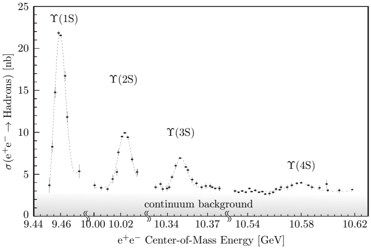
Feasibility study of $B^0 \to \pi^0\pi^0$ at the Belle II Experiment

Fernando Abudinén

28. March, 2017



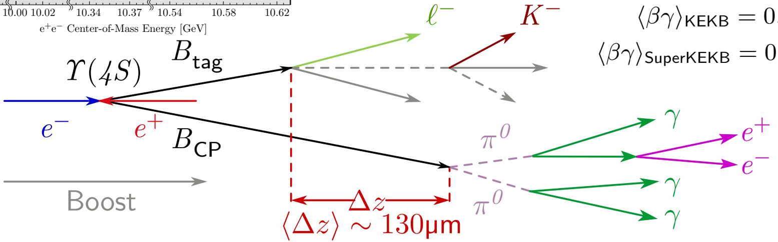
- $\Upsilon(4S)$ above $B\overline{B}$ prod. threshold

$\Rightarrow$ B-Factory

- $\sim$ 51 % are B^+B^-
- $\sim$ 49 % are $B^0\overline{B}^0$

$\langle\beta\gamma\rangle_{\text{KEKB}} = 0.425$

$\langle\beta\gamma\rangle_{\text{SuperKEKB}} = 0.284$

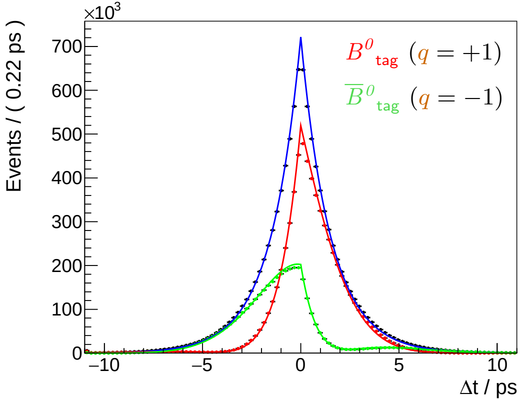


- $B^0\overline{B}^0$ at rest in CMS $\Delta t = \frac{\Delta z}{\langle\beta\gamma\rangle c} \Rightarrow$

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

Generated Asymmetry

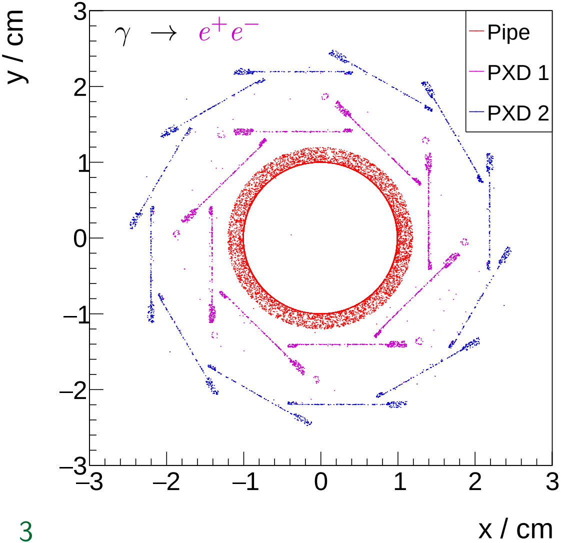
$$\mathcal{P}^{\mathsf{Sig}}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q\left(\mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)\right)\right]$$



- $\mathcal{A}_{CP}{}^{\pi^0\pi^0} = 0.44$ (PDG)
- $\mathcal{S}_{CP}{}^{\pi^0\pi^0} = \sqrt{1 - \mathcal{A}_{CP}{}^2}\,\sin 2 \cdot (\alpha - \Delta\alpha^*) \;\approx 0.78$

*hep-ex/0703039

Vertex of γ-Conversions in $B^0 \to \pi^0\pi^0$



- $\Upsilon(4S) \to B^0{}_1 B^0{}_2 \to$
  $B_1 \to$ generic
  $B_2 \to \pi^0\pi^0$
- $\pi^0{}_{\gamma\gamma} \to \gamma\gamma \quad (\mathcal{B} = 98.82\%)$
- $\pi^0{}_{\text{dal}} \to e^+e^-\gamma \ (\mathcal{B} = 1.17\%)$
- $N_{\text{Belle II}} =$

$\mathcal{L}_{\text{Belle II}}$	$\cdot$	$\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)$
	$\cdot$	$2 \cdot \mathcal{B}(B^0 \to \pi^0\pi^0) \sim$
50ab^{-1}	$\cdot$	$1.1\text{nb} \cdot 0.49$
	$\cdot$	$2 \cdot 1.91 \cdot 10^{-6}$

~ 100k events.

- Accept.: $\theta \in [17, 150]^\circ$
- ECL: $\theta \in [12.4, 155.1]^\circ$

B^0 Reconstruction

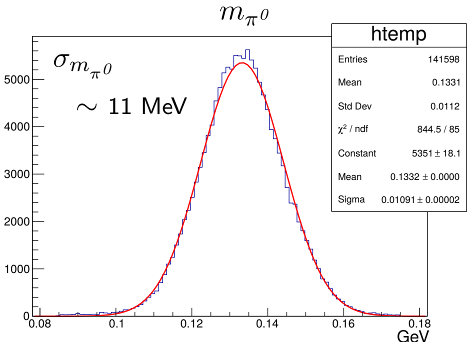
1 $B^0 \to \pi^0{}_{\gamma\gamma}\pi^0{}_{\gamma\gamma}$

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

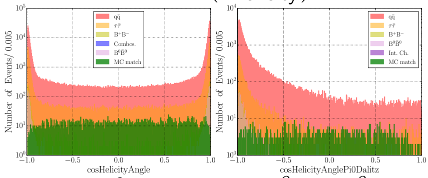
3 $B^0 \to \pi^0{}_{\gamma_c\gamma}(\to \gamma(\to e^+e^-)\gamma)\pi^0{}_{\gamma\gamma}$

Reconstruction of π^0s:

- 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 $\sim \pm 2.5 \cdot \sigma_{m_{\pi^0}}$
- $|\cos(\theta_{\text{helicity}})| < 0.95$



$\cos(\theta_{\text{helicity}})$



$\pi^0{}_{\gamma\gamma}$ $\quad$ $\pi^0{}_{\text{dal}}/\pi^0{}_{\gamma_c\gamma}$

B^0 Vertex Reconstruction

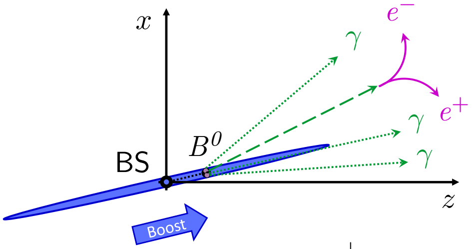
- Vertex Reconstruction with iptube constrain.
- If conversion in beam pipe and $e^{\pm}$ with PXD hits

$\Rightarrow$ $\pi^0{}_{\mathrm{c}}$ and $\pi^0{}_{\mathrm{dal}}$ kinematically indistinguishable.

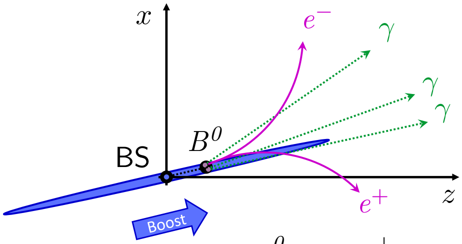
- $\tau_{\pi^0} \sim 0.9$ as $\cong$ 0.1 nm

$\Rightarrow$ π^0 Vertex $\hat{=}$ B^0 Vertex.

- Check with MC truth.



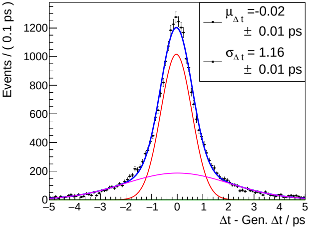
$\gamma_{\mathrm{c}} \to e^+e^-$



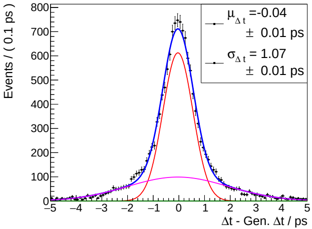
$\pi^0{}_{\mathrm{dal}} \to e^+e^-\gamma$

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

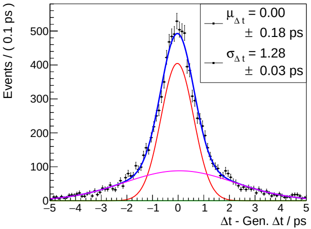
$\hookrightarrow e^+\ e^-\ \gamma$



Dalitz and Conversion case

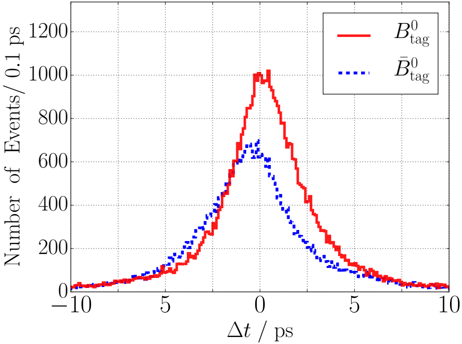


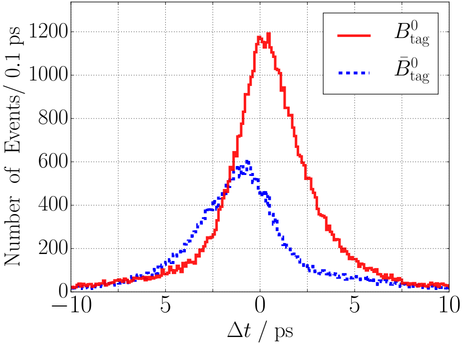
Only Dalitz (58% of Events)



Only Conversion (42% of Events)

Flavor Tagger with Δt





$q \cdot r$

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

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

MC Flavor

Final Selection and Efficiency

- $m_{bc} = \sqrt{{E^*_{\text{beam}}}^2 - \mathbf{p}_{B^0}} > 5.26$ GeV$/c^2$
- $\Delta E = E^*_{\text{beam}} - E_{B^0} \in [-0.3, 0.2]$ GeV
- Continuum Suppr. $y_{\text{FBDT}} > 0.976$

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

- Flavor Dilution $r > 0.1$
- Multiplicity $\lesssim 1.01$

$\Rightarrow$ Ranking according to Dilution

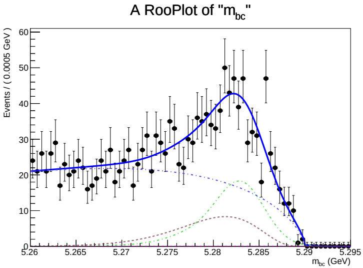
Decay. Channel	$\frac{n_{\text{acc}}}{n_{\text{gen}}}$ [%]	$\frac{n_{\text{rec}}}{n_{\text{acc}}}$ [%]	$\frac{n^{\text{FS}}_{\text{rec}}}{n_{\text{acc}}}$ [%]
$B^0 \to \pi^0{}_{\text{dal}}\ \pi^0{}_{\gamma\gamma}$	2.0	52.0	7.0
$B^0 \to \pi^0{}_{\gamma_c\gamma}\ \pi^0{}_{\gamma\gamma}$	3.0	48.8	4.0
Dal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

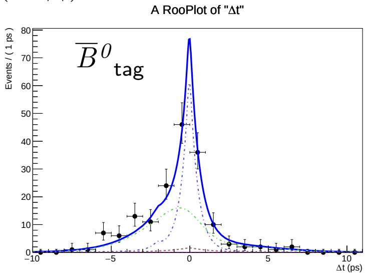
Decay. Channel	Purity [%]	$\frac{n_{\text{combin}}}{n_{\text{sig}}+n_{\text{combin}}}$ [%]
Dal + Conv	17.7	0.8
$B^0 \to \pi^0{}_{\gamma\gamma}\ \pi^0{}_{\gamma\gamma}$	15.8	1.0

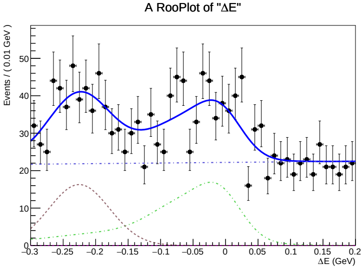
$$\text{Purity} = \frac{n_{\text{sig}}}{n_{\text{sig}} + n_{\text{combin}} + n_{\text{cont}} + n_{B\overline{B}}}$$

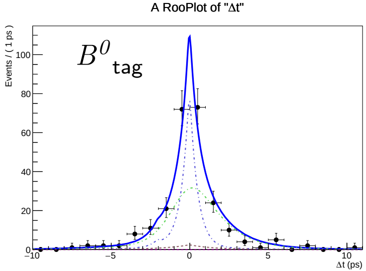
Toy MC Projections

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



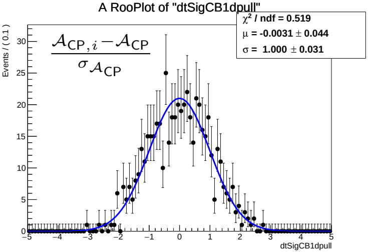


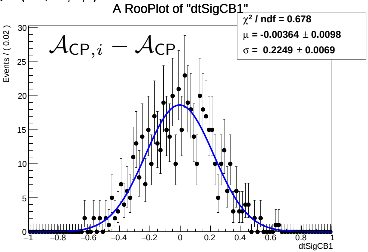


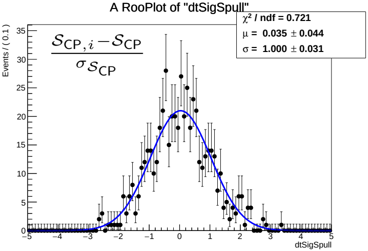


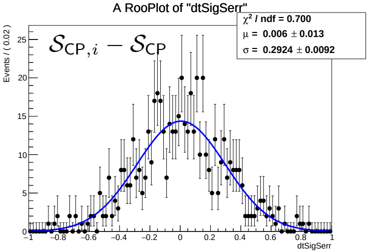
$\mathcal{A}_{\mathrm{CP}}$ and $\mathcal{S}_{\mathrm{CP}}$ Pulls and Statistical Uncertainties

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





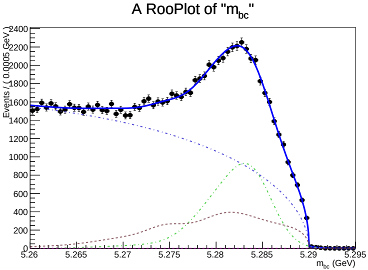


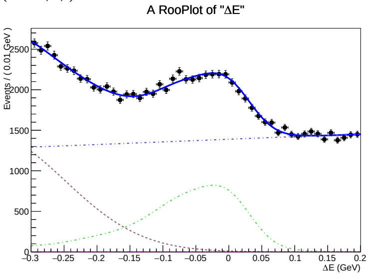


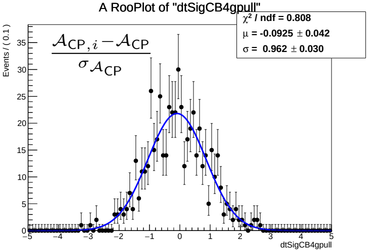
$$\Rightarrow \Delta\mathcal{S}_{\mathrm{CP}}(\mathrm{stat}) = 0.29$$

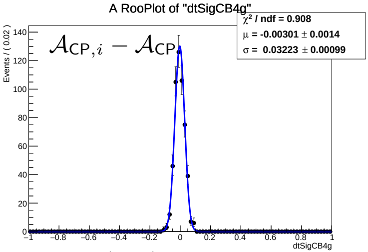
Toy MC and $\mathcal{A}_{CP}$ Pull and Uncertainty

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



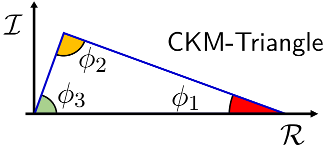






$\Rightarrow \Delta\mathcal{A}_{CP}(\text{stat}) = 0.03$

Extraction of ϕ_2 from $B \to \pi\pi$



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

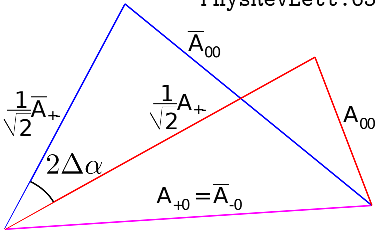
$\Rightarrow$ Extr. $\Delta\phi_2$ through isospin analysis:

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

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

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

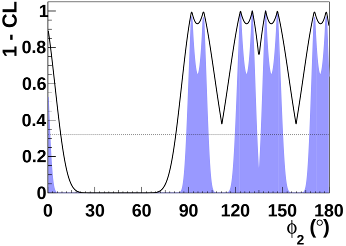
PhysRevLett.65.3381



- Isospin analysis input:
  $\mathcal{B}(B^0 \to \pi^+\pi^-)$, $\mathcal{B}(B^0 \to \pi^0\pi^0)$, $\mathcal{B}(B^+ \to \pi^+\pi^0)$
  $\mathcal{A}_{\text{CP}}(B^0 \to \pi^+\pi^-)$, $\mathcal{S}_{\text{CP}}(B^0 \to \pi^+\pi^-)$,
  $\mathcal{A}_{\text{CP}}(B^0 \to \pi^0\pi^0)$, $[\mathcal{S}_{\text{CP}}(B^0 \to \pi^0\pi^0)]$

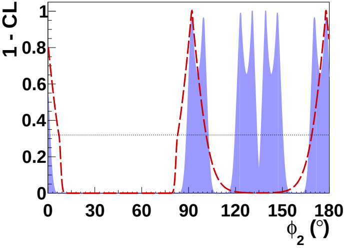
Result of Isospin analysis

1 ab^{-1} and 50 ab^{-1}

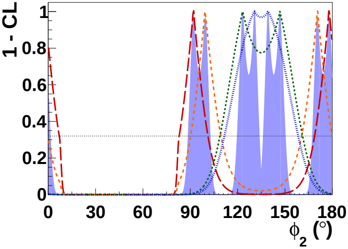


	Value	0.8 ab^{-1}	50 ab^{-1}
$^{a}\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm0.21 \pm 0.18$	$\pm0.03 \pm 0.08$
$^{b}\mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.31	$\pm0.19 \pm 0.18$	$\pm0.04 \pm 0.04$
$^{c}\mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm0.26 \pm 0.38$	$\pm0.03 \pm 0.09$
$^{c}\mathcal{A}_{\pi^+\pi^-}$	0.33	$\pm0.06 \pm 0.03$	$\pm0.01 \pm 0.03$
$^{c}\mathcal{S}_{\pi^+\pi^-}$	-0.64	$\pm0.08 \pm 0.03$	$\pm0.01 \pm 0.01$
$^{b}\mathcal{A}_{\pi^0\pi^0}$	0.14	$\pm0.36 \pm 0.12$	$\pm0.05 \pm 0.01$
$\mathcal{S}_{\pi^0\pi^0}$	-0.07		$\pm0.29 \pm 0.03$

with and w/out $\mathcal{S}_{\pi^0\pi^0}$



Comparison diff. $\mathcal{S}_{\pi^0\pi^0}$



[a] PRD 87 031103
[b] Belle Draft
[c] PRD 88 092003

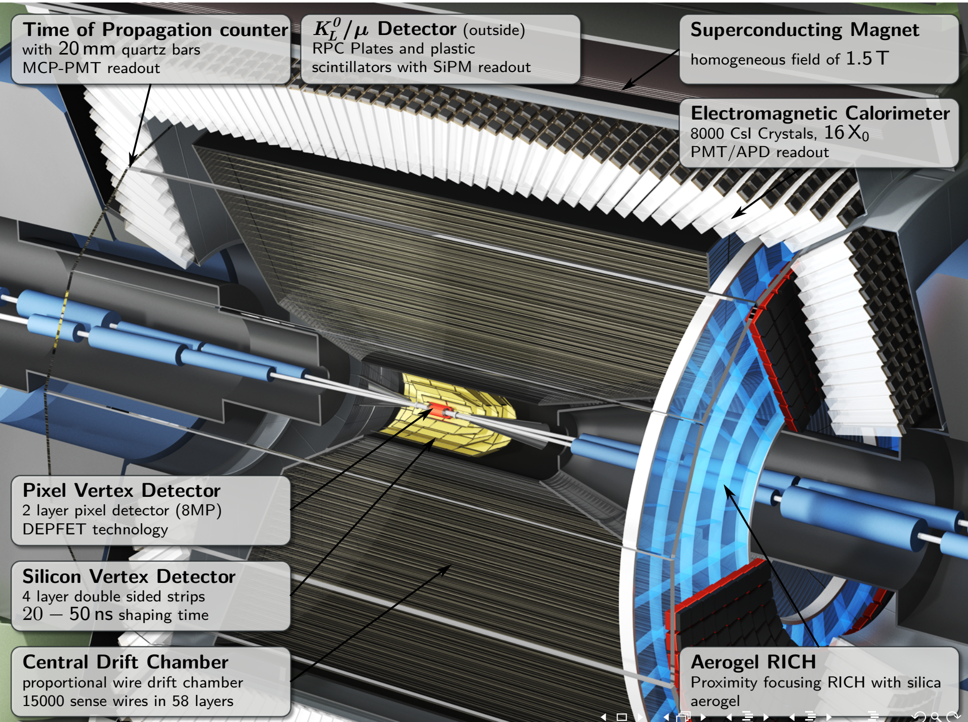
Summary and Outlook

- Statistical Uncertainties from Toy MC:
  $\Delta\mathcal{S}_{\pi^0\pi^0} = \pm 0.29$,
  $\Delta\mathcal{A}_{\pi^0\pi^0} = \pm 0.03$,
  $\Delta\mathcal{B}_{\pi^0\pi^0} = \pm 0.04 \cdot 10^{-6}$

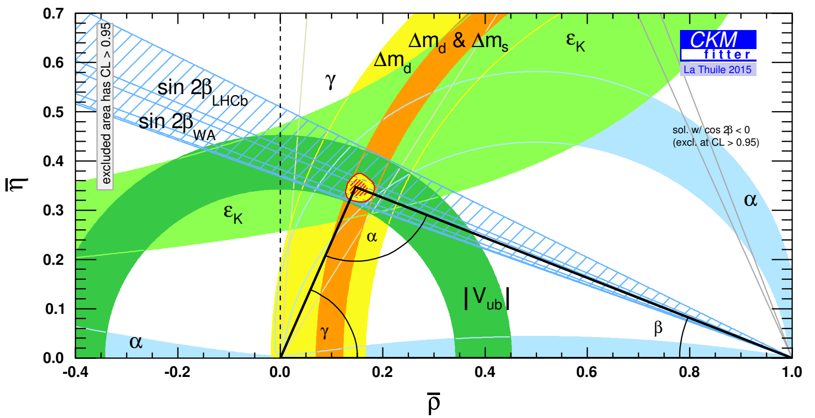
- Projection of Systematical Uncertainties:
  $\Delta\mathcal{S}_{\pi^0\pi^0} = \pm 0.03$,
  $\Delta\mathcal{A}_{\pi^0\pi^0} = \pm 0.02$,
  $\Delta\mathcal{B}_{\pi^0\pi^0} = \pm 0.04 \cdot 10^{-6}$

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

$\Rightarrow$ Uncertainty should be extracted without $\mathcal{S}_{\pi^0\pi^0}$.


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

CKM-Triangle

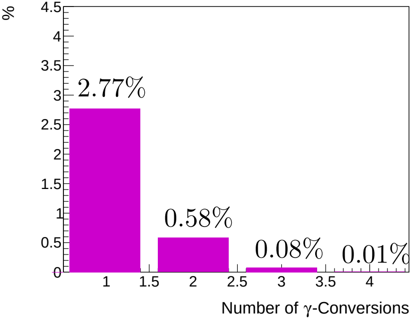


$$\bar\rho = \left(1 - \frac{\lambda^2}{2}\right)\rho \qquad \bar\eta = \left(1 - \frac{\lambda^2}{2}\right)\eta$$

Events with γ-Conversions

a) If there is an event with γ-conversions

$\Rightarrow$ How Many?



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

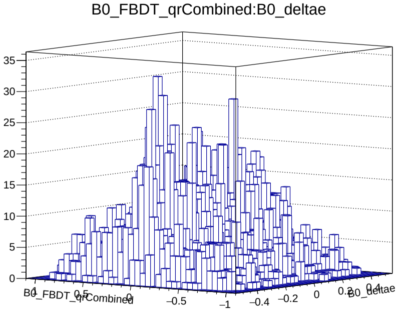
Vertex in	Events %
Beam Pipe	2.00 %
1st. PXD Layer	0.60 %
2nd. PXD Layer	0.50 %
Total inside PXD	3.10 %

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

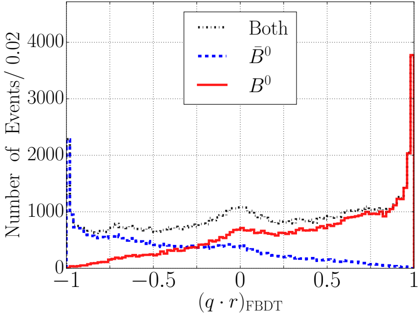
$\pi^0 \to e^+e^-\gamma$	2.00 %
Total $\pi^0 \cup \gamma$	5.05 %

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

Flavor Tagger Output



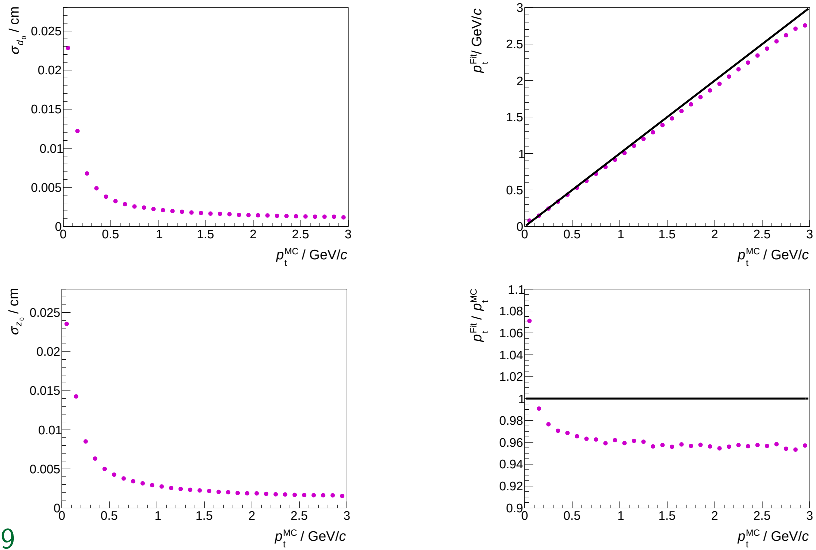
Distribution of Continuum



Distribution on signal $B^0 \to \pi^0 \pi^0{}_{\text{dal}}$

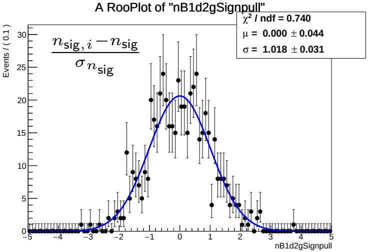
e^+, e^- Track Reconstruction

- e^+, e^-

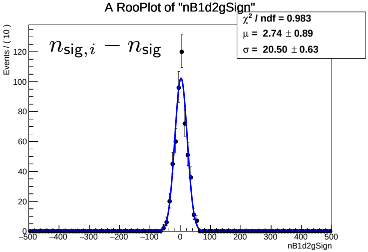


Pull and Uncertainties on Signal Yields

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

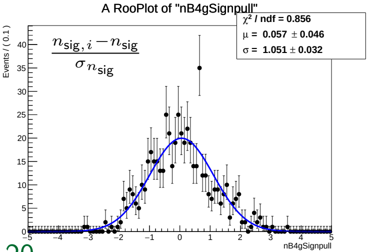


$\frac{n_{\text{sig},i} - n_{\text{sig}}}{\sigma_{n_{\text{sig}}}}$

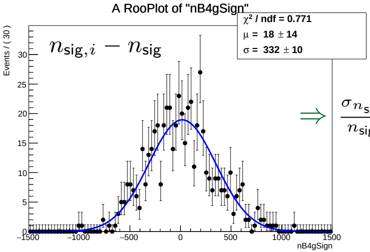


$n_{\text{sig},i} - n_{\text{sig}}$

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



$\frac{n_{\text{sig},i} - n_{\text{sig}}}{\sigma_{n_{\text{sig}}}}$



$n_{\text{sig},i} - n_{\text{sig}}$

$$\Rightarrow \frac{\sigma_{n_{\text{sig}}}}{n_{\text{sig}}} = 2.2\%$$

Systematic Uncertainties

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

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

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

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
$B\overline{B}$ 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

[a] Belle Draft M. Sevior
[b] BaBar PRD 87 052009

Systematic Uncertainties

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

Source	Belle[a] [%]	$50\,\frac{1}{\text{ab}}$ [%]
Signal PDF	0.50	0.06
$B\overline{B}$ 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-accross	1.50	0.19
PHOTOS	0.80	0.80
Total	3.42	1.63

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

Source	Belle[a] [%]	$50\,\frac{1}{\text{ab}}$ [%]
Signal PDF	0.73	0.09
$B\overline{B}$ 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-accross	1.19	0.15
π^0 det. eff.	4.00	0.51
Total	6.52	1.59

[a] Belle PRD 87 031103

Systematic Uncertainties

$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-)$

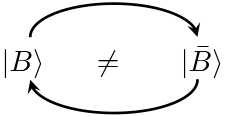
Source	Belle[a] $[10^{-2}]$	$50\,\frac{1}{\text{ab}}$ [%]
Track Helix	0	0
Δt Sel.	0.01	0.001
Missalign.	0.40	0.051
Δz Bias	0.50	0.063
IP Profile	0.13	0.016
Flavor Tagging	0.40	0.051
m_d and τ	0.12	0.015
Fit Bias	0.54	0.068
Tag-Side Int.	3.18	3.18
B_{tag} Track Sel.	0.30	0.038
Vertex Sel.	0.37	0.047
MC 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

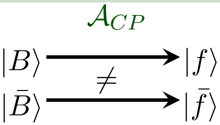
$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-)$

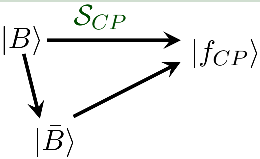
Source	Belle[a] $[10^{-2}]$	$50\,\frac{1}{\text{ab}}$ [%]
Track Helix	0.01	0.001
Δt Sel.	0.03	0.004
Missalign.	0.20	0.025
Δz Bias	0.40	0.051
IP Profile	1.19	0.151
Flavor Tagging	0.31	0.039
m_d and τ	0.09	0.011
Fit Bias	0.86	0.109
Tag-Side Int.	0.17	0.170
B_{tag} Track Sel.	0.33	0.042
Vertex Sel.	0.23	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

[a] Belle PRD 88 092003

Time-dependent CP-Analysis





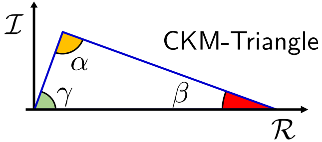


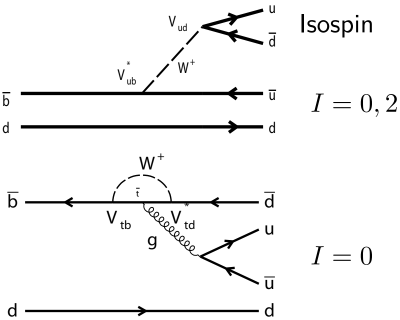
For $B \to \pi\pi$: tree and penguin diags. contribute!

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

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

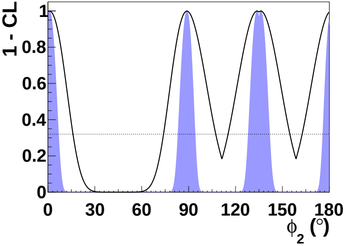
$\Rightarrow \alpha^{\text{eff}} = \alpha - \Delta\alpha$





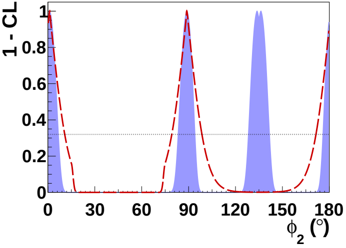
Result of Isospin analysis

$1\,\mathrm{ab}^{-1}$ and $50\,\mathrm{ab}^{-1}$

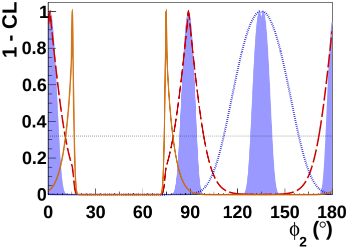


	Value	$0.8\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$^{a}\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm 0.21 \pm 0.18$	$\pm 0.03 \pm 0.08$
$^{b}\mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.91	$\pm 0.28 \pm 0.27$	$\pm 0.04 \pm 0.04$
$^{c}\mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm 0.26 \pm 0.38$	$\pm 0.03 \pm 0.09$
$^{c}\mathcal{A}_{\pi^+\pi^-}$	0.33	$\pm 0.06 \pm 0.03$	$\pm 0.01 \pm 0.03$
$^{c}\mathcal{S}_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$	$\pm 0.01 \pm 0.01$
$^{b}\mathcal{A}_{\pi^0\pi^0}$	0.44	$\pm 0.36 \pm 0.12$	$\pm 0.03 \pm 0.01$
$\mathcal{S}_{\pi^0\pi^0}$	0.03		$\pm 0.29 \pm 0.03$

with and w/out $\mathcal{S}_{\pi^0\pi^0}$



Comparison diff. $\mathcal{S}_{\pi^0\pi^0}$



[a] PRD 87 031103
[b] PDG 2016
[c] PRD 88 092003