CPV search in charm sector at LHCb

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Outline

I. *CPV* theory introduction

II. LHCb detector

III. Experimental results

   I. Mixing $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

   II. *CPV* in $\Lambda_c^+ \to \mathrm{p}\mathrm{K}^+\mathrm{K}^-$ and $\Lambda_c^+ \to \mathrm{p}\pi^+\pi^-$

   III. *CPV* in $\mathrm{D}^+_{(s)} \to \eta'\pi^+$

IV. Novel effect at the $\mathrm{D}^+_{(s)} \to \mathrm{K}^0_\mathrm{S}\mathrm{h}^+$ decays

V. Conclusion

CPV introduction

- *CP* symmetry violation (*CPV*) is one of the three necessary conditions for the Baryon asymmetry of the Universe [JETP Lett. 5, 24-27]
- *CPV* is present in the Standard model (**SM**) via CKM mechanism, but is too weak to explain the Baryon asymmetry
- Today *CPV* is confirmed at strange and bottom sector, no observation in charm
- Two types of *CPV*: <u>Indirect</u> (*CPV* in mixing, *CPV* in interference) and <u>Direct</u>

<u>*CPV* in mixing</u>

- Not depending on final state
- Different mixing rates $\mathrm{D}^0 \to \bar{\mathrm{D}}^0$ and $\bar{\mathrm{D}}^0 \to \mathrm{D}^0$

$$|\frac{q}{p}| \neq 1$$

- Accessible via the using flavor specifics decays
- No mass difference or *CPV* in mixing observed so far

<u>*CPV* in interference</u>

- Possibility of mixing and decay amplitudes interference

$$\phi = arg(\frac{q\bar{A}_f}{pA_f})$$

- Can be observed as a decay-time-dependent difference in decay rates and as a time-integrated difference

<u>Direct *CPV*</u>

- Only possible CPV for charged hadrons
- Occurs in the case:

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

- Observable as difference:

$$A_{raw} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$

- Typically (for SCS modes): $A_{CP} < 10^{-3} - 10^{-4}$

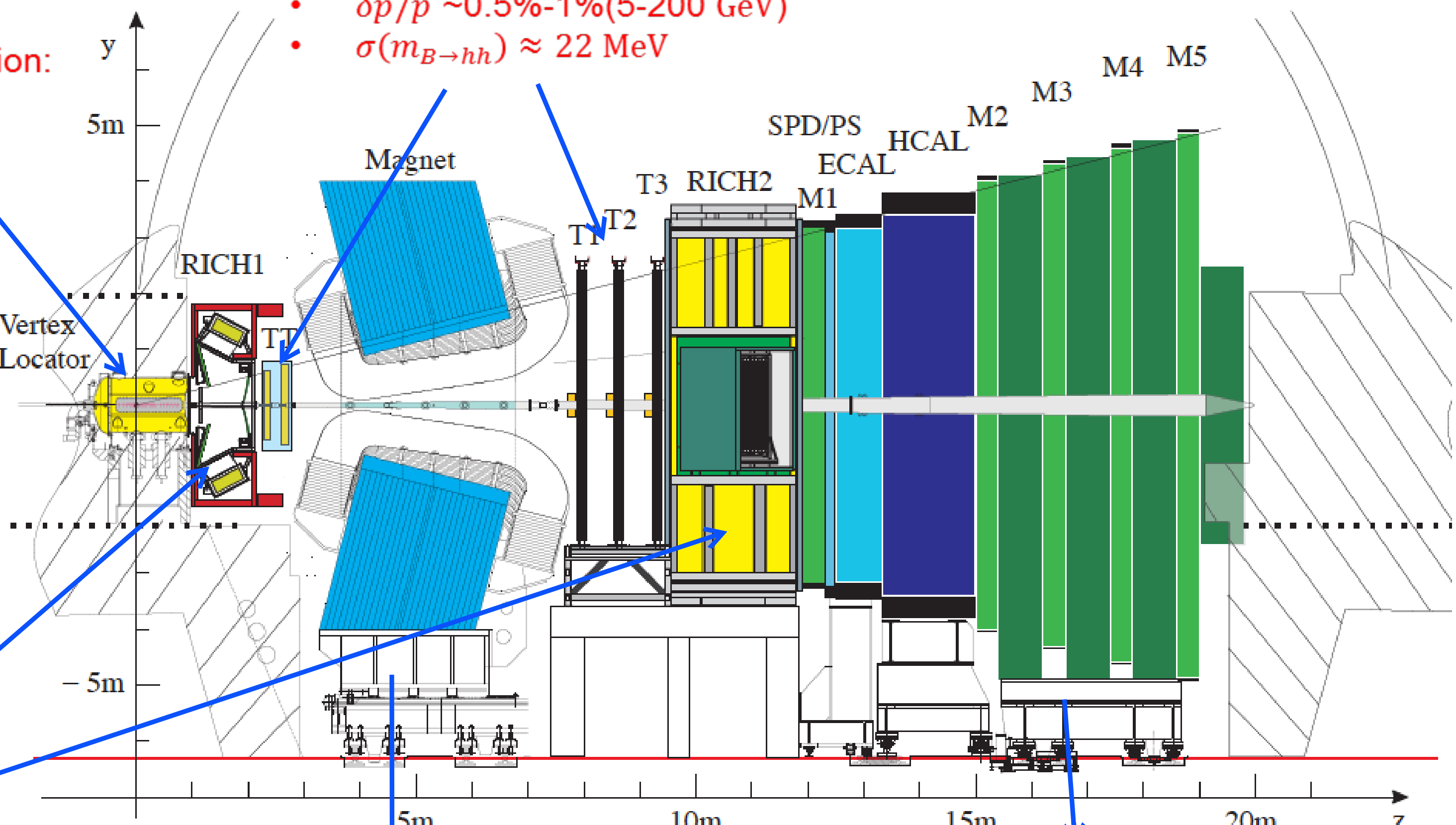
LHCb detector

→ Single-arm forward spectrometer focused on heavy flavor physics

Vertex Locator(vertex reconstruction)
- Impact parameter resolution: 20 μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)

Tracking system(particle reconstruction)
- ϵ(Tracking) ~96%
- $\delta p/p$ ~0.5%-1%(5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



RICH: particle ID
- $\varepsilon(K\to K)$ ~95%
- Mis-ID: $\varepsilon(\pi\to K)$ ~5%

Magnet
Bending power: 4 Tm

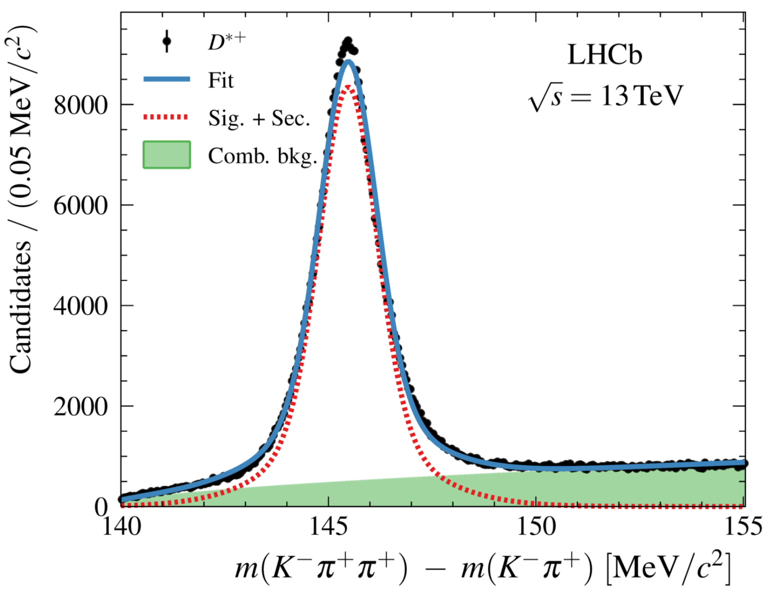
Muon system
- μ ID: $\varepsilon(\mu\to\mu)$ ~97%
- Mis-ID: $\varepsilon(\pi\to\mu)$ ~1-3%

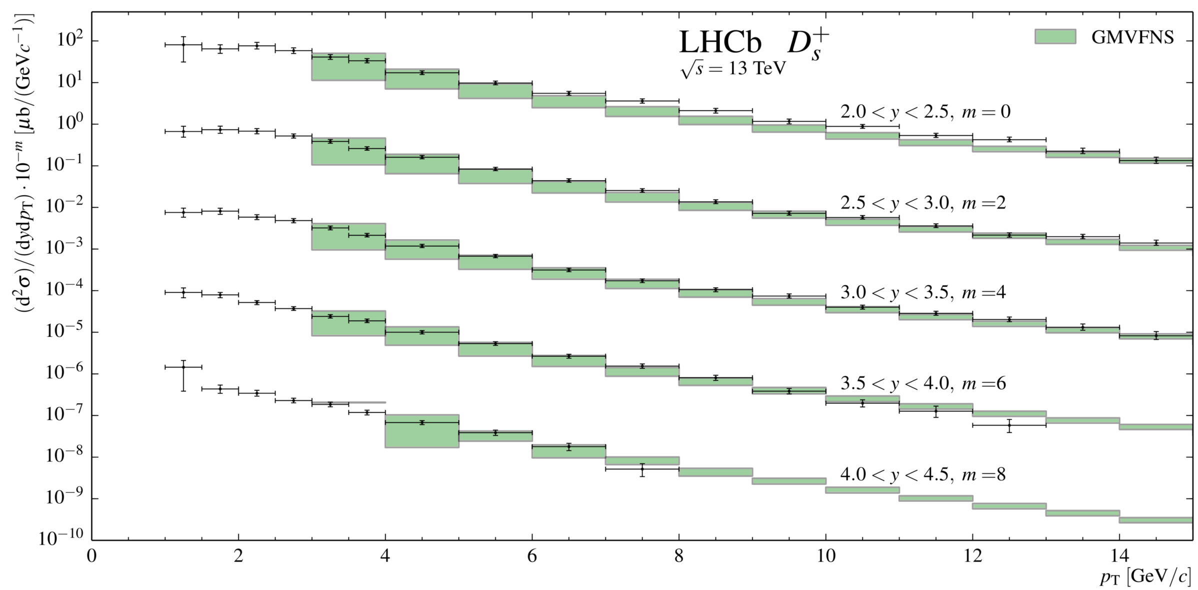
Measurement of charm at LHCb

- LHCb is primarily designed for bottom physics but also performs very well in the field of charm physics
- Charm cross section: $\sigma(pp \to c\bar{c}) = \begin{array}{l} [1419 \pm 12\ (stat.) \pm 116\ (syst.) \pm 65\ (frag.)]\mu\text{b @ 7 TeV} \\ [2369 \pm 3\ (stat.) \pm 152\ (syst.) \pm 118\ (frag.)]\mu\text{b @ 13 TeV} \end{array}$

For $p_{\mathrm{T}} < 8GeV/c, 2.0 < y < 4.5$ NPB871(2016)1, JHEP05(2017)074

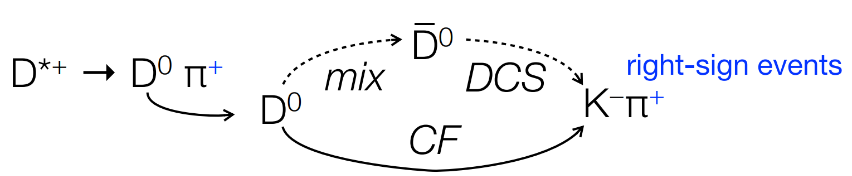
- Significant statistics collected during Run I (2011-2012, 7+8 TeV, 3 fb^{-1}):
  - About 5×10^{12} D^0 and 2×10^{12} D^{*+} collected
- Run II: higher collision energy and improved trigger$\rightarrow$more statistics than Run I

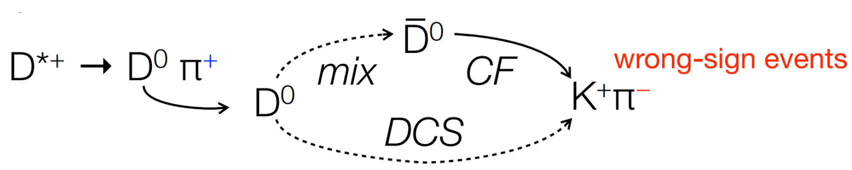




Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

- The $\mathrm{D}^0 - \bar{\mathrm{D}}^0$ mixing first observed by the BaBar and Belle experiments [Phys. Rev. Lett. 98 211802 and Phys. Rev. Lett. 98 211803 (2007)]
- To this day, $\mathrm{D}^0 - \bar{\mathrm{D}}^0$ mixing is very well established (~ 11 σ effect)
- New LHCb analysis using data from Run I (3 fb^{-1}) and Run II (2 fb^{-1})
- Study of $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ (Right-sign) and $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ (Wrong-sign) decays:





- Measurement of time-dependent WS/RS ratio $R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}}y'\frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4}(\frac{t}{\tau})^2$
- Significant yields: 1.77×10^8 RS and 7.22×10^5 WS decays
- For each fit 208 RS/WS ratio points were used: 13 time bins, magnet polarity (Up and Down), distinguishing D^{*+} and D^{*-} decays, data set

Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

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

$R^+ \neq R^-$ direct CPV

$x'^+ \neq x'^-$ CPV in mixing

$y'^+ \neq y'^-$ and interference

→ Three scenarios were studied:

a) *CPV* alloved

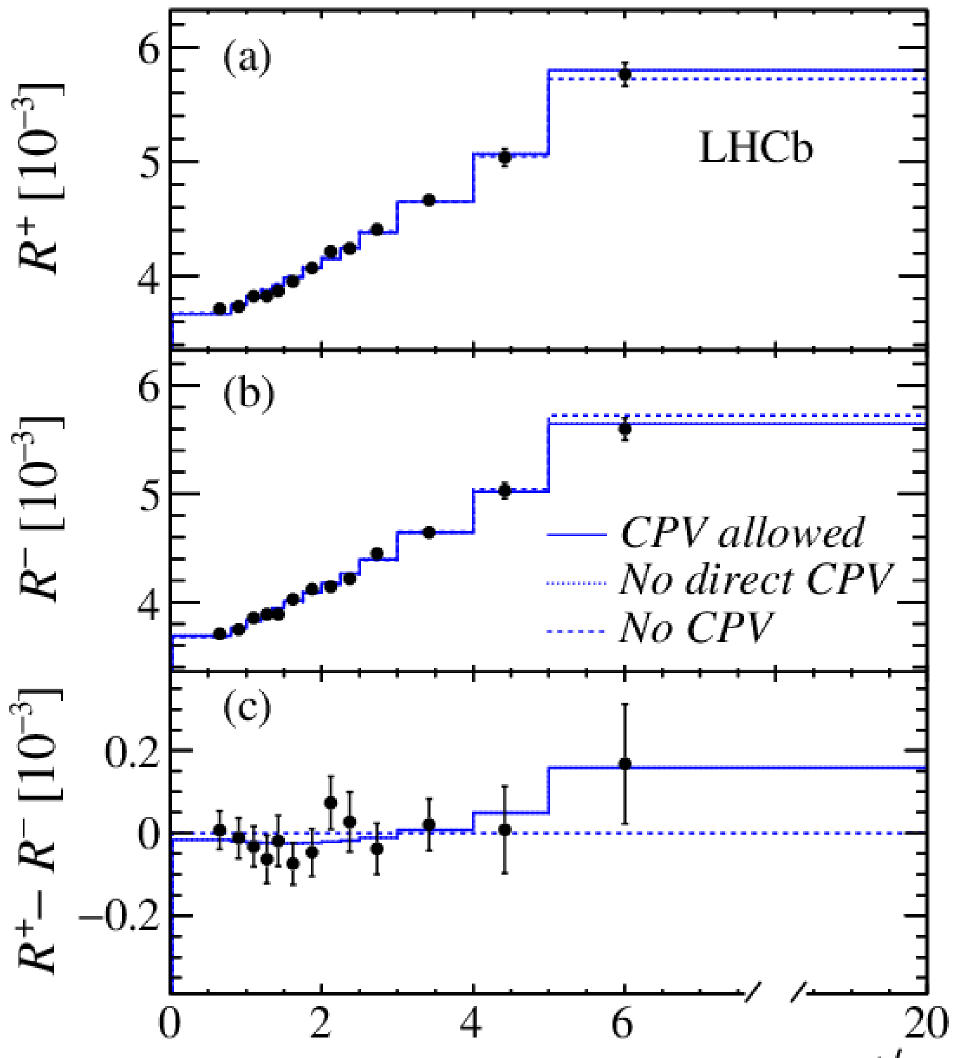
- direct and indirect *CPV* allowed

b) No Direct *CPV*

- imposed condition $R_D^+ = R_D^-$

c) No *CPV*

- *CP*-conservation hypothesis fit: all mix. parameters same for D^0 and $\bar{\mathrm{D}}^0$



arXiv: 1712.03220

Mixing of $\mathrm{D}^0 - \bar{\mathrm{D}}^0$

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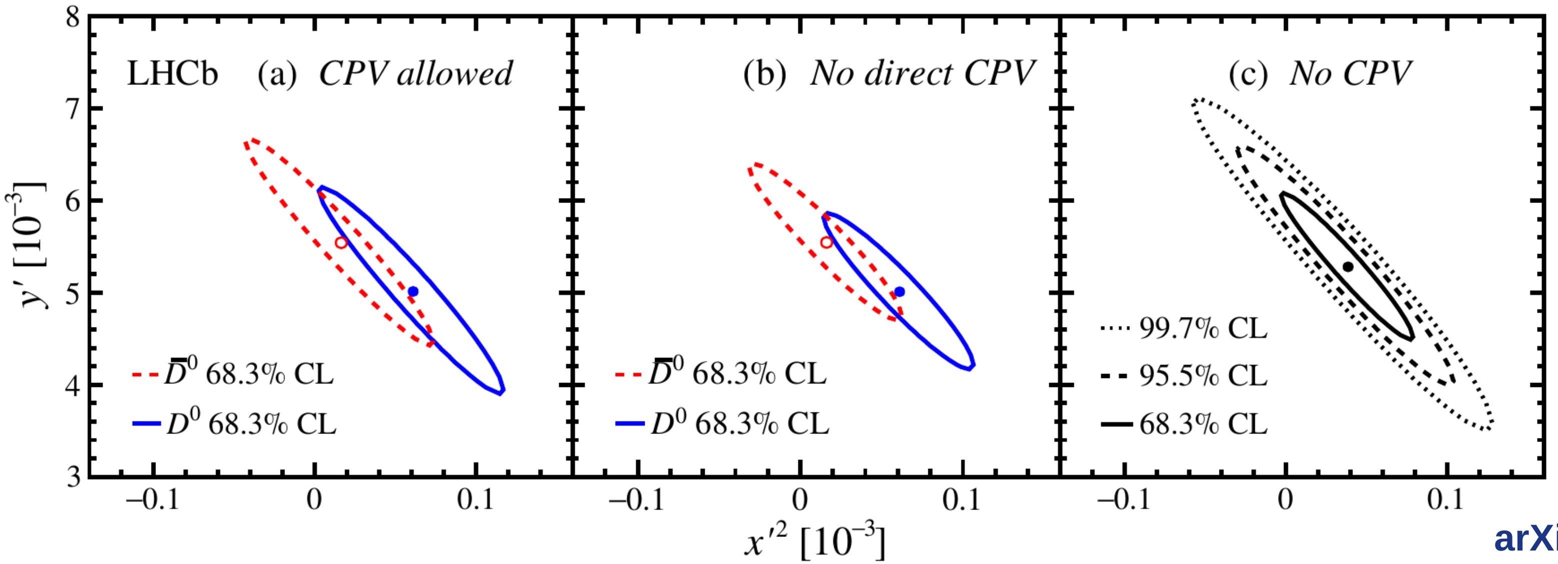

arXiv: 1712.03220

→ *CPV* parameter: $A_D = (-0.1 \pm 9.1) \times 10^{-3}$

→ Determination of $|q/p|$: $1.00 < |q/p| < 1.35$ at 68.3 % confidence level
$0.82 < |q/p| < 1.45$ at 95.5 % confidence level

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

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

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- Three scenarios were studied:
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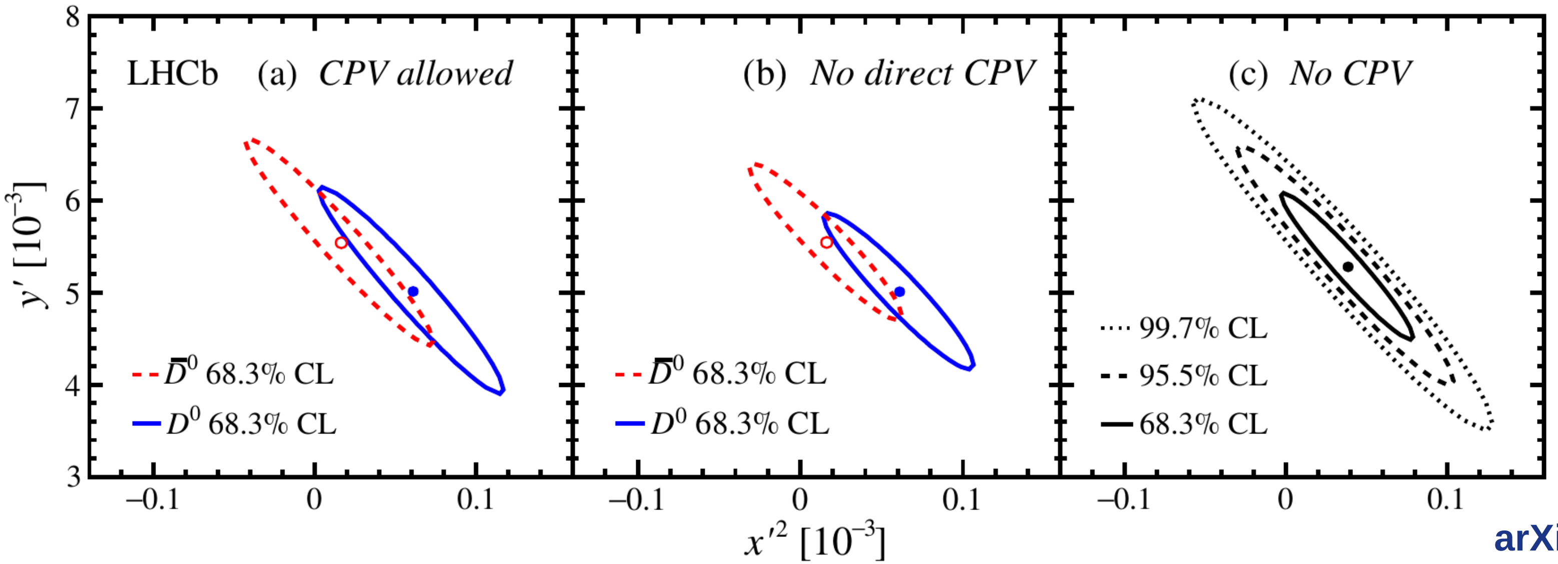
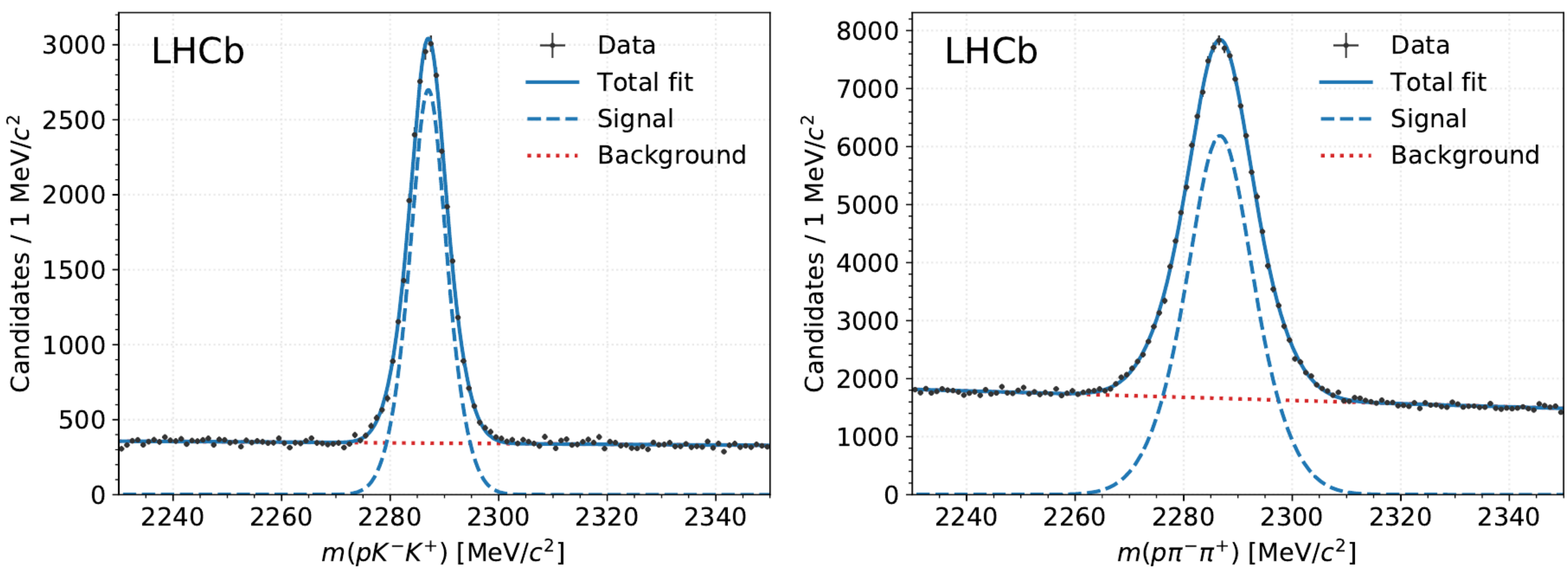


arXiv: 1712.03220

- The results are twice as precise as previous LHCb results based only on Run I data
- No evidence for CPV observed

CPV in $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$

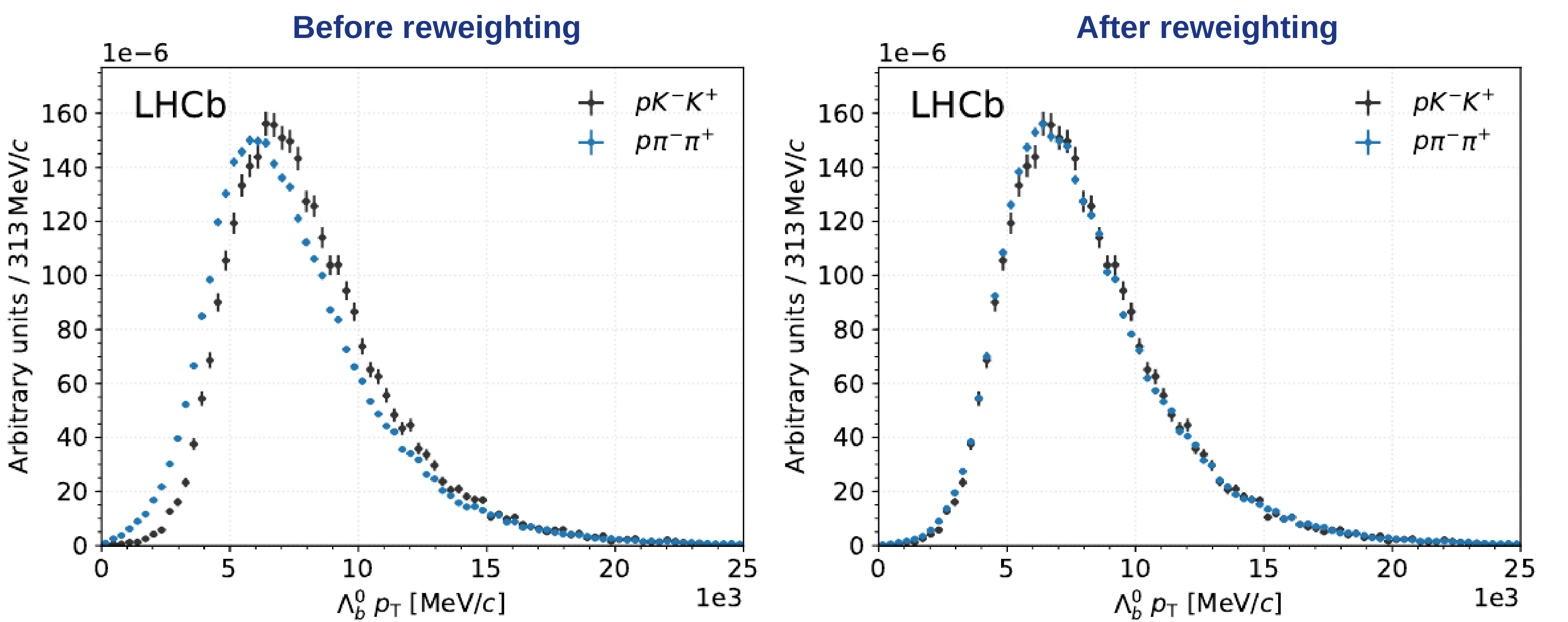
- First measurement of CPV parameters in three-body Λ_c^+ decays
- Run I (2011-2012, 3 fb^{-1}) data used
- The $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ decay channel used in order to reduce prompt background
- Two SCS decays studied: $\Lambda_c^+ \to pK^-K^+$ (25 k) $\Lambda_c^+ \to p\pi^-\pi^+$ (160 k)
- Measurement of difference $\Delta\mathcal{A}_{CP} = \mathcal{A}_{raw}(pK^-K^+) - \mathcal{A}_{raw}(p\pi^-\pi^+)$ in order to cancel production and detection asymmetry



arXiv: 1712.07051

***CPV* in $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$**

- CP asymmetry extracting: $$\Delta\mathcal{A}_{CP} = \mathcal{A}_{raw}(pK^-K^+) - \mathcal{A}_{raw}(p\pi^-\pi^+) \approx \mathcal{A}_{CP}(pK^-K^+) - \mathcal{A}_{CP}(p\pi^-\pi^+)$$
  - Production and detection asymmetries depends on the particles kinematics and pseudo-rapidity
  - Need to equalize Λ_b, p, μ kinematics between pK^-K^+ and $p\pi^-\pi^+$ data sets
  - Novel technique using GBDT (Gradient BDT) was applied for simultaneous 6D kinematic reweighting

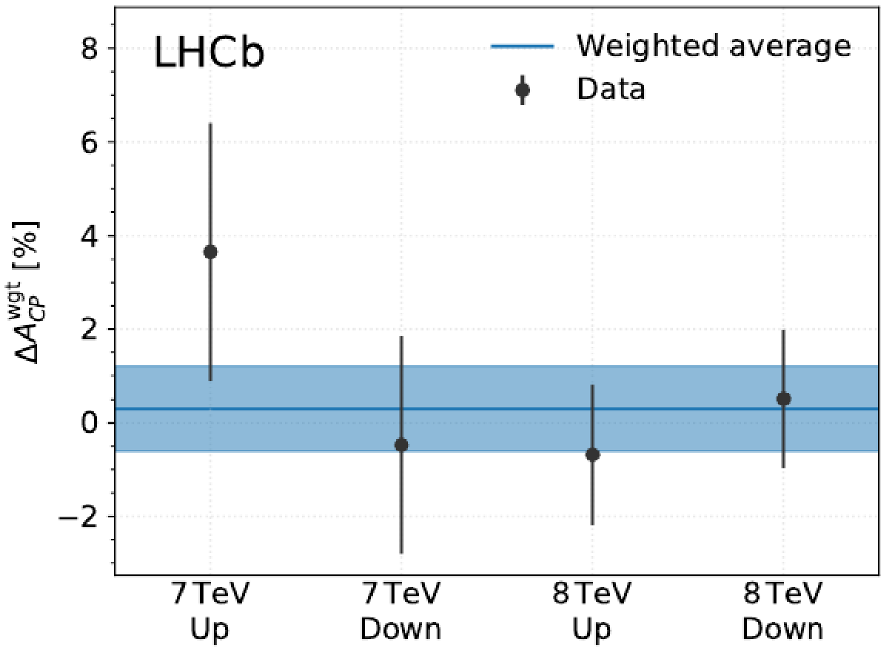


arXiv: 1712.07051

CPV in $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$

- Obtained results in the 4 bins: collision energy and magnet polarity
- First result of search for direct *CPV* search in three-body Λ_c^+ decays:

$$\Delta\mathcal{A}_{CP} = [0.30 \pm 0.91\ (\text{stat.}) \pm 0.61\ (\text{syst.})]\ \%$$

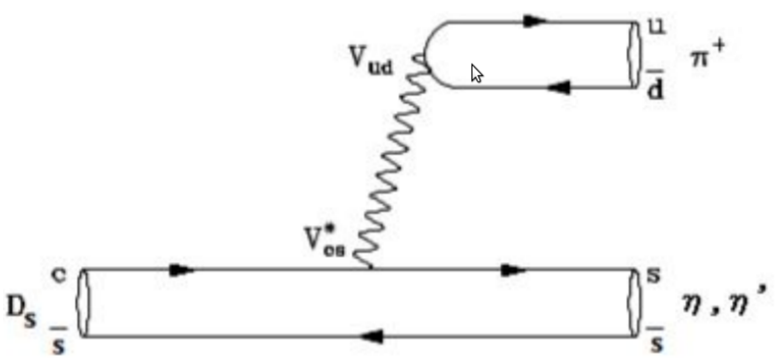


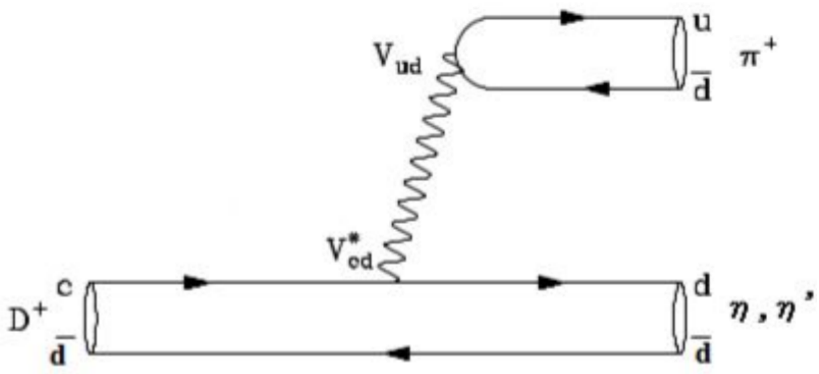
arXiv: 1712.07051

- Result shows no sign of direct *CPV*
- More data required for more precise measurement

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

- Study of CF $D_s^+ \to \eta'\pi^+$ and SCS $D^+ \to \eta'\pi^+$ decays:





- Full reconstruction chain: $D^+_{(s)} \to \eta'(\to \pi^+\pi^-\gamma)\pi^+$
- First measurement at hadron collider (very challenging photon background)
- Measurement is done via the difference parameter $\Delta\mathcal{A}_{CP}$
- For difference (and for tracking and detection asymmetries canceling) the control channels $D^+ \to K^0_s\pi^+$ and $D_s^+ \to \phi\pi^+$ are used
- Systematics is very limited by the photonic background

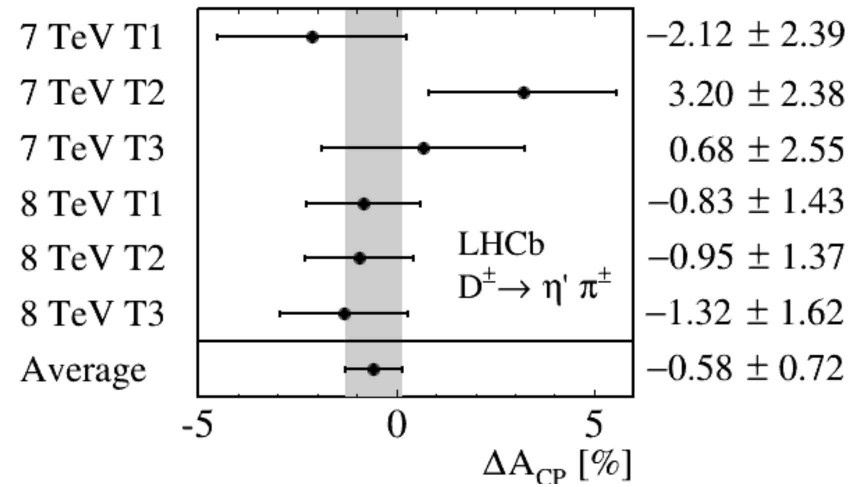
CPV in $\mathrm{D}^+_{(\mathrm{s})} \to \eta'\pi^+$

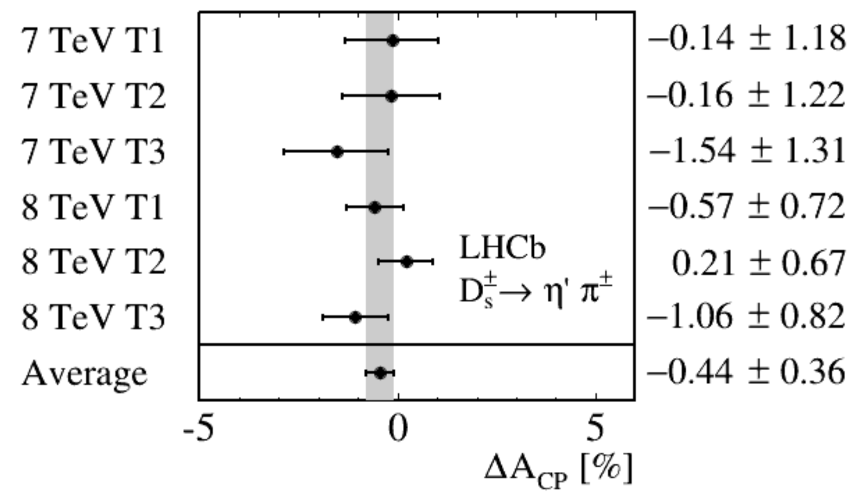
- Based on Run I data (2011-2012, 3 fb^{-1})
- Systematics is very limited by the photonic background
- CP asymmetries is then calculated as:

$$\Delta\mathcal{A}_{CP}(\mathrm{D}^\pm \to \eta'\pi^\pm) \equiv \mathcal{A}_{CP}(\mathrm{D}^\pm \to \eta'\pi^\pm) - \mathcal{A}_{CP}(\mathrm{D}^\pm \to \mathrm{K^0_S}\pi^\pm)$$
$$= \mathcal{A}_{raw}(\mathrm{D}^\pm \to \eta'\pi^\pm) - \mathcal{A}_{raw}(\mathrm{D}^\pm \to \mathrm{K^0_S}\pi^\pm) + \mathcal{A}(\bar{\mathrm{K}}^0 - \mathrm{K}^0)$$
$$\underline{\Rightarrow \mathcal{A}_{CP} \approx \Delta\mathcal{A}_{CP}(\mathrm{D}^\pm \to \eta'\pi^\pm) + \mathcal{A}_{CP}(\mathrm{D}^\pm \to \mathrm{K^0_S}\pi^\pm)}$$

$$\Delta\mathcal{A}_{CP}(\mathrm{D^\pm_s} \to \eta'\pi^\pm) \equiv \mathcal{A}_{CP}(\mathrm{D^\pm_s} \to \eta'\pi^\pm) - \mathcal{A}_{CP}(\mathrm{D^\pm_s} \to \phi\pi^\pm)$$
$$= \mathcal{A}_{raw}(\mathrm{D^\pm_s} \to \eta'\pi^\pm) - \mathcal{A}_{raw}(\mathrm{D^\pm_s} \to \phi\pi^\pm)$$
$$\underline{\Rightarrow \mathcal{A}_{CP} \approx \Delta\mathcal{A}_{CP}(\mathrm{D^\pm_s} \to \eta'\pi^\pm) + \mathcal{A}_{CP}(\mathrm{D^\pm_s} \to \phi\pi^\pm)}$$

Trigger selections: T1, T2, T3





- The most precise results to date:

$$\mathcal{A}_{\mathbf{CP}}(\mathrm{D}^\pm \to \eta'\pi^\pm) = [\mathbf{-0.61 \pm 0.72}\ (\mathbf{stat.}) \pm \mathbf{0.53}\ (\mathbf{syst.}) \pm \mathbf{0.12}\ (\mathrm{K^0_s}\pi^\pm)]\ \%$$

$$\mathcal{A}_{\mathbf{CP}}(\mathrm{D^\pm_s} \to \eta'\pi^\pm) = [\mathbf{-0.82 \pm 0.36}\ (\mathbf{stat.}) \pm \mathbf{0.22}\ (\mathbf{syst.}) \pm \mathbf{0.27}\ (\phi\pi^\pm)]\ \%$$

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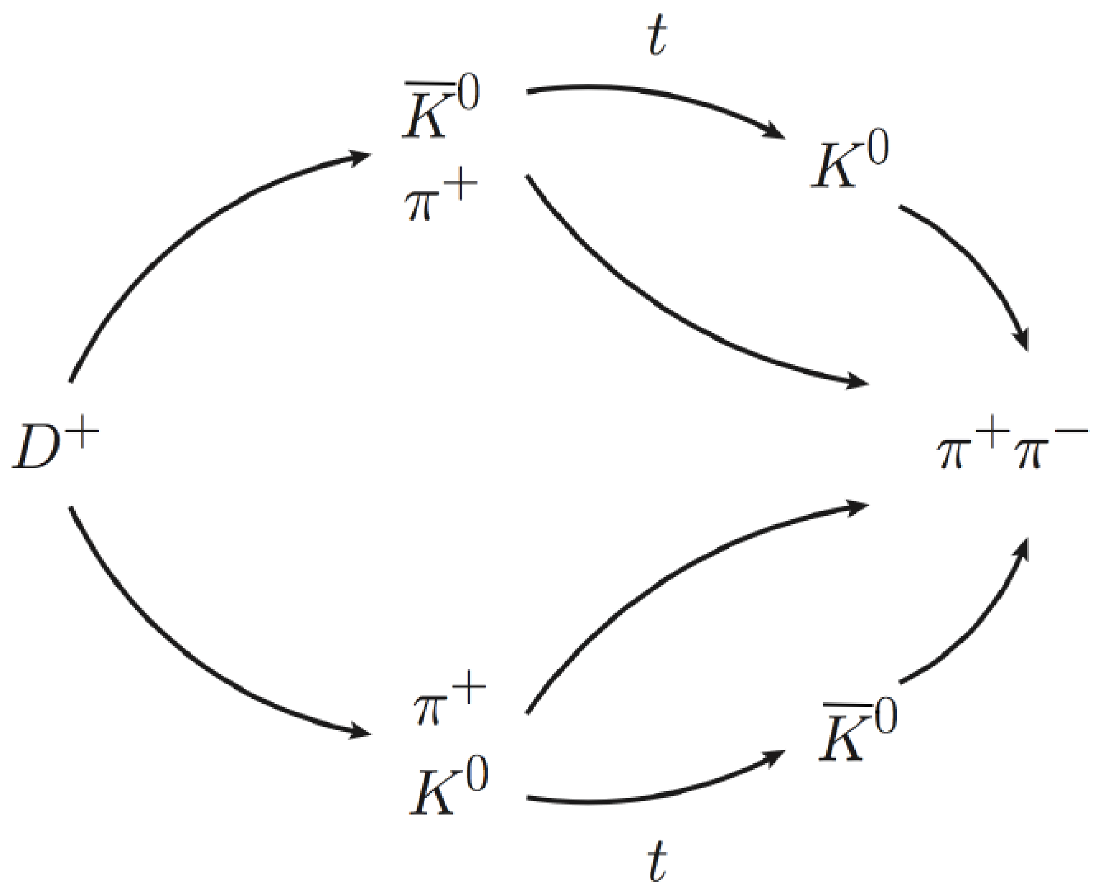
Novel effect at $\mathbf{D_{(s)}^+ \to K_S^0 h^+}$ decays

- Example: $\mathrm{D^+ \to K_S^0 \pi^+}$



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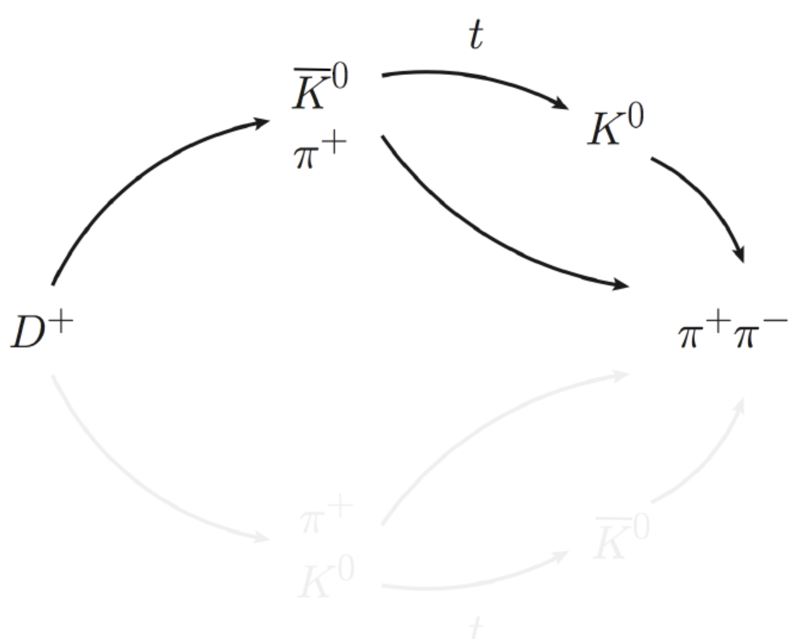


Dominant

- Belle experiment (w/o Kaon mix.)

$$\mathcal{A}_{CP}^{\mathrm{D^+ \to K^0_S}\pi^+} = (-0.024 \pm 0.094 \pm 0.067)\ \%$$

[Phys. Rev. Lett. 109, 021601 (2012)]

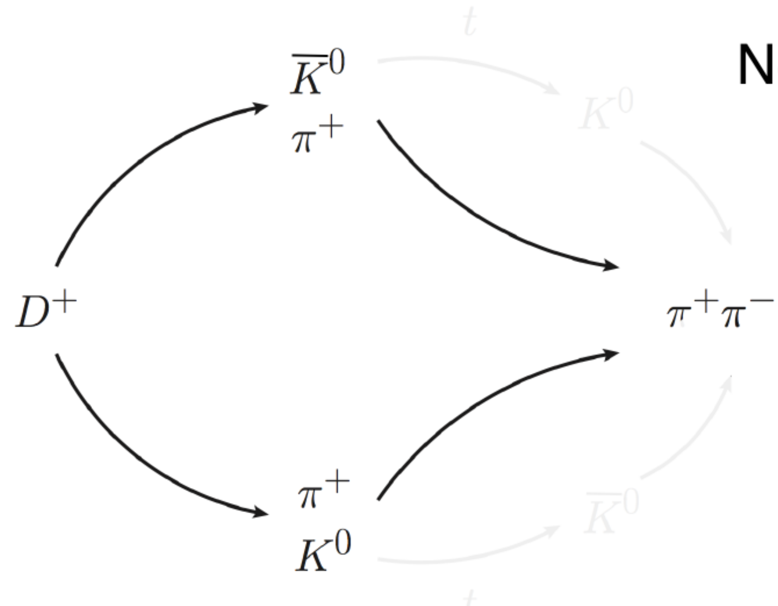
- Effect of the the Kaon mixing:

$$\mathcal{A}_{CP}^{\mathrm{K^0 - \bar{K}^0}} = (-0.339 \pm 0.007)\ \%$$

- [Phys. Rev. D. 81, 052013 (2010)]

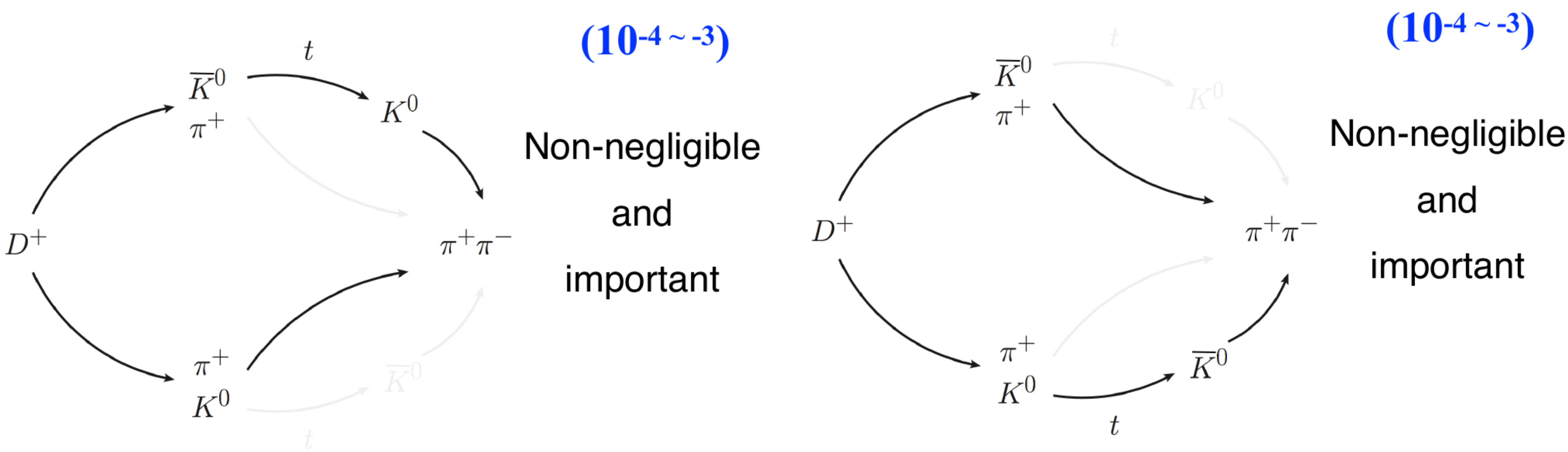
- Direct CPV in charm decays, is expected to be of order 10^{-5} in **SM**

Negligible in SM



Novel effect at $\mathrm{D}^+_{(\mathrm{s})} \to \mathrm{K^0_S h^+}$ decays

- A new CPV effect in charm decays into the neutral kaons arising from the CF and DCS amplitudes interference is suggested by YU Fu-Sheng [Phys. Rev. Lett. 119, 181802 (2017)]



- This effect is estimated to be in order 10^{-3} $\rightarrow$ experimentally accessible by the **LHCb** and Belle-II

Mode-independent measurement

- The mode-independent measurement of new CPV effect can be done via constructing the $\Delta\mathcal{A}_{CP}$ of $\mathrm{D_s^+} \to \mathrm{K_S^0K^+}$and $\mathrm{D^+} \to \mathrm{K_S^0}\pi^+$ decay channels:

$$\begin{aligned}\Delta\mathcal{A}_{CP} &\equiv \mathcal{A}_{CP}(\mathrm{D^+} \to \mathrm{K_S^0}\pi^+) - \mathcal{A}_{CP}(\mathrm{D_s^+} \to \mathrm{K_S^0K^+}) \\ &= [\mathcal{A}_{raw}(\mathrm{D^+} \to \mathrm{K_S^0}\pi^+) - \mathcal{A}_{raw}(\mathrm{D^+} \to \mathrm{K^-}\pi^+\pi^+)] \\ &- [\mathcal{A}_{raw}(\mathrm{D_s^+} \to \mathrm{K_S^0K^+}) - \mathcal{A}_{raw}(\mathrm{D_s^+} \to \mathrm{K^-}\pi^+\mathrm{K^+})]\end{aligned}$$

- The $\mathrm{D^+} \to \mathrm{K^-}\pi^+\pi^+$ and $\mathrm{D_s^+} \to \mathrm{K^-}\pi^+\mathrm{K^+}$ decay channels are taken as a control modes to cancel the K/π tracking asymmetry
- Also the $\mathrm{D_{(s)}^+}$ production asymmetry and $\mathrm{K_S^0}$ detection asymmetry should be mostly removed
- LHCb Run II data will be used for this analysis, utilizing the largest measured sample of charm decays
- Sensitivity expectation with Run II data (prospect with the full Run II data):

$$\mathrm{D^+} \to \mathrm{K_S^0}\pi^+ : \ \delta\mathcal{A}_{CP}^{raw} = 0.03\ \%$$

$$\mathrm{D_s^+} \to \mathrm{K_S^0K^+} : \ \delta\mathcal{A}_{CP}^{raw} = 0.07\ \%$$

Conclusion

- Charm physics is still of a great importance
- Precision measurements of *CPV* are a fundamental tools to probe **SM**

  at energy scales and couplings unaccessible at the energy frontier
- Most recent results regarding measurements of charmed mesons *CPV* were presented
  - New results on $\mathrm{D}^0 - \bar{\mathrm{D}}^0$ mixing are twice as precise as previous results
  - First measurement of Direct CPV in $\mathrm{D}^+_{(\mathrm{s})} \to \eta' \pi^+$ decay channels
  - Also presented first *CPV* measurement in charmed baryons three-body decays: $\Lambda_\mathrm{c}^+ \to \mathrm{pK}^-\mathrm{K}^+$ and $\Lambda_\mathrm{c}^+ \to \mathrm{p}\pi^-\pi^+$
- Still <u>no signal of *CPV* (Direct or Indirect) in charm sector observed</u>
- Key measurements are mainly limited by the statistics $\to$ with Run II data the 10^{-3} precision now becoming possible
- Such a precision open a way to measure a novel effect suggested in $\mathrm{D}^+_{(\mathrm{s})} \to \mathrm{K}^0_\mathrm{S}\mathrm{h}^+$ decays

Thank you for your attention

BACKUP
Slides

CPV theory introduction

Indirect *CPV* can be divided into two groups: *CPV* in mixing (not depending on final state) and *CPV* in interference

I. *CPV* in mixing

- D mesons are produced as flavor eigenstates, but decays as mass eigenstates D_1 and D_2: $|\mathrm{D}_1\rangle = p|\mathrm{D}^0\rangle + q|\bar{\mathrm{D}}^0\rangle$, $|\mathrm{D}_2\rangle = p|\mathrm{D}^0\rangle - q|\bar{\mathrm{D}}^0\rangle$, $|q|^2 + |p|^2 = 1$
- Associated mixing parameters: $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{\Gamma}$, where: $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$
- Mixing occurs in the case: $\Delta M = M_1 - M_2 \neq 0$ or $\Delta\Gamma = \Gamma_1 - \Gamma_2 \neq 0$
- Accessible using flavor specifics decays
- No mass difference or *CPV* in mixing observed so far

II. *CPV* in interference

- Possibility of mixing and decay amplitudes interference
- Associated parameter: $\phi = arg(\frac{q\bar{A}_f}{pA_f})$
- Can be observed as a decay-time-dependent difference in decay rates and as a time-integrated difference

→ More precise measurement of x and y are needed

CPV theory introduction

- Direct *CPV* occurs in the case of different decay amplitudes for D and $\bar{\mathrm{D}}$

$$\begin{aligned} A_f &= \langle f|H|\mathrm{D}\rangle \\ \bar{A}_{\bar{f}} &= \langle \bar{f}|H|\bar{\mathrm{D}}\rangle \end{aligned} \longrightarrow \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

- Direct *CPV* can be observed as difference in decay rates between particles and antiparticles: $$A_{raw} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$

- Depends on decay mode, typically $A_{CP} < 10^{-3} - 10^{-4}$ for Singly Cabbibo Suppresed decays in **SM**

- Measurements are time independent

- Experimentally challenging due to need of canceling several production and detection asymmetries

- Only *CPV* type possible for charged charmed hadrons

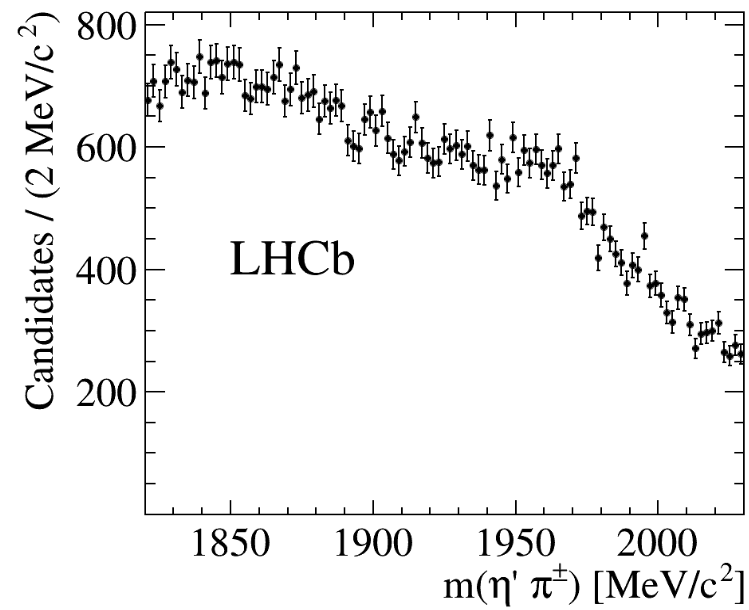
- No direct *CPV* in charm sector observed so far

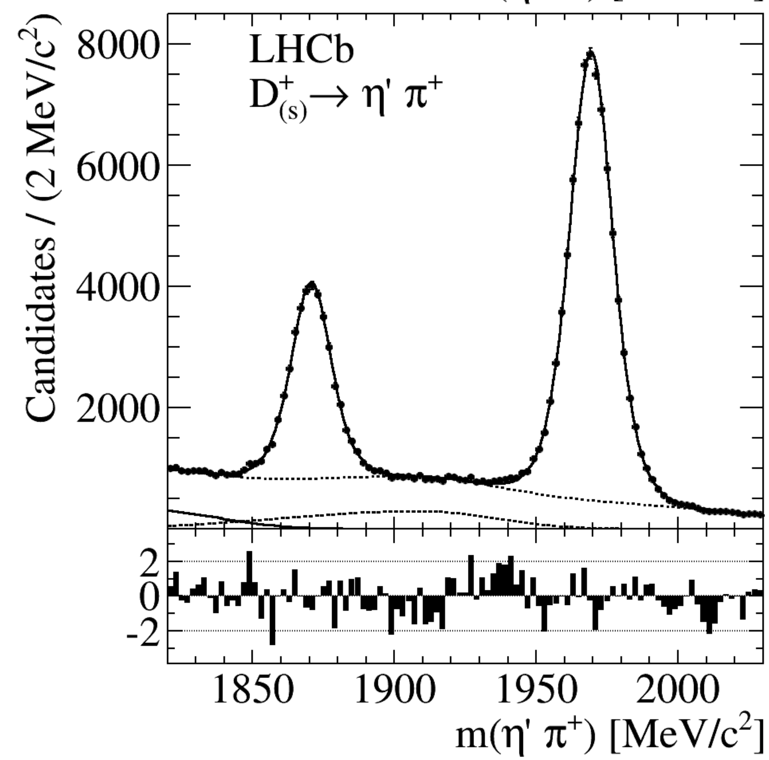
CPV in $D^+_{(s)} \to \eta'\pi^+$

- Data from Run I (2011-2012, 3 fb^{-1})
- Full reconstruction chain:

  $D^+_{(s)} \to \eta'(\to \pi^+\pi^-\gamma)\pi^+$

- First measurement at hadron collider (very challenging photon background)
- Data divided into 12 subsamples:
  - Energy (7 and 8 TeV)
  - Magnet polarity (Up and Down)
  - 3 Trigger selections
- Each subsample then divided into 3(p_T) x 3(η) bins based on bachelor pion
- Systematics limited by the background





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$R^+ \neq R^-$ direct CPV

$x'^+ \neq x'^-$ CPV in mixing

$y'^+ \neq y'^-$ and interference

- Previous results based on Run I data
- Three scenarios were studied:
  - a) *CPV* allowed - direct and indirect *CPV* allowed
  - b) No Direct *CPV* - imposed condition $R_D^+ = R_D^-$
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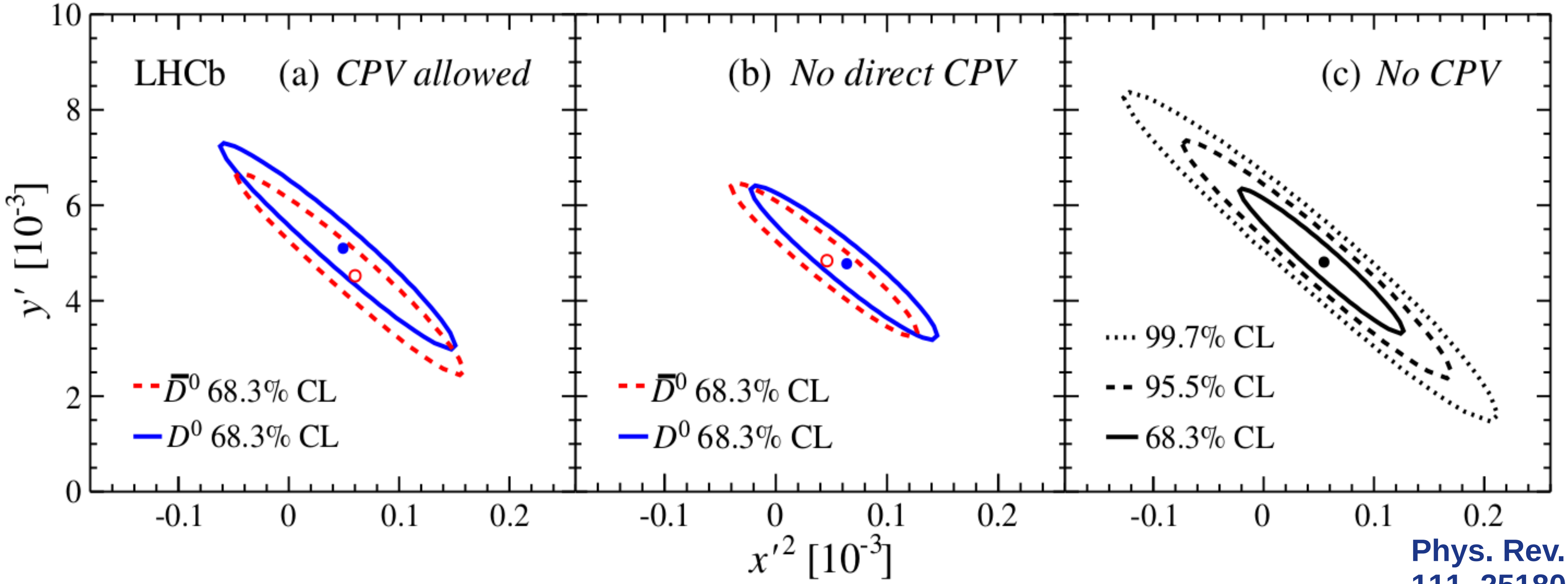

Phys. Rev. Lett. 111, 251801 (2013)

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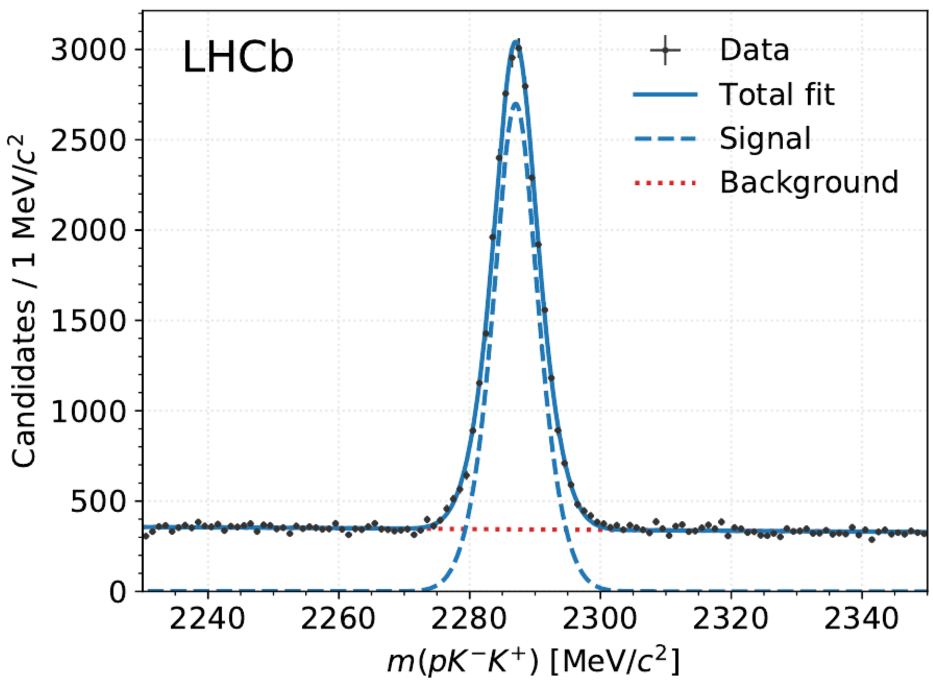
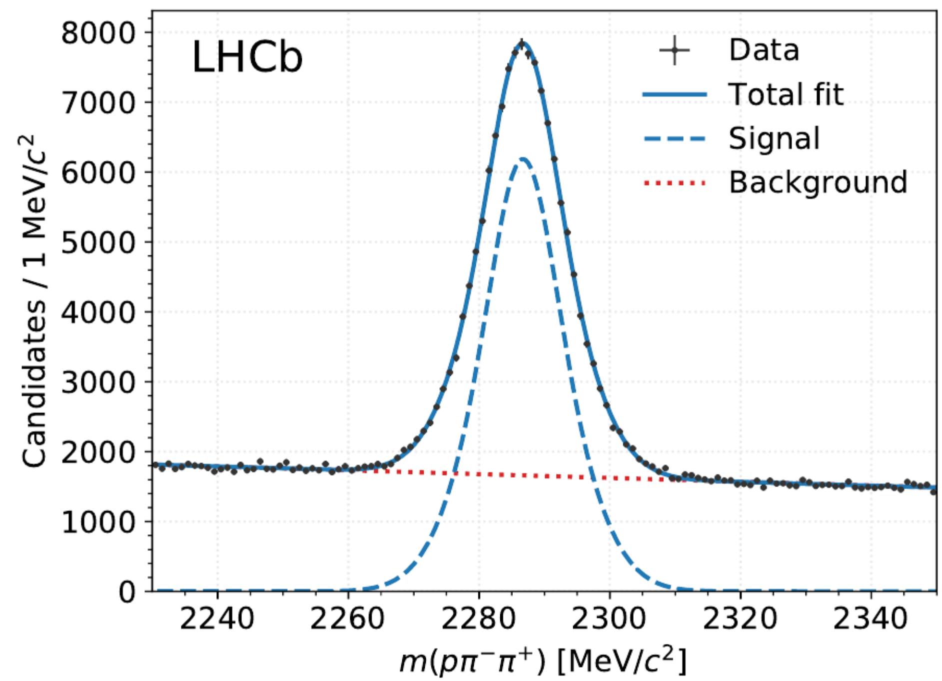
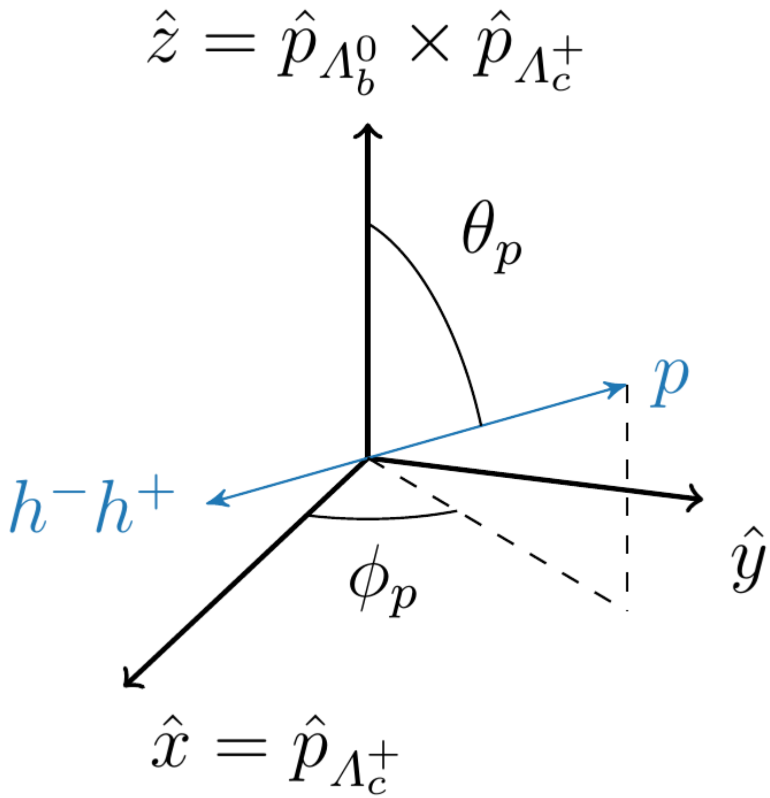
- First measurement of CPV parameters in three-body Λ_c^+ decays
- Run I (2011-2012, 3 fb^{-1}) data used
- The $\Lambda_b^0 \to \Lambda_c^+\mu^- X$ decay channel used in order to reduce prompt background
- Two decays studied: $\Lambda_c^+ \to pK^-K^+$ (25 k) $\Lambda_c^+ \to p\pi^-\pi^+$ (160 k)
- Measurement of difference $\Delta A_{CP} = A_{raw}(pK^-K^+) - A_{raw}(p\pi^-\pi^+)$ in order to cancel production and detection asymmetry

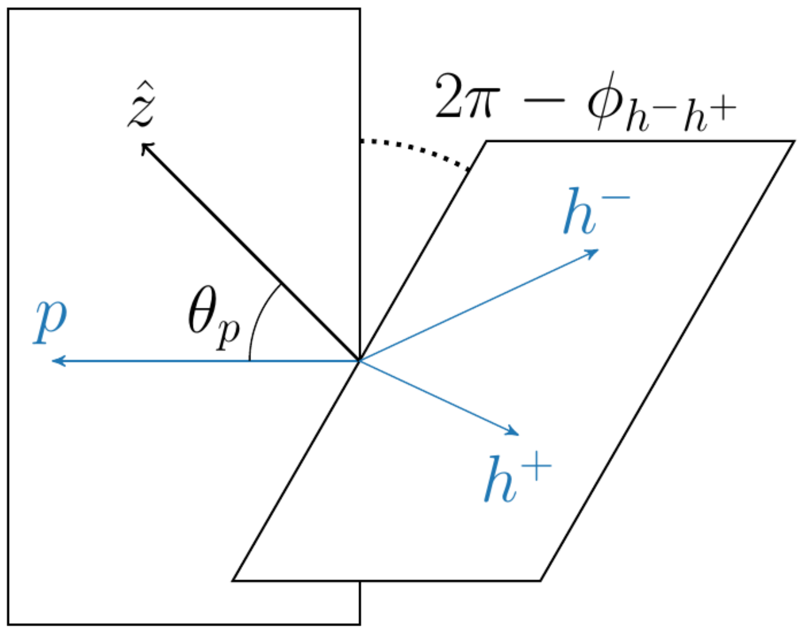




arXiv: 1712.XXXXX

Λ_c^+ - coordinate system





- Definition of coordinate system for Lambda_c analysis

Λ_c^+ - uncertainties

- Main source of systematics uncertainties arise from the size of MC sample

Source	Uncertainty [%]
Fit model	0.20
Residual asymmetries	0.10
Finite MC	0.57
Prompt Λ_c^+	—
Total	0.61

Λ_c^+ - dalitz ploy