CPV and mixing in charm sector at LHCb

Sergey Barsuk, LAL Orsay

on behalf of the LHCb collaboration

Selected LHCb results on

- LHCb as LHCc, **key detector elements and data sample**
- Treasury of $D^0 \to h^- h^+$: **$D\bar{D}$ mixing and** search for **CP violation**
- Search for **direct CP violation** via 2-body $D_{(s)}^+$ decays
- Search for **CP violation** in multi-body D-decays $D \to 3h$, $4h$

Outline :   文藝復興時期的魅力物理學

(Some) Related presentations

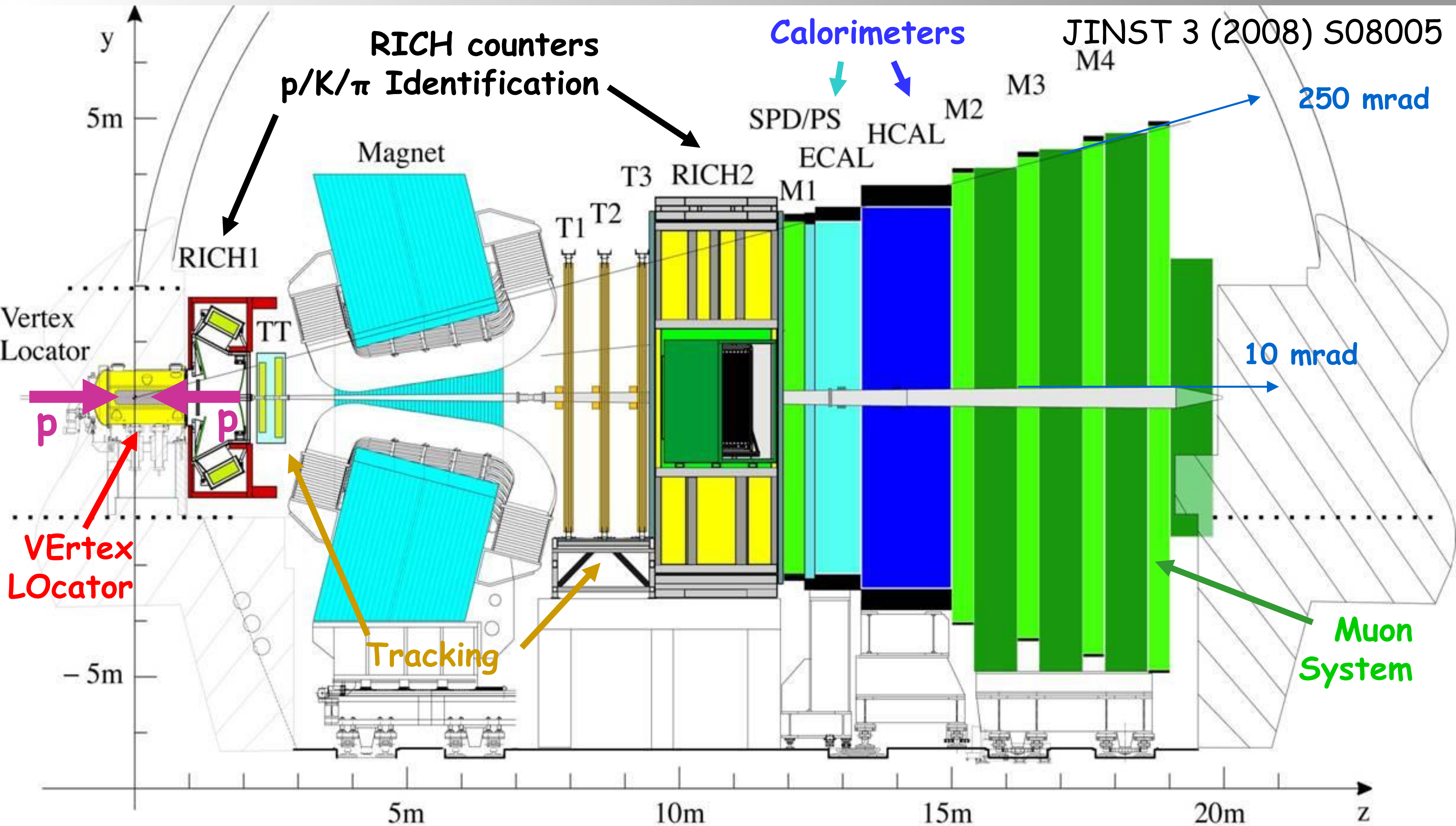
- *CPV and mixing in charm sector at B-factories* : talk by Alexey Garmash
- *Relevant theory* : talks by Svjetlana Fajfer, Alexey Petrov *et al.*
- *Other LHCb results* (charm rare decays and XYZ) in talks by Liming Zhang and Chengping Shen

Mixing and CPV in charm sector: sample and tools

Essentials:

- LHCb detector and components important to study mixing and CP-violation (CPV) in charm sector
- Data sample and operation

LHCb detector – single-arm forward spectrometer 10-250 mrad (V), 10-300 mrad (H)



Vertex reconstruction:
VELO

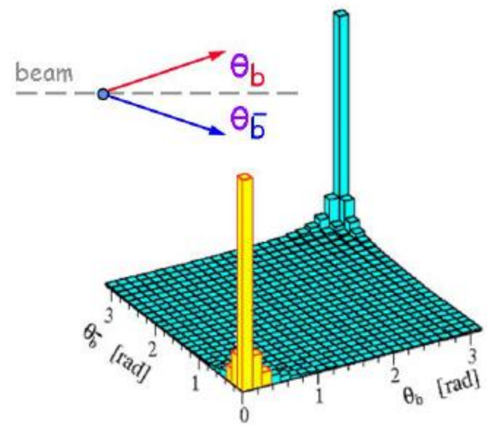
Kinematics:
Magnet
Tracker
Calorimeters

PID:
RICHs
Calorimeters
Muon Chambers

Trigger:
Muon Chambers
Calorimeters
Tracker

Probing mixing and CPV in charm sector: sample and tools

- LHCb physics: precision studies of rare effects in b- and c-physics, production measurements at new energy scale in the forward region
- **Correlated $b\bar{b}$ production**, second b in acceptance once the first b is in (flavour tagging)
- LHCb covers forward region: $1.9 < \eta < 4.9$
  - optimized for forward peaked heavy-quark (HQ) production at the LHC
  - only ~4% of solid angle, but ~40% of HQ production cross section



- Charm at LHC(b): **prolific production, all c-species produced,** at $\sqrt{s}$ = 7 TeV about 600 kHz $\mathbf{c\bar{c}}$ pairs go in the LHCb acceptance

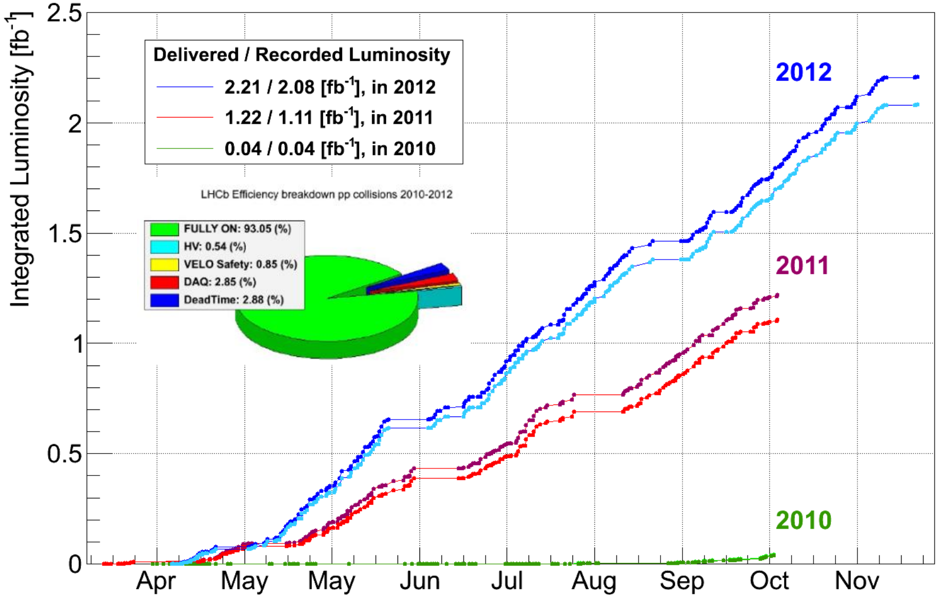
$$\boxed{\sigma(c\bar{c})_{p_T<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\,\mu\mathrm{b}}$$

Nucl. Phys. B871 (2013) 1

- **Large boost**, $\beta\gamma$ of O(10) vs. ~1 at B-factories; D flies few mm, decay time resolution ~0.1 τ_D
- Flavour **tagging**: charge of the slow pion π_S from $D^{*+} \rightarrow D^0 \pi_S^+$ (p ~2 GeV/c)
  charge of the μ from semileptonic decay $B \rightarrow D^0 \mu^- X$
- **Asymmetries**: detector asymmetries → swap dipole magnet polarity
  production asymmetries → measure using control modes

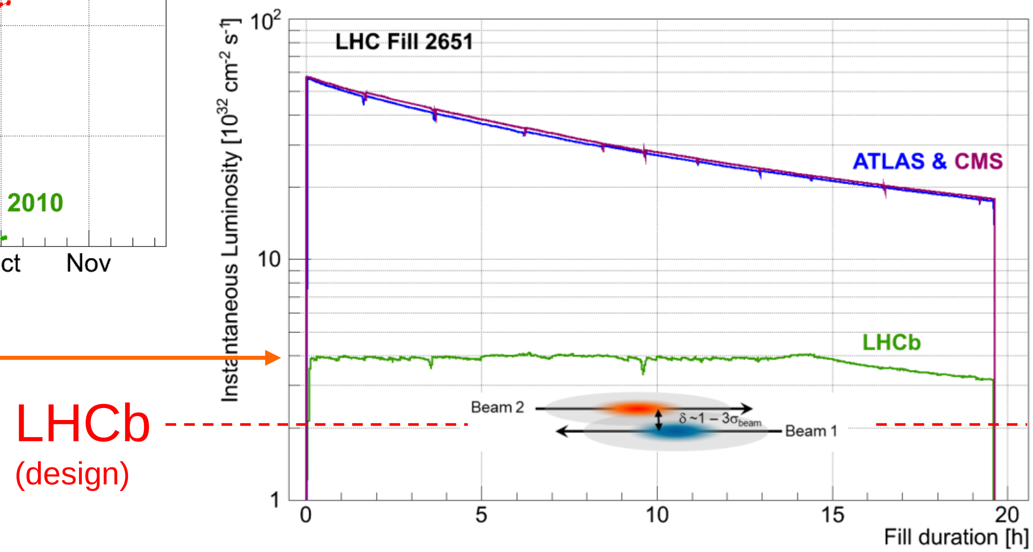
LHCb operation

- **LHCb collected data** correspond to ∫Ldt ~38 pb^{-1} in 2010 and 1.1 fb^{-1} in 2011 at $\sqrt{s}$ = 7 TeV, and 2.1 fb^{-1} in 2012 at $\sqrt{s}$ = 8 TeV



- **Stable LHCb operation**
- Recording >1pb^{-1}/hour running at up to L~4x10^{32} $cm^{-2}s^{-1}$ (higher, than nominal, 2x10^{32} $cm^{-2}s^{-1}$) in auto-leveling mode

LHCb luminosity levelling



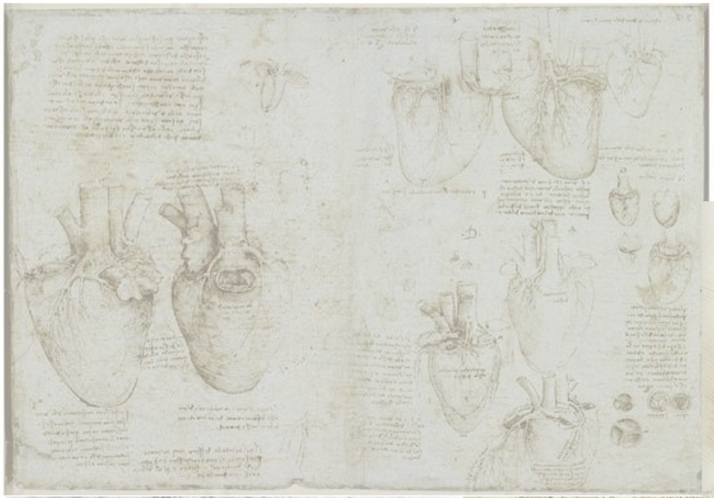
- Visual average **number of vertices** is higher, μ ~1.4, compared to nominal μ =0.4
- Higher μ → higher track multiplicity, 1 primary vertex (PV) gives 30 tracks/rapidity range, more difficult reconstruction

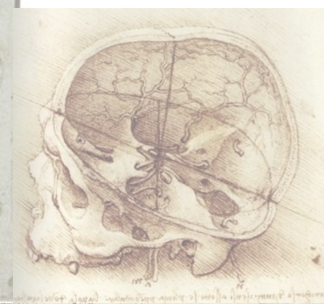
→ background for D and B decay vertex reconstruction and matching

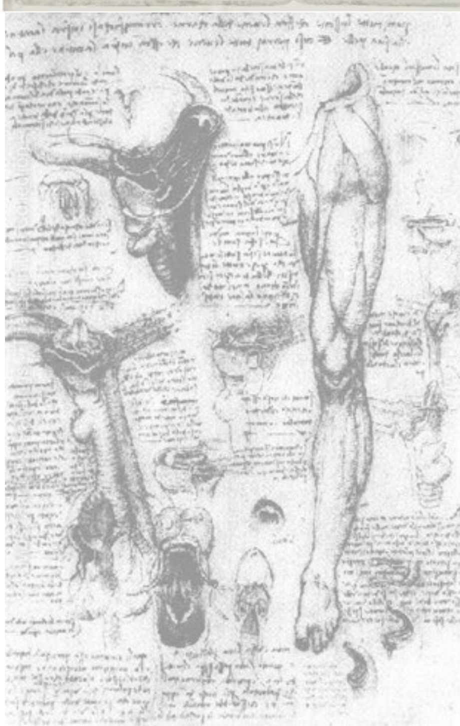
average minimum distance between 4 PVs ~12 mm, comparable to average B travel distance ~10 mm

LHCb: key detector systems to study rare effects in charm sector

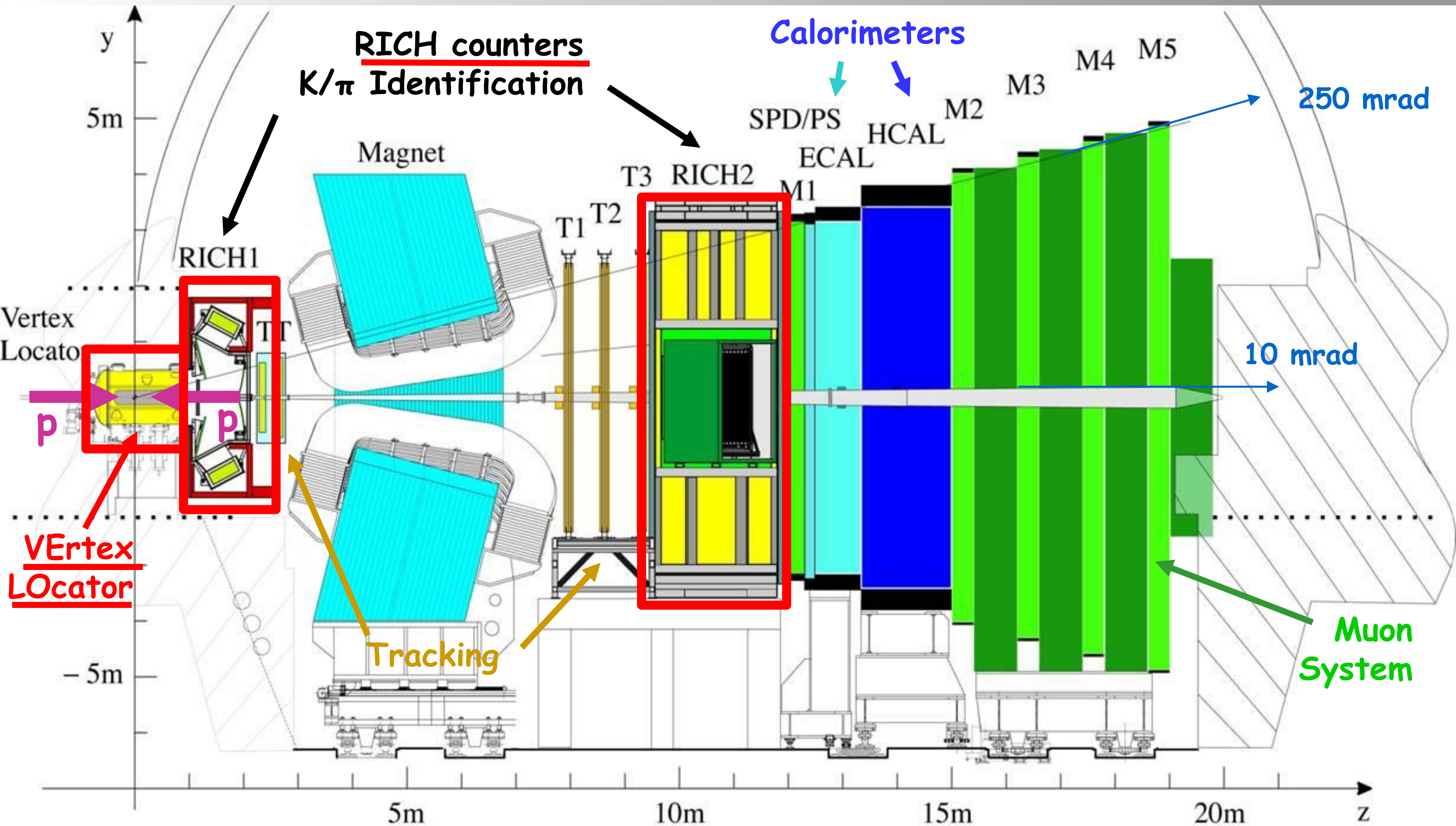
Curious/useful to have an idea of the internal structure even when it is hidden …







LHCb: key detector systems to study rare effects in charm sector



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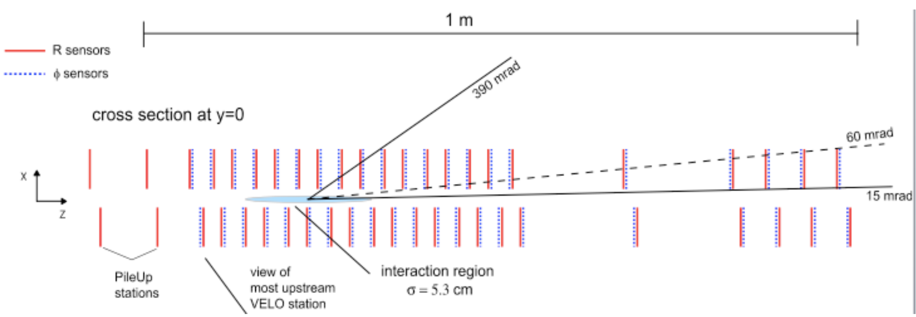
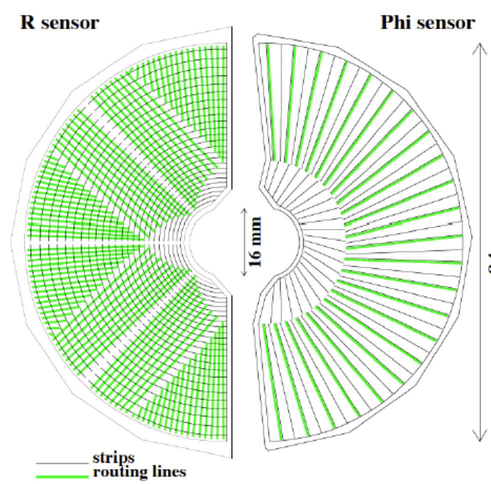
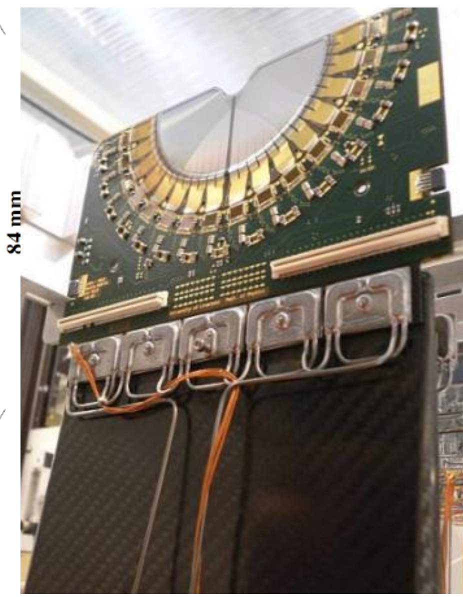
JINST 8 (2013) P08002, arXiv:1405.7808

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout, in each module
- 300μ thick n-on-n sensors
- Strip pitches from 40 to 120μ





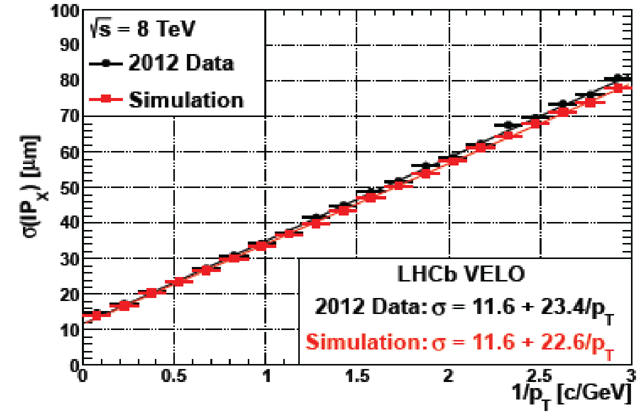


- **First active strip at 8.2mm from the beam axis**
- Moves away every fill and centers around the beam with self measured vertices

VELO: precise reconstruction of tracks and vertices

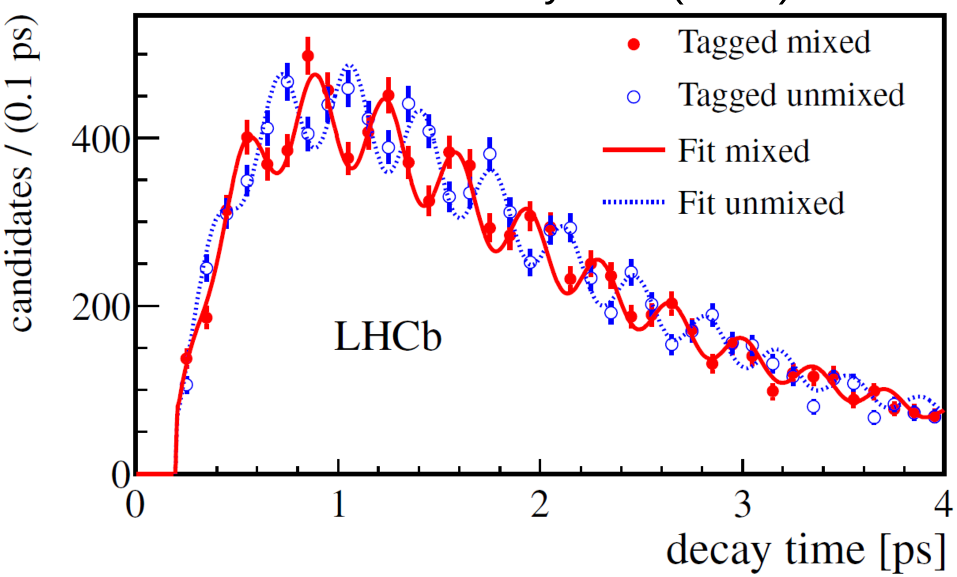
- Excellent **spatial resolution**, down to 4μ for single tracks
- Precise **impact parameter** measurement,
  σ_{IP} = 11.6 + 23.4/pT [μ]
- Precise **primary vertex** reconstruction,
  $\sigma_x = \sigma_x = 13\mu$, $\sigma_z = 69\mu$ for a vertex of 25 tracks

Impact parameter resolution



- Detector well understood, simulation describes data
- VELO provides excellent **proper time** resolution

New J. Phys. 15 (2013) 053021



- **Vertex resolution** allows to resolve fast (x~27) $B_s\overline{B}_s$ oscillations

$B_s^0 \to D_s^- \pi^+$

$D_s^- \to \phi(K^+K^-)\pi^-$
$D_s^- \to K^{*0}(K^+\pi^-)K^-$
$D_s^- \to K^+K^-\pi^-$ nonresonant
$D_s^- \to K^-\pi^+\pi^-$
$D_s^- \to \pi^-\pi^+\pi^-$

$$\boxed{\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}}$$

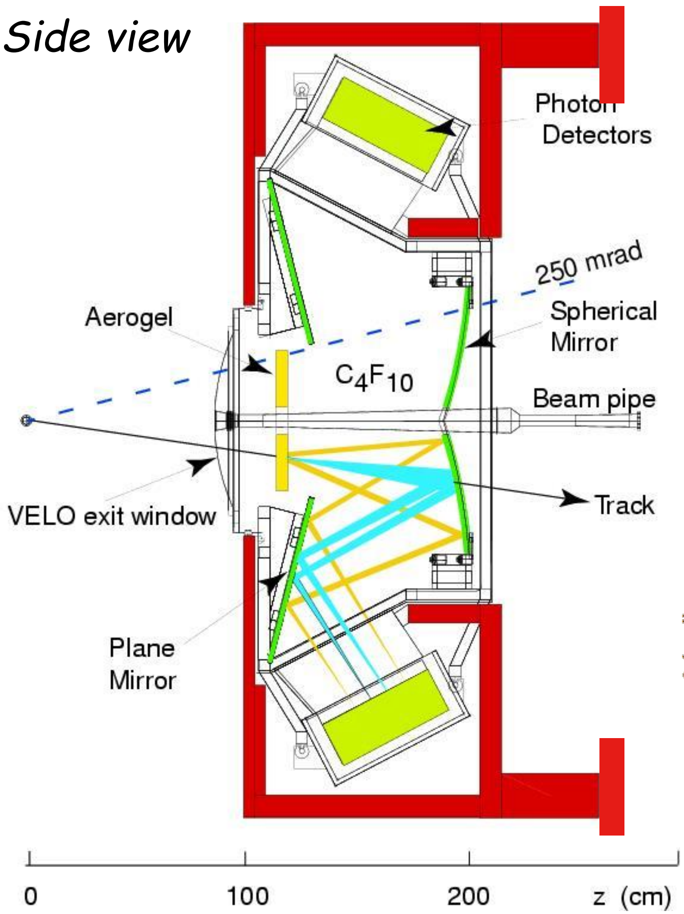
Charged hadron identification: RICH detectors

***2 Ring Imaging Cherenkov Detectors (RICH)**: **3 Radiators**, photons from Cerenkov cone focused onto rings recorded by **Hybrid Photon Detector** (HPD) arrays, out of acceptance*

RICH 1

Acceptance 25-300 mrad

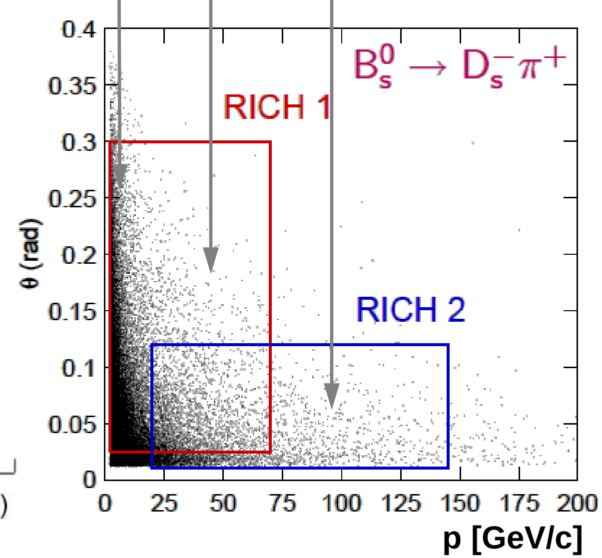
Side view



Silica Aerogel:
n=1.03
1-10 GeV/c

C_4F_{10}:
n=1.0014
Up to ~70 GeV/c

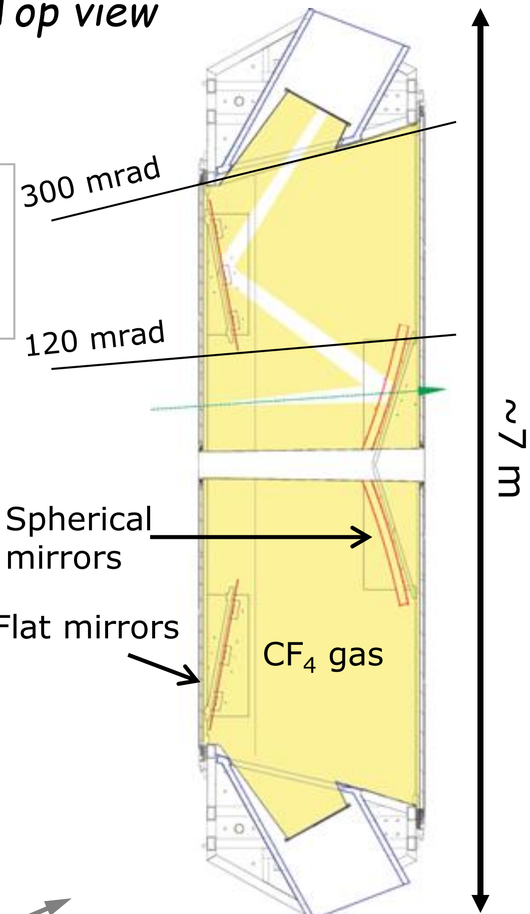
CF_4:
n=1.0005
Up to ~100 GeV/c



RICH 2

Acceptance 15-120 mrad

Top view

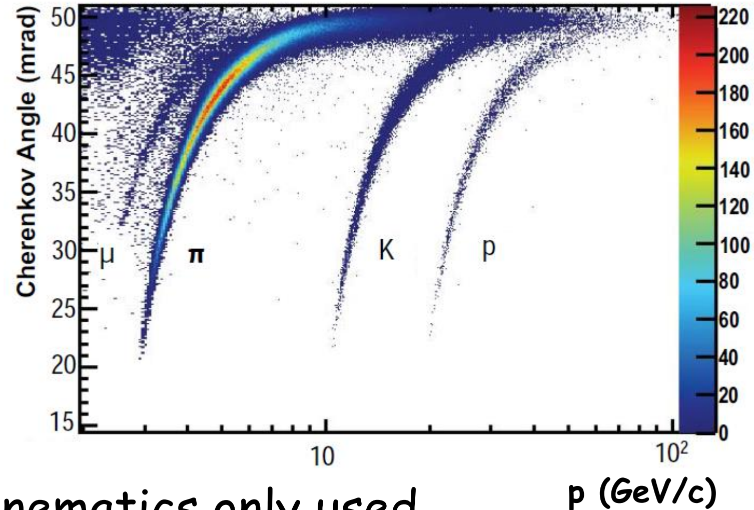


Note scale difference

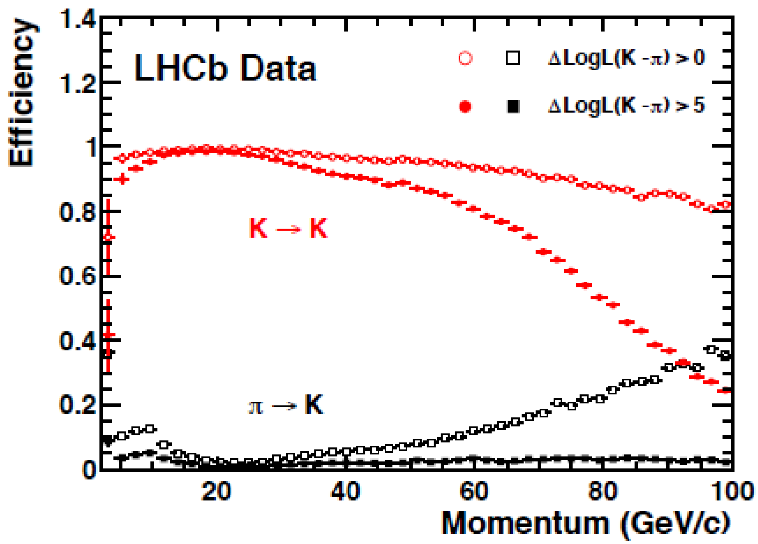
RICH detectors : charged particles identification performance

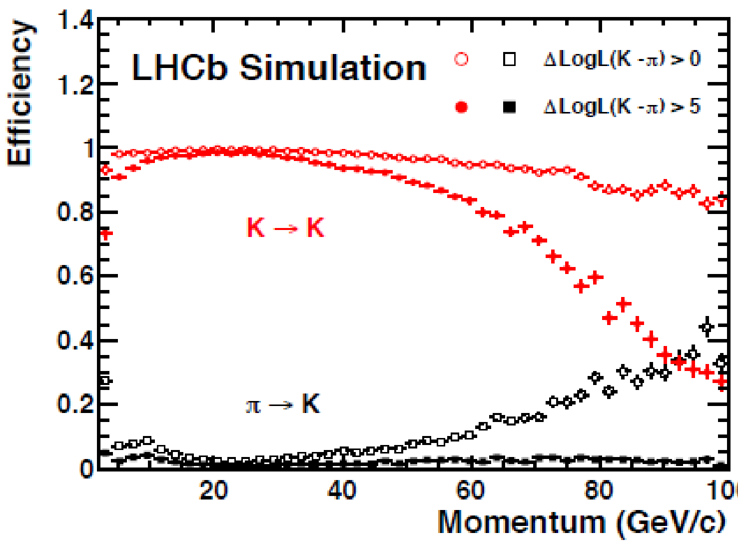
Eur. Phys. J. C73 (2013) 2431

- Reconstructed **Cherenkov angle for isolated tracks**, as a function of track momentum in the **C_4F_{10} radiator**



- Genuine π/K/p samples identified from kinematics only used to evaluate particle identification (PID) performance from data
- **Efficiency/rejection:** reasonable **agreement between data and simulation**

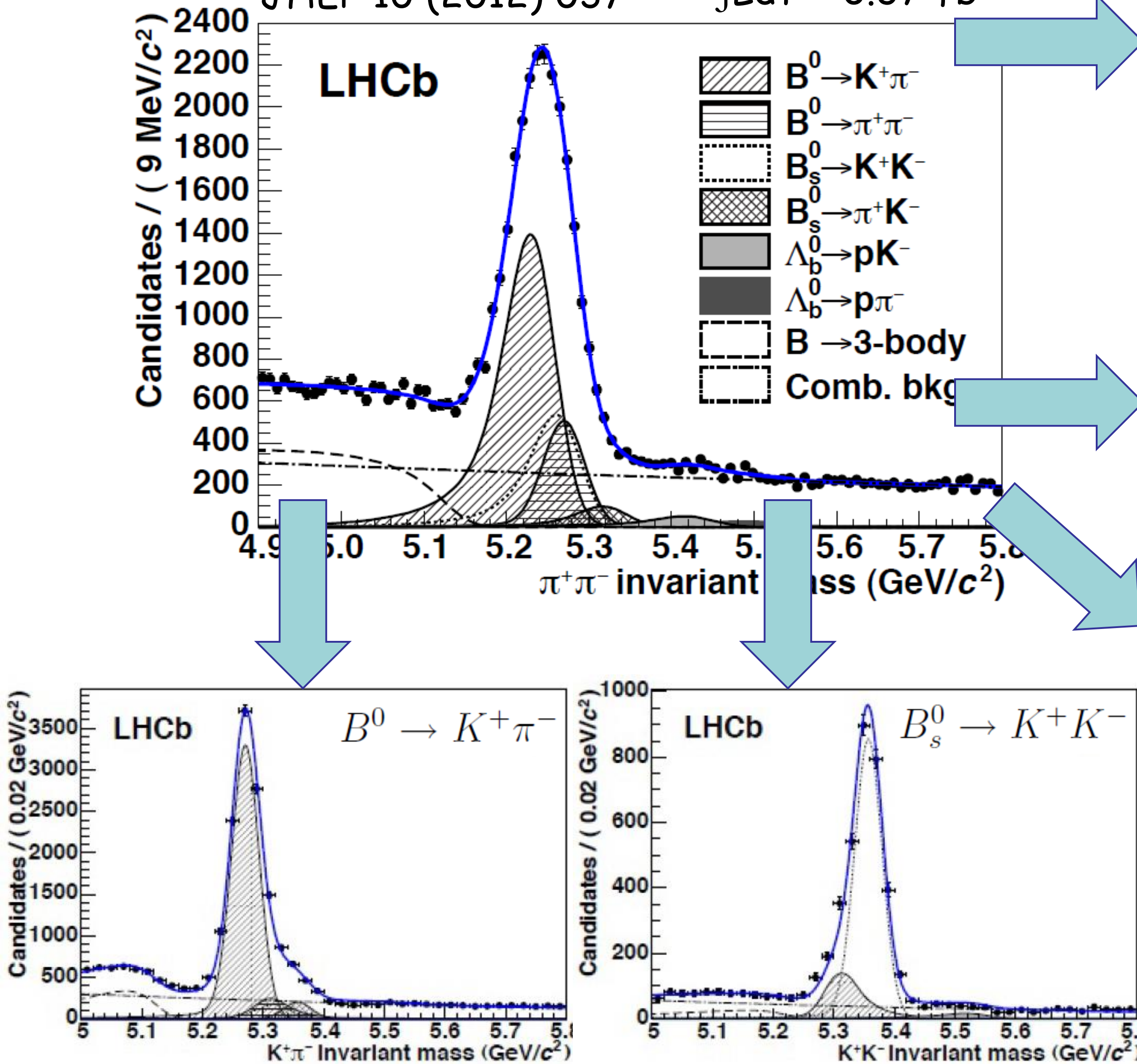


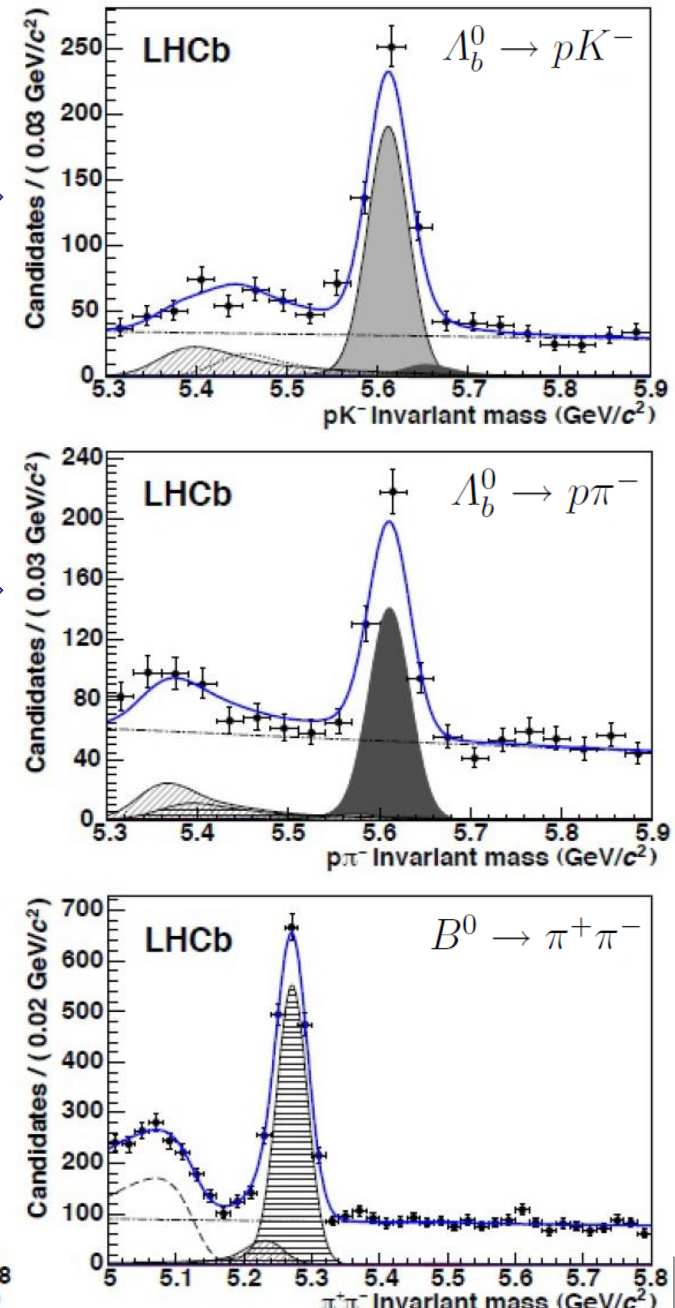


Charged hadron ID with RICH : charmless two-body b-hadron decays

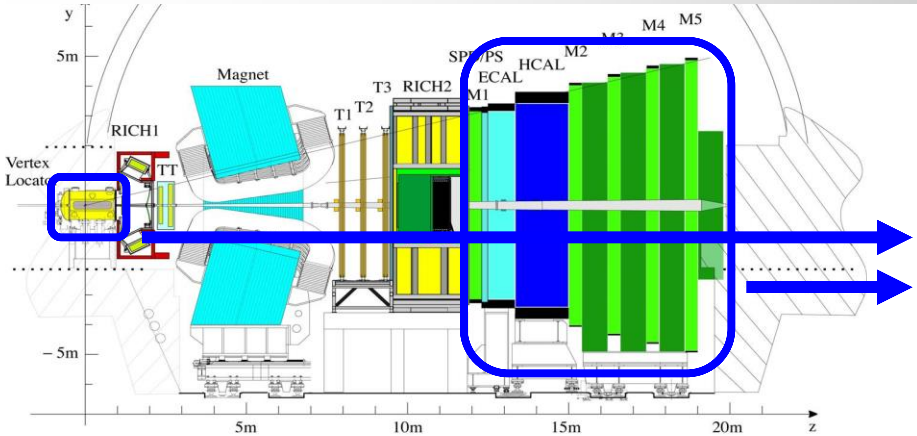
- *b-physics serves as a proof of principle/calibration to probe tiny effects in the charm sector*

JHEP 10 (2012) 037 $\int L dt \sim 0.37\ fb^{-1}$





Trigger



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	**400 kHz $\mu/\mu\mu$**	**150 kHz e/γ**

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological	**2 kHz Inclusive/ Exclusive Charm**	**1 kHz Muon and DiMuon**

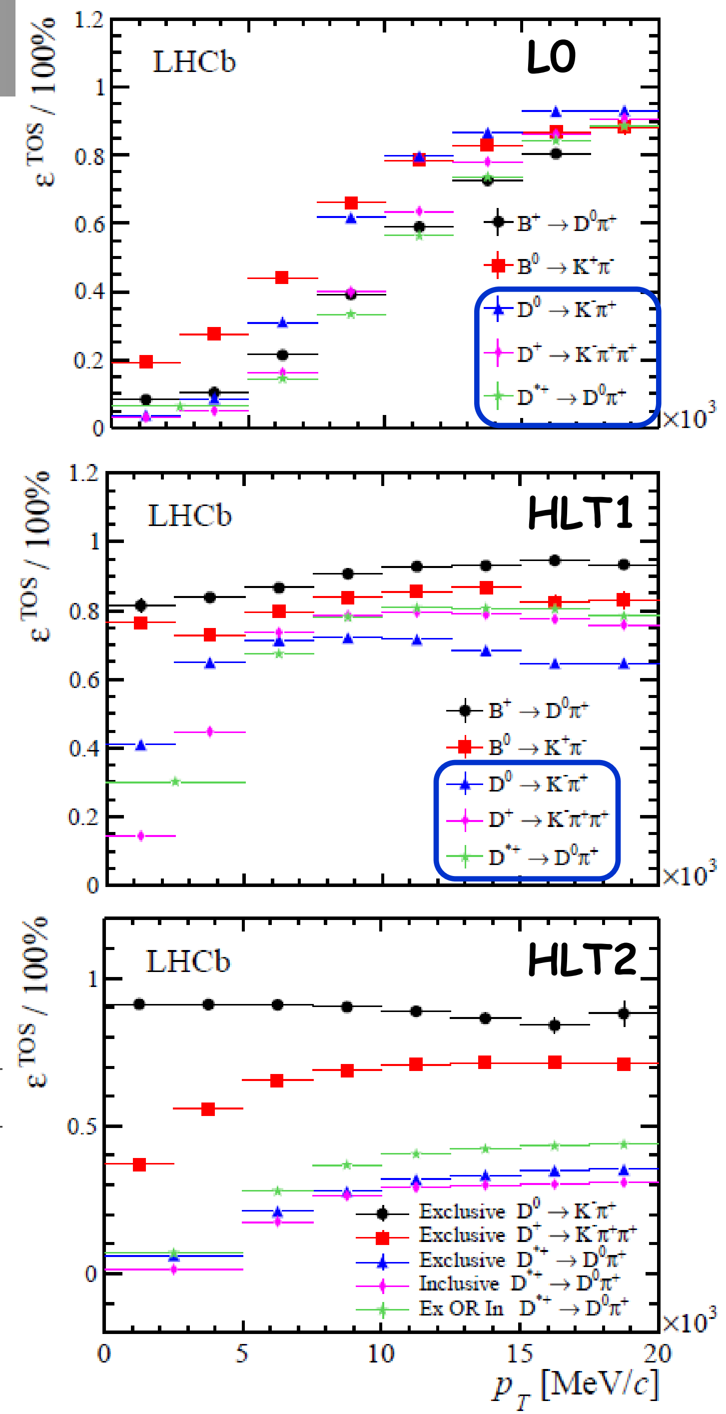
- Performant LHCb trigger: hardware **L0**, software **HLT**, and software **deferred trigger** implemented in 2012 to use the farm during the inter-fill periods

Trigger

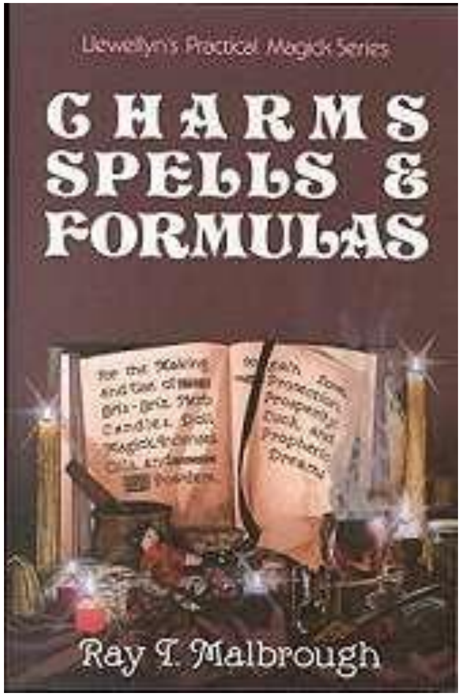
- Trigger on Signal (TOS): signal candidate triggers the event, a technique to **determine trigger efficiency on data**

  LHCb-PUB-2014-039
- **L0 hadron trigger** performance for different charm decay modes
- **HLT1 trigger** performance for various channels as a function of D p_T
- **HLT2 charm trigger** performance for inclusive and exclusive selections
- Total output rate of all charm selections ~2 kHz
- High efficiencies for key channels

channel	L0	HLT1	HLT2
$B^0 \to D^+\pi^-$, $D^+ \to K^-\pi^+\pi^+$	59%	98%	77%
$D^+ \to K^-\pi^+\pi^+$	44%	89%	91%
$D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$	49%	93%	30%



(Brief) Introduction to mixing and CPV in charm sector



- Alexey will do it much better after my talk
- Reminder of some definitions
- What is special about mixing and CPV with charm

Introduction : $D\bar{D}$ mixing and CPV in charm sector

- Both flavour mixing and CP violation well-established in K and B sectors.
- Charm is the **unique up-type system**, where these effects can occur.
- Mass eigenstates vs. flavour eigenstates : $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$
- In the limit of CP conservation p = q (correction of $O(10^{-4})$ in the SM)
- Decay becomes modulated by mixing : $$\frac{e^{-\Gamma t}}{4}\Big(\underbrace{e^{\frac{\Delta\Gamma}{2}t}+e^{-\frac{\Delta\Gamma}{2}t}}_{\cosh\left(\frac{\Delta\Gamma}{2}t\right)} \pm 2\cos\Delta m t\Big)$$

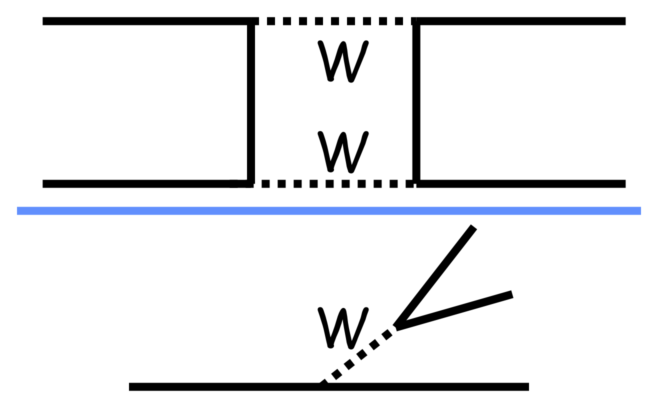
Mixed : $\bar{D}^0 \to D^0$ or $D^0 \to \bar{D}^0$

Unmixed : $\bar{D}^0 \to \bar{D}^0$ or $D^0 \to D^0$

$$A_{mix}(t) \equiv \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})}(t) = \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}$$

Mixing parameters: $x=\Delta m/\Gamma$; $y=\Delta\Gamma/2\Gamma$

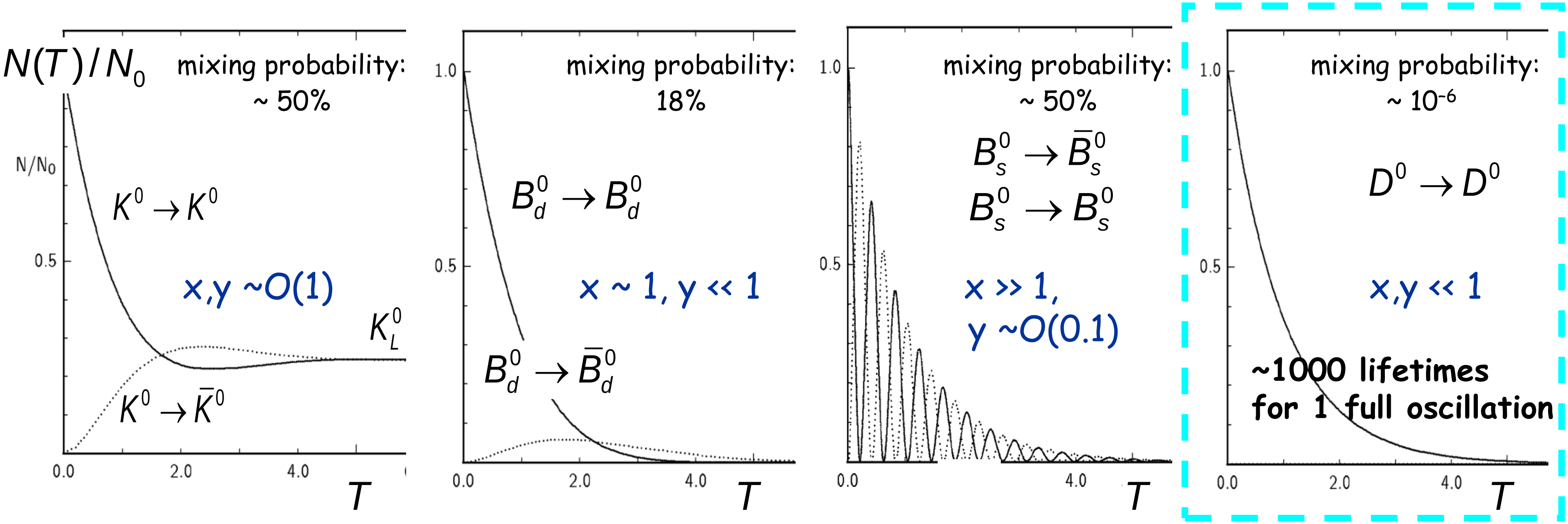
x,y ~



x: mixing frequency in units of lifetime

x>>1 rapid oscillation
x<<1 slow oscillation

Introduction : $D\bar{D}$ mixing and CPV in charm sector



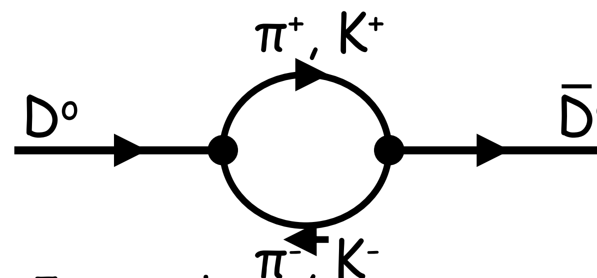
Discovered in 1950s, textbook to illustrate QM effects

Observed in 1987, first hint of the heavy top quark

Observed in 2006, rapid oscillations → high decay time resolution required

Observed in 2007, tiny effect → large samples and clean detection/ID required

- Unlike $B_{(S)}$ -mesons, no strong heavy (t) quark contribution to the box diagram, **contribution from b-quark suppressed** by λ^{10} by the CKM matrix elements !
- Non-perturbative long-range effects more difficult to calculate, typically 10^{-3} with large uncertainty   **e.g. Falk,Grossman,Ligeti,Nir,Petrov PRD 69 114021**



- **$D\bar{D}$ mixing well-established**, but until 2013 no single 5σ result.

Grossman, Kagan, Nir, PRD 75 (2007) 036008
Grossman, Nir, Perez, PRL 103 (2009) 071602

Three types of CPV

- **Direct CPV** between tree and penguin diagram (charged and neutral)
  → **Cabibbo-suppressed decays** (CSD)
  - expected to be up to few x $O(10^{-3})$ in the SM
  - potentially New Physics contributions, e.g. sypersymmetric QCD penguin

$A_f = \langle f|H|D\rangle$, $\bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{D}\rangle$, $|\bar{A}_{\bar{f}} / A_f| \neq 1$

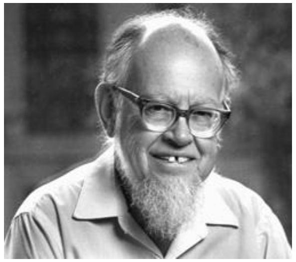
Study: asymmetries in 2-body CSD
asymmetries across the phase space in multi-body decays

- **Indirect CPV**
  - **CPV in mixing**, $|p| \neq |q|$ or weak phase ϕ = **arg(q/p) ≠ 0** (neutral)
    expected to be $O(10^{-4})$ in the SM
  - **CPV in interference** between the decay to final state *f* with and without mixing → common final state, **$\arg(q/p\ \bar{A}_f/A_f) \neq 0$** (neutral)

Indirect CPV ≤ $O(10^{-3})$, precisely calculated in SM.
***Precision** needed to see if observed effect is enhanced by NP*

The Cabibbo-Kobayashi-Maskawa matrix

in Wolfenstein parametrization



elements relevant for charm sector

CS D decays, $D\bar{D}$-mixing

V_{ub} enters via loops

$$V_{CKM} = \begin{array}{c} u \\ c \\ t \end{array} \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta)+A\lambda^5(\rho+i\eta)/2 & -A\lambda^2 + A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$$\begin{array}{ccc} d & s & b \end{array}$$

η - CP-violating phase

SM: single CP-violating phase ➔ strong predictive power for CP asymmetries !

$D^0\bar{D}^0$ mixing and search for CPV with $D \to hh$ decays

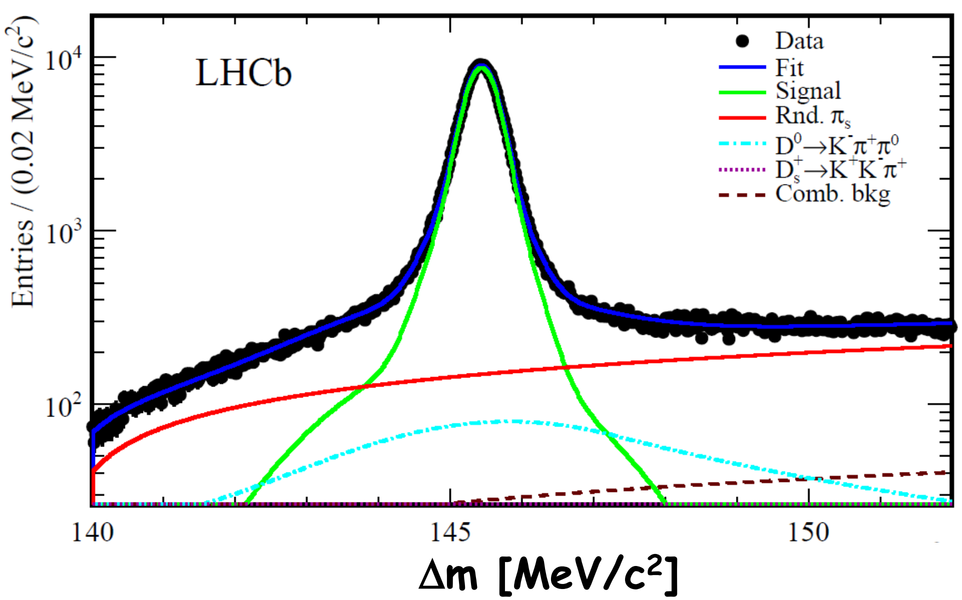
- Mixing by now well established
- $y > 0$: CP-even eigenstate is shorter lived than CP-odd eigenstate
- $x > 0$?: mass splitting not yet clear

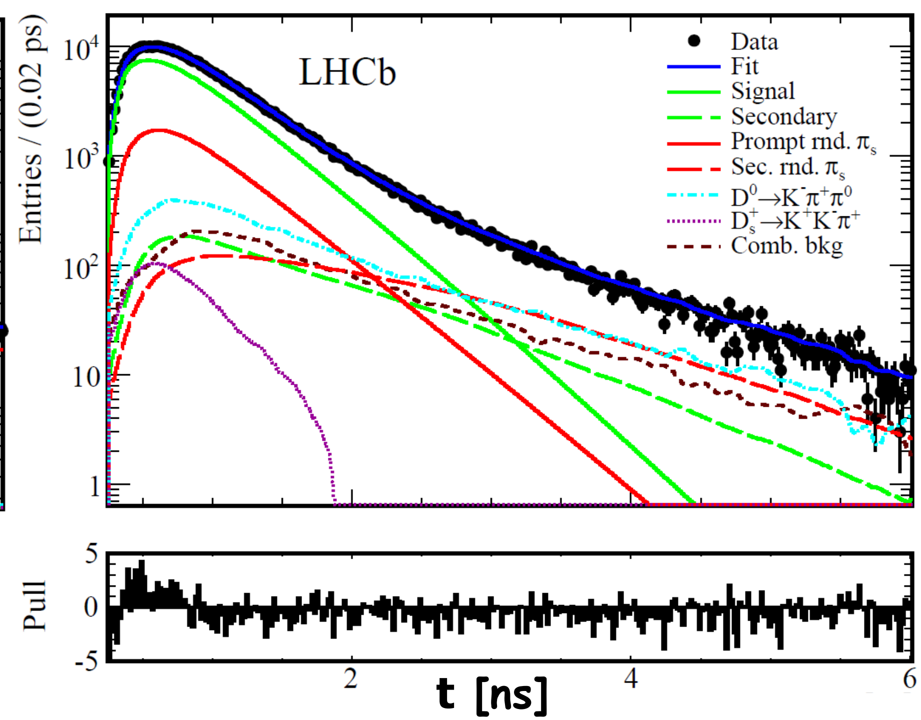
PRL 112 (2014) 041801
$\int L dt \sim 1\ fb^{-1}$

- Measure **lifetime asymmetry A_Γ**

$$A_\Gamma = \frac{\tau^- - \tau^+}{\tau^- + \tau^+} \approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\ cos\ \phi_f - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\ sin\ \phi_f\right]$$

- If no direct CPV, $A_\Gamma = - a_{CP}^{ind}$
- About 3M $D^0 \to K^- K^+$ and 1M $D^0 \to \pi^- \pi^+$ decays selected, D* tags D flavour
- Multivariate unbinned maximum likelihood fits to the subsamples
- Fit projections for Δm and **decay time** for a subset of early $D^0 \to K^- K^+$ data :

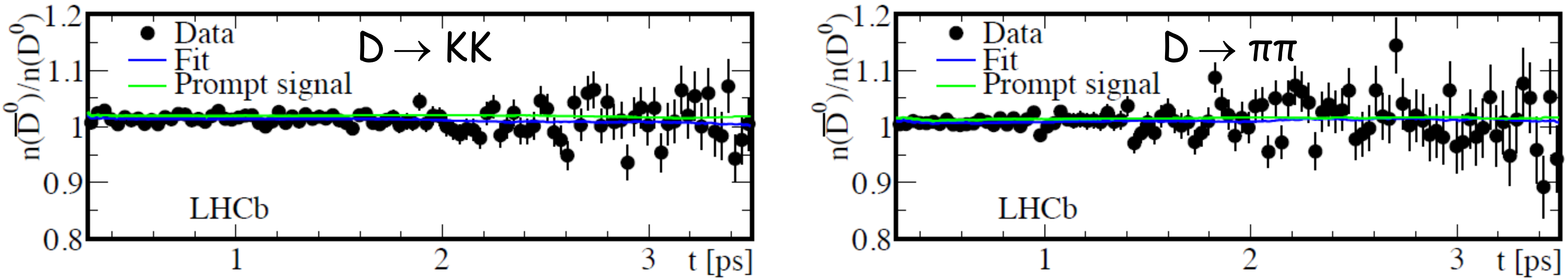




PRL 112 (2014) 041801

$\int L dt \sim 1\ fb^{-1}$

- Ratio of D^0 to $\overline{D}^0$ and fit model for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ data



- World best measurement

$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

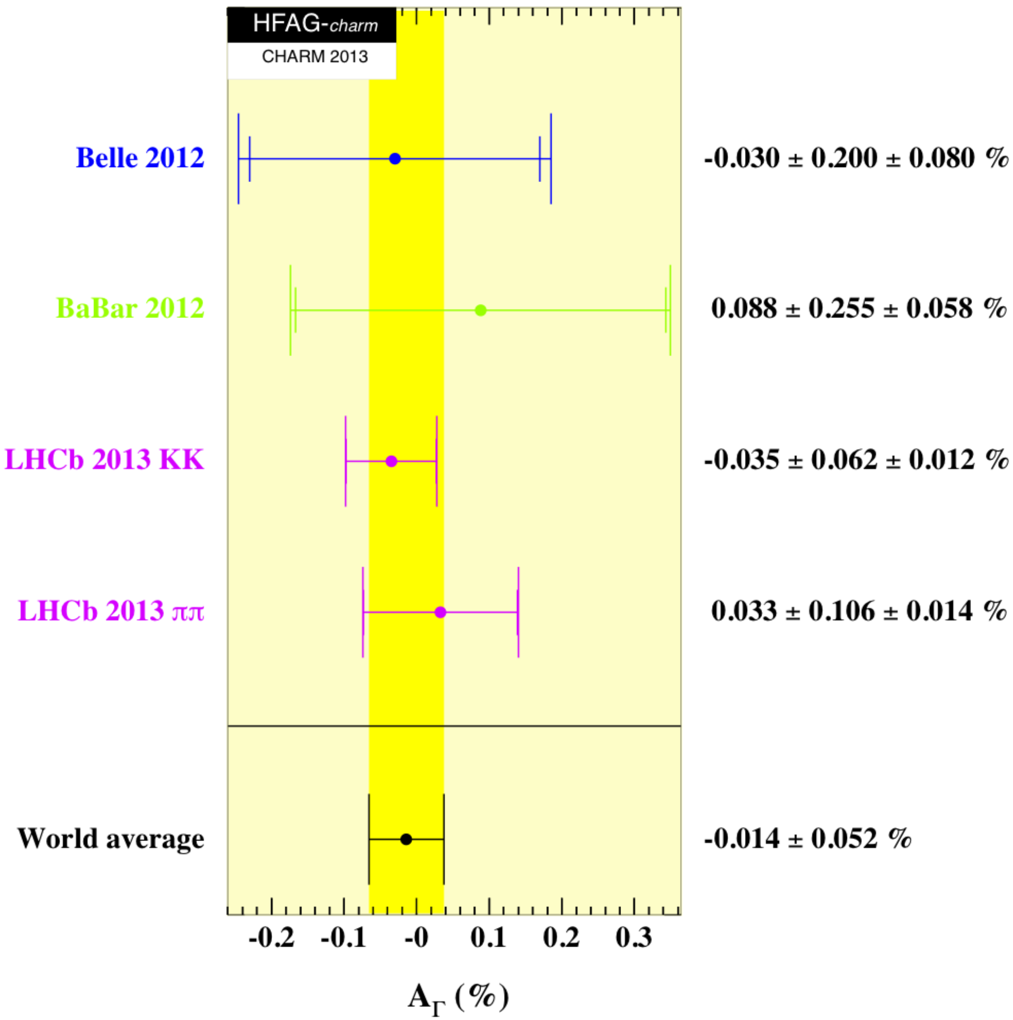
- Consistent result for binned method (no decay-time acceptance model required)

No indirect CPV to the level of 0.1%

- Sensitivity for Run I: $\sigma(A_\Gamma) \sim 3.6 \times 10^{-4}$
- Expected sensitivity for Run II: $\sigma(A_\Gamma) \sim 2.1 \times 10^{-4}$
- In addition, μ-tagged D from $B \to DX\mu\nu$ (~1/3 of prompt sample)

D^0 lifetime asymmetry A_Γ, HFAG average

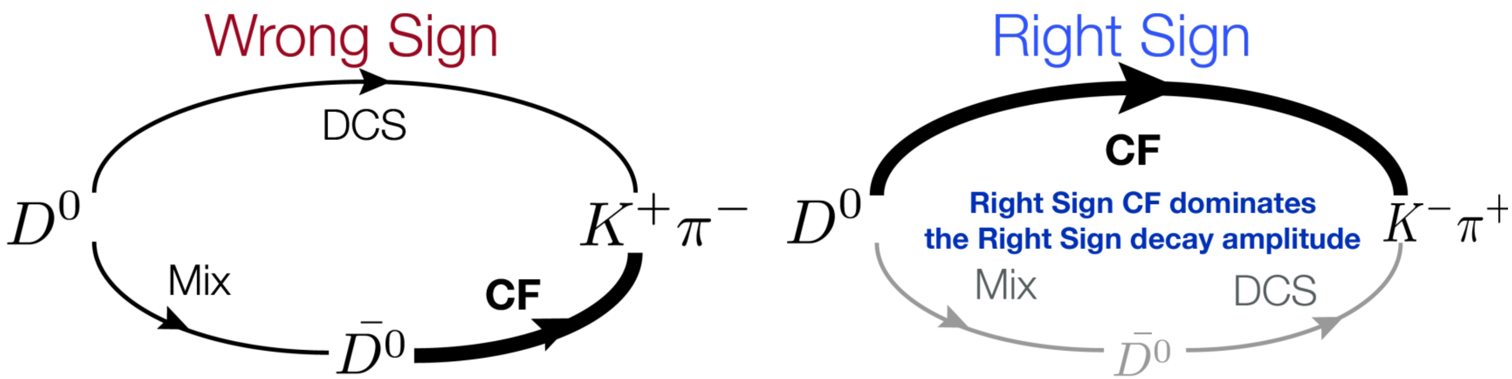
http://www.slac.stanford.edu/xorg/hfag/charm



PRL 111 (2013) 251801

$\int L dt \sim 1\ fb^{-1}$

Time-dependent "wrong-sign" decay rates:
cocktail of **mixing** and **Doubly Cabibbo Suppressed** (DCS) decay amplitudes
in about equal portions according to your taste.



Assuming $|x|,|y| \ll 1$ and *CP* conservation,

Wrong sign: $dN_{ws}/dt \approx e^{-\Gamma t} \times [\, \underbrace{(x'^2+y'^2)/2 \cdot \Gamma^2 t^2/2}_{\textit{mixing}} + \underbrace{D^2_{DCS}}_{\textit{DCSD}} + \underbrace{D_{DCS} \cdot y' \cdot \Gamma t}_{\textit{interference}} \,]$

Ratio: $N_{ws}/N_{rs}(t) \approx (x'^2+y'^2)/2 \cdot \Gamma^2 t^2/2 \; \underbrace{+ R_D + \sqrt{R_D} \cdot y' \cdot \Gamma t}_{\text{vanishes for SL decays}}$

$$\frac{\bar{A}(K^-\pi^+)}{A(K^-\pi^+)} = \sqrt{R_D}\, e^{-i\delta},\ \delta \text{ - strong phase between } A \text{ and } \bar{A}$$

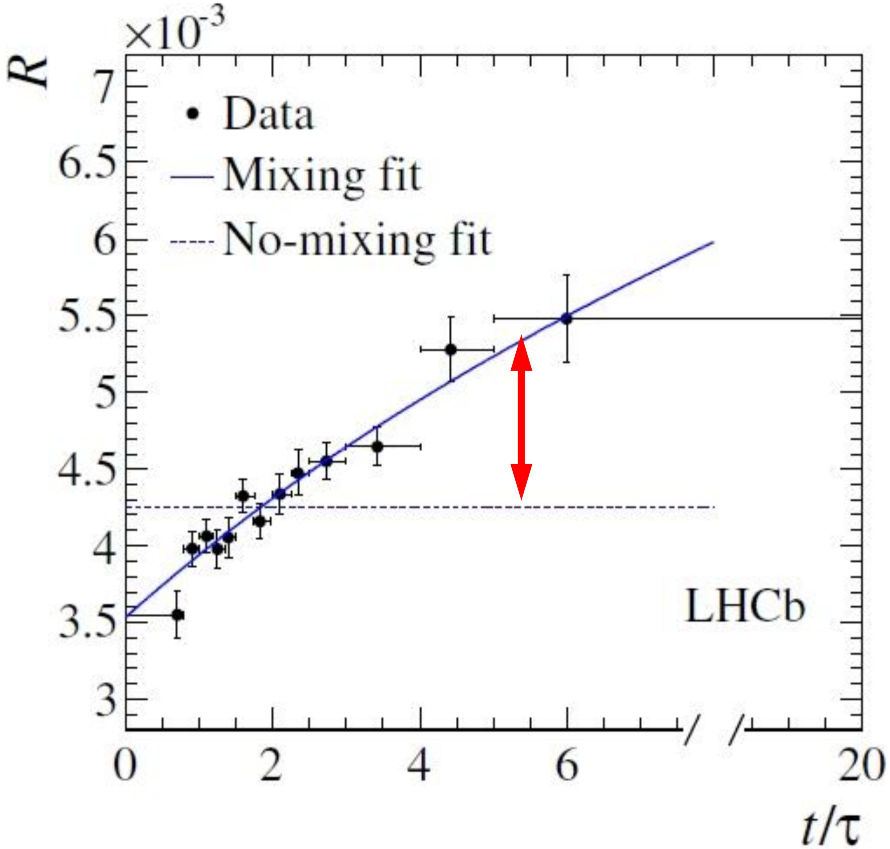
$$y' = y \cos\delta - x \sin\delta$$
$$x' = x \cos\delta + y \sin\delta$$

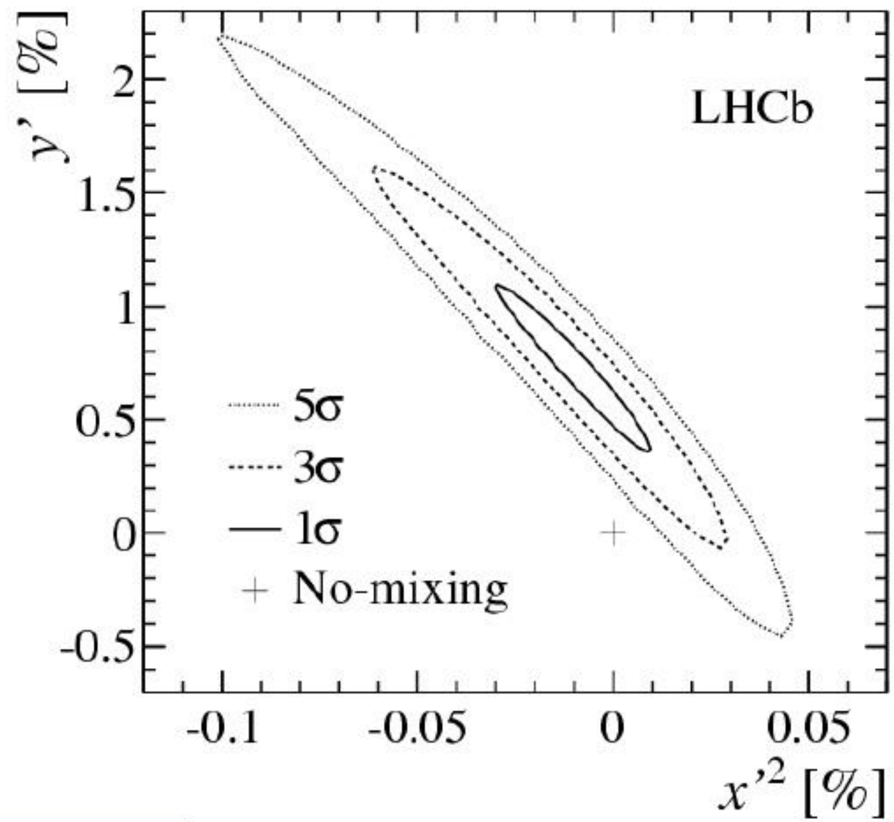
→ x^2+y^2

→ x'^2, y'

Time-dependent WS $D^0 \to K\pi$ decay rate, 1 fb^{-1} result

PRL 110 (2013) 101802
$\int L dt \sim 1\ fb^{-1}$





Fit type	Parameter	Fit result (10^{-3})
Mixing	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing	R_D	4.25 ± 0.04

No mixing hypothesis excluded at > 9σ.

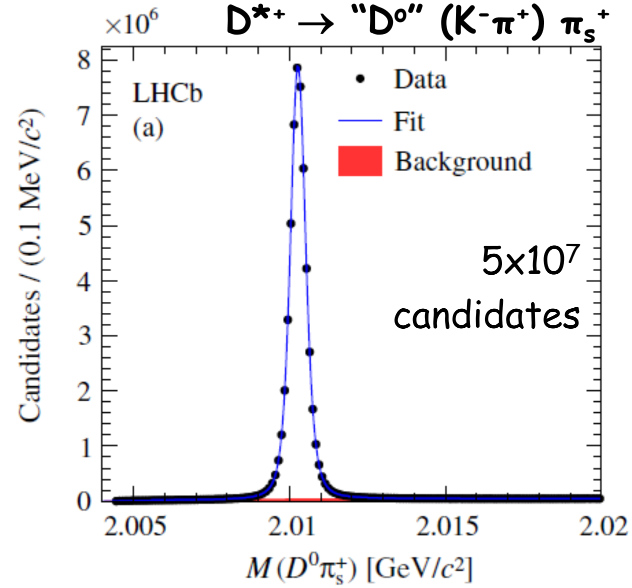
Time-dependent WS $D^0 \to K\pi$ decay rate, 3 fb^{-1} update

PRL 111 (2013) 251801

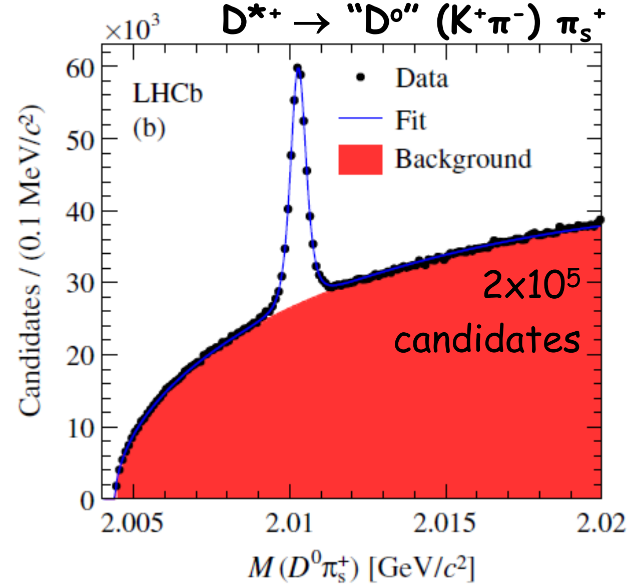
$\int L dt \sim 3$ fb^{-1}

- Use prompt $D^{*+} \to D^0 \pi_S^+$, charge of π_S **tags the initial flavor of the D^0**
- D^0 and π_s^+ required to form vertex constrained to PV
- Background of Wrong Sign (WS) data dominated by real D^0 and a random π.
- Contamination from $B \to D^0X$ reduced by IP cuts on D^0 and π_S^+.
- Right sign (RS) **and WS yields determined in D^0 decay time bins**

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



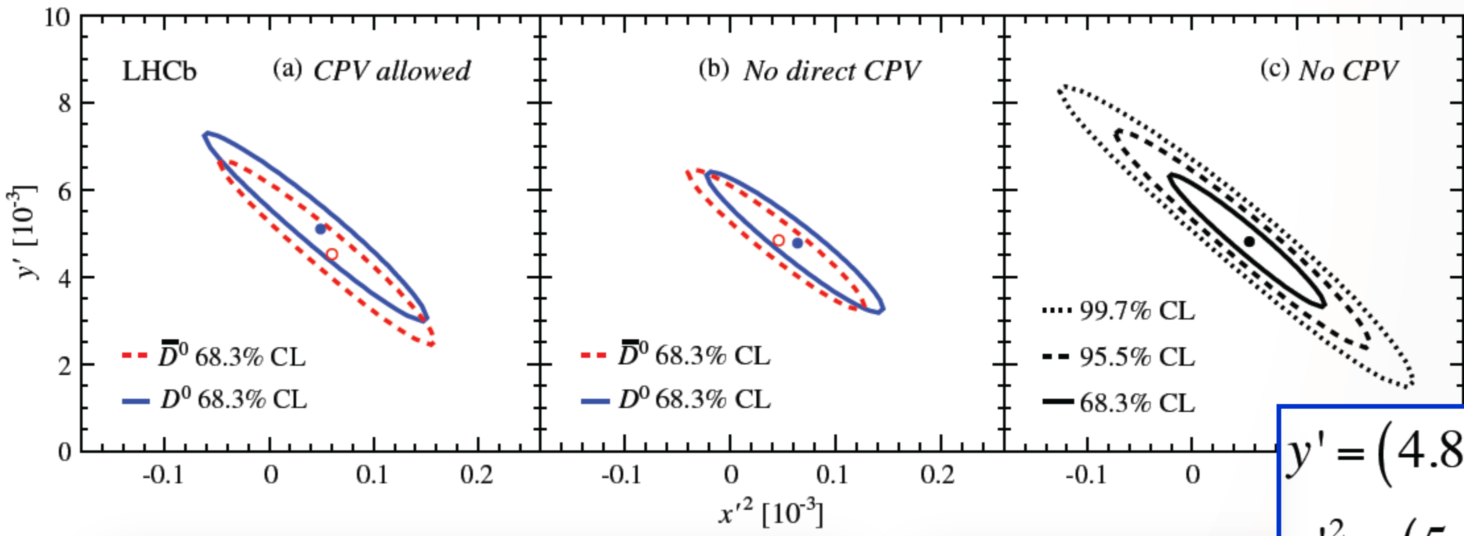
$D^{*+} \to$ "D^0" $(K^+\pi^-)\ \pi_s^+$



WS $D^0 \to K\pi$ decay rate, update with 3 fb^{-1}

- Most significant mixing observation

PRL 111 (2013) 251801
$\int L dt \sim 3\ fb^{-1}$

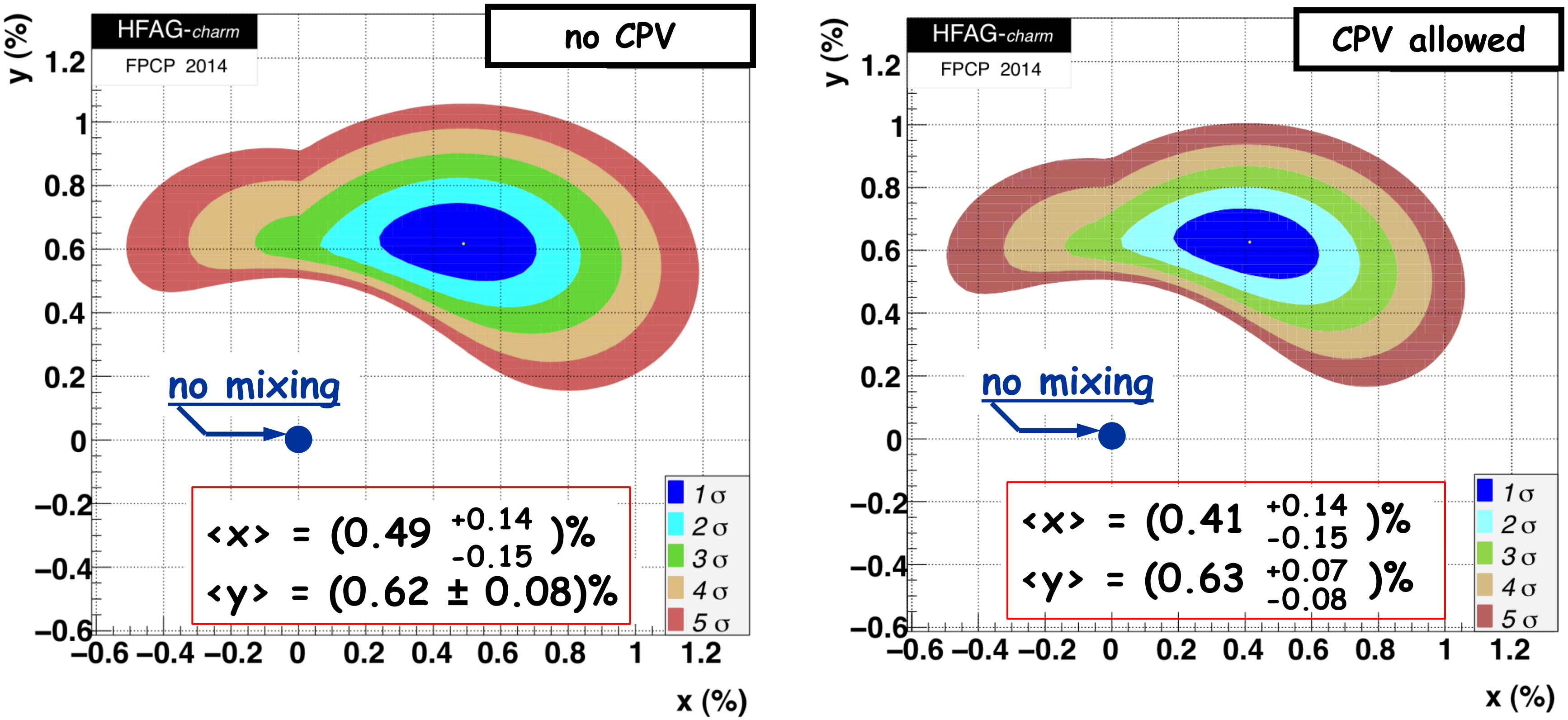


$$y' = (4.8 \pm 0.8 \pm 0.5) \times 10^{-3}$$
$$x'^2 = (5.5 \pm 4.2 \pm 2.6) \times 10^{-5}$$

- Expected sensitivity for Run II: $\sigma(x'^2) \sim 4\times10^{-5}$ $\sigma(y') \sim 0.8\times10^{-3}$
- Similar study possible using $D^0 \to K\pi\pi^0$, $D^0 \to K3\pi$

$D^0\bar{D}^0$ mixing : HFAG averages

http://www.slac.stanford.edu/xorg/hfag/charm



no CPV:

$\langle x \rangle = (0.49\ ^{+0.14}_{-0.15})\%$

$\langle y \rangle = (0.62 \pm 0.08)\%$

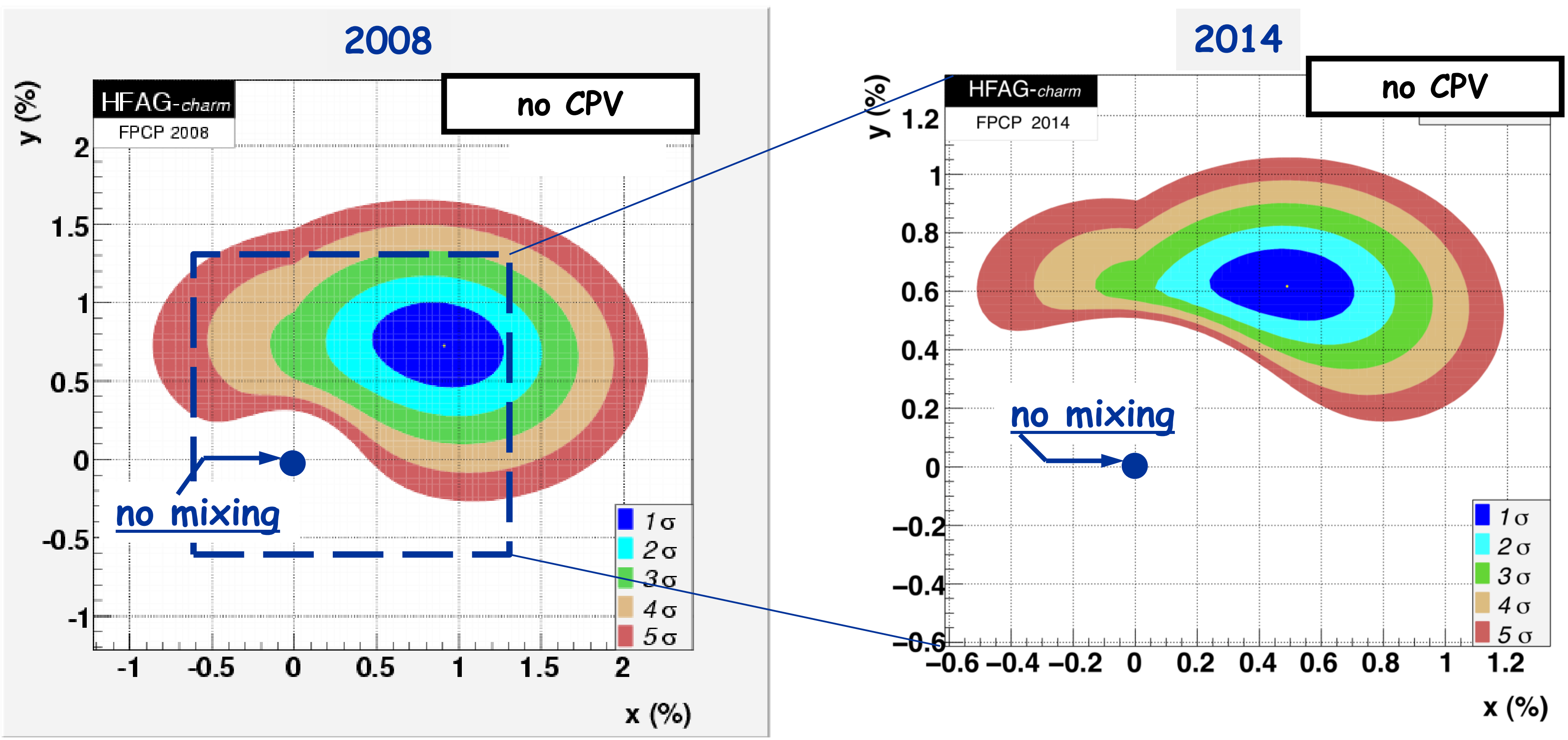
CPV allowed:

$\langle x \rangle = (0.41\ ^{+0.14}_{-0.15})\%$

$\langle y \rangle = (0.63\ ^{+0.07}_{-0.08})\%$

$D^0\bar{D}^0$ mixing : HFAG average evolution over 6 years

http://www.slac.stanford.edu/xorg/hfag/charm



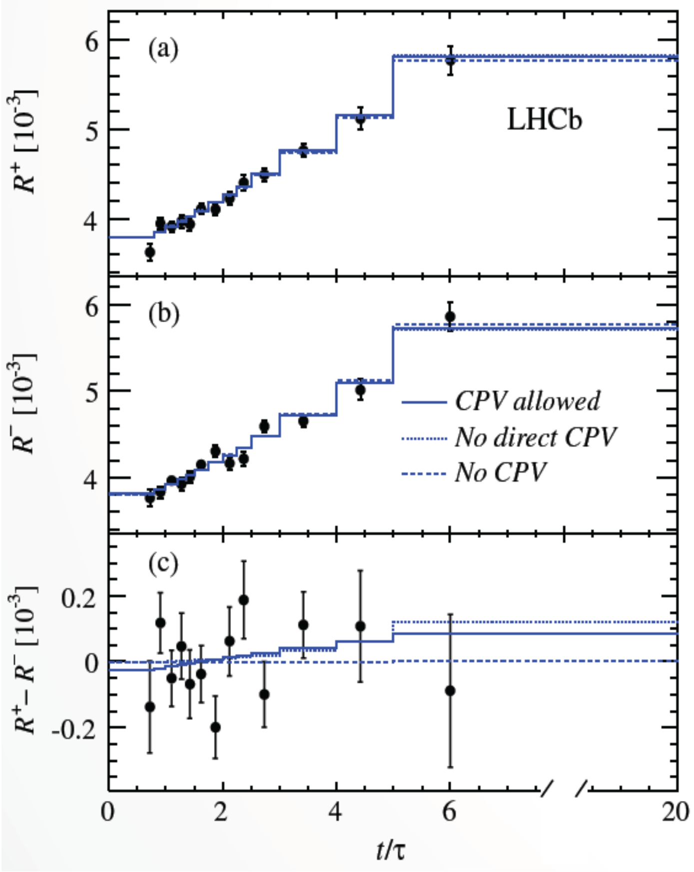
PRL 111 (2013) 251801

$\int L dt \sim 3\ fb^{-1}$

- **Split by flavour to search for CPV**

$$x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$$
$$y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$$

- Efficiency-corrected WS-to-RS yield ratios for D^{*+} and D^{*-} decays, and their differences as functions of decay time in units of D^0 lifetime



Direct and indirect CPV

R_D^+	(10^{-3})	$3.545 \pm 0.082 \pm 0.048$
y'^+	(10^{-3})	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	(10^{-5})	$4.9 \pm 6.0 \pm 3.6$
R_D^-	(10^{-3})	$3.591 \pm 0.081 \pm 0.048$
y'^-	(10^{-3})	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	(10^{-5})	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		$85.9/98$

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

$$0.75 < |q/p| < 1.24 @ 68\% CL$$

No indication for direct or indirect CPV

- Similar study possible using $D^0 \to K\pi\pi^0$, $D^0 \to K3\pi$

Search for time-integrated CPV in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$

- Time-dependent CP asymmetry for D^0 decays to a CP eigenstate f (e.g. $D^0 \to K^- K^+, \pi^- \pi^+$):

$$A_{CP}(f,t) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx a_{CP}^{dir}(f) + t/\tau \, a_{CP}^{ind}$$

universal to a good approximation

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) = a_{CP}^{dir}(K^- K^+) - a_{CP}^{dir}(\pi^- \pi^+) + \Delta\langle t\rangle/\tau \, a_{CP}^{ind}$$

difference in average decay time

- Tag D^0 flavour using prompt $D^{*+} \to D^0 \pi_S^+$
- To first order $A_{raw}(f) = A_{CP}(f) + A_{det}(f) + A_{det}(\pi_S^+) + A_{prod}(D^{*+})$
- $A_{det}(K^- K^+) = A_{det}(\pi^- \pi^+) = 0$, $A_{det}(\pi_S^+)$ and $A_P(D^{*+})$ independent of f

➔ $\boxed{\Delta A_{CP} = A_{raw}(K^- K^+) - A_{raw}(\pi^- \pi^+)}$

- Expect **indirect CPV** to ~cancel in difference (common mixing process)
  direct CPV to differ for different final states
  → non-zero result in presence of direct CPV

Search for time-integrated CPV in $D^o \to K^- K^+$ and $D^o \to \pi^- \pi^+$

Status of measurements by the end of 2012

Exp.	Ref.	ΔA_{CP} (%)
LHCb (prompt D*)	PRL 108 (2012) 111602	-0.82 ± 0.21 ± 0.11
CDF	PRL 109 (2012) 111801	-0.62 ± 0.21 ± 0.10
BELLE	arXiv:1212.1975 (prelim.)	-0.87 ± 0.41 ± 0.06
BaBar	PRL 100 (2008) 061803	+0.24 ± 0.62 ± 0.26

Agreement with no CP violation : CL = 2.0×10^{-5}

- Since then new LHCb results :

$b \to D^o \mu X$ **ΔA_{CP} = (+0.14 ± 0.16 ± 0.08)%** $\int L dt \sim 3\ fb^{-1}$

JHEP 07 (2014) 041

Prompt D^* **ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)%** $\int L dt \sim 1\ fb^{-1}$

update, preliminary

LHCb-CONF-2013-003

- **Individual asymmetries** are expected to have opposite sign due to CKM structure

EPJC 73 (2013) 2373

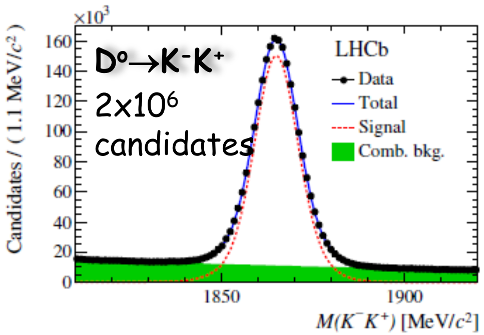
Search for time-integrated CPV in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$: $b \to D^0 \mu X$

$A_{CP}(K^- K^+) = A_{raw}(K^- K^+) - A_{raw}(K^- \pi^+) + A_D(K^- \pi^+)$

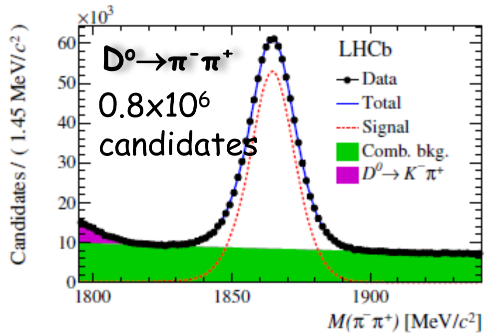
JHEP 07 (2014) 041

$\int L dt \sim 3\ fb^{-1}$

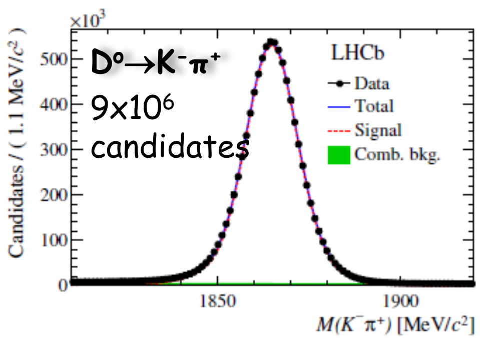
$A_D(K^- \pi^+) = A_{raw}(D^+ \to K^- \pi^+ \pi^+) - A_{raw}(D^+ \to \bar{K}^0 \pi^+) - A_{K^0}$



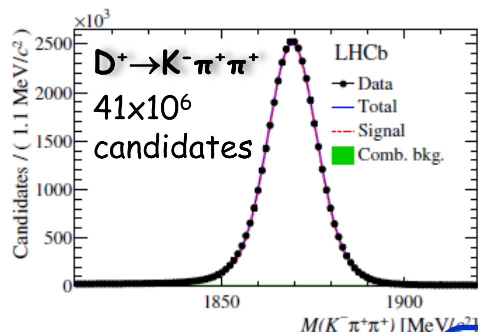
(a)



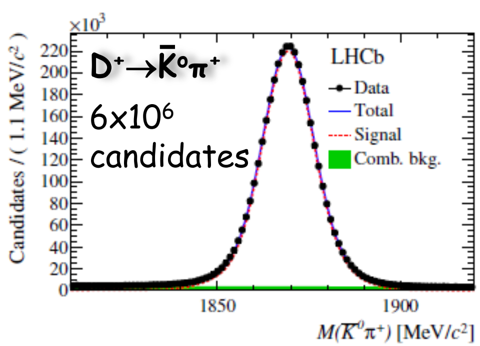
(b)



(c)



(d)



- No CPV in Cabibbo Allowed Decays (CAD) is assumed
- **K^0 asymmetry** from CPV and mixing in the neutral kaon system and difference in the interaction with the material:

$$A_{K^0} = (0.054 \pm 0.014)\%$$

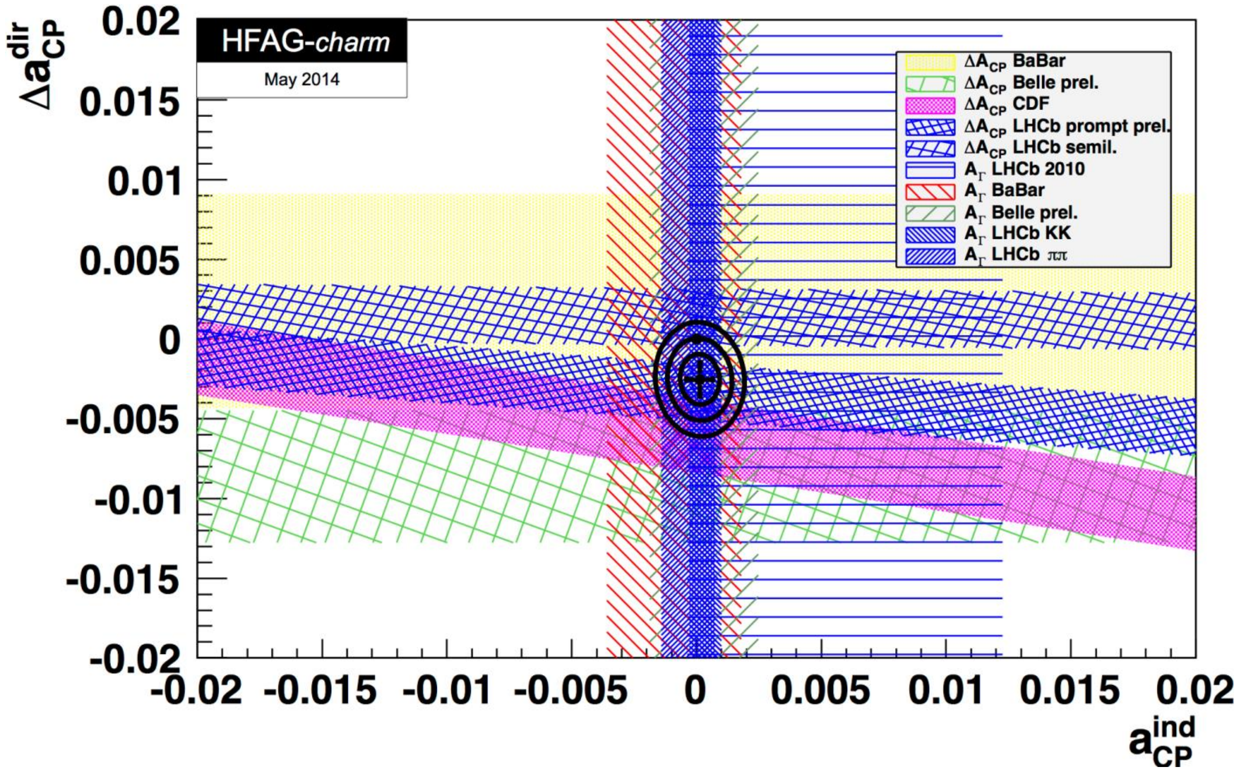
- **Most precise time-integrated CP asymmetry measurement** to date :

$$A_{CP}(D^0 \to K^- K^+) = (-0.06 \pm 0.15 \pm 0.10)\%$$
$$A_{CP}(D^0 \to \pi^- \pi^+) = (-0.20 \pm 0.19 \pm 0.10)\%$$

Consistent with no CPV hypothesis

- Sensitivity on ΔA_{CP} from prompt sample
Run I: σ_{stat}~0.08%, Run II: σ_{stat}~0.05%

http://www.slac.stanford.edu/xorg/hfag/charm



Data consistent with no CPV at CL = 5.1%

Δa_{CP}^{dir} = (-0.253 ± 0.104)%, a_{CP}^{ind} = (-0.013 ± 0.052)%

No evidence (yet) of CPV in D sector

Direct CPV in 2-body D-decays

JHEP 1410 (2014) 25
$\int Ldt \sim 3\ fb^{-1}$

- Search for direct CPV in CSD $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$
- Charged D two-body modes are more difficult due to neutral particles involved

$$A_{CP}^{D_{(s)}^{\pm} \to K_s^0 h^{\pm}} \equiv \frac{\Gamma(D_{(s)}^{+} \to K_s^0 h^{+}) - \Gamma(D_{(s)}^{-} \to K_s^0 h^{-})}{\Gamma(D_{(s)}^{+} \to K_s^0 h^{+}) + \Gamma(D_{(s)}^{-} \to K_s^0 h^{-})}$$

- Measured **raw asymmetries** contain additional asymmetries to be subtracted :

$$A_{raw} \approx A_{CP} - A_D(h) + A_P(D_{(s)}^+) + A_{K^0}$$

  - K^0 asymmetry from CPV and mixing in the neutral kaon system and difference in the interaction with the material: $A_{K^0} = (0.07 \pm 0.02)\%$
  - Use CAD $D_s^+ \to K_S^0 K^+$, $D^+ \to K_S^0 \pi^+$ — JHEP 1407 (2014) 041

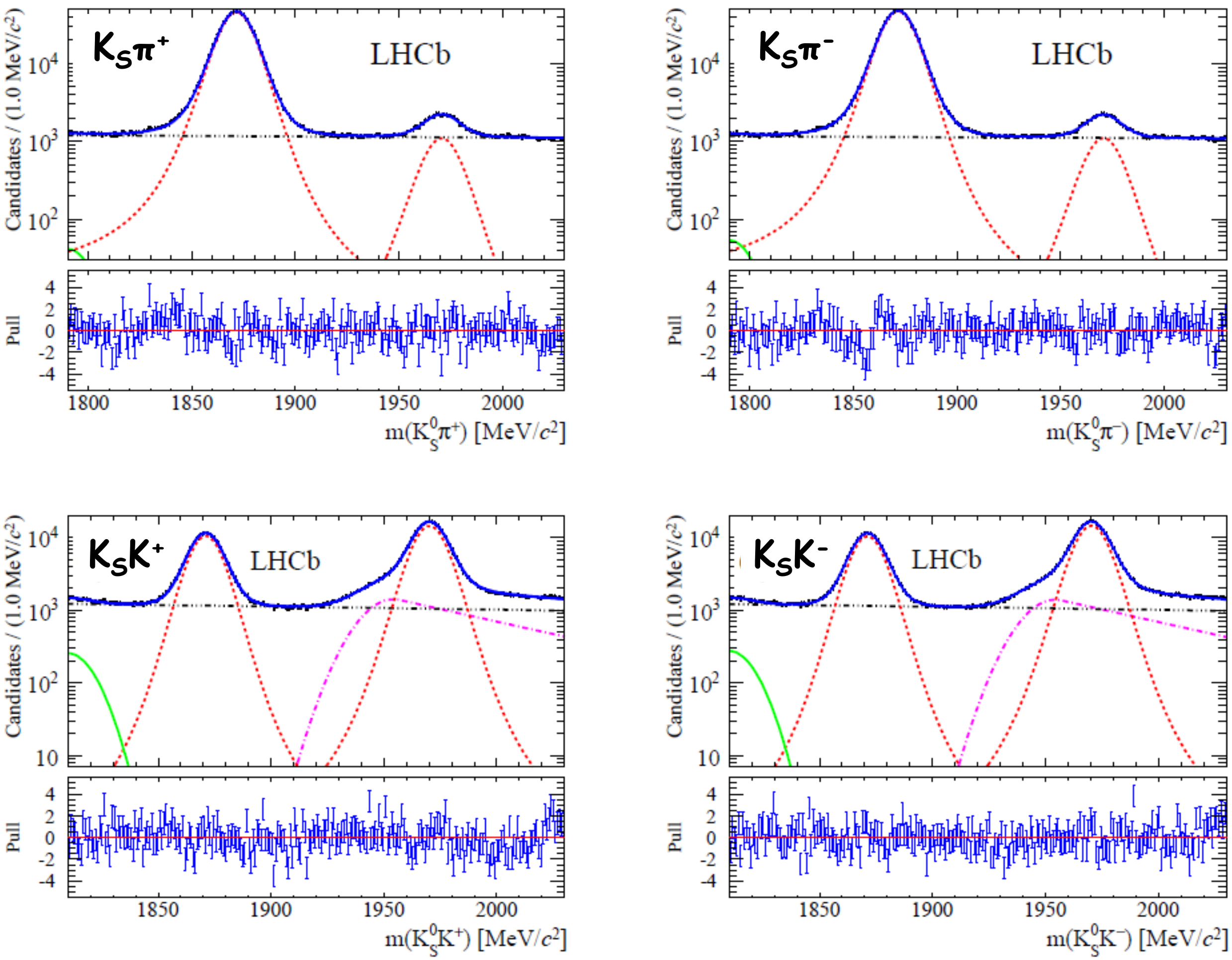
- Construct **double difference** to cancel detection and production asymmetries :

$$A_{CP}^{D^{\pm} \to K_S^0 K^{\pm}} + A_{CP}^{D_s^{\pm} \to K_S^0 \pi^{\pm}} = [\, A_{raw}(D_s^+ \to K_S^0 \pi^+) - A_{raw}(D_s^+ \to K_S^0 K^+) \,] - [\, A_{raw}(D^+ \to K_S^0 \pi^+) - A_{raw}(D^+ \to K_S^0 K^+) \,] - 2A_{K^0}$$

- Combine with CAD $D_s^+ \to \phi \pi^+$ to obtain individual CP asymmetries

Direct CPV in 2-body D-decays

- Uses weighted control mode kinematics, average dipole magnet polarities



JHEP 1410 (2014) 25
$\int L dt \sim 3\ \mathrm{fb}^{-1}$

- Signal yields

Decay mode	Yield
$D^\pm \rightarrow K^0_S\pi^\pm$	$4\,834\,440 \pm 2\,555$
$D^\pm_s \rightarrow K^0_S\pi^\pm$	$120\,976 \pm 692$
$D^\pm \rightarrow K^0_S K^\pm$	$1\,013\,516 \pm 1\,379$
$D^\pm_s \rightarrow K^0_S K^\pm$	$1\,476\,980 \pm 2\,354$
$D^\pm \rightarrow \phi\pi^\pm$	$7\,020\,160 \pm 2\,739$
$D^\pm_s \rightarrow \phi\pi^\pm$	$13\,144\,900 \pm 3\,879$

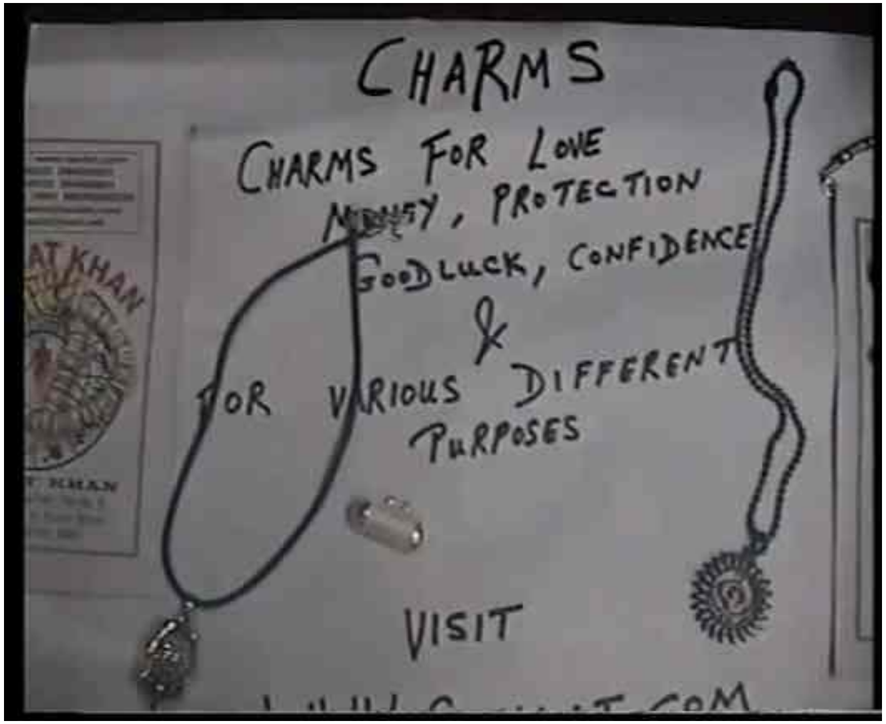
$A_{CP}^{D^+\rightarrow K_S^0K^+} = (+0.03 \pm 0.17 \pm 0.14)\%$

$A_{CP}^{D_s^+\rightarrow K_S^0\pi^+} = (+0.38 \pm 0.46 \pm 0.17)\%$

$A_{CP}^{D^+\rightarrow K_S^0K^+} + A_{CP}^{D_s^+\rightarrow K_S^0\pi^+} = (0.41 \pm 0.49 \pm 0.26)\%$

No evidence for CPV

CP asymmetries in multi-body D-decays



- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases
- Majority of D non-CP eigenstates are resonances → study local asymmetries
  - Fit all contributions to phase-space and look for differences in fit parameters
  - Or look for asymmetries in regions of phase space

- **Dalitz-plot-like techniques** (talk by Franz Niecknig) allow to sum up several resonances
  - Increased statistics
  - Extract information about strong phase

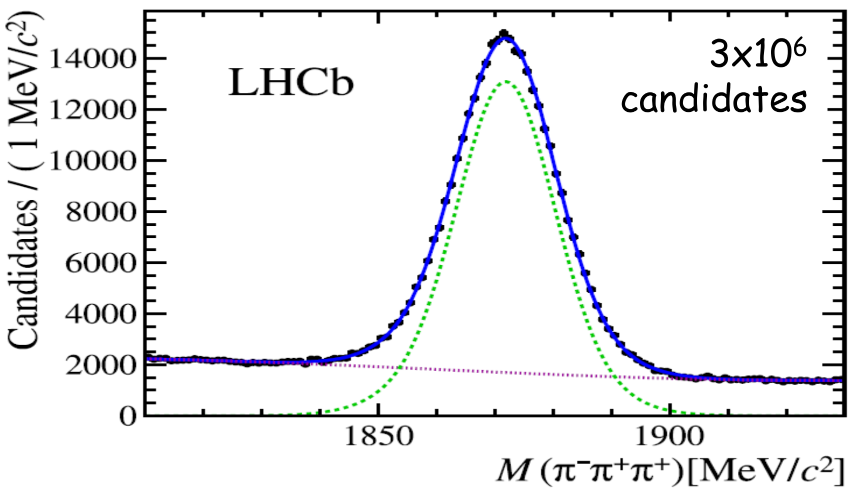
- **Model-dependent** Dalitz plot analysis

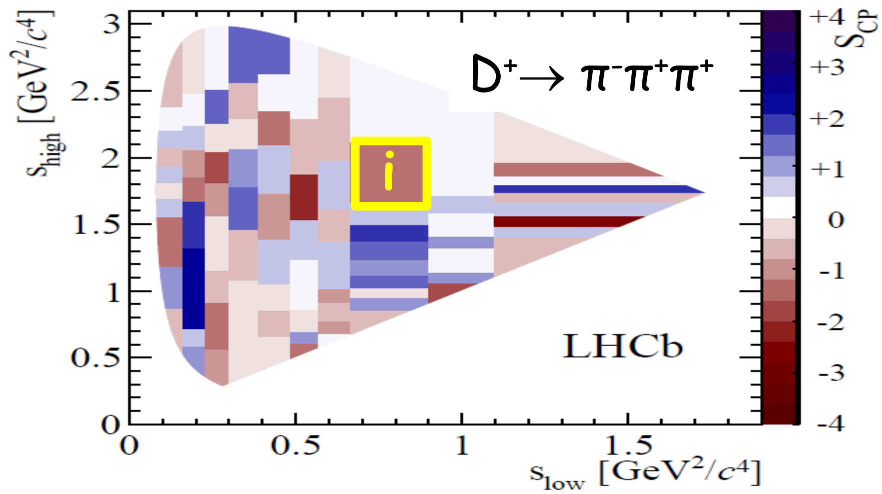
- **Model-independent** Dalitz plot analysis :
  - Binned technique: S_{CP} (or Miranda) method
  - Unbinned technique: Energy Test, kNN

- Triple-product asymmetries (talk by Adrian Bevan), complementary to other methods

- Model-independent search for CPV

PLB 728 (2014) 585 $\int L dt \sim 1\ fb^{-1}$

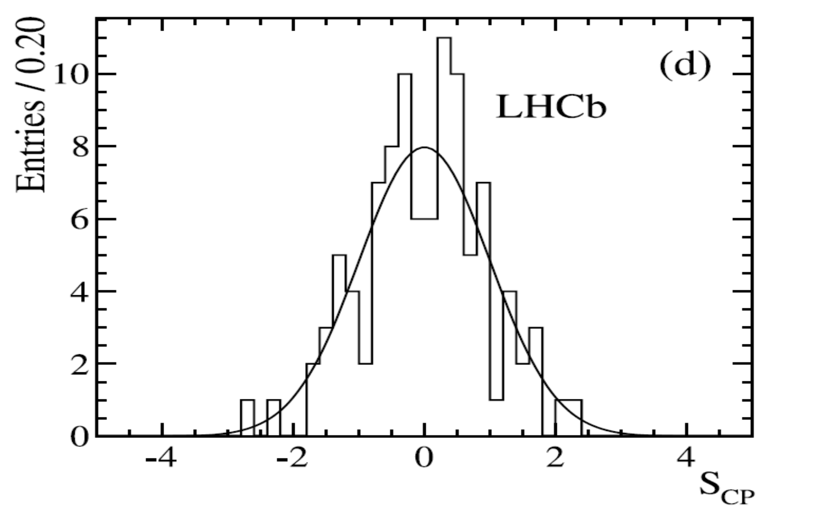




- Search for **asymmetry significances in bins of phase space**

$$S_{CP}^{i} = \frac{N^{i}(D^{+}) - \alpha N^{i}(D^{-})}{\sqrt{N^{i}(D^{+}) + \alpha^{2} N^{i}(D^{-})}} \quad \alpha = \frac{N(D^{+})}{N(D^{-})}$$

→ removes sensitivity to global asymmetries

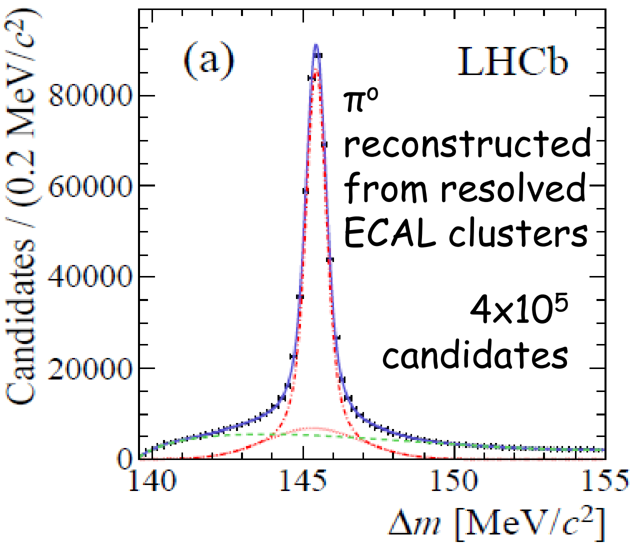


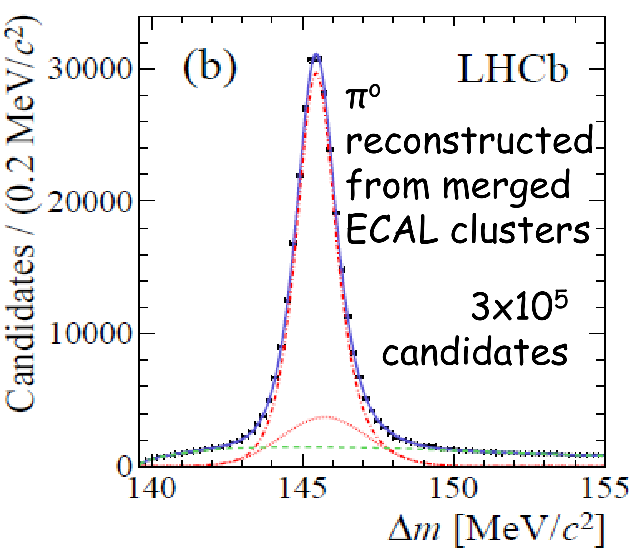
$\chi^2 = \sum (S_{CP}^{i})^2$: agrees with Gaussian distribution = **no-CPV hypothesis**, p-values > 50% for different binnings

- Search for local asymmetries via unbinned comparison with nearest neighbours (kNN technique), **no-CPV hypothesis**, p-values > 20% for different n_k

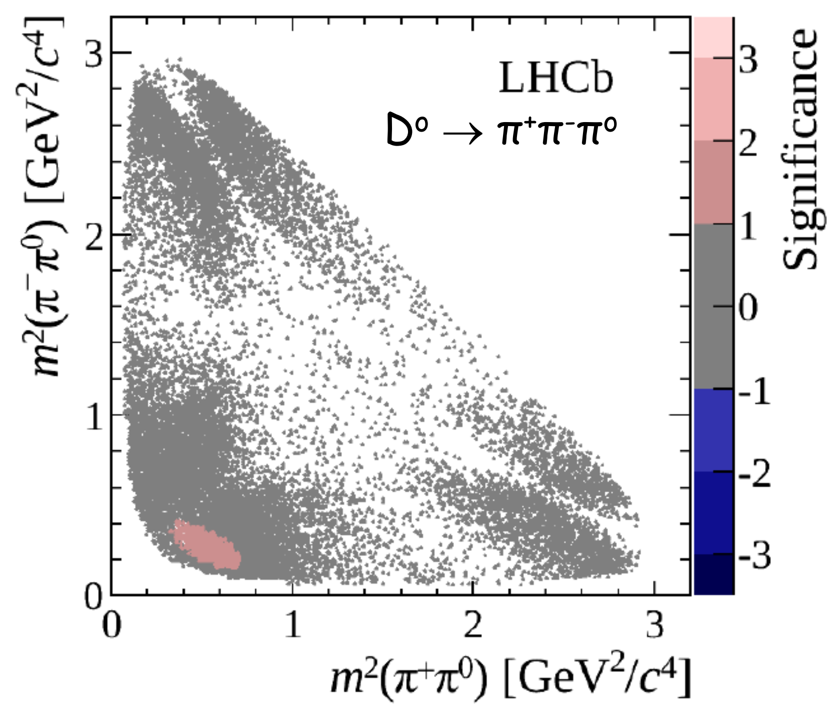
- **Energy Test**: unbinned, model-independent technique, significance of local asymmetry for each event is obtained NIM A537 (2005) 626, Phys. Rev. D84 (2011) 054015

PLB 740 (2015) 158
$\int L dt \sim 2\ fb^{-1}$





- Control mode $D^0 \to K^- \pi^+ \pi^0$ to assess charged pion detection asymmetries
- Visualisation of **local asymmetry significance** :

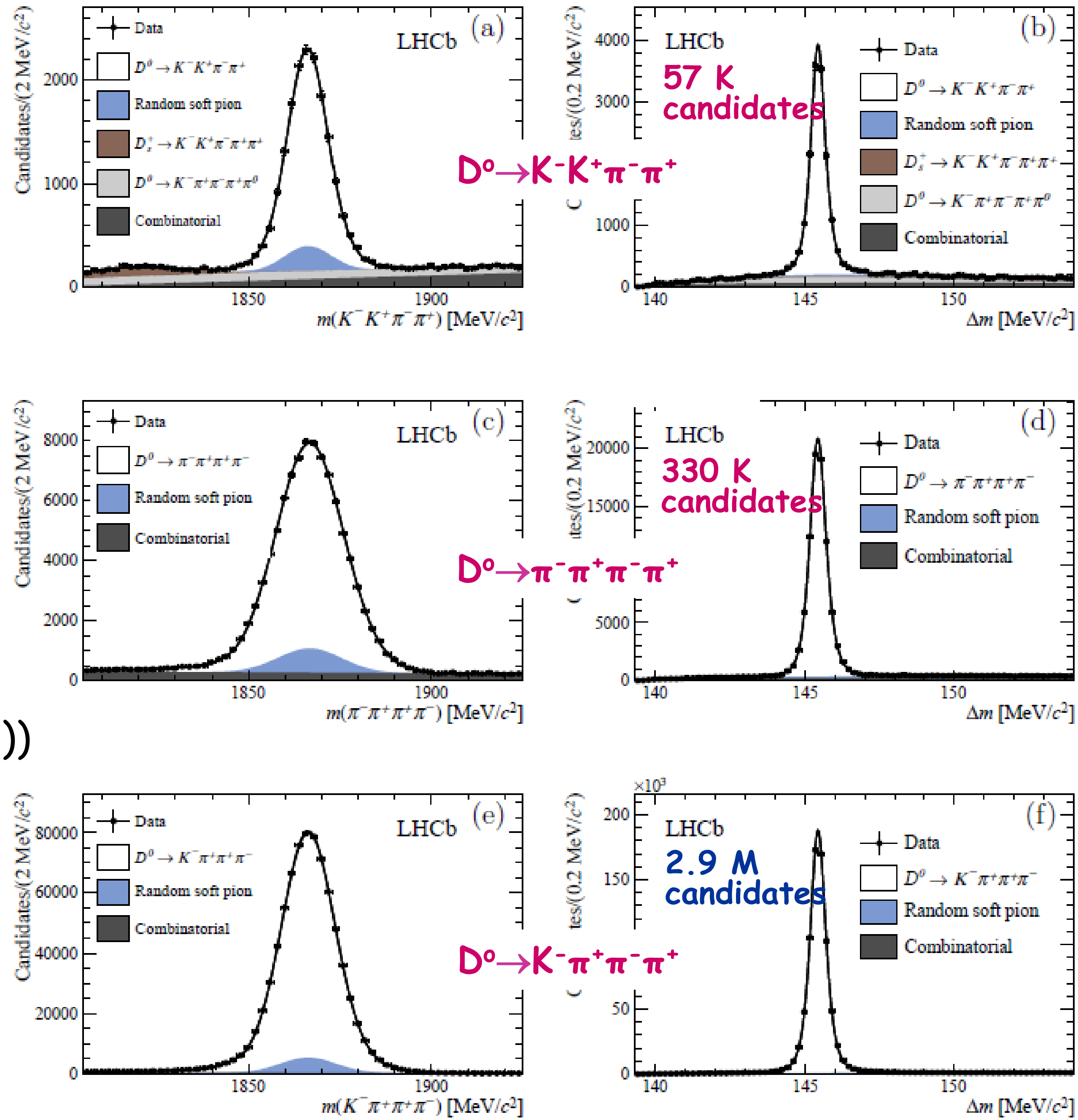


- Consistent with **no-CPV** hypothesis with a p-value of (2.6 ± 0.5)%

Multi-body D^0 decays : $D^0 \to K^- K^+ \pi^- \pi^+$, $D^0 \to \pi^- \pi^+ \pi^- \pi^+$

PLB 726 (2013) 623

$\int L dt \sim 1\ fb^{-1}$



- Use prompt sample $D^{*+} \to D^0 \pi_S^+$
- Tag D^0 flavour using π_S
- Signal extraction via sPlot technique
- **Fit $(m, \Delta m)$ plane to extract sWeights,**

$(m(D), \Delta m = m(D\, \pi_S^+) - m(D))$

Multi-body D^0 decays : $D^0 \to K^- K^+ \pi^- \pi^+$, $D^0 \to \pi^- \pi^+ \pi^- \pi^+$

PLB 726 (2013) 623

$\int L dt \sim 1\ fb^{-1}$

- **Miranda method**: significance in equally populated bins of 5D phase space :

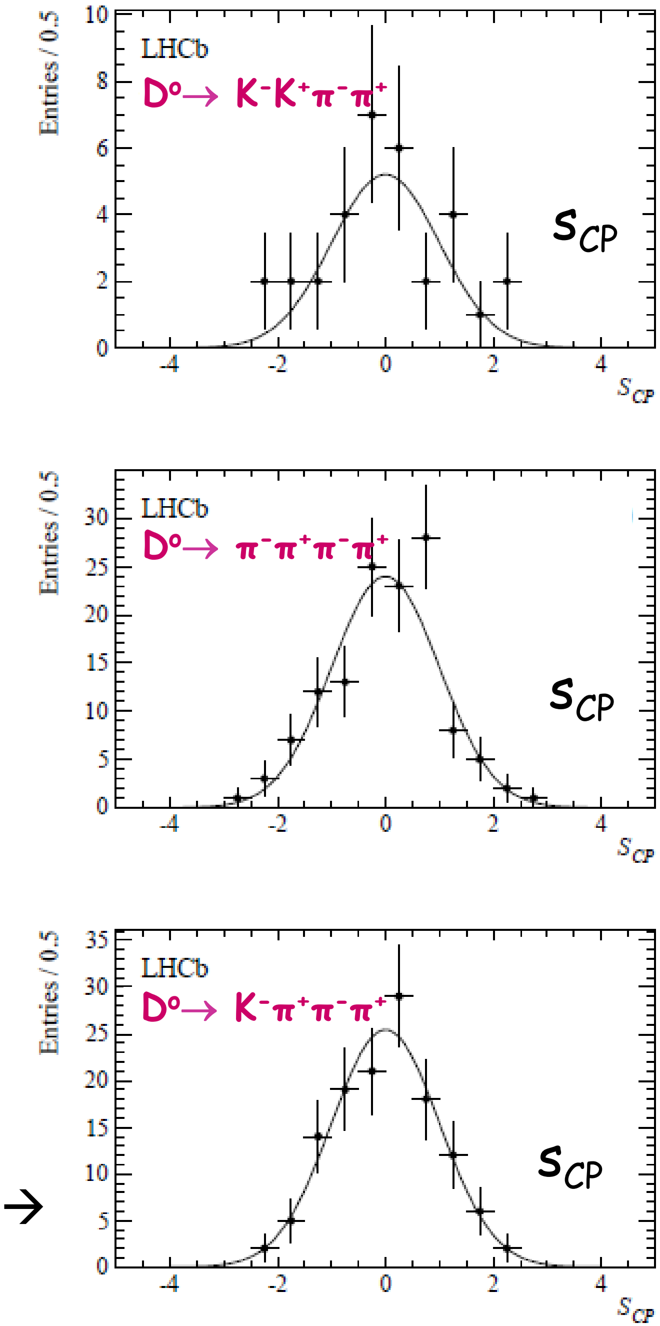
$$s_{CP}^{i} = \frac{N_i(D^0) - \alpha\, N_i(\bar{D}^0)}{\sqrt{\alpha\,(\,\sigma_i^2\,(D^0) - \sigma_i^2\,(\bar{D}^0)\,)}}\ , \quad \alpha = \frac{\Sigma_i\, N_i(D^0)}{\Sigma_i\, N_i(\bar{D}^0)}$$

- No-CPV = Gaussian distribution

- p-values for no-CPV hypothesis are 9.1% for $KK\pi\pi$ and 41% for 4π

Consistent with no CPV

No evidence for local asymmetries →



- From **triple products** in D^0 c.m.s., D^0 : $C_T \equiv \vec{p}_{K+} \cdot (\vec{p}_{\pi+} \times \vec{p}_{\pi-})$

  $\overline{D}^0$: $\overline{C}_T \equiv \vec{p}_{K-} \cdot (\vec{p}_{\pi-} \times \vec{p}_{\pi+})$

  construct **T-odd observables** :

$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)} \quad \overline{A}_T \equiv \frac{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) - \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) + \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}$$

- Final state interactions (FSI) could introduce fake asymmetries
- FSI effects cancel out in the **CPV observable** $a_{CP}^{T\text{-odd}} \equiv \frac{1}{2}(A_T - \overline{A}_T)$

  sensitive to interference between even and odd partial waves

- Effective CPV differs depending on strong phase difference of the two interfering amplitudes, $\mathbf{a_{CP}^{T\text{-odd}} \sim \sin(\varphi_1 - \varphi_2) \times \cos(\delta_1 - \delta_2)}$

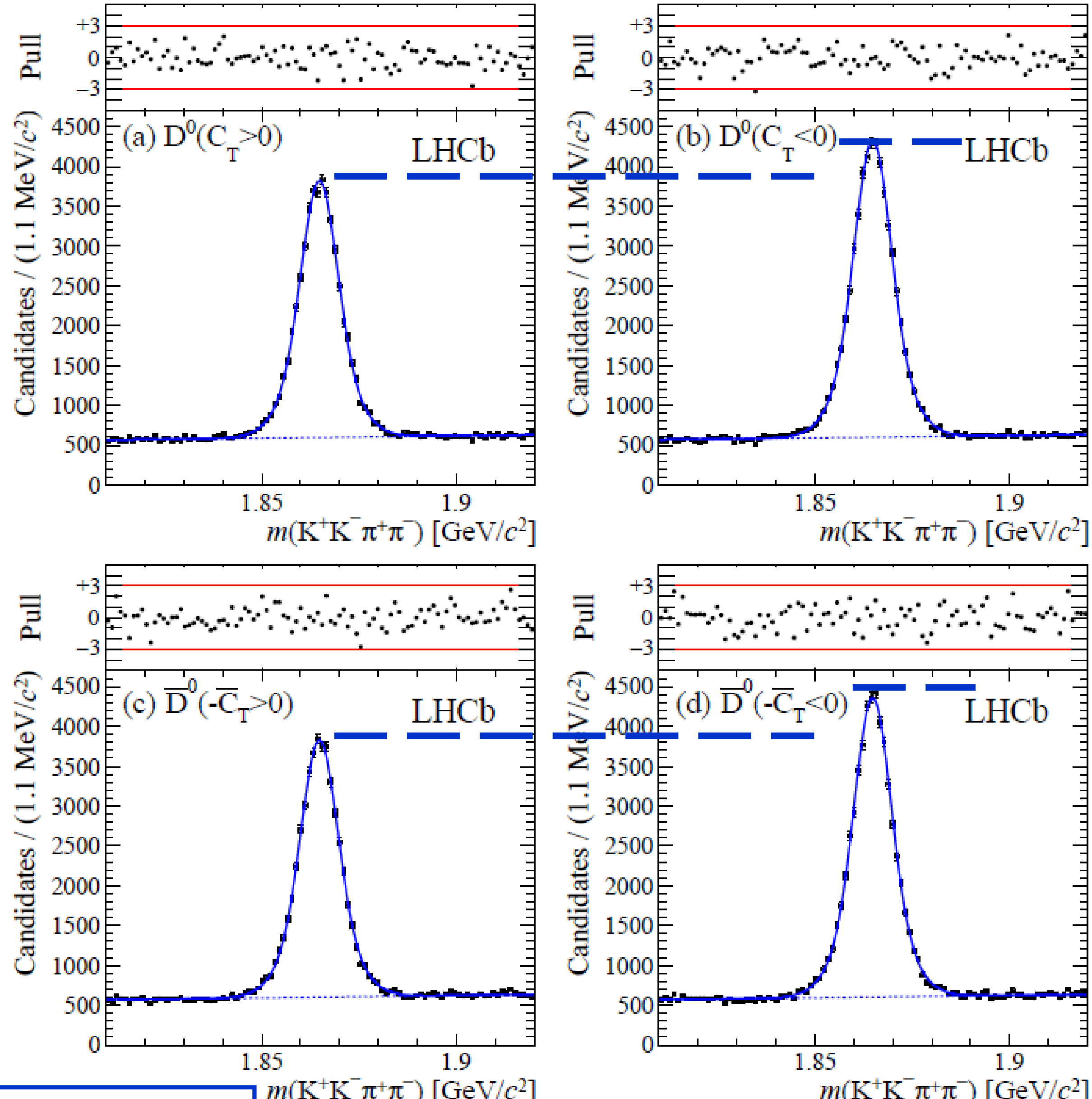
  weak phases strong phases

- $a_{CP}^{T\text{-odd}}$ ~ is maximal for small $(\delta_1 - \delta_2)$

CPV with T-odd correlations : $D^0 \to K^- K^+ \pi^- \pi^+$

JHEP 1410 (2014) 5
$\int L dt \sim 3\ fb^{-1}$

- 1.7×10^5 secondary $D^0 \to K^- K^+ \pi^- \pi^+$ decays



- Measure **phase-space integrated T-odd observables and CP-asymmetry**:

$A_T = (-7.18 \pm 0.41 \pm 0.13)\%$
$\overline{A}_T = (-7.55 \pm 0.41 \pm 0.12)\%$

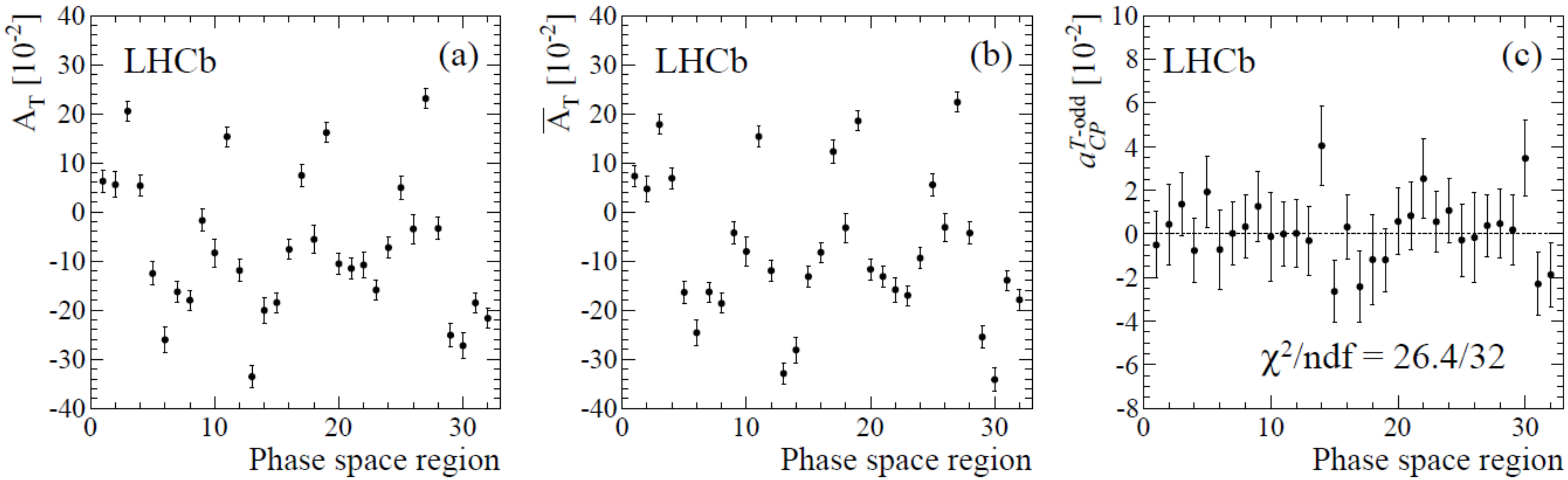
$$\boxed{a_{CP}^{T-odd}\left(D^0 \to KK\pi\pi\right) = \left(0.18 \pm 0.29 \pm 0.04\right)\%}$$

WA: (0.17 ± 0.27)%

CPV with T-odd correlations : $D^0 \to K^- K^+ \pi^- \pi^+$

JHEP 1410 (2014) 5
$\int L dt \sim 3\ fb^{-1}$

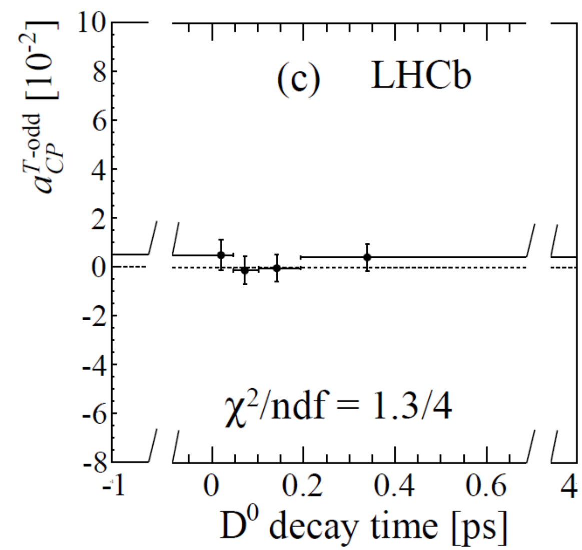
- Variations of T-odd variable with 5D phase space cancel in $a_{CP}^{T\text{-odd}}$



- No variations with D decay time, which excludes effects of indirect CPV

- Precision on $a_{CP}^{T\text{-odd}}$ significantly improved

Consistent with no CPV



(Very biased) outlook

http://charm.cs.uiuc.edu/software

What next ?

- **LHCb, Run II** until 2018: $\sqrt{s}$ = 13 TeV, L ~ 4 x 10^{32} cm^{-2} s^{-1}, bunch crossing spacing of 25 ns, μ = 1.4
  - By the end of LHC-Run II, Belle II enters in the game
- **Upgraded LHCb, Run III** from 2019-2020 on: $\sqrt{s}$ = 14 TeV, L ~ 10^{33} cm^{-2} s^{-1} (newcoming detectors designed to operate at L ~ 2 x 10^{33} cm^{-2} s^{-1}), bunch crossing spacing of 25 ns, μ = 2, improved trigger efficiency for charm $\int$Ldt ~ 5 fb^{-1} /year
- Projections to the LHCb sensitivity with $\int$Ldt ~ 50 fb^{-1}

EPJ C73(2013)2373

Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb^{-1} by the upgraded experiment.

Type	Observable	Reference precision		LHCb 2018	**Upgrade** ($50\,fb^{-1}$)
Charm	A_Γ	**HFAG, early 2012**	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}
CP violation	ΔA_{CP}	**LHCb, 0.62 fb^{-1}**	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}

What next ?

EPJ C73(2013)2373

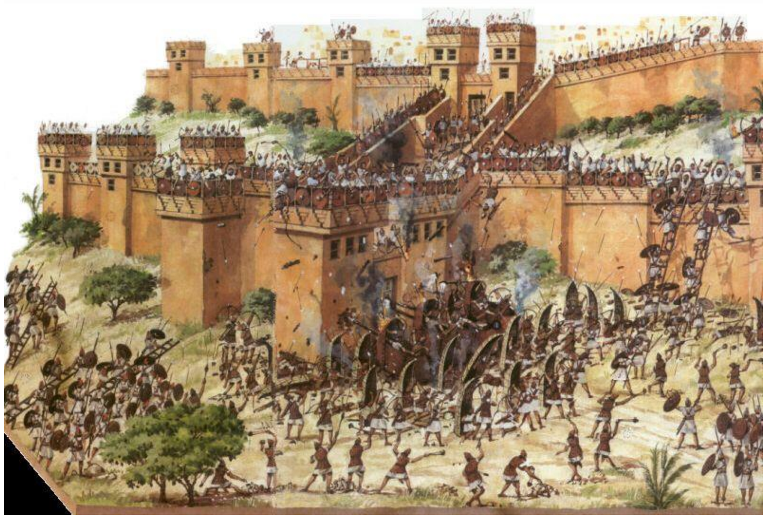
Table 12: Estimated statistical uncertainties for mixing and CP violation measurements which can be made with the projected samples for 50 fb^{-1} described in Table 10.

Sample	Parameter(s)	Precision
WS/RS $K\pi$	$(x_D'^2, y_D')$	$\mathcal{O}[(10^{-5}, 10^{-4})]$
WS/RS $K\mu\nu$	r_M	$\mathcal{O}(5\times10^{-7})$
WS/RS $K\mu\nu$	$\lvert p/q\rvert_D$	$\mathcal{O}(1\%)$
$D^{*+}\to D^0\pi^+;\ D^0\to K^-K^+, \pi^-\pi^+$	$\Delta\mathcal{A}_{CP}$	0.015%
$D^{*+}\to D^0\pi^+;\ D^0\to K^-K^+$	$\mathcal{A}_{CP}$	0.010%
$D^{*+}\to D^0\pi^+;\ D^0\to \pi^-\pi^+$	$\mathcal{A}_{CP}$	0.015%
$D^{*+}\to D^0\pi^+;\ D^0\to K^0_S\pi^-\pi^+$	(x_D, y_D)	(0.015%, 0.010%)
$D^{*+}\to D^0\pi^+;\ D^0\to K^-K^+, (\pi^-\pi^+)$	y_{CP}	0.004% (0.008%)
$D^{*+}\to D^0\pi^+;\ D^0\to K^-K^+, (\pi^-\pi^+)$	A_Γ	0.004% (0.008%)
$D^{*+}\to D^0\pi^+;\ D^0\to K^-K^+\pi^-\pi^+$	$\mathcal{A}_T$	2.5×10^{-4}

Strategic attack on the $D^0\overline{D}{}^0$ mixing and CPV in charm sector:

LHCb : unprecedented samples with decays to charged particles

Belle II : access to specific important modes (in particular direct CPV)



Summary

- Important sample of **high quality data** delivered by LHCb
- Low background even in many rare decays → continuously improving sensitivities
- Keep improving precision of **indirect CPV** search, now $\sigma(A_\Gamma)\sim5\times10^{-4}$
- Adding modes/methods in search for **direct CPV**, $D^0 \to \pi^+\pi^-\pi^0$, $D^+ \to \pi^-\pi^+\pi^+$, actual A_{CP} precision up to 10^{-3}, still no evidence
- Not yet fully exploited 3 fb^{-1} of collected Run I data, **updates and new analyses ongoing**
- Many more ongoing studies: $D^+ \to \pi^+\pi^0$, $D^0 \to K_SK_S$, ΔA_{CP} from $D\to hh\pi$, $\Lambda_c\to hhp$, $D^0 \to K_S\pi\pi$ Dalitz, $D^0 \to 4\pi$ ET, $D\to K_SK\pi\pi$ T-odd
- Some improvement of sensitivity expected in Run II
- LHCb upgrade: new level of sensitivity

  together with Belle II
- Many other interesting studies

  with Panda, HIEPA *et al.*

Backup

Energy test

- Test statistic to compare average distances in phase space

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}$$

weighted average distance of events in one flavour sample to events of the opposite flavour sample

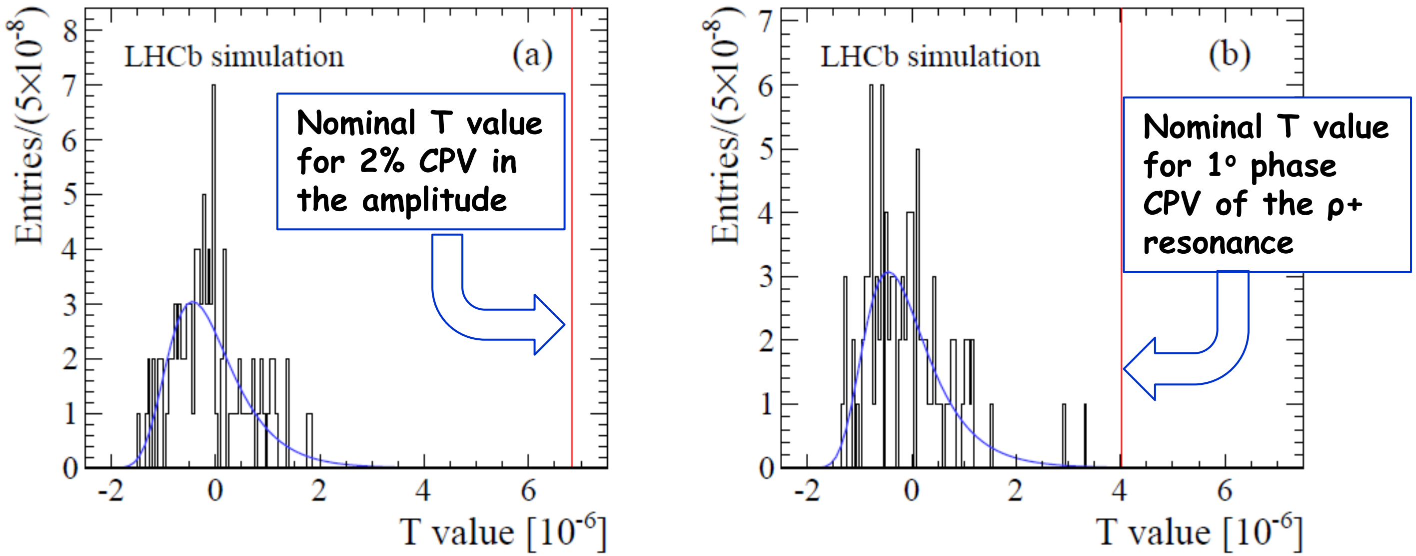
- Metric functions correspond to events i,j belonging to two samples of opposite flavour.
- Normalisation factors in the denominator remove impact of global asymmetries.
- If the distributions of events in both flavour samples are identical, T fluctuates around a value close to zero.
- Choose Gaussian metric $\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$, that decreases with a distance to improve sensitivity to local asymmetries
- Remove dependence on the choice of Dalitz plot axes by choosing d_{ij} as

$$\Delta\vec{x}_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$$

- Larger CP asymmetries lead to larger T values → determine p-value under hypothesis of CP symmetry by comparing nominal T value from data to a distribution of T values from permutation samples, where the flavour of each candidate is randomly reassigned to simulate samples without CPV
- p-value for the no CPV hypothesis is obtained as the fraction of permutation T values greater than the nominal T value

Energy test

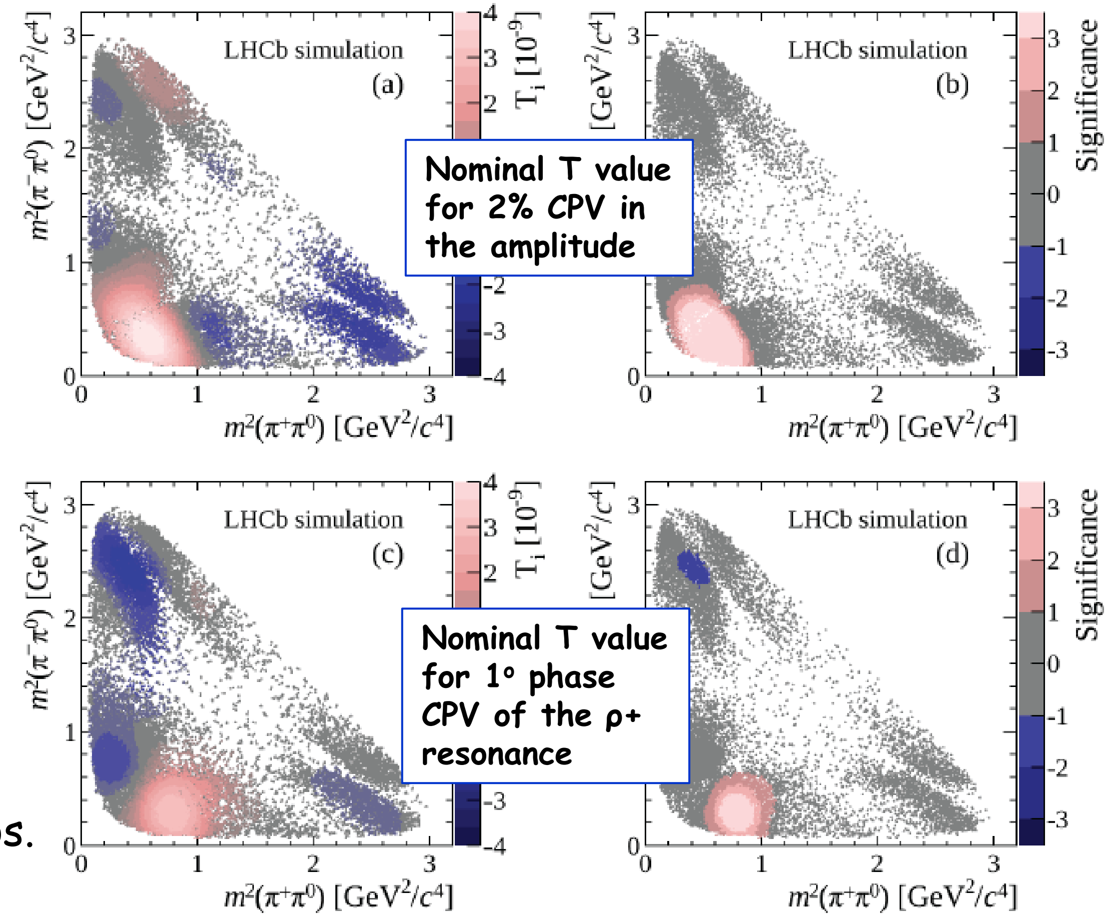
- Permutation T values fitted with a GEV function



- Visualisation of regions of significant asymmetry is obtained by assigning asymmetry significance to each event. Contributions to the total T value of a single event:
- one flavour :
$$T_i = \frac{1}{2n\,(n-1)}\sum_{j\neq i}^{n}\psi_{ij} - \frac{1}{2n\overline{n}}\sum_{j}^{\overline{n}}\psi_{ij},$$
- opposite favour :
$$\overline{T}_i = \frac{1}{2\overline{n}\,(\overline{n}-1)}\sum_{j\neq i}^{\overline{n}}\psi_{ij} - \frac{1}{2n\overline{n}}\sum_{j}^{n}\psi_{ij}.$$
- Permutation method to define the level of significance, distributions of the smallest negative (T^{min}_i) and largest positive (T^{max}_i) T_i values of each permutation.
- Positive (negative) local asymmetry significances : T_i values greater (smaller) than the fraction of the T^{max}_i (T^{min}_i) distribution that corresponds to the significance level.
- Same procedure for anti-T_i distribution, Dalitz plot with an inverted asymmetry pattern.

Energy test

- Amplitude difference between CP-conjugate states of a resonance → region of significant asymmetry as a band around the mass of the resonance
- Phase difference → regions of positive and negative asymmetry around the resonance

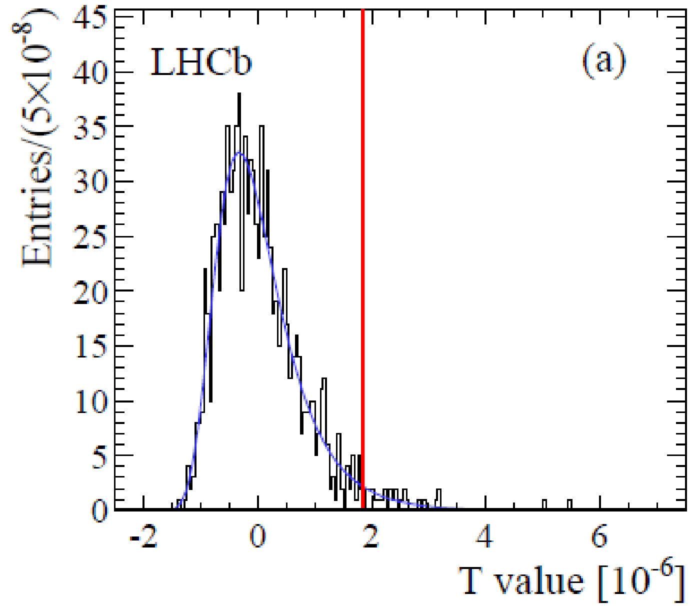


- Sensitivities to various CPV scenarios. ΔA and Δ φ: change in amplitude and phase of the resonance R

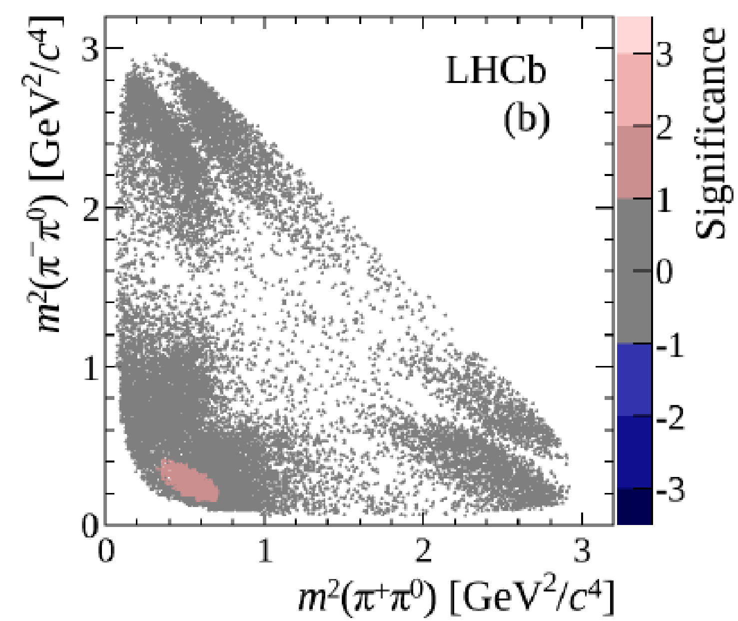
R (ΔA, $\Delta\phi$)	p-value (fit)	Upper limit
ρ^0 (4%, 0°)	$3.3^{+1.1}_{-3.3} \times 10^{-4}$	4.6×10^{-4}
ρ^0 (0%, 3°)	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ (2%, 0°)	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ (0%, 1°)	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- (2%, 0°)	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- (0%, 1.5°)	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

Energy test

Permutation T value distribution showing the fit function and the measured T value as a red line



Visualisation of local asymmetry significances.
Positive (negative) asymmetry significance : D^0 candidates having positive (negative) contribution to the measured T value



Results for various metric parameter values. The p-values are obtained with the counting method

σ [GeV$^2/c^4$]	p-value
0.2	$(4.6 \pm 0.6) \times 10^{-2}$
0.3	$(2.6 \pm 0.5) \times 10^{-2}$
0.4	$(1.7 \pm 0.4) \times 10^{-2}$
0.5	$(2.1 \pm 0.5) \times 10^{-2}$

k-Nearest neighbour analysis technique

Ann. Stat. 16 (2) (1988) 772
J. Am. Stat. Assoc. 81 (1986) 799
Phys. Rev. Lett. 86 (2001) 770

- Use nearest neighbour events in a combined D+ and D– samples to test whether they share the same parent distribution function
- n_k nearest neighbour events of each D+ and D– event: Euclidean distance between points in the Dalitz plot is used
- Test statistic (mean fraction of like-charged neighbour pairs in the combined *D*+ and *D*– decays sample) for the null hypothesis :

$$T = \frac{1}{n_k(N_+ + N_-)} \sum_{i=1}^{N_+ + N_-} \sum_{k=1}^{n_k} I(i,k)$$

1 if the i^{th} event and its k^{th} nearest neighbour have the same charge

0 otherwise

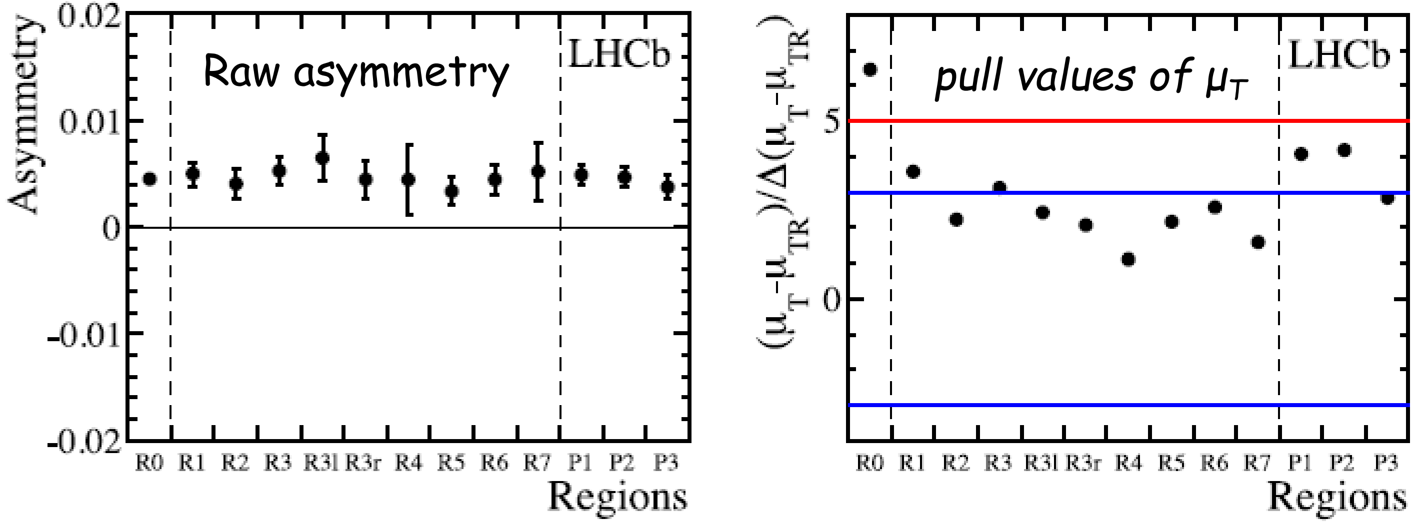
- Calculation of T is simple/fast, for null hypothesis expect Gaussian distribution with mean μ_T and variance σ_T^2 :

$$\mu_T = \frac{N_+(N_+ - 1) + N_-(N_- - 1)}{N(N-1)} \qquad \lim_{N, n_k, D \to \infty} \sigma_T^2 = \frac{1}{N n_k}\left(\frac{N_+ N_-}{N^2} + 4\frac{N_+^2 N_-^2}{N^4}\right)$$

- For $N^+ = N^-$ a reference value : $\mu_{TR} = \frac{1}{2}\left(\frac{N-2}{N-1}\right)$ and for large N $\mu_T \to \mu_{TR}$
- Calculate $\mu_T - \mu_{TR}$
- σ_T can be obtained with a good approximation even for space dimension D = 2 for the current values of N^+, N^- and n_k

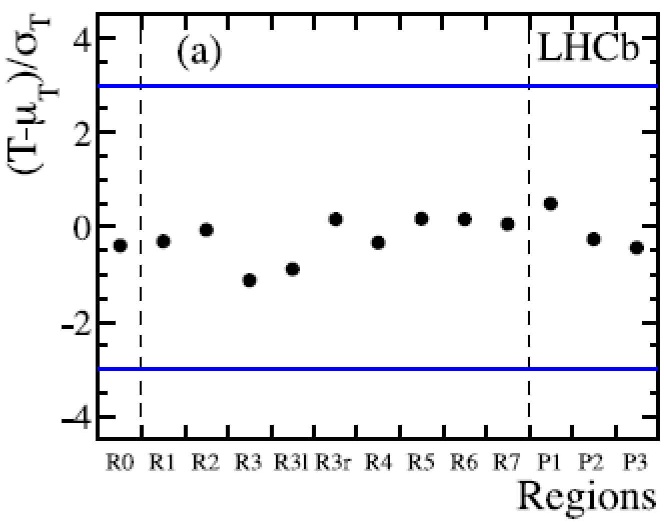
- kNN method applied to search for CPV in a given region of the Dalitz plot in two ways:
  - looking at "normalization" asymmetry ($N^+ \neq N^-$ in a given region) using a pull $(\mu_T - \mu_{TR})/\Delta(\mu_T - \mu_{TR})$ variable
  - looking for a "shape" or pdf asymmetry using another pull $(T - \mu_T)/\sigma_T$ variable
- As in the binned method, this technique provides no model-independent way to set an UL if no CPV is found
- Sensitivity of the kNN method is tested with the pseudo-experiments

$D^+ \to \pi^-\pi^+\pi^+$ candidates restricted to regions.
Horizontal lines : pull values +3 and +5

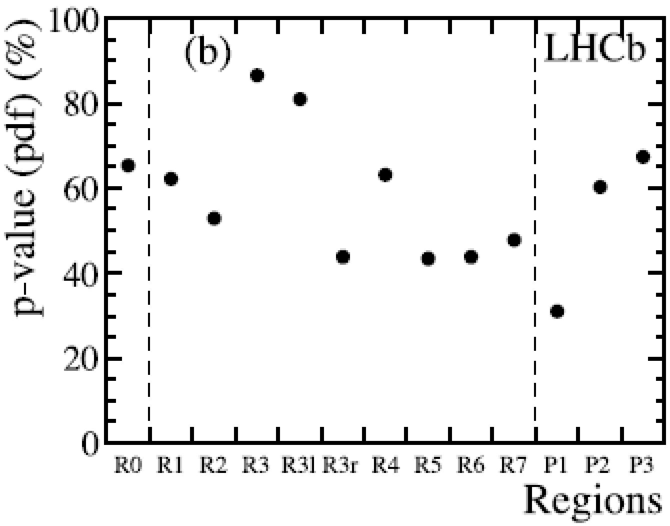


$D^+ \to \pi^-\pi^+\pi^+$ candidates in regions from kNN method with n_k = 20.
Horizontal lines : pull values −3 and +3.

Pull values of T



p-values



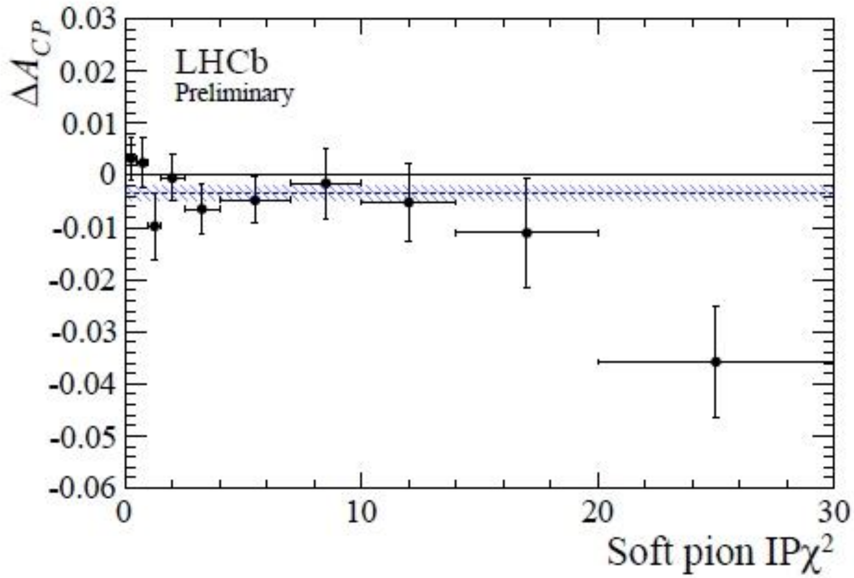
ΔA_{CP} : tag D° via prompt D*+, LHCb update 2013

LHCb-CONF-2013-003

2011 data, 1 fb^{-1}

- Fiducial cuts to exclude kinematic regions with large π_S^+ detection asymmetry.
- IP cut to reduce contamination from D° originated from b-hadron decays.
- Constrain the D*+ vertex to match the PV improves ΔM resolution.
- Data divided into several disjoint samples (magnet polarity, hardware trigger).
- Signal yields extracted from a fit to $\Delta M = M(h^- h^+ \pi^+) - M(h^- h^+) - M(\pi^+)$
- Weighting to account for differences in kinematics of two final states, needed for proper cancellation of production and detection asymmetries

source	Uncertainty(%)
Fiducial cut	0.02
Peaking Background	0.04
Fit model	0.03
Multiple candidates	0.01
Weighting	0.01
Soft pion IP$_{\chi^2}$	0.08
Total	0.10



ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)%