# The NA62 experiment at CERN

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# Rare Kaon Decays program at CERN

## Phase I (2007-2008) : Lepton Universality

Measurement of $R_K$ at 0.4% level

$$R_K = \frac{\Gamma(K^{\pm} \to e^{\pm}\nu)}{\Gamma(K^{\pm} \to \mu^{\pm}\nu)}$$

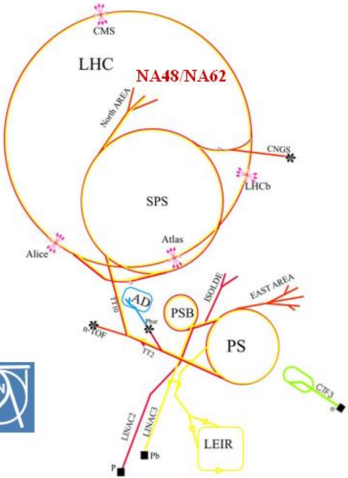
## Phase II (2012-2015) :

Detection of $\mathcal{O}(100)$ $K^+ \to \pi^+\nu\bar{\nu}$ with a $\sim$10% background

$$\mathrm{BR}_{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$

- In common : Decay in Flight Technique
- Different : Beam line and experimental setup

# NA62 : Rare Kaon Decays at SPS

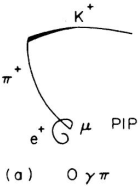



- NA62 is a fixed target experiment at SPS
  - High intensity proton beam
  - 400 GeV/c on a Be target
- Well known beam line
  - Instrumentation
  - Simulation tools
- Consolidated collaboration
  - NA48, NA31
- Inherited equipment from NA48
  - Decay channel
  - Calorimeters at the end of the decay channel

# $K^{\pm}$ experiments : Decay in flight vs. Decay at rest

## $K^{\pm}$ decay at rest

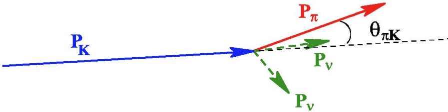
- Low energy photons
- Hermeticity
- Compact experiments
- ANL and BNL
- protons ∼25 GeV




Ljung, Cline, Phys. Rev. (1973)

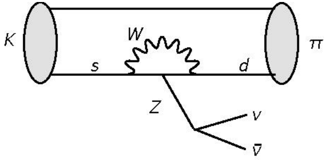
## $K^{\pm}$ decay in flight

- Energetic photons
- Boosted events
- Long baseline experiments
- CERN
- protons ∼400 GeV
- $K^{\pm}$ ∼75 GeV



# Rare Kaon Decays

- Rare decays provide an unique tool to test NP
- Golden modes : FCNC and helicity suppressed decays
  - Short distance dynamics constitutes the dominant contribution of the decay amplitude. New Physics may appear in loops.
  - Long distance contributions (low energy QCD) can obscure New Physics effects
- If long distance contributions under control $\rightarrow$ Excellent SM predictions $\mathcal{O}$(few%)
- NP contributions accessible experimentally due to the suppression of the SM value

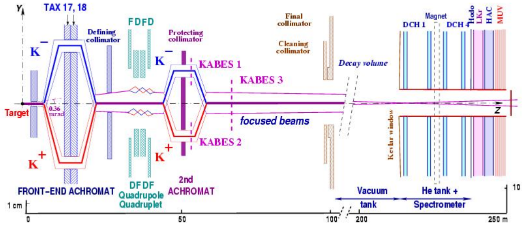


## NA62 Phase I (2007-2008) : Lepton Universality

Measurement of $R_K$ at 0.4% level

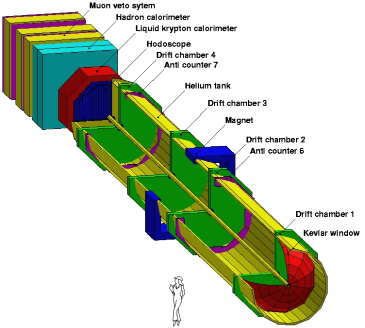
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)}$$

# NA62 Phase-I : Beam line and detector




- Narrow momentum $K^{\pm}$ beams :

  $P_K = 74$ GeV/c, $\delta P_K/P_K \sim 1\%$
- 90% $K^+$, 10% $K^-$




- Magnetic Spectrometer
  - 4 view Drift chambers

    $\Delta P/P = 0.47\% + 0.020\% P[\text{GeV/c}]$
- Hodoscope
  - Fast trigger, $\sigma_t = 150$ ps
- Electromagnetic calorimeter (LKr)
  - High granularity and homogeneity

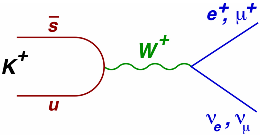
    $\sigma_X = \sigma_Y = 4.2\text{mm}/E^{1/2} + 0.6\text{mm (GeV)}$

    $\sigma_E/E = 3.2\% E^{1/2} + 9\%/E + 0.42\%$ (GeV)

# $R_K = K_{e2}/K_{\mu 2}$ in the SM

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)\left(1 + \delta R_k^{rad}\right)$$

- $K_{e2}$ is helicity suppressed
- Individual decays note usable because of hadronic incertitudes
- Cancellation in the ratio
- Excellent sub-permille accuracy in the SM




$$\boxed{R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}}$$

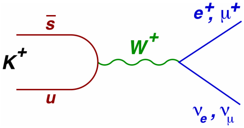
Cirigliano, Rosell, PRL 99 (2007) 231801

$$\frac{\delta R_K}{R_K} \sim 0.04\%$$

# ... and Beyond

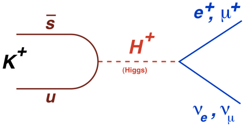
- 2HDM : presence of extra charged Higgs introduces LFV at one-loop level

$$R_K^{LFV} = R_K^{SM}\left[1 + \left(\frac{m_K^4}{m_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$




Masiero, Paradisi, Petronzio, PRD 74 (2006) 011701 ; JHEP 0811 (2008) 042

$$\left.\begin{aligned} \Delta_{13} &= 5\times10^{-4} \\ \tan\beta &= 40 \\ m_H &= 500\mathrm{GeV/c^2} \end{aligned}\right\} \rightarrow \quad R_K^{LFV} = R_K^{SM}(1+0.013)$$




- $\sim$1% effect in MSSM

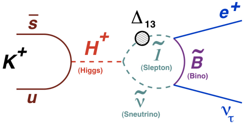
  (Girrbach,Nierste, arXiv :1202.4906)

- Limited by recent $B_s \rightarrow \mu^+\mu^-$ measurements

  (Fonseca, Romao, Teixeira, arXiv :1205.1411)

- Sensitive to SM extensions with $4^{th}$ generation

  (Lacker, Menzel, JHEP 1007 (2010) 006)



# NA62-I : $R_K$ measurement

- $K_{e2}$ and $K_{\mu 2}$ measured simultaneously
  - Independent of kaon flux
  - Cancellation of many systematic effects

- Counting experiment in 10 momentum bins

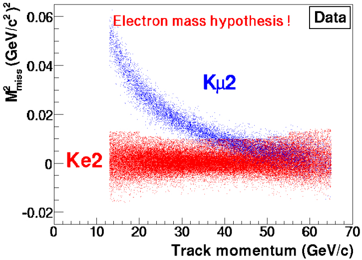
$$R_K = \frac{1}{D} \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_\mu \times \varepsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \frac{1}{f_{LKR}}$$

| | |
|---|---|
| $N(K_{e2}), N(K_{\mu 2})$ | number of selected $K_{\ell 2}$ candidates |
| $N(K_{e2}), N(K_{\mu 2})$ | number of background events |
| $A(K_{e2}, A(K_{\mu 2}$ | geometric acceptance (MC) |
| $f_e, f_\mu$ | particle ID efficiencies (data) |
| $\varepsilon(K_{e2}), \varepsilon(K_{\mu 2})$ | trigger efficiency |
| $f_{LKR} = 0.9980(3)$ | global LKR readout efficiency |
| $D = 150$ | downscaling of the $K_{\mu 2}$ trigger |

# $K_{e2}$ and $K_{\mu2}$ selection

## Kinematic separation

- Missing mass $\boxed{M^2_{miss} = (P_K - P_\ell)^2}$
  $P_K$ : average measured with $K_{3\pi}$ decays
- Sufficient $K_{e2}/K_{\mu2}$ separation at $P_{track} < 30$ GeV/c

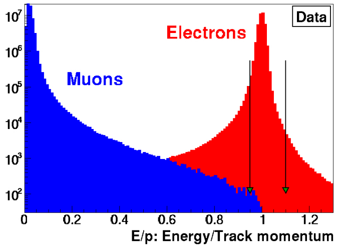



## Lepton identification

- E/P = LKR energy deposition/track momentum

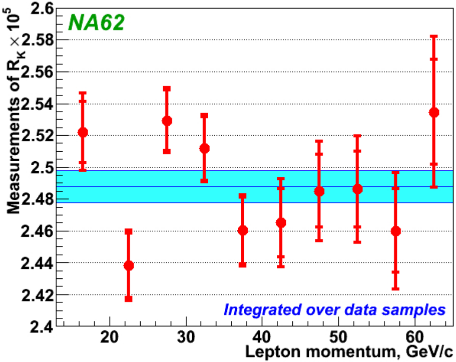
  0.95<E/P<1.1 for electrons

  E/P<0.85 for muons
- $\mu^{\pm}$ suppression in the $e^{\pm}$ sample $\sim 10^6$



# $R_K$ result : Full data sample

$$R_K = (2.488 \pm 0.07_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5}$$

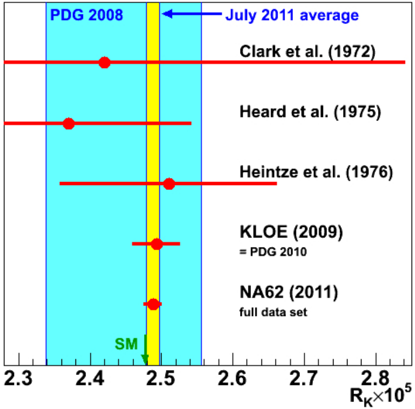


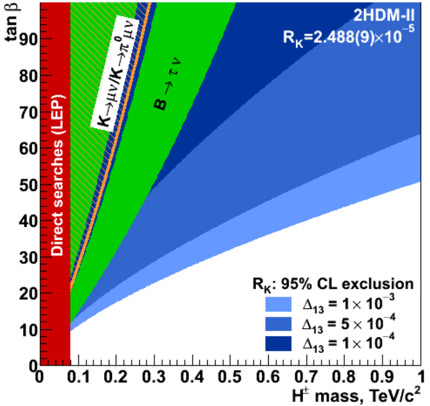

| Source | $\delta R_K \times 10^5$ |
|---|---|
| Statistical | 0.007 |
| $K_{\mu 2}$ background | 0.004 |
| $K^\pm \to e^\pm \nu\gamma(SD^+)$ | 0.002 |
| $K_{e3}, K_{2\pi}$ | 0.003 |
| Beam halo background | 0.002 |
| Matter composition | 0.003 |
| Acceptance correction | 0.002 |
| DCH alignment | 0.001 |
| Electron identification | 0.001 |
| 1TRK trigger efficiency | 0.001 |
| LKR readout efficiency | 0.001 |
| Total uncertainity | 0.010 |

Partial (40% data set : PLB 698 (2011) 105

Full data set : paper to be submitted in summer 2012

# $R_K$ world average




| World Average | $R_K \times 10^5$ | Precision |
|---|---|---|
| PDG 2008 | $2.447 \pm 0.109$ | 4.5% |
| PDG 2010 | $2.493 \pm 0.031$ | 1.3% |
| July 2011 | $2.488 \pm 0.009$ | 0.4% |
| SM | $2.477 \pm 0.001$ | 0.04% |

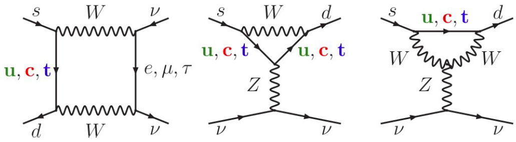
### NA62 Phase II (2012-2015) :

Detection of $\mathcal{O}(100)$ $K^+ \to \pi^+ \nu \bar{\nu}$ with a ~10% background

$$\mathrm{BR}_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$

# $K \to \pi\nu\bar{\nu}$

- FCNC processes described with penguin and box diagrams




- With the highest CKM suppression

$$\begin{array}{ccc} b \to s & b \to d & s \to d \\ |V_{tb}^* V_{ts}| \sim \lambda^2 & |V_{tb}^* V_{td}| \sim \lambda^3 & |V_{ts}^* V_{td}| \sim \lambda^5 \end{array}$$

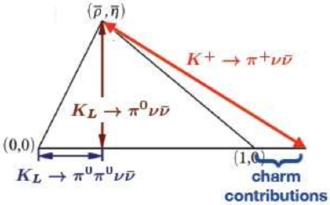
- $K_{\ell 3}$ can be used to compute the hadronic matrix element
- SM predictions with a ∼10% precision. Error dominated by CKM parametrization

$$\boxed{\begin{array}{lcl} BR(K^+ \to \pi^+\nu\bar{\nu}) & = & (7.81 \pm 0.75 \pm 0.29)\times 10^{-11} \\ BR(K^0 \to \pi^0\nu\bar{\nu}) & = & (2.43 \pm 0.39 \pm 0.06)\times 10^{-11} \end{array}}$$

Brod et al., PRD83 (2011) 034030

# $K \to \pi\nu\bar{\nu}$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto \sigma\bar{\eta}^2 + (\bar{\rho}_c - \bar{\rho})^2$$
$$BR(K^0 \to \pi^0\nu\bar{\nu}) \propto \bar{\eta}^2$$



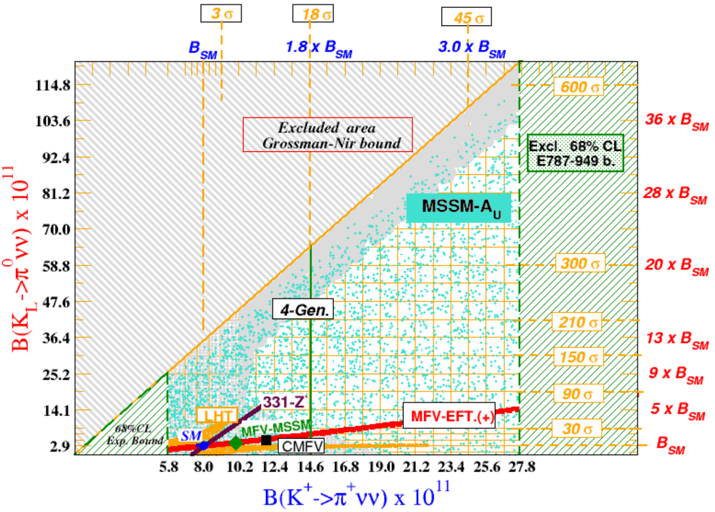

- $K^+ \to \pi^+\nu\bar{\nu}$ allows the measurement of $|V_{td}|$ independently form $B - \bar{B}$
  $\delta BR/BR = 10\% \to \delta|V_{td}|/|V_{td}| = 7\%$
- Measurement of both branching rations will allow an independent measurement of $\sin 2\beta$

Experimental situation : far from theory precision

| | | |
|---|---|---|
| $BR(K^+ \to \pi^+\nu\bar{\nu})$ | $=$ | $(17.3\ ^{+11.5}_{-10.5})\times10^{-11}$ |
| $BR(K^0 \to \pi^0\nu\bar{\nu})$ | $<$ | $2.6\ \times10^{-8}$ |

E787/E949 (BNL) PRL 101 (2008) 191802
E391a (KEK) PRD 81 (2010) 072004

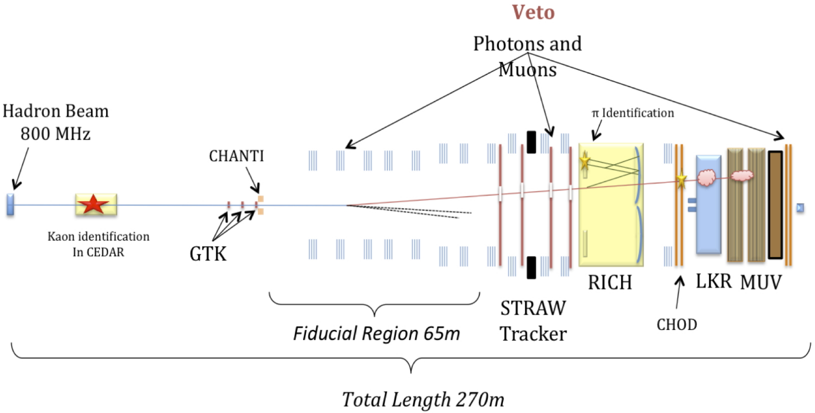
# $K \to \pi\nu\bar{\nu}$ and New Physics




Mescia, Smith (Flavianet)

# NA62 Phase II : beam and detector

- SPS primary protons @ 400 GeV/c
- 75 GeV/c hadron bean (p/$\pi$/K), $\Delta P/P \sim 1\%$
- 750 MHz $\rightarrow$ 50 MHz Kaons (6%) $\rightarrow$ 6 MHz decays
- $4.8 \times 10^{12}$ kaon decays per year

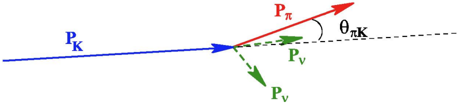


# NA62 : Decay signature and requirements

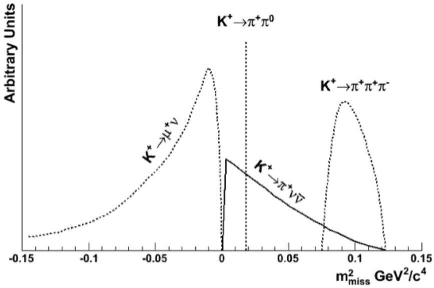
- High momentum $K^+$ to improve rejection
  - Pion id in (15-35 GeV) $\rightarrow$ >40 GeV missing energy.
  - Particles with E>40 GeV cannot be missed

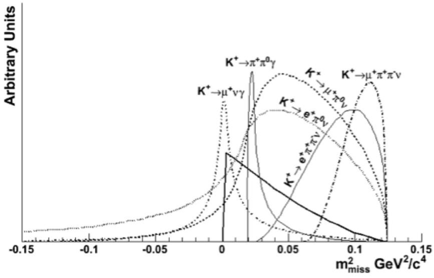
1. Precise timing $\mathcal{O}(100\text{ ps})$
   - Associate decayed and incoming K
2. Kinematical rejection : $\mathcal{O}(10^{-5})$
   - Two spectrometers : GTK for kaons and Straw for pions

$$m^2_{miss} \simeq m^2_K \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$



# Kinematical rejection




- 92% of background kinematically constrained
- $K^+ \to \pi^+\pi^0$ splits signal region
- Rejection power :
  $\sim 10^4$ for $K^+ \to \pi^+\pi^0$
  $\sim 10^5$ for $K^+ \to \mu^+\nu$

- 8% of Kaon decays
- Hadronic interactions in GTK
  Beam - gas in decay volume
- Needed particle id and photon and muon vetoes

# NA62 : Decay signature and requirements

3. Performant vetoes
   - Photon vetoes : LKR,LAV and SAC.
     Radiative decays and $K^+ \to \pi^+\pi^0$
     $\sim 10^8$ rejection
   - Muon vetoes :
     $K^+ \to \mu^+\nu \sim 10^{11}$ rejection. No single detector can do this

4. Particle identification
   - K/$\pi$ with CEDAR.
   - $\pi/\mu$ with RICH

# NA62 sensitivity

| Signal | 45 events/year |
|---|---|
| $K^+ \to \pi^+\pi^0$ | 4.3% |
| $K^+ \to \mu^+\nu$ | 2.2% |
| $K^+ \to$ 3 charged tracks | <4.5% |
| $K^+ \to \pi^+\pi^0\gamma$ | ∼2% |
| $K^+ \to \mu^+\nu\gamma$ | ∼0.7% |
| Total | <13.5% |

# Summary and Outlook

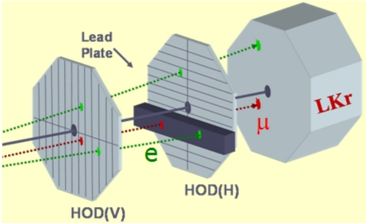
- NA62 is developing a full experimental program in rare kaon decays
- Phase I (2007-2008) :
  - Most precise measurement of $R_K$ performed
  - In agreement with SM
- Phase II (2012-) :
  - Measurement of the rare decay $K^+ \to \pi^+ \nu \bar{\nu}$
  - Detector and beam line under construction
  - Dry run in July 2012
  - First technical run in October 2012
- Experimental program is NOT reduced to one channel
  - Large number of K decays available
  - Foreseen dedicated runs to study radiative decays, semileptonic decays, forbidden decays .....
- Long term goal : $K^0 \to \pi^0 \nu \bar{\nu}$

# SPARES

# $K_{\mu 2}$ background on $K_{e2}$

- Main background source for $K_{e2}$ are muon catastrophic energy loss in LKR
  - Emission of energetic bremsstrahlung photons
  - $P_{\mu e} \sim 3 \times 10^{-6} \rightarrow P_{\mu e}/R_K \sim 10\%$

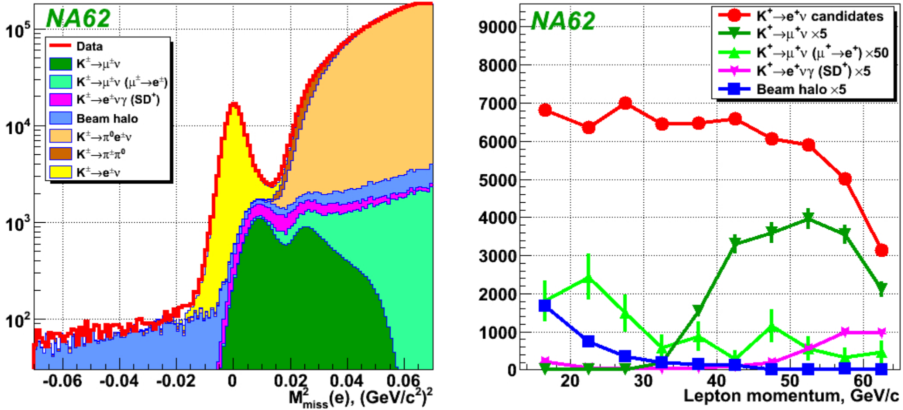
- Solution : Direct measurement of $P_{\mu e}$




| | |
|---|---|
| Thickness | $\sim 10X_0$ (Pb+Fe) |
| Width | 240 cm (=HOD size) |
| Height | 18 cm (∼3 counters) |
| Area | 20% HOD area |
| Duration | 50% of $R_K$ data taking |

- Lead wall (9.2 $X_0$) in front of LKR
- Suppression of electron cont. from $\mu \rightarrow e$
- Tracks with $p > 30 GeV/c$ + $E/P > 0.95$ traversing the wall are pure catastrophic bremsstrahlung
- $P_{\mu e}$ modified by Pb wall (ionization loss + bremsstrahlung)
  Correction evaluated with simulation

# $K_{e2}$ sample



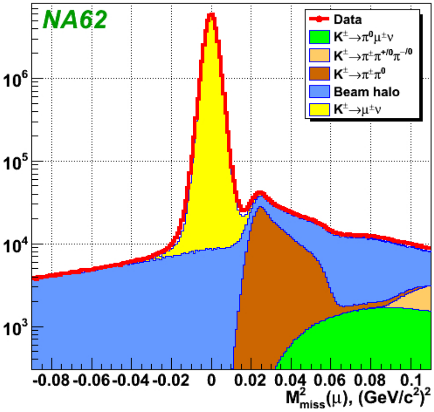

145.958 $K^{\pm} \rightarrow e^{\pm}\nu$ candidates

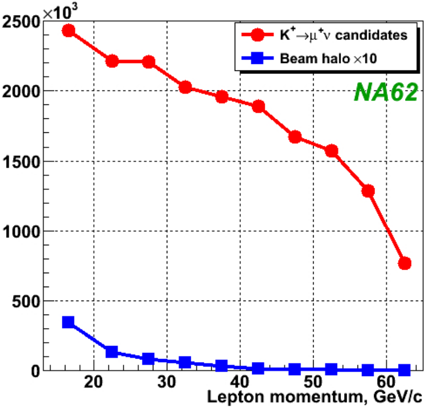
Background : B/(S+B) = (10.95± 0.27)%

Electron Id. eff : (99.28 ±0.05)%

| Main sources | B/(S+B) |
|---|---|
| $K_{\mu 2}$ | (5.64 ± 0.20)% |
| $K_{\mu 2}(\mu \rightarrow e)$ | (0.26 ± 0.03)% |
| $K_{e2\gamma}(SD^{+})$ | (2.60 ± 0.11)% |
| Beam halo | (2.11 ± 0.09)% |
| ... | ... |
| Total | (10.95 ± 0.27)% |

# $K_{\mu 2}$ sample




42.817 M (pre-scaled) $K^{\pm} \to \mu^{\pm}\nu$ candidates
Background : B/(S+B) = (0.50$\pm$ 0.01)%
background dominated by muon halo