$B_s^0 \to K^{*0}\overline{K}^{*0}$ and $B_{(s)}^0 \to \mu\mu$ at LHCb

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Outline

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LHCb overview

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- VELO: Provides precise information of PV and SV. Good IP resolution ($16 \ \mu\text{m} + 30 \ \mu\text{m}/p_T$ (GeV/c)).
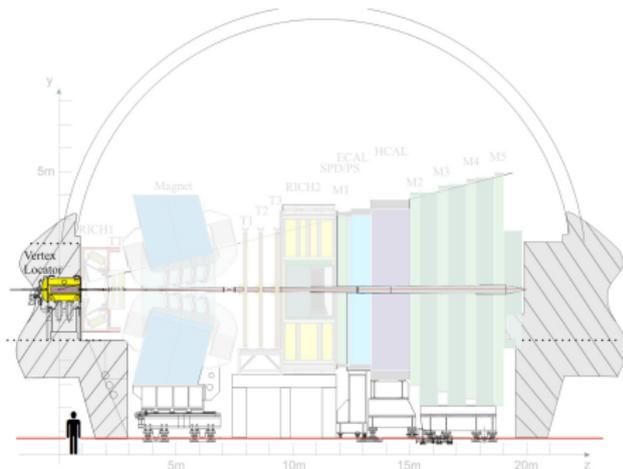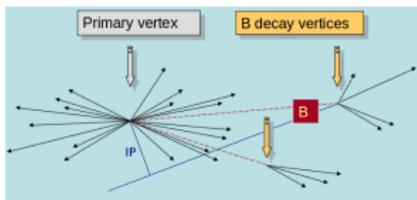
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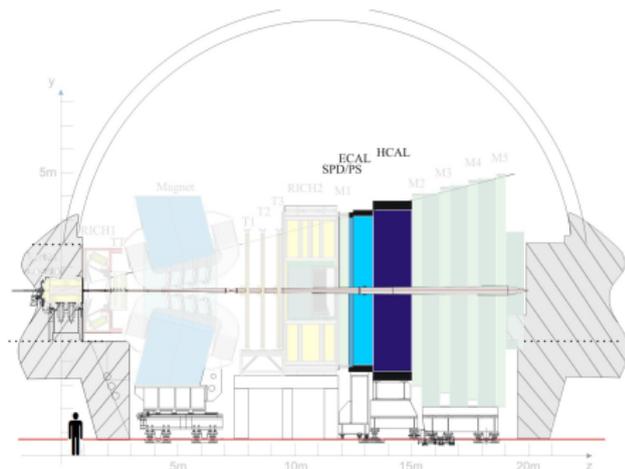- Calorimeter system: Identifies electrons and hadrons. Energy measurement.
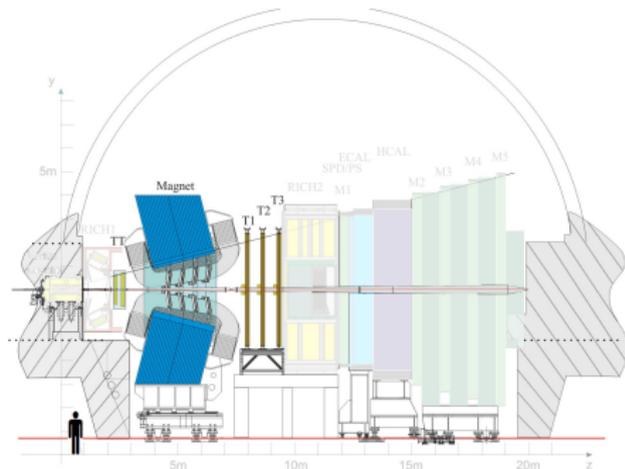
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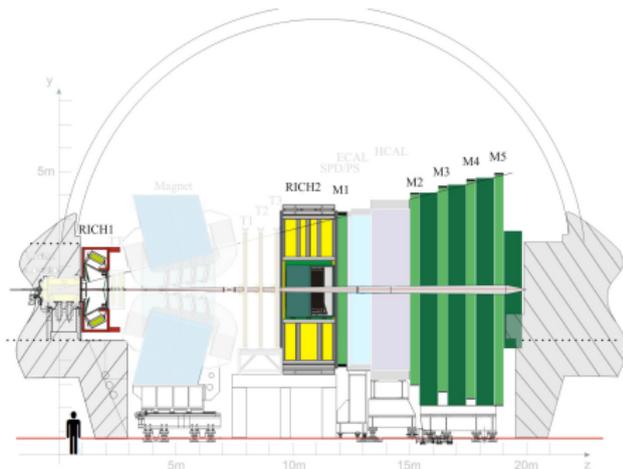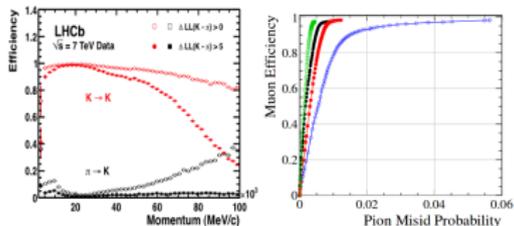- Calorimeter system: Identifies electrons and hadrons. Energy measurement.

LHCb overview

- RICH and Muon detectors:
  Particle identification
  ($K - \pi$ separation and
  muon ID)

See LHCb plenary talk by Hugo Ruiz: "Status and latest results from LHCb" for more details

Outline

1. LHCb overview

2. $B_s^0 \rightarrow K^{*0}\overline{K}^{*0}$
   - Introduction
   - $M(K\pi)$-dependent angular analysis
   - $B_s^0 \rightarrow \phi\phi$
   - Conclusions

3. $B_{(s)}^0 \rightarrow \mu\mu$
   - Introduction
   - Analysis description
   - Conclusions

Introduction

- $B_s^0 \to K^{*0}\overline{K}^{*0}$ is a $b \to s$ transition $\Rightarrow$ Only allowed in the SM by loops.

- Loops are particularly sensitive to New Physics: New heavy particles entering the loops $\Rightarrow$ Observable deviations from SM
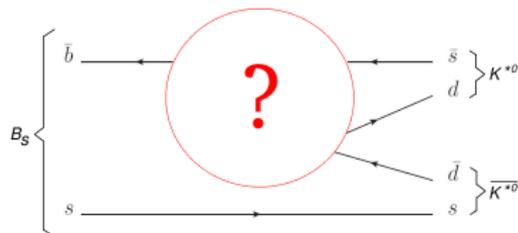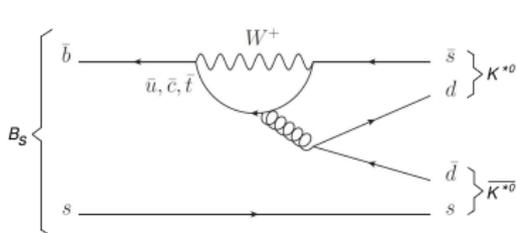
- CP-violation: Weak phases $sin(2\beta)$ ($B^0 \to \phi K_S$) or ϕ_S ($B_s^0 \to K^{*0}\overline{K}^{*0}$, $B_s^0 \to \phi\phi$) in SM.

- $B \to VV$ polarization puzzle: Observed $f_T/f_L \simeq 1$ in $B^0 \to \phi K^{*0}$ (BaBar, Belle), in opposition to the expectation that $f_T \ll f_L$

Introduction

- $B_s^0 \to K^{*0}\overline{K}^{*0}$ is very interesting for precision CP-violation studies, where $B^0 \to K^{*0}\overline{K}^{*0}$ channel is used to control the theoretical error (Ciuchini, Pierini and Silvestrini, hep-ph/0703137 ; Bhattacharya, Datta, Imbeault and London, hep-ph/1203.3435 (2011); Descotes-Genon, Matías and Virto, hep-ph/1111.4882 (2011))

   Standard Model $\Rightarrow$ Negligibly small ϕ_S.

- U-spin rotations, $d \leftrightarrow s$, are flavour symmetries. Standard EW and QCD physics predict small breaking
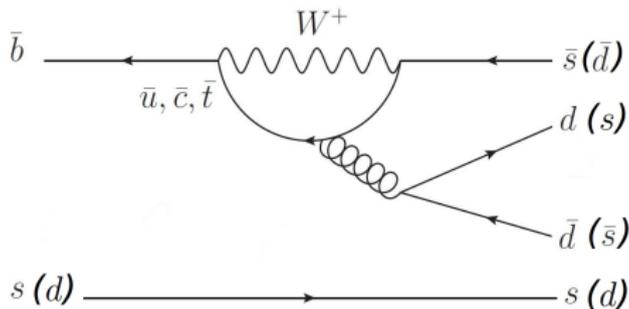
Experimental Status

- First observation with $35pb^{-1}$ of 2010 data at LHCb

$$\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) = (2.81 \pm 0.46(stat)$$
$$\pm 0.45(syst)$$
$$\pm 0.34(f_s/f_d)) \times 10^{-5}$$

- Untagged, time-integrated angular fit to helicity angles

$$f_L = 0.30 \pm 0.12(stat) \pm 0.04(syst)$$

$$f_\perp = 0.38 \pm 0.11(stat.) \pm 0.04(syst.)$$

$(B^0 \to K^{*0}\overline{K}^{*0}$ from BaBar:
$f_L = 0.80 \pm 0.12(stat) \pm 0.04(syst))$.

- Update the results with $\sim 1fb^{-1}$ 2011 data
  - S–wave: NR + $K_0^{*0}(1430)$
  - $M(K\pi)$-dependent angular fit
  - Measure Triple Products Asymmetries

LHCb Collaboration, R. Aaij et al., Phys. Lett. B709, 50

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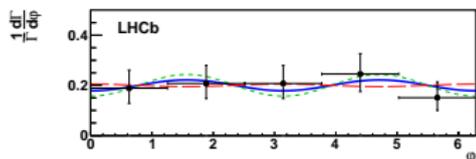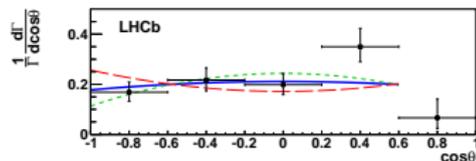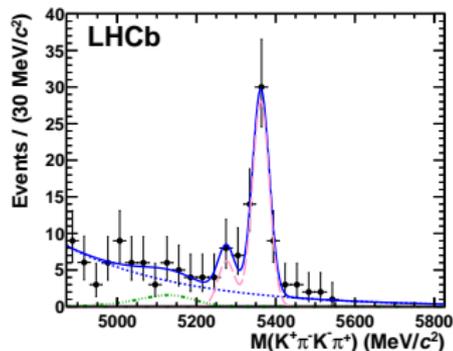
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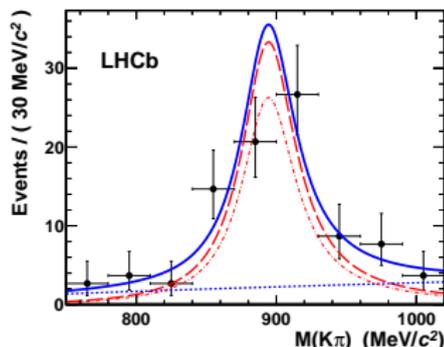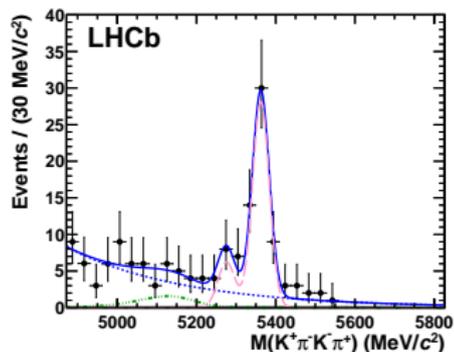
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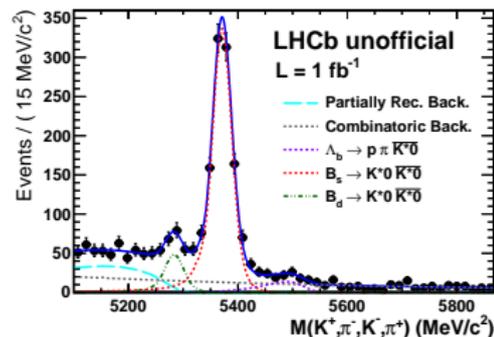 - $M(K\pi)$-dependent angular fit
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LHCb Collaboration, R. Aaij et al., Phys. Lett. B709, 50

Analysis overview

- Selection: Apply some cuts to the $B_s^0 \to K^+\pi^-K^-\pi^+$ candidates to remove most of the background (IP, p_T, mass windows, vertex quality, fight distance...)

- MVA clasifier (Geometrical Likelihood) to improve the significance of the signal.

- Extract the number of $B_s^0 \to K^{*0}\overline{K}^{*0}$ from a fit to the invariant mass distribution of the $K\pi K\pi$ candidates, for the determination of the BR.

$N_{B_s^0 \to K^{*0}\overline{K}^{*0}}$	897 ± 33
$N_{B^0 \to K^{*0}\overline{K}^{*0}}$	128^{+28}_{-32}

- Select events within a $\pm 30\,\mathrm{MeV}/c^2$ mass window around the B_s^0 mass and perform the $M(K\pi)$-dependent angular analysis.

$M(K\pi)$-dependent angular analysis

- $B_s^0 \rightarrow K^{*0}\overline{K}^{*0}$: Three polarization amplitudes A_0, $A_\parallel$ and $A_\perp$
- Our *S–wave* model: Two possible final states, $|K^{*0}(K^-\pi^+)_0\rangle$ and $|\overline{K}^{*0}(K^+\pi^-)_0\rangle$, that can be expressed as combinations of

$$
\begin{aligned}
|s^+\rangle &= \frac{1}{\sqrt{2}} \left(|K^{*0}(K^-\pi^+)_0\rangle + |\overline{K}^{*0}(K^+\pi^-)_0\rangle \right) \\
|s^-\rangle &= \frac{1}{\sqrt{2}} \left(|K^{*0}(K^-\pi^+)_0\rangle - |\overline{K}^{*0}(K^+\pi^-)_0\rangle \right)
\end{aligned}
$$

  which are CP-even and CP-odd eigenstates, respectively, and define two *S–wave* amplitudes A_s^+ and A_s^-.

- Since the normalization of $|A_i|$, $i = 0, \parallel, \perp$ depends on the *S–wave* component, we will provide

$$
f_{L,\parallel,\perp} = \frac{|A_{0,\parallel,\perp}|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}
$$

$M(K\pi)$-dependent angular analysis

$$
\frac{d^5\Gamma}{d\Omega dm_1 dm_2} \propto \Big| \quad \Big(A_0 F_0(\Omega) + A_\parallel F_\parallel(\Omega) + A_\perp F_\perp(\Omega)\Big)\mathcal{M}_1(m_1)\mathcal{M}_1(m_2)
$$
$$
+ A_s^+ \Big(F_s(\Omega)\mathcal{M}_1(m_1)\mathcal{M}_0(m_2) + F_s'(\Omega)\mathcal{M}_0(m_1)\mathcal{M}_1(m_2)\Big)
$$
$$
+ A_s^- \Big(F_s(\Omega)\mathcal{M}_1(m_1)\mathcal{M}_0(m_2) - F_s'(\Omega)\mathcal{M}_0(m_1)\mathcal{M}_1(m_2)\Big) \quad \Big|^2
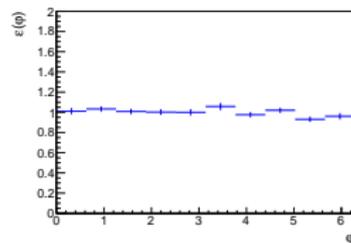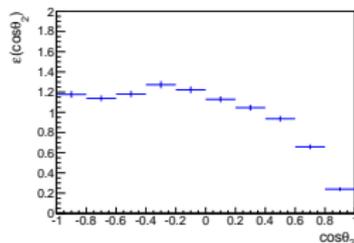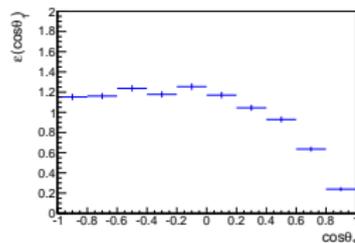$$
$$
+ |\mathcal{A}_{ph}|^2 P(m_1, m_2)
$$

- F_i are angular functions (helicity basis)
- $\mathcal{B}_1$ is the relativistic spin 1 Breit-Wigner propagator.
- $\mathcal{B}_0$ is the relativistic spin 0 BW + non resonant.
- $P(m_1, m_2)$ is a four-body phase space term.
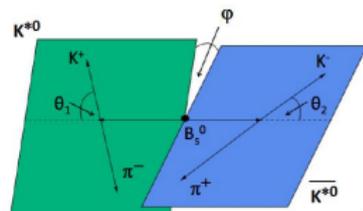
Angular acceptance

- Need to parametrize the effect of reconstruction, selection and trigger.

$$p.d.f._{Sig}(\Omega) = \text{Phys}(\Omega) \times \text{Acc}(\Omega)$$

- Acceptance extracted from MC11
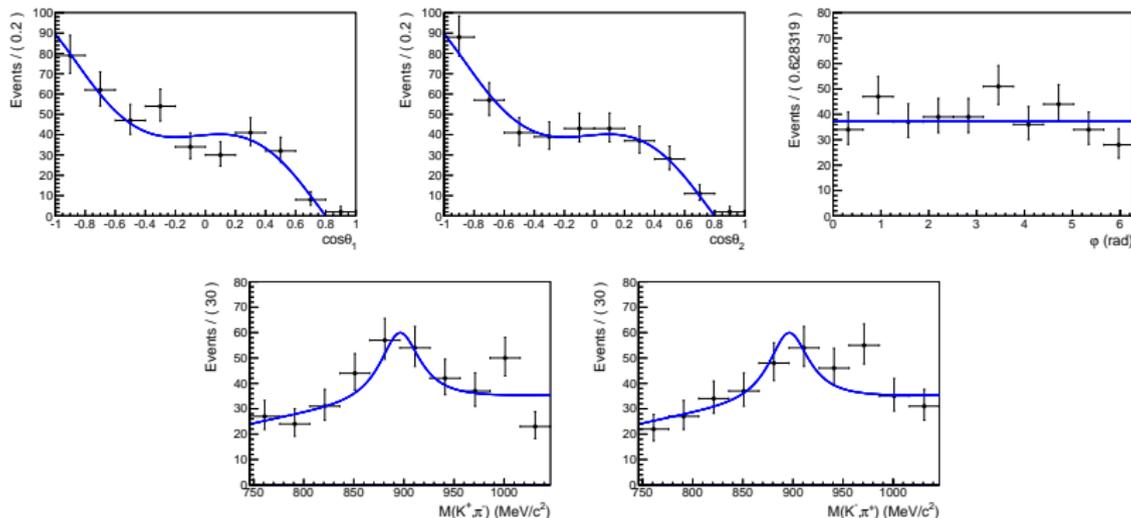

Since the acceptance is flat in φ we use a 2D histogram $\varepsilon(cos\theta_1, cos\theta_2)$ as our acceptance. The efficiency from MC is flat as a function of $M(K\pi)$ and shows no correlation with the helicity angles.

Background $p.d.f.$

- Background distribution extracted from B mass right-hand sideband.

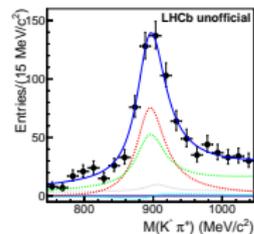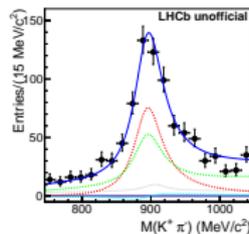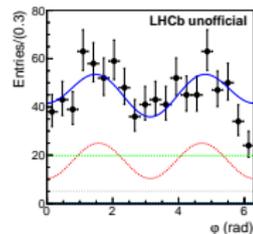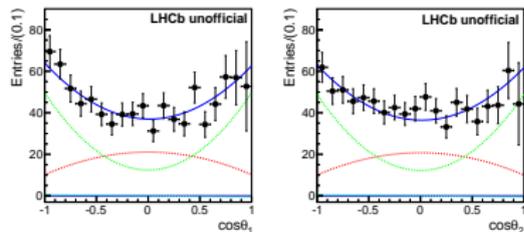
$$p.d.f._{Bkg}(\Omega, m1, m2) = M_{Bkg}(m1) \times M_{Bkg}(m2) \times Pol_5(\theta_1) \times Pol_5(\theta_2)$$

$$M_{Bkg}(m) = f_{\mathcal{B}}|\mathcal{B}_1(\mu^m, \Gamma^m; m)|^2 + (1 - f_{\mathcal{B}})log(c^m m)$$

Fit results

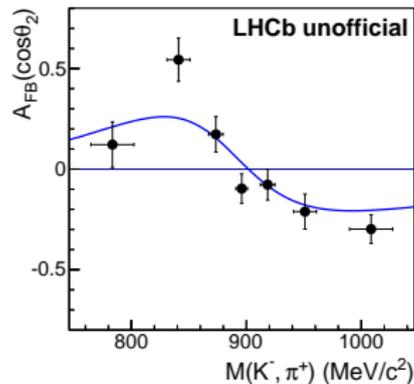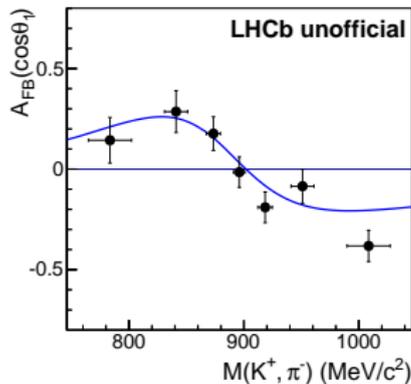| Parameter	Value ($\pm$ stat.)
f_L	$0.208^{+0.048}_{-0.046}$
$f_\parallel$	$0.220^{+0.039}_{-0.036}$
$|A_s^+|^2$	$0.444^{+0.043}_{-0.044}$
$|A_s^-|^2$	$0.082^{+0.032}_{-0.029}$
$\delta_\parallel$	-0.87 ± 0.21
$\delta_\perp$	0.49 ± 0.33
δ_s^+	$-0.49^{+0.16}_{-0.17}$
δ_s^-	2.65 ± 0.26
$|A_{ph}|^2$	$0.114^{+0.036}_{-0.035}$

$|M(K\pi) - m_{K^{*0}}| < 150\,\mathrm{MeV}/c^2$

Fit results

- FB Asymmetry as a function of $M(K\pi)$

$$A_{FB}(cos\theta_i) = \frac{\sqrt{3}\Re(A_0^* A_s^+ \mathcal{B}_1^*(m_i)\mathcal{B}_0(m_i))}{(|A_P|^2 + \frac{|A_s^+|^2 + |A_s^-|^2}{2})|\mathcal{B}_1^*(m_i)|^2 + \frac{|A_s^+|^2 + |A_s^-|^2}{2}|\mathcal{B}_0^*(m_i)|^2}$$

Triple Product Asymmetries

- Search for NP with no need of tagging or time-dependent analysis
  (Datta and London, arXiv:hep-ph/0303159)
- Interference terms $\Im(A_0^* A_\perp)$ and $\Im(A_\parallel^* A_\perp)$ are proportional to the triple products:

$$
\begin{aligned}
(1): && \sin\varphi &= (\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1 \\
(2): && \sin(2\varphi)/2 &= (\hat{n}_1 \cdot \hat{n}_2)(\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1
\end{aligned}
$$

- TP are odd under time reversal:
  Non zero TP asymmetries measurement will be a sign of *CP*-violation (*CPT* conservation)

$$
\begin{aligned}
\mathcal{A}_T^{(1)} &= -\frac{2\sqrt{2}}{\pi} \frac{\Im(A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*)}{(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2) + (|\bar{A}_0|^2 + |\bar{A}_\parallel|^2 + |\bar{A}_\perp|^2)} \\
\mathcal{A}_T^{(2)} &= -\frac{4}{\pi} \frac{\Im(A_\perp A_\parallel^* - \bar{A}_\perp \bar{A}_\parallel^*)}{(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2) + (|\bar{A}_0|^2 + |\bar{A}_\parallel|^2 + |\bar{A}_\perp|^2)}
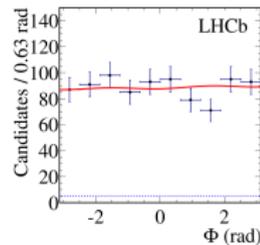\end{aligned}
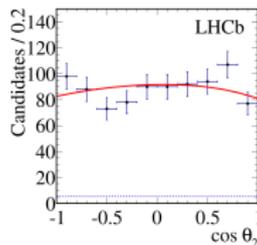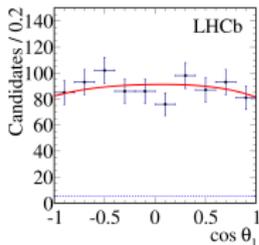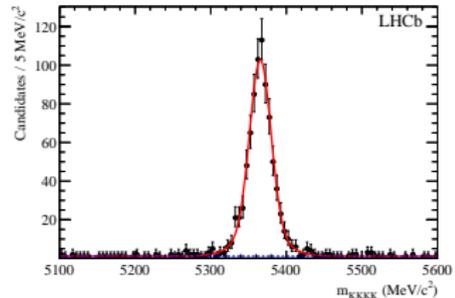$$

$B_s^0 \to \phi\phi$

- Golden mode for measurement of ϕ_s
  (Raidal, arXiv, hep-ph/0209091)

- 801 ± 29 candidates in the full 2011 dataset
  $(1fb^{-1})$, S-wave component in $\pm 25\,\mathrm{MeV}/c^2$
  window around ϕ mass $\sim 1.3\%$.

- Polarization amplitudes in good agreement
  with CDF measurement.

$$f_L = 0.365 \pm 0.022(stat) \pm 0.012(syst)$$

$$f_\perp = 0.291 \pm 0.024(stat) \pm 0.010(syst)$$

$$cos(\delta_{\parallel}) = -0.844 \pm 0.068(stat) \pm 0.029(syst)$$
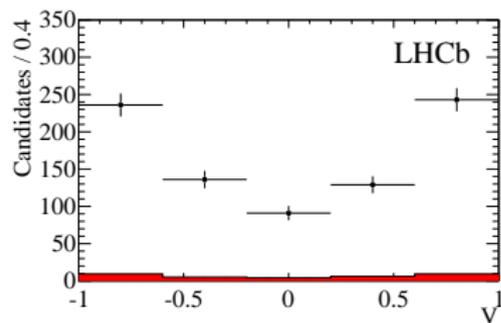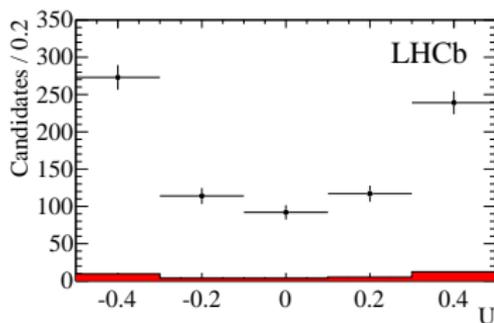
LHCb Collaboration Phys.
Lett. B713, 369-377

$B_s^0 \to \phi\phi$: Triple Product Asymmetries

- TP can also be calculated as

$$A_T^{(1)} = \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)} \quad A_T^{(2)} = \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)}$$

where $U = \sin\varphi$ and $V = \operatorname{sign}(\cos\theta_1 \cos\theta_2) \sin(2\varphi)$.

- Results are in good agreement with CDF and consistent with the hypothesis of *CP* conservation.

$$A_U = -0.055 \pm 0.036(stat) \pm 0.018(syst)$$
$$A_V = 0.010 \pm 0.036(stat) \pm 0.018(syst)$$

Conclusions

- After the discovery of $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay at LHCb, an update with 2011 data ($1fb^{-1}$) is being prepared.

- More sophisticated angular analysis, that includes two S–wave amplitudes and $M(K^+\pi^-)$ and $M(K^-\pi^+)$ information.

- Determination of the Triple Product asymmetries, $A_T^{(1)}$ and $A_T^{(2)}$. Non zero TP will be a sign of CPV.

- Extension of these analysis (time-dependent CPV anaylysis) and new ones ($B^0 \to \phi K^{*0}$ and $B_s^0 \to \phi \overline{K}^{*0}$) expected with 2011 (&2012) data. (See tomorrow the talk by Antonio Romero: *Triple products in $B^0 \to \phi K^{*0}$*)

Outline

Introduction

- $B^0_{(s)} \to \mu\mu$ are FCNC, NP through new virtual particles entering the loops up to high energy scales.

- Very supressed in the SM:
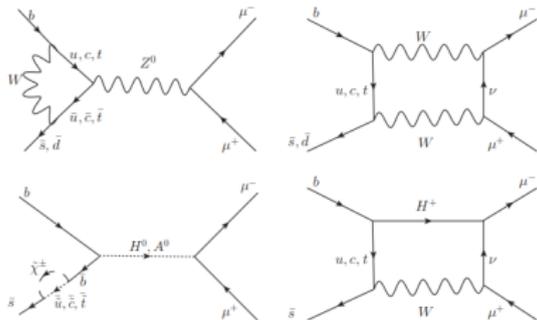
  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.54\pm0.30)\times10^{-9}$

  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07\pm0.10)\times10^{-10}$

  Buras, Girrbach, Guadagnoli and Isidori,
  Eur. Phys. J. C72 (2012)
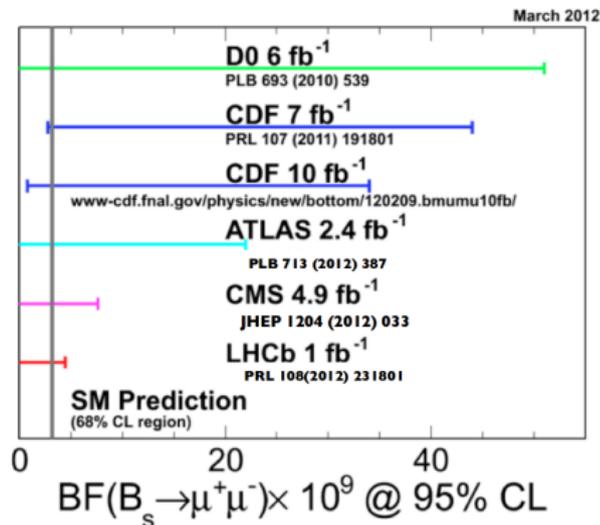 De Bruyn et al., PRL 109, 041801 (2012)

- Important observable to constrain possible deviations from the Standard Model.

Experimental Status

- March 2012: Very close to get sensitivity for observing a SM rate.

- June 2012: LHC combination (LHCb-CONF-2012-017, CMS-PAS-BPH-12-009, ATLAS-CONF-2012-061)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) < 4.2 \times 10^{-9} \text{ at 95\% CL}$$

Analysis strategy

- Dataset: $1 fb^{-1}$ at 7 TeV (2011) (reanalyzed) + 1.1 fb^{-1} at 8 TeV (2012)
- Selection: Pairs of opposite charged muons, making a vertex displaced with respect to the primary vertex and $m_{\mu\mu}$ in the range [4900-6000] MeV/c^2.
- Events are classified using two variables:
  - Dimuon invariant mass.
  - MVA classifier including kinematic and topological information (BDT)
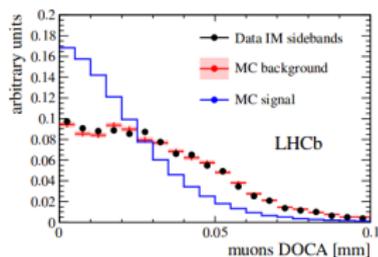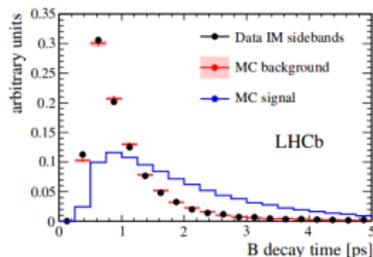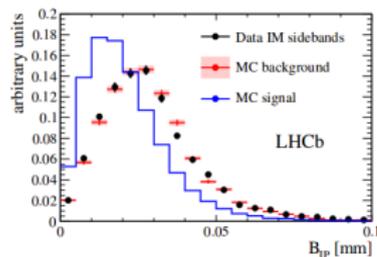
Analysis strategy

- Invariant mass and BDT calibration using $B^0_{(s)} \to h^+ h'^-$ for signal and dimuon mass sidebands for background
- Background estimation
  - Combinatorial $b\bar{b} \to \mu\mu X$
  - Double mis-identified $B^0_{(s)} \to h^+ h'^-$
  - Detailed studies on various exclusive backgrounds
- Normalization to control channels $B^+ \to J/\psi K^+$ and $B^0 \to K^+ \pi^-$
- Signal region on 8 TeV data kept blind until analysis completion.

After unblinding:

- Determination of limits and significance with CLs method
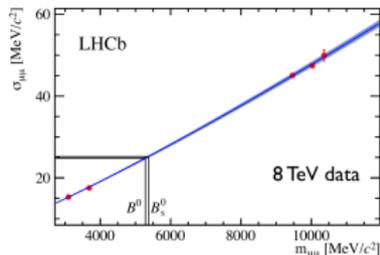 Signal window: $m(B^0_s) \pm 60 \, \mathrm{MeV}/c^2$

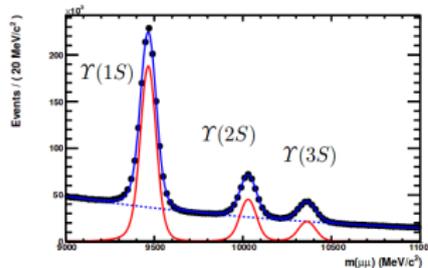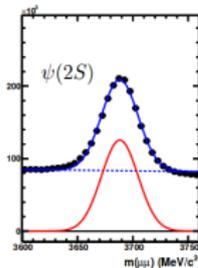# Calibration

Analysis is performed in BDT and invariant mass bins, so the fraction of signal in each bin is needed.
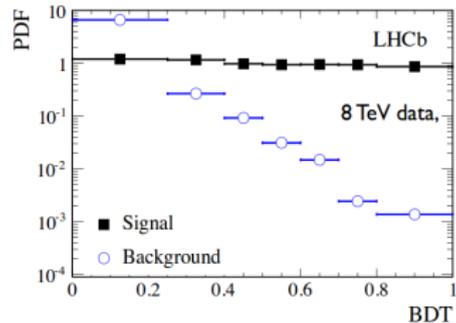
- BDT calibration: $B \to h^+ h'^-$ triggered independently of signal.

- Mass peak position and resolution: $B \to h^+ h'^-$ and interpolation of dimuon resonances.
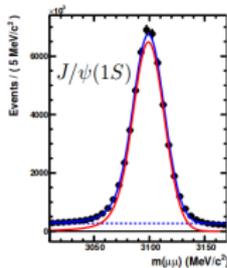
Background estimation

The expected background yield in the signal region is evaluated from a fit to the mass sidebands, for each of the 7 BDT bins separately.

- The main background source is combinatorial from $b\bar{b} \to \mu^+\mu^- X$ Exponential shape assumed.
- Various exclusive decays could fake signal:
  - misID of one or two hadrons: $B^0 \to \pi^-\mu^+\nu_\mu$, $B^0_{(s)} \to h^+h'^-$
  - two muons coming from the same vertex: $B^{+(0)} \to \pi^{+(0)}\mu^+\mu^-$

  They are included in the mass sideband fits (constrained to their expected yields)
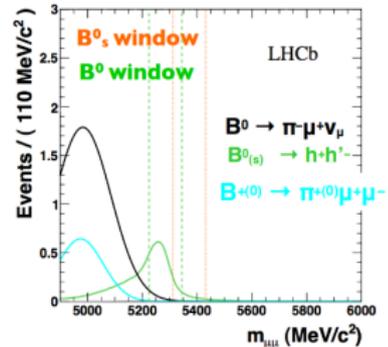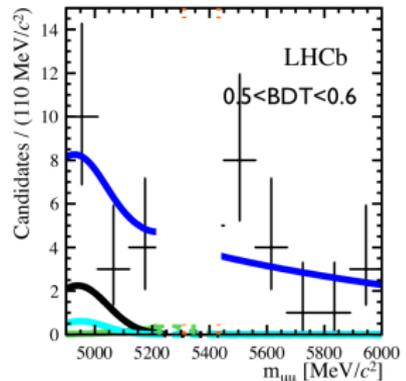
Normalization

$$\text{BR} = \text{BR}_{\text{cal}} \times \frac{\epsilon^{\text{REC}}_{\text{cal}} \epsilon^{\text{SEL|REC}}_{\text{cal}} \epsilon^{\text{TRIG|SEL}}_{\text{cal}}}{\epsilon^{\text{REC}}_{\text{sig}} \epsilon^{\text{SEL|REC}}_{\text{sig}} \epsilon^{\text{TRIG|SEL}}_{\text{sig}}} \times \frac{f_{\text{cal}}}{f_{B^0_q}} \times \frac{N_{B^0_q \to \mu^+\mu^-}}{N_{\text{cal}}} = \alpha_{\text{cal}} \times N_{B^0_q \to \mu^+\mu^-}$$

Evaluated from MC, cross-checked with data

Measured on data

Ratio of probabilities for a b quark to hadronize to a given meson

- With 2 independent channels: $B^+ \to J/\psi K^+$ (similar trigger, one more track) and $B^0 \to K^+\pi^-$ (Different trigger, same topology).
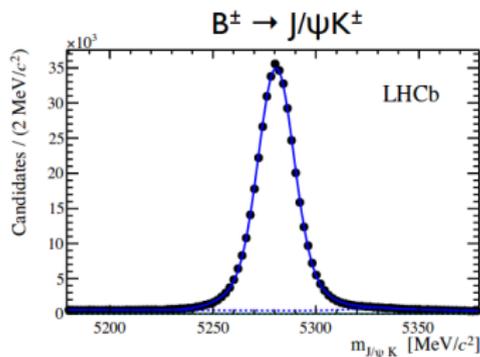
$$\alpha_{cal}(B^0_s \to \mu^+\mu^-) = (2.52 \pm 0.23) \times 10^{-10}$$
$$\alpha_{cal}(B^0 \to \mu^+\mu^-) = (6.45 \pm 0.30) \times 10^{-11}$$

Results: Limit computation

Computing the limit:

- Count the number of observed candidates.

- Compute the expected number of signal and background events.

- Use the $\mathrm{CL_S}$ method to evaluate the compatibility of the observed distribution of events with that expected for a given branching fraction hypothesis ($\mathrm{CL_{S+B}}$ and $\mathrm{CL_B}$).

Limit on $\mathcal{B}(B^0 \to \mu^+\mu^-)$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% CL

Background only p-value: 16%
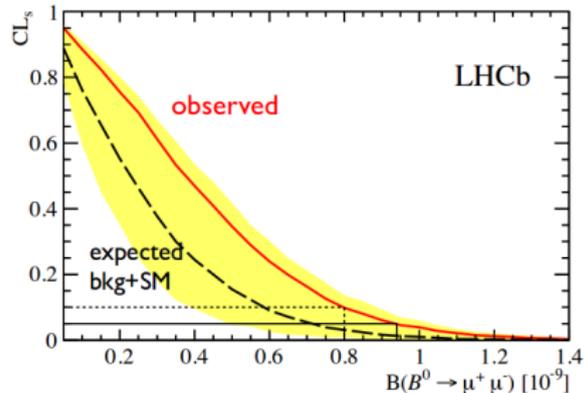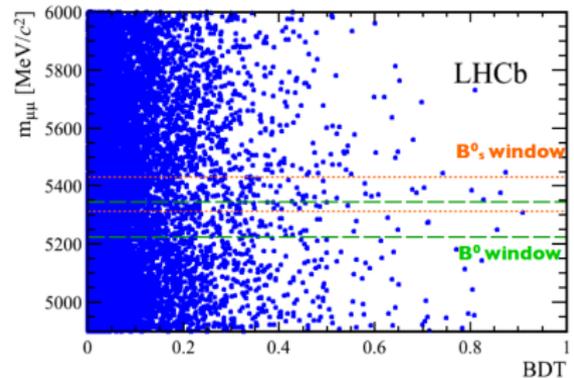
Results: Limit computation

With 7 TeV $(1.1 fb^{-1})$ + 8 TeV $(1.1 fb^{-1})$

$1.1 \times 10^{-9} < \mathcal{B}(B^0_s \to \mu^+\mu^-) < 6.4 \times 10^{-9}$
at 95% CL

Background only p-value: 5×10^{-4}
(3.5σ excess)

First evidence of the decay $B^0_s \to \mu\mu$!

Results: Branching Fraction measurement

- Simultaneous unbinned maximum-likelihood fit to the mass spectra, in the full mass range [4900-6000] MeV/c^2.
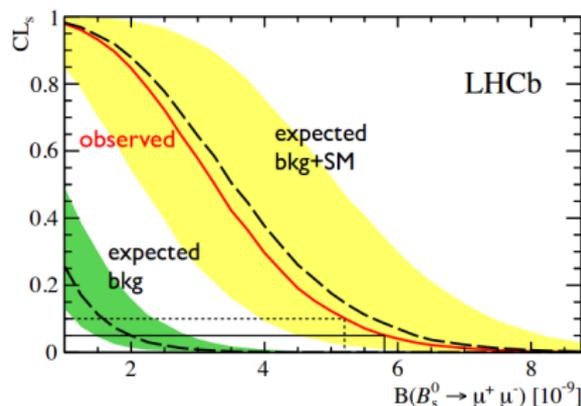- Free parameters are $\mathcal{B}(B^0_s \to \mu^+\mu^-)$, $\mathcal{B}(B^0 \to \mu^+\mu^-)$ and the combinatorial background parameters.
- Signal yield in each bin is constrained to the expectations from calibration.
- Exclusive backgrounds yields and shapes constrained to their expectations.
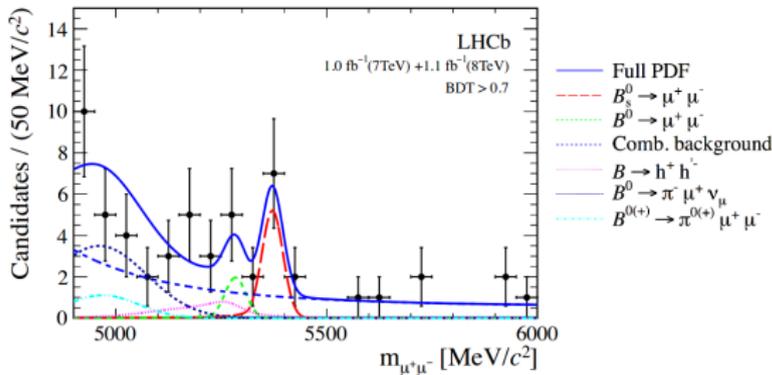
LHCb Collaboration
(arXiv:1211.2674 [hep-ex])

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

$B^0_s \to \mu^+\mu^-$ candidate

8 TeV data

13.5. 2012 8:24:38
Run 115275 Event 1941832142   bId 1447
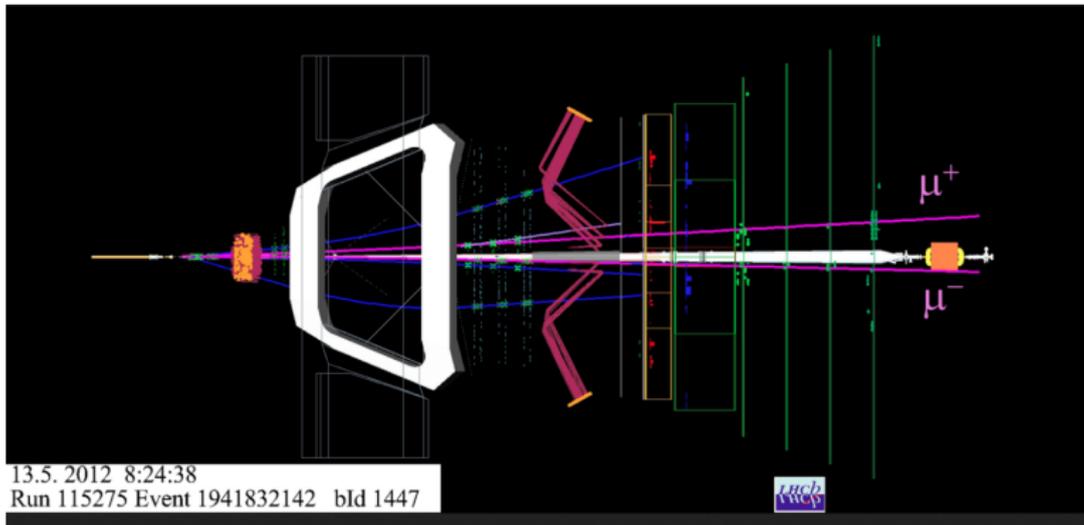
B candidate: $m_{\mu\mu} = 5353.4$ MeV/c^2 BDT = 0.826
                   $p_T = 4077.4$ MeV/c   t = 2.84 ps

muons: $p_{T\mu^+} = 2329.5$ MeV/c $p_{T\mu^-} = 4179.4$ MeV/c

Conclusions

- An updated search for $B^0_s \to \mu^+\mu^-$ combining 7TeV($1fb^{-1}$) and 8 TeV ($1.1fb^{-1}$) data has been presented.

- LHCb has set the world best upper limit in the $\mathcal{B}(B^0 \to \mu^+\mu^-)$.

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ at 95\% CL}$$

- An excess of $B^0_s \to \mu^+\mu^-$ signal above the background expectation has been observed with a significance of 3.5σ (p-value 5×10^{-4}), the first evidence of this decay.

- The branching fraction of $B^0_s \to \mu^+\mu^-$ has been measured and it is in agreement with the SM prediction ($\mathcal{B}^{SM}(B^0_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$).

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

- This result is a constraint for all models trying to extend the SM.

THANKS FOR YOUR ATTENTION

BACKUP

True and Fake Triple Products

- Gronau & Rosner (arXiv:1107.1232 [hep-ph])

It has been pointed out [1, 3] that the two quantities $\mathrm{Im}(A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*)$ and $\mathrm{Im}(A_\perp A_\parallel^* - \bar{A}_\perp \bar{A}_\parallel^*)$, occurring in the sum (rather than the difference) of decay distributions (20) and (33) for $B_{(s)}$ and $\bar{B}_{(s)}$ for $\bar{\theta}_1 = \theta_1, \bar{\theta}_2 = \theta_2, \bar{\phi} = \phi$, are genuinely CP-violating and do not require nonzero CP conserving phases. For instance, assuming that each of the transversity amplitudes is dominated by a magnitude, $|A_\lambda|$, a single CP-conserving phase, δ_λ, and a single CP-violating phase, ϕ_λ (which amounts to assuming no direct CP violation),

$$A_\lambda = |A_\lambda| e^{i\delta_\lambda} e^{i\phi_\lambda} , \quad \bar{A}_\lambda = |A_\lambda| e^{i\delta_\lambda} e^{-i\phi_\lambda} \quad (\lambda = 0, \parallel, \perp) , \qquad (34)$$

implies

$$\mathrm{Im}(A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*) = 2|A_\perp||A_0|\cos(\delta_\perp - \delta_0)\sin(\phi_\perp - \phi_0) . \qquad (35)$$

This "true" CP violating quantity is nonzero also when the CP-conserving phase difference $\delta_\perp - \delta_0$ vanishes, provided that the CP-violating phase difference $\phi_\perp - \phi_0$ between the two transversity amplitudes $A_\perp$ and A_0 is nonzero. In contrast, a quantity occurring in the difference of rates for $B_{(s)}$ and $\bar{B}_{(s)}$,

$$\mathrm{Im}(A_\perp A_0^* + \bar{A}_\perp \bar{A}_0^*) = 2|A_\perp||A_0|\sin(\delta_\perp - \delta_0)\cos(\phi_\perp - \phi_0) , \qquad (36)$$

is not CP-violating as it is nonzero also when CP-violating phases vanish. Such a quantity will sometimes be referred to as a "fake" asymmetry.
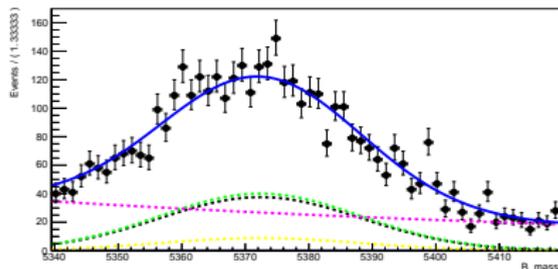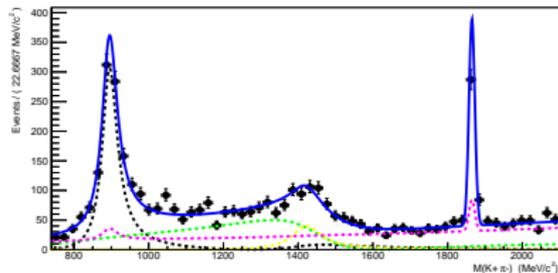
Polarization puzzle
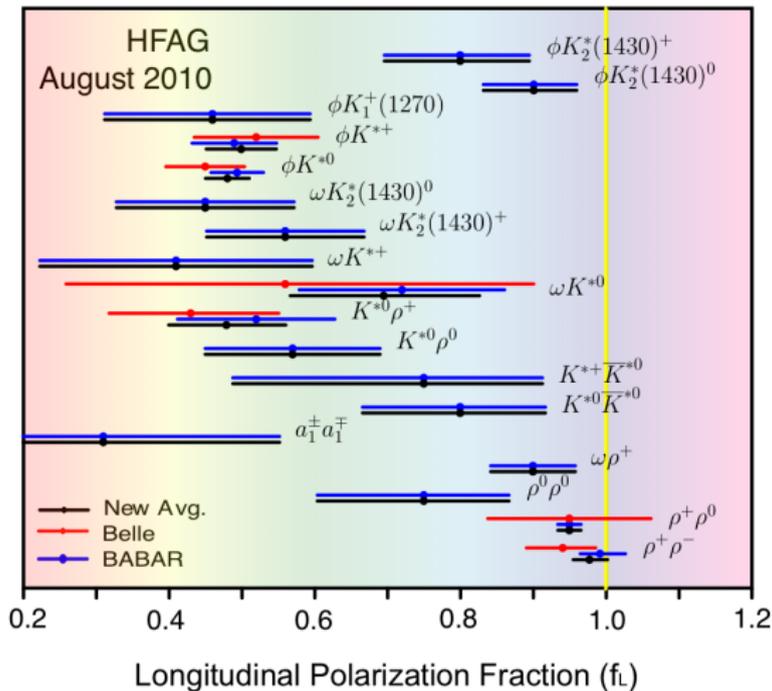
Wide $M(K\pi)$ window

2D fit $(M(K\pi), M(K\pi K\pi))$ including:

- S–wave: $K_0^*(1430) + non-resonant$
- P–wave: $K^{*0} + K_1^*(1410)$
- D–wave: $K_2^*(1430)$
- Combinatoric background
- D^0 peak

S–wave fraction in the $\pm 150\,\text{MeV}/c^2$ window

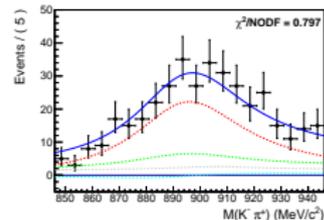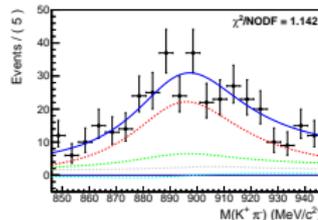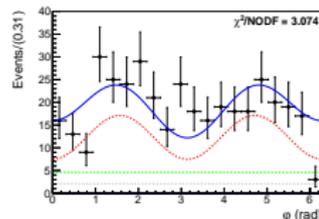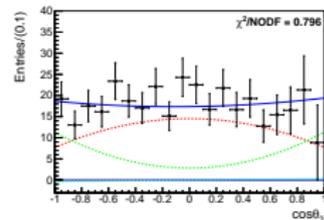$$f_{s-wave} = \frac{|A_s^+|^2 + |A_s^-|^2}{2} = 0.224 \pm 0.020$$

$M(K\pi)$-dependent angular analysis: Narrow window

Parameter	Value
f_L	0.220 ± 0.054
$f_{\parallel}$	0.227 ± 0.043
$|A_s^+|^2$*	0.490 ± 0.068
$|A_s^-|^2$*	0.051 ± 0.039
$\delta_{\parallel}$	-0.94 ± 0.25
$\delta_{\perp}$	0.79 ± 0.85
δ_s^+	-0.59 ± 0.19
δ_s^-	3.05 ± 0.75
$|A_{ph}|^2$*	0.00 ± 0.11

* Normalized to the $\pm 150 \, \mathrm{MeV}/c^2$ $K\pi$ mass window.
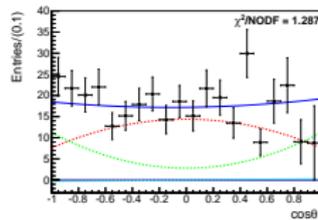
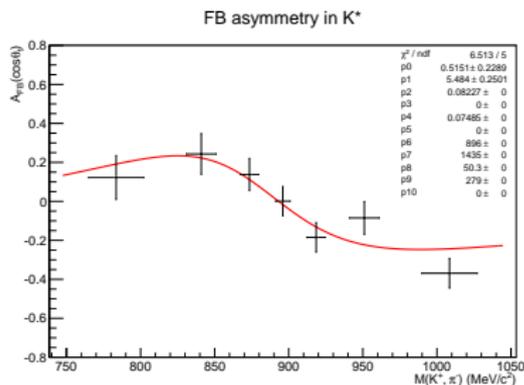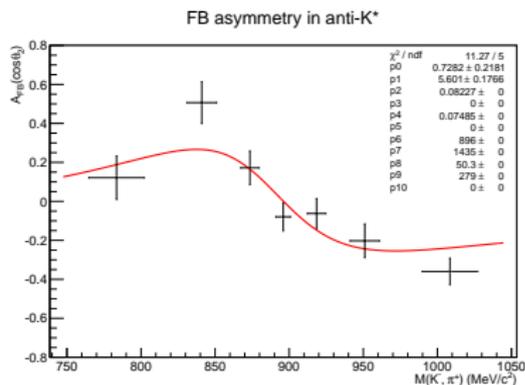# Fit to the FB asymmetry

1D fit to the FB Asymmetry

$$|A_s^+|^2 = 0.52 \pm 0.23$$
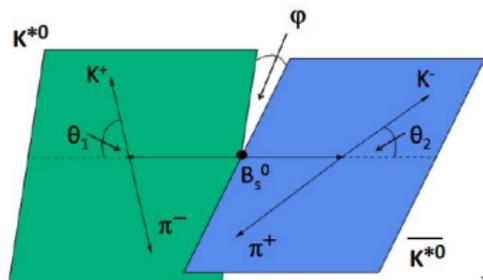

$$|A_s^+|^2 = 0.73 \pm 0.22$$

Angular distribution

$$I(\theta_1, \theta_2, \varphi) = \frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_1 \, \mathrm{d}\cos\theta_2 \, \mathrm{d}\varphi} = \left(\frac{1}{\Gamma_L} \quad |A_0|^2 \quad \cos^2\theta_1 \cos^2\theta_2 + \right.$$

$$\frac{1}{\Gamma_L} \quad |A_\parallel|^2 \quad \frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \cos^2\varphi +$$

$$\frac{1}{\Gamma_H} \quad |A_\perp|^2 \quad \frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \sin^2\varphi +$$

$$\left. \frac{1}{\Gamma_L} \quad |A_0| \quad |A_\parallel| \cos\delta_\parallel \frac{1}{2\sqrt{2}}\sin 2\theta_1 \sin 2\theta_2 \cos\varphi \right)$$

$$A_0 = H_0$$
$$A_\parallel = \frac{1}{\sqrt{2}}(H_{+1} + H_{-1})$$
$$A_\perp = \frac{1}{\sqrt{2}}(H_{+1} - H_{-1})$$

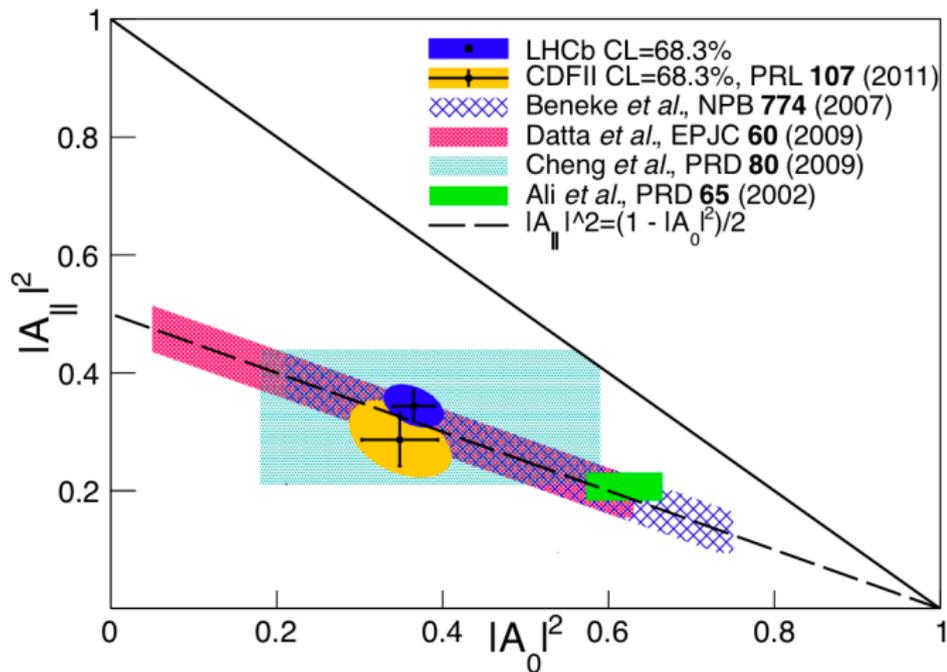Normalization $\Rightarrow |A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$

$B_s^0 \to K^{*0} \overline{K}^{*0}$ systematics

Table: Estimated systematic error sources in the $\mathcal{B}\,(BsKstKst)$ measurement.

Systematic effect	Error (%)
Trigger efficiency	11
Global angular acceptance	7.2
S-wave fraction	5
Background subtraction	4.7
$B_s^0 \to J/\psi\,K^{*0}$ and $J/\psi \to \mu\mu$ BR uncertainty	4.6
Selection efficiency	3.4
Total	15.9

Polarization amplitudes $B_s^0 \to \phi\phi$

$B_s^0 \to \phi\phi$ systematics

Source	$|A_0|^2$	$|A_\perp|^2$	$|A_\parallel|^2$	$\cos\delta_\parallel$
S-wave	0.007	0.005	0.012	0.001
Time Acceptance	0.006	0.006	0.002	0.007
Angular Acceptance	0.007	0.006	0.006	0.028
Trigger category	0.003	0.002	0.001	0.004
Background model	0.001	-	0.001	0.003
Total	0.012	0.010	0.014	0.029

$B_s^0 \rightarrow \phi\phi$ systematics

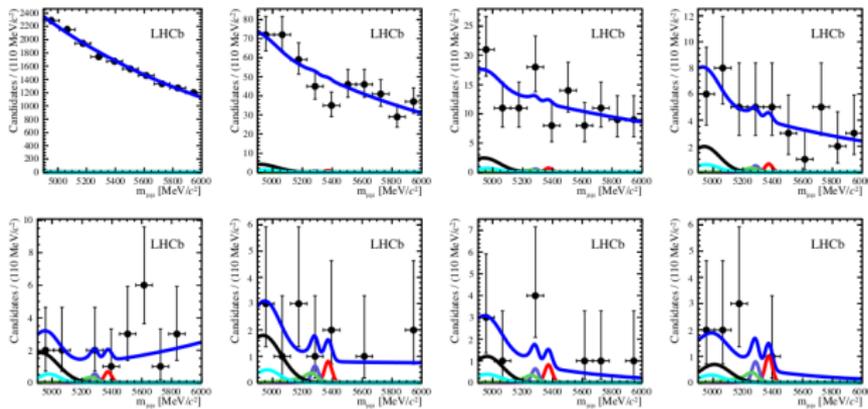| Source	A_U	A_V	Chosen uncertainty
Angular acceptance	0.009	0.006	0.009
Decay time acceptance	0.006	0.014	0.014
Fit model	0.004	0.005	0.005
Total			0.018

$\mathcal{B}(B^0 \to \mu^+\mu^-)$ upper limit
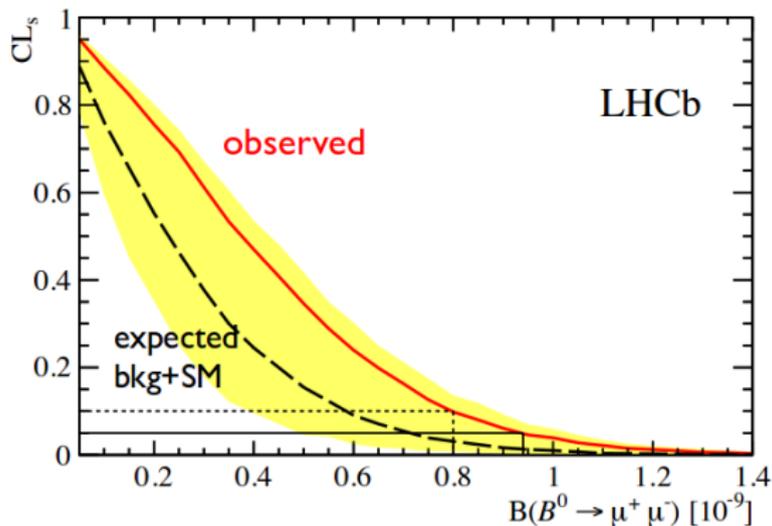
Observed upper limit:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

$B_s^0 \to \mu^+ \mu^-$ fit slices

7 TeV data, 1.0 fb⁻¹
8 BDT bins

$B^0_s \to \mu^+ \mu^-$
$B^0 \to \mu^+ \mu^-$
$B^0_{(s)} \to h^+ h'^-$
$B^0 \to \pi^- \mu^+ \nu_\mu$
$B^{\pm,0} \to \pi^{\pm,0} \mu^+ \mu^-$
total

8 TeV data, 1.1 fb⁻¹
7 BDT bins