LHCb Overview

On behalf of the LHCb Collaboration

QFTHEP-2013 Conference
Saint Petersburg, Russia

Sajan Easo
June 25, 2013

RAL

LHCb Overview

- Introduction
    - LHCb detector, Performance of its sub systems
- Focus on results from
    - CP violation in $B_s \rightarrow J/\psi KK$, $B^+ \rightarrow D K$ and other B-decays
    - CP violation in charm decays

Most results from 2011 dataset

- Other selected results
- LHCb Upgrade
- Summary

More Info

- 3 other LHCb presentations at this conference
- http://lhcb.cern.ch

Beauty and Charm production at LHC

- Huge production of b and c quarks at $\sqrt{s} = 7\,\mathrm{TeV}$

- LHCb: Forward spectrometer : $2 < \eta < 5$

In LHCb acceptance :

$$\sigma(\mathrm{pp}) = 59.9 \pm 2.7\ \mathrm{mb}$$

J. Instrum. 7 (2012) P01010

$$\sigma(\mathrm{pp} \to \mathrm{b}\bar{\mathrm{b}}\mathrm{X}) = (75.3 \pm 5.4 \pm 13.0)\ \mu\mathrm{b}$$

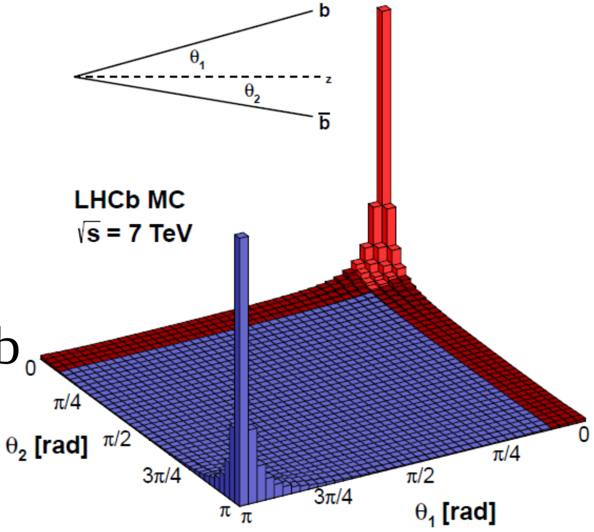
for $2<\eta<6$

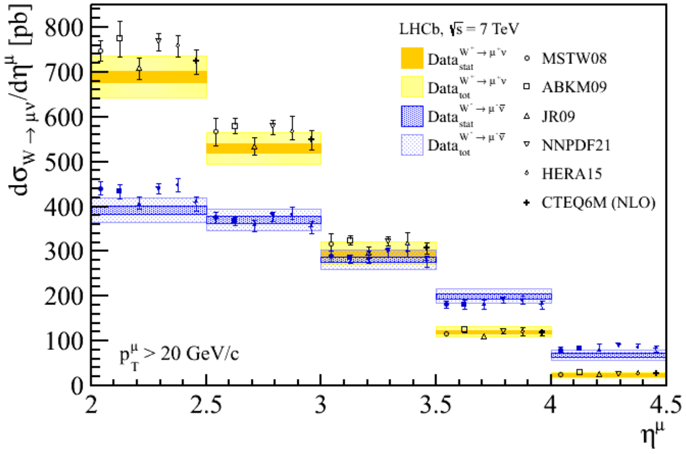
Phys.Lett. B 694 (2010) 209 -216

$$\sigma(\mathrm{pp} \to \mathrm{c}\bar{\mathrm{c}}\mathrm{X}) = (1419 \pm 12(\mathrm{stat}) \pm 116(\mathrm{syst}) \pm 65(\mathrm{frag}))\ \mu\mathrm{b}$$

for P_T< 8 GeV/c, 2.0<y<4.5

Nucl. Phys. B 871 (2013)1-20





W differential cross-section

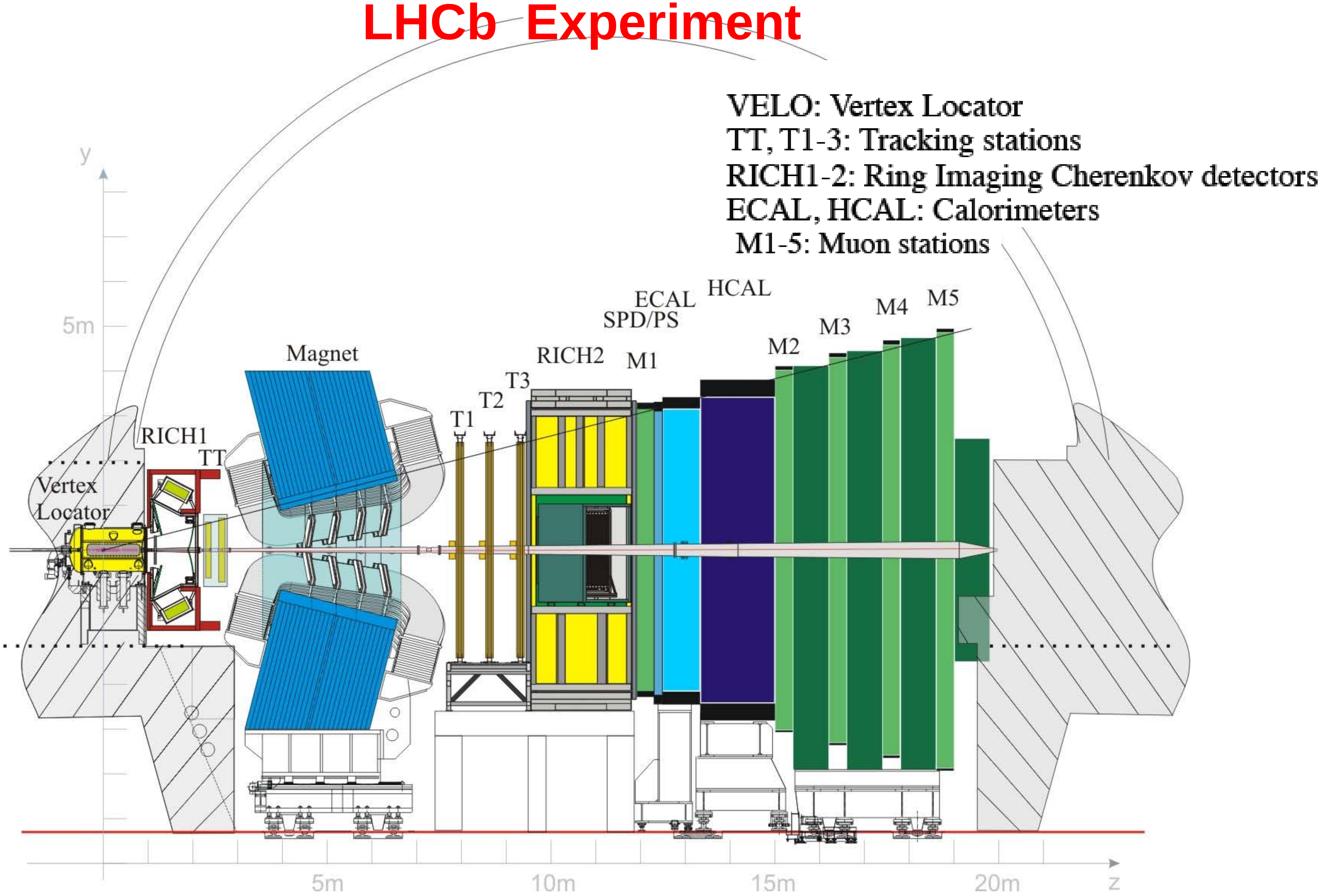
- LHCb: Mainly flavour physics,
  but not limited to this.
  - QCD, Electroweak Physics

$$\mathrm{W}^+ \to \mu^+ \nu$$

$$\mathrm{W}^- \to \mu^- \bar{\nu}$$

JHEP 06(2012)058

LHCb Experiment



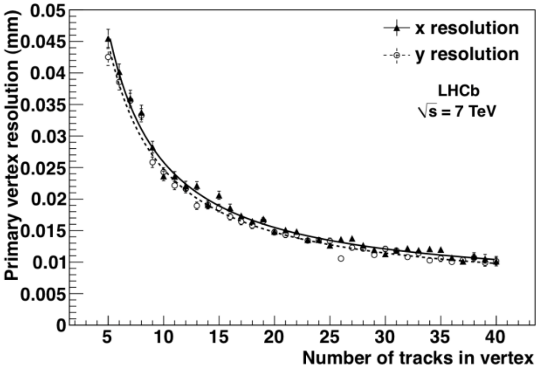
~ 760 Members from 60 institutes in 16 countries

~ Includes St. Petersburg (Gatchina PNPI), Moscow(ITEP,SINP MSU, INR RAN), Protvino (IHEP) and Novosibirsk (SB RAS) from Russia

Detectors in LHCb : Velo

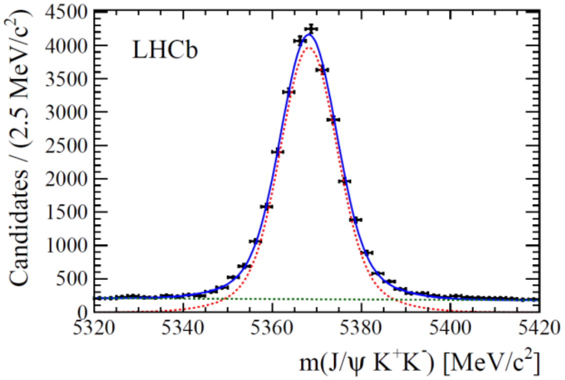
- 21 stations measuring R and ϕ coordinates, with silicon strips
- 8 mm from the beam during data taking.

Vertex resolution: for 25 tracks σ_x ~16 μm , σ_y ~ 16 μ m
σ_z ~ 76 μm



J. Instrum. 7 (2012) P01010

$B_s \rightarrow J/\psi\ K^+K^-$



B_s mass resolution=6 MeV/c^2

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LHCb beholds more than beauty

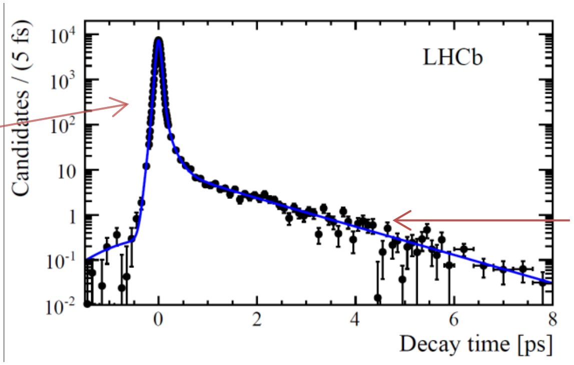
INTERVIEW

INDUSTRY

NUCLEAR REACTORS

April 2012

Propertime resolution (Velo+tracking)



Prompt J/ψ background

$B_s \rightarrow J/\Psi\ K^+K^-$

arXiv:1304.2600

Resolution from prompt J/ψ:
σ_t = 45 fs

Decay time in $B_s \rightarrow J/\psi\ KK$

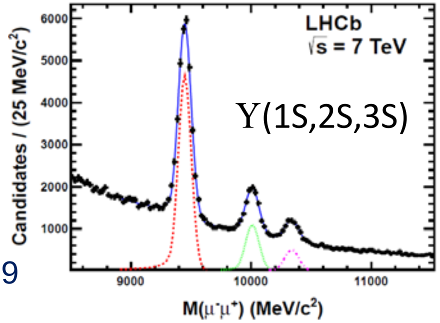
Detectors in LHCb

Tracking System:

- Stations upstream and downstream of the magnet.
- Upstream and inner downstream parts: Silicon
- Outer downstream part: Drift chambers
- Magnetic field reversed for different data taking periods.
- Momentum resolution :

  $\Delta p/p = 0.35 \rightarrow 0.55$ %

$\sigma_{\mu\mu}$=43 MeV/c^2 for Υ(1S)



arXiv:1202.6579

Muon Stations:

5 stations, excellent μ/π separation:,
single hadron mis-id rate: 0.7%

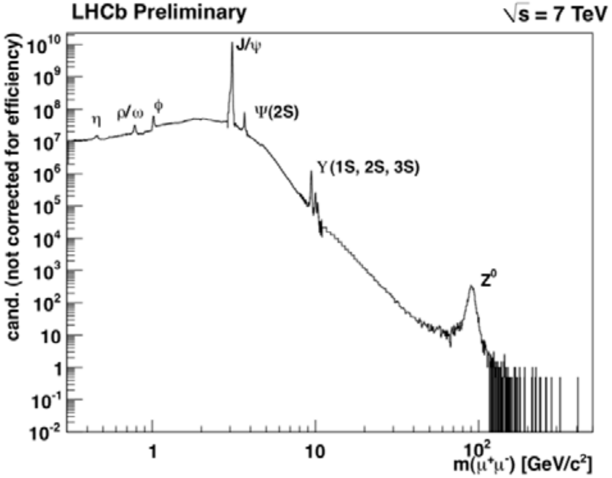
Calorimeters:

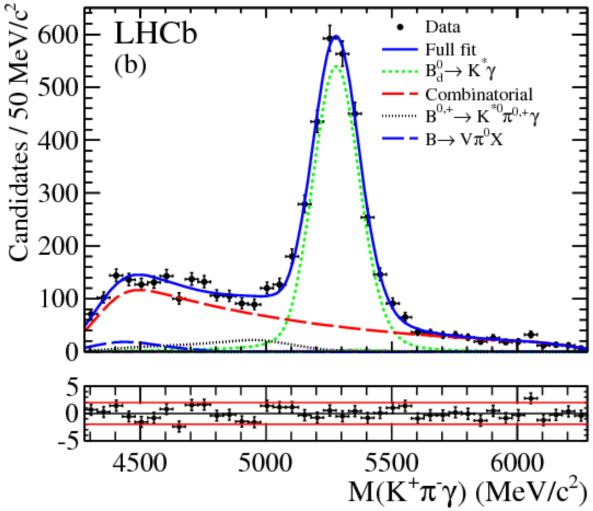
ECAL: Shashlik technology with Pb-Scintillator

$s(E)/E = 10\%/\sqrt{E} + 1\%$

HCAL: Fe-Scintillator , $s(E)/E = 80\%/\sqrt{E} + 10\%$

‘raw’ dimuon mass spectrum





$B^0 \rightarrow K^* \gamma$

Nucl.Phys. B 867 (2013) 1-18

Detectors in LHCb

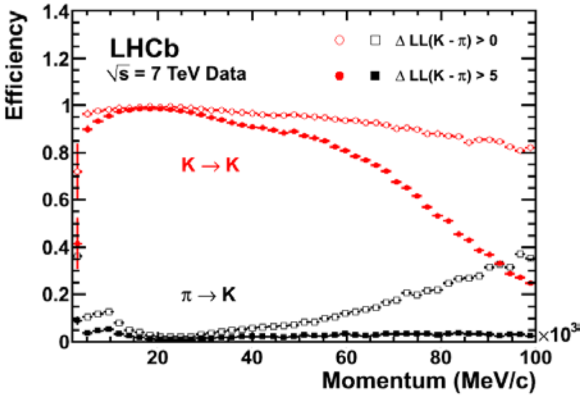
EPJ C (2013), 73:2431

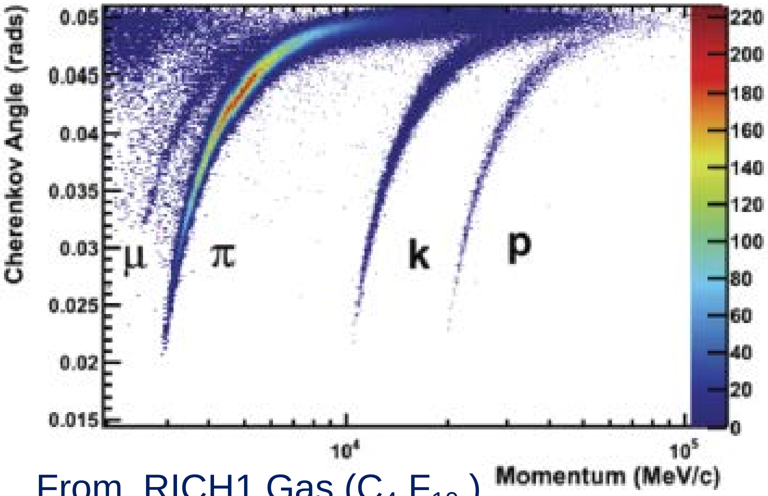
Particle Identification:

Two RICH detectors covering a momentum range 1-100 GeV/c
with 3 radiators: aerogel, $C_4\,F_{10}$, CF_4

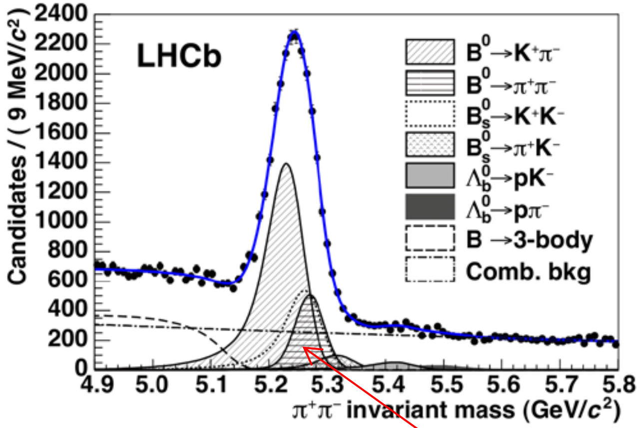
Cover picture of EPJ C vol3 , 5, May 2013

PID performance from calibration data

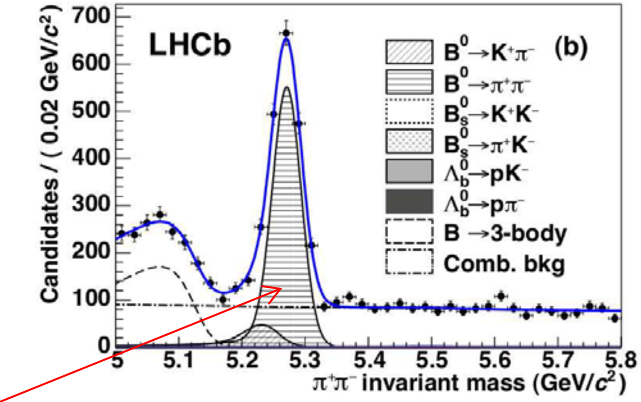




From RICH1 Gas ($C_4\,F_{10}$)



Before RICH PID



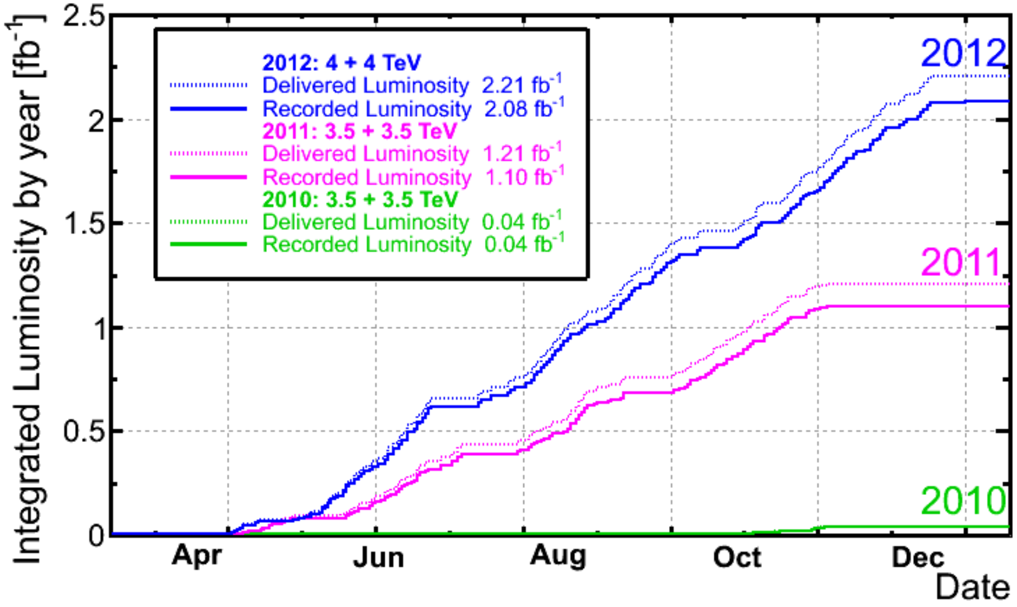
After RICH PID

JHEP 10 (2012) 037

Without RICH PID, the $B^0 \rightarrow \pi^+\pi^-$ is completely dominated by $B^0 \rightarrow K^+\pi^-$

2010-12 Data taking

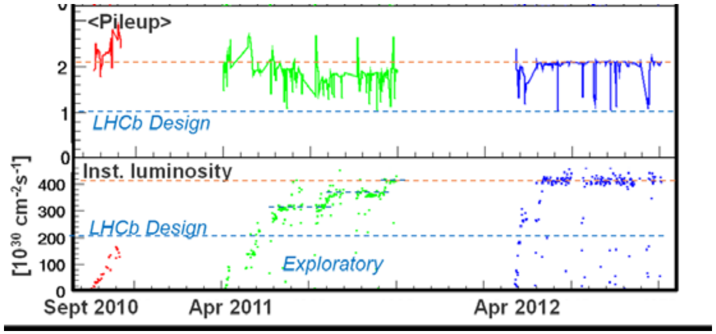
LHCb integrated luminosity during 2010-12



Excellent efficiency

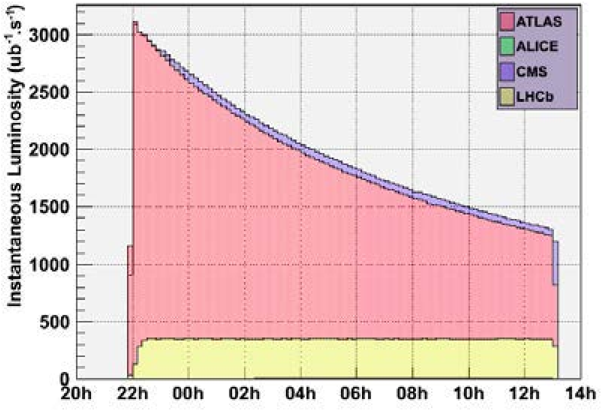
Recorded/delivered ≈ 94 %

$\int L$ =0.035 + 1.1 + 2.0 fb^{-1}
in 2010 + 2011+ 2012



Automatic luminosity leveling

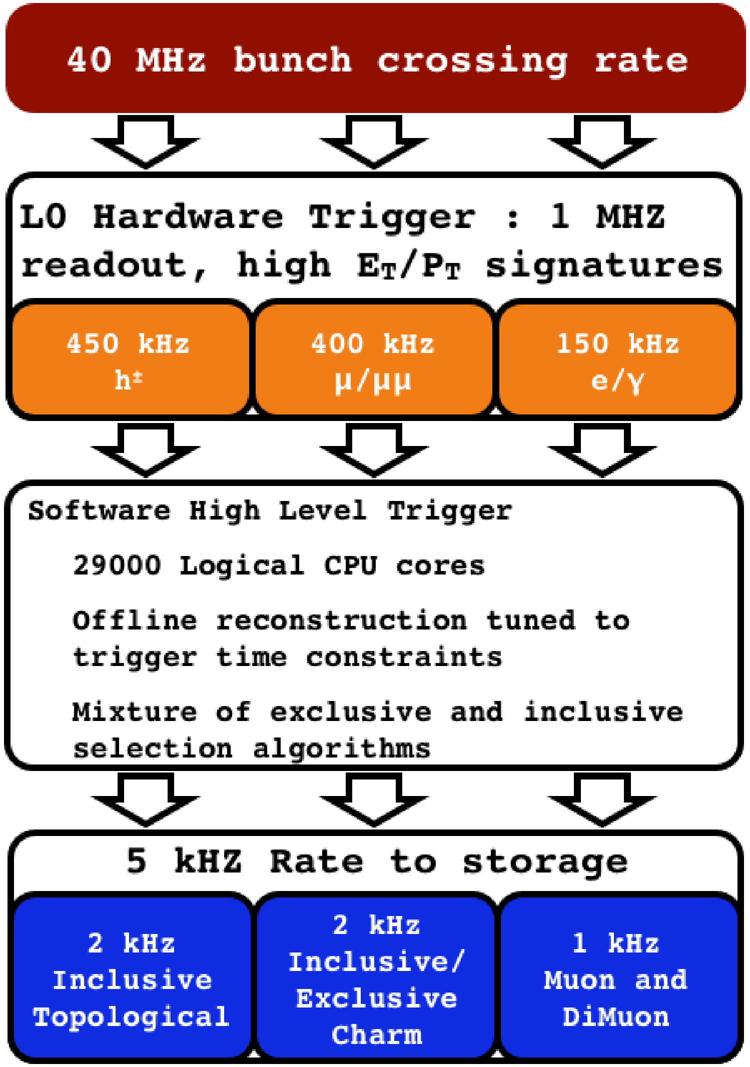
obtained through vertical beam displacements



Luminosity: Design: 2 x 10 ^{32} cm^{-2} s^{-1}
Actual: Typically 4 x 10 ^{32} cm^{-2} s^{-1}

We managed with higher occupancies than those foreseen from LHCb design

LHCb Trigger System



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

450 kHz
$h^\pm$

400 kHz
$\mu/\mu\mu$

150 kHz
e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

2 kHz
Inclusive
Topological

2 kHz
Inclusive/
Exclusive
Charm

1 kHz
Muon and
DiMuon

Goal: To select interesting beauty and charm decays while maintaining the managable data rates

Level-0: Hardware

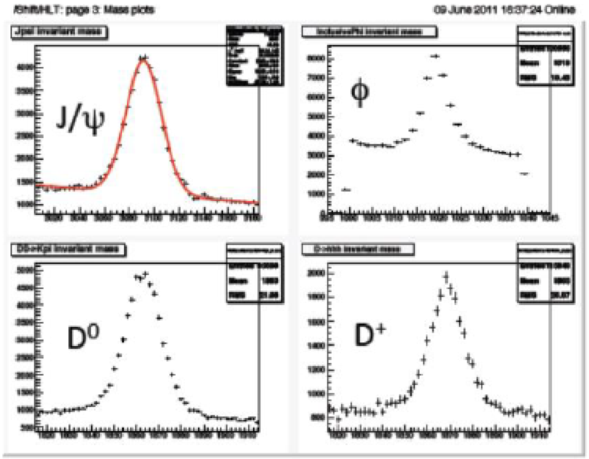
- Using custom electronics to get 1 MHz output
- Largest P_T (or E_T) of hadron/e/γ/μ used for selection
- Typical thresholds 1.5 → 3.5 GeV/c

HLT: Software

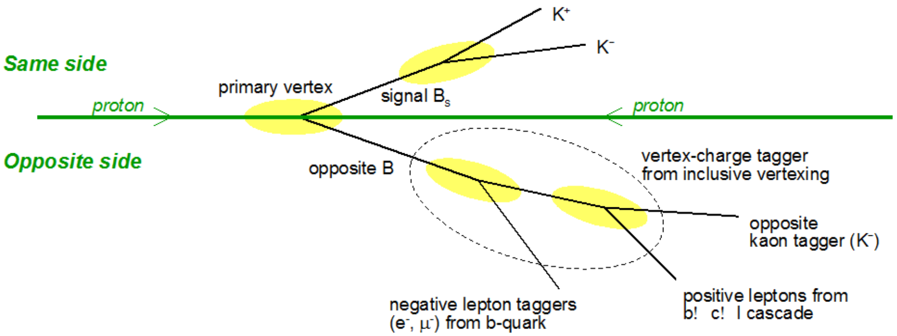
- Stage1: Partial event reconstruction, selection based on IP, P_T
- Stage 2: Full event reconstruction, apply mass cuts

„On-line charm and strange signals”

Signal/background ratio used to inspect data quality



LHCb Data Analysis



- Selection of events:
  - Event kinematics+ topology information

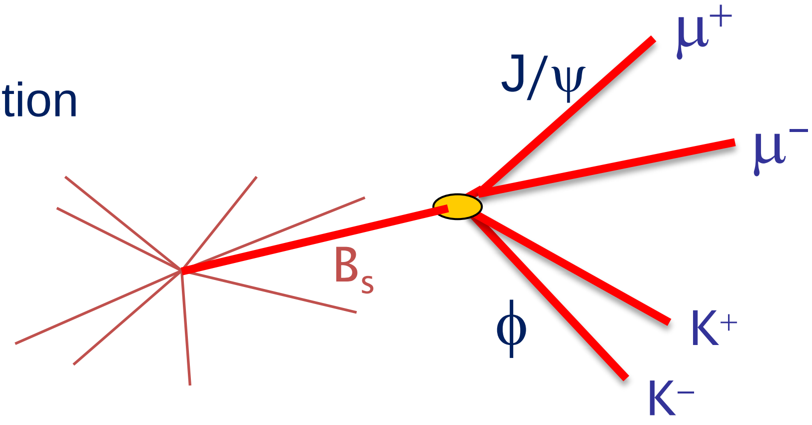
    P, P_T of the tracks,
    Vertex quality,
    impact parameters of tracks, etc

  - PID information
  - Cut based or multivariate selection

    Boosted Decision Tree (BDT),
    Neurobayes etc.

  - Optimize selection

    Using MC data
    Using small sample of real data



- Flavour tagging , if needed

LHCb Data Analysis

Indirect search for New Physics (NP)

- Measure FCNC transitions, where NP is likely to emerge
  Example: OPE expansion for b →s transitions

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{left-handed\ \ part} + \underbrace{C_i^{'}(\mu) O_i^{'}(\mu)}_{\substack{right-handed\ \ part \\ \text{suppressed in SM}}}]$$

Misiak 93,
Buras, Münz 95

NP may
- modify Wilson coefficients , $C_i^{'}$
- add new operators, $O_i^{'}$

- Measure CKM elements in different ways
  Any inconsistency may be a sign of NP

LHCb Data Analysis

LHCb-rare decays:
Next talk by Nigel Watson,
Talk by Indrek Sepp this afternoon

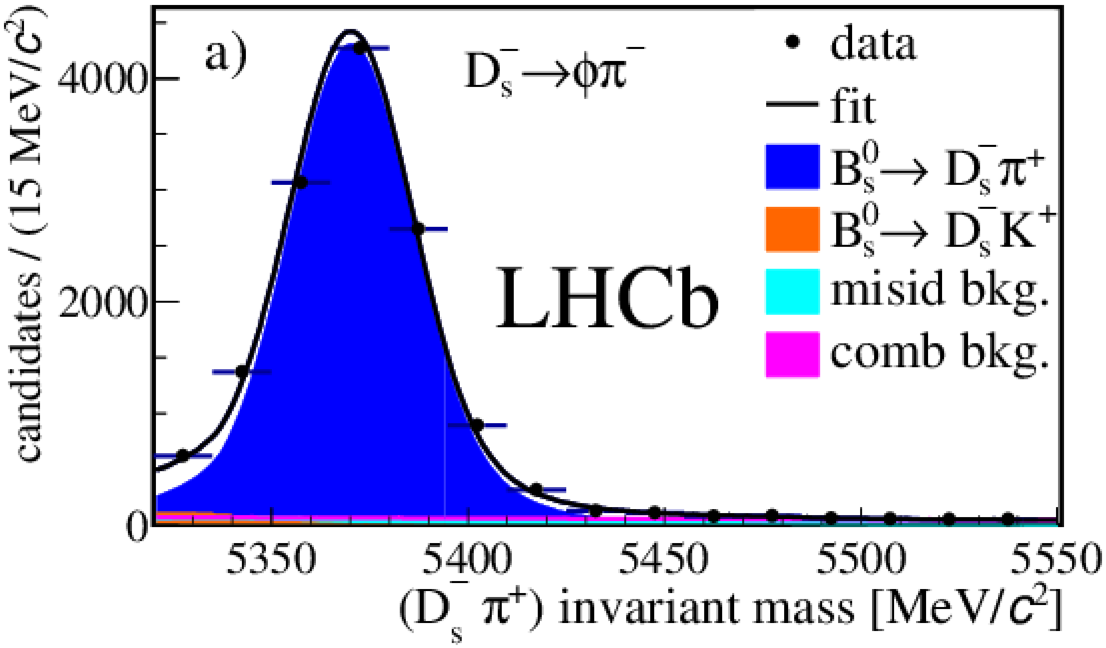
- Rare-decays:
  - LHCb has recently measured $B_s \rightarrow \mu\mu$ branching fraction and set the best limits so far on $B^0 \rightarrow \mu\mu$ branching fraction
  - Several electroweak penguin decays have been discovered and analysed to look for NP contributions. (eq: $B^+ \rightarrow \pi^+ \mu^+ \mu^-$)
- Charmonium Production cross-sections:

Talk by Maksym Teklishyn this afternoon

- This presentation :
  - A selected set of CP violation measurements in B and D decays.

B_s^0 Oscillations

NJP 15 053021
arXiv:1304.4741



- Using $B_s \to D_s\pi$ with 5 D decay modes

$$D_s^- \to \varphi(K^+K^-)\pi^- \quad ,$$
$$D_s^- \to K^{*0}(K^+\pi^-)K^- \; ,$$
$$D_s^- \to K^+K^-\pi^-$$
$$D_s^- \to K^+K^-\pi^- \, ,$$
$$D_s^- \to \pi^-\pi^+\pi^-$$

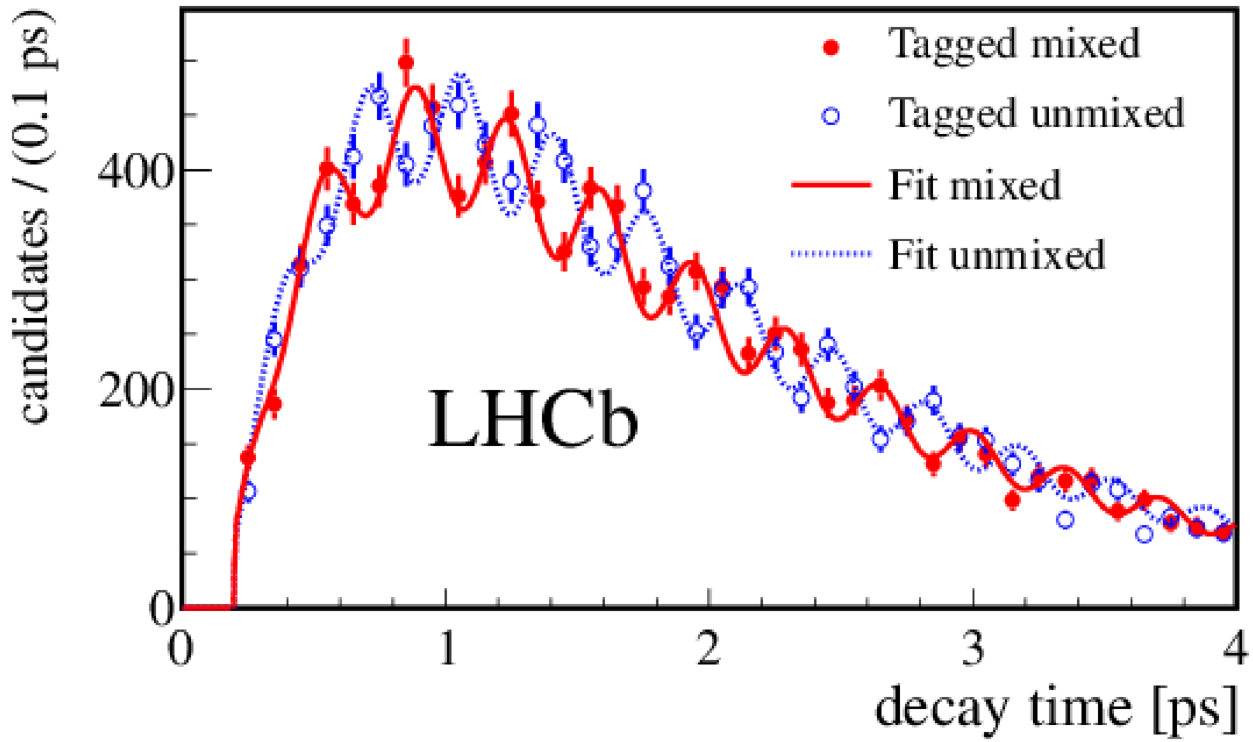
- Using 34000 candidates from 1 fb^{-1} of data in 2011,
- The frequency was determined by fitting to a PDF for decay time (t). It was made by the convolution of different functions:
  - a theoretical distribution using: decay width (Γ_s) and Heaviside step function (θ)

$$P_t \; \alpha \; \Gamma_s \exp(-\Gamma_s \; t) \cosh(\Delta\Gamma_s t / 2) \; \theta_t$$

  - decay time resolution function
  - decay time acceptance function
  - information from flavour tagging

B_s^0 Oscillations

NJP 15 053021
arXiv:1304.4741



At production and decay
different flavour: mixed
same flavour : unmixed

$$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}$$

Current world average for $\Delta m_s = 17.69 \pm 0.08\,\text{ps}^{-1}$

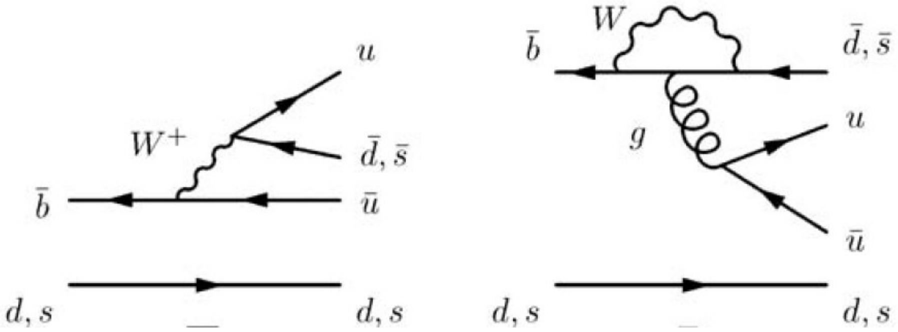
LHCb has the most precise measurement to date on this.

CP asymmetry in $B^0_{(d,s)} \rightarrow K^- \pi^+$

- Measurement of direct CP violation

$$A_{CP} = \frac{X - Y}{X + Y}\text{, where } X = \Gamma(\bar{B}^0_{(s)} \rightarrow \bar{f}_{(s)}) \text{ and } Y = \Gamma(B^0_{(s)} \rightarrow f_{(s)})$$

$$\text{and } f = K^+\pi^- \text{ and } f_s = K^-\pi^+$$

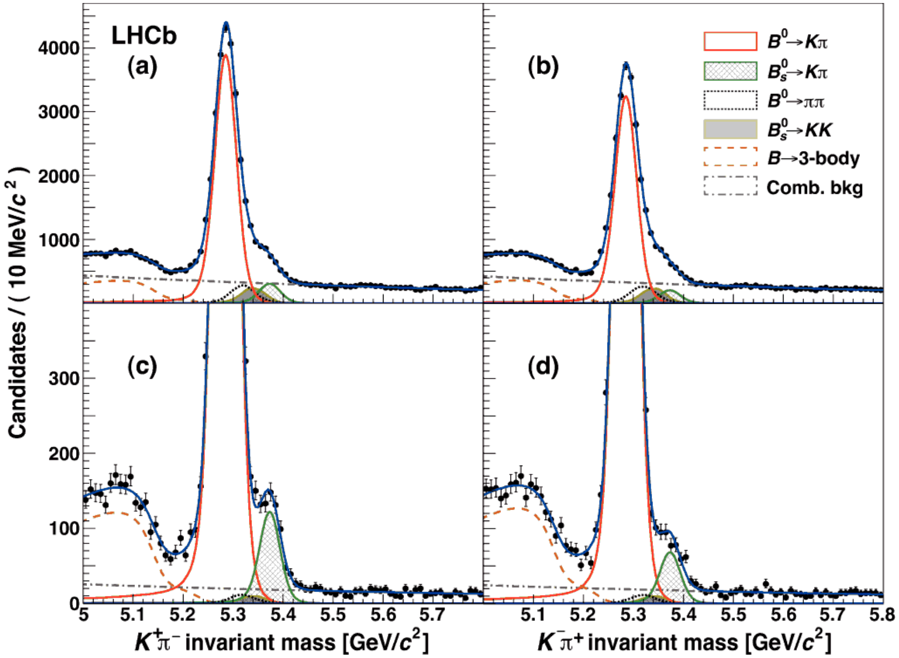


- Decay amplitudes have contributions from tree and penguin diagrams and their interference allows this measurement.
- Sensitive to V_{ub} phase and CKM angle γ
- New Physics can contribute to penguin loop.

- LHCb used 1 fb^{-1} of data from 2011 for this measurement

CP asymmetry in $B^0_{(d,s)} \to K^-\pi^+$

- Offline selections optimized for the A_{CP} measurement in these two channels
- Use particle ID to identify sub samples for $\pi^+\pi^-, K^+\pi^-, K^-\pi^+, K^+K^-$
- Raw asymmetries obtained from maximum likelihood fits to invariant mass spectra



$$B^0 \to K\pi$$

$$N_{sig} = 41420 \pm 300$$

$$A_{raw} = -0.091 \pm 0.006$$

$$B^0_s \to K\pi$$

$$N_{sig} = 1065 \pm 55$$

$$A_{raw} = 0.28 \pm 0.04$$

arXIV 1304.6173
Phys.Rev.Lett 110 ,221601(2013)

CP asymmetry in $B^0_{(d,s)} \to K^- \pi^+$

- The Raw asymmetry (A_{raw}) has A_{CP} along with instrumental (A_D) and production (A_P) asymmetries.

$$A_{raw} = A_{CP} + A_{\Delta} \text{ , where } A_{\Delta} = \varsigma_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)})$$

$$\text{and } \varsigma_d = 1, \varsigma_s = -1$$

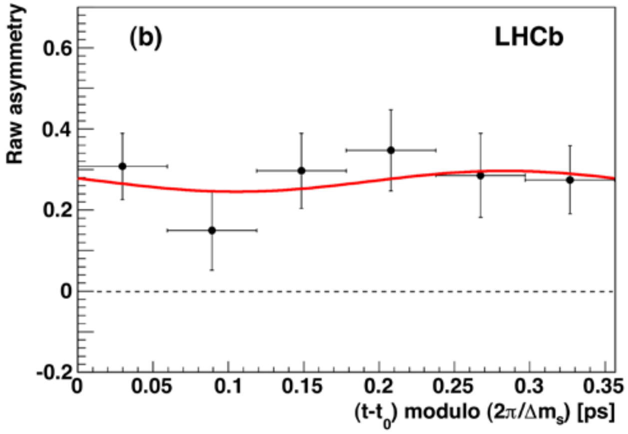
- A_D is determined from charm control samples in real data :

$$D^{*+} \to D^0(K^-\pi^+)\pi^+ \text{ and } D^{*+} \to D^0(K^+K^-)\pi^+ \text{ decays}$$

- A_P , K determined from the time-dependent decay rate spectra.

$$k_d = 0.303 \pm 0.005 \text{ and } k_s = -0.033 \pm 0.003.$$

These account for dilutions due to $B^0_{(s)}$ mixing.



Raw asymmetry for B_s

arXIV 1304.6173
Phys.Rev.Lett 110 ,221601(2013)

CP asymmetry in $\mathrm{B}^0_{(\mathrm{d,s})} \rightarrow \mathrm{K}^- \pi^+$

$$A_{CP}(\mathrm{B}^0 \rightarrow \mathrm{K}^+ \pi^-) = -0.080 \pm 0.007(\mathrm{stat}) \pm 0.003(\mathrm{syst})$$

$$A_{CP}(\mathrm{B}^0_s \rightarrow \mathrm{K}^+ \pi^-) = 0.27 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

10.5σ

6.5σ

- First observation of direct CP violation in $\mathrm{B_s}$ system
- Most precise measurement to date of $A_{CP}(\mathrm{B}^0 \rightarrow \mathrm{K}^- \pi^+)$
- These are in agreement with SM

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{\mathcal{B}(B^0_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0.$$

H.J.Lipkin
PLB 621(2005)126

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

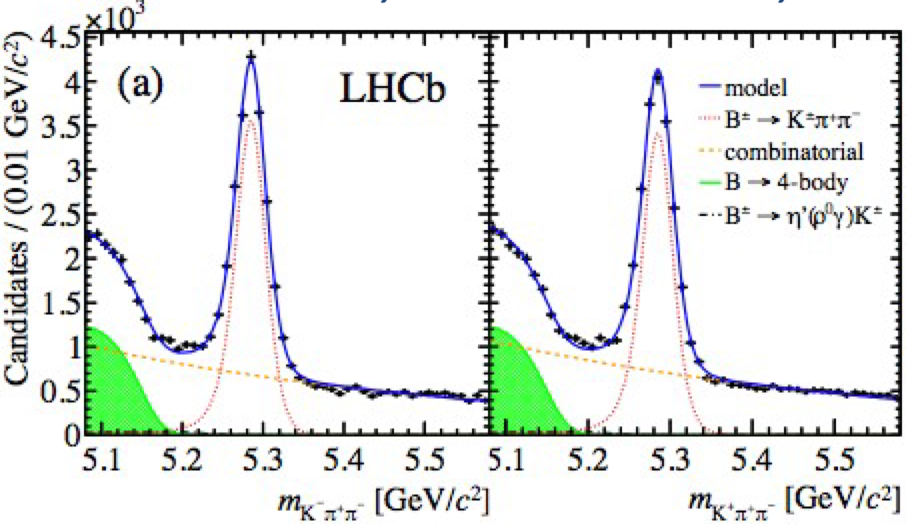
arXIV 1304.6173
Phys.Rev.Lett 110 ,221601(2013)

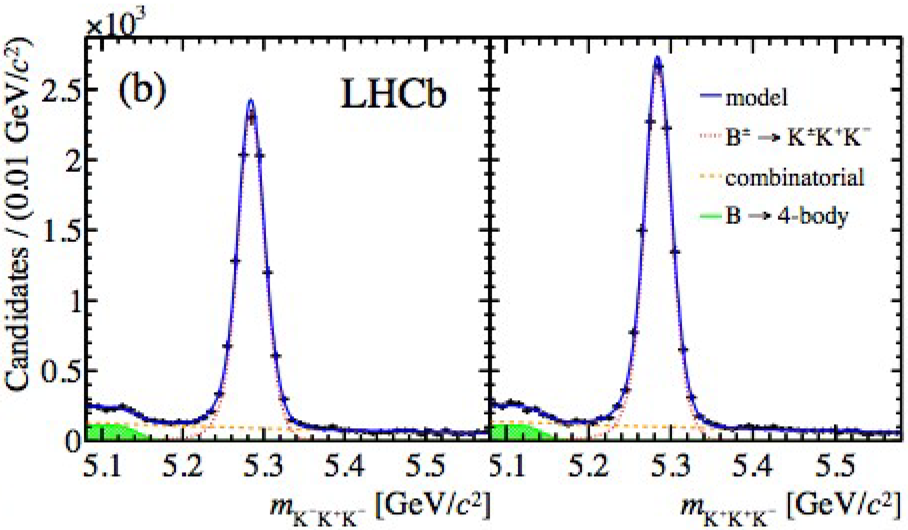
arXiV 1306.1246

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

- Very recently LHCb measured CP violation in these channels using the 1 fb^{-1} of data from 2011.

B⁻ decay *B⁺ decay* *B⁻ decay* *B⁺ decay*





- 36K events in the Kππ mode and 22K events in the KKK mode after selections
- Use $B^{\pm} \to J/\psi\, K^{\pm}$ as control channel. Last error below, from the systematics of the CP asymmetry of this control channel.

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = 0.032 \pm 0.008\,(stat) \pm 0.004\,(syst) \pm 0.007$$

2.8σ

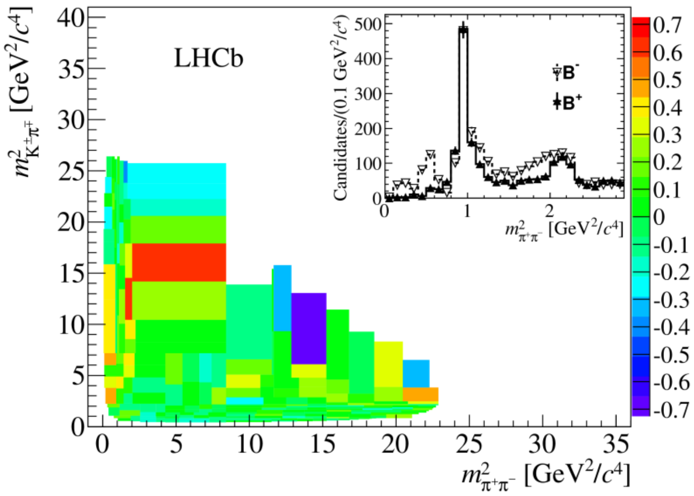
$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.043 \pm 0.009\,(stat) \pm 0.003\,(syst) \pm 0.007$$

3.7σ

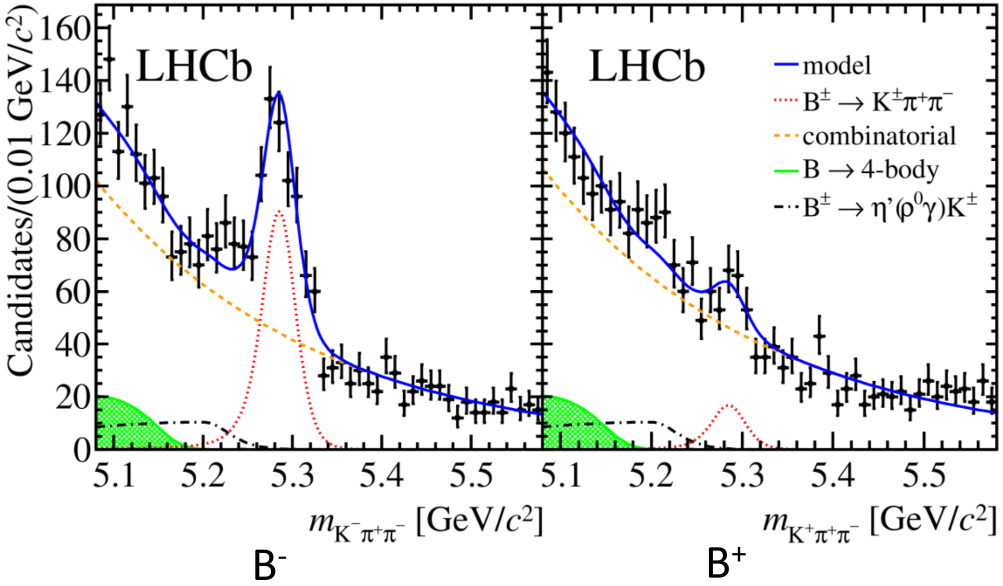
CP Asymmetry measured at 2.8 σ and 3.7 σ levels

CP Asymmetry in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ phase space

arXiV 1306.1246



- Asymmetries in bins of the background subtracted Dalitz plot.
- Positive asymmetry at low $m_{\pi\pi}$ near the $\rho(770)$ and above the f(980) resonances
- No significant asymmetry in $m_{K\pi}$



B^- B^+

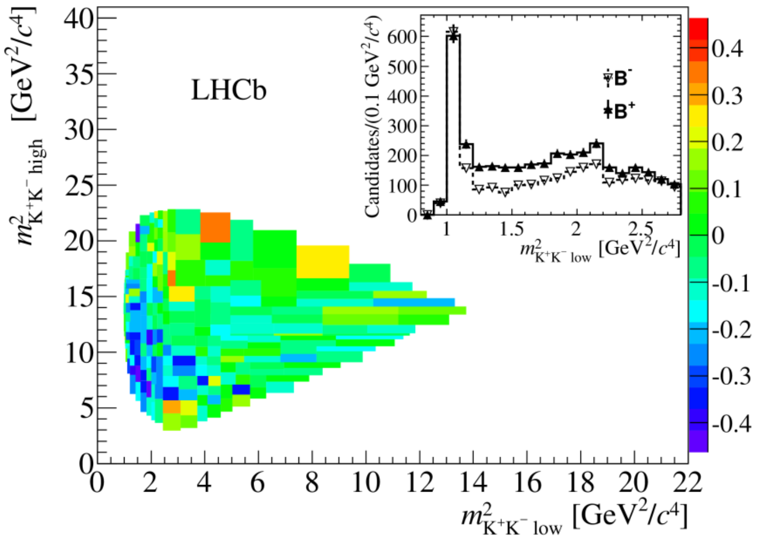
- CP asymmetry in the region $0.08 < m^2_{\pi\pi} < 0.66$ GeV^2/c^4 and $m^2_{K\pi} < 15$ GeV^2/c^4

$A_{CP}(K\pi\pi)=0.678\pm0.078\pm0.032\pm0.007$

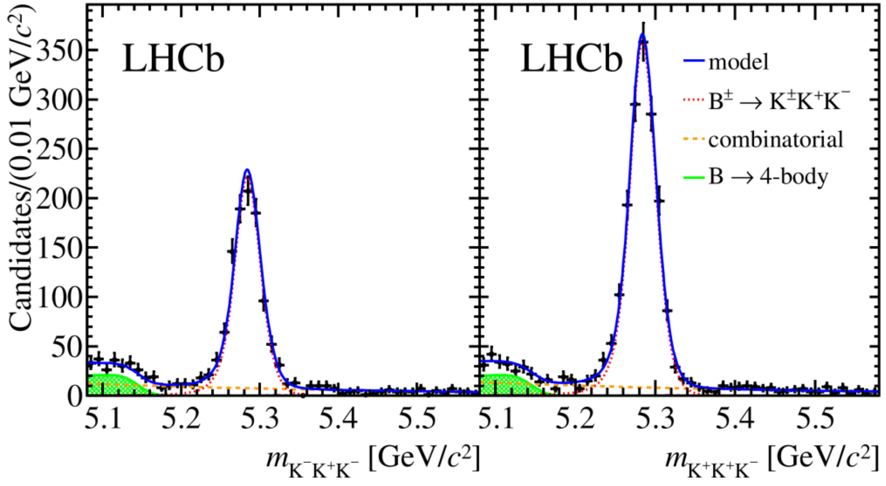
8σ

CP Asymmetry in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ phase space

arXiV 1306.1246



- Asymmetries in bins of background subtracted Dalitz plot. ($m^2_{\mathrm{KK\,low}} < m^2_{\mathrm{KK\,high}}$)
- Negative asymmetry at low values of $m^2_{\mathrm{KK\,low}}$ and $m^2_{\mathrm{KK\,high}}$
- No significant asymmetry at $\phi(1020)$ resonance



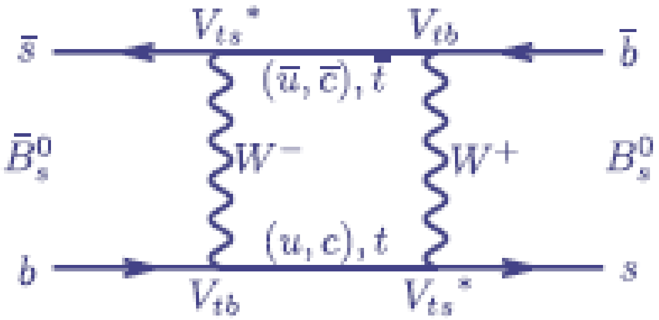
- CP asymmetry in the region $1.2 < m^2_{\mathrm{KK\,low}} < 2.0$ GeV^2/c^4 and $m^2_{\mathrm{KK\,high}} < 15$ GeV^2/c^4

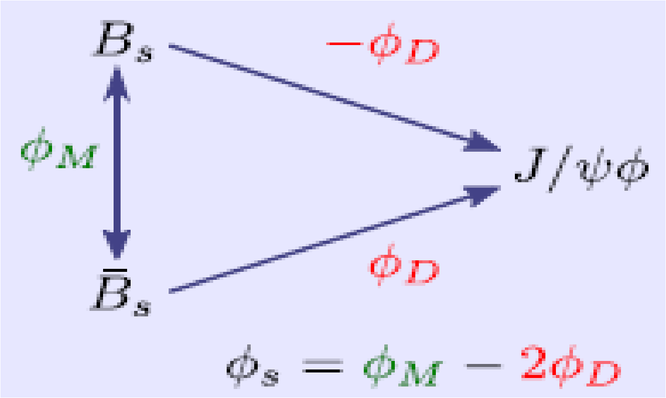
$A_{CP}(KKK) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007$

$10.5\,\sigma$

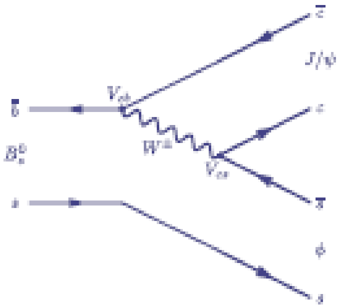
CP violation in $B_s \rightarrow J/\psi$ KK and $B_s \rightarrow J/\psi\ \pi\pi$

- CP violation : Interference between B_s mixing and decay to the same final state.
- Recent measurements of ϕ_s, Γ_s and $\Delta\Gamma_s$ from 1 fb^{-1} of data from 2011.
- Mixing phase: $\phi_M = 2\arg V_{ts} V_{tb}^* \simeq -2\beta_s$
  Sensitive to NP.
- For the decay: $\phi_D = \arg V_{cs} V_{cb}^* \simeq 0$





$\phi_s = \phi_M - 2\phi_D$



Measurement of ϕ_s

$B_s^0 \rightarrow J/\psi K^+ K^-$

- ➢ Proceeds via $B_s^0 \rightarrow J/\psi\,\phi,\ \varphi \rightarrow K^+K^-$ (P - wave) and the non-resonant K^+K^- (S-wave) (mass range ±30 MeV/c^2 around ϕ)

- ➢ P-wave is a mixture of CP even and CP odd (l=0,1,2) and S-wave is CP odd
- ➢ These are disentangled using distribution of decay angles (Ω) of final state particles, defined in the helicity basis.
- ➢ Differential decay rate equations : 3 P-wave amplitudes and 1 S-wave amplitude and their interference terms , resulting in a total of 10 terms.

$B_s^0 \rightarrow J/\psi\pi^+\pi^-$

arXiv 1204.5643

- ➢ Mainly S-wave : CP odd fraction > 97.7 % at 95% CL
- ➢ No angular analysis needed; decay rate equation with only 1 term

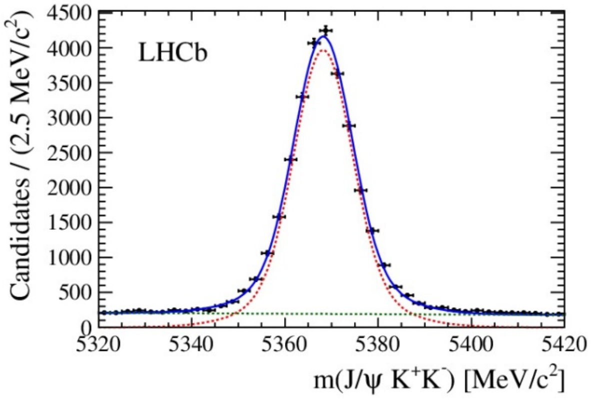
- Maximum likelihood fit to mass and decay time.
- For both channels , one essentially measures :

$$\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$$

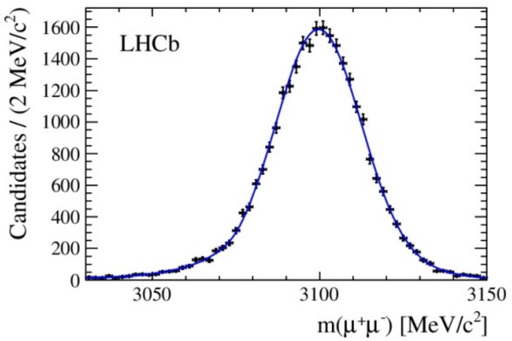
Decay time resolution

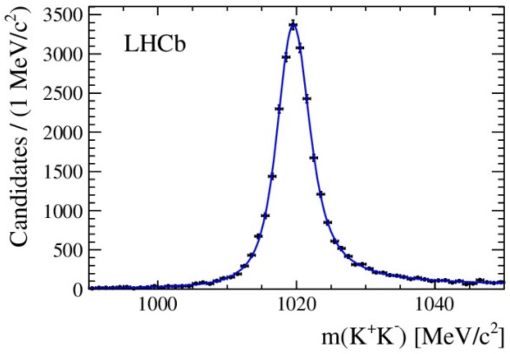
Dilution from flavour tagging

Measurement of ϕ_s

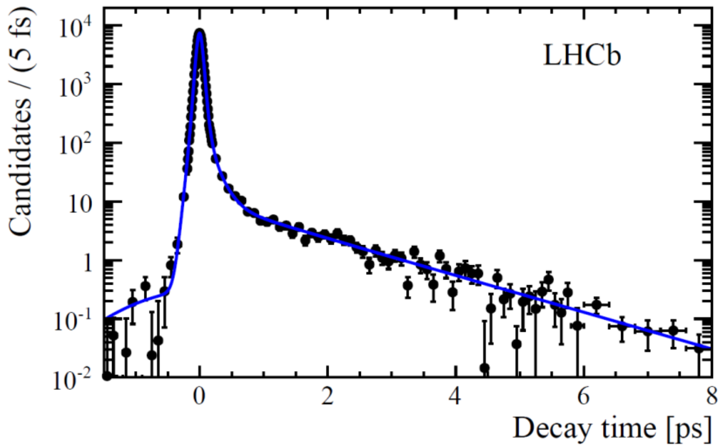


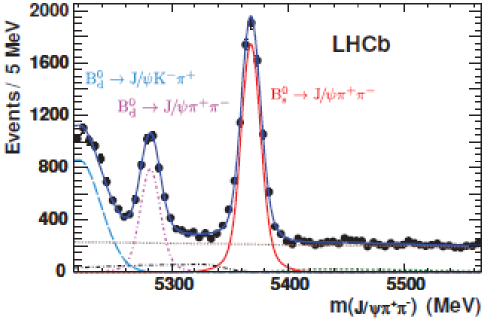
- After selections N_{signal} ~ 27600 for $B_s^0 \rightarrow J/\psi K^+K^-$
- Time resolution from prompt J/ψ : σ_t = 45 fs





arXiv 1304.2600





- N_{signal} = 7400 for $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ after selections using BDT

Measurement of ϕ_s

Calibration of flavour tagging : use control channels in real data

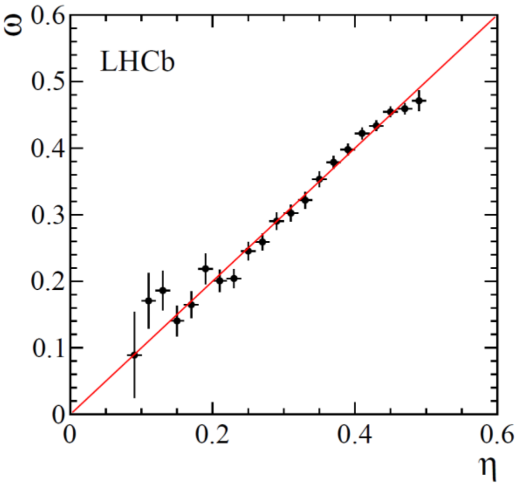
- Opposite side tagging (OST):
  - Relies on pair production of $b\bar{b}$ quarks
  - Infers signal B flavour from that of the other b-hadron
  - Calibration from self tagging channel: ex: $B^+ \to J/\psi K^+$
- Same side tagging (SST):

  Uses the $\bar{b}$ hadronization process.

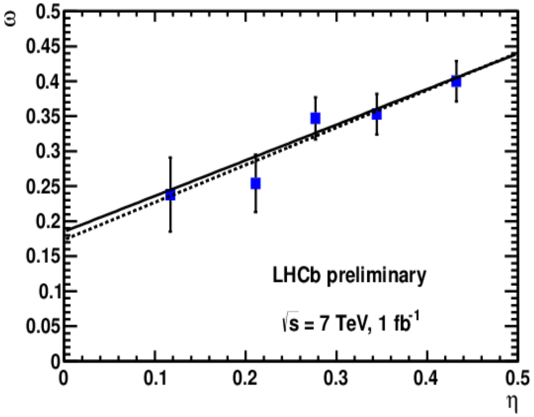
  Ex: $\bar{b}$ fragmentation may create an extra $\bar{s}$, which may form a hadron (often a kaon) whose charge identifies the initial flavour.
  - Calibration from a fit of time evolution in $B_s^0 \to D_s^- \pi^+$
  - Optimized on MC

Effective tagging power	$\varepsilon(1-2\omega)^2[\%]$
OST	0.89±0.017
SST	2.29±0.06
OST+SST	3.13±0.12±0.20

LHCb-CONF-2012-033
EPJC 72(2012)2022, arXiv:1202.4979



OST wrong tag probability: measured(ω) vs estimated (η) in $B^+ \to J/\psi K^+$



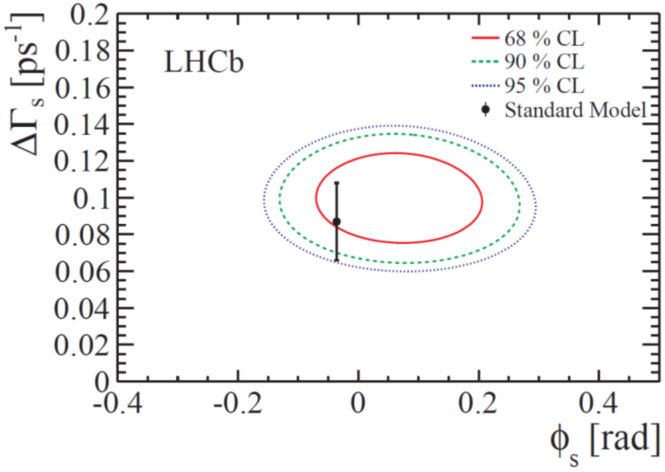
SST wrong tag probability:

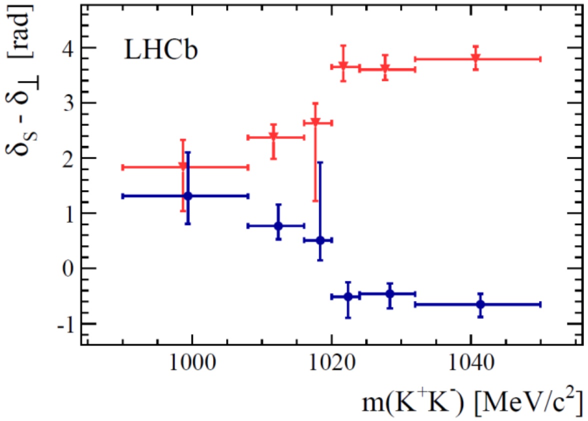
measured(ω) vs. estimated (η)

in $B_s^0 \to D_s^- \pi^+$

Measurement of ϕ_s

$B_s^0 \to J/\psi K^+ K^-$





Blue: $\Delta\Gamma_s$ positive

Red : $\Delta\Gamma_s$ negative

arXiV:0908.3627

- *Two solutions to decay rates*
- *Physical solution has $\delta_s - \delta_\perp$ decreasing across ϕ resonance with m(K$^+$K$^-$)*
- *This solution has $\Delta\Gamma_s$ positive.*
- *Heavy B_s meson lives longer*

ϕ_s = 0.07 ± 0.09 (stat) ±0.01 (syst) rad
$\Delta\Gamma_s$ = 0.100 ± 0.016 (stat)±0.003(syst) ps^{-1}

$$\varphi_s^{SM} = -2\beta_s = (-0.0363^{+0.0016}_{-0.0015})rad$$

$$\text{In SM}: \ \Delta\Gamma_s = 0.087 \pm 0.021\,\text{ps}^{-1}$$

arXiv:1106.4041v2 , arXiv:1102.4274

For $B_s^0 \to J/\psi\pi^+\pi^-$ Γ_s and $\Delta\Gamma_s$ constrained to those from $B_s^0 \to J/\psi K^+ K^-$

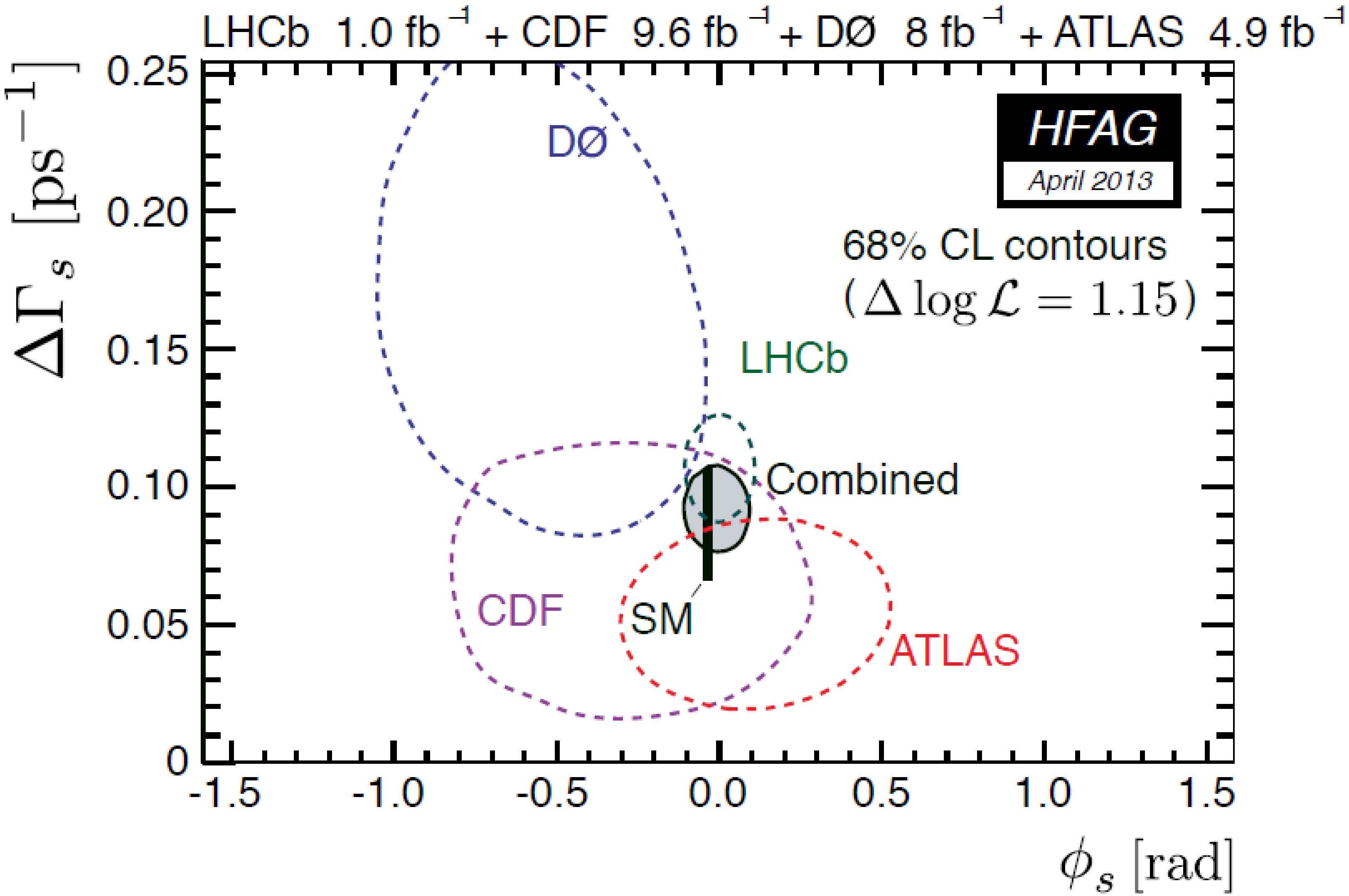
$$\varphi_s = -0.14^{0.17}_{-0.16} \pm 0.01\,\text{rad}$$

Combined fit for the two channels:

ϕ_s = 0.01 ± 0.07 (stat) ±0.01 (syst) rad
$\Delta\Gamma_s$ = 0.106 ± 0.011 (stat)±0.007(syst) ps $^{-1}$

arXiv 1304.2600

Measurement of ϕ_s

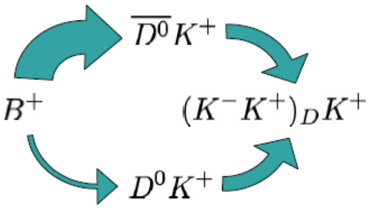


LHCb measurement is the most precise one, to date.

Towards a measurement of CKM angle γ

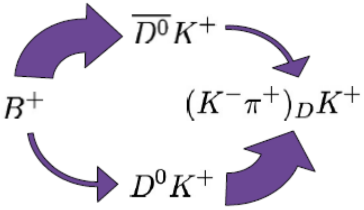
- LHCb uses several methods to measure γ from B →DK decays

“GLW”

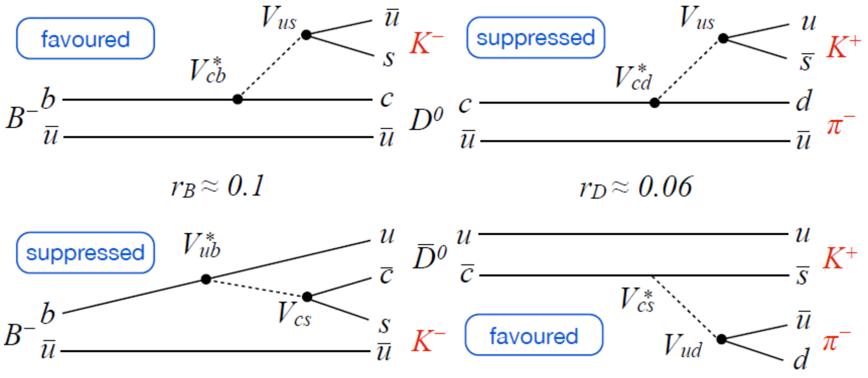


Phys.Lett. B253 (1991) 483
Phys.Lett. B265 (1991) 172
Gronau, London, Wyler

“ADS”, “suppressed”



Phys.Rev.Lett 78 (1997) 3257
Phys.Rev. D63 (2001) 036005
Atwood, Dunietz, Soni



“GGSZ”, “Dalitz”

- Use 3-body self-conjugate modes such as **$D \to K_s\pi^+\pi^-$**
- hadronic D parameters vary across Dalitz plot
- Giri, Grossman, Soffer, Zupan, hep-ph/0303187

relative amplitude:

$$\left|\frac{V_{cs}\,V_{ub}^*}{V_{us}\,V_{cb}^*}\right| f_{col}$$

$$= r_B$$

weak phase difference:

$$\arg\left(\frac{V_{cs}\;V_{ub}^*}{V_{us}\;V_{cb}^*}\right)$$

$$= \arg\left(-\frac{V_{ub}^*}{V_{cb}^*}\right)$$

$$= \gamma$$

relative strong phase:

$$= \delta_B$$

GLW, ADS :

R= Ratio of partial widths, A=Asymmetry

$$R_{CP+} = 1 + {r_B}^2 + 2 r_B \cos\delta_B \cos\gamma$$

$$A_{CP+} = \frac{2 r_B \sin\delta_B \sin\gamma}{1 + {r_B}^2 + 2 r_B \cos\delta_B \cos\gamma}$$

$$R^{ADS} = \frac{{r_B}^2 + {r_D}^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

$$A^{ADS} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{{r_B}^2 + {r_D}^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

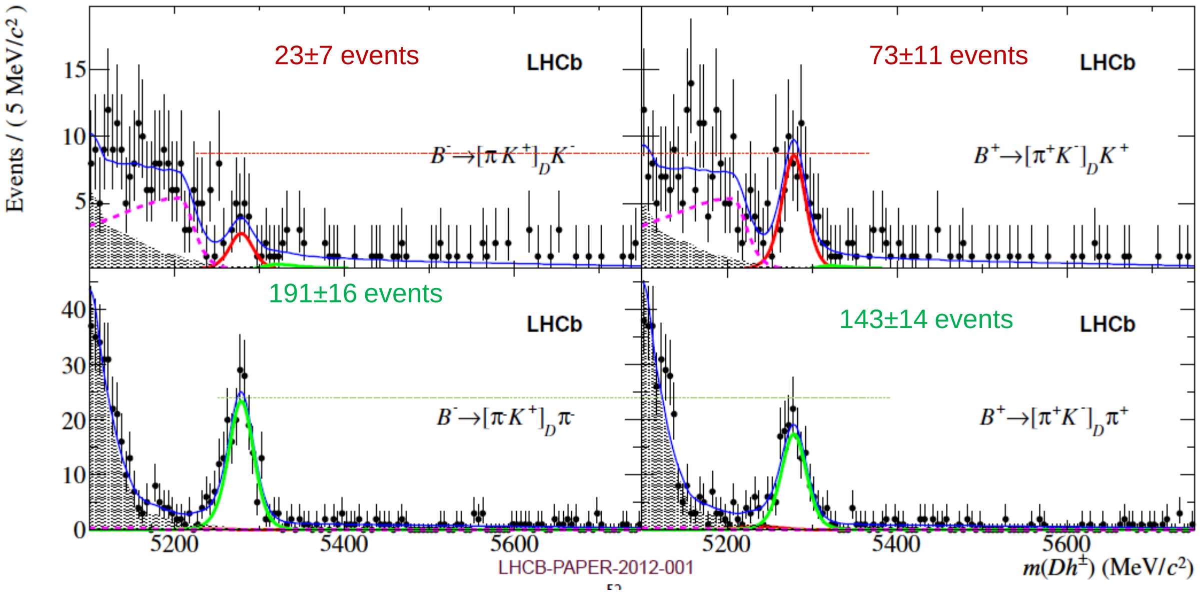
Towards a measurement of CKM angle γ

arXiv:1203:3662
PLB 712:203-212,2012

B→Dh , D→(KK,ππ,Kπ)

Fit to 16 data samples (2 (B charge) x 2 (Bachelor ID) x 4 (D decays))
to get 13 observables.
Selection of events using BDT, kinematics cuts, PID cuts for K/π.

Example in ADS mode:



$$Br(B \to D_{ADS} K^{\pm}) \approx 2 \times 10^{-7}$$

red: B->DK
green: B→Dπ

Large negative asymmetry in B→DK and a hint of positive asymmetry in B→Dπ

Towards a measurement of CKM angle γ

Using 1 fb^{-1} of data from 2011, in $B^{\pm} \rightarrow Dh$, $D \rightarrow (KK, \pi\pi, K\pi)$ (h= $K^{\pm}$ or $\pi^{\pm}$)

arXiv:1203:3662
PLB 712:203-212,2012

R_{ADS} (K) = 0. 0152 ±0.0020±0.0004

A_{ADS}(K) = -0.52 ±0.15±0.02

$R_{ADS}(\pi)$= 0.00410 ±0.00025±0.00005

$A_{ADS}(\pi)$ = 0.143±0.062±0.011

R_{CP+} = 1.007 ±0.038 ±0.012

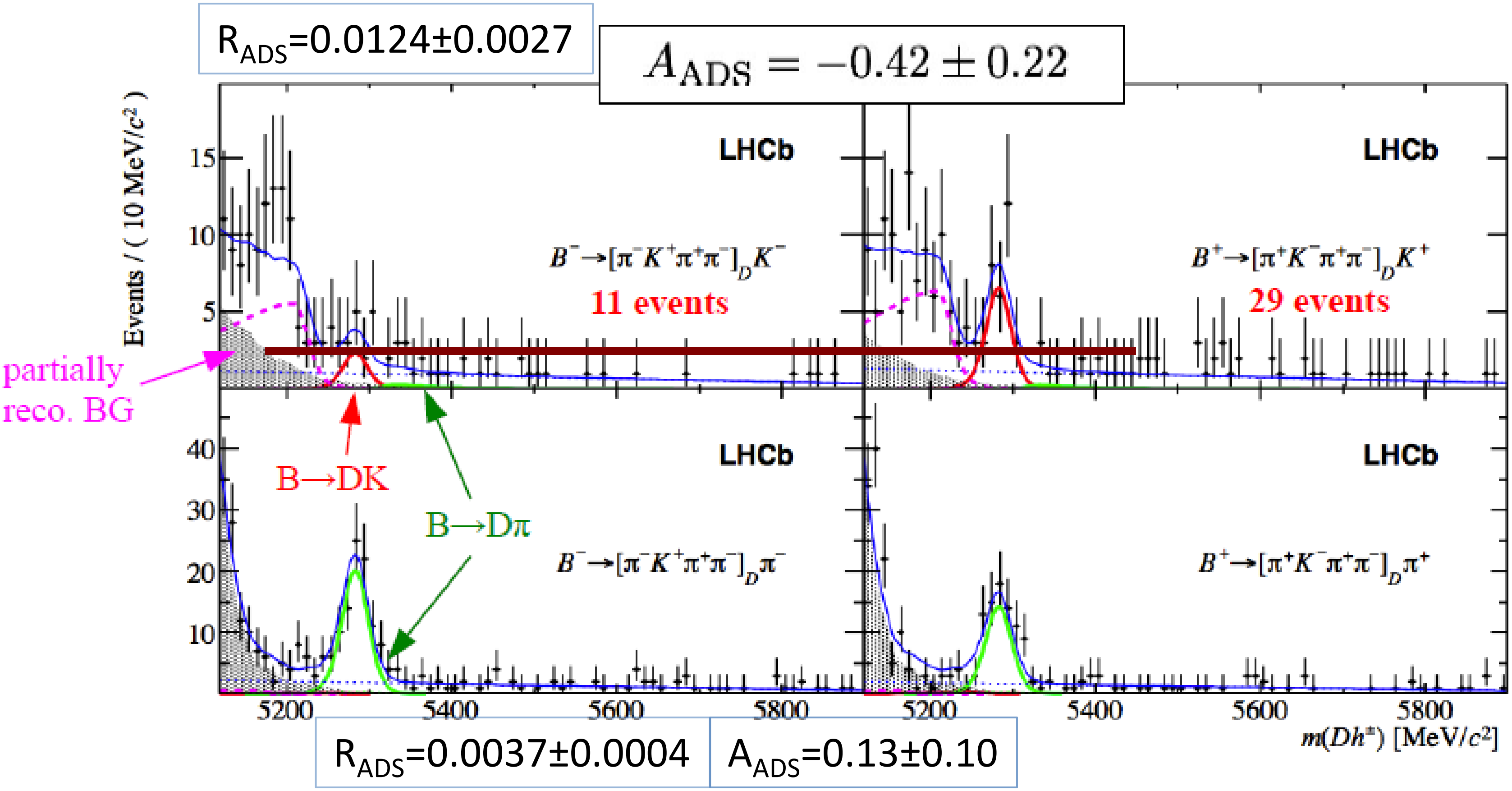
A_{CP+}=0.145±0.032±0.010

CP asymmetry observed in:

$B^{\pm} \rightarrow DK^{\pm}$ ADS mode, at 4σ level,
$B^{\pm} \rightarrow D\pi^{\pm}$ ADS mode , at 2.4 σ level.
KK and $\pi\pi$ modes, the combined asymmetry , at 4.5 σ level

Towards a measurement of CKM angle γ

$B \to D(\pi K \pi\pi)h$: suppressed ADS mode



$R_{ADS}=0.0124\pm0.0027$

$A_{ADS} = -0.42 \pm 0.22$

$R_{ADS}=0.0037\pm0.0004$

$A_{ADS}=0.13\pm0.10$

Phys. Lett . B 723 (2013) 44-53

GGSZ in B→DK

- D final state: $K_s\pi\pi$, K_sKK
- $B^+ \rightarrow [K_shh]_D K^+$ amplitude

$$\mathcal{A}_B(m^2_{K_sh^+}, m^2_{K_sh^-}) = \mathcal{A}_{\bar{D}^0\to K_sh^+h^-}(m^2_{K_sh^+}, m^2_{K_sh^-}) + r_B e^{i(\delta_B+\gamma)} \mathcal{A}_{D^0\to K_sh^+h^-}(m^2_{K_sh^+}, m^2_{K_sh^-})$$

- $(m^2_{K_sh^+}, m^2_{K_sh^-})$ is a point in the D→$K_s$hh Dalitz space

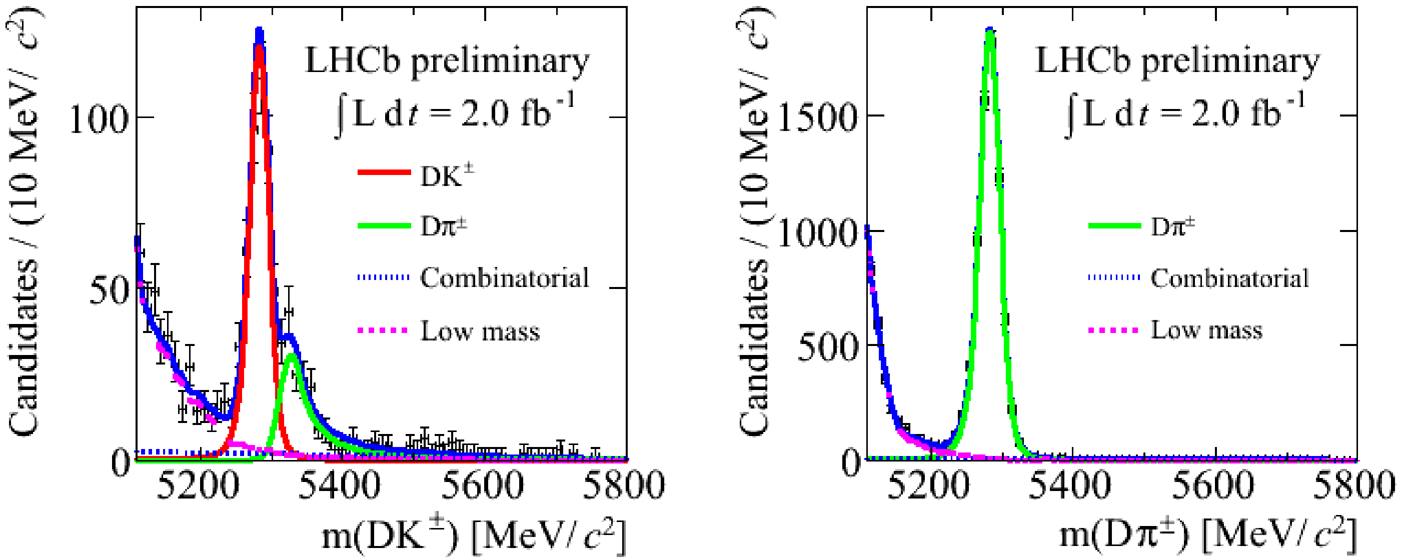
LHCb-CONF-2013-004
2 fb^{-1}, 8 TeV, 2012

Binned Dalitz plot analysis

Observables:

- $x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$
- $y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$

$$B^+ \rightarrow DK^+,\ B^+ \rightarrow D\pi^+,\ D \rightarrow K_s\pi^+\pi^-$$

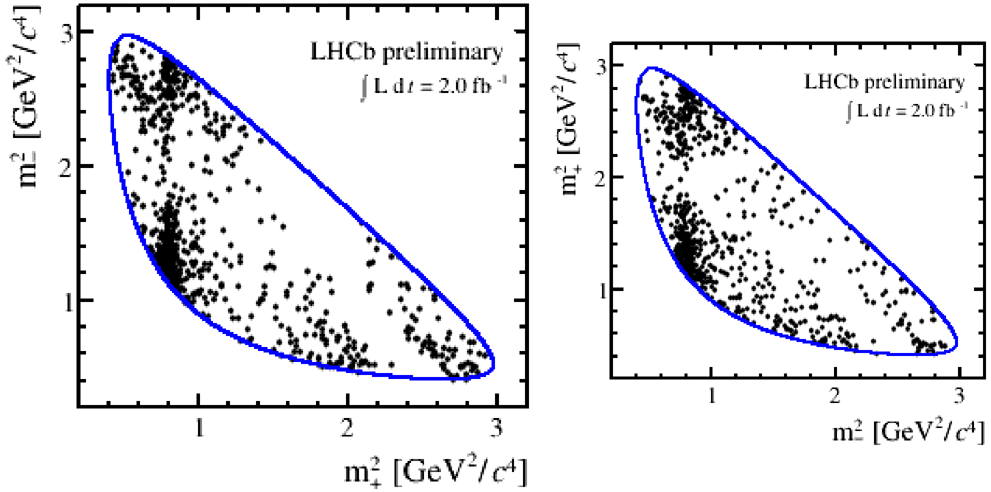


GGSZ in B→DK

LHCb-CONF-2013-004

$$B^{\pm} \rightarrow (K_{\mathrm{S}}^{0}\pi^{+}\pi^{-})_{D}K^{\pm}$$

B+



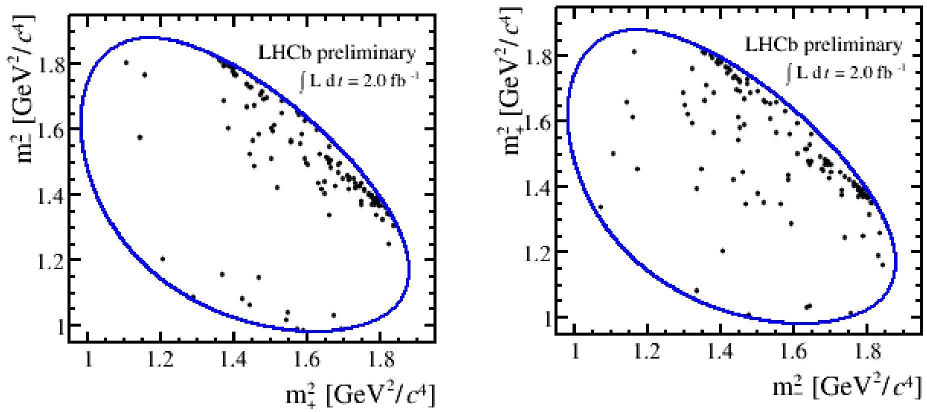
B-

Mass fits to candidates in each Dalitz bin to extract the observables.

$$x_{+} = (-8.7 \pm 3.1 \pm 1.6 \pm 0.6) \times 10^{-2}$$
$$x_{-} = (5.3 \pm 3.2 \pm 0.9 \pm 0.9) \times 10^{-2}$$
$$y_{+} = (0.1 \pm 3.6 \pm 1.4 \pm 1.9) \times 10^{-2}$$
$$y_{-} = (9.9 \pm 3.6 \pm 2.2 \pm 1.6) \times 10^{-2}$$

last term: error on the strong phase measurement used in fit from CLEO

B+



B-

$$B^{\pm} \rightarrow (K_{\mathrm{S}}^{0}K^{+}K^{-})_{D}K^{\pm}$$

Measurement of CKM angle γ

All the results obtained so far are combined to into a likelihood fit to extract γ

***D* final states used:**

- K^+K^-
- $\pi^+\pi^-$
- $K^\pm\pi^\mp$
- $K^\pm\pi^\mp\pi^\pm\pi^\mp$

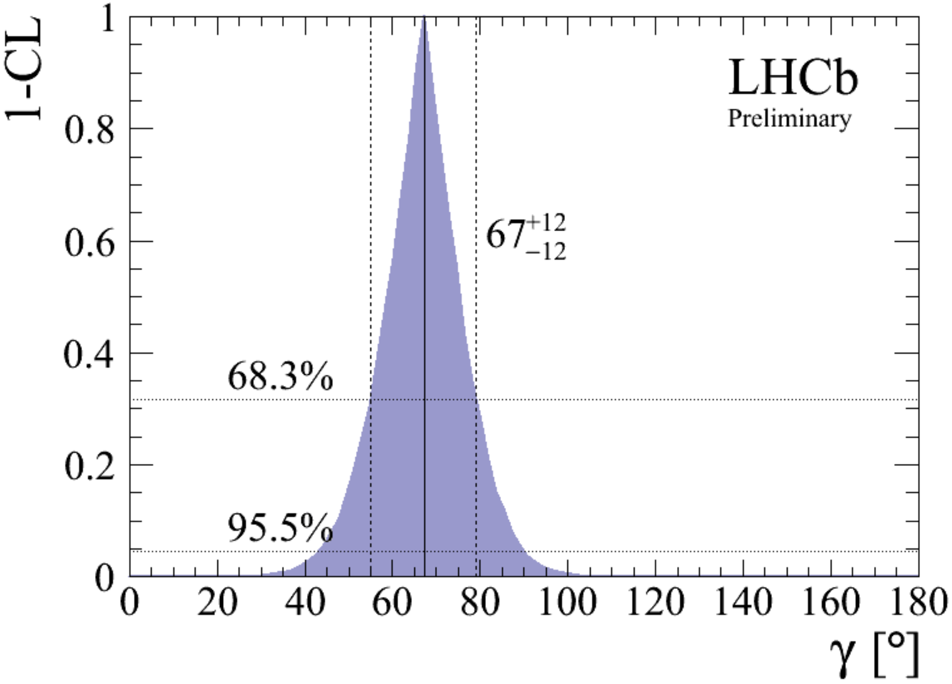
→ 1fb^{-1} of 7TeV 2011 data.

- $K_S^0\pi^+\pi^-$
- $K_S^0K^+K^-$

→ 1fb^{-1} 7TeV + 2fb^{-1} 8TeV.

Confidence intervals are evaluated from a “Feldman-Cousins” based toy Monte Carlo method (plug -in)

LHCb-CONF-2013-006

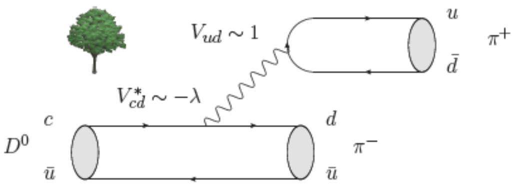


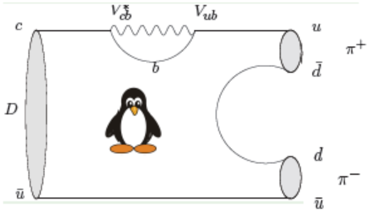
$$\gamma = (67 \pm 12)^\circ \text{ @ } 68\% \text{ CL}$$

- BABAR: 69^{+17}_{-16}° [Babar Collaboration, arxiv:1301.1029].
- BELLE: 68^{+15}_{-14}° [Belle Collaboration, arxiv:1301.2033].

CP Violation in CHARM Decays

- CP asymmetry : $A_{CP}(f,t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$
- The time dependence can be approximated as: $A_{CP}(f,t) \approx a_{CP}^{dir}(f) + \frac{t}{\tau} a_{CP}^{ind}$
- Time-integrated difference: $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta a_{CP}^{dir} + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{ind}$
- ΔA_{CP} mainly measures direct CP violation
- Assuming $SU(3)_F$ symmetry: $a_{CP}^{dir}(K^+K^-) = -a_{CP}^{dir}(\pi^+\pi^-)$
- In SM: direct CP violation from the interference between tree and penguin in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (Single Cabibbo Suppressed)





$$a_{CP}^{dir} < 0.1\%$$

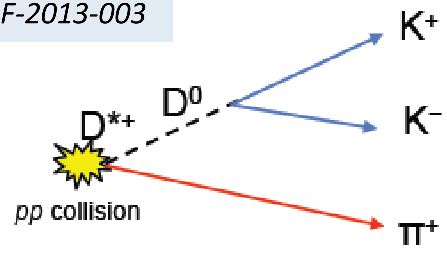
From naive suppression of penguin amplitude

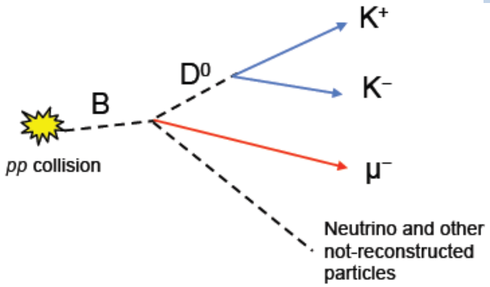
CP Violation in CHARM Decays

- LHCb measured ΔA_{CP} from two different channels using 1 fb^{-1} of data from 2011.
  (a) Prompt D* decays (b) semi-leptonic B decays.

PLB 723(2013)33-43

LHCb-CONF-2013-003





- Measured asymmetry: $A_{raw} = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)} = A_{CP} + A_D + A_P$

Detection Asymmetry

Production Asymmetry

$$\Delta A_{CP} = A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

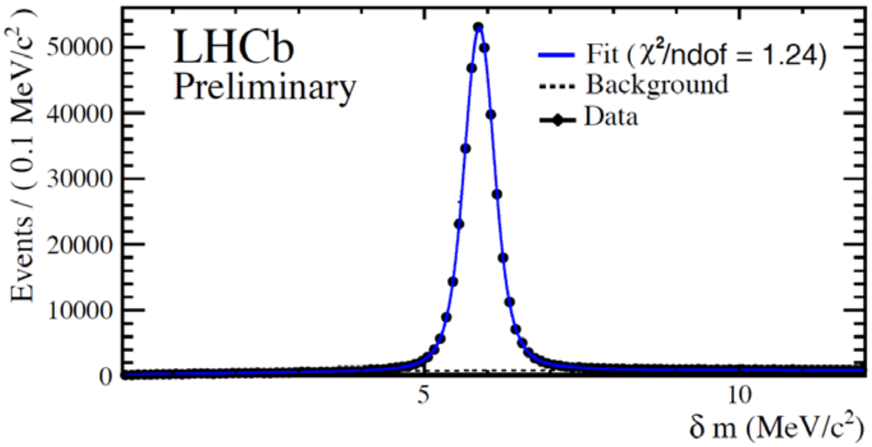
(A_D and A_P cancel out)

CP Violation in CHARM Decays

For the D* analysis, $\delta m = m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$

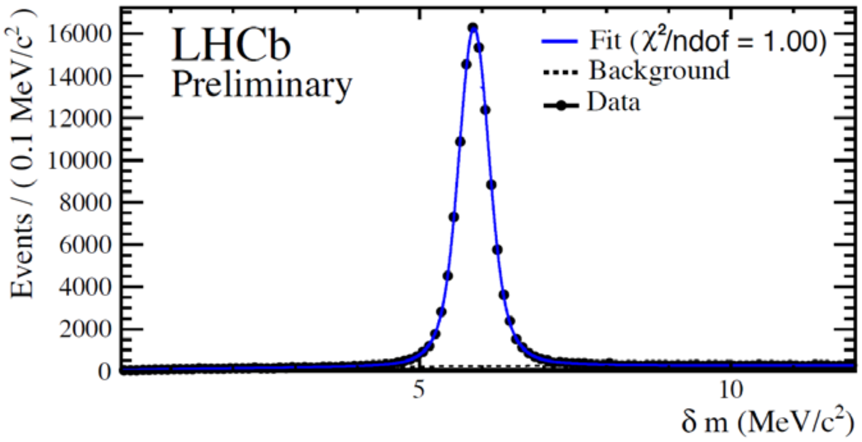
Clean signals after selection : 2.24M events in K^+K^- and 0.69M event in $\pi^+\pi^-$

Typical δm in K^+K^-

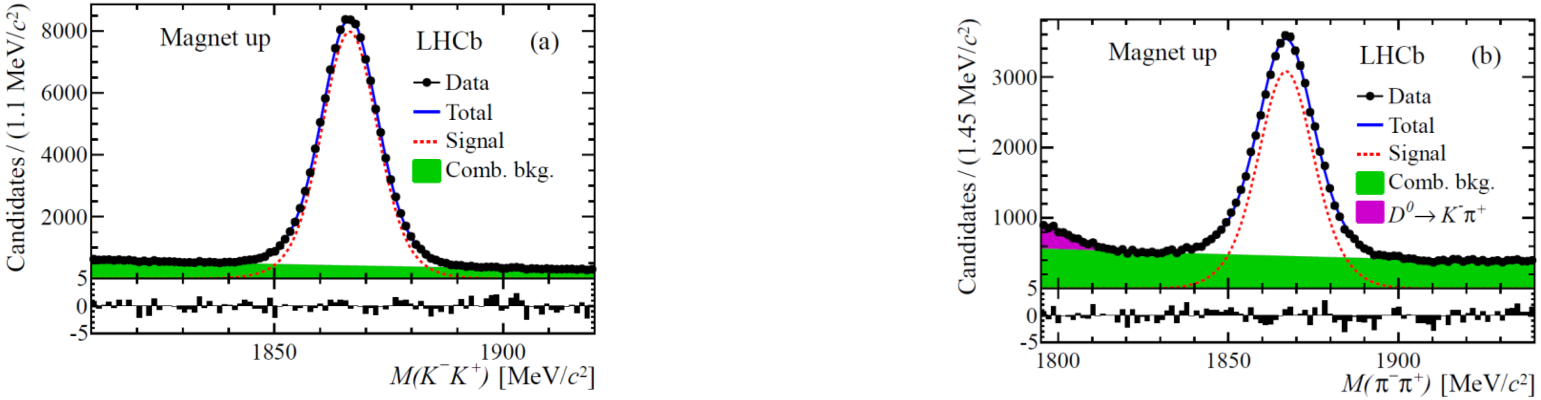


Typical δm in $\pi^+\pi^-$

LHCb-CONF-2013-003



Signals for semi-leptonic analysis also very clean: PLB 723(2013)33-43



559 K events in K^+K^- and 222K events in $\pi^+\pi^-$ after selection in semi-leptonic channel

CP Violation in CHARM Decays

LHCb-CONF-2013-003

From the D* analysis:

$$\frac{\Delta\langle t\rangle}{\tau}=[11.19\pm0.13(\mathrm{stat})\pm0.17(\mathrm{syst})]\%$$

$$\Delta\mathrm{A}_{\mathrm{CP}}=[-0.34\pm0.15(\mathrm{stat})\pm0.10(\mathrm{syst})]\%$$

Compared to earlier LHCb result, these use more data with improved calibration and improved analysis methods.

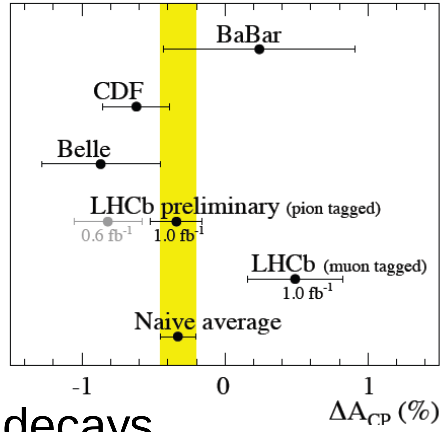
From the semi-leptonic analysis:

$$\frac{\Delta\langle t\rangle}{\tau}=0.018\pm0.002(stat)\pm0.007(syst)$$

PLB 723(2013)33-43

$$\Delta\mathrm{A}_{\mathrm{CP}}=[+0.49\pm0.30(stat)\pm0.14(syst)]\%$$

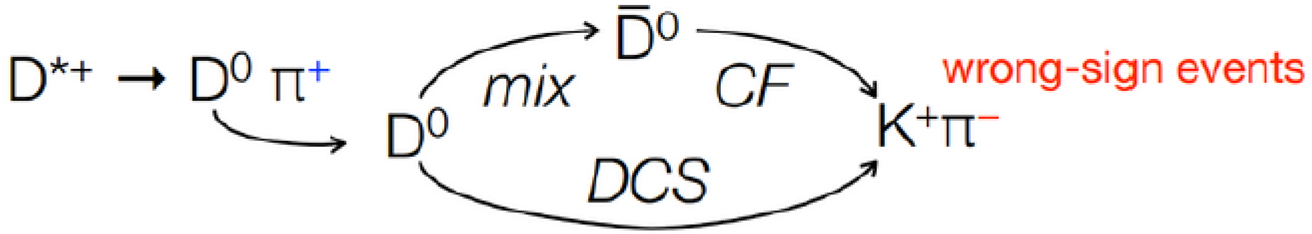
- Difference between the two results = 2.2 σ
- Preliminary weighted average: ΔA_{CP} = (-0.15±0.16)%



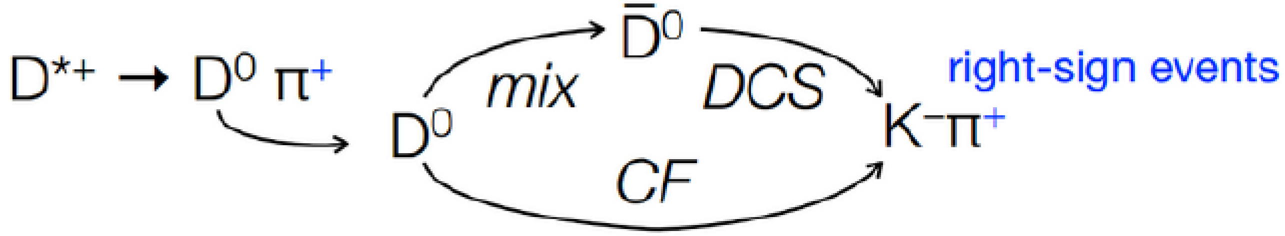
LHCb does not confirm evidence of CP violation in Charm decays

CHARM Mixing

- LHCb observed $\mathrm{D}^0 - \overline{\mathrm{D}}^0$ oscillations using 1 fb^{-1} of data from 2011



(WS)



(RS)

- The ratio of the time dependent decay rates:

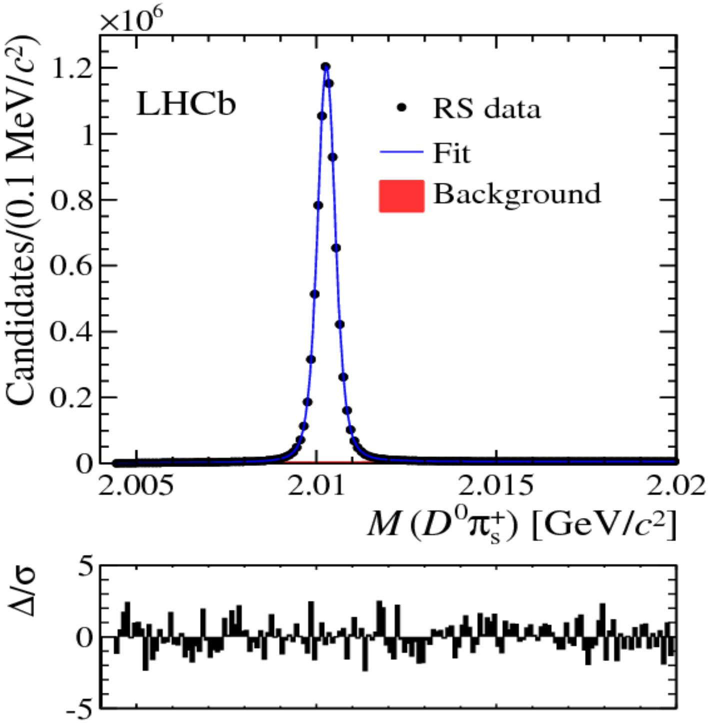
$$\frac{\Gamma(\mathrm{D}^0(t)\rightarrow \mathrm{K}^+\pi^-)}{\Gamma(\mathrm{D}^0(t)\rightarrow \mathrm{K}^-\pi^+)} = \mathrm{R(t)} \approx \mathrm{R_D} + \underbrace{\sqrt{\mathrm{R_D}}\,y'\left(\frac{t}{\tau}\right)}_{\textit{interference}} + \underbrace{\frac{x'^2+y'^2}{4}\left(\frac{t}{\tau}\right)^2}_{\textit{mixing}}$$

$\tau = \textit{average}\ \mathrm{D}^0\ \textit{lifetime},\ \mathrm{x} = \Delta m/\Gamma,\ y = \Delta\Gamma/\Gamma,\ \ x' = x\cos\delta + y\sin\delta,\ \ y' = y\cos\delta - x\sin\delta$

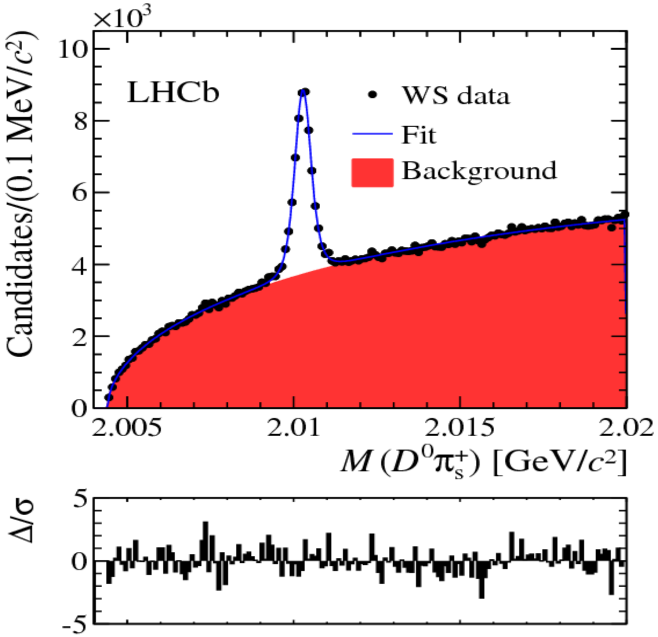
$\delta = \textit{strong phase difference between}\ \mathrm{DCS}\ \textit{and}\ \mathrm{CF}\ \textit{amplitudes}$

CHARM Mixing

PRL 110 (2013) 101802



8.4 M events

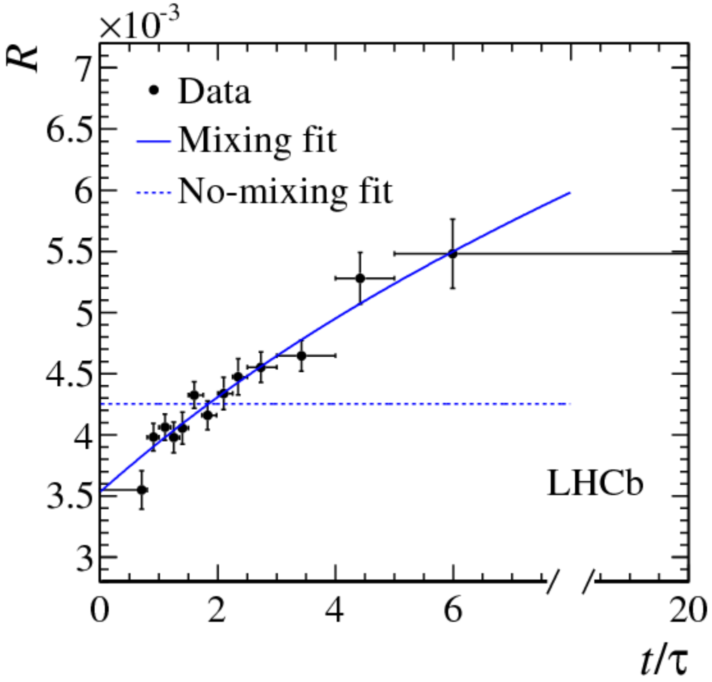


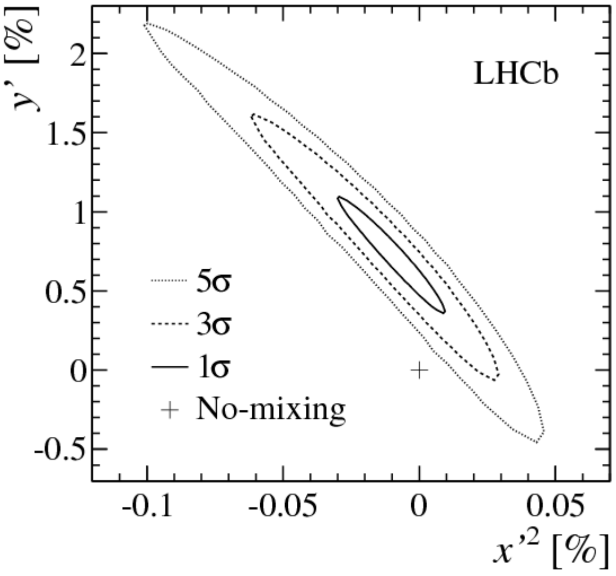
3.6 M events

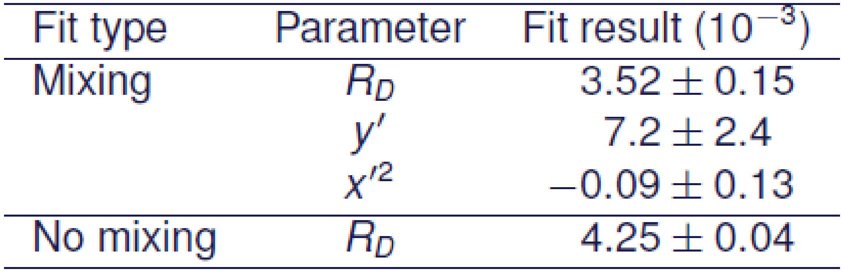
- Soft pion (π_s) tags the flavour of D^0
- Background of WS dominated by (D^0 + random π) combinations
- Contamination from B→D^0X reduced by IP requirements on D^0 and π_s
- D^0 and π_s required to form a vertex, constrained to PV.
- Data divided into 13 time bins, and ratio R= WS/RS determined for each bin
- Most systematics cancel out in the ratio.
- A χ2 minimization used to extract the three parameters (R_D ,x'^2, y').

CHARM Mixing

PRL 110 (2013) 101802





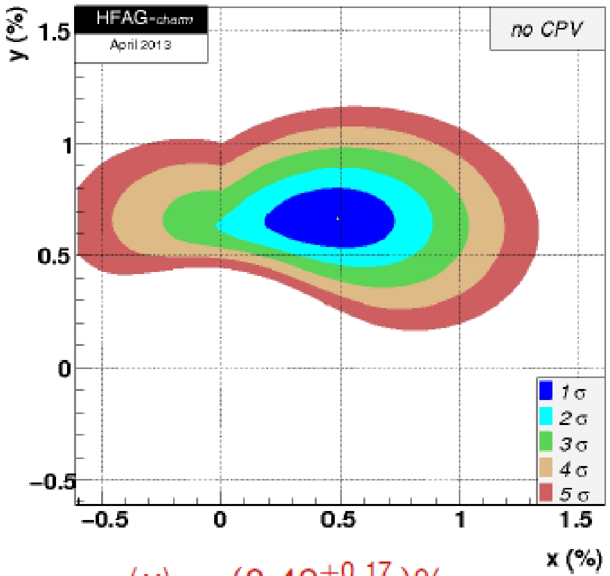


Fit type	Parameter	Fit result (10^{-3})
Mixing	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing	R_D	4.25 ± 0.04

'No mixing' hypothesis excluded at 9.1 σ

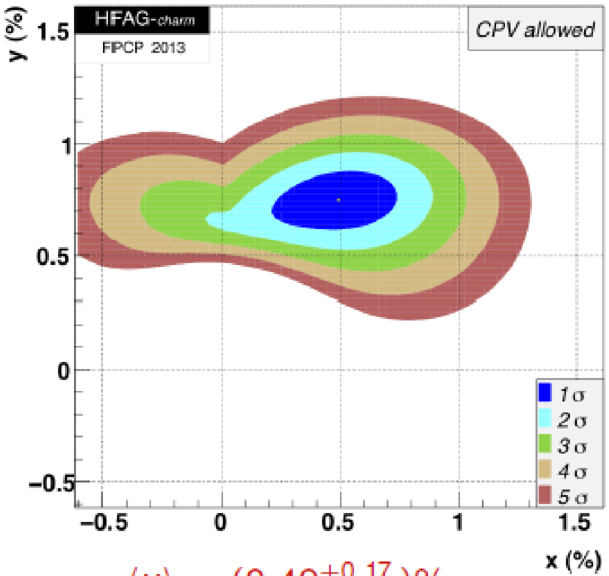
CHARM Mixing

HFAG averages



$\langle x \rangle = (0.49^{+0.17}_{-0.18})\%$

$\langle y \rangle = (0.66 \pm 0.09)\%$



$\langle x \rangle = (0.49^{+0.17}_{-0.18})\%$

$\langle y \rangle = (0.74 \pm 0.09)\%$

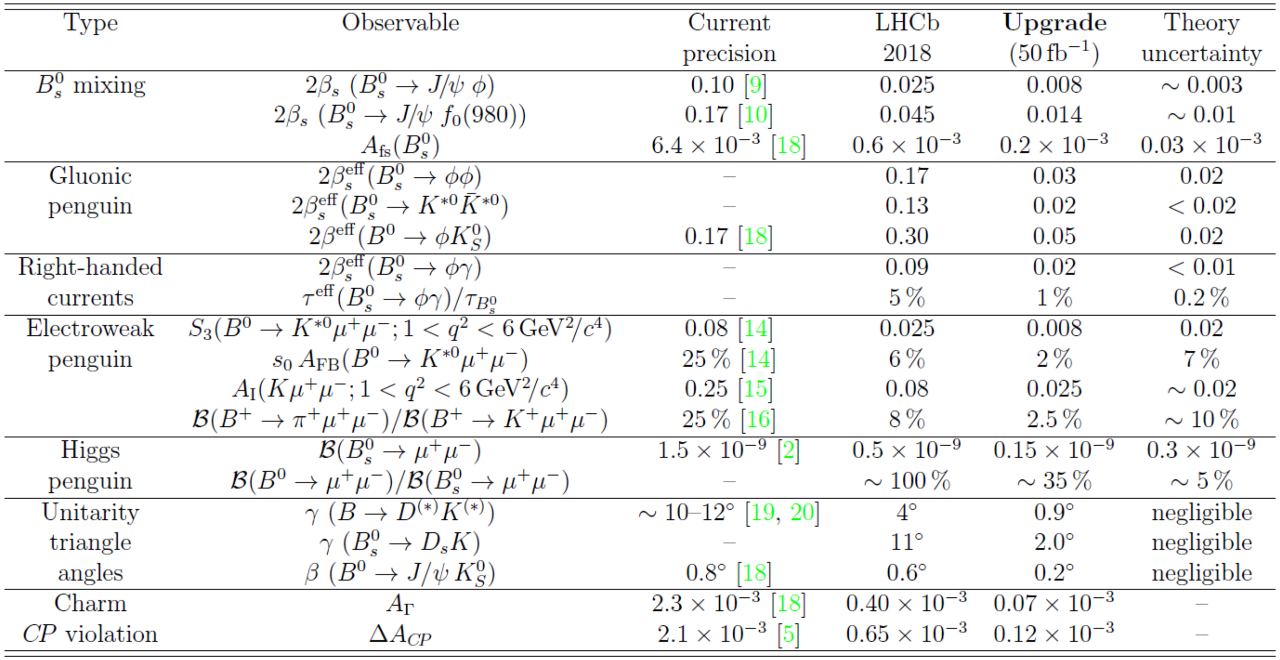
`http://www.slac.stanford.edu/xorg/hfag/charm`

Latest results on "WS" $D^0 \to K\pi$ decay.

Exp.	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13
Belle	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18

LHCb Upgrade

- LHCb searches for new physics in CP violation and rare decays using FCNC processes mediated by box and penguin diagrams.
- With high luminosity and high energy available from 2019 onwards, aim to collect 50 fb^{-1} of data and reach sensitivities which are comparable or better than theoretical uncertainties.

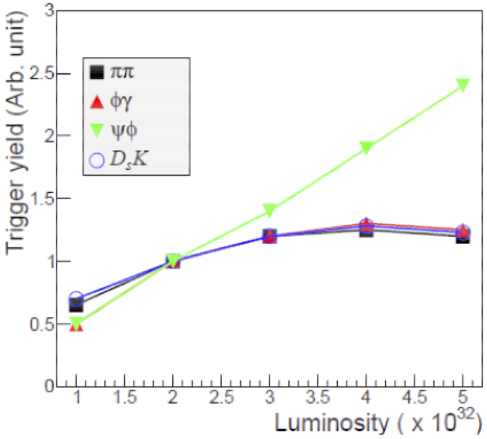


Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim$ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

CERN-LHCC: 2012-007
arXiv:1208.3355

LHCb trigger upgrade

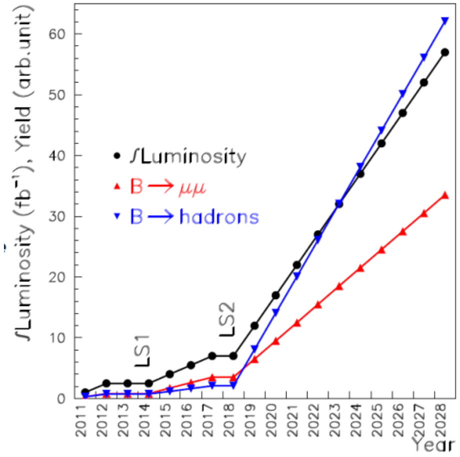
- The current trigger scheme has some limitations for using for upgrade conditions.
  - Front-end readout time ~ 900ns and hence L0 rate ~ 1 MHz.
  - Due to the available bandwidth and discrimination power of hadronic L0 trigger, the trigger yield saturates at high luminosities.



- The proposed solution is to readout the whole detector at 40 MHz and use fully software triggers. Use the hardware first level as a 'throttle mechanism ' during the early phases of upgrade.

- Plan for a maximum luminosity of $2X10^{33}$ cm^{-2} s^{-1}

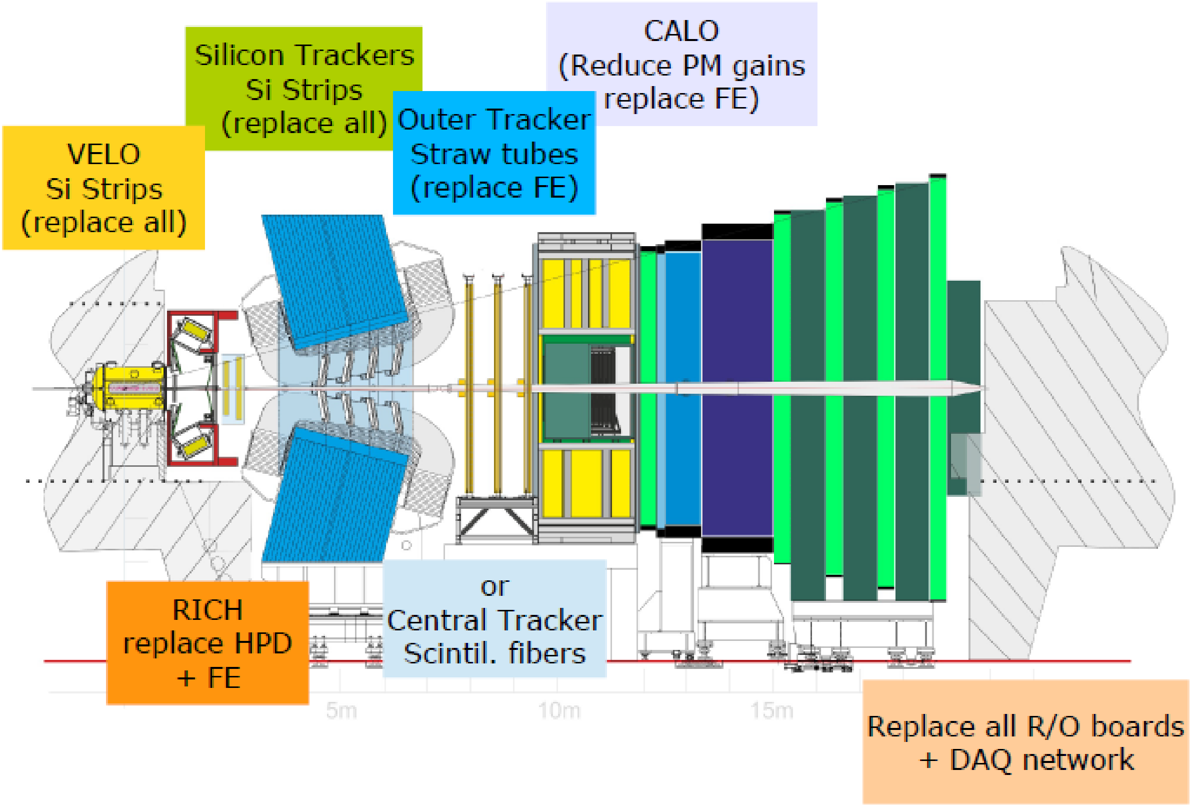
- Increase in annual yields wrt to 2011:
  - Factor of 20 for hadronic channels
  - Factor of 10 for leptonic channels



- The readout of the LHCb detectors will be upgraded accordingly.

Baseline version of the LHCb upgrade

40 MHz Detector Upgrade



VELO
Si Strips
(replace all)

Silicon Trackers
Si Strips
(replace all)

Outer Tracker
Straw tubes
(replace FE)

or
Central Tracker
Scintil. fibers

CALO
(Reduce PM gains
replace FE)

RICH
replace HPD
+ FE

Replace all R/O boards
+ DAQ network

Summary and Prospects

- Excellent performance of the LHCb detector in 2011-12 has led to several physics results.
  LHCb has become a “flavour factory”.
- LHCb has started to
  - Explore new territory in searching for NP
  - Test SM with unprecedented precision
  - Make CP violation measurements in different channels
- Excellent prospects to enhance its discovery potential
  - > 5 fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$ during 2014-2017
- An active upgrade program to run at (1-2) x 10^{33} $\text{cm}^{-2}\text{s}^{-1}$ with $\sqrt{s} = 14\,\text{TeV}$ from 2019, is underway.
  It would produce 5 fb^{-1} of data per year with improved trigger efficiency.
  - Full detector readout at 40 MHz and flexible software trigger

EXTRA SLIDES

Search for $B_{(s)} \rightarrow \mu^+ \mu^-$

Talk by Nigel Watson.
Indrek Sepp

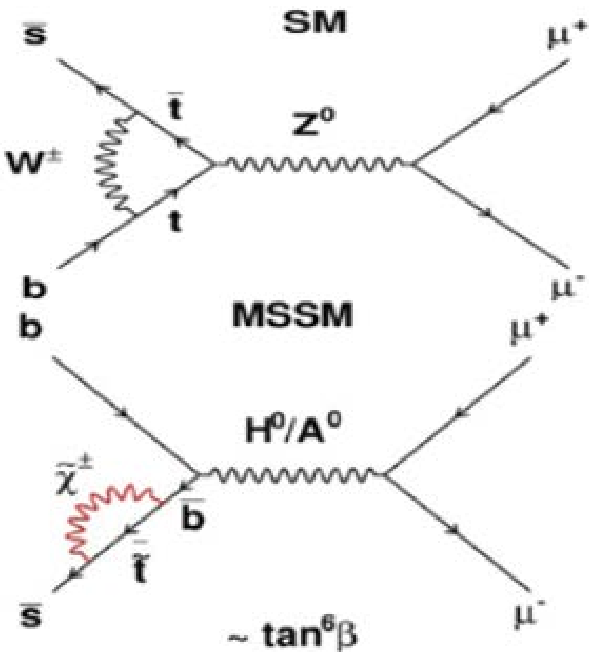
- Rare decay : FCNC
- Standard Model: Helicity suppressed

  arXiv:1005.5310, arXiv:1012.1447
  Buras et.al , JHEP 10 (2010) 009

  Branching fractions at 10^{-9} *level*

- Branching ratio sensitive to NP
  eg: MSSM with large tan β
- Can provide constraints on $C^{(')}_{S,P}$
- LHCb used 1 fb^{-1} (7 TeV) data from 2011
  + 1.1 fb^{-1} (8TeV) data from 2012

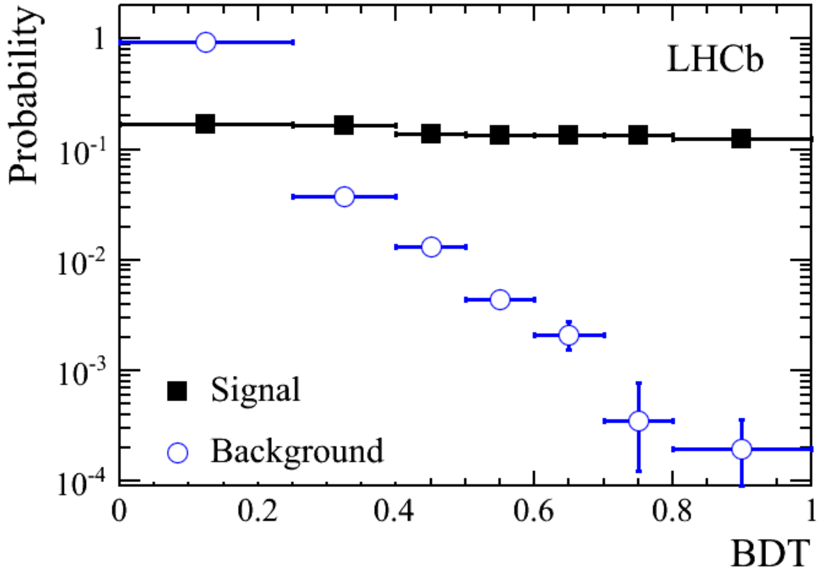
PRL 110, 021801 (2013)



Search for $B_{(s)} \rightarrow \mu^+ \mu^-$

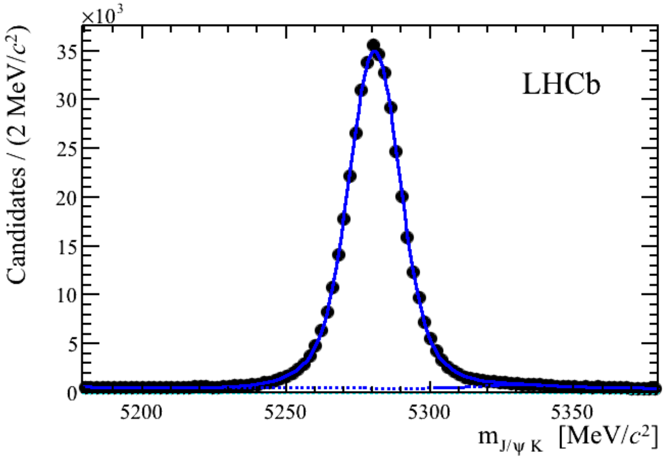
- Event Selection : BDT , trained on MC and calibrated using real data

Signal : $B \rightarrow h^+ h^-$ (h= K or π)
Background : B_s mass sidebands



- **Branching Fraction:**
  Normalized after similar event selection in $B^+ \rightarrow J/\psi K^+$, $B \rightarrow K \pi$

$$B = B_{norm} \times \frac{\mathcal{E}_{norm}}{\mathcal{E}_{sig}} \times \frac{f_{norm}}{f_s} \times \frac{N_{sig}}{N_{norm}}$$

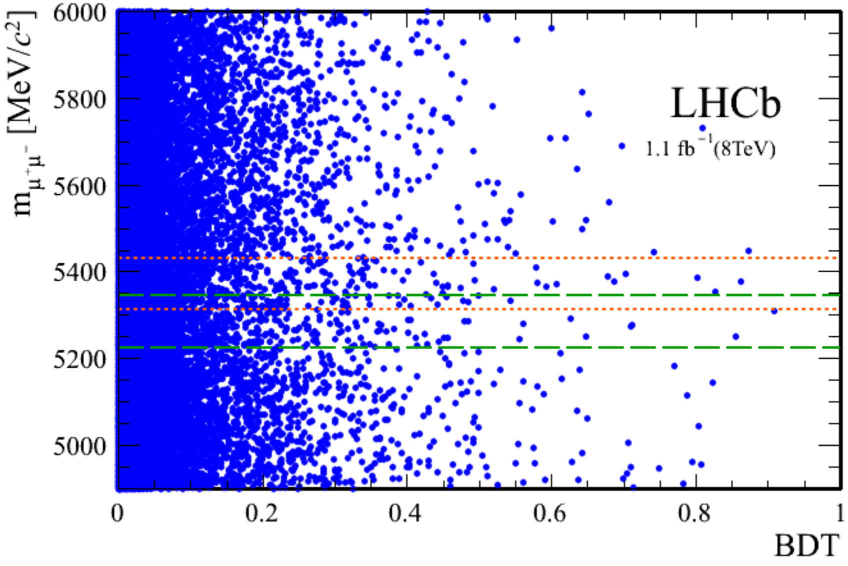


A control channel

$$\boxed{f_s / f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020}$$

LHCb: PRL 107(2011)211801

Search for $B_{(s)} \rightarrow \mu^+\mu^-$



Branching Fraction :

- ➢ Mass vs BDT :
  8 bins in BDT and 9 bins in mass
- ➢ Estimate signal and background events in each bin using CLs method.

$$Br(B_s^0 \rightarrow \mu\mu) = (3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(syst))\times 10^{-9}$$

Compatible with SM : $(3.54 \pm 0.30)\times 10^{-9}$

arXiV:1204.1737

Signal significance : 3.5 σ

$B_s^0 \rightarrow \mu\mu$

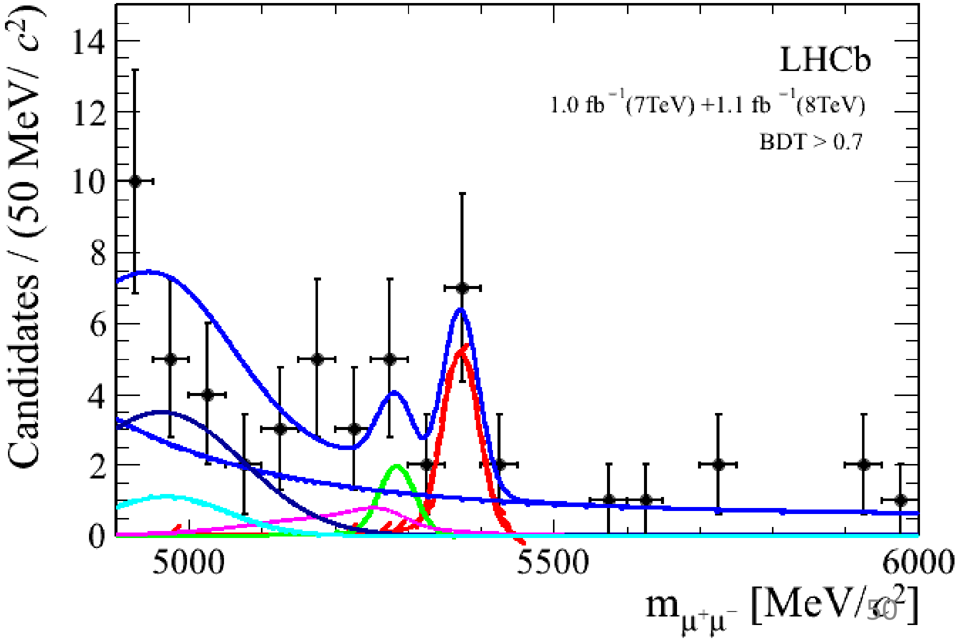
$B^0_{(s)} \rightarrow h^+h^-$

$B^{0(+)} \rightarrow \pi^{0(+)}\mu^+\mu^-$

$B^0 \rightarrow \mu\mu$

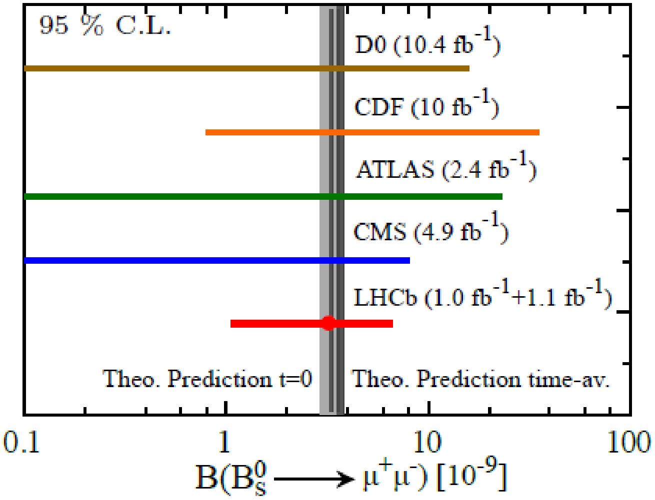
$B^0 \rightarrow \pi^-\mu^+\nu_\mu$

combinatorial background

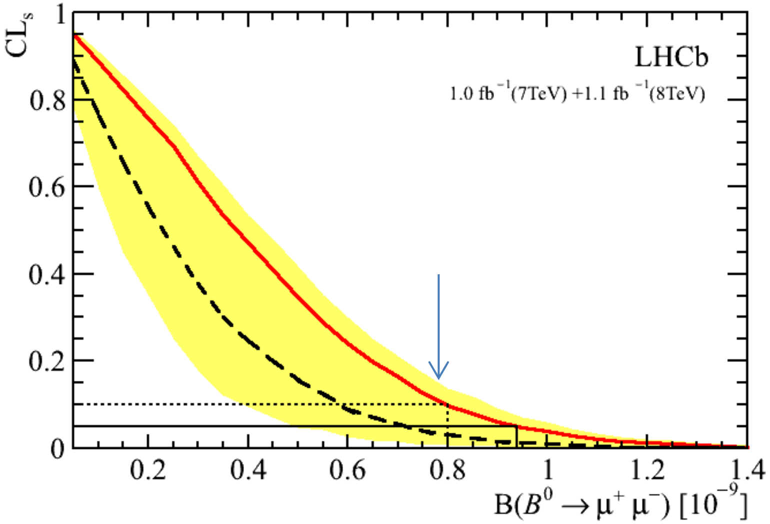


Search for $B_{(s)} \rightarrow \mu^+ \mu^-$

Current status of $B_s^0 \rightarrow \mu\mu$



LHCb: $B^0 \rightarrow \mu\mu$



At 95% CL :

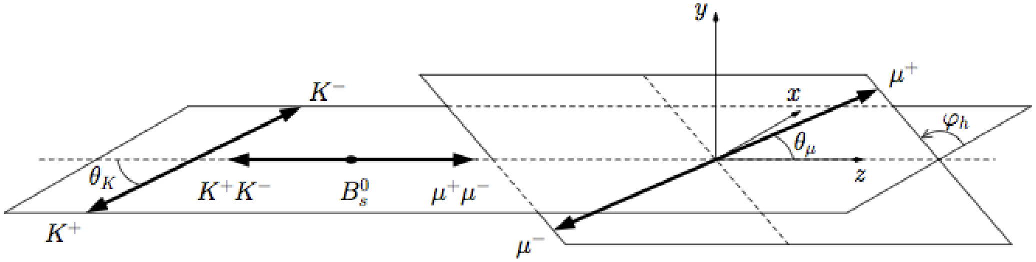
$$Br(B^0 \rightarrow \mu\mu) < 9.4 \times 10^{-10}$$

Approaching SM: $(1.07 \pm 0.10) \times 10^{-10}$

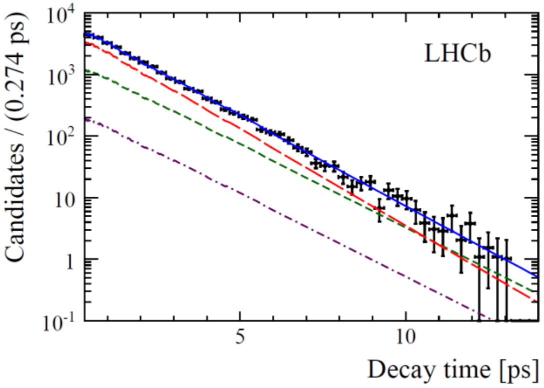
Measurement of ϕ_s

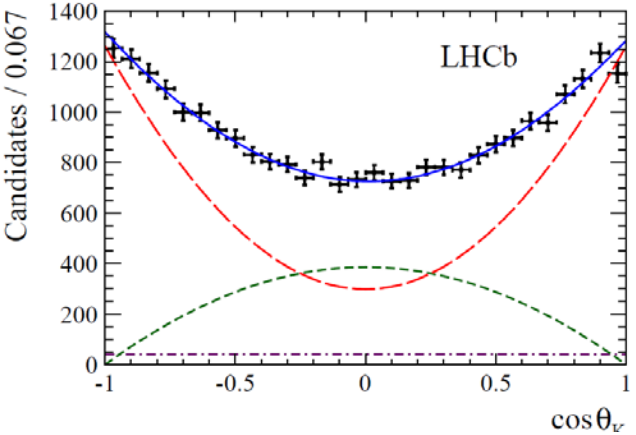
$$B_s^0 \rightarrow J/\psi K^+K^-$$

Decay angles in helicity basis



Projections:



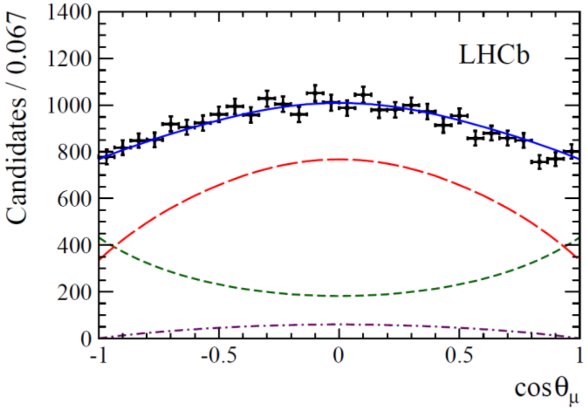


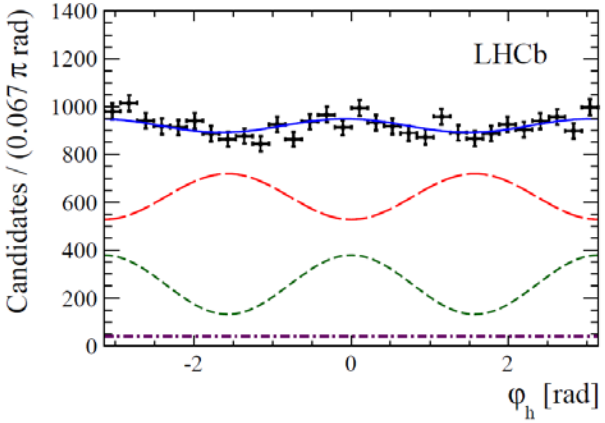
Blue: Total

Red:CP-even

Green: CP-odd

Purple: S-wave

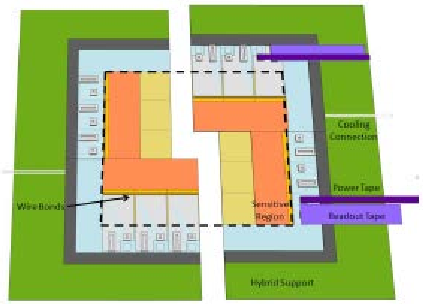




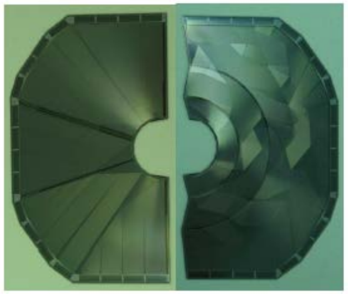
Vertex detector (VELO) upgrade

Enlarge acceptance at high η	Move closer to the beam Inner aperture reduce from 5 to 3.5 mm
Irradiation dose	370 Mrad or 8×10^{15} n_{eq}/cm^2
Low material budget	Sensor thickness 200 μm Thickness of the RF foil 300 → 150 μm CO_2 cooling using micro channels
High output data rate	2.8 Tbit/s (pixel) 2.4 Tbit/s (strip)

Two options considered



- Square pixel 55×55 μm²
- VELOPix chip
- Channels 41×10^6



- Inner pitch 30 μm
- SALT chip
- Channels 215×10^3

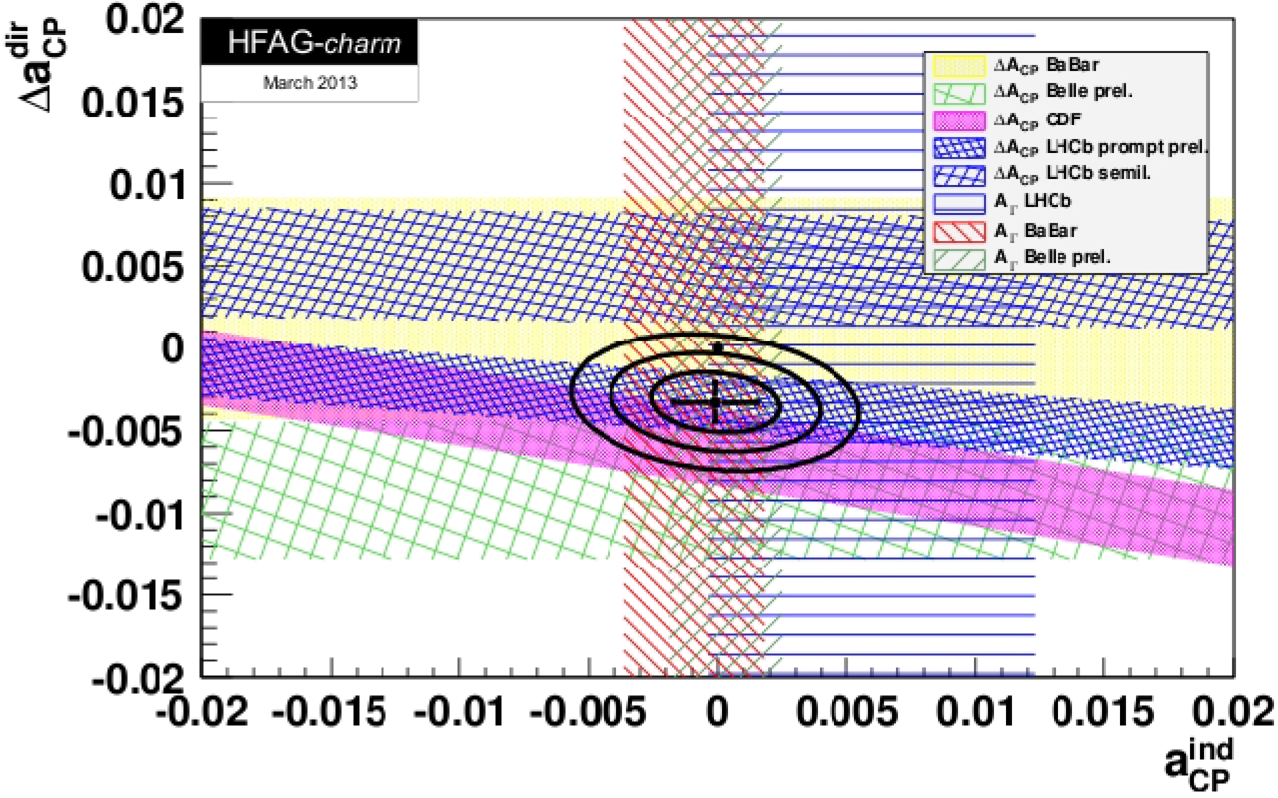
Strip with (r, φ) sensors

CP Violation in CHARM Decays

HFAG average : ΔA_{CP}

$\Delta a_{CP}^{dir} = (-0.329 \pm 0.121)\%, \qquad \Delta a_{CP}^{ind} = (-0.010 \pm 0.162)\%$

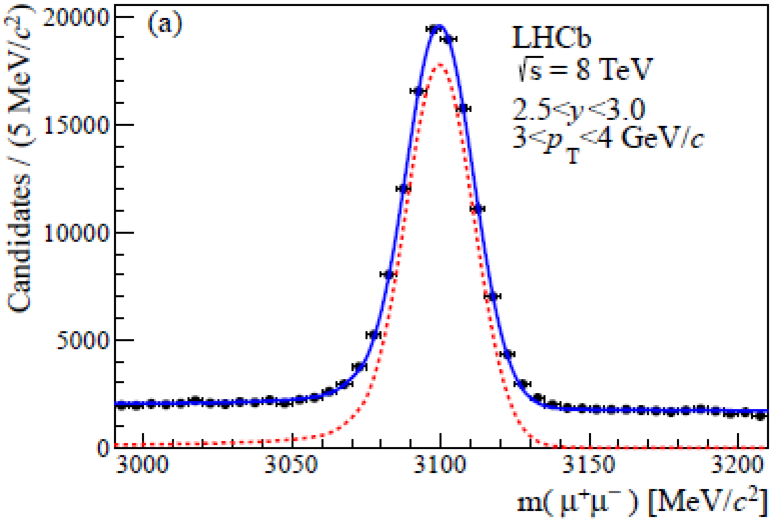
Agreement with NO CPV hypothesis - CL = 2.1 x 10^{-2}.



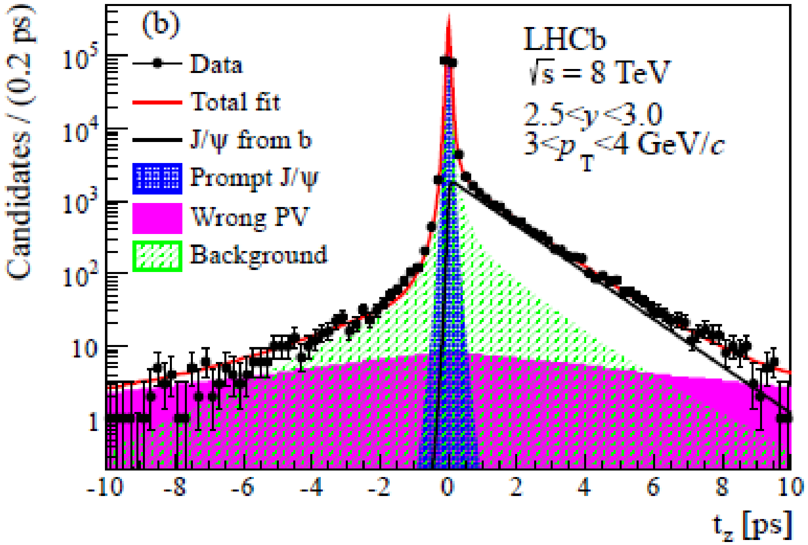
No evidence of CPV in *D* decays.

J/ψ and Υ production

- Measure prompt J/ψ and Υ production cross-sections as a function of p_T and y at $\sqrt{s}$ = 8 TeV using 51 pb^{-1} of data from 2012



Pseudo decay time:



$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \times M_{J/\psi}}{p_z}$$

- J/ψ yields extracted from a 2D fit in each ($p_{T,}$y) bin
- Cross section of J/ψ from b also measured.

- J/ψ and Υ assumed to be unpolarized

- Full set of results in the LHCb papers

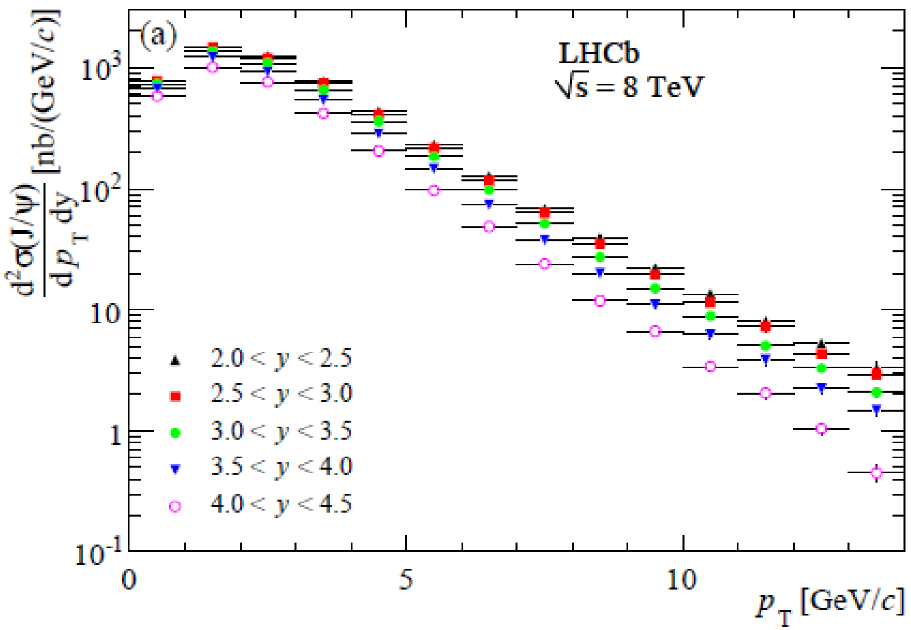
LHCb-paper-2013-071
arxiV:1304.6977

J/ψ and Υ production

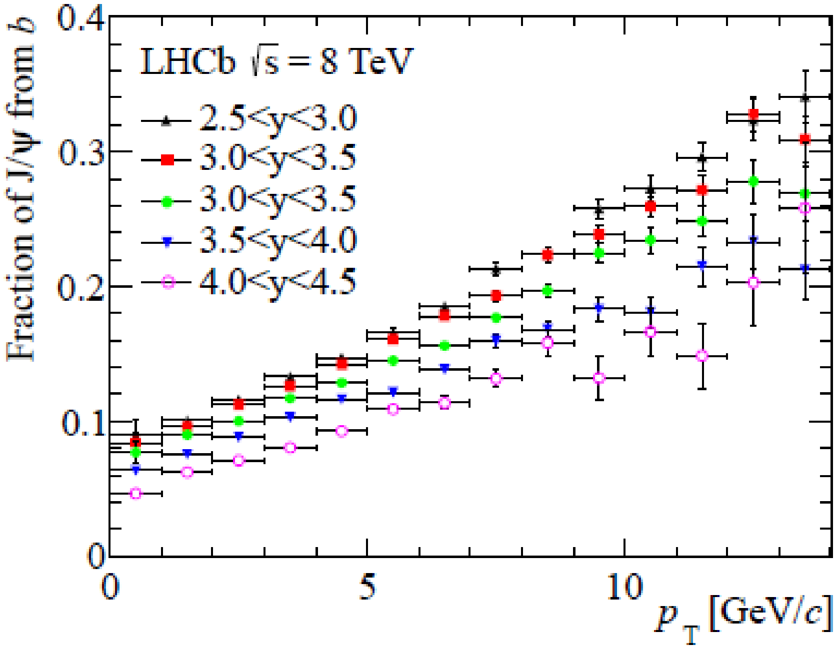
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}(pp\to VX) = \frac{N\left(V\to\mu^+\mu^-\right)}{\mathcal{L}\times\epsilon_{\mathrm{tot}}\times\mathcal{B}\left(V\to\mu^+\mu^-\right)\times\Delta y\times\Delta p_{\mathrm{T}}}$$

(V= J/ψ or Υ, ε= detection efficiency
L= integrated luminosity, $\Delta y=0.5, \Delta p_T=0.5$ GeV/c)

Use the known branching fraction : *B*(J/ψ → μμ) = (5.94 ± 0.06) X10^{-2}

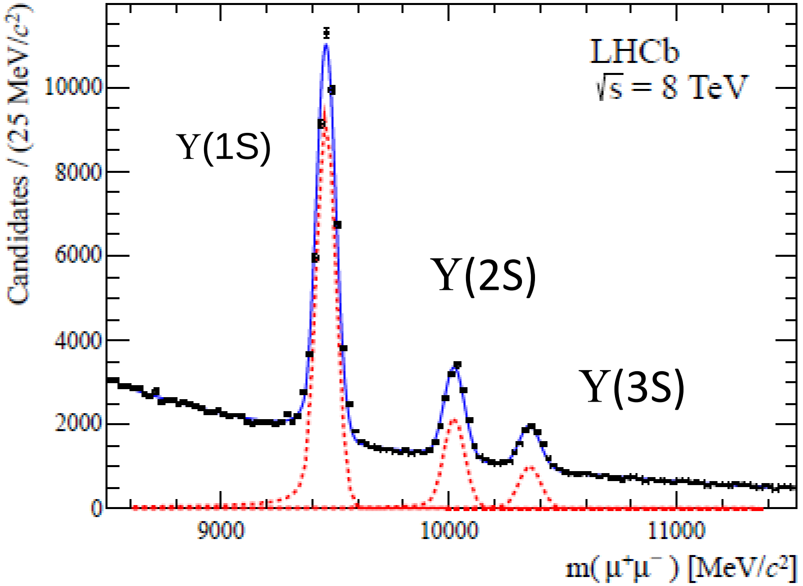


Differential cross–section of prompt J/ψ

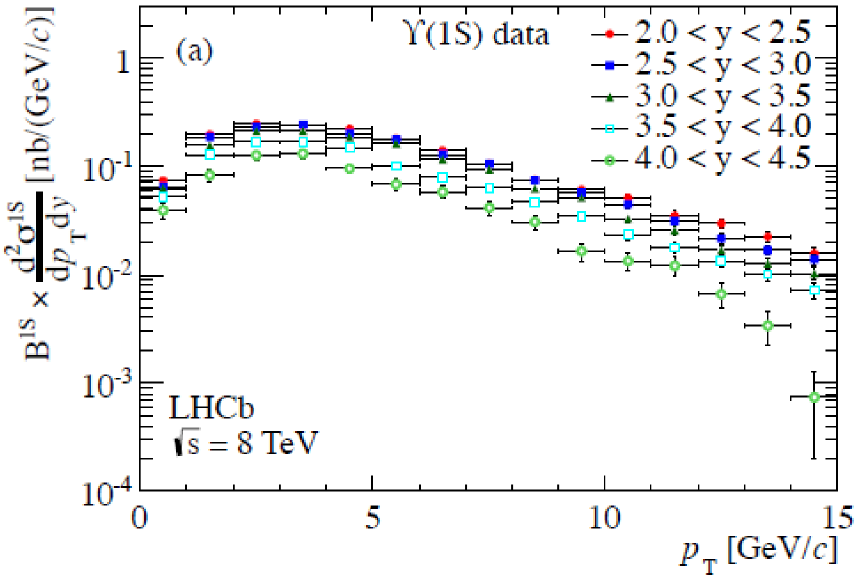


Fraction of J/ψ from b

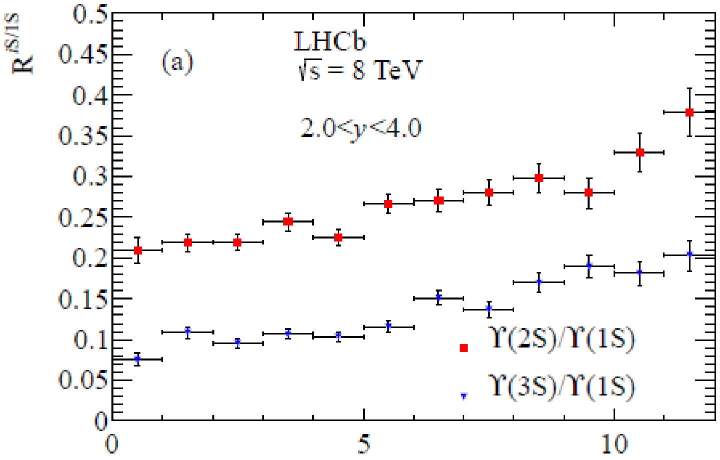
J/ψ and Υ production



Differential cross-section of Υ(1S)



- cross-section X branching fraction quoted here for Υ

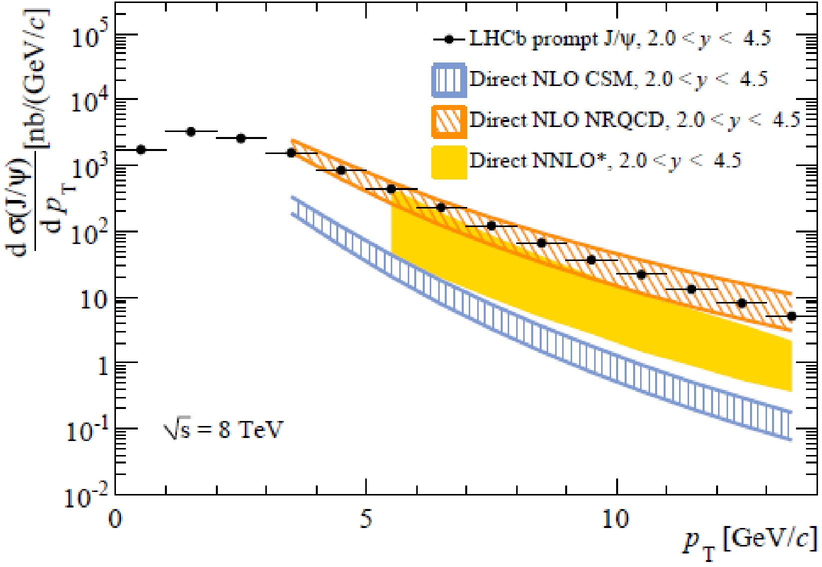


Ratio of Υ cross-sections

J/ψ and Υ production

Comparison to theory

Prompt J/ψ cross-section

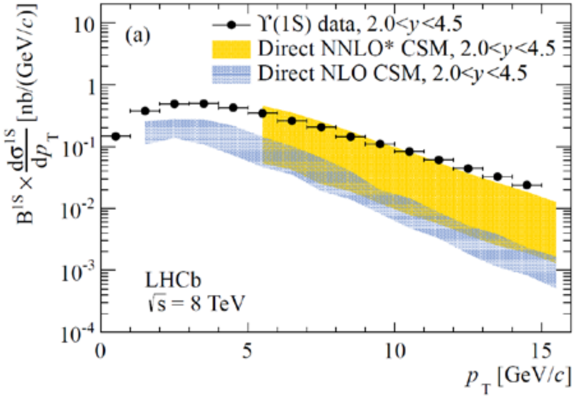


J/ψ

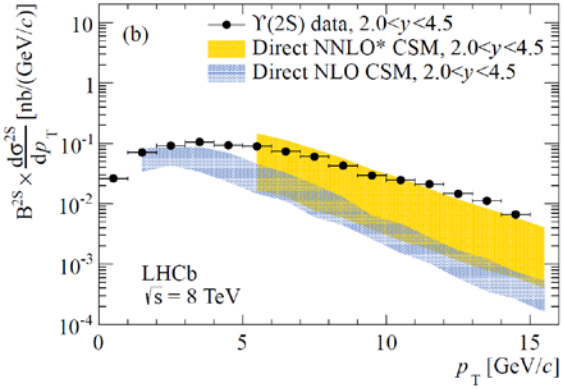
- Feeddown from $\psi(2S)$ and χ_c not included in theory (~30% in total Phys. Lett. B718 (2012)431)
- Reasonable agreement with NLO NRQCD and NNLO* CSM

Υ

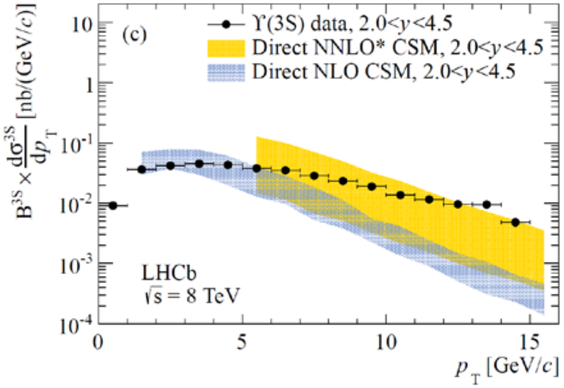
- Feeddown from χ_b not included in theory (~20% for $\chi_b(1P) \rightarrow \Upsilon(1S)\gamma$ JHEP 11(2012)31)
- NNLO needed to describe the measurements



Prompt cross-section: $\Upsilon(1S)$

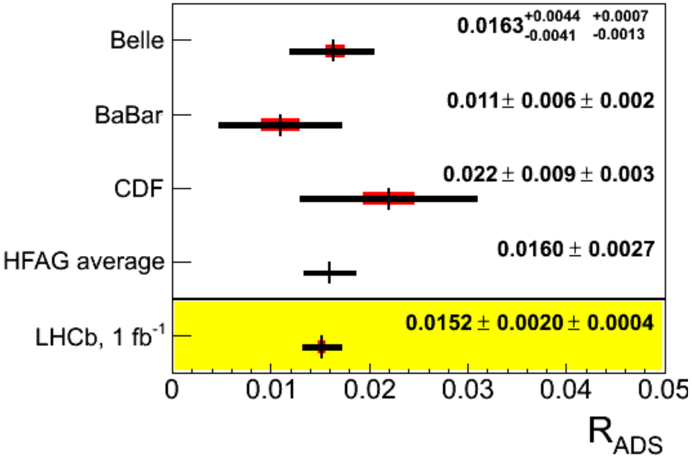


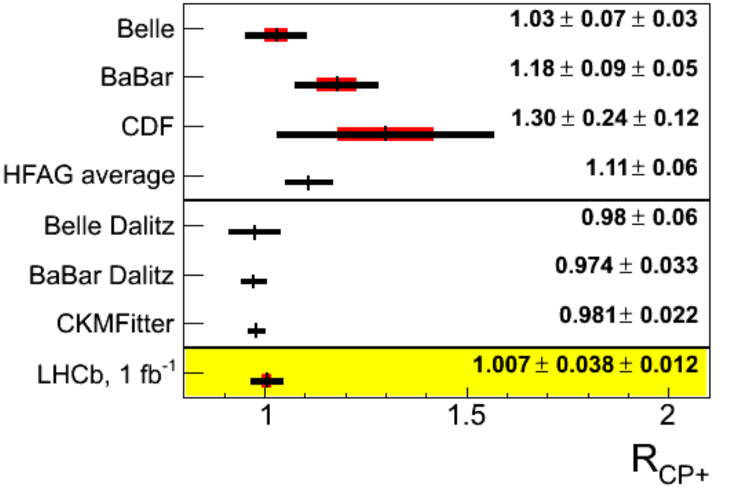
$\Upsilon(2S)$

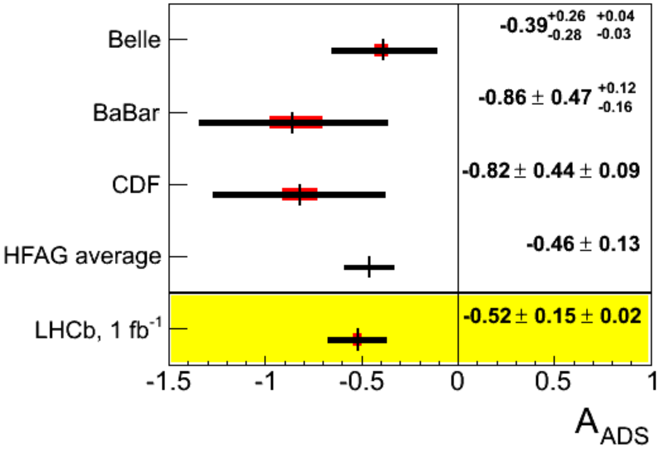


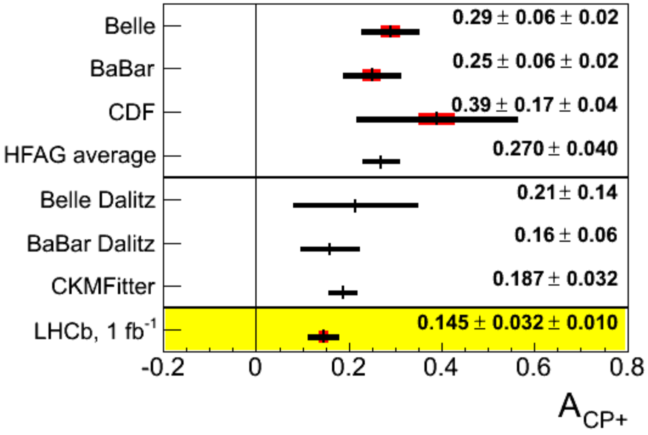
$\Upsilon(3S)$

Towards a measurement of CKM angle γ









LHCb has some of the most precise measurements on these.