

Ricerca di violazione diretta di CP nei decadimenti dei mesoni D^0 a LHCb



**Federico Betti per conto della
Collaborazione LHCb**

Incontri di Fisica delle Alte Energie 2019

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- Violazione di CP nel settore del charm **non ancora osservata**
- I decadimenti del charm permettono di testare la violazione di CP in quark di **tipo up**
- **Complementare** agli studi con mesoni K e B
- Predizioni del Modello Standard difficili da calcolare, ma piccole asimmetrie di CP sono previste ($\sim 10^{-4} - 10^{-2}$)

PLB 222 (1989) 501
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Ann. Rev. Nucl. Part. Sci. 58 (2008) 249
PLB 774 (2017) 235
... e molti altri

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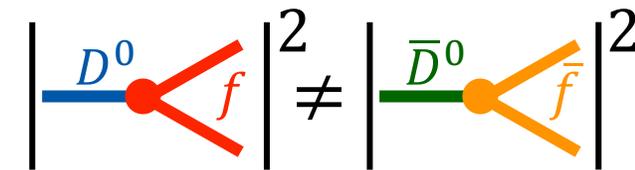
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Violazione di CP diretta e indiretta

$$A_{CP}(f) = \frac{\Gamma(M \rightarrow f) - \Gamma(\bar{M} \rightarrow \bar{f})}{\Gamma(M \rightarrow f) + \Gamma(\bar{M} \rightarrow \bar{f})}$$

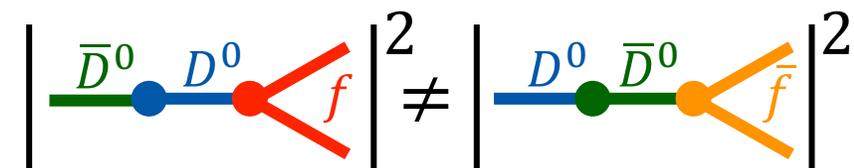


- Violazione **diretta** di CP quando $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$
- Per **mesoni neutri** che oscillano $|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle$

- Violazione di CP nell'**oscillazione** quando $|p| \neq |q|$

- Violazione di CP nell'**interferenza** tra decadimento e oscillazione quando

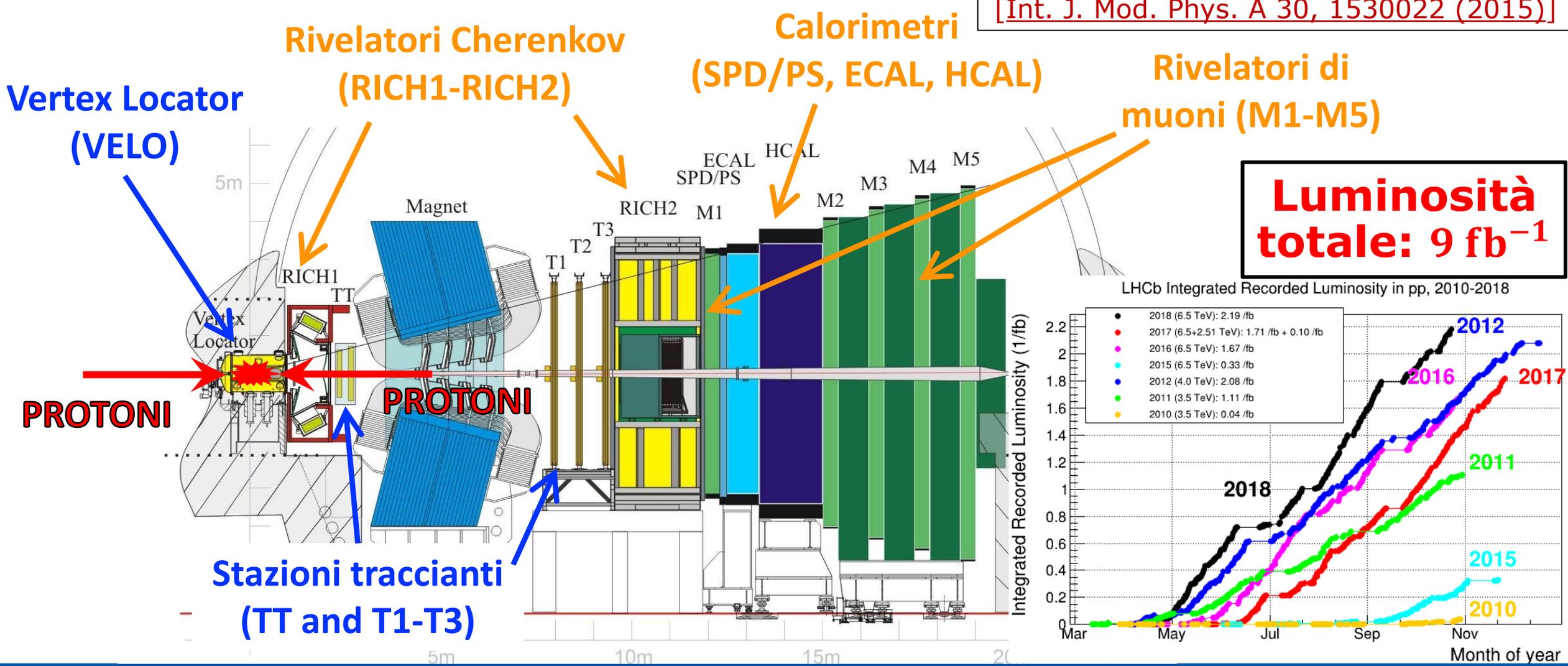
$$\arg\left(\frac{q \bar{A}_f}{p A_f}\right) \neq -\arg\left(\frac{q \bar{A}_{\bar{f}}}{p A_{\bar{f}}}\right)$$



Il rivelatore LHCb



[Int. J. Mod. Phys. A 30, 1530022 (2015)]



Luminosità totale: 9 fb^{-1}

A_{CP} in $D_S^+ \rightarrow K_S^0 \pi^+$, $D^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow \phi \pi^+$

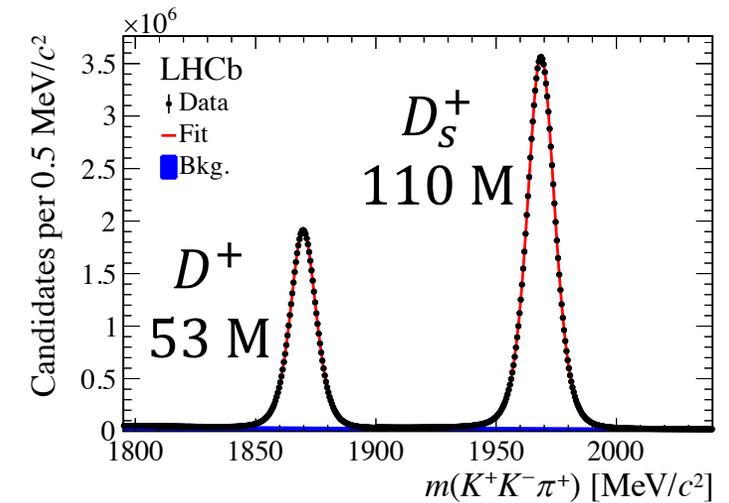
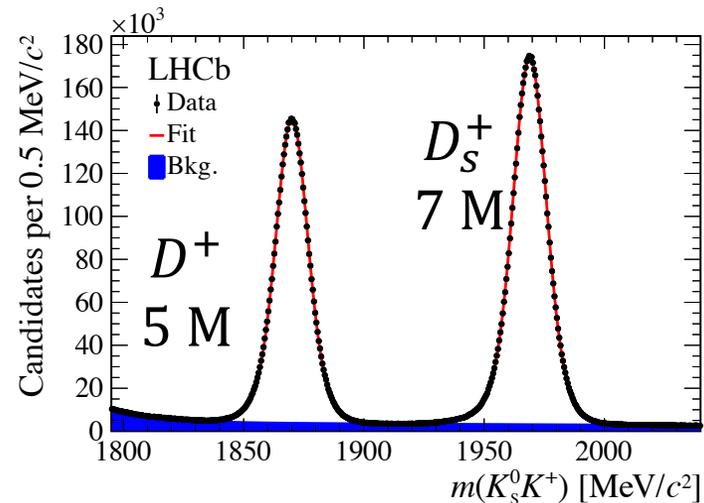
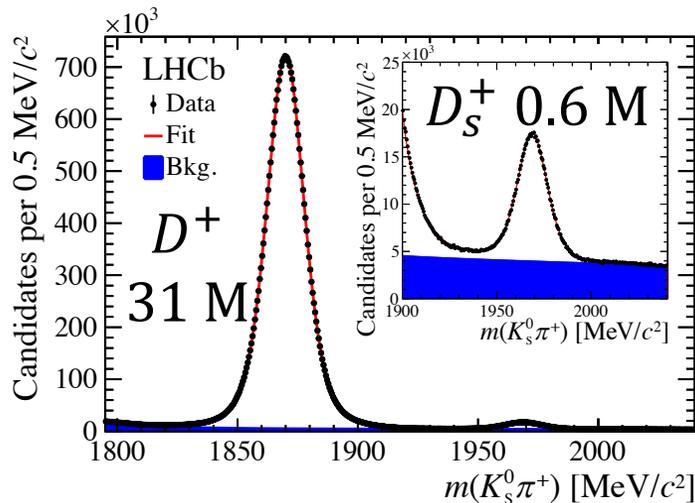
arXiv:1903.01150

$$A_{CP}(D_S^+ \rightarrow K_S^0 \pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3}$$

$$A_{CP}(D^+ \rightarrow K_S^0 K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}$$

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3}$$

Run 2
(3.8 fb⁻¹)



Consistente con conservazione di CP

Misura di ΔA_{CP}

ΔA_{CP} – Stato attuale

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

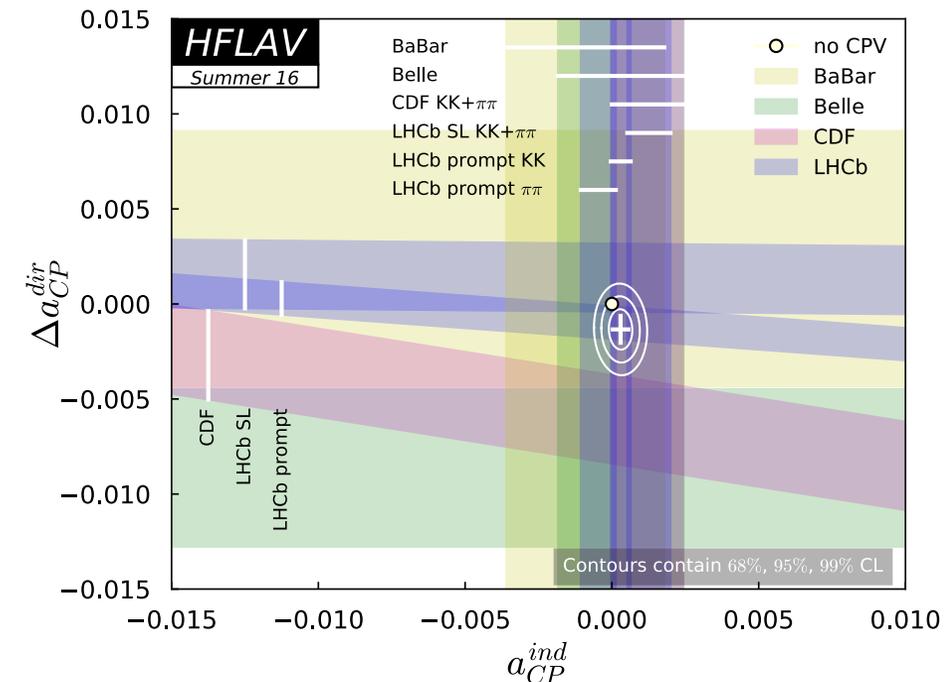
$$\simeq \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

Assunzione:
 a_{CP} nell'interferenza
 decadimento/oscilla
 zione e universale

$$\overline{\langle t \rangle} = (\langle t \rangle_{KK} + \langle t \rangle_{\pi\pi})/2$$

$$\Delta t = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$$

- a_{CP}^{ind} vincolato principalmente da misure di A_Γ
- ΔA_{CP} maggiormente sensibile a $\Delta a_{CP}^{\text{dir}}$



ΔA_{CP} – Stato attuale

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

$$\simeq \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

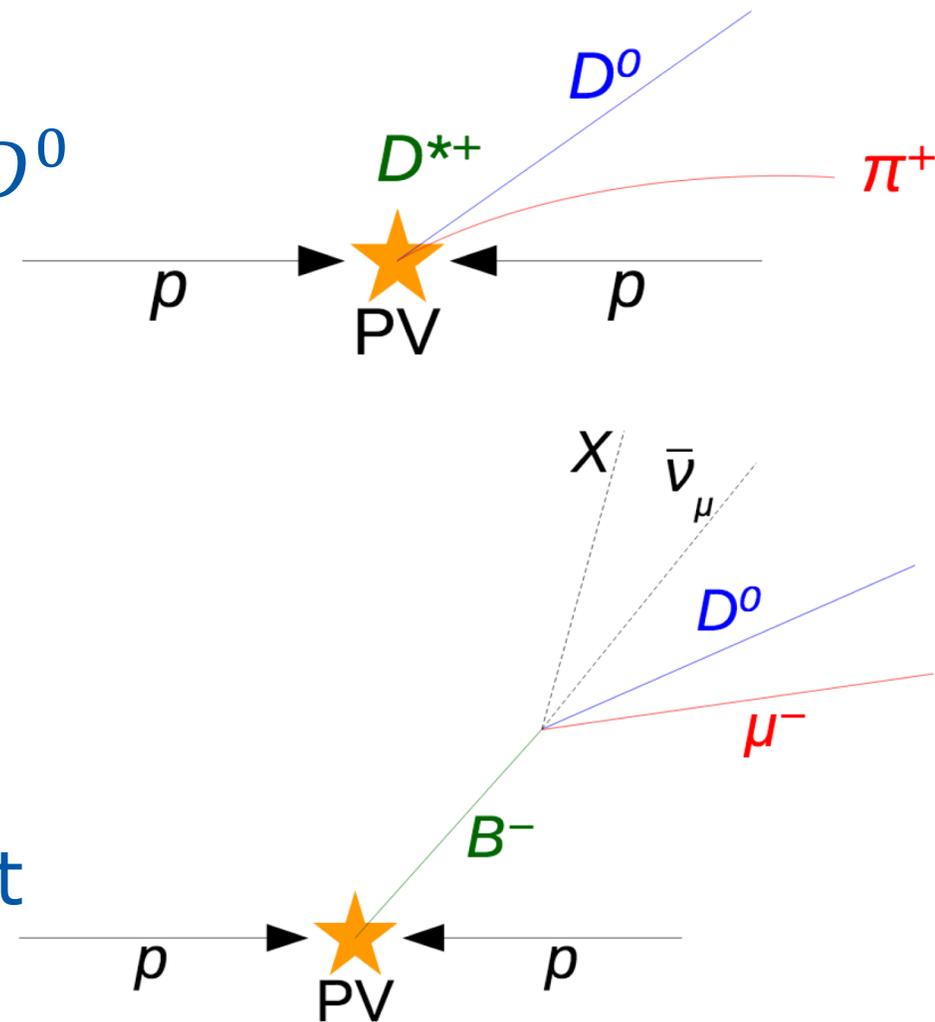
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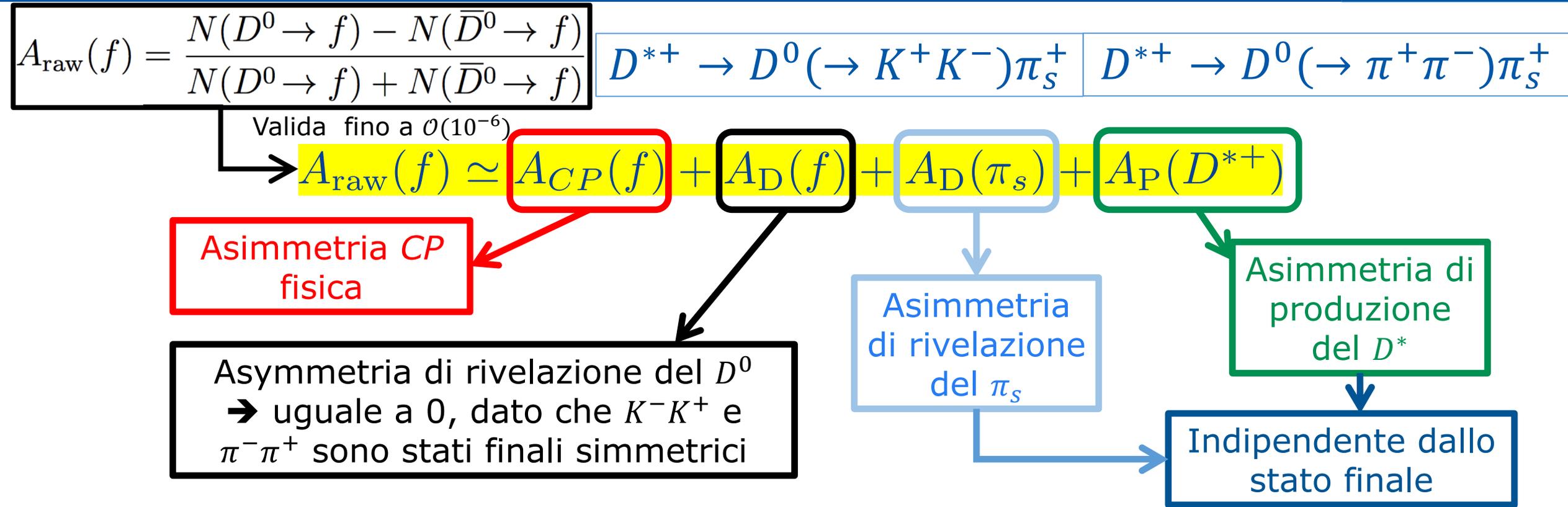
Experiment	ΔA_{CP}	
CDF	$(-62 \pm 21 \pm 10) \times 10^{-4}$	PRL 109 (2012) 111801
BaBar	$(+24 \pm 62 \pm 26) \times 10^{-4}$	PRL 100 (2008) 061803
Belle	$(-87 \pm 41 \pm 6) \times 10^{-4}$	arXiv:1212.1975
LHCb (3.0 fb ⁻¹ , muon-tagged)	$(+14 \pm 16 \pm 8) \times 10^{-4}$	JHEP 07 (2014) 041
LHCb (3.0 fb ⁻¹ , pion-tagged)	$(-10 \pm 8 \pm 3) \times 10^{-4}$	PRL 116 (2016) 191601

- Misure più **precise** effettuate da LHCb con i dati del Run 1
- Oggi: misura con **tutto il Run 2 (6 fb⁻¹)**

- Consiste nel guardare la **carica** della particella che accompagna il D^0
- Da vertice primario (**prompt**):
 $D^{*\pm} \rightarrow D^0 \pi^\pm$
 - Il D^0 punta al vertice primario (PV)
 - Accettanza sul tempo di decadimento
- **Semileptonico**: $B \rightarrow D^0 \mu^\pm X$
 - Il D^0 non punta al PV
 - Statistica più bassa rispetto al prompt



Strategia – Identificazione prompt



Se le **cinematiche** del D^{*+} e del π_s per i due modi di decadimento sono uguali

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

Strategia – Identificazione SL

$$A_{\text{raw}}(f) = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)}$$



Valida fino a $\mathcal{O}(10^{-6})$

$$A_{\text{raw}}(f) \simeq A_{CP}(f) + A_D(f) + A_D(\mu^-) + A_P(\bar{B})$$

Asimmetria CP fisica

Asimmetria di rivelazione del D^0
 \rightarrow uguale a 0, dato che $K^- K^+$ e $\pi^- \pi^+$ sono stati finali simmetrici

Asimmetria di rivelazione del μ^-

Asimmetria di produzione del \bar{B}

Indipendente dallo stato finale

Se le **cinematiche** del \bar{B} e del μ^- per i due modi di decadimento sono uguali

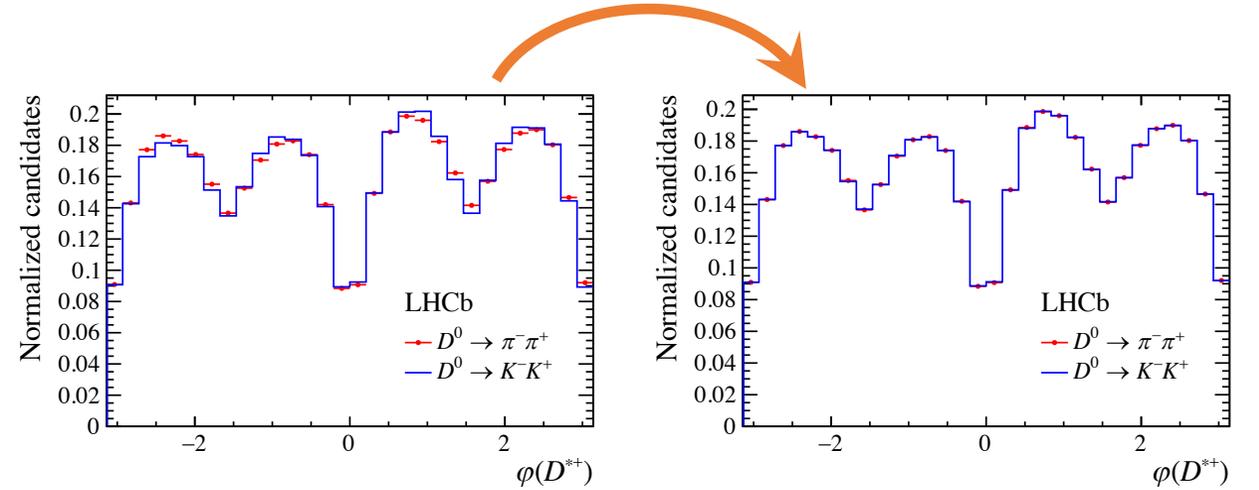
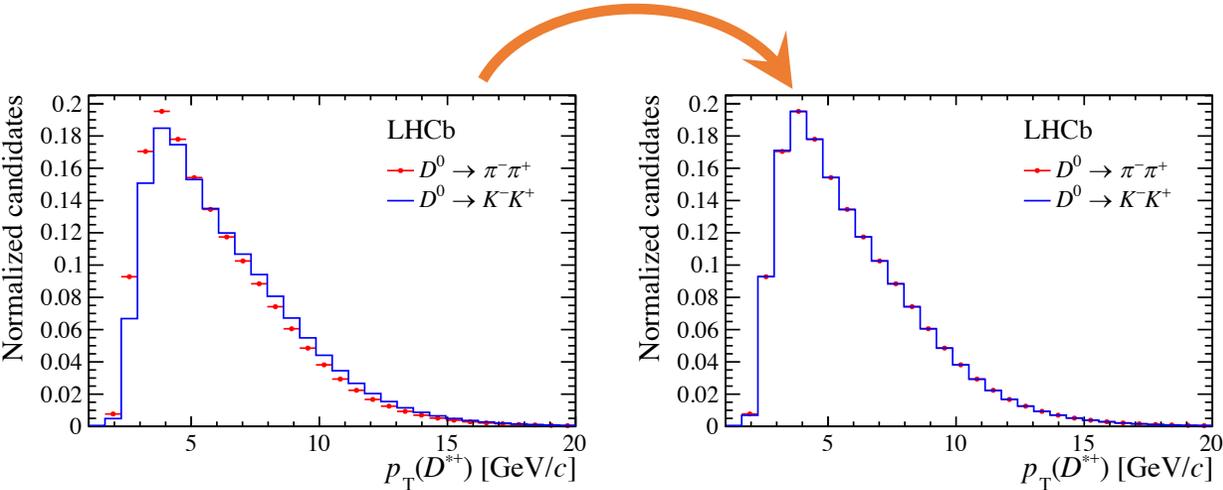
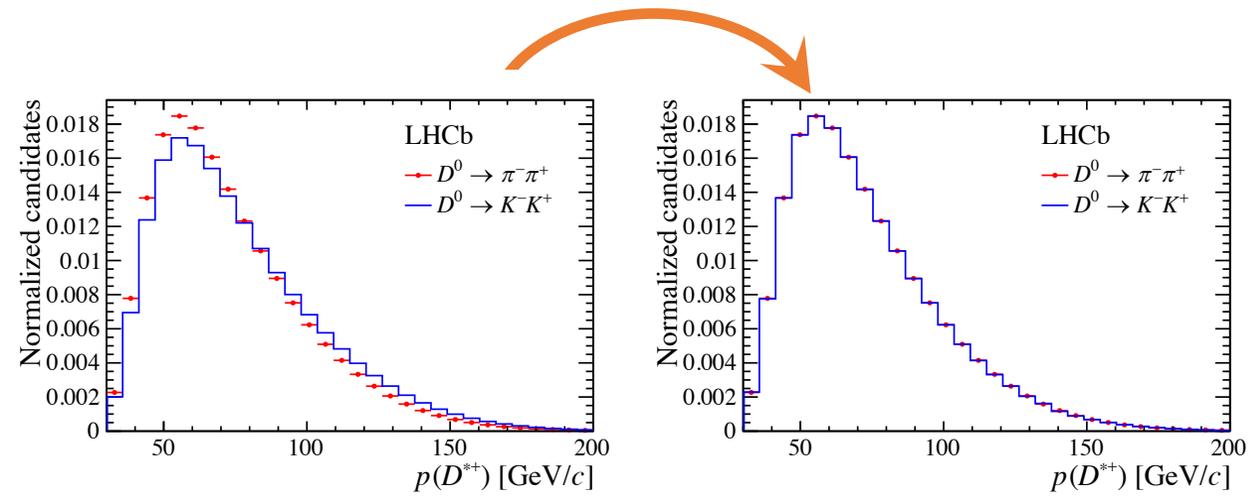
$$\Rightarrow A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) = A_{\text{raw}}(K^- K^+) - A_{\text{raw}}(\pi^- \pi^+)$$

Ripesamento della cinematica

Ripesamento della cinematica del KK al $\pi\pi$:

- **Prompt:** $p_T(D^*), p(D^*), \phi(D^*)$
- **SL:** $p_T(D^0), p(D^0), \phi(D^0)$

Cambiamento molto piccolo di ΔA_{CP}

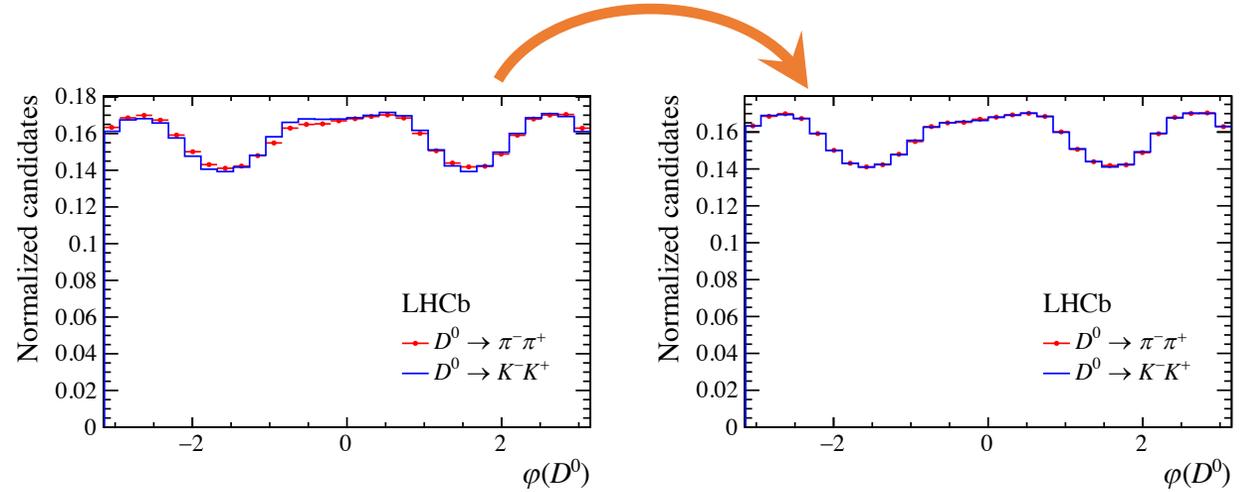
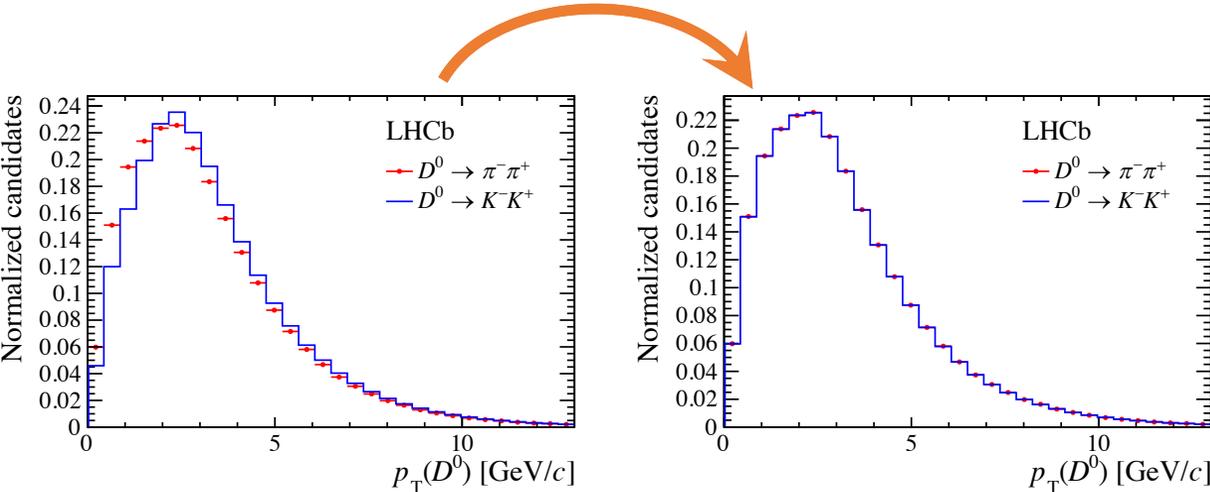
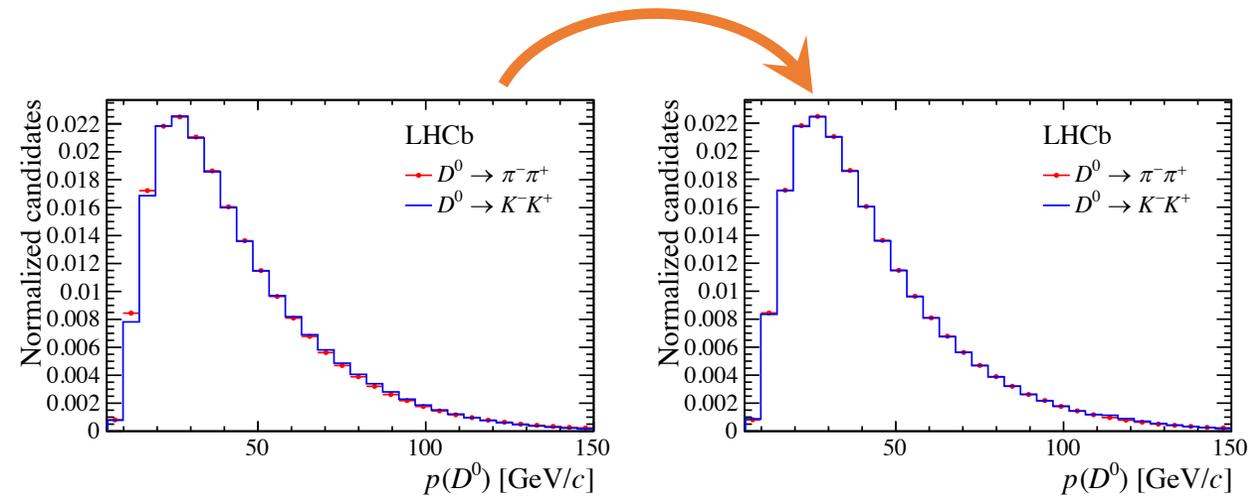


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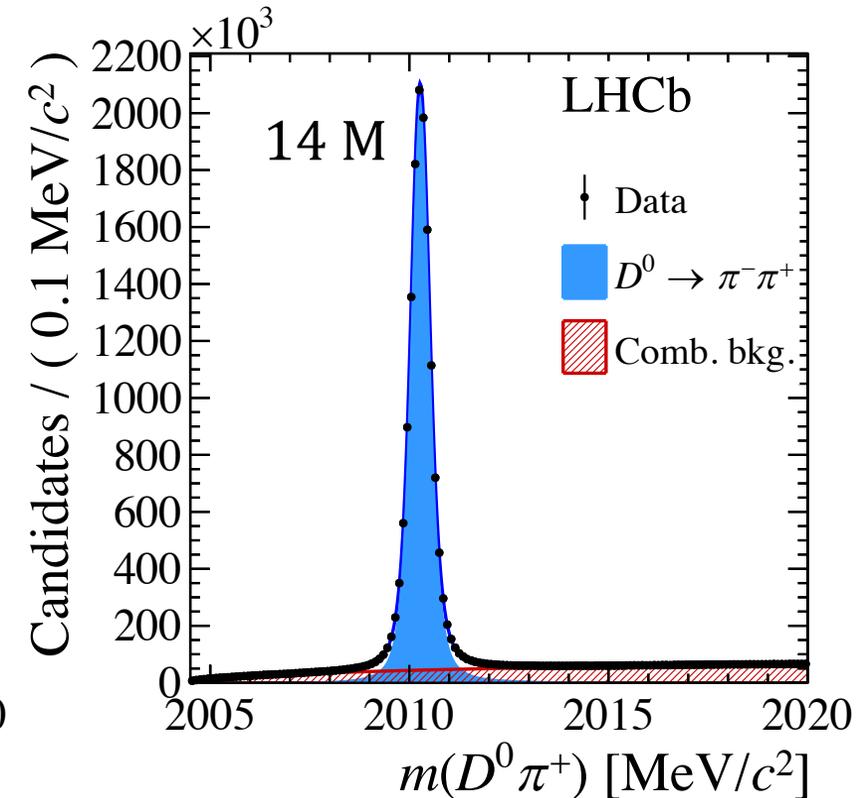
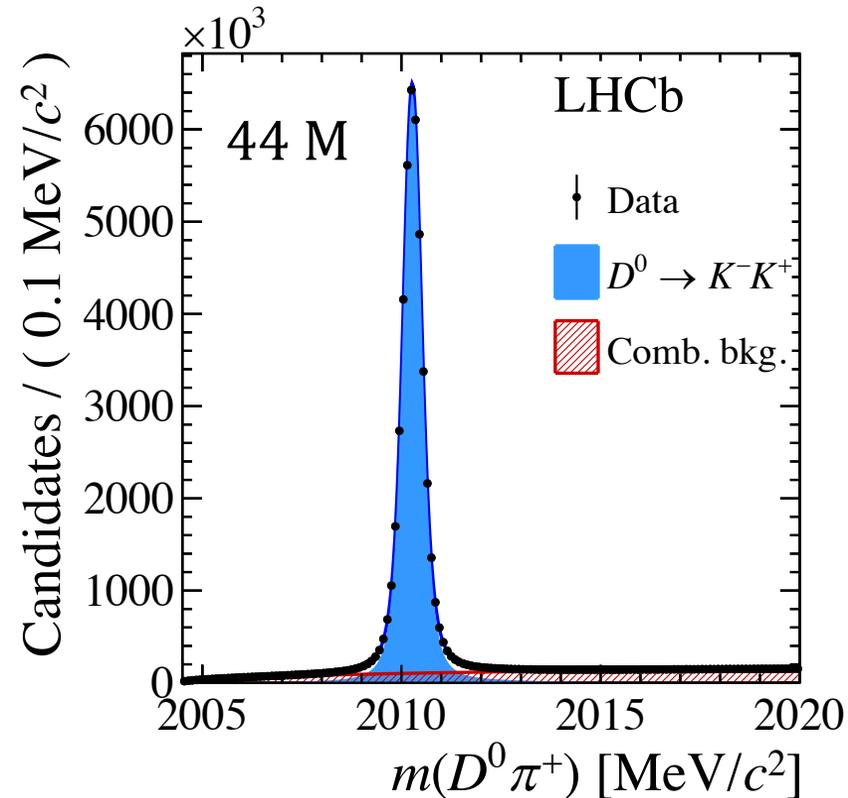
- **Prompt:** $p_T(D^*), p(D^*), \phi(D^*)$
- **SL:** $p_T(D^0), p(D^0), \phi(D^0)$

Cambiamento molto piccolo di ΔA_{CP}



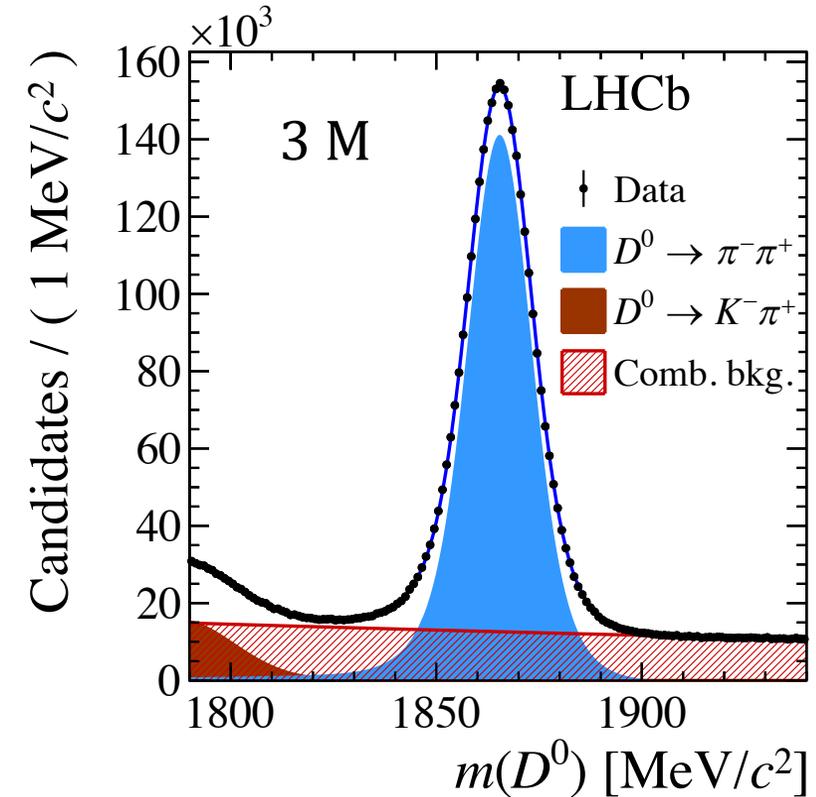
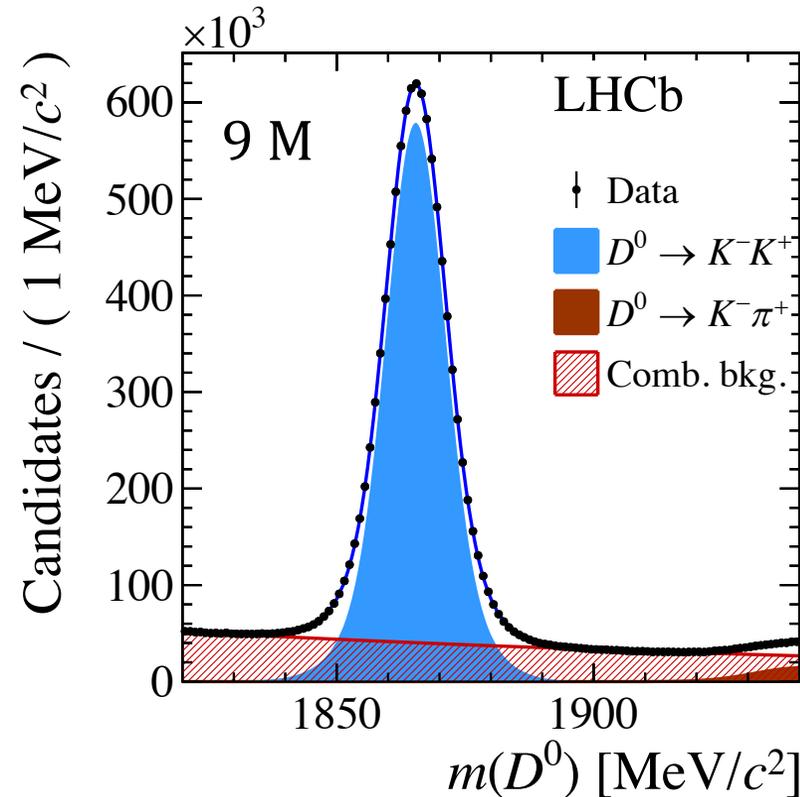
PROMPT

- Fit alla distribuzione di $m(D^0 \pi)$
- **Parametro A_{raw}** condiviso tra D^{*+} e D^{*-}
- Circa **44 milioni** di eventi di segnale per $K^- K^+$ e **14 milioni** per $\pi^- \pi^+$



SL

- Fit alla distribuzione di $m(D^0)$
- **Parametro A_{raw}** condiviso tra D^0 and \bar{D}^0
- Circa **9 milioni** di eventi di segnale per K^-K^+ e **3 milioni** per $\pi^-\pi^+$



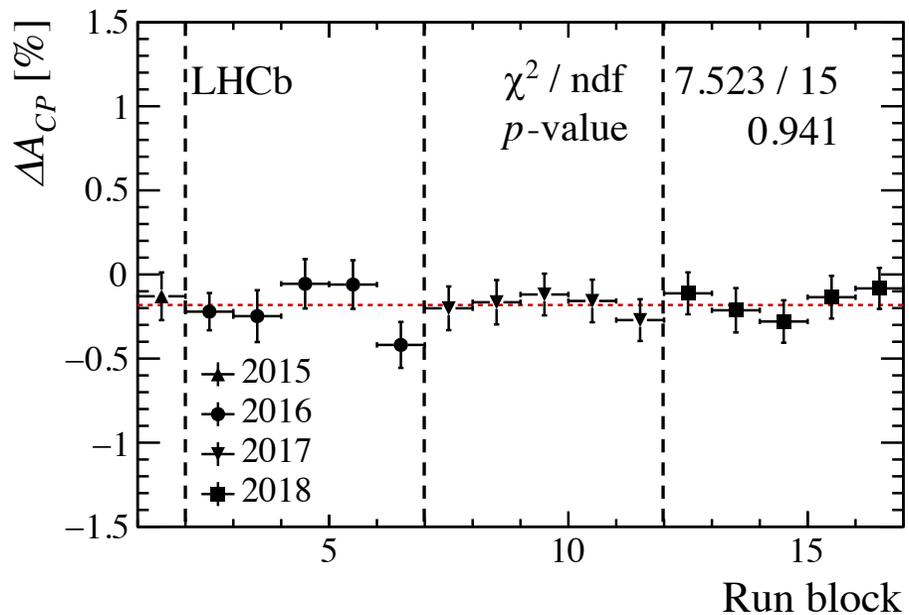
- **Prompt** dominato da:

- **Modello di fit** → stimato con l'utilizzo di modelli alternativi su pseudoesperimenti
- **Fondo da particelle mal identificate** ($D^0 \rightarrow K^- \pi^+ \pi^0$, $D^0 \rightarrow \pi^- l^+ \nu_l$) piccano in $m(D^0 \pi)$ → valutato misurando numero di eventi e asimmetrie dei fondi nelle distribuzioni di $m(D^0)$

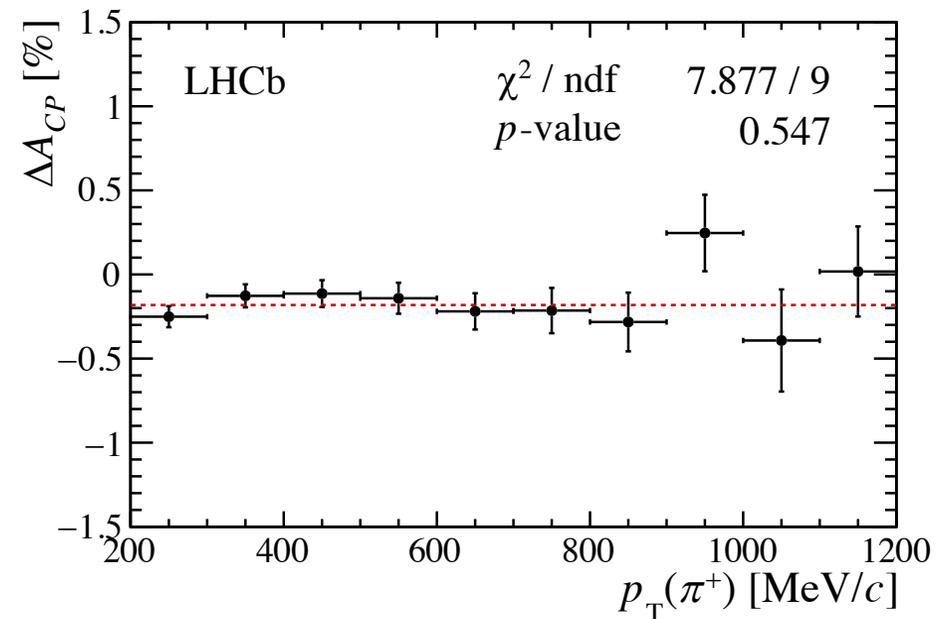
- **SL** dominato da **muone sbagliato** → valutato sul campione di controllo $B \rightarrow D^0 (\rightarrow K^- \pi^+) \mu X$

Sorgente	Prompt [10^{-4}]	SL [10^{-4}]
Modello di fit	0.6	2
Errata identificazione del muone	-	4
Ripesamento	0.2	1
Decadimenti secondari	0.3	-
Frazioni dei B	-	1
Efficienza di ricostruzione dei B	-	2
Fondo da particelle mal identificate	0.5	-
Totale	0.9	5

- Campione diviso secondo **anno** e **polarità** del magnete
 - ΔA_{CP} misurata in funzione di varie quantità **cinematiche/geometriche**
 - **Selezioni** alternative (es. PID più stringenti) sono state testate
- Nessuna evidenza di dipendenze inattese



PROMPT



$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2 (\text{stat.}) \pm 0.9 (\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8 (\text{stat.}) \pm 5 (\text{syst.})] \times 10^{-4}$$

- Compatibile con i **precedenti** risultati di LHCb e con la **media mondiale**

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- La **combinazione** con LHCb Run 1 è:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

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Violazione di CP osservata a **5.3 σ !!**

- Per l'**interpretazione**, $\Delta\langle t \rangle / \tau(D^0)$ e $\overline{\langle t \rangle} / \tau(D^0)$ sono necessari
- Per l'intero campione di dati di LHCb (9fb^{-1}):

$$\Delta\langle t \rangle / \tau(D^0) = 0.115 \pm 0.002, \quad \overline{\langle t \rangle} / \tau(D^0) = 1.71 \pm 0.10$$

- Usando le medie di LHCb:

- $y_{CP} = (5.7 \pm 1.5) \times 10^{-3}$

$$\Delta A_{CP} \simeq \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP} \right) + \frac{\Delta\langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

- $A_{\Gamma} = (-2.8 \pm 2.8) \times 10^{-4} \simeq -a_{CP}^{\text{ind}}$

$$\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9) \times 10^{-4}$$

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ΔA_{CP} sensibile principalmente
a violazione diretta di CP

- Nuova misura di LHCb di A_{CP} in $D_s^+ \rightarrow K_s^0 \pi^+$, $D^+ \rightarrow K_s^0 K^+$,
 $D^+ \rightarrow \phi \pi^+$ (Run 2)

→ **nessuna violazione di CP nei decadimenti dei $D_{(s)}^+$**

- Nuova misura di ΔA_{CP} con il campione completo di LHCb raccolto nel Run 2 → $\Delta A_{CP} \neq 0$ a più di 5σ

**PRIMA OSSERVAZIONE DI
VIOLAZIONE DI CP NEI
DECADIMENTI DEGLI ADRONI CHARM**

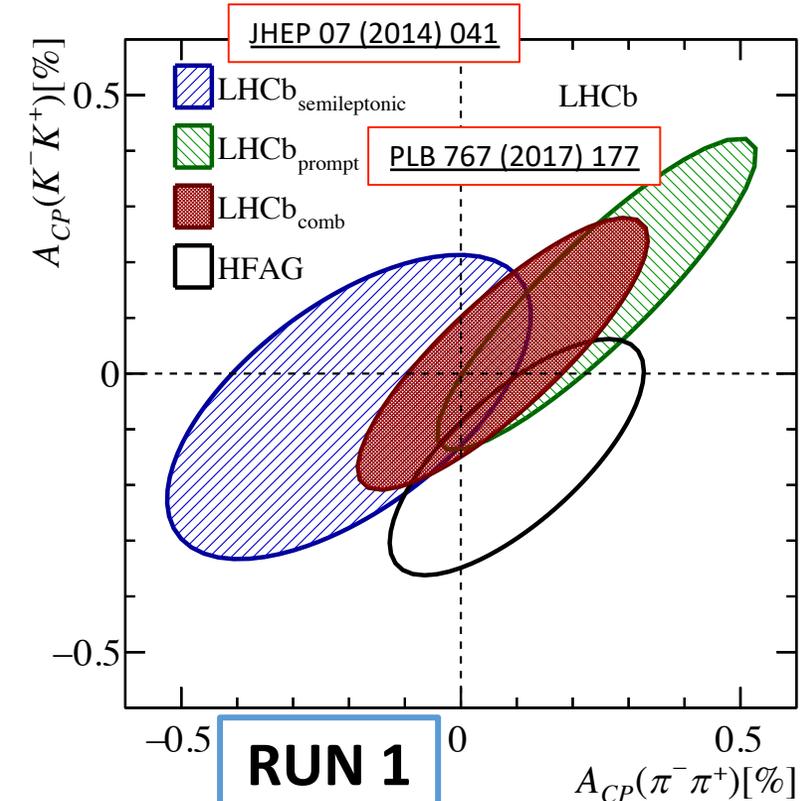
Backup slides

$A_{CP}(K^-K^+)$ and $A_{CP}(\pi^-\pi^+)$

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

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

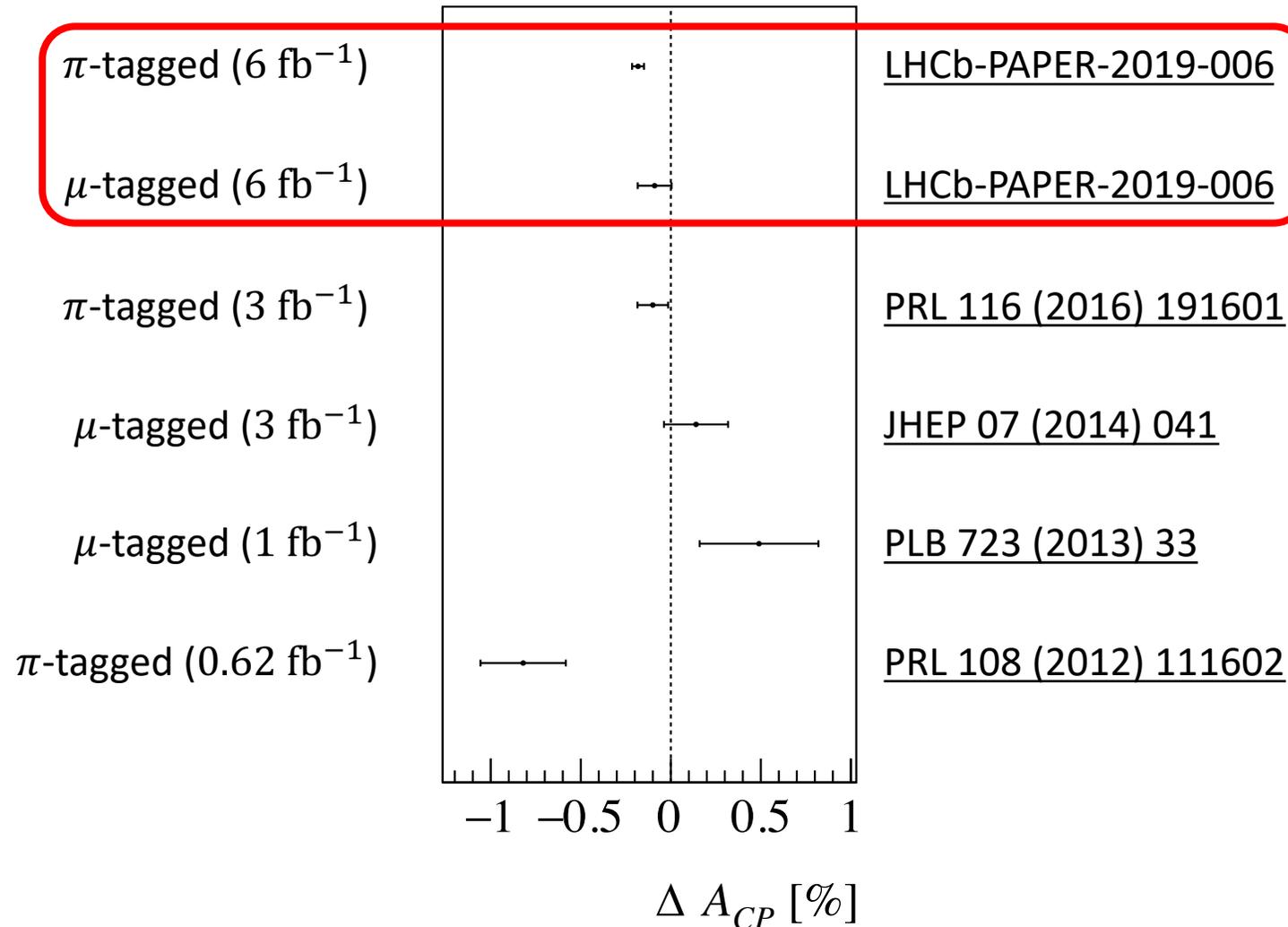
- $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow \bar{K}^0\pi^+$ **control samples** are needed
- **Trickier** than ΔA_{CP} , weighting is not simple and systematic associated to PID asymmetry must be carefully evaluated
- **Work already started** to measure $A_{CP}(h^-h^+)$ on the full **Run 1 + Run 2**



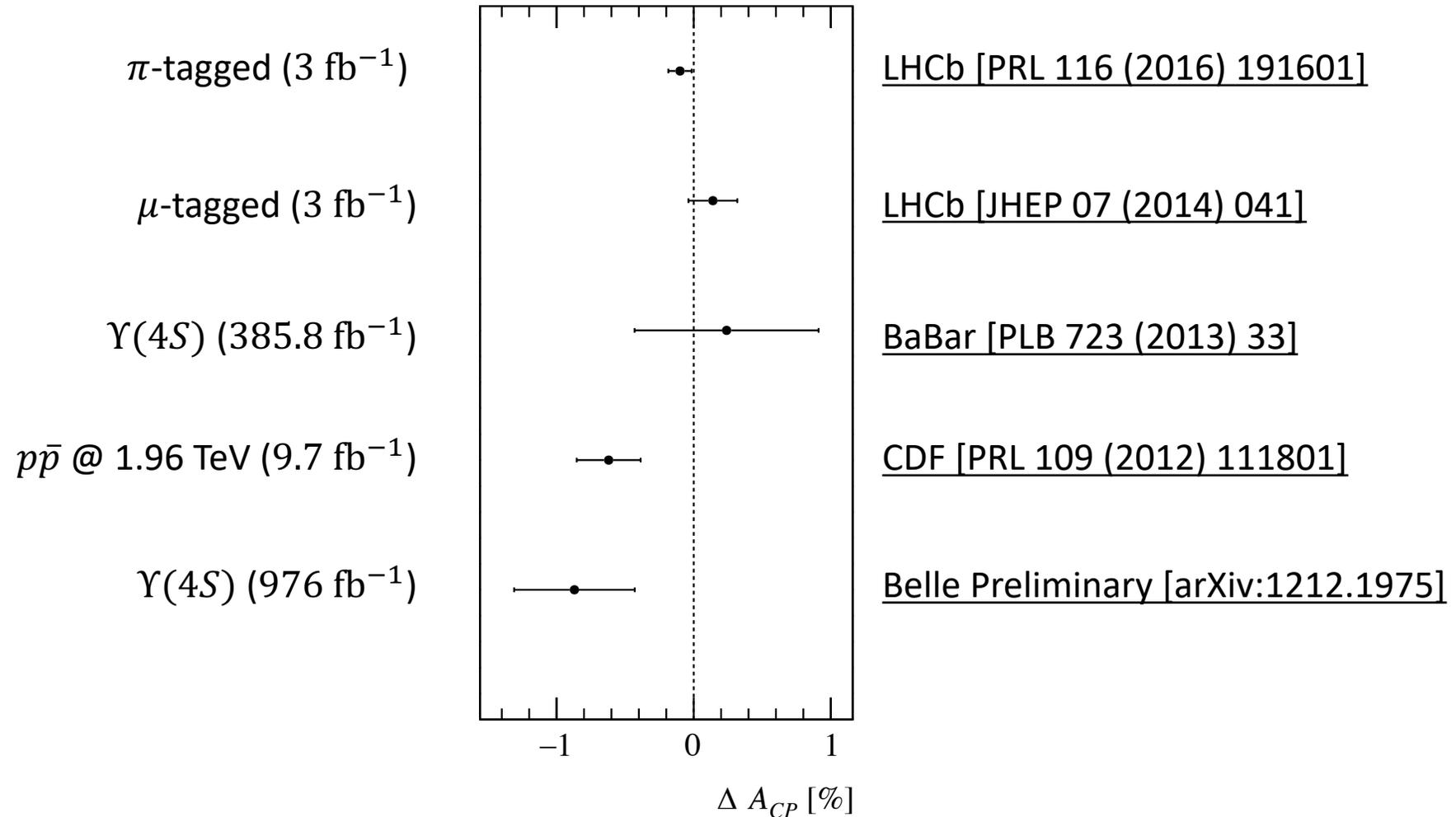
$$A_{CP}(K^-K^+) = (0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14 \pm 0.11)\%$$

ΔA_{CP} at LHCb – History + Run 2



ΔA_{CP} – History



New World Average

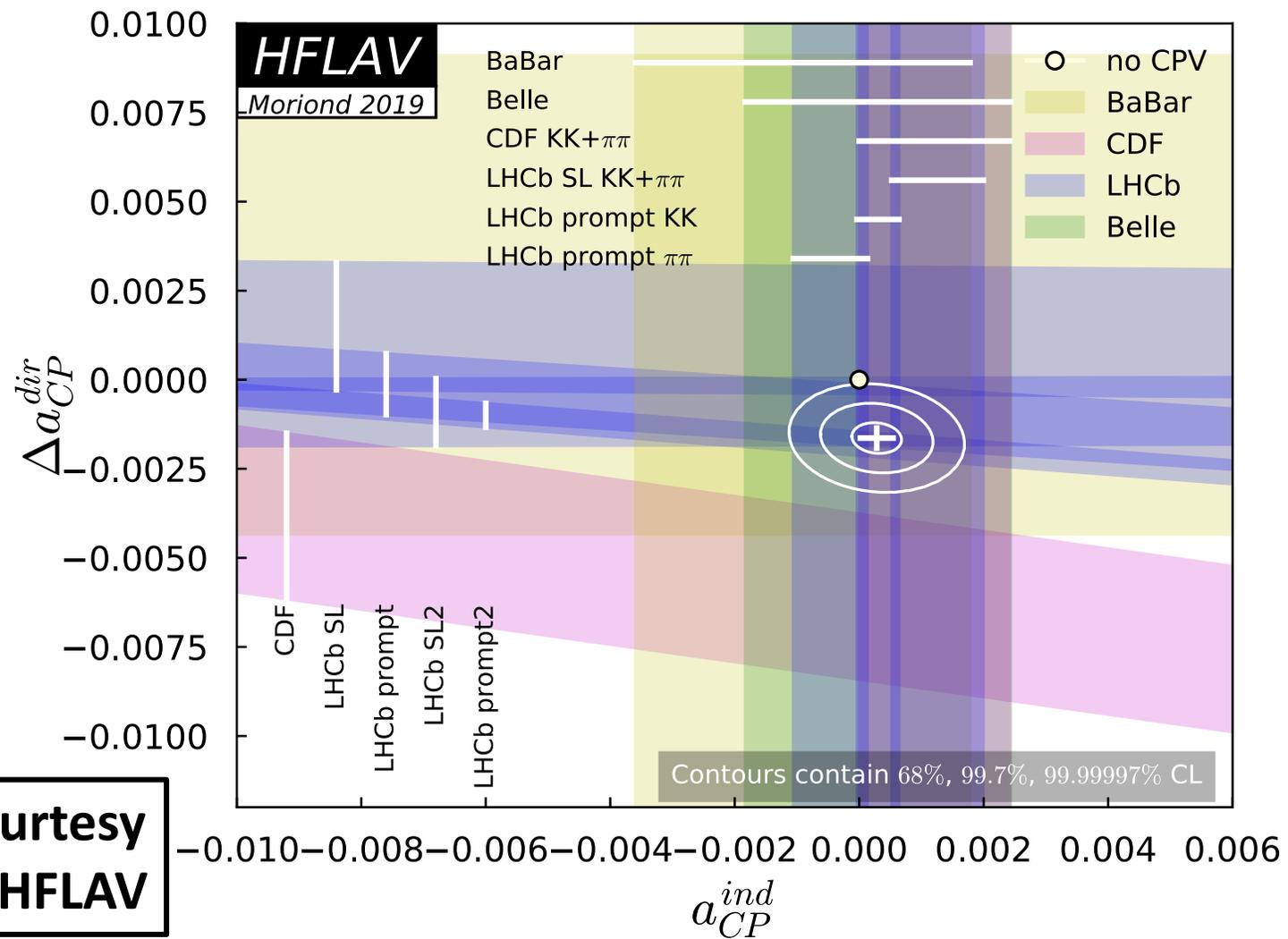
Including new γ_{CP} and ΔA_{CP} measurements:

$$\Delta a_{CP}^{dir} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$a_{CP}^{ind} = (2.8 \pm 2.6) \times 10^{-4}$$

Consistency with
NO CPV hypothesis:
 5.4×10^{-8} (5.44σ)

Courtesy
of HFLAV



- The result is **consistent** with, although at the **upper end** of, **SM expectations**, which lie in the range $10^{-4} - 10^{-2}$
- **Further measurements** with charmed particles, along with possible **theoretical improvements**, will help clarify the physics picture
→ establish whether this result is consistent with the **SM** or indicates the presence of **new dynamics** in the up-quark sector

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... and many others

ΔA_{CP} – Future prospects

LHCB-PUB-2018-009

Sample (\mathcal{L})	Tag	Yield		$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
		$D^0 \rightarrow K^- K^+$	$D^0 \rightarrow \pi^- \pi^+$		
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

- With Upgrade-I $\sigma_{stat}(\Delta A_{CP})$ expected to be $\mathcal{O}(10^{-4})$
- $\sigma_{stat}(\Delta A_{CP}) \sim 3 \times 10^{-5}$ including Run 5 (Upgrade-II)

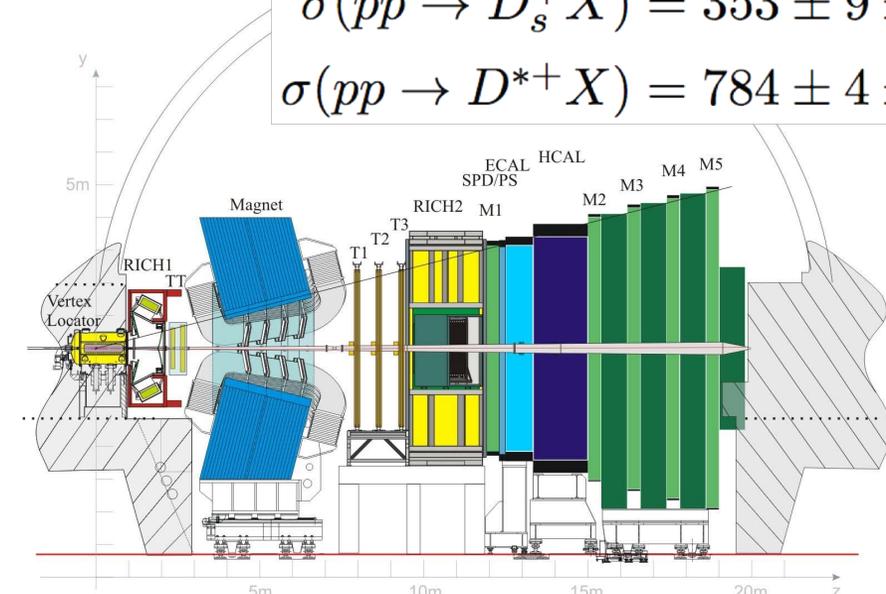
- Large $c\bar{c}$ production cross section
 $\sigma(pp \rightarrow c\bar{c}X)_{\sqrt{s}=13 \text{ TeV}} = (2369 \pm 3 \pm 152 \pm 118) \mu\text{b}$

JHEP 05 (2017) 074

- More than 1 billion $D^0 \rightarrow K^- \pi^+$ decays reconstructed with the full LHCb data sample

$$\begin{aligned}\sigma(pp \rightarrow D^0 X) &= 2072 \pm 2 \pm 124 \mu\text{b} \\ \sigma(pp \rightarrow D^+ X) &= 834 \pm 2 \pm 78 \mu\text{b} \\ \sigma(pp \rightarrow D_s^+ X) &= 353 \pm 9 \pm 76 \mu\text{b} \\ \sigma(pp \rightarrow D^{*+} X) &= 784 \pm 4 \pm 87 \mu\text{b}\end{aligned}$$

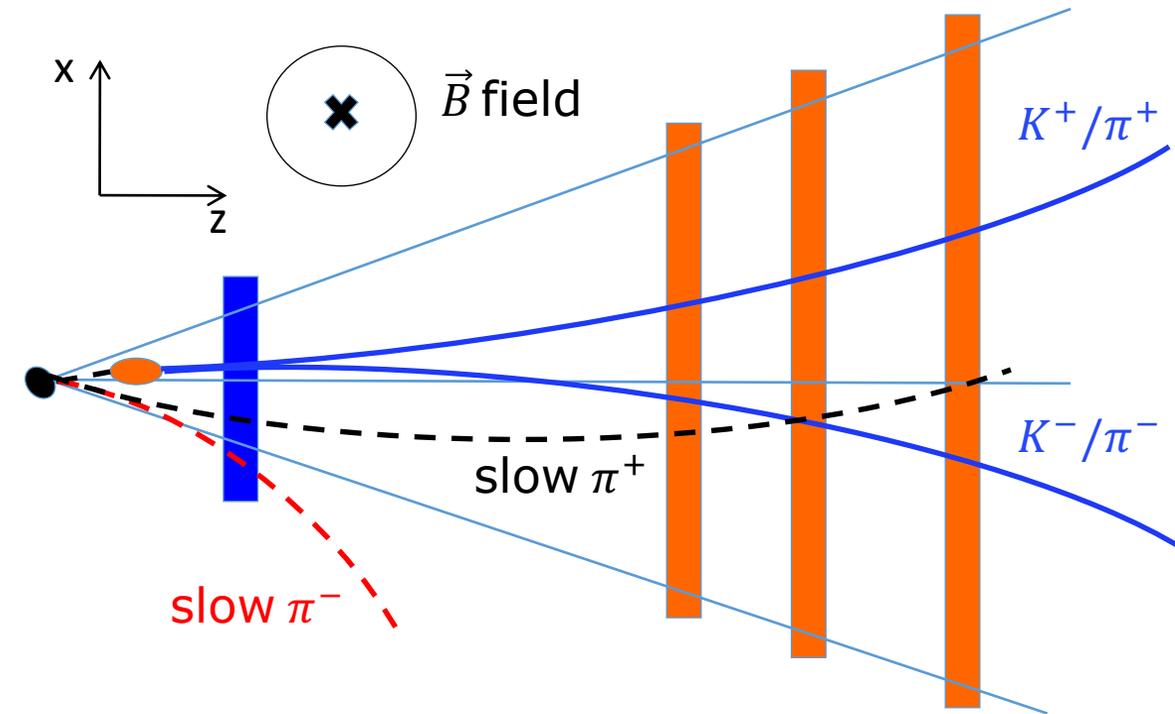
- LHCb detector: JINST 3 (2008) S08005
 - Excellent **IP** resolution ($\sim 20 \mu\text{m}$)
 - Very good **momentum** resolution ($\delta p/p \sim 0.5\%$)
 - Excellent **PID** capabilities



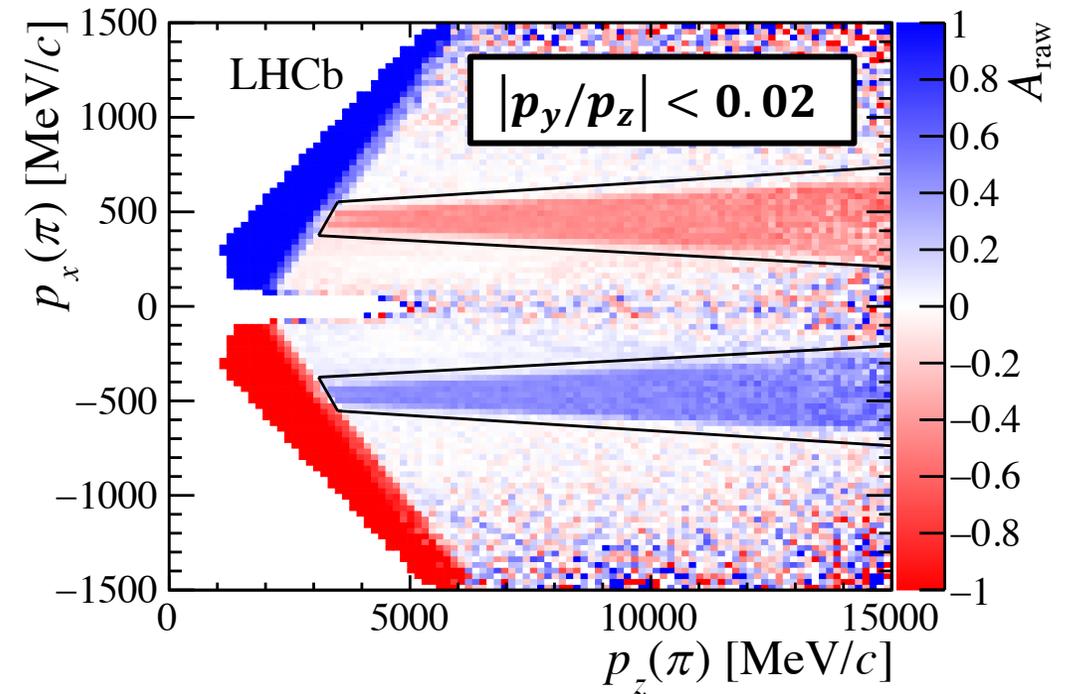
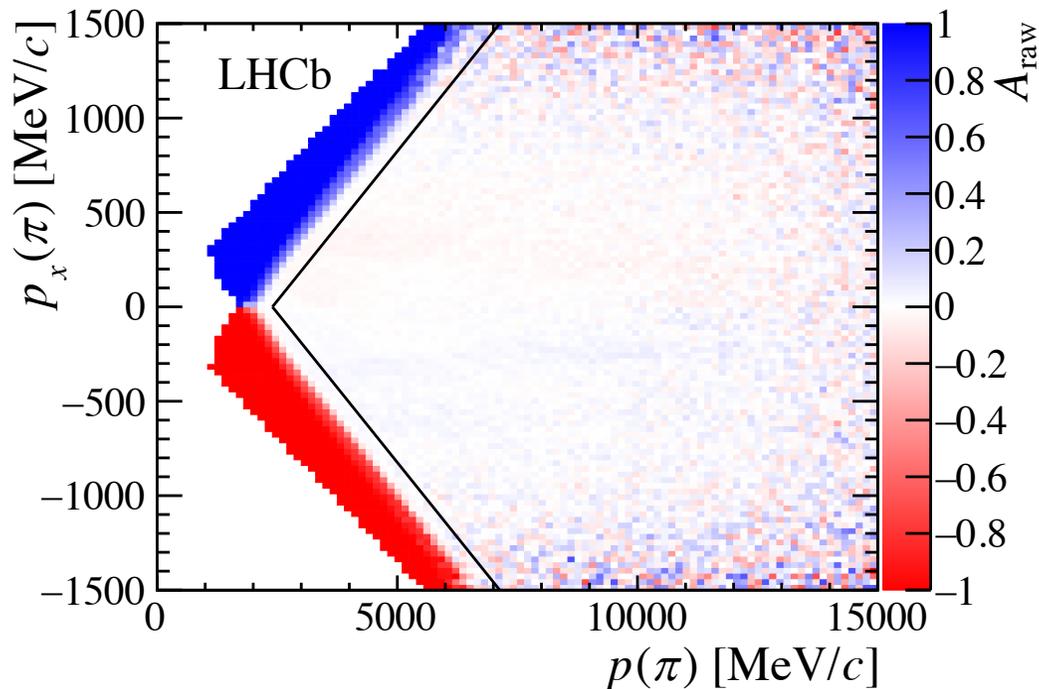
- Reconstruction performed online (**Turbo** stream)
- **Requirements** placed on:
 - Quality and PID information of tracks
 - p_T of tracks and D^0
 - D^0 vertex quality
 - IP of D^0
 - $m_{corr} = \sqrt{m(D^0\mu) + p_T'(D^0\mu) + p_T'(D^0\mu)}$ for SL
 - $m(D^0)$ for prompt and $m(D^0\mu)$ for SL
- SL candidates are further filtered with a **MVA** using as input the quality of the vertices, the D^0 flight distance, the IP and p_T of the D^0 decay products

Comput. Phys. Commun. 208 (2016) 35

- For some regions of phase space, the soft pion of a specific charge is **kicked out** from the detector acceptance by the magnetic field
- In such regions very large values of the raw asymmetries are found



- Remove soft pion kinematic regions when the **raw asymmetry is very high**
- Similarly for the muon in the SL sample



- Prompt case:

- Signal: sum of three Gaussian and a Johnson SU

- Background: empirical function $[m(D^0\pi^+) - m(D^0) - m(\pi^+)]^\alpha e^{\beta m(D^0\pi^+)}$

- Semileptonic case:

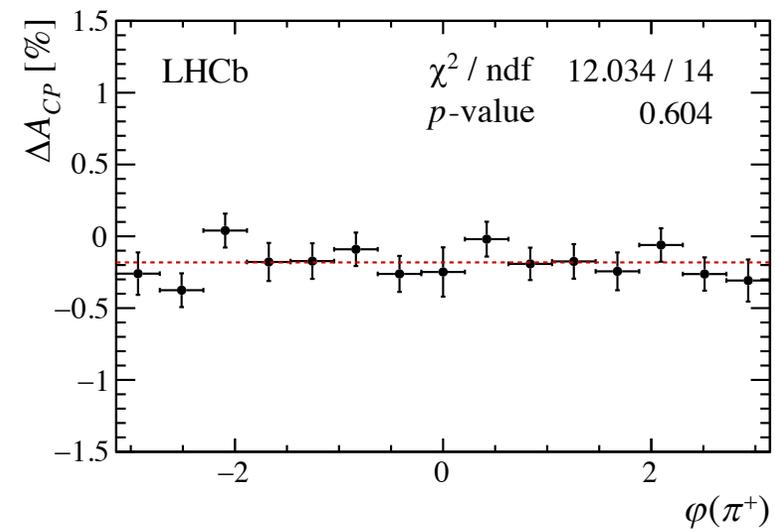
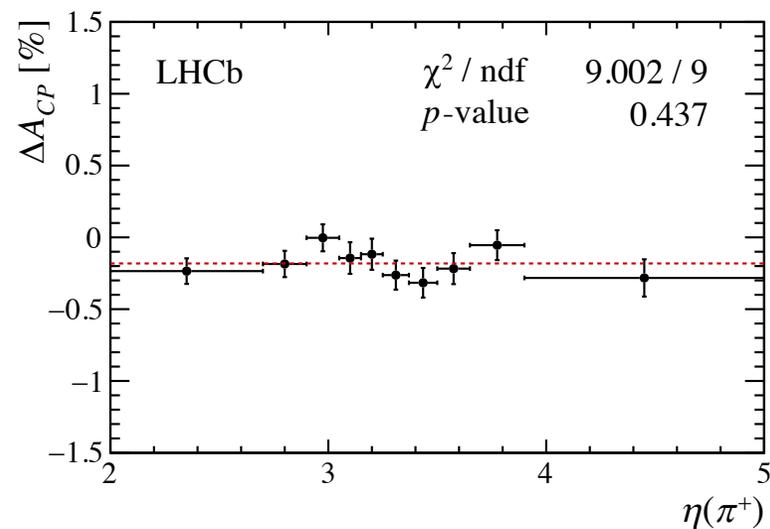
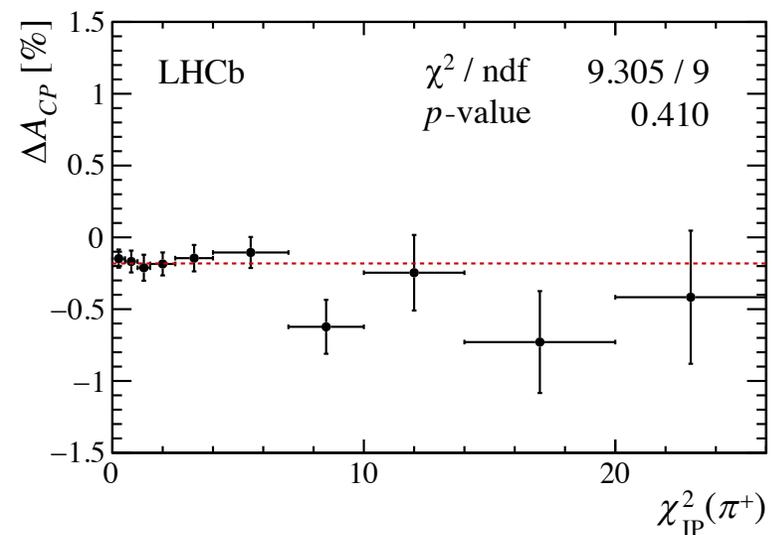
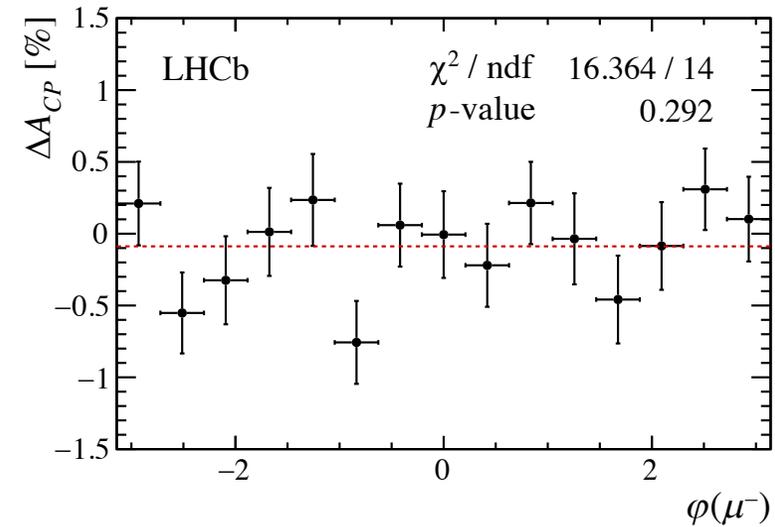
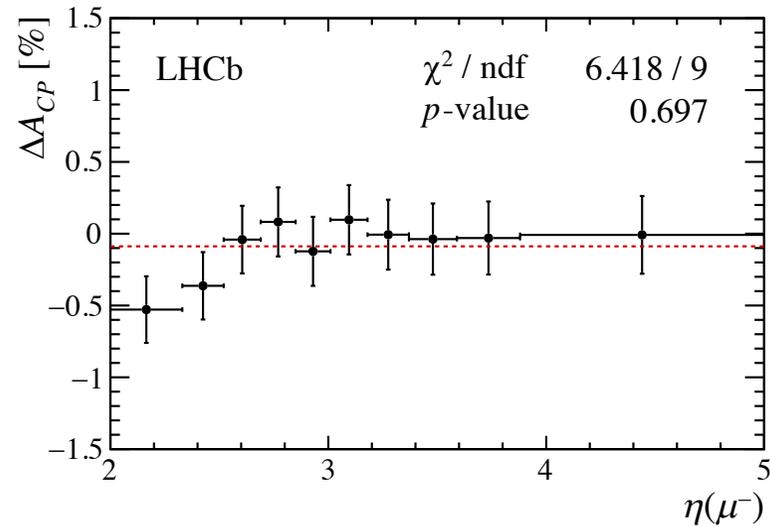
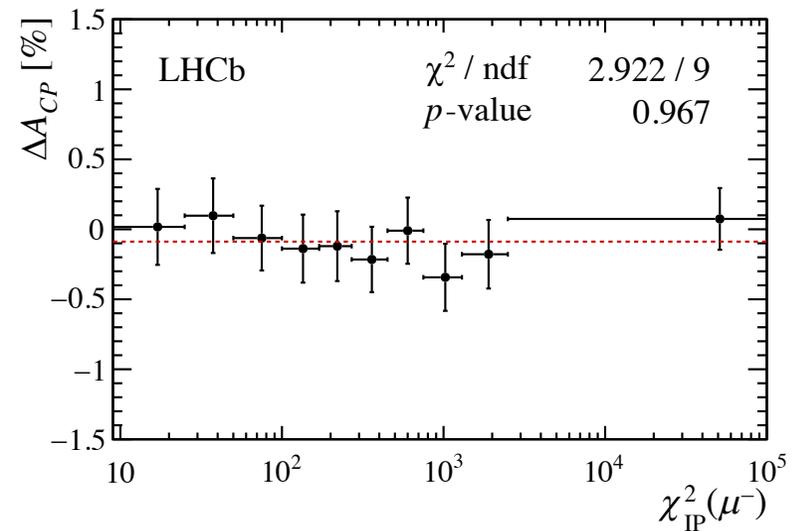
- Signal: sum of two Gaussian functions convolved with a power-law function

- Background: exponential function

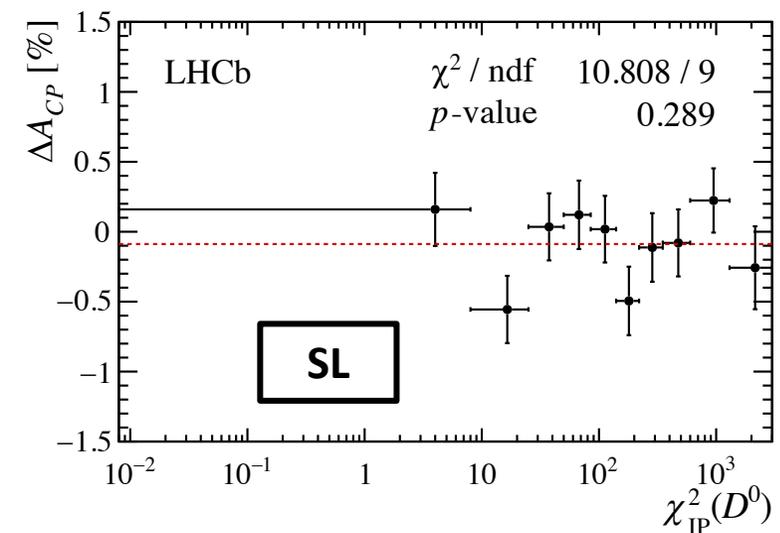
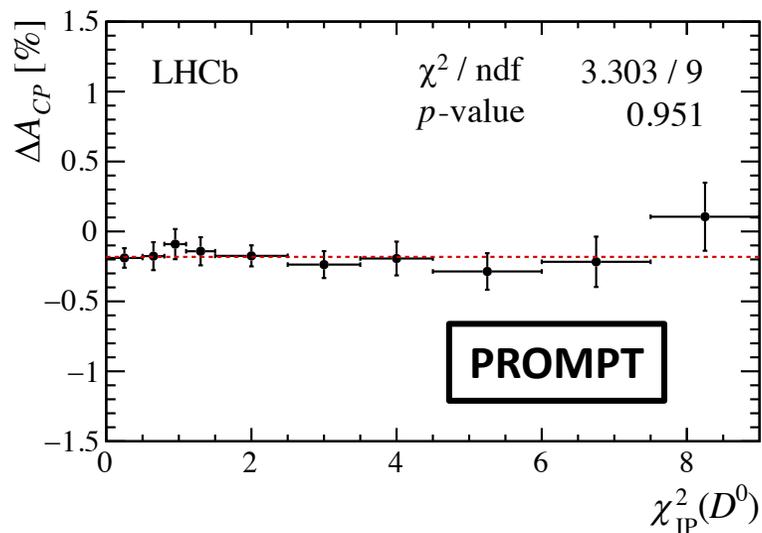
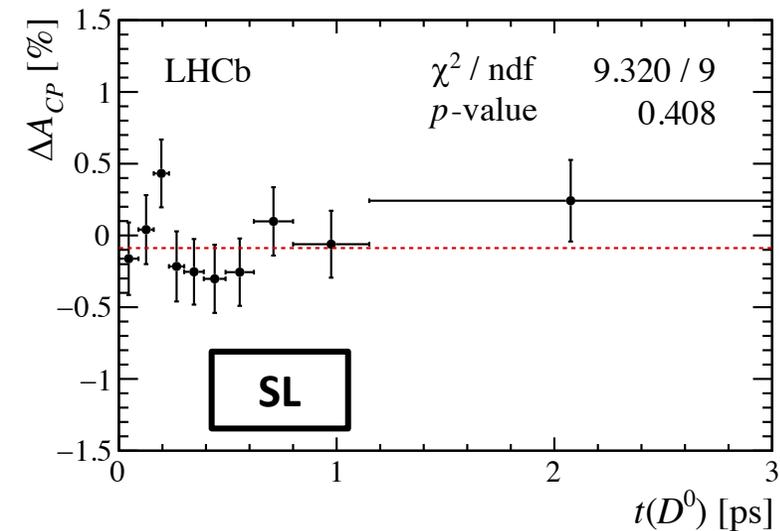
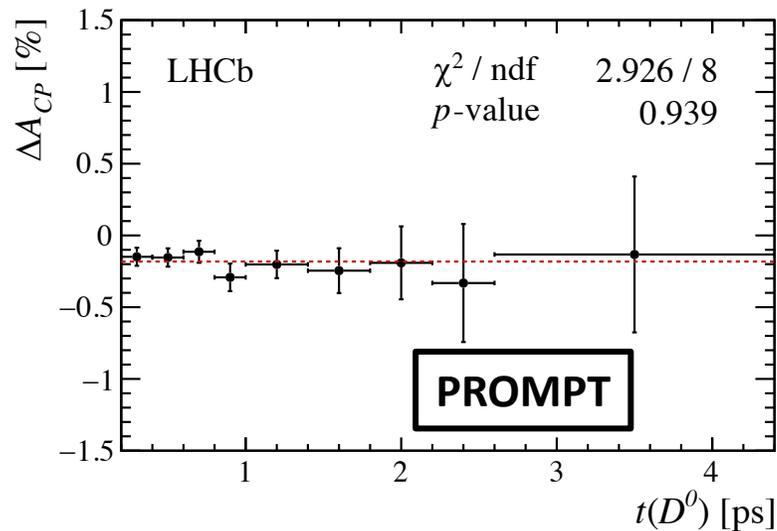
- misID $D^0 \rightarrow K^-\pi^+$: tail of a Gaussian

$$\mathcal{J}(m; \mu_J, \sigma_J, \delta_J, \gamma_J) = \frac{e^{-\frac{1}{2} \left[\gamma_J + \delta_J \sinh^{-1} \left(\frac{m - \mu_J}{\sigma_J} \right) \right]^2}}{\sqrt{1 + \left(\frac{m - \mu_J}{\sigma_J} \right)^2}}$$

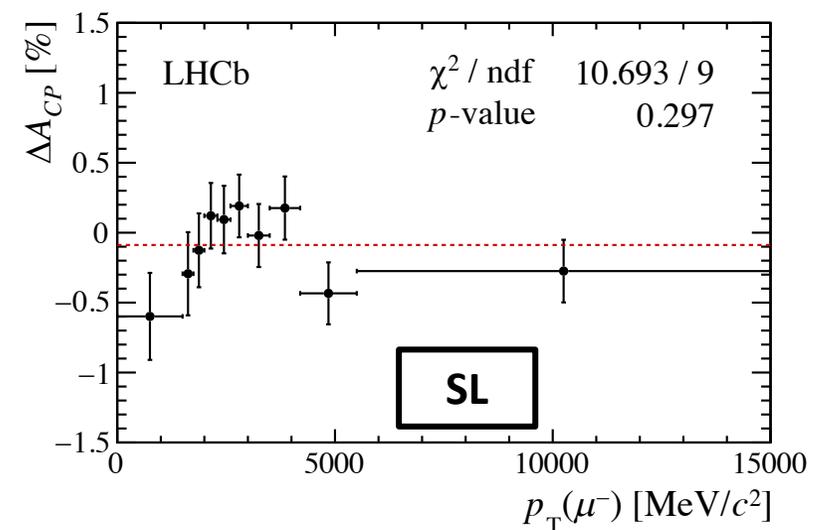
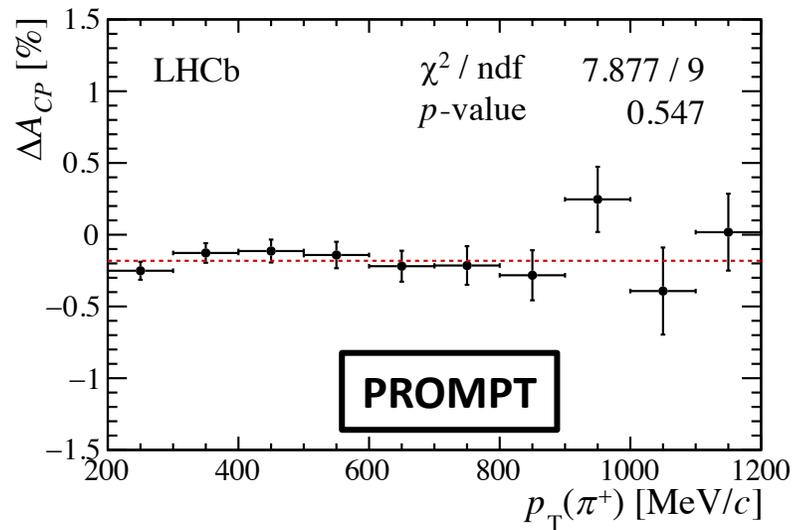
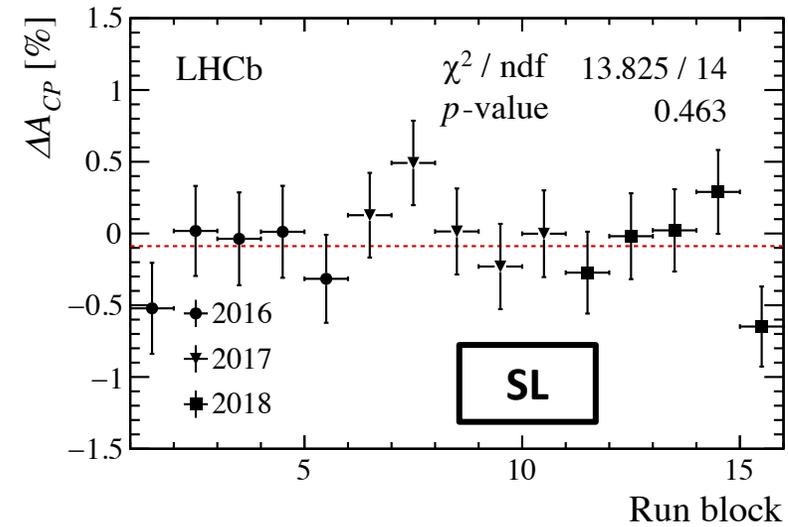
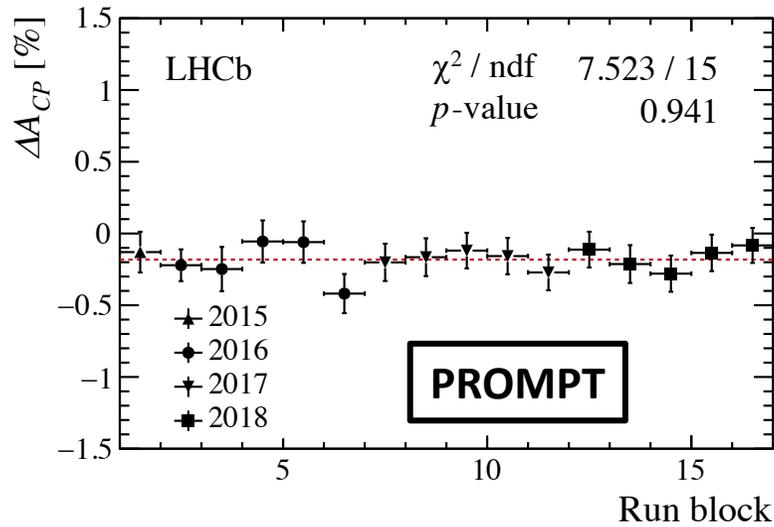
ΔA_{CP} – Stability



ΔA_{CP} – Stability



ΔA_{CP} – Stability



- Found variations compatible with **statistical fluctuation** on ΔA_{CP} measured with:
 - Alternative PID cuts
 - Alternative fiducial cuts
 - Alternative hardware trigger categories
 - All multiple candidates kept (baseline is to keep only one)
- $\Delta A_{bkg} = (-0.023 \pm 0.041)\%$ \rightarrow compatible with 0 at 0.6σ
- ΔA_{CP} measured by **counting** events after sideband subtraction \rightarrow differences well below the systematic uncertainty

ΔA_{CP} – Fit model systematic

- Choose 6 **alternative** fit models
 - **1000 toys** for each subsample → generate with baseline → fit with baseline and alternative → calculate $\Delta A_{CP,alt} - \Delta A_{CP,nom}$
 - **Sum in quadrature** mean and σ of $\Delta A_{CP,alt} - \Delta A_{CP,nom}$ distribution for each model
 - As a conservative choice, take the maximum as systematic uncertainty
- 0.6×10^{-4} for prompt and 2×10^{-4} for SL

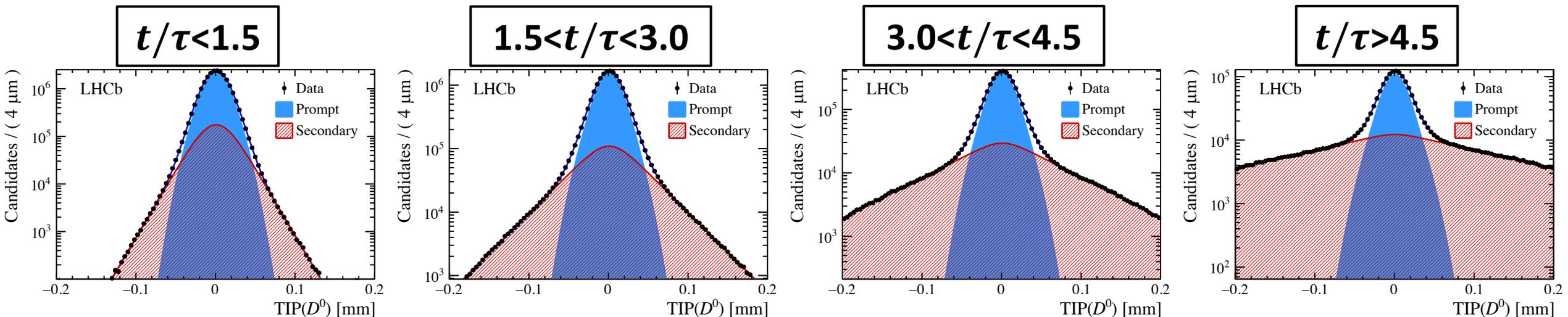
- Uncertainty on weighting function due to **limited statistics**
- Gaussian extraction of **alternative weight** event by event
→ fit to get $\Delta A_{CP,alt}$
- Perform **300** tests
- Uncertainty is the sum in quadrature of mean and σ of $\Delta A_{CP,alt} - \Delta A_{CP,nom}$
- 0.2×10^{-4} for prompt and 1×10^{-4} for SL

ΔA_{CP} – Secondaries (Prompt)

$$\Delta_{\text{sec}} = \frac{f_{\text{sec}}^{K^+K^-} - f_{\text{sec}}^{\pi^+\pi^-}}{2} [A_{\text{raw}}^{\text{sec}}(KK) + A_{\text{raw}}^{\text{sec}}(\pi\pi) - A_{\text{raw}}^{\text{prompt}}(KK) - A_{\text{raw}}^{\text{prompt}}(\pi\pi)]$$

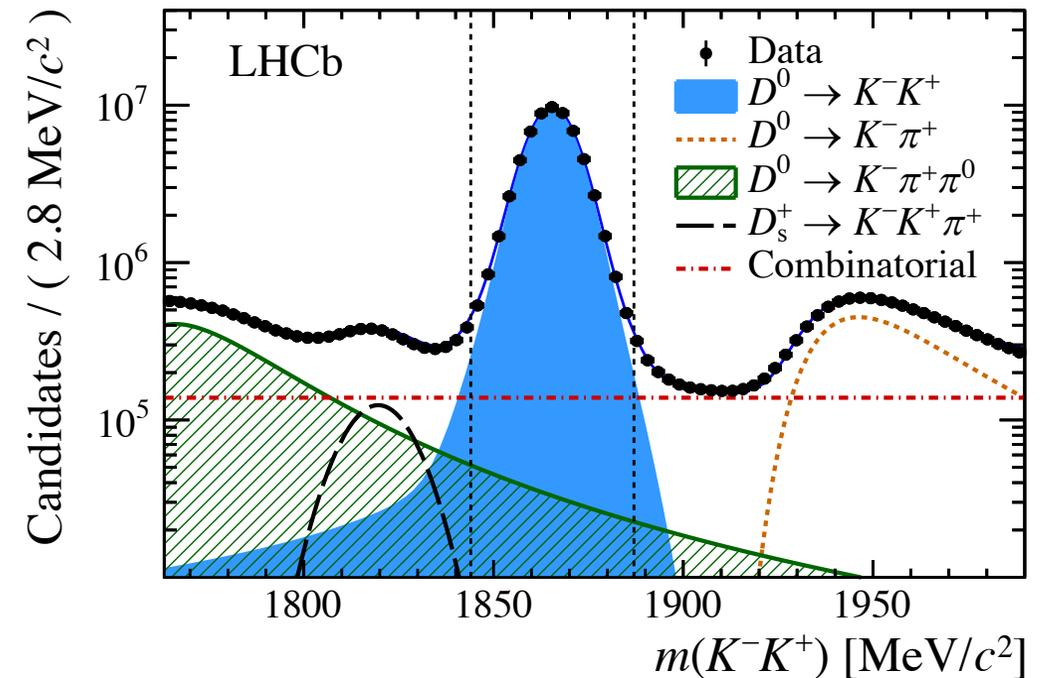
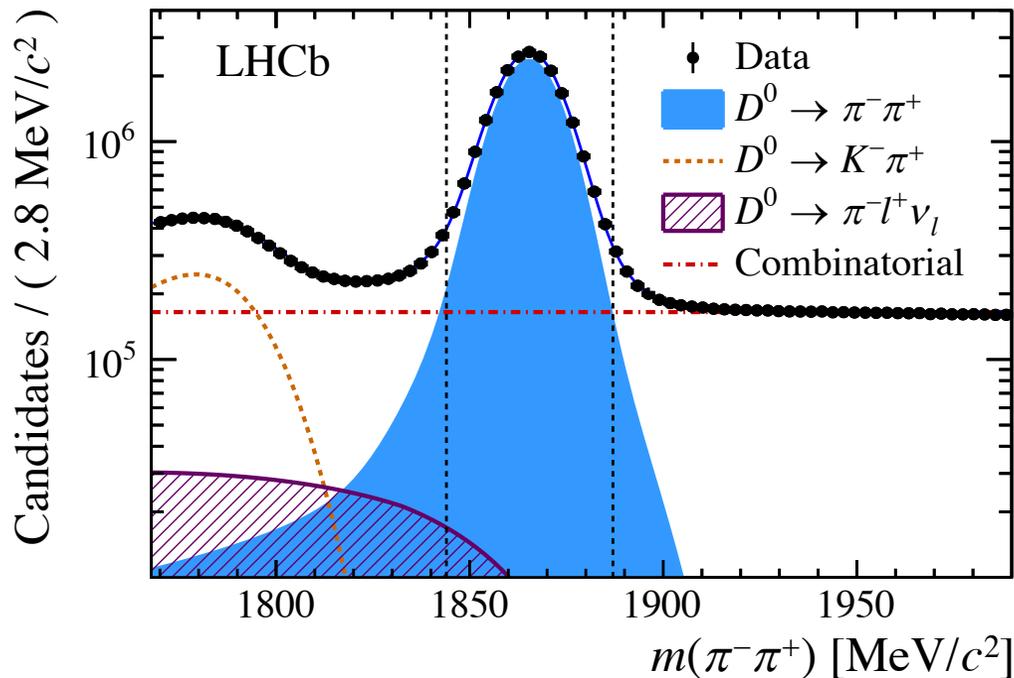
- Measure fraction of **secondary** D^0 by fitting the distribution of the D^0 IP in the plane transverse to the beam (**TIP**)
- Study performed in **bins of $t/\tau(D^0)$** to have a better control on the resolution

$$\text{TIP} = \frac{\hat{n}_z \wedge \vec{p}}{|\hat{n}_z \wedge \vec{p}|} \cdot (\vec{x}_{\text{DV}} - \vec{x}_{\text{PV}})$$



ΔA_{CP} – Peaking background (prompt)

The yields and raw asymmetries of $D^0 \rightarrow K^- \pi^+ \pi^0$ ($D^0 \rightarrow \pi^- l^+ \nu_l$) are measured by fits to $m(K^- K^+)$ ($m(\pi^- \pi^+)$) and extrapolated to the signal region $[1844, 1887] \text{ MeV}/c^2$



- Effective D^0 production asymmetry in SL B decays:
$$A_{P,\text{eff}}(D^0) = A_P(B^+) + f(B^0)[A_P(B^0) \cdot D - A_P(B^+)]$$
- In Run 1 analysis: **difference in $f(B^0)$** is $(0.34 \pm 0.18)\%$ between KK and $\pi\pi$ due to difference in B^0 and B^+ reconstruction **efficiencies**
- $A_P(B^0)$ and $A_P(B^+)$ measured by LHCb (PLB 774 (2017) 139)
- Conservative assumption $\rightarrow f(B^0)$ difference is **1%**
 - \rightarrow difference in $A_{P,\text{eff}}(D^0)$ is $(-0.0001 \pm 0.0058)\%$
 - \rightarrow take **1×10^{-4}** as syst uncertainty

- Effective D^0 production asymmetry in SL B decays:

$$A_{P,eff}(D^0) = A_P(B^+) + f(B^0)[A_P(B^0) \cdot D - A_P(B^+)]$$

- That depends also on $D = 1 - 2\mathcal{P}_{osc}$, so also on **lifetime acceptance** (slightly different between KK and $\pi\pi$)

$$\mathcal{P}_{osc} = \frac{\Gamma_d}{2} \int_{t_0}^{\infty} e^{-\Gamma_d t} (1 - \cos(\Delta m_d t)) t$$

- Syst uncertainty taken **unchanged** from Run1 analysis
→ estimated to be maximum 2×10^{-4}

Mistag rate (SL)

$$\delta_{\omega} = \Delta A_{CP} - \Delta A_{\text{raw}} = 2\omega_{KK} A_{CP}(K^{-}K^{+}) - 2\omega_{\pi\pi} [A_{CP}(K^{-}K^{+}) - \Delta A_{CP}] + 2A_{P,\text{eff}}(D^0)(\omega_{KK} - \omega_{\pi\pi}) + \Delta\omega_{KK} - \Delta\omega_{\pi\pi},$$

- Measure mistag on $D^0 \rightarrow K\pi$ sample
- Take into account also **mixed** $D^0 \rightarrow K\pi$
- Use $A_{CP}(KK)$ and ΔA_{CP} from Run 1 SL
- Assume $A_{P,\text{eff}}(D^0) = 3\%$
- Systematic uncertainty is 4×10^{-4}

Some theoretical references



Golden et. al., PLB 222 (1989) 501

Buccella et al., PRD 51 (1995) 3478

Bianco et al., Riv. Nuovo Cim . 26N7 (2003) 1

Grossman et al, PRD 75 (2007) 036008

Artuso et al., Ann . Rev. Nucl. Part. Sci. 58 (2008) 249

Khodjamirian et al., PLB 774 (2017) 235

Pirtskhalava et al. , PLB 712 (2012) 81

Cheng et al., PRD 85 (2012) 034036

Feldmann et al., JHEP 06 (2012) 007

Li et al., PRD 86 (2012) 036012

Franco et al., JHEP 05 (2012) 140

Brod et al., JHEP 10 (2012) 161

Atwood et al., PTEP 2013 (2013) 093B05

Hiller et al., PRD 87 (2013) 014024

Grossman et al., JHEP 04 (2013) 067

Müller et al., PRL 115 (2015) 251802

Buccella et al., (2019) arXiv:1902.05564

A_{CP} in $D_S^+ \rightarrow K_S^0 \pi^+$, $D^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow \phi \pi^+$

- **Singly-Cabibbo-suppressed** decays
- $A_{CP} \sim 10^{-4} - 10^{-3}$
- Sensitive to **QCD** penguin and from chromomagnetic dipole operators ([PRD 75 \(2007\) 036008](#))
- Already measured by LHCb with **Run 1** ([JHEP 06 \(2013\) 112](#), [JHEP 10 \(2014\) 025](#))

Channel	A_{CP} (%)	Dataset
$D_S^+ \rightarrow K_S^0 \pi^+$	$+0.38 \pm 0.46$ (stat) ± 0.17 (syst)	2011-2012 (3.2/fb)
$D^+ \rightarrow K_S^0 K^+$	$+0.03 \pm 0.17$ (stat) ± 0.14 (syst)	
$D^+ \rightarrow \phi \pi^+$	-0.04 ± 0.14 (stat) ± 0.14 (syst)	2011 (1.1/fb)

A_{CP} in $D_s^+ \rightarrow K_S^0 \pi^+$, $D^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow \phi \pi^+$

- To cancel **production** and **detection** asymmetries, **control samples** are used: $D_s^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow K_S^0 \pi^+$, $D_s^+ \rightarrow \phi \pi^+$
- CP asymmetries are obtained from the raw asymmetries differences:

$$A_{CP}(D_s^+ \rightarrow K_S^0 \pi^+) = [A(D_s^+ \rightarrow K_S^0 \pi^+) - A_D(K^0)] - A(D_s^+ \rightarrow \phi \pi^+)$$

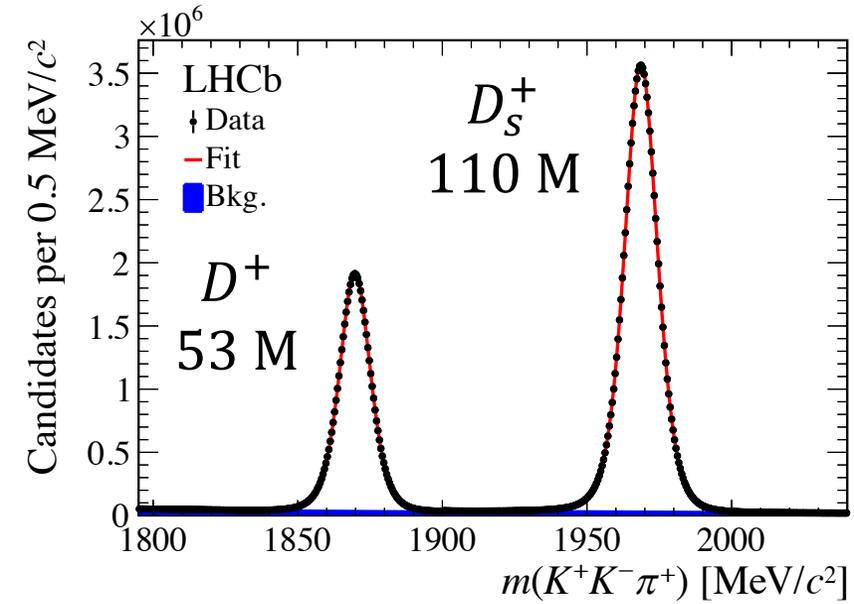
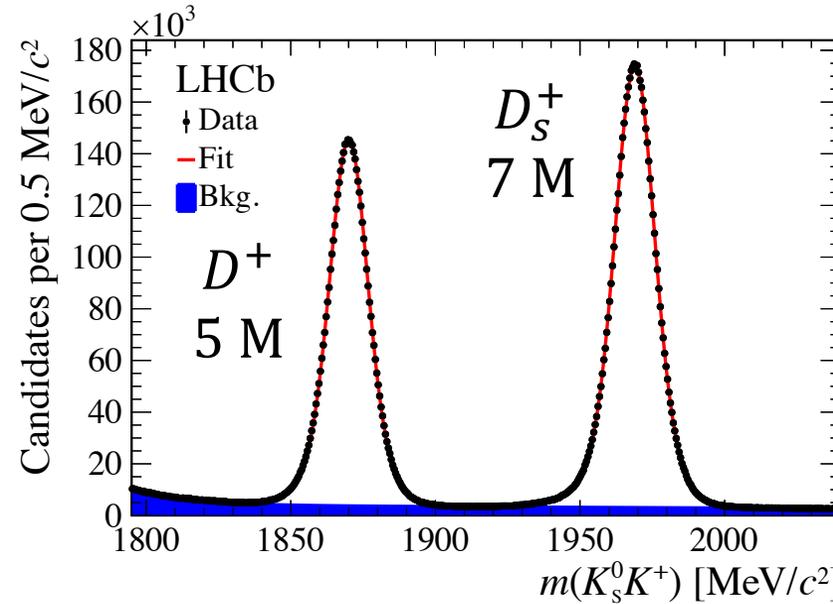
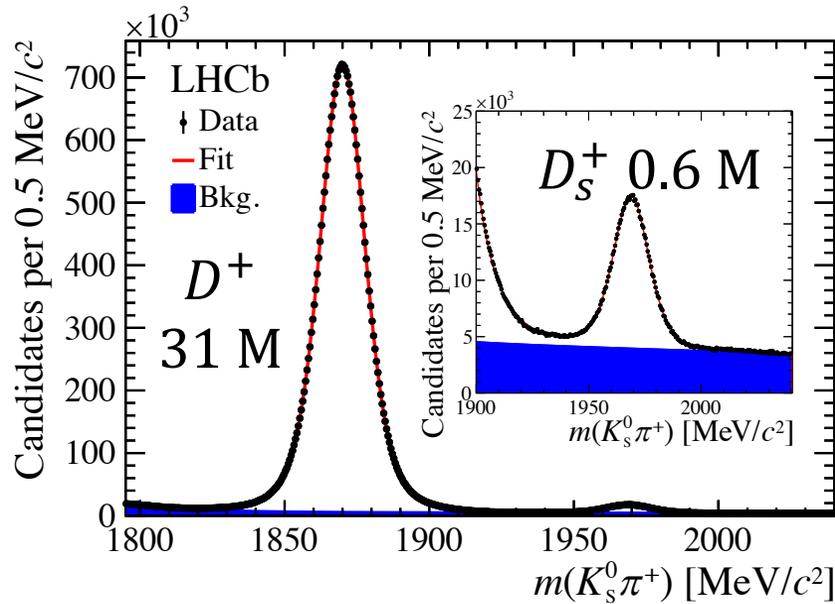
$$A_{CP}(D^+ \rightarrow K_S^0 K^+) = [A(D^+ \rightarrow K_S^0 K^+) - A_D(\bar{K}^0)] - [A(D^+ \rightarrow K_S^0 \pi^+) - A_D(\bar{K}^0)] \\ - [A(D_s^+ \rightarrow K_S^0 K^+) - A_D(\bar{K}^0)] + A(D_s^+ \rightarrow \phi \pi^+)$$

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = A(D^+ \rightarrow \phi \pi^+) - [A(D^+ \rightarrow K_S^0 \pi^+) - A_D(\bar{K}^0)]$$

- Kinematics of $D_{(s)}^+$, π^+ and K^+ are weighted
- $A_D(K^0)$ is estimated by using simulation ([JHEP 1407 \(2014\) 041](#))

A_{CP} in $D_S^+ \rightarrow K_S^0 \pi^+$, $D^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow \phi \pi^+$

arXiv:1903.01150



$$A_{CP}(D_S^+ \rightarrow K_S^0 \pi^+) = (1.3 \pm 1.9 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-3}$$

$$A_{CP}(D^+ \rightarrow K_S^0 K^+) = (-0.09 \pm 0.65 \text{ (stat)} \pm 0.48 \text{ (syst)}) \times 10^{-3}$$

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = (0.05 \pm 0.42 \text{ (stat)} \pm 0.29 \text{ (syst)}) \times 10^{-3}$$

Run 2 - 3.8 fb⁻¹

No CP violation

A_{CP} in $D_S^+ \rightarrow K_S^0 \pi^+$, $D^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow \phi \pi^+$

Combination with Run 1

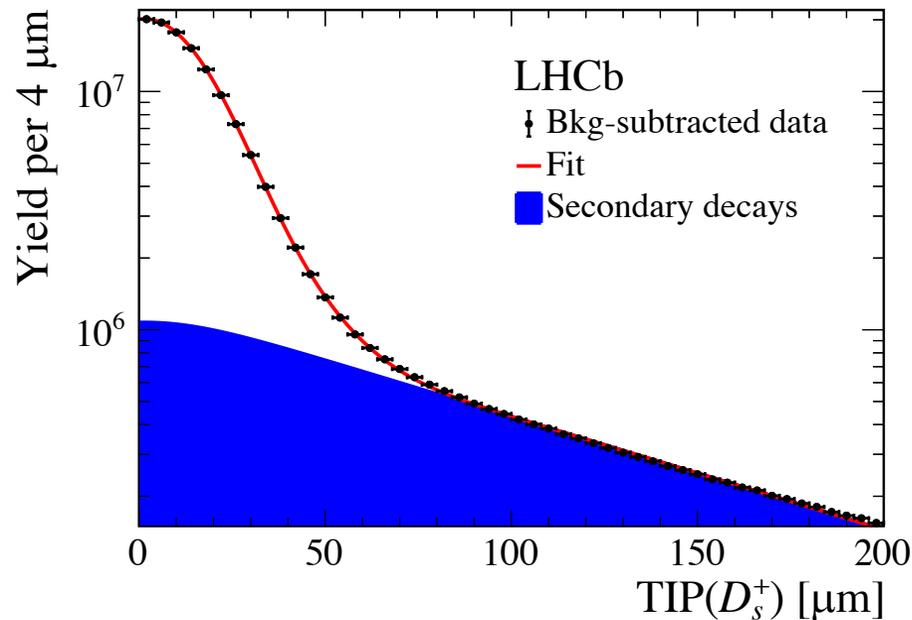
$$\mathcal{A}_{CP}(D_S^+ \rightarrow K_S^0 \pi^+) = (1.6 \pm 1.7 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-3}$$

$$\mathcal{A}_{CP}(D^+ \rightarrow K_S^0 K^+) = (-0.04 \pm 0.61 \text{ (stat)} \pm 0.45 \text{ (syst)}) \times 10^{-3}$$

$$\mathcal{A}_{CP}(D^+ \rightarrow \phi \pi^+) = (0.03 \pm 0.40 \text{ (stat)} \pm 0.29 \text{ (syst)}) \times 10^{-3}$$

A_{CP} in $D_S^+ \rightarrow K_S^0 \pi^+$, $D^+ \rightarrow K_S^0 K^+$, $D^+ \rightarrow \phi \pi^+$

Systematic uncertainties fit model and secondary decays are dominant



Source	$\mathcal{A}_{CP}(D_s^+ \rightarrow K_S^0 \pi^+)$	$\mathcal{A}_{CP}(D^+ \rightarrow K_S^0 K^+)$	$\mathcal{A}_{CP}(D^+ \rightarrow \phi \pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic differences	0.09	0.09	0.04
Neutral kaon asymmetry	0.05	0.05	0.04
Charged kaon asymmetry	0.08	0.09	0.15
Total	0.51	0.48	0.29

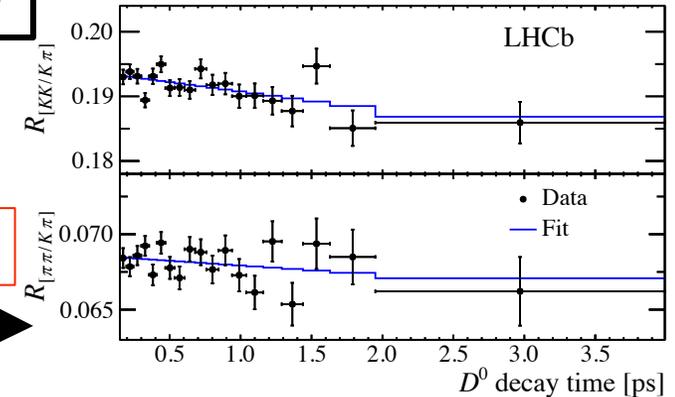
Mixing and CP violation

Run 1
(3 fb⁻¹)

- **Measurement of y_{CP} with $D^0 \rightarrow h^+ h^-$**

- $y_{CP} = [0.57 \pm 0.13 \text{ (stat)} \pm 0.09 \text{ (syst)}]\%$

- Compatible with and precise as the **World Average** (0.84 ± 0.16)% PRL 122 (2019) 011802



- **Measurement of x_{CP} and Δx with**

arXiv:1903.03074 $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- $x_{CP} = [0.27 \pm 0.16 \text{ (stat)} \pm 0.04 \text{ (syst)}]\%$

- $\Delta x = [-0.053 \pm 0.070 \text{ (stat)} \pm 0.022 \text{ (syst)}]\%$

- **Most precise** determination of x from a single experiment

- Combination with current global knowledge gives

$x > 0$ at more than 3σ

No CP violation observed

