Direct CPV in Charm decays at LHCb

Lorenzo Pica
On behalf of the LHCb collaboration

10th International Workshop on Charm Physics - CHARM 2020
31 May - 4 June 2021

Introduction

Direct CP violation in Charm decays

CP violation (CPV) is the non-invariance of Nature under Parity (P) and Charge conjugation (C)

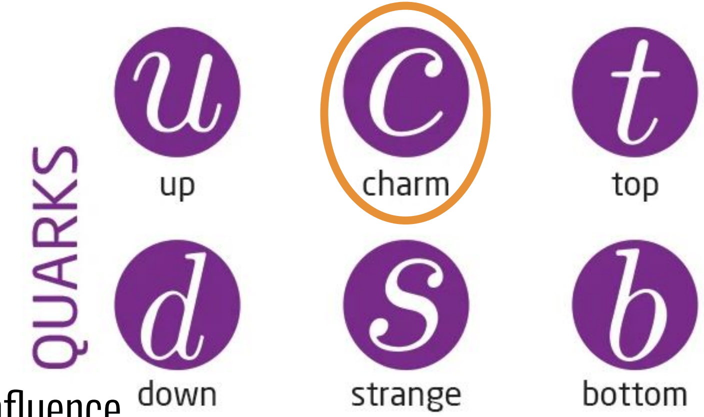
CPV in the decay (direct CPV) present when $|\mathcal{A}(D^0 \to f)|^2 \neq |\mathcal{A}(\overline{D}^0 \to \bar{f})|^2$

Studying Charm CPV is challenging:

- A_{CP} expected size $O(10^{-3} - 10^{-4})$

But also extremely interesting:

- small SM CPV provides excellent probe to test New Physics influence
- only up-type quark allowing CP asymmetry measurements
  $\longrightarrow$ complementary to B and K



Measuring A_{CP} at LHCb

The presence of CPV can be measured through the observable:

$$\mathcal{A}_{raw}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \bar{f})} \simeq \mathcal{A}_{CP}(f) + \mathcal{A}_P(f) + \mathcal{A}_D(f)$$

A_{CP} is the physical asymmetry

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

A_P is the flavour asymmetry at production

A_D is the asymmetry induced by the detector different acceptance for opposite sign particles

A_P and A_D disentangled from A_{CP} exploiting calibration samples (large samples with known A_{CP})

Discovery of direct CPV in Charm decays

LHCb has the perfect environment to study charm decays

$\rightarrow \quad \sigma(pp \rightarrow Xc\bar{c}) \cdot \mathcal{L}_{ist} \sim 1\text{MHz}$ + precision vertexing + large bandwidth trigger system

Thanks to the huge collected statistics it was possible to reach 5σ-significance on ΔA_{CP}:

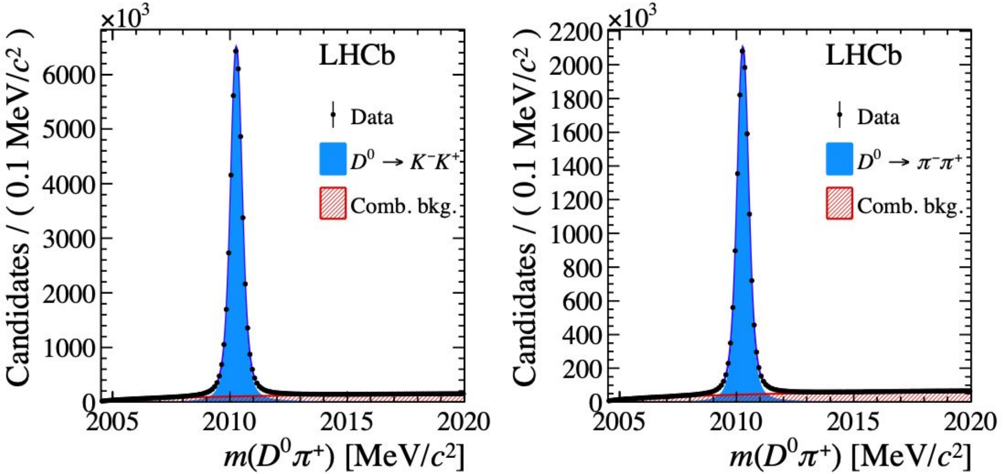
$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(K^+K^-) - \mathcal{A}_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$

This is only the starting point!

Is this in agreement with the theory?

Measurement of other decay channel can help constrain theory

Additional measurements are needed!



PRL 122 (2019) 211803

Search for CP violation in $D_{(s)}^+ \to h^+\pi^0$ and $D_{(s)}^+ \to h^+\eta$ $(h^+ = \pi^+, K^+)$

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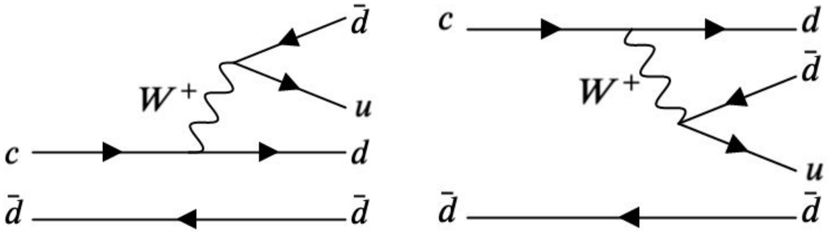
Motivations

[LHCB-PAPER-2021-001]

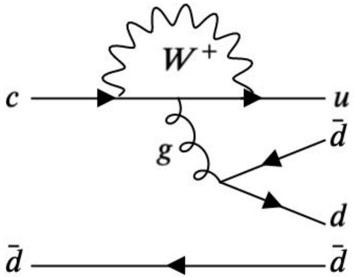
Eight different decays, most interesting are Singly-Cabibbo-suppressed (SCS) ones:

- $D_s^+ \to K^+\pi^0$, $D^+ \to \pi^+\eta$ and $D_s^+ \to K^+\eta$ decays
  $\to$ CPV allowed at tree level, $V_{cd}V_{ud}^*$ and $V_{cs}V_{us}^*$ contributions
  $\to$ expected size of A_{CP} $O(10^{-3} - 10^{-4})$ [PRD 86 (2012) 036012]

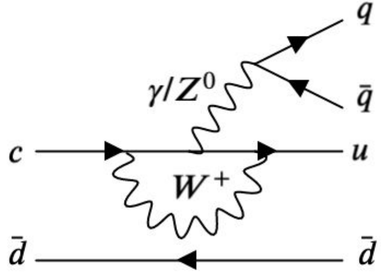
- $D^+ \to \pi^+\pi^0$ decay is of particular interest $\to$ SM prediction for A_{CP} is zero



Same weak phase for the two tree-level contributions



Not allowed in SM due to ΔI=3/2 gluon transition



EW penguin decay, suppressed by a factor α

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Decay chain reconstruction

First $A_{CP}(D_{(s)}^{+} \to h^{+}h^{0})$ measurement at an hadronic collider

Challenging neutral mesons final state

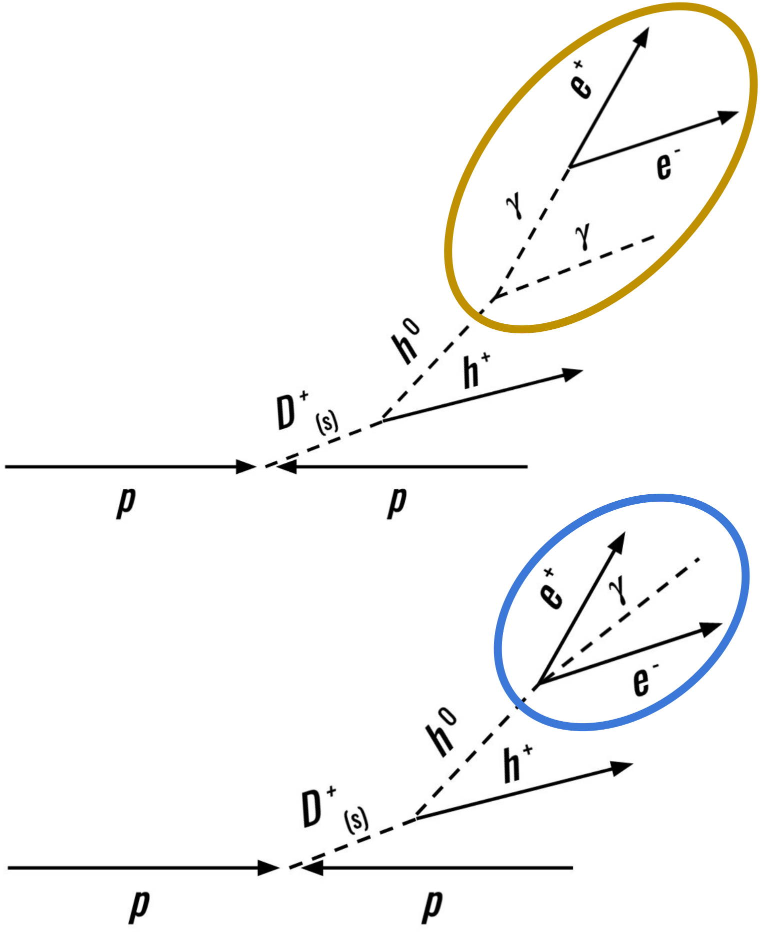
$\longrightarrow$ large combinatorial background

$D_{(s)}^{+}$ vertex reconstruction impossible with one single charged track

$e^{+}e^{-}\gamma$ final state for neutral meson exploited

$\longrightarrow$ 2-body $h^{0} \to \gamma(\to e^{+}e^{-})\gamma$ with one converted photon

$\longrightarrow$ 3-body $h^{0} \to e^{+}e^{-}\gamma$ decay



Candidate selection

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Combinatorial is the most abundant background:

- random tracks (pure combinatorial)
- random π^0 and tracks

→ rejected by →

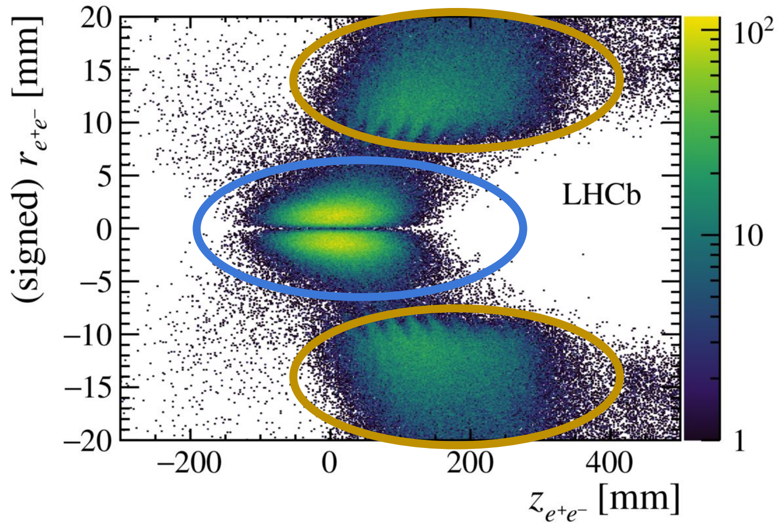
Track quality and displacement

Candidates p_T and vertex quality

Candidates dominated by the $h^0 \to \gamma\gamma$ decay:

- $h^0 \to \gamma(\to e^+e^-)\gamma$ 86% of the sample
- $h^0 \to \gamma e^+e^-$ 14% of the sample

Decay	Branching fraction
$\pi^0 \to \gamma\gamma$	$98.8 \pm 0.03\%$
$\pi^0 \to e^+e^-\gamma$	$1.17 \pm 0.04\%$
$\eta \to \gamma\gamma$	$39.41 \pm 0.20\%$
$\eta \to e^+e^-\gamma$	$0.68 \pm 0.04\%$



Yield extraction

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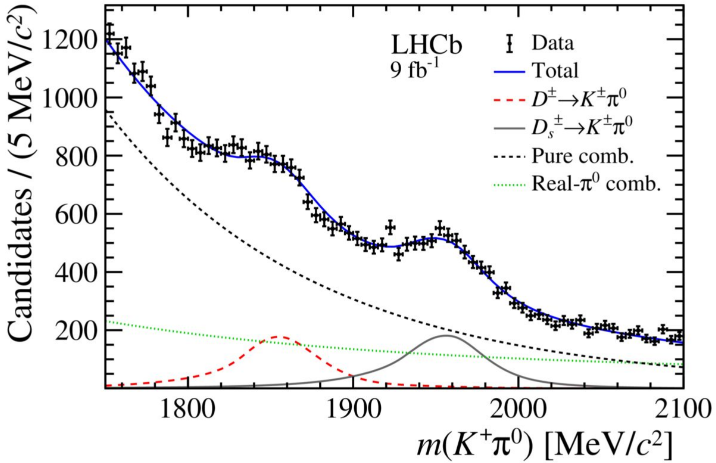
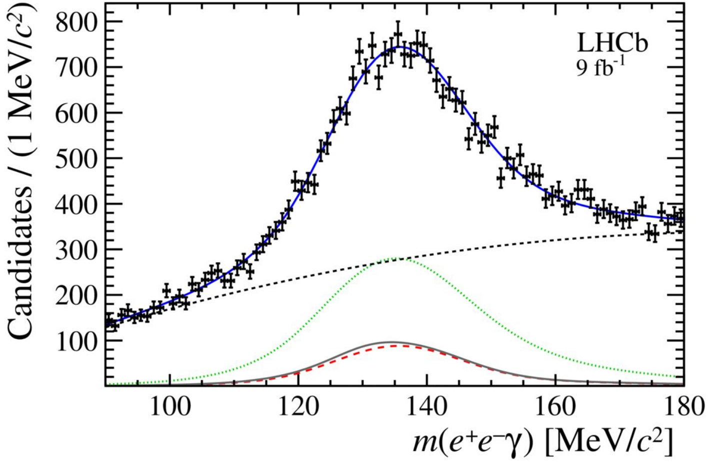
$D_{(s)}^{+} \to h^{+}\pi^{0}$ Run 1 and Run 2 (9 fb^{-1})
$D_{(s)}^{+} \to h^{+}\eta$ Run 2 (6 fb^{-1})
(no dedicated trigger in Run 1)



Fitted invariant masses:

- $m(e^{+}e^{-}\gamma)$
- $m(h^{+}h^{0})$

} A_{RAW} and yields extracted through 2D maximum likelihood fit



2D PDFs taken from MC simulation

→ fine-tuning parameters allowed fitting real data to account for possible data-simulation differences

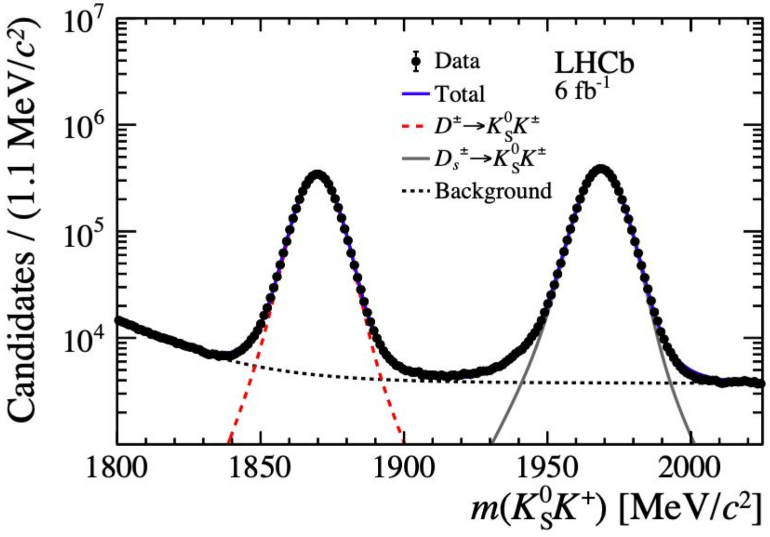
Control sample

$D_{(s)}^+ \rightarrow K_S^0 h^+$ samples exploited to subtract A_P and A_D

$\rightarrow$ A_{CP} measured with high precision

$\rightarrow$ control sample reweighted to match

$A_{D/P}(D_{(s)}^+ \rightarrow K_S^0 h^+)$ and $A_{D/P}(D_{(s)}^+ \rightarrow h^0 h^+)$



Asymmetries and yields extracted with same strategy of published analysis (PRL 122 (2019), 191803)

Subtraction between raw asymmetries allows A_{CP} extraction:

Fit to signal sample

Input from previous measurements

$$A_{CP}(D_{(s)}^+ \rightarrow h^0 h^+) = A_{RAW}(D_{(s)}^+ \rightarrow h^0 h^+) - A_{RAW}(D_{(s)}^+ \rightarrow K_S^0 h^+) + A_{CP}(D_{(s)}^+ \rightarrow K_S^0 h^+) + A_{MIX}(K_S^0)$$

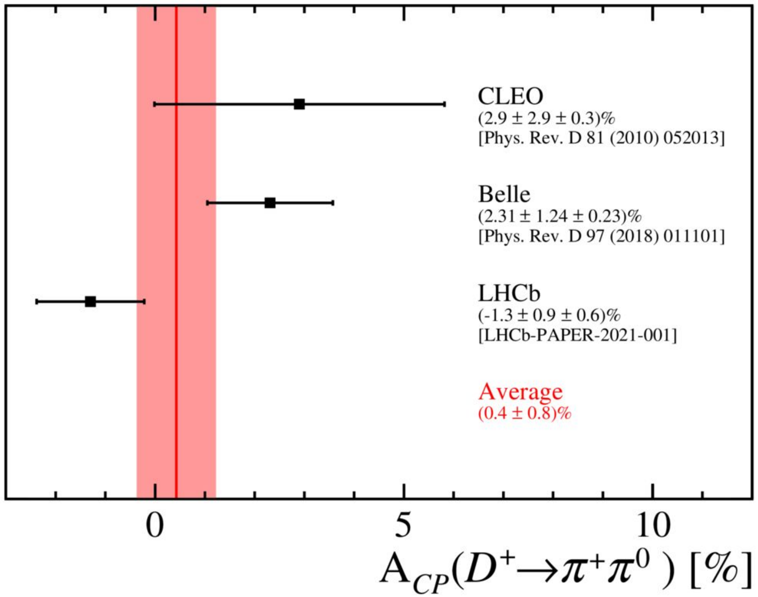
Fit to control sample

K_S^0 CPV decay + mixing + regeneration

Results

Measured CP asymmetries are:

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$



- all results **compatible with CP symmetry**
- first five represent the **most precise measurements to date**

Main systematics:

- fitting model
- control mode in case of $D_s^+ \to \pi^+\eta$ ($D_s^+ \to K_S^0\pi^+$ has the lowest statistics)

Measurement of CP asymmetry in $D^0 \to K_S^0 K_S^0$ decays

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Motivations

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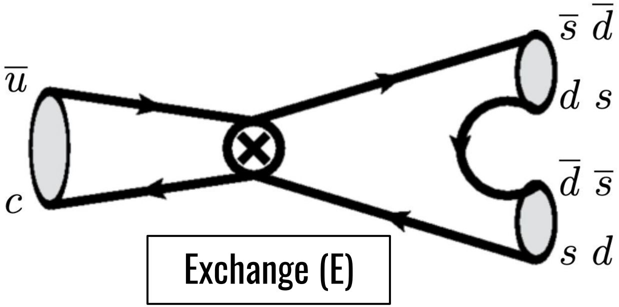
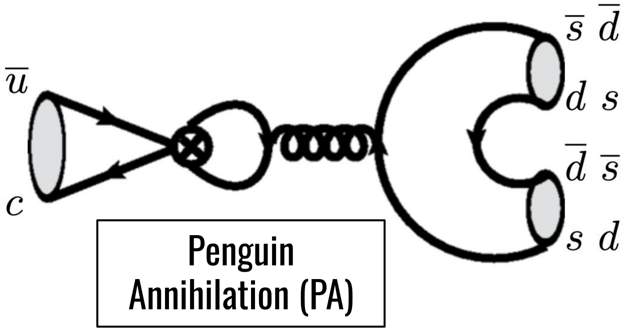
The search for CP violation in $D^0 \to K_S^0 K_S^0$ decays is interesting because:

- it has been proposed that A_{CP} can be large up to 1%





→ PA loop suppressed
→ E can have similar size (SU(3) suppressed)

PRD 92 (2015) 054036
PRD 92 (2015) 014004

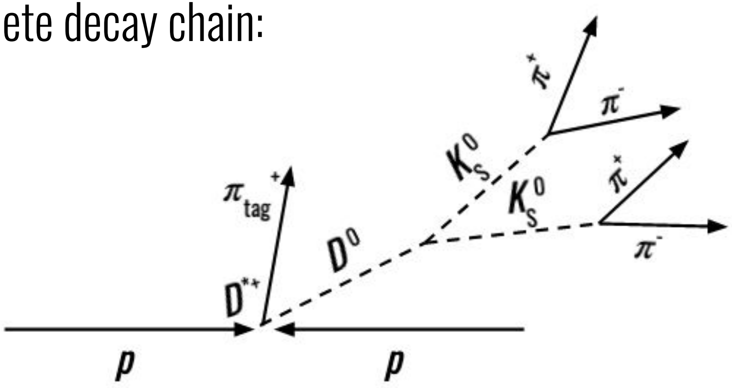
→ candidate for Charm CPV confirmation

- decay sensitive to different amplitude mix w.r.t. $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

Run 2 sample analyzed (6 fb^{-1})
→ 2015 - 2016 data reanalyzed (JHEP 11 (2018) 048) → ~ 30% sensitivity improvement

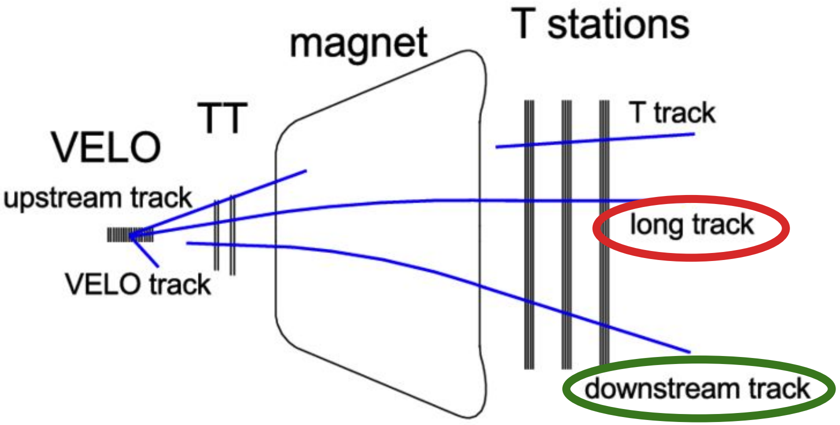
Decay chain and different categories

Complete decay chain:



→ π_{tag} sign exploited to tag the D^0 flavor

→ K_S^0 can decay outside the vertex detector (VELO)



Three "categories" are identified:

- LL → both K_S^0 are Long
- LD → one K_S^0 is Long and the other is Downstream
- DD → both K_S^0 are Downstream

Different resolution → separately analyzed

Background sources

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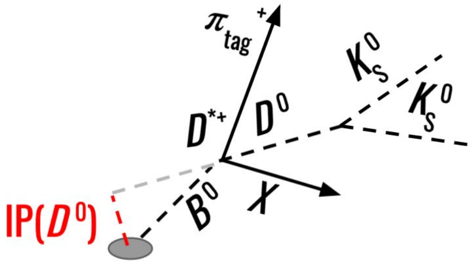
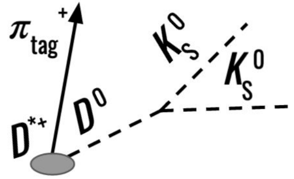
Main background sources:

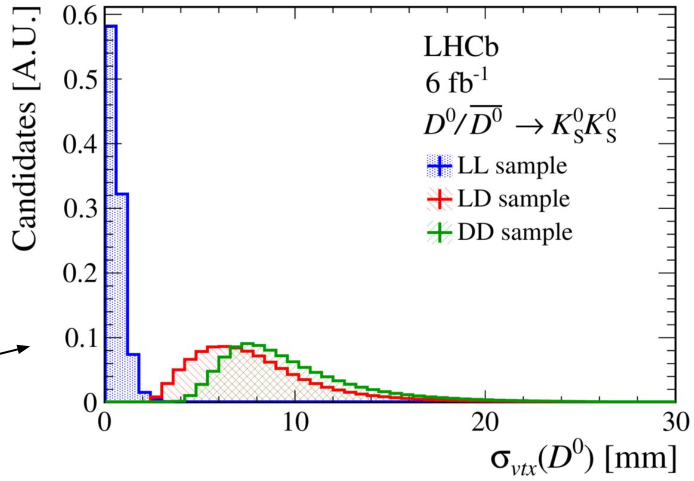
- $D^0 \to K_S^0 \pi^+ \pi^-$ $\to$ mostly removed by cut on K_S^0 flight distance, then disentangled in the fit
- combinatorial $\to$ partially rejected by a multivariate kinematics/vertex quality cut (kNN)
  $\to$ disentangled in the fit

D^* coming from a Beauty hadron decay present in the sample





Difficult to discriminate prompt/from-B candidates



A_P and A_D removed with a dedicated calibration channel
$\to$ same mixture as for signal sample

Their rejection would cause significant statistics loss

Nuisance asymmetries cancellation

Calibration sample: large sample of $D^0 \to K^+K^-$ w/o cuts on variables with different resolution (vertices)

Selections equalized between signal and calibration sample when possible

Nuisance asymmetries eliminated by **reweighting signal sample**:

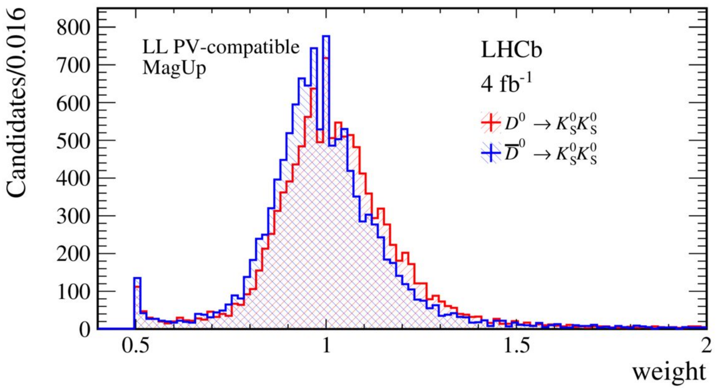
Calibration sample local density

$$w^{\pm}(\boldsymbol{p}) = \frac{n^{+}_{KK}(\boldsymbol{p}) + n^{-}_{KK}(\boldsymbol{p})}{2n^{\pm}_{KK}(\boldsymbol{p})} \cdot [1 \pm \mathcal{A}_{CP}(KK)]$$

D^0 three-momentum

Taken from PLB 767 (2017) 177-187

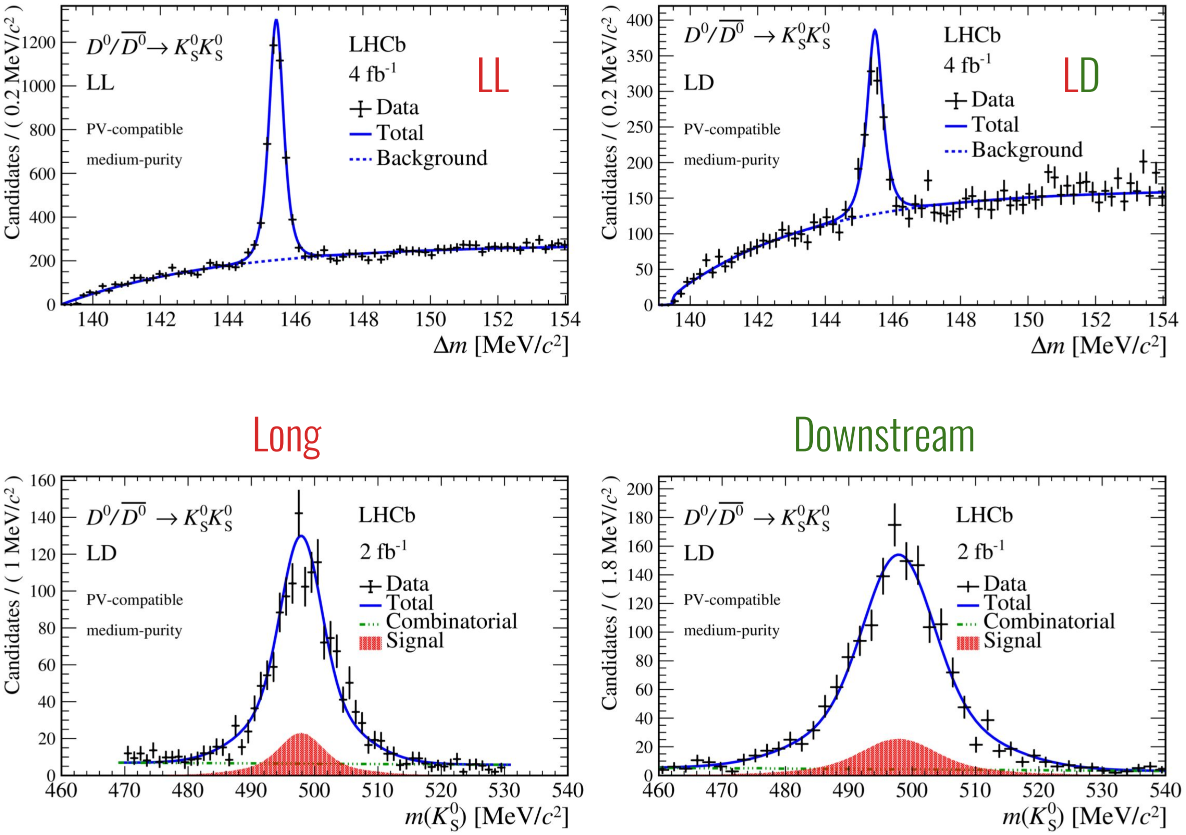
Local density numerically estimated through kNN



Fit strategy

Sample splitted to maximize sensitivity:

- LL, LD, DD
- 2015-2016, 2017-2018 (different trigger selections)
- purity level
- compatibility for D^* to come from PV



Asymmetries and yields extracted through 3D ML fit:

- $\Delta m = m(K_S^0 K_S^0 \pi^+) - m(K_S^0 K_S^0)$
- two $m(\pi^+\pi^-)$ distributions

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Results

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Combined result is:

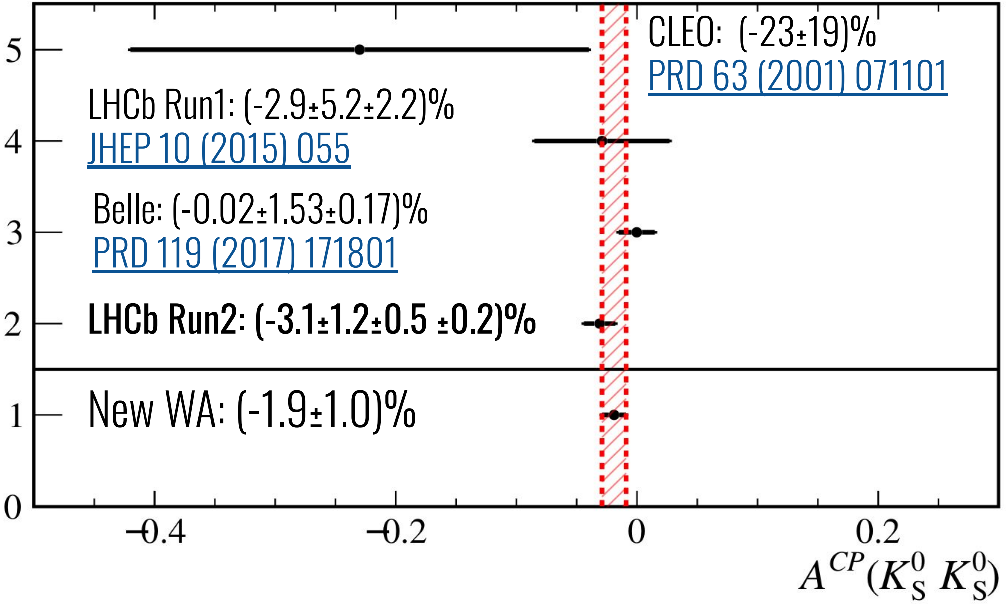
$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-3.1 \pm 1.2\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.2\ (A_{CP}(D^0 \rightarrow K^+ K^-))\ )\%$$

→ systematic dominated by knowledge on fitting model

Most precise measurement to date

Compatible with zero within 2.4 σ

WA is approaching for the first time upper end of SM predictions



Conclusions

LHCb collected the largest samples of D^0 decays to date, leading to first CPV observation in Charm decays

Efforts now focused on confirming and expanding this result

- LHCb producing world-best measurements in different channels
  $\rightarrow$ decays with neutral mesons (π^0, η, K_S^0) in the final state included!

No further observations of CPV yet

- new data from next year with LHC Run 3
- LHCb will work at higher luminosity, with upgraded detector and trigger system
  $\rightarrow$ expecting increased trigger efficiency for hadronic modes

Latest addition: work ongoing to bring K_S^0/Λ^0 identification and selection at first trigger level (HLT1), to enhance efficiency of these interesting modes in Run 3

Stay tuned!

Backup slides

Direct CP violation

CP violation (CPV) is the non-invariance of laws of Nature under Parity (P) and Charge conjugation (C)

→ matter and antimatter does not always behave the same when weak interaction is involved

It can manifest in three different ways:

- **CPV in the decay (direct CPV)**

$$|\mathcal{A}(D^0 \to f)|^2 \neq |\mathcal{A}(\overline{D}^0 \to \bar{f})|^2$$

- CPV in the mixing

$$\mathcal{P}(D^0 \to \overline{D}^0) \neq \mathcal{P}(\overline{D}^0 \to D^0)$$

- CPV in the interference between decay and mixing

$$|\mathcal{A}(D^0 \to \overline{D}^0 \to f)|^2 \neq |\mathcal{A}(\overline{D}^0 \to D^0 \to f)|^2$$

Decay amplitudes definition

Decay amplitudes are defined as:

$$\mathcal{A}(D^0 \to f) = \mathcal{A}_f^T e^{i\phi_f^T} \left[1 + r_f e^{i(\delta_f + \phi_f)}\right]$$

$$\mathcal{A}(\overline{D}^0 \to \bar{f}) = \eta_{CP} \mathcal{A}_f^T e^{-i\phi_f^T} \left[1 + r_f e^{i(\delta_f - \phi_f)}\right]$$

A^T_f is the magnitude of the dominant SM amplitudes (tree level)

ϕ^T_f is an unobservable weak phase

$\eta_{CP} = \pm 1$ is the CP eigenvalue of f

CPV size

ACP can be expressed as:

Relative magnitude of subleading amplitudes w.r.t dominant ones

$$\mathcal{A}_{CP}(f) \simeq -2\, r_f \sin \delta_f \sin \phi_f$$

Relative **strong** and **weak** phases between subleading and dominant amplitudes

To have CPV at least two different processes have to contribute to the decay amplitude, with different strong and weak phases

→ leading order term usually defined as **tree amplitude**

→ second successive order terms usually defined as **penguin amplitude**

ACP in charm decays expected size is *O* $(10^{-3} - 10^{-4})$, because of:

- suppression factor is due to involved CKM matrix elements in Charm decays

$$\mathrm{Im}(V_{cb}V_{ub}^*/V_{cs}V_{us}^*) \approx -6 \times 10^{-4}$$

- additional loop factor *O* (10^{-1})

ΔA_{CP} related literature

Grossman et al. 2007 PRD 75 (2007) 036008
Li et al. 2012 PRD 86 (2012) 036012
Cheng & Chiang 2012 PRD 85 (2012) 024036
Khodjamirian & Petrov PRB 774 (2017) 235-242

Chala et al. 2019 JHEP 07 (2019) 161
Grossman & Schacht 2019 JHEP 07 (2019) 020
Buccella et al. 2019 PRD 99 (2019) 11, 113001
Cheng & Chiang 2019 PRD 100 (2019) 9, 093002
Soni 2019 arXiv 1905.00907
Dery & Nir 2019 JHEP 12 (2019) 104
Li et al. 2019 arXiv 1903.10638
Wang et al 2020 arXiv 2001.09460
Bause et al. 2020 PRD 101 (2020) 11, 115006
Dery et al. 2021 JHEP 05 (2021) 179

Decays phenomenology

Eight different decays are considered, with different phenomenology:

- $D^+_s \to \pi^+\pi^0 \to$ highly suppressed

- $D^+_s \to \pi^+\eta \to$ Cabibbo-favored (CF)

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

$\}\to$ Doubly-Cabibbo-suppressed (DCS)

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

$\}\to$ Singly-Cabibbo-suppressed (SCS)

Main background sources

Purely combinatorial	Real π^0 combinatorial	Misidentification background	Partially reconstructed decays
Random combination of tracks and photons	Random combination of real π^0 and random tracks	Signal decays where a π^+ track has been incorrectly assigned the K^+ mass hypothesis (or vice versa)	Charm mesons decays to h^+h^0X final states (X is unreconstructed)

Rejected applying selections on:

h^+, e^+, e^- track quality and displacement h^0 and $D_{(s)}^+$ candidates invariant mass h^0 and $D_{(s)}^+$ candidates transverse momentum $D_{(s)}^+$ quality vertex	MVA-based particle identification (PID) variables → looser on π^+, e^+, e^- → tighter on K^+ (more abundant π^+ mode)	$D_{(s)}^+$ candidate momentum pointing toward the primary vertex

Selections are applied in different steps: by the trigger during data taking and offline during analysis

Sample splitting during fit

Sample is split into multiple categories and simultaneously fitted:

- data taking period (only for $D_{(s)}^{+} \to h^{+}\pi^{0}$)
  $\to$ different data taking period
- number of bremsstrahlung photons (0 or 1, 2+ events are rejected due to poor resolution)
  $\to$ different resolution
- charged-hadron type (π^{+} or K^{+})
  $\to$ allow signal yield in each category to determine misidentification background yields
- candidate charge
  $\to$ extract raw asymmetry

Control sample reweighting

Reweighting is applied to equalize:

- kinematic distributions (*p*, η and ϕ of $D_{(s)}^+$ and h^+)
  → 2D reweighting is performed on this variables (*e.g.* $p(D_{(s)}^+)$-$p(h^+)$), to take into account correlations
- equalize relative fraction of different trigger categories population
  → each category passed different selection criteria that differently affected A_D
- equalize impact parameter (IP, distance of closest approach between PV and $D_{(s)}^+$ flight direction) distributions
  → equalize prompt/from *B* decays relative fraction candidates, that have different A_P

Raw asymmetries correlation

Raw asymmetries are correlated

- $\longrightarrow$ fitted variable $m(h^+h^0) = m(h^+e^+e^-\gamma) - m(e^+e^-\gamma) + M(h^0)_{\mathrm{PDG}}$
- $\longrightarrow$ reduce correlation between fitted dimensions

Correlations between raw asymmetries are present due to D^+ and $D_{(s)}^+$ signal distributions overlap

	$D^+\to\pi^+\pi^0$	$D^+\to K^+\pi^0$	$D_s^+\to K^+\pi^0$
$D^+\to\pi^+\pi^0$	1.00		
$D^+\to K^+\pi^0$	−0.01	1.00	
$D_s^+\to K^+\pi^0$	−0.09	0.10	1.00

	$D^+\to\pi^+\eta$	$D^+\to K^+\eta$	$D_s^+\to\pi^+\eta$	$D_s^+\to K^+\eta$
$D^+\to\pi^+\eta$	1.00			
$D^+\to K^+\eta$	−0.00	1.00		
$D_s^+\to\pi^+\eta$	0.01	0.00	1.00	
$D_s^+\to K^+\eta$	−0.06	0.10	−0.00	1.00

$D_{(s)}^{+} \to h^{+}\pi^{0}$ mass distributions

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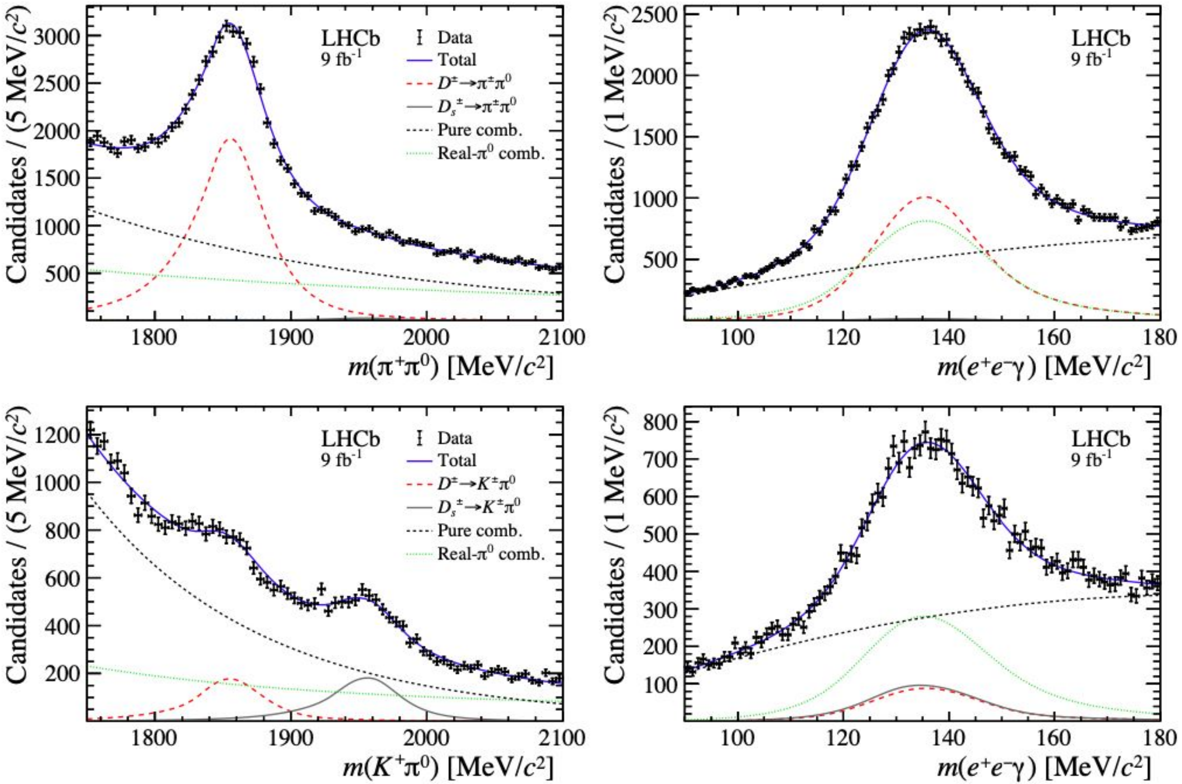

$D_{(s)}^+ \to h^+\eta$ mass distributions

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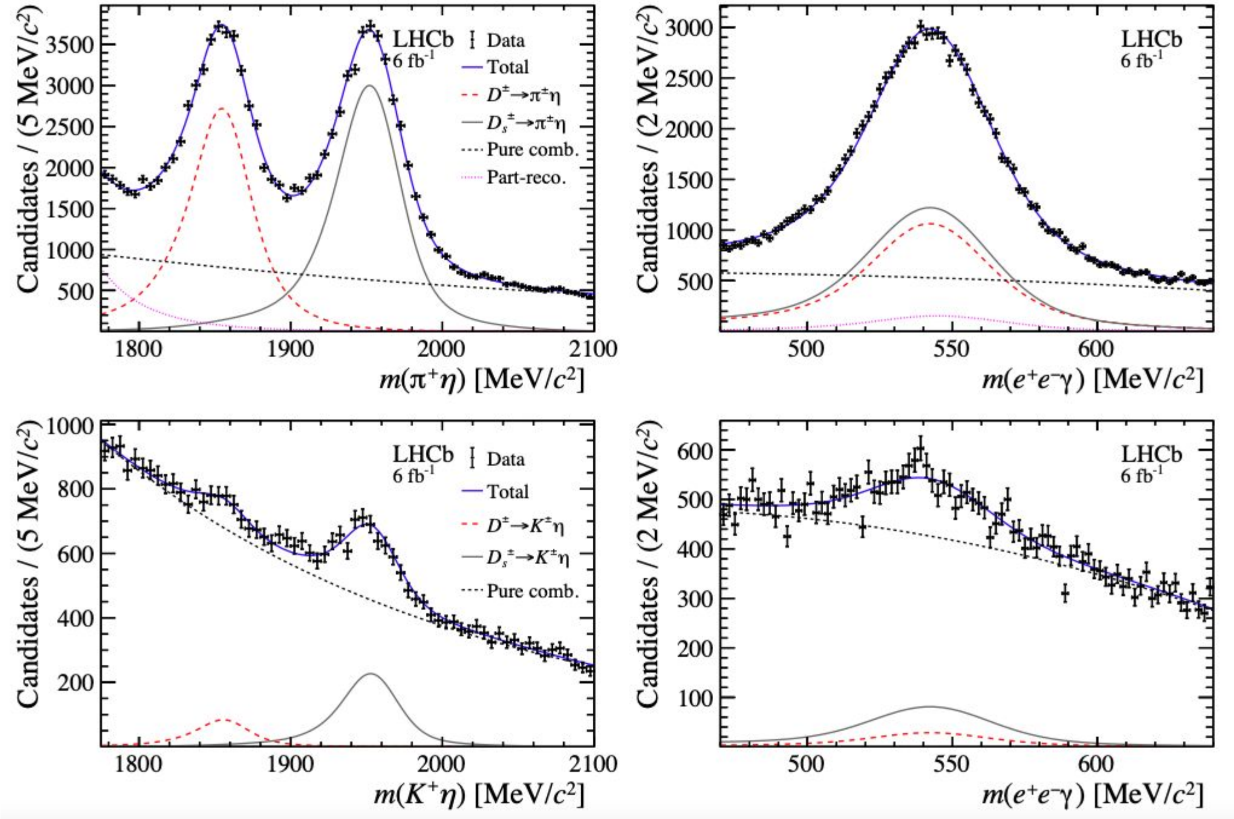

Signal sample complete fit results

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Mode	Yield 2011	Yield 2012	Yield Run 2	A_{Raw} (%)
$D^+ \to \pi^+\pi^0$	740 ± 60	$2\,240 \pm 120$	$25\,750 \pm 430$	-1.64 ± 0.93
$D_s^+ \to \pi^+\pi^0$	20 ± 30	-50 ± 50	450 ± 120	-
$D^+ \to K^+\pi^0$	10 ± 13	90 ± 30	$2\,440 \pm 110$	-2.53 ± 4.75
$D_s^+ \to K^+\pi^0$	54 ± 13	150 ± 30	$2\,580 \pm 90$	-0.25 ± 3.87
$D^+ \to \pi^+\eta$	-	-	$32\,760 \pm 380$	-0.55 ± 0.76
$D_s^+ \to \pi^+\eta$	-	-	$37\,950 \pm 340$	0.75 ± 0.65
$D^+ \to K^+\eta$	-	-	880 ± 70	-5.39 ± 10.40
$D_s^+ \to K^+\eta$	-	-	$2\,520 \pm 70$	1.28 ± 3.67

Control sample complete fit results

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Mode	$A_{\text{Raw}}^{\text{Weighted}}(D_{(s)}^{+} \to K_{\text{S}}^{0} h^{+})$	MC binning syst.
$D^{+} \to \pi^{+}\pi^{0}$	-0.446 ± 0.021	0.008
$D^{+} \to K^{+}\pi^{0}$	0.577 ± 0.081	0.008
$D_{s}^{+} \to K^{+}\pi^{0}$	0.595 ± 0.068	0.008
$D^{+} \to \pi^{+}\eta$	-0.458 ± 0.043	-
$D_{s}^{+} \to \pi^{+}\eta$	-0.018 ± 0.365	-
$D^{+} \to K^{+}\eta$	0.331 ± 0.100	0.082
$D_{s}^{+} \to K^{+}\eta$	0.357 ± 0.099	-

Main background sources $D^0 \to K_S^0 K_S^0$

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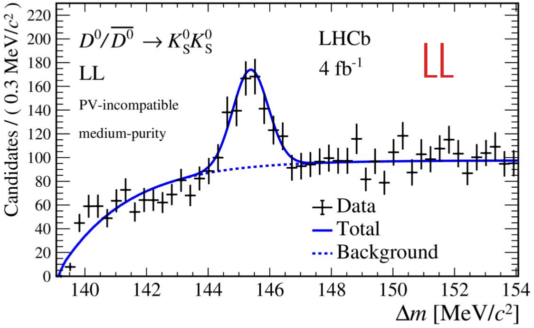
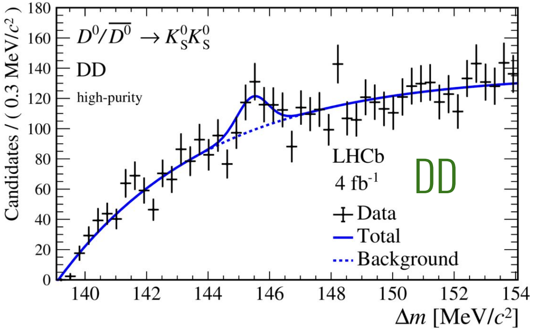
Partially reconstructed decays	Non-D^0 decays	$D^0 \to K_S^0\pi^+\pi^-$ decays	Combinatorial
Partially reconstructed D^0 decays, coming from D^* *e.g.* $D^0 \to K_S^0 K_S^0 \pi^0$	Main contributor is $D_S^+ \to K_S^0 K_S^0 \pi^+$	With the $\pi^+\pi^-$ pair identified as a K_S^0 it mimics signal	Random association of tracks, K_S^0 and D^0, forming fake candidates

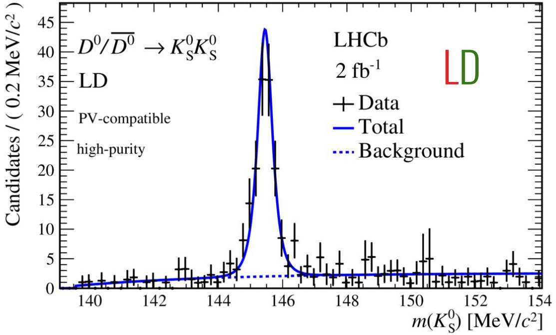
Treated with:

Partially reconstructed decays / Non-D^0 decays	$D^0 \to K_S^0\pi^+\pi^-$ decays	Combinatorial
Effectively suppressed accepting only D^0 candidates with $m(D^0)$ around the known D^0 mass	Selection on K_S^0 flight distance and disentangled from signal in the fit	Selection on the output of a k-nearest-neighbour classifier (kNN)

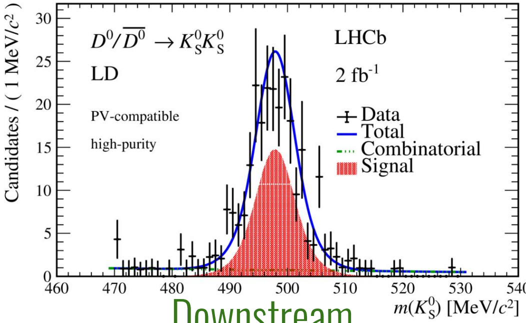
Fitted mass distributions examples



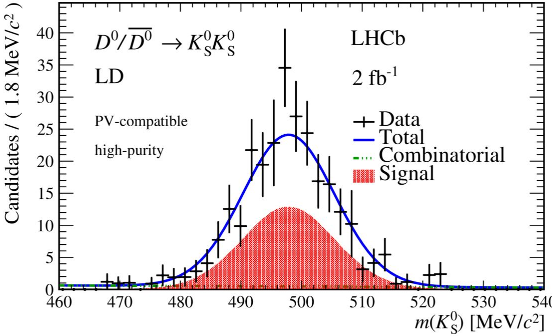




Long



Downstream



Subsamples results

First uncertainty is statistical

Second uncertainty is systematic

Sample	2015 + 2016 ($2\ fb^{-1}$) Yield	2015 + 2016 ($2\ fb^{-1}$) $\mathcal{A}^{CP}$ [%]	2017 + 2018 ($4\ fb^{-1}$) Yield	2017 + 2018 ($4\ fb^{-1}$) $\mathcal{A}^{CP}$ [%]
LL PV-comp.	1388 ± 41	$0.3 \pm 2.5 \pm 0.6$	4056 ± 77	$-4.3 \pm 1.6 \pm 0.4$
LL PV-incomp.	178 ± 31	$-11 \pm 17 \pm 2$	430 ± 41	$-3.0 \pm 7.9 \pm 1.1$
LD PV-comp.	411 ± 25	$-7.2 \pm 5.8 \pm 1.1$	1145 ± 49	$-2.9 \pm 3.8 \pm 0.7$
LD PV-incomp.	58 ± 18	$-10 \pm 31 \pm 4$	349 ± 64	$-5 \pm 17 \pm 2$
DD	–	–	87 ± 28	$-35 \pm 47 \pm 6$