CP Violation sensitivity at Belle II

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CP Violation in the Standard Model

- CP Violation (CPV) in the Standard Model (SM) occurs in weak interactions through the CKM mechanism. $\Rightarrow \mathbf{V}_{CKM}$.
- The CKM matrix $\mathbf{V}_{CKM}$ rotates the mass eigenstates into the weak eigenstates.

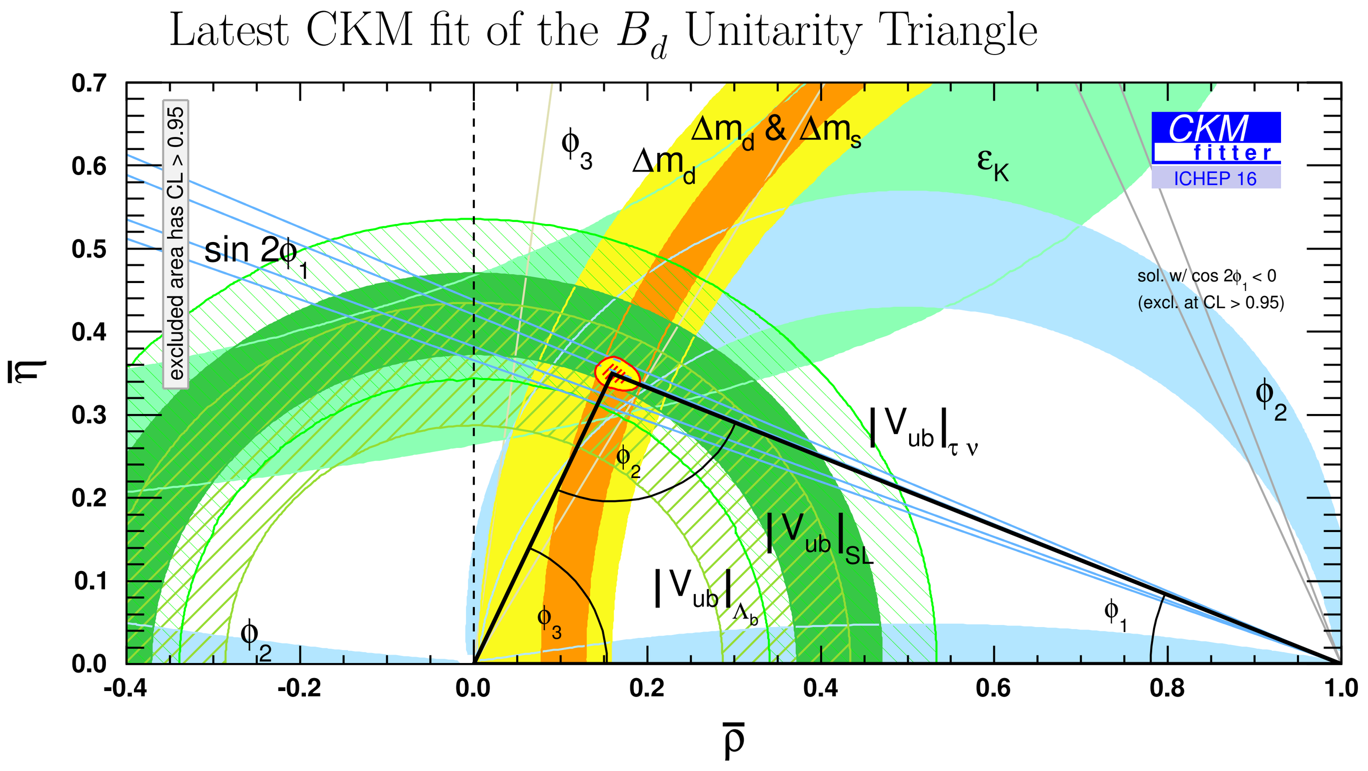
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Free parameters: 3 real and 1 imaginary. The latter is responsible for the CP Violation in the SM.
- Unitarity $\Sigma_k V_{ki}^* V_{kj} = 0$ leads to 6 relations represented by triangles in the complex plane. One of the triangles is related to the B_d system $\Rightarrow$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$\mathcal{O}(\lambda^3) \quad \mathcal{O}(\lambda^3) \quad \mathcal{O}(\lambda^3)$$

$\Rightarrow$ largest CPV within the B_d system.

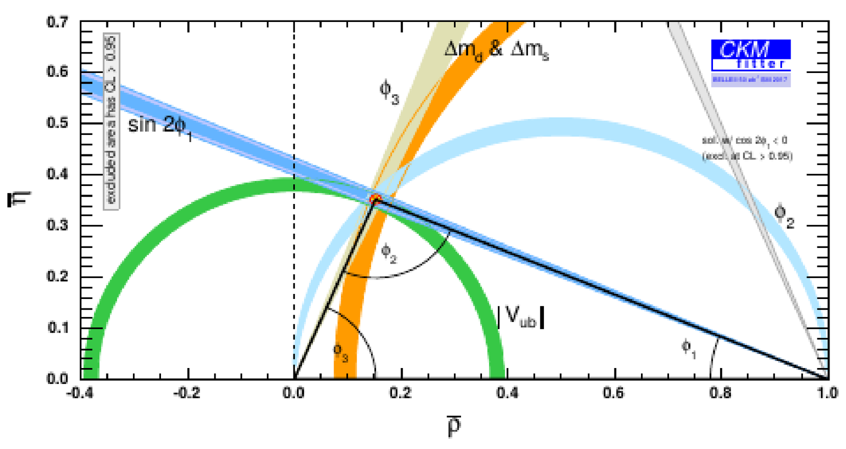
Latest CKM fit of the B_d Unitarity Triangle



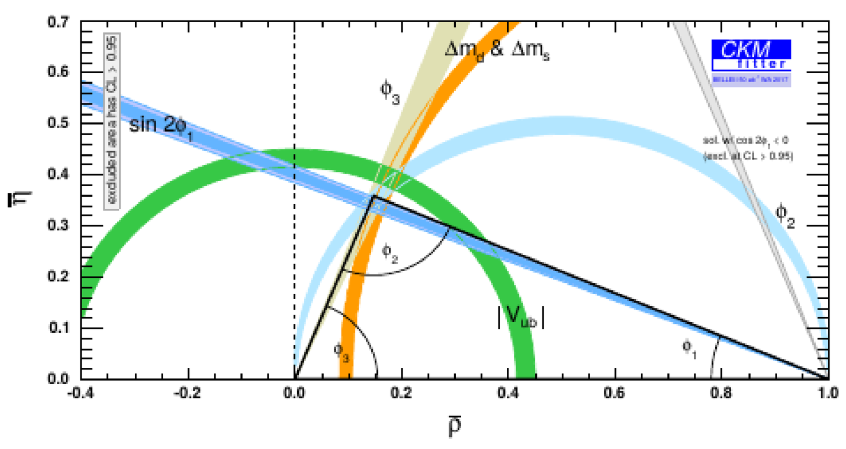
Sides ∼ Branching frac. + $B^0\bar{B}^0$ Mixing

Angles ∼ CP Asymm.

Possible scenarios with $\int \mathcal{L} \cdot dt = 50$ ab^{-1} at Belle II $\Rightarrow$

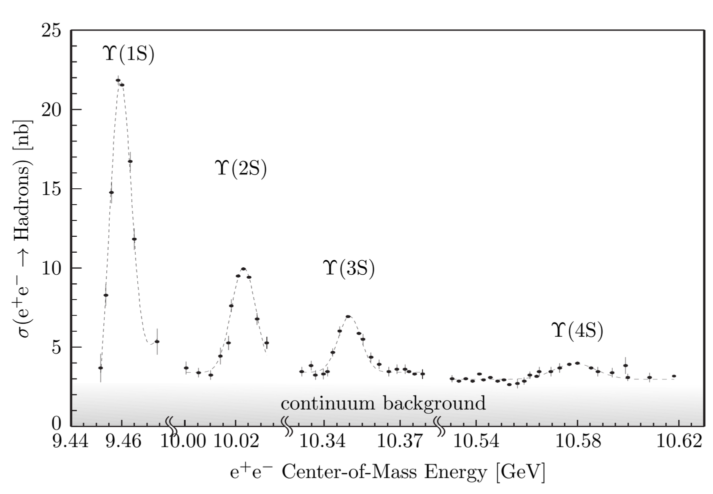


SM-like scenario



New physics scenario

Time Dependent CP-Violation Analysis

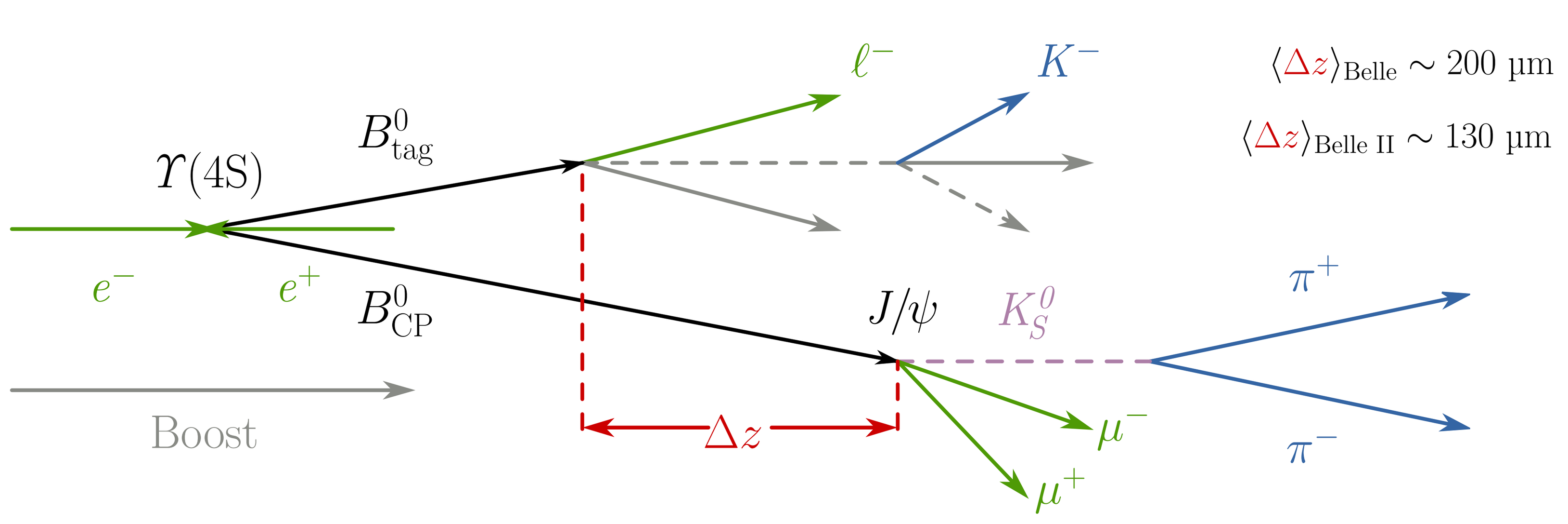


B-Factories at $\Upsilon(4S)$:

- Just above $B\bar{B}$ production threshold.

$\Rightarrow$ No underlying event.

- $\Upsilon(4S) \rightarrow B\bar{B} > 96$ %.
- $\frac{\Gamma(B^+B^-)}{\Gamma(B^0\bar{B}^0)} \sim 1.06$



- Due to asymmetric beam energies $\Rightarrow \Upsilon(4S)$ is produced with boost:

$\Rightarrow \Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$ since the $B^0\bar{B}^0$ pair is at rest in $\Upsilon(4S)$ frame.

- The $B^0\bar{B}^0$ pair is quantum mechanically entangled in order to keep the $\Upsilon(4S)$ wave function properties. For a given Δt, the probability that one B^0 decays to a CP eigenstate $f_{\rm CP}$ and that the other B^0 has the flavor q ($q_{B^0,\bar{B}^0} = 1, -1$) at the time of its decay is described by

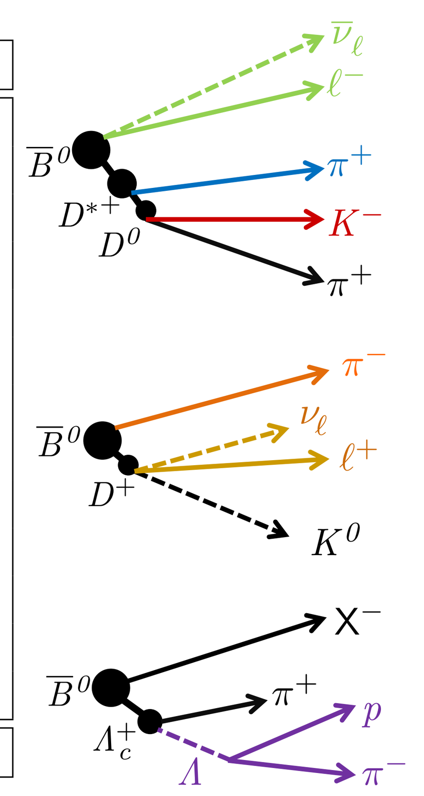
$$\mathcal{P}^{\rm Sig}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q\left(\mathcal{A}_{\rm CP}\cos(\Delta m \Delta t) + \mathcal{S}_{\rm CP}\sin(\Delta m \Delta t)\right)\right].$$

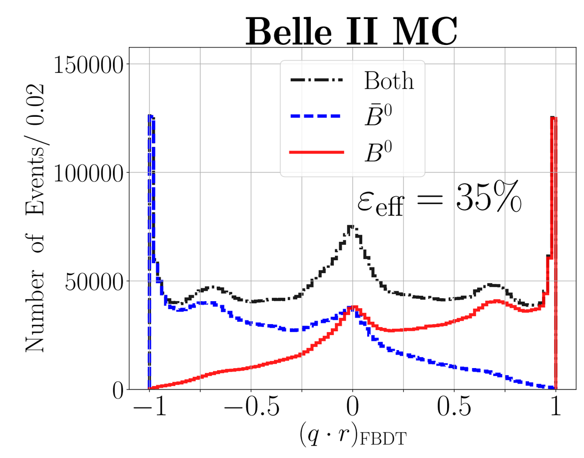
- $\mathcal{A}_{\rm CP}$: CP violation in decay (Direct CP violation). $\mathcal{S}_{\rm CP}$: CP violation in the interference between mixing and decay (Mixing-Induced CP violation).
- In order to measure the CP asymmetries $\mathcal{A}_{\rm CP}$ and $\mathcal{S}_{\rm CP}$ by fitting $\mathcal{P}^{\rm Sig}(\Delta t, q)$, three tasks are required: Reconstruction of $B^0_{\rm CP} \rightarrow f_{\rm CP}$, reconstruction of both B^0 vertices (Δz) and determination of the flavor q of the accompanying $B^0_{\rm tag}$.

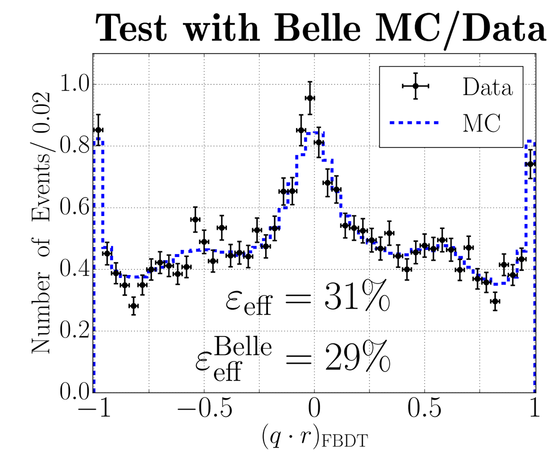
The Flavor Tagger

- The flavor tagger is responsible for the determination of the flavor q of $B^0_{\rm tag}$. It considers decays with flavor specific signatures (charges of final state tracks) and sizeable branching fractions ($\mathcal{B} > 2\%$).
- The information related to the kinematics and the particle identification of the tracks and the clusters which remain from the reconstruction of $B^0_{\rm CP} \rightarrow f_{\rm CP}$ is combined using boosted decision trees (BDT). The method returns the flavor $q = +1(-1)$ for $B^0(\bar{B}^0)$ multiplied by a dilution factor $r \in [0, 1]$.

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	





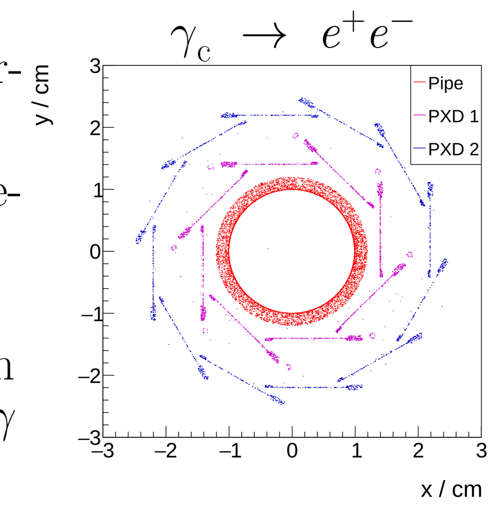


Time Dependent CP-analysis of $B^0 \rightarrow \pi^0\pi^0$

- The CP asymmetries of $B^0 \rightarrow \pi^0\pi^0$ are required to determine the CKM angle ϕ_2.
- At present, there is not enough data to perform the time-dependent analysis.

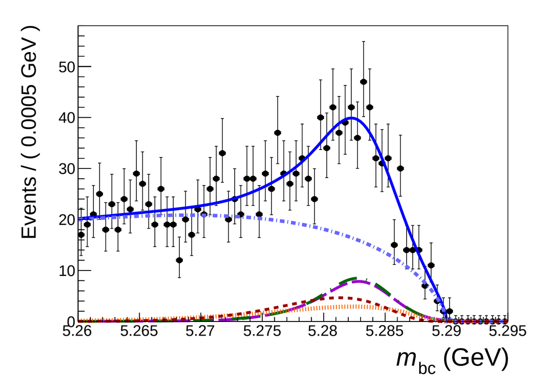
$\Rightarrow$ 8-fold ambiguity in ϕ_2 from $B \rightarrow \pi\pi$.

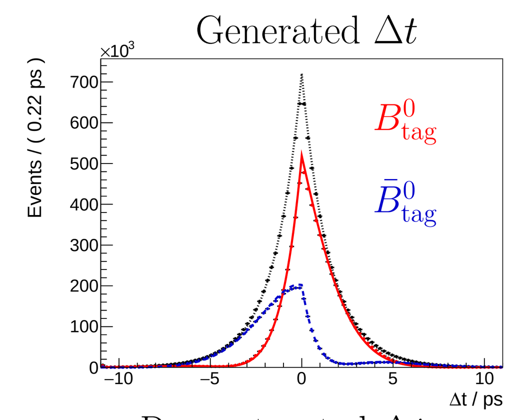
- Belle II will have enough data to exploit rare events with converted photons $\gamma_c \rightarrow e^+e^-$ and with $\pi^0_{\rm Dalitz} \rightarrow e^+e^-\gamma$ decays.



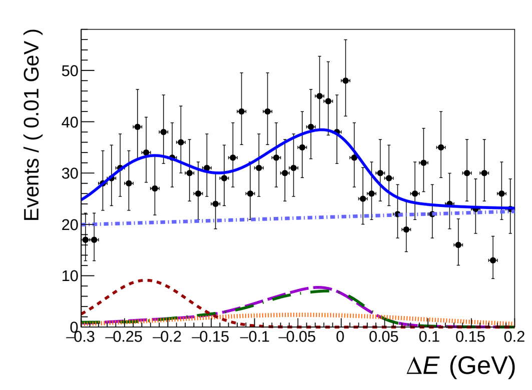
Variables for Maximum Likelihood Fit

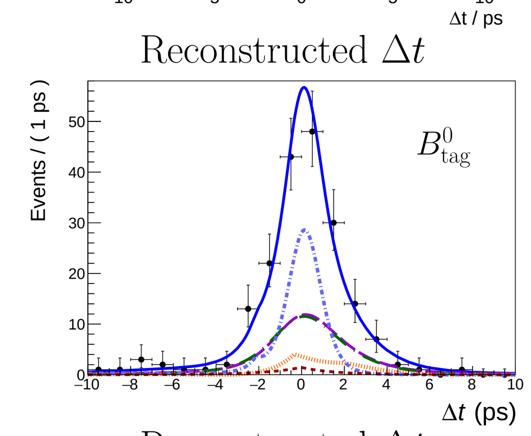
- $m_{\rm bc} = \sqrt{{E^*_{\rm beam}}^2 - \mathbf{p}^2_{B^0_{\rm CP}}}$



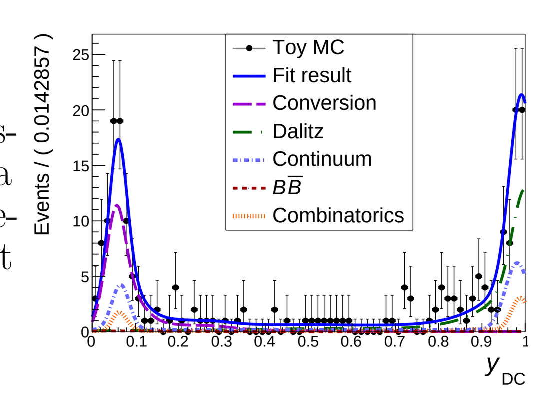


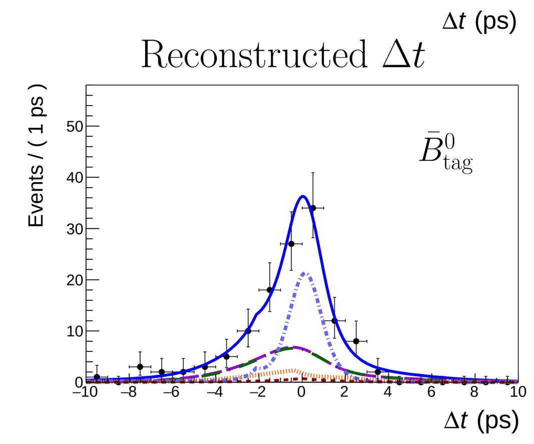
- $\Delta E = E^*_{\rm beam} - E_{B^0_{\rm CP}}$





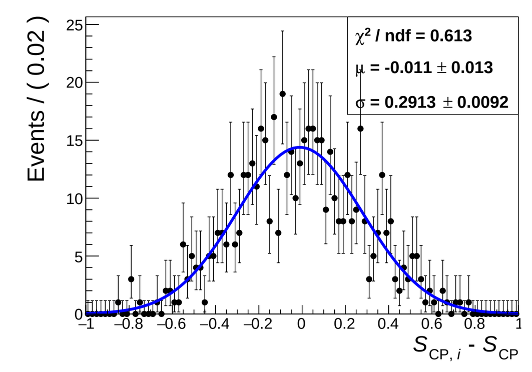
- Output of a BDT trained to distinguish between events with a $\pi^0_{\rm dalitz}$ and with a γ_c. This is required because of their different Δt resolutions.

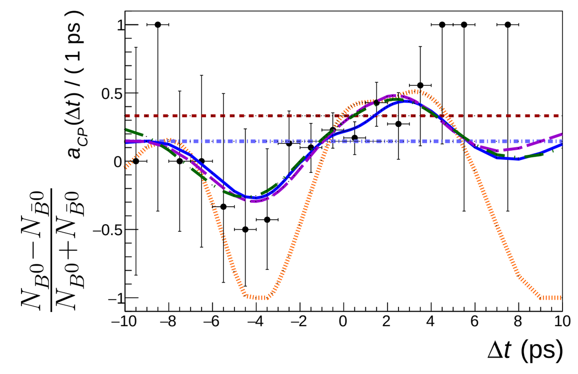




$S_{\pi^0\pi^0}$ sensitivity from Toy MC experiments $\Rightarrow$

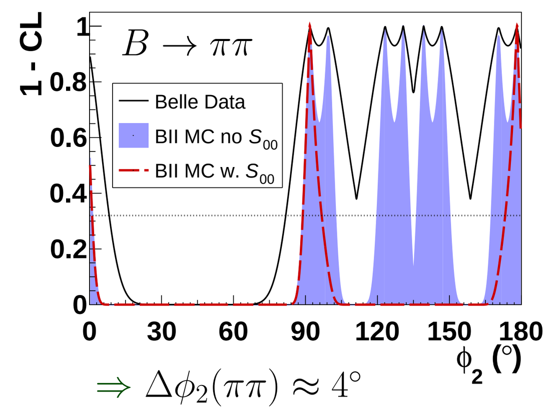
$\Delta\mathcal{S}_{\pi^0\pi^0} = 0.29 \Leftarrow$



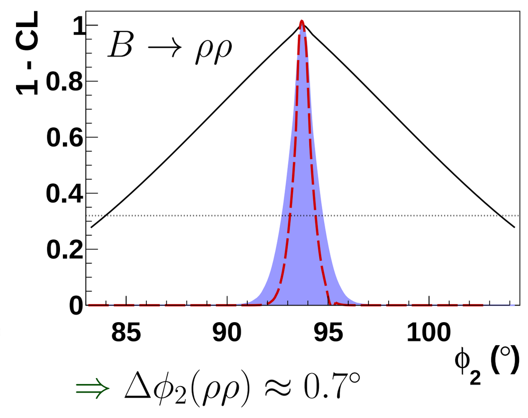


Determination of ϕ_2 via Isospin Analysis

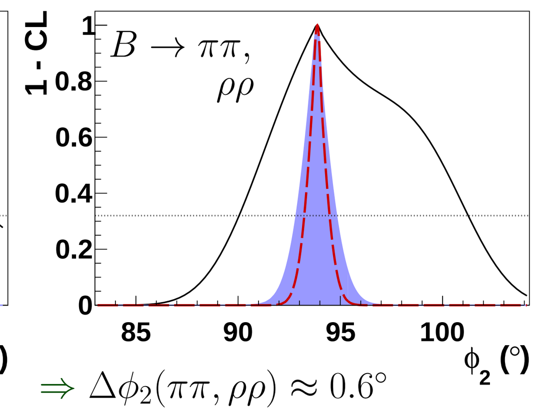
- The CKM angle ϕ_2 is related to the CP asymmetries of the decays $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$. However, because of non-negligible penguin contributions, the value of ϕ_2 cannot be extracted directly. The way out: isospin symmetry gives rise to two relations between the decay amplitudes from which one can extract the value of ϕ_2.
- The isospin analysis requires the branching fractions $\mathcal{B}_{+0}$, $\mathcal{B}_{+-}$, $\mathcal{B}_{00}$ together with the CP asymmetries $\mathcal{A}_{+-}$, $\mathcal{S}_{+-}$, $\mathcal{A}_{00}$ and $\mathcal{S}_{00}$ (the subscripts denote the pion or rho charges). Without $\mathcal{S}_{00}$, the ϕ_2 value has an 8-fold ambiguity in the case of $B \rightarrow \pi\pi$, and is less precise in the case of $B \rightarrow \rho\rho$.



$\Rightarrow \Delta\phi_2(\pi\pi) \approx 4°$



$\Rightarrow \Delta\phi_2(\rho\rho) \approx 0.7°$



$\Rightarrow \Delta\phi_2(\pi\pi, \rho\rho) \approx 0.6°$