Rare decays and $\mathcal{CP}$ violation studies at LHCb

Anton Poluektov

The University of Warwick, UK,
Budker Institute of Nuclear Physics, Novosibirsk, Russia

7th January 2013

On behalf of the LHCb collaboration

Preface

- Many thanks to Pierre-Francois Giraud and Serguei Ganjour for inviting me to give this seminar.
- LHCb, as other LHC and Tevatron experiments, produces a lot of interesting physics results which are impossible to cover in detail in one talk.
  - 84 papers on arXiv.
  - 101 conference papers.

  I will show a few recent results related to New Physics searches in rare decays and $\mathcal{CP}$ violation.

LHCb physics programme

Detector performance optimised for studies of $\mathcal{CP}$ violation and rare decays of B mesons. The physics programme includes

- Rare B decays
  - $B_s^0 \to \mu^+\mu^-$
  - $B^0 \to K^*\ell^+\ell^-$
  - Radiative B decays
- CP violation in B system (B^+, B^0, B_s)
  - Measurement of γ in tree-level processes ($B \to DX$)
  - Measurement of γ in loop-mediated processes (charmless B decays)
  - CP violation in B_s mixing: ϕ_s phase
- Production and spectroscopy studies
  - Quarkonia (conventional and exotic)
  - B hadrons (B^*, heavy baryons)
- Charm studies
  - Charm spectroscopy
  - CP violation and mixing in charm
- Soft QCD physics
- Electroweak physics

LHCb physics programme

Detector performance optimised for studies of $\mathcal{CP}$ violation and rare decays of B mesons. The physics programme includes

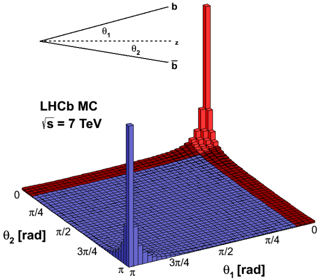
- Rare B decays (and not only B)
  - $B_s^0 \to \mu^+\mu^-$ and $K_S^0 \to \mu^+\mu^-$
  - $B^0 \to K^*\ell^+\ell^-$
  - Radiative B decays
- CP violation in B system (B^+, B^0, B_s)
  - Measurement of γ in tree-level processes ($B \to DX$)
  - Measurement of γ in loop-mediated processes (charmless B decays)
  - CP violation in B_s mixing: ϕ_s phase
- Production and spectroscopy studies
  - Quarkonia (conventional and exotic)
  - B hadrons (B^*, heavy baryons)
- Charm studies
  - Charm spectroscopy
  - CP violation and mixing in charm
- Soft QCD physics
- Electroweak physics

Flavor physics at the LHC

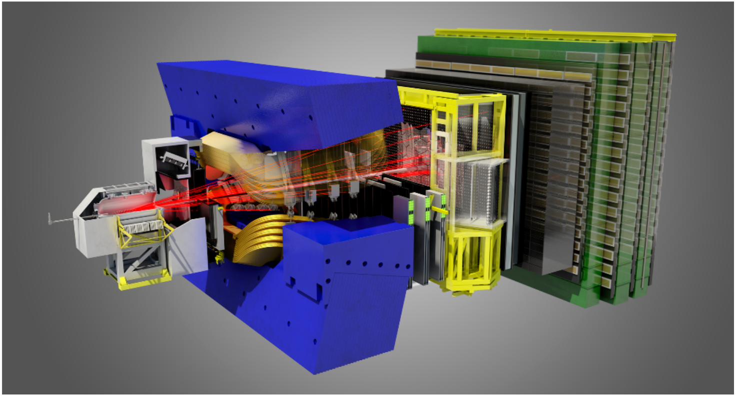
$b\bar{b}$ cross-section: 280 μb (7 TeV) [LHCb, Phys. Lett. B **694** 209-216 (2010)]
$b\bar{b}$ pairs are produced mostly in forward and backward directions.
Flavor ratio: 40% B^+ : 40% B^0 : 10% B_s^0 : 10% Λ_b^0 : 0.1% B_c.

Requirements

- Ability to reconstruct (and trigger on) low p_t tracks
- Efficient trigger for leptonic and purely hadronic B decays
- Good vertexing for time-dependent measurements (esp. for fast B_s^0 oscillations)
- Good PID ($\pi/K/p/\mu/e$ separation) for final state selection and flavor tagging.
- Good momentum/invariant mass resolution for background suppression.



LHCb detector

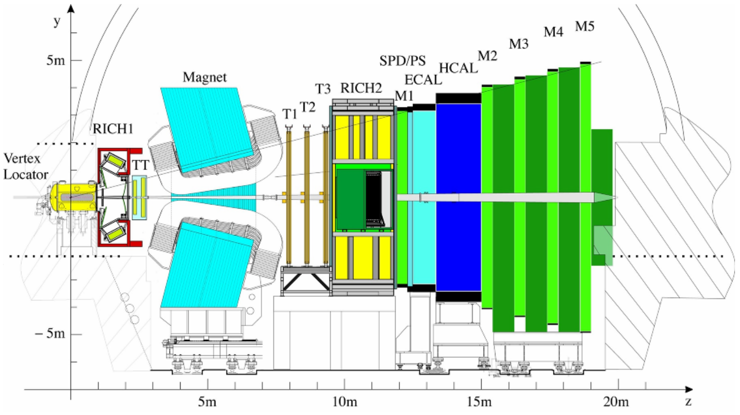


B mesons are produced predominantly in forward and backward regions, do not necessarily need a 4π detector. Additional advantages of forward geometry:

- Large boost means better decay time resolution.
- Ability to trigger down to lower values of p_T.

LHCb detector

A. A. Alves Jr. (LHCb collaboration), 2008 JINST 3 S08005



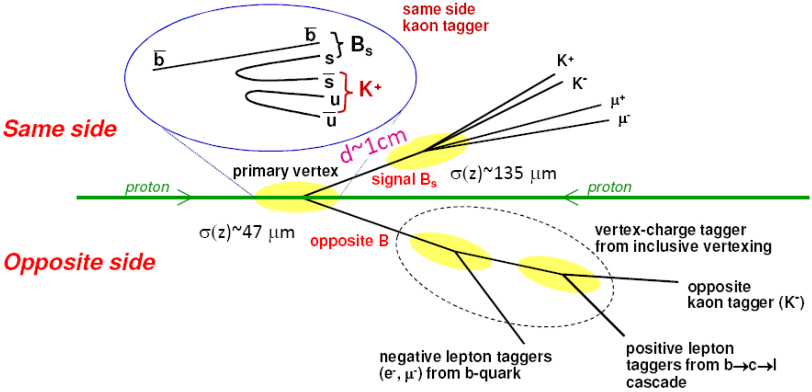
- One-arm forward spectrometer, $2 < \eta < 5$ ($15 - 300$ mrad)
- Ability to switch direction of magnetic field, to control systematics in $\mathcal{CP}$ asymmetries.
- Trigger: L0 (hardware): 1 MHz, HLT (software): 3–4 kHz
- Design luminosity 2×10^{32} cm^{-2}s^{-1}

Analysis techniques

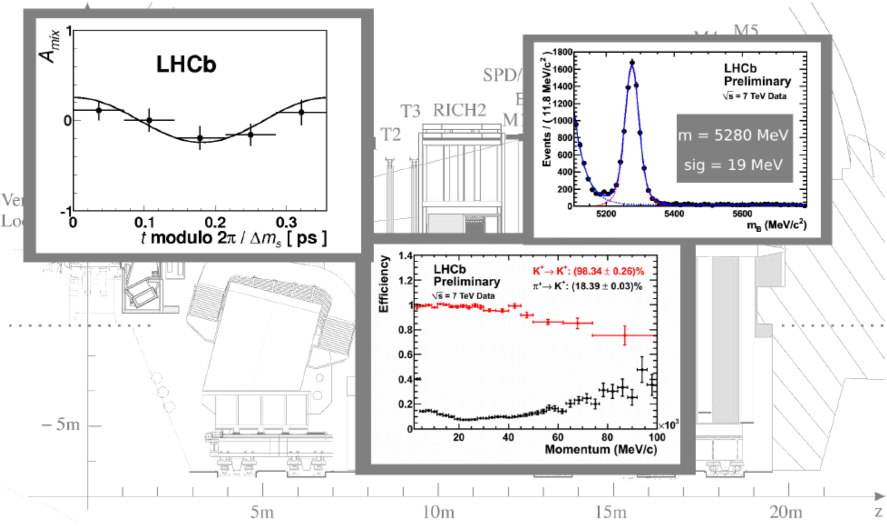
Background suppression based on event topology (impact parameters, vertex displacement for B and charm)

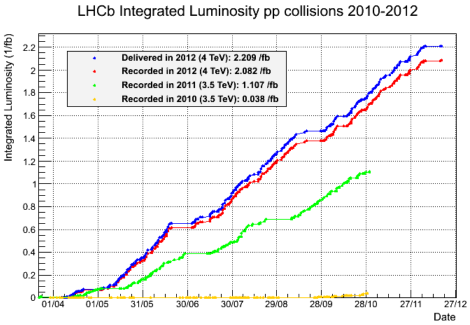
Time-dependent measurements: measure lifetime based on vertex displacement ($\sigma_t \simeq 40$ fs)

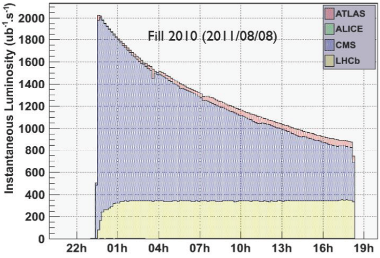
Flavor tagging: use decay products of the opposite-side B (OS) and π, K associated with same-side B (SS)



LHCb performance







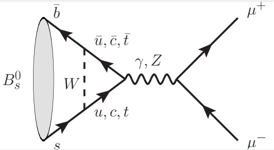
- Luminosity leveling: beam position continuously adjusted to maintain stable luminosity, 3.5×10^{32} cm^{-2}s^{-1} (in 2011), 4×10^{32} cm^{-2}s^{-1} (in 2012). Double the design value.
- 2011 data sample: 1.1 fb^{-1} at 7 TeV.
- 2012 sample: 2.1 fb^{-1} at 8 TeV ($\sim 10\%$ higher B cross section), improved charm trigger.

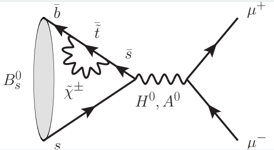
If not explicitly written, analyses presented are based on 1 fb^{-1} sample of 2011.

Rare B decays

In Standard Model, occur via second-order electroweak transitions.

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



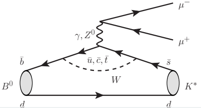


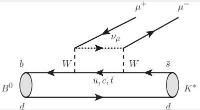
FCNC, helicity suppression
SM expectation: $(3.5 \pm 0.3) \times 10^{-9}$

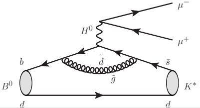
E. Gamiz *et al.*, Phys. Rev. D 80 014503 (2009)

Sensitive to NP contributions
MSSM: $Br(B_s \to \mu^+\mu^-) \simeq \frac{\tan^6\beta}{M_A^4}$

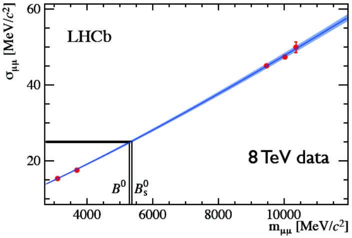
$B^0 \to K^*\mu^+\mu^-$

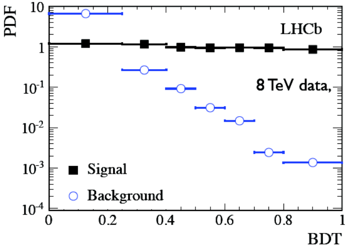
SM: 



NP: 

FCNC, $Br \simeq 1 \times 10^{-6}$
Study angular distribution, description in terms of Wilson coefficients: C_7, C_9, C_{10}





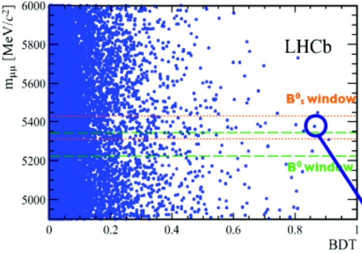
[LHCb-PAPER-2012-043, arXiv:1211.2674]

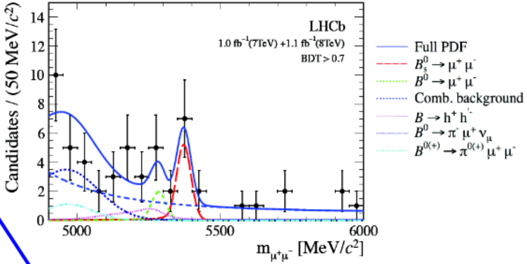
Use two variables:

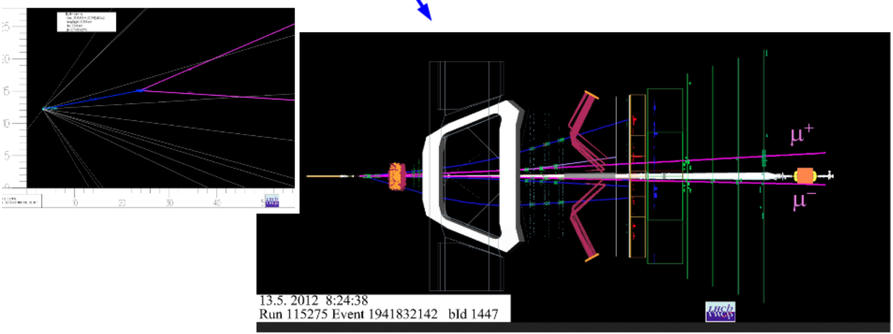
- $\mu^+\mu^-$ invariant mass. Resolution (24 MeV$/c^2$) is calibrated on data by interpolating between $\psi \to \mu^+\mu^-$, $\Upsilon \to \mu^+\mu^-$, and $B^0 \to hh$ as a cross-check.
- BDT that includes
  - B vertex quality
  - B vertex separation from PV
  - B flight direction angle
  - B impact parameter wrt. best PV
  - μ impact parameter wrt. any PV
  - Distance between muon tracks

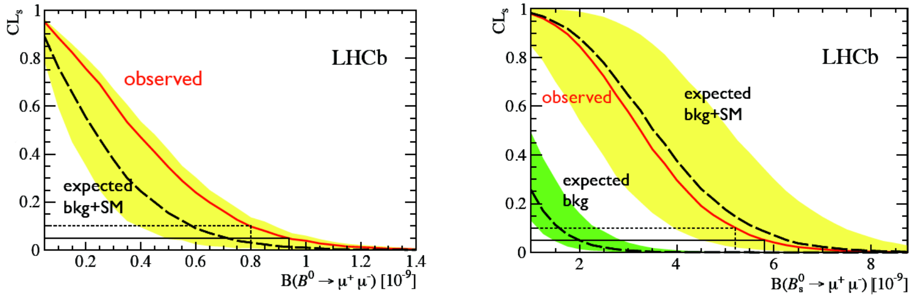
  Trained on simulation, calibrated in data ($B \to hh$ and sidebands).

Br normalisation channels: $B^0 \to K^+\pi^-$, $B^+ \to J/\psi K^+$.


LHCb
B^0_s window
B^0 window
$m_{\mu\mu}$ [MeV/c^2]
6000
5800
5600
5400
5200
5000
0
0.2
0.4
0.6
0.8
1
BDT


LHCb
1.0 fb^{-1}(7TeV) +1.1 fb^{-1}(8TeV)
BDT > 0.7
Candidates / (50 MeV/c^2)
$m_{\mu^+\mu^-}$ [MeV/c^2]
5000
5500
6000
Full PDF
$B^0_s \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
Comb. background
$B \to h^+h^{'-}$
$B^0 \to \pi^-\mu^+\nu_\mu$
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$


μ^+
μ^-
13.5. 2012 8:24:38
Run 115275 Event 1941832142 bId 1447



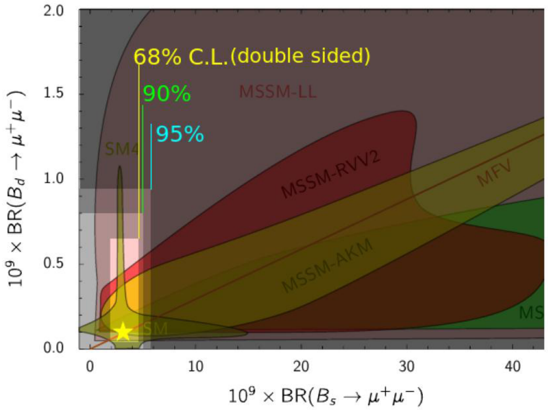
3.5σ evidence, $p = 5.3 \times 10^{-4}$.

	CDF	CMS	Atlas	LHCb	SM
Int. luminosity (fb^{-1})	10	4.9	2.4	1.0+1.1	
Br($B^0_d \to \mu^+\mu^-$), 95% CL ($\times 10^{-9}$)	4.6	1.8		0.94	
Br($B^0_d \to \mu^+\mu^-$), central value ($\times 10^{-9}$)					0.10 ± 0.01
Br($B^0_s \to \mu^+\mu^-$), 95% CL ($\times 10^{-9}$)	31	7.7	22		
Br($B^0_s \to \mu^+\mu^-$), central value ($\times 10^{-9}$)	13^{+9}_{-7}			$3.2^{+1.4+0.5}_{-1.2-0.3}$	3.5 ± 0.3

[PLB 713(2012)387, JHEP 1204(2012)033, LHCb-PAPER-2012-043]

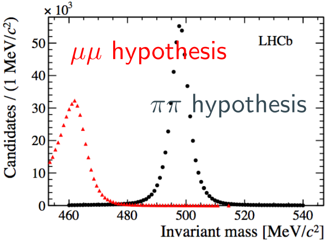
Rare decays: $B^0_{(s)} \to \mu^+\mu^-$

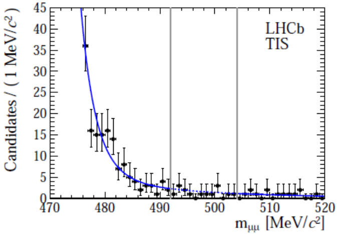
With the new result, we greatly restrict the phase space for possible SUSY scenarios:



With complete 2011+2012 samples, together with CMS and Atlas, we expect the first observation of $B_s \to \mu\mu$. In the upgraded phase, will enter the regime of precision measurement ($Br(B_d \to \mu\mu)/Br(B_s \to \mu\mu)$ is basically free from theory uncertainties)

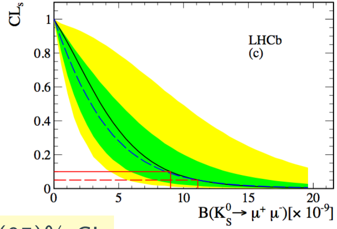
[arXiv:1209.4029]





Background from $K^0_S \to \pi^+\pi^-$ is shifted due to $\mu - \pi$ mass difference.

BDT trained on $K_S \to \pi^+\pi^-$ decays, same mode used for Br normalisation.



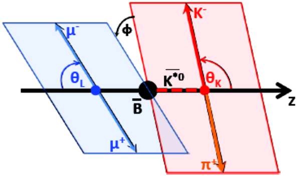
Measured: $Br(K^0_S \to \mu\mu) < 9(11) \times 10^{-9}$ @ 90(95)% CL

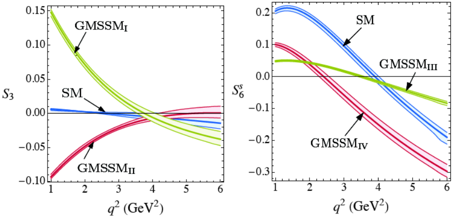
$\times 30$ better than latest result [CERN PS, PLB 44 (1973) 217]

SM expectation:

$Br(K^0_S \to \mu\mu) < (5.0 \pm 1.5) \times 10^{-12}$ [Isidori, Unterdorfer, JHEP 0401(2004)]

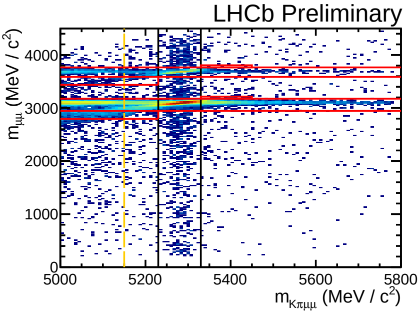
Rare decays: $B^0 \to K^* \mu^+ \mu^-$

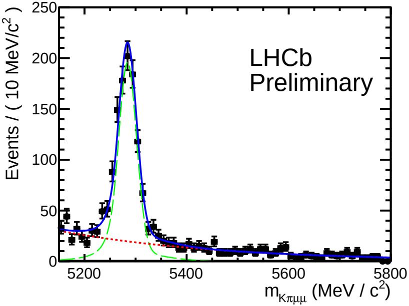




- Decay described by 3 angles, 6 helicity amplitudes (q^2-dependent). Two examples:
  - S_3: term, proportional to $\cos 2\phi$;
  - Forward-backward asymmetry $A_{FB} = -S_6$: term, proportional to $\cos\theta_\mu$. $q^2(A_{FB} = 0)$ (zero-crossing point) is well predicted by theory.
- Other interesting observables: CP asymmetries, isospin asymmetries as functions of q^2.

$1\ \text{fb}^{-1}$ at 7 TeV [LHCb-CONF-2012-008]

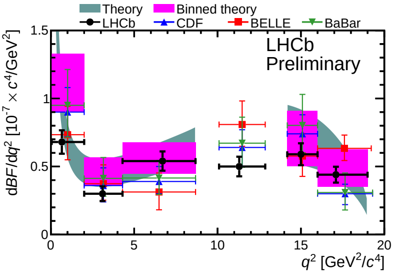


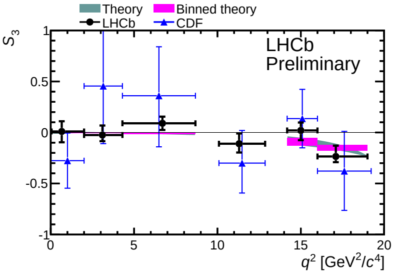


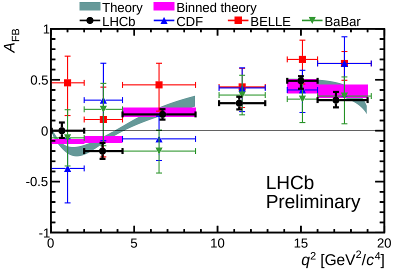
- Veto regions of $J/\psi K^*$ and $\psi' K^*$ (used to train selection).
- 900 ± 34 signal events in the full q^2 range.

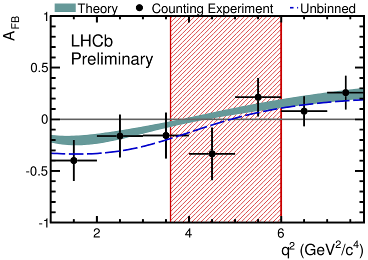
Rare decays: helicity amplitudes in $B^0 \to K^* \mu^+ \mu^-$

1 fb^{-1} at 7 TeV [LHCb-CONF-2012-008]









Angular observables are in a good agreement with SM.

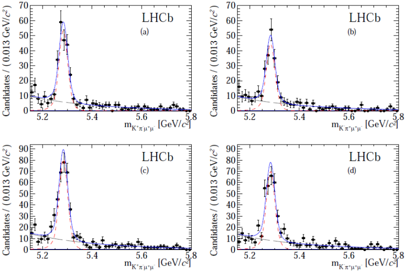
Rare decays: $\mathcal{CP}$ violation in $B^0 \to K^* \mu^+ \mu^-$

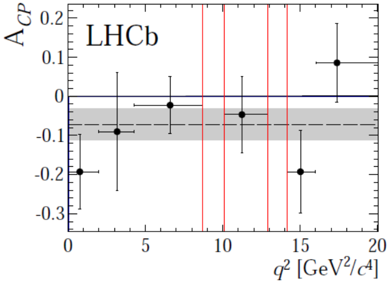
$\mathcal{CP}$-asymmetry: [arXiv:1210:4492]

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

- SM expectation: $\sim 10^{-3}$, can be enhanced up to 15% by new physics.
- Observed asymmetry can be affected by production and detection asymmetries, use $B^0 \to J/\psi K^{*0}$ to cancel them:

$$A_{\mathcal{CP}} = A_{raw}(B^0 \to K^{*0}\mu^+\mu^-) - A_{raw}(B^0 \to J/\psi K^{*0}) = -0.071 \pm 0.040 \pm 0.005$$



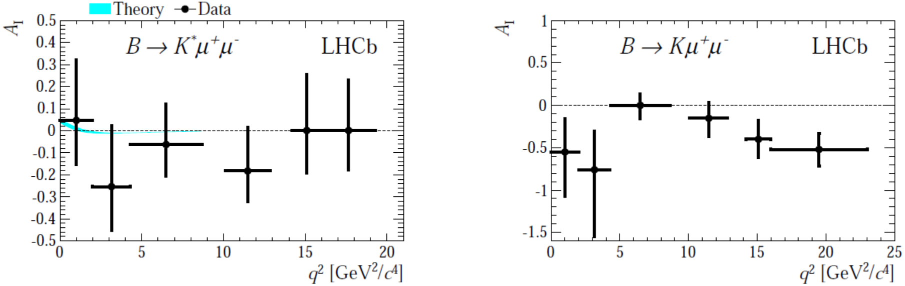


Rare decays: Isospin asymmetry in $B^0 \to K^{(*)}\mu^+\mu^-$

Isospin asymmetry: [JHEP 07 (2012) 133]

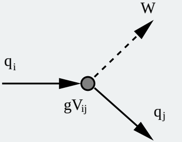
$$A_I = \frac{\Gamma(B^0 \to K^0\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^0 \to K^0\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)}$$

- SM expectation: $\sim -1\%$ below J/ψ, except for very low q^2 (O(10%)).
- $B^0 \to K^*\mu^+\mu^-$; well agrees with SM (no asymmetry)
- $B^0 \to K\mu^+\mu^-$: significant negative asymmetry (4.4σ deviation).



$\mathcal{CP}$ violation in the Standard Model

Cabibbo-Kobayashi-Maskawa mechanism



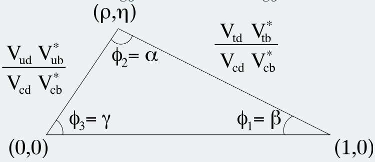
Charged current:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L) V_{CKM} \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W^+_\mu ,$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The Unitarity Triangle

Unitarity: $\frac{V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}} + 1 + \frac{V^*_{tb}V_{td}}{V^*_{cb}V_{cd}} = 0$



Sides and angles are observable:

$$\phi_1 \equiv \beta = \arg\left(\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$$

$$\phi_2 \equiv \alpha = \arg\left(\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right)$$

$$\phi_3 \equiv \gamma = \arg\left(\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

$\mathcal{CP}$ violation phenomenology

B meson system as an example.

Direct $\mathcal{CP}$ violation

Asymmetry in decay amplitudes:
$|\mathcal{A}_f/\overline{\mathcal{A}}_f| \neq 1$

$$A_{\pm} = \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)}$$

The only possibility for charged mesons.

$\mathcal{CP}$ violation in mixing

If transitions $B^0 \leftrightarrow \overline{B}^0$ are allowed:

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

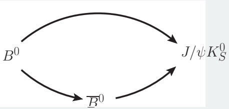
$\mathcal{CP}$ violation if $|q/p| \neq 1$
Can be observed in the asymmetry of "wrong-sign" decays $(\mu^{\pm}\mu^{\pm})$

$$A_{SL} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

Indirect $\mathcal{CP}$ violation (in interference)

Interference between $B^0 \to f$ and $B^0 \to \overline{B}^0 \to f$
Even if $|\mathcal{A}_f/\overline{\mathcal{A}}_f| = 1$ and $|q/p| = 1$, $\mathcal{CP}$ is violated if

$$\mathcal{I}m\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) \neq 0$$



Can be measured in the time-dependent asymmetry:

$$\frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}(\Delta t) = S_{f_{CP}} \sin(\Delta m_d \Delta t) + A_{f_{CP}} \cos(\Delta m_d \Delta t)$$

$\mathcal{CP}$ in B decays

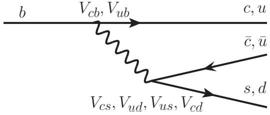
Trees with penguin admixture

$b \to c\bar{c}s$	$B^0 \to J/\psi K^0$	β
$b \to c\bar{c}d$	$B^0 \to J/\psi\pi^0,\ D^+D^-$	β_{eff}
$b \to u\bar{u}s$	$B^0 \to K\pi,\ K\pi\pi,\ KKK$	γ
$b \to u\bar{u}d$	$B^0 \to \pi\pi, \pi\rho, \rho\rho$	α

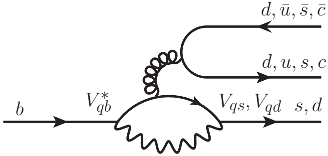
Pure penguins

$b \to s(\bar{s}s)$	$B^0 \to \phi K^0, KKK^0$	β_{eff}
$b \to s(\bar{d}d)$	$B^0 \to K^0\pi^0, K^0\pi\pi$	
$b \to d(\bar{s}s)$	$B^0 \to K^0K^0$	0

Two topologies with first-order weak transition:



Tree diagram



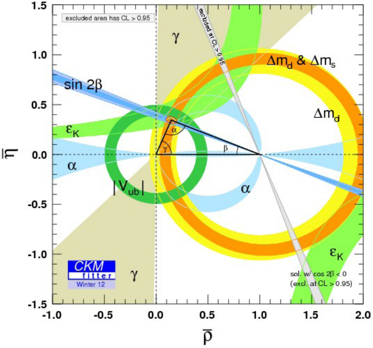
QCD penguin

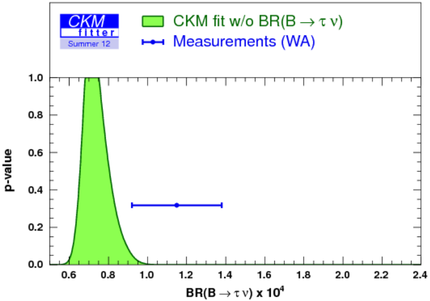
Pure trees

$b \to c(\bar{u}d),\ u(\bar{c}d)$	$B^0 \to D^0\pi^0, D^0\pi\pi, D\pi$	$\beta,\ 2\beta+\gamma$
$b \to c(\bar{u}s),\ u(\bar{c}s)$	$B^0 \to D^0K^0$	$2\beta+\gamma,\ \gamma$

CKM measurements: current status

Various experimental inputs (sides and angles of the Unitarity Triangle) are combined by averaging groups (CKMfitter and UTfit) to get the general picture. Reasonable consistency so far, although some tensions exist.

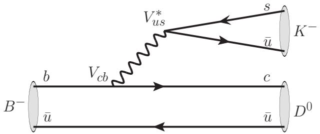




Precision of some measurements are much worse than the others.
Notably, γ is the least well-measured angle of the Unitarity Triangle.
Other unitarity triangles exist, though they are degenerate (e.g. related to B_s^0 mixing phase).

$\mathcal{CP}$ violation in $B \to DK$

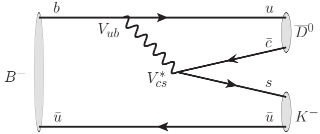
$B^- \to D^0 K^-$:



$A \sim V_{cb} V_{us}^* \sim A\lambda^3$

$+$

$B^- \to \overline{D}^0 K^-$:



$A \sim V_{ub} V_{cs}^* \sim A\lambda^3(\rho - i\eta)$

If D^0 and $\overline{D}^0$ decay into the same final state: $|\tilde{D}\rangle = |D^0\rangle + r_B e^{i\theta} |\overline{D}^0\rangle$

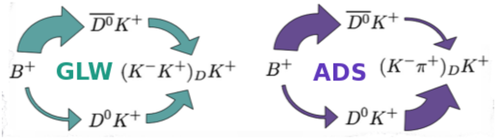
Relative phase for $B^+ \to DK^+$: $\theta = +\gamma + \delta$,

$B^- \to DK^-$: $\theta = -\gamma + \delta$.

Ratio of two amplitudes: $r_B = \left| \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| = \left| \frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*} \right| \times$ [Color supp] ~ 0.1

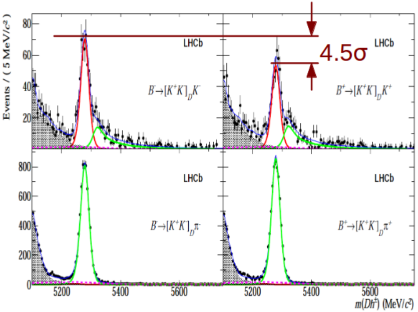
- **Gronau-London-Wyler (GLW)** [PLB 265, 172 (1991)]
  D in $\mathcal{CP}$-eigenstate ($D \to KK$, $\pi\pi$).
- **Atwood-Dunietz-Sony (ADS)** [PRL 78, 3257 (1997)]
  D Cabibbo-allowed ($D^0 \to K^- \pi^+$) and doubly Cabibbo-suppressed ($D^0 \to K^+ \pi^-$) states.
- **Giri-Grossman-Soffer-Zupan, Bondar (GGSZ, Dalitz)**
  D in three-body final state ($K_S \pi^+ \pi^-$). [PRD 68, 054018 (2003)]

$\mathcal{CP}$ violation in $B \to DK$, $D \to hh'$ decays

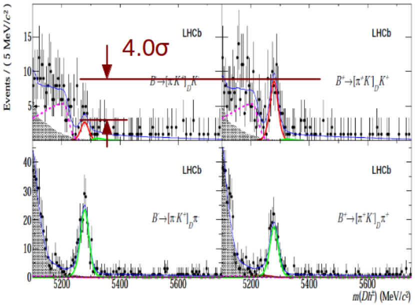


[Phys Lett B 712 (2012), 203]

$B^+ \to D^0 K^+$ and $B^+ \to \overline{D}^0 K^+$ followed by $D \to K^+K^-$ decay.



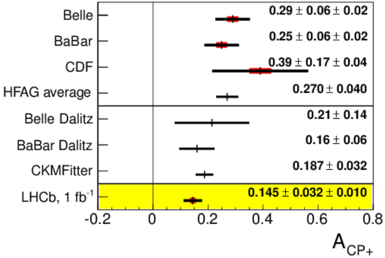
Suppressed $B^+ \to D^0 K^+$ followed by allowed $D^0 \to K^-\pi^+$ interferes with allowed $B^+ \to \overline{D}^0 K^+$ followed by suppressed $\overline{D}^0 \to K^-\pi^+$ decay.

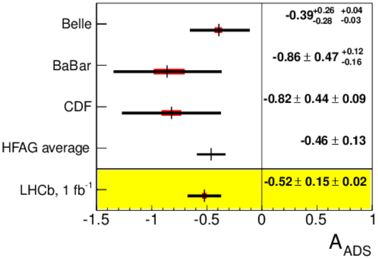


$\mathcal{CP}$ violation in $B \to DK$, $D \to hh'$ decays

Measure quantities that include information about γ, as well other unknown parameters (r_B, δ_B), e.g. $\mathcal{CP}$ asymmetries ($A = \frac{\Gamma(B^-)-\Gamma(B^+)}{\Gamma(B^-)+\Gamma(B^+)}$):

$$A_{CP} = \frac{2r_B \sin\delta_B \sin\gamma}{1+r_B^2+2r_B \cos\delta_B \cos\gamma} \qquad A_{ADS} = \frac{2r_B r_D \sin(\delta_B+\delta_D) \sin\gamma}{r_B^2+r_D^2+2r_B r_D \cos(\delta_B+\delta_D) \cos\gamma}$$





In principle, parameters measured in $B \to DK$, $D \to hh$ decays (asymmetries presented here, as well as ratios such as $R = \frac{\Gamma(B\to D(hh)K)}{\Gamma(B\to D(K\pi)K)}$) are sufficient to constrain γ.

However, such a measurement suffers from discrete ambiguities. There is a technique free from this limitation: Dalitz plot analysis of three-body D^0 decay.

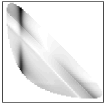
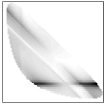
$B^+ \to DK^+$, $D \to K_S^0\pi^+\pi^-$ Dalitz plot analysis

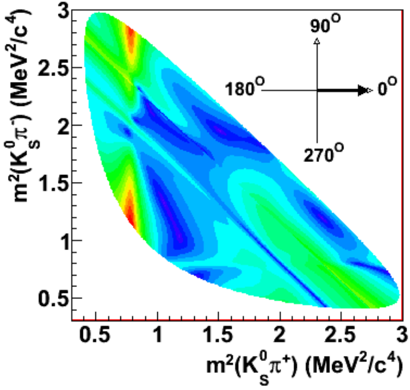
Giri, Grossman, Soffer, Zupan, PRD 68, 054018 (2003)
Bondar, Belle Dalitz analysis meeting (2002)

$D \to K_S^0\pi^+\pi^-$ Dalitz distribution:
$d\sigma(m_+^2, m_-^2) \sim |A|^2 dm_+^2 dm_-^2$
where $m_\pm^2 = m_{K_S\pi^\pm}^2$

$\mathcal{CP}$ conservation in D decays:
$\overline{A}_D(m_+^2, m_-^2) = A_D(m_-^2, m_+^2)$

D decay amplitude from $B^+ \to DK^+$:
$A_B(m_+^2, m_-^2) =$


$+ r_B e^{i\delta_B \pm i\gamma}$




Rotation of phase $\delta_B + \gamma$
$r_B = 0.1$

$D \to K_S^0\pi^+\pi^-$ amplitude is obtained from $D^{*\pm} \to D\pi^\pm$, parametrized by the isobar model. Only $|f_D|^2$ is observable $\Rightarrow$ Model uncertainty.

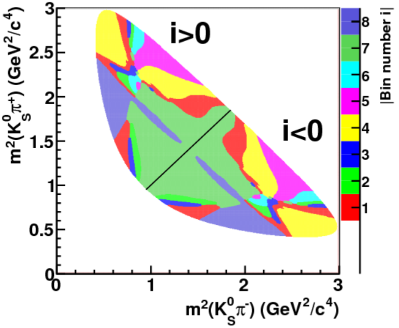
Model-independent Dalitz plot analysis

Solution: divide phase space into bins, work with the number of events in bins.

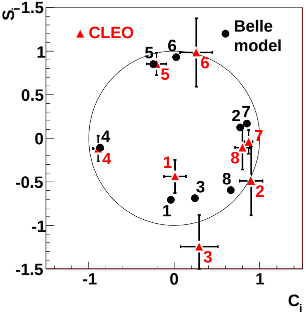
[A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018 (2003)]

[A. Bondar, A. P. EPJ C **47**, 347 (2006); EPJ C **55**, 51 (2008)]

Average strong phase difference in bins: $c_i = \langle \cos \Delta\delta_D \rangle$, $s_i = \langle \sin \Delta\delta_D \rangle$ **measured** in quantum-correlated $\psi(3770) \to D\overline{D} \to (K^0_S\pi^+\pi^-)_D(K^0_S\pi^+\pi^-)_{\overline{D}}$ decays (CLEO).



Optimum phase space binning (16 bins, $\sim$ constant phase difference across each bin)

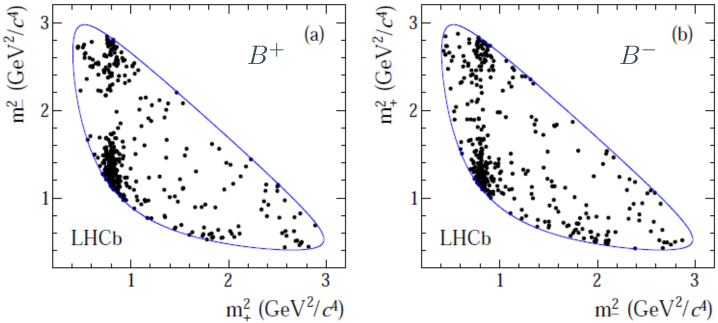


c_i, s_i measured and predicted by the model [Belle, PRD 85, 112014 (2012)]

$B \to DK$, $D \to K_S^0 h^+ h^-$ at LHCb

[arXiv:1209.5869]

Dalitz plots for $D^0 \to K_S^0 \pi^+ \pi^-$ from $B^\pm \to DK^\pm$. Can you see the difference between B^+ and B^-?

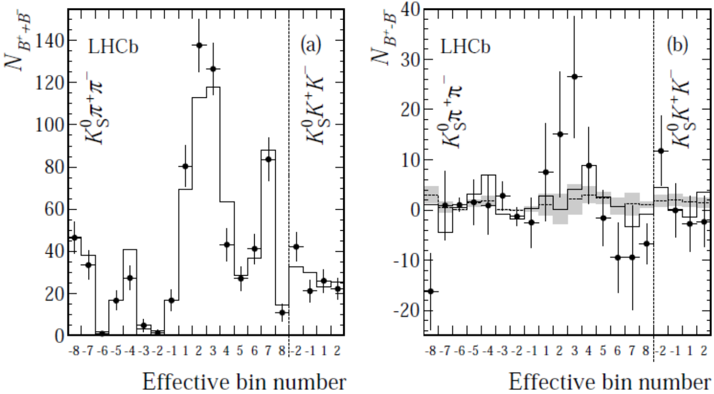


Count the number of events in binned plots, separately for B^+ and B^-.
Same with $D \to K_S^0 K^+ K^-$ plots.

$B \to DK$, $D \to K_S^0 h^+ h^-$ at LHCb

[arXiv:1209.5869]

Asymmetry in the number of events in bins manifests presence of CP violation.

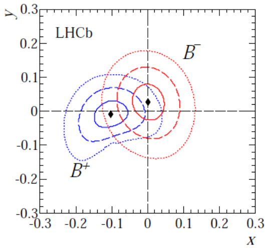


Max. likelihood fit to obtain parameters $x_\pm$, $y_\pm$ in the amplitude:

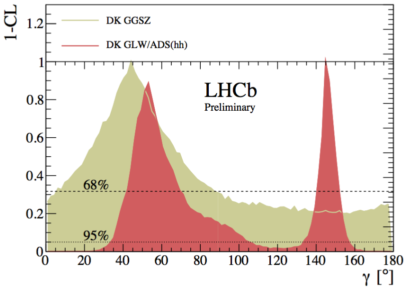
$$A_{B^\pm} = A_D + (x_\pm + iy_\pm)\overline{A}_D, \quad x_\pm = r_B \cos(\pm\gamma + \delta_B),\ y_\pm = r_B \sin(\pm\gamma + \delta_B)$$

$B \to DK$, $D \to K^0_S h^+ h^-$ at LHCb

[arXiv:1209.5869] [LHCb-CONF-2012-032]



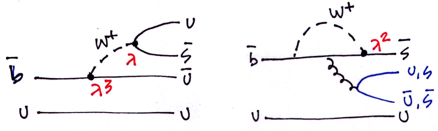
Constraints on (x, y) obtained in analysis of $B \to DK$, $D \to K^0_S h^+ h^-$.



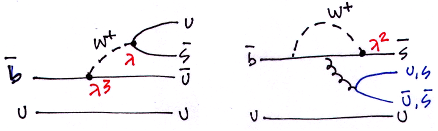
γ constraints for GGSZ (D Dalitz) and ADS+GLW ($D \to hh$) analyses.

Combination of all modes (also including measurement with $D \to K3\pi$ not presented here) gives: $\gamma = 71^{+17}_{-16}{}^\circ$.
Similar precision achieved at B-factories, world average should give precision $\sim 10^\circ$.
Good prospects for measurement with 1° precision with upgraded LHCb and super flavour factories.

Charmless B decays, in principle, also give access to the value of γ, although they can be affected by the New Physics due to penguin contribution:



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

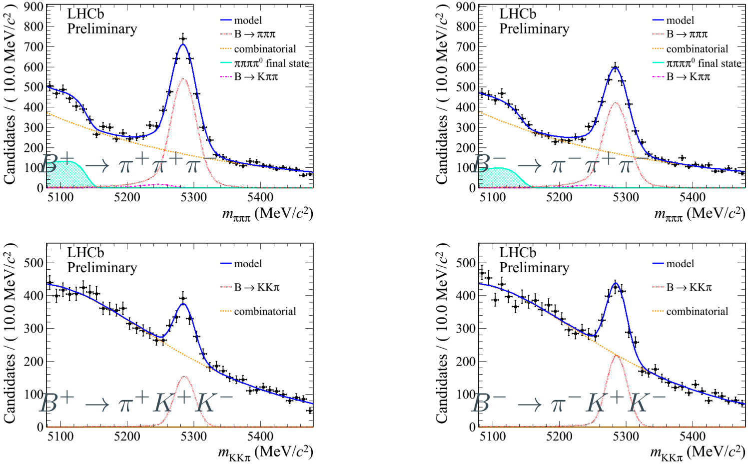


$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

Study integrated $\mathcal{CP}$ asymmetries, as well as local asymmetries over the phase space.

$$A_{CP} = \frac{\Gamma(B^{-}) - \Gamma(B^{+})}{\Gamma(B^{-}) + \Gamma(B^{+})}$$

[LHCb-CONF-2012-028]



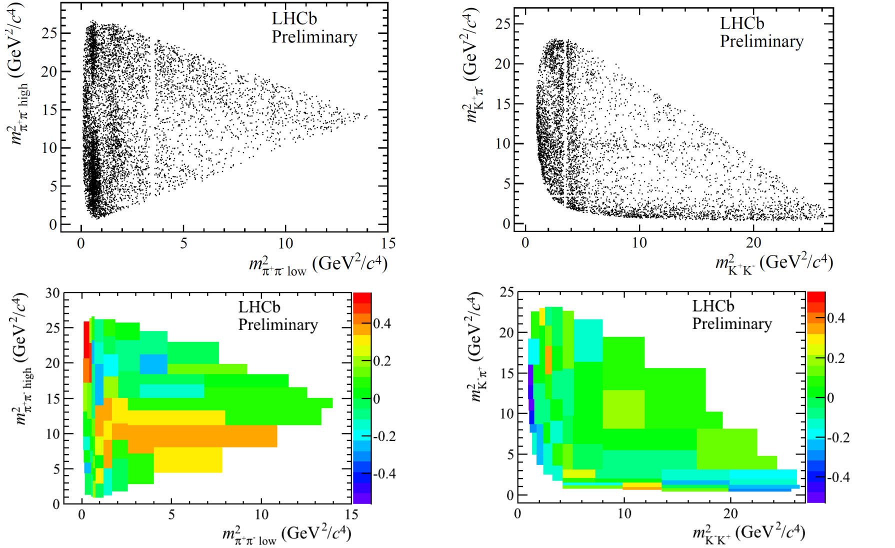
Integrated asymmetries: (preliminary)

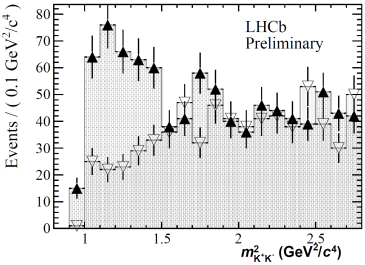
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +\,0.120 \pm 0.020 \pm 0.019 \pm 0.007(J/\psi K^{+})$$

$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -\,0.153 \pm 0.046 \pm 0.019 \pm 0.007(J/\psi K^{+})$$

$\mathcal{CP}$ violation in $B \to hhh$

Investigate local $\mathcal{CP}$ asymmetry in bins of the Dalitz plot. [LHCb-CONF-2012-028]





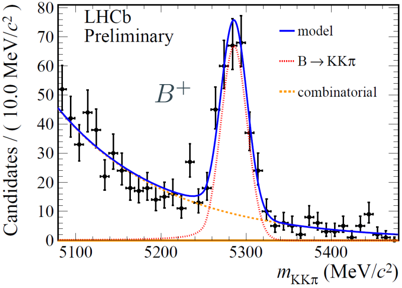
[LHCb-CONF-2012-028]

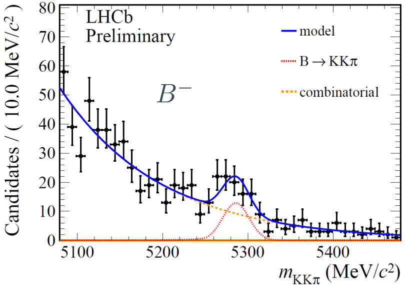
Very large **negative** $\mathcal{CP}$ asymmetry in low KK mass region not associated to resonances.

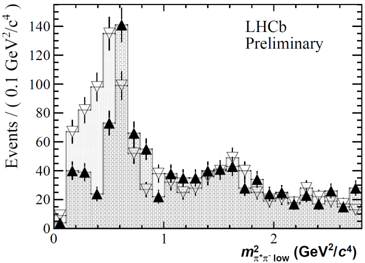
$$A_{CP} = -0.671 \pm 0.067 \pm 0.028 \pm 0.007 (J/\psi K)$$

(preliminary)

$> 9\sigma$ significance







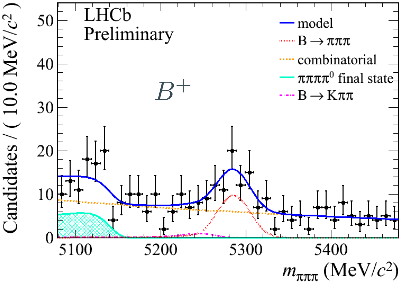
[LHCb-CONF-2012-028]

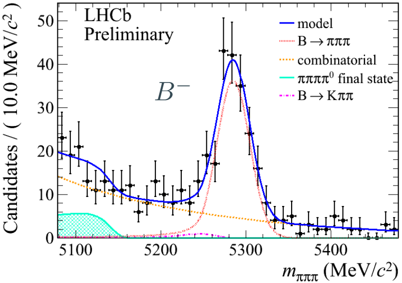
Very large **positive** $\mathcal{CP}$ asymmetry
in low $\pi\pi$ mass region
not associated to resonances.

$$A_{CP} = +0.622 \pm 0.075 \pm 0.032 \pm 0.007 (J/\psi K)$$

(preliminary)

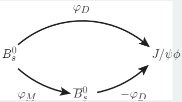
$> 7\sigma$ significance



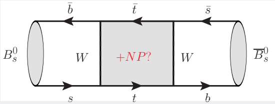


Motivation

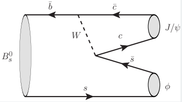
Measure CP violation in the interference of decays with and w/o mixing



φ_M:



φ_D:

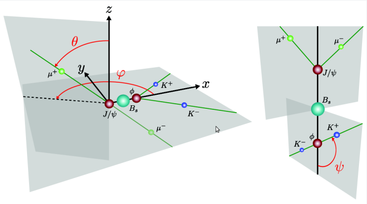


CP violating phase $\varphi_s = \varphi_M - 2\varphi_D$; $\varphi_s^{SM} \simeq -2\beta_s = 0.0363 \pm 0.0017$

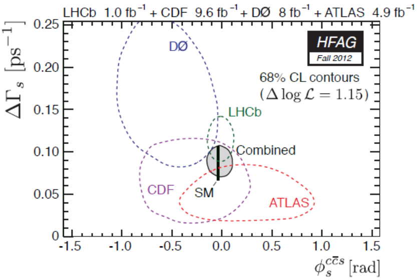
Measurement technique

- Time-dependent flavor-tagged decay rate
- Angular analysis to distinguish between CP-even and CP-odd components

7D fit! (m, t, tag, mistag rate, 3 angles)



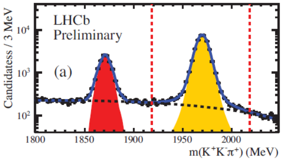
[LHCb-CONF-2012-002]

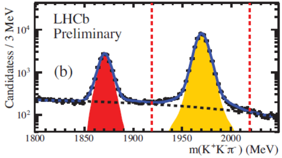


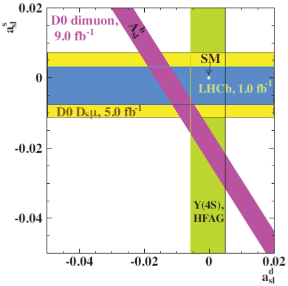
$$\phi_s = -0.001 \pm 0.101 \pm 0.027$$
$$\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066$$
$$\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006$$

- Two modes are used in ϕ_s measurement:
  - $B_s \to J/\psi\phi$: $P \to VV$ mode, contains both $\mathcal{CP}^+$ and $\mathcal{CP}^-$ components, angular analysis to disentangle them.
  - $B_s \to J/\psi\pi\pi$: dominated by $\mathcal{CP}^-$ amplitude, no angular analysis.

Time-dependent analysis in both cases, flavour tagging to identify the initial flavour of B_s.







[LHCb-CONF-2012-022]

Semileptonic asymmetry probes $\mathcal{CP}$ violation in mixing. Study $D_s^+\mu^-$ and $D_s^-\mu^+$ combinations.

$$A_{\rm meas} = \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a_{\rm sl}^s}{2} + \left[a_{\rm p} - \frac{a_{\rm sl}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh\frac{\Delta\Gamma_s t}{2}\epsilon(t)dt},$$

Fast B_s oscillations wash out production asymmetry.

$$a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\%$$

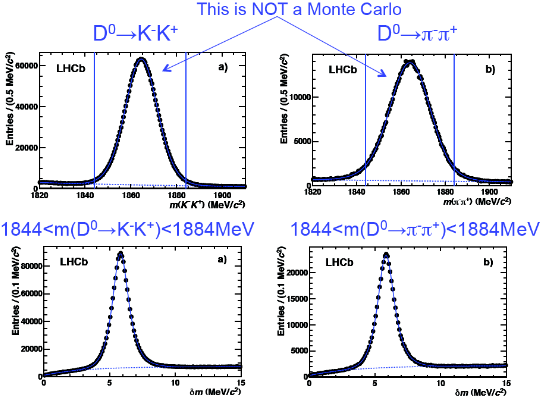
Earlier, D0 measured significant dimuon asymmetry [PRD84,052007(2011)]

$$A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\% \sim a_{sl}^d + a_{sl}^s$$

We are currently consistent with both SM and D0 measurement.

0.62 fb^{-1} at 7 TeV [PRL 108, 111602 (2011)]

Measure difference of $\mathcal{CP}$ asymmetries between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$.



- Use $D^{*\pm} \to D^0\pi^\pm$ as a source of flavour-tagged D^0.
  - 1.44M $D^0 \to \pi\pi$
  - 0.38M $D^0 \to KK$
- Production and detection asymmetries cancel in $\Delta A_{\mathcal{CP}}$.

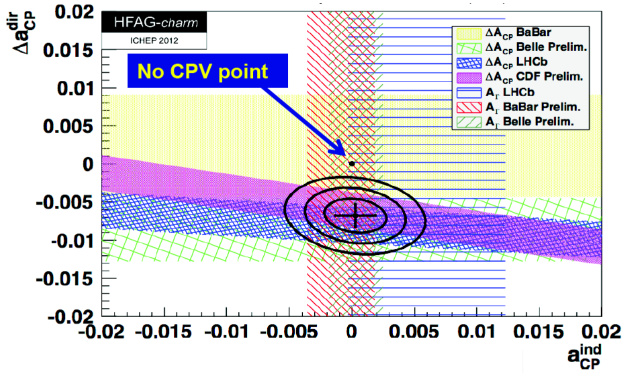
$$\Delta A_{\mathcal{CP}} = A_{\mathcal{CP}}(KK) - A_{\mathcal{CP}}(\pi\pi) = -(0.82 \pm 0.21 \pm 0.11)\%$$

3.5σ evidence for $\mathcal{CP}$ violation.

$\Delta A_{\mathcal{CP}}$ contains contributions of direct and indirect $\mathcal{CP}$ violations:

$$\Delta A_{\mathcal{CP}} = \Delta a^{dir}_{\mathcal{CP}} + \frac{\Delta\langle t\rangle}{\tau} a^{ind}_{\mathcal{CP}}$$

Contribution of indirect CPV depends on the acceptance as a function of proper time.

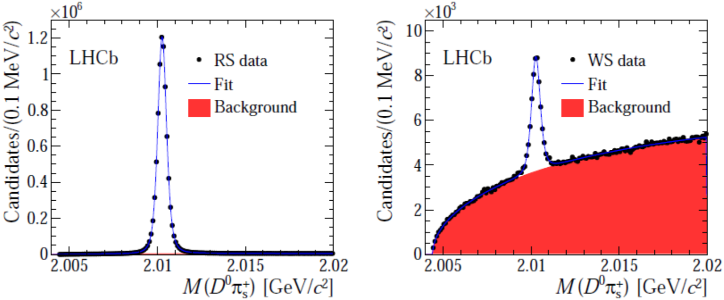


Negative asymmetry is confirmed (with less precision) by Belle and CDF.

Charm mixing

[arXiv:1211.1230, LHCb-PAPER-2012-038]

Use $D^{*\pm} \to D^0\pi^\pm$, $D^0 \to K^-\pi^+$ (RS) or $D^0 \to K^+\pi^-$ (WS) decays



WS contribution is due to doubly Cabibbo-suppressed amplitude (at $t = 0$) and mixing ($t > 0$).

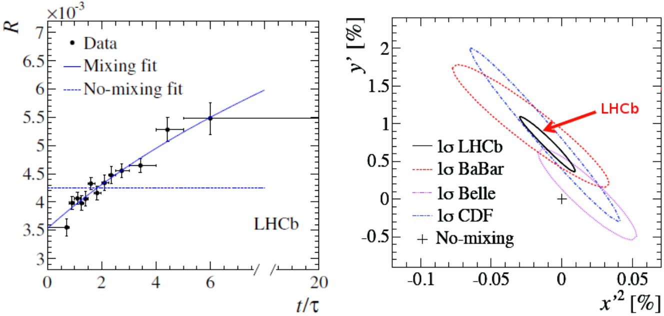
Measure time-dependent WS/RS decay rate

$$R(t) = R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\frac{t^2}{\tau^2}$$

[arXiv:1211.1230, LHCb-PAPER-2012-038]

Use $D^{*\pm} \to D^0\pi^\pm$, $D^0 \to K^-\pi^+$ (RS) or $D^0 \to K^+\pi^-$ (WS) decays
Measure time-dependent WS/RS decay rate

$$R(t) = R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2+y'^2}{4}\frac{t^2}{\tau^2}$$



$R_D = (3.52 \pm 0.15) \times 10^{-3}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$, $x'^2 = (-0.09 \pm 0.13) \times 10^{-3}$

No-mixing hypothesis is excluded at 9.1σ.
First observation of charm mixing in a single analysis.

Summary

- First evidence of $B_s \to \mu^+\mu^-$ decay with 1(7 TeV)+1(8 TeV) fb^{-1}, $Br = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$ (3.5σ). We exclude large NP contributions to $B_s \to \mu^+\mu^- \Rightarrow$ no TeV-scale SUSY with large $\tan\beta$. Looking forward to LHCb and CMS updates with entire 2012 data.
- Upper limit on $K^0_S \to \mu\mu$ has been improved by 30 times since the previous measurement. Entering the region where constraint becomes interesting, though SM is still a long way to go.
- Angular distributions in $B^0 \to K^*\mu\mu$ are perfectly consistent with SM, but large isospin asymmetry in $B^0 \to K\mu\mu$ may suggest something interesting.
- Improving precision of Unitarity Triangle measurements. Constraint on γ, which is a SM reference point, reaches precision of B factories. Good prospects for precision measurement (1°) in future.
- Interesting signatures with huge $\mathcal{CP}$ violation in charmless three-body B decays. Need more theory input, as well as amplitude analysis.
- Significant $\mathcal{CP}$ asymmetry in $D \to hh$ decays may or may not be the sign of New Physics.