Search for CP violation in two-body charm decays at LHCb

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on behalf of the LHCb collaboration

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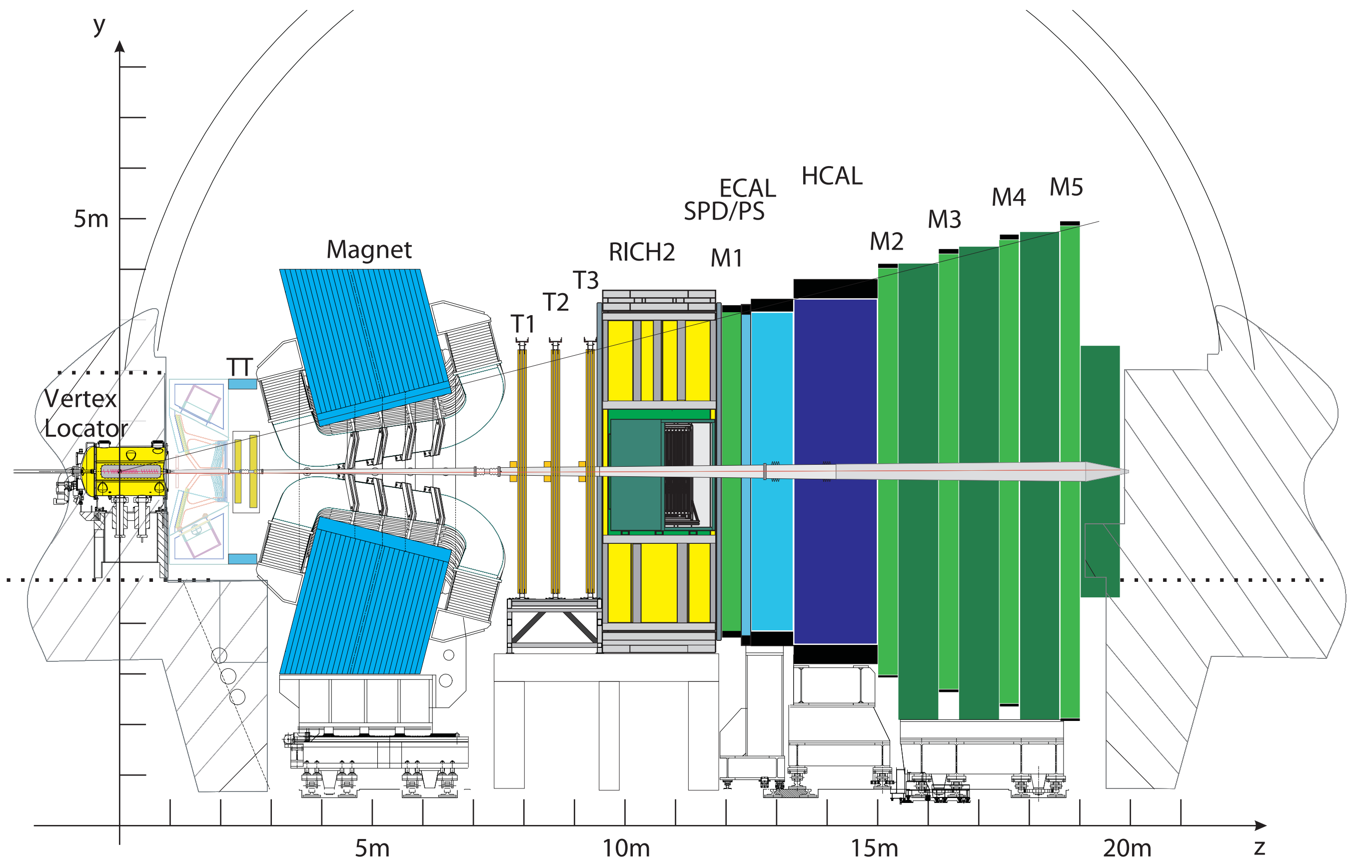
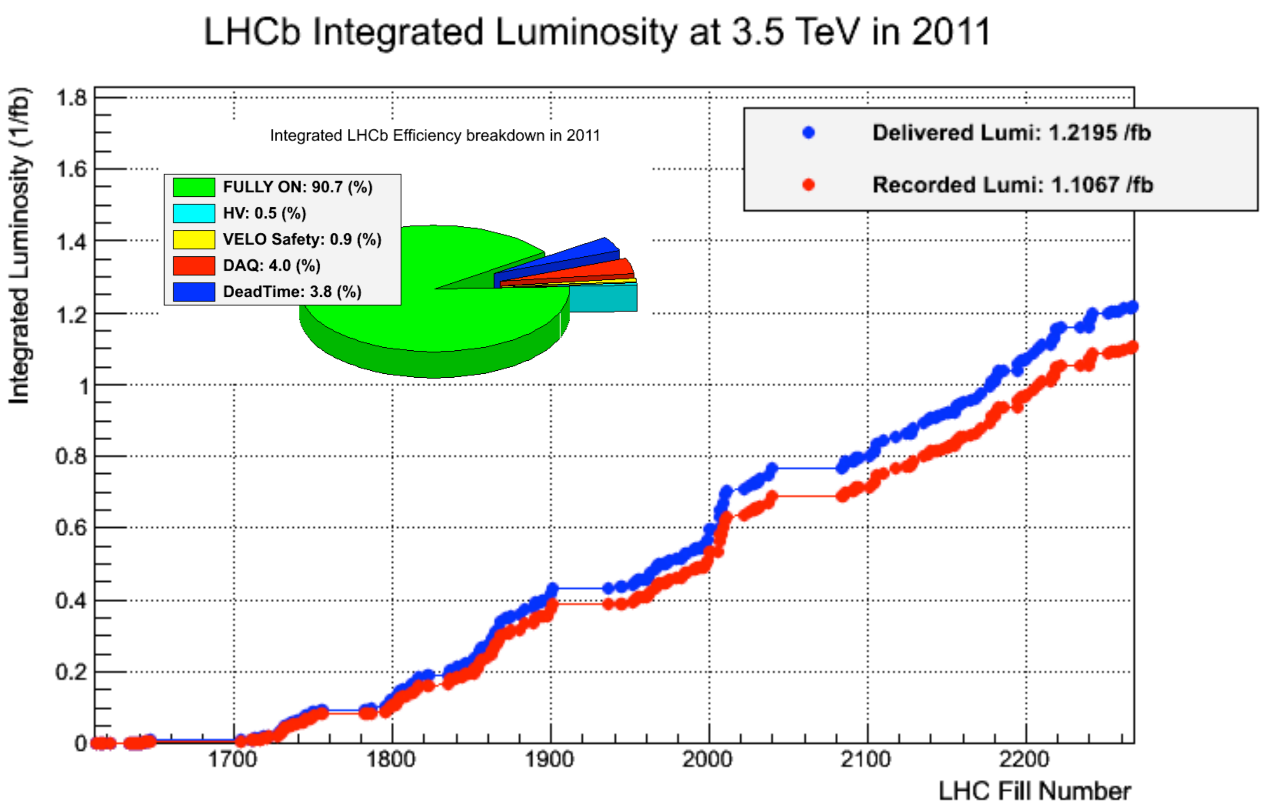
Overview

- Introduction to LHCb
- CP violation in charm
- Time-integrated search for CPV in $D^0 \rightarrow K^- K^+$ vs $\pi^- \pi^+$
- Conclusions

Disclaimer: All results are preliminary

LHCb data sample





2011: 1.1 fb^{-1}

- Analysis shown today: 580 pb^{-1}, 2011 data only

CP violation

- 3 types of CP violation:
  - In decay: amplitudes for a process and its conjugate differ
  - In mixing: rate of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ
  - In interference between mixing and decay diagrams

Direct

Indirect

- In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates
  - Perhaps $O(10^{-3})$ for CPV parameters => $O(10^{-5})$ for observables like A_Γ
- Direct CP violation can be larger in SM, very dependent on final state (therefore we must search wherever we can)
  - Negligible in Cabibbo-favoured modes (SM tree dominates everything)
  - In singly-Cabibbo-suppressed modes: up to $O(10^{-4}$ -- $10^{-3})$ plausible
- Both can be enhanced by NP, in principle up to O(%)

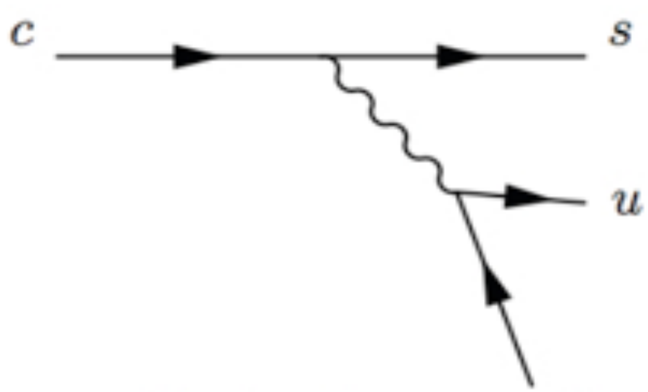
Bianco, Fabbri, Benson & Bigi, Riv. Nuovo. Cim 26N7 (2003)
Grossman, Kagan & Nir, PRD 75, 036008 (2007)
Bigi, arXiv:0907.2950

Bobrowski, Lenz, Riedl & Rorhwild, JHEP 03 009 (2010)
Bigi, Blanke, Buras & Recksiegel, JHEP 0907 097 (2009)

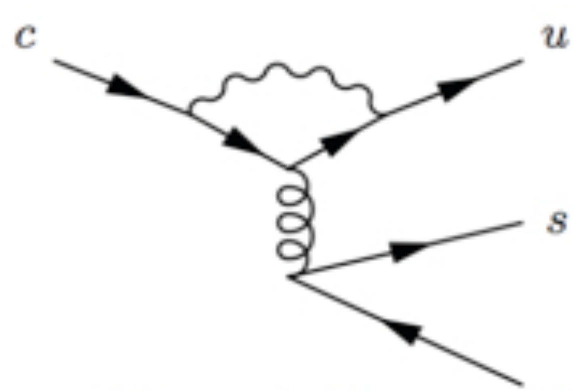
CPV in charm not yet seen experimentally

Where to look for direct CPV

- Remember: need (at least) two contributing amplitudes with different strong and weak phases to get CPV.
- Singly-Cabibbo-suppressed modes with gluonic penguin diagrams very promising
  - Several classes of NP can contribute
  - ... but also non-negligible SM contribution



(a) *Tree diagram.*



(b) *Penguin diagram.*

Today: difference between $A_{CP}(D^0 \to K^+ K^-)$, $A_{CP}(D^0 \to \pi^+ \pi^-)$

- Expectation from U-spin: $A^{dir}(KK) = -A^{dir}(\pi\pi)$...
- Conclusion could be softened by large U-spin violation in power corrections [Kagan]

Grossman, Kagan & Nir, PRD 75, 036008 (2007)

$D^0 \to K^+ K^-, \pi^+ \pi^-$ measurements

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2010	CDF	M.J. Morello (CDF Collab.), Preprint (CHARM 2010).	+0.0022 ± 0.0024 ± 0.0011
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	+0.0043 ± 0.0052 ± 0.0012
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0020 ± 0.0022

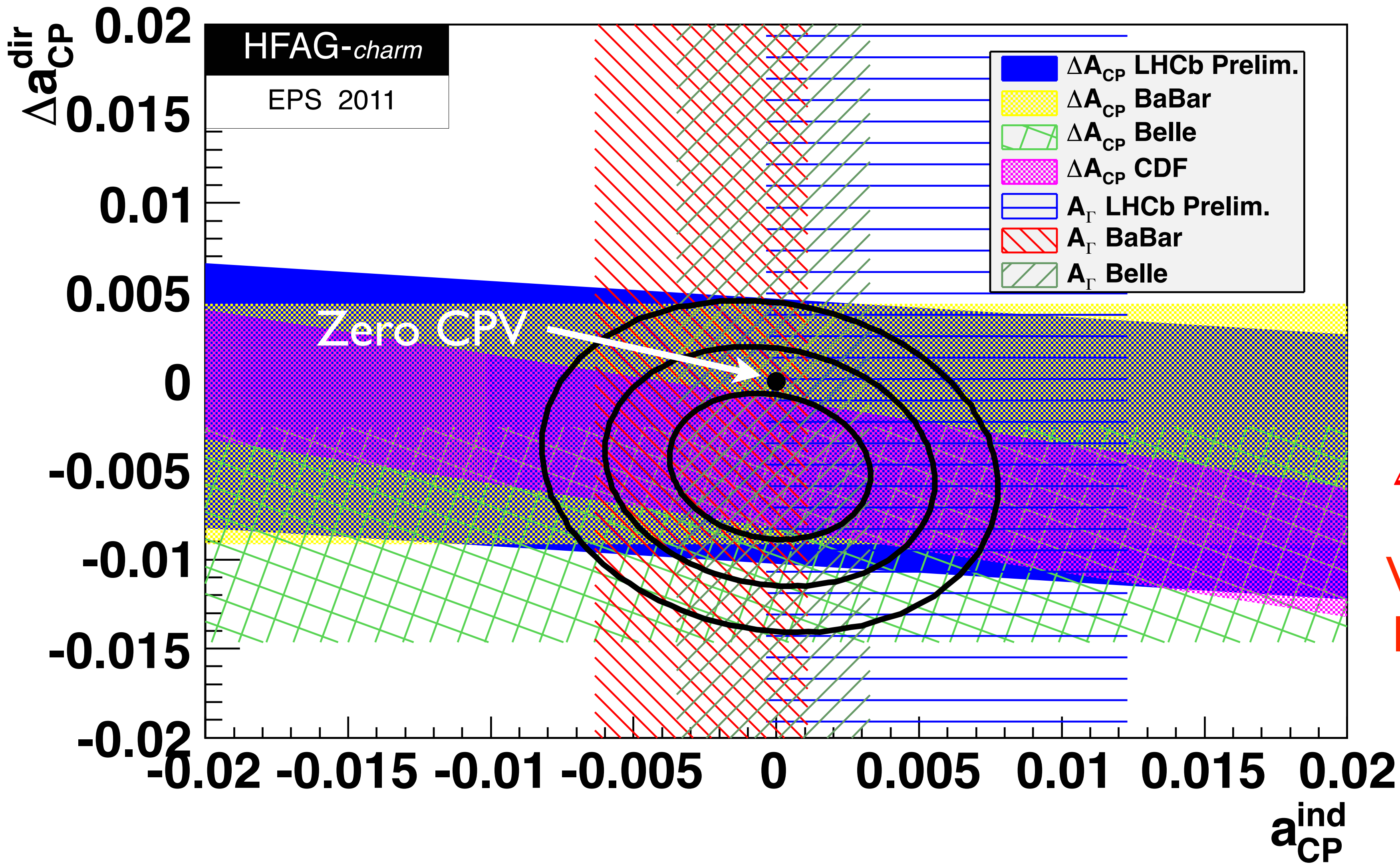
Year	Experiment	CP Asymmetry in the decay mode D0 to K+K-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2011	CDF	A. Di Canto (CDF Collab.), Preprint (BEAUTY 2011).	-0.0024 ± 0.0022 ± 0.0010
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	+0.080 ± 0.061
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0023 ± 0.0017

Dominated by CDF, especially for $D^0 \to \pi^+ \pi^-$

K^+K^- and $\pi^+\pi^-$ values consistent with zero but have opposite sign.

Indirect vs direct CP violation

- Both indirect & direct CPV can contribute.
- Indirect CPV is universal => cancels in A(KK)-A(ππ)...
  ... IF equal proper time acceptance for both (e.g. BABAR, Belle)
- If not equal, residual contribution: $A^{ind}[\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle]/\tau_0$



Consistency with no CPV hypothesis: 20%

$$a_{CP}^{\mathrm{ind}} = (-0.023 \pm 0.232)\%$$

$$\Delta a_{CP}^{\mathrm{dir}} = (-0.447 \pm 0.270)\%$$

World avg ΔA_{CP} negative and about 1.7σ from zero

See: CDF, arXiv:1012.2415
See also: Bigi, Paul & Recksiegel, JHEP05 089 (2011)

Formalism

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of soft pion

Production asymmetry

- ... so when we take $A_{RAW}(f)^* - A_{RAW}(f')^*$ the production and soft pion detection asymmetries will cancel. Moreover...
- No detector asymmetry for D^0 decays to $(K^+ K^-)$, $(\pi^+ \pi^-)$

... i.e. all the D^*-related production and detection effects cancel.

This is why we measure the CP asymmetry difference: very robust against systematics.

Shorthand: $\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$

Assumptions

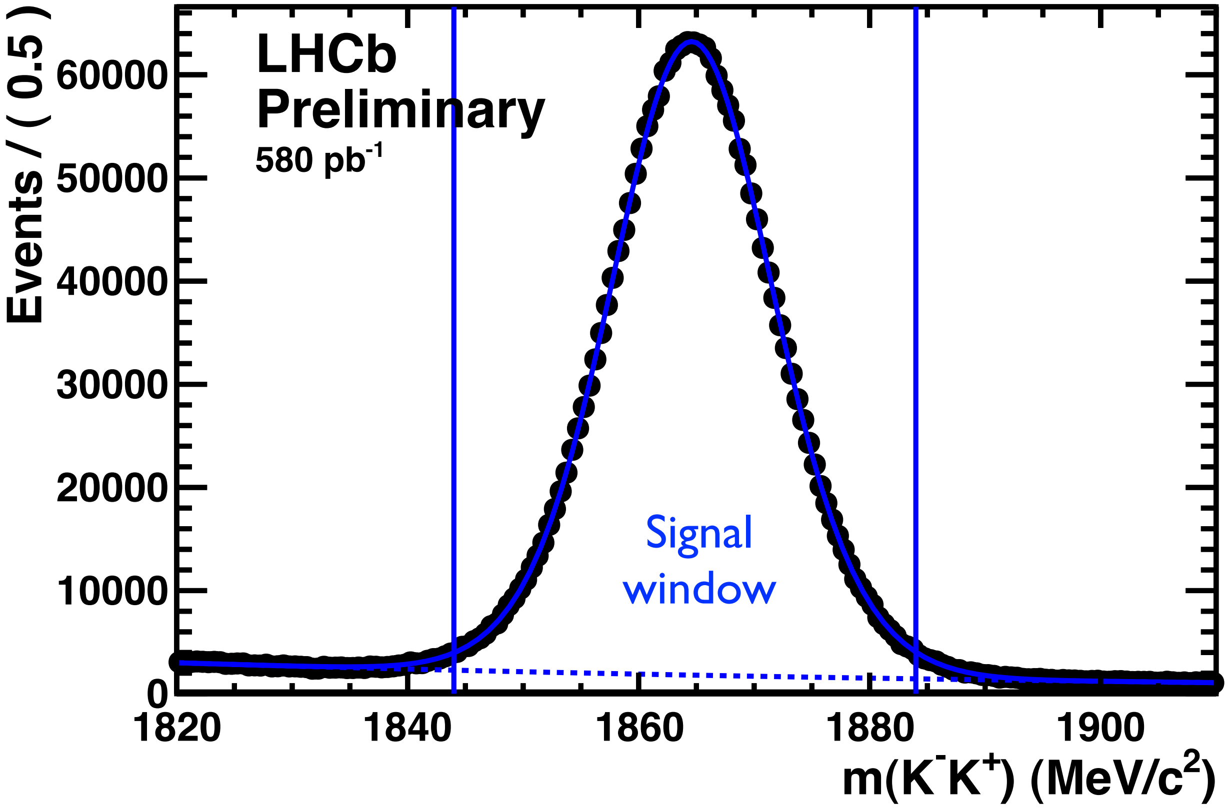
- Double-difference robust against systematics.
- In order to break the formalism, you need a detector effect that induces different fake asymmetries for KK and ππ.
- Two known mechanisms:
  - Correlation between KK/ππ efficiency ratio and D^{*+}/D^{*-} asymmetry (from production or soft pion efficiency)
    - e.g. correlated variation of A_P and A_D with kinematics (p_t, η)
    - Solution: divide data into bins of the variable (such that no correlation within bin) and treat each bin independently.
  - Asymmetric peaking background different between KK, ππ
    - Comes from mis-reconstructed $D^{*+} \to D^0 \pi^+$
    - This is a small effect at LHCb due to excellent hadron ID: from D^0 mass sidebands, size of peaking background O(1%) of signal... and background asymmetry O(%) so effect $O(10^{-4})$
- First-order expansion assumes raw asymmetry not large.
  - ... which is true: O(%).

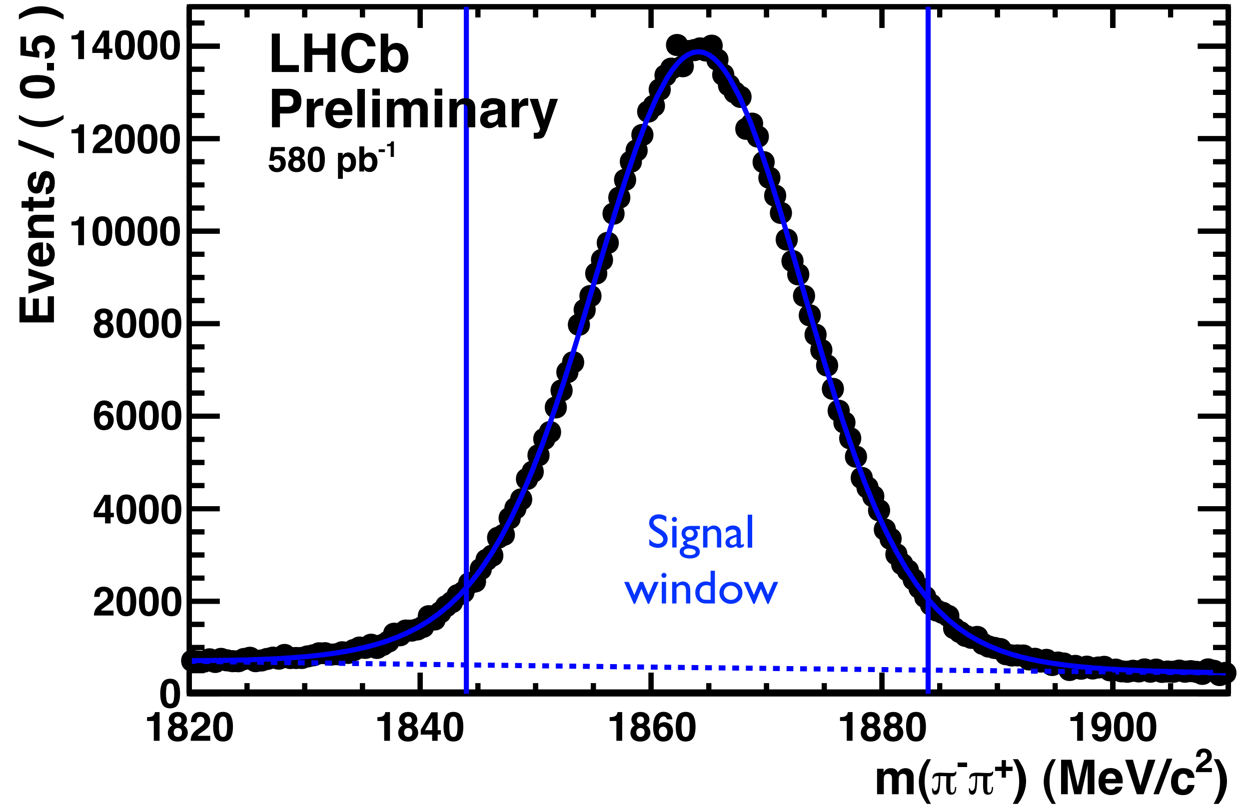
Selection

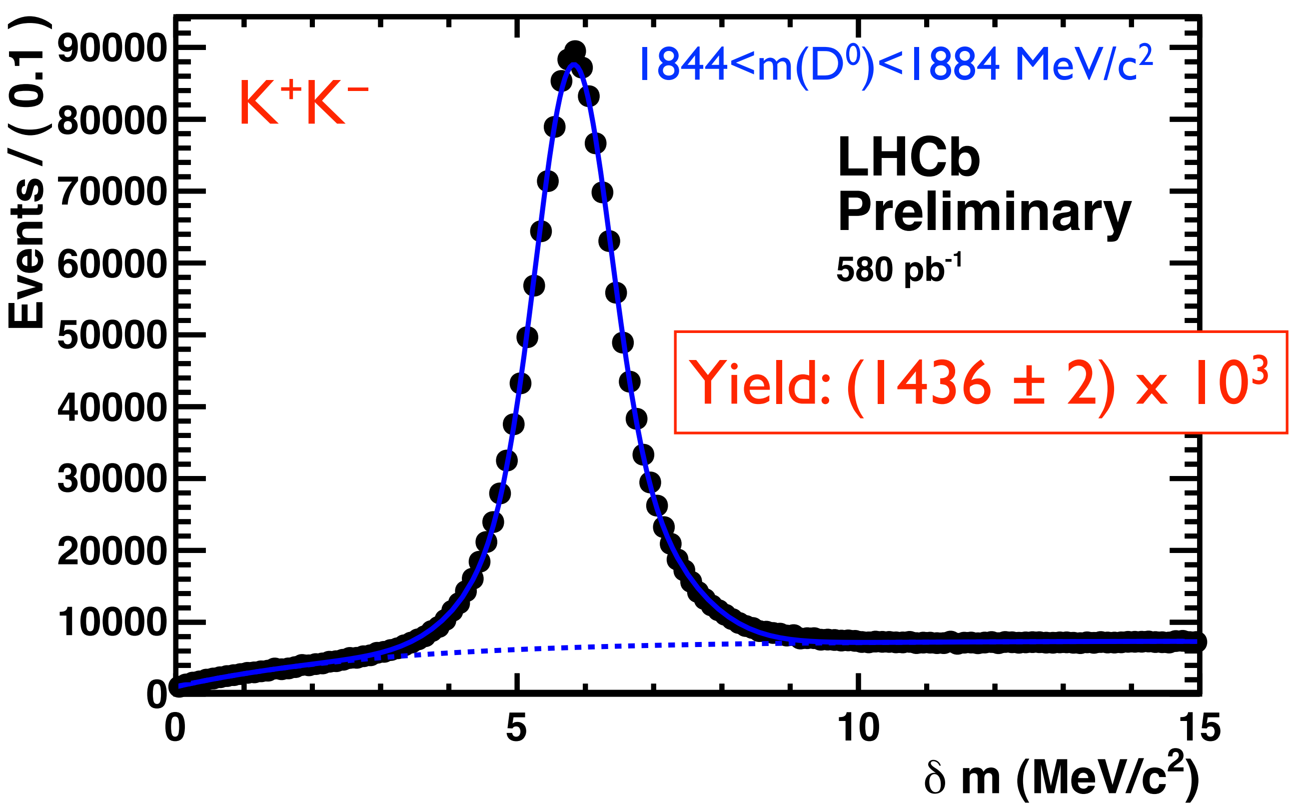
- Kinematic and geometrical selection cuts, including:
  - Track fit quality for all three tracks
  - D^0 and D^{*+} vertex fit quality
  - Transverse momentum of D^0: $p_T > 2$ GeV/c
  - Proper lifetime of D^0: $ct > 100$ μm
  - Helicity angle of D^0 decay: $\cos\theta_h < 0.9$
  - D^0 must point back to primary vertex (IP $\chi^2 < 9$)
  - D^0 daughter tracks must not point back to primary vertex
  - Hard kaon/pion hadron ID cuts imposed with RICH information
  - Fiducial cuts to exclude edges where B-field causes large D^{*+}/D^{*-} acceptance asymmetry
- Software trigger required to fire explicitly on the D^0 candidate.
- D^0 mass window: 1844 --1884 MeV/c^2 (next slide)

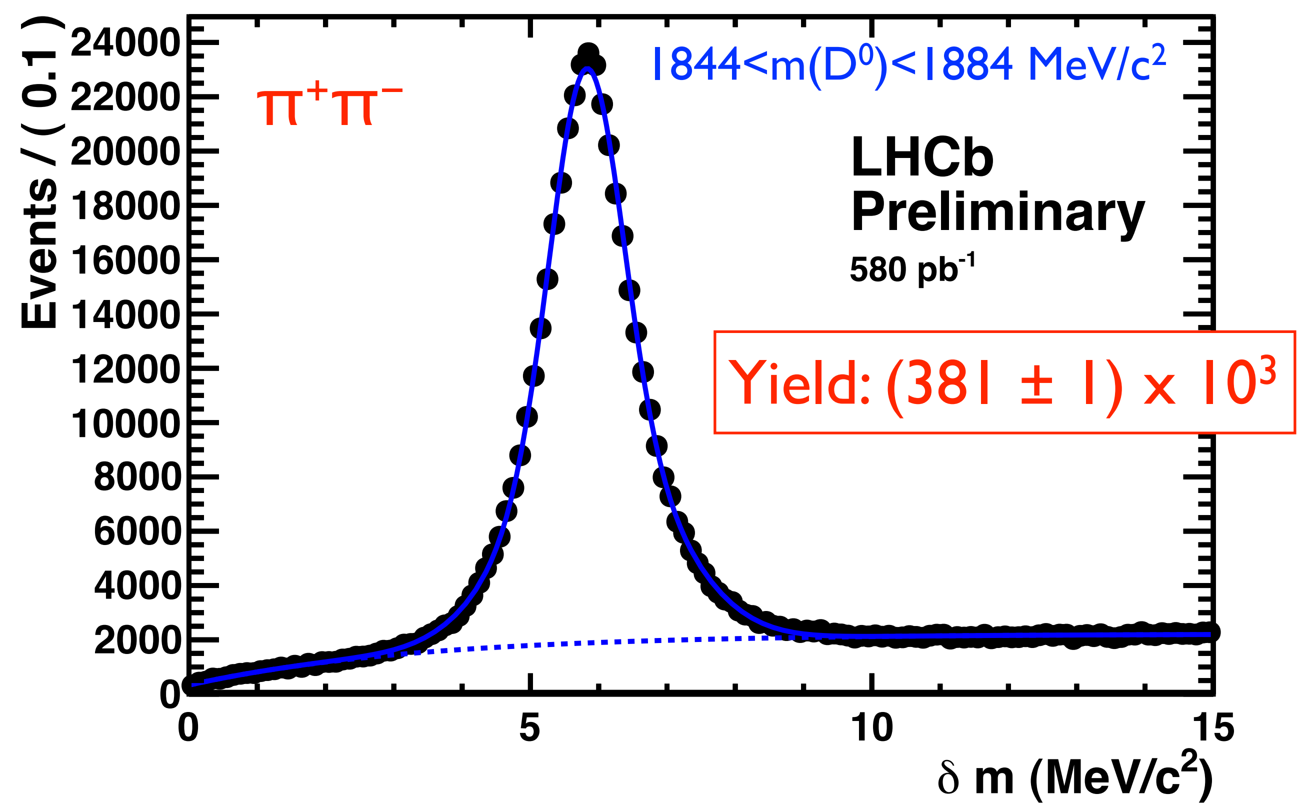
Mass spectra

Showing D^0 candidate mass for D^{*+} candidates within $0<\delta m<15$ MeV/c^2; $\delta m = m(D^0\,\pi^+) - m(D^0) - m(\pi^+)$









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For illustration; not used in calculating ΔA_{CP}

Kinematic binning

- Recap: kinematic binning needed to suppress second-order effects of correlated asymmetries.
- Divide data into kinematic bins of (p_T of D^{*+}, η of D^{*+}, p of soft pion, left/right hemisphere) -- 54 bins
- Along similar lines:
  - split by magnet polarity (field pointing up, pointing down)
  - split into two run groups (before & after technical stop)
- Fit final states $D^0 \rightarrow K^+ K^-$ and $\pi^+ \pi^-$ separately => 432 independent fits.

Fit procedure

- Use 1D fits to mass difference $\delta m = m(D^0 \pi^+) - m(D^0) - m(\pi^+)$
- Signal model: double-Gaussian convolved with asymmetric tail:

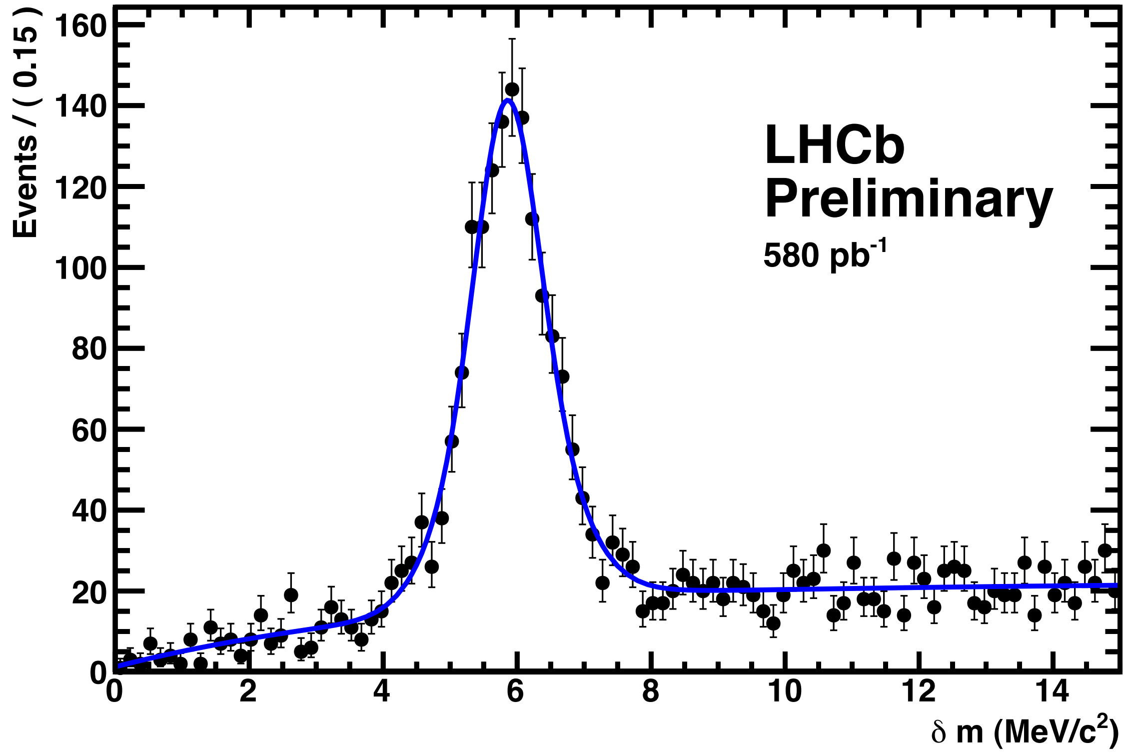
$$g(\delta m) = [\Theta(\delta m' - \mu)\, A(\delta m' - \mu)^s] \otimes G_2(\delta m - \delta m'; f_{\rm core}, \sigma_{\rm core}, \sigma_{\rm tail})$$

Phys. Lett. B 633 (2006) 309; LHCb-PUB-2009-031

- D^{*+} and D^{*-} are allowed to have different mass and resolution.
  - ... though $f_{\rm core}$ and $(\sigma_{\rm core}/\sigma_{\rm tail})$ are shared
- Background model:

$$h(\delta m) = B\left[1 - \exp\left(-\frac{\delta m - \delta m_0}{c}\right)\right]$$

δm_0 fixed from fit to high-statistics $D^0 \rightarrow K^- \pi^+$ channel
Special handling of tricky cases (single Gaussian for low-statistics bins, background parameters loosened in some kinematic regions).



Example fit (first kinematic bin of first run block, magnet polarity up, $D^0 \rightarrow K^+ K^-$)

Consistency for ΔA_{CP} among individual fits: $\chi^2/NDF = 211/215$ (56%)
Stat error: 0.21% absolute

Systematic uncertainties

- Kinematic binning: 0.02%
  - Evaluated as change in ΔA_{CP} between full 54-bin kinematic binning and "global" analysis with just one giant bin.
- Fit procedure: 0.08%
  - Evaluated as change in ΔA_{CP} between baseline and not using any fitting at all (just sideband subtraction in δm for KK and $\pi\pi$ modes)
- Peaking background: 0.04%
  - Evaluated with toy studies injecting peaking background with a level and asymmetry set according to D^0 mass sidebands (removing signal tails).
- Multiple candidates: 0.06%
  - Evaluated as mean change in ΔA_{CP} when removing multiple candidates, keeping only one per event chosen at random.
- Fiducial cuts: 0.01%
  - Evaluated as change in ΔA_{CP} when cuts are significantly loosened.
- Sum in quadrature: 0.11%

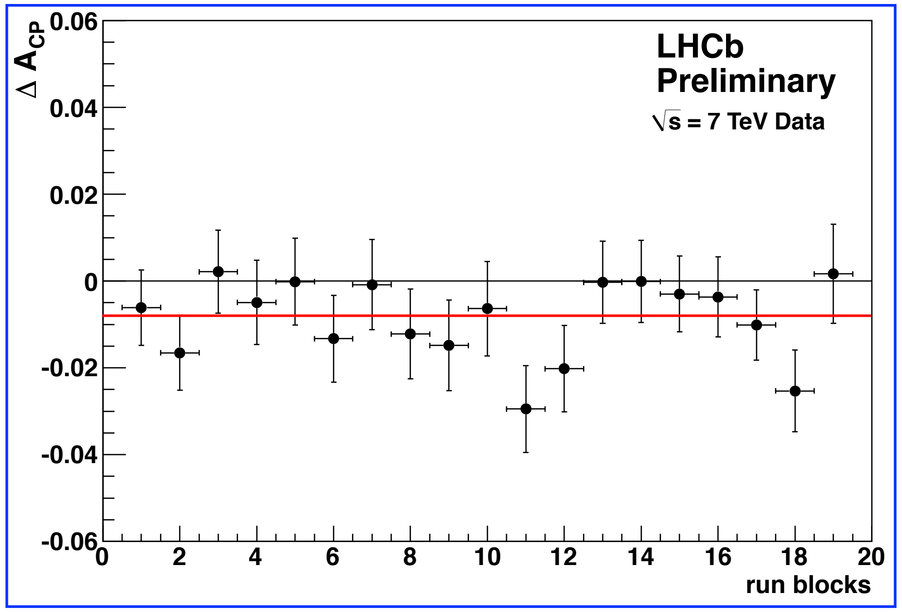
Result

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})]\,\%$$

Significance: 3.5 σ

Further crosschecks

- Numerous crosschecks carried out, including:
  - Electron and muon vetoes on the soft pion and on the D^0 daughters
  - Different kinematic binnings
  - Stability of result vs time
  - Toy MC studies of fit procedure, statistical errors
  - Tightening of PID cuts on D^0 daughters
  - Tightening of kinematic cuts
  - Variation with event track multiplicity
  - Use of other signal, background lineshapes in the fit
  - Use of alternative offline processing (skimming/stripping)
  - Internal consistency between subsamples (splitting left/right, magnet up/down, etc)



- All variation within appropriate statistical/systematic uncertainties.

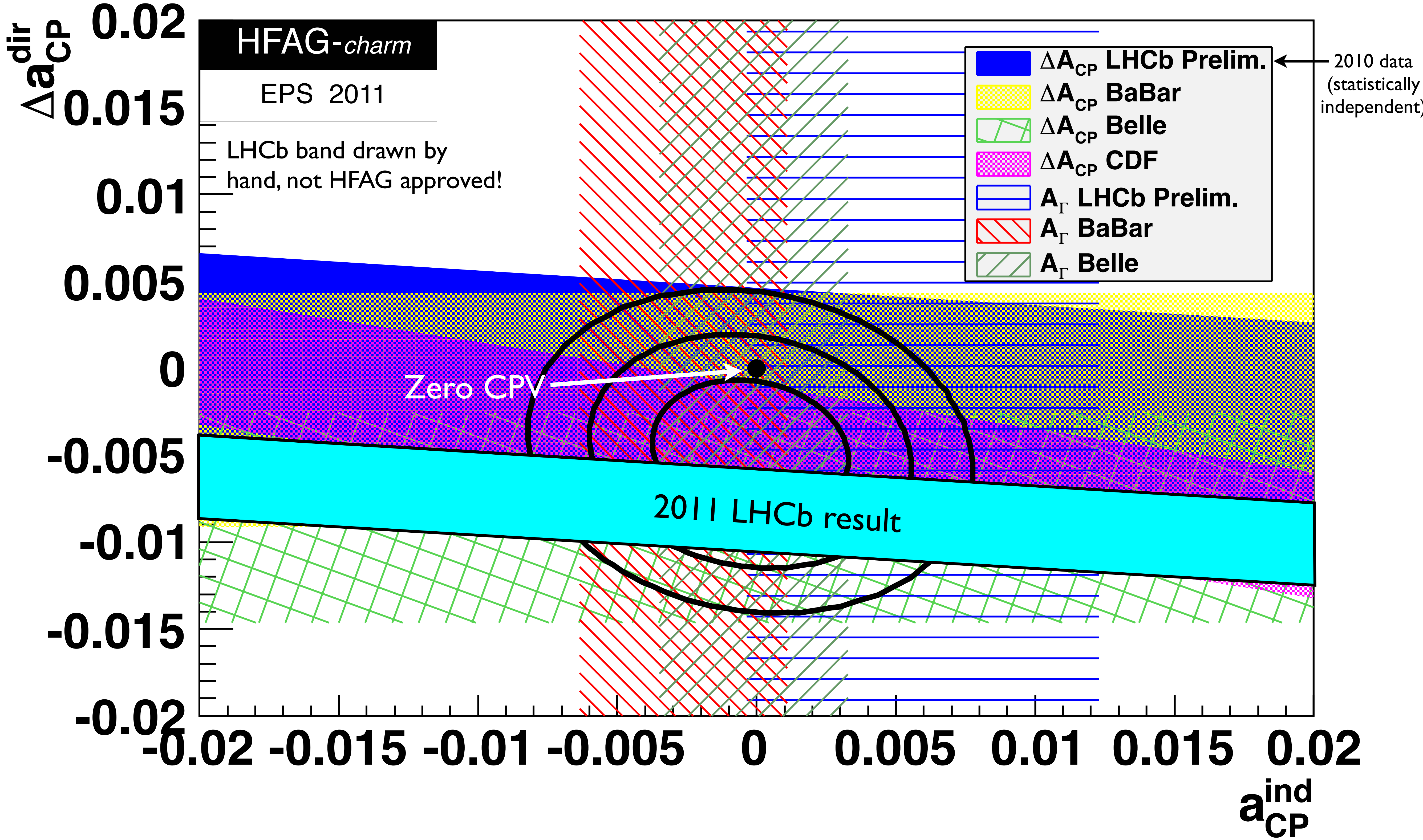
Interpretation: lifetime acceptance

- Lifetime acceptance differs between $D^0 \rightarrow K^+ K^-$, $\pi^+ \pi^-$
  - e.g. smaller opening angle => short-lived $D^0 \rightarrow K^+ K^-$ more likely to fail cut requiring daughters not to point to PV than $\pi^+ \pi^-$
- Need this to compute how much indirect CPV could contribute.
- Fit to background-subtracted samples passing the full selection, correcting for ~ 3% secondary charm, and extract:

$$\frac{\Delta\langle t\rangle}{\tau} = \frac{\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle}{\tau} = (9.8 \pm 0.9)\%$$

- ... so indirect CP violation contribution mostly cancels.

Comparison with world average



LHCb value consistent with HFAG averages
given our time-acceptance (approx 1.0σ)

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Summary

- We have measured the difference in time-integrated CP asymmetries of $D^0 \to K^- K^+, \pi^- \pi^+$ at LHCb
- World's most sensitive search for CPV in SCS charm decays.
- Result: $\Delta A_{CP} = -0.82 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{sys})\ \%$
- Significance 3.5σ (incl. statistical and systematic uncertainties)
- Indirect CP violation suppressed in the difference ($\Delta \langle t \rangle / \tau = 9.8 \pm 0.9\%$) so sensitive mainly to direct CPV.
- Our value is consistent with HFAG average (1σ apart) but more negative.
- Magnitude of central value larger than current SM expectation
  - ... but charm is notoriously difficult to pin down theoretically
  - ... and this is still only 3.5σ
- Another 500 pb^{-1} on tape: watch this space.

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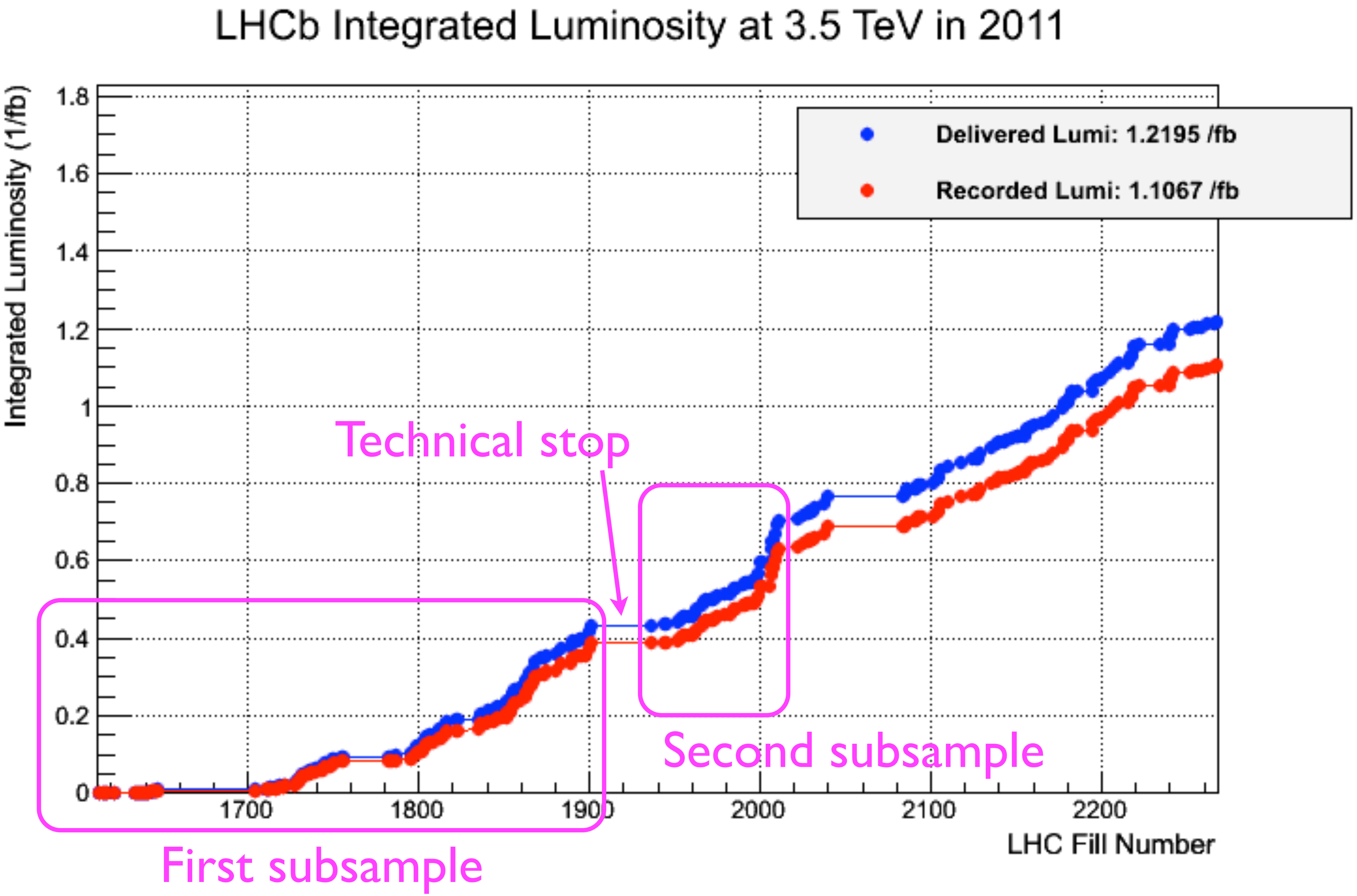
First evidence of CP violation in charm.

LHCb

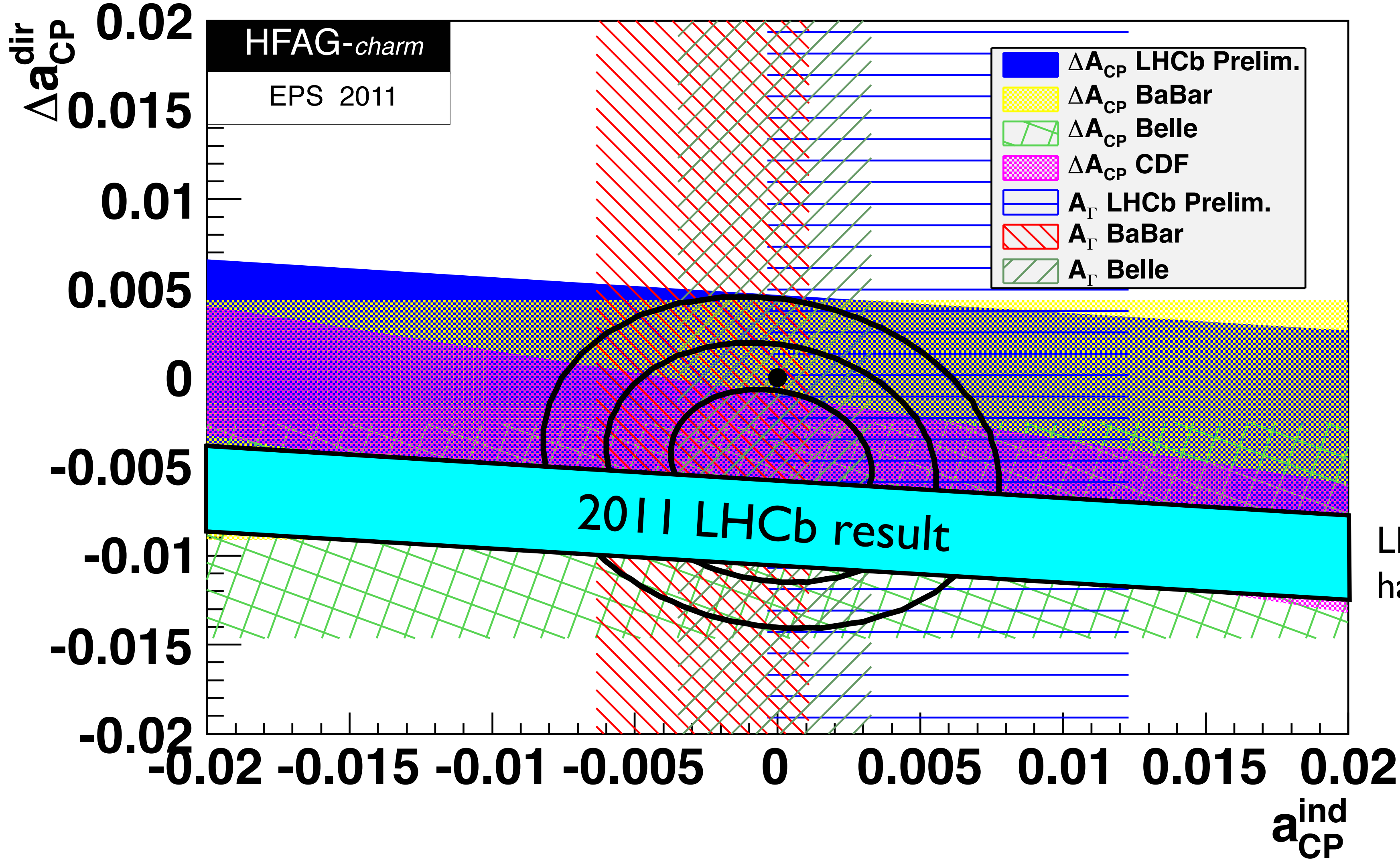
fin

Integrated luminosity



Showing online luminosity (not final calibration)

Comparison with world average



LHCb band drawn by hand, not HFAG approved!

- Taking existing HFAG world-average values for ΔA_{CP} and A_Γ and propagating them to the LHCb lifetime acceptance, get:

$$\Delta A_{CP} = \Delta a_{CP}^{\mathrm{dir}} + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}} = (-0.45 \pm 0.27)\,\%$$

LHCb value is 1.0σ away (approx)

Caution: preliminary. Neglects correlations in world-avg values.