Measurement of $K^0_{\mu 3}$ form factors with the NA48 detector

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Outline

- **$K_{\ell 3}$ decays**
- **$|V_{us}|$ and CKM Unitarity**
  - Experimental Inputs
  - Theory Inputs
- **$K_{\mu 3}$ Decays and Physics beyond the SM**
  - f_0 at the Callan-Treiman Point
  - Dispersive Parametrization for f_0
- **The NA48 Detector**
- **$K_{\mu 3}$ Form Factor Analysis**
- **Comparison with other experimental results**
- **f_0 and the RHCs**
- **Summary**

$K_{\ell 3}$ Decays – Introduction

- $s \rightarrow u$ transitions are involved in the semi–leptonic kaon decays

$$K^0 \rightarrow \pi^{\pm}\, \ell^{\mp}\, \nu_\ell \qquad K^{\pm} \rightarrow \pi^0\, \ell^{\pm}\, \nu_\ell \qquad (\ell = \mu,\; e)$$

- These decays are known to be the *"golden"* modes to extract $|V_{us}|$ and one of the main playgrounds for low–energy theories such as ChPT

- $|V_{us}|$ and $|V_{ud}|$ are by far the most precisely known CKM matrix elements

  $\Rightarrow$ Precision frontier in CKM studies: $\sigma_{|V_{ud}|}/|V_{ud}| \simeq 0.03\%$

  $\sigma_{|V_{us}|}/|V_{us}| \simeq 1\%$

- **NEW** Precision test of SM and physics beyond it in $K_L \rightarrow \pi^{\pm}\mu^{\mp}\nu_\mu$ decays

  $\Rightarrow$ Test the existence of right handed quarks coupled to the standard W

$K_{\ell 3}$ Decays – Introduction

- Only the vector part of the weak current contributes to the $K_{\ell 3}$ decays

  $\Rightarrow$ Theoretically clean

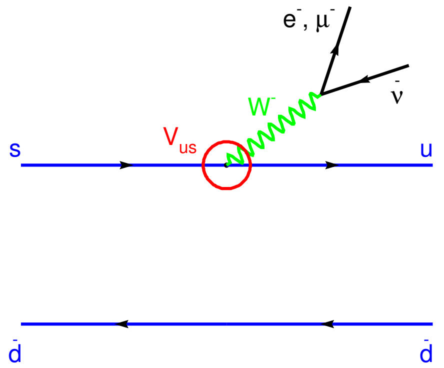
- The m.e. can be written in terms of two dimensionless form factors $f_{\pm}$:

$$\mathfrak{M} = G_F/\sqrt{2}\,|V_{us}\,|\,[f_+(t)\,(p_K + p_\pi)^\mu + f_-(t)\,(p_K - p_\pi)^\mu]\,\bar{u}_{\ell_\mu}\gamma_\mu(1-\gamma_5)u_{\nu_\mu}$$

- t is the four–momentum squared transferred to the lepton system

$$t = q^2 = (p_\ell + p_\nu)^2 = (p_K - p_\pi)^2 = m_K^2 + m_\pi^2 - 2m_K E_\pi^*$$

- The form factors appear because the π and the K are not pointlike particles



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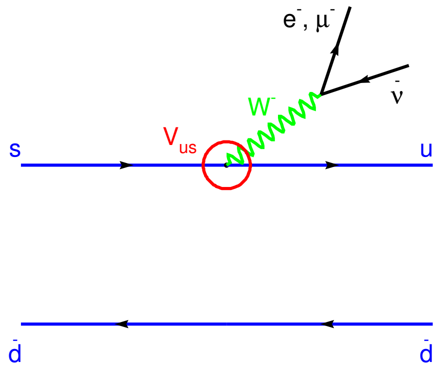
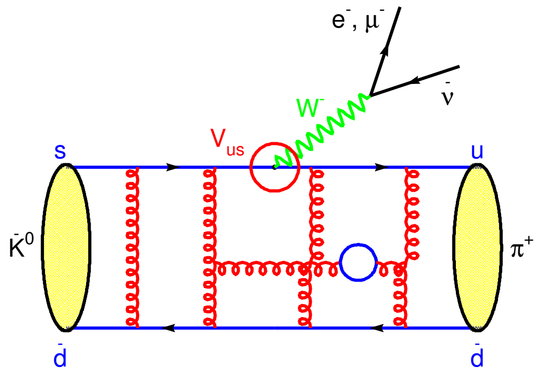




Include the effects of the strong force using form factors

$K_{\ell 3}$ Decays – Form Factors

In the $\mathfrak{M}^2$ expression $f_-(t)$ is multiplied to a term $\propto\ m_\ell^2/m_K^2$

Need only f_+ to describe K_{e3} decays

f_- can be measured ONLY in $K_{\mu 3}$ decays

Describe $K_{\mu 3}$ decays using f_+ and f_0 instead of f_-:

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 + m_\pi^2)}\ f_-(t)$$

In the CM of the dilepton system:

$f_+(t)$ is related to $\vec{V}^{(\Delta S=1)}$ and describes 1^- transitions $\rightarrow$ VECTOR f.f.

$f_0(t)$ is related to $V_0^{(\Delta S=1)}$ and describes 0^+ transitions $\rightarrow$ SCALAR f.f.

$K_{\ell 3}$ Decays – Form Factors

Well known parametrizations of the form factors are: **Linear, Quadratic and Pole**

$$f_{+,0}(t) = f_+(0)\left(1 + \lambda_{+,0}\, t/m_\pi^2\right) \qquad \text{LINEAR}$$

$$f_{+,0}(t) = f_+(0)\left[1 + \lambda'_{+,0}\, t/m_\pi^2 + \tfrac{1}{2}\,\lambda''_{+,0}\,(t/m_\pi^2)^2\right] \qquad \text{QUADRATIC}$$

$$f_{+,0}(t) = f_+(0)\,\frac{m_{V,S}^2}{m_{V,S}^2 - t} \qquad \text{POLE}$$

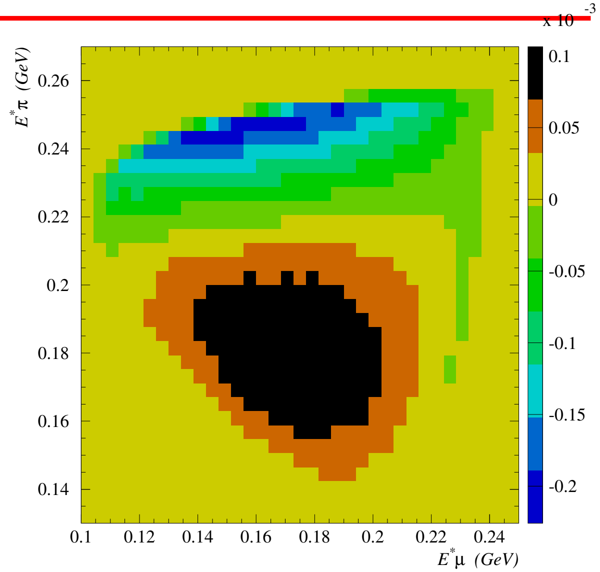
Linear & Quadratic $\rightarrow$ Taylor expansions around $t = 0$

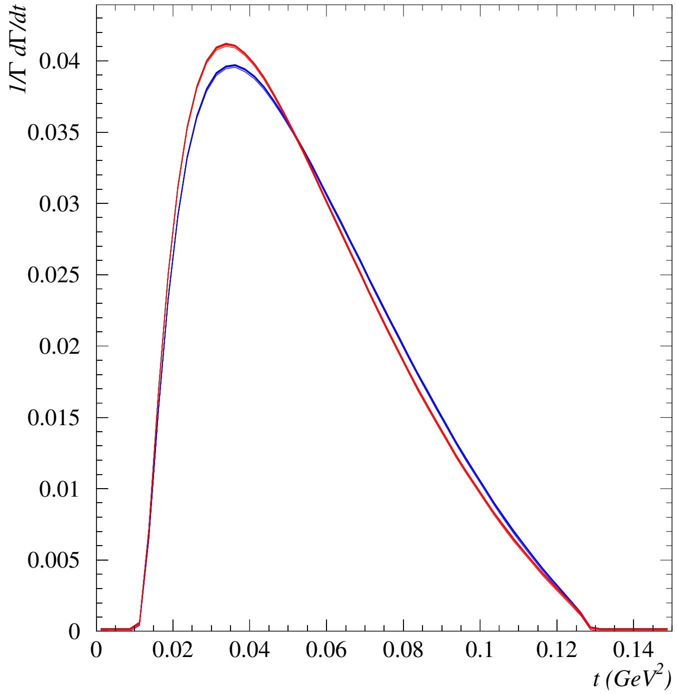
Experiments measure the normalized form factors: $\hat{f}(t) = f_{+,0}(t)/f_+(0)$

In the pole model the form factors acquire a physical meaning: they are related to the exchange of K^* resonances with spin–parity $1^-/0^+$ and mass m_V/m_S

- The vector form factor is dominated by $K^*(892)$
- One parameter fit: $\lambda'_{+,0} = \left(\frac{m_\pi}{m_{V,S}}\right)^2 \qquad \lambda''_{+,0} = 2\lambda'_{+,0}$

$K_{\mu 3}$ Form Factors Measurement





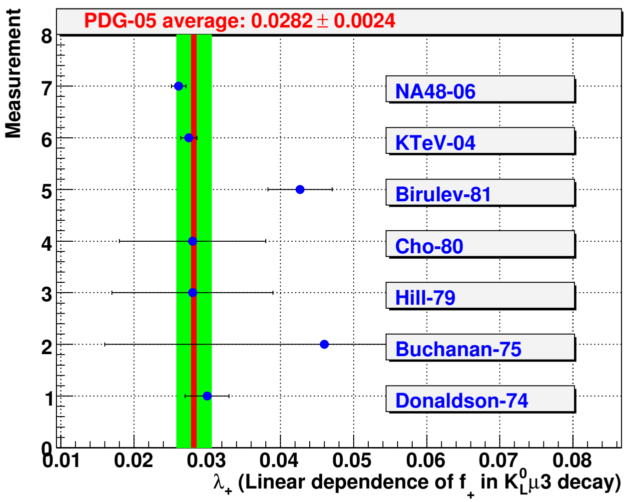
$\lambda_+ = 0$

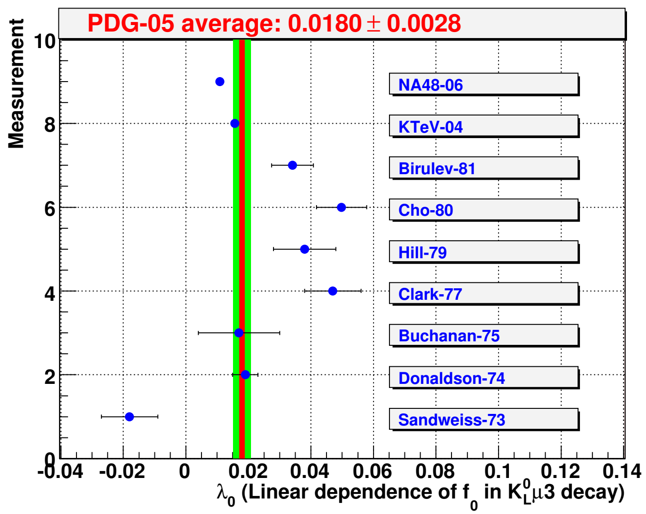
$\lambda_0 = 0$

$\lambda_+ = 0.0267$

$\lambda_0 = 0.0117$

- After more than 50 years of investigations "reliable" results only nowadays
- σI_K^ℓ was the largest source of uncertainty for $|V_{us}|$





λ_0 has always been very hard to measure

Two ff and 4 parameters to fit in $K_{\mu 3}$

High correlations $\rightarrow$ big errors

Direct measurement of λ_0' and λ_0''

$\rightarrow$ Not possible (P. Franzini KAON07)

Importance of one parameter fit

$|V_{us}|$ and $K_{\ell 3}$ Decays – Master Formula

The master formula for the $K_{\ell 3}$ decay rates:

$C^2_{K^0} = 1$
$C^2_{K^\pm} = 1/2$

Short Distance
EW Corrections
$S_{EW} = 1.0232$

Calculated f.f. @ t=0
2^{nd} order SU(3)

$\Delta^{K^0}_{SU(2)} = 0$

$\Delta^{K_\ell}_{EM} \approx 0$ for $K^\pm$
larger for K^0

$$\frac{BR(K_{\ell 3(\gamma)})}{\tau_K} = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^\ell(f_{+0})(1 + 2\Delta^K_{SU(2)} + 2\Delta^{K_\ell}_{EM})$$

Measured BR and Lifetime

Phase Space integral
depends on f.f.

Experiments supply BR, τ and form factors measurements
Theory provides S_{EW}, $f_+(0)$, $\Delta^K_{SU(2)}$ and $\Delta^{K_\ell}_{EM}$

CKM Unitarity Test in the 1^{st} Row

Test CKM unitarity using the 1^{st} row:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

($|V_{ub}| \simeq 10^{-3}$ can be neglected)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \delta$$

PDG 2004 $\delta = 0.0033 \pm 0.0015$ (2.3σ discrepancy)

Long standing problem...
CKM unitarity ?
Hint of new physics ?

2003 BNL 865 measures $BR(K^+ \to \pi^0 e^+ \nu_e) = 5.13(10)\%$
2.3σ higher then PDG
The value for $|V_{us}|$ consistent with unitarity

Experimental Inputs

PDG04 used data mainly from experiments dating back to the seventies...

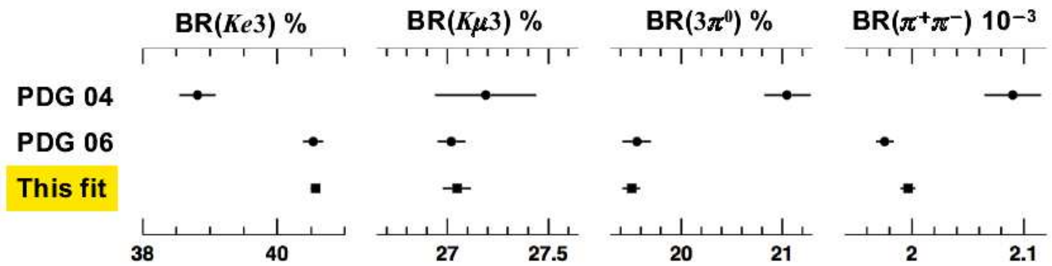
Much effort on the experimental side in these last 2-3 years !

KLOE	K_L	4 BRs, form factors, lifetime
	K_S	BR(K_{Se3}), charge asymmetry
	$K^{\pm}$	BR(K_{e3}), BR$(K_{\mu 3})$, lifetime
KTeV	K_L	main 6 BRs, form factors
ISTRA+	K^-	BR(K_{e3}), form factors
NA48	K_L	3 BRs, form factors
	$K^{\pm}$	BR(K_{e3}), BR$(K_{\mu 3})$

A LOT OF WORK !

Experimental Inputs

- Much higher statistics than older experiments
- Radiative corrections
- Remarkable evolution of BRs
  - Confirm the increase of BR(K^+_{e3}), as firstly reported by BNL E865
  - BR(K_{e3}) significantly increased, BR$(3\pi^0)$ and BR(2π) significantly decreased



- Improved precision in form factors → can use both e and μ results for $I^{\ell}_K(f_{+0})$
- Proper treatment of correlations between measurements

PDG 2006 has replaced, wherever possible, the old results with the new ones

$$\delta \ = \ 0.0008 \pm 0.0011$$

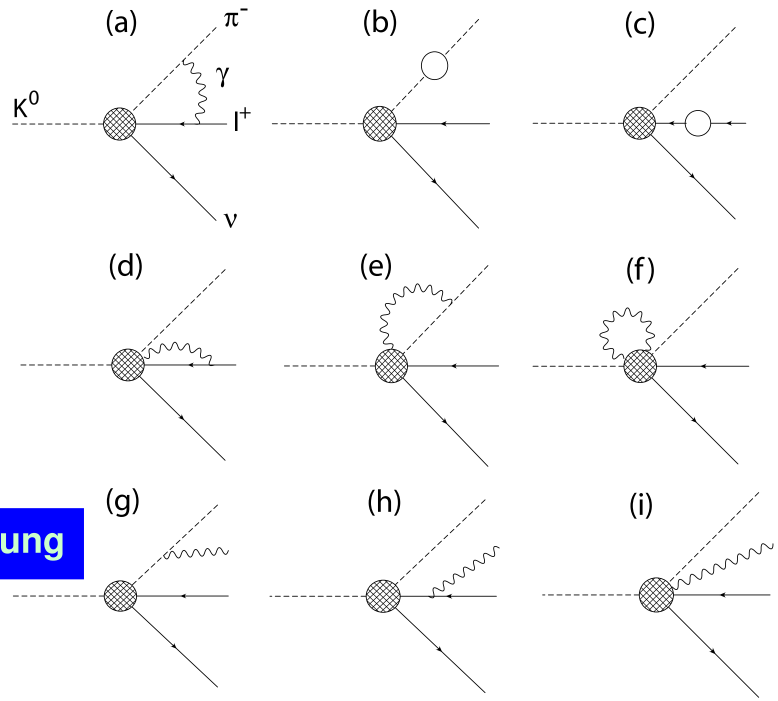
CKM unitarity "restored"...BUT...what about the theory inputs ?

Theory Inputs: $\Delta^{K_\ell}_{EM}$

$\Delta^{K_\ell}_{EM}(\%)$	ChPT Cirigliano 02	ChPT Neufeld	Hadr. Model Andre 04
K^0_{e3}	+0.52±0.10	+0.57±0.15	+0.65±0.15
$K^0_{\mu3}$		+0.80±0.15	+0.95±0.15
K^+_{e3}	+0.03±0.10	+0.08±0.15	
$K^+_{\mu3}$		-0.12±0.15	

Virtual Corrections

Inner–Bremsstrahlung



- $\Delta^{K_\ell}_{EM}$ for full phase space
- Different estimate of $\Delta^{K_\ell}_{EM}$ agree within the quoted errors
- First estimate of $\Delta^{K^+_{\mu3}}_{EM}$ from Neufeld removes dominant contribution to the error on $|V_{us}|f_+(0)$ for this mode
- Larger effect in K^0 decays, as espected from Coulomb interaction

Need common set of definitive values of $\Delta^{K_\ell}_{EM}$

Theory Inputs: $\Delta^{K^\pm}_{SU(2)}$

- Difference between K^0 and $K^\pm$ due to the isospin breaking corrections

$$1 + \Delta^{K^\pm}_{SU(2)} = \frac{f_+^{K^+}(0)}{f_+^{K^0}(0)} \qquad \Delta^{K^\pm}_{SU(2)} = (+2.31 \pm 0.22)\%$$ [CHPT Cirigliano et al. (2002)]

- ChPT to O(p^4) relates $\Delta^{K^\pm}_{SU(2)}$ to ratios of quark masses

Quak mass ratios $\rightarrow$ Predict $\Delta^{K^\pm}_{SU(2)}$

- Data and EM corrections are becoming precise enough to determine $\Delta^{K^\pm}_{SU(2)}$
- Turn it around and determine $\Delta^{K^\pm}_{SU(2)} \rightarrow$ Quark mass ratios
- Indeed the values of $|V_{us}|f_+(0)$ obtained from $K^\pm$ and K^0 show a little difference...
- Use $K^\pm$ results without isospin corrections and compare to K^0 mode

➜ $\Delta^{K^\pm}_{SU(2)} \approx 3\%$

- If the data are OK this has consequences on the quark masses
- The underestimation of the isospin breaking corrections would result in an artificial increase of the extracted value of $|V_{us}|$

Theory Inputs: $f_+(0)$

Still dominant source of uncertainty on $|V_{us}|$

- In $SU(3)$ limit $f_+(0) = 1$
- Ademollo–Gatto theorem (1964) $\Rightarrow$ only 2^{nd} order $SU(3)$ breaking effects

$$f_+(0) = 1 - \mathcal{O}[(m_s - m_u)^2]$$

- Two players in the game: ChPT and Lattice QCD
- The ChPT expansion of $f_+(0)$ reads:

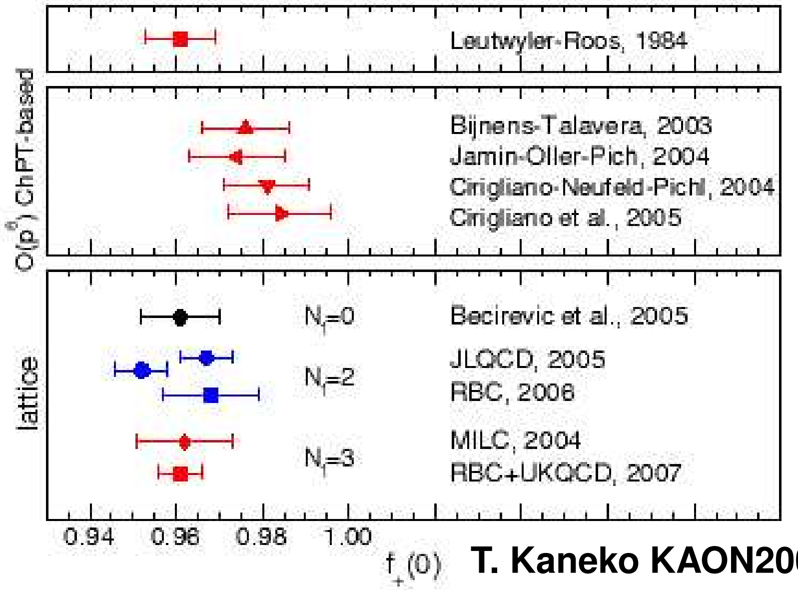
$$f_+(0) = 1 + f_{p^4} + f_{p^6} + \ldots$$

f_{p^4}	One-loop	$f_{p^4} = -0.023$ [Gasser & Leutwyler (1985)]
f_{p^6}	Two-loops	Quark model estimate [Leutwyler-Roos (1984)] Analytic calculations [Bijnens-Talavera (2003)] LECs can be constrained by λ_0', λ_0''

Presently the L&R 84 value is the conventional choice used to extract $|V_{us}|$

$$f_+(0) = 0.961 \pm 0.008$$

Theory Inputs: $f_+(0)$



T. Kaneko KAON2007

- Very promising activity in the field of the Lattice QCD
- Calculation of $f_+(0)$ with 1% accuracy is feasible
- Work in progress towards fully "unquenched" calculations
- Major systematics
  - Interpolation in t: $f_+(t_{max}) \to f_+(0)$
  - Chiral extrapolation to physical masses
    $300 < m_\pi < 600$ MeV
- Lattice calculations generally agree with the LR value
- Not good agreement with analytic calculations

Meaningful extraction of $|V_{us}|$ only when $f_+(0)$ will be correctly determined

$K_{\mu 3}$ Decays and the Physics Beyond SM

New idea on $K_{\mu 3}$ decays [V. Bernard, M. Oertel, E. Passemar, J. Stern **PLB 638**(2006) 480]

A measurement of the value of the scalar form factor of the (neutral) $K_{\mu 3}$ decay at the Callan–Treiman point can provide a significant test of electro–weak coupling of right handed quarks to the standard W boson

- The Callan–Treiman low–energy theorem gives the value of $f_0(t)$ at the point $t = \Delta_{K\pi} = (m_K^2 - m_\pi^2)$

$$C = \hat{f}_0(\Delta_{K\pi}) = \frac{F_{K+}}{F_{\pi+}\ f_+(0)} + \Delta_{CT}$$

- Δ_{CT} evaluated at NLO in ChPT [Gasser and Leutwyler (1985)] $(m_u = m_d)$

$$\Delta_{CT} \simeq -3.5\ 10^{-3}$$

- NNLO to be determined $\rightarrow$ Should not change the order of magnitude
- For $K^{\pm}$ the effect of isospin breaking is larger: $\Delta_{CT} \sim$ few 10^{-2}

$K_{\mu 3}$ Decays and the Physics Beyond SM

Scenario: Low Energy Effective Theory (LEET)

- Very high energy $E > \Lambda \ \rightarrow$ New symmetries
- $E < \Lambda$ not complete decoupling $\rightarrow$ High energy simmetries constrains the interactions at low energy

The quark CC interaction is modified at NLO

- Existence of direct coupling of right handed quarks to W: ϵ
- Modifications of the left handed couplings: δ
- NO effects on leptonic CC
- Effective couplings for the vector and axial quark currents

$$\mathcal{V}^{ij}_{eff} = (1+\delta)V^{ij}_L + \epsilon V^{ij}_R + \mathrm{NNLO}$$

$$\mathcal{A}^{ij}_{eff} = -(1+\delta)V^{ij}_L + \epsilon V^{ij}_R + \mathrm{NNLO}$$

$i = u, c, t;\ j = d, s, b.\ \ V_L,\ V_R$ left and right unitary flavour mixing matrices

SM $\rightarrow\ \ \delta = \epsilon = 0$ $\qquad \mathcal{V}_{eff} = -\mathcal{A}_{eff} = V_{CKM}$

$K_{\mu 3}$ Decays and the Physics Beyond SM

The presence of RHCs modifies the expression for C

With RHCs we do not measure directly the low energy QCD parameters but a combination of them and the non standard EW couplings

$$C = f_0(\Delta_{K\pi}) = \left|\frac{F_{K^+}\mathcal{A}^{us}_{eff}}{F_{\pi^+}\mathcal{A}^{ud}_{eff}}\right| \frac{1}{|f_+(0)\mathcal{V}^{us}_{eff}|} |\mathcal{V}^{ud}_{eff}| \left|\frac{\mathcal{A}^{ud}_{eff}\mathcal{V}^{us}_{eff}}{\mathcal{V}^{ud}_{eff}\mathcal{A}^{us}_{eff}}\right| + \Delta_{CT}$$

$$C = B_{exp} r + \Delta_{CT}$$

$$r = \left|\frac{\mathcal{A}^{ud}_{eff}\mathcal{V}^{us}_{eff}}{\mathcal{V}^{ud}_{eff}\mathcal{A}^{us}_{eff}}\right| = 1 + 2(\epsilon_S - \epsilon_{NS}) + \mathcal{O}(\epsilon^2) \neq 1$$

$$\epsilon_{NS} = \epsilon \,\mathrm{Re}\left(\frac{V_R^{ud}}{V_L^{ud}}\right), \quad \epsilon_S = \epsilon \,\mathrm{Re}\left(\frac{V_R^{us}}{V_L^{us}}\right)$$

Strenghts of $\bar{u}d$ and $\bar{u}s$ RHCs

$K_{\mu 3}$ Decays and the Physics Beyond SM

To constrain the RHCs contributions compare the SM prediction for C...

$$C_{SM} = \left|\frac{F_{K^+} V^{us}}{F_{\pi^+} V^{ud}}\right| \frac{1}{|f_+(0) \quad V^{us}|} |V^{ud}| + \Delta_{CT}$$

0.27618(48) Br $\frac{K^+_{l2}(\gamma)}{\pi^+_{l2}(\gamma)}$ Phys.Rev. D74:074009 (2006)	0.2169(9) $\Gamma_{K_{\ell 3(\gamma)}}$ PDG06	0.97377(27) $0^+ \to 0^+$ PDG06

$$C_{SM} = 1.2399 \pm 0.0056 + \Delta_{CT}$$

$$\ln C_{SM} = 0.2151 \pm 0.0045 + \tilde{\Delta}_{CT} \qquad (\tilde{\Delta}_{CT} = \Delta_{CT}/1.24)$$

...to a **DIRECTLY** measured value of C

Dispersive Parametrization for $f_0(t)$

To extract $\ln C$ use the new proposed parametrization of the scalar form factor

$\Rightarrow$ Connection between the experimentally accessible region of $f_0(t)$ and its value at the unphysical point $t = \Delta_{K\pi}$

The parametrization is based on a dispersive approach with a relation subtracted twice $(t = 0,\ t = \Delta_{K\pi})$

$$f_0(t) = f_+(0) \exp\Big[\frac{t}{\Delta_{K\pi}}(\mathrm{lnC} - \mathrm{G(t)})\Big]$$

$\mathrm{G(t)} = \frac{\Delta_{K\pi}(\Delta_{K\pi}-t)}{\pi} \int_{t_{\pi K}}^{\infty} \frac{dx}{x} \frac{\phi(x)}{(x-\Delta_{K\pi})(x-t-i\epsilon)}$

ϕ phase of form factor $\rightarrow\ f_0(t) = |f_0(t)| \exp(i\phi(t))$

One parameter describes simultaneously the slope and the curvature of the form factor

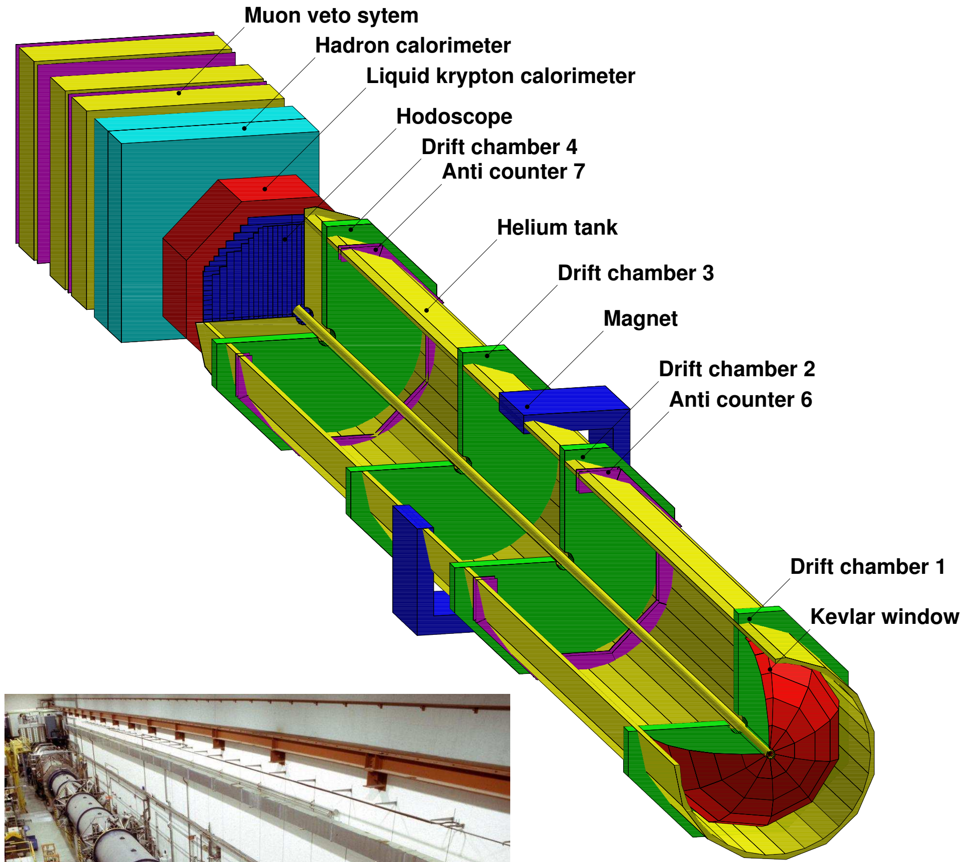
$$\lambda_0' = \frac{m_\pi^2}{\Delta_{K\pi}} [\ln \mathrm{C} - G(0)]$$
$$\lambda_0'' = \lambda_0'^2 - 2\frac{m_\pi^4}{\Delta_{K\pi}} G'(0) = \lambda_0'^2 + (4.16 \pm 0.50) \times 10^{-4}$$

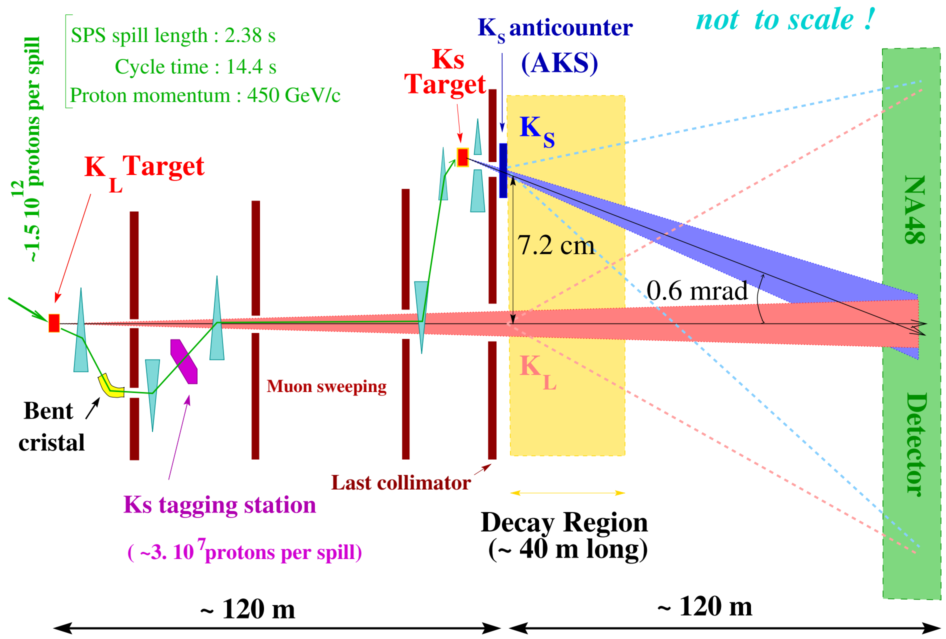
New parametrization also for $f_+(t)$

$$f_+(t) = f_+(0) \exp\Big[\frac{t}{m_\pi^2}(\Lambda_+ + \mathrm{H(t)})\Big]$$

Accurate polynomial approximations for the dispersive integrals $\mathrm{G(t)}$ and $\mathrm{H(t)}$

The NA48 Detector

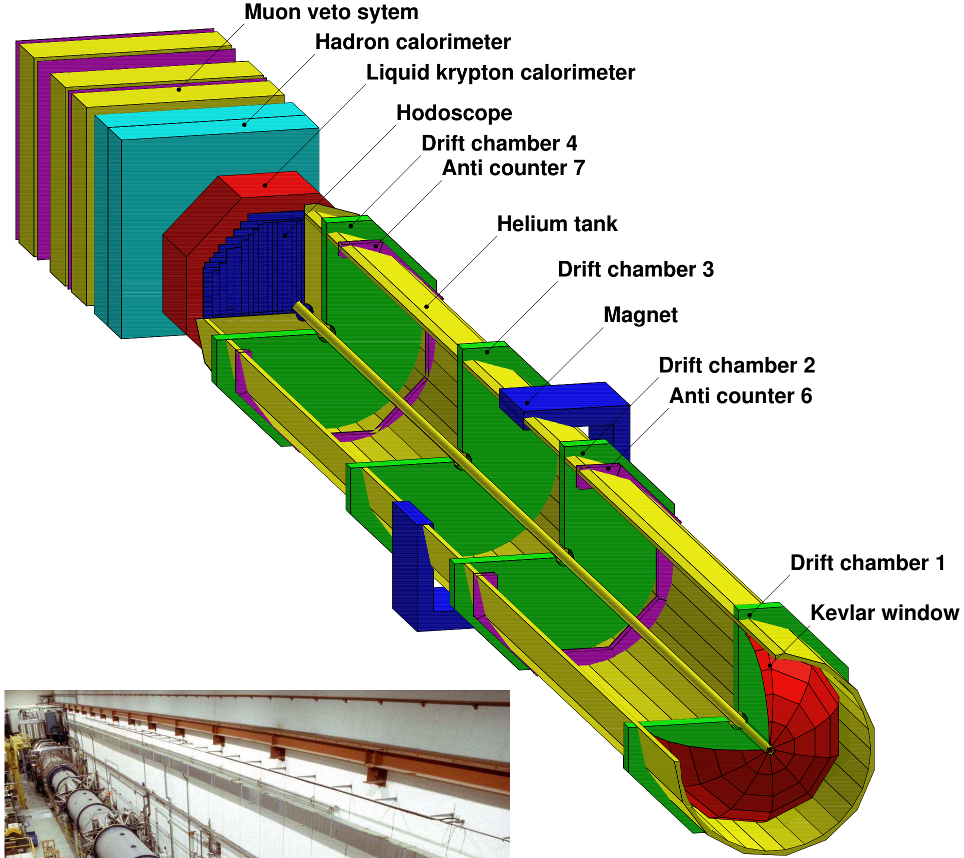


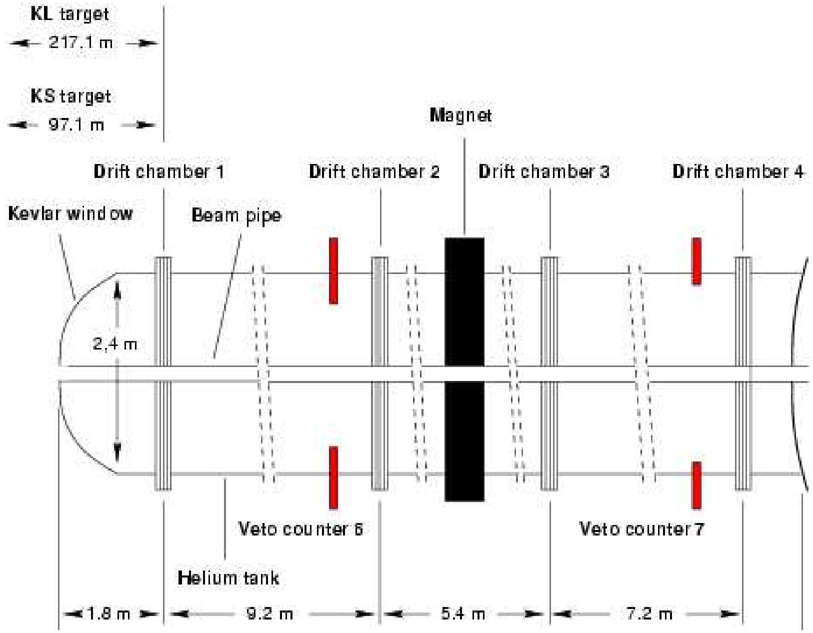


K_L Beam

- 450 GeV/c p beam on Be target
- K_L target: 241 m from EM calo
- 126 m from decay region
- Useful p range: $70 < p_{K_L} < 170$ GeV/c
- Decay region 90 m (vacuum)

The NA48 Detector

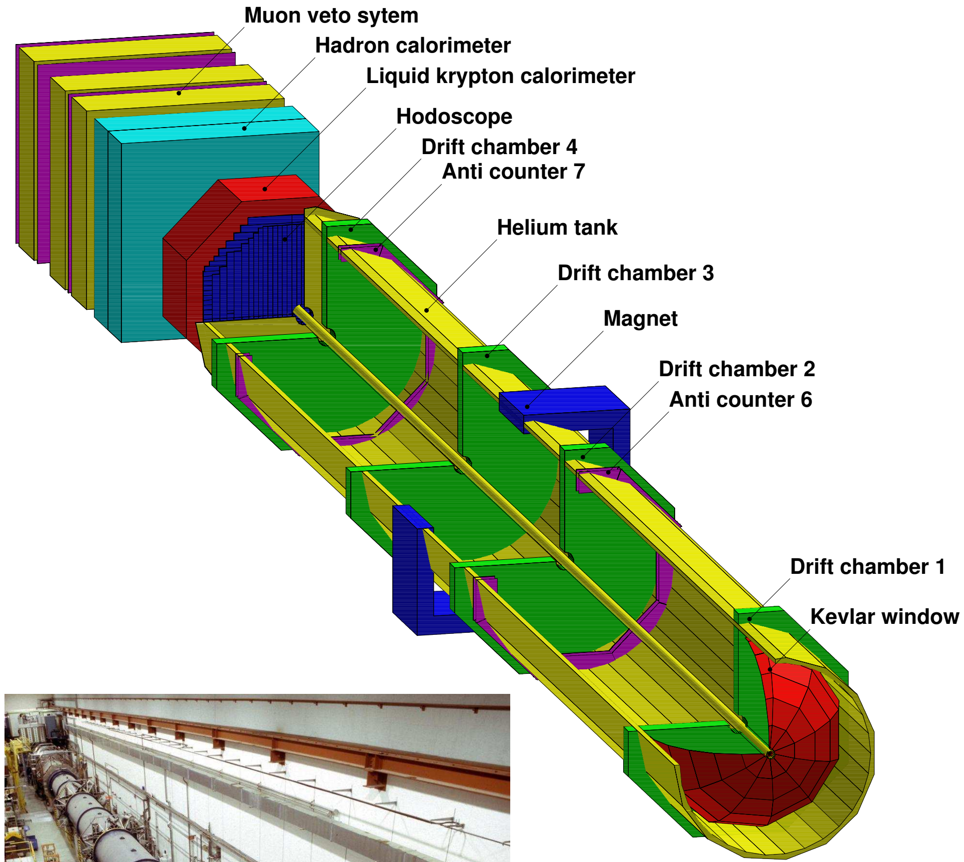


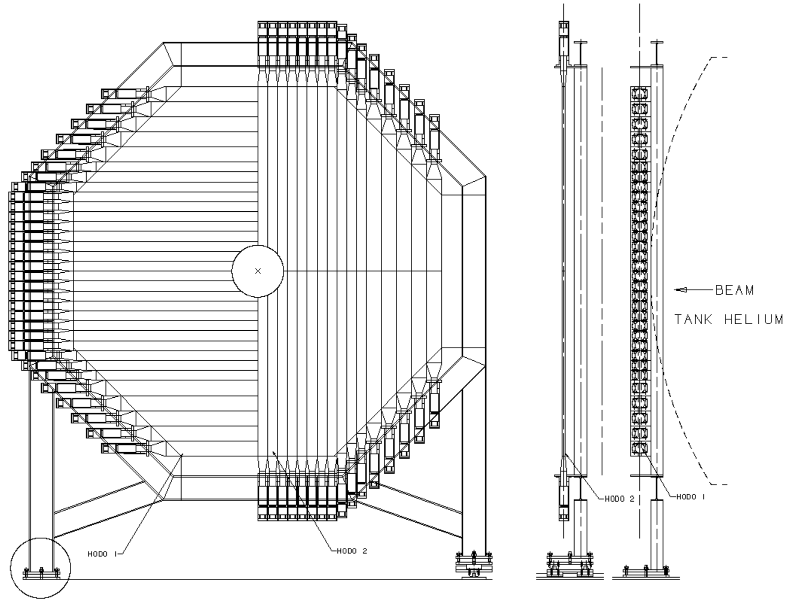


Magnetic Spectrometer

- 4 drift chambers inside He tank
- Dipole magnet with 265 MeV/c p_T kick
- $\frac{\sigma_p}{p}(\%) = 0.48 \oplus 0.009\, p$ (GeV/c)

The NA48 Detector

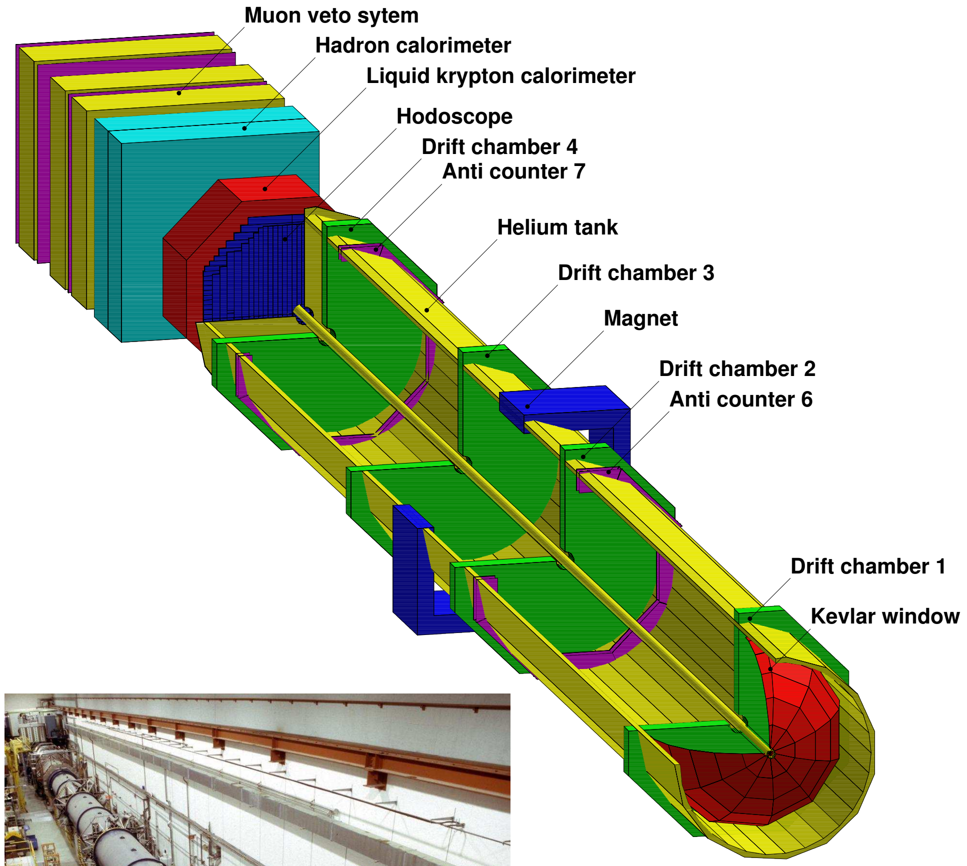


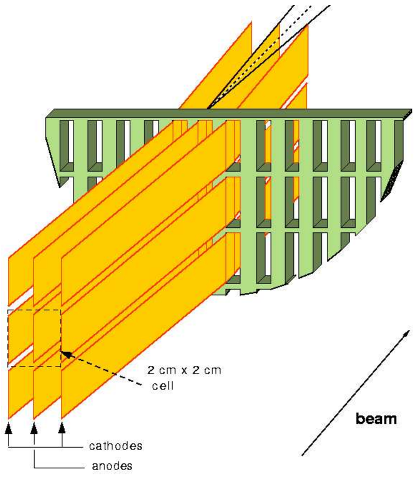


Hodoscope

- Two ⊥ planes of scintillators
- Fast trigger
- Precise time measurement
- $\sigma_t \simeq 150$ ps

The NA48 Detector

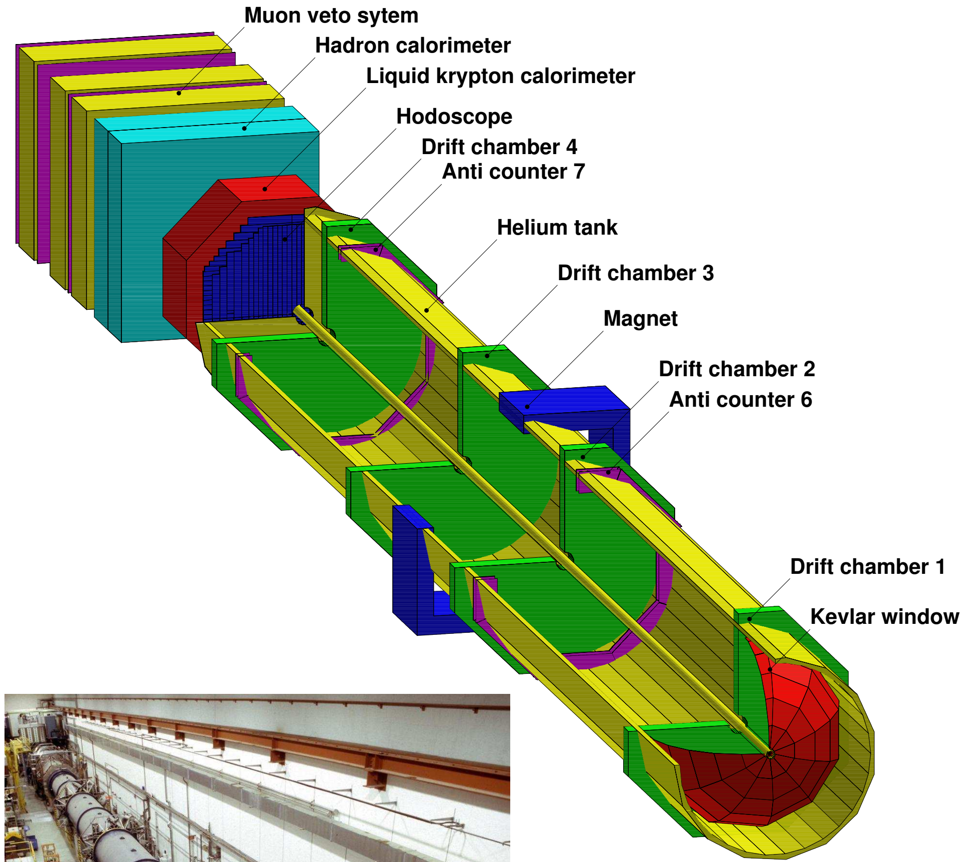


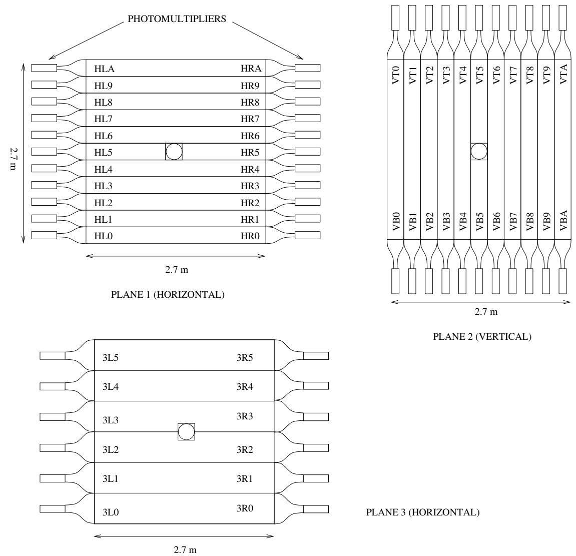


EM Calorimeter

- Liquid krypton
- 13248 cells of 2×2 cm^2
- $\frac{\sigma_E}{E}(\%) = \frac{3.2}{\sqrt{E}} \oplus \frac{9.0}{E} \oplus 0.42$ (GeV)

The NA48 Detector





Muon Counter

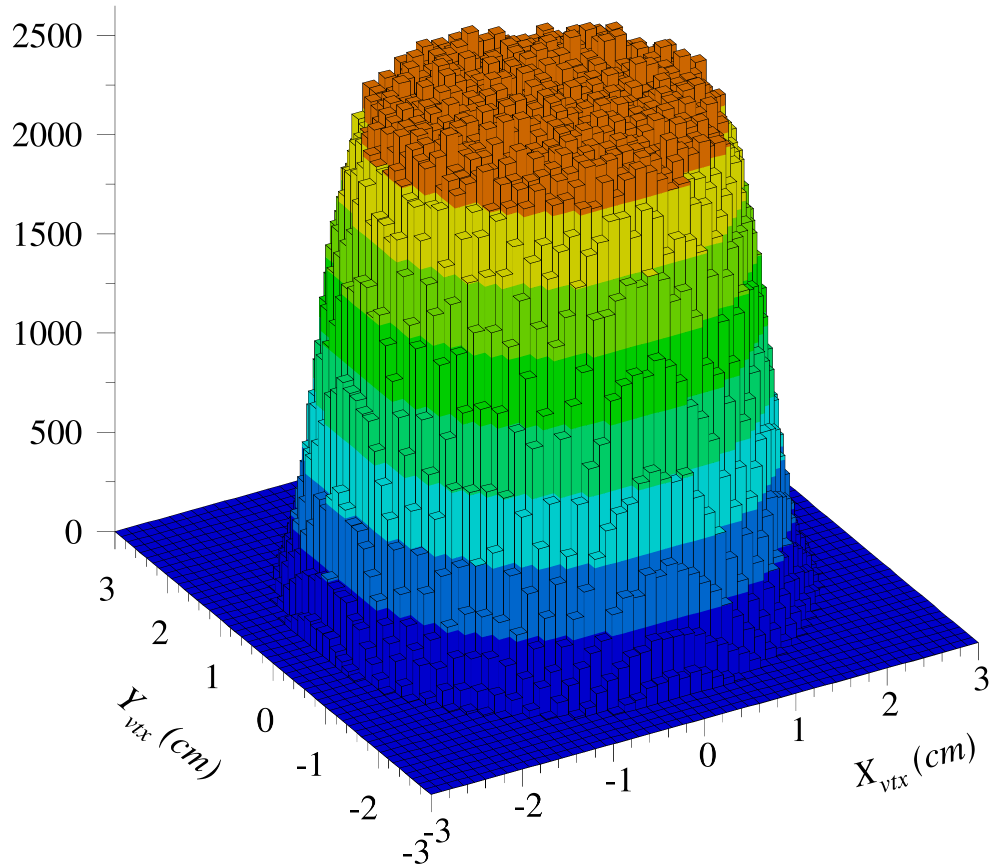
- 3 planes of scintillators
- 80 cm iron shield each
- 25cm $\times$ 25cm cells
- $\sigma_t \simeq 350$ ps

$K_{\mu 3}$ Event Selection

- K_L collected during 1999 $\epsilon^{'}/\epsilon$ data taking
- Special minimum bias run (2 days)
- K_L beam only
- 100 M events on tape

Event Selection

- Good vertex (Z, R, cda, 2 tracks $\pm$, Δtime)

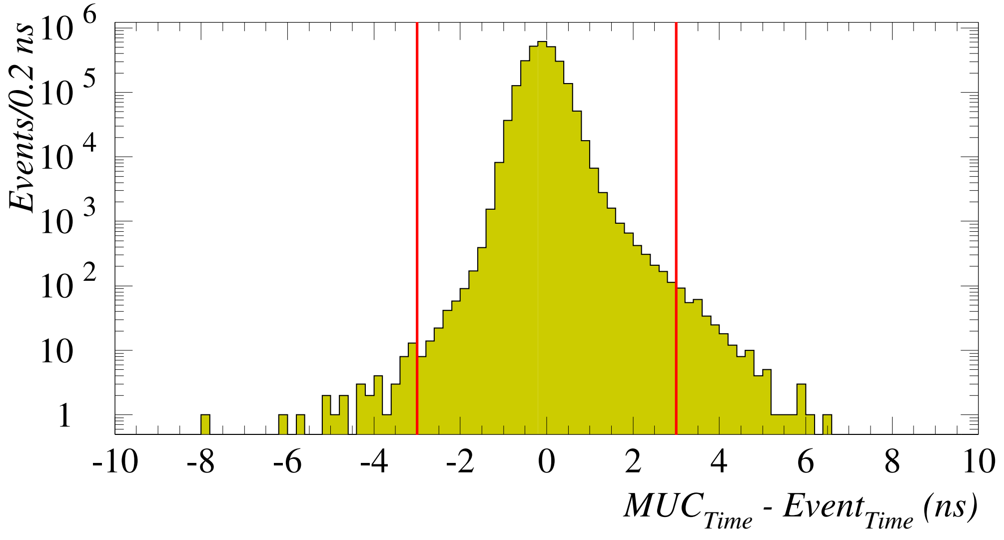


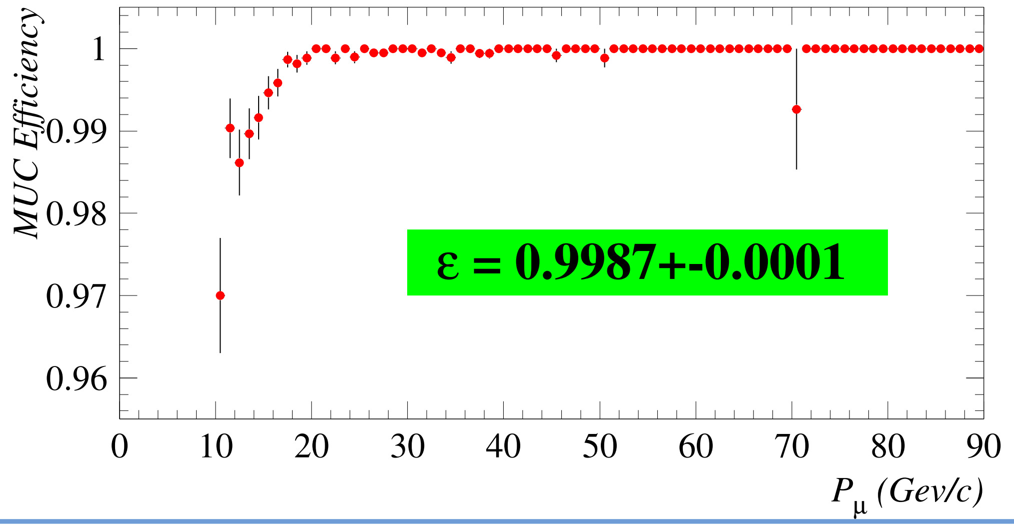
$K_{\mu 3}$ Event Selection

- K_L collected during 1999 ϵ'/ϵ data taking
- Special minimum bias run (2 days)
- K_L beam only
- 100 M events on tape

Event Selection

- Good vertex (Z, R, cda, 2 tracks $\pm$, Δtime)
- μ id. (Hit in time in MUC)



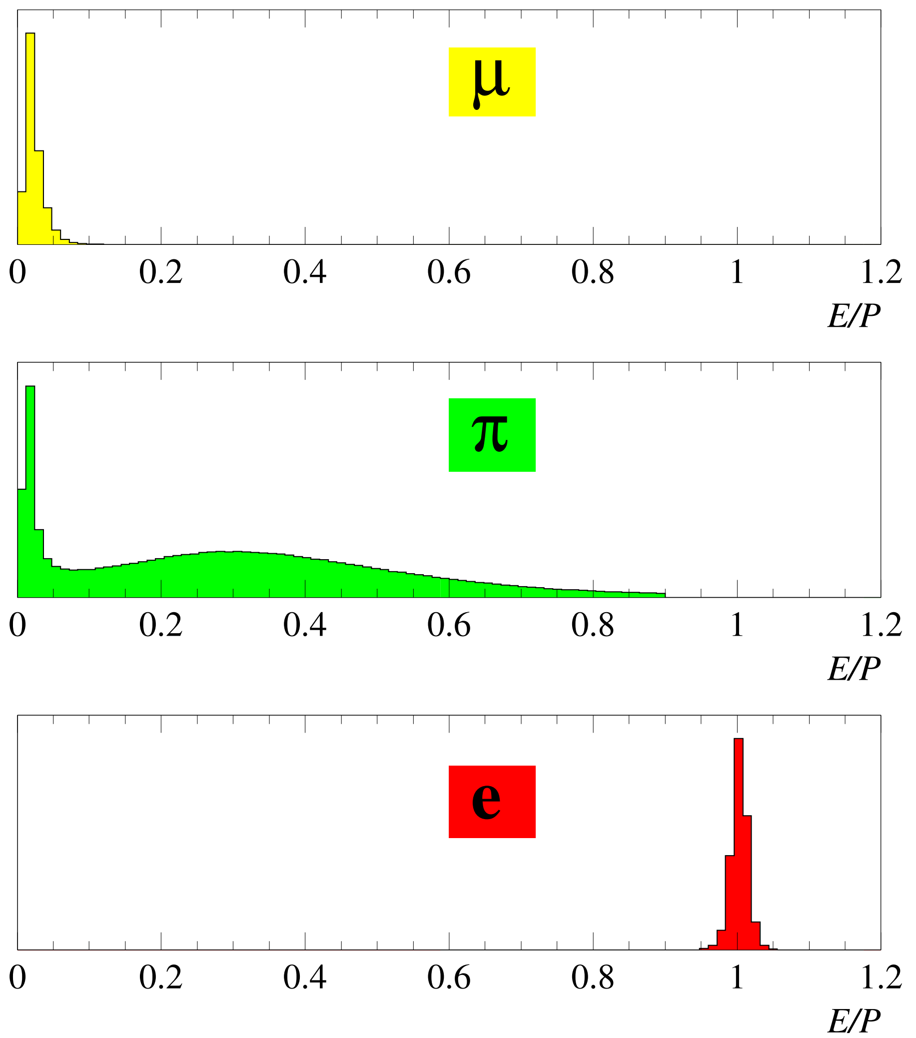


$K_{\mu 3}$ Event Selection

- K_L collected during 1999 ϵ'/ϵ data taking
- Special minimum bias run (2 days)
- K_L beam only
- 100 M events on tape

Event Selection

- Good vertex (Z, R, cda, 2 tracks $\pm$, Δtime)
- μ id. (Hit in time in MUC)
- π id. $(E/p < 0.9)$



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Event Selection

- Good vertex (Z, R, cda, 2 tracks $\pm$, Δtime)
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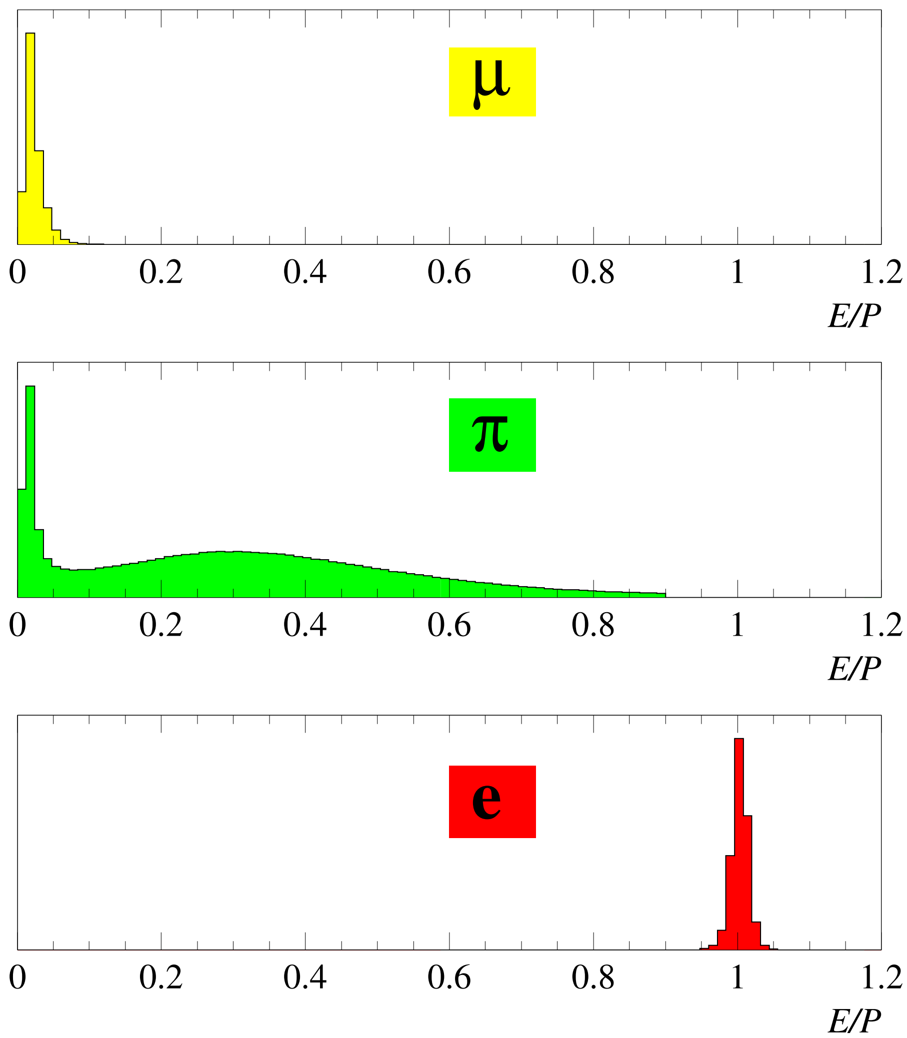
- π id. $(E/p < 0.9)$
- no e (against K_{e3})



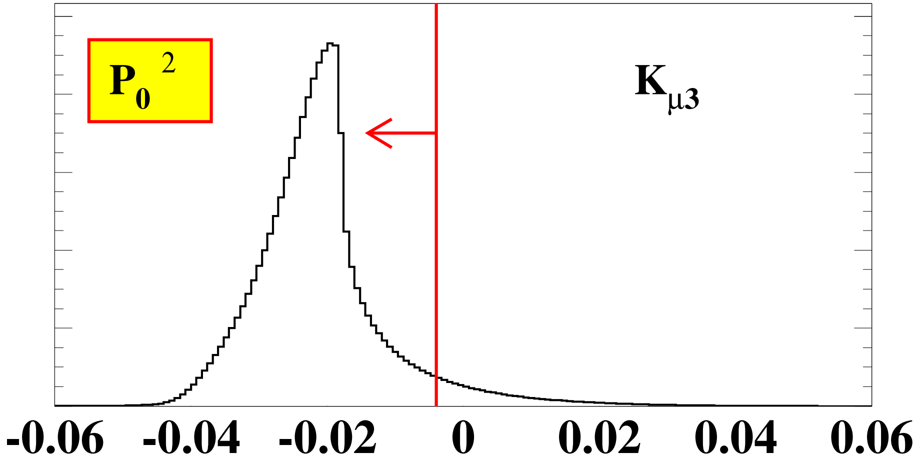
$K_{\mu3}$ Event Selection

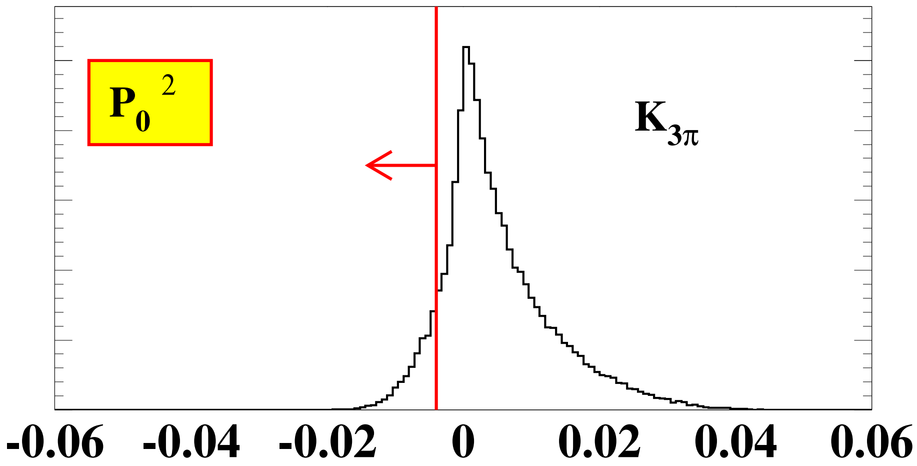
- K_L collected during 1999 ϵ'/ϵ data taking
- Special minimum bias run (2 days)
- K_L beam only
- 100 M events on tape

Event Selection

- Good vertex (Z, R, cda, 2 tracks $\pm$, Δtime)
- μ id. (Hit in time in MUC)
- π id. $(E/p < 0.9)$
- no e (against K_{e3})
- no $K_{3\pi}$ ($P_0'^2 < -0.004$ (GeV/c)^2)

Selected 2.3×10^6 events



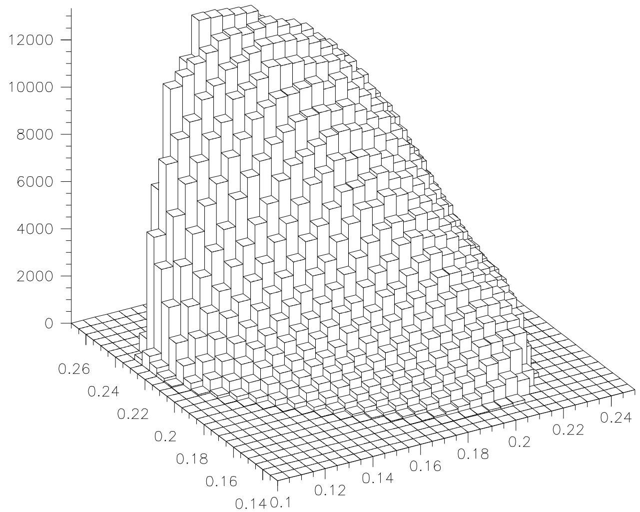


$K_{\mu 3}$ Form Factors Analysis

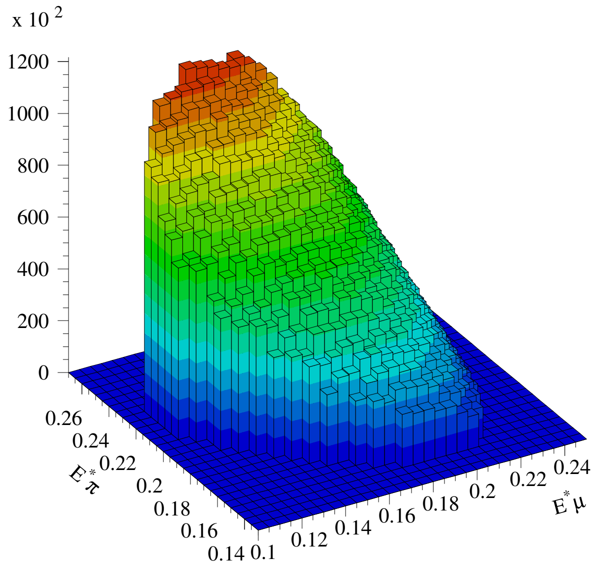
Dalitz Plot analysis: to extract the f.f. perform a fit to the DP density

$$\rho(E^*_\mu, E^*_\pi) = \frac{d^2N(E^*_\mu, E^*_\pi)}{dE^*_\mu \, dE^*_\pi} \propto Af_+^2(t) + Bf_+(t)f_-(t) + Cf_-^2(t)$$

E^*_μ, E^*_π are the energies of μ and π in the kaon CMS
$A,\ B$ and C are kinematical terms



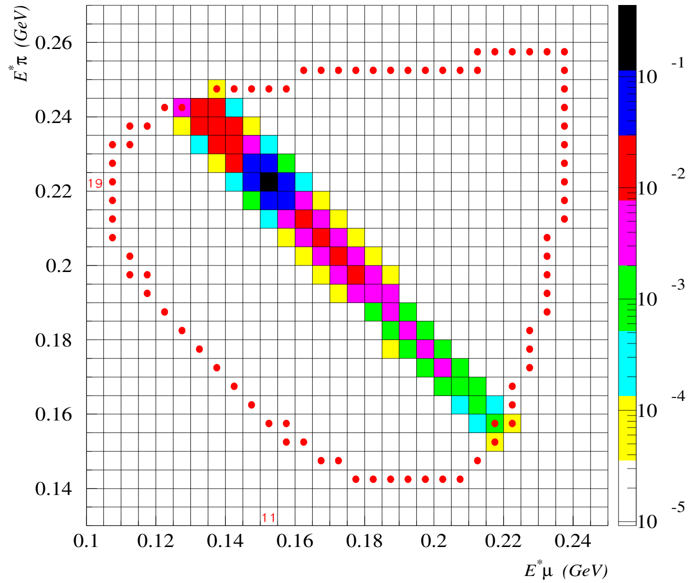
- Acceptance
- K_L energy ambiguity
- Radiative Corrections
- Background



K_L Energy Ambiguity

- The K_L energy is not known
- It cannot be determined unambigously due to the undetected ν

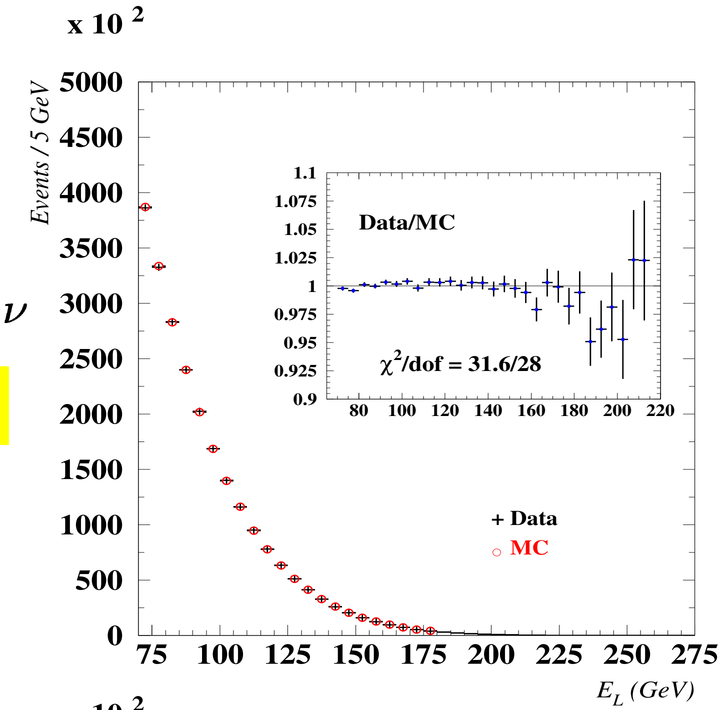
For every event there are two energy solutions E_L and E_H

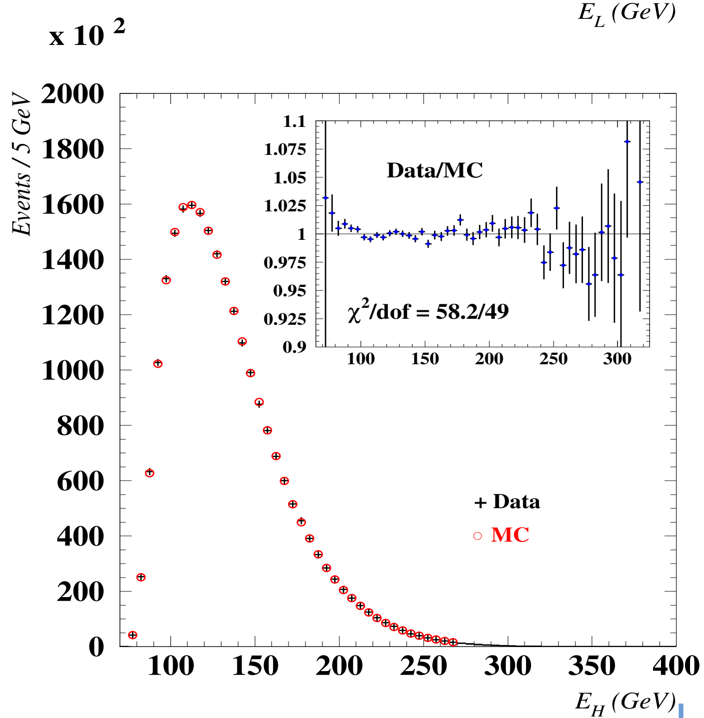


Use the LOW solution

- $4\times$ 4 MeV^2 cells
- Correct solution in 61% of events
- 39% of events reconstructed in the same cell where generated

$$\epsilon = \frac{\rho(E^*_{\mu(LOW)}, E^*_{\pi(LOW)})^{MC\ Rec}}{\rho(E^*_{\mu(TRUE)}, E^*_{\pi(TRUE)})^{MC\ Gen}}$$





Radiative Corrections

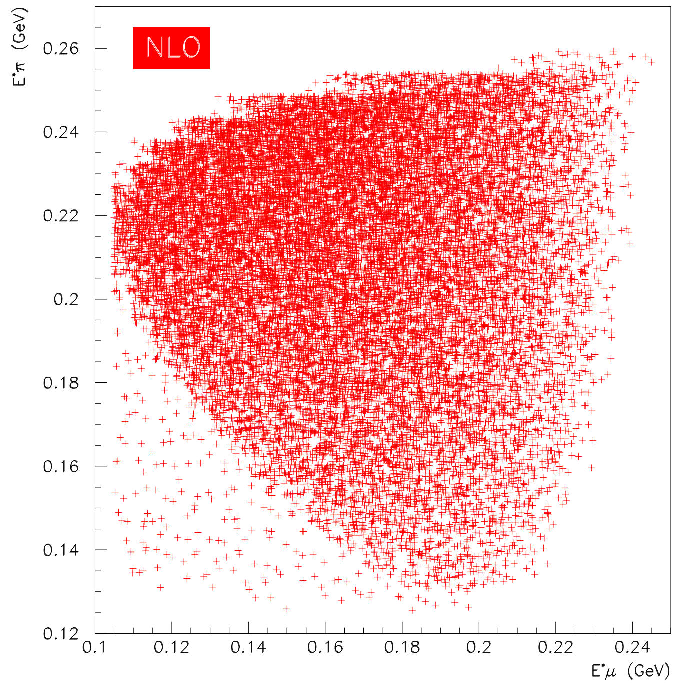
Simulation with `KLOR`
by T. Andre (hep–ph0406006v3)

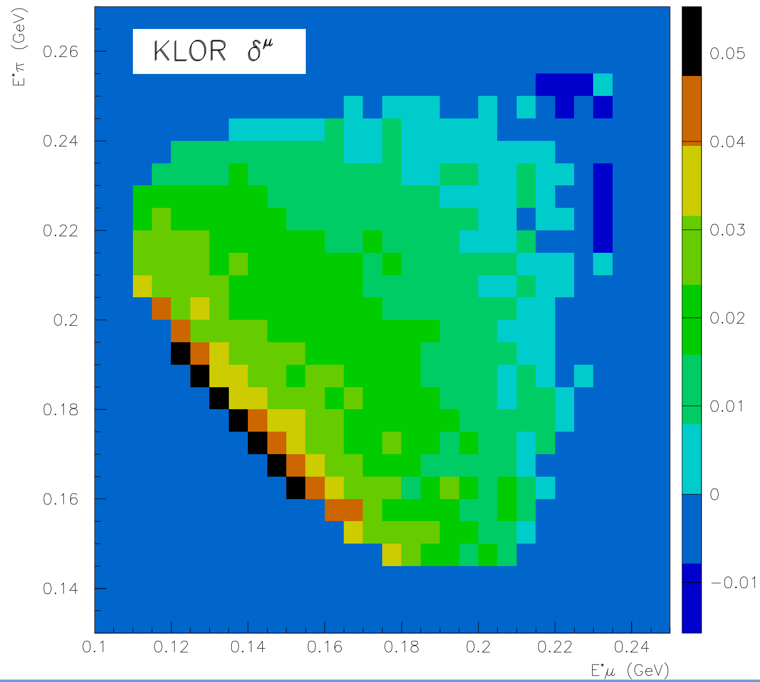
Revisited version of the phenomenological model of Ginsberg (1966)

$$\Gamma^{NLO}_{K\mu3}/\Gamma^{BORN}_{K\mu3} = (1+\delta^{\mu}_{EM})$$

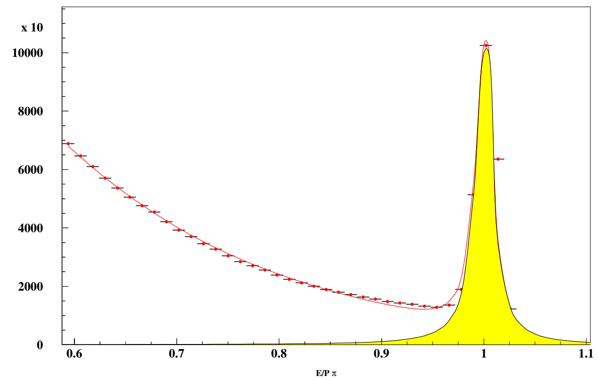
$$\delta^{\mu}_{EM} = 2\Delta^{K_\mu}_{EM} = (1.9 \pm 0.3)\%$$

- Small effect on the acceptance
- Significant distortions on the Dalitz plot





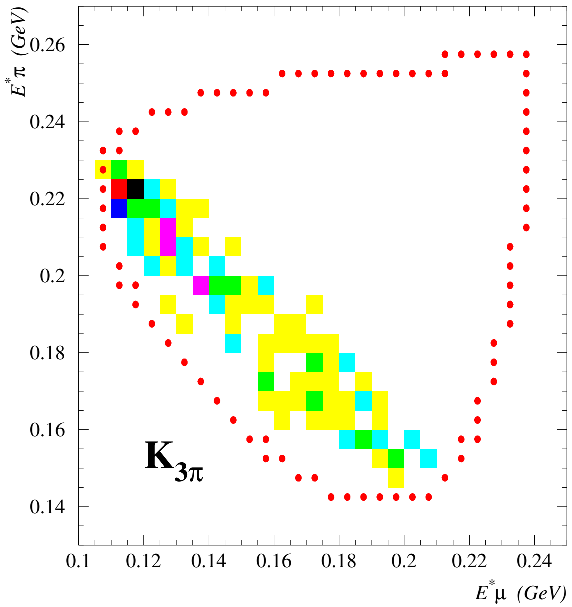
Background



$K_L \rightarrow \pi^{\pm} e^{\mp} \nu_e$
Removed by E/p cut

$\mathcal{P}^{cont}_{Ke3} = (6.59 \pm 0.09) \times 10^{-4}$

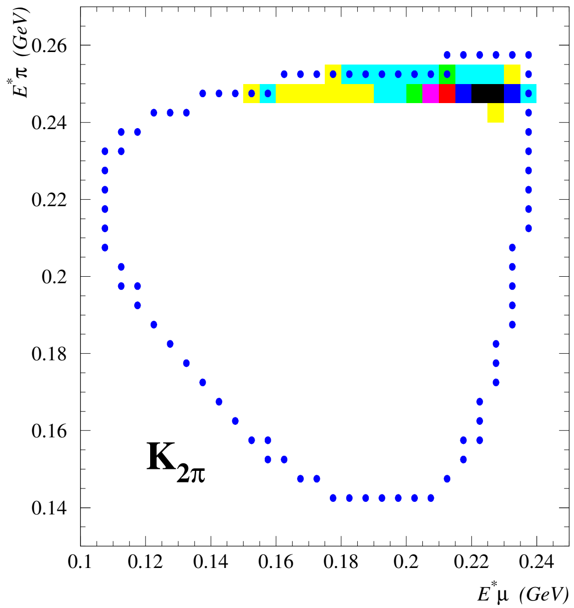
$\rightarrow$ Negligible effect on f.f.



$K_L \rightarrow \pi^+ \pi^- \pi^0$
Removed by $P_0'^2$ cut

$\mathcal{P}^{cont}_{3\pi} = (6.31 \pm 0.16) \times 10^{-4}$

$\rightarrow$ Small effect on f.f.



All of these sources need a $\pi \rightarrow \mu$ decay

$K_L \rightarrow \pi^+ \pi^-$
Disfavoured by the small BR

$\mathcal{P}^{cont}_{2\pi} = (5.63 \pm 0.16) \times 10^{-4}$

$\rightarrow$ Big effect on f.f.

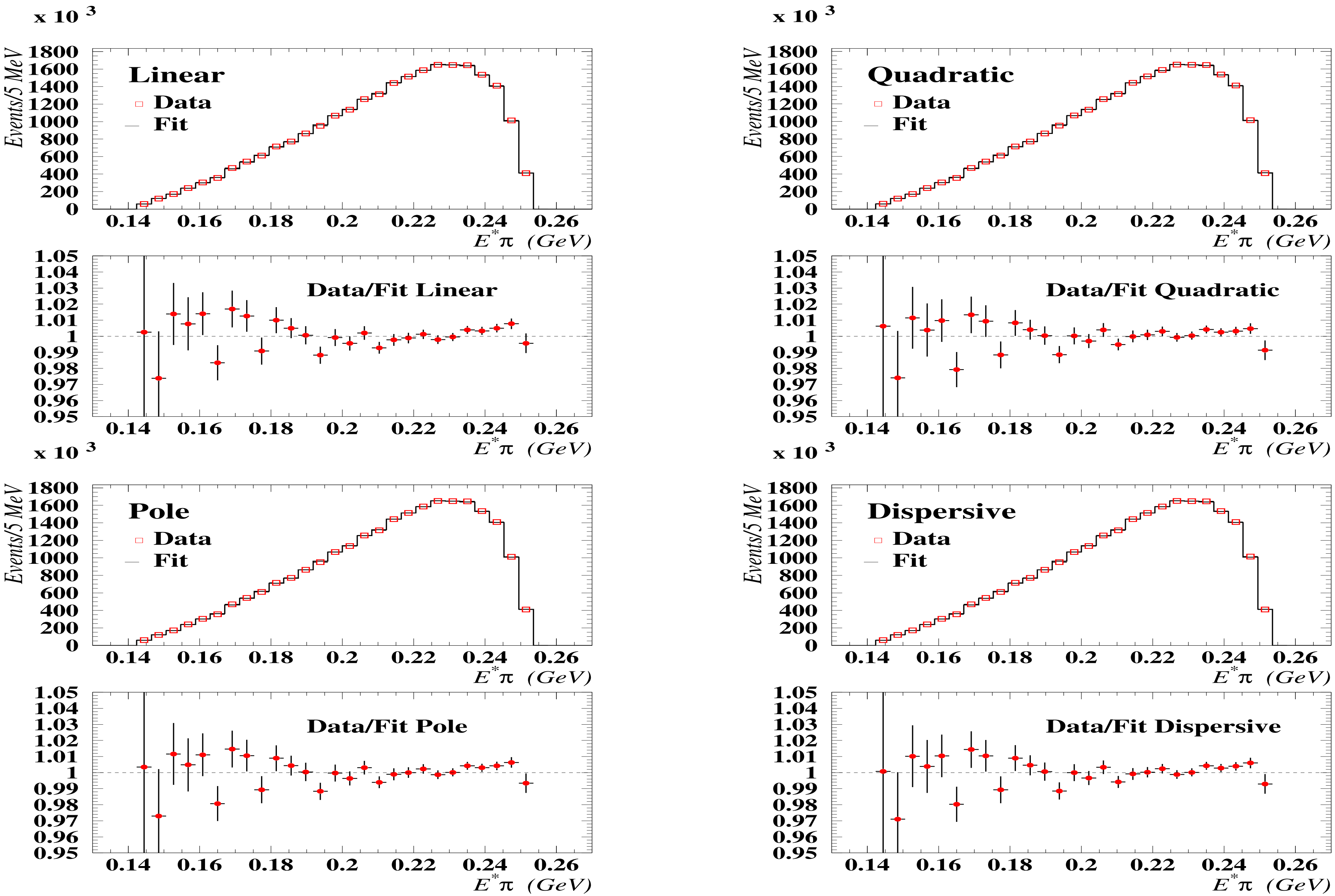
The NA48 Results for the $K_{\mu 3}$ Form Factor Slopes

Linear ($\times 10^{-3}$)			Quadratic λ_+ ($\times 10^{-3}$)		
λ_+	=	26.7±0.6±0.8	λ_+'	=	20.5±2.2±2.4
λ_0	=	11.7±0.7±1.0	λ_+''	=	2.6±0.9±1.0
χ^2/ndf	=	604.0/582	λ_0	=	9.5±1.1±0.8
			χ^2/ndf	=	595.9/581

Pole (MeV/c^2)			Dispersive ($\times 10^{-3}$)		
m_V	=	905±9±17	Λ_+	=	23.3±0.5±0.8
m_S	=	1400±46±53	$\ln\ C$	=	143.8±8.0±11.2
χ^2/ndf	=	596.7/582	χ^2/ndf	=	595.0/582

- Like other exp. we observe a quadratic term in the expansion of $f_+(t)$
- λ_0 is smaller than what recently reported

Data vs. Fit Comparison



Current Data on $K_{\ell 3}$ Form Factor Slopes

Using the quadratic fit results for comparison

	$\lambda'_+ \times 10^3$	$\lambda''_+ \times 10^3$	$\lambda_0 \times 10^3$	Events	Analysis	Ref.
KLOE	25.5±1.8	1.4±0.8		2.0×10^6 K_{e3}	t from K_S	PLB 632 (2006)
	Use K_{e3}	Use K_{e3}	15.6±2.6	1.8×10^6 $K_{\mu 3}$	$E_\nu + K_{e3}$	Preliminary
KTeV	21.7±2.0	2.9±0.8		1.9×10^6 K_{e3}	$t_\perp^\pi$	PRD 70 (2004)
	17.0±3.7	4.4±1.5	12.8±1.8	1.5×10^6 $K_{\mu 3}$	$t_\perp^\pi$	
ISTRA+	24.9±1.7	1.9±0.9		0.9×10^6 K_{e3}^-	$\rho(E_\mu, E_\pi)$	PLB 589 (2004)
	23.0±6.4	2.3±2.3	17.1±2.2	0.9×10^6 $K_{\mu 3}^-$	$\rho(E_\mu, E_\pi)$	PLB 581 (2004)
NA48	28.0±2.4	0.4±0.9		5.6×10^6 K_{e3}	$\rho(t_l, t_h, E_\nu)$	PLB 604 (2004)
	20.5±3.3	2.6±1.5	9.5±1.4	2.3×10^6 $K_{\mu 3}$	$\rho(E_\mu, E_\pi)_l$	PLB 647 (2007)

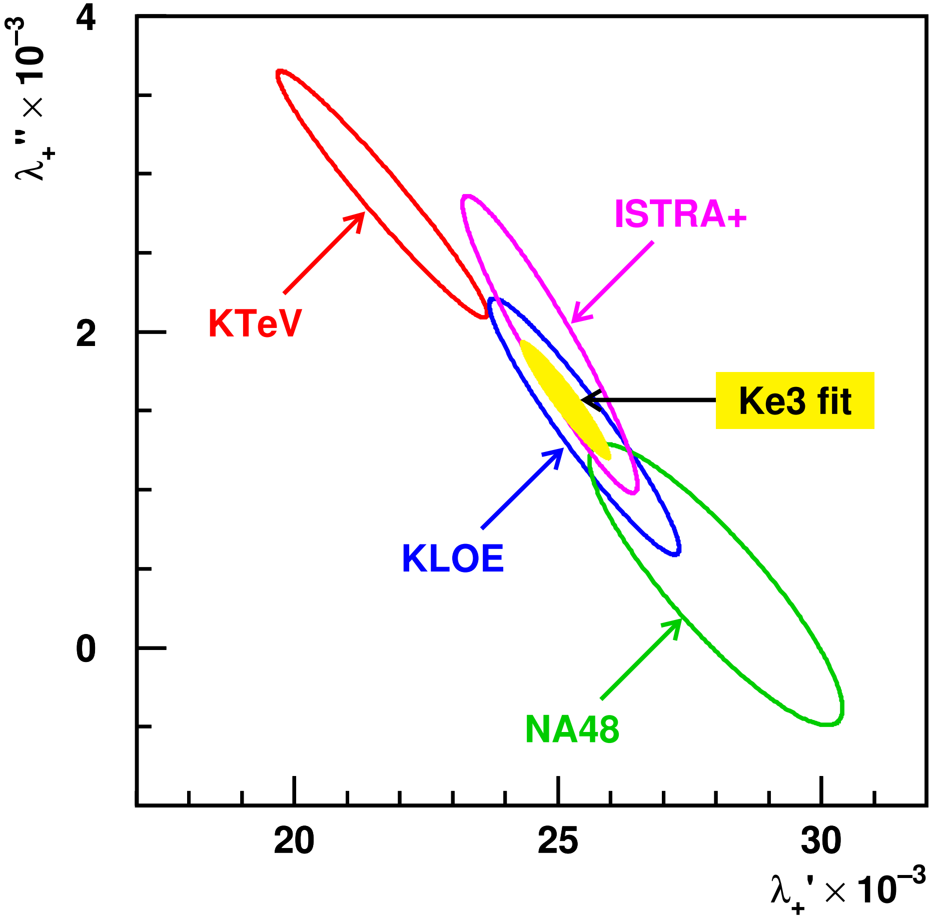
ISTRA+ Multiplied by $(m_{\pi^+}/m_{\pi^0})^2$=1.069. No systematic errors nor correlations given in the paper

K_ℓ Form Factor Slopes

K_{e3} slopes only

$$\lambda'_+ = (25.1 \pm 0.9) \times 10^3$$
$$\lambda''_+ = (1.6 \pm 0.4) \times 10^3$$

Correlation $\rho = -94.1\%$

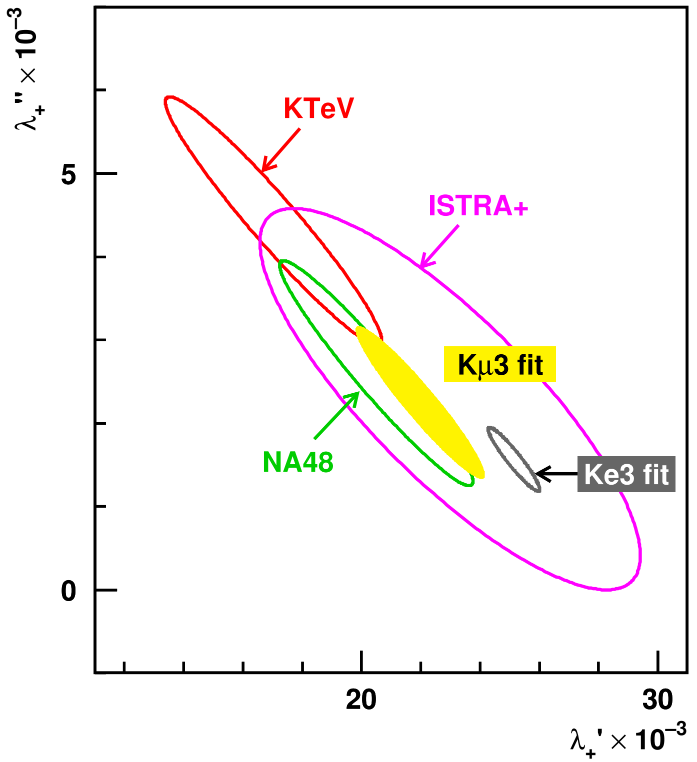


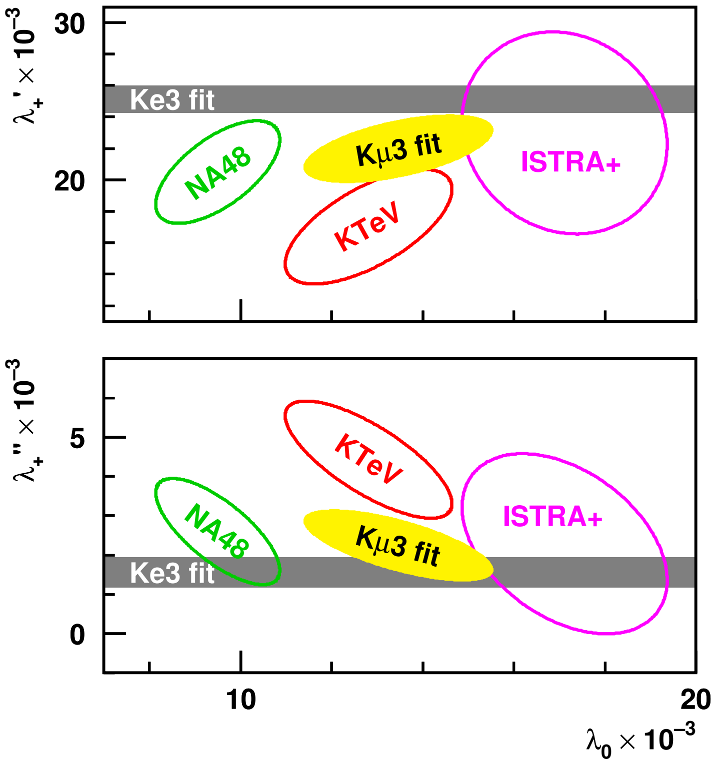
(Ellipses = 1 σ contour)

K_ℓ Form Factor Slopes

$K_{\mu 3}$ slopes only

$$\lambda'_+ = (22.1 \pm 2.2) \times 10^3$$
$$\lambda''_+ = (2.3 \pm 0.9) \times 10^3$$
$$\lambda_0 = (13.5 \pm 2.1) \times 10^3$$



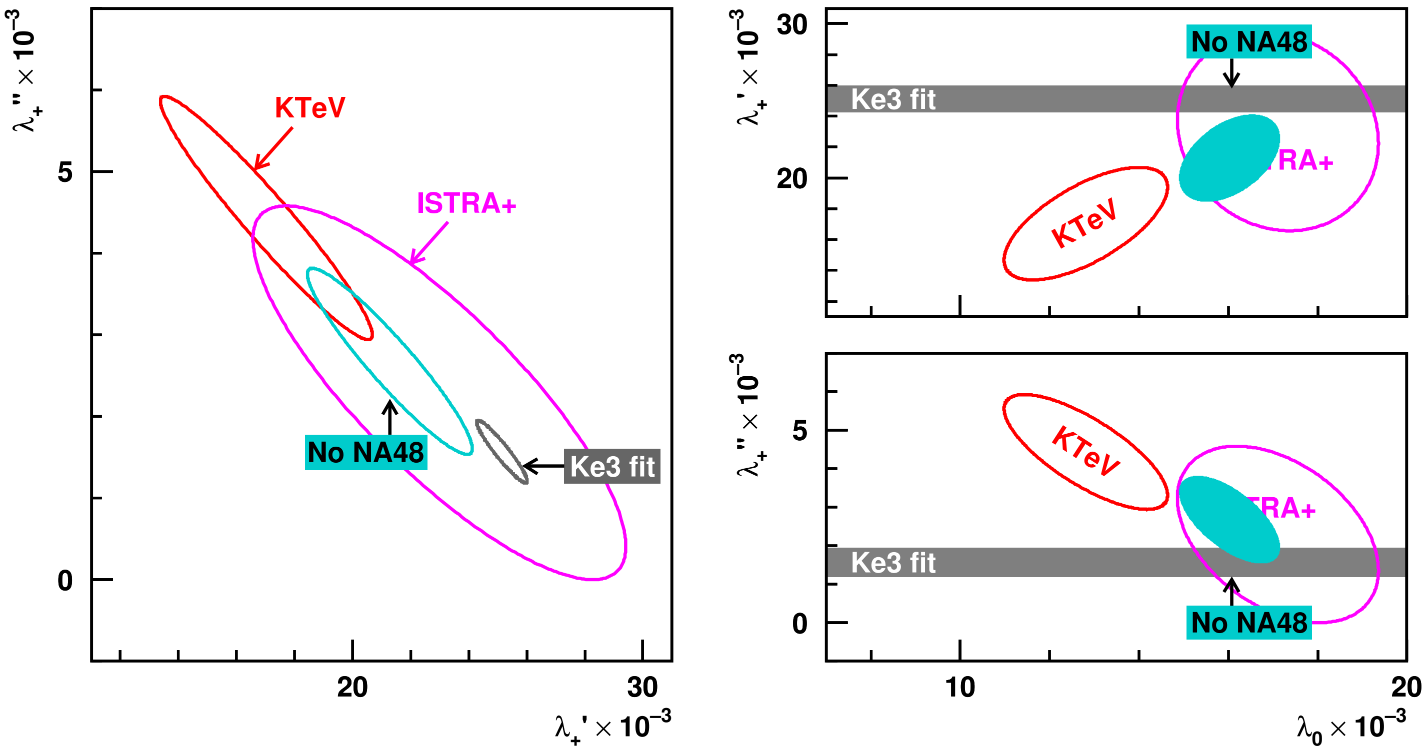


	λ'_+	λ''_+
λ'_+		-0.949
λ_0	0.540	-0.679

Agreement with K_{e3} poor, mostly driven by NA48 value on λ_0

K_ℓ Form Factor Slopes

Excluding NA48 $K_{\mu3}$ from the fit



FlaviA (net) fit to K_ℓ Form Factor Slopes

Slope Parameters $\times 10^3$				Integrals	
λ'_+	24.82	$\pm$1.10	S=1.4	$I(K^0_{e3})$	0.15454(29)
λ''_+	1.64	$\pm$0.44	S=1.3	$I(K^\pm_{e3})$	0.15889(30)
λ_0	13.38	$\pm$1.19	S=1.9	$I(K^0_{\mu 3})$	0.10209(31)
χ^2/ndf	53/13 (10^{-6})			$I(K^\pm_{\mu 3})$	0.10504(32)

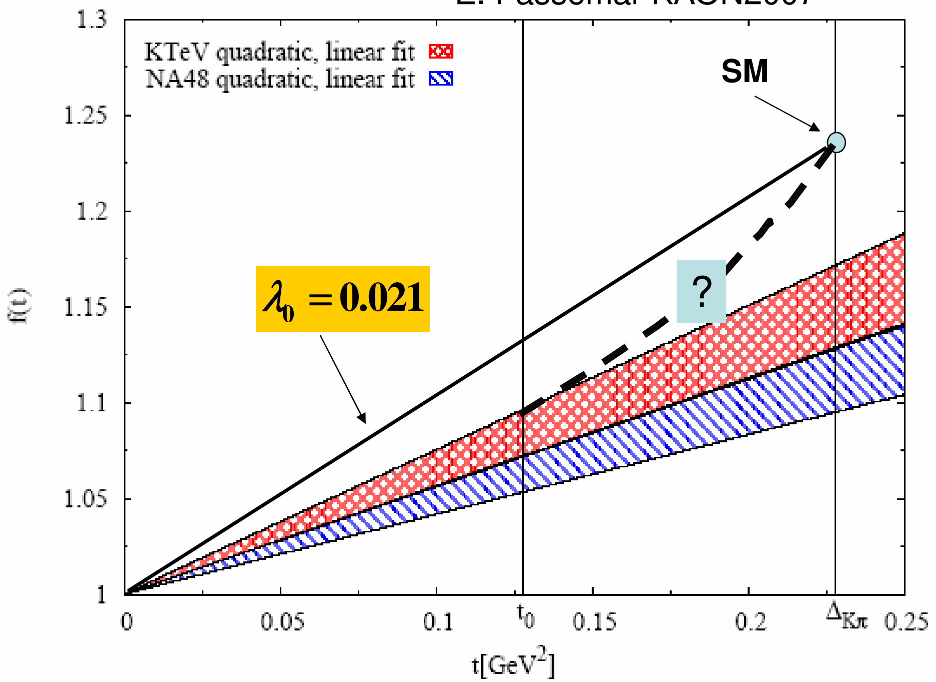
All Experiments

The rescaling of the errors and the change in λ_0 has anyway a negligible effect on $|V_{us}|$

λ_0 and the Callan–Treiman Point

- λ_0 is the slope of the power expansion of $f_0(t)$ around $t = 0$
- In order to satisfy the CT theorem a value of λ_0 bigger than what measured in any of the recent experiments is needed

E. Passemar KAON2007



- Curvature of the ff cannot be neglected going up to $\Delta_{K\pi}$

Use the new dispersive parametrization

f_0 and the RHCs

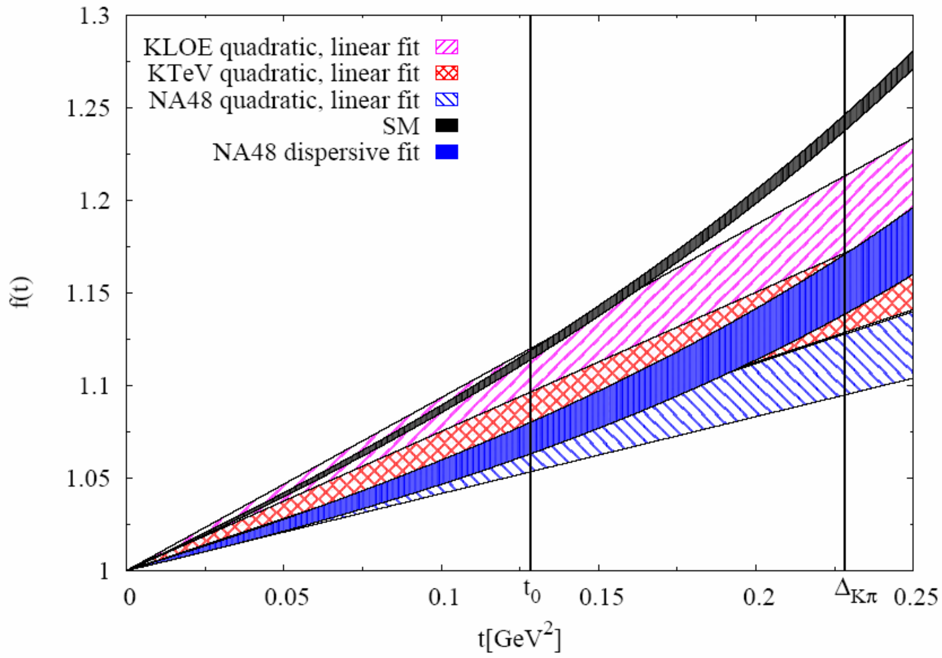
- NA48 has done the first direct measurement of $\ln C$ using the dispersive parametrization

$$\ln C = 0.1438 \pm 0.0080_{stat} \pm 0.0112_{syst}$$

- One parameter allows to extract slope and curvature of $f_0(t)$

$$\lambda_0' = 0.0089 \pm 0.0012$$
$$\lambda_0'' = (4.95 \pm 0.54)10^{-4}$$

E. Passemar KAON2007



- Big discrepancy with $\ln C_{SM}$

$$\ln C_{SM} = 0.2151 \pm 0.0045 + \tilde{\Delta}_{CT}$$

- Interpreted in terms of RHCs

$$\Delta(\epsilon) = 2(\epsilon_S - \epsilon_{NS}) + \tilde{\Delta}_{CT} = -0.071 \pm 0.014_{NA48} \pm 0.002_{theo} \pm 0.005_{ext}$$

f_0 and the RHCs

$\Rightarrow$ NA48 sees effect (5σ) in $K_{\mu 3}$ at the Callan-Treiman point

f_0 and the RHCs

⇒ NA48 sees effect (5σ) in $K_{\mu3}$ at the Callan-Treiman point

Did one observe couplings of right handed quarks to W ?

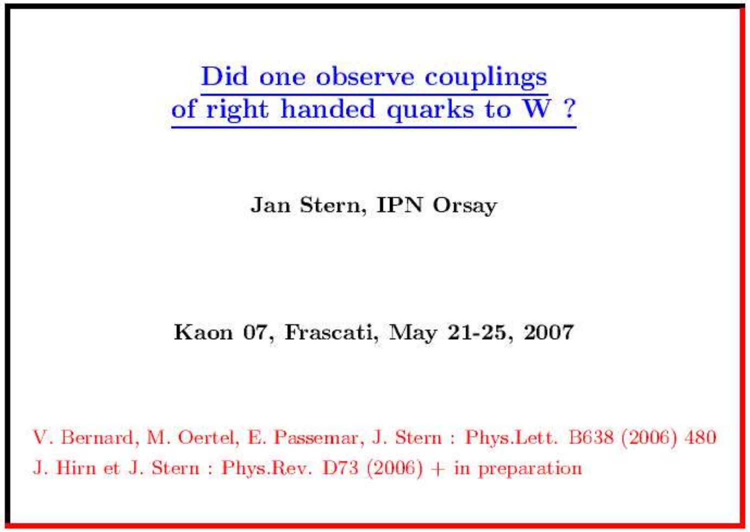
Jan Stern, IPN Orsay

Kaon 07, Frascati, May 21-25, 2007

V. Bernard, M. Oertel, E. Passemar, J. Stern : Phys.Lett. B638 (2006) 480
J. Hirn et J. Stern : Phys.Rev. D73 (2006) + in preparation

f_0 and the RHCs

⇒ NA48 sees effect (5σ) in $K_{\mu 3}$ at the Callan-Treiman point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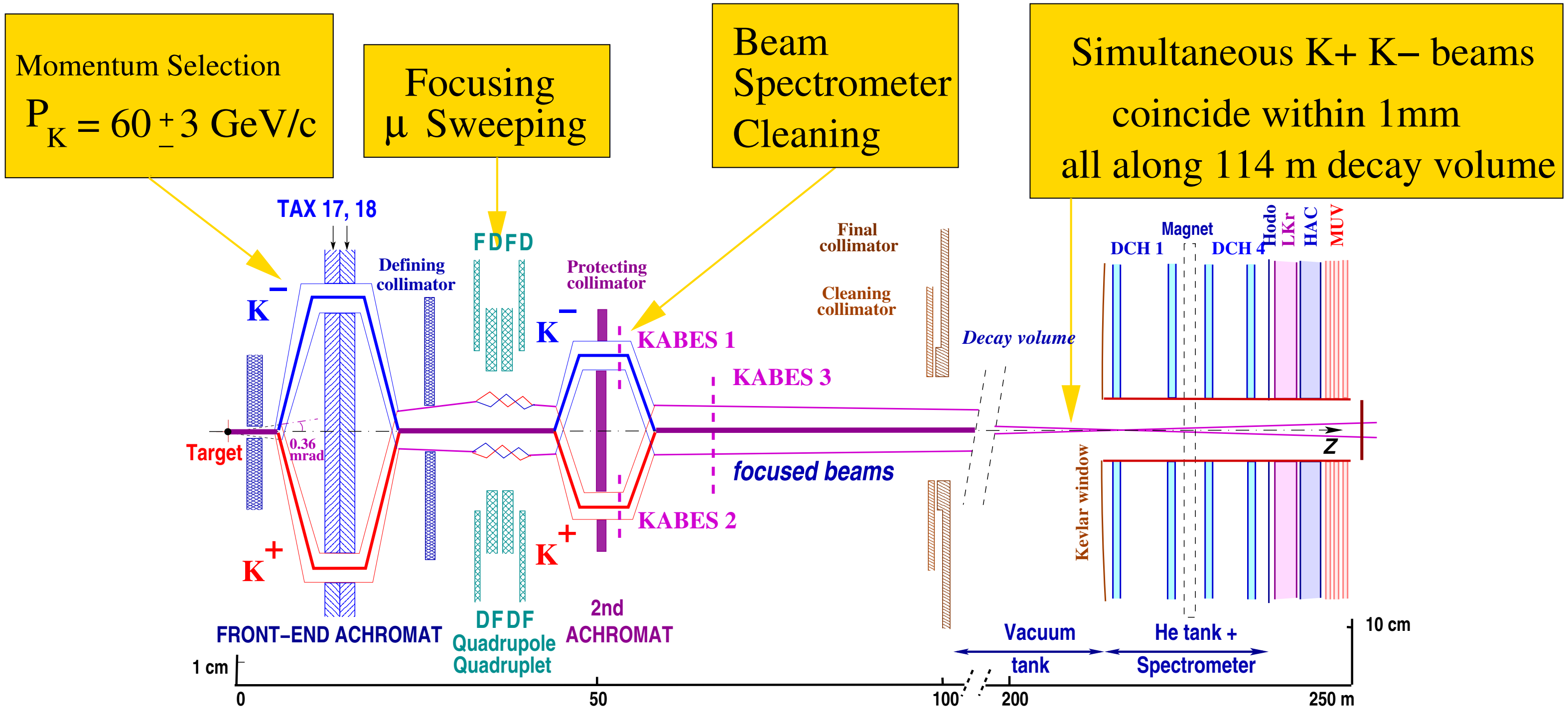
- A good question ! ...No answer yet...
- No other experiment has performed yet a fit with the dispersive parametrization
- Other experiments disagree with NA48 in the slope λ_0 of the scalar form factor
- Data of other experiments need to be investigated

Situation to be clarified

$K^{\pm}_{\ell 3}$ Form Factors @ NA48/2

- $K^{\pm}$ collected during 2003-2004 data taking **NA48/2 Experiment**

  (Main purpose search for direct CP violation in $K^{\pm} \rightarrow 3\pi$ decays)
- Special low intensity ($\times$1/8) minimum bias runs
- Simultaneous K^{+} and K^{-} beams
- K^{+} flux $\simeq 3.2 \times 10^{6}$; $K^{+}/K^{-} \simeq 1.78$ (production rate @target)



Summary

- **$K_{\ell 3}$ decays & CKM unitarity**
  - Very intense activity in the last 3 years in the $K_{\ell 3}$ decays both on the exp and theory side
  - $|V_{us}|$ is one of the best known CKM matrix element
    $\Rightarrow$ Precision frontier in CKM studies: $\sigma|V_{us}f_+(0)| \sim 0.2\%$
  - Dominant contribution to uncertainty on $|V_{us}|$ still from $f_+(0)$
  - Slight difference between the values for $f_+(0)$ obtained with analytic calculations and Lattice QCD
  - The LECs appearing in the ChPT O(p^6) expansion could be determined by the slope and curvature of f_0
    $\Rightarrow$ But they cannot be determined experimentally...
  - Waiting the progresses of Lattice QCD...in the meanwhile use for $f_+(0)$ the LR value
  - Differences in $|f_+(0)V_{us}|$ obtained in K^0 and $K^\pm$ decays
    $\Rightarrow$ Isospin correction underestimated by $\sim 1\%$?

Summary

- **$K_{\mu 3}$ decays & non SM physiscs**
  - The $K_{L\mu 3}$ decays can be used to test the existence of new physics
  - The value of f_0 at the Callan-Treiman point determines the amount of RHCs
  - New dispersive parametrization for f_0 (and f_+)

- **The NA48 $K_{\mu 3}$ form factor analysis**
  - Big discrepancy w.r.t SM predictions for $\ln C$
  - No other experiment has performed a fit with the dispersive parametrization
  - The result of the scalar form factor however is controversial

  $\Rightarrow$ Not possible to draw any conclusion yet, more experimental input is needed

Additional Material

Systematic Uncertainties

- Systematic and total uncertainty for the four form factor parametrizations analysed

	$\Delta\lambda_+$	$\Delta\lambda_0$	$\Delta\lambda'_+$	$\Delta\lambda''_+$	$\Delta\lambda_0$	Δm_V	Δm_S	$\Delta\Lambda_+$	$\Delta \ln C$
			$\times 10^{-3}$			MeV/c^2		$\times 10^{-3}$	
Background	±0.0	±0.1	±0.2	±0.1	±0.0	±0	±5	±0.0	±1.2
Acceptance	±0.4	±0.5	±0.7	±0.4	±0.4	±7	±22	±0.4	±5.0
TRK_{dist} @ LKr	±0.4	±0.4	±0.5	±0.4	±0.3	±10	±20	±0.4	±5.4
P_{MIN}	±0.1	±0.3	±0.4	±0.1	±0.3	±1	±20	±0.1	±3.1
$P^*_\nu - P_{\nu T}$	±0.2	±0.2	±0.5	±0.2	±0.2	±6	±10	±0.2	±2.2
K_L spectrum	±0.2	±0.4	±0.0	±0.0	±0.3	±4	±20	±0.2	±4.1
HIGH solution	±0.3	±0.0	±0.6	±0.2	±0.2	±8	±12	±0.4	±1.9
MUV reconstruction	±0.1	±0.1	±0.1	±0.0	±0.1	±2	±5	±0.2	±0.8
Radiative corrections	±0.2	±0.4	±2.0	±0.7	±0.3	±2	±20	±0.1	±4.3
Cell Size	±0.3	±0.3	±0.5	±0.3	±0.3	±5	±20	±0.2	±4.0
Total Systematic	±0.8	±1.0	±2.4	±1.0	±0.8	±17	±53	±0.8	±11.2
Statistical	±0.6	±0.7	±2.2	±0.9	±1.1	±9	±46	±0.5	±8.0
Total Error	±1.0	±1.2	±3.3	±1.3	±1.4	±19	±70	±0.9	±13.8

Data-MC Comparison