Search for CP violation in the charm sector at LHCb

Matt Coombes

on behalf of the LHCb collaboration

29/05/2012

University of BRISTOL

Rencontres de Blois

Contents

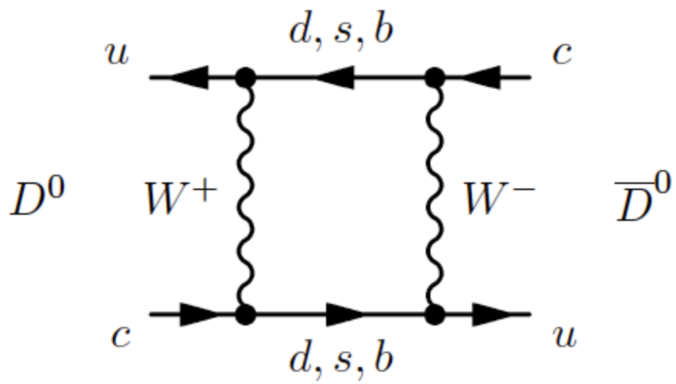
Why LHCb?

- Alvaro talked about B-physics at LHCb. LHCb also has large charm physics program
- LHCb has **huge charm samples**. Charm cross section ≈ **20 x b cross section** within the LHCb acceptance:
  - $\sigma(cc)$LHCb = 1742 ± 267 μb (LHCb-CONF-2010-013),
  - $\sigma(bb)$LHCb = 75.3 ± 5.4 ± 13.0 μb (Phys.Lett.B694, 209).
- In 1fb^{-1} roughly **10^{12} $c\bar{c}$** and **10^{11} $b\bar{b}$** produced!
- LHCb can make **precision measurements in charm** and study loop-sensitive processes.
- These measurements include **searches for CPV**.
  - Theory calculations are difficult in charm
  - Use to be a clean prediction of CPV < $\mathcal{O}(10^{-3})$
  - Recently effects of a few $\mathcal{O}(10^{-3})$ could be possible in SM

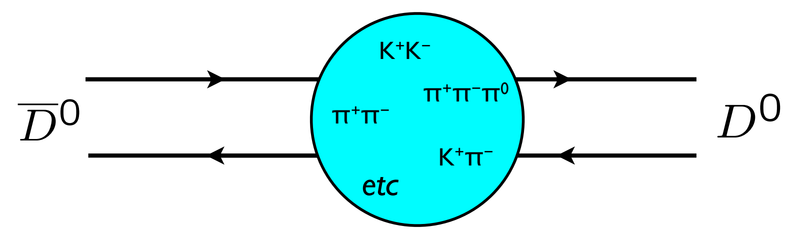
Phys.Rev. D75 (2007) 036008

D^0 mixing

- Observed in 2007 by BaBar and Belle
  [arXiv:hep–-ex/0703020; arXiv:hep–-ex/0703036]
- **>10σ** in HFAG average, but **no single >5σ measurement**



Mixing via box-diagram
Short range



Mixes via hadronic intermediate states
Long range

Time-evolution described by Schrödinger equation:

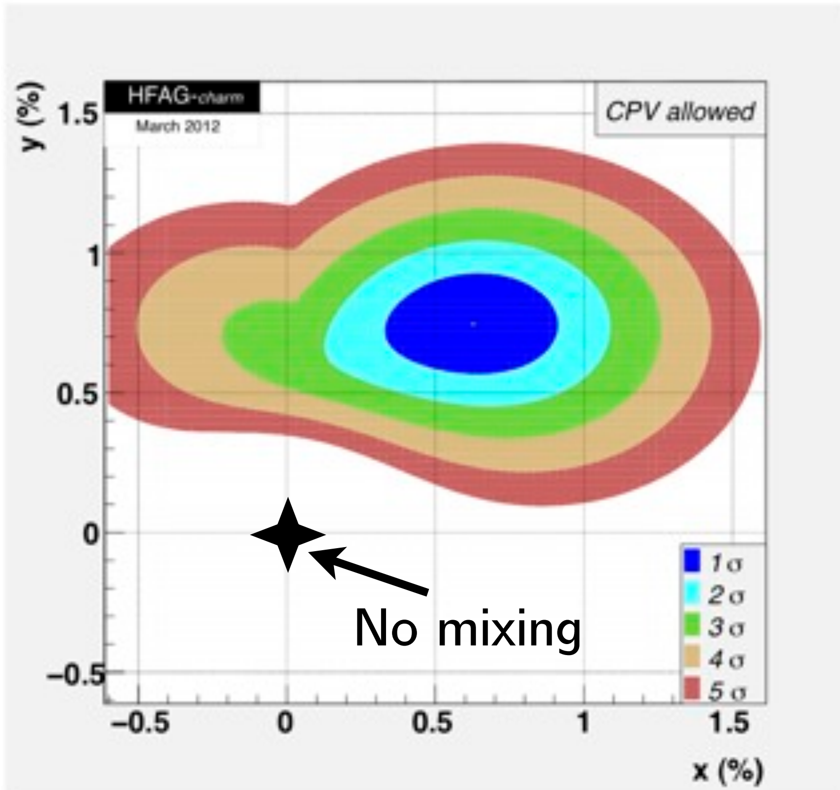
$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = (M - i\Gamma)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

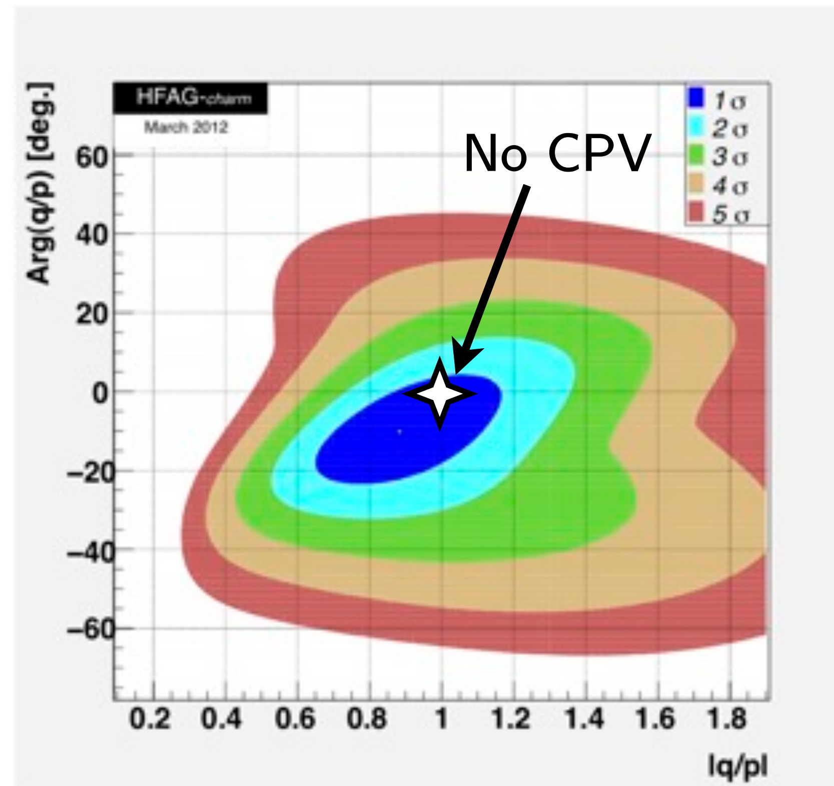
Mass eigenstates are $| D_{1,2}\rangle = p \,| D^0\rangle \pm q \,| \overline{D}^0\rangle$

Size of mixing characterised by $x = \frac{m_2 - m_1}{\Gamma}$, $\quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$

Mixing if **x ≠ 0** or **y ≠ 0** CPV if **|q/p| ≠ 1** or **arg(q/p) ≠ 0**

World average time dependent CPV and mixing





No mixing ruled out at **>10σ**

No CPV if **$|q/p| \neq 1$** or **$\arg(q/p) \neq 0$**

At this stage **no evidence for CPV** in mixing in charm sector

Measurement of mixing and CP violation parameters in two-body charm decays

JHEP 1204 (2012) 129

Two-body mixing and CPV

Compare lifetimes of non-eigenstate decay $D^0 \to K^-\pi^+$ and CP even decays $D^0 \to K^+K^-(\pi^+\pi^-)$

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

$$= y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi$$

If no CPV $y_{CP} = y$

Tagging the **D⁰ flavour using the slow pion** from the D^{*+},

$$D^{*+} \to D^0(f)\pi_s^+ \quad \text{or} \quad D^{*-} \to \bar{D}^0(f)\pi_s^-$$

allows us to define:

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

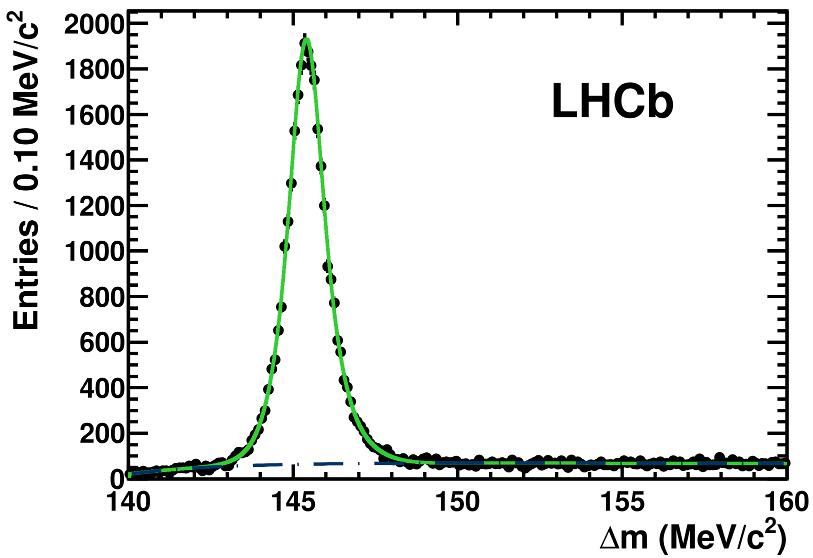
$$\approx \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - x\sin\phi$$

A_Γ **sensitive to CPV in mixing** ($|q/p| \neq 1$)

M. Gersabeck et al, J. Phys G 39 (2012) 045005.

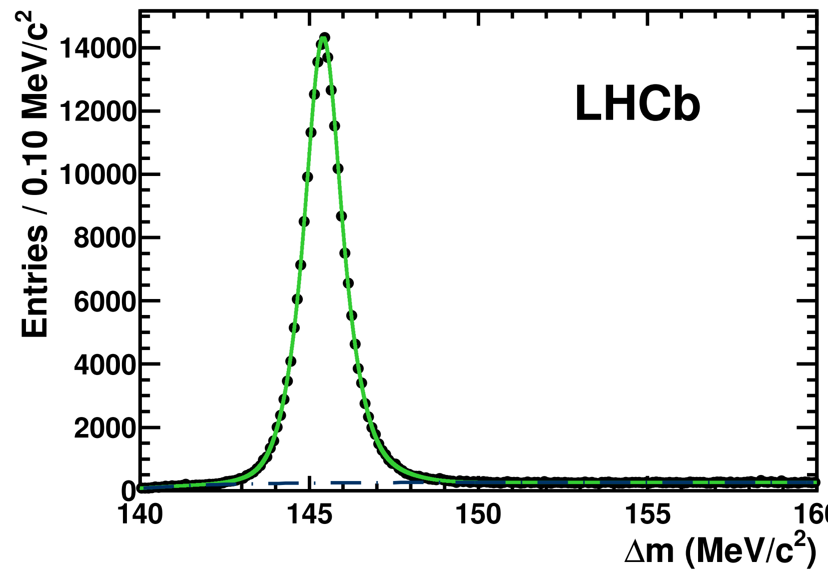
y_{CP} and A_Γ at LHCb

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



39K candidates with 29pb^{-1}

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



286K candidates with 29pb^{-1}

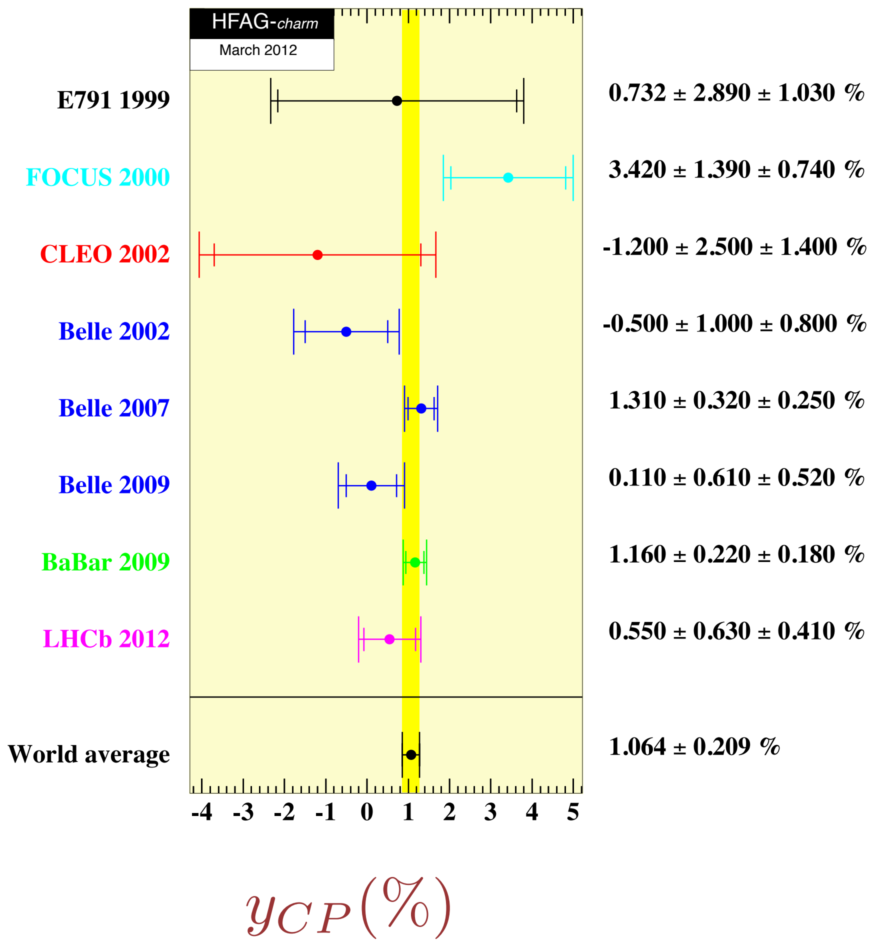
Performed on 29pb^{-1} update on 1fb^{-1} in progress

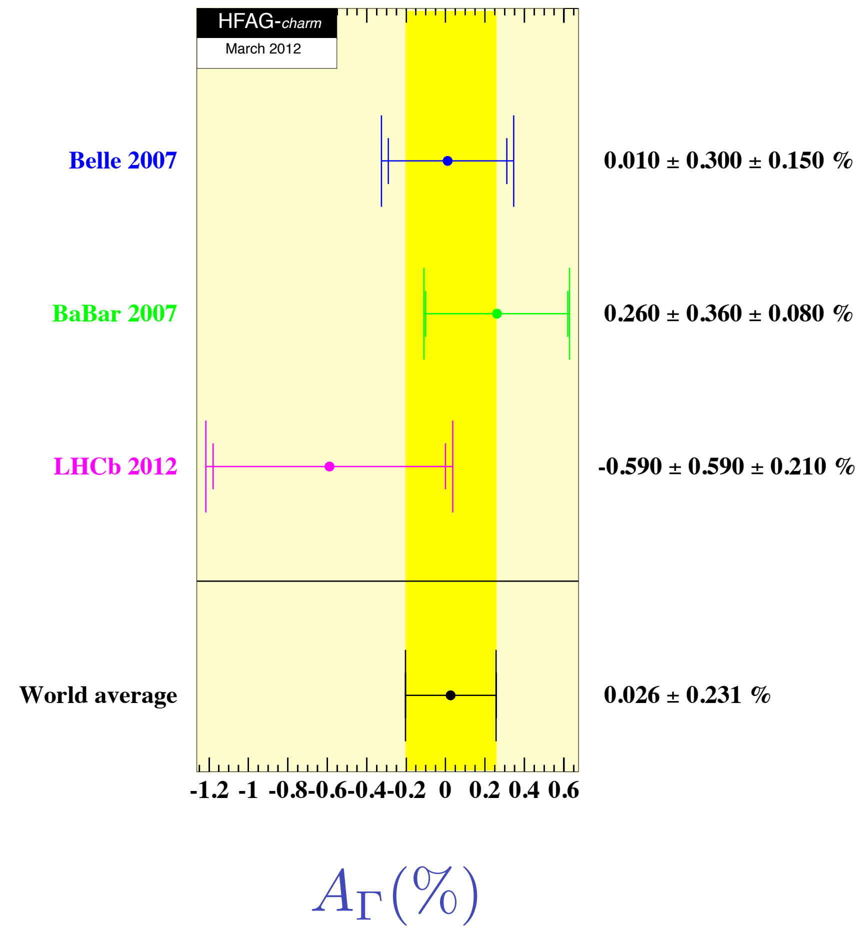
JHEP 1204 (2012) 129

y_{CP} and A_Γ at LHCb

$$y_{CP} = (0.55 \pm 0.63 \pm 0.41)\%$$

$$A_\Gamma = (-0.59 \pm 0.59 \pm 0.21)\%$$





Performed on 29pb^{-1} update on 1fb^{-1} in progress

Update with more data and improved systematics

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Measurement of ΔA_{cp} ($D^0 \to K^- K^+$ - $D^0 \to \pi^- \pi^+$)

Phys. Rev. Lett. 108 (2012) 111602

Direct CPV in Singly Cabibbo Suppressed Decays

Time-integrated CP asymmetry defined as:

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

SM predictions do not rule out a few 10^{-3}

NP could enhance up to $\mathcal{O}(10^{-2})$

LHCb study final state f : $\pi^- \pi^+$ or $K^- K^+$

D^0 flavour determined by the sign of the slow pion in decay:

$$D^{*+} \to D^0(f)\pi_s^+ \quad \text{or} \quad D^{*-} \to \bar{D}^0(f)\pi_s^-$$

ΔAcp

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

want

f's detection asymmetry

π_s detection asymmetry

Production asymmetry

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ΔAcp

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

want

f's detection asymmetry

π_s detection asymmetry

Production asymmetry

Zero for self-conjugate final states

ΔAcp

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

π_s detection asymmetry

Production asymmetry

Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and slow pion detection asymmetries will cancel

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

- Indirect and direct CPV can contribute **Phys.Rev. D80 (2009) 076008**
- Indirect CPV is ~universal => cancels in $A(K^+K^-) - A(\pi^+\pi^-)$
  - If lifetime acceptance same for KK and ππ
  - If not contribution $A^{ind}[\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle]/\tau_0$

LHCb

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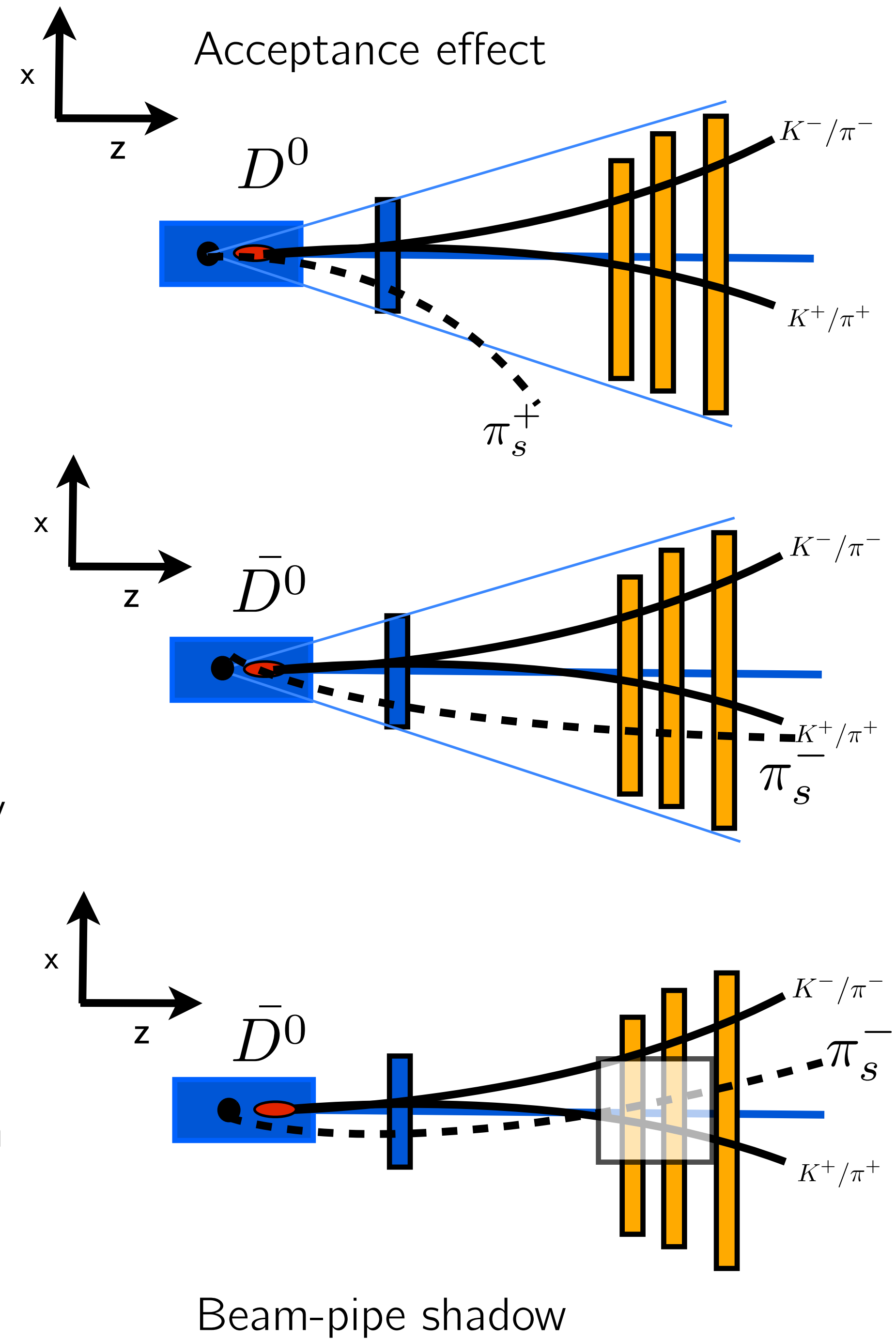
ΔAcp

- Magnetic field induces left/right differences between the D^{*+} and D^{*-} due to the slow pion
  - Acceptance effect at edges of detector
  - Beam-pipe shadow
- We remove this asymmetry
  - We remove areas of large asymmetry to avoid secondary effects
  - Frequently flip the magnetic field
  - Detector asymmetries removed in difference between RAW asymmetries



ΔAcp

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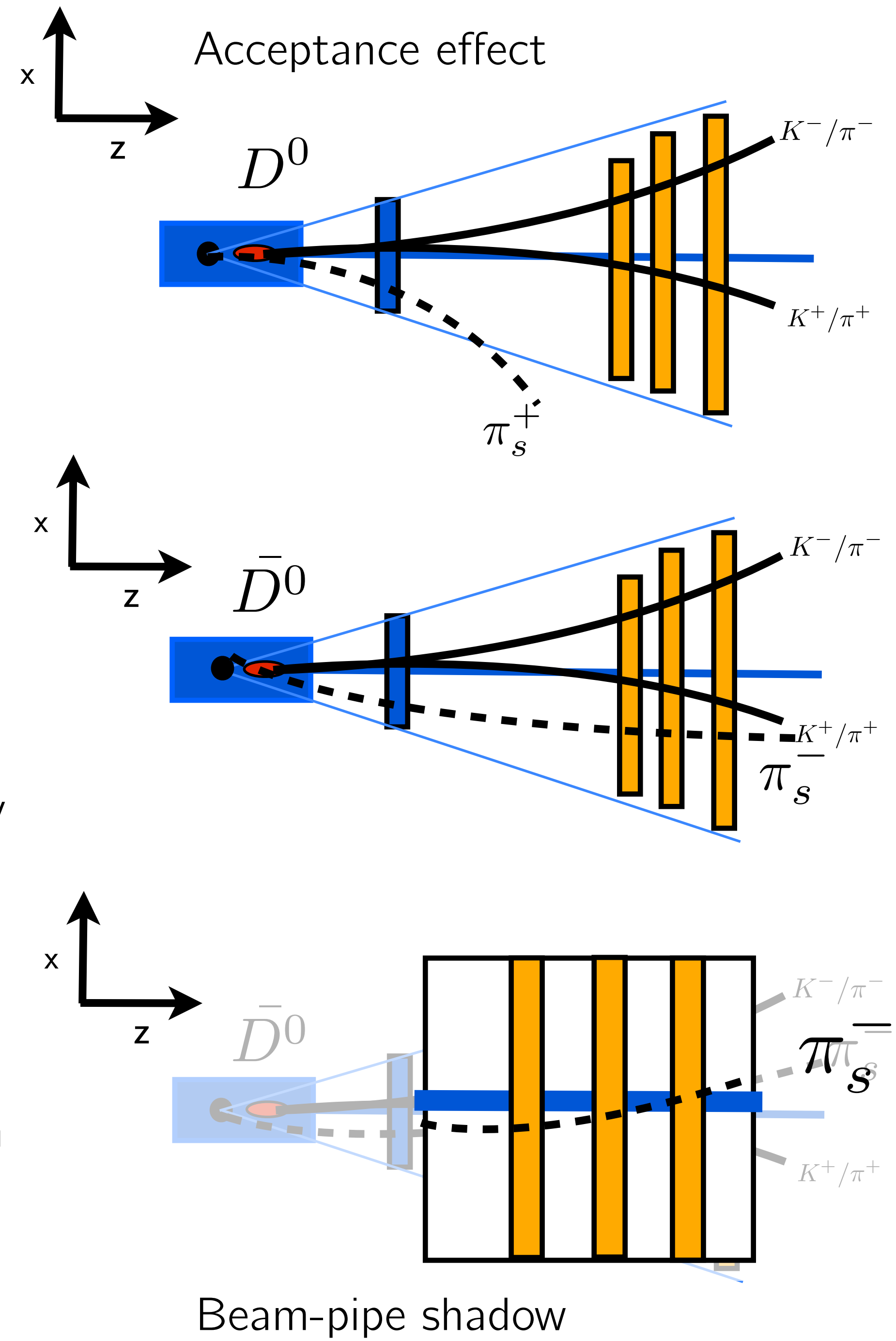

ΔAcp

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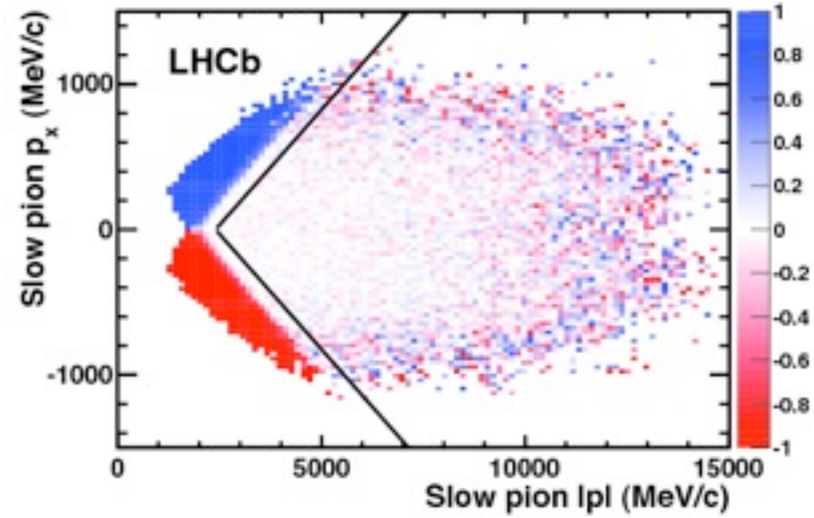
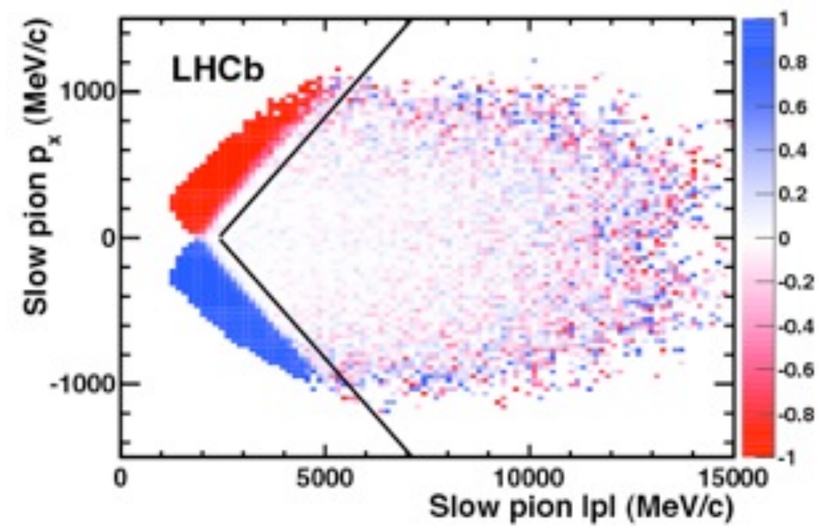
magnetic field up polarity

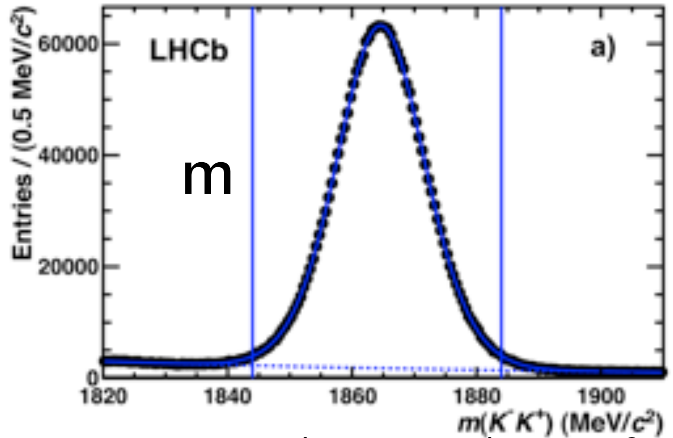


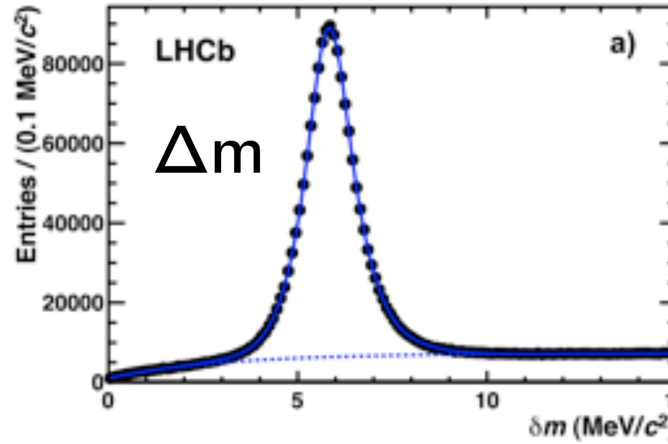
magnetic field down polarity



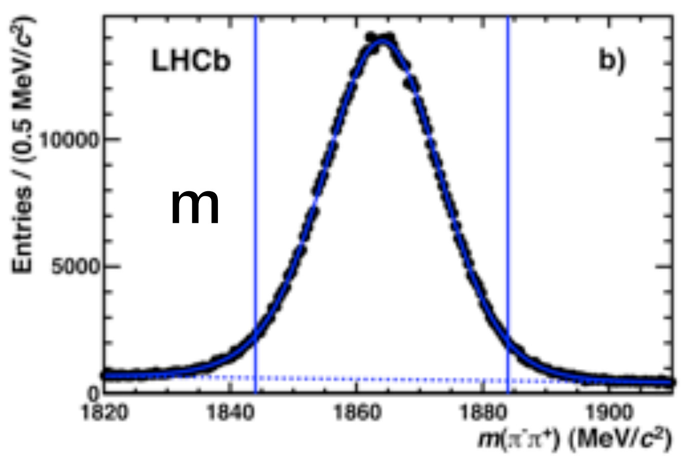
Phys. Rev. Lett. 108 (2012) 111602

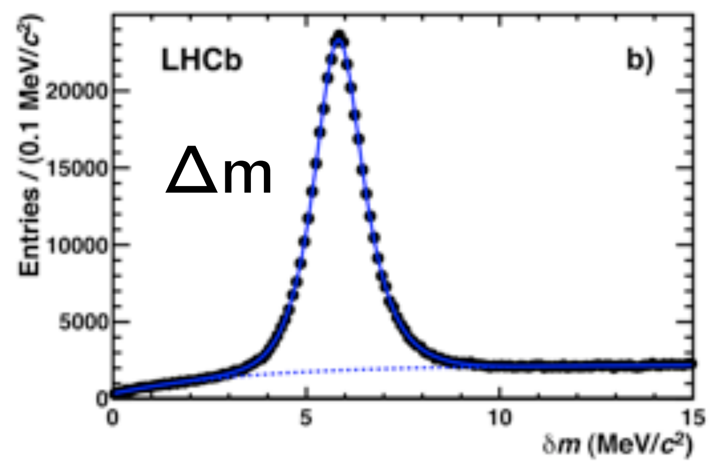
ΔAcp





K^-K^+ Yield: $(1436 \pm 2) \times 10^3$





$\pi^-\pi^+$ Yield: $(381 \pm 1) \times 10^3$

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

First evidence of CP violation in charm with significance 3.5σ

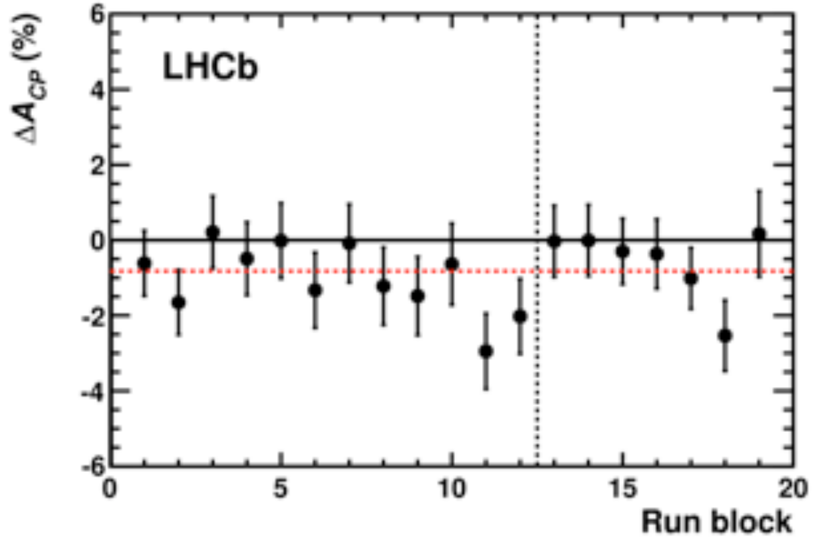
Carried out on $0.6 fb^{-1}$

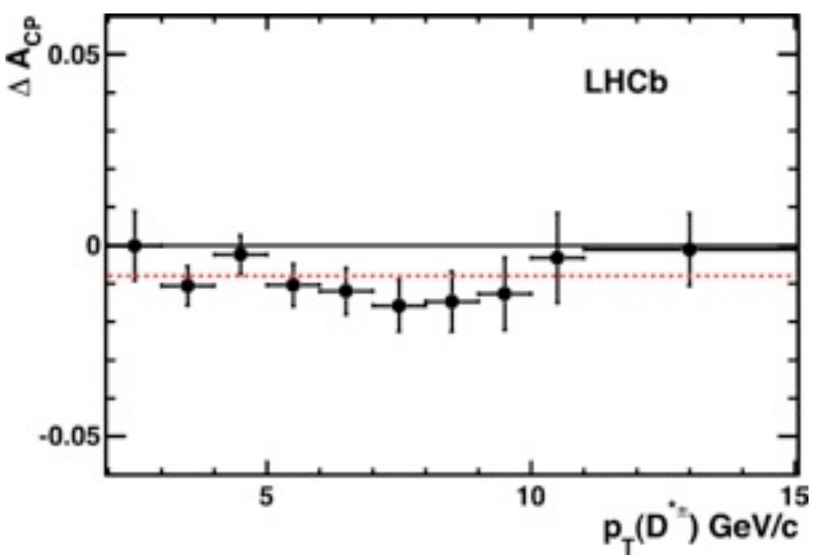
Phys. Rev. Lett. 108 (2012) 111602

Cross-checks

Many cross-checks performed, e.g:

- Stability of result vs data taking runs
- Stability vs D* Pt
- Stability vs D* ETA
- Consistency between subsamples (field up/ field down, etc)





Phys. Rev. Lett. 108 (2012) 111602

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Search for CPV in the charm at LHCb

Charm physics at LHCb

D0 mixing

y_{CP} and A_Γ

Direct CPV

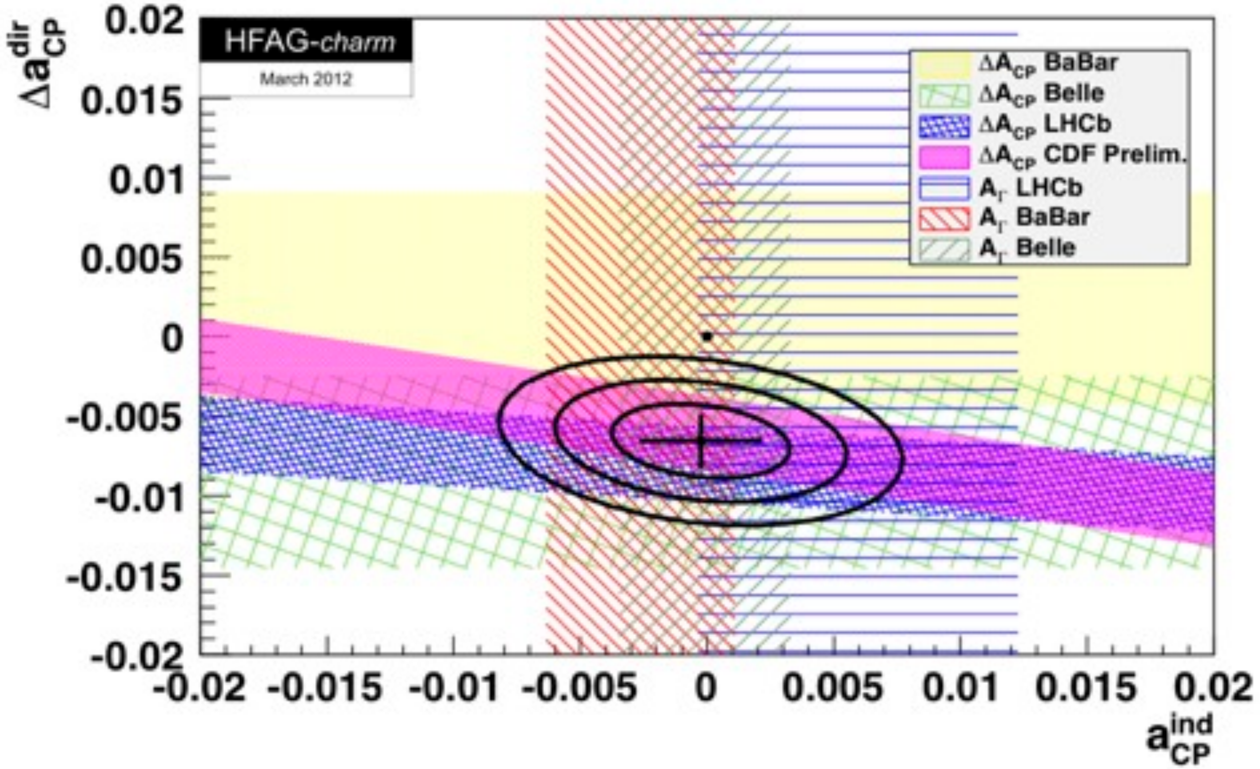
ΔAcp

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

Outlook

ΔAcp Result

World average



Includes CDF result $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$

arXiv:1202.2866v2

Many Interpretations. See:

Isidori, Kamenik, Ligeti, Perez (**arXiv:1111.4987**)
Brod, Kagan, Zupan (**arXiv:1111.5000**)
Cheng, Chaing (**arXiv:1201.0785**)
Pirtskhalava, Uttayarat (**arXiv:1112.5451**)
Bhattacharya, Gronau, Rosner (**arXiv:1201.2351**)
Feldmann, Nandi, Soni (**arXiv:1202.3795**)

Search for CP violation in $D^+ \to K^- K^+ \pi^+$ decays

Phys. Rev. D 84 (2011) 112008

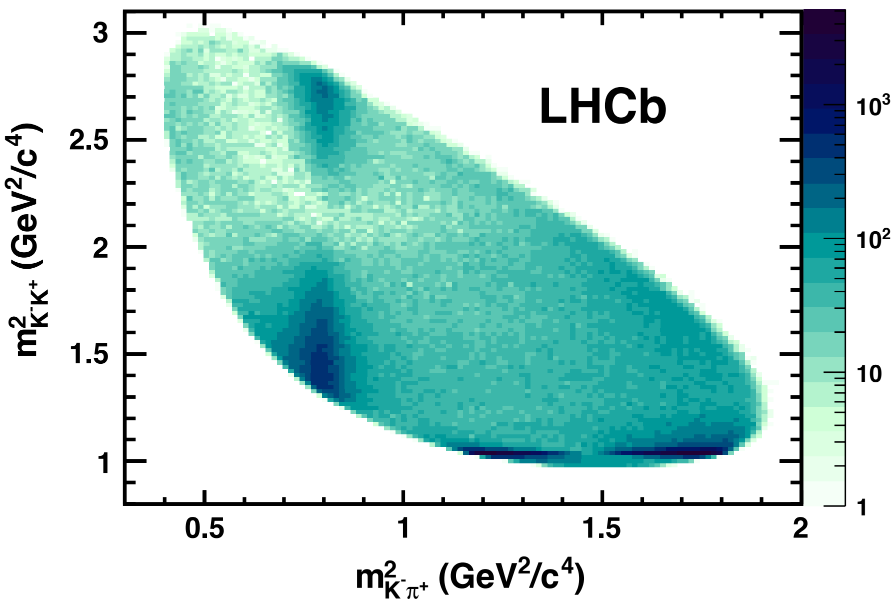
Model-independent searches for CPV in multi-body decays

Search for direct CP violation in three-body decays

Look for CPV in **SCS** decay $D^+ \to K^+ K^- \pi^+$

Search for **local asymmetries** across Dalitz space

Model independent method based on binning Dalitz plot and comparing corresponding bins



Phys. Rev. D 84 (2011) 112008

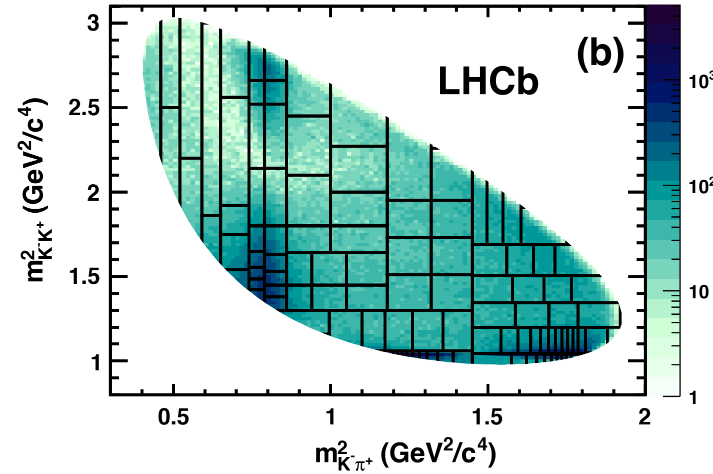
Model-independent searches for CPV in multi-body decays

Bin Dalitz space and compare bins between D⁻ and D⁺ Dalitz space

Based on the Miranda method

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

$$S_{CP} = \frac{N_i - \alpha \bar{N}_i}{\sqrt{N_i + \alpha^2 \bar{N}_i}} \qquad \alpha = \frac{N_{\text{total}}}{\bar{N}_{\text{total}}}$$

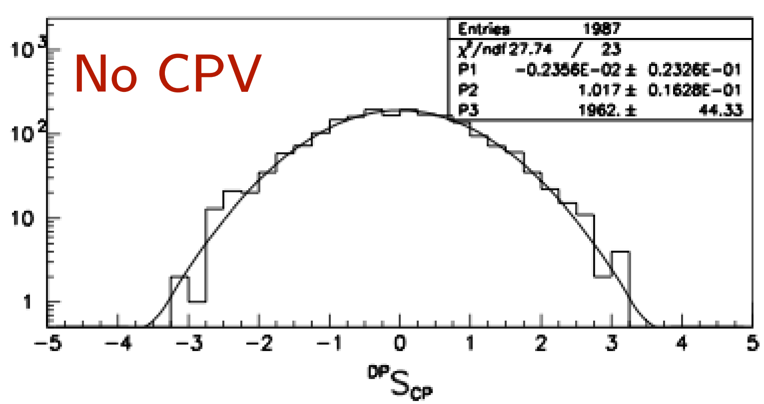


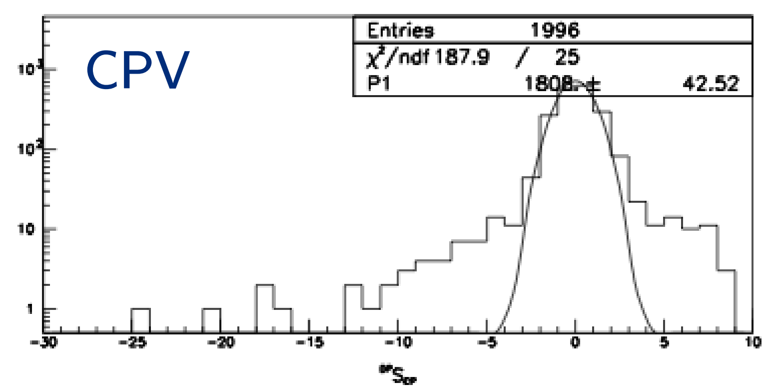
Phys. Rev. D 84 (2011) 112008

α normalise away overall asymmetry, but also removes **production and detection effects**

Plotting for all bins: if NO CPV Gaussian with μ = 0; σ = 1

Calculate $\chi^2 = \sum (S^i_{CP})^2$ and p-values under assumption of no CPV





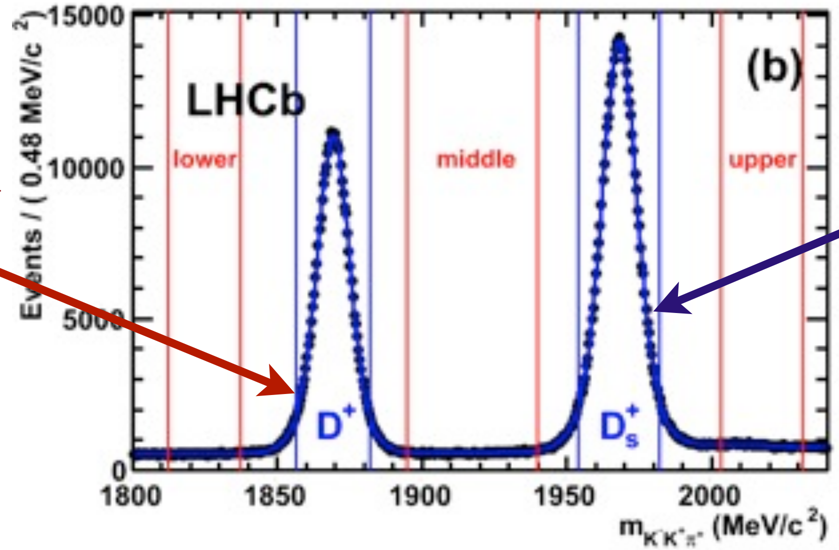
Simulation by Bediaga et al, Phys.Rev.D80:096006,2009

Model-independent searches for CPV in multi-body decays

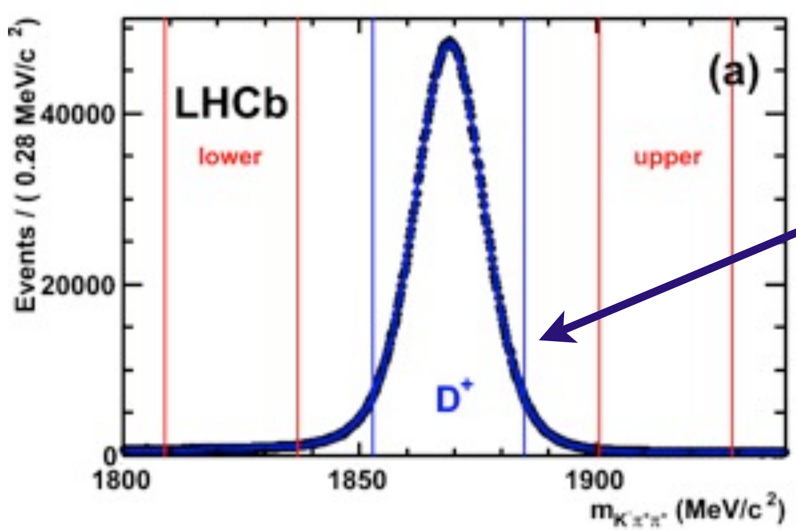
Use **CF** where **NO CPV** expected to check for detector asymmetries

Yields for $35 pb^{-1}$

SCS 0.33M
$D^+ \to K^+ K^- \pi^+$



CF
0.46M
$D_s^+ \to K^+ K^- \pi^+$



CF
3.38M
$D^+ \to K^+ \pi^- \pi^+$

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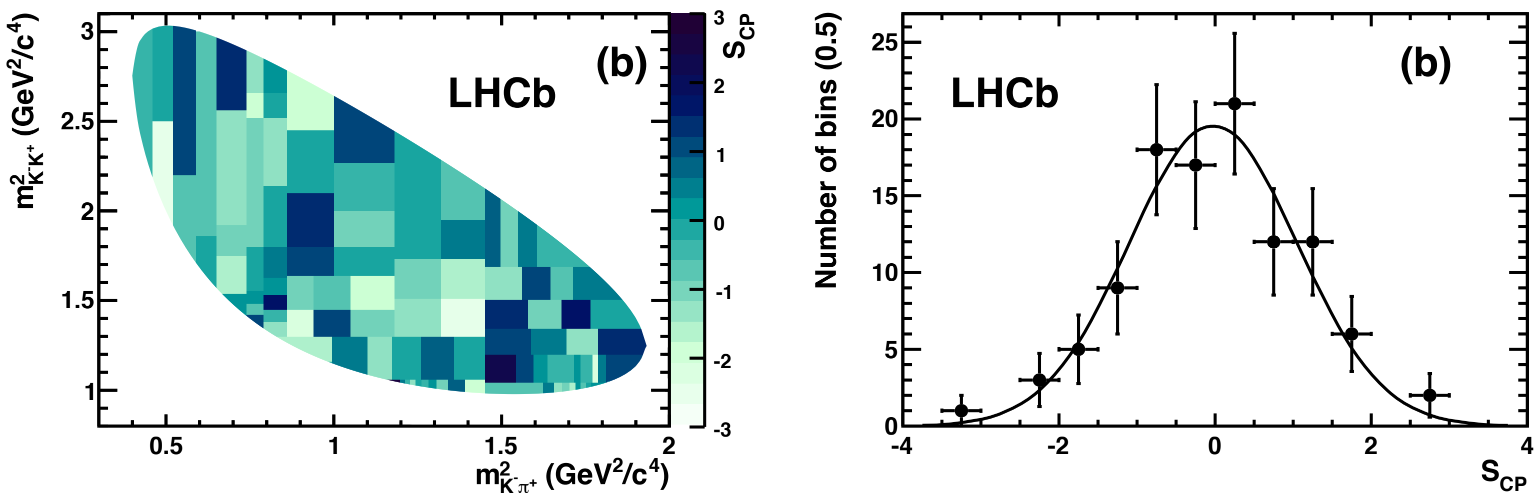
Model-independent searches for CPV in multi-body decays



Several binnings used

All consistent with no CPV. Binning shown agrees with hypothesis of **no CPV with a p-value of 10.6%**

Phys. Rev. D 84 (2011) 112008

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Outlook

- **First evidence of CPV in charm** sector observed
  - **Exciting result**
  - Open to discussion and interpretation
  - **Huge amounts of data available at LHCb** will help us understand CPV in charm
  - **More precision measurements being carried** out to help understand this result
- **Lots more for LHCb to contribute** to charm physics:
  - **Forthcoming analysis with 1fb^{-1}** from 2011 running
  - **Charm sample more than double with 2012 data**
- 2012 is going to be **golden year for charm physics** at LHCb

Fin

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Search for CPV in the charm at LHCb

Charm physics at LHCb

D0 mixing

y_{CP} and A_Γ

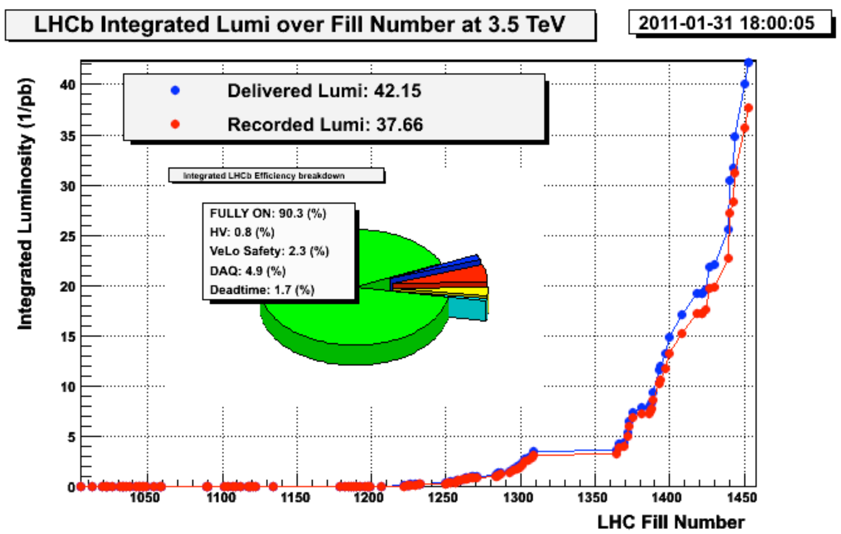
Direct CPV

ΔAcp

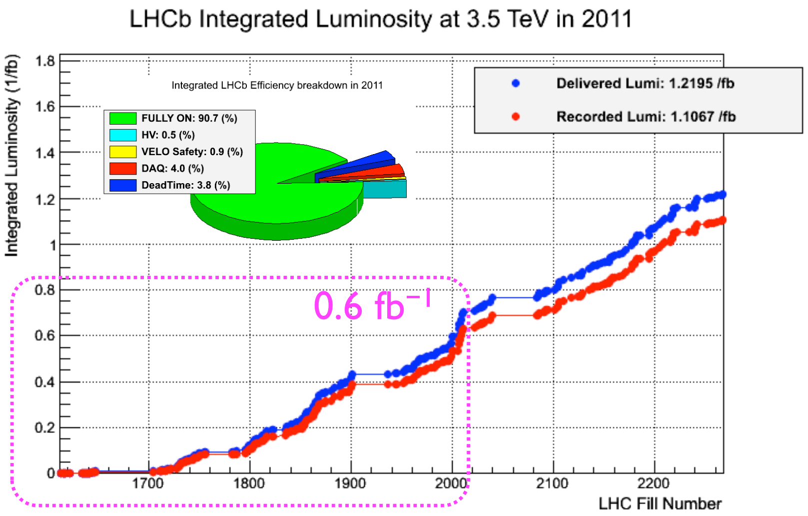
$D^+ \to K^- K^+ \pi^+$

Outlook

Data taking at LHCb



2010: 38 pb^{-1}

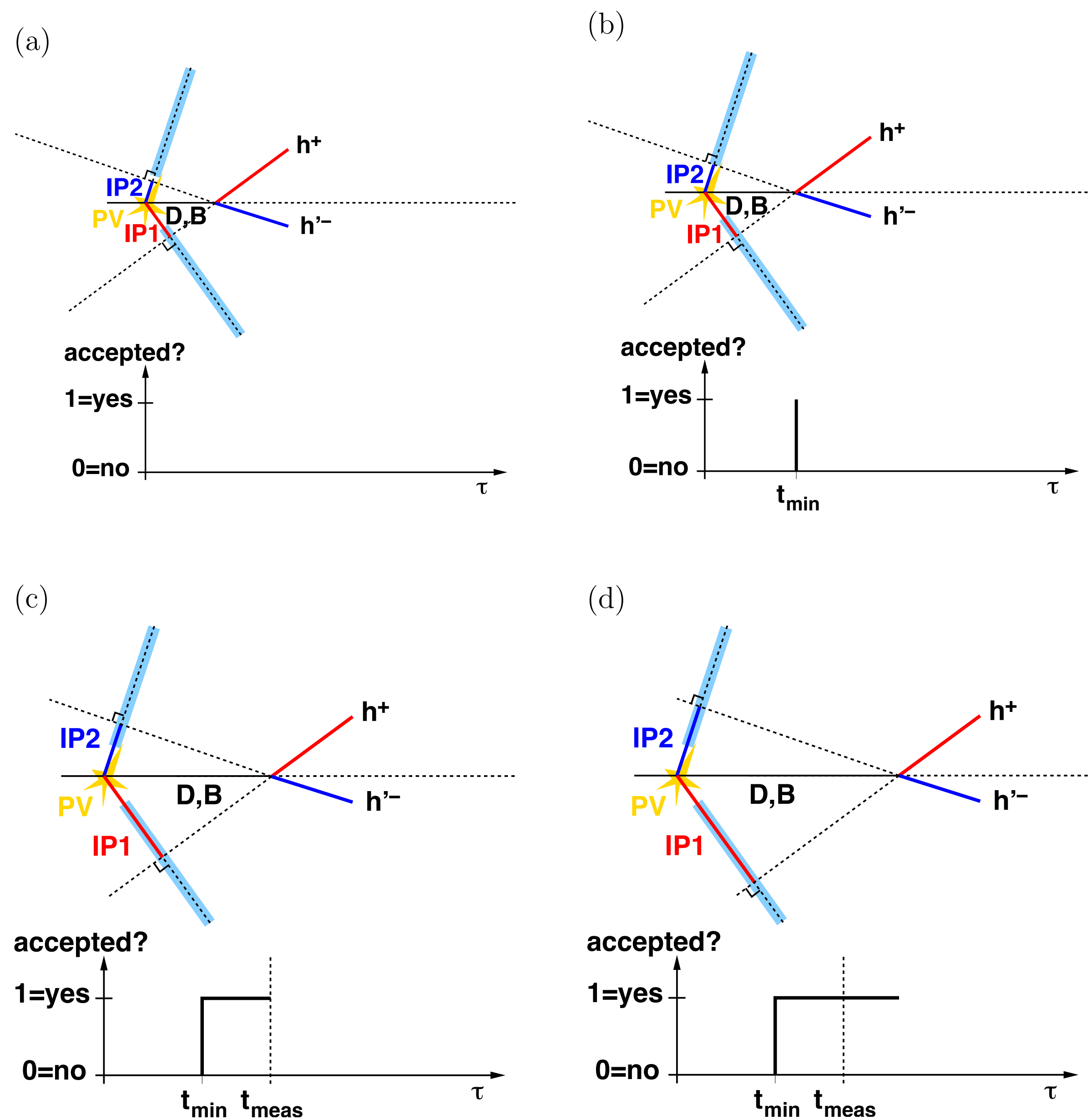


2011: 1 fb^{-1}

Lifetime dependence measurements of charm

Want to measure how acceptance varies with lifetime for each candidate

By shifting PV for each candidate we evaluate the trigger decision for each possible lifetime of each decay



y_{CP} and A_Γ at LHCb

Improving systematics for 2011

- Dominant uncertainties from the background
  - Statistical component in secondary charm uncertainty will improve with more data from 2011
  - Easier to control background in 2011 data with improved triggers.

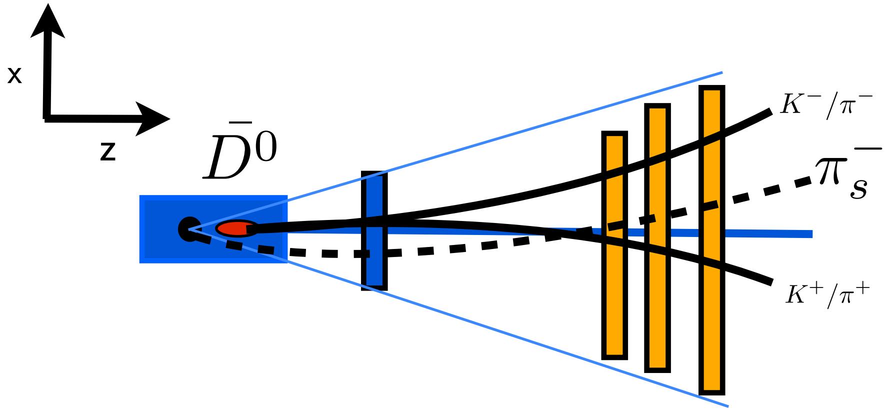
Table 1: Summary of systematic uncertainties.

Effect	y_{CP} (10^{-3})
VELO length scale	negligible
Turning point bias	± 0.1
Turning point scaling	± 0.1
Combinatorial background	± 0.8
Proper-time resolution	± 0.1
Minimum proper-time cut	± 0.8
Maximum proper-time cut	± 0.2
Secondary charm background	± 3.9
Total	± 4.1

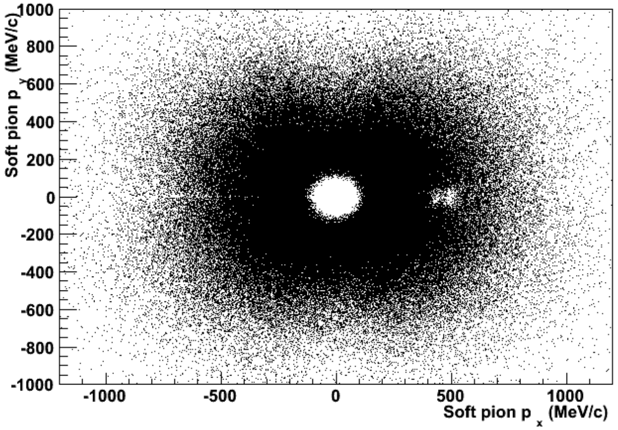
ΔAcp RAW asymmetries

Beam pipe shadow from slow pion

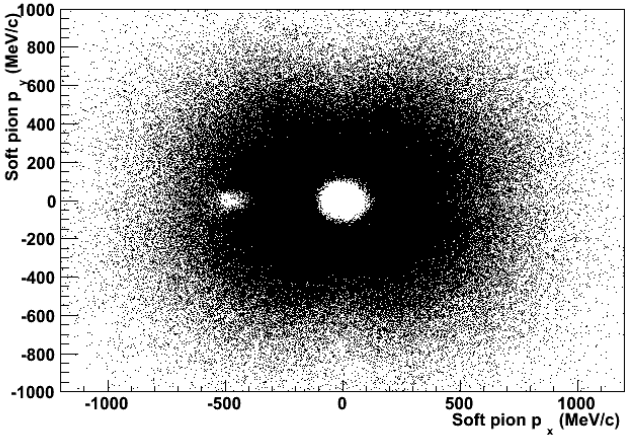
Area removed with fiducial cuts



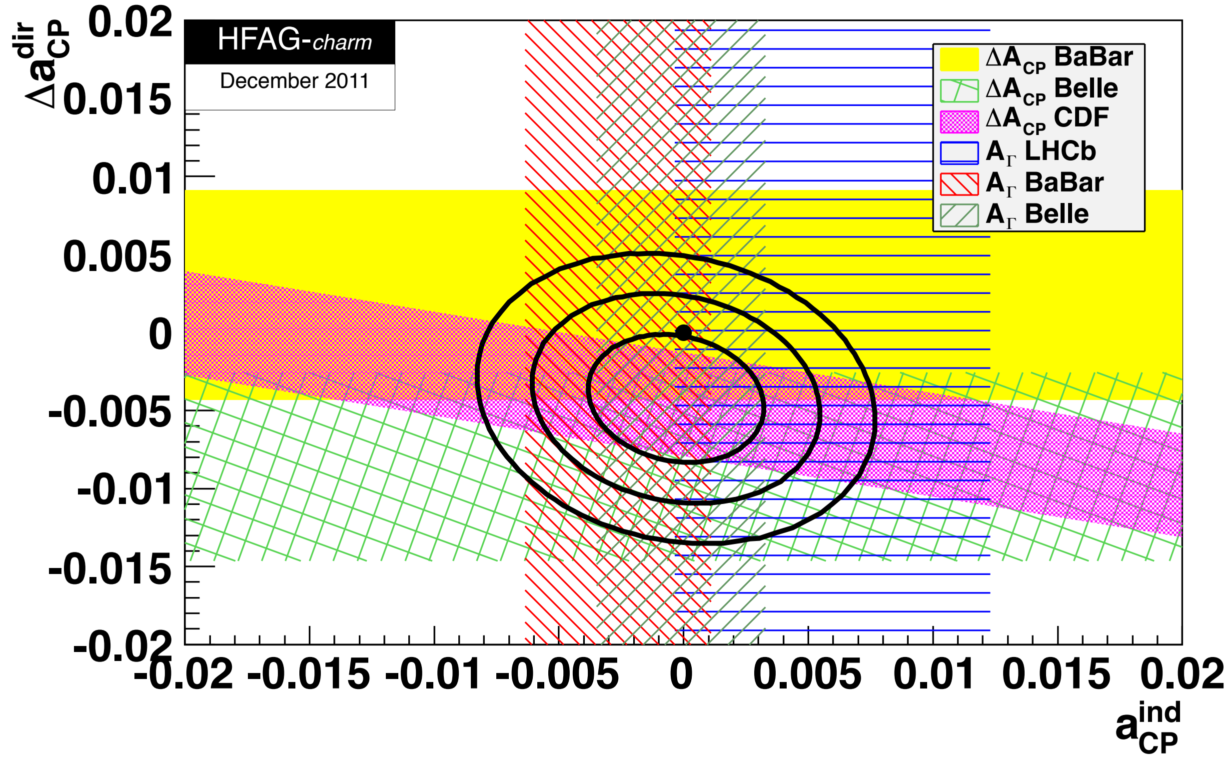
magnetic field up polarity



magnetic field down polarity

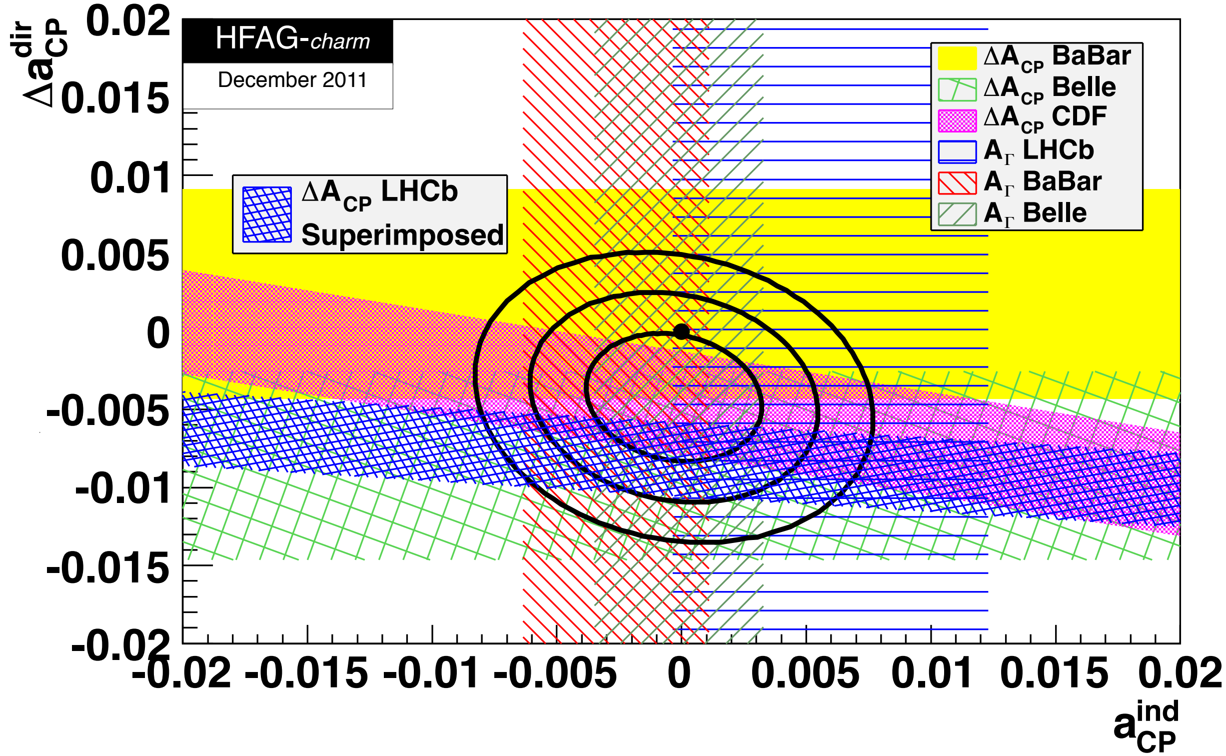


ΔAcp Result



Before this measurement

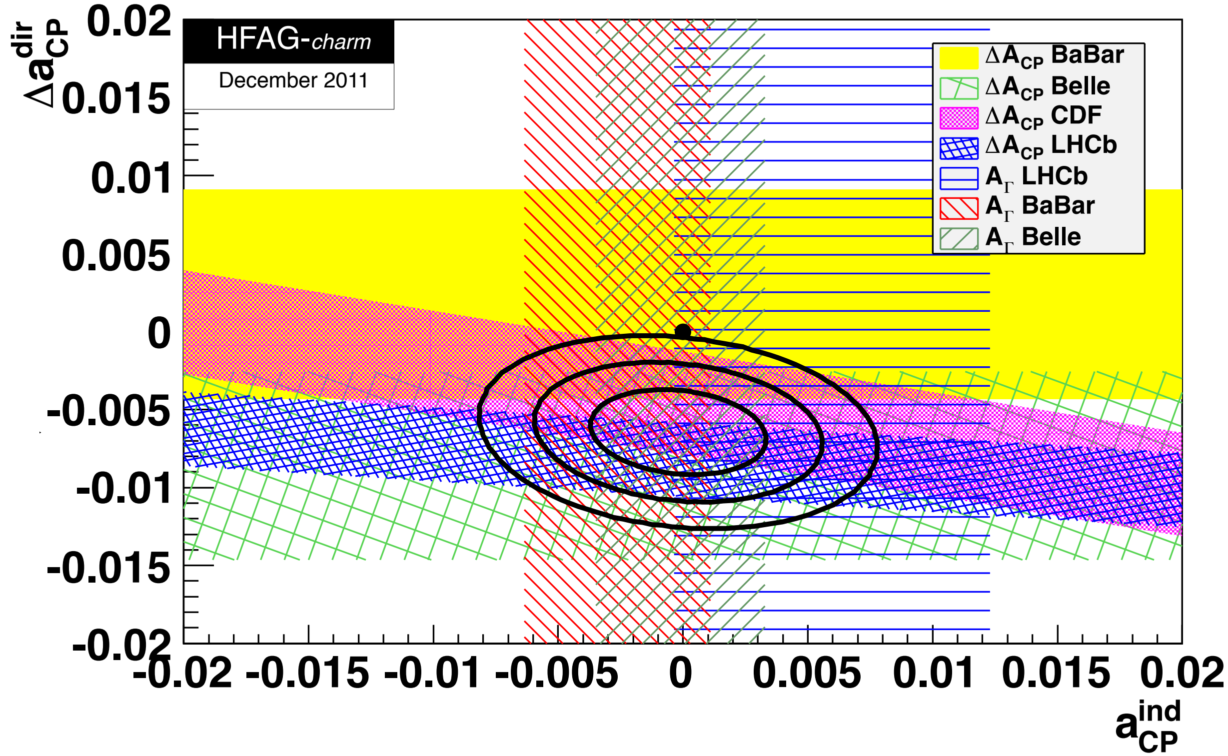
ΔAcp Result



Before this measurement

Superimposing the LHCb result

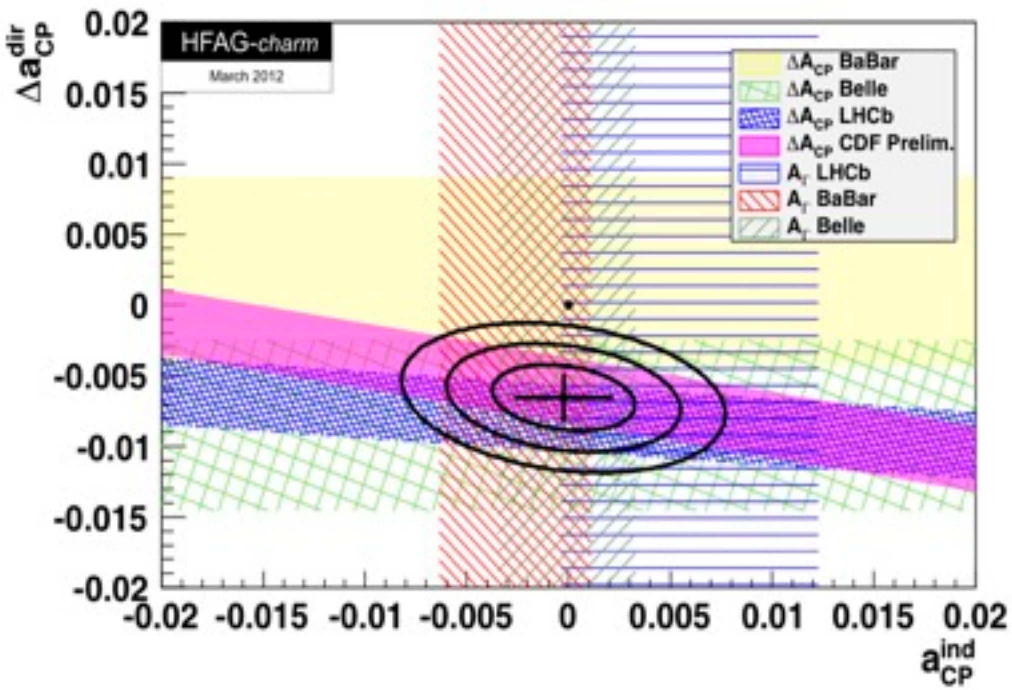
ΔAcp Result



Average including LHCb's result

Result

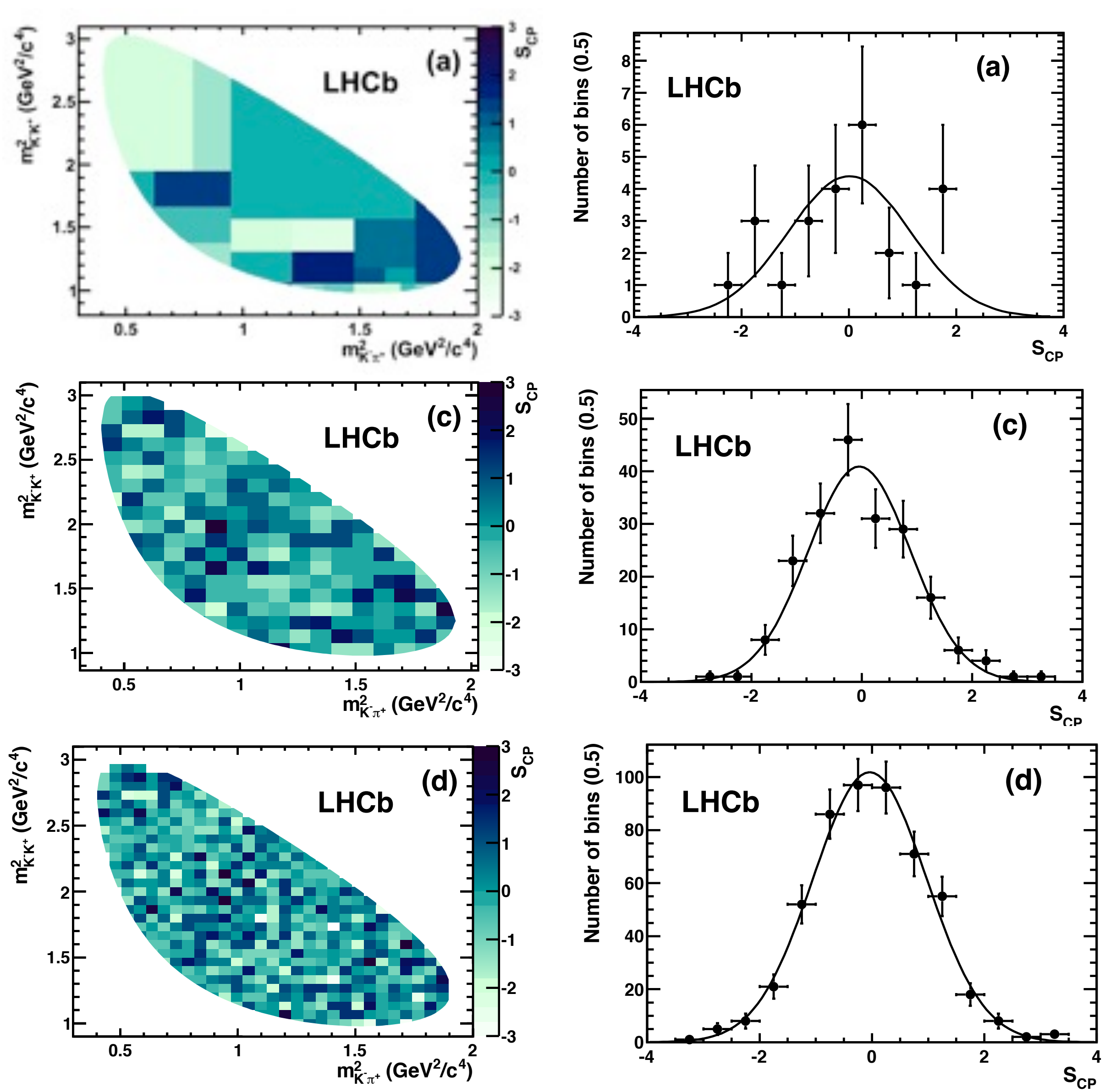
- A_{CP} from direct CPV and indirect CPV
- Slanted constraints from different lifetime acceptances for KK and ππ
- Consistency with no CPV hypothesis: 6×10^{-5}



LHCB-PAPER-2011-032 ;arXiv:1112.4698 (submitted to JHEP)

Model-independent searches for CPV in multi-body decays

Additional binnings



p-value
12.7%
82.1%
60.5%

Phys. Rev. D 84 (2011) 112008

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Search for CPV in the charm at LHCb