T and CPT tests in transitions of neutral kaons

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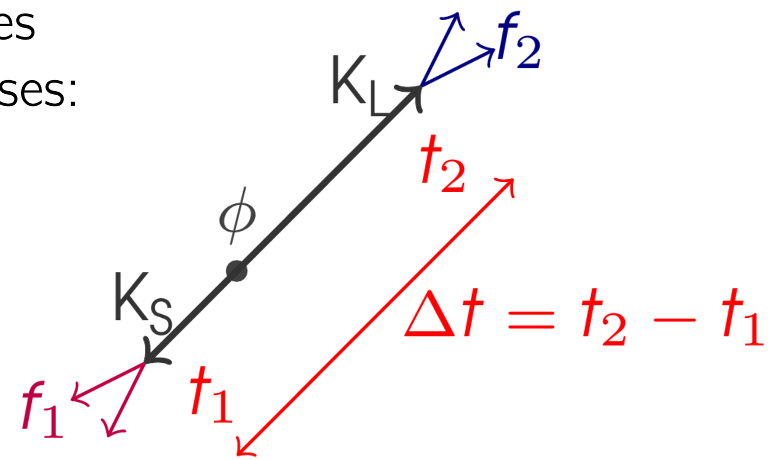
Motivation – Direct T and CPT symmetry tests

A direct test of the T or CPT symmetry requires and comparison of rates of the following processes:

- $\Phi \to K_S K_L \to \pi e \nu, 3\pi^0$
- $\Phi \to K_S K_L \to \pi^+\pi^-, \pi e \nu$



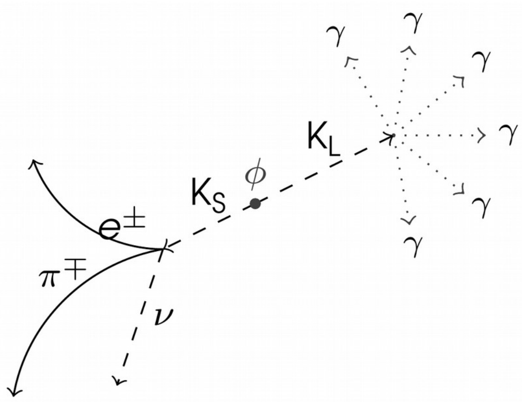
$$R^{exp}_{2,\mathcal{CPT}}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$$R^{exp}_{4,\mathcal{CPT}}(\Delta t) = \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

Focusing on the asymptotic region $\Delta\tau >> \tau_S$

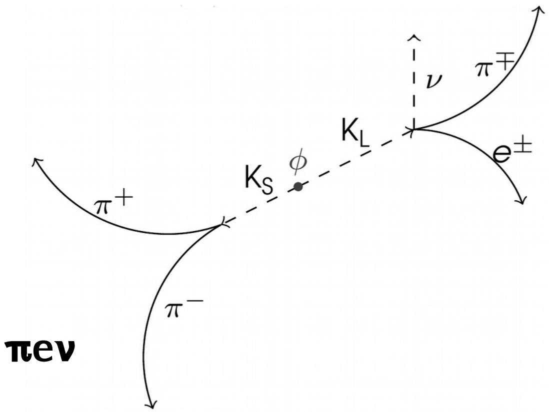
- J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, *Direct test of time-reversal symmetry in the entangled neutral kaon system at a Φ factory*, Nucl. Phys. B 868 (2013) 102
- J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, *Probing CPT in transitions with entangled neutral kaons,* JHEP 1510 (2015) 139

Selection and analysis steps



$K_S K_L \to \pi e \nu\ 3\pi^0$

- **Preselection:**
  - Vtx with 2 tracks close to IP
  - 6 neutral clusters' set
  - Reconstructing $K_L \to 3\pi^0$
- Reconstruction of kaon decay times and Δt
- **Analysis:**
  - basic $K_s \to \pi e \nu$ selection cuts
  - TCA requirement for 2 tracks
  - Time of flight analysis and cuts
  - Cut on R/(T*c) for neutral clusters to reject $K_s \to \pi^0\pi^0$
  - Cut on d_{PCA} vs $\Delta E(\pi,e)$ to reject $K_s \to \pi^+\pi^-$
  - Kinematic fit
  - ANN-based classification of e/π and e/μ EMC clusters and tracks

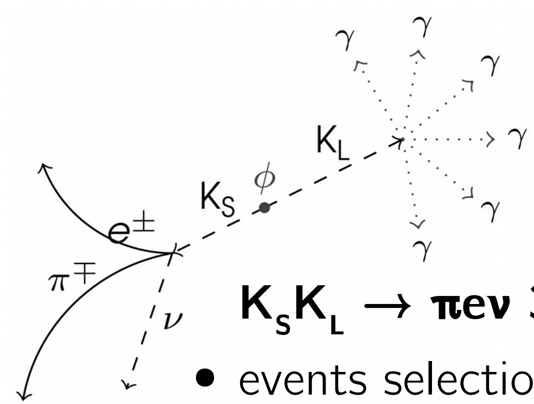


$K_S K_L \to \pi^+\pi^-\ \pi e \nu$

- **Preselection:**
  - vtx with 2 tracks close to IP
  - M(ππ) and |p| cuts for 2 tracks
  - Another vtx with 2 tracks correctly extrapolating to the EMC, with associated clusters and having passing TOF cuts
- Reconstruction of kaon decay times and Δt
- **Analysis:**
  - Missing mass cuts
  - TCA requirement for 2 tracks from K_L decay vertex
  - Time of flight analysis and cuts

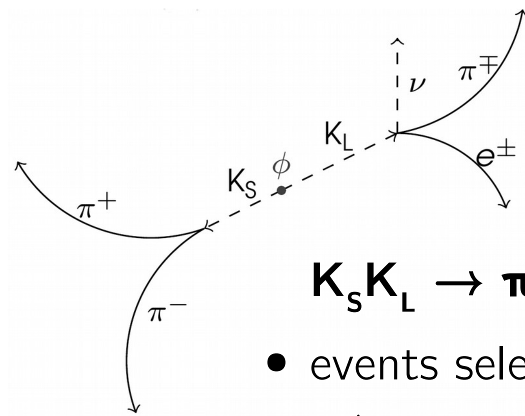
Steps of determination of R^T and R^{CPT}

Best obtained results of event subsample selection:



$K_SK_L \rightarrow \pi e \nu\ 3\pi^0$

- events selection efficiency ~11%
- S/B = 33.5



$K_SK_L \rightarrow \pi$+π- $\pi e \nu$

- events selection efficiency ~14 %
- S/B = 64

Further analysis steps:

- Division of each class of processes into 2 subsamples by lepton charge
- Selection efficiency estimation with control samples selected from data

$K_SK_L \rightarrow \pi e^\pm \nu\ 3\pi^0$

→ **$K_S \rightarrow \pi e \nu$ K_L(EMC)**

→ **$K_SK_L \rightarrow \pi^+\pi^-\ 3\pi^0$**

$K_SK_L \rightarrow \pi^+\pi^-\ \pi e^\pm \nu$

→ **$K_S \rightarrow \pi$+π- K_L(EMC)**

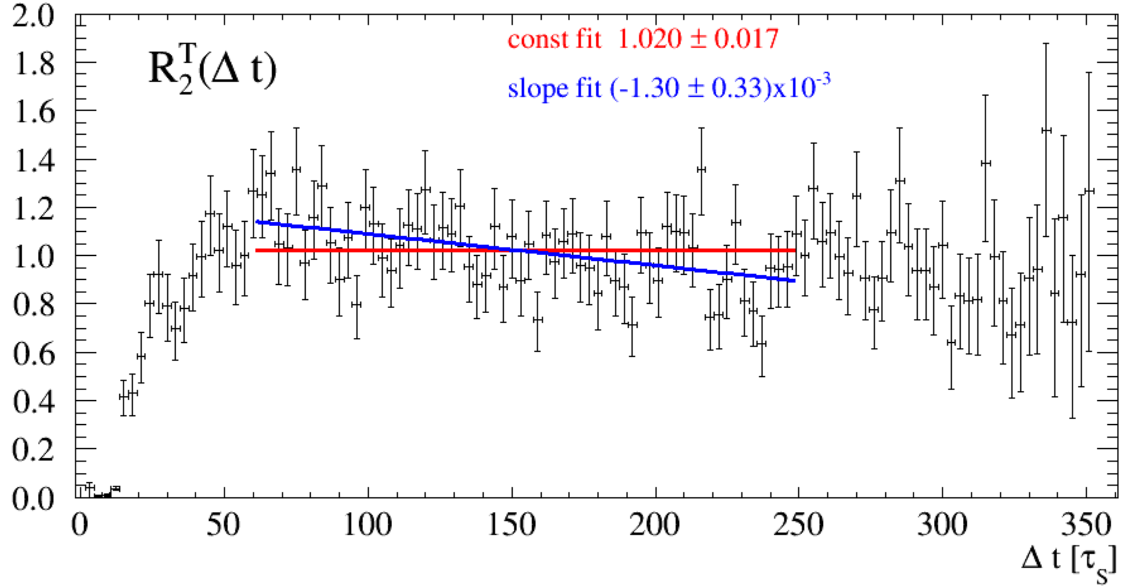
→ **$K_SK_L \rightarrow \pi^0\pi^0\ \pi e \nu$**

- Calculation of the single and double T and CPT asymmetric ratios
- Fit of a constant level to the $\Delta t >> \tau_S$ region of the ratios with a dedicated ML fit

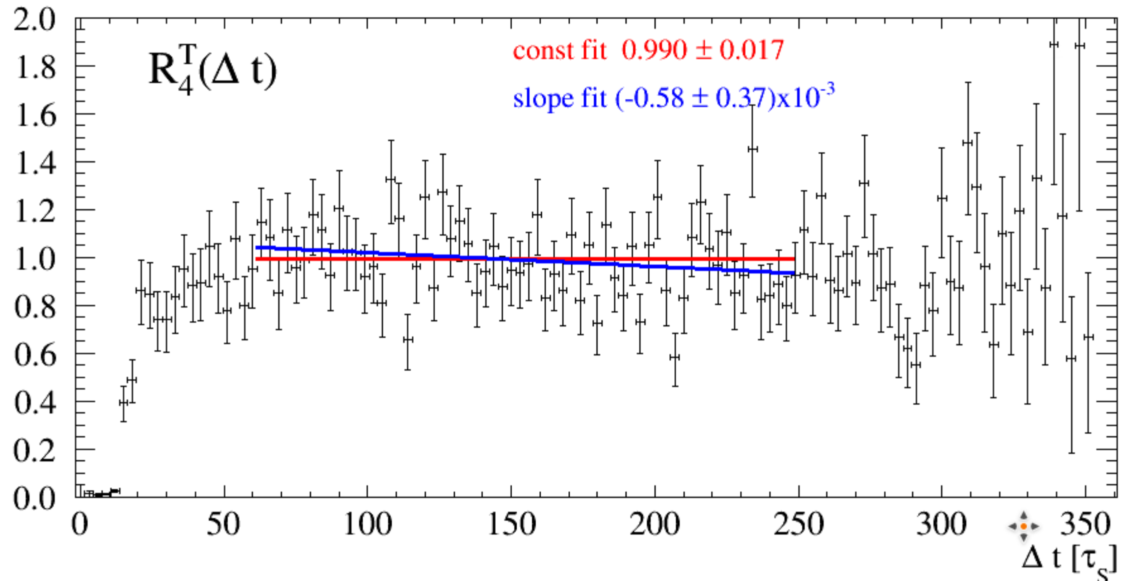
T asymmetric ratios

With efficiencies from data control samples
except for the d_{PCA} vs $\Delta E(\pi,e)$ cut where MC-based efficiency correction is used

$$R_2^T = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



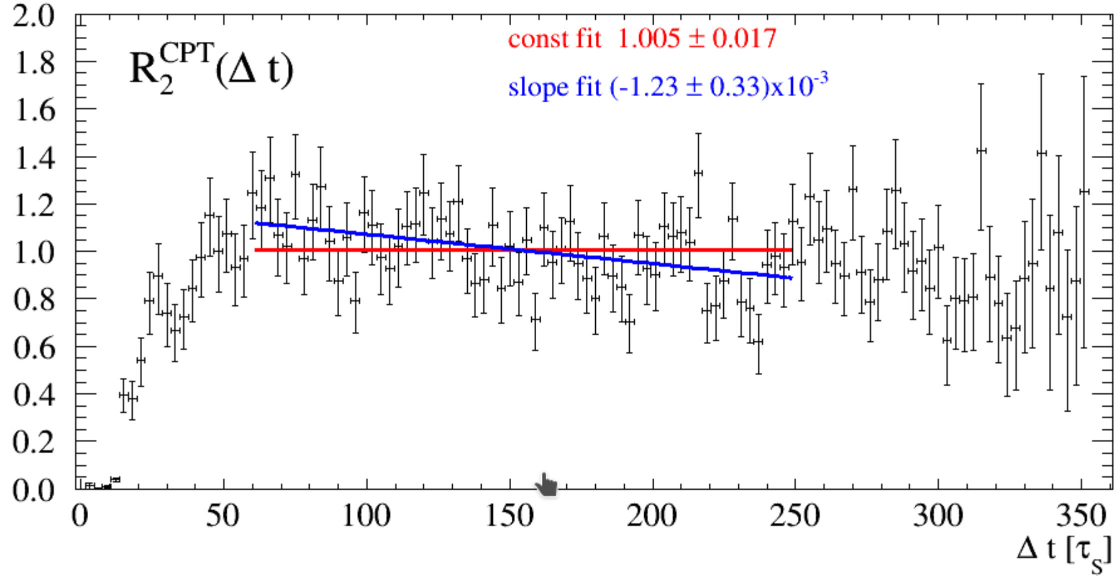
$$R_4^T = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



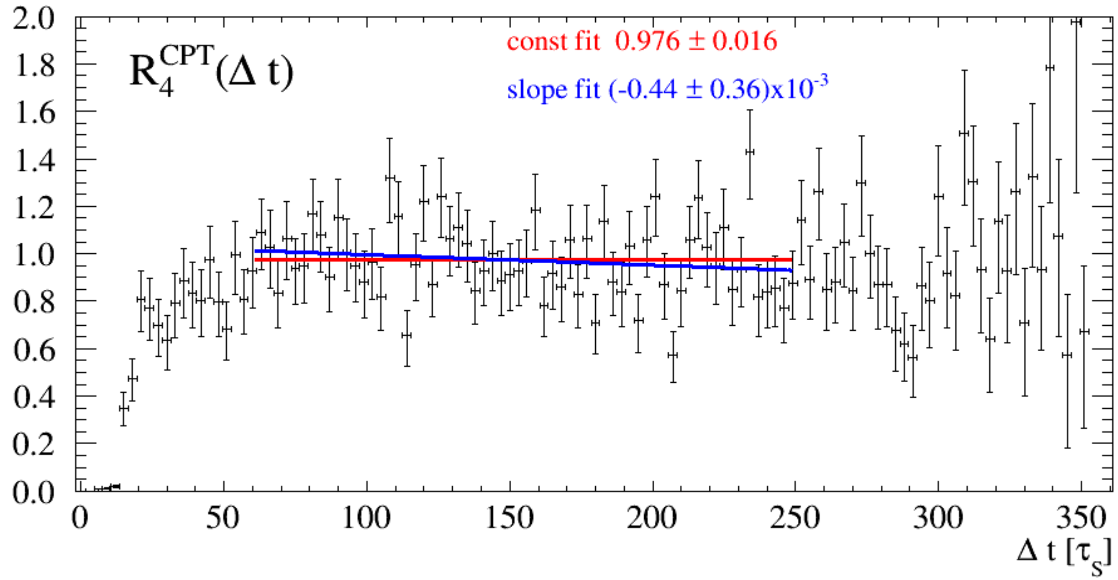
CPT asymmetric ratios

With efficiencies from data control samples
except for the d_{PCA} vs $\Delta E(\pi,e)$ cut where MC-based efficiency correction is used

$$R_2^{CPT} = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$

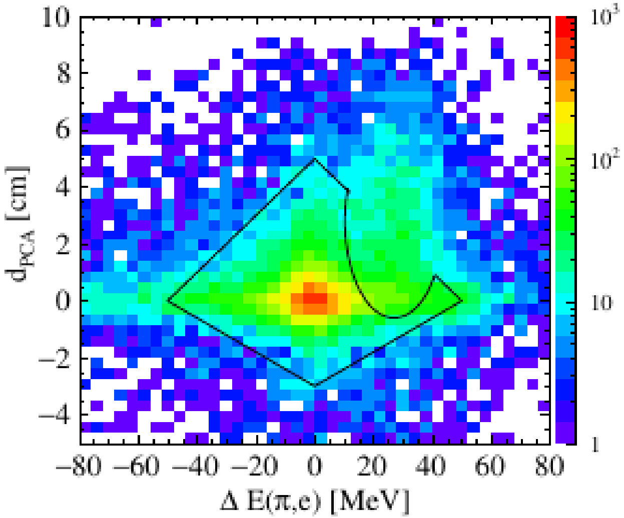


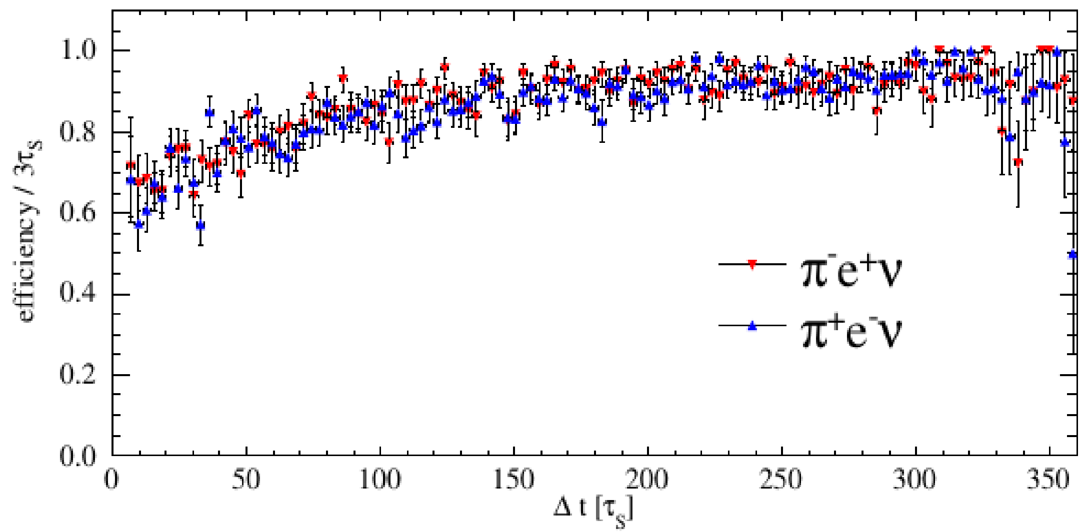
$$R_4^{CPT} = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



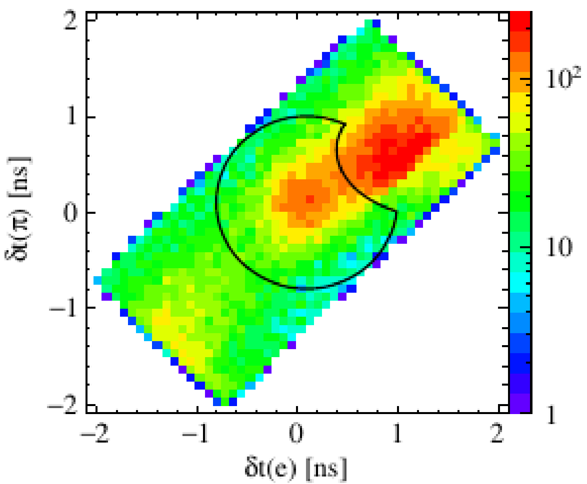
Open issues in the analysis

- One cut (2D on the dPCA vs ΔE(π,e) values) has an efficiency which cannot be reproduced by the presently used control samples and requires MC-based input to analysis efficiency

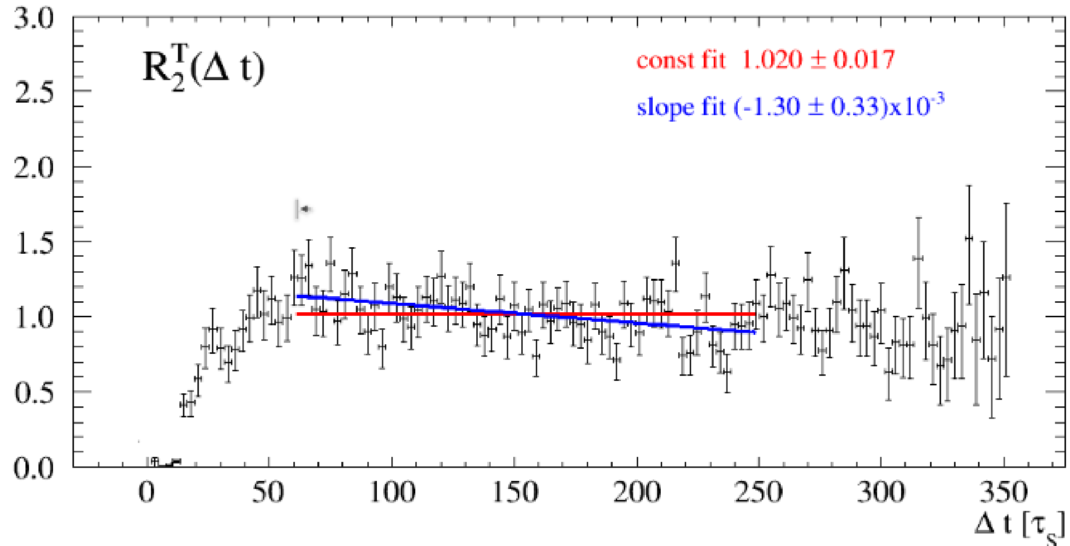




- The above cut as well as the last of TOF cuts have a large systematic effect on the result of the analysis



- There is an apparent slope in the R2(Δt) and R4(Δt) distributions



Tested attempts to replace the "problematic" cuts

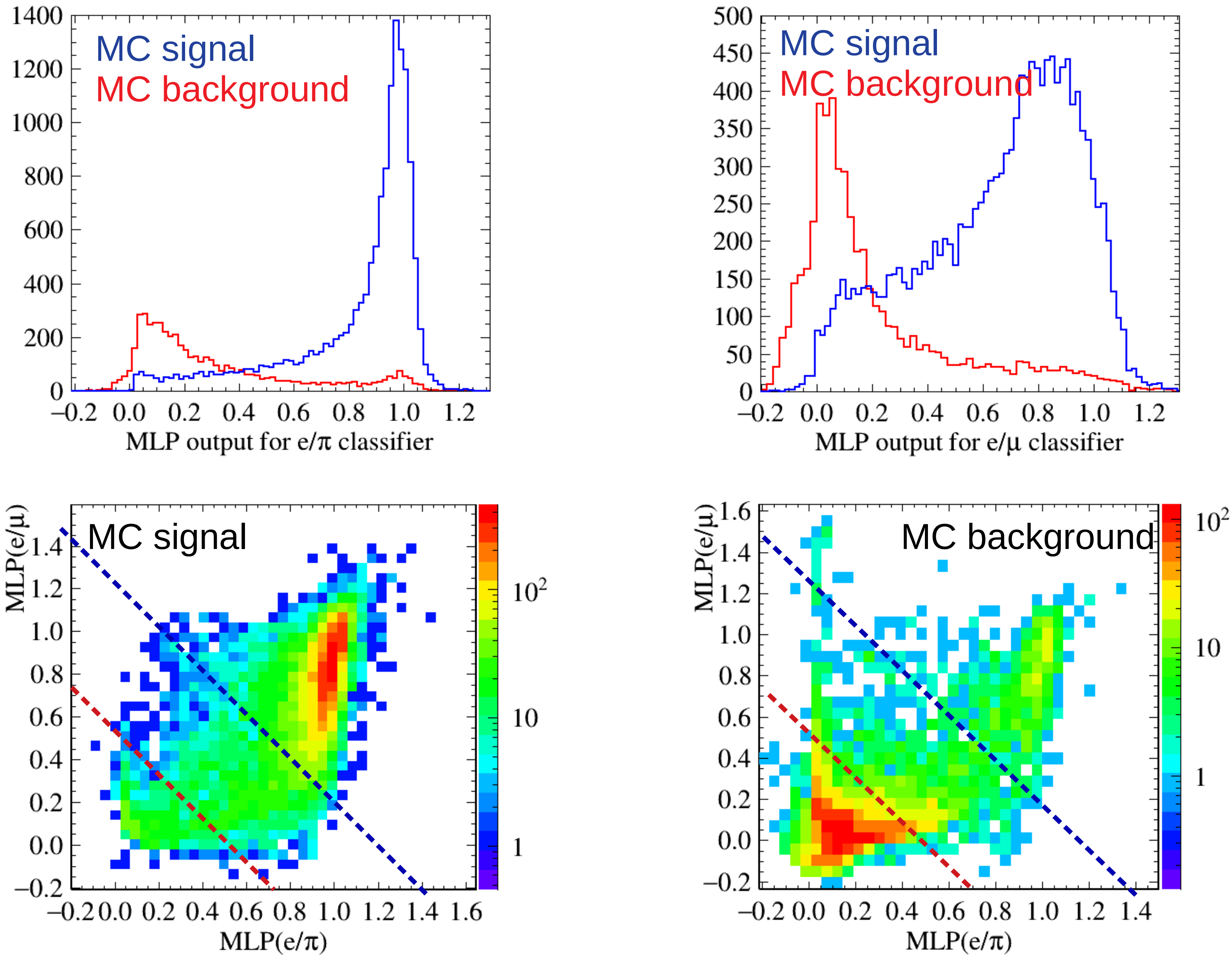
Reference: (S/B after the present event selection is 33.5)

- **Stronger cut on the outputs of e/π and e/μ particle classifiers**
  - **achieved S/B = 16 without the dPCA vs ΔE(π,e) cut with the same total efficiency**
- Cutting on the kinematic variables M^2_{miss}, $M^2(e)$ calculated so that their resolution does not depend on the K_L decay point
  - Poor resolution, no significant S/B improvement obtained after possible cuts
- Studying the spatial location of EMC clusters associated to tracks identified as e and π in the signal ($K_S \to \pi e \nu$) and background ($K_S \to \pi^+\pi^-$, $K_S \to \pi^+\pi^- \to \pi\mu\nu$)
  - No strong difference between signal and background
- **Restricting the reconstructed K_S decay vertex location to a smaller volume around the IP**
  - **S/B = 28 without the dPCA vs ΔE(π,e) cut**
  - **96% of the old analysis efficiency**

Removing the d_{PCA} vs. $\Delta E(\pi,e)$ cut
in favour of stricter cuts on:

- results of e/π and e/μ particle classification
- reconstructed K_S decay vertex location

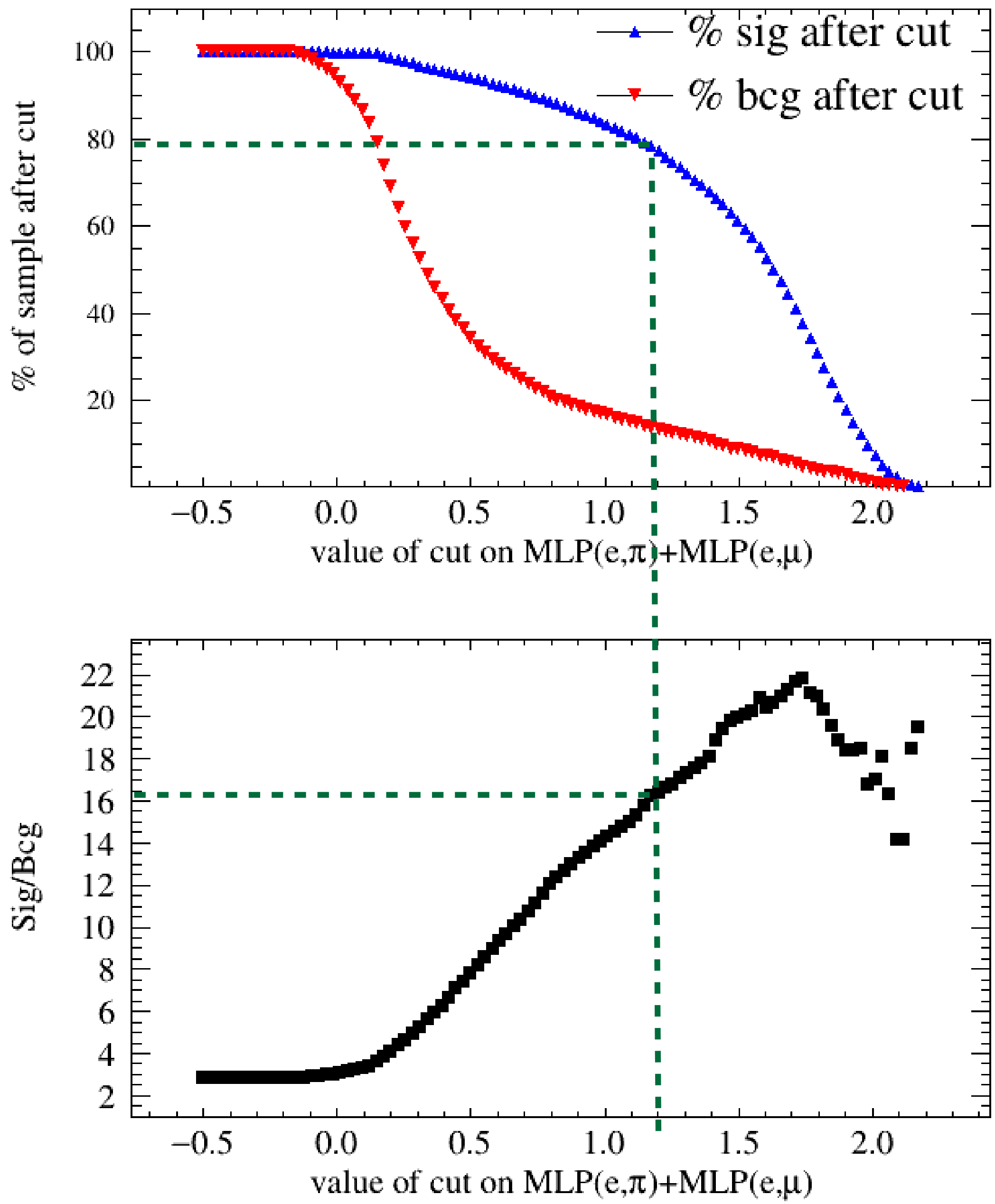
Reminder: e/π and e/μ classifiers



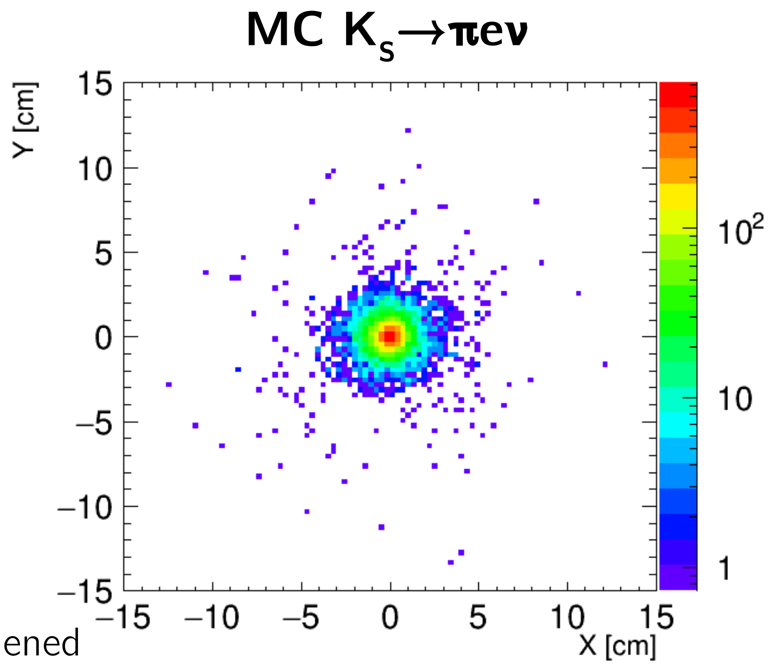
Strengthening the cut on MLP(e,π) + MLP(e,μ)

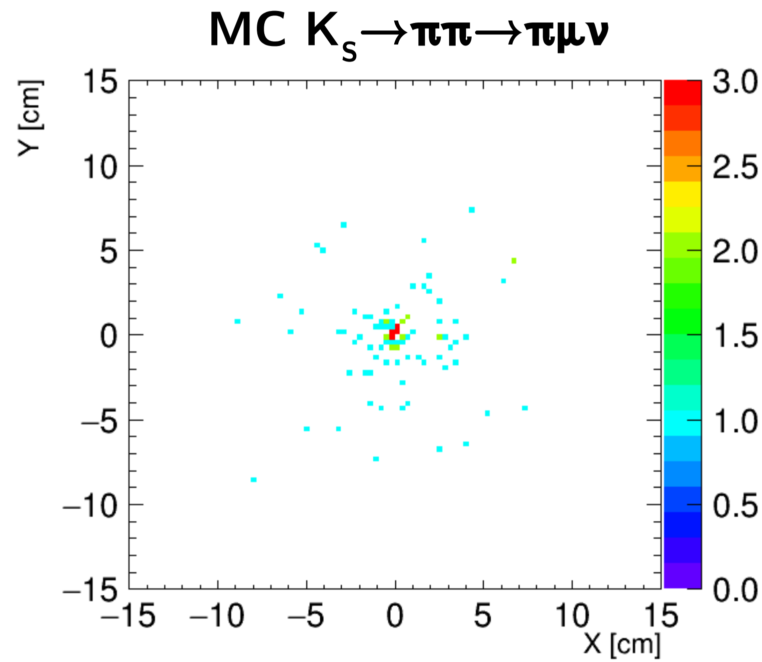
Performance of the particle classification cuts tested on a MC sample with the d_{PCA} vs $\Delta E(\pi,e)$ cut excluded from event selection.

Retaining the same total efficiency of the old analysis scheme while strengtening the particle classification cut allows for:
S/B = 16
(previously 33.5 with the d_{PCA} vs $\Delta E(\pi,e)$ cut)

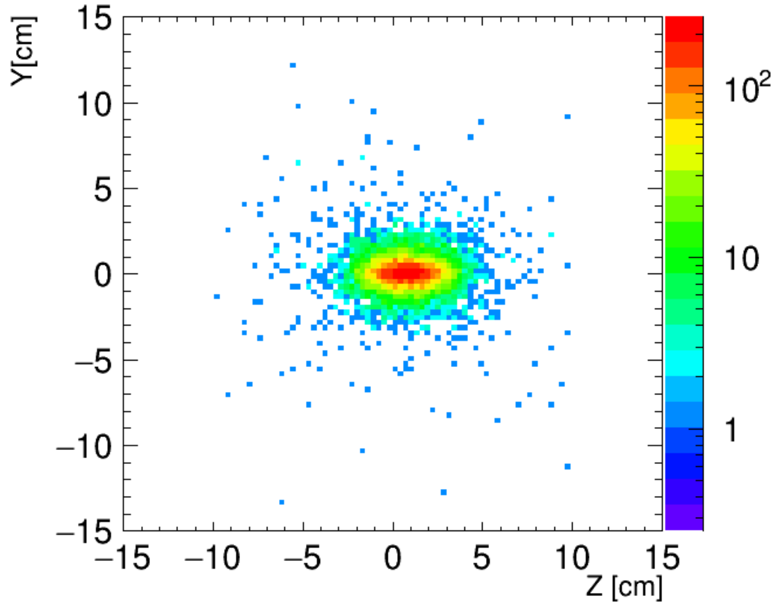


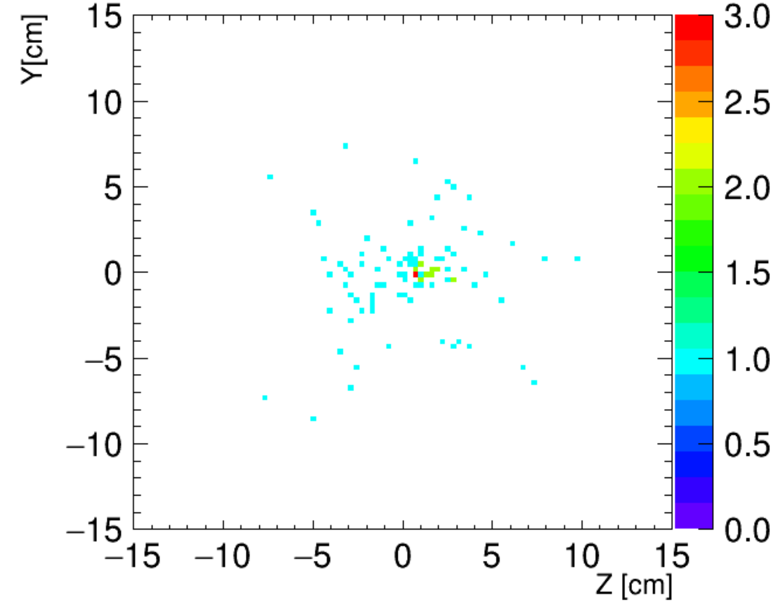
$K_S \to \pi e \nu$ and $K_S \to \pi \mu$ reconstructed vertices location





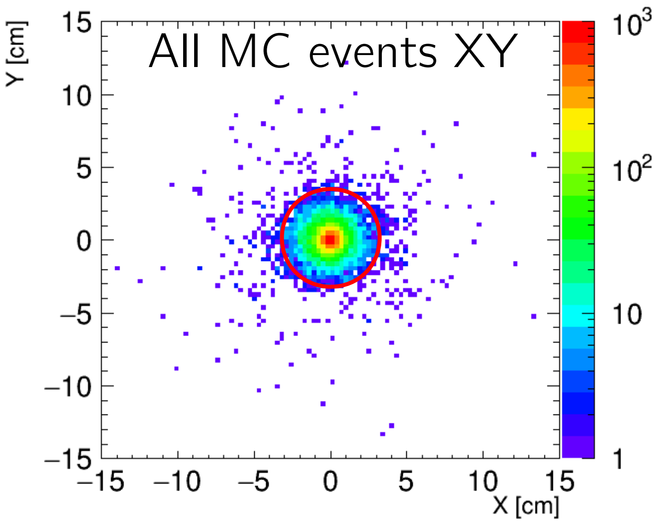
After all cuts except d_{PCA} vs ΔE, including the strengthened cut on particle classifiers' output

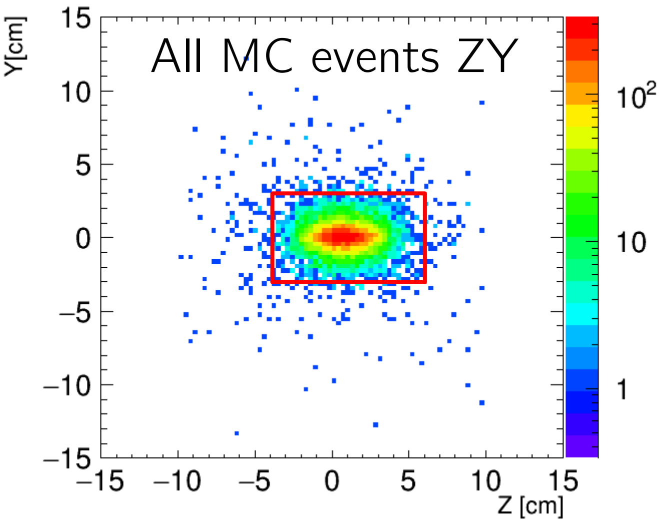




Adding a cut on Ks vertex position

- For the event sample after all steps of the present selection of $K_S K_L \to \pi e \nu\ 3\pi^0$
  - except the cut on d_{PCA} vs $\Delta E(\pi,e)$
  - with the cut on particle classifiers' outputs strengthened as shown in the previous slides
  - **With a tighter cut on the K_S vertex location around the center of distributions for MC signal: $R_T < 3$ cm and $|Z - 0.8\ \text{cm}| < 4.5$ cm**





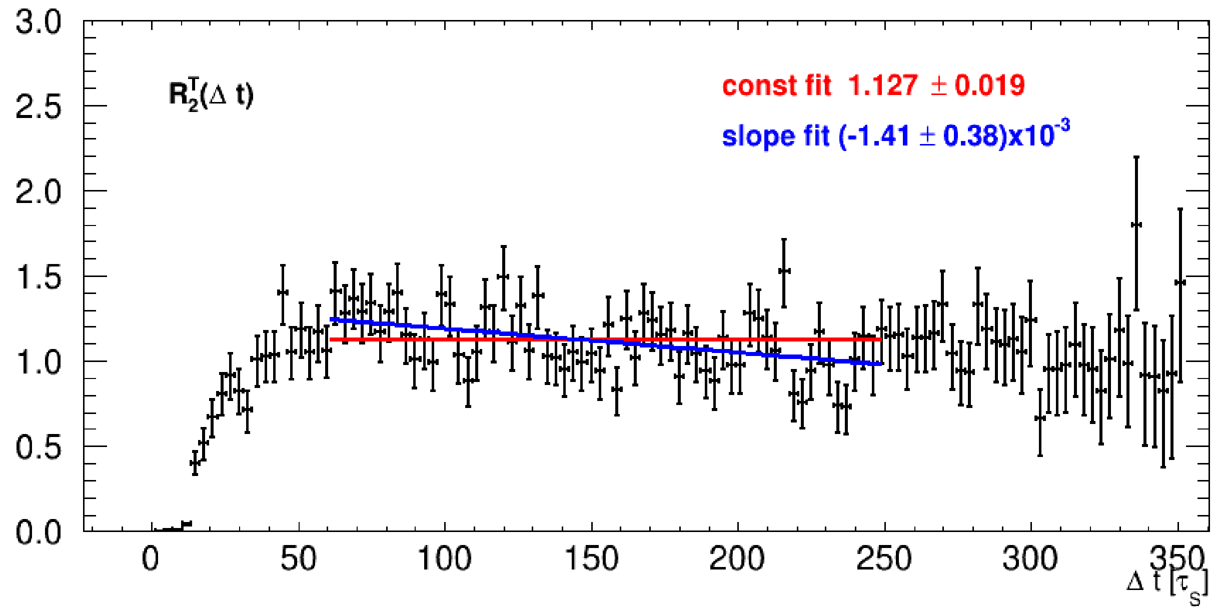
- The achieved event selection performance on MC is:
  - S/B = 28 (previously 33.5 with the d_{PCA} vs $\Delta E(\pi,e)$ cut)
  - Efficiency for signal reduced by 96% w.r.t. selection with the d_{PCA} vs $\Delta E(\pi,e)$ cut

R_2 and R_4 ratios for T and CPT
after removal of the d_{PCA} vs. $\Delta E(\pi,e)$ selection cut
(and the corresponding MC contribution
to estimated selection efficiencies)

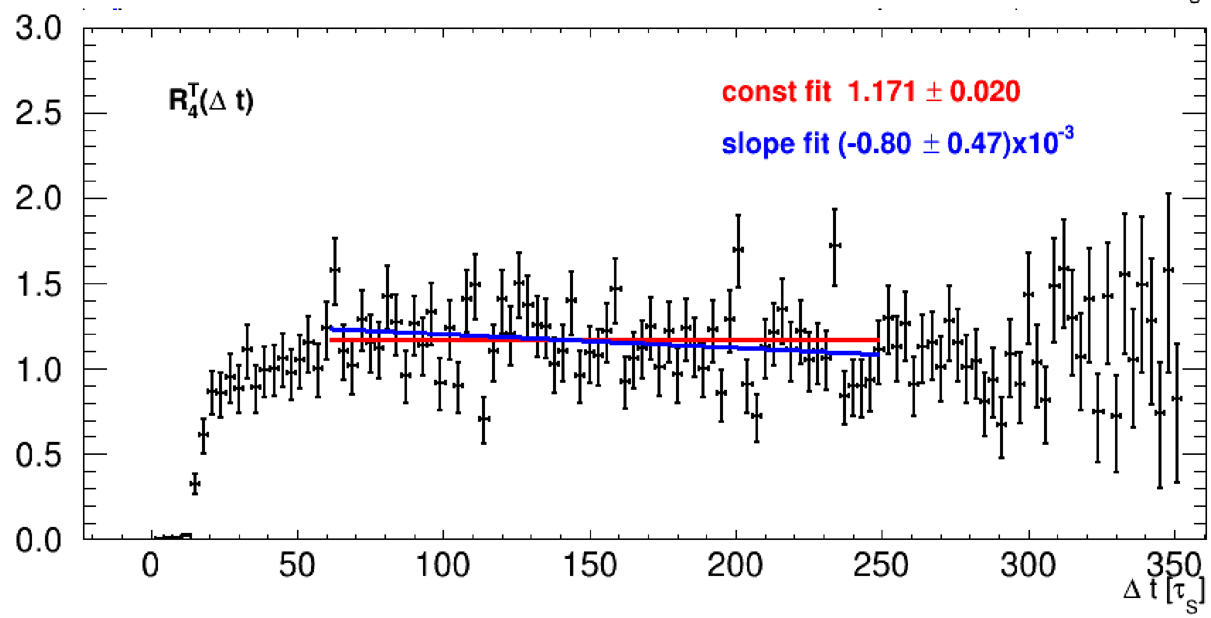
T asymmetric ratios - new

With efficiencies **only from data control samples**

$$R_2^T = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



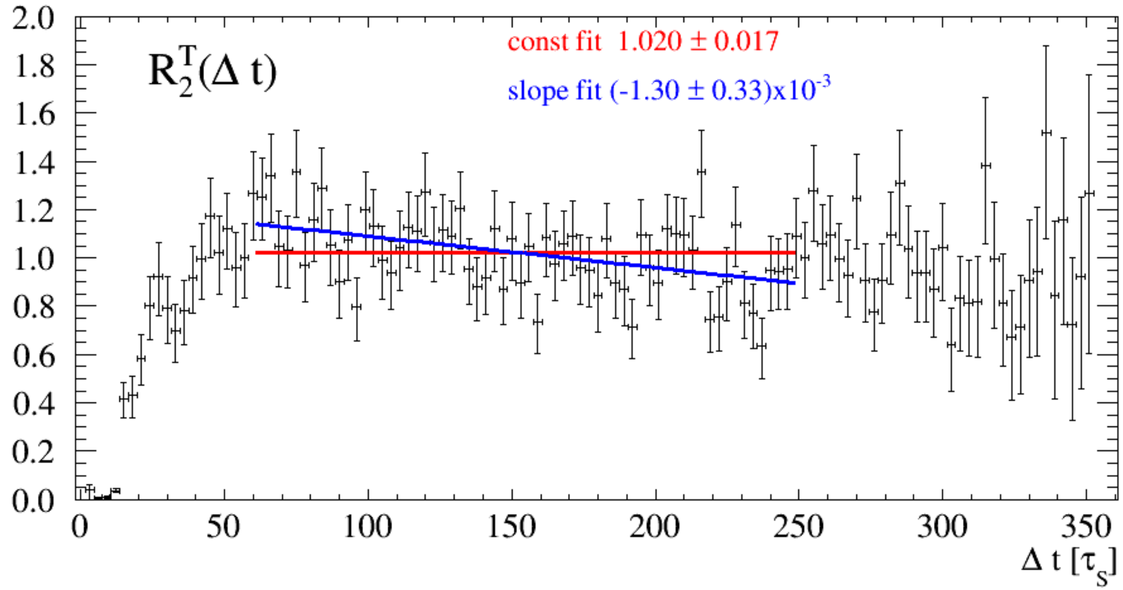
$$R_4^T = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



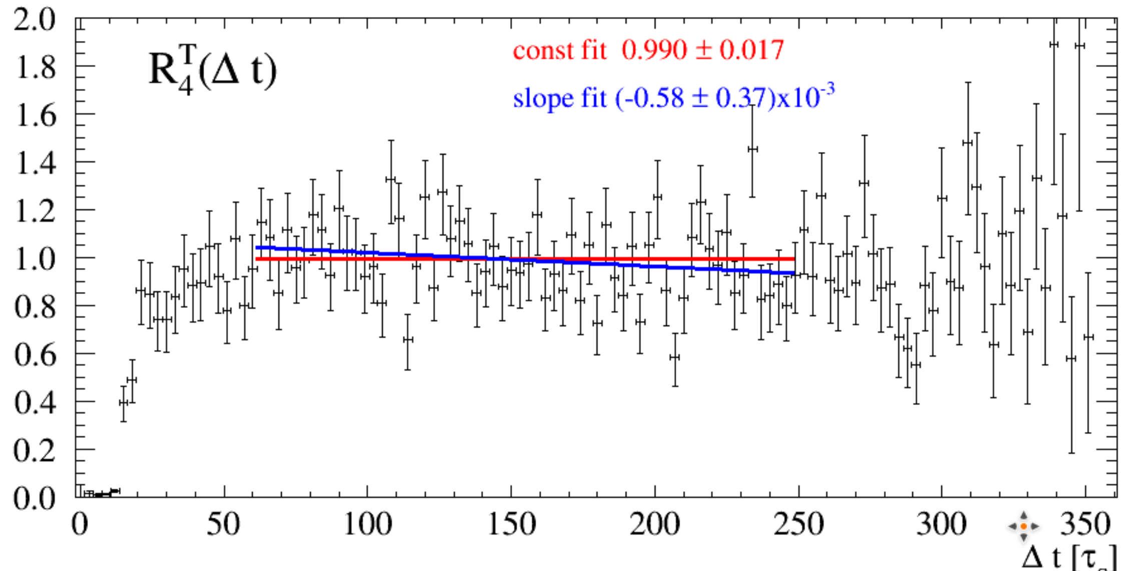
For reference: T ratios before

With efficiencies from data control samples
except for the d_{PCA} vs $\Delta E(\pi,e)$ cut where MC-based efficiency correction is used

$$R_2^T = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



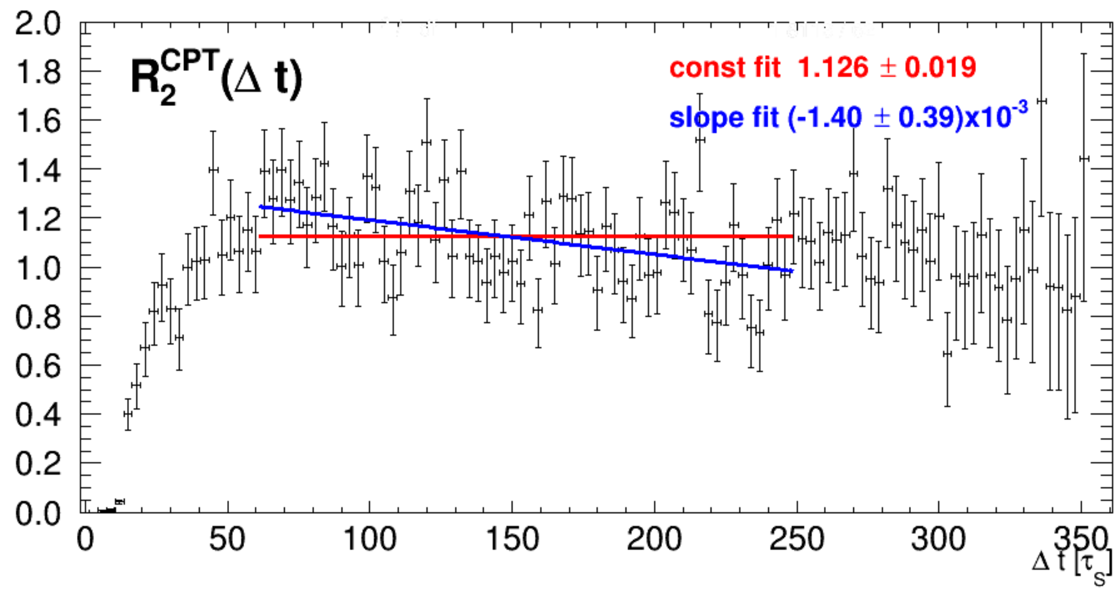
$$R_4^T = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



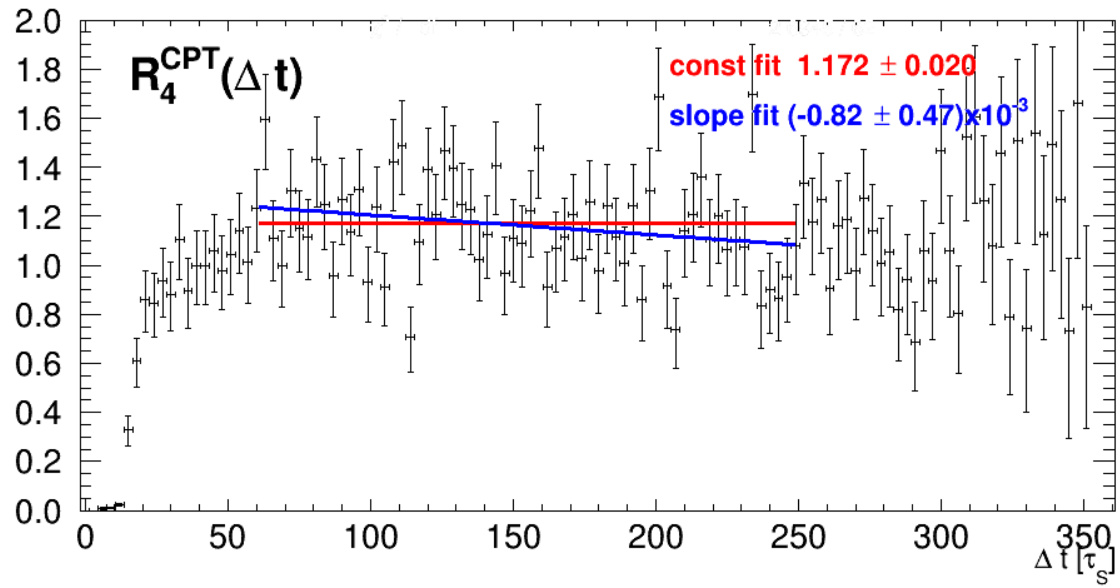
CPT asymmetric ratios

With efficiencies **only from data control samples**

$$R_2^{CPT} = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



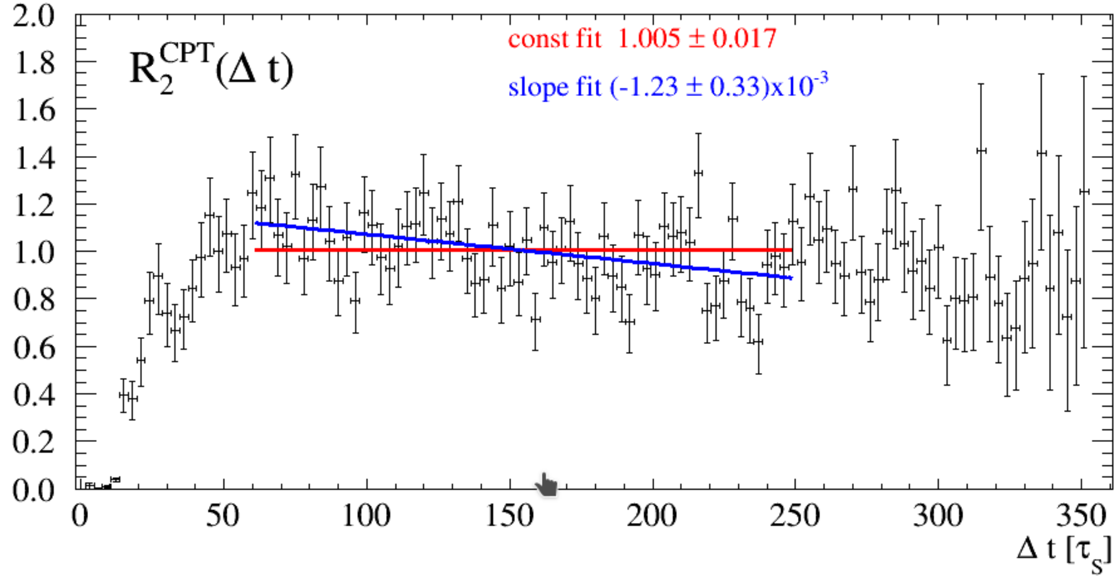
$$R_4^{CPT} = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



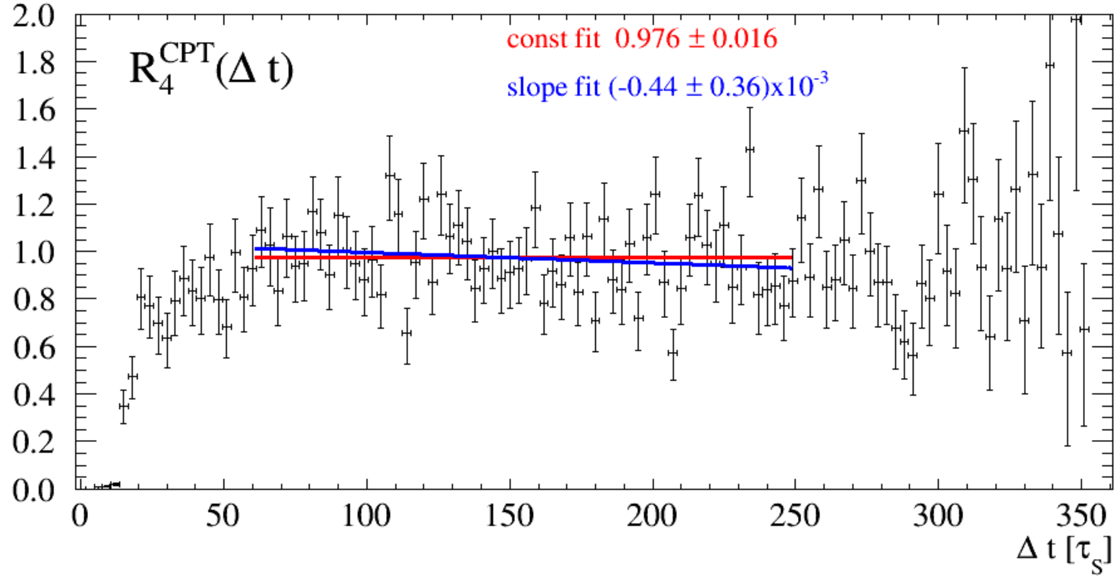
For reference: CPT ratios before

With efficiencies from data control samples
except for the d_{PCA} vs $\Delta E(\pi, e)$ cut where MC-based efficiency correction is used

$$R_2^{CPT} = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$

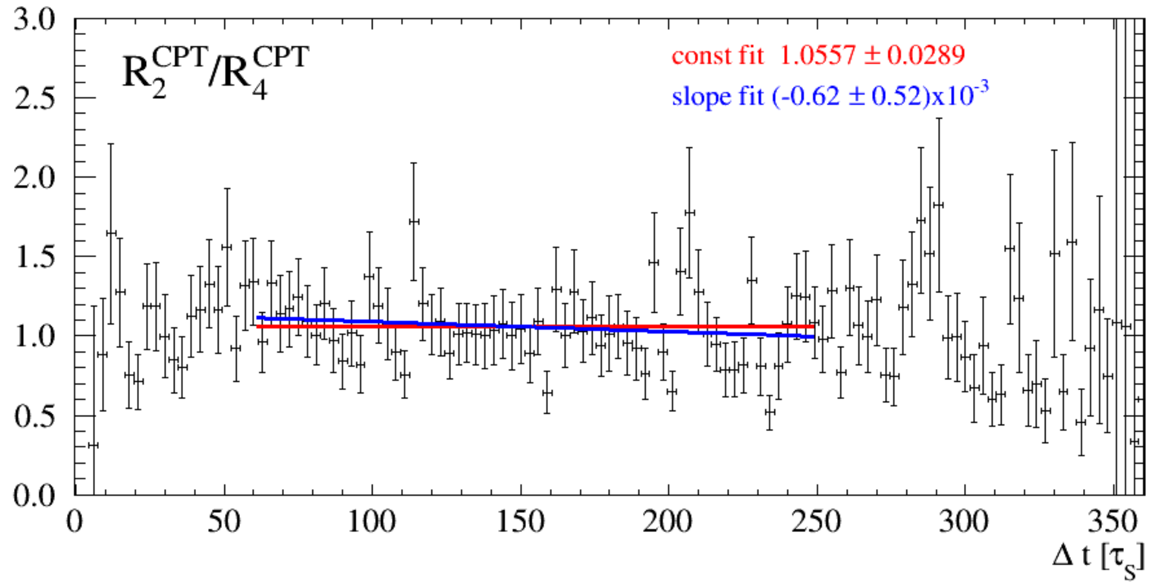


$$R_4^{CPT} = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$

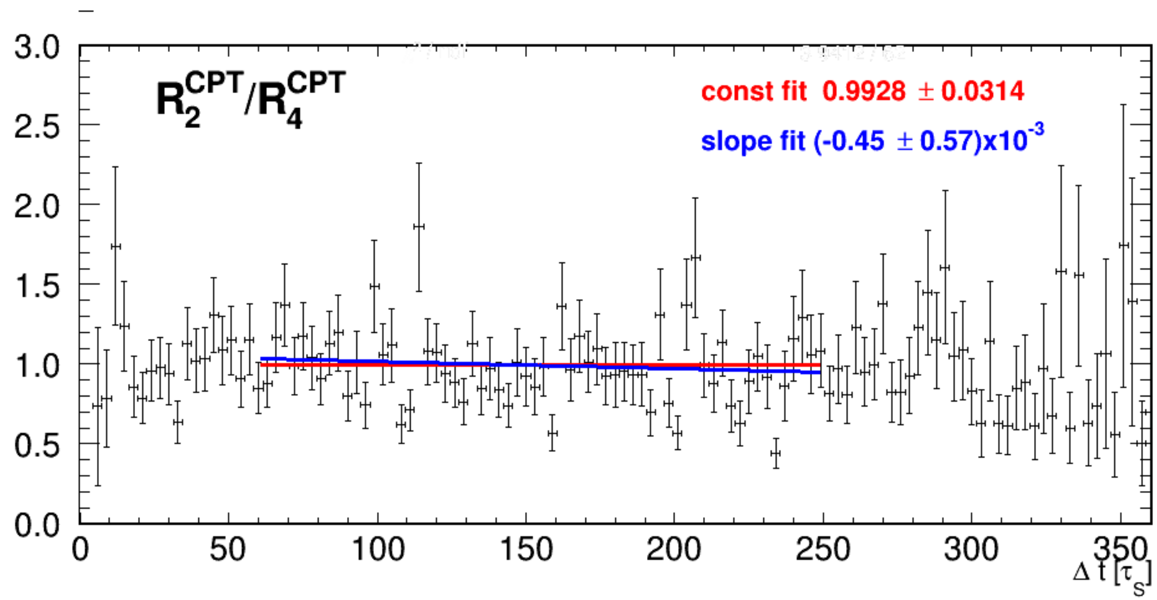


CPT double ratio

With efficiencies from data control samples except for the d_{PCA} vs $\Delta E(\pi,e)$ cut where MC-based efficiency correction is used



With efficiencies **only from data control samples**



Plans

- Prepare a thorough check of event selection performance in all of the control samples to ensure that each step of event selection works equally in the main and control samples
  - test efficiencies of each selection step using MC for both main and control samples
  - compare total efficiencies obtained from control samples selected from data and MC
- Search for other possible sources of the offset and slope in the T and CPT asymmetric ratios
- Perform a detailed evaluation of the systematic effects in the analysis
  - The systematics study included in the PhD thesis was not detailed enough
  - Recent changes to the event selection must be accounted for

Thank you

for your attention!

Backup Slides

Rejection the of remaining $K_S \rightarrow \pi^+\pi^-$ ($\rightarrow \pi\mu\nu$) background

Remaining $K_S \to \pi^+\pi^-$ ($\to \pi\mu\nu$) background

MC Composition of the selected $K_S K_L \to \pi^+\pi^-$ $\pi e\nu$ event sample:

90% - $K_S \to \pi e\nu$ and $K_L \to 3\pi^0$ (signal)

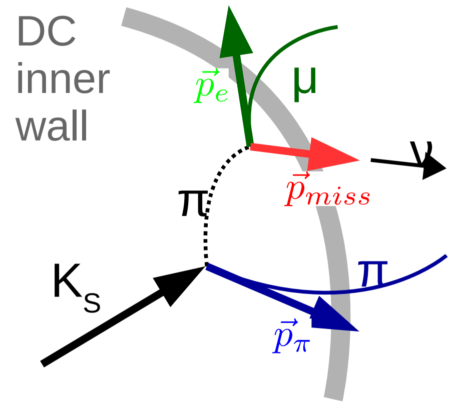
2.9% - $K_S \to \pi^+\pi^-$ and $K_L \to 3\pi^0$

2.4% - $K_S \to \pi^+\pi^- \to \pi\mu\nu$ and $K_L \to 3\pi^0$

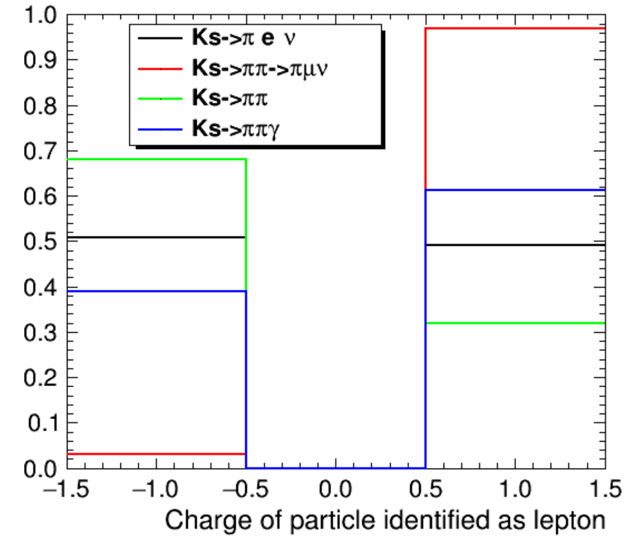
1.6% - $K_S \to \pi^+\pi^-\gamma$ and $K_L \to 3\pi^0$

1.6% - other background components

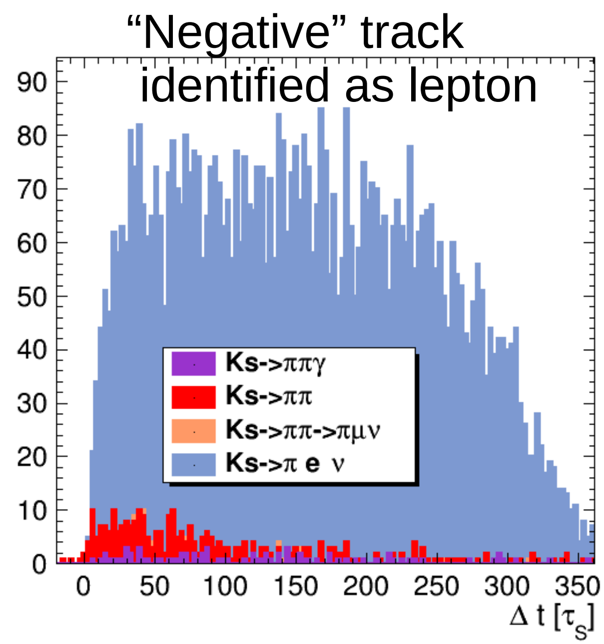
S/B = 11.5

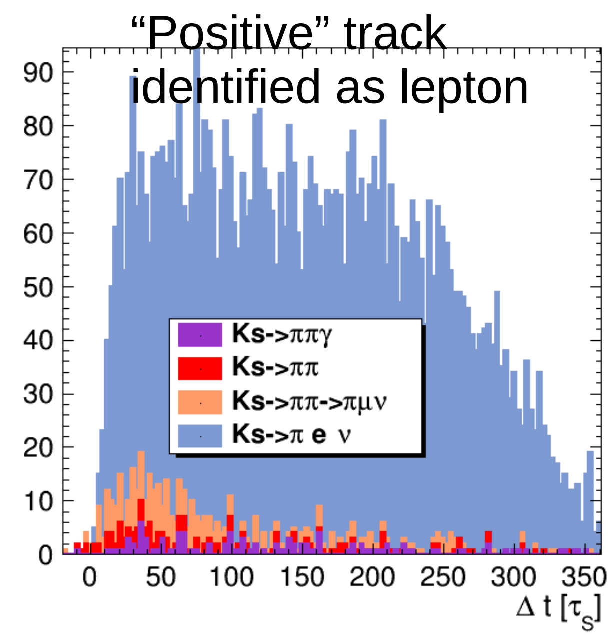


The remaining background is strongly charge-asymmetric!



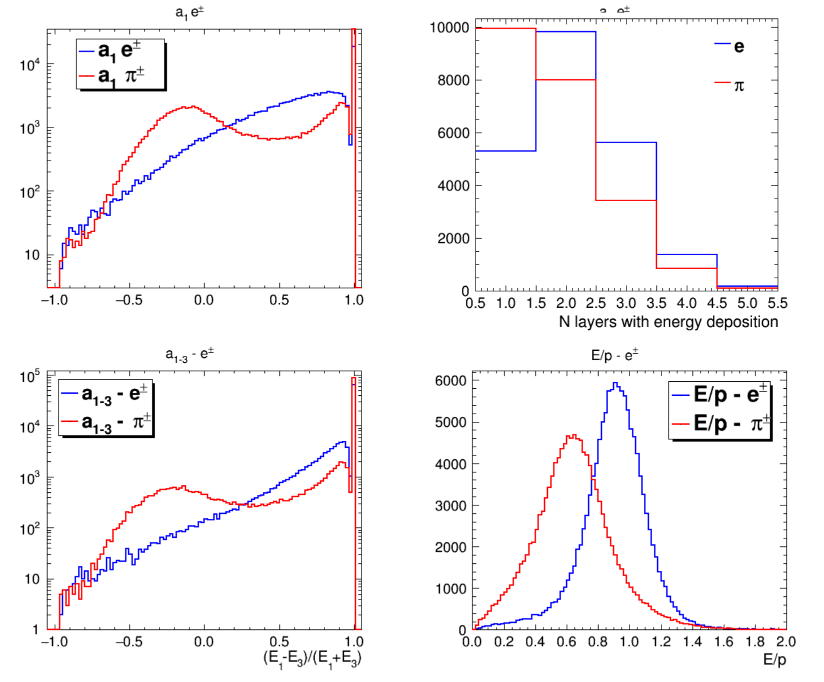
MC Distribution of background components vs Δt (stacked histograms)





Track and cluster classification for $K_S \to \pi^+\pi^-(\to \pi\mu)$ rejection

- using particle classifiers applied to a (track, cluster) pair
- classifiers use the following information:
  - track |**p**|
  - E of the associated cluster
  - no. EMC layers with $E_{dep}>0$ in cluster
  - differences between E_{dep} in 1^{st} and next layers of the EMC cluster
- Using classification algorithms from TMVA for binary classifications of track+cluster pairs:
  - electrons or pions
  - electrons or muons



$K_SK_L \to \pi^+\pi^-\ \pi e\nu$ data

training with data

$K_SK_L \to \pi^+\pi^-\ \pi\mu\nu$ data

After training, both classifiers are subsequently applied to the track+cluster identified as electron in the $K_SK_L \to \pi e\nu\ 3\pi^0$ sample

e / π classifier

e / μ classifier

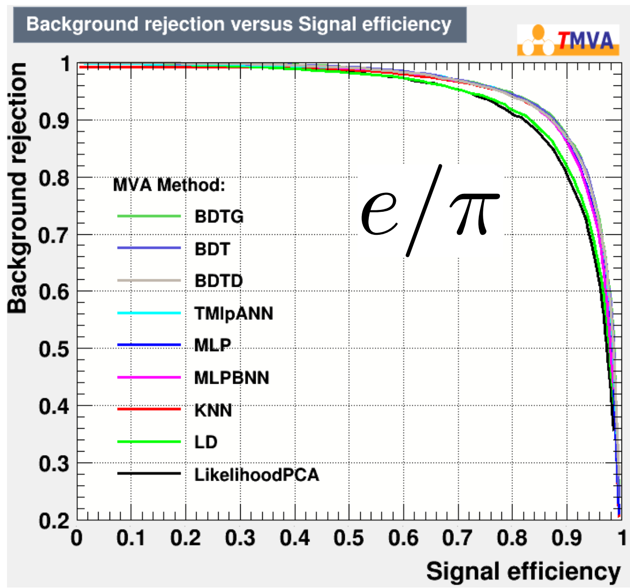
output value 1

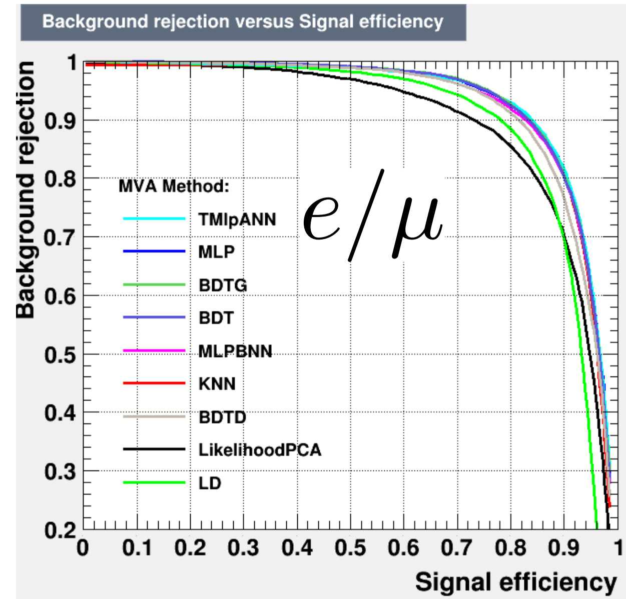
output value 2

A cut is performed on output values of both classifiers

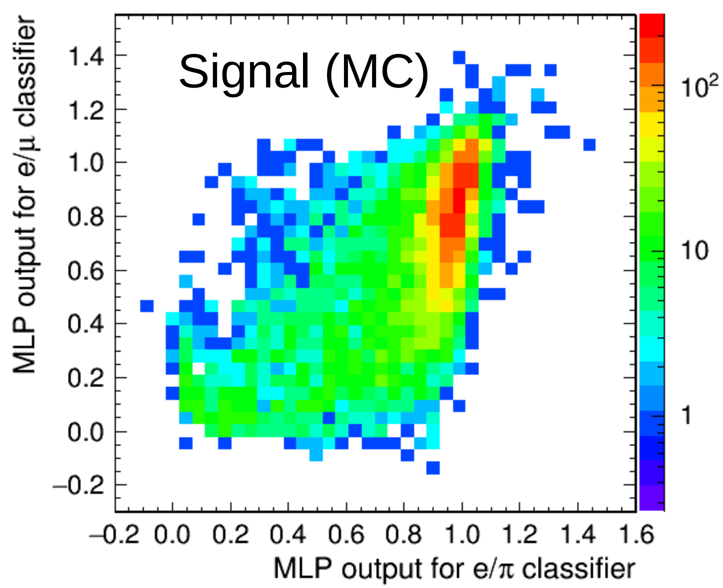
MLP-based classifier performance tests

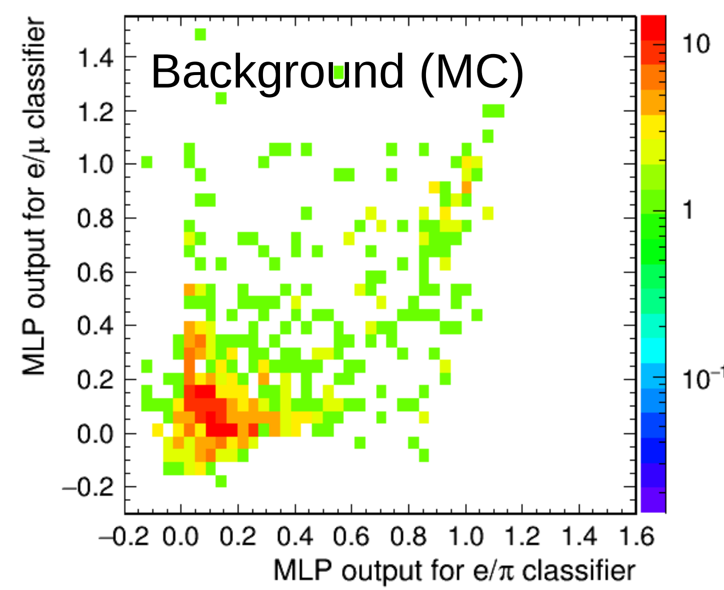
Classifier performance tested with a training sample (data)





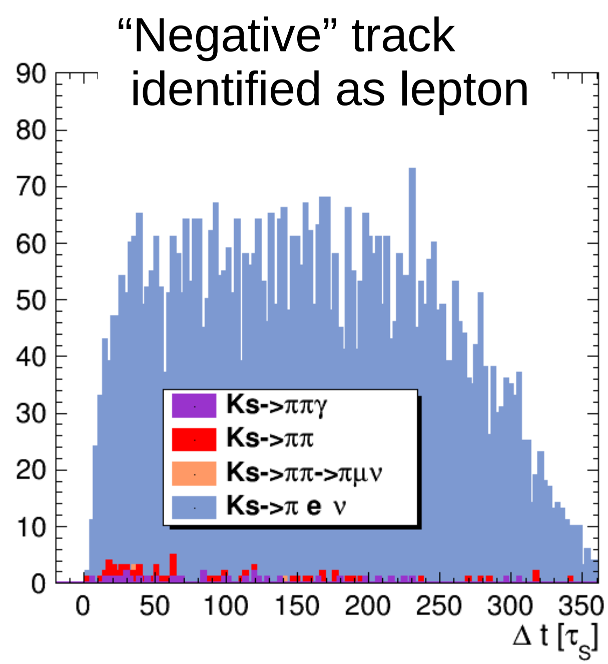
e / π vs e / μ classifier output when applied to KLOE MC

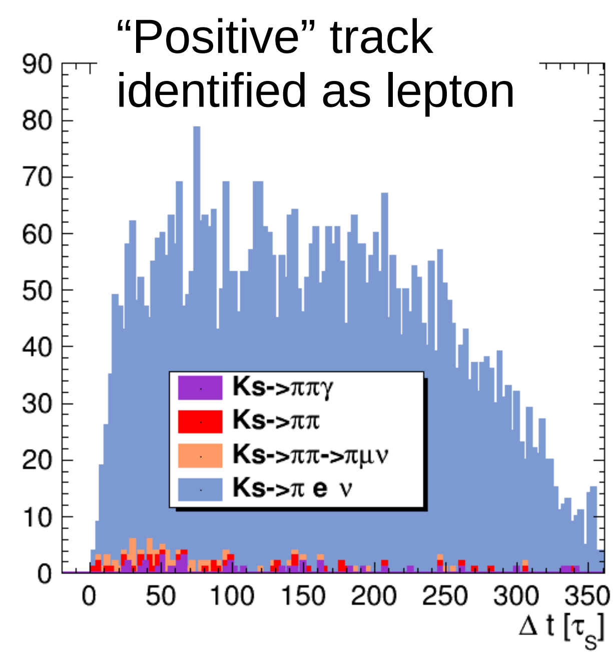




MC Sample composition – after cut on MLP classifier ouputs

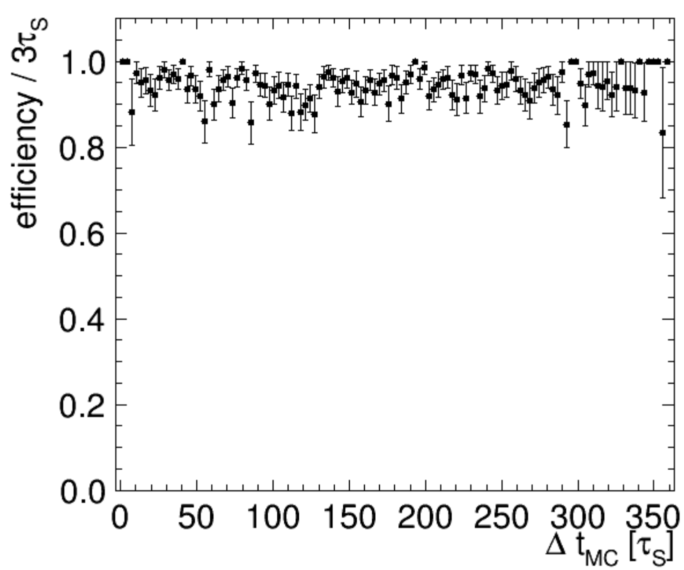
MC Distribution of background components vs Δt
after the cut on the sum of e/π and e/μ classifier outputs
(stacked histograms)

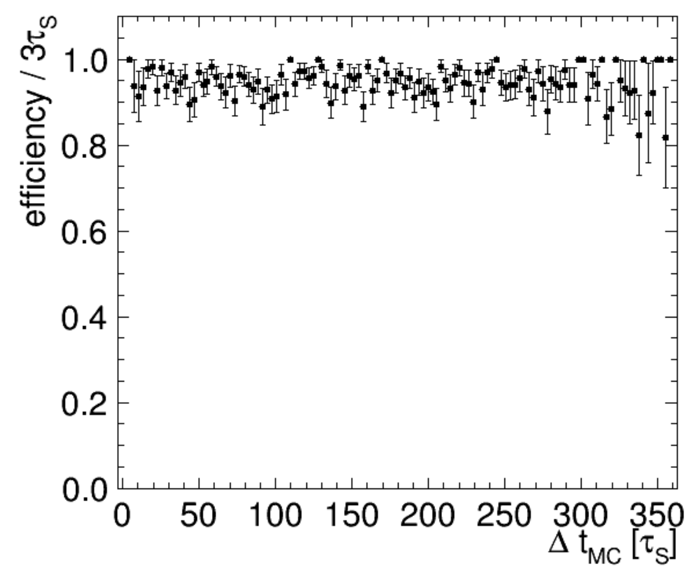




S / B: 11.5 → 33.5

Signal efficiency
of this cut:
~94 %



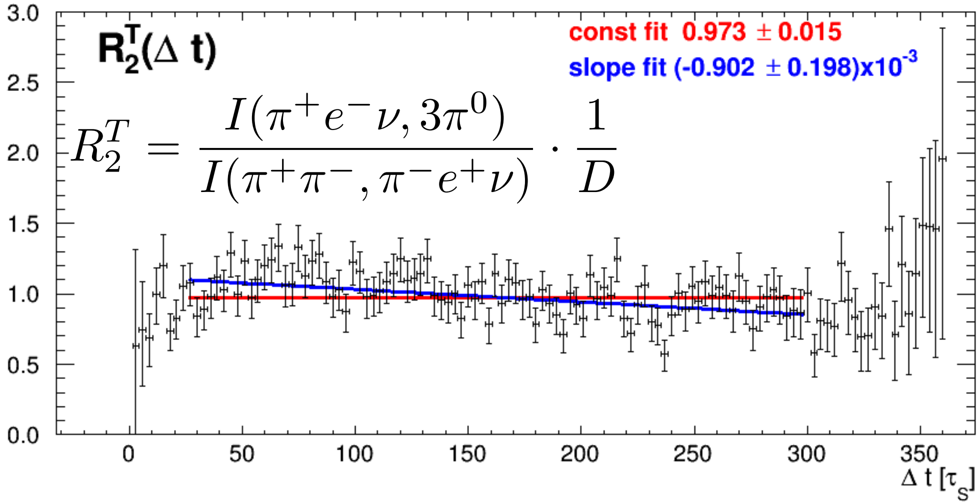


Dedicated maximum likelihood fit
to fit the level of T and CPT asymmetric ratios

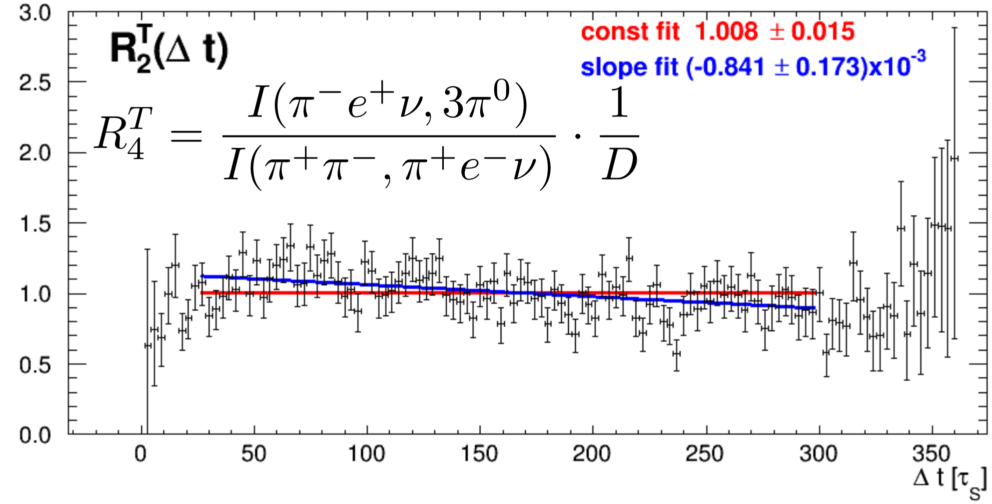
Problems with the χ^2 fit to asymmetric ratios

- The χ^2 fit directly compares uncertainties between particular points
  - As these uncertainties originate from poissonian errors, the relative uncertainty matters
  - The χ^2 fit was giving much significantly lower results if errors were taken into account than if just fitting to points alone

χ^2 fit, errorbars used



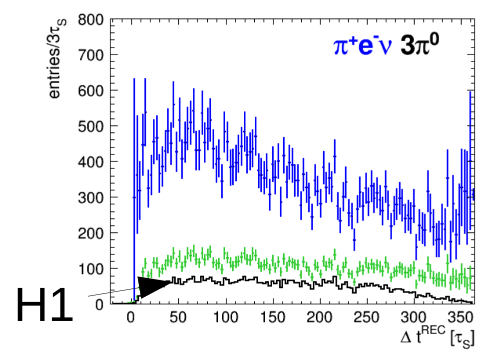
χ^2 fit, errorbars ignored

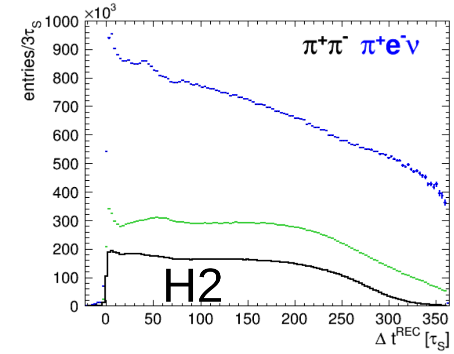


Maximum Likelihood fit to single ratios

Previously:

- raw Δt distributions were corrected for efficiency bin-by-bin then divided bin-by-bin to obtain the R(Δt) plot
- at each step, normal error propagation was perfomed
- a χ^2 fit to the points in the R(Δt) plot was used





New approach

- input to the fit:
  - 2 raw Δt histograms from data, $\mathbf{H_1}$ and $\mathbf{H_2}$
  - 2 efficiency plots
- assuming poissonian uncertainties for numbers of events in raw histogram bins
- assuming uncertainty in the second histogram is negligible w.r.t. first histogram

$H_X(t)$ – number of events in the bin of histogram H_X corresponding to Δt = t
$\varepsilon_X(t)$ – efficiency for registration of events in histogram H_X in a bin corresponding to Δt = t
R(t) – value of the fitted function (costant or linear) in a bin corresponding to Δt = t

$$D = \frac{BR(K_L \to 3\pi^0)}{BR(K_S \to \pi^+\pi^-)} \frac{\tau_S}{\tau_L}$$

$$\forall_{t \in \text{fit range}} : \frac{H_1(t)/\varepsilon_1(t)}{H_2(t)/\varepsilon_2(t)} = R(t) \cdot D$$

$$log\mathcal{L}(R) = \sum_{t \in \text{fit range}} log\left(p\left(H_1(t),\ R(t) D H_2(t) \frac{\varepsilon_1(t)}{\varepsilon_2(t)} \right) \right)$$

poissonian probability

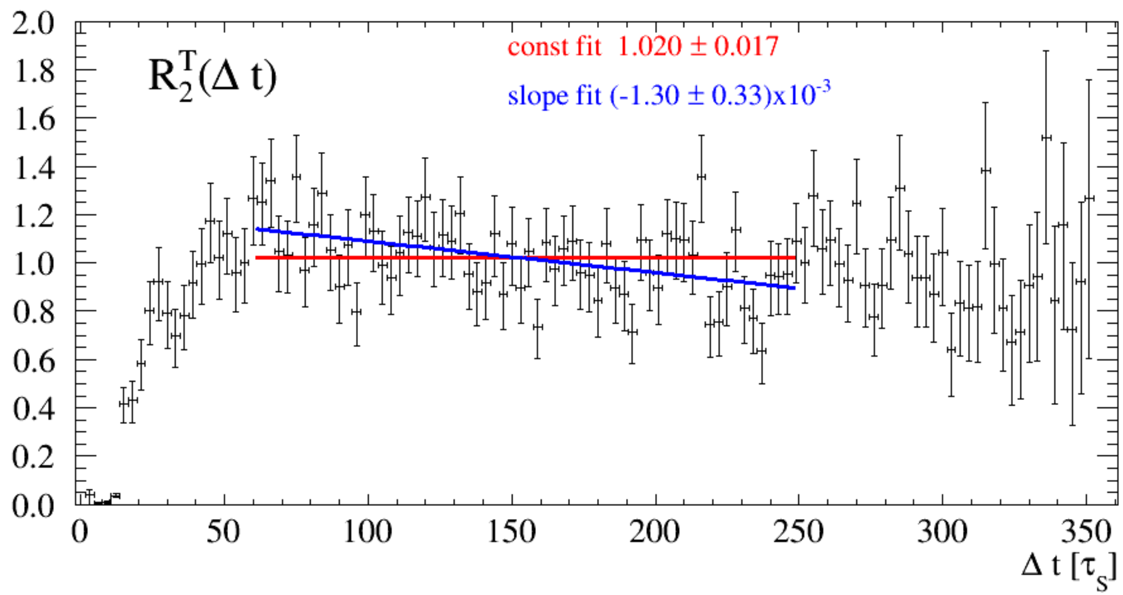
expected no. evts in bin

T, CP and CPT asymmetric ratios

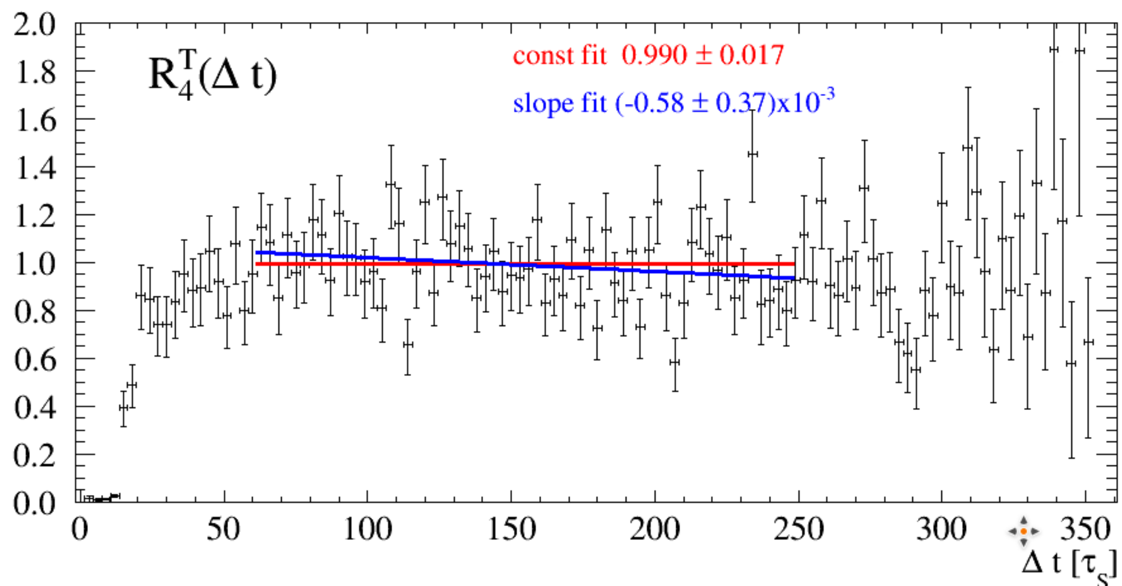
T asymmetric ratios

With efficiencies from data control samples.

$$R_2^T = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



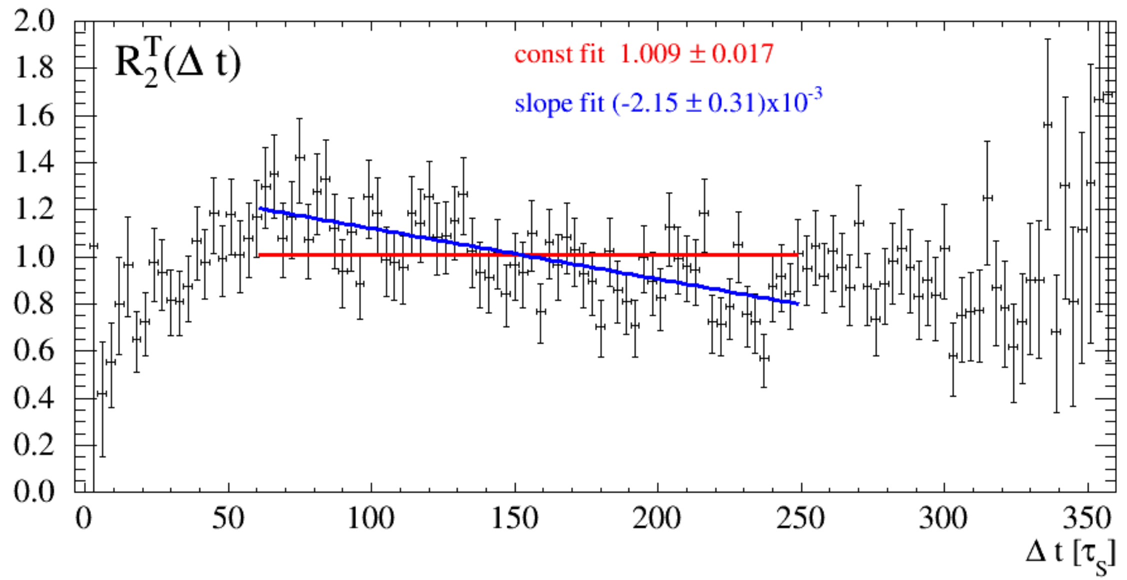
$$R_4^T = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



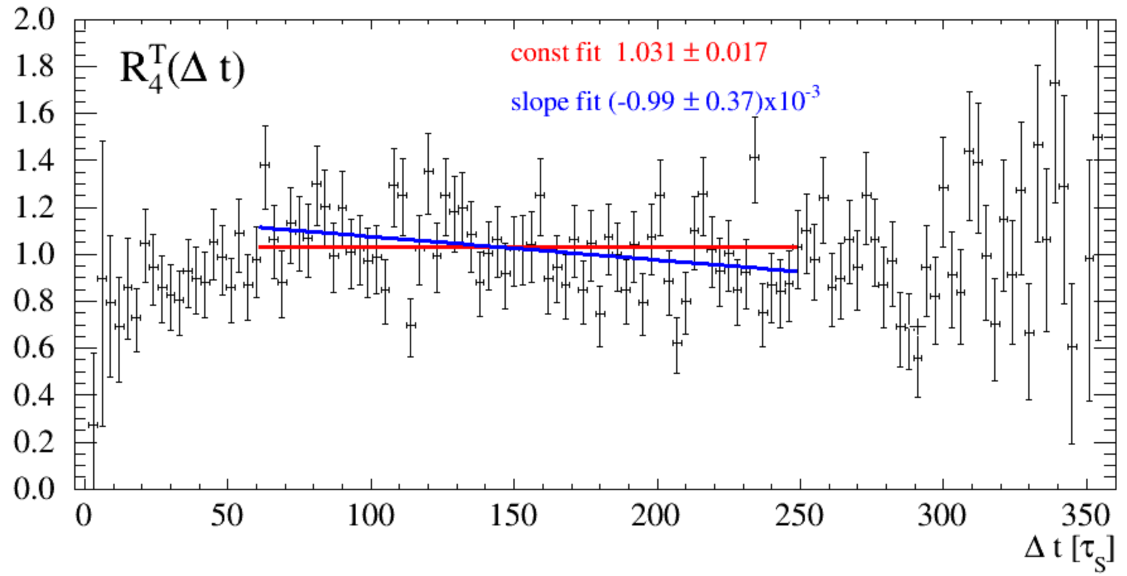
T asymmetric ratios

With efficiencies from MC

$$R_2^T = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



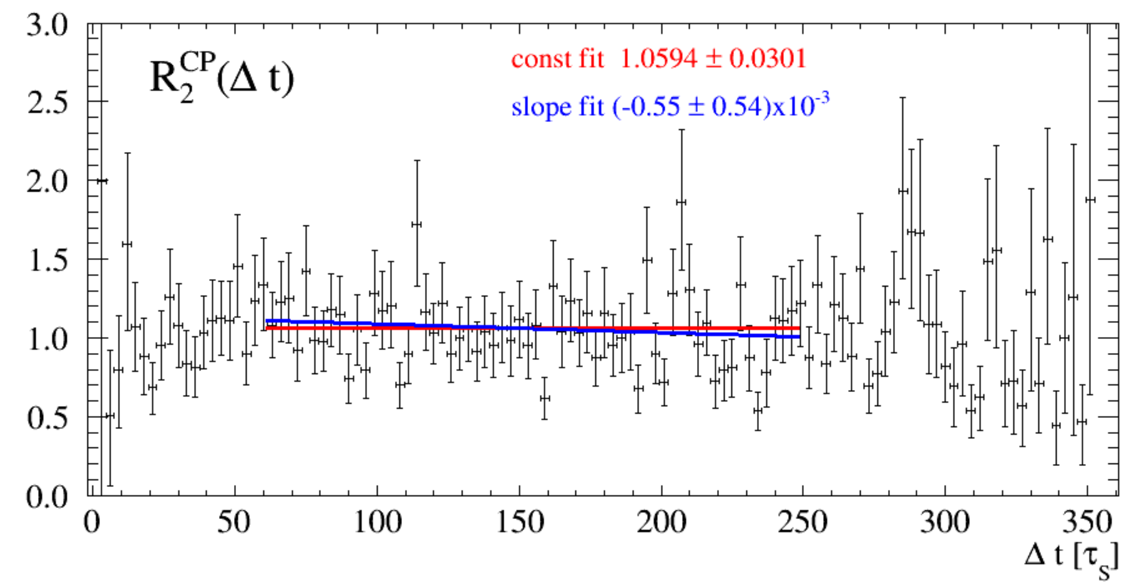
$$R_4^T = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



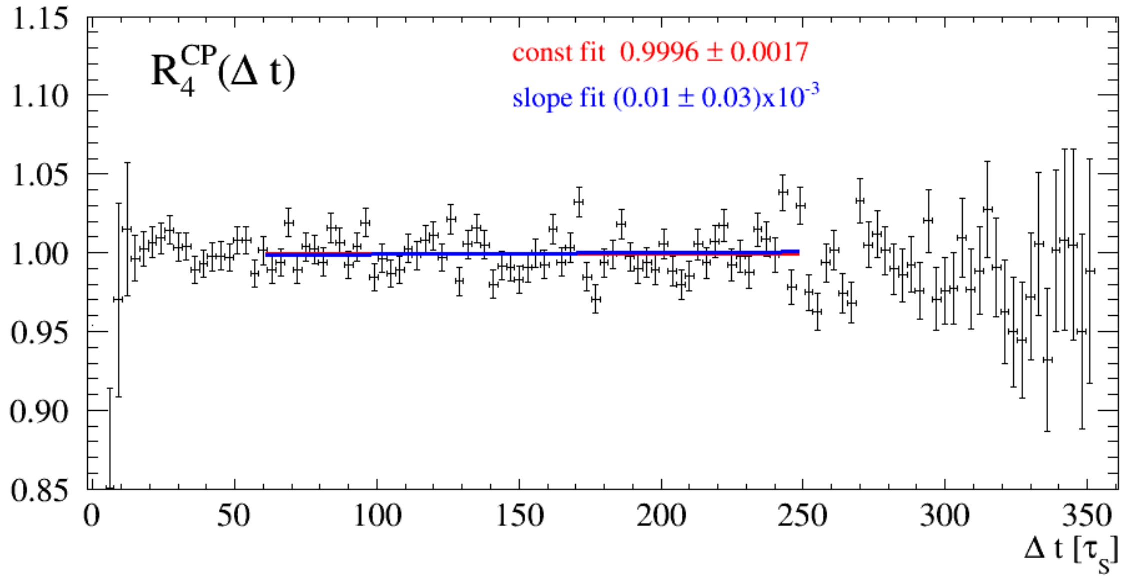
CP asymmetric ratios

With efficiencies from data control samples.

$$R_2^{CP}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}$$



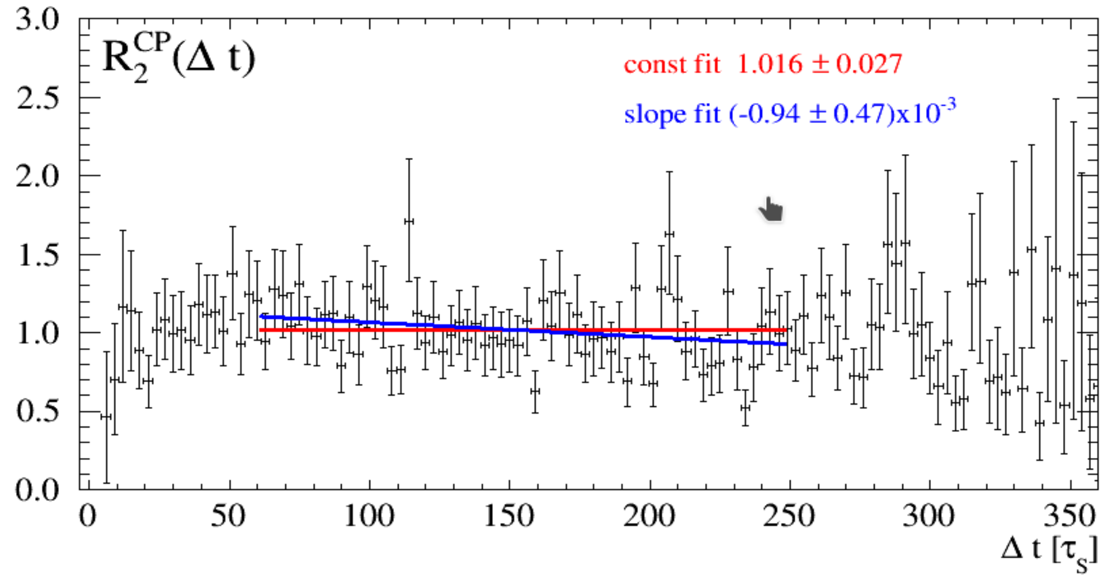
$$R_4^{CP}(\Delta t) = \frac{I(\pi^+ \pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+ \pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$



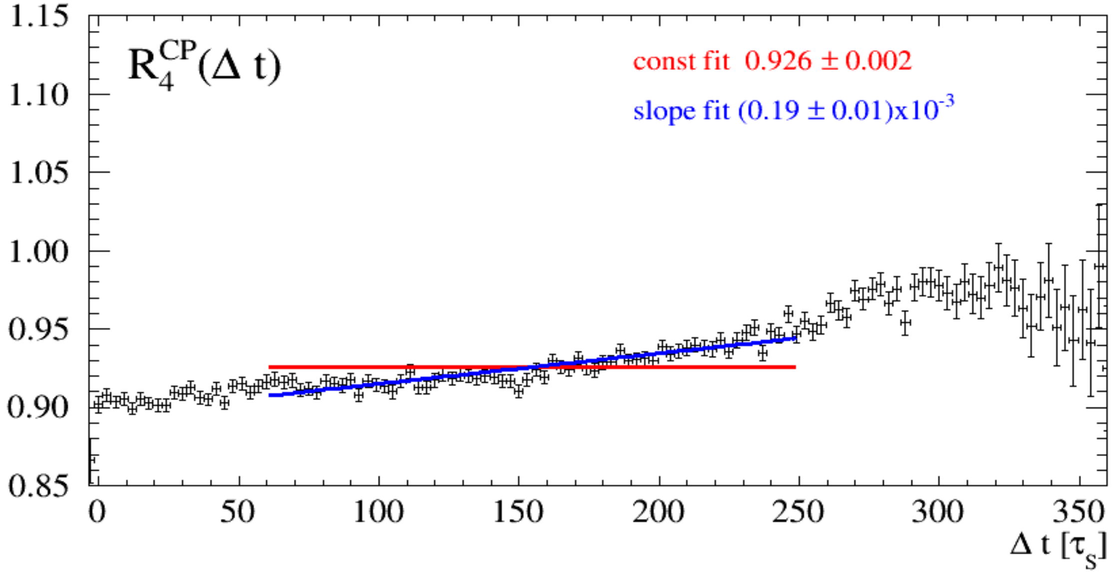
CP asymmetric ratios

With efficiencies from MC

$$R_2^{CP}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}$$



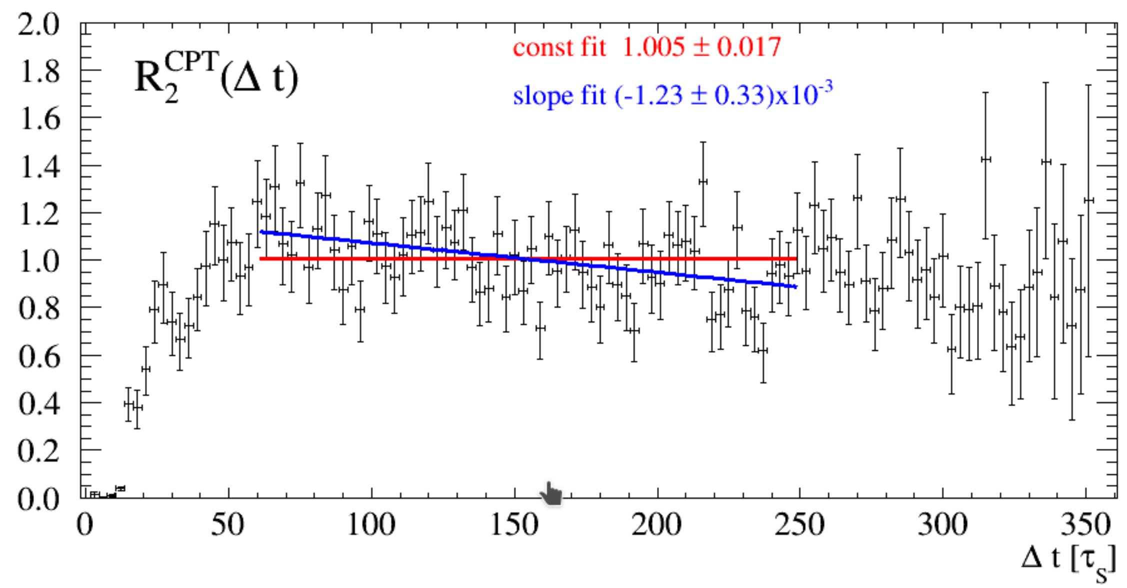
$$R_4^{CP}(\Delta t) = \frac{I(\pi^+ \pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+ \pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$



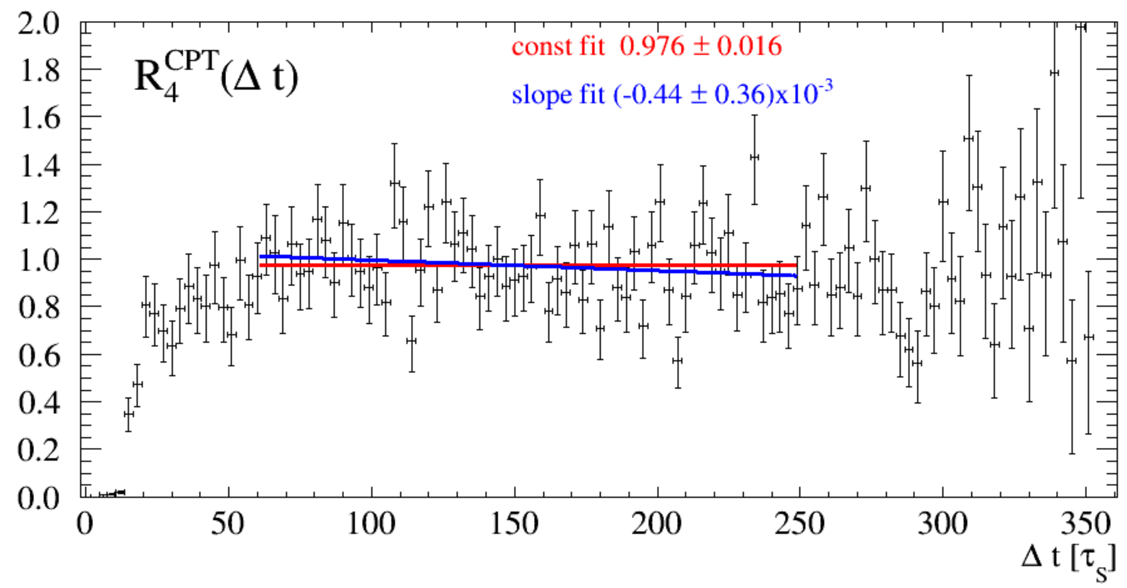
CPT asymmetric ratios

With efficiencies from data control samples.

$$R_2^{CPT} = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



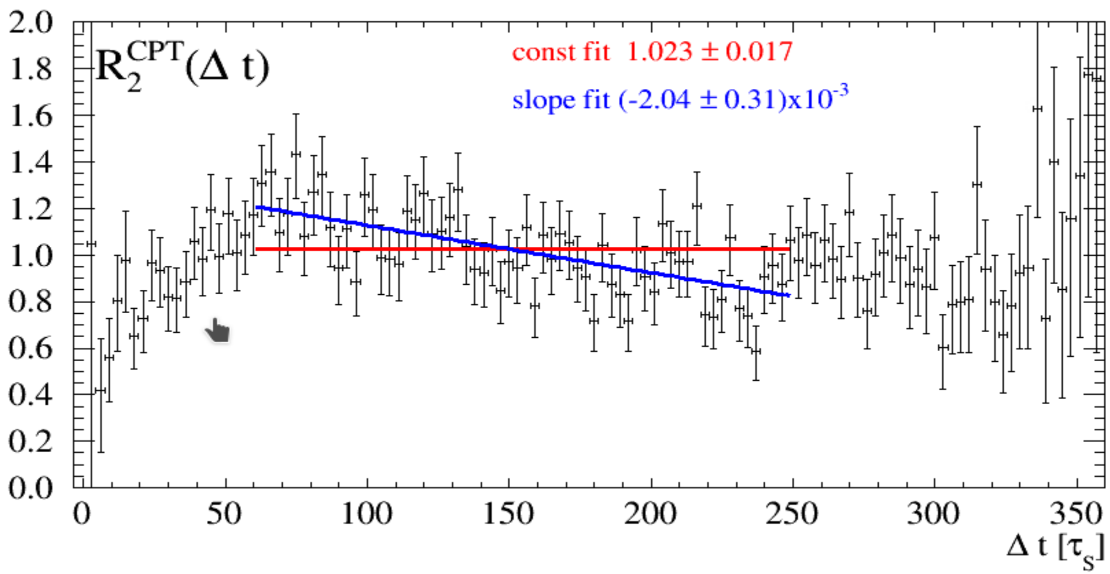
$$R_4^{CPT} = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



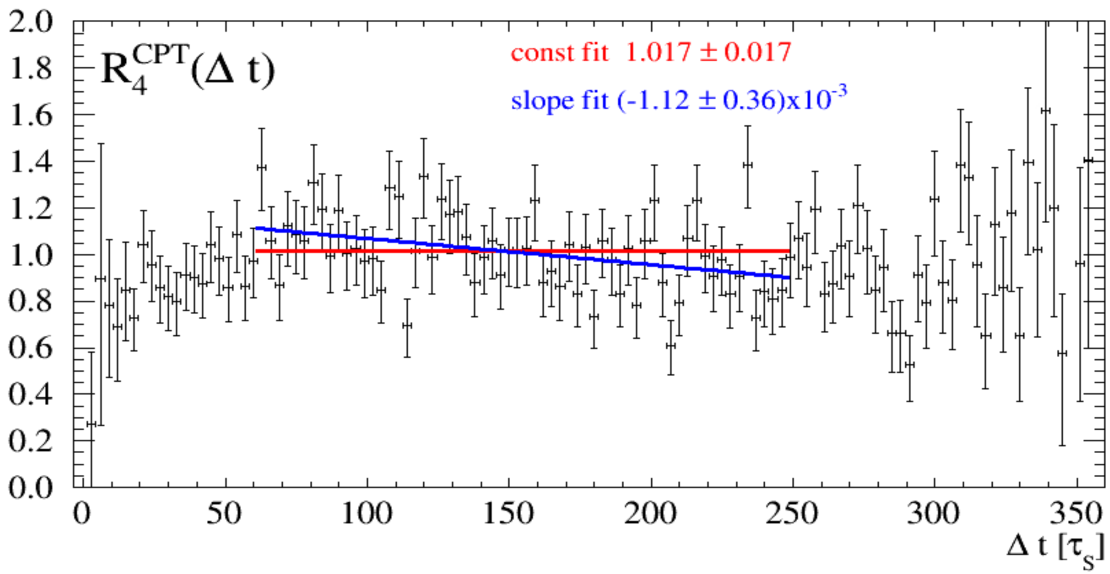
CPT asymmetric ratios

With efficiencies from MC

$$R_2^{CPT} = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$



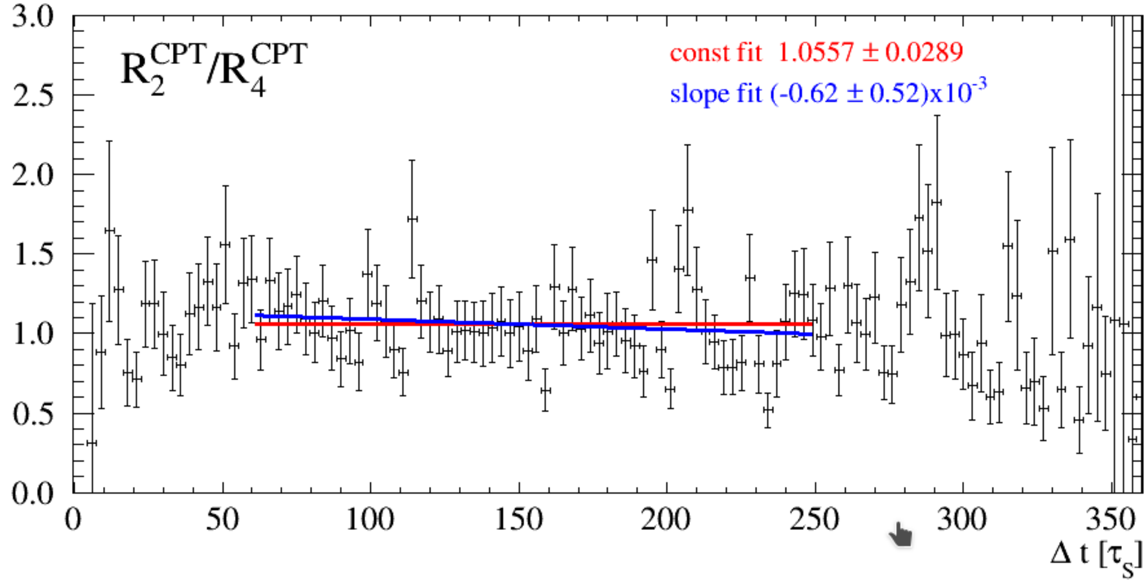
$$R_4^{CPT} = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$



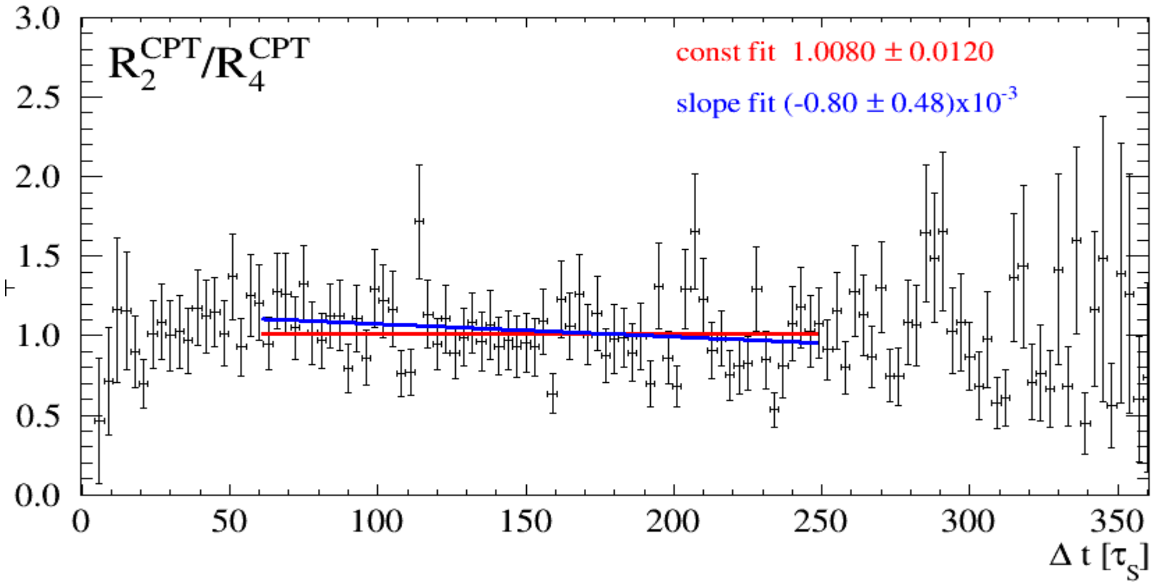
CPT double ratio

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

With efficiencies from data control samples.



With efficiencies from MC



Attempts to replace the problematic cuts tested so far

(S/B after the present event selection: 33.5)

- Strenghtening the cut on the outputs of e/π and e/μ particle classifiers
  - avievable S/B = 16 without the dPCA vs ΔE(π,e) cut with the same total efficiency

- Cutting on the kinematic variables M^2_{miss}, $M^2(e)$ calculated so that their resolution does not depend on the K_L decay point
  - Very poor resolution, no significant S/B improvement obtained after possible cuts

- Studying the spatial location of EMC clusters associated to tracks identified as e and π in the signal ($K_S \to \pi e \nu$) and background ($K_S \to \pi^+\pi^-$, $K_S \to \pi^+\pi^- \to \pi\mu\nu$)
  - No strong difference between signal and background
  - Additional checks in the next slides

- Performing the e/π and e/μ particle clasification separately in particlular intervals of particle momentum and incidence angle on the EMC
  - Little improvement in sample purity
  - Additional checks in the next slides

- Restricting the reconstructed "K_S decay vertex" to a smaller volume around the IP
  - S/B = 28 without the dPCA vs ΔE(π,e) cut at 96 % of the old analysis efficiency
  - Results of the tests in the next slides

D factor for $R_{2/4}$ asymmetry determination

$$D = \frac{BR(K_L \to 3\pi^0)}{BR(K_S \to \pi^+\pi^-)} \frac{\tau_S}{\tau_L} \qquad R_2 = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D} \qquad R_4 = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$

$$D_{PDG} = \frac{0.1952 \pm 0.0012}{0.6920 \pm 0.0005} \frac{0.89564 \pm 0.00033}{511.6 \pm 2.1} = 0.4938 \pm 0.0037 \times 10^{-3}$$

$$D_{KLOE} = \frac{0.1997 \pm 0.0020}{0.69196 \pm 0.00051} \frac{0.89562 \pm 0.00052}{508.4 \pm 2.3} = 0.5084 \pm 0.0056 \times 10^{-3}$$

As pointed out by prof. Ceradini, the main source of discrepancy between D calculated with PDG fit data and with KLOE data are $BR(K_L \to 3\pi^0)$ and τ_L

	PDG fit	KLOE	PDG average	KLOE, no ∑BR=1
$BR(K_L \to 3\pi^0)$	0.1952 ± 0.0012	0.1997 ± 0.0020	0.1969 ± 0.0026	
τ_L [10^{-10} s]	511.6 ± 2.1	508.4 ± 2.3	509.9 ± 2.1	509.2 ± 3.0

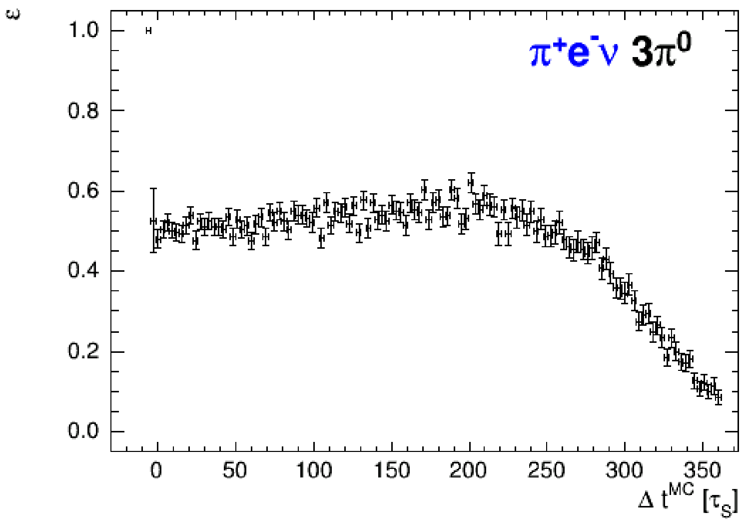
If the PDG average values are used for D_{PDG} and the non-consrained τ_L value from KLOE, compatible results are obtained:

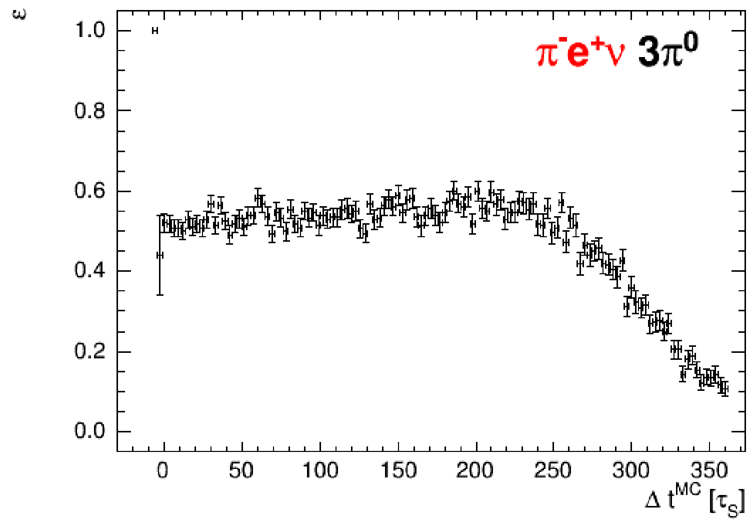
$$D_{PDG} = \frac{0.1969 \pm 0.0026}{0.6920 \pm 0.0005} \frac{0.89564 \pm 0.00033}{509.9 \pm 2.1} = 0.4998 \pm 0.0069 \times 10^{-3}$$

$$D_{KLOE} = \frac{0.1997 \pm 0.0020}{0.69196 \pm 0.00051} \frac{0.89562 \pm 0.00052}{509.2 \pm 3.0} = 0.5076 \pm 0.0059 \times 10^{-3}$$

This value is used in the following results

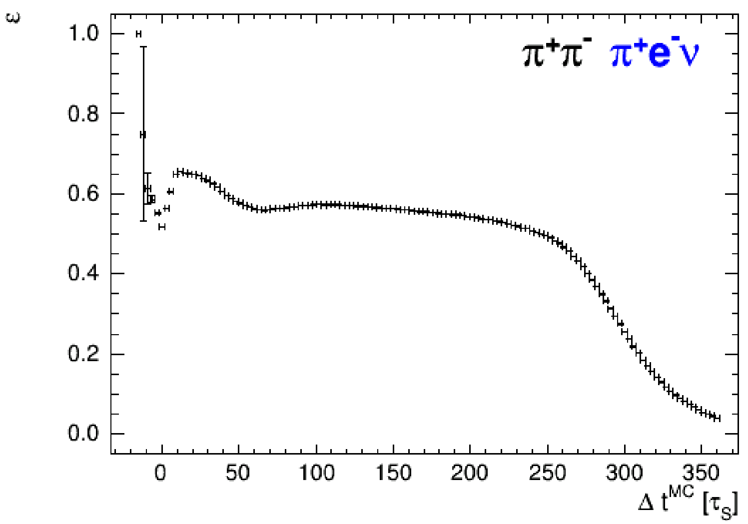
Selection efficiencies

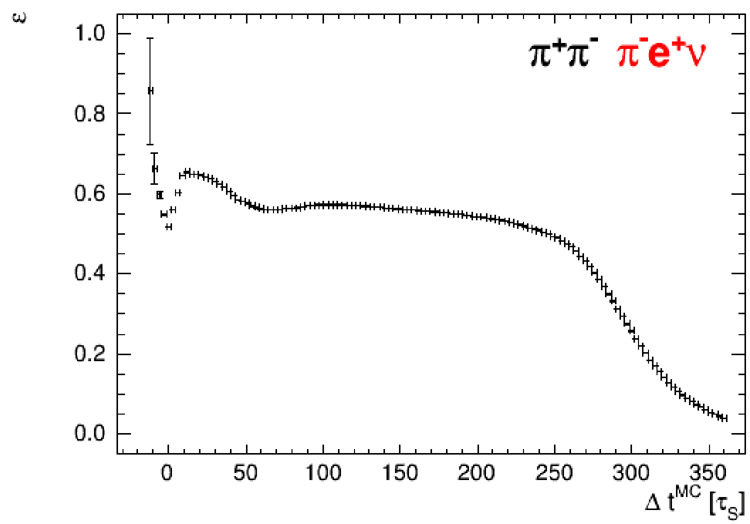




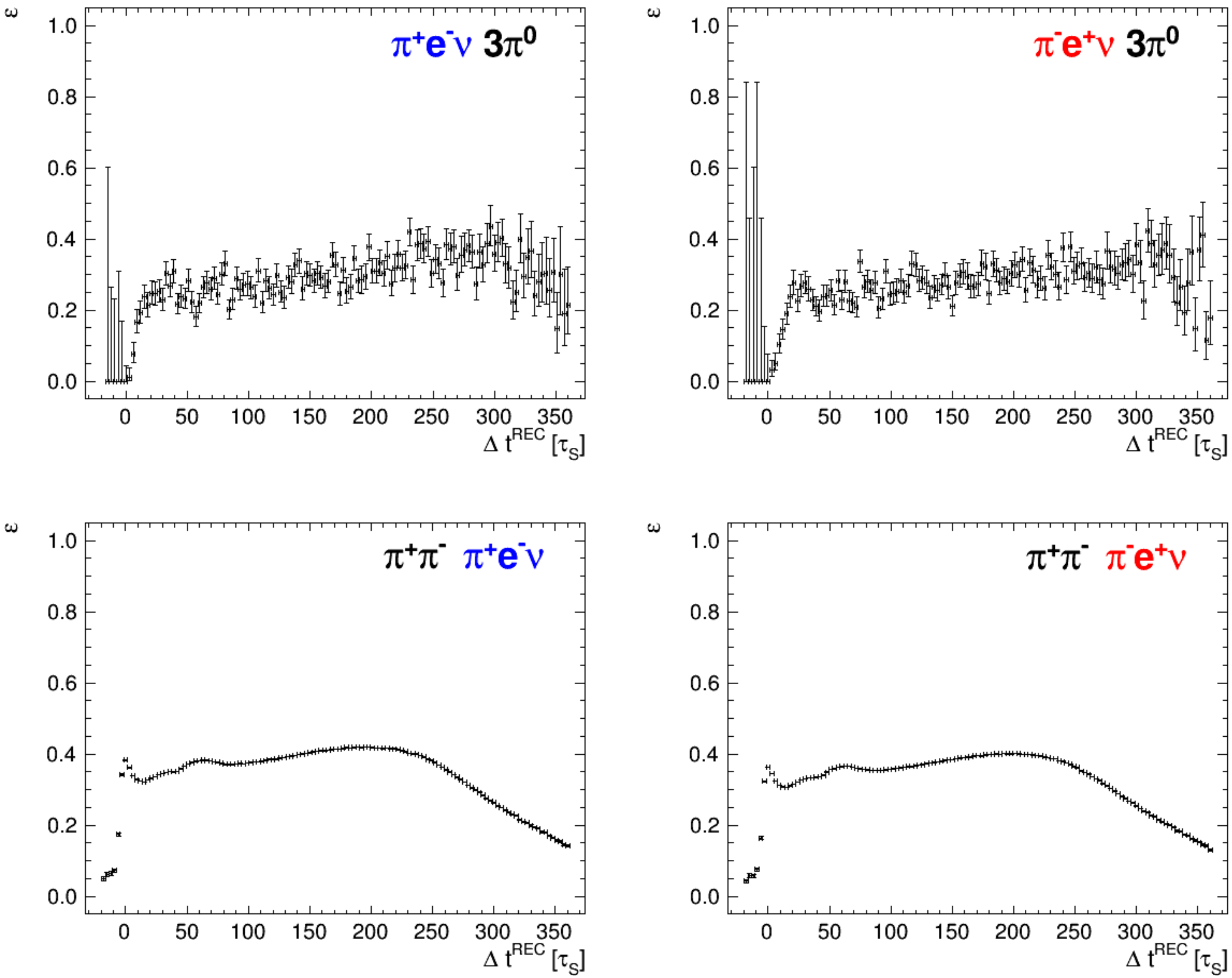
Large statistical errors in efficiency for $K_SK_L \to \pi e\nu, 3\pi^0$

This can be improved by using additional all_phys MC productions





Analysis Efficiencies



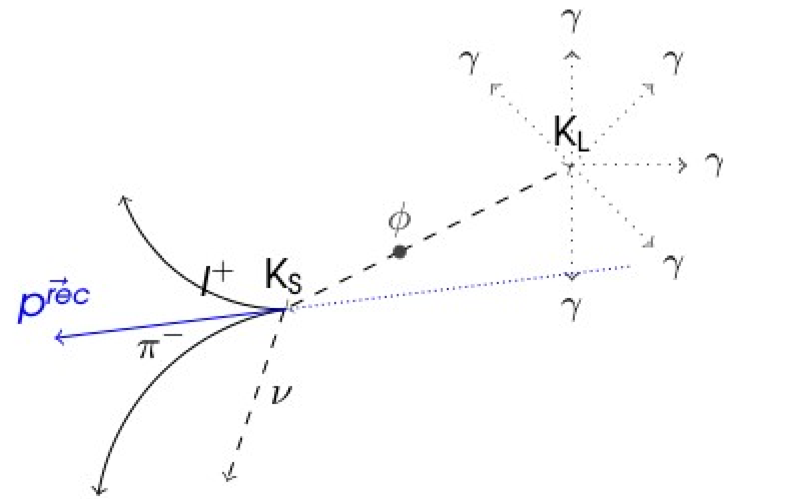
Large statistical errors in efficiency for $K_SK_L \rightarrow \pi e\nu, 3\pi^0$

This can be improved by using additional all_phys MC productions

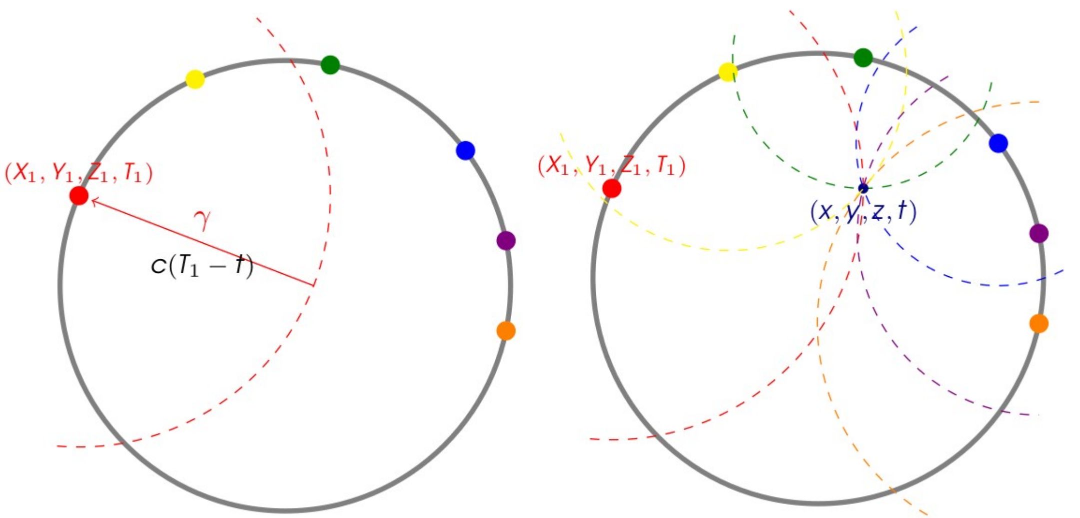
$K_L \to 3\pi^0 \to 6\gamma$ reconstruction

We need to reconstruct the time of K_L decay with a resolution $O(1\tau_S)$

$K_L K_S \to \pi e \nu, 3\pi^0$ Requires reconstruction independent of K_S momentum



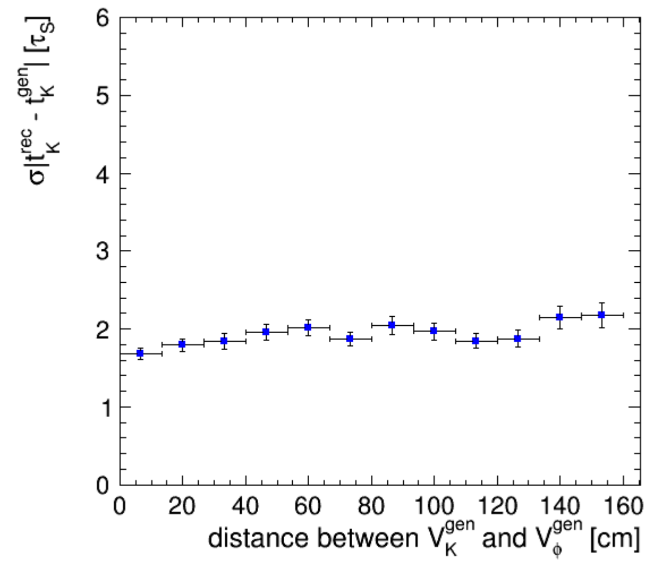
A special reconstruction method was prepared for $K_L \to 3\pi^0$:



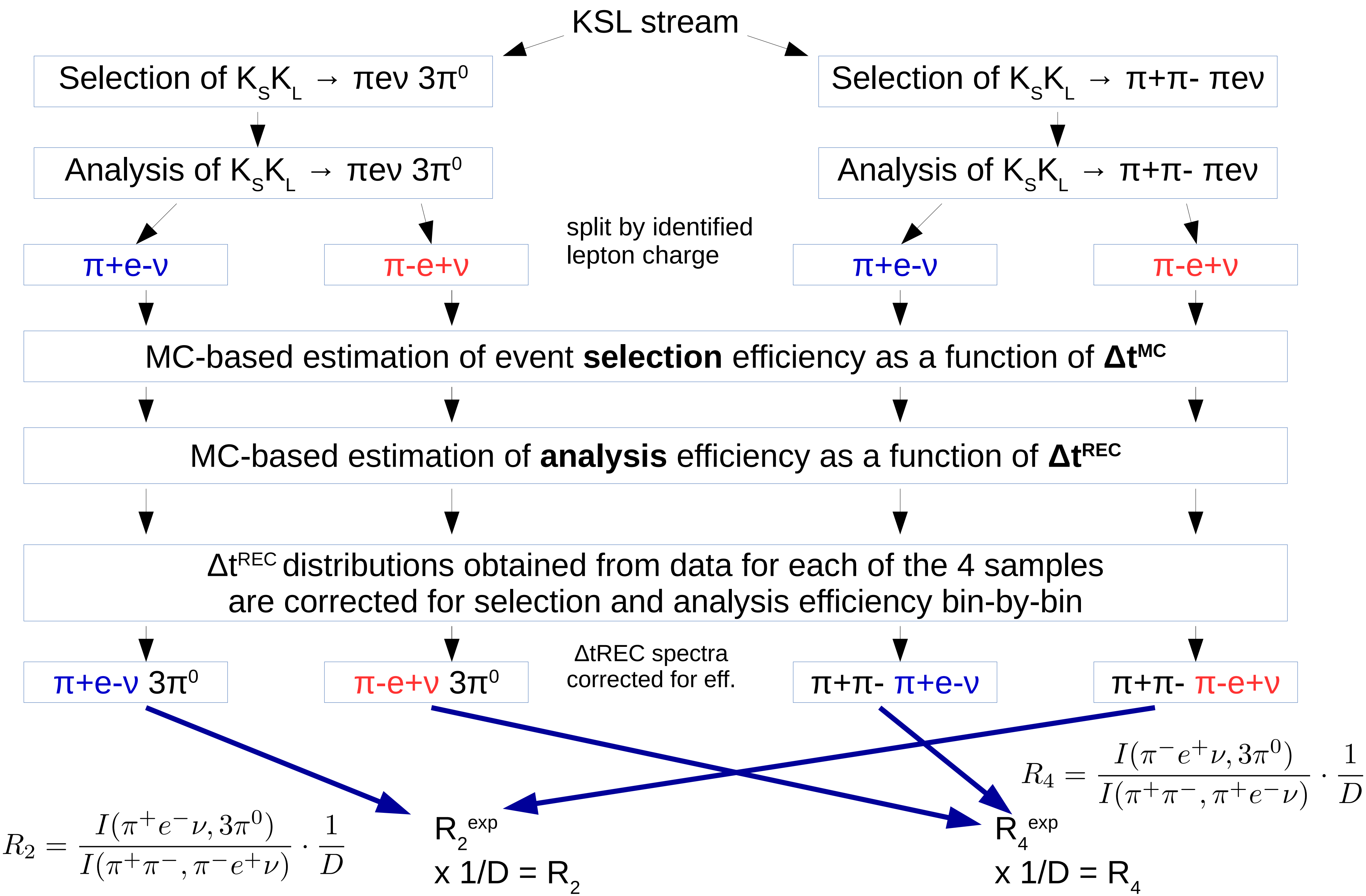
$$(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2, \quad i = 1, \ldots, 6$$

$$\Rightarrow x, y, z \text{ and } t$$

Resolution of $K_L \to 3\pi^0$ decay time with the “GPS-like” reconstruction and a kinematic fit



Present procedure to obtain $R_{2/4}$

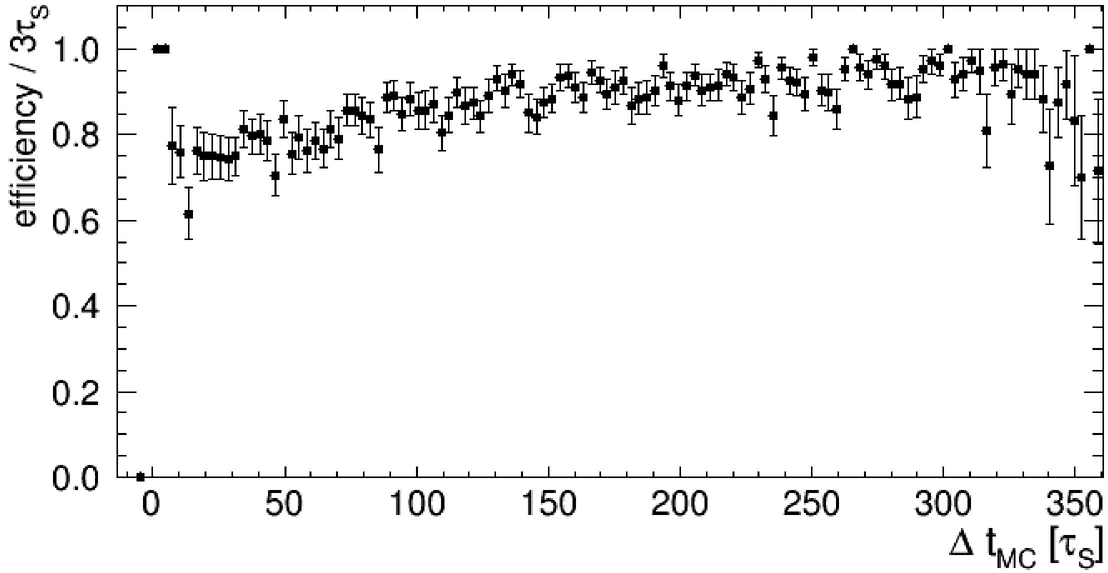


$$R_4 = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)} \cdot \frac{1}{D}$$

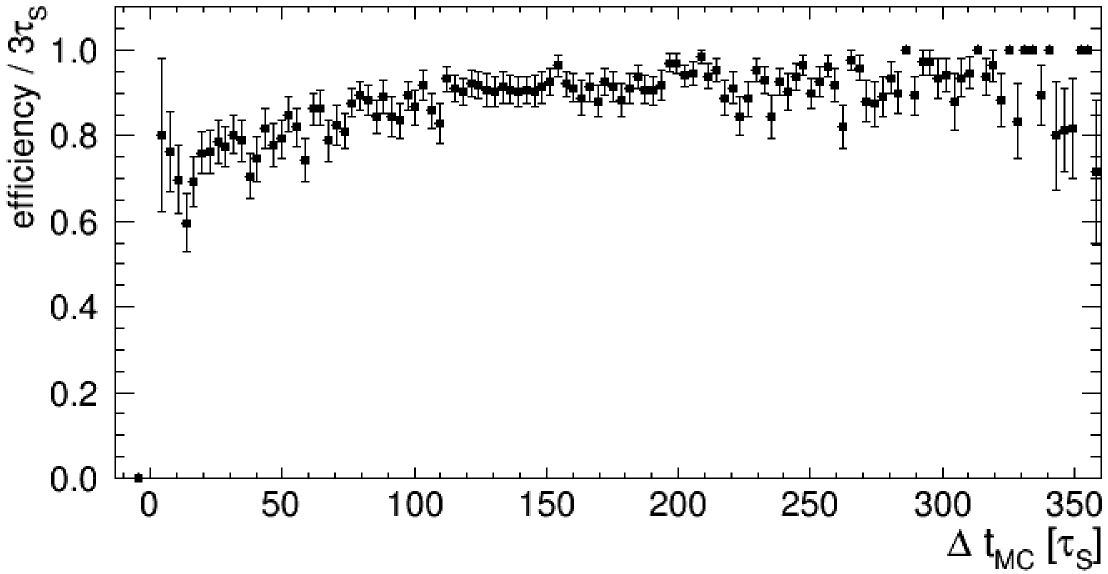
$$R_2 = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)} \cdot \frac{1}{D}$$

d_{PCA} vs $\Delta E(\pi,e)$ cut efficiency

"Negative" track identified as lepton

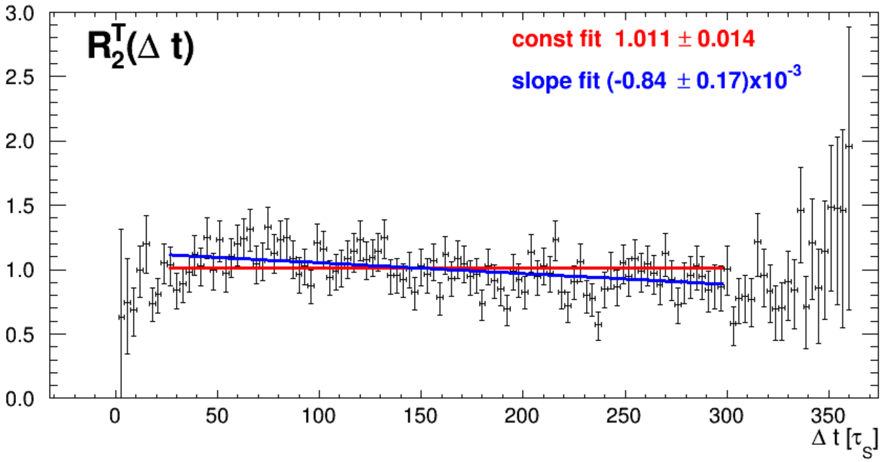


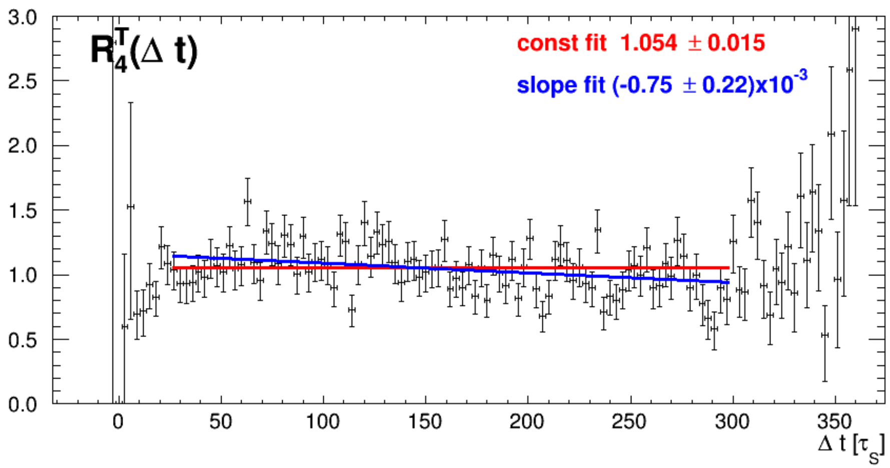
"Positive" track identified as lepton



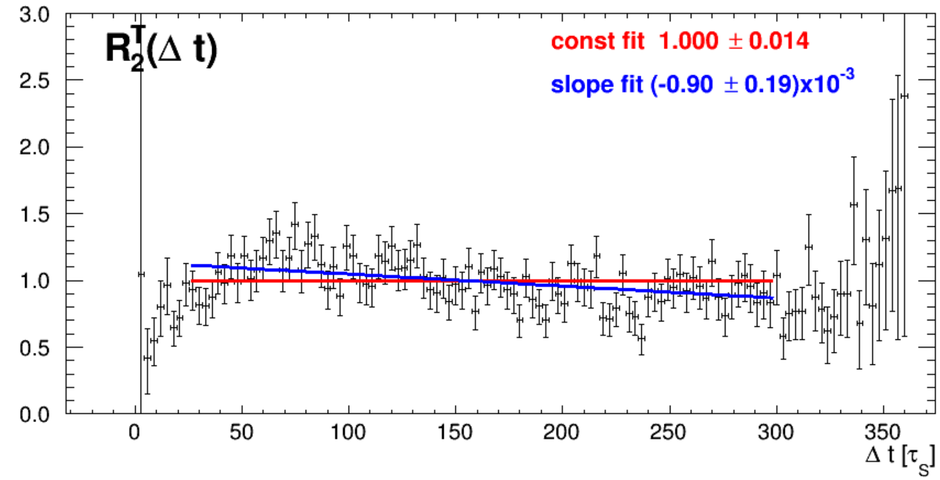
T-asymmetric ratios

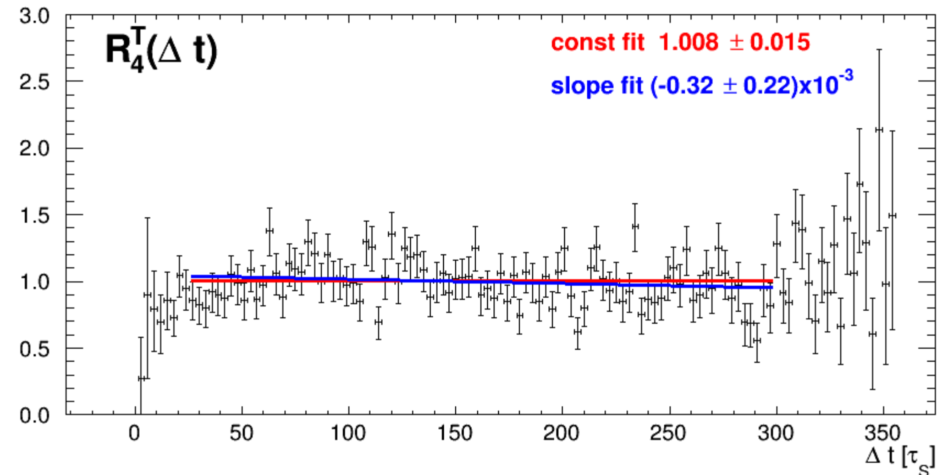
ML fit, before $K_S \to \pi^+\pi^-$ ($\to \pi\mu$) bcg rejection





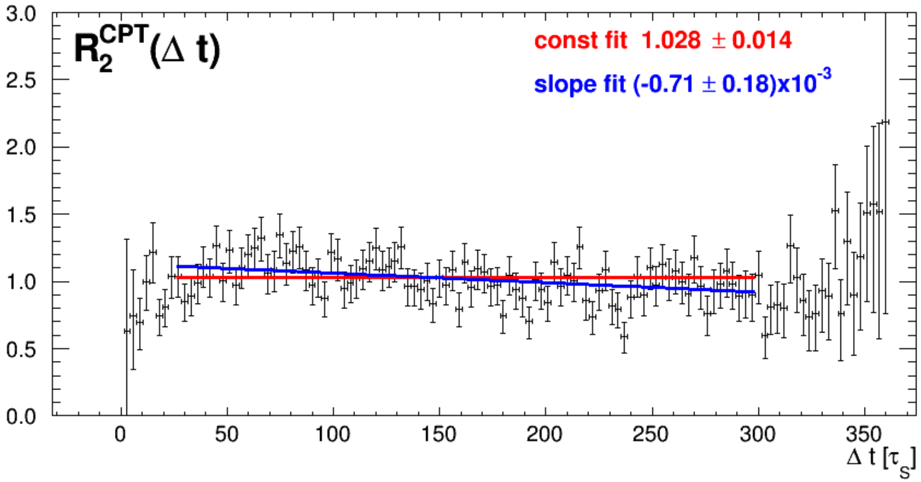
ML fit, after $K_S \to \pi^+\pi^-$ ($\to \pi\mu$) bcg rejection

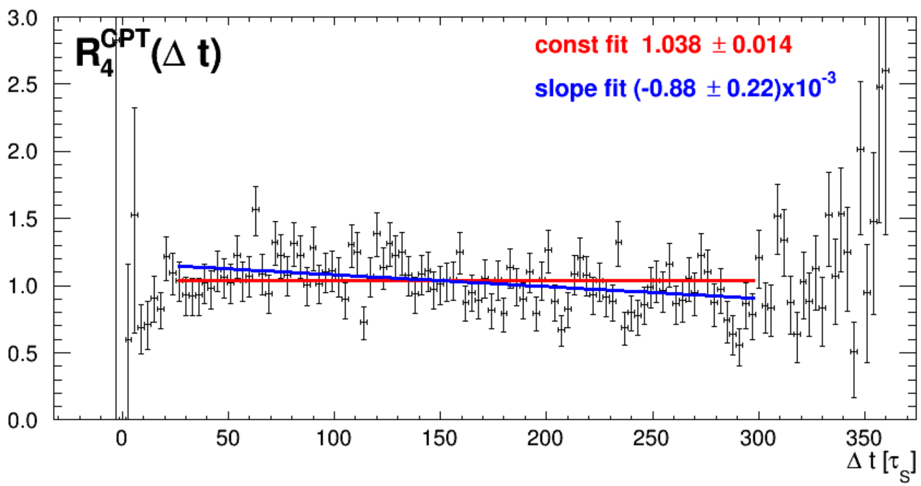




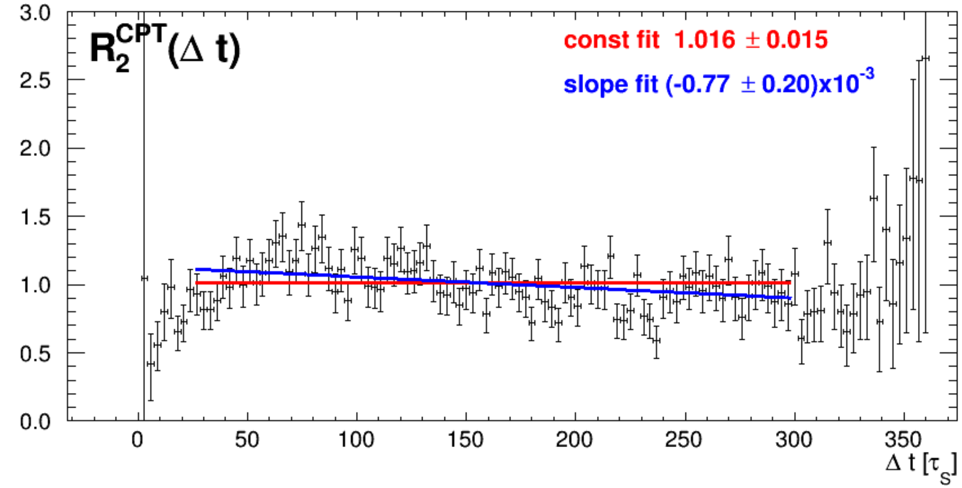
CPT-asymmetric ratios

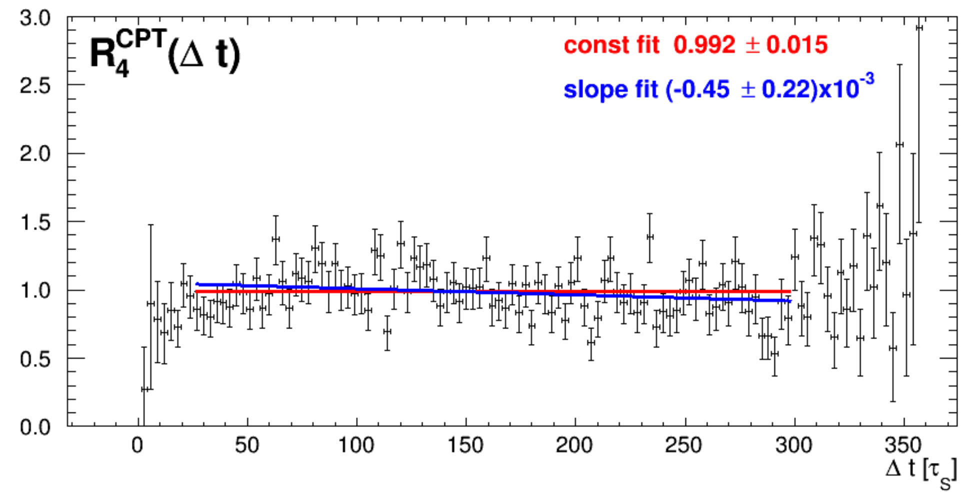
ML fit, before $K_S \to \pi^+\pi^-$ ($\to \pi\mu$) bcg rejection





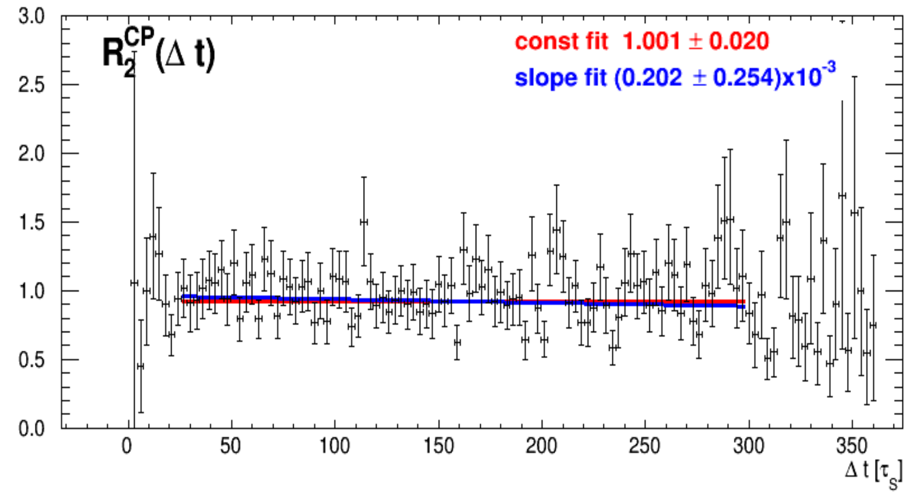
ML fit, after $K_S \to \pi^+\pi^-$ ($\to \pi\mu$) bcg rejection

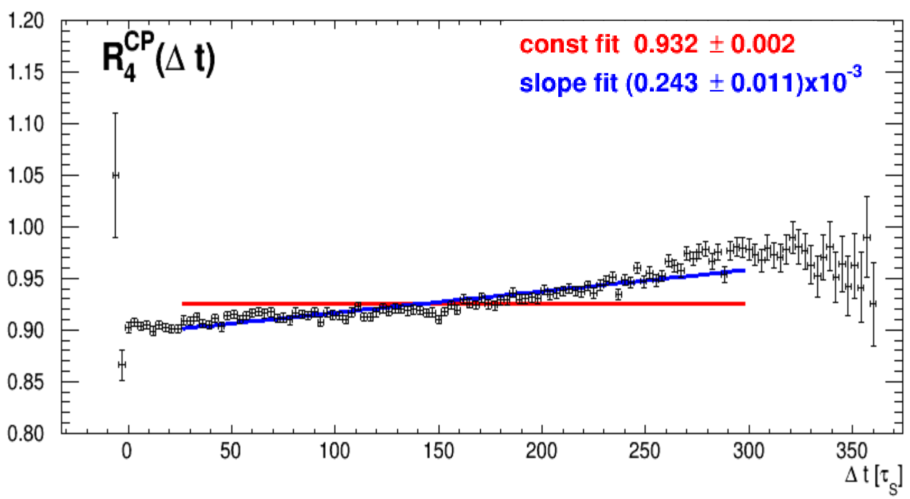




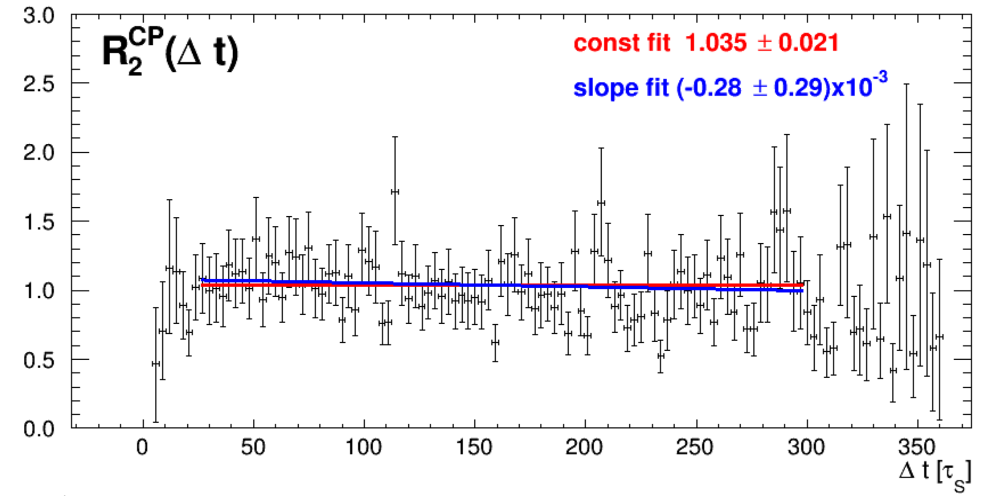
CP-asymmetric ratios

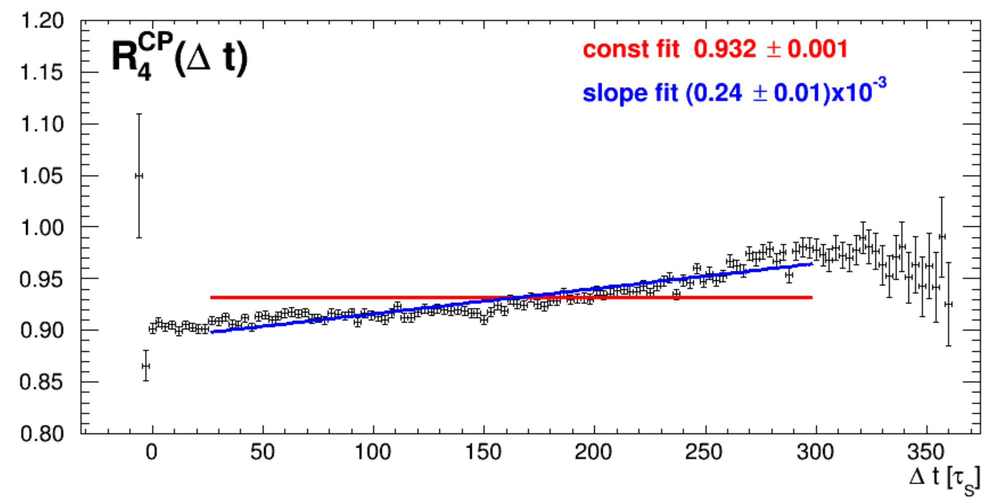
ML fit, before $K_S \rightarrow \pi+\pi-$ ($\rightarrow \pi\mu$) bcg rejection





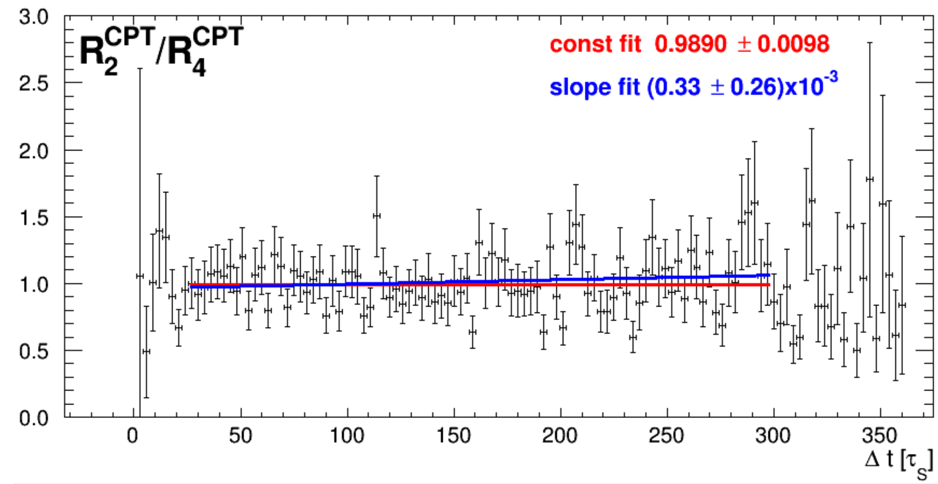
ML fit, after $K_S \rightarrow \pi+\pi-$ ($\rightarrow \pi\mu$) bcg rejection

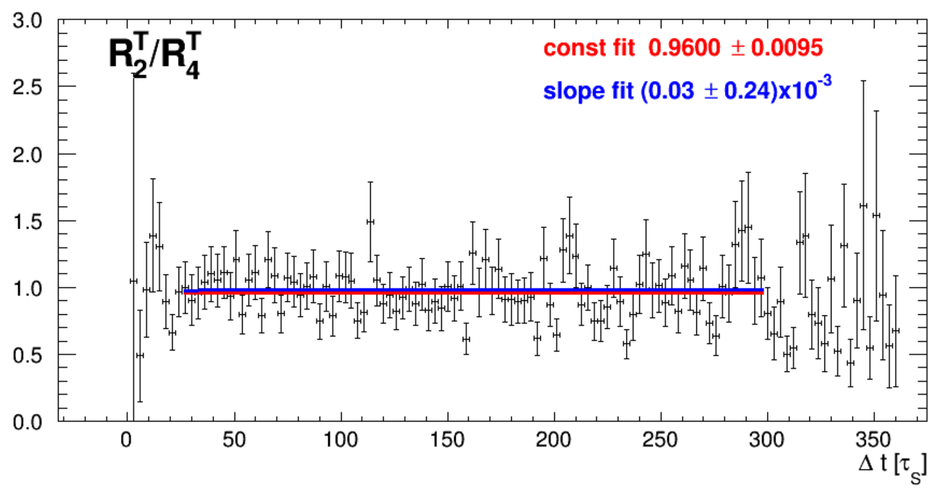




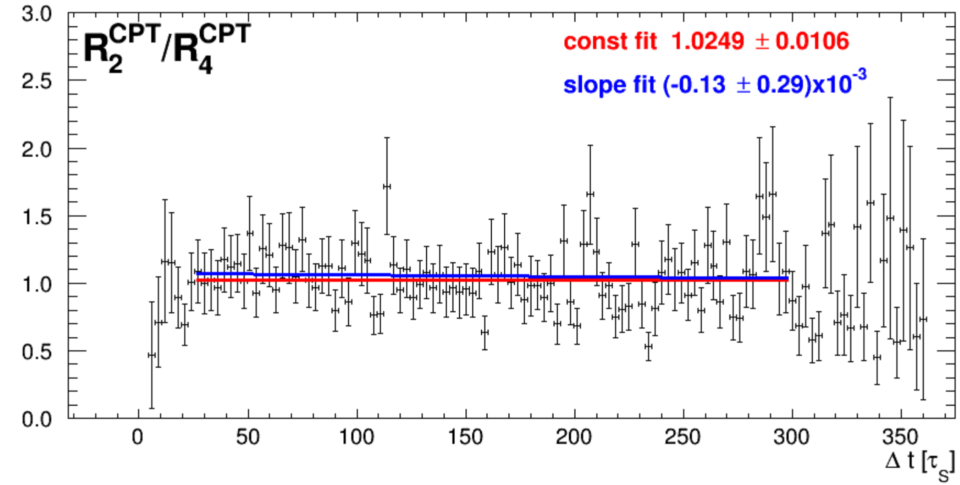
Double ratios (CPT and T asymmetric)

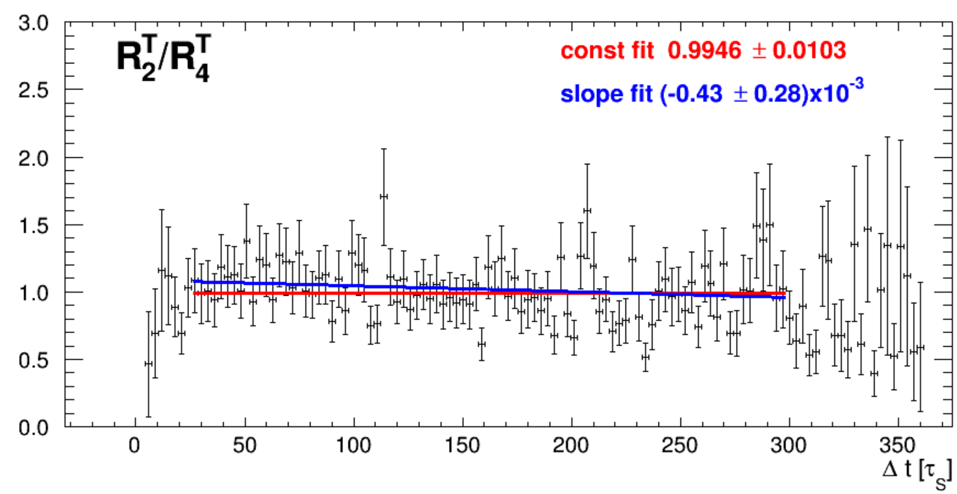
ML fit, before $K_S \rightarrow \pi+\pi-$ ($\rightarrow \pi\mu$) bcg rejection





ML fit, after $K_S \rightarrow \pi+\pi-$ ($\rightarrow \pi\mu$) bcg rejection





Recent activity: PhD thesis

- Available here:

http://sphinx.if.uj.edu.pl/~alek/thesis/phd_thesis_gajos.pdf

- Topis:
  - direct T test with KLOE data
  - preliminary studies for symmetry tests with J-PET

Doctoral dissertation
Prepared in the Institute of Physics
of the Jagiellonian University
Submitted to the Faculty of Physics,
Astronomy and Applied Computer Science
of the Jagiellonian University

Investigations of fundamental symmetries with the electron-positron systems

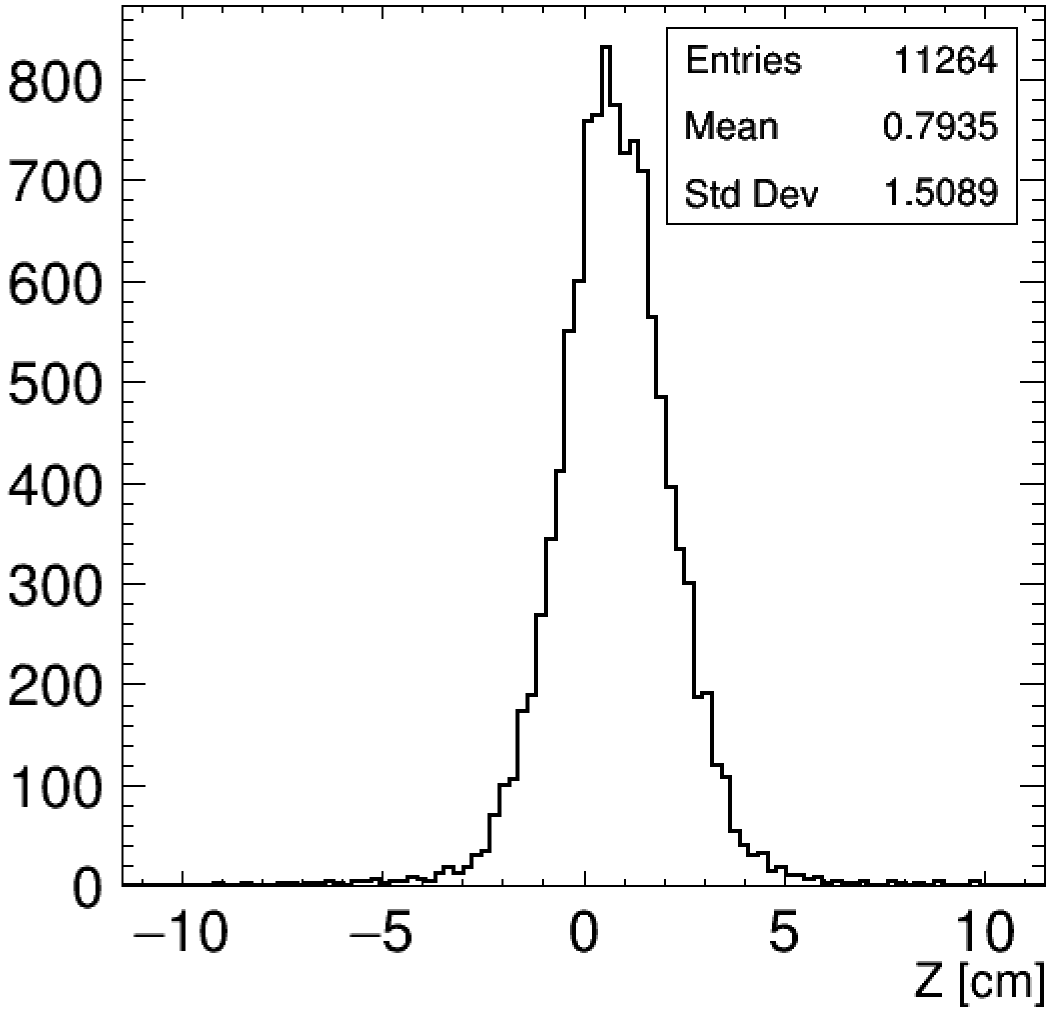
Aleksander Gajos

Supervised by:
prof. dr hab. Paweł Moskal

Co-supervised by:
dr Eryk Czerwiński

Cracow, 2018

Centre of the K_s vertex cut



Z in (0.8 +/- 4.5) cm