# Charm Production, Mixing and CP Violation

**Tadeusz Lesiak**

**Institute of Nuclear Physics**
**Polish Academy of Sciences, Kraków**

**On behalf of the LHCb Collaboration**

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# Outline

1. LHCb detector & Charm Physics.

2. Observation of Charm Oscillations.

3. Searches for CP Violation in Charm Sector:

- ✓ $\Delta A_{CP}$ from $D^*$ Decays,
- ✓ $\Delta A_{CP}$ from B Semileptonic Decays,
- ✓ $A_\Gamma$ Measurement.

3a. CPV in $D^0 \to h^+h^-$ Decays:

3b. CPV in $D^+ \to \phi\pi^+$ and $D^+_s \to K^0_S\pi^+$ Decays,

3c. CPV in $D^0 \to 4h$ and $D^+ \to \pi^-\pi^+\pi^+$ Decays.

4. Charm Spectroscopy:

4a. Spin-Parity of the X(3872),

4b. Excited Mesons $D_J$ and $D_{sJ}$,

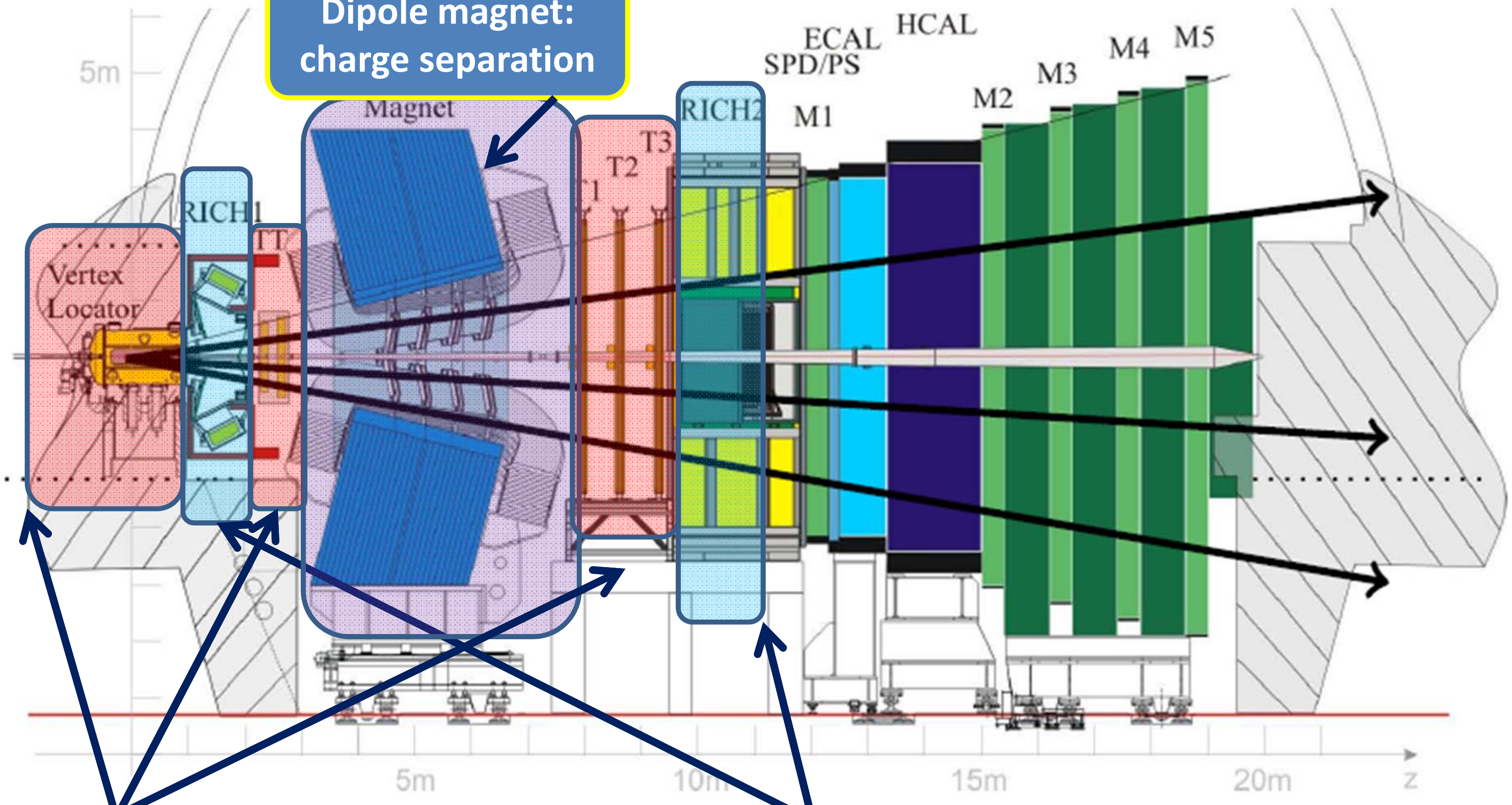
4c. Search for the $\Xi_{cc}^+$ baryon.

Most results are based on 1 $fb^{-1}$ data sample collected in 2011.

# LHCb Detector

**LHCb is a forward arm spectrometer with a unique pseudorapidity range $2 < \eta < 5$**

Dipole magnet: charge separation




Excellent vertexing, tracking, time and momentum resolution

Two RICH detectors crucial for K/π separation

# Charm Physics at LHCb

**LHCb is designed for b physics BUT…**

**it offers very favourable conditions for charm as well !**

$$\sigma_{c\bar{c}} = (1419 \pm 133)\ \mu b \qquad (1)$$

$$\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu b \qquad (2)$$

$$\frac{\sigma_{c\bar{c}}}{\sigma_{b\bar{b}}} \approx 20$$

**~350M** reconstructed charm decays in 2011 data (1fb$^{-1}$, s$^{1/2}$ = 7 TeV).

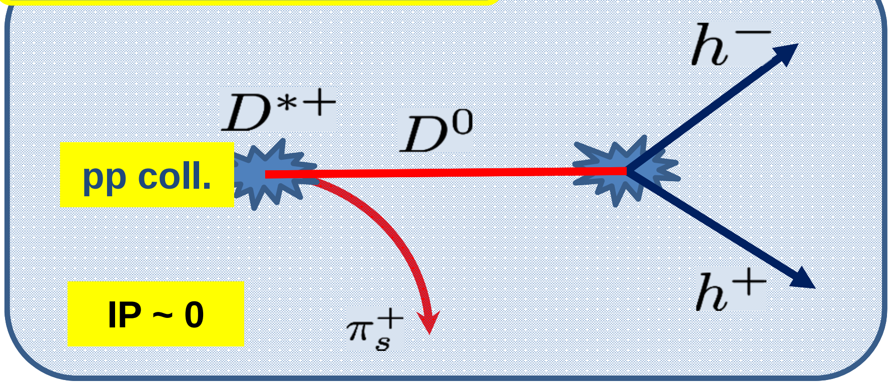
(1) Nucl. Phys. B 871 (2013), 1

(2) Phys. Lett. B 694 (2010), 209

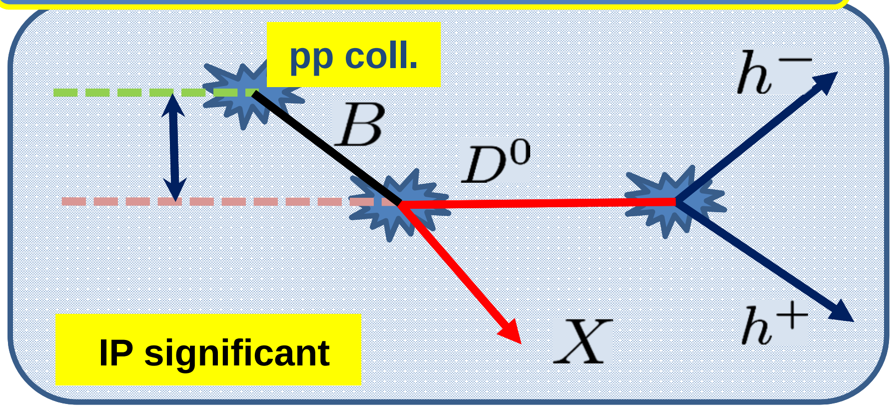
**Dedicated charm trigger !**

**Two mechanisms of charm production:**

**1) DIRECT (prompt):**




**2) SECONDARY (from b-hadron decays):**



# Mixing in the Charm Sector

The mass eigenstates $|D_1^0>, |D_2^0>$ do not coincide with the flavour eigenstates $|D^0>, |\overline{D}^0>$

$$|D_1>=p|D^0>+q|\overline{D}^0>$$ $$|D_2>=p|D^0>-q|\overline{D}^0>$$ $$|p|^2+|q|^2=1$$

A $D^0, (\overline{D}^0)$ meson, produced in a pure flavour eigenstate, then evolves as a superposition of its mass eigenstates of masses $m_1$ and $m_2$, and widths $\Gamma_1$ and $\Gamma_2$.

→ MIXING (CHARM OSCILLATIONS)

Two dimensionless parameters characterising the mixing phenomenon:

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

Charm mixing rate is predicted to be small: $|x|,\ |y| \le o(10^{-2})$

Large contributions from long-range processes and potential enhancements due to NP.

For charm the first evidence for mixing in 2007 (BaBar, Belle, CDF)

BUT… until 2013 no single 5σ observation.

# Observation of $D^0 - \bar{D}^0$ Mixing

**LHCb (1 $fb^{-1}$) :**

**Study of the decay** $D^{*+} \to D^0 \pi_s^+$ (+c.c.) .

Phys. Rev. Lett. 110 (2013), 101802

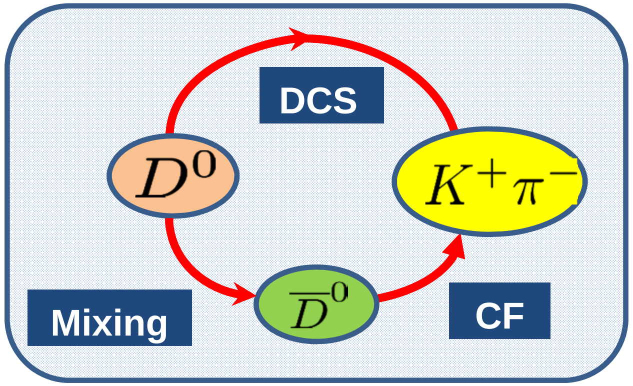
The charge of the soft pion $\pi_s$ determines the $D^0$ flavour at the production time.

**Right-sign:** $D^0 \to K^- \pi^+$

- dominated by Cabibbo Favoured (CF) amplitude.

**Wrong-sign** contributions from:

1) doubly-Cabibbo- suppressed (DCS) $D^0 \to K^+ \pi^-$ decay,
2) $D^0 \to \overline{D}^0$ mixing, followed by the CF decay.




$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)}$$

$$R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

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

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

**τ** – the average $D^0$ lifetime. **δ** – the strong phase difference between the DCS and CF amplitudes.

**Results:** $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$ $y' = (7.2 \pm 2.4) \times 10^{-3}$

**No mixing hypothesis excluded at 9.1σ**
**First >5σ observation by a single expt.**

**More details → the talk by Liang Sung about the search for CP violation in WS $D^0 \to K^+\pi^-$ decays (3 $fb^{-1}$ data sample)**

# Search for CPV in $D^0 \rightarrow h^+h^-$ Decays

**Charm** - the only up-type heavy quark;
small effects of CP violation; large hadronic uncertainties.

Two time-dependent CP asymmetries are studied:

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

The final states: $f = K^+K^-, \quad \pi^+\pi^-$

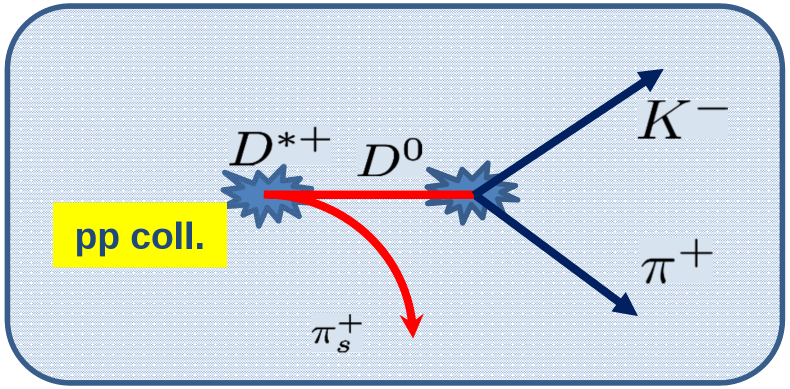
The flavour of the initial state is tagged by:

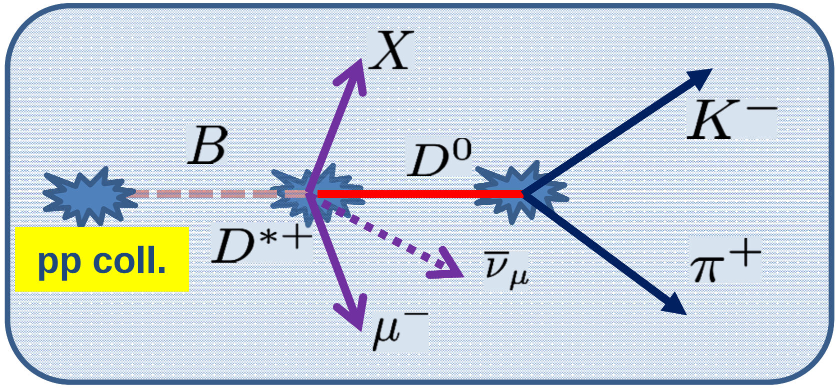
1) the charge of the soft pion from the $D^{*\pm}$

$D^{*+} \to D^0 \pi_s^+$ $\quad$ $D^{*-} \to \overline{D^0} \pi_s^-$

2) The charge of the muon from semileptonic decays of b-hadrons („B”)

$\overline{B} \to D^0 \mu^- X$ $\quad$ $B \to \overline{D^0} \mu^+ X$



# $\Delta A_{CP}$ from D* Decays

**Main variable: the difference between time-integrated asymmetries:**

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

**the raw asymmetry (π tag):**

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

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

Asymmetry in selecting the $D^0$ decay into the final state f:

$$A_D(K^+K^-) = 0$$

$$A_D(\pi^+\pi^-) = 0$$

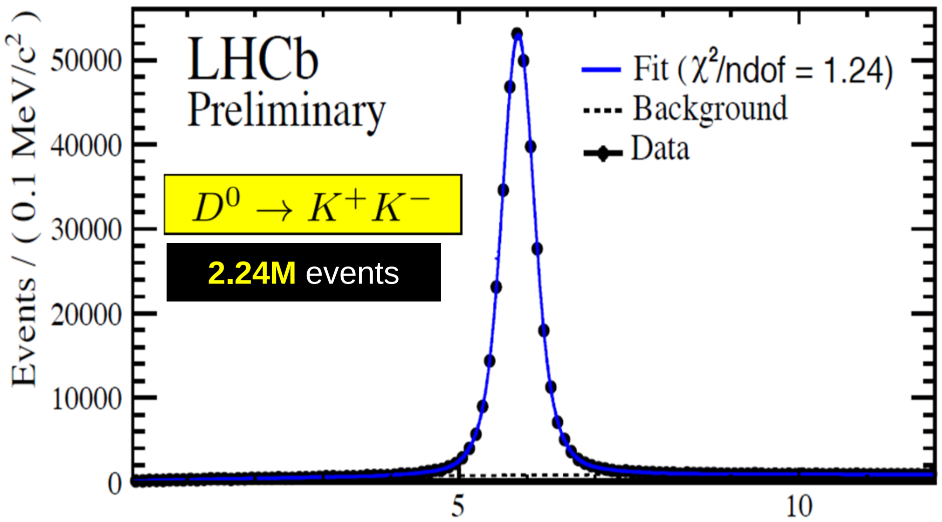
Asymmetry in selecting the $\pi_s$ from the D* decay chain

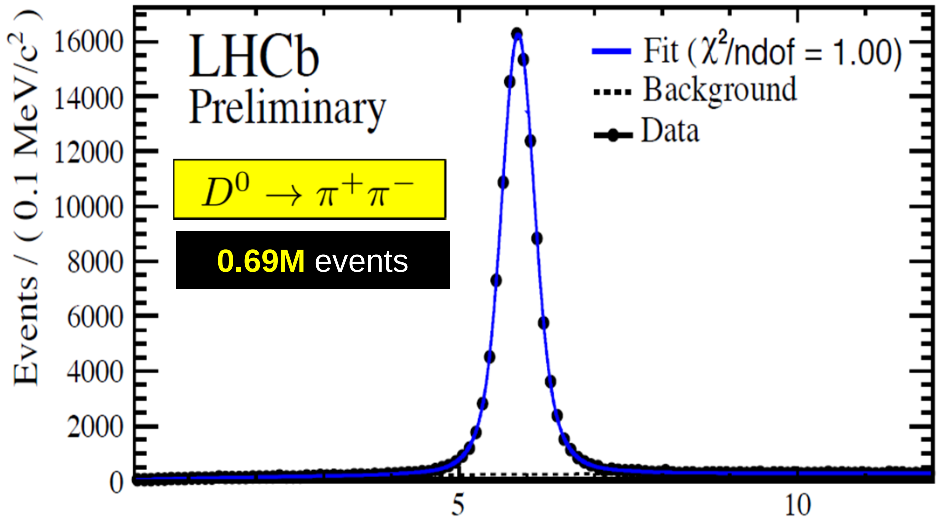
Asymmetry in the production for D* mesons

If kinematics of the $\pi_s$ and D* are the same for $D^0 \to KK$ and $D^0 \to \pi\pi$,
each of these two terms is identical for KK and ππ
➔ cancellation in the difference.

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

# $\Delta A_{CP}$ from $D^*$ Decays




$$\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) \quad [\mathrm{MeV}/c^2]$$

$$h = K, \pi$$

$$\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\ \%$$

LHCb-CONF-2013-003

# $\Delta A_{CP}$ from B Semileptonic Decays

**the raw asymmetry (muon tag):**

$$A_{raw}(f) = \frac{N(\overline{B}\to D^0(f)\mu^- X) - N(B\to \overline{D}^0(f)\mu^+ X)}{N(\overline{B}\to D^0(f)\mu^- X) + N(B\to \overline{D}^0(f)\mu^+ X)}$$

$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\mu) + A_P(B)$$

Asymmetry in selecting the $D^0$ decay into the final state f:

$A_D(K^+K^-) = 0$

$A_D(\pi^+\pi^-) = 0$

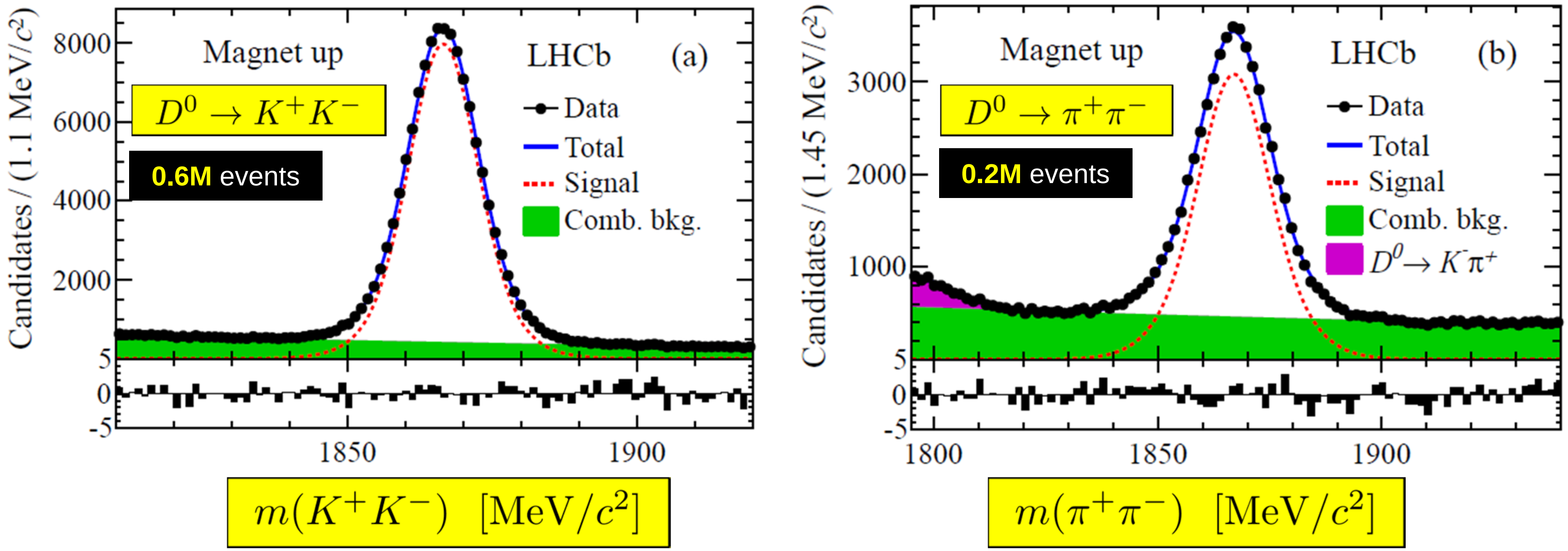
Asymmetry in the muon detection.

Asymmetry in b-hadron production

If kinematics of the muon and b-hadron are the same for $D^0 \to KK$ and $D^0 \to \pi\pi$,
each of these two terms is identical for KK and ππ
➔ cancellation in the difference.

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

# $\Delta A_{CP}$ from B Semileptonic Decays



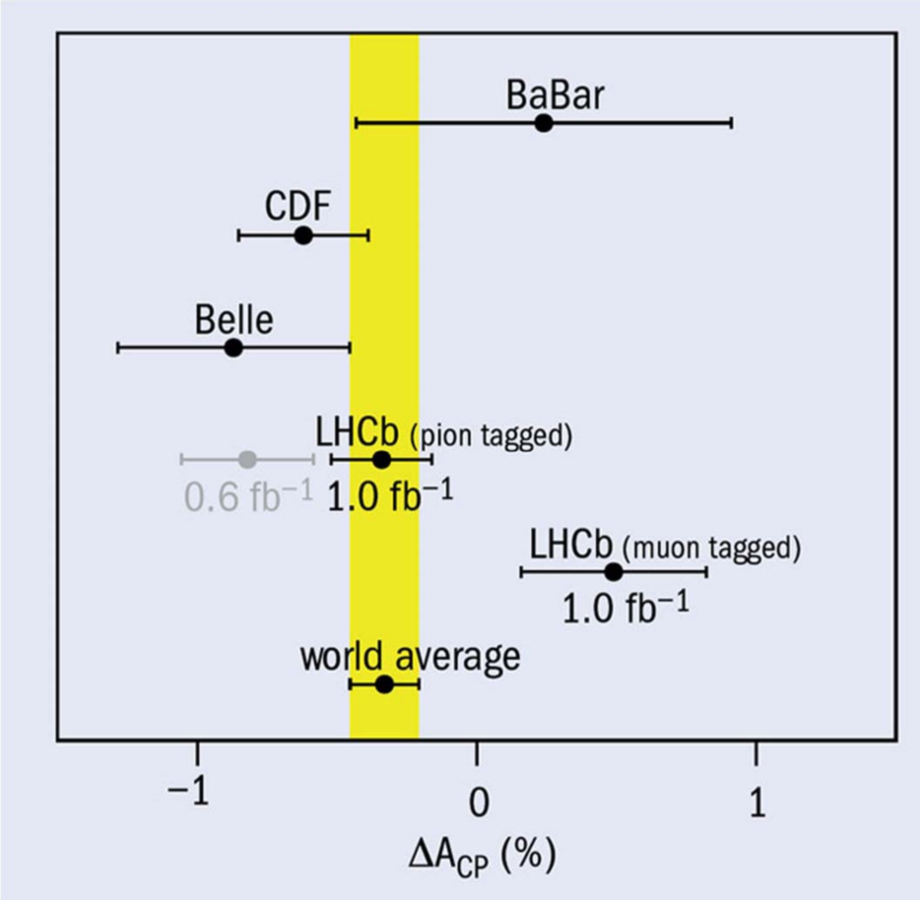

$$\Delta A_{CP} = (+0.49 \pm 0.30 \pm 0.14)\ \%$$

Phys. Lett. B 723 (2013), 33

# Search for CPV in $D^0 \rightarrow h^+h^-$ Decays

World average (HFAG):

$$\Delta A_{CP} = (-0.329 \pm 0.121)\ \%$$




LHCb average:

$$\Delta A_{CP} = (-0.15 \pm 0.16)\ \%$$

Both LHCb measurements are consistent with each other and with other results at the 2σ level.

No confirmation of the previous evidence of CP violation in the charm sector.

Better precision expected after analysis of data collected in 2012.

# Indirect CP Asymmetries $A_\Gamma$ in $D^0 \to h^+h^-$

LHCb-PAPER--2013-057, arXiv:1310.7201

**The CP violation observable:**

The mean lifetimes of the $D^0$ and $\overline{D}^0$ extracted via a fit to their decay times.

$$A_\Gamma = \frac{\hat\Gamma(D^0 \to h^+h^-) - \hat\Gamma(\overline{D}^0 \to h^+h^-)}{\hat\Gamma(D^0 \to h^+h^-) + \hat\Gamma(\overline{D}^0 \to h^+h^-)} \approx \frac{A_m + A_d}{2} y\cos\phi - x\sin\phi$$

$h = K, \pi$

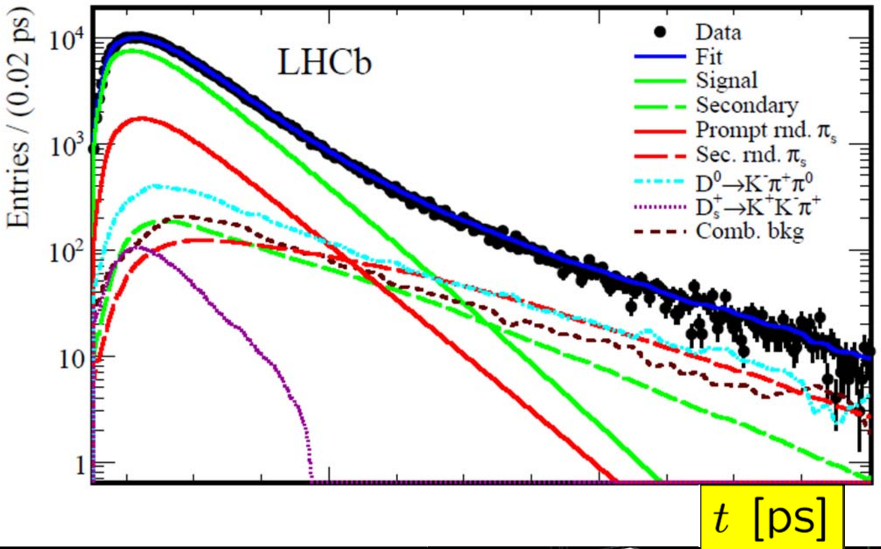
The asymmetries due to CP violation in mixing and decay.

$\phi$ – the interference phase between mixing and decay

The size of direct CPV effects below the current experimental sensitivity.

The measurement of $A_\Gamma$ yields an estimate of INDIRECT CPV.

$$A_m = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$




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

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

**The most precise measurement of $A_\Gamma$ at the moment.**

**No evidence for indirect CPV.**
**No difference in $A_\Gamma$ between KK and $\pi\pi$.**

# Search for Direct CPV in $D^+ \to \phi\pi^+$ and $D^+_s \to K^0_s \pi^+$ Decays

Charged initial charm states ⇒ a non-zero CP asymmetry ⇔ the presence of direct CPV

**1**

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

$$\phi \to K^+K^-$$

The control channel:

$$D^+ \to K^0_S\pi^+,\ K^0_S \to \pi^+\pi^-$$

$$A^{SM}_{CP}(D^+ \to K^0_s\pi^+) = 10^{-4}$$

the CPV asymmetry assumed ZERO
no penguin amplitudes → NP effects negligible

**2**

A concurrent measurement:

$$D^+_s \to K^0_S\pi^+$$

The control channel:

$$D^+_s \to \phi\pi^+,\ \phi \to K^+K^-$$

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

The raw asymmetry:

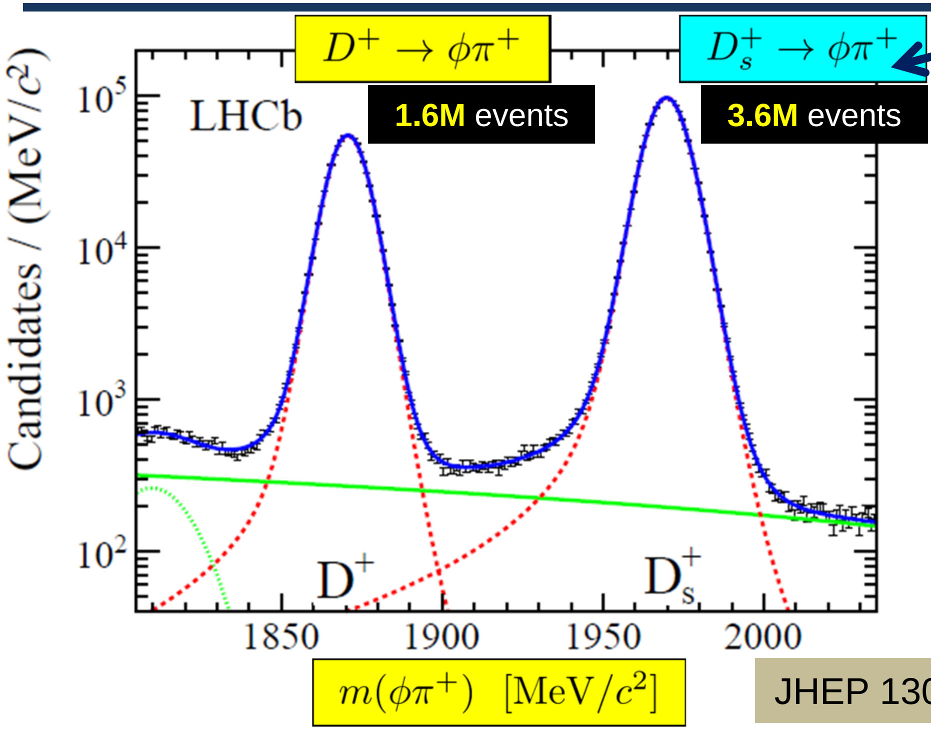
$$A_{\rm raw}(f) = \frac{N(D^+\to f)-N(D^-\to \bar{f})}{N(D^+\to f)+N(D^-\to \bar{f})}$$

$$f = \phi\pi^+,\ K^0_S\pi^+$$

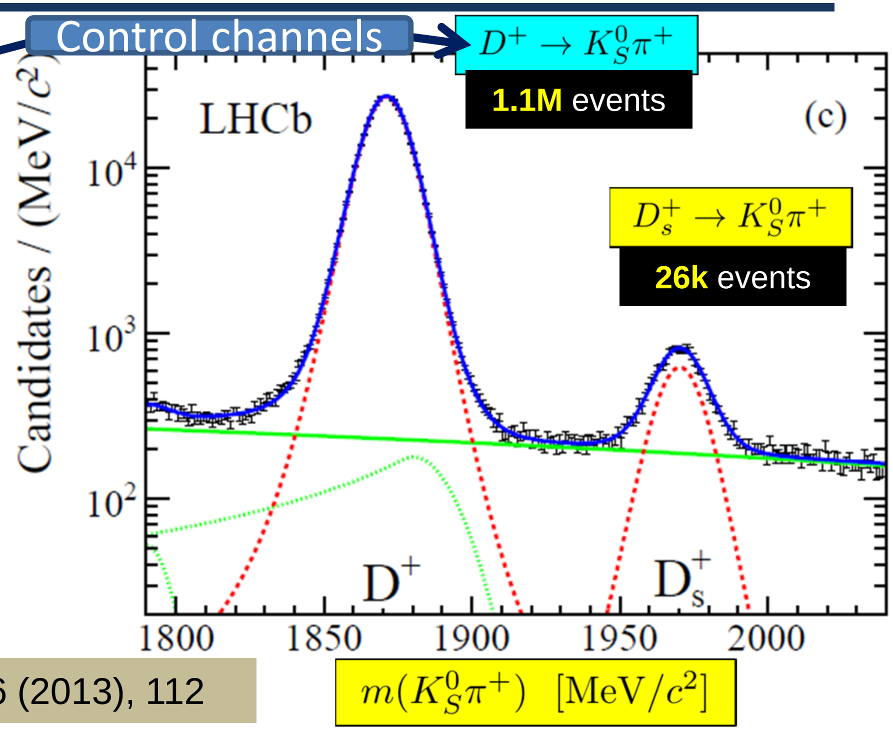
Asymmetry due to the CPV in the neutral kaon system: (-0.028 ± 0.028)%

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

# Search for Direct CPV in $D^+ \to \phi\pi^+$ and $D^+_s \to K^0_s \pi^+$ Decays




Control channels



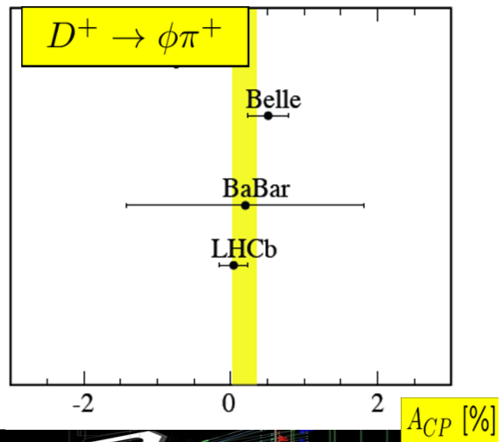

JHEP 1306 (2013), 112

$$A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.14)\ \%$$

Very strong constraints on the presence of direct CPV in $D^+ \to \phi\pi^+$.

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = (+0.61 \pm 0.83 \pm 0.14)\ \%$$

No evidence for direct CPV in $D_s^+ \to K_S^0\pi^+$. More data needed.



# Search for CPV in $D^0 \rightarrow 4h$

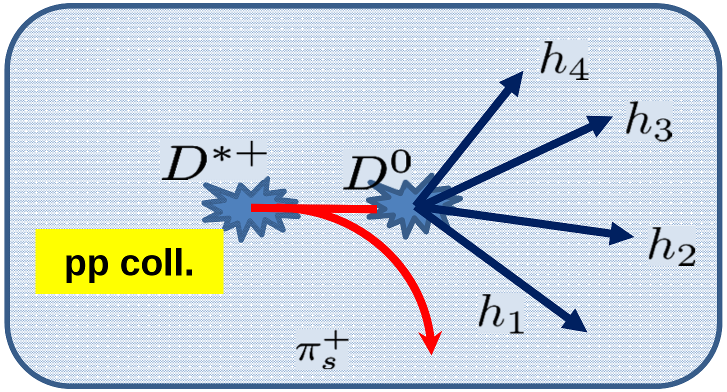
**Multibody charm decays → rich resonance structures with interferring amplitudes,**
**→ sensitivity to CPV localized in certain phase space regions.**

**Singly-Cabibbo-Suppressed (SCS) decays studied:** $D^0 \to K^- K^+ \pi^- \pi^+$ , $D^0 \to \pi^- \pi^+ \pi^- \pi^+$

**The control channel (CF):** $D^0 \to K^- \pi^+ \pi^- \pi^+$

Phys. Lett. B 726 (2013), 623

**The charge of the soft pion from the decay $D^{*+} \to D^0 \pi^+$ tags the flavour of the D meson.**




4-body final states →
decay dynamics described by FIVE invariants:
s(1,2), s(2,3), s(1,2,3), s(2,3,4), s(3,4) ($D^0$ → 1 2 3 4).

**The 5D phase space is partitioned into $N_{bins}$ volumes.**
In each of them, the significance of the difference in population between CP conjugate decays is calculated:

$$S^i_{CP} = \frac{N_i(D^0) - \alpha N_i(\overline{D^0})}{\sqrt{\alpha\left[\sigma_i^2(D^0) + \sigma_i^2(\overline{D^0})\right]}}$$

$$\alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(\overline{D^0})}$$

(removes the contribution of global asymmetries)

**No localised CPV asymmetries ⇔ Gaussian distr. of the $S^i_{CP}$**

# Search for CPV in $D^0 \to 4h$

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

**330k** signal events

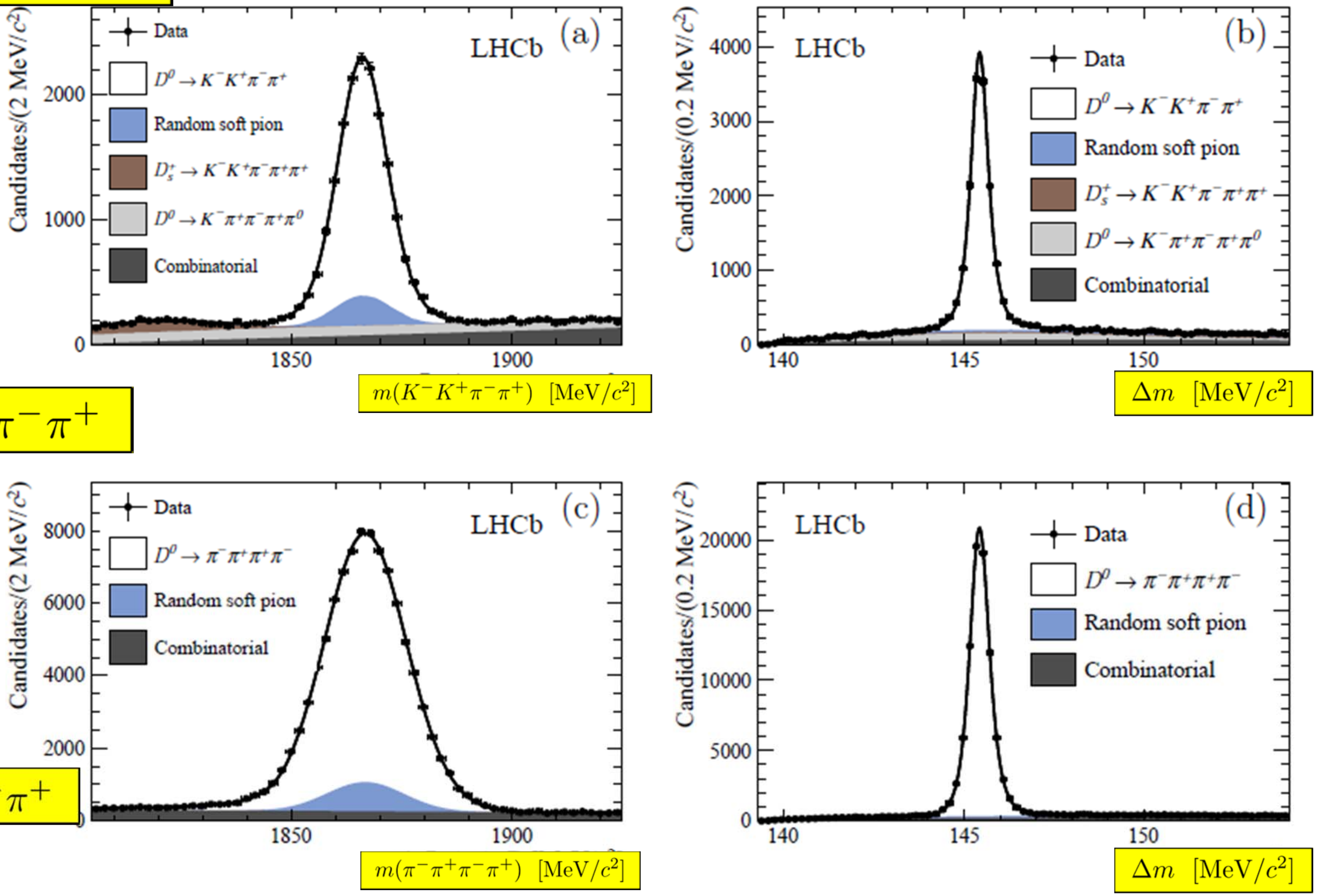
$D^0 \to \pi^- \pi^+ \pi^- \pi^+$

**57k** signal events

**Control channel:**

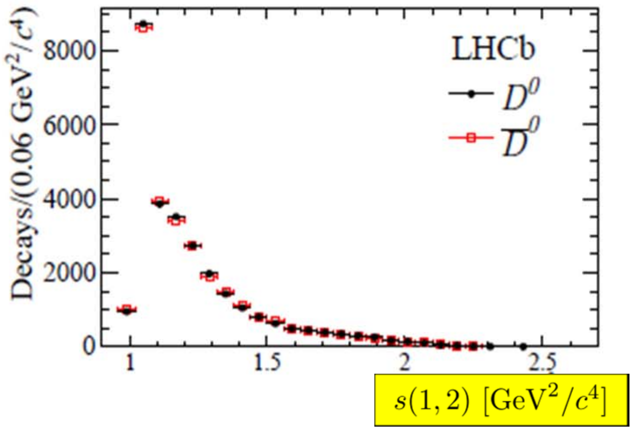
$D^0 \to K^- \pi^+ \pi^- \pi^+$

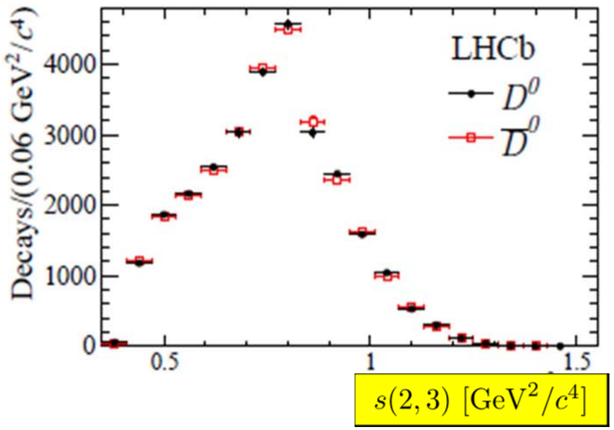
**2.9M** events

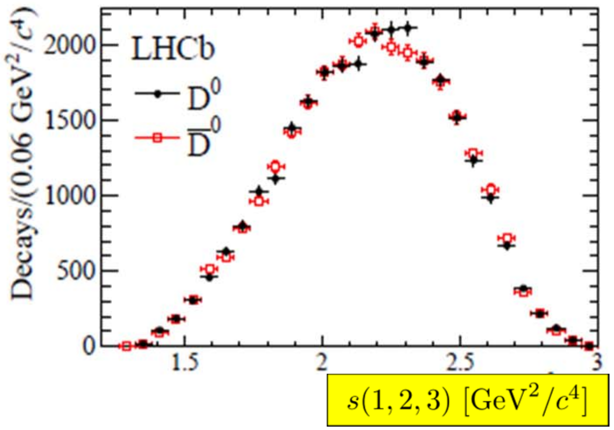


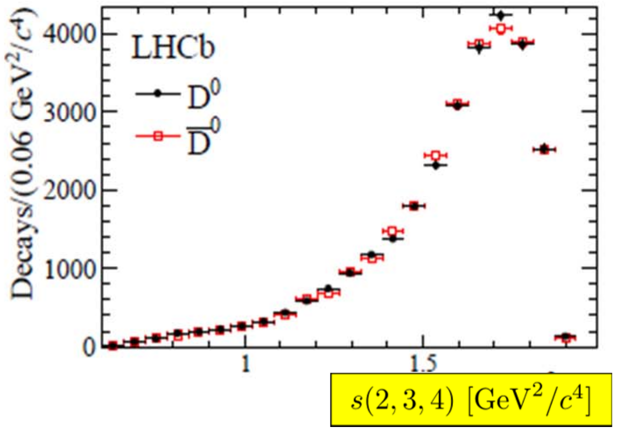
# Search for CPV in $D^0 \rightarrow$ 4h

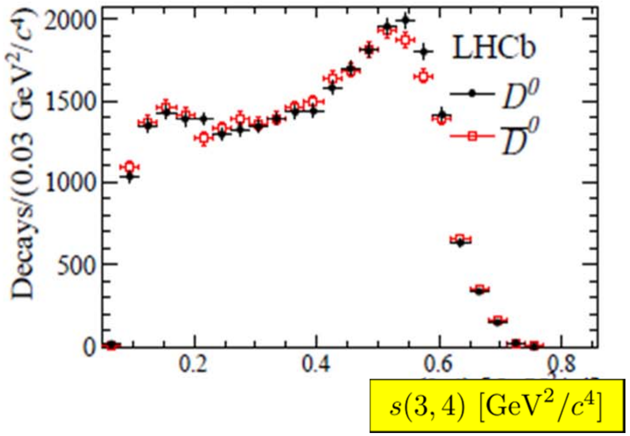
**Invariant mass-squared distributions for $D^0(\overline{D^0}) \rightarrow K^-K^+\pi^-\pi^+$**



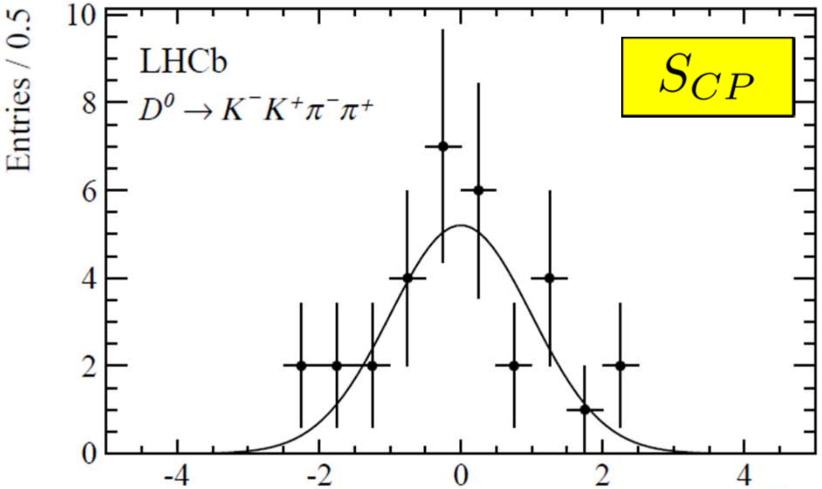



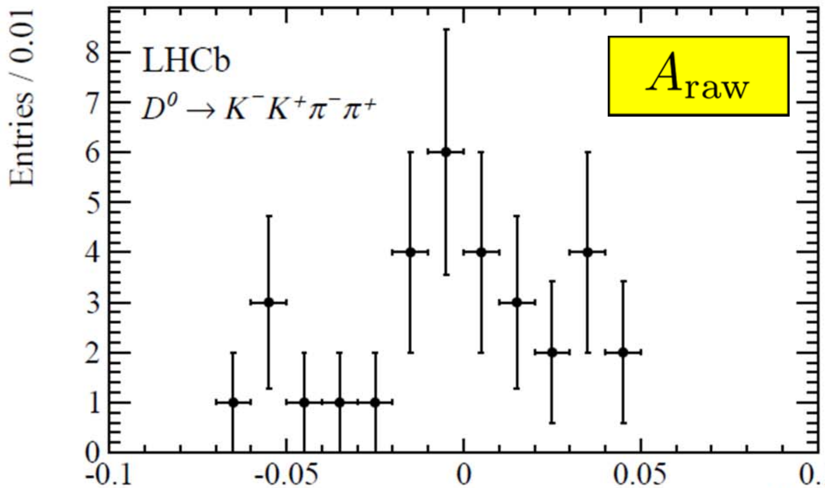




| | |
|---|---|
| black | $D^0$ |
| red | $\overline{D}^0$ |

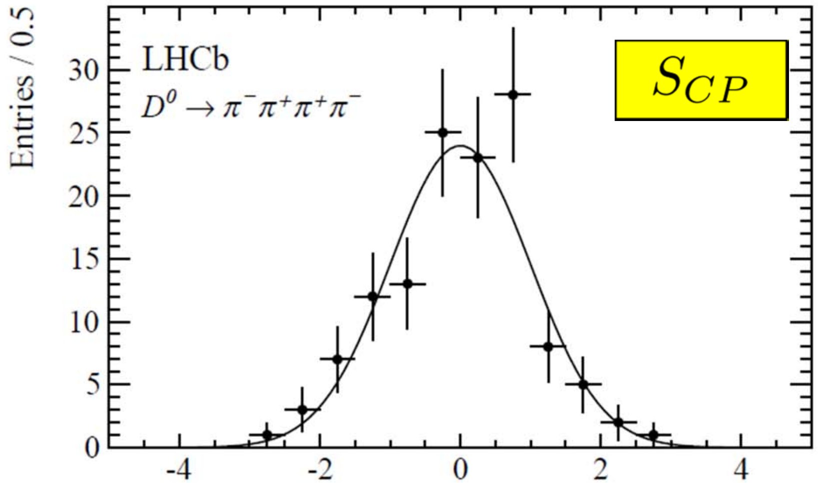
# Search for CPV in $D^0 \rightarrow$ 4h

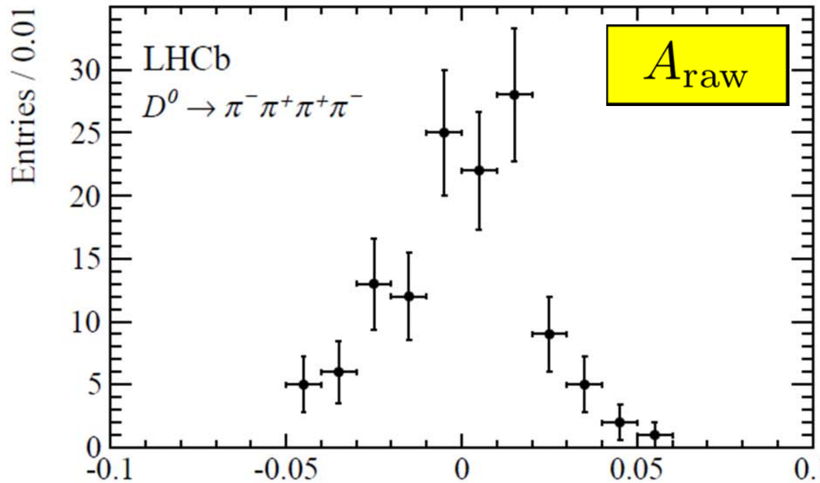
$D^0 \rightarrow K^- K^+ \pi^- \pi^+$ **(partitioned with 32 „bins”)**




$D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ **(partitioned with 128 „bins”)**



# Search for CPV in $D^0 \rightarrow$ 4h

Numerical estimate of any localised CPV asymmetries: the $\chi^2$ test:

$$\chi^2 = \sum_i \left(S^i_{CP}\right)^2$$

$$\text{ndf} = N_{\text{bins}} - 1$$

p-value: probability of getting observed results if the no CPV hypothesis is assumed.

$D^0 \rightarrow K^- K^+ \pi^- \pi^+$

| Bins | $p$-value (%) | $\chi^2/\text{ndf}$ |
|---|---|---|
| 16 | 9.1 | 22.7/15 |
| 32 | 9.1 | 42.0/31 |
| 64 | 13.1 | 75.7/63 |

$D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$

| Bins | $p$-value (%) | $\chi^2/\text{ndf}$ |
|---|---|---|
| 64 | 28.8 | 68.8/63 |
| 128 | 41.0 | 130.0/127 |
| 256 | 61.7 | 247.7/255 |

Phys. Lett. B 726 (2013), 623

**No evidence for localised CPV asymmetries in $D^0 \rightarrow$ 4h.**

# Search for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

**The same approach as applied to D0 → 4h:**

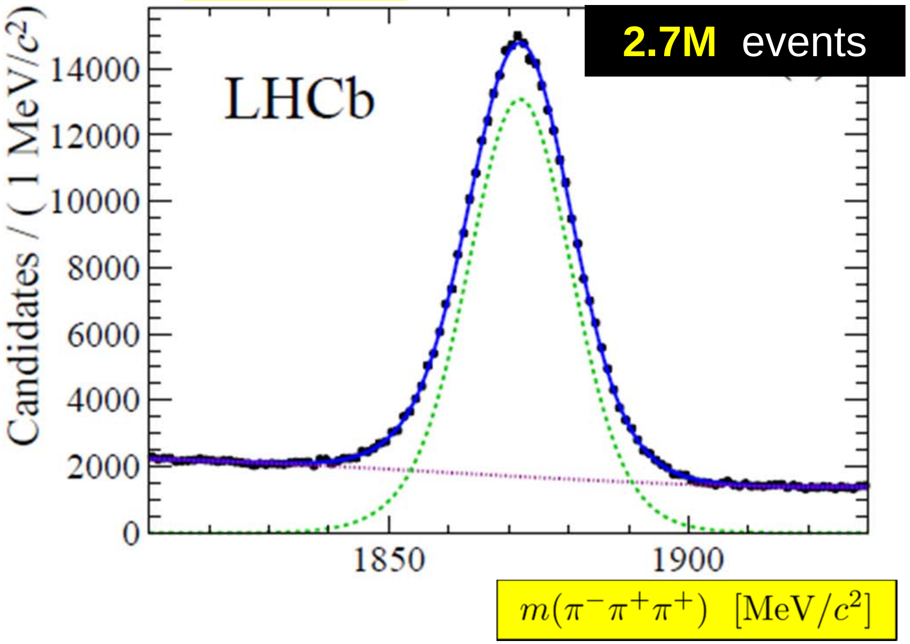
$$S_{CP}^i = \frac{N_i(D^+) - \alpha N_i(D^-)}{\sqrt{\alpha[N_i(D^+)+N_i(D^-)]}}$$

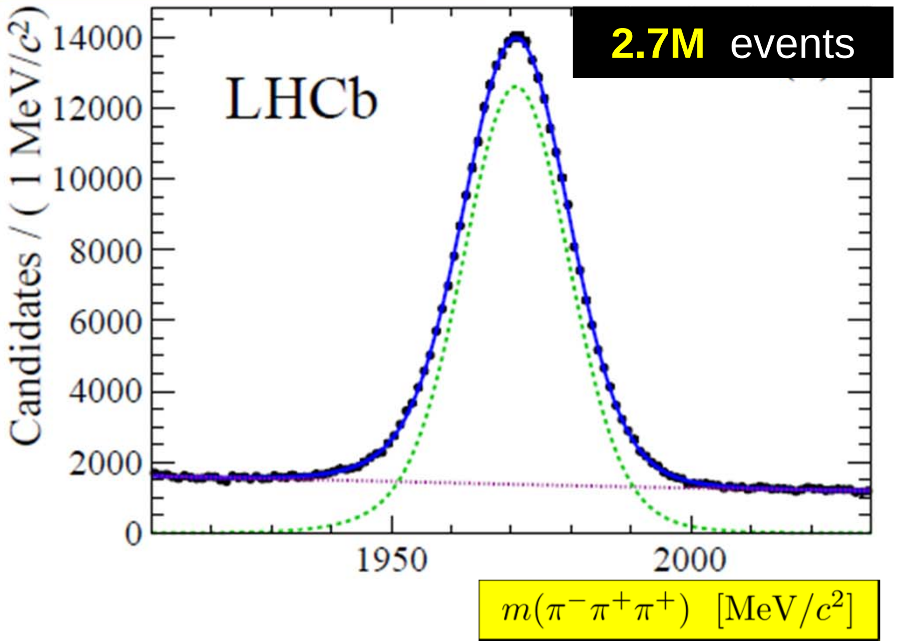
$$\alpha = \frac{\sum_i N_i(D^+)}{\sum_i N_i(D^-)}$$

Phys. Lett. B 728 (2014), 585

The signal: $D^+ \rightarrow \pi^-\pi^+\pi^+$

The control channel (CF): $D_s^+ \rightarrow \pi^-\pi^+\pi^+$



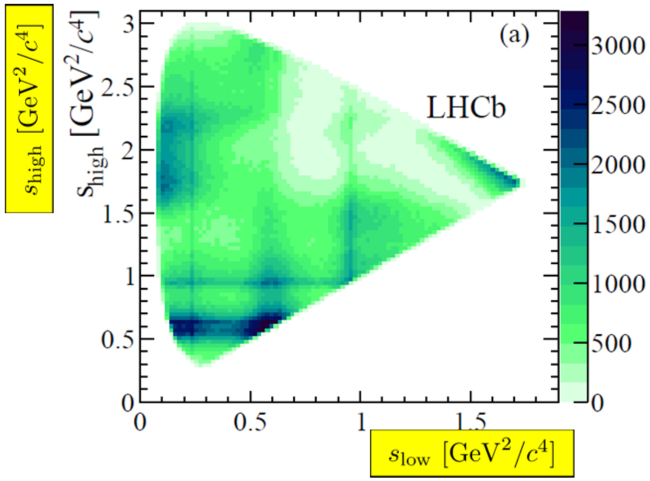




The decay dynamics described by TWO invariants (Dalitz plots):

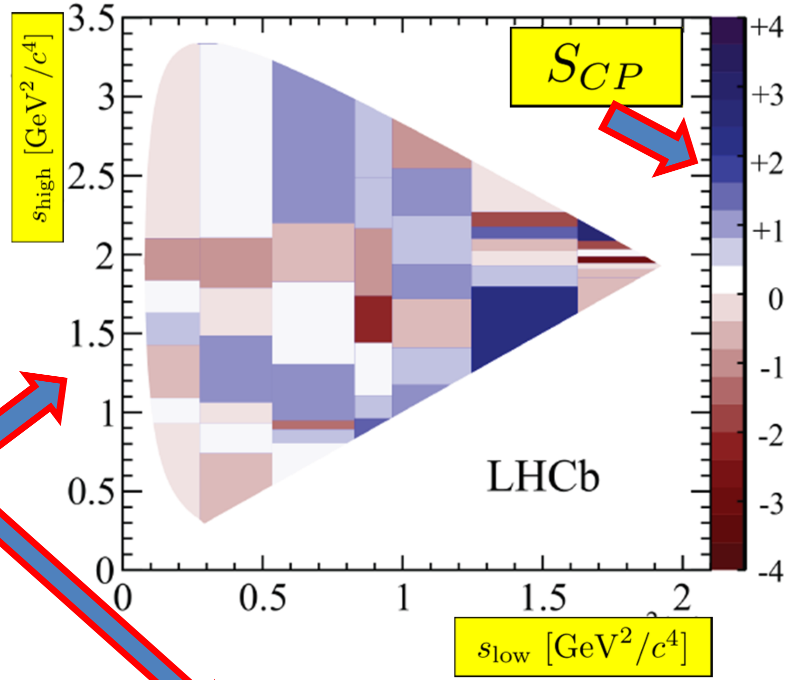
$s_{low}$ and $s_{high}$: the lowest and highest invariant mass squared combination $M^2(\pi^+\pi^-)$.

# Search for CPV in $D^+ \to \pi^-\pi^+\pi^+$

The Dalitz plot for: $D^+ \to \pi^-\pi^+\pi^+$

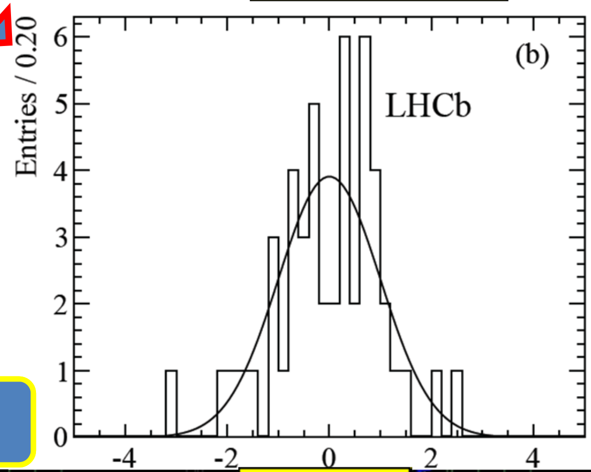



Distributions of the $S^i_{CP}$ with 49 adaptive bins of equal population in the Dalitz plot:




| Number of bins | $\chi^2$ | p-value (%) |
|---|---|---|
| 20 | 14.0 | 78.1 |
| 30 | 28.2 | 50.6 |
| 40 | 28.5 | 89.2 |
| 49 | 26.7 | 99.5 |
| 100 | 89.1 | 75.1 |

p-values for null CPV hypothesis span the range (50-99)%.




Similar results for an unbinned search based on the nearest neighbour method ( M.F.Schilling, J. Am. Stat. Assoc. 81 (2013), 799).

**No evidence for localised CPV asymmetries in $D^+ \to \pi^-\pi^+\pi^+$.**

$S_{CP}$

# X(3872) Quantum Numbers

X(3872) first observed by Belle (2003) in $B^{\pm} \to X(3872)K^{\pm}, \quad X(3872) \to J/\psi\pi^{+}\pi^{-}$

Still lacking a clear-cut interpretation - no unambiguous determination of the $J^P$: $1^+$ vs $2^-$
($C=+1$ from the observation of $X(3872) \to \gamma J/\psi$ ).

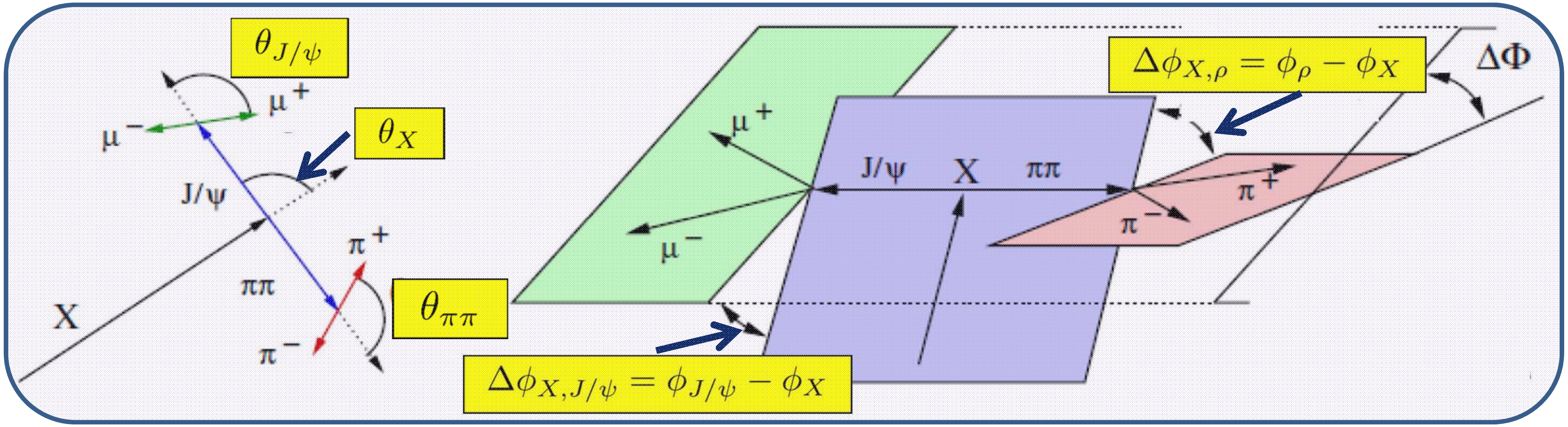
**$1^+$** $D^{*0}\overline{D}^0$ molecule, tetraquark, charmonium $\chi_{c1}(2^3P_1)$

**$2^-$** charmonium $\eta_{c2}(1^1D_2)$

**LHCb:** full angular analysis of the decay chain: $B^{+} \to X(3872)K^{+}, \quad X \to (J/\psi \to \mu^{+}\mu^{-})(\rho \to \pi^{+}\pi^{-})$

Five variables: $\theta_X, \ \theta_{J/\psi}, \ \theta_{\pi\pi}, \ \Delta\phi_{X,\rho} \ \Delta\phi_{X,J/\psi}$

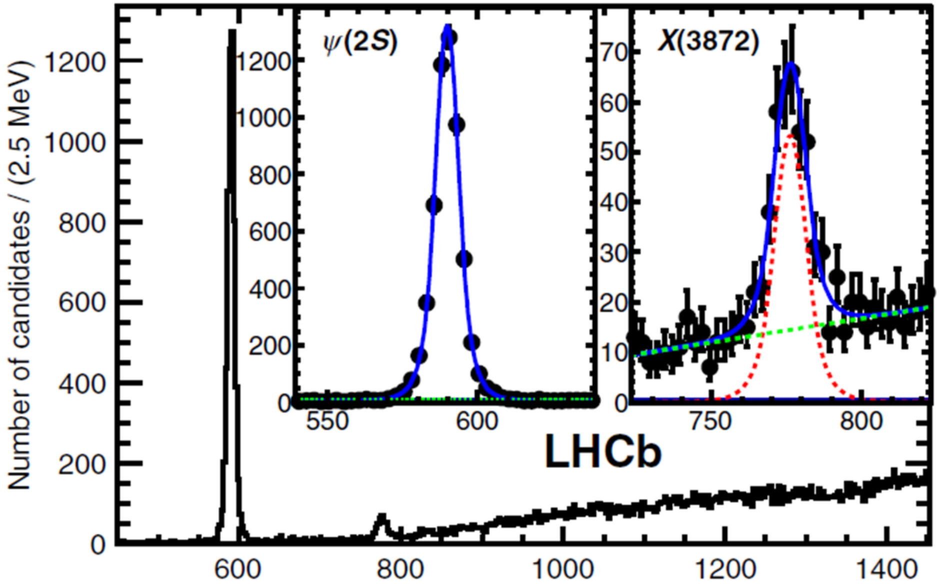
Eur. Phys. J. C72 (2012) 1972



# X(3872) Quantum Numbers

ψ(2S): 5.6k events

X(3872): $313 \pm 26$ events

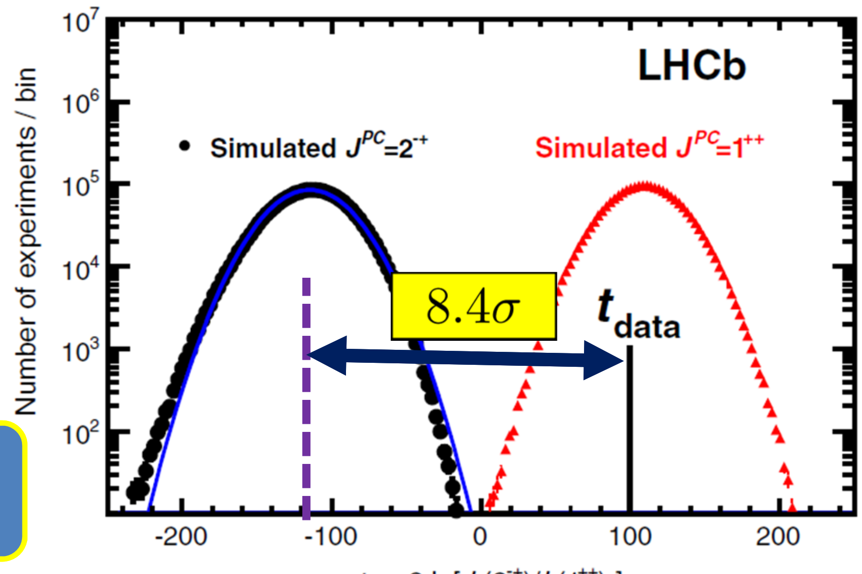



$m(J/\psi\pi\pi) - m(J/\psi)$ [MeV/$c^2$]

**Test statistic:**

Likelihood ratio test to distinguish between $1^{++}$ and $2^{-+}$ assignments.

$$t = -2 \ln \frac{\mathcal{L}(2^{-+})}{\mathcal{L}(1^{++})}$$



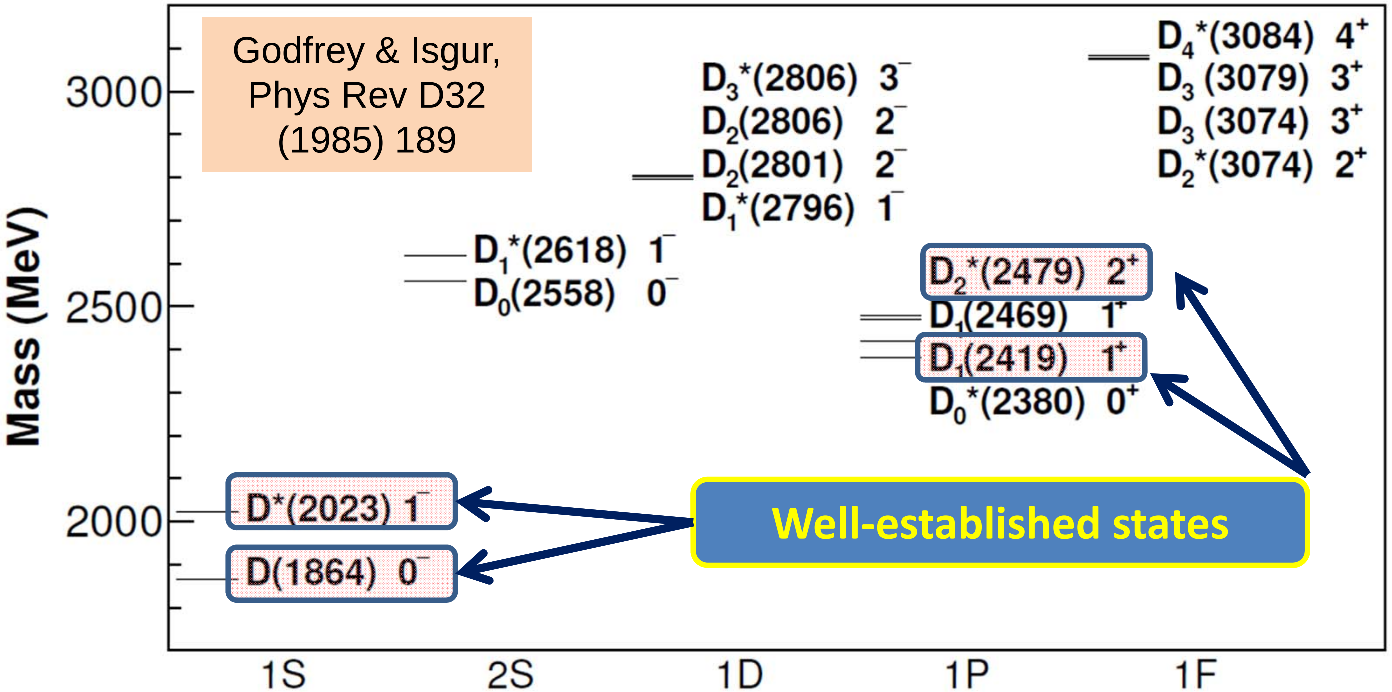

**The $2^{-+}$ hypothesis is excluded with a significance of more than 8σ. $\eta_{c2}(1^1D_2)$ ruled out.**

$$J^{PC} = 1^{++}$$

**- unambiguously established for the X(3872).**

Eur. Phys. J. C72 (2012) 1972

# Excited $D_J$ States




**LHCb:**

Search for $D_J$ mesons in $D^+\pi^-$, $D^0\pi^+$, $D^{*+}\pi^-$ final states.

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

Observation of $D_1(2420)^0$ in the $D^{*+}\pi^-$

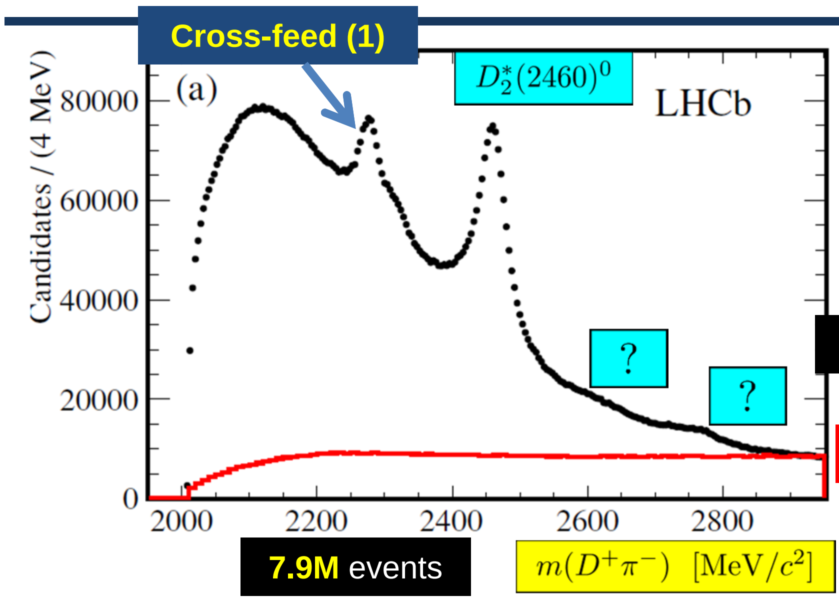
Observation of $D_2^*(2460)$ in the $D^+\pi^-$, $D^0\pi^+$, $D^{*+}\pi^-$

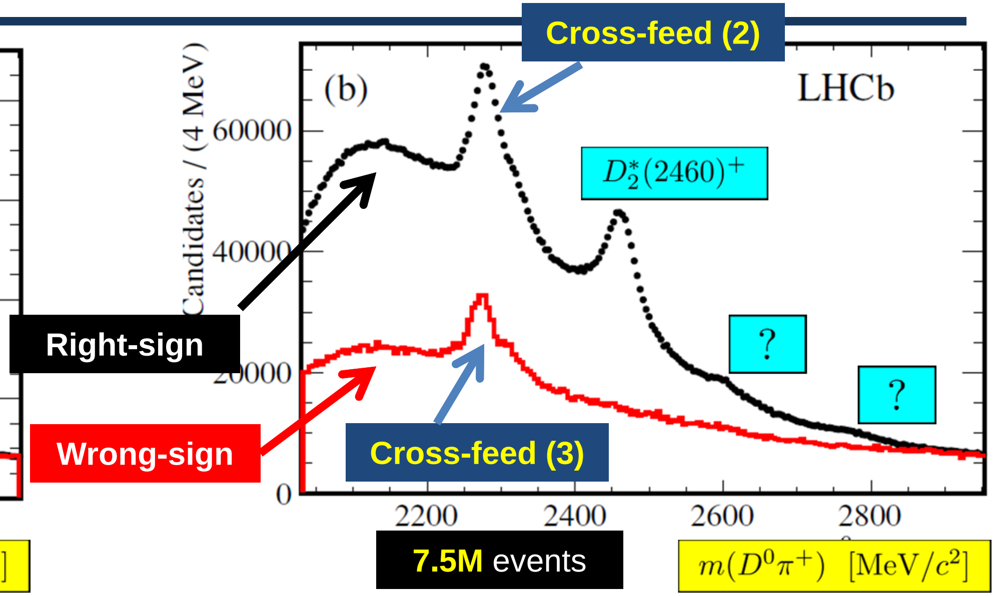
Several structures observed in the mass region between 2.5 and 3 GeV.

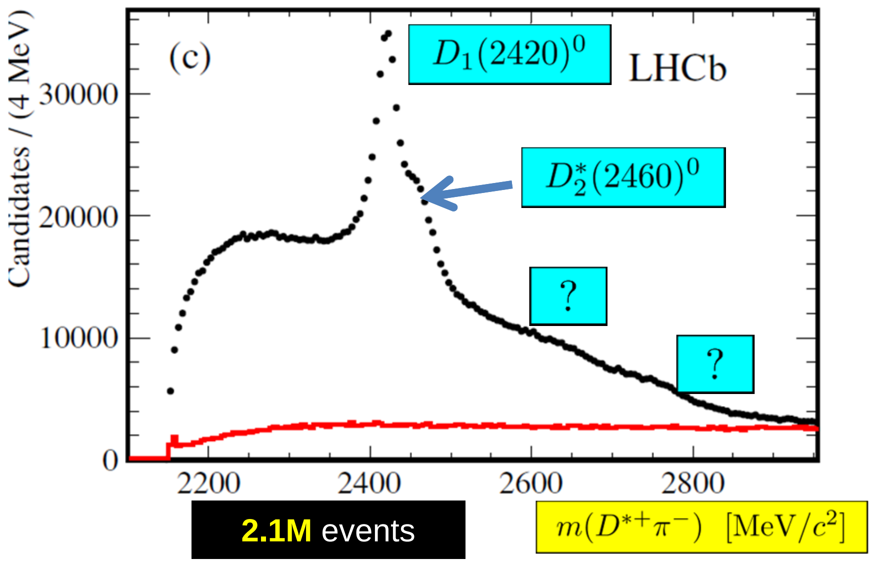
Spin-parities assigned for most of these states.

JHEP 09 (2013), 145

# Excited $D_J$ States




**(1)** $D_1(2420)^0$ or $D_2^*(2460)^0 \to \pi^- D^{*+}(\to D^+ \pi^0/\gamma)$

**(2)** $D_1(2420)^+$ or $D_2^*(2460)^+ \to \pi^+ D^{*0} \; (\to D^0 \pi^0/\gamma)$

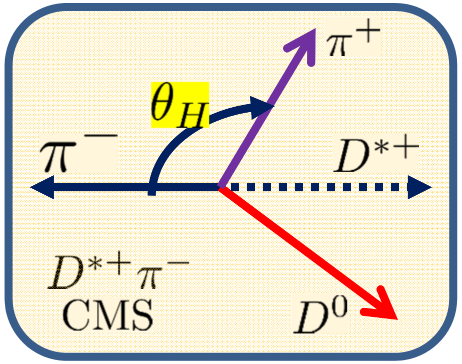
**(3)** $D_1(2420)^0$ or $D_2^*(2460)^0 \to \pi^- D^{*+} \; (\to D^0 \pi^+)$

# Excited $D_J$ States

The $D^{*+}\pi^-$ (3-body) final state → information about the spin-parity assignment of a given resonance.

**The helicity angle:**

$D^{*+}\pi^-$ | $D^{*+} \to D^0\pi^+$




**Natural parity:**

$P = (-1)^J$

$J^P = 0^+, 1^-, 2^+, \ldots$

$\propto \sin^2\theta_H$

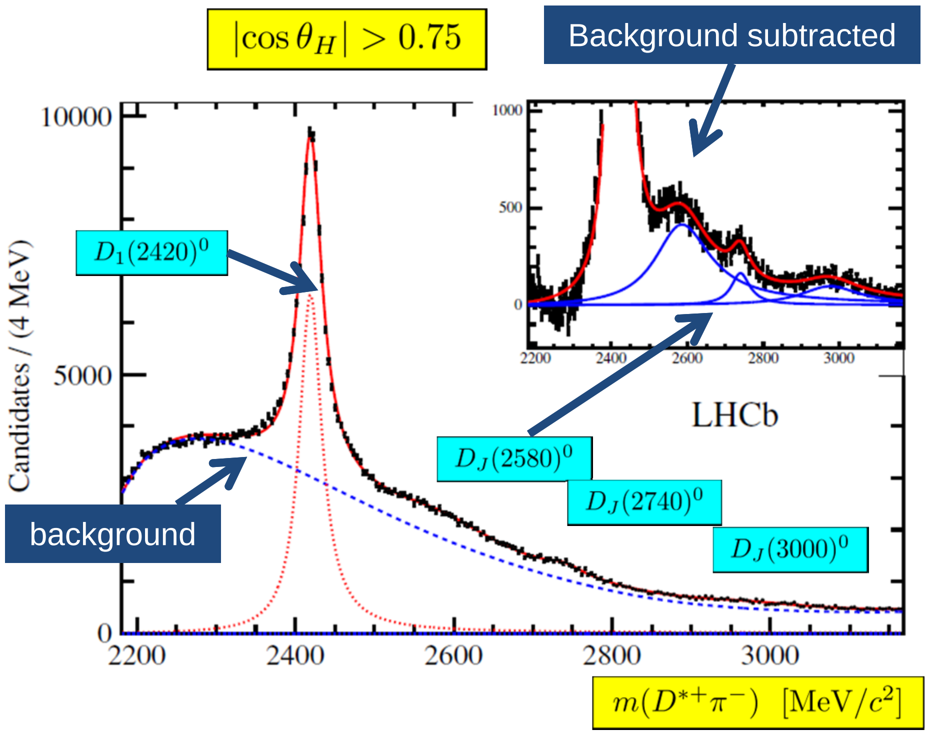
**Unnatural parity:**

$P = (-1)^{J+1}$

$J^P = 0^-, 1^+, 2^-, \ldots$

$\propto 1 + h\cos^2\theta_H$

Enhanced unnatural parity sample:



# Excited $D_J$ States: Results

Masses, widths and yields determined for all the abovementioned resonances.

| Resonance | Final state | Mass (MeV) | Width (MeV) | Yields $\times 10^3$ | Significance ($\sigma$) |
|---|---|---|---|---|---|
| $D_1(2420)^0$ | $D^{*+}\pi^-$ | $2419.6 \pm 0.1 \pm 0.7$ | $35.2 \pm 0.4 \pm 0.9$ | $210.2 \pm 1.9 \pm 0.7$ | |
| $D_2^*(2460)^0$ | $D^{*+}\pi^-$ | $2460.4 \pm 0.4 \pm 1.2$ | $43.2 \pm 1.2 \pm 3.0$ | $81.9 \pm 1.2 \pm 0.9$ | |
| $D_J^*(2650)^0$ | $D^{*+}\pi^-$ | $2649.2 \pm 3.5 \pm 3.5$ | $140.2 \pm 17.1 \pm 18.6$ | $50.7 \pm 2.2 \pm 2.3$ | 24.5 |
| $D_J^*(2760)^0$ | $D^{*+}\pi^-$ | $2761.1 \pm 5.1 \pm 6.5$ | $74.4 \pm 3.4 \pm 37.0$ | $14.4 \pm 1.7 \pm 1.7$ | 10.2 |
| $D_J(2580)^0$ | $D^{*+}\pi^-$ | $2579.5 \pm 3.4 \pm 5.5$ | $177.5 \pm 17.8 \pm 46.0$ | $60.3 \pm 3.1 \pm 3.4$ | 18.8 |
| $D_J(2740)^0$ | $D^{*+}\pi^-$ | $2737.0 \pm 3.5 \pm 11.2$ | $73.2 \pm 13.4 \pm 25.0$ | $7.7 \pm 1.1 \pm 1.2$ | 7.2 |
| $D_J(3000)^0$ | $D^{*+}\pi^-$ | $2971.8 \pm 8.7$ | $188.1 \pm 44.8$ | $9.5 \pm 1.1$ | 9.0 |
| $D_2^*(2460)^0$ | $D^+\pi^-$ | $2460.4 \pm 0.1 \pm 0.1$ | $45.6 \pm 0.4 \pm 1.1$ | $675.0 \pm 9.0 \pm 1.3$ | |
| $D_J^*(2760)^0$ | $D^+\pi^-$ | $2760.1 \pm 1.1 \pm 3.7$ | $74.4 \pm 3.4 \pm 19.1$ | $55.8 \pm 1.3 \pm 10.0$ | 17.3 |
| $D_J^*(3000)^0$ | $D^+\pi^-$ | $3008.1 \pm 4.0$ | $110.5 \pm 11.5$ | $17.6 \pm 1.1$ | 21.2 |
| $D_2^*(2460)^+$ | $D^0\pi^+$ | $2463.1 \pm 0.2 \pm 0.6$ | $48.6 \pm 1.3 \pm 1.9$ | $341.6 \pm 22.0 \pm 2.0$ | |
| $D_J^*(2760)^+$ | $D^0\pi^+$ | $2771.7 \pm 1.7 \pm 3.8$ | $66.7 \pm 6.6 \pm 10.5$ | $20.1 \pm 2.2 \pm 1.0$ | 18.8 |
| $D_J^*(3000)^+$ | $D^0\pi^+$ | 3008.1 (fixed) | 110.5 (fixed) | $7.6 \pm 1.2$ | 6.6 |

All significances are well above 5σ.

Helicity angle distributions → spin-parity assignments.

# Summary of Excited $D_J$ States

**LHCb:** JHEP 09 (2013), 145

$D_J^*(2760)^0$ — Natural P

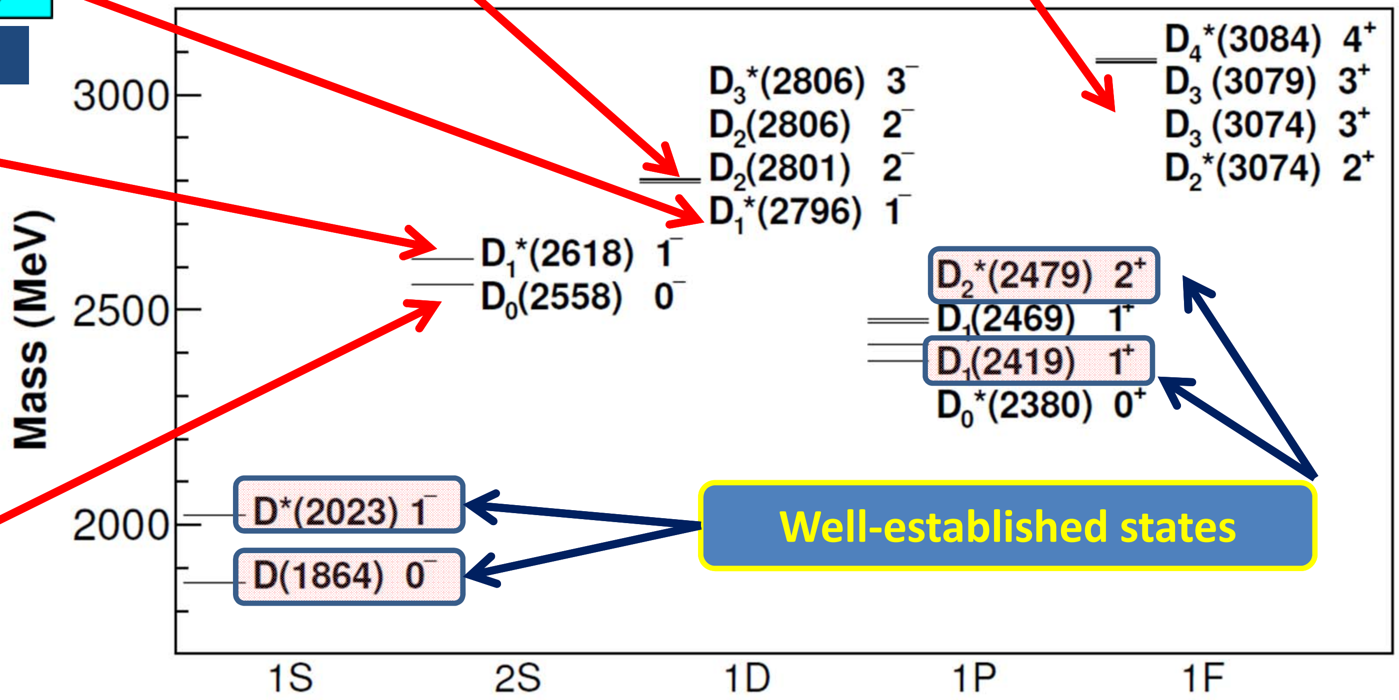
$D_J^*(2650)^0$ — Natural P

$D_J(2740)^0$ — Unnatural P

$D_J(3000)^0$ — Unnatural P

Most probably superposition of several states.

$D_J(2580)^0$ — Unnatural P




**Well-established states**

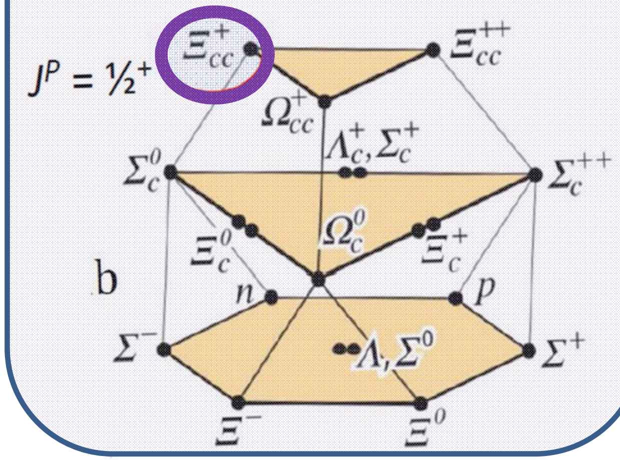
**LHCb:** Similar study of $D_{sJ}$ ( $D^+K_S^0$ and $D^0K^+$ final states): JHEP 10 (2012), 151

# Search for $\Xi^+_{cc}$

**Quark model expectations**

$m(\Xi^+_{cc}) \in [3500, 3700]$ MeV/c$^2$

$\tau(\Xi^+_{cc}) \in [100, 250]$ fs




LHCb: $\sigma \sim 10^2$ nb

Observable:

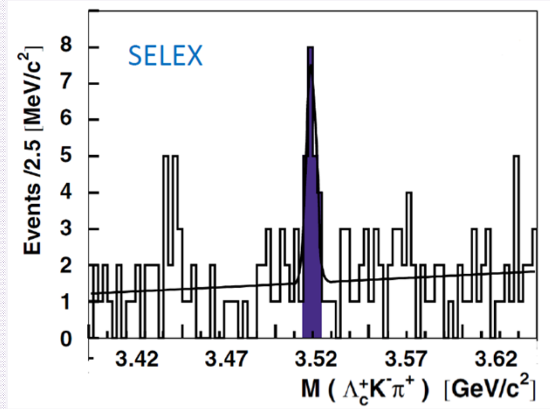
$$R = \frac{\sigma(\Xi^+_{cc})}{\sigma(\Lambda^+_c)} \times \mathcal{B}(\Xi^+_{cc} \to \Lambda^+_c K^- \pi^+)$$

Data sample: 0.65 fb$^{-1}$ (@ 7 TeV).

JHEP 1312 (2013) 090

**SELEX claim**

Observation of $\Xi^+_{cc} \to \Lambda^+_c K^- \pi^+$ ( $\Lambda^+_c \to p K^- \pi^+$ )

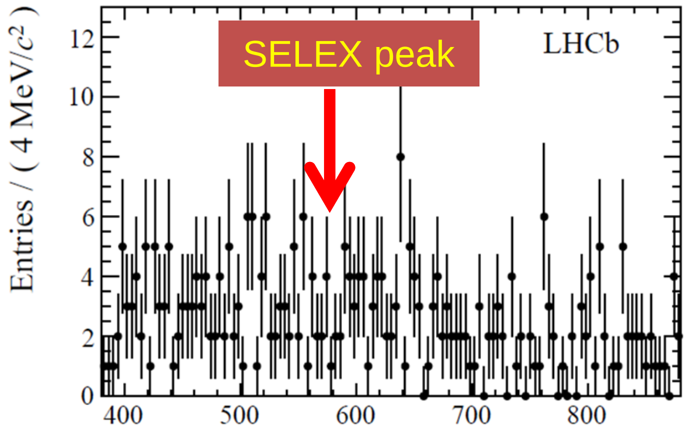



$m(\Xi^+_{cc}) = (3519 \pm 2)$ MeV/c$^2$

$\tau(\Xi^+_{cc}) < 30$ fs

Phys. Rev. Lett. 89 (2002), 112001

No confirmation by FOCUS, BaBar and Belle.




$\delta m$ [MeV/c$^2$]

LHCb: no signal.

| | |
|---|---|
| $R < 1.4 \times 10^{-2}$ | τ = 100 fs |
| $R < 3.4 \times 10^{-4}$ | τ = 400 fs |

**Future studies:**
- ✓ more data,
- ✓ Additional decay modes.

$$\delta m = m(\Lambda^+_c K^- \pi^+) - m(\Lambda_c) - m(K^-) - m\pi^+$$

# Summary

**Charm Mixing:** unambiguosly established;
LHCb provided the first evidence with significance (far) above 5σ.

**CP Violation in Charm Sector:**

- ✓ $\Delta A_{CP}$ in $D^0 \rightarrow h^+h^-$: consistent with zero with the updated data sample,
- ✓ the $A_\Gamma$ measurement gives no indication of indirect CPV,
- ✓ no evidence for the direct CPV in $D^+ \rightarrow \phi\pi^+$ and $D^+_s \rightarrow K^0_S\,\pi^+$ decays,
- ✓ no observation of localised CPV asymmetries in $D^0 \rightarrow 4h$ and $D^+ \rightarrow \pi^-\pi^+\pi^+$.

**Charm Spectroscopy:**

- ✓ X(3872): spin-parity determined,
- ✓ $D_J$: Several new states observed, spin-parities assigned,
- ✓ $\Xi_{cc}$+: upper limits for the production given,
- ✓ Many other spectroscopy results e.g. about J/ψ and $\chi_c$ not discussed in this talk...