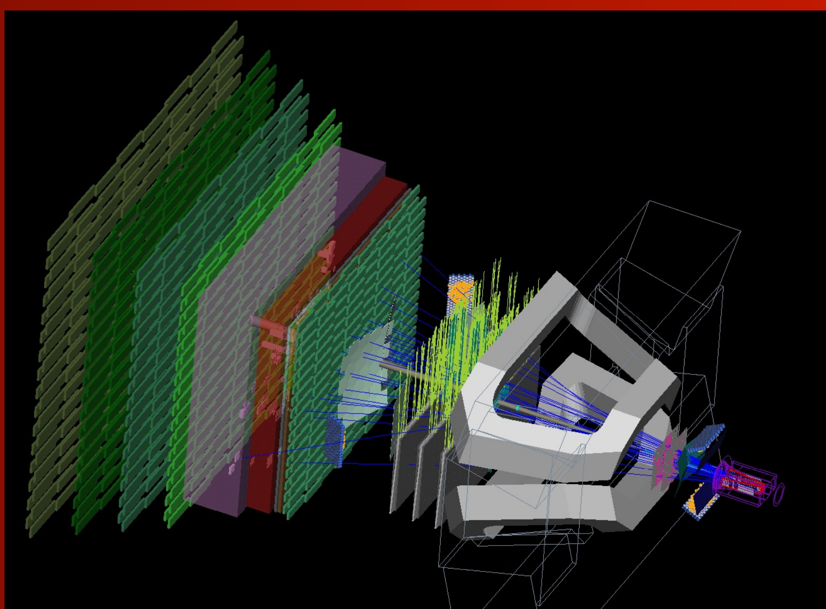
Charm Mixing and CP Violation at LHCb

Paras Naik

University of BRISTOL

on behalf of the LHCb collaboration



Charm at LHC*b*?

- We are, above all, a B physics experiment...
  - However, the same properties that optimize LHCb for B physics also make it **an excellent charm physics experiment**.

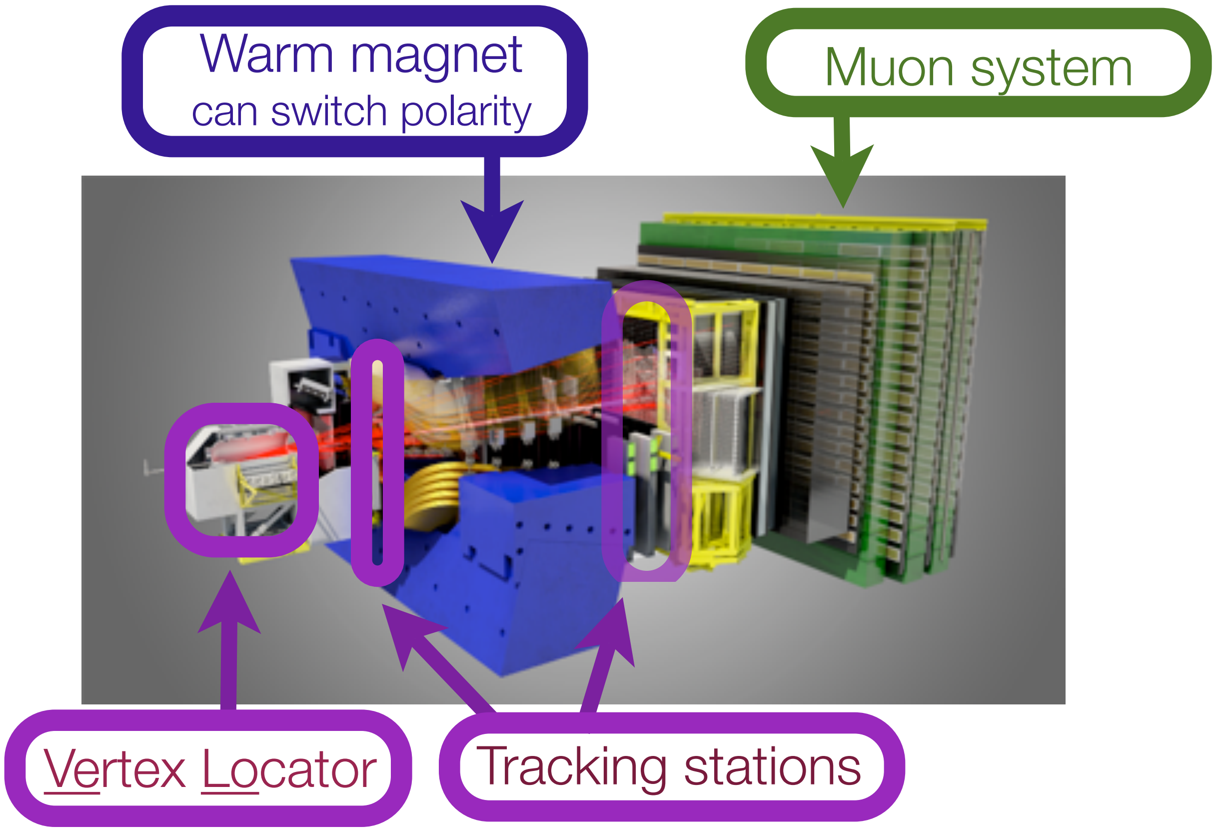
- We have immense charm samples...
- The charm cross section is ~20 times larger than the b cross section.
  - **$\sigma(c\bar{c})_{LHCb}$ = 1419 ± 133 μb (Nucl. Phys. B 871 (2013), 1)**
  - **$\sigma(b\bar{b})_{LHCb}$ = 75.3 ± 14.1 μb (Phys. Lett. B 694 (2010), 209)**

  @ $\sqrt{s}$ = 7 TeV
- In 2011 roughly a trillion $c\bar{c}$ were produced!

- LHCb can make precision measurements in charm with high sensitivity to New Physics...
  - The only **mixing** meson with up-type quarks.
  - The big prize: **CP violation** (**CPV**) in charm.

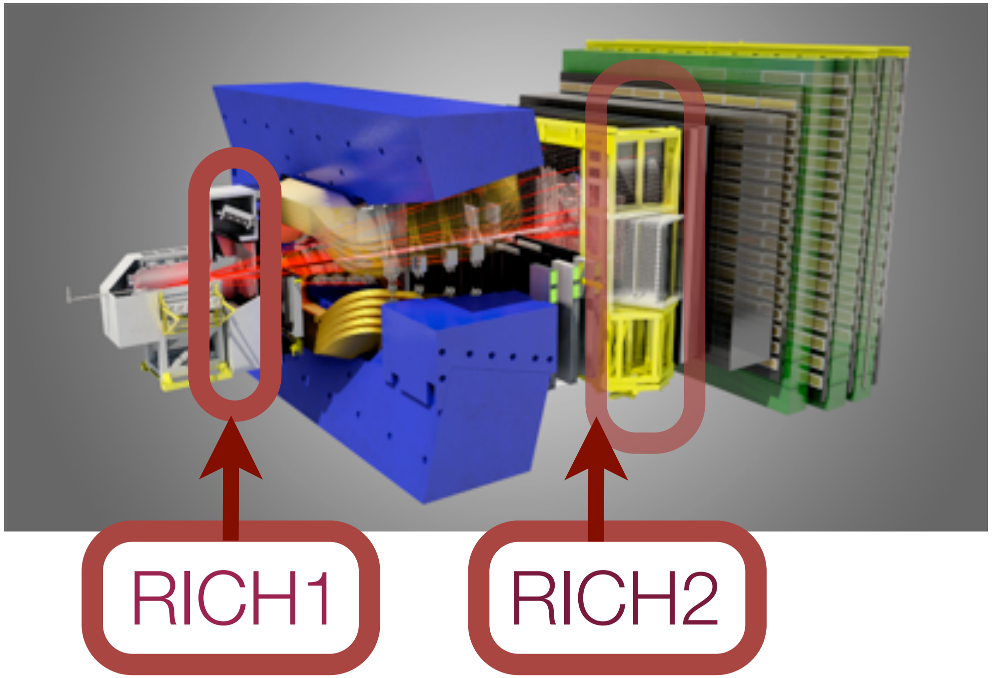
LHCb Experiment: Tracking

- Accurate decay time resolution from our vertex locator (VELO)
- High muon reconstruction efficiency from muon stations
- Good momentum resolution from tracking stations, Δp/p = 0.35% — 0.55%



LHCb Experiment: Charged kaon/pion separation

- K/π separation provided by Ring Imaging Cherenkov (**RICH**) detectors

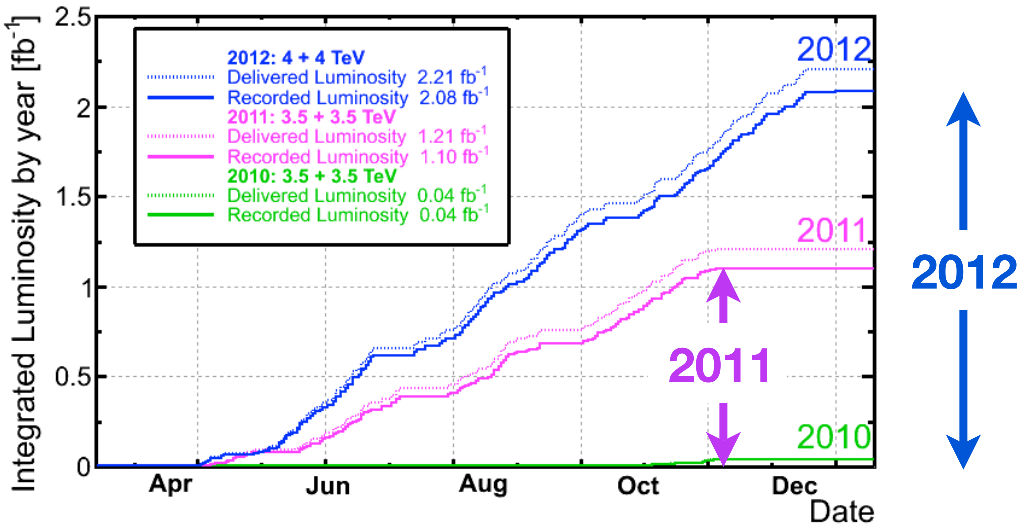


- The ability to identify particles at LHCb is critical to many of our analyses.

Charm Trigger and LHCb recorded luminosty

- We have an excellent **Trigger** for charm decays
- Charm trigger uses 33% (2011) - 40% (2012) of our trigger bandwidth
- Ability to trigger on tracks with lower p_T

- **1.0 fb^{-1} at 7 TeV** collected by LHCb in **2011**
  - **Today's Analyses**
- 2 fb^{-1} at 8 TeV collected by LHCb in 2012 (future analyses)
- Instantaneous luminosity delivered to LHCb fixed at $\mathscr{L} = 4 \times 10^{32}\ cm^{-2}s^{-1}$



Knowledge of the Neutral Charm System in 2012

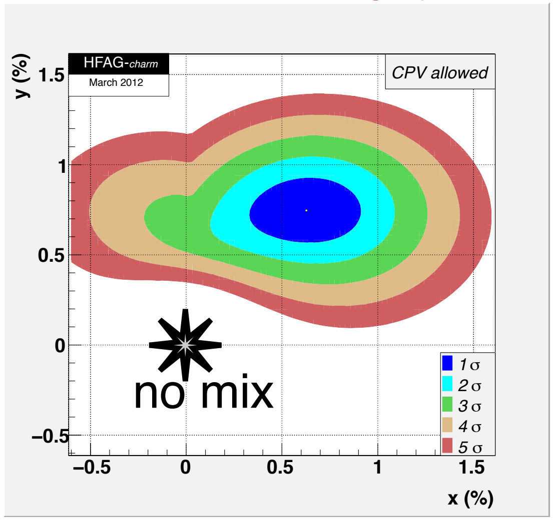
- Neutral D mass eigenstates: $D_{1,2} = p|D\rangle \pm q|\bar{D}\rangle$

  $\phi = \arg(q/p)$

  - $x = \dfrac{m_2 - m_1}{\Gamma}$ ~mixing frequency
  - $y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$ ~lifetime difference

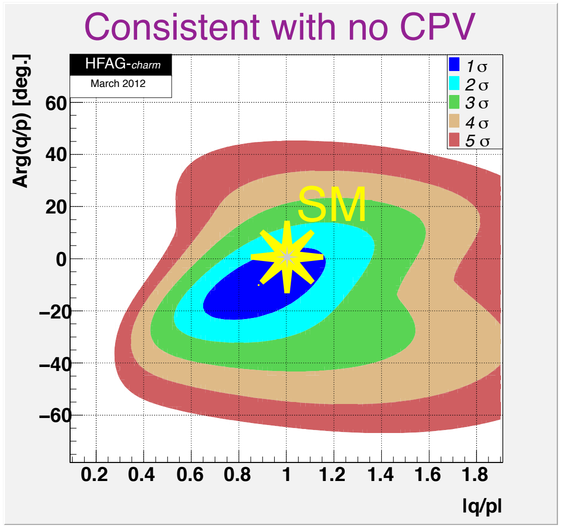
(Belle), PRL 96, 151801 (2006).
(BaBar), PRL 98, 211802 (2007).
(CDF), PRL 100, 121802 (2008).
and others

Inconsistent w/no-mixing hypothesis



- CP-violation (CPV) if $|q/p| \neq 1$ or CPV phase $\phi \neq 0$
- Standard Model (SM): x, y at most 10^{-2}, small CPV
- $x = (0.63 \pm 0.20)\%$, $y = (0.75 \pm 0.12)\%$
- $|q/p| = 0.88 \pm 0.18$, $\phi = -10.1° \pm 9.5°$

Consistent with no CPV



Averages by HFAG (March 2012)
The errors on x, |p/q|, and φ are asymmetric, I show the larger error.

Charm Mixing via $D \rightarrow K\pi$ decays

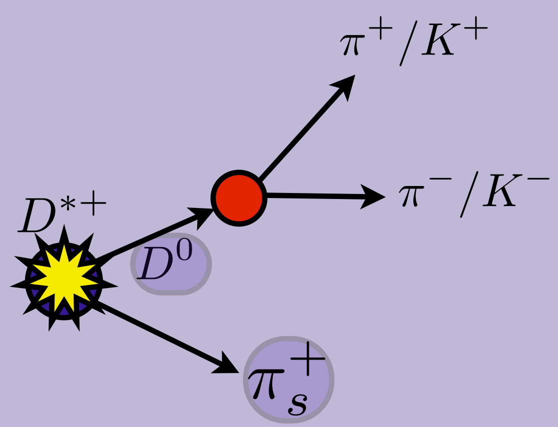
Flavor Tagging

We can use neutral D mesons from D* decays to tag flavor of the D

D* decays (Prompt)

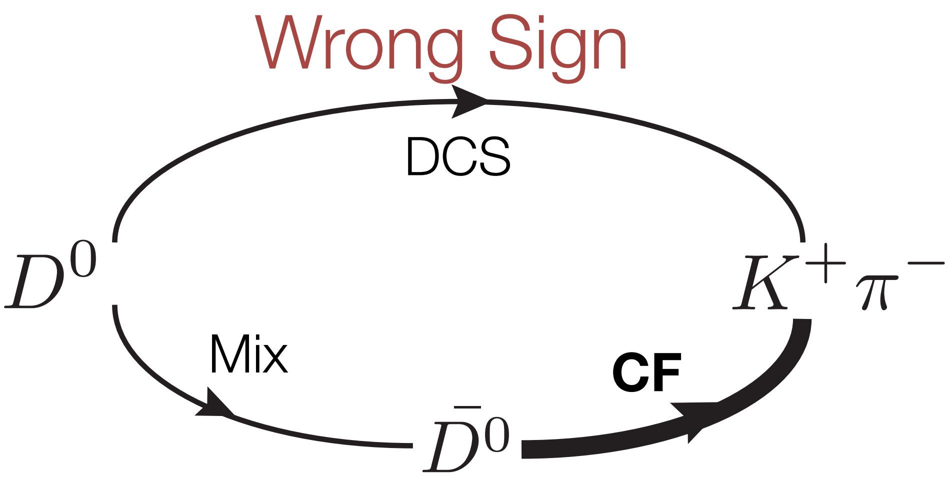
Use slow pion from D* decays to tag D flavor: $D^{*+} \to D^0 \pi_s^+$ or

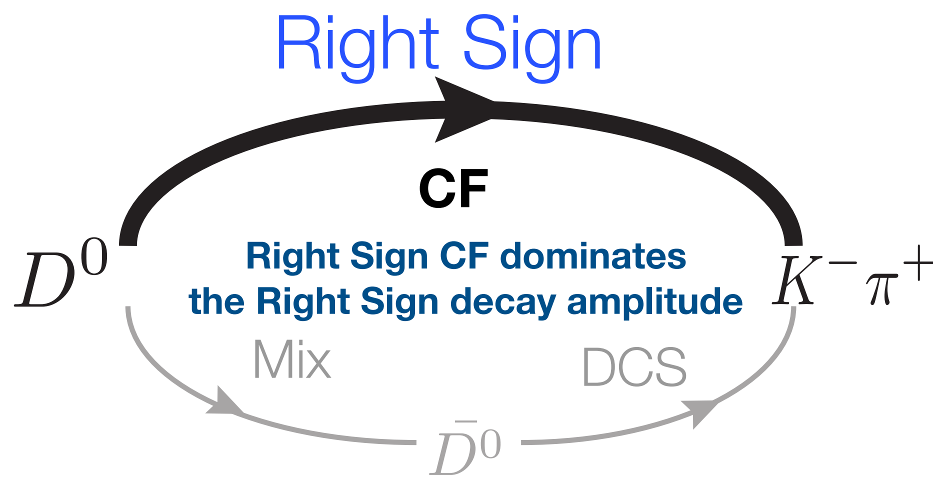
$D^{*-} \to \bar{D}^0 \pi_s^-$

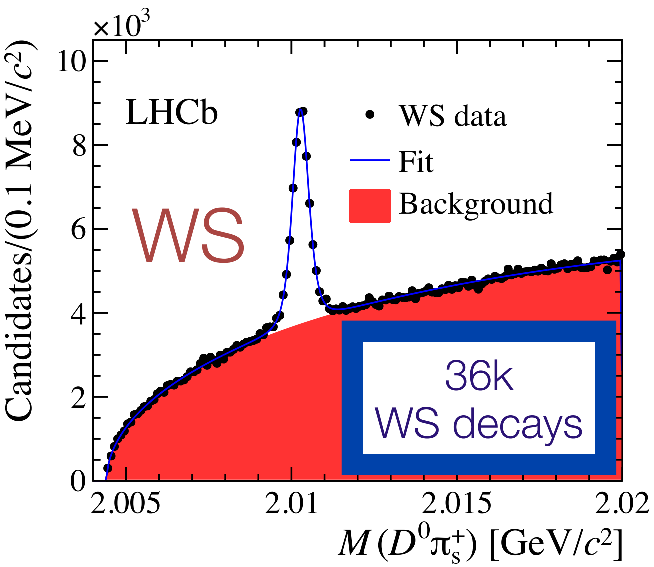


D^0 mixing at LHCb

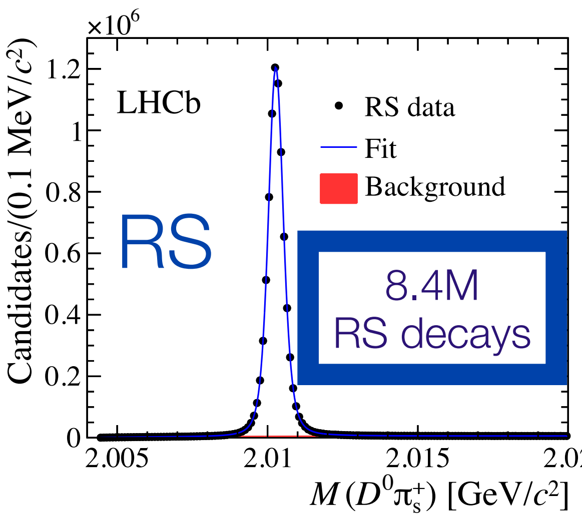
PRL 110, 101802 (2013)
1.0fb^{-1} collected during 2011







- Use D^* decays to tag the initial flavor of the D.
- 36k WS decays
  - More signal than found in the three most sensitive experiments to date.
- 8.4M RS decays
- Divide into 13 D^0 decay time bins



D^0 mixing at LHCb

PRL 110, 101802 (2013)
$1.0\,fb^{-1}$ collected during 2011

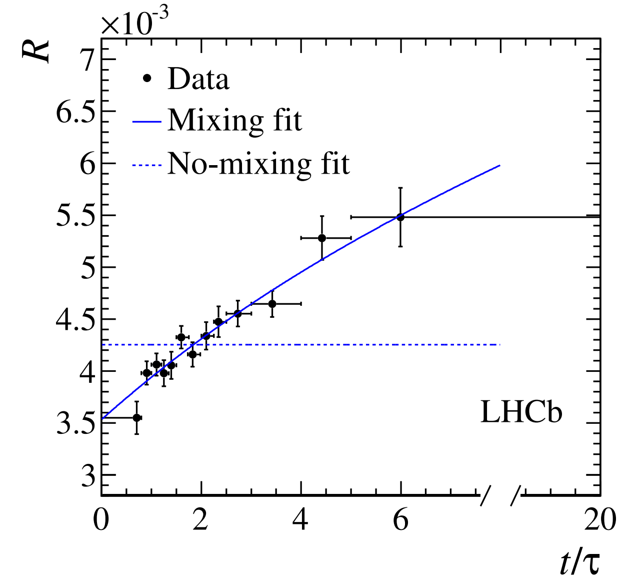
- Take the time-dependent ratio of wrong sign to right sign decays

for no CPV

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} \simeq R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$

$$x' = x\cos(\delta) + y\sin(\delta)$$
$$y' = y\cos(\delta) - x\sin(\delta)$$

strong phase

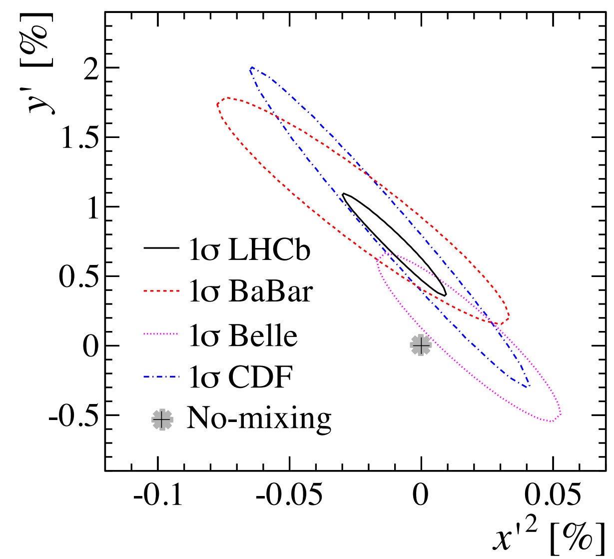


- Most systematics cancel in ratio

$x'^2 = (-0.09 \pm 0.13)\times 10^{-3}$
$y' = (7.2 \pm 2.4)\times 10^{-3}$

no mixing hypothesis excluded at **9.1σ**

- First single measurement with over 5σ significance



Search for direct CPV in charm

Search for direct CPV in Charm

Time-integrated CP asymmetry defined as:

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

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

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

Phys.Rev. D75 (2007) 036008

Analysis techniques

- Magnetic field frequently flipped.
  - Using both 'magnet up' and 'magnet down' data cancels many asymmetries
- Kinematic areas with large detection asymmetries can be removed

A_{CP} from D^* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

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

measure | **want** | f's detection asymmetry | π_s detection asymmetry | Production asymmetry

A_{CP} from D* decays

LHCB-CONF-2013-003
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$$A_{RAW}(f) \simeq A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_p(D^{*+})$$

measure	want	f's detection asymmetry	π_s detection asymmetry	Production asymmetry

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

If the effect of $A_D(f) - A_D(f')$ is negligible:

$$A_{RAW}(f) - A_{RAW}(f') \simeq A_{CP}(f) - A_{CP}(f')$$

Charged D decay modes

CPV in $D^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow K_S^0\pi^+$

arXiv:1303.4906
$1.0\,\mathrm{fb}^{-1}$ collected during 2011

- Define A_{CP} for $D^+ \rightarrow \phi\pi^+$

$$A_{CP}(D^+ \to \phi\pi^+) = A_{\mathrm{raw}}(D^+ \to \phi\pi^+) - A_{\mathrm{raw}}(D^+ \to K^0_{\mathrm{S}}\pi^+) + A_{CP}(K^0/\overline{K}^0)$$

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$$A_{\text{raw}} = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}$$

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Control channel where charm CPV is negligible

Removes* **detection/production** asymmetries

* The effect of the final state asymmetry difference between KKπ and πππ final states is small, accounted for in our systematics.

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Control channel where charm CPV is negligible

Correction due to CPV in neutral Kaon system

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CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

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$1.0 fb^{-1}$ collected during 2011

- Define A_{CP} for $D^+ \to \phi\pi^+$

$$A_{CP}(D^+ \to \phi\pi^+) = A_{\text{raw}}(D^+ \to \phi\pi^+) - A_{\text{raw}}(D^+ \to K^0_S\pi^+) + A_{CP}(K^0/\overline{K}^0)$$

$$A_{\text{raw}} = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}$$

Control channel where charm CPV is negligible

Correction due to CPV in neutral Kaon system

- Also for $D_s^+ \to K_S^0\pi^+$

$$A_{CP}(D_s^+ \to K^0_S\pi^+) = A_{\text{raw}}(D_s^+ \to K^0_S\pi^+) + A_{CP}(K^0/\overline{K}^0) - A_{\text{raw}}(D_s^+ \to \phi\pi^+)$$

CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

arXiv:1303.4906
1.0fb^{-1} collected during 2011

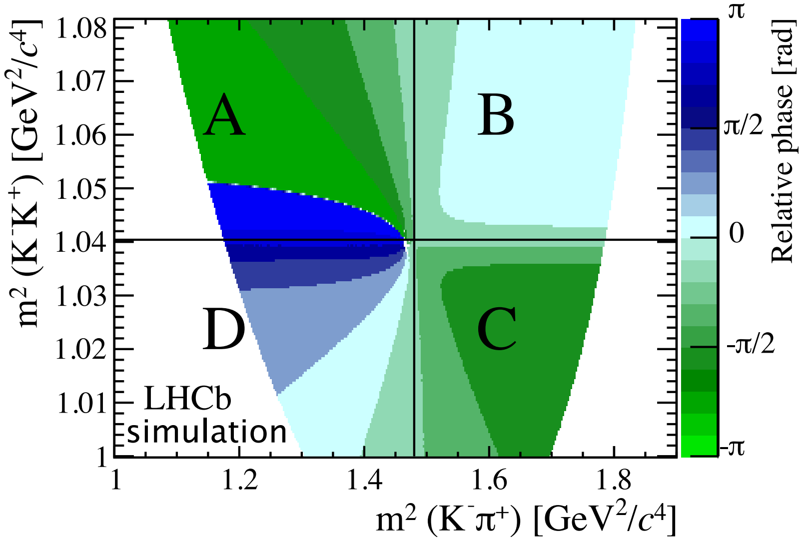
- Variation in phase across the ϕ resonance could mean that CPV asymmetries might be canceled out.
- We can improve sensitivity to CPV by splitting up the decay phase space into regions of similar phase.
- Define a third variable

$$A_{CP}|_S = \frac{1}{2}\left(A^A_{\text{raw}} + A^C_{\text{raw}} - A^B_{\text{raw}} - A^D_{\text{raw}}\right)$$

which is also sensitive to CP.

- We found that some types of CPV can be observed more effectively with A_{CP} and others with $A_{CP}|_S$

LHCb simulation



used CLEO to model phase change across ϕ resonance

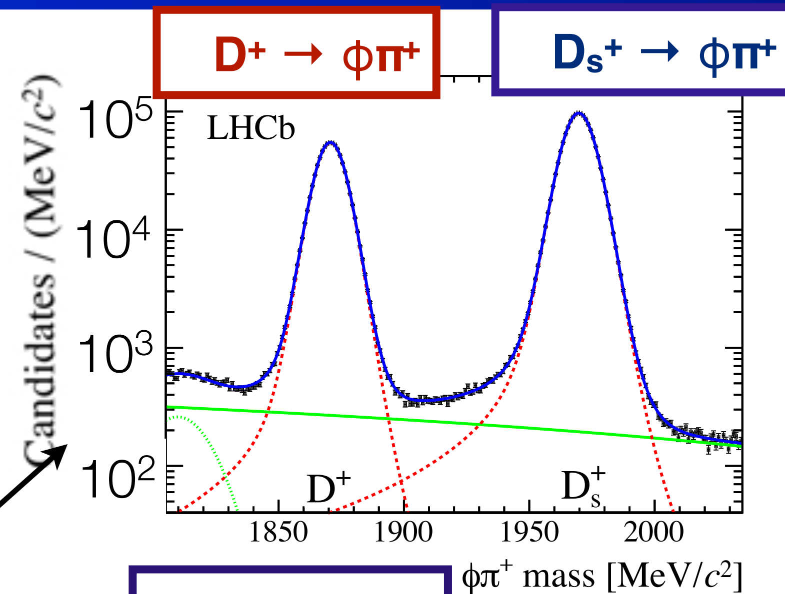
Phys. Rev. D78 (2008) 072003

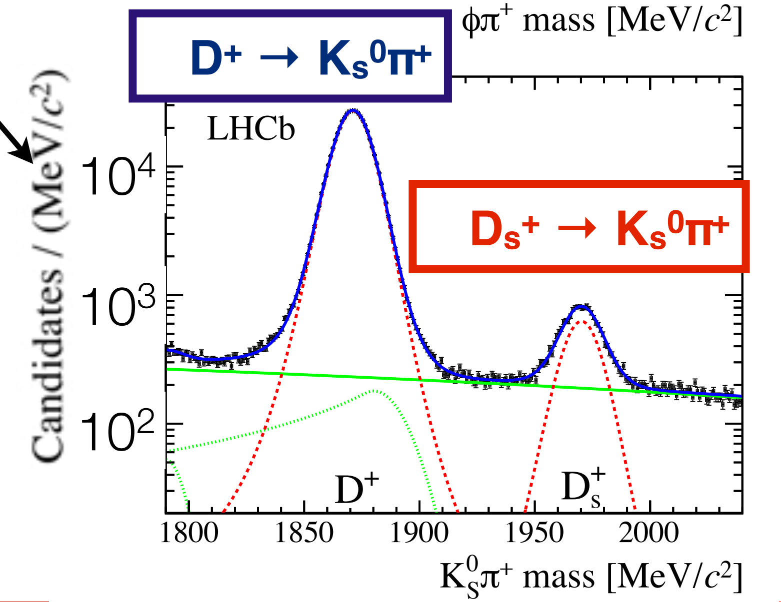
CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

arXiv:1303.4906
1.0fb^{-1} collected during 2011

- **Very low background levels**
  - **1.6M $D^+ \to \phi\pi^+$**
  - **3.6M $D^+ \to K_S^0\pi^+$**
  - **26k $D_s^+ \to K_S^0\pi^+$**
  - **1.1M $D_s^+ \to \phi\pi^+$**

Log Scale





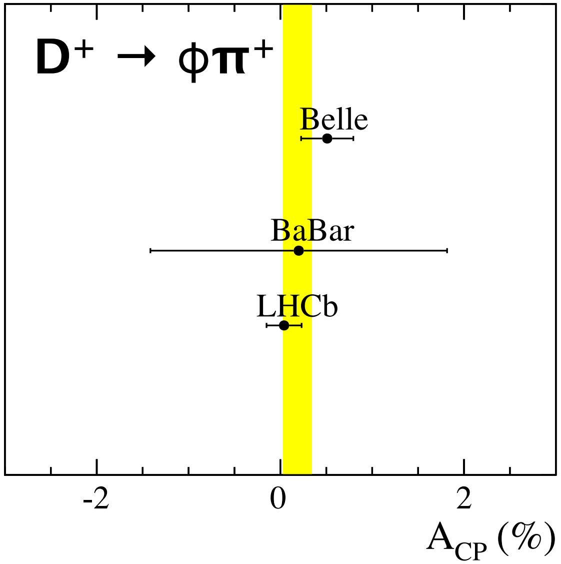
CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

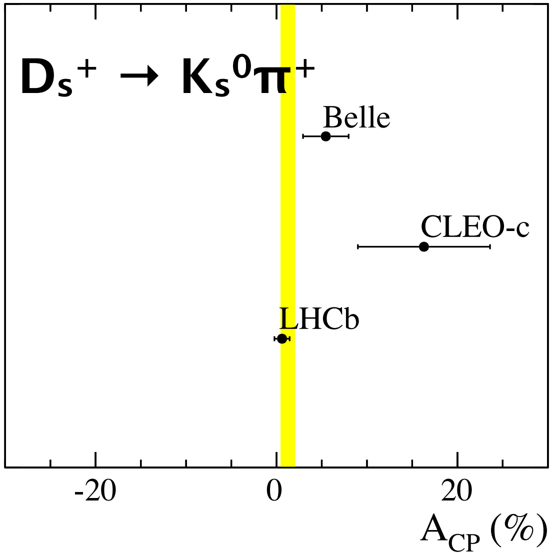
arXiv:1303.4906
1.0fb^{-1} collected during 2011

- **No evidence of CPV observed**

$$A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%,$$
$$A_{CP}|_S = (-0.18 \pm 0.17 \pm 0.18)\%,$$
$$A_{CP}(D_s^+ \to K_S^0\pi^+) = (0.61 \pm 0.83 \pm 0.13)\%,$$

- **Most precise measurement to date for both $D_s^+ \to K_S^0\pi^+$ and $D^+ \to \phi\pi^+$**





Previous measurements $D^+ \to \phi\pi^+$

- Belle (Phys.Rev.Lett. 108 071801 (2012))
- BaBar (Phys. Rev. D 71, 091101(R) (2005))

Previous measurements $D_s^+ \to K_s^0\pi^+$

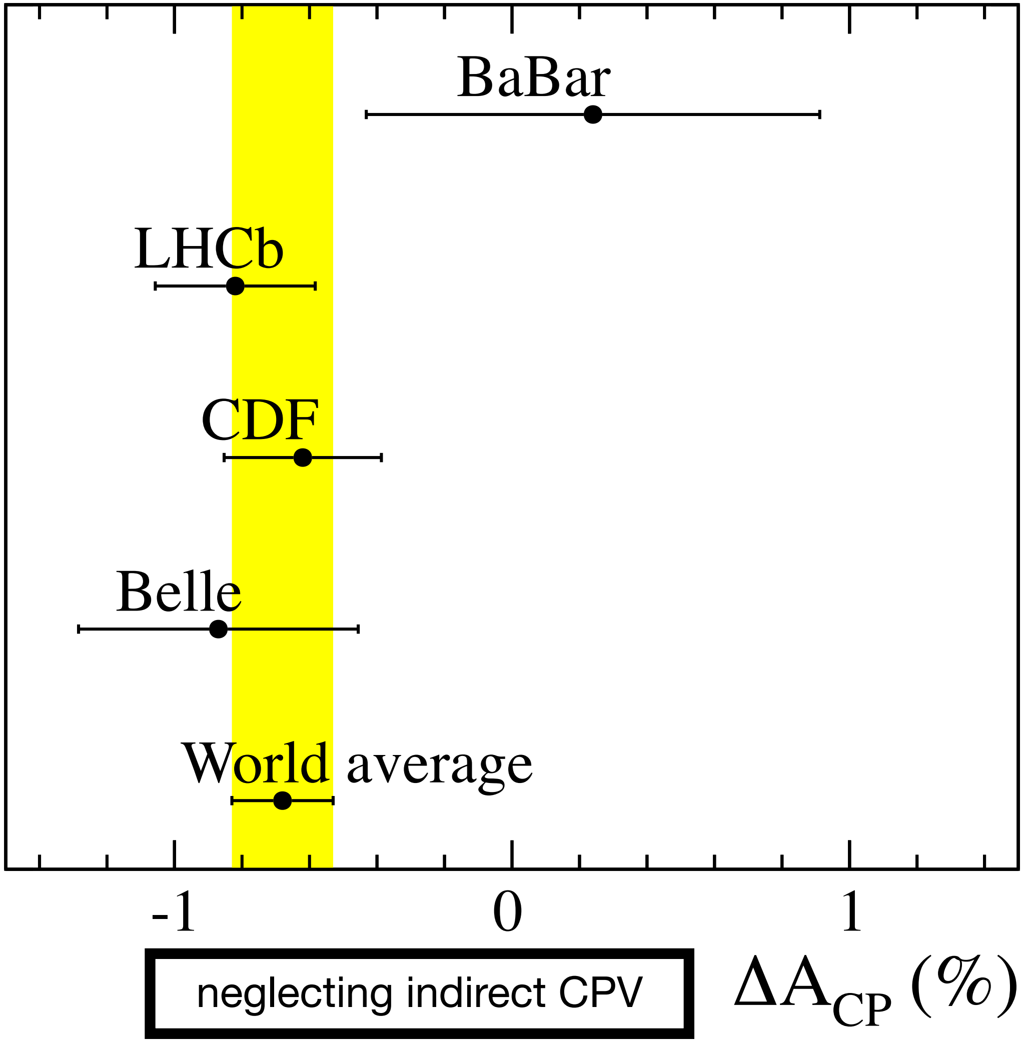
- Belle (Phys. Rev. Lett. 104, 181602 (2010))
- CLEO-c (Phys. Rev. D 81, 052013 (2010))

Neutral D decay modes

ΔA_{CP} status (pre-Moriond 2013)

$\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-)$

- ΔA_{CP} measured by
  - BaBar (Phys. Rev. Lett. 100 (2008))
  - Belle (arXiv:1212.5320)
  - LHCb (Phys. Rev. Lett. 108 (2012))
  - CDF (Phys. Rev. Lett. 109 (2012))
- World average 4.6σ deviation from zero
- Level of CP violation potentially accommodated within SM (arXiv:1202.3795, many more)
- Can also be explained by NP (arXiv:1202.2866, many more)
- Lively debate amongst theorists.



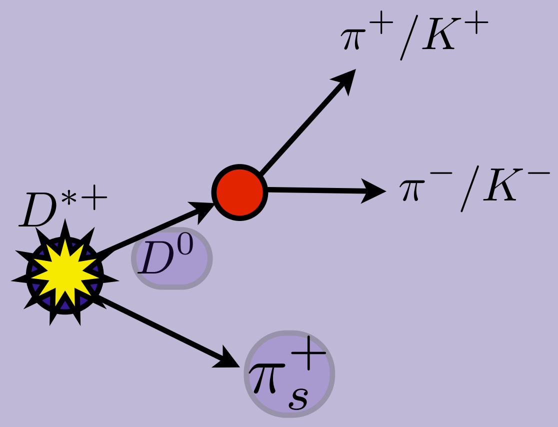
ΔA_{CP} Tagging

LHCb uses two methods to tag the D^0 flavor

Update

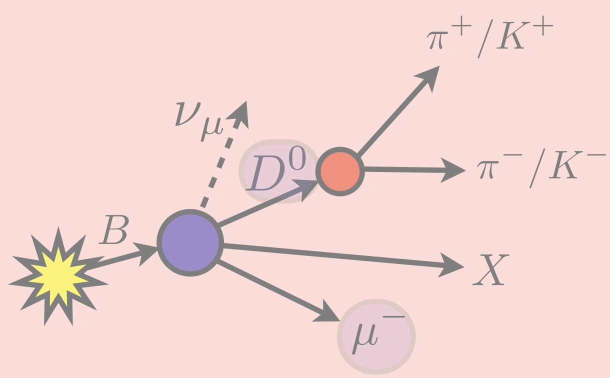
D* decays (Prompt)
Use slow pion from D* decays to tag D flavor $D^{*+} \to D^0 \pi_s^+$ or

$D^{*-} \to \bar{D}^0 \pi_s^-$



Semileptonic B decay (Secondary)
Use muon charge to tag D flavor
$B \to \bar{D}^0 \mu^+ \nu_\mu X$ or

$B \to D^0 \mu^- \nu_\mu X$



ΔA_{CP} from D* decays

- Update of analysis from 2011 **0.6 fb^{-1} → 1.0 fb^{-1}** (full 2011 dataset)
- Update includes new reconstruction
- **Improved tracking alignment**
- **Improved particle identification** from RICH calibration.
- **Constrain the D* vertex to the primary vertex**
- $\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$
- Improves δm resolution by factor ~2.5.
- **Kinematic re-weighting of D* (ensures $D^0 \to KK$ and $D^0 \to \pi\pi$ have the same kinematics)**

A_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

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

measure | **want** | ~~f's detection asymmetry~~ | π_s detection asymmetry | Production asymmetry

Zero for self-conjugate final states ($K^+K^-/\pi^+\pi^-$)

ΔA_{CP} from D* decays

LHCB-CONF-2013-003
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$$A_{RAW}(f) \simeq A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s^+) + A_p(D^{*+})$$

measure | want | ~~f's detection asymmetry~~ | π_s detection asymmetry | Production asymmetry

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

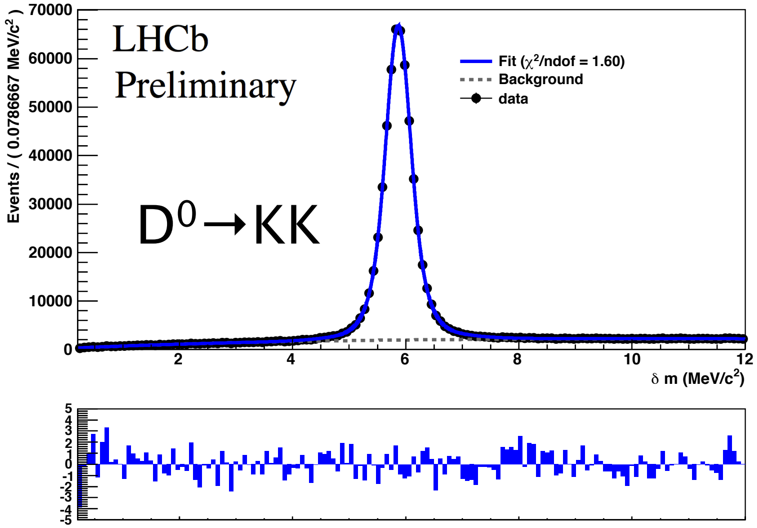
$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

Phys.Rev. D80 (2009) 076008

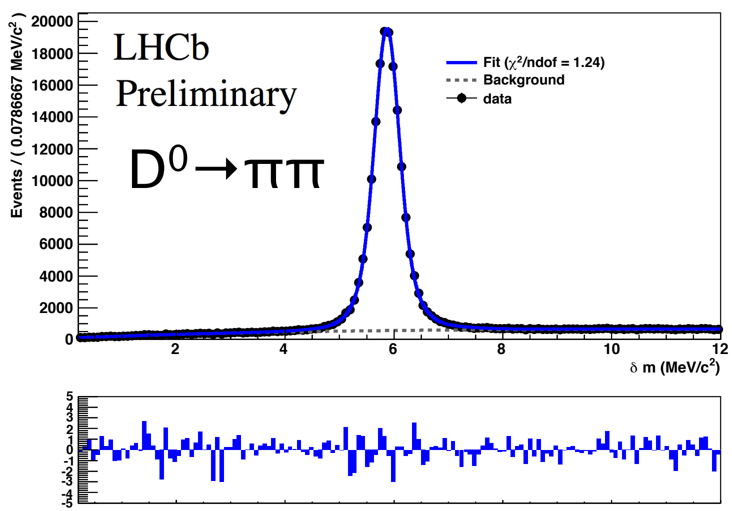
ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- Fit in δm
- $\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$



- **Extremely clean signal**
- 2.2 million $D^0 \rightarrow K^+K^-$ candidates
- 0.7 million $D^0 \rightarrow \pi^+\pi^-$ candidates



ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- Preliminary result

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.}))\%$$

- Considerably closer to zero than previous result
- **Larger data set**
- **Improved detector alignment and calibration**
- **Improvement in analysis technique**
- **Detailed systematic studies**
- **Many cross checks confirm our result**

ΔA_{CP} Tagging

LHCb uses two methods to tag the D^0 flavor

Update

D* decays (Prompt)
Use slow pion from D* decays to tag D flavor $D^{*+} \to D^0 \pi_s^+$ or
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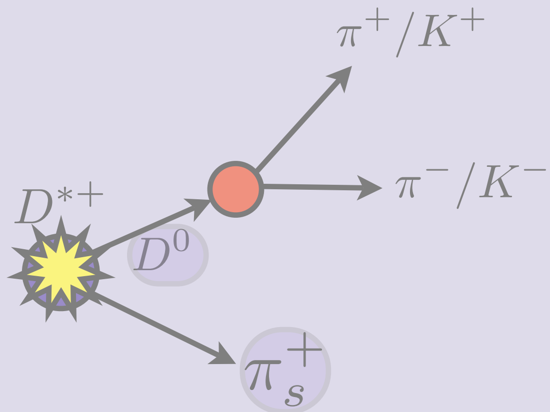

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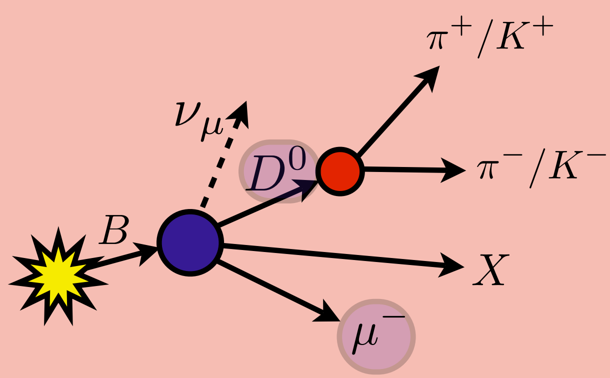


ΔA_{CP} from semileptonic B decays

arXiv:1303.2614
1.0fb^{-1} collected during 2011

$$A_{RAW}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_D(\mu^+) + A_p(B)$$

μ detection asymmetry

b-hadron production asymmetry

Detection and production asymmetries **independent** from D* analysis

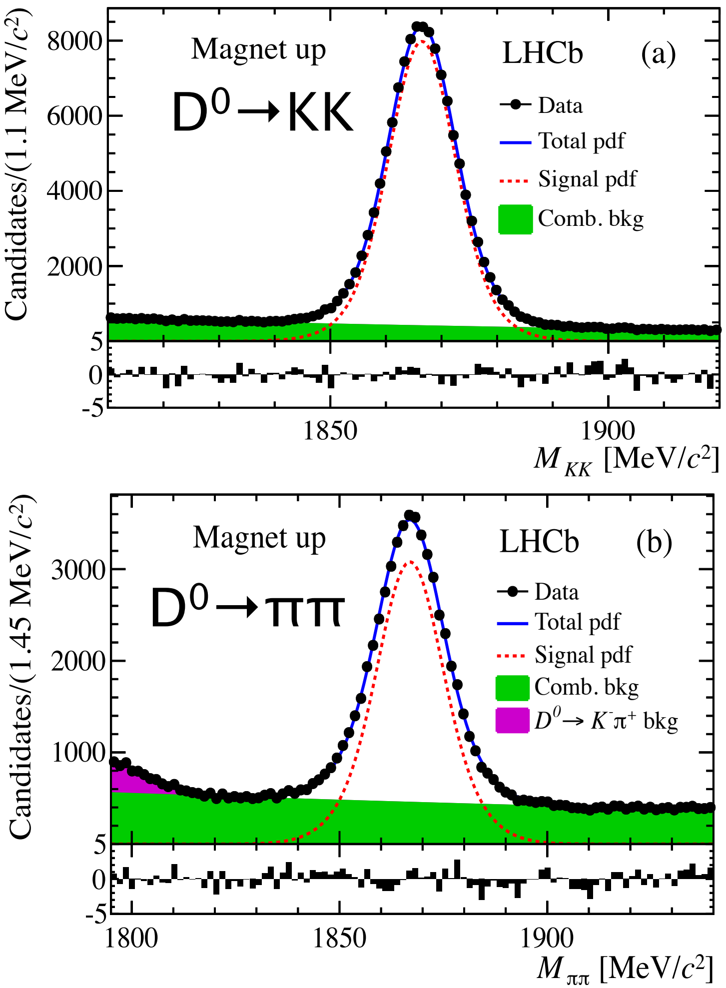
Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and muon detection asymmetries cancel.

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

ΔA_{CP} from semileptonic B decays

arXiv:1303.2614
1.0fb^{-1} collected during 2011

- Clean signal
- 0.6M $D \rightarrow K^+K^-$ candidates
- 0.2M $D \rightarrow \pi^+\pi^-$ candidates



Comparison of D* and semileptonic ΔA_{CP}

(Prompt) D* decays Preliminary

LHCB-CONF-2013-003

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\%$$

Semileptonic decays

arXiv:1303.2614

$$\Delta A_{CP} = (0.49 \pm 0.30\,(\text{stat}) \pm 0.14\,(\text{syst}))\%$$

- These measurements are compatible at 3% level ($\chi^2 = 4.85$)
- **Statistical correlation** between the two data samples is **negligible**
- **Systematic uncertainties** essentially **uncorrelated**

Preliminary combination: $\Delta A_{CP} = [-0.15 \pm 0.16]\,\%$

neglecting indirect CPV

- See Alan Schwartz's talk for a discussion of the impact of these measurements

Conclusion

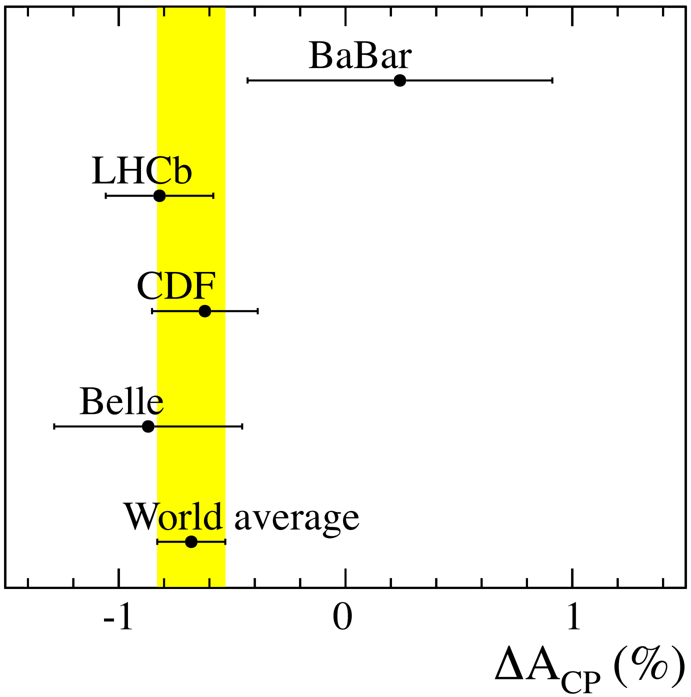
- **First single D^0 mixing measurement** above **5σ** [PRL 110, 101802 (2013)]
- **Best limits on CPV** for $D^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow K_S^0\pi^+$ (arXiv:1303.4906)
- Using D^0 from D* decays and D^0 from B decays, we have measured:
  - **ΔA_{CP} = (–0.34 ± 0.15(stat.) ± 0.10(syst.))%** via D* decays (LHCB-CONF-2013-003)
  - **ΔA_{CP} = (0.49 ± 0.30(stat) ± 0.14(syst))%** via semileptonic B decays (arXiv:1303.2614)
  - Many cross checks performed
  - Preliminary combination **ΔA_{CP} = (–0.15 ± 0.16)%** (not including indirect CPV)
- These analyses were performed on 1.0 fb^{-1} @ 7 TeV data from 2011.
  - **2 fb^{-1} data @ 8 TeV from 2012 still to be added** to our many CPV searches.
  - The LHCb detector is working beautifully, look forward to more results soon!

Additional Slides

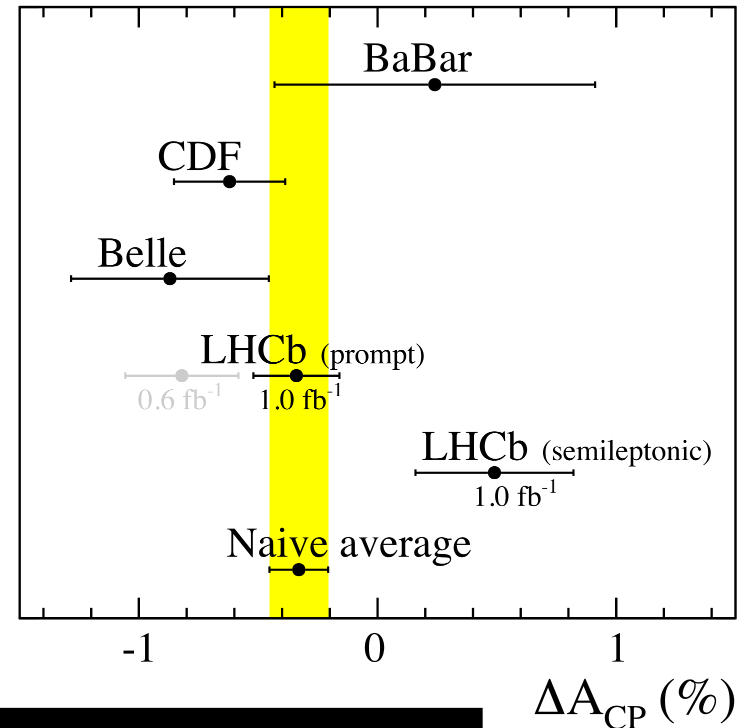
ΔA_{CP} Preliminary new world average

arXiv:1303.2614
LHCB-CONF-2013-003

- New average includes BaBar, CDF, Belle and new LHCb results

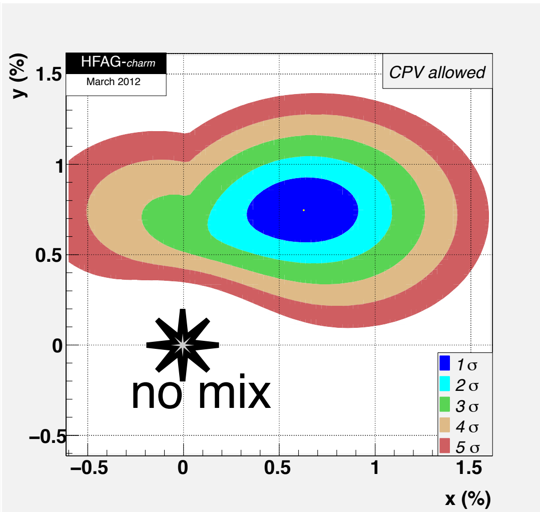


Update

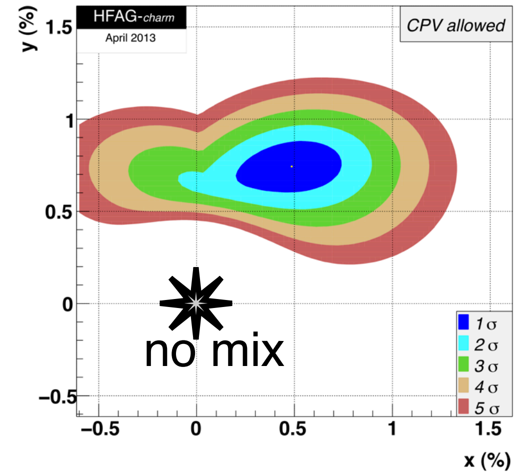


naive average
neglecting indirect CPV

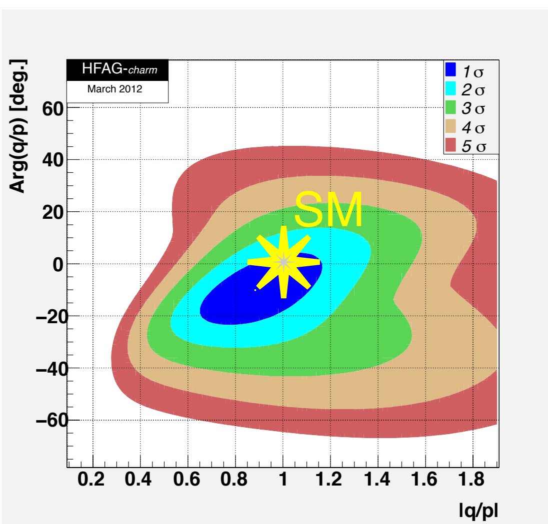
Knowledge of the Neutral Charm System

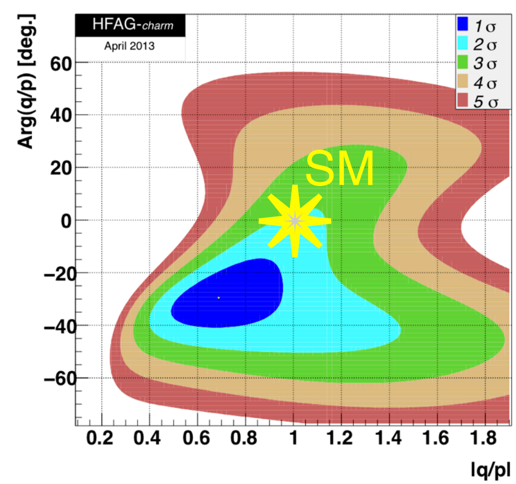


March 2012



April 2013



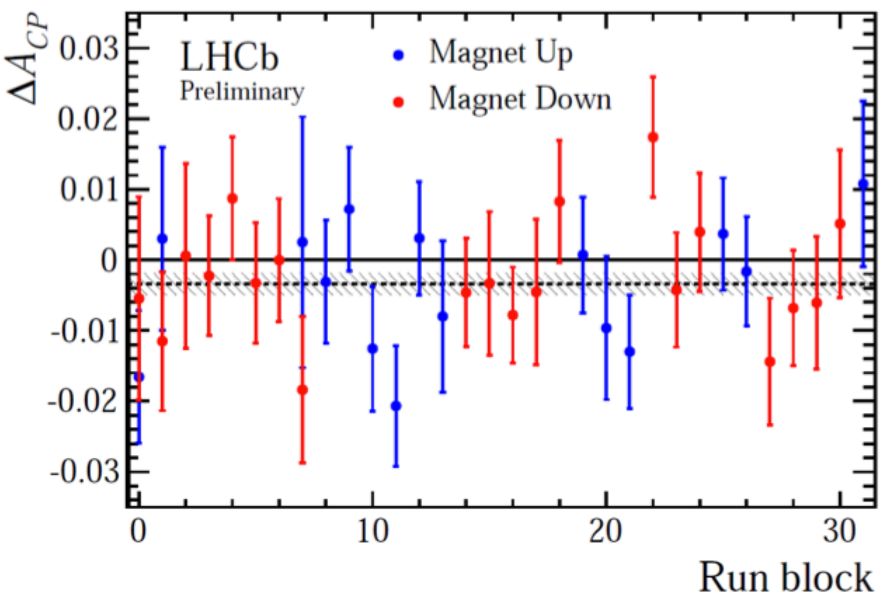


Averages by HFAG (March 2012, April 2013)

ΔA_{CP} from D* decays : Cross checks

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- ΔA_{CP} stability checked
- Against time at which data was taken
- Various reconstructed quantities:
  - D^0 p_T
  - D^0 η
  - D^0 p
  - D^0 decay time
- Analysis performed on large Monte Carlo samples to check for bias
- Many more



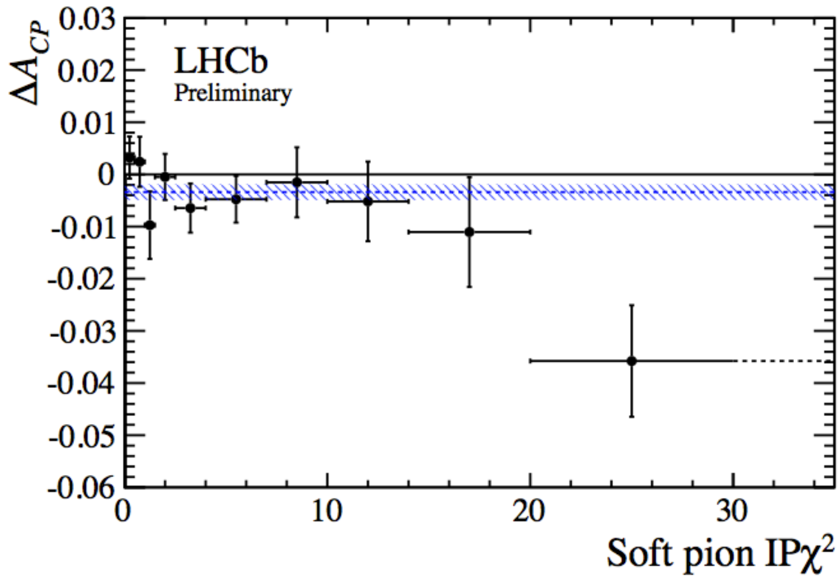
ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

- Preliminary result

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\%$$

- Source of systematic uncertainties
- Soft pions with large IPχ^2 for pointing to PV
- Effect due to multiple scattering
  - Results in poor mass distribution
  - Should not depend on D^0 decay mode
    - Raw asymmetry observed in these candidates
- Analysis repeated with these candidates removed
- **Dominant systematic 0.08%**



ΔA_{CP} via Semileptonic: Cross checks

arXiv:1303.2614
$1.0 fb^{-1}$ collected during 2011

- Many cross checks carried out
- **ΔA_{CP} stable with**
- reconstructed quantities:
  - **D^0 decay time**
  - **B flight distance**
  - **reconstructed D^0–μ mass**
  - **angle between μ and D^0 daughters**
  - **p_T of D^0 and μ**
  - **η of D^0 and μ**
- **data taking period**
- many more

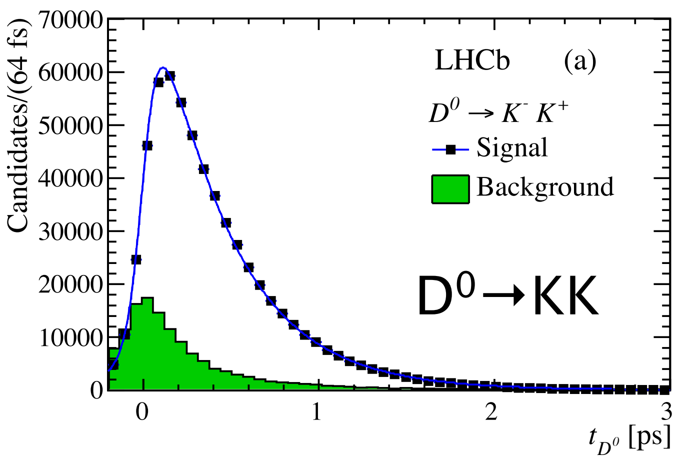
ΔA_{CP} from semileptonic B decays

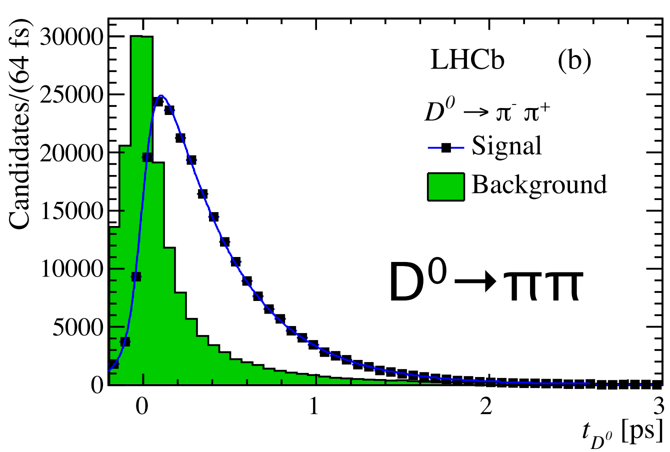
arXiv:1303.2614
1.0fb^{-1} collected during 2011

- Result

$$\Delta A_{CP} = (0.49 \pm 0.30\,(\mathrm{stat}) \pm 0.14\,(\mathrm{syst}))\%$$

- Main source of systematic from low lifetime background in $D^0 \to \pi^+\pi^-$ decays
- More low lifetime background in $D^0 \to \pi^+\pi^-$ than $D^0 \to K^+K^-$
- We required positive decay times in our analysis
- Analysis repeated including negative decay times
- Systematic uncertainty of 0.11%





ΔA_{CP} D^* comparison to 2011 result

LHCB-CONF-2013-003

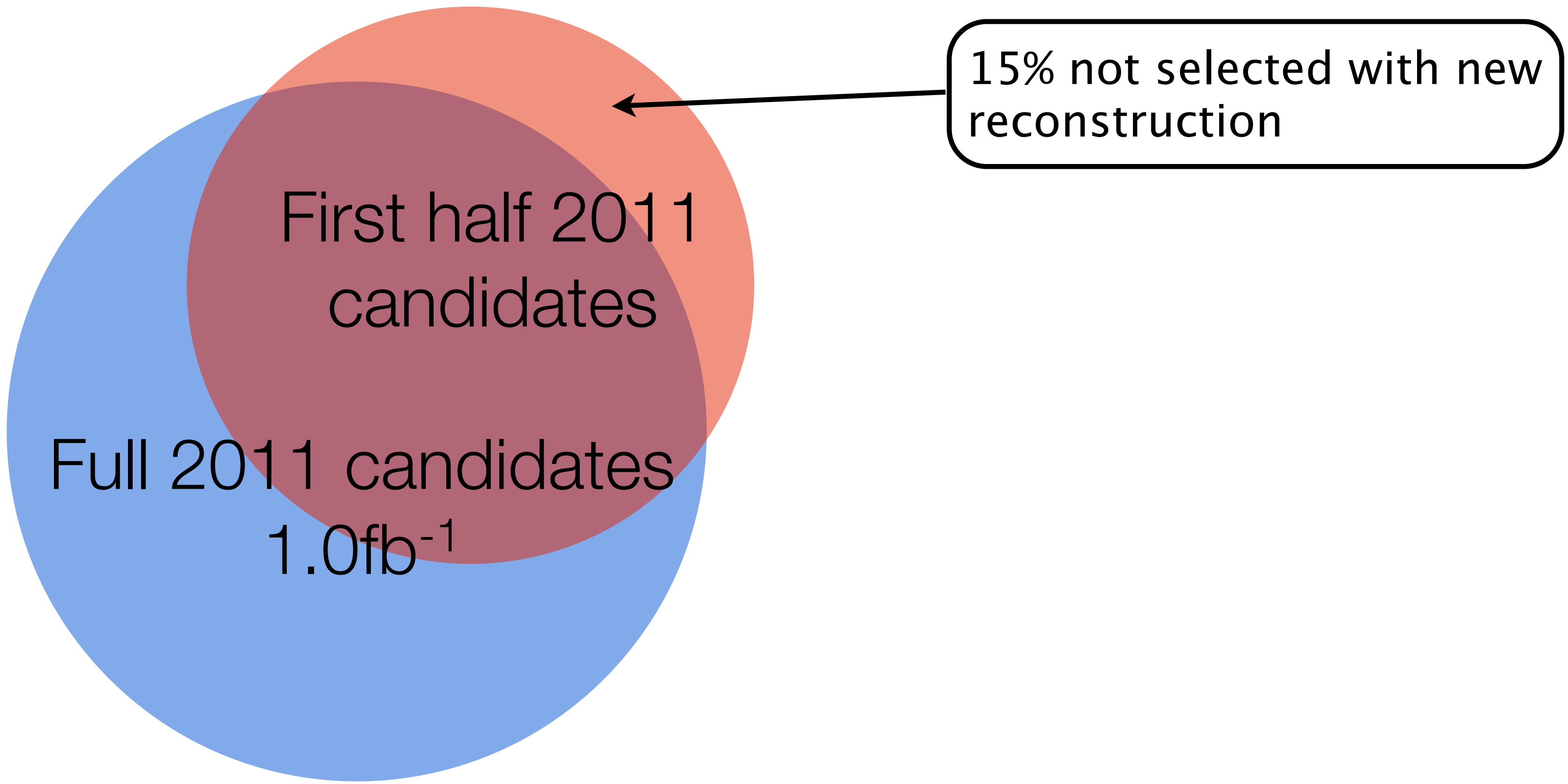
ΔA_{cp} from D^* decays comparison to 2011 result

Analysis using method from 2011

First half 2011 candidates ($600pb^{-1}$)

ΔA_{CP} from D* decays comparison to 2011 result

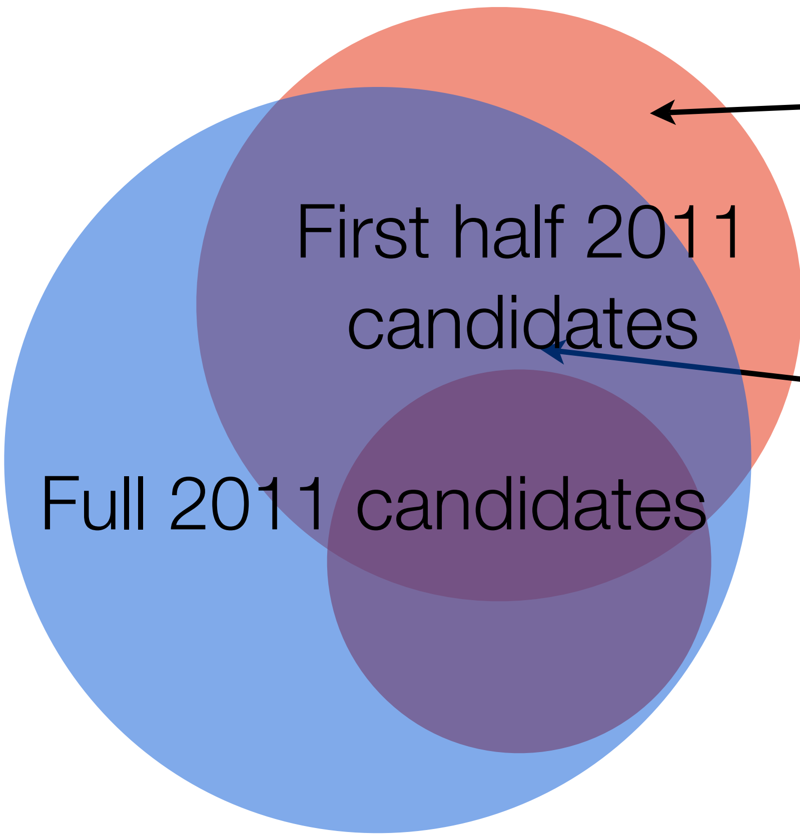
Analysis using method from 2011



LHCB-CONF-2013-003

ΔA_{CP} from D* decays comparison to 2011 result

Analysis using method from 2011



15% not selected with new reconstruction

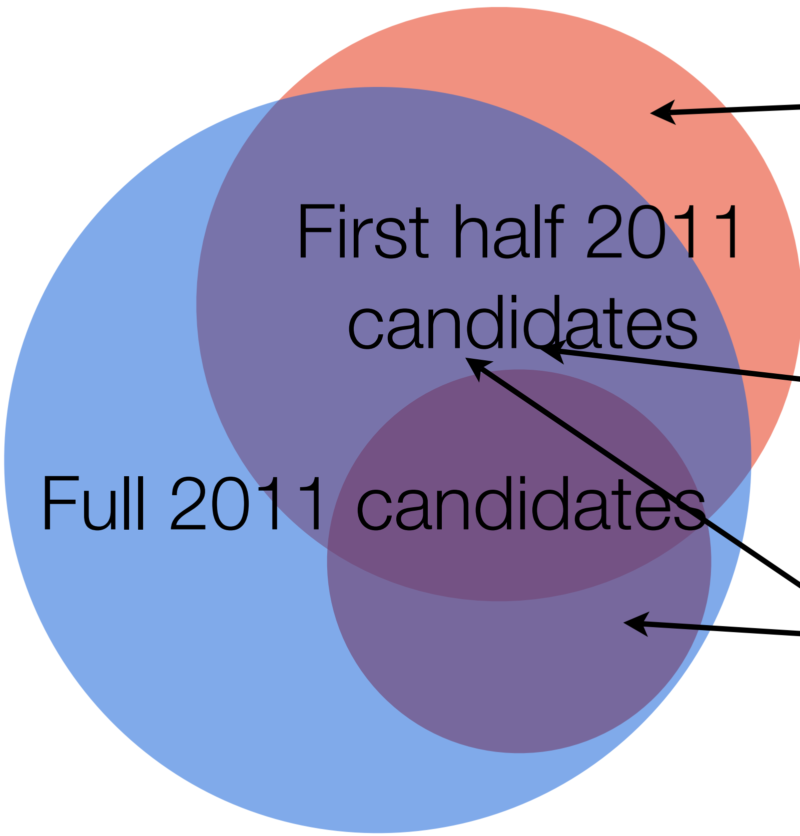
$\Delta A_{CP} = (-0.80 \pm 0.23)\%$

New Reconstruction

$\Delta A_{CP} = (-0.78 \pm 0.23)\%$

ΔA_{CP} from D* decays comparison to 2011 result

Analysis using method from 2011



15% not selected with new reconstruction

$\Delta A_{CP} = (-0.80 \pm 0.23)\%$

New Reconstruction

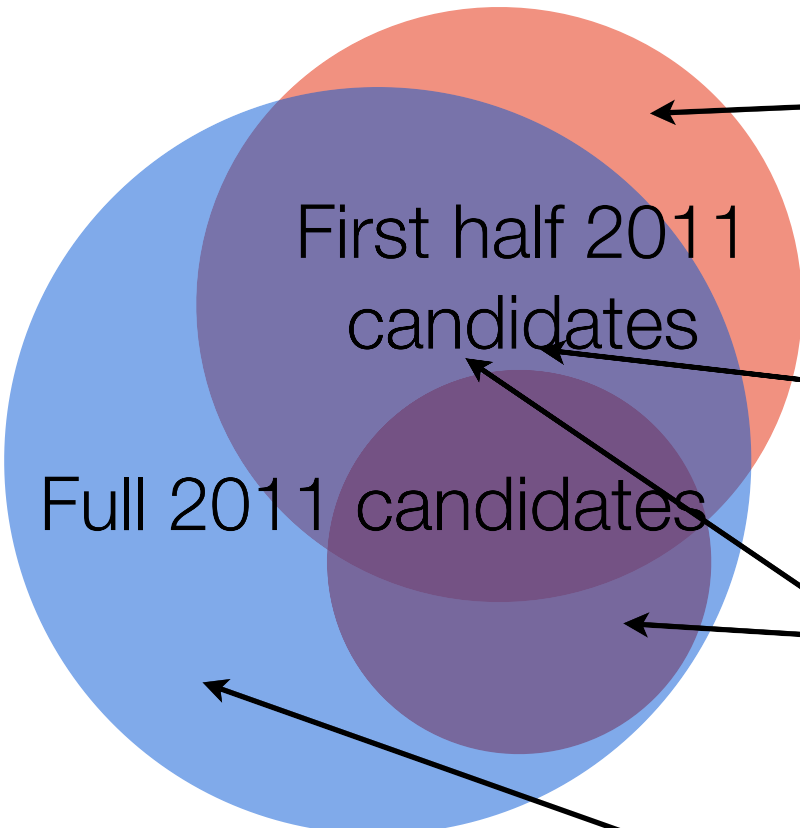
$\Delta A_{CP} = (-0.78 \pm 0.23)\%$

first 600 pb^{-1} including additional **17% KK** and **34% ππ** (improved RICH calibration)

LHCB-CONF-2013-003

ΔA_{CP} from D* decays comparison to 2011 result

Analysis using method from 2011



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New Reconstruction

$\Delta A_{CP} = (-0.78 \pm 0.23)\%$

first 600 pb^{-1} including additional **17% KK** and **34% ππ** (improved RICH calibration)

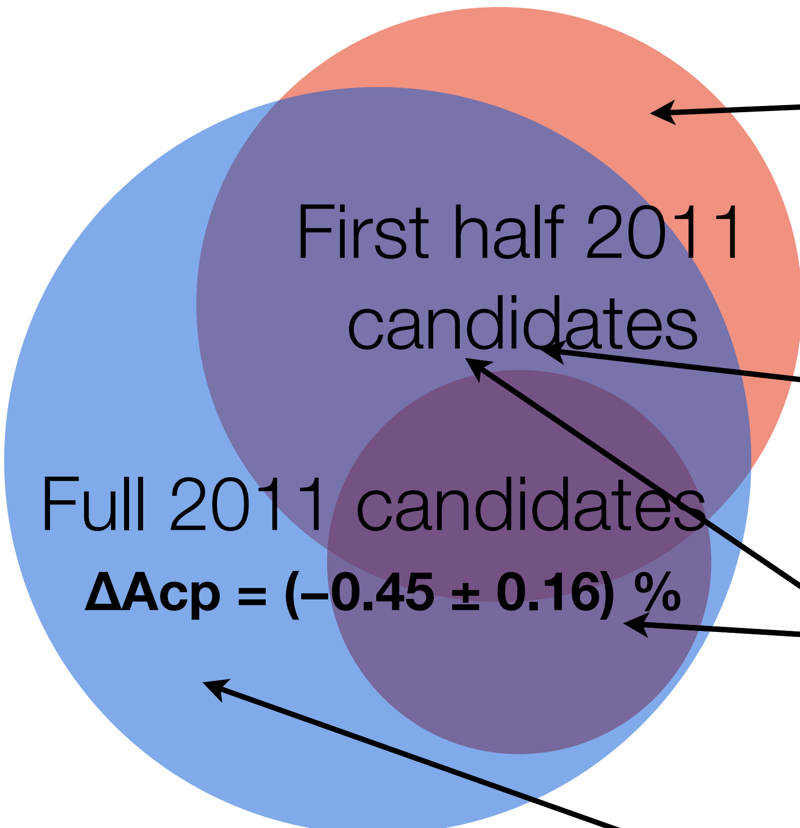
last 400pb^{-1} recorded by LHCb 2011

$\Delta A_{CP} = (-0.28 \pm 0.26)\%$

LHCB-CONF-2013-003

ΔA_{CP} from D* decays comparison to 2011 result

Analysis using method from 2011



15% not selected with new reconstruction

ΔA_{CP} = (–0.80 ± 0.23)%

New Reconstruction

ΔA_{CP} = (–0.78 ± 0.23)%

first 600 pb^{-1} including additional **17% KK** and **34% ππ** (improved RICH calibration)

last 400pb^{-1} recorded by LHCb 2011

ΔA_{CP} = (–0.28 ± 0.26)%

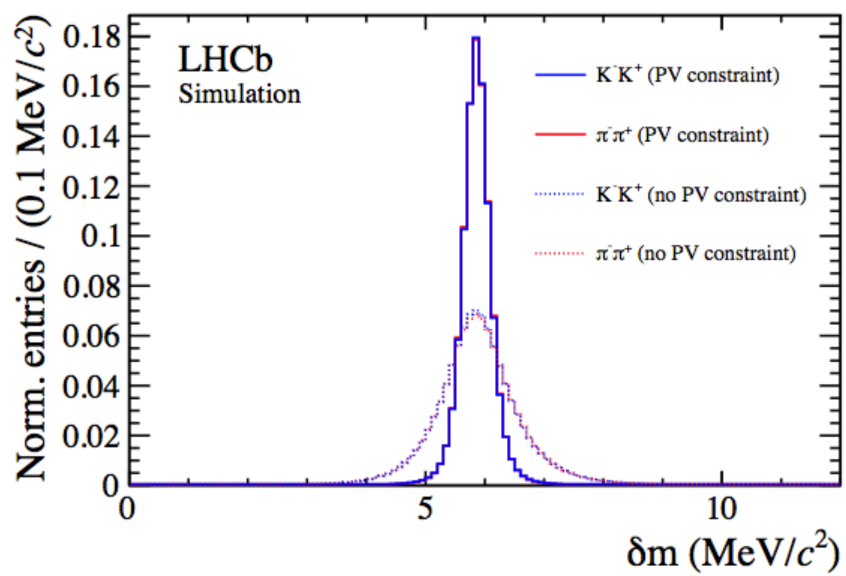
ΔA_{CP} from D* decays

kinematic re-weighting

$\Delta A_{cp} = (-0.45 \pm 0.16)$ % → $\Delta A_{cp} = (-0.45 \pm 0.17)$ %

force D* vertex to the Primary Vertex

$\Delta A_{cp} = (-0.45 \pm 0.17)$ % → **$\Delta A_{cp} = (-0.34 \pm 0.15)$ %**



ΔA_{CP} from D* decays

ΔA_{CP} from D* decays

- Previous results:

Experiment	ΔA_{CP}	
LHCb	$(-0.82 \pm 0.21 \pm 0.11)\%$	Phys. Rev. Lett. 108 (2012) 111602
CDF	$(-0.62 \pm 0.21 \pm 0.10)\%$	Phys. Rev. Lett. 109 (2012) 111801
Belle	$(-0.87 \pm 0.41 \pm 0.06)\%$	arXiv:1212.5320
BaBar	$(+0.24 \pm 0.62 \pm 0.26)\%$	Phys. Rev. Lett. 100 (2008)

ΔA_{CP} from D^* decays

Analysis technique

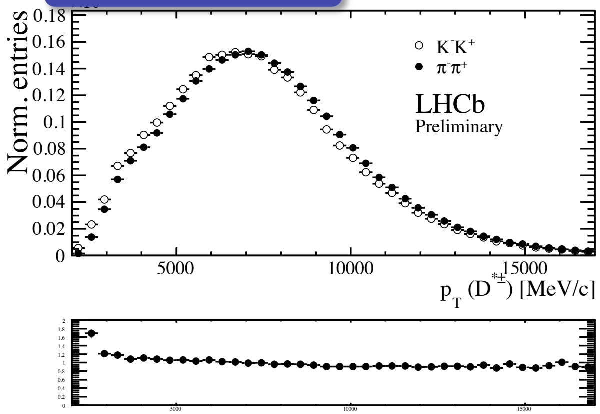
- **D^* re-weighted in p and p_T** ($D^0 \to KK$ and $D^0 \to \pi\pi$ same kinematics)
- Break dataset into 4 subsets
  - Hardware trigger (**L0**) on D^0 daughters (Trigger on Signal)
    - **Magnet Up**
    - **Magnet Down**
  - Hardware trigger (**L0**) on other particles from pp collision (Trigger Independent of Signal)
    - **Magnet Up**
    - **Magnet Down**
- ΔA_{CP} calculated for each subset and result is weighted average

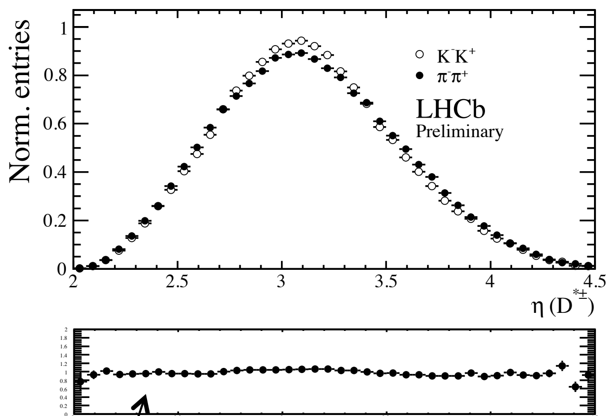
ΔA_{CP} from D^* decays

- Kinematic Re-weighting
- Re-weight D^* candidates so both $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ have the same kinematics

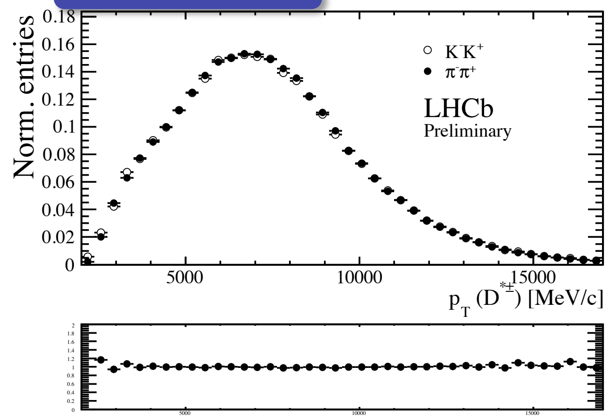
ΔA_{CP} from D* decays

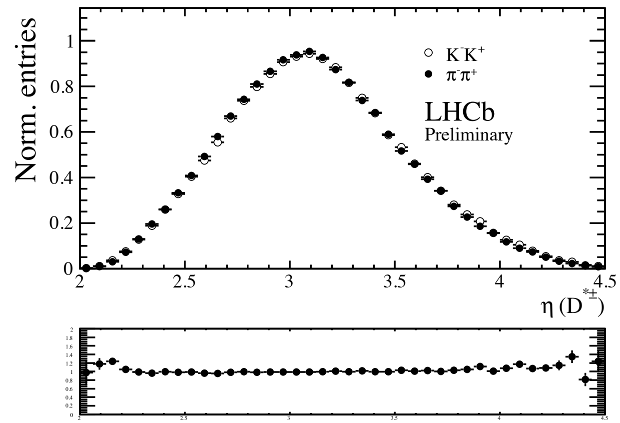
Before weighting





After weighting



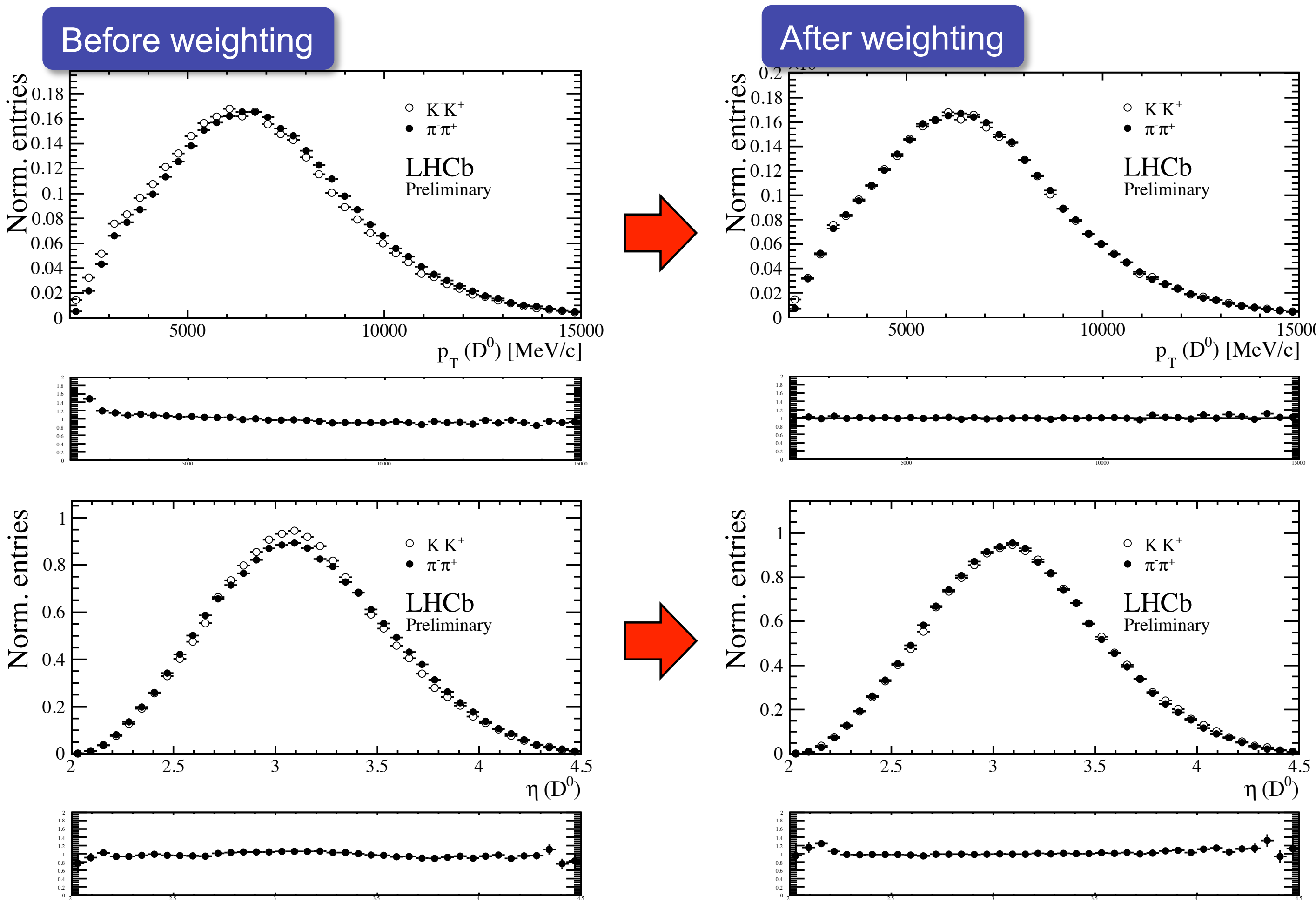


Only small differences before weighting

Obviously, D* kinematics agree after weighting for D* kinematics

ΔA_{CP} from D* decays

LHCB-CONF-2013-003



Also D^0 distributions agree after weighting for D* kinematics

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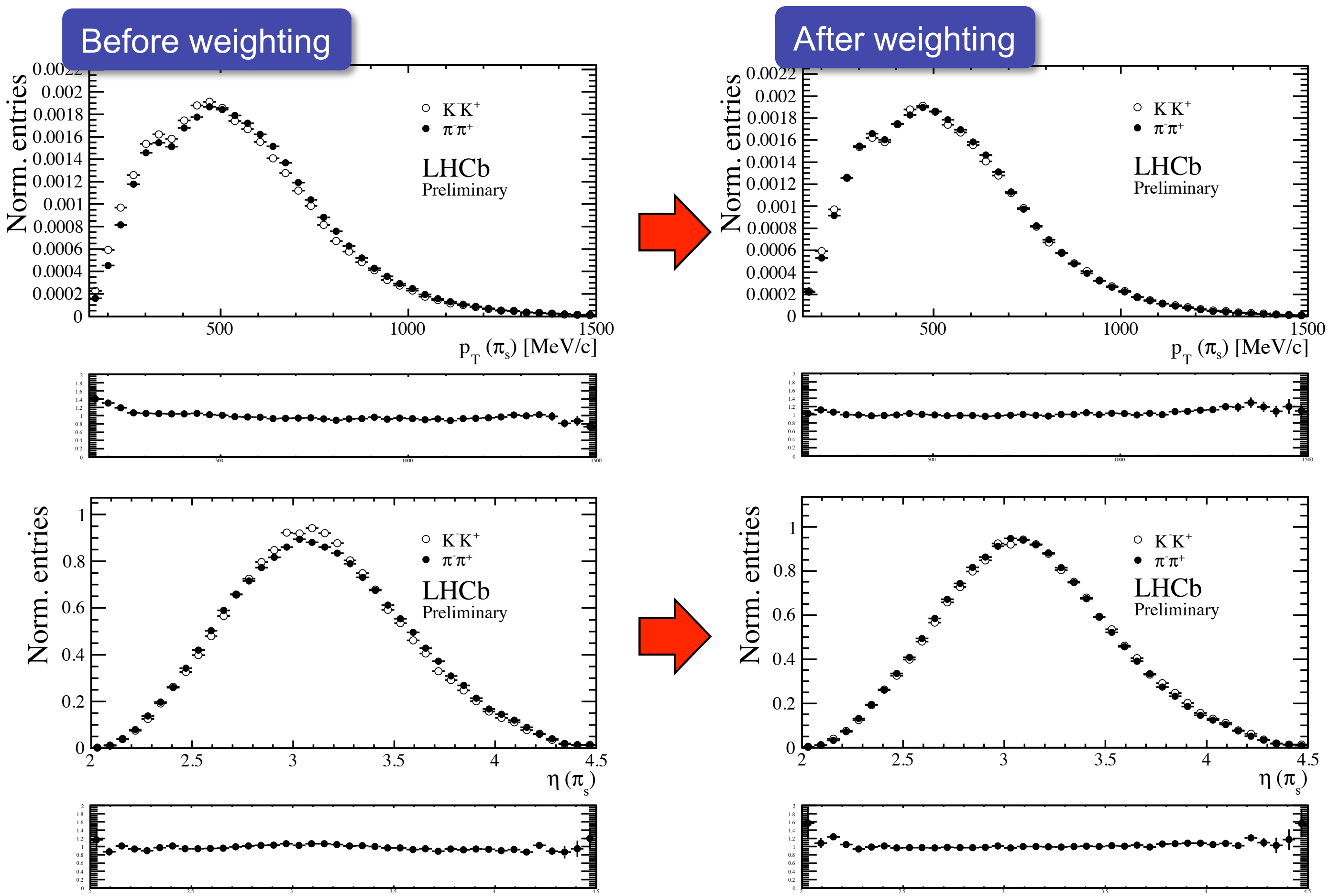
ΔA_{CP} from D^* decays



Also slow pion distributions agree after weighting for D^* kinematics

ΔA_{CP} from D* decays : Cross checks

- Effects investigated for systematics
  - Peaking backgrounds
  - Tighter particle ID cuts
  - Different D* selection
  - Comparing results with and without kinematic re-weighting
- ΔA_{CP} stability checked
  - Against time which data was taken
  - Various reconstructed quantities:
    - D^0 p_T
    - D^0 η
- Analysis performed on large Monte Carlo samples to check for bias
- $\Delta\langle t\rangle/\tau(D^0) = (11.27 \pm 0.13)\%$
- many more

Systematic uncertainties ΔA_{CP}

- Sources of systematic uncertainties for D* analysis

Source	Uncertainty
Multiple candidates	0.01%
Peaking background	0.03%
Fit model	0.03%
Reweighting	0.01%
Soft pion IPχ^2	0.08%
Fiducial cut	0.02%
Total	0.10%

Systematic uncertainties ΔA_{CP}

- Soft pions which do not point to primary vertex (before constraint)
  - Effect due to multiple scattering
    - Results in poor mass distribution
    - Should not depend on D^0 decay mode
      - Raw asymmetry observed in these candidates
  - Analysis repeated with these candidates removed
  - **Dominant systematic 0.08%**

Source	Uncertainty
Multiple candidates	0.01%
Peaking background	0.03%
Fit model	0.03%
Reweighting	0.01%
Soft pion IPχ^2	0.08%
Fiducial cut	0.02%
Total	0.10%

Systematic uncertainties ΔA_{CP}

- Tighter particle identification cut
  - Analysis repeated with tighter particle identification cuts.
- Fiducial cuts
  - Analysis repeated with altered fiducial cuts.
- Re-weighting
  - Re-weighting D^0 such that $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ kinematics match.
  - Analysis repeated without kinematic re-weighting.

Source	Uncertainty
Multiple candidates	0.01%
Peaking background	0.03%
Fit model	0.03%
Reweighting	0.01%
Soft pion IPχ^2	0.08%
Fiducial cut	0.02%
Total	0.10%

Systematic uncertainties ΔA_{CP}

- Multiple candidates
  - Analysis repeated with a random candidate in events with multiple candidates removed.
- Peaking background
  - D mass peaks used to test for potential peaking background contributions.
- Fit model
  - Analysis repeating with the asymmetry extracted through sideband subtraction instead of a fit.

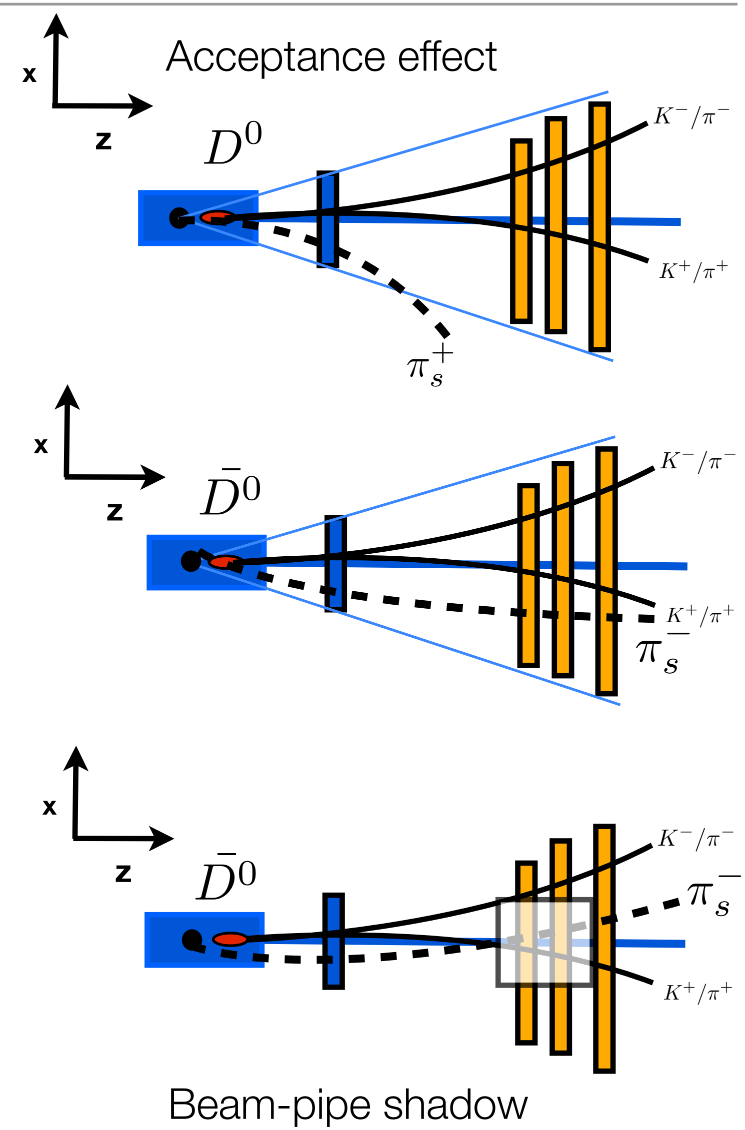
Source	Uncertainty
Multiple candidates	0.01%
Peaking background	0.03%
Fit model	0.03%
Reweighting	0.01%
Soft pion IPχ^2	0.08%
Fiducial cut	0.02%
Total	0.10%

ΔA_{CP}

- Magnetic field induces left/right differences between the D^{*+} and D^{*-} due to the slow pion

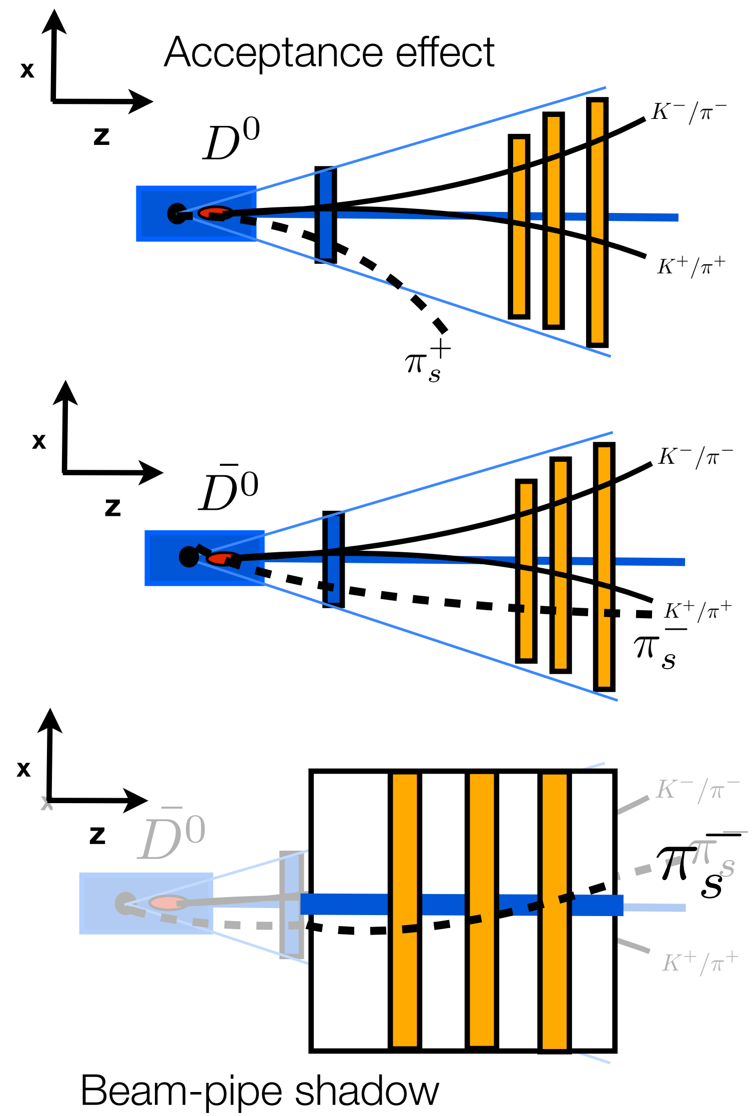
- Acceptance effect at edges of detector
- Beam-pipe shadow

- 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



ΔA$_{CP}$

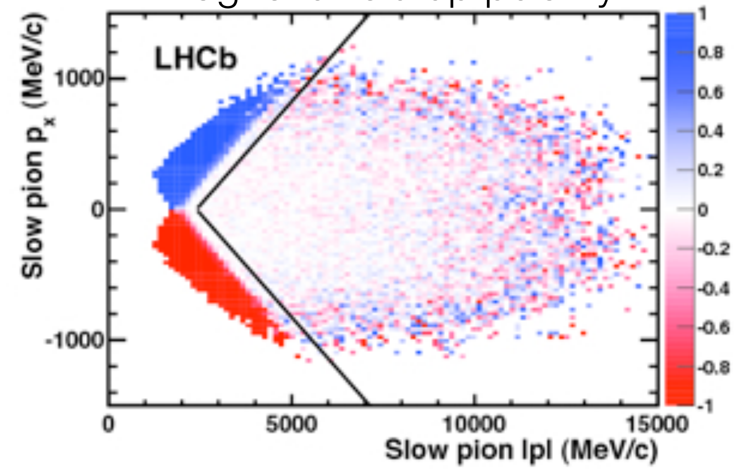
- Magnetic field induces left/right differences between the D*+ and D*− due to the slow pion
- Acceptance effect at edges of detector
- Beam−pipe shadow
- We remove this asymmetry
- We remove areas of large asymmetry to avoid secondary effects
- Frequently flip the magnetic field
- Detector asymmetries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



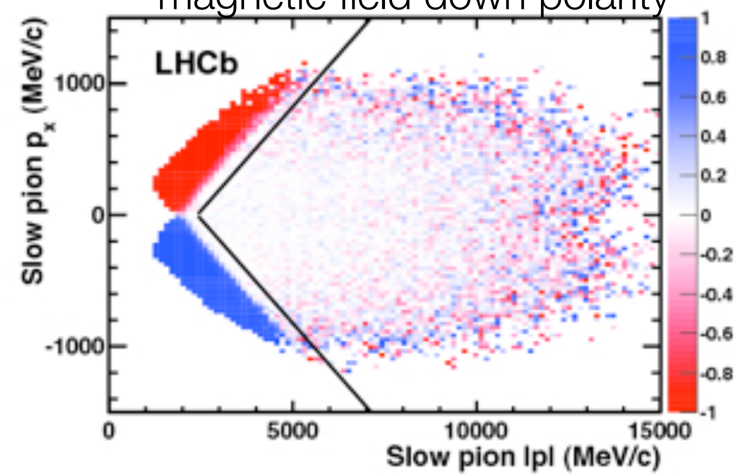
ΔA$_{CP}$

- 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

magnetic field up polarity



magnetic field down polarity

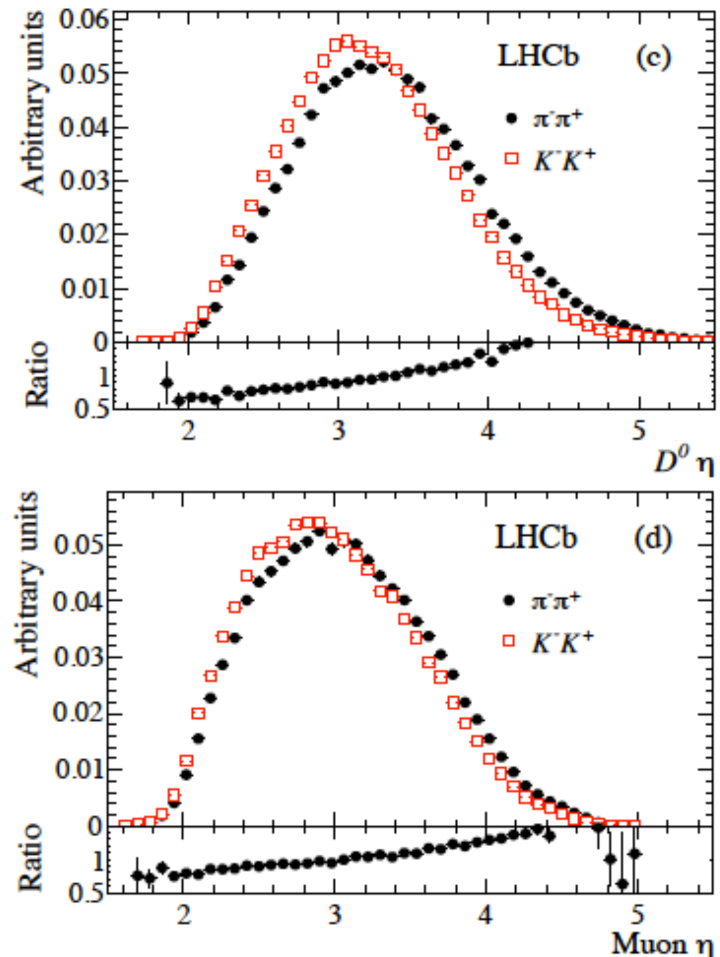


Phys. Rev. Lett. 108 (2012) 111602

ΔA_{CP} from semileptonic B decays

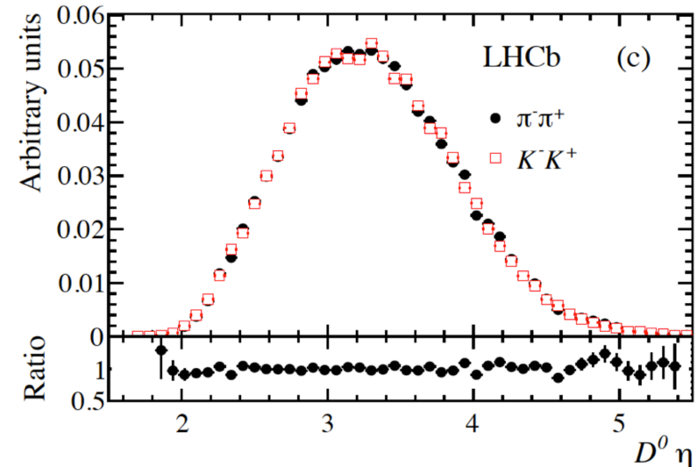
ΔA_{CP} from semileptonic B decays

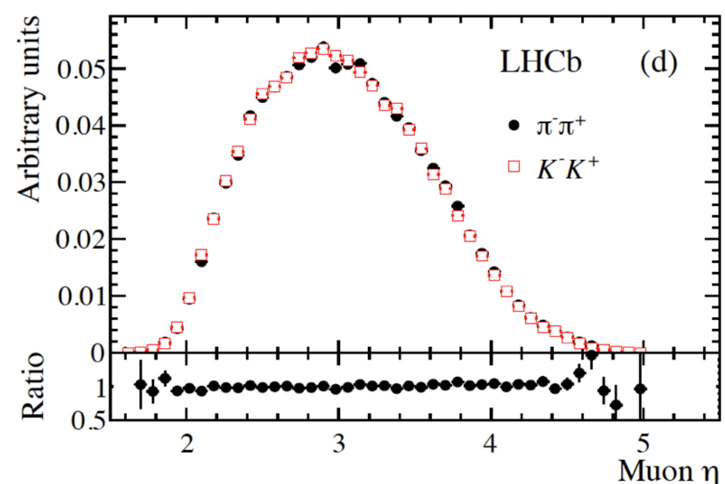
- **D^0 candidates** given weight depending on **p_T and η distribution**



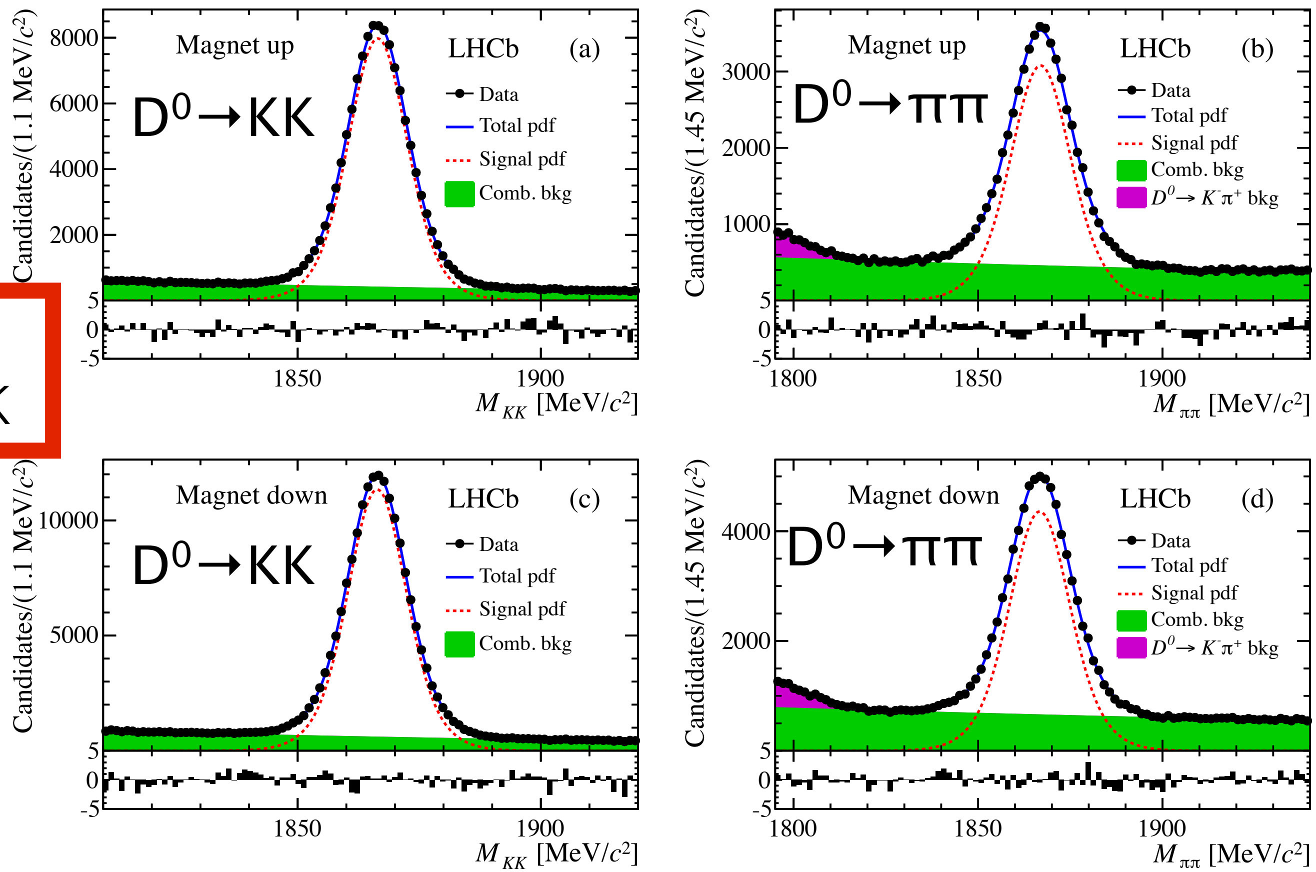
ΔA_{CP} from semileptonic B decays

- **D^0 candidates** given weight depending on **p_T and η distribution**
- **Muon** kinematics also in good agreement after **re-weighting**





ΔA_{CP} from semileptonic B decays



559k
$D^0 \rightarrow KK$

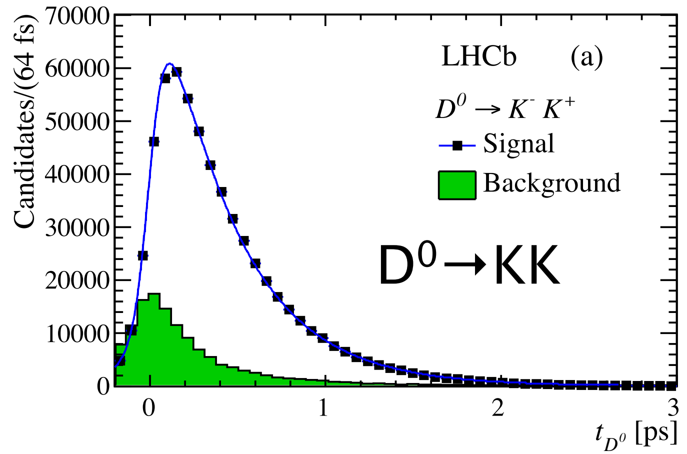
222k
$D^0 \rightarrow \pi\pi$

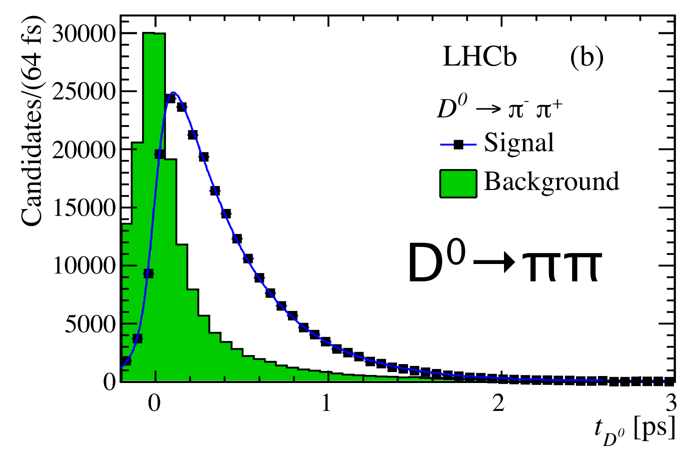
$$\Delta A_{CP} = (0.49 \pm 0.30\,(\text{stat}) \pm 0.14\,(\text{syst}))\% \ .$$

Systematic uncertainties

- Pairing a D^0 with random muon (mistag)
  - Dilutes signal
  - Difference in mistag probability between D^0 and anti-D^0 is (0.006 ± 0.021)%
- Decay Time
  - Decay time acceptance can differ between KK and ππ.
  - Difference in direct and indirect CPV component
  - Small Δ<t> → $\Delta A_{CP} = \Delta a_{CP}^{dir}$

$$\Delta\langle t\rangle/\tau(D^0) = 0.018 \pm 0.002\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst})$$
$$\overline{\langle t\rangle}/\tau(D^0) = 1.062 \pm 0.001\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst})$$





Contain LHCb acceptance effects

ΔA_{CP} from semileptonic B decays

- Raw asymmetries and ΔA_{CP} split for each magnet polarity

	Magnet up	Magnet down	Mean
$A_{\mathrm{raw}}(K^-K^+)$	-0.39 ± 0.23	-0.20 ± 0.19	-0.29 ± 0.15
$A_{\mathrm{raw}}(\pi^-\pi^+)$	-1.25 ± 0.40	-0.29 ± 0.34	-0.77 ± 0.26
ΔA_{CP}	0.86 ± 0.46	0.09 ± 0.39	0.48 ± 0.30

ΔA_{CP} from semileptonic B decays

- Source of systematic uncertainties

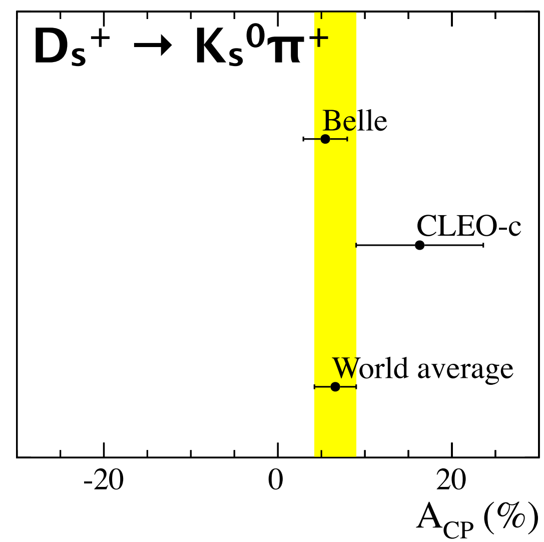
Source of uncertainty	Uncertainty
Production asymmetry:	
Difference in b-hadron mixture	0.02%
Difference in B decay time acceptance	0.02%
Production and detection asymmetry:	
Different weighting	0.05%
Background from real D^0 mesons:	
Mistag asymmetry	0.02%
Background from fake D^0 mesons:	
D^0 mass fit model	0.05%
Low lifetime background in $D^0 \to \pi^-\pi^+$	0.11%
Λ_c^+ background in $D^0 \to K^-K^+$	0.03%
Quadratic sum	0.14%

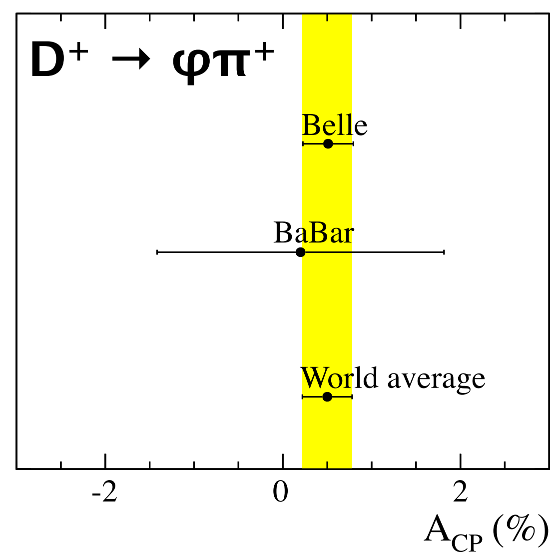
CP violation in $D^+ \rightarrow \varphi\pi^+$ and $D_S^+ \rightarrow K_S^0\pi^+$

CP violation in $D^+ \to \varphi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

Current status

- $D_s^+ \to K_s^0\pi^+$ previously measured by
  - CLEO-c
  - Belle
- $D^+ \to \phi\pi^+$ measured by
  - Belle
  - BaBar





LHCB-PAPER-2012-052

$1 fb^{-1}$ collected during 2011

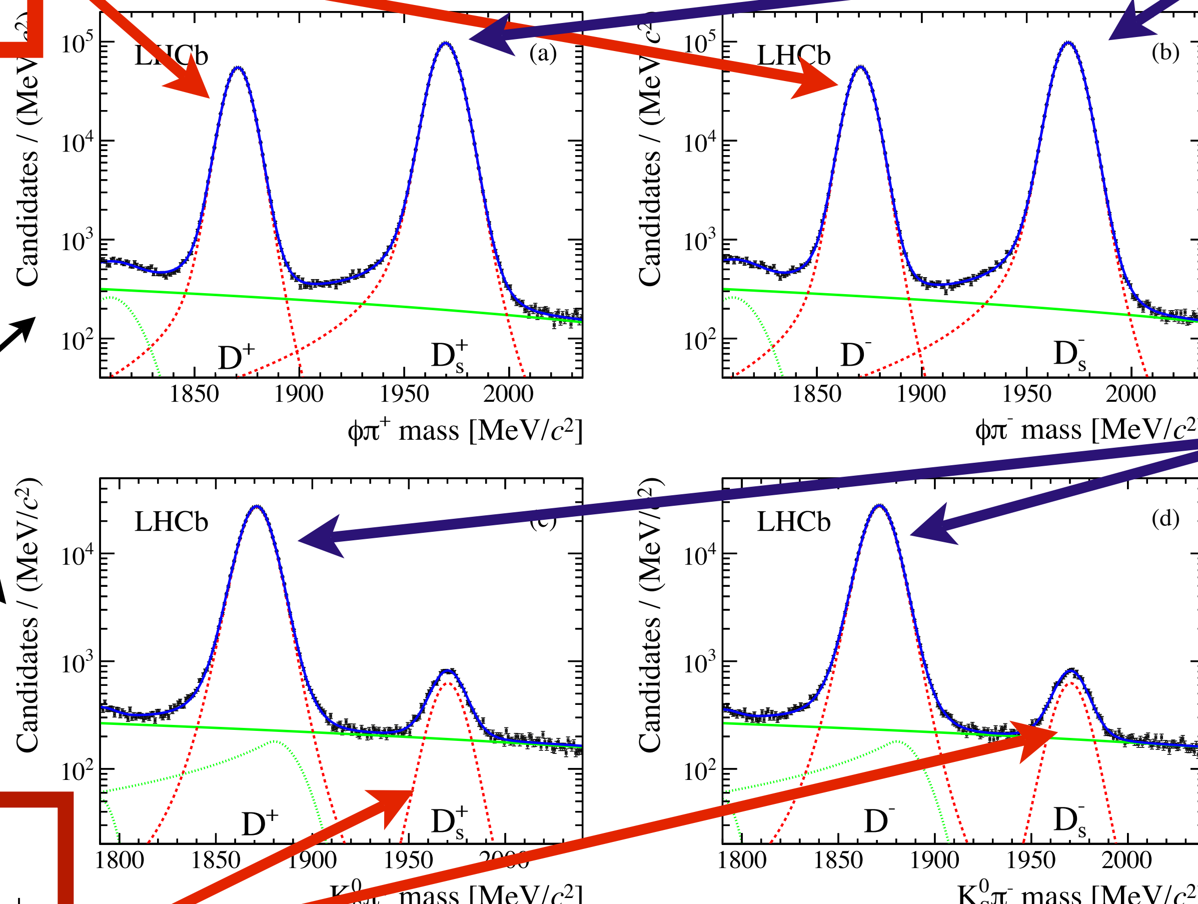
CP violation in $D^+ \to \varphi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

1.6M
$D^{+/-} \to \varphi\pi^{+/-}$

3.6M
$D_s^+ \to \varphi\pi^+$

1.1M
$D^+ \to K_S^0\pi^+$

Log Scale



26K
$D_s^+ \to K_S^0\pi^+$

Very low background

LHCB-PAPER-2012-052

$1 fb^{-1}$ collected during 2011

CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

- Main sources of systematic uncertainty
  - Detector efficiency differences (magnet up/magnet down)
  - Uncertainties in background model
  - kaon interaction asymmetries
  - CP violation in the neutral kaon system

Source	A_{CP} (D^+) [%]	A_{CP} (D_s^+) [%]	$A_{CP}\|_S$ [%]
Triggers	0.114	0.114	n/a
D_s^+ control sample size	n/a	n/a	0.169
Kaon asymmetry	0.031	0.002	0.009
Binning	0.029	0.029	n/a
Resolution	0.007	0.006	0.056
Fitting	0.033	0.033	n/a
Kaon *CP* violation	0.028	0.028	n/a
Fiducial effects	0.022	0.022	n/a
Backgrounds	0.008	n/a	0.007
D from *B*	0.003	0.015	0.003
Regeneration	0.010	0.010	n/a
Total	0.132	0.128	0.178

D^0 mixing

D^0 mixing

- Majority of systematic uncertainties cancel in ratio
- Main sources of systematics which do not cancel in ratio
  - Pollution from D^0's from B decays results in wrong time.
  - Some double mis-ID events ($D^0 \rightarrow K^- \pi^+$ seen as $D^0 \rightarrow K^+ \pi^-$) pollutes WS sample
  - Other sources of uncertainty (production/detection efficiencies) of order 10^{-4} can be neglected.
- Systematics account for ~10% of overall uncertainty

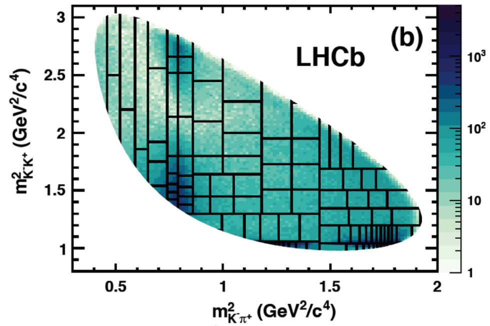
Search for CP asymmetries in $D^0 \to \pi^+\pi^+\pi^-\pi^-$ decays

Method

- $D^0 \to \pi^+\pi^+\pi^-\pi^-$ is singly Cabibbo-suppressed, and the SM can allow (very) small CP Violation effects due to penguin diagrams.

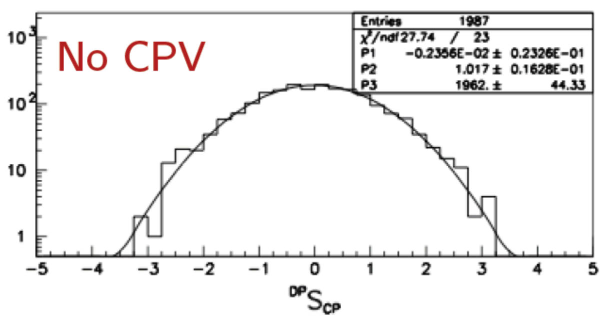
- Adaptively bin the five parameter phase space to search for local CP asymmetries in this channel.
  - Model-independent Miranda method (PRD 80, 096006)

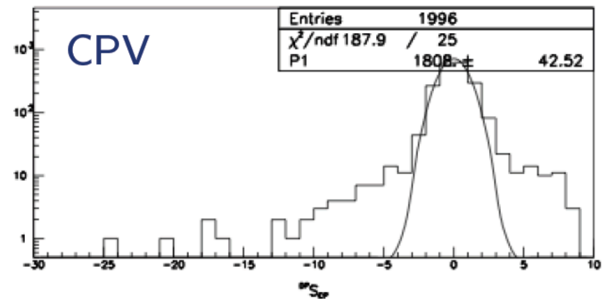
$$S_{CP} = \frac{N_i - \alpha \bar{N}_i}{\sqrt{N_i + \alpha^2 \bar{N}_i}} \qquad \alpha = \frac{N_{\text{total}}}{\bar{N}_{\text{total}}}$$



Example from $D^+ \to K^+K^-\pi^+$
PRD 84 (2011) 112008

  - Plot histogram of number of bins vs. SCP
  - Expected distribution for no CPV has a mean of 0 and width of 1





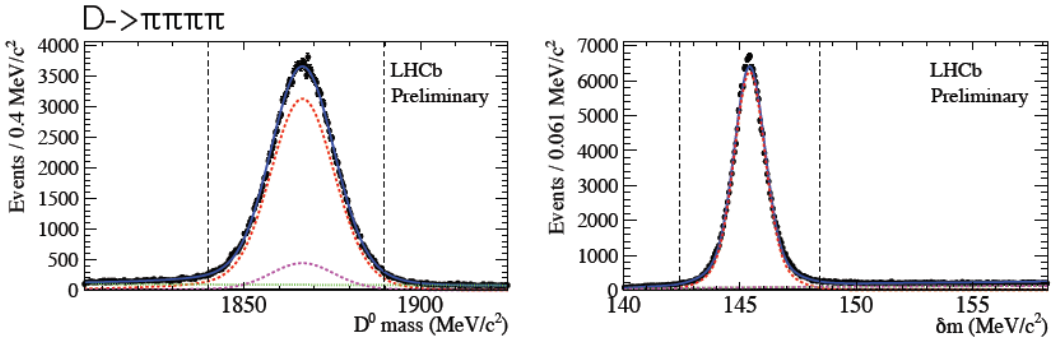
Simulation by Bediaga et al. (PRD 80, 096006)

Preliminary Results

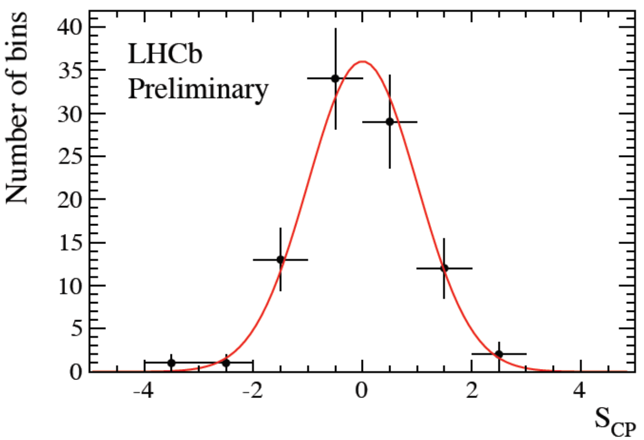
- Using 1.0 fb^{-1} of data (~1.8 x 10^5 $D^0 \rightarrow \pi^+\pi^+\pi^-\pi^-$ decays) we calculate:

$$\chi^2 = \sum (S^i_{CP})^2$$

and p-values under the assumption of no CPV.



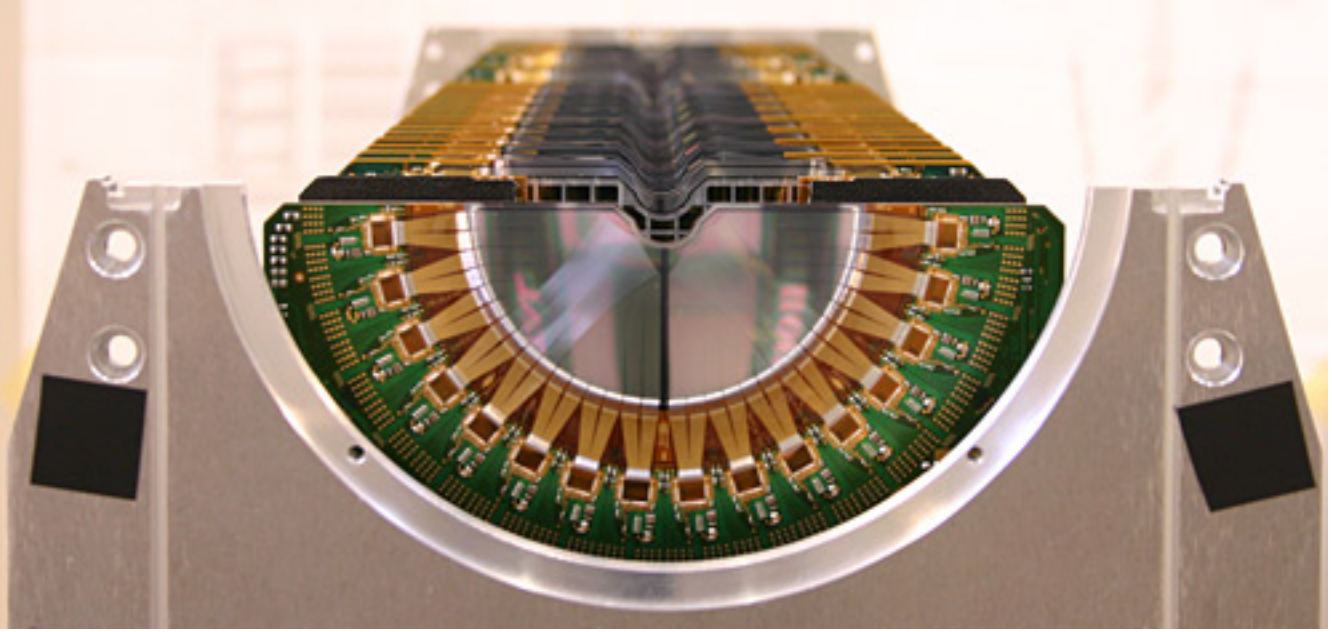
- Observe no CPV with probability value of 99.8%
  - 66 bins, result stable with different bin choices



More Slides

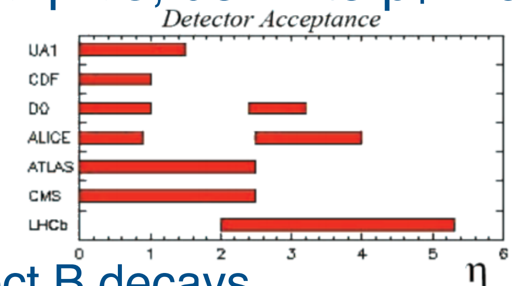
Vertex Locator (VELO)

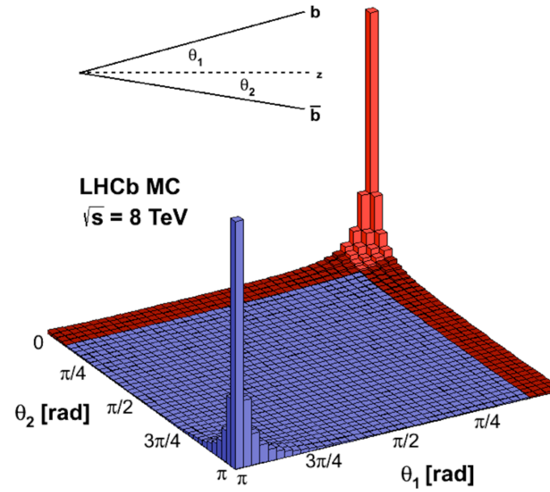
- Reconstruction of primary and (displaced) secondary vertices
- Excellent Impact Parameter resolution of ~ 20 μm
- Proper time resolution 30 to 50 fs



Experiment Overview

- The LHCb detector is a single arm forward spectrometer with a polar angular coverage from 10 to 300 mrad in the horizontal plane and 250 mrad in the vertical plane.
- Unique regime: $2 < \eta < 5$, down to $p_T \sim 0$

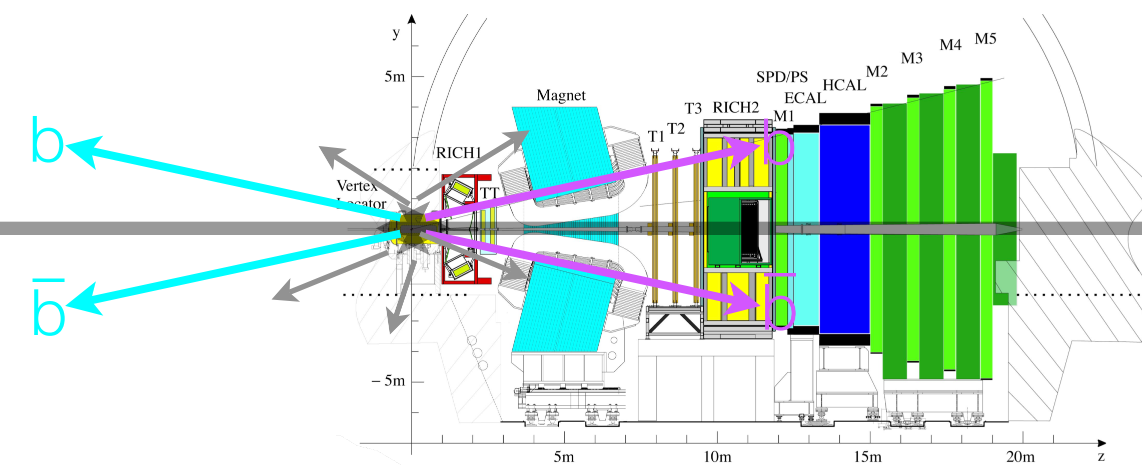




- Trigger
  - Designed to select B decays.
  - Also favors higher p_T secondary charm.

Designed for b!

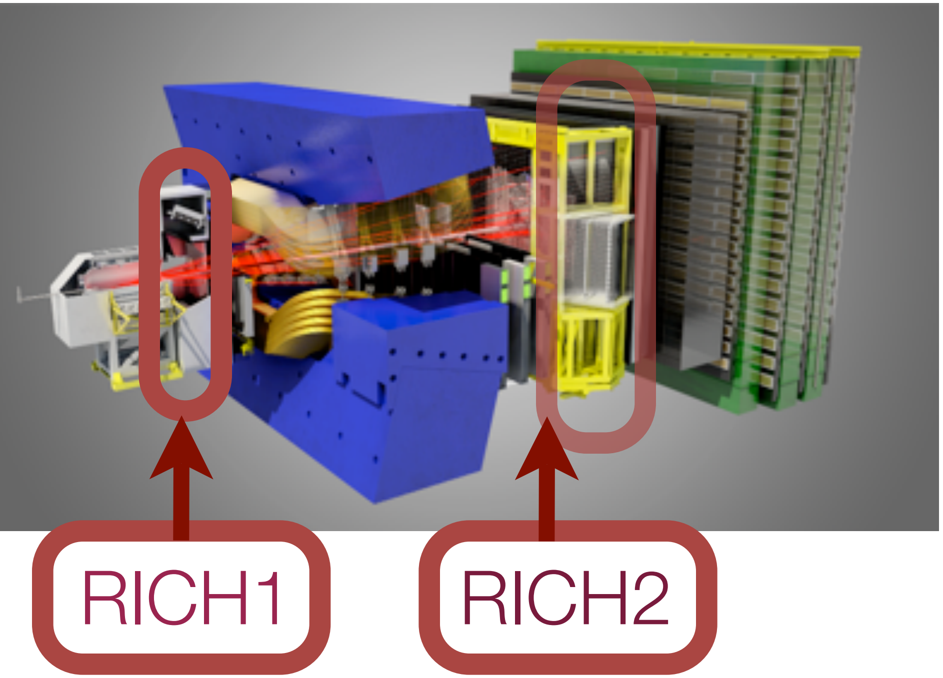
(Also good for c!)

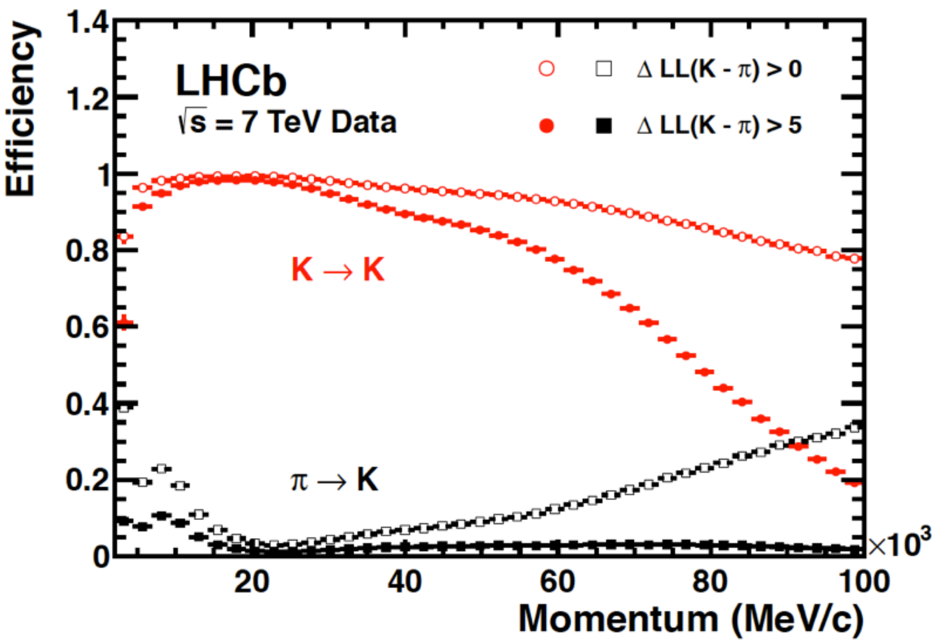


Even More Slides

LHCb Experiment: Particle ID

- Particle ID provided by Ring Imaging Cherenkov (RICH) detectors
  - Particles traveling faster than the speed of light through a medium of refractive index n will emit photons through Cherenkov radiation:
    - $\cos(\theta) = 1/n\beta$
- The Cherenkov angle and the momentum of the particle allows PID.





- The ability to identify particles at LHCb is critical to many of our analyses.

ΔA_{CP} from D* decays

LHCB-CONF-2013-003
1.0fb^{-1} collected during 2011

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

π_s detection asymmetry

Production asymmetry

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

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

Phys.Rev. D80 (2009) 076008

- Indirect and direct CPV can contribute
- Indirect CPV is ~universal
  - Indirect CPV cancels in $A(K^+K^-)-A(\pi^+\pi^-)$ if lifetime acceptance same for KK and ππ
  - If not contribution $A^{ind}[\langle t_{KK}\rangle_{acc} - \langle t_{\pi\pi}\rangle_{acc}]/\tau_0$

LHCb Experiment

- Smooth running of the detector thanks to over 800 members.
- High beam quality provided by the LHC makes our analyses possible.

z ←

D^0 mixing at LHCb

PRL 110, 101802 (2013)
1.0fb^{-1} collected during 2011

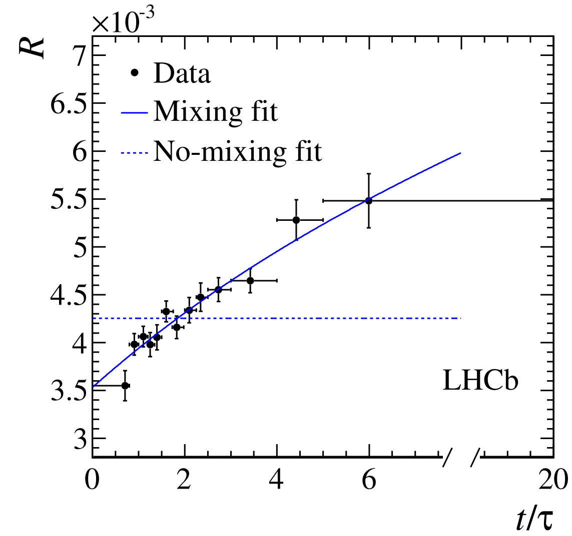
- Take the time-dependent ratio of wrong sign to right sign decays

for no CPV

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} \simeq R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$

$$x' = x\cos(\delta) + y\sin(\delta)$$
$$y' = y\cos(\delta) - x\sin(\delta)$$

strong phase



- Most systematics cancel in ratio

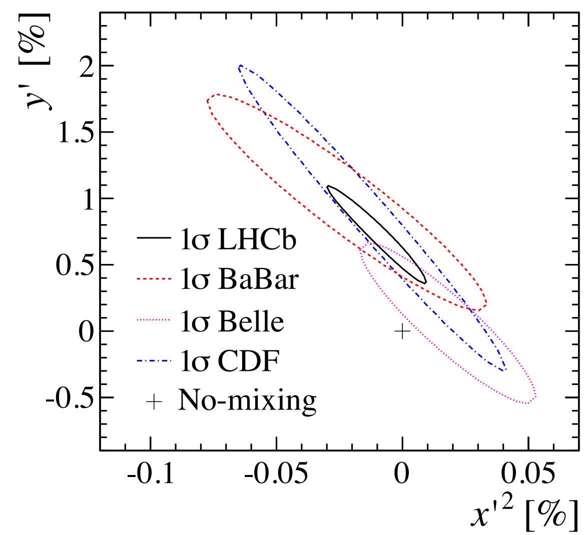
$x'^2 = (-0.09 \pm 0.13)\times 10^{-3}$

$y' = (7.2 \pm 2.4)\times 10^{-3}$

no mixing hypothesis excluded at **9.1σ**

systematics uncertainties are 11% of $\sigma(x'^2)$, 10% of $\sigma(y')$

- First single measurement with over 5σ significance



LHCb 1σ inc. systematics

ΔA_{CP} from semileptonic B decays

arXiv:1303.2614
1.0fb[-1] collected during 2011

$$A_{RAW}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_D(\mu^+) + A_p(B)$$

μ detection asymmetry

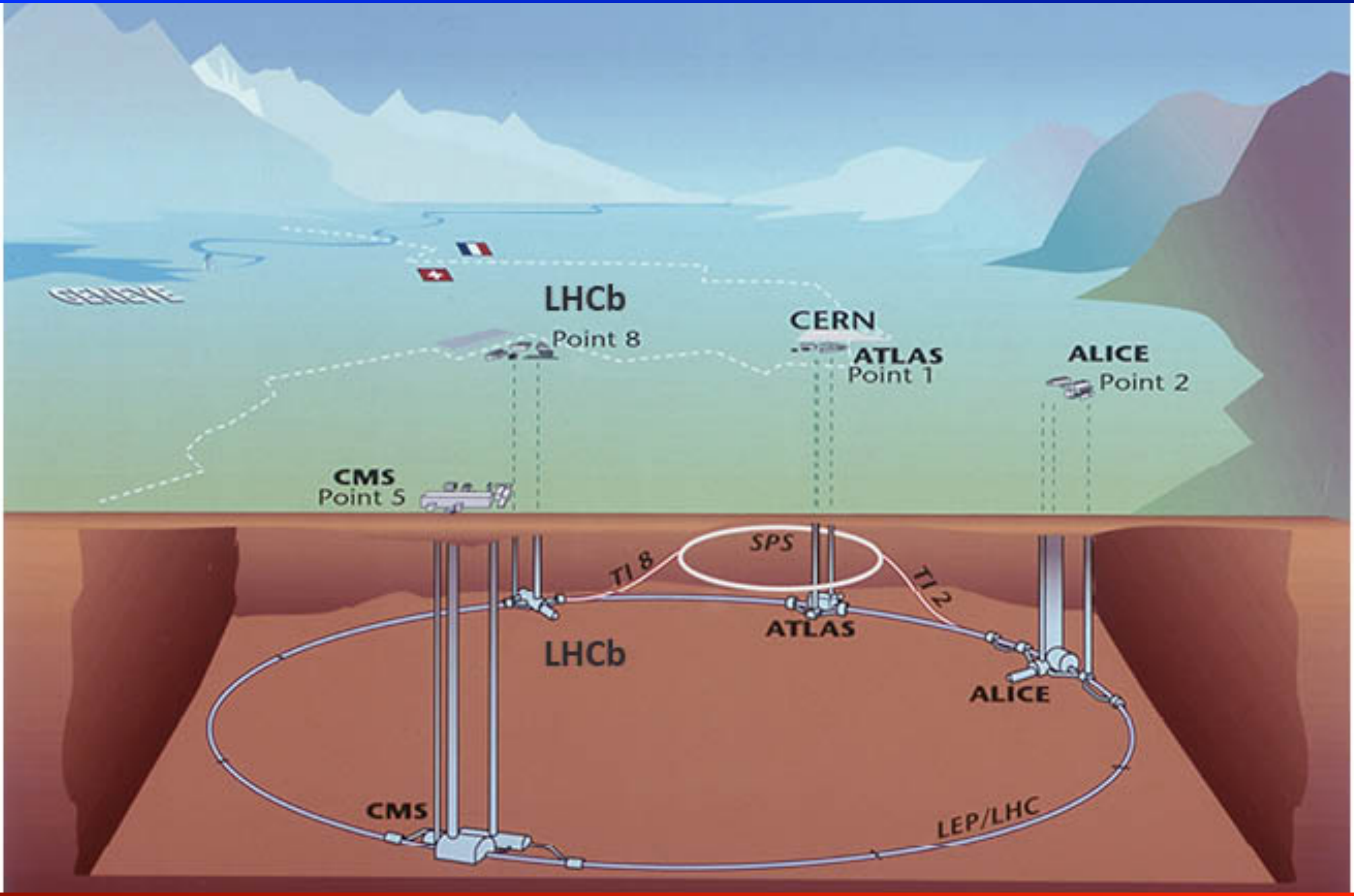
b-hadron production asymmetry

Detection and production asymmetries **independent** from D* analysis

Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and muon detection asymmetries will cancel **if kinematics of muon and B meson are the same for both** $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

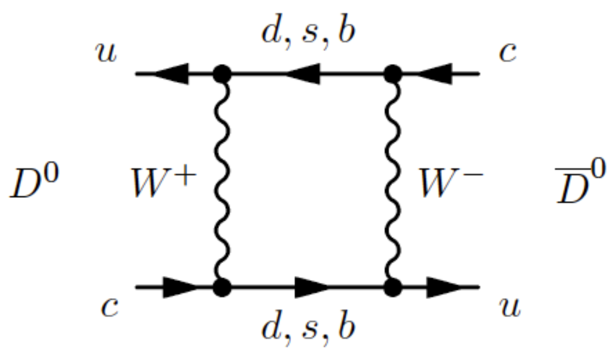
$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

LHCb Experiment

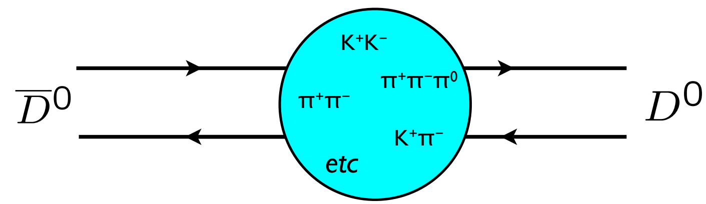


D^0 mixing

- First evidence in 2007 by BaBar and Belle
  - [Phys.Rev.Lett. 98 (2007) 211802, Phys.Rev.Lett. 98 (2007) 211803]



Mixing via box-diagram
Short range



Mixing 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 $\mid D_{1,2}\rangle = p \mid D^0\rangle \pm q \mid \overline{D}^0\rangle$

Size of mixing characterized by $x = \dfrac{m_2 - m_1}{\Gamma}, \qquad y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$

Mixing if **x ≠ 0** or **y ≠ 0**

Common Strategies for D Mixing & CP Violation

- Use control modes / normalization channels for initial studies with data
- Perform systematic studies on data
  - Prompt-secondary distinction
  - Lifetime acceptance correction
- Using prompt charm
  - More events
  - Need to measure contribution from secondary
- Using charm from B decays
  - Lower cross-section, but higher p_T = higher trigger efficiency
  - Need to precisely measure D production vertex

Mixing using WS Kπ decays

- Two contributions to decay:
  - DCS decay
  - CF decay after D0 mixing

$$
\begin{aligned}
R_M &= (x^2 + y^2)/2 = (x'^2 + y'^2)/2 \\
x' &\equiv x \cos\delta + y \sin\delta \\
y' &\equiv y \cos\delta - x \sin\delta
\end{aligned}
$$

$$
r_{\mathrm{WS}}(t) \propto e^{-\Gamma t}\left(R_D + \sqrt{R_D}\,y'(\Gamma t) + \frac{1}{2}R_M(\Gamma t)^2\right)
$$

- Measure time x'^2 and y' in evolution of WS decays
- δ: relative strong phase between two decay amplitudes
- R_D: ratio between DCS decay rate and CF decay rate
- BR(WS) ~ BR(RS) / 250
- WS selection needs to be much tighter than RS to suppress background
- Expect dataset for significant improvement in mixing measurement in the course of next year

y_{CP} & A_Γ

- Two ways to measure CPV in mixing:
  - Lifetime ratio y_{CP} shows CPV if different from y

$$y_{CP} = \frac{\Gamma(CP\ \text{even}) - \Gamma(CP\ \text{odd})}{\Gamma(CP\ \text{even}) + \Gamma(CP\ \text{odd})} = \frac{\hat{\tau}(D \to \pi^+ K^-)}{\hat{\tau}(D \to K^+ K^-)} - 1 = y\cos\phi - x\sin\phi\,\frac{A_m}{2}$$

  - Lifetime difference in decay to CP eigenstate shows CPV if ≠0

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} = \tfrac{1}{2}A_M y\cos\phi - x\sin\phi$$

- y_{CP}: can use untagged D⁰ decays

y_{CP} = $(1.107 \pm 0.217)\%$ current world-average dominated by BaBar using 2.7M Kπ and 260k KK events in 0.38/ab
BaBar: Phys.Rev.D80:071103,2009

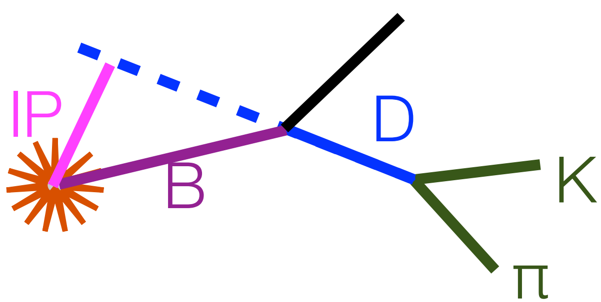
- A_Γ: need flavor-tagged D⁰ decays...
  - $D^{*+} \to D^0\pi^+$, $D^{*-} \to \bar{D}^0\pi^-$
  - The slow pion tags the flavor of the D⁰.

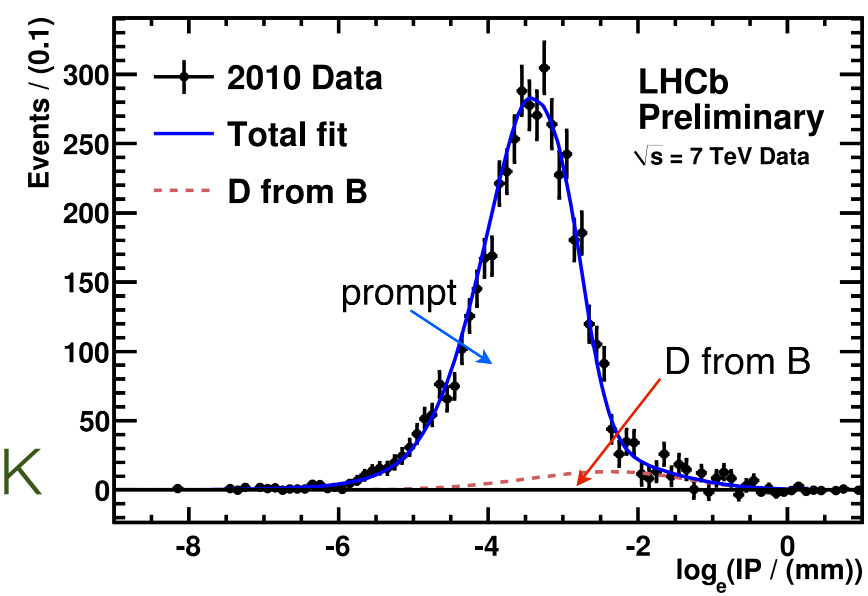
A_Γ = $(0.123 \pm 0.248)\%$ current world-average based on ~2M Kπ, ~180,000 KK, ~80,000 ππ events at BaBar + Belle
Belle: Phys.Rev.Lett.98:211803,2007
BaBar: Phys.Rev.D78:011105,2008

$A_m = |q/p|^2 - 1$ and $\varphi = \arg(q/p)$ parameterize CPV in mixing – very small in SM

Prompt-Secondary Separation

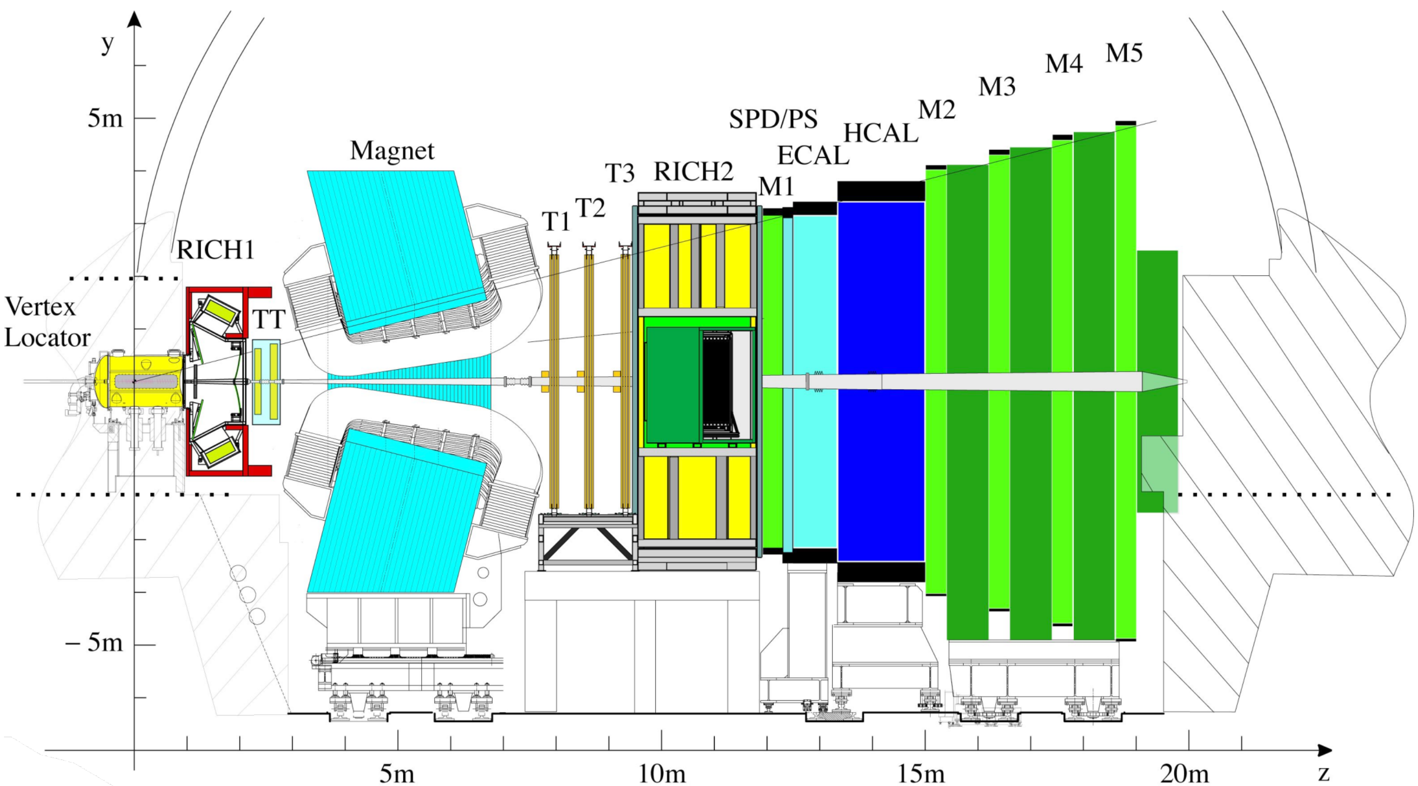
- Separate prompt and secondary charm
  - Prompt charm
    - Defined as charm mesons produced at the primary interaction point.
    - This includes if they are from quickly decaying resonances
      - Examples: via D* decays, ψ(3770)
  - Secondary charm
    - Residual background from charm mesons decaying from long-lived particles.
- We can measure the prompt fraction
  - Look at impact parameter distribution of the charm meson



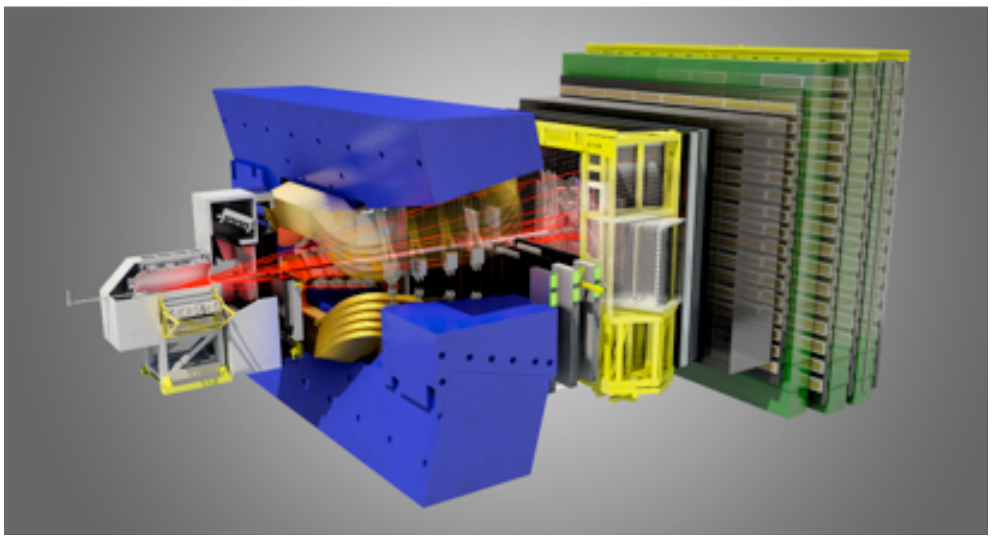


Experiment Overview (2)

- Accurate decay time resolution from our vertex locator (VELO)
- Particle ID provided by Ring Imaging Cherenkov (RICH) detectors
- High muon reconstruction efficiency from muon stations
- Good momentum resolution from tracking stations, Δp/p = 0.35% — 0.55%

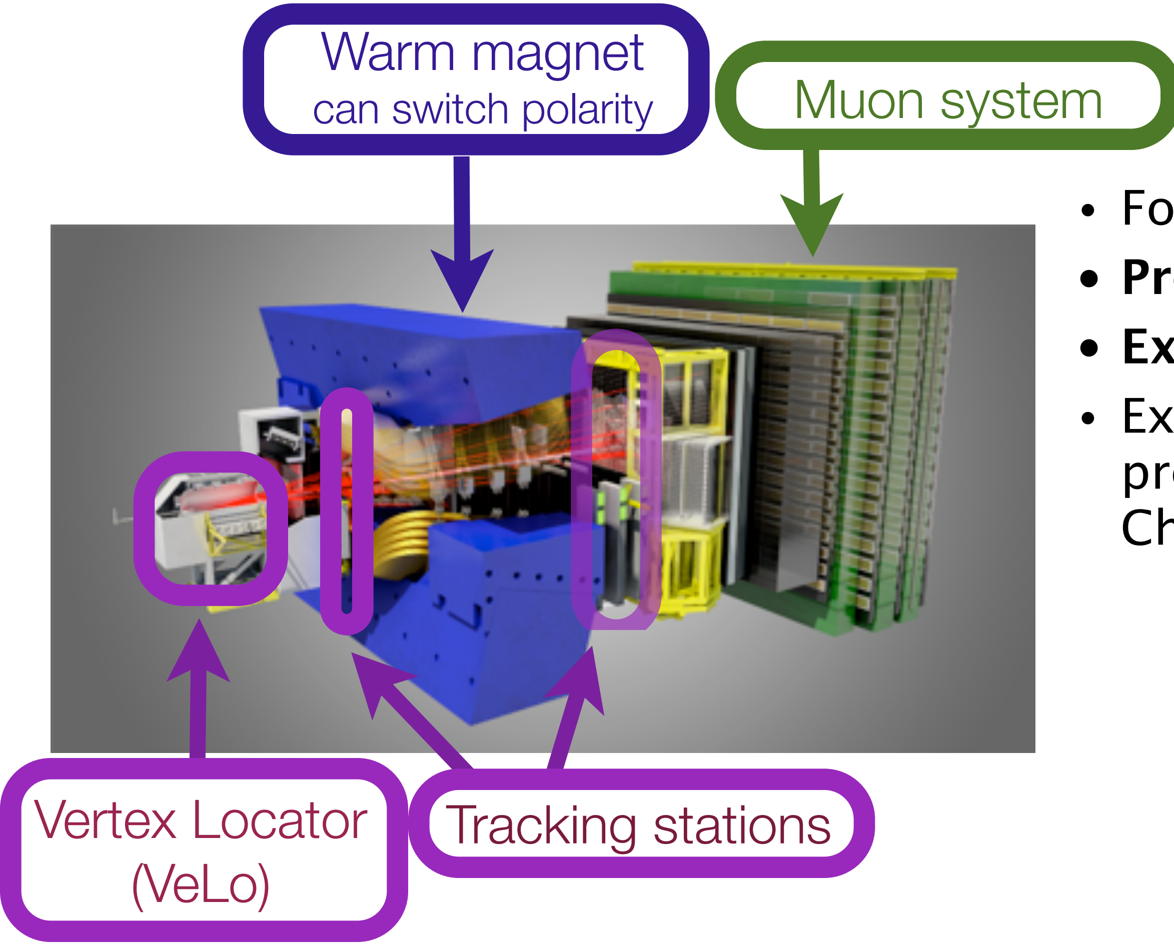


LHCb detector



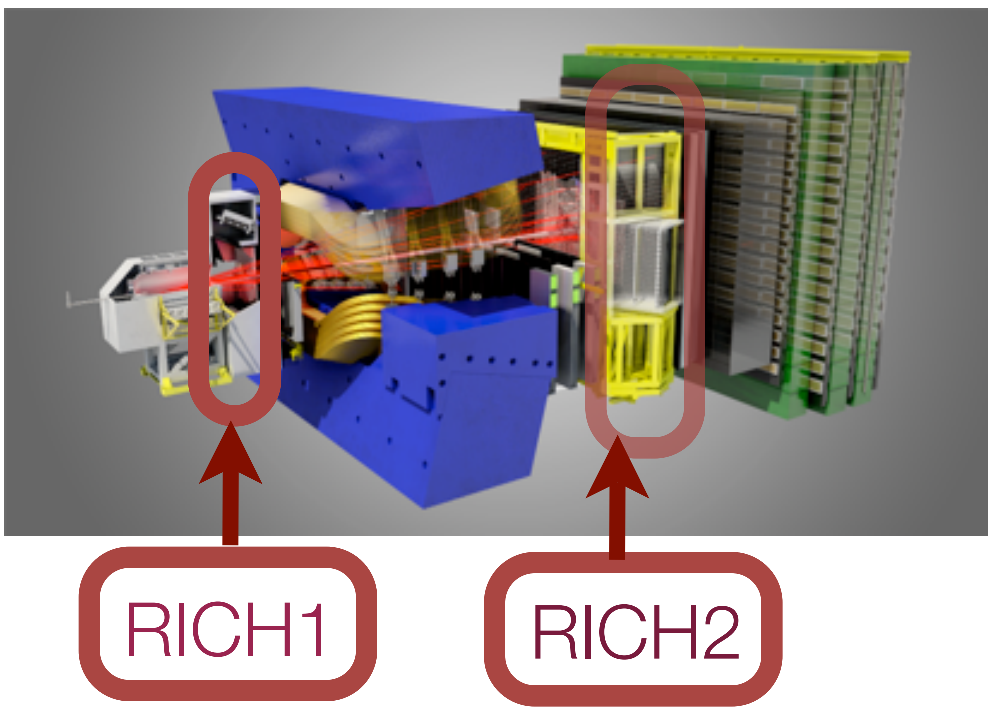
- **Forward detector**
- Precision tracking
- Excellent vertex resolution
- Excellent K/π separation provided by two Ring Imaging Cherenkov detectors

LHCb detector



- Forward detector
- **Precision tracking**
- **Excellent vertex resolution**
- Excellent K/π separation provided by two Ring Imaging Cherenkov detectors

LHCb detector



- Forward detector
- Precision tracking
- Excellent vertex resolution
- **Excellent K/π separation provided by two Ring Imaging Cherenkov detectors**

Luminosity

- **1.0 fb^{-1} at 7 TeV** collected by LHCb in **2011**
  - **Today's Analyses**
- 2 fb^{-1} at 8 TeV collected by LHCb in 2012 (future analyses)

- Nominal instantaneous luminosity: $\mathscr{L} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- LHCb instantaneous luminosity kept constant (luminosity leveling).