An introduction to hadronic charmless b-hadron decays in the LHCb experiment

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Outline of the presentation

1. Introduction: the hadronic charmless b-hadron decays in the framework of flavour physics and CP violation.

2. Mixing-induced CP violation results (including NP in the decays).

3. Direct CP violation results.

4. Amplitude analyses.

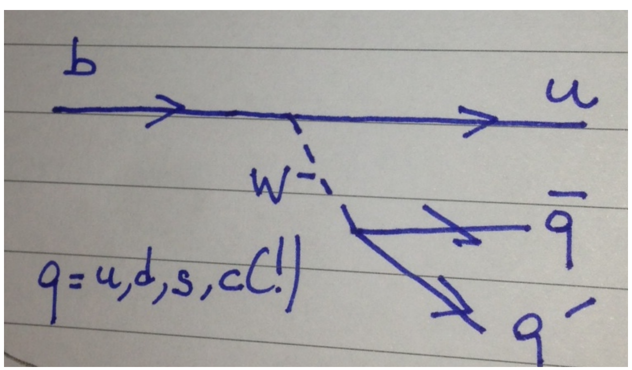
5. Overview of the forthcoming analyses.

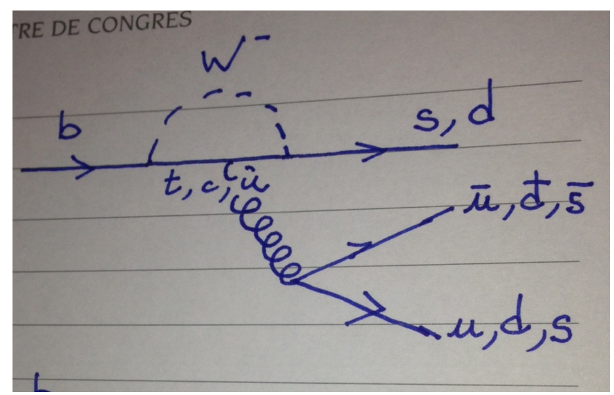
1. Introduction to hadronic charmless b decays

Hadronic charmless b-hadron decays is a two-fold laboratory to search for New Physics:

- Tree processes (left diagram) are felt to behave in a standard way and do exhibit the weak phase in the $b \rightarrow u$ (as soon as there are interferences). Hence, it is an important ingredient of global consistency check of the Standard Model. Any deviation to the SM CKM profile etc..

- Loop processes (right diagram - penguin) are Flavour Changing Neutral Current amplitudes such as $b \rightarrow s$ or $b \rightarrow d$ transitions and may welcome new heavy bosons or fermions. Indirect probe of NP contributions.

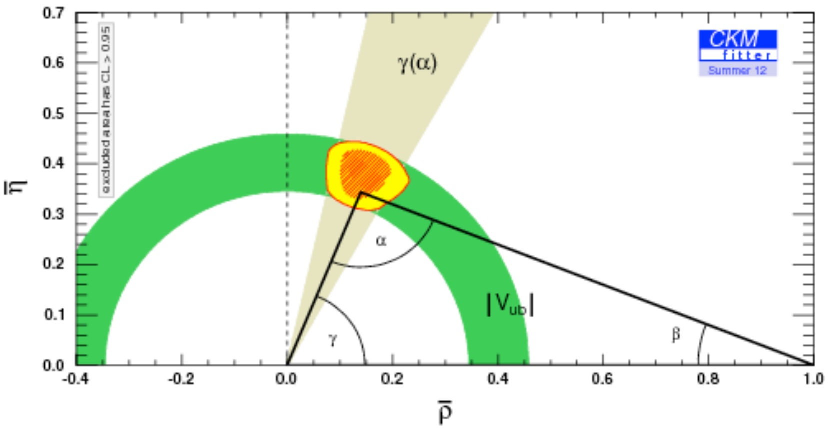


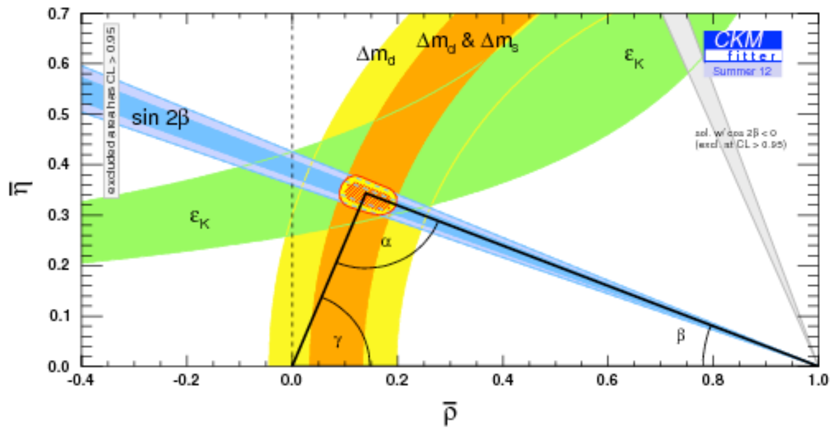


1. Introduction to hadronic charmless b decays

- In the global CKM picture: comparison of observables constraints.

Trees against Loops.



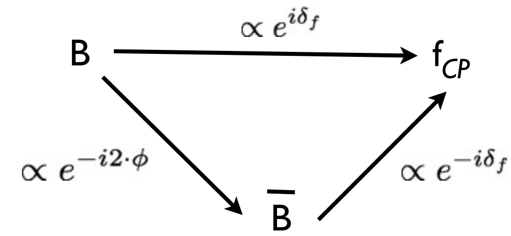


- Tree-level processes are thought to be pure SM. Loops could have NP. Note that in the right plot, loop processes are meson mixing observables only.

- Wherever it is looked at in B and K physics, the SM hypothesis succeeded so far. In particular, fair agreement between (loop) mixing and tree processes. Search in the decay too.

2. CKM metrology - α and γ w/ charmless 2-body B decays.

• The decays into CP eigenstates $B_d \to \pi\pi$ or $B_s \to KK$ exhibits CP-violating phases both in the mixing and the decay.



$$A_{CP}(t) = \frac{\Gamma(\bar{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\bar{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

• becomes: $$A_{CP}(t) = \frac{A_{\mathrm{dir}} \cos(\Delta m t) + A_{\mathrm{mix}} \sin(\Delta m t)}{\cosh(\frac{\Delta\Gamma}{2} t) - A_\Delta \sinh(\frac{\Delta\Gamma}{2} t)}$$

• where direct and mixing-induced CP asymmetries are introduced.

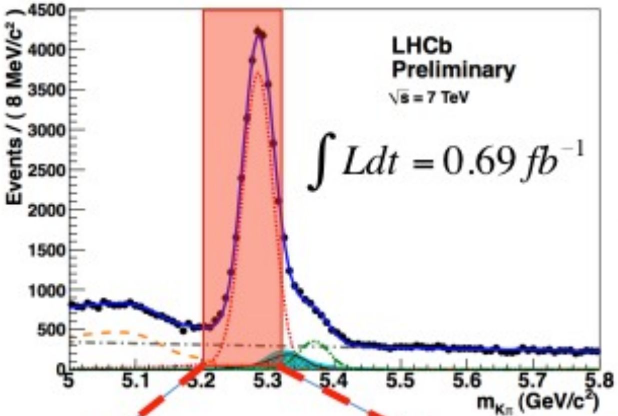
• Key ingredients:

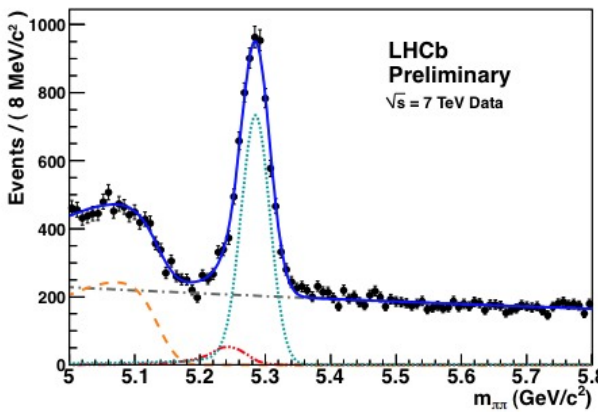
- Flavour tagging at production (performance is determined from the data by making use of the self-tagged mode $B_d \to K\pi$)
- Time-dependent analysis (reconstruction of the proper time of the decay).
- Particle Identification (RICHes).

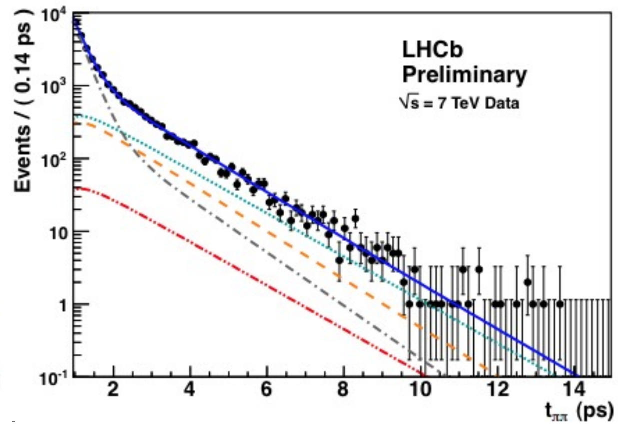
2. CKM metrology - α and γ w/ charmless 2-body B decays.

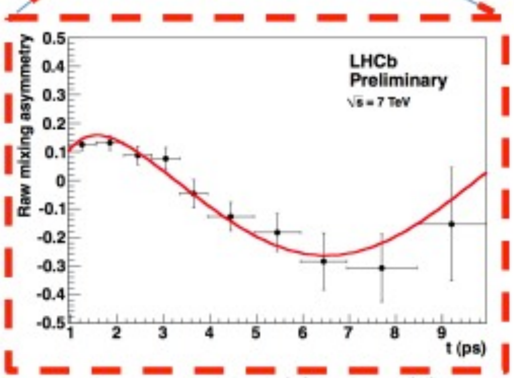
LHCb-CONF-2012-007

- Flavour tagging, mass distribution, proper time distribution









$$A(t) = \frac{\Gamma_{unmix}(t) - \Gamma_{mix}(t)}{\Gamma_{unmix}(t) + \Gamma_{mix}(t)}$$

$$A_{\pi\pi}^{\mathrm{dir}} = 0.11 \pm 0.21 \pm 0.03$$

$$A_{\pi\pi}^{\mathrm{mix}} = -0.56 \pm 0.17 \pm 0.03$$

$$\rho(A_{\pi\pi}^{\mathrm{dir}}, A_{\pi\pi}^{\mathrm{mix}}) = -0.34$$

This is the first evidence of mixing induced CP violation at an hadron collider(3.2σ)

Only 0.67 /fb analysed. Update at the summer time.

2. CKM metrology - α and γ w/ charmless 2-body B decays.

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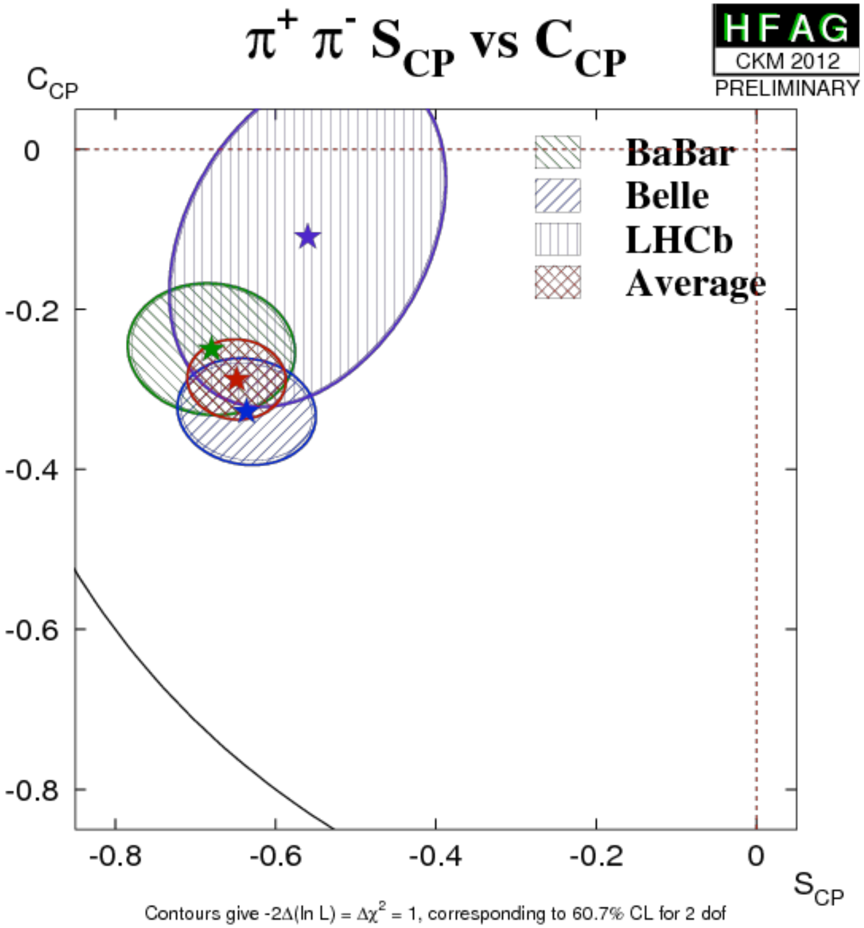
- Comparison w/ B-factories and outlook:



- Already contributing to constrain the CKM angle α. Update with full 2011 data will be competitive with B factories.

- Using the measurements of Adir($\pi\pi$), Amix($\pi\pi$), Adir (KK), Amix(KK), BR ($\pi\pi$), BR(KK), ϕ_d and allowing for U-spin symmetry breaking up to a certain extent, one can solve for γ and ϕ_s.

- Also next at LHCb: contribution to the α angle determination w/ $B_d \to \rho\rho$ (see Marc Grabalosa's talk).

2. Mixing-induced CPV in $B_s^0 \to \phi\,\phi\ (K^+K^-K^+K^-)$

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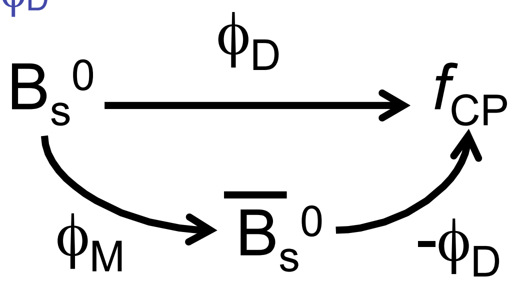
- Study the CP violation asymmetry in interference between decay and mixing in $B_s^0 \to \phi\,\phi$ and compare it to both SM and the weak mixing phase measured in $B_s^0 \to J/\psi\ (\mu^+\mu^-)\ \phi\ (K^+K^-)$ decays: CP violating phase $\phi_S = \phi_M - 2\phi_D$



- In the Standard Model, ϕ_S is well determined: $\phi_S = -2\beta_S = -0.0363 \pm 0.0017$ rad, up to penguin diagram phase contributions (10^{-4}–10^{-3}). Null test of the SM hypothesis.

- The mixing phase, $\phi_M \approx 0$ in Standard Model can be modified by New Physics and hence measured by ϕ_S. NP in mixing for $B_s^0 \to J/\psi\ (\mu^+\mu^-)\ \phi\ (K^+K^-)$, NP in mixing and decay for $B_s^0 \to \phi\,\phi$.

- Key ingredients:
    - Flavour tagging
    - Time-dependent analysis
    - Amplitude (angular) analysis to quantify the amount of each CP eigenstates.

2. Mixing-induced CPV in $B_s^0 \to \phi\,\phi\,(K^+K^-K^+K^-)$

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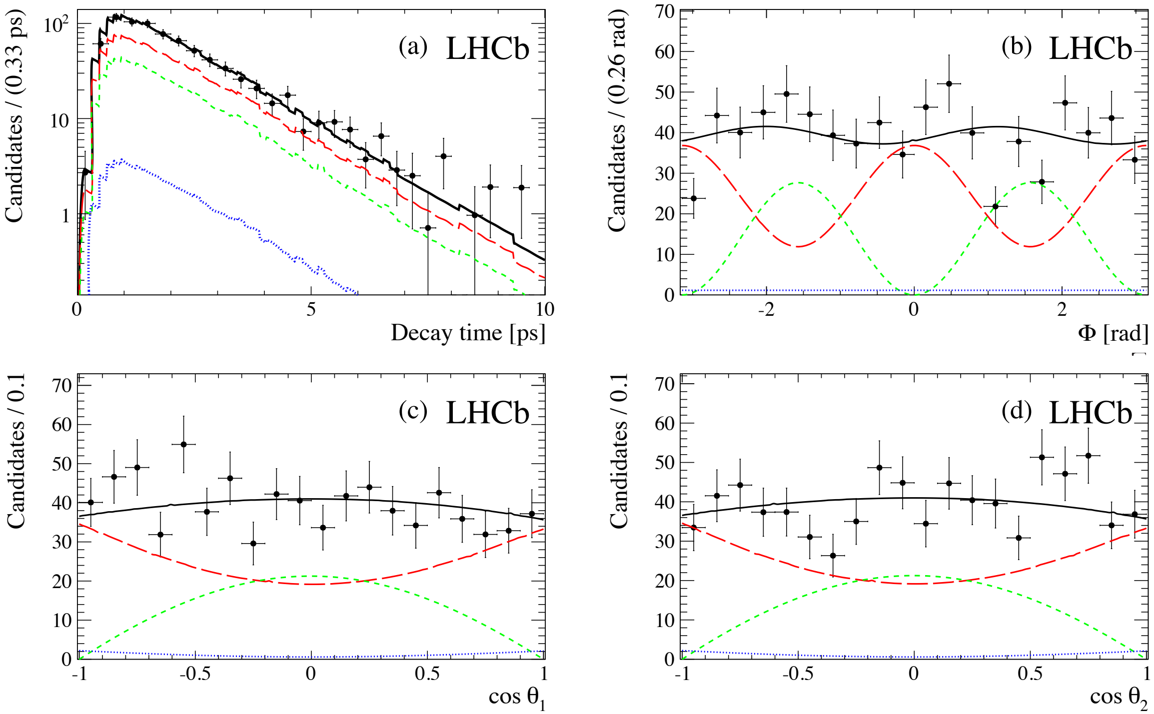
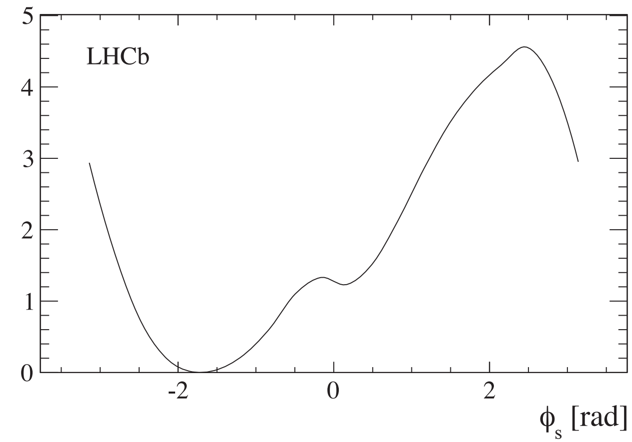
- With 2011 data, the precision is about a radian. One of the utmost importance mode for the LHCb upgrade physics case.





3. Direct CP violation in hadronic charmless 2-body B decays.

- Direct CP violation starting by charmless 2-body decays:

- Compare the decay rates of self-tagged modes $K\pi$

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

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

- These raw asymmetries must be corrected for detection asymmetry and B production asymmetry (both data-driven estimates):

$$A_\Delta(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)} \to K\pi)$$

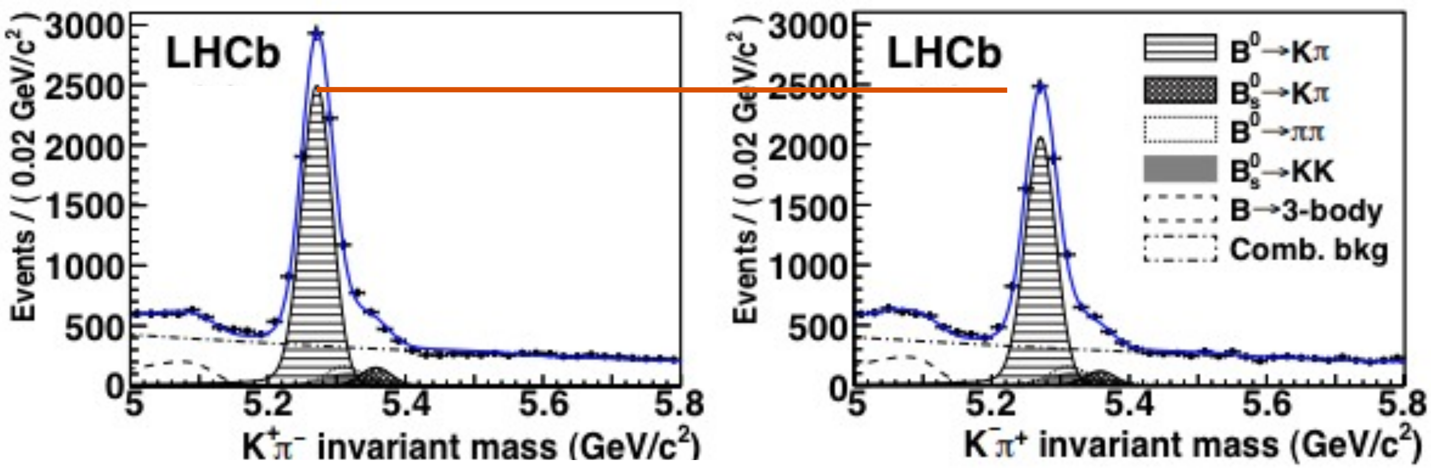
- Key ingredients: these analyses are heavily relying on Particle Identification performance.

3. Direct CP violation in hadronic charmless 2-body B decays.

LHCB-PAPER-2011-029

- Direct CP violation starting by charmless 2-body decays:

- Compare the decay rates of self-tagged modes $K\pi$: B^0



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

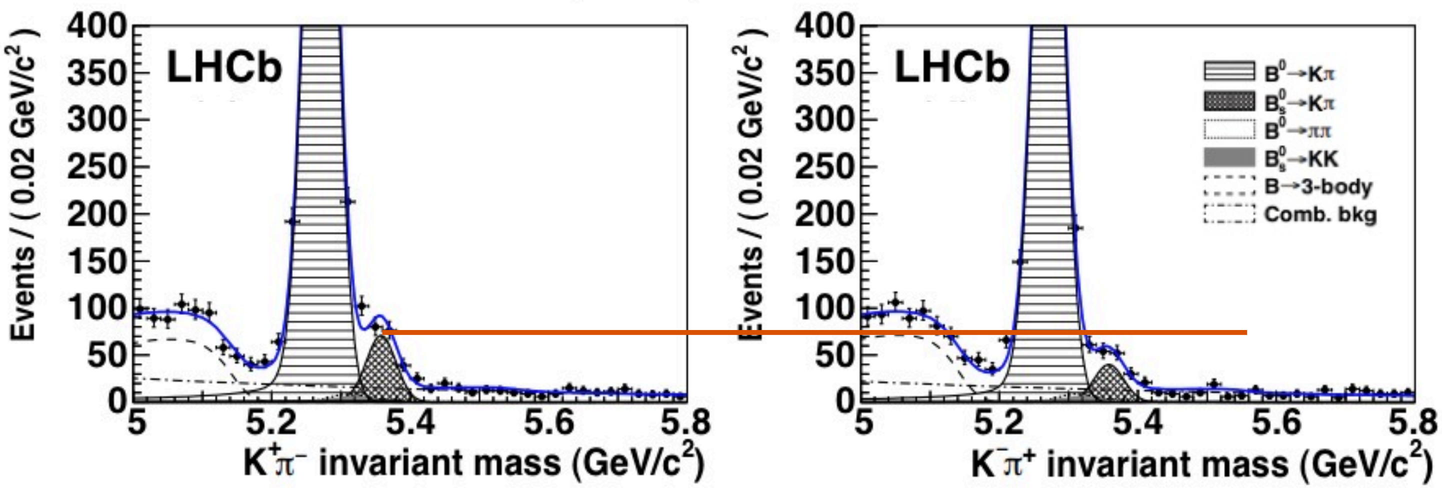
- World's most precise determination (0.35 /fb !).

3. Direct CP violation in hadronic charmless 2-body B decays.

LHCB-PAPER-2011-029

- Direct CP violation starting by charmless 2-body decays:

- Compare the decay rates of self-tagged modes $K\pi$: B^0_s



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

- First evidence of CP violation in the B_s system (0.35 /fb !).

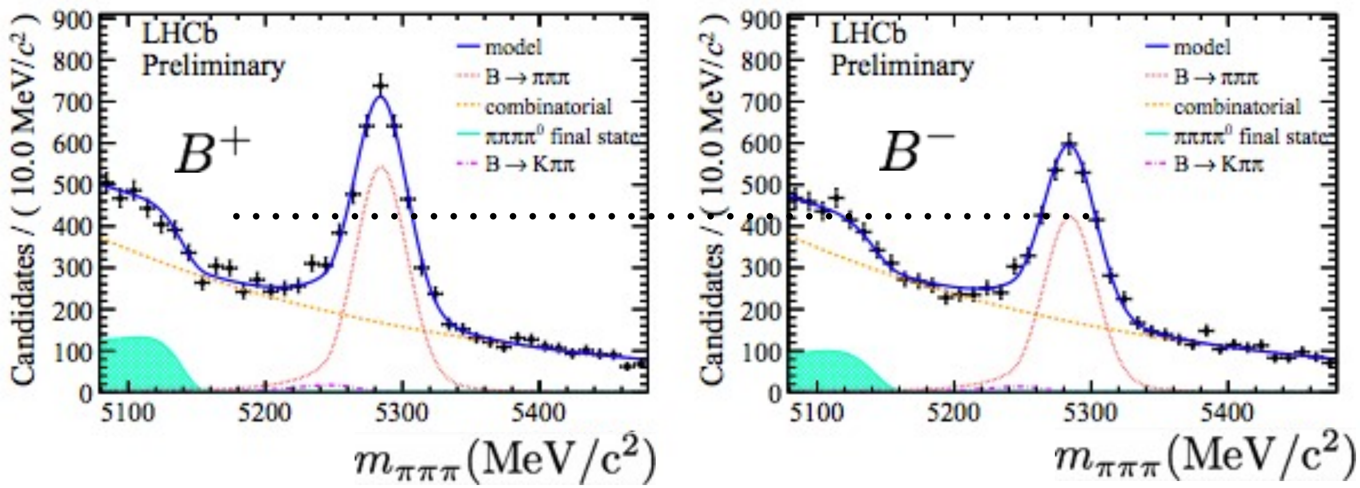
3. Direct CP violation in hadronic charmless 3-body B decays.

LHCb-CONF-2012-028

- Direct CP violation continuing with charmless 3-body decays:

- Compare the decay rates of B^+ vs $B^- \to K\pi\pi$, KKK, $KK\pi$, $\pi\pi\pi$

- The same comment is in order to go from raw asymmetries to CP asymmetries as in 2-body case. One illustration $\pi\pi\pi$:



$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.120 \pm 0.020(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(J/\psi K^\pm)$$

- First evidence of CP violation in the three-body charged *B* system.

3. Direct CP violation in hadronic charmless 3-body B decays.

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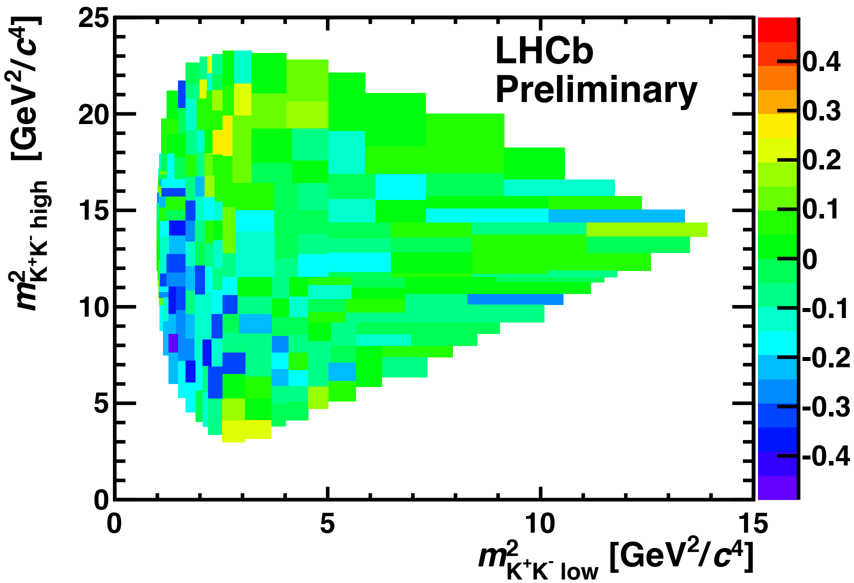
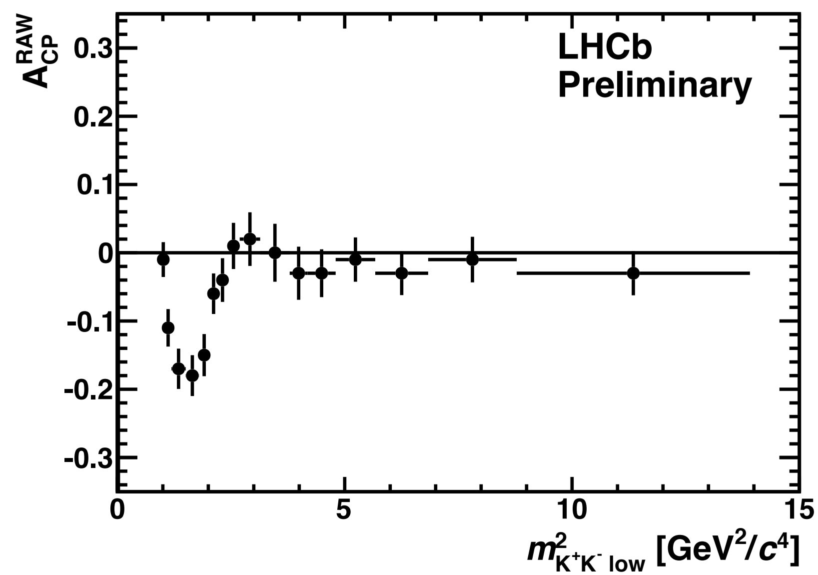
- More interestingly one can scrutinize where the CP asymmetry lies in the Dalitz Plane of the decay: illustration with $B \rightarrow KKK$.





- Very large asymmetries are observed. Not likely connected everywhere to the resonant structures in the Dalitz projections.

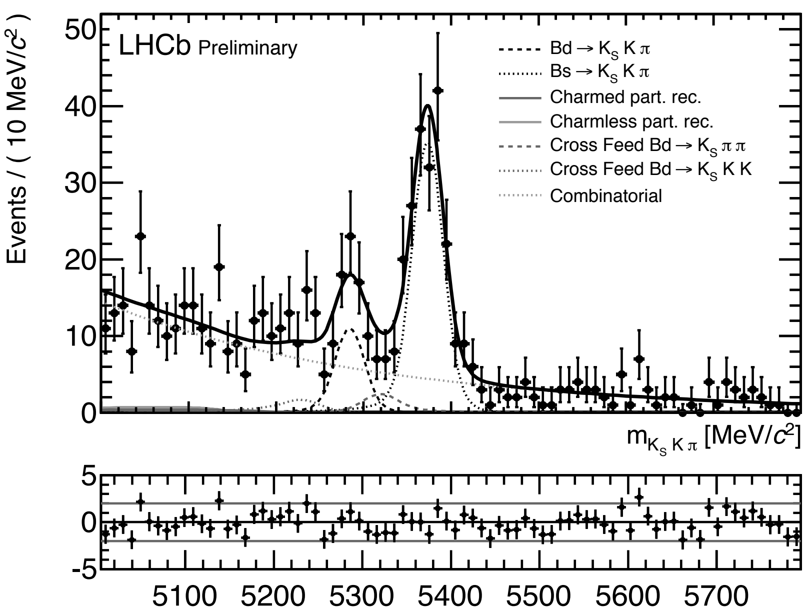
- Outlook: full Dalitz amplitude analysis is the next step.

4. Amplitude analyses in hadronic charmless decays.

LHCb-CONF-2012-023

- Hadronic charmless 3-body decays w/ neutrals.

- LHCb started to investigate 3-body modes w/ neutral kaons. Interesting probes of NP in the decay since they proceed mostly through penguins diagrams.



$$\frac{\mathcal{B}(B_s^0 \to K_S^0 K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} = 1.96 \pm 0.15\,(\text{stat.}) \pm 0.20\,(\text{syst.}),$$

$$\frac{\mathcal{B}(B^0 \to K_S^0 K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} = 0.117 \pm 0.018\,(\text{stat.}) \pm 0.018\,(\text{syst.}).$$

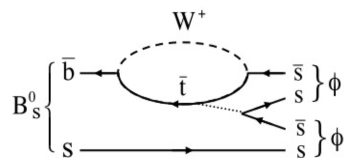
- Outlook: Dalitz Amplitude at first; time-dependent to follow, in particular for the Q2-body CP final states.
- Note that 3-body w/ neutral pions are also emerging.

- Observation of most of the families (See Diego Milanes's talk).

LHCB-PAPER-2012-004

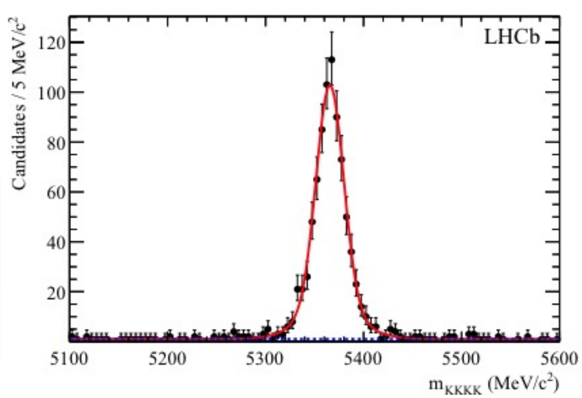
- Continuing with multibody VV decay modes:

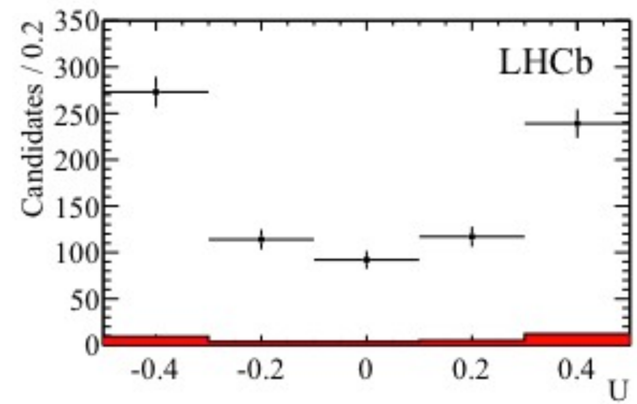
- Most appealing laboratories (again flavour changing neutral currents in penguin topologies) for studying NP in the decay through mixing-induced CP asymmetries . For the time being, establish the signals and scrutinize time-integrated CP- and T-violating observables. *Bs* →ϕϕ as an illustration.



$$\sin \Phi = (\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1 ,$$
$$\sin(2\Phi)/2 = (\hat{n}_1 \cdot \hat{n}_2)(\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1 ,$$

$$A_U = -0.055 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$A_V = 0.010 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$





- T-violating asymmetries predicted to vanish in the SM. Measured consistent with 0.

- Next to come in this family are *Bs* →*K*K**, *Bs* →ϕ*K** ...

5. Summary for ongoing analyses in had. charmless B decays

- 2-body decays (crossing data + theo. assumption → ($\gamma+\phi_s$)) now.
  - $B_d \to hh(')$ family: TD addressing both direct and mixing-induced CP violation.
  - But also $B_d \to p\bar{p}$, $B_{d,s} \to K_S h$, Λ_b, $\Xi_b \to ph'$ ... in the pipeline.

- 3-body decays (towards amplitude analysis to deconvolute strong phases → α, γ, ϕ_s, ϕ_d).
  - $B^\pm \to 3h$ family: the series $B^\pm \to K\pi\pi$, KKK, $KK\pi$, $\pi\pi\pi$, $pp\pi$ and ppK. BF and integrated CP asymmetries are measured, amplitude analyses to be performed with 3 /fb.
  - $B_{d,s} \to K_S hh^{(')}$ family: $B_{d,s} \to K_S\pi\pi$, $B_{d,s} \to K_S K\pi$, $B_d \to K_S KK$. Signals all established, BF on the way to publication w/ 1/fb, amplitude analyses to be performed w/ 3/fb. But also Λ_b, $\Xi_b \to pK_S h$, $\Lambda hh^{(')}$, Λ_b, $\Xi_b \to \Lambda K_S h$,
  - $B_{d,s} \to hh(')\pi^0$ family: $B_d \to \pi\pi\pi^0$, $B_{d,s} \to K\pi\pi^0$, $B_s \to KK\pi^0$, Signals all established. BF to be measured w/ 1/fb. Amplitude analyses to be performed w/ 3/fb.

- 4(n)-body decays (angular analyses): α and ϕ_s
  - $B_{d,s} \to VV$ family, among which $B_s \to \Phi\Phi$, K^*K^*, $B_{d,s} \to \Phi K^*$, $B_{d,s} \to \rho\rho$, $K^*\rho$. Amplitude analyses already published w/ 1/fb or on their way to publication.
  - But also, $\Lambda_b \to \Lambda^* V$, $N^* V$ and more ...

8. Outlook: physics reach for 50 /fb

LHCb-PUB-2012-009

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [32]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [29]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [40, 41]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [63]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012.