Measurement of mixing and CPV parameters in two-body decays at LHCb

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on behalf of the LHCb collaboration

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LHCb

Overview

- Introduction
- Mixing & indirect CPV:
  - y_{CP} and A_Γ in $D^0 \to K^- K^+$, $D^0 \to K^- \pi^+$
  - Wrong-sign $D^0 \to K^+ \pi^-$
- Time-integrated searches for CPV
- Conclusions

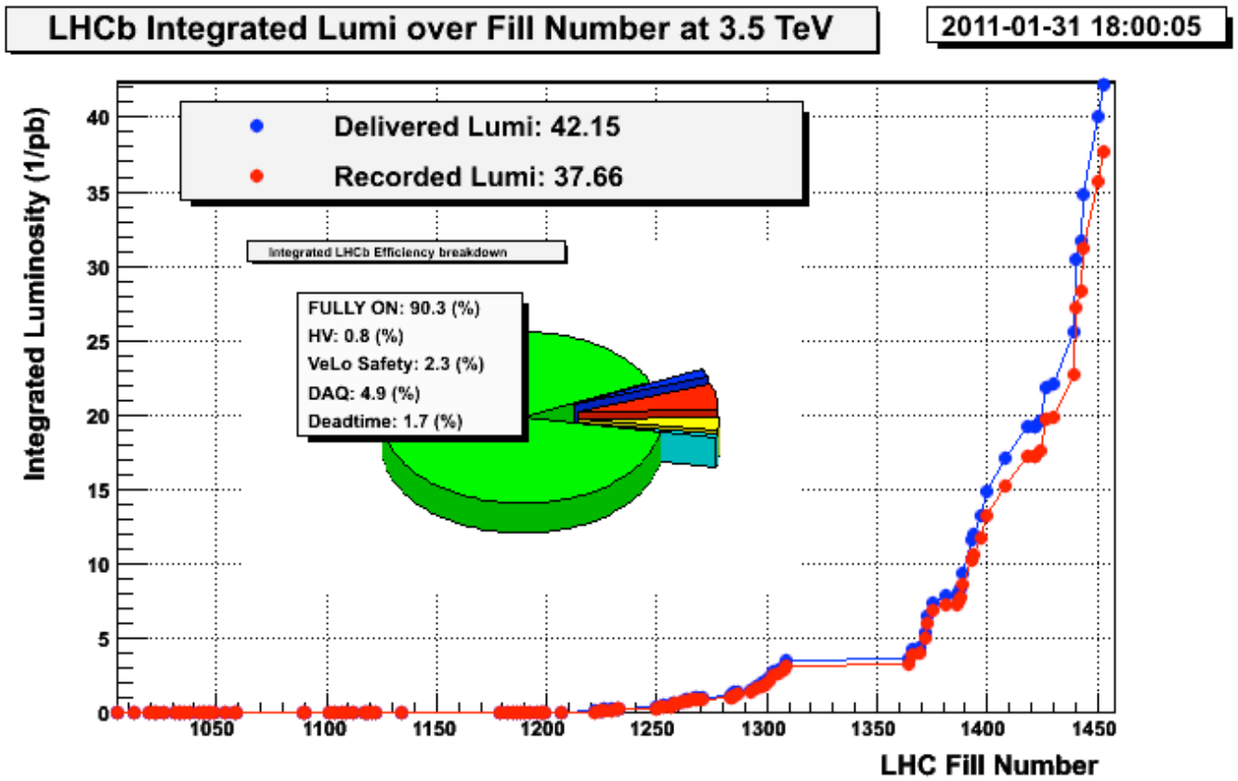
Physics goals of LHCb

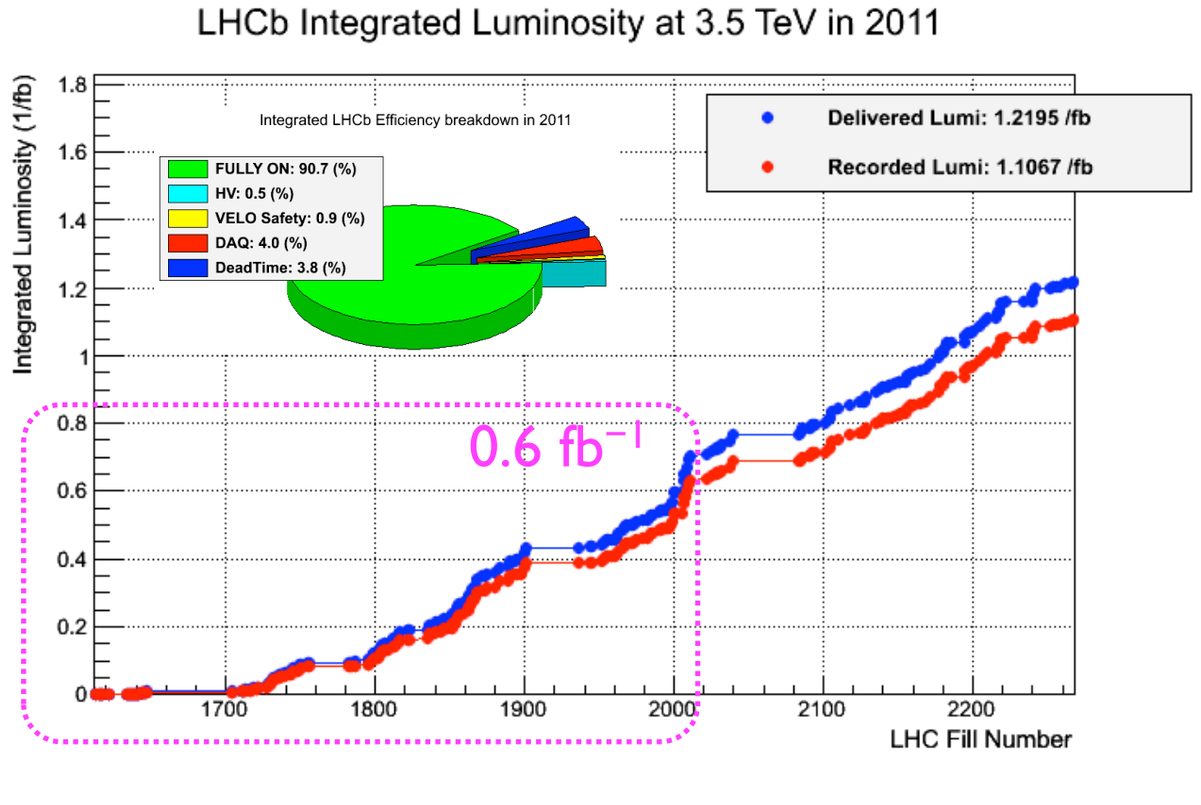
- Main strategy: indirect searches for NP in b, c decays.
  - Look for evidence of new, heavy particles in loop diagrams
  - Complementary to ATLAS/CMS direct searches
  - ... and a broader physics program too, e.g. forward electroweak
- Why heavy flavour?
  - In short: an excellent source of loop diagrams.
  - CP violation: SM CPV insufficient to explain baryogenesis
  - Rare decays: Tiny & precise SM predictions, enhanced by many NP models
- Why at the LHC?
  - Enormous $b\bar{b}$, $c\bar{c}$ cross-sections -- precision is the name of the game
  - Also: high momentum/boost great for time-dependent measurements

In our acceptance: $\sigma(c\bar{c})$=1200μb and $\sigma(b\bar{b})$=75μb.
So in 1 fb^{-1} roughly 10^{12} $c\bar{c}$ and 10^{11} $b\bar{b}$ produced!

Phys. Lett. B694: 209-216, 2010
LHCb-CONF-2010-013

Data-taking





2010: 38 pb^{-1}

2011: 1 fb^{-1}

- Factor 30 more integrated luminosity in 2011
- Luminosity-leveling working nicely to control pile-up.

CP violation in charm

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

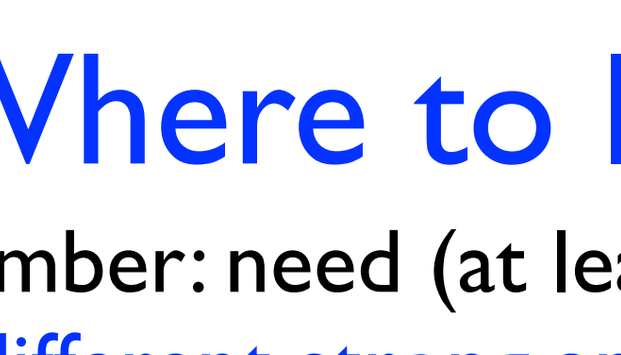
Indirect

- In the SM, indirect CP violation in charm is expected to be very small and nearly 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 generic singly-Cabibbo-suppressed modes: up to $O(10^{-3})$ plausible, and few × 10^{-3} possible -- see Soumitra & Joachim's talks.
- 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)
Giudice, Isidori & Paradisi, arXiv:1201.6204
Feldmann, Nandi & Soni, arXiv:1202.3795
... and more...

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.*

- Doubly Cabibbo-suppressed decays:
  - Much lower SM background to CPV => good sensitivity to NP.
  - But low BF => need lots of data!

Mixing & indirect CPV with $D^0 \to h^- h'^+$

Standard mixing formalism

Mixing occurs for neutral mesons M^0 = K^0, D^0, B^0, B_s^0

Decompose into mass eigenstates $|M_{1,2}\rangle$:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad \text{for} \quad |q|^2 + |p|^2 = 1$$

$$|M_{1,2}(t)\rangle = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}|M_{1,2}(t=0)\rangle$$

... and we can invert to get $|M^0(t)\rangle$ given $m_{1,2}$, $\Gamma_{1,2}$, q/p...

General time evolution:

$$|M(t)\rangle = \frac{1}{2p}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

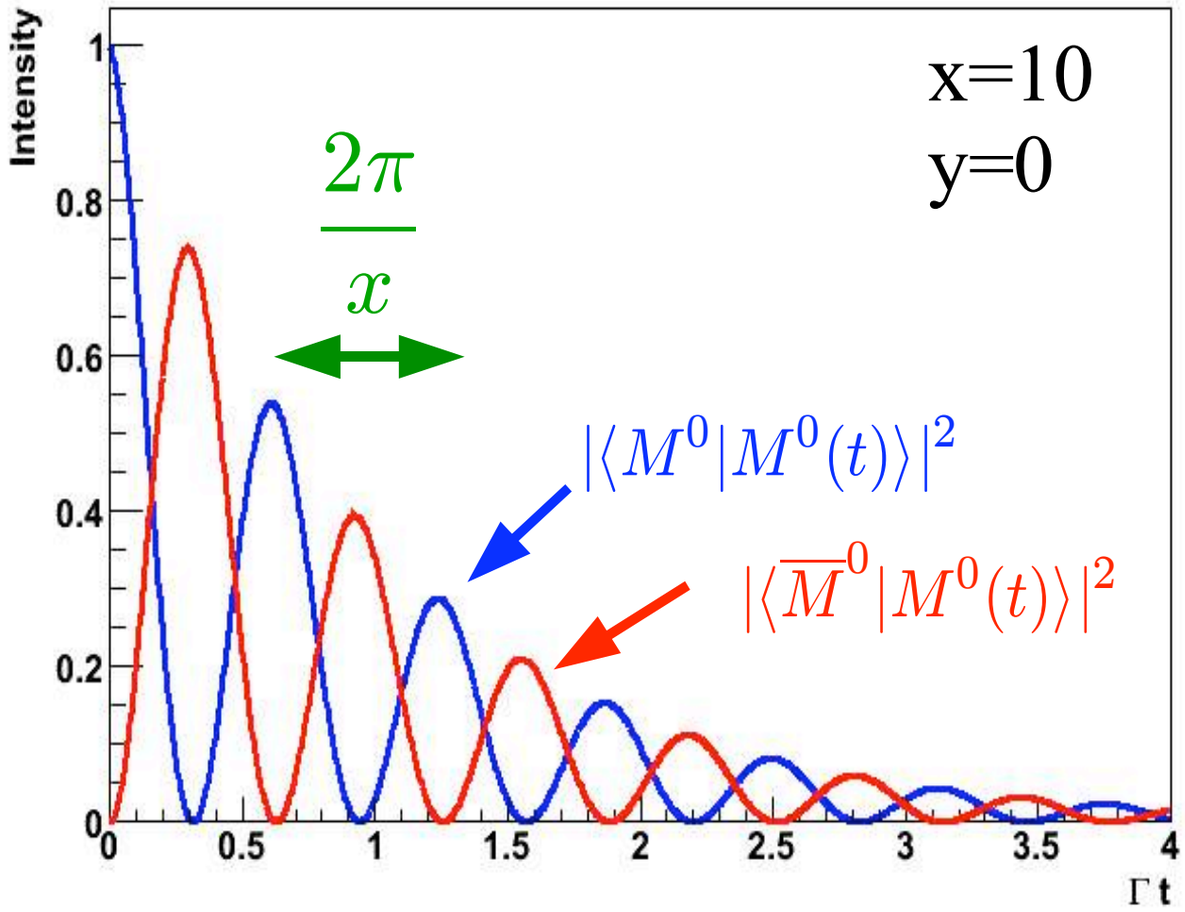
$$|\overline{M}(t)\rangle = \frac{1}{2q}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

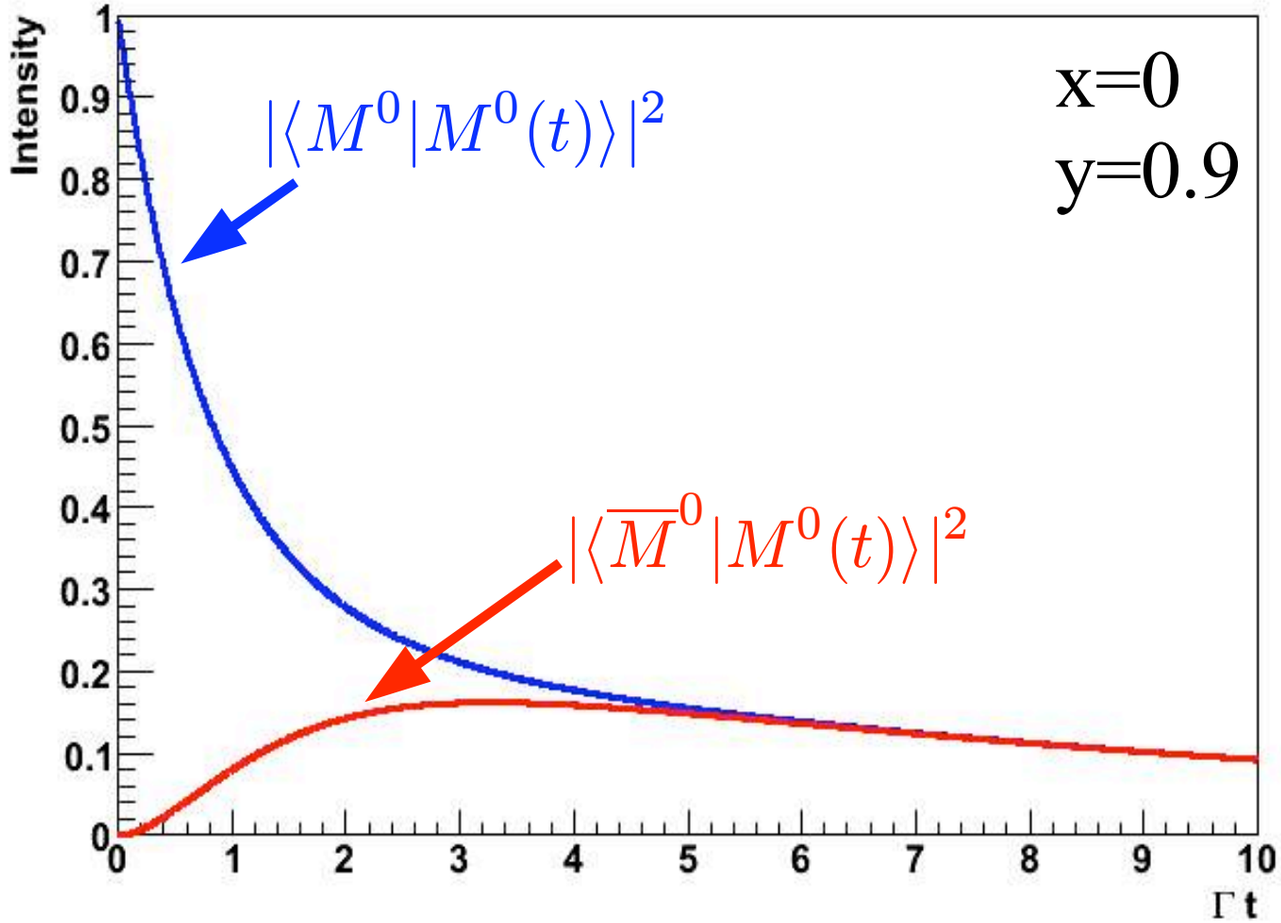
Cartoon of mixing

For convenience, define:

$$\Gamma = \frac{\Gamma_2 + \Gamma_1}{2} \qquad x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

and $R_M = \dfrac{x^2 + y^2}{2}$

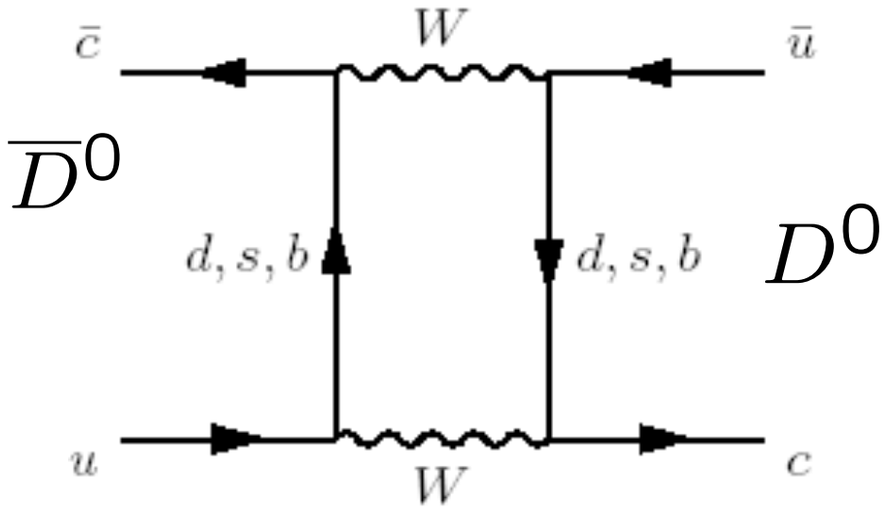




Mixing in charmed mesons

Charm mixing small compared to other mesons in SM:

Mixing via box diagram (short-range)



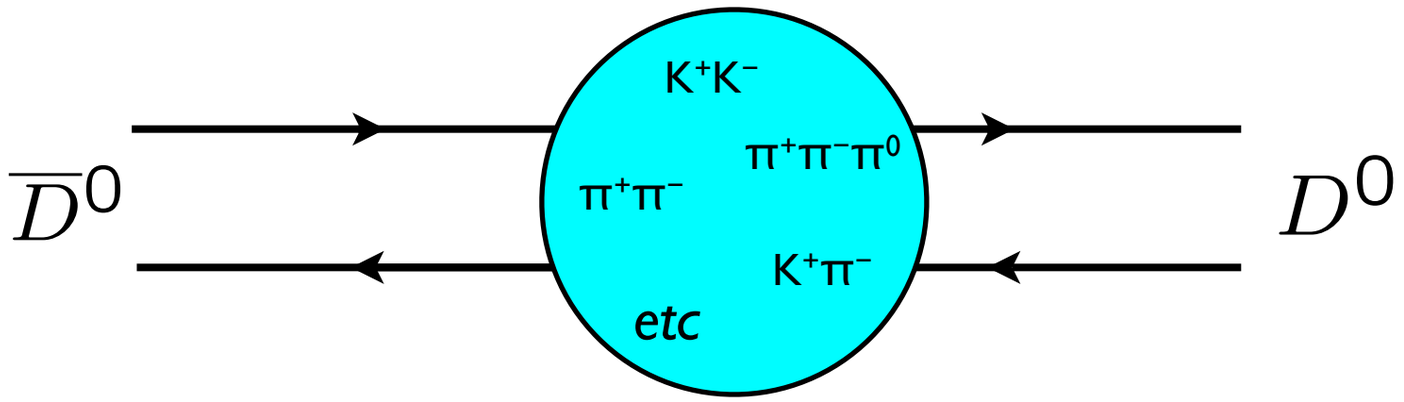
Contributes mainly to x

Intermediate b: CKM-suppressed
Intermediate d,s: GIM-suppressed

$$x \propto \frac{(m_s^2 - m_d^2)^2}{m_c^2} \sim 10^{-5}$$

Tiny!

Mixing via hadronic intermediate states (long-range)



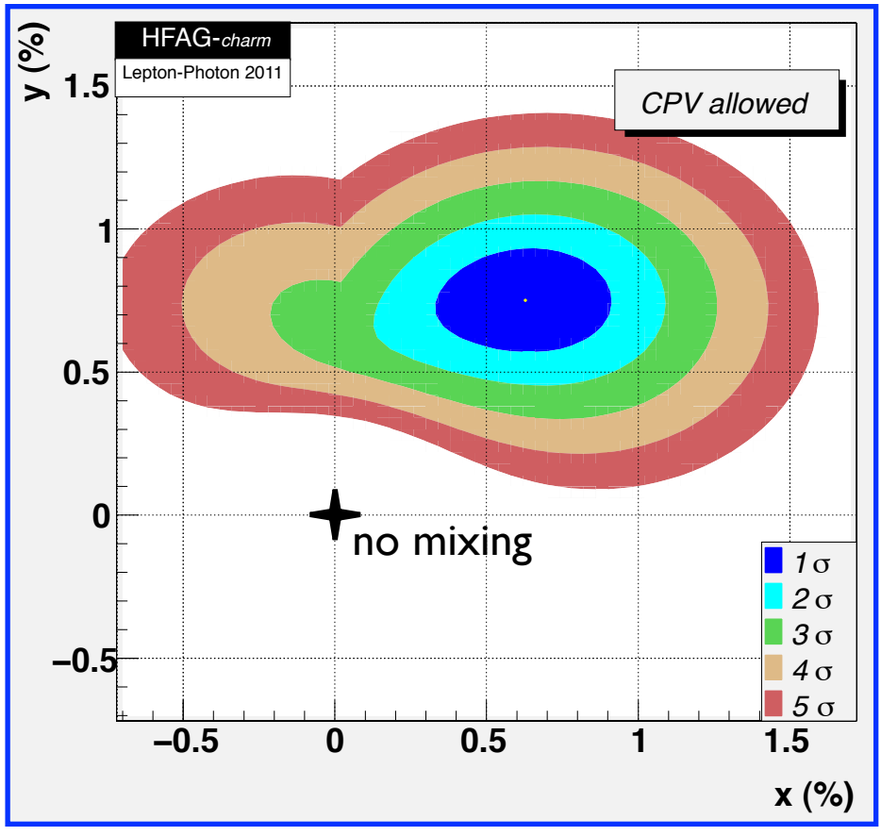
Non-perturbative; hard to predict SM contribution.

Currently: $|x| \leq 0.01$, $|y| \leq 0.01$ – less tiny!

e.g. PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

Mixing and indirect CPV

- D^0 mesons undergo mixing like K^0, B^0, $B_s{}^0$
- But unlike the others, D^0 mixing is small.
  - Mixing parameters x, y order of 10^{-2}
- First seen by BABAR & Belle in 2007
- Now well-established: HFAG average → excludes no-mixing hypothesis by 10σ
- Smallness of mixing parameters makes CP asymmetries doubly small, e.g.

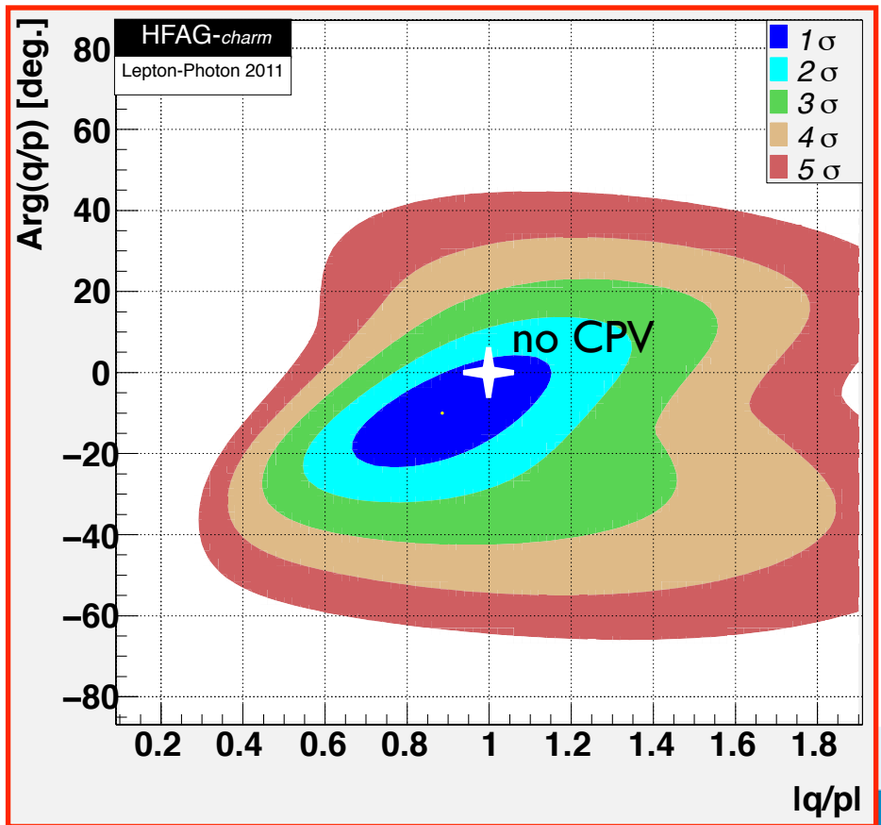


$$A_\Gamma \equiv \frac{\tau(\overline{D}{}^0 \to K^-K^+) - \tau(D^0 \to K^-K^+)}{\tau(\overline{D}{}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)}$$

$$\approx \frac{1}{2}(A_m + A_d)\, y \cos\phi - x \sin\phi$$

Mixing parameters $O(10^{-2})$

CP-violating terms < 10^{-2} in SM



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

Two-body analyses

- Two basic paths here:
  - Compare lifetimes of final states with different CP. Gives access to y_{CP}, A_Γ.
  - Measure time-dependent ratio of wrong-sign to right-sign decays. Gives access to y', (x^2+y^2), indirect CPV.
- Each has different experimental challenges.
  - y_{CP} has best statistical precision, but toughest systematics because we compare two different final states (e.g. $D^0 \to K^- \pi^+$ to $K^- K^+$).
  - WS/RS ratio has the nice feature that the final states are identical (save tagging pion charge), but low BR and high relative background from double mis-ID.
- NB: Multi-body decays covered elsewhere.

Lifetime ratios

Define $y_{CP} = \dfrac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$

$D^0 \to K^- \pi^+$: Mixture of CP states

$D^0 \to K^- K^+$: CP-even eigenstate

y_{CP} related to y and CP parameters by:

$$y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$$

$A_M \neq 0$: CPV in mixing (asymmetry in R_M between D^0 and D^0)

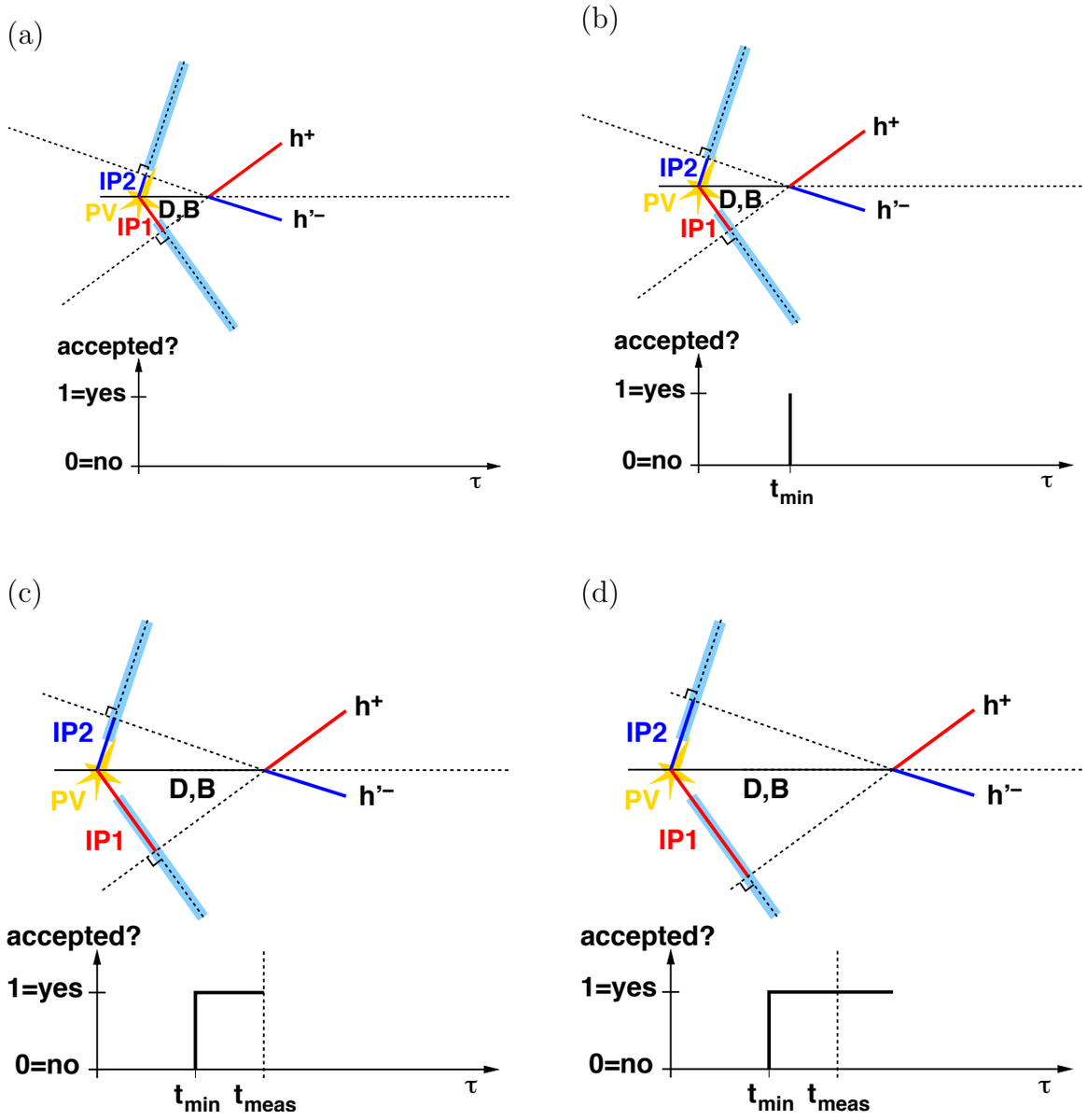
$\cos\phi \neq 1$: CPV in interference between mixing and decay

CP observable A_Γ defined as before:

$$\begin{aligned} A_\Gamma &\equiv \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^-K^+)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)} \\ &\approx \frac{1}{2}(A_{\rm m} + A_{\rm d})\, y\cos\phi - x\sin\phi \end{aligned}$$

Dealing with lifetime bias

- Swimming technique used at CDF (and DELPHI, and NA11)
- Ideally suited to LHCb where our software trigger can be recreated exactly offline.



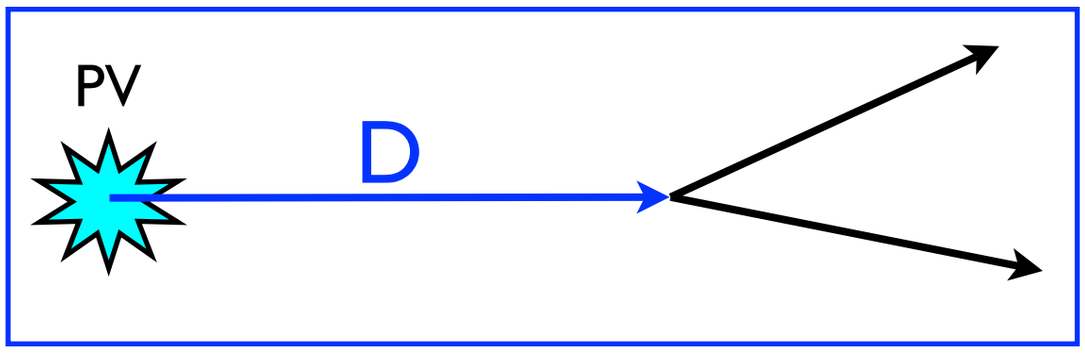
Trying to measure how acceptance varies with lifetime candidate-by-candidate.

... so that we can pull it directly from the data instead of having to model it on signal MC.

Ideally, would shift D^0 decay vertex, but this is a nightmare (imagine trying to move VELO hits).

Instead, shift primary vertex in opposite sense (*nearly* the same thing; systematic for difference)

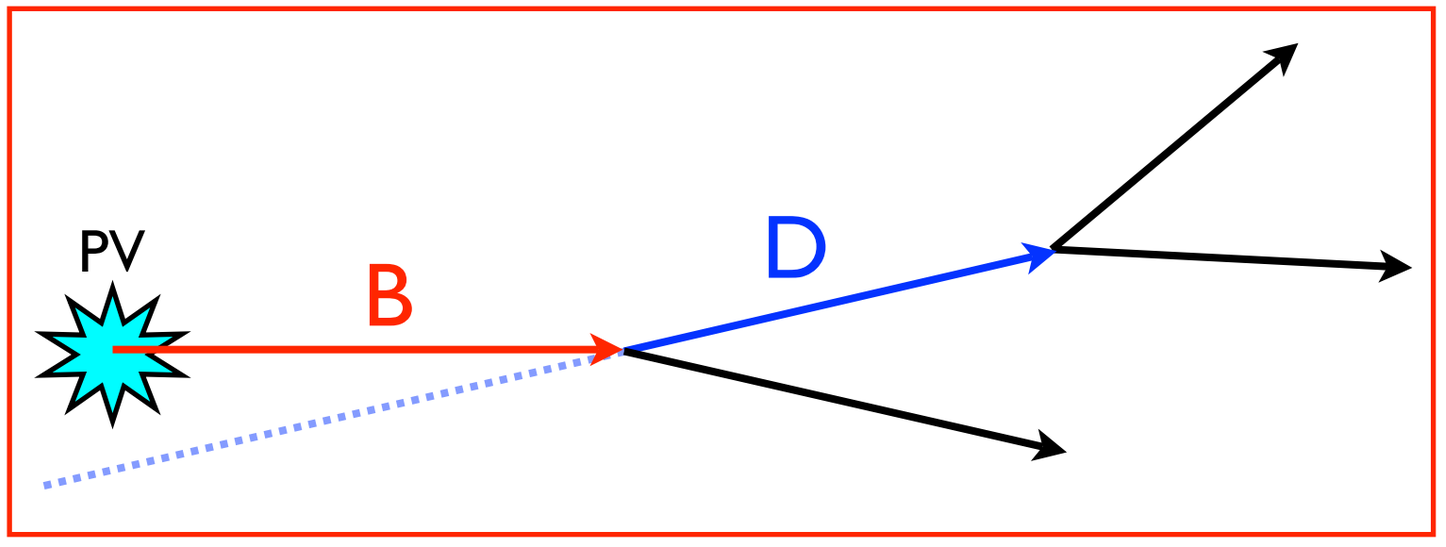
Prompt-secondary discrimination



Prompt charm:

D points to primary vertex

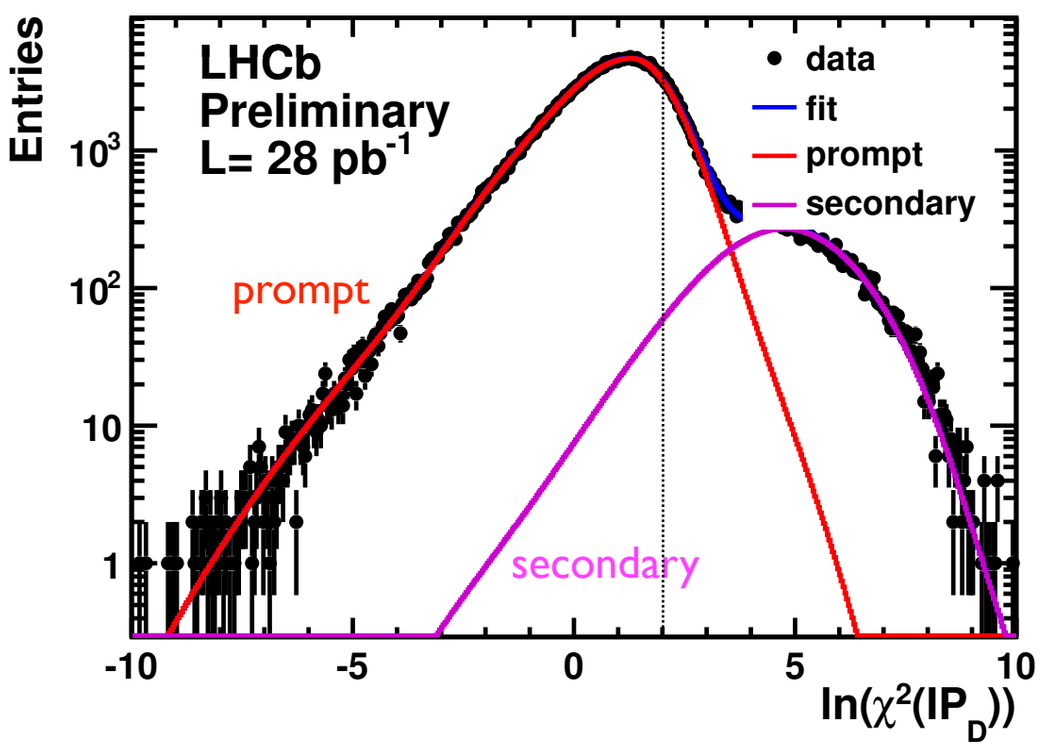
Daughters of D don't in general

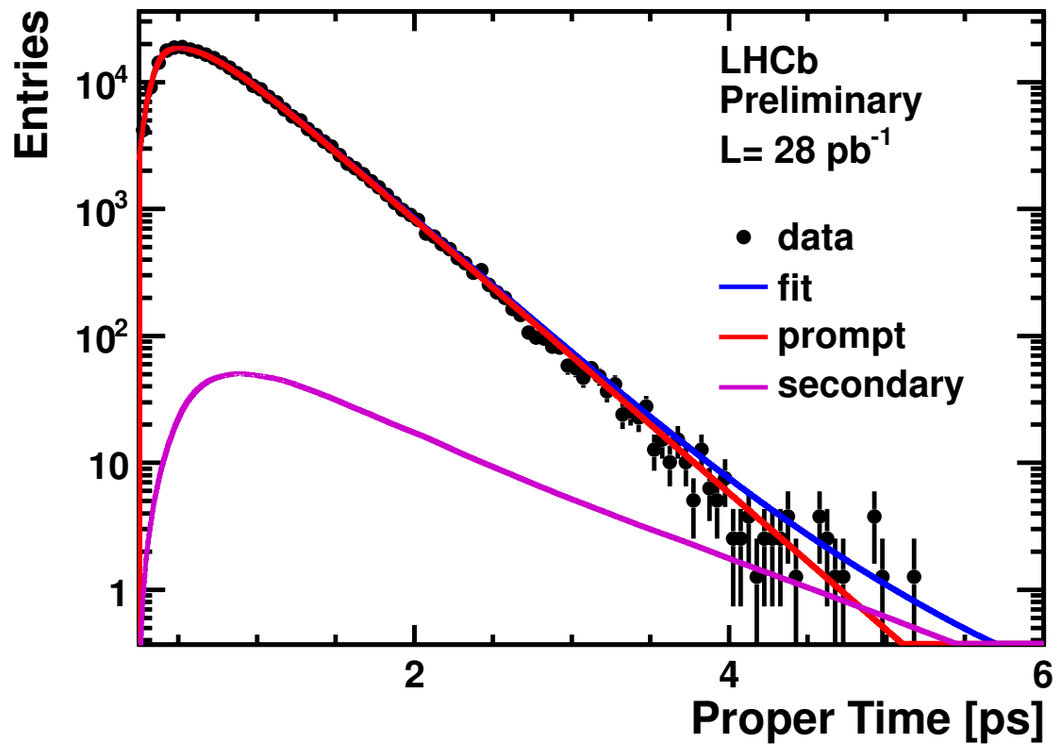


Secondary charm:

D doesn't point to PV in general

- Use impact parameter χ^2 to distinguish between these.
- 2D fit to (time, IP χ^2). 1D projections for tagged $D^0 \to K^- \pi^+$:





nb log y-axis

Cut of $IPX^2<2$ applied in final fit to reduce secondary contamination

Results for y_{CP} in 2010 data

- Lifetime of $D^0 \to K^- \pi^+$: 410.2 ± 0.9 fs (stat err only)
  - Important test of the method. Compare to world-avg: 410.1 ± 1.5 fs
- $y_{CP} = (5.5 \pm 6.3 \pm 4.1) \times 10^{-3}$
- Dominant uncertainties from background.
  - Will be easier to control in 2011 after improvements to trigger
  - Statistical component in secondary charm uncertainty -- again, will improve with 2011 data.

29 pb^{-1}
arXiv:1112.4698
(accepted by JHEP)

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

HFAG world avg: y_{CP} = (1.107 ± 0.217)%

Indirect CPV: A_Γ in 2010 data

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

$$\approx \frac{1}{2}(A_m + A_d)\, y \cos\phi - x \sin\phi$$

29 pb^{-1}
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- $A_\Gamma = (-5.9 \pm 5.9 \pm 2.1) \times 10^{-3}$
- Systematic uncertainties smaller
  - Better cancellation since both final states use the same D^0 decay mode.
  - Again, background effects dominate and will improve with more data.

Table 1: Summary of systematic uncertainties.

Effect	A_Γ (10^{-3})
VELO length scale	negligible
Turning point bias	negligible
Turning point scaling	± 0.1
Combinatorial background	± 1.3
Proper time resolution	± 0.1
Minimum proper-time cut	± 0.1
Maximum proper-time cut	± 0.2
Secondary charm background	± 1.6
Total	± 2.1

HFAG world avg: $A_\Gamma = (0.123 \pm 0.248)\%$

Does not include recent Belle measurement of $A_{CP}(D^0 \to K_S\, \pi^0)$

Wrong-sign $D^0 \to K\pi$

Three contributions with different lifetime dependence:

$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}}_{\text{Interference}}(\Gamma t) + \underbrace{\frac{x'^2 + y'^2}{4}}_{\text{Mixing}}(\Gamma t)^2\right)$$

[Limit of $|x| \ll 1$, $|y| \ll 1$, and no CPV.]

Wrong-sign $D^0 \to K\pi$

Three contributions with different lifetime dependence:

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[Limit of $|x| \ll 1$, $|y| \ll 1$, and no CPV.]

Note primes: x and y are rotated by a strong phase.
(Phase between CF and DCS amplitudes; a priori unknown.)

Wrong-sign $D^0 \to K\pi$

Three contributions with different lifetime dependence:

$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}}_{\text{Interference}}(\Gamma t) + \underbrace{\frac{x'^2 + y'^2}{4}}_{\text{Mixing}}(\Gamma t)^2 \right)$$

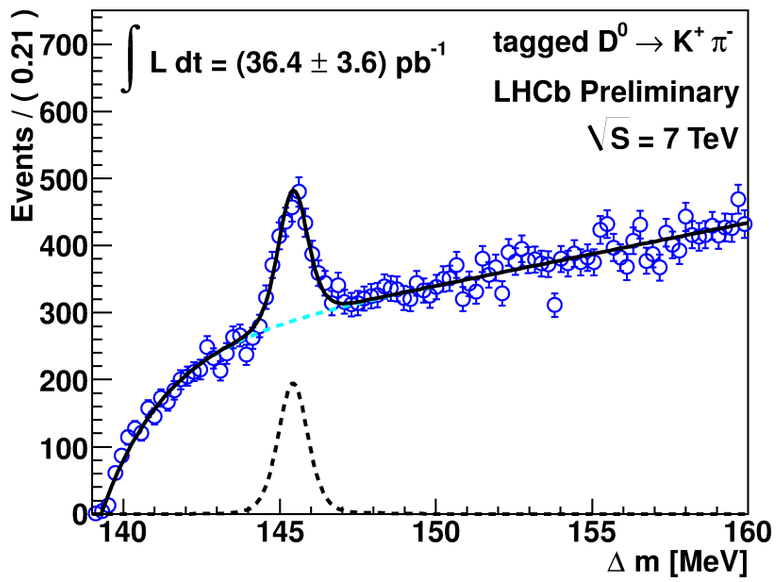
[Limit of $|x| \ll 1$, $|y| \ll 1$, and no CPV.]

Our lifetime acceptance is not flat => affects relative weighting.

- Start with raw WS/RS time-integrated ratio.
- Determine our efficiency(t) using PDG D0 lifetime as input
- Determine correction using HFAG mixing parameters as input
- Compute lifetime-acceptance-corrected WS/RS ratio.

	WS/RS of $D \to K\pi$ decays (%)
$R_{measured}$	$0.442 \pm 0.033\ (stat.)\ \pm 0.042\ (sys.)$
$R_{acc\,cor}$	$0.409 \pm 0.031\ (stat.)\ \pm 0.039 (sys.)\ ^{+0.028}_{-0.020}\ (sys.\ mixing)$
$R(PDG)$	0.380 ± 0.018

Preliminary: 2010 data, 38 pb^{-1}



Cross-check consistent with PDG average.

LHCB-CONF-2011-029

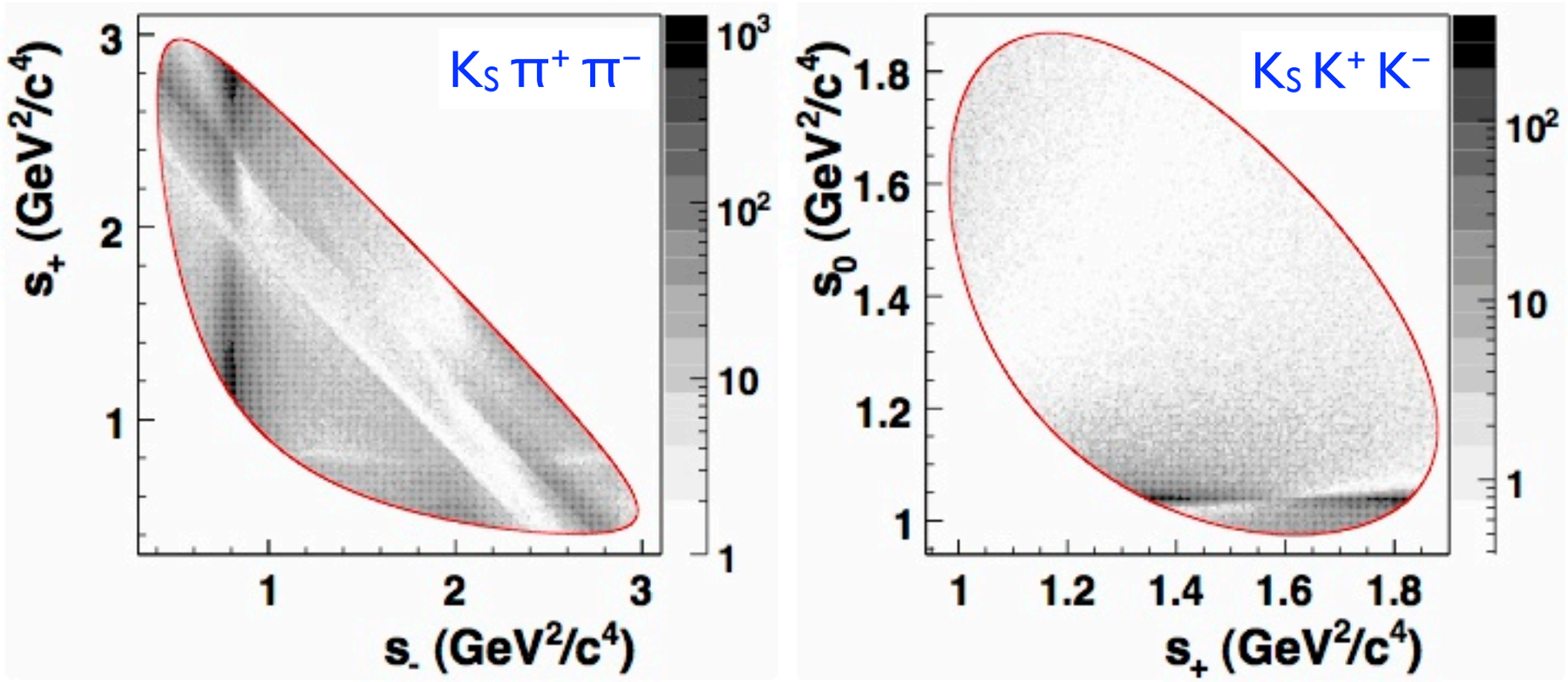
A few words on $D^0 \to K_S\, h^+\, h^-$

A few words on $D^0 \to K_S\, h^+\, h^-$

This is a 2-body decay for sufficiently large values of 2.

Why $D^0 \to K_S h^+ h^-$ is interesting

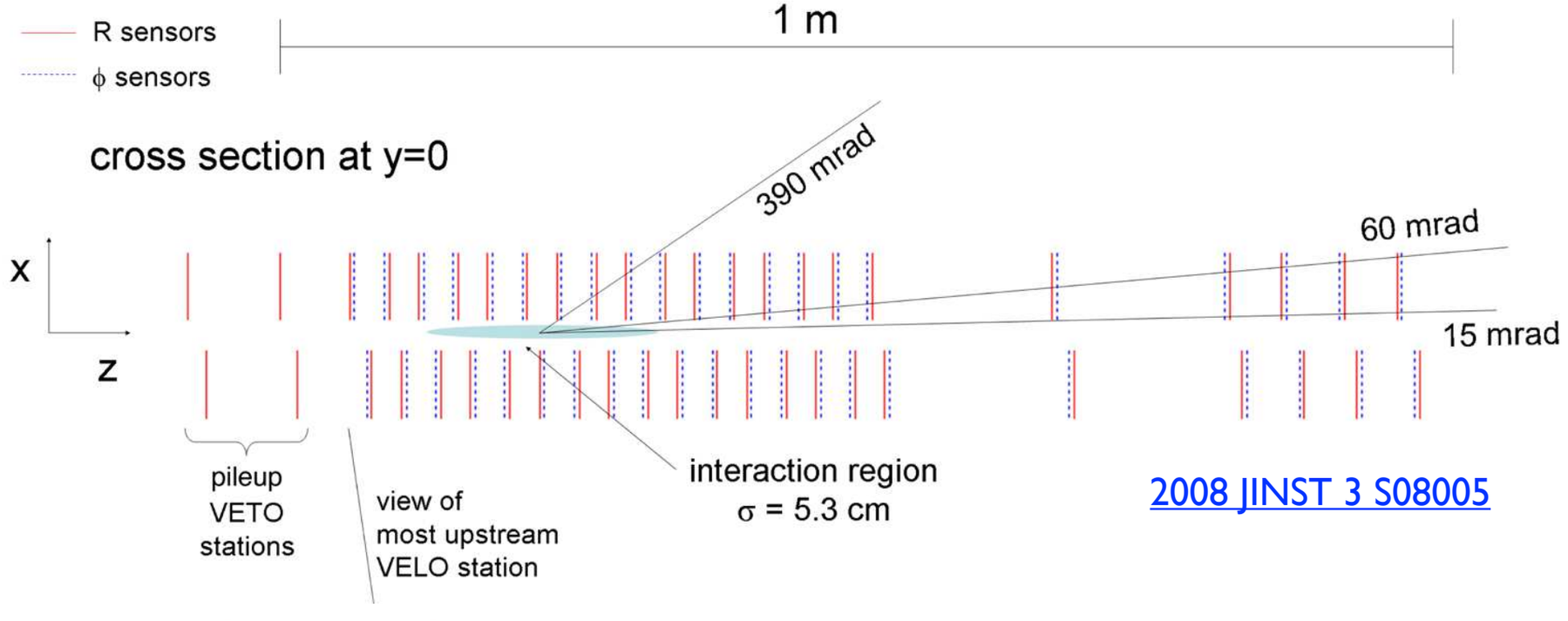
BaBar: Phys. Rev. Lett. 105 (2010) 081803



- Can do time-dependent rate measurement as before...
- ... except this time the CF and DCS amplitudes appear in the same Dalitz plot so you can measure the strong phase δ between them.
  - And more generally, use these + CP eigenstates + interference
- Result: extract x and y directly (and |q/p|, and ϕ)

Belle: Phys. Rev. Lett. 99:131803,2007

Why $D^0 \to K_S h^+ h^-$ is tough



2008 JINST 3 S08005

- This time, our boost hurts us.
  - Average momentum scale of K_S in D^0 decay: 35-40 GeV/c
  - Mean lifetime 90ps => mean distance flown in lab frame: 2 metres
  - Consequence: large majority of K_S daughters don't leave good VELO tracks.
- 2011 data: tagged $D^0 \to K_S \pi^+ \pi^-$ yield from "long tracks" will be smaller than but of same order as Belle, BABAR
- Trigger improvements being deployed for 2012 data-taking (incl. tracking for downstream decays)

Time-integrated asymmetries

Time-integrated asymmetries

- Measured asymmetry includes direct & indirect CPV
- To control systematics, look first at double-differences. (Consequence: indirect component largely cancels)
  - e.g. difference in A_{CP} between $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$
  - e.g. difference in A_{CP} between $D^+ \to K_S \pi^+$ and $D^+ \to \phi \pi^+$
- Efforts to extract individual asymmetries underway, but these are tougher.

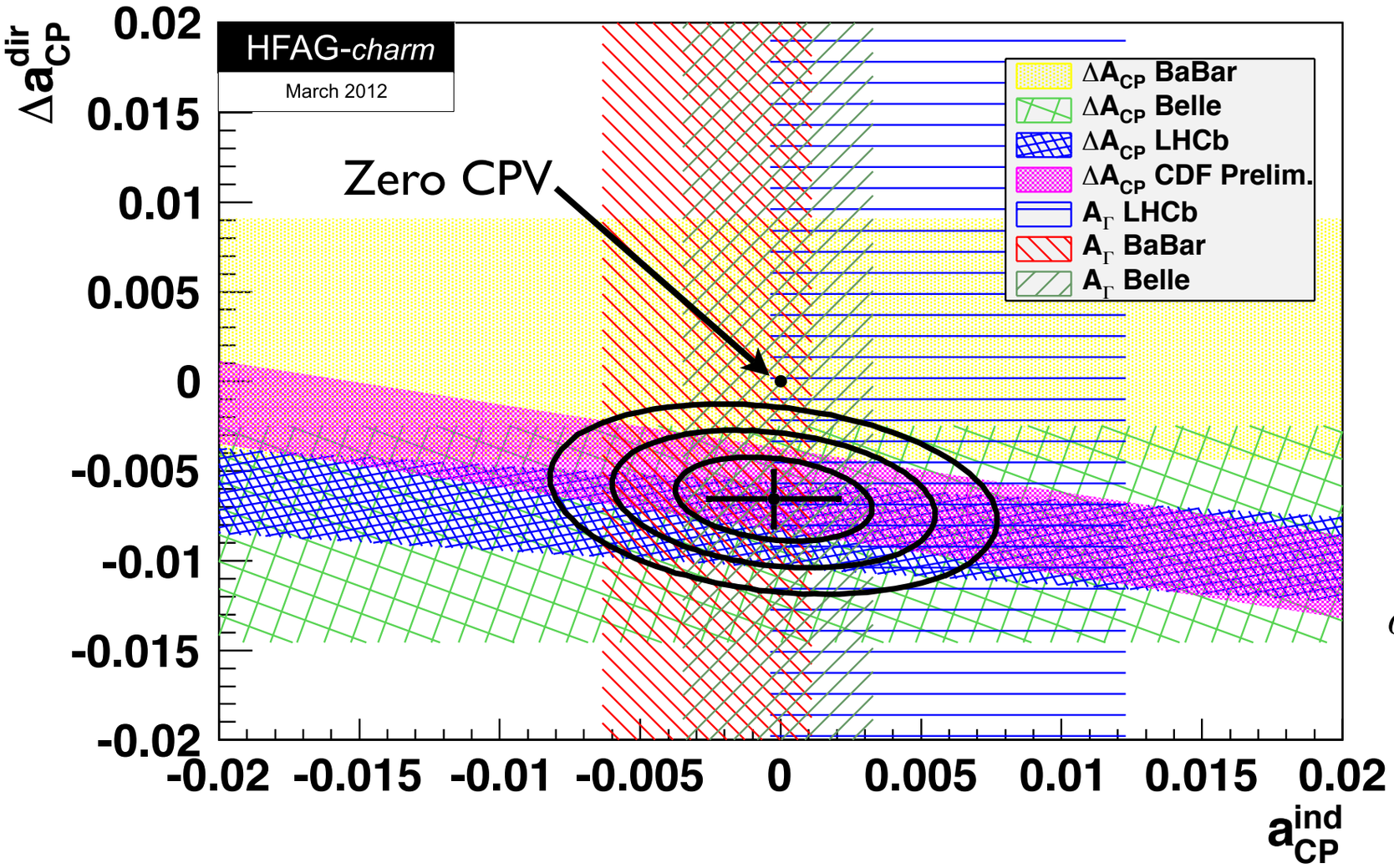
Time-integrated asymmetries in $D^0 \to K^- K^+, \pi^- \pi^+$

$0.6\ fb^{-1}$

Phys. Rev. Lett. 108 (2012) 111602

Indirect vs direct CP violation

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



Consistency with no CPV hypothesis: 6×10^{-5}

$$a_{CP}^{\rm ind} = (-0.025 \pm 0.231)\%$$
$$\Delta a_{CP}^{\rm dir} = (-0.656 \pm 0.154)\%$$

$$a_{CP} \sim a_{CP}^{\rm ind} + a_{CP}^{\rm dir}$$
$$A_\Gamma \sim a_{CP}^{\rm ind}$$

See: CDF, Phys. Rev. D 85, 012009 (2012).
See also: Bigi, Paul & Recksiegel, JHEP05 089 (2011)

Few words on formalism

First-order Taylor expansion:

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

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 $(K^+ K^-)$, $(\pi^+ \pi^-)$

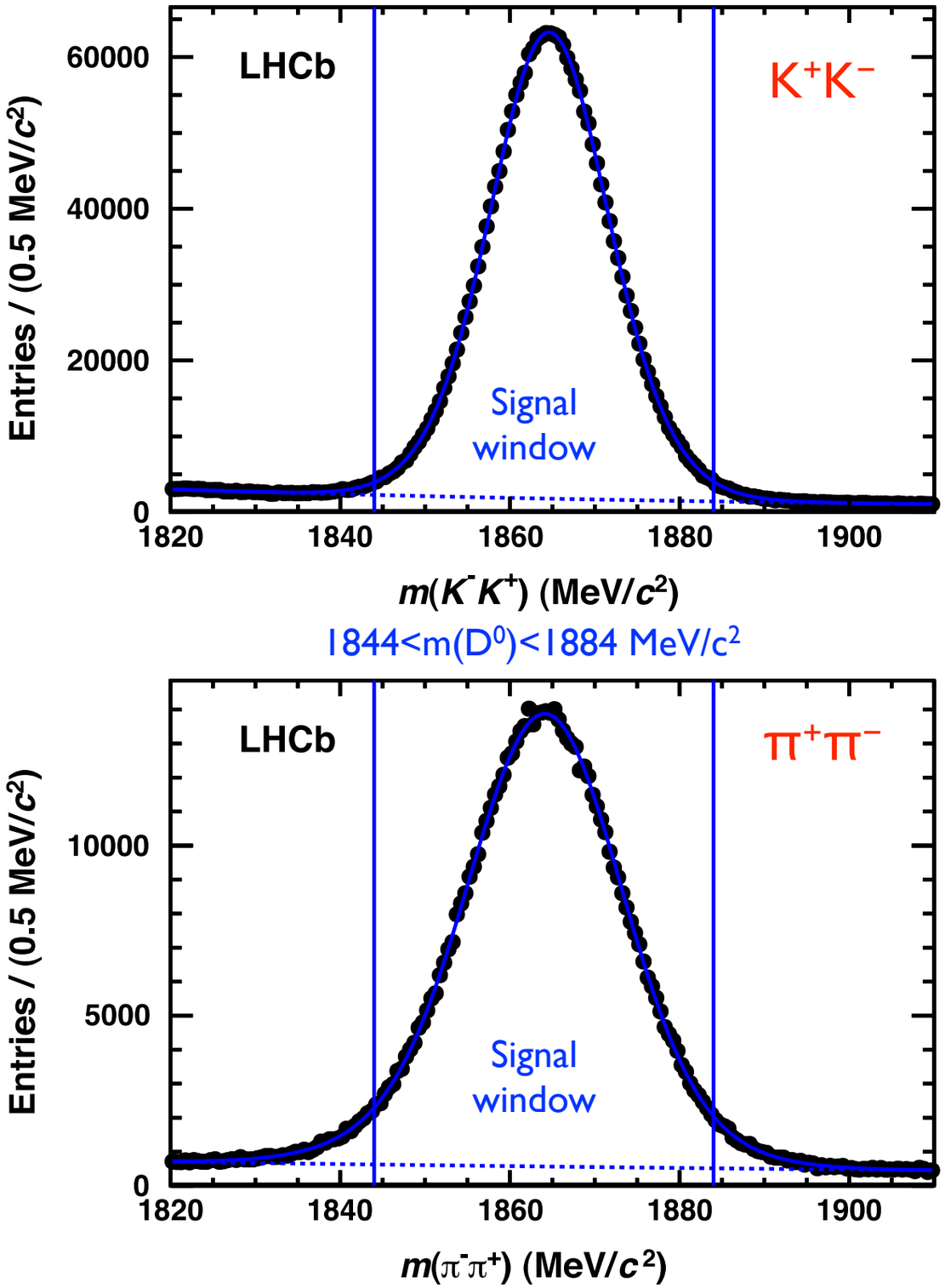
... i.e. all the D^*-related production and detection effects cancel.

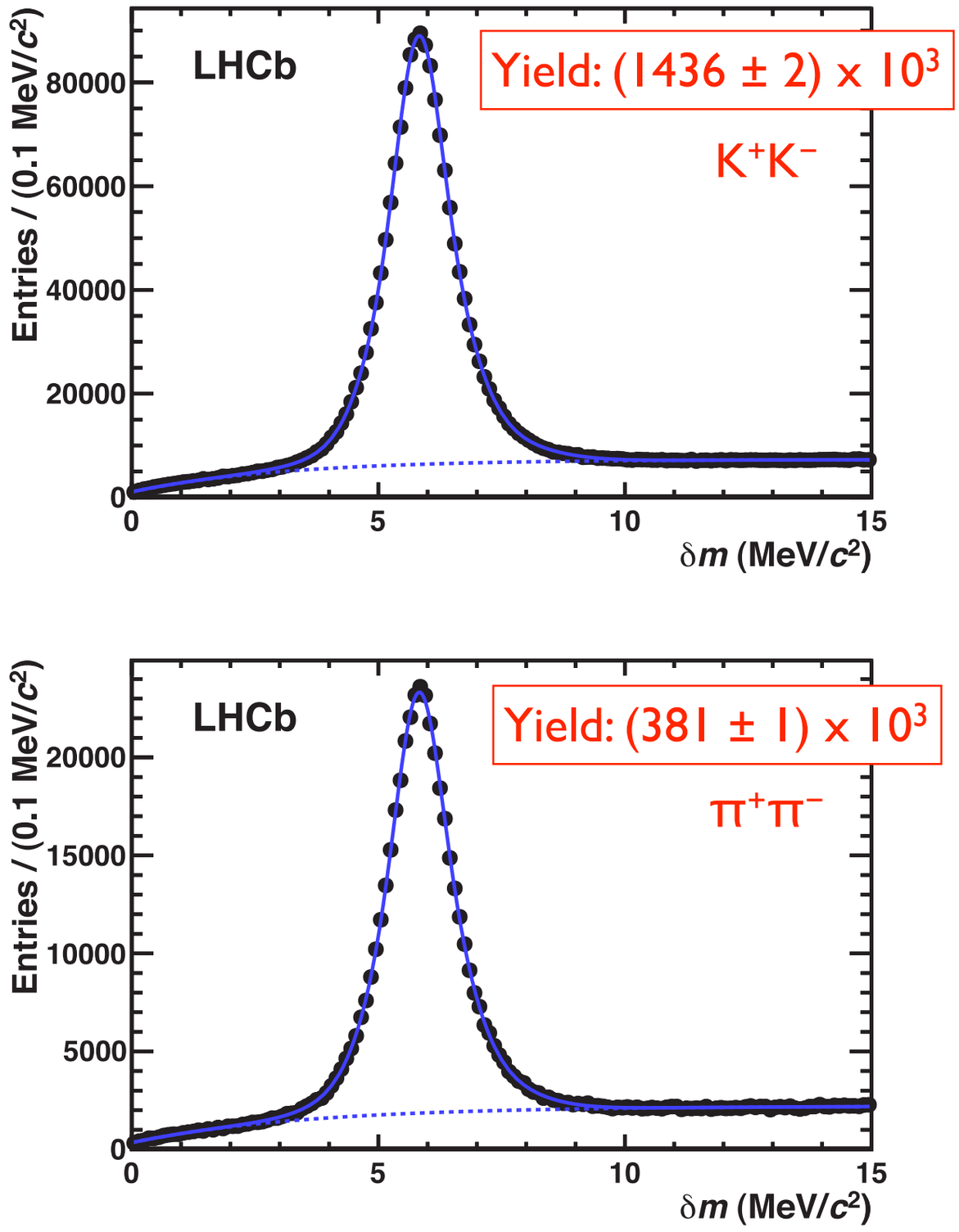
This is why we measure the CP asymmetry difference: very robust against systematics.

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

Mass spectra

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





For illustration; not used in calculating ΔA_{CP}

Systematics & result

Kinematic binning	0.02%
Fit procedure	0.08%
Peaking background	0.04%
Multiple candidates	0.06%
Fiducial cuts	0.01%
Sum in quadrature	0.11%

Several of the systematic uncertainties have a statistical component -- should come down as data sample grows.

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

Interpretation

- Joachim, Soumitra, Jernej, and Cedric will discuss the theory interpretation better than I can, so I defer to them.
- But I think the consensus is now:
  - Central value for ΔA_{CP} is larger than was expected...
  - ... but can be accommodated within the SM if strong effects conspire...
  - ... and it is plausible that they do (e.g. backwards ratio of BFs).
- And, of course, we are not at 5σ.

See, e.g.,
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)

Summary

- LHCb has an important charm physics programme.
- Several two-body analyses:
  - Mixing & indirect CPV from lifetime ratios
  - Mixing & indirect CPV from time-dep. wrong-sign/right-sign ratio
  - Directly CPV from time-integrated asymmetries
- Initial results published.
- Results on full 2011 sample (1 fb^{-1}) forthcoming.
- More to follow from 2012 run.

fin

Assumptions

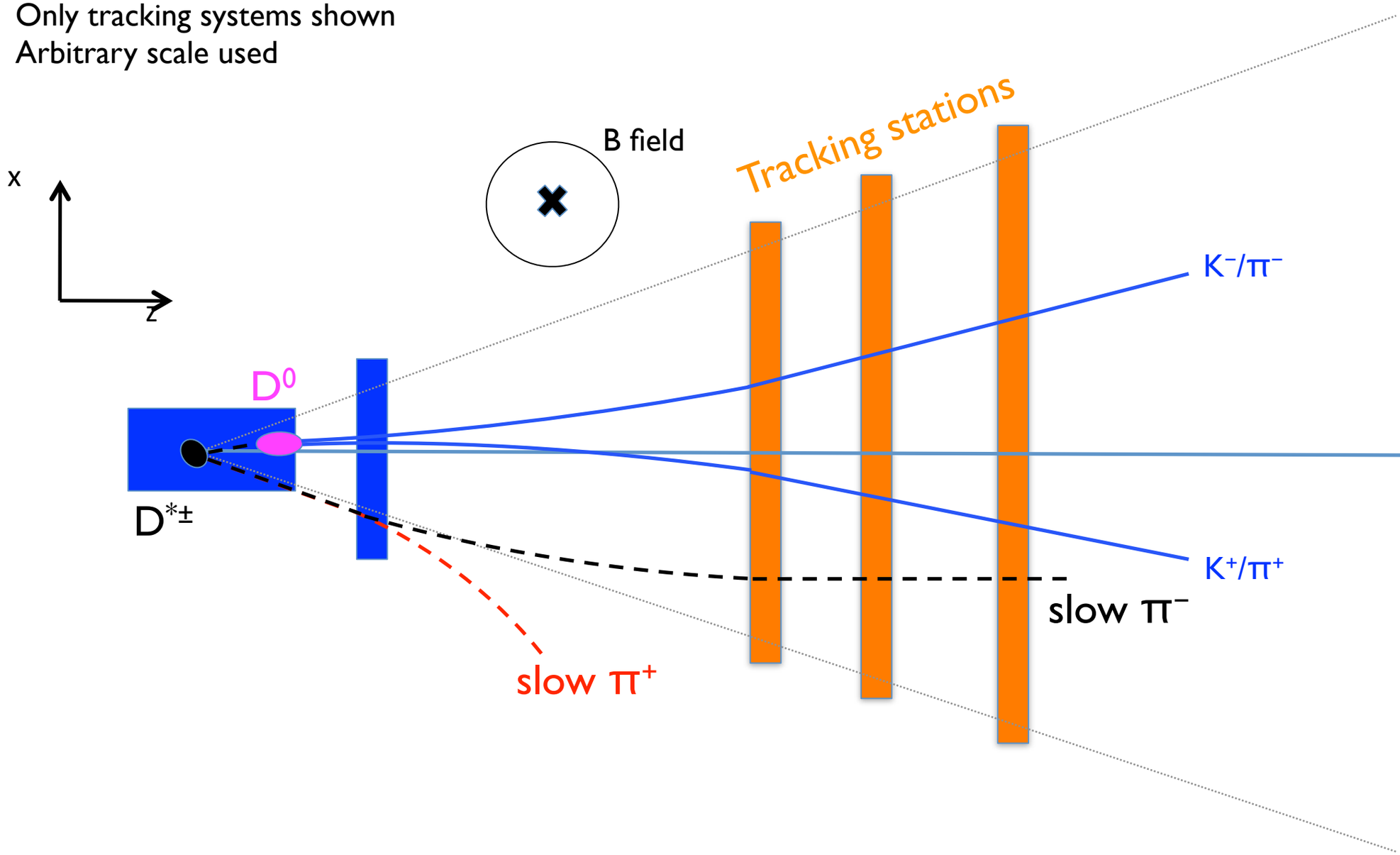
- Double-difference robust against systematics.
- In order to break the formalism, you need a detector effect that induces different fake asymmetries for KK and ππ.
- Two known mechanisms:
  - Correlation between KK/ππ efficiency ratio and D^{*+}/D^{*-} asymmetry (from production or soft pion efficiency)
    - 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
  - Decay 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 (few slides' time)

Fiducial cuts: cartoon of detector

LHCb simplified bending plane view
Only tracking systems shown
Arbitrary scale used



- B-field breaks symmetry between D^{*+} and D^{*-}

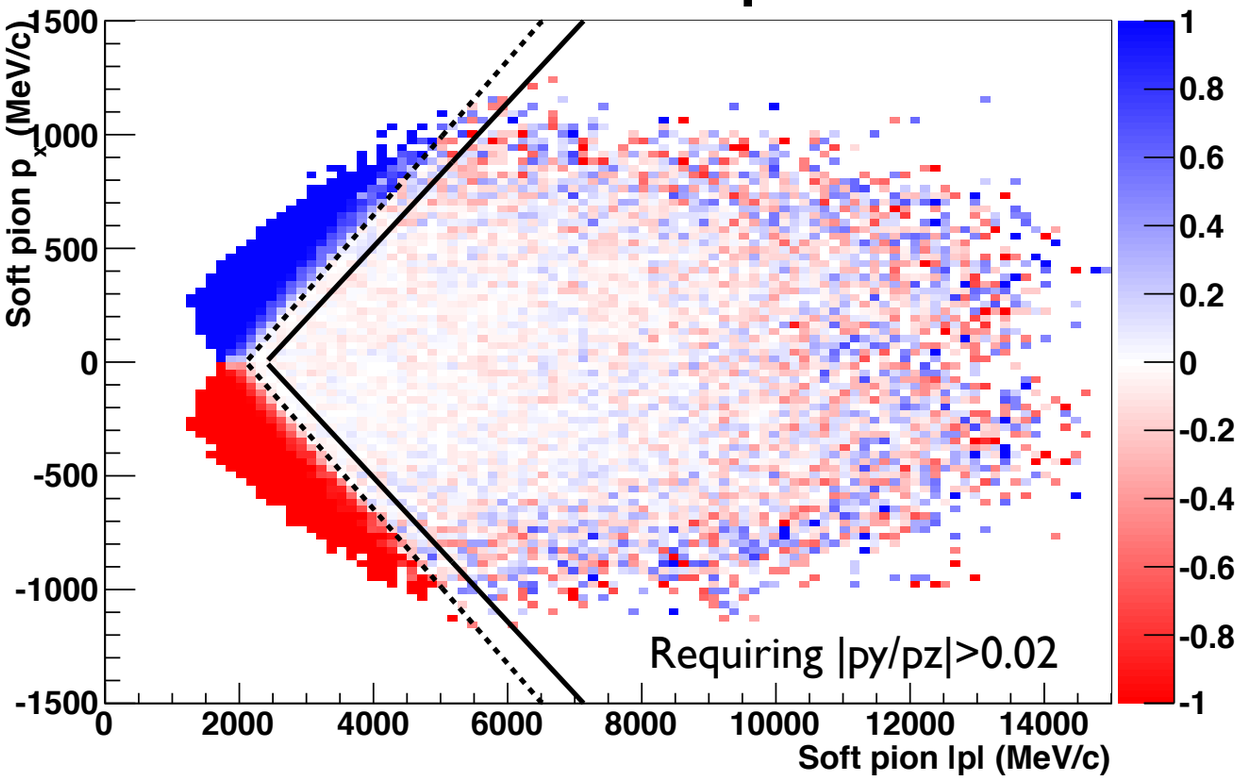
Fiducial cuts

- ∃ regions of kinematic space where one charge of slow pion winds up inside acceptance but other does not.
  - Main example: edges of acceptance (prev. slide)
  - Also downstream beampipe
- Result: large local raw asymmetries.
- These are independent of the D^0 decay mode but:
  - break the assumption that raw asymmetries are small
  - risk of second-order effects if bin includes border region where raw asymmetry is changing rapidly *and* ratio of efficiencies of ($D^0 \to K^-K^+$) vs ($D^0 \to \pi^-\pi^+$) is also varying
- Therefore exclude them.

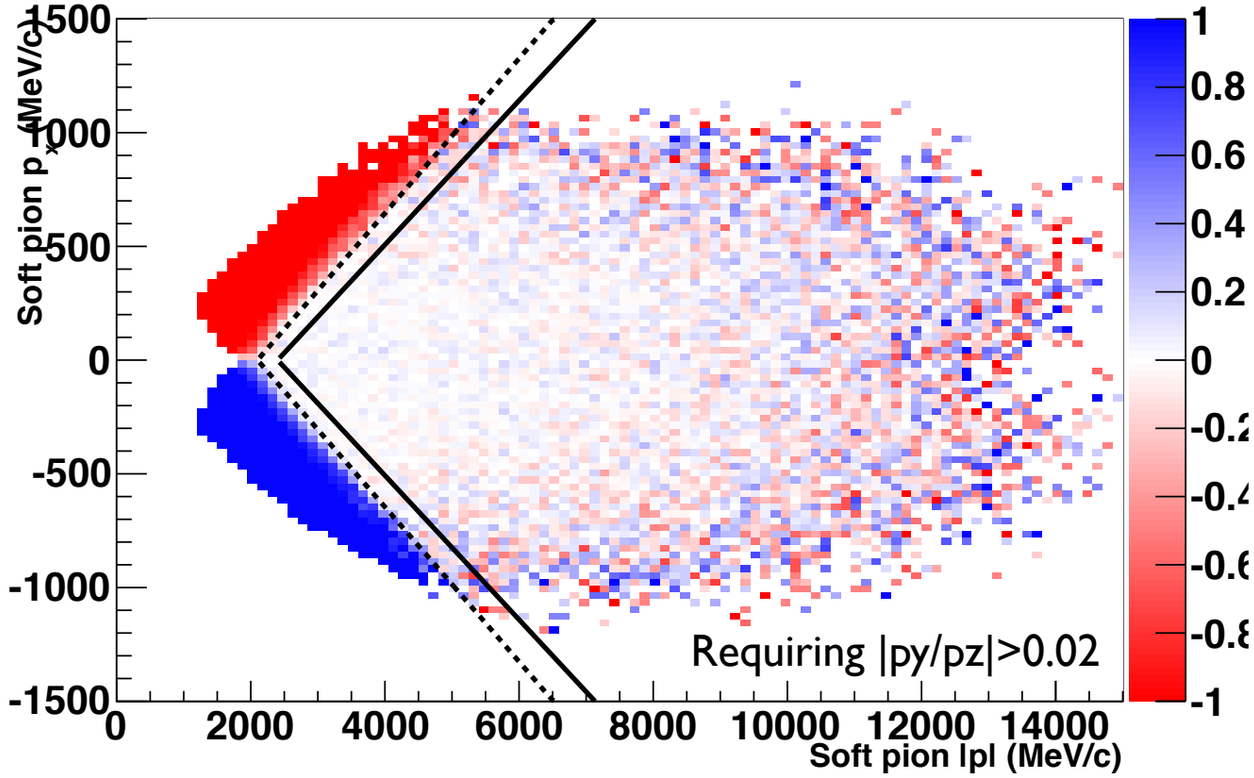
Fiducial cuts: edge region

Raw asymmetry of $D^{*\pm} \rightarrow D^0(K^-K^+)\,\pi^+$ in the $(p_x, |p|)$ plane of the tagging slow pion:

B-field up



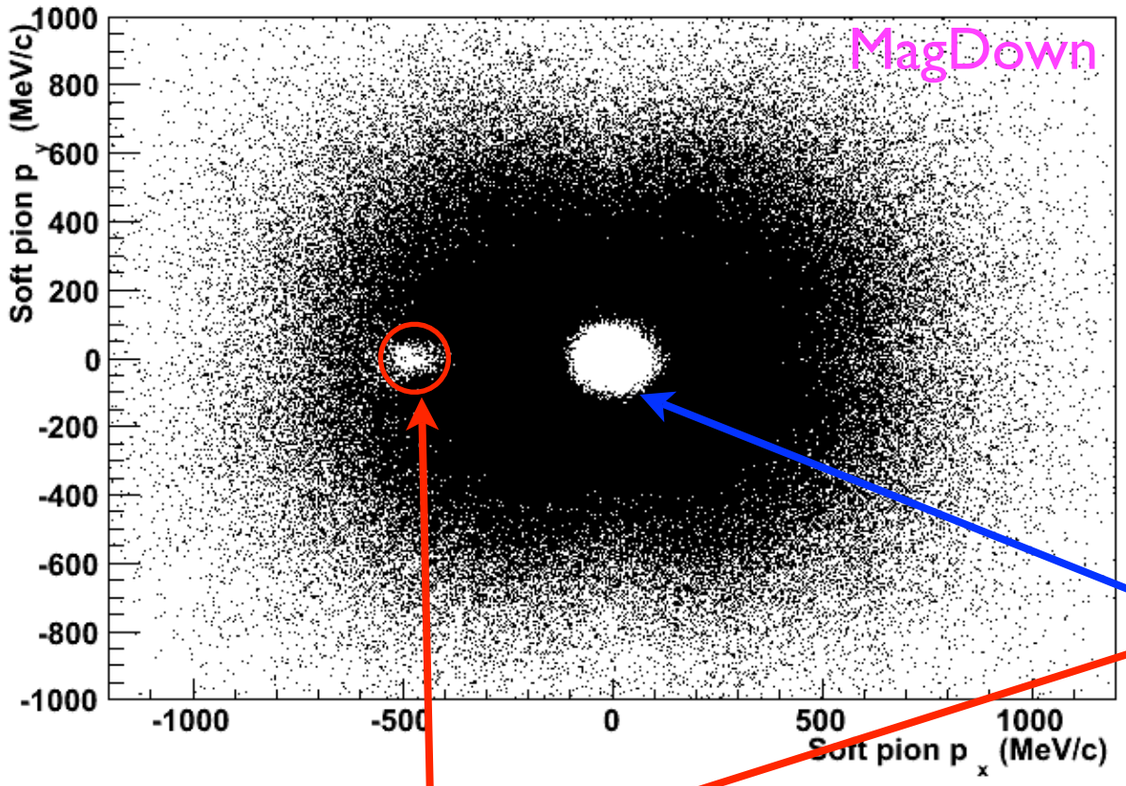
B-field down



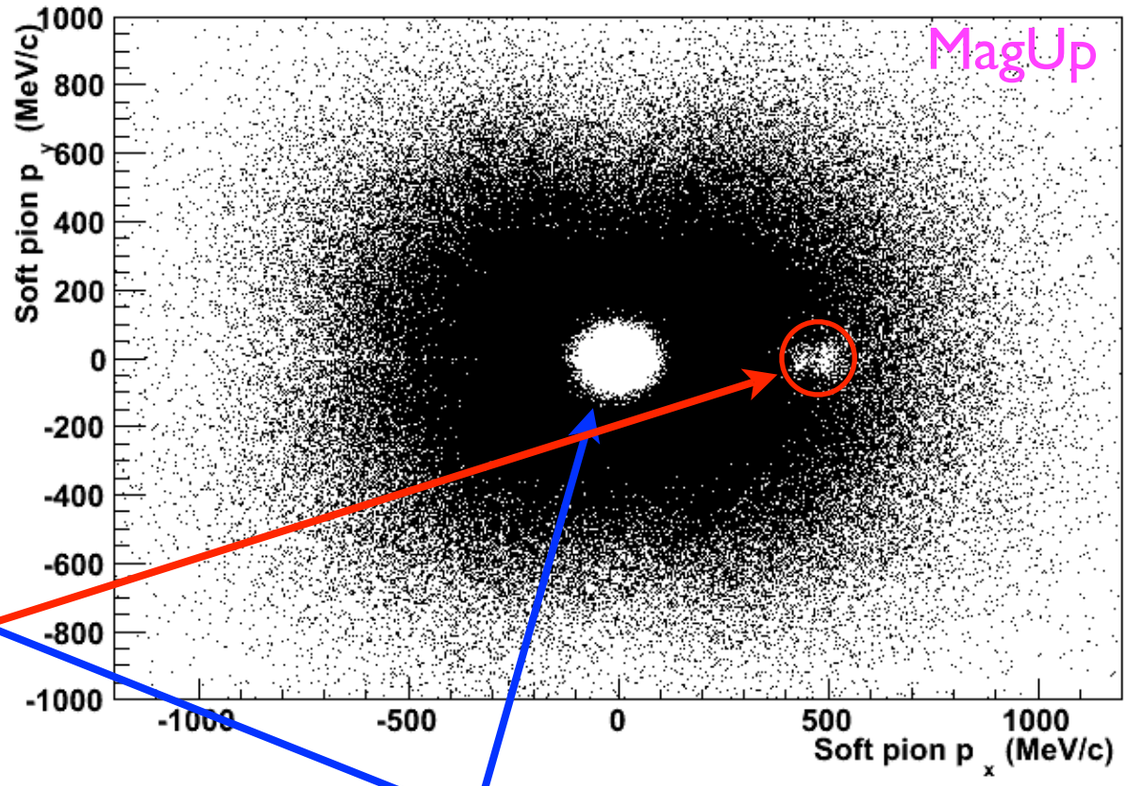
- Solid line: fiducial cuts applied
- Dotted line: looser cuts used for crosscheck.

Fiducial cuts: downstream beampipe

Plot slot pion p_y vs p_x (D^{*+} only):



Lost from acceptance hole downstream

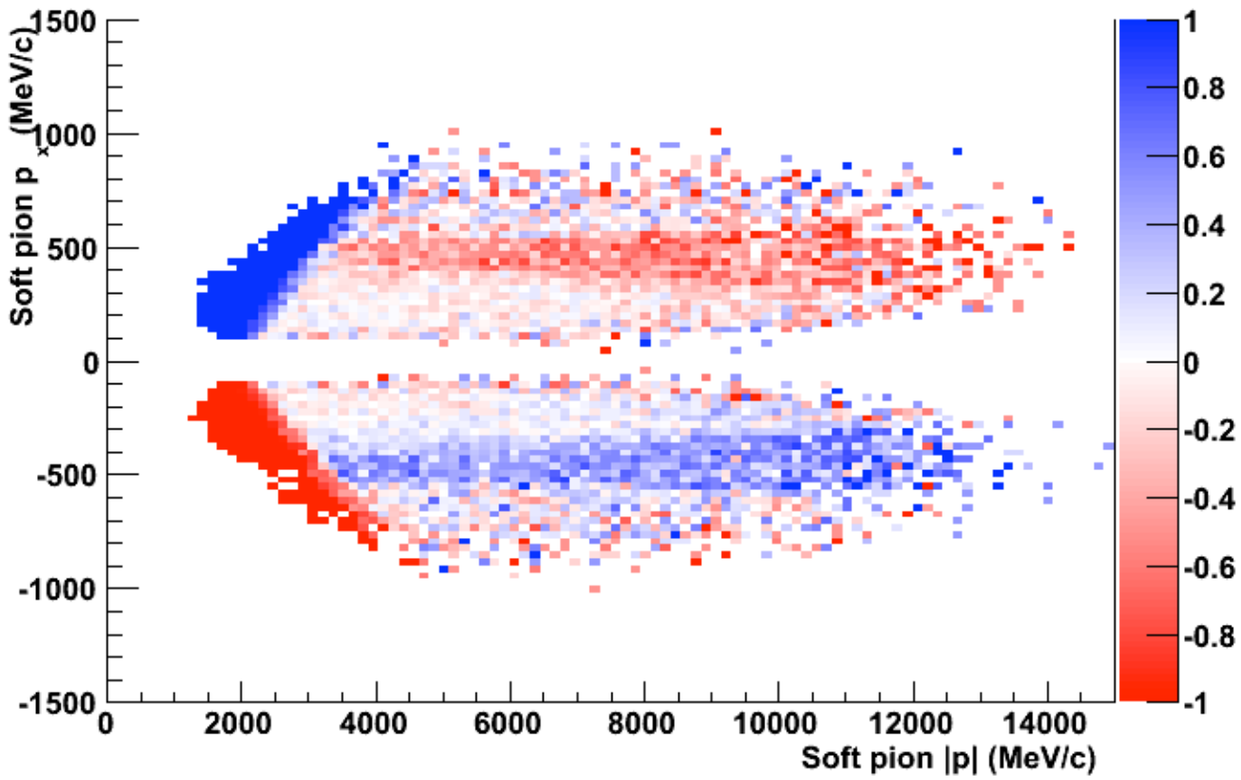


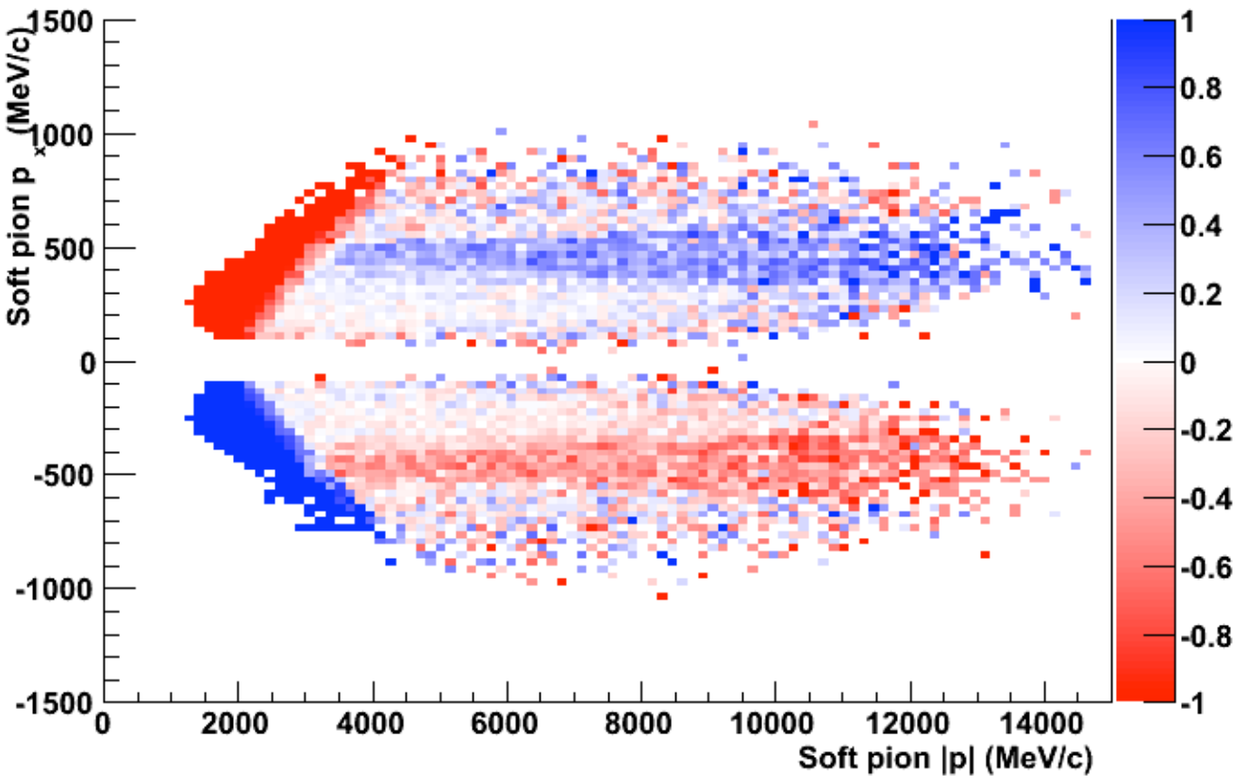
Lost from acceptance hole upstream

- Upstream acceptance is charge-independent
- Downstream acceptance has left-right asymmetry

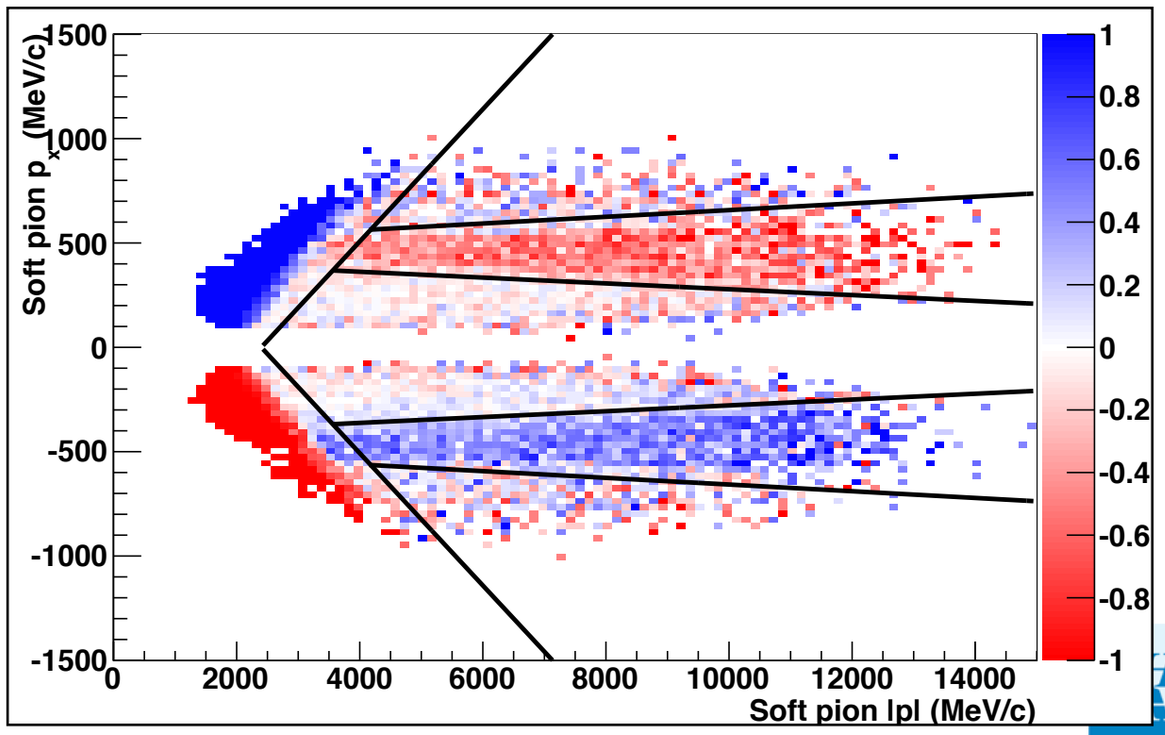
Fiducial cuts: downstream beampipe

Raw asymmetry plots again, this time requiring $|p_y/p_z|<0.02$:





- Very clear effect.
- Impose cuts to remove this region too:
  - Only applied for $|p_y/p_z|<0.02$



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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 $D^0 \to K^+ K^-$ 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:

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

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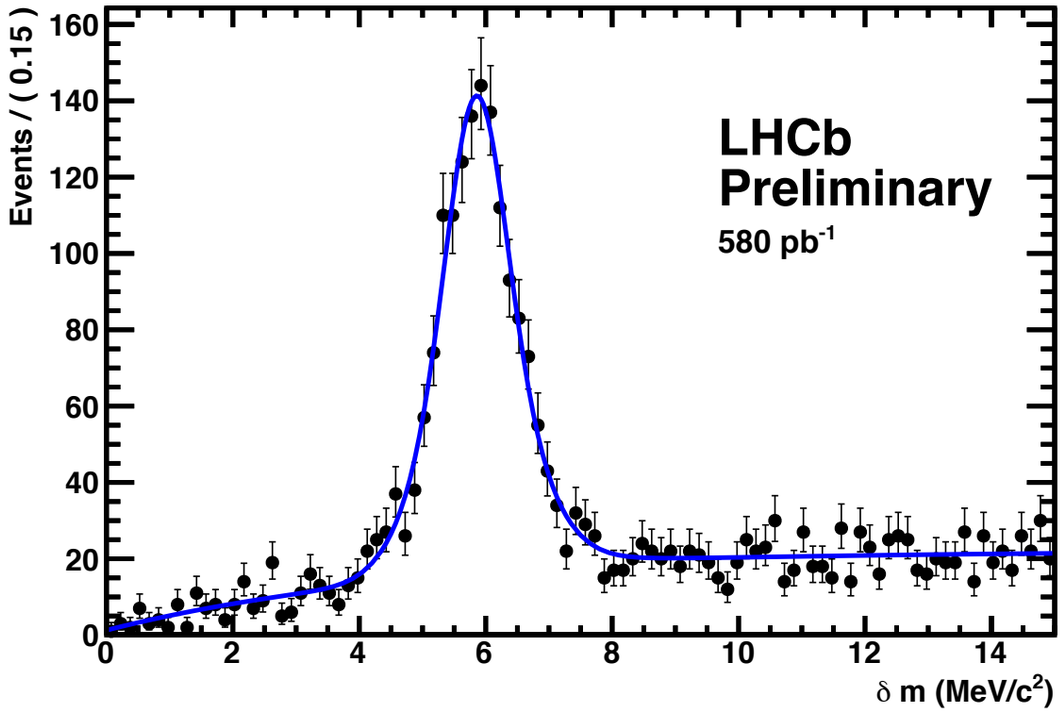
- D^{*+} and D^{*-} are allowed to have different mass and resolution.
  - ... though f_{core} and $(\sigma_{core}/\sigma_{tail})$ are shared
- Background model:

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

δm_0 fixed from fit to high-statistics $D^0 \to K^- \pi^+$ 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, $D^0 \to K^+ K^-$)

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

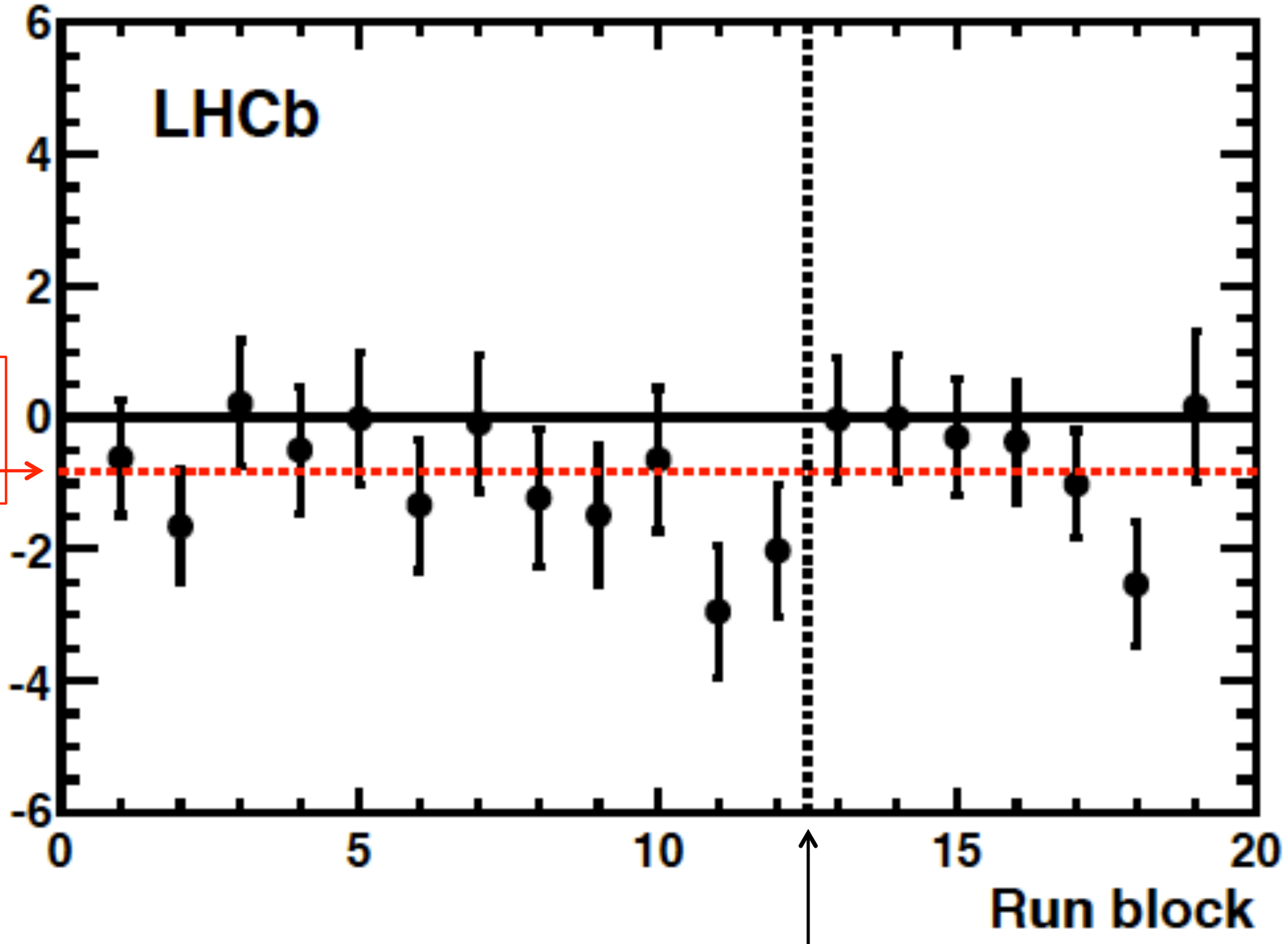
Systematic uncertainties

- 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%

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
  - Stability with kinematic variables
  - 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 of data
- All variation within appropriate statistical/systematic uncertainties.

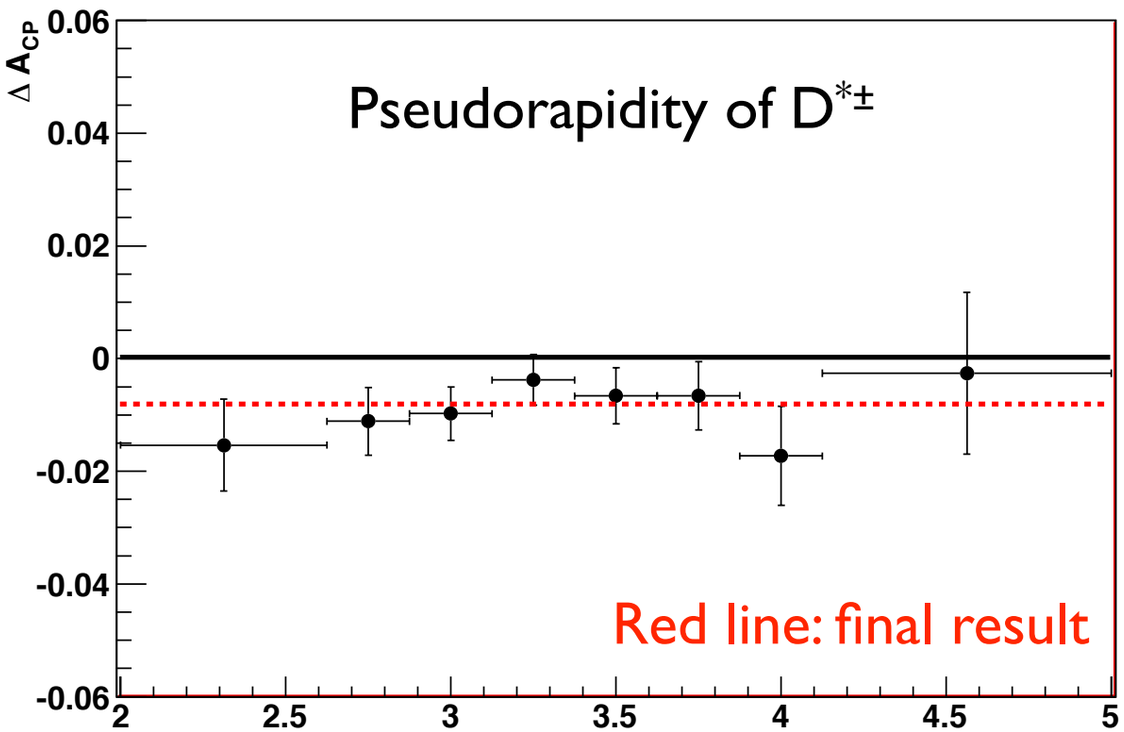
Stability vs time

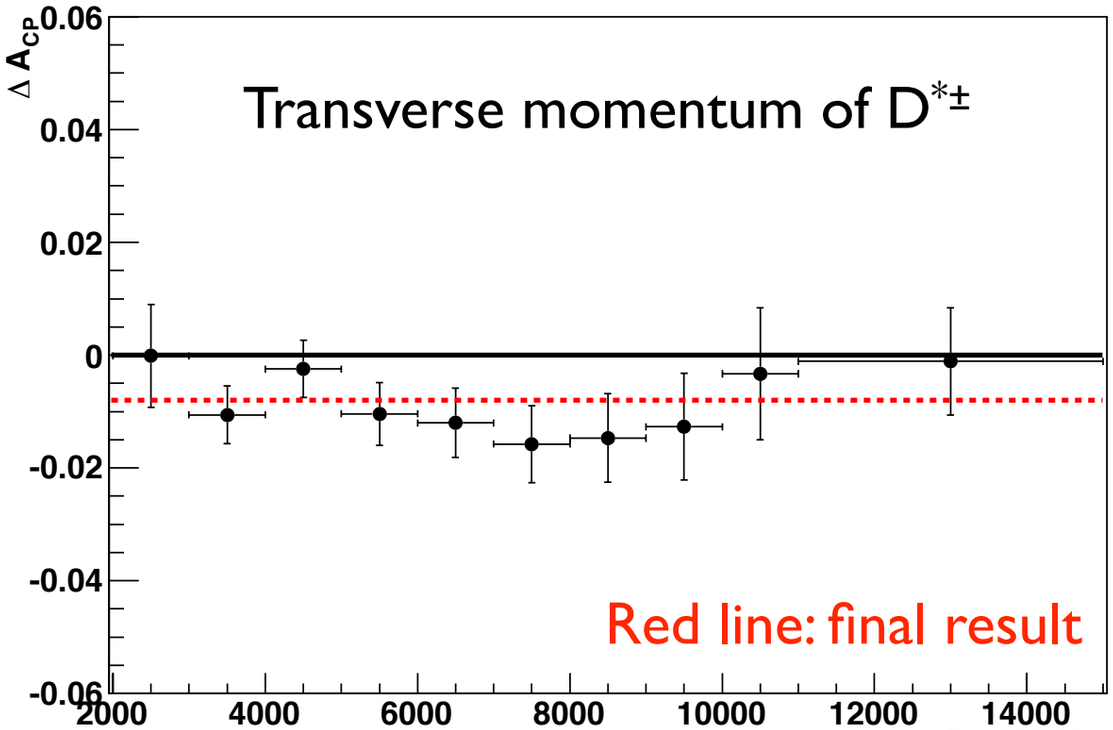


Final result(dashed line)

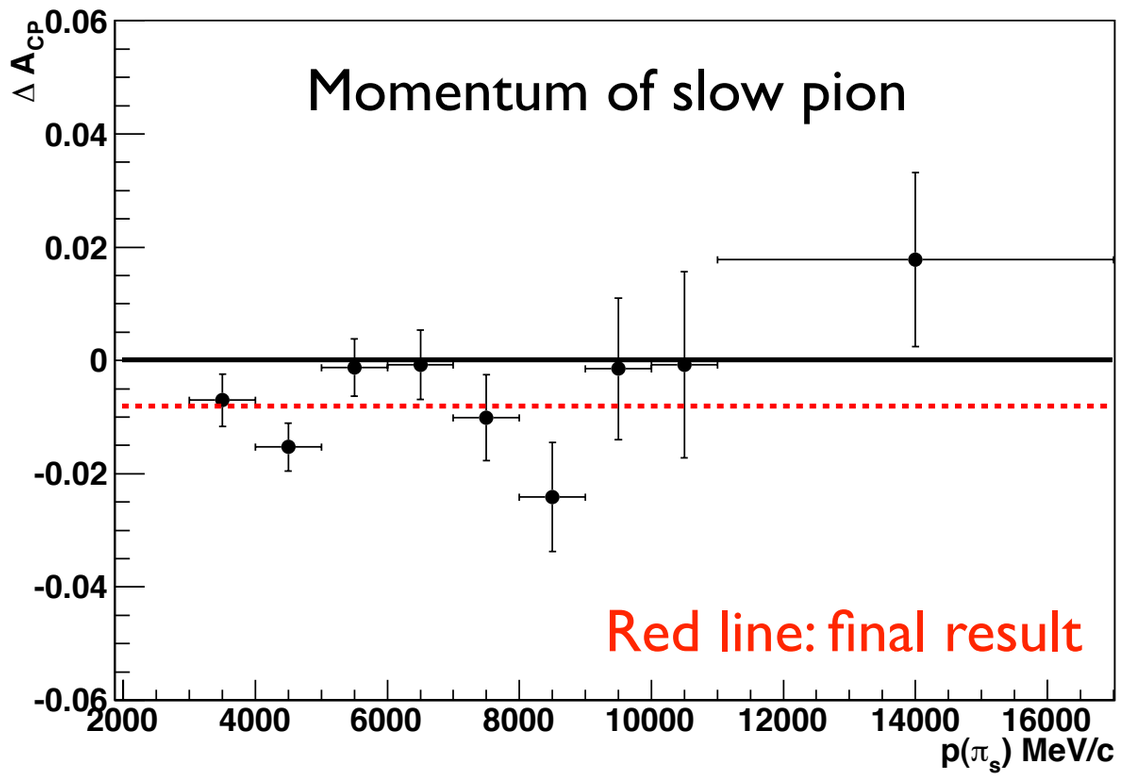
Before and after a technical stop

Stability with kinematic variables





- No evidence of dependence on relevant kinematic variables.



Consistency among subsamples

Subsample	ΔA_{CP}	χ^2/ndf
Pre-TS, field up, left	$(-1.22 \pm 0.59)\%$	$13/26(98\%)$
Pre-TS, field up, right	$(-1.43 \pm 0.59)\%$	$27/26(39\%)$
Pre-TS, field down, left	$(-0.59 \pm 0.52)\%$	$19/26(84\%)$
Pre-TS, field down, right	$(-0.51 \pm 0.52)\%$	$29/26(30\%)$
Post-TS, field up, left	$(-0.79 \pm 0.90)\%$	$26/26(44\%)$
Post-TS, field up, right	$(+0.42 \pm 0.93)\%$	$21/26(77\%)$
Post-TS, field down, left	$(-0.24 \pm 0.56)\%$	$34/26(15\%)$
Post-TS, field down, right	$(-1.59 \pm 0.57)\%$	$35/26(12\%)$
All data	$(-0.82 \pm 0.21)\%$	$211/215(56\%)$

- Split by:
  - Before/after technical stop (about 60% of data before)
  - Magnetic field polarity
  - Charge of slow pion
- Consistency among subsamples: X^2/NDF = 6.7/7 (45%)

Interpretation: lifetime acceptance

- Lifetime acceptance differs between $D^0 \to K^+K^-, \pi^+\pi^-$
  - e.g. smaller opening angle => short-lived $D^0 \to K^+K^-$ 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:

$$\frac{\Delta\langle t\rangle}{\tau} = \frac{\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle}{\tau} = [9.83 \pm 0.22(\text{stat.}) \pm 0.19(\text{syst.})]\,\%$$

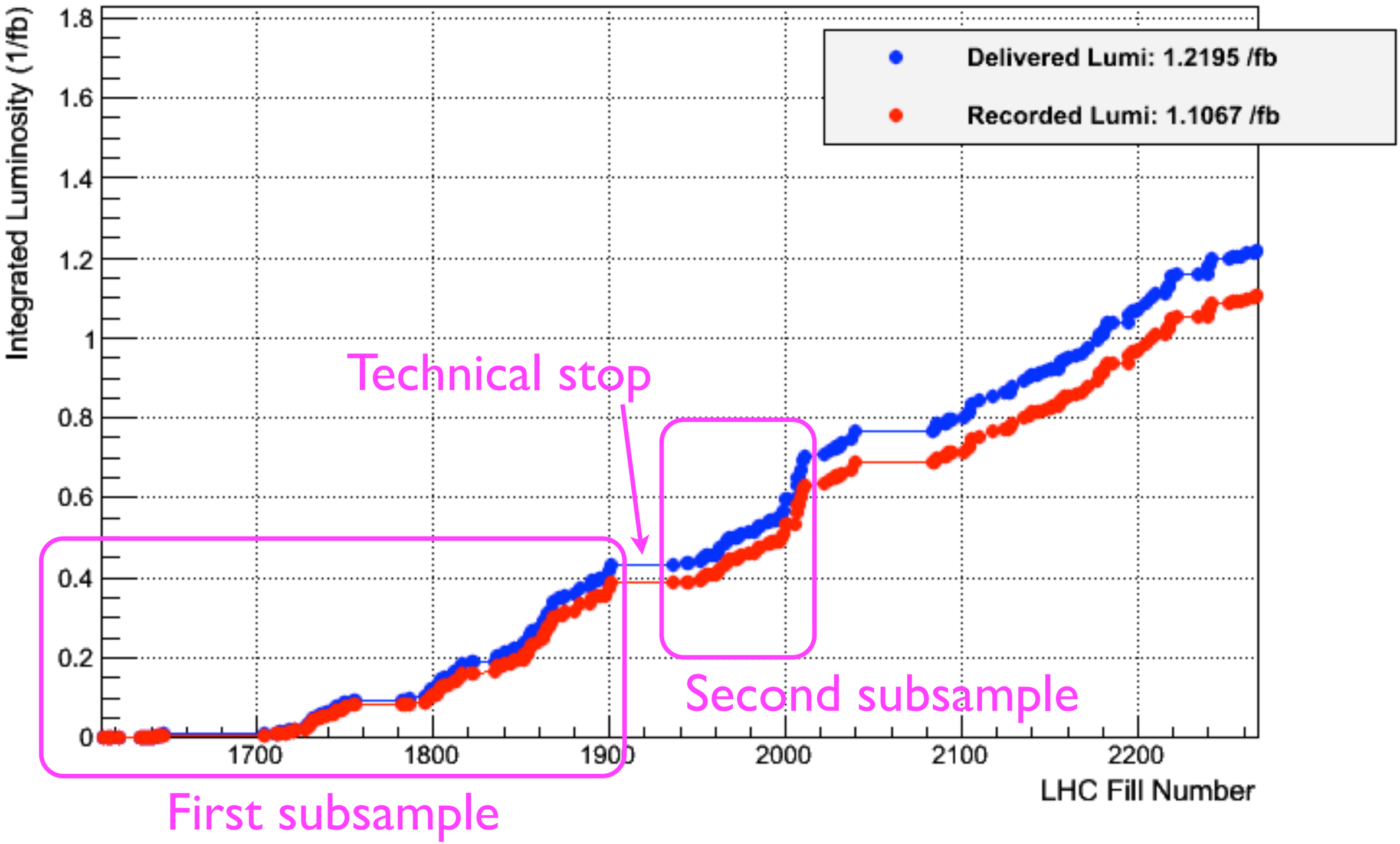
Systematics: secondary charm fraction (0.18%), world average D^0 lifetime (0.04%), background-subtraction procedure (0.04%)

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

LHCb value (−0.82 ± 0.21 ± 0.11)% consistent with HFAG average of non-LHCb results given our time-acceptance (approx 1.2σ)

$$a_{CP}^{\text{ind}} = (-0.03 \pm 0.23)\%$$
$$\Delta a_{CP}^{\text{dir}} = (-0.42 \pm 0.27)\%$$

Integrated luminosity



Showing online luminosity (not final calibration)

Can the SM stretch?

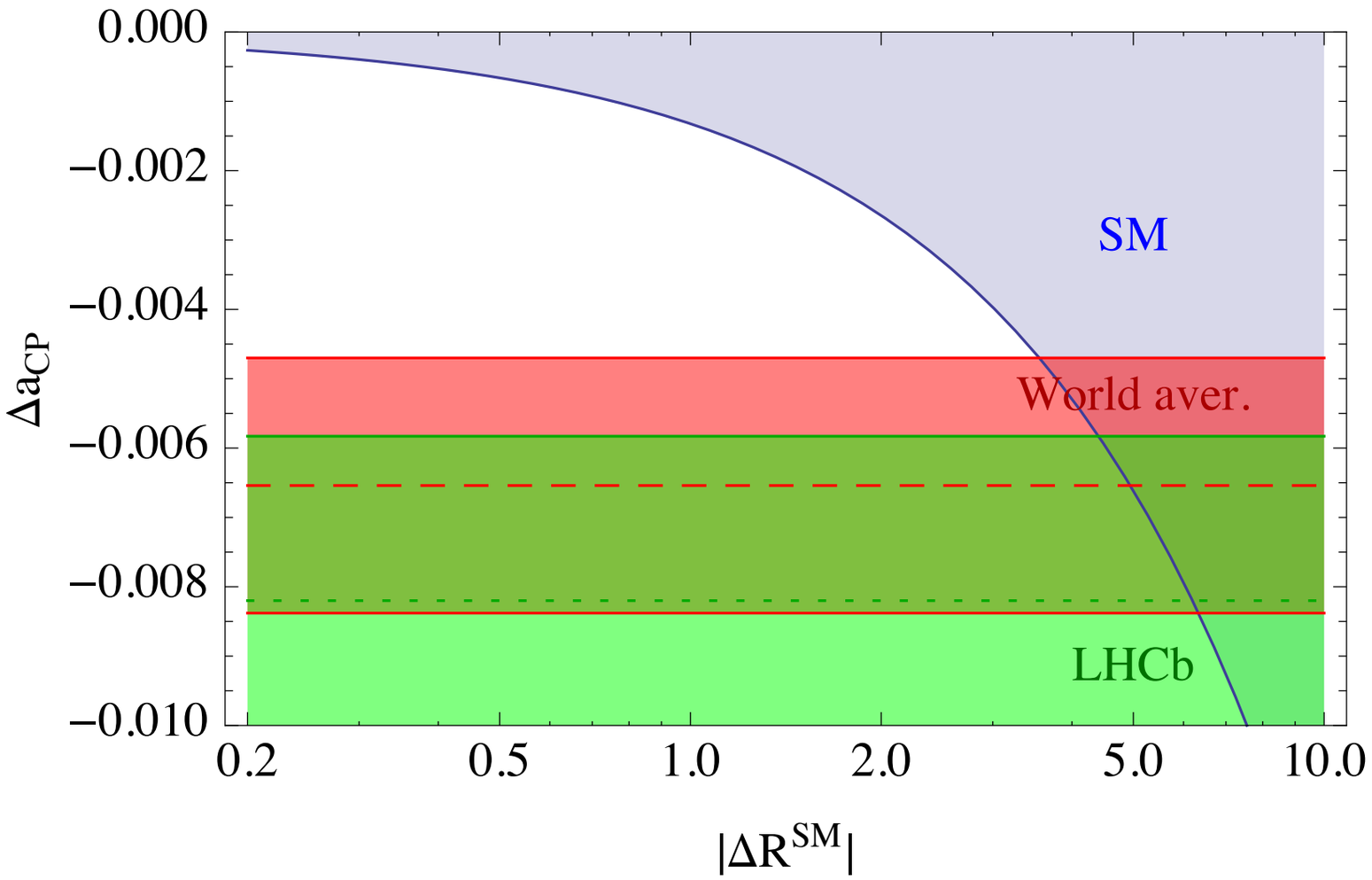


Figure 1: Comparison of the experimental Δa_{CP} values with the SM reach as a function of $|\Delta R^{\rm SM}|$.

- Well above naive expectation... but not excluded from first principles.