Lepton Universality Test and the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Experiment at the CERN SPS

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on behalf of the NA48/2 Collaboration:
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

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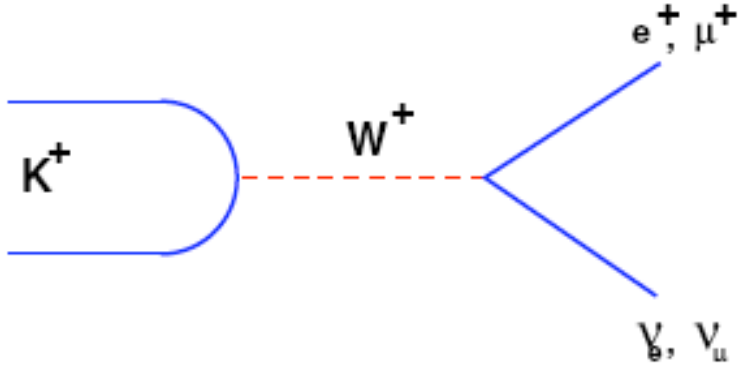
Outline

- Measurement of $R_K = \Gamma(K_{e2}) / \Gamma(K_{\mu 2})$
  - Physics motivation
  - The NA48/2 experiment at CERN SPS
  - Results from 2003 and 2004 data taking
  - Dedicated 2007 run
- The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay
  - Introduction
  - Principle of the experiment
  - Detector layout
- Conclusions

$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$: motivation



- Very well predicted ratio within the Standard Model
  - hadronic uncertainties cancel in R_K
  - K_{e2} strongly helicity suppressed

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K) = (2.472 \pm 0.001)\cdot 10^{-5}$$

[M. Finkemeier, Phys. Lett. B 387 (1996)]

[V. Cirigliano and I Rosell, JHEP 0710:005 (2007)]

$$(2.477 \pm 0.001)\cdot 10^{-5}$$

$\delta R_K / R_K = 0.04\%$

δR_K includes IB but not SD

- The value of R_K could be different in case of SUSY Lepton Flavor Violation [A. Masiero, P. Paradisi, R. Petronzio, Phys. Rev. D 74 011701 (2006)]
  - the difference w.r.t SM could be as high as ±3%
- A precise measurement of R_K probes μ-e universality and provides a stringent test of the SM

Experimental status

- Poor experimental knowledge of R_K so far
  - PDG 2006 average based on 3 experiments from the 70's

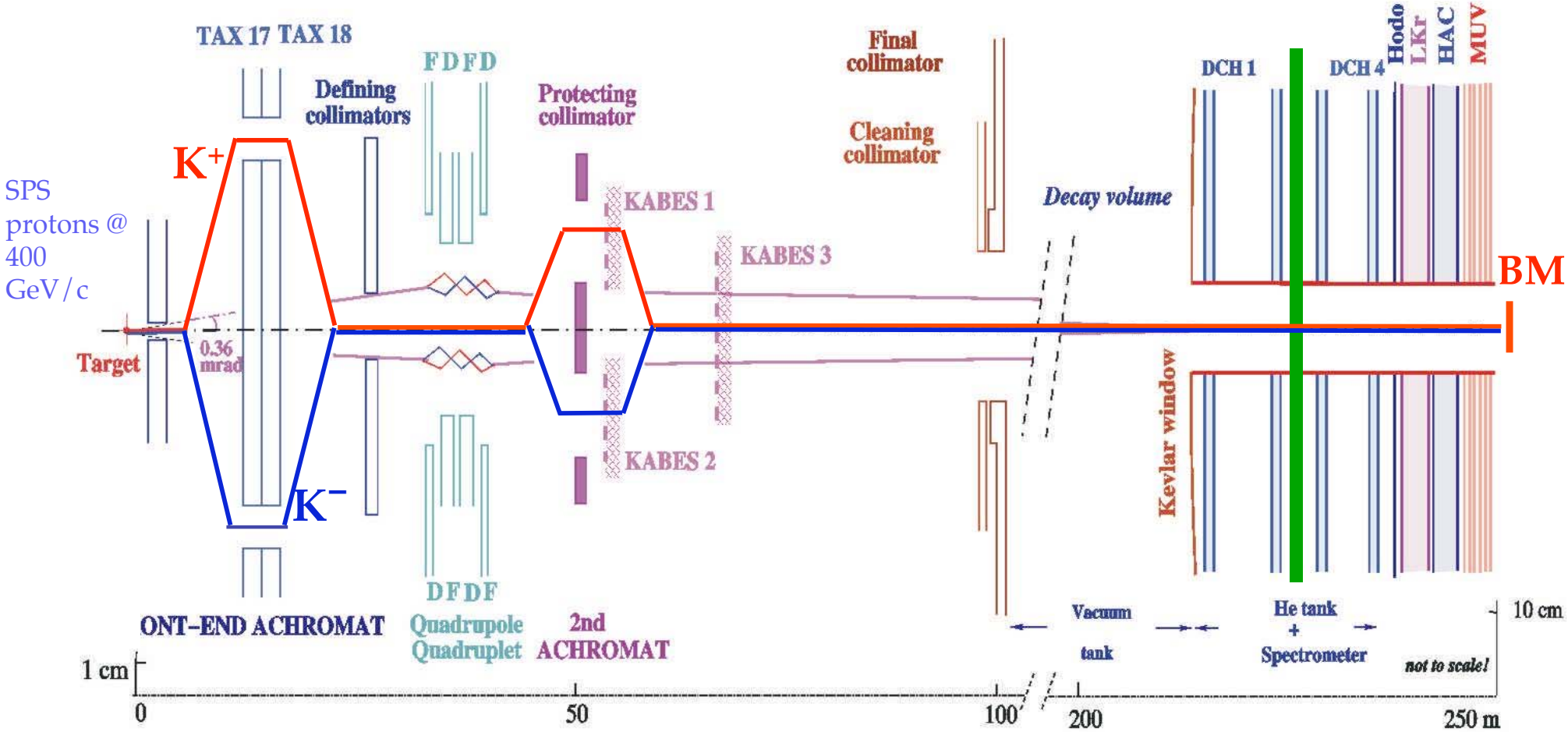
$$R_K^{PDG} = (2.45 \pm 0.11) \cdot 10^{-5} \qquad \delta R_K / R_K = 4.5\%$$

  - Experimental error ~10^2 larger than theoretical one

- Preliminary result on R_K from NA48/2 Collaboration
  - 2003 data taking
  - 2004 data taking (56 hours "minimum bias" run)
- KLOE also presented a preliminary result
- Description of 2007 run dedicated to a sub-percent precision measurement of R_K (NA62 Collaboration)

The NA48/2 simultaneous beams

- NA48/2 primarily designed for the search of direct CPV in $K^{\pm} \rightarrow 3\pi$
- Simultaneous, almost collinear K^+/K^- beams ($K^+/K^- \approx 1.8$)
  - 60±3 GeV/c momentum
  - beams coincide within 1 mm along the 114 m decay region



NA48/2 detector

- **Spectrometer:**

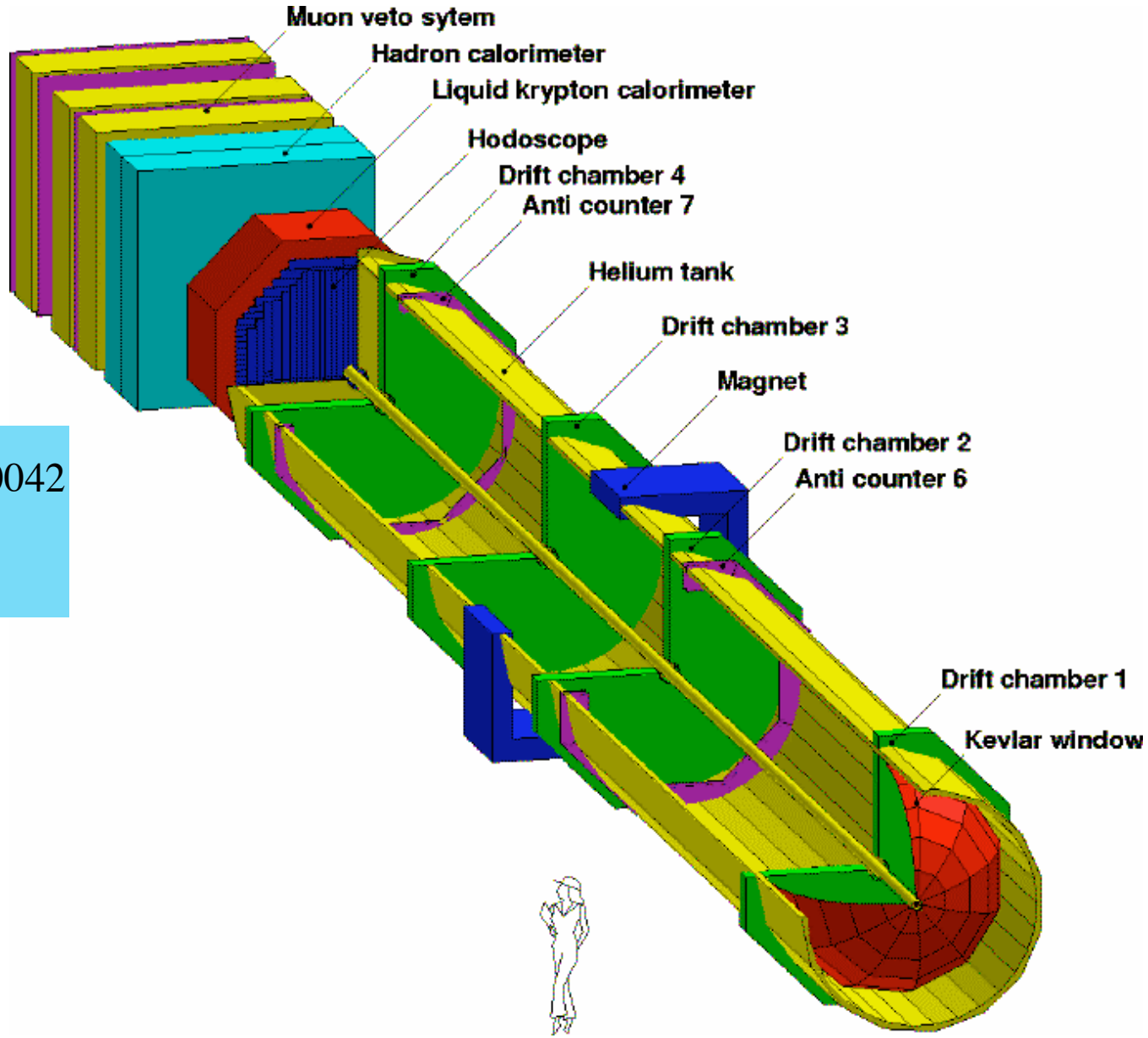
$$\frac{\sigma(p)}{p} = 1.02\% \oplus \left(0.044 \cdot p[GeV/c]\right)\%$$

- **LKR calorimeter**

$$\frac{\sigma(E)}{E} = \frac{0.09}{E[GeV]} \oplus \frac{0.032}{\sqrt{E[GeV]}} \oplus 0.0042$$

$$\sigma(t) < 300\,ps$$

- **Hodo**, AKL
- **MUV**, **HAC**
- **Kabes**



2003 and 2004 runs

- 2003 sample (1 month during the asymmetry run)
  - Trigger:
    - Kμ2: downscaled 1 track hodoscope trigger (downscaling D)
    - Ke2: 1 track hodoscope trigger + E_{LKR} + Level 2 trigger mass cut
- 2004 sample (56 hours with minimum bias trigger)
  - reduced beam intensity
  - no Level 2 trigger mass cut

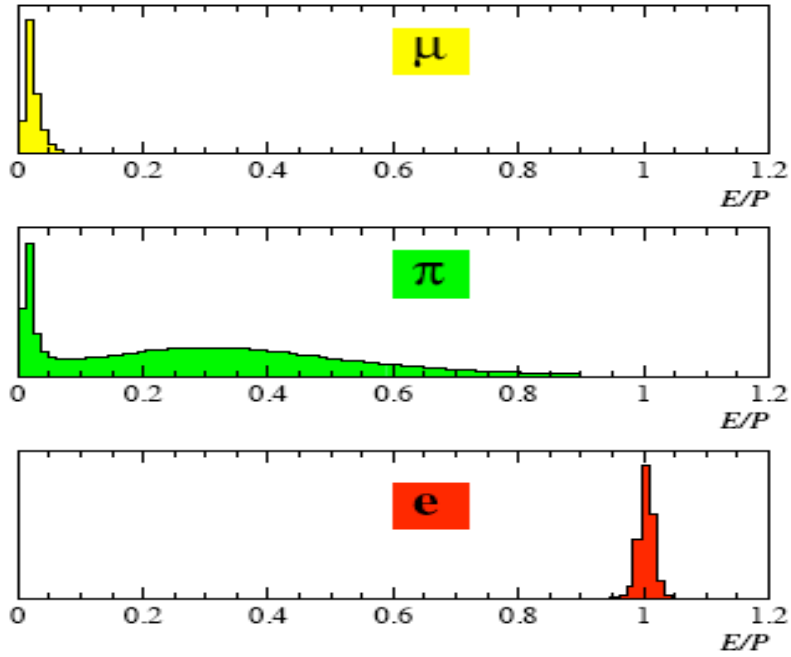
Similar statistics

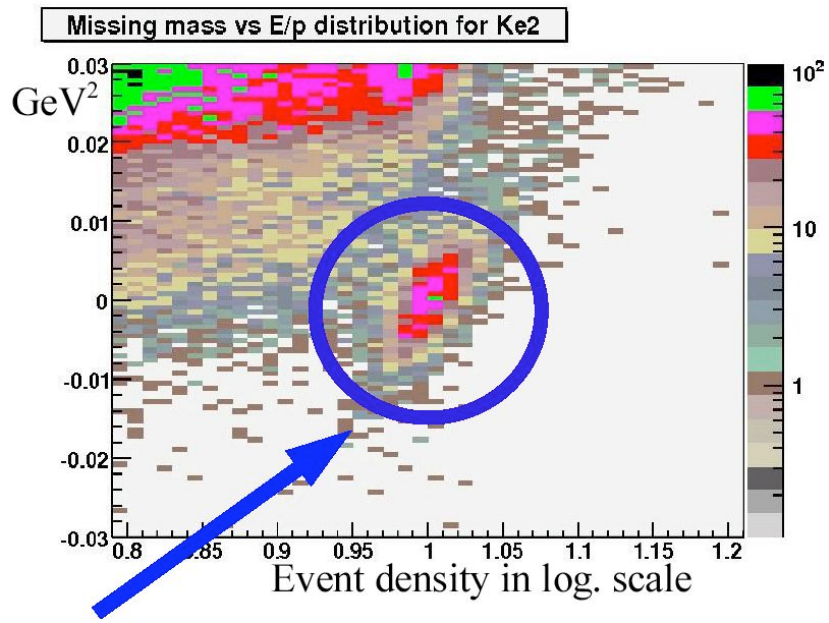
- Analysis strategy: counting number of K_{e2} / $K_{\mu 2}$ candidates collected simultaneously
  - Result is independent of the knowledge of kaon flux
  - Several systematic effects cancel in the ratio

$$R_K = \frac{N(K_{e2}) - N_{BACK}(K_{e2})}{N(K_{\mu 2}) - N_{BACK}(K_{\mu 2})} \cdot \frac{1}{D} \cdot \frac{Acc(K_{\mu 2}) Eff_{TR}(K_{\mu 2}) Eff_{PID}(K_{\mu 2})}{Acc(K_{e2}) Eff_{TR}(K_{e2}) Eff_{PID}(K_{e2})}$$

Event selection

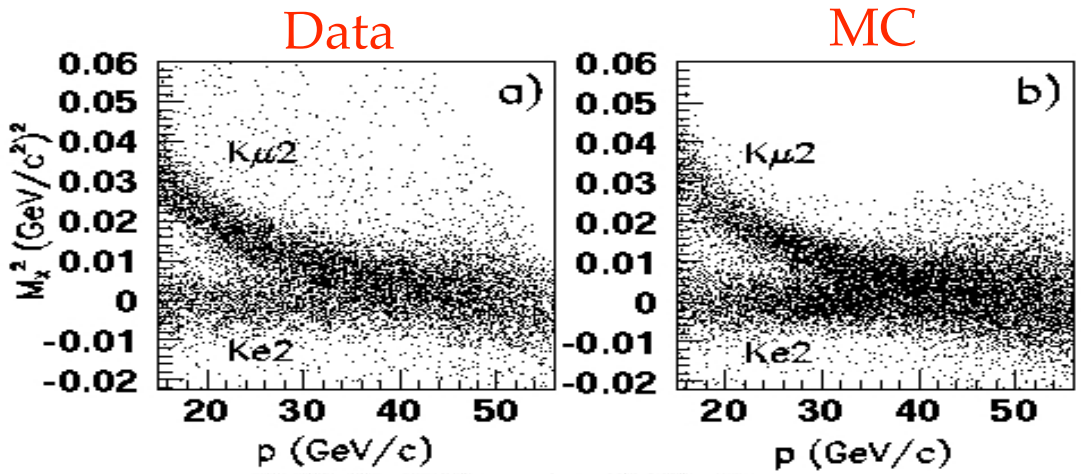
- Geometry
  - 1 track topology
  - $15 < p < 50$ [GeV/c]
  - Good reconstructed vertex
  - Geometrical acceptance cut
- Particle ID (E_{LKR}/p_{spectr})
  - e ($E/p > 0.95$)
  - μ ($E/p < 0.2$)
- Kinematics
  - Missing mass: $M_{miss}^2 = (P_K - P_l)^2$ (kaon momentum := 60 GeV/c)
  - $-0.015 < M_{miss}^2 < 0.015$ [GeV²/c⁴]

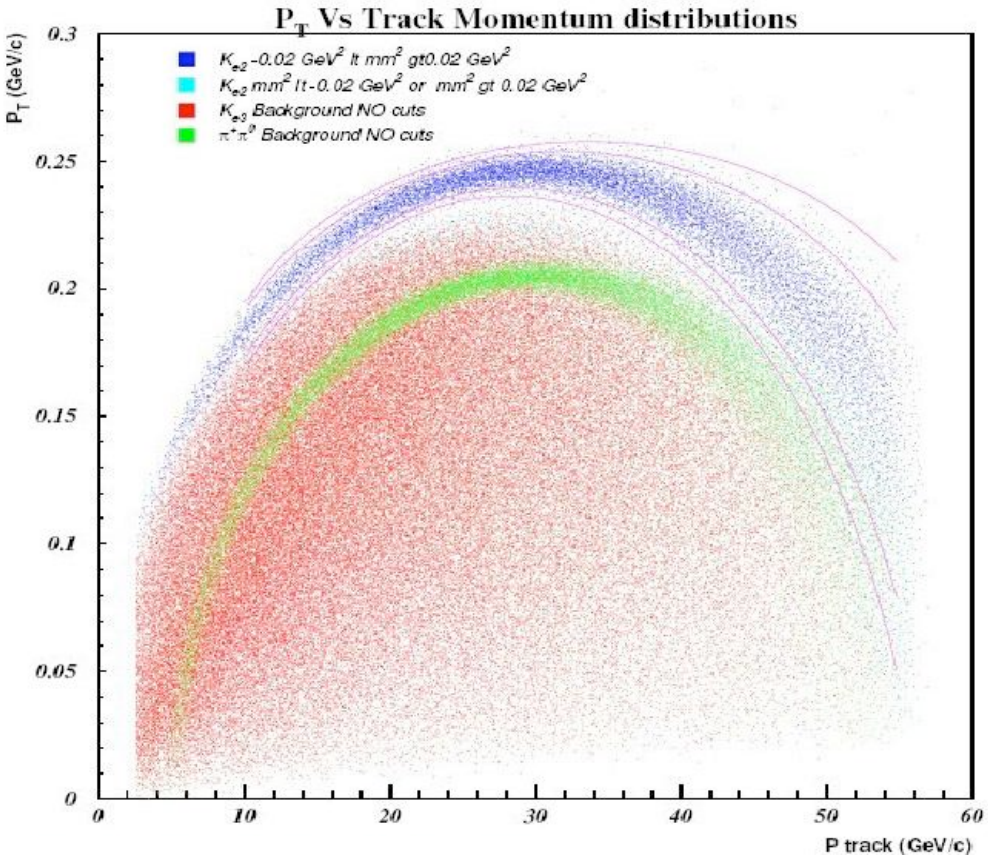




Background

- Dominant background source in the K_{e2} sample is due to $K_{\mu 2}$
  - Kinematically undistinguishable at high momenta
  - The μ (with a probability of ~few×10^{-6}) can undergo a catastrophic energy loss in LKR → (E/p ~ 1) thus faking an electron
  - This background is measured from data in momentum bins
- Contribution from K_{e3} obtained by Monte Carlo
- $\pi^{\pm}\pi^{0}$ background in $K_{\mu 2}$ sample is negligible





Preliminary results

- 2003 data
  - $(4670 \pm 77_{stat}\ ^{+29}_{-8\ syst})$ events
  - trigger efficiency is the biggest systematic effect

$$R_K = (2.416 \pm 0.043 \pm 0.024) \cdot 10^{-5}$$

- 2004 data
  - $(3407 \pm 63_{stat} \pm 54_{syst})$ events
  - the biggest systematic is the $K_{\mu 2}$ background subtraction

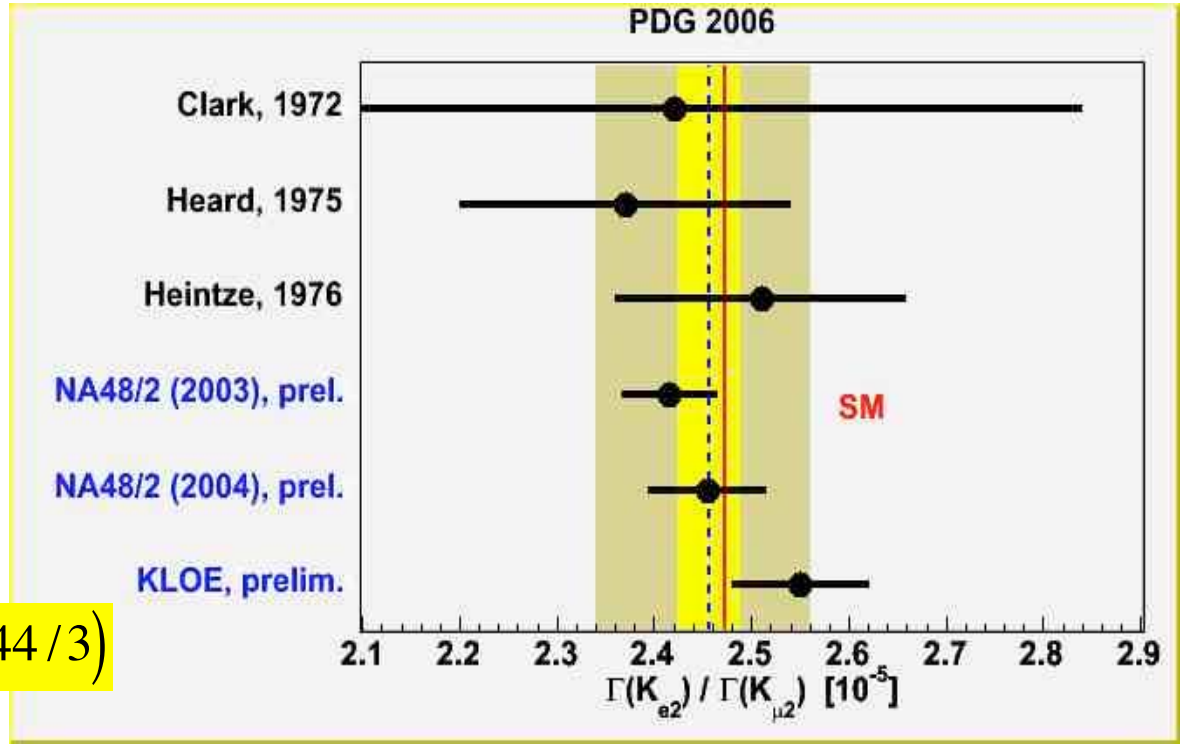
$$R_K = (2.455 \pm 0.045 \pm 0.041) \cdot 10^{-5}$$

- KLOE
  - ~ 8000 events [arXiv:0707.4623]
  - based on 1.7 fb^{-1}

$$R_K = (2.55 \pm 0.05 \pm 0.05) \cdot 10^{-5}$$

- Combining results
  - great improvement w.r.t PDG (now $\delta R_K / R_K \sim 1.3\%$)

$$R_K = (2.457 \pm 0.032) \cdot 10^{-5} \qquad (\chi^2 / ndf = 2.44/3)$$



NA62 (P326) 2007 Run

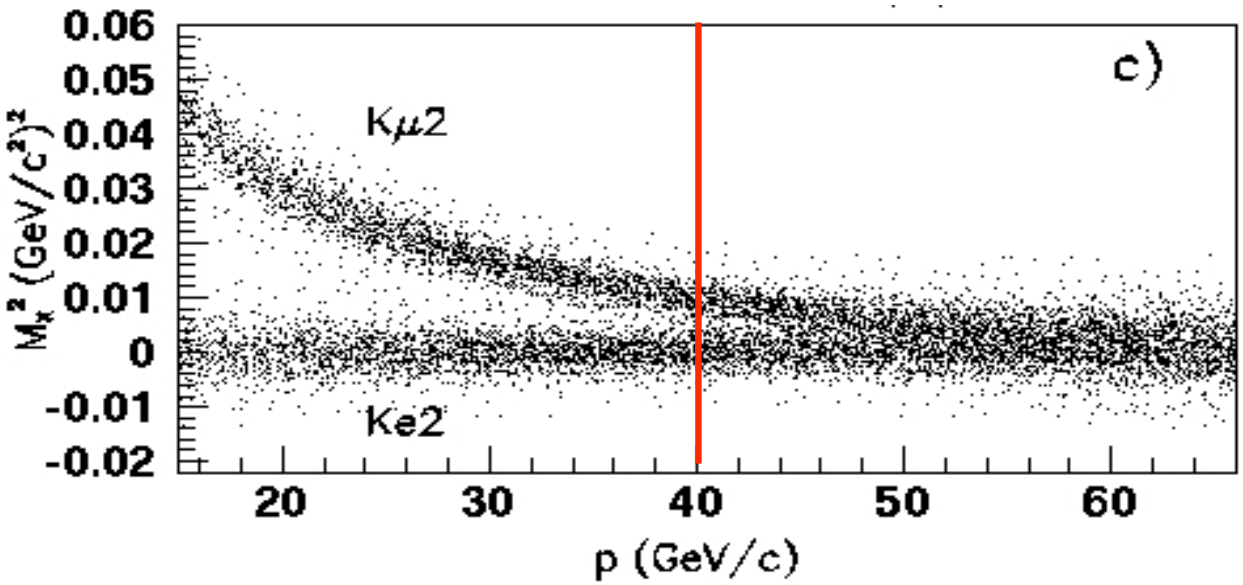
- The NA62 Experiment (former NA48) was approved for a dedicated measurement of R_K in 2007 (in addition to tests for the future $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ experiment)
  - 4 months of data taking (excluding detectors prototype tests)
  - Collected ~1×10^5 Ke2 events
  - Aims to a precision better than 0.5 % on $\delta R_K / R_K$
- Big reduction of systematics
  - New beam and spectrometer configuration
    - Kaon momentum: (60 ± 3) GeV/c → (75.0 ± 2.5) GeV/c
    - p_T kick from spectrometer magnet: 120 MeV/c → 263 MeV/c

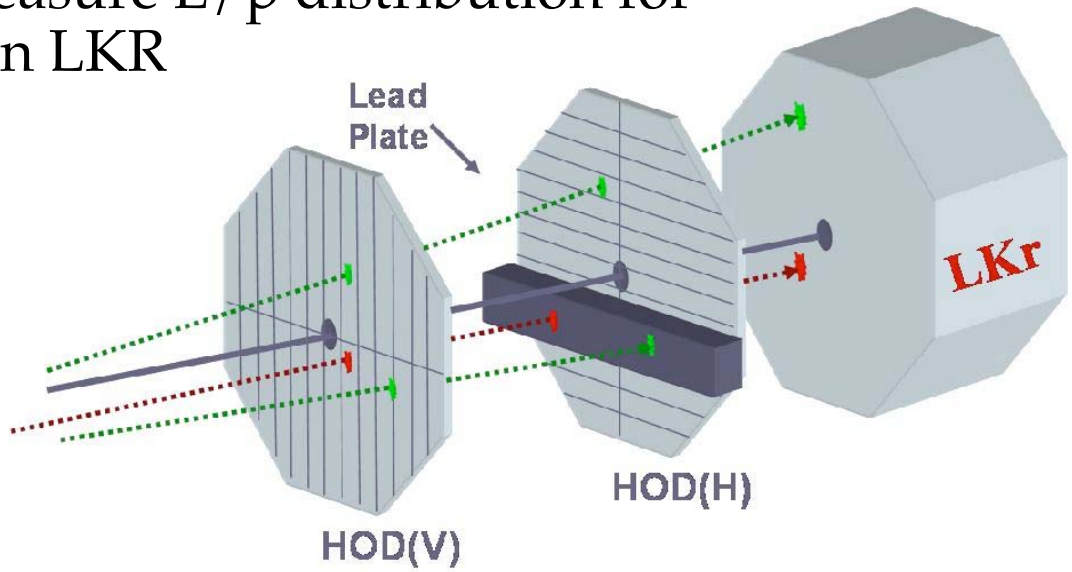
      → improved missing mass resolution

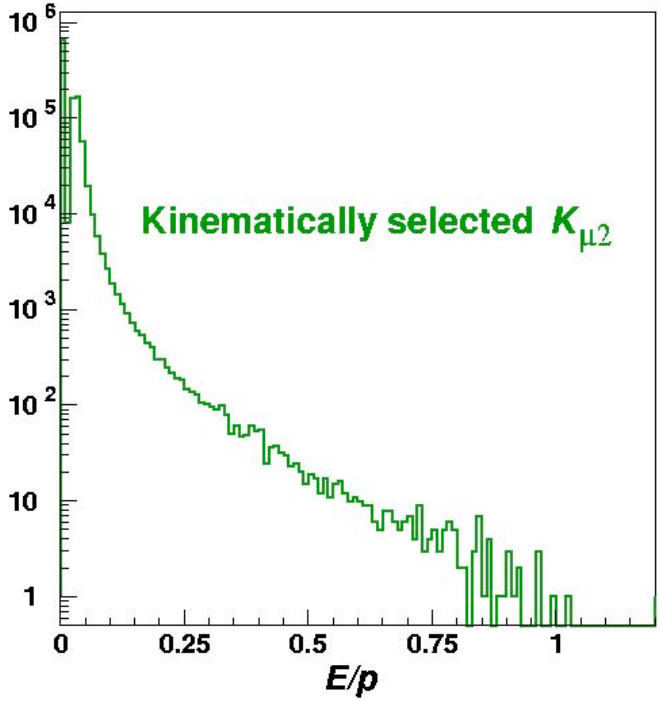
      → improved K_{e2} / $K_{\mu 2}$ kinematic separation
  - Precise measurement of $K_{\mu 2}$ background and electron mis-identification probability
  - Minimum bias trigger (as for 2004 run)

$K_{\mu 2}$ background

- for p > 40 GeV/c use E/p
- Measurement of $K_{\mu 2}$ during the run
- Put a 9 X_0 lead bar between the HODO planes, in front of the LKR
- Lose 18% acceptance
- e are stopped (only μ pass)
- Measure E/p distribution for μ in LKR

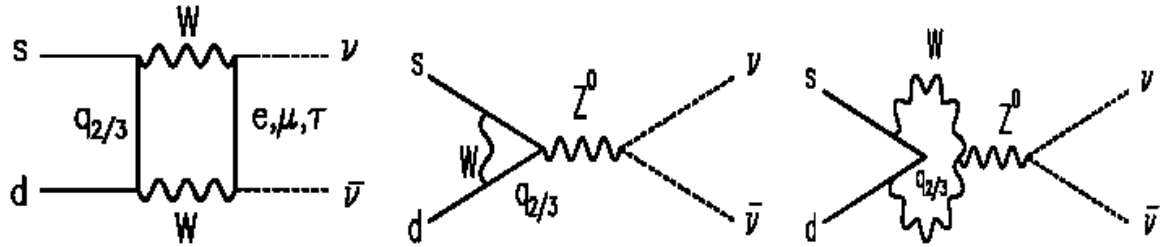






The $K^+ \to \pi^+ \nu\bar{\nu}$ decay: introduction

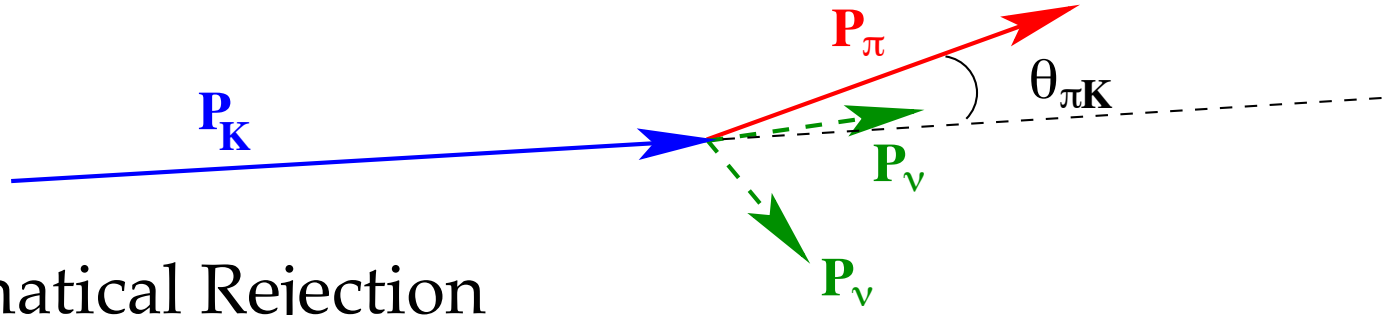
- FCNC loop processes



- Theoretically very clean: hadronic matrix element can be related to measured quantites
- SM predictions (uncertainties from CKM elements):
  - $BR(K^+ \to \pi^+ \nu\nu) \approx (1.6\times10^{-5})\,|V_{cb}|^4[\sigma\eta^2+(\rho_c-\rho)^2] \rightarrow (8.0 \pm 1.1)\times10^{-11}$
  - $BR(K_L \to \pi^0 \nu\nu) \approx (7.6\times10^{-5})\,|V_{cb}|^4\eta^2 \rightarrow (3.0 \pm 0.6)\times10^{-11}$
- The $K\to\pi\nu\nu$ decays represent a theoretically clean environment sensitive to new physics

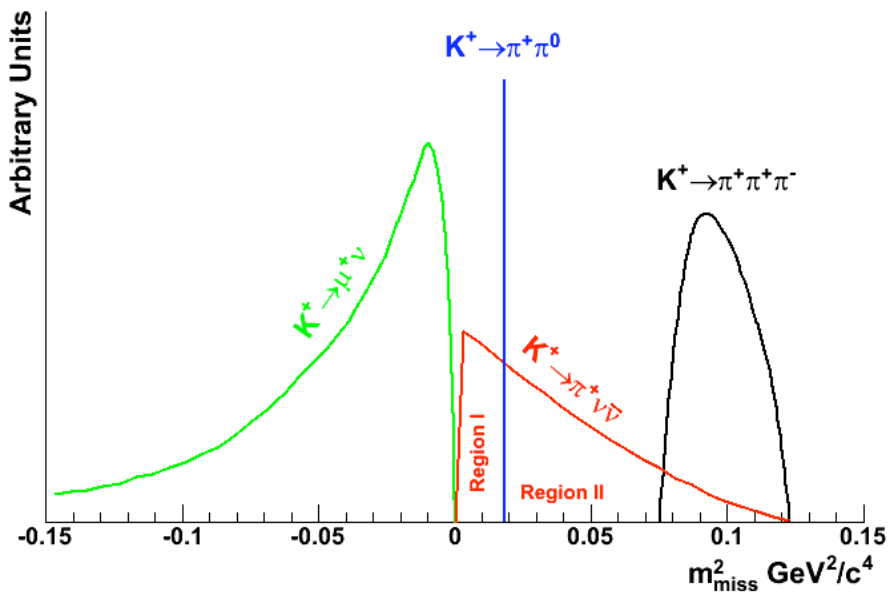
- The NA62 Collaboration (former NA48) aims to measure $\mathcal{O}(100)$ $K^+\to\pi^+\nu\nu$ events with ~10% background at the CERN SPS

Principle of the experiment



- Kinematical Rejection

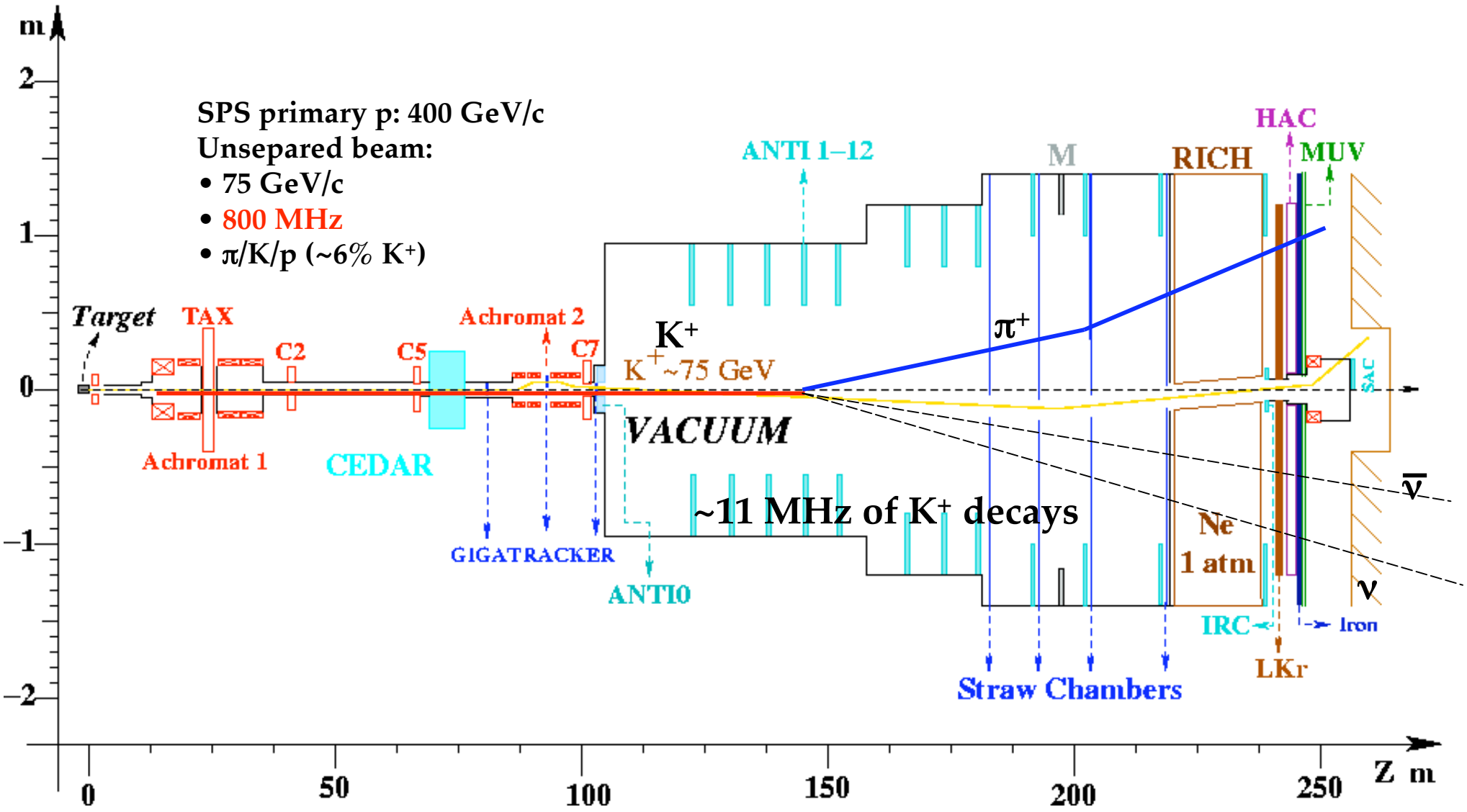
$$m_{miss}^2 \approx m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta_{\pi K}^2$$



- Photon vetoes to reject $K^+ \to \pi^+\pi^0$
  - $p(K^+) = 75$ GeV/c
  - Requiring $p(\pi^+) < 35$ GeV/c
  - $p(\pi^0) > 40$ GeV/c

    It can hardly be missed in the calorimeters
- PID for $K^+ \to \mu^+\nu$ rejection

Detector Layout



Proposal to Measure the Rare Decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at the CERN SPS (P326)

CERN-SPSC-2005-013
SPSC-P-326

CERN, Dubna, Ferrara, Florence, Frascati, Mainz, Merced, Moscow, Naples, Perugia, Protvino, Pisa, Rome, Saclay, San Luis Potosi, Sofia, Triumf, Turin

NA62 Collaboration

Located in the same hall of NA48

Schedule

- September 2005: presented at CERN SPSC
- December 2005: R&D endorsed by CERN Research Board
- Start of the Gigatracker project
- Start of test beams at CERN in 2006
- 2007: prototypes construction and test beams at CERN and Frascati
- 2008 – 2010: Technical design and construction
- Start of data taking 2011

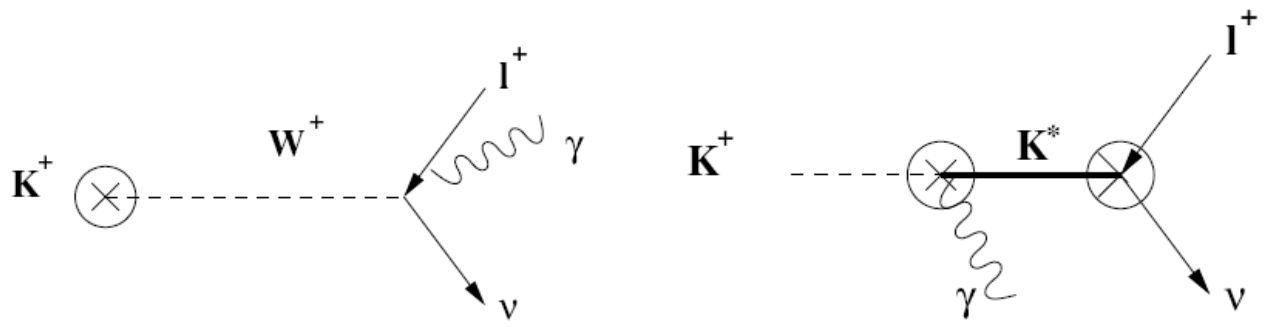
Conclusions

- K_{l2} decays provide a very challenging opportunity to test physics beyond the Standard Model
- NA48/2 has presented two preliminary measurements of R_K, with data collected in 2003 and 2004, both compatible with SM predictions
- The NA62 experiment took data in 2007 with the aim of measuring R_K with an accuracy better than 0.5%, in order to provide a stringent SM test
- The NA62 Collaboration proposed a new experiment for the measurement of $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with a ~10% accuracy
  - The R&D program is well advanced: during the 2007 run the Collaboration tested successfully a full length (18 m) RICH counter prototype and a full-length straw prototype in the actual vacuum tube

SPARE SLIDES

Radiative corrections

- Radiative decays receive 2 types of contribution: inner bremsstrahlung (IB) and structure-dependent (SD)



- SD gives the dominant contribution to K_{e2} decay rate
- All experiments measure inclusive $\Gamma(K_{e2(\gamma)})/\Gamma(K_{\mu 2\,(\gamma)})$ and subtract SD contribution
- There are more than one model for SD process, which lead to quite different E_γ spectra
- Effects on acceptance

Other NA48/2 results (1)

- Measurement of direct CP violating charge asymmetries of the Dalitz plot linear slopes $A_g = (g^+ - g^-)/(g^+ + g^-)$ in the decay $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ and $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$
  - $A_g^c = (-1.5 \pm 2.2) \times 10^{-4}$ from 3.11×10^9 $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ decays
  - $A_g^n = (1.8 \pm 1.8) \times 10^{-4}$ from 9.13×10^7 $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ decays
  - limited by statistics (not by systematics)

- "Cusp" effect observed in $\pi^0\pi^0$ invariant mass for $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$, due to final state charge exchange scattering process $\pi^+\pi^- \rightarrow \pi^0\pi^0$ in $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$
  - provides very precise determination of (a_0-a_2)
  - $(a_0-a_2)m_+ = (0.264 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.013_{ext})$

Other NA48/2 results (2)

- First measurement of Direct Emission and Interference terms in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ has been performed in the region $0\ \text{MeV} < T_{\pi}^{*} < 80\ \text{MeV}$
  - Frac(DE) = $(3.35 \pm 0.35_{stat} \pm 0.25_{syst})$ %
  - Frac(INT) = $(-2.67 \pm 0.81_{stat} \pm 0.73_{syst})$ %
  - First evidence of a non vanishing interference term

- New measurement of $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ (K_{e4})
  - Analyzed a partial sample of more than 6.7×10^{5} events (2003 run)
  - Form factors of the hadronic currents (F,G,H) and $\pi\pi$ scattering phase shift (δ_0^0-δ_1^1) have been measured in a model-independent way
  - An improved accuracy of a factor of 2 is reached when extracting the $\pi\pi$ scattering length a_0^0

Other NA48/2 results (3)

- Measured ratios of decay rates:
  - $R_{Ke3/K2\pi} = (0.2496 \pm 0.0009_{stat} \pm 0.0004_{syst})$
  - $R_{K\mu3/K2\pi} = (0.1637 \pm 0.0006_{stat} \pm 0.0003_{syst})$
  - Using PDG average for $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ normalisation, both values are larger than the current PDG values and lead to a larger value of $|V_{us}|$ than previously accepted
  - When combined with the PDG value of $|V_{ud}|$, the result is in agreement with unitarity of the CKM matrix
  - $R_{K\mu3/Ke3} = (0.656 \pm 0.003_{stat} \pm 0.001_{syst})$

- The decay $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$ has been observed for the first time
  - 120 candidates with (7.3 ± 1.7) estimated background events
  - $BR(K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma;\ m_{ee\gamma}>260\,MeV/c^{2}) = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \times 10^{-8}$