Belle achievements and Belle II prospects for CP violation

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DISCRETE 2016

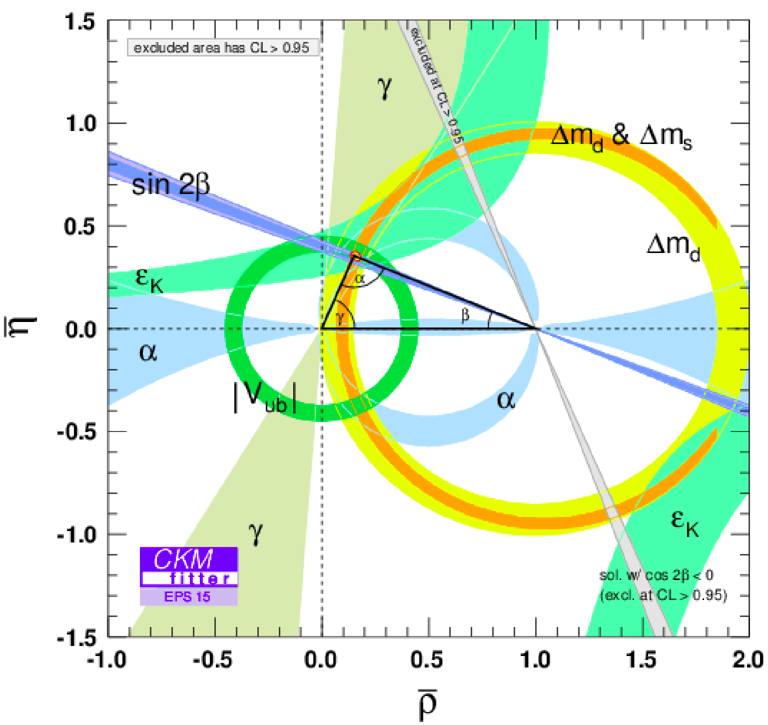
Warsaw – November 30th 2016

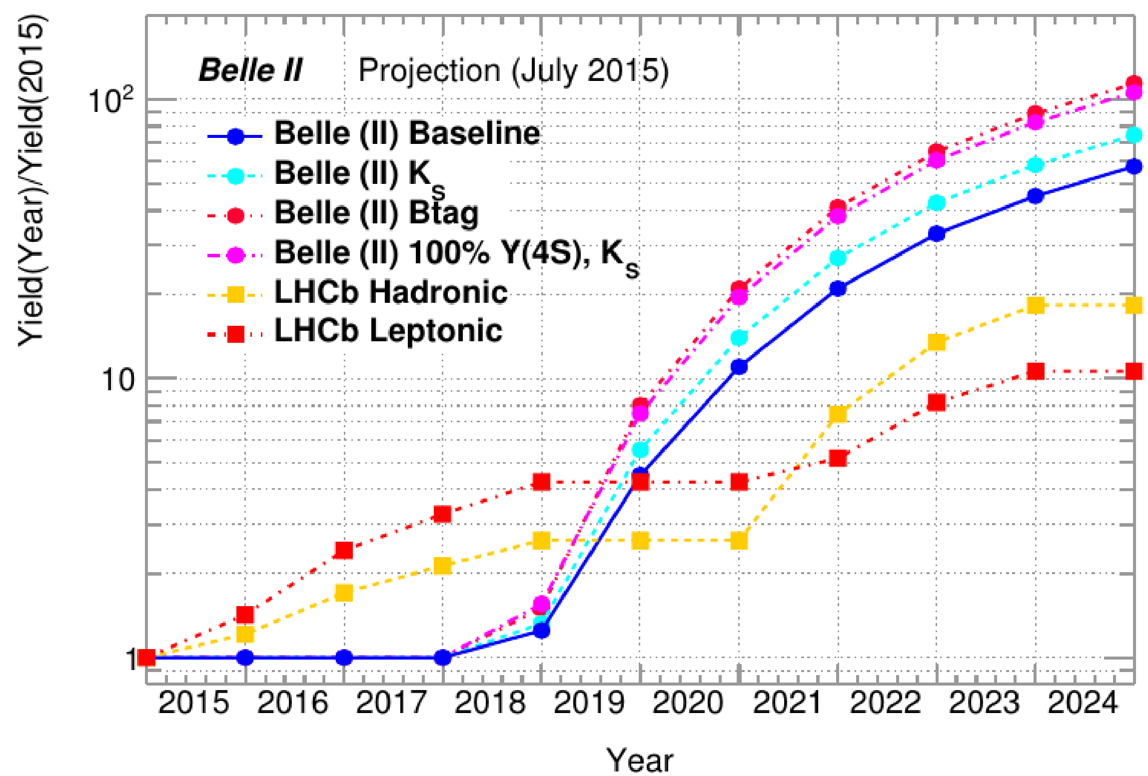
The Unitarity Triangle

$$
\begin{array}{ccccc}
 & d & s & b & \\
V \approx & \left(\begin{array}{ccc} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{array}\right) & & & \begin{array}{c} u \\ c \\ t \end{array}
\end{array}
$$

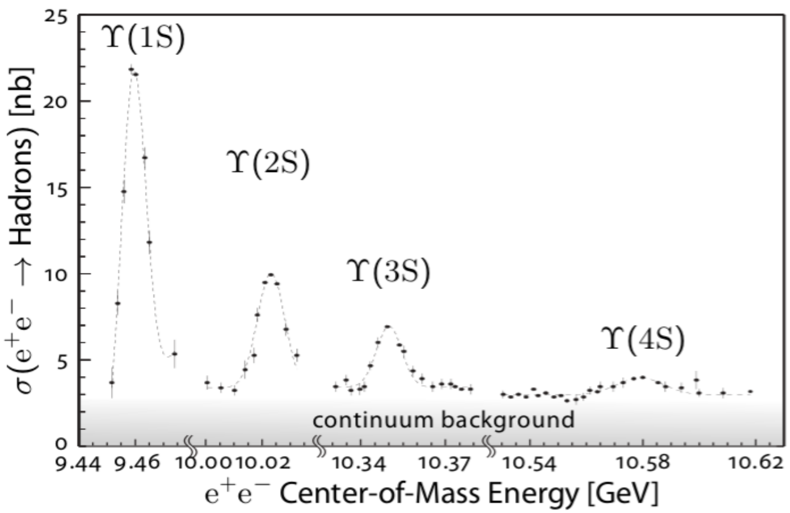
$\lambda \approx 0.22$: Cabibbo angle

- 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 !



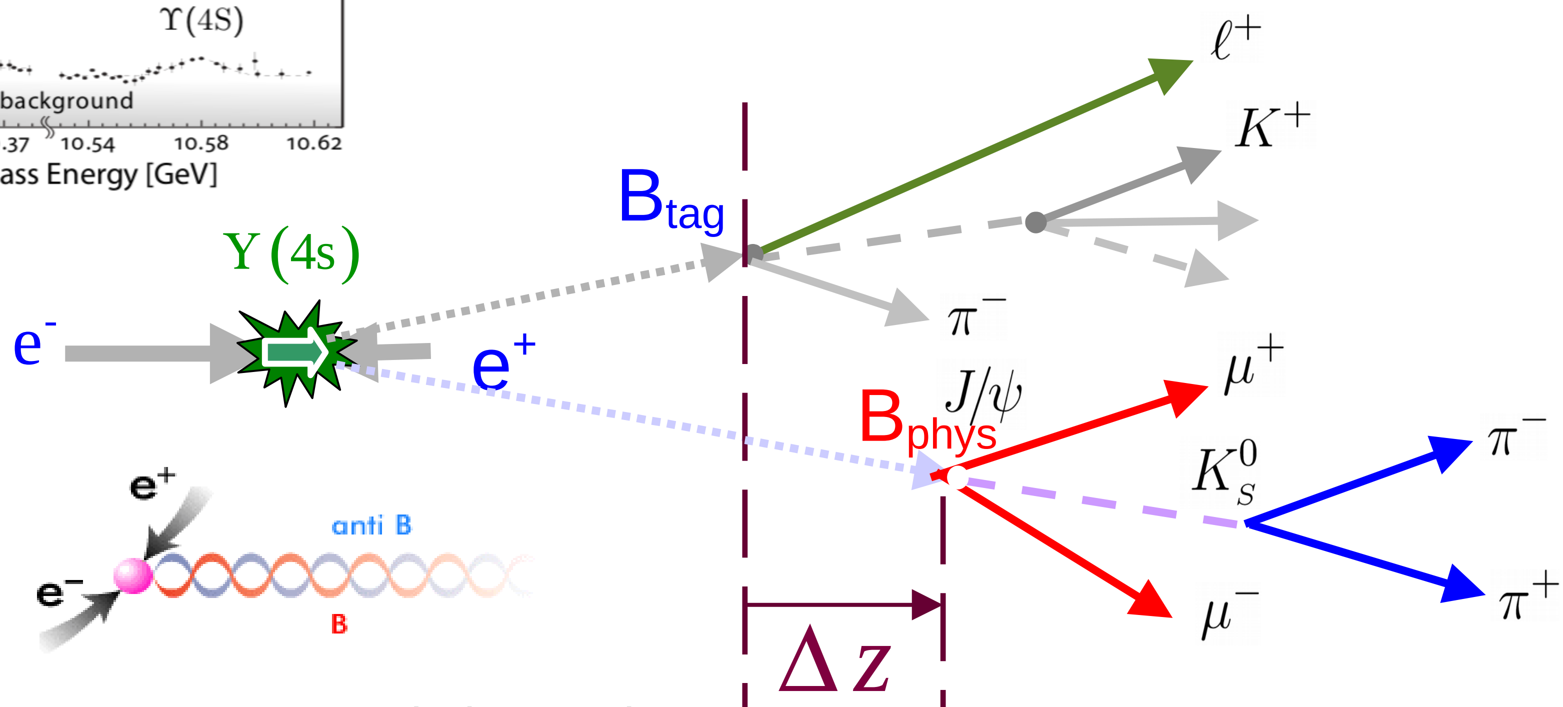


Time dependent measurements



- Y(4S) is the first resonance just above the $B\bar{B}$ production threshold
- Only $B\bar{B}$ 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 $\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t\right)\right]$

Sin(2β) : b → $c\bar{c}s$

Phys. Rev. Lett. 108 171802 (2012)

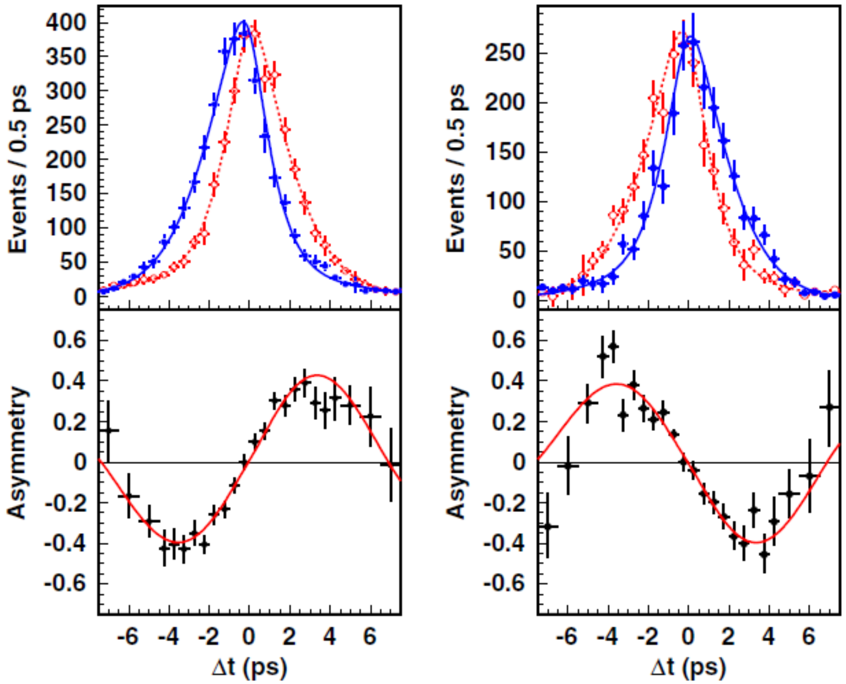


FIG. 2 (color online). The background-subtracted Δt distribution (top) for $q = +1$ (red) and $q = -1$ (blue) events and asymmetry (bottom) for good tag quality ($r > 0.5$) events for all CP-odd modes combined (left) and the CP-even mode (right).

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	$+0.667 \pm 0.023 \pm 0.012$	$+0.006 \pm 0.016 \pm 0.012$

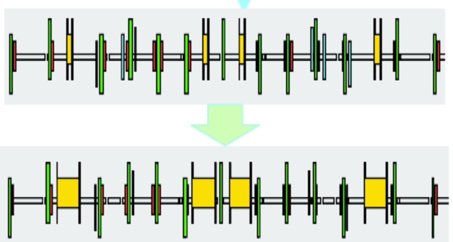
Source	Irreducible	Error on $\mathcal{S}$	Error on $\mathcal{A}$
Vertexing	X	± 0.007	± 0.007
Δt resolution		± 0.007	± 0.001
Tag-side interference	X	± 0.001	± 0.008
Flavor tagging		± 0.004	± 0.003
Possible fit bias		± 0.004	± 0.005
Signal fraction		± 0.004	± 0.002
Background Δt PDFs		± 0.001	< 0.001
Physics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

Irreducible systematic errors:

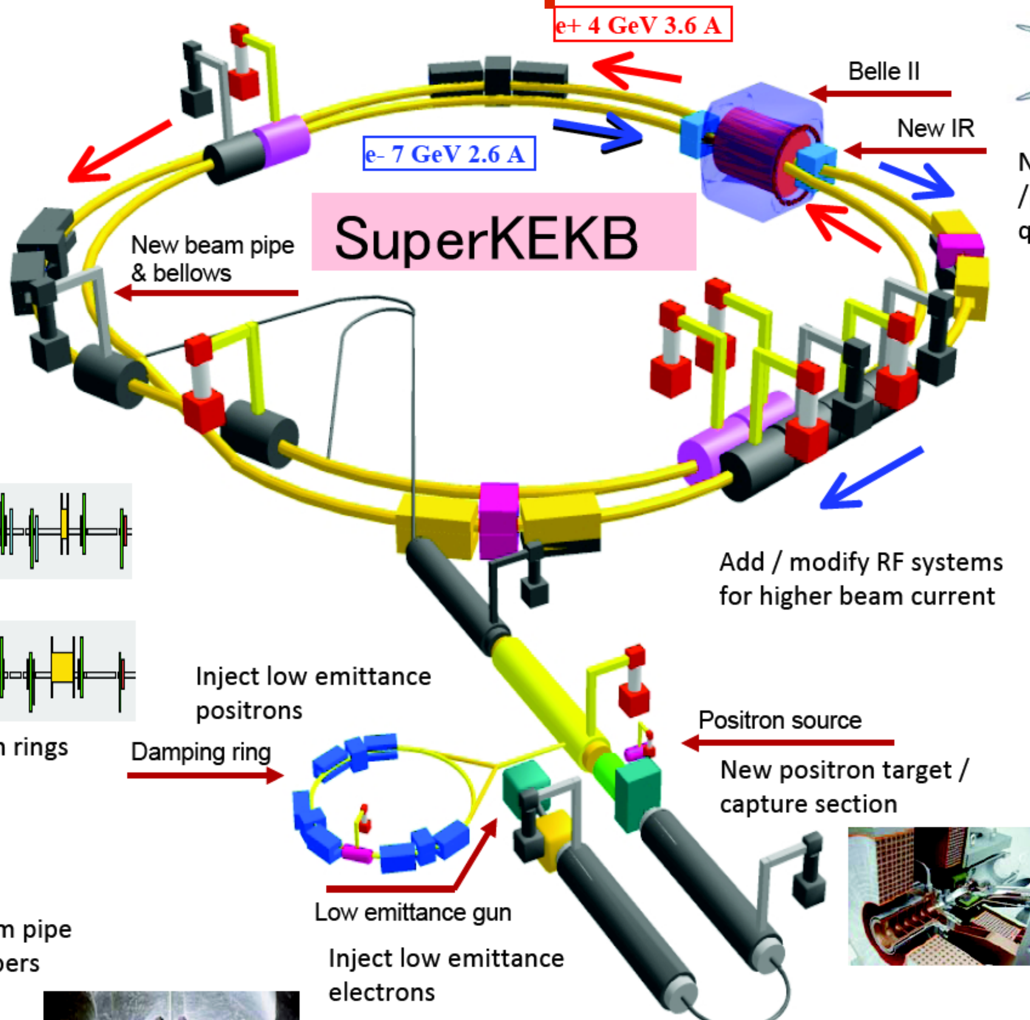
- Vertexing (without detector upgrade)
- Tag-side interference
  - More sophisticated treatment will be considered

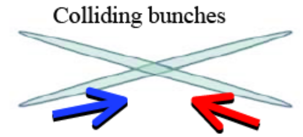
SuperKEKB

Replace short dipoles
with longer ones (LER)



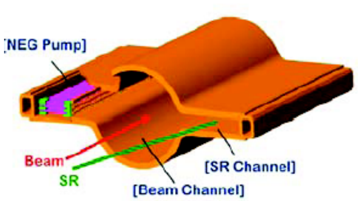
Redesign the lattices of both rings
to reduce the emittance

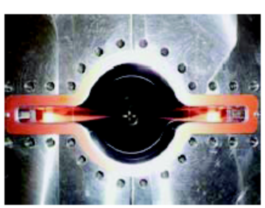




New superconducting
/permanent final focusing
quads near the IP

TiN-coated beam pipe
with antechambers



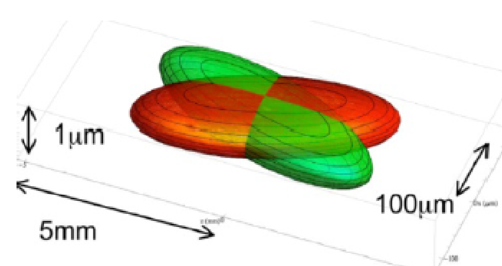


Peak luminosity

- KEKB = 2.11x10^{34} cm^{-2} s^{-1}
- SuperKEKB = 8 x10^{35} cm^{-2} s^{-1}

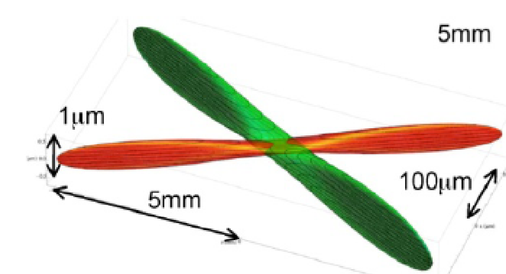
e$^+$e$^-$ beams energy

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

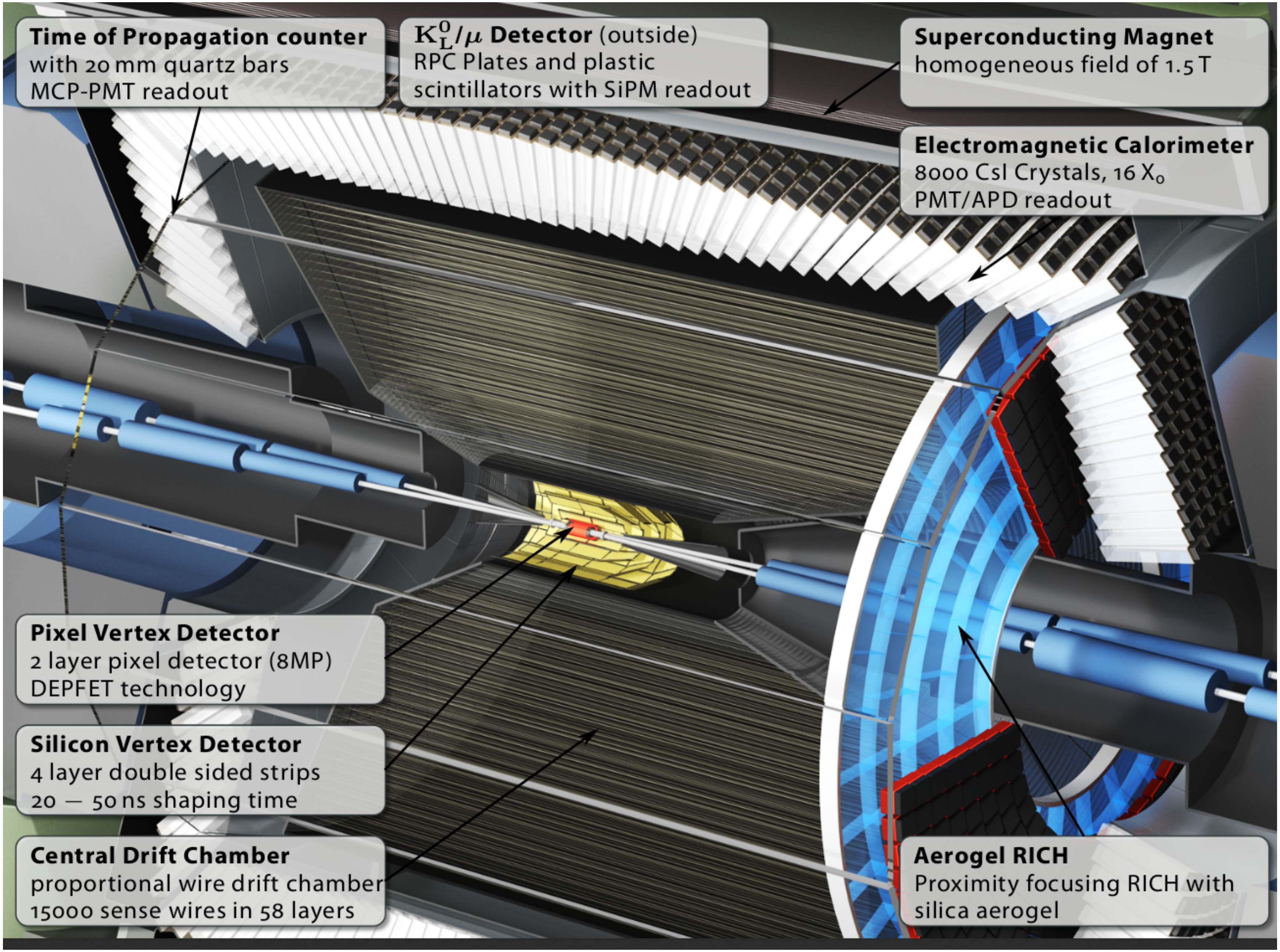


KEKB

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

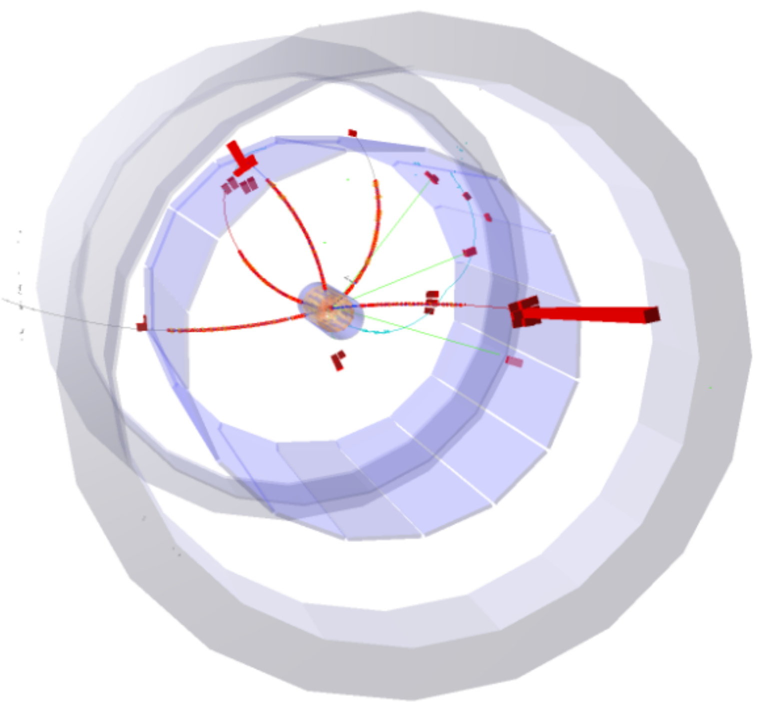
- 40 times increase of luminosity → higher background
- Lower boost → smaller separation between the B mesons

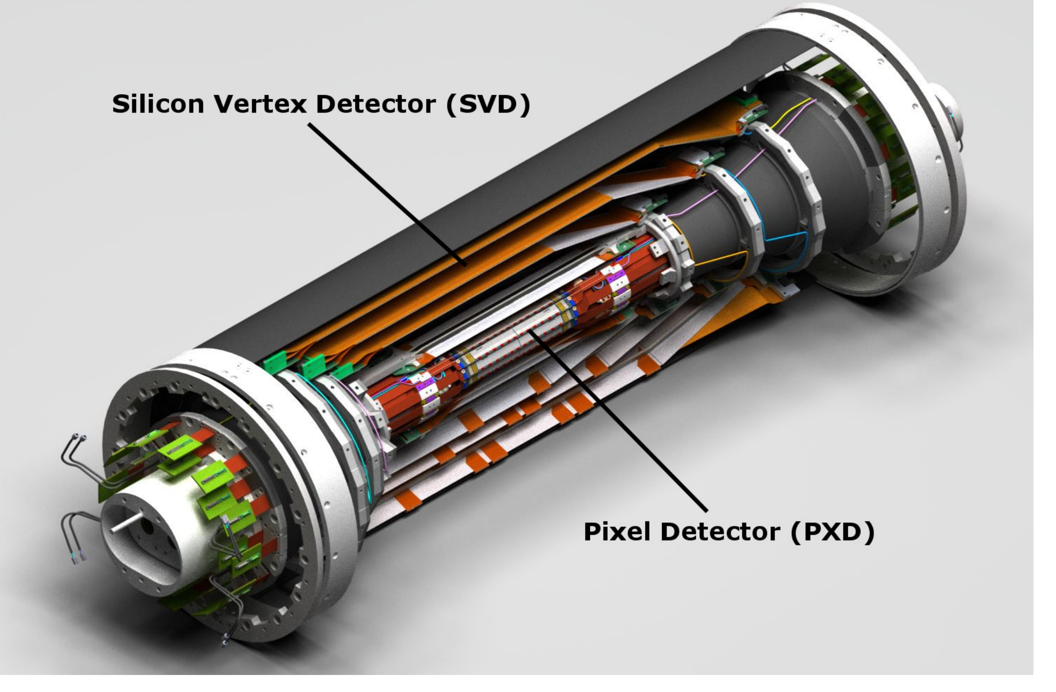
→ Pixel detector needed

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

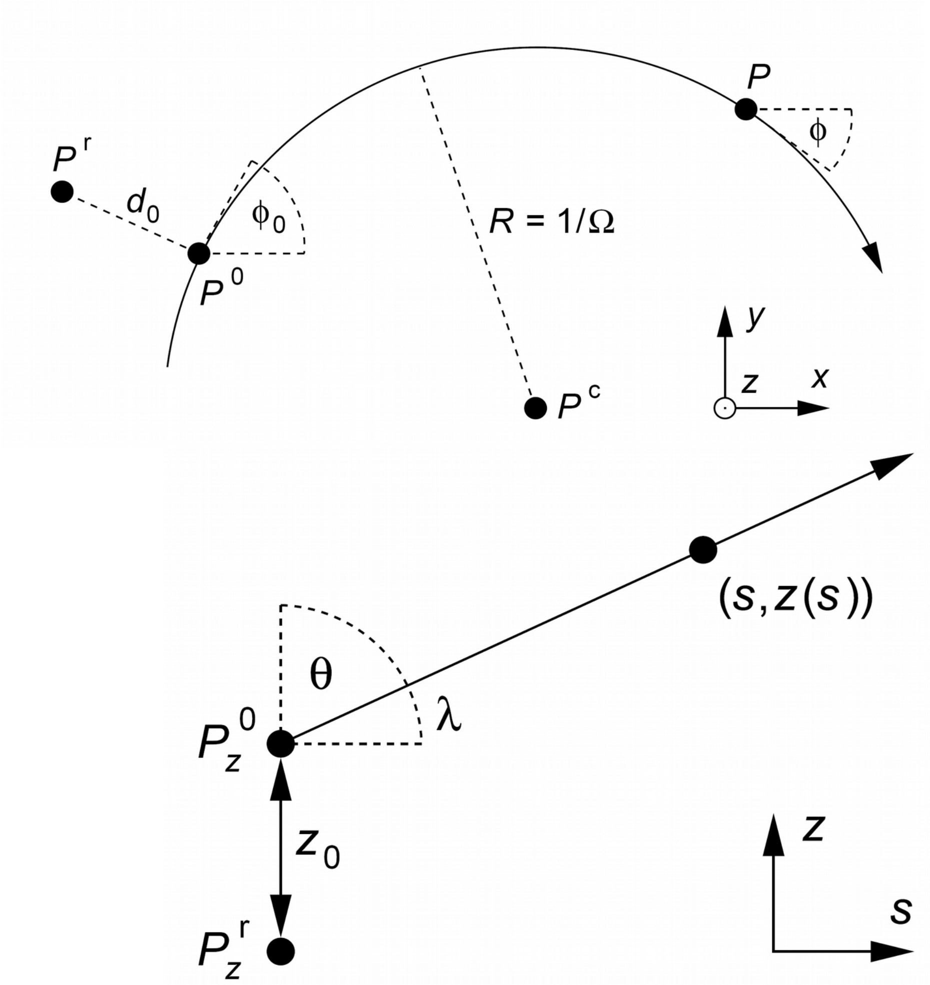


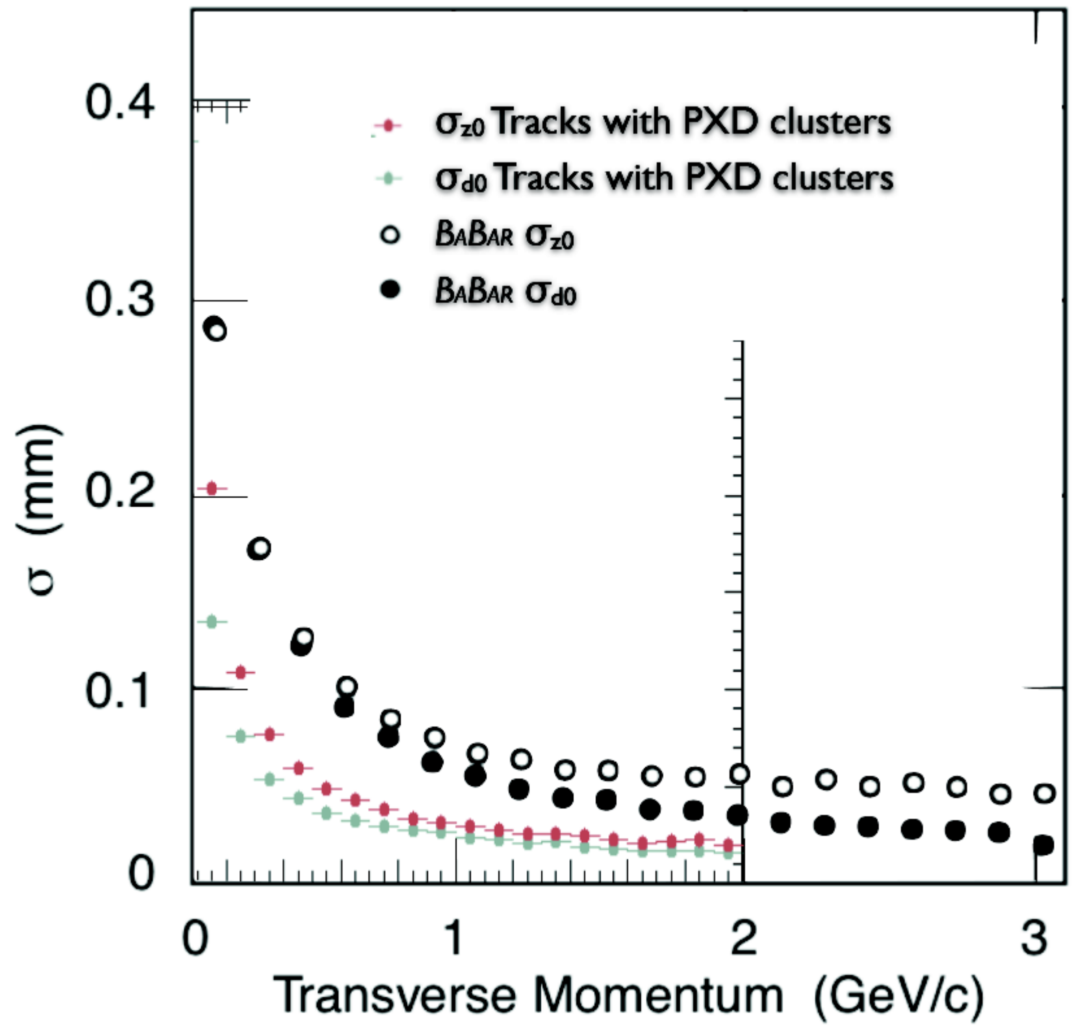


The impact parameter

The impact parameters: d_0 and z_0

- defined as the projections of distance from the point of closest approach to the origin
- good measure of the overall performance of the tracking system
- used to find the optimal tracker configuration

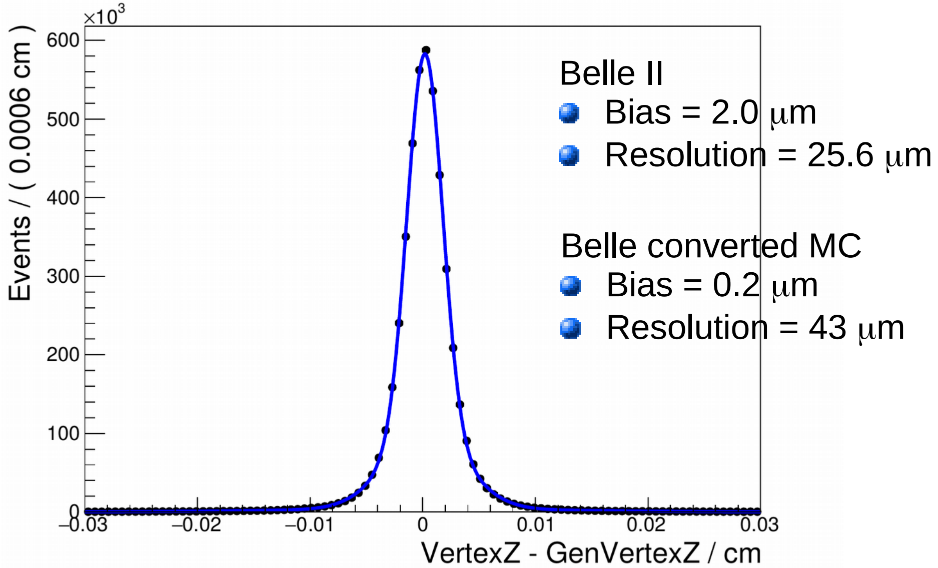




Almost a factor 2 improvement respect to BaBar

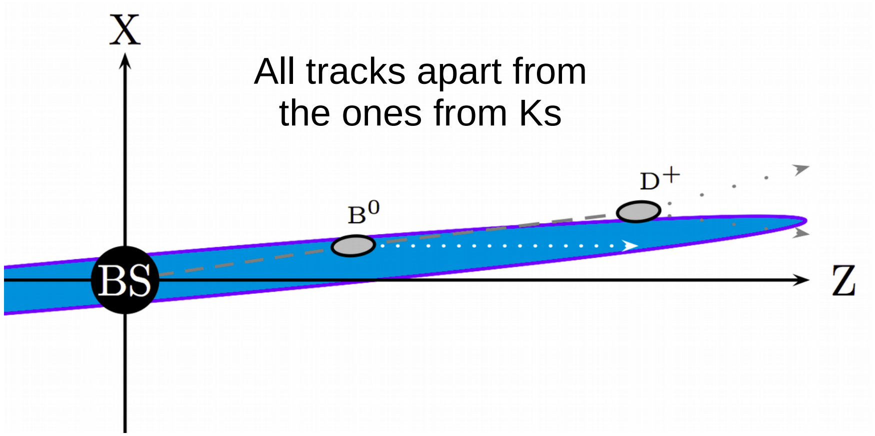
Vertex fit

Kinematic fit: $J/\psi \rightarrow \mu\ \mu$

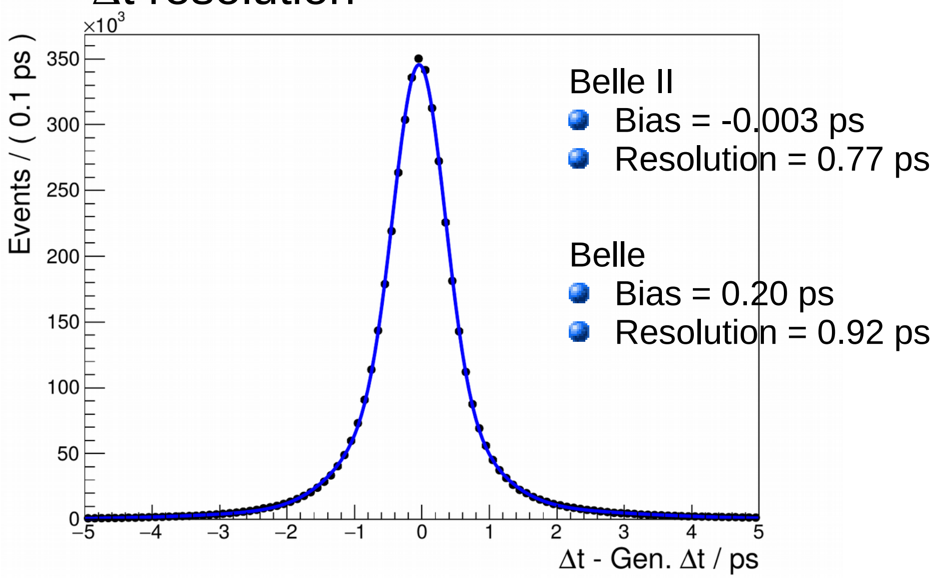


Tag side vertex fit: Using RAVE Adaptive Vertex Fit (AVF) algorithm:

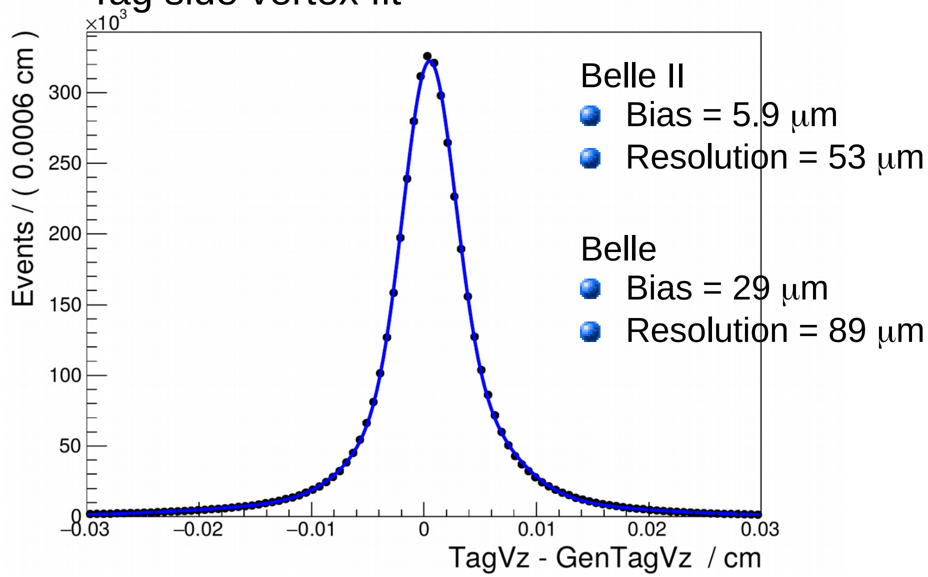
Down-weights outliers dynamically, instead of using hard cutoffs (important for 3+ track vertices). CMS NOTE 2008/033.



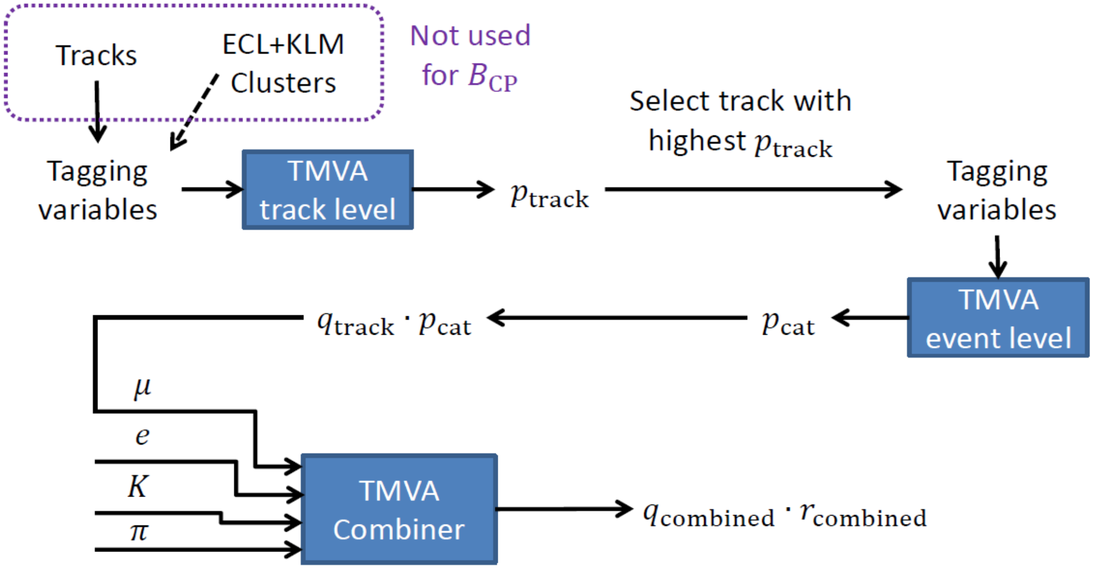
Δt resolution



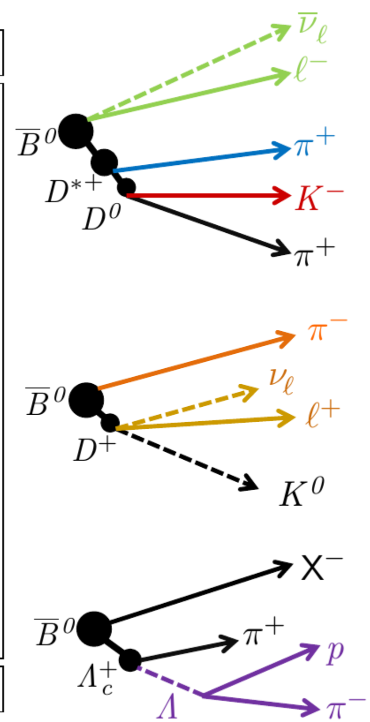
Tag side vertex fit

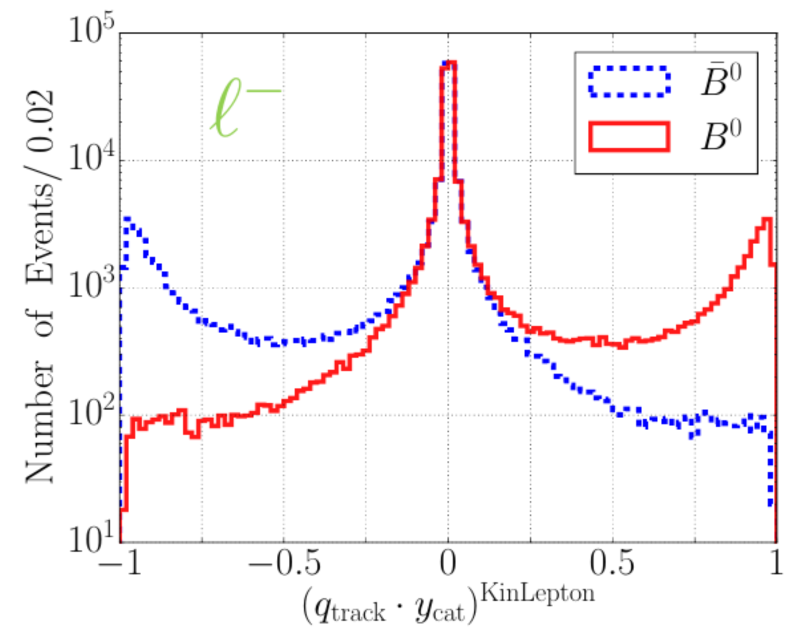


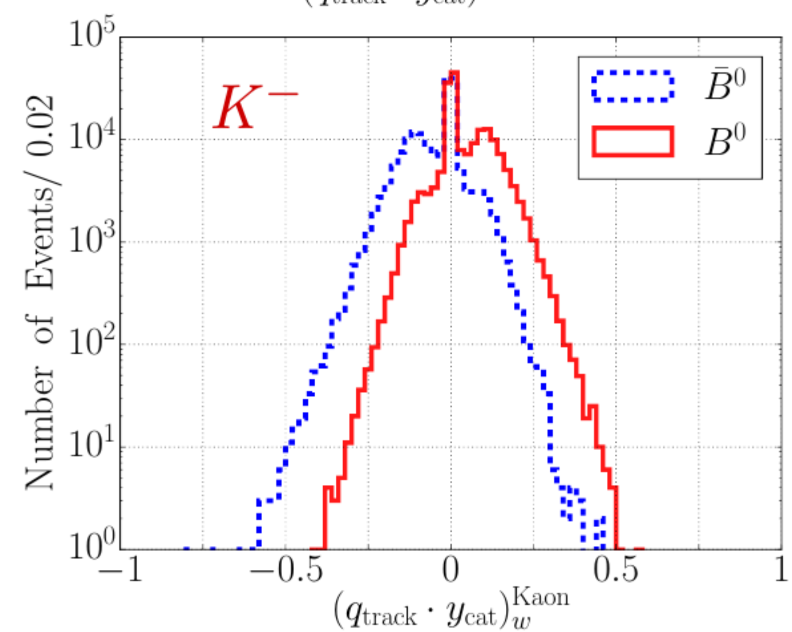
Flavor tagging



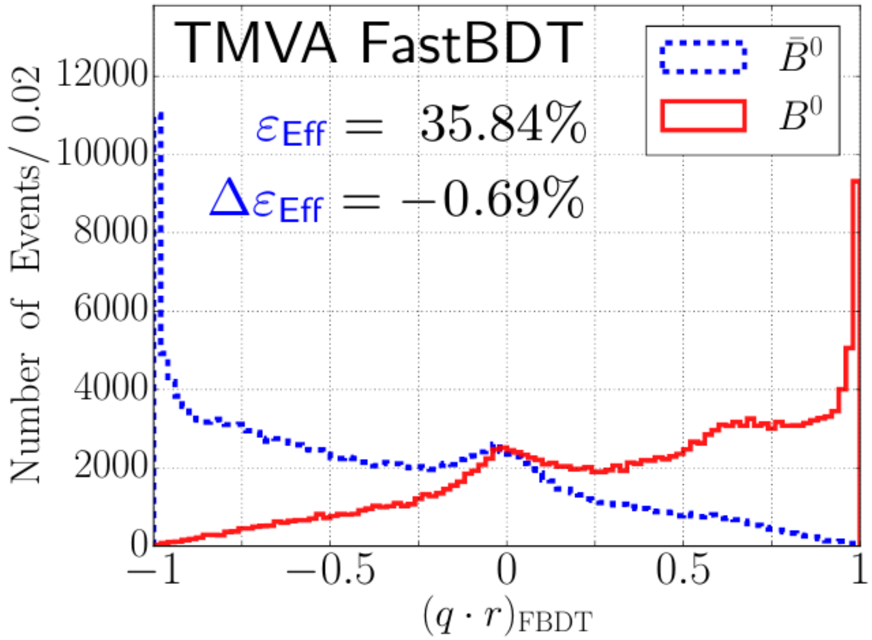
Categories	Targets
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
KinLepton	e^-
Intermediate KinLepton	ℓ^+
Kaon	K^-
KaonPion	K^-, π^+
SlowPion	π^+
FastPion	π^-
MaximumP	ℓ^-, π^-
FSC	ℓ^-, π^+
Lambda	Λ
Total= 13	

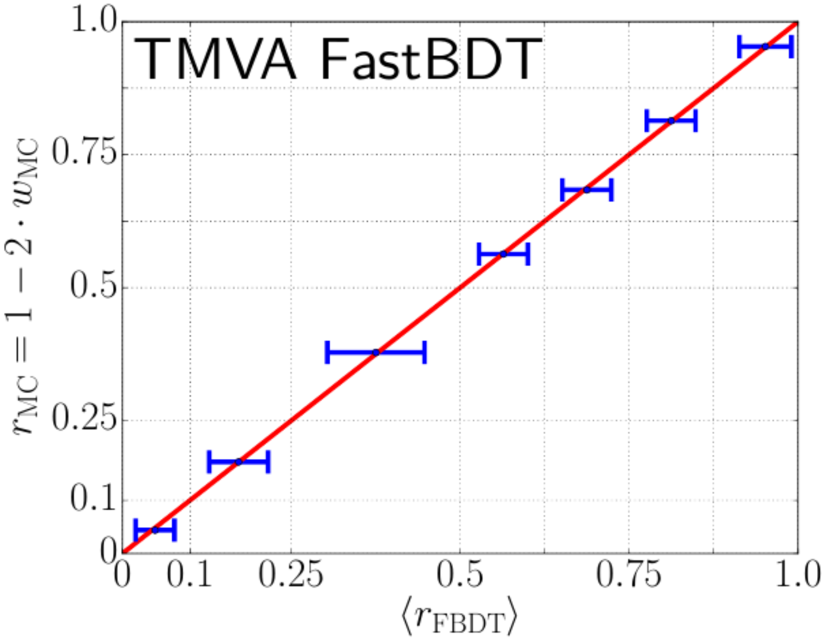


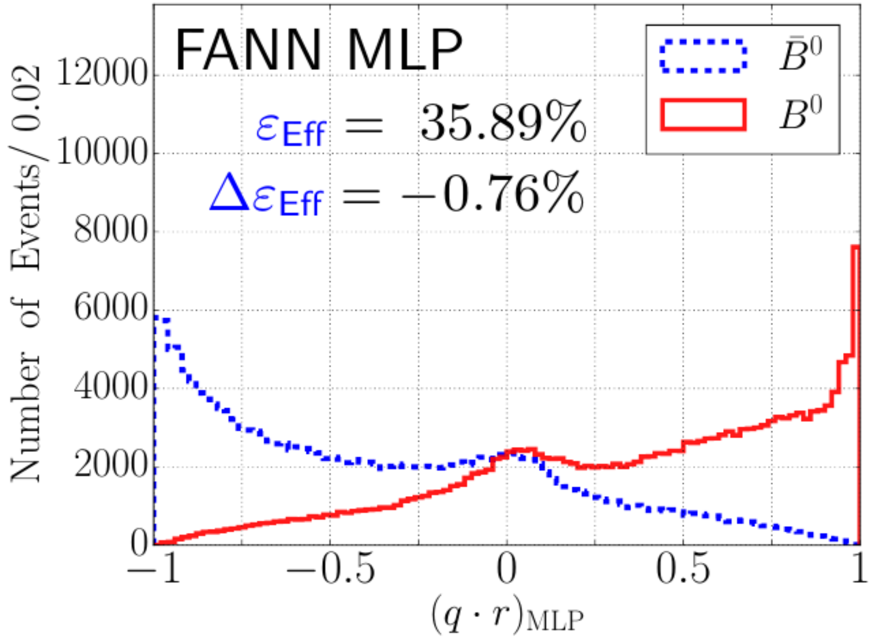


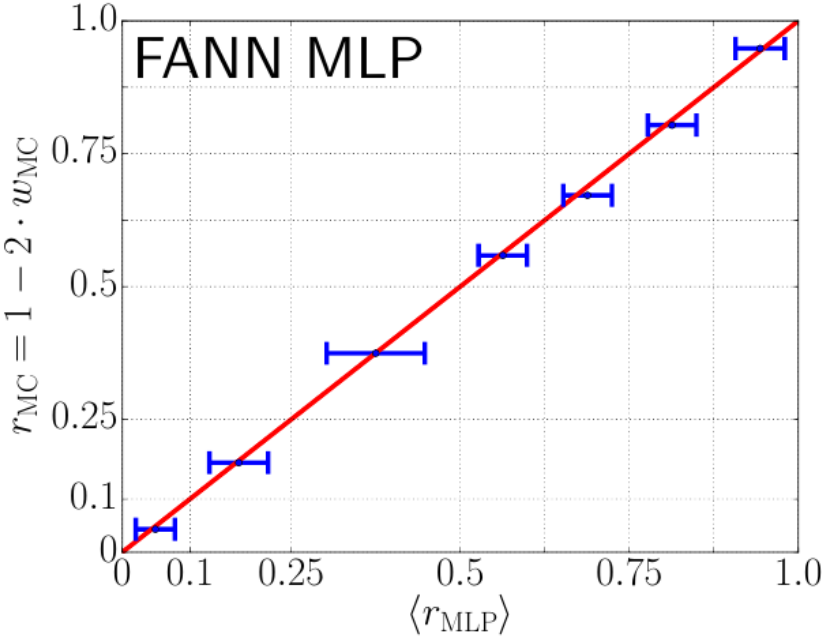


Combiner output

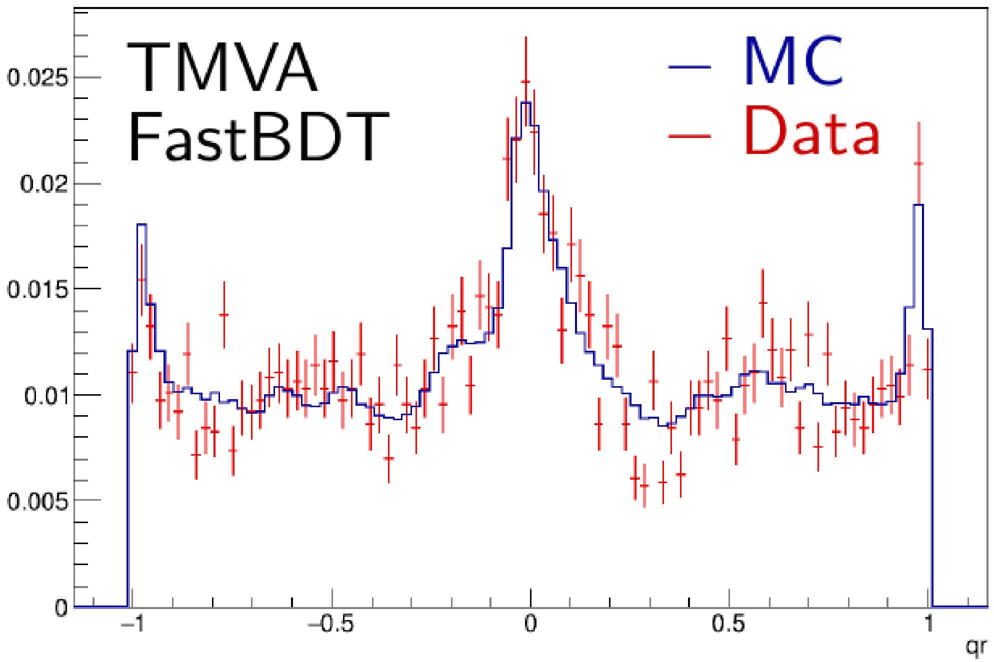




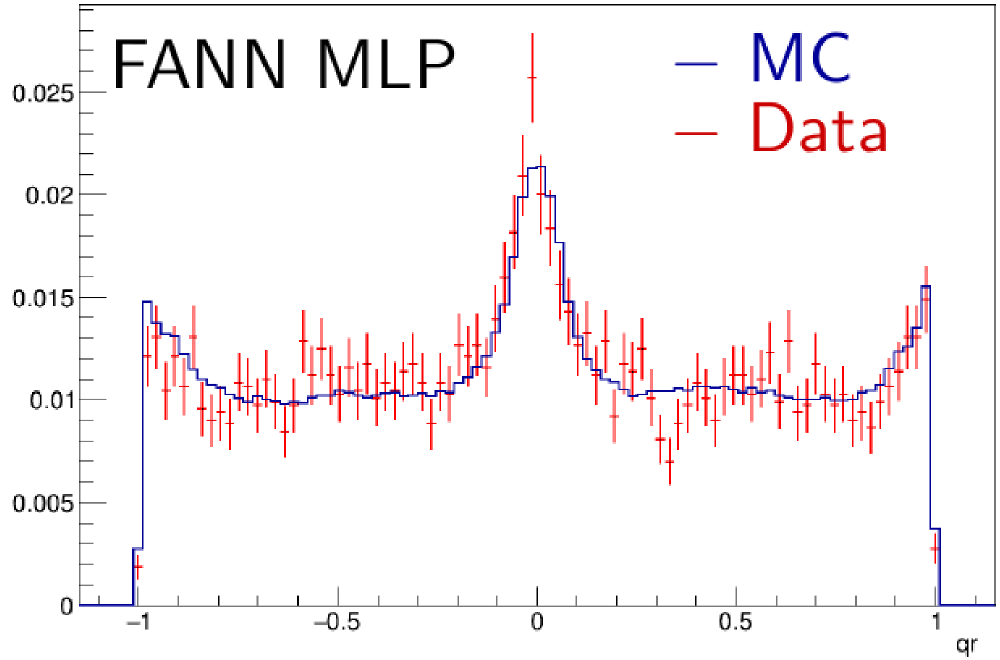




Belle Data – MC comparison



- Belle MC and data
- Belle II flavor tagging algorithm



Efficiency

- Belle Converted MC = 32 %
- Belle = 29 %

Sin(2β) : expected errors

$$\sigma_{total} = \sqrt{(\sigma(stat)^2_{Belle} + \sigma(systRed)^2_{Belle}) \times L_{Belle}/L + \sigma(systNonRed)^2_{Belle}}$$

B2TIP report: to be published

$B^0 \to J/\psi\, K_S$	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

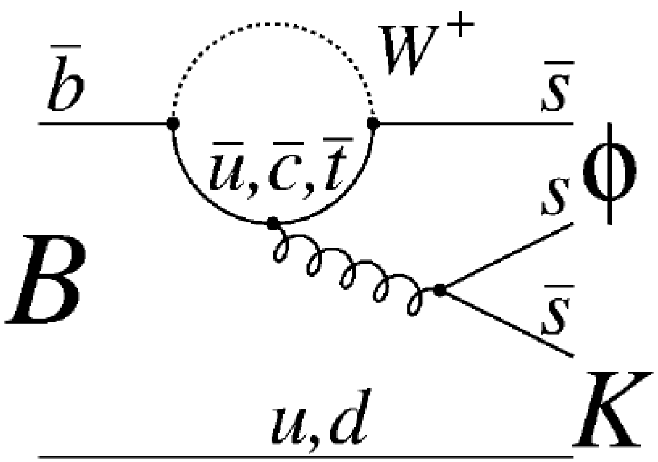
$b \to c\bar{c}s$	Belle	Belle II	leptonic categories
S (50 ab^{-1})			
stat.	0.0027	0.0027	0.0048
syst. reducible	0.0026	0.0026	0.0026
syst. irreducible	0.0070	0.0036	0.0035
A (50 ab^{-1})			
stat.	0.0019	0.0019	0.0033
syst. reducible	0.0014	0.0014	0.0014
syst. irreducible	0.0106	0.0087	0.0035

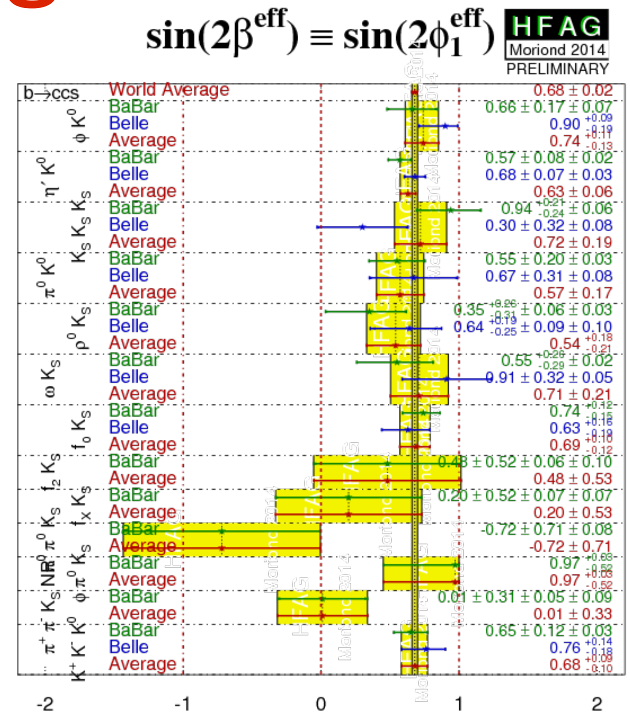
- Sin(2β) will remain the most precise measurement on the Unitarity Triangle parameters
- In Belle II the measurement will be dominated by systematics
  - Effort concentrated in understand and reducing them

- Belle measurement statistical error
- Belle measurement reducible systematic error
- Belle measurement non reducible systematic error
- Integrated luminosity used in Belle measurement
- Belle II expected integrated luminosity

Three hypotheses:
- Belle: same Belle non reducible systematics
- Belle II: vertex systematic ∗ ½
- Leptonic category: only leptonic categories for the flavor tagging

Sin(2β): b → q$\bar{q}$s





In principle measures sin2β, but sensitive to new physics

B2TIP report: to be published

Mode	QCDF [33]	QCDF (scan) [33]	$SU(3)$	Data
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [47]	$-0.11^{+0.17}_{-0.17}$
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$		$-0.14^{+0.18}_{-0.21}$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_d)\sin\gamma$ [48]	-0.05 ± 0.06
ηK_S	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$		—
ϕK_S	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_d)\sin\gamma$ [48]	$0.06^{+0.11}_{-0.13}$
ωK_S	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$		$0.03^{+0.21}_{-0.21}$

Table 1.4: ΔS_f predictions for charmless two-body final states, compared to experimental values calculated from the HFAG (Summer 2016) averages [2].

$B^0 \rightarrow \phi K_s$

1) $\phi \; K_S^0 \rightarrow \pi^+\pi^-$; $\phi \rightarrow K^+K^-$

Cleanest mode, all charged particles in final state

2) $\phi \; K_S^0 \rightarrow \pi^0\pi^0$; $\phi \rightarrow K^+K^-$

Lower statistics and harder (because of π^0's)

3) $\phi \; K_S^0 \rightarrow \pi^+\pi^-$; $\phi \rightarrow \pi^+\pi^-\pi^0$

Never tried before at BaBar and Belle

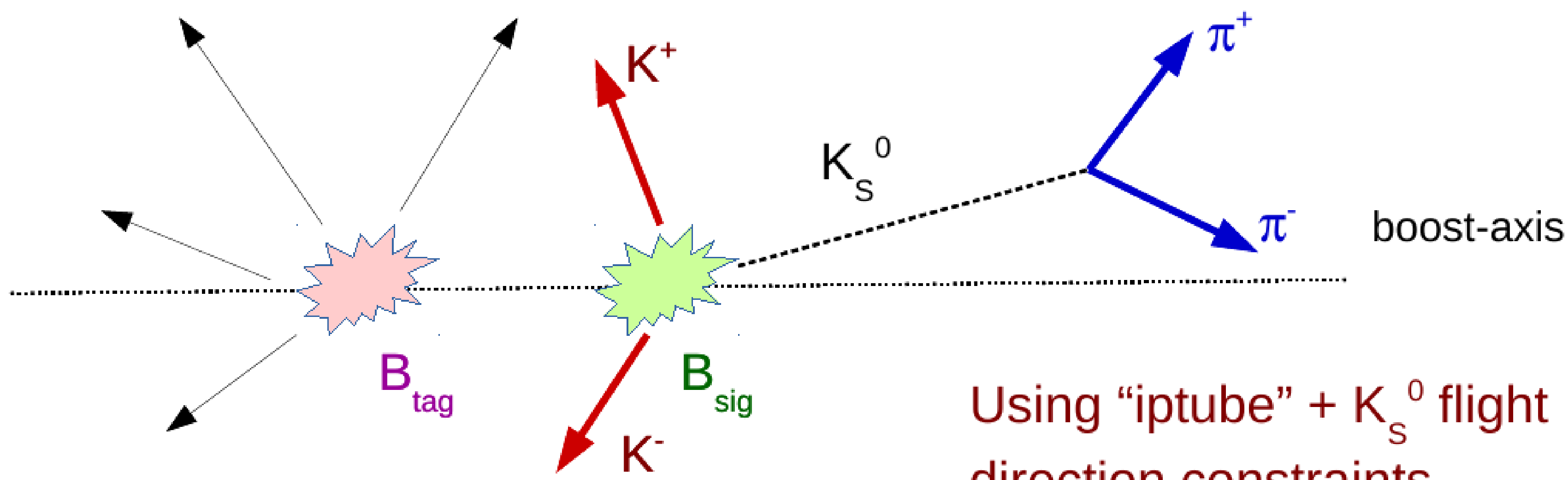
4) $\phi \; K_L^0$; $\phi \rightarrow K^+K^-$

Not yet started looking at K_L^0's

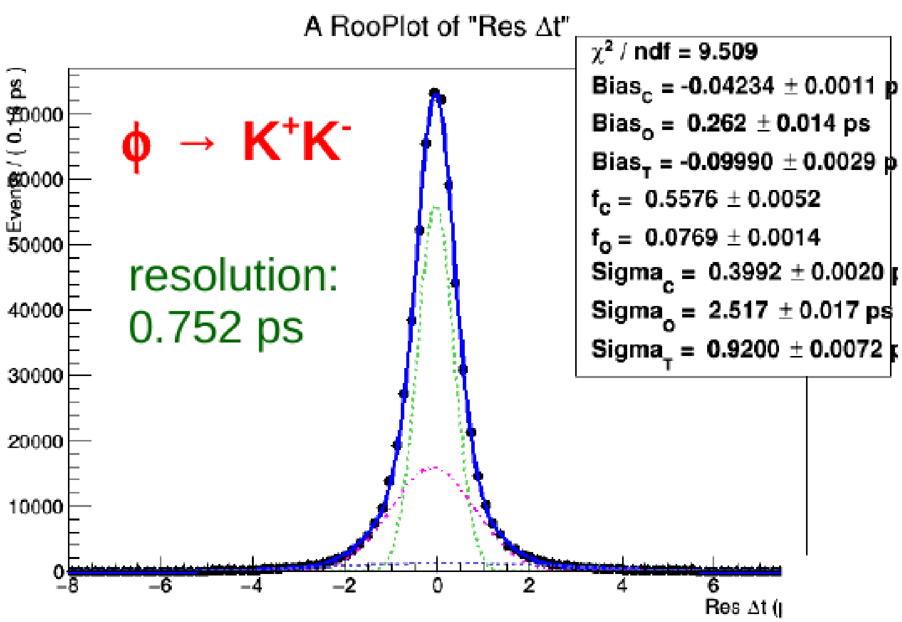
$BF(\phi \rightarrow K^+K^-) \sim 50\%$
$BF(\phi \rightarrow \pi^+\pi^-\pi^0) \sim 15\%$

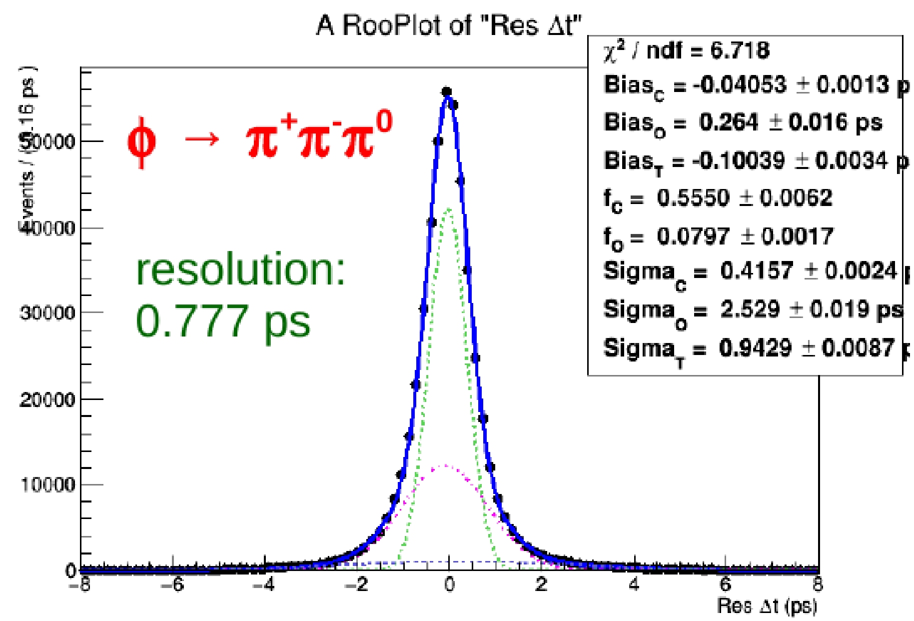
$BF(K_S \rightarrow \pi^+\pi^-) \sim 69\%$
$BF(K_S \rightarrow \pi^0\pi^0) \sim 31\%$

Vertex resolution



Using “iptube” + K_S^0 flight direction constraints





Expected sensitivity

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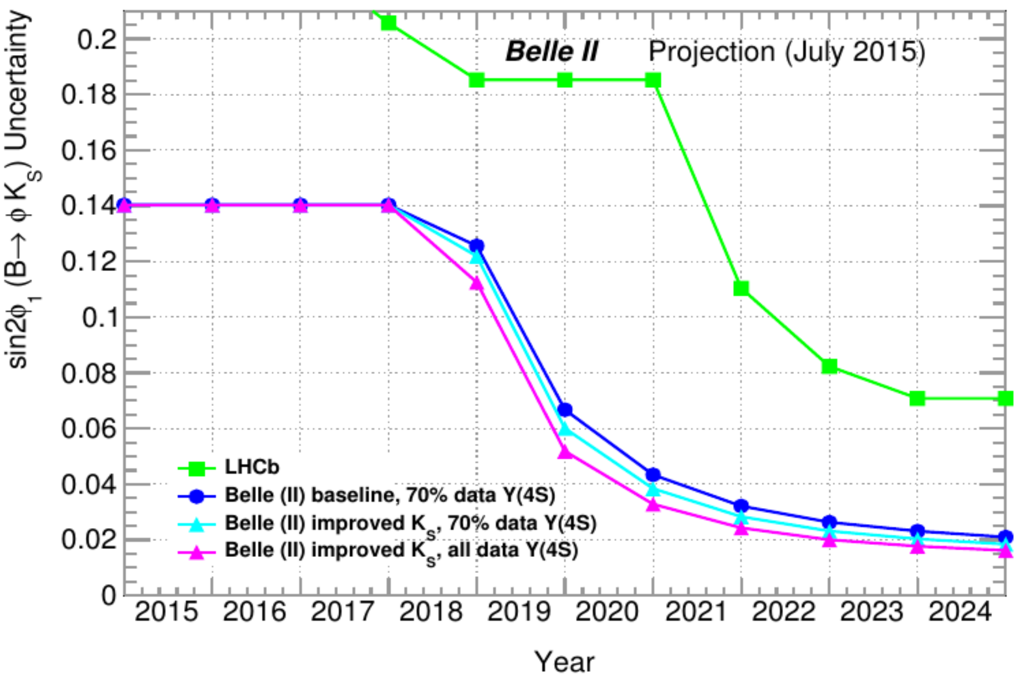
Channel	ε_{reco}	Yield	$\sigma(S)$
1 ab^{-1} scenario:			
$\phi(K^+K^-)K_S(\pi^+\pi^-)$	35%	456	0.174
$\phi(K^+K^-)K_S(\pi^0\pi^0)$	25%	153	0.295
$\phi(\pi^+\pi^-\pi^0)K_S(\pi^+\pi^-)$	28%	109	0.338
K_S modes combination			0.135
$K_S + K_L$ modes combination			0.108
5 ab^{-1} scenario:			
$\phi(K^+K^-)K_S(\pi^+\pi^-)$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

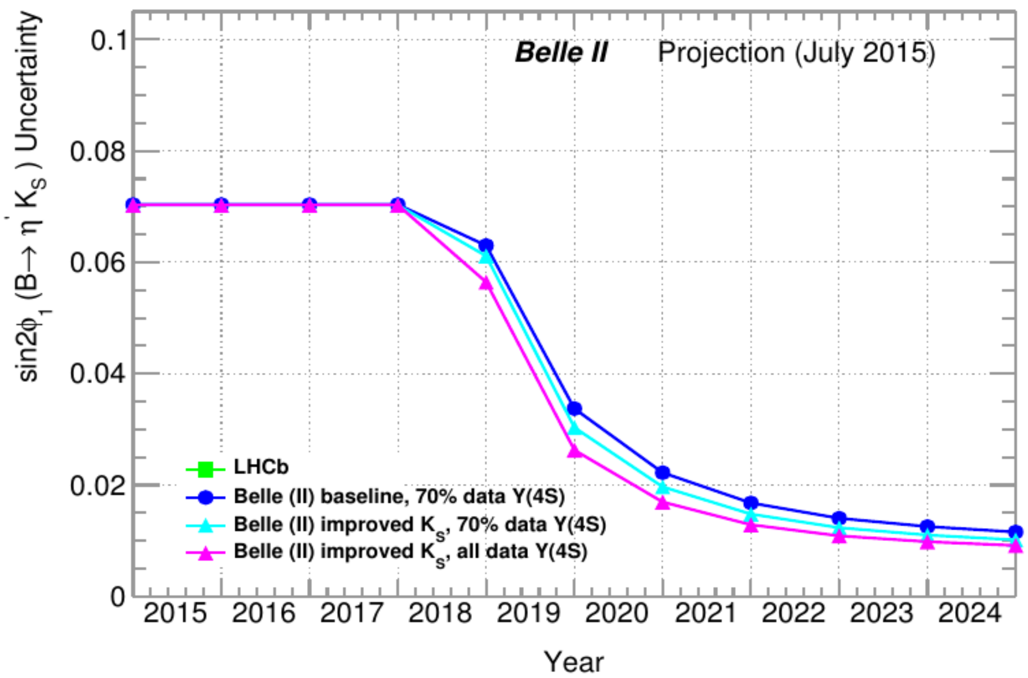
Sensitivity study

$B^0 \to \eta' K_S$: expected sensitivity

B2TIP report: to be published

Table 1.12: Δt resolution for true, SxF and all selected candidates, for $\eta(2\gamma)K^0_S(\pi^\pm)$ and $\eta(3\pi)K^0_S(\pi^\pm)$ channels.

Channel	True	SxF	All
$\eta(2\gamma)K^0_S(\pi^\pm)$	1.22 ps	2.87 ps	1.45 ps
$\eta(3\pi)K^0_S(\pi^\pm)$	1.17 ps	2.36 ps	1.50 ps



Similar Belle sensitivity given the same integrated luminosity

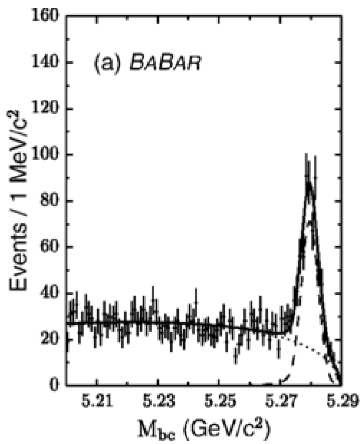
Table 1.13: Estimated rms from Toy MC studies for CP-violation parameters S and C for an integrated luminosity of 1 and 5 ab^{-1} for the different channels.

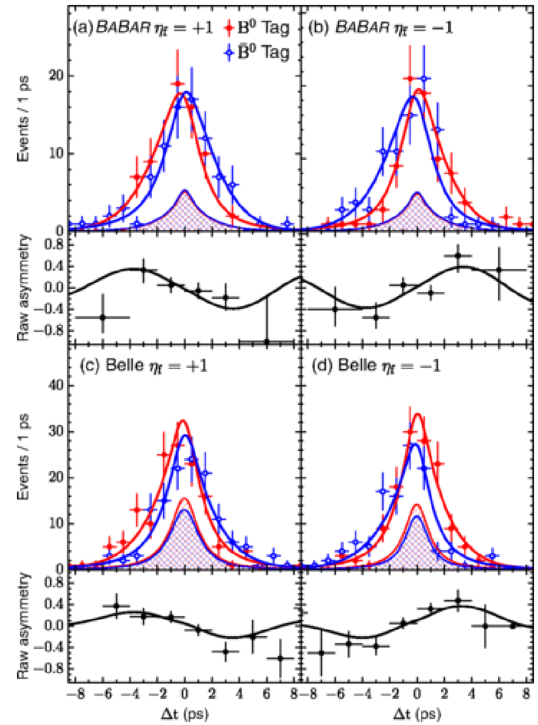
		1 ab^{-1}				5 ab^{-1}			
Channel	Strategy	S	rms S	C	rms C	S	rms S	C	rms C
$\eta(2\gamma)K^0_S(\pi^\pm)$	C	0.71	0.07	-0.11	0.06	0.71	0.04	-0.11	0.03
$\eta(3\pi)K^0_S(\pi^\pm)$	B	0.74	0.17	-0.131	0.10	0.73	0.07	-0.13	0.04

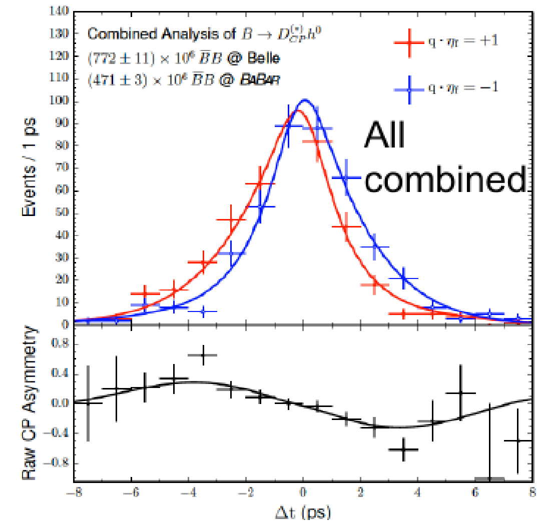
BaBar + Belle $B^0 \to D_{CP}\, h^0$

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







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

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

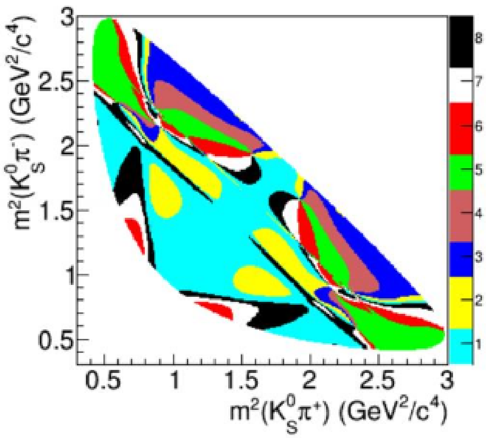
$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}),$$
$$\mathcal{C} = -0.02 \pm 0.07\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.}).$$

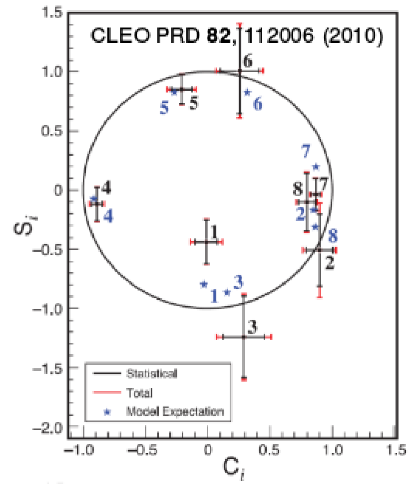
- First observation of CPV(5.4σ)
- Belle II : δ(β) ~ 0.015
- Important test for $b \to c\,\bar{c}\,s$

cos 2β with $B^0 \to D_{CP}\, h^0$

Phys. Rev. D **94** 052004 (2016)

D^0 multi-body decay: $D^0 \to K_S\, \pi\, \pi$ model independent
cos 2β and sin 2β can be extracted independently PLB 6241 (2005)





$$C_i = \frac{\int_{\mathcal{D}_i} |\mathcal{A}_D| \, |\overline{\mathcal{A}}_D| \cos \Delta\delta_D \, dm_+^2 dm_-^2}{\sqrt{K_i K_{-i}}}$$

$$S_i = \frac{\int_{\mathcal{D}_i} |\mathcal{A}_D| \, |\overline{\mathcal{A}}_D| \sin \Delta\delta_D \, dm_+^2 dm_-^2}{\sqrt{K_i K_{-i}}}$$

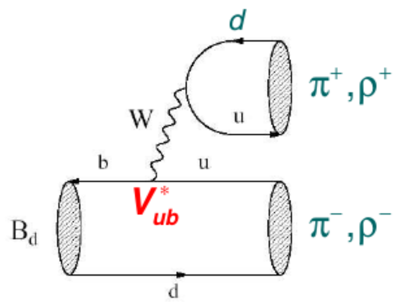
$$\mathcal{P}_i(\Delta t, \varphi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q_B \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos(\Delta m_B \Delta t) + 2 q_B \xi_{h^0} (-1)^L \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin(\Delta m_B \Delta t) \left(S_i \cos 2\varphi_1 + C_i \sin 2\varphi_1 \right) \right]$$

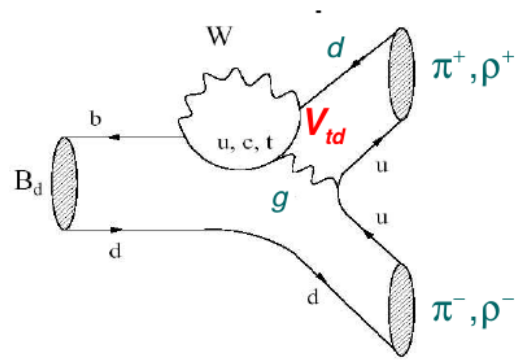
$$\sin 2\varphi_1 = 0.43 \pm 0.27(\mathrm{stat}) \pm 0.08(\mathrm{syst}),$$
$$\cos 2\varphi_1 = 1.06 \pm 0.33(\mathrm{stat})^{+0.21}_{-0.15}(\mathrm{syst}),$$
$$\varphi_1 = 11.7^\circ \pm 7.8^\circ(\mathrm{stat}) \pm 2.1^\circ(\mathrm{syst}).$$

Measurement of α

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

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





Used decay modes:

- $B \to \pi\ \pi$
- $B \to \rho\ \rho$
- $B \to \rho\ \pi$

Extra weak and strong phases + |P/T| modify α by $\Delta\alpha$:

$\sin(2\alpha) \to \sin(2\alpha_{eff})$ $\alpha_{eff} = \alpha + \Delta\alpha$

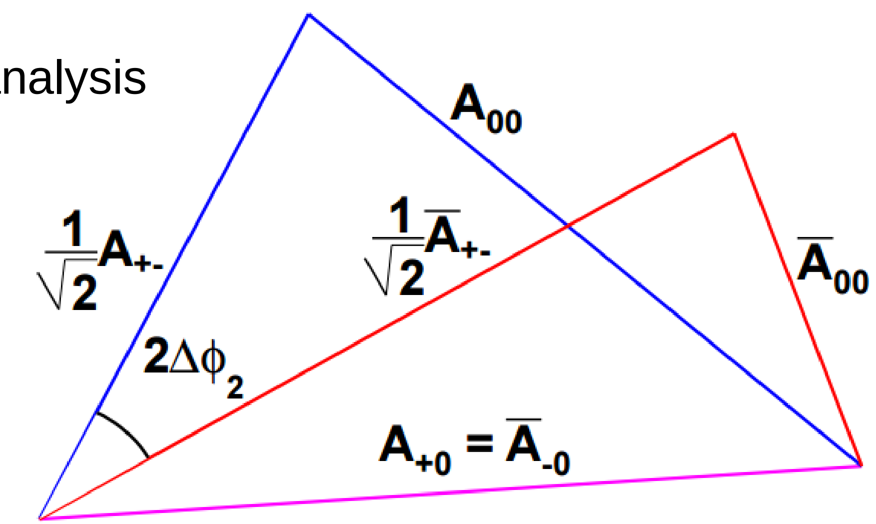
To relate α to α_{eff}:

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

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

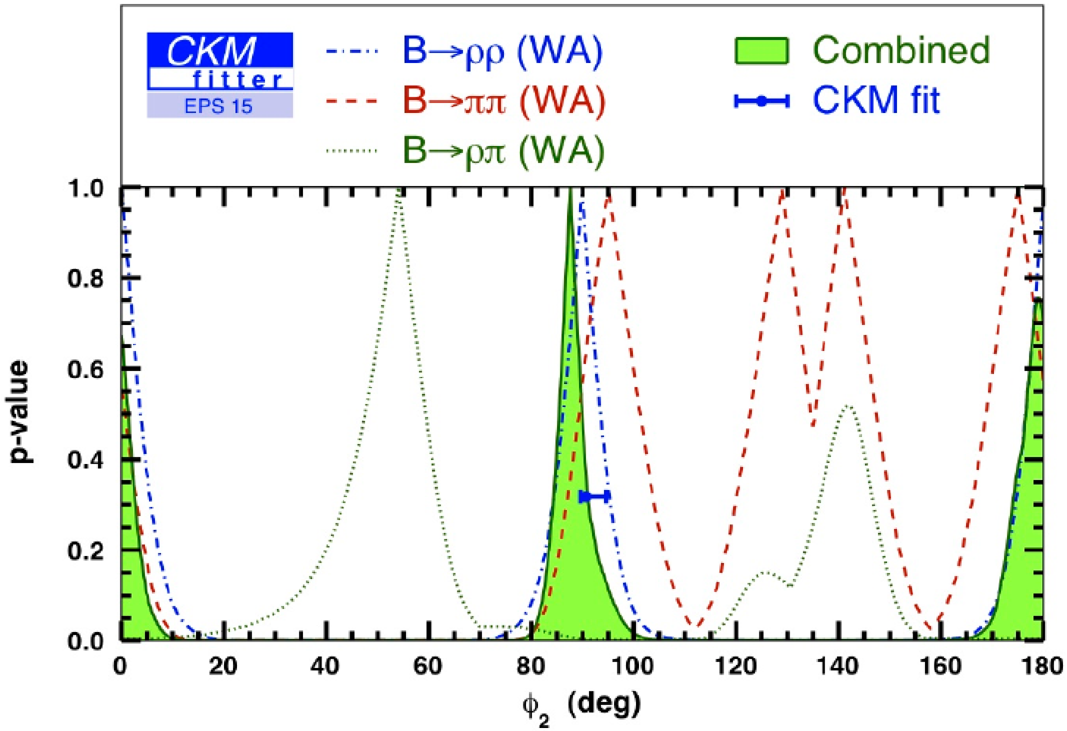
$$A^{+0} = \bar{A}^{-0} \text{ (pure tree)}$$

Isospin analysis



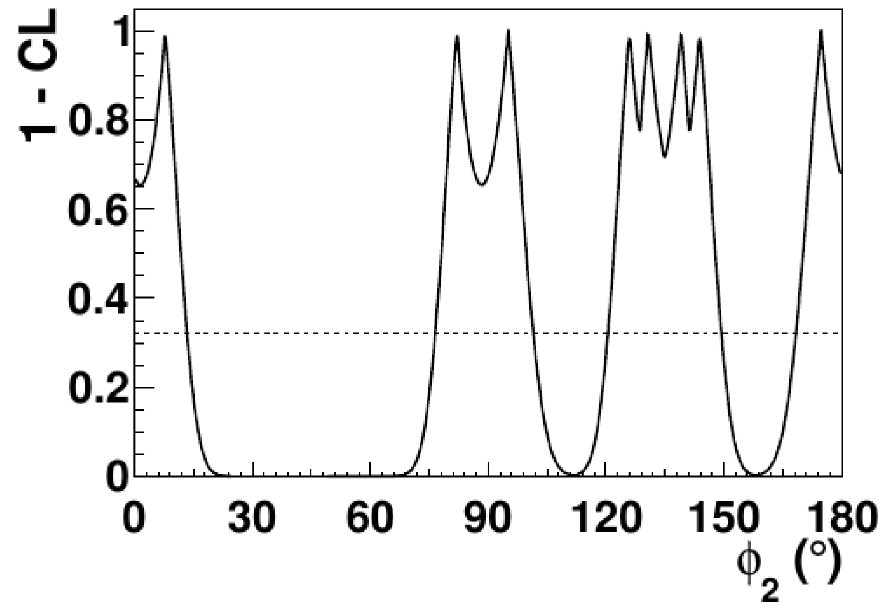
$B \to \pi\,\pi$

P. Vanhoefer @ 3rd B2TIP



$\phi_2=\alpha=90.6$ +3.9/-1.1 °

extrapolated to $50ab^{-1}$ (wo/ $\mathcal{S}_{CP}^{\pi^0\pi^0}$)



- stat error $\times 0.15$ ($\sim 50ab^{-1}$)
- syst error $\times 0.7$ (conservative guess)

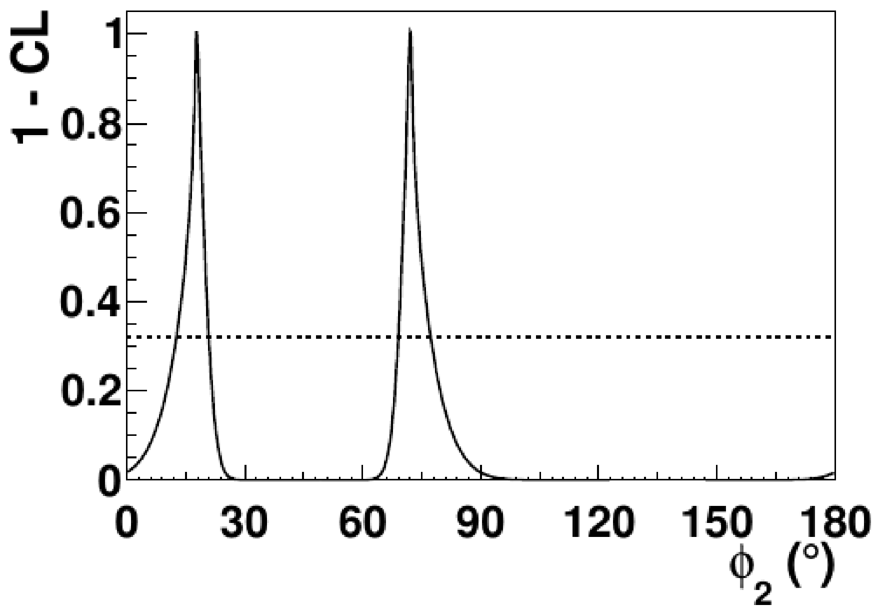
8 fold ambiguity!

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

P. Vanhoefer @ 3rd B2TIP

with $\mathcal{S}_{CP}^{\pi^0\pi^0} = 0.92 \pm 0.26$

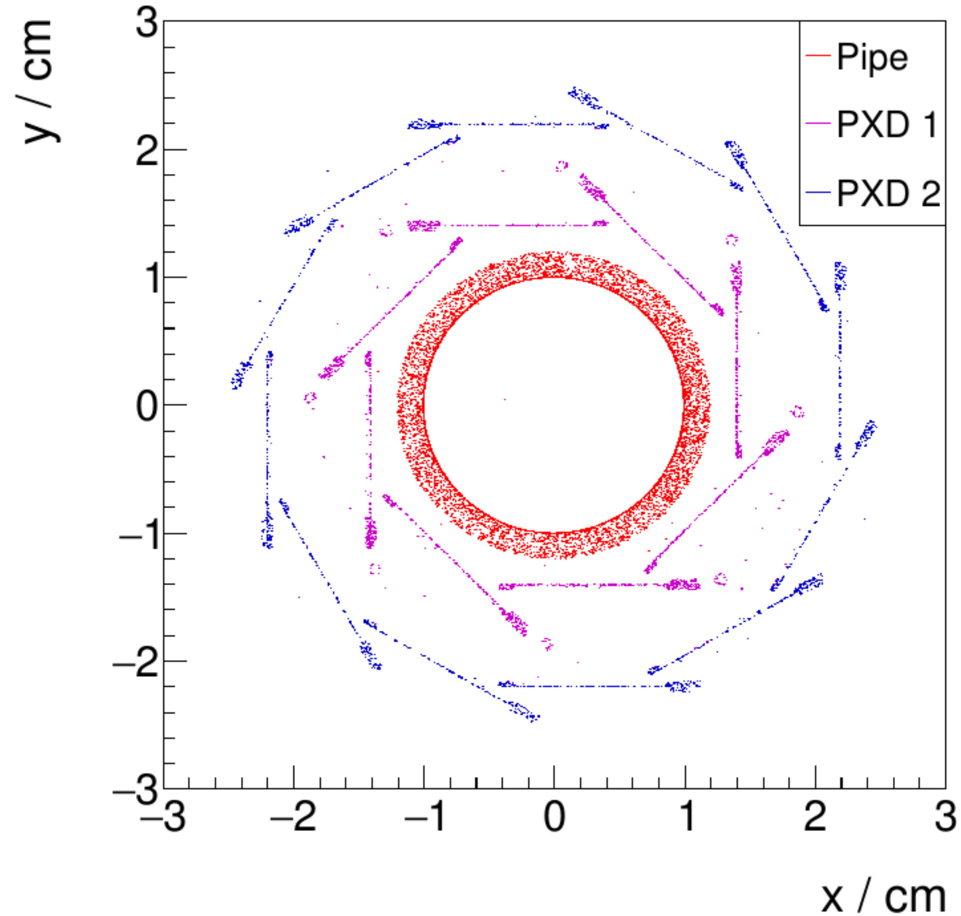
(*arXiv:hep-ex/0703039*)



- $\mathcal{S}_{CP}^{\pi^0\pi^0} \to$ 2 fold ambiguity $(\sin(2\phi_2))$
- $\delta\phi_2 \sim 3°$

mean values important, too!

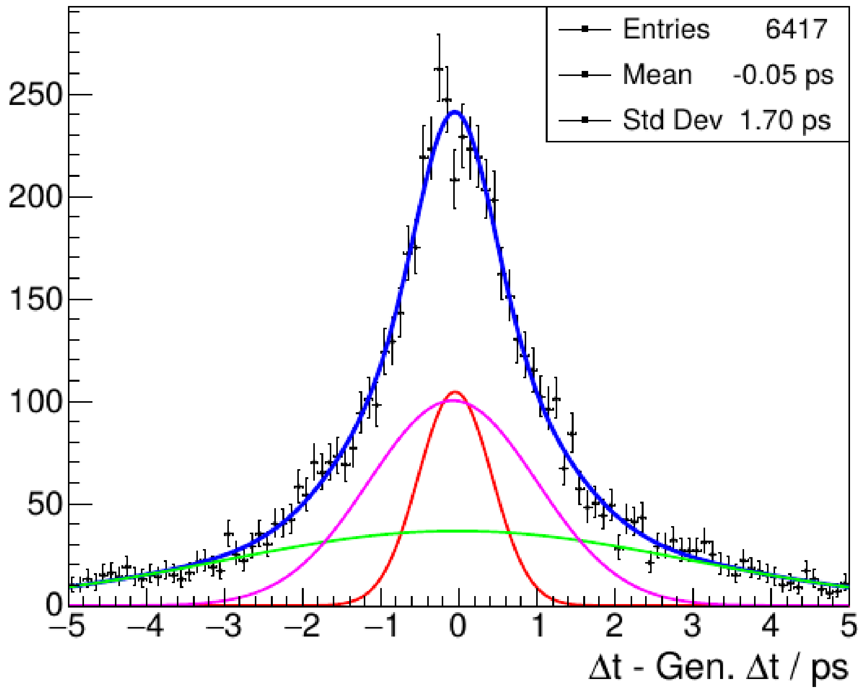
F. Abudinén @ 5th B2TIP



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

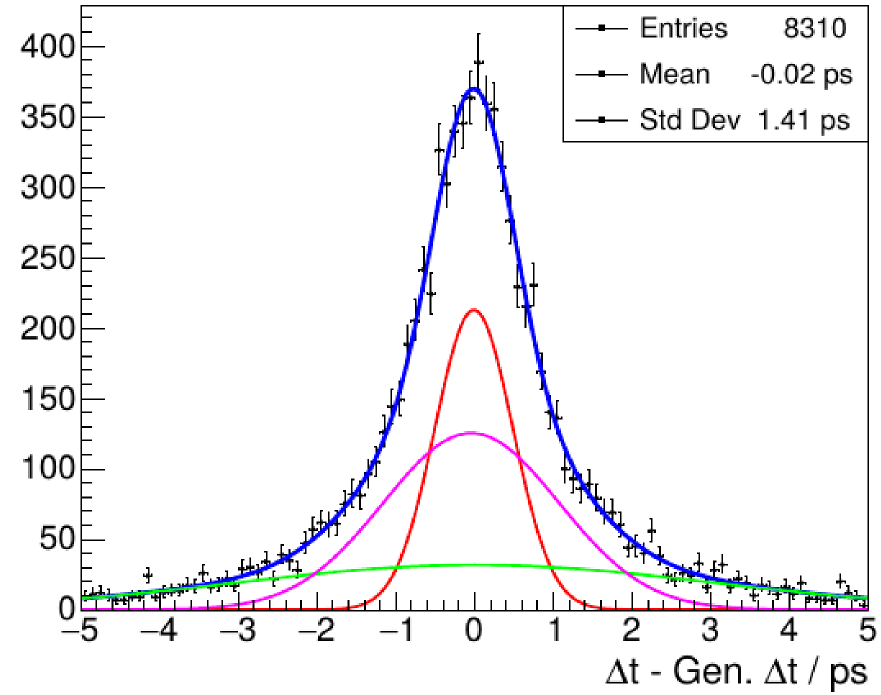
Δt resolution

$B^0_{sc} \rightarrow \pi^0_{ss}\ \pi^0_{sc}$
$\hookrightarrow \gamma_s\ \gamma_c$
$\hookrightarrow e^+ e^-$



At least one track (e^+ or e^-) has one PXD Hit

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

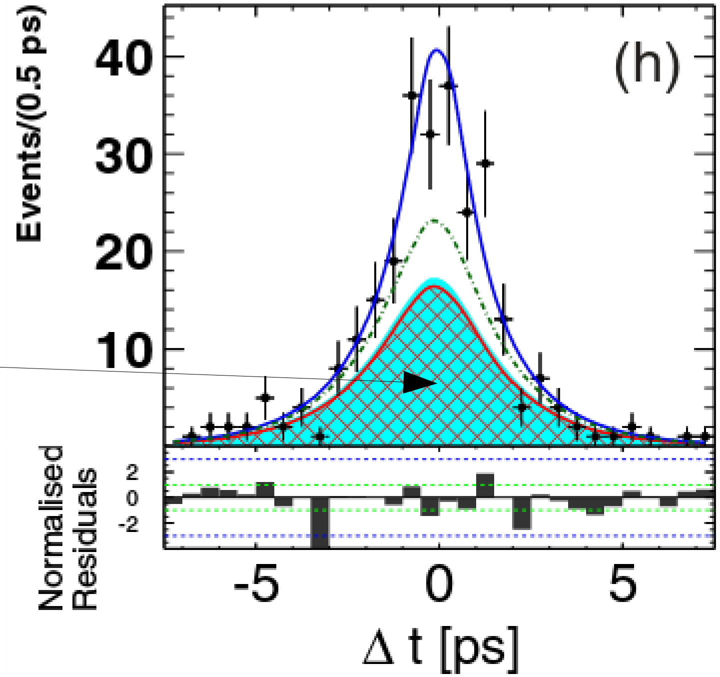


At least one track (e^+ or e^-) has one PXD Hit

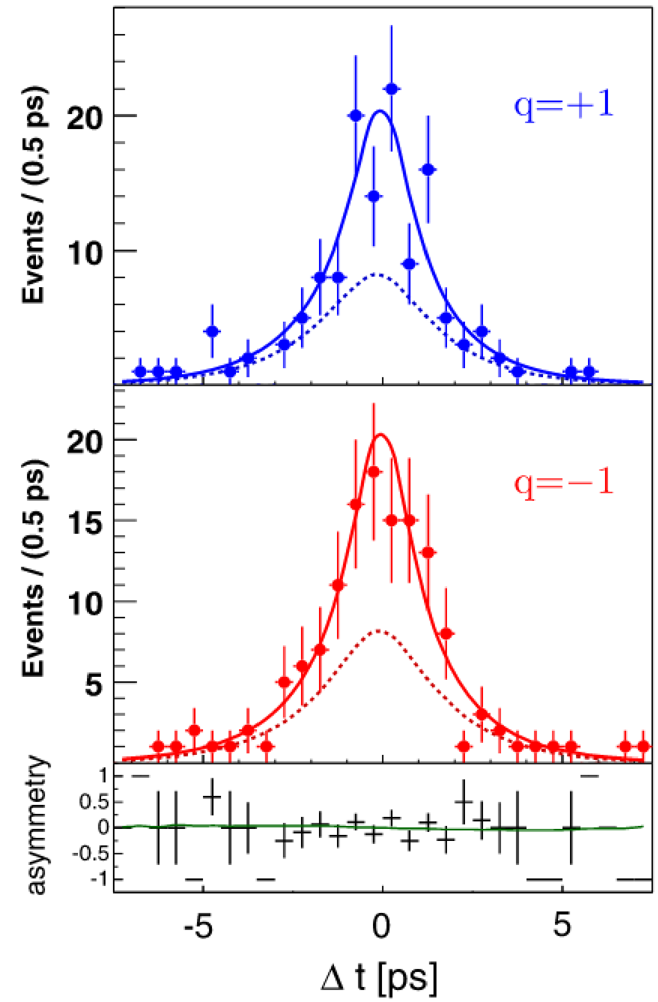
$B^0 \rightarrow \rho^+ \rho^-$

Phys. Rev. D **93** 032010 (2016)

Flavor integrated



Four pion final state

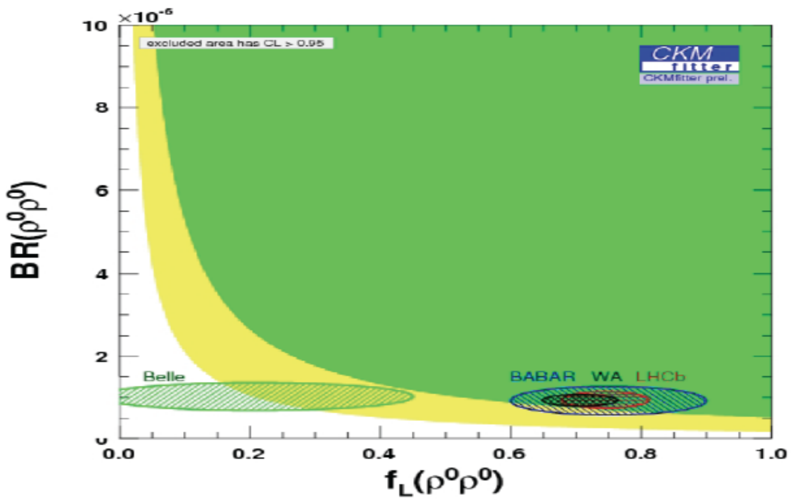


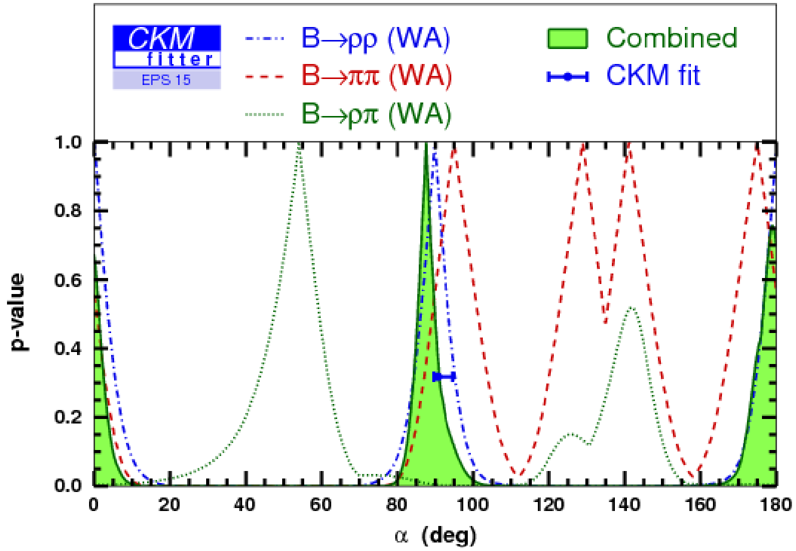
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (28.3 \pm 1.5\,(\text{stat}) \pm 1.5\,(\text{syst})) \times 10^{-6},$$
$$f_L = 0.988 \pm 0.012\,(\text{stat}) \pm 0.023\,(\text{syst}),$$
$$\mathcal{A}_{CP} = 0.00 \pm 0.10\,(\text{stat}) \pm 0.06\,(\text{syst}),$$
$$\mathcal{S}_{CP} = -0.13 \pm 0.15\,(\text{stat}) \pm 0.05\,(\text{syst}).$$

- Precision improvement with respect to the previously published result is factor 2.
- Increase of data, simultaneous extraction of observables and analysis optimization for high signal yield.

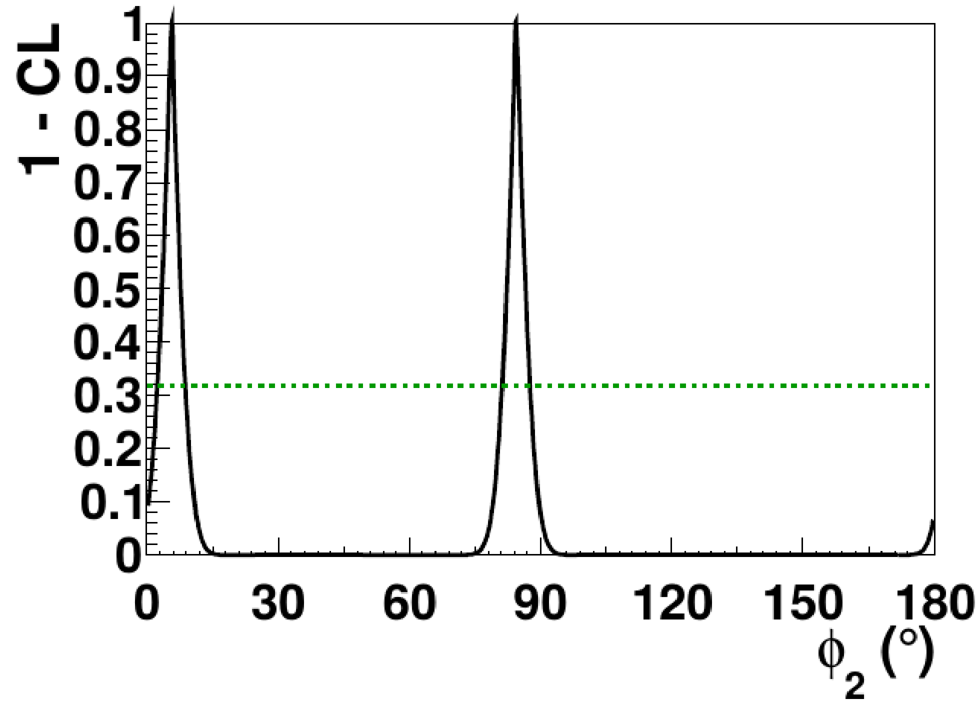
B → ρ ρ

P. Vanhoefer @ 3rd B2TIP





extrapolated to $50ab^{-1}$ (wo/$S_{CP}^{\rho^0\rho^0}$)



(stat error$\times 0.15$, syst error $\times 0.7$)

$\delta\phi_2 \sim 3^\circ$

error depends also on mean values, isospin triangles do not close!

Belle2:

$S_{CP}^{\rho^0\rho^0}$ will provide an additional constraint

Photon polarization

Radiative B decays, with $b \to s\,\gamma$ 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)):

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

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

- 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)

$$\mathcal{S}^{\mathrm{SM}} = -\sin 2\phi_1 \frac{m_s}{m_b}\left[2 + \mathcal{O}(\alpha_s)\right] + \mathcal{S}^{\mathrm{SM},s\gamma g}$$

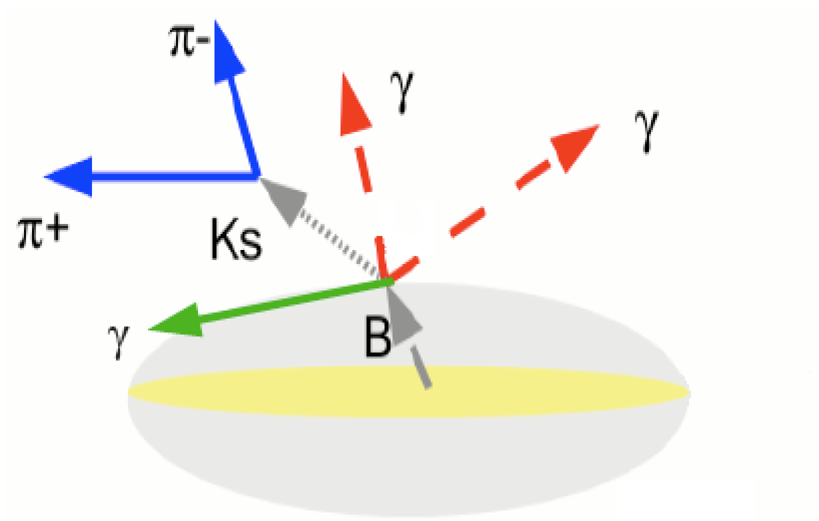
C < 0.01 (direct CP violation) (Greub at al., Nucl. Phys B 434, 39 (1995))

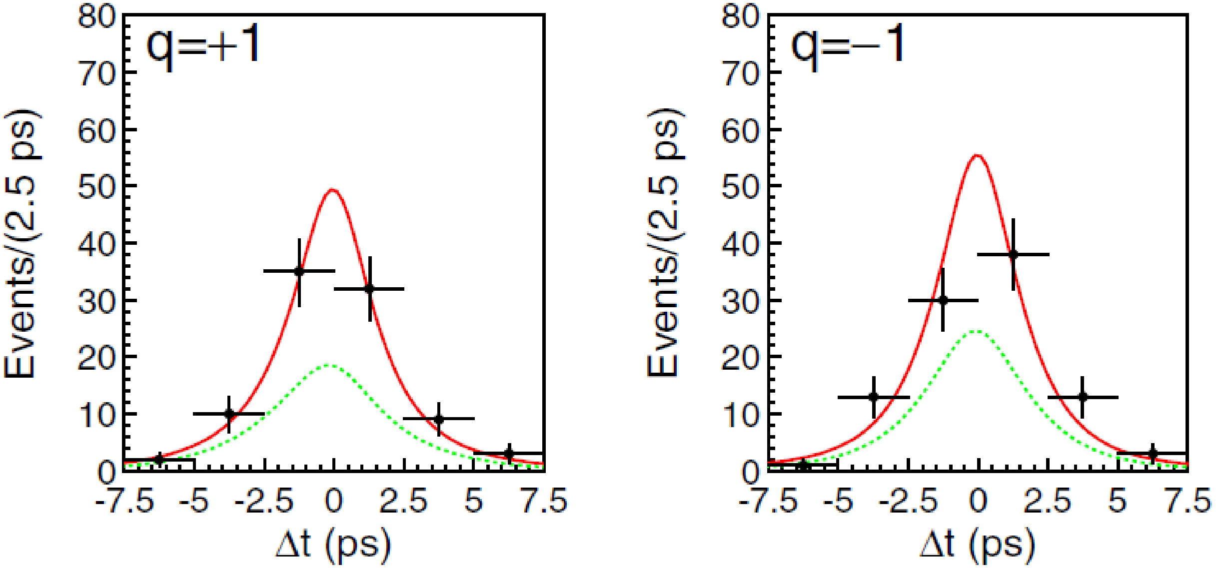
- TD CP asymmetry measurements give an indirect measurement of photon polarization

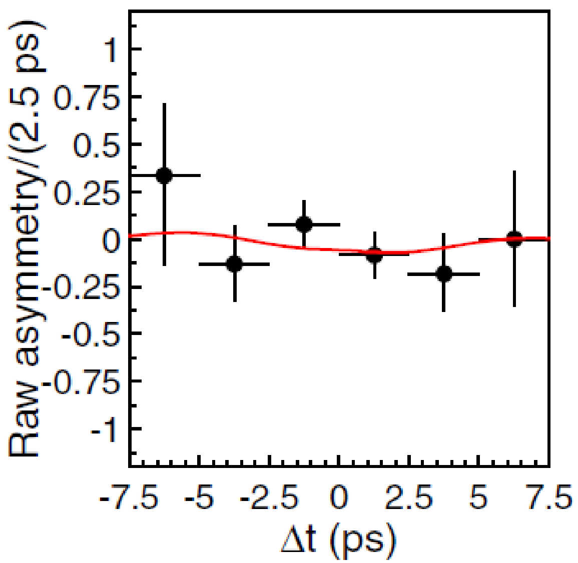
$B^0 \to K_S \pi^0 \gamma$: TD analysis

Phys. Rev. D 74, 111104(R) (2006)

B vertex reconstruction







$$\mathcal{S}_{K_S^0\pi^0\gamma} = -0.10 \pm 0.31(\text{stat}) \pm 0.07(\text{syst}),$$

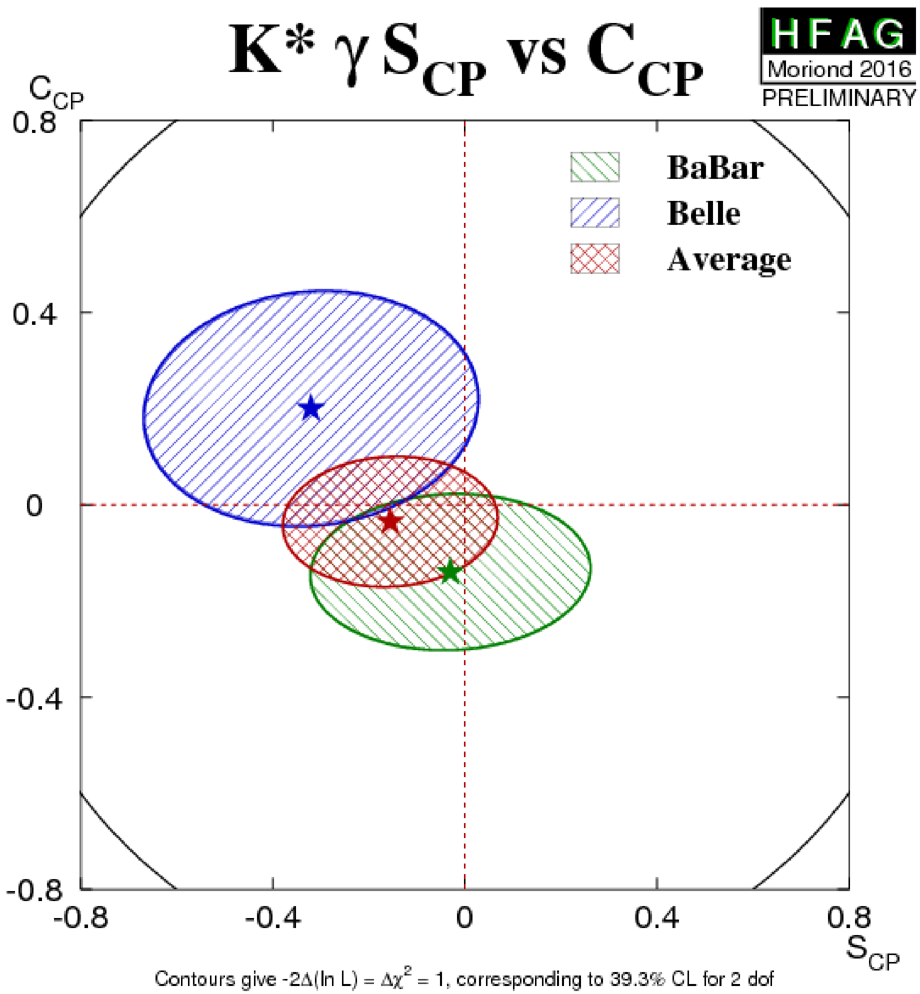
$$\mathcal{A}_{K_S^0\pi^0\gamma} = -0.20 \pm 0.20(\text{stat}) \pm 0.06(\text{syst}),$$

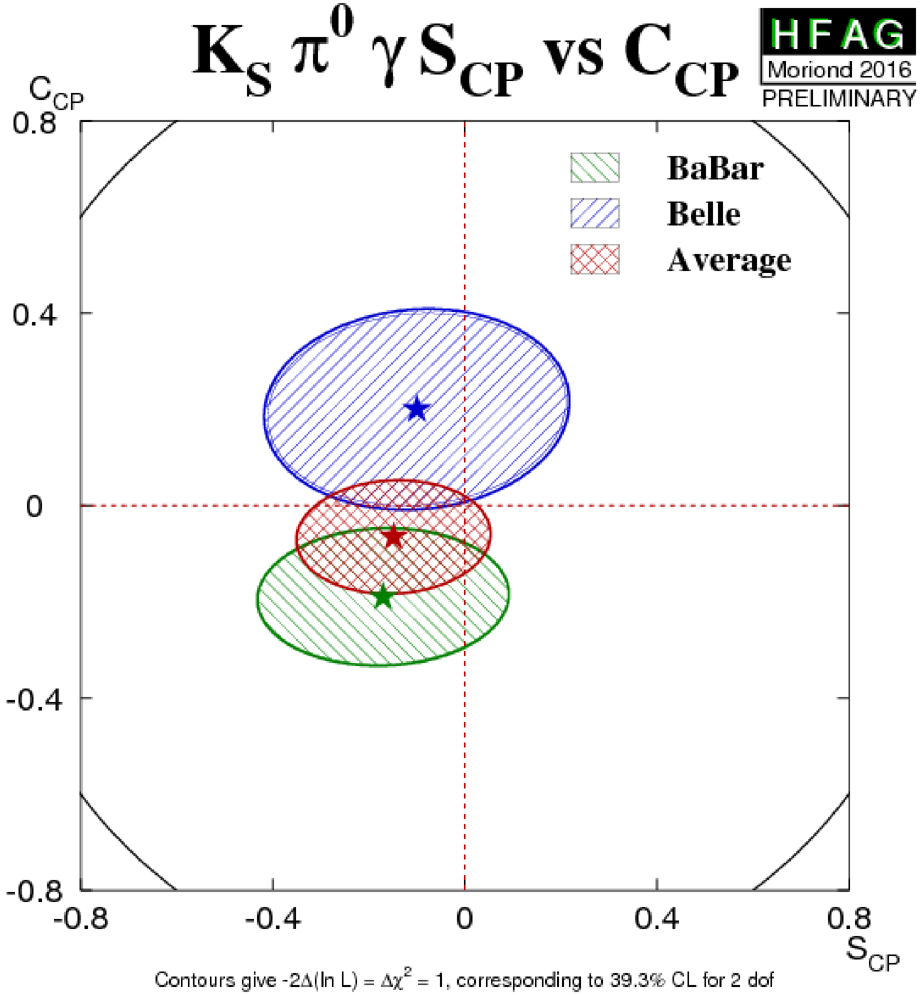
No significant CP asymmetry

$$\mathcal{S}_{K^{*0}\gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05$$

$$\mathcal{A}_{K^{*0}\gamma} = -0.20 \pm 0.24 \pm 0.05$$

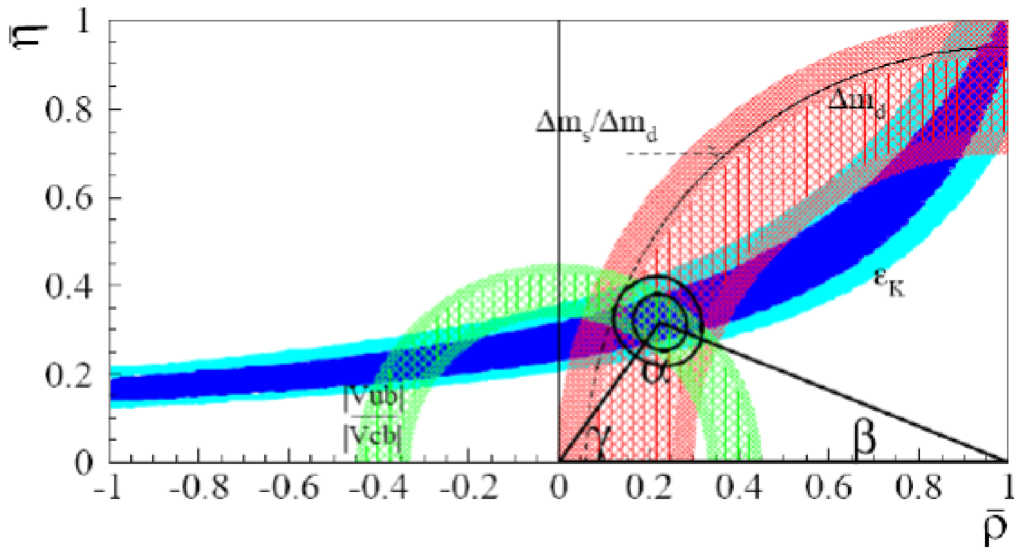
$B^0 \to Ks\, \pi^0 \gamma$



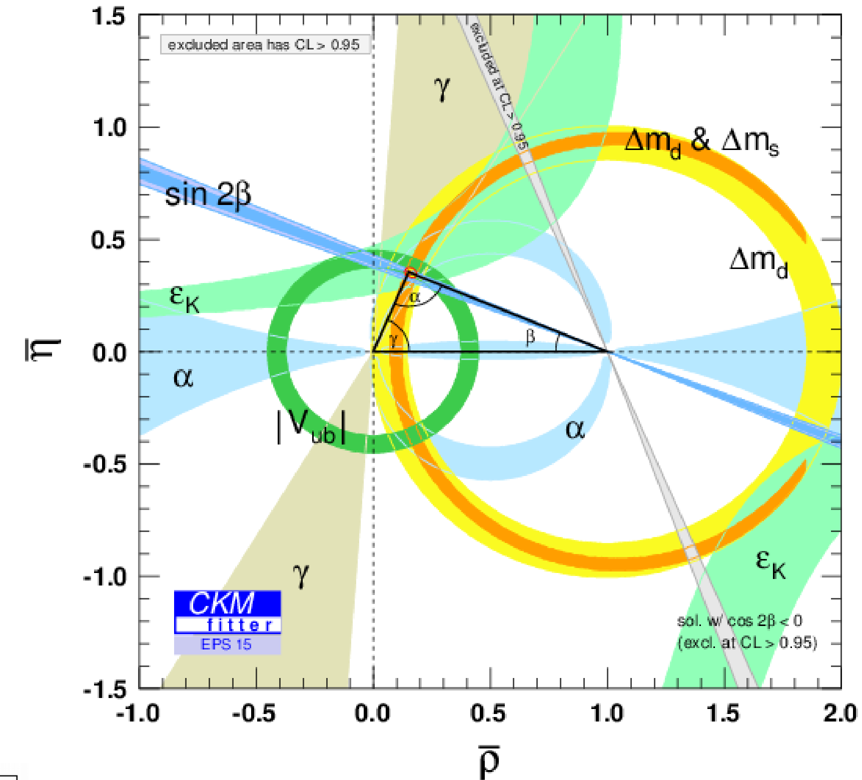


Very important decay mode for Belle II

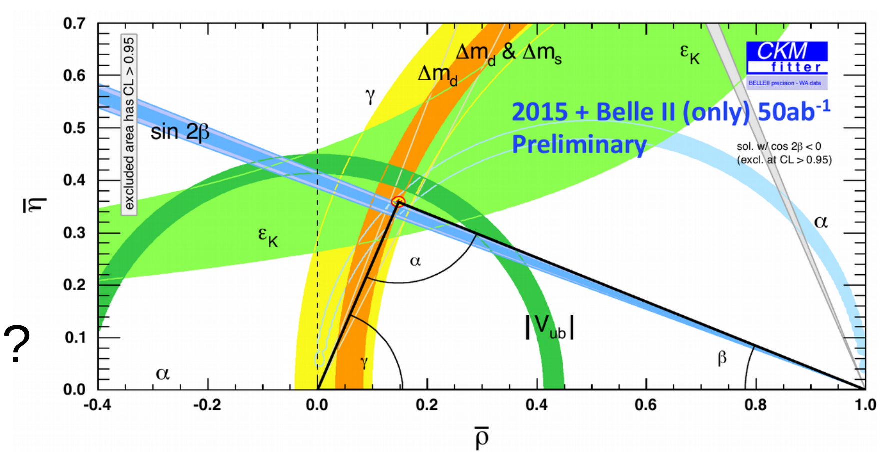
Outlook



Before the B-factories



After the B-factories



After Belle II ?

Lucky scenario

CKM mechanism will be tested at 1% level