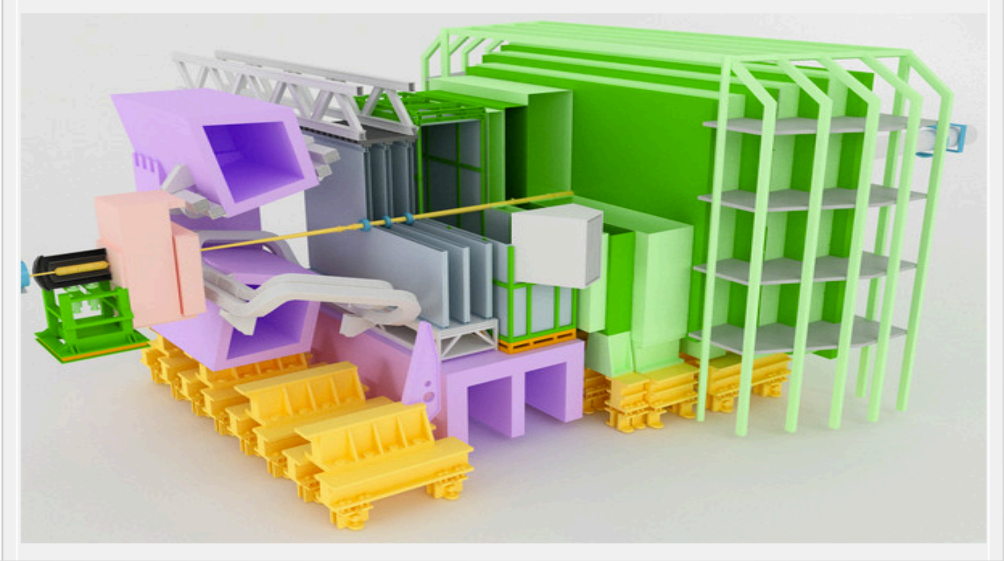
CP Violation in Hadronic Decays @ LHCb

Lars Eklund



VIA VERITAS VITA
University of Glasgow

LHCb

Outline

- Operational performance in 2011
- CP violation in two-body hadronic charm decays
- CP violation in two-body hadronic beauty decays
- Look ahead: time dependent CP asymmetries

Heavy Flavour Experiment @ LHC

- Precision measurements of CP violation and rare decay
  - Indirect searches for physics beyond the standard model
  - Access to unprecedented statistics
  - Challenging at a hadron collider

$b\bar{b}$ cross sections any yields in the detector acceptance

	L (fb^{-1})	σ_{acc}(μ b)	bb/10^9
ATLAS/CMS	5.2	75	390
LHCb	1.1	75	82
CDF/D0	9.5	2.8	26
Belle + BaBar	832 + 426	0.0011	1.4

PLB 694 (2010) 209-216

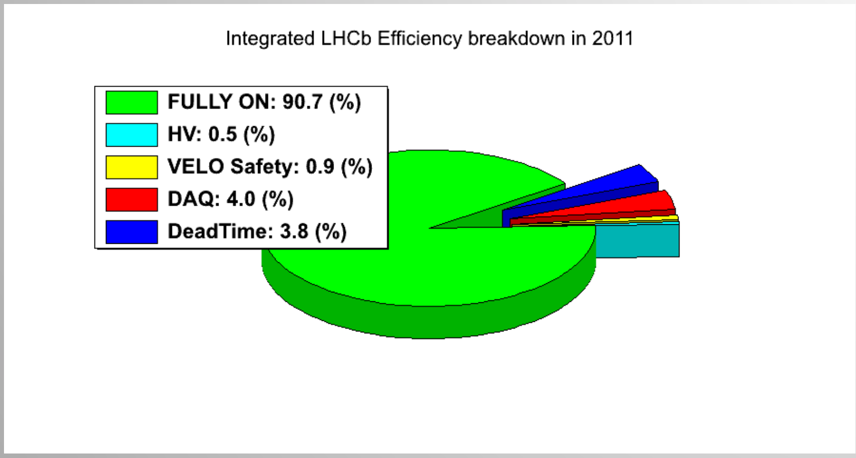
Charm cross-section @ 7 TeV: σ_{acc} = 1.2 mb

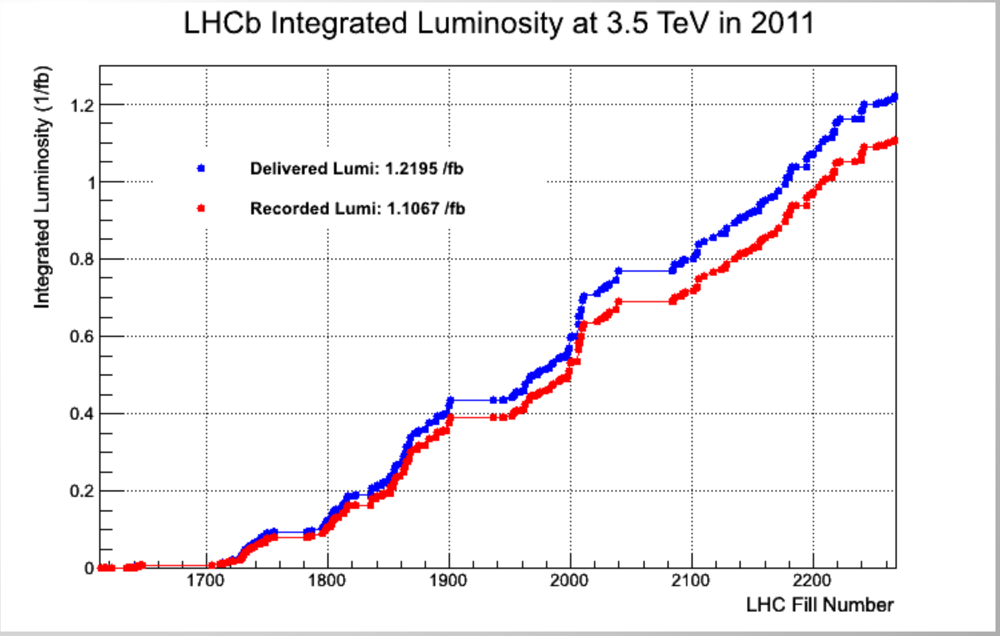
LHCb-CONF-2010-013

⇨ $1.3\cdot 10^{12}$ $c\bar{c}$ pairs produced in the LHCb acceptance

Operational performance 2011

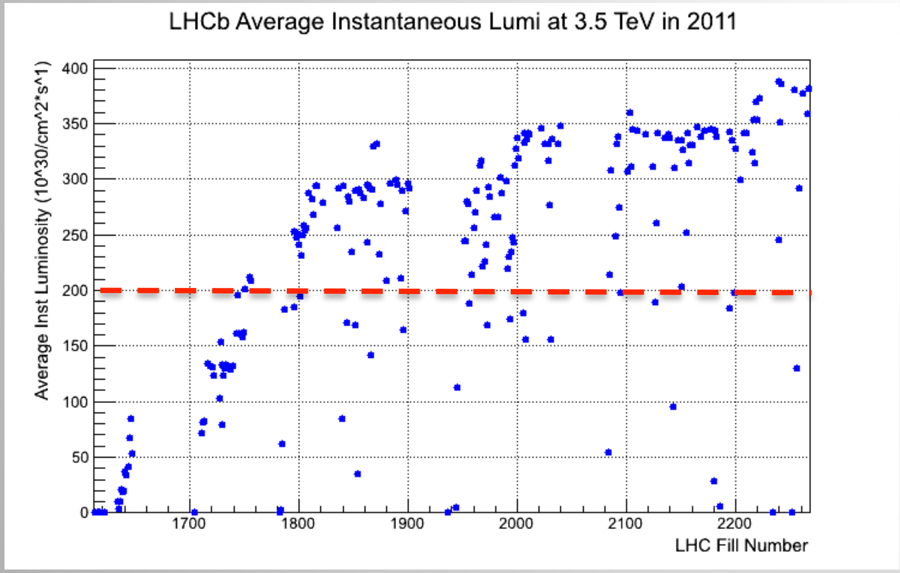
- Smooth operation – high data quality
  - 1.22 /fb delivered, 1.107 /fb recorded (90.7 %)
    - NB: online calibrated luminosity
  - 99% flagged OK for offline
  - 1.025 /fb analysis grade data
    - NB: offline calibrated luminosity
- Velo Closing + start of run
  - < 1% data loss

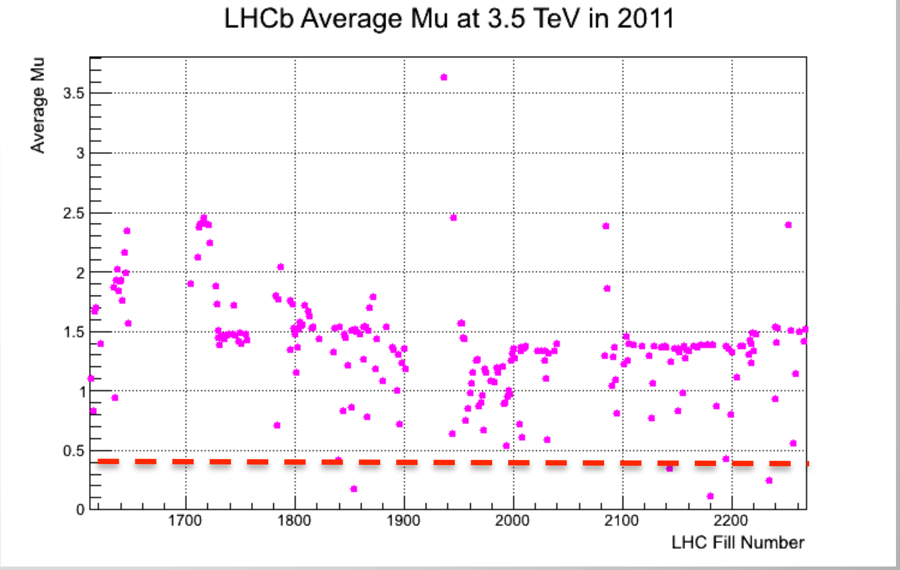




Operating conditions 2011

- LHCb design luminosity: $2 * 10^{32}$
  - 2808 bunches, μ =0.4, 14 TeV
- Operating conditions 2011: 1380 bunches, 7 TeV
  - Roughly half $b\bar{b}$ cross section compared to 14 TeV

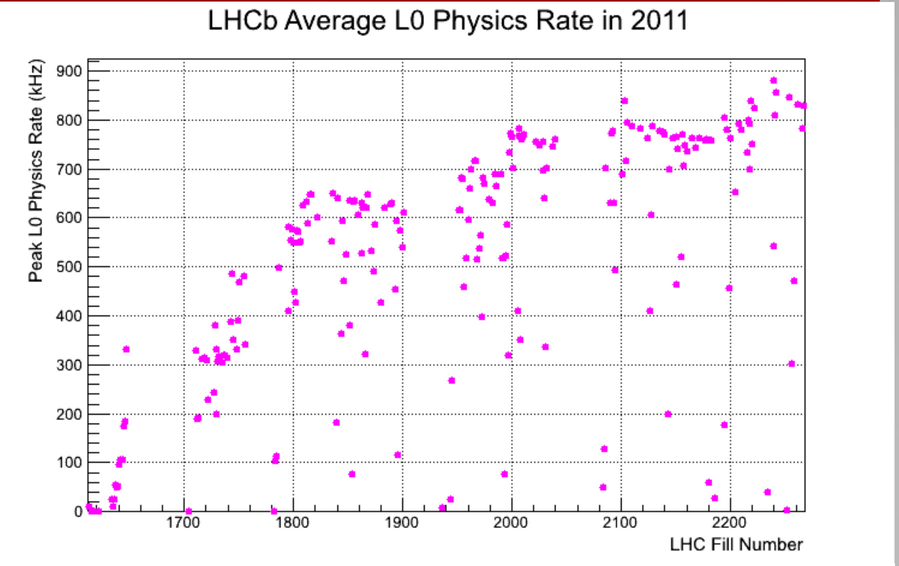


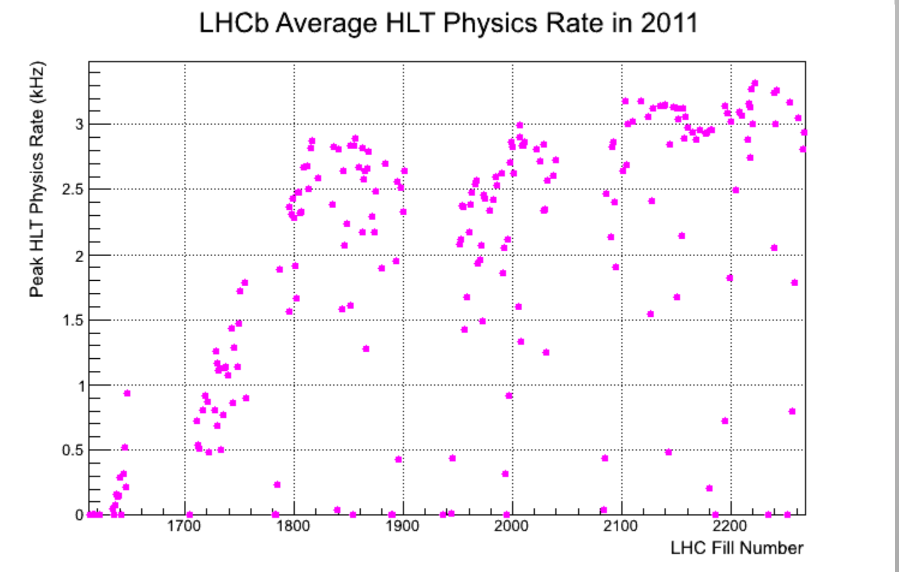


μ : average number of interactions per bunch crossing

Trigger Rates and Luminosity

- L0 Trigger: muons and calorimetry
  - Limited to 8-900 kHz
- Pushing the operational limit
  - Accept some dead time
- HLT: Full (online) reconstruction
  - B-physics 1 kHz
  - Charm 1 kHz
  - Other 1 kHz (E/W, di-muon, …)
- Luminosity Levelling
  - Displace beams to regulate the instantaneous luminosity

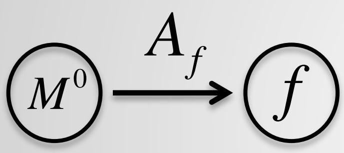


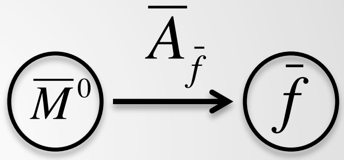


CP Violation: brief reminder

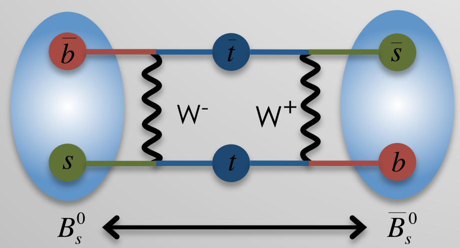
- Def: Observable not invariant under CP transformation

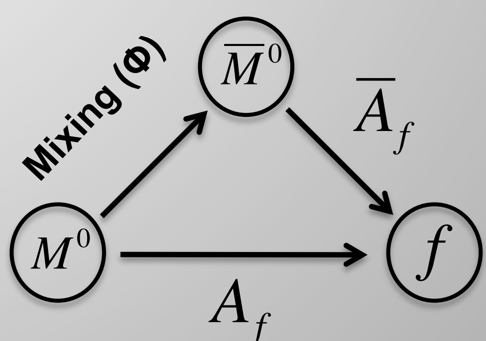
- Direct CP violation: difference in decay amplitude





- Indirect CP violation: only for neutral mesons
  - Mixing: $P(M^0 \rightarrow \overline{M}) \neq P(\overline{M}^0 \rightarrow M^0)$
  - Interference between mixing and decay





Charm

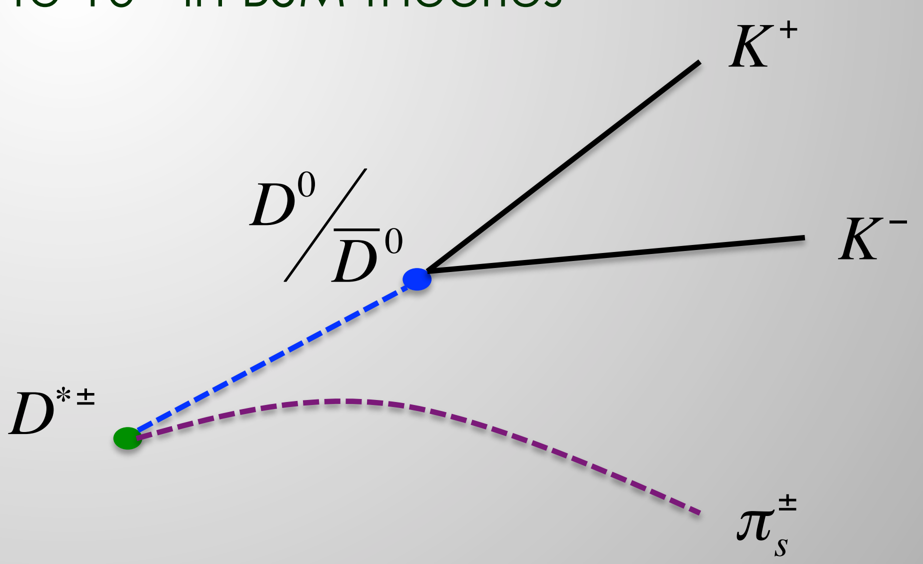
Mixing and CP violation in charm

- Mixing in D^0 mesons experimentally established

$$x = \frac{\Delta m}{\Gamma} = 0.63 \pm {}^{+0.19}_{-0.20}\,\% \qquad y = \frac{\Delta\Gamma}{2\Gamma} = 0.75 \pm 0.12\,\%$$

- CP violation is expected to be very small
  - 10^{-4} – 10^{-3} in Standard Model
  - Could be enhanced up to 10^{-2} in BSM theories

- Self-tagging decay mode



*HFAG Average, CPV allowed

ΔA_{CP} Measurement

- The time-integrated CP asymmetry is defined as

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})},$$

- Measured quantity

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

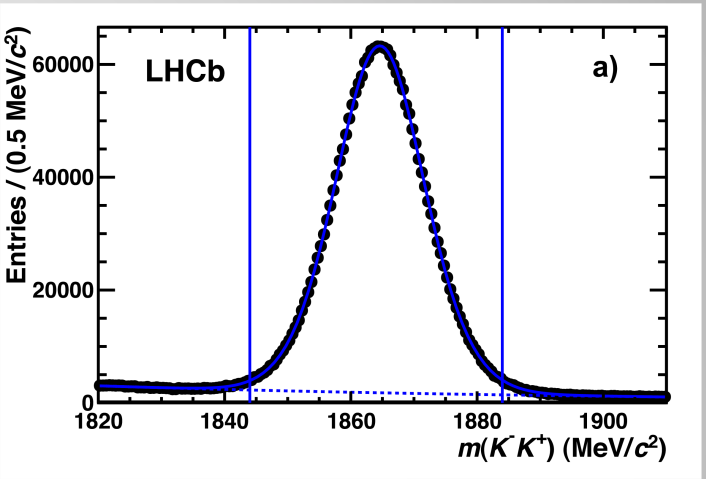
Detection asymmetry **Production asymmetry**

- Measure difference in CP asymmetry

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

ΔA_{CP} Measurement - Results

1.4 M K^+K^- candidates

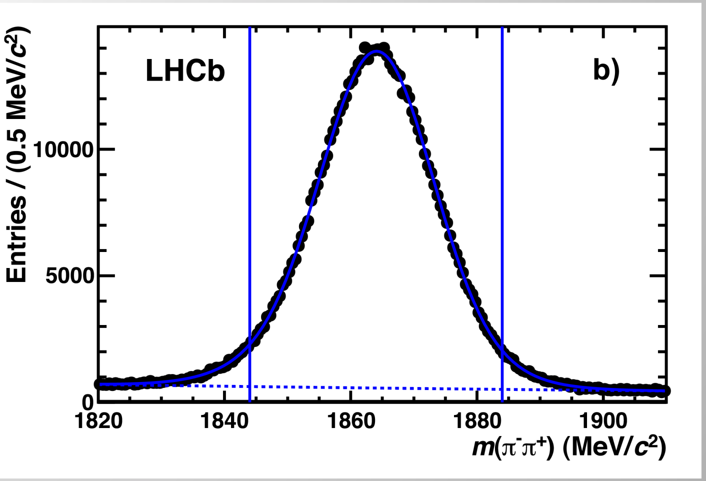


- Results with 0.62 fb^{-1} data

$$\Delta A_{CP} = 0.82 \pm 0.21\,(stat) \pm 0.11\,(syst)\,\%$$

arXiv:1112.0938

- First evidence of CP violation in the charm sector
  - 3.5 σ from zero

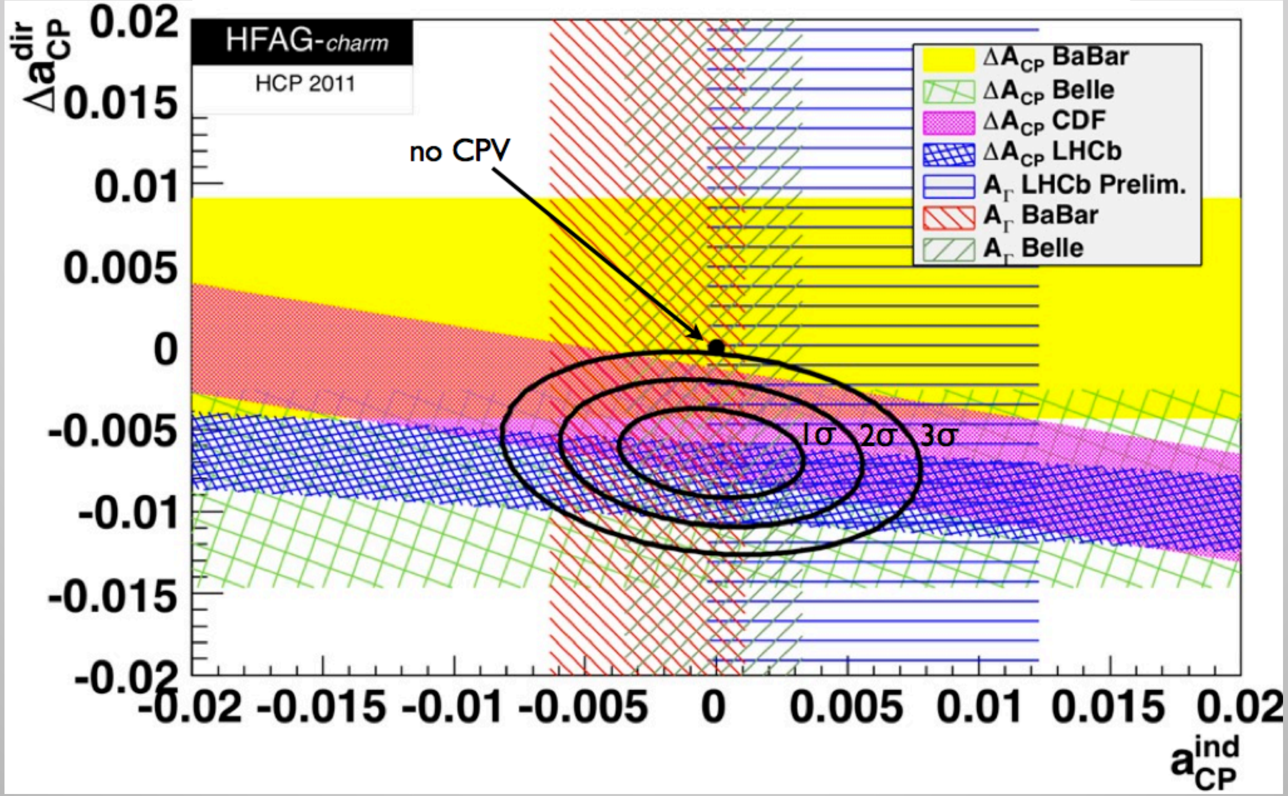


400 k $\pi^+\pi^-$ candidates

ΔA_{CP} Measurement - Interpretation

- ΔA_{CP} is mainly a measure of direct CP violation
  - Indirect largely cancel in the difference

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \quad (3)$$
$$= \left[a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind},$$



D^0 Lifetime asymmetries

- Many other charm CPV observables accessible by LHCb
  - Two of them covered here

$$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1,$$

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-) - \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^+K^-) + \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}.$$

lifetime ratio:
CP eigen-state & flavour specific

Compare with $y = \frac{\Delta\Gamma}{2\Gamma}$

Any deviation is a sign of CP violation

lifetime difference:
Decays to CP eigen-state

$$A_\Gamma \approx -a_{CP}^{ind} - a_{CP}^{dir}\, y \cos\phi$$

M. Gersabeck et al.
arXiv:1112.09384

Largely a measure of indirect CP violation

Orthogonal constraint to ΔA_{CP}

D^0 Lifetime asymmetries - Measurement

- Measure lifetimes with un-binned ML fit
  - D^0s from B-decays main experimental challenge
  - Lifetime acceptance bias determined from data
    - a.k.a swimming method

- Result from 2010 data (0.03 fb^{-1})

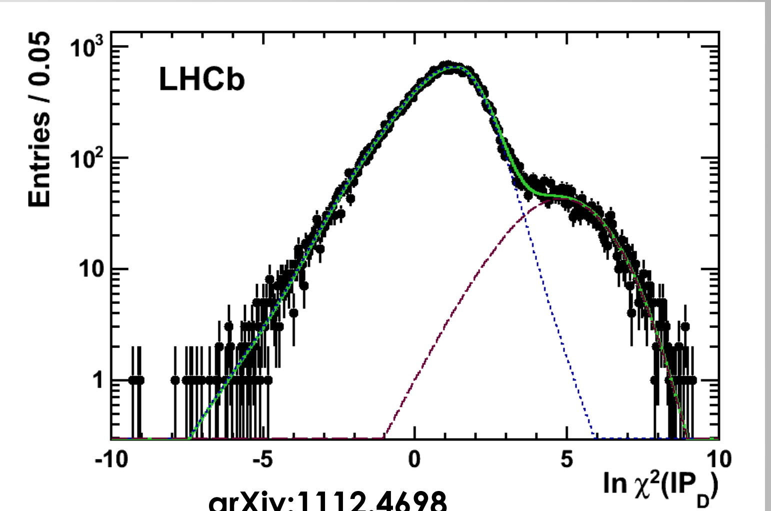
$$y_{CP} = (5.5 \pm 6.3\,(stat) \pm 4.1\,(syst)) \times 10^{-3}$$

Compatible with $y = \frac{\Delta\Gamma}{2\Gamma} = 0.75 \pm 0.12\,\%$

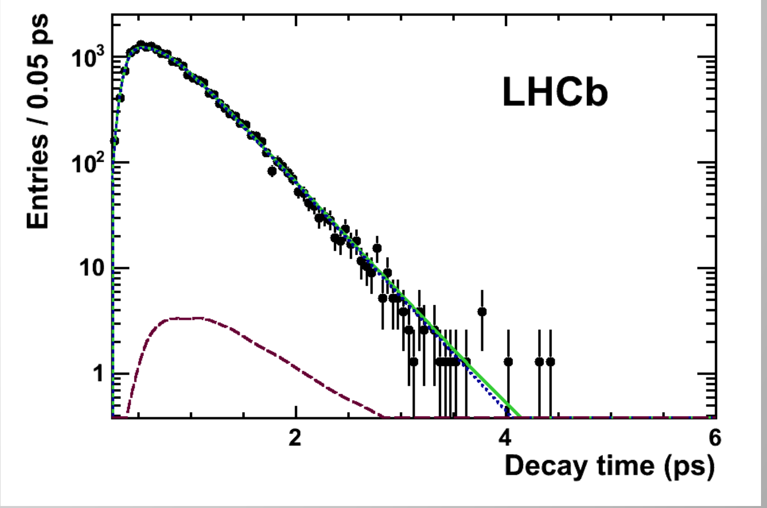
$$A_\Gamma = (5.9 \pm 5.9\,(stat) \pm 2.1\,(syst)) \times 10^{-3}$$

- Update with full 2011 data set for the winter conferences

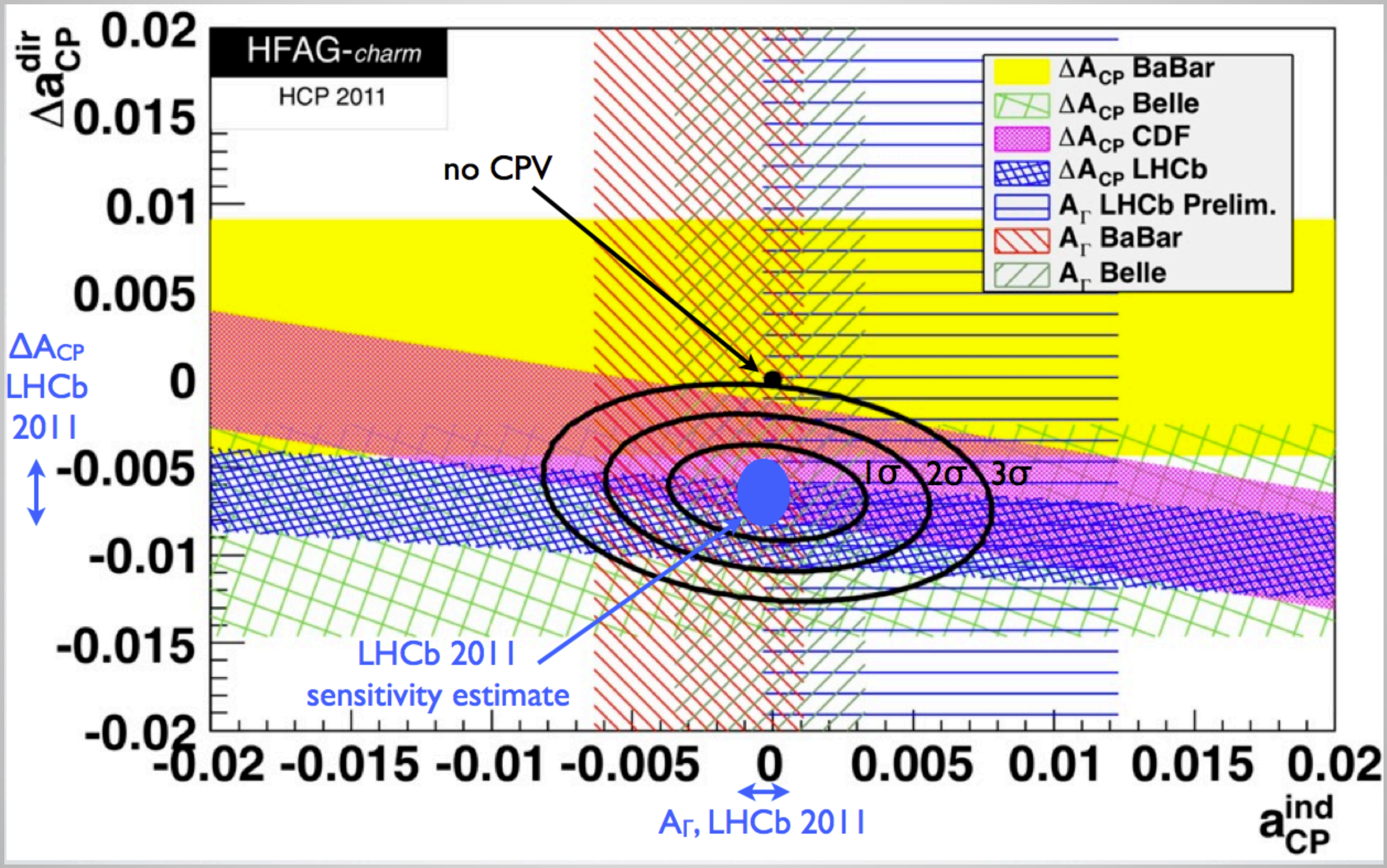
IP & decay distributions for $D^0 \to K^+ K^-$



arXiv:1112.4698



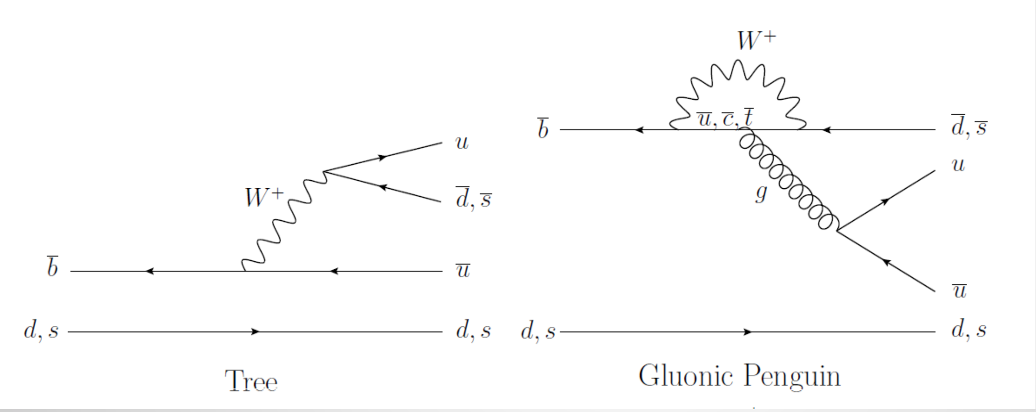
Direct vs. indirect CP violation



Beauty

CP Violation in B -> hh'

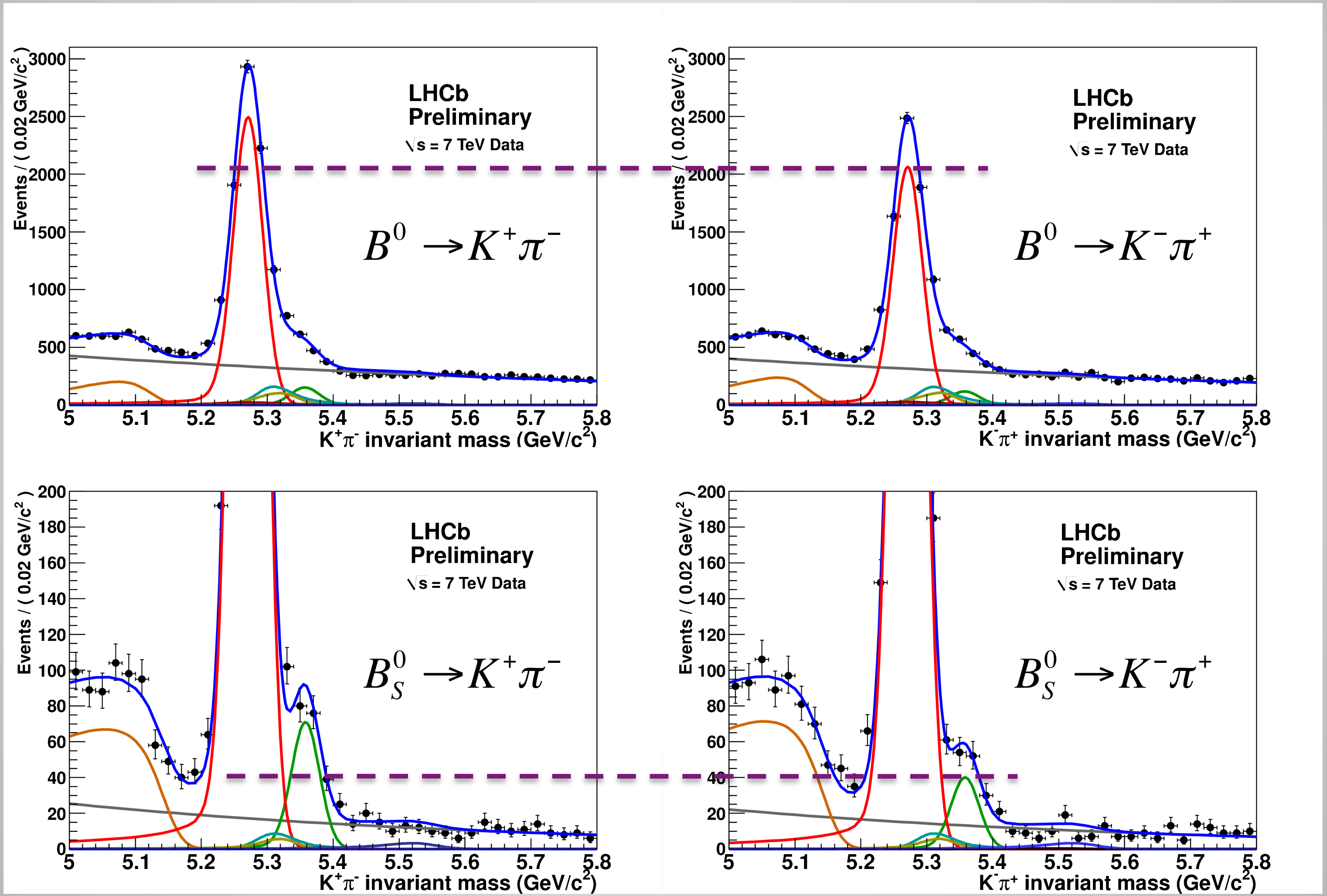
- $B^0_{(S)}$ meson decays into two charged charmless hadrons
  - Loop dominated decay: BSM sensitivity



- Time integrated CP asymmetries
  - Flavour specific decay $B^0_{(S)} \rightarrow K\pi$
  - No need to tag the initial flavour

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

The raw Kπ asymmetries



The physical Kπ asymmetries

- Similarly to the ΔA_{CP} measurement

$$A_{CP} = A_{CP}^{raw} - A_D - \kappa \cdot A_P$$

κ is a smearing factor from the oscillation

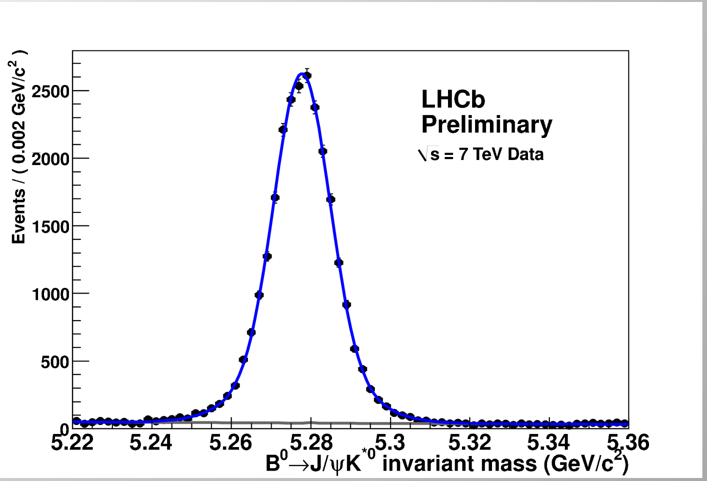
Production asymmetry

Detection asymmetry

- Production asymmetry $\sigma(B^0) \neq \sigma(\overline{B}^0)$
  - Washed out for B_s^0 by the fast oscillations
  - Measured for B^0 in $B^0 \rightarrow J/\Psi K^{*0} \quad \rightarrow (\mu^+\mu^-)(K^+\pi^-)$

Detection asymmetry (K π) identical

A_{CP} negligible for this decay



The physical Kπ asymmetries

- Detection asymmetry determined from charm decays

$$D^{*+} \to D^0(K\pi)\pi_s^+$$
$$D^{*+} \to D^0(KK)\pi_s^+$$
$$D^{*+} \to D^0(\pi\pi)\pi_s^+$$
$$D^0 \to K\pi$$

Four measured raw asymmetries

A_{CP} from PDG (or assumed zero)

Two production and two detection asymmetries

- Putting it all together (using 320 pb^{-1})

$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011\,(stat) \pm 0.008\,(syst)$$

World best measurement (>5 σ)

$$A_{CP}(B_S^0 \to K\pi) = 0.27 \pm 0.08\,(stat) \pm 0.02\,(syst)$$

First evidence (>3 σ) in this decay

CERN-LHCb-CONF-2011-011, paper in preparation

Lifetime measurements in B -> hh'

- Decay time distribution of B_S^0 mesons are described by

$$\Gamma_{B_s^0 \to f}(t) = R_H \cdot e^{-\Gamma_H t} + R_L \cdot e^{-\Gamma_L t} \quad \text{since} \quad \frac{\Delta\Gamma_s}{\Gamma_s} \sim 10\%$$

  - where R_H and R_L depend on the decay mode
- Specific lifetime of decay to a CP-even final state (e.g. $B_s^0 \to K^+K^-$)
  - CP conserved: $R_H = 0$
  - Sensitive to a_{CP}^{dir}, a_{CP}^{ind} and $\Delta\Gamma_s$

- Constrain these parameters by comparing to other decay modes
  - E.g. flavour specific $B_s^0 \to D_s\pi$ **RH = RL (mod. CPV in decay)**
  - and CP odd $B_s^0 \to J/\Psi f_0(980)$ **RL = 0 if CP conserved**

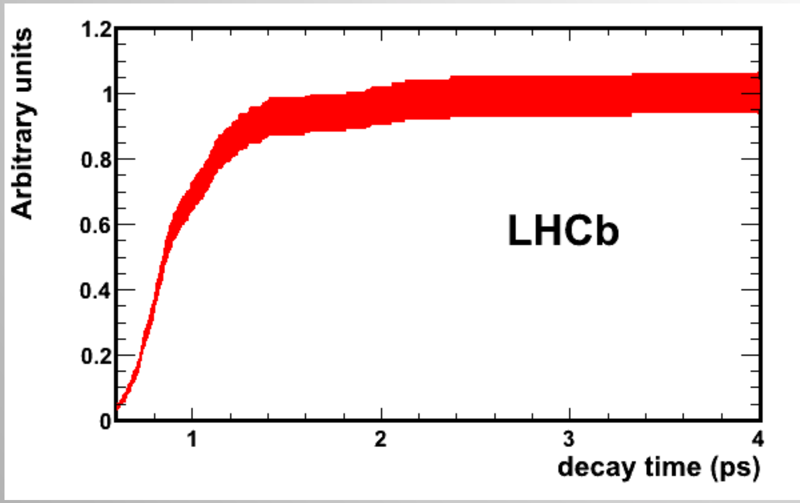
B_s -> K^+ K^- lifetime measurement

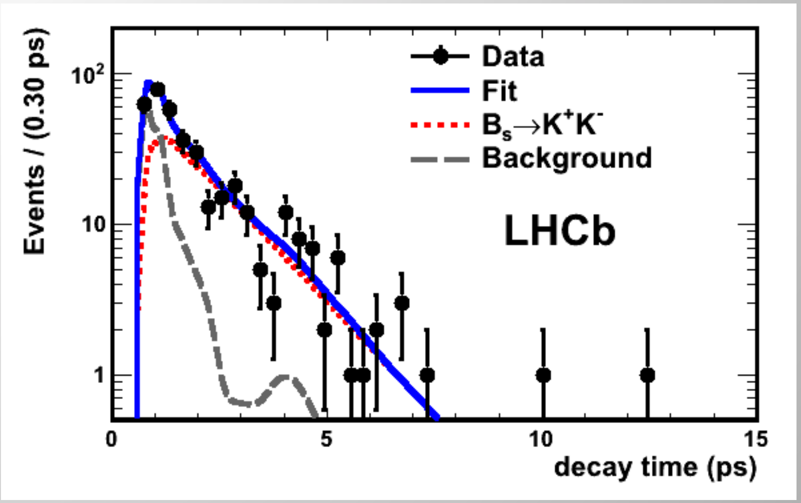
- Main experimental challenge in lifetime measurements
  - Correct for bias introduced by event selection
  - Two independent methods were used
- Result with 2010 data (37 pb^{-1})

$$\tau_{B_s^0 \to K^+K^-} = 1.440 \pm 0.096\,(stat) \pm 0.08\,(syst) \pm 0.03(\mathrm{mod}\,el)\ ps$$

- Update with full 2011 data set in preparation

PLB 707 (2012) 349-356

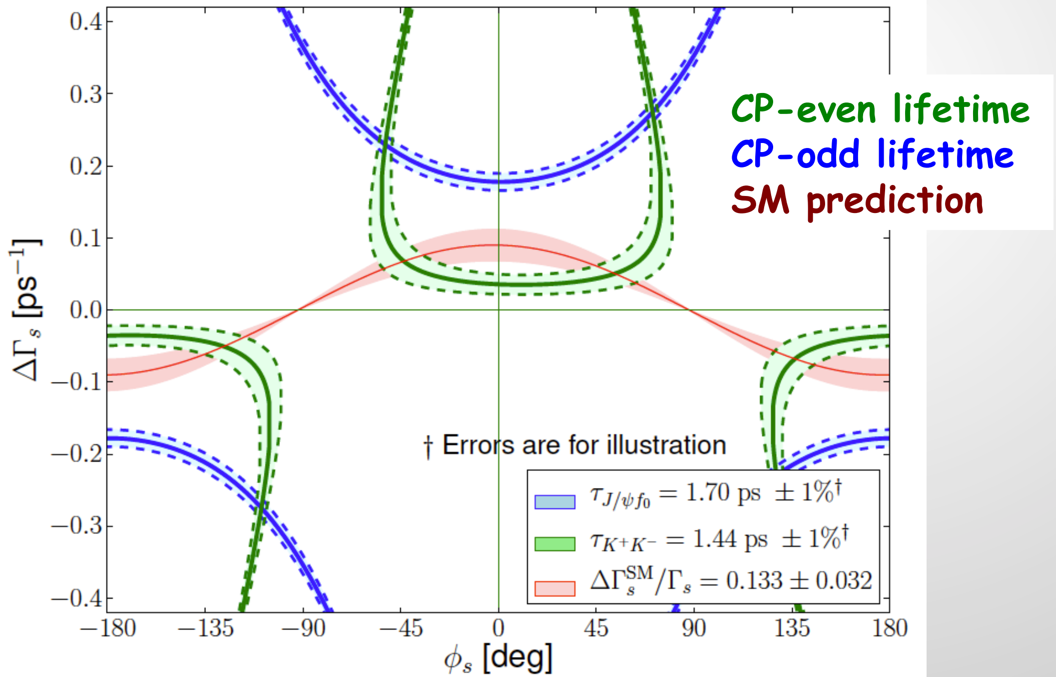




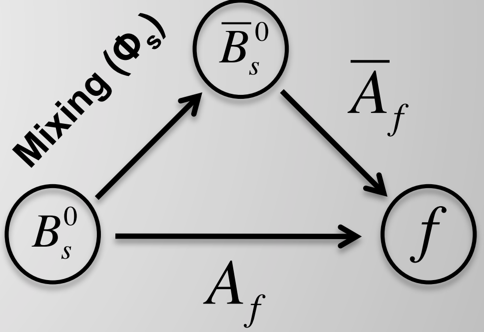
Combining CP-odd & CP-even lifetimes

- They give complementary constraints on B_s^0 mixing parameters
  - Lifetime difference between the mass states
  - Weak mixing phase Φ_s

Fleischer, Knegjens, arXiv:1109.5115v1



Example of constraints from a 1% measurement



$$\Delta\Gamma = \frac{1}{\tau_L} - \frac{1}{\tau_H}$$

Time dependent CPV

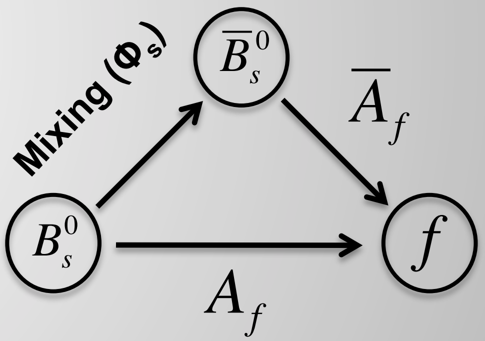
Time dependent CP asymmetries

- Decay rate into a common final state

$$\Gamma\left(B_q^0 \to f\right) \propto e^{-\Gamma_s t} \cdot \left[A_{dir}\cos(\Delta m t) + A_{mix}\sin(\Delta m t) - \cosh\left(\Delta\Gamma_q t/2\right) - A_{\Delta\Gamma}\sinh\left(\Delta\Gamma_q t/2\right)\right]$$

- Tag initial flavour state and fit

$$\mathcal{A}_f^{\mathcal{CP}}(t) = \frac{\Gamma_{\overline{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\overline{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



- Determine independently A_{dir} and A_{mix}

Determine CKM angle γ from A_{dir} & A_{mix}

- A_{dir} and A_{mix} from $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$
  - γ from loop-dominated decays
  - Sensitive to BSM processes

LHCb Roadmap
arXiv:0912.4179

- A_{dir} and A_{mix} from $B_s^0 \to D_s K$ and $B^0 \to D^{(*)}\pi$
  - γ from tree-dominated decays
  - Insensitive to BSM processes

- First time dependent CP asymmetry measurements in preparation

Tree-dominated γ can also be measured at LHCb from time-integrated rates (ADS/GWL methods) and Dalitz analysis.

Summary

- Fruitful year of data taking 2011
  - Looking forward to 2012
- First evidence of CP violation in Charm
  - Rich programme to further constrain the CPV parameters in the charm sector
- Several world-best measurements in hadronic B decays
  - CP asymmetries
  - Lifetime measurements
- First time dependent CP asymmetries in preparation
  - Determine γ with and w/o BSM contributions