.13	0.016
Flavor Tagging	0.40	0.051
m_d and τ	0.12	0.015
Fit Bias	0.54	0.068
Tag-Side Int.	3.18	3.18
B_{tag} Track Sel.	0.30	0.038
Vertex Sel.	0.37	0.047
MC Shape	0.15	0.019
Δt Res.	0.83	0.415
Bkg. Shape	0.15	0.019
Bkg. NP. S.	0.37	0.047
Total	3.48	3.21

$$S_{CP}(B^0 \rightarrow \pi^+\pi^-)$$

Source	Belle ^a [10 ⁻²]	50 _{ab} [%]
Track Helix	0.01	0.001
Δt Sel.	0.03	0.004
Missalign.	0.20	0.025
Δz Bias	0.40	0.051
IP Profile	1.19	0.151
Flavor Tagging	0.31	0.039
m_d and τ	0.09	0.011
Fit Bias	0.86	0.109
Tag-Side Int.	0.17	0.170
B_{tag} Track Sel.	0.33	0.042
Vertex Sel.	0.23	0.029
MC Shape	0.19	0.024
Δt Res.	2.02	1.010
Bkg. Shape	0.28	0.035
Bkg. NP. S.	0.57	0.072
Total	2.68	1.05



For $B \rightarrow \pi\pi$: tree and penguin
diags. contribute!

: $\mathcal{A}_{CP} = 0$
 $\mathcal{S}_{CP} = \sin(2\alpha)$

+ : $\mathcal{A}_{CP} \neq 0$
 $\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}^2} \sin(2\alpha^{\text{eff}})$

$\Rightarrow \alpha^{\text{eff}} = \alpha - \Delta\alpha$

