Direct *CP* violation in *B* decays at LHCb

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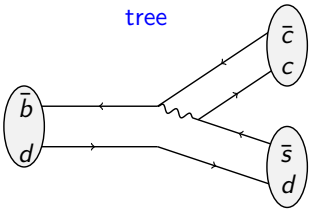
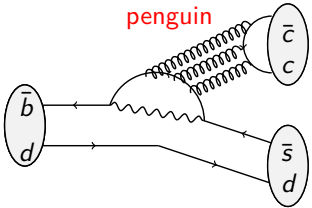
CP violation in $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi \phi$

K. De Bruyn, R. Fleischer [JHEP 03 (2015) 145]





- New physics could contribute to direct and mixing-induced *CP* violation in angles $\phi_d \equiv 2\beta$ and ϕ_s (F. Dordei's talk this morning)
- "Golden modes" $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi \phi$ measure effective angles:

$$\phi^{\text{obs}}_{d/s} = \phi^{\text{tree}}_{d/s} + \Delta\phi^{\text{peng}}_{d/s} + \phi^{\text{NP}}_{d/s}$$

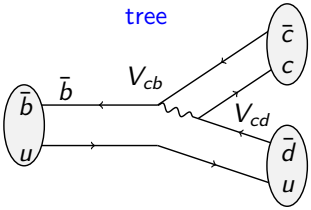
$\phi^{\text{obs}}_{d/s}$ and $\phi^{\text{tree}}_{d/s}$ known precisely $\Rightarrow$ Need good knowledge of contribution from penguin amplitude $\Delta\phi^{\text{peng}}_{d/s}$ to probe for $\phi^{\text{NP}}_{d/s}$

current exp. precision

$\sigma(\phi^{\text{obs}}_d) \approx 1.6^\circ$
$\sigma(\Delta\phi^{\text{peng}}_d) \approx 0.8^\circ$

Determination of Penguin contribution to ϕ_d^{eff}

K. De Bruyn, R. Fleischer [JHEP 03 (2015) 145]



- $A(B^+ \to J/\psi\,\pi^+) = V_{cd}\mathcal{A}$

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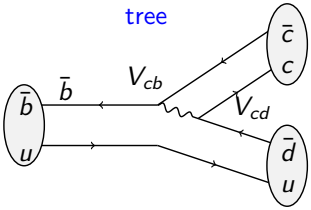

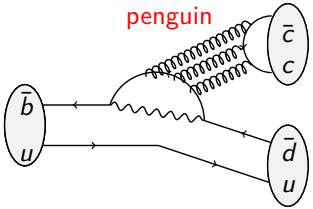

- $A(B^+ \to J/\psi \pi^+) = V_{cd}(1 - a e^{i\theta} e^{i\gamma}) \mathcal{A}$

  $a e^{i\theta}$ relative strength of topology and strong phase difference of penguin wrt tree

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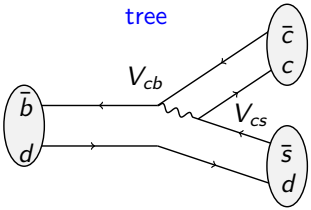

- $A(B^+ \to J/\psi\,\pi^+) = V_{cd}(1 - a e^{i\theta} e^{i\gamma})\mathcal{A}$
- $A'(B^0 \to J/\psi\,K_S^0) = V_{cs}\mathcal{A}'$

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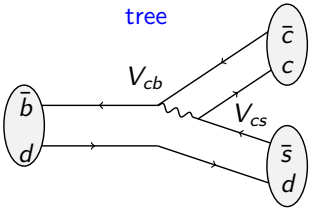

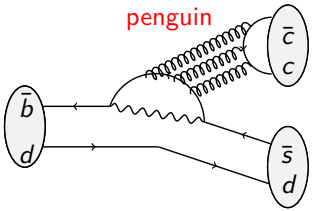

- $A(B^+ \to J/\psi\,\pi^+) = V_{cd}(1 - a e^{i\theta} e^{i\gamma})\mathcal{A}$ $\Leftarrow$ penguin not suppressed
- $A'(B^0 \to J/\psi\,K_S^0) = V_{cs}(1 + \epsilon a' e^{i\theta'} e^{i\gamma})\mathcal{A}'$ $\Leftarrow$ penguin suppressed

$a e^{i\theta}$ relative strength of topology and strong phase difference of penguin wrt tree,
$\epsilon = \frac{\lambda^2}{1-\lambda^2} \approx 0.05$ relative CKM suppression of penguin between $b \to ccs$ and $b \to ccd$

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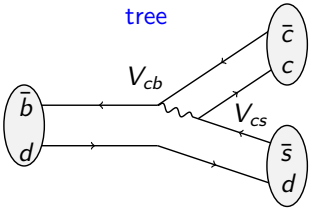

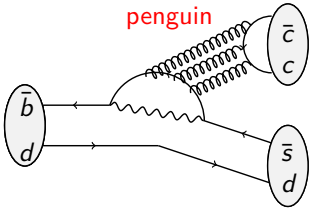

- $A(B^+ \to J/\psi\,\pi^+) = V_{cd}(1 - a e^{i\theta} e^{i\gamma})\mathcal{A}$ $\Leftarrow$ penguin not suppressed
- $A'(B^0 \to J/\psi\,K_S^0) = V_{cs}(1 + \epsilon a' e^{i\theta'} e^{i\gamma})\mathcal{A}'$ $\Leftarrow$ penguin suppressed
- $\text{SU}(3)_f$: $a = a'$, $\theta = \theta'$ $\Rightarrow$ Determine $\Delta\phi_d^{\text{peng}}$ from $\mathcal{A}^{CP}$ and $\mathcal{B}$ in $\text{SU}(3)_f$ related modes

$a e^{i\theta}$ relative strength of topology and strong phase difference of penguin wrt tree,
$\epsilon = \frac{\lambda^2}{1-\lambda^2} \approx 0.05$ relative CKM suppression of penguin between $b \to ccs$ and $b \to ccd$

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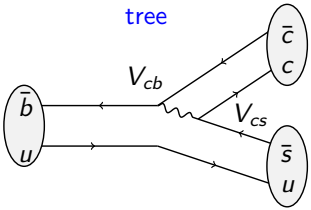
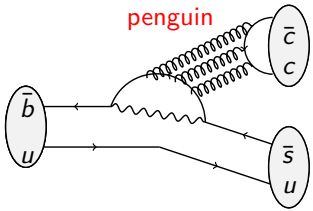




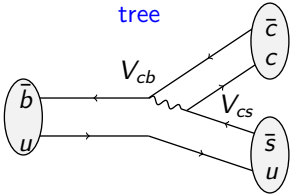
- $A(B^+ \to J/\psi\,\pi^+) = V_{cd}(1 - a e^{i\theta} e^{i\gamma})\mathcal{A} \Leftarrow$ penguin not suppressed
- $A'(B^0 \to J/\psi\,K_S^0) = V_{cs}(1 + \epsilon a' e^{i\theta'} e^{i\gamma})\mathcal{A}' \Leftarrow$ penguin suppressed
- $\text{SU}(3)_f$: $a = a'$, $\theta = \theta' \Rightarrow$ Determine $\Delta\phi_d^{\text{peng}}$ from $\mathcal{A}^{CP}$ and $\mathcal{B}$ in $\text{SU}(3)_f$ related modes
- additional mode: $A''(B^+ \to J/\psi\,K^+) = V_{cs}(1 + \epsilon a'' e^{i\theta''} e^{i\gamma})\mathcal{A}'' \Leftarrow$ penguin suppressed

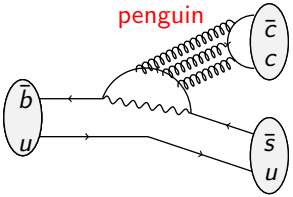
$\lambda \approx -V_{cd} \approx 0.2$, $a e^{i\theta}$ relative strength of topology and strong phase difference of penguin wrt tree, $\epsilon = \frac{\lambda^2}{1-\lambda^2} \approx 0.05$ relative CKM suppression of penguin between $b \to ccs$ and $b \to ccd$

Direct *CP* violation in $B^+ \to J/\psi K^+$ from Run I data

[Phys. Rev. D 95, 052005 (2017)]

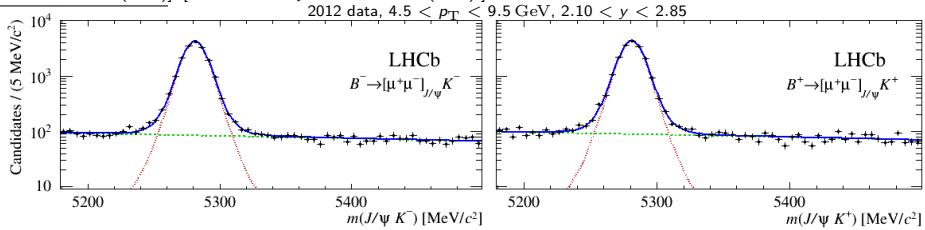
- Interference between color-suppressed tree and penguin leads to direct *CP* violation
- Related to $B^0 \to J/\psi K^0_S$ by swapping spectator $u \leftrightarrow d$
- $\mathcal{A}_{CP}^{\mathrm{dir}}(B^+ \to J/\psi K^+)$ constrains $\Delta\phi_d^{\mathrm{peng}}$





Direct *CP* violation in $B^+ \to J/\psi K^+$ from Run I data

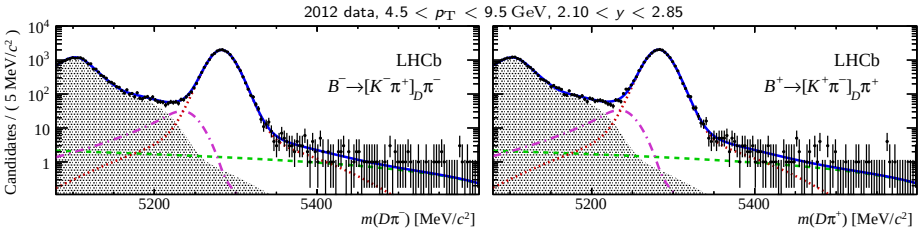
[Phys. Rev. D 95, 052005 (2017)], [PDG, Chin. Phys. C, 40, 100001 (2016)]



- Extract raw asymmetries from fit to mass $m(J/\psi K^+)$: $\mathcal{A}_{\rm raw} = \frac{N(B^-\to f) - N(B^+\to \bar{f})}{N(B^-\to f) + N(B^+\to \bar{f})}$
- Need to correct for production and detection asymmetries:
  $\mathcal{A}_{\rm raw} = \mathcal{A}^{\rm J/\psi K}_{\rm prod}(B^+) + \mathcal{A}^{\rm J/\psi K}_{\rm det} + \mathcal{A}^{J/\psi K}_{CP}$
- Measure relative to $B^+ \to \overline{D}^0\pi^+$ to cancel $\mathcal{A}^{\rm prod}$:
  $\mathcal{A}^{J/\psi K}_{\rm raw} - \mathcal{A}^{D\pi}_{\rm raw} = \mathcal{A}^{\rm J/\psi K}_{CP} - \mathcal{A}^{D\pi}_{CP} + \mathcal{A}^{\rm J/\psi K}_{\rm det} - \mathcal{A}^{\rm D\pi}_{\rm det} + \cancel{\mathcal{A}^{\rm J/\psi K}_{\rm prod}(B^+)} - \cancel{\mathcal{A}^{\rm D\pi}_{\rm prod}(B^+)}$
- $\sigma(\mathcal{A}^{D\pi}_{CP}) \approx 0.005 \times 10^{-2}$
- $\mathcal{A}^{\rm J/\psi K}_{\rm det} - \mathcal{A}^{\rm D\pi}_{\rm det}$ evaluated using large control samples

Direct *CP* violation in $B^+ \to J/\psi K^+$ from Run I data

[Phys. Rev. D 95, 052005 (2017)], [(PDG, Chin. Phys. C, 40, 100001 (2016)]



parameters depend on kinematics ⇒ Determine all asymmetries in bins of p_T, y, and year of data taking ⇒ 18 bins totalling $N_{sig} = 230k$

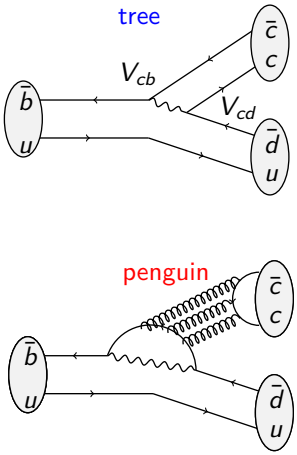
$$\mathcal{A}_{CP}^{dir}(B^+ \to J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$$

previous world average: $\mathcal{A}_{CP}^{dir}(B^+ \to J/\psi K^+) = (0.30 \pm 0.60) \times 10^{-2}$
use as a reference mode and to constrain $\Delta\phi_d^{peng}$

Direct *CP* Violation in $B^+ \to J/\psi\,\pi^+$ from Run I data

[JHEP 03 (2017) 036]

- Related to $B^0 \to J/\psi\, K^0_S$ via swap of $d \leftrightarrow s$ and spectator $u \leftrightarrow d$
- Cabibbo-suppressed tree $\Rightarrow$ large sensitivity to penguin amplitude
- $\mathcal{A}_{CP}^{\rm dir}(B^+ \to J/\psi\,\pi^+)$ and Ratio of branching fractions $\frac{\mathcal{B}(B^+\to J/\psi\,\pi^+)}{\mathcal{B}(B^+\to J/\psi\,K^+)}$ constrain $\Delta\phi_d^{\rm peng}$



Direct *CP* Violation in $B^+ \to J/\psi\,\pi^+$ from Run I data

[JHEP 03 (2017) 036], [PDG, Chin. Phys. C, 40, 100001 (2016)]

- Measure $\Delta\mathcal{A}_{CP}^{\rm dir}$ wrt $B^+ \to J/\psi\,K^+$
  $\mathcal{A}_{CP}^{J/\psi\,\pi} - \mathcal{A}_{CP}^{J/\psi\,K} = \mathcal{A}_{\rm raw}^{J/\psi\,\pi} - \mathcal{A}_{\rm raw}^{J/\psi\,K} - \delta\mathcal{A}_{\rm det}^{\pi K}$
- Modes have similar kinematics $\Rightarrow$ No binning in $p_{\rm T}$ or y necessary
- Fit 19k $B^+ \to J/\psi\,\pi^+$ and 250k $B^+ \to J/\psi\,K^+$ events

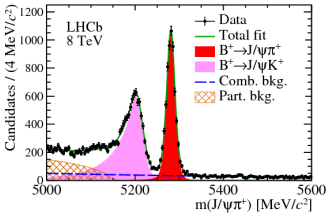
With new $\mathcal{A}_{CP}^{\rm dir}(B^+ \to J/\psi\,K^+)$ result:

$$\mathcal{A}_{CP}^{\rm dir}(B^+ \to J/\psi\,\pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}$$

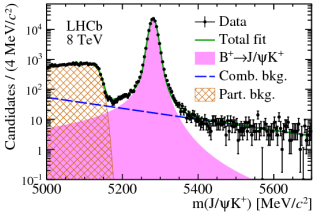
previous world average:

$$\mathcal{A}_{CP}^{\rm dir}(B^+ \to J/\psi\,\pi^+) = (0.10 \pm 2.80) \times 10^{-2}$$

$B^+ \to J/\psi\,\pi^+$



$B^+ \to J/\psi\,K^+$



Controlling the Penguin Pollution in ϕ_d

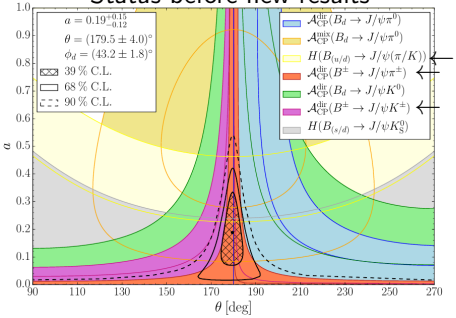
K. De Bruyn, R. Fleischer [JHEP 03 (2015) 145]

- Combined results from $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi \pi^+$ with measurements of $\mathcal{A}^{CP}$ in $B^0 \to J/\psi \pi^0/K^0$ to determine $\Delta\phi_d^{peng}$
- use *e.g.* $\mathcal{A}_{CP}^{dir}(B^+ \to J/\psi \pi^+) = \frac{2a \sin\theta \sin\gamma}{1-2a\cos\theta\cos\gamma+a^2}$ and then $\tan\Delta\phi_d^{peng} = -\frac{2a\epsilon\cos\theta\sin\gamma - a^2\epsilon^2\sin 2\gamma}{1-2a\epsilon\cos\theta\cos\gamma+a^2\epsilon^2\cos 2\gamma}$

$$\Delta\phi_d^{peng} = (-1.10^{+0.70}_{-0.85})^\circ$$

assumed $\sigma(\mathcal{A}_{CP}^{\rm dir}(B^+ \to J/\psi\pi^+)) = 2.3\,\%$

Status before new results



Update with new results in the making

Now $\sigma(\mathcal{A}_{CP}^{\rm dir}(B^+ \to J/\psi\pi^+)) < 1\,\% \Rightarrow$ will reduce $\sigma(\Delta\phi_d^{peng})$ significantly

Controlloing Penguin Pollution in ϕ_s

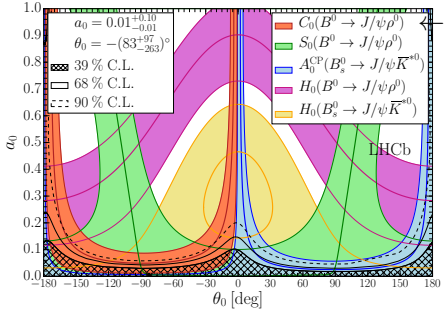
[JHEP11(2015)082], [Phys. Lett. B 742 (2015) 38]

Can do the same for ϕ_s:

- additional complication: $B_s^0 \to J/\psi\,\phi$ is $P \to VV$ decay $\Rightarrow$ each amplitude can have different $\Delta\phi_{s,i}^{peng}$ $i \in \{0, \|, \perp\}$
- combined results $SU(3)_f$ related modes $B_s^0 \to J/\psi\,K^{*0}$ and $B^0 \to J/\psi\,\rho^0$ to get $\Delta\phi_s^{peng}$

$$\Delta\phi_{s,0}^{peng} = 0.000^{+0.009}_{-0.011}(\text{stat})^{+0.004}_{-0.009}(\text{syst})\text{rad}$$
$$\Delta\phi_{s,\|}^{peng} = 0.001^{+0.010}_{-0.014}(\text{stat}) \pm 0.008(\text{syst})\text{rad}$$
$$\Delta\phi_{s,\perp}^{peng} = 0.003^{+0.010}_{-0.014}(\text{stat}) \pm 0.008(\text{syst})\text{rad}$$

[HFLAV]: $\phi_s = -0.021 \pm 0.031$ rad



work in progress:

Additional input from
$\mathcal{A}_{CP}^{\text{dir}}(B^+ \to J/\psi\,\rho^+) = C(B^0 \to J/\psi\,\rho^0)$

Conclusion

- LHCb keeps increasing the precision on ϕ_d and ϕ_s from B decays to charmonia
- Run 2 results just around the corner
- Ultimate precision depends also on the exact determination of the penguin pollution
  $\Rightarrow$ determine with CP observables from SU(3) and U-symmetry related modes

Thanks for your attention!

Backup

The LHCb detector

[JINST 3 (2008) S08005]

- Forward spectrometer designed for study of beauty and charm physics
- momentum resolution (0.5 - 1.0)% up to 200 GeV
- impact parameter resolution (15 $+29/p_{\mathrm{T}}$ [GeV]) $\mu\mathrm{m}$
- tracking and PID efficiency >90%

pseudorapidity: $2 < \eta < 5$