Feasibility study on using $\phi \to K^0\overline{K}^0$ at LHCb to test for CPT invariance

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CPT Violation in neutral kaon systems

$$|\phi\rangle \rightarrow \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle\left|\overline{K}^0\right\rangle - \left|\overline{K}^0\right\rangle\left|K^0\right\rangle\right) = \frac{N}{\sqrt{2}}\left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right)$$

- K_S and K_L are not CP eigenstates
- $K_L \rightarrow \pi^+\pi^-$ as well as $K_S \rightarrow \pi^+\pi^-$
- Interference in decay intensity:

$$I(t_1, t_2) \propto e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)(t_1+t_2)}\cos\left(\Delta m\left(t_1 - t_2\right)\right)$$

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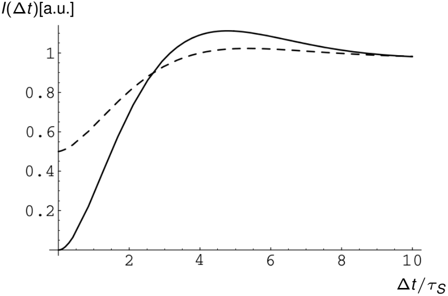


[CPT and Quantum Mechanics Tests with Kaons, J. Bernabeu et al., arXiv:hep-ph/0607322]

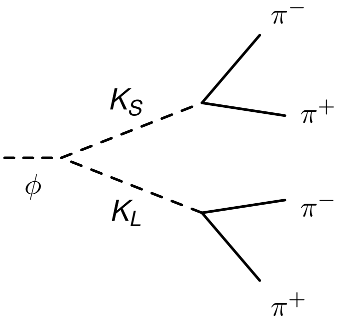
$\Rightarrow$ Excess of 4π decays for small Δt

[1] There are different decoherence models, but we will stick with this one for now for the sake of simplicity.

Comparison of two approaches

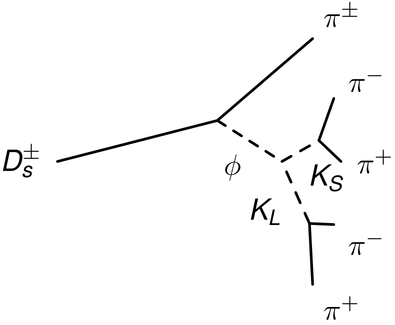
Prompt ϕ

- high production cross section



$D_s^\pm \to \phi\pi^\pm$

- lower rate ($\sim$1%)
- possibly better handle on background rejection

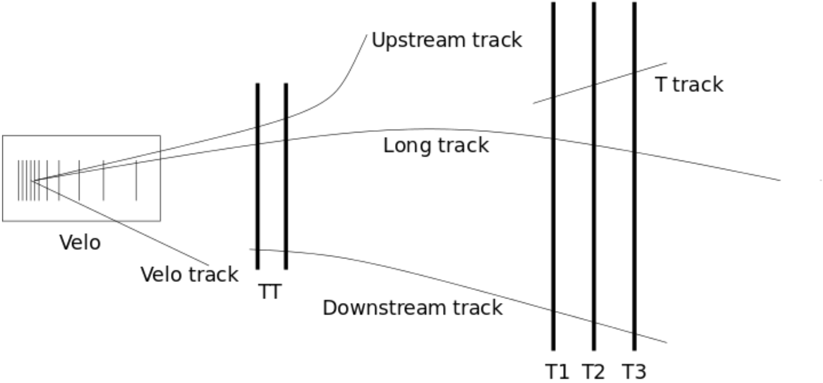


- First study on the prompt ϕ approach
- Compare with D_s approach

Terminology

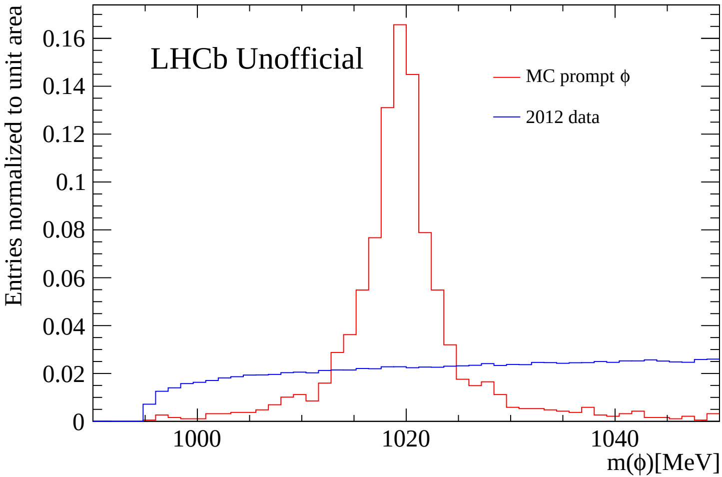
Signal:	Excess of $\phi \to$ 2 neutral kaons $\to \pi^+\pi^-\pi^+\pi^-$ for Δt small due to CPT violation
SM background:	Resulting from CPV, $\phi \to K_L K_S \to \pi^+\pi^-\pi^+\pi^-$
Regeneration background:	Regeneration $K_L \to K_S$ in material
Combinatoric background:	Prompt kaons and pions

Terminology



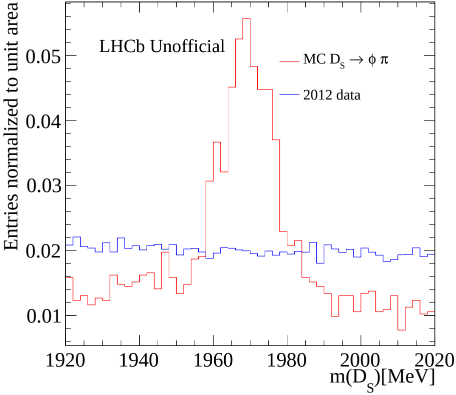
Selection

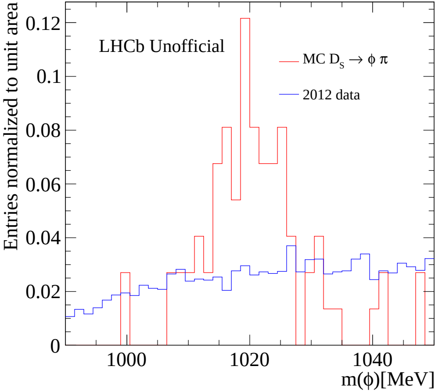
- Stripping for the prompt ϕ approach already existed



Selection

- Developed selection for $D_s \to \phi\pi$
  - Cuts on the mass regions of ϕ and D_s
  - Cuts on the χ^2 of the impact parameter of ϕ to exclude prompt ϕ





Efficiencies

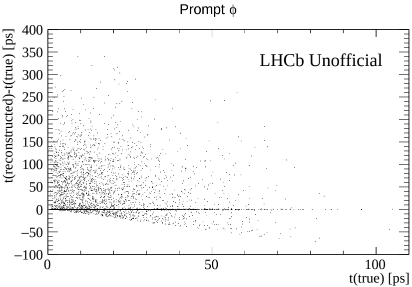
	Prompt ϕ	$D_s \to \phi\pi$
Cross section (14 TeV), LHCb acceptance	3516 µb	388 µb
Branching fractions	34.2%	4.5% · 34.2%
Fiducial cuts efficiency	2.5%	7.0%
Prob. $K_s K_s \to 4\pi$, exactly 1 (2) decays inside bp	15.1% (2.8%)	
Prob. $K_s K_L \to 4\pi$ (CPV), exactly 1 (2) decays inside bp	$3.98 \cdot 10^{-7}$ ($4.99 \cdot 10^{-10}$)	
Upper limit KLOE prob. $K_s K_L \to 4\pi$ (CPV + CPTV), exactly 1 (2) decays inside bp	$5.13 \cdot 10^{-7}$ ($1.64 \cdot 10^{-8}$)	
Reconstruction & selection efficiency	7.9% (7.6%)	1.4% (3.9%)
L0 efficiency	16.1% (18.6%)	23.0% (19.5%)
HLT1 efficiency	13.7% (16.7%)	35.6% (25.0%)
HLT2 efficiency	65.6% (100.0%)	68.8% (100.0%)
Total efficiency SM background	$4.39 \cdot 10^{-5}$ ($5.85 \cdot 10^{-5}$)	$8.18 \cdot 10^{-5}$ ($1.32 \cdot 10^{-4}$)
Expected events SM background / fb^{-1}	21 ($3.51 \cdot 10^{-2}$)	$1.94 \cdot 10^{-1}$ ($3.94 \cdot 10^{-4}$)
Upper limit for signal (KLOE)	27 (1.15)	$2.5 \cdot 10^{-1}$ ($1.29 \cdot 10^{-2}$)
Background (data 2012) / fb^{-1}	163110 (29120)	450 (2030)

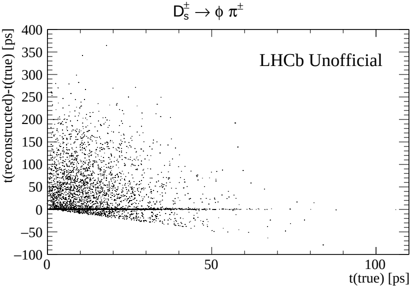
Efficiencies

Conclusion:

- Background dominates over signal for both approaches
- For the D_s approach, both signal and background rate go down by two orders of magnitude compared to the prompt ϕ approach
  - There is no big improvement in the signal to background ratio (factor 4)

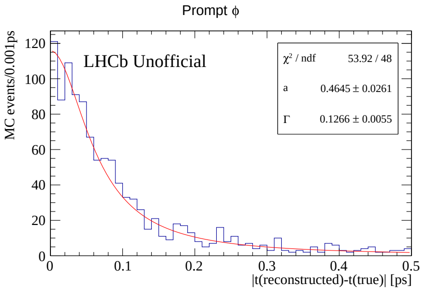
DecayTreeFitter - Long tracks

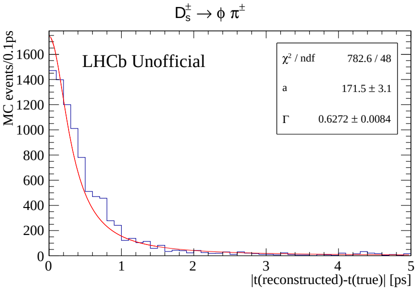




$$t(\text{reconstructed}) - t(\text{true}) \geq -t(\text{true}),$$

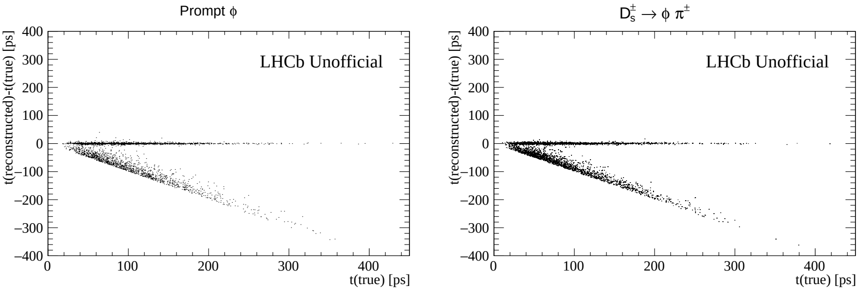
DecayTreeFitter - Long tracks





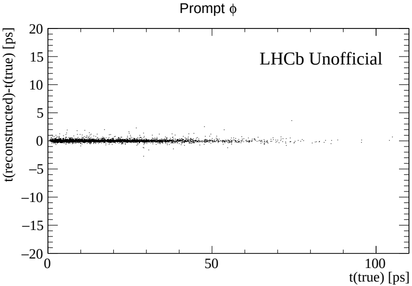
$$N(\delta t) = \frac{a}{(\delta t - \mu)^2 - \Gamma^2/4}, \qquad \delta t = t(\text{reconstructed}) - t(\text{true})$$

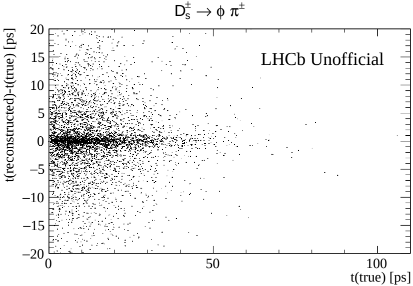
DecayTreeFitter - Downstream tracks

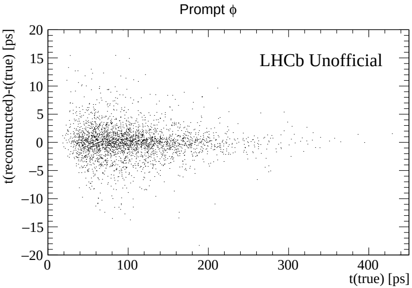


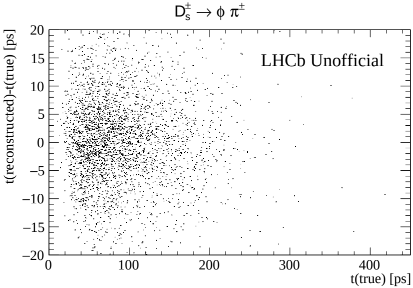
Bias towards short decay times, maybe due to a lack of information.

TupleToolPropertime









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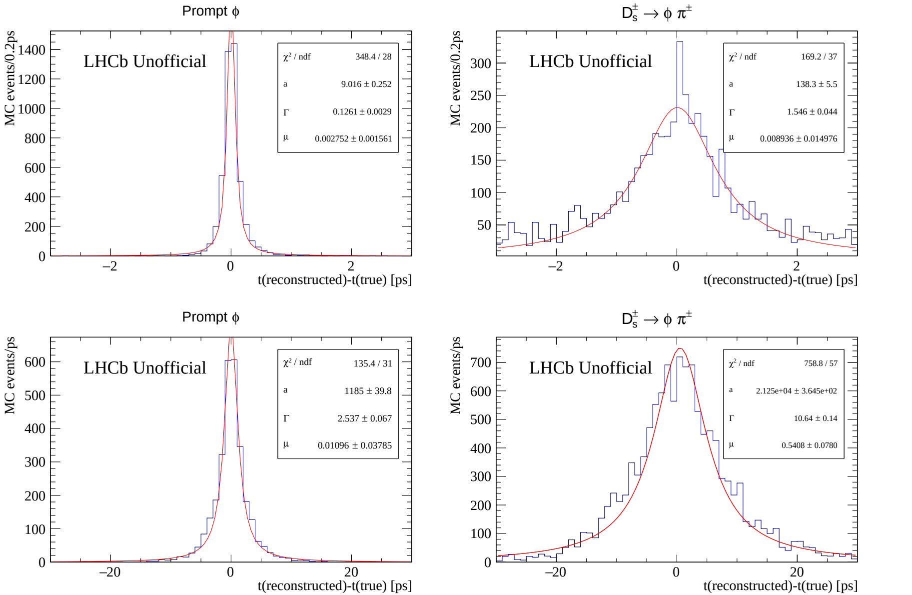
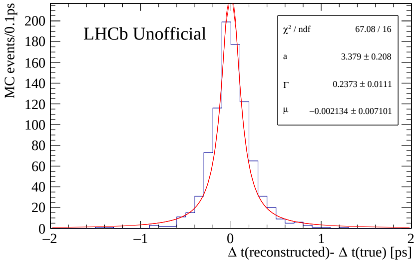
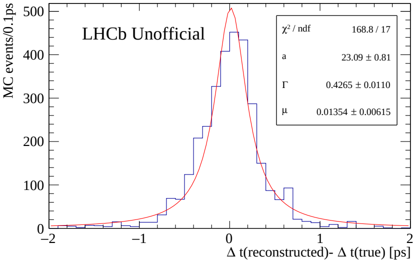


Resolution Δt for LLLL and LLDD

Prompt ϕ



$D_s^\pm \to \phi\, \pi^\pm$



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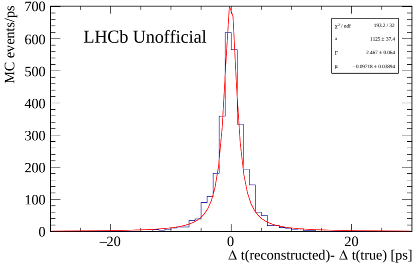

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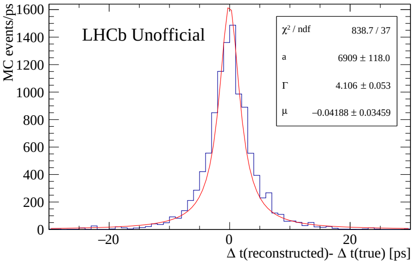
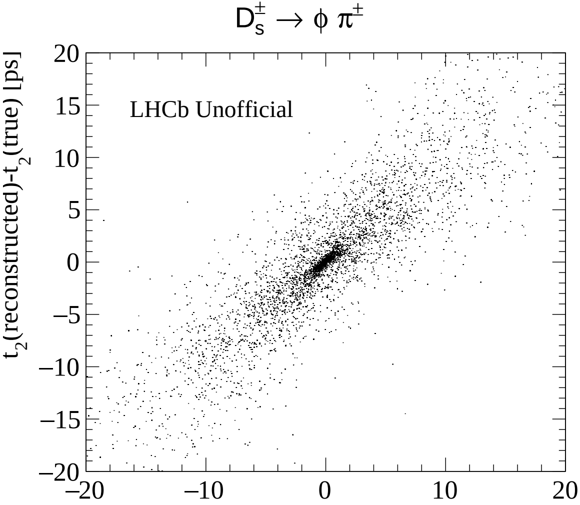


Correlation due to common ”vertex“



Backgrounds

Estimates from minimum bias MC (42 M events). The number in brackets is the number of background events with physical K_s.

Background category	prompt ϕ	$D_s \to \phi\pi$
light flavour	17(17)	0
$b\overline{b}$	1(1)	0
different PV	3(2)	0
physical bkg, partl. reconstructed	1(1)	1(1)
ghosts	0	1(0)
total	21(20)	2(1)

Remaining background for prompt ϕ is mostly irreducible.

Feasibility study for prompt ϕ

Studies of minimum bias Monte Carlo suggest that 80% background is prompt K_S

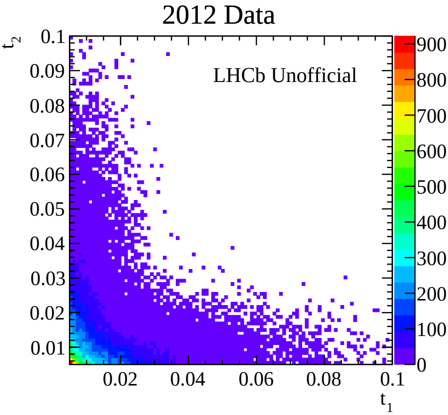
- this background is irreducible
- $I(t_1, t_2) \propto e^{-\Gamma_S t_1} e^{-\Gamma_S t_2}$

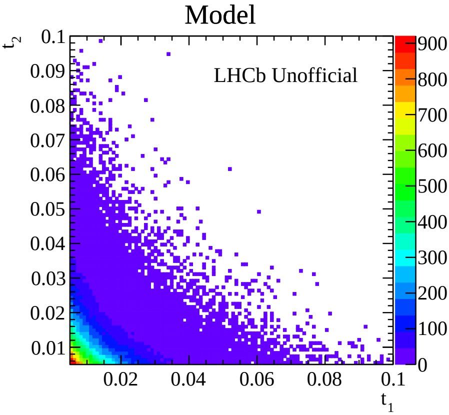
Toy study with RooFit!

- decay intensity
- momentum distribution
- 1 kaon decaying inside beampipe
- regeneration not taken into account

But first: Studying resolution for toy study

Feasibility study for prompt ϕ



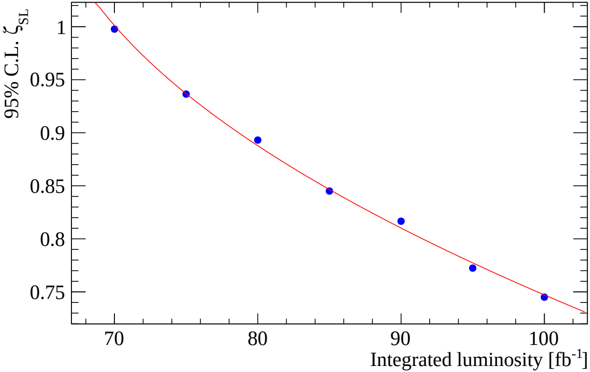


Toy study

- Generated toy data as the weighted sum of two distributions in decay times:
  1. Combinatoric background of prompt K_S with decay intensity
  $$I(t_1, t_2) \propto e^{-\Gamma_S t_1} e^{-\Gamma_S t_2}$$
  2. SM background with decay intensity
  $$\begin{aligned} I(t_1, t_2) \propto & e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} \\ & - 2e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)(t_1 + t_2)} \cos\left(\Delta m\,(t_1 - t_2)\right) \end{aligned}$$
- Ratio of SM background to combinatoric background from efficiency study
- Fitted to
$$\begin{aligned} I(t_1, t_2) \propto & e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} \\ & - 2(1 - \zeta_{SL}) e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)(t_1 + t_2)} \cos\left(\Delta m\,(t_1 - t_2)\right) \end{aligned}$$
- Derived limit on ζ_{SL} from fit result

Feasibility study for prompt ϕ

- Using optimistic signal to background ratio of $4 \cdot 10^{-4}$
- RooStats profile likelihood calculator
- Fitted with square root of luminosity



For KLOE limit
$\zeta_{SL} = 0.098$
$\Downarrow$
$\int L\, dt \approx 275\ \text{fb}^{-1}$,
extrapolated
from fit

Summary

- Selection for $D_s \to \phi\pi$ implemented
- Compared the prompt ϕ and the D_s approach
  - For both strategies, the background dominates.
- The time resolution is a few ps
- Performed a toy study for the prompt ϕ approach to estimate limits we can set on CPTV

After my studies, the prospects for this analysis look bleak.