CPT Violation in $\phi \to K^0\overline{K}^0$

Can we study it in LHCb?

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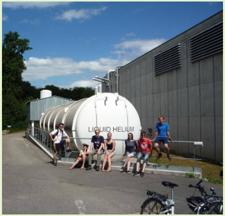
CERN LHCb MANCHESTER 1824 The University of Manchester technische universität dortmund

Who I am

- Master student at the TU Dortmund, Germany
- Last summer:
  - Bachelor thesis with ATLAS (top physics)
  - Quantum information processing summer school
- This fall:
  - Start of my master thesis (ATLAS exotics)
- This summer:



- And of course the project I am about to show you!

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 $K_S \rightarrow \pi^+\pi^-$, $\mathcal{BR}(K_L \rightarrow \pi^+\pi^-) \sim 2 \cdot 10^{-3}$
- 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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$$I(t_1, t_2) \propto e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2(1 - \zeta_{SL})e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)(t_1 + t_2)} \cos\left(\Delta m\left(t_1 - t_2\right)\right)$$

Intrinsical violation of CPT introduces decoherence term.

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Intrinsical violation of CPT introduces decoherence term.[1]

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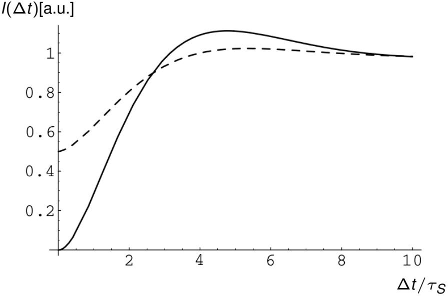


[CPT and Quantum Mechanics Tests with Kaons, J. Bernabeu et al., arXiv:hep-ph/0607322]

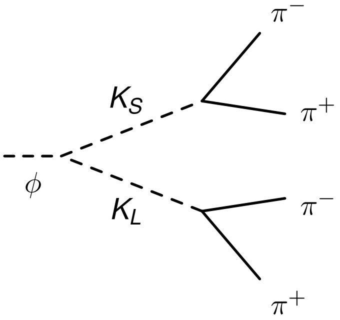
$\Rightarrow$ Excess of 4π decays for small Δt

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

Comparison of two approaches

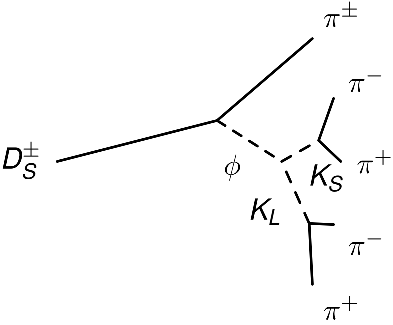
Prompt ϕ

- high production cross section



$D_S^\pm \to \phi\pi^\pm$

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



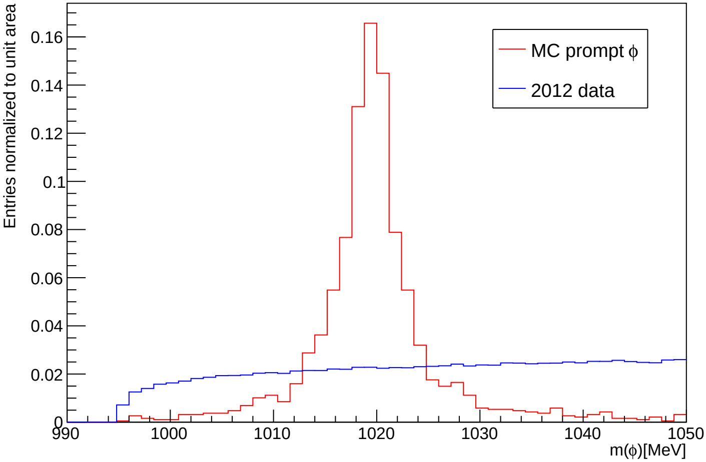
- First study on the prompt ϕ approach
- Compare with D_S approach

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

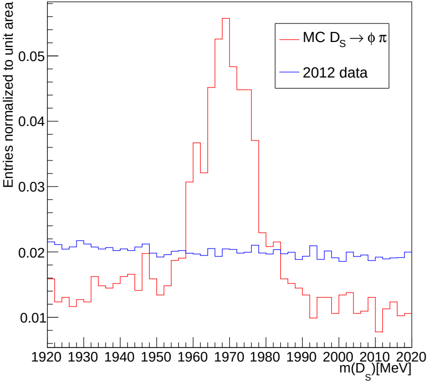
Selection

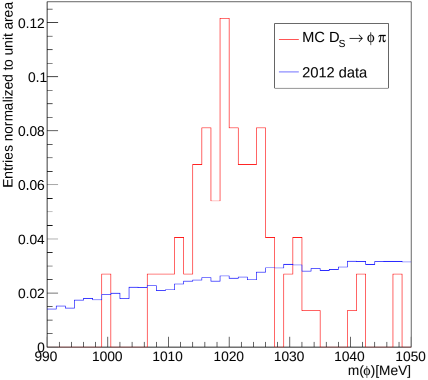
- Stripping for the prompt ϕ approach already existed



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% (4.2%)
L0 efficiency	16.1% (18.6%)	22.4% (18.2%)
LT1 efficiency	13.7% (16.7%)	45.5% (25.0%)
HLT2 efficiency	65.6% (100.0%)	75.0% (100.0%)
Total efficiency SM background	$4.39 \cdot 10^{-5}$ ($5.85 \cdot 10^{-5}$)	$1.02 \cdot 10^{-4}$ ($1.32 \cdot 10^{-4}$)
Expected events SM background / fb^{-1}	21 ($3.51 \cdot 10^{-2}$)	$2.43 \cdot 10^{-1}$ ($3.94 \cdot 10^{-4}$)
Upper limit for signal (KLOE)	27 (1.15)	$3.13 \cdot 10^{-1}$ ($1.29 \cdot 10^{-2}$)
Background (data 2012) / fb^{-1}	163110 (29120)	1170 (6100)

Efficiencies new

	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 %
Generator cut efficiency	2.5 %	7.0 %
Probability of $K_s K_L \to 4\pi$ with exactly 1 (2) decays in the beam pipe with limit on decoherence of KLOE	$5.13 \cdot 10^{-7}(1.64 \cdot 10^{-8})$	
Probability of $K_s K_L \to 4\pi$ with exactly 1 (2) decays in the beam pipe	$3.98 \cdot 10^{-7}(4.99 \cdot 10^{-10})$	
Probability of $K_s K_s \to 4\pi$ with exactly 1 (2) decays in the beam pipe	15.1%(2.8%)	
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

Feasibility study for prompt ϕ

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

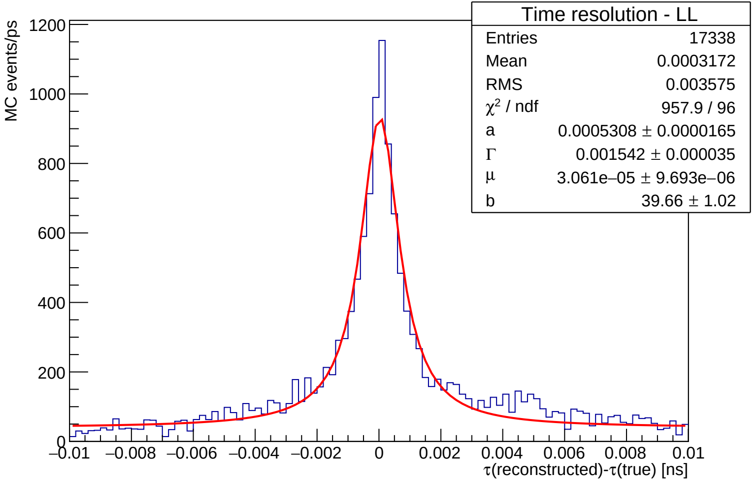
- this background is irreducible
- $I(t_1, t_2) \propto e^{-\Gamma_S t_1} e^{-\Gamma_S t_2}$

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

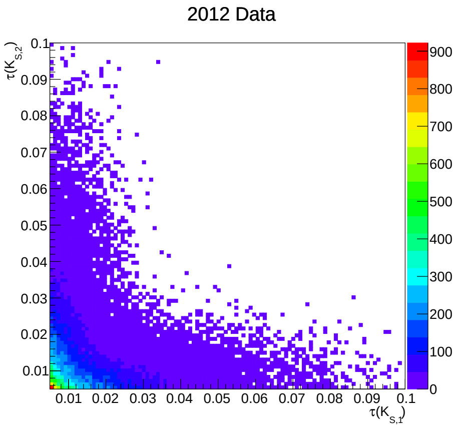
Time resolution

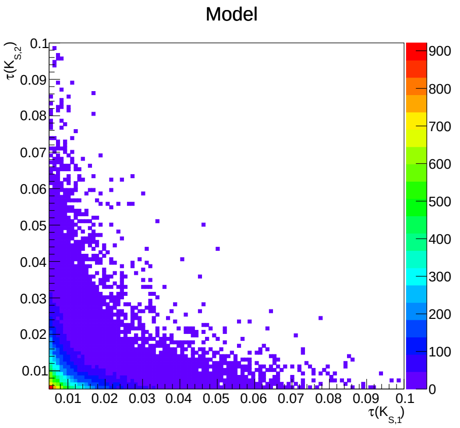


Resolution of the core of the distribution is a few ps

$\Rightarrow$ 5 ps binning in toy study

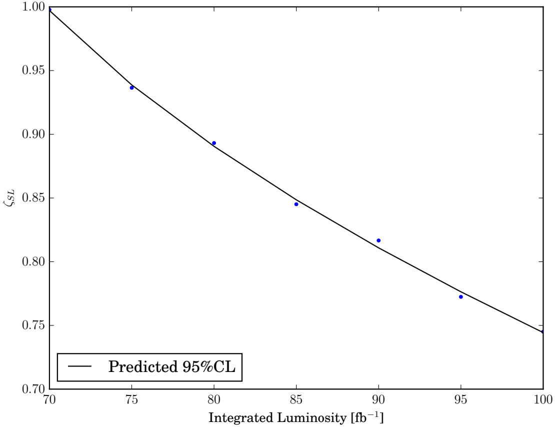
Feasibility study for prompt ϕ





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
$\zeta_{SL} = 0.098$
$\Downarrow$
$\int L\, dt \approx 275$ 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.

Summary

- Selection for $D_S \to \phi\pi$ implemented
- Compared the prompt ϕ and the D_S approach
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Thank you for your attention!

BACKUP

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

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

- Ratio of SM background to combinatoric background from efficiency study
- Fitted to

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

- Derived limit on ζ_{SL} from fit result

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 - $D_s \to \phi\pi$

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

$\pi(K_S)$
- PT $>$ 150 MeV
- BPVIPCHI2() $>$ 1.0
- TRCHI2DOF $<$ 5
- TRGHOSTPROB $<$ 0.3

K_S
- ADMASS('KS0') $<$ 35 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

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

D_S
- ADMASS('D_s+') $<$ 150MeV
- (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)

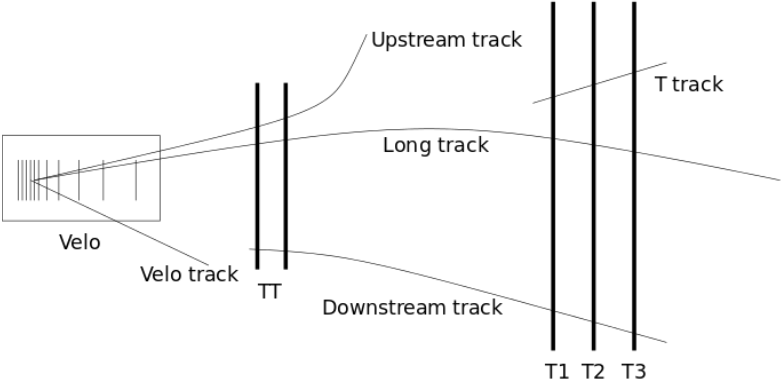
Backgrounds

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	$D_s \to \phi\pi$
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.

Terminology



Time resolution