ϕ -> $K_S K_S$
or
Is it possible to test Quantum Mechanics and CPT with entangled neutral kaons at LHCb?

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Rare'n'Strange Workshop on rare strange decays at LHCb
CERN, 6 December 2013

* speaker

The Physics case

CPT theorem (Luders, Jost, Pauli, Bell 1955 -1957):
Exact CPT invariance holds for any quantum field theory (flat space-time) which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.

Extension of CPT theorem to a theory of quantum gravity far from obvious (e.g. CPT violation appears in some models with space-time foam backgrounds).

No predictive theory incorporating CPT violation => only phenomenological models to be constrained by experiments.

The neutral kaon system offers unique possibilities to test CPT invariance e.g. :

$$\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}, \quad \left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}, \quad \left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$$

The Physics case

Feynman described the phenomenon of interference as containing “the only mistery” of quantum mechanics.

Entanglement is one of the most fascinating phenomenon at the heart of quantum mechanics. It is connected with the Einstein-Podolsky-Rosen paradox (EPR) and Bell’s theorem.

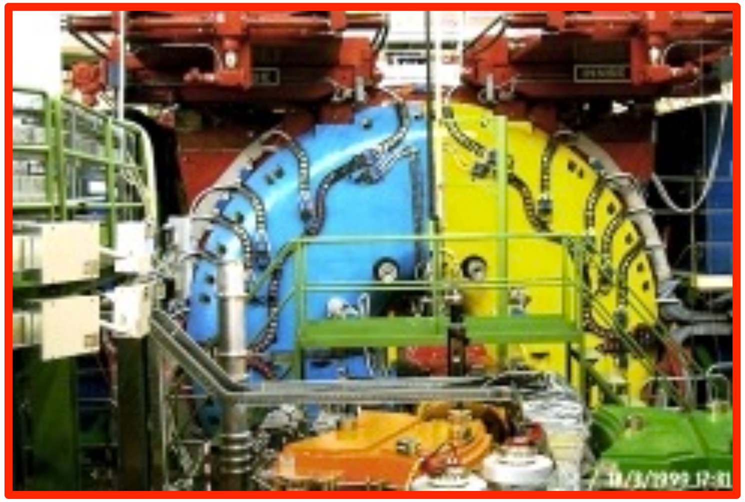
The “quantum” coherence of entangled pairs can be tested only in few physical systems:
-optical photons
-gamma rays
-beryllium ions
-S-wave protons
-neutral K,B,D mesons

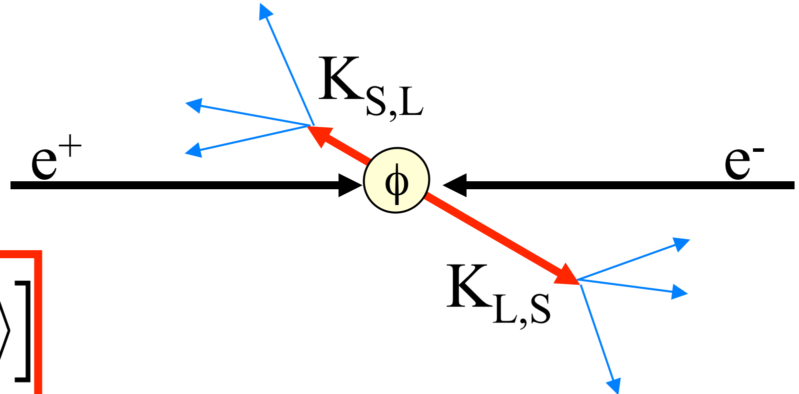
The best precision is obtained with neutral kaons!

Neutral kaons at a ϕ-factory: KLOE at DAΦNE (Frascati)

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \rightarrow \phi$ $\quad \sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- BR($\phi \rightarrow K^0\bar{K}^0$) $\sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:





$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\bar{K}^0(-\vec{p})\right\rangle - \left|\bar{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$

$$= \frac{N}{\sqrt{2}}\left[\left|K_S(\vec{p})\right\rangle\left|K_L(-\vec{p})\right\rangle - \left|K_L(\vec{p})\right\rangle\left|K_S(-\vec{p})\right\rangle\right]$$

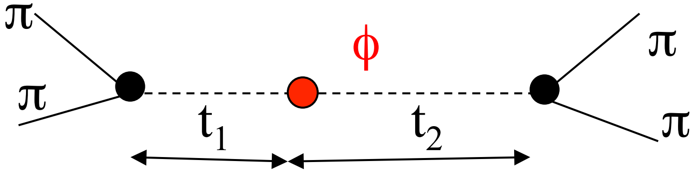
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

p_K = 110 MeV/c
λ_S = 6 mm $\quad \lambda_L$ = 3.5 m

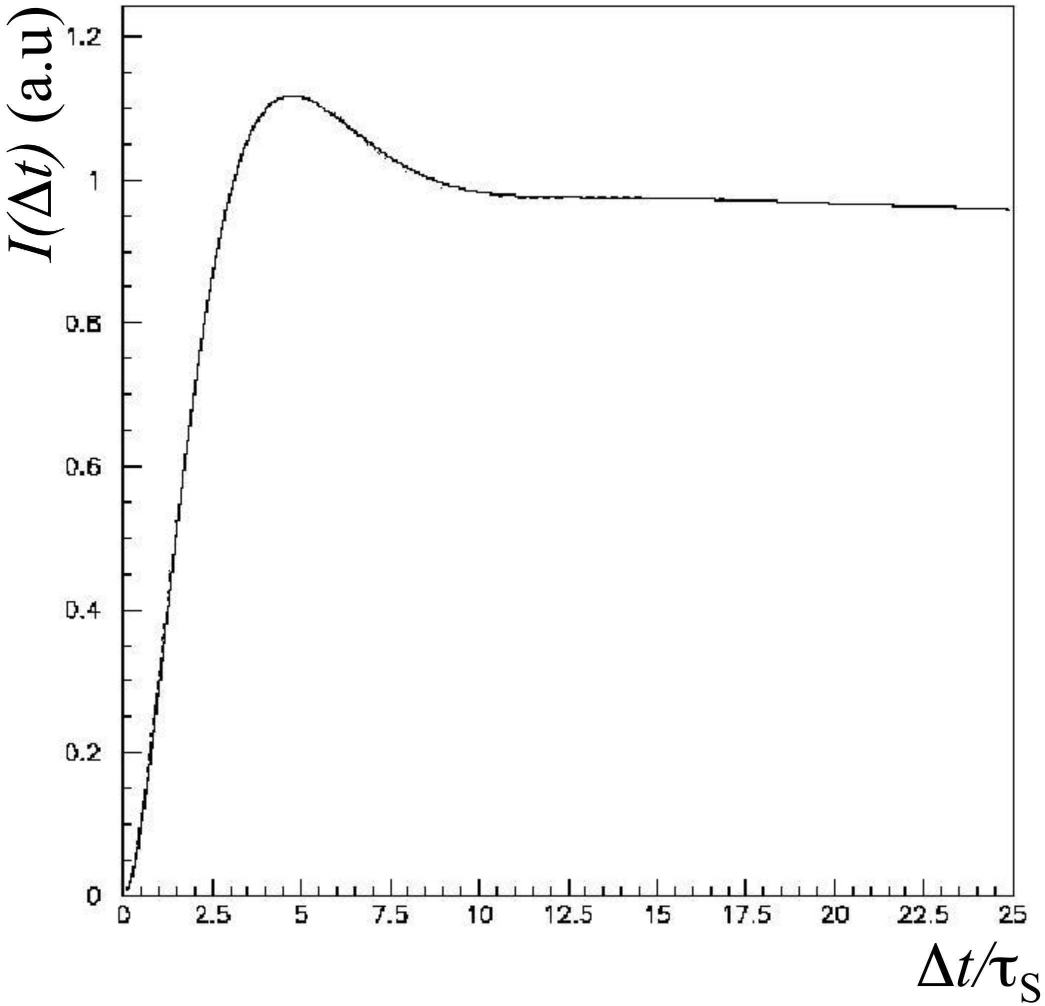
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$

$$\Delta t = |t_1 - t_2|$$



Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$



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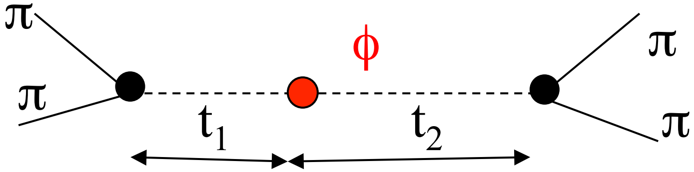
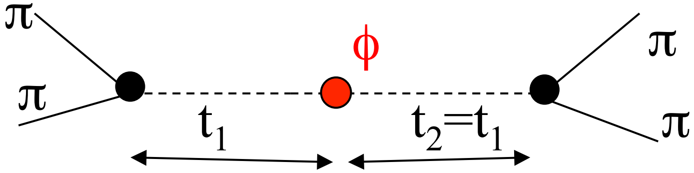
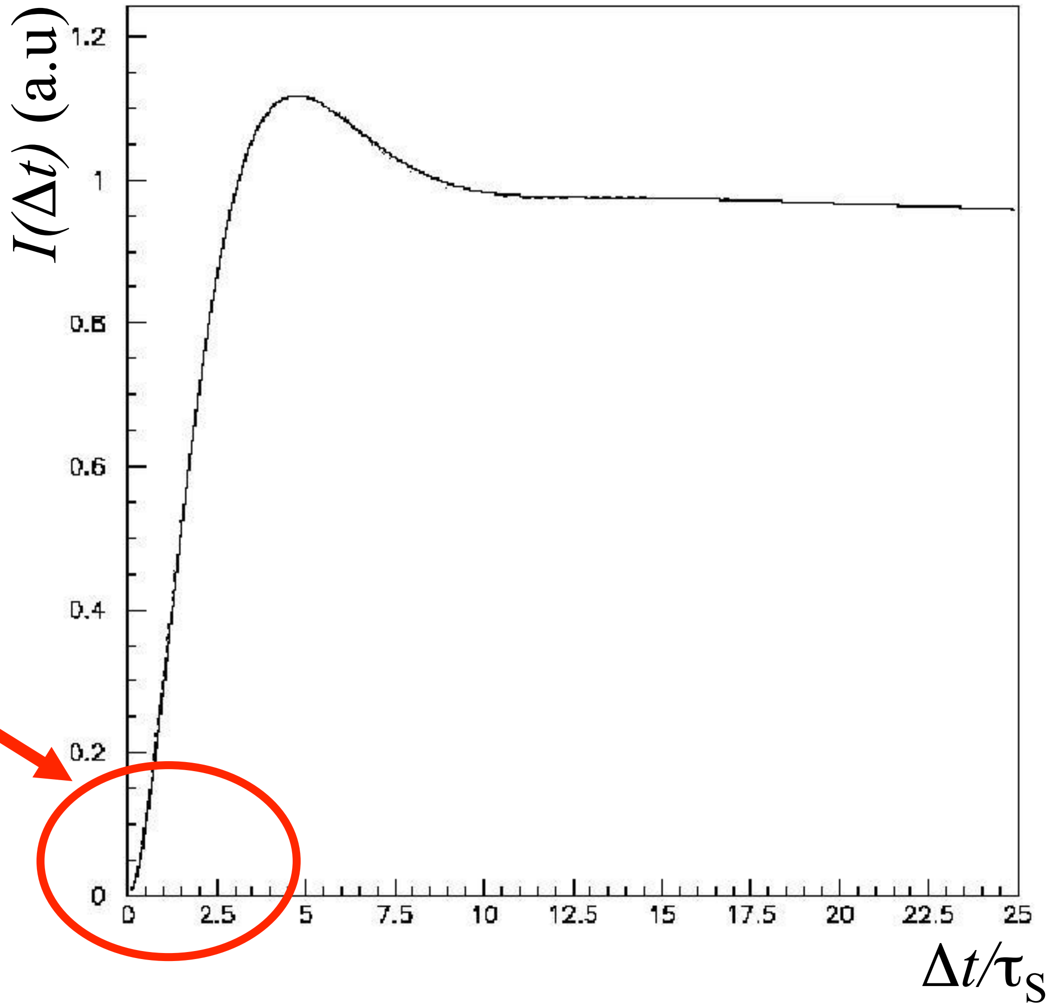


EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference





$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \, \pi^+\pi^-$

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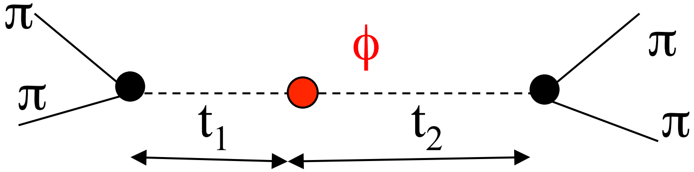

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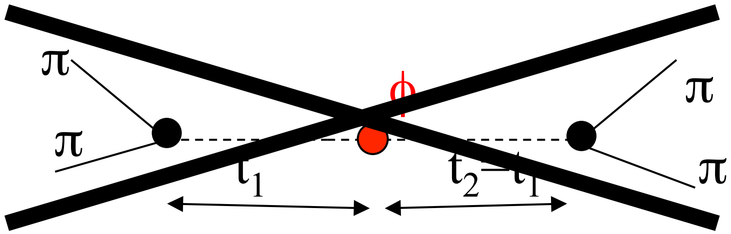

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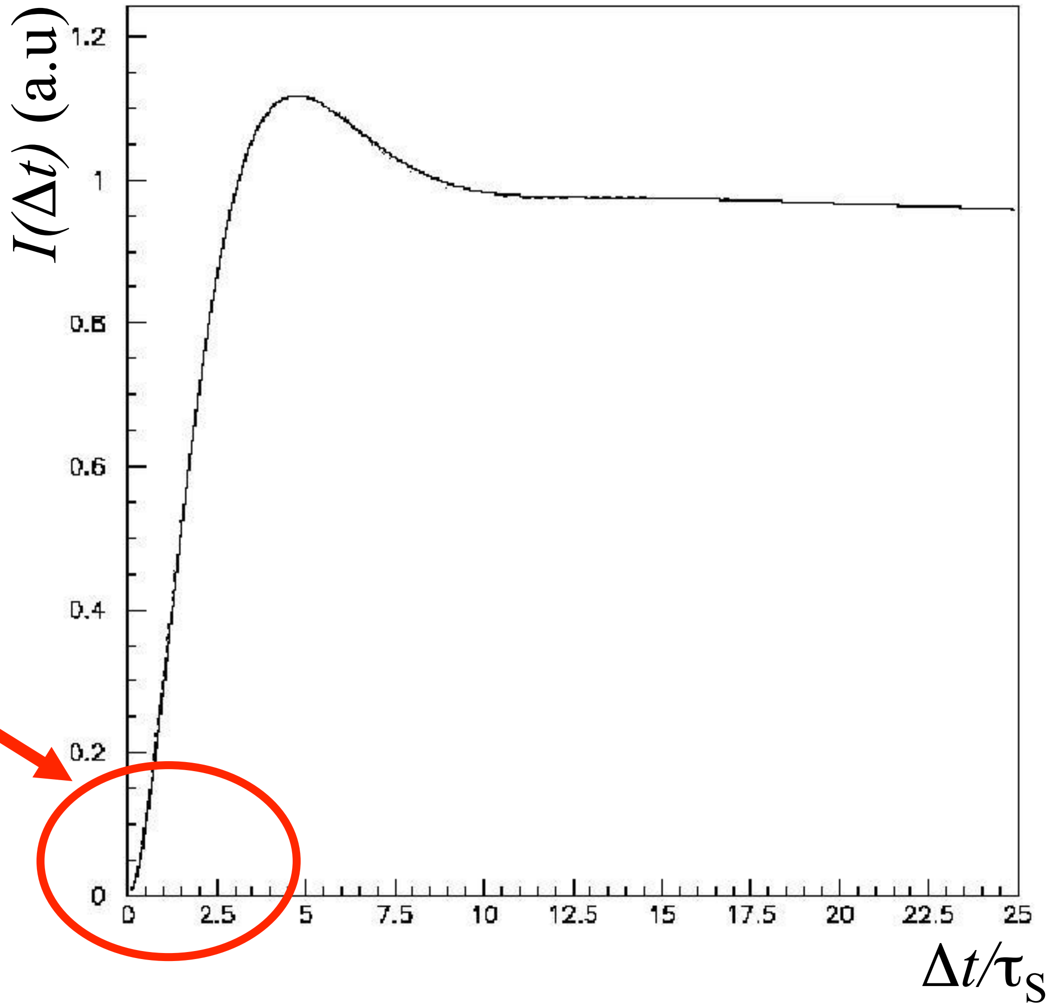

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\left[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle\right|^2\right.$$
$$\left. -2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\right]$$

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$$\left.-\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\left\langle\pi^+\pi^-,\pi^+\pi^-\middle|K^0\overline{K}^0(\Delta t)\right\rangle\left\langle\pi^+\pi^-,\pi^+\pi^-\middle|\overline{K}^0K^0(\Delta t)\right\rangle^*\right)\right]$$

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$$-\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\langle \pi^+\pi^-,\pi^+\pi^- | K^0\overline{K}^0(\Delta t)\rangle \langle \pi^+\pi^-,\pi^+\pi^- | \overline{K}^0 K^0(\Delta t)\rangle^*\right)\Big]$$

Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \rightarrow \quad$ QM

$\zeta_{0\bar{0}} = 1 \quad \rightarrow \quad$ total decoherence

(also known as Furry's hypothesis
or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

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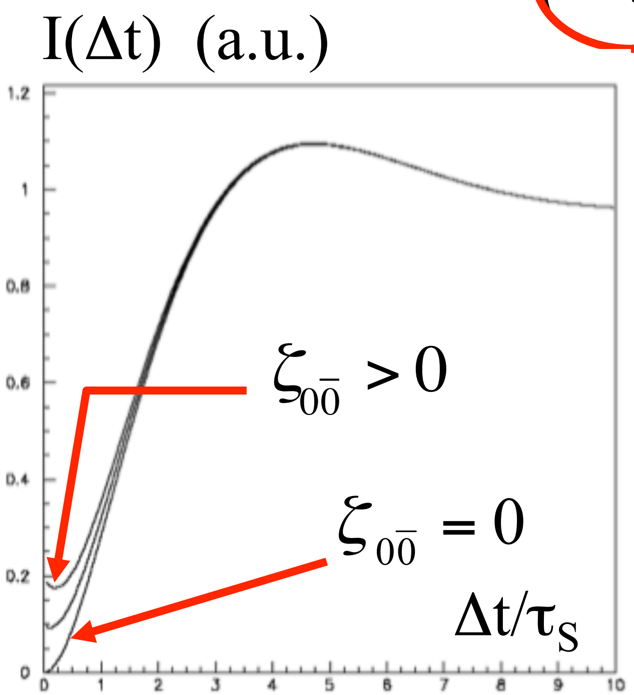

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$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: L=1.5 fb^{-1}
- Fit including Δt resolution and efficiency effects + regeneration

KLOE result: PLB 642(2006) 315 Found. Phys. 40 (2010) 852

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}) \times 10^{-7}$$

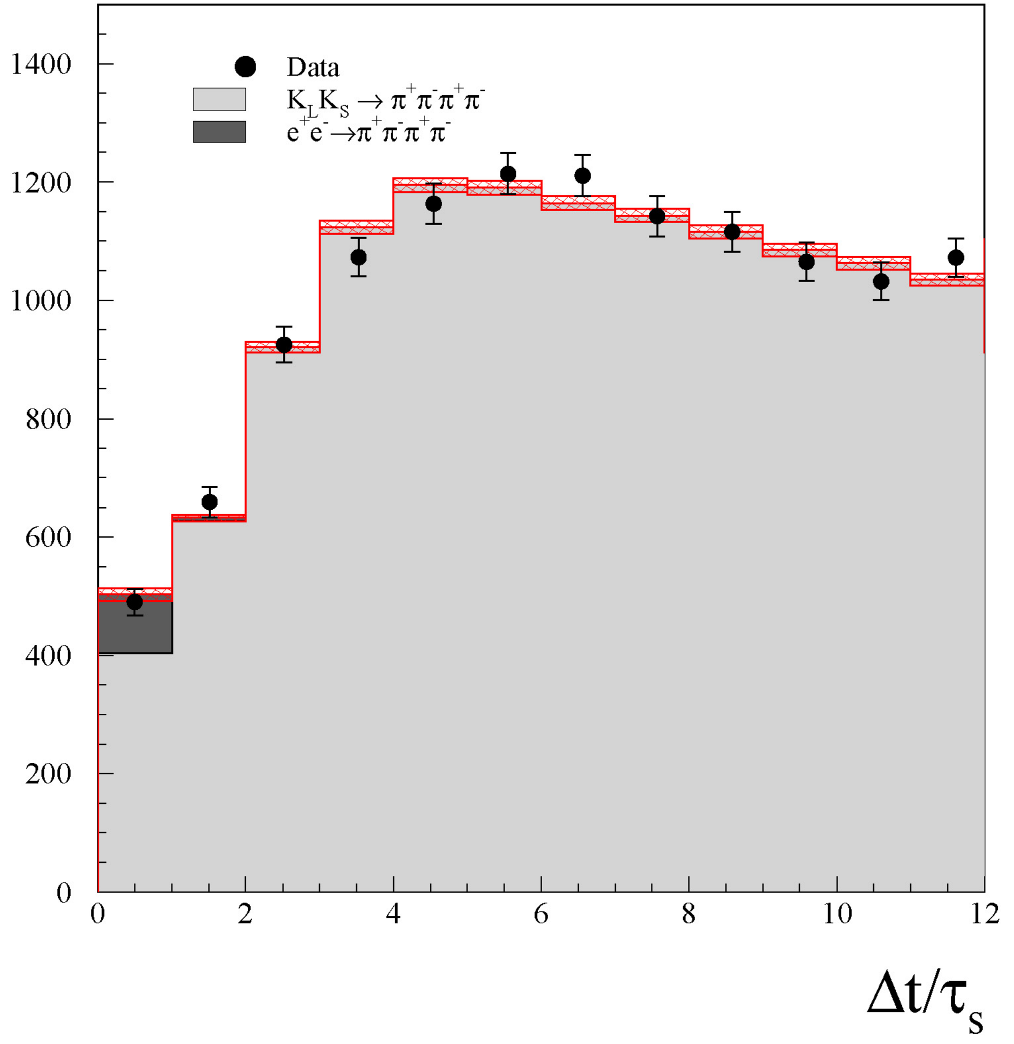
as CP viol. $O(|\varepsilon|^2) \sim 10^{-6}$ => high sensitivity to $\zeta_{0\bar{0}}$

From CPLEAR data, Bertlmann et al. (PR D60 (1999) 114032) obtain:

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$



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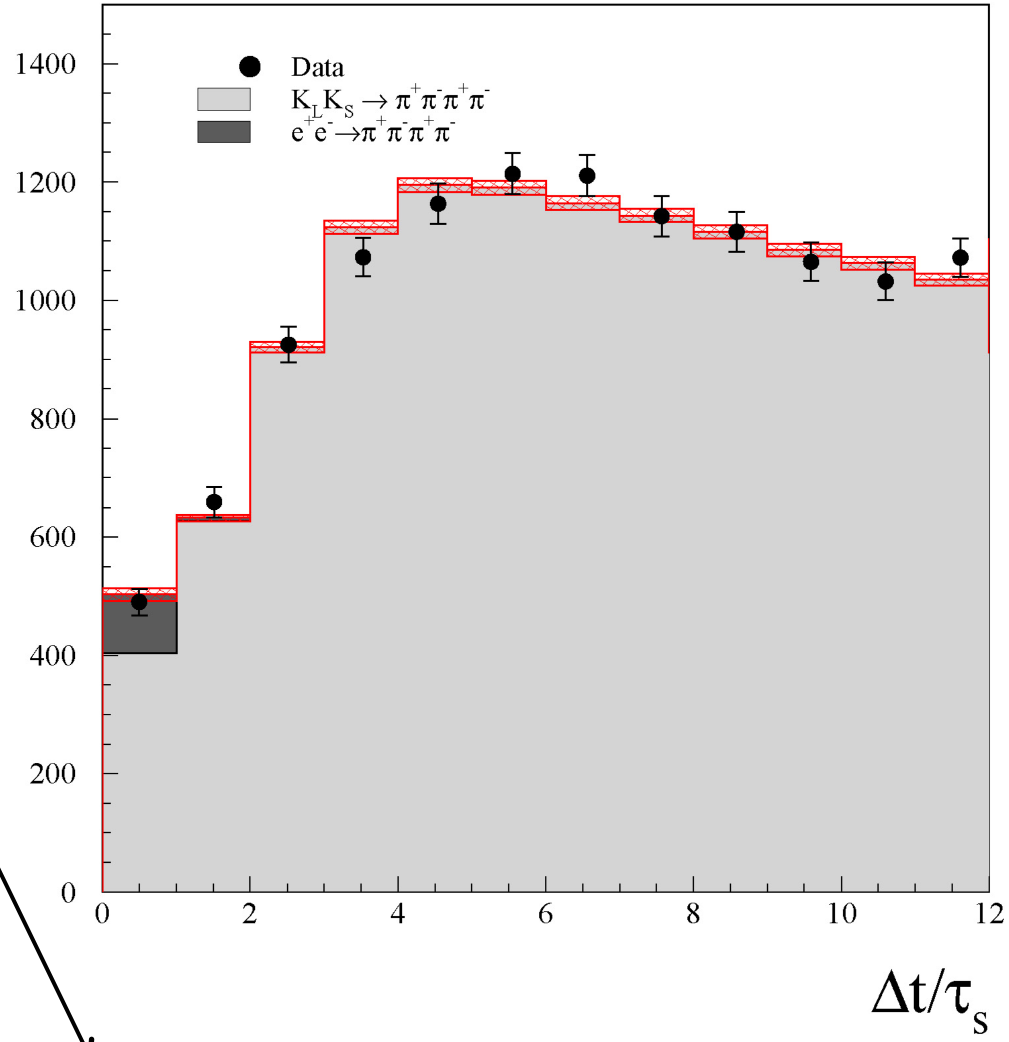


Best precision achievable in an entangled system

Decoherence and CPT violation

Modified Liouville – von Neumann equation for the density matrix of the kaon system:

$$\dot{\rho}(t) = \underbrace{-iH\rho + i\rho H^{+}}_{\text{QM}} + L(\rho)$$

extra term inducing decoherence:
pure state => mixed state

Possible decoherence due quantum gravity effects:

Black hole information loss paradox => Possible decoherence near a black hole.

Hawking [1] suggested that at a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations (generically space-time foam) could give rise to decoherence effects, which would necessarily entail a violation of CPT [2].

J. Ellis et al.[3-6] => model of decoherence for neutral kaons => 3 new CPTV param. α,β,γ:

$$L(\rho) = L(\rho;\alpha,\beta,\gamma)$$

$$\alpha,\gamma > 0 \quad , \quad \alpha\gamma > \beta^2$$

At most: $\alpha,\beta,\gamma = O\left(\frac{M_K^{\ 2}}{M_{PLANCK}}\right) \approx 2\times10^{-20}$ GeV

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; PRD53 (1996)3846 [4] Huet, Peskin, NP B434 (1995) 3; [5] Benatti, Floreanini, NPB511 (1998) 550 [6] Bernabeu, Ellis, Mavromatos, Nanopoulos, Papavassiliou: Handbook on kaon interferometry [hep-ph/0607322]

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: decoherence & CPTV by QG

Study of time evolution of **single kaons**
decaying in $\pi^+\pi^-$ and semileptonic final state

CPLEAR PLB 364, 239 (1999)

$$\alpha = (-0.5 \pm 2.8) \times 10^{-17} \text{ GeV}$$
$$\beta = (2.5 \pm 2.3) \times 10^{-19} \text{ GeV}$$
$$\gamma = (1.1 \pm 2.5) \times 10^{-21} \text{ GeV}$$

single kaons

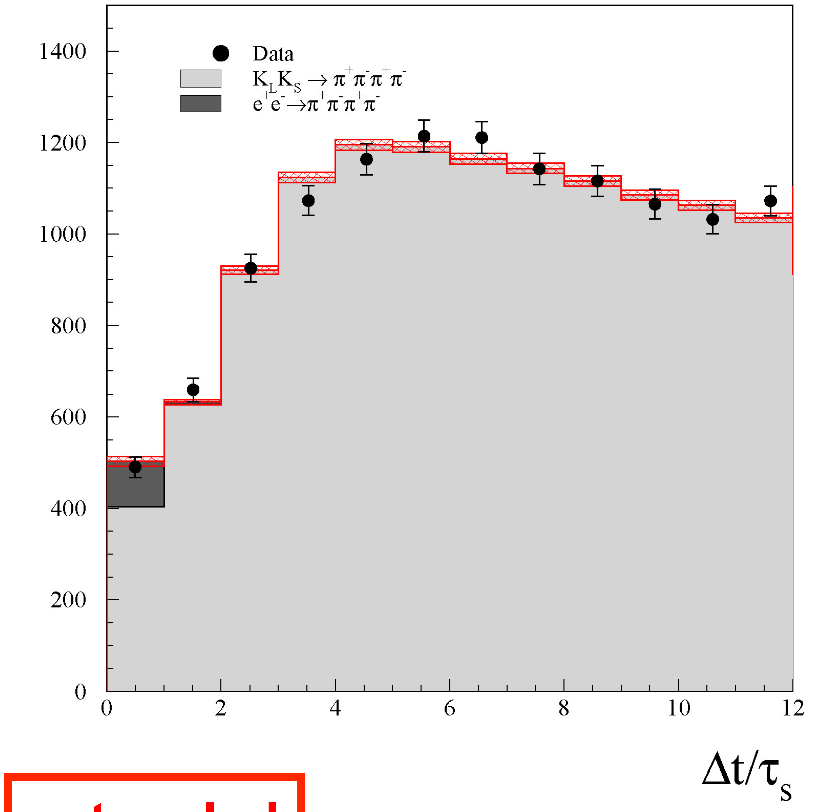
In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$
=> only one independent parameter: γ

The fit with $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\gamma)$ gives:

KLOE result L=1.5 fb^{-1}

$$\gamma = (0.7 \pm 1.2_{STAT} \pm 0.3_{SYST}) \times 10^{-21} \text{ GeV}$$

PLB 642(2006) 315
Found. Phys. 40 (2010) 852



entangled kaons

$\phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$: CPT violation in entangled K states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

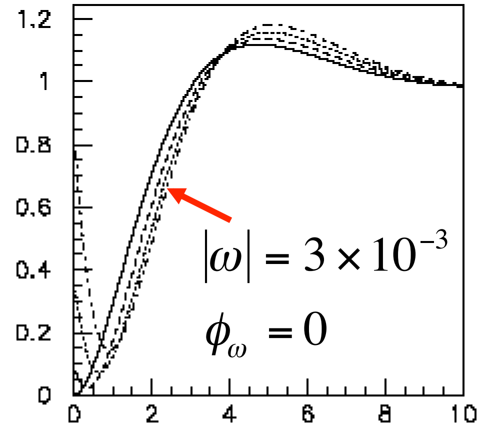
$$|i\rangle \propto \left(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right) + \omega\left(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle\right)$$

$$\propto \left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right) + \omega\left(|K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle\right)$$

at most one expects:

$$|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}$$

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



$\Delta t/\tau_S$

In some microscopic models of space-time foam arising from non-critical string theory:
[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

$$|\omega| \sim 10^{-4} \div 10^{-5}$$

The maximum sensitivity to ω is expected for $f_1=f_2=\pi^+\pi^-$
All CPTV effects induced by QG ($\alpha,\beta,\gamma,\omega$) could be simultaneously disentangled.

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled K states

Fit of $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$:

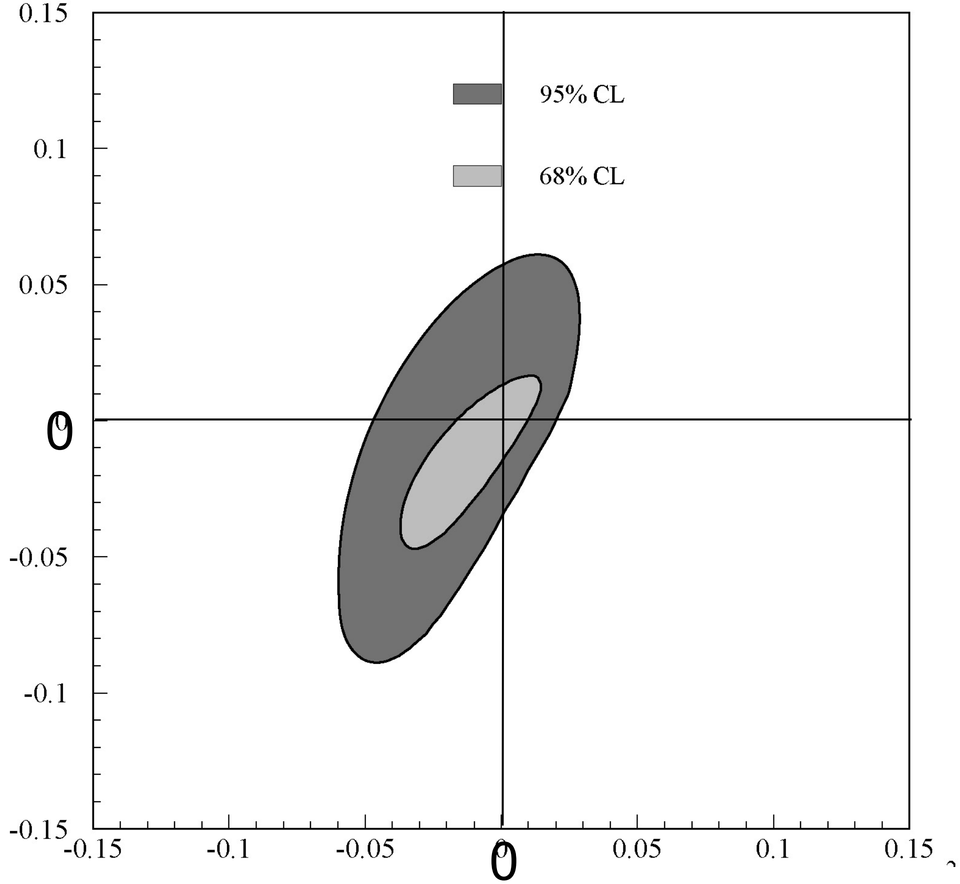
- Analysed data: 1.5 fb^{-1}

KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right) \times 10^{-4}$$

$$|\omega| < 1.0 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$



In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

$$-0.0084 \le \Re\omega \le 0.0100 \quad \text{at } 95\% \text{ C.L.}$$

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb

PROS:

- ϕ mesons are copiously produced at LHC (see next slide)

- Due to ϕ momentum and LHCb acceptance, only $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ decays with both kaons decaying at short times ($< 1\ \tau_S$) can be reconstructed.
This is precisely the most interesting region for QM and CPT tests.

- The Δt resolution, due to the excellent LHCb vertex resolution, is of the order of $2 \times 10^{-3}\ \tau_S$ (from T. Ruf) translating into a high sensitivity to decoherence/CPTV effects in the $\Delta t \sim 0$ region.

- Useful to measure K_S regeneration parameters which limit charm direct CPV measurements

CONS:

- Background

- Trigger efficiency at present too low -> special trigger required

Other interesting channels at LHCb

-In principle one could also look at $J/\Psi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ decays, same physics, different kaon momenta.
In this case there is a reduction due to the unfavorable BR and lower production cross section → severe limitations on signal statistics:

$\sigma(pp \to J/\Psi X) \sim 10\ \mu b$
in LHCb acceptance: $2.0<y<4.5$; $0<P_T<14$ GeV/c (from EPJC71 (2011) 1645)
$BR(J/\Psi \to K_S K_L) \sim 1.5 \times 10^{-4}$

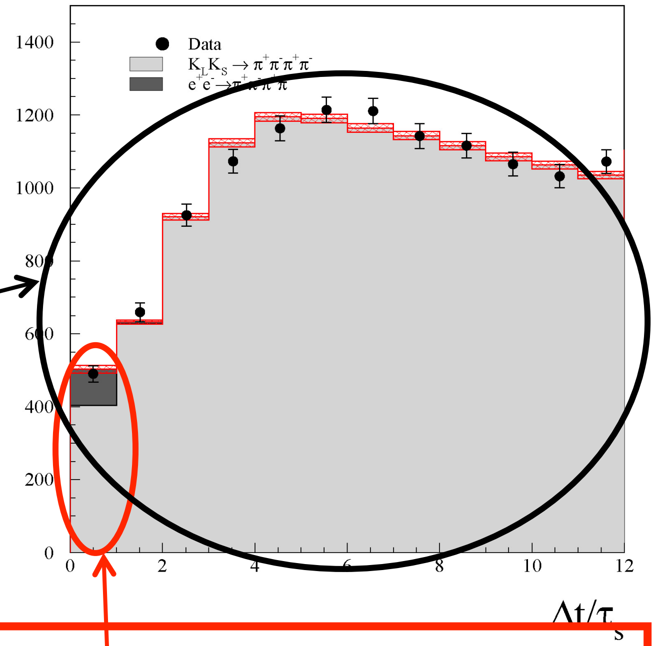
$\sigma(pp \to \phi X) \sim 1800\ \mu b$
in LHCb acceptance: $2.44<y<4.06$; $0.6<P_T<5$ GeV/c (from PLB 703(2011) 267)
$BR(\phi \to K_S K_L) \sim 0.34$

$N(J/\Psi \to K_S K_L) / N(\phi \to K_S K_L) \sim 2.5 \times 10^{-6}$

- Also interesting $D^0 \to K^0 \underline{K}^0$ symmetric state which yield $D^0 \to K_S K_S - K_L K_L$ as a $K_S K_S$ control sample

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: statistics

at KLOE
λ_S~6 mm (P=110 MeV/c)
L=1.5 fb-1
4.4×10^9 ϕ's
1.5×10^9 $K_S K_L$ pairs
efficiency ~ 30%
~12150 in 0-12 τ_S range



At LHCb:
~0.2 < λ_S~ 0.8 m (~3 < P < ~20 GeV/c)
σ(pp->ϕX)~1800 μb -> 1.8×10^{12} ϕ's /fb^{-1}

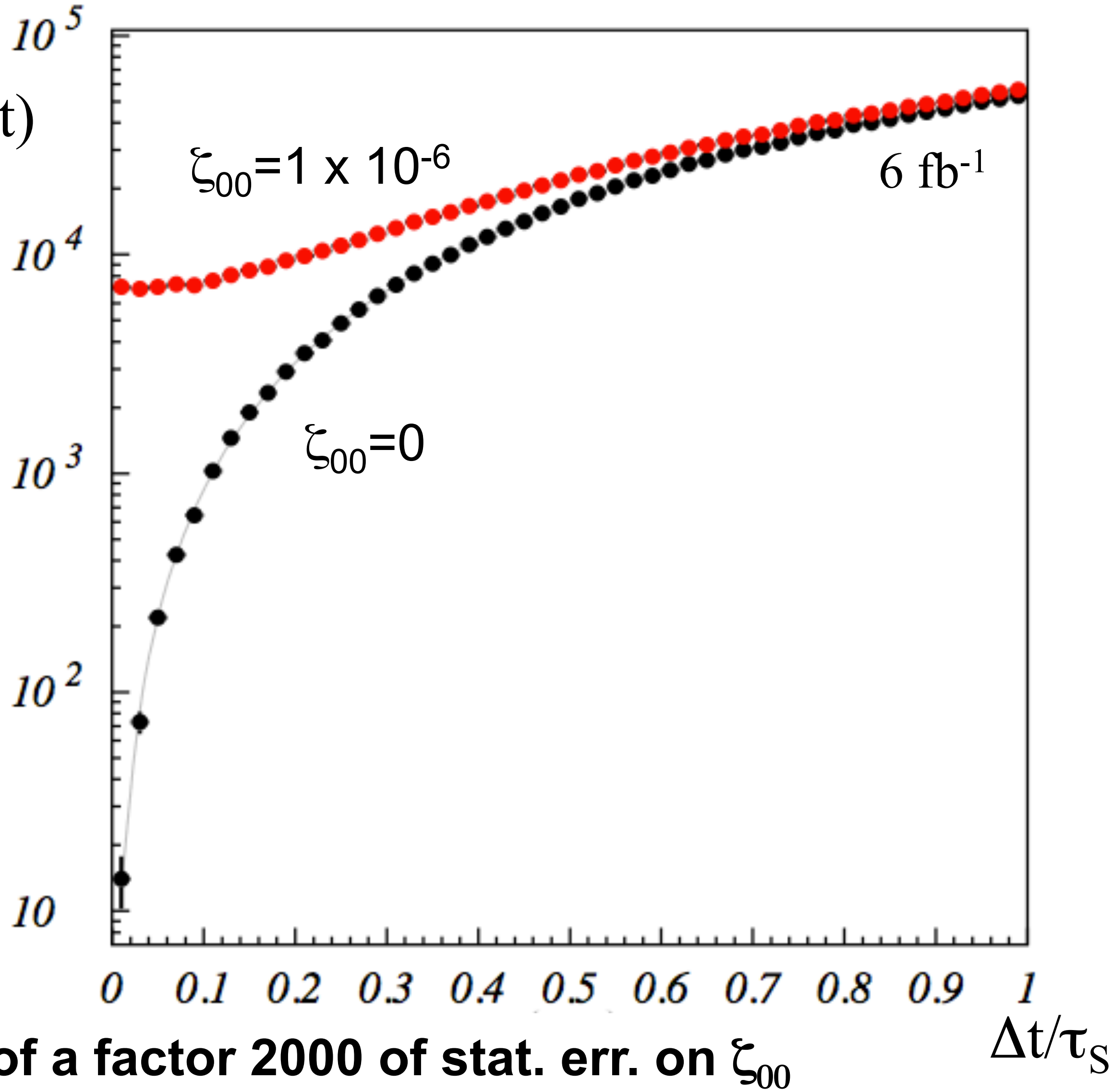
NOT including the efficiency one expects:
N(ϕ-> $K_S K_L$->$\pi^+\pi^-\pi^+\pi^-$) = 1.5×10^5 evts/fb^{-1} in 0-1 τ_S range

x 6 fb^{-1} ~ 9.0×10^5 evts
x 50 fb^{-1} ~ 7.5×10^6 evts

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

FIT in 0 -1 τ_S range
N events = 10^6

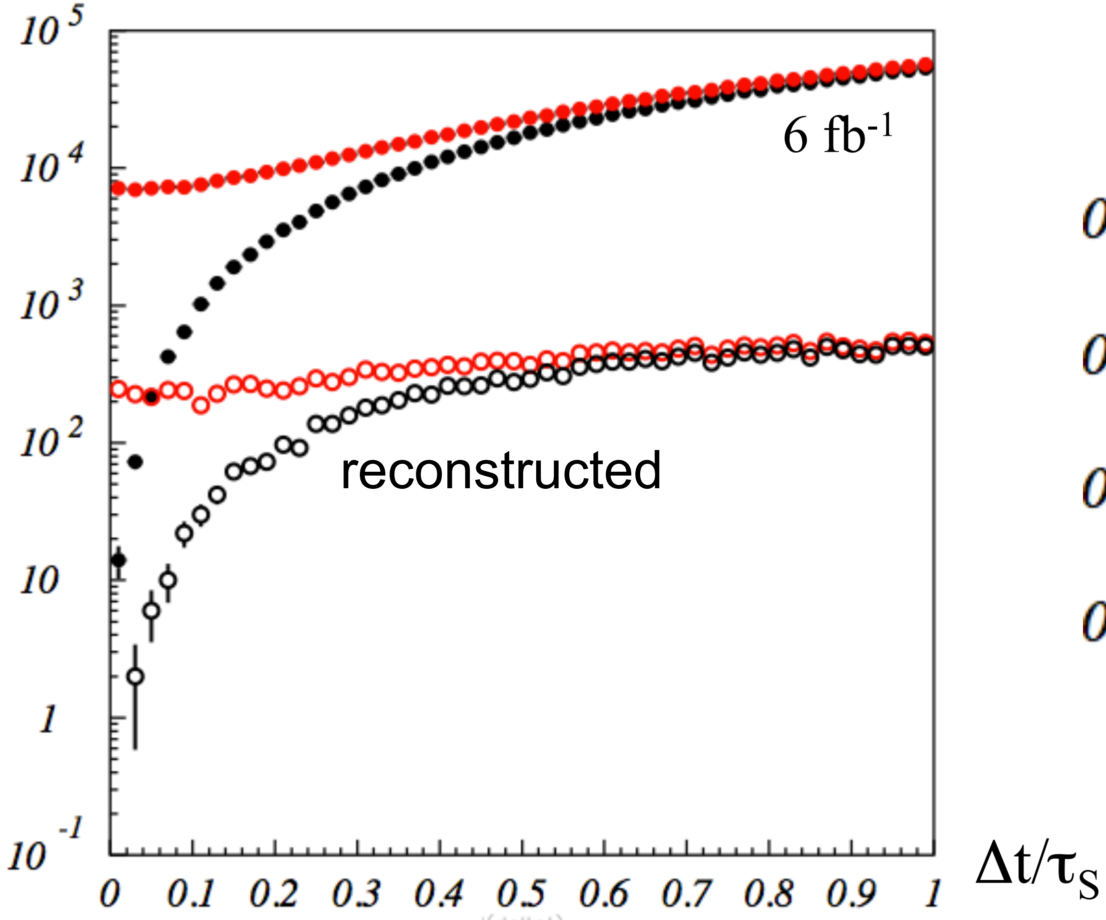
	$\sigma(\zeta_{00})$
KLOE 1.5 fb^{-1}	$\pm1.0\times10^{-6}$
LHCb 6 fb^{-1}	$\pm0.5\times10^{-9}$



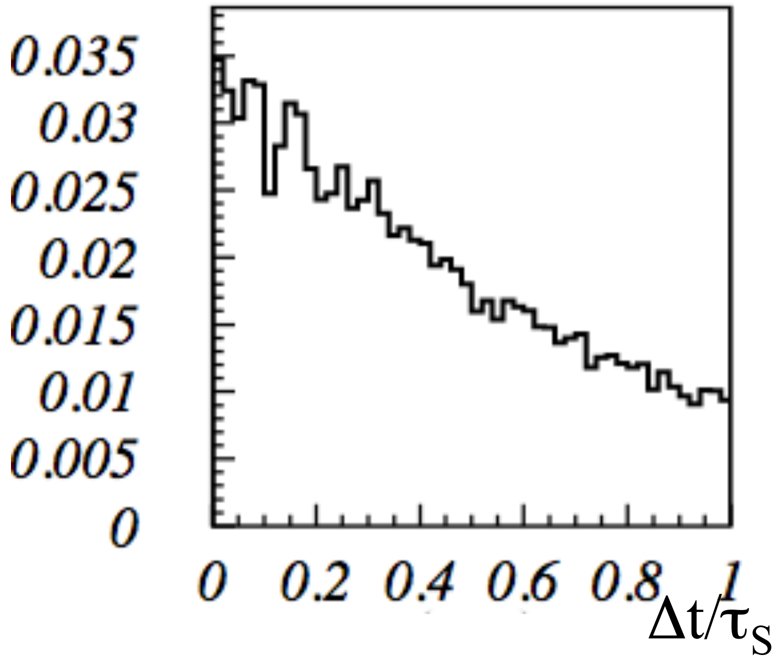
in principle reduction of a factor 2000 of stat. err. on ζ_{00}

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

- ϕ mesons generated in LHCb acceptance according to $d^2\sigma/dydp_T$.
- The LHCb reconstruction efficiency of a single $K_S \rightarrow \pi^+\pi^-$ as a function of vertex longitudinal coordinate z is ~ 30% for 0<z<200 mm, ~15% for 200<z<600 mm and drops to zero for z>600 mm (no VELO reconstruction) (from T. Ruf).
- Δt resolution effects totally negligible!

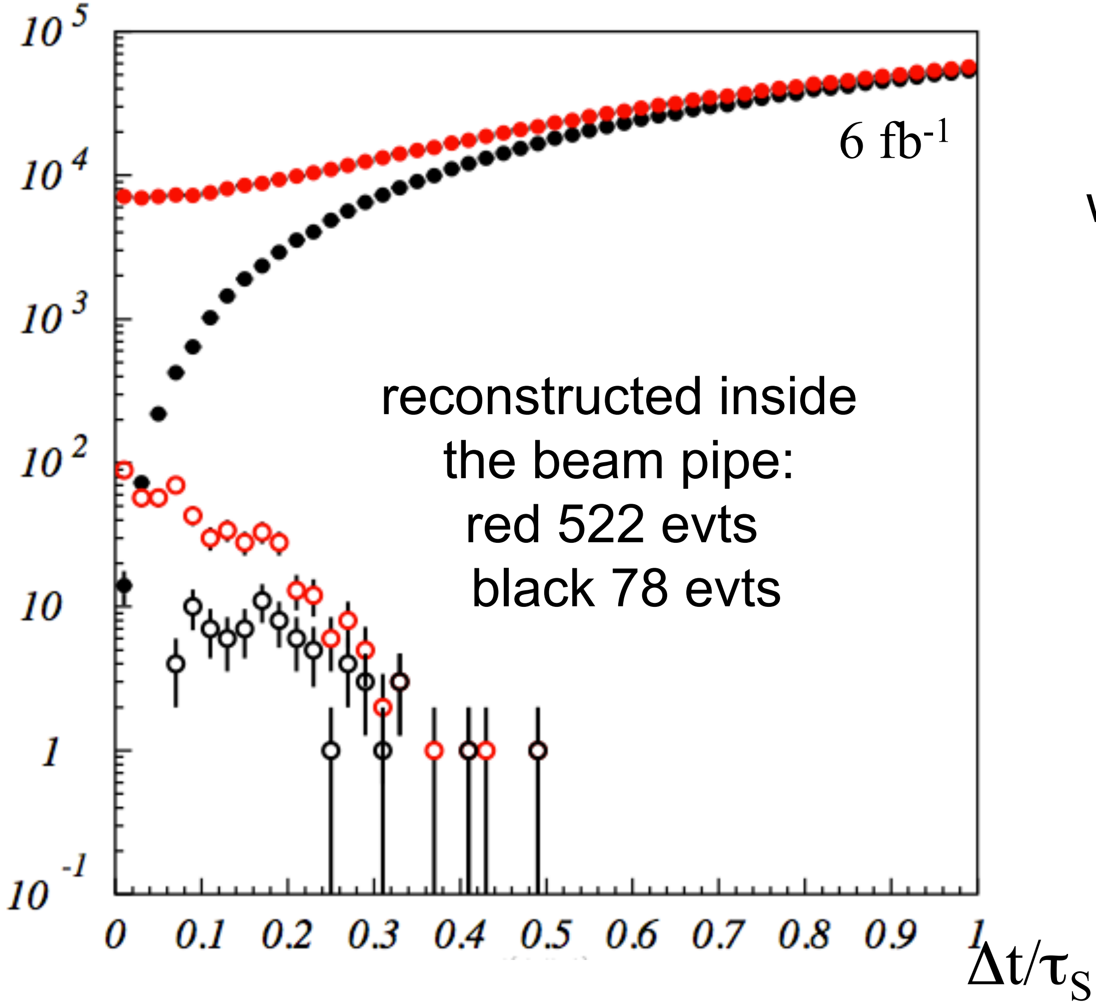


reconstruction efficiency for $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$

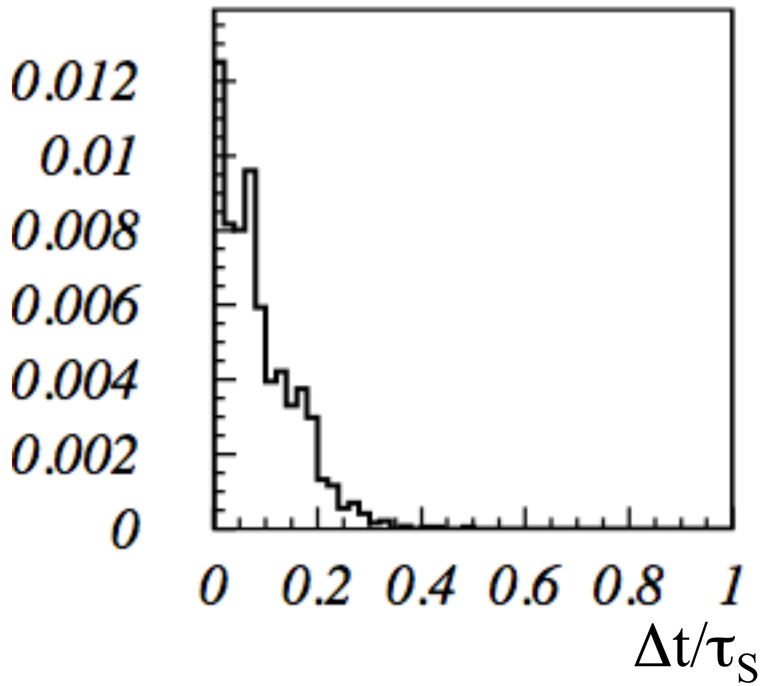


$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

-In order to avoid K_S regeneration on the beam pipe, both kaon vertices are required to be reconstructed inside the beam pipe: r< 5 mm

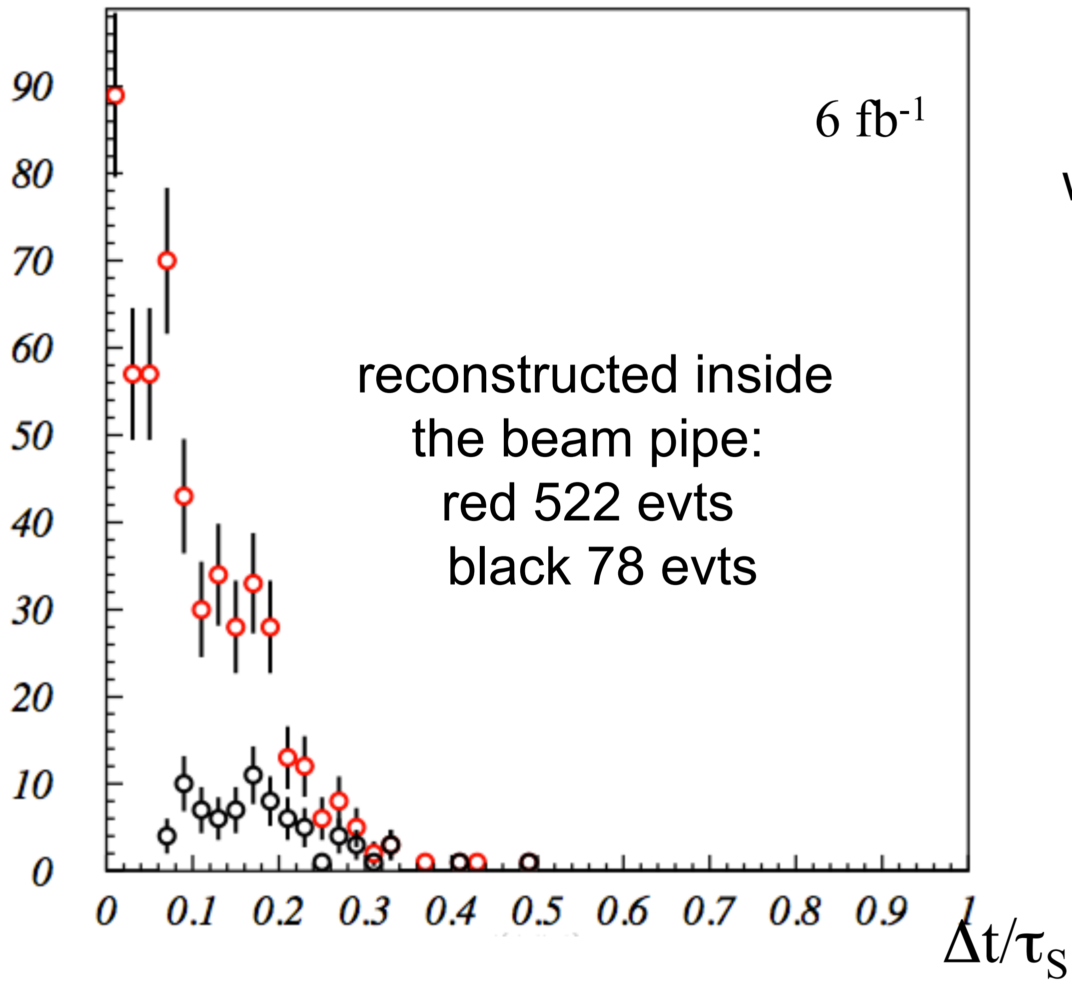


reconstruction efficiency for
$\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$
with both kaons inside the beam pipe

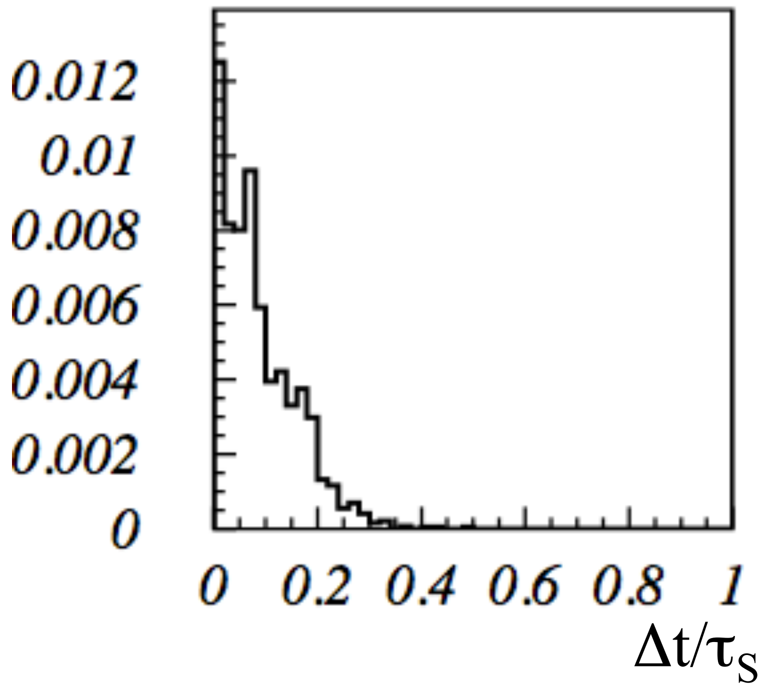


$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

-In order to avoid K_S regeneration on the beam pipe, both kaon vertices are required to be reconstructed inside the beam pipe: r< 5 mm



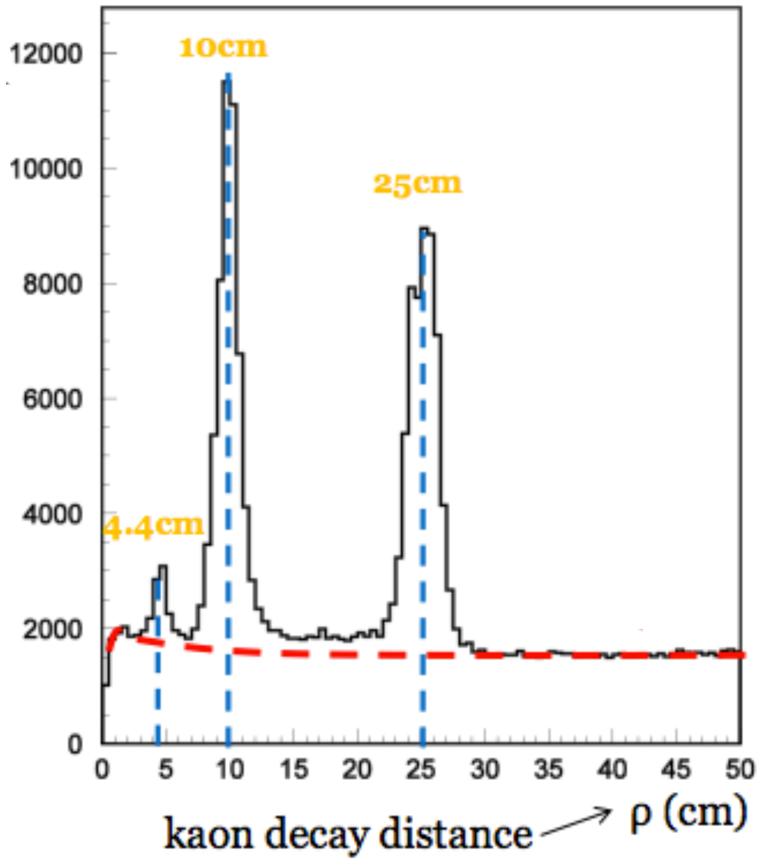
reconstruction efficiency for $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ with both kaons inside the beam pipe

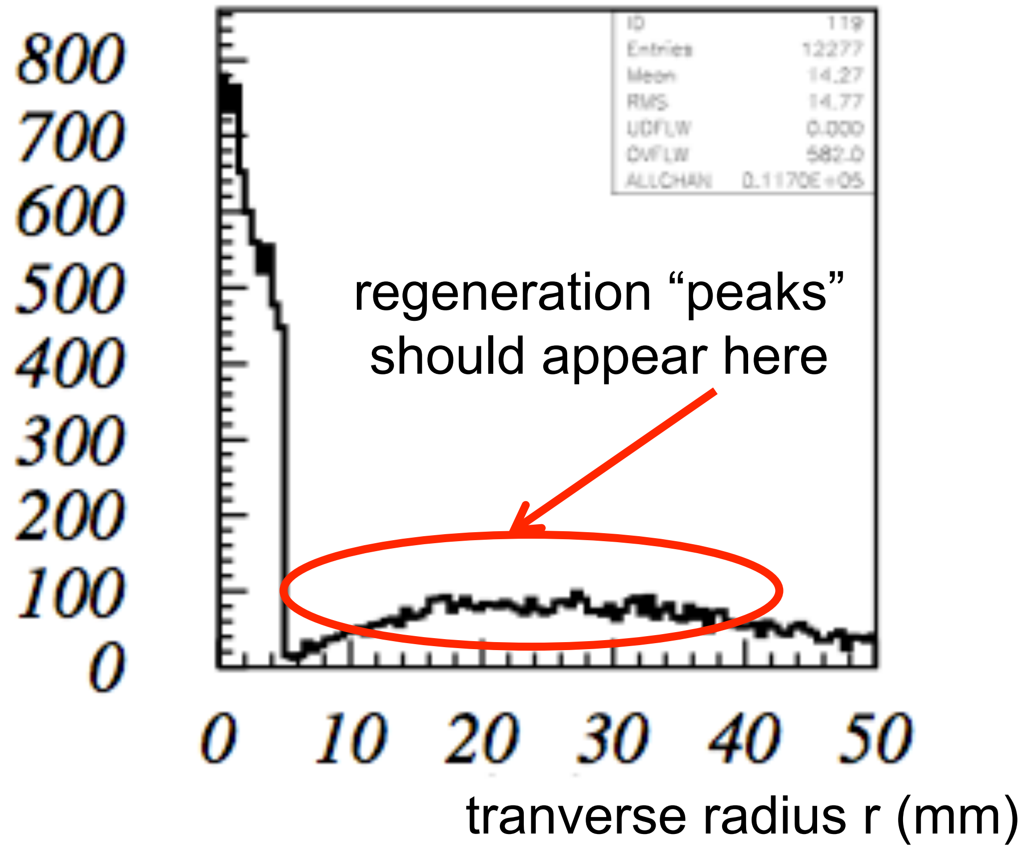


$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

-In order to study K_S regeneration on the beam pipe, AT LEAST one kaon vertex is required to be reconstructed inside the beam pipe: r< 5 mm.

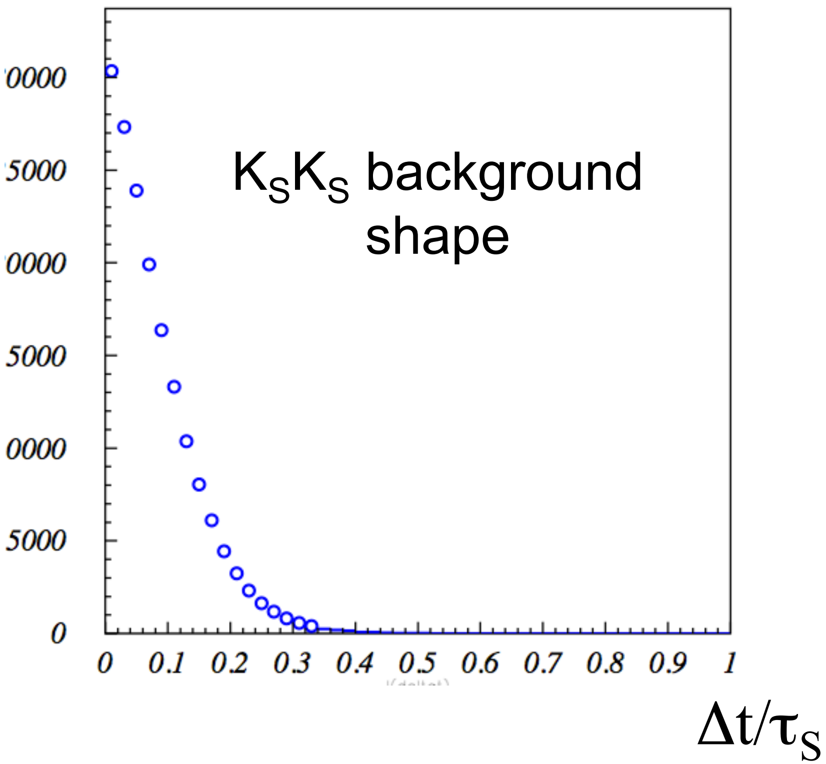
regeneration in KLOE

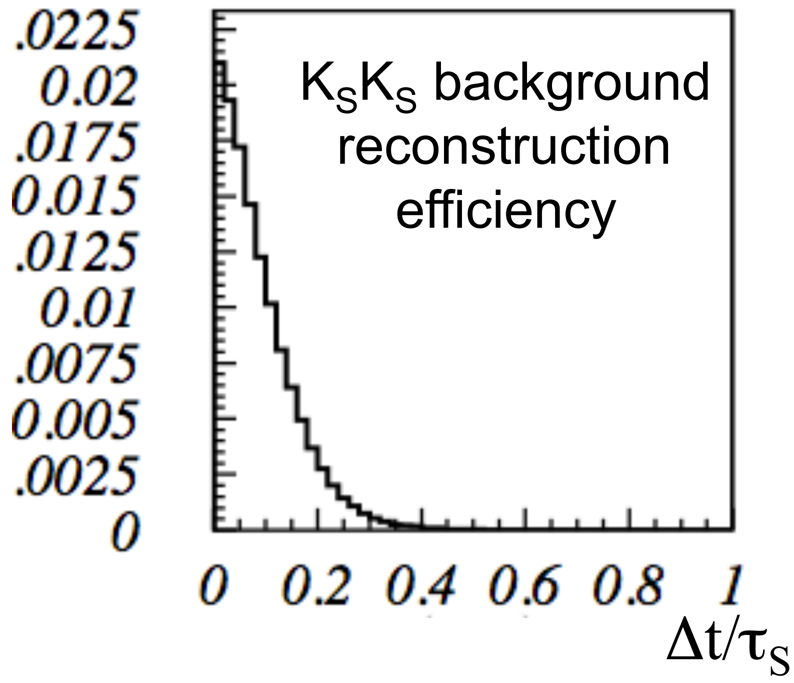




$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: background

- one expects combinatorial background coming from incoherent combination of two K^0's which has a dominant $K_S K_S \rightarrow \pi^+\pi^-\pi^+\pi^-$ contribution
- Requiring both kaons inside the beam pipe from the toy MC simulation we get:





$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: background & trigger

-Reject combinatorial $K_S K_S$ background on the basis of invariant mass spectrum.
-$K_S K_S$ invariant mass resolution is $\sigma\sim$ 3 MeV (for a single kaon is $\sigma\sim$ 4 MeV)
(ϕ width is $\Gamma_\phi\sim$4.3 MeV)

-First very preliminary $\phi\text{->}K_S K_S$, K^+K^- analysis of data recorded on tape (T. Ruf)
→ see next slide

- At the moment most of ϕ decays are recorded "by accident".
From analysis of $\phi\text{->} K^+K^-$ we get $N_\phi \sim 5\text{x}10^8$ ϕ's /fb^{-1} which approximately agrees with the expected trigger "retention" rate: 1/15 x 5kHz/1 MHz ~ 0.3 x 10^{-3} . Special Trigger required.

First look at ϕ-> KK data

$\Phi \rightarrow K_s K_s$

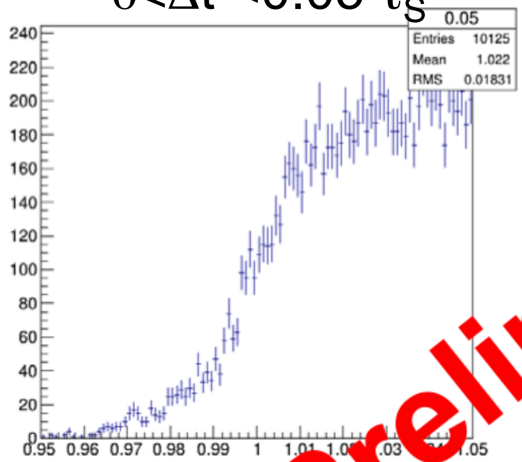
600 files of 2012 ~ 0.15fb^{-1}

long tracks, $r_1, r_2 < 5mm$

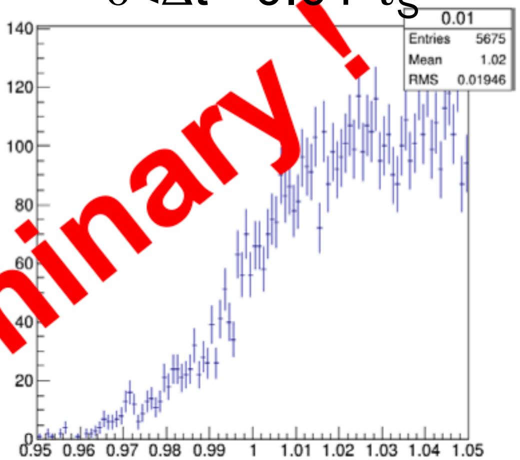
$\Delta t = 0.05\tau_s \quad 0.01\tau_s$

both vertices inside the beam pipe

0<Δt <0.05 τ_S



0<Δt <0.01 τ_S



Minv (GeV)

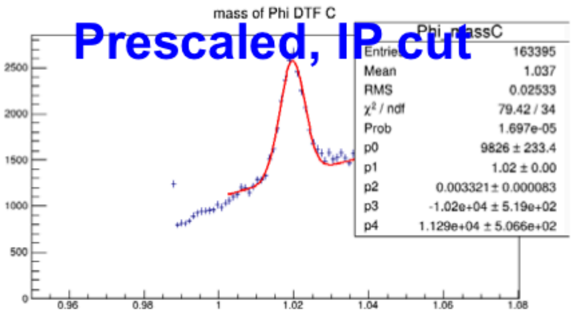
vertices outside the beam pipe

downstream tracks

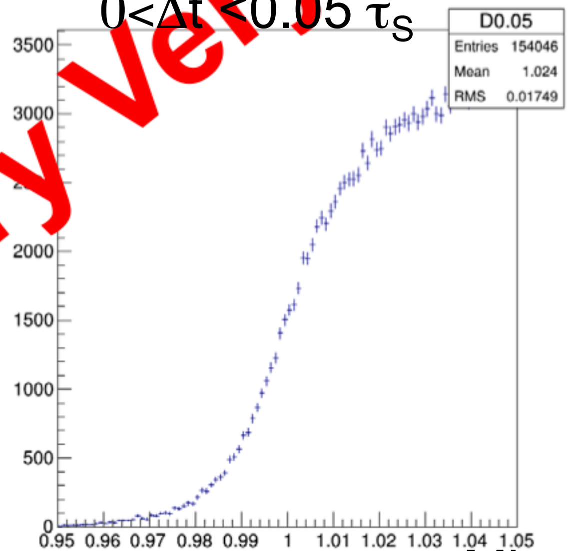
$\Delta t = 0.05\tau_s \quad 0.01\tau_s$

$\Phi \rightarrow K^+ K^-$

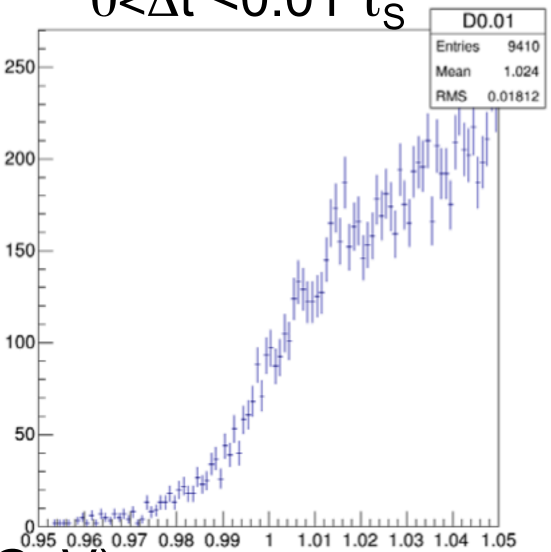
Prescaled, IP cut



0<Δt <0.05 τ_S



0<Δt <0.01 τ_S



Minv (GeV)

Very Very Preliminary !

First look at ϕ-> KK data

$\Phi \rightarrow K_s K_s$

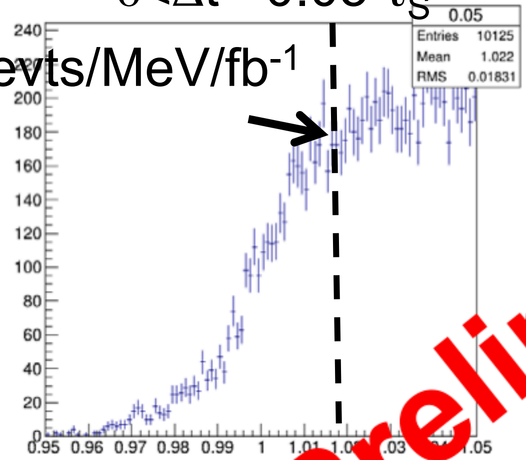
600 files of 2012 ~ 0.15fb^{-1}

long tracks, $r_1, r_2 < 5mm$

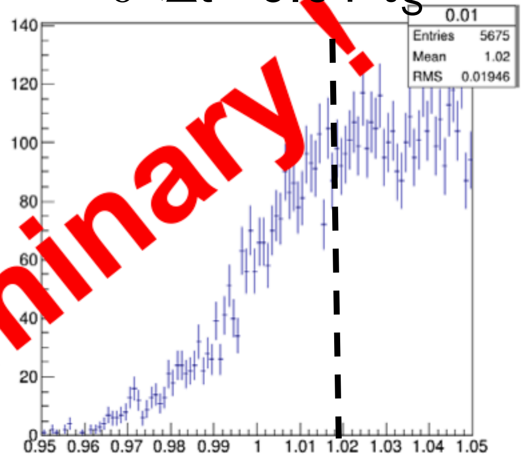
$\Delta t = 0.05\tau_s \quad 0.01\tau_s$

both vertices inside the beam pipe

$0<\Delta t<0.05\ \tau_S$



$0<\Delta t<0.01\ \tau_S$



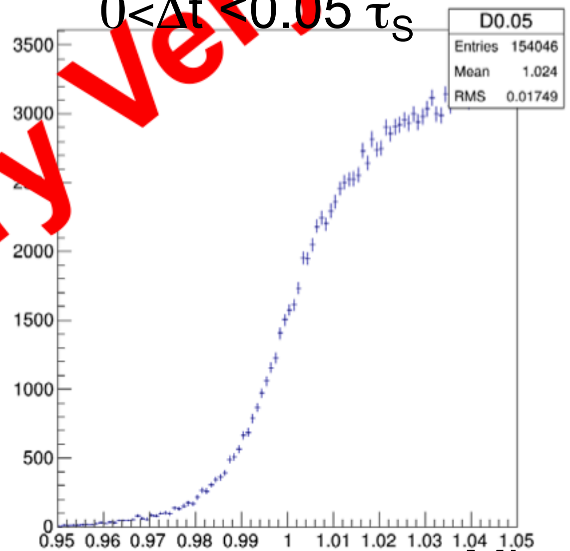
Minv (GeV)

vertices outside the beam pipe

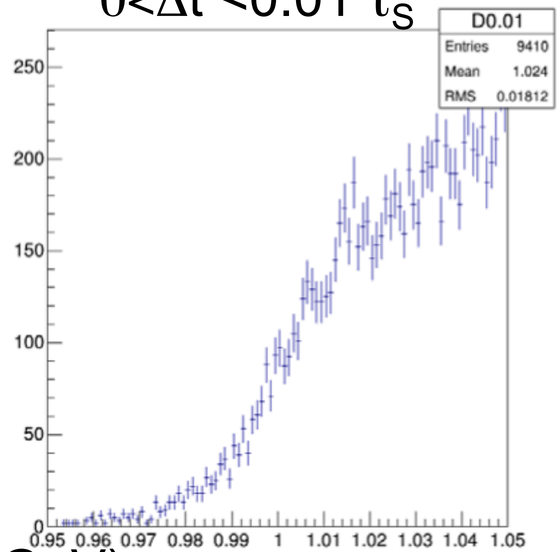
downstream tracks

$\Delta t = 0.05\tau_s \quad 0.01\tau_s$

$0<\Delta t<0.05\ \tau_S$



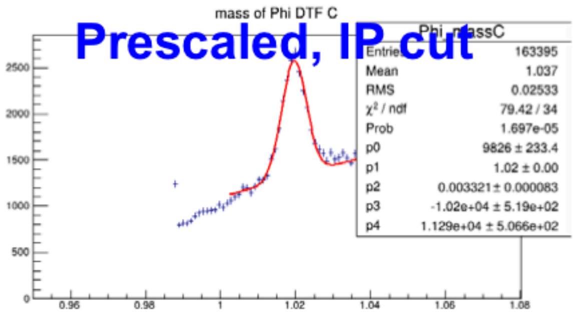
$0<\Delta t<0.01\ \tau_S$



Minv (GeV)

$\Phi \rightarrow K^+ K^-$

Prescaled, IP cut



Very Very Preliminary !

prospects for $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb

- The KLOE-2 experiment is going to start a new data taking campaign at DAFNE which should improve the limits on the QM and/or CPT violation parameters by a factor at least ~4, depending on the collected luminosity [EPJC68(2010)619] (x 2 is expected from the improved Δt resolution due to a new inner tracker).

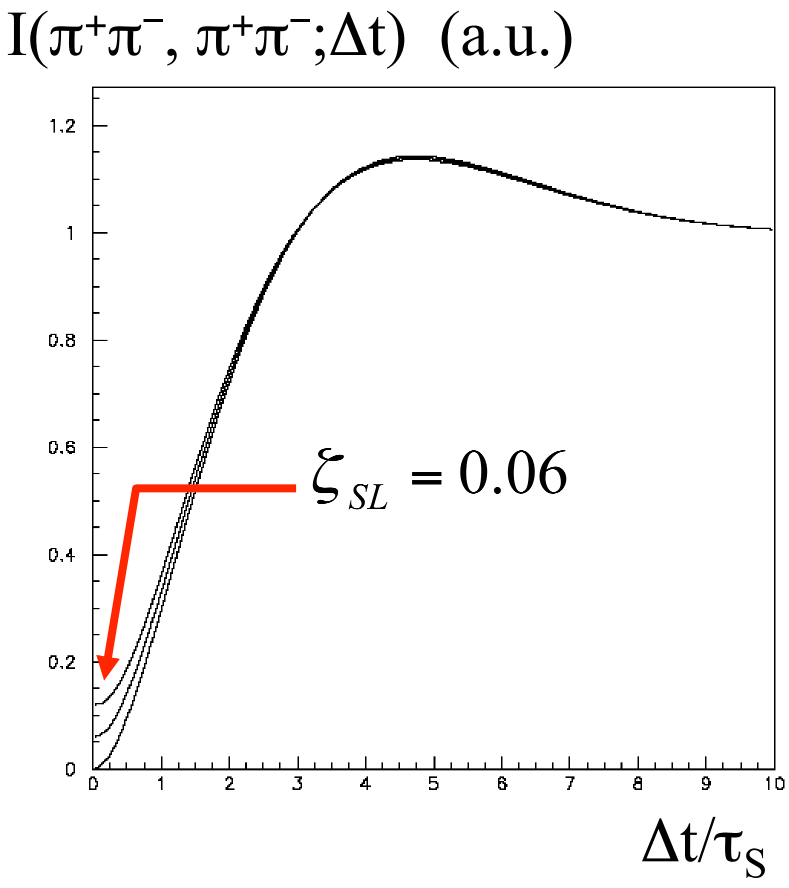
- LHCb might potentially improve these limits.
- The main advantages are:
  copious ϕ production rate
  reconstruction capabilities in the interesting $\Delta t \sim 0$ region
  accurate Δt reconstruction → negligible Δt resolution

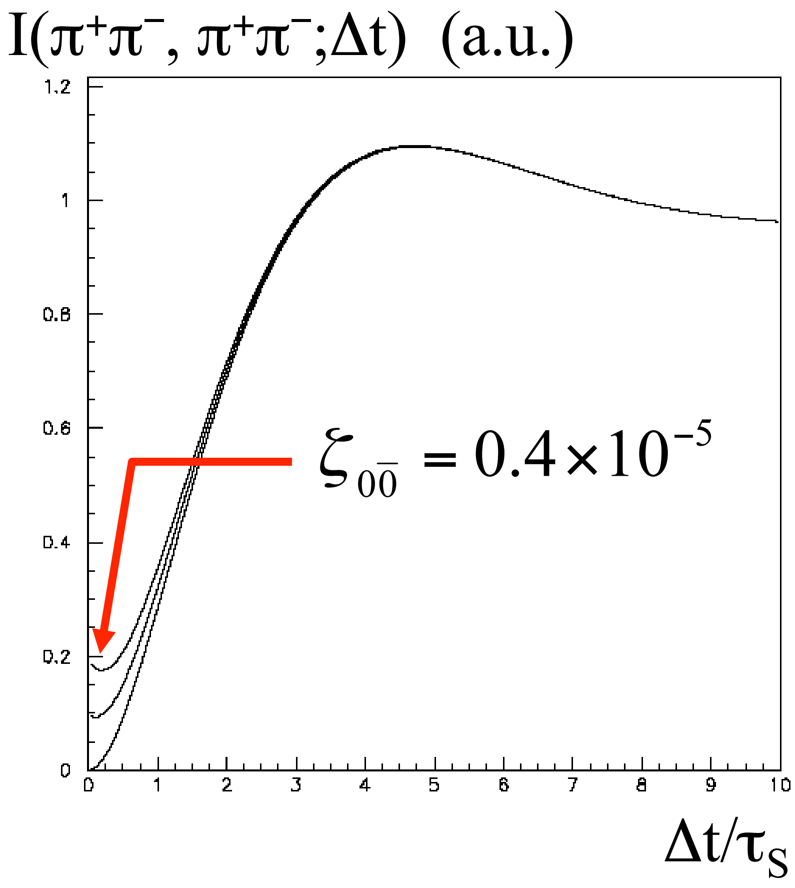
- The main challenging issues at LHCb are:
  background rejection and subtraction
  trigger efficiency

- More studies are required to fight the huge combinatorial background
- It is mandatory to implement a special trigger for $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ events. It should not cost very much in terms of data volume and trigger rate increase.

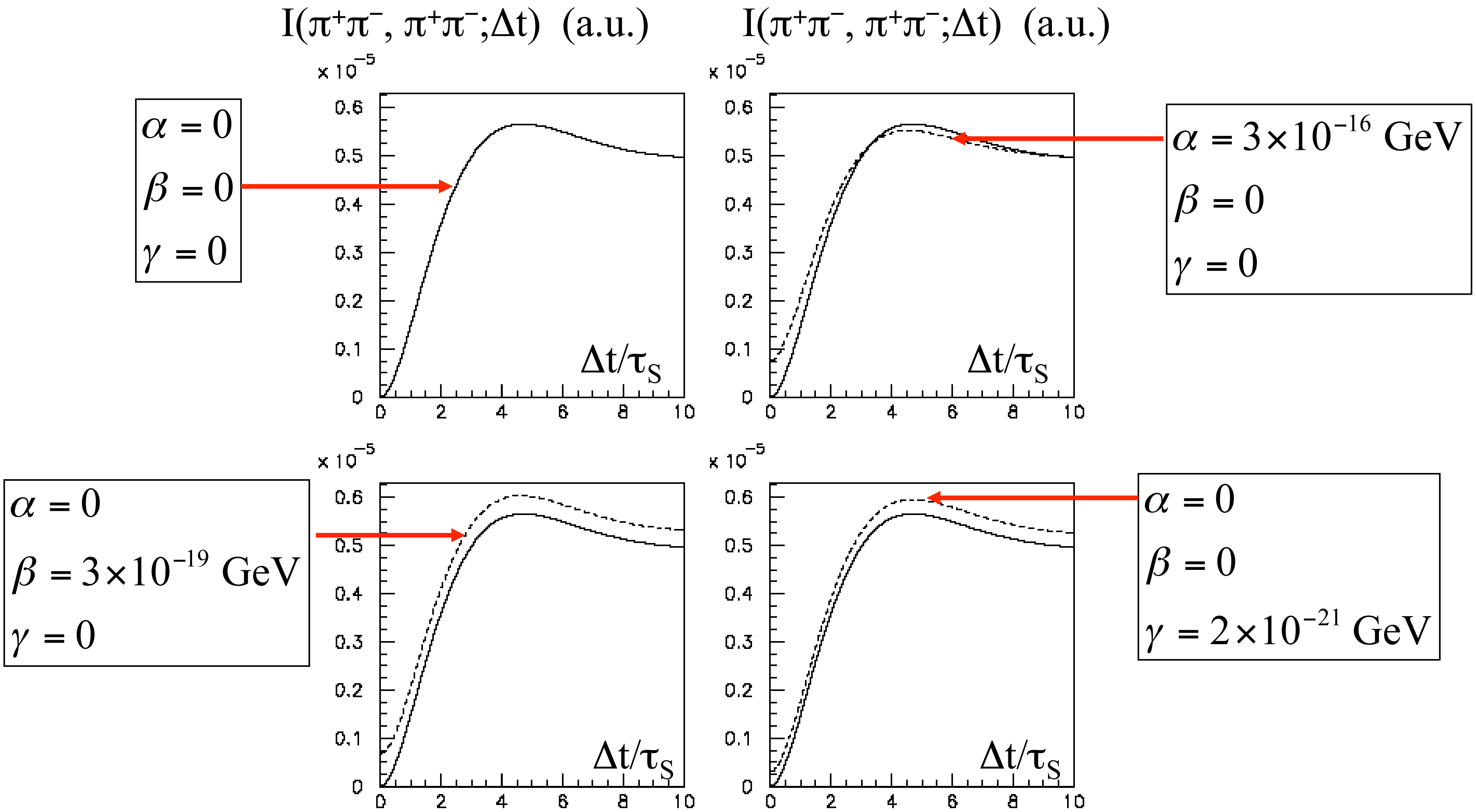
Back up slides

A simple model for decoherence





Decoherence & CPTV induced by quantum gravity



Decoherence & CPTV induced by quantum gravity