Measurement of BR($K^+ \to \pi^+ \pi^0 (\gamma)$)

E. De Lucia

Measurement of BR($K^+ \to \pi^+\pi^0 (\gamma)$)

A new measurement is crucial in order to perform the fit to $K^\pm$ BR's:

- only Kl3 and Kl3/Kπ2 measured recently
- Kl3 and Kπ2 are strongly correlated
- the available measurement dates back to Chiang '72
  BR($K^\pm \to \pi^\pm\pi^0$) = (21,18 ± 0.28)% ΔBR/BR = $1,3 \times 10^{-2}$
- but no radiative corrections & no correlations available

This decay enters in the normalization of BR($K^\pm l3$) by NA48, ISTRA+, E865 used for Vus

The absolute BR($K_{\pi 2}$) measurement

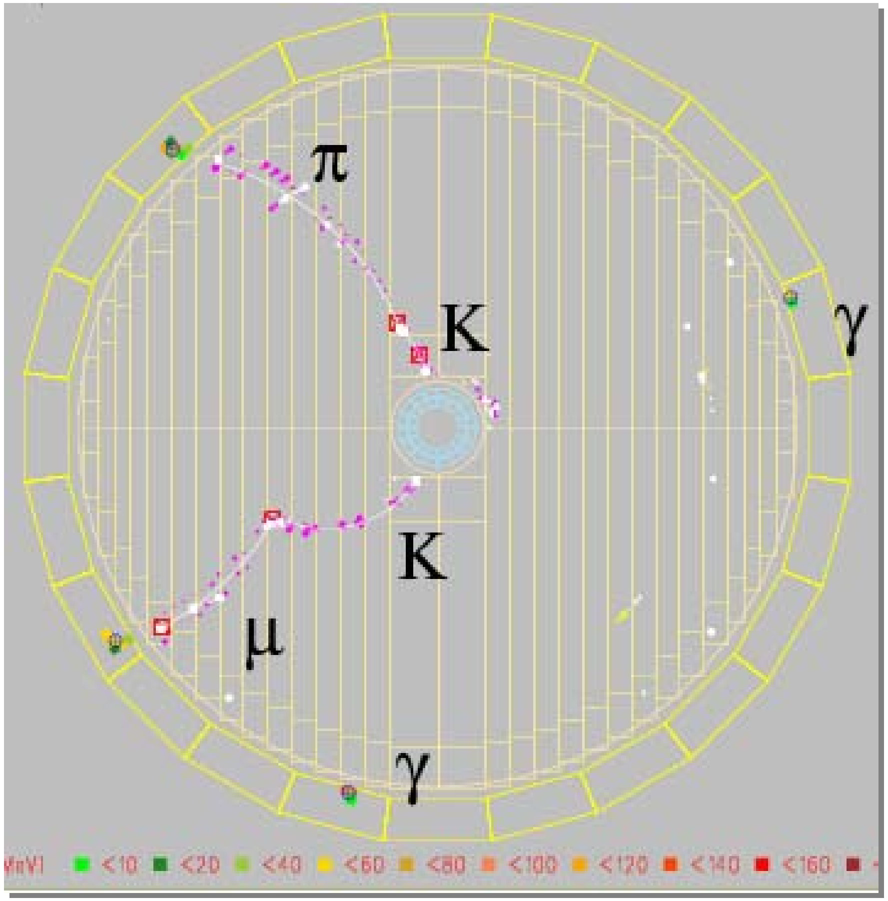
- Normalization sample is given by $K^- \to \mu^- \nu$ tag
- Number of $K^\pm \to \pi^\pm\pi^0$ decays from the fit of the distribution of the momentum of the charged decay particle in the kaon rest frame assuming the pion mass (p*)
- Selection efficiency related to Drift Chamber information only and measured directly on DATA using the $K^\pm \to X^\pm\pi^0$ control sample identified from $\pi^0 \to \gamma\gamma$ decay vertex

Signal selection

1) *tag on one side with $K \to \mu\nu$*

- preselection
  - $|z_{PCA}| < 20$cm
  - $\rho_{PCA} < 10$cm
  - $p_K \in (70,130)$ MeV
- selection
  - $\rho_{VTX} \in (40,150)$ cm
  - $dp \in (-320,-120)$ MeV
  - $p^*(m_\pi) \in (180,270)$ MeV
- self-triggering tag

  (2 trigger sectors fired)

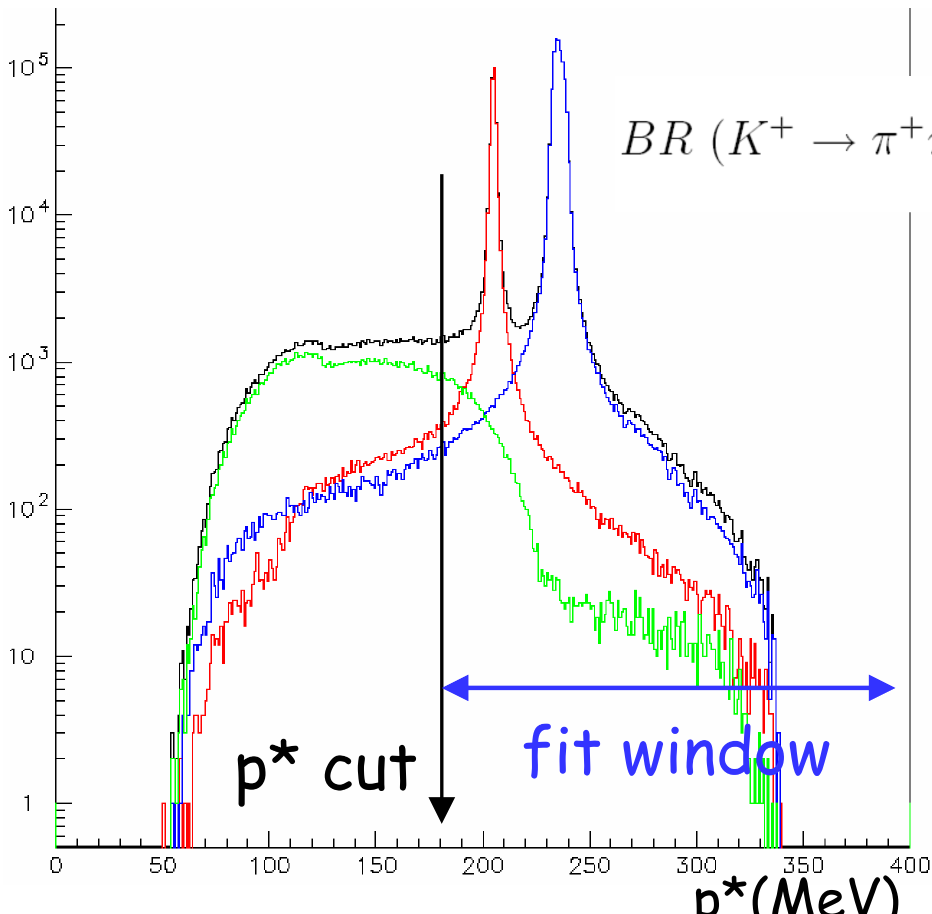


2) *look for signal on the other side*

- vertex in fiducial volume $\rho_{VTX} \in (40,150)$ cm
- kaon track can be extrapolated to the I.P. (time info)

The method

- $\mu\nu$ peak — p*(π mass) distribution from DATA control sample selected using calorimetric information only + bin by bin MC corrections
- $\pi\pi^0$ peak — p*(π mass) distribution from DATA control sample selected using calorimetric information only + bin by bin MC corrections
- 3-body decays — p*(π mass) distribution from MC smeared



$$BR\left(K^+ \to \pi^+\pi^0\,(\gamma)\right) = \frac{N_{K^+\to\pi^+\pi^0\ (\gamma)}\big|_{\mathrm{Fit}}}{N_{\mathrm{Tag}}} \times \frac{1}{\epsilon\, C_{\mathrm{CRV}}\, C_{\mathrm{FF}}\, C_{\mathrm{TB}}}$$

$$\varepsilon(p^*_{cut}) = \varepsilon_{DATA} \times \frac{\varepsilon^{MC}_{TRUE}}{\varepsilon^{MC}_{METHOD}}$$

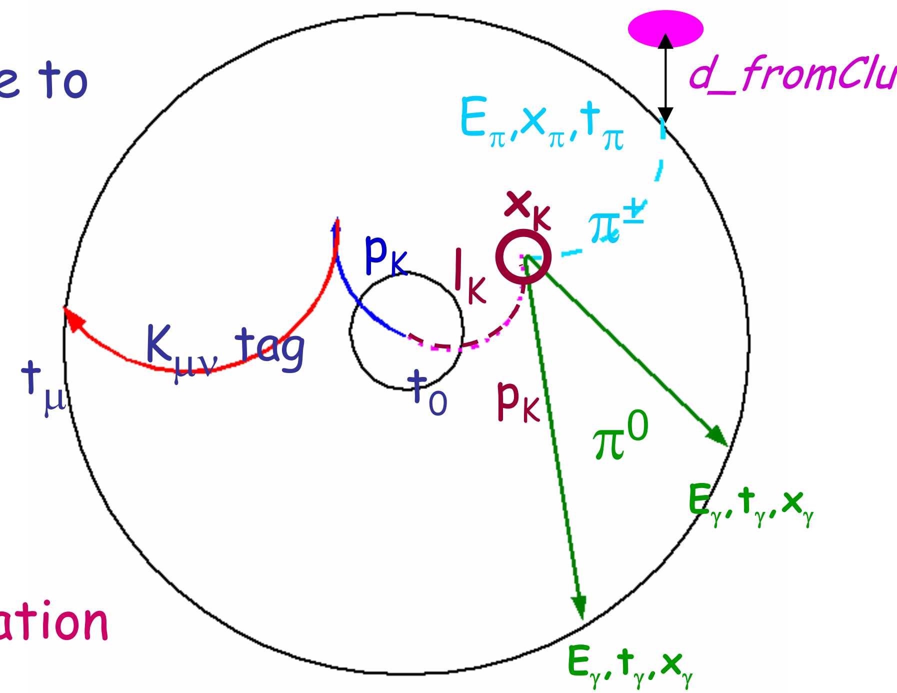
Tag bias estimated from MC kpm04

Efficiency evaluation

Efficiency: control sample selection

$K^{\pm} \to X^{\pm}\pi^0$ decays in the signal FV are identified by their $\pi^0 \to \gamma\gamma$ decay

1) the K^- track of the tagging side is extrapolated to the signal hemisphere to build the virtual K+ helix



2) photon candidates of $\pi^0 \to \gamma\gamma$ decay among the neutral clusters with:
$24^\circ < \theta_{CLU} < 156^\circ$ and $t\phi < t_{CLU} < t\phi + 70$ ns

3) step along the virtual helix of the K^+ to find the point giving the best evaluation of the the $\pi^0 \to \gamma\gamma$ decay vertex
($\chi 2$-like variable using γs invariant mass and
Δt, $t^{DECAY}(\pi^0)$- $t^{DECAY}(K)$)

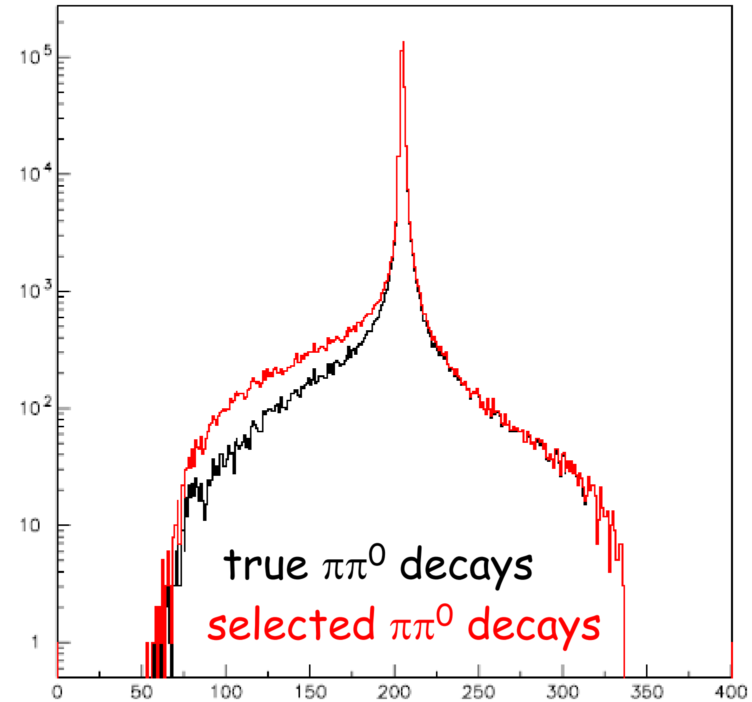
4) Estrapolate from the decay vertex, x_K, to EMC with two-body hyp and evaluate the distance to the closest cluster and apply *d_fromClu* < 30 cm

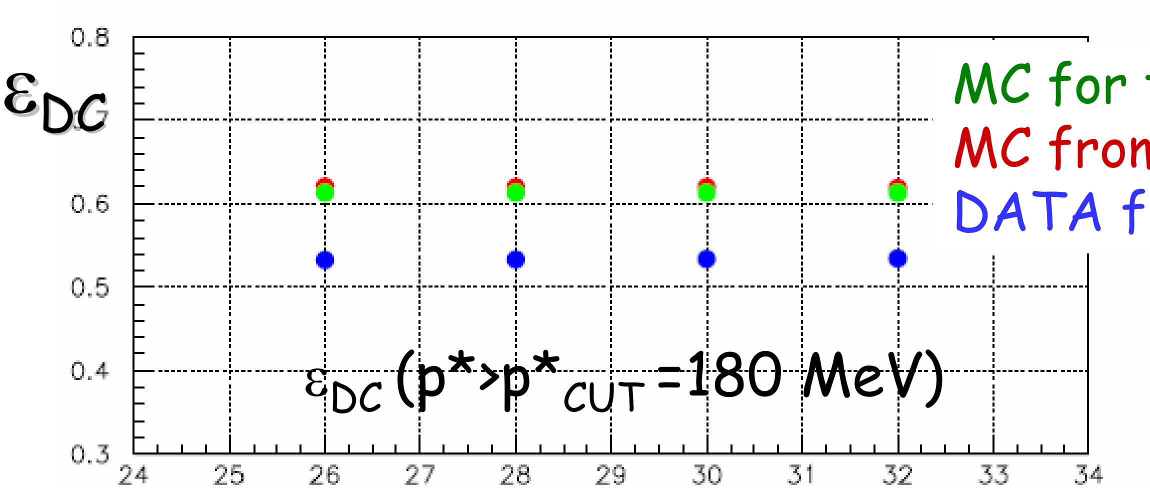
Efficiency: DATA vs MC

If we ask for:

- efficiency control sample selection
- decay vertex from signal selection

3% contamination from Kl3 decays





$$\frac{\varepsilon^{MC}_{TRUE}}{\varepsilon^{MC}_{METHOD}} = 0.9896 \pm 0.0013$$

N.B. The geometrical acceptance,needed for efficiency evaluation from MC

Results

Result on 2002 DATA sample

$$BR\left(K^+ \to \pi^+\pi^0\ (\gamma)\right) = \frac{N_{K^+\to\pi^+\pi^0\ (\gamma)}\big|_{\mathrm{Fit}}}{N_{\mathrm{Tag}}} \times \frac{1}{\epsilon\, C_{\mathrm{CRV}}\, C_{\mathrm{FF}}\, C_{\mathrm{TB}}}$$

$N_{TAG} = 12{,}113{,}686$

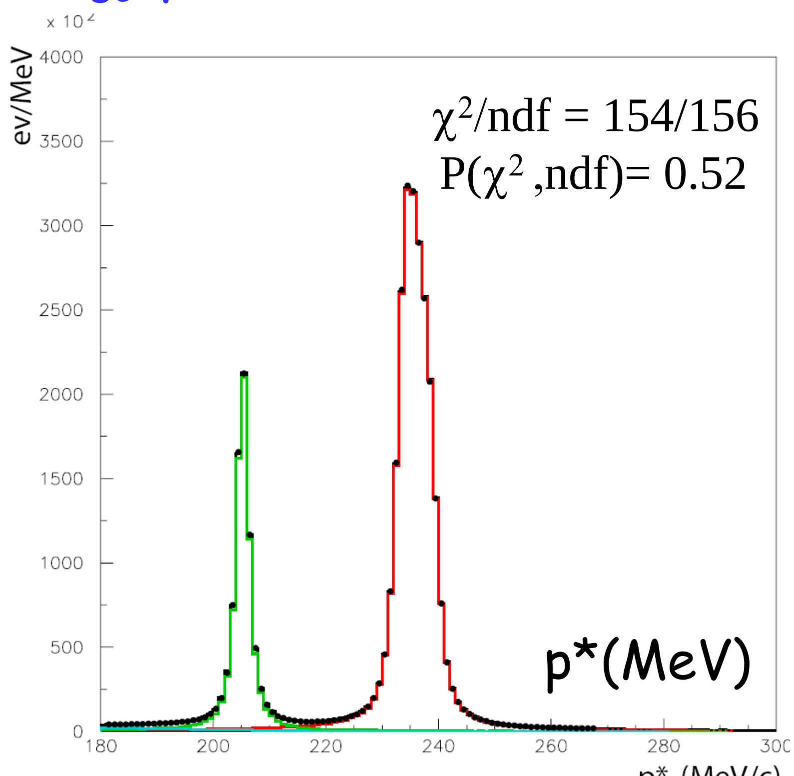
$N_{\pi\pi}\big|_{FIT} = 818{,}347 \pm 1{,}912$

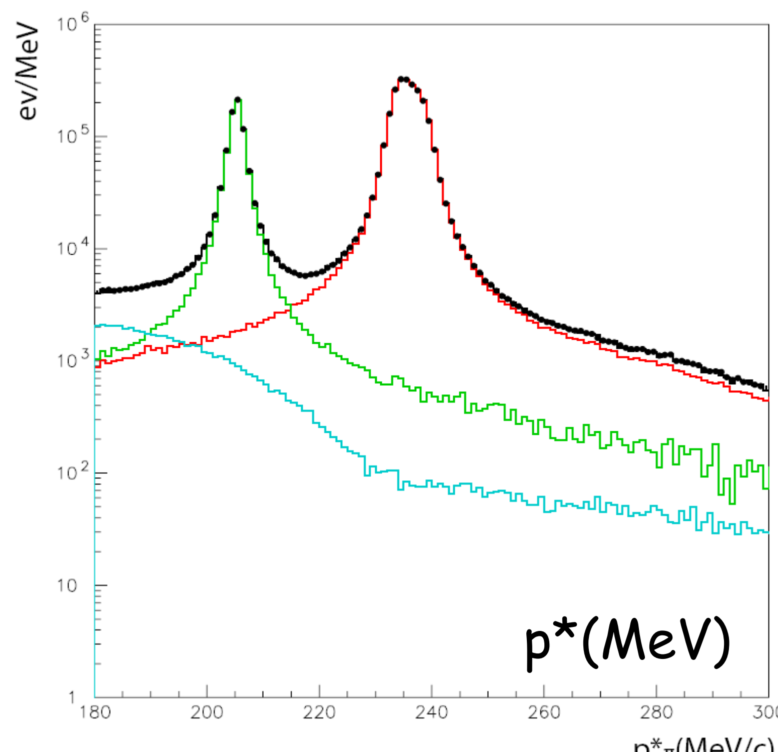
$\varepsilon = \varepsilon_{DC}(p^*\,\mathrm{cut}) = 0.3176 \pm 0.0005$

$\alpha_{Filfo} = 1/C_{FF} = 0.9819 \pm 0.0003$

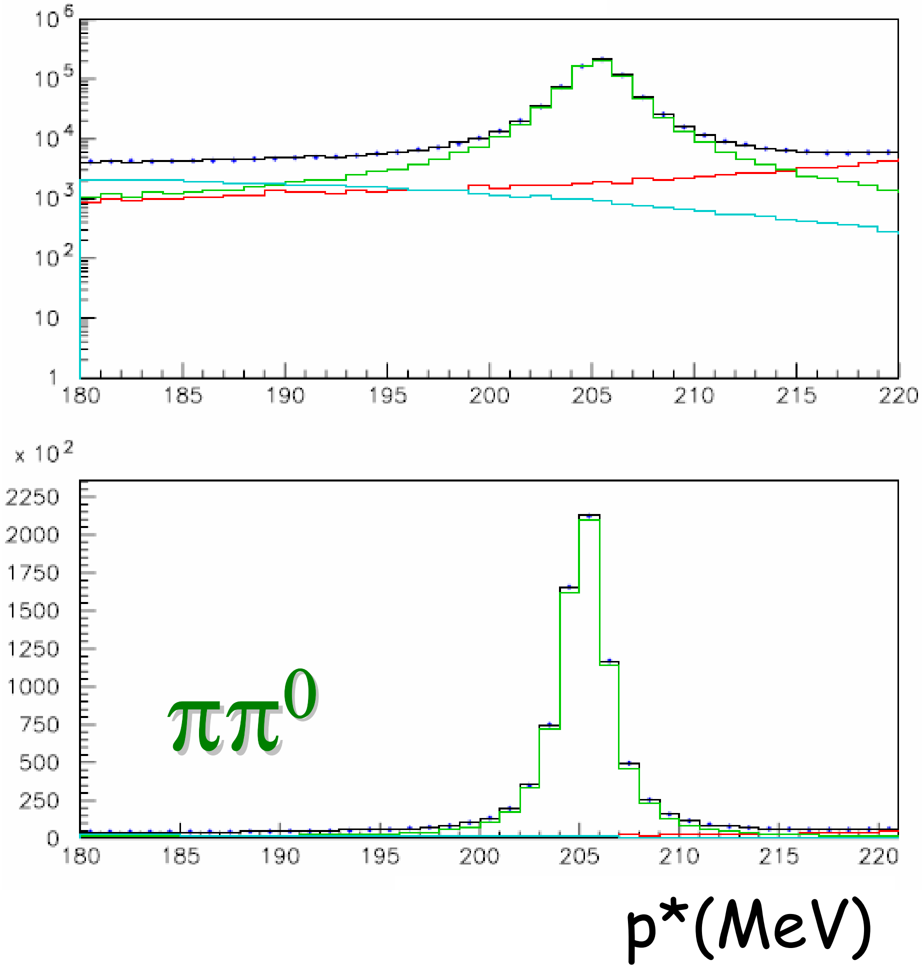
$C_{TB} = 1.0106 \pm 0.0005_{stat} \pm 0.0001_{syst}$

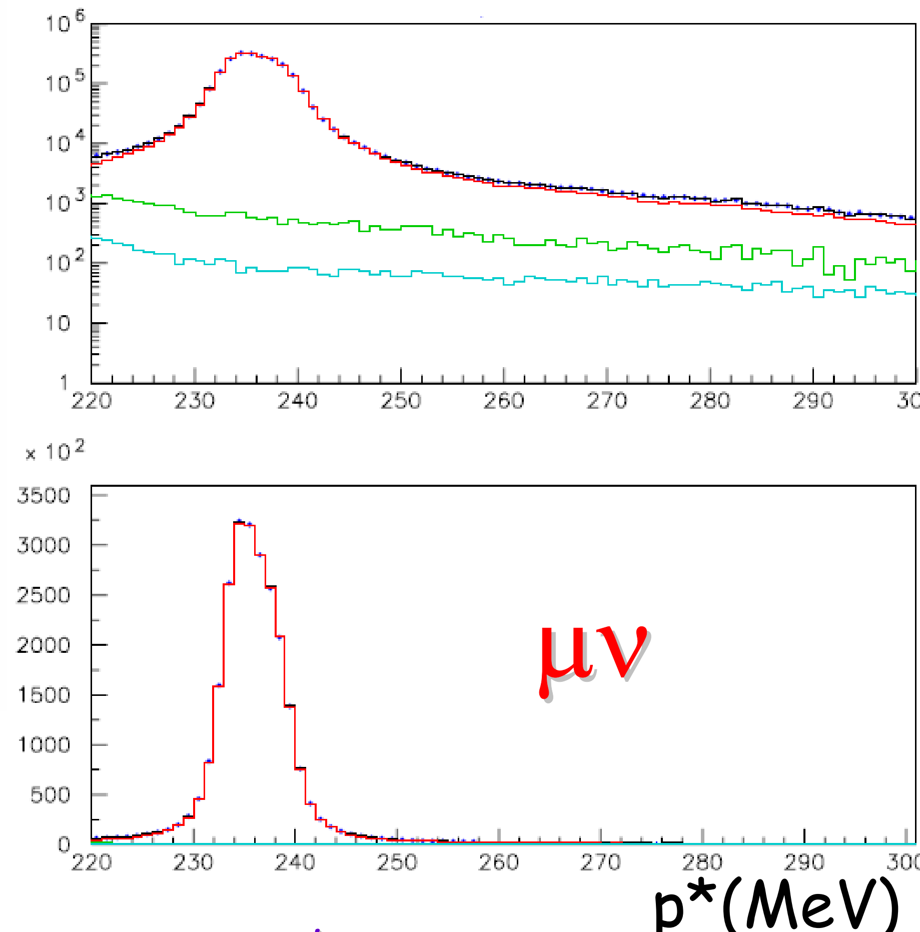
$C_{CRV} = 1.0005 \pm 0.0003$



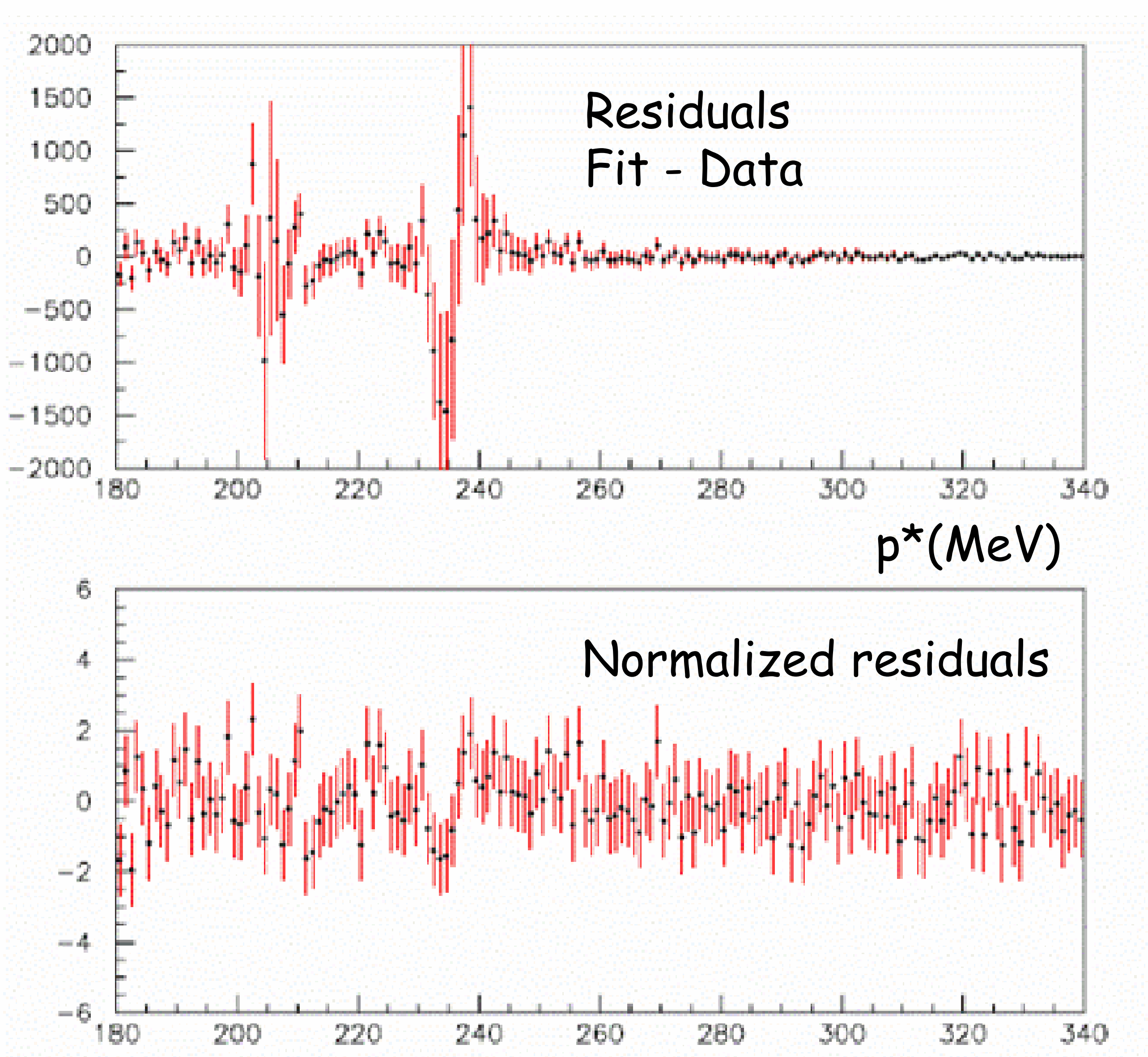


Zoom on peaks





Fit residuals



Result using Tag $K_{\mu 2}$

$$BR(K^+ \to \pi^+\pi^0(\gamma))|_{Tag\ K_{\mu 2}} = 0.20658 \pm 0.00062_{\text{stat}} \pm 0.00087_{\text{syst}}$$

Summary table of fractional statistical uncertainties using $K_{\mu 2}$ tag.

Source of statistical uncertainty	Fractional value
signal counting	0.23%
global efficiency	0.13%
FILFO and CRV-T3 filter	0.04%
efficiency MC correction	0.12%
Tag	0.05%
Total fractional statistical uncertainty	0.30%

Summary table of fractional systematic uncertainties using $K_{\mu 2}$ tag.

Source of systematic uncertainty	Fractional value
fit window p^*_{cut}	0.06%
efficiency	0.3%
$K_{\pi 2}$ shape	0.16%
$K_{\mu 2}$ shape	0.12%
Tag bias	0.01%
MC Lifetime*	0.12%
ρ_V^{min} *	0.17%
Nuclear interactions	$< 0.06\%$
Total fractional systematic uncertainty	0.42%

* Updated

Systematic effect (I): $K^{\pm}$ lifetime in MC

The geometrical acceptance is taken from MC simulation and its value is strongly related to the charged kaon lifetime.

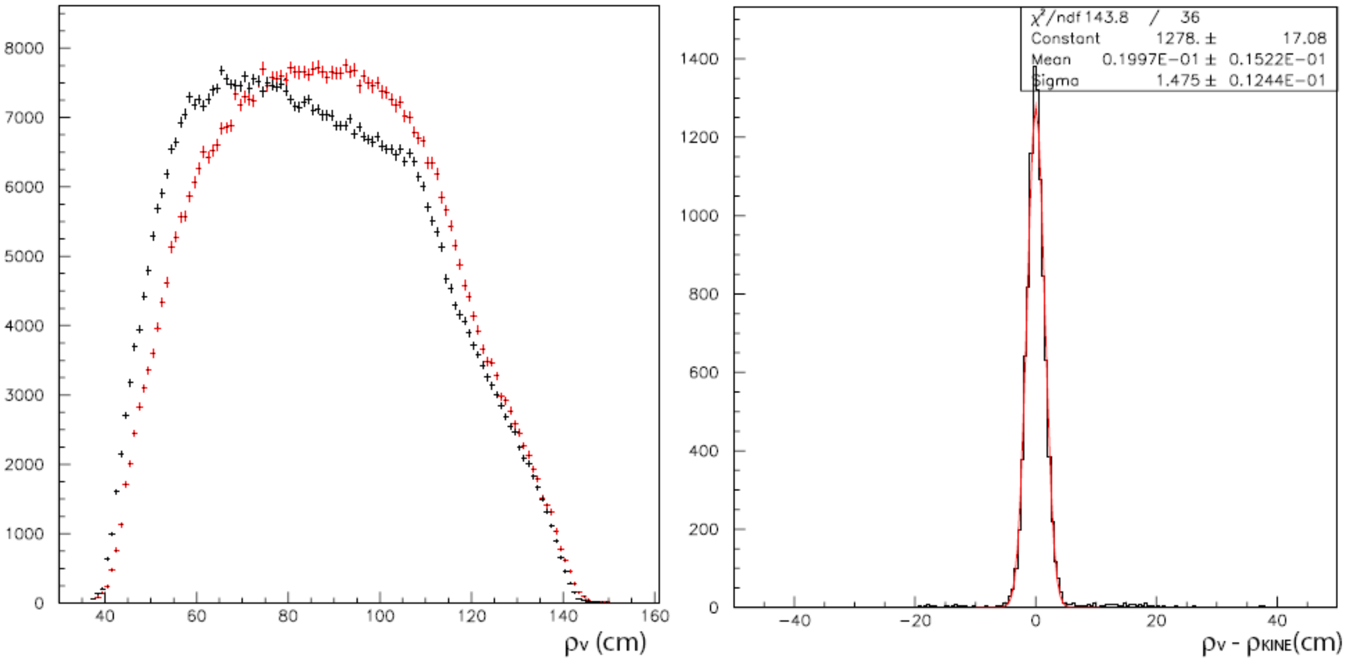
The relation between BR and lifetime τ values has been obtained varying the lifetime in a range of ±1% around the value used in our MC $\tau_{K^\pm}^{MC} = 12.36\ \mathrm{ns}$

$$\frac{BR(\tau) - BR(\tau_{K^\pm}^{MC})}{BR(\tau_{K^\pm}^{MC})} = -0.49 \times \frac{\tau - \tau_{K^\pm}^{MC}}{\tau_{K^\pm}^{MC}}$$

According to the present uncertainty of the KLOE lifetime measurement $\delta\tau_{K\pm} / \tau_{K\pm} = 0.24\%$ we get: ***$\delta BR/BR = 0.12\%$***

Systematic effect (II): FV lower bound

The requirement on the position of the signal decay vertex in the transverse plane (ρ_{VTX}) is: $\rho_{VTX}(min) < \rho_{VTX} < \rho_{VTX}(max)$ $\begin{cases} \rho_{VTX}(min) = 40 \text{ cm} \\ \rho_{VTX}(max) = 150 \text{ cm} \end{cases}$



The resolution on the "neutral" vertex used for ε_{DC} wrt the kine value is $\sigma_{\rho neu} \approx 1.5$ cm at $\rho_{VTX}(min) = 40$ cm.

We have moved ρ_{VTX} (min) from 38 to 42 cm using 1 cm steps, evaluating signal count, efficiency and correction to the efficiency.

The contribution to the systematic uncertainty is *$\delta BR/BR = 0.17\%$*

Cross-check: tagging with $K_{\pi 2}$

The two tags, Tag $K\mu 2$ and Tag $K\pi 2$, exhibit very different corrections due to the FILFO filter

Table of corrections		
	Tag $K_{\mu 2}$	Tag $K_{\pi 2}$
CRV and T3 filter correction	1.0005 ± 0.0003	1.0007 ± 0.0003
$\alpha_{\rm Filfo}$ correction	0.9820 ± 0.0003	0.99907 ± 0.00006
Tag bias correction	1.0106 ± 0.0005	1.009 ± 0.0006

$\alpha_{Filfo} = 1/C_{FF}$

Therefore the measurement of $BR(K^+ \to \pi^+\pi^0(\gamma))$ with the Tag $K\pi 2$ provides us an excellent cross-check of $BR(K^+ \to \pi^+\pi^0(\gamma))$ done with the Tag $K\mu 2$ (*)

$$BR\left(K^+ \to \pi^+\pi^0\ (\gamma)\right) = \frac{N_{K^+ \to \pi^+\pi^0\ (\gamma)}\big|_{\rm Fit}}{N_{\rm Tag}} \times \frac{1}{\epsilon\ C_{\rm CRV}\ C_{\rm FF}\ C_{\rm TB}}$$

$N_{TAG} = 9{,}352{,}915$

$N_{\pi\pi}\big|_{FIT} = 621{,}612 \pm 1{,}678$

$\varepsilon = \varepsilon_{DC}(p^* cut) = 0.3182 \pm 0.0005$

(*) the same efficiency corrections have been used

Result using Tag $K_{\pi 2}$

$$BR(K^+ \to \pi^+\pi^0(\gamma))|_{Tag\ K_{\pi 2}} = 0.20689 \pm 0.00068_{\rm stat} \pm 0.00089_{\rm syst}$$

Summary table of fractional statistical uncertainties using $K_{\pi 2}$ tag.

Source of statistical uncertainty	Fractional value
signal counting	0.27%
global efficiency	0.13%
FILFO and CRV-T3 filter	0.03%
efficiency MC correction	0.13%
Tag	0.05%
Total fractional statistical uncertainty	0.33%

Summary table of fractional systematic uncertainties using $K_{\pi 2}$ tag.

Source of systematic uncertainty	Fractional value
fit window $p^*_{\rm cut}$	0.07%
efficiency	0.3%
$K_{\pi 2}$ shape	0.17%
$K_{\mu 2}$ shape	0.14%
Tag bias	0.01%
MC Lifetime	0.12%
$\rho_{\rm V}^{\rm min}$	0.17%
Nuclear interactions	$< 0.06\%$
Total fractional systematic uncertainty	0.43%

Conclusions (1)

- The measurement of the absolute BR($K^+ \to \pi^+\pi^0(\gamma)$), inclusive of final state radiation, has been presented using both $K_{\mu 2}$ and $K_{\pi 2}$ tags:

$$BR(K^+ \to \pi^+\pi^0(\gamma))|_{Tag\ K_{\mu 2}} = 0.20658 \pm 0.00062_{\text{stat}} \pm 0.00087_{\text{syst}}$$

$$BR(K^+ \to \pi^+\pi^0(\gamma))|_{Tag\ K_{\pi 2}} = 0.20689 \pm 0.00068_{\text{stat}} \pm 0.00089_{\text{syst}}$$

- The weighted average of these two results, accounting for correlations is:

$$BR(K^+ \to \pi^+\pi^0(\gamma)) = 0.2067 \pm 0.0005_{\text{stat}} \pm 0.0008_{\text{syst}}$$

- The *BR* dependence on the lifetime value τ has been measured

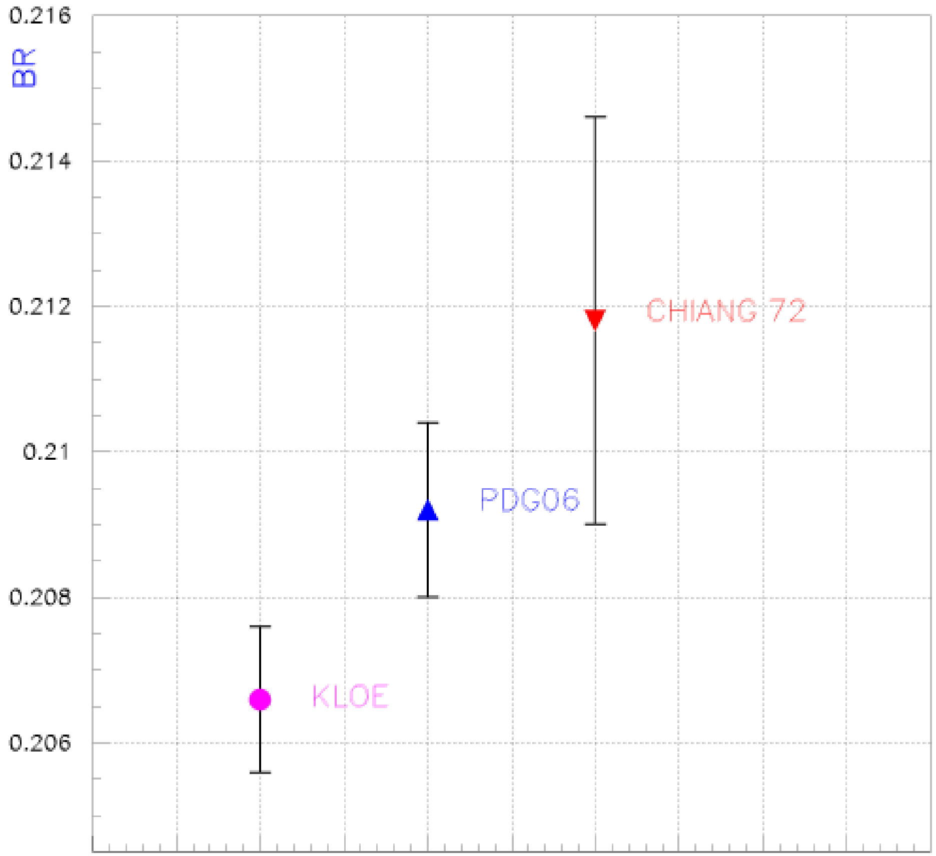
- The measurement of BR($K^+ \to \mu^+\nu(\gamma)$) using the fit of the p* distribution has been performed and it is in agreement with our published value.

The correlation factor with BR($K^+ \to \pi^+\pi^0(\gamma)$) has been measured.

Conclusions (II)

PDG fit ‘06 $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}) = (20,92 \pm 0.12)\%$ $\Delta BR/BR = 5,7\text{x}10^{-3}$

CHIANG ’72 $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}) = (21,18 \pm 0.28)\%$ $\Delta BR/BR = 1,3\text{x}10^{-2}$

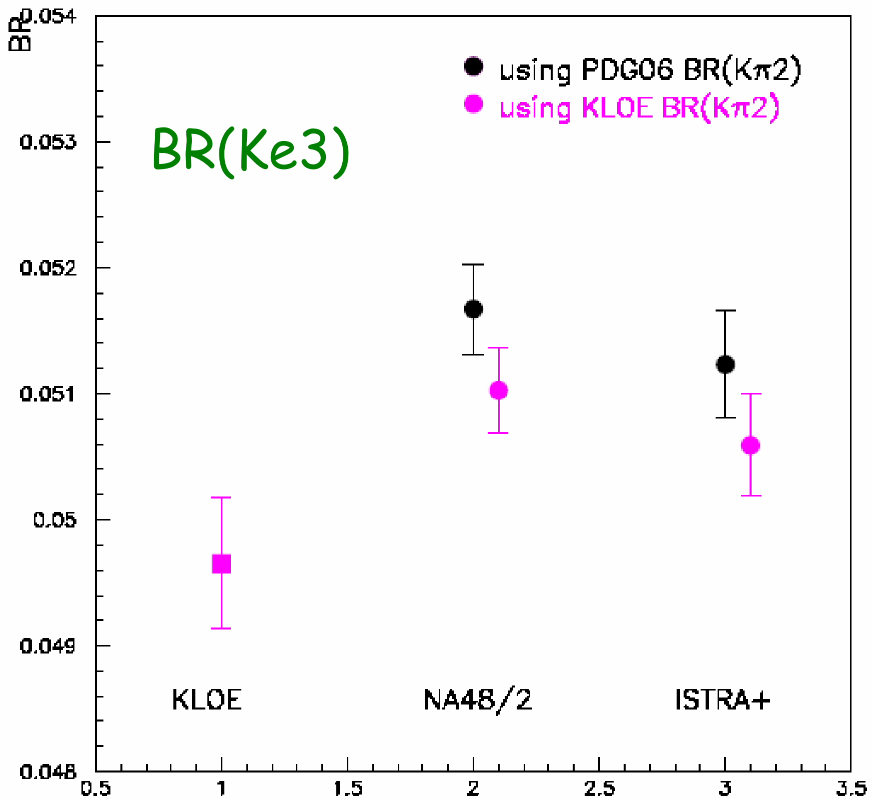


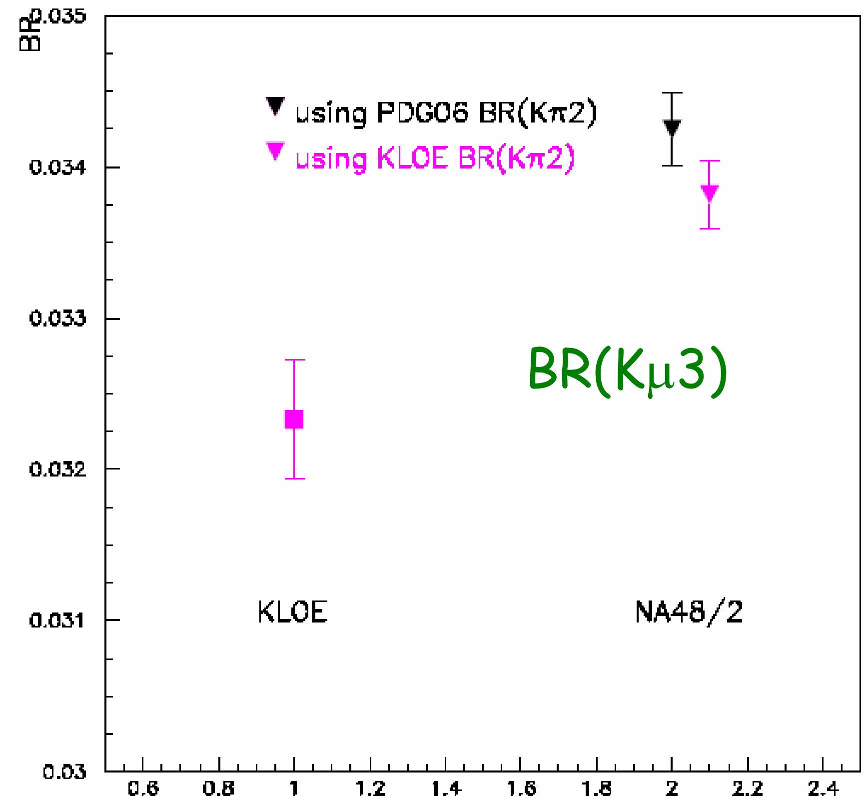
KLOE $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}) = (20,67 \pm 0.05_{stat} \pm 0.08_{syst})\%$ $\Delta BR/BR = 4,6\text{x}10^{-3}$

FLAVIANET $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}) = (20,644 \pm 0.080)\%$ $\Delta BR/BR = 3,9\text{x}10^{-3}$

Conclusions (III)

- The impact of the KLOE BR($K_{\pi 2}$) on the BR(Kl3) measurements using as normalization the $K_{\pi 2}$ channel (NA48/2 and ISTRA+).
- Comparison with what obtained with PDG BR($K_{\pi 2}$) and KLOE BR(Kl3)





BR($K_{\pi 2}$): PDG06 = (20,92 ± 0.12)% KLOE = (20,67 ± 0.05$_{stat}$ ±0.08$_{syst}$)%

SPARES

DATA/MC smeared shapes

- DATA and MC exhibit significant differences in the resolution of quantities measured from the DC track fit procedure

  the main source is $K^{\pm}$ track reconstruction

- Smear MC momenta to improve the DATA/MC agreement:
  - use $K\pi 2$ and $K\mu 2$ DATA control samples;
  - smear MC momenta according to the fractional error a priori on the track curvature (track fit error matrix);
  - extract the smearing parameters from a combined fit to the p* distributions from the DATA control samples with MC distributions obtained using smeared momenta.

- Best DATA/MC agreement obtained applying a shift to the momentum scale and 3 gaussian smearings, one for each component of the track momenta

MC smearing

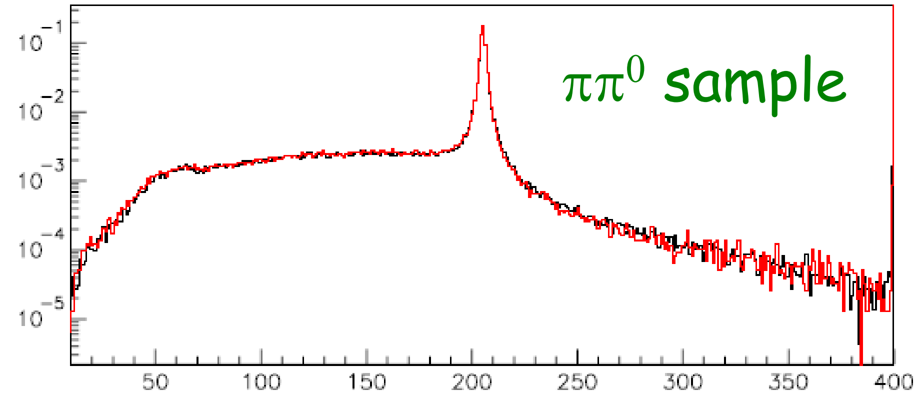
$p(i) = p(i) \times (1 + scala)$ i=1,2,3

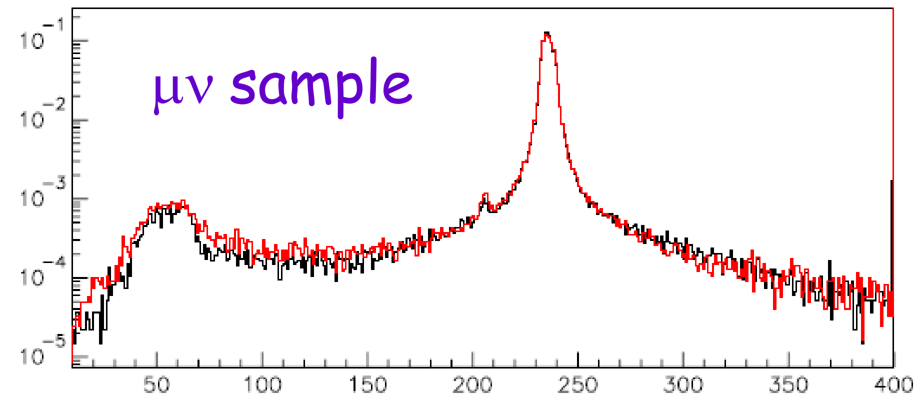
$p(i) = p(i) \times (1 + sme \times random \times xer)$ i=1,2,3

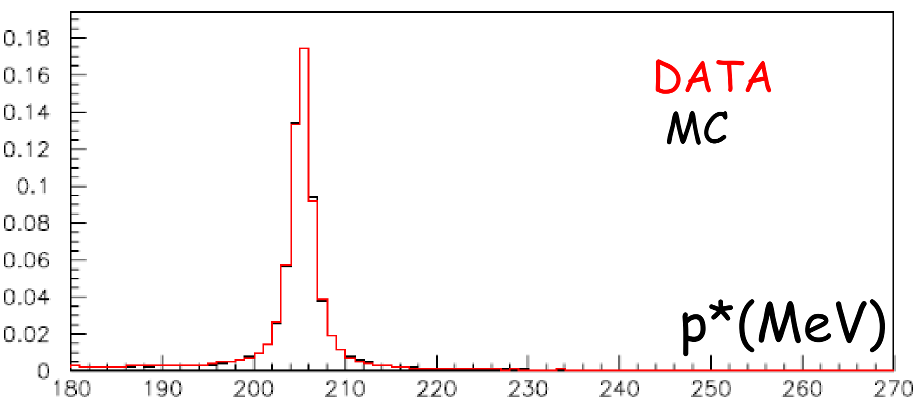
scala = $0.61\mathrm{x}10^{-3}$

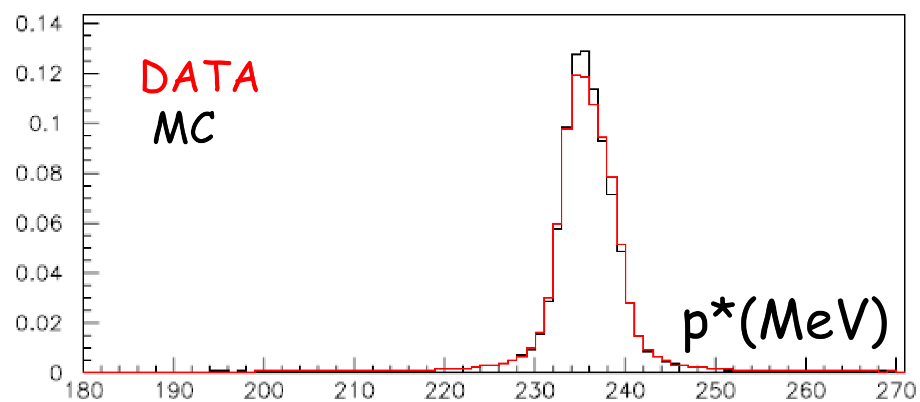
90% of events with sme = 0.57

8% with sme = 7 and 2% with sme = 100







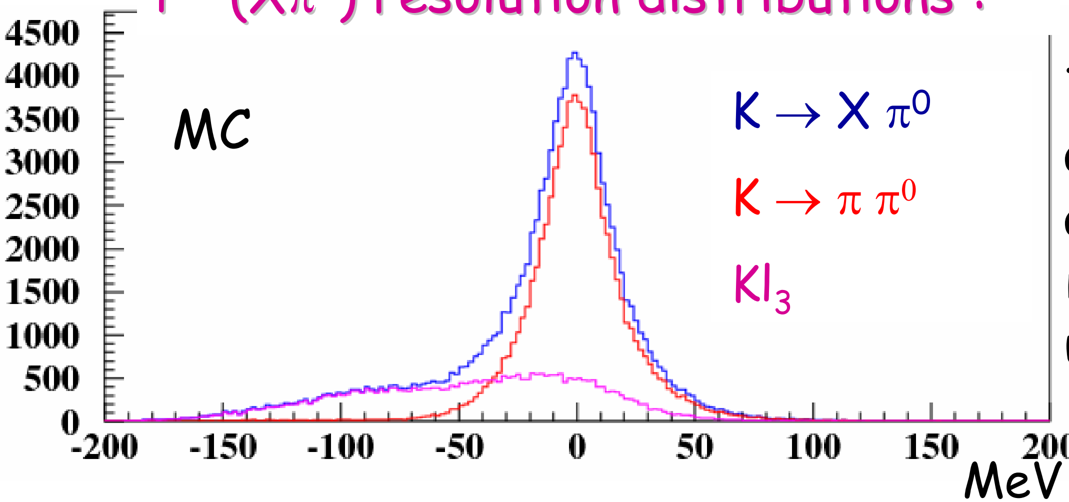


$\pi\pi^0$ peak is very well reproduced while $\mu\nu$ peak still exhibits a disagreement

- *DATA shapes & bin by bin MC smeared corrections for 2-body decays*
- *3-body shape from MC smeared*

Efficiency: π^+ momentum resolution

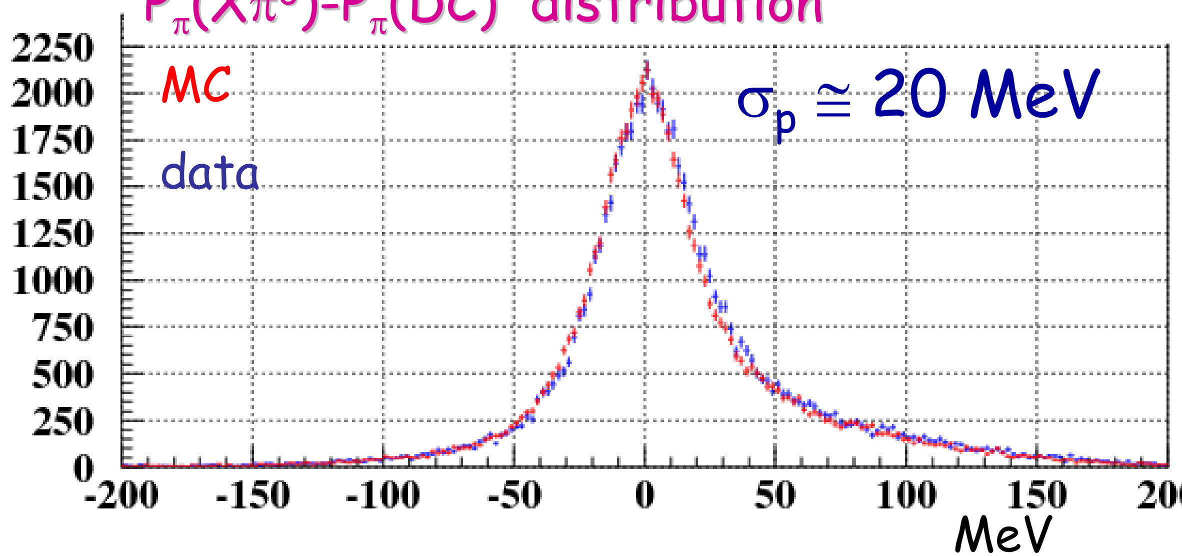
$P^*(X\pi^0)$ resolution distributions :



The control sample exhibits a contamination from Kl3 decays at the level of tens of %, even if we apply a strong cut on $p^*(\pi^0)$ using two-body hypothesis

$P_\pi(X\pi^0)$-$P_\pi(DC)$ distribution

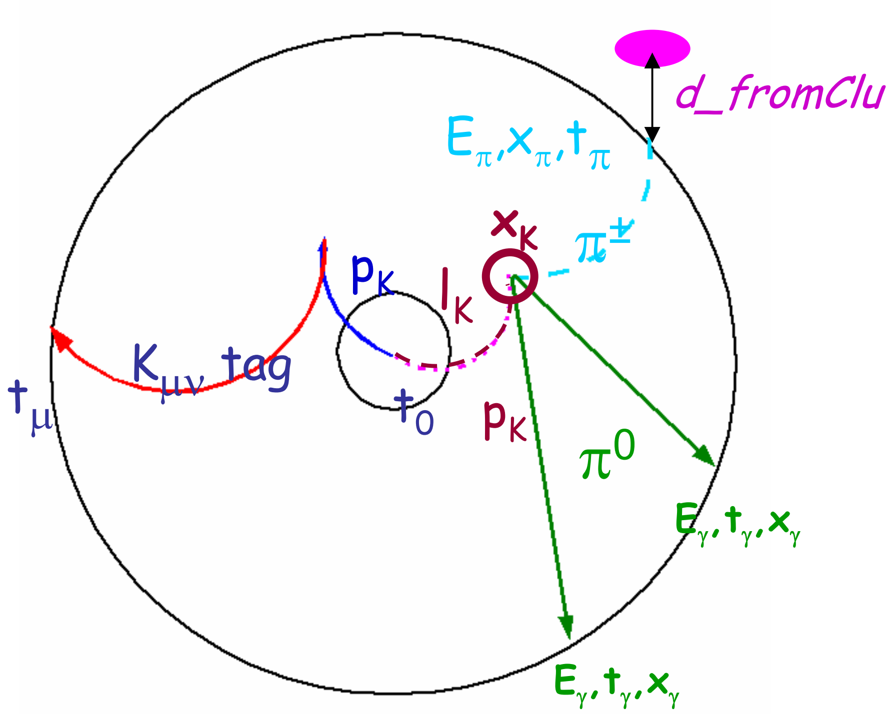
the π^+ momentum $P_\pi(X\pi^0)$ is estimated using P_K , $P_{\pi 0}$ and the two-body hyp.

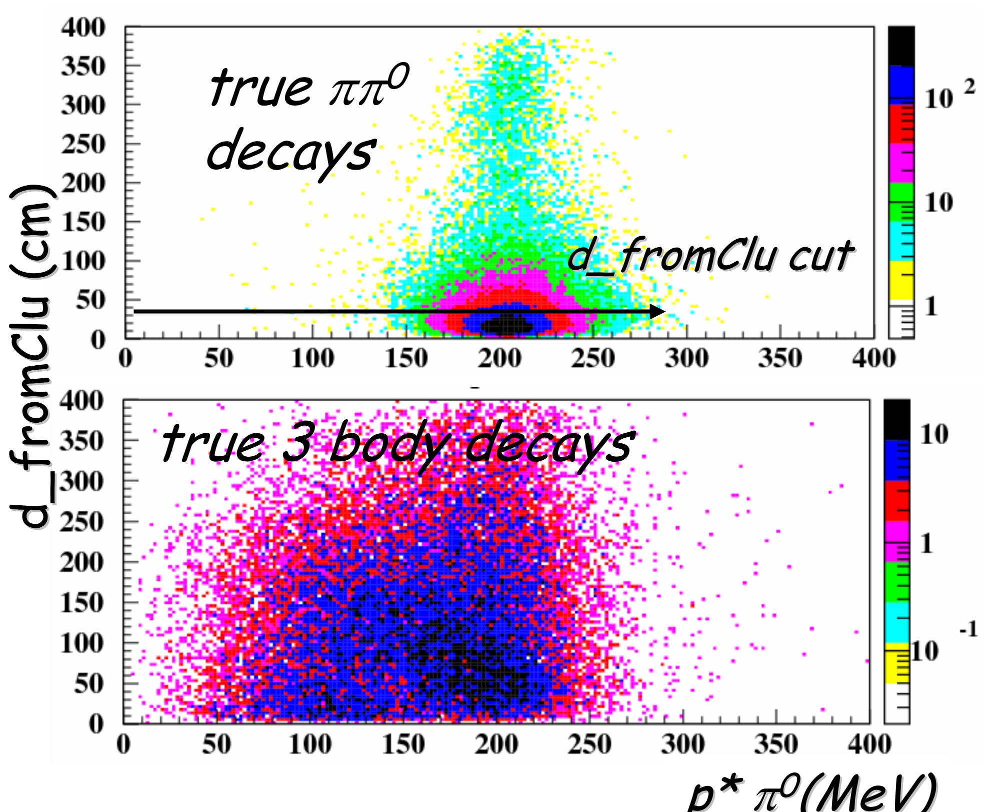


Efficiency: control sample selection (II)

To reduce to few % the contamination of the control sample coming from Kl3 decays, we apply a further cut.

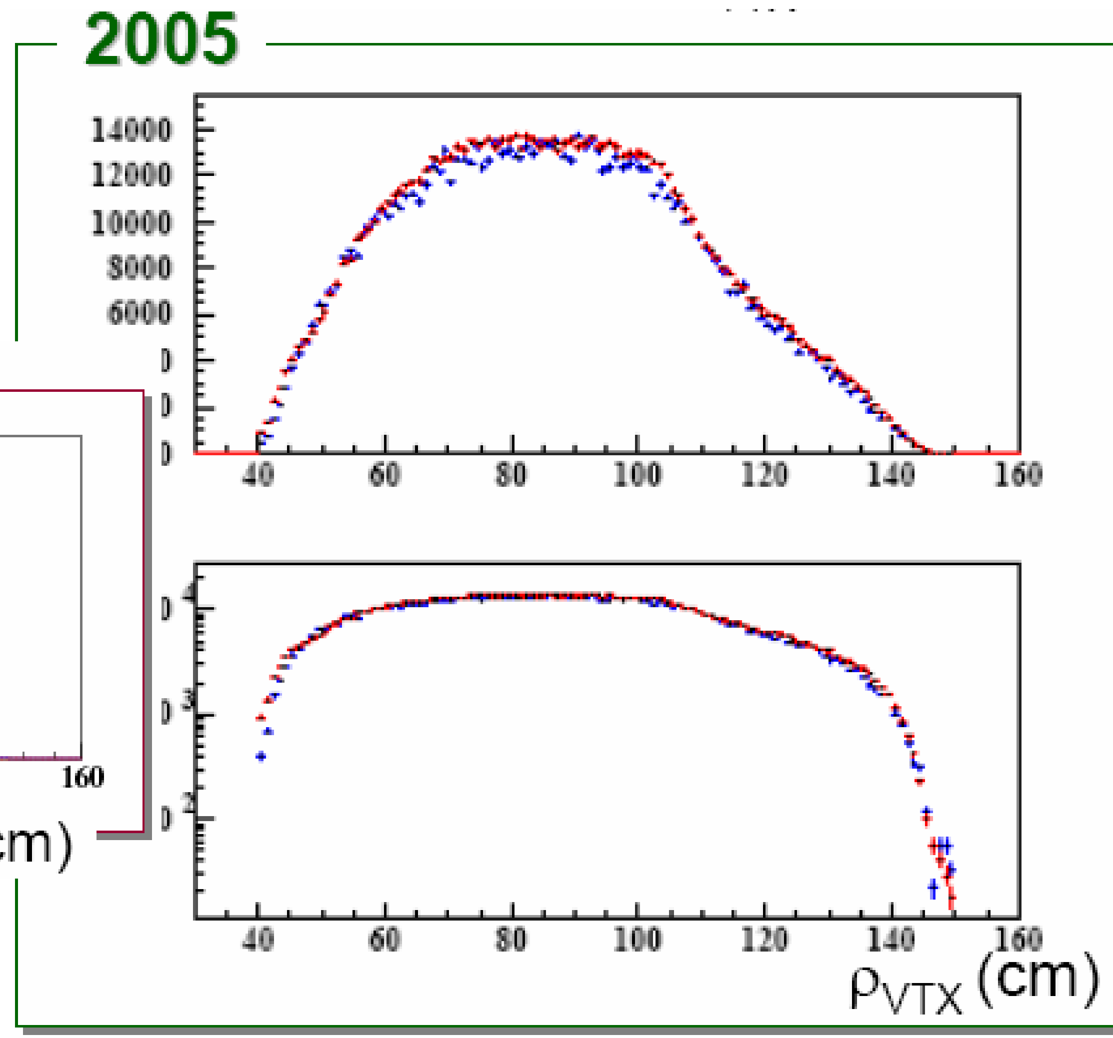
We extrapolate from the $K \to X\pi^0$ decay vertex, x_K, to EMC with two-body hypothesis and evaluate the distance to the closest cluster (*d_fromClu*)

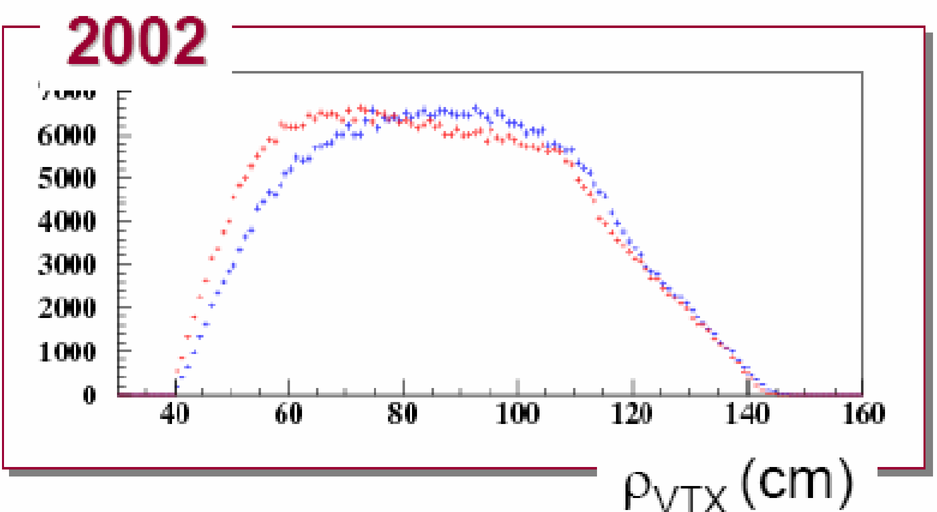




The final cut for the control sample selection is d_fromClu cut = 30. cm

Systematic effect (II): FV lower bound cont.

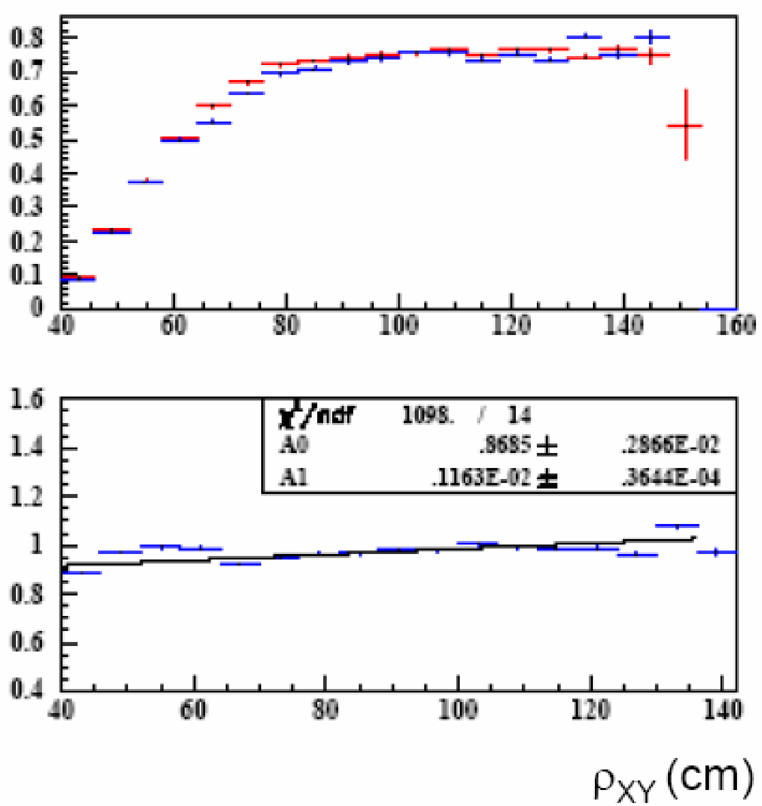




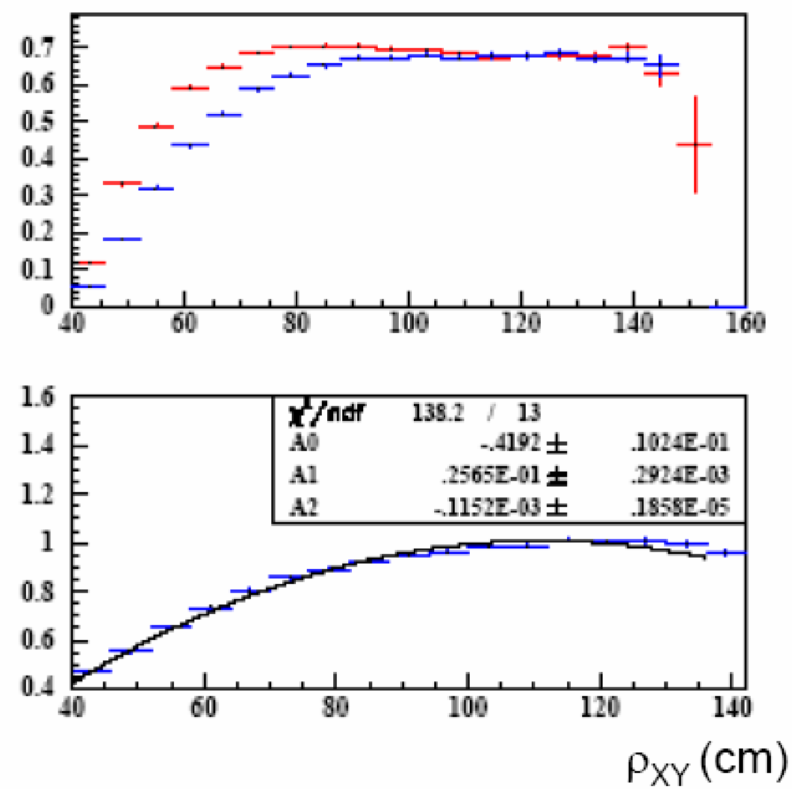
Systematic effect (II): FV lower bound cont.

$\varepsilon_{trk+vtx}$ as a function of ρ_{xy}

2005



2002



E. De Lucia -- Offline meeting, November 16th 2006

T3FILTER correction

Using the 2002 DATA sample:

$$\frac{N_{SIG}}{N_{TAG}} \Rightarrow \frac{N_{SIG} + \mathbf{64} x N_{SIG}^{T\mathbf{3}FLAG=\mathbf{1}}}{N_{TAG} + \mathbf{64} x N_{TAG}^{T\mathbf{3}FLAG=\mathbf{1}}}$$

$BR(K^{+} \rightarrow \pi^{+}\pi^{0}(\gamma)) \Rightarrow BR \times C_{T3}$

$C_{T3} = 0.9994 \pm 0.0003$

FILFO correction

$$C_{FILFO} = \frac{1-\rho_{TAG}}{1-\rho_{TAG}^{SIG}} \qquad \rho_i = \frac{N^i_{AFILFO}}{N^i_{AFILFO}+N^i_{FILFO}}$$

Set of runs for DATA and MC from BR($K\to\mu\nu(\gamma)$) studies:

C_{FILFO} = 0.9832 ± 0.0003 (DATA)
C_{FILFO} = 0.99347 ± 0.00012 (MC)
C_{FILFO} = 0.99223 ± 0.00008 (MC true $K\pi2$)

In agreement within the errors with numbers obtained from a small sample of DATA processed with DBV-22 in which downscaled events rejected by FILFO are easily selected using a flag, as done on MC

$$BR(K^+\to\pi^+\pi^0(\gamma)) \Rightarrow BR \times C_{FILFO} \times C_{FILFO} / C_{FILFO}$$

Systematic effect (I): ε_{DC} & p^* cut

Using the 2002 data sample and varying:

- the starting point of the fit window
- the d_fromClu cut for the efficiency evaluation

ε_{DC}

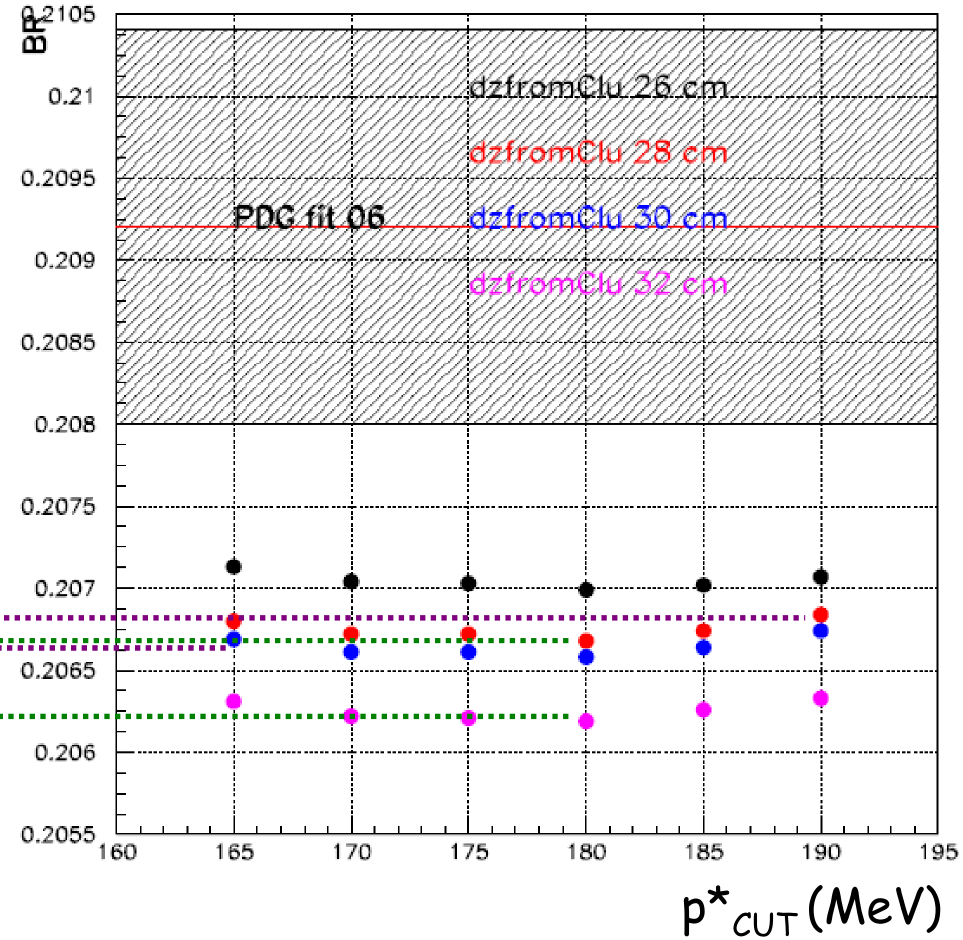
cut 28 (26*) -> 32 cm

$\delta BR/BR = 0.24$ %

p^*_{CUT}

165 -> 190 MeV

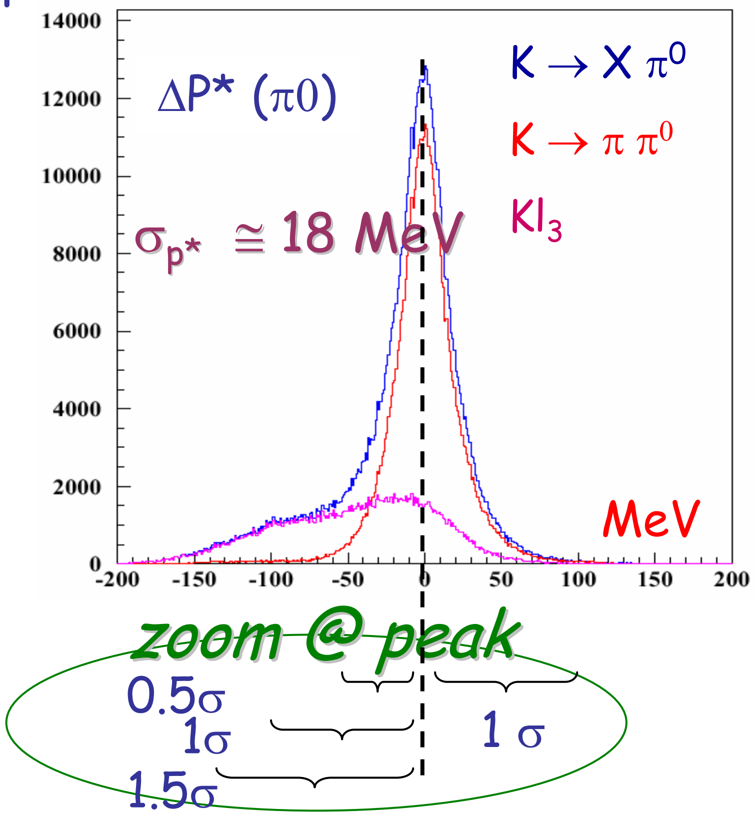
$\delta BR/BR = 0.06$ %



(*) distorts the distribution used for efficiency evaluation

Systematic effect (I): ε_{DC} with old method

We have also considered a different selection for the efficiency control sample, using an asymmetric cut around the peak of the distribution of p*(π0) in two-body hyp.



The two control samples for the efficiency are very different:

- asymmetric p*(π^0) cut (*old method*)
  ~12% correction from mc_method/mc_true
  11% Kl3 contamination
- d_fromClu cut (*current method*)
  ~1% correction from mc_method/mc_true
  3% Kl3 contamination

$$\varepsilon_{DC}(p^*\,\text{cut}) = \varepsilon_{DATA} \times \frac{\varepsilon^{MC}_{TRUE}}{\varepsilon^{MC}_{METHOD}}$$

With the old efficiency control sample (-0.5σ < Δp*< σ): *δBR/BR = 0.28 %*

Using a conservative approach, the systematic contribution to BR(Kπ2) from the efficiency evaluation is considered as δBR/BR = 0.3%

Systematic effect(I): more on ε_{DC} control sample

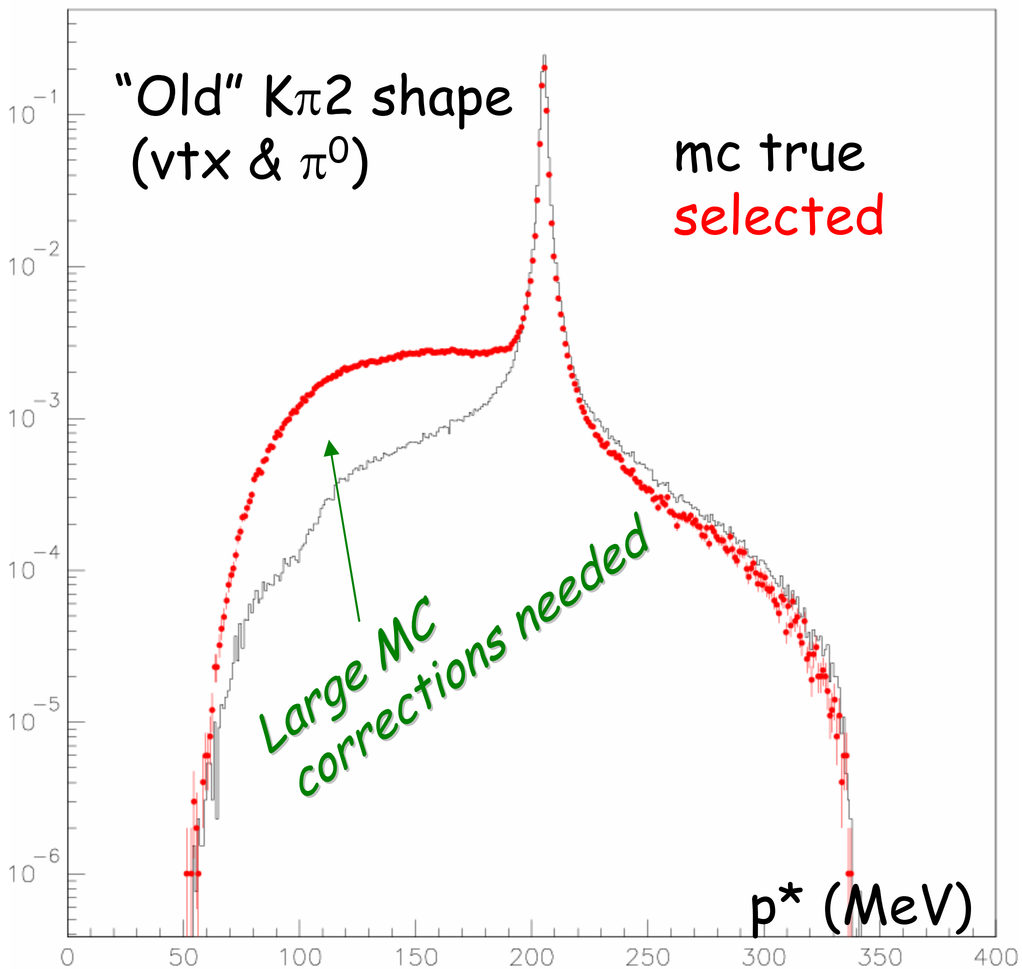
new

The effect of the cuts used for the selection of the efficiency control sample has been studied, namely:

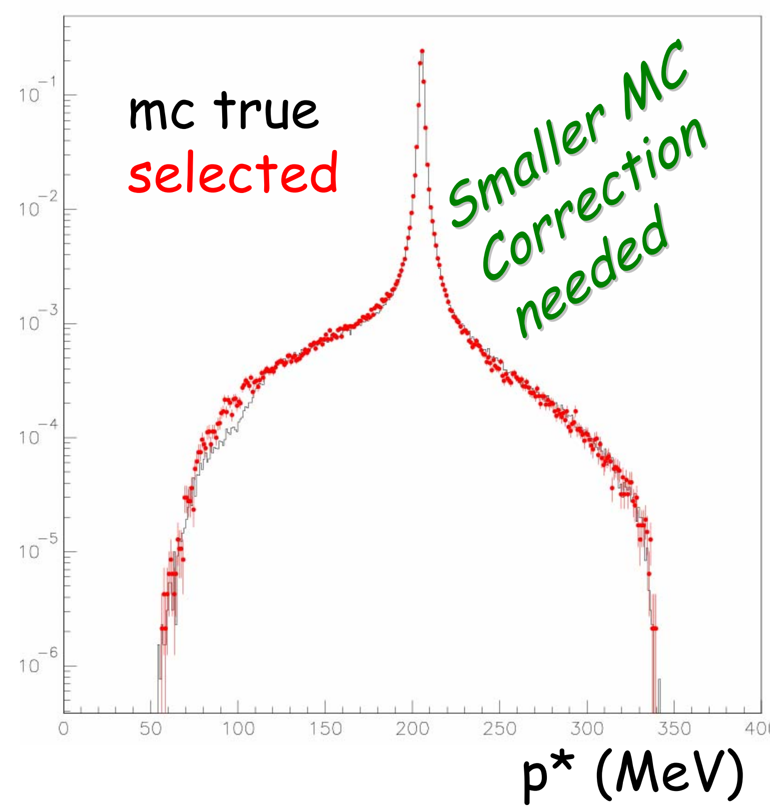
- the cuts to reject machine background in the pre-selection of neutral clusters:
  - $24° < \theta_{CLU} < 156°$ $\Rightarrow$ $14° < \theta_{CLU} < 166°$ $\delta BR/BR$ negligible
  - $t\phi < t_{CLU} < t\phi + 70$ ns $\Rightarrow$ $t\phi < t_{CLU} < t\phi + 55$ ns $\delta BR/BR$ negligible
- the cut on the invariant mass of the two photons from $\pi^0 \to \gamma\gamma$
  - $80 < \Delta m_{\gamma\gamma} < 200$ MeV $\Rightarrow$ $65 < \Delta m_{\gamma\gamma} < 215$ $\delta BR/BR = 0.03\%$

Systematic effect (II): $K\pi2$ shape

This systematic contribution is estimated using two shapes both obtained from DATA but with very different bin by bin MC corrections



"New" Kπ2 shape (currently used)

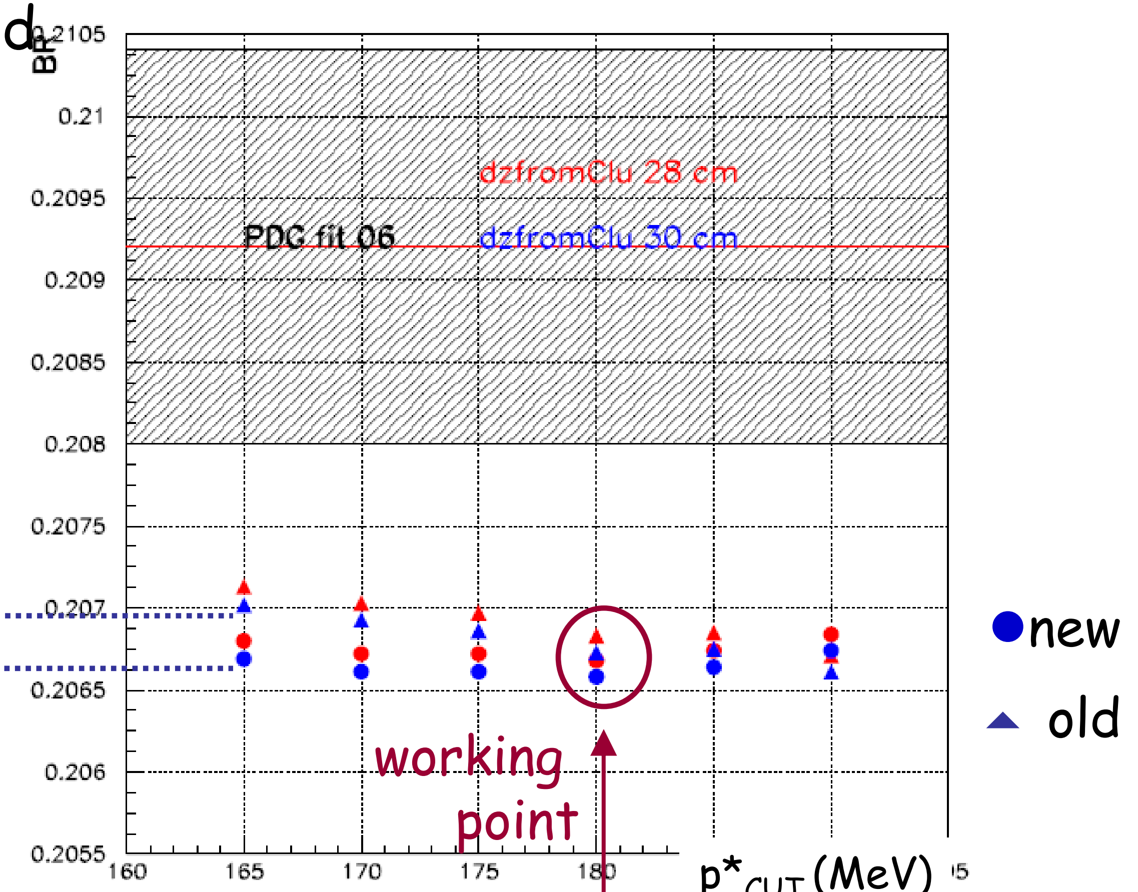


$$\text{shape}^{FIT} = \text{shape}^{DATA}(\text{vtx} + \pi0) \times \frac{\text{shape}^{MC}(\text{true } K\pi2)}{\text{shape}^{MC}(\text{selected})}$$

Systematic effect (II): $K\pi 2$ shape

Using the 2002 data sample and comparing the results obtained with the "New" and the "Old" $K\pi 2$ shapes

New vs Old shape
using the same d_fromClu
maximum difference
$\delta BR/BR$ = 0.16 %



New vs Old shape
d_fromClu = 30 cm
and p*= 180 MeV
$\delta BR/BR$ = 0.07 %

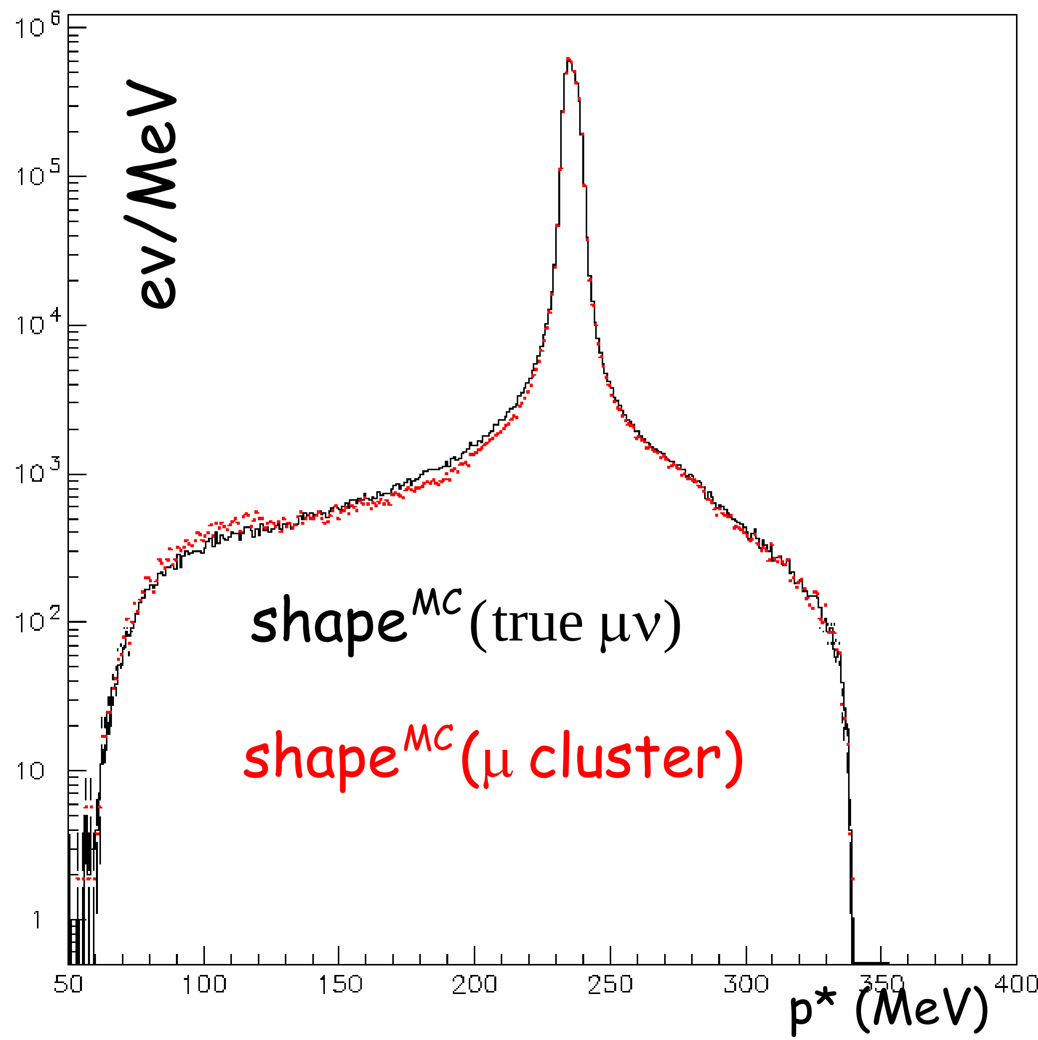
Using a conservative approach, the systematic contribution to BR($K\pi 2$) from the $K\pi 2$ shape is considered as $\delta BR/BR$ = 0.16%

Systematic effect (III) : Kμ2 shape

Change the selection of the "μ-cluster" control sample used for the Kμ2 shape varying the E_{CLU} *allowed range*

1) *tag on one side with $K \to \mu\nu$*
2) *isolate muon cluster of the tag*
3) *ask for :*
   - *1 cluster with $80 < E_{CLU} < 320$ MeV*
   - *no clusters with $20 < E_{CLU} < 80$ MeV*
   - *everything with $E_{CLU} < 20$ MeV*
4) *vertex in fiducial volume*

$\delta BR/BR = 0.12\%$



Systematic effect (VI): tag bias

This systematic contribution has been evaluated varying the requirements defining the tag.

The dedicated MC production for Charged Kaons of 2002 data taking has been used.

We moved separately the following cuts:

$p_K \in (70{,}130)$ MeV
$\rho_{VTX} \in (40{,}150)$ cm
$dp \in (-320{,}-120)$ MeV
$p^*(m_\pi) \in (180{,}270)$ MeV

$p_K \in (60{,}140)$ MeV
$\rho_{VTX} \in (30{,}160)$ cm
$dp \in (-340{,}-100)$ MeV
$p^*(m_\pi) \in (150{,}300)$ MeV

The contribution to the fractional systematic uncertainty is
$\delta BR/BR = 0.01\%$

Cross-check (II): measure BR(Kμ2(γ))

- From the fit of the p* distribution we can extract the number of Kμ2 decays with p*>225 MeV, integrating the Kμ2 shape

$$BR(K^+ \to \mu^+\nu(\gamma)) = \frac{N_{\mu\nu}\big|_{P*CUT}}{N_{TAG}} \frac{1}{\varepsilon_{DC}(p*cut)} \frac{1}{tagb} \times C_{FILFO} \times C_{T3}$$

For the efficiency evaluation and correction, we have followed the same strategy used for our published paper and used the "μ-cluster" sample.

$N_{TAG} = 12113686$

$\varepsilon^{MC}_{TRUE} / \varepsilon^{MC}_{METHOD} = 0.9984 \pm 0.0007$

$C_{FILFO} = 1.0001 \pm 0.0003$

$C_{T3} = 0.9995 \pm 0.0003$

$N_{\mu\nu}\big|_{P*CUT} = 2443780 \pm 2443$

$tagb = 1.0164 \pm 0.0002_{stat}$

$$BR(K^+ \to \mu^+\nu(\gamma)) = 63.63 \pm 0.09_{stat}$$

KLOE '06: PLB 632 $BR(K^+ \to \mu^+\nu(\gamma)) = 63.66 \pm 0.09_{stat} \pm 0.15_{syst}$

- Dividing 2002 data set in 7 sub-samples of 25 pb^{-1} each we have measured -0.21 correlation between BR(Kπ2) and BR(Kμ2)