Study of the rare decay $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ and high precision measurement of the form factors of the semileptonic decays $K\rightarrow\pi^{0}\ell\nu$

Dr. M. Raggi

INFN – Laboratori Nazionali di Frascati

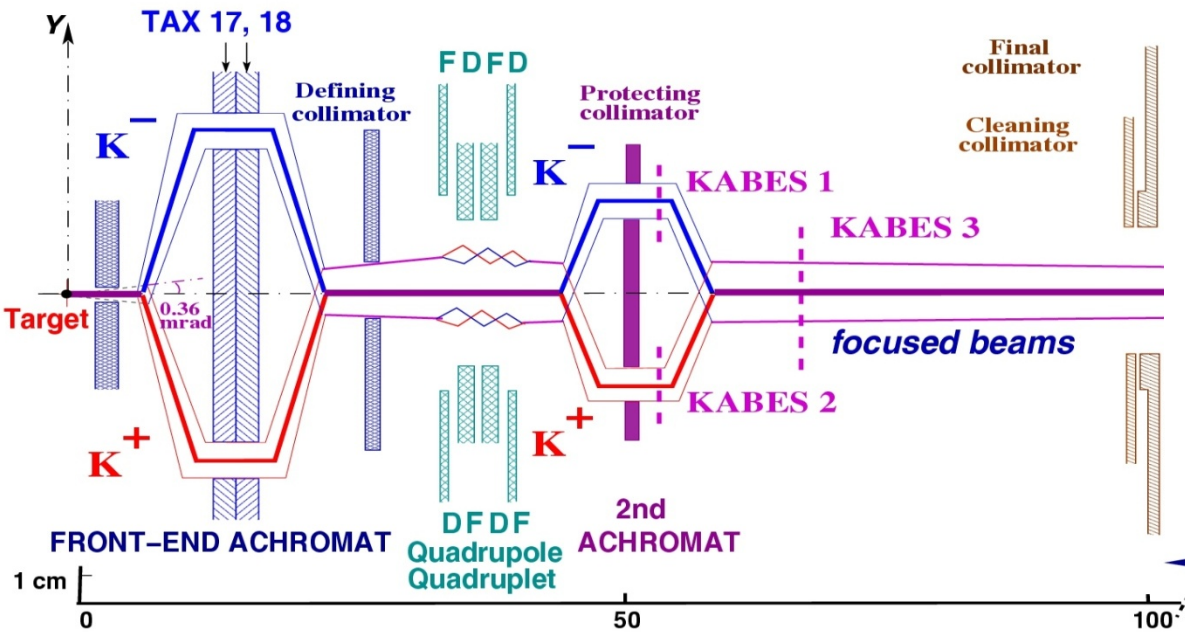
on behalf of the NA48/2 and NA62 collaborations

Outline

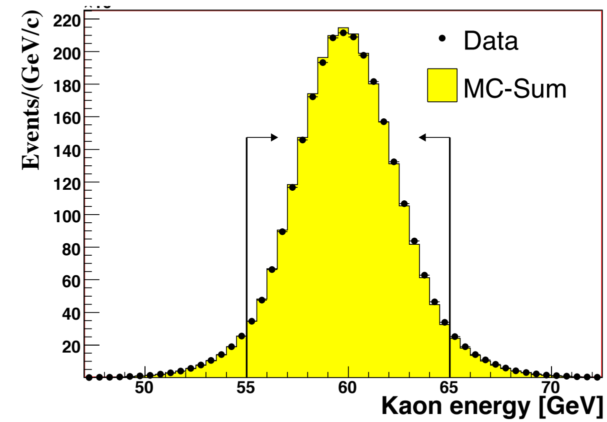
- The NA48/2 experiment
  - Beam line, detector, and data taking periods
- Semileptonic Kaon decays
- Recent results on Kμ3 and Ke3 Form Factors slopes
  - Kℓ3 form factor slopes fits status
- Recent result of NA48/2 and NA62 on $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$
- Conclusions

The NA48/2 and NA62 beam line

Simultaneous K^+ and K^- beam with N_{K+}/N_{K-} ~1.8



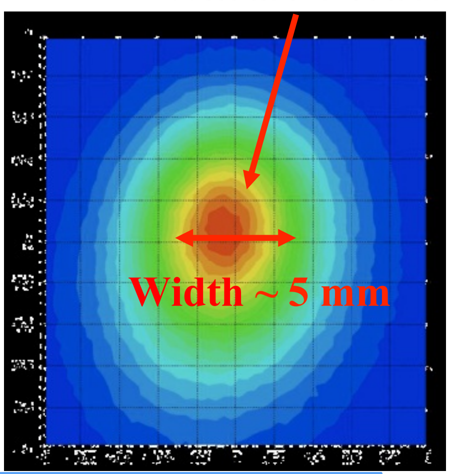
K momentum



NA48/2=60±2.2 GeV/c

NA62 = 74±1.4 GeV/c

Beams within 1 mm



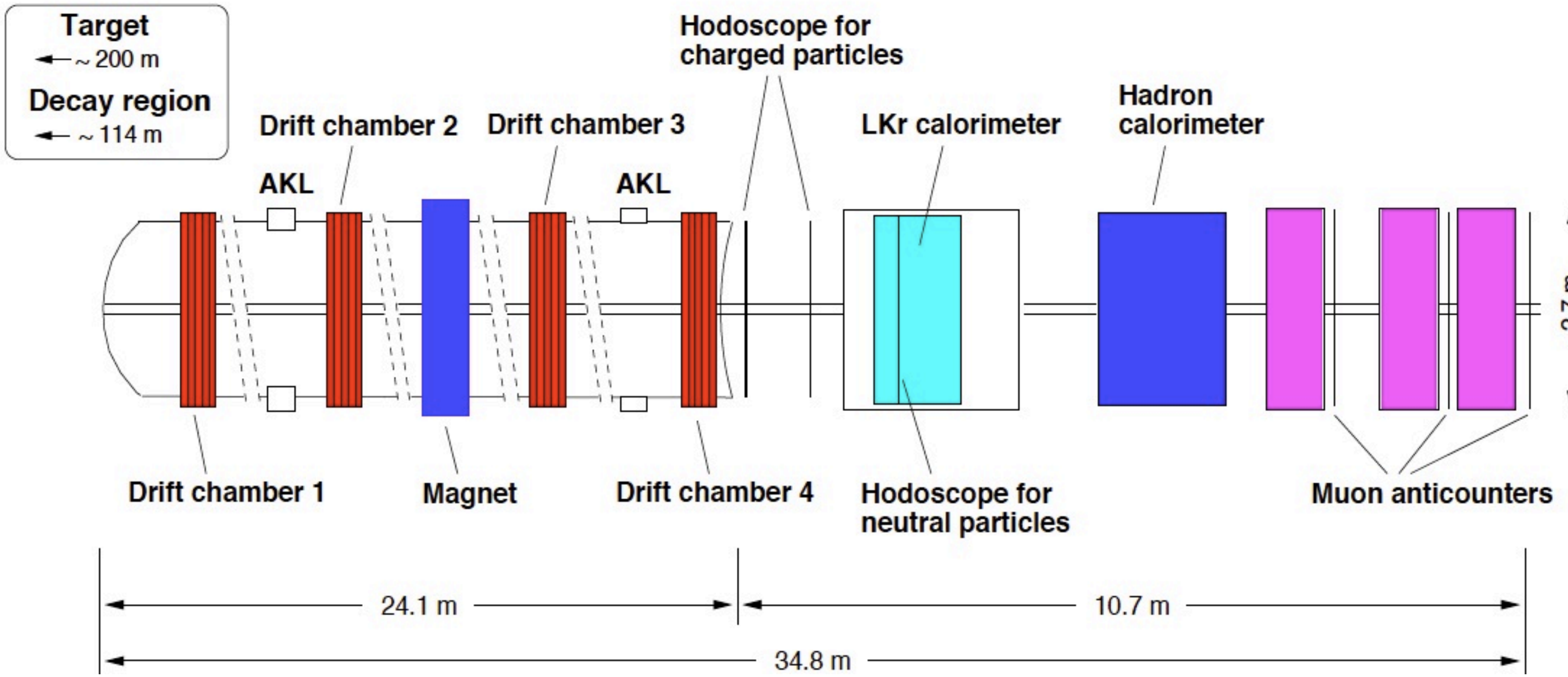
NA48/2 Data taking:

- 4 months in 2003 ($K^{\pm}$) + 4 months in 2004 ($K^{\pm}$)

NA62-RK Data taking:

- 2007 mostly K^+

The NA48/2 and NA62 detector



Magnetic Spectrometer

- 4 drift chambers and a dipole magnet

$$\left.\frac{\sigma(p)}{p}\right|_{NA48} = (1.02 \oplus 0.044\,p)\%$$

$$\left.\frac{\sigma(p)}{p}\right|_{NA62} = (0.48 \oplus 0.009\,p)\%$$

p in GeV

Liquid Krypton EM calorimeter (LKr)

- High granularity (13248 cells of 2x2 cm^2)
- Quasi-homogeneous, 7m^3 liquid Kr (27X_0)

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\%$$

E in GeV

The K^+ semileptonic decays

- $K^{\pm}\to\pi^0\ell^{\pm}\nu$ decays provide the **most accurate** and **theoretically cleanest** way to **access** $|V_{US}|$:

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} \, |V_{US}|^2 |f_+(0)|^2 \, I_K^{\ell}(\lambda_{+0})(1+\delta_{SU(2)}+\delta_{EM}^{\ell})^2$$

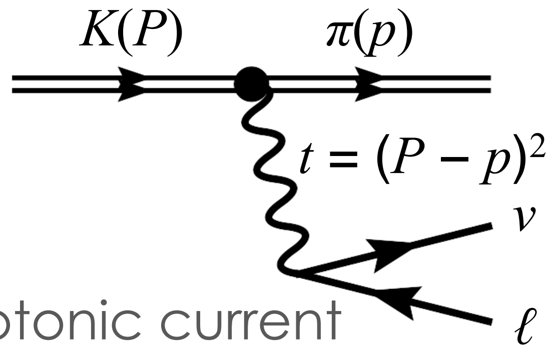
Experimental Inputs:

- $\Gamma(K\ell 3)$ Branching ratios and Kaon lifetimes
- $I^{\ell}_K(\lambda_{+0})$ Phase space integral depends on the form factors

Theory Inputs:

- S_{EW} Universal short distance EW corrections(1.0232±0.0003)
- $f_+(0)$ Form factor at zero momentum transfer(0.959(5)) (EPJC 69 2010, 399-424)
- $\delta_{SU(2)}$ Correction for isospin breaking (ch. mode only ~(2.9±0.4)%) (EPJC 69 2010, 399-424)
- δ^{ℓ}_{EM} Long distance EM effects

Kℓ3 Form Factors



Hadronic matrix element:

$$\langle \pi | J_\alpha | K \rangle = f(0) \times \left[\tilde{f}_+(t)(P+p)_\alpha + \tilde{f}_-(t)(P-p)_\alpha \right]$$

f_- term multiplied by m_ℓ when contracted with leptonic current

Ke3 decays: Only **vector form factor:** $\tilde{f}_+(t)$

Kμ3 decays: Also need **scalar form factor:** $\tilde{f}_0(t) = \tilde{f}_+ + \tilde{f}_- \frac{t}{m_K^2 - m_\pi^2}$

$f_+(0)$ cannot be directly measured, therefore the form factors are normalised to $f_+(0)$:

$$\tilde{f}_+(t) = \frac{f_+(t)}{f_+(0)} \qquad \tilde{f}_0(t) = \frac{f_0(t)}{f_+(0)}$$

For V_{us}, need integral over phase space of squared matrix element

Parameterize form factors and fit distributions in t (or related variables)

Form Factor parameterizations

Linear and quadratic parameterization (Taylor expansion):

$$\tilde{f}_{+,0}(t) = 1 + \lambda_{+,0}\left(\frac{t}{m^2_{\pi^+}}\right)$$

$$\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\left(\frac{t}{m^2_{\pi^+}}\right) + \lambda''_{+,0}\left(\frac{t}{m^2_{\pi^+}}\right)^2$$

Notes:

Many parameters: λ_+', λ_+'', λ_0', λ_0''

Large correlations, unstable fits

Limited sensitivity to $\lambda''_{+,0}$

Pole parameterization:

Assumes the exchange of vector and scalar resonances K* with spin-parity $1^-/0^+$ and masses m_V/m_S,

$f_+(t)$ described by K*(892), for $f_0(t)$ no obvious dominance is seen:

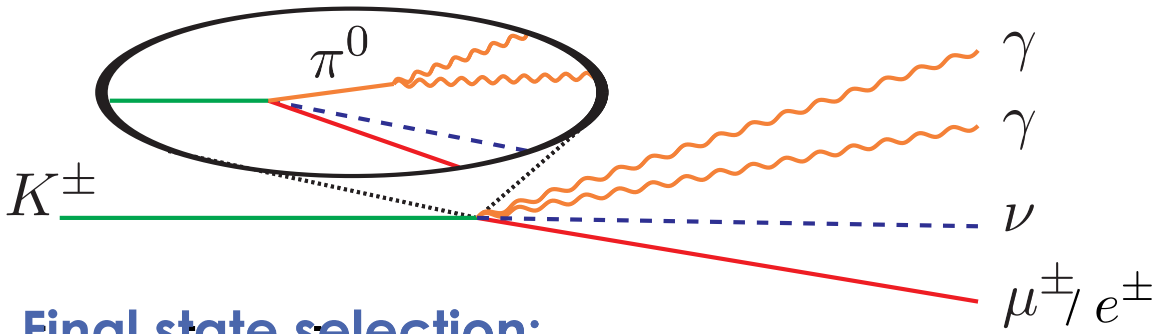
$$\tilde{f}_+(t) = \frac{m_V^2}{m_V^2 - t} \qquad \tilde{f}_0(t) = \frac{m_S^2}{m_S^2 - t}$$

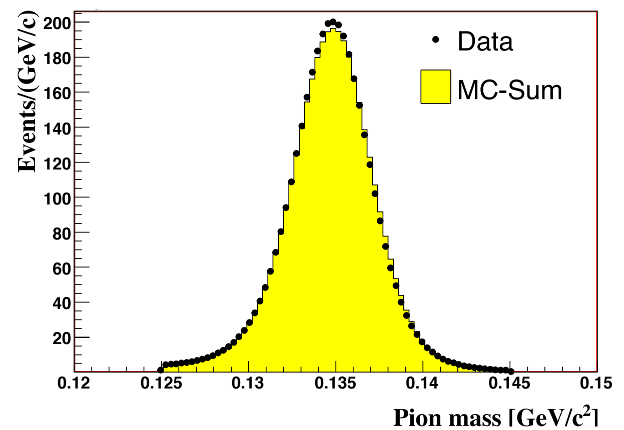
Dispersion relations:

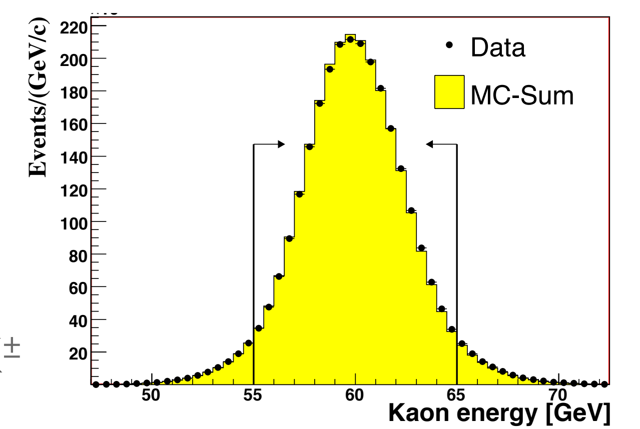
$$\tilde{f}_+(t) = \exp\left[\frac{t}{m_\pi^2}(\Lambda_+ - H(t))\right] \qquad \tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2}(\ln C - G(t))\right]$$

Not yet used in NA48/2 analysis. (PLB 638(2006) 480, PRD 80(2009) 034034)

Kℓ3 event selection







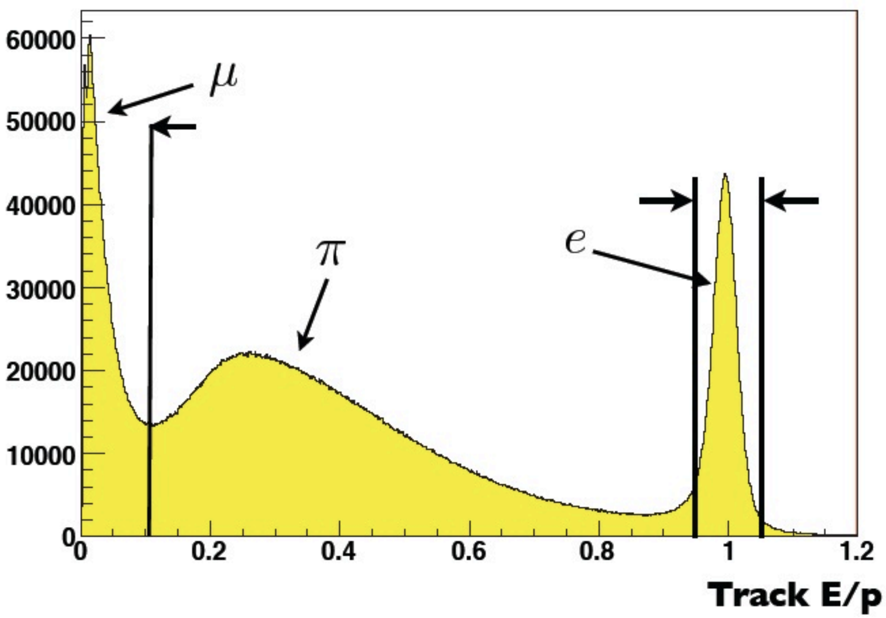
Final state selection:

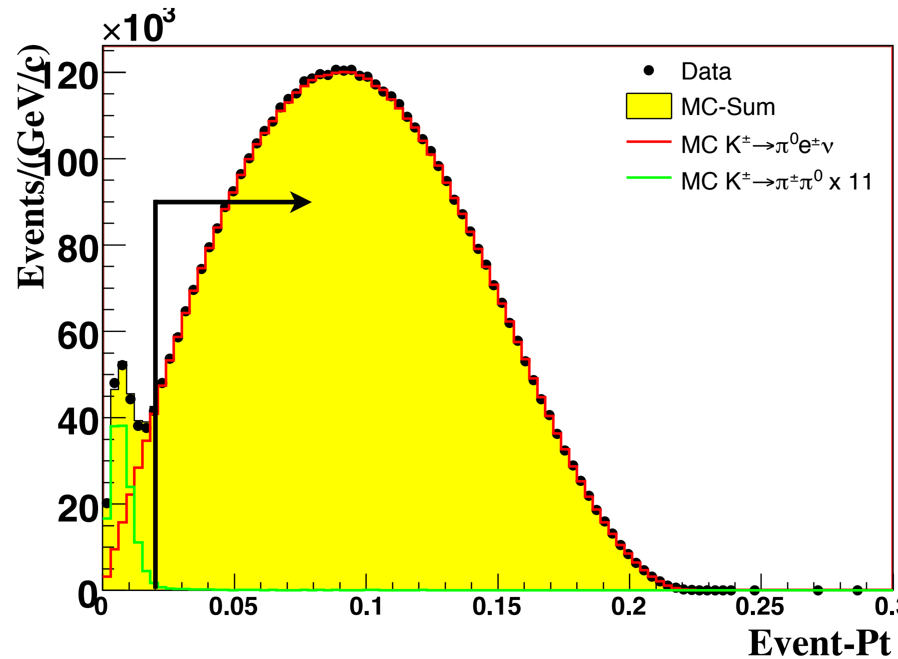
- 1 good track with particle ID cuts
  - Muon identified by muon veto and E/p<0.1
  - Electron identified by 0.95<E/p<1.05
- 1 good $\pi^0 \rightarrow \gamma\gamma$: $|m_{\gamma\gamma} - m_{PDG}(\pi^0)| < 10$ MeV

Event reconstruction:

- LKr clusters and lepton track consistent in time
- Missing mass compatible with Mν=0 using 60GeV $K^\pm$ hypothesis:
  - $M^2_{K\ell 3} = (P_K - P_\ell - P_{\pi 0})^2 < 10$ MeV^2
- K energy reconstructed under the assumption of a missing undetected neutrino:
  55 GeV < $E^\pm_K$ < 65 GeV

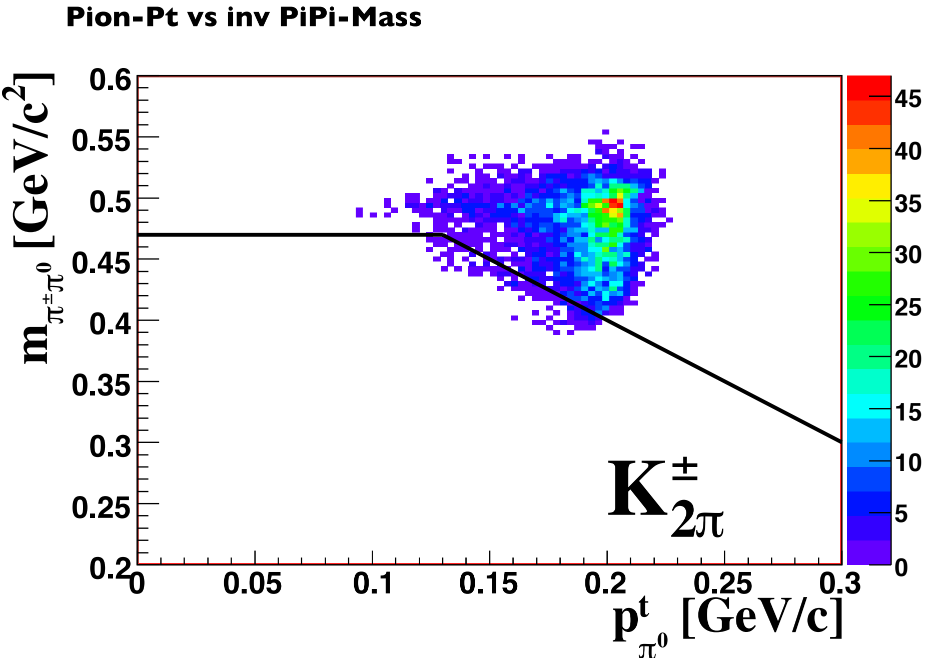
$\pi^+\pi^0$ background Ke3

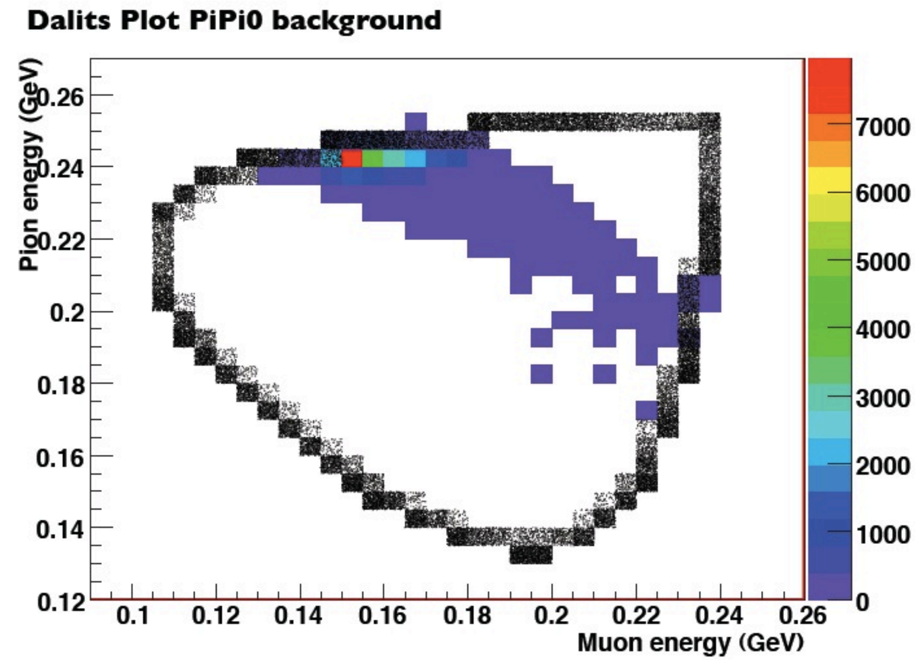




- Pion with E/P > 0.95 can fake a $K^{\pm}_{e3}$ decay: $\pi^0 e_{fake}$ + missing E
  - Missing energy coming from wrong assignment of electron mass to π^+
  - $\pi^+\pi^0$ will in any case have a small P_T due to no missing momentum
- Keep only events with: p^T_{event} >0.02 GeV/c
  - Background contamination reduced to < 0.1%
  - Only about 3% of genuine $K^{\pm}_{e3}$ events are lost

$\pi^+\pi^0$ background Kμ3





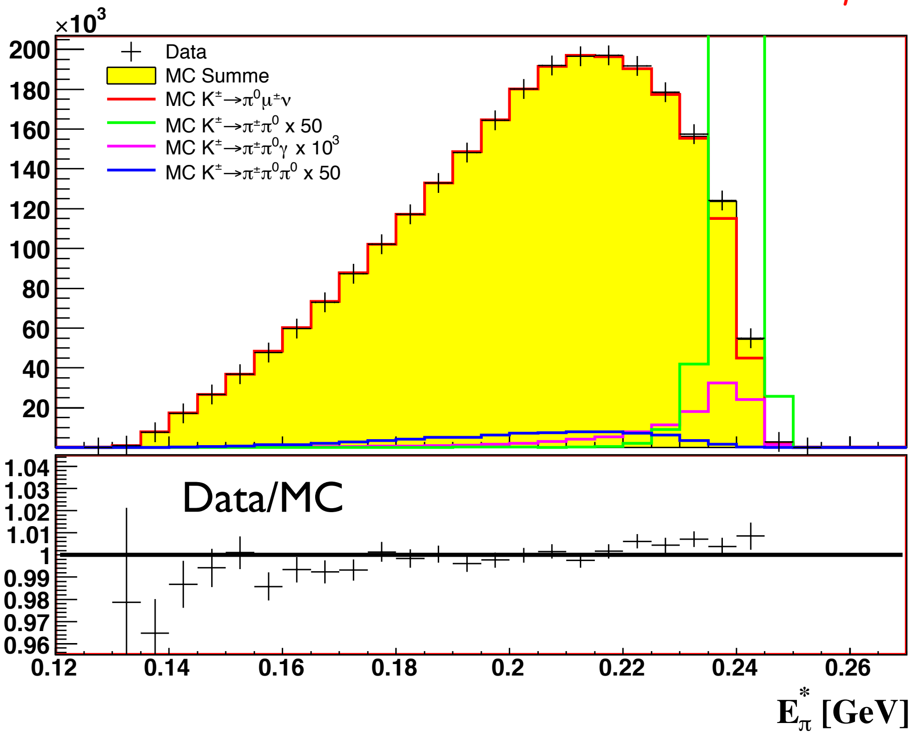
- $K^\pm \to \pi^\pm\pi^0$ with $\pi^\pm \to \mu^\pm\nu$ has same final state of the signal 2γ and 1μ
  - Without suppression, $K^\pm \to \pi^\pm\pi^0$ background at the level of 20%
- Cut in the invariant $\pi^\pm\pi^0$ mass and the transverse momentum of the pion:
  - Background contamination reduced to 0.5%
  - About 24% of $K^\pm\mu3$ events are lost
  - Background is well localized in the Dalitz plot

Data – MC comparison $E^*_{\pi 0}$

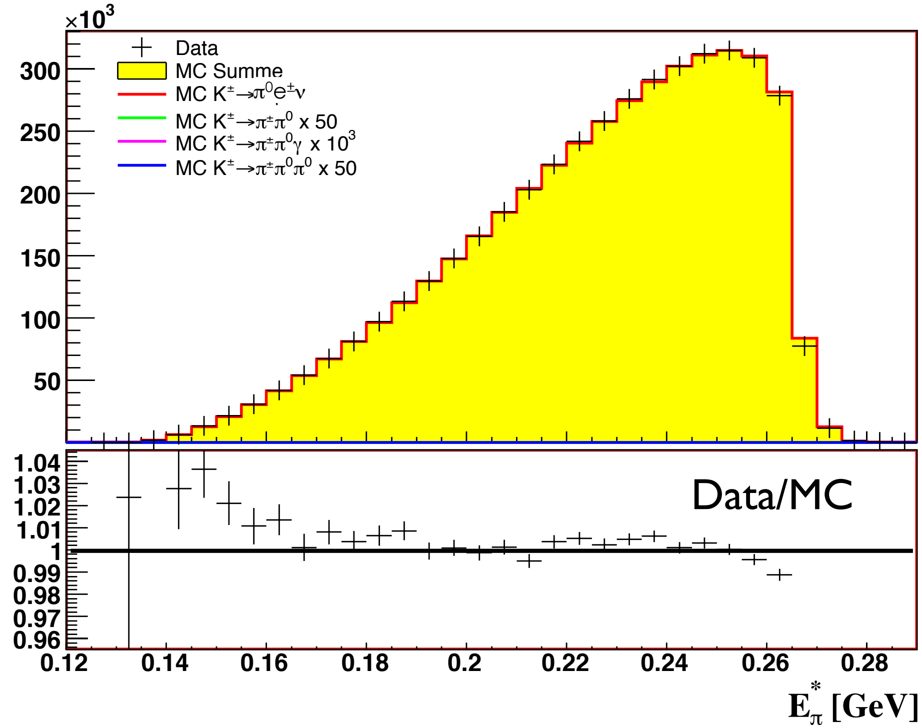
Kμ3 data sample
2.5×10^6 Kμ3 events
0.5% BG from $K^\pm \to \pi^\pm \pi^0$

Ke3 data sample
4.0×10^6 Ke3 events
BG <0.1% from $K^\pm \to \pi^\pm \pi^0$

- **Pion energy in the kaon rest frame: $K^\pm_{\mu 3}$**



- **Pion energy in the kaon rest frame: $K^\pm_{e3}$**



Radiative corrections

The Kℓ3 decay rate including first order radiative corrections can be written as:

$$\Gamma_{K\ell 3} = \Gamma^0_{K\ell 3} + \Gamma^1_{K\ell 3} = \Gamma^0_{K\ell 3}(1 + 2\delta_{EM})$$

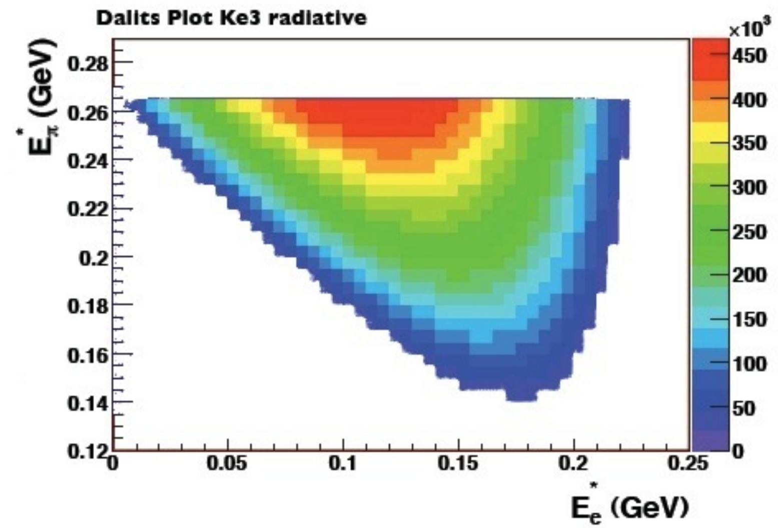
Simulation code provided by KLOE: author C. Gatti, *EPJ C45 (2006) 417*

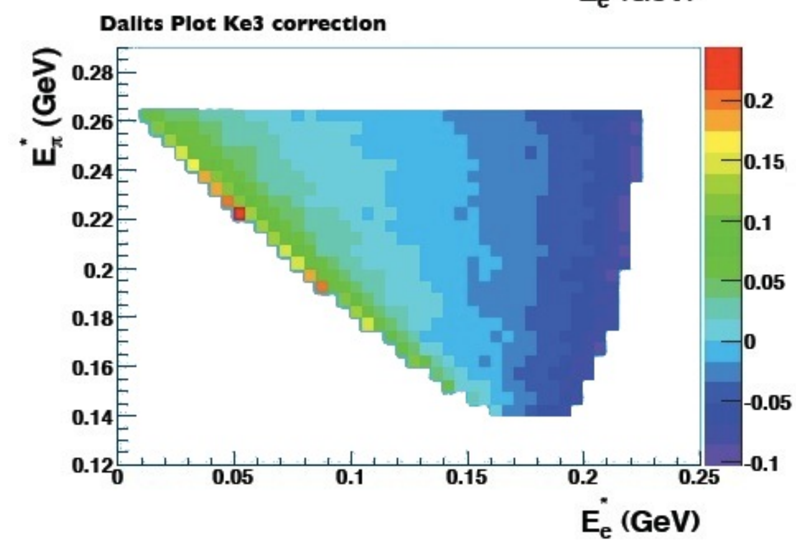
Parameters used for the normalization:

Mode	$\delta_{EM}(\%)$
$K^{\pm}e3$ *(JHEP 11 (2008) 006)*	0.050±0.125
$K^{\pm}\mu3$ *(JHEP 11 (2008) 006)*	0.008±0.125

Effects on the Ke3 acceptance are bigger with respect to Kμ3:

- ~10% effect on the Dalitz plot slope for Ke3
- ~1% effect on slope for Kμ3





Form factors fitting procedure

To extract the form factors a fit to the Dalitz plot density is performed:

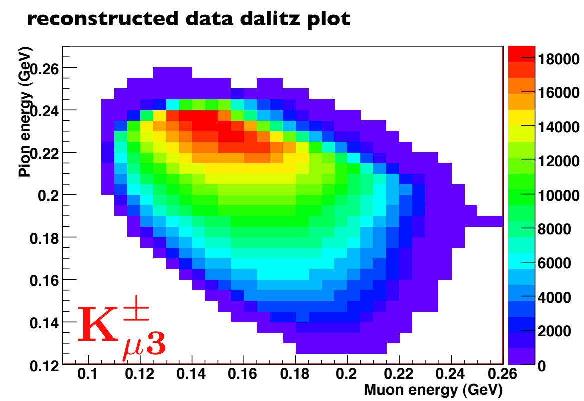
$$\rho(E_l^*, E_\pi^*) = \frac{d^2N(E_l^*, E_\pi^*)}{dE_\mu^* dE_\pi^*} \propto Af_+^2(t) + Bf_+(t)(f_0 - f_+)\frac{m_K^2 - m_\pi^2}{t} + C\left[(f_0 - f_+)\frac{m_K^2 - m_\pi^2}{t})\right]^2$$

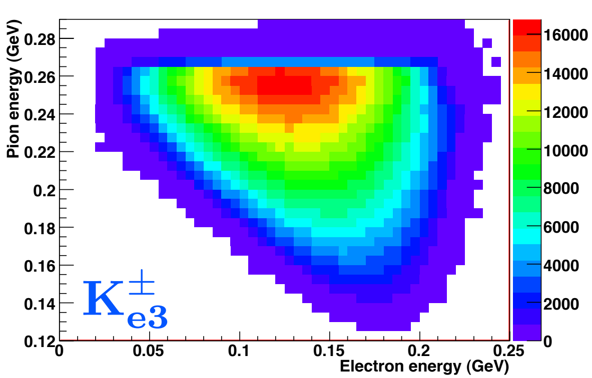
E_l^* and $E\pi^*$ are the energy of the lepton and of the pion in the kaon rest frame

A, B and C are kinematical terms

The fit is performed in cells of 5x5 MeV^2

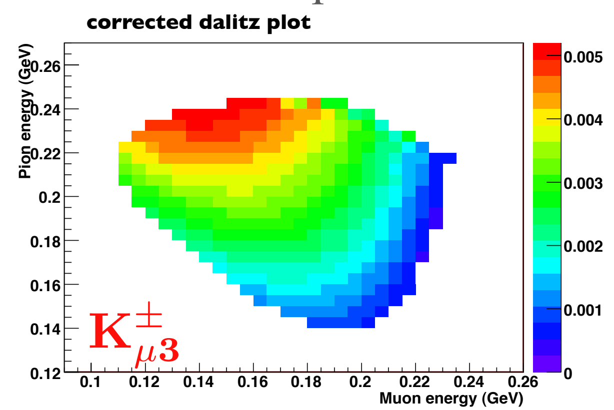
Cells which are outside or crossing the border of the physical region of the Dalitz plot are not used in the fit.

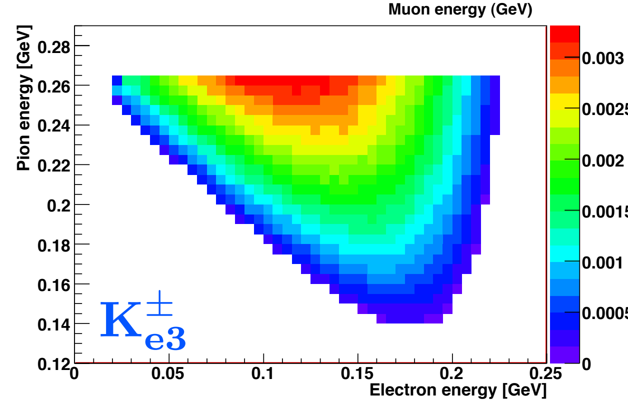




Applied corrections:

- Background subtraction
- Acceptance
- Radiative corrections





FF fit preliminary results

NA48/2 Form Factors fits preliminary results

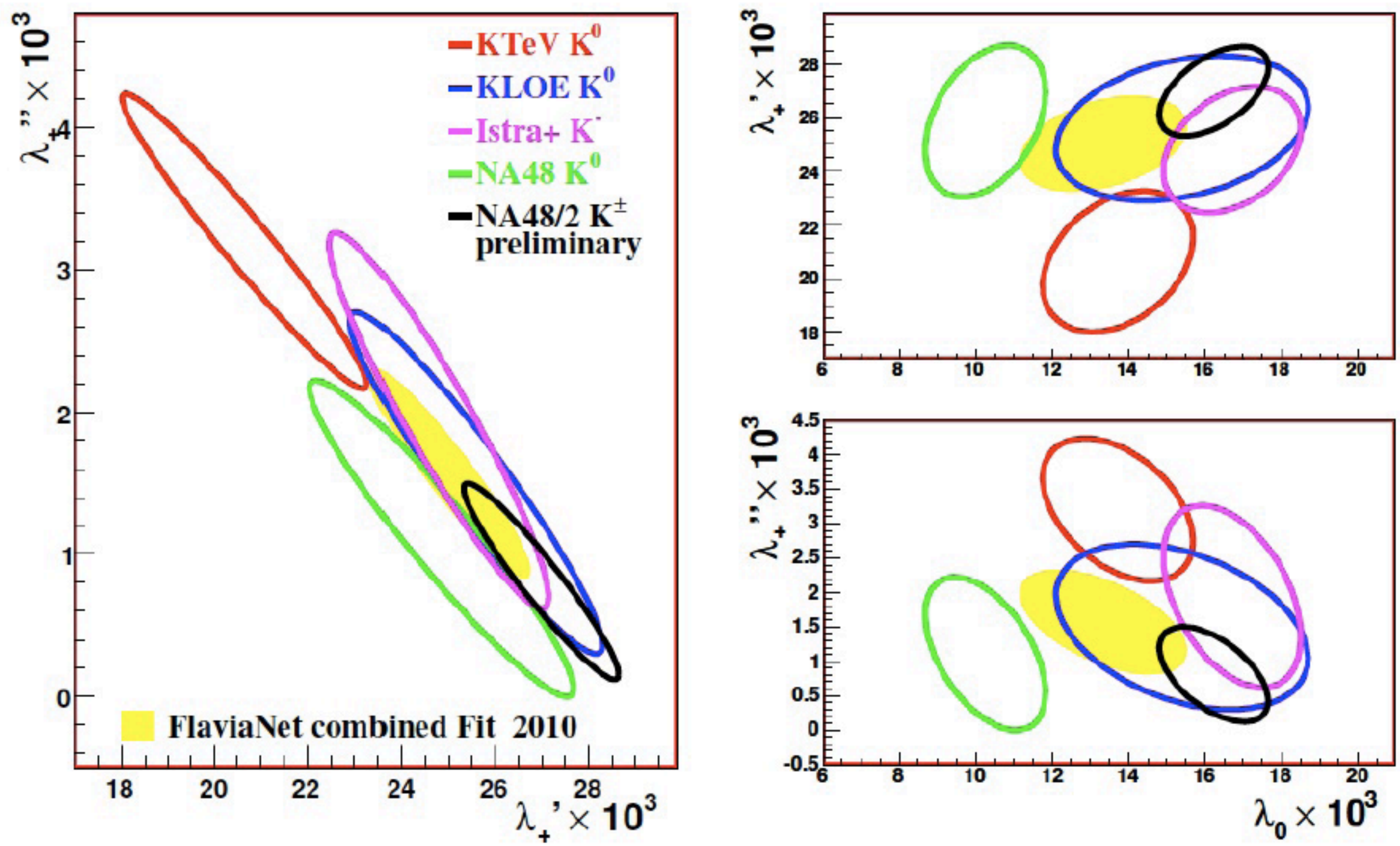
Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^\pm_{\mu3}$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K^\pm_{e3}$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
Pole (MeV/c^2)	m_V		m_S
$K^\pm_{\mu3}$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K^\pm_{e3}$	$879 \pm 3_{stat} \pm 7_{syst}$		

Systematic errors

$K^\pm_{\mu3}$	$\Delta\lambda'_+$ ($\times 10^{-3}$)	$\Delta\lambda''_+$ ($\times 10^{-3}$)	$\Delta\lambda_0$ ($\times 10^{-3}$)	Δm_V (MeV/c^2)	Δm_S (MeV/c^2)
Kaon Energy	±0.1	±0.0	±0.3	±1	±8
Vertex	±1.0	±0.5	±0.1	±2	±7
Bin size	±0.8	±0.4	±0.7	±3	±10
Energy scale	±0.3	±0.1	±0.1	±0	±1
Acceptance	±0.2	±0.1	±0.3	±2	±5
$K_{2\pi}$ background	±1.7	±0.5	±0.6	±3	±0
2nd Analysis	±0.1	±0.1	±0.2	±2	±5
FF input	±0.3	±0.8	±0.1	±7	±3
Systematic	±2.2	±1.1	±1.0	±9	±16
Statistical	±3.0	±1.1	±1.4	±8	±31

$K^\pm_{e3}$	$\Delta\lambda'_+$ ($\times 10^{-3}$)	$\Delta\lambda''_+$ ($\times 10^{-3}$)	Δm_V (MeV/c^2)
Kaon Energy	±0.3	±0.1	±6
Vertex	±0.2	±0.1	±0
Bin size	±0.0	±0.1	±2
Energy scale	±0.1	±0.0	±0
Acceptance	±0.2	±0.0	±3
2nd Ana	±0.9	±0.4	±1
FF input	±0.4	±0.0	±1
Sytematic	±1.1	±0.4	±7
Statistical	±0.7	±0.3	±3

Fit results comparison



Combined quadratic fit results for Kℓ3 decays.
The ellipses are 68% CL contours.
For comparison the combined fit from the FlaviaNet kaon working group is shown in yellow. Eur. Phys. J. C 69, 399 (2010)

FF fit preliminary results: combined

Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu3}K^{\pm}_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
$K^{\pm}_{\mu3}K^{\pm}_{e3}$ combined	877 ± 6		1176 ± 31

Status of experimental measurements

- $K^0_L \to \ell 3$: KLOE, KTeV and NA48
- $K^- \to \ell 3$: from ISTRA+
- $K^\pm \to \ell 3$: NA48/2 has the first measurement with Ke3 and Kμ3
  - NA48/2 results for Ke3 and Kμ3 are in good agreement
  - NA48/2 combined result has the smallest error.

$K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ decay

$K^\pm \rightarrow \pi^\pm\gamma\gamma$ decay theory

In the ChPT framework the differential rate of the decay $K^\pm(p) \rightarrow \pi^\pm(p_3)\gamma(q_1)\gamma(q_2)$ process (no $O(p^2)$ contribution) is:

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_{K^\pm}}{(8\pi)^3} \cdot \left[z^2 \cdot \left(|A+B|^2 + |C|^2 \right) + \left(y^2 - \frac{1}{4}\lambda(1,z,r_\pi^2) \right)^2 \cdot \left(|B|^2 + |D|^2 \right) \right]$$

$$y = \frac{p \cdot (q_1 - q_2)}{m_{K^\pm}^2} \qquad z = \frac{m_{\gamma\gamma}^2}{m_{K^\pm}^2}$$

relevant only @ low $m_{\gamma\gamma}$

- The leading $O(p^4)$ contribution is given by $A(z,\hat{c})$ (loops) which is responsible for a cusp at $m_{\gamma\gamma} = m_{2\pi}$

$$\Gamma_A = (2.80 + 0.87\hat{c} + 0.17\hat{c}^2) \cdot 10^{-20}\, MeV$$

- C (WZW) corresponds to ~10% of A at $O(p^4)$

[Ecker, Pich, de Rafael, Nucl. Phys. B303 (1988), 665]

- B, D = 0 @ $O(p^4)$

- The $\hat{c}$ value can be related to fundamental ChPT parameters:

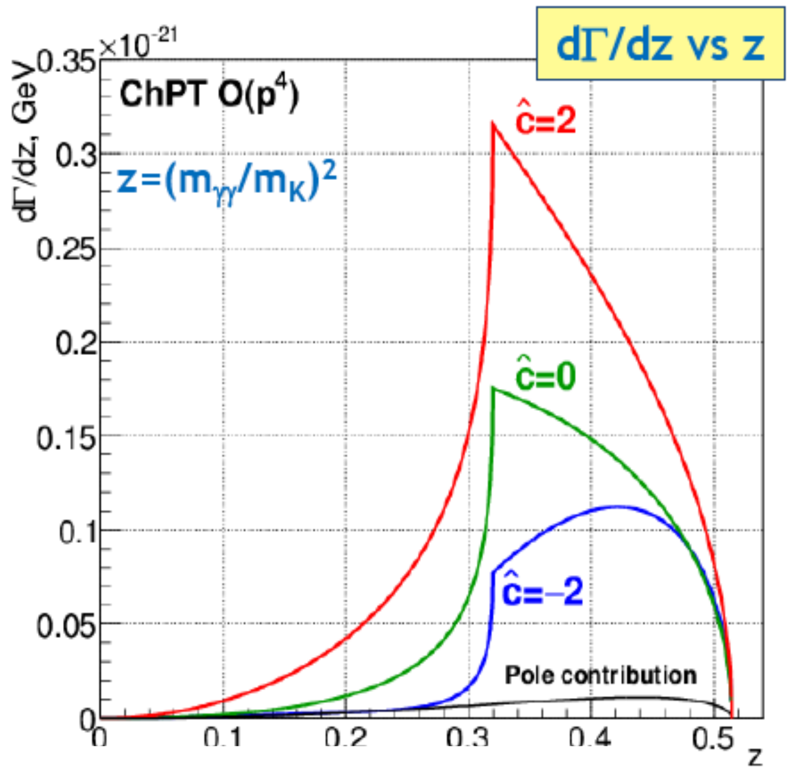
[D'Ambrosio, Portoles, PLB 386 (1996), 403]

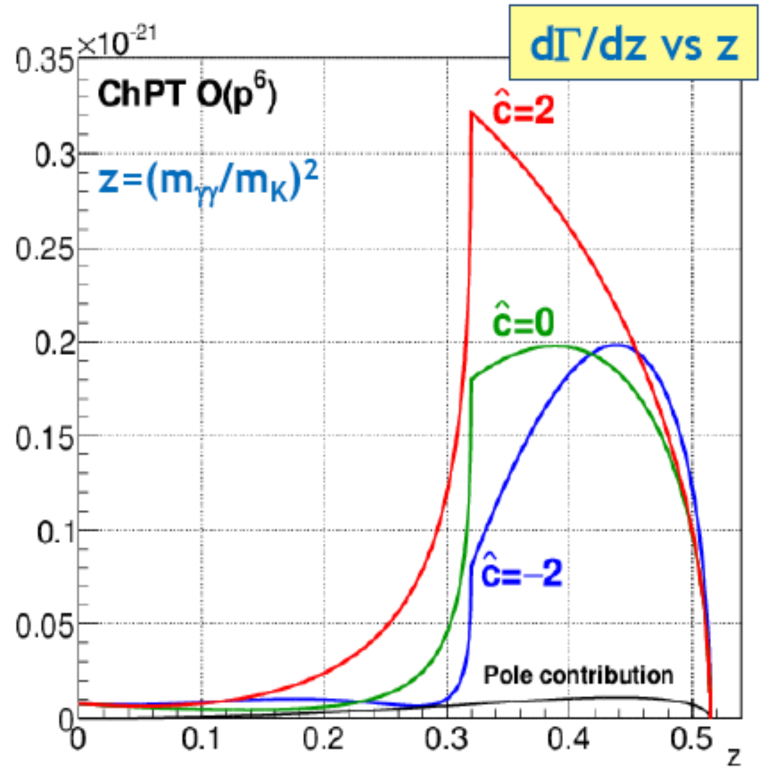
$$\hat{c} = \frac{128\pi^2}{3}\left[3(L_9 + L_{10}) + N_{14} - N_{15} - 2N_{18}\right]$$

Weak Chiral Lagrangian
QCD loop and counterterms

$K^{\pm}\longrightarrow\pi^{\pm}\gamma\gamma$ decay, ChPt $O(p^4)$ vs $O(p^6)$

- $O(p^6)$ loop amplitude correction, evaluated from $K\longrightarrow 3\pi$ @ $O(p^4)$
- $O(p^6)$ A term gets y dependence, sizable correction to $d\Gamma/dz$ for z<z+





$O(p^6)$ unitarity corrections may increase the BR by 30÷40%

[D'Ambrosio, Portolés, PLB386 (1996) 403]

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay experimental status

Present PDG average based on:

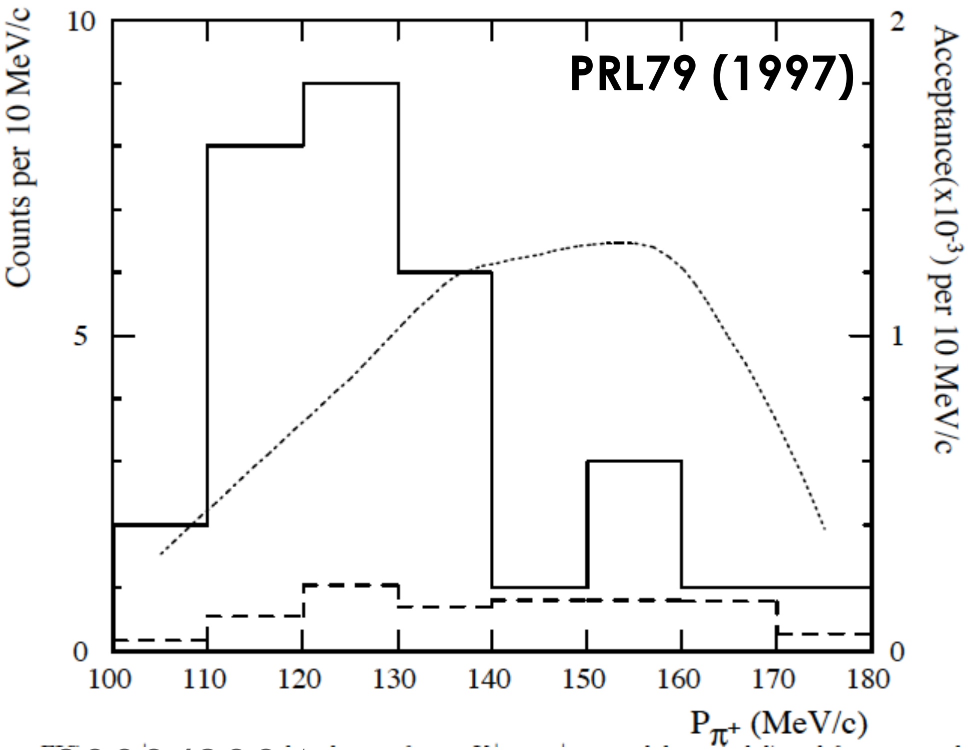
E787 (1997): BR = $(1.10 \pm 0.32) \times 10^{-6}$

31 candidates, 5 exp. Bkg

$\hat{c}$ value = 1.6 ± 0.6 $O(p^4)$

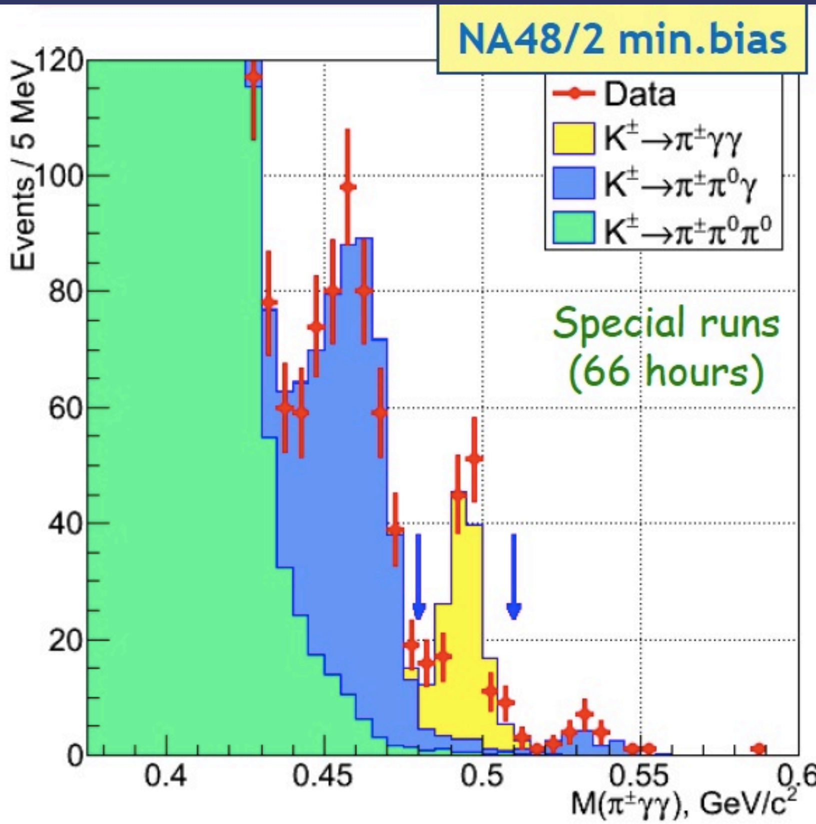
= 1.8 ± 0.6 $O(p^6)$

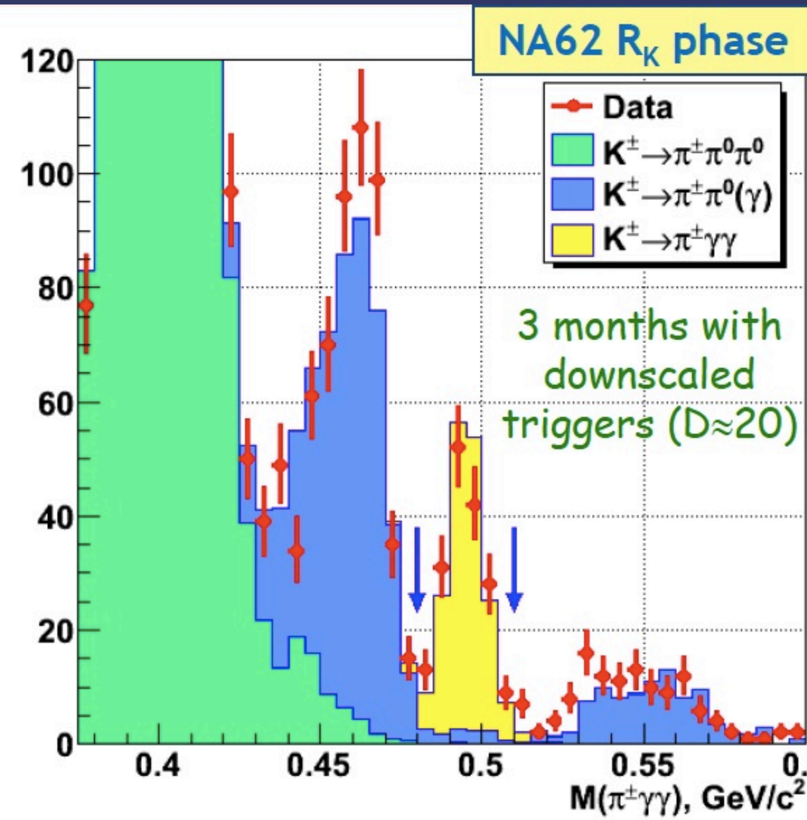
[PRL79 (1997) 4079]



- NA48/2 main data set preliminary 2003/2004: measurement hindered by low trigger efficiency. Abandoned!
- New strategy: minimum bias trigger samples from NA48/2 and NA62.
  - 2004 data taking (66 hours special minimum bias run)
  - 2007 data taking (3 month control trigger downscaled by 20)

Minimum bias data samples





$\pi^{\pm}\gamma\gamma$ candidates	149
BG($\pi^{\pm}\pi^{0}\gamma$)	11.4±0.6
BG($\pi^{\pm}\pi^{0}\pi^{0}$)	4.1±0.4
Signal ($\pi^{\pm}\gamma\gamma$)	134±12

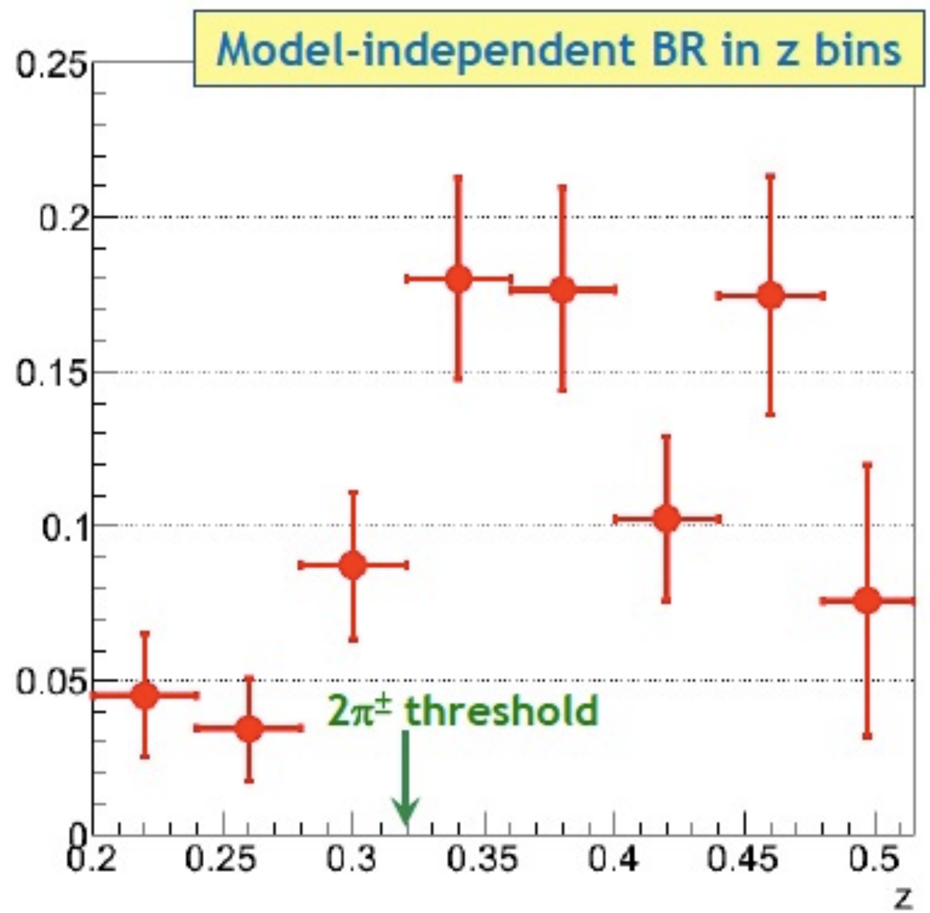
$\pi^{\pm}\gamma\gamma$ candidates	175
BG($\pi^{\pm}\pi^{0}\gamma$)	11.1±1.0
BG($\pi^{\pm}\pi^{0}\pi^{0}$)	1.3±0.3
Signal ($\pi^{\pm}\gamma\gamma$)	163±13

~300 candidates 10 times the present world sample

Model independent BR NA48/2

z range	N_j	N_j^B	A_j	$\mathcal{B}_j \times 10^6$
0.20–0.24	13	4.89	0.194	0.045 ± 0.020
0.24–0.28	9	2.73	0.198	0.034 ± 0.016
0.28–0.32	18	2.33	0.194	0.087 ± 0.024
0.32–0.36	33	1.30	0.190	0.180 ± 0.033
0.36–0.40	31	0.98	0.184	0.177 ± 0.033
0.40–0.44	18	1.61	0.173	0.103 ± 0.027
0.44–0.48	23	1.21	0.135	0.175 ± 0.038
$z > 0.48$	4	0.52	0.049	0.076 ± 0.044

Sufficiently small **z** bins: acceptance almost independent of kinematical distribution

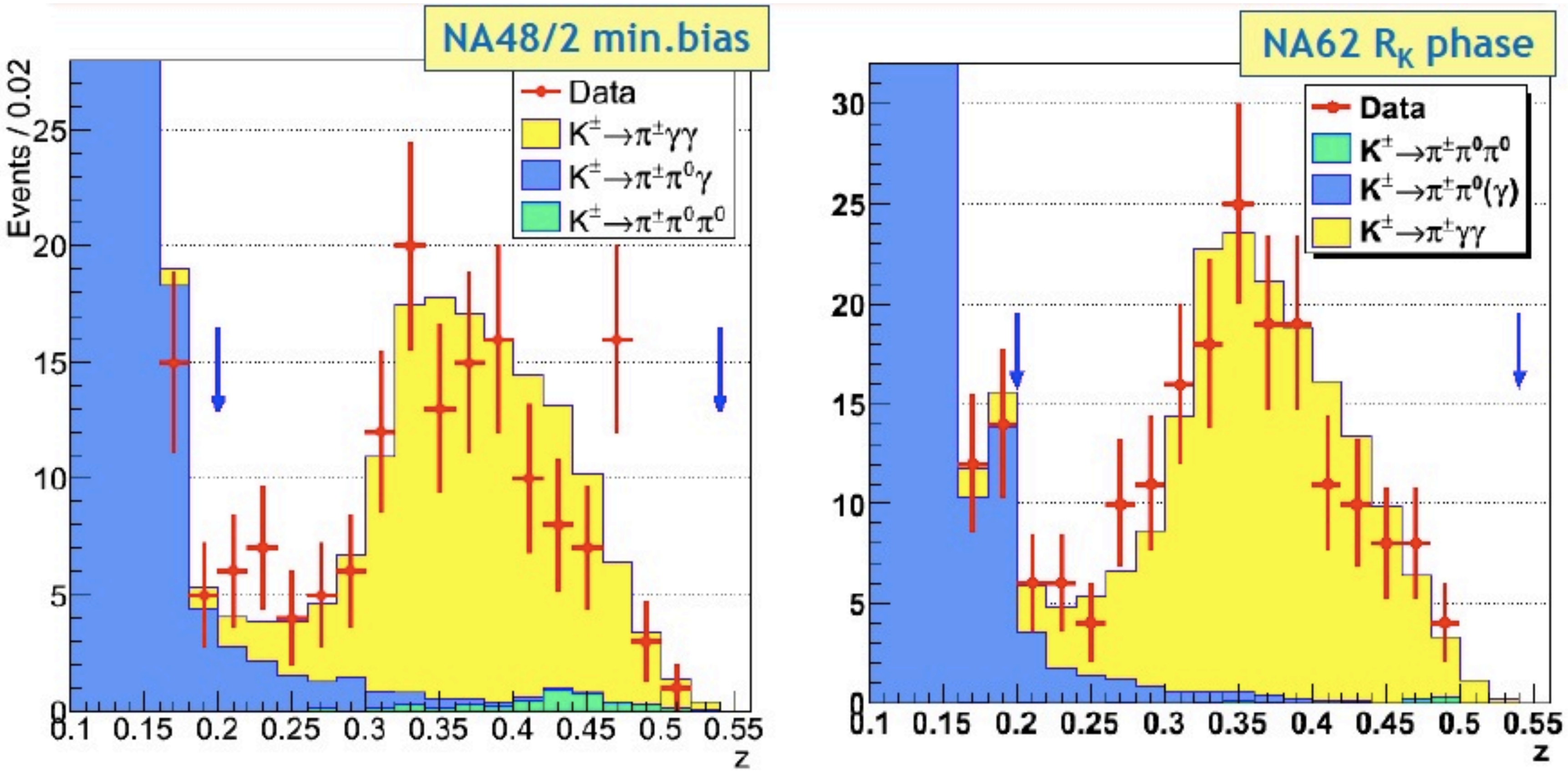


FINAL NA48/2 Model Independent BR:

$BR_{MI}(z>0.2) = (0.877 \pm 0.087_{stat} \pm 0.017_{syst})\times10^{-6}$

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ ChPT fit $O(p^6)$ (preliminary)

External parameters of the $O(p^6)$ fit:
K3π amplitude parameters: from fit to experimental data [NPB648 (2003) 317];
Polynomial contributions: η_1=2.06, η_2=0.24, η_3=−0.26 [PLB386 (1996) 403].



ChPT $O(p^4)$: $\hat{c}$ = 1.36 ± 0.34
ChPT $O(p^6)$: $\hat{c}$ = 1.67 ± 0.40

ChPT $O(p^4)$: $\hat{c}$ = 1.71 ± 0.30
ChPT $O(p^6)$: $\hat{c}$ = 2.21 ± 0.32

Combined fit results (preliminary)

NA48/2 and NA62-RK combined ChPT $O(p^4)$ fit:

$\hat{c} = 1.56 \pm 0.22_{stat} \pm 0.07_{syst} = 1.56 \pm 0.23$

NA48/2 and NA62-RK combined ChPT $O(p^6)$ fit:

$\hat{c} = 2.00 \pm 0.24_{stat} \pm 0.09_{syst} = 2.00 \pm 0.26$

Using ChPT formulation: D'Ambrosio, Portolés, PLB386 (1996) 403

Combined Model Dependent BR in full phase space:

$BR_{Op6} = (1.01 \pm 0.06) \times 10^{-6}$

To be compared with PDG(BNL E787): $BR_6 = (1.10 \pm 0.32) \times 10^{-6}$

Summary and outlook

- NA48/2 has released a preliminary results on the $K^{\pm}\ell 3$ form factors:
  - Quadratic and Pole parameterizations used
  - First results studying both K^{+} and K^{-} decays
  - Competitive result for $K\mu 3$ and smallest error for Ke3 and combined fits
  - Possibility to remeasure $K^{\pm}\ell 3$ BR and form factors in NA62-RK data set
    - A K^{0}_{L} data set has been also collected allowing measurement in neutral kaons as well
- $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ decay has been studied in NA48/2 and NA62-RK data sets
  - NA48/2 final result on model independent branching ratio:
    $BR_{MI}(z>0.2)=(0.877\pm0.087_{stat}\pm0.017_{syst})\times10^{-6}$
  - NA48/2 and NA62-RK combined Model Dependent BR in full phase space:
    $BR_{Op6}=(1.01\pm0.06)\times10^{-6}$ preliminary
  - Measurement of $\hat{c}$ NA48/2 and NA62-RK combined ChPT $O(p^{6})$ fit:

$$\hat{c} = 2.00\pm0.24_{stat}\pm0.09_{syst} = 2.00\pm0.26$$ preliminary

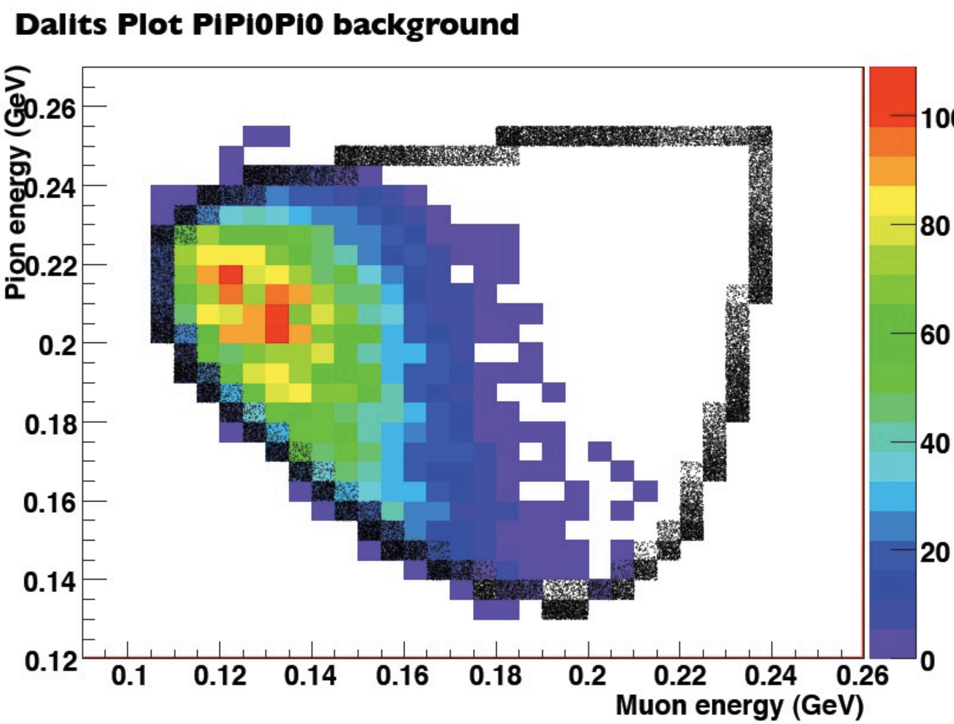
Back up slides

11/09/2013

$\pi^{\pm}\pi^0\pi^0$ background

- Background to Kμ3
  - $\pi \rightarrow \mu$ decay + 2 lost photons from π^0-decays.
  - **Small** but introduces slope in the Dalitz plot.
  - **No dedicated cut** to reduce the background is applied.
  - A correction is applied to take the background into account.
  - Without the correction the result shifts by $\sim 0.5\sigma_{stat}$

- Background to Ke3
  - Negligible



Dominant K± BR in the V_{US} fit

Absolute BR of Ke3 and Kμ3 from PDGlive

Ke3(PDG) =(5.07 ± 0.04) % **0.8%** error
Kμ3(PDG) =(3.353 ± 0.034)% **1.0%** error

Ratio of Ke3 and Kμ3 in NA48/2 2003 data

$$\mathcal{R}_{Ke3/K2\pi} = 0.2470 \pm 0.0009\,(\mathrm{stat}) \pm 0.0004\,(\mathrm{syst})$$
$$\mathcal{R}_{K\mu3/K2\pi} = 0.1637 \pm 0.0006(\mathrm{stat}) \pm 0.0003(\mathrm{syst})$$
$$\mathcal{R}_{K\mu3/Ke3} = 0.663 \pm 0.003\,(\mathrm{stat}) \pm 0.001\,(\mathrm{syst})$$

BR(Ke3)/BR(K2π)=0.4% error dominated by statistic with $87\text{x}10^3$ Ke3
BR(Kμ3)/BR(K2π)=0.4% error dominated by statistic with $77\text{x}10^3$ Kμ3