Belle results for ϕ_3 $(= \gamma)$ and prospects for Belle II by 2021

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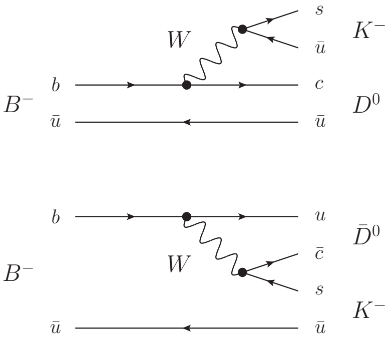
Methods for measuring ϕ_3

- Best theoretically clean way of measuring ϕ_3 is based on **interference** between $b \to \bar{u}cs$ and $b \to u\bar{c}s$ tree level amplitudes
- E.g., $B^{\pm} \to D^{(*)}K^{\pm}$ followed by $D \to f$ and $B^{\pm} \to \bar{D}^{(*)}K^{\pm}$ followed by $\bar{D} \to f$, where f is a **common final state**



- **No penguin contribution** $\Rightarrow$ theoretically clean
- The only CP-violating parameter that can be measured solely in tree-level processes
- ϕ_3 precision is limited by small branching ratios

GLW Method [8, 9]

- D meson is reconstructed from **CP-even** (D_{CP+}) or **CP-odd** (D_{CP-}) final states
- B can decay weakly to either D^0 or $\bar{D}^0$, but when reconstructing a CP eigenstate, actually selecting superposition $(D^0 \pm \bar{D}^0)/\sqrt{2}$

$$R_{CP\pm} = 2\frac{\Gamma(B^- \rightarrow D_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D_{fav}K^-) + \Gamma(B^+ \rightarrow D_{fav}K^+)} = 1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\phi_3)$$

$$A_{CP\pm} = \frac{\Gamma(B^- \rightarrow D_{CP\pm}K^-) - \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D_{CP\pm}K^+)} = \pm r_B\sin(\delta_B)\sin(\phi_3)/R_{CP\pm}$$

ADS Method [2]

- Doubly Cabibbo suppressed (DCS) D decays can also be used to measure ϕ_3
- E.g., $[K^+\pi^-]_D K^-$ can be reached in two ways:
  - Cabibbo favored (CF) $B^- \to D^0 K^-$ followed by DCS $D^0 \to K^+\pi^-$
  - DCS $B^- \to \bar{D}^0 K^-$ followed by CF $D^0 \to K^-\pi^+$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}$$
$$= r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\phi_3)$$

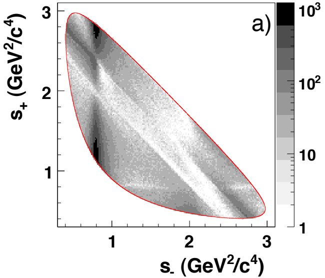
$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}$$
$$= 2r_B r_D \sin(\delta_B + \delta_D)\sin(\phi_3)/R_{ADS}$$

- Additional vars r_D and δ_D
- Can be obtained from charm factories

GGSZ Method (Dalitz) [7, 4]

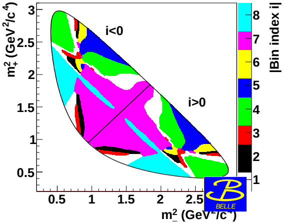
- For self-conjugate multi-body D final states, e.g., $K_S^0\pi^+\pi^-$
- The amplitude for $B^+ \to DK^+$, with $s_\pm = m^2_{K_S^0\pi^\pm}$:

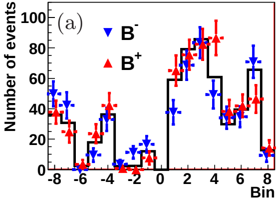
$$A_{B^+}(s_+, s_-) = \bar{A}_D + r_B e^{i(\delta_B+\phi_3)} A_D$$
$$A_{B^-}(s_+, s_-) = A_D + r_B e^{i(\delta_B+\phi_3)} \bar{A}_D$$



- $A_D(s_+, s_-)$ is the amplitude of the D decay

$B^- \to D^0 K^-$, $D^0 \to K_S^0 \pi^+ \pi^-$ (GGSZ)





- Dominating measurement of ϕ_3 at B-factories
- **First model-independent** Dalitz analysis
  $\phi_3 = (77^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$ [1]
- In recent model-dependent analyses, model uncertainty $3^\circ - 9^\circ$
- Latest **model-dependent** result (incl. D^*K)
  $\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$ [14]
- For future experiments, model uncertainty is expected to dominate (more statistics and BES-III results will supersede CLEO-c)

Model independent

- Model uncertainty replaced by statistical uncertainty from CLEO-c
- But ~80% of statistical precision

- Full data set: 772M B pairs
- B-factory exclusive measurement (low E π^0/γ; CP-)

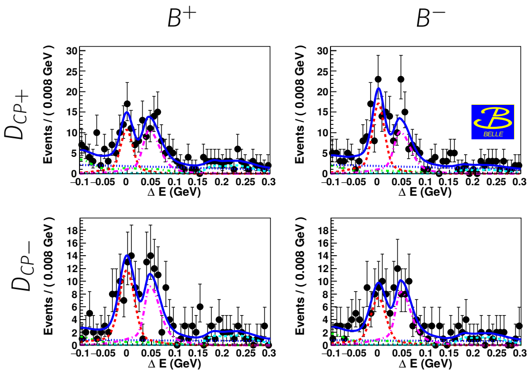
GLW

- Combining results for $D^* \rightarrow D\pi^0, D\gamma$ yields:

$$A_{CP+} = -0.14 \pm 0.10 \pm 0.01$$

$$A_{CP-} = +0.22 \pm 0.11 \pm 0.01$$

...



ADS

$$R_{D^*K,D\pi^0} = [1.0^{+0.8}_{-0.7}(\text{stat})^{+0.1}_{-0.2}(\text{syst})] \times 10^{-2}$$

$$R_{D^*K,D\gamma} = [3.6^{+1.4}_{-1.2}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-2}$$

...

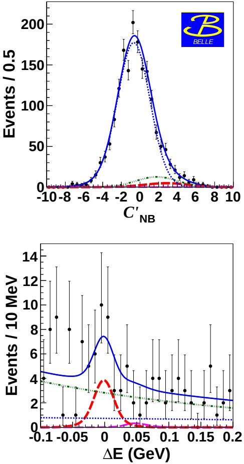
- To be published soon

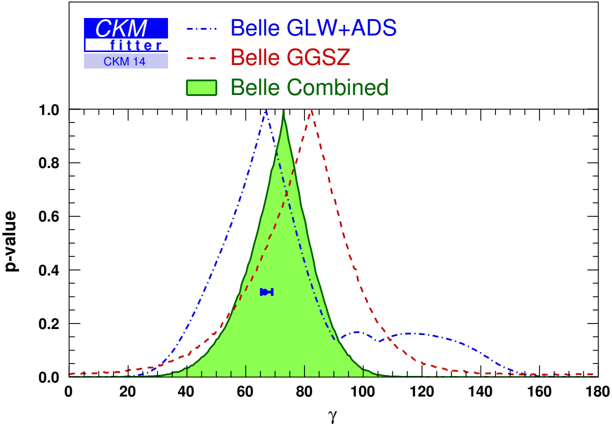
$B^- \to D^0 K^-$, $D^0 \to K^+\pi^-\pi^0$ (ADS)

- Full data set: 772M B pairs
- Caveat: strong phase from the D decay δ_D can vary over **multi-particle** phase space, which can dilute CP-violation effects
- However, this effect is quite small here (coherence factor close to 1 [10])

$$R_{DK} = (1.98 \pm 0.62 \pm 0.24) \times 10^{-2}$$
$$A_{DK} = 0.41 \pm 0.30 \pm 0.05$$

- First evidence for suppressed $B \to DK$ decay; **significance 3.2σ** [11]





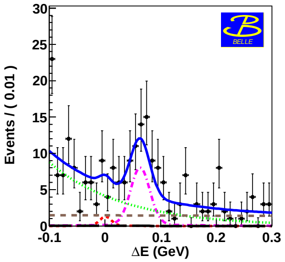
$$\phi_3 = (73^{+13}_{-15})^\circ$$

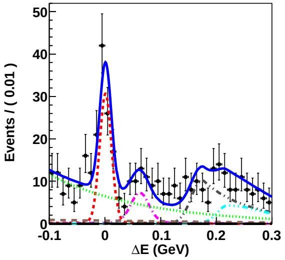
$B^0 \to D^0 K^{*0}$, $K^{*0} \to K^+\pi^-$, $D^0 \to K^-\pi^+$ (ADS)

- Full data set: 772M B pairs
- **Self-tagging** channel because of the K^* decay
- ADS but with $D[K^+\pi^-]_{K^*} \to$ slightly different $R_{DK^{*0}}$ definition

$$R_{DK^{*0}} = (4.1^{+5.6+2.8}_{-5.0-1.8}) \times 10^{-2}$$

- As the $R_{DK^{*0}}$ value is not significant, an **upper limit** was established [12]
- $R_{DK^{*0}} < 0.16 \quad (95\%\ \text{C.L.})$

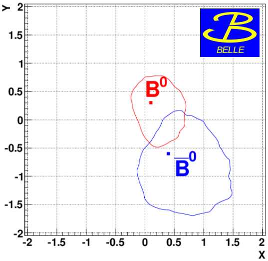




- 1st model-independent Dalitz analysis of $B^0 \to D^0 K^{*0}$ [13]
- Full data set: 772M B pairs
- Results given in Cartesian coordinates (Gaussian, easy to combine)

$$x_- = +0.4^{+1.0+0.0}_{-0.6-0.1} \pm 0.0$$
$$y_- = -0.6^{+0.8+0.1}_{-1.0-0.0} \pm 0.1$$
$$x_+ = +0.1^{+0.7+0.0}_{-0.4-0.1} \pm 0.1$$
$$y_+ = +0.3^{+0.5+0.0}_{-0.8-0.1} \pm 0.1$$

$$r_S < 0.87 \quad 68\% \; C.L.$$

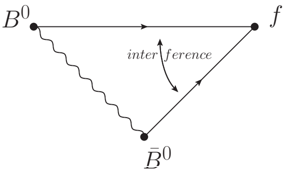


$$x_\pm = r_S \cos(\delta_S \pm \phi_3)$$
$$y_\pm = r_S \sin(\delta_S \pm \phi_3)$$

Model independent

- Model uncertainty replaced by statistical uncertainty from CLEO-c
- But ~80% of statistical precision

- All of the measurements presented so far were time-independent
- Time-dependent measurements also possible
- Channels like:
  - $B^0 \to D^{(*)}\pi$ [3]
  - $B^0 \to D^{(*)}\rho$
- Mixing induced CPV
- In order to extract ϕ_3 from $B \to SS/SV$ decays we must supply $r = |A_{\mathrm{DCS}}/A_{\mathrm{CF}}|$ externally, usually assuming $SU(3)$ symmetry
- In $B \to VV$ decays one can extract all physics parameters from data

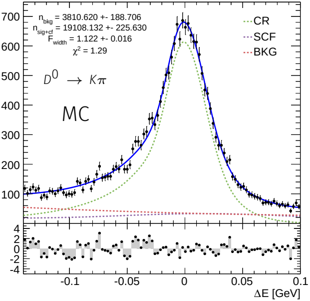


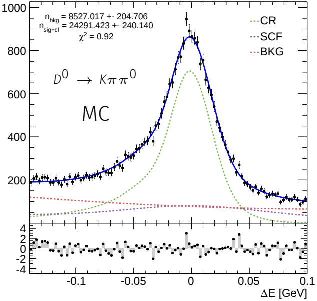
$D^* \rho$

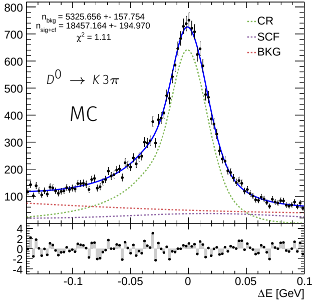
- $B \to VV$
- 3 helicity configurations; $A = \sum_\lambda A_\lambda$
- $\Gamma = |A|^2 \Rightarrow$ interference terms (more info about A_λ gets preserved)
- In principle we can extract $\rho_\lambda = r_\lambda e^{i(-2\phi_1 - \phi_3 + \delta_\lambda)}$ and $\bar{\rho}_\lambda = r_\lambda e^{i(+2\phi_1 + \phi_3 + \delta_\lambda)}$
- However, when r_λ are small fitting can fail ($r = 0$ is a pole in sensitivity of other vars)
- We use Cartesian coordinates $\{r_\lambda, \delta_\lambda, \phi_w\} \to \{x_\lambda, y_\lambda, \bar{x}_\lambda, \bar{y}_\lambda\}$
- $\rho_\lambda = x_\lambda + iy_\lambda$ and $\bar{\rho}_\lambda = \bar{x}_\lambda + i\bar{y}_\lambda$
- This introduces 5 new vars; successive step has to be made to extract the physical parameters

$D^* \rho$ Yield

- 60k events in the Belle dataset
- $r = |A_{DCS}/A_{CF}|$ is expected to be $\sim 1-2\%$; small CPV effect
- Realistic yield fits







$D^*\rho$ Realistic Angular Time-dependent Fit

MC sample generated with:

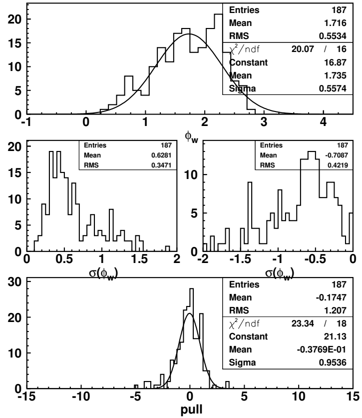
- 60k events
- Helicity amplitudes from CLEO [6]
- $r_\lambda = 1\%$
- Random values for strong phases:
  - $\delta_+ = -0.393$
  - $\delta_0 = 0.785$
  - $\delta_- = 1.571$
- $2\phi_1 + \phi_3 = 1.79371$

Var	Fit	σ
$\lvert a_{\vert\vert} \rvert$	0.2861	0.0022
$(a_{\vert\vert})$	0.5919	0.0130
$\lvert a_0 \rvert$	0.9306	0.0008
$(a_\perp)$	3.1159	0.0110
$x_{\vert\vert}$	0.0530	0.0222
x_0	0.0640	0.0137
$x_\perp$	0.0700	0.0228
$y_{\vert\vert}$	0.0109	0.0143
y_0	-0.0131	0.0046
$y_\perp$	-0.0369	0.0225
$\bar{x}_{\vert\vert}$	0.0669	0.0240
$\bar{x}_0$	0.0829	0.0114
$\bar{x}_\perp$	0.0530	0.0249
$\bar{y}_{\vert\vert}$	0.0123	0.0168
$\bar{y}_0$	0.0055	0.0046
$\bar{y}_\perp$	0.0297	0.0235

Realistic Toy Fit

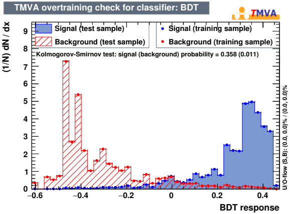
$D^{*}\rho$ Expected Uncertainty

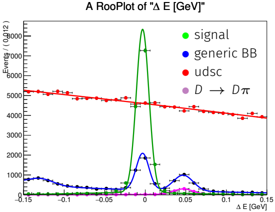
- Based on simpler (generator level) more optimistic (higher yield) toy MC
- Robust $2\phi_1 + \phi_3$ extraction from x, y
- Adjusted for actual yield, resolution, flavor tagging:
  - $\sigma(2\phi_1 + \phi_3) \approx 80^{\circ}$(stat) for Belle
  - $\sigma(2\phi_1 + \phi_3) \approx 11^{\circ}$(stat) for Belle II at 50ab^{-1}
- Without any external input
- We can decrease σ, if we take, e.g., r_λ from other measurements ($D_s^{*}\rho$)

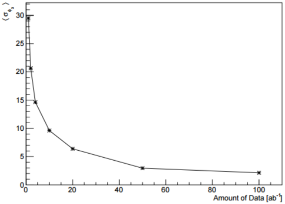


Belle II Sensitivity Simulation

- Sensitivity simulation study $B \to [K_S h^+ h^-]_D K$ (GGSZ)
- The study was **not finalized**, not fully tuned:
  - Continuum suppression
  - Particle ID
- Full Belle II simulation w/ reconstruction
- Statistical uncertainties (for the chosen channel)
  - $\sigma(\phi_3) = 9.5°$ with $10\,\mathrm{ab}^{-1}$
  - $\sigma(\phi_3) = 2.9°$ with $50\,\mathrm{ab}^{-1}$
- Overall precision improvement as expected
- Incomplete, conservative estimate







ϕ_3 Combination Projection

- Belle II based on $B \to D^{(*)}K^{(*)}$
- LHCb based on $B \to DK^+$, $D\pi^+$ and DK^{*0}

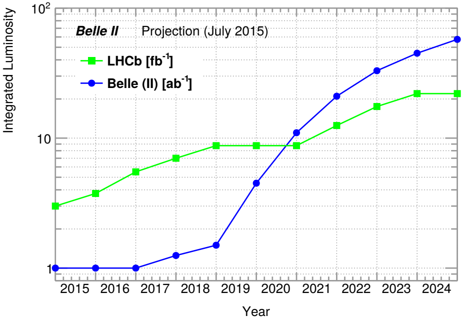
Both with

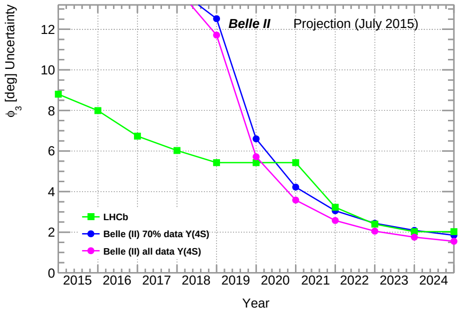
- $D \to KK$, $D \to \pi\pi$, $D \to K\pi$
- $D \to K\pi\pi\pi$
- $D \to K_S\pi\pi$

Both experiments have/will include more modes

Work ongoing to estimate sensitivity more precisely

LHCb values based on extrapolation from LHCb-PAPER- 2014-041





- New Physics (NP) in ϕ_3 searches: usually compare tree-level with penguins
- Recent studies show that NP contributions to tree-level C_1 and C_2 of $\mathcal{O}(40\%)$ and $\mathcal{O}(20\%)$ are not excluded
- Rough estimate shows that deviations in ϕ_3 of $\mathcal{O}(4^\circ)$ are consistent with current experimental constraints [5]
- Motivation for theoretical and experimental study of ϕ_3

Thank you!

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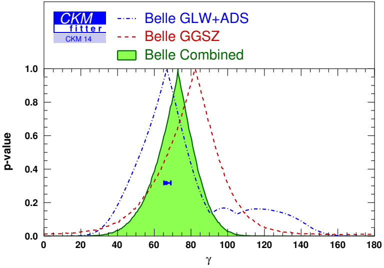
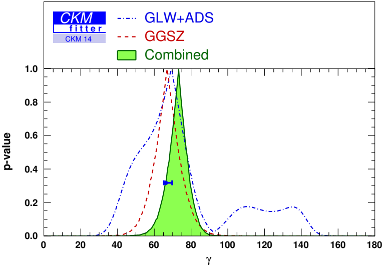
Backup

Belle



$\phi_3 = (73^{+13}_{-15})^\circ$

World



$\phi_3 = (73.2^{+6.3}_{-7.0})^\circ$

The world combination doesn't include LHCb's recent measurements. LHCb alone now reached $\gamma = (72.2^{+6.8}_{-7.3})^\circ$