Direct CP violation in B decays at LHCb

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Overview

- CP violation in charmless two-body $B_s^0 \to \pi K$ and $B^0 \to K\pi$ decays:

  $0.35\,\mathrm{fb}^{-1}$, Phys. Rev. Lett. 108 (2012) 201601

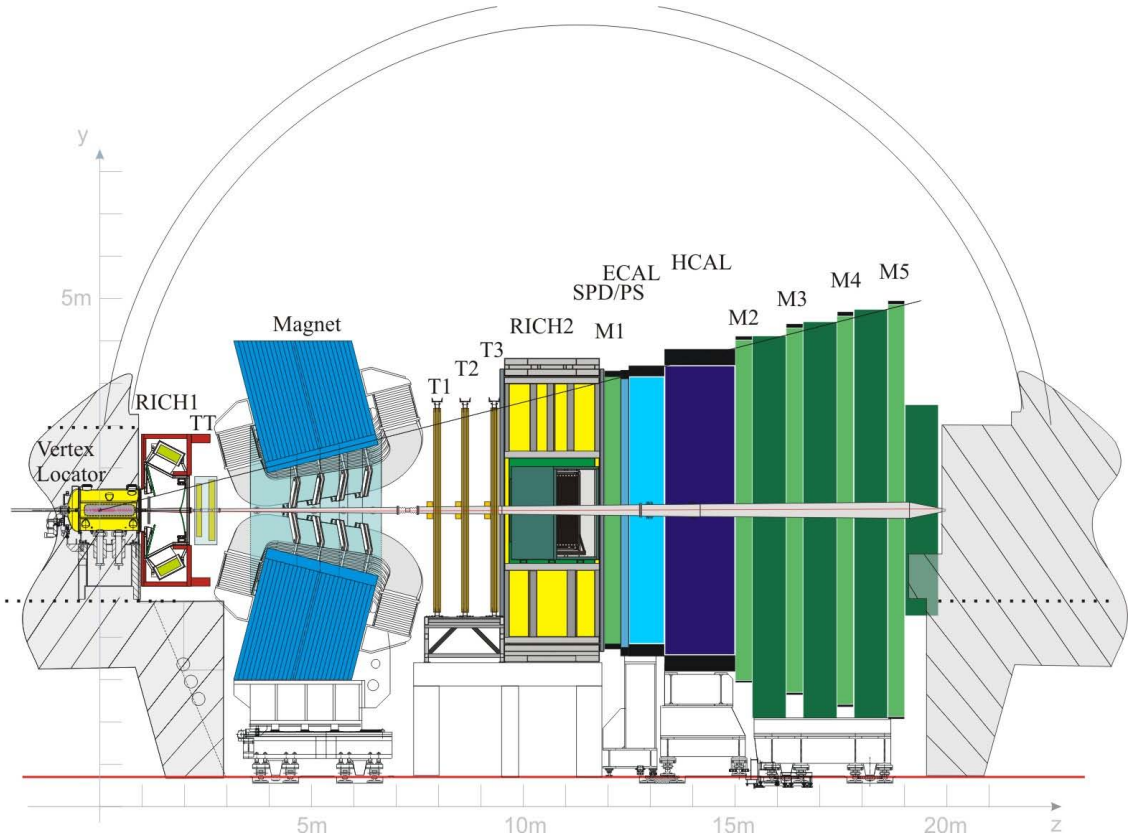
- CP violation in $B \to DK$:

  $1.0\,\mathrm{fb}^{-1}$, Physics Letters B 712 (2012)

- CP violation in charmless three-body $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ decays

  $1.0\,\mathrm{fb}^{-1}$, PRELIMINARY, LHCb-CONF-2012-018

LHCb



- Momentum resolution: $\Delta p/p = 0.4\%$ at $5\,\mathrm{GeV}/c$ to 0.6% at $100\,\mathrm{GeV}/c$
- ECAL resolution: $1\% + \frac{10\%}{\sqrt{E[GeV]}}$
- Impact parameter resolution: $20\,\mu\mathrm{m}$
- Invariant mass resolution: $\sim 22\,\mathrm{MeV}/c^2$ for two-body B decays

Charmless two-body decays:

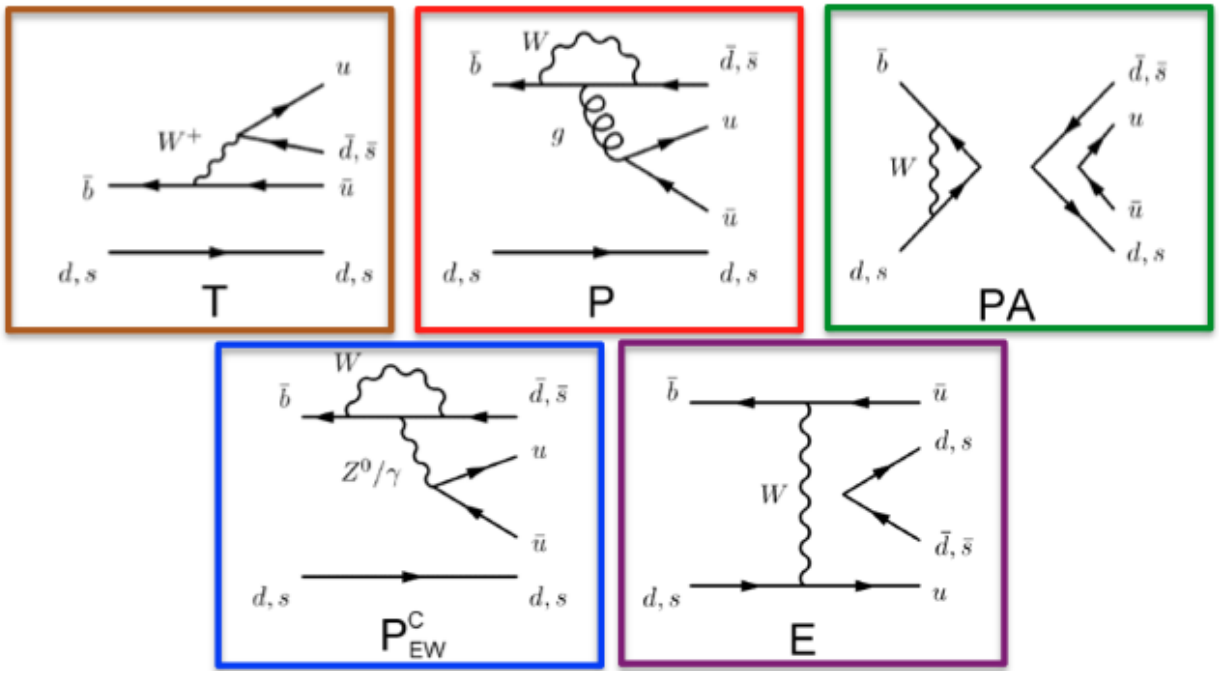
$B_s \to \pi K$ and $B_d \to K\pi$

$0.35\,\mathrm{fb}^{-1}$

Phys. Rev. Lett. 108 (2012) 201601

Charmless two-body decays

- Sensitive probes of the CKM mechanism
- Potentially sensitive to New Physics
- Extensively studied at the B factories and Tevatron
- Loop level determination of γ
- CP from the interference of tree and loop diagrams



$B_{d,s} \to K\pi$

$$A_{\rm CP}(B^0 \to K\pi) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$
$$A_{\rm CP}(B_s^0 \to \pi K) = \frac{\Gamma(\bar{B}_s^0 \to \pi^- K^+) - \Gamma(B_s^0 \to \pi^+ K^-)}{\Gamma(\bar{B}_s^0 \to \pi^- K^+) + \Gamma(B_s^0 \to \pi^+ K^-)}$$

- CP asymmetry is well established in $B^0 \to K\pi$
- Consider CP violation in B_s system: 14 times lower decay rate, 4 time lower production rate, stronger rejection of combinatorial background required

	$A_{\rm CP}(B^0 \to K\pi)$	$A_{\rm CP}(B_s^0 \to \pi K)$
BaBar[1]	$-0.107 \pm 0.018^{+0.07}_{-0.004}$	
Belle[2]	$-0.094 \pm 0.018 \pm 0.008$	
CLEO[3]	$-0.04 \pm 0.016 \pm 0.02$	
CDF[4]	$-0.086 \pm 0.023 \pm 0.009$	$0.39 \pm 0.15 \pm 0.08$
PDG	-0.097 ± 0.012	0.39 ± 0.17

[1] Phys.Rev.Lett 99 (2007) 021603

[2] Nature 452 (2008) 332

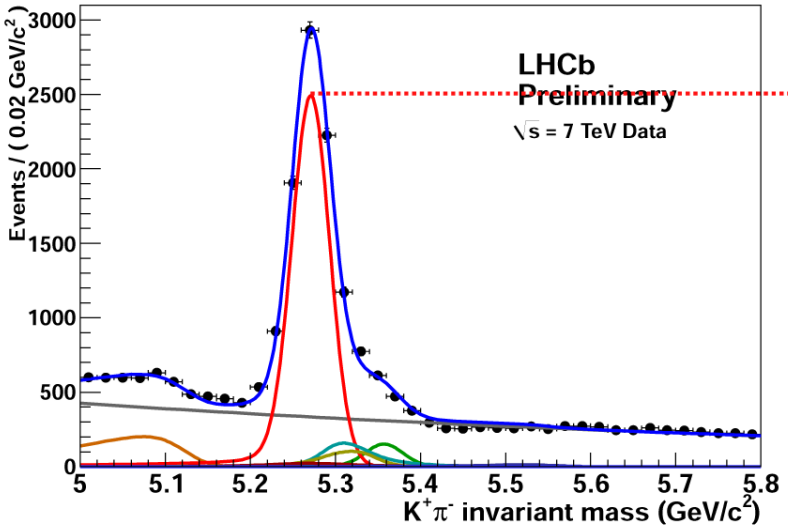
[3] Phys.Rev.Lett 85 (2000) 525

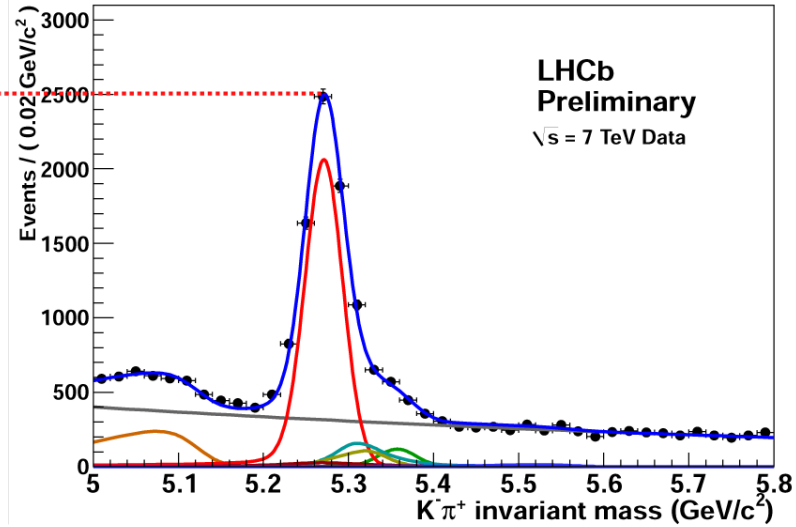
[4] Phys.Rev.Lett 106 (2011) 181802

$A_{\rm CP}$ Analysis Procedure

- Excellent performance of the hadronic trigger
- Two sets of offline selection criteria optimized to have better sensitivities on $A_{\rm CP}(B^0 \to K\pi)$ and on $A_{\rm CP}(B^0_s \to K\pi)$
- Crucial aspect: events reconstructed under the same pion mass hypothesis and then subdivided into different final states using the Particle Identification (PID) provided by two RICH detectors
  - PID calibration: control PID efficiency and mis-ID rate from data using calibration sample of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$, reweighted according to the momentum distribution of B daughters
  - Shape of cross-feed backgrounds obtained from simulations
- Unbinned Maximum Likelihood fit performed to extract "raw" asymmetries (including B production asymmetries and detection asymmetries)

$B^0_{(s)} \to K\pi$


LHCb
Preliminary
√s = 7 TeV Data
Events / (0.02 GeV/c²)
K⁺π⁻ invariant mass (GeV/c²)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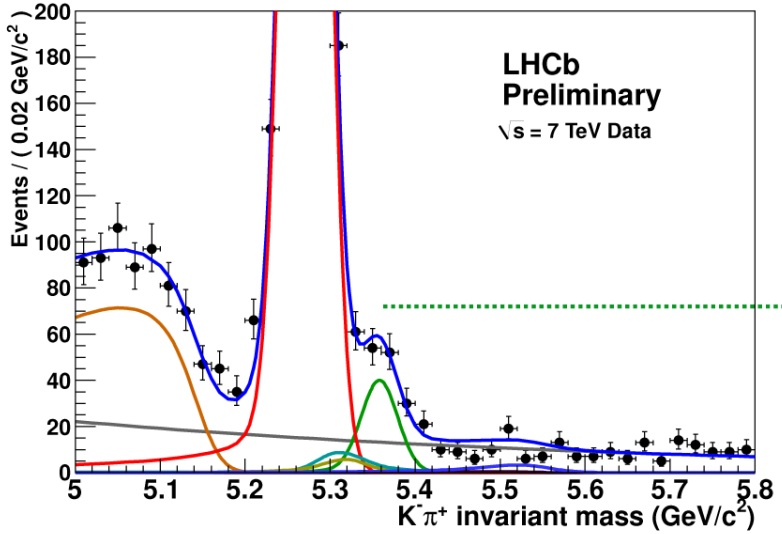
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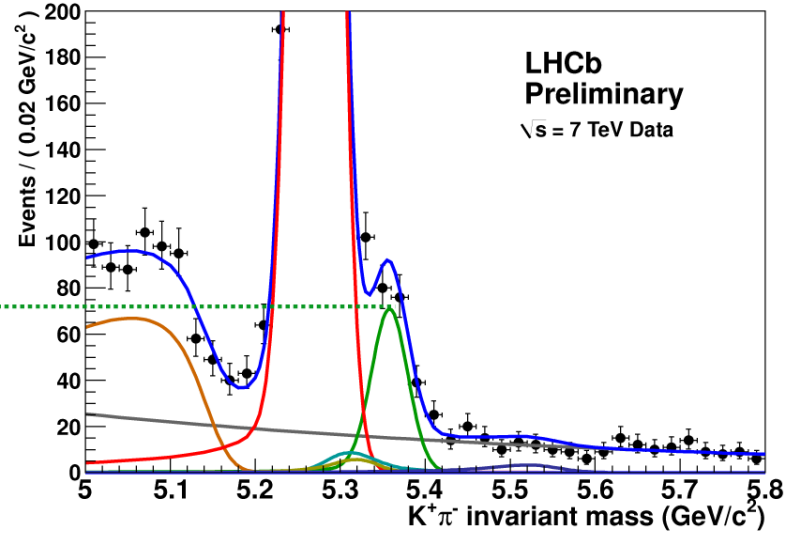

LHCb
Preliminary
√s = 7 TeV Data
Events / (0.02 GeV/c²)
K⁺π⁻ invariant mass (GeV/c²)

From "raw" to physical asymmetries

The "raw" $A_{\rm CP}$ measured in the data needs correction factors:

$$A_{\rm CP} = A_{raw} - \zeta_{d(s)} A_D(K\pi) - \kappa_{d(s)} A_P(B^0_{(s)})$$

- $\zeta_d = 1$ and $\zeta_s = -1$
- Instrumental asymmetry (effects induced by the detector acceptance and event reconstruction, strong interactions of final state particles with the detector material)
- Measured from data using sample of tagged D^* and untagged $D \to hh$
- $A_D = -0.010 \pm 0.02$
- $B^0_{(s)}$-$\bar{B}^0_{(s)}$ production asymmetry
- Estimated from $A_{\rm raw}(B^0 \to J/\psi K^{*0})$
- κ takes into account the dilution due to neutral $B^0_{(s)}$ mixing
- $A_P(B^0) = 0.010 \pm 0.013$
- κ_s small, $A_P(B^0_s)$ negligible

$$A_\Delta(B^0 \to K\pi) = (-0.7 \pm 0.6)\%$$
$$A_\Delta(B^0_s \to \pi K) = (1.0 \pm 0.2)\%$$

Results

$$A_{\mathrm{CP}}(B^0 \to K\pi) = -0.088 \pm 0.011(stat) \pm 0.008(syst)$$

- Good agreement with World Average
- Most precise measurement
- First observation $(> 6\sigma)$ of CP violation at a hadron collider

$$A_{\mathrm{CP}}(B_s^0 \to \pi K) = 0.27 \pm 0.08(stat) \pm 0.02(syst)$$

- First evidence $[3.3\sigma]$ of CP violation in B_s decay
- Agreement with the only measurement available (CDF, Phys.Rev.Lett 106 (2011) 181802)

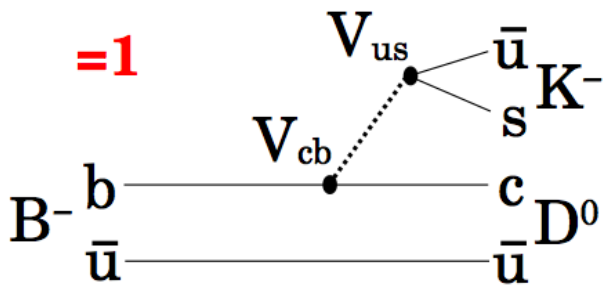
CP violation in $B \to DK$

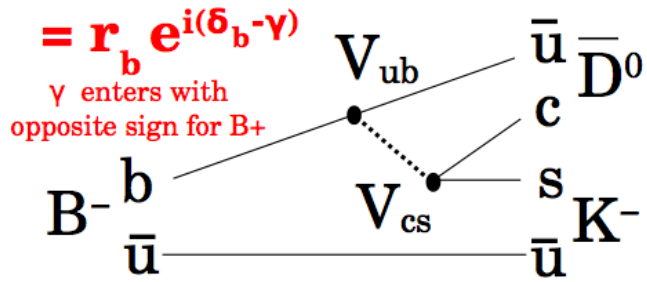
$1.0\,\mathrm{fb}^{-1}$

Physics Letters B 712 (2012)

Study of $B \to DK$

- Tree level measurement of weak phase γ, no contribution from penguins $\rightarrow$ theoretically clean:





- If D final state accessible for both D^0 and $\bar{D}^0$: interference sensitivity to γ and may exhibit direct CP violation:
  - CP eigenstates: K^+K^- and $\pi^+\pi^-$ (GLW[a])
  - Large interference: $D \to \pi^- K^+$ (ADS[b]: favoured and suppressed)
  - Combined measurement to gain sensitivity to γ

[a] Phys.Lett. B, 265 17 (1991)
[b] Phys.Rev.Lett 78 (1997) 3257-3260

Analysis and observables

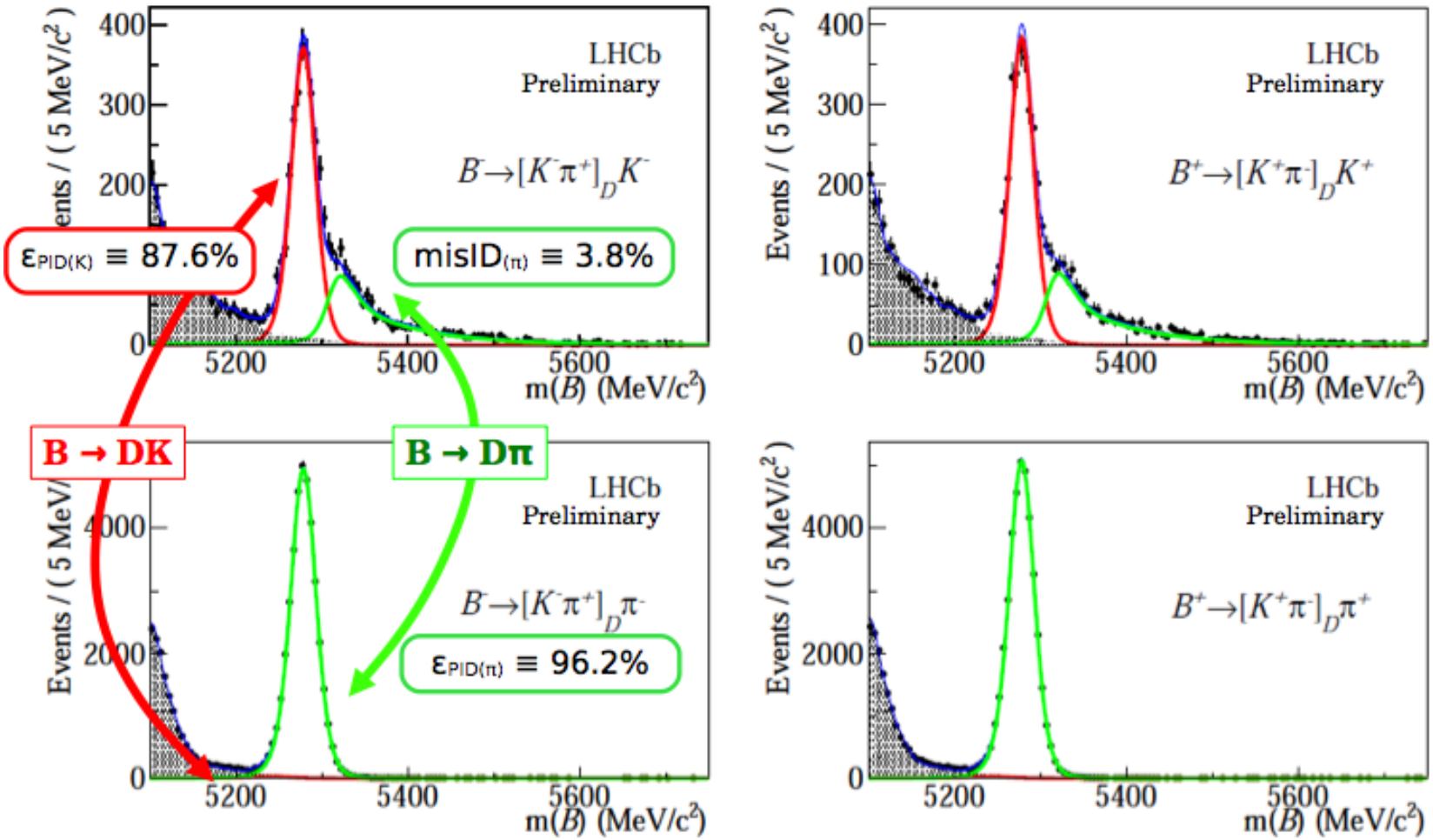
- Consider every combination $B \to [h^{'} h^{''}]_{\rm D} h^{'''}$ where $h = \pi, K$
- Extract Ratios and Asymmetries with simultaneous fit

13 measured observables

- 3 ratios of partial widths: $R^f_{K/\pi} = \frac{\Gamma(B^- \to [f]_D K^-) - \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) - \Gamma(B^+ \to [f]_D \pi^+)}$
- 6 CP asymmetries: $A^f_h = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}$
- 4 charge-separated partial widths of the suppressed mode relative to the favoured: $R^\pm_h = \frac{(\Gamma(B^\pm \to [\pi^\pm K^\mp]_D h^\pm)}{(\Gamma(B^\pm \to [K^\pm \pi^\mp]_D h^\pm)}$
- Considered final states $[f]_D = KK, \pi\pi, K\pi, \pi K$

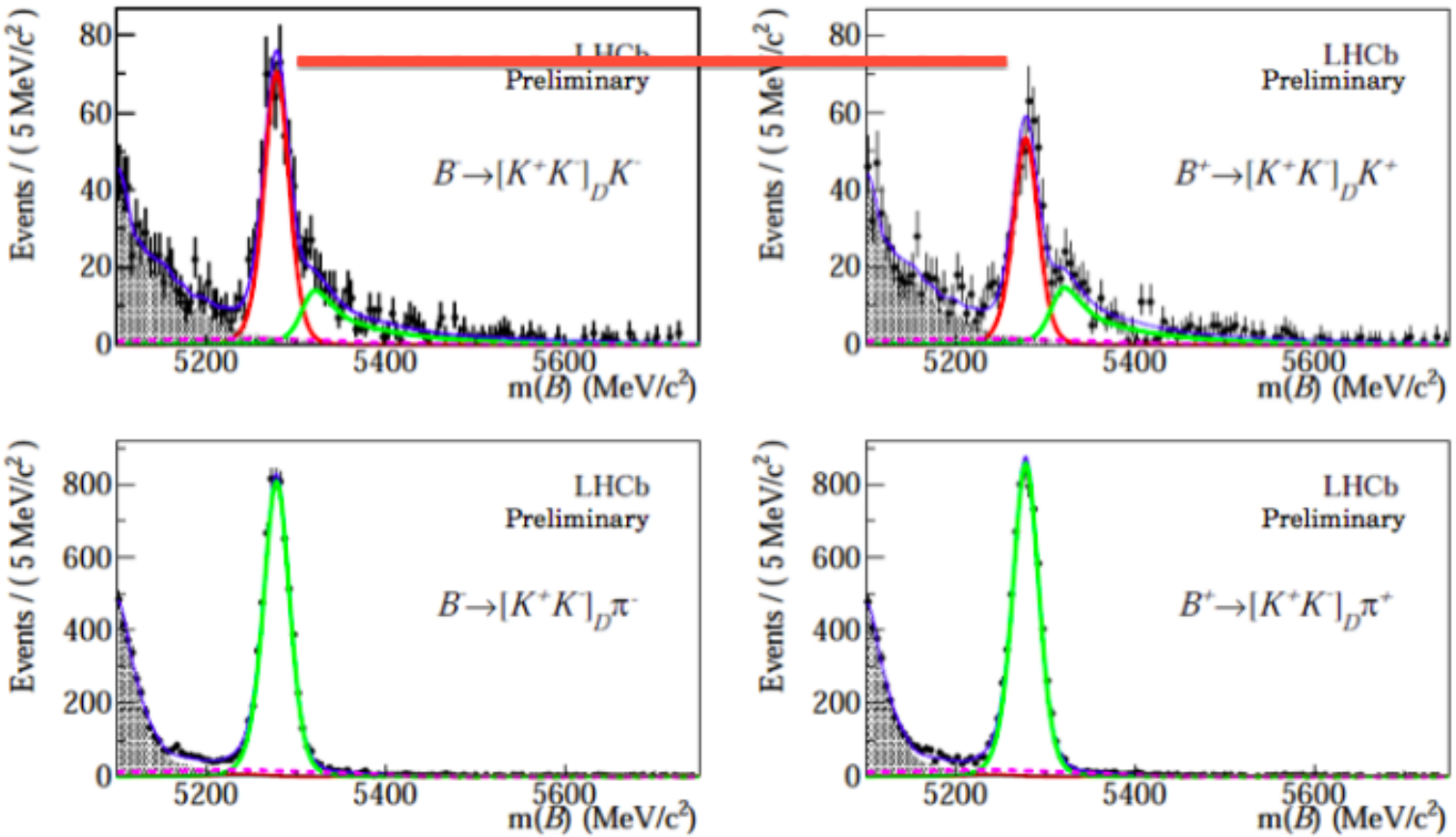
- Multivariate analysis to suppress combinatorial backgrounds
- Simultaneous fit of 16 slices:
  2 (charges) x 4 (D modes) x 2 ($DK/D\pi$)

$B^{\pm} \to [K\pi]_D h^{\pm}$: favoured ADS mode

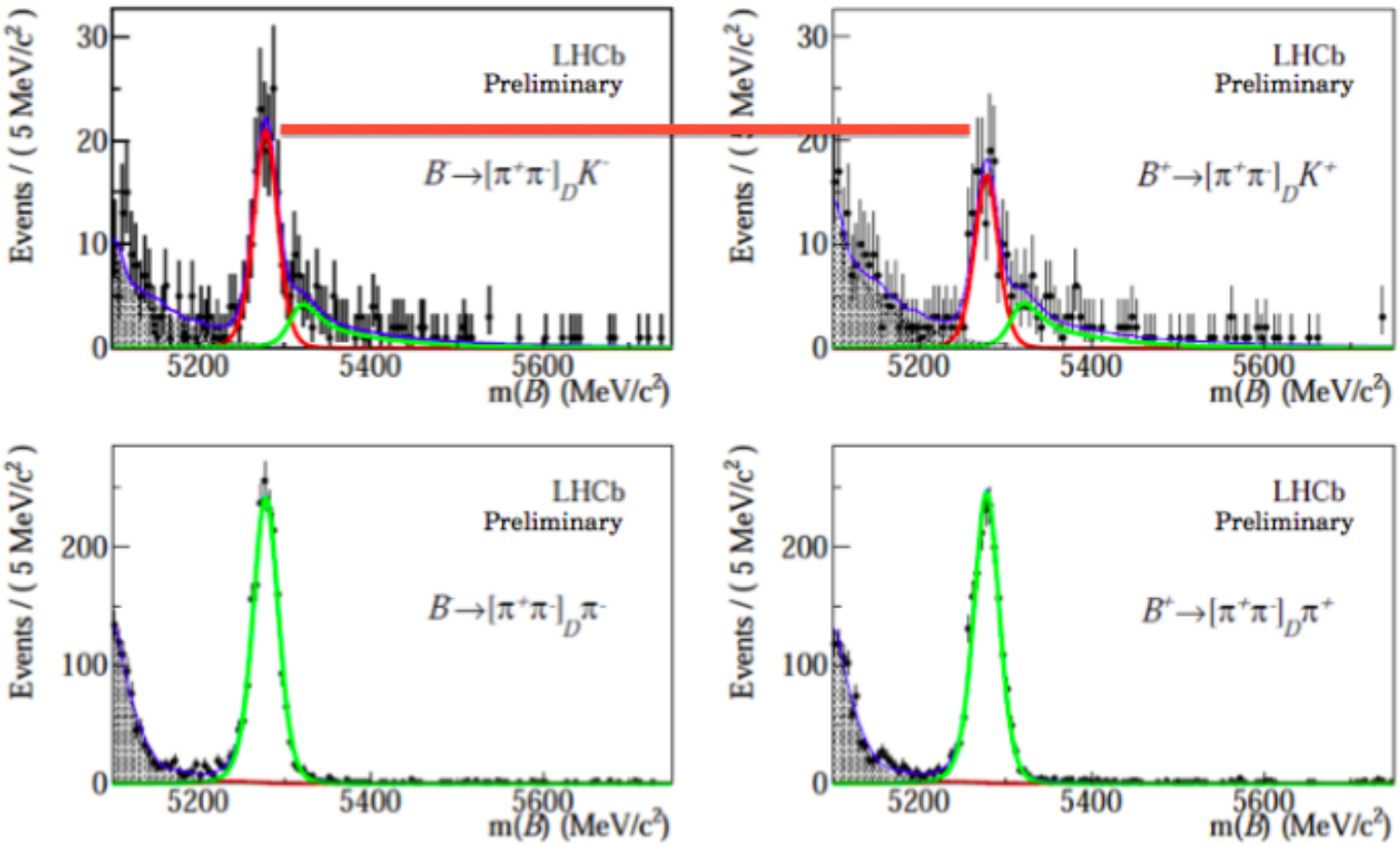


- Not CP violation expected in these most abundant modes

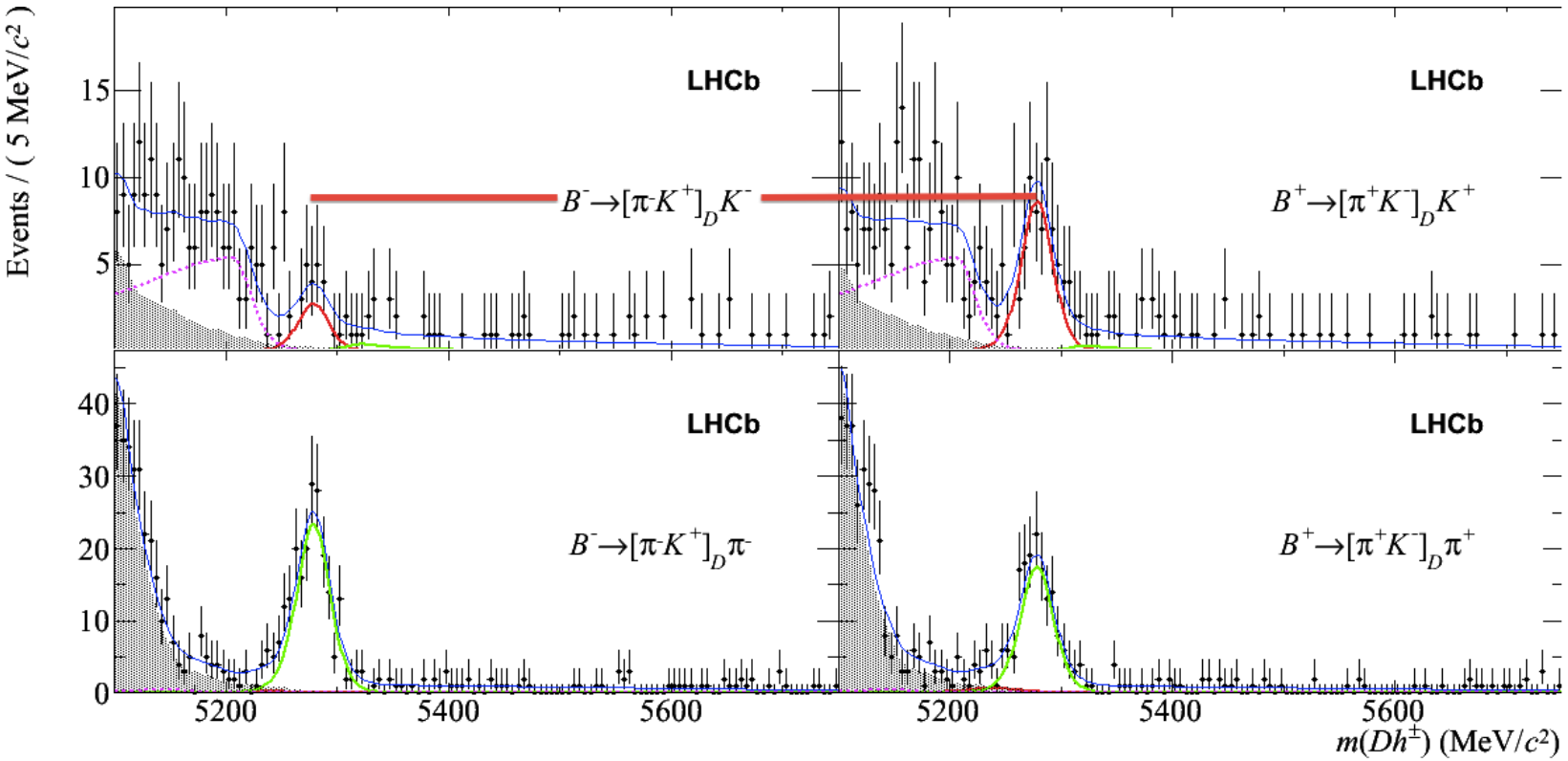
$B^{\pm} \to [KK]_D h^{\pm}$: GLW CP mode



$B^{\pm} \to [\pi\pi]_D h^{\pm}$: GLW CP mode



$B^{\pm} \to [\pi K]_D h^{\pm}$: suppressed ADS mode



- Suppressed ADS mode (kaon with wrong sign)
- $B^- \to D_{\rm ADS} K^- = 23$ events, $B^+ \to D_{\rm ADS} K^+ = 73$ events
- First observation of $B^+ \to D_{\rm ADS} K^+$

Results

$$
\begin{aligned}
R_{K/\pi}^{K\pi} &= 0.0774 \pm 0.0012 \pm 0.0018 \\
R_{K/\pi}^{KK} &= 0.0773 \pm 0.0030 \pm 0.0018 \\
R_{K/\pi}^{\pi\pi} &= 0.0803 \pm 0.0056 \pm 0.0017 \\
A_{\pi}^{K\pi} &= -0.0001 \pm 0.0036 \pm 0.0095 \\
A_{K}^{K\pi} &= 0.0044 \pm 0.0144 \pm 0.0174 \\
A_{K}^{KK} &= 0.1480 \pm 0.0369 \pm 0.0097 \\
A_{K}^{\pi\pi} &= 0.1351 \pm 0.0661 \pm 0.0095 \\
A_{\pi}^{KK} &= -0.0199 \pm 0.0091 \pm 0.0116 \\
A_{\pi}^{\pi\pi} &= -0.0009 \pm 0.0165 \pm 0.0099 \\
R_{K}^{-} &= 0.0073 \pm 0.0023 \pm 0.0004 \\
R_{K}^{+} &= 0.0232 \pm 0.0034 \pm 0.0007 \\
R_{\pi}^{-} &= 0.00469 \pm 0.00038 \pm 0.00008 \\
R_{\pi}^{+} &= 0.00352 \pm 0.00033 \pm 0.00007
\end{aligned}
$$

Total significance of 5.8σ: direct CP violation in $B^+ \to DK^+$ is observed

GLW observables

- $R_{\mathrm{CP}+} =< R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi} > / R_{K/\pi}^{K\pi} = 1.007 \pm 0038 \pm 0.012$
- $A_{\mathrm{CP}+} =< A_{K}^{KK}, A_{K}^{\pi\pi} >= 0.145 \pm 0.032 \pm 0.010$
- Both KK and $\pi\pi$ modes show positive asymmetries
- The combined asymmetry significance is 4.5σ

ADS observables

- $R_{\mathrm{ADS(K)}} = 0.0152 \pm 0.0020 \pm 0.0004$
- $A_{\mathrm{ADS(K)}} = -0.520 \pm 0.150 \pm 0.021$
- $R_{\mathrm{ADS}(\pi)} = 0.00410 \pm 0.00025 \pm 0.00005$
- $A_{\mathrm{ADS}(\pi)} = 0.143 \pm 0.062 \pm 0.011$
- $B \to D_{\mathrm{ADS}} K$ observed with 10σ and evidence (4σ) of negative asymmetry
- $B \to D_{\mathrm{ADS}} \pi$ shows hint of positive asymmetry (2.4σ)

CP violation in charmless three-body $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ decays

$1.0\,\mathrm{fb}^{-1}$

PRELIMINARY, LHCb-CONF-2012-018

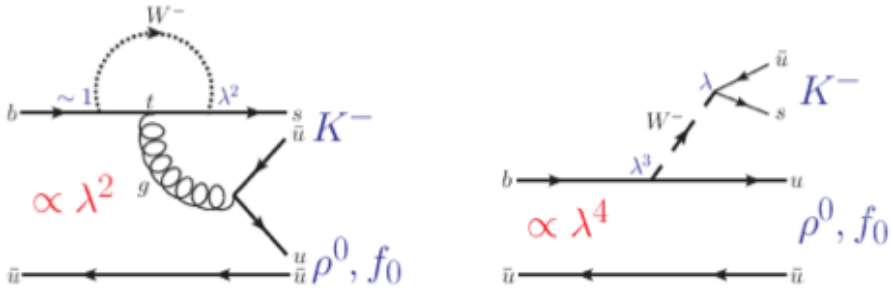
Study of three-body charmless $B^{\pm}$ decays

- Possibility to study the weak phase in interference patterns between two-body resonance in the Dalitz plot
- Leading diagrams: $b \to s$ penguin and $b \to u$ tree

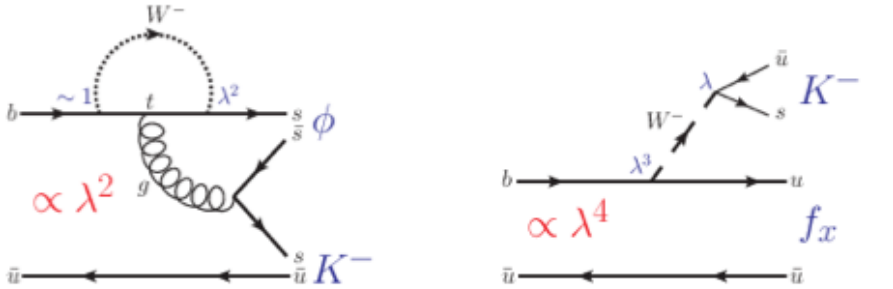
Current knowledge

- $A_{\rm CP}(B^+ \to K^+\pi^+\pi^-) = 0.038 \pm 0.022$
- Belle[1] and BaBar[2] claimed evidence of CP violation in $B^+ \to \rho^0 K^+$
- $A_{\rm CP}(B^+ \to K^+K^+K^-) = -0.017 \pm 0.030$
- BaBar[3] claimed evidence of CP violation in $B^+ \to \phi(1020)K^+$

$B^{\pm} \to K^{\pm}\pi^+\pi^-$



$B^{\pm} \to K^{\pm}K^+K^-$



[1] Phys.Rev.Lett. 96 (2006) 251803

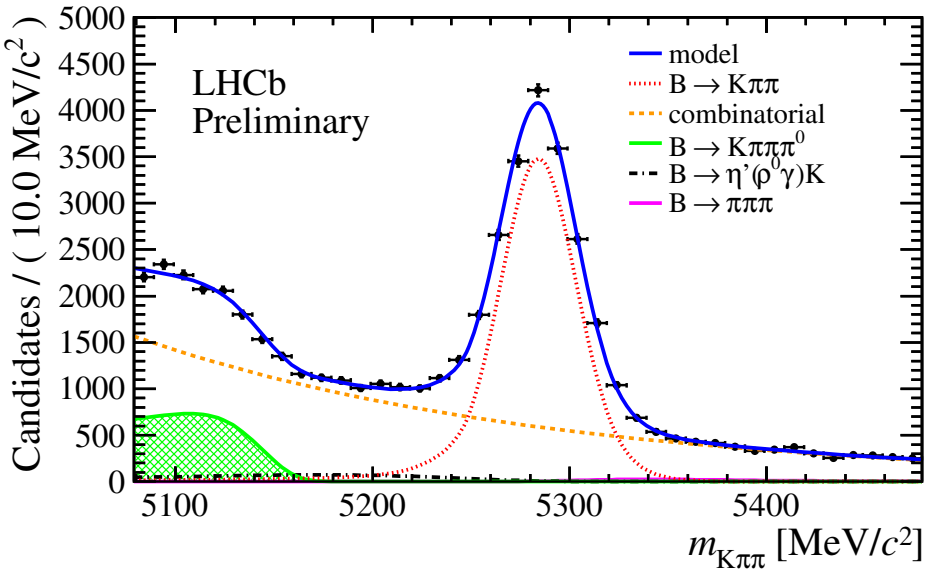
[2] Phys.Rev.Lett. D78 (2008) 012004

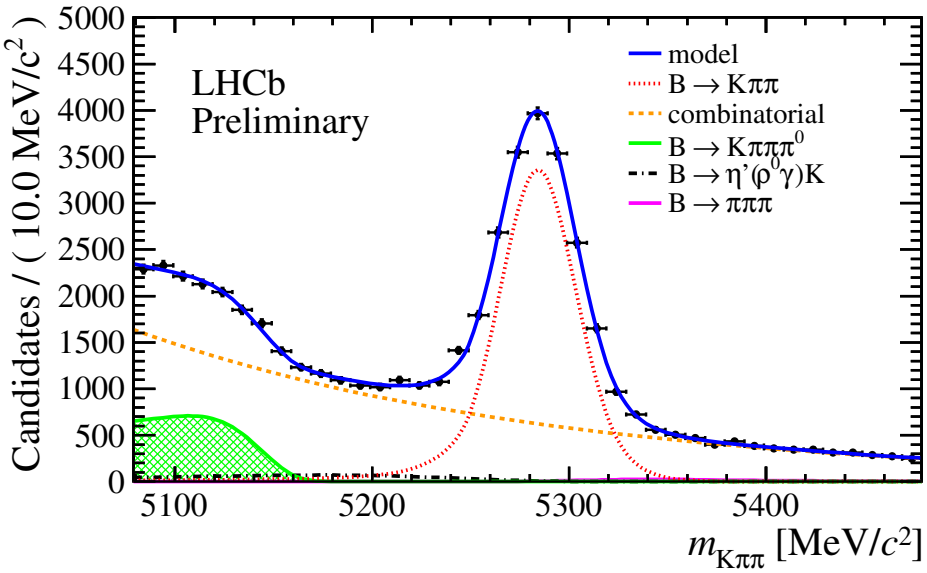
[3] arXiv: 1201.5897

- Measurement of the integrated charge asymmetry, $A_{\rm CP}$
- Measurement of the asymmetry distributions in the Dalitz plot
- Control channel $B^+ \to J/\psi K^+$ to extract physical CP violation from raw asymmetry
  - No expected CP violation: sensible only to detector and production effects
  - Similar kinematically, same three-body topology
  - Same production asymmetry (B^+)
  - Same asymmetry due to kaon interaction (odd number of kaons in the final state)

- Common kinematic selection for all the three-body charmless decays (topological similarities)
- PID requirements to separate kaons from pions
- Muon PID veto to suppress contributions from decays with muons
- veto in the invariant mass of D^0 $(B^+ \to \bar{D}^0(\to h^+h^-)h^+)$ and J/ψ $(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)$

CP asymmetry in $B^+ \to K^+\pi^+\pi^-$





$N(B^-) = 18168 \pm 170$

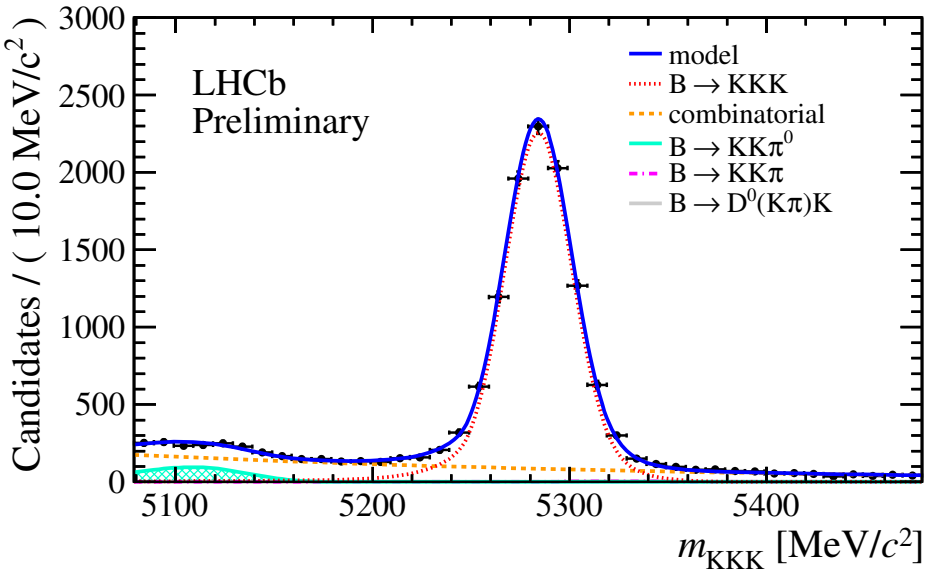
$N(B^+) = 17540 \pm 169$

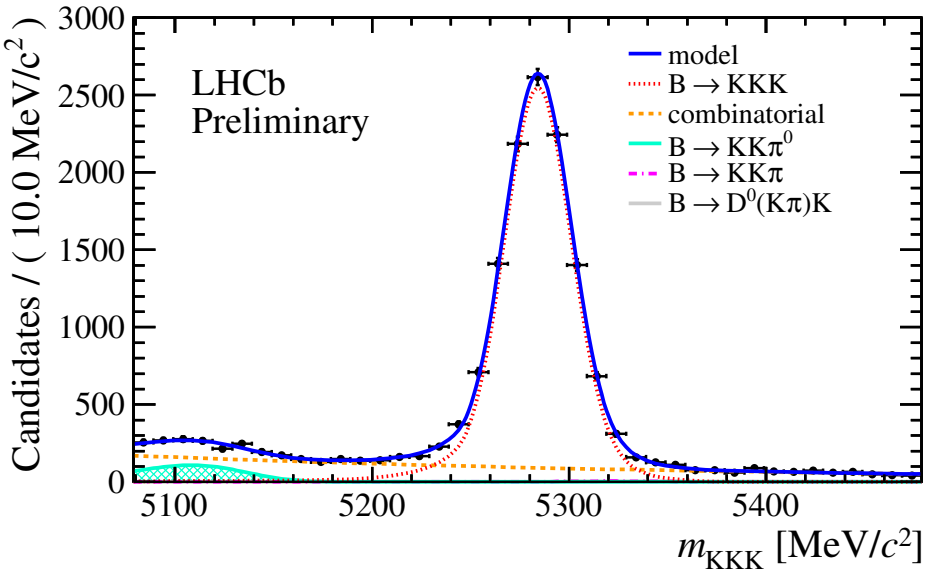
Preliminary

$$A_{CP}(K\pi\pi) = A_{CP}^{RAW}(K\pi\pi) - A_{CP}^{RAW}(J/\psi K) + A_{CP}(J/\psi K) =$$
$$= +0.034 \pm 0.009(stat) \pm 0.004(syst) \pm 0.007(J/\psi K)$$

Significance of 2.8σ

CP asymmetry in $B^+ \to K^+K^+K^-$





$N(B^-) = 11606 \pm 117$

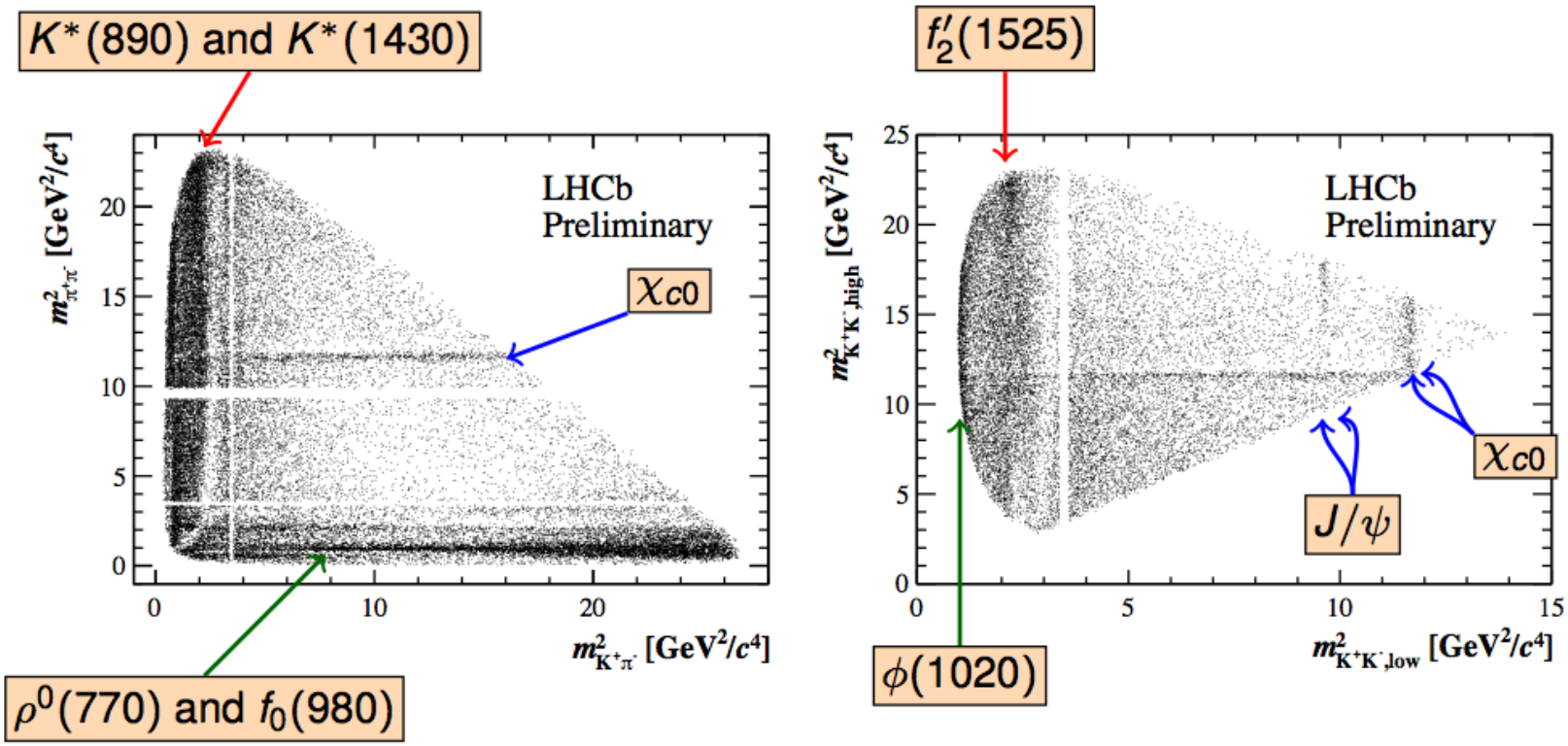
$N(B^+) = 10289 \pm 110$

Preliminary

$$A_{\rm CP}(KKK) = A_{\rm CP}^{\rm RAW}(KKK) - A_{\rm CP}^{\rm RAW}(J/\psi K) + A_{\rm CP}(J/\psi K) = \\ = -0.046 \pm 0.009(stat) \pm 0.005(syst) \pm 0.007(J/\psi K)$$

First evidence of inclusive CP asymmetry in charmless three-body B^+ decays (Significance of 3.7σ)

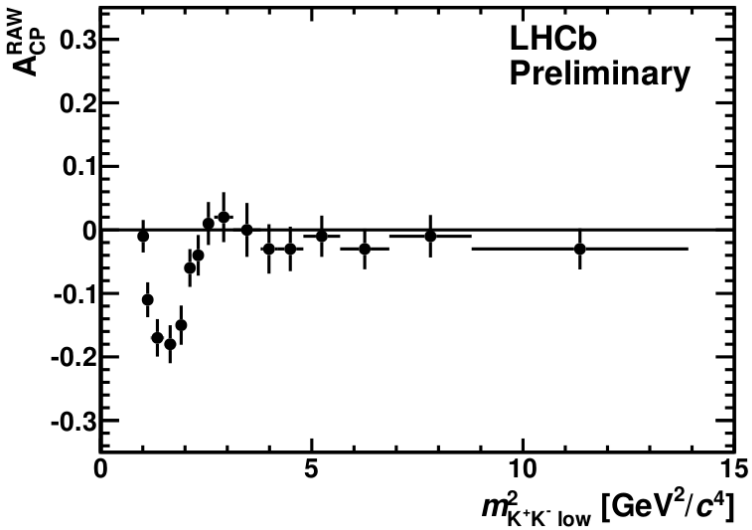
Dalitz plot

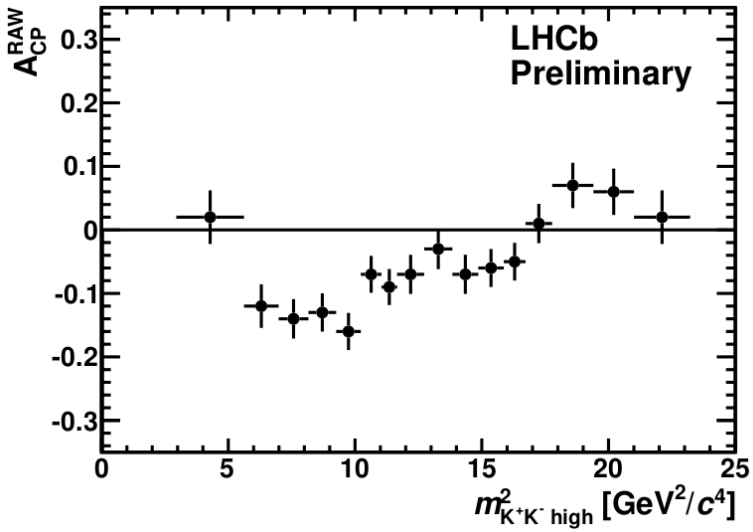


- Two-body invariant masses: $(m^2_{\pi^+\pi^-}, m^2_{K^+\pi^-})$ and $(m^2_{K^+K^-\text{low}}, m^2_{K^+K^-\text{high}})$ with $m^2_{K^+K^-\text{low}} < m^2_{K^+K^-\text{high}}$
- Candidates within mass range $\pm 40\,\text{MeV}/c^2$ around B mass
- Not mass constrained, not background subtracted

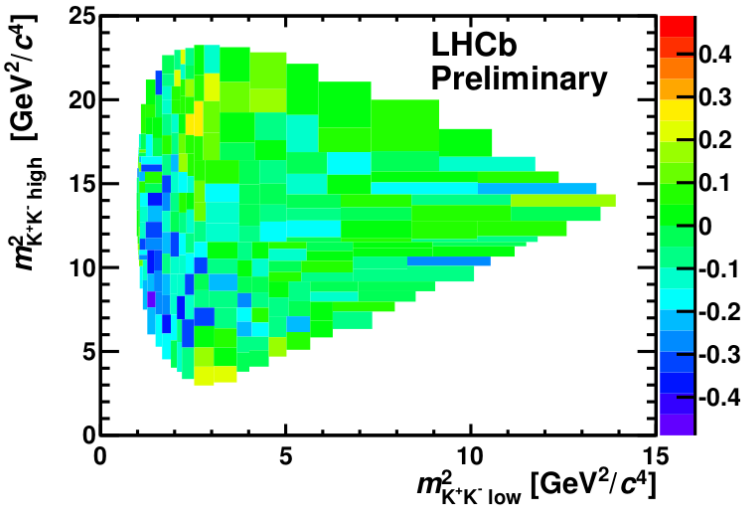
CP asymmetry in phase space:

$B^+ \to K^+K^+K^-$

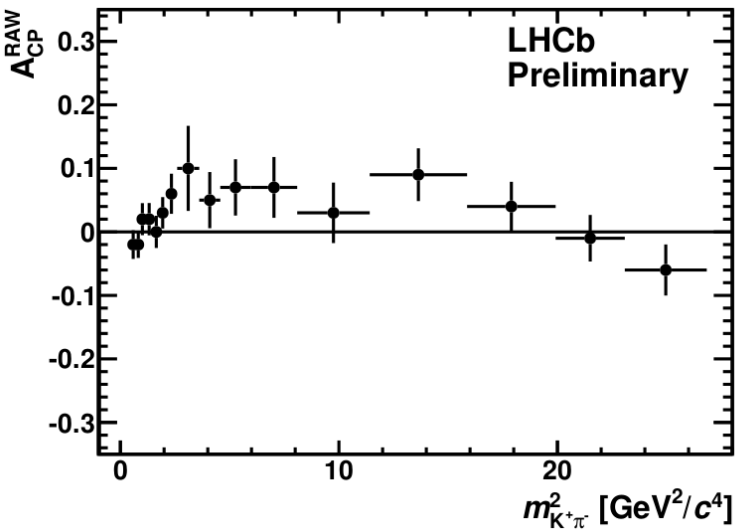


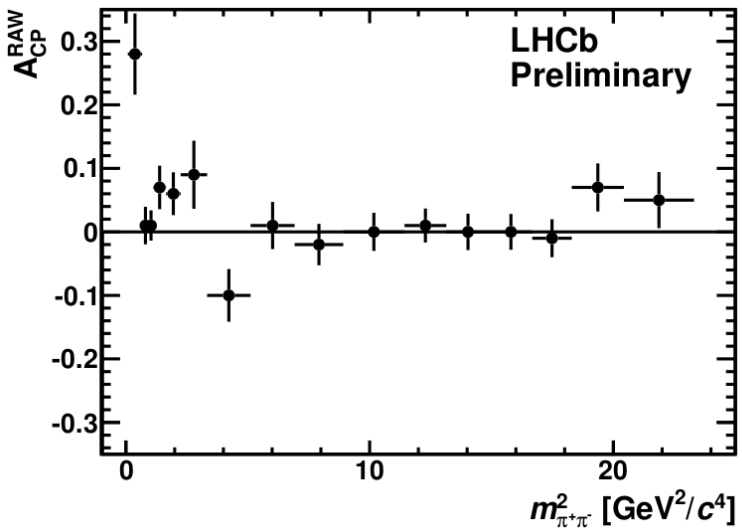


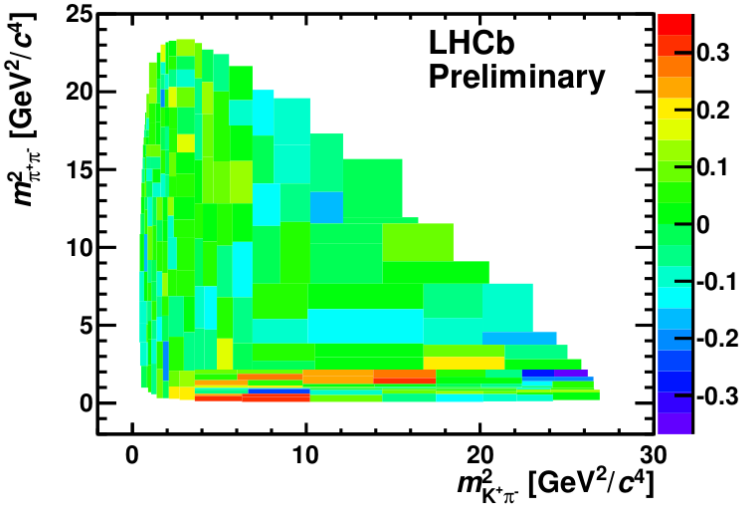
- Raw asymmetries in bins of the two body invariant mass projections
- Signal yield in each bin from simplified mass fit
- Dalitz plot in bins with equal number of entries, no background subtraction, $A_{\rm CP}^N = \frac{N^- - N^+}{N^- + N^+}$
- No clear asymmetry around $\phi(1020)$ or $f_2(1525)$, large between the two resonances



CP asymmetry in phase space: $B^+ \to K^+\pi^+\pi^-$







- Raw asymmetries in bins of the two body invariant mass projections
- Signal yield in each bin from simplified mass fit
- Dalitz plot in bins with equal number of entries, no background subtraction, $A^N_{\rm CP} = \frac{N^- - N^+}{N^- + N^+}$
- Clear asymmetry around $\rho(770)$

Conclusions

- CP violation in charmless two-body, $0.35\,\mathrm{fb}^{-1}$, Phys. Rev. Lett. 108 (2012) 201601
  - $B_s \to \pi K$: first evidence of CP violation in B_s decay (3.3σ)
  - $B_d \to K\pi$: World most precise measurement and first observation $[> 6\sigma]$ of the CP violation at hadron collider
- CP violation in $B \to DK$, $1.0\,\mathrm{fb}^{-1}$, Physics Letters B 712 (2012)
  - total significance of 5.8σ
- CP violation in charmless three-body $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$ decays, $1.0\,\mathrm{fb}^{-1}$, PRELIMINARY, LHCb-CONF-2012-018
  - $B^+ \to K^+K^+K^-$: first evidence of inclusive CP violation (3.7σ)
  - $B^+ \to K^+\pi^+\pi^-$: inclusive CP violation @ 2.8σ
  - CP asymmetry appears to be concentrated in regions of the Dalitz plot
- Results are limited by statistical uncertainties, expected more data this year

Backup Slides

Selection for $A_{\rm CP}(B^0 \to K\pi)$ and $A_{\rm CP}(B^0_s \to K\pi)$

Variable	$A_{CP}(B^0 \to K\pi)$	$A_{CP}(B^0_s \to K\pi)$
Track quality χ^2/ndf	< 3	< 3
Track $p_{\rm T}$ [GeV/c]	> 1.1	> 1.2
Track $d_{\rm IP}$ [mm]	> 0.15	> 0.20
$\max(p^K_{\rm T}, p^\pi_{\rm T})$ [GeV/c]	> 2.8	> 3.0
$\max(d^K_{\rm IP}, d^\pi_{\rm IP})$ [mm]	> 0.3	> 0.4
$d_{\rm CA}$ [mm]	< 0.08	< 0.08
$p^B_{\rm T}$ [GeV/c]	> 2.2	> 2.4
$d^B_{\rm IP}$ [mm]	< 0.06	< 0.06
$t_{\pi\pi}$ [ps]	> 0.9	> 1.5

B mixing dilution factor

$$\kappa_{d(s)} = \frac{\int_0^\infty e^{-\Gamma_{d(s)}t}\cos\left(\Delta m_{d(s)}t\right)\varepsilon(B^0_{(s)} \to K\pi;\, t)\mathrm{d}t}{\int_0^\infty e^{-\Gamma_{d(s)}t}\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right)\varepsilon(B^0_{(s)} \to K\pi;\, t)\mathrm{d}t}$$

where ϵ are the acceptances as functions of the decay time for the two reconstructed decays.

- $\Delta\Gamma_d = 0$
- Γ_d, Γ_s, Δm_d, Δm_s, $\Delta\Gamma_s$ world averaged (PDG)
- $\kappa_d = 0.303 \pm 0.05$
- $\kappa_s = -0.033 \pm 0.003$, small since B^0_s oscillation frequency is large

Systematic uncertainties for $A_{\rm CP}(B^0 \to K\pi)$ and $A_{\rm CP}(B^0_s \to K\pi)$

Systematic uncertainty	$A_{CP}(B^0 \to K\pi)$	$A_{CP}(B^0_s \to K\pi)$
[a] PID calibration	0.0012	0.001
[b] Final state radiation	0.0026	0.010
[b] Signal model	0.0004	0.005
[b] Combinatorial background	0.0001	0.009
[b] 3-body background	0.0009	0.007
[b] Cross-feed background	0.0011	0.008
[c] Instr. and prod. asym. (A_Δ)	0.0078	0.005
Total	0.0084	0.019

$B \to DK$

- $A_{\rm prod} = (-0.8 \pm 0.7)\%$ (simulation suggests a small excess of B^+ over B^-), observed raw asymmetry of $B^+ \to J/\psi K^+$
- $A_{\rm K} = (-0.5 \pm 0.7)\%$ in the detection of $K^\pm$ due to their different interaction lenghts (assigned for each occurence of strangeness in the final state)
- $A_\pi = (0.0 \pm 0.7)\%$

Systematic uncertainties

$\times 10^{-3}$	PID	PDFs	Sim	$A_{\rm instr.}$	Total
$R^{K\pi}_{K/\pi}$	1.4	0.9	0.8	0	1.8
$R^{KK}_{K/\pi}$	1.3	0.8	0.9	0	1.8
$R^{\pi\pi}_{K/\pi}$	1.3	0.6	0.8	0	1.7
$A^{K\pi}_{\pi}$	0	1.0	0	9.4	9.5
$A^{K\pi}_{K}$	0.2	4.1	0	16.9	17.4
A^{KK}_{K}	1.6	1.3	0.5	9.5	9.7
$A^{\pi\pi}_{K}$	1.9	2.3	0	9.0	9.5
A^{KK}_{π}	0.1	6.6	0	9.5	11.6
$A^{\pi\pi}_{\pi}$	0.1	0.4	0	9.9	9.9
R^{-}_{K}	0.2	0.4	0	0.1	0.4
R^{+}_{K}	0.4	0.5	0	0.1	0.7
R^{-}_{π}	0.01	0.03	0	0.07	0.08
R^{+}_{π}	0.01	0.03	0	0.07	0.07

Systematic uncertainties for $B^+ \to K^+K^+K^-$ and $B^+ \to K^+\pi^+\pi^-$

Contribution	$K^\pm\pi^+\pi^-$	$K^\pm K^+K^-$
Signal fixed parameters	0.002	0.002
Signal model	0.0001	0.0001
Signal shape	0.0012	0.0001
Background model	0.0003	0.00002
Background asymmetry	0.0002	0.0001
Acceptance	0.001	0.0015
Trigger correction	0.0011	0.001
Subtraction method	0.003	0.004
Total	0.004	0.005