Overview of the CP violation and mixing in the charm sector

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on behalf of the LHCb collaboration with results from BELLE, BESIII, BaBar and CLEO-c legacy data

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UNIVERSITÄT
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Outline

- Mixing and CP violation basics
- Flavour factories
- Mixing and CPV in $D^0 \to K^+\pi^-$ decays
- Indirect CPV in charm (A_Γ and y_{CP} with $D^0 \to h^+h^{(')-}$)
- Direct CPV searches in two-body $D^0 \to h^+h^-$ charm decays
- Direct CPV searches in other two- or three-body charm decays
- Direct CPV searches in multi-body charm decays ($D^0 \to \pi^+\pi^-\pi^+\pi^-$)
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Mixing parameters

Mass eigenstates   Flavour eigenstates

Assuming *CPT* symmetry, the physical eigenstates can be expressed as a superposition of the flavour eigenstates

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

with complex coefficients p,q satisfying

$$|p|^2 + |q|^2 = 1$$

The transition probability

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

dimensionless

$$y \equiv \Delta\Gamma/(2\Gamma)$$

$$x \equiv \Delta m/\Gamma$$

$$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$$

$$\Delta m \equiv m_2 - m_1$$

Width difference
→ Lifetime difference

Mass difference
→ Oscillation

CPV in K,B,D mesons

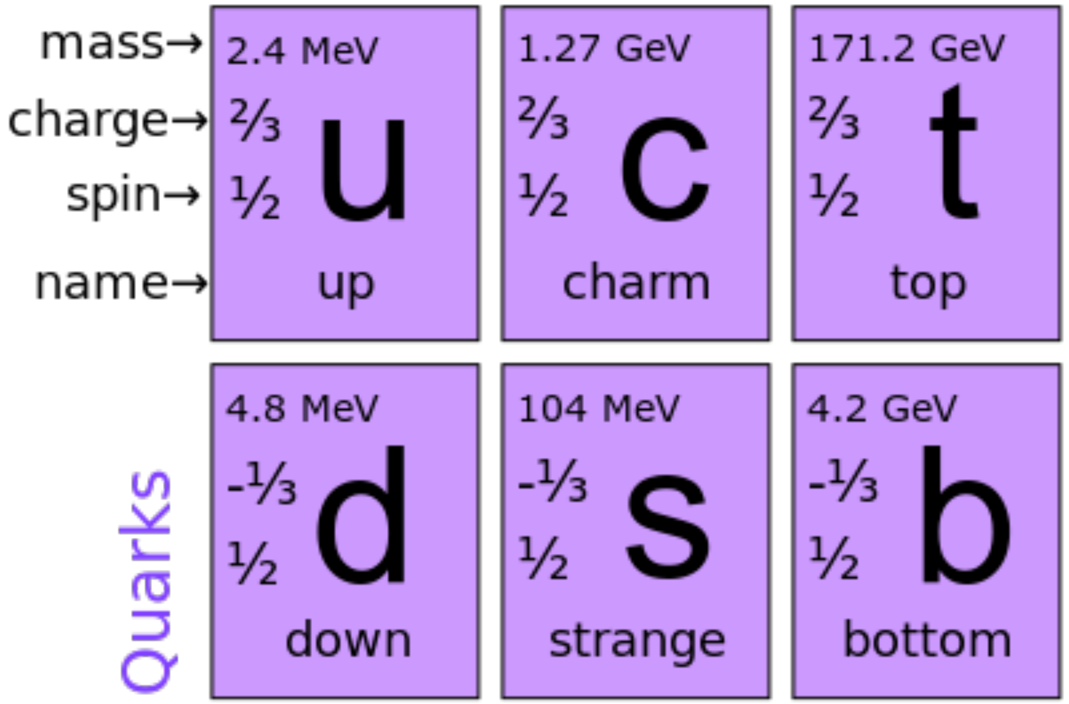
CP symmetry applies to processes invariant under the combined transformation of

charge conjugation (C): exchange of particle and anti-particle

and parity (P): spatial inversion

CP symmetry conserved in the strong and the EM interaction

- CPV discovered in weak decays of strange and beauty mesons containing quarks from the down sector
- What about the up-sector?



Charm

- Charm is unique: only bound up-type quark system where mixing and CP violation can occur

d s b

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho} - i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

u c t

No CP violation at first order:
imaginary part of V_{cd} very small

- Making precise SM predictions in the D-meson sector is difficult
  - Perturbative QCD valid at energies >> 1 GeV
  - Chiral perturbation theory valid between 0.1 GeV and 1 GeV
  - D^0 mass = 1.864 GeV

Types of CPV

The symmetry under CP transformation can be violated in different ways: Present if λ_f is not equal to 1

$$\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right|e^{i\phi}$$

$$|\bar{A}_{\bar{f}}/A_f| \neq 1$$

direct CPV

depends on the decay mode

$$|q/p| \neq 1$$

CPV in mixing

The transition probability of particles to anti-particles compared to the reverse process differs.

CPV in the interference

φ, the CP-violating relative phase between q/p and $\bar{A}_{\bar{f}}/A_f$, is non-zero

The indirect CP violation is independent of the decay mode.

It involves neutral particles

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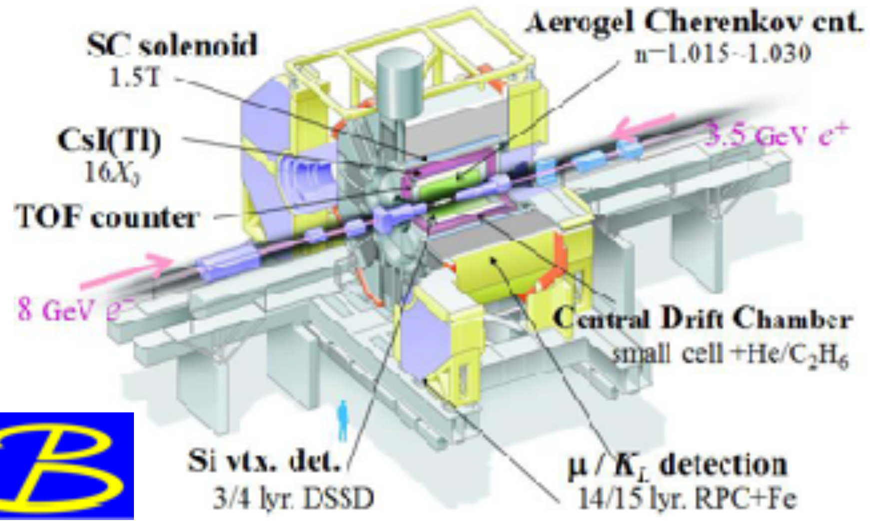
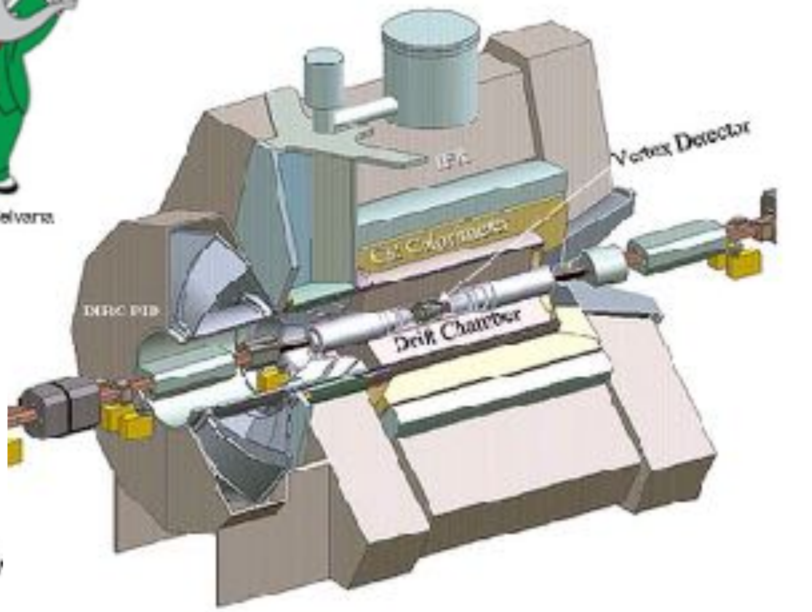
Flavour factories

Nucl. Instrum. Methods Phys. Res. Sect. A 479, 117 (2002)

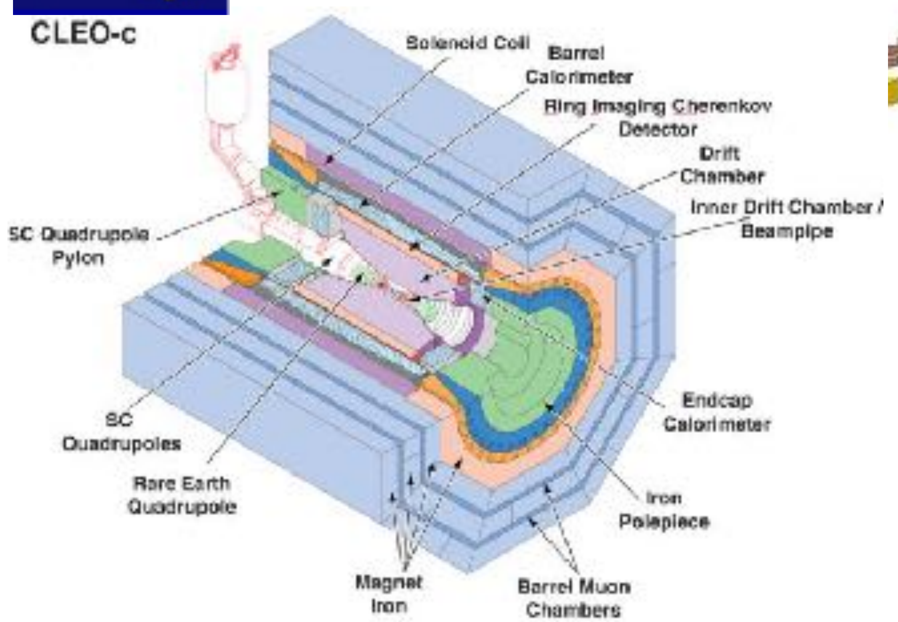


Nucl. Instrum. Meth.A479:1-116,2002



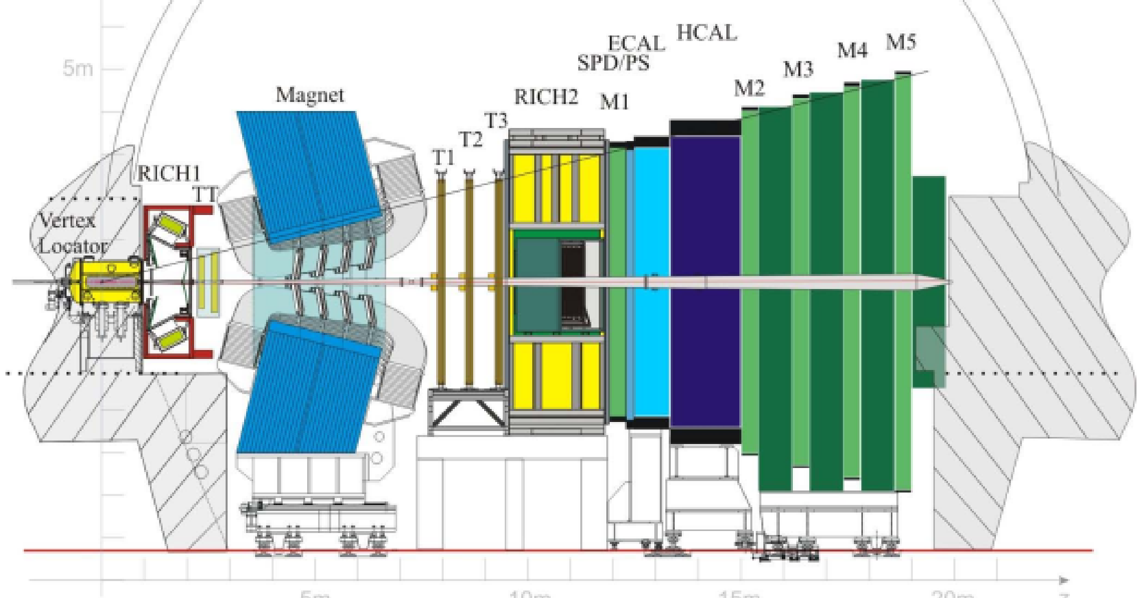
CLNS-01-1742

CLEO-c

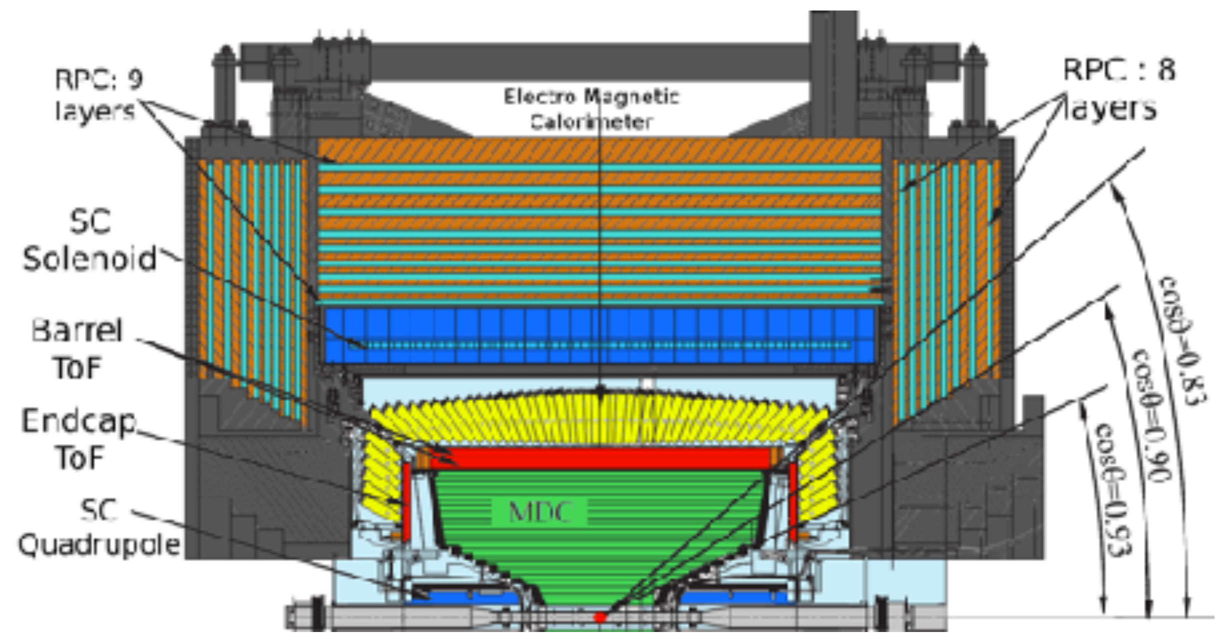


JINST 3 (2008) S08005

Int. J. Mod. Phys. A 30 1530022



Nucl. Instrum. Meth. A614, 345 (2010)



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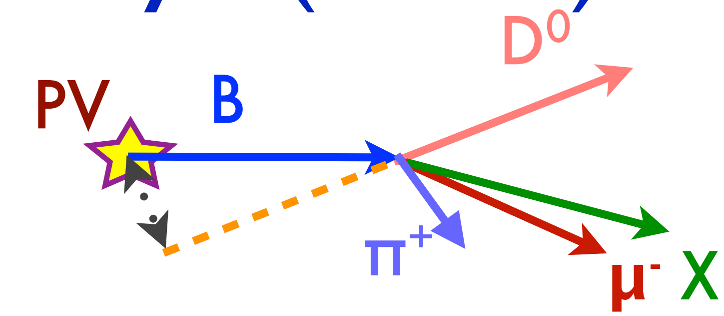
Mixing in doubly-tagged $D^0 \to K^+\pi^-$ decays (3 fb^{-1})

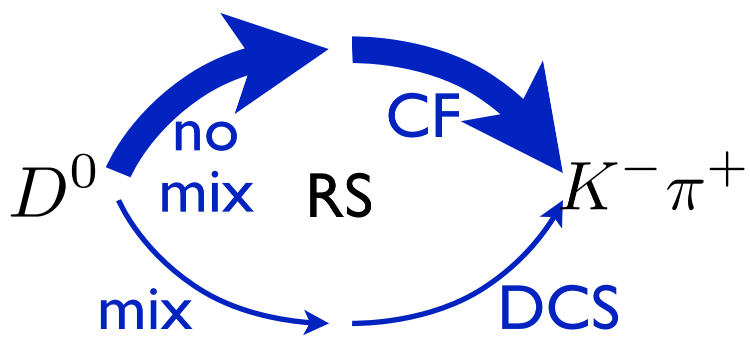


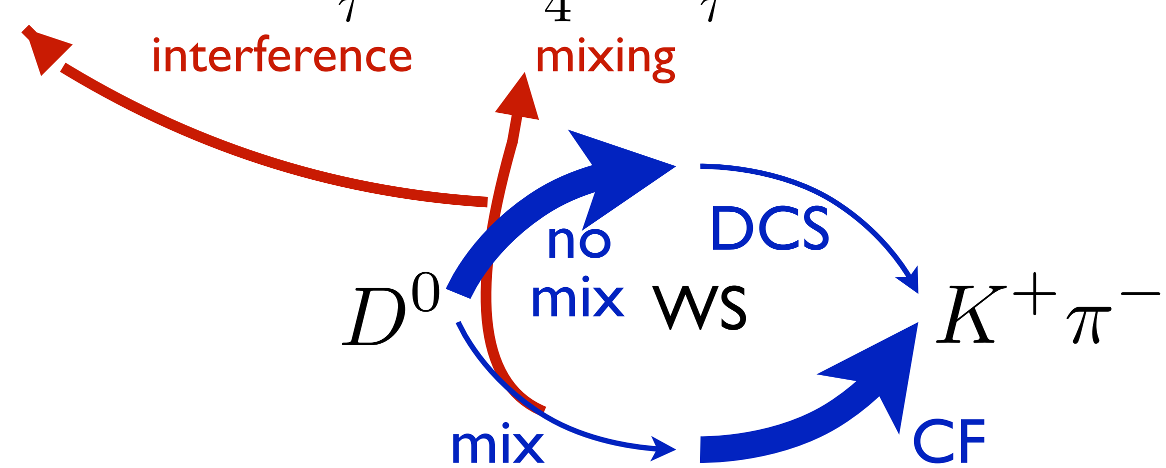
Measure the decay rates of WS to RS events: two paths to reach the final state

ratio of WS to RS decays

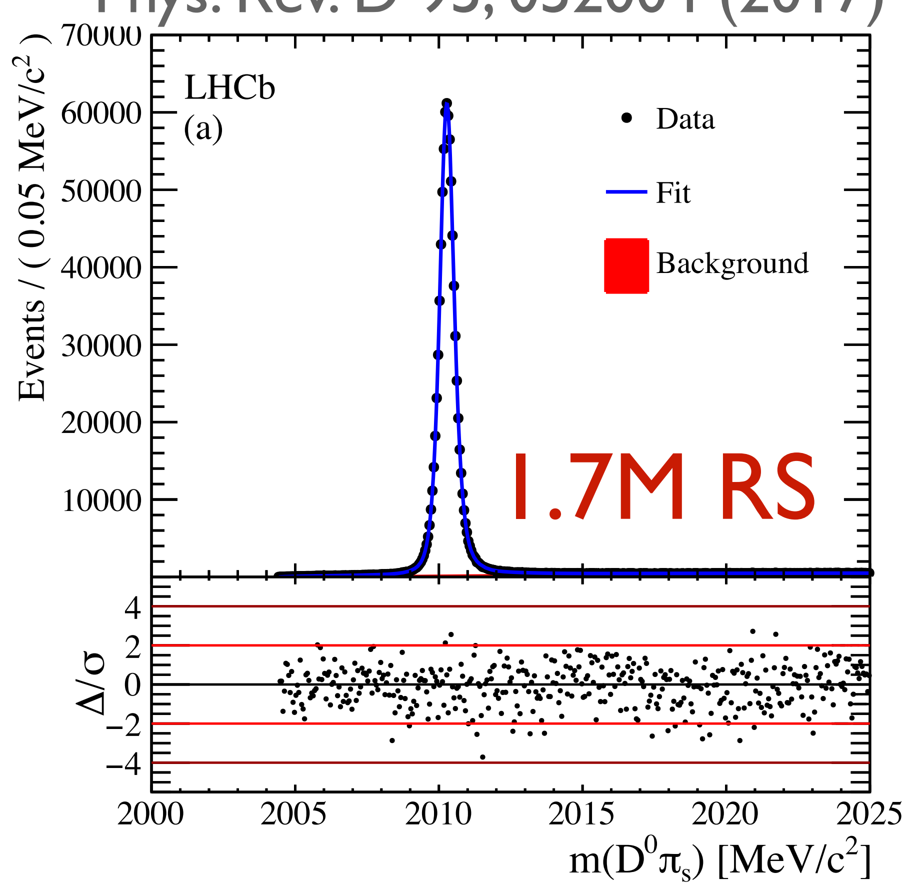
$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

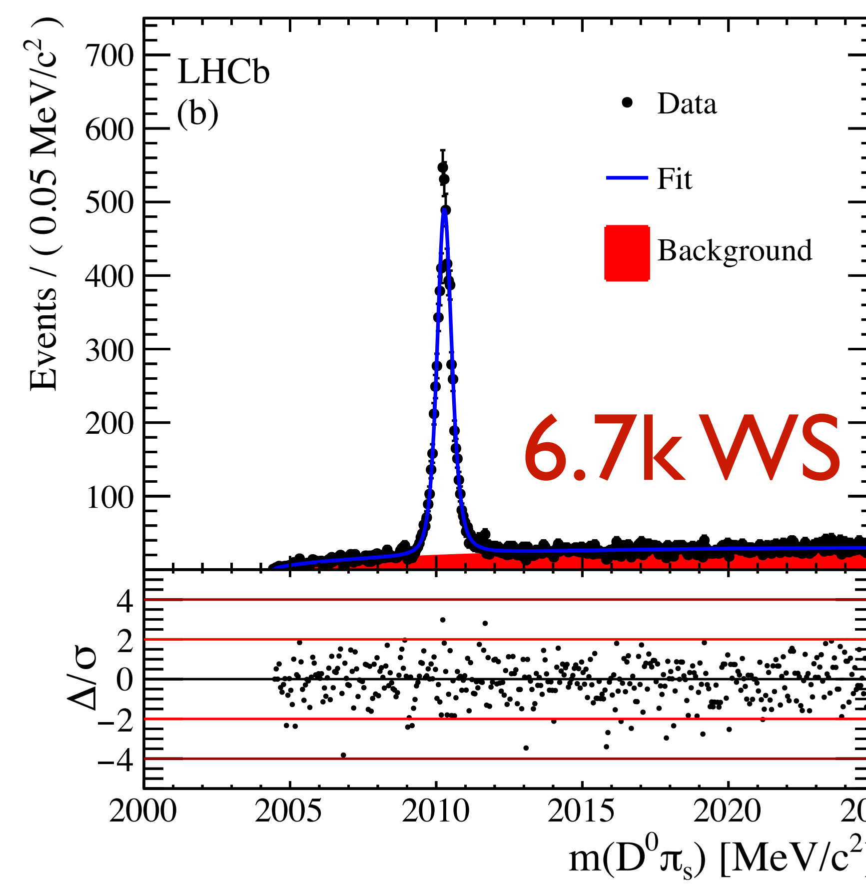
interference mixing



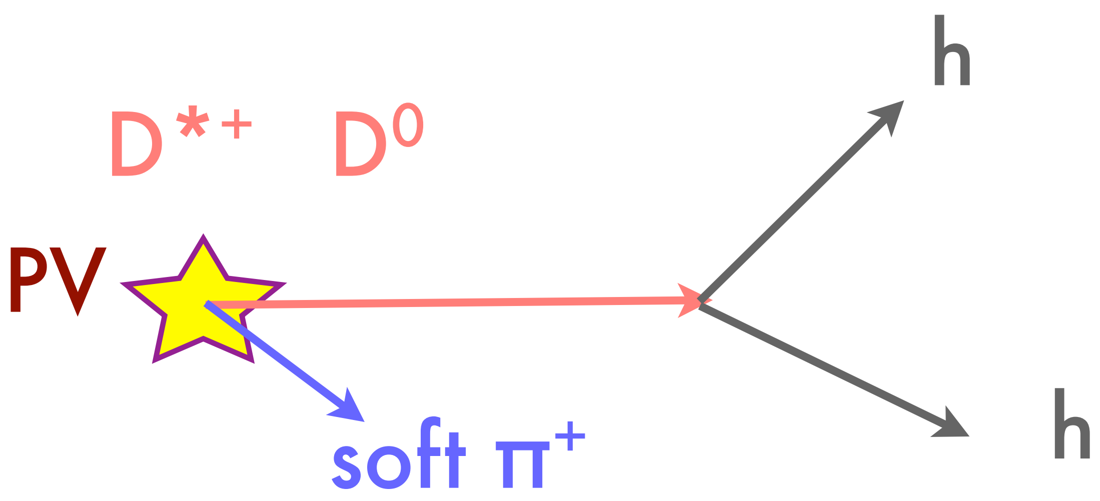


Phys. Rev. D 95, 052004 (2017)





How do we identify the flavour of the neutral D mesons?



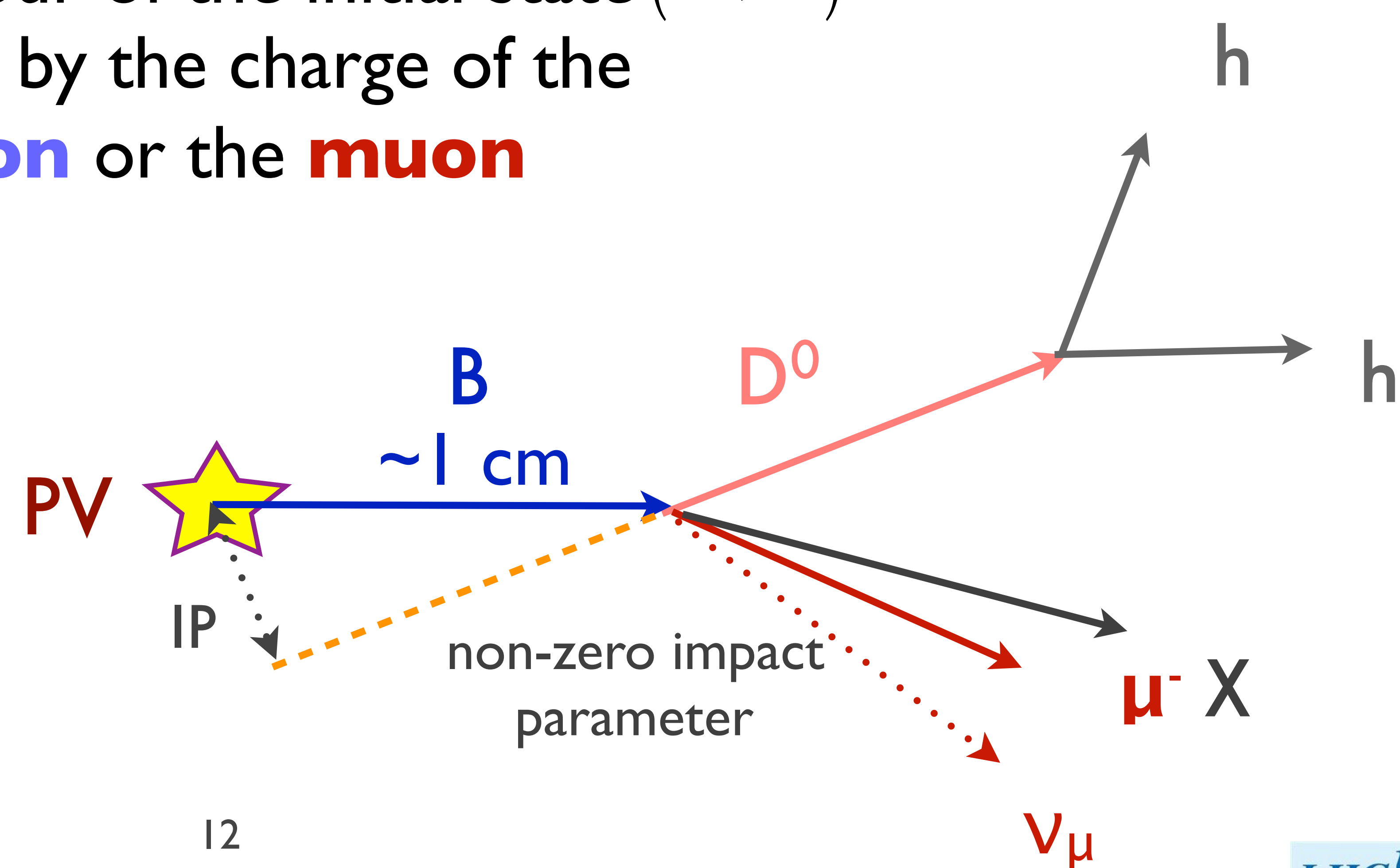
$h = \pi^{\pm}$ or $K^{\pm}$

Prompt charm:
D points to primary vertex
Daughters of D don't in general

The flavour of the initial state $(D^0, \bar{D}^0)$ is tagged by the charge of the **soft pion** or the **muon**

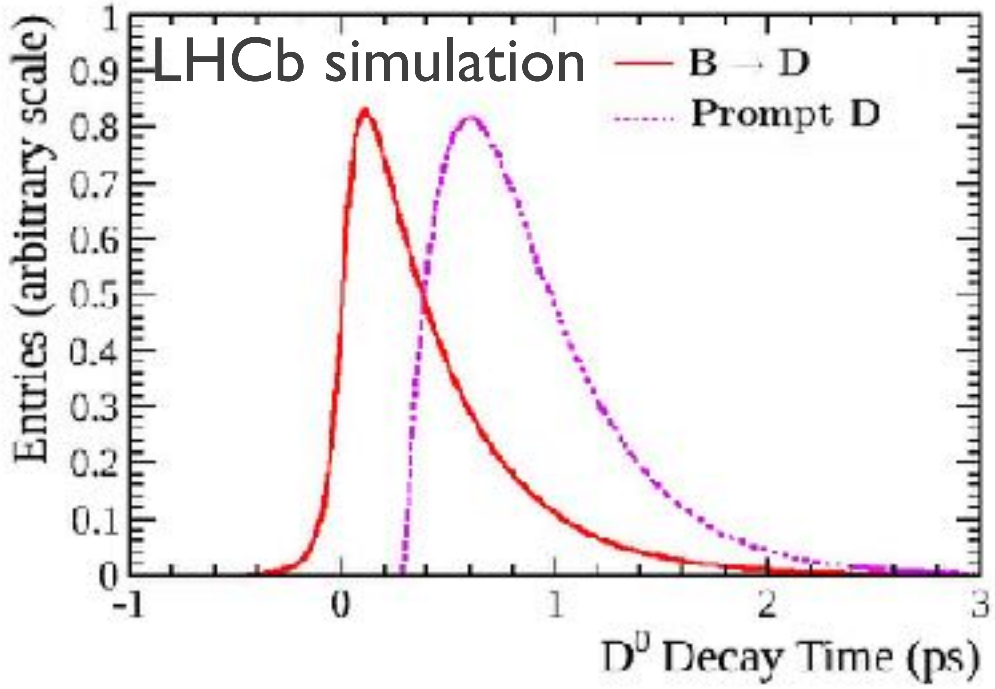
Secondary charm:
D doesn't point to PV

If $B \to D^{*\pm}(\to D^0\pi^{\pm})\mu^{\mp}\nu$:
doubly-tagged decays
low mistag rate
lower statistics



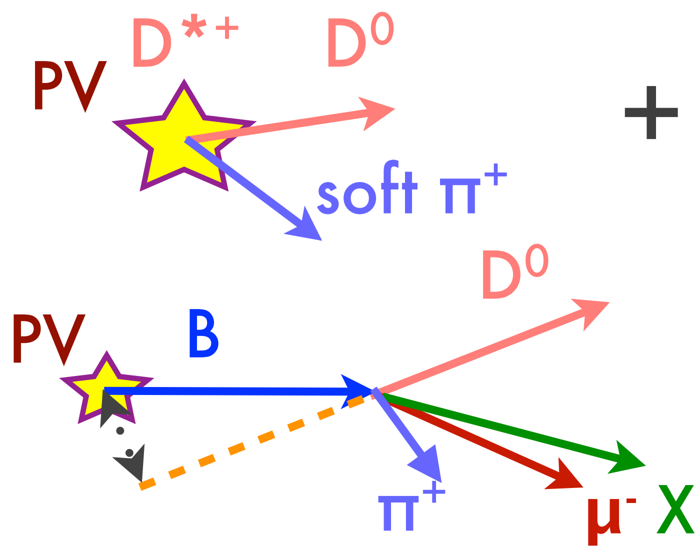
Prompt vs secondary decays

- Reconstructed prompt D^0 decays ≈ 3x muon -tagged D^0 decays
- More efficient triggering for secondary decays
- Small IP parameter for prompt decays; larger for muon-tagged decays
- Smaller flight distance for prompt decays; larger for the muon-tagged decays
- Different decay-time acceptances



Convolution of (decay time x time resolution) and acceptance

Combined LHCb results

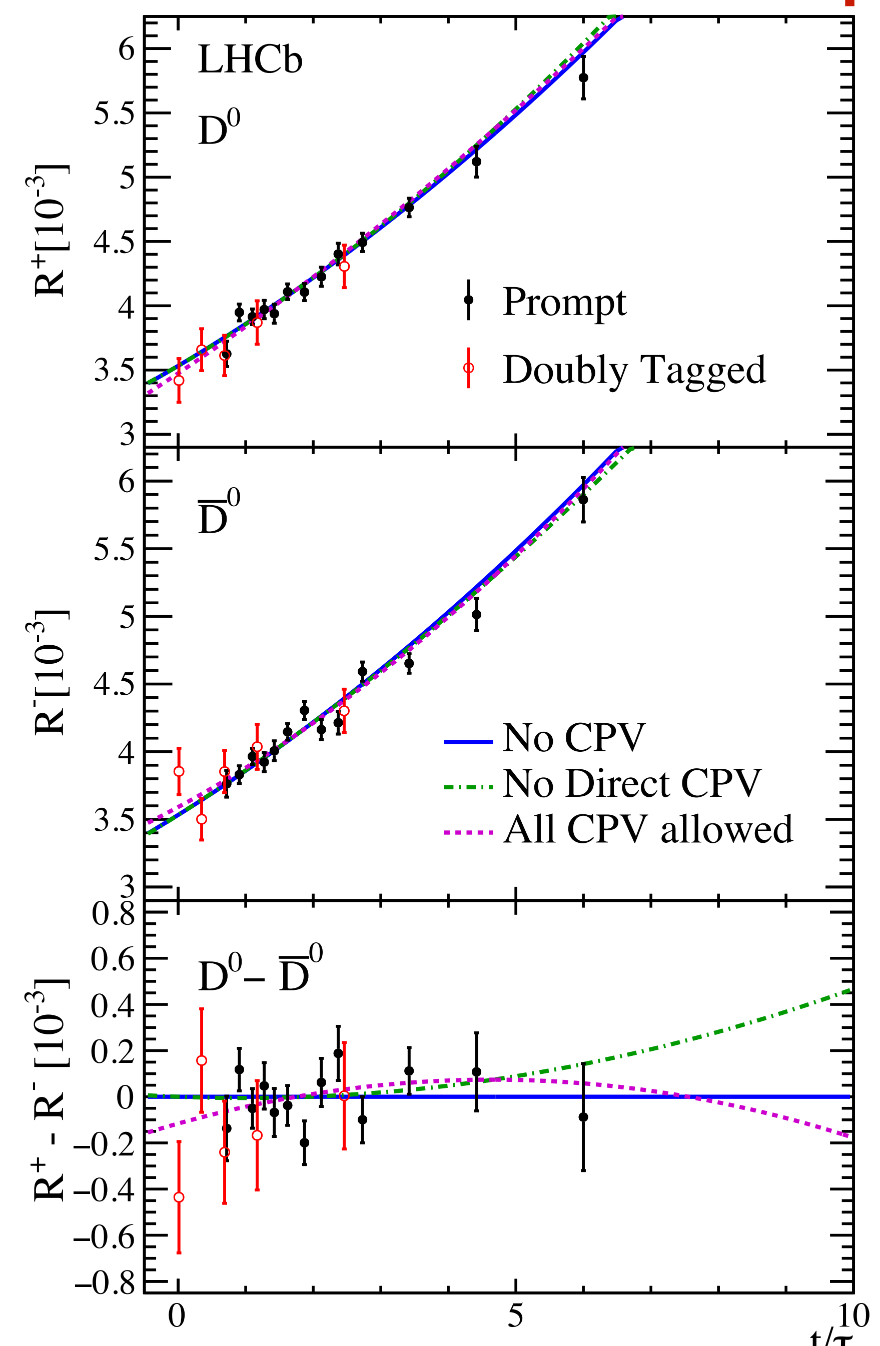


- Combined fit using two independent data samples (no CPV, no direct CPV, CPV)
  - Double-tagged (DT) sample
  - Prompt sample PRL 111, 251801 (2013)
- Precision improves by 10-20% when adding DT data (2.5% of signal)

All CPV allowed		
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2\,[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2\,[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	$95.0/108$	$85.9/98$

- Gain from complementary decay-time coverage, and higher signal purity.

No evidence for CPV in mixing or decay



Phys. Rev. D 95, 052004 (2017)

Mixing parameters with $D^0 \to h^0\pi^+\pi^-$

$D^0 \to \pi^0\pi^+\pi^-$ BaBar

PhysRevD 93 (2016) 112014

- Time-dependent Dalitz plot analysis: unbinned logL fit to $(t, s(\pi^-\pi^0), s(\pi^+\pi^0))$

$x = (1.5 \pm 1.2 \pm 0.6)\%$

$y = (0.2 \pm 0.9 \pm 0.5)\%$

$D^0 \to K_S\pi^+\pi^-$ LHCb (1fb-1)

JHEP 04 (2016) 033

- Model independent technique: uses info from Cleo-c: yields T_i and strong phase differences $\Delta\delta_{D,i}$ in Dalitz bins

$x = (-0.86 \pm 0.53 \pm 0.17)\%$

$y = (0.03 \pm 0.46 \pm 0.13)\%$

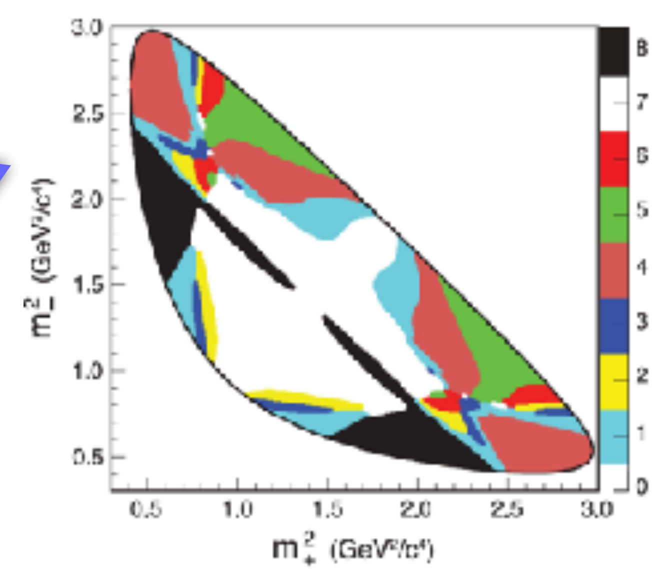
- The way to go in the future!

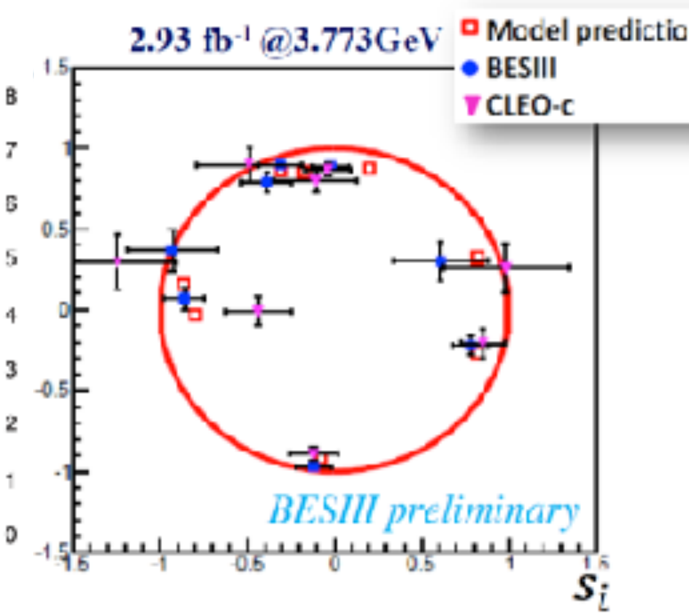
Dalitz modelling adds irreducible systematics!

$D^0 \to K_S\pi^+\pi^-$ BESIII

preliminary at CHARM & others

- Quantum correlations in $\psi(3370)$ to tag D flavour and CP
- Obtain $c_i = \cos(\Delta\delta_{D,i})$ and $s_i = \sin(\Delta\delta_{D,i})$
- 4x Cleo-c statistics
- Fundamental for the GGSZ method for γ - uncertainty due to c_i, s_i can be halved with the existing statistics





BaBar 2008 optimal binning

CLEO, PRD 82 (2010) 112006

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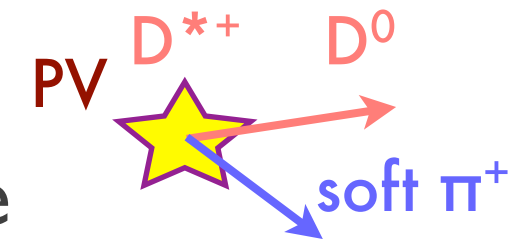
A_Γ: Indirect CPV in $D^0 \rightarrow h^+h^-$ decays



Comprises CPV in mixing and in the interference

$$A_\Gamma \approx \eta_{CP}[1/2(A_M + A_d)y \cos\phi + x \sin\phi] \equiv -a_{CP}^{ind}$$

A_M - CPV from mixing A_d - direct CPV   CPV phase ϕ x,y - mixing parameters

Time dependent: Measure asymmetries of effective lifetimes of decays to CP eigenstates

$$A_\Gamma \equiv [\tau(\bar{D}^0 \rightarrow h^+ h^-) - \tau(D^0 \rightarrow h^+ h^-)] / [\tau(\bar{D}^0 \rightarrow h^+ h^-) + \tau(D^0 \rightarrow h^+ h^-)]$$

Universal: does not depend on the decay mode

SM predicts $A_\Gamma < 10^{-4}$ Enhancements up to 1 order of magnitude are possible in BSM models

Large A_Γ or final state dependence will indicate NP

2 independent analyses using different approaches

Pseudo A_Γ (using CF $D^0 \rightarrow K\pi$ decays) is a null test of the methodology

Indirect CP violation in $D^0 \to h^+h^-$ ($1fb^{-1}+2fb^{-1}$)(unbinned)

Measurements use prompt $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays ($1\ fb^{-1}+2\ fb^{-1}$)

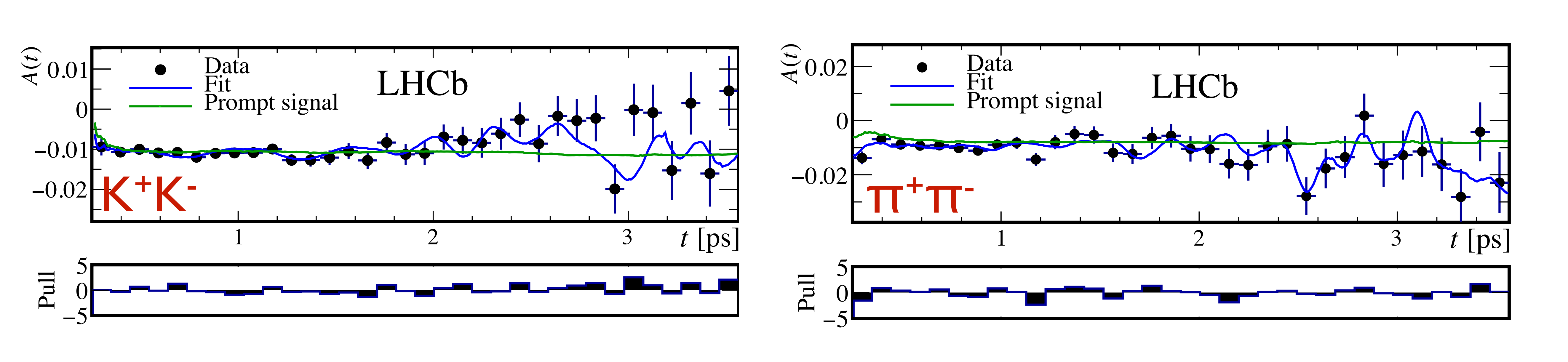
Fit the asymmetries between the decay times in 2 two-stages fit involving $m(D^0)$ and Δm ($= m(D^{*+}) - m(D^0)$); then fit D^0 decay time and $\ln(IP\chi^2_{D^0})$

$A_\Gamma(K^+K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3}$

$A_\Gamma(\pi^+\pi^-) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3}$

Largest source of systematic uncertainty: modelling of secondary backgrounds

PRL 112 (2014) 041801

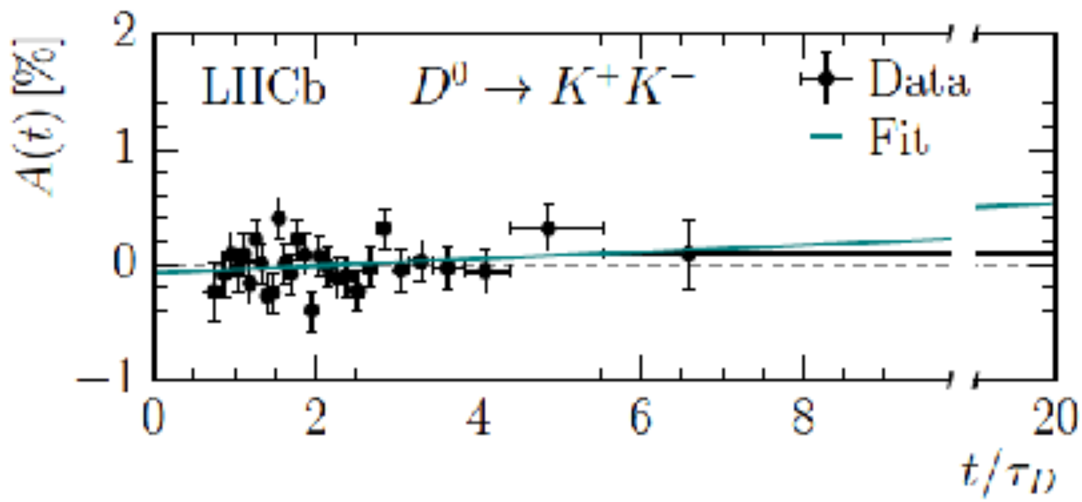


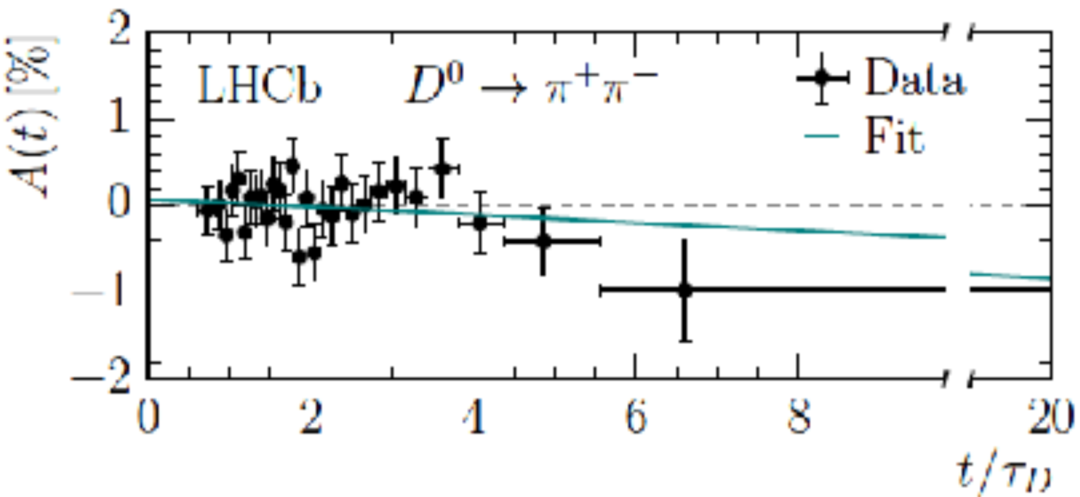
Asymmetry between $D^0/\overline{D}^0$ data overlaid by the total unbinned maximum likelihood fit

Indirect CP violation in $D^0 \to h^+h^-$ (3 fb^{-1})(binned)

- Correct for detector non-uniformities and presence of secondary decays
- Split data in bins of D^0 decay time; extract yield by fitting Δm (=$m(D^{*+})$ - $m(D^0)$)
- Extract A_Γ via a linear fit for background subtracted events

$$A_{raw}(t) = \frac{\Gamma_{D^0_{rec}}(t) - \Gamma_{\bar{D}^0_{rec}}(t)}{\Gamma_{D^0_{rec}}(t) + \Gamma_{\bar{D}^0_{rec}}(t)} = \frac{dN(t, D^0_{rec}) - dN(t, \bar{D}^0_{rec})}{dN(t, D^0_{rec}) + dN(t, \bar{D}^0_{rec})} \approx \boxed{A_0} - \frac{t}{\tau}\boxed{A_\Gamma}$$





- Direct CPV, production and detection asymmetry are not time-dependent

Largest source of systematic uncertainty: peaking backgrounds

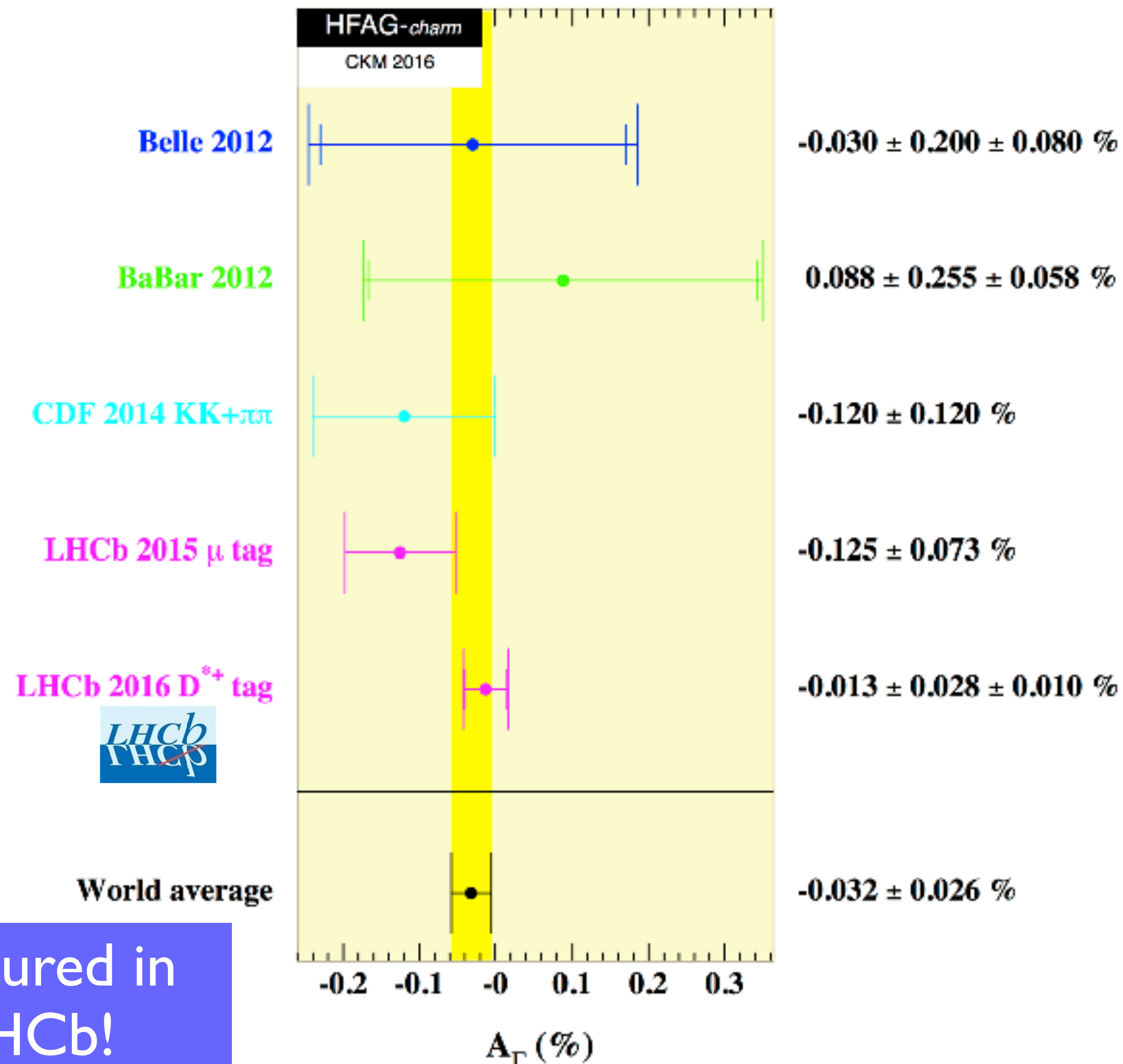
$A_\Gamma(K^+K^-)$ = (–0.30±0.32±0.10)x10^{-3}

$A_\Gamma(\pi^+\pi^-)$ = (0.46±0.58±0.12)x10^{-3}

Overview of A_Γ

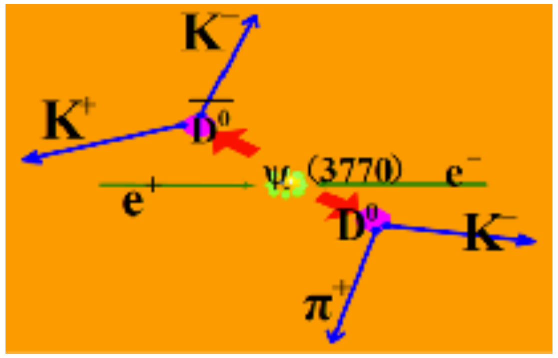
Combination with statistically independent muon-tagged charm decays results on $3fb^{-1}$ available in JHEP 04 (2015) 043

$$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

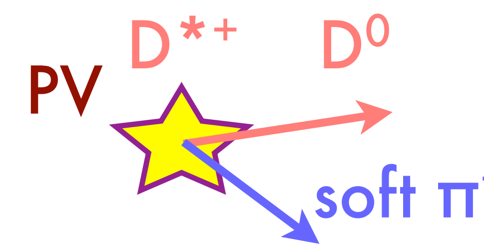


Best precision asymmetry measured in the charm system done by LHCb!

A_Γ and y_{CP} from BELLE and BESIII



$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^-h^+)} - 1 \cong y\cos\phi + \frac{1}{8}A_m^2\, y\cos\phi - \frac{1}{2}A_m\, x\sin\phi$$



BES III PLB 744 (2015) 339

Quantum-entangled pairs

CP-tagging technique:

- CP tags(K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$, $K_S\pi^0$, $K_S\eta$, $K_S\omega$) vs flavour tags $Ke\nu$ and $K\mu\nu$

$$y_{CP} \approx \frac{1}{4}\left(\frac{\Gamma_{l;CP+}\Gamma_{CP-}}{\Gamma_{l;CP-}\Gamma_{CP+}} - \frac{\Gamma_{l;CP-}\Gamma_{CP+}}{\Gamma_{l;CP+}\Gamma_{CP-}}\right)$$

Assuming no direct CP violation,

y_{CP} = (-2.0±1.3±0.7)%

New preliminary results

CP tags($K_L\pi^0$, $K_S\pi^0$) vs flavour tags $Ke\nu$

y_{CP} = (-0.98±2.43(stat.))%

See the talk of Xiaokang Zhou for details

Belle PLB 753 (2016) 412

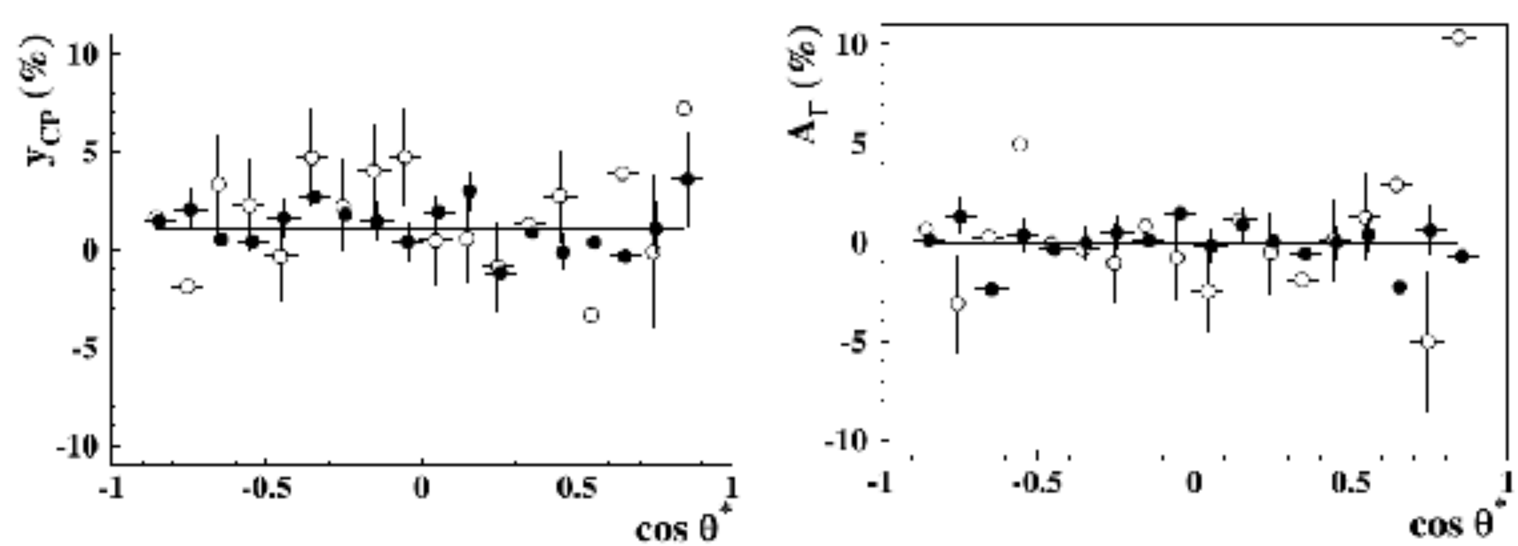
Final data set

Simultaneous fit to $D^0 \to K^-\pi^+$, $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

Fits in bins of cosθ*

y_{CP} = (1.11±0.22±0.09)%

A_Γ = (-0.03±0.20±0.07)%



θ* polar angle of D^0 in CMS with respect to the direction of e^+

in case of no CPV $y = y_{CP}$

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The CP asymmetries

Measure the time integrated asymmetry in the SCS decays $D^0 \to hh$ decays ($h=K$ or π)

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

But A_{CP} this is not what we measure. We measure

$$A_{raw}(f) = \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-)}$$

$f = \bar{f} = K^+K^-$
or
$f = \bar{f} = \pi^+\pi^-$

where N(X) refers to the number of reconstructed events of decay X after background subtraction

We measure the physical CP asymmetry plus asymmetries due to detection effects and production

$$A_{raw} = A_{CP} + A_{production} + A_{detection}$$

ΔA_{CP}

Main experimental challenge: separate the asymmetries nuisance asymmetries ~O(1%)

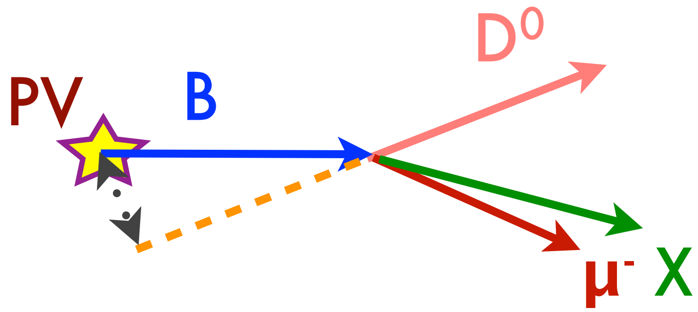
$$A_{raw} = A_{CP} + A_{production} + A_{detection}$$

if we take the raw asymmetry difference:
experimentally more robust

1st order

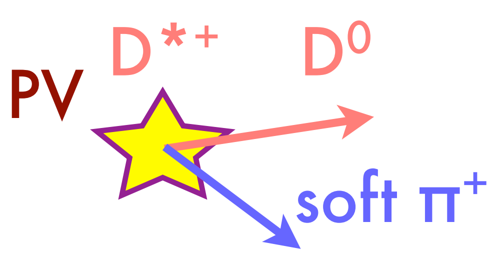
$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

$\Delta A_{CP\ \text{muon-tagged}} = (+0.14 \pm 0.16 \pm 0.08)\%$



JHEP 1407 (2014) 041

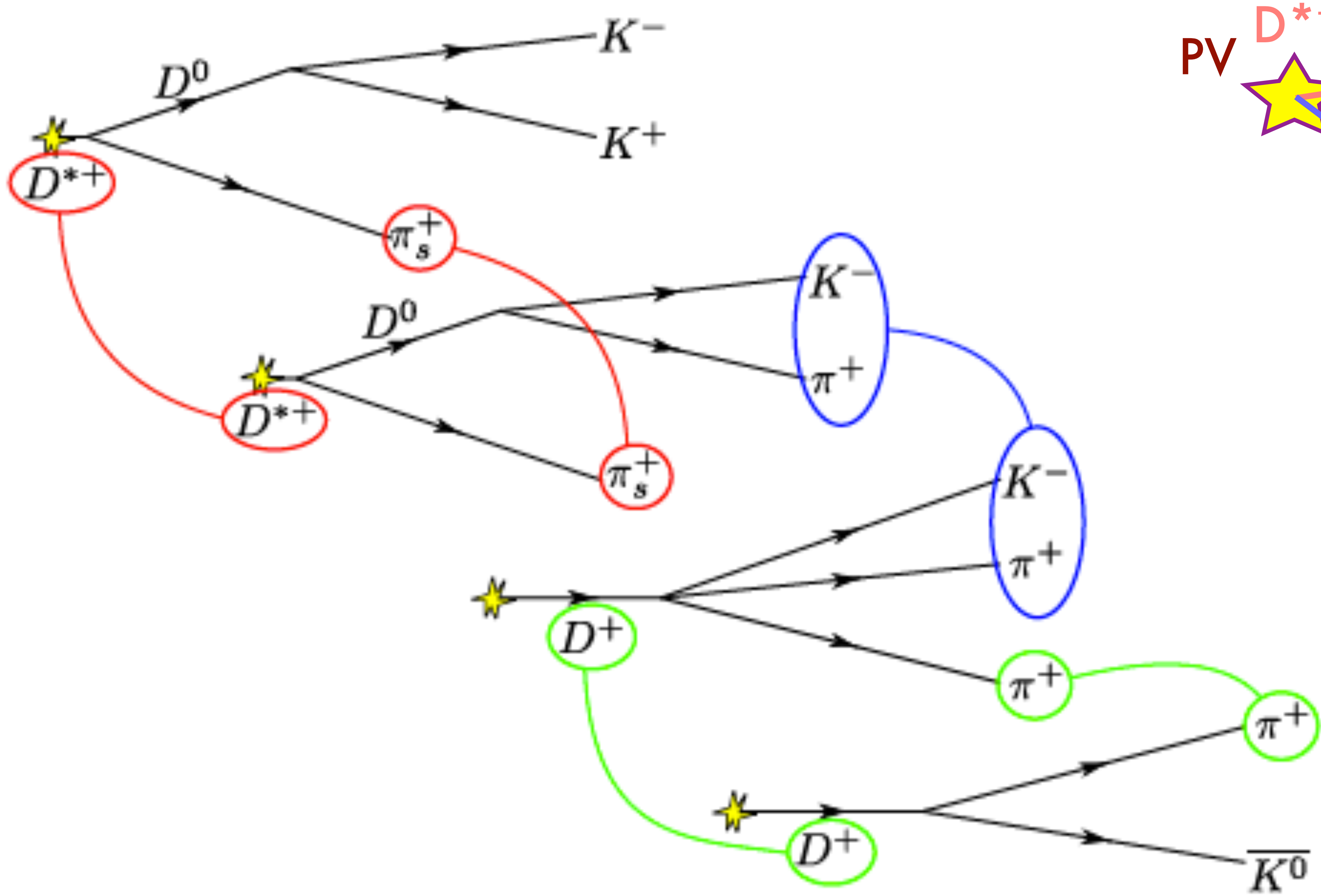
$\Delta A_{CP\ \text{prompt}} = (-0.10 \pm 0.08 \pm 0.03)\ \%$

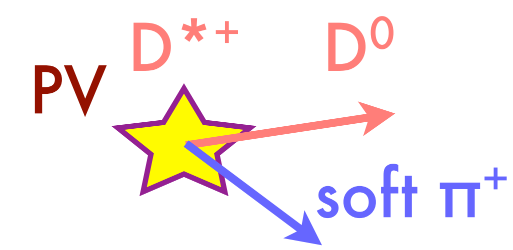


Phys. Rev. Lett. 116, 191601 (2016)

Individual asymmetries: use CF decay control channels

$$A_{raw}(K^+K^-) = A_{cp}(K^+K^-) + A_D(\pi_s) + A_P(D^{*+})$$



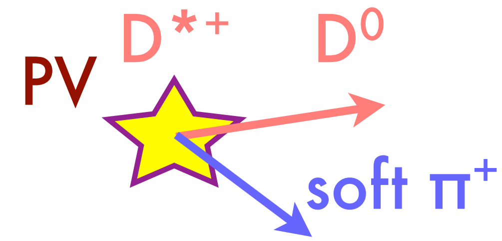


$$\rightarrow A_{cp}(K^+K^-) = A_{raw}(K^+K^-) - A_{raw}(K^-\pi^+) + A_{raw}(K^-\pi^+\pi^+) - A_{raw}(\overline{K}^0\pi^+) + A_D(\overline{K}^0)$$

Phys. Lett. B 767 177-187

$A_{CP}(h^- h^+)$ results with LHCb Run 1 data

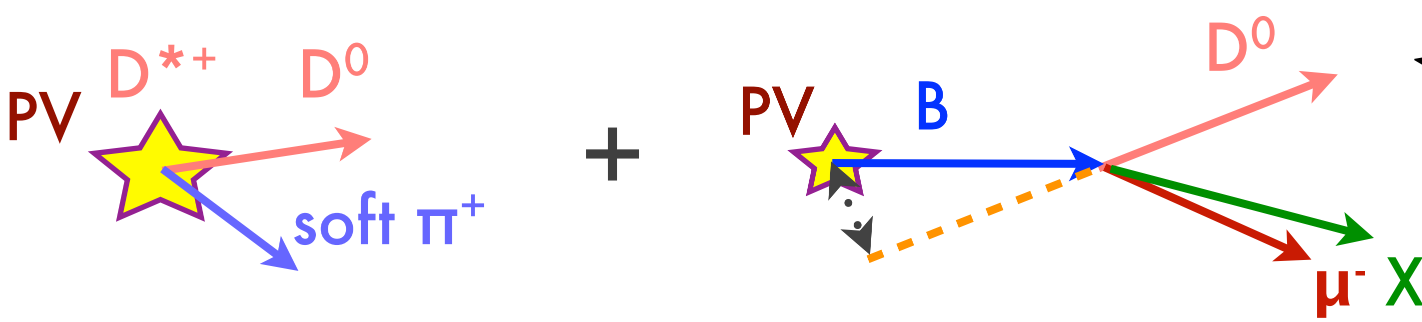
$A_{CP}^{prompt}(K^-K^+) = (0.14 \pm 0.15(stat) \pm 0.10(syst))\%$



Combination with the prompt ΔA_{CP} measurement

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$\approx \Delta a_{CP}^{dir}(1 + y_{CP}\langle t\rangle/\tau) + a_{CP}^{ind}\Delta\langle t\rangle/\tau$$

$A_{CP}^{prompt}(\pi^-\pi^+) = (0.24 \pm 0.15(stat) \pm 0.11(syst))\%$

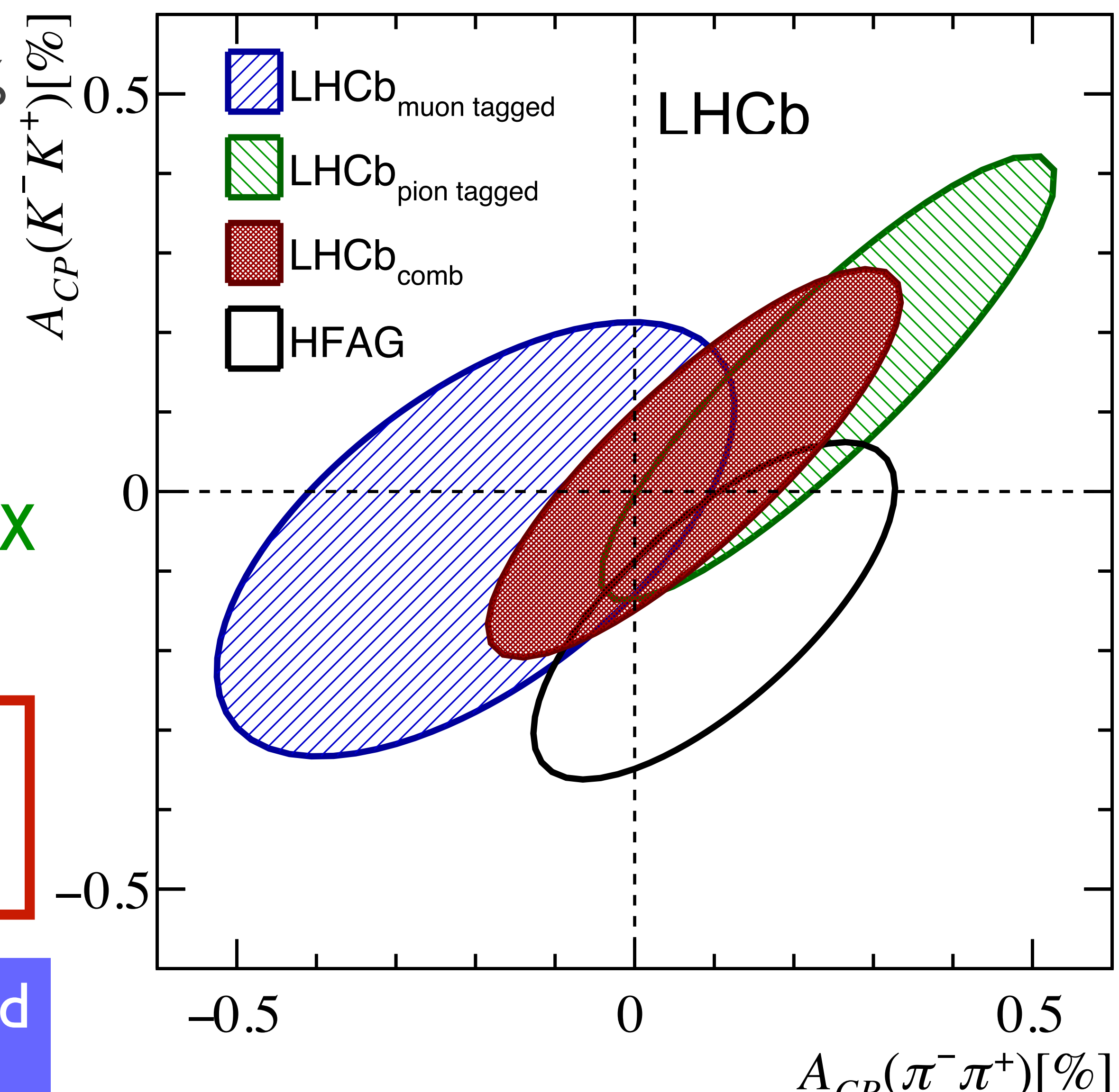


Combination with the LHCb muon-tagged results

$A_{CP}^{comb}(K^-K^+) = (0.04 \pm 0.12(stat) \pm 0.10(syst))\%$
$A_{CP}^{comb}(\pi^-\pi^+) = (0.07 \pm 0.14(stat) \pm 0.11(syst))\%$

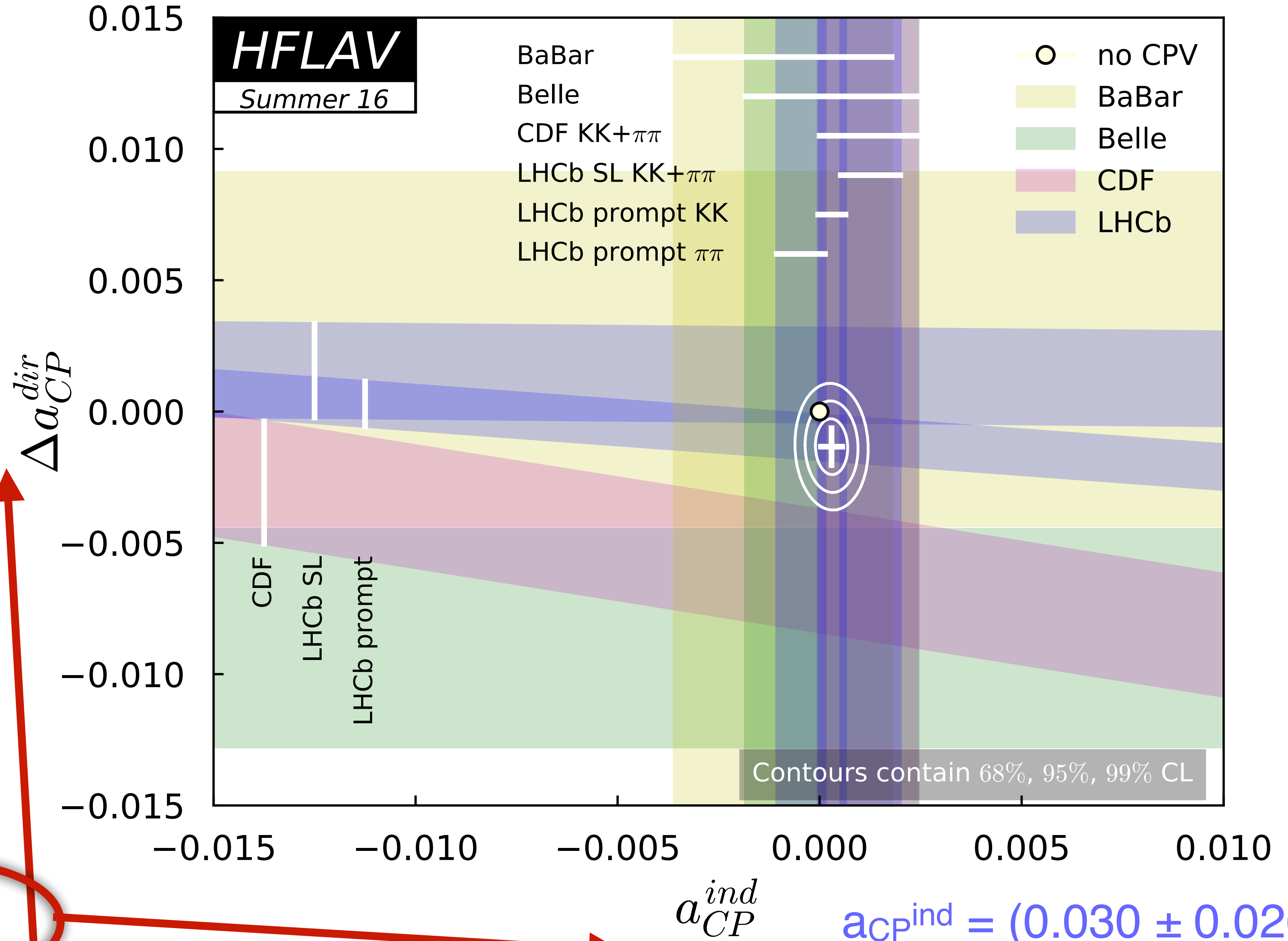
Most precise measurement of charm time-integrated CP asymmetry

Phys. Lett. B 767 177-187



HFLAV averages including the latest results

Compatible with no-CPV in the charm sector at 9.3% CL



$A_\Gamma \approx -a_{CP}^{ind}$

$a_{CP}^{ind} = (0.030 \pm 0.026)\%$

$\Delta a_{CP}^{dir} = (-0.134 \pm 0.070)\%$

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$$

$$\approx \Delta a_{CP}^{dir} (1 + y_{CP} \overline{\langle t \rangle} / \tau) + a_{CP}^{ind} \Delta \langle t \rangle / \tau$$

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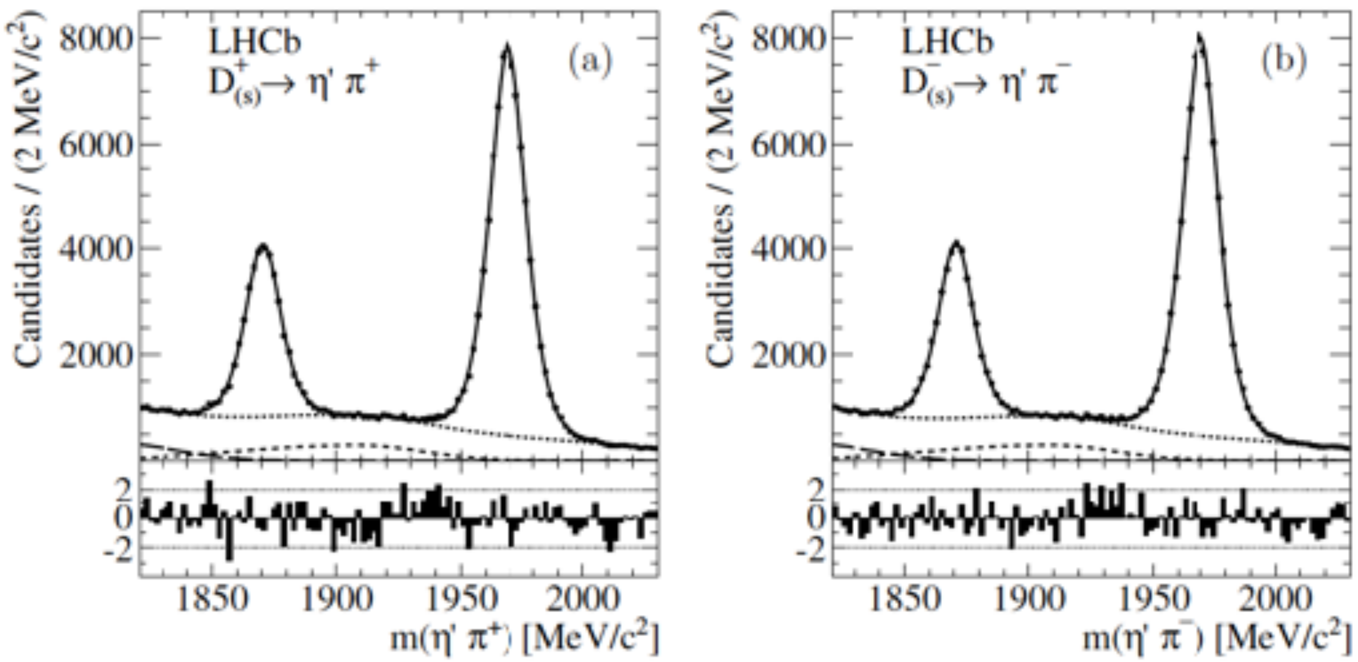
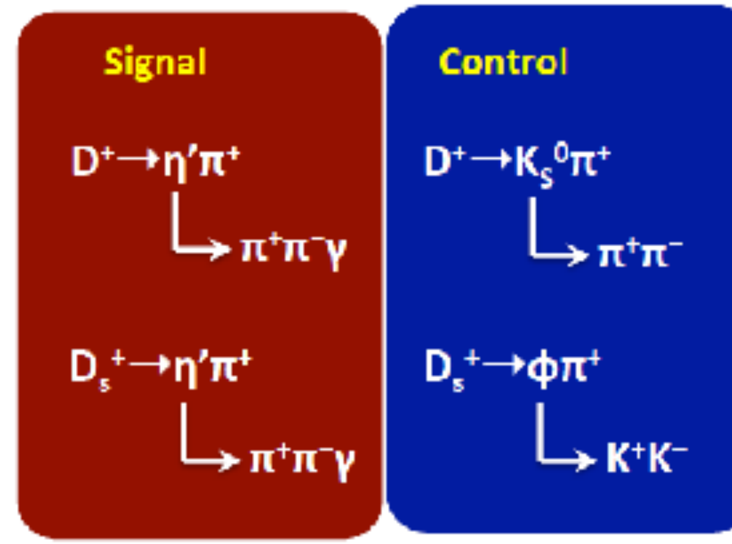
- **Direct CPV searches in other two- or three-body charm decays**
- Direct CPV searches in multi-body charm decays ($D^0 \to \pi^+\pi^-\pi^+\pi^-$)
- Conclusions and prospects

Direct CPV search in $D^+_{(s)} \to \eta'\pi^+$ ($3fb^{-1}$)

arXiv: 1701.01871 submitted to PLB



Data sample: 63k $D^\pm$ and 152k $D^\pm_s$



Yes, we can do γ !

- **Usual strategy**: Subtract detector asymmetries using control channels

$$A_{CP}(D^+ \to \eta'\pi^+) \equiv A_{raw}(D^+ \to \eta'\pi^+) - A_{raw}(D^+ \to K_S\pi^+) + A_{CP}(D^+ \to K_S^0\pi^+) + A_{mix}(K_S^0)$$

$$A_{CP}(D_s^+ \to \eta'\pi^+) \equiv A_{raw}(D_s^+ \to \eta'\pi^+) - A_{raw}(D_s^+ \to \phi\pi^+) + A_{CP}(D_s^+ \to \phi\pi^+)$$

Fit $m(\eta'\pi^\pm)$ to extract raw asymmetry

Control channel asymmetry

External input (D0, Belle)

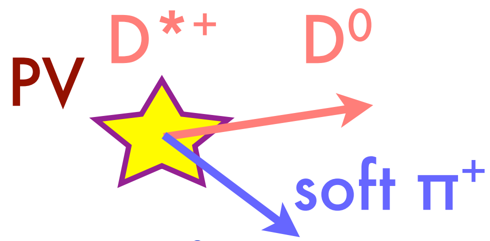
$$A_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\,\%$$

$$A_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\,\%$$

Consistent with CP conservation

Most precise measurements to date of these variables

Complementary searches in two- or three-body decays



$D^0 \to K_S K_S$ Belle

CONF-1609 ArXiv 1609.06393

- Interference with NP amplitudes could lead to large nonzero CPV. Upper SM limit 1.1% @ Nierste & Schach Phys. Rev. D92, 054036 (2015)

A_{CP} = (-0.02 ±1.53 ±0.17)%

- To be compared to the recent LHCb

JHEP 10 (2015) 055

A_{CP} = (2.9 ±5.2 ±2.2)%

See the talk of Varghese Babu for details

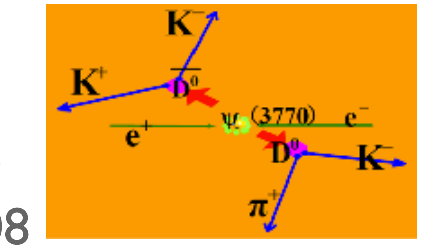
$D^0 \to V\gamma$ Belle

Phys. Rev. Lett. 118, 051801 (2017)

- Radiative decays sensitive to NP (chromomagnetic dipole operators)

$A_{CP}(D^0 \to \varphi\gamma)$= (-9.4 ±6.6 ±0.1)%
$A_{CP}(D^0 \to K^*\gamma)$= (-0.3 ±2.0 ±0.0)%
$A_{CP}(D^0 \to \rho\gamma)$= (5.6 ±15.2 ±0.6)%

$D^+ \to K_L e^+ \nu_e$



PRD 92 (2015) 112008

$A_{CP}(D^+)$ = (-0.59 ±0.60 ±1.48)%

See the talk of Xiaokang Zhou for details

$D^+ \to K_{S,L} K^+ (\pi^0)$ BESIII

arXiv:1611.01256

Mode	$\mathcal{A}_{CP}$ (%)
$K^0_S K^\pm$	-1.5 ± 2.8 ± 1.6
$K^0_S K^\pm \pi^0$	1.4 ± 4.0 ± 2.4
$K^0_L K^\pm$	-3.0 ± 3.2 ± 1.2
$K^0_L K^\pm \pi^0$	-0.9 ± 4.1 ± 1.6

Most uncertainties still O (%)
Still room for NP

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Multi-body decays and local asymmetries

- Many ways to reach multi-body final states through intermediate resonances

- Local asymmetries potentially larger than the phase space integrated ones

Discover CPV

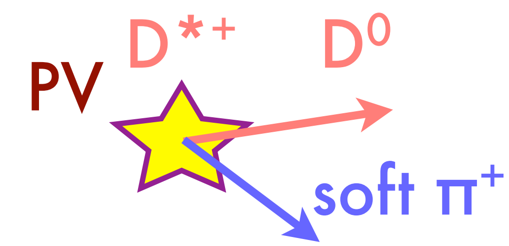
- Model-independent:
  Look for asymmetries in regions of phase space by "counting"
  - binned (χ^2 difference method)
  - unbinned (Energy test, kNN)

Stat. Comp. Simul. 75, Issue 2 109-119 (2004), Nucl. Instrum. Methods A537, 626-636 (2005)

Origin of CPV

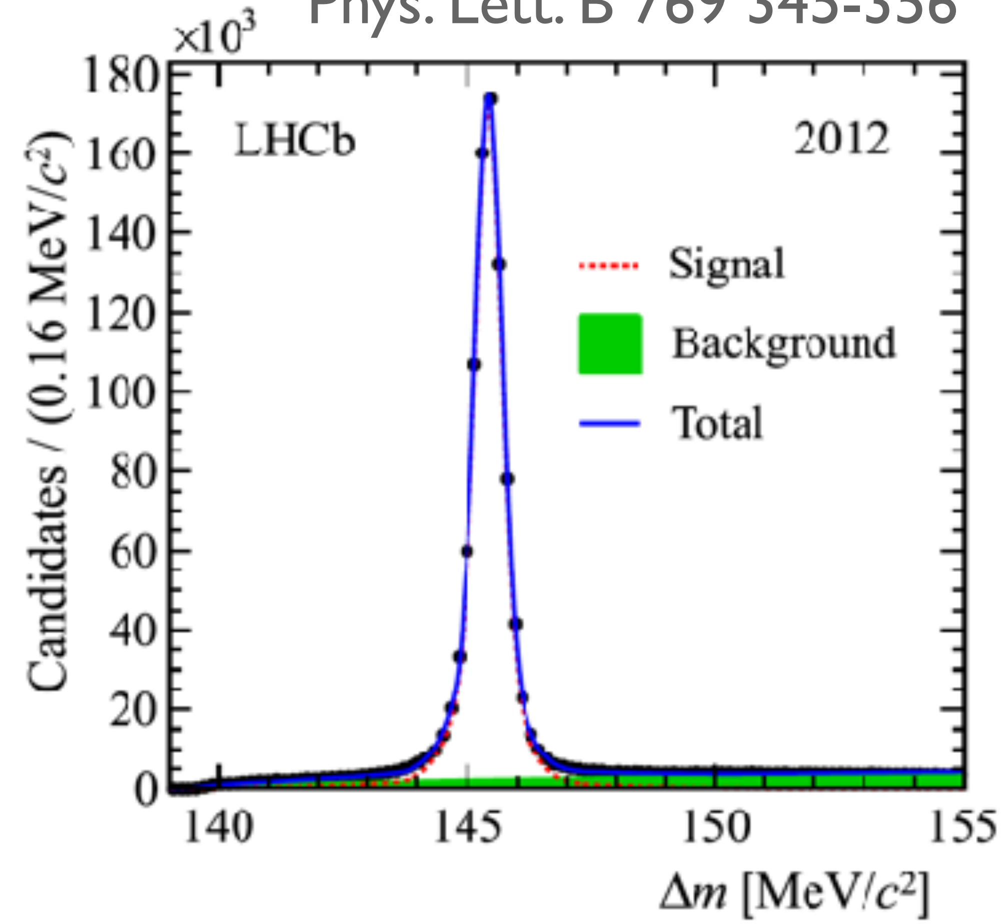
- Model-dependent:
  Fit all contributing amplitudes and look for differences in fit parameters

LHCb signal sample of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays



- Pion tagged *D^0* decays
  - $D^{*+} \to D^0 \pi_s^+$
- ~1M signal candidates
- Purity ~96%
- Use all LHCb Run 1 sample
  - 2011+2012

Phys. Lett. B 769 345-356



- Previous LHCb $D^0 \to \pi^+\pi^-\pi^+\pi^-$ analysis using 2011 data, with binned approach, and *P*-even observables [PLB726 (2013) 623]

Unbinned method: Energy test

Energy test: unbinned sample comparison used to assign p-value for hypothesis of identical distributions (= no CPV)

Test statistic $T \approx \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(\Delta\vec{x}_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(\Delta\vec{x}_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\Delta\vec{x}_{ij})$.

- Compare average pair-wise distance in Dalitz plot between: all D^0 events; all $\overline{D}^0$ events; all D^0 to $\overline{D}^0$ events
  - no CP violation → $T \approx 0$
  - CP asymmetry → $T > 0$

First application of the method for a CPV search in $D^0 \to \pi^- \pi^+ \pi^0$ PLB 740 (2015) 158-167

- For 4-body decays, introduce triple product C_T as parity sensitive variable

$$C_T = \vec{p}(\pi_3) \cdot [\vec{p}(\pi_1) \times \vec{p}(\pi_2)]$$

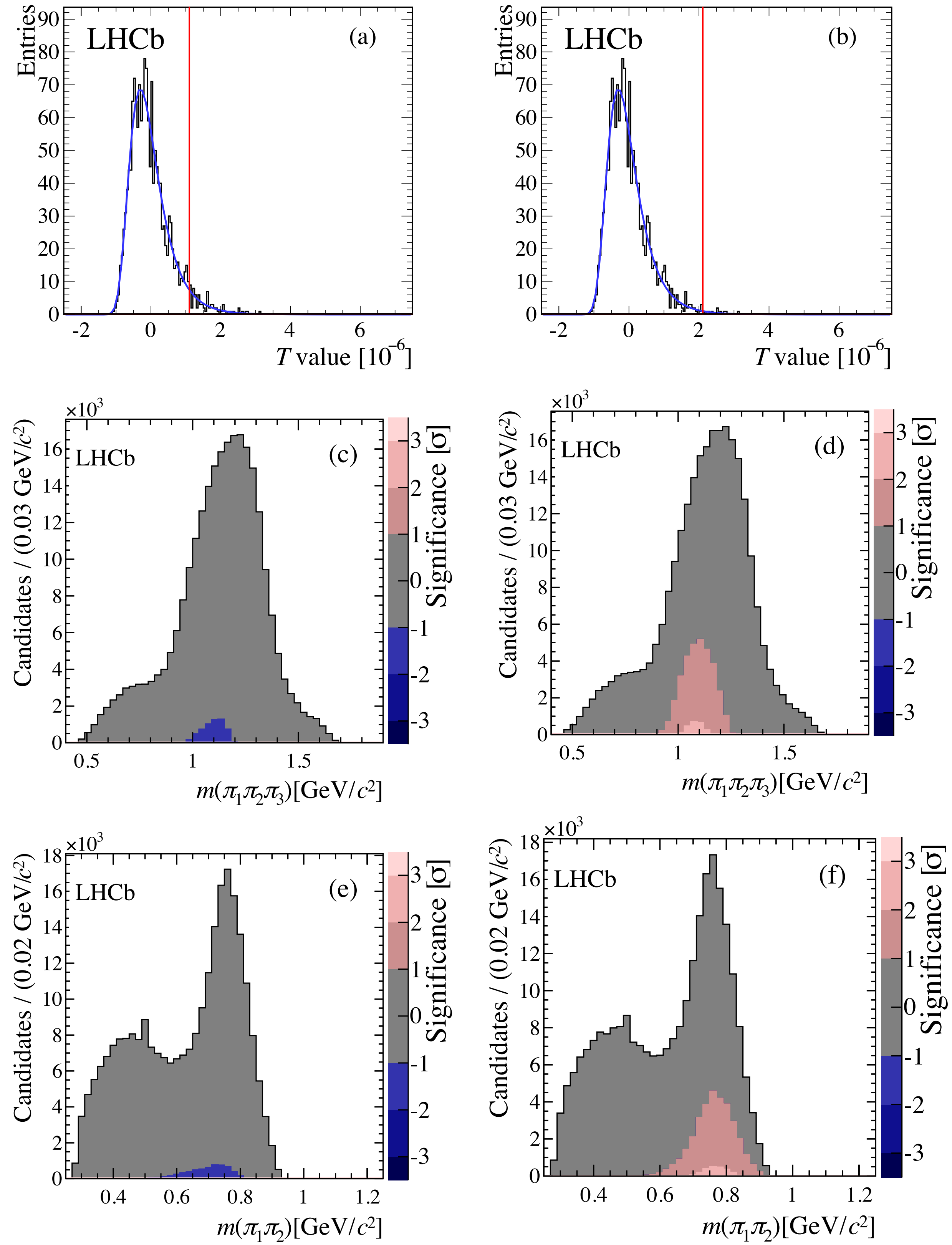
- Analyse different flavours and signs of C_T regions

Direct CPV searches in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays (LHCb)

P-even

p-value:
(4.6±0.5)%

P-even test consistent with *CP symmetry*



P-odd

p-value:
(0.6±0.2)%
2.7σ

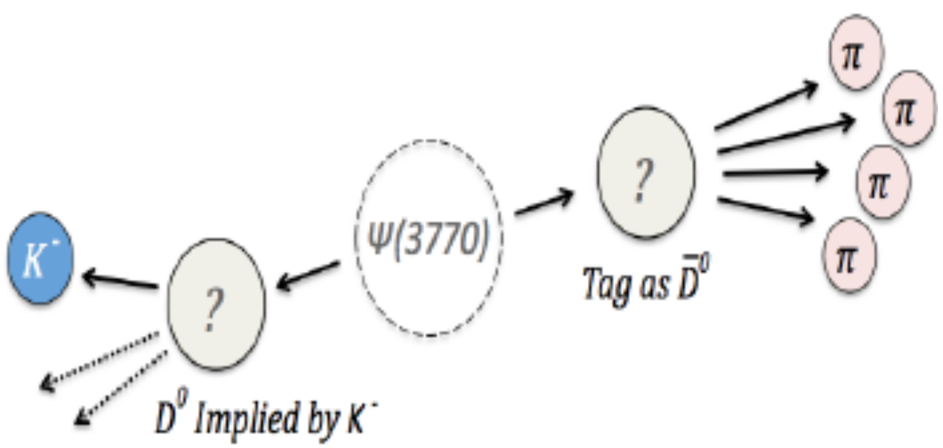
P-odd test only marginally consistent with no-*CPV* hypothesis

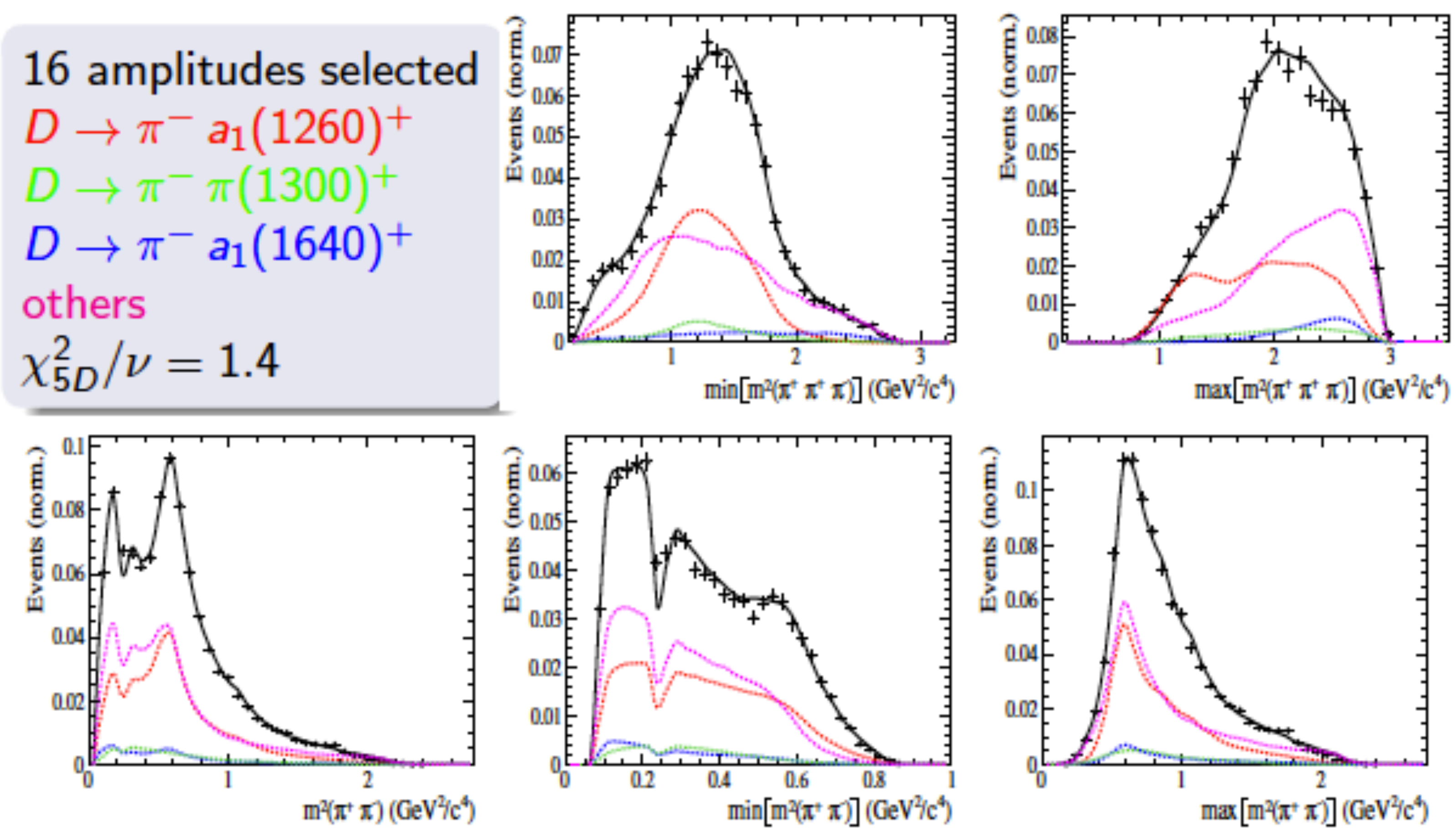
Phys. Lett. B 769 345-356

D→4π and D→KKππ with CLEOc legacy data

- Quantum-entangled states $e^+e^- \to \Psi(3770) \to D_a D_b$
- Tagging: $K^\pm$ e.g. $D_b \to K^- e^+ \nu$ then $D_a = \bar{D}^0$
- 7k flavoured tagged $D_b \to 4\pi$ candidates

CLEO-c legacy data





P. d'Argent,... EG et al. arXiv:1703.08505 accepted for publication by JHEP

Amplitude model and CPV search (CLEO-c legacy data)

$$F_i = \frac{\int |a_i A_i|^2 d\Phi}{\int |\sum_i a_i A_i|^2 d\Phi}$$

Decay channel	F_i (%)
$D^0 \to \pi^- [a_1(1260)^+ \to \pi^+ \rho(770)^0]$	$38.1 \pm 2.3 \pm 3.2 \pm 1.7$
$D^0 \to \pi^- [a_1(1260)^+ \to \pi^+ \sigma]$	$10.2 \pm 1.4 \pm 2.1 \pm 2.5$
$D^0 \to \pi^+ [a_1(1260)^- \to \pi^- \rho(770)^0]$	$3.1 \pm 0.6 \pm 0.5 \pm 0.9$
$D^0 \to \pi^+ [a_1(1260)^- \to \pi^- \sigma]$	$0.8 \pm 0.2 \pm 0.1 \pm 0.4$
$D^0 \to \pi^- [\pi(1300)^+ \to \pi^+ \sigma]$	$6.8 \pm 0.9 \pm 1.5 \pm 3.1$
$D^0 \to \pi^+ [\pi(1300)^- \to \pi^- \sigma]$	$3.0 \pm 0.6 \pm 2.0 \pm 2.0$
$D^0 \to \pi^- [a_1(1640)^+[D] \to \pi^+ \rho(770)^0]$	$4.2 \pm 0.6 \pm 0.9 \pm 1.8$
$D^0 \to \pi^- [a_1(1640)^+ \to \pi^+ \sigma]$	$2.4 \pm 0.7 \pm 1.1 \pm 1.3$
$D^0 \to \pi^- [\pi_2(1670)^+ \to \pi^+ f_2(1270)]$	$2.7 \pm 0.6 \pm 0.7 \pm 0.9$
$D^0 \to \pi^- [\pi_2(1670)^+ \to \pi^+ \sigma]$	$3.5 \pm 0.6 \pm 0.8 \pm 0.9$
$D^0 \to \sigma f_0(1370)$	$21.2 \pm 1.8 \pm 4.2 \pm 5.2$
$D^0 \to \sigma \rho(770)^0$	$6.6 \pm 1.0 \pm 1.2 \pm 3.0$
$D^0[S] \to \rho(770)^0 \rho(770)^0$	$2.4 \pm 0.7 \pm 1.1 \pm 1.0$
$D^0[P] \to \rho(770)^0 \rho(770)^0$	$7.0 \pm 0.5 \pm 1.6 \pm 0.3$
$D^0[D] \to \rho(770)^0 \rho(770)^0$	$8.2 \pm 1.0 \pm 1.7 \pm 3.5$
$D^0 \to f_2(1270) f_2(1270)$	$2.1 \pm 0.5 \pm 0.3 \pm 2.3$
Sum	$122.0 \pm 4.0 \pm 6.4 \pm 7.6$

P. d'Argent,... EG et al. arXiv:1703.08505
accepted for publication by JHEP

$$\mathcal{A}^i_{CP} = \frac{F_i - \bar{F}_i}{F_i + \bar{F}_i}$$

Decay channel	$\mathcal{A}^i_{CP}$ (%)	Significance (σ)
$D^0 \to \pi^- a_1(1260)^+$	$+4.7 \pm 2.6 \pm 4.3 \pm 2.4$	0.9
$D^0 \to \pi^+ a_1(1260)^-$	$+13.7 \pm 13.8 \pm 9.8 \pm 5.8$	0.8
$D^0 \to \pi^- \pi(1300)^+$	$1.6 \pm 12.9 \pm 5.0 \pm 4.4$	0.1
$D^0 \to \pi^+ \pi(1300)^-$	$-5.6 \pm 11.9 \pm 25.6 \pm 10.3$	0.2
$D^0 \to \pi^- a_1(1640)^+$	$+8.6 \pm 17.8 \pm 16.0 \pm 10.8$	0.3
$D^0 \to \pi^- \pi_2(1670)^+$	$+7.3 \pm 15.1 \pm 8.0 \pm 6.6$	0.4
$D^0 \to \sigma f_0(1370)$	$14.6 \pm 16.5 \pm 9.3 \pm 1.3$	0.8
$D^0 \to \sigma \rho(770)^0$	$+2.5 \pm 16.8 \pm 13.8 \pm 14.6$	0.1
$D^0 \to \rho(770)^0 \rho(770)^0$	$-5.6 \pm 5.0 \pm 2.2 \pm 1.9$	1.0
$D^0 \to f_2(1270) f_2(1270)$	$28.3 \pm 12.3 \pm 18.5 \pm 9.7$	1.2

$$\mathcal{A}^{4\pi}_{CP} = \frac{\Gamma(D^0 \to \pi^+\pi^-\pi^+\pi^-) - \Gamma(\bar{D}^0 \to \pi^+\pi^-\pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-\pi^+\pi^-) + \Gamma(\bar{D}^0 \to \pi^+\pi^-\pi^+\pi^-)}$$

$$= \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}} = [+0.54 \pm 1.04 \pm 0.51]\%$$

$$\mathcal{A}^{KK\pi\pi}_{CP} = [+1.84 \pm 1.74 \pm 0.30]\%$$

Check the backup for D→KKππ amplitude model and CP fractions results

CLEO-c legacy data

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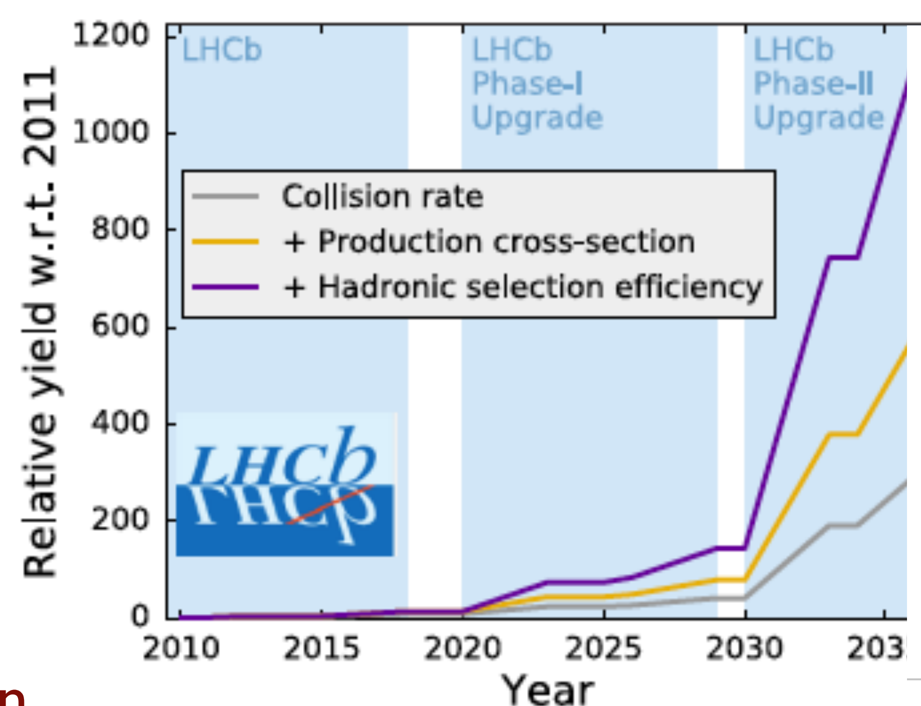
Conclusions

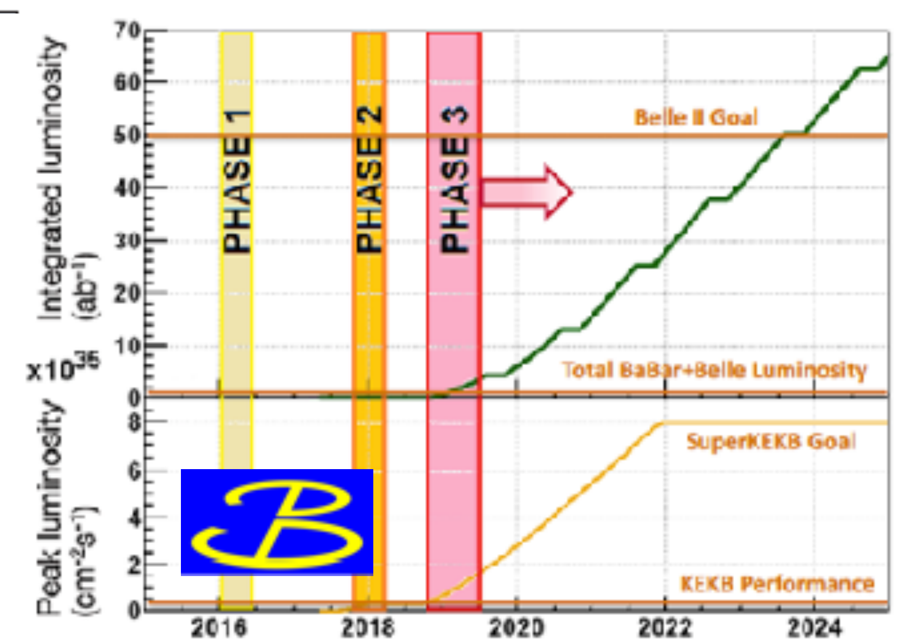
- Latest precision measurements in the charm sector at LHCb, BELLE, BESIII, BaBar, CLEO-c legacy data presented
  - CPV in charm not yet observed: All searches consistent with no direct or indirect CPV - some only marginally
  - 10^{-3} precision reached in direct CPV searches and 10^{-4} in the indirect CPV searches
  - no-mixing hypothesis excluded at $>10\sigma$ already with LHCb Run I prompt data; different results agree well
  - measurement of the mixing parameters x and y is urgent: BESIII input is critical for precision measurements
- The key measurements are still statistically limited; systematics reduces with statistics

What comes next?

- Several key LHCb Run I analyses still ongoing; LHCb Run II analyses ongoing
- Factor two gain in statistics seen with Run II LHCb data due to trigger optimisation, and even more with the upgraded LHCb experiment is expected
- More data from LHCb and BESIII
- BELLE2 will start taking data soon

upgrade of inner tracker plan





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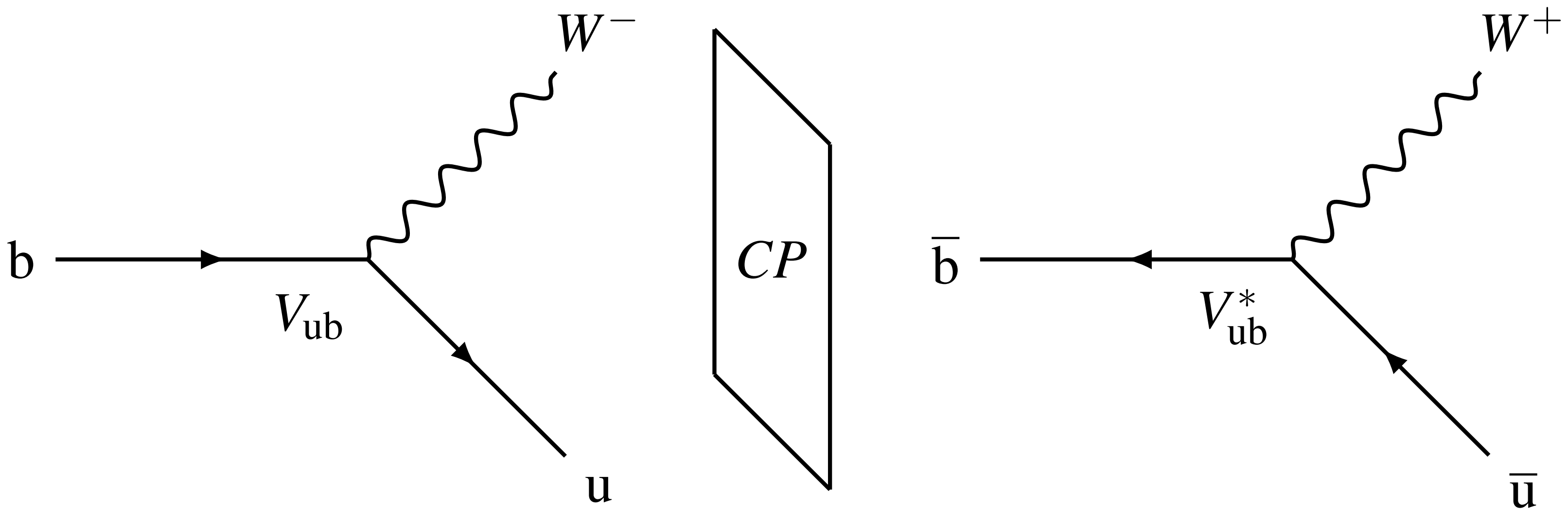
Backup

CP violation

CP symmetry applies to processes invariant under the combined transformation of

charge conjugation (C): exchange of particle and anti-particle

and parity (P): spatial inversion



CP violation discovered in 1964 in weak interactions of neutral Kaon decays by Cronin and Fitch

CP symmetry conserved in the strong and the EM interaction

The symmetry under CP transformation can be violated in different ways

Types of CPV: direct CPV

The decay rate of a particle to a final state f, A_f, is different to the rate of the anti-particle decay to the CP conjugate final state $\bar{f}$, $\bar{A}_{\bar{f}}$.

$$|\bar{A}_{\bar{f}}/A_f| \neq 1$$

Direct CPV occurs for non-zero Ad

$$A_d \equiv (|A_f|^2 - |\bar{A}_f|^2)/(|A_f|^2 + |\bar{A}_f|^2)$$

This type of CPV depends on decay mode.

Types of CPV: indirect CPV

CPV in mixing (involves neutral particles)

The transition probability of particles to anti-particles compared to the reverse process differs.

$$P(M^0(t) \to \overline{M}^0) \neq P(\overline{M}^0(t) \to M^0)$$

Occurs if: $|q/p| \neq 1$

Where p,q - complex coefficients relating the mass and the flavour eigenstates

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

Types of CPV: indirect CPV

CPV in interference (mixing and decay amplitudes can interfere)

Present if the imaginary part of λ_f is non-zero

$$\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\eta_{CP} \left|\frac{q}{p}\right| \left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

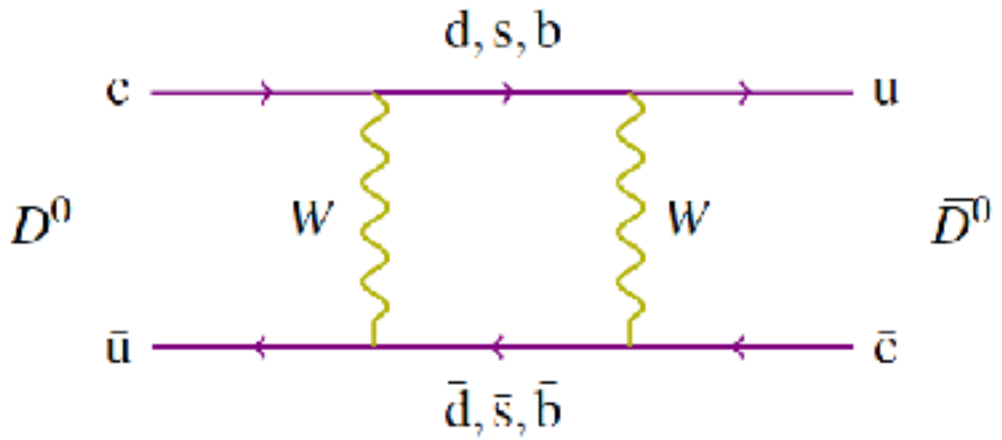
φ is the CP violating relative phase between q/p and $\bar{A}_{\bar{f}}/A_f$

It involves neutral particles

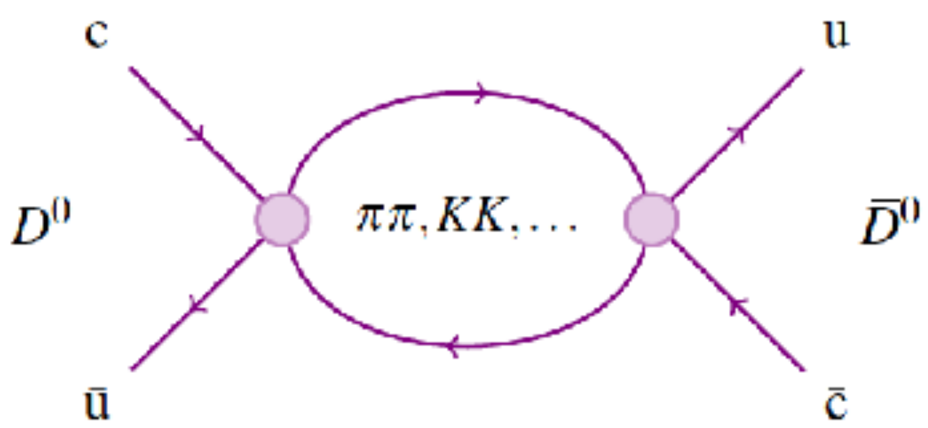
The indirect CP violation is independent of the decay mode.

Neutral D mesons

The neutral mesons can mix into each other via:



Short distance process



Long distance process

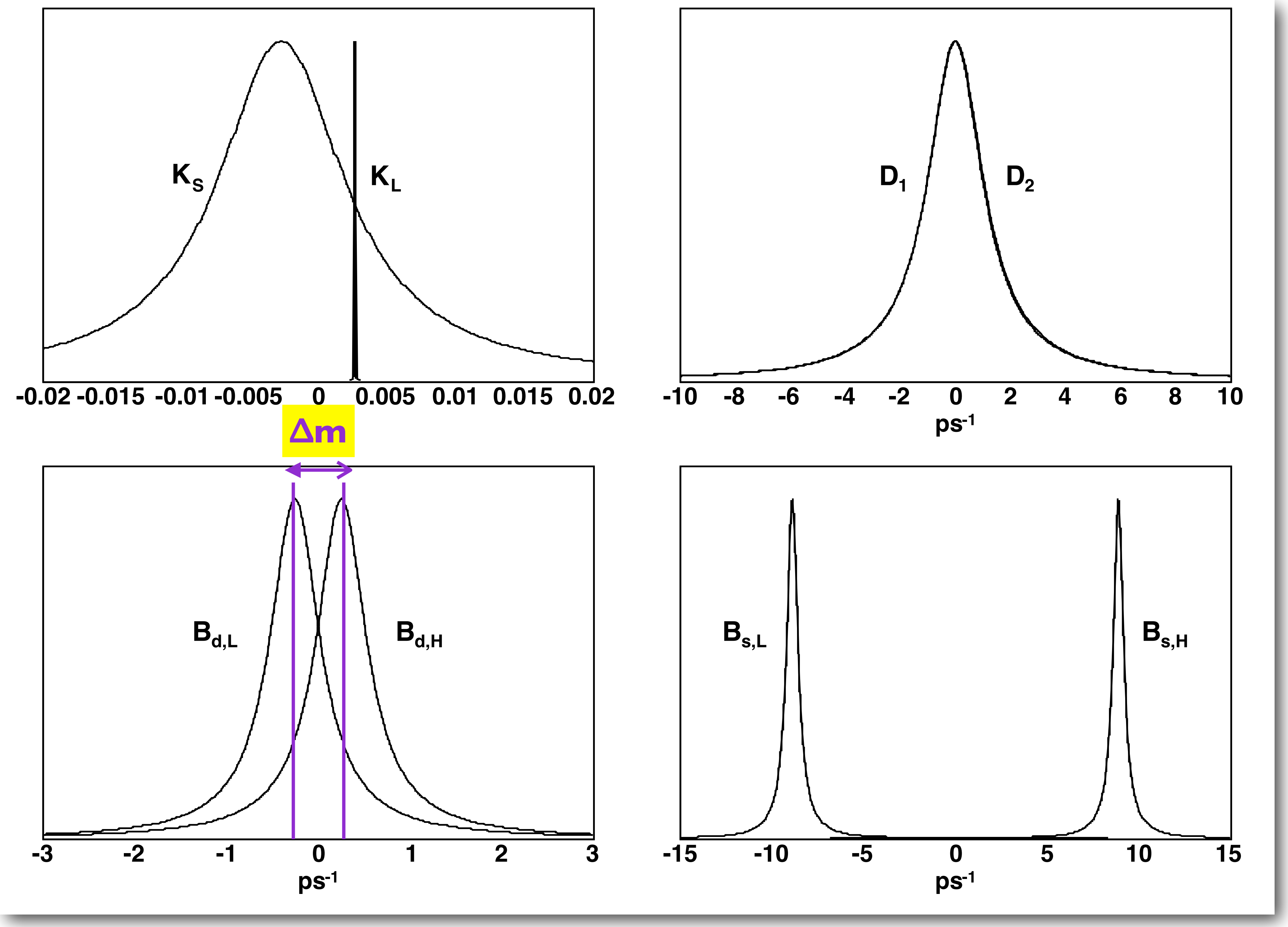
- Mixing box contains down-type quarks
- No dominance of top mass as in B sector
- CKM-suppression balances the GIM suppression

➡ Long-distance effects are important (but difficult to calculate)

For neutral mesons, the mass eigenstates, *i.e.* the physical particles, do not *a priori* coincide with the flavour eigenstates

The mass and width differences for the neutral

Δm negligible: very slow mixing



Δm large: very fast mixing

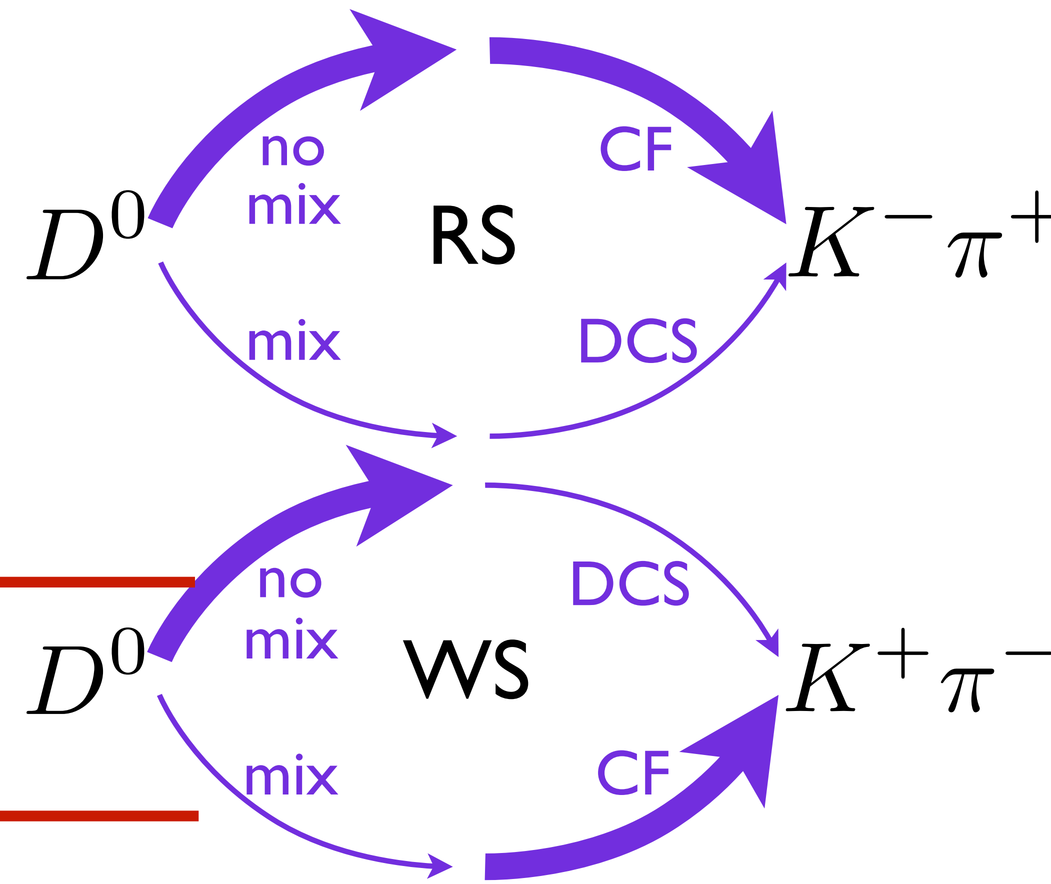
- Over 1000 lifetimes for 1 full oscillation
- Difficult to measure

➡ CP violation even more tricky to discover

Mixing in $D^0 \rightarrow K^+\pi^-$ decays

Measure the decay rates of WS to RS events:

two paths to reach the final state



interference

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}(\frac{t}{\tau})^2$$

mixing

ratio of WS to RS decays

Mixing parameters

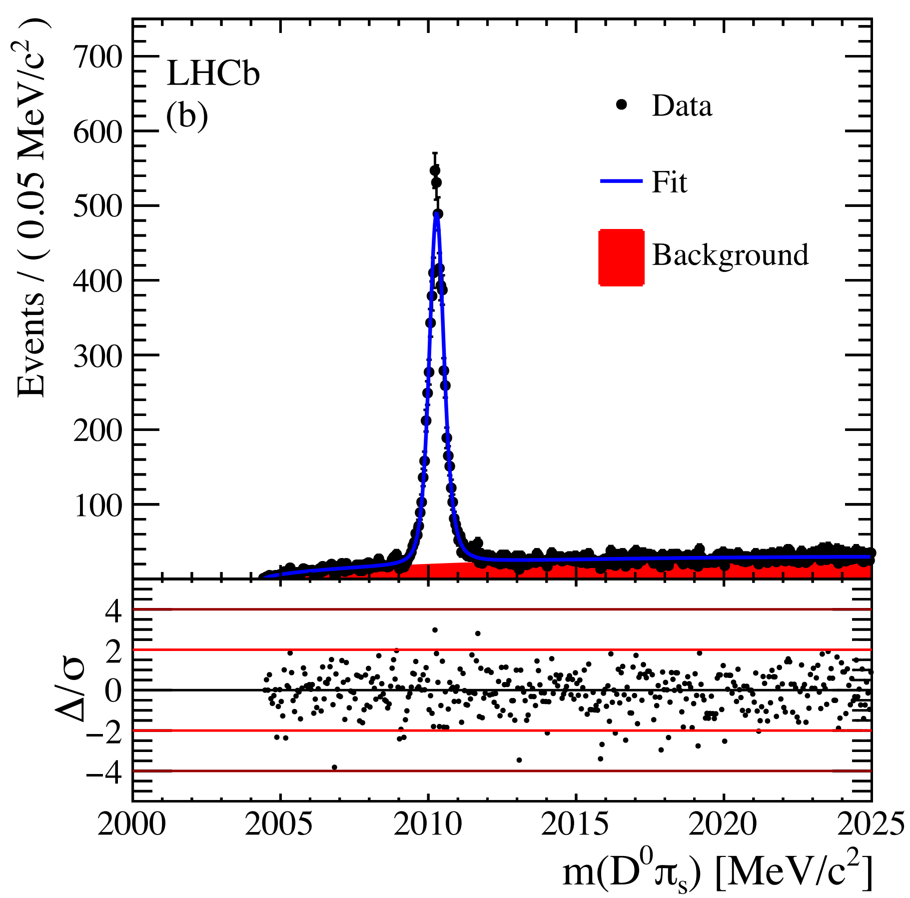
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

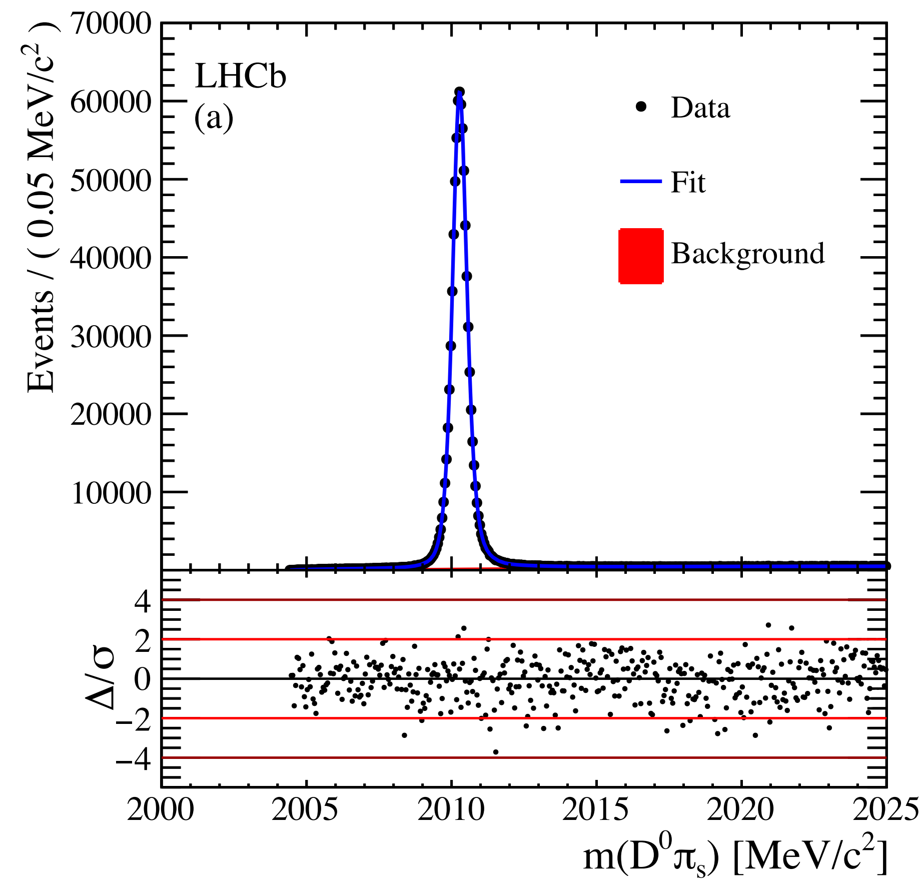
$$\mathcal{A}(D^0 \rightarrow K^+\pi^-)/\mathcal{A}(\overline{D}^0 \rightarrow K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$$

delta is the strong phase between CF and DCS

Yield extraction of doubly-tagged $D^0 \to K^+\pi^-$ decays

- Use Run 1 data
- Doubly-tagged candidates
- 1.7M RS and 6.7k DCS candidates
- Fit m(D*) in 5 different decay-time bins



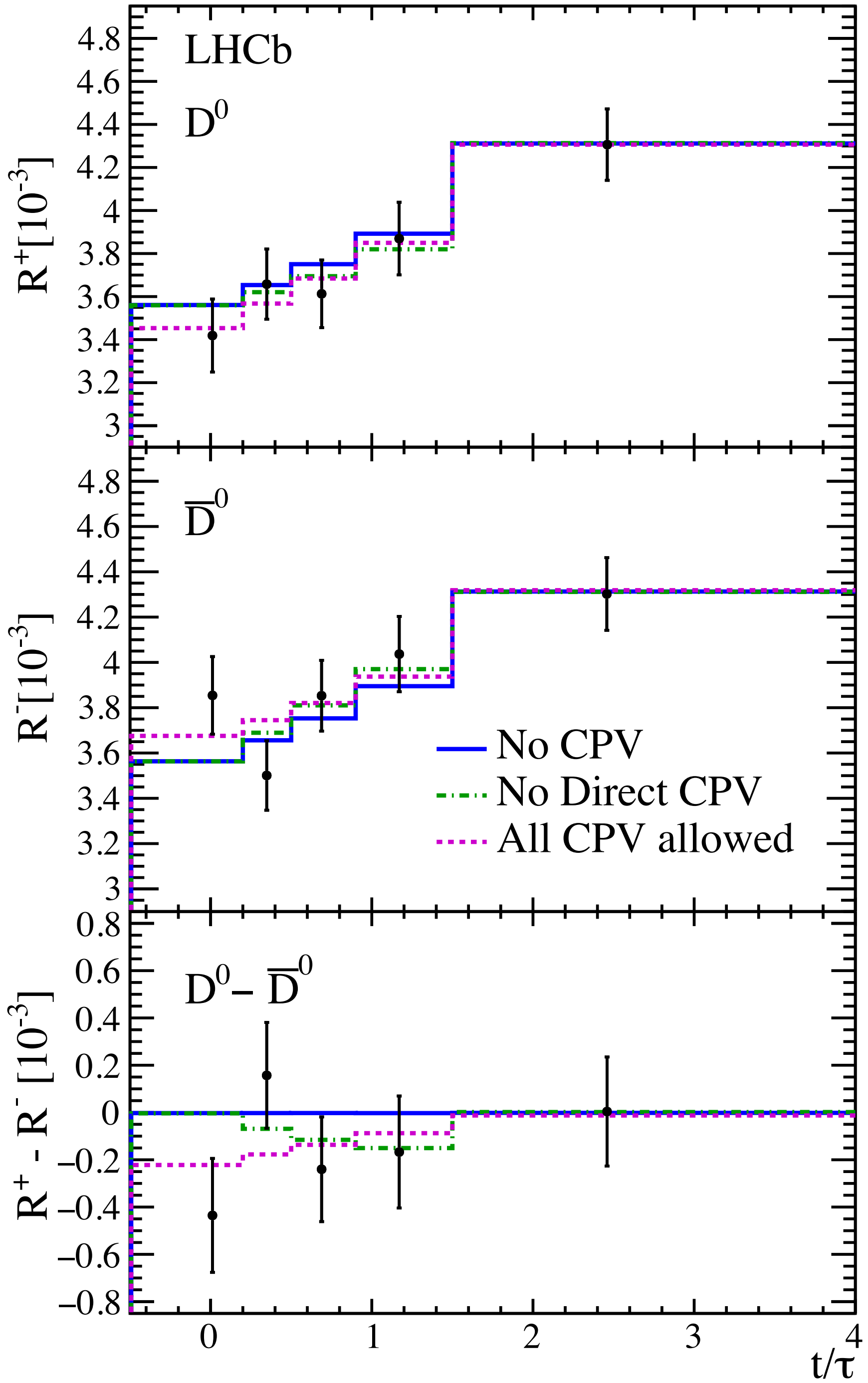


Phys. Rev. D 95, 052004 (2017)

Mixing in doubly-tagged $D^0 \rightarrow K^+\pi^-$ decays

- Measure R(t) in bins of decay time:(*separate signal and background)
  - flat: no mixing
  - non-flat: mixing
- Efficiency-corrected data fitted to extract under three hypotheses:
  - No CPV
  - No direct CPV ($R_D^+ = R_D^-$)
  - All CPV allowed
- No evidence for CPV in mixing or decay
- Statistical uncertainties dominate
- Inconsistent with no-mixing hypothesis at 4.6σ

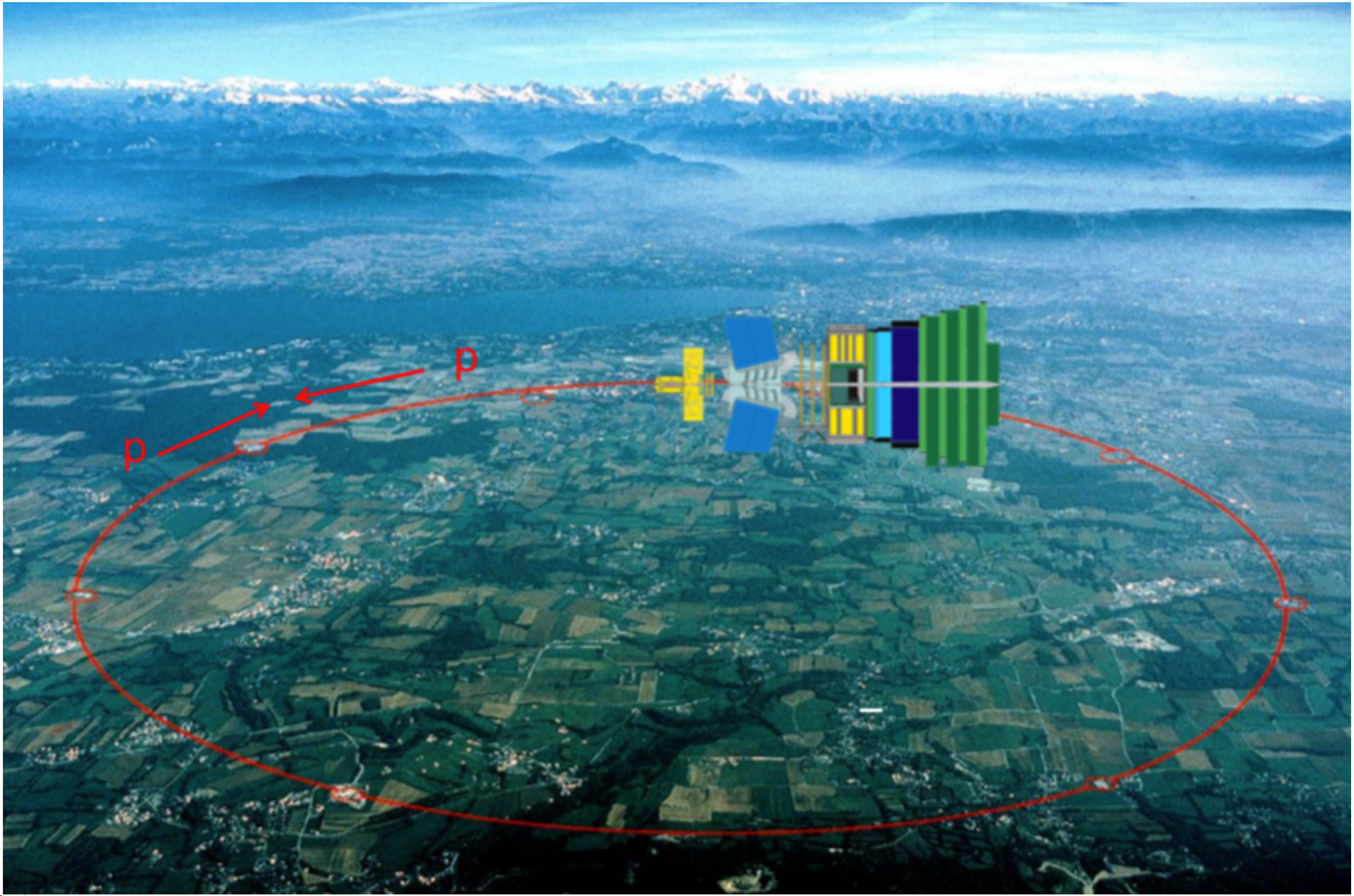
(Reminder: Results exclude the no-mixing hypothesis at 9.1σ already with 2011 LHCb prompt data)



Parameter	Value
No CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^2[10^{-4}]$	$0.28 \pm 3.10 \pm 0.11$
$y'[10^{-3}]$	$4.60 \pm 3.70 \pm 0.18$
χ^2/ndf	6.3/7

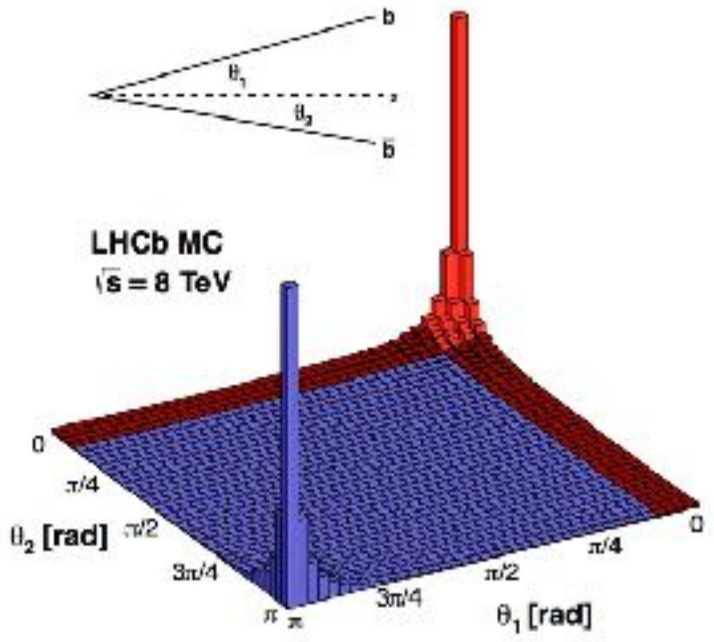
—Phys. Rev. D 95, 052004 (2017)

LHC & LHCb



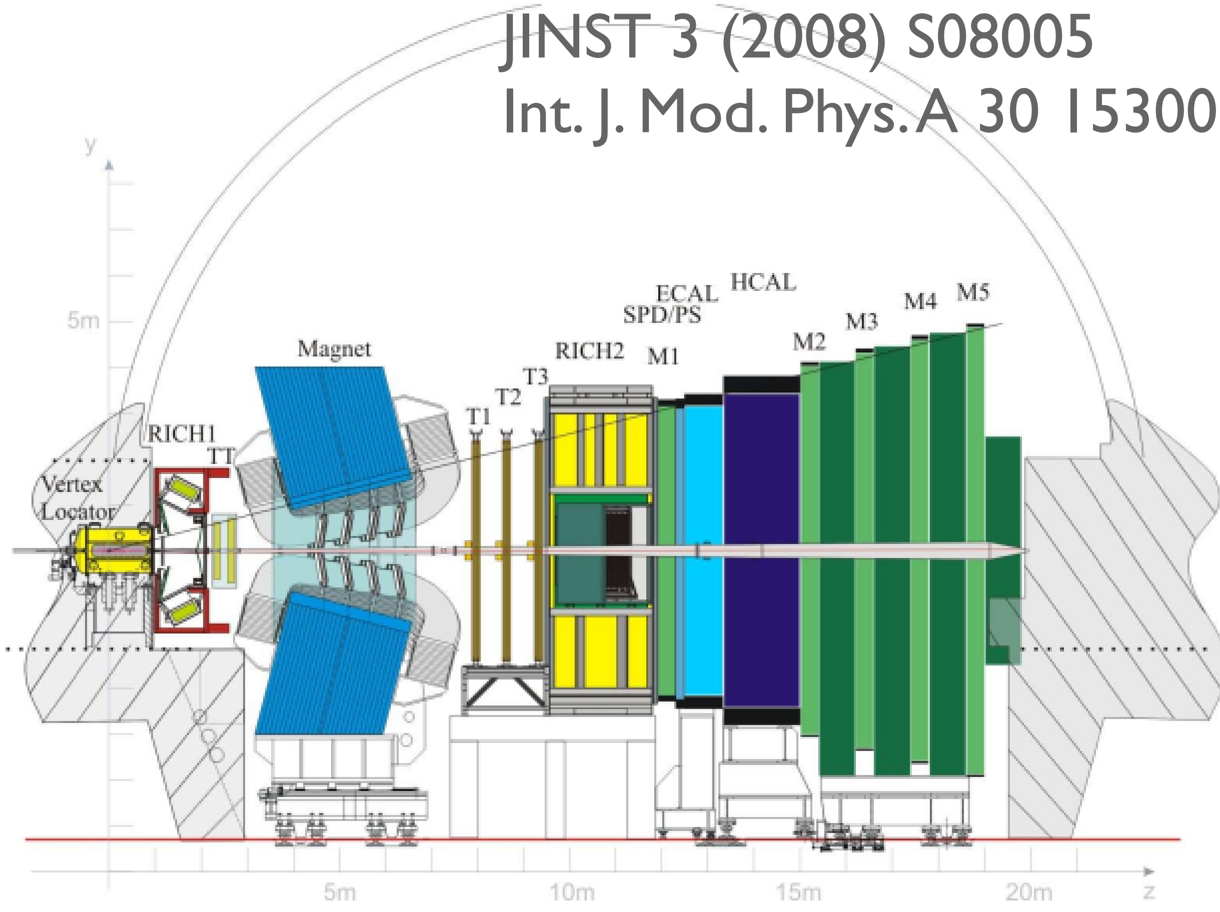
Forward spectrometer at LHC

LHCb is optimised for heavy flavour physics



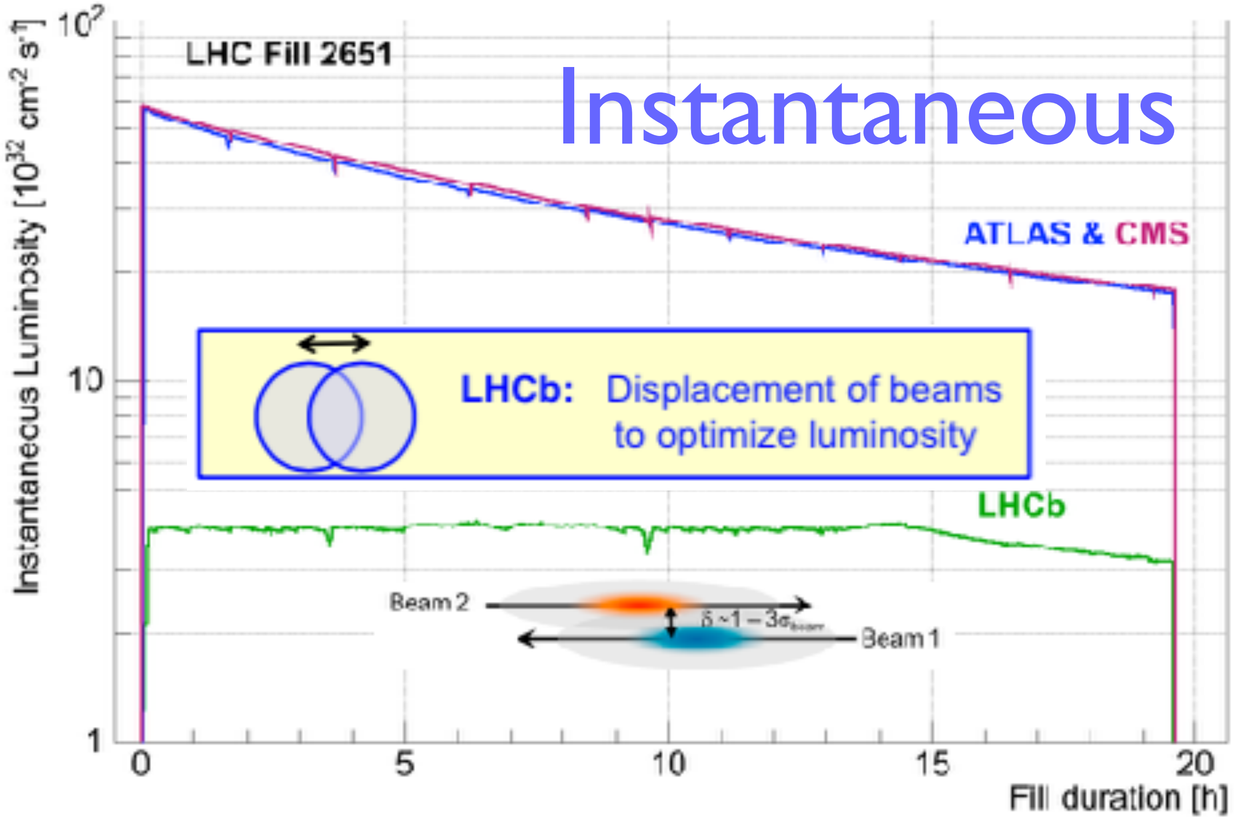
$b\bar{b}$ (and $c\bar{c}$) production angles strongly correlated: heavily boosted in the forward or backward direction

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 1530022



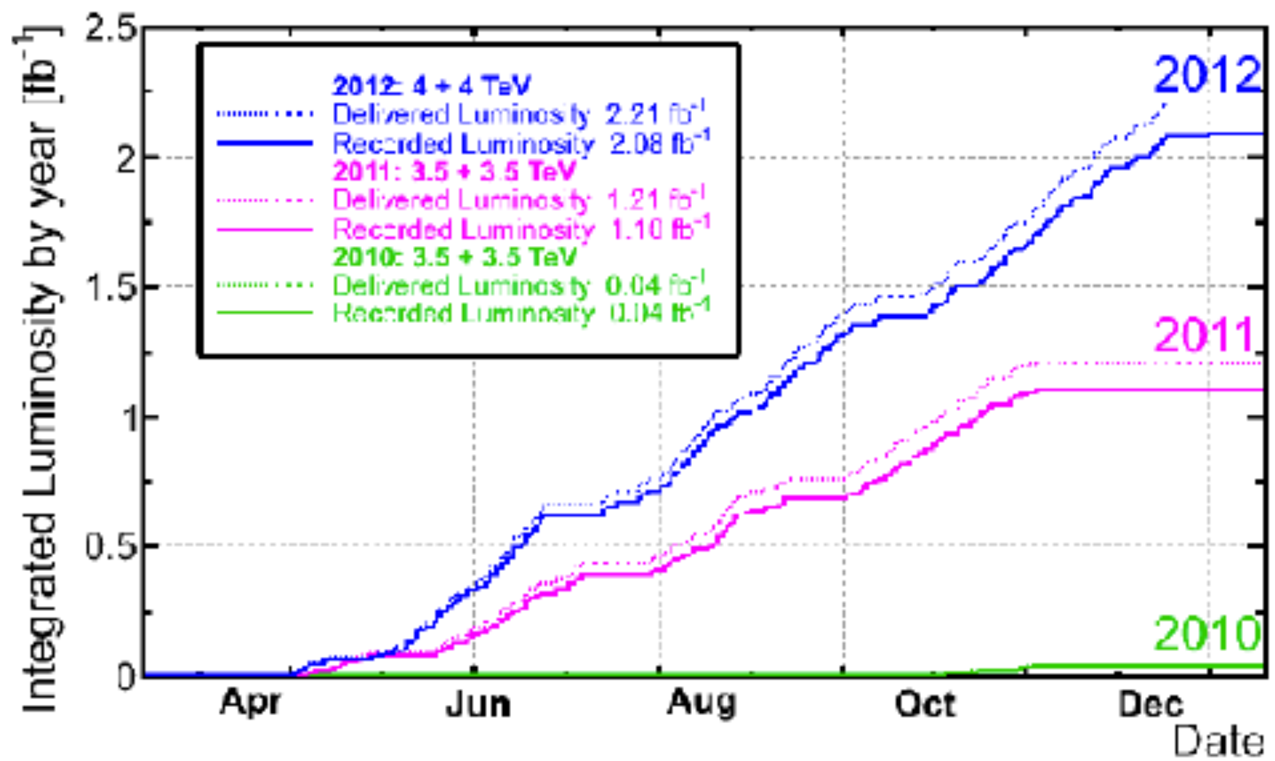
- Forward acceptance 2<η<5
- Precise vertex reconstruction
- Precise & efficient tracking
- Excellent decay time resolution ~0.1τD
- Hadron identification: RICHes
- Dipole magnet with reversible polarity

Run 1 performance



Luminosity levelling unlike ATLAS and CMS: uniform operating conditions

- In total:
  - 2010: 37 pb^{-1} @ 7 TeV
  - 2011: 1 fb^{-1} @ 7 TeV
  - 2012: 2 fb^{-1} @ 8 TeV



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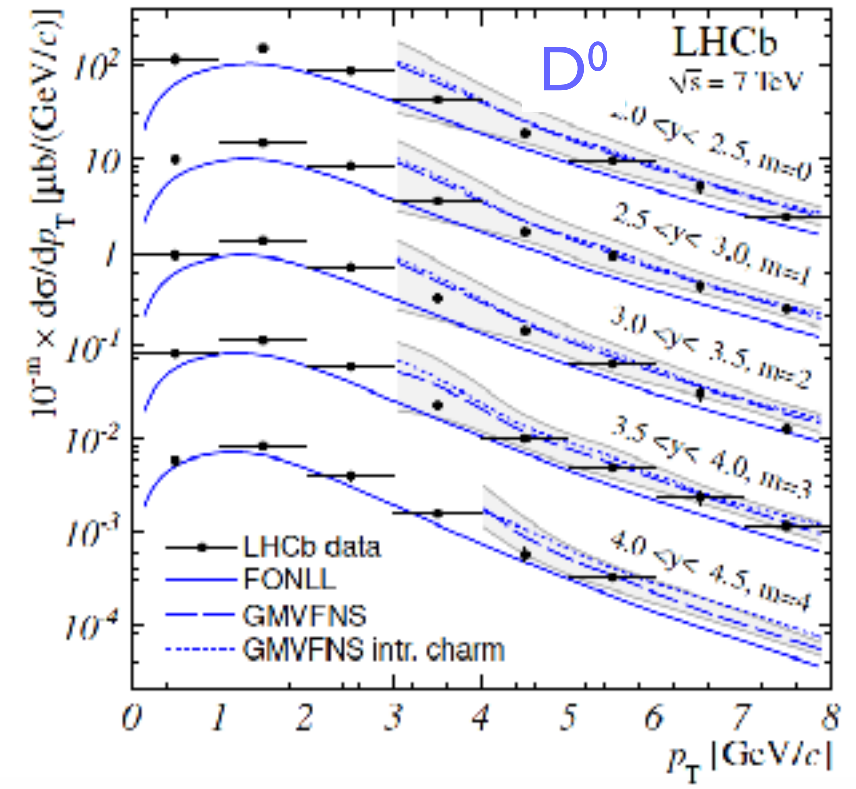
Charm production cross-sections @ 7TeV in LHCb acceptance

All c species produced at LHCb

$$\sigma(D^0) = 1661 \pm 129\,\mu b$$
$$\sigma(D^+) = 645 \pm 74\,\mu b$$
$$\sigma(D^{*+}) = 677 \pm 83\,\mu b$$
$$\sigma(D_s^+) = 197 \pm 31\,\mu b$$
$$\sigma(\Lambda_c^+) = 233 \pm 77\,\mu b$$



- Cross section for $c\bar{c}$ in LHCb acceptance

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

2010 data
Nucl.Phys. B871 (2013) 1-20

  - ~5x10^{12} D^0 mesons produced in LHCb acceptance in run1

- Huge statistics of prompt and secondary charm: worlds' best sensitivity to very small CP asymmetries

Direct CPV

- Condition for direct CPV: $|A/\bar{A}| \neq 1$
- Need A and $\bar{A}$ to consist of (at least) two parts: with different weak (φ) and strong (δ) phases
- Divide amplitudes into leading and sub-leading parts:

$$A(D \to f) = C(1+re^{i(\delta+\phi)})$$
$$\bar{A}(\bar{D} \to \bar{f}) = C(1+re^{i(\delta-\phi)})$$

- C is the leading amplitude
- r is the ratio of sub-leading over leading amplitude

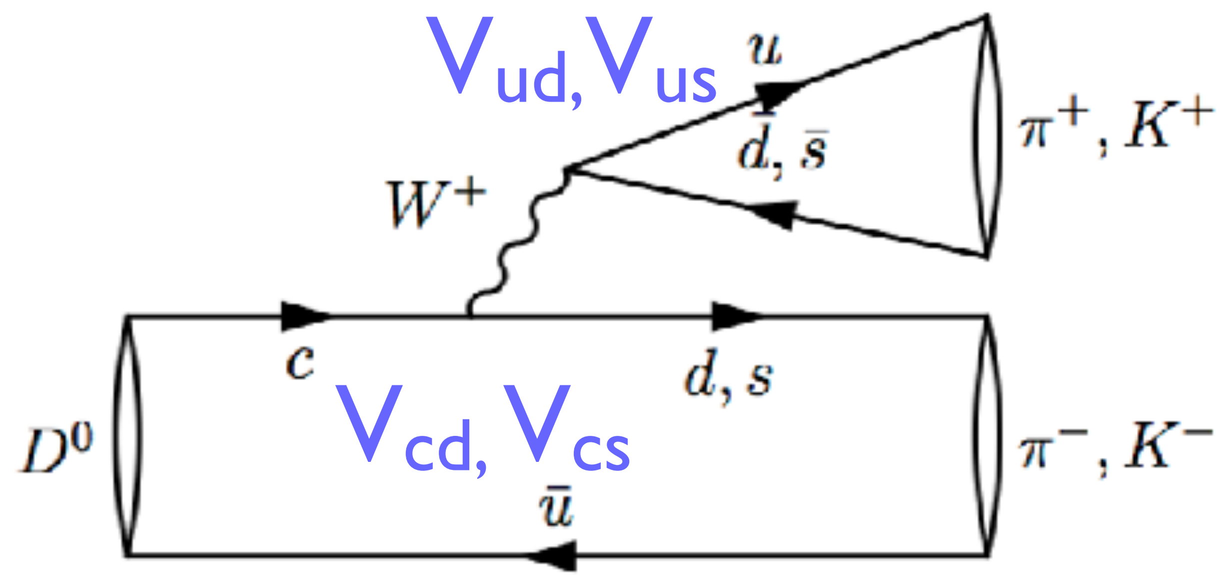
- CP violation requires difference in strong (δ) and weak phase (ϕ):
$$a_{CP} \equiv (|A|^2-|\bar{A}|^2)/(|A|^2+|\bar{A}|^2) = 2\, r \sin(\delta) \sin(\phi)$$

CPV in decay: SCS $D^0 \to h^+h^-$ decays

Often realised by "tree" and "penguin" diagrams

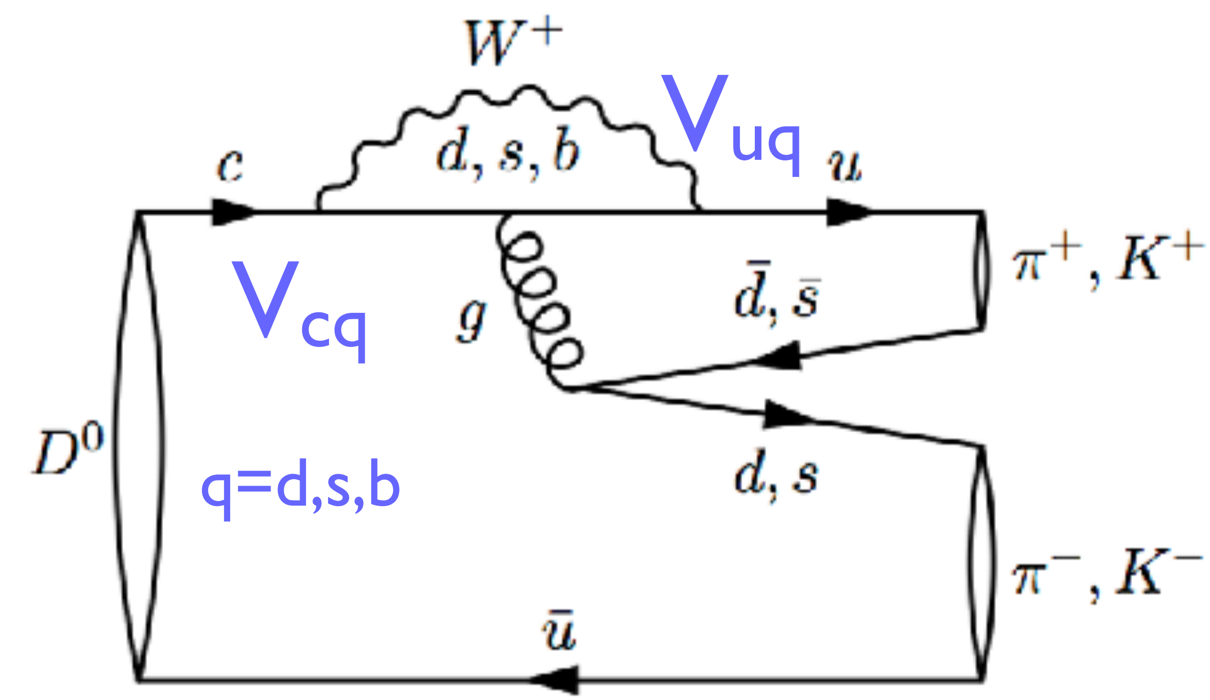
Tree-level weak decay amplitude.

- involves the CKM matrix elements
  - V_{us} and V_{cs} for $D^0 \to K^+K^-$
  - V_{ud} and V_{cd} for $D^0 \to \pi^+\pi^-$



One-loop amplitude ("penguin")

- b-loop involves $V_{ub} V_{cb}^*$: tiny
- s and d loops: similar magnitude, opposite sign



$V_{us} \approx -V_{cd} \approx 0.22$ gives the Cabbibo suppression

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What to expect?

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

$$A(\overline{D}^0 \to \pi^+\pi^-, K^+K^-) = \mp\tfrac{1}{2}\left(V_{cs}V_{us}^* - V_{cd}V_{ud}^*\right)(T \pm \delta S) - V_{cb}V_{ub}^*\left(P \mp \tfrac{1}{2}\delta P\right),$$

Direct CP violation depends on the decay mode: can be different for different final states

Expect non-zero $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$ result in presence of direct CP violation

ΔA_{CP}

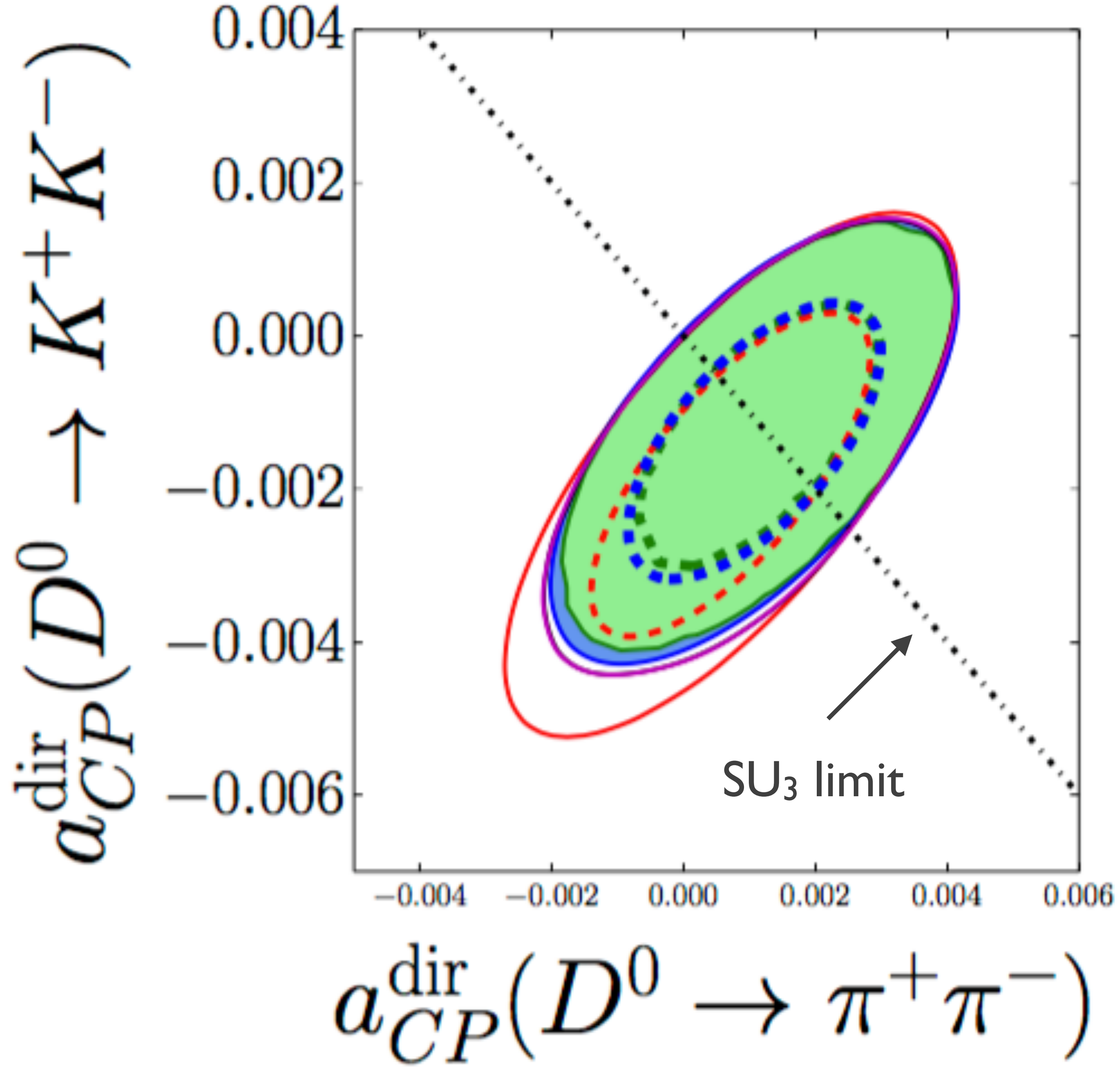
$$A_{CP}(f) \approx a_{CP}^{\text{dir}}(f)\left(1+\frac{\langle t(f)\rangle}{\tau}y_{CP}\right)+\frac{\langle t(f)\rangle}{\tau}a_{CP}^{\text{ind}}$$ where $y_{CP} \equiv \frac{\Gamma_{CP\pm}}{\Gamma} - 1$

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a_{CP}^{\text{dir}}\left(1+\frac{\overline{\langle t\rangle}}{\tau}y_{CP}\right)+\frac{\Delta\langle t\rangle}{\tau}a_{CP}^{\text{ind}}\end{aligned}$$

Mostly a measure of direct CPV

The indirect CPV is expected to cancel but a small amount could be present due to the different decay time acceptance of the two decays

Theoretical expectations



$a_{CP}^{dir} < 10^{-2}$ within the SM

Enhancements up to 1 order of magnitude possible in some BSM models

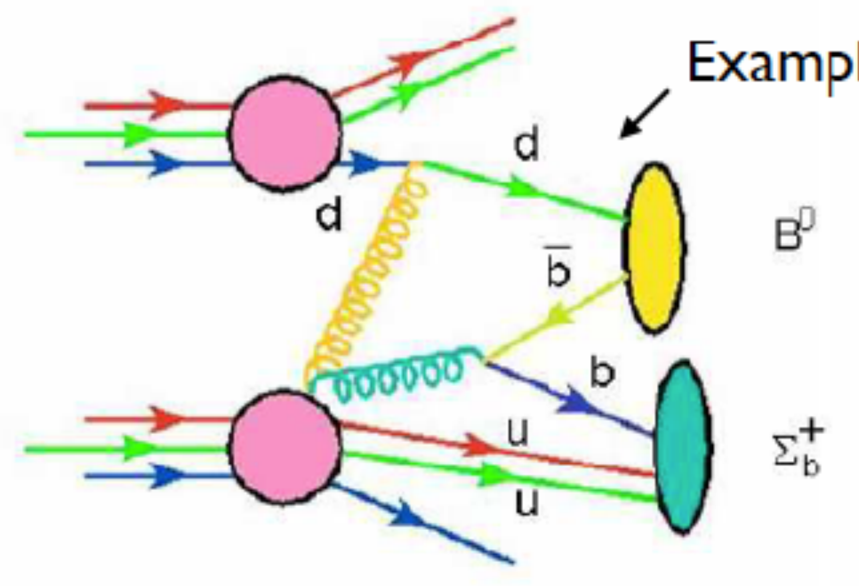
Global fit of D->hh branching ratios to topological amplitudes including linear $SU(3)_F$ breaking and 1/Nc-counting

Müller, Nieste, Schacht, Phys. Rev. Lett. 115, 251802 (2015)

Production asymmetries

Production rates of B^0 and $\overline{B}^0$ (or D^0 and $\overline{D}^0$) are not the same

gluon fusion, quarks combine with valence quark from the beam protons, valence quark scattering, etc.



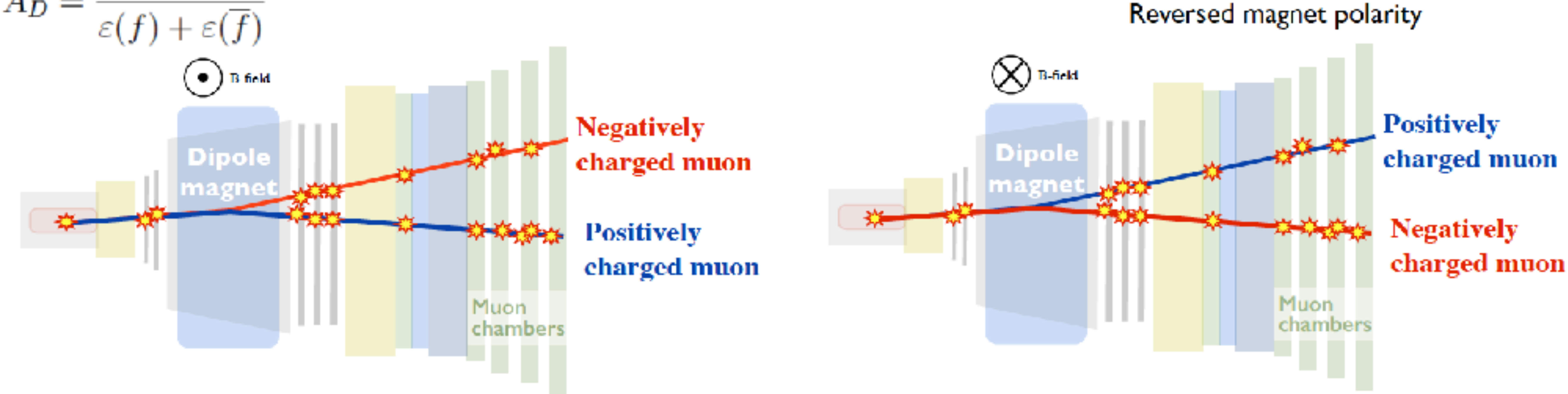
Expected to be around 1%

$$a_P = \frac{\sigma(pp \to \bar{B}) - \sigma(pp \to B)}{\sigma(pp \to \bar{B}) + \sigma(pp \to B)}$$

Detection asymmetries (1)

- Detector asymmetries

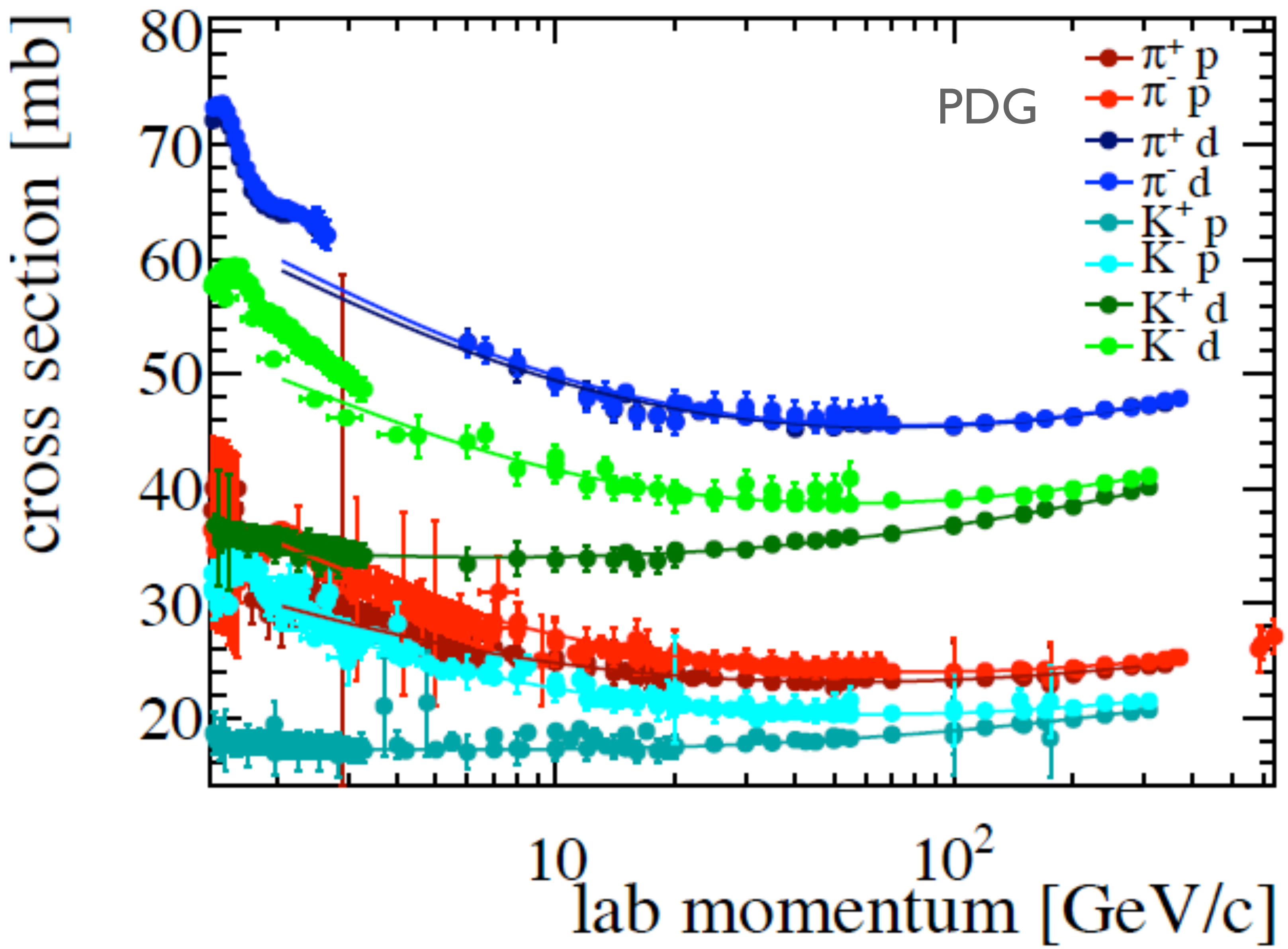
$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$



- Cancel left-right asymmetries by swapping dipole field
- But do not rely only on it (detectors move, alignment changes etc.)

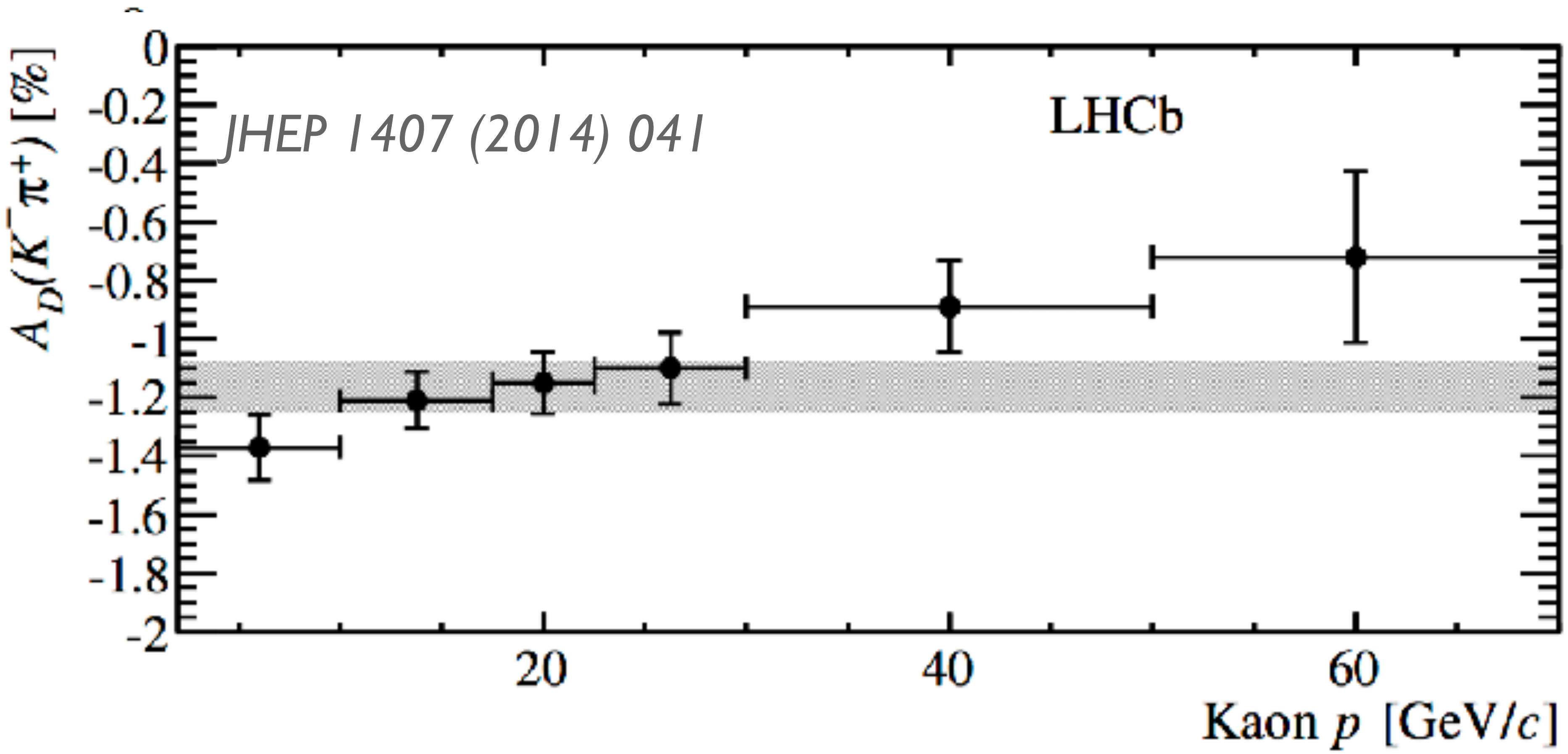
Detection asymmetries (11)

- Interaction asymmetries: e.g. K^+ cross-section for interaction with matter differs from K^- cross-section



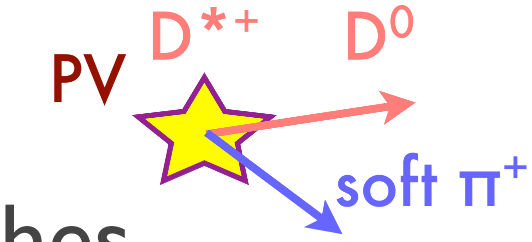
Cancellation of nuisance asymmetries

The detection asymmetries as well as the production asymmetries depend on the kinematics of the decay



A_D, A_P (~1%) cancel to 1st order but if the decays are kinematically very different there would be a residual nuisance asymmetry: equalise the KK and ππ kinematical distributions by re-weighting

Strategy



- 2 independent analyses using different approaches
- Binned analysis using 3fb^{-1}
- Unbinned analysis using 2fb^{-1}@ 8TeV, and a statistical combination with the previous measurement using 1fb^{-1} @ 7 TeV
- Both analyses use pion-tagged D^0
- Both methods have different systematic uncertainties
- Both methods have been validated by measuring a value for pseudo A_Γ compatible with 0
- Muon-tagged charm decays results on 3fb^{-1} available in JHEP 04 (2015) 043

Unbined method: strategy

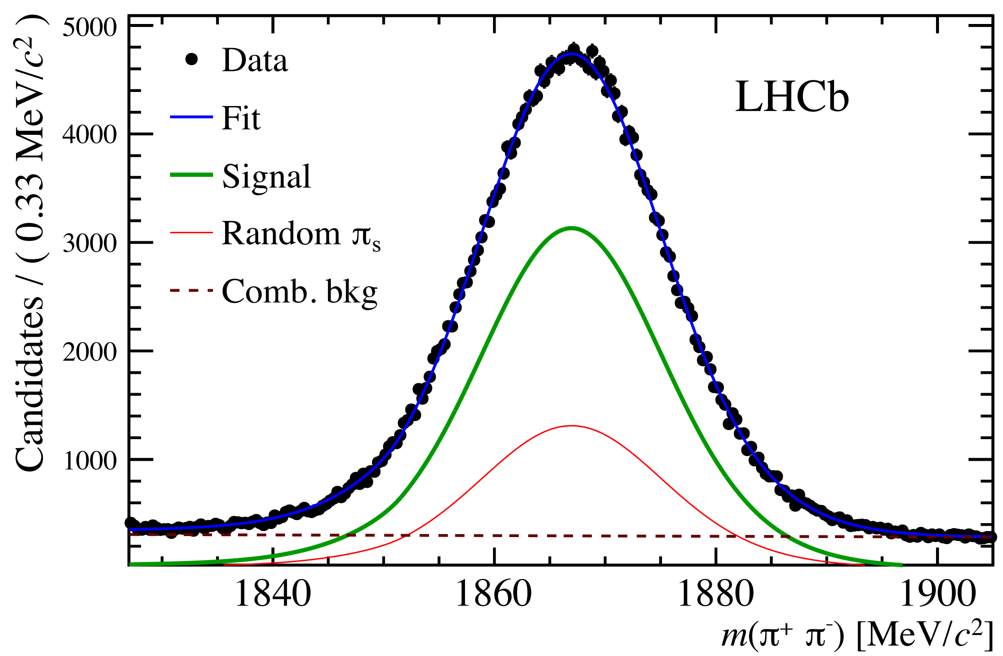
- Analyse 2012 data only, 2011 data have been analysed using the same approach PRL 112 (2014) 041801
- Blind analysis
- Measure the effective lifetimes of D^0 and $\overline{D}^0$ decays
- Empirically evaluating the per-event proper-time acceptance
- Two stage fit: first fit $m(D^0)$ and Δm (= $m(D^{*+})$ - $m(D^0)$); then fit D^0 decay time and $\ln(IP\chi^2_{D^0})$

Example of the two-staged fit using $D^0 \to \pi\pi$ decays

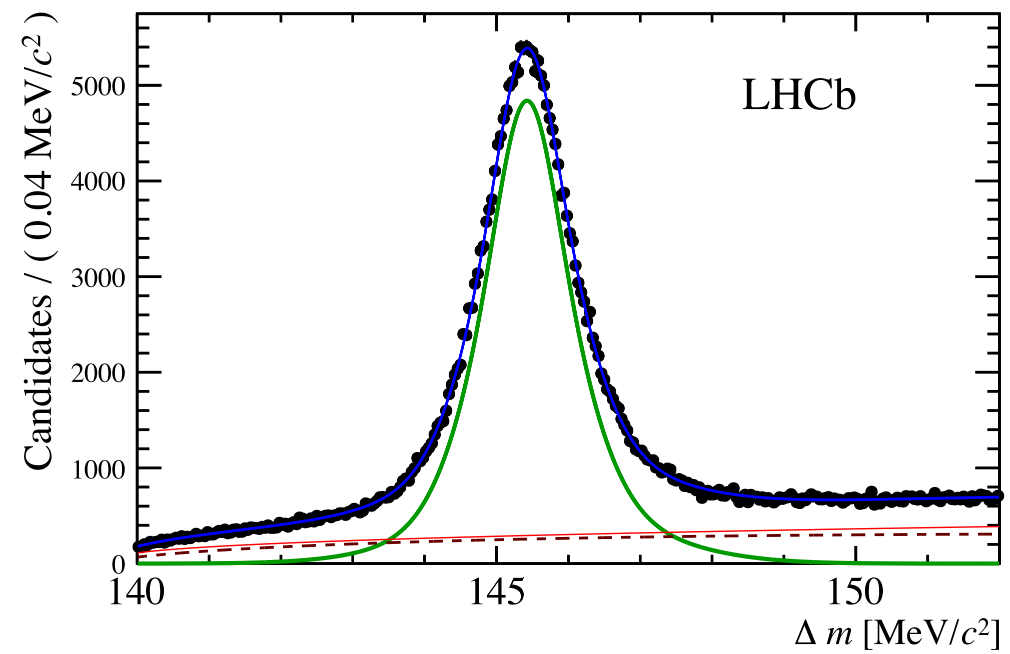
PRL 112 (2014) 041801

1

$m(D^0)$

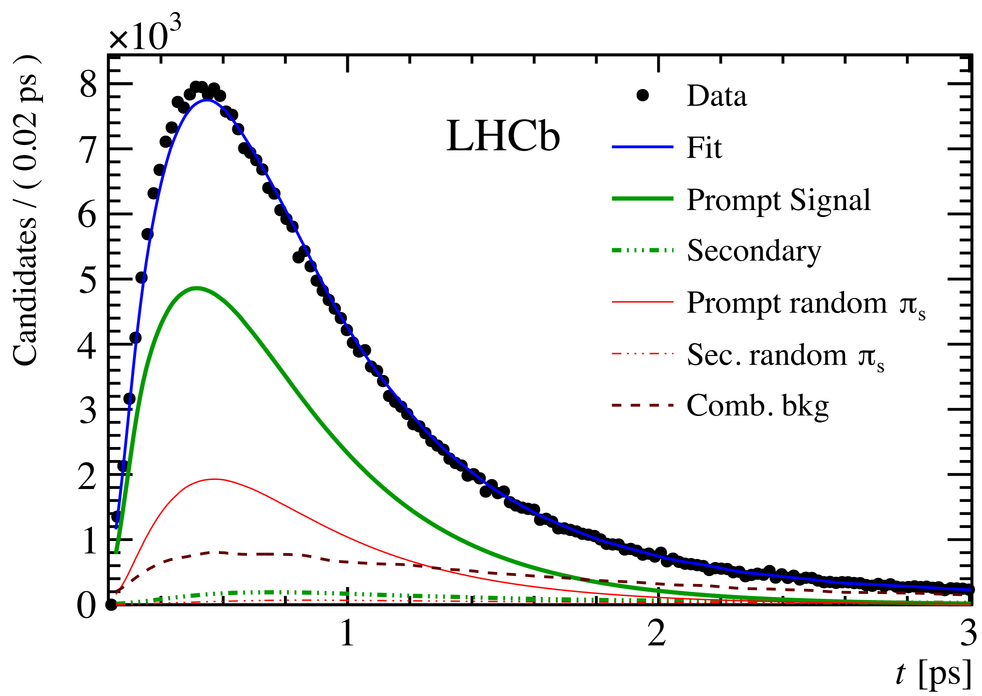


Δm

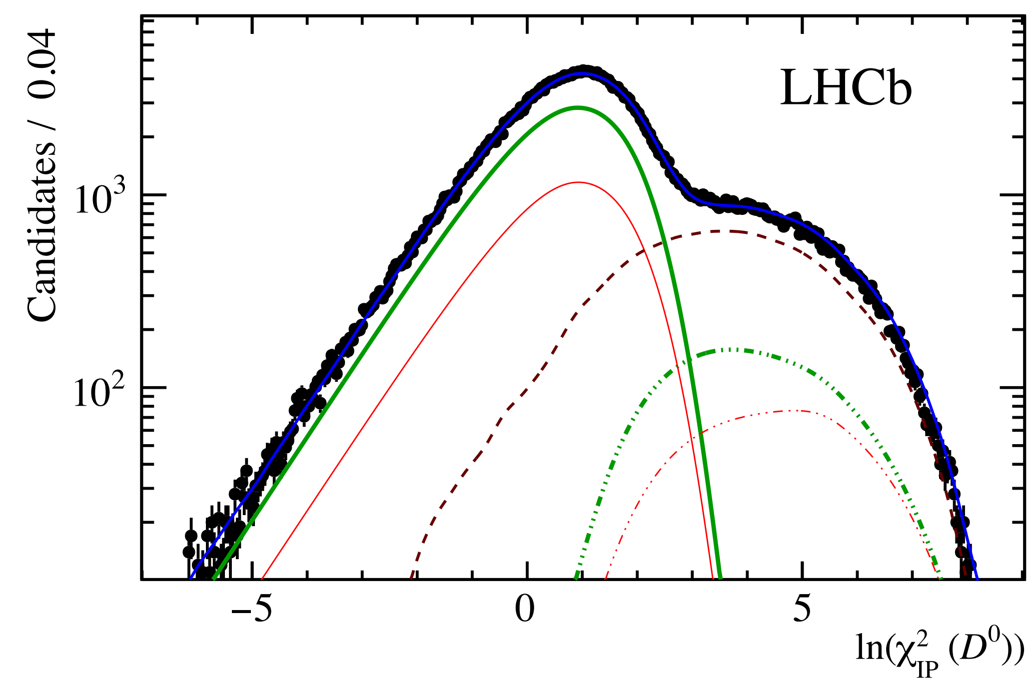


2

D^0 decay time



$\ln(IP\chi^2_{D^0})$

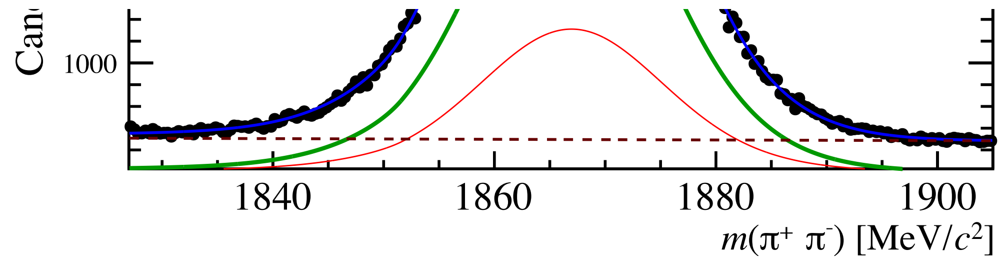


Example of the two-staged fit using $D^0 \to \pi\pi$ decays

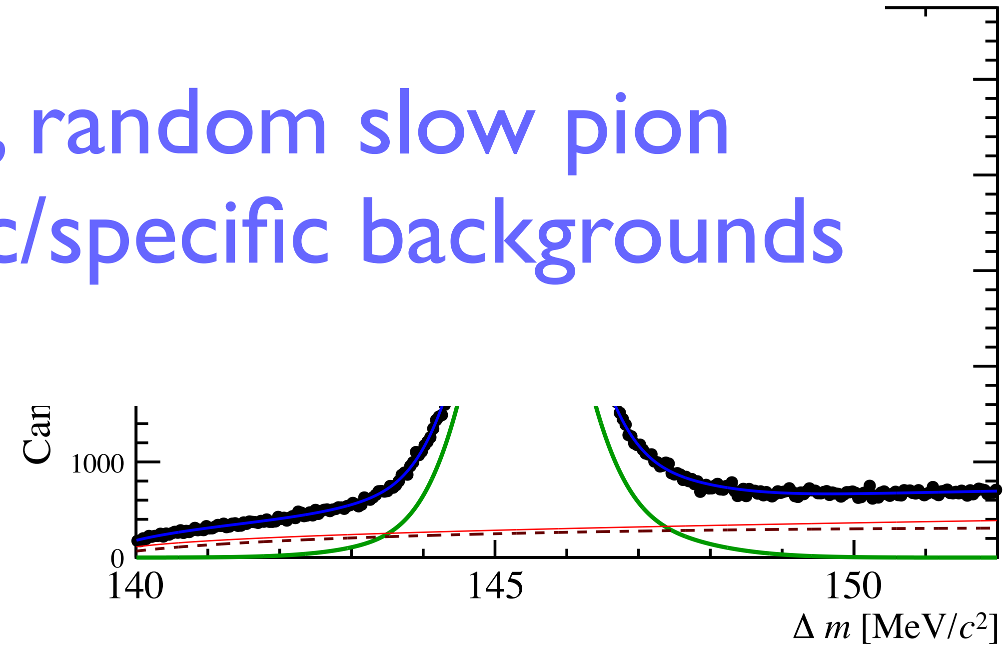
PRL 112 (2014) 041801

1 Separation between signal, random slow pion background and combinatoric/specific backgrounds

m(D^0)

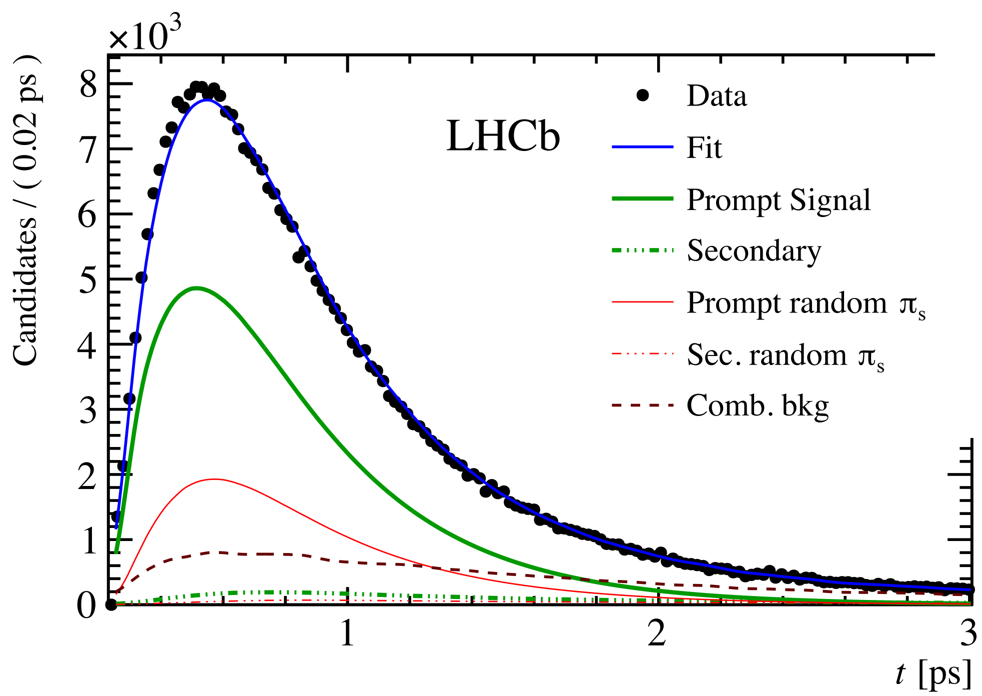


Δm

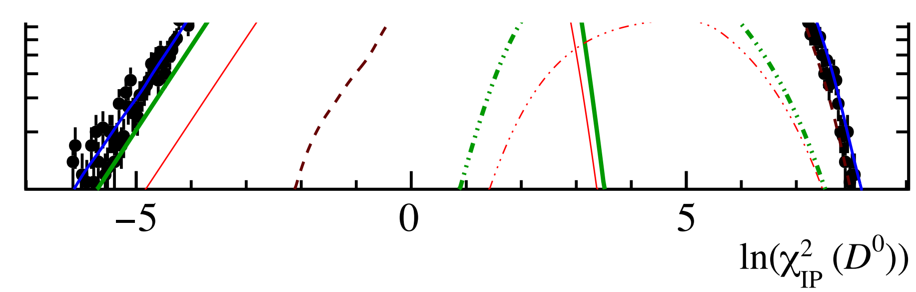


2 Separation between prompt and secondary decays

D^0 decay time



ln(IP$\chi^2_{D^0}$)



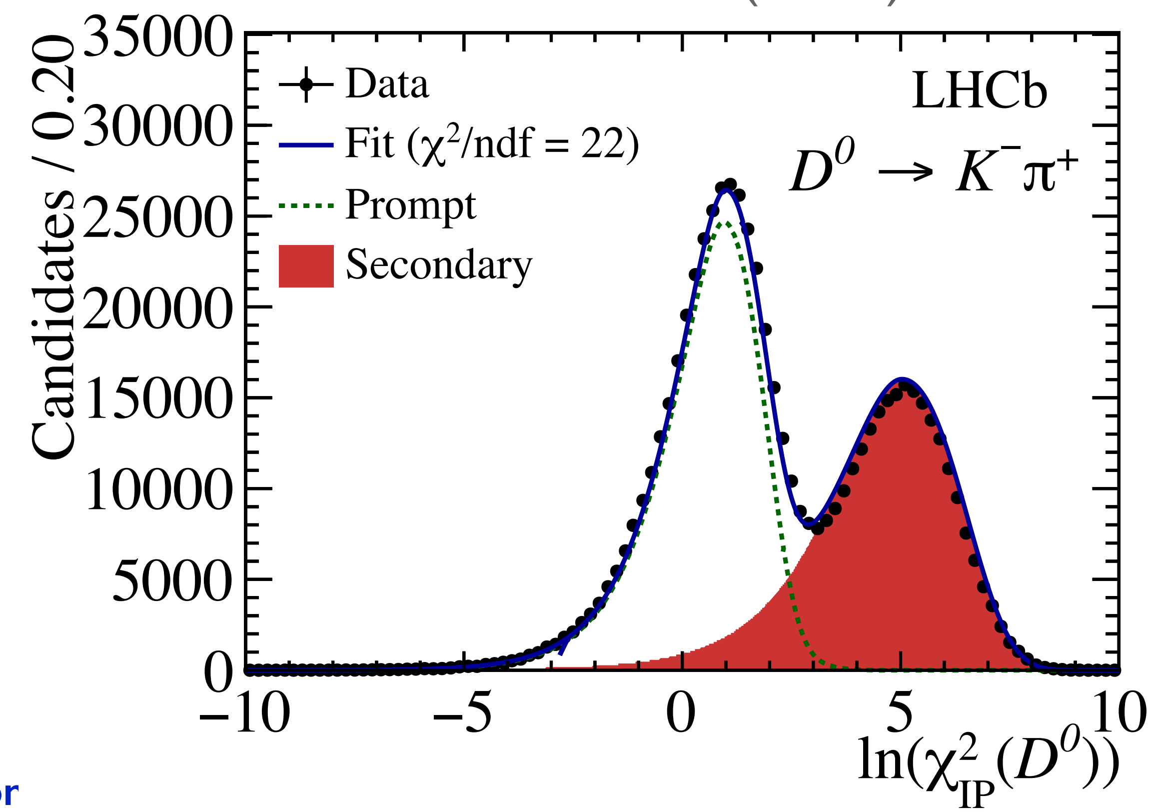
Indirect CP violation in $D^0 \rightarrow h^+h^-$ (3 fb^{-1})(binned)

- Analyse 2011+2012 data, blind analysis
- Flavour tagged using the sign of the pion in the strong decay $D^{*+} \rightarrow D^0\pi$
- Split data in bins of D^0 decay time; extract yield by fitting Δm (= $m(D^{*+})$ - $m(D^0)$)
- Correct for detector non-uniformities and presence of secondary decays

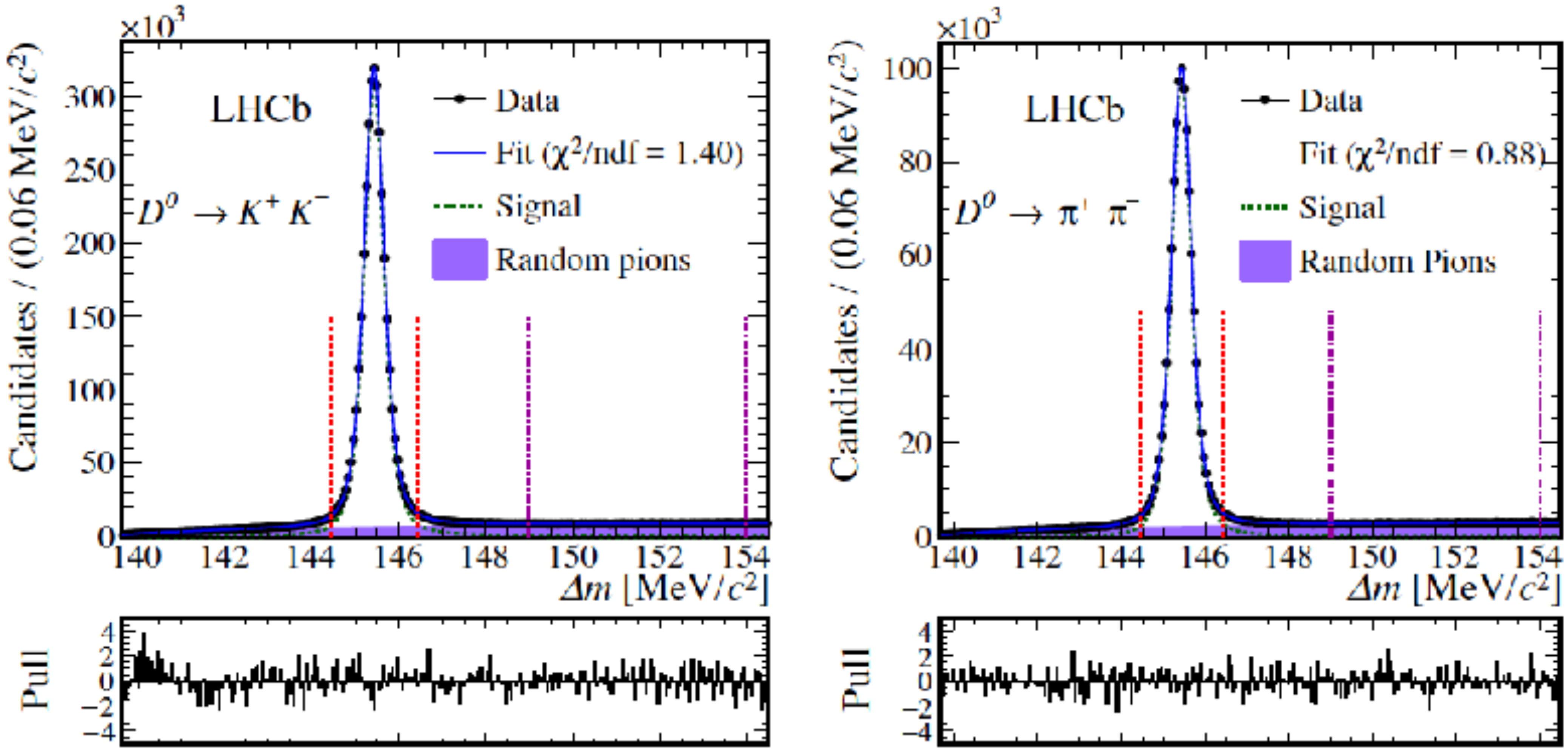
PRL 112 (2014) 041801

Assuming only indirect contribution assumed to be universal, the average

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$



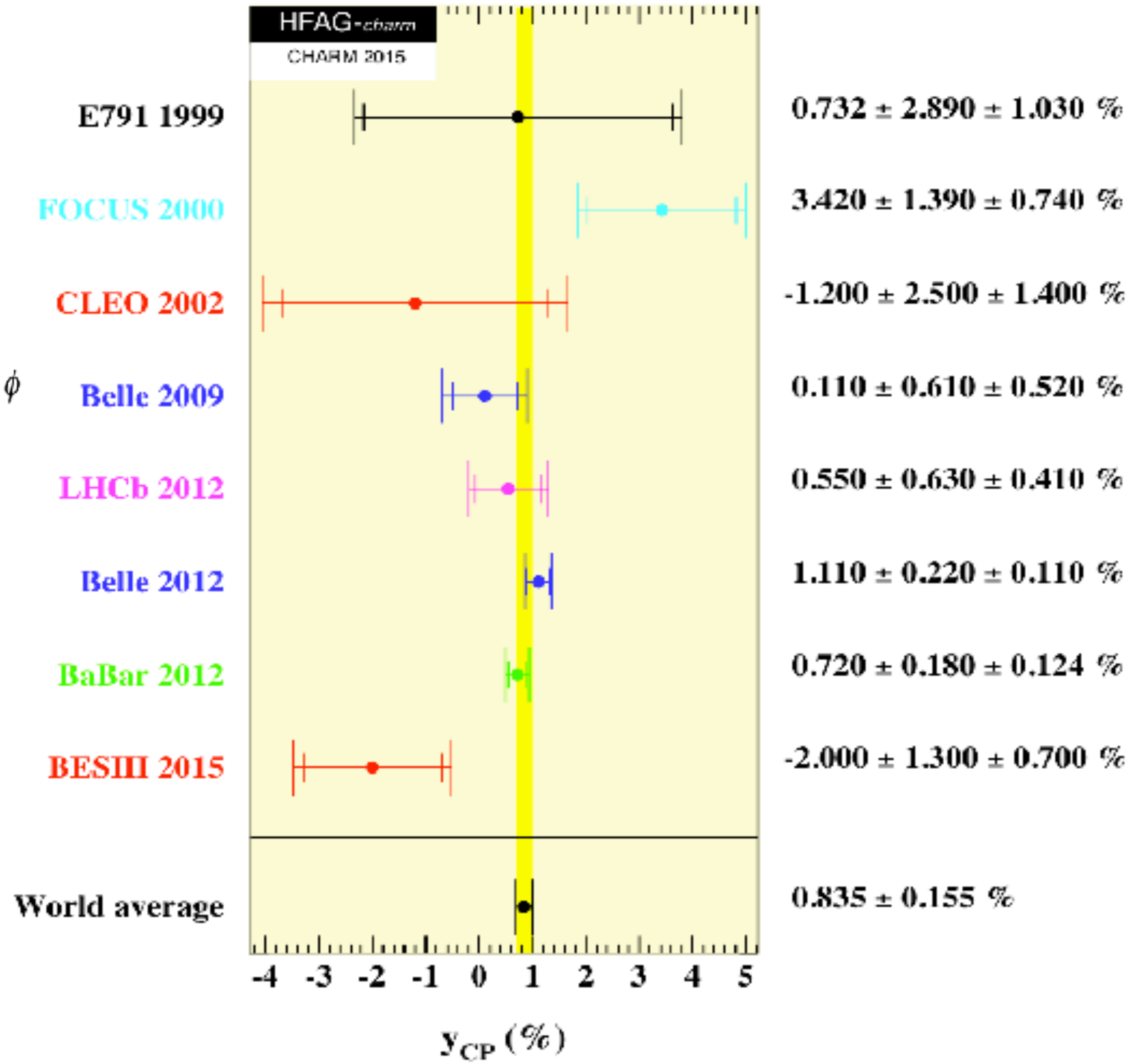
A_Γ measurement



y_{CP}

- Mixing parameter, if no CPV
  $y_{CP}=y$

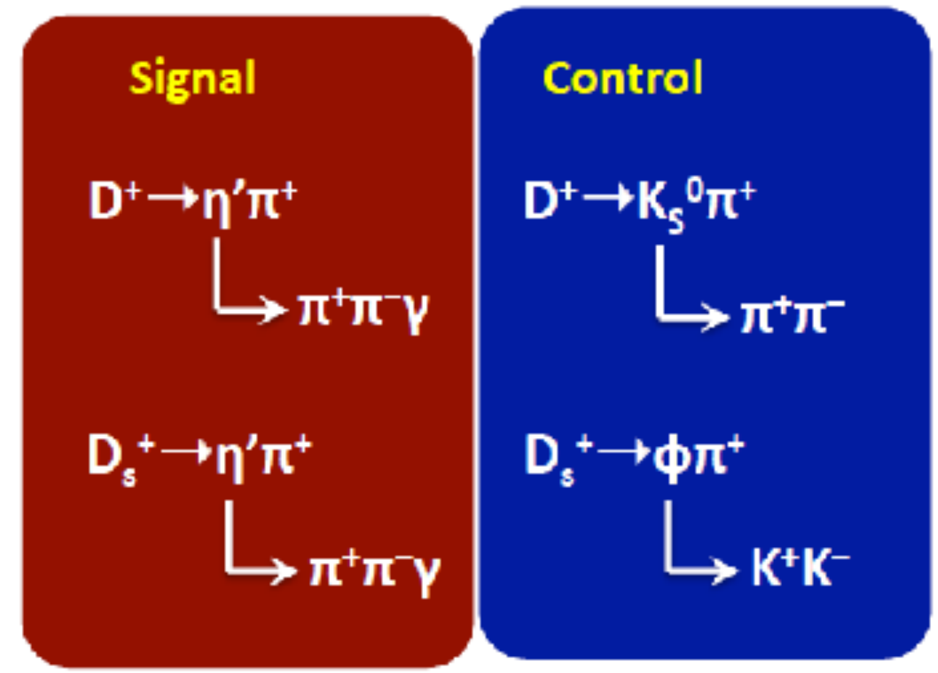
$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^-h^+)} - 1 \cong y\cos\phi + \frac{1}{8}A_m^2\, y\cos\phi - \frac{1}{2}A_m\, x\sin\phi$$



Category	**Systematic uncertainty[%]**
Determination of raw asymmetries:	
Fit model	0.025
Peaking background	0.015
Cancellation of nuisance asymmetries:	
Additional fiducial cuts	0.040
Weighting configuration	0.062
Weighting simulation	0.054
Secondary charm meson	0.039
Neutral kaon asymmetry	0.014
Total	0.10

Phys. Lett. B 767 177-187

Direct CPV search in $D^+_{(s)} \to \eta' \pi^+$



- No CPV yet observed in any charm decays
- Can strongly depend on final state
- ⇒ investigate more channels

- CP asymmetries in decays to η' poorly constrained – not yet measured at hadron collider.
- Small (<0.1%) in SM
- Usual strategy: Subtract detector asymmetries using control channels
- Main challenge: Background modelling.Main physics BG from $D(s)^+ \to \pi^+ (\varphi \to \pi^+\pi^-\pi^0)$

Direct CPV search in $D^+_{(s)} \to \eta'\pi^+$: Method

$$A_{CP}(D^+ \to \eta'\pi^+) \equiv A_{raw}(D^+ \to \eta'\pi^+) - A_{raw}(D^+ \to K_S\pi^+) + A_{CP}(D^+ \to K^0_S\pi^+) + A_{mix}(K^0_S)$$

$$A_{CP}(D^+_s \to \eta'\pi^+) \equiv A_{raw}(D^+_s \to \eta'\pi^+) - A_{raw}(D^+_s \to \phi\pi^+) + A_{CP}(D^+_s \to \phi\pi^+)$$

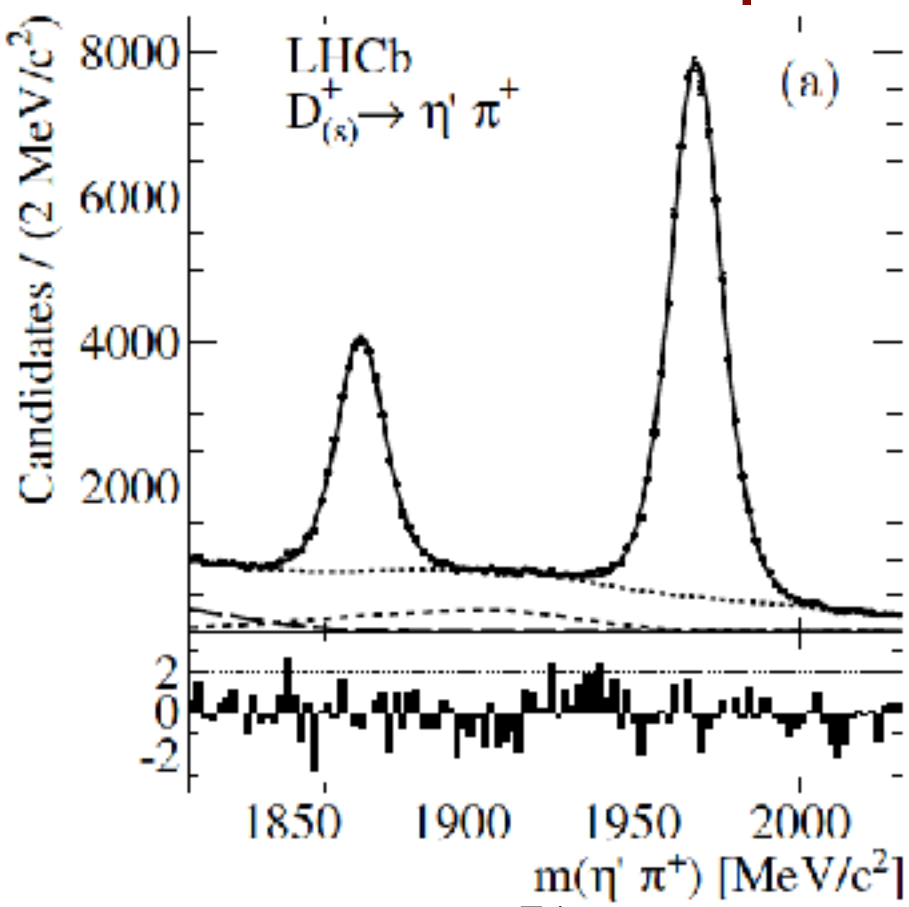
Fit m(η'π±) to extract raw asymmetry

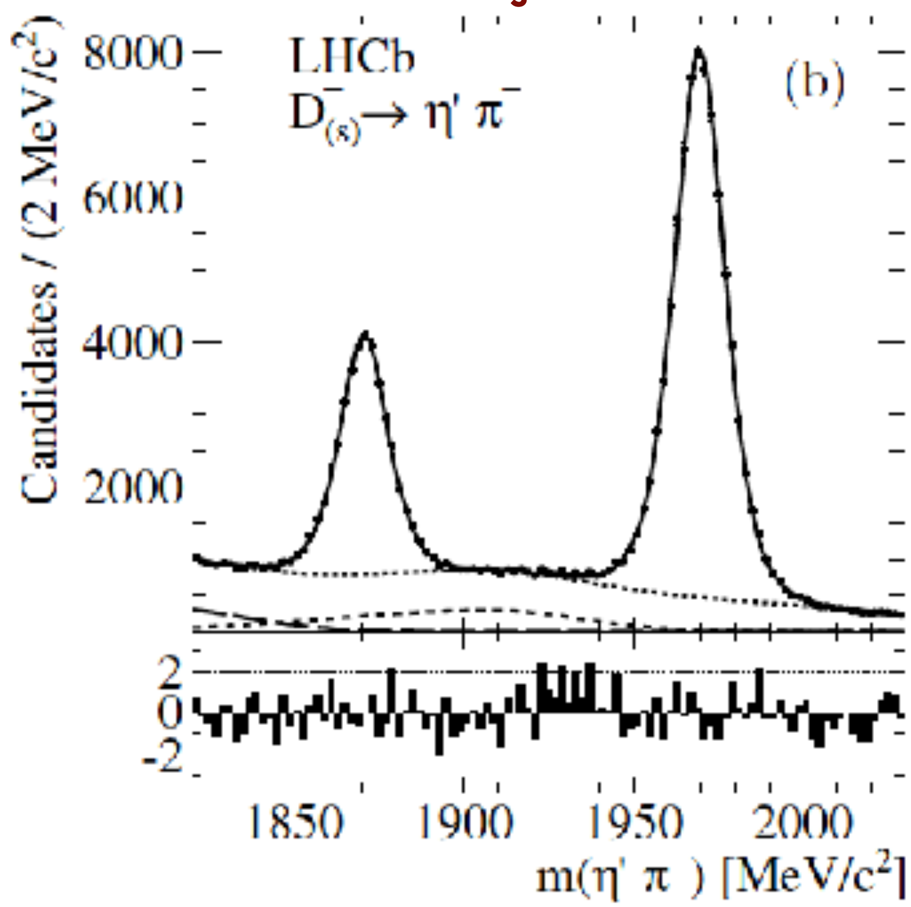
Control channel asymmetry

External input (D0, Belle)

arXiv:1701.01871 submitted to PLB

Data sample: 63k $D^\pm$ and 152k $D^\pm_s$





Separate by magnet polarity and collision energy.

Bin in η(π), $p_T(\pi)$ to improve cancellation of detector asymmetries

Direct CPV search in $D^+_{(s)} \to \eta'\pi^+$

- Main challenge: Background modelling. Main physics BG from $D(s)^+ \to \pi^+(\varphi \to \pi^+\pi^-\pi^0)$
- Also gives largest systematic uncertainty
- Statistically limited
- Additional uncertainty from external A_{CP}(control) inputs

Bin in $\eta(\pi)$, $p_T(\pi)$ to improve cancellation of detector asymmetries

arXiv:1701.01871 submitted to PLB

Source	$\delta[\Delta\mathcal{A}_{CP}(D^\pm)]$	$\delta[\Delta\mathcal{A}_{CP}(D_s^\pm)]$
Non-prompt charm	0.03	0.03
Trigger	0.09	0.09
Background model	0.50	0.19
Fit procedure	0.16	0.09
Sideband subtraction	0.03	0.02
K^0 asymmetry	0.08	–
$D^\pm_{(s)}$ production asymmetry	0.07	0.02
Total	0.55	0.24

$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\,\%$$
$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\,\%$$

Consistent with CP conservation

Most precise measurements to date of these variables

Multi-body decays and local asymmetries

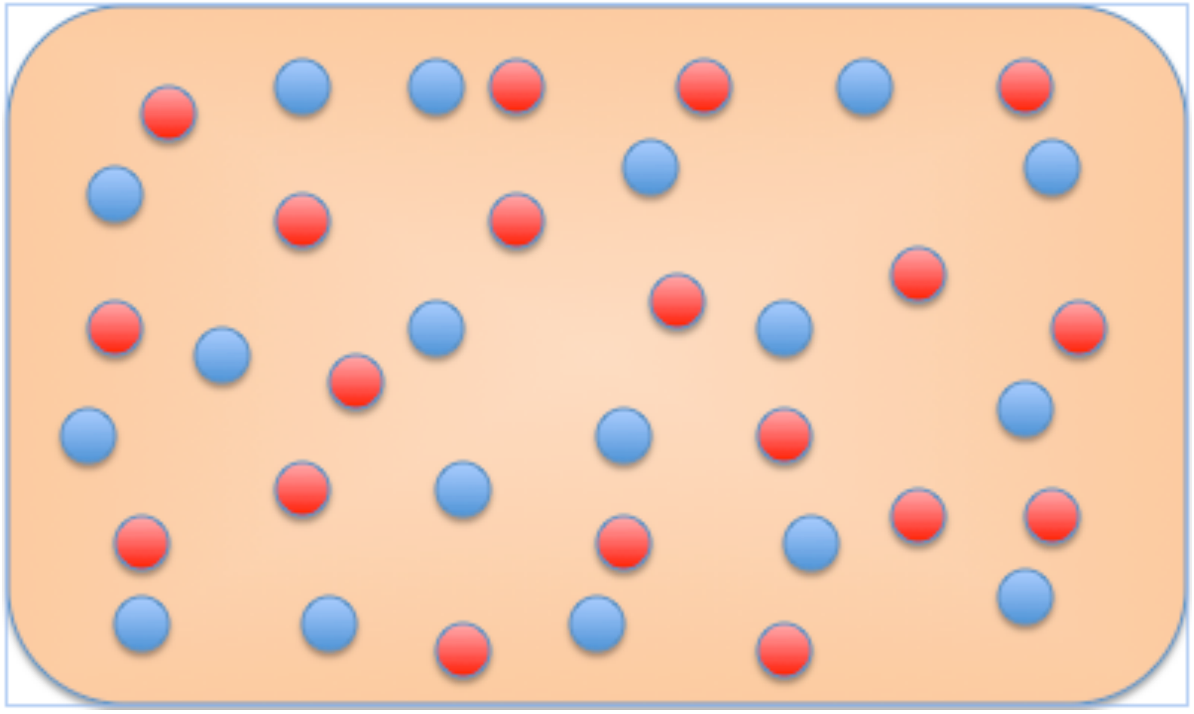
- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases: Superb playground for CP violation

Local asymmetries

- potentially larger than the phase space integrated ones
- may change sign across the phase space
- additional information about the dynamics

Energy test

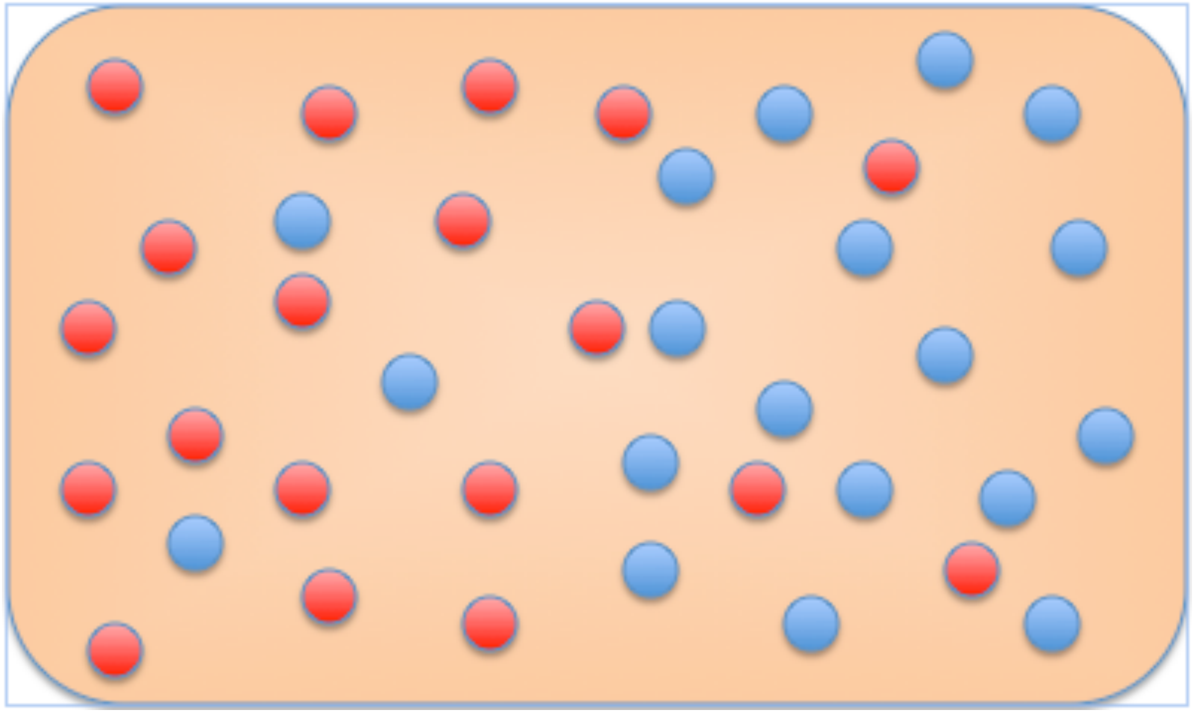
- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy



+q and −q equally distributed,
electric potential energy = 0

Energy test

- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy



+q and −q equally distributed,
electric potential energy = 0

+q and −q distributions different,
electric potential energy > 0

Energy test

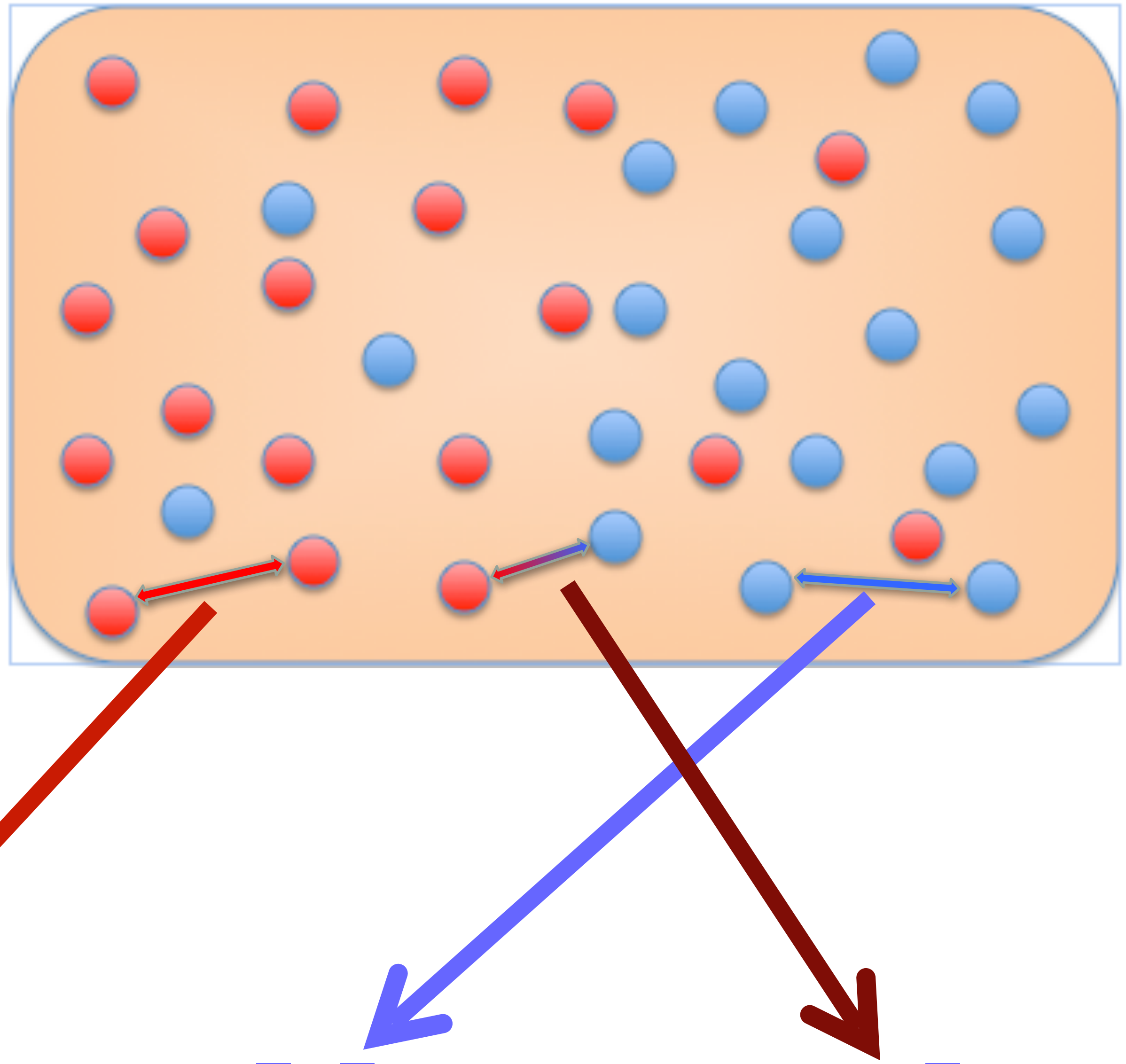
System → phase space
+q /−q → opposite flavoured decays

$\psi(d_{ij}) = e^{-d_{ij}/2\delta^2}$: interaction potential

$n, \bar{n}$: number of $D^0, \bar{D}^0$ candidates

d_{ij} : distance in phase space

δ - tunable parameter:
effectively, radius in the phase space in which a local asymmetry is measured



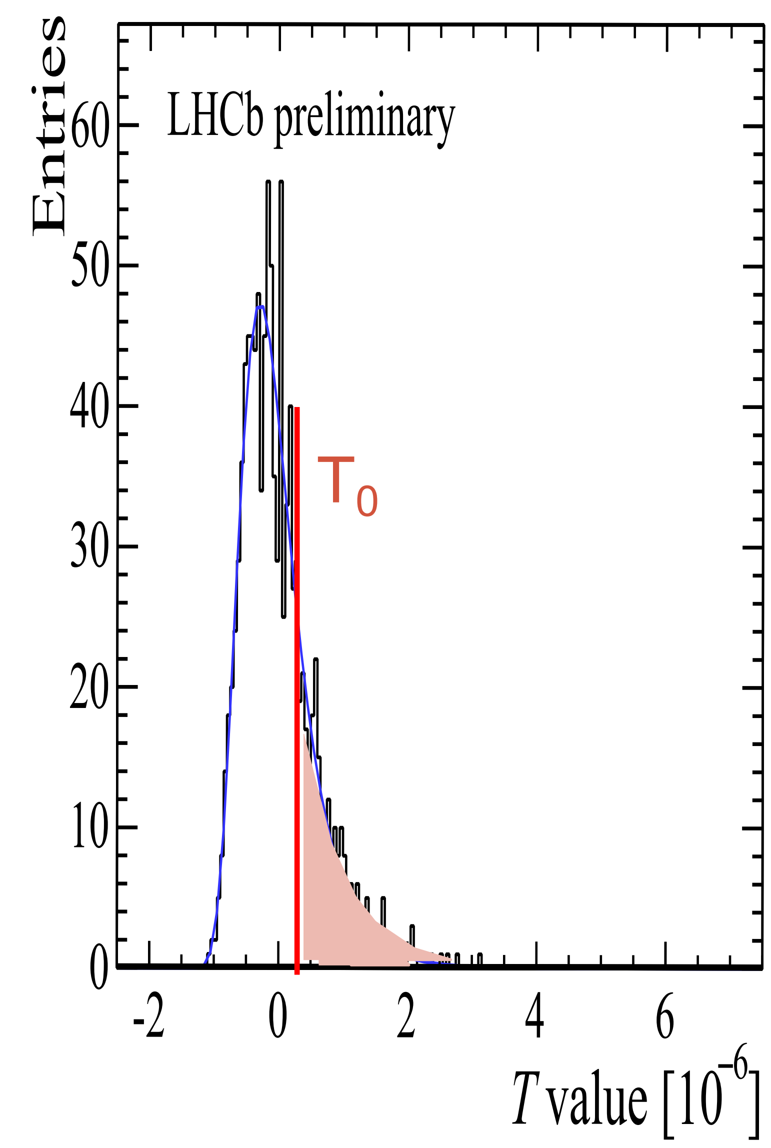
D^0-D^0 $\bar{D}^0$-$\bar{D}^0$ D^0-$\bar{D}^0$

Test statistic: $$T = \frac{1}{n(n-1)}\sum_{i,j>i}^{n}\psi(d_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)}\sum_{i,j>i}^{\bar{n}}\psi(d_{ij}) - \frac{1}{n\bar{n}}\sum_{i,j}^{n,\bar{n}}\psi(d_{ij})$$

Energy test p-value

- Calculate p-value for no CPV hypothesis
- Compare T-value from tested sample (T_0) with T-values from no-*CPV* samples
- No-*CPV* sample from permutation of data: randomly assign flavour tags
- p-value: fraction of permutation T-values above T_0

Phys. Lett. B 769 345-356



Large *p*-value, no-*CPV*

New *P*-odd observables

- In decays to four or more pseudo-scalars, there is the possibility of using *P*-parity-odd observables for *CP* violation searches
- Four-body-decay kinematics cannot be described unambiguously using only invariant-mass-squared variables, as these are all parity even
- Introduce triple product C_T as parity sensitive variable

$$C_T = \vec{p}(\pi_3) \cdot [\vec{p}(\pi_1) \times \vec{p}(\pi_2)]$$

- Analyse different flavours and signs of C_T regions

Detection / tracking / production asymmetries

- Cancellations occur due to method
- Verified with a control sample of Cabibbo-favoured $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decays
  - Split into ten sub-samples equal in size to signal mode
  - Sensitive with neither *P*-even nor *P*-odd tests
- *p*-value distributions for reference sample

Sensitivity tests with Monte Carlo

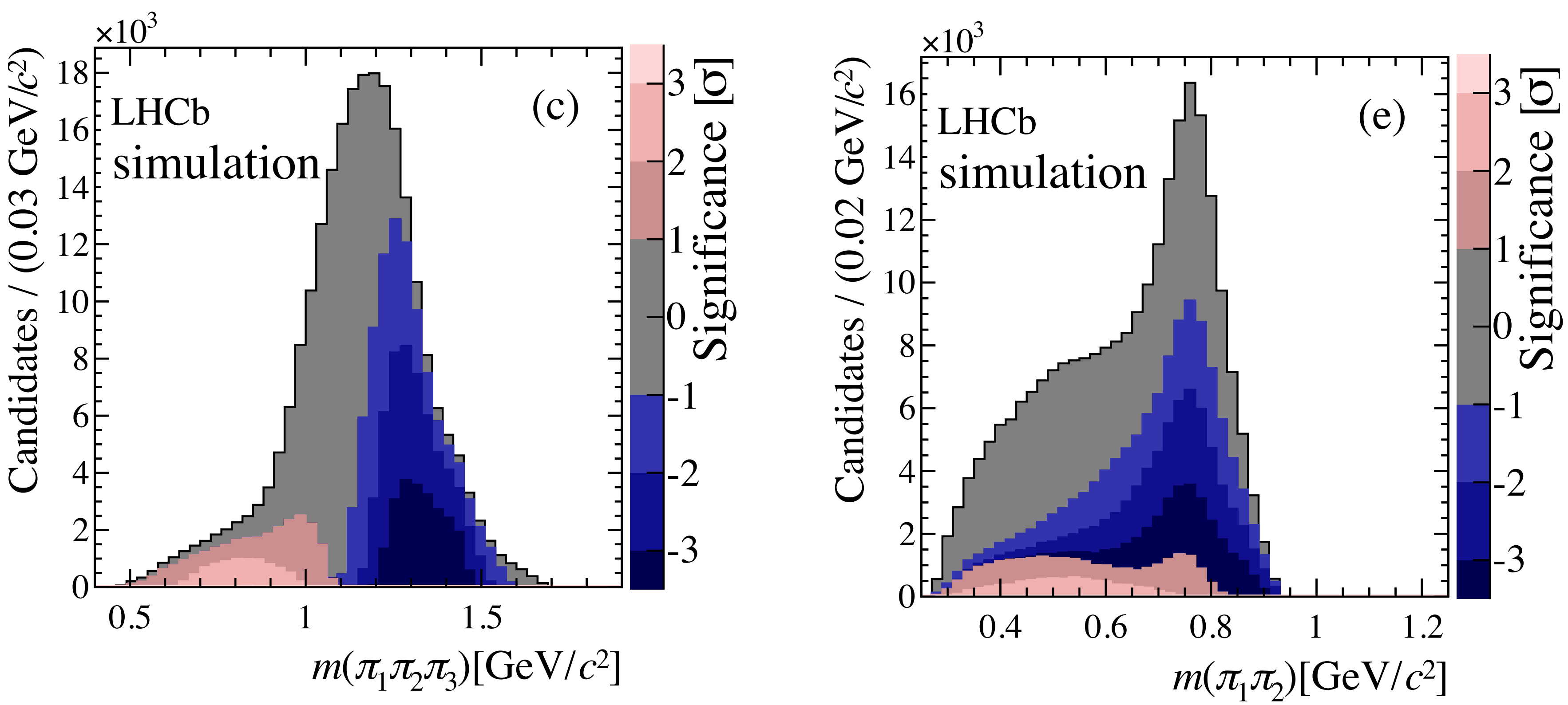
- Performed for both *P*-even and *P*-odd tests
- Insert *CP* violation to simulated samples*, apply energy test, determine the sensitivity
- Visualise significance of asymmetries by assigning per-event T-values
- Highlight those >1,2,3σ positive in pink, negative in blue

Phys. Lett. B 769 345-356

R (partial wave) (ΔA, $\Delta\phi$)	p-value (fit)
$a_1 \to \rho^0\pi$ (S) $(5\%, 0°)$	$2.6^{+3.4}_{-1.7} \times 10^{-4}$
$a_1 \to \rho^0\pi$ (S) $(0\%, 3°)$	$1.2^{+3.6}_{-1.2} \times 10^{-6}$
ρ^0 ρ^0 (D) $(5\%, 0°)$	$3.8^{+2.9}_{-1.9} \times 10^{-3}$
ρ^0 ρ^0 (D) $(0\%, 4°)$	$9.6^{+24}_{-7.2} \times 10^{-6}$
ρ^0 ρ^0 (P) $(4\%, 0°)$	$3.0^{+1.2}_{-0.9} \times 10^{-3}$
ρ^0 ρ^0 (P) $(0\%, 3°)$	$9.8^{+4.4}_{-3.8} \times 10^{-4}$

P-even

P-odd



Example:
3° phase difference in $D^0 \to a_1(1260)^+\pi^-$ Amplitude
(*P*-even test)

*Amplitude model taken from P. d'Argent, N. Skidmore … E.Gersabeck et al. arXiv:1703.08505

D→KKππ amplitude model and CPV search

Decay channel	F_i (%)
$D^0 \to K^- [K_1(1270)^+ \to \pi^+ K^*(892)^0]$	$5.5 \pm 1.4 \pm 2.7 \pm 2.0$
$D^0 \to K^- [K_1(1270)^+ \to \pi^+ K^*(1430)^0]$	$6.1 \pm 1.2 \pm 1.3 \pm 1.3$
$D^0 \to K^- [K_1(1270)^+ \to K^+ \rho(770)^0]$	$9.1 \pm 1.5 \pm 1.9 \pm 0.1$
$D^0 \to K^+ [\bar{K}_1(1270)^- \to K^- \rho(770)^0]$	$5.4 \pm 0.7 \pm 1.1 \pm 0.7$
$D^0 \to K^- [K_1(1270)^+ \to K^+ \omega(782)]$	$0.6 \pm 0.3 \pm 0.4 \pm 0.2$
$D^0 \to K^- [K_1(1400)^+ \to \pi^+ K^*(892)^0]$	$12.4 \pm 2.6 \pm 3.9 \pm 5.0$
$D^0 \to K^- [K^*(1680)^+ \to \pi^+ K^*(892)^0]$	$3.6 \pm 0.8 \pm 1.0 \pm 0.3$
$D^0[S] \to K^*(892)^0 \bar{K}^*(892)^0$	$4.5 \pm 0.8 \pm 1.1 \pm 1.7$
$D^0[P] \to K^*(892)^0 \bar{K}^*(892)^0$	$3.6 \pm 0.7 \pm 1.4 \pm 0.5$
$D^0[D] \to K^*(892)^0 \bar{K}^*(892)^0$	$4.0 \pm 0.6 \pm 0.7 \pm 0.2$
$D^0[S] \to \phi(1020) \rho(770)^0$	$28.1 \pm 1.3 \pm 1.7 \pm 0.3$
$D^0[P] \to \phi(1020) \rho(770)^0$	$1.6 \pm 0.3 \pm 0.6 \pm 0.3$
$D^0[D] \to \phi(1020) \rho(770)^0$	$1.7 \pm 0.4 \pm 0.4 \pm 0.2$
$D^0 \to K^*(892)^0 (K^-\pi^+)_S$	$5.8 \pm 1.2 \pm 2.1 \pm 0.0$
$D^0 \to \phi(1020) (\pi^+\pi^-)_S$	$4.0 \pm 0.6 \pm 1.3 \pm 1.7$
$D^0 \to (K^+K^-)_S (\pi^+\pi^-)_S$	$11.1 \pm 1.2 \pm 2.1 \pm 0.7$
Sum	$106.9 \pm 4.5 \pm 6.9 \pm 6.1$

Decay channel	A^i_{CP} (%)	Significance (σ)
$D^0 \to K^- K_1(1270)^+$	$+25.3 \pm 9.7 \pm 9.2 \pm 8.8$	1.6
$D^0 \to K^+ \bar{K}_1(1270)^-$	$50.4 \pm 12.0 \pm 15.9 \pm 2.4$	2.5
$D^0 \to K^- K_1(1400)^+$	$+9.2 \pm 15.1 \pm 20.3 \pm 1.1$	0.4
$D^0 \to K^- K^*(1680)^+$	$17.1 \pm 21.8 \pm 18.0 \pm 4.2$	0.6
$D^0 \to K^*(892)^0 \bar{K}^*(892)^0$	$-4.6 \pm 9.0 \pm 9.8 \pm 5.7$	0.3
$D^0 \to \phi(1020) \rho(770)^0$	$+1.5 \pm 4.6 \pm 8.0 \pm 0.5$	0.1
$D^0 \to K^*(892)^0 (K^-\pi^+)_S$	$-13.1 \pm 17.9 \pm 29.7 \pm 9.4$	0.4
$D^0 \to \phi(1020) (\pi^+\pi^-)_S$	$-4.0 \pm 18.0 \pm 44.6 \pm 1.2$	0.1
$D^0 \to (K^+K^-)_S (\pi^+\pi^-)_S$	$+8.2 \pm 10.9 \pm 16.9 \pm 2.7$	0.4

P. d'Argent,... EG et al. arXiv:1703.08505
accepted for publication by JHEP

$$F_+ = \frac{N_{CP+}}{N_{CP+}+N_{CP-}} = \frac{1}{2}\left(1 + \frac{1}{N}\int |A_D|\,|A_{\overline{D}}|\,cos(\delta_D)\,\mathrm{d}\phi_4\right)$$

- $F_+^{4\pi}$(flavour-tagged, model-dependent) = $(72.9 \pm 0.9 \pm 1.5 \pm 1.0)\%$
- $F_+^{4\pi}$(CP-tagged, model-independent) = $(73.7 \pm 2.8)\%$ [Malde et al., PLB 747 (2015) 9]
- $F_+^{KK\pi\pi}$(flavour-tagged, model-dependent) = $(75.3 \pm 1.8 \pm 3.3 \pm 3.5)\%$

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LHCb

but before that

Prospects
Run11 and beyond

Improved trigger strategies for Run II

- Turbo stream of the trigger:
  - Data are ready for analysis directly after the trigger
  - Smaller size of raw events: reduce pre-scaling
- More efficient exclusive charm triggers
  - Split high level trigger in 2 stages: gain CPU power
  - Events from lower trigger levels can be buffered on disk while performing real-time alignment and calibration
  - Improved speed of the algorithms

Run 2 cross-sections & estimated integrated luminosity

- More data!!! Higher cross-sections in LHCb acceptance x2 @ 13TeV

JHEP03(2016)159; JHEP09(2016)013; JHEP05(2017)074

$$\sigma(pp \to c\bar{c}X)_{p_T < 8\ \mathrm{GeV}/c,\, 2.0 < y < 4.5} = 2369 \pm 3 \pm 152 \pm 118\,\mu\mathrm{b}$$

compare to Run 1 @ 7TeV

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

2010 data
Nucl.Phys. B871 (2013) 1-20

Run1	Run2	Run3	Run4	Run5
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

Δa_{CP}: uncertainty 10^{-4} at 50 fb^{-1}

upgrade; gain more data by removing the L0 thresholds