Precise measurement of the Decay $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$

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on behalf of the NA48/2 Collaboration

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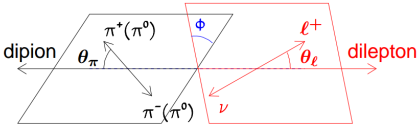
Outline

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ ($K^{00}_{\mu 4}$) state of the art

$K \to \pi\pi\mu\nu(K_{l4})$ depends on F, G, R, H form-factors.
Cabibbo-Maksymowicz variables: S_π (dipion mass squared), S_l (dilepton mass squared) and angles θ_π (in the dipion frame), θ_l (in the dilepton frame), ϕ.



- For $K^{00}_{\mu 4}$, s-wave for $\pi^0\pi^0$, there are no dependence on $\cos\theta_\pi, \phi$, and only F and R contribute.
- Unlike K^{00}_{e4} case, R plays some role due to μ mass.

K_{l4} mode	BR $[10^{-5}]$	N_{cand}	
${K_{e4}}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
${K_{e4}}^{00}$	2.55 ± 0.04	65210	NA48/2 (2014)
${K_{\mu 4}}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
${K_{\mu 4}}^{00}$	?	0	

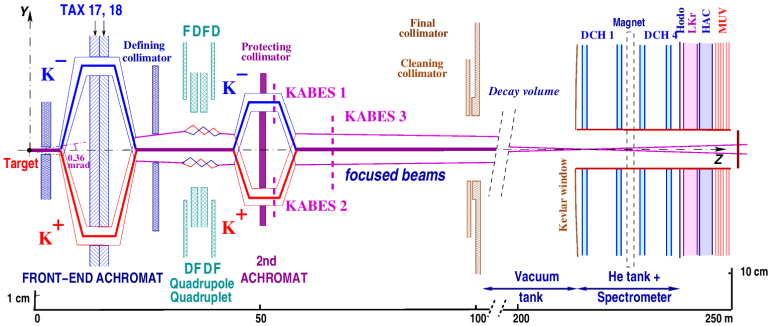
$K^{00}_{\mu 4}$: first observation, ChPT test, check of R presence, potential study of $\pi\pi$ rescattering effects in the $F(S_\pi)$.

$K_{\mu 4}$: huge bkg $K^{\pm} \to \pi\pi(\pi^{\pm} \to \mu^{\pm}\nu)$.

- According to lepton universality, experimental $F(S_\pi, S_l)$ parameterization from K^{00}_{e4} [NA48/2 JHEP 08 (2014) 159] may be used for $K^{00}_{\mu 4}$.
- The only available source of $R(S_\pi, S_l)$ is ChPT calculation [J.Bijnens, G.Colangelo, J.Gasser, Nucl.Phys.B 427 (1994) 427].

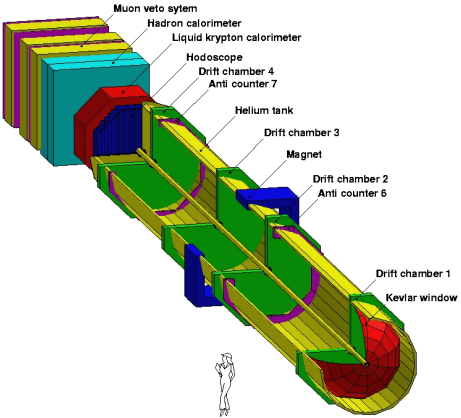
NA48/2 beamline (CERN SPS, 2003-2004)

NA48/2 main goal were $K_{3\pi}$ charge asymmetry studies; additional rare decys program.



- Two charged beams:
  - 6% of $K^{\pm}$
  - $\langle P_K \rangle \approx 60$ GeV/c
  - $\Delta P_K / \langle P_K \rangle \approx \pm 3.8\%$
- KABES (Kaon Beam Spectrometer) resolutions:
  - $\sigma(X, Y) \sim 800\ \mu$m
  - $\sigma(P_K)/P_K \sim 1\%$
  - $\sigma(T) \sim 600$ ps

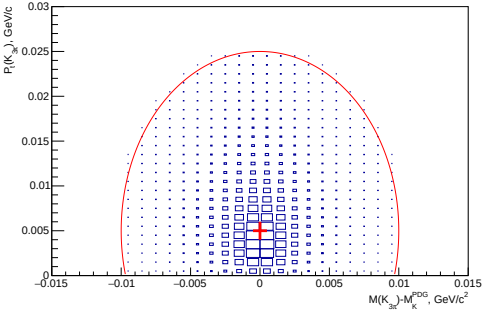
NA48/2 setup (CERN SPS, 2003-2004)



- Magnetic spectrometer (drift chambers DCH1–DCH4):
  - $\sigma(X, Y) \sim$90 μm per chamber
  - $\sigma(P_{DCH})/P_{DCH} = (1.02 \oplus 0.044 \cdot P_{DCH})\%$ (P_{DCH} in GeV/c)
- Scintillator hodoscope (HOD):
  - $\sigma(T) \sim$150 ps
- Liquid Krypton EM calorimeter (LKr):
  - $\sigma_x = \sigma_y = (0.42/\sqrt{E_\gamma} \oplus 0.06)$ cm
  - $\sigma(E_\gamma)/E_\gamma = (3.2/\sqrt{E_\gamma} \oplus 9.0/E_\gamma \oplus 0.42)\%$ (E_γ in GeV)
- Hadronic calorimeter, muon system MUV.

Events selection

- Signal $K_{\mu 4}$ is $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$
- Normalization $K_{3\pi}$ is $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$
- Trigger chain: L1 trigger using HOD and LKr, followed by L2 trigger using DCH for online momentum calculation.
- Event selection: 4 isolated photons consistent with $2\pi^0$ in time-spatial matching with a KABES beam track and a DCH track.



Normalization $K_{3\pi}$ kinematic selection ellipse:

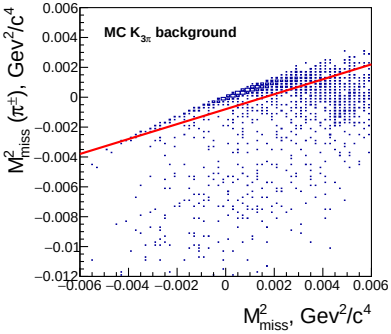
- center:
  - $M(K_{3\pi}) = M_K^{PDG}$
  - $P_t = 5$ MeV/c
- semi-axes:
  - $\Delta M(K_{3\pi}) = 10$ MeV/c^2
  - $\Delta P_t = 20$ MeV/c
- 72.99×10^6 $K_{3\pi}$ selected data events.

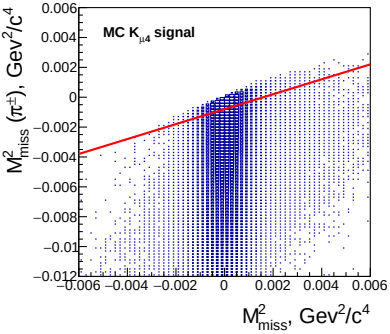
$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ signal events selection

- Off the $K_{3\pi}$ kinematic ellipse
- DCH track has associated MUV response

$$M^2_{miss} = (\mathrm{P}_K - \mathrm{P}(\pi^0_1) - \mathrm{P}(\pi^0_2) - \mathrm{P}(\mu^{\pm}))^2$$

$$M^2_{miss}(\pi^{\pm}) = (\mathrm{P}_K - \mathrm{P}(\pi^0_1) - \mathrm{P}(\pi^0_2) - \mathrm{P}(\pi^{\pm}))^2$$

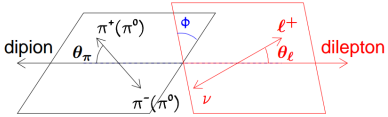


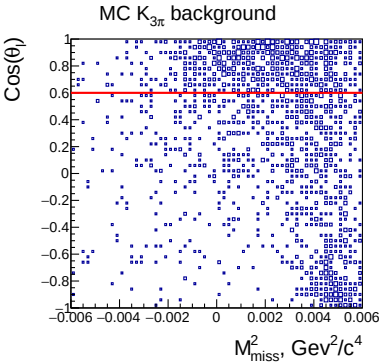


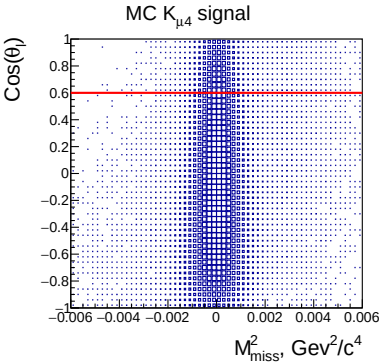
- $M^2_{miss}(\pi^{\pm}) < 0.5 M^2_{miss} - 0.0008\ \mathrm{GeV}^2/c^4$

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ signal events selection

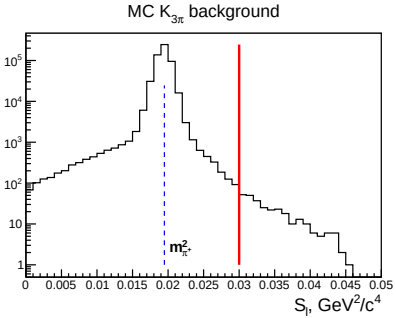
- $cos(\Theta_l) < 0.6$

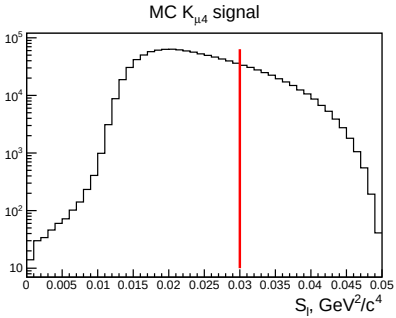






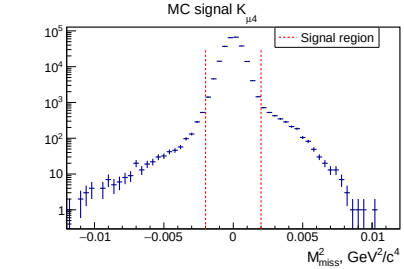
$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ signal events selection

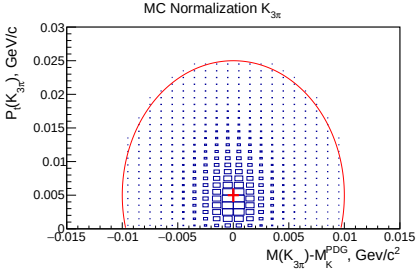




- $S_l = m(\mu\nu)^2 > 0.03$ GeV$^2/c^4$ (to reject $\pi^{\pm} \to \mu^{\pm}\nu$).
- 3718 $K_{\mu 4}$ data candidates selected
- 2437 data candidates in M^2_{miss} signal region [-0.002,0.002] GeV$^2/c^4$
- The MC M^2_{miss} signal region contains 98.2% of all selected MC events

Acceptances





- $K^{00}_{\mu 4}$ signal accepance is

$$A_S = \frac{N^{MC}_{Selected\ in\ signal\ region}}{N^{MC}_{Generated}(all\ \ S_l^{true})} = (0.651 \pm 0.001)\%,$$

- However, for the restricted phase space region $S_l^{true} > 0.03\ \mathrm{GeV}^2/c^4$, the signal acceptance is

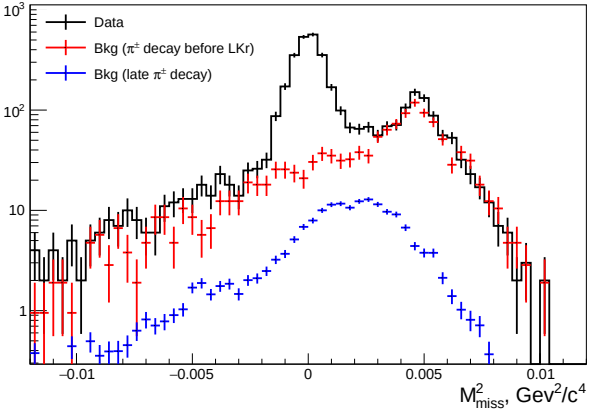
$$A^r_S = \frac{N^{MC}_{Selected\ in\ signal\ region}}{N^{MC}_{Generated}(S_l^{true}>0.03)} = (3.453 \pm 0.007)\%.$$

- $K_{3\pi}$ normalization channel acceptance is

$$A_N = \frac{N^{MC}_{Selected}}{N^{MC}_{Generated}} = (4.477 \pm 0.002)\%$$

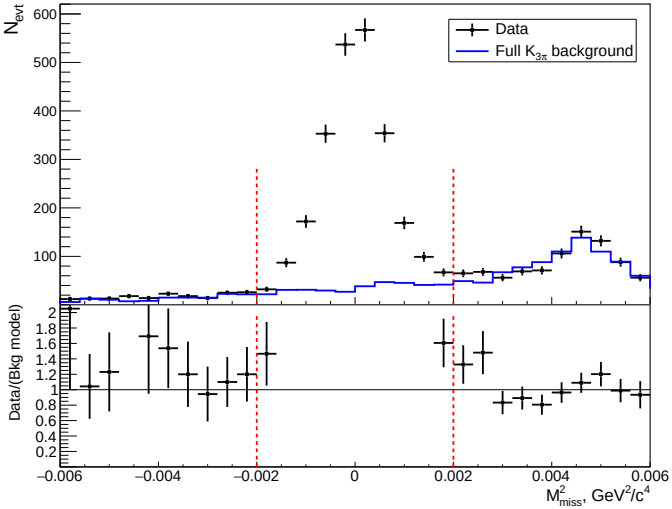
Residual background

- $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$,
- followed by $\pi^{\pm} \to \mu\nu$ before MUV with a probability $\approx 10\%$ for $P(\pi^{\pm}) \approx 10$ GeV/c.



- $K_{3\pi}$ background with $\pi^{\pm}$ decay before LKr: from MC.
- $K_{3\pi}$ background with late $\pi^{\pm}$ decay or muon emission in a late hadron shower:
  - Can not be easily simulated
  - Data-driven method of estimation
  - Background-enhansed control sample, selected using E_{LKr} and P_{DCH}

$K^{00}_{\mu 4}$ signal extraction fit



- 2437 candidates in the signal region.
- Fit in the M^2_{miss} interval [-0.003,0.006] GeV$^2/c^4$, ignoring the signal region to decrease sensitivity to the imperfect MC resolution.
- Data fit by a linear combination of background and MC signal tails.
- $354 \pm 33_{stat} \pm 62_{syst}$ background events.
- The background-related systematics are determined by varying the way the background is estimated.

Signal versus S_π, S_l

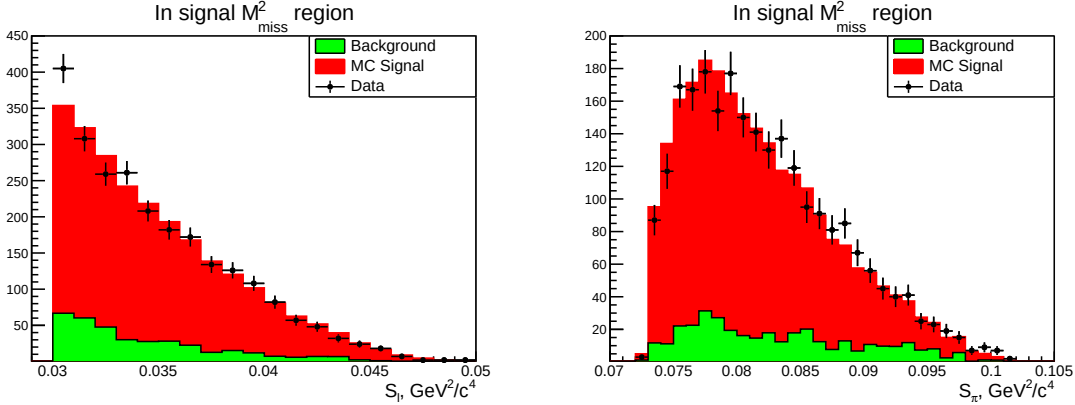


Figure: 1D projections comparison for $S_l > 0.03$ GeV^2/c^4

- The branching ratio is measured for the restricted phase space $S_l^{true} > 0.03$ GeV^2/c^4.
- Extrapolation to the full phase space depends on the theory.

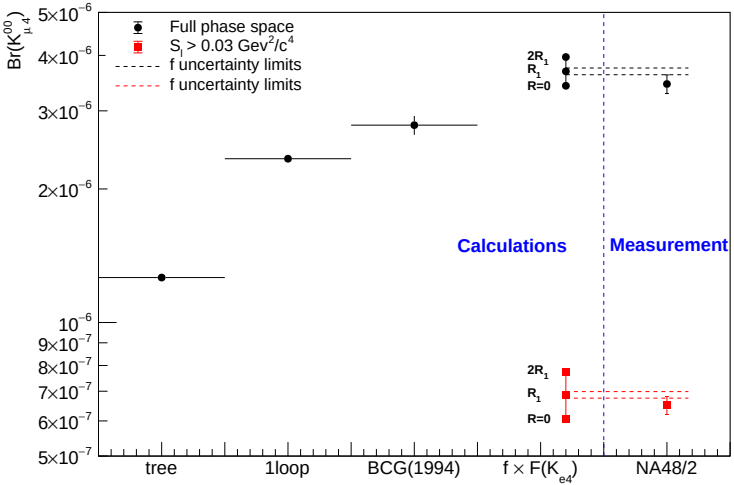
Preliminary result: Central values and errors budget

$$BR(K^{00}_{\mu 4}) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{trig} \cdot BR(K^{00}_{3\pi}).$$

	Full phase space		$S_l > 0.03$ GeV^2/c^4	
$BR(K_{\mu 4})$ central value [10^{-6}]	3.45		0.651	
	$\delta BR[10^{-6}]$	$\delta BR/BR$	$\delta BR[10^{-6}]$	$\delta BR/BR$
Data stat. error	0.10	2.85%	0.019	2.85%
MC stat. error	0.01	0.21%	0.001	0.21%
Trigger	0.01	0.18%	0.001	0.18%
Background	0.10	2.96%	0.019	2.96%
Accidentals	0.01	0.32%	0.002	0.32%
MUV inefficiency	0.06	1.65%	0.011	1.65%
Form Factor modelling	0.05	1.37%	0.001	0.14%
$BR(K_{3\pi})$ error (external)	0.05	1.31%	0.009	1.31%
Total error	0.17	4.83%	0.030	4.64%

- Accidentals obtained from side bands of time distributions;
- MUV inefficiency uncertainty taken as full inefficiency effect.

Preliminary result: Comparison to theory



Theory:

- J. Bijnens, G. Colangelo, J. Gasser, Nucl. Phys. B, 427 (1994) 427:
  - Tree approximation;
  - 1-loop;
  - BCG(1994): 'beyond 1-loop' with measured F from [Rosselet etc. Phys. Rev. D 15 (1977) 574].
- Re-calculated now:
  - $F(K_{e4})$ from NA48/2 (2015);
  - $R_1 = R(1loop)$;
  - 1-loop (F,R) phase;
  - 2020 PDG constants.

Conclusion

A first observation and branching fraction precise measurement of $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ decay is performed by NA48/2 experiment at SPS in CERN

- We observe 2437 signal candidates with an estimated background of $354 \pm 33_{stat} \pm 62_{syst}$ events, Signal/Background ratio is $5.9 \pm 1.4_{tot}$
- Preliminary result for restricted phase space ($S_l > 0.03$) is

$$BR(K^{00}_{\mu 4}, S_l > 0.03) = (0.65 \pm 0.019_{stat} \pm 0.024_{syst}) \times 10^{-6} = (0.65 \pm 0.03) \times 10^{-6};$$

- Preliminary full phase space result is

$$BR(K^{00}_{\mu 4}) = (3.4 \pm 0.10_{stat} \pm 0.13_{syst}) \times 10^{-6} = (3.4 \pm 0.2) \times 10^{-6}.$$

- The results are consistent with a contribution of the R form factor, as computed at 1-loop ChPT.