CP Violation sensitivity at the Belle II experiment

A.Mordá

on behalf of the Belle II Collaboration

INFN - Padova

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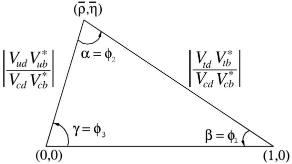
CP Violation in B meson systems

B mesons exhibit large CPV effects

The B^0 Unitarity Triangle



$\phi_1 \sim \phi_2 \sim \phi_3$!

The angle ϕ_3 (γ) related to relative phase of tree level bc & bu couplings

ϕ_1, ϕ_2 (β, α) depend on top-beauty coupling accessible through B^0 oscillation processes

$\phi_1^{WA}|_{1\sigma} = (21.85^{+0.68}_{-0.67})^\circ$, $\phi_2^{WA}|_{1\sigma} = (88.8^{+2.3}_{-2.3})^\circ$

[CKMFitter, Summer '16]

ϕ_1 & ϕ_2 enter the expression of time dependent rate asymmetry of B meson decays into CP eigenstates

$$a_{f_{CP}}(t) \equiv \frac{\Gamma[B(t)] - \Gamma[\bar{B}(t)]}{\Gamma[B(t)] + \Gamma[\bar{B}(t)]} = C\cos(\Delta M t) - S\sin(\Delta M t)$$

$C \propto \Gamma[B] - \Gamma[\bar{B}]$: **Direct CPV**

$S \equiv \sin(2\phi_i^{eff})$: **mixing induced CPV**

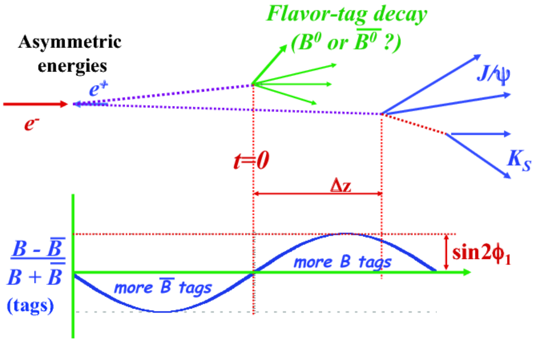
Time-dependent CPV at B-factories

Time dependent rate asymmetry of B meson decays into CP eigenstates

$$a_{f_{CP}}(\Delta t) \equiv \frac{\Gamma[B(\Delta t)] - \Gamma[\bar{B}(\Delta t)]}{\Gamma[B(\Delta t)] + \Gamma[\bar{B}(\Delta t)]} = C\cos(\Delta M \Delta t) - S\sin(\Delta M \Delta t)$$

Asymmetric *B-factories* @ $\Upsilon(4S)$

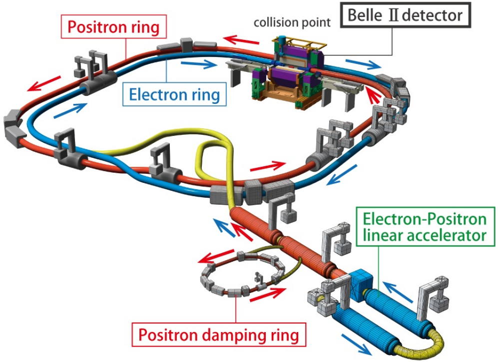
- $B\bar{B}$ pair from $\Upsilon(4S)$ are in entangled state
  - decay of ***tag*** B into **flavor specific** final state provides
  - t_0 & ***signal B*** flavor at t_0
- **Asymmetric kinematics**
  - $B\bar{B}$ are $\sim$ at rest from $\Upsilon(4S)$
  - measurement of time from displacement between B decay vertexes



$\Delta t \simeq \Delta z / \beta\gamma c$

SuperKEKB ...

$$CPV \sim \frac{1}{\mathcal{BR}} \Rightarrow$$ **large data set is needed for precision measurements**



	KEKB	SuperKEKB
$\mathcal{L}$ $(10^{34} s^{-1} \cdot cm^{-2})$	2.11	80
$\int \mathcal{L}$dt (ab^{-1})	0.8	50
e^- energy (GeV)	8	7
e^+ energy (GeV)	3.5	4
$\beta\gamma$	0.45	0.28
$< \Delta z >$	$\sim 200\ \mu$m	$\sim 130\ \mu$m

1 ab^{-1} $\sim$ 1 billion $B\bar{B}$

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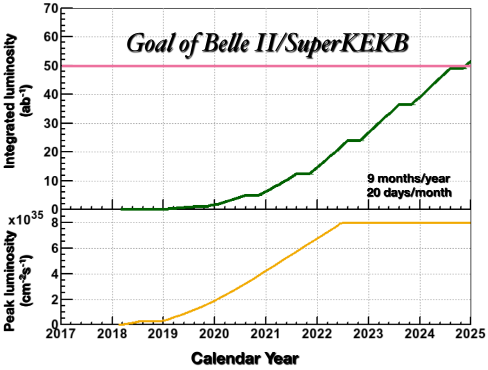

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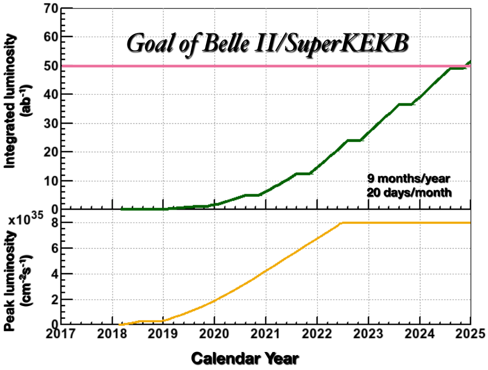

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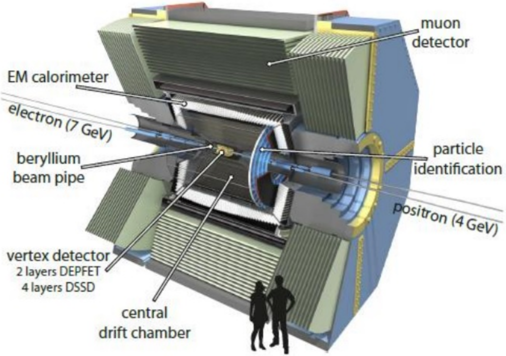
Reduced $\Upsilon(4S)$ boost
Higher background
} **Detector improvement**

... & the Belle II detector

Full coverage of interaction region



Extended VXD region

Small cell size & longer level arm in CDC

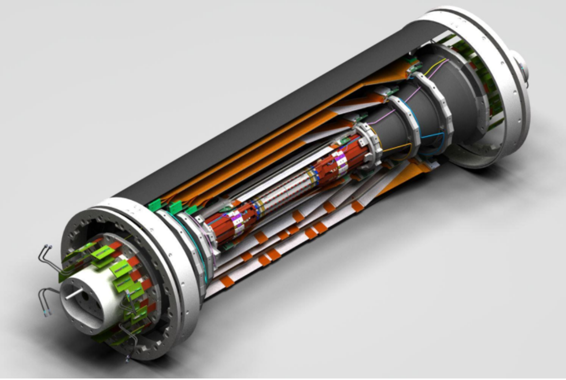
Improved electronics and light yield for EM calorimeter

Improved K/π separation & K_S^0 reconstruction

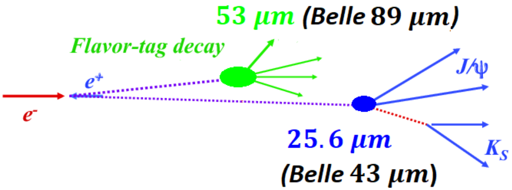
See Carlos Marinas' talk on Friday for more details

… & the Belle II detector

Improvement in vertexing capabilities



Time dependent analysis: Vertex resolution on z



Resolution on Δt in $B^0 \to J/\psi(\mu\mu)K^0_S$

Belle II	Belle
0.77 ps	0.92 ps

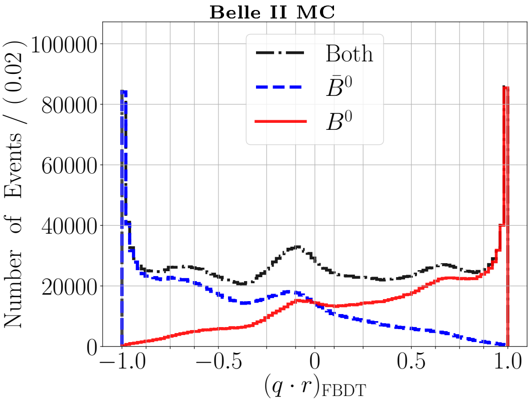
Relevant improvement from vertexing (despite reduced $\Upsilon(4S)$) boost

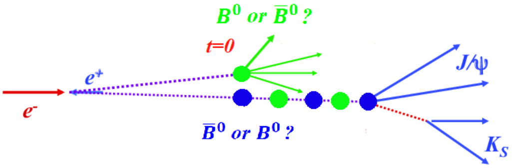
Two benchmark scenarios:

no improvement, factor 2 improvement

... & the Belle II detector

Time dependent analysis: Flavor tagging





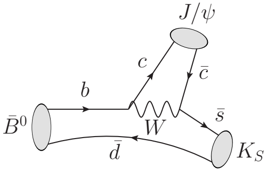
Improvements wrt Belle/BaBar

- new tagging categories
- tracking & PID improvements

Tagging efficiency (on $B^0 \to J/\psi(\mu\mu)K_S^0$)

Belle II MC	37.16 ± 0.03 %
Belle Data	33.6 ± 0.5 %
B-factories	~ 30 %
LHCb	5.9 %

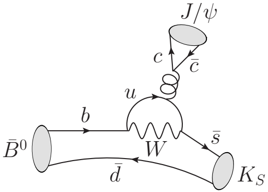
$\sin(2\phi_1)$ in tree dominated $b \to c\bar{c}s$ transitions



Decay dominated by a single weak phase

$S \simeq \sin(2\phi_1)$

Penguin contribution



Irreducible systematics from vertexing & tag-side interference: **depend on real performance of detector**

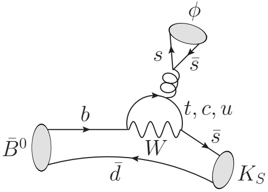
Reducible systematics are expected to scale with luminosity (*e.g.* fit bias, signal fraction)

Current status from Belle [PRL 108 171802]					Belle II expected uncertainties @ 50 ab^{-1}			
uncertainties (10^{-3})		Value	stat	syst	stat	syst: reducible	irreducible	
$J/\psi K^0_S$	S	+0.670	29	13	3.5	1.2	8.2	4.4
	$\mathcal{A} \equiv -C$	-0.015	21	+45,-23	2.5	0.7	+43,-22	+42, - 11
$c\bar{c}s$	S	+0.667	23	12	2.7	2.6	7.0	3.6
	$\mathcal{A} \equiv -C$	+0.006	16	12	1.9	1.4	10.6	8.7

Precision better than 1% is expected on ϕ_1 from $b \to c\bar{c}s$

$\sin(2\phi_1)$ in penguin dominated $b \to q\bar{q}s$: $B^0 \to \phi K^0$

Loop process, same weak phase as $b \to c\bar{c}s$



Current status from Belle: $S_{\phi K_S^0} = +0.9^{+0.09}_{-0.19}$

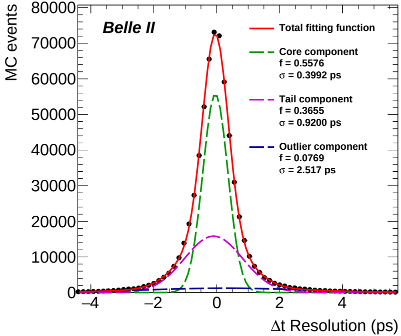
Expected sensitivity @ 5 ab^{-1}

Channel	$\sigma(S)$	$\sigma(C)$
$\phi(K^+K^-)K_S^0(\pi^+\pi^-)$	0.08	0.05
$\phi(K^+K^-)K_S^0(\pi^0\pi^0)$	0.13	0.10
$\phi(\pi^+\pi^-\pi^0)K_S^0(\pi^+\pi^-)$	0.15	0.11
K_S^0 modes	0.06	0.04
$K_S^0 + K_L^0$ modes	0.05	0.03

Sensitivity studies without beam induced background

Time resolution of ~ 0.77 ps

$\Delta t^{rec} - \Delta t^{MC}$ in $\phi(K^+K^-)K_S^0(\pi^+\pi^-)$



$\sin(2\phi_1)$ in penguin dominated $b \to q\bar{q}s$: $B^0 \to \eta' K^0$

Current status from Belle: $S_{\eta' K^0_S} = +0.68 \pm 0.07 \pm 0.03$ [JHEP 10 165]

Large $\mathcal{BR} \sim 10^{-5}$

Crucial aspect is $\boldsymbol{\pi^0, \eta^0}$ reconstruction

Non negligible fraction of mis-reconstructed signal

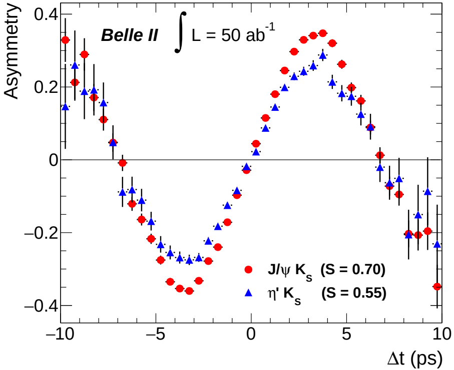
Sensitivity studies accounting for beam induced background

Expected sensitivity @ 5 ab^{-1}

Channel	$\sigma(S)$	$\sigma(C)$
$\eta'(\eta_{\gamma\gamma}\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.06	0.04
$\eta'(\eta_{3\pi}\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.11	0.08
K^0_S modes	0.03	0.02
$K^0_S + K^0_L$ modes	0.03	0.02
Syst	**0.021** (**0.017**)	

Syst 1 (2) scenarios

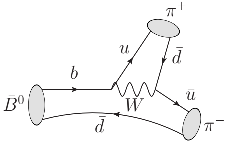
In "best case" scenario

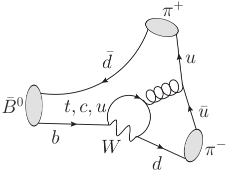


$\boldsymbol{B^0 \to \eta' K^0}$ **is the first** $\boldsymbol{b \to q\bar{q}s}$ **mode systematic dominated @** $\boldsymbol{\mathcal{L} \sim 10(20)}$ **ab^{-1}**

ϕ_2 measurement: isospin analysis in $B \to \pi\pi, \rho\rho$

Two amplitudes of comparable size and different weak phase





Penguin enters $B^0 \to \pi^+\pi^-, \pi^0\pi^0$ **but not** $B^\pm \to \pi^\pm\pi^0$

$$\phi_2 = \widehat{(\bar{A}^{+0}, A^{+0})},\ \phi_2^{eff} = \widehat{(\bar{A}^{+-}, A^{+-})}$$

Isospin constraints B^0 and $B^\pm$ amplitudes to the following triangular relations (**Gronau-London** [PRL 64 3381 (1990)])

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

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

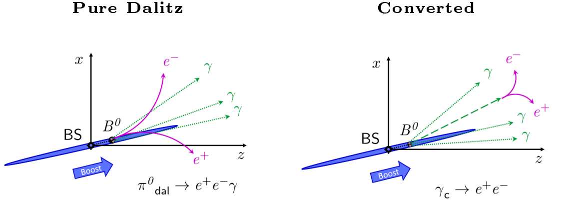
$$|A^{+0}| = |\bar{A}^{+0}|$$

- magnitude and relative phase between A^{+-} & $\bar{A}^{+-}$ determined from $B^0 \to \pi^+\pi^-$
- modulus of A^{00} & $\bar{A}^{00}$ known from $\mathcal{BR}$ & $C_{\pi^0\pi^0}$ in $B^0 \to \pi^0\pi^0$
- need measurement of $S_{\pi^0\pi^0}$ **in** $B^0 \to \pi^0\pi^0$

ϕ_2 measurement: $B \to \pi^0\pi^0$ sensitivity

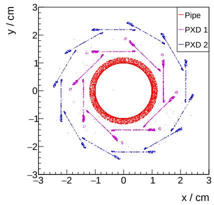
First attempt to measure $S_{\pi^0\pi^0}$

Final state	$\mathcal{BR}(\%)$	exp @ 50 ab^{-1}
$\pi^0_{\gamma\gamma}(\gamma\gamma)\ \pi^0_{\gamma\gamma}(\to\gamma\gamma)$	98.823	
$\pi^0_{dal}(\to e^+e^-\gamma)\ \pi^0_{\gamma\gamma}(\to\gamma\gamma)$	1.174	270
$\pi^0_{\gamma_c\gamma}(\to\gamma_c(\to e^+e^-)\gamma)\ \pi^0_{\gamma\gamma}(\to\gamma\gamma)$	-	50

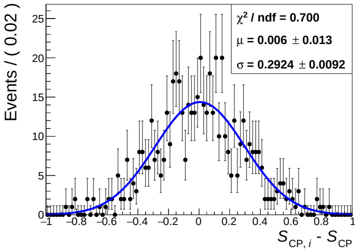


- Only Dalitz decay candidates are used for time dependent analysis
  - Non negligible fraction of converted γ reconstructed as Dalitz candidates
- The two topologies can be separated on a statistical basis

Conversion vertices in the innermost part of detector



Statistical uncertainty estimated with pseudo-experiments



$\sigma(S) \sim 0.29$

ϕ_2 measurement: $B \to \pi^0\pi^0$ sensitivity

First attempt to measure $S_{\pi^0\pi^0}$

Final state	$\mathcal{BR}(\%)$	exp @ 50 ab^{-1}
$\pi^0_{\gamma\gamma}(\gamma\gamma)\ \pi^0_{\gamma\gamma}(\to\gamma\gamma)$	98.823	
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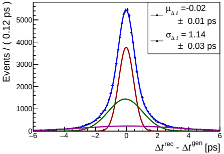
$\pi^0_{\gamma_c\gamma}(\to\gamma_c(\to e^+e^-)\gamma)\ \pi^0_{\gamma\gamma}(\to\gamma\gamma)$	-	50

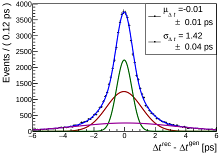
Pure Dalitz

$\delta(\Delta t) = 1.14 \pm 0.03$



Converted

$\delta(\Delta t) = 1.42 \pm 0.04$



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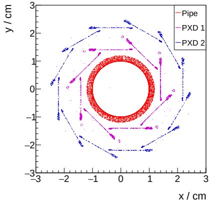

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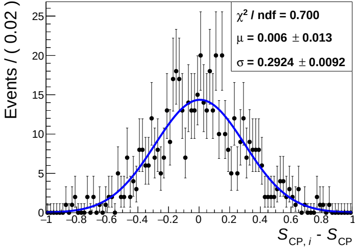


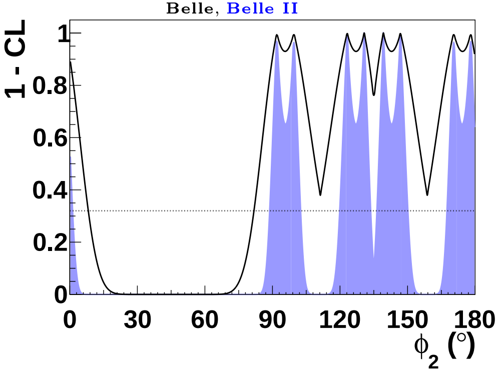
$\sigma(S) \sim 0.29$

ϕ_2 measurement: $B \to \pi\pi$

Isospin analysis input in $B \to \pi\pi$

	Value	Belle @ 0.8 ab^{-1}	Belle II @ 50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm 0.21 \pm 0.18$ [2]	$\pm 0.03 \pm 0.08$
$\mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.31	$\pm 0.19 \pm 0.18$ [1]	$\pm 0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm 0.26 \pm 0.38$ [2]	$\pm 0.03 \pm 0.09$
$C_{\pi^+\pi^-}$	-0.33	$\pm 0.06 \pm 0.03$ [3]	$\pm 0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$ [3]	$\pm 0.01 \pm 0.01$
$C_{\pi^0\pi^0}$	-0.14	$\pm 0.36 \pm 0.12$ [1]	$\pm 0.03 \pm 0.01$

[1]: arXiv:1705.02083, [2]: PRD 87(3) 031103, [2]: PRD 88(9) 092003



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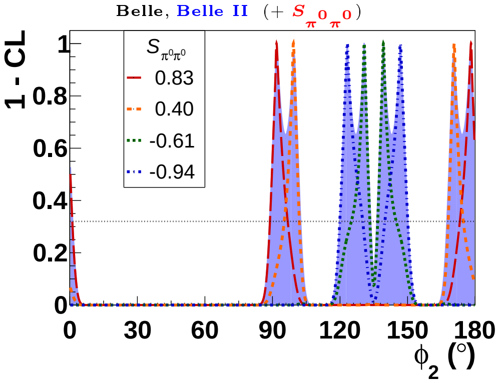
Adding $S_{\pi^0\pi^0}$ input

$$\Delta\phi_{2,\pi\pi}^{exp}\big|_{1\sigma}^{88^\circ} \sim 4^\circ$$



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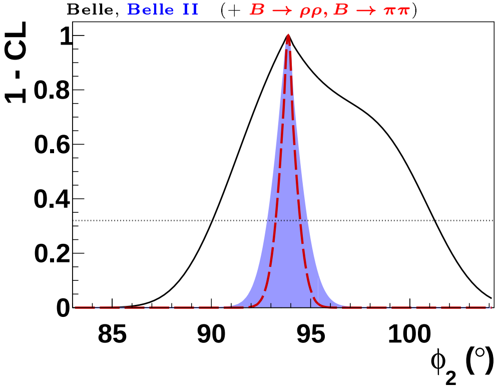
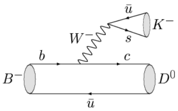


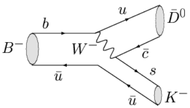
All $B \to hh$ inputs

$\Delta\phi_{2,hh}^{exp}|_{1\sigma} \sim 0.6^\circ$

ϕ_3 measurement

CPV arises from interference of tree level diagrams of differing weak and strong phases.





No B mixing, nor penguin amplitudes involved

Current status

$$\phi_3^{Belle} = (78^{+15}_{-16})^\circ,\ \phi_3^{LHCb} = (76.8^{+5.1}_{-5.7})^\circ$$

Belle II Golden Mode

$$B^\pm \to [K_S^0\pi^+\pi^-]_D K^\pm$$

- large Branching ratio
- good K_S^0 reconstruction

Dalitz-plot analysis of self-conjugate D decays (GGSZ) [PRD68, 054018 (2003)]

Strong phase measurement requires

- Dalitz plot analysis
- external inputs (from CLEO-c that will be improved by BESIII)

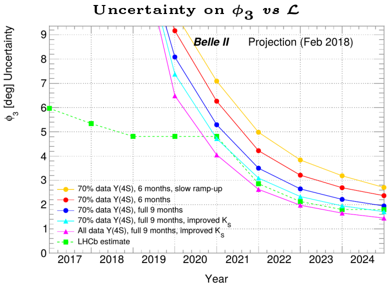
ϕ_3 measurement - prospects

Sensitivity studies on $B^\pm \to [K^0_S\pi^+\pi^-]_D K^\pm$

Expected uncertainty on ϕ_3 @ 50 ab^{-1} of 3°

Improvements expected from

- inclusion of GGSZ modes ($D^0 \to K^0_S K^+ K^-$, $B^\pm \to D^{\star 0} K^\pm$)
- refinement of analysis, according to real performances of Belle II



Extrapolation of combination

- inclusion of ADS/GLW modes $B^+ \to D^\star(D\{\gamma,\pi^0\})K^+$
- assuming 10fb^{-1} BESIII data @ $\psi(3770)$ to constraint strong phase

Expected uncertainty on ϕ_3

3.6° (1.6°) @ 10 (50) ab^{-1}

ϕ_3 measurement - prospects

Sensitivity studies on $B^{\pm} \to [K_S^0 \pi^+ \pi^-]_D K^{\pm}$

Expected uncertainty on ϕ_3 @ 50 ab^{-1} of 3°

Improvements expected from

- inclusion of GGSZ modes ($D^0 \to K_S^0 K^+ K^-$, $B^{\pm} \to D^{\star 0} K^{\pm}$)
- refinement of analysis, according to real performances of Belle II

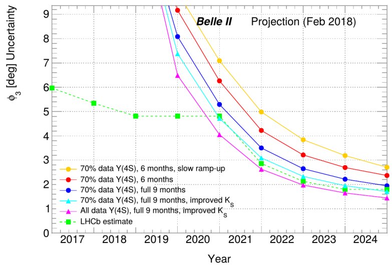
Extrapolation of combination

- inclusion of ADS/GLW modes $B^+ \to D^{\star}(D\{\gamma, \pi^0\})K^+$
- assuming 10fb^{-1} BESIII data @ $\psi(3770)$ to constraint strong phase

Expected uncertainty on ϕ_3

3.6° (1.6°) @ 10 (50) ab^{-1}

Uncertainty on ϕ_3 *vs* $\mathcal{L}$



... ***en plus*** (not done in Belle/BaBar)

- ***D* final states with neutrals & significant $\mathcal{BR}$**, *e.g.*
  - CP-even: $\pi^0\pi^0$, $K_S^0\eta\pi^0$, $K_S^0K_S^0K_S^0$
  - CP-odd: $\eta\pi^0\pi^0$, $\eta'\pi^0\pi^0$, $K_S^0K_S^0K_L^0$
- **double Dalitz analysis of $B^0 \to D(K^0\pi^+\pi^-)K^+\pi^-$**
  - $B^{\pm} \to [K_S^0\pi^+\pi^-\pi^0]_D K^{\pm}$

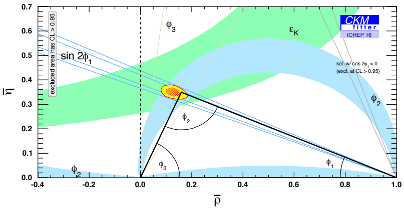
Conclusions

The Belle II program

- large dataset ⊕ improved detector and physics software (flavor tagging, vertex reconstruction)
- unique possibilities for modes with final state with neutral particles

- **sin $(2\phi_1)$** will remain the most precise measurement on the UT parameters (precision level of penguin pollution)
- $\boldsymbol{\phi_2}$ determination will benefit of reduced errors and new inputs ($S_{\pi^0\pi^0}$, $B \to \rho\pi$ mode) for isospin analysis
- $\boldsymbol{\phi_3}$ measurement will reduce uncertainty of 1 order of magnitude, tough competition with LHCb
- other time dependent CP-violation analysis feasible @ Belle II ($B^0 \to K^\star(\to \pi^0 K^0_S)\gamma$)

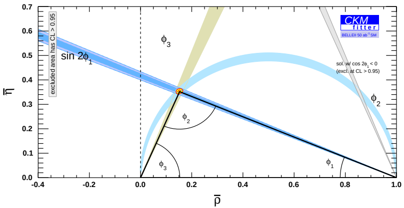
Current world average



CPV only inputs

More details in the Belle II Physics Book

Belle II projection @ 50ab^{-1}



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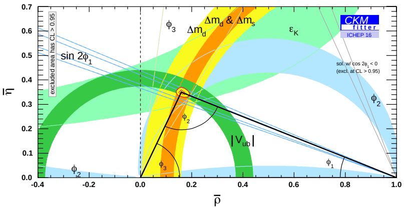
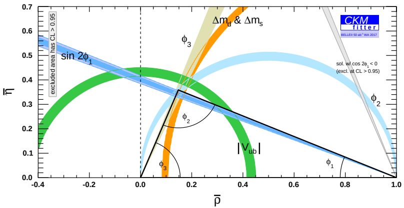


All inputs

More details in the Belle II Physics Book

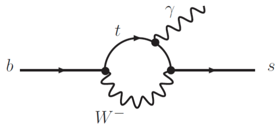
Belle II projection @ 50ab^{-1}



Backup

Time dependent studies *beyond* CP-violation

Photon polarization in $b \to s\gamma$ transition



Indirect probe of photon polarization by measuring

$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\bar{B}(t) \to f_{CP}\gamma) - \Gamma(B(t) \to f_{CP}\gamma)}{\Gamma(\bar{B}(t) \to f_{CP}\gamma) + \Gamma(B(t) \to f_{CP}\gamma)} \simeq -2\left(\frac{m_s}{m_b}\right)\sin(2\beta)\sin(\Delta m \cdot t)$$

generated by **interference** between favored $\boldsymbol{B^0 \to f_{CP}\gamma_R}$ and **suppressed** $\boldsymbol{B^0 \to \bar{B}^0 \to f_{CP}\gamma_R}$ amplitudes.

Belle 2 performed sensitivity studies for the *golden mode* $\boldsymbol{B^0 \to K^\star(K^0_S\pi^0)\gamma}$

K^0_S reconstructed in the $\pi^+\pi^-$ final state (to fit B^0 decay vertex)

Current status

$$S^{SM}_{K^0_S\pi^0\gamma} = -(2.3 \pm 1.6)\%$$

$$S^{Belle}_{K^0_S\pi^0\gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05$$

Expected statistical uncertainties

no beam induced background effects in simulation

$\mathcal{L}$ ab^{-1}	$\sigma(S)$	$\sigma(C)$
2	0.15	0.10
10	0.07	0.05
50	0.03	0.02

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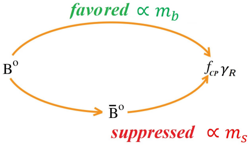

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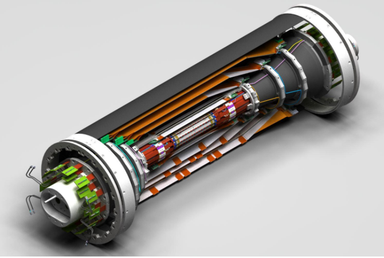
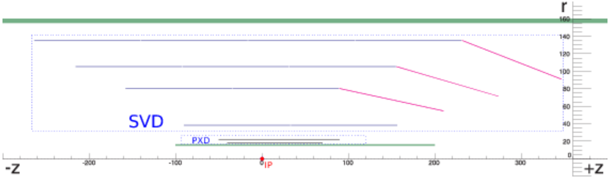
Belle2 Vertexing



DEPFET Technology

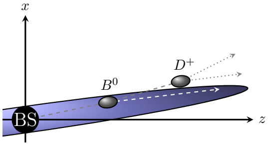


Benchmark modes

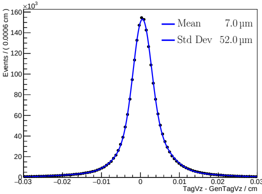
$J/\psi \to \mu\mu$ in $B^0 \to J/\psi K_S^0$

$\Delta z \sim 26\mu\text{m}$

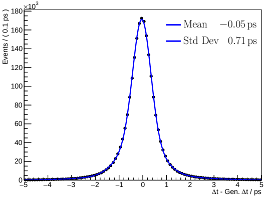
B tag in $B^0 \to J/\psi K_S^0$



B tag vtx residuals



Δt residuals



$\sin(2\beta)$ in $b \to c\bar{c}s$ transitions

	No improvement	Vertex improvement	Leptonic categories
$S_{J/\psi K^0_S}$ (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
$A_{J/\psi K^0_S}$ (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

	No improvement	Vertex improvement	Leptonic categories
$S_{J/\psi \pi^0}$ (50 ab^{-1})			
stat.	0.027	0.027	0.047
syst. reducible	0.009	0.009	0.009
syst. irreducible	0.050	0.025	0.025
$A_{J/\psi \pi^0}$ (50 ab^{-1})			
stat.	0.020	0.020	0.035
syst. reducible	0.004	0.004	0.004
syst. irreducible	0.045	0.042	0.017

	No improvement	Vertex improvement	Leptonic categories
$S_{c\bar{c}s}$ (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
$A_{c\bar{c}s}$ (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

Penguin pollution in $\sin(2\beta)$ from $B^0 \to J/\psi K_S^0$

Let us denote the $\mathcal{O}(\lambda_u^s/\lambda_c^s)$ terms in by $\Delta S_{J/\psi K_S^0}$

$$S_{J/\psi K_S^0} \equiv \sin 2\phi_1 + \Delta S_{J/\psi K_S^0} \equiv \sin(2\phi_1 + \delta\phi_{J/\psi K_S^0})$$

$\delta\phi_{J/\psi K_S^0} \sim \mathcal{O}(\lambda_u^s/\lambda_c^s)$. Small parameters $\Delta S_{J/\psi K_S^0}$ or $\delta\phi_{J/\psi K_S^0}$ referred to as the 'penguin pollution' in the extraction of ϕ_1 from $S_{J/\psi K_S^0}$.

Need strategies to either compute, bound or control $\Delta S_{J/\psi K_S^0}$.

$$\Delta S_{J/\psi K_S^0} = 2\bar{\lambda}^2 \mathrm{Re}\frac{P_f}{T_f} \sin\phi_3 \cos 2\phi_1 + \mathcal{O}(\bar{\lambda}^4)$$

Strategy	$\Delta S_{J/\psi K_S^0}$ [%]	$\delta\phi_{J/\psi K_S^0}$ [°]
QCDF/pQCD [1,2]	$\lvert\ \ \rvert \lesssim 0.1$	$(\lvert\ \ \rvert \lesssim 0.1)$
OPE [3]	$(\lvert\ \ \rvert \lesssim 0.9)$	$\lvert\ \ \rvert \lesssim 0.68$
Broken U-spin [4,5]	0 ± 2	(0.0 ± 1.6)
Broken U-spin [6]	$([-5, -0.5])$	$[-2.0, -0.4]$
$SU(3)$ at $\mathcal{O}(\varepsilon)$ [7]	$\lvert\ \ \rvert \lesssim 1$	$\lvert\ \ \rvert \lesssim 0.8$
Broken $SU(3)$ [8]	$(-(1.4^{+0.9}_{-1.1}))$	$-(1.10^{+0.70}_{-0.85})$

[1]: PRD 70 036006, [2]: JHEP 03 009, [3]: PRL 115 061802, [4]: PRL 95 221804, [5]: arXiv:1102.0392, [6]: PRD79 014030, [7]: PRD 86 053008, [8]: JHEP 1503 145

Penguin pollution in sin(2β) from $B^0 \to J/\psi K^0_S$

U-spin-breaking corrections are parametrized by the parameter $\varepsilon \sim m_s/\Lambda_{QCD} \sim 0.2$.

Flavor breaking corrections cannot be controlled with a single partner mode, and hence such U-spin analyses require additional assumptions

$$(1+\bar{\lambda}^2)\sin 2\phi_1 = S_{J/\psi K^0_S} - \bar{\lambda}^2 S_{J/\psi \pi^0} - 2(\Delta_K + \bar{\lambda}^2\Delta_\pi)\cos 2\phi_1 \, \tan\phi_3$$

where penguin pollution effects are cancelled to $\mathcal{O}(\varepsilon)$ and leading corrections arise from isospin-breaking terms. Here $\Delta_{K,\pi}$ are splittings of the charged and neutral CP-averaged rates,

$$\Delta_K \equiv \frac{\bar{\Gamma}_{B_d \to J/\psi K^0} - \bar{\Gamma}_{B^+ \to J/\psi K^+}}{\bar{\Gamma}_{B_d \to J/\psi K^0} + \bar{\Gamma}_{B^+ \to J/\psi K^+}}$$

$$\Delta_\pi \equiv \frac{2\bar{\Gamma}_{B_d \to J/\psi \pi^0} - \bar{\Gamma}_{B^+ \to J/\psi \pi^+}}{2\bar{\Gamma}_{B_d \to J/\psi \pi^0} + \bar{\Gamma}_{B^+ \to J/\psi \pi^+}}$$

Expected uncertainty of $\sim 0.1^\circ$ on ϕ_1 from $B^0 \to J/\psi K^0_S$, when estimating penguin pollution and ignoring for now the $\mathcal{O}(\epsilon^2)$ effects from SU(3) breaking.

$\sin(2\beta)$ in $b \to c\bar{c}s$ transitions - systematics from Belle

		$J/\psi K_S^0$	$\psi(2S)K_S^0$	$\chi_{c1}K_S^0$	$J/\psi K_L^0$	All
Vertexing	$\mathcal{S}_f$	±0.008	±0.031	±0.025	±0.011	±0.007
	$\mathcal{A}_f$	±0.022	±0.026	±0.021	±0.015	±0.007
Δt	$\mathcal{S}_f$	±0.007	±0.007	±0.005	±0.007	±0.007
resolution	$\mathcal{A}_f$	±0.004	±0.003	±0.004	±0.003	±0.001
Tag-side	$\mathcal{S}_f$	±0.002	±0.002	±0.002	±0.001	±0.001
interference	$\mathcal{A}_f$	$^{+0.038}_{-0.000}$	$^{+0.038}_{-0.000}$	$^{+0.038}_{-0.000}$	$^{+0.000}_{-0.037}$	±0.008
Flavor	$\mathcal{S}_f$	±0.003	±0.003	±0.004	±0.003	±0.004
tagging	$\mathcal{A}_f$	±0.003	±0.003	±0.003	±0.003	±0.003
Possible	$\mathcal{S}_f$	±0.004	±0.004	±0.004	±0.004	±0.004
fit bias	$\mathcal{A}_f$	±0.005	±0.005	±0.005	±0.005	±0.005
Signal	$\mathcal{S}_f$	±0.004	±0.016	< 0.001	±0.016	±0.004
fraction	$\mathcal{A}_f$	±0.002	±0.006	< 0.001	±0.006	±0.002
Background	$\mathcal{S}_f$	< 0.001	±0.002	±0.030	±0.002	±0.001
Δt PDFs	$\mathcal{A}_f$	< 0.001	< 0.001	±0.014	< 0.001	< 0.001
Physics	$\mathcal{S}_f$	±0.001	±0.001	±0.001	±0.001	±0.001
parameters	$\mathcal{A}_f$	< 0.001	< 0.001	±0.001	< 0.001	< 0.001
Total	$\mathcal{S}_f$	±0.013	±0.036	±0.040	±0.021	±0.012
	$\mathcal{A}_f$	$^{+0.045}_{-0.023}$	$^{+0.047}_{-0.027}$	$^{+0.046}_{-0.026}$	$^{+0.017}_{-0.041}$	±0.012

Systematic errors in $\mathcal{S}_f$ and $\mathcal{A}_f \equiv \mathcal{C}_f$ in each f_{CP} mode and for the sum of all modes [PRL 108 171802]

$b \to q\bar{q}s$ modes efficiencies

$B^0 \to \eta' K^0$

Channel	Strategy	ε	ε_{SxF}
$\eta'(\eta_{\gamma\gamma}\pi^{\pm})K_S^{(\pm)}$	C$\star$	23.0 %	3.8 %
$\eta'(\eta_{3\pi}\pi^{\pm})K_S^{(\pm)}$	A	6.7 %	2.6%
	B$\star$	8.0 %	6.0%
	C	9.5 %	28.6%

Selection efficiency ε and fraction of signal cross feed candidates ε_{SxF} for the $\eta'(\eta_{\gamma\gamma}\pi^{\pm})K_S^{(\pm)}$ and $\eta'(\eta_{3\pi}\pi^{\pm})K_S^{(\pm)}$ channels when selecting only one (A), two (B), or all (C) the candidates in the event. The selected strategy is labeled with $\star$.

$B^0 \to \omega K^0$

$\omega(\pi^+\pi^-\pi^0)K_S^0(\pi^{\pm})$

L (ab^{-1})	yield	$\sigma(S)$	$\sigma(A)$
1	334	0.17	0.14
5	1670	0.08	0.06
50	16700	0.024	0.020

Extrapolated sensitivity for the ωK_S^0 mode. The Δt resolution is taken from the $\eta' K_S^0$ study, while we assume a reconstruction efficiency of 21%

$B^0 \to \phi K^0$

Channel	ε_{reco}	Yield	$\sigma(S_{\phi K^0})$	$\sigma(A_{\phi K^0})$
1 ab^{-1} lumi.:				
$\phi(K^+K^-)K_S^0(\pi^+\pi^-)$	35%	456	0.174	0.123
$\phi(K^+K^-)K_S^0(\pi^0\pi^0)$	25%	153	0.295	0.215
$\phi(\pi^+\pi^-\pi^0)K_S^0(\pi^+\pi^-)$	28%	109	0.338	0.252
K_S^0 modes combination			0.135	0.098
$K_S^0 + K_L^0$ modes combination			0.108	0.079
5 ab^{-1} lumi.:				
$\phi(K^+K^-)K_S^0(\pi^+\pi^-)$	35%	2280	0.078	0.055
$\phi(K^+K^-)K_S^0(\pi^0\pi^0)$	25%	765	0.132	0.096
$\phi(\pi^+\pi^-\pi^0)K_S^0(\pi^+\pi^-)$	28%	545	0.151	0.113
K_S^0 modes combination			0.060	0.044
$K_S^0 + K_L^0$ modes combination			0.048	0.035

Sensitivity estimates for $S_{\phi K^0}$ and $A_{\phi K^0}$ parameters. The efficiency ε_{reco} used in this estimate has not been taken from the simulation, but is rather an estimate taking into account the expected improvements. Systematic uncertainties, negligible for these integrated luminosities, are not included

$\sin(2\beta)$ expected sensitivities

Channel	$\int \mathcal{L}$	Event yield	$\sigma(S)$	$\sigma(S)_{2017}$	$\sigma(A)$	$\sigma(A)_{2017}$
$J/\psi K^0$	50 ab^{-1}	$1.4 \cdot 10^6$	0.0052	0.022	0.0050	0.021
ϕK^0	5 ab^{-1}	5590	0.048	0.12	0.035	0.14
$\eta' K^0$	5 ab^{-1}	27200	0.027	0.06	0.020	0.04
ωK^0_S	5 ab^{-1}	1670	0.08	0.21	0.06	0.14
$K^0_S \pi^0 \gamma$	5 ab^{-1}	1400	0.10	0.20	0.07	0.12
$K^0_S \pi^0$	5 ab^{-1}	5699	0.09	0.17	0.06	0.10

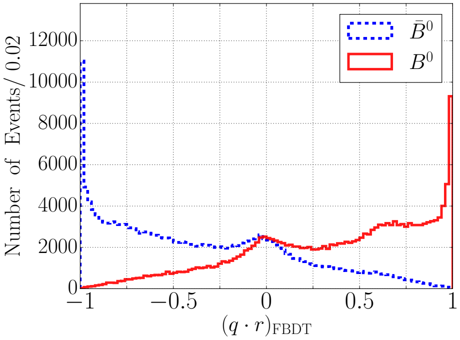
Expected yields and uncertainties on the S and A parameters for the channels sensitive to $\sin(2\phi_1)$ discussed in this chapter for an integrated luminosity of 50 (5) ab^{-1} for $J/\psi K^0$ (penguin dominated modes). In the 5th and the last column are shown the present WA errors on each of the observables (HFAG summer 2016).

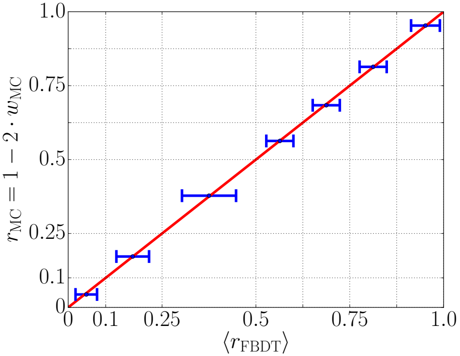
Flavor tagging ε & w

Fast BDT Combiner

r- bin	$\varepsilon_i(\%)$	$\Delta\varepsilon_i(\%)$	$w_i(\%)$	$\Delta w_i(\%)$	$\varepsilon_{\text{eff},i}(\%)$	$\Delta\varepsilon_{\text{eff},i}(\%)$
0.000 – 0.100	12.4	0.0	47.6	0.0	0.0	0.0
0.100 – 0.250	14.4	−0.1	41.4	0.0	0.4	0.0
0.250 – 0.500	21.0	−0.1	31.2	−0.1	3.0	0.0
0.500 – 0.625	11.5	0.3	21.8	0.0	3.7	0.2
0.625 – 0.750	12.0	0.4	15.6	0.1	5.7	0.4
0.750 – 0.875	11.8	−0.1	9.4	0.0	7.8	−0.1
0.875 – 1.000	16.9	−0.6	2.4	0.1	15.3	−1.2
Total	$\varepsilon_{\text{eff}} = \sum_i \varepsilon_i \cdot \langle 1 - 2w_i \rangle^2 = 35.8\%$				$\Delta\varepsilon_{\text{eff}} = -0.7\%$	

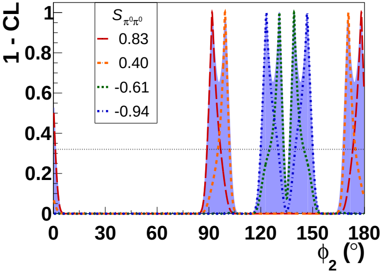
Flavor tagging ε & w

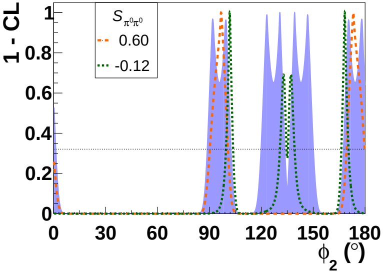




$B \to \pi\pi$, $B \to \rho\rho$

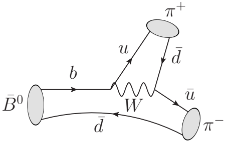
$$\chi^2 = -2\log\left[\frac{\exp\left(\frac{1}{2}\left(\mathbf{x}_{\mathrm{data}} - \mathbf{x}_{\mathrm{theo}}\right)^T \Sigma^{-1} \left(\mathbf{x}_{\mathrm{data}} - \mathbf{x}_{\mathrm{theo}}\right)\right)}{\sqrt{(2\pi)^n \det\Sigma}}\right]$$

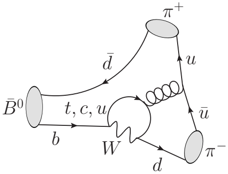




ϕ_2 measurement: isospin analysis in $B \to \pi\pi, \rho\rho$

Two amplitudes of comparable size and different weak phase





Penguin enters $B^0 \to \pi^+\pi^-, \pi^0\pi^0$ **but not** $B^\pm \to \pi^\pm\pi^0$

$$\phi_2 = \widehat{(\bar{A}^{+0}, A^{+0})},\ \phi_2^{eff} = \widehat{(\bar{A}^{+-}, A^{+-})}$$

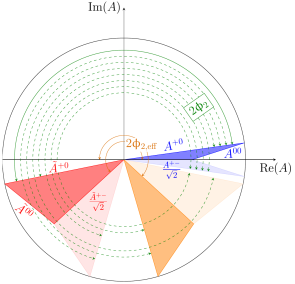
Isospin constraints B^0 and $B^\pm$ amplitudes to the following triangular relations

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

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

$$|A^{+0}| = |\bar{A}^{+0}|$$

Gronau-London method [PRL 64 3381 (1990)]

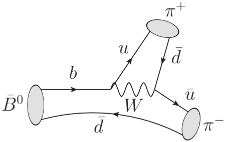


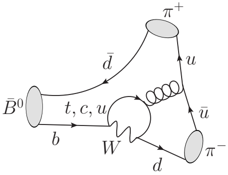
- measure $\mathcal{BR}$ & asymmetries in $\pi^+\pi^-$, π^0, π^0
- fix side lengths & relative orientation of triangles

- $S_{\pi^+\pi^-}$ leaves an 8-fold ambiguity in ϕ_2

ϕ_2 measurement: isospin analysis in $B \to \pi\pi, \rho\rho$

Two amplitudes of comparable size and different weak phase





Penguin enters $B^0 \to \pi^+\pi^-, \pi^0\pi^0$ **but not** $B^\pm \to \pi^\pm\pi^0$

$$\phi_2 = \widehat{(\bar{A}^{+0}, A^{+0})}, \ \phi_2^{eff} = \widehat{(\bar{A}^{+-}, A^{+-})}$$

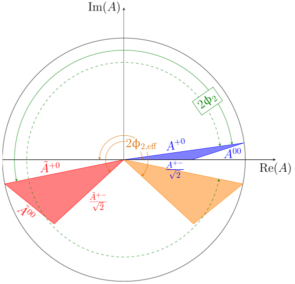
Isospin constraints B^0 and $B^\pm$ amplitudes to the following triangular relations

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

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

$$|A^{+0}| = |\bar{A}^{+0}|$$

Gronau-London method [PRL 64 3381 (1990)]



- measure $\mathcal{BR}$ & asymmetries in $\pi^+\pi^-, \pi^0, \pi^0$
- fix side lengths & relative orientation of triangles

- $S_{\pi^+\pi^-}$ leaves an 8-fold ambiguity in ϕ_2
- reduced by **time dependent $B^0 \to \pi^0\pi^0$ analysis**

ϕ_2 measurement: $B \to \rho\rho$

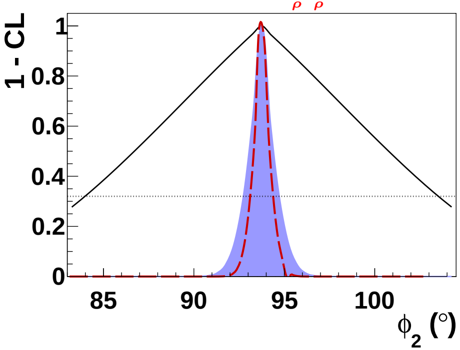
Isospin analysis input in $B \to \rho\rho$

	Value	Belle @ 0.8 ab^{-1}	Belle II @ 50 ab^{-1}
$f_{L,\rho^+\rho^-}$	0.988	$\pm0.012 \pm 0.023$ [1]	$\pm0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm0.20 \pm 0.15$ [2]	$\pm0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm1.5 \pm 1.5$ [1]	$\pm0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ [10^{-6}]	1.02	$\pm0.30 \pm 0.15$ [2]	$\pm0.04 \pm 0.02$
$C_{\rho^+\rho^-}$	0.00	$\pm0.10 \pm 0.06$ [1]	$\pm0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm0.15 \pm 0.05$ [1]	$\pm0.02 \pm 0.01$
	Value	**Belle @ 0.08 ab^{-1}**	**Belle II @ 50 ab^{-1}**
$f_{L,\rho^+\rho^0}$	0.95	$\pm0.11 \pm 0.02$ [3]	$\pm0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm7.1 \pm 5.3$ [3]	$\pm0.3 \pm 0.5$
	Value	**BaBar @ 0.5 ab^{-1}**	**Belle II @ 50 ab^{-1}**
$C_{\rho^0\rho^0}$	0.2	$\pm0.8 \pm 0.3$ [4]	$\pm0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm0.7 \pm 0.2$ [4]	$\pm0.07 \pm 0.01$

[1]: PRD 93(3) 032010, [2]: Add PRD 89 no.11 119903,
[3]: PRL 91 221801, [4]: PRD 78 071104

$B \to \rho\rho$

Belle, Belle II (+ $S_{\rho^0\rho^0}$)



$\Delta\phi^{exp}_{2,\rho\rho}|_{1\sigma} \sim 0.7°$

ϕ_2 measurement: $B \to \rho\rho$

Isospin analysis input in $B \to \rho\rho$

	Value	Belle @ 0.8 ab^{-1}	Belle II @ 50 ab^{-1}
$f_{L,\rho^+\rho^-}$	0.988	$\pm0.012 \pm 0.023$ [1]	$\pm0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm0.20 \pm 0.15$ [2]	$\pm0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm1.5 \pm 1.5$ [1]	$\pm0.19 \pm 0.4$
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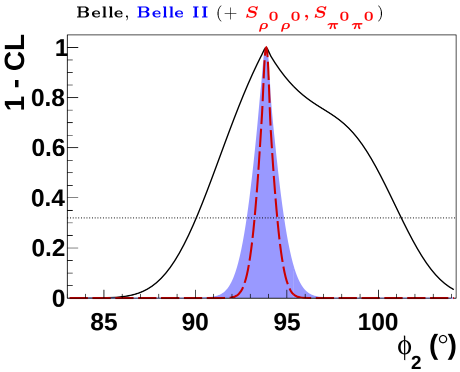
$f_{L,\rho^+\rho^0}$	0.95	$\pm0.11 \pm 0.02$ [3]	$\pm0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm7.1 \pm 5.3$ [3]	$\pm0.3 \pm 0.5$
	Value	BaBar @ 0.5 ab^{-1}	Belle II @ 50 ab^{-1}
$C_{\rho^0\rho^0}$	0.2	$\pm0.8 \pm 0.3$ [4]	$\pm0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm0.7 \pm 0.2$ [4]	$\pm0.07 \pm 0.01$

[1]: PRD 93(3) 032010, [2]: Add PRD 89 no.11 119903,
[3]: PRL 91 221801, [4]: PRD 78 071104

$B \to \rho\rho$ & $B \to \pi\pi$



$\Delta\phi^{exp}_{2,hh}|_{1\sigma} \sim 0.6°$