CP Violation prospects at the Belle II Experiment

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“From Flavour to New Physics”

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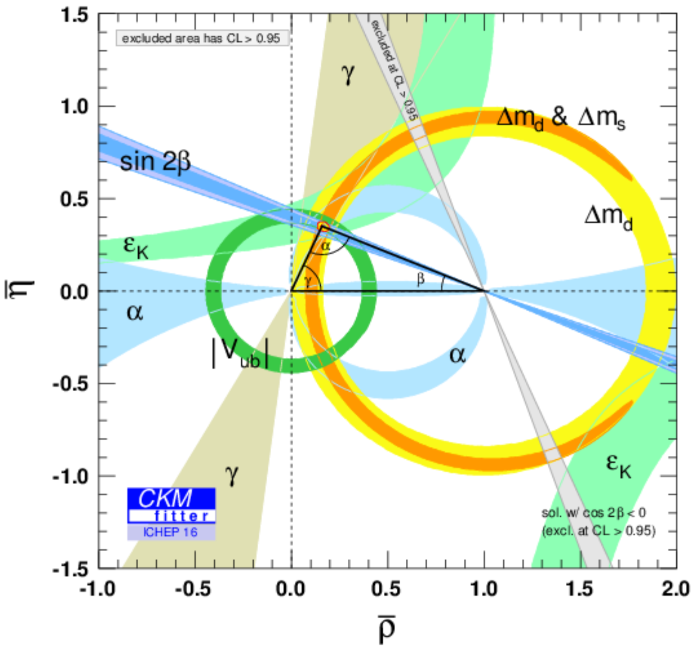
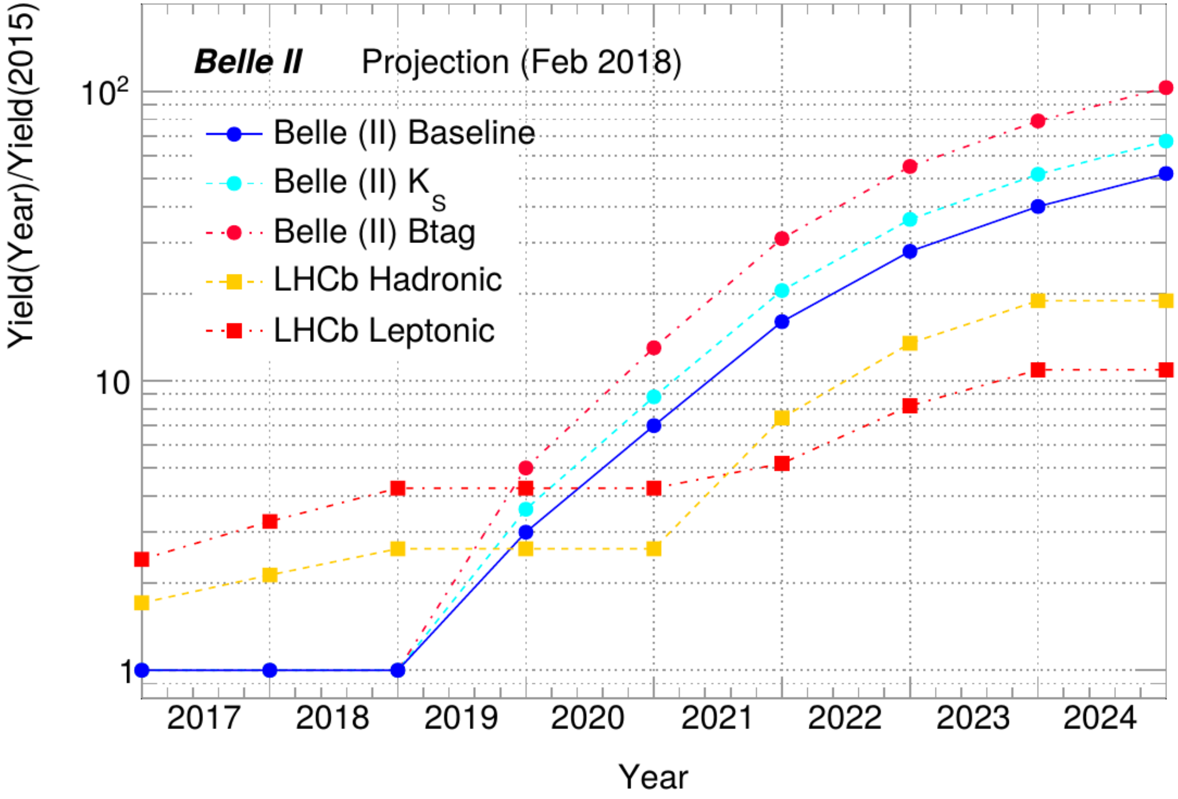
The Unitarity Triangle

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

$\lambda \approx 0.22$: Cabibbo angle

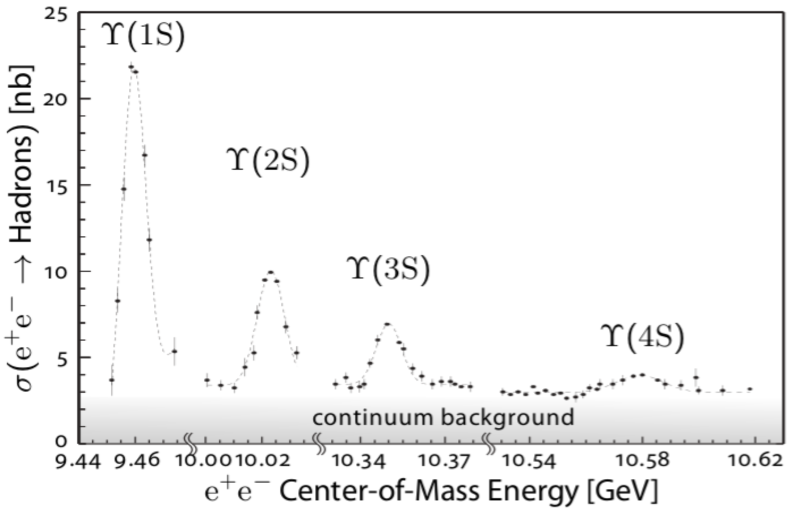
- All flavor variables constrained in the SM CKM fit are in good agreement with experimental observations
- Some variables still to be measured precisely
  - therefore a lot of room for surprises !





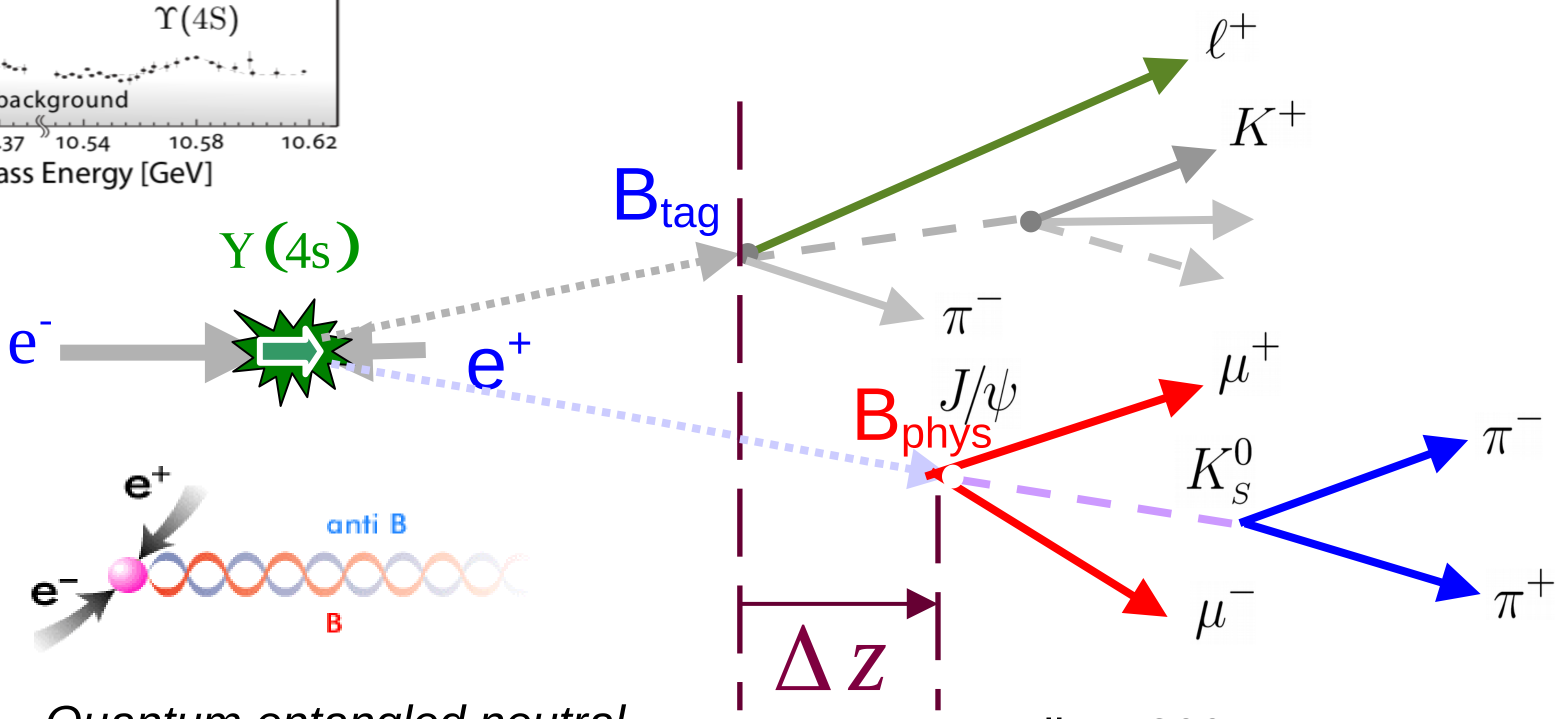
Two notations for the CKM angles: α, β, γ or $\varphi_1, \varphi_2, \varphi_3$

Time dependent measurements



- Y(4S) is the first resonance just above the $B\overline{B}$ production threshold
- Only $B\overline{B}$ pairs are produced, and are at rest in the Y(4S) frame

$$\Delta t = \frac{\Delta z}{\beta \gamma c}$$



Resolution on Δt will be dominated by the resolution of the tagging side vertex

Quantum entangled neutral B meson pair production

Belle ~ 200 μm
Belle II ~ 130 μm

Δt probability parametrization $\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B0}}}{4\tau_{B0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d\Delta t + \mathcal{S}_{CP}\sin\Delta m_d\Delta t\right)\right]$

Sin(2β) : $b \to c\bar{c}s$

Phys. Rev. Lett. 108 171802 (2012)

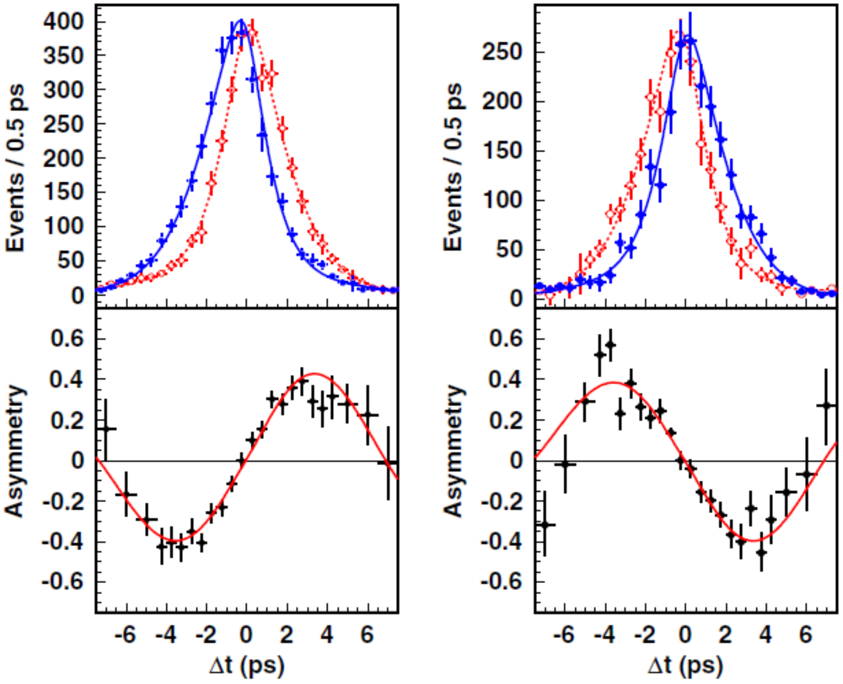


FIG. 2 (color online). The background-subtracted Δt distribution (top) for $q = +1$ (red) and $q = -1$ (blue) events and asymmetry (bottom) for good tag quality ($r > 0.5$) events for all CP-odd modes combined (left) and the CP-even mode (right).

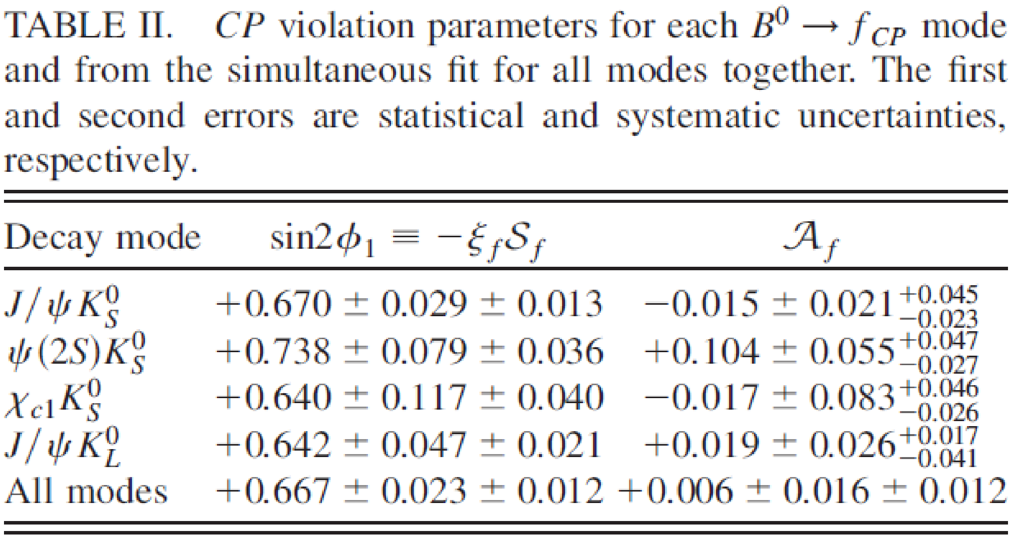
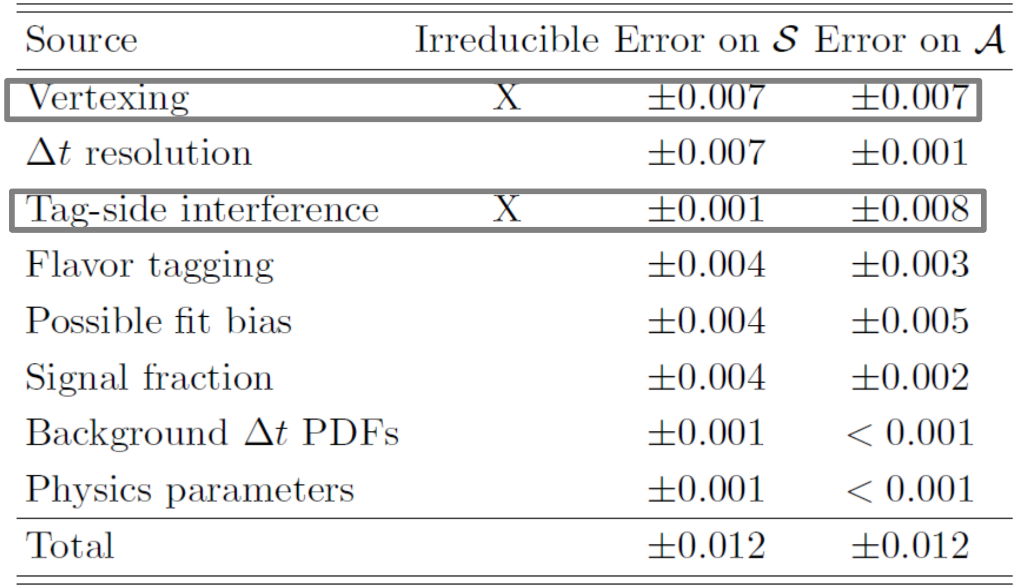


TABLE II. CP violation parameters for each $B^0 \to f_{CP}$ mode and from the simultaneous fit for all modes together. The first and second errors are statistical and systematic uncertainties, respectively.

Decay mode	$\sin 2\phi_1 \equiv -\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$J/\psi K_S^0$	$+0.670 \pm 0.029 \pm 0.013$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$
$\psi(2S) K_S^0$	$+0.738 \pm 0.079 \pm 0.036$	$+0.104 \pm 0.055^{+0.047}_{-0.027}$
$\chi_{c1} K_S^0$	$+0.640 \pm 0.117 \pm 0.040$	$-0.017 \pm 0.083^{+0.046}_{-0.026}$
$J/\psi K_L^0$	$+0.642 \pm 0.047 \pm 0.021$	$+0.019 \pm 0.026^{+0.017}_{-0.041}$
All modes	$+0.667 \pm 0.023 \pm 0.012$	$+0.006 \pm 0.016 \pm 0.012$



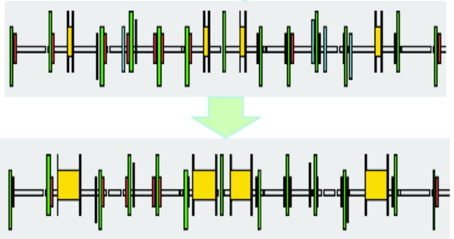
Source	Irreducible	Error on $\mathcal{S}$	Error on $\mathcal{A}$
Vertexing	X	±0.007	±0.007
Δt resolution		±0.007	±0.001
Tag-side interference	X	±0.001	±0.008
Flavor tagging		±0.004	±0.003
Possible fit bias		±0.004	±0.005
Signal fraction		±0.004	±0.002
Background Δt PDFs		±0.001	< 0.001
Physics parameters		±0.001	< 0.001
Total		±0.012	±0.012

Irreducible systematic errors:

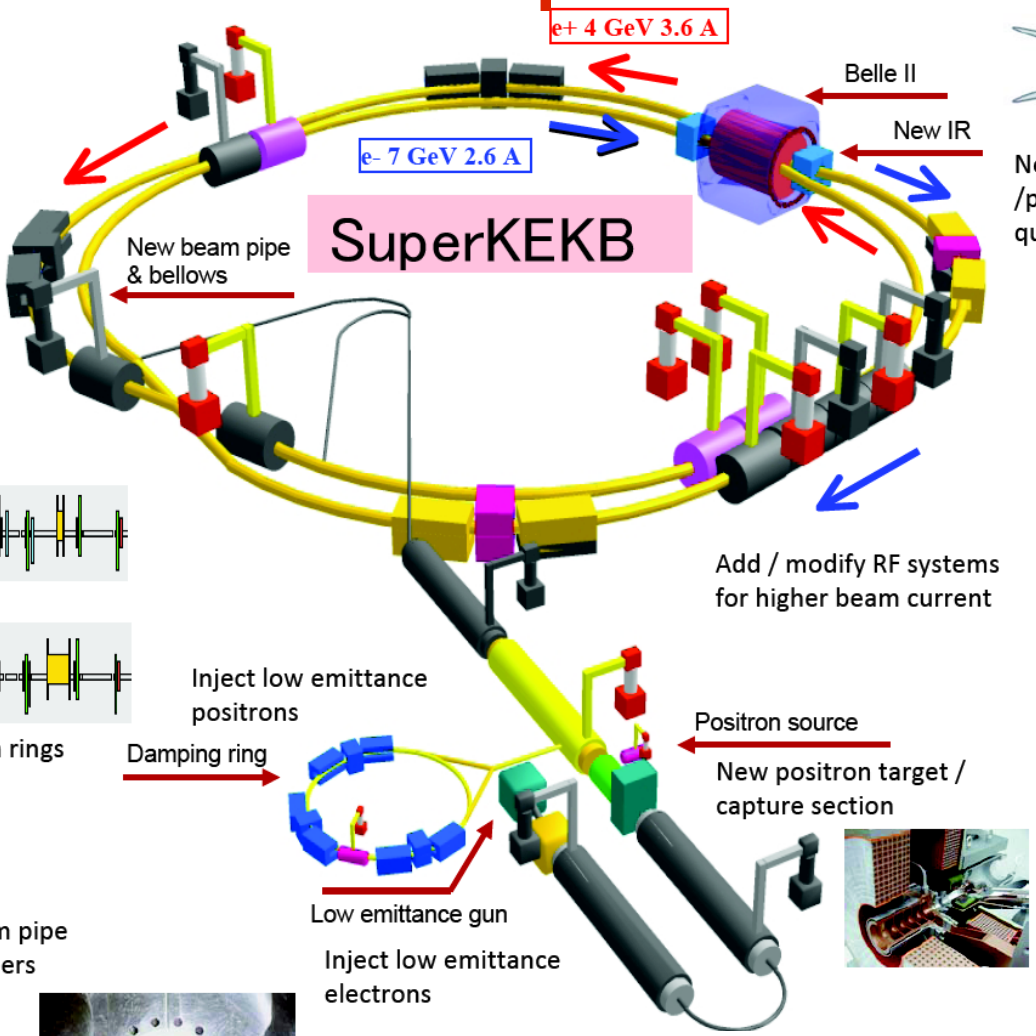
- Vertexing (without detector upgrade)
- Tag-side interference
  - More sophisticated treatment will be considered

SuperKEKB

eplace short dipoles
vith longer ones (LER)



Redesign the lattices of both rings
to reduce the emittance

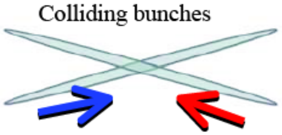


Add / modify RF systems
for higher beam current

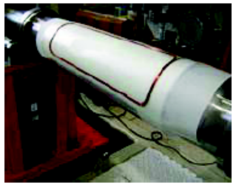
Inject low emittance
positrons

New positron target /
capture section

Inject low emittance
electrons



New superconducting
/permanent final focusing
quads near the IP



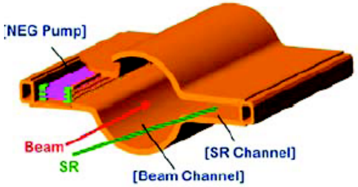
Peak luminosity

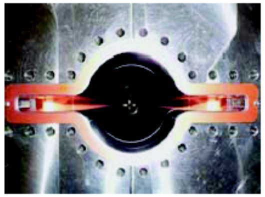
- KEKB =
  2.11×10^{34} cm^{-2} s^{-1}
- SuperKEKB =
  8×10^{35} cm^{-2} s^{-1}

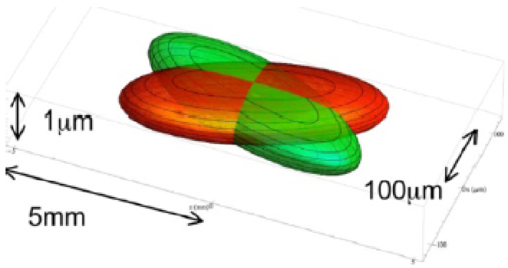
e^+e^- beams energy

- KEKB =
  8 GeV / 3.5 GeV
- SuperKEKB =
  7 GeV / 4 GeV

TiN-coated beam pipe
with antechambers

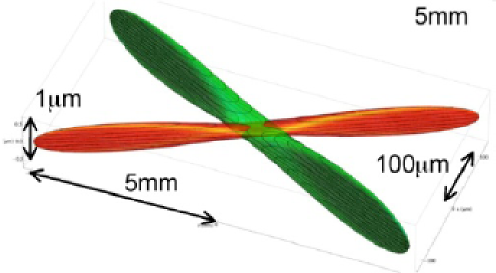




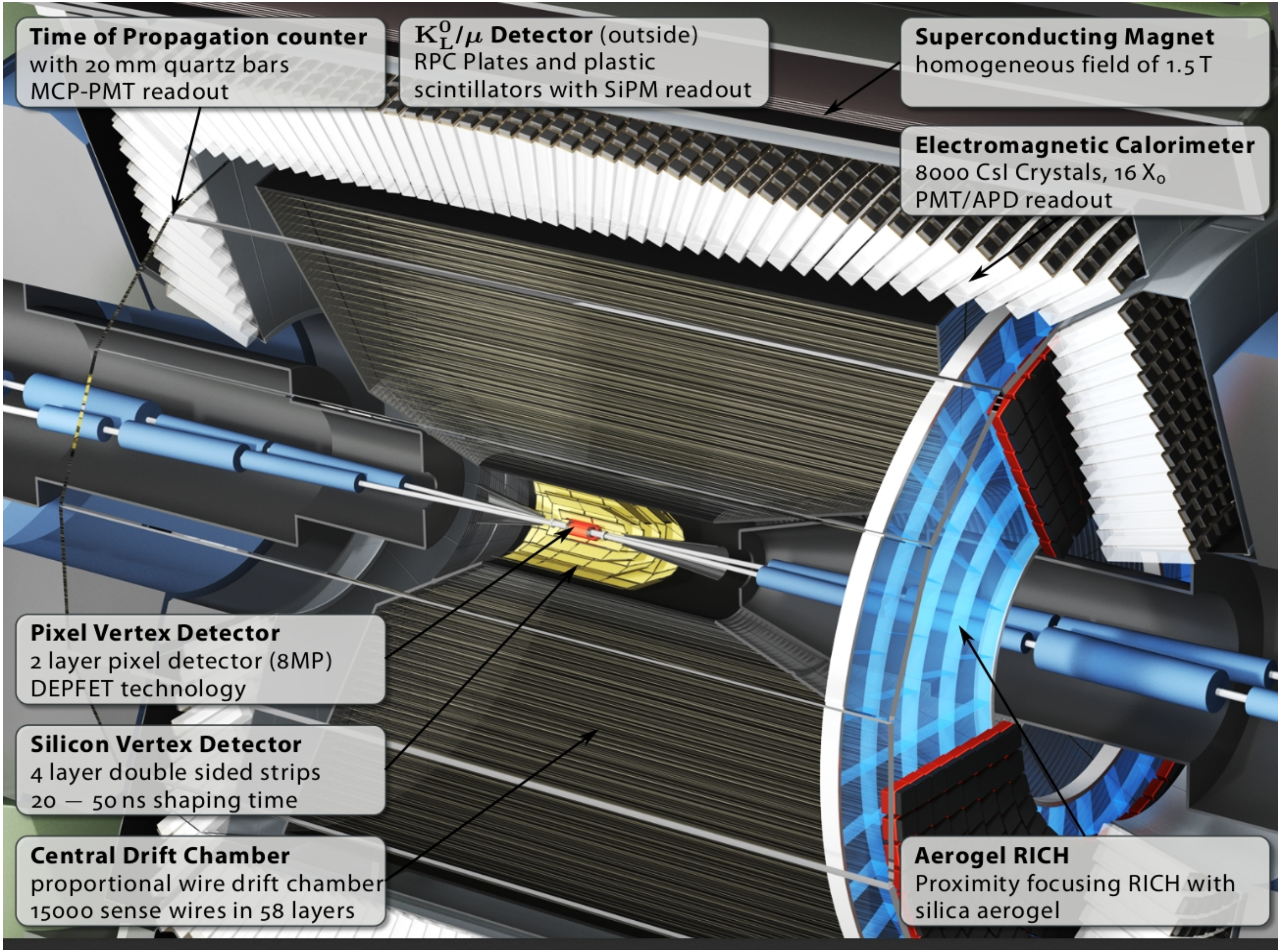


KEKB

SuperKEKB
Nanobeam



Belle II



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

Belle II Pixel Vertex Detector

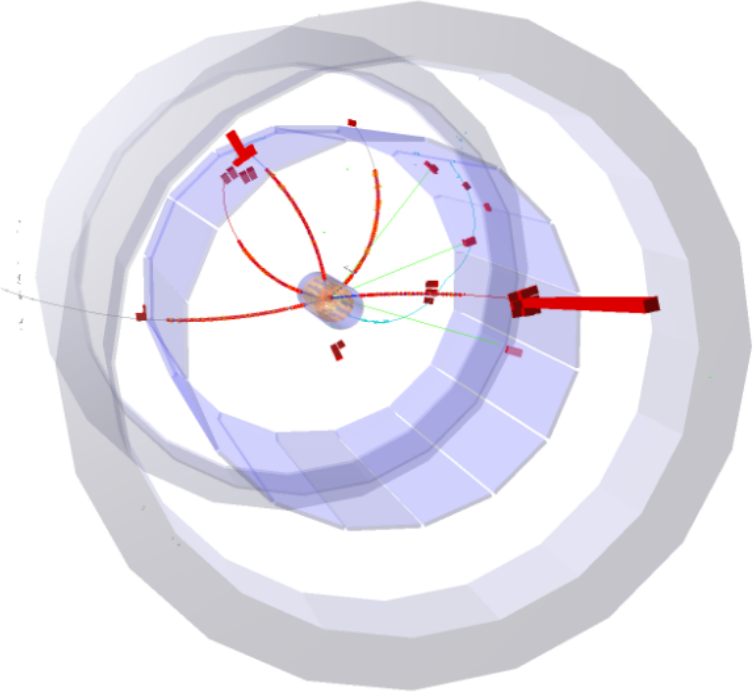
- 40 times increase of luminosity → higher background
- Lower boost → smaller separation between the B mesons

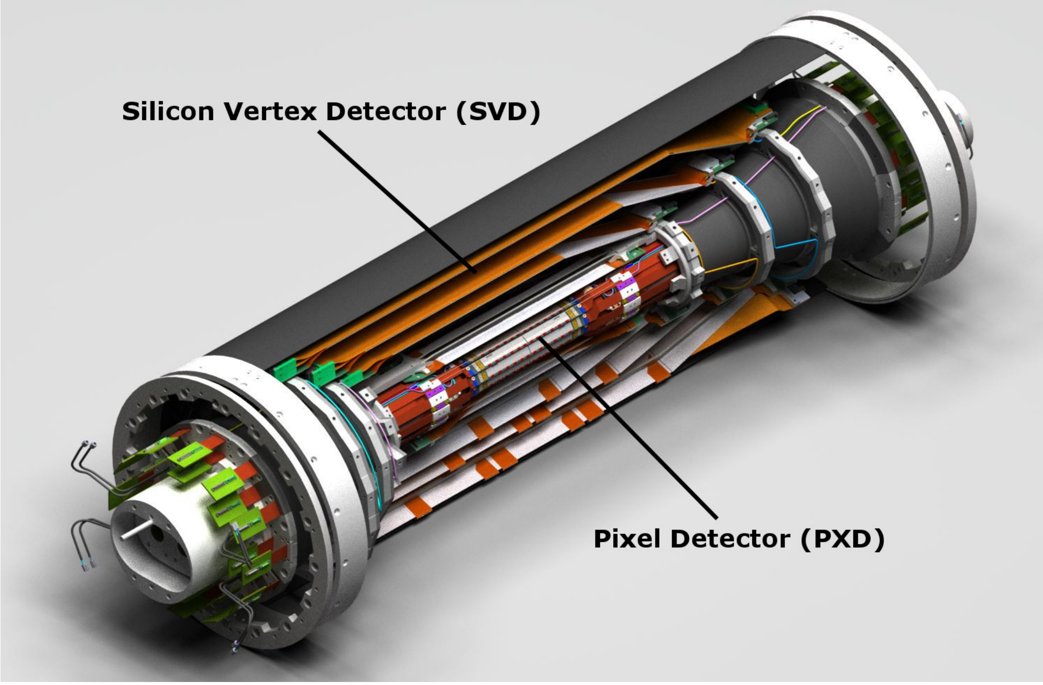
Pixel detector needed

Most suited technology : DEPFET

- Innermost detector system as close as possible to IP
- Highly granular pixel sensors provide most accurate 2D position information

- Reconstruction of primary and secondary vertices of short-lived particles
  - Decay of particles is typical in the order of 100µm from the IP

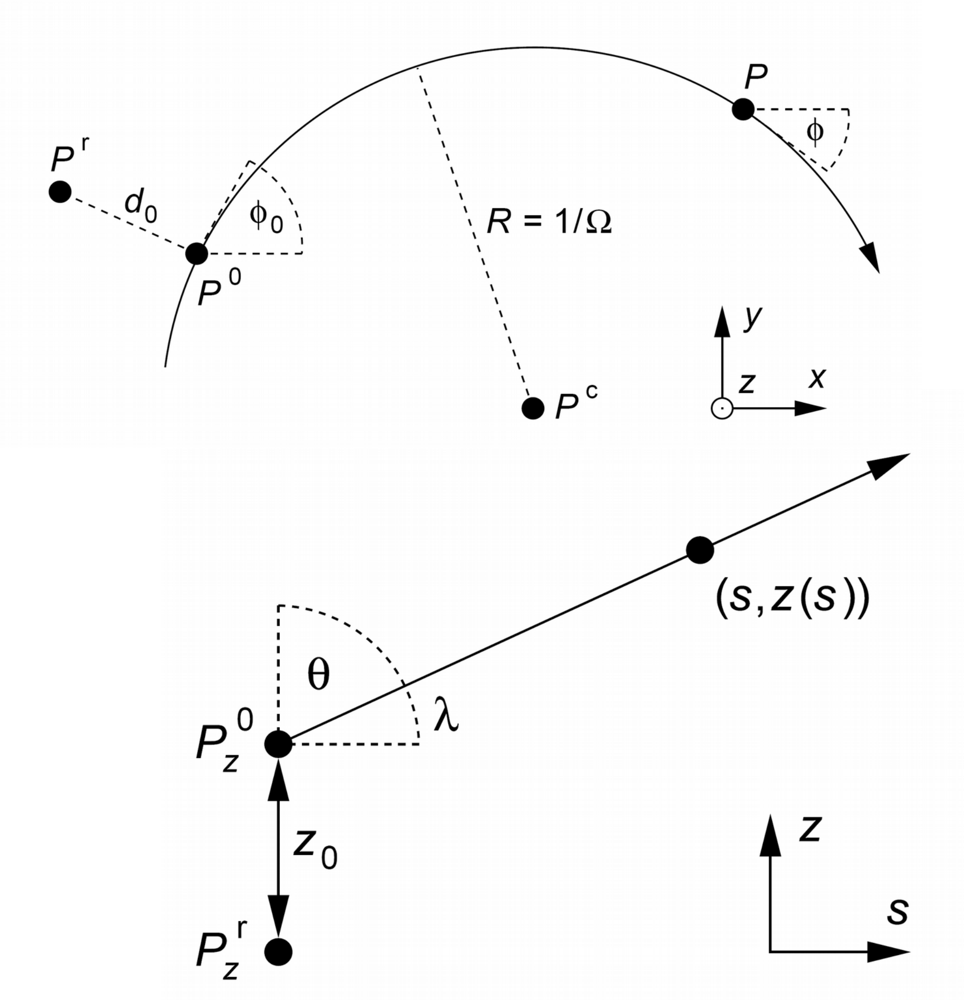


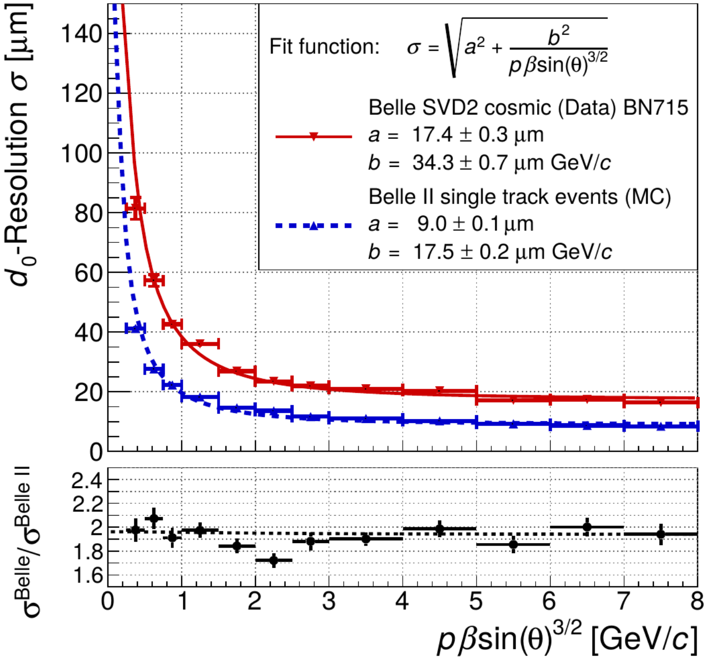


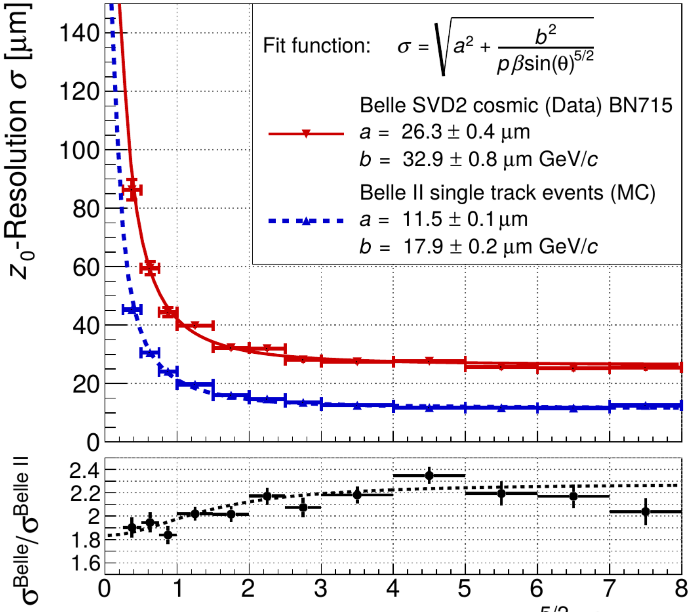
The impact parameter

The impact parameters: d_0 and z_0

- defined as the projections of distance from the point of closest approach to the origin



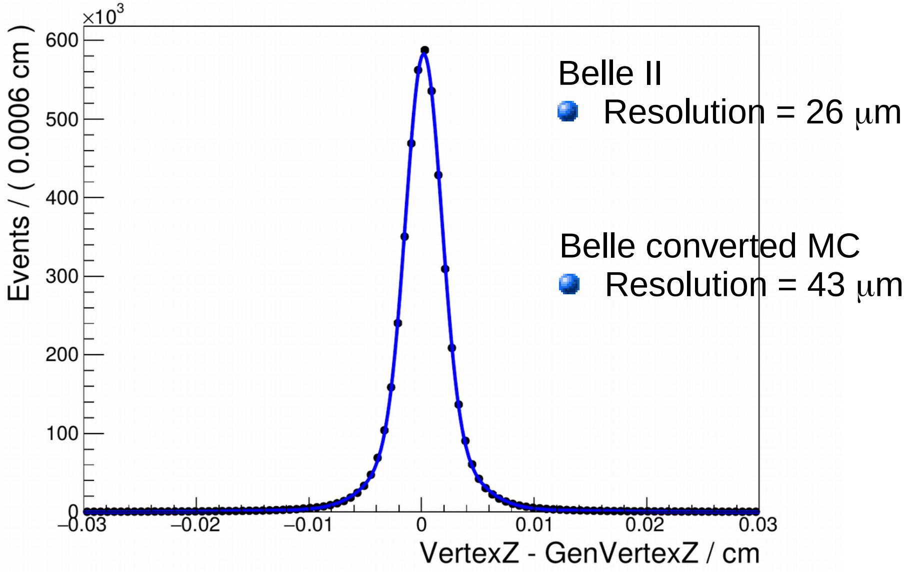




A factor 2 improvement with respect to Belle

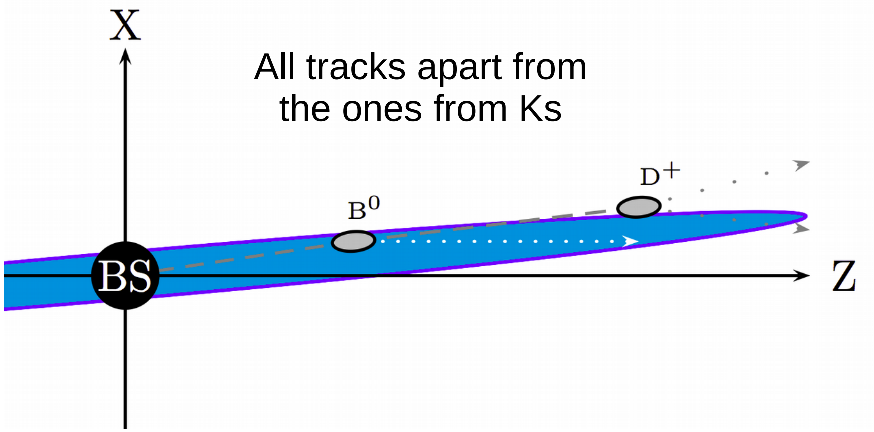
Vertex fit

Kinematic fit: J/ψ → μ μ

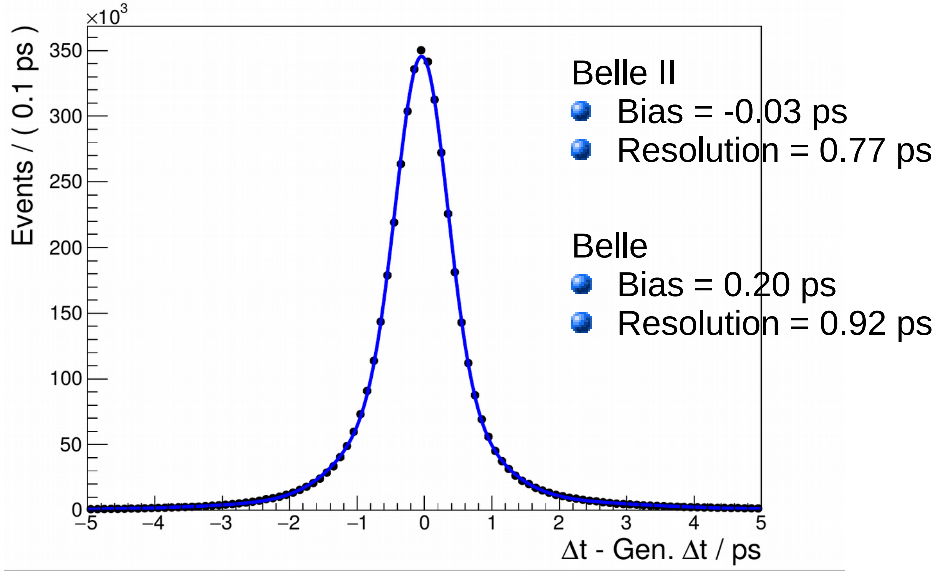


Tag side vertex fit: Using RAVE Adaptive Vertex Fit (AVF) algorithm:

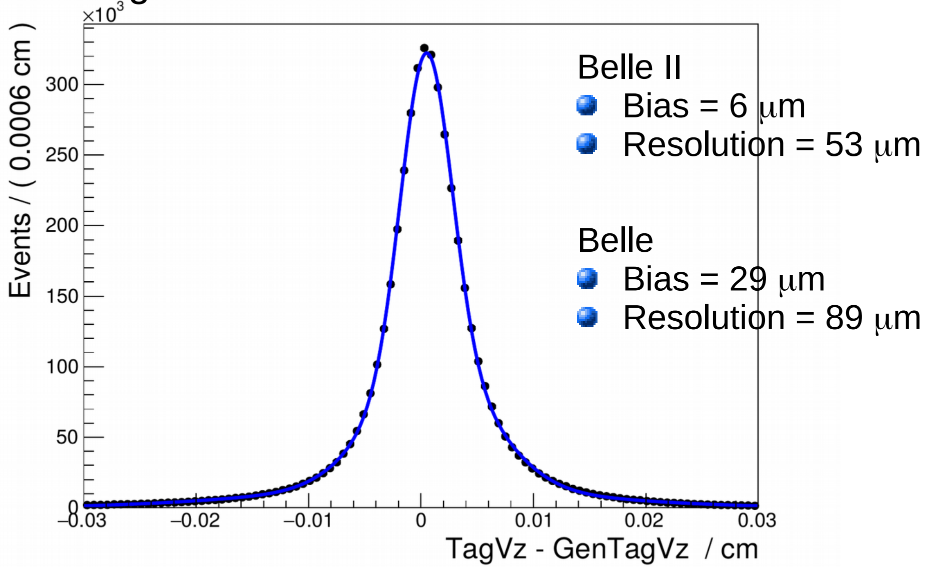
Down-weights outliers dynamically, instead of using hard cutoffs (important for 3+ track vertices). CMS NOTE 2008/033.



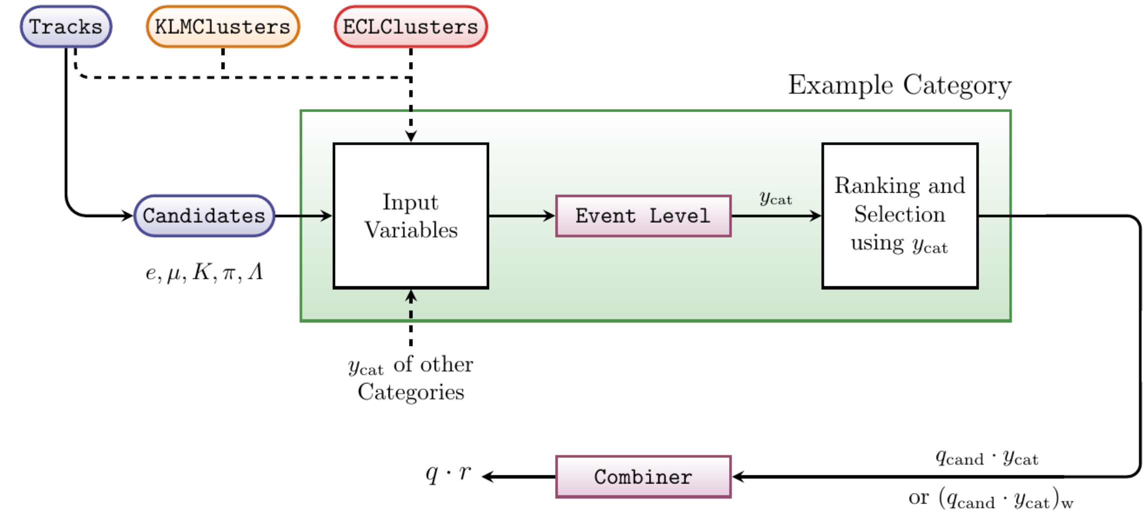
Δt resolution



Tag side vertex fit



Flavor tagger



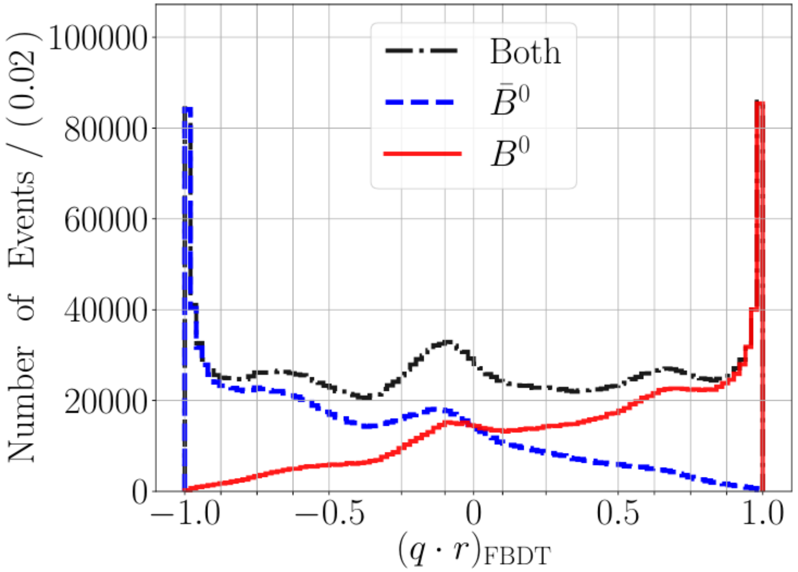
Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	l^-
Intermediate Kinetic Lepton	l^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum P*	l^-, π^-
Fast-Slow-Correlated (FSC)	l^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

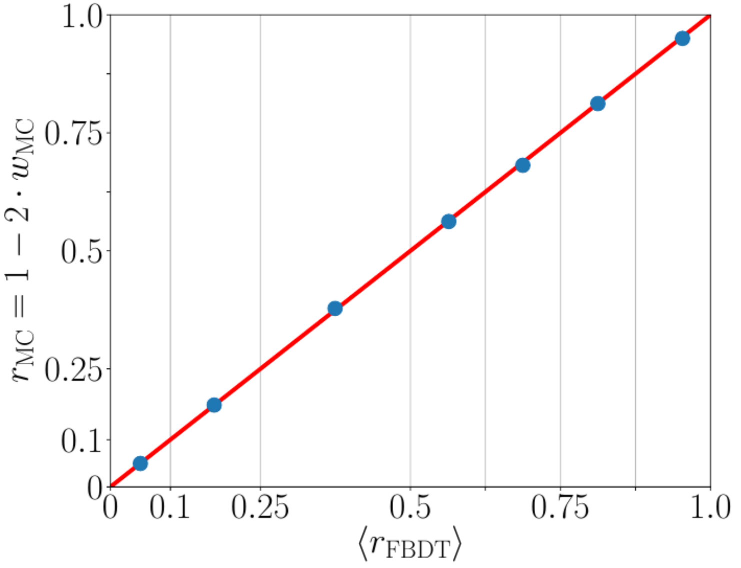
$\overline{B}^0 \to D^{*+}\ \overline{\nu}_\ell\ \ell^-$
$\hookrightarrow D^0\ \pi^+$
$\hookrightarrow X\ K^-$

$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$
$\hookrightarrow K^0\ \nu_\ell\ \ell^+$

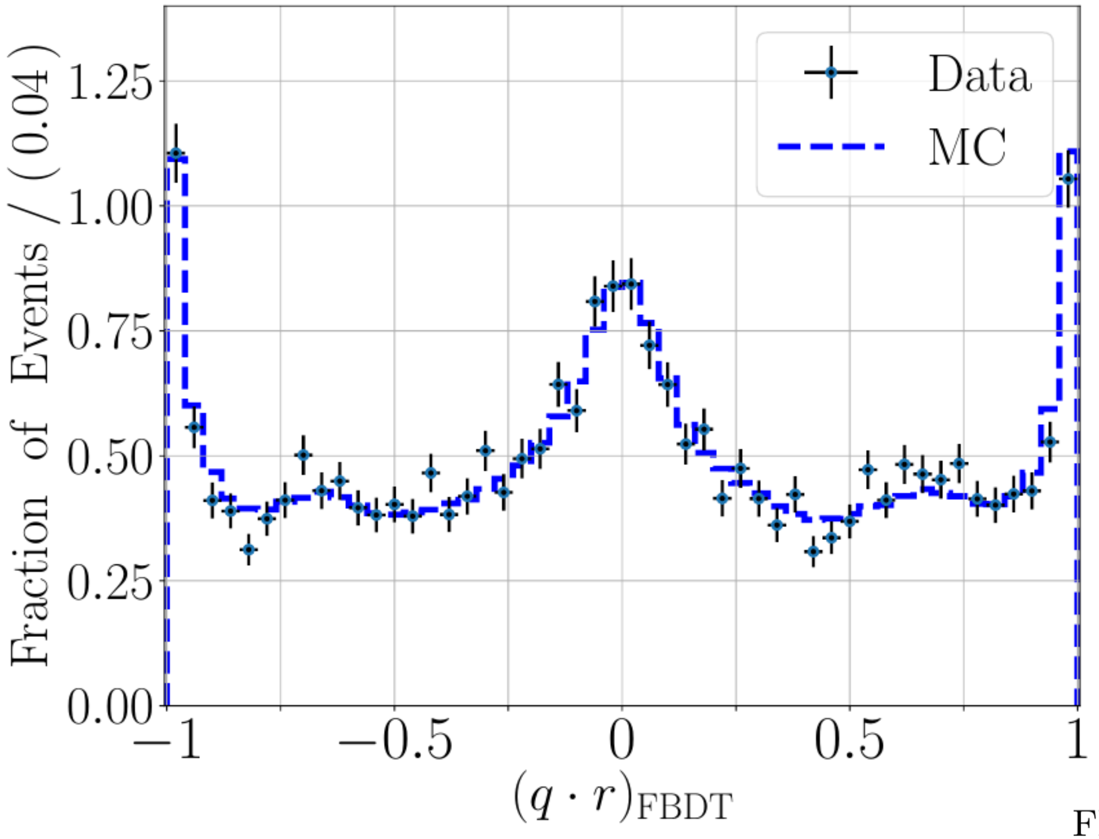
$\overline{B}^0 \to \Lambda_c^+\ X^-$
$\hookrightarrow \Lambda\ \pi^+$
$\hookrightarrow p\ \pi^-$



Belle II MC = 37.16 ± 0.03 %

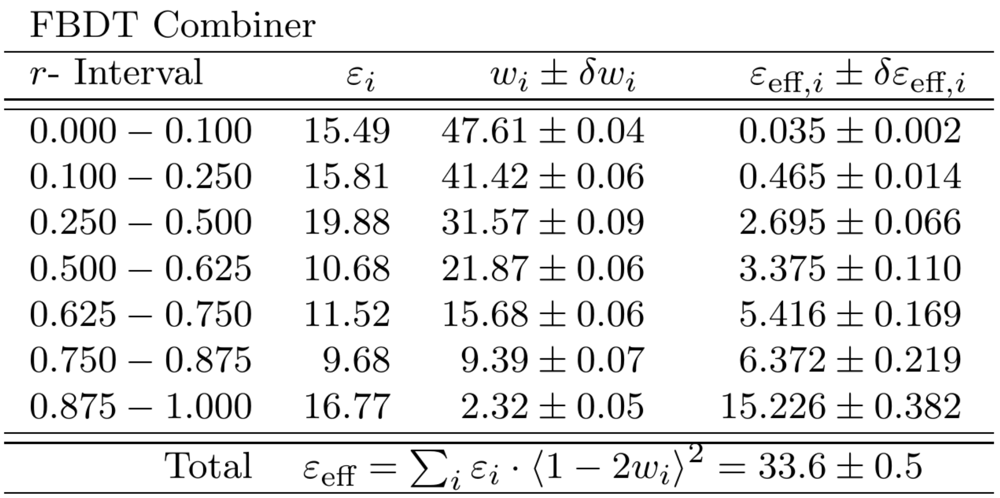


Belle Data – MC comparison



- Belle MC and data
- Belle II flavor tagging algorithm

More than 10% efficiency increase on the same dataset



FBDT Combiner

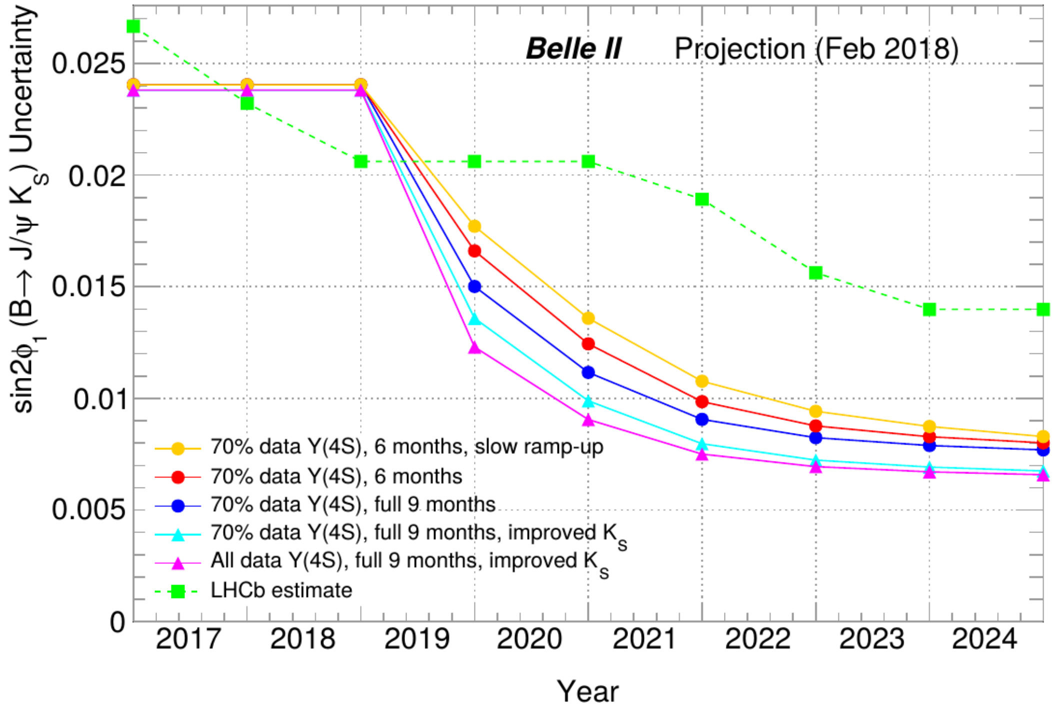
r- Interval	ε_i	$w_i \pm \delta w_i$	$\varepsilon_{\mathrm{eff},i} \pm \delta\varepsilon_{\mathrm{eff},i}$
0.000 – 0.100	15.49	47.61 ± 0.04	0.035 ± 0.002
0.100 – 0.250	15.81	41.42 ± 0.06	0.465 ± 0.014
0.250 – 0.500	19.88	31.57 ± 0.09	2.695 ± 0.066
0.500 – 0.625	10.68	21.87 ± 0.06	3.375 ± 0.110
0.625 – 0.750	11.52	15.68 ± 0.06	5.416 ± 0.169
0.750 – 0.875	9.68	9.39 ± 0.07	6.372 ± 0.219
0.875 – 1.000	16.77	2.32 ± 0.05	15.226 ± 0.382
Total	$\varepsilon_{\mathrm{eff}} = \sum_i \varepsilon_i \cdot \langle 1 - 2w_i \rangle^2 = 33.6 \pm 0.5$		

Efficiency

- Belle Data (assuming linearity) = 33.6 ± 0.5 %
- Belle Converted MC = 34.18 ± 0.03 %
- Belle old FT Data = 30.1 ± 0.4 %
- Belle II MC = 37.16 ± 0.03 %

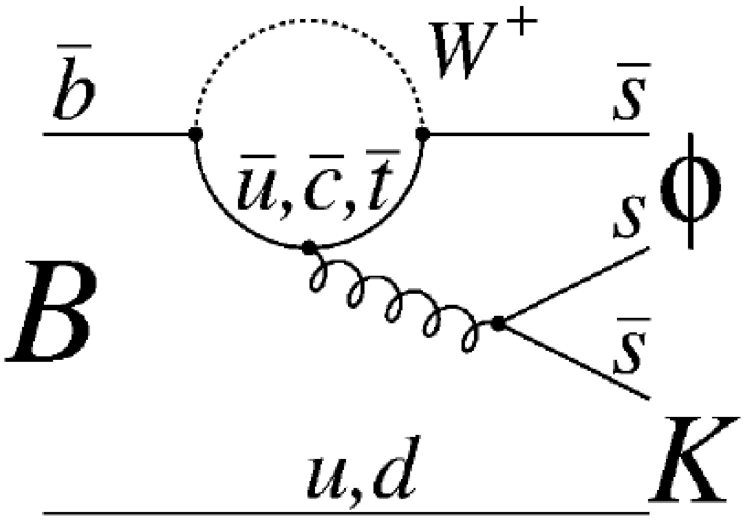
Sin(2β) : expected errors

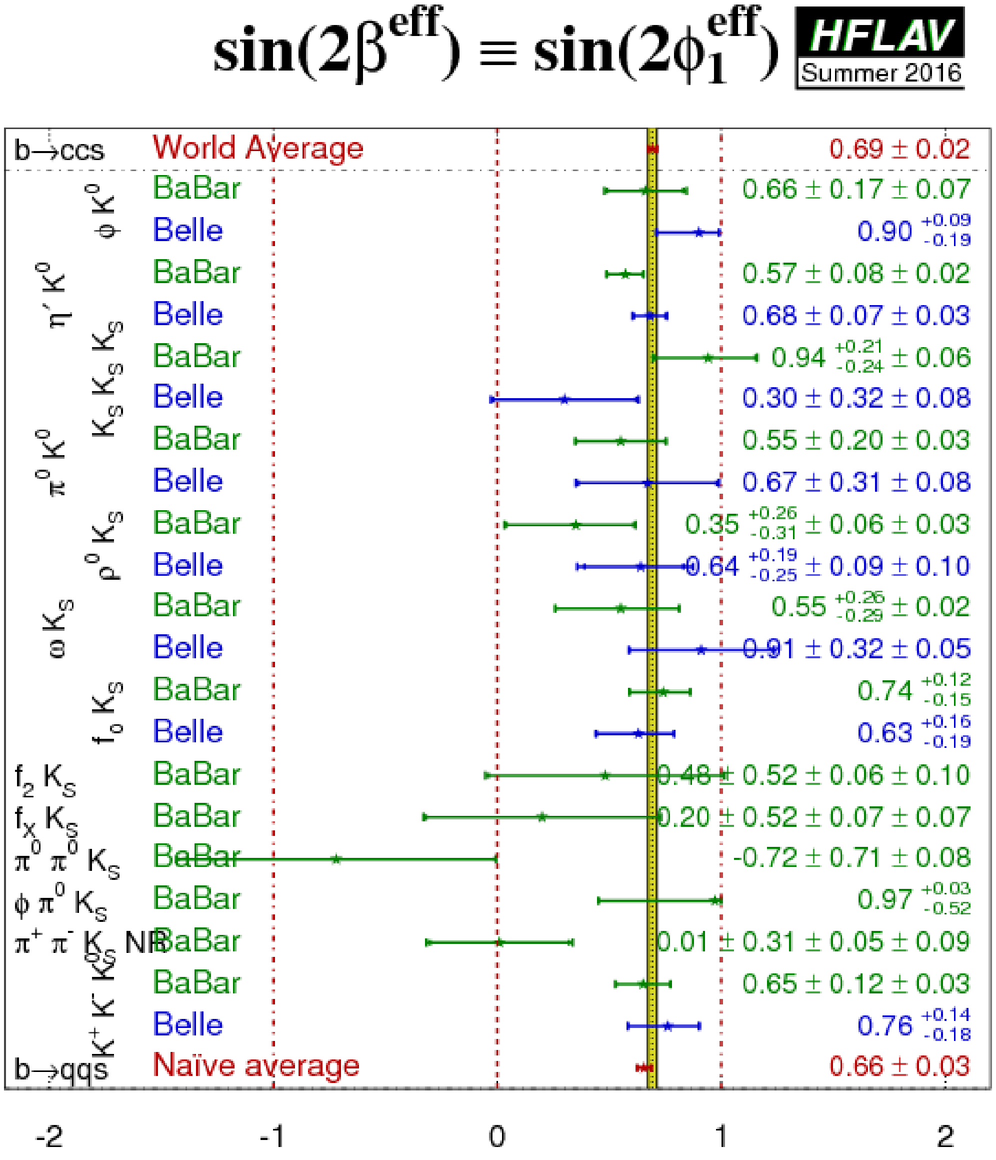
	WA (2017)		$5\ \text{ab}^{-1}$		$50\ \text{ab}^{-1}$	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020



- Sin(2β) will remain the most precise measurement on the Unitarity Triangle parameters
- In Belle II the measurement will be dominated by systematics
  - Effort concentrated in understand and reducing them
  - A precision of 1% is expected using the b → $c\bar{c}s$ decay modes

Sin(2β): $b \to q\bar{q}s$



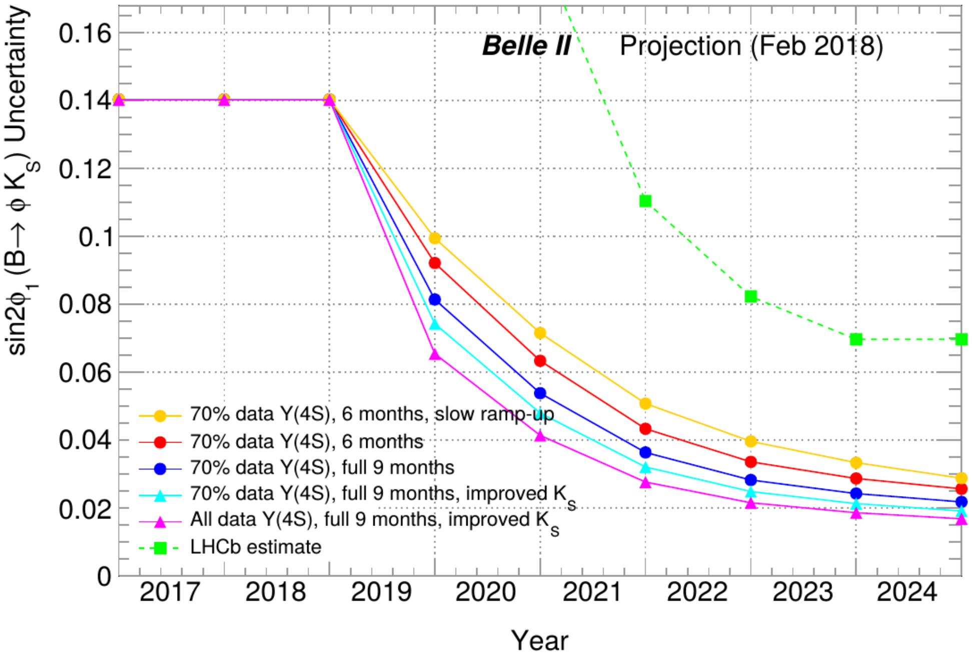


In principle measures sin2β, but sensitive to new physics

B^0 → ϕ Ks: expected sensitivity

Channel	ε_{reco}	Yield	$\sigma(S)$
1 ab^{-1} scenario:			
$\phi(K^+K^-)K_S(\pi^+\pi^-)$	35%	456	0.174
$\phi(K^+K^-)K_S(\pi^0\pi^0)$	25%	153	0.295
$\phi(\pi^+\pi^-\pi^0)K_S(\pi^+\pi^-)$	28%	109	0.338
K_S modes combination			0.135
$K_S + K_L$ modes combination			0.108
5 ab^{-1} scenario:			
$\phi(K^+K^-)K_S(\pi^+\pi^-)$	35%	2280	0.078
$\phi(K^+K^-)K_S(\pi^0\pi^0)$	25%	765	0.132
$\phi(\pi^+\pi^-\pi^0)K_S(\pi^+\pi^-)$	28%	545	0.151
K_S modes combination			0.060
$K_S + K_L$ modes combination			0.048

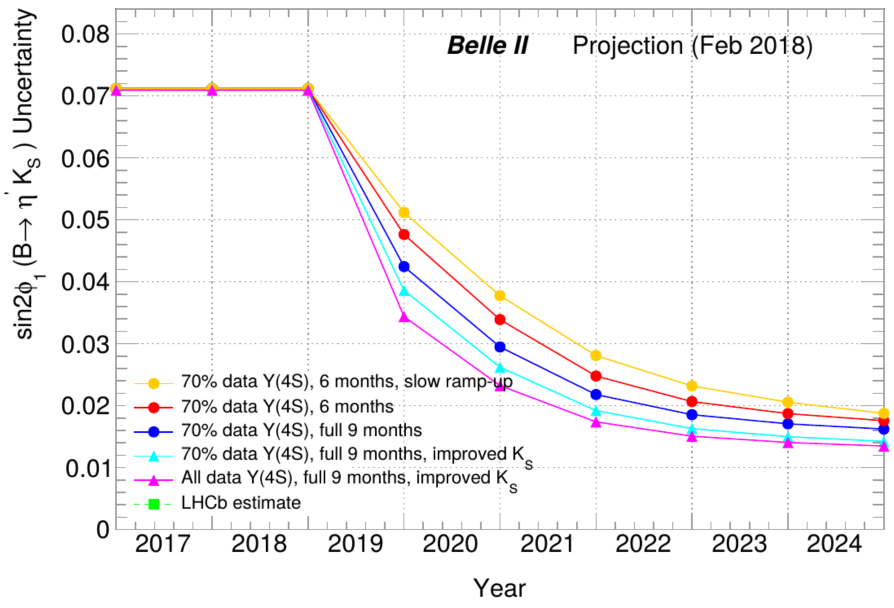
we estimate the expected yield of ϕK_L^0 based on previous BaBar and Belle analyses (but use the same Δt resolution we estimate in $\phi \to K^+K^-$ for Belle II).

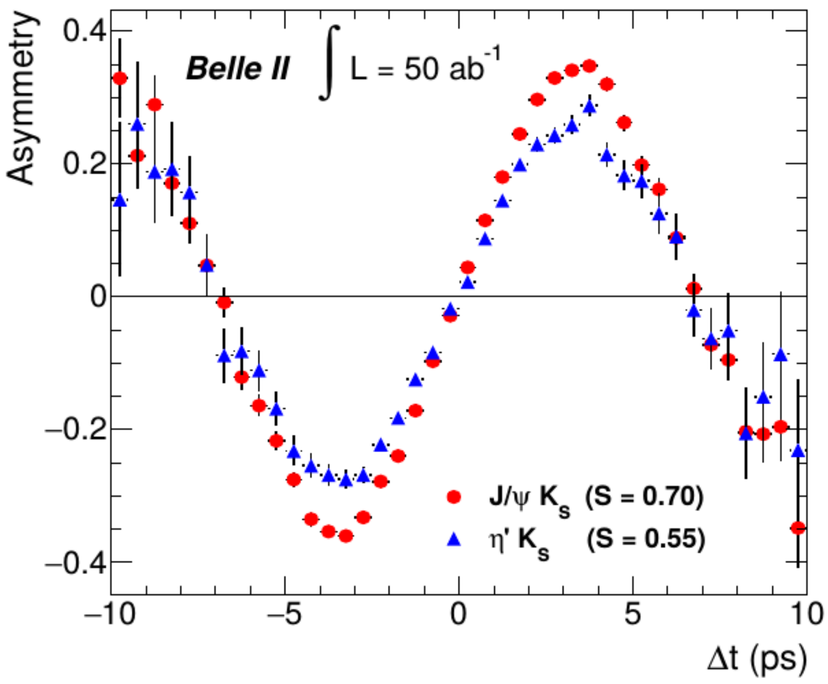


Belle II projection

Sensitivity study

$B^0 \rightarrow \eta' K_s$: expected sensitivity





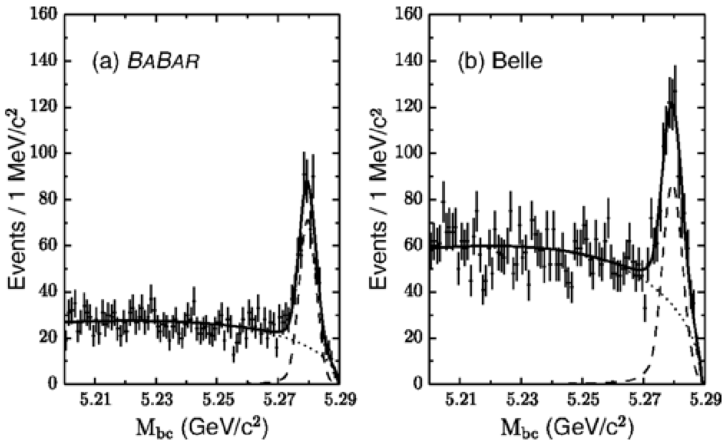
Similar Belle sensitivity given the same integrated luminosity

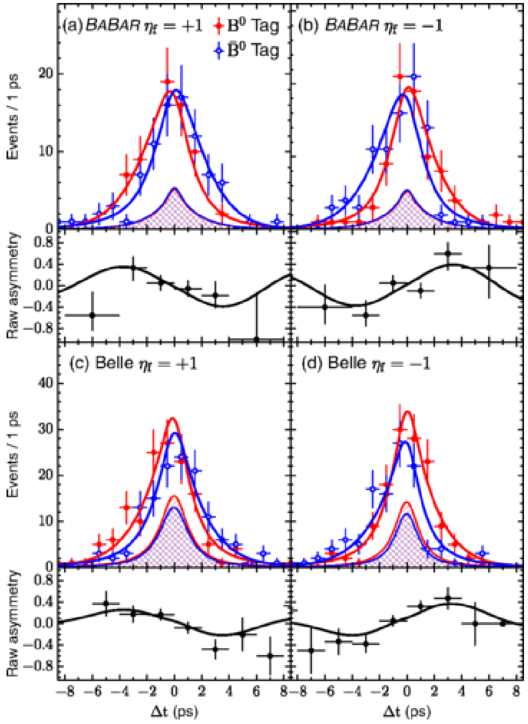
Channel	yield	$\sigma(S_f)$	$\sigma(A_f)$
$1\ \mathrm{ab}^{-1}$			
$\eta'(\eta_{\gamma\gamma}\pi^\pm)K_S^{(\pm)}$	969	0.13	0.08
$\eta'(\eta_{\gamma\gamma}\pi^\pm)K_S^{(00)}$	215	0.27	0.17
$\eta'(\eta_{3\pi}\pi^\pm)K_S^{(\pm)}$	283	0.25	0.16
$\eta'(\rho\gamma)K_S^{(\pm)}$	2100	0.09	0.05
$\eta'(\rho\gamma)K_S^{(00)}$	320	0.22	0.14
K_S^0 modes	3891	0.065	0.040
K_L^0 modes	1546	0.17	0.11
$K_S^0 + K_L^0$ modes	5437	0.060	0.038
$5\ ab^{-1}$			
$\eta'(\eta_{\gamma\gamma}\pi^\pm)K_S^{(\pm)}$	4840	0.06	0.04
$\eta'(\eta_{\gamma\gamma}\pi^\pm)K_S^{(00)}$	1070	0.12	0.09
$\eta'(\eta_{3\pi}\pi^\pm)K_S^{(\pm)}$	1415	0.11	0.08
$\eta'(\rho\gamma)K_S^{(\pm)}$	10500	0.04	0.03
$\eta'(\rho\gamma)K_S^{(00)}$	1600	0.10	0.07
K_S^0 modes	19500	0.028	0.021
K_L^0 modes	7730	0.08	0.05
$K_S^0 + K_L^0$ modes	27200	0.027	0.020

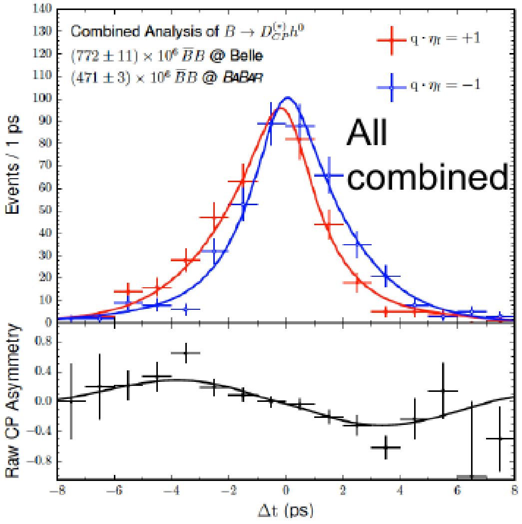
BaBar + Belle $B^0 \to D_{CP}\ h^0$

Phys. Rev. Lett. 115, 121604

- Leading order: tree
- Sub-leading order: tree, phase within the SM
- Independent form NP in loops
- Suitable to measure β
- Branching fraction is the limiting factor







B0 → $D(*)^0\ h^0$, $h^0=\pi^0$, η, ω
$D^0 \to K^+K^-$, Ks π^0 and Ks ω
Yields =

- 508±31events(BaBar)
- 757±44events(Belle)

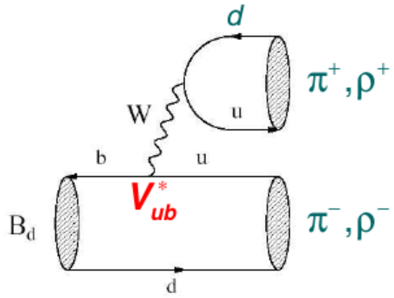
$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.}),$$
$$\mathcal{C} = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.}).$$

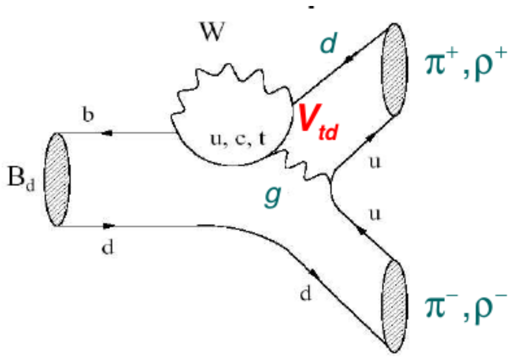
- First observation of CPV(5.4σ)
- Belle II : δ(β) ~ 0.015
- Important test for $b \to c\bar{c}s$

Measurement of α

M. Gronau and D. London, PRL 65 3381 (1990)

Proceeds mainly through b→u$\bar{u}$d tree diagram,
but penguin contributions introduce additional phases





Used decay modes:

- B → π π
- B → ρ ρ
- B → ρ π

Extra weak and strong phases + |P/T| modify α by Δα:

$\sin(2\alpha) \rightarrow \sin(2\alpha_{\text{eff}}) \quad \alpha_{\text{eff}} = \alpha + \Delta\alpha$

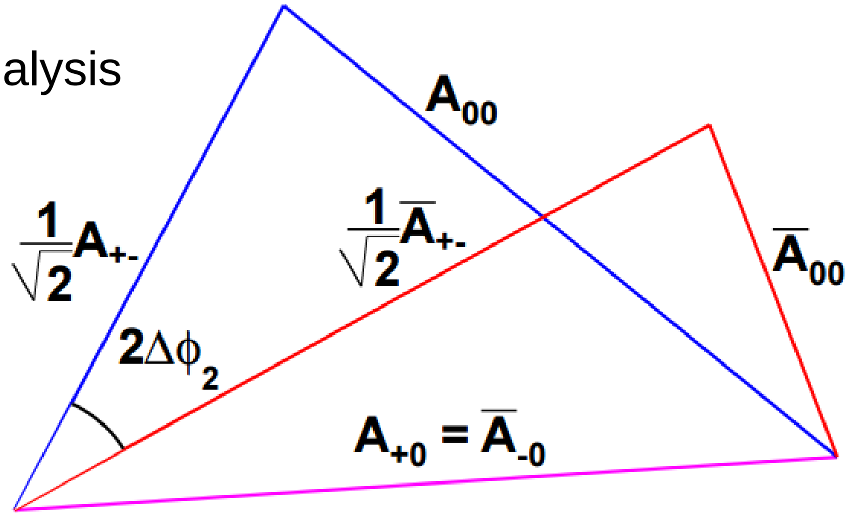
To relate α to α_{eff}:

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

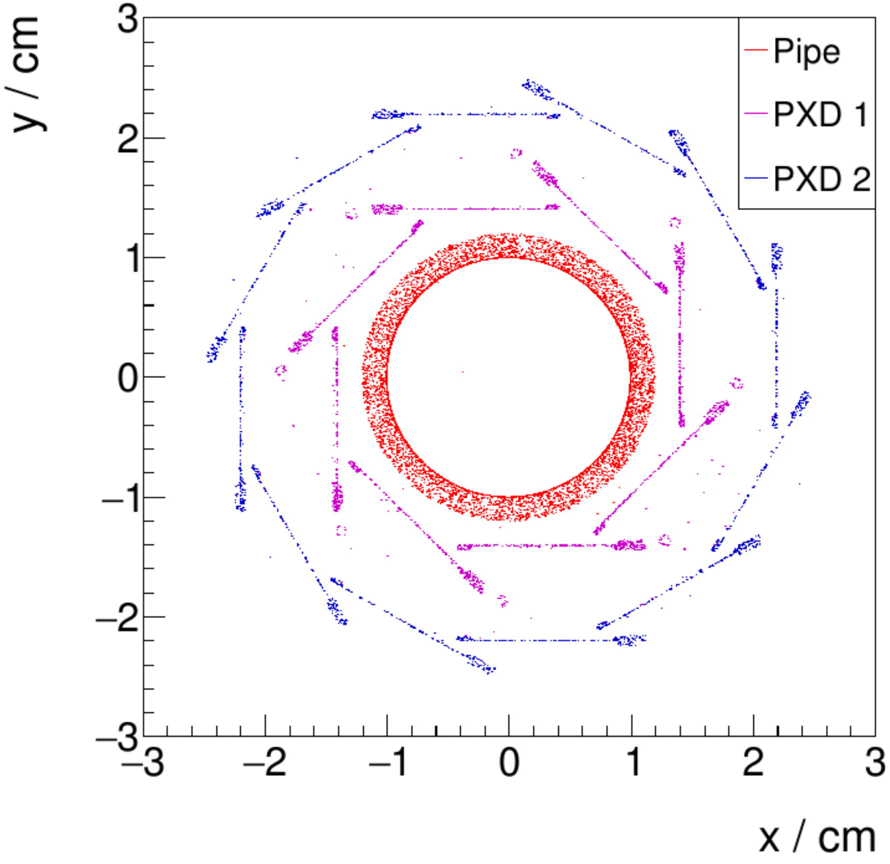
$$\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$$

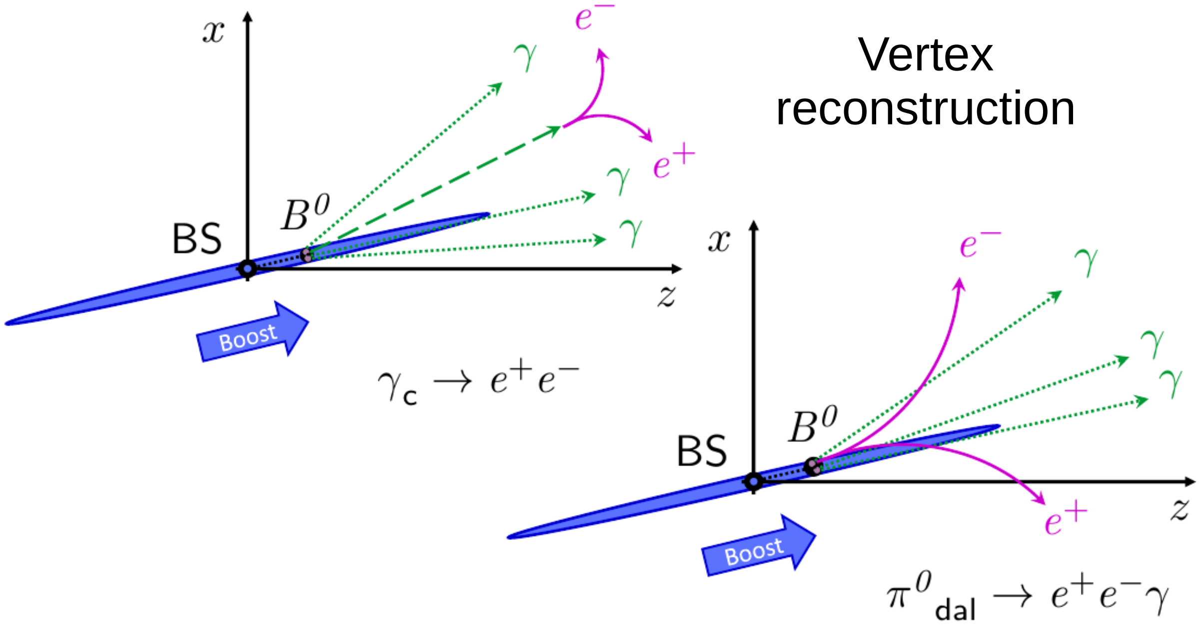
$$A^{+0} = \bar{A}^{-0} \text{ (pure tree)}$$

Isospin analysis



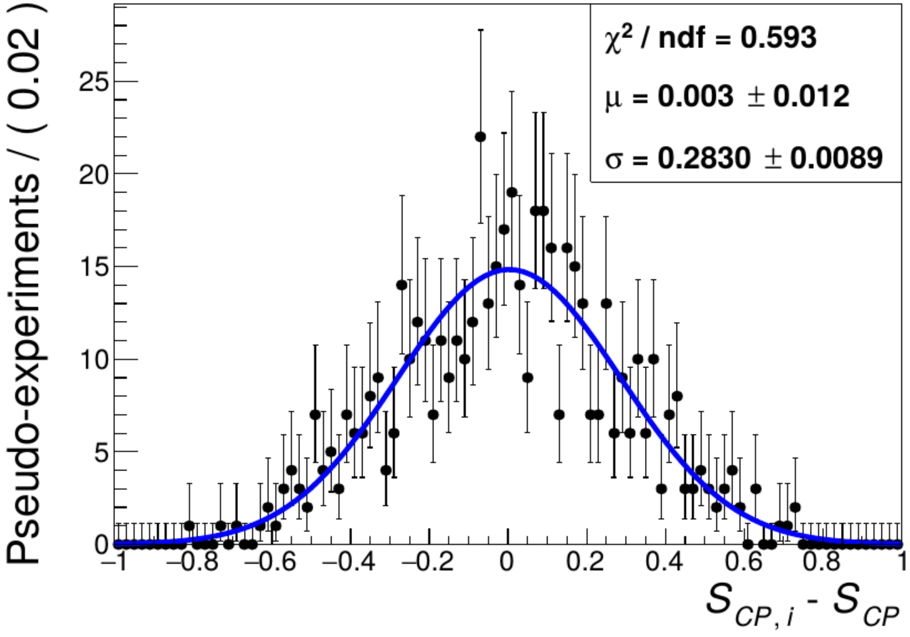
$B^0 \rightarrow \pi^0\pi^0$: converted photons



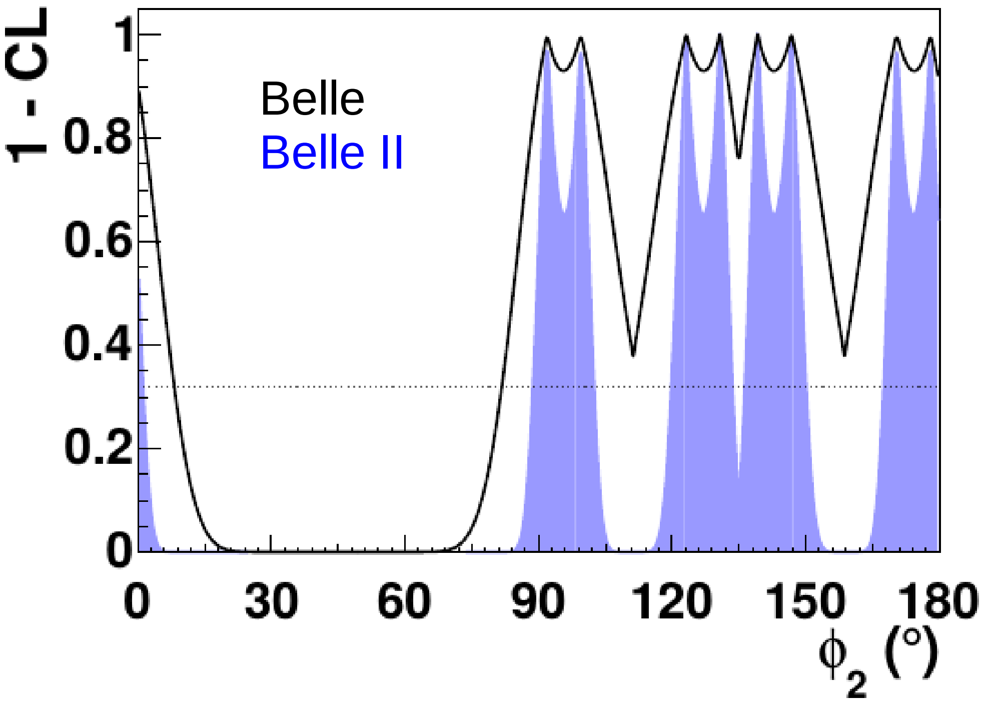


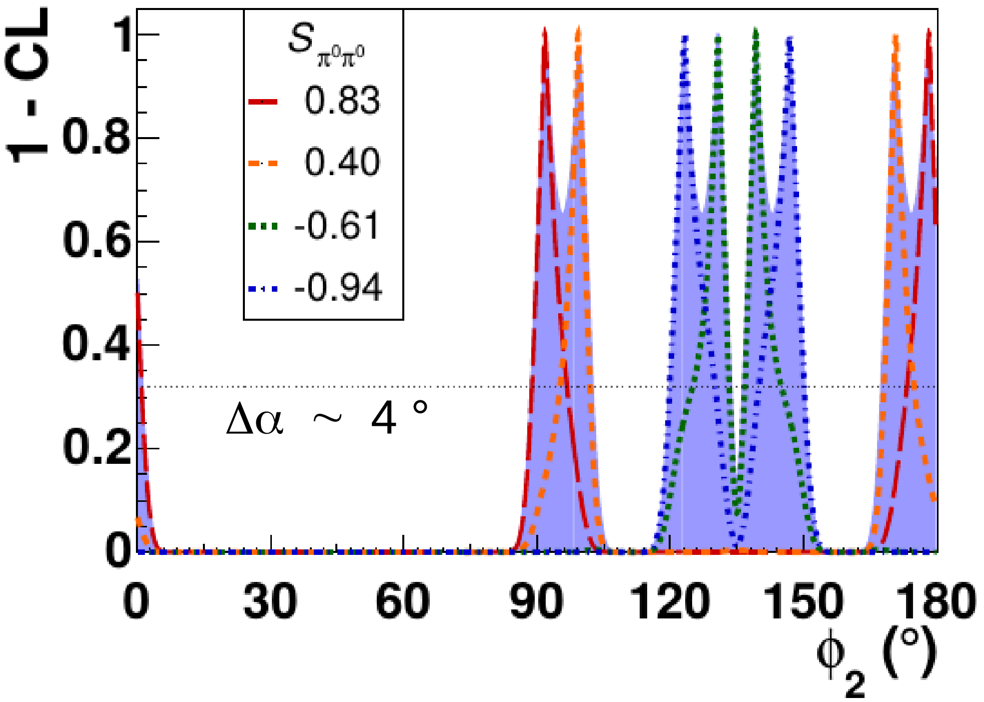
Vertex reconstruction

- Photon conversion inside the Belle II detector (Beam pipe + PXD)
- 3 % of $B^0 \rightarrow \pi^0\,\pi^0$ events
- ~ 5 % including π^0 Dalitz decay
- Reconstruction efficiency will be crucial



Isospin analysis: B → π π





	Value	0.8 ab^{-1}	50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm 0.21 \pm 0.18$ [79]	$\pm 0.03 \pm 0.08$
$\mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.31	$\pm 0.19 \pm 0.18$ [78]	$\pm 0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm 0.26 \pm 0.38$ [79]	$\pm 0.03 \pm 0.09$
$C_{\pi^+\pi^-}$	-0.33	$\pm 0.06 \pm 0.03$ [80]	$\pm 0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$ [80]	$\pm 0.01 \pm 0.01$
$C_{\pi^0\pi^0}$	-0.14	$\pm 0.36 \pm 0.12$ [78]	$\pm 0.03 \pm 0.01$

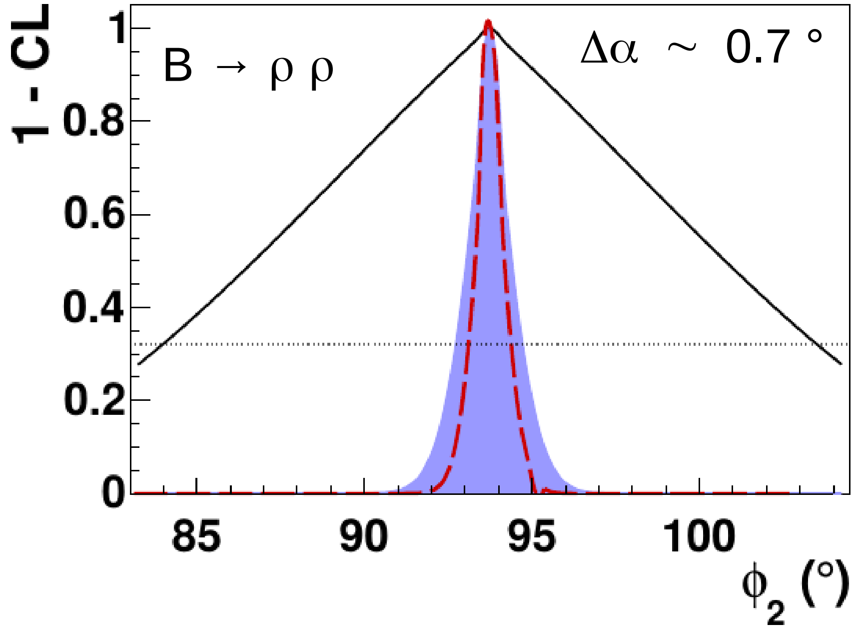
$\Delta S(\pi^0\pi^0) = \pm 0.28 \pm 0.03$

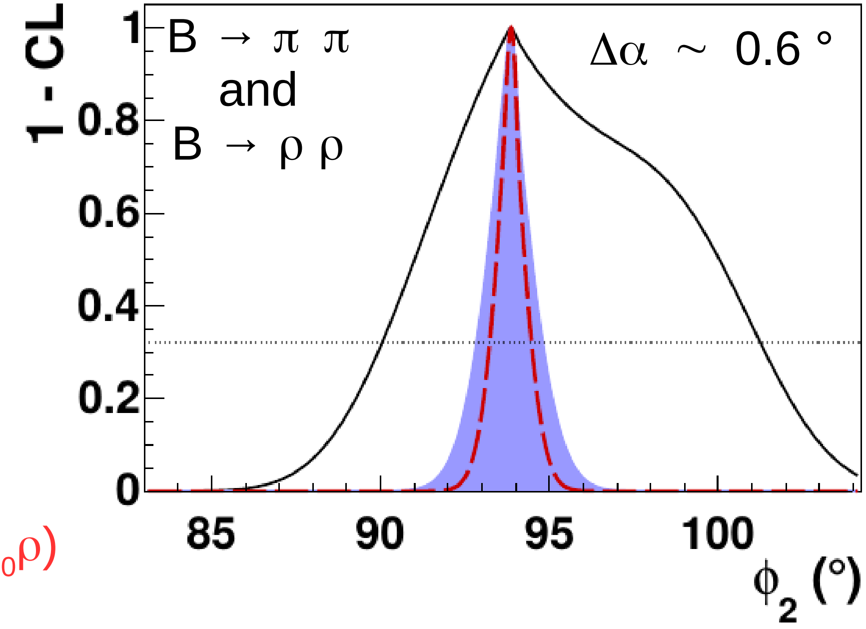
78: arXiv:1705.02083
79: Phys. Rev., D87(3), 031103 (2013)
80: Phys. Rev., D88(9), 092003 (2013)

Isospin analysis: $B \to \rho\ \rho$

	Value	0.8 ab^{-1}	50 ab^{-1}
$f_{L,\rho^+\rho^-}$	0.988	$\pm0.012 \pm 0.023$ [74]	$\pm0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm0.20 \pm 0.15$ [81]	$\pm0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm1.5 \pm 1.5$ [74]	$\pm0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ [10^{-6}]	1.02	$\pm0.30 \pm 0.15$ [81]	$\pm0.04 \pm 0.02$
$C_{\rho^+\rho^-}$	0.00	$\pm0.10 \pm 0.06$ [74]	$\pm0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm0.15 \pm 0.05$ [74]	$\pm0.02 \pm 0.01$
	Value	0.08 ab^{-1}	50 ab^{-1}
$f_{L,\rho^+\rho^0}$	0.95	$\pm0.11 \pm 0.02$ [65]	$\pm0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm7.1 \pm 5.3$ [65]	$\pm0.3 \pm 0.5$
	Value	0.5 ab^{-1}	50 ab^{-1}
$C_{\rho^0\rho^0}$	0.2	$\pm0.8 \pm 0.3$ [64]	$\pm0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm0.7 \pm 0.2$ [64]	$\pm0.07 \pm 0.01$

64: Phys. Rev., D78, 071104 (2008)
65: Phys. Rev. Lett., 91, 221801 (2003)
74: Phys. Rev., D93(3), 032010 (2016)
81: [Addendum: Phys. Rev.D89,no.11, 119903(2014)] (2012),

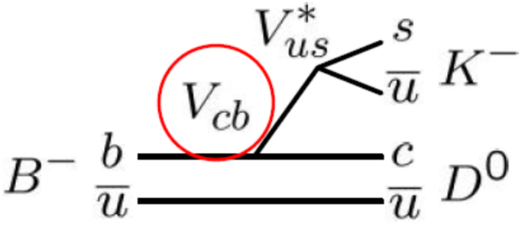




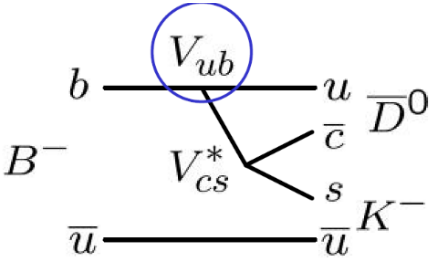
Belle Belle II Belle II + ($S_{00}\pi$ & $S_{00}\rho$)

Measurement of γ with $B \rightarrow D^0 K$

γ is the phase between b → u and b → c

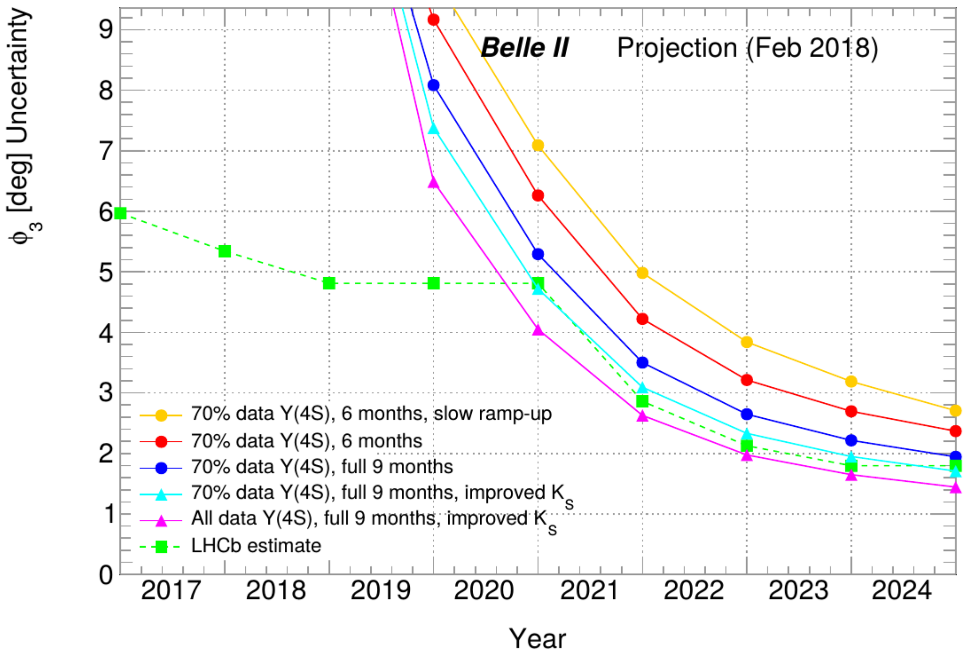


$e^{i\delta_B}\ e^{-i\gamma}$

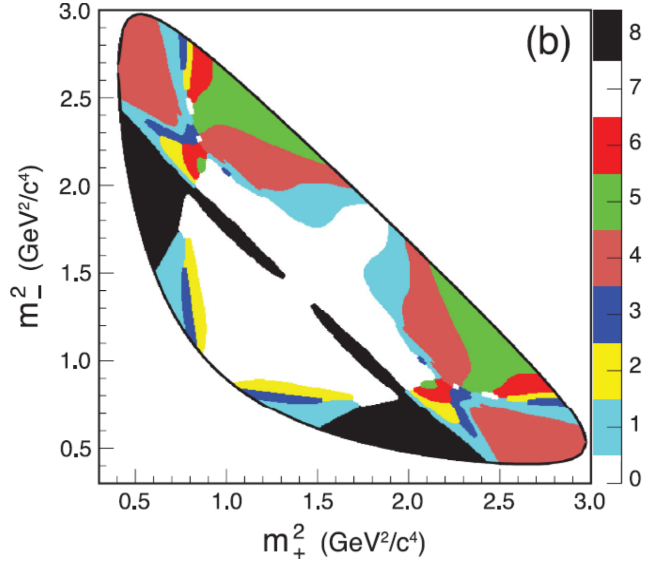


Interference between these amplitudes with $D^0/\overline{D}^0$ decaying in the same final state

- From tree level processes
- Not affected from NP in loops



Strong phase differences can be measured at a charm factory



- CLEO result Phys. Rev. D 82, 112006(2010)
- Improvement expected from BES III

An error of 1.6° is expected

- Including more $D^{(*)}$ decay modes
- Integrated luminosity = 50 ab^{-1}
- Assuming BES III will collect 10 fb^{-1}

Photon polarization

Radiative B decays, with b→s γ transitions, dominated by loop (penguin) diagrams
New physics could enter at same order (1-loop) as Standard Model

Standard Model makes definite prediction of photon helicity
(D. Atwood et al., Phys. Rev. Lea. 79, 185 (1997)):

- $B^0 \rightarrow X_s \gamma_R$
- $\overline{B}^0 \rightarrow X_s \gamma_L$

If a helicity flip occurs, the photon will also flip its helicity, producing $B^0 \rightarrow X_s \gamma_L$

- Rate ~ m_s/m_b at the leading contribution (P. Ball and R. Zwicky, Phys. Lea. B 642, 478 (2006))
- Corrections can increase this value

No common final state for B^0 and $\overline{B}^0$

- Suppression of asymmetry S due to interference between B^0 mixing and decay diagrams (TD CP asymmetry)

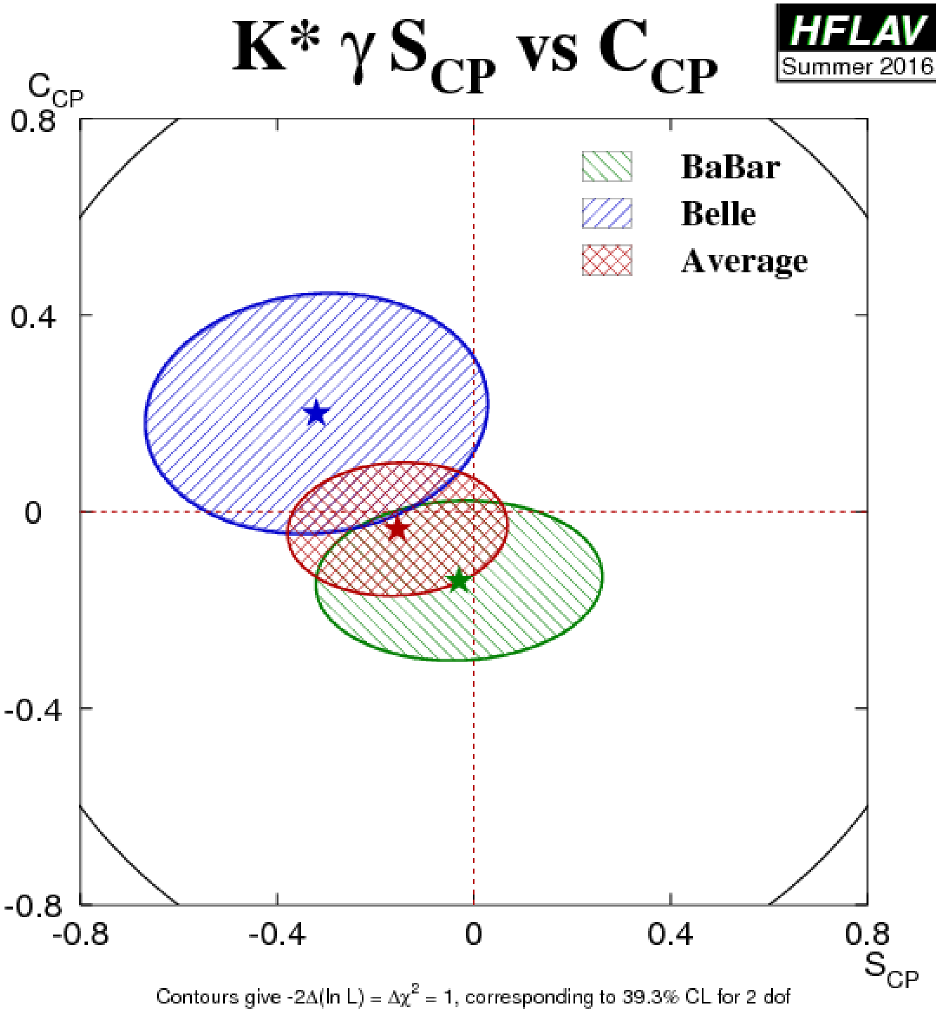
$$S^{\rm SM}_{K^0_S\pi^0\gamma} \sim -2\frac{m_s}{m_b}\sin 2\phi_1 = -(2.3 \pm 1.6)\%$$

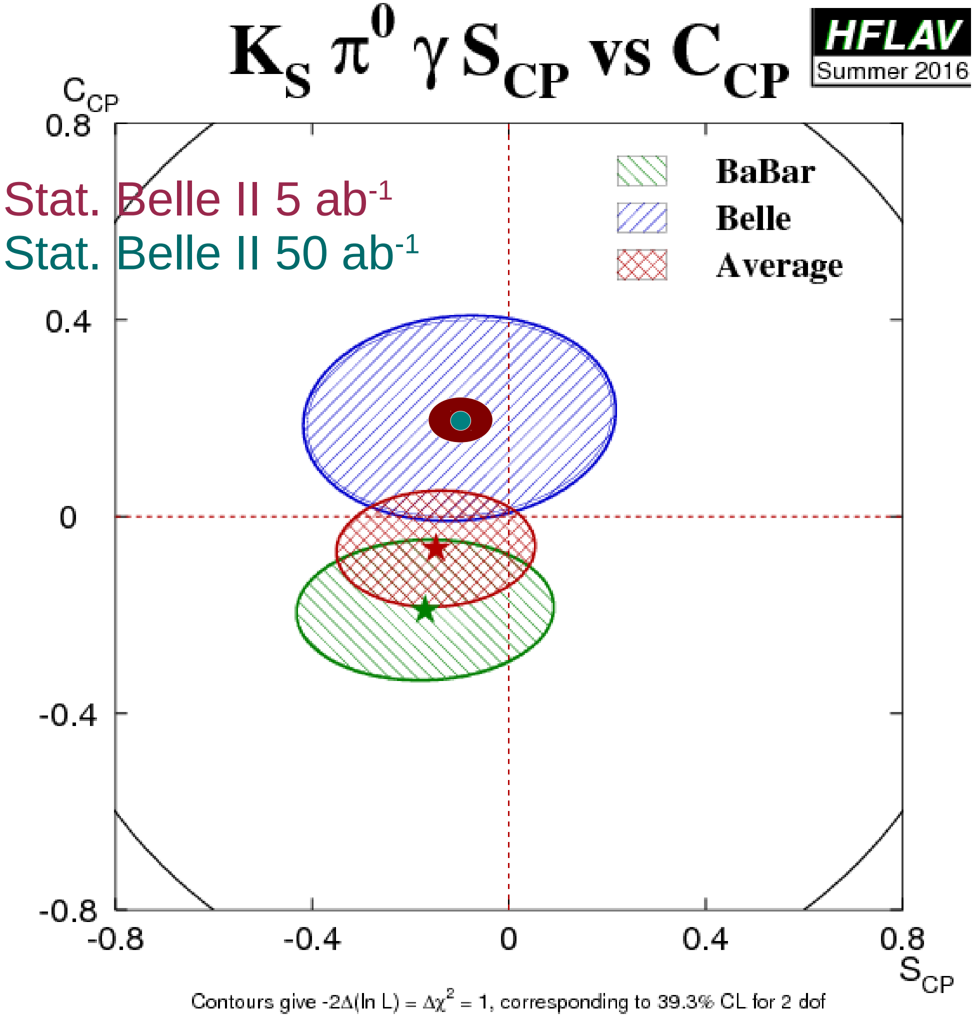
P. Ball, G. W. Jones, and R. Zwicky, Phys. Rev., D75, 054004 (2007)

C < 0.01 (direct CP violation) (Greub at al., Nucl. Phys B 434, 39 (1995))

- TD CP asymmetry measurements give an indirect measurement of photon polarization

$B^0 \rightarrow Ks\ \pi^0\ \gamma$

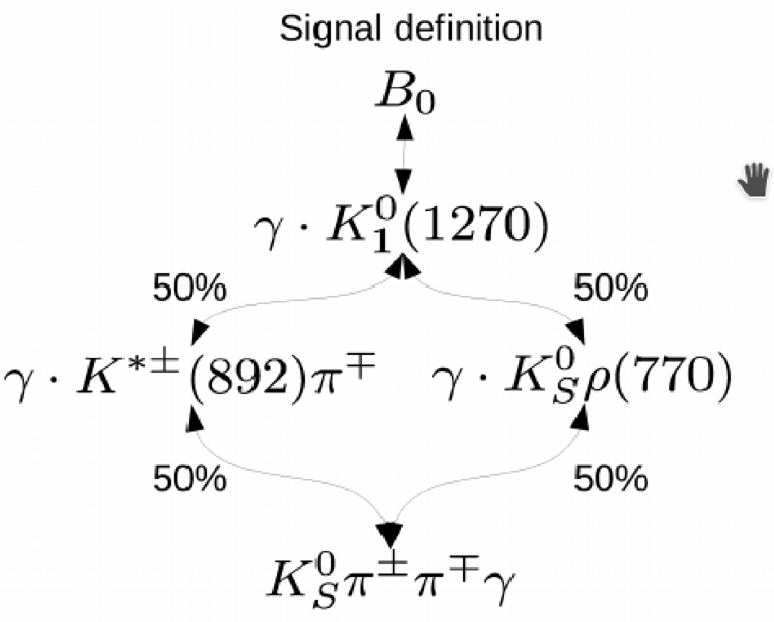


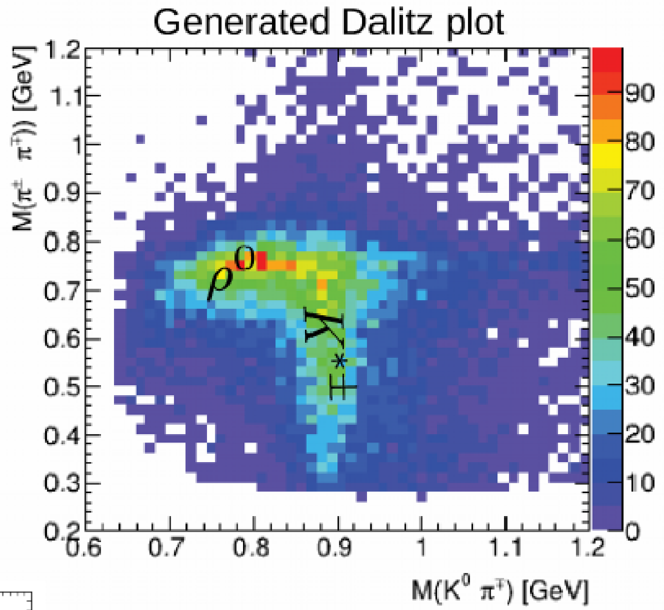


Very important decay mode for Belle II

$B^0 \rightarrow Ks\ \pi^+\ \pi^- \gamma$

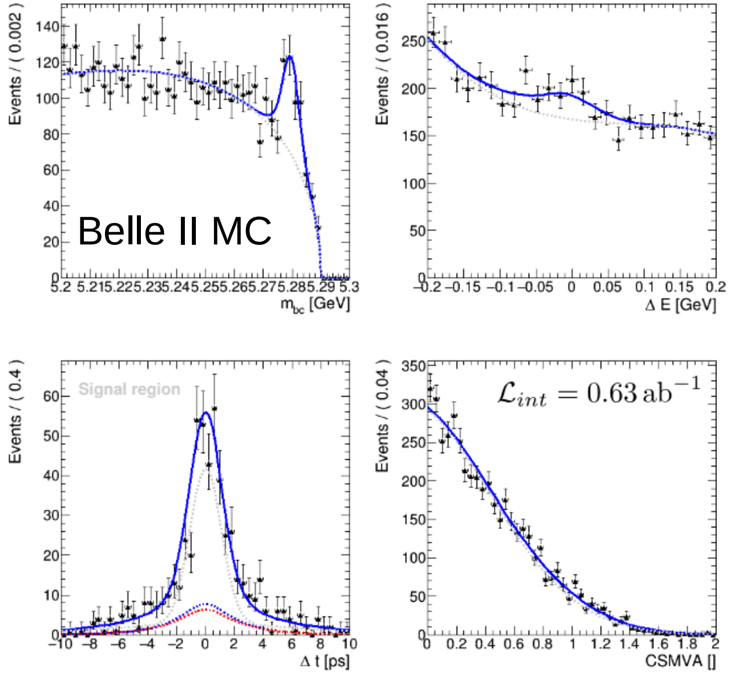
BaBar: PRD 93 (2016) 052013
Belle: PRL 101 (2008) 251601

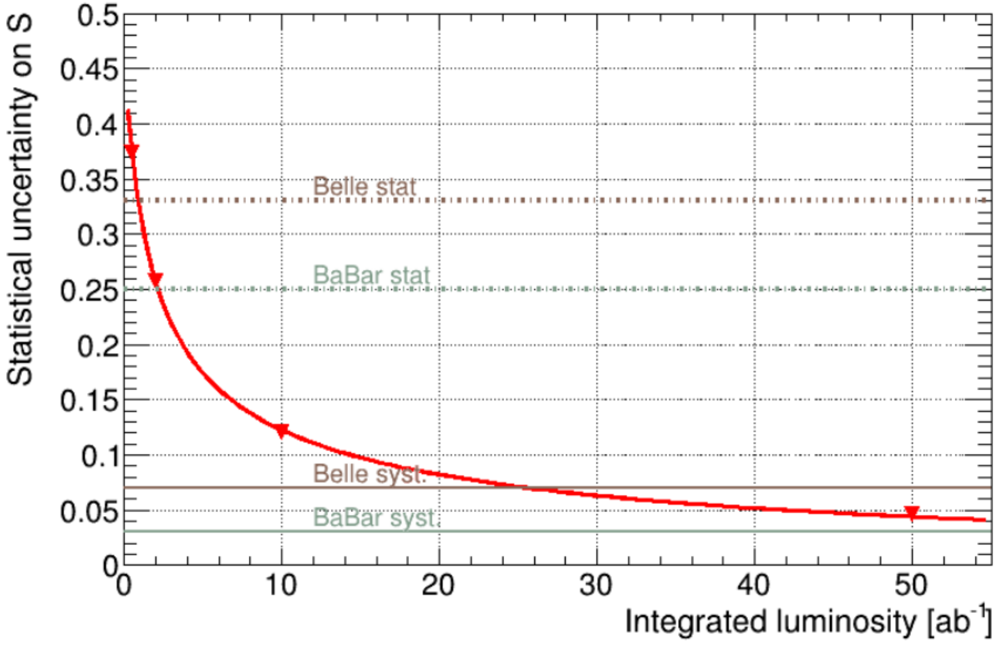




- TDCVP analysis
- Fit the Dalitz plot
- Maximize the sensitivity

Complete sensitivity study

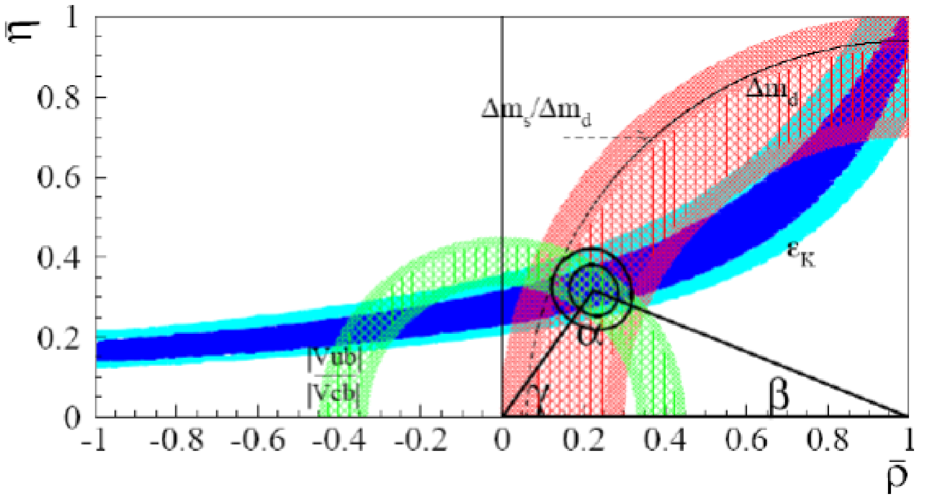




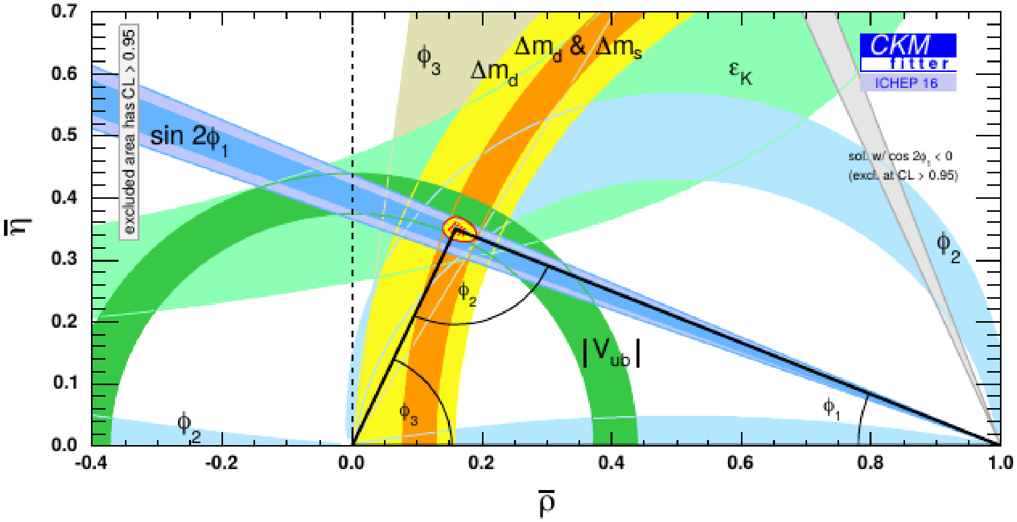
Outlook

The Belle II Physics Book: https://confluence.desy.de/display/BI/B2TiP+WebHome

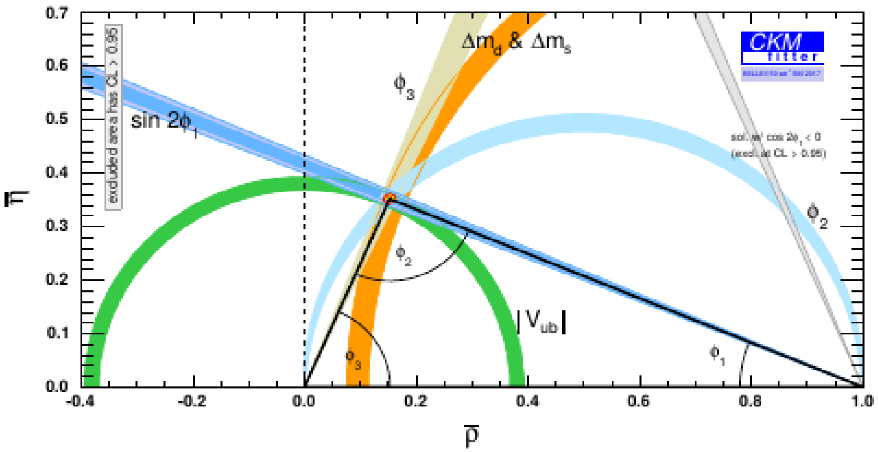
Before the B-factories

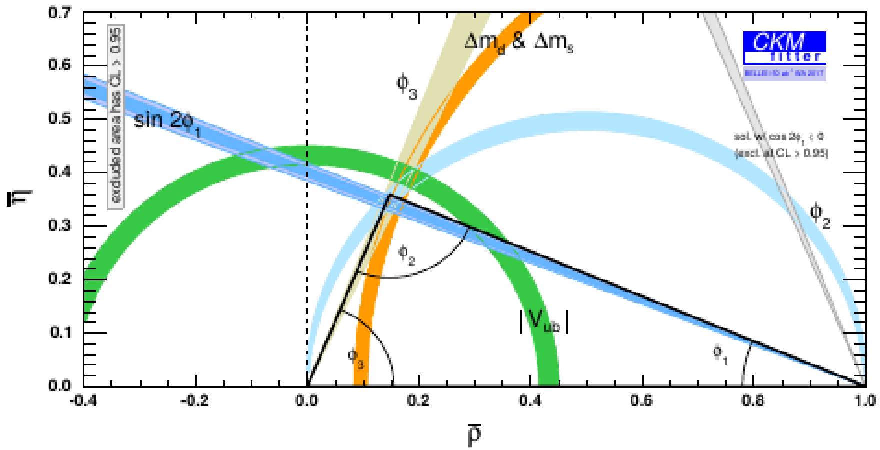


After the B-factories



CKM mechanism will be tested at 1% level

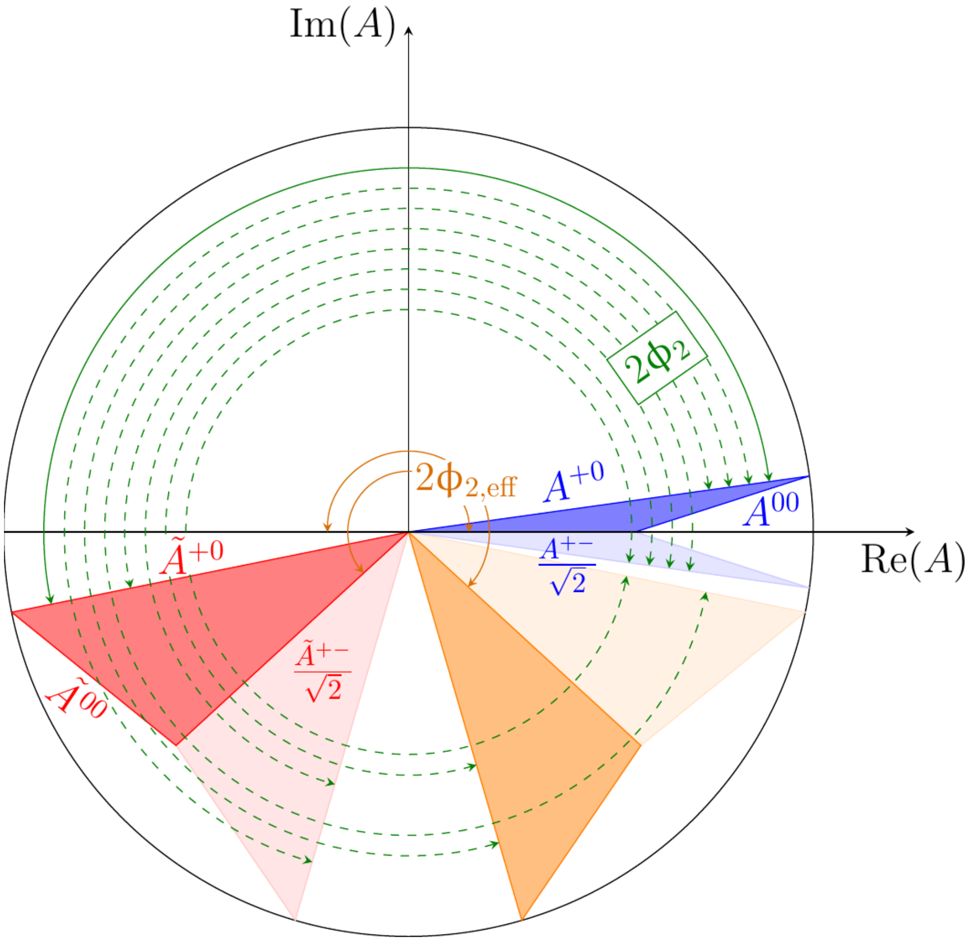




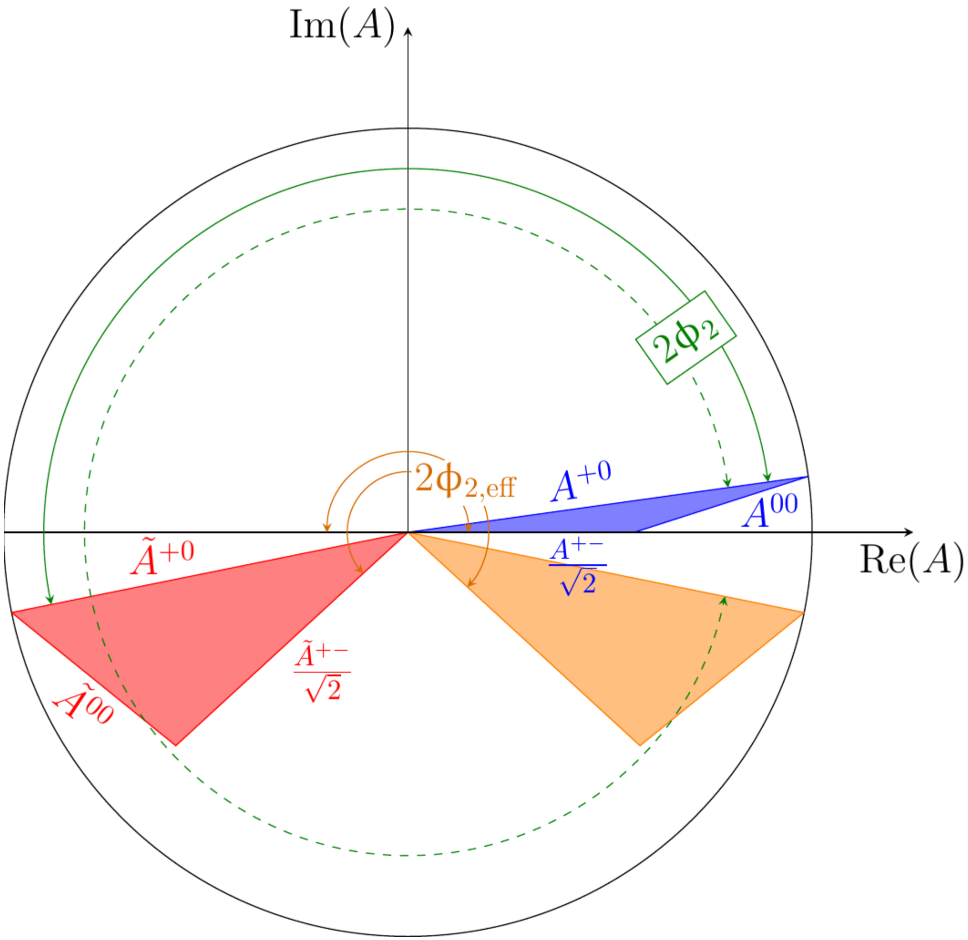
Backup slides

B → π π: Isospin Triangle

Parametrization by M. Pivk and F. R. Le Diberder Eur.Phys.J. C39 (2005) 397-409

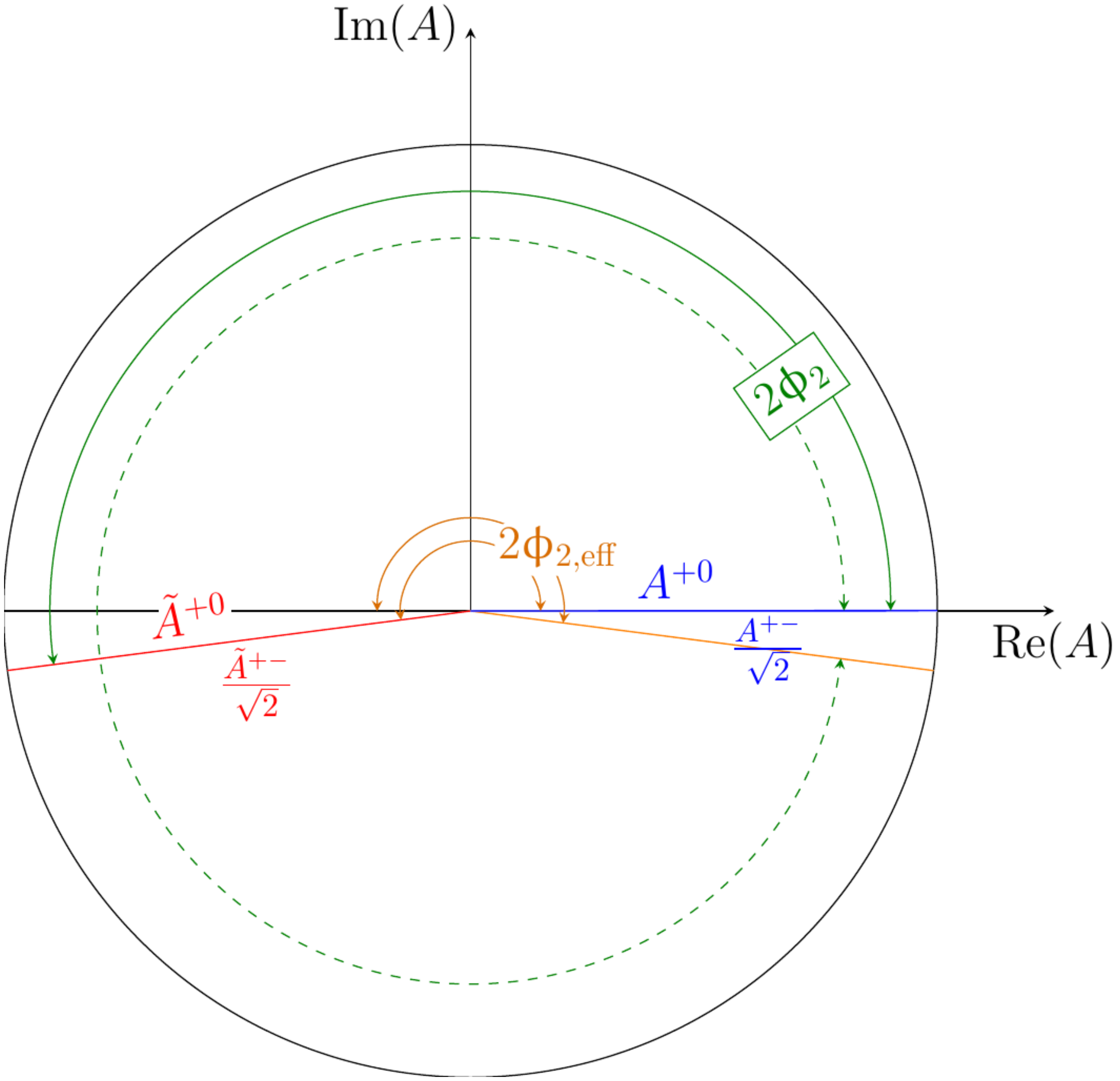


Without S($\pi^0\pi^0$)



With S($\pi^0\pi^0$)

B → ρ ρ : Isospin Triangle



Sin(2β) : expected errors

$B^0 \rightarrow J/\psi\ Ks$

	Belle	Belle II	leptonic categories
S (50 ab^{-1})			
stat.	0.0035	0.0035	0.0060
syst. reducible	0.0012	0.0012	0.0012
syst. irreducible	0.0082	0.0044	0.0040
A (50 ab^{-1})			
stat.	0.0025	0.0025	0.0043
syst. reducible	0.0007	0.0007	0.0007
syst. irreducible	$^{+0.043}_{-0.022}$	$^{+0.042}_{-0.011}$	0.011

$b \rightarrow c\bar{c}s$

	Belle	Belle II	leptonic categories
S (50 ab^{-1})			
stat.	0.0027	0.0027	0.0048
syst. reducible	0.0026	0.0026	0.0026
syst. irreducible	0.0070	0.0036	0.0035
A (50 ab^{-1})			
stat.	0.0019	0.0019	0.0033
syst. reducible	0.0014	0.0014	0.0014
syst. irreducible	0.0106	0.0087	0.0035

- Sin(2β) will remain the most precise measurement on the Unitarity Triangle parameters
- In Belle II the measurement will be dominated by systematics
  - Effort concentrated in understand and reducing them

Three hypotheses

- Belle: same Belle non reducible systematics
- Belle II: vertex systematic / 2
- Leptonic category: only leptonic categories for the flavor tagging