Warsaw Spring Workshop

LHCb results on CP violation

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Outline

- **Introduction**
  - ✧ Why are we interested in flavour physics?
  - ✧ Three ways of CPV
  - ✧ Phenomenology of mixing

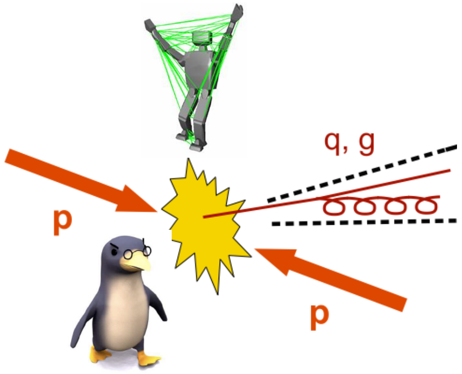
- **Selected measurements at LHCb (**only a few spectacular ones**)**
  - ✧ The LHCb detector
  - ✧ Mixing and CPV for beauty
    - ✧ Phase ϕ_s from $B^0_s \rightarrow J/\psi\ \phi$
    - ✧ CKM angle γ from $B^{\pm} \rightarrow D^0K^{\pm}$
    - ✧ Rare decays of $B \rightarrow K^*\mu\mu$
  - ✧ Mixing and CPV for charm
    - ✧ Searches for mixing and CPV in $D^0 \rightarrow K^{\pm}\pi^{\mp}$
    - ✧ A_Γ asymmetry from $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$
    - ✧ Model-independent searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$, $D^0 \rightarrow \pi^-\pi^+\pi^0$
    - ✧ A_T asymmetry from $D^0 \rightarrow K^-K^+\pi^-\pi^+$, $D^0 \rightarrow \pi^-\pi^+\pi^-\pi^+$

- **Summary**

Why are we interested in flavour physics?

The main goal of particle physics is to search for physics beyond the Standard Model (SM)

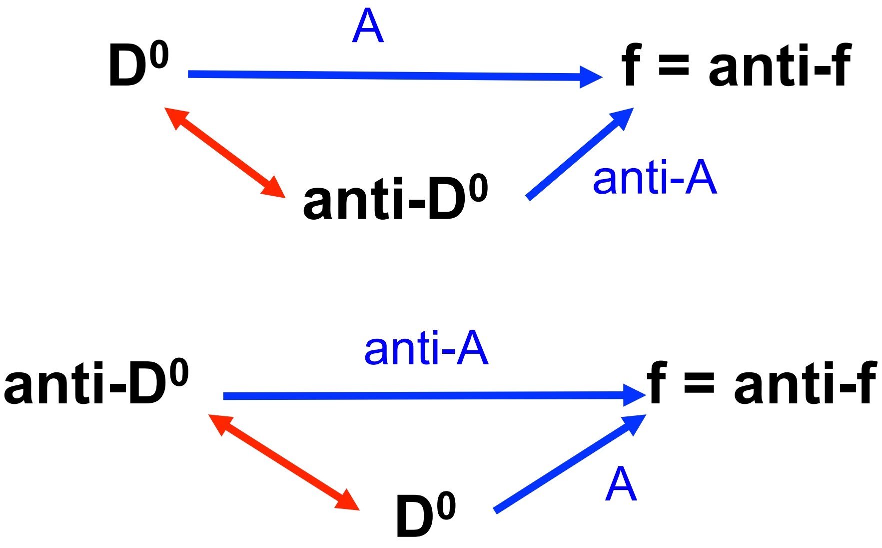
There are two ways of search for New Physics:



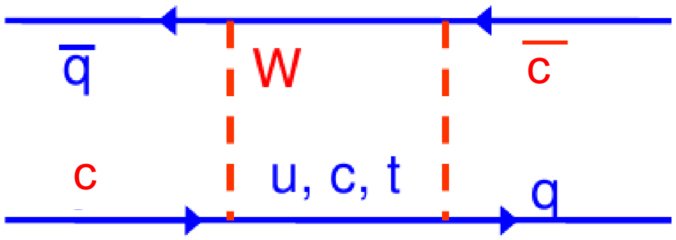
- direct searches for produced new objects (Atlas and CMS)
- LHCb contributes to indirect searches:
    - ✧ testing of the SM by precision measurements of especially processes which are very well predicted
    - ✧ finding of disagreements is indirect indication for the existence of new objects
    - ✧ in particular we are interested in:
        - ➢ CPV in B and D
            - – CPV in SM is too small to explain the observed size of matter domination over antimatter in the Universe
            - – it is a good tool in searches for New Physics
        - ➢ and very rare decays (B and D) – highly suppressed in the SM

Three ways of CP violation

D^0 – as an example, the same for B^0, B^0_s



1. in mixing (indirect)
   $D^0 \rightarrow$ anti-D^0 ≠ anti-$D^0 \rightarrow D^0$
2. in decay amplitudes (direct)
   $D \rightarrow f$ ≠ anti-$D \rightarrow$ anti-f
3. in interference (indirect)
   between direct decays and decays with mixing



- Mixing is described by box diagrams and direct decays by tree and penguin diagrams
- In loops new particles could be exchanged

- CPV in mixing does not depend on final state (universal)
- Direct CPV depends on final states and it has to be searched everywhere it is possible: $D \rightarrow hh, hhh, hhhh$, ……

Mixing of neutral mesons

Neutral mesons can oscillate between matter and anti-matter:

$$K^0 - \bar{K}^0 \quad , \qquad (d\bar{s}) - (\bar{d}s)$$

$$B^0 - \bar{B}^0 \quad , \qquad (d\bar{b}) - (\bar{d}b) \quad ; \qquad B_s^0 - \bar{B}_s^0 \quad , \qquad (s\bar{b}) - (\bar{s}b)$$

$$D^0 - \bar{D}^0 \quad , \qquad (c\bar{u}) - (\bar{c}u)$$

mass eigenstates are different from flavor eigenstates

$$i\frac{d}{dt}\begin{pmatrix}|D^0\rangle \\ |\bar{D}^0\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12} \\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|D^0\rangle \\ |\bar{D}^0\rangle\end{pmatrix}$$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

(D^0 – as an example, the same for B^0, B^0_s)

Two parameters describe mixing:

mass difference Δm:

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}$$

decay width difference ΔΓ:

$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

$$m \equiv (m_1 + m_2)/2$$

$$\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$$

experiment theory

$$\Delta m = M_H - M_L = 2|M_{12}|\left(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2} sin^2\phi + ...\right)$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}|cos\phi\left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2} sin^2\phi + ...\right)$$

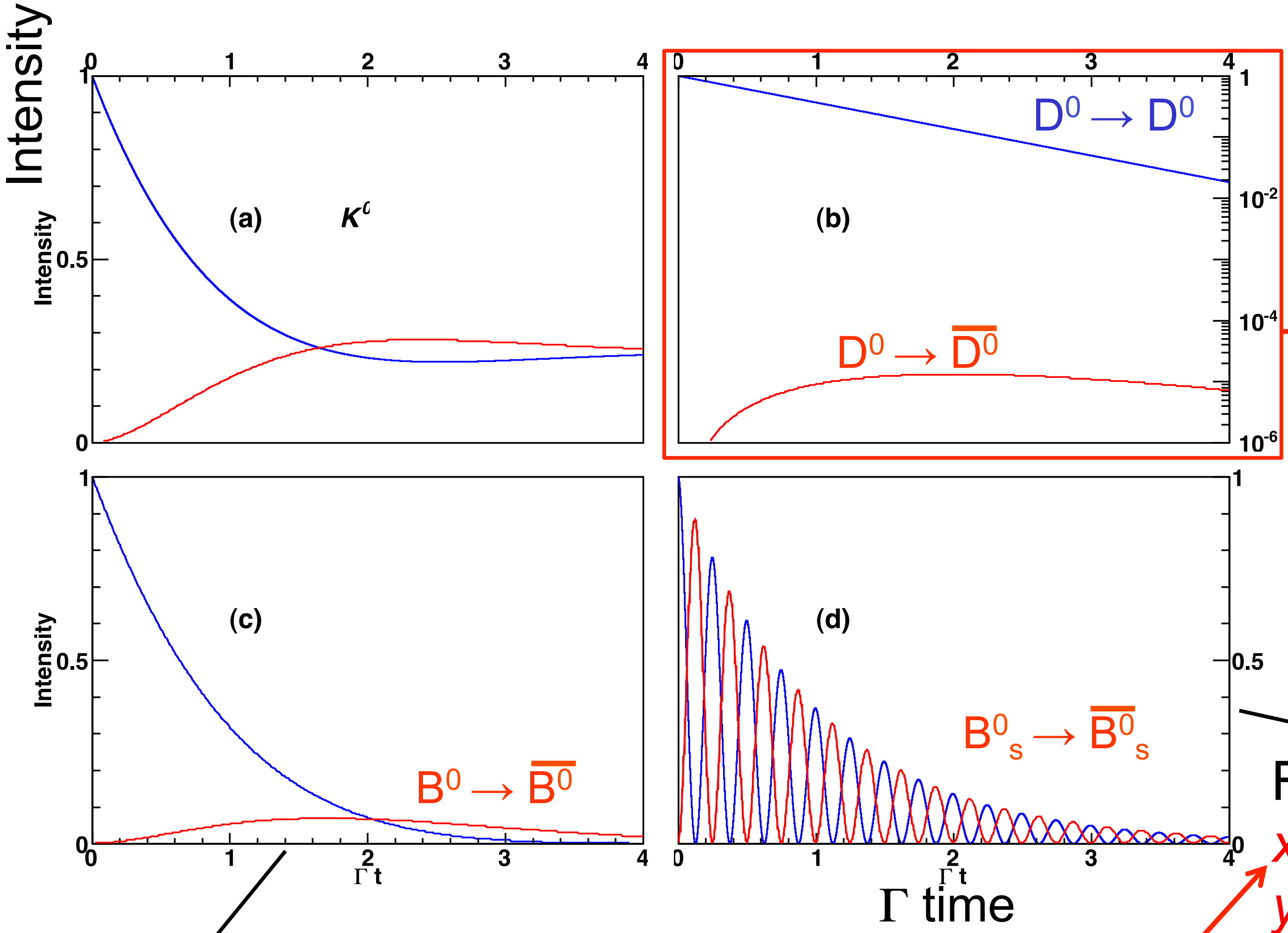
For B^0_s: $\Delta\Gamma_s = \Gamma_L - \Gamma_H$

weak phase: $\phi \equiv arg(-M_{12}/\Gamma_{12})$

Δm, ΔΓ, φ – measured experimentally

Mixing of neutral mesons

Chavez, Cowan, Lockman, Int.J.M.Phys.A27(2012)1230019



- D^0 mesons: *very, very* slowly
- K^0 mesons: very slowly
- B_d mesons: slowly
- B_s mesons: fast!

For charm:

$x \approx 0.0074$

$y \approx 0.0048$

- x, y very small
- mixing is very slow
- very precise measurements needed

For B^0_s:

$x \approx 26.82$ (large)

$y \approx 0.058$ (much smaller than x)

For B^0:

$x \approx 0.775$

$y \approx 0.007$ (very small)

The frequency of B^0_s – anti-B^0_s oscillations is the highest. On average, a B^0_s meson changes its flavour 9 times between production and decay

LHCb – precision detector

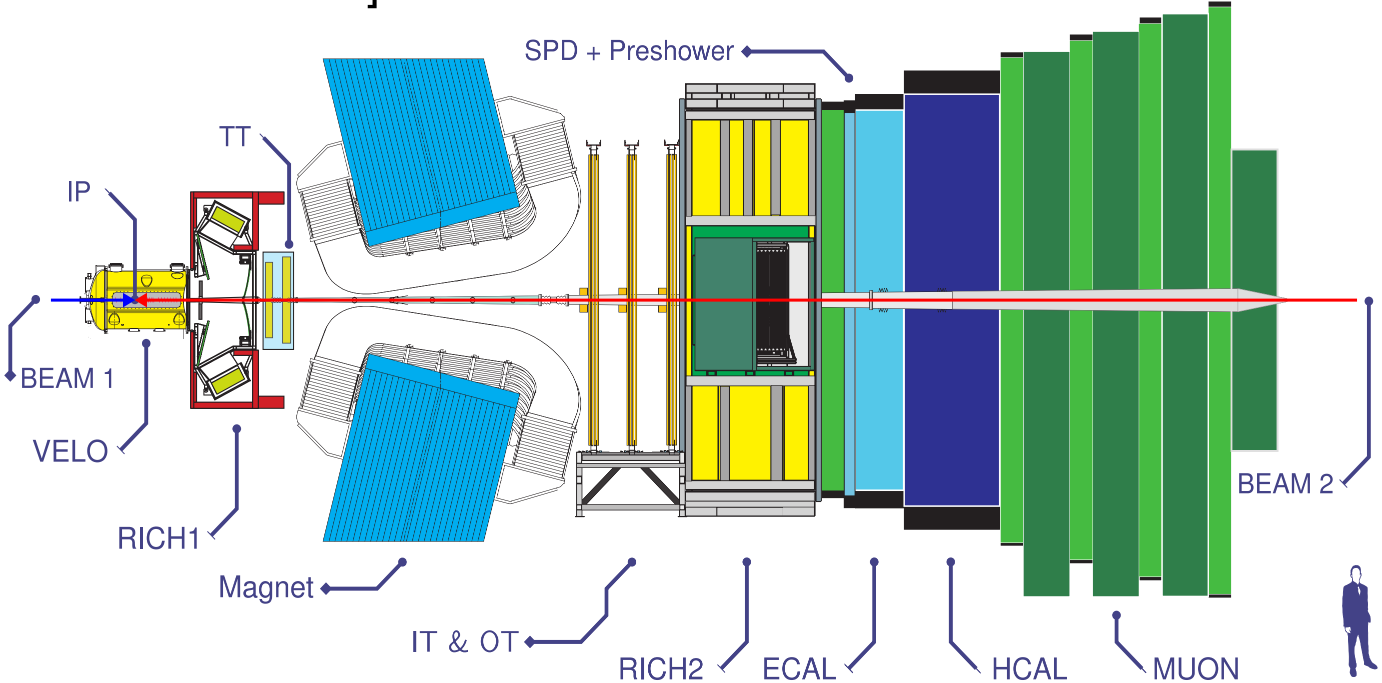
Single-arm forward spectrometer covering range: $2<\eta<5$

$$\sigma(b\bar{b}) = 284 \pm 53\mu\text{b}$$ [PLB 694 (2010) 209]

$$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$$ [LHCb-CONF-2010-013]

Run 1:
1/fb (2011), 2/fb (2012)

For each 1/fb:
~28k $B^0_s \rightarrow J/\psi(\mu\mu)\,\phi(K^+K^-)$
~2M $D^{*\pm} \rightarrow D^0(\rightarrow K^-K^+)\pi^\pm$



- VELO – resolution of IP: 20 μm, decay lifetime resolution ~ 45 fs: 0.1 $\tau(D^0)$
- Excellent tracking resolution: $\Delta p/p$ = 0.4% at 5 GeV to 0.6% at 100 GeV
- RICH – very good particle identification for π and K
- Dedicated trigger lines for beauty and charm with high efficiency
- The polarity of the magnet is reversed repeatedly during data taking
- LHCb has possibilities of precise measurements of beauty and charm particles

Beauty part

(the selected LHCb measurements on B meson decays)

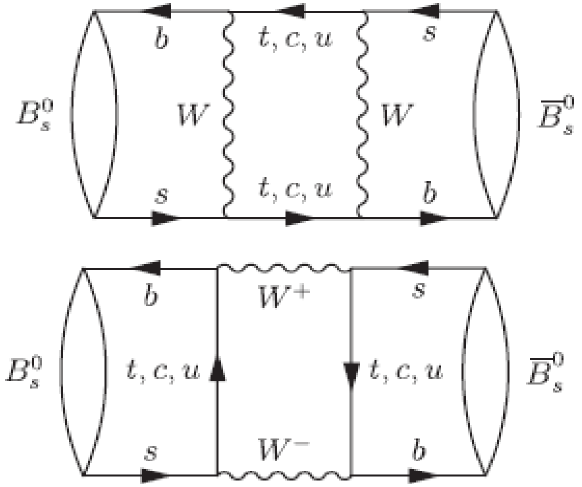
Measurement of the B^0_s – anti-B^0_s oscillation

We use flavour-specific decay mode:

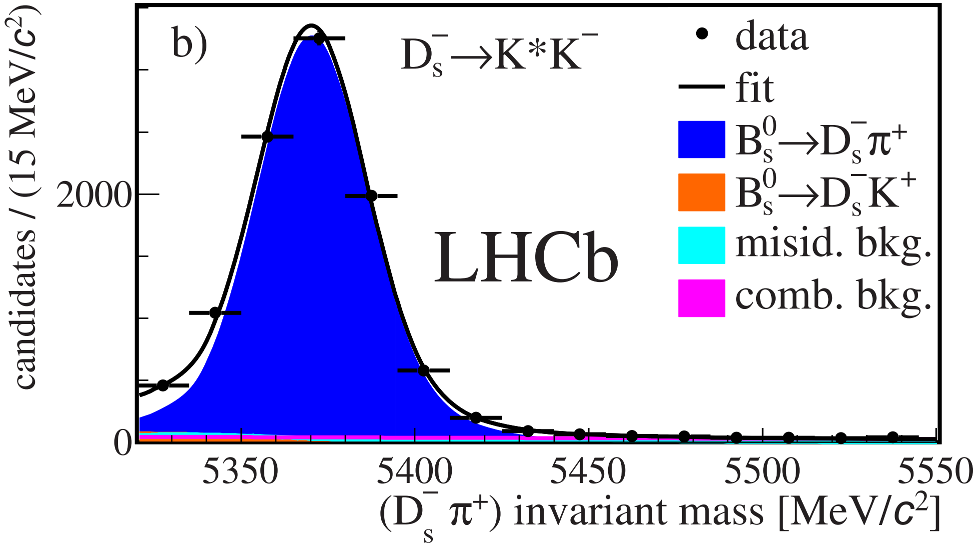
$B^0_s \rightarrow D^-_s\pi^+$

five D^-_s decay modes:

- $D^-_s \rightarrow \phi(K^+K^-)\pi^-$
- $D^-_s \rightarrow K^{*0}(K^+\pi^-)K^-$
- $D^-_s \rightarrow K^+K^-\pi^-$
- $D^-_s \rightarrow K^-\pi^+\pi^-$
- $D^-_s \rightarrow \pi^-\pi^+\pi^-$

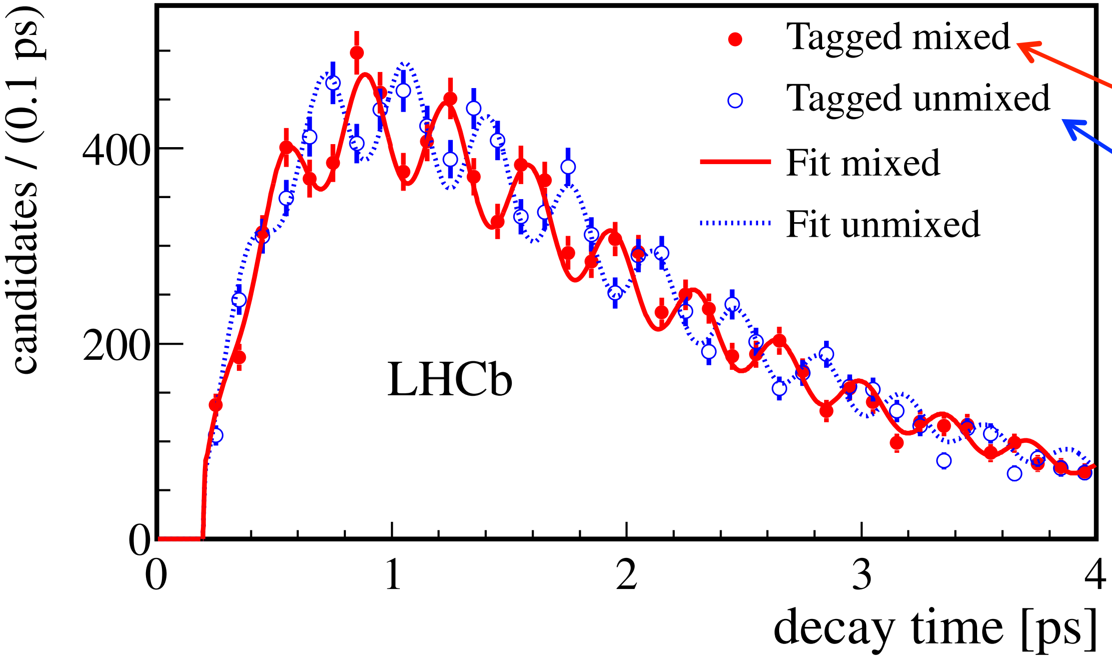


Example: $D^-_s \rightarrow K^{*0}K^-$



LHCb: 1/fb 2011, 34000 $B^0_s \rightarrow D^-_s\pi^+$

New J.Phys.15(2013)053021



different flavour → at decay and production

the same flavour → at decay and production

The oscillation frequency:

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

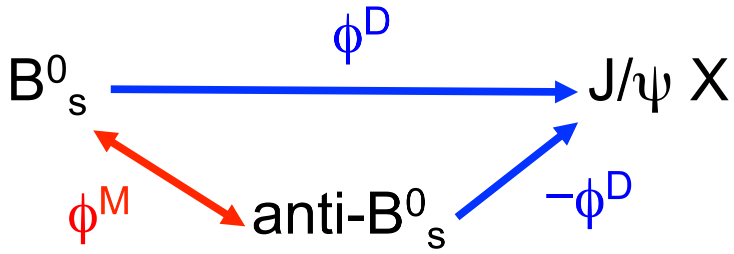
Most precise measurement to date

agrees with world av. $17.69 \pm 0.08\ ps^{-1}$

The CPV phase ϕ_s from B^0_s decays

The measurement of ϕ_s is crucial in LHCb:

- measured from $B^0_s \to J/\psi\, X$, mainly: $B^0_s \to J/\psi(\mu\mu)\, \phi(KK)$ (golden mode)

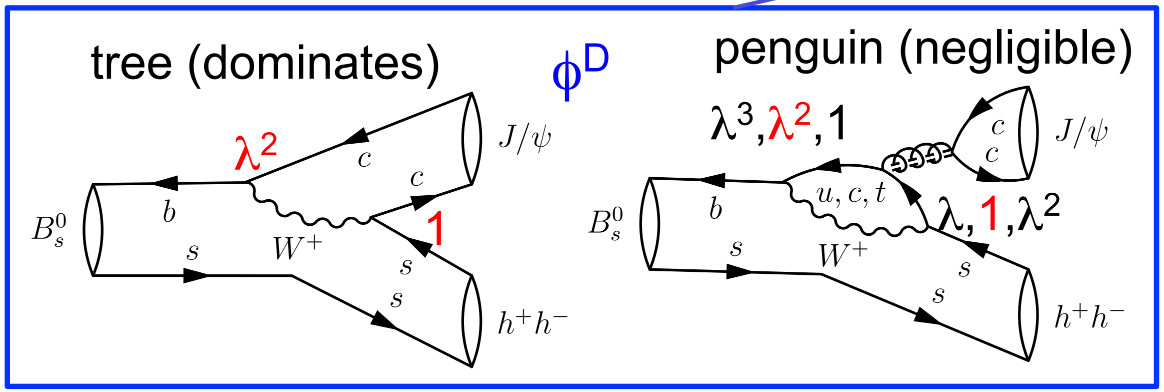


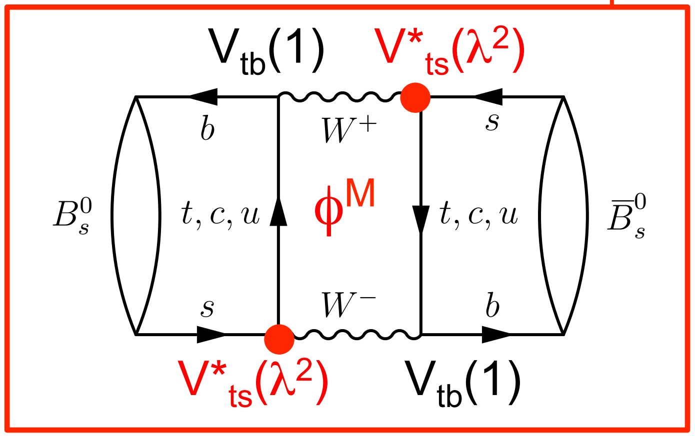
$\phi_s = \phi^M - 2\phi^D$

$$\phi_s = -2\beta_s = -2arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

from direct decays:
$\phi^D = \arg(V_{cs}V^*_{cb})$

from mixing:
$\phi^M = 2\arg(V_{ts}V^*_{tb})$





- interference between direct decays (D) and decays with mixing (M) allows us to measure the value of ϕ_s
- if new particles are exchanged in box diagram, then value of ϕ^M will be different
- very well predicted in the SM: $\phi^{SM}_s = -0.0368 \pm 0.0017$ rad

The CPV phase ϕ_s from $B^0_s \to J/\psi\, K^+K^-$ decays

$B^0_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$

pseudo scalar

vectors

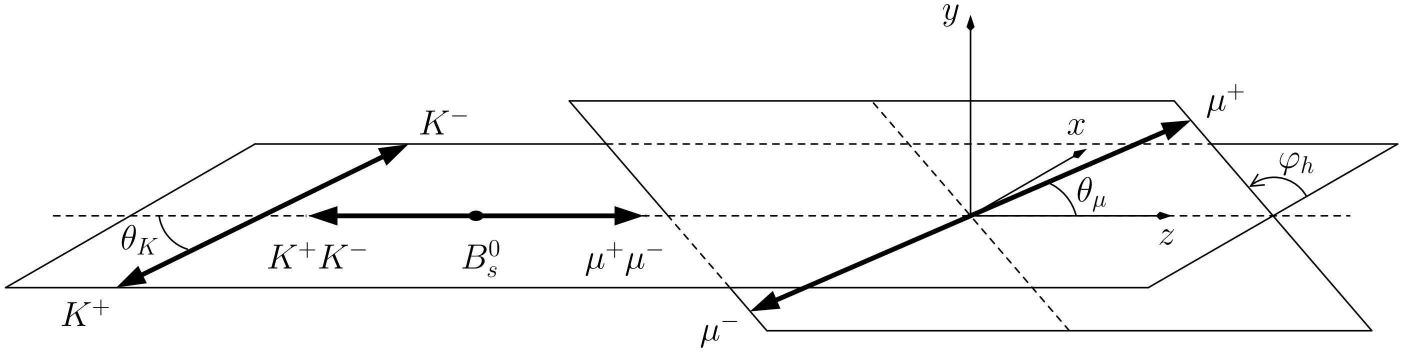
The relative orbital angular momentum of the final state (mixture of CP-even and CP-odd):

$L = 0 \quad 1 \quad 2$

CP even

CP odd

The various components of CP can be separated statistically by measurement of three angles



depends on three angles

The decay rate:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

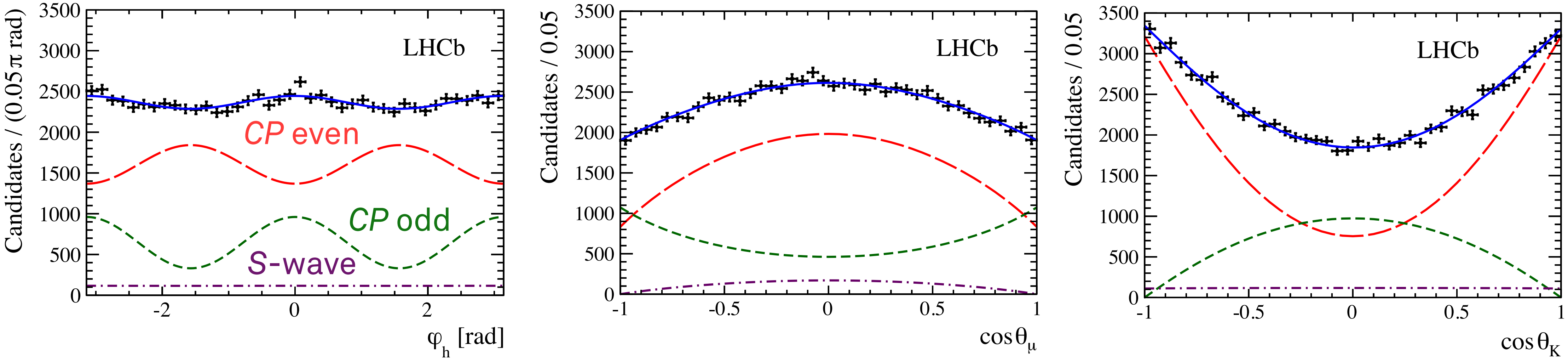
contains Γ_s, $\Delta\Gamma_s$, ϕ_s, Δm_s, t

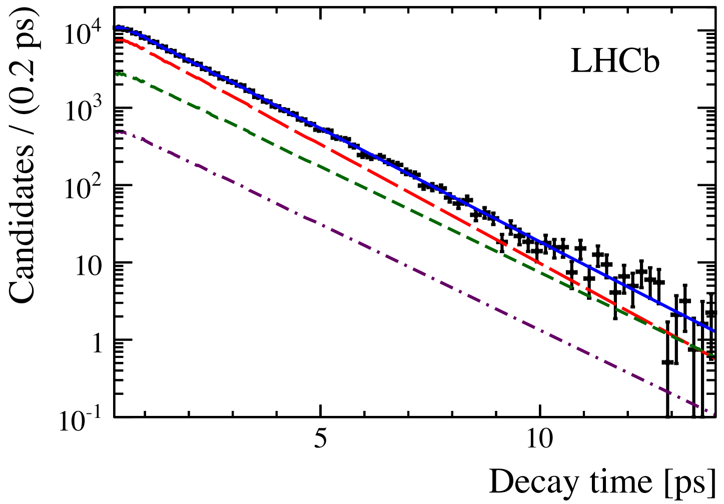
The phase is accessible experimentally via a time-dependent angular analysis to measure the time-dependent CP asymmetry

The CPV phase ϕ_s from $B^0_s \to J/\psi(\mu^+\mu^-) K^+K^-$ decays

LHCb: 3/fb , ~ 96 000 signal candidates

Phys.Rev.Lett.114(2015)041801





The most precise measurement:

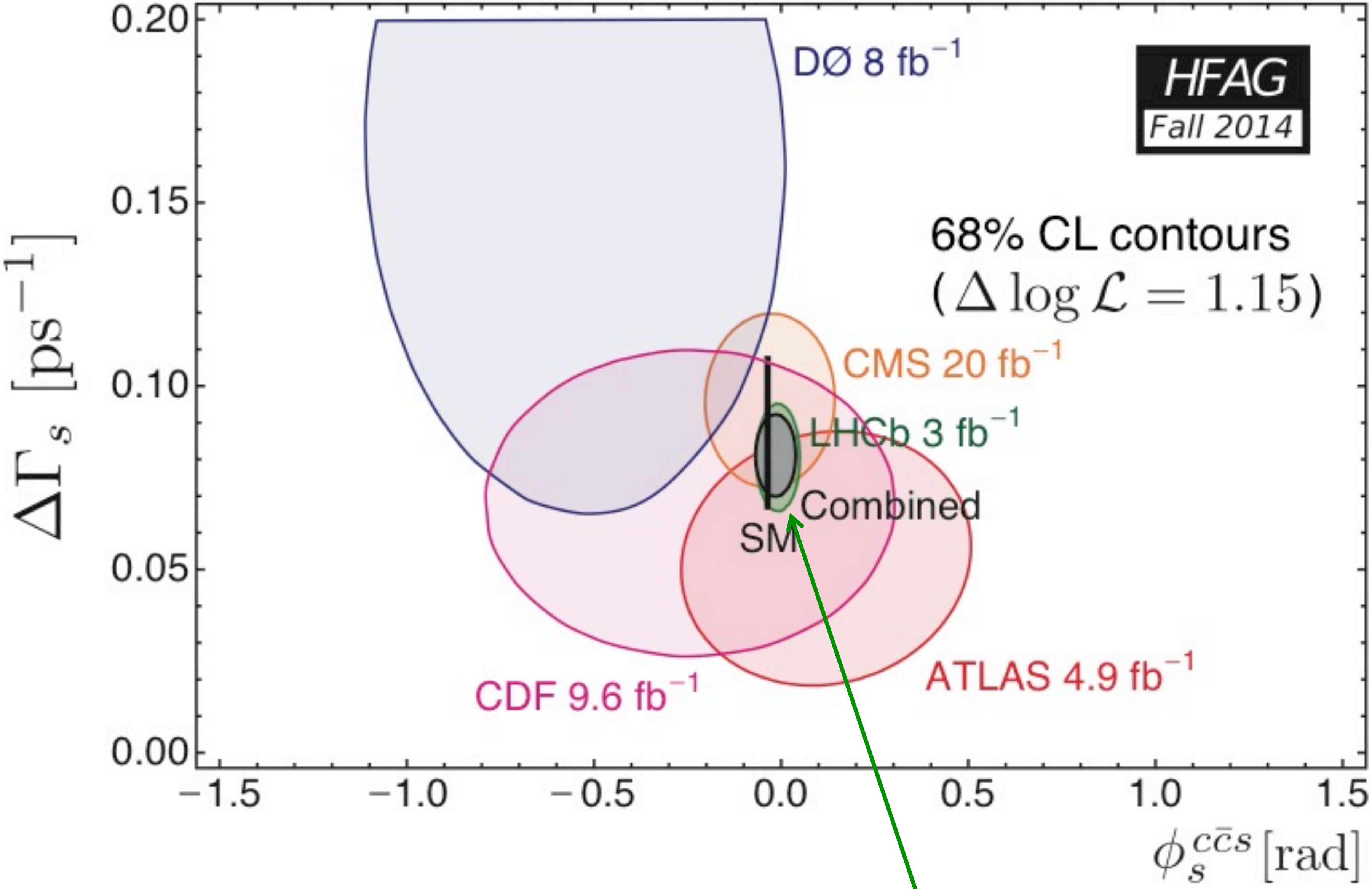
ϕ_s = - 0.058 ± 0.049(stat) ± 0.006(syst)

agree with the SM: ϕ^{SM}_s = -0.0368 ± 0.0017

The statistical error is higher than systematic.
It will be reduced using data which will be recorded soon

In Warsaw we work on $B^0_s \to J/\psi(e^+e^-)\, \phi(K^+K^-)$

The CPV phase ϕ_s from B^0_s decays



LHCb measurements: the world most precise,
agree with other experiments, agree with SM predictions

CKM angle γ

The γ is the only CKM angle that can be directly measured at tree-level

$$\boxed{\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)}$$

$$V_{ub} = |V_{ub}|\, e^{i\gamma}$$

- theory:
  γ is known very well $\delta\gamma/\gamma \approx O(10^{-7})$ [JHEP1401(2014)051]

- experiment:
  - ✧ γ is not known very well
  - ✧ Many different channels to study – typically $B^\pm \rightarrow DK^\pm$ decays
    interference between $b \rightarrow c$ anti-u s and $b \rightarrow u$ anti-c s transitions
    (colour suppressed)

    gives γ sensitivity
  - ✧ It is quite challenging to measure since the decay rates are very small

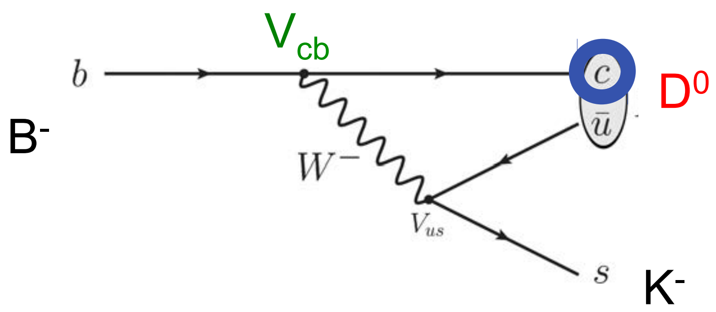
$$\mathrm{BR}(B^- \rightarrow DK^-, D \rightarrow \pi K) \approx 2 \times 10^{-7}$$

  - ✧ Some final states with K^0_s (hard to reconstruct)

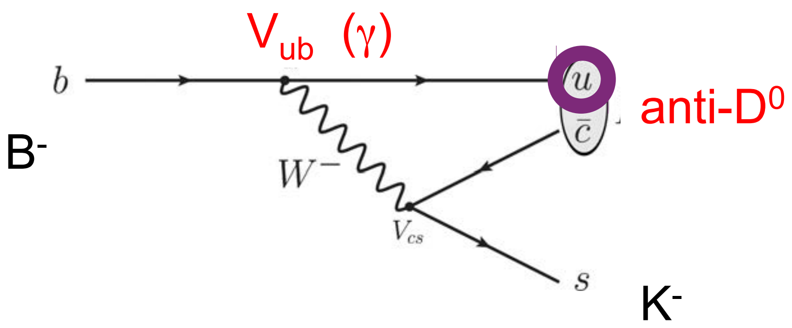
Measuring γ from B decays

Many different channels to study – typically $B^{\pm} \to DK^{\pm}$ decays

- interference between $D^0 \to f$ and anti-$D^0 \to f$ gives γ sensitivity



Colour Favoured



Colour Supressed

Parameters of interest:

$$r_B = \left|\frac{A(\mathrm{SUP})}{A(\mathrm{FAV})}\right|$$ ratio $B^- \to$ anti-D^0K^- to $B^- \to D^0K^-$ amplitudes

$$\delta_B = \phi_{\mathrm{FAV}} - \phi_{\mathrm{SUP}}$$ strong phase difference

$$\Gamma(B^- \to (hh)_D K^-) \propto 1 + r_B^2 + \underline{2\, r_B \cos(\delta_B - \boxed{\gamma})}$$

The equivalent expression for the charge-conjugated decay $B^+ \to D^0K^+$ is obtained by making the substitution $\gamma \to -\gamma$

CP-violating parameters: $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$ $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$

Today: world's most precise single measurement

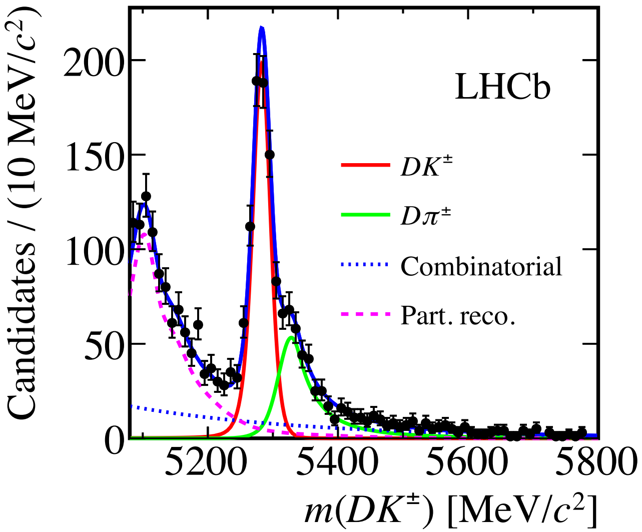
Measuring γ from B decays

To enrich sample we reconstruct: $B^\pm \rightarrow D^0h^\pm$, $D^0 \rightarrow K^0_s h^+h^-$, where h = K or π
$K^0_s \rightarrow \pi^+\pi^-$

LHCb: 3/fb (2011+2012)

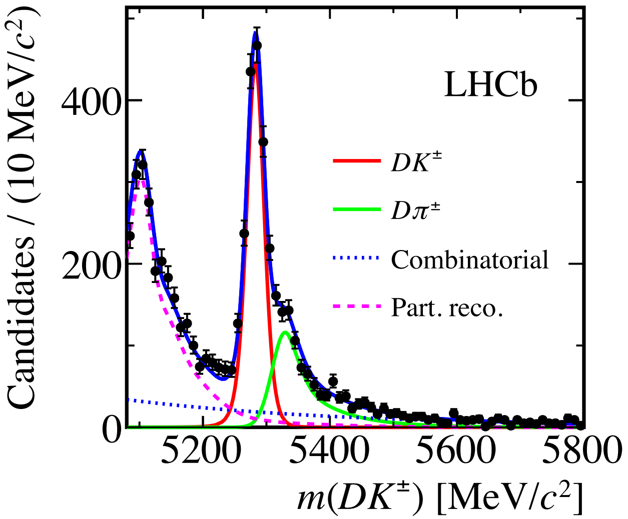
Example for the decay chain: $B^\pm \rightarrow D^0K^\pm$, $D^0 \rightarrow K^0_s\pi^+\pi^-$, ~2.6k candidates

long K^0_s category, ~0.8k events

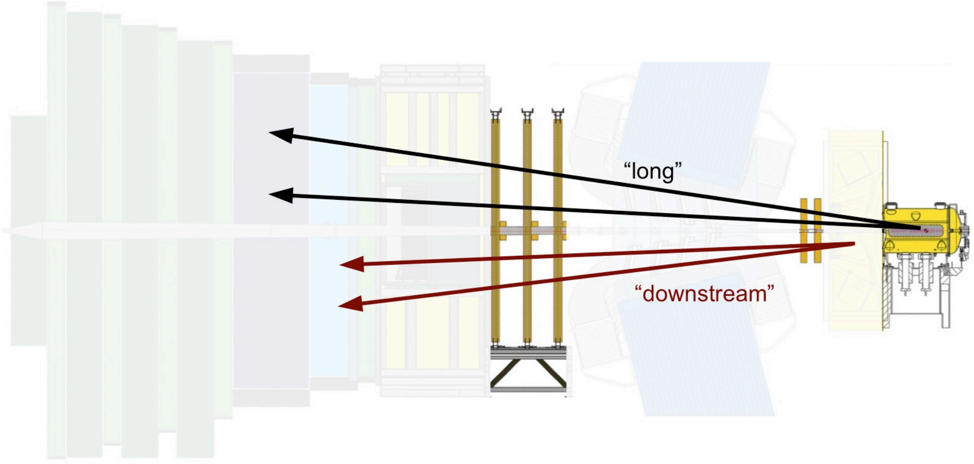


downstream K^0_s category, ~1.8k events

JHEP10(2014)97



The γ measurement does not depend on the K^0_s category



The two K^0_s categories:

1O: long – the K^0_s vertex is reconstructed in the VELO

2O: downstream – track segments of the pions cannot be formed in the VELO

Measuring γ from B decays

LHCb: 3/fb, $B^{\pm} \rightarrow D^0 K^{\pm}$, $D^0 \rightarrow K^0{}_s \pi^+ \pi^-$

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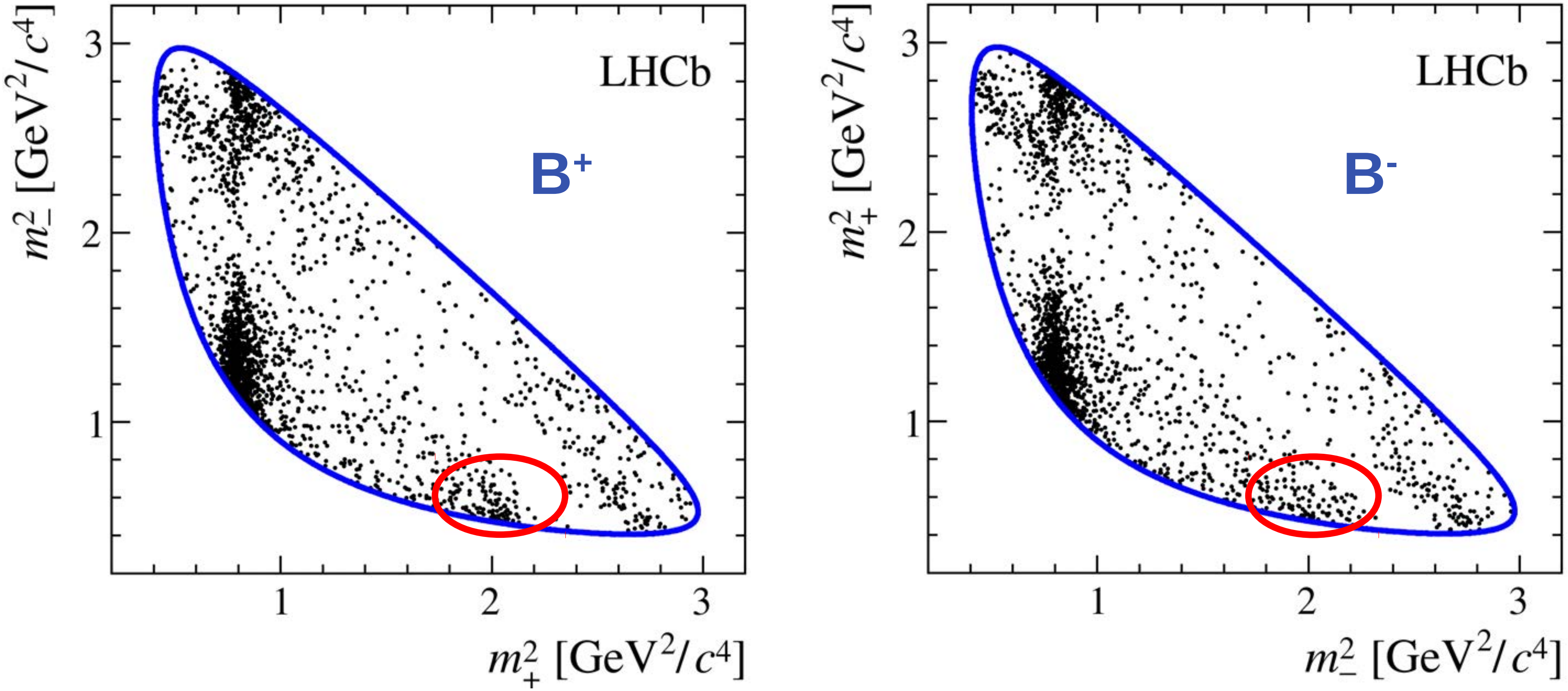


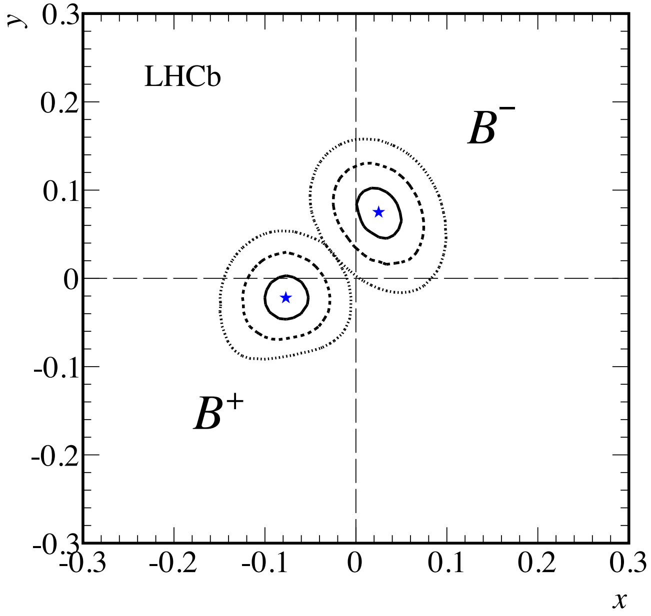
$$m_{\pm}^2 \equiv m^2(K_S^0 \pi^{\pm})$$

- The analysis is performed in bins of the D decay Dalitz plot and existing measurements of the CLEO-c experiment are used to provide input of the D decay strong-phase parameters
- The CP asymmetries are not uniformly distributed in the phase space, some regions of the phase space are more sensitive, it shows importance of a strong phase.

Measuring γ from B decays

JHEP10(2014)97

Confidence levels



LHCb: 3/fb, $B^\pm \to D^0K^\pm$, $D^0 \to K^0_s\pi^+\pi^-$

The Dalitz plot fit is used to measure CP-violating parameters:

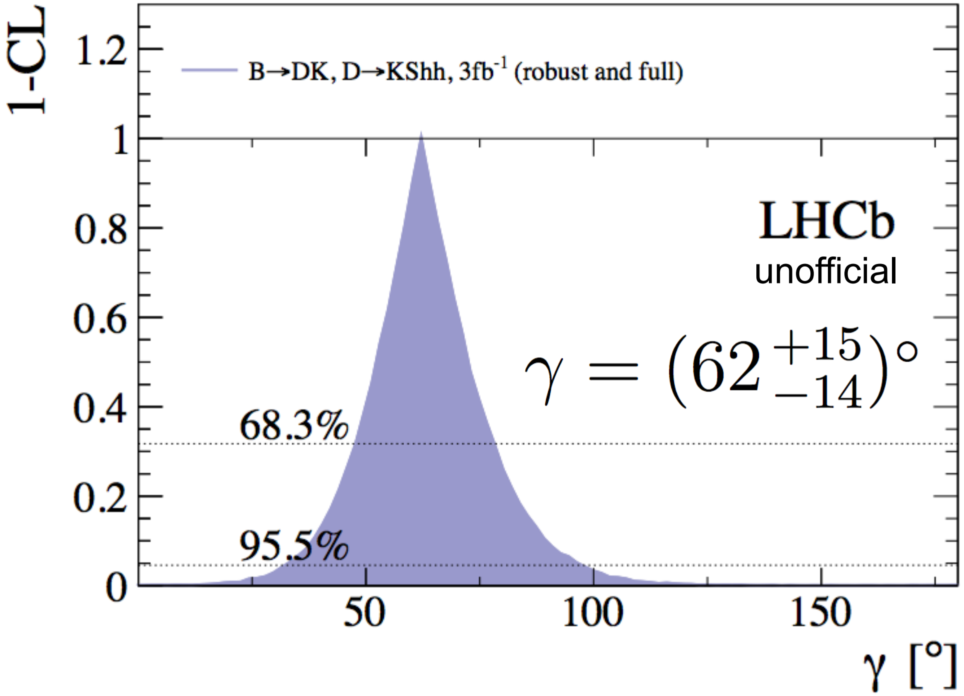
B+

$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2},$$
$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2},$$

B-

$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2},$$
$$y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2},$$

The third error arises from the experimental knowledge of the D decay strong-phase parameters

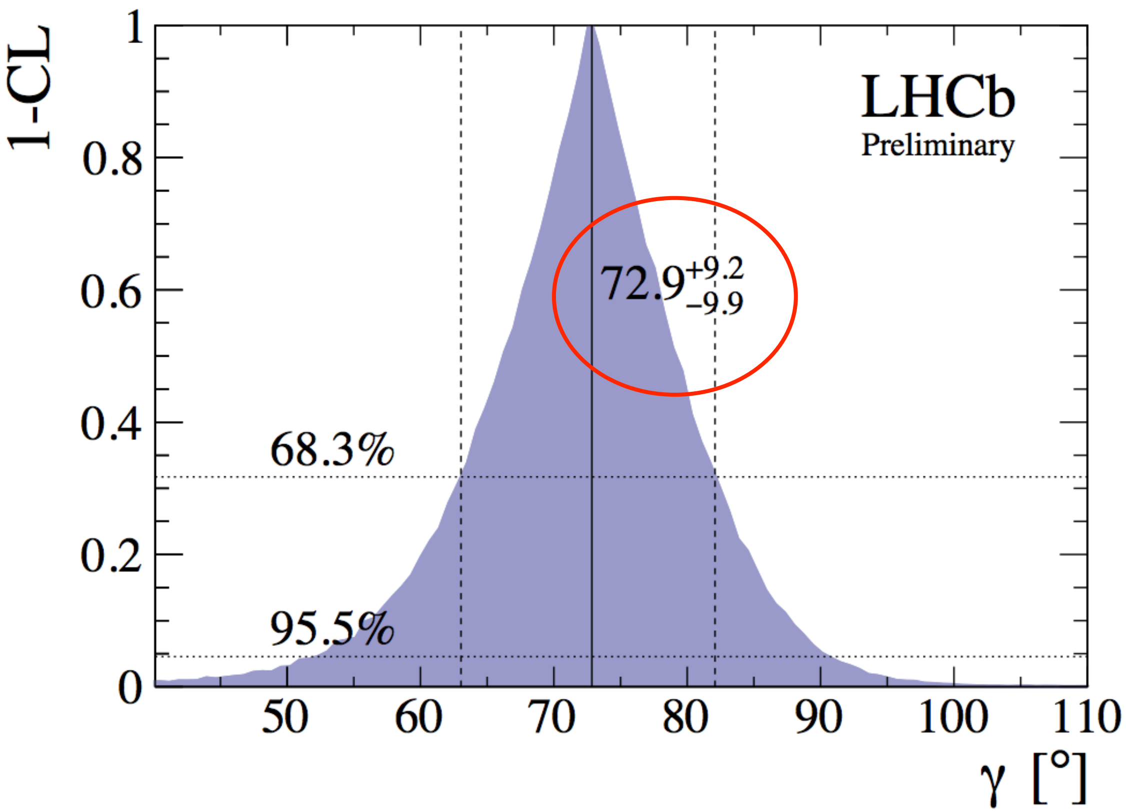


- The measured values are consistent with the world average of results from previous experiments
- World’s most precise single measurement

Measuring γ from B decays

Combining all LHCb tree-level γ measurements

LHCb-CONF-2014-004



Expected sensitivities:

σ(γ) [deg]	2018	2022	2025?
LHCb	4 (8fb^{-1})	1.0 (50fb^{-1})	LHCb Run4?

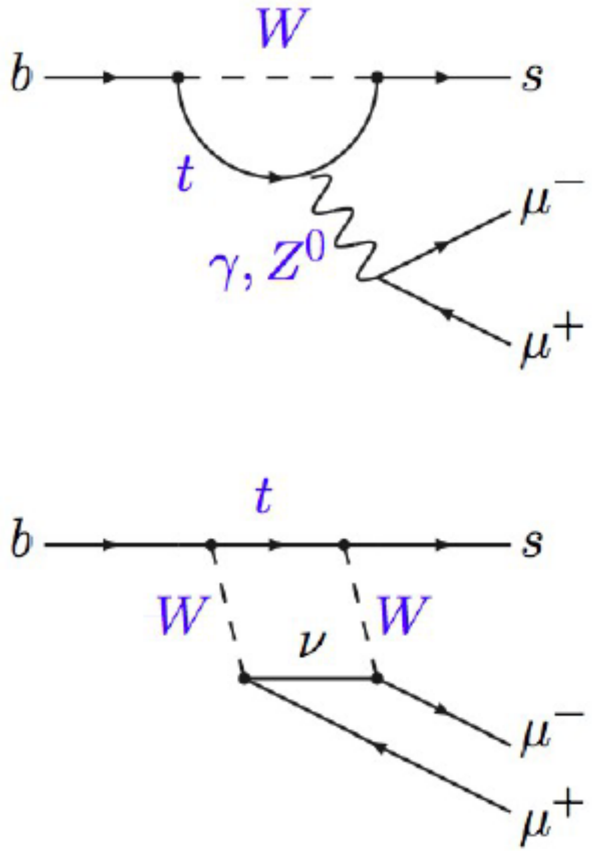
LHCb: arXiv:1208.3355

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

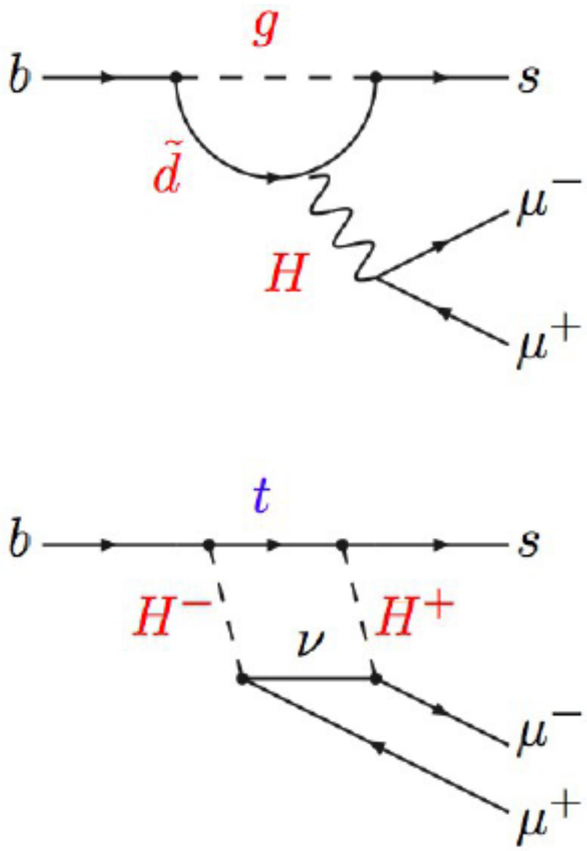
- Rare flavour changing neutral current (FCNC) decay (proceeds via a b- to s-quark) is forbidden at tree level in the SM

- It only occurs via electroweak penguin and box processes

SM diagrams



NP diagrams

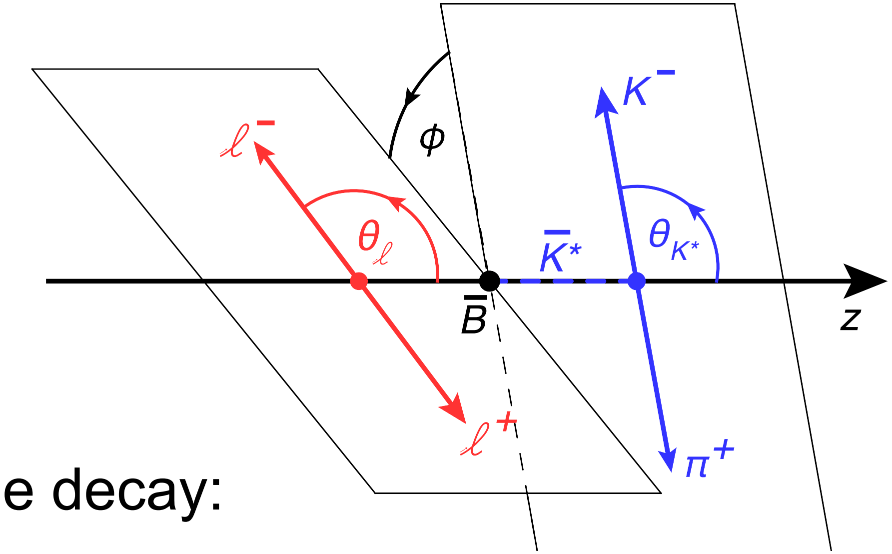


New, heavy particles can enter in competing processes and can significantly change

- the branching fraction of the decay
- and the angular distribution of the final state particles

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

The final state of the decay can be fully described by three angles and $q^2 = m^2_{\mu\mu}$



The CP-averaged angular distribution of the decay:

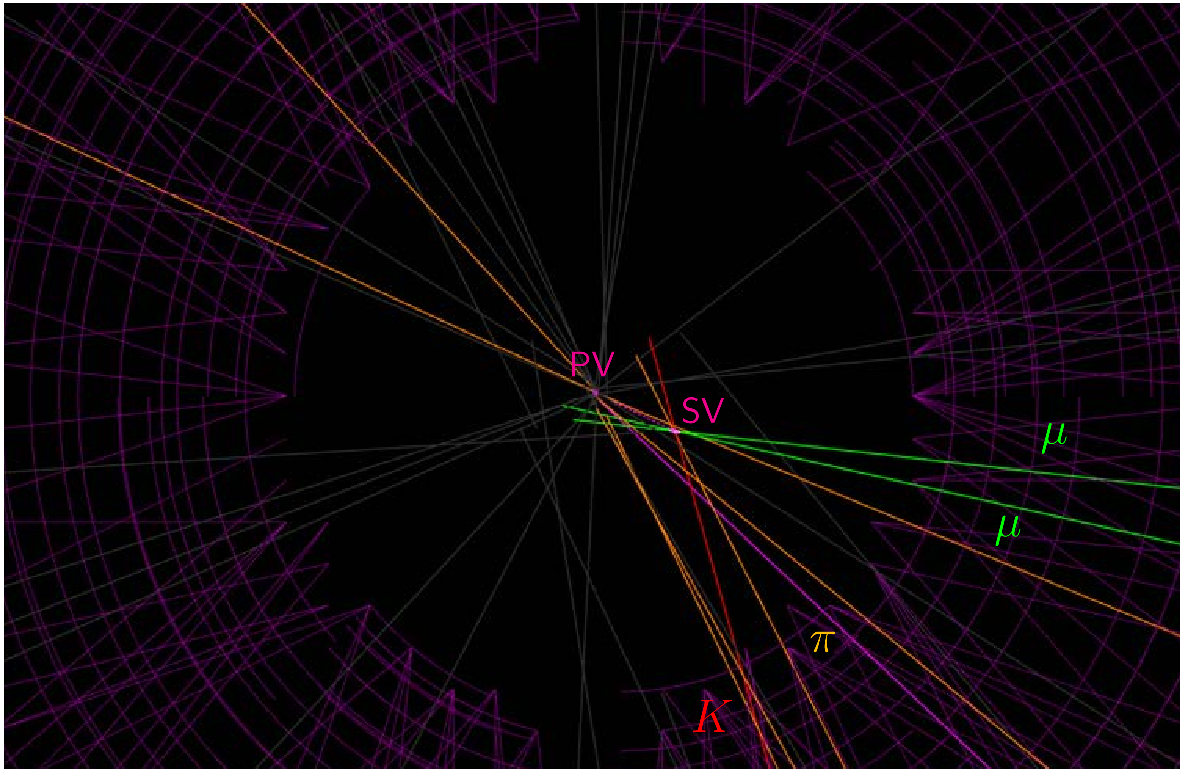
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

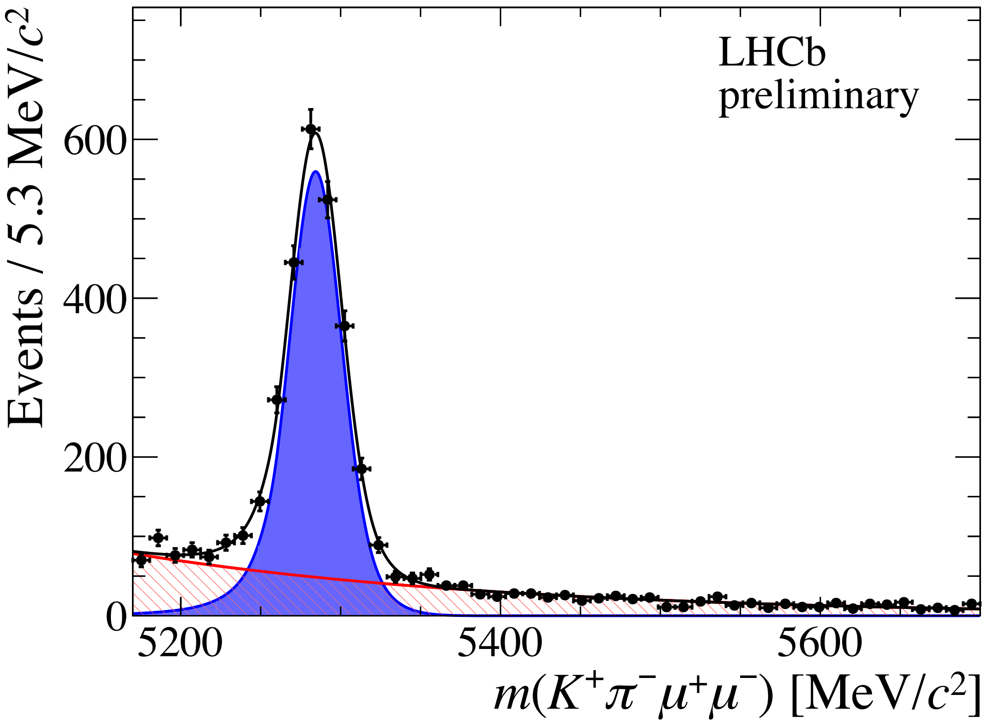
S_j – CP-averaged observables (relationships reduce the number of observable)
F_L (= S_1) – the longitudinal polarisation fraction of the K^{*0}
A_{FB} (= 3/4 S_6) – the forward-backward asymmetry of the dimuon system

Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\,\mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012

LHCb-CONF-2015-002





Full q^2 range: 2398 ± 57 events

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

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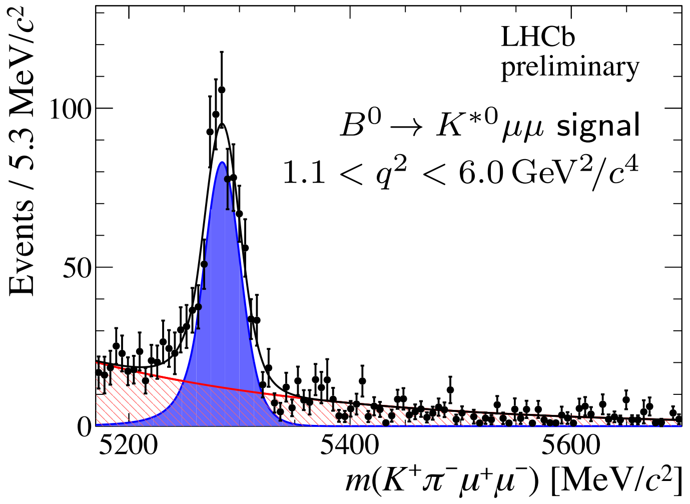
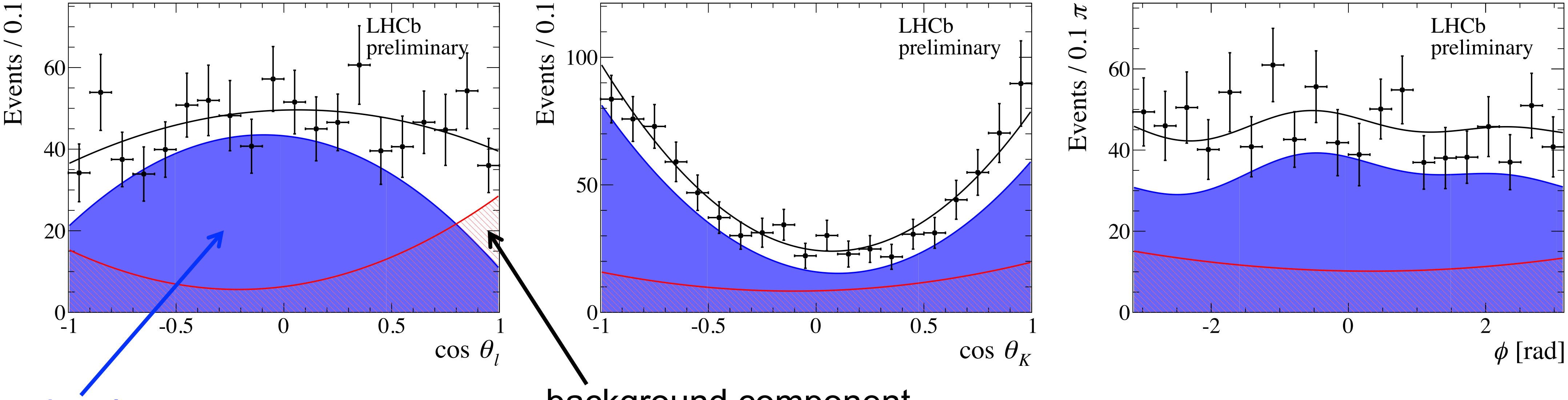
Example in one q^2 bin



The CP-averaged observables F_L, A_{FB} and S_j are determined from a simultaneous unbinned maximum likelihood fit to three angles and invariant mass distributions in q^2 bins

Good agreement of the fitted function with the data is observed

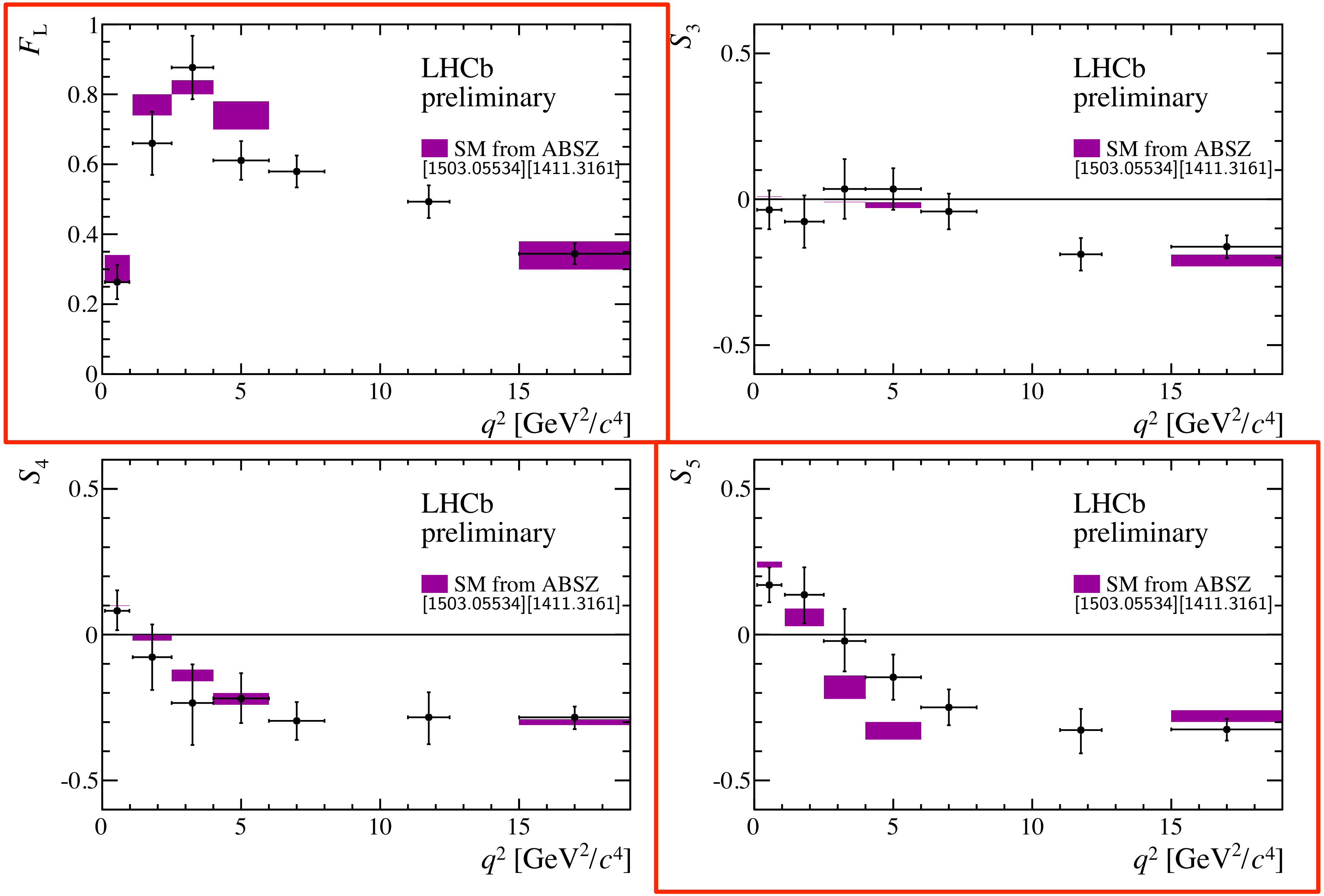


signal component

background component

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

The measured CP-averaged observables F_L, S_3, S_4, S_5 (LHCb-CONF-2015-002)



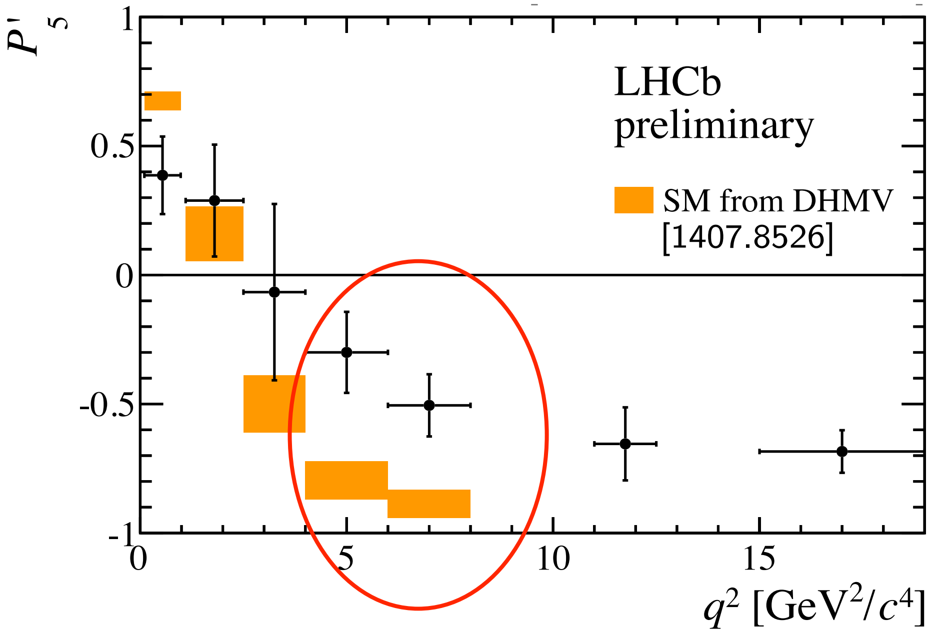
examples

We determine the P' series observables:

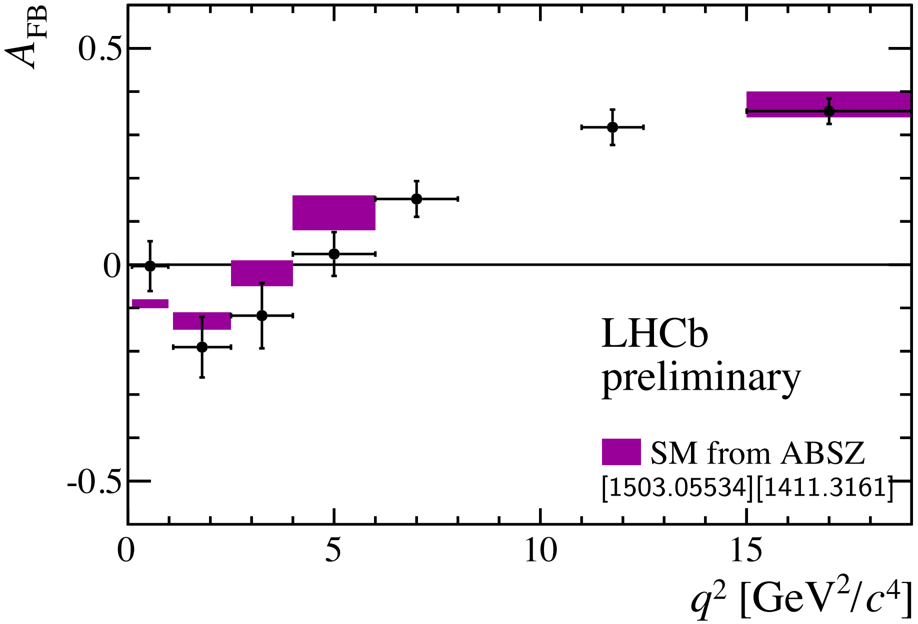
$$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$$

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$



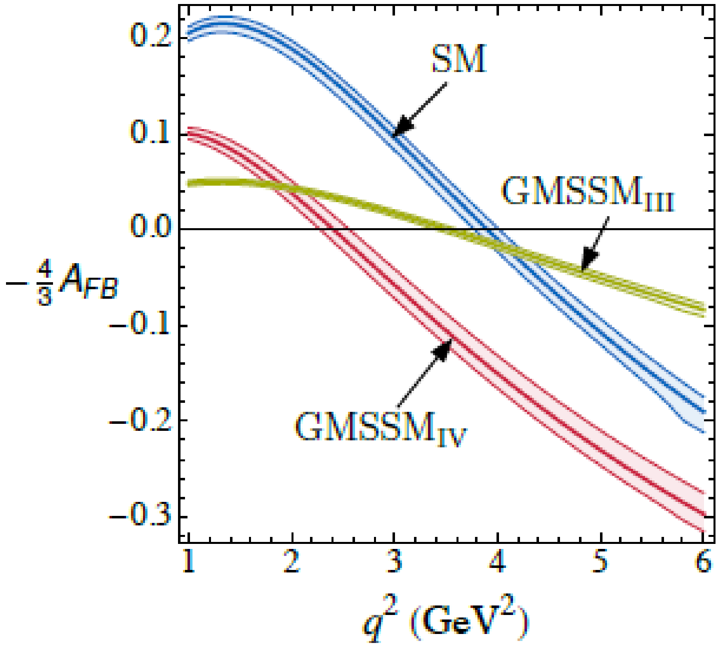
LHCb-CONF-2015-002



A naïve combination of the deviations in two bins of P'_5: $4 < q^2 < 8$ GeV^2 give a significance of 3.7σ agreement with the SM prediction

The q^2 at zero of A_{FB} is a good probe of New Physics. The zero-crossing point of A_{FB} is determined to be $3.7^{+0.8}_{-1.1}$ GeV^2, which is in good agreement with the SM prediction

Altmannshofer et al. [arXiv:0811.1214]



So far:

- LHCb experiment has broad and important beauty program
- Many world's most sensitive measurements:
  - ✧ precise measurement of $\phi_s = -0.058 \pm 0.049(\mathrm{stat}) \pm 0.006(\mathrm{syst})$
  - ✧ CKM angle $\gamma = 72.9^{+9.2}_{-9.9}{}^{0}$ from B decays
  - ✧ Some interesting deviations in rare $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays: observable P'_5 in $4 < q^2 < 8$ GeV^2 give a significance of 3.7σ agreement with the Standard Model

Charm part

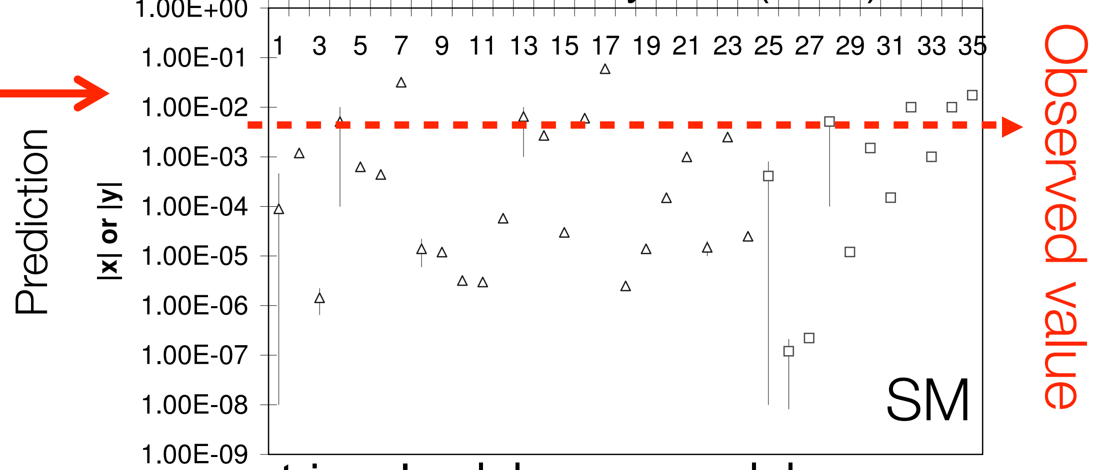
(the selected LHCb measurements on D meson decays)

SM predictions for charm

- In SM:
  - ✧ expected CPV in charm sector is small $\lesssim 10^{-3}$ (much smaller than in the beauty sector)
  - ✧ SM predictions vary widely
  - ✧ New Physics contributions can enhance CPV up to 10^{-2}

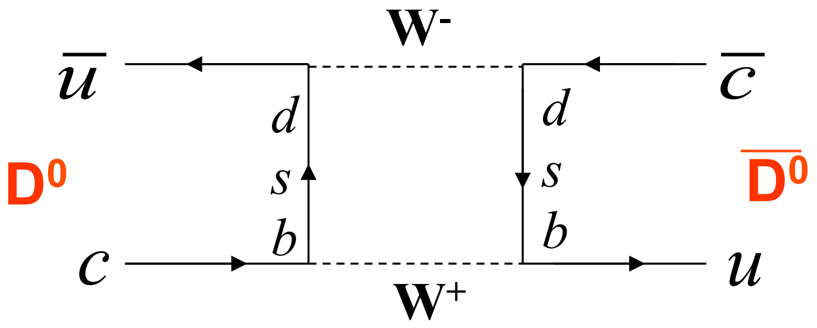
    Int.J.Mod.Phys.A21(2006)5381 ;
    Ann.Rev.Nucl.Part.Sci.58(2008)249

Int.J.Mod.Phys.A21(2006)5686

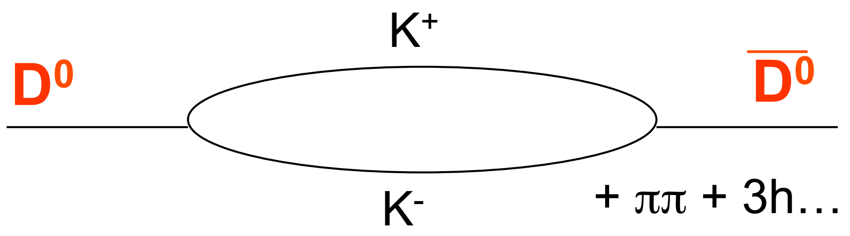


triangles |x| ; squares |y|

- Perfect place for New Physics searching (<u>small background from SM</u>)



Mixing via box-diagram, short range



Mixing via hadronic intermediate states, long range (difficult to calculate)

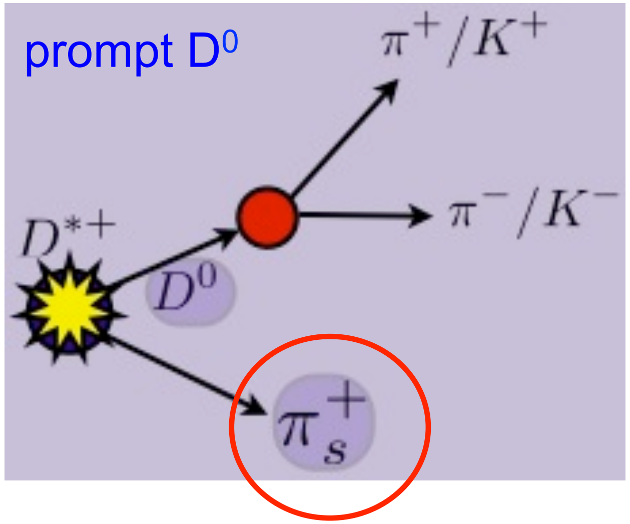
The tagging of D^0 flavour

LHCb uses two statistically independent methods to identify D^0 flavour

- ✧ pion-tagged method (exclusive)
  the sign of slow pion from D* decays is used to tag the initial D^0 flavour

  $D^{*+} \rightarrow D^0 \pi^+_s$

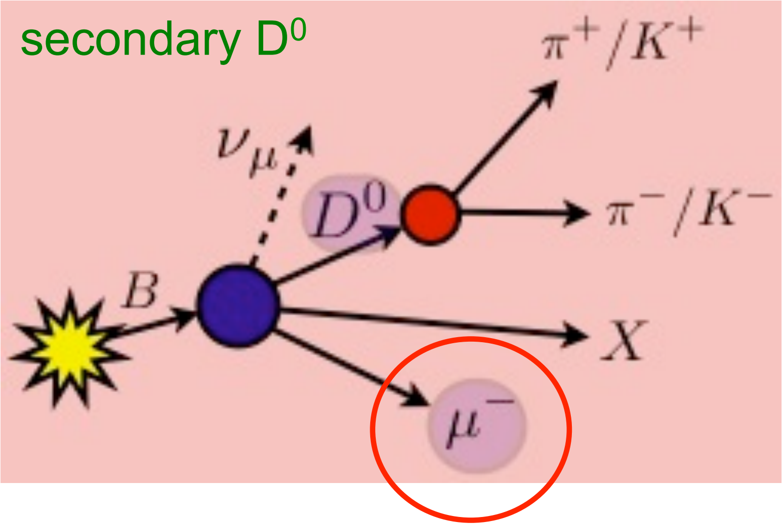
  $D^{*-} \rightarrow \text{anti-}D^0 \pi^-_s$



- ✧ muon-tagged method (inclusive)
  the sign of muon from semileptonic B decays is used to tag D^0 flavour

  B^- (anti-B^0) $\rightarrow D^0 \mu^-$ anti-ν_μ X

  B^+ (B^0) $\rightarrow$ anti-D^0 $\mu^+ \nu_\mu$ X



D^0 – anti-D^0 mixing

Measure the time-dependent ratio of D^0 decays with Wrong Sign to Right Sign

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

PRL 111 (2013) 251801

In the limit of small mixing |x|,|y| << 1 and for no CPV:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = \underbrace{R_D}_{\text{the ratio of DCS to CF decay rates}} + \underbrace{\sqrt{R_D}\,y' t}_{\text{the interference of the DCS and mixed decays}} + \underbrace{\frac{x'^2 + y'^2}{4} t^2}_{\text{mixing parameters}}$$

$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$

DCS – double Cabibbo suppressed
CF – Cabibbo favoured

If CPV not negligible
$R^+(t)$ (for D^0) $\neq$ $R^-(t)$ (for anti-D^0)

δ is a strong phase difference between DCS and CF amplitudes

Results for D^0 – anti-D^0 mixing

We determine the time-dependent WS/RS ratios in thirteen D^0 decay time bins

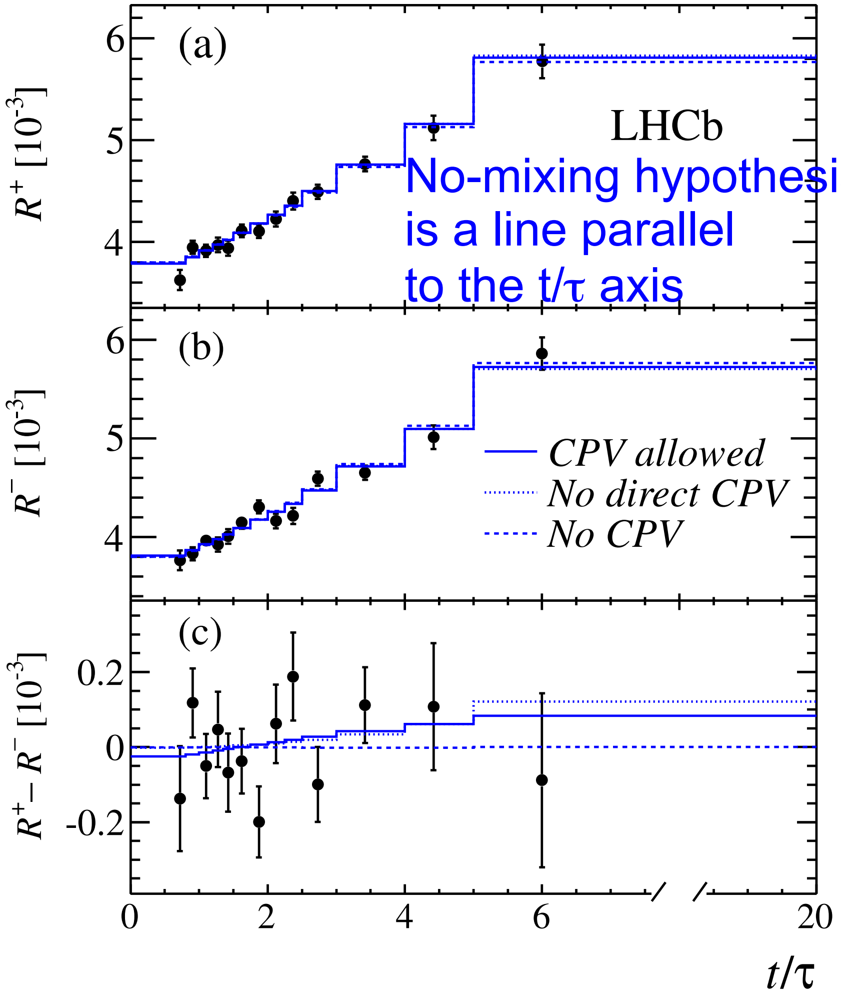
R^+ for $D^{*+} \to D^0 \pi^+_s$
R^- for $D^{*-} \to \text{anti-}D^0 \pi^-_s$

PRL 111 (2013) 251801

LHCb 3/fb (2011+2012):

0.23M WS decays
$D^0 \to K^+\pi^-$

54M RS decays
$D^0 \to K^-\pi^+$



No-mixing hypothesis is a line parallel to the t/τ axis

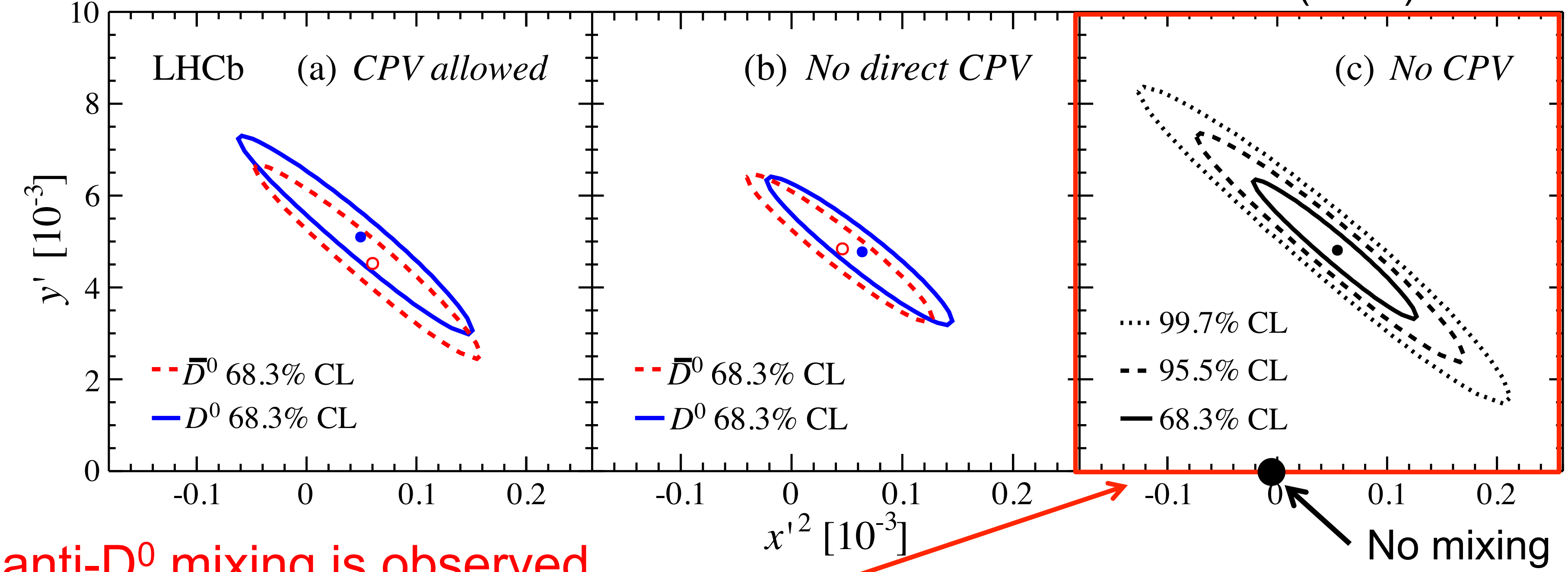
Direct and indirect CP violation		
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		$85.9/98$
No direct CP violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'^+	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2+}	$[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$
y'^-	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2-}	$[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf		$86.0/99$
No CP violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'	$[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
x'^2	$[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf		$86.4/101$

D^0 – anti-D^0 mixing is observed

Translation into D^0 – anti-D^0 mixing parameters

Estimated confidence-level (CL) regions

PRL 111 (2013) 251801



D^0 – anti-D^0 mixing is observed

Results assuming CP conservation:

$x'^2 = (5.5 \pm 4.9) \times 10^{-5}$

$y' = (4.8 \pm 1.0) \times 10^{-3}$

$R_D = (3.568 \pm 0.066) \times 10^{-3}$

x'^2 is very small

Measurement is more sensitive to y'

CP-violating parameters:

1. CPV in mixing
   $0.75 < |q/p| < 1.24$ (68.3% CL)
2. Direct CPV

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

No indication of direct or indirect CPV

A_Γ asymmetry

The asymmetry of the inverse of effective lifetimes in decays of D^0 and anti-D^0 to CP eigenstate: K^-K^+ and $\pi^-\pi^+$

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)} \approx \left(\frac{1}{2}\underset{\substack{\uparrow \\ \text{in mixing}}}{A_m} + \underset{\substack{\uparrow \\ \text{direct}}}{A_d}\right) y\cos\phi - x\sin\phi$$

$$A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2} \qquad A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

A_Γ makes a measurement of indirect CPV, as the contributions from direct CPV are measured to be small compared to the current precision

M.Gersabeck et al, J.Phys.G39 (2012) 045005

We measure A_Γ in two ways:

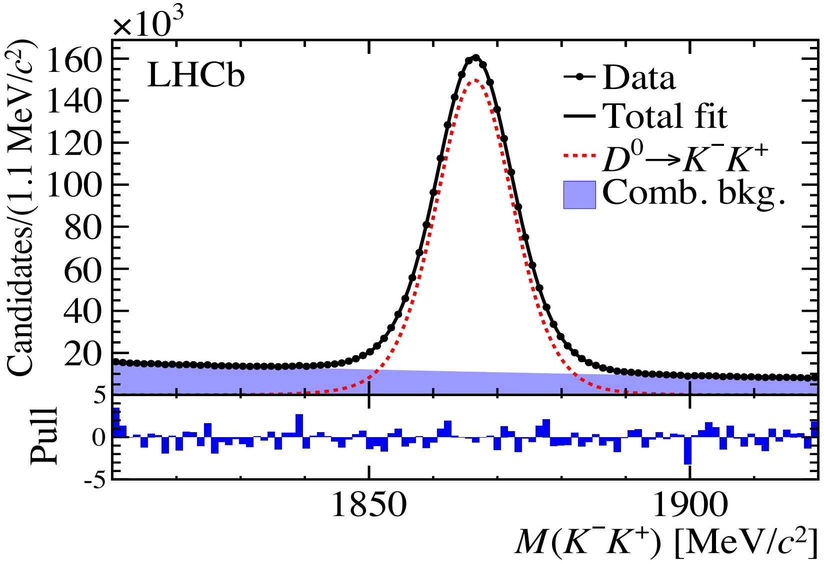
1) in B → $D^0 \mu^- X$ and B → anti-$D^0 \mu^+ X$ (arXiv:1501.06777)

2) in $D^{*+} \to D^0 \pi^+_s$ and $D^{*-} \to$ anti-$D^0 \pi^-_s$ (PRL 112 (2014) 041801)

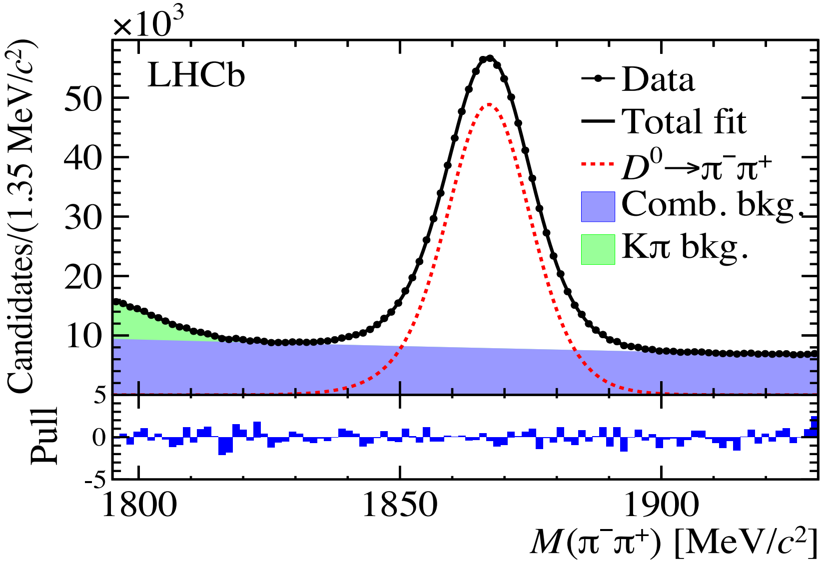
A_Γ asymmetry

B → D^0 μ$^-$ X and B → anti-D^0 μ$^+$ X (arXiv:1501.06777, L = 3/fb)

D^0,anti-D^0 → K$^-$K$^+$, 2.3M events



D^0,anti-D^0 → π$^-$π$^+$, 0.8M events



- The raw CP asymmetry (A^{raw}) is determined from fits to the mass distributions in 50 bins of the D^0 decay time
- The value of A_Γ is determined from a χ^2 fit to the time-dependent asymmetry

$$A_{CP}^{raw}(t) \approx A_0 - A_\Gamma \frac{t}{\tau}$$

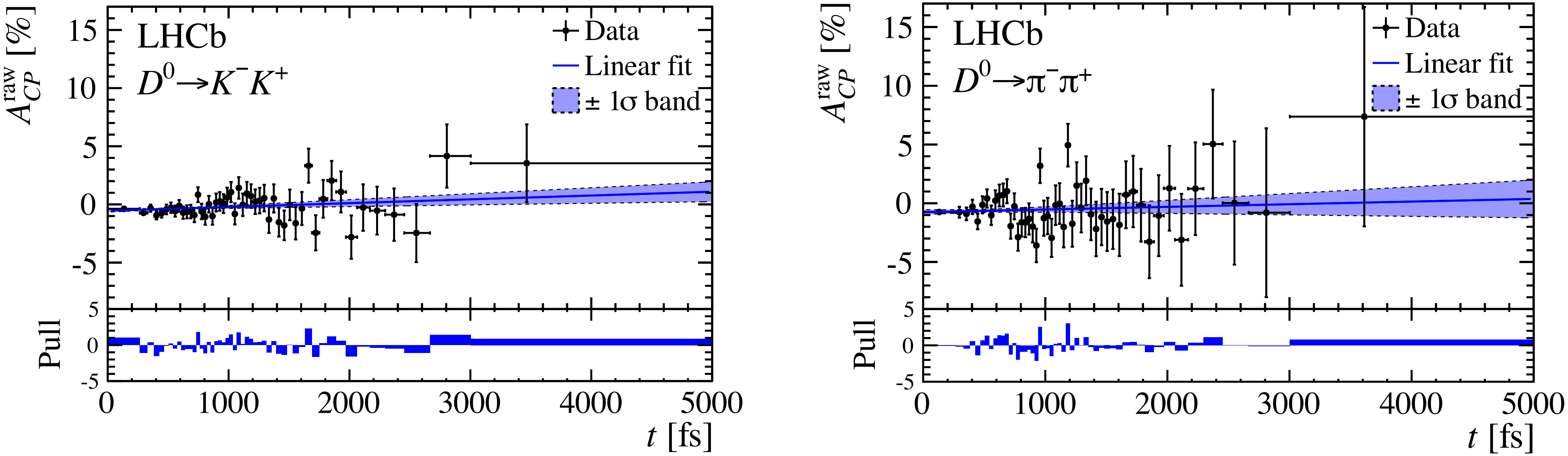
Phys.Rev.D85(2012)012009

- The A^{raw} is affected by the detection and production asymmetries which introduce shift to the constant term. It introduces a bias on A^{dir}_{CP} ($A_{CP} \approx A^{dir}_{CP} - A_\Gamma\, t/\tau$) but not on A_Γ.

A_Γ asymmetry

1) In B → D^0 μ^- X and B → anti-D^0 μ^+ X (arXiv:1501.06777, L = 3/fb)

D^0,anti-D^0 → K^-K^+ D^0,anti-D^0 → $\pi^-\pi^+$



$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})$ %

$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})$ %

2) Consistent with previous measurements in $D^{*+} \to D^0 \pi^+_s$ and $D^{*-} \to$ anti-D^0 π^-_s (PRL 112 (2014) 041801, L = 1/fb)

$A_\Gamma(K^-K^+) = (-0.035 \pm 0.062 \pm 0.012)$ %

$A_\Gamma(\pi^-\pi^+) = (0.033 \pm 0.106 \pm 0.014)$ %

- No significant difference between the two final states
- No evidence for indirect CPV within 1 per mil

(Expected value of CPV in SM is small $\lesssim 10^{-3}$, predictions vary widely)

Searches for CPV in multi-body charm decays

- Decay products form many resonance states visible in Dalitz plot
  ⇒ strong phases vary from region to region

$$A_{CP} \propto \underbrace{sin(\phi_1 - \phi_2)}_{\text{weak phases}}\underbrace{sin(\delta_1 - \delta_2)}_{\text{strong phases}}$$

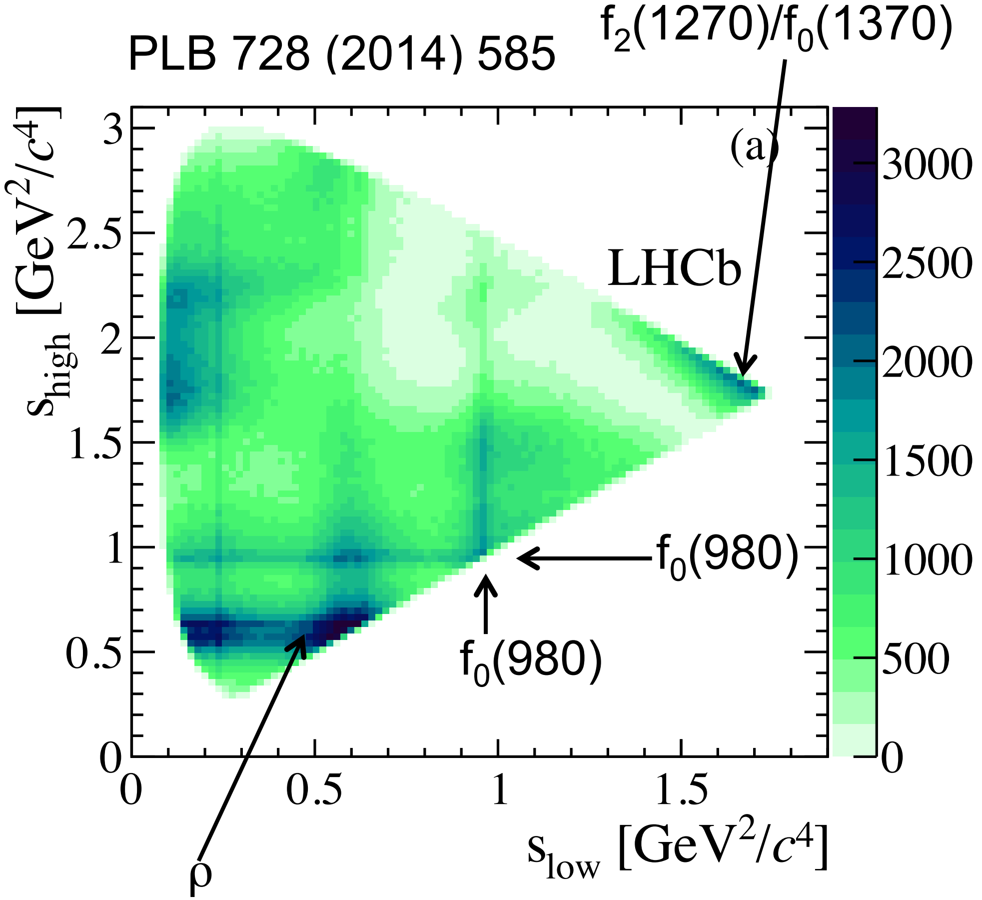
- The charge asymmetry can be measured locally in the regions of Dalitz plots

- No clear indications where CPV would appear

- To find asymmetries we compare locally Dalitz plots for D^+ and D^- (we perform here searches based on techniques that are model-independent)

$D^+ \rightarrow \pi^-\pi^+\pi^+$

PLB 728 (2014) 585



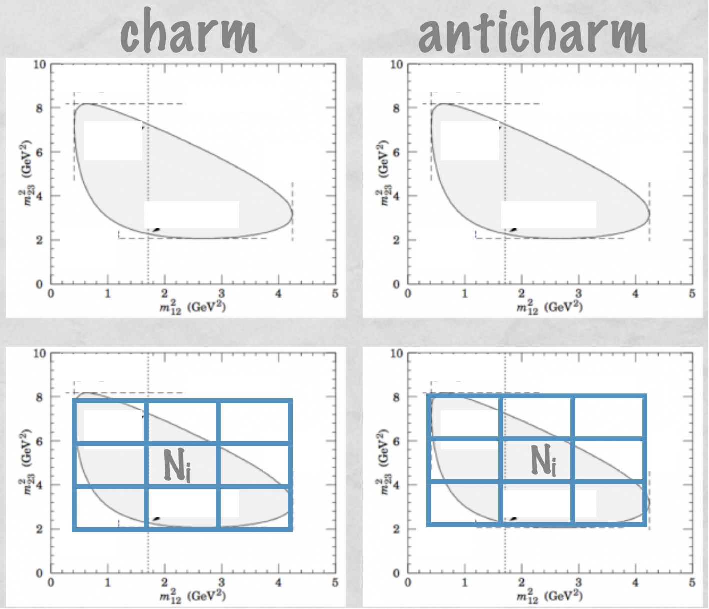
Searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

PLB 728 (2014) 585

Binned method

- In each bin we calculate a significance of a difference between D^+ and D^-

$$S^i_{CP} \equiv \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} \qquad \alpha = \frac{N(D^+)}{N(D^-)}$$



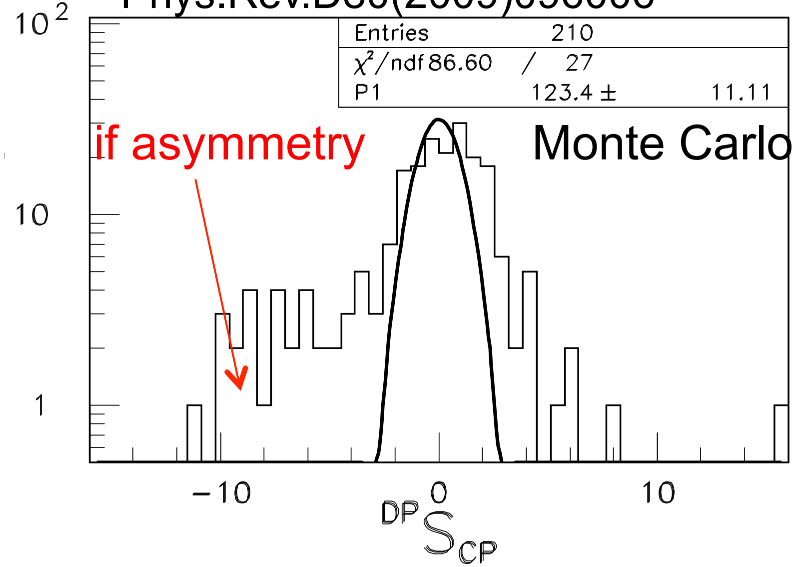
- To cancel global asymmetries (production asymmetry, etc.) we normalize Dalitz plots

- If no CPV (only statistical fluctuations) then S_{CP} is Gauss distributed (μ=0, σ=1)

- We calculate $\chi^2 = \Sigma S^{i\,2}_{CP}$ to obtain p-value for the null hypothesis to test if D^+ and D^- distributions are statistically compatible

p-value $\ll$ 1 in case of CPV

Bediaga et al.
Phys.Rev.D80(2009)096006



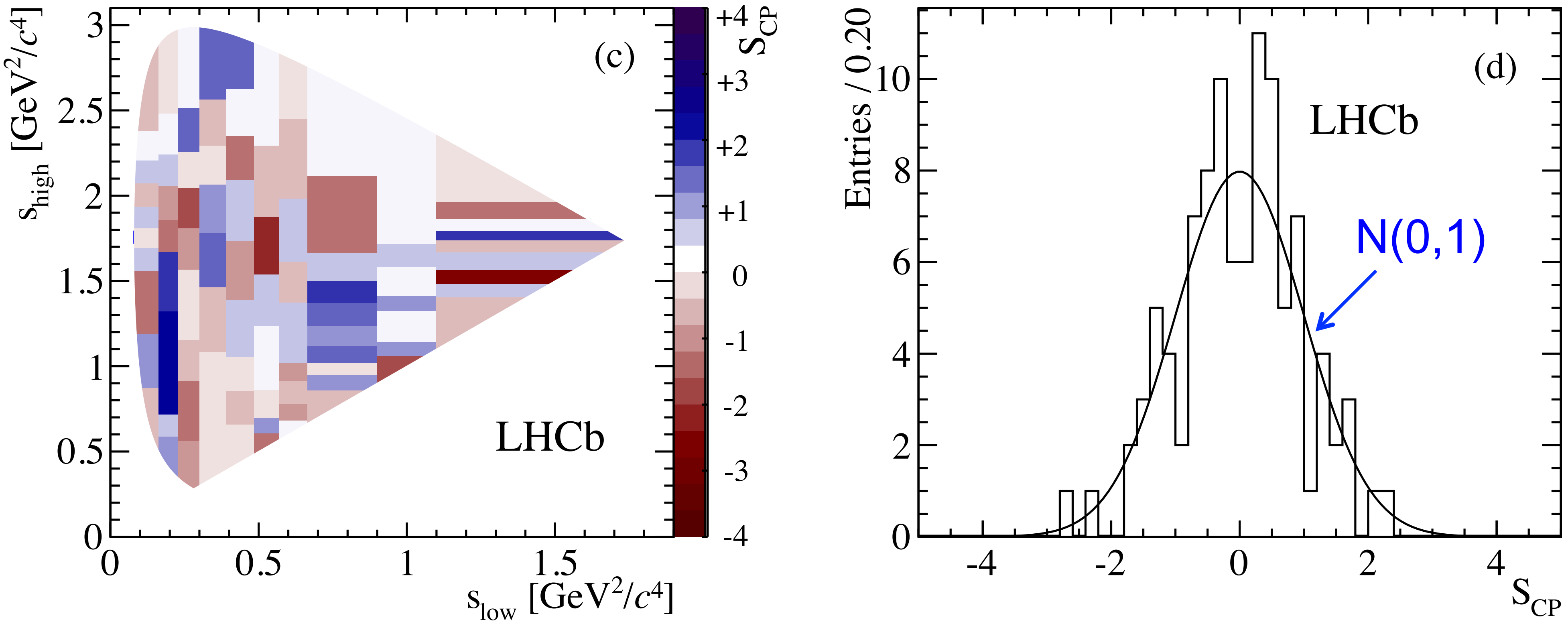
Searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

Binned method

PLB 728 (2014) 585

LHCb 2011, 1/fb ~3.1M $D^+ \rightarrow \pi^-\pi^+\pi^+$

100 adaptive bins



We tested uniform and adaptive binning schemes with different bin numbers

S_{CP} distributions agree with the normal Gaussian function

No evidence for CP asymmetry using binned method

Searches for CPV in $D^+ \to \pi^-\pi^+\pi^+$

Unbinned k-nearest neighbour method (kNN)

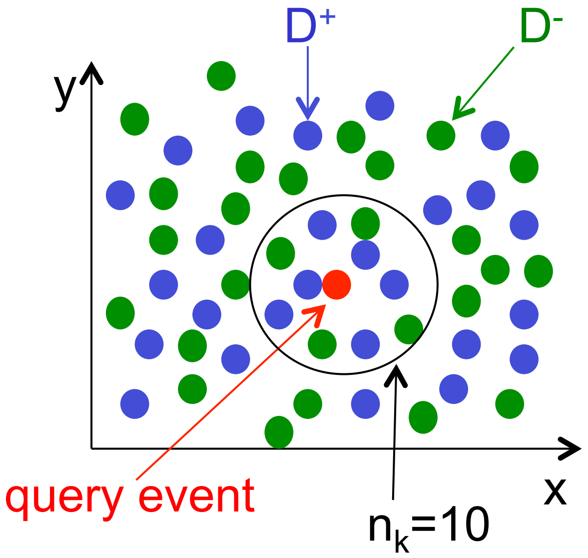
PLB 728 (2014) 585

- To compare D^+ and D^- we define a test statistic T which is based on the counting particles with the same sign to each event for a given number of the nearest neighbour events

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

I(i,k) = 1 if i^{th} event and its k^{th} nearest neighbor have the same charge (D^+—D^+ , D^-—D^-)

I(i,k) = 0 if pair has opposite charge (D^+—D^-)



- T is the mean fraction of like pairs in the pooled sample of the two datasets

- We calculate p-value for case of no CPV by comparing T with expected mean μ_T and variance σ_T

p-value $\ll$ 1 in case of CPV

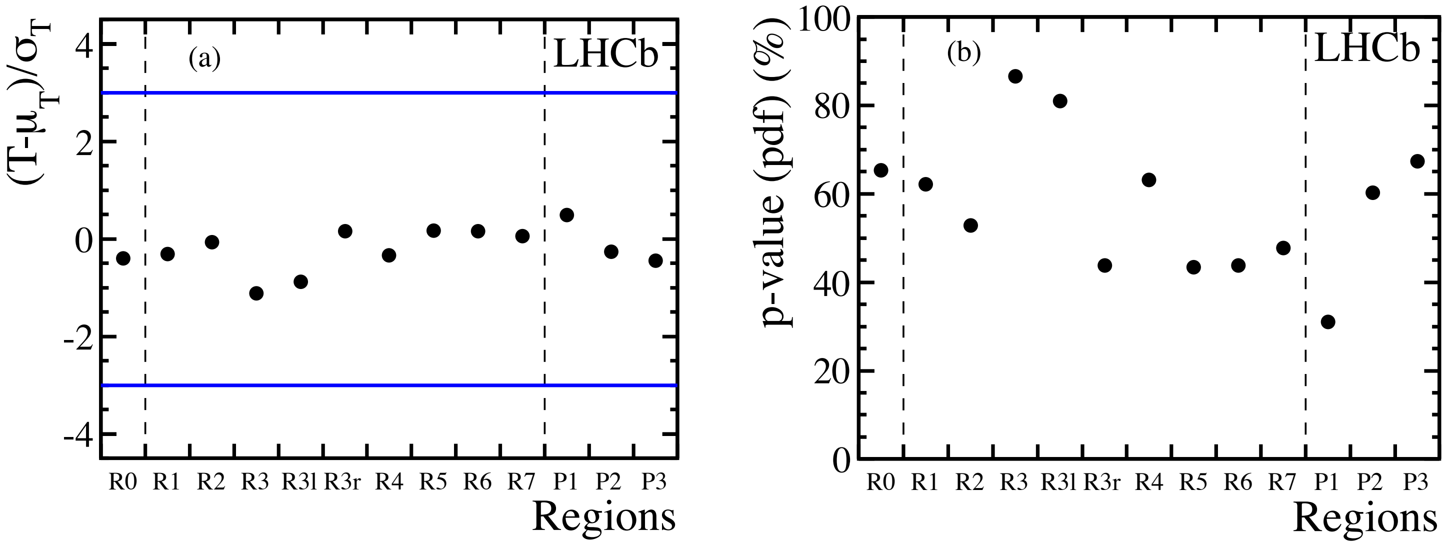
Searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

Unbinned kNN method

PLB 728 (2014) 585

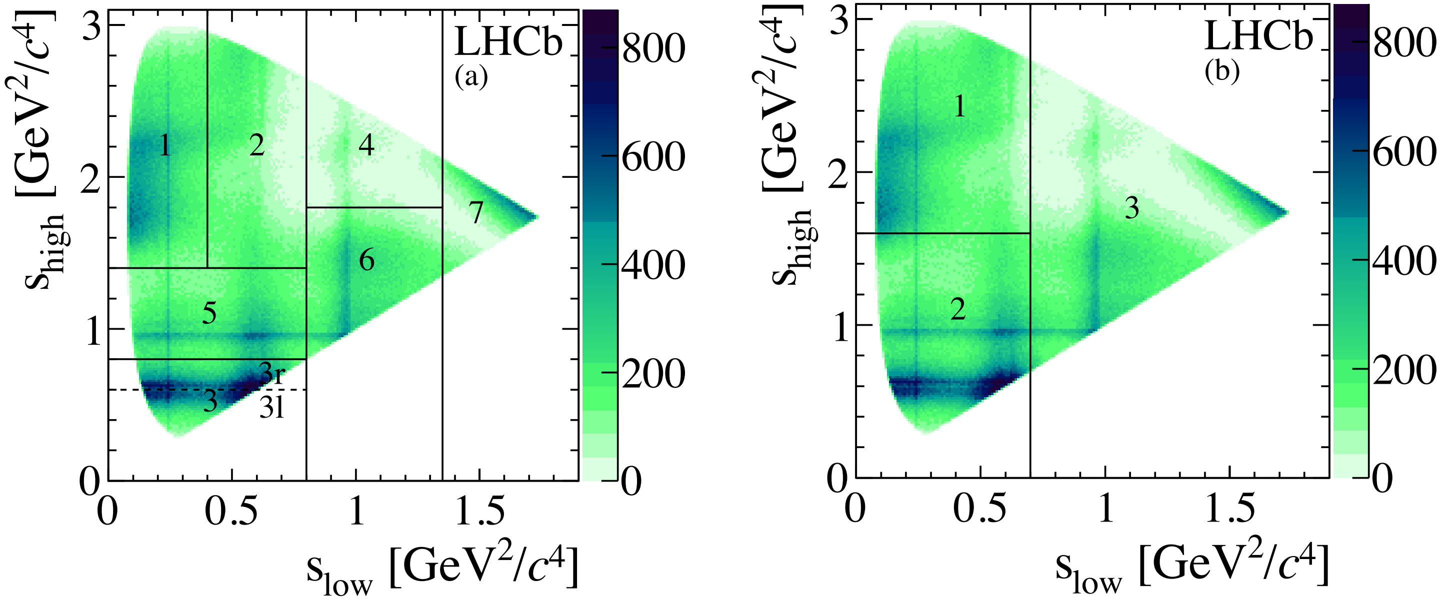
To increase the sensitivity of the method we divide the Dalitz plot into regions

Two different divisions:
7 and 3 regions defined around resonances



All p-values are above 30%

No evidence for CPV using binned and unbinned methods and both methods provide similar sensitivities for CPV searches



Searches for CPV in $D^0 \to \pi^-\pi^+\pi^0$

Unbinned energy test method

- We define a test statistic T, which depends on the distance between events pairs in the Dalitz plot Δx_{ij}

$$T = \underbrace{\frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(\overrightarrow{\Delta x}_{ij})}_{\text{i,j are } D^0 \text{ tagged events}} + \underbrace{\frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(\overrightarrow{\Delta x}_{ij})}_{\text{i,j are } \bar{D}^0 \text{ tagged events}} - \underbrace{\frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\overrightarrow{\Delta x}_{ij})}_{\text{i(j) is a } D^0(\bar{D}^0) \text{ tagged event}}$$

$$\overrightarrow{\Delta x}_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$$

$$\psi(\overrightarrow{\Delta x}_{ij}) = \exp \overrightarrow{\Delta x}_{ij}^2 / 2\sigma^2 \text{ is the metric used in the analysis}$$

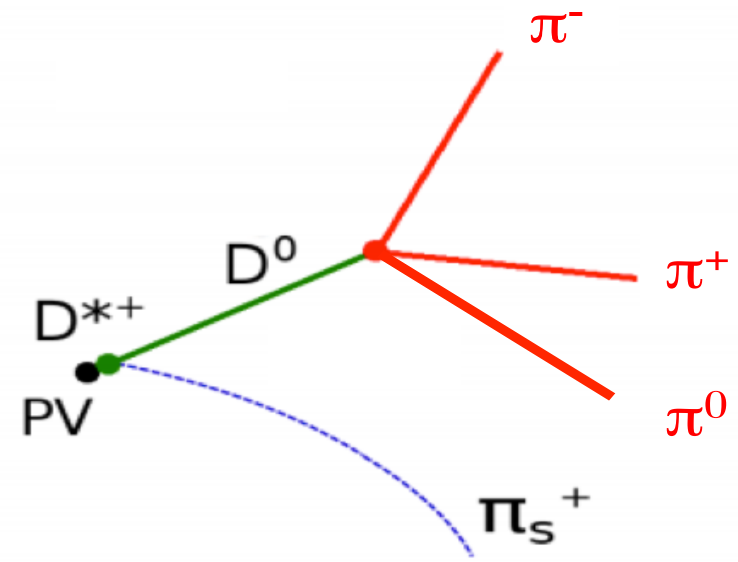
B.Aslan, G. Zech, NIM A537 (2005) 626
M.Williams, Phys.Rev.D84 (2011) 054015

- It is analogy to the electrostatic energy for negative and positive statistical charge distributions which is at minimum if the distributions agree

- If no CPV then T will fluctuate around a value close to zero
- T > 0 in case of CPV and a corresponding p-value is calculated

Searches for CPV in $D^0 \rightarrow \pi^-\pi^+\pi^0$

Phys.Lett.B740(2015)158



660k $D^0 \rightarrow \pi^-\pi^+\pi^0$ decays (2012, 2/fb)

Decay dominated by ρ^{770} resonances:
$\rho^0\pi^0$, $\rho^+\pi^-$, $\rho^-\pi^+$

- Using unbinned energy test method, for no CPV hypothesis:

p-value = (2.6 ± 0.5) %

- Result consistent with no CP violation

Search for CPV in $D^0 \to K^+K^-\pi^+\pi^-$

JHEP10(2014)005

We measure CP-violating observable $\mathcal{A}_T$ which is built using triple products of final state particle momenta in the D^0 center-of-mass frame

for D^0: $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ $\quad A_T \equiv \frac{\Gamma_{D^0}(C_T>0)-\Gamma_{D^0}(C_T<0)}{\Gamma_{D^0}(C_T>0)+\Gamma_{D^0}(C_T<0)}$

for anti-D^0: $\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$ $\quad \bar{A}_T \equiv \frac{\Gamma_{\bar{D}^0}(-\bar{C}_T>0)-\Gamma_{\bar{D}^0}(-\bar{C}_T<0)}{\Gamma_{\bar{D}^0}(-\bar{C}_T>0)+\Gamma_{\bar{D}^0}(-\bar{C}_T<0)}$

But A_T and anti-A_T can be non zero if there are final state interactions

$$\mathcal{A}_T \equiv \tfrac{1}{2}(A_T - \bar{A}_T)$$

- CPV vanishes when strong phase of two interfering amplitudes (δ_1-δ_2) is zero
- while $\mathcal{A}_T$ is maximal

$$A_{CP} \propto sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

weak phases strong phases

$$\mathcal{A}_T \propto sin(\phi_1 - \phi_2) cos(\delta_1 - \delta_2)$$

Search for CPV in $D^0 \rightarrow K^+K^-\pi^+\pi^-$

To probe direct and indirect CPV, $\mathcal{A}_T$ is measured:

LHCb 3/fb (2011+2012)
LHCb-PAPER-2014-046

1) in integrated the phase space

for D^0: $A_T = (-7.18 \pm 0.41 \pm 0.13)\%$

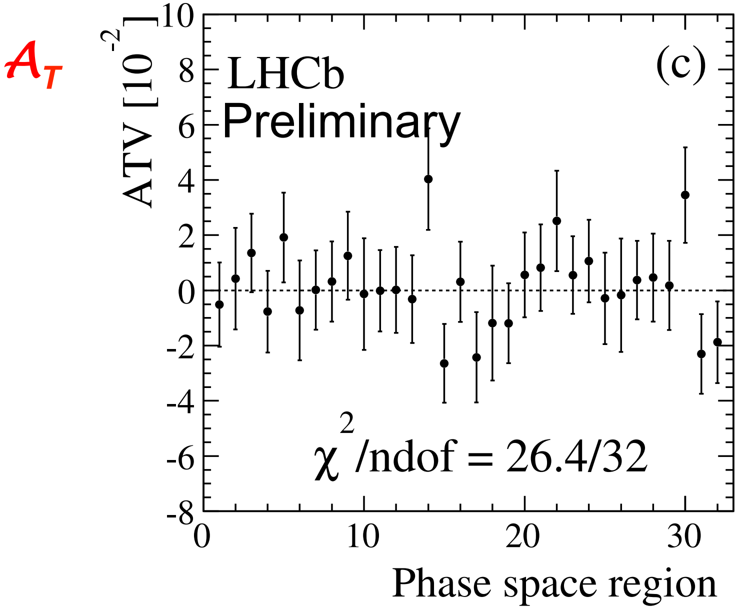
for anti-D^0: anti-$A_T = (-7.55 \pm 0.41 \pm 0.12)\%$

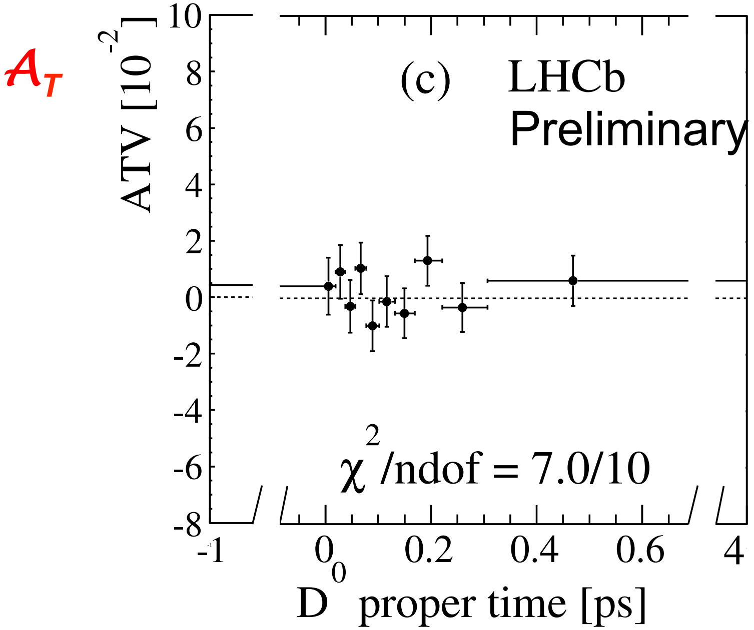
$\mathcal{A}_T = (0.18 \pm 0.29 \pm 0.04)\%$

Large asymmetries can be explained with final state interaction effects

2) in different regions of the phase space done by dividing the sample using variables $m^2(K^+K^-)$, $m^2(\pi^+\pi^-)$, $\cos(\theta(K^+))$, $\cos(\theta(\pi^+))$, ϕ

3) as a function of D^0 proper time





No evidence for CP asymmetry

Measurements have small syst. uncertainties (larger datasets will improve result)

Summary

So far:

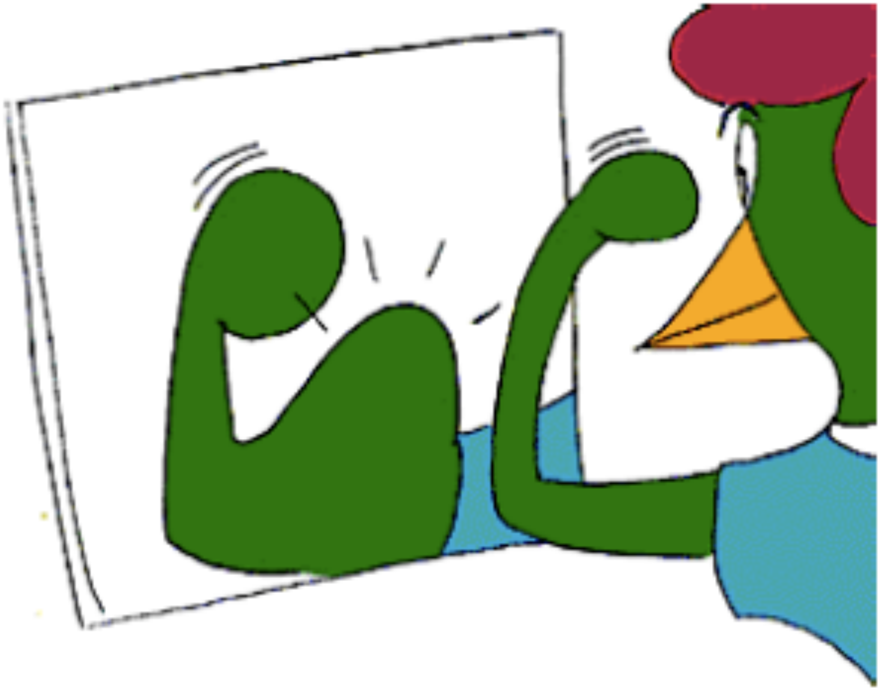
- LHCb experiment has broad and important beauty and charm physics program
- LHCb has performed spectacularly well in Run 1 (2011+2012, 3/fb) confirming so far the robustness of the Standard Model
- Many world's most sensitive measurements:
  - ✧ precise measurement of $\phi_s = -0.058 \pm 0.049(\mathrm{stat}) \pm 0.006(\mathrm{syst})$
  - ✧ CKM angle $\gamma = 72.9^{+9.2}_{-9.9}{}^{0}$ from B decays
  - ✧ Some interesting deviations in rare $B^0 \to K^{*0}\mu^+\mu^-$ decays: observable P'_5 in $4 < q^2 < 8\ \mathrm{GeV}^2$ give a significance of 3.7σ agreement with the Standard Model
  - ✧ first observation of charm mixing in a single measurement
  - ✧ so far, all results are consistent with CP conservation in charm, but we are within 1 per mil sensitivity for CP searches in (very close to the SM)

Prospects

Future:

- We enhance discovery potential during 2015-18 > 8/fb at $\sqrt{s}$=14TeV (Run 2)
- We add new measurements and improve existing ones with more statistics, for example $\delta\gamma \sim 4^0$
- LHCb upgrade (starting 2019) plans to collect ~50/fb data in 2022 and reach sensitivity which are comparable or better than theoretical uncertainties
- CP violation at LHCb has a large room for improvements!

Backup



LHCb upgrade

EPJ C73(2013)2373

Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb^{-1} by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_{\rm S}^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

γ angle

$$\boxed{\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)}$$

Several D decays are used:

- Counting analysis:
  - **GLW:** CP eigenstates (e.g. D → KK) [1,2]
  - **ADS:** flavoured states (e.g. D → Kπ) [3-5]
  - **GLS:** singly Cabbibo suppressed (e.g. D → K^0_sKπ) [6]
- Amplitude analysis:
  - **GGSZ:** 3-body CP conjugate states (e.g. D → K^0_sππ) [7,8]

} Decay width **asymmetries** and **ratios**

} **Dalitz plot** distributions

Depending on the final state f_D the method is called:

“GLW”

Gronau, London, Wyler (1991)

Phys. Lett. B253 (1991) 483
Phys. Lett. B265 (1991) 172

“ADS”

Atwood, Dunietz, Soni (1997, 2001)

Phys. Rev. D63 (2001) 036005
Phys. Rev. Lett. 78 (1997) 3257

“GGSZ” Giri, Grossman, Soffer, Zupan, hep-ph/0303187;

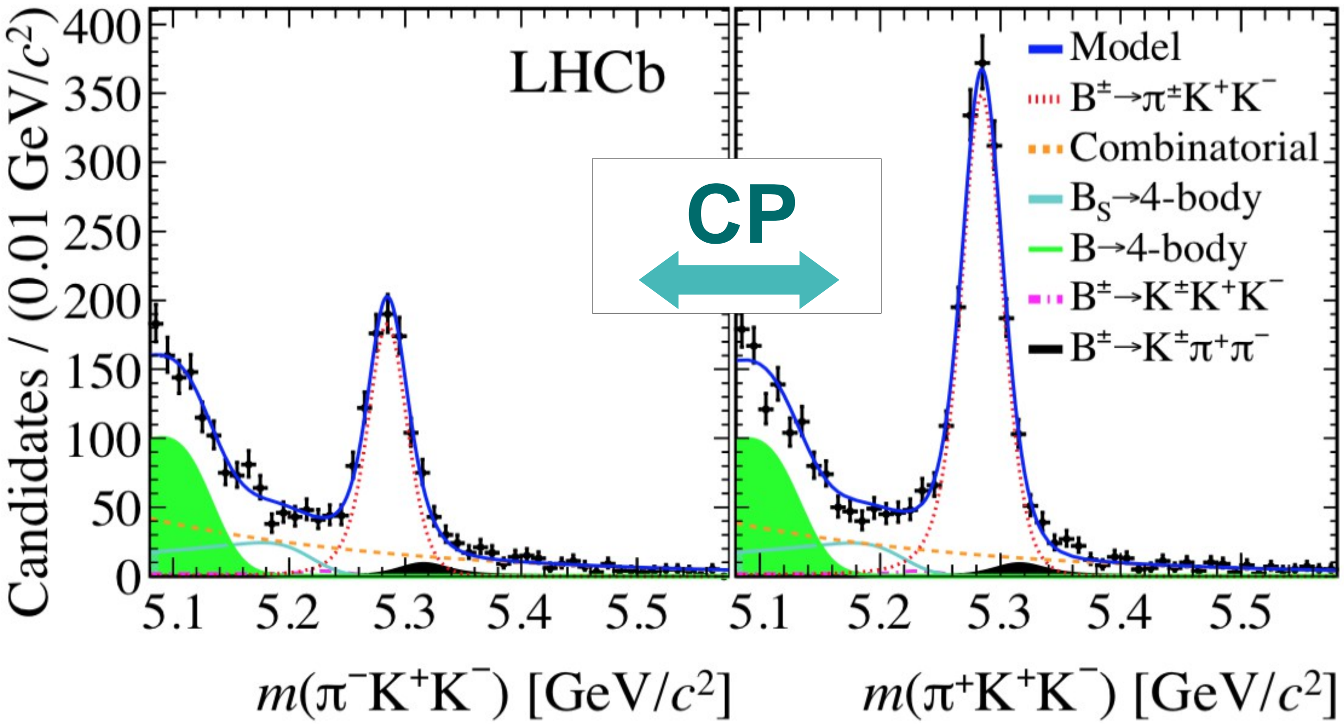
CP violation

Huge direct CP violation in decay amplitudes seen in B^-/B^+ decays

LHCb 2011+2012, 3/fb

Phys.Rev.D90(2014)112004

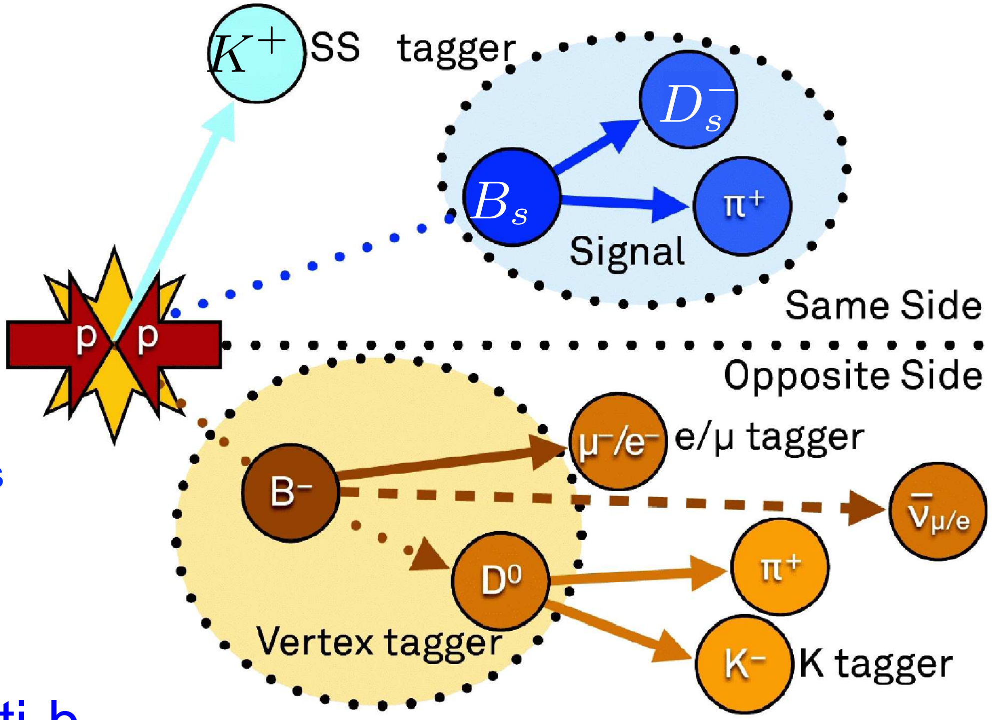
$B^- \to K^+K^-\pi^-$ $B^+ \to K^+K^-\pi^+$



A_{CP} = -0.123 ± 0.017 ± 0.012

Neutral particles give possibilities to measure CP violation in three ways: in decay amplitudes, in mixing and in interference

Identification of B^0_s flavour



- same-side (SS)
  - ✧ uses the fact that s quark needed for the hadronization of the B^0_s is produced in association with anti-s quark
  - ✧ in about 50%, anti-s quark forms a charged kaon
  - ✧ uses charge of kaon correlated with B^0_s

- opposite-side (OS)
  - ✧ uses the fact that b quarks at LHC are predominantly produced in pair with anti-b
  - ✧ uses charge of lepton or kaon from second B decay or global charge of particles coming from secondary vertex (vertex of B)

- LHCb uses both sides to identify flavour of B^0_s

- Total effective tagging efficiency: $\varepsilon(1-2\omega)^2$

  ε – efficiency of each tagging algorithm, ω – frequency of events with wrong tagging

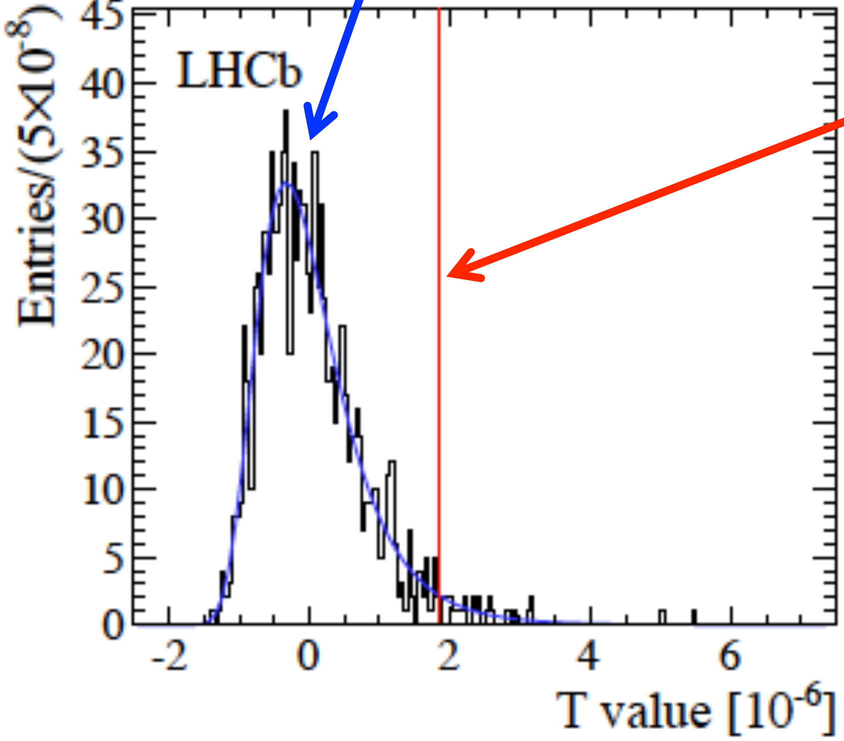
  SS_K: Eff = (1.2 ± 0.3)% OS: Eff = (2.6 ± 0.4)%

Searches for CPV in $D^0 \rightarrow \pi^-\pi^+\pi^0$

The nominal T value measured in data is compared to a distribution of T values obtained from 1000 permutation samples

- where the flavour of each candidate is randomly reassigned to simulate samples without CPV

Phys.Lett.B740(2015)158



Measured: $T = 1.84 \times 10^{-6}$

For no CPV hypothesis:
p-value = (2.6 ± 0.5) %

World best sensitivity for CPV in $D^0 \rightarrow \pi^-\pi^+\pi^0$

Result consistent with no CP violation