

CPT Violation in $\phi \rightarrow K^0 \bar{K}^0$

Can we study it in LHCb?

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CPT Violation in neutral kaon systems

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

- 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:

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

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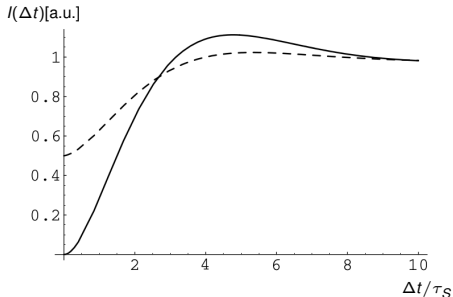
$$I(t_1, t_2) \propto e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} \\ - 2(1 - \zeta_{SL}) e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)(t_1 + t_2)} \cos(\Delta m(t_1 - t_2))$$

Intrinsical violation of CPT introduces decoherence term.

CPT Violation in neutral kaon systems

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

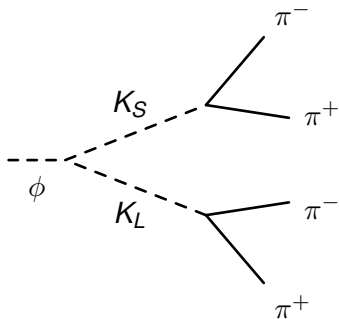
⇒ Excess of 4π decays
for small Δt

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

Comparison of two approaches

Prompt ϕ

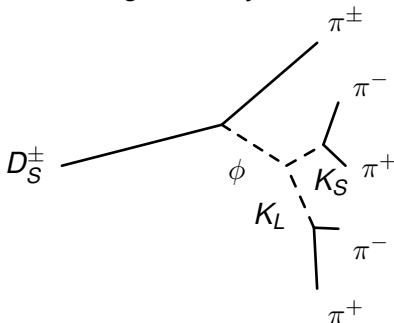
- high production cross section



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

$D_S^\pm \rightarrow \phi \pi^\pm$

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



Terminology

Signal: Excess of $\phi \rightarrow 2$ neutral kaons
 $\rightarrow \pi^+ \pi^- \pi^+ \pi^-$ for Δt small due to
CPT violation

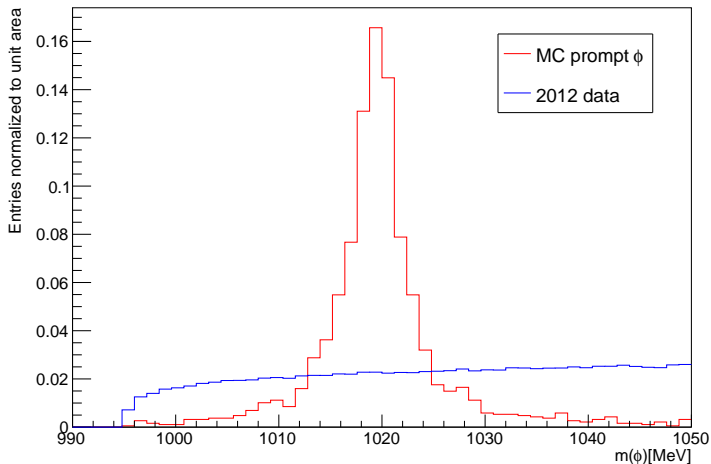
SM background: Resulting from CPV,
 $\phi \rightarrow K_L K_S \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

Regeneration background: Regeneration $K_L \rightarrow K_S$ in material

Combinatoric background: Prompt kaons and pions

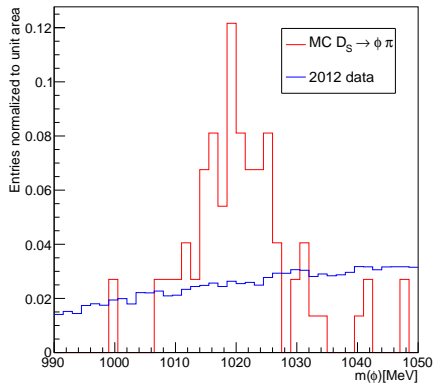
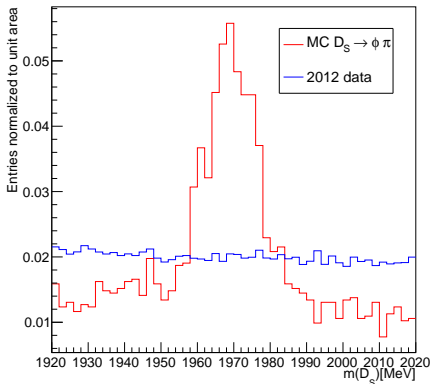
Selection

- Stripping for the prompt ϕ approach already existed



Selection

- Developed selection for $D_S \rightarrow \phi \pi$
 - ▶ 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

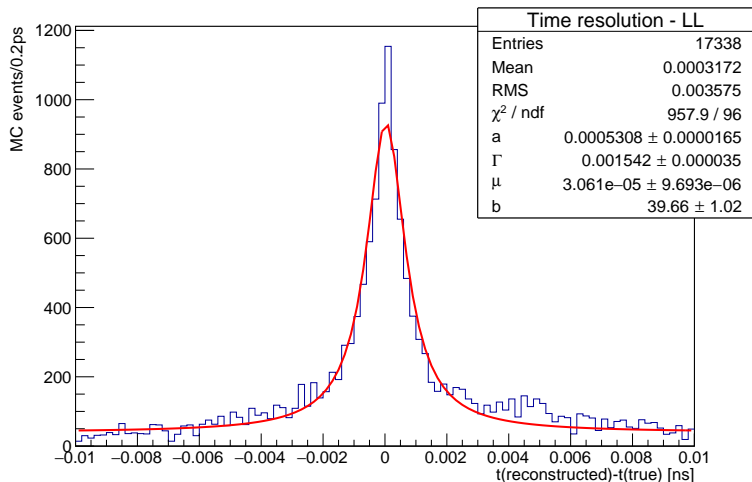
	Prompt ϕ	$D_s \rightarrow \phi\pi$
Cross section (14 TeV), LHCb acceptance	3516 μb	388 μb
Branching fractions	34.2%	4.5% \cdot 34.2%
Fiducial cuts efficiency	2.5%	7.0%
Prob. $K_S K_S \rightarrow 4\pi$, exactly 1 (2) decays inside bp	15.1% (2.8%)	
Prob. $K_S K_L \rightarrow 4\pi$ (CPV), exactly 1 (2) decays inside bp	$3.98 \cdot 10^{-7}$ ($4.99 \cdot 10^{-10}$)	
Upper limit KLOE prob. $K_S K_L \rightarrow 4\pi$ (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:

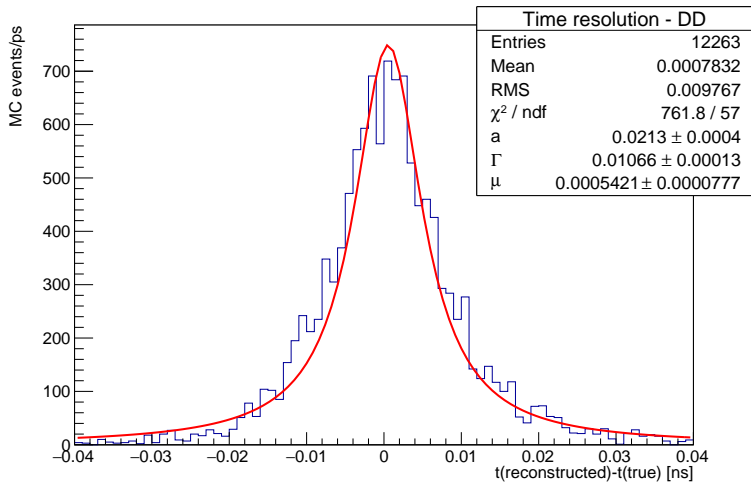
- Background dominates over signal for both approaches
- For the D_S approach, both signal and background rate go down by two orders of magnitude compared to the prompt ϕ approach
 - ▶ There is no big improvement in the signal to background ratio (factor 4)

Time resolution

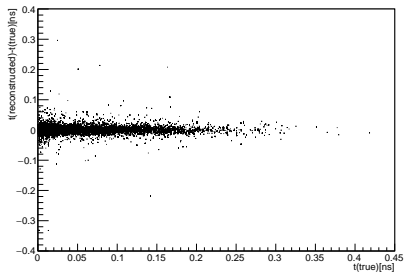


Resolution of the core of the distribution is a few ps

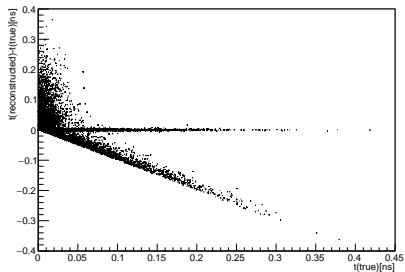
Time resolution



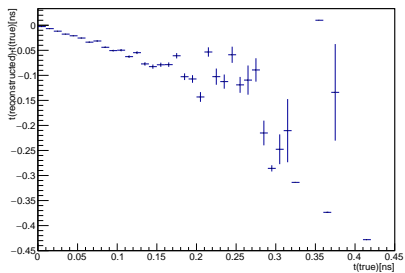
all



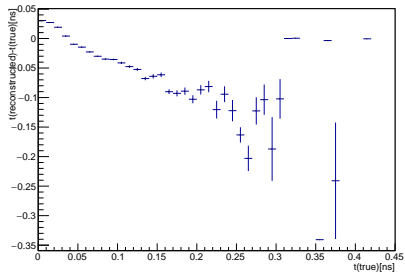
all-DTF



all



all-DTF



Feasibility study for prompt ϕ

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

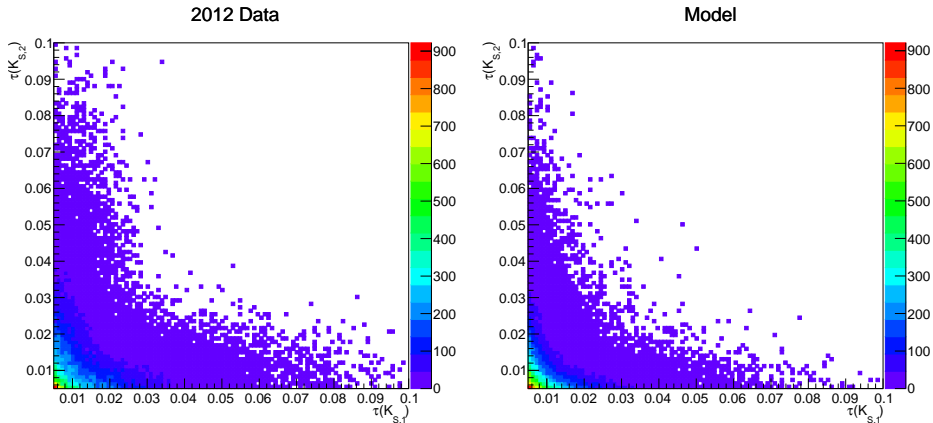
- this background is irreducible
- $I(t_1, t_2) \propto e^{-\Gamma_S t_1} e^{-\Gamma_S t_2}$

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

$$l(t_1, t_2) \propto e^{-\Gamma_S t_1} e^{-\Gamma_S t_2}$$

2. SM background with decay intensity

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

- Ratio of SM background to combinatoric background from efficiency study

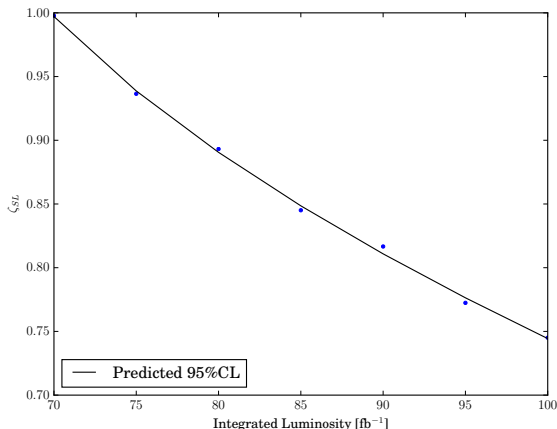
- Fitted to

$$l(t_1, t_2) \propto e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2(1 - \zeta_{SL})e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)(t_1 + t_2)} \cos(\Delta m(t_1 - t_2))$$

- 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

$$\zeta_{SL} = 0.098$$



$\int L dt \approx 275 \text{ fb}^{-1}$,
extrapolated
from fit

Summary

- Selection for $D_S \rightarrow \phi\pi$ 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.

Selection - prompt ϕ

Prompt ϕ production

■ Stripping PhiToKSKS_PhiToKsKsLine

π TRGHOSTPROB < 0.35

P > 2.GeV

MIPCHI2DV(PRIMARY) > 9.

K_S ADMASS('KS0') < 35.MeV

VFASPF(VCHI2) < 25.

ϕ LL or LD combinations *)

APT > 400 MeV

VFASPF(VCHI2/VDOF) < 6

MIPCHI2DV(PRIMARY) < 9

M < 1100 MeV

■ 1010 MeV < phi_M < 1030 MeV

*) because of regeneration, KLOE follows the same approach

Selection - $D_s \rightarrow \phi\pi$

- Selection (inspired by PhiToKSKS_PhiToKsKsLine and other charm lines) on CHARMCOMPLETEEVENT.DST

$\pi(K_S)$ PT > 150 MeV
 BPVIPCHI2() > 1.0
 TRCHI2DOF < 5
 TRGHOSTPROB < 0.35

K_S ADMASS('KS0') < 50 MeV
 VFASPF(VCHI2) < 2.
 PT > 200 MeV
 BPVVD > 10.0 mm
 BPVVDCHI2 > 100
 VFASPF(VCHI2PDOF) < 10
 BPVDIRA > 0.999

ϕ LL or LD combinations
 ADMASS('phi(1020)') < 70 MeV
 VFASPF(VCHI2/VDOF) < 6
 APT > 400 MeV
 ACUTDOCACHI2 < 20

$\pi(D_S)$ TRGHOSTPROB < 0.35
 P > 2 GeV
 MIPCHI2DV(PRIMARY) > 9

D_S ADMASS('D_s+') < 150 MeV
 (BPVVDCHI2 > 16.0) or
 (BPVLTIME() > 0.150 ps)
 VFASPF(VCHI2/VDOF) < 25.0

- 1010 MeV < phi_M < 1030 MeV & 1955 MeV < Ds_M < 1985 MeV
- IPCHI2 \geq 15, (possible to tighten cut if more MC statistics available)

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	$D_S \rightarrow \phi\pi$
light flavour	17(17)	0
$b\bar{b}$	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.

Terminology

