MANCHESTER 1824

The University of Manchester

Measurements of mixing and indirect CPV in two-body charm decays at LHCb

Kevin S. Maguire, on behalf of LHCb and University of Manchester

CKM2016, TIFR Mumbai, December 1st, 2016

Charm at LHCb

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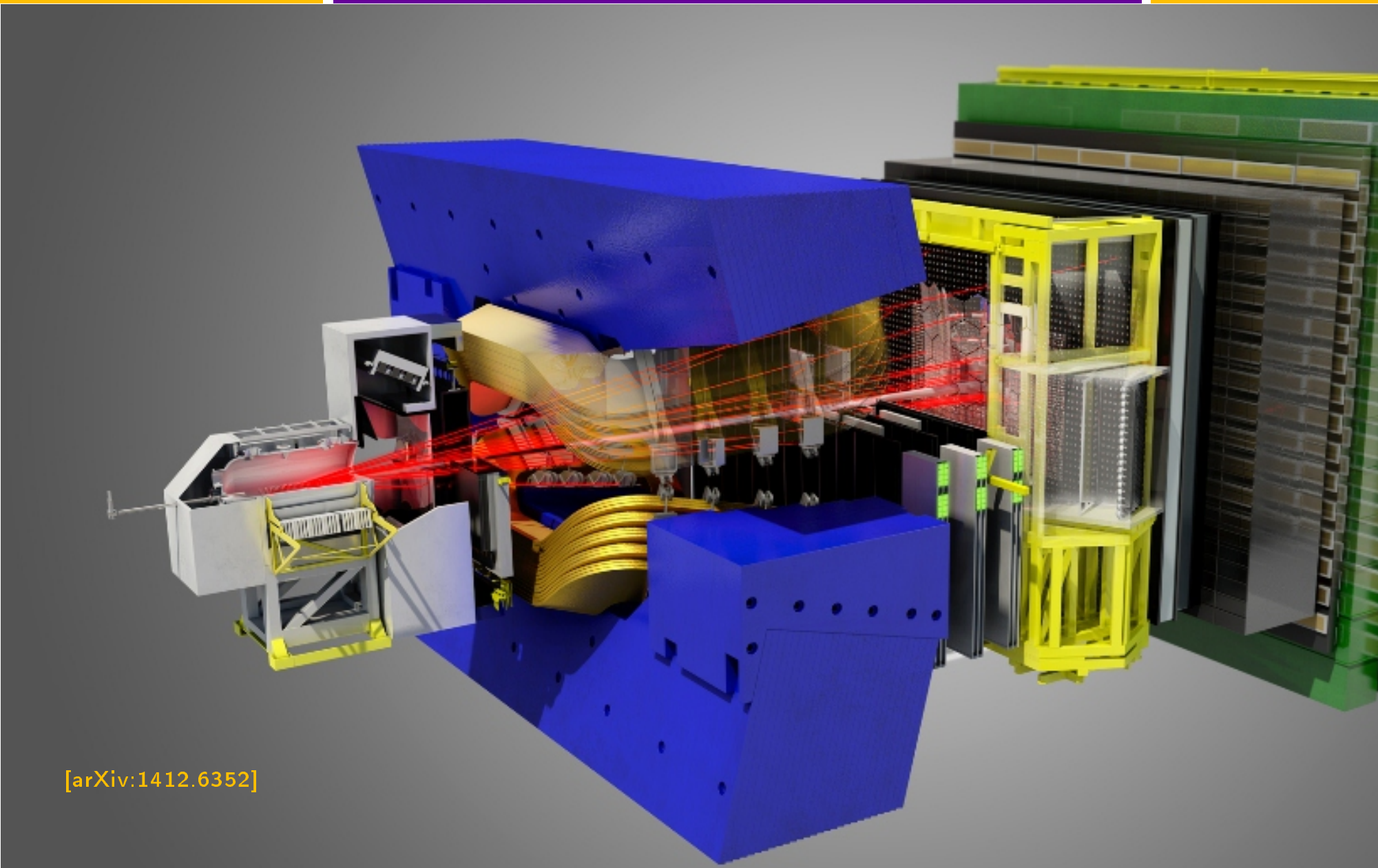

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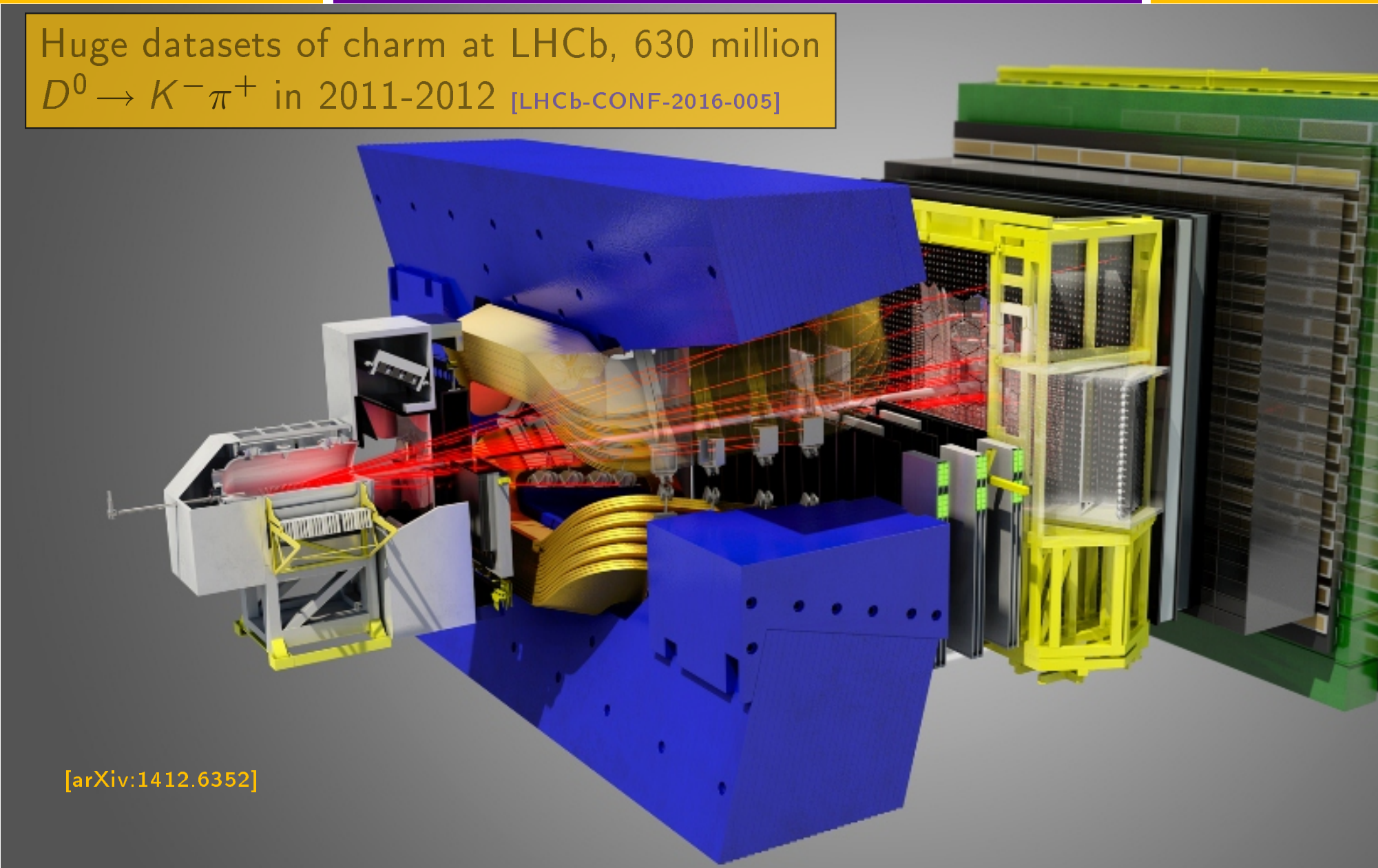

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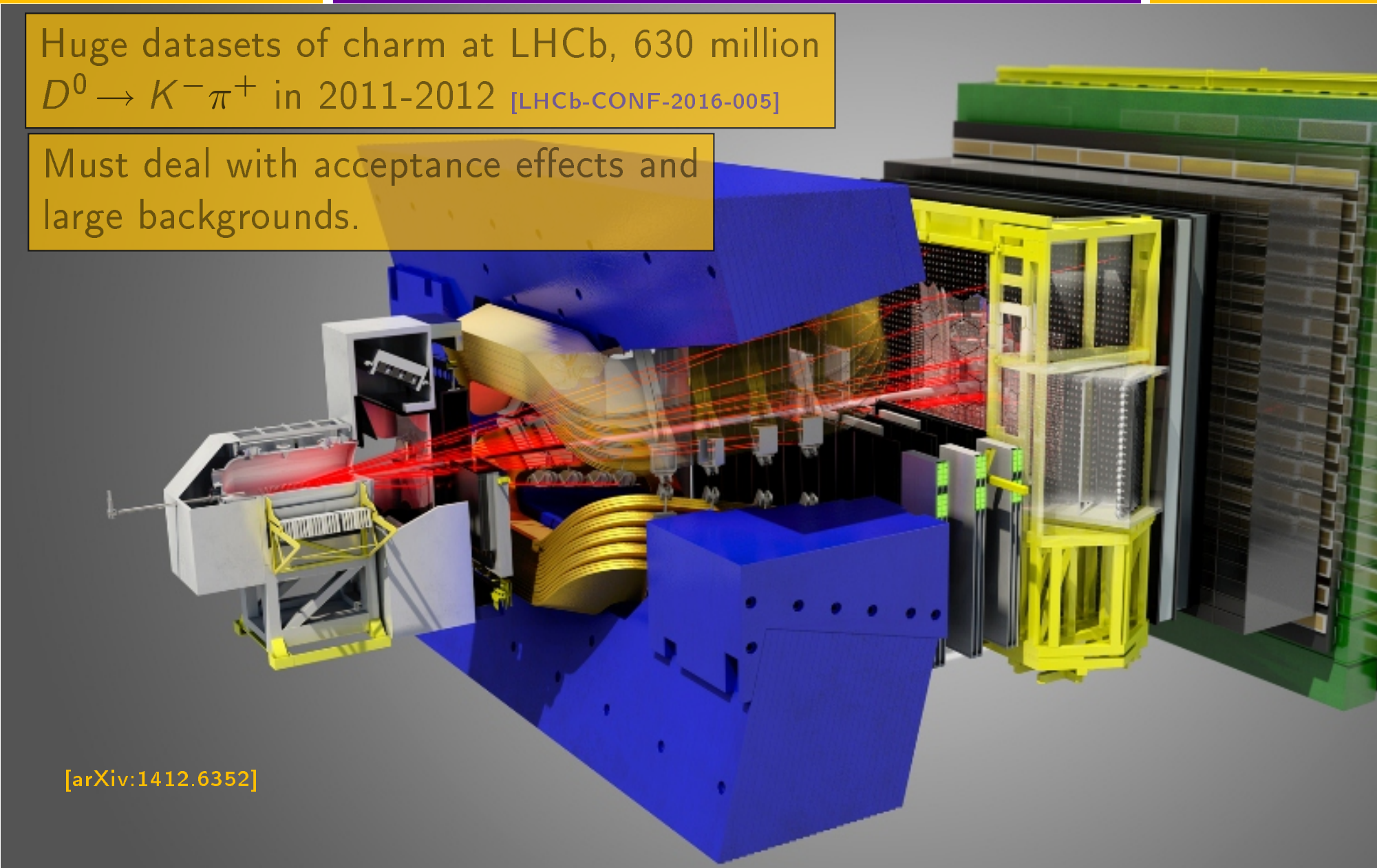

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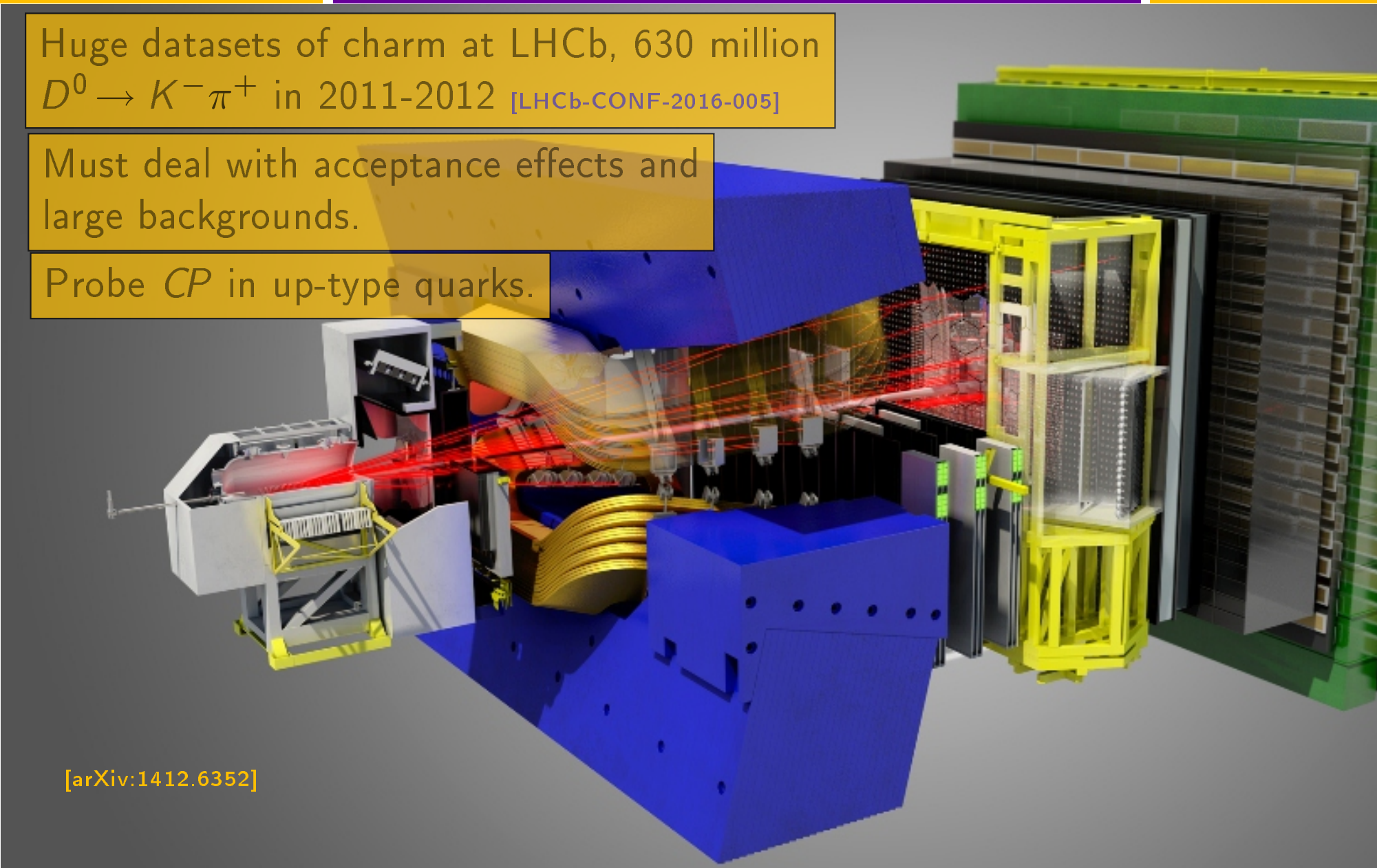

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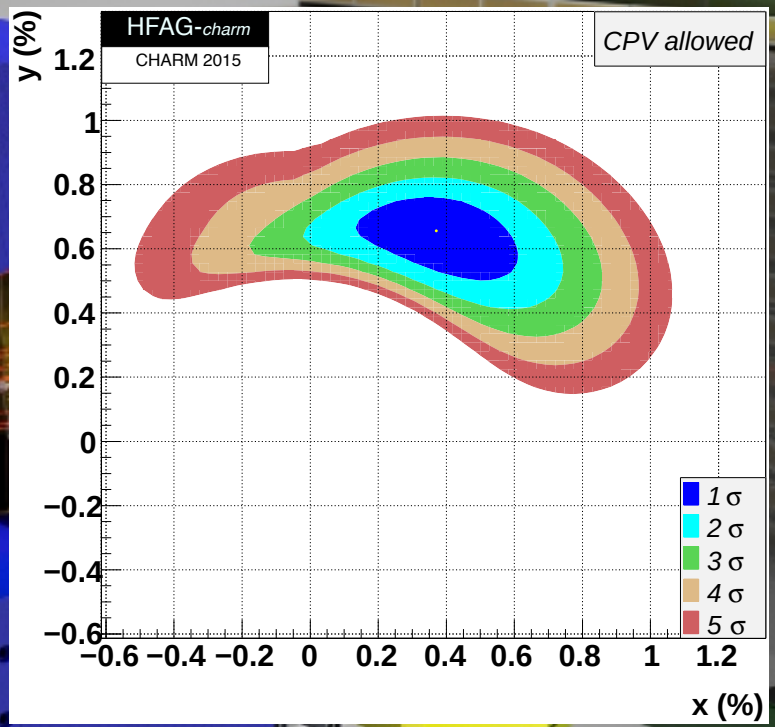

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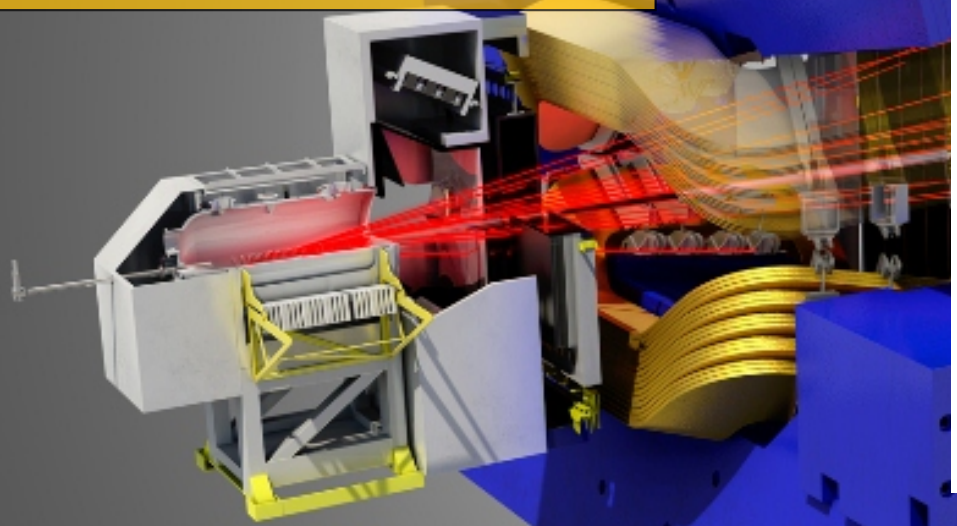

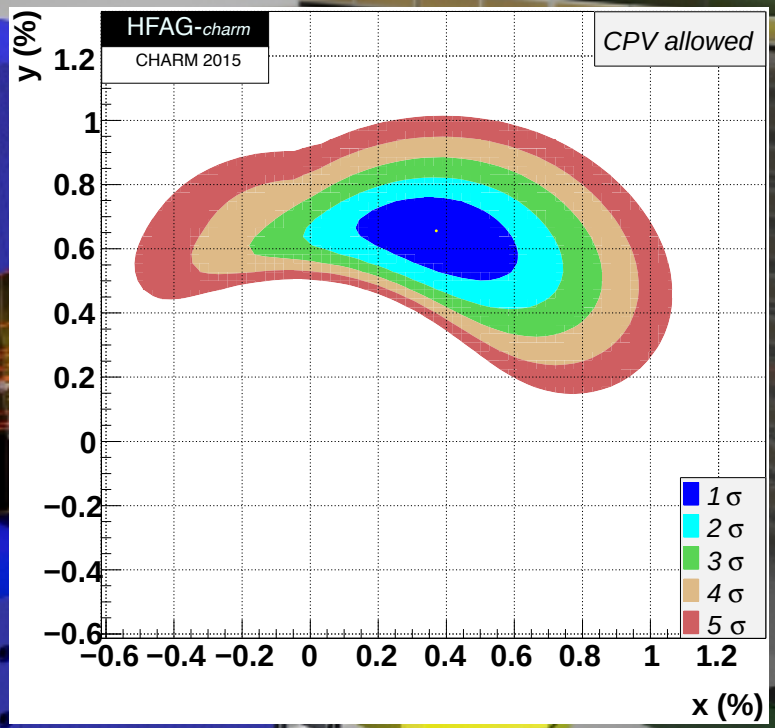

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CP violation not observed in *D* system.

Introduction

1. A_Γ measurements in $D^0 \to K^+K^-, \pi^+\pi^-$.
2. Charm mixing and CPV ($R(t)^{\pm}$) in $D^0 \to K^{\pm}\pi^{\mp}$.

A_Γ measurements

Two Methods

1. Unbinned maximum likelihood of effective decay times [LHCb-CONF-2016-010].
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- Both flavour tagged with $D^{*+} \to D^0 \pi^+$.
- Same dataset and selection, except for one condition.
- A paper including both measurements is in preparation.

A_Γ Observable

- Asymmetry of the effective decay widths, $\hat{\Gamma}(D^0 \to f)$ to CP-eigenstates f,

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)}.$$

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- Improvements in precision are now valuable for testing SM predictions.

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- represent CPV in **mixing** and in the **interference** of decays.
- x and y are the charm mixing parameters,
- $\phi = \arg\left((q\overline{A}_f)/(pA_f)\right)$,
- where $A_f(\overline{A}_f)$ is the amplitude of $D^0 \to f(\overline{D}^0 \to f)$ decay,
- $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$.

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[LHCb-CONF-2016-010]

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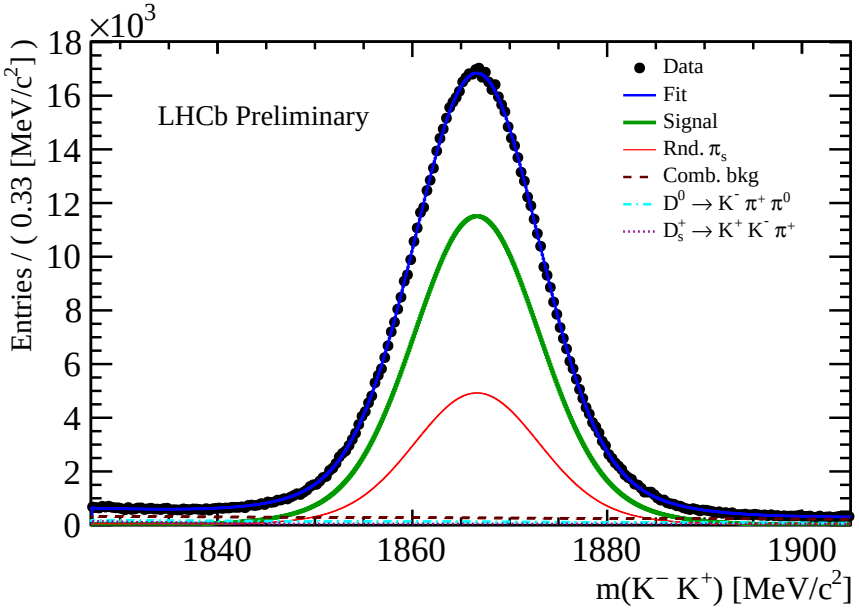
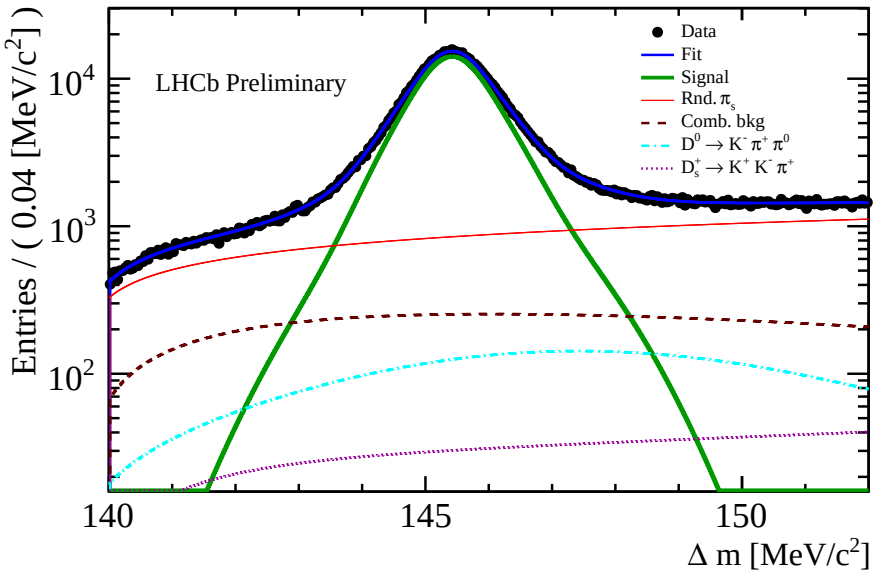
- First stage:

D^0 Invariant mass



$\Delta m = D^{*+} - D^0$ mass difference



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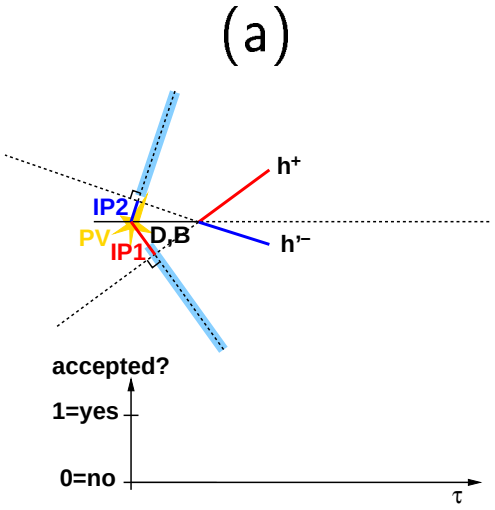

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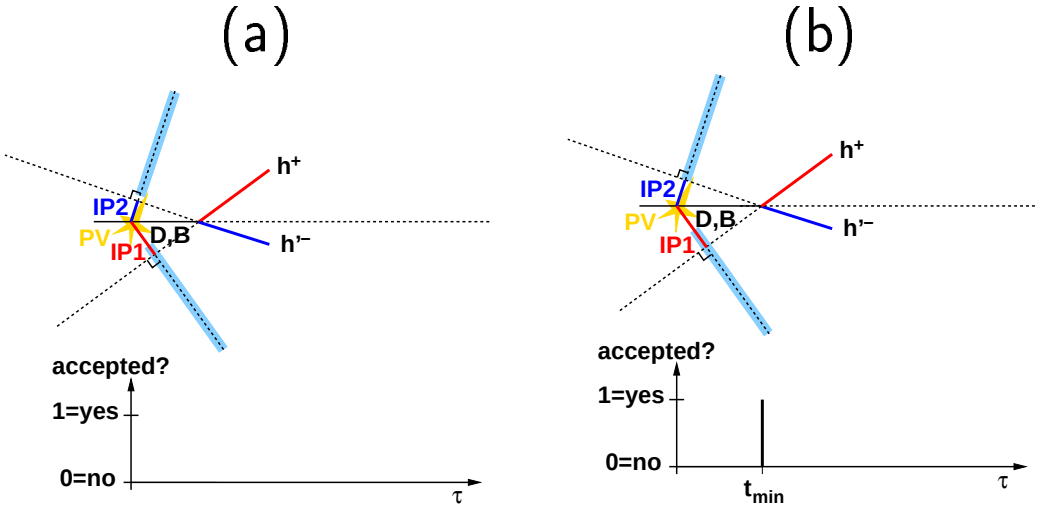

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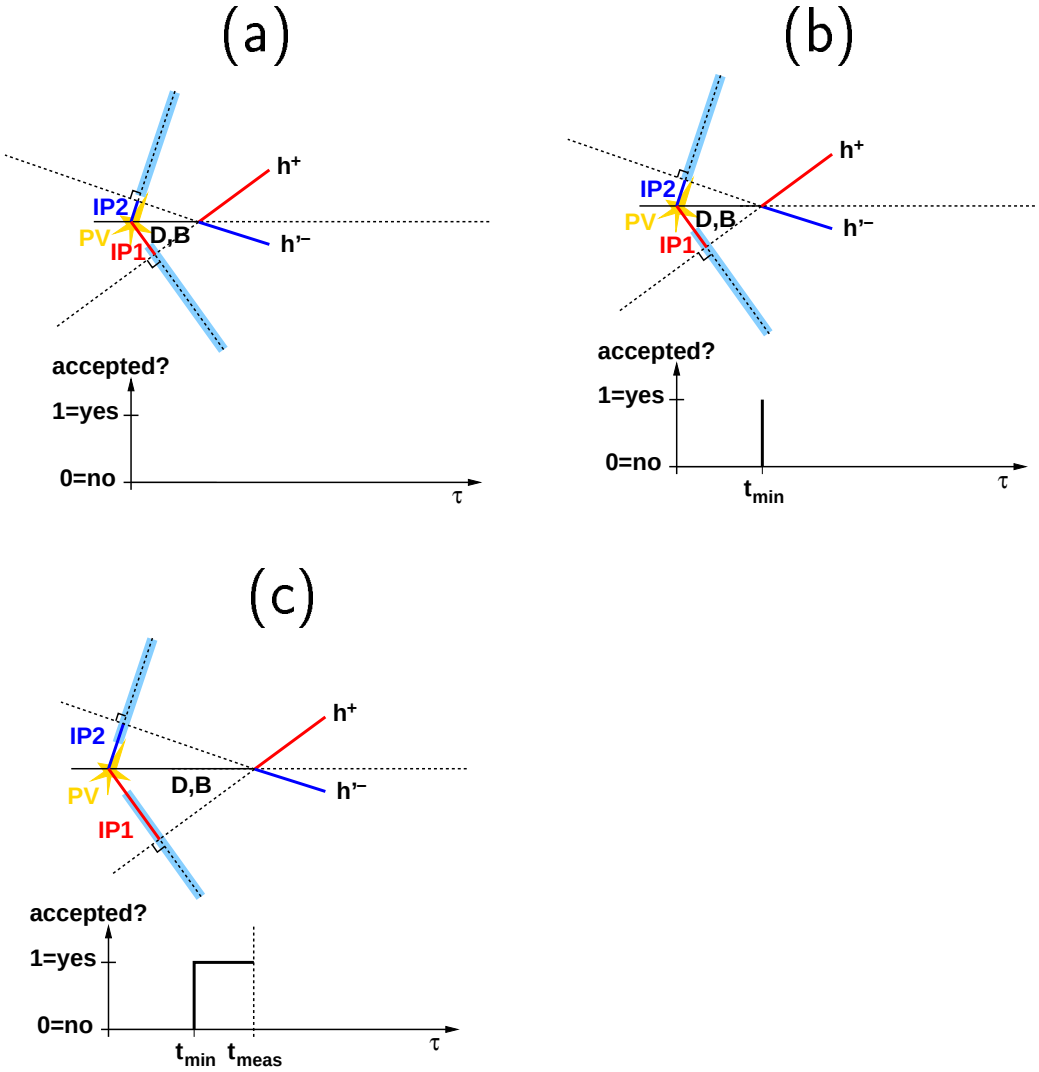

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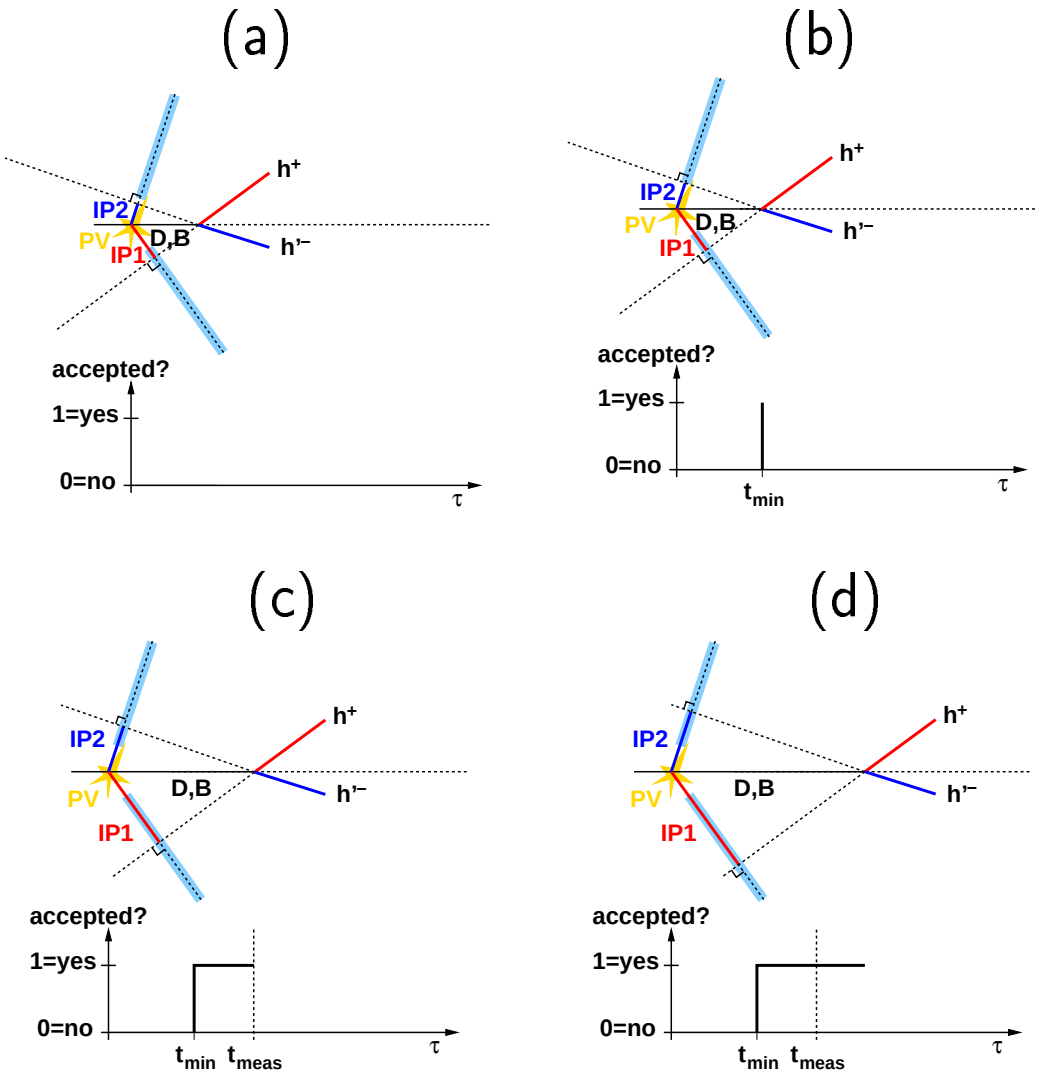

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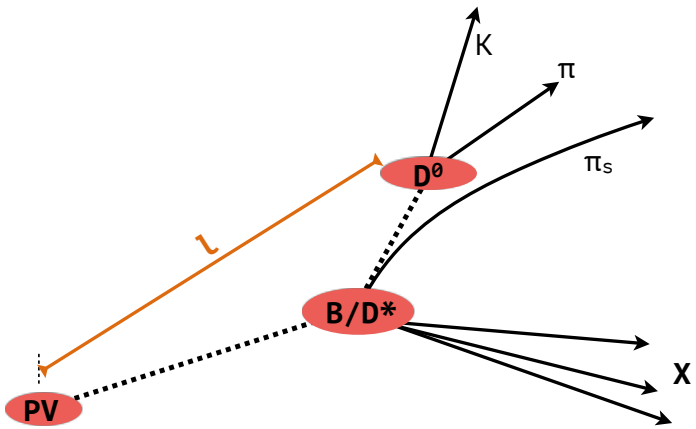

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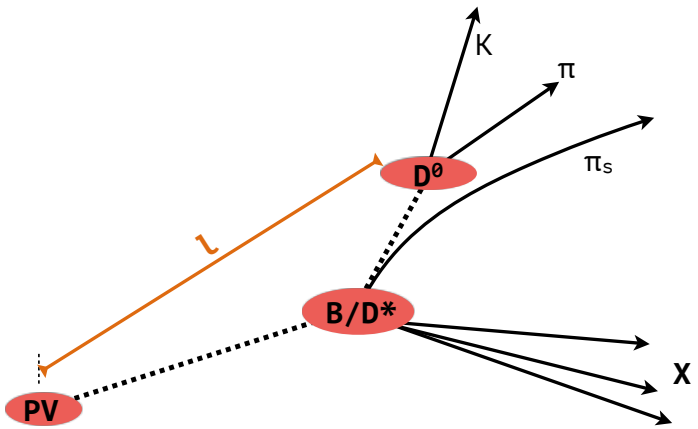
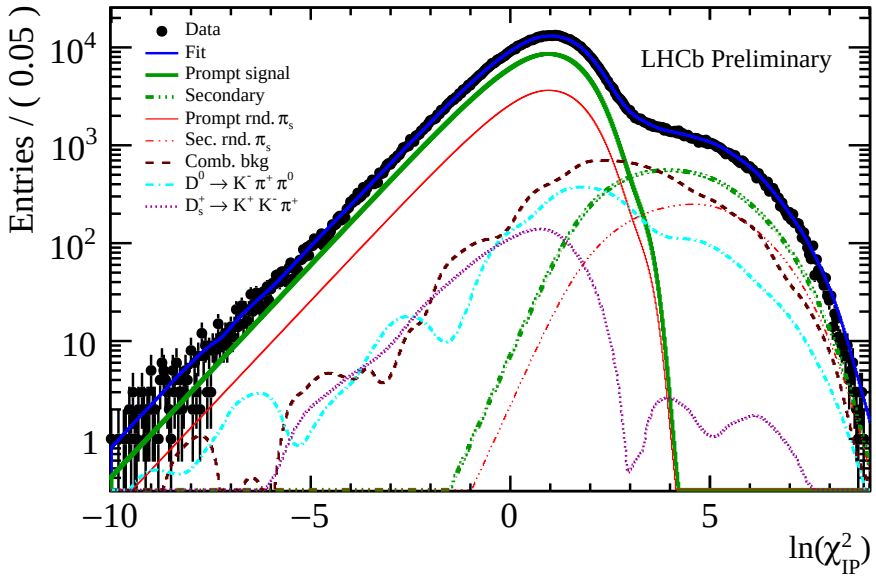
- Separated using $ln(\chi^2_{IP})$. Where χ^2_{IP} is defined as the difference between the χ^2 of the PV reconstructed with and without the considered particles.





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- Per-candidate probability density function (PDF) for prompt signal:

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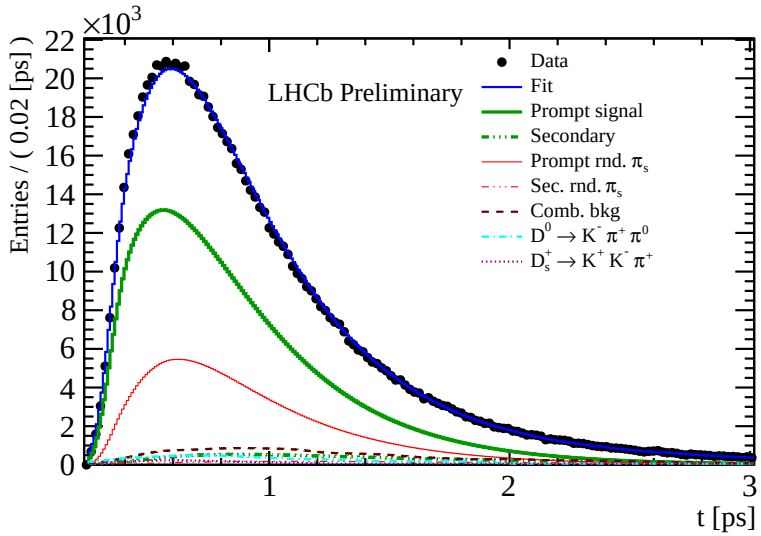

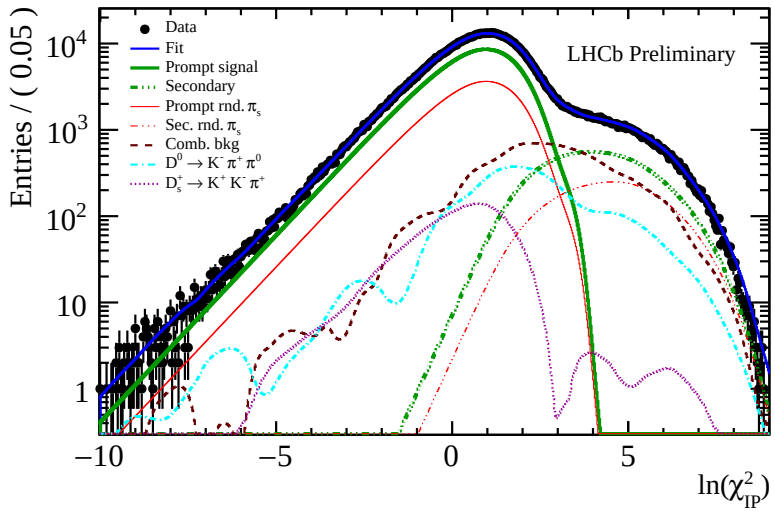

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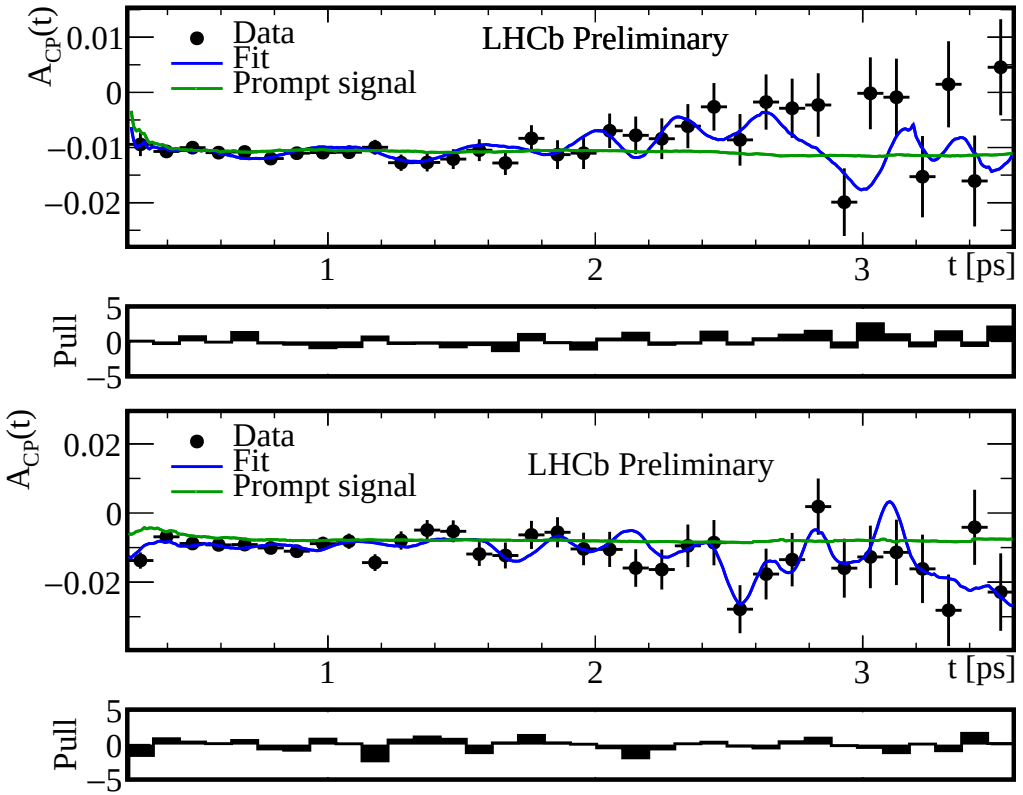

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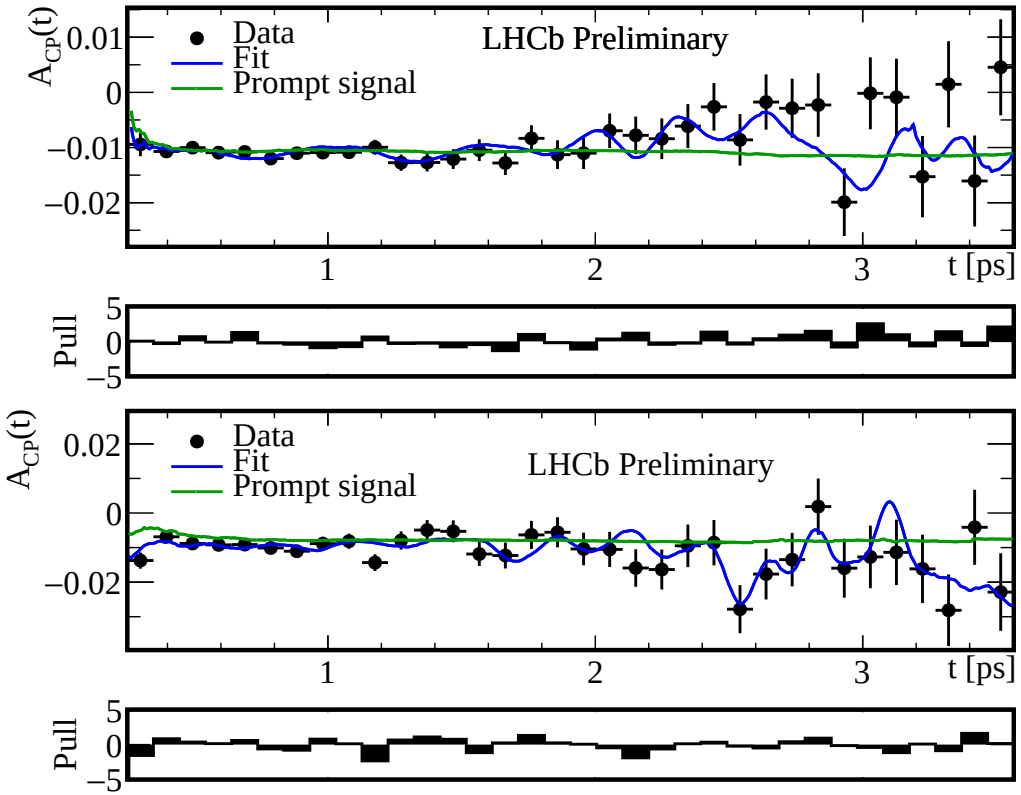

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- Main systematics from **mismodelling** of low decay-time, **secondary** contamination, ignored **correlations** and **combinatoric** backgrounds.

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$$\Delta A_\Gamma = (0.28 \pm 0.73 \pm 0.05) \times 10^{-3},$$
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Method 2: Binned yield asymmetry

- Simple counting experiment in bins of decay time.

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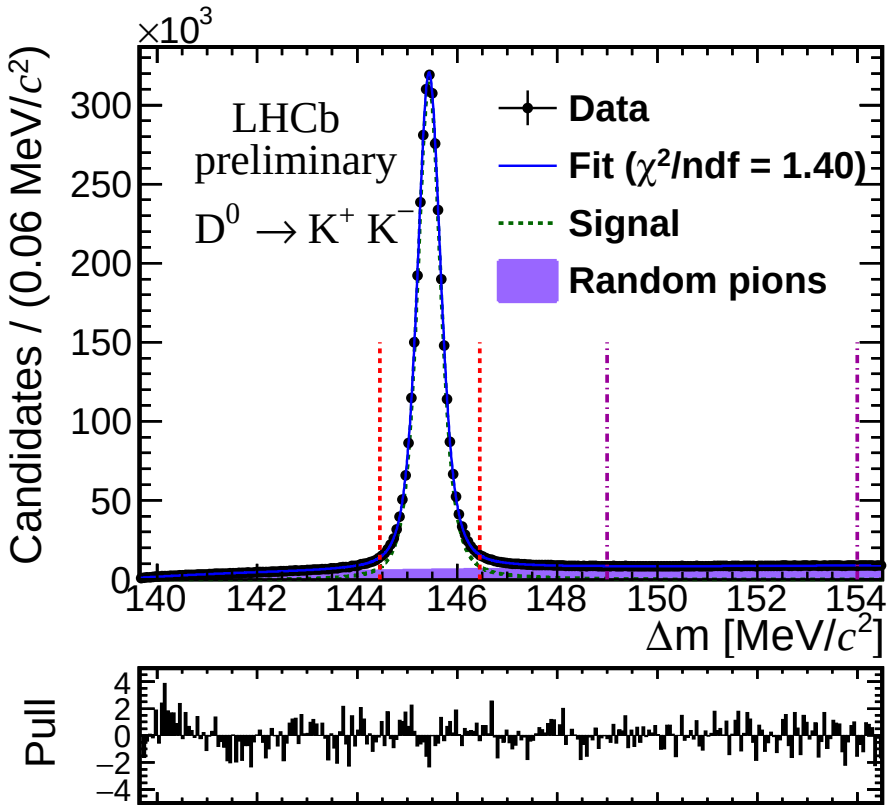
- Straight line fit.

$$A_{\text{raw}}(t) = A_0 - \frac{t}{\tau_{D^0}} A_\Gamma$$

Background Subtraction

[LHCb-CONF-2016-009]



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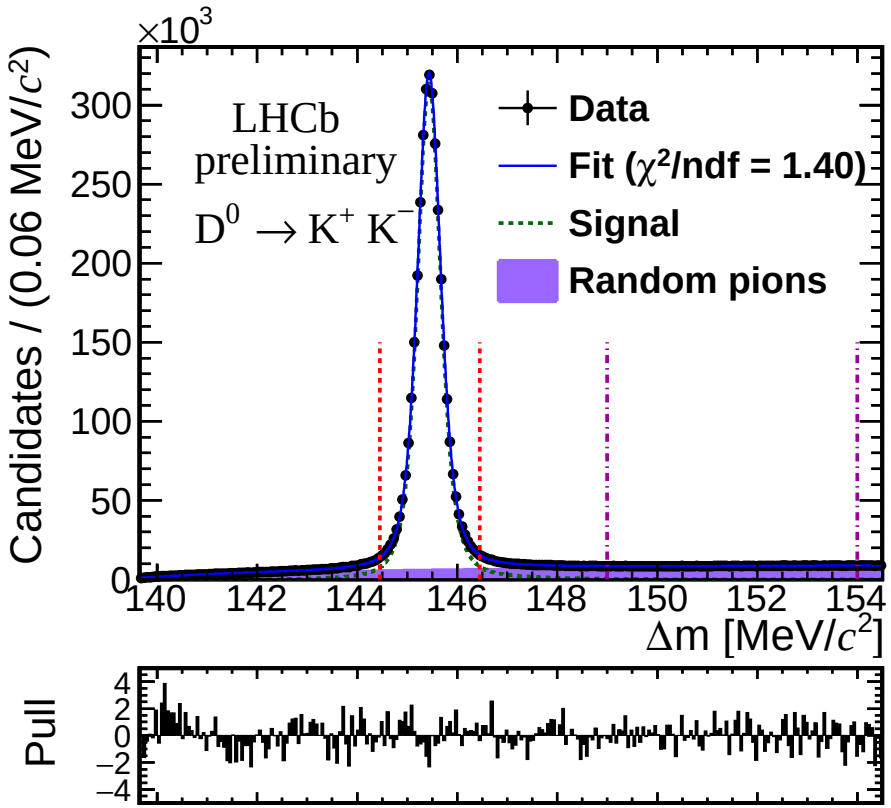

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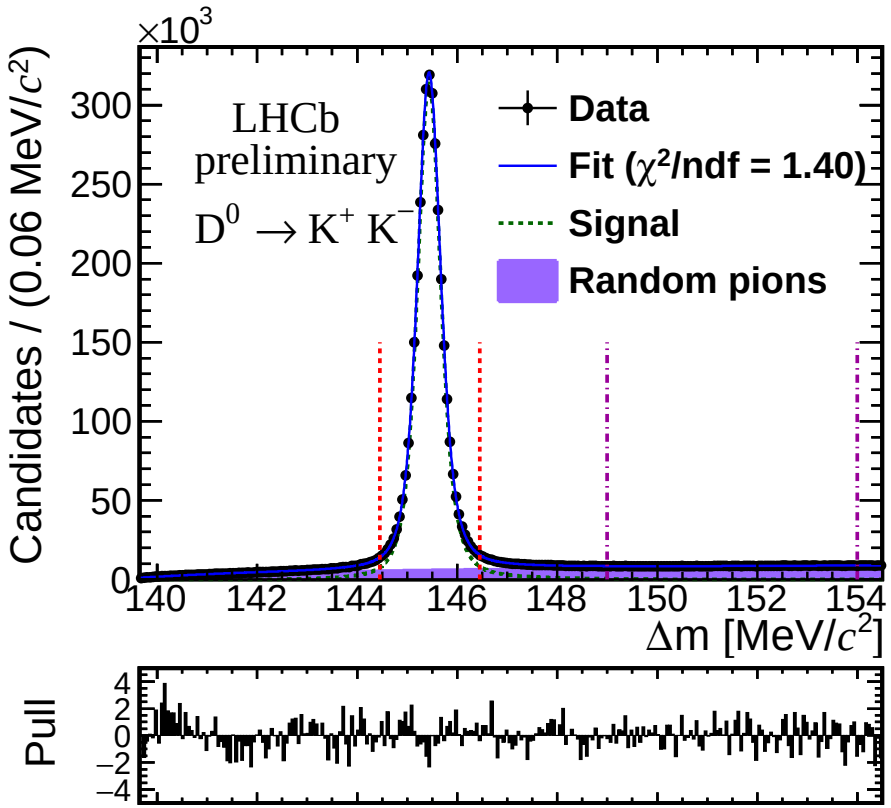

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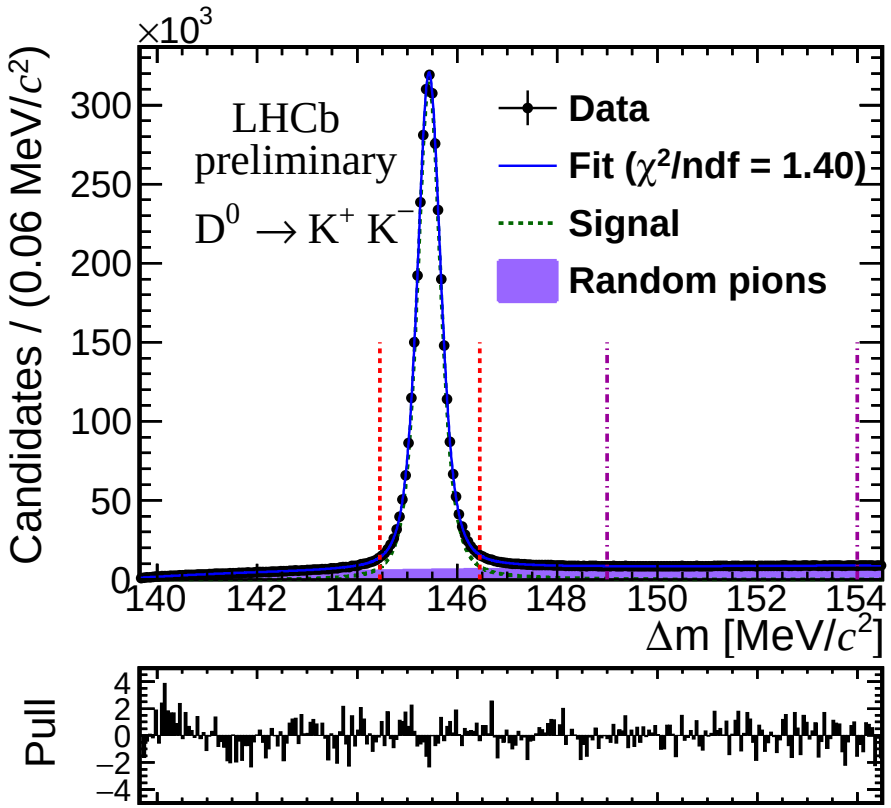

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- Candidates in the sideband region are given negative weights.
- Cut on $\ln(\chi^2_{IP}) < 2$ removes secondaries. Systematic assigned for residual contamination.

CP Symmetrisation(New Technique)

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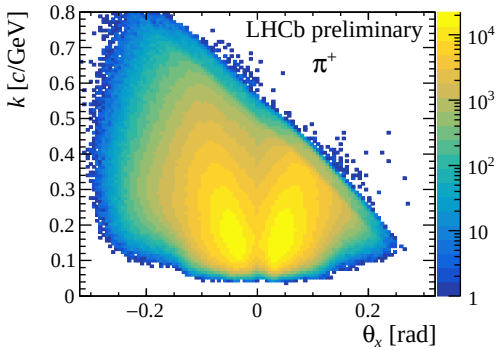
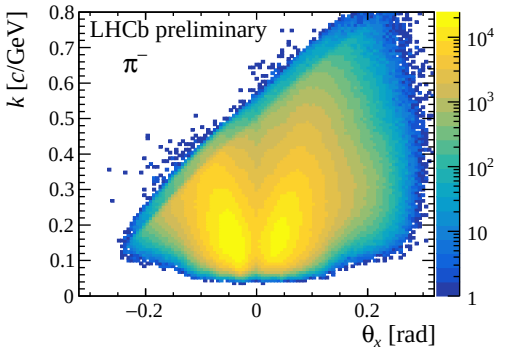
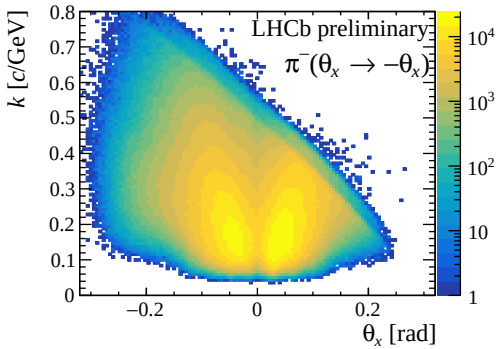






$$k = \frac{1}{\sqrt{p_x^2 + p_x^2}},$$

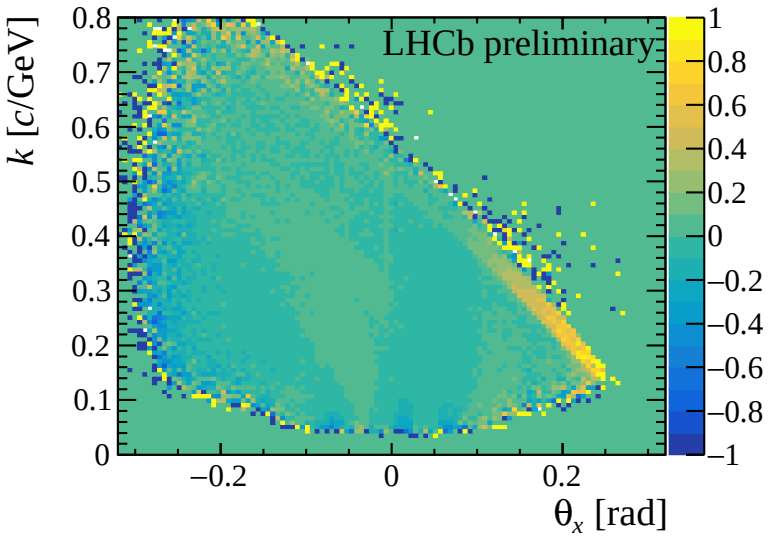
$$\theta_x = \arctan(p_x/p_y),$$

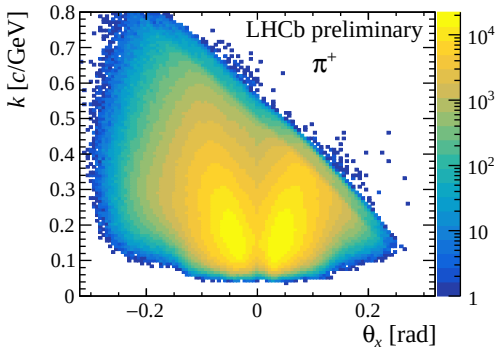
$$\theta_y = \arctan(p_y/p_z)$$

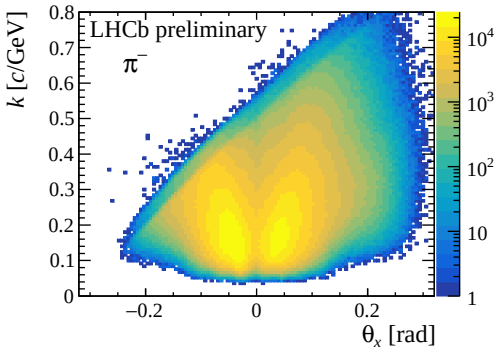
CP Symmetrisation(New Technique)

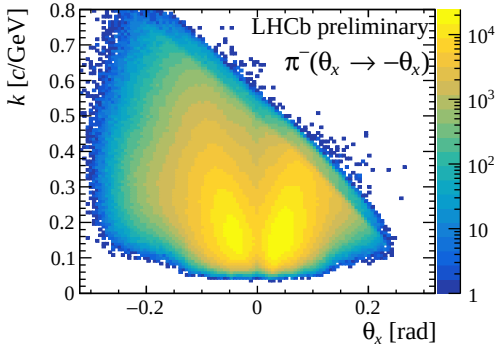
[LHCb-CONF-2016-009]

- Momentum dependent charge-asymmetry in detection of "soft" pions creates a time-dependent detection asymmetry.
- Due to D^0 momentum and decay-time correlation.









$$k = \frac{1}{\sqrt{p_x^2 + p_x^2}},$$

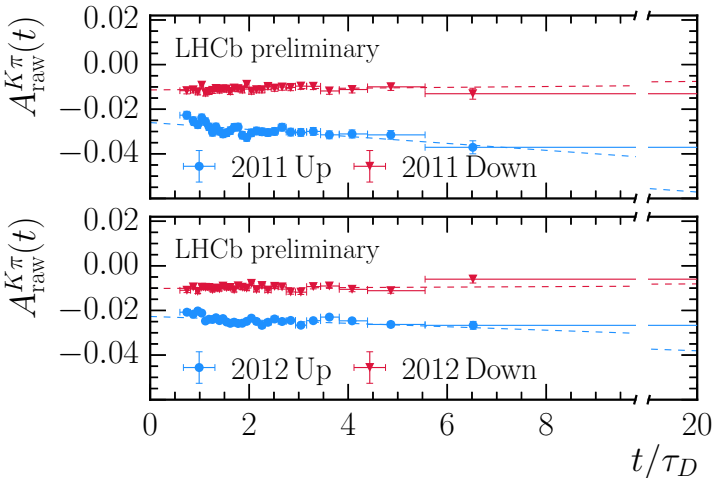
$$\theta_x = \arctan(p_x/p_y),$$

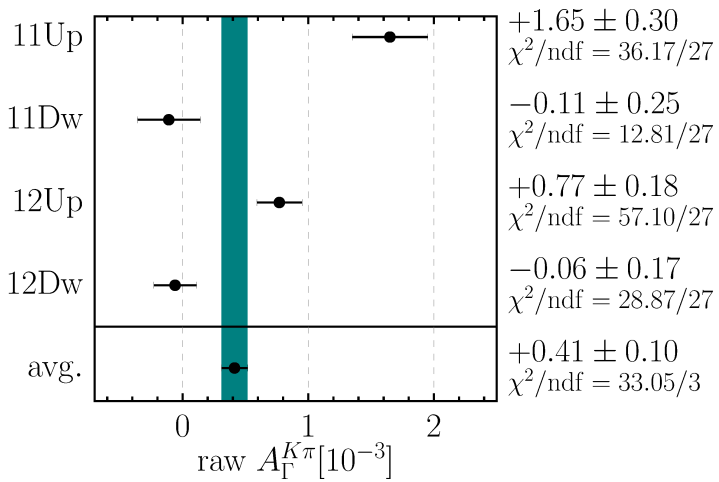
$$\theta_y = \arctan(p_y/p_z)$$

- Equalise the asymmetries with (k, θ_x, θ_y).
- $R = \frac{(k,\theta_x,\theta_y)_{\pi^+}}{(k,\theta_x,\theta_y)_{\pi^-(\theta_x \to -\theta_x)}}$
- Reweight R to 1.

Pseudo-A_Γ

Preliminary: Before Correction: [LHCb-CONF-2016-009]





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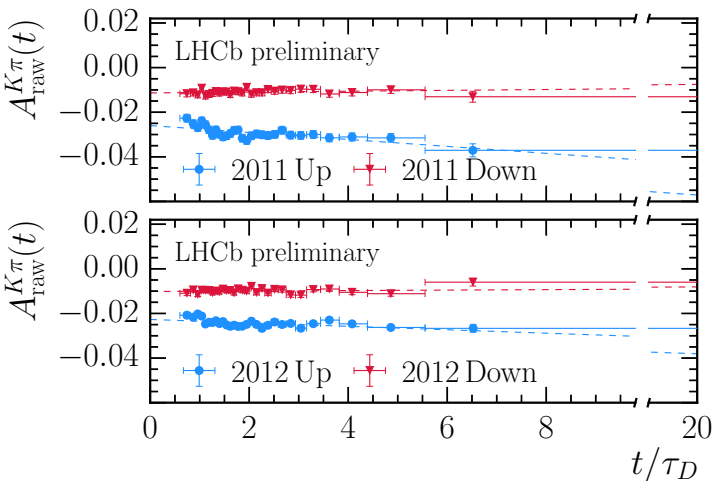

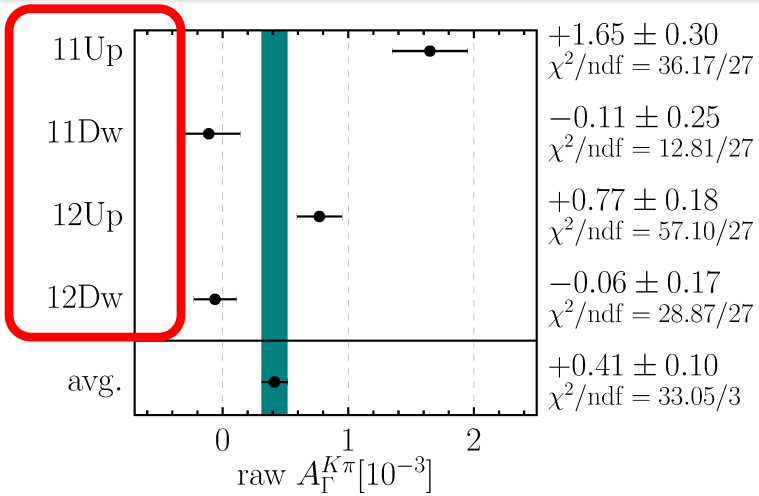

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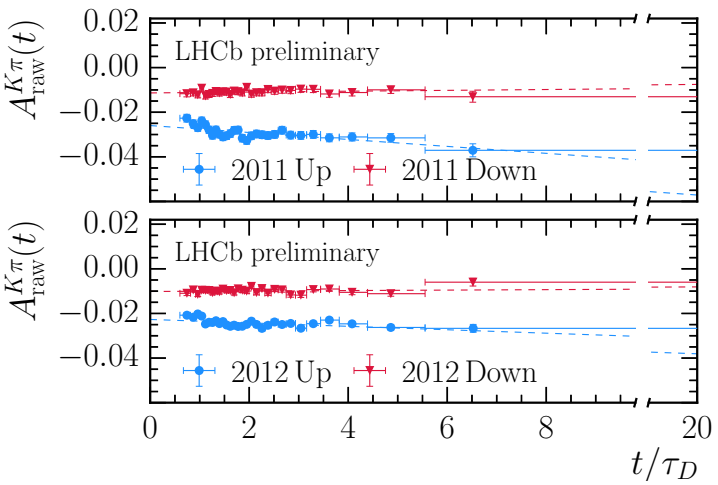

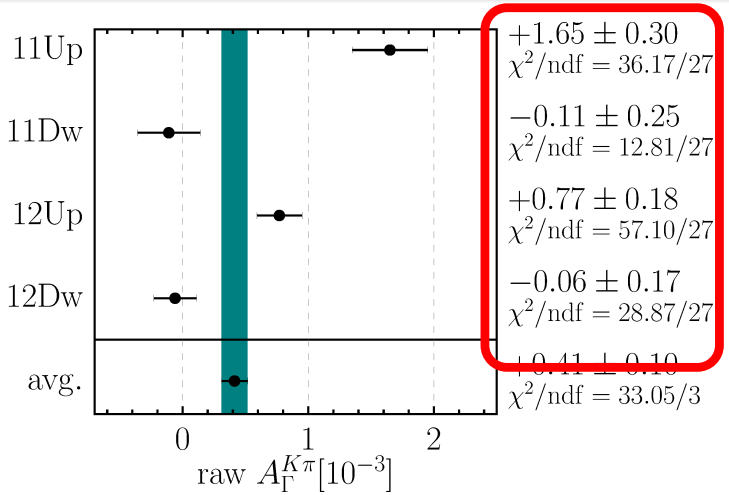

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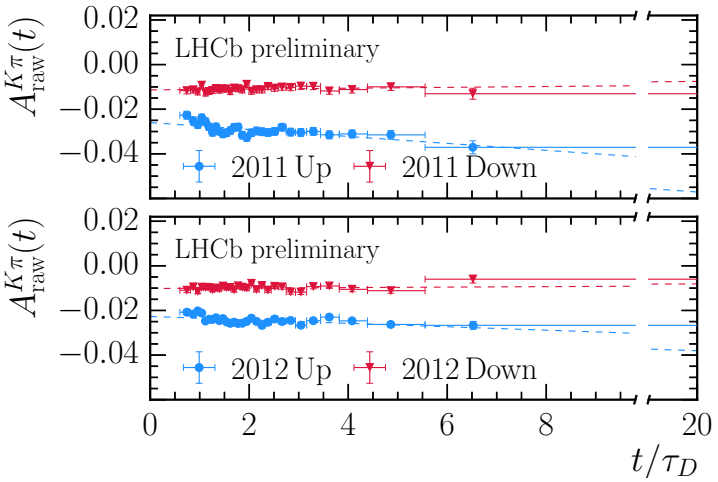

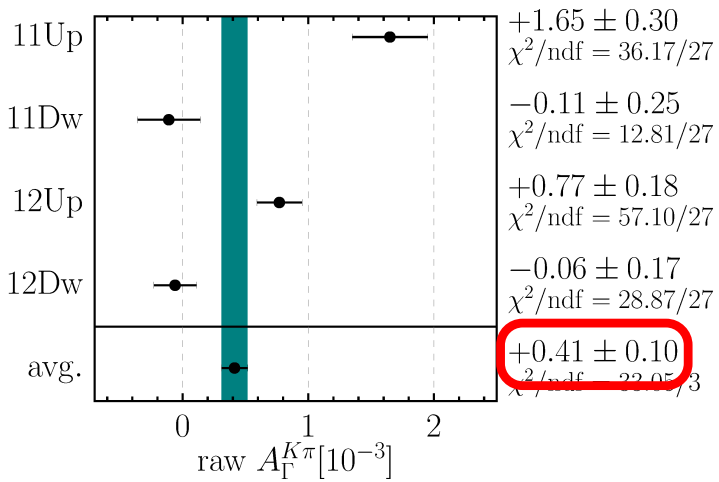

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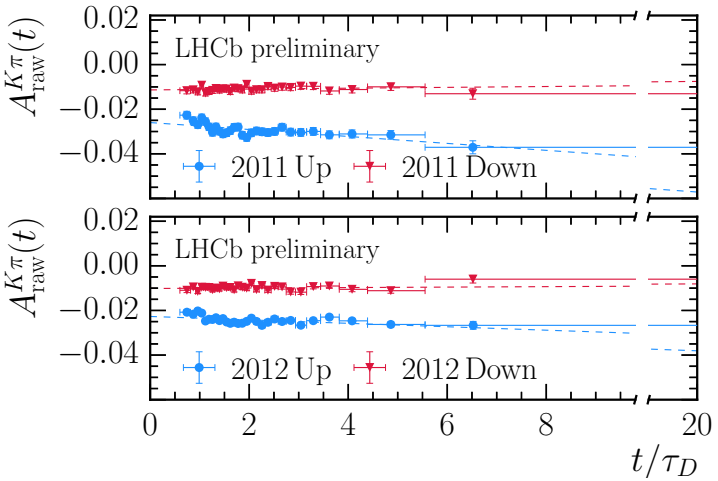

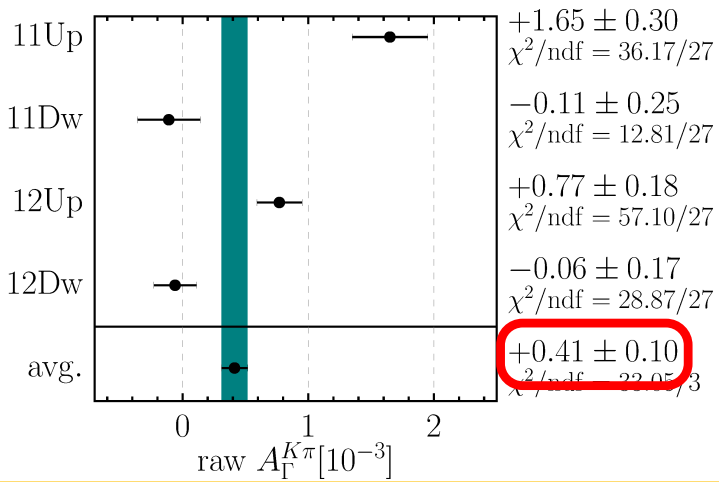

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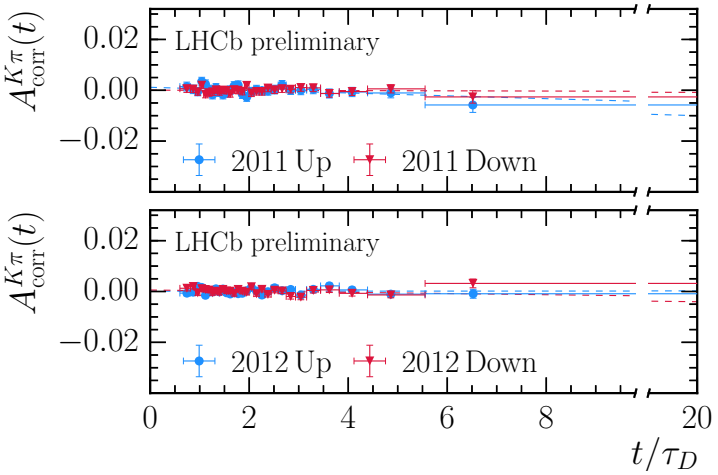

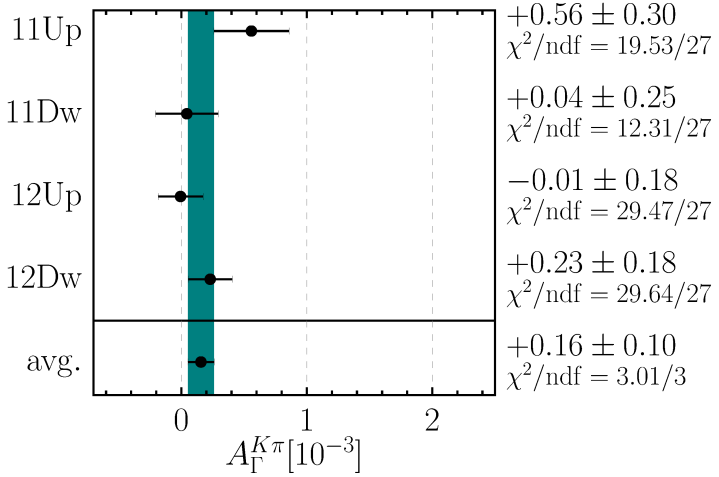

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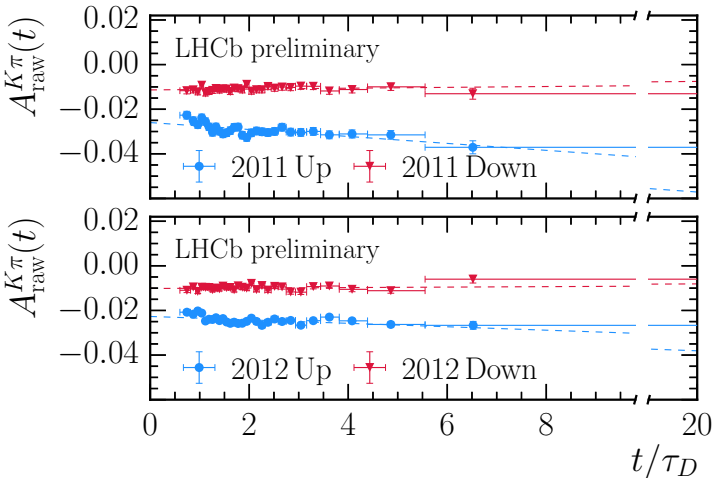

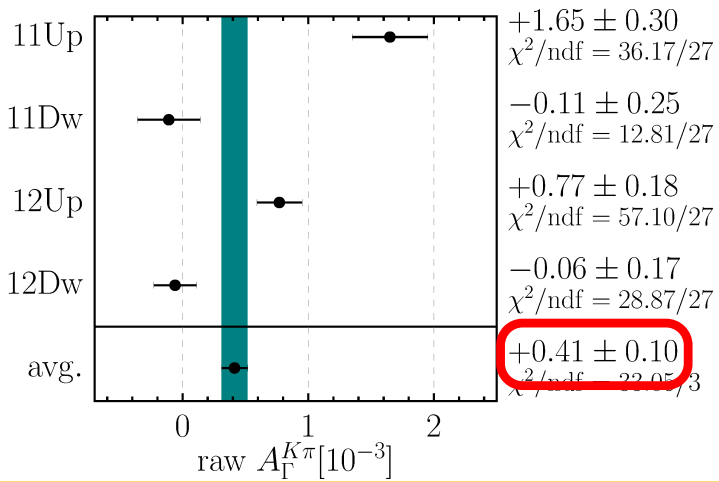

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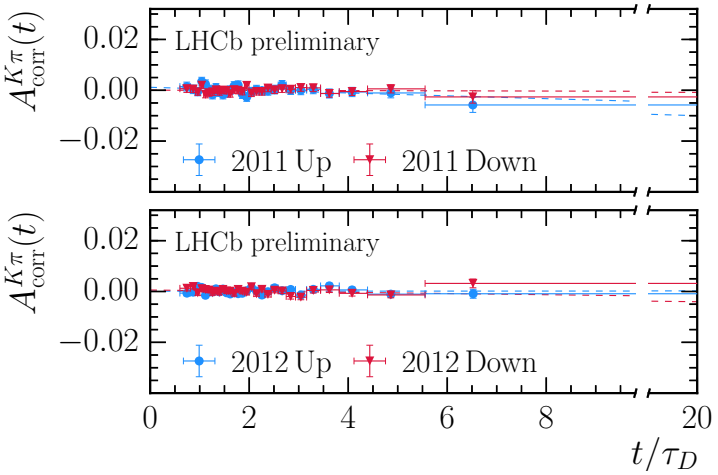
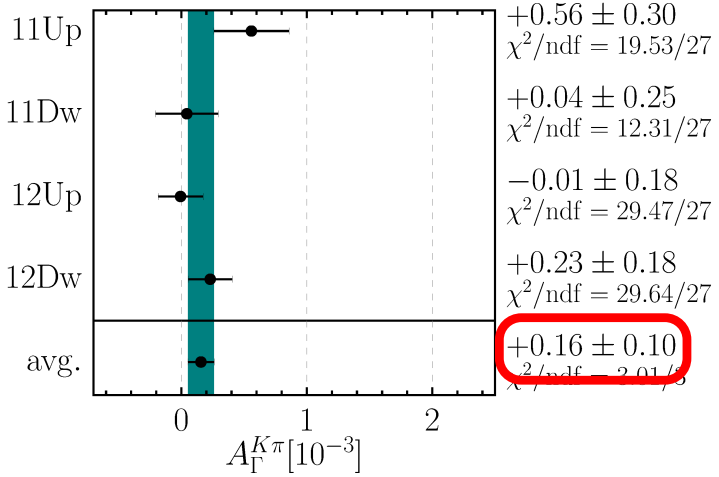
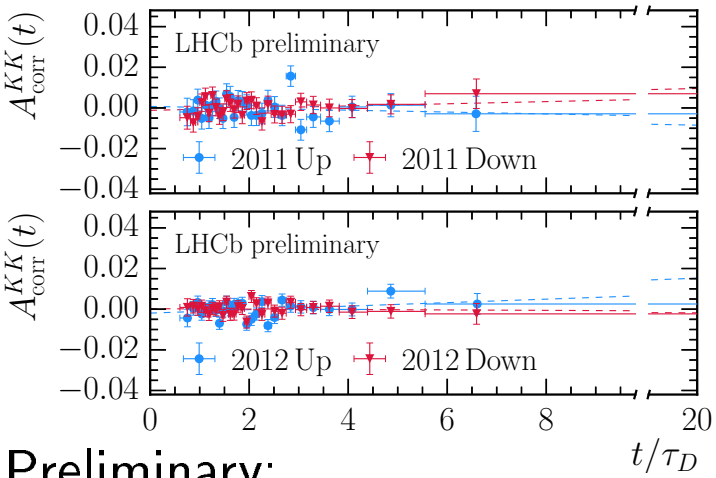




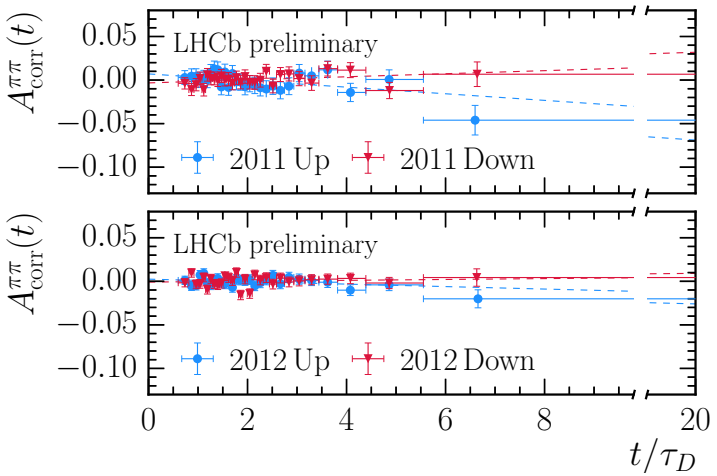
Method 2: Results

[LHCb-CONF-2016-009]

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



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



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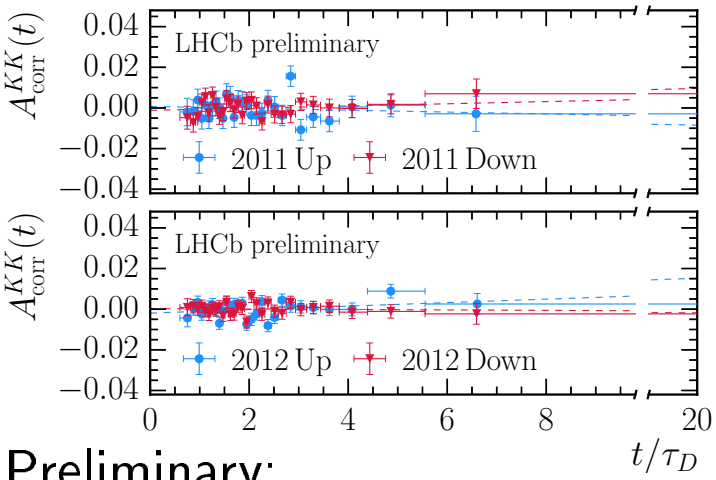

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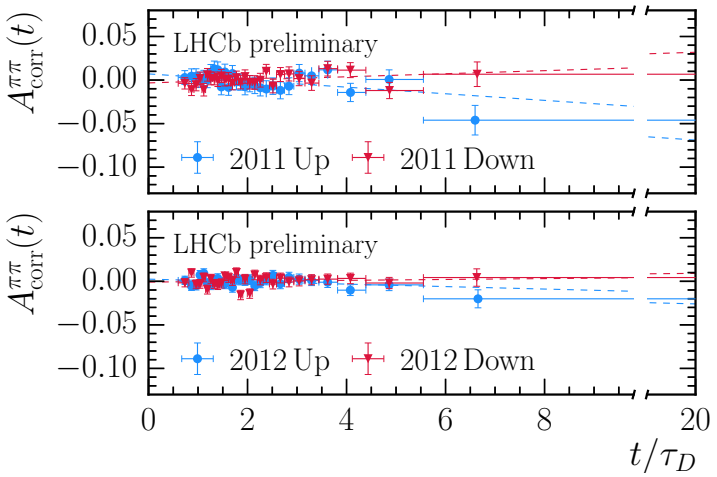

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$$A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3},$$
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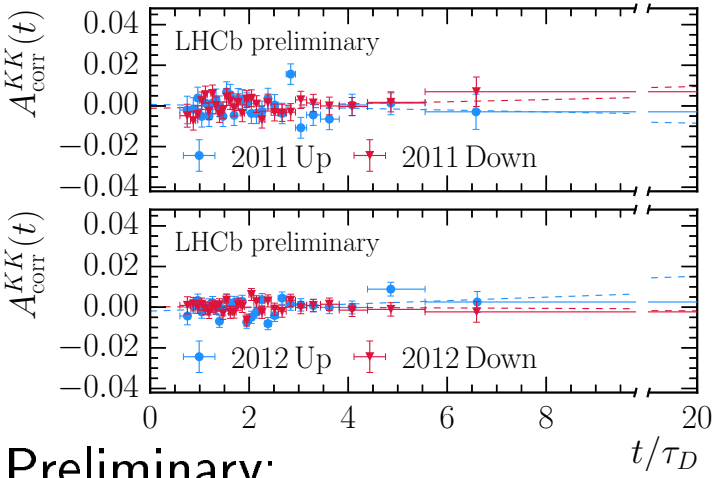

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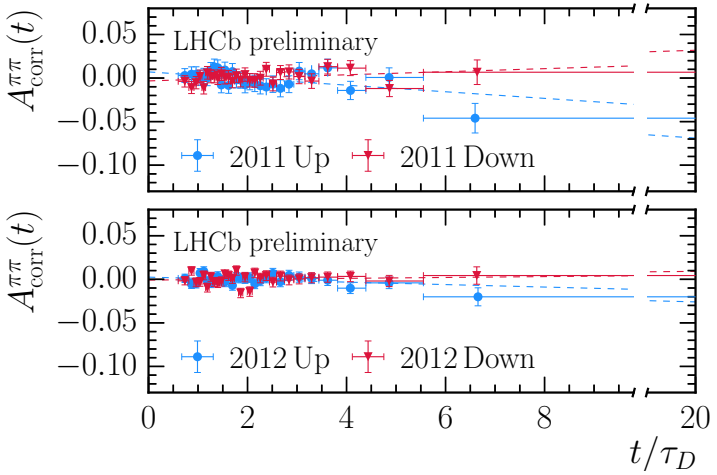

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World's best measurement!

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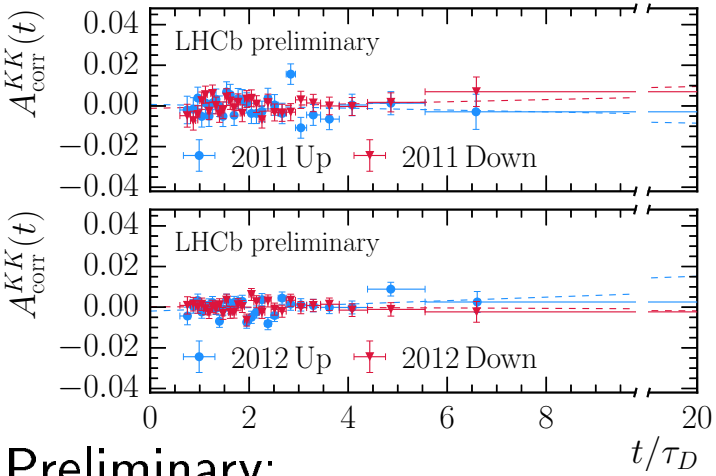

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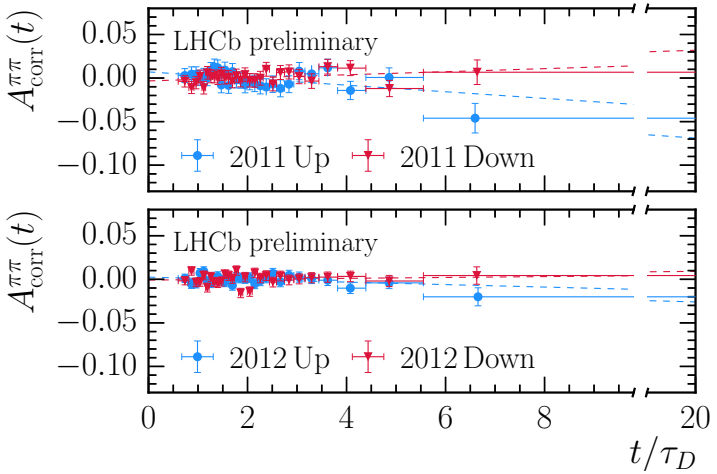

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$$\Delta A_\Gamma = (-0.76 \pm 0.66 \pm 0.04) \times 10^{-3},$$
$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3},$$

Preliminary Result

Unbinned maximum likelihood [LHCb-CONF-2016-010]

$$A_\Gamma(D^0 \to K^+K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3},$$
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Yield asymmetry in bins(more accurate) [LHCb-CONF-2016-009]

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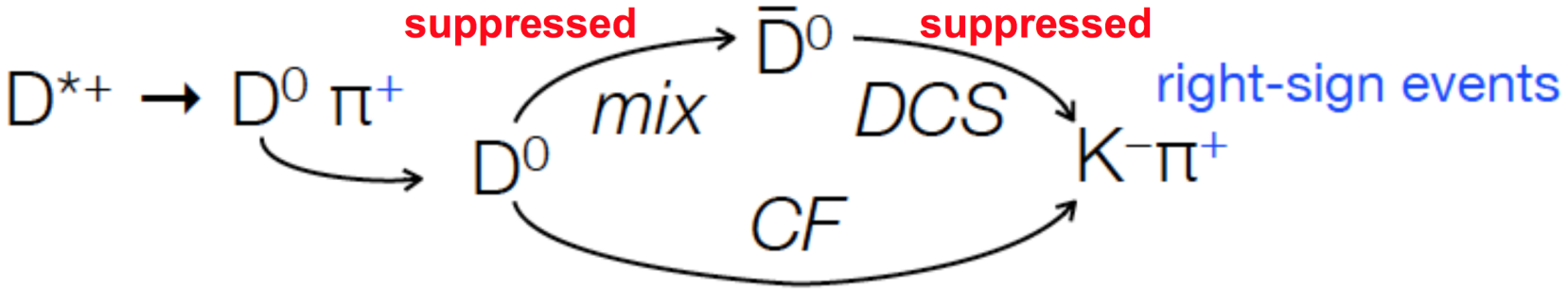
- The more accurate yield asymmetry in bins is taken as the final result.
- Toy tests using both methods on datasets with randomised flavour tags show that the results are compatible.

$R^{\pm}(t)$ of $D^0 \longrightarrow K^{\pm}\pi^{\mp}$

$D^0 \to K^-\pi^+$(Right Sign)(CF),



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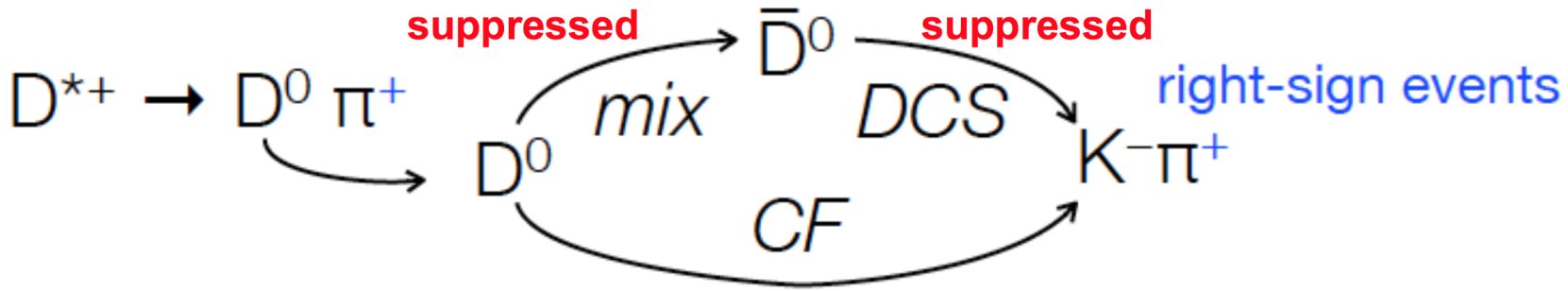
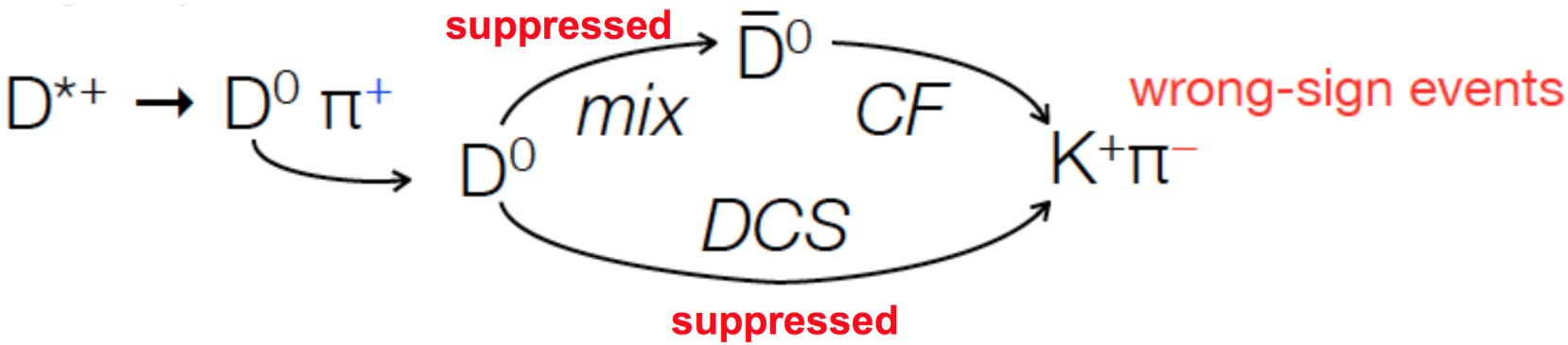


$D^0 \to K^+\pi^-$(Wrong Sign)(DCS),



Theory

- Time dependent ratio of amplitudes for small x and y(sign indicates flavour tag):

$$\frac{WS^{\pm}(t)}{RS^{\pm}(t)} := R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} \Gamma t + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} (\Gamma t)^2$$

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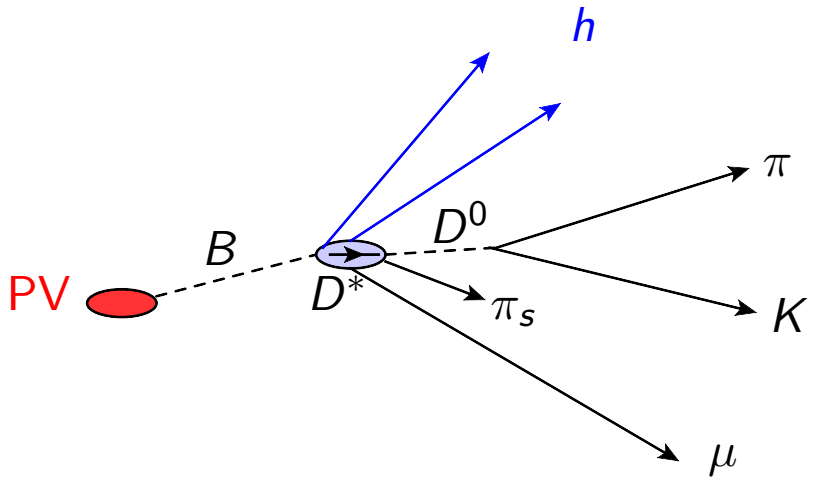
- Three models
  - CP symmetry: $R^+ = R^-, (x'^+)^2 = (x'^-)^2, y'^+ = y'^-$.
  - CP symmetry in decay amplitudes: $R^+ = R^-$.
  - All CP violation allowed.

Tagging

- Single tag prompt with "soft" pion only

  [Phys. Rev. Lett., 111:251801, 2013].
- Double tag (DT) secondary B decays with muon and "soft" pion [arXiv:1611.06143].



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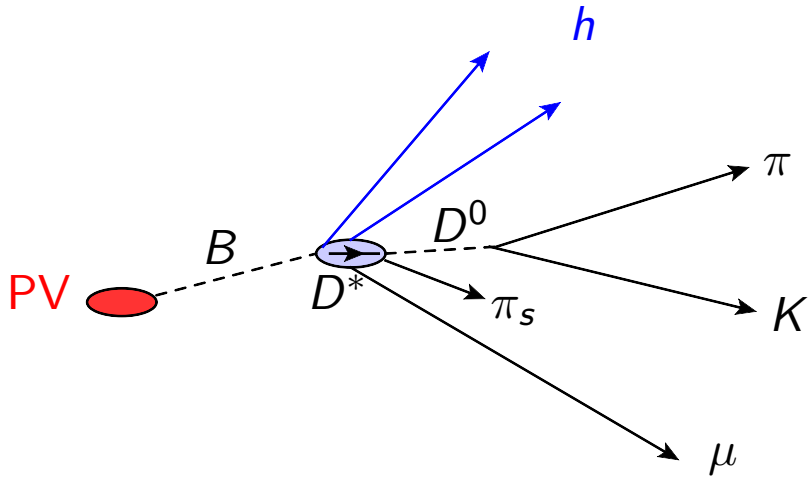

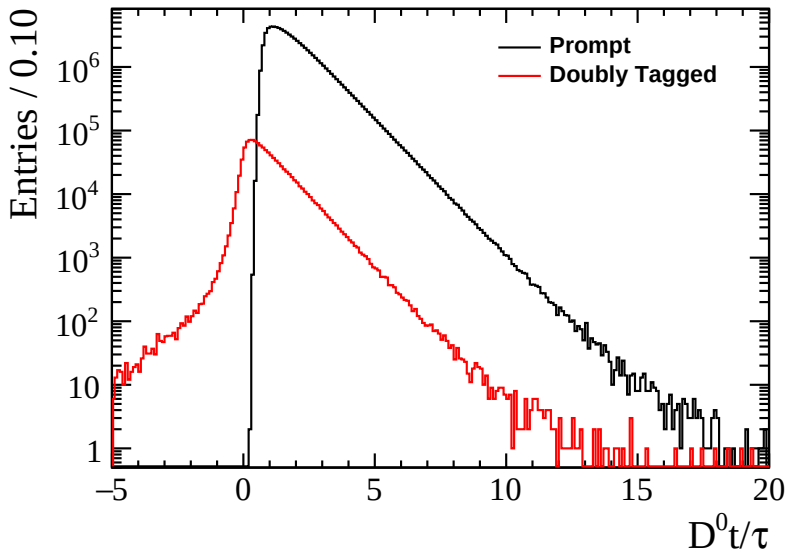

- DT cleaner and provides measurements at low decay times.
- Single tag has larger statistics and covers longer decay times.
- DT adds 3% of the statistics but removes 10%-20% from the errors.

Backgrounds and Yields

[arXiv:1611.06143]

- Make unphysical sample of $\overline{B} \to \mu^+ D^{*+} X$ (same sign).
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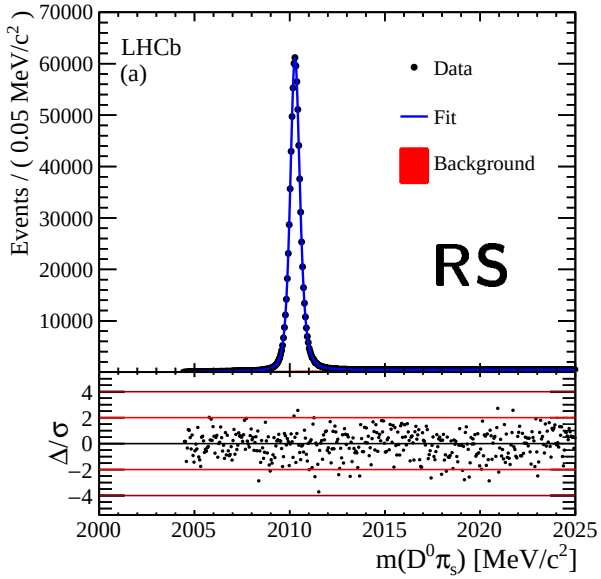
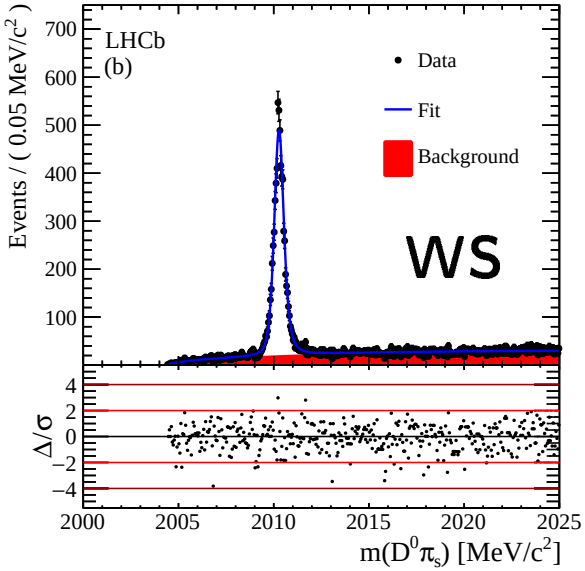


- Extract the signal yields from Δm in bins of time.



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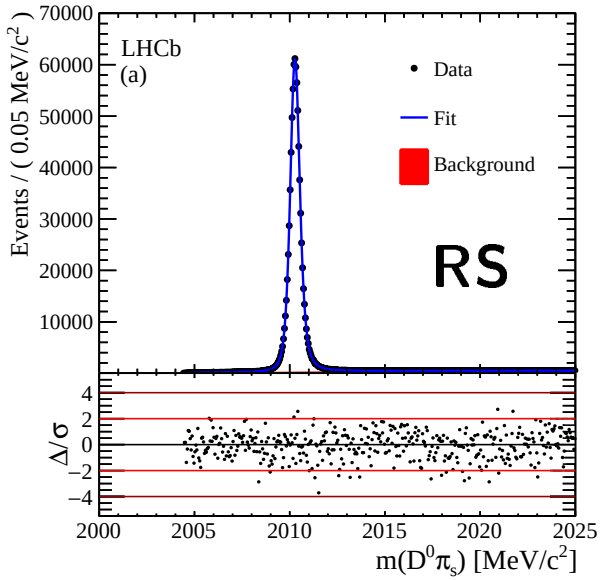
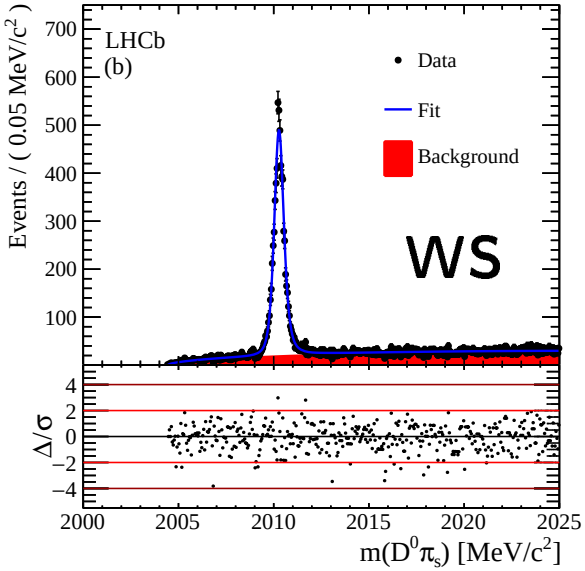


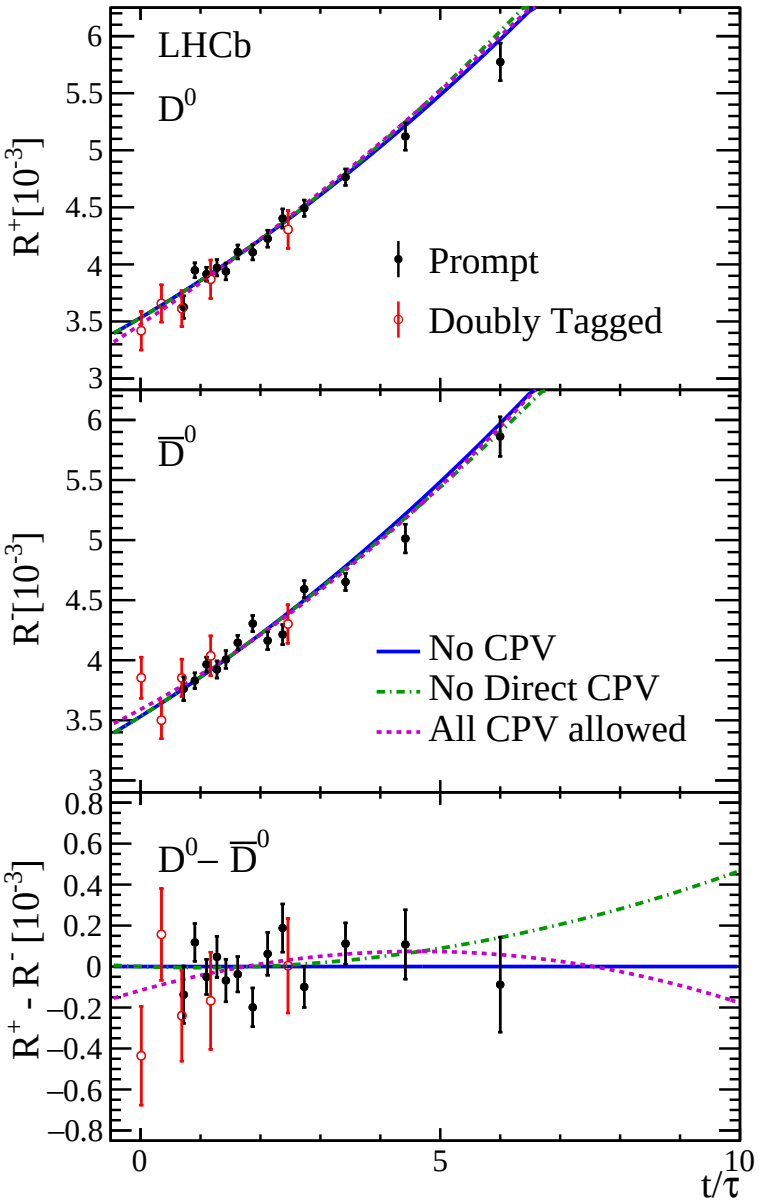
- Extract the signal yields from Δm in bins of time.
- One Δm fit of the time-integrated RS data is used to constrain the signal parameters for all bins.
- Do this for RS and WS and both flavours.



$R(t)^{\pm}$ fits

[arXiv:1611.06143]

- Use the three mixing hypotheses to fit the measured $R(t)^{\pm}$.
- **(top)** The ratio of D^0 to WS over D^0 to RS.
- **(middle)** The ratio of $\overline{D}^0$ to WS over $\overline{D}^0$ to RS.
- **(bottom)** The difference of the two.



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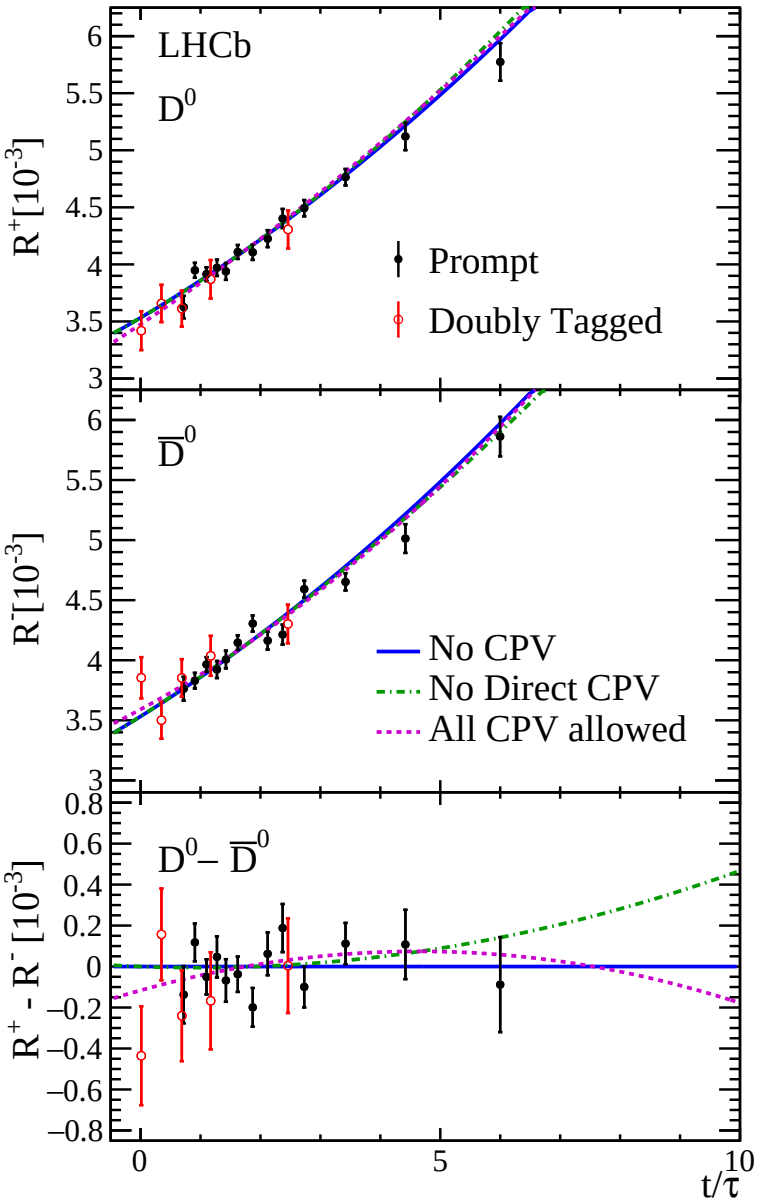
Consistent with the No CPV, mixing only hypothesis.



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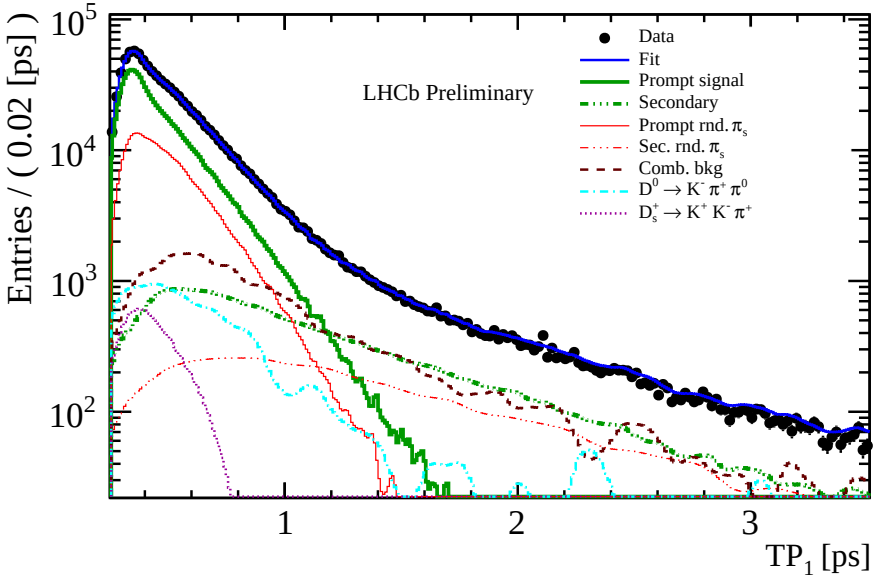
All results consistent with No CPV in D.

Backup

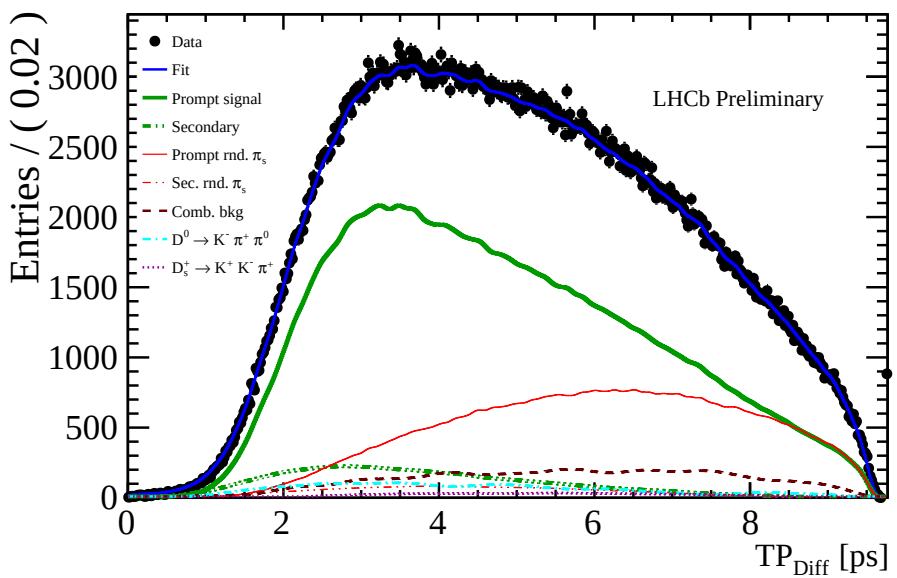
decay-time Acceptance

- Swimming returns a tuple of turning points (TPs) which define decay-time acceptance intervals.
- Only the first acceptance interval is considered.
- The acceptance for each fit component is determined using an iterative process of unfolding.
- Validate by comparing the sum of the component TP distributions to data.

First TP, TP_1



First TP - Second TP, TP_{diff}



Acceptance corrected decay-time fit

- The per-candidate probability density functions (PDFs) are normalised in the accepted interval.

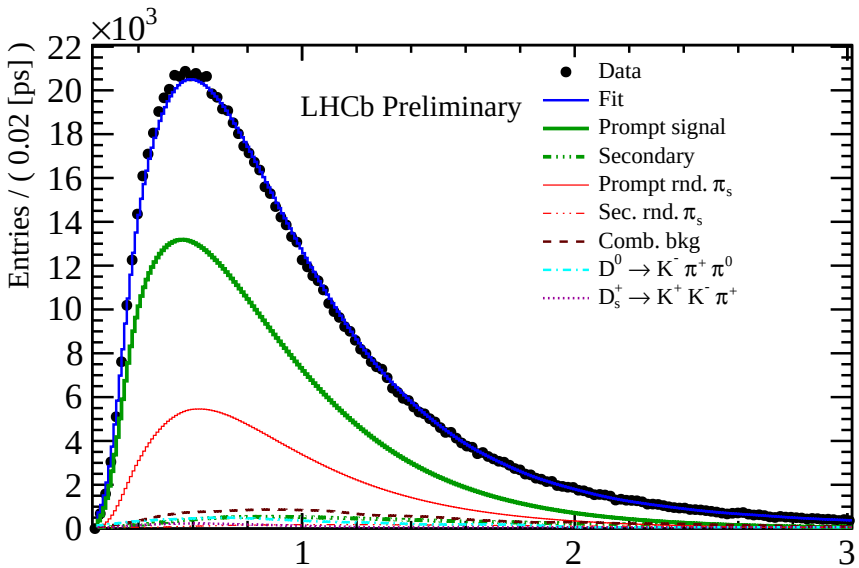
$$f(t|\mathrm{TP}_1, \mathrm{TP}_{\mathrm{diff}}, class) = \frac{f(t|class)\Theta(t-\mathrm{TP}_1)\Theta(\mathrm{TP}_1+\mathrm{TP}_{\mathrm{diff}}-t)}{\int_{\mathrm{TP}_1}^{\mathrm{TP}_1+\mathrm{TP}_{\mathrm{diff}}} f(t|class)dt}$$

- where $\Theta(t)$ is the heavy-side function.
- $f(t|\mathrm{class})$ is the "unbiased" PDF, for prompt signal:

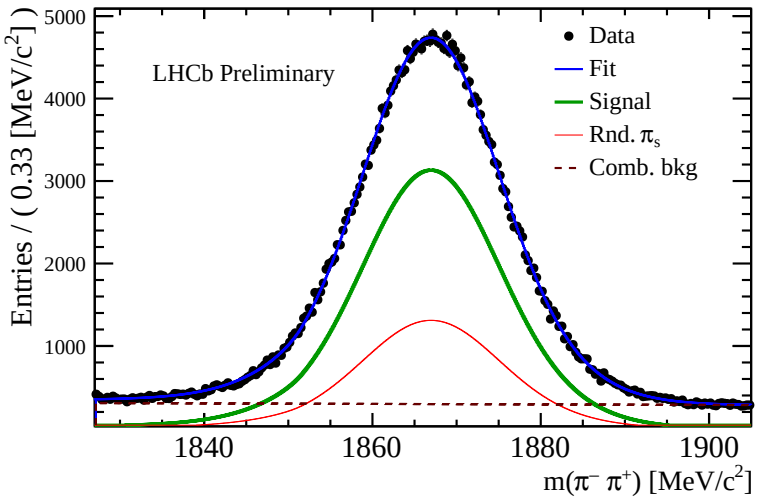
$$f(t|sig., prompt) = \frac{1}{\tau}e^{-t'\tau} \otimes R(t', t)$$

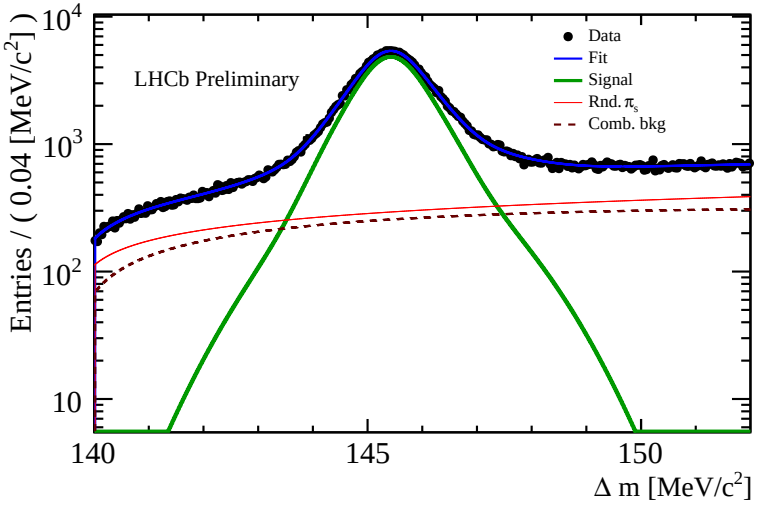
- Where $R(t', t)$ is the detector decay-time resolution.

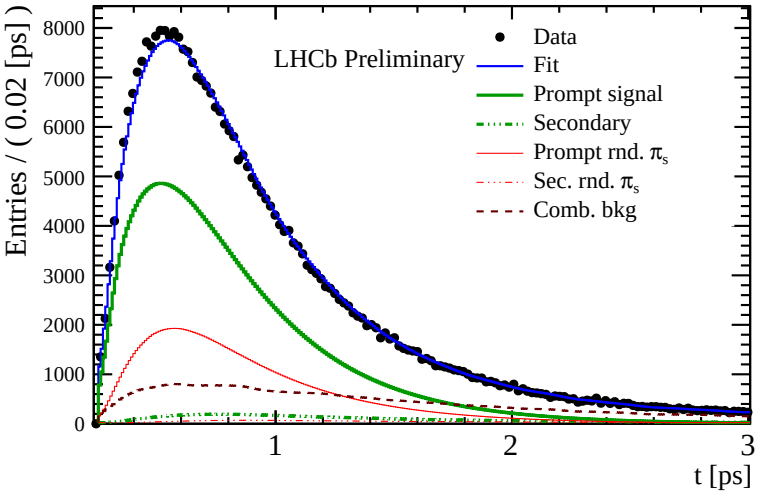
t projection

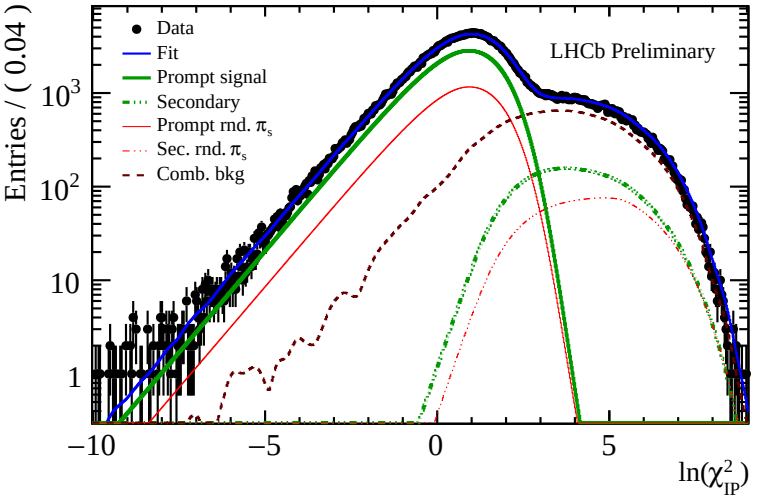


$\pi^+\pi^-$ unbinned likelihood fits

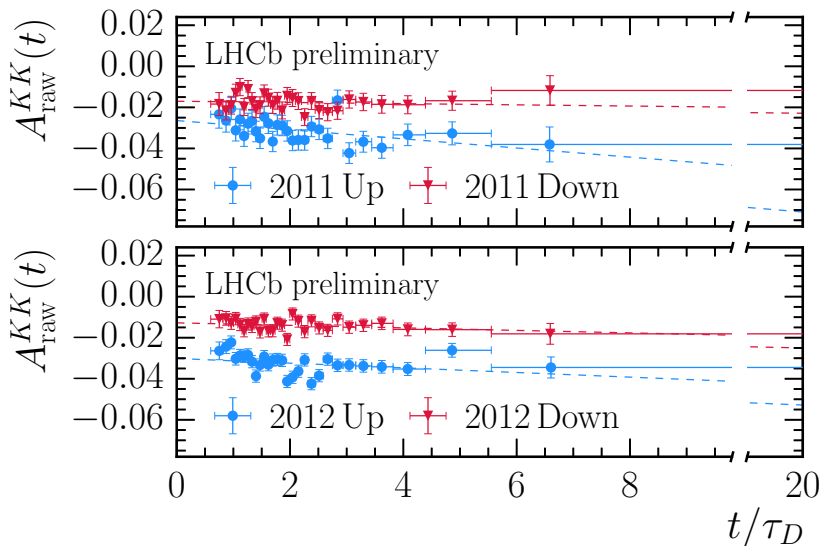


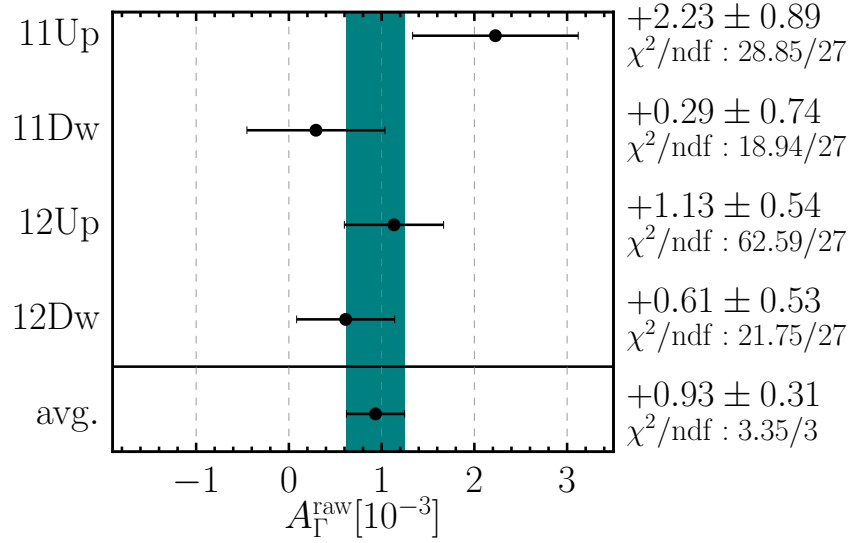


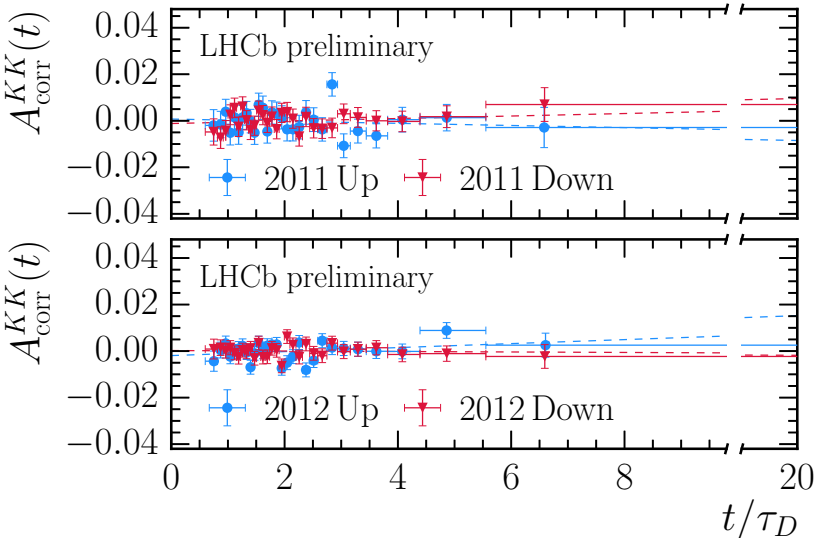


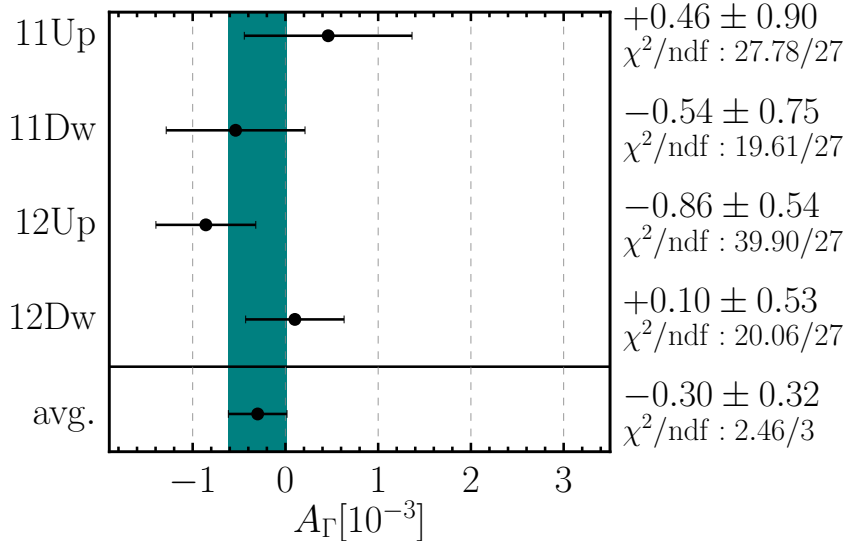


K^+K^- binned A_Γ fits

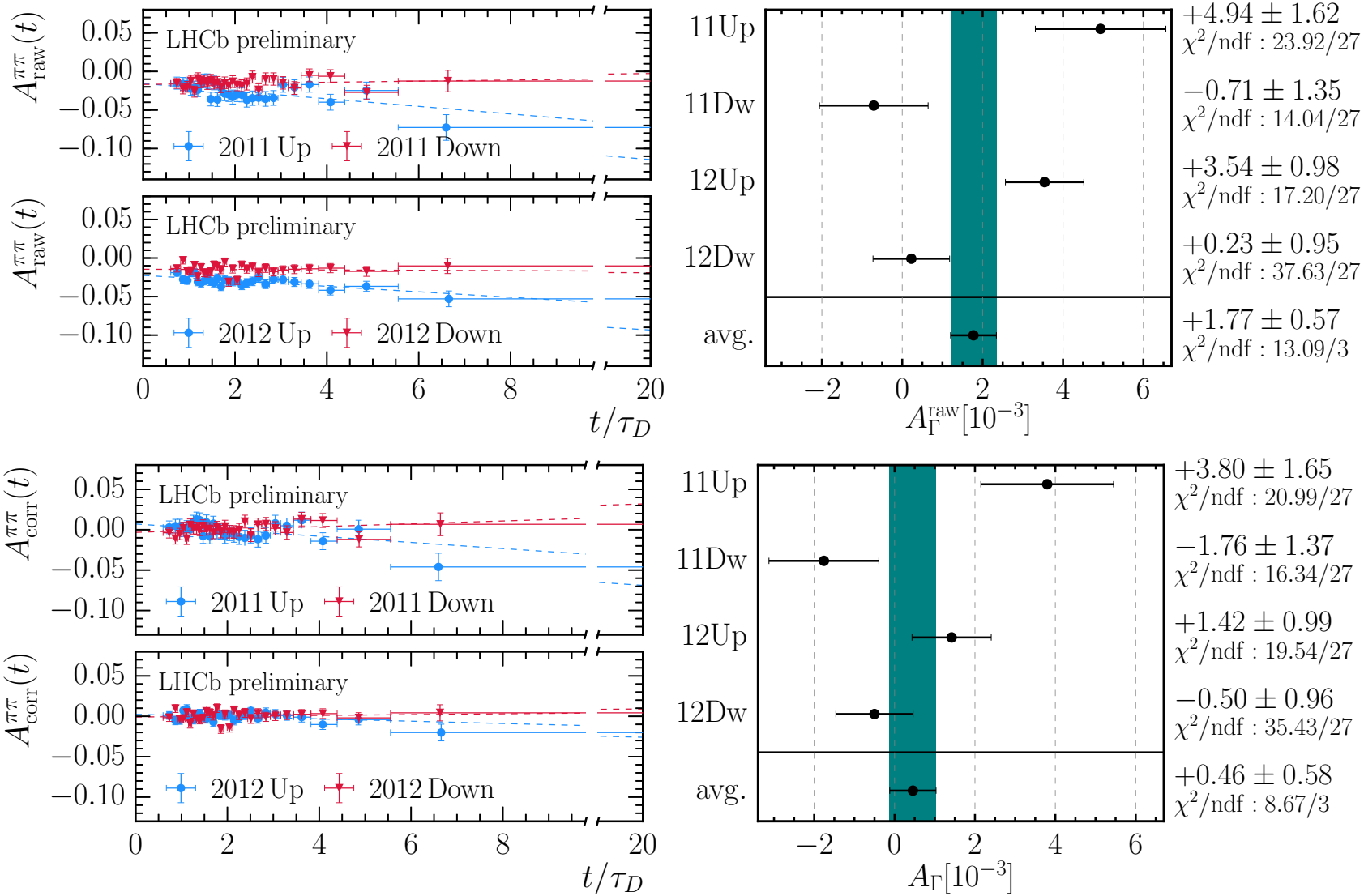








$\pi^+\pi^-$ binned A_Γ fits



D system parameters

- Define mixing parameters: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

$$x := \frac{\delta m}{\Gamma} := \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2},\ y := \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1},\ \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

Measurement and efficiencies

- Counting experiment for N observed WS and RS decays for two flavours ($\pm$).

$$R(t)^{\pm}_{\text{obs}} = R(t)^{\pm}(1 - \Delta^{\pm}_{p}) \left(\frac{\epsilon(K^{+}\pi^{-})}{\epsilon(K^{-}\pi^{+})} \right)^{\pm 1} + p^{\pm}_{\text{other}}$$

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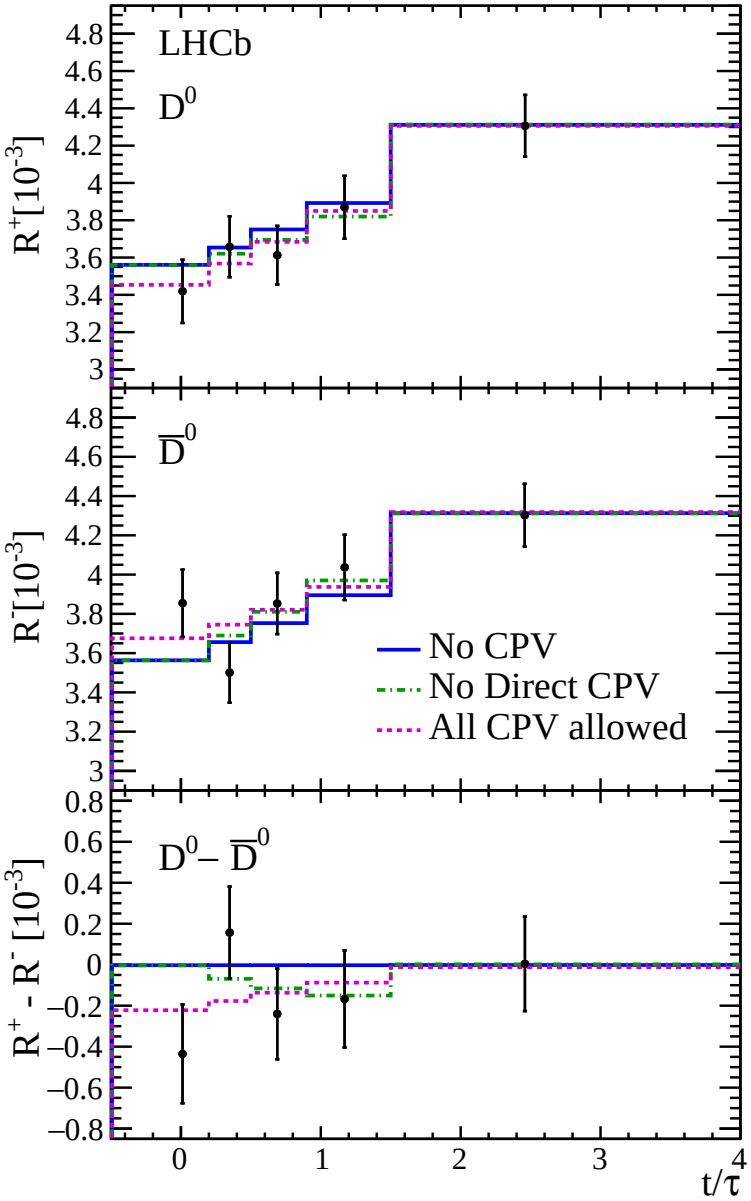
- Time-dependent ratio.
- $\propto$ fraction of prompt in DT sample.
- Detection efficiency asymmetry.
- MisID and peaking backgrounds.

$R(t)^{\pm}$ fit parameters

Parameter	DT + Prompt	Prompt-only
	No CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$x'^2[10^{-4}]$	0.36 ± 0.43	0.55 ± 0.49
$y'[10^{-3}]$	5.23 ± 0.84	4.8 ± 0.9
χ^2/ndf	96.6/111	86.4/101
	No direct CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$(x'^+)^2\,[10^{-4}]$	0.49 ± 0.50	0.64 ± 0.56
$y'^+[10^{-3}]$	5.14 ± 0.91	4.8 ± 1.1
$(x'^-)^2\,[10^{-4}]$	0.24 ± 0.50	0.46 ± 0.55
$y'^-[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.1
χ^2/ndf	96.1/109	86.0/99
	All CPV allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2\,[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2\,[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	95.0/108	85.9/98

$R(t)^{\pm}$ DT only fits.



DT only fit results

Parameter	Value
No CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^2[10^{-4}]$	$0.28 \pm 3.10 \pm 0.11$
$y'[10^{-3}]$	$4.60 \pm 3.70 \pm 0.18$
χ^2/ndf	6.3/7
No direct CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$(x'^+)^2\,[10^{-4}]$	$1.94 \pm 3.67 \pm 1.17$
$y'^+[10^{-3}]$	$2.79 \pm 4.27 \pm 0.98$
$(x'^-)^2\,[10^{-4}]$	$-1.53 \pm 4.04 \pm 1.68$
$y'^-[10^{-3}]$	$6.51 \pm 4.38 \pm 1.66$
χ^2/ndf	5.6/5
All CPV allowed	
$R_D^+[10^{-3}]$	$3.38 \pm 0.15 \pm 0.06$
$(x'^+)^2\,[10^{-4}]$	$-0.19 \pm 4.46 \pm 0.32$
$y'^+[10^{-3}]$	$5.81 \pm 5.25 \pm 0.31$
$R_D^-[10^{-3}]$	$3.60 \pm 0.15 \pm 0.07$
$(x'^-)^2\,[10^{-4}]$	$0.79 \pm 4.31 \pm 0.38$
$y'^-[10^{-3}]$	$3.32 \pm 5.21 \pm 0.40$
χ^2/ndf	4.5/4