Highlights on rare charged kaon decays

Mauro Raggi

On behalf of the NA48/2 Collaboration

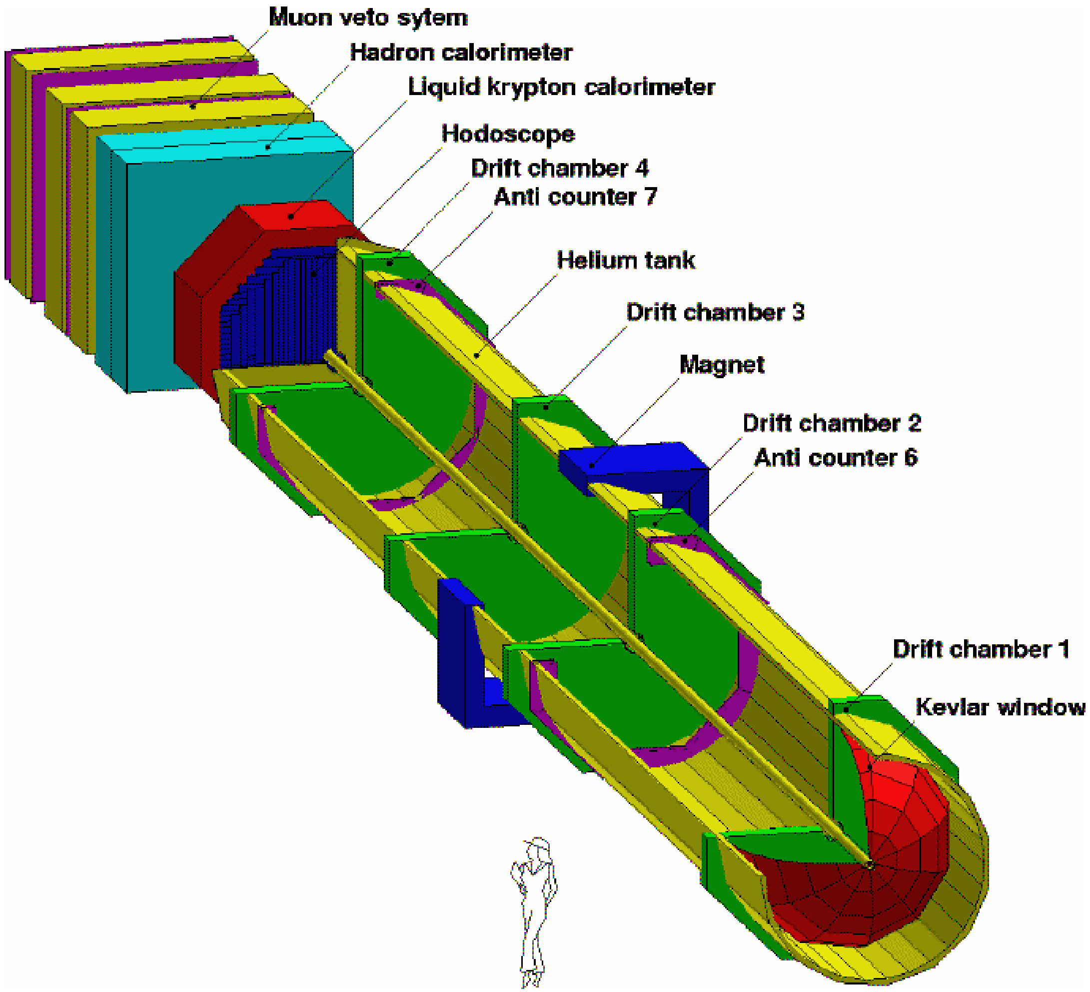
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara,
Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

BEACH 2006 Lancaster, 2-9 July 2006

Outline

- ✓ NA48/2 experiment
- ✓ The decay $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$:
  - formalism
  - experimental status
- ✓ NA48/2 measurement $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$ ***NEW***
- ✓ NA48/2 measurement K_{e4}^{00} BR and form factors ***NEW***
- ✓ Other rare K charged decays in NA48/2

NA48/2 detector



LKr EM calorimeter

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.1}{E} \oplus 0.5\%$$

$$\sigma_{x,y} < 1.3mm$$

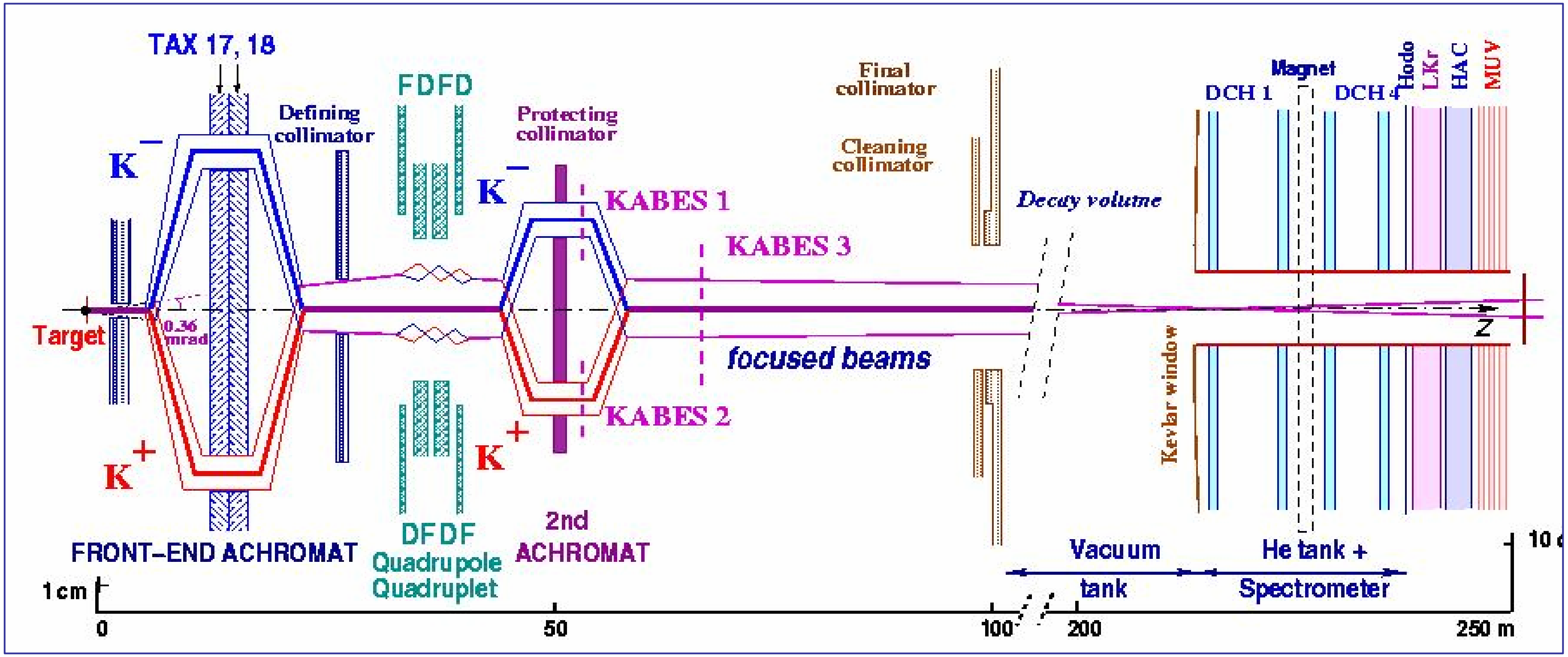
Spectrometer

- 4 Drift Chambers (DCH)
- Magnet

$$\frac{\sigma(p)}{p} = 1.\% \oplus 0.044 \times p(GeV)$$

$$\sigma_{VTX}^{x,y} \sim 2mm$$

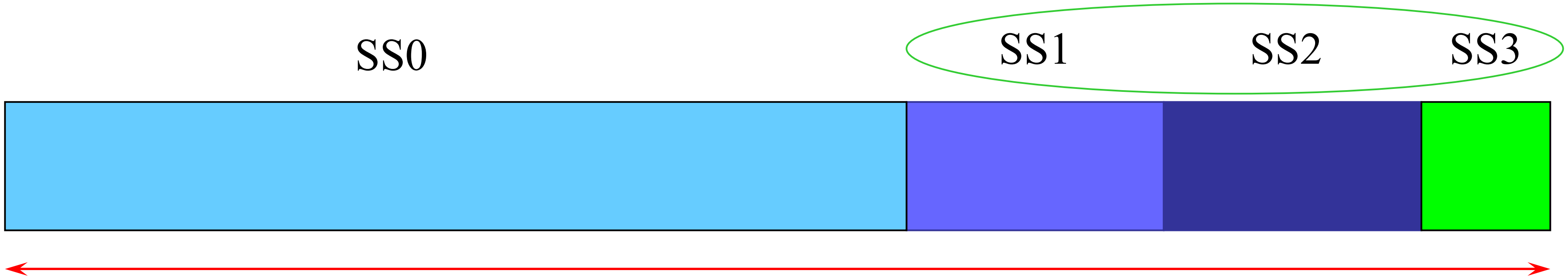
NA48/2 beam line



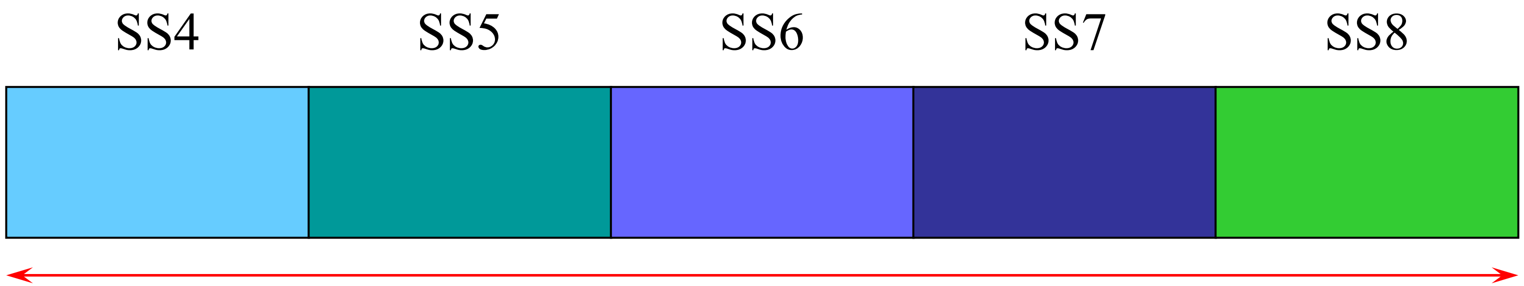
$$P_K = (60 \pm 3) GeV$$

$$\frac{K^+}{K^-} = 1.8$$

NA48/2 data taking periods



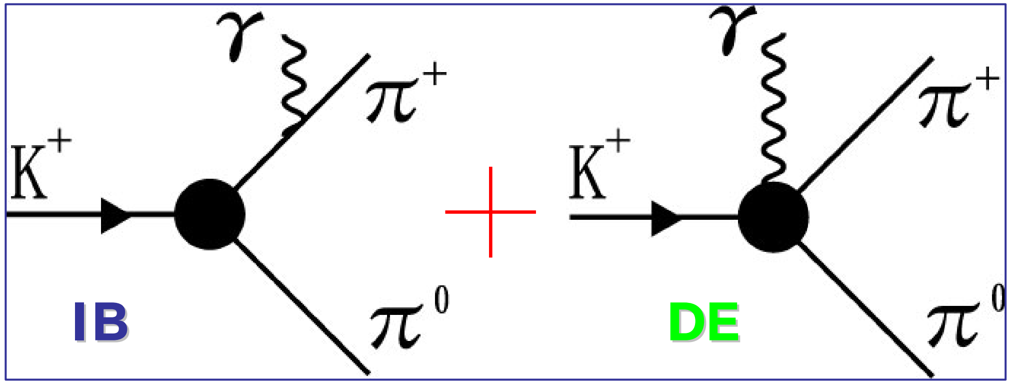
50 days during summer 2003



~ 60 days during summer of 2004

NA48/2 RARE DECAYS:
1. $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$

Gamma production mechanism



$$\frac{d\Gamma^{\pm}}{dW} \simeq \underbrace{\left(\frac{d\Gamma^{\pm}}{dW}\right)_{IB}}_{\text{IB}} \left[1 + \underbrace{2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi)}_{\text{INT}} + \underbrace{\left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)}_{\text{DE}}\right]$$

Inner Bremsstrahlung(IB)	: $(2.75 \pm 0.15) \cdot 10^{-4}$	PDG (2005)	$(55 < T^*_\pi < 90$ MeV)
Direct Emission (DE)	: $(4.4 \pm 0.8) \cdot 10^{-6}$	PDG (2005)	$(55 < T^*_\pi < 90$ MeV)
Interference (INT)	: not yet measured		

$K \rightarrow \pi\pi\gamma$ amplitudes

- Two type of contributions:
  - Electric ($J=l\pm1$) dipole (E_1)
  - Magnetic ($J=l$) dipole (M_1)
  - Electric contributions are dominated by the Inner Bremsstrahlung (E_{IB}) term
- Thanks to Low's theorem **IB** contribution can be related to the non radiative decay $\pi^{\pm}\pi^{0}$ using QED corrections.
- **DE** shows up only at order $O(p^4)$ in CHPT
- Is generated by both E and M contributions:
  - Magnetic contributions are dominated by chiral anomaly
  - Electric contributions come from L^4 CHPT lagrangian and loops L^2
- Present experimental results seem to suggest a M dominated DE

General expression for decay rate

$$\frac{d\Gamma^\pm}{dW} \simeq \underbrace{\left(\frac{d\Gamma^\pm}{dW}\right)_{IB}\Big[1}_{\textbf{IB}} + 2\left(\frac{m_\pi}{m_K}\right)^2 \underbrace{W^2|E|cos((\delta_1-\delta_0)\pm\phi)}_{\textbf{INT}} + \underbrace{\left(\frac{m_\pi}{m_K}\right)^4 W^4(|E|^2+|M|^2)}_{\textbf{DE}}\Big]$$

$\Gamma^\pm$ depends on 2 variables (W e T^*_π) that can be reduced to only one integrating over T^*_π, leading to the above formula where W is a Lorentz invariant variable.

The above formula shows the 3 contributions separately: **IB, DE, INT.**

The **INT** may arise only between the electrical contribution of DE and the IB term.

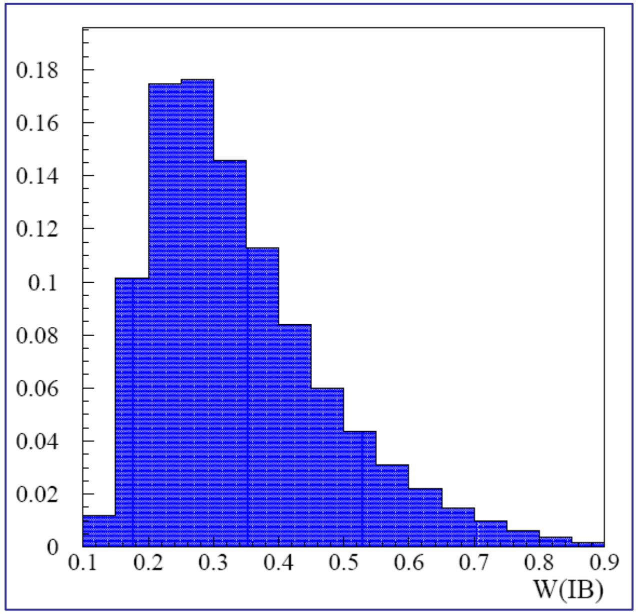
If the INT term near 0 the electrical contributions in the DE term has to be very small.

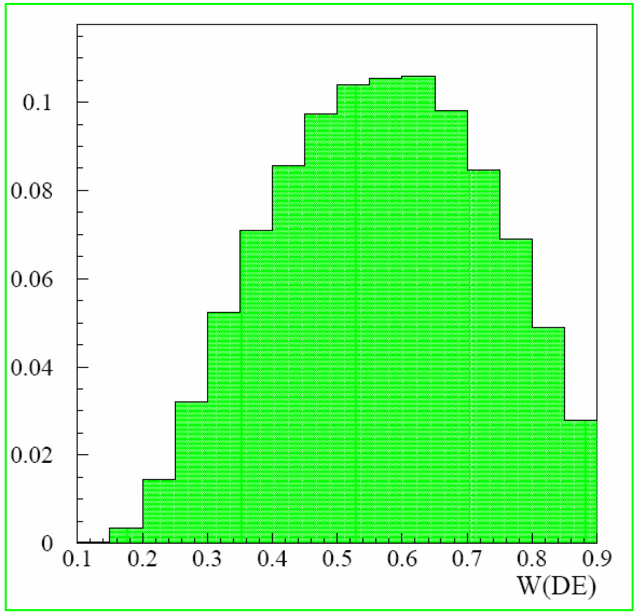
With this parametrization the ratio data/MC(IB) has the form $1+\alpha W^2+\beta W^4$

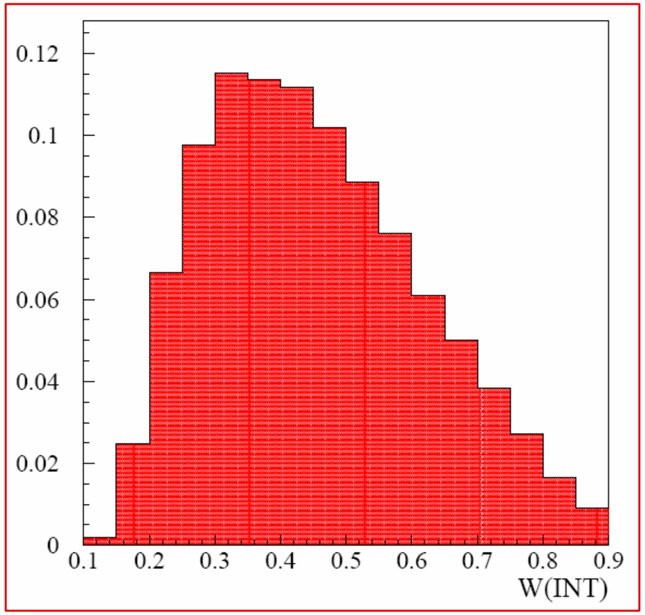
$$\boxed{W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_k m_\pi)^2}}$$

P^*_K=4-momentum of the $K^\pm$
P^*_π=4-momentum of the $\pi^\pm$
P^*_γ=4-momentum of the radiative γ

W distributions for IB, DE, INT



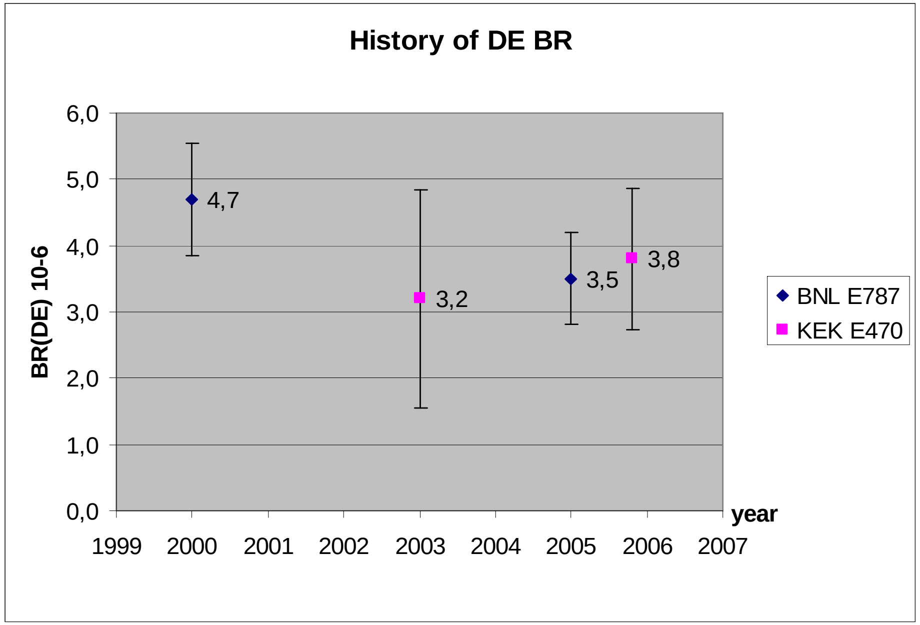




The distributions of **IB** and **DE** have very different shapes.
The distributions are not in scale (IB/DE) ~ 60 because otherwise you can hardly see them but the IB one!

Experimental results for DE and INT

Experiment	year	# of events	DE BR 10^{-6}
Abrams [5]	1972	2100	$15.6 \pm 3.5 \pm 5.0$
Smith [18]	1976	2461	23 ± 32
Bolotov [19]	1987	140	$20.5 \pm 4.6^{+3.9}_{-2.3}$
E787 [20]	2000	19836	$4.7 \pm 0.8 \pm 0.3$
E470 [21]	2003	4434	$3.2 \pm 1.3 \pm 1.0$
E787 [22]	2005	20571	$3.5 \pm 0.6^{+0.3}_{-0.4}$
E470 [23]	2005	10154	$3.8 \pm 0.8 \pm 0.7$



All the measurements have been performed in the T^*_π region 55-90 MeV to avoid $\pi^\pm\pi^0\pi^0$ BG

All of them are assuming the Interference term to be = 0

Interference measurements:

$\boxed{\begin{array}{l}\mathrm{INT}=(-0.58^{+0.91}_{-0.83})\%\text{ of IB} \\ \mathrm{INT}=(-0.4 \pm 1.6)\%\text{ of IB}\end{array}}$

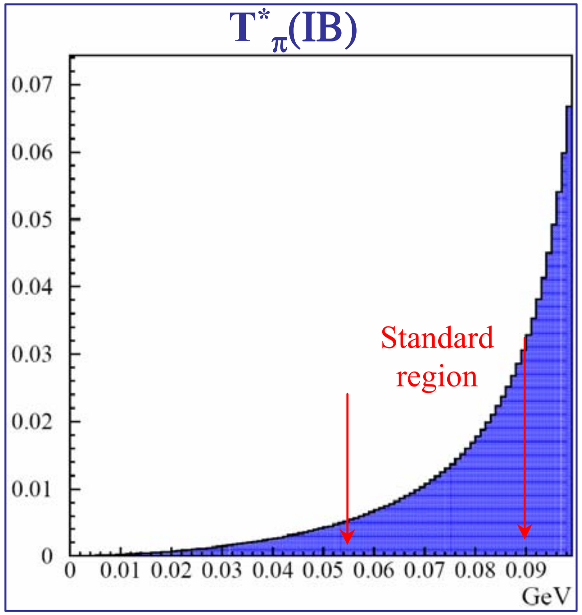
BNL E787

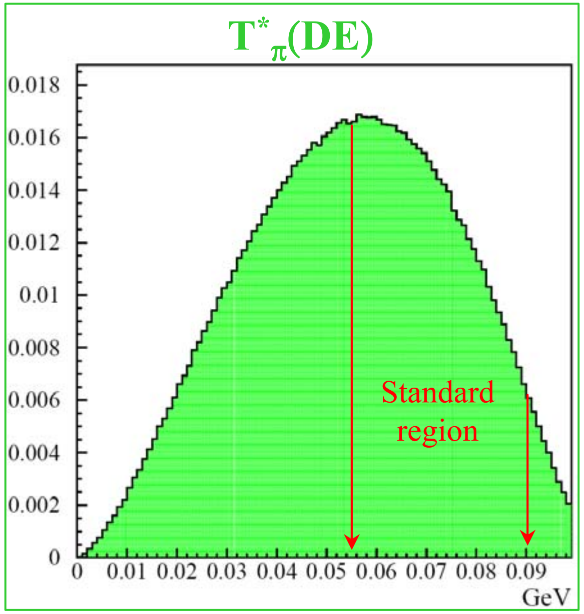
KEK E470

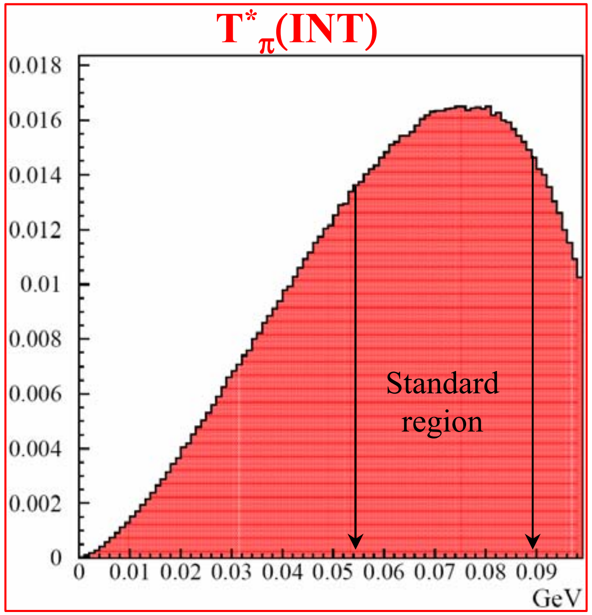
What's new in NA48/2 measurement

- In flight Kaon decays
- Both K^+ and K^- in the beam (possibility to check the CP violation)
- **Very high statistics** (220K $\pi^{\pm}\pi^0\gamma$ candidates of which 124K used in the fit)
- **Enlarged T^*_π region** in the low energy part ($0<T^*_\pi<80$ MeV)
- Negligible **background** contribution **< 1%** of the **DE** component
- Good W resolution mainly in the high statistic region
- More bins in the fit to enhance sensitivity to INT
- **Order ‰ γ mistagging probability** for IB, DE and INT

Enlarging T^*_π region







Use the standard region $55<T^*_\pi<90$ MeV is a safe choice for BG rejection (K3πn)

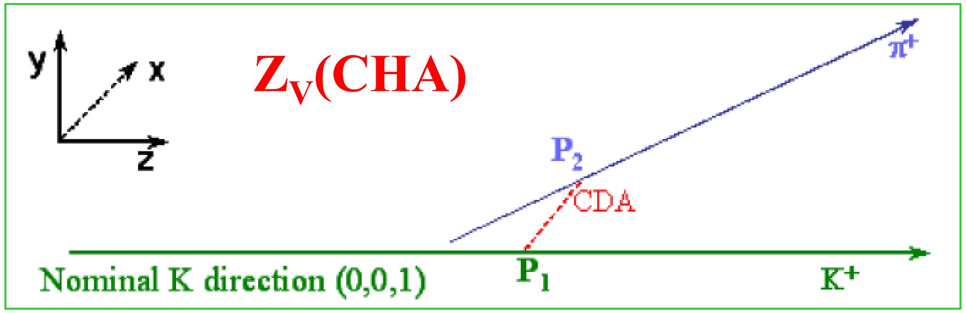
Unfortunately the region below 55 MeV is the most interesting for DE and INT measurement

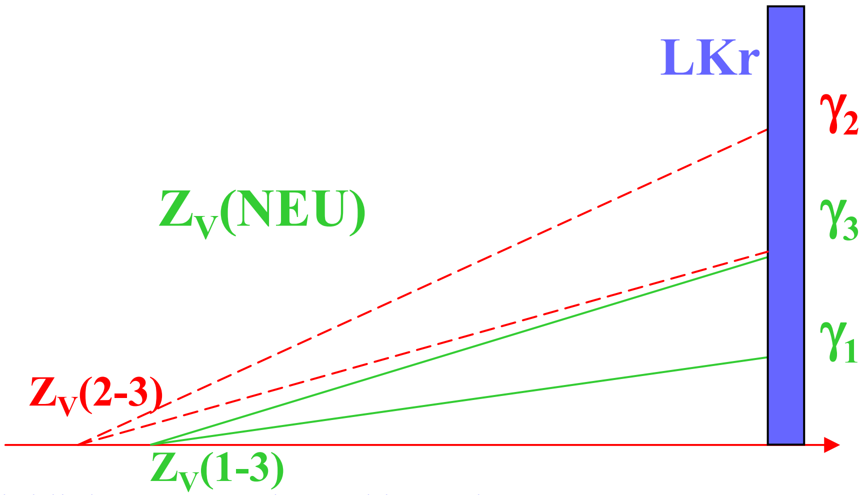
This measurement will be performed in the region $0<T^*_\pi<80$ MeV to improve statistics and fit stability.

Reconstruction strategy

We can get two independent determination of the K decay vertex:

- The charged vertex Z_V(CHA) using the K and π flight directions (spectrometer)
- The neutral vertex Z_V(NEU) imposing π^0 mass to gamma couples (LKr)





For the neutral vertex we have 3 values: $Z_V(12)$, $Z_V(23)$, $Z_V(13)$ but only one of those is the correct one.

We evaluate the kaon mass for all of them and then choose the vertex giving the best kaon mass.

Once the neutral vertex has been chosen we also know what the radiated γ is.

$K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ selection

Track Selection

- # tracks = 1.
- $P_{\pi+} > 10$ GeV
- E over P < 0.85
- No muon veto hits
- 0 MeV < $T^{*}_{\pi+}$ < 80 MeV

Gamma selection

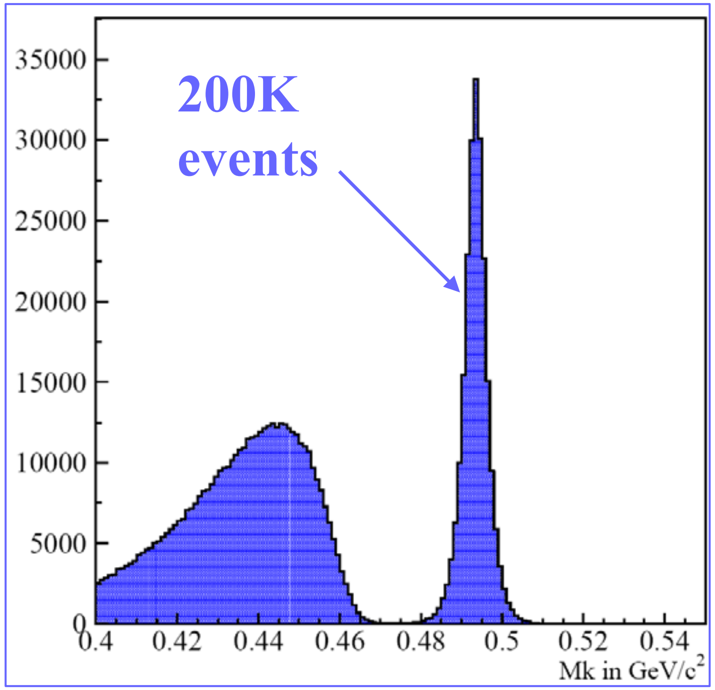
- $N_{\gamma} = 3$. (well separated in time LKr clusters)
- Minimum γ energy > 3 GeV (>5 for the fit)

Gamma tagging optimization

- CHA and NEU vertex compatibility
- Only one compatible NEU vertex

BG rejection cuts

- COG < 2 cm
- Overlapping γ cuts
- $|M_{K}-M_{KPDG}| < 10$ MeV

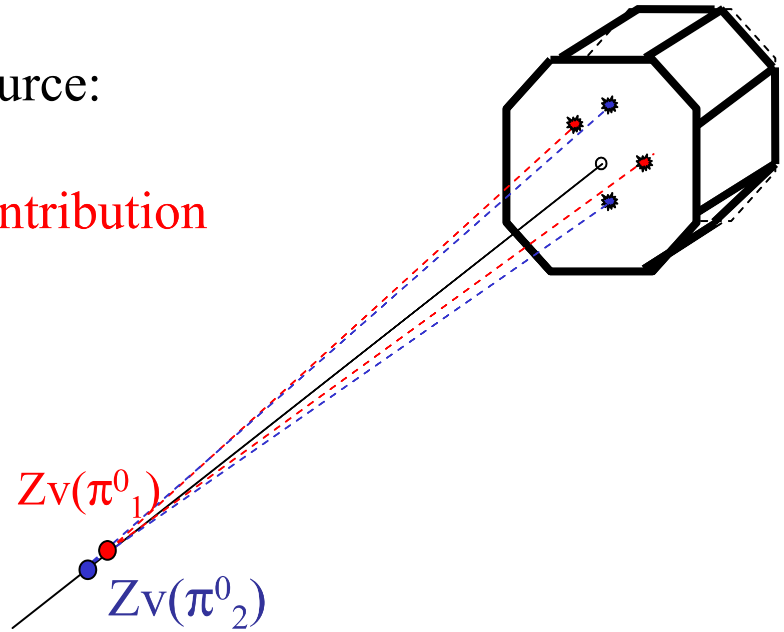


Main BG sources

Decay	BR	Background mechanism
$K^\pm \to \pi^\pm \pi^0$	$(21.13\pm0.14)\%$	+1 accidental or hadronic extra cluster
$K^\pm \to \pi^\pm \pi^0 \pi^0$	$(1.76\pm0.04)\%$	-1 missing or 2 overlapped gammas
$K^\pm \to \pi^0 e^\pm \nu$	$(4.87\pm0.06)\%$	+1 accidental γ and e misidentified as a π
$K^\pm \to \pi^0 \mu^\pm \nu$	$(3.27\pm0.06)\%$	+1 accidental γ and μ misidentified as a π
$K^\pm \to \pi^0 e^\pm \nu(\gamma)$	$(2.66\pm0.2)\cdot 10^{-4}$	e misidentified as a π
$K^\pm \to \pi^0 \mu^\pm \nu(\gamma)$	$(2.4\pm0.85)\cdot 10^{-5}$	μ misidentified as a π

- ✓ Physical BG rejection:
  - For $\pi^\pm\pi^0$ we can relay on the cut in $T^*_\pi < 80$ MeV, M_K and COG, cuts
  - For $\pi^\pm\pi^0\pi^0$ we have released the T^*_π cut, but we can anyway reach required rejection (kaon mass cut (missing γ) and overlapping γ cut (fused γ))
- ✓ Accidental BG rejection ($\pi^\pm\pi^0$, $K_{e3}(\pi^0 \varepsilon^\pm \nu)$, $K_{\mu 3}(\pi^0 \mu^\pm \nu)$)
  - Clean beam, very good time, space, and mass resolutions.

Fused γ rejection:overlapping γ cut



Fused gamma events are very dangerous BG source:
- M_K, and COG cut automatically satisfied!
- Releasing the T^*_π cut they can give sizable contribution

NA48 calorimeter is very good to reject them:
- very high granularity (2x2 cm) cells
- very good resolution in vertex Z coordinate

Multi step algorithm looped over clusters:

Split 1 out of the 3 clusters in two γ of energies:
$\varepsilon\gamma_1 = xE_{CL}$ $\varepsilon\gamma_2 = (1-x)E_{CL}$
now we got 4 γs and we star reconstructing the event as a $\pi^\pm\pi^0\pi^0$.

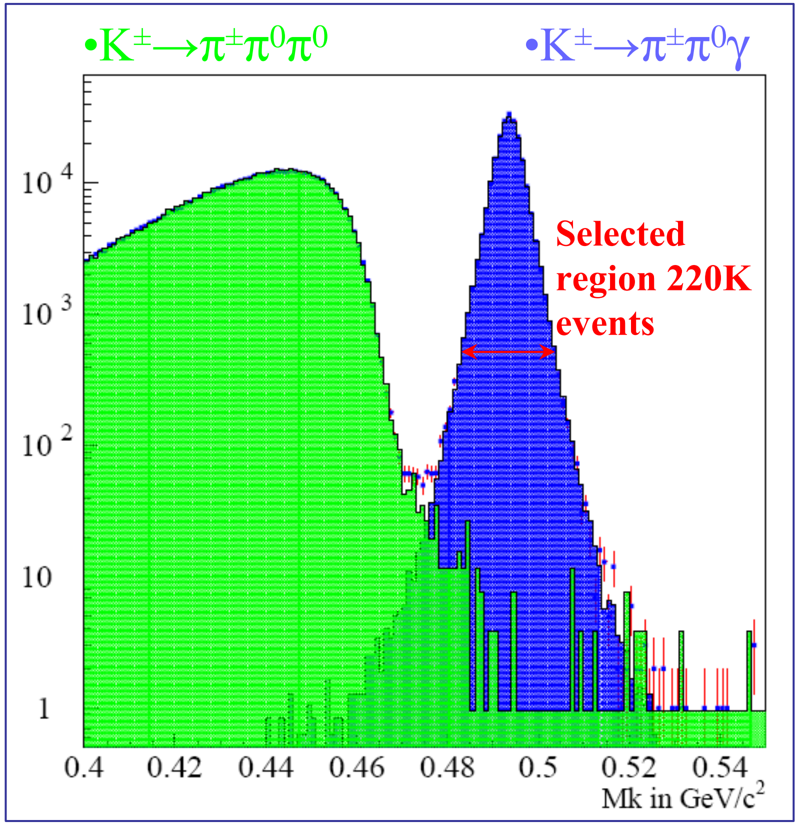
Evaluate the $Z_V(x)$ pairing the gammas and extract x imposing that:
$Zv(\pi^0_1) = Zv(\pi^0_2)$ same K decay vertex: the $2\pi^0$ came from the same K!

Put x back in the $Zv(\pi^0_2)$ to get the real Z_V(neu)
If the |Zv(CHA)-ZV(neu)|<400 cm ➡ the γ are really fused and so we discard the event

BG rejection performance

Thanks to the overlapping gamma cut and to MK and COG resolutions, the BG coming from $\pi^{\pm}\pi^0\pi^0$ is under control.

Source	**%IB**	**%DE**
$\pi^{\pm}\pi^0\pi^0$	$\sim 1\cdot 10^{-4}$	$\sim 0.61\cdot 10^{-2}$
Accidental	$<0.5\cdot 10^{-4}$	$\sim 0.3\cdot 10^{-2}$



All physical BG can be explained in terms of the $\pi^{\pm}\pi^0\pi^0$ events only. Very small contribution from accidentals neglected

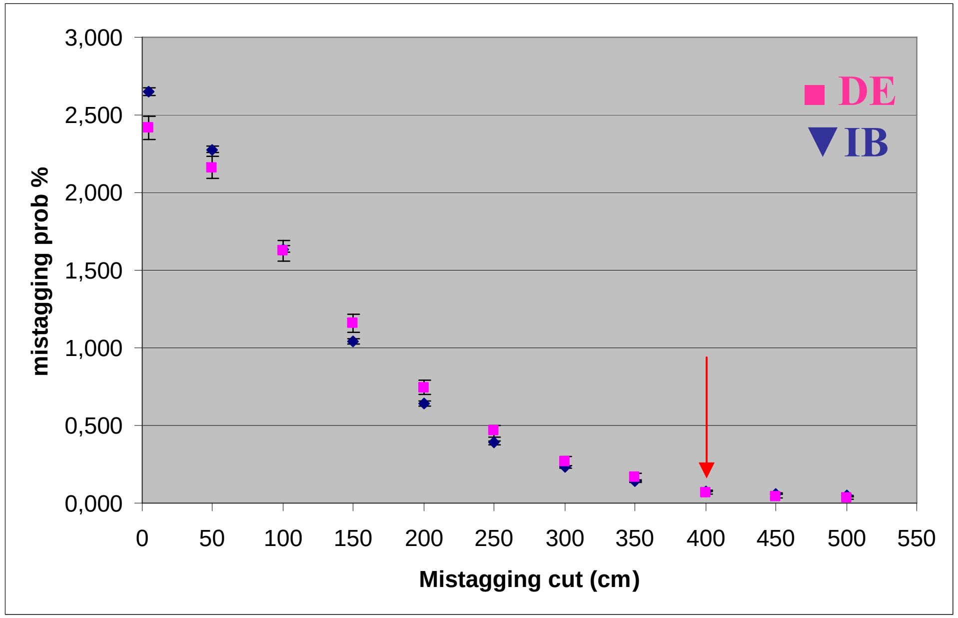
Total BG is less than 1% with respect to the expected DE contribution even in the range $0<T^*_\pi<80$ MeV

The mistagged γ events: a self BG

The **mistagged gamma** events behave **like BG** because they can induce fake shapes in the W distribution. In fact due to the slope of IB W distribution they tend to populate the region of high W simulating DE events.

The rejection of mistagged events has 2 steps:

1. Compatibility of charged and neutral vertices (2.5% mistagging)
2. Distance between best and second best neutral vertices > xx cm



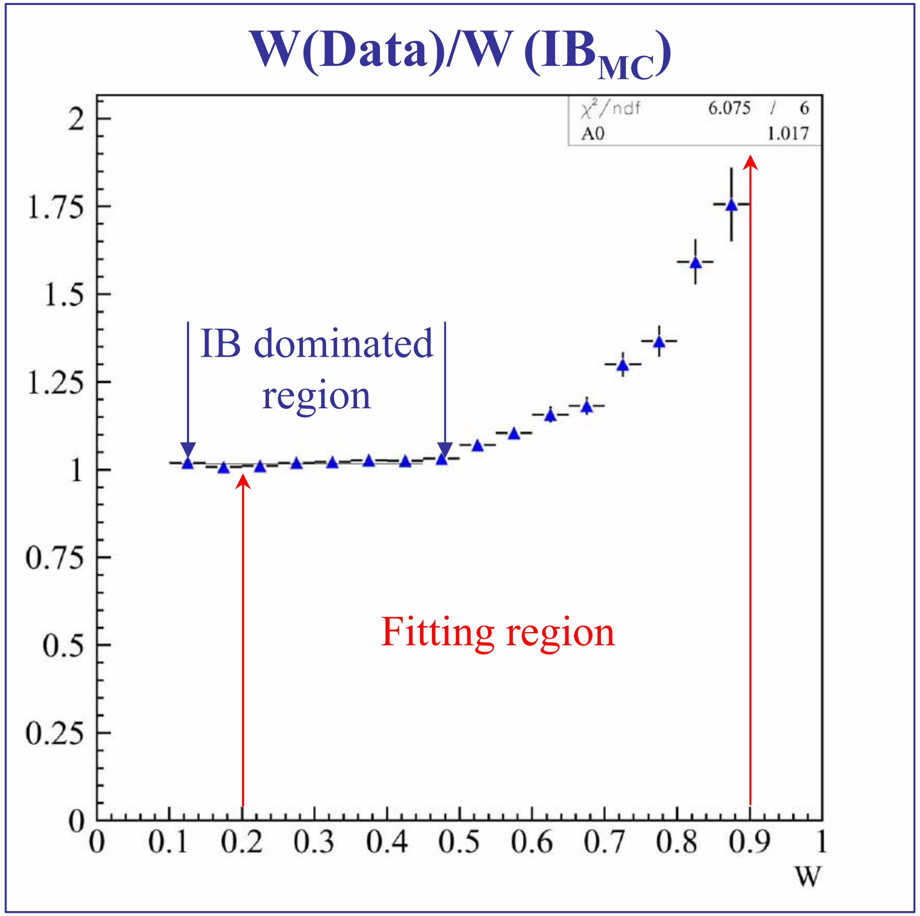
The **mistagging probability** has been evaluated in MC as a function of the mistagging cut to be **1.2‰ at 400 cm**

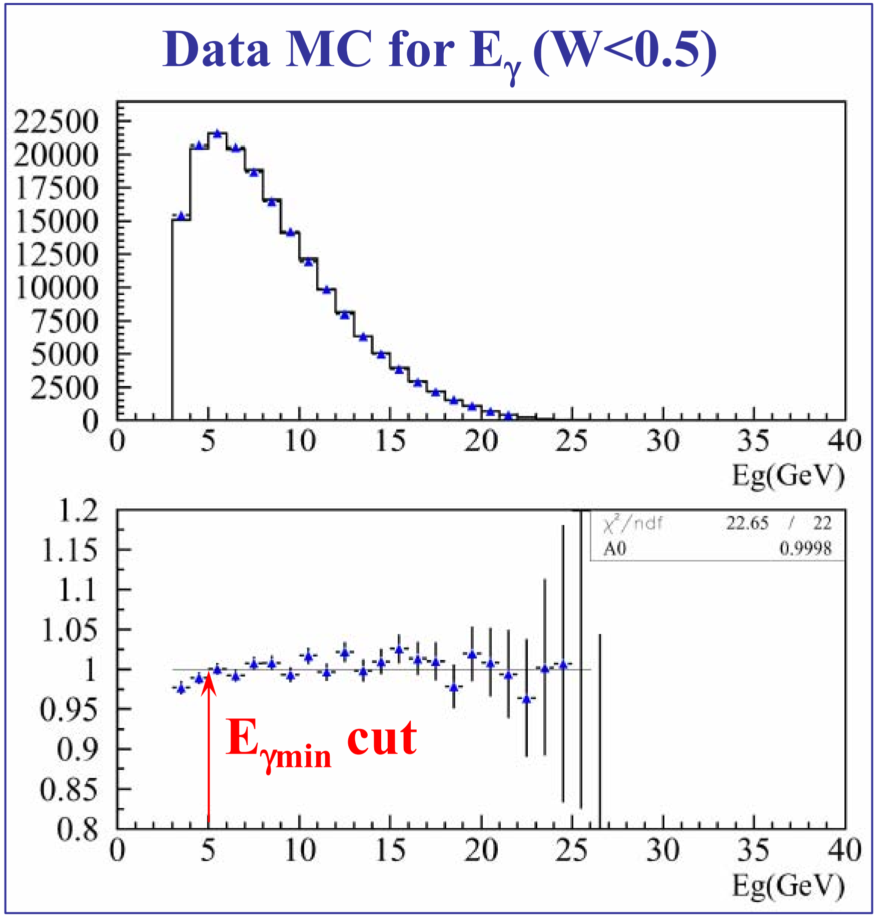
Mistagging probabilities for IB and DE events are very similar.

Data MC comparison

The IB dominated part of the data W spectrum is very well reproduced by MC

The radiated γ energy (for the IB part of the spectrum) is very well reproduced





Fitting algorithm

To get the fractions of **IB(α)**, **DE(β)**, **INT(γ)**, from data we use an extended maximum likelihood approach:

$$\boxed{\nu_k = \nu\beta_k\alpha + \nu\delta_k\beta + \nu j_k\gamma} \qquad \boxed{\alpha + \beta + \gamma = 1}$$

$$\boxed{\ln L = \sum_{k=1}^{nbin}\left[n_k \ln \nu_k - \nu_k + b_k \ln \pi_k - \pi_k + d_k \ln \tau_k - \tau_k + I_k \ln \iota_k - \iota_k\right]}$$

The fit has been performed in 14 bins, between **0.2-0.9,** with a minimum γ energy of **5 GeV**, using a **data sample of 124K events**.

To get the fractions of DE and INT the raw parameter are corrected for different acceptances

Systematic uncertainties

Many systematic checks have been performed using both data and Monte-Carlo

Effect	Syst. DE	Syst. INT
Energy scale	+0.09	-0.21
Fitting procedure	0.02	0.19
LVL1 trigger	±0.17	±0.43
Mistagging	_	±0.2
LVL2 Trigger	±0.17	±0.52
Resolutions difference	<0.05	<0.1
LKr non linearity	<0.05	<0.05
BG contributions	<0.05	<0.05
TOTAL	**±0.25**	**±0.73**

Systematic effects dominated by the trigger!

Learning from experience both LVL1 and LV2 triggers have been modified in 2004. We are confident that both systematics will be reduced in 2004 data set.

Fit results

$$Frac(DE)_{0<T_\pi^*<80MeV} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\%$$

$$Frac(INT)_{0<T_\pi^*<80MeV} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\%$$

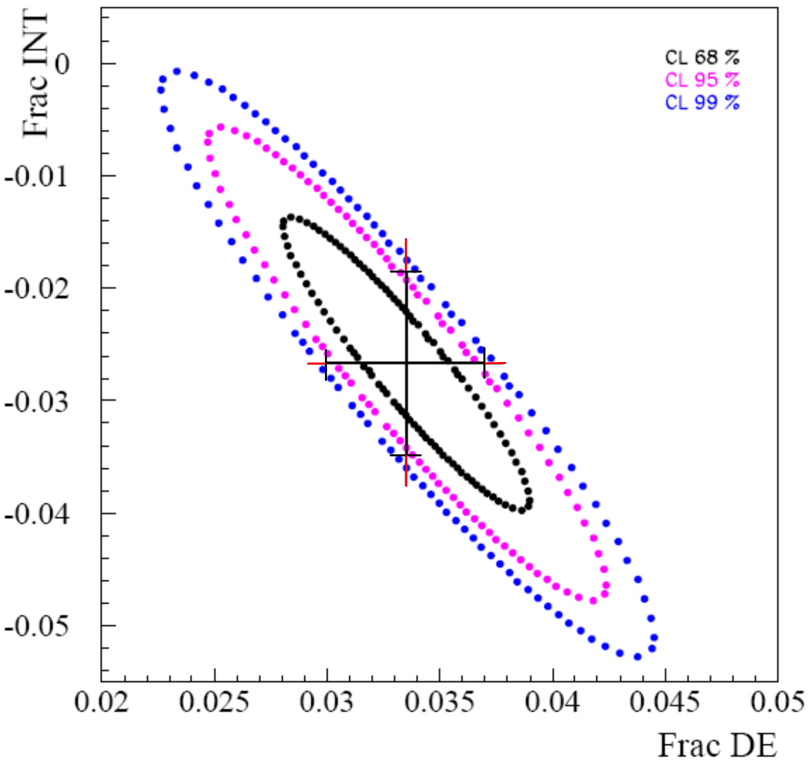
Preliminary

First measurement:

in the **region $0<T^*_\pi<80$ MeV** and
of the **DE term with free INT term**.

First evidence of a non zero INT term

The error on the results is still dominated by statistics and we could profit of SS0 and 2004 data to reduce statistical uncertainties.



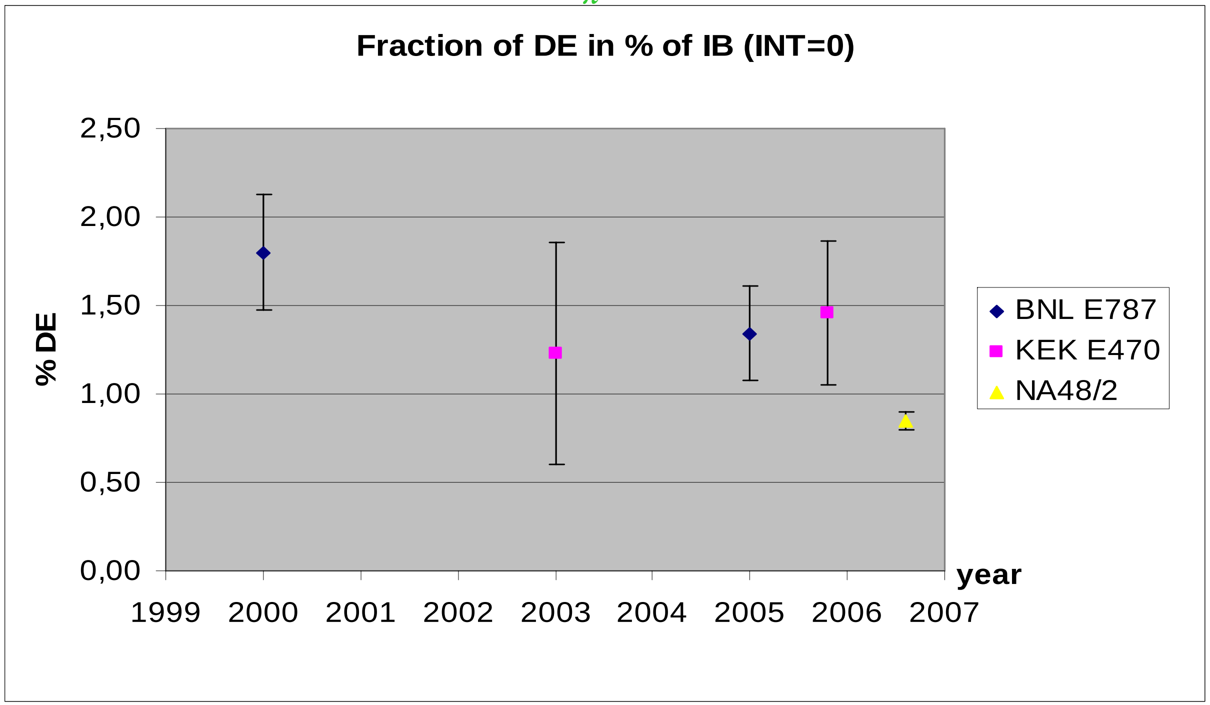
Unfortunately parameters are highly correlated

INT=0 fit: just for comparison

Just for comparison with what other experiments did we have also extracted the fraction of DE, with the INT term fixed to 0 in the region 55-90 MeV. A likelihood fit using IB & DE MC only has been performed in the region $0<T^*_\pi<80$ MeV.

Extrapolating to the 55-90 region using MC we get:

$$Frac(DE)^{INT=0}_{55<T^*_\pi<90\,MeV} = (0.85 \pm 0.05_{stat} \pm 0.02_{syst})\%$$



The analysis of fit residuals shows a bad χ^2

Description in term of IB+DE only is unable to reproduce W data spectrum.

NA48/2 RARE DECAYS:
2. $K^{\pm}\rightarrow\pi^{0}\pi^{0}e^{\pm}\nu$ ($K^{00}{}_{e4}$)

Introduction to K_{e4}^{00}

- ✓ Form factors are good constraint for CHPT Lagrangian
- ✓ Low energies π–π pairs can be used for scattering length measurements as in K_{e4}^{C}
- ✓ Also K_{e4}^{00} is expected to have a CUSP
- ✓ Best measurement by E470 based on 216 events
  - $BR(K_{e4}^{00})=(2.29 \pm 0.33)\cdot 10^{-5}$
  - Attempt to fit form factor F

Measurement technique for BR

- ✓ The Kaon flux has been measured using $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$:

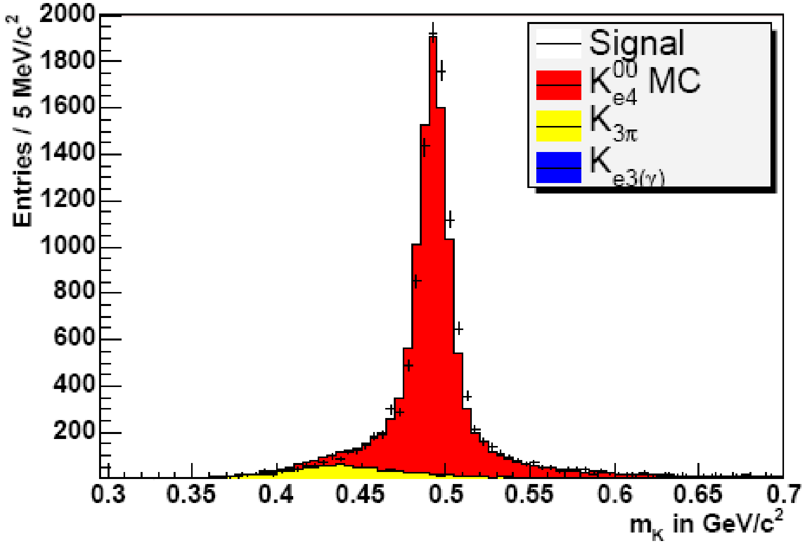
$$\phi(K) = \frac{N(\pi^{\pm}\pi^{0}\pi^{0})}{BR(\pi^{\pm}\pi^{0}\pi^{0}) \cdot ACC(\pi^{\pm}\pi^{0}\pi^{0}) \cdot Trig_{eff}(\pi^{\pm}\pi^{0}\pi^{0})}$$

- ✓ For the $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0})$ new result from KLOE has been used:

$$BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0})=1.763\pm0.013\pm0.022$$

Event selection

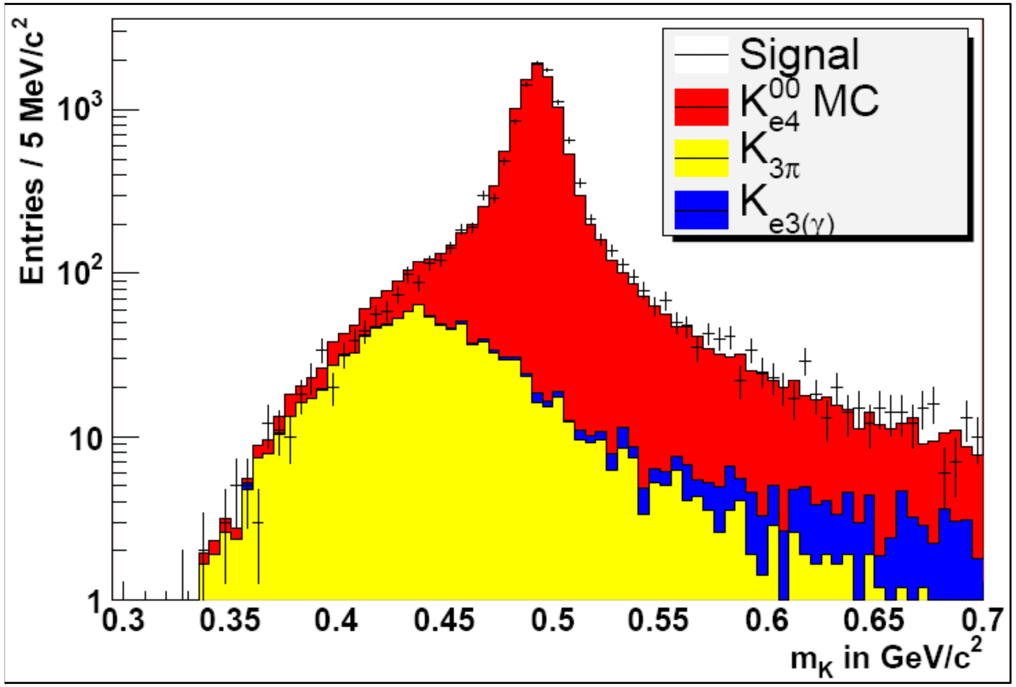
- ≥ 4 good γ clusters in LKr
- ≥ 1 good track with $E/p \geq 0.95$
- 2 good π^0 with similar Z_V vertex position (Neutral vertex)
- shower width cut to distinguish e and π
- Use the K for momentum from KABES to evaluate ν momentum assuming P_T=0
- The Kaon mass can be evaluated



BG estimates

1. $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ $\rightarrow$same final state of signal IF π misidentified as an e
   - E over P and shower width cut to identify hadronic showers from EM ones
   - Elliptic cut in the P_T and $M_K(\pi^{\pm}\pi^{0}\pi^{0})$ plane to identify $\pi^{\pm}\pi^{0}\pi^{0}$ decays

2. $K^{\pm}\rightarrow e^{\pm}\pi^{0}\nu(\gamma)$ $\rightarrow$ plus an accidental γ



9642 events with the following BG:

260±94 from $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$

16 ± 2 accidental BG form $K_{e3}(\gamma)$

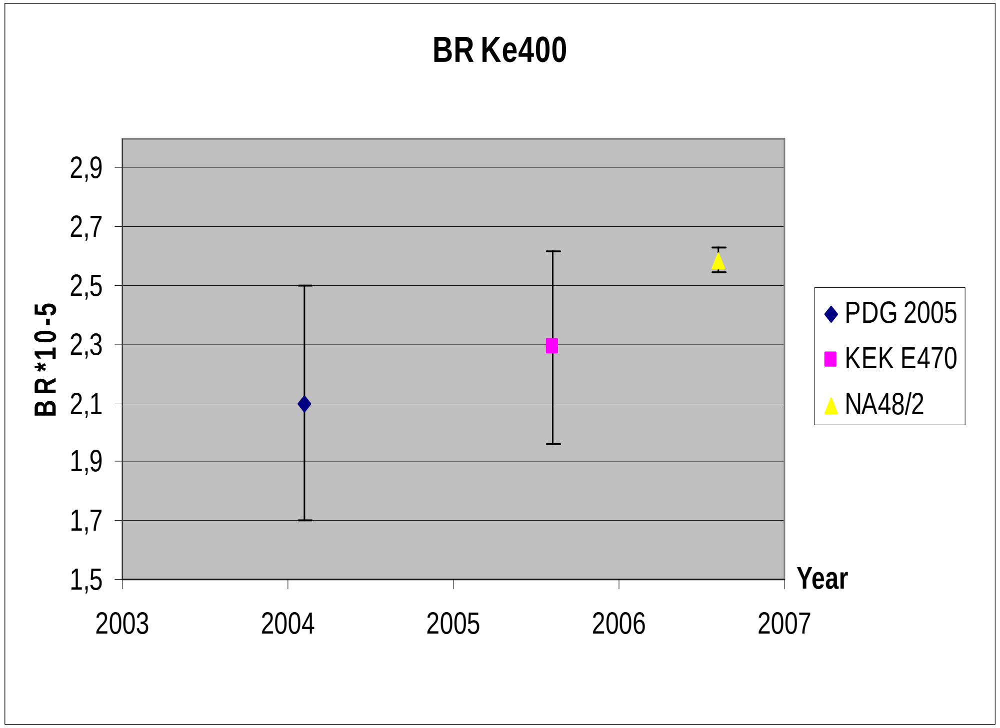
Quite clean sample BG less than 3%

Final result BR

Using only the SS123 part of the 2003 data (9642 events) the Branching Ratio of the K_{e4}^{00} decay has been measured:

$$BR(K_{e4}^{00}) = (2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{ext}) \cdot 10^{-5}$$

Preliminary



The result has been crosschecked using also Ke3 as normalization channel leading to consistent result.

The statistical error can be further reduced using the 2004 data set (28K events)

The K_{e4}^{00} form factors

In this case we have only 1 form factor F (2 identical π^0):

$$F = f_s + f_s' q^2 + f_s'' q^4 + f_e \left(S_e / 4 m_\pi^{\ 2} \right) + ..$$

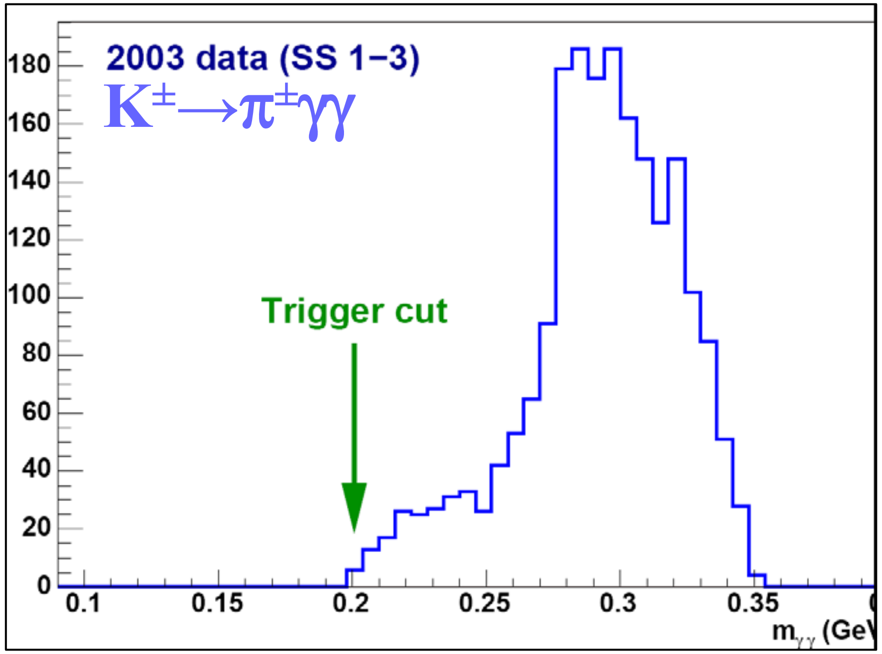
The fit has been performed using both 2003 and 2004 data (~38K events)

No sensitivity to f_e reached $\rightarrow f_e$ set to 0.
Under this assumption we get:

Parameter	Measured value
f_s'/f_s	$0.129 \pm 0.036_{stat} \pm 0.020_{syst}$
f_s''/f_s	$-0.040 \pm 0.034_{stat} \pm 0.020_{syst}$

Those values are consistent with the ones measured by NA48/2 in K_{e4}^{C}
See **detailed talk by B. Bloch-Devaux at QCD 2006 conference.**

$K^\pm \to \pi^\pm\gamma\gamma$ and other NA48/2 rare decays



Low $m_{\gamma\gamma}$ spectrum limited in the main trigger by a trigger cut around 200 MeV/c^2

Maybe we can look in the lower region using minimum bias triggers and 2004 dataset

Decay	# Ev. NA48/2	# Events	BR
$K^\pm \to \pi^\pm\gamma\gamma$	2000 (SS123)	31 (E787)	$BR_{(100<P<180)}=(6.0\pm1.5_{sta}\pm0.7_{sys})10^{-7}$
$K^\pm \to \pi^\pm e^\pm e^\pm$	4000(SS123)	10K (E787)	$(2.88\pm0.13)\cdot10^{-7}$
$K^\pm \to \pi^\pm \mu^\pm \mu^\pm$		402 PDG '05	$(8.1\pm1.4)\cdot10^{-8}$

Conclusions

- ✓ NA48/2 has performed the first measurement of the **DE and INT** terms in the region $0<T^{*}_{\pi}<80$ MeV for the decay $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$:

$$\boxed{\begin{aligned} Frac(DE)_{0<T_{\pi}^{*}<80\,MeV} &= (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\% \\ Frac(INT)_{0<T_{\pi}^{*}<80\,MeV} &= (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\% \end{aligned}}$$

Preliminary

- ✓ The results seem to indicate the presence of a negative, non vanishing, interference and therefore a non negligible contribution of E terms to the DE.
- ✓ A new measurement of the BR and form factor parameters for the K_{e4}^{00} decays has also been performed:

$$BR(K_{e4}^{00}) = (2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{ext}) \cdot 10^{-5}$$

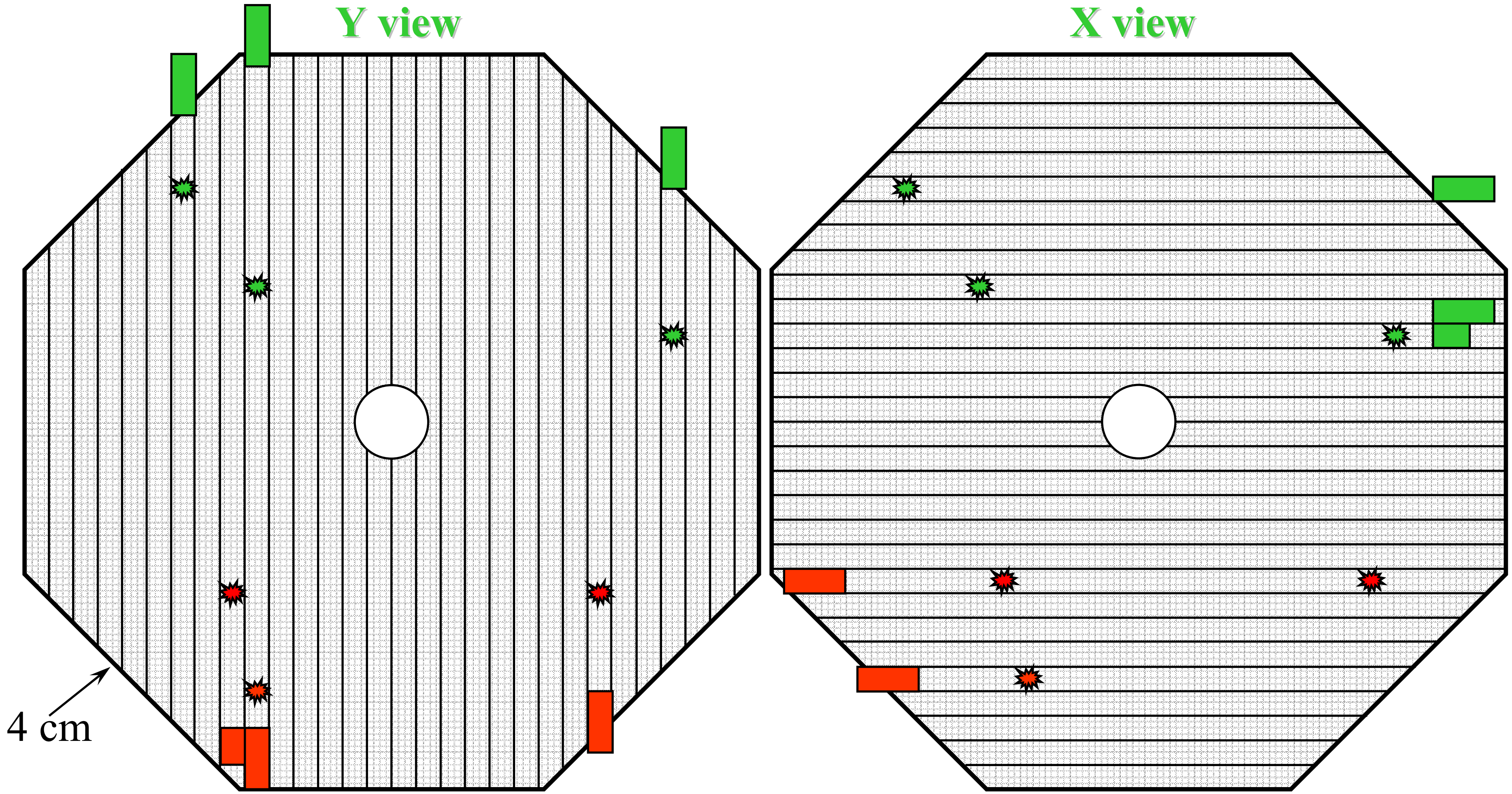
Preliminary

- ✓ Both results can be further improved using SS0 and 2004 statistics
- ✓ Much more to come in other rare decays

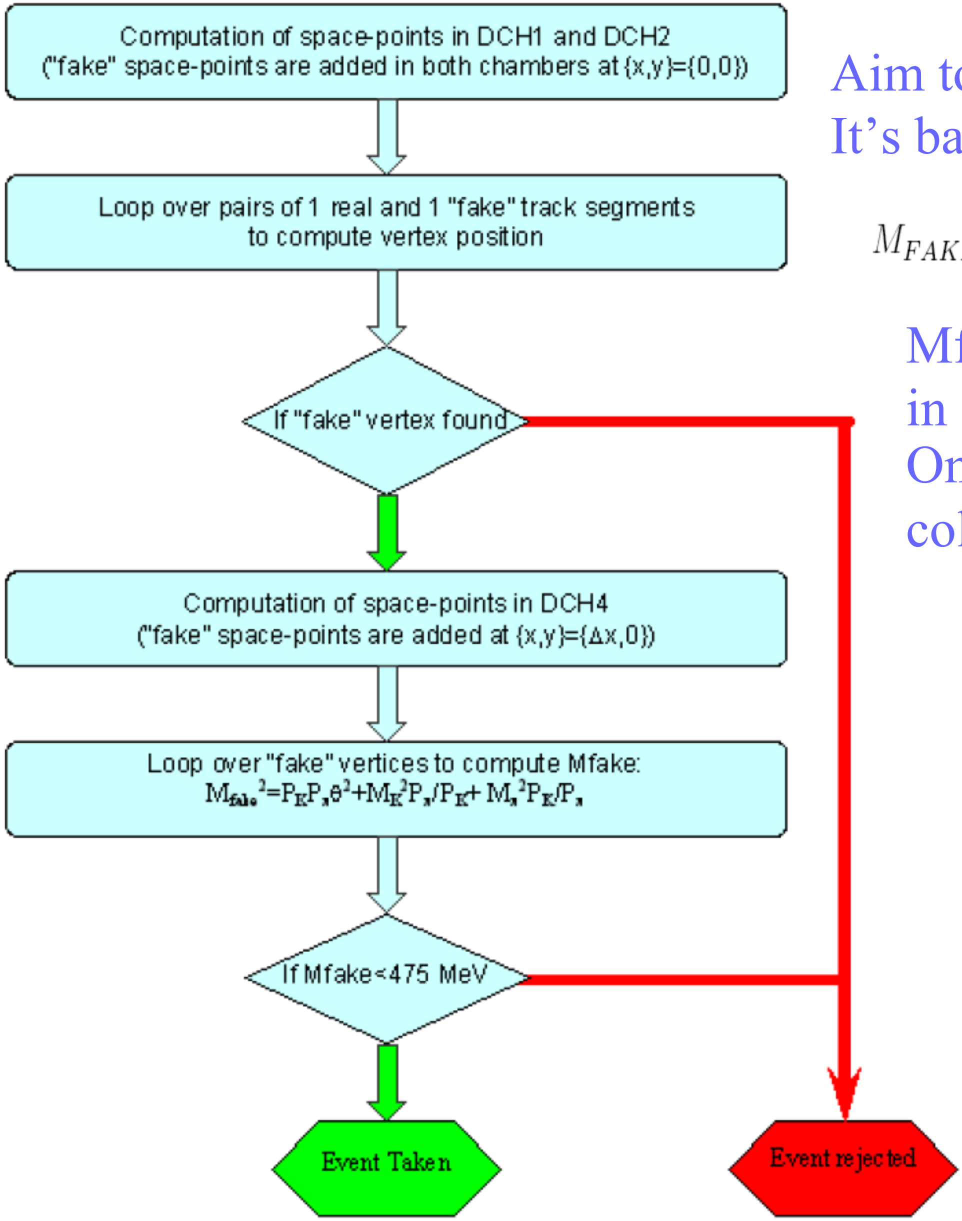
Backup slides

L1 trigger NT-PEAK

X OR Y > 2 view



MBX1TR-P LVL2 trigger



Aim to reject $K^\pm \to \pi^\pm \pi^0$ events and get $\pi^\pm \pi^0 \pi^0$.
It's based on the online computation of Mfake:

$$M_{FAKE} = P_K P_\pi \theta^2 + M_K^2 \frac{P_\pi}{P_K} + M_\pi^2 \frac{P_K}{P_\pi} = m_K^2 + m_\pi^2 - MM^2 = 2 m_k E_\pi^*$$

Mfake ~ M_K for $K^\pm \to \pi^\pm \pi^0$ events in fact $m_\pi^2 - MM^2 \sim 0$.
Only events with M_{FAKE} < 475 MeV, are collected by the trigger