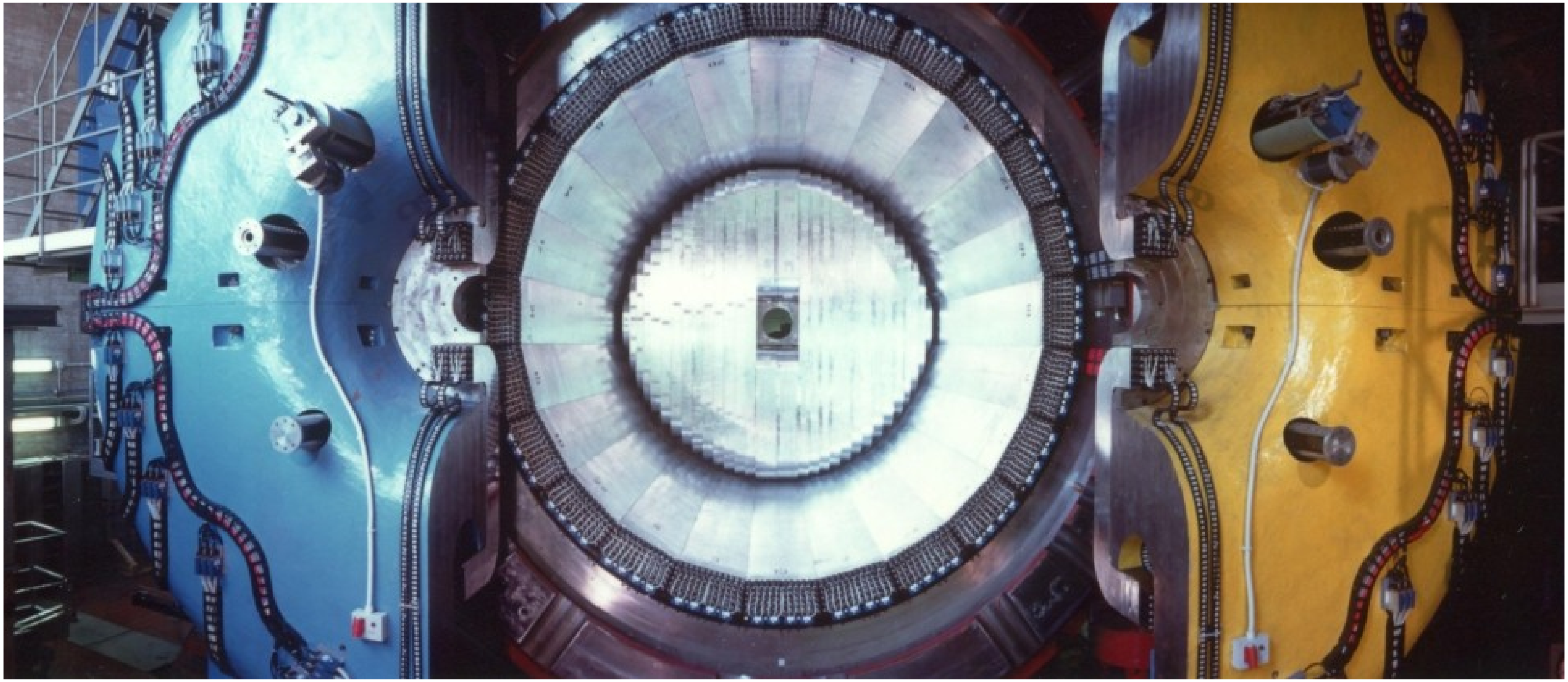
Studies of the K_S and K_L lifetimes and $BR(K^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-})$ with KLOE



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on behalf of the KLOE Collaboration

KAON09 Tsukuba June 9th 2009

** INFN and University of "Roma Tre"*

Outline

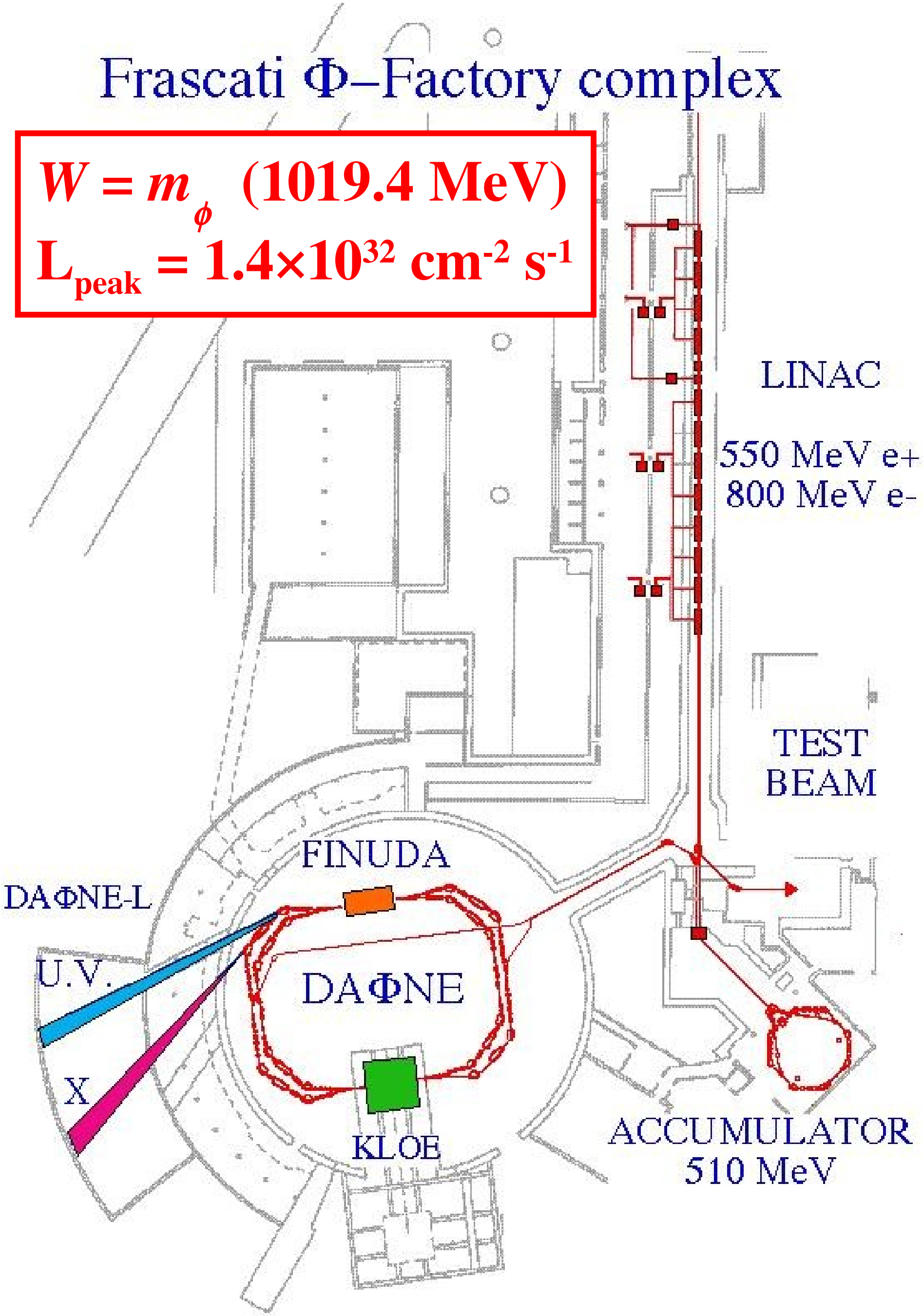
- DAΦNE and KLOE experiment

- study of the K_S lifetime

- K_L lifetime: preliminary update with new data

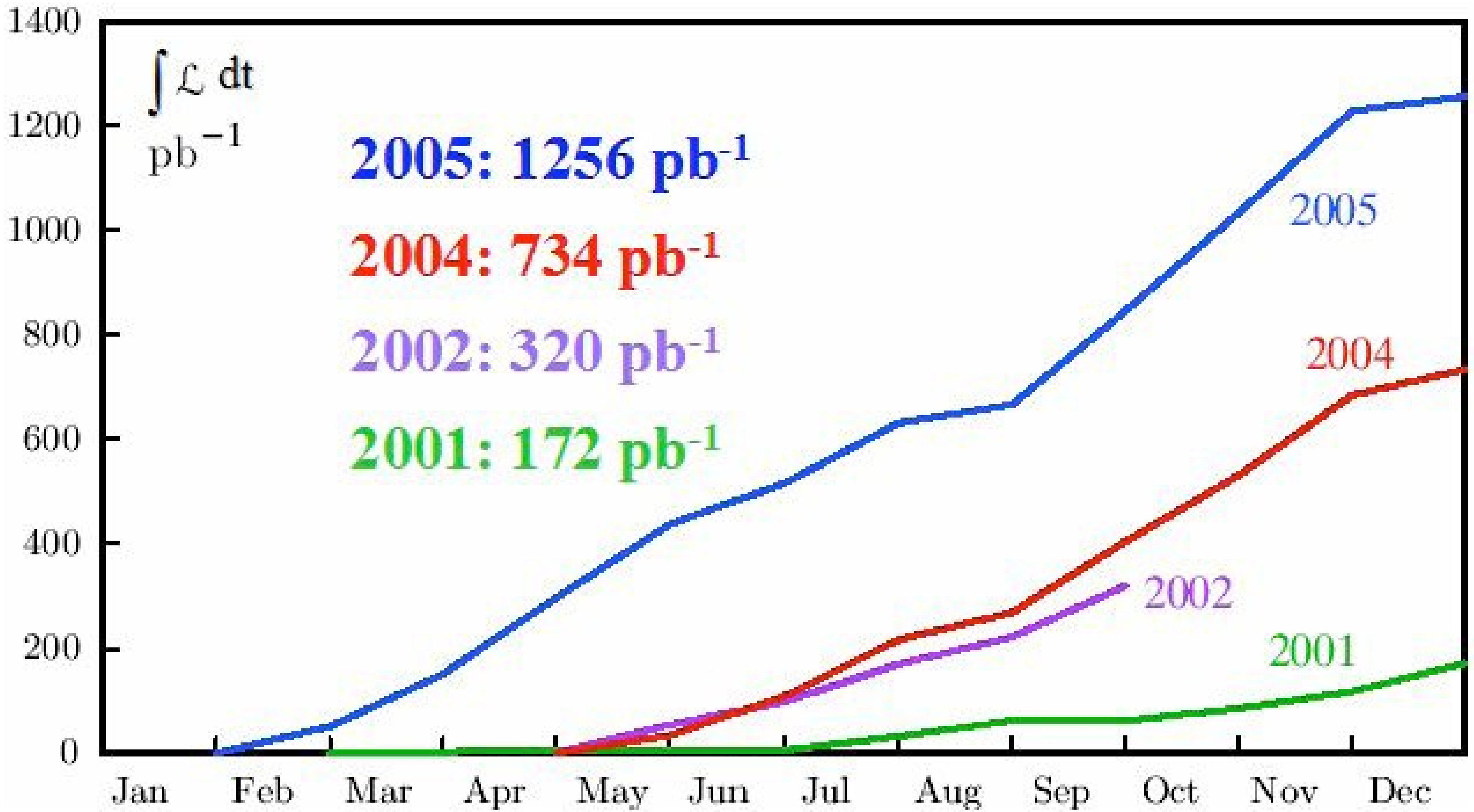
- study of the BR($K^+ \rightarrow \pi^+ \pi^- \pi^+$)

The DAΦNE e^+e^- *collider*



- **Collisions at cm energy around $\sqrt{s}$ ~1019.4 MeV (m_ϕ)**
- **Angle between the beams @ IP: α ~π-2*12.5 mrad**
- **Residual laboratory momentum of ϕ: p_ϕ~13 MeV**
- **Cross section for ϕ production @ peak: σ_ϕ ~ 3.1μb**

Summary of KLOE data taking



Integrated luminosity L = 2.5 fb^{-1}

about 2.5×10^{9} K_SK_L; 3.6×10^{9} K^+K^-

Kaon Physics at the ϕ resonance

the ϕ decay at rest provides monochromatic and pure kaon beams

they are produced in a pure $J^{PC} = 1^{--}$ state

$\sigma(e^+e^- \rightarrow \phi) \approx 3\,\mu b$ $\qquad K_S, K^+ \longleftarrow \phi \longrightarrow K_L, K^-$

detection of a K_S (K_L) guarantees the presence of a K_L (K_S) with known momentum and direction (the same for K^+K^-) $\Rightarrow$ **tagging**

pure kaon beam obtained $\Rightarrow$ normalization (N_{tag}) sample

$\Rightarrow$ allows precision measurements of absolute BRs

K^+K^-

BR $\simeq$ 49%

p_{lab} = 127 MeV/c

$\lambda_{\pm}$ = 95 cm

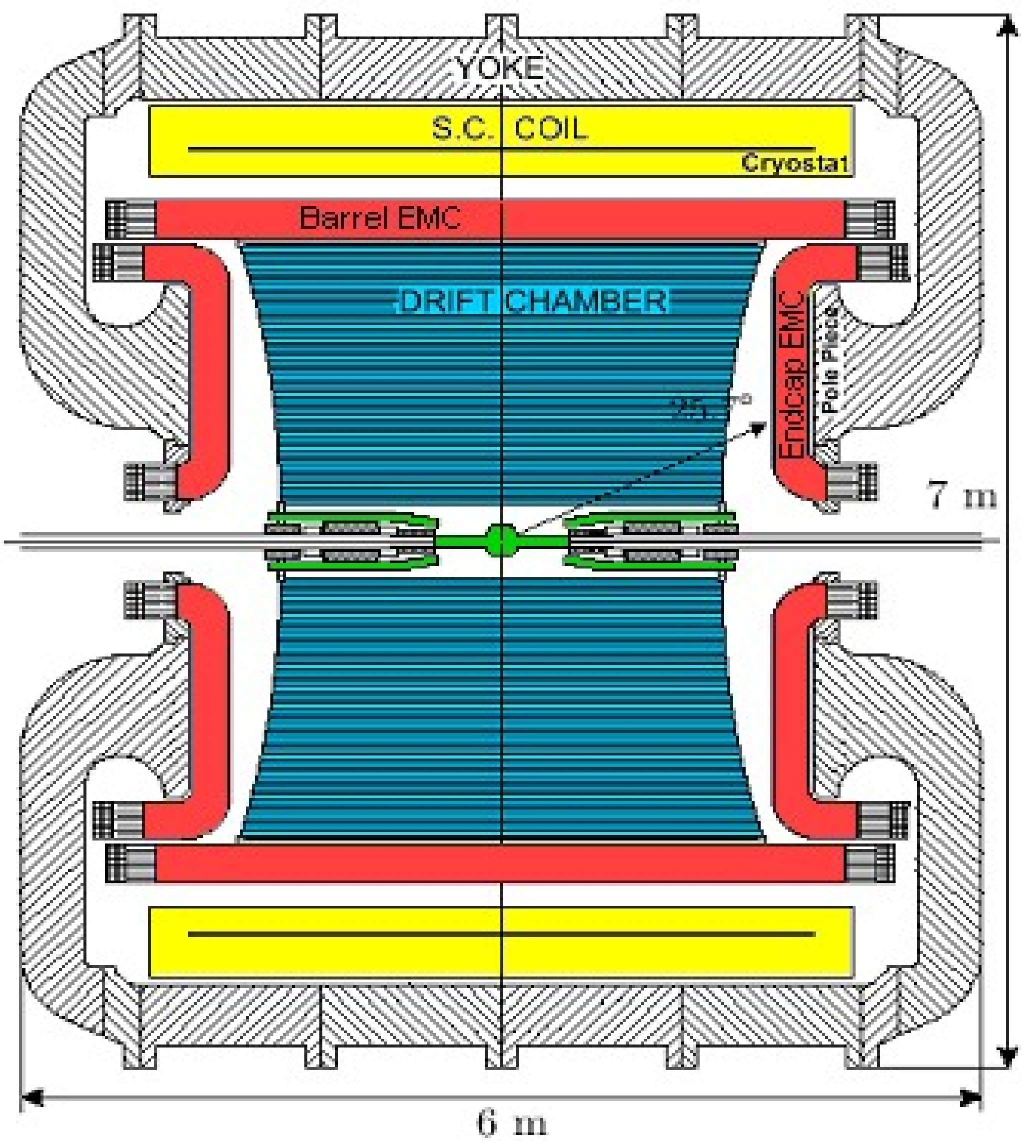
K_LK_S

BR $\simeq$ 34% ; p_{lab} = 110 MeV/c

λ_S = 0.6 cm K_S decays near interaction point

λ_L = 340 cm Large detector to keep reasonable acceptance for K_L decays (~0.5 λ_L)

The KLOE experiment



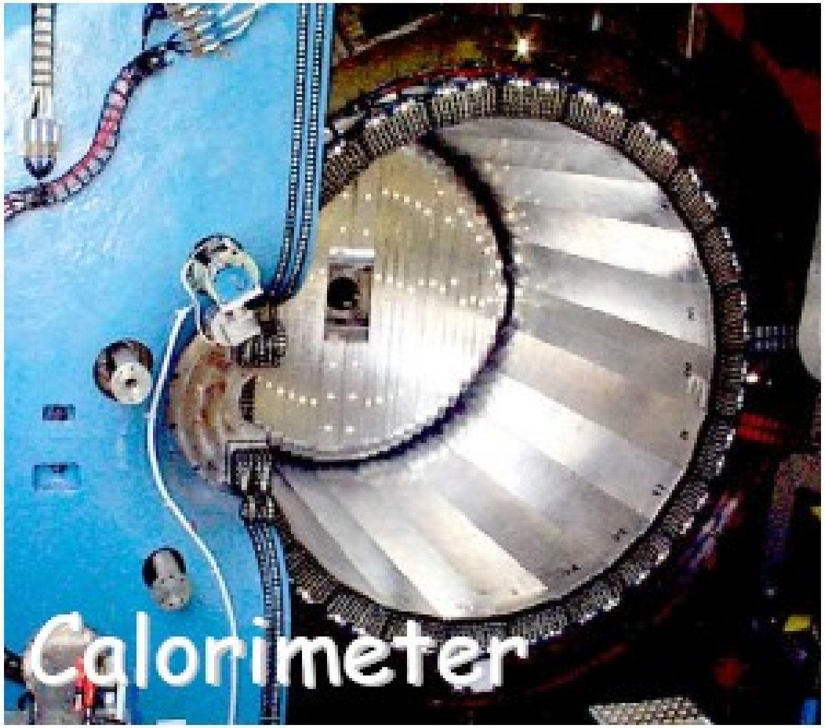
Be beam pipe (0.5 mm thick), r =10 cm (K_S fiducial volume)
Instrumented permanent magnet quadrupoles (32 PMT's)

Drift chamber (4 m Ø × 3.3 m)
90% He + 10% IsoB, CF frame
12582 stereo sense wires

Electromagnetic calorimeter
Lead/scintillating fibers
4880 PMT's, cover 98% of the solid angle

Superconducting coil
B = 0.52 T ($\int B dl$ = 2 T·m)

KLOE detector performance



$\sigma_E/E \cong 5.7\% / \sqrt{E(GeV)}$

$\sigma_t \cong 57\ ps / \sqrt{E(GeV)} \oplus 140\ ps$

$\sigma_{\gamma\gamma} \sim 2$ cm (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

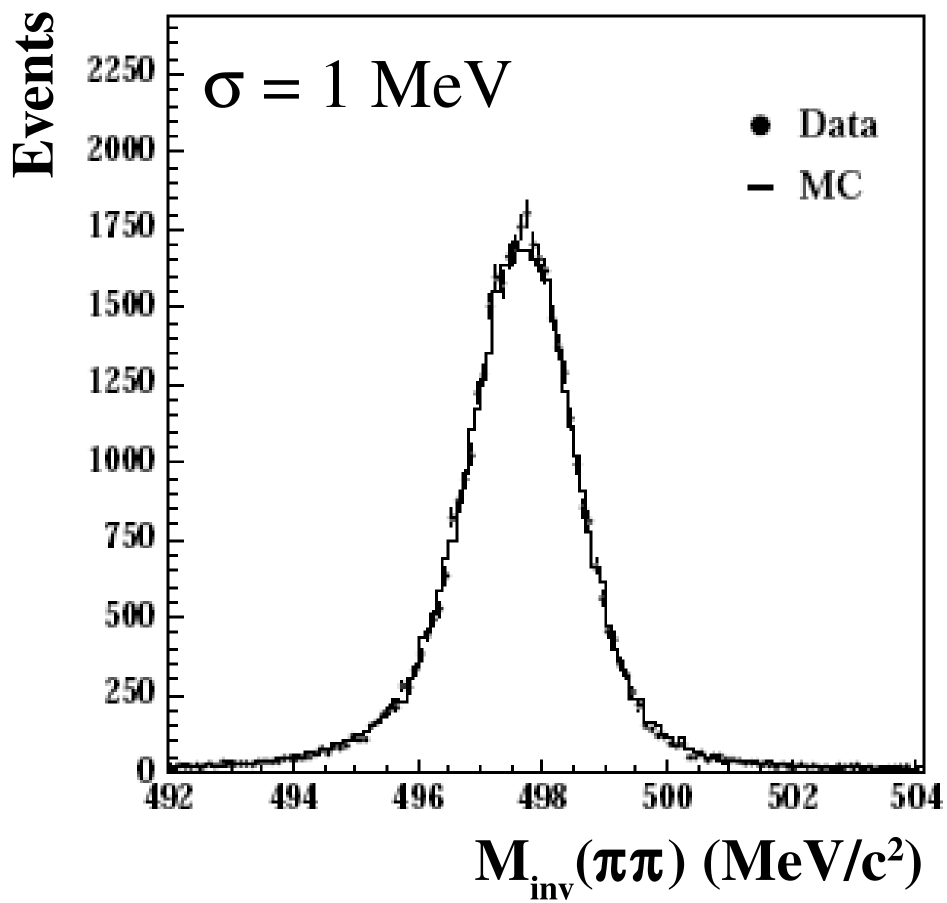
$\sigma_p/p \cong 0.4\ \%$ (tracks with $\theta > 45°$)

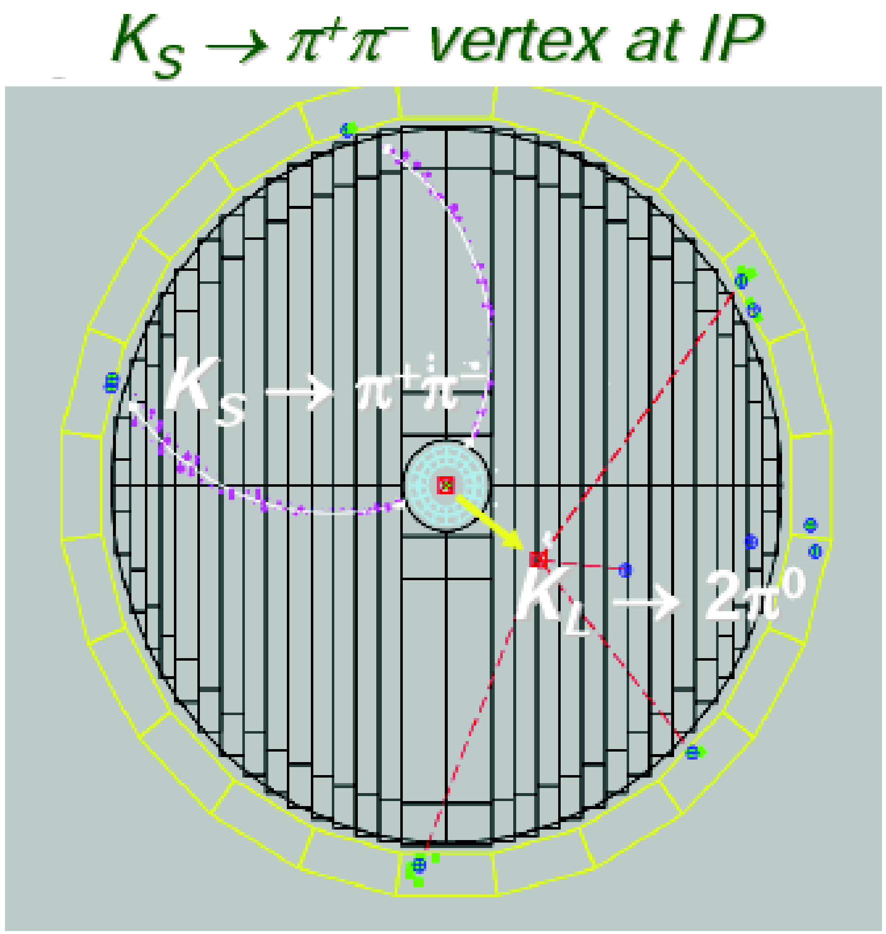
$\sigma_x^{hit} \cong 150\ \mu m\ (xy),\ 2\ mm\ (z)$

$\sigma_x^{vertex} \sim 3$ mm

Reconstruction of $K_S \to \pi^+\pi^-$

$K_S \to \pi^+\pi^-$ decay selection:
- 2 tracks of opposite sign
- invariant mass consistent with M_K





ε ~70% (mainly geometrical)

K_S angular resolution ~ 1°

K_S momentum resolution of 1 MeV from track momenta $\mathbf{p}_{KS}=\mathbf{p}_{\pi+}+\mathbf{p}_{\pi-}$

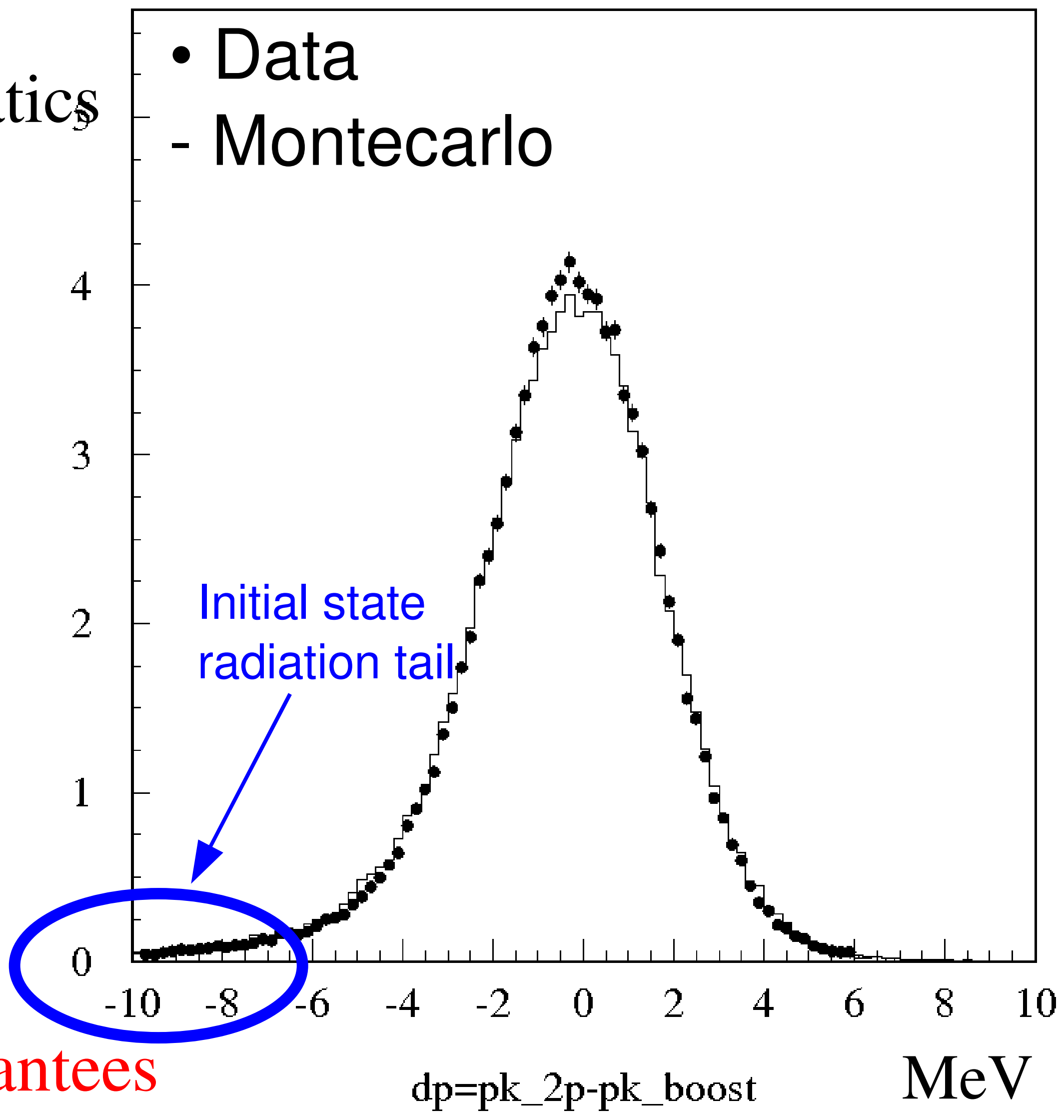
K_S momentum determination

At a ϕ-factory, we have a redundant $\mathbf{p}_{KS}$ measurement

For each event we measure:

1) $\mathbf{p}_{KS}$ from √s and from kinematics of ϕ → KK two-body decay resolution ~ 1 MeV dominated by beam energy spread

2) $\mathbf{p}_{KS}$ from pion momenta measurements in the drift chamber σ ~ 1 MeV



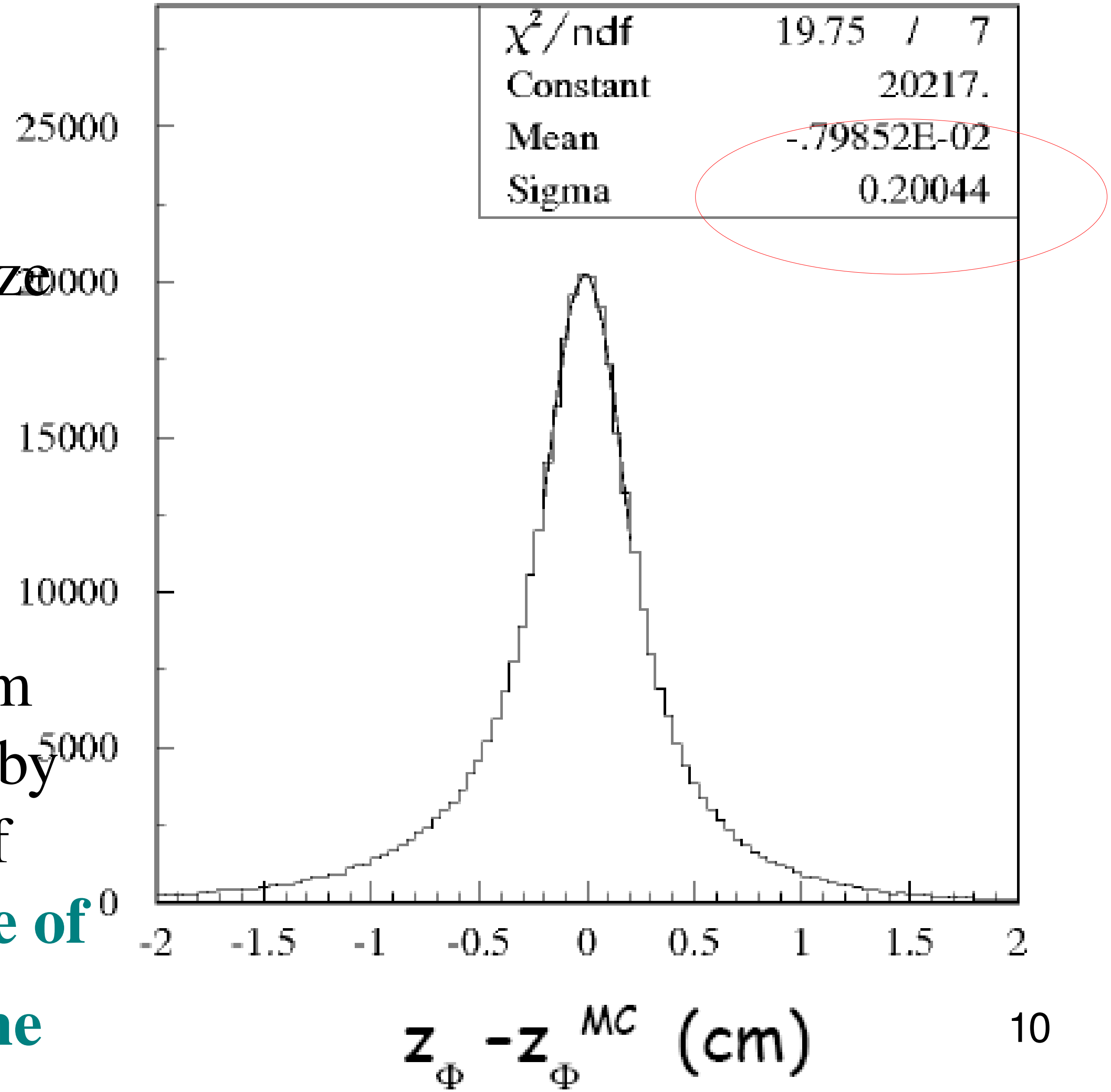
Requiring consistency between momentum measurements guarantees good track quality

ϕ *decay point*

Average ϕ decay point determined with Bhabha events on a run by run basis.

Resolution = beam spot size (σ_x~1mm, σ_y=O(10 μm), σ_z ~ 1.5 cm)

A better determination of decay point along the beam line (z) is evaluated event by event by using the point of closest approach of **K_S line of flight** to the **beam axis line**



K_S lifetime

Measurement of the K_S lifetime

Motivation:

- first measurement with **pure K_S beam** and with an **event-by-event** knowledge of K_S momentum
- KLOE is well suited to perform τ_S measurement as a function of sidereal time which is interesting to test QM, CPT and Lorentz invariance
- $\mathbf{V_{us}}$ from K_S with KLOE data (we measured BR(K_se3) at 1.3%, we can reach 0.5% on the whole data set)

Method:

lifetime obtained from fit to proper time t^* distribution of $K_S \to \pi^+ \pi^-$ decay

$$t^* = \frac{L}{\beta \gamma c} = \frac{L M_K}{pc}$$

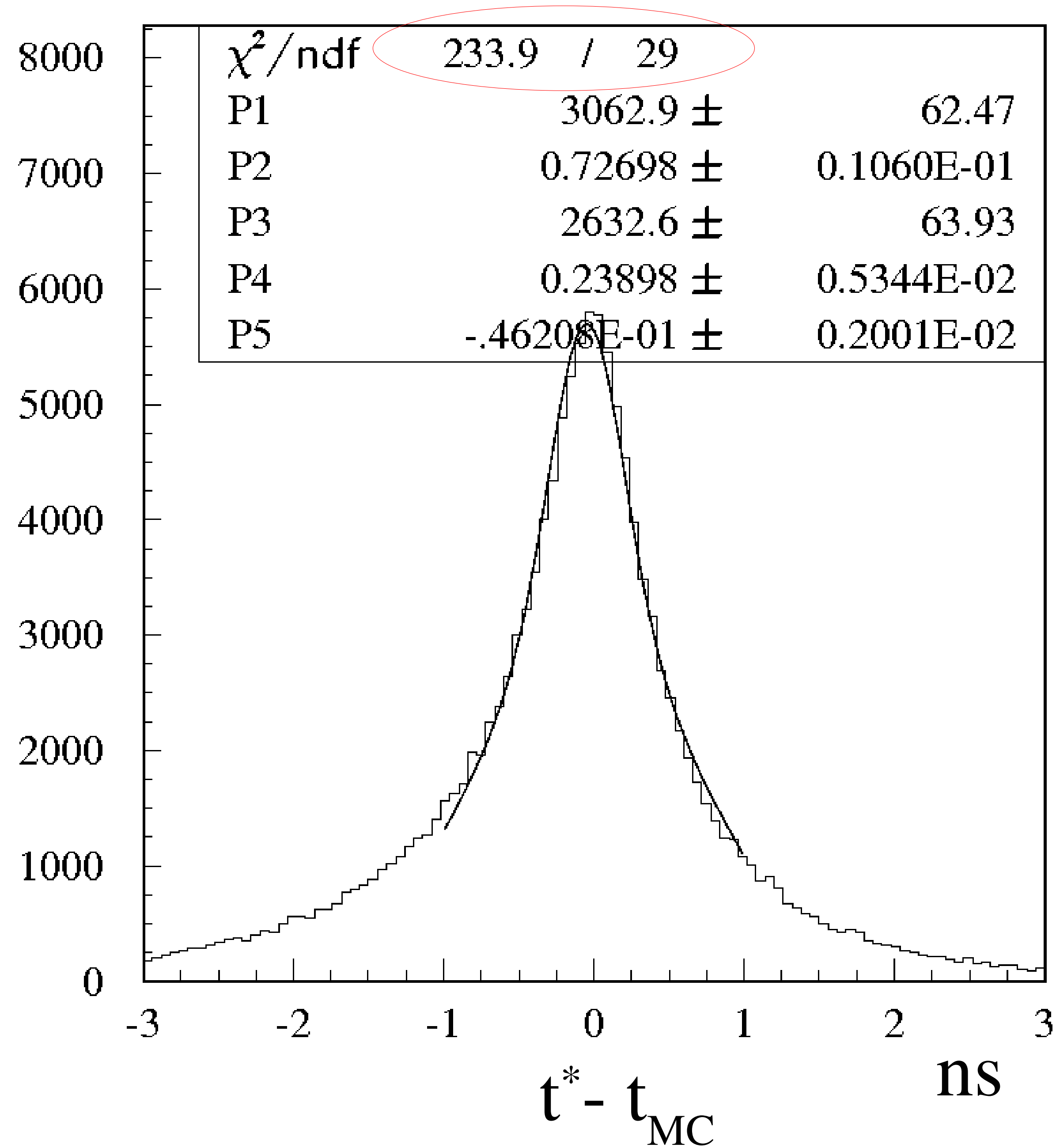
Raw Time resolution

$$t^* = \frac{L}{\beta\gamma c} = \frac{LM_K}{pc}$$

This first attempt produces a resolution function *not centered around zero*

→ not appropriate
for a < 0.1% measurement!

So see next transparency...



Improvement of K_S decay length resolution

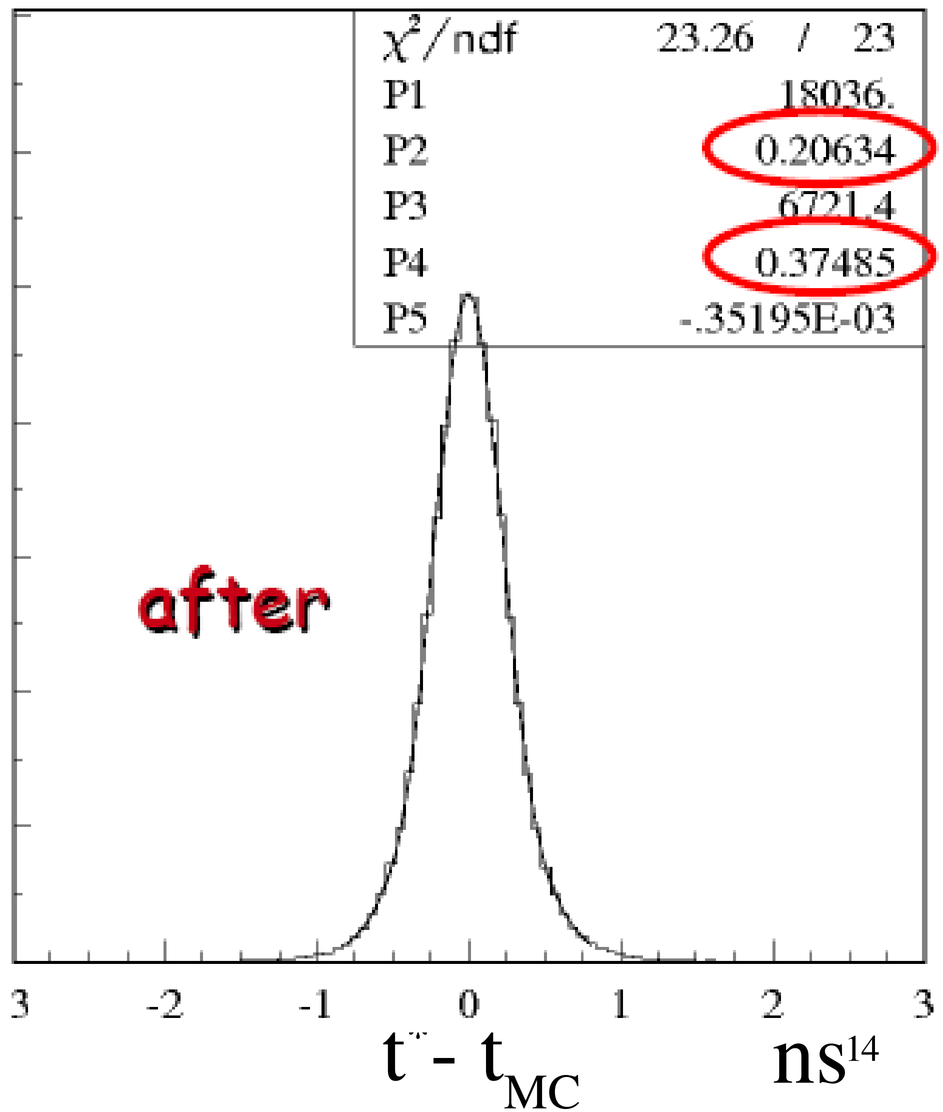
1) Further improve reconstruction of IP event-by-event using full geometrical fit

2) Optimize the selection criteria, requiring pions to decay at large angle with respect to the K_S line of flight

3) Use only well measured tracks: cut on the χ^2 value from the track fit

20 million events selected in 600 pb^{-1}

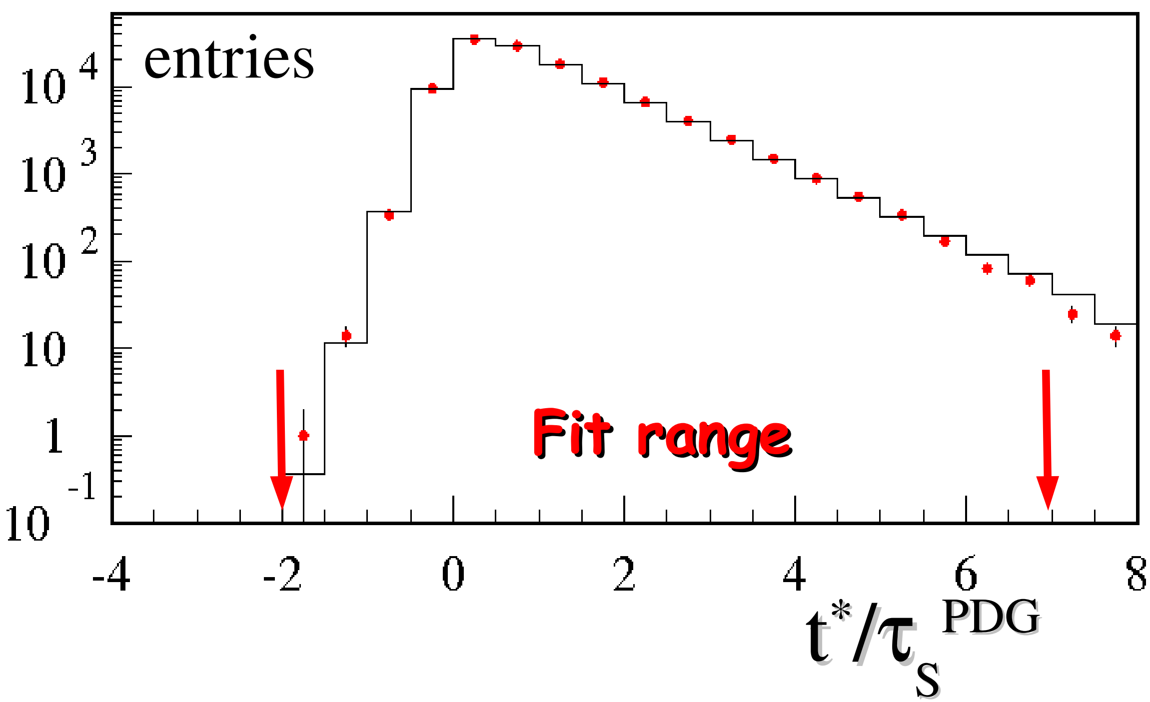
Path length resolution improved by factor of 3

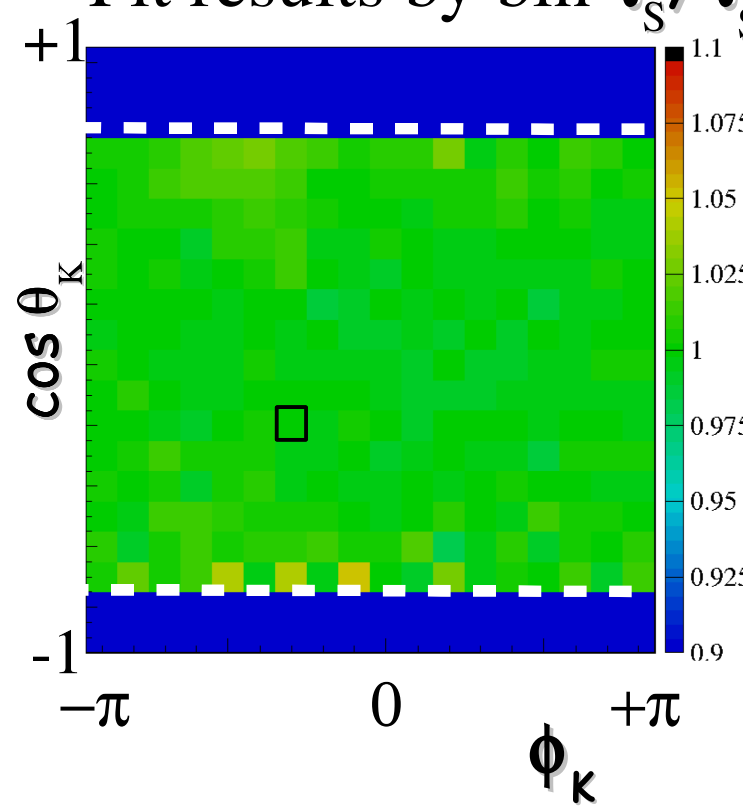


Fit to the lifetime

Since resolution depends on K beam direction, fit is done for each of 270 bins in $\cos\theta_K$ and ϕ_K.

This is also necessary to measure τ_S as a function of sidereal coordinates





Fit range: from -2 to 7 t^*/τ_S

Fit function: exponential convoluted with two gaussians

(5 parameters: lifetime, 2 normalizations, 2 widths)

Systematics

Source	Value (τ/τ_S x 10^{-4})
Selection cuts	3.3
$\cos\theta_K$ cut	5.7
Momentum calibration	0.4
Fit range	5.0

We expect a total error competitive with the precise measurements from KTeV and NA48

K_L lifetime with $K_L \rightarrow \pi^0\pi^0\pi^0$ decay channel

K_L lifetime measurement

direct measurement: ($d\tau/\tau \sim 0.6\%$) $\tau_L = (50.92 \pm 0.17 \pm 0.25)$ ns

uses 10 M $K_L \rightarrow \pi^0\pi^0\pi^0$ events from 2001-2002 data

PLB 626 (2005) 15

indirect measurement: $\tau_L = (50.72 \pm 0.11 \pm 0.35)$ ns

uses constraint $\sum BR(K_L)=1$

PLB 632 (2006) 43

The error on τ_L is now the main limiting factor on V_{us} accuracy from K_L decay rates:

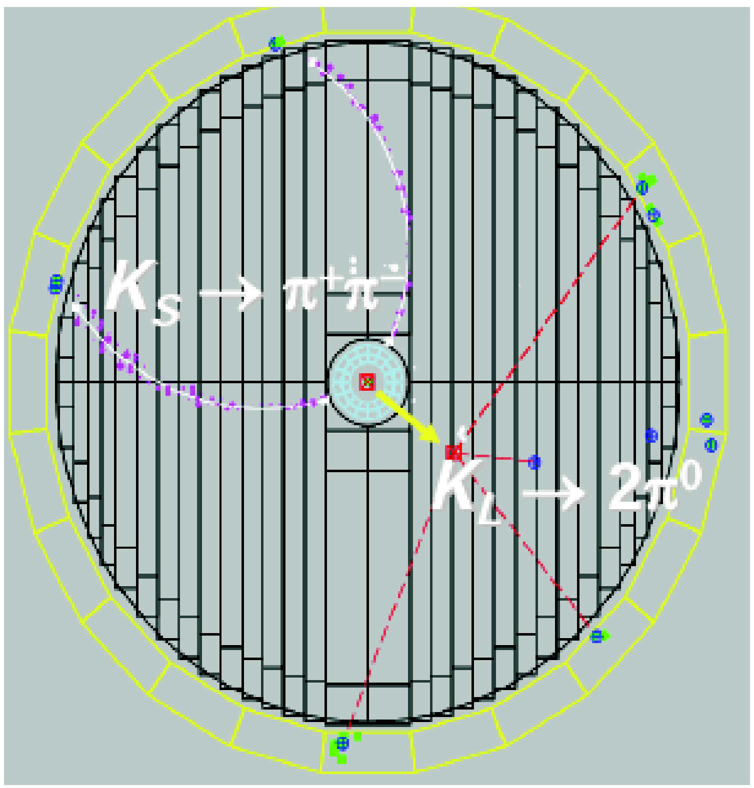
$$BR/\tau = \Gamma(K \rightarrow \pi \ell \nu(\gamma)) = \frac{G^2 m_K^5}{768\pi^3} C_K^2 \, |V_{us}|^2 \, |f_+^{K\pi}(0)|^2 \, I_K^\ell \, S_{ew} \, \left[1 + \delta_{SU(2)} + \delta_{em}\right]$$

τ_L direct measurement can be improved both in statistical and systematic accuracy using the 2004-05 data sample

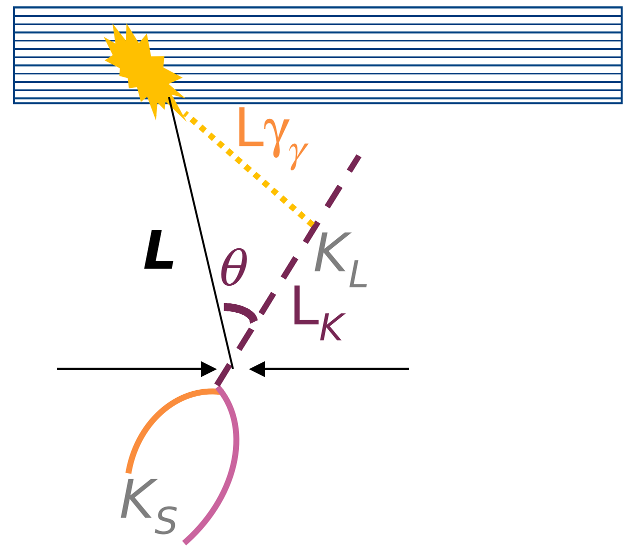
$\delta(V_{us} f_+(0))/(V_{us} f_+(0)) =$	0.1% $\oplus$	0.2% $\oplus$	0.1% $\oplus$	0.1%
	BR	τ_L	Radiative corrections	Phases space integral

$K_L \to \pi^0\pi^0\pi^0$ decay vertex

Reconstruction of $K_S \to \pi^+\pi^-$ determines K_L momentum within 1 MeV and 1 degree



Vertex reconstruction from the neutral clusters on the calorimeter



$$t_{clu} = \frac{L_K}{\beta_K c} + \frac{L_\gamma}{c}$$

$$L^2 + L_K^2 - 2\,L\,L_K \cos\theta = L_\gamma^2$$

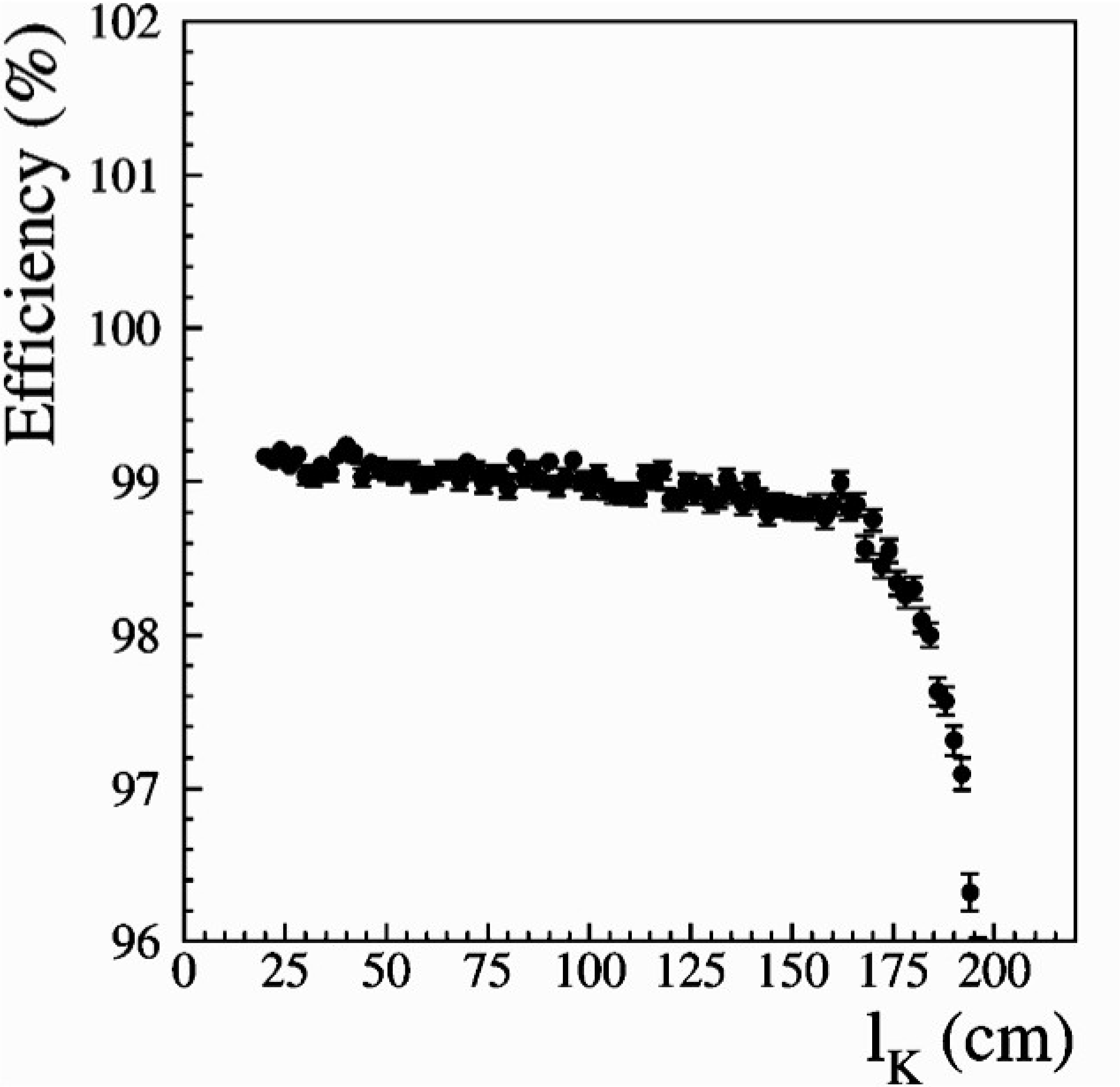
Can extract L_K, L_γ

Neutral vertex reconstruction efficiency

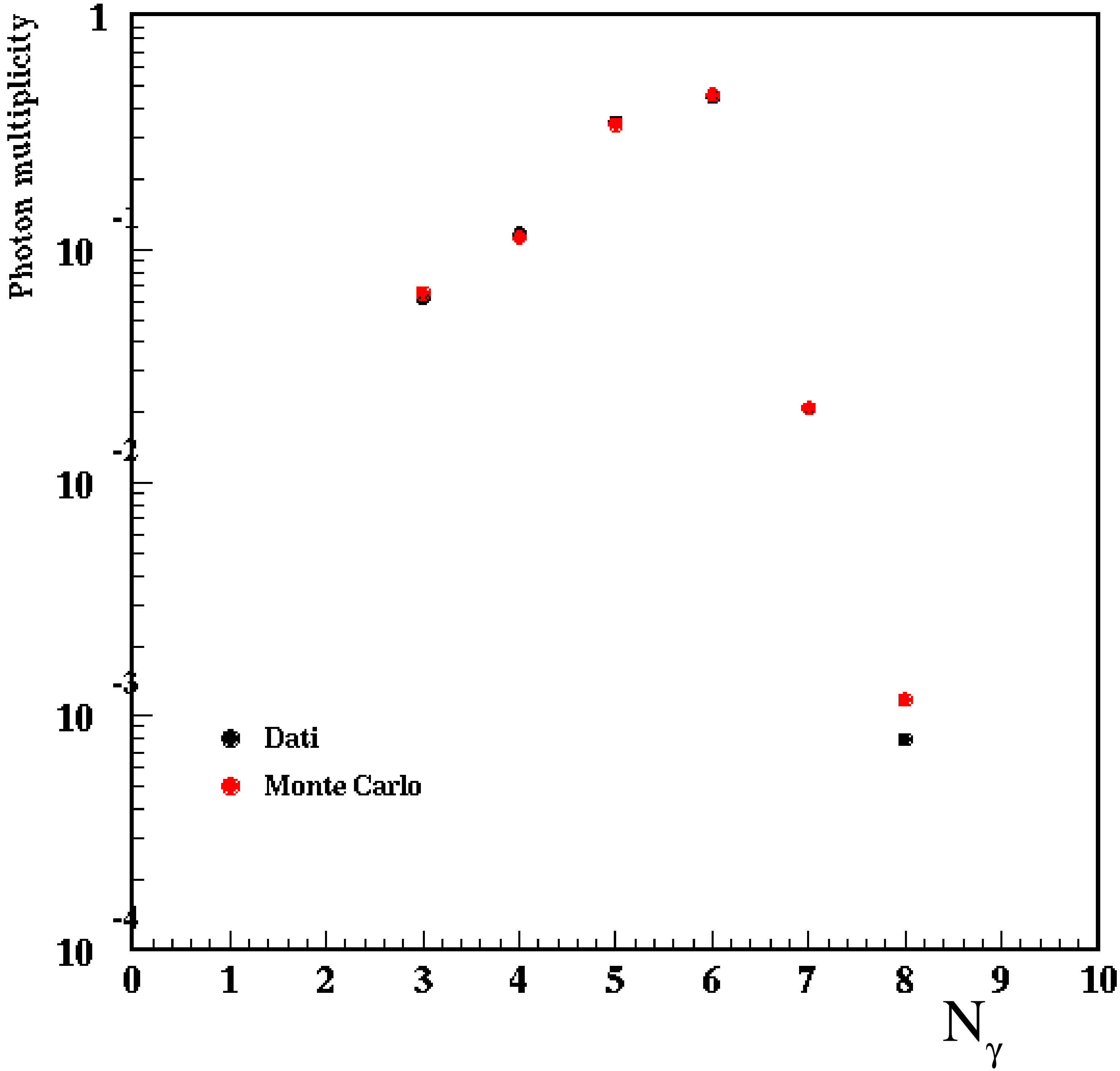
Multiphoton vertex evaluated from vertices given by the neutral clusters on the EmC

To reconstruct the K_L vertex, we require at least 3 photons from the $\pi^0\pi^0\pi^0$ decay

Reconstruction efficiency for $K_L \rightarrow \pi^0\pi^0\pi^0$ with $N_\gamma \geq 3$ is high and uniform over a broad interval in L_K



Photon multiplicities

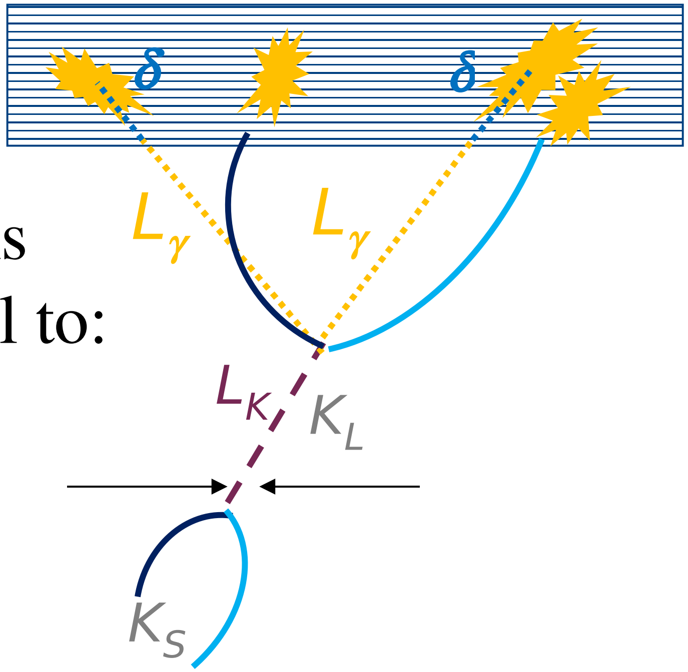


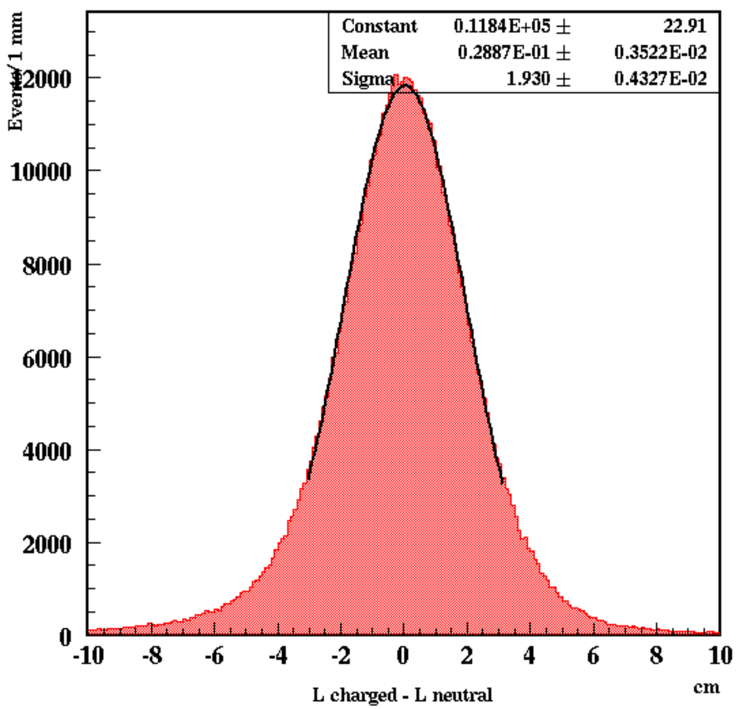
Only retain N≥3
for the analysis

Neutral vertex calibration

Use of a control sample of $K_L \rightarrow \pi^+\pi^-\pi^0$ decays allows comparison between the vertex given by the reconstructed pion tracks and the neutral vertex, which is fundamental to:

1) calibrate the time scale
2) study the neutral vertex resolution





$$\Delta R = R_{cha} - R_{neu}$$

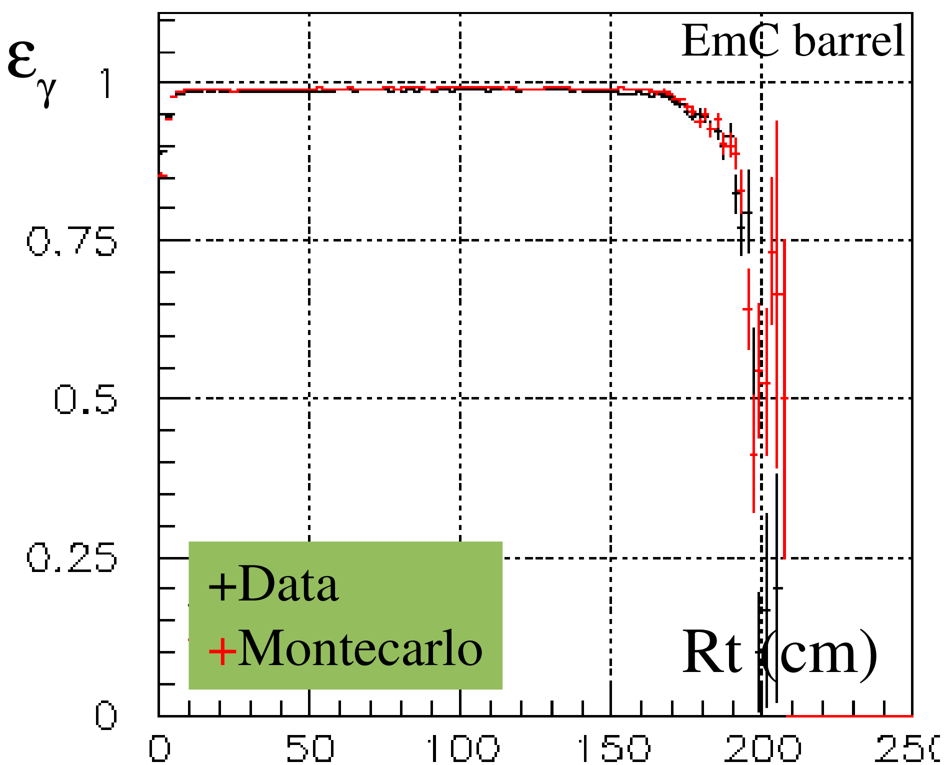
Spatial resolution ~ 2 cm

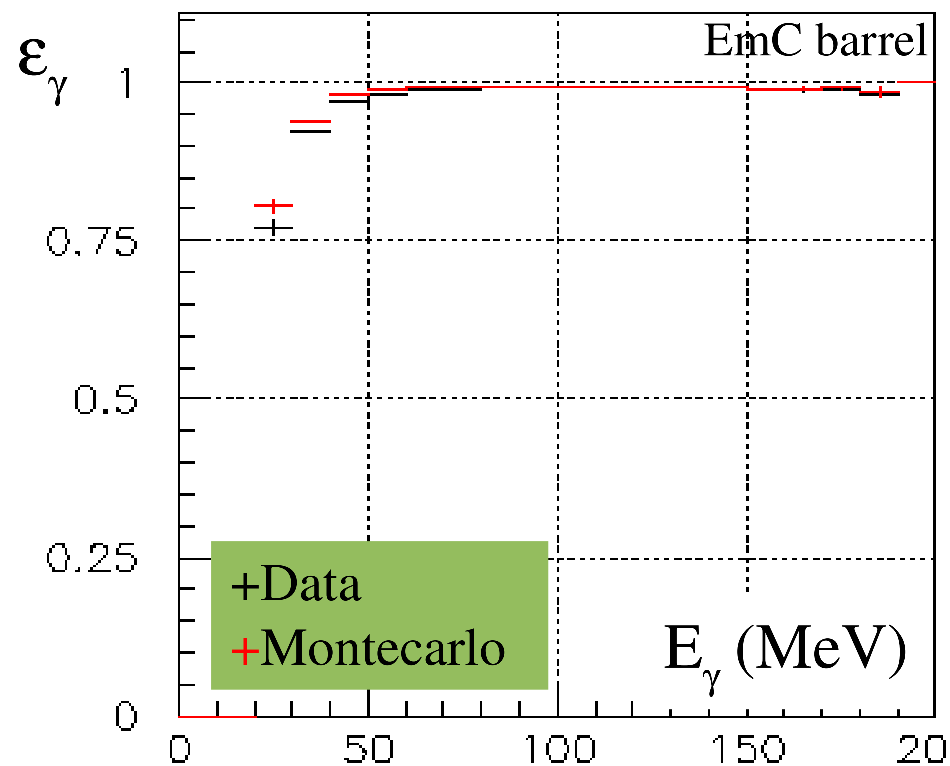
Single γ reconstruction efficiency

Use of the control sample $K_L \rightarrow \pi^+\pi^-\pi^0$ allow to measure the vertex reconstruction efficiency from the single photon

$$\varepsilon_\gamma = \frac{N_{\gamma\, rec}}{N_{\gamma\, tag}}$$

- $N_{\gamma\, rec}$ → Number of events in which a second photon is detected where we expect to find from kinematics
- $N_{\gamma\, tag}$ → Number of events in which at least one photon is detected

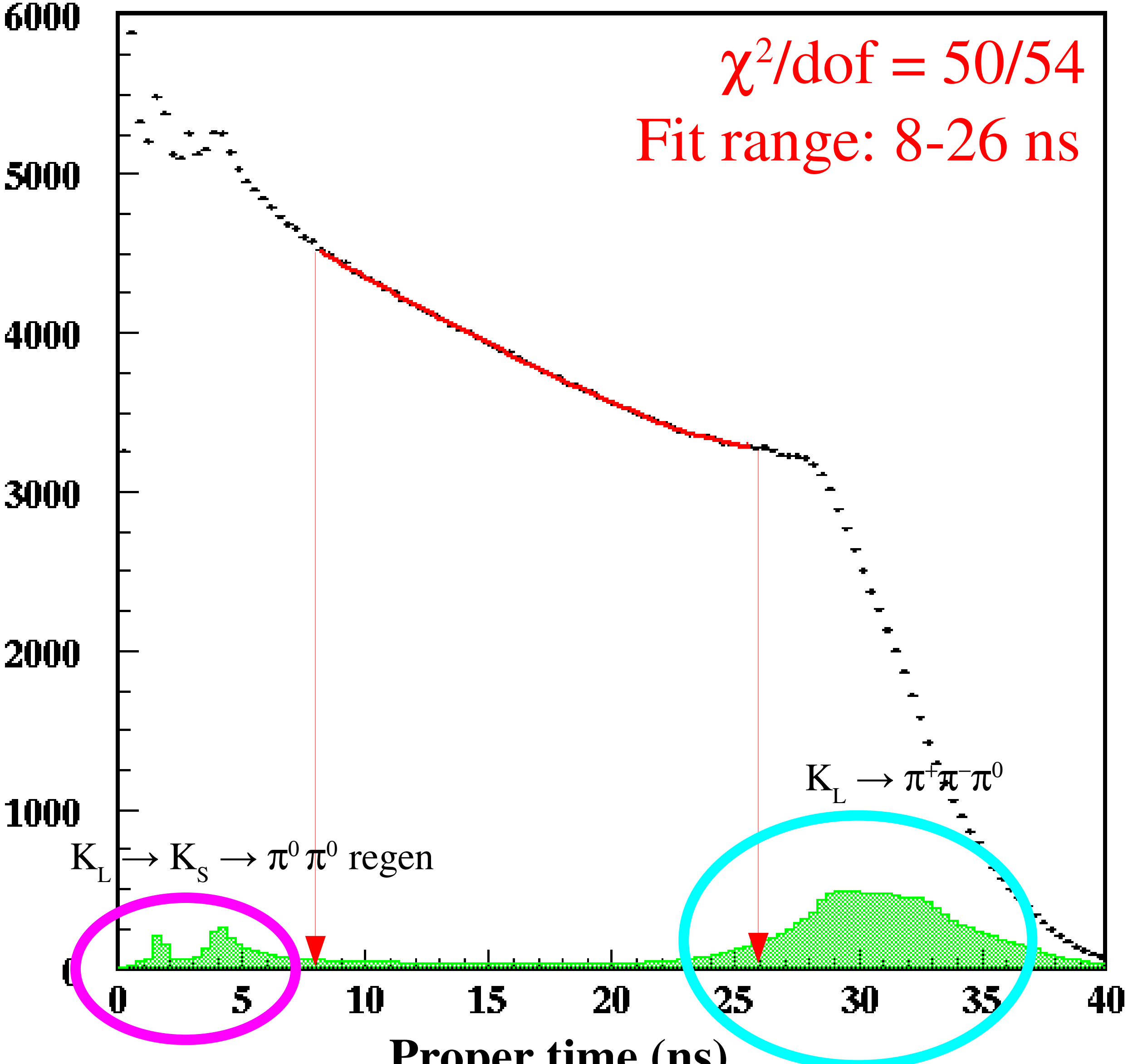




We correct the MC efficiency with the ratio $\varepsilon_{data}/\varepsilon_{MC}$

Fit result

Fit performed with $f(t^*) = \epsilon_{sel}(t^*)\, N \cdot e^{-t^*/\tau} + f_{bck}\, B(t^*)$

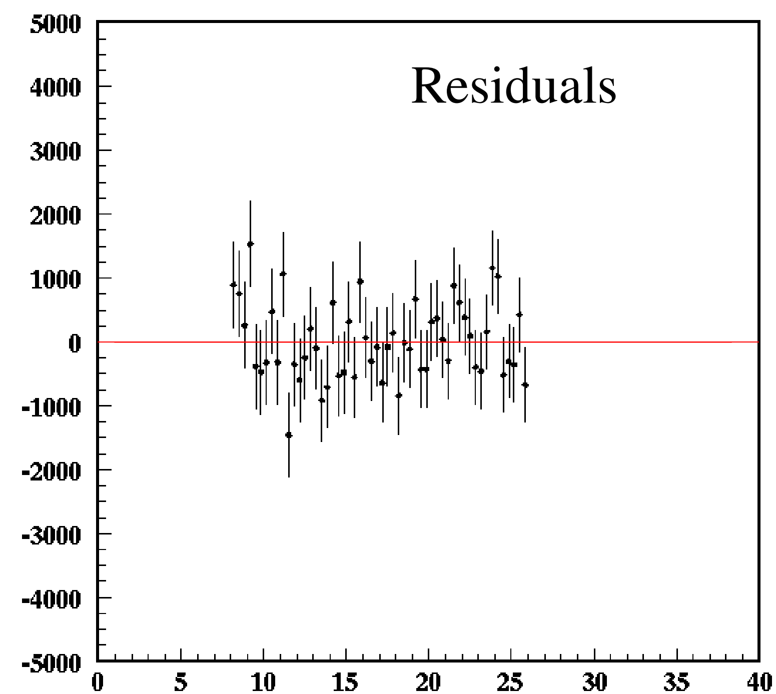


In the fit region:

data events: 46 millions

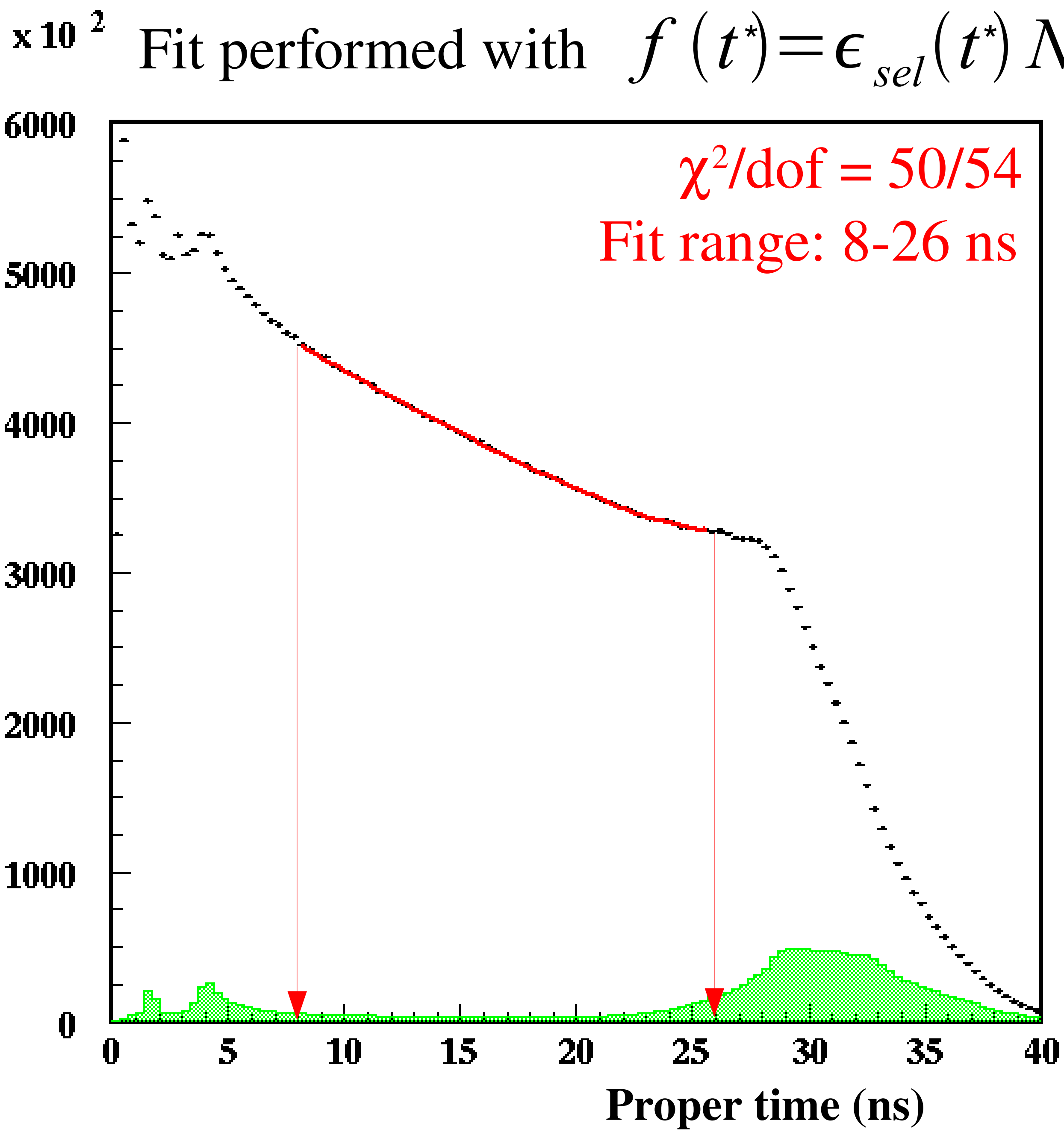
background after cuts: 1.81%

$1.1\,pb^{-1}$



Fit result

Fit performed with $f(t^*) = \epsilon_{sel}(t^*) N_0 e^{-t^*/\tau} + f_{bck} B(t^*)$



Fit result:

$\tau_L = (50.56 \pm 0.14)$ ns

Statistical error can be improved by decreasing the lower limit of the fit region (taking into account of the K_L beam losses on the regenerating surfaces)

Systematics

Source	$\Delta\tau/\tau$	$\Delta\tau$
Tag efficiency	0.34%	0.17 ns
Preselection efficiency	0.16%	0.08 ns
Selection efficiency	*negligible*	*negligible*
Time scale	0.12%	0.06 ns
Nuclear interaction	0.16%	0.08 ns
Total		0.21 ns

Preliminary

$$\tau_L = (50.56 \pm 0.14_{stat} \pm 0.21_{syst})\ \text{ns}$$

K_L lifetimes

Comparison with previous KLOE measurements:

$\tau_L = (50.92 \pm 0.17_{stat} \pm 0.13_{syst\ uncorr} \pm 0.27_{syst\ corr})$ ns

KLOE
PLB 626 (2005)

$\Delta=1.4\sigma$, taking into account the correlation between syst. errors

$\tau_L = (50.72 \pm 0.11_{stat} \pm 0.35_{syst})$ ns $\quad \sum_i BR_i = 1$

KLOE
PLB 635 (2006)

$\Delta=0.4\sigma$

Preliminary

$$\tau_L = (50.56 \pm 0.14_{stat} \pm 0.21_{syst}) \text{ ns}$$

For final result:

1) add 2004 data set $\sigma_{stat} \rightarrow 0.11$ ns

2) reduce systematic error on the tagging efficiency

Absolute $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ *branching ratio*

Tagging K^+K^- beams

$K^\pm$ beam tagged from

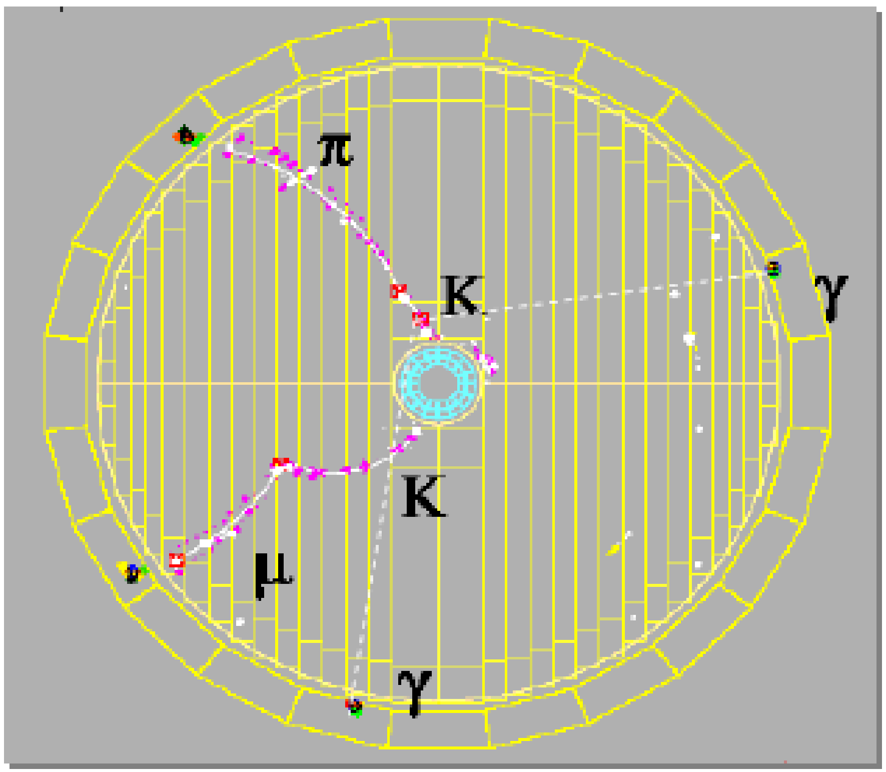
$K^\pm \rightarrow \pi^\pm\pi^0,\ \mu^\pm\nu$ (85% of $K^\pm$ decays)

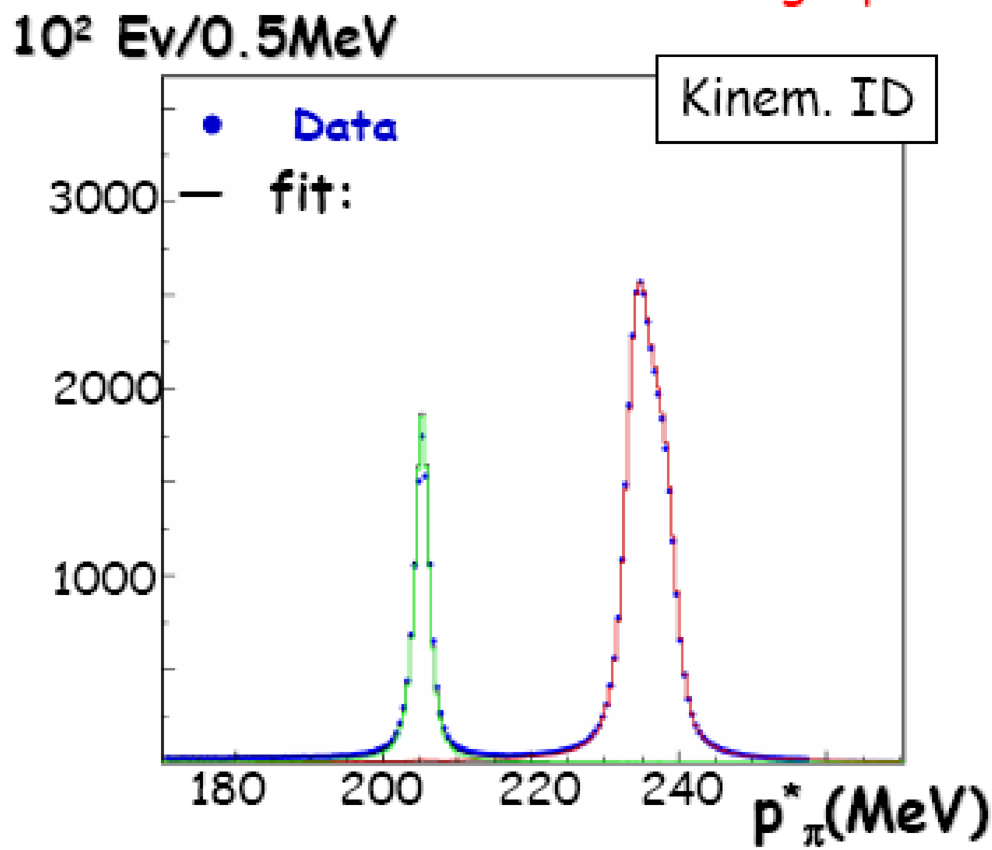
$\cong 1.5 \times 10^6\ K^+K^-$ evts/pb^{-1}

two-body decays identified as peaks in the momentum spectrum of secondary tracks in the kaon rest frame → $P^*(m_\pi)$

$\varepsilon_{tag} \cong 25\% \Rightarrow \cong 3.4 \times 10^5\ \mu\nu$ tags/pb^{-1}

$\cong 1.1 \times 10^5\ \pi\pi^0$ tags/pb^{-1}





Absolute BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$)

- *this measurement completes the KLOE program of precise and fully inclusive $K^\pm$ dominant BR's*

$K^+ \rightarrow \mu\nu$	0.6366(18)	0.3%	*PLB 632(2006)*
$K^+ \rightarrow \pi^+\pi^0$	0.2065(9)	0.5%	*PLB 666(2008)*
$K^\pm \rightarrow \pi^0 e^\pm \nu$	0.0497(5)	1.0%	*JHEP 02(2008)*
$K^\pm \rightarrow \pi^0 \mu^\pm \nu$	0.0324(4)	1.2%	*JHEP 02(2008)*
$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$	0.0176(3)	1.7%	*PLB 597(2004)*
$\tau^\pm$	12.347(30) ns	0.24%	*JHEP 01 (2008)*

- needed to perform a global fit to $K^\pm$ BR's
- available measurement dates back to '72 (no information on radiation cut-off)

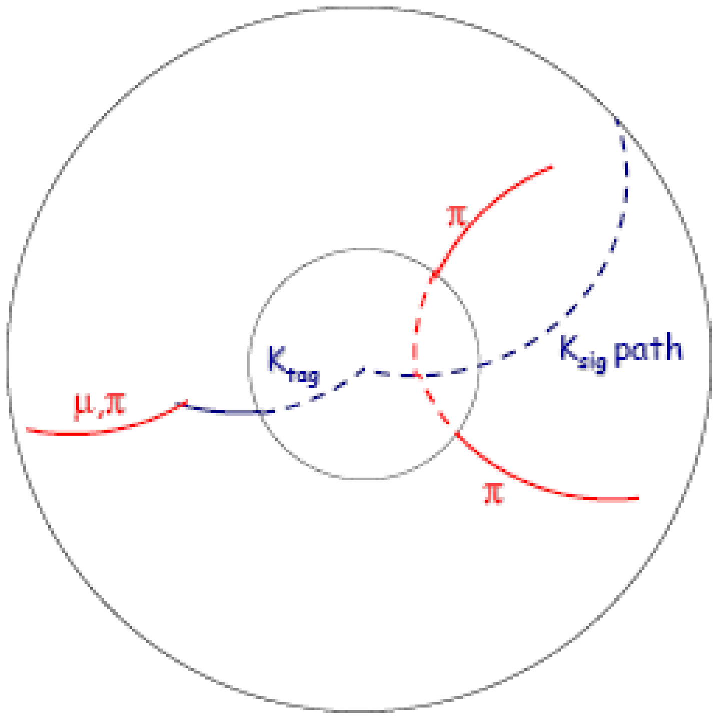
CHIANG $_{(2330\ \text{evts})}$ $BR(K \rightarrow \pi^+\pi^-\pi^+) = (5{,}56 \pm 0.20)\%$ $\Delta BR/BR = 3{,}6 \times 10^{-2}$

2002 KLOE data set enough to reach

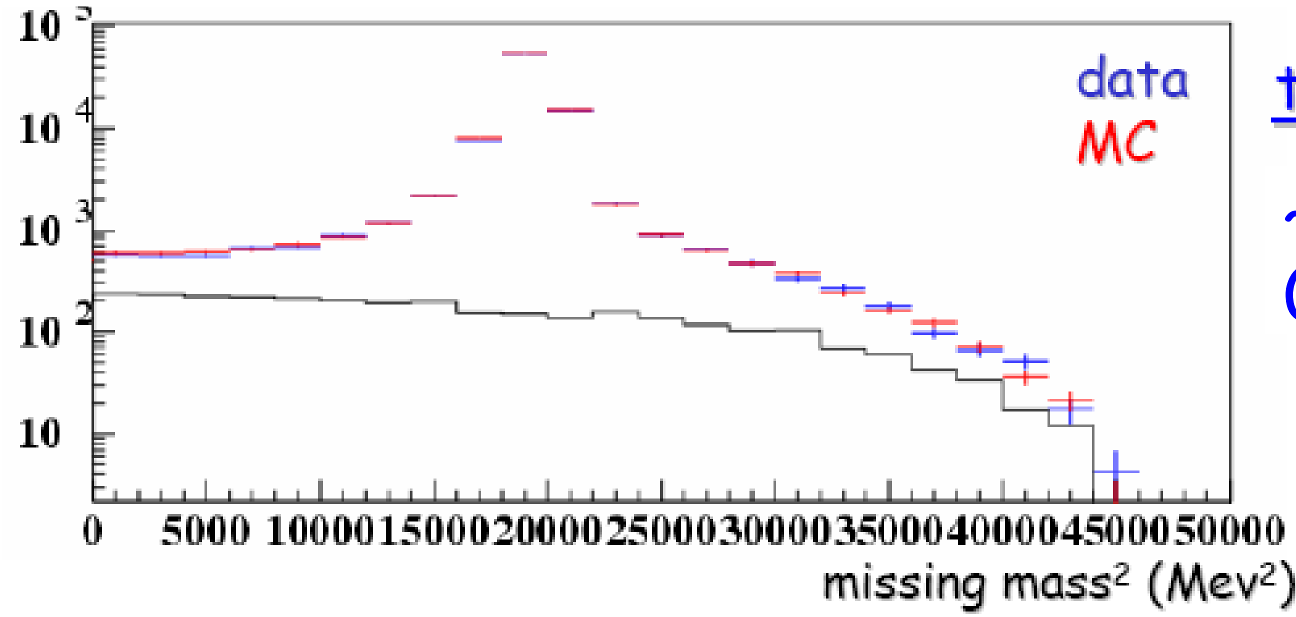
statistical relative error at few permil level

Signal selection

- 2 indipendent normalization samples given by the $\mu\nu$ and $\pi\pi^0$ tags
- the track of the **tagging K** is backward extrapolated to the IP
- the known kinematic of $\phi \to K^+K^-$ defines the signal K path (direction and momentum)
- we require two reconstructed tracks making a vertex along the K path *before the inner wall of the DC* ($\alpha_{geo} \approx 26$ %)
- we count the signal decays in the *missing mass spectrum*

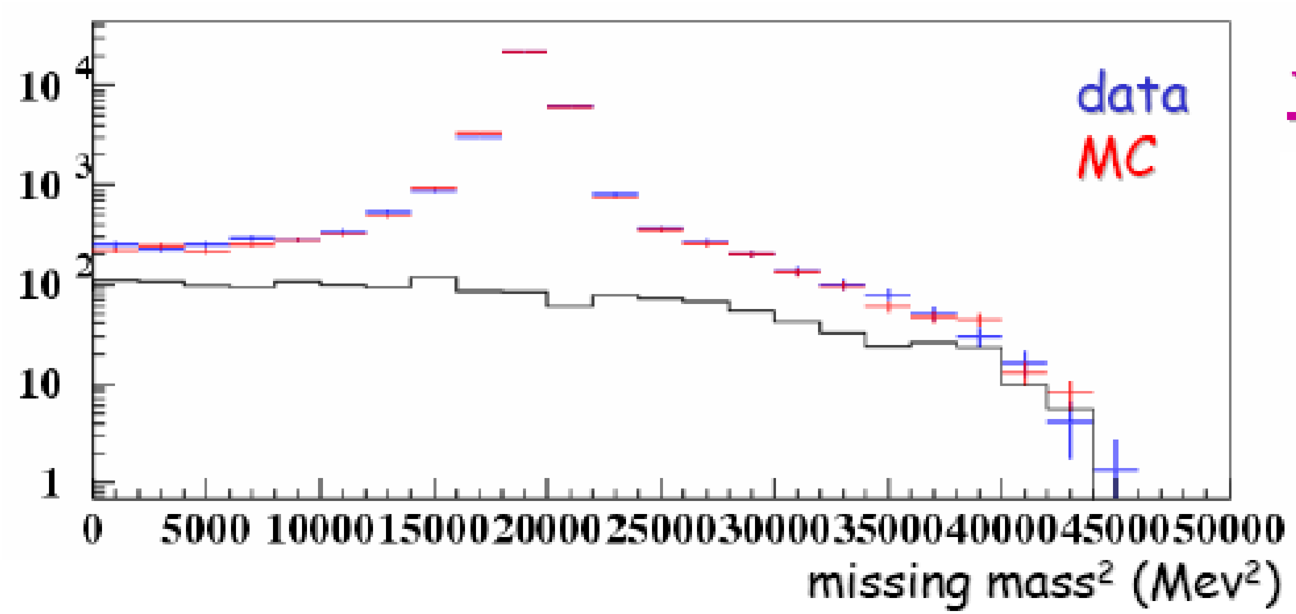


The selected sample



tag μν

~ 60000 $K^+ \rightarrow 3\pi$ events
(background subtracted)



tag $\pi\pi^0$

~ 25000 $K^+ \rightarrow 3\pi$ events
(background subtracted)

Signal selection efficiency

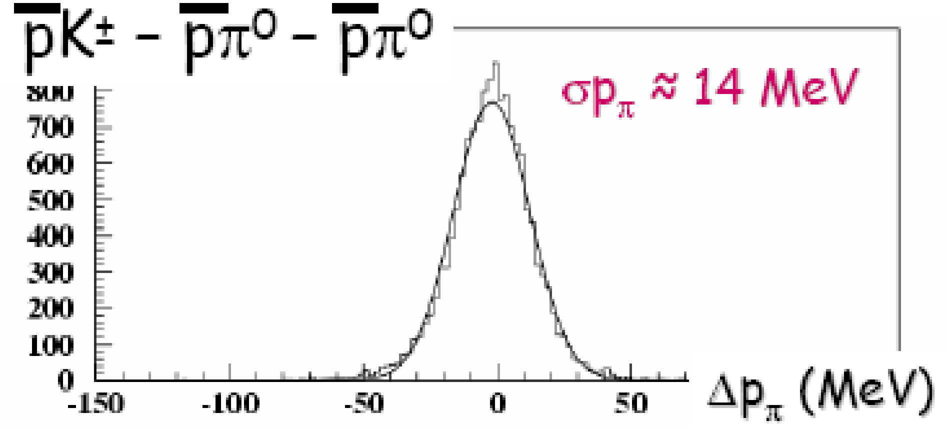
signal selection efficiency measured on MC and folded with $\frac{\varepsilon_{\text{single trk}}(\text{data})}{\varepsilon_{\text{single trk}}(\text{MC})}$

$K \to \pi \pi^0 \pi^0$ *control sample to measure* $\varepsilon_{\text{single trk}}$

control sample selection

- K path from the tagged K track and ϕ kinematic
- reconstruct neutral vertex $K \to \pi^0 \pi^0 X$ decays looking for 4 γ's with time measurements

$\overline{p}\pi^{\pm} = \overline{p}K^{\pm} - \overline{p}\pi^0 - \overline{p}\pi^0$



the purity of the sample is $\cong$ 99%

Conclusions

KLOE will soon have a competitive result on the measurement of τ_S taking advantage of pure sample of $K_S \rightarrow \pi^+\pi^-$ and precise determination of event kinematics

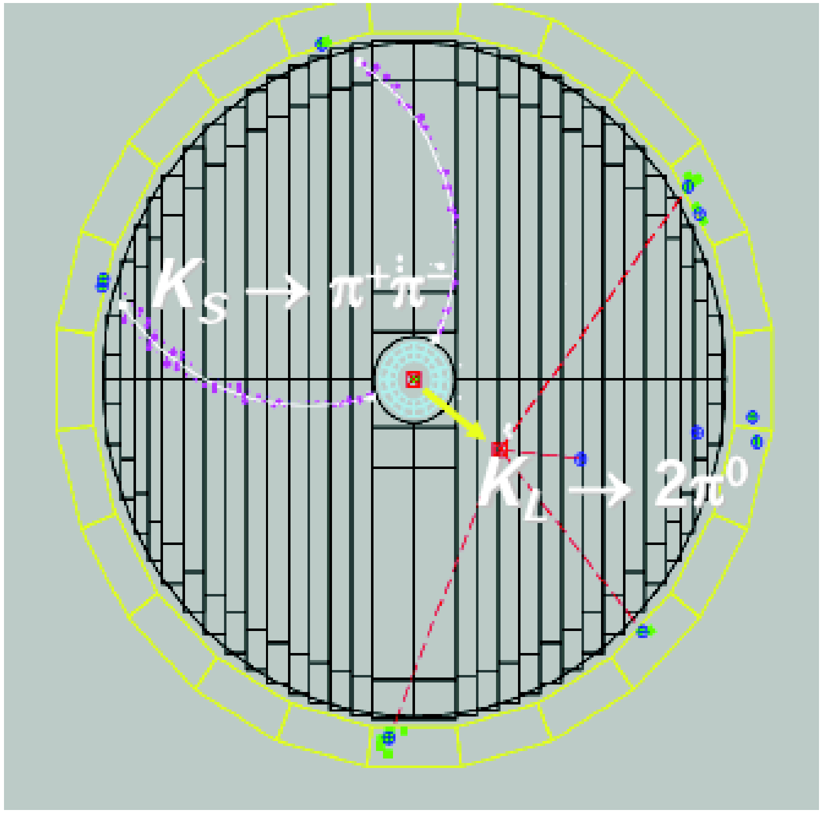
KLOE has a new preliminary measurement of τ_L based on 2005 data. The final measurement will include 2004 data and will have a significantly reduced systematic error

We are finalizing the measurement of the absolute $BR(K^+ \rightarrow \pi^+\pi^-\pi^+)$; this will allow to constrain the sum of the dominant K^+ decay modes

Spare slides

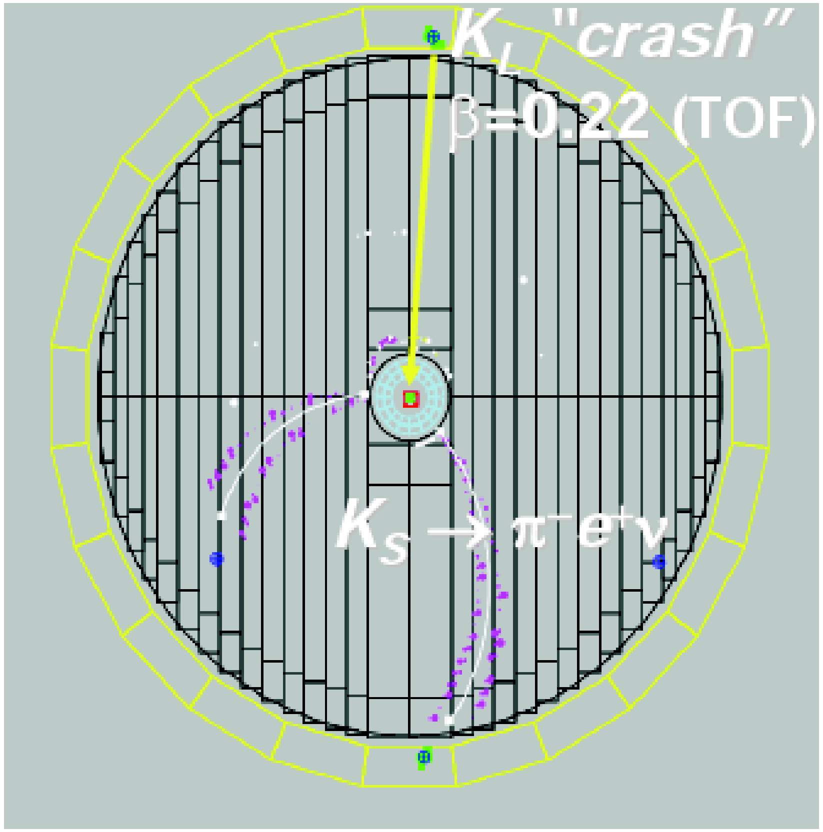
Tagging of $K_S K_L$ beams

K_L tagged
by $K_S \to \pi^+\pi^-$ vertex at IP



ε ~ 70% (mainly geometrical)
K_L angular resolution: ~ 1°
K_L momentum resolution: ~ 1 MeV

K_S tagged
by K_L interaction in EmC



ε ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in ϕ)
K_S momentum resolution: ~ 1 MeV

Tagging of K^+K^- beams (II)

to minimize the impact of the trigger efficiency on the signal side we restrict our normalization sample N_{tag} to 2-body decays that provide themselves the Emc trigger of the event **self-triggering tags**

Emc trigger given by 2 trigger sectors over threshold ~ 50 MeV

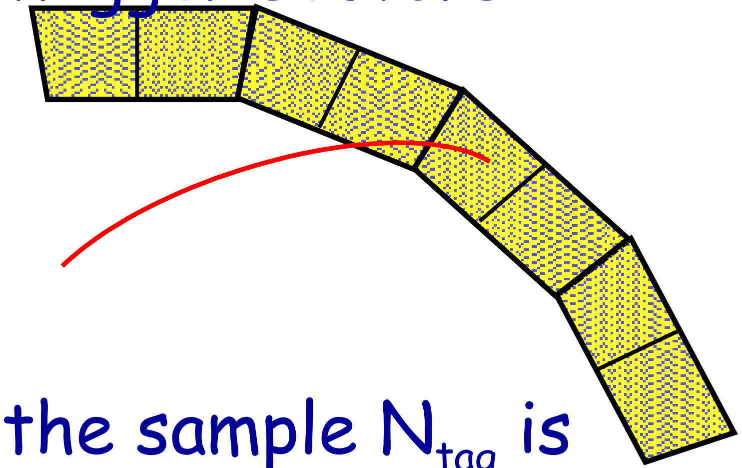
tag $\pi\ \pi^0$

π^0 clusters must satisfy the Emc trigger

the sample N_{tag} is reduced by $\cong$ 75%

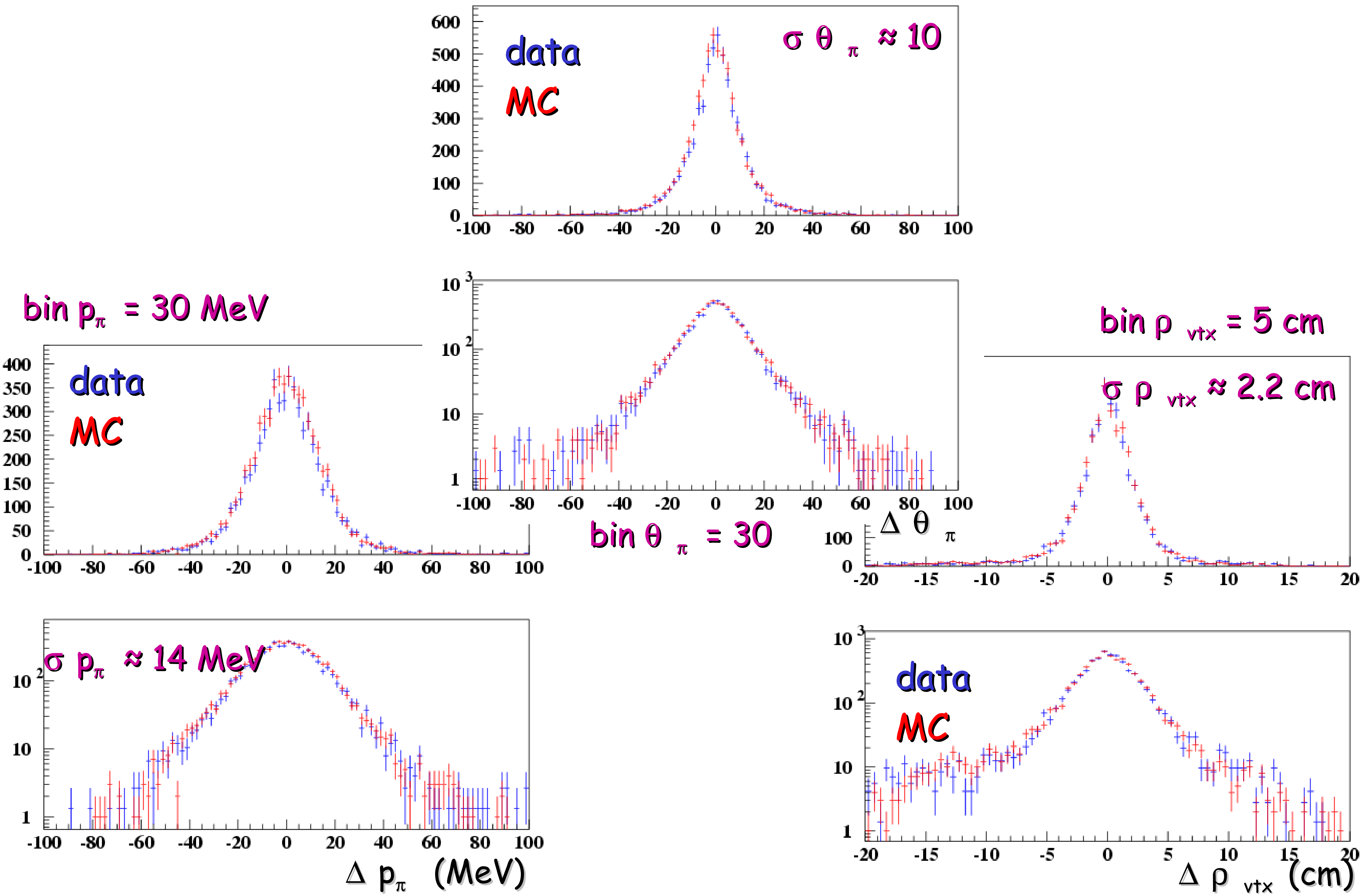
tag $\mu\ \nu$

the μ cluster fires 2 trigger sectors



the sample N_{tag} is reduced by $\cong$ 35%

resolutions: neutral VTX vs DC reconstructed quantities

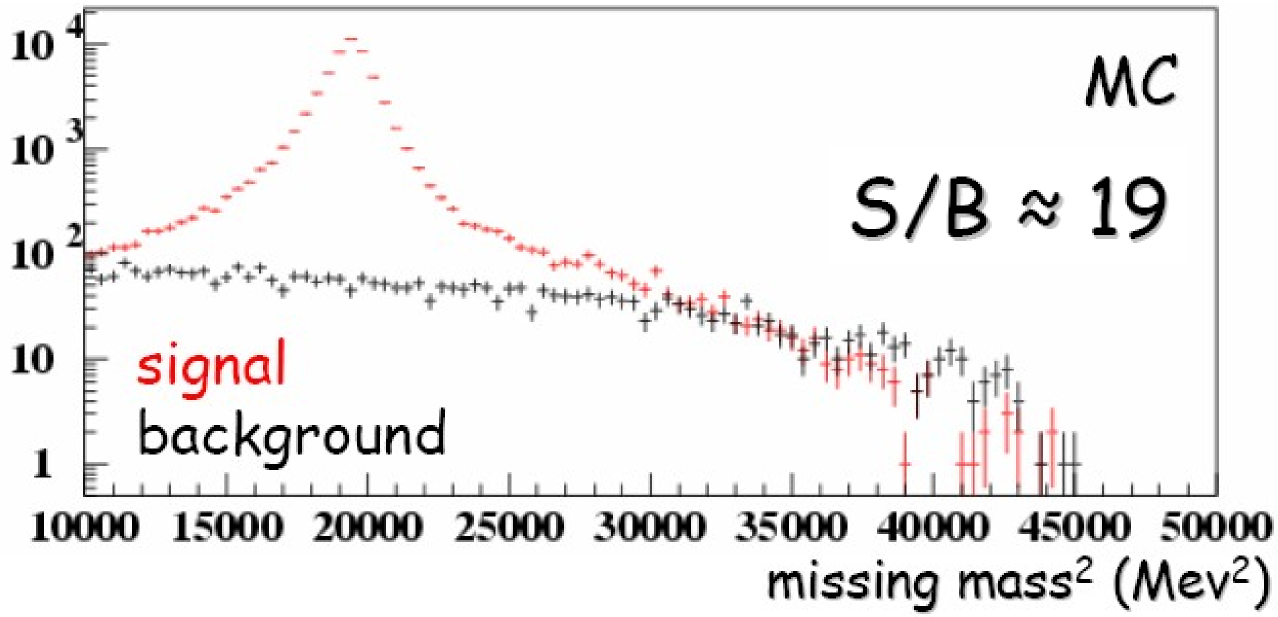


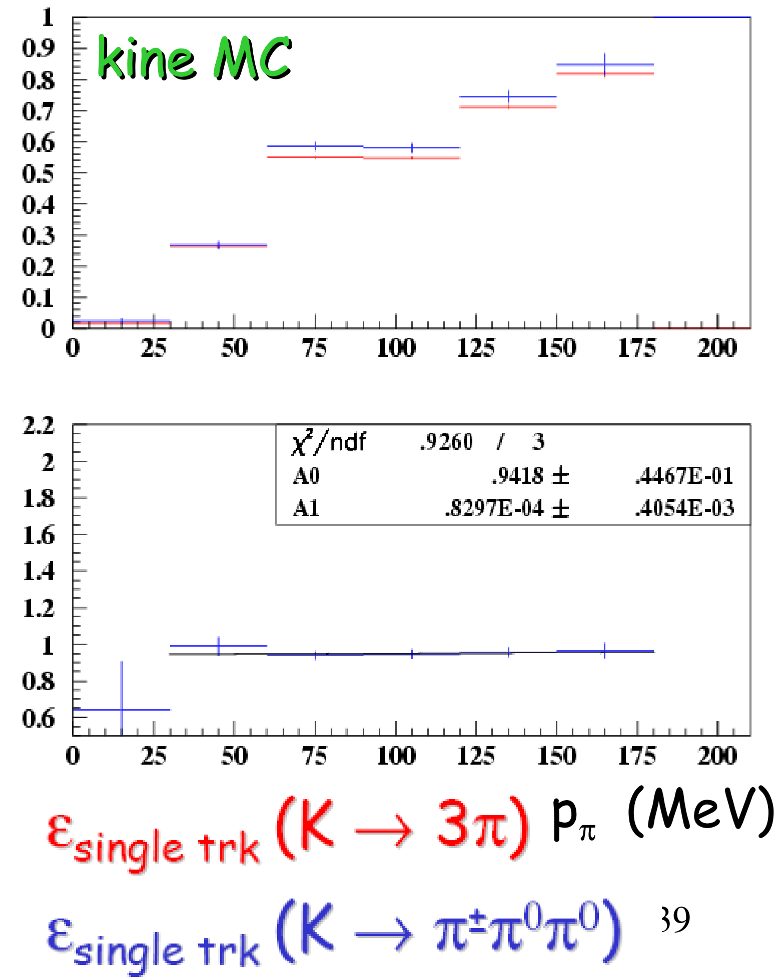
$BR(K^+ \to \pi^+\pi^-\pi^+)$

- PDG 04 average: Δ BR/BR = 1.8% CHIANG '72: Δ BR/BR = 3.6%
  $\Sigma_f BR(K^\pm \to f) = 1$ and no info on rad. cut-off

Signal selection

- 2-tracks vertex before DC inner wall and along the K path obtained from backward extrapolation of the tagging kaon track to the I.P.
- Signal peak in the missing mass spectrum ($\sim m_\pi^2$)





- Correct MC efficiency with single track efficiency DATA/MC from $K^\pm \to \pi^\pm\pi^0\pi^0$ control sample