Charmless B decays: 2 body and B→VV

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on behalf of the LHCb collaboration

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Outline

- Introduction.
- B decays into $K^{*\pm}h^{\mp}$.
  - $B^0_s \to K^{*\pm}K^{\mp}$ discovery.
  - $B^0_s \to K^{*-}\pi^+$ evidence.
  - Branching fraction measurements.
- $B \to V_1V_2$ decays.
  - $B^0 \to \phi K^{*0}$.
    - Angular analysis.
    - Direct and CP-asymmetries.
    - Triple products.
  - $B_s^0 \to \phi\phi$.
    - Time-angular analysis.
    - Polarization parameters.
    - CP-violating phase measurement ϕ_s.
    - Direct CP parameter $|\lambda|$.
    - Triple products.
- Conclusions.

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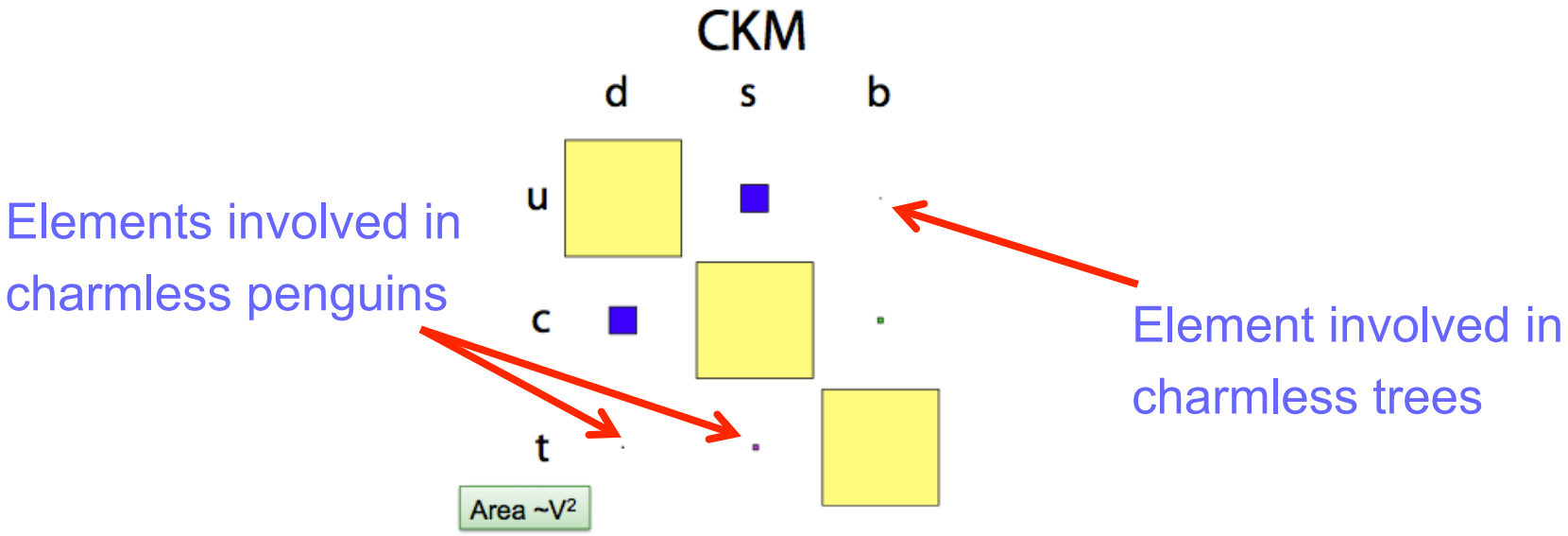
Charmless decays

- Suppressed compared to charmed:
  - b→u tree.
  - b→s, b→d loops.
- More sensitive to New Physics.



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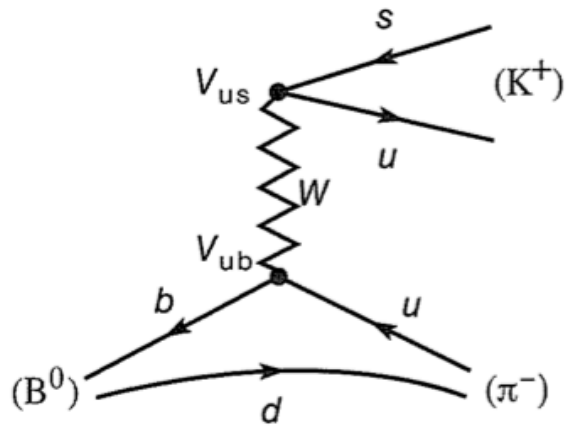
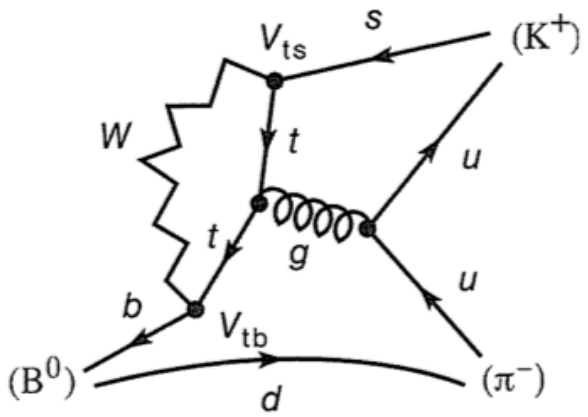
Direct CP Violation in B meson decays

Decays with Tree and Penguin contributions: interfere ⇒ CPV

-$\phi_{1,2}$ weak phases. -$\theta_{1,2}$ strong phases.

$$A_1 = |A_1| e^{i\phi_1} e^{i\theta_1} \qquad A_2 = |A_2| e^{i\phi_2} e^{i\theta_2}$$
$$\overline{A}_1 = |A_1| e^{-i\phi_1} e^{i\theta_1} \qquad \overline{A}_2 = |A_2| e^{-i\phi_2} e^{i\theta_2}$$





$$\left|\frac{\overline{A}}{A}\right|^2 = \left|\frac{\overline{A}_1 + \overline{A}_2}{A_1 + A_2}\right|^2 \neq 1 \Leftrightarrow \phi_1 \neq \phi_2 \;\&\&\; \theta_1 \neq \theta_2$$

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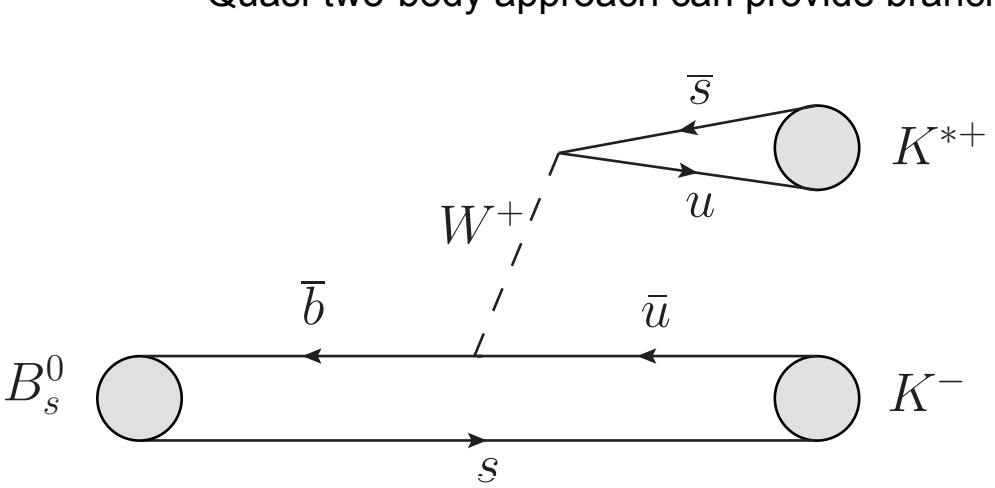
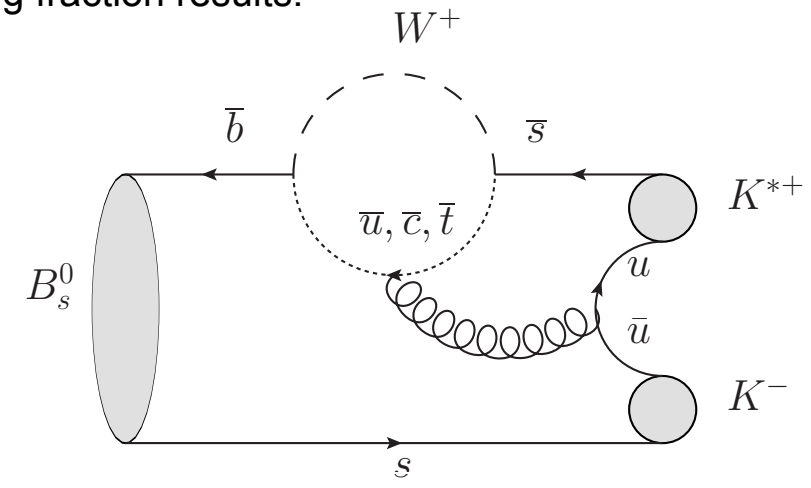
B decays into $K^{*\pm}h^{\mp}$

NEW

- 1 fb^{-1} 2011 data sample.
- $B^0_{d,s} \to K^{*\pm}h^{\mp}$ charmless VP modes.
  - Decay into $K^0_S(\pi^+\pi^-)\pi^+h^-$ final states.
  - If h=π only $B^0_s \to K^{*-}\pi^+$.
- Interference of penguin and tree contributions at the origin of CP-violating effects.
- Tests of U-spin symmetry, probe New Physics in loops and measure gamma.
- Full Dalitz plot treatment required to obtain better control of the hadronic uncertainties.
  - Eg. information on the relative phase between $B^0 \to K^{*+}h^-$ and $B^0 \to K^0_S\rho^0$.
  - Will only be possible in the future with larger data samples.
- Undiscovered channels.
  - Quasi-two-body approach can provide branching fraction results.





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Selection of $B \to K^{*\pm} h^{\mp}$

NEW

Trigger

- L0 Trigger (hardware):
  - Removes events with large occupancies in the scintillating-pad detector.
  - Requires one candidate with ET > 3.5 GeV.
- High Level Trigger (software):
  - 2-4 track secondary vertex.
  - High sum of the pT of the tracks.
  - Significant displacement from the primary pp vertices.

Generic Offline Selection

- 1st filter with loose selections on topological variables:
  - Flight distance of the B candidate.
  - Direction of B momentum.
- Combinations of tracks consistent signal hypothesis categorized:
  - **"Long": both tracks from the $K_S^0 \to \pi^+\pi^-$ decay contain VELO hits.**
  - **"Downstream": none of these tracks contain VELO hits.**
- Long candidates: better mass, momentum and vertex resolution.
  - Different selection requirements for the two categories.
- Muon veto on the two "bachelor" tracks.
- Mass vetoes on charm and charmonia intermediate states.
- Particle identification mainly based on RICH information.

Multivariate Selection

- NeuroBayes Multivariate discriminator with input variables:
  - Impact parameter χ^2.
  - Vertex χ^2 for the K^0_S and B candidates.
  - Angle between the B candidate flight direction and PV-SV line.
  - The χ^2 of the separation between the PV and the decay vertex.
  - The B candidate p_T.
- Trained with simulated data and high four-body mass sideband.
- Optimized for maximizing the signal significance.

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Mass Spectra and Yields of $B \to K^{*\pm} h^{\mp}$

NEW

- Extended unbinned maximum likelihood fit of candidates with masses inside windows:
  - $5000 < m(K_S^0 h^{\pm} \pi^{\mp}) < 5500$ MeV/c^2
  - $650 < m(K_S^0 \pi^{\mp}) < 1200$ MeV/c^2
- **Single 4- and 3-body simultaneous fit to candidates with both K_S^0 categories.**
- Separate fits performed for $K^{*\pm}K^{\mp}$ and $K^{*\pm}\pi^{\mp}$ candidates.
- Fit components:
  - B^0 and B_s^0 signal.
  - B^0 and B_s^0 non-resonant components.
  - Misidentified $B^0 \to K^{*\pm} h^{\mp}$ cross-feed.
  - Backgrounds from charmless decays with missing particles: $\Lambda_b^0 \to K^{*-} p$ and $B^+ \to D^0 h^+$, $D^0 \to K_S^0 \pi^+ \pi^-$.
  - Combinatorial background.
- Several pdf parameters constrained with simulated data and known physics magnitudes.

	B^0		B_s^0	
	long	downstream	long	downstream
$K^{*\pm}K^{\mp}$	0 ± 4	4 ± 3	40 ± 8	62 ± 10
$K^{*\pm}\pi^{\mp}$	80 ± 10	165 ± 16	5 ± 4	23 ± 8

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$K^{*\pm}K^{\mp}$ and $K^{*\pm}$ Mass Spectra

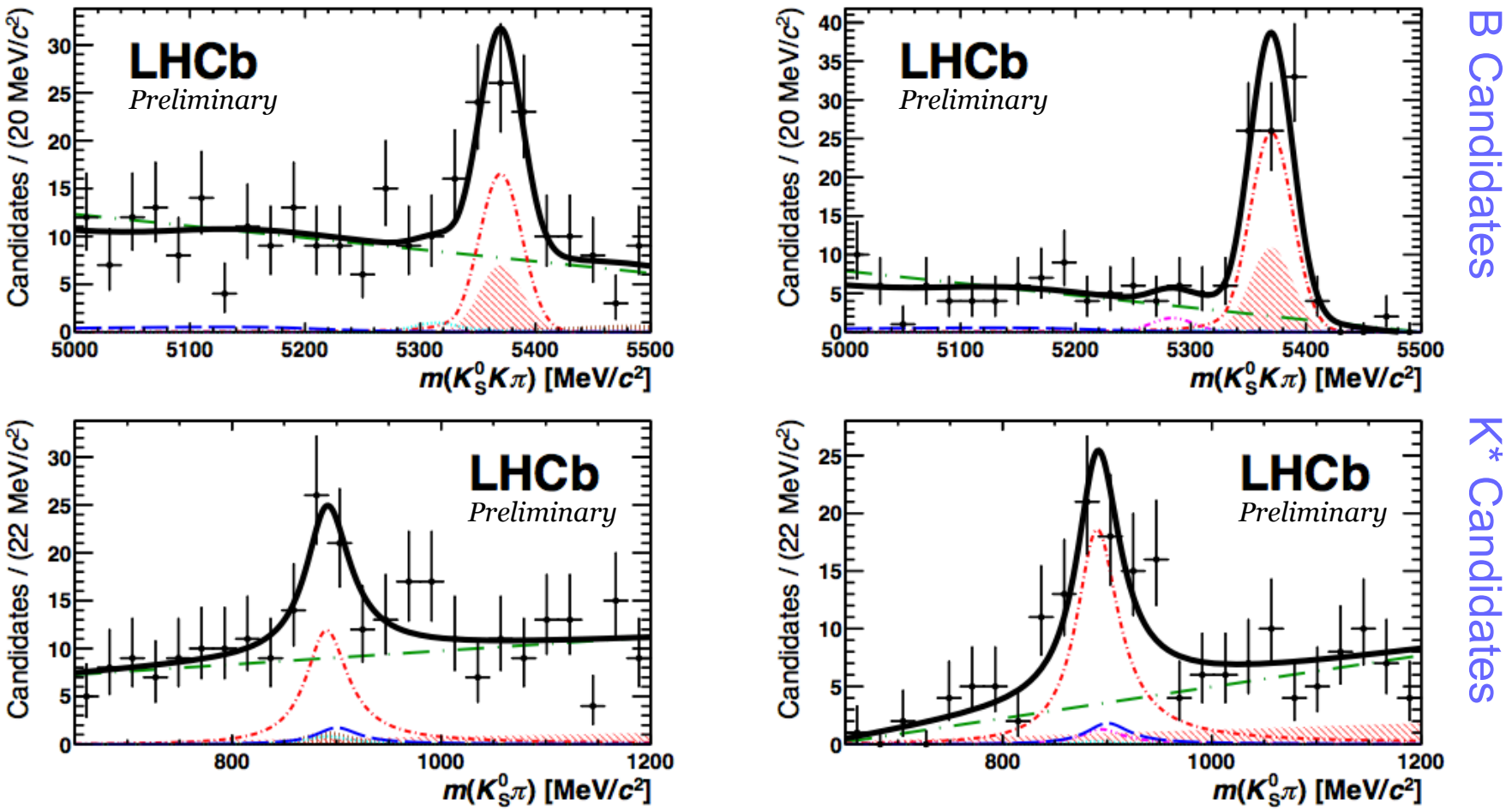
NEW

Long Category

Downstream Category

B Candidates

K* Candidates



$B^0_s \to K^{*\pm}K^{\mp}$ $B^0 \to K^{*\pm}K^{\mp}$ $B^0_s \to K_S{}^0\pi^{\pm}K^{\mp}$ $\Lambda^0_b \to K^{*-}p$ Combinatorial+Other $B^0 \to K^{*+}\pi^-$

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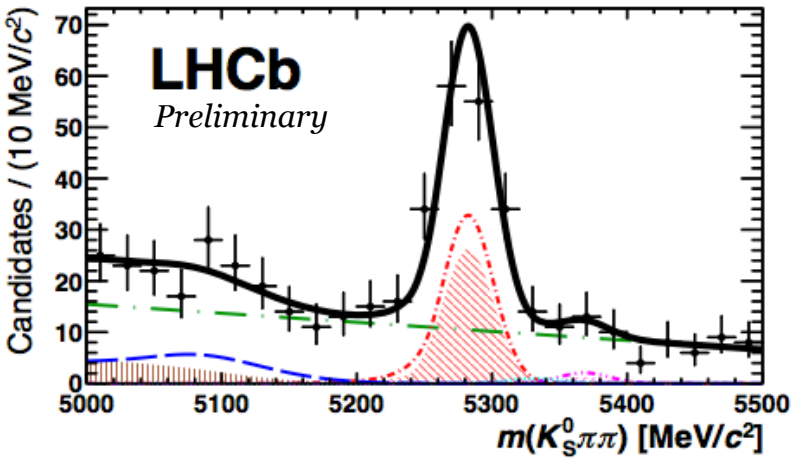
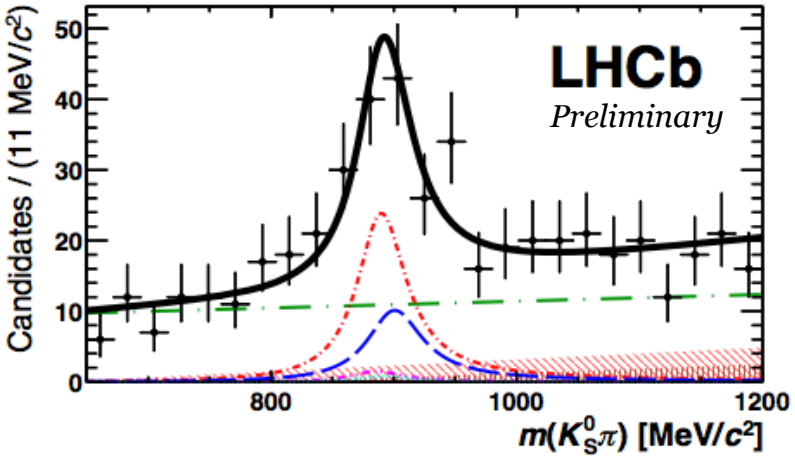
$K^{*\pm}\pi^{\mp}$ and $K^{*\pm}$ Mass Spectra

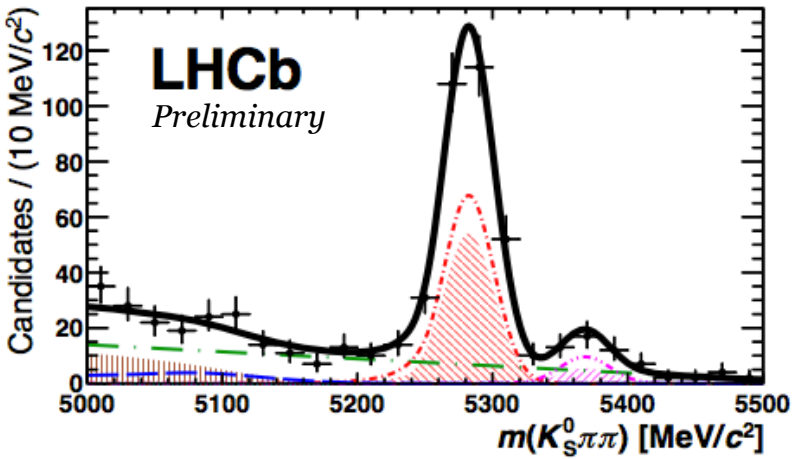
NEW

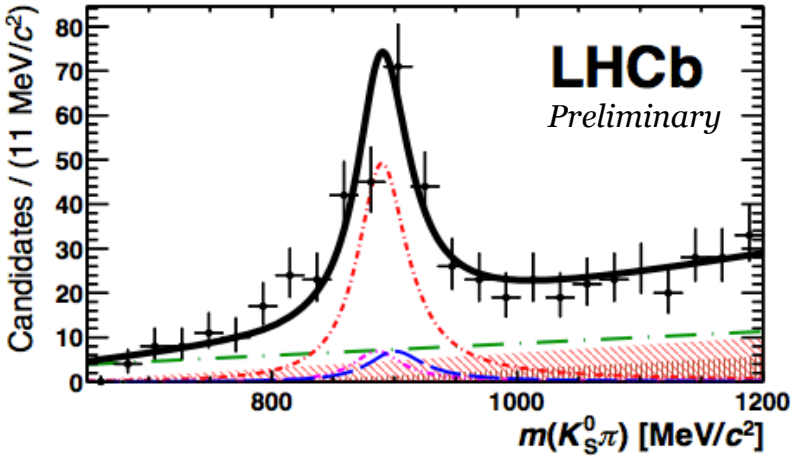
Long Category





Downstream Category





B Candidates

K* Candidates

$B^0 \to K^{*\pm}\pi^{\mp}$ $B^0 \to K_S^0\pi^{\pm}\pi^{\mp}$ $B^0_s \to K^{*\pm}\pi^{\mp}$ $B^0_s \to K_S^0\pi^{\pm}\pi^{\mp}$ $B \to K^{*\pm}\pi^{\mp}\pi$ Combinatorial $B \to D\pi$

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Branching Fractions of $B_{(s)}^0 \to K^{*\pm}h^{\mp}$

NEW

- The previous results translate into the measurement of the decay modes $B^0_s \to K^{*\pm}K^{\mp}$ with 12.5σ and $B^0_s \to K^{*-}\pi^+$ with 3.9σ significance.
  - The observed signal significance for the decay $B^0 \to K^{*\pm}K^{\mp}$ is below 2σ.
- With the obtained yields the corresponding branching fractions are determined.
- The reference channel is $B^0 \to K^{*\pm}\pi^{\mp}$.
  - $\mathcal{B}(B^0 \to K^{*+}\pi^-) = (8.5 \pm 0.7) \times 10^{-6}$ [HFAG arXiv:1207.1158]
- And the results:

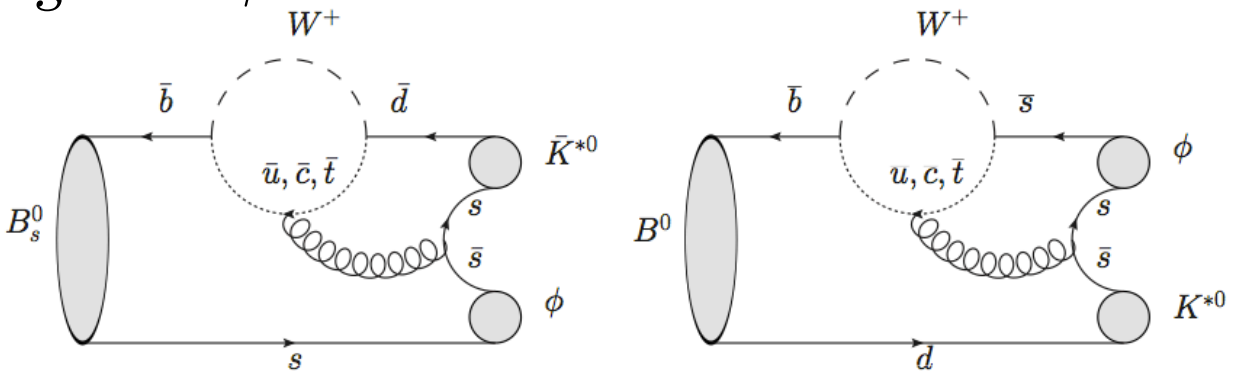
$$\begin{aligned}
\mathcal{B}(B^0_s \to K^{*\pm}K^{\mp}) &= (12.7 \pm 1.9\,(\text{stat}) \pm 1.9\,(\text{syst})) \times 10^{-6} \\
\mathcal{B}(B^0 \to K^{*\pm}K^{\mp}) &= (0.17 \pm 0.15\,(\text{stat}) \pm 0.05\,(\text{syst})) \times 10^{-6} \\
&< 0.4\ (0.5) \times 10^{-6} \text{ at } 90\,\%\ (95\,\%)\ \text{CL} \\
\mathcal{B}(B^0_s \to K^{*-}\pi^+) &= (3.3 \pm 1.1\,(\text{stat}) \pm 0.5\,(\text{syst})) \times 10^{-6}
\end{aligned}$$

$B \to V_1 V_2$ Penguins

•Dominated by penguin diagrams. No tree level contribution:

$$B_s^0 \to K^{*0}\overline{K}^{*0} \qquad B_s^0 \to \phi\phi \qquad B^0 \to K^{*0}\overline{K}^{*0}$$

$$B_s^0 \to \phi\overline{K}^{*0} \qquad B^0 \to \phi K^{*0}$$



•**Angular analysis of Vector mesons** in final state particularly interesting.

•Access to angular variables.

•Sensitive to direct CPV.

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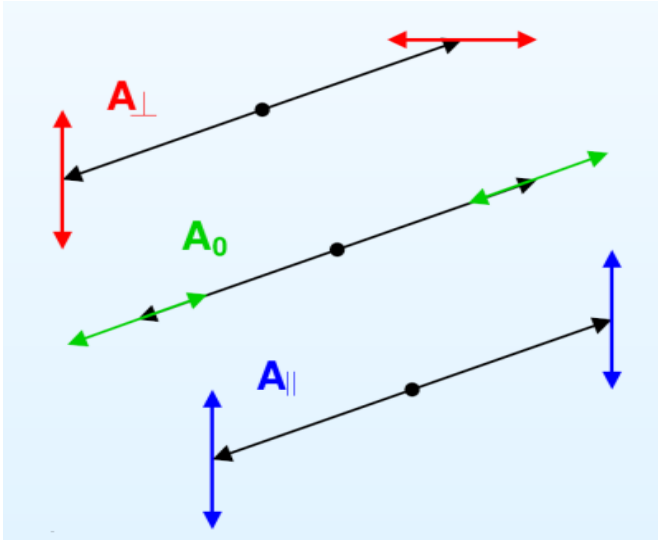
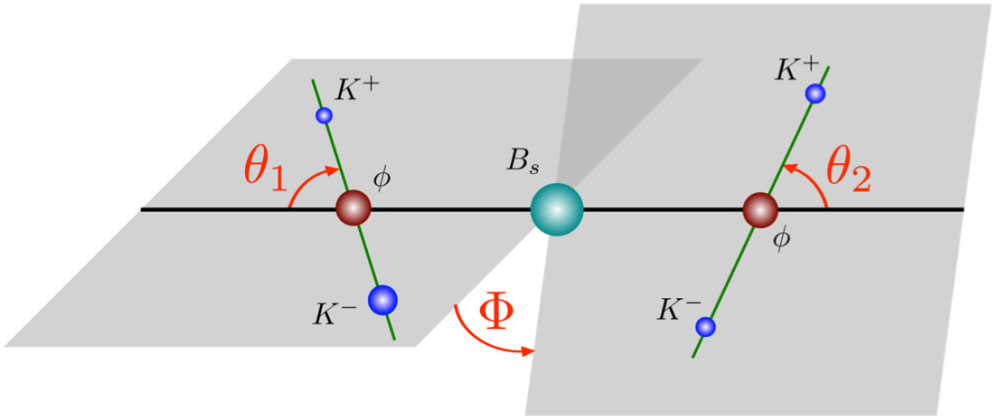
Angular Analysis of $B \to V_1 V_2$

- V_1 and V_2 can have angular momentum L = 0,1,2.
- High longitudinally polarization naïvely expected:
  - V−A structure of weak interaction.
  - Helicity conservation in strong interaction.
- Accounting for additional effects, such as rescattering, produces smaller polarizations.
- Angular pdf depends on:
  - Polarization fractions: $|A_0|^2$, $|A_{||}|^2$, $|A_\perp|^2$
  - Strong phases: $\delta_{||}$, $\delta_\perp$
  - If the final state is common to B_s^0 and $\overline{B}_s^0$:
    - CP–violating phase: ϕ_s in time dependent analysis.





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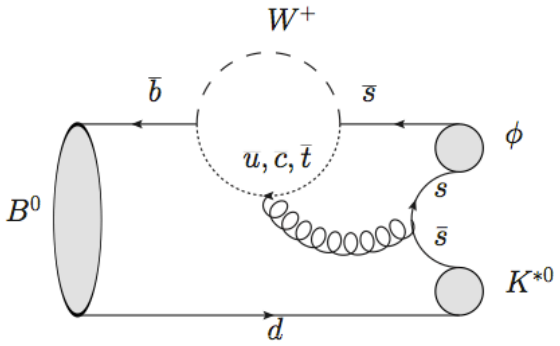
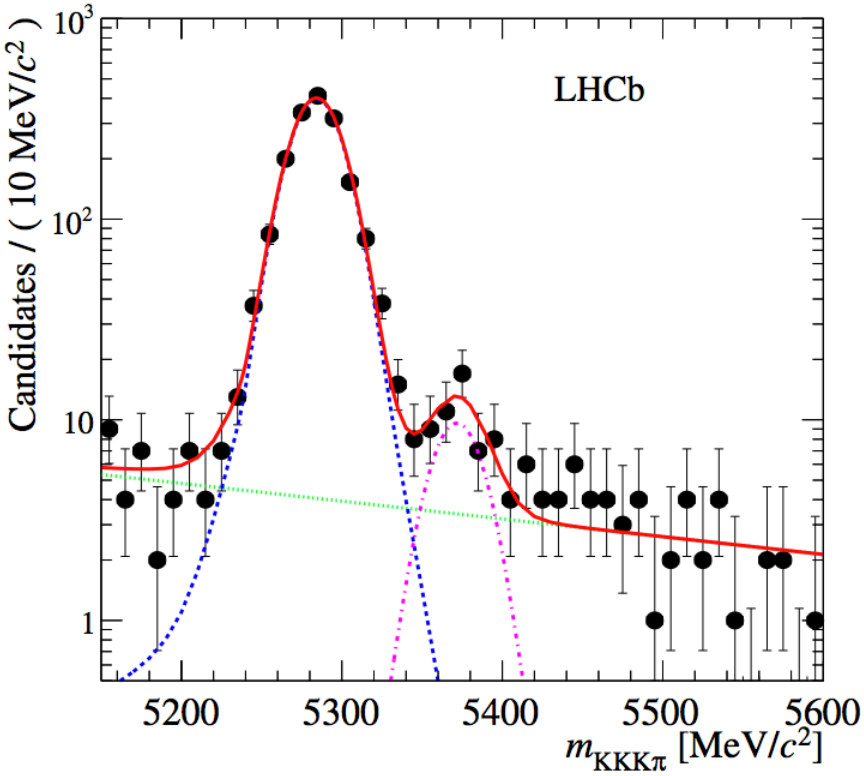
JHEP05(2014)069

$B^0 \to \phi K^{*0}$



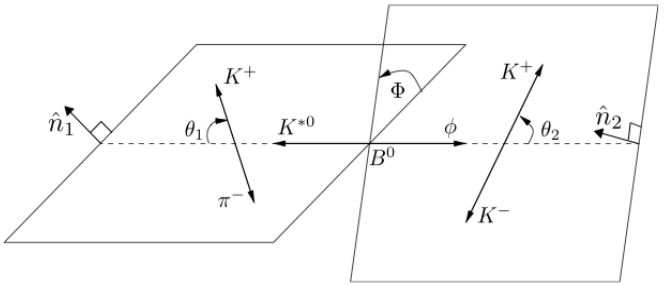
- $b \to s\bar{s}s$ FCNC penguin in the SM.
- Sensitive to NP contributions in the loop.
- $K^+K^-K^+\pi^-$ final state.
- Self tagged mode.
- 1655±42 signal candidates with 2011 data.



Selection

- Same relevant selection variables as for $B_{(s)}^0 \to K^{*\pm}h^{\mp}$
- Two steps:
  - Loose rectangular cuts.
  - Powerful Multivariate method combined with Particle ID cuts.
- 5-dimensional unbinned maximum likelihood fit.
  - M_{KK}, $M_{K\pi}$, $\cos\theta_1$, $\cos\theta_2$, Φ

$$d^5\Gamma = \frac{9}{8\pi}\sum_{i=1}^{15} h_i \; f_i(\theta_1, \theta_2, \Phi)\mathcal{M}_i(m_{K\pi}, m_{KK})d\Omega(KKK\pi)$$



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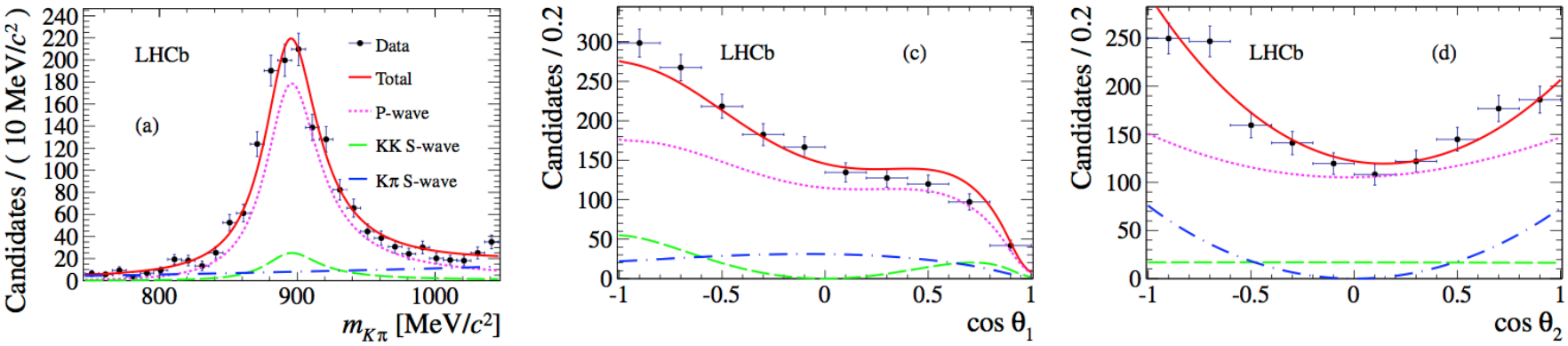
Polarization of $B^0 \to \phi K^{*0}$



Intermediate longitudinal polarisation.

CP asymmetries compatible with zero.

Parameter	LHCb	BaBar	Belle
f_L	$0.497 \pm 0.019 \pm 0.015$	$0.494 \pm 0.034 \pm 0.013$	$0.499 \pm 0.030 \pm 0.018$
$f_\perp$	$0.221 \pm 0.016 \pm 0.013$	$0.212 \pm 0.032 \pm 0.013$	$0.238 \pm 0.026 \pm 0.008$
$\delta_\perp$	$2.633 \pm 0.062 \pm 0.037$	$2.35 \pm 0.13 \pm 0.09$	$2.37 \pm 0.10 \pm 0.04$
$\delta_\parallel$	$2.562 \pm 0.069 \pm 0.040$	$2.40 \pm 0.13 \pm 0.08$	$2.23 \pm 0.10 \pm 0.02$
$\mathcal{A}_0^{CP}$	$-0.003 \pm 0.038 \pm 0.005$	$+0.01 \pm 0.07 \pm 0.02$	$-0.030 \pm 0.061 \pm 0.007$
$\mathcal{A}_\perp^{CP}$	$+0.047 \pm 0.072 \pm 0.009$	$-0.04 \pm 0.15 \pm 0.06$	$-0.14 \pm 0.11 \pm 0.01$
$\delta_\perp^{CP}$	$+0.062 \pm 0.062 \pm 0.006$	$+0.21 \pm 0.13 \pm 0.08$	$+0.05 \pm 0.10 \pm 0.02$
$\delta_\parallel^{CP}$	$+0.045 \pm 0.068 \pm 0.015$	$+0.22 \pm 0.12 \pm 0.08$	$-0.02 \pm 0.10 \pm 0.01$

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Polarization Summary of $B \to V_1 V_2$

- Large Longitudinal polarization confirmed in b→u tree dominated decays (f_L~1) .
- Penguin decays show intermediate or small longitudinal polarization fractions.
  - Exception in $B^0 \to K^{0*}\bar{K}^{*0}$.
  - Polarization puzzle.

Decay Mode	$B^0 \to \rho^+\rho^-$ BaBar arXiv0607098	$B^0 \to \rho^0 K^{*0}$ BaBar PRD 85 072005	$B^0 \to \phi\phi$ LHCb arXiv 1407.2222	$B_s^0 \to K^{0*}\bar{K}^{0*}$ LHCb PLB709 50	$B^0 \to K^{0*}\bar{K}^{*0}$ BaBar PRL 100 081801	$B^0 \to \phi K^{*0}$ LHCb JHEP 1405 069	$B_s^0 \to \phi \bar{K}^{*0}$ LHCb JHEP 1311 092
f_L	0.977 ±0.028	0.40 ±0.14	**0.364 ± 0.015**	0.31 ± 0.13	0.80 ± 0.13	**0.497 ± 0.024**	0.51 ± 0.16

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CP-asymmetries in $B^0 \to \phi K^{*0}$

Difference in direct CP asymmetries between $B^0 \to \phi K^{*0}$ and $B^0 \to J/\psi K^{*0}$ decays found to be

$$\Delta A_{CP} = (+1.5 \pm 3.2 \pm 0.5)\,\%$$

$$A_{CP} = \frac{\Gamma(\overline{B}^0 \to \phi \overline{K}^{*0}) - \Gamma(B^0 \to \phi K^{*0})}{\Gamma(\overline{B}^0 \to \phi \overline{K}^{*0}) + \Gamma(B^0 \to \phi K^{*0})}$$

$$\Delta A_{CP} = A_{CP}(\phi K^{*0}) - A_{CP}(J/\psi K^{*0})$$

- Triple-product asymmetries.
- Non-zero triple-product asymmetries imply a T-violating phase or a CP-conserving phase and final-state interactions.
  - With CPT symmetry a T-violating phase implies CP violation.

$$\sin\Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$
$$\sin 2\Phi = 2(\hat{n}_{V_1} \cdot \hat{n}_{V_2})(\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$

$$A_U = \frac{\Gamma(\sin 2\Phi > 0) - \Gamma(\sin 2\Phi < 0)}{\Gamma(\sin 2\Phi > 0) + \Gamma(\sin 2\Phi < 0)}$$

$$A_V = \frac{\Gamma(s \sin\Phi > 0) - \Gamma(s \sin\Phi < 0)}{\Gamma(s \sin\Phi > 0) + \Gamma(s \sin\Phi < 0)}$$

$$s = \mathrm{sign}(\cos\theta_1 \cos\theta_2)$$

Asymmetry	Measured value
A_U	$-0.007 \pm 0.012 \pm 0.002$
A_V	$+0.004 \pm 0.014 \pm 0.002$

- Two additional Triple-Products based on S-wave also compatible with zero.
- Large fake triple products, relying on flavour identification reveal large strong phases.

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$B_{(s)}^0$-$\bar{B}_{(s)}^0$ mixing

Time development of the mixing described by

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} B^0_{(s)} \\ \overline{B}^0_{(s)} \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B^0_{(s)} \\ \overline{B}^0_{(s)} \end{pmatrix}$$

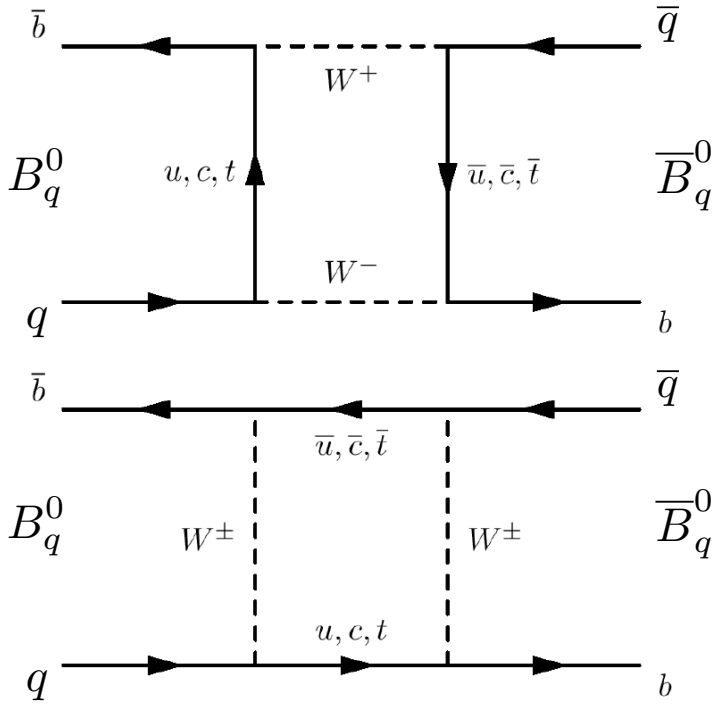
$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix};\quad \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

Diagonalizing in terms of mass eigenstates

$$i\frac{\mathrm{d}}{\mathrm{d}t}B_L = (m_L - \tfrac{i}{2}\Gamma_L)B_L$$
$$i\frac{\mathrm{d}}{\mathrm{d}t}B_H = (m_H - \tfrac{i}{2}\Gamma_H)B_H$$

Mass eigenstates ≠ flavour eigenstates

$$|B_L\rangle = p|B^0_{(s)}\rangle + q|\overline{B}^0_{(s)}\rangle$$
$$|B_H\rangle = p|B^0_{(s)}\rangle - q|\overline{B}^0_{(s)}\rangle$$



Mixing Parameters

- Mass difference: $\Delta m = m_H - m_L$
- Lifetime difference: $\Delta\Gamma = \Gamma_H - \Gamma_L$
- Mixing phase: $\boldsymbol{\phi_M = \arg(-M_{12}/\Gamma_{12})}$

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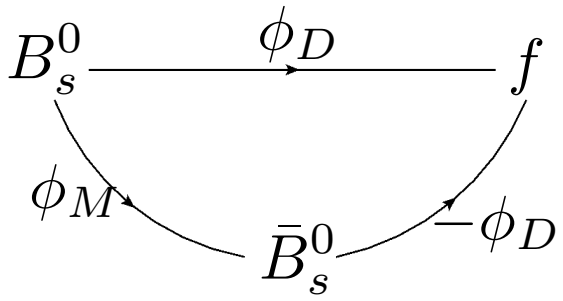
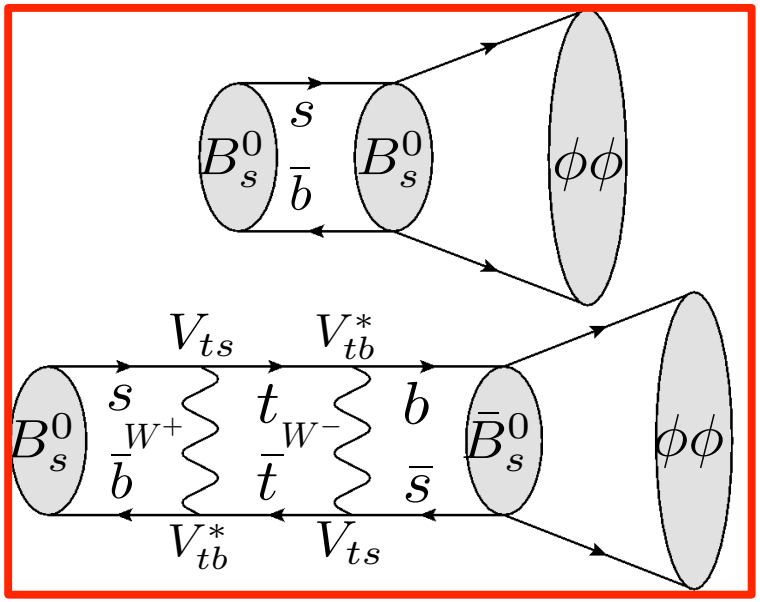
$B_s^0 \to \phi\phi$ time dependent analysis

- Interference between:
  - Decay.
  - Decay after mixing.





- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\,\Phi_D$
- Standard Model prediction for $B_s^0 \to \phi\phi$.
  - Cancellation between decay + mixing phases:
  - $\phi_s = 0.01 \pm 0.02$ [arXiv:0810.0249]

•Direct CP violation also possible $\quad |\lambda| = \left|\frac{q}{p} \cdot \frac{\overline{A}}{A}\right| \qquad |\lambda| \neq 1$

Direct CP

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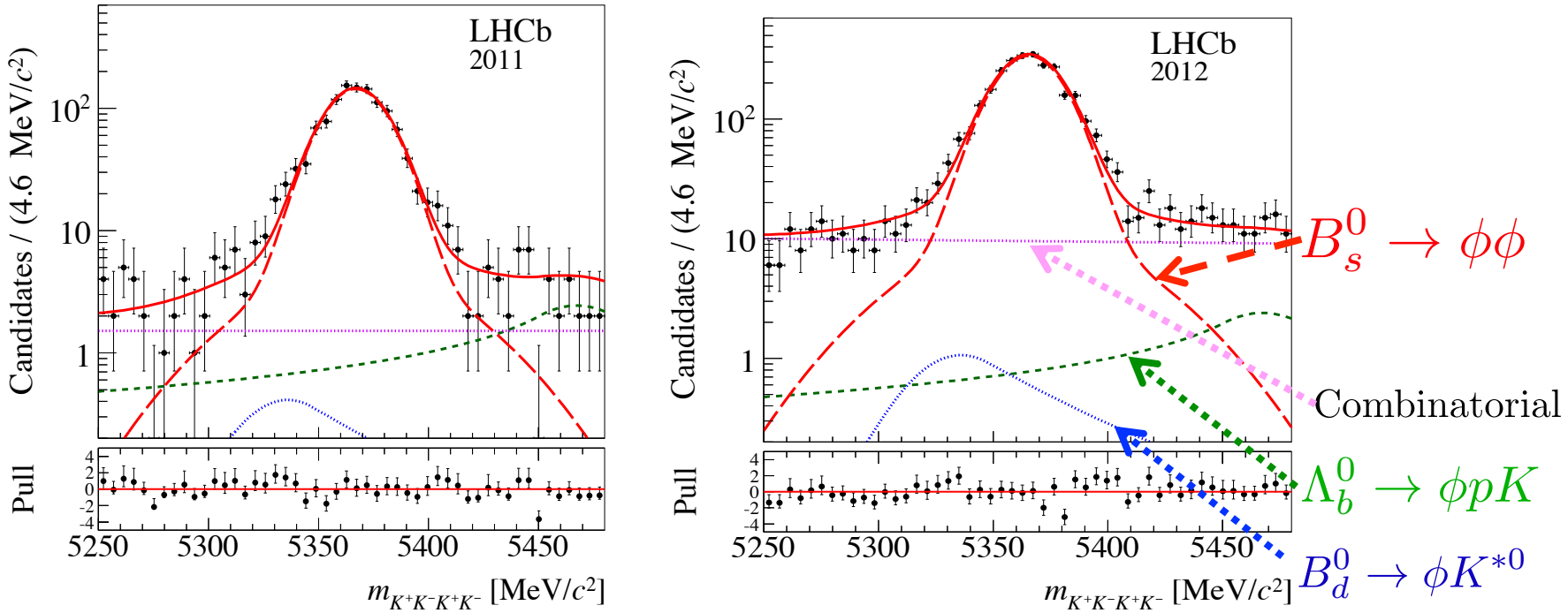
arXiv hep-ex-1407.2222

$B_s^0 \to \phi\phi$ sample



- Full 2011+2012 dataset.
- Re-optimized multivariate selection.
- 3950 signal candidates
- 4.5 times as many events as in the analysis in [PRL 110, 241802]

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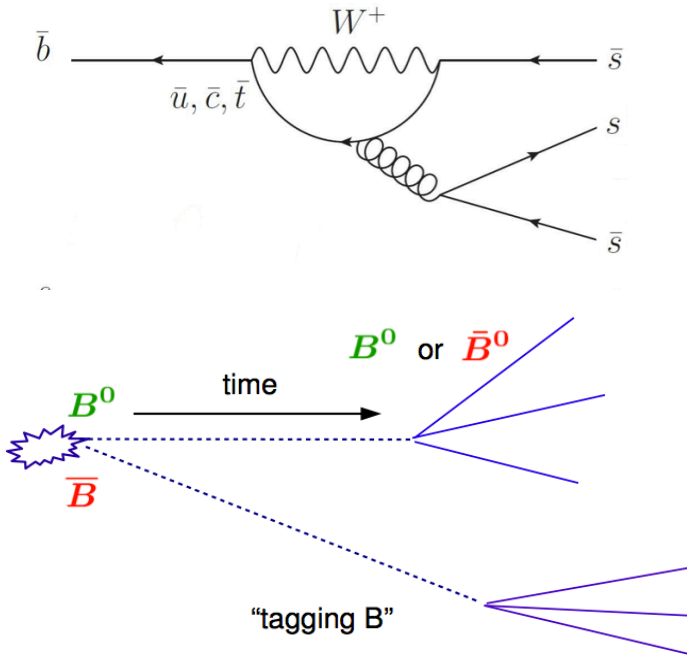
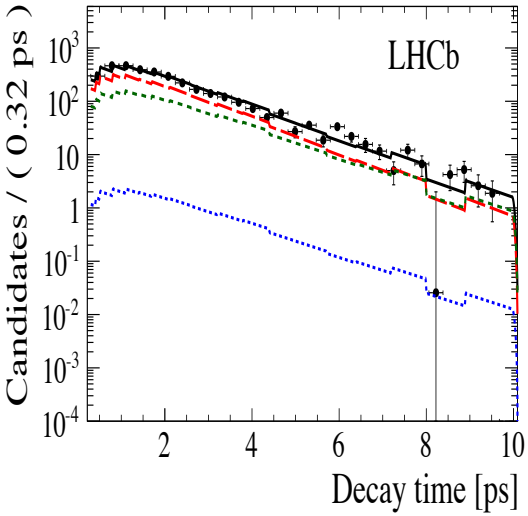
arXiv hep-ex-1407.2222

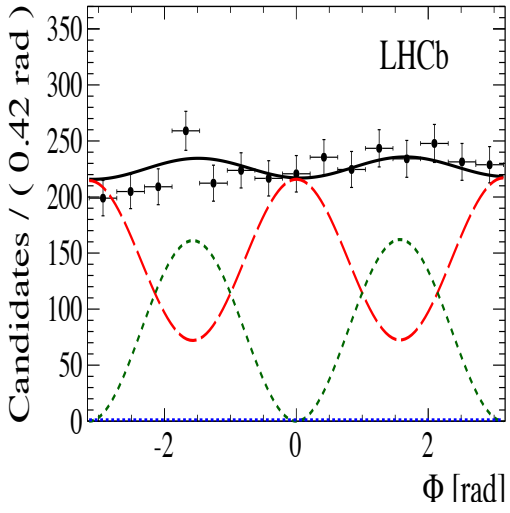
$B_s^0 \to \phi\phi$

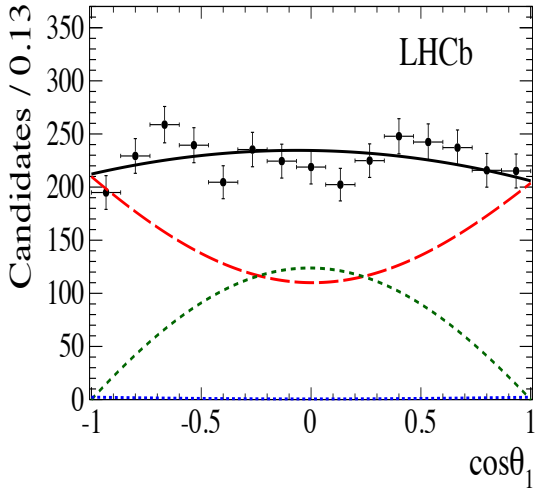
- Unbinned max. likelihood fit.
- 4-dimension: 3 angles + time dependent tagged analysis:
  - Γ_s and $\Delta\Gamma_s$ from $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ LHCb PRD 87 112010
  - Δm_s from $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$, LHCb *New J. Phys.* ***15 053021***
- Time resolution model from simulation. Calibrated on data: $\sigma_t \sim 43$ fs
- Angular acceptance for signal from simulation
- Time acceptance from $B_s \to D_s\pi$ data

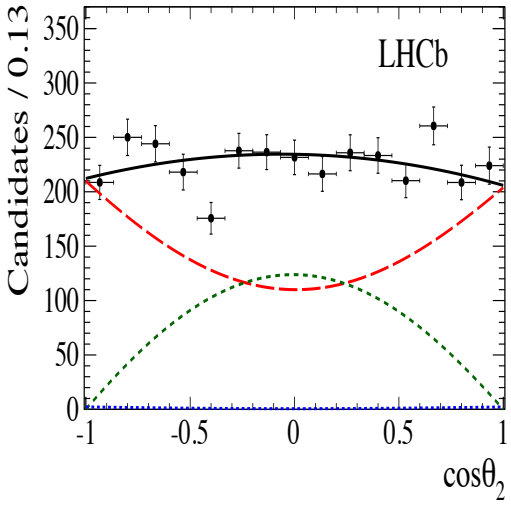


Total CP–even CP–odd S–wave









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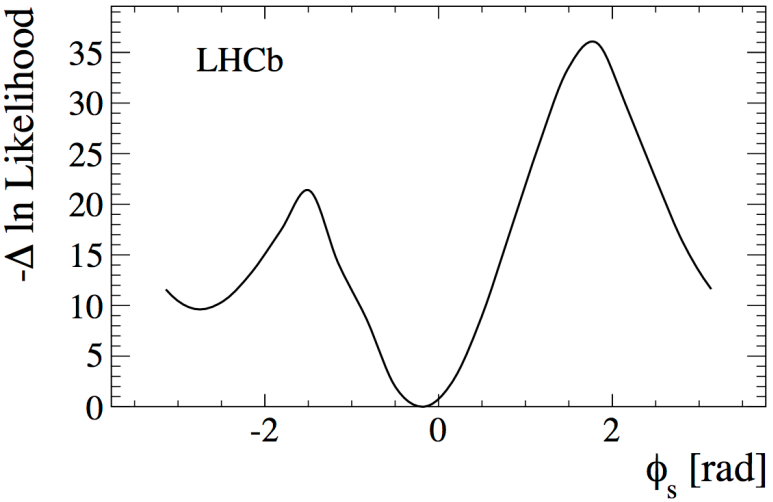
arXiv hep-ex-1407.2222

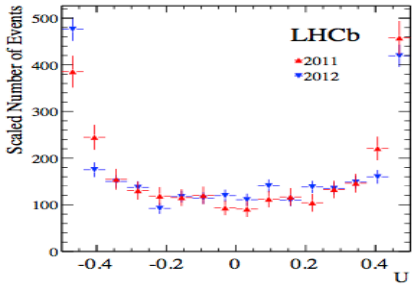
$B_s^0 \to \phi\phi$ results

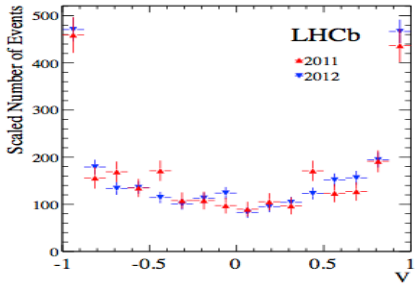
- No large CP violation present.
  - In B_s^0-B_s^0 mixing.
  - In the $b \to s\bar{s}s$ decay amplitude.
- Measured f_L in $B_s^0 \to \phi\phi$ almost equal to $B_s^0 \to K^{*0}K^{*0}$.
  - Agreement with QCD factorization predictions.
  - Disfavours pQCD estimates.
- Triple-product asymmetries determined from separate time integrated fit.
  - B_s^0 flavorless decays: non-zero triple products indicate different CP-violating phases for CP-even (0,||) and CP-odd (⊥) eigenstates.



Time-dependent analysis

Parameter	Result
ϕ_s	$-0.17 \pm 0.15 \pm 0.03$
$\lvert\lambda\rvert$	$1.04 \pm 0.07 \pm 0.03$
f_L	$0.364 \pm 0.012 \pm 0.009$
$f_\perp$	$0.305 \pm 0.013 \pm 0.005$





Time-integrated analysis

Parameter	Result
A_U	$-0.003 \pm 0.017 \pm 0.006$
A_V	$-0.017 \pm 0.017 \pm 0.006$

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Conclusions

$B_{(s)}^0 \to K^{*\pm}h^{\mp}$

- Observation of the mode $B^0_s \to K^{*\pm}K^{\mp}$ with 12.5σ significance
- Evidence of the $B^0_s \to K^{*-}\pi^+$ mode with 3.9σ significance.
- Branching Fraction measurements:

$$\begin{aligned}
\mathcal{B}\left(B_s^0 \to K^{*\pm}K^{\mp}\right) &= \left(12.7 \pm 1.9\,(\text{stat}) \pm 1.9\,(\text{syst})\right) \times 10^{-6} \\
\mathcal{B}\left(B^0 \to K^{*\pm}K^{\mp}\right) &= \left(0.17 \pm 0.15\,(\text{stat}) \pm 0.05\,(\text{syst})\right) \times 10^{-6} \\
&< 0.4\ (0.5) \times 10^{-6} \text{ at } 90\,\%\ (95\,\%)\ \text{CL} \\
\mathcal{B}\left(B_s^0 \to K^{*-}\pi^+\right) &= \left(3.3 \pm 1.1\,(\text{stat}) \pm 0.5\,(\text{syst})\right) \times 10^{-6}
\end{aligned}$$

$B^0 \to \phi K^{*0}$

- Determination of CP-violation asymmetries
  - $\Delta A_{CP} = (+1.5 \pm 3.2 \pm 0.5)\%$
  - $A_U = -0.007 \pm 0.012 \pm 0.002$, $A_V = +0.004 \pm 0.014 \pm 0.002$.
- Measurement of angular parameters
  - $f_L = 0.497 \pm 0.019 \pm 0.015$

$B_s^0 \to \phi\phi$

- Time-angular analysis.
  - Extraction of $\phi_s = -0.17 \pm 0.015 \pm 0.03$ and $|\lambda| = 1.04 \pm 0.07 \pm 0.03$.
  - $f_L = 0.364 \pm 0.012 \pm 0.009$
- Time-integrated analysis.
  - $A_U = -0.003 \pm 0.017 \pm 0.006$, $A_V = -0.017 \pm 0.017 \pm 0.006$.

Everything seems to be consistent with the small CP-violation of the SM

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Thank You

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Backup Slides

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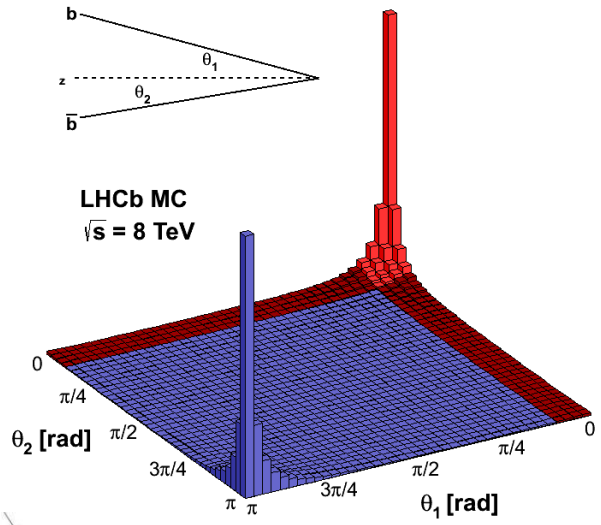
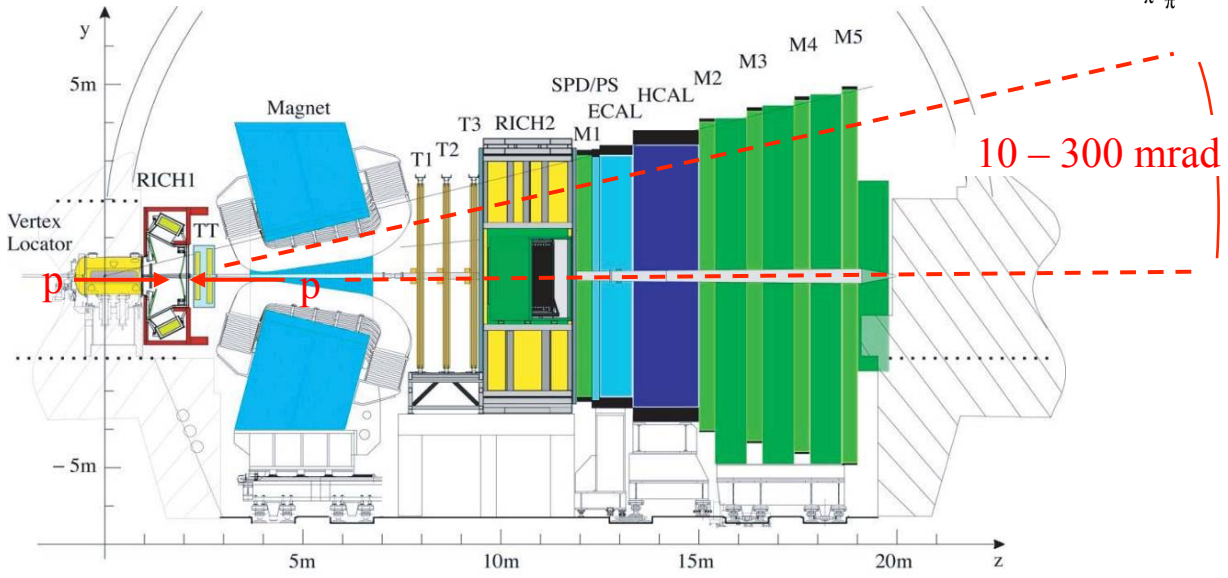
LHCb

- Low angle production → LHCb spectrometer design:
  - forward (operating in collider mode).
- LHC bb x-section = 284 ± 53 μb (pp at √s = 7 TeV). [PLB **694** 209]
  ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories)
  Charm production factor 20 higher! [CONF-2010-013]
- Main features:
  - Decay time resolution.
  - Particle ID.
  - Trigger on hadronic channels.
- Accumulated data 2010: 37 pb^{-1}. 2011: 1.1 fb^{-1}. 2012: 2.2 fb^{-1}.





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Angular Analysis of $B \to V_1 V_2$

- Final state: identical to decays with intermediate scalar resonances, B → SV , B → V S or B → SS (S–wave):

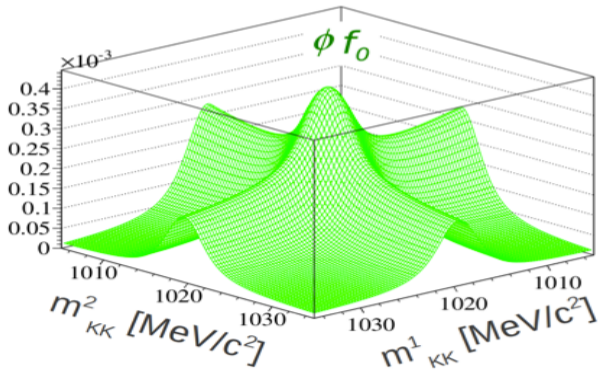
$$A(B \to VV) = \ldots + \frac{A_{SV}}{\sqrt{3}}(\cos\theta_1 + \cos\theta_2) + \frac{A_{SS}}{3}$$

- Decay rate:
  - f_i: angular functions.
  - K_i time dependent terms.
  - a_i, b_i, c_i, d_i coefficients.

$$\frac{\mathrm{d}\Gamma}{\Gamma \mathrm{d}\Omega \mathrm{d}t} = \sum_i K_i(t) f_i(\Omega)$$

$$K_i(t) = N_i e^{-\Gamma_s t}\left[\pm c_i \cos(\Delta m_s t) \pm d_i \sin(\Delta m_s t) + a_i \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_i \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right)\right]$$

- Depend on:
  - Polarization fractions: $|A_0|^2$, $|A_{||}|^2$, $|A_\perp|^2$
  - Strong phases: $\delta_{||}$, $\delta_\perp$
  - CP–violating phase: ϕ_s (CP eigenstates)



LHCb–PAPER–2013–007, PRL 110, 241802

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