First measurement of the $K^{\pm} \rightarrow \pi^0 \pi^0 \mu^{\pm} \nu$ ($K^{00}_{\mu 4}$) decay with the NA48/2 experiment at CERN

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The NA48/2 Collaboration

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Outline

- The NA48/2 beam and detector
- The measurement of $K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu$
- Prospects and conclusions

Kaons at CERN: NA48 and NA62

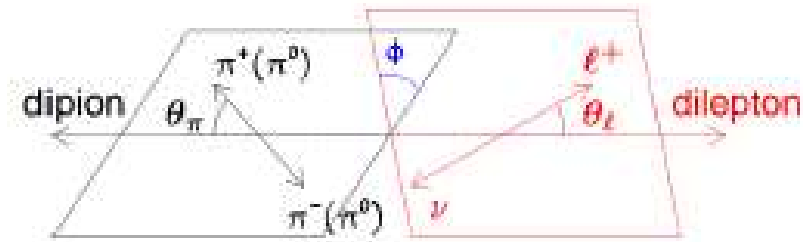
Kaon decay in flight experiments.
NA48/2: ~120 participants, 15 institutes

Earlier: NA31

NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 R_K phase	2007: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 –18 : $K^+\to\pi^+\nu\nu$ run	
	2021 – : $K^+\to\pi^+\nu\nu$ run	

$K^{\pm} \rightarrow \pi^0 \pi^0 \mu^{\pm} \nu$ ($K^{00}_{\mu 4}$)

The decay is characterized using the 5 Cabibbo-Maksymowicz variables:
S_π (dipion mass squared), S_l (dilepton mass squared) and the angles θ_π (in the dipion frame, θ_l (in the dilepton frame) and ϕ



The amplitude depends on 4 form factors, named F, G, R, H

- With the two π^0 in s-wave, no dependence on cos θ_π, ϕ. Only F and R contribute
- Unlike K^{00}_{e4}, R plays some role due to the non-negligible μ mass

- Use the $F(S_\pi,S_l)$ experimental parametrization from K^{00}_{e4}, according to lepton universality.
    - NA48/2 JHEP 08 (2014) 159
- For $R(S_\pi,S_l)$ use ChPT calculation
    - Bijnens, Colangelo, Gasser, Nucl.Phys.B 427(1994) 427

Current status

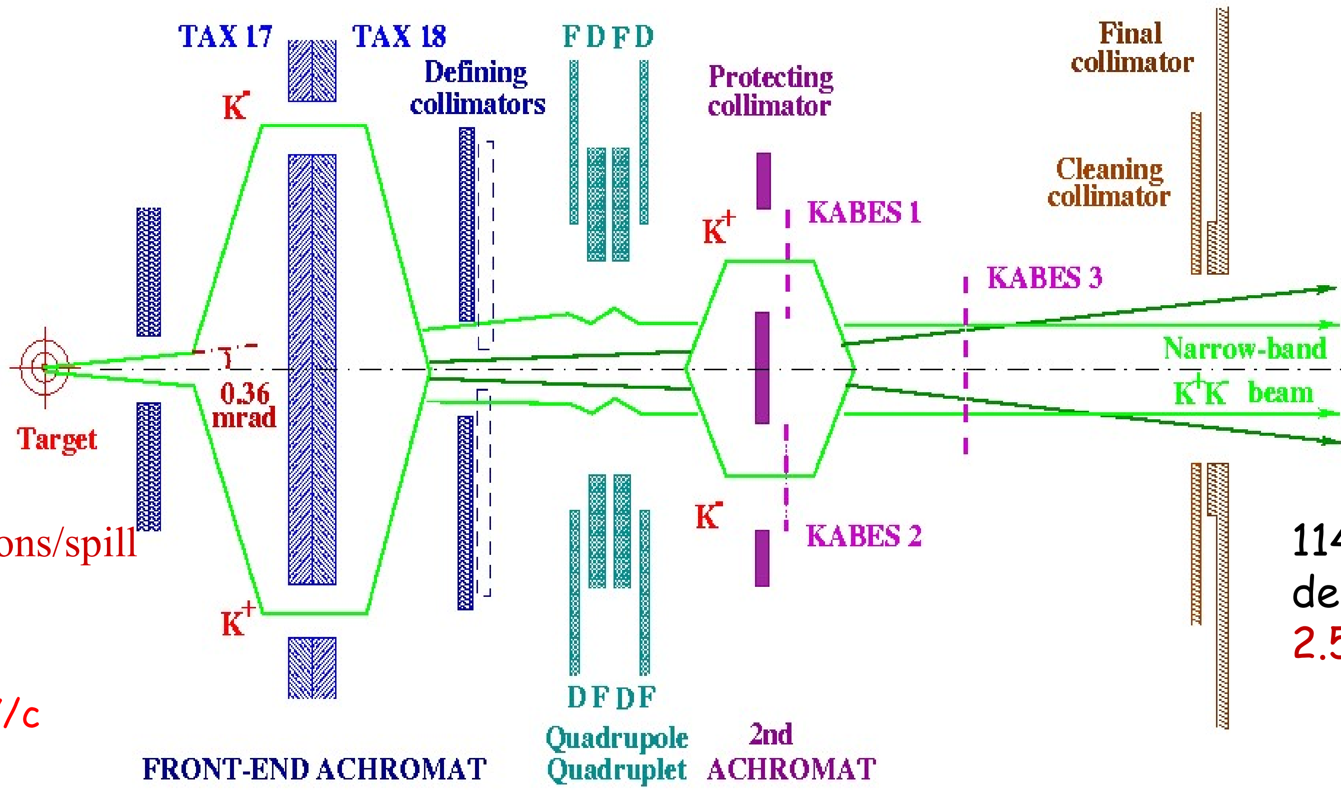
K_{l4} mode	BR $[10^{-5}]$	N_{cand}	
$K_{e4}{}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
$K_{e4}{}^{00}$	2.55 ± 0.04	65210	NA48/2 (2014)
$K_{\mu 4}{}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu 4}{}^{00}$	?	0	

- Goals: first observation and check of the ChPT prediction
- Analysis challenge: suppression of the huge background from $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ $(\pi^{\pm} \to \mu^{\pm}\nu)$

The NA48/2 Beam

NA48/2 beam (2003-2004): simultaneous K^+/K^-

$N(K^+)/N(K^-) = 1.8$



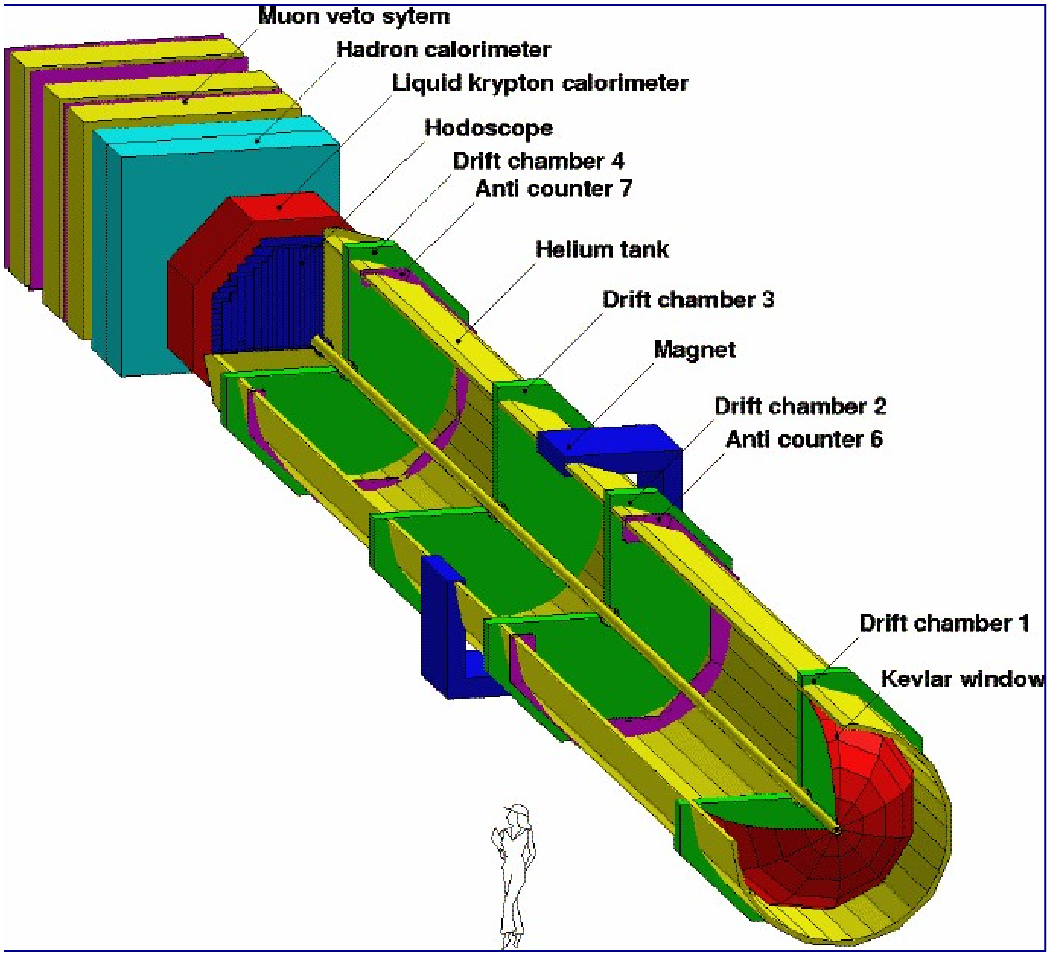
1.8×10^{12} protons/spill
400 GeV/c

$P_K = (60 \pm 3)$ GeV/c

114 m long decay volume
2.5×10^7 K/spill

K decays in the vacuum tank: 22%
Beam size: 4x4 mm^2, 10x10 μr

The NA48/2 Detector



LKr Calorimeter:
$\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$

$\sigma(x) = \sigma(y) \cong (4.2/\sqrt{E} \oplus 0.6)$mm $\cong$ 1.5mm@ 10 GeV

Spectrometer:

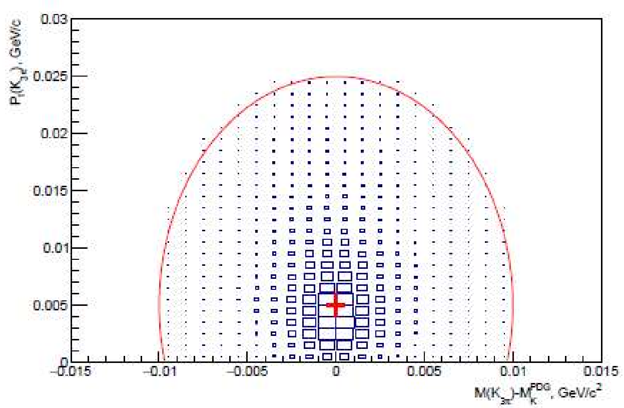
$\sigma(P)/P \cong 1.02\% \oplus 0.044\ P[GeV/c]\%$

Scintillator hodoscope: fast trigger and good time resolution (150 ps)

Efficient trigger chain using the hodoscope hits and LKr energy deposits at L1 and 1 DCH track consistent with a kaon decay in the FV at L2

Event selection – Common selection

- The normalization channel is $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$
- First set of common cuts for signal and normalization
  - First-order cancellations in BR computation
  - Kaon track selected using the KABES beam spectrometer
  - Triggered using HOD and LKr at L1, momentum calculation with DCH at L2
  - Event selection: 4 isolated photons consistent with $2\pi^0$ in time with a beam track and a DCH one, spatial matching between the 2 π^0 vertex and the kaon-DCH track vertex



Normalization selection: ellipse cut

Center: $M(K_{3\pi}) = M_K$, P_t = 5 MeV/c

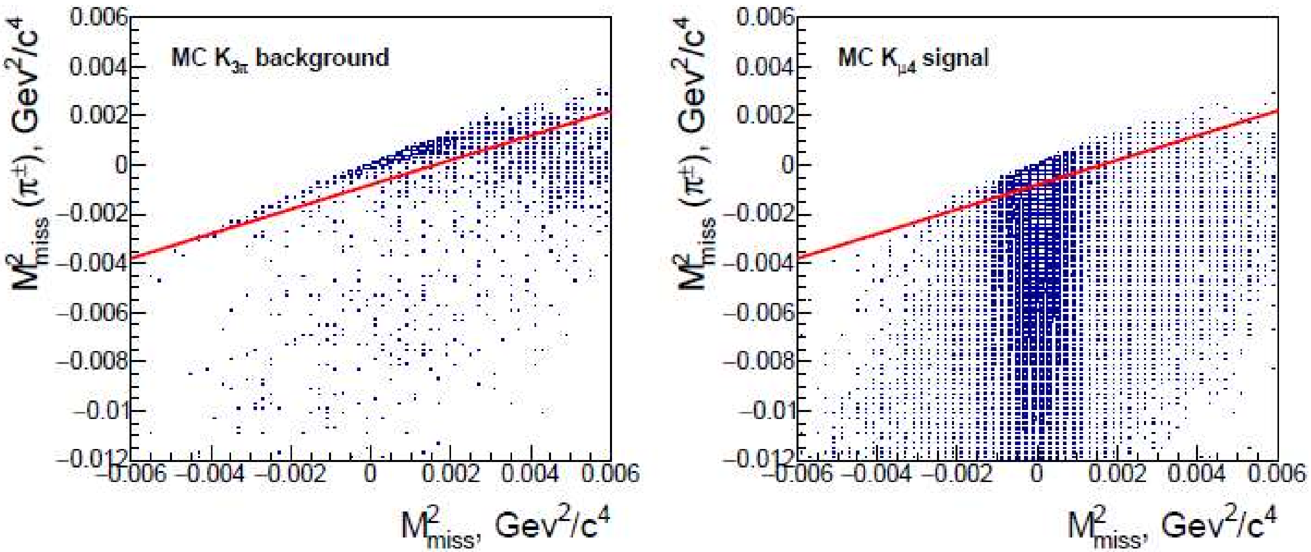
Semi-axes: $\Delta M(K_{3\pi})$ = 10 MeV/c^2, ΔP_t = 20 MeV/c

Selection of 72.99×10^6 $K_{3\pi}$ events

Event selection - signal

- Events outside the $K_{3\pi}$ ellipse
- Association of the charged track with MUV response
- Define two invariant masses

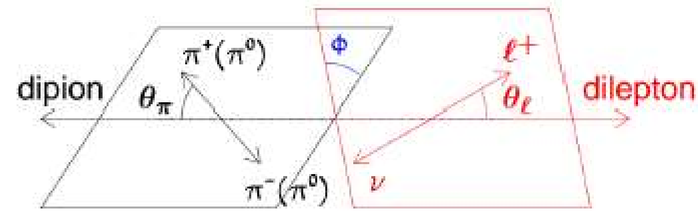
$$M^2_{miss} = (P_K - P(\pi^0_1) - P(\pi^0_2) - P(\mu^\pm))^2 \qquad M^2_{miss}(\pi^\pm) = (P_K - P(\pi^0_1) - P(\pi^0_2) - P(\pi^\pm))^2$$

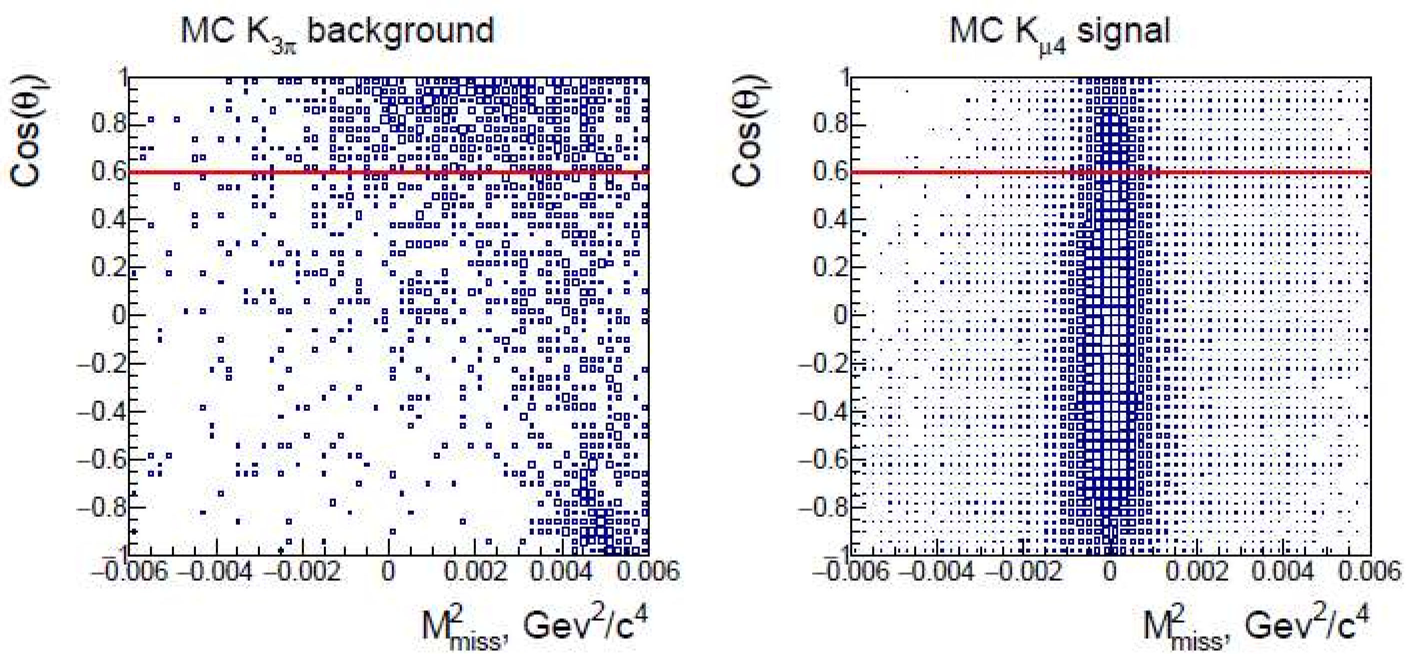


- Selection cut: $M^2_{miss}(\pi^\pm) < 0.5 \cdot M^2_{miss} - 0.0008 \frac{GeV^2}{c^4}$

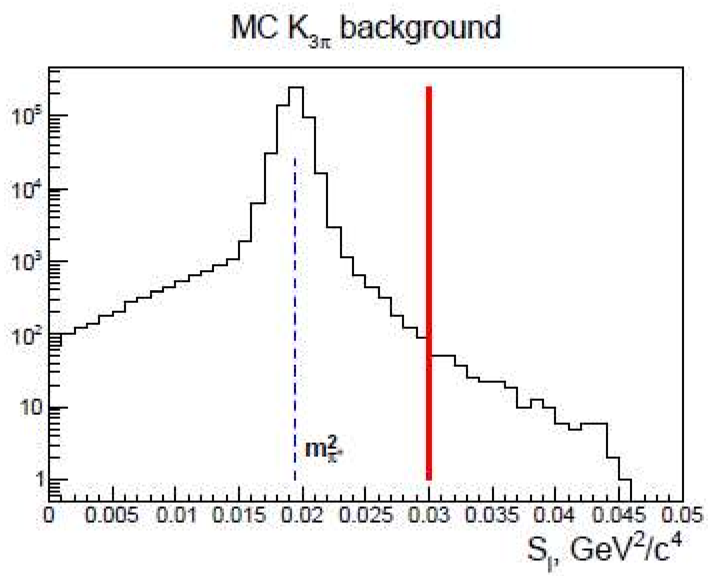
Event selection - signal

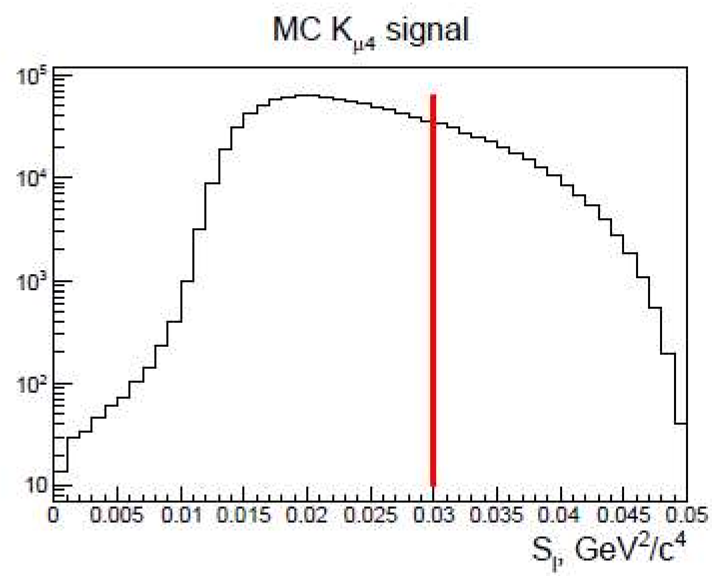
Cut on $\cos(\theta_l) < 0.6$





Event selection - signal

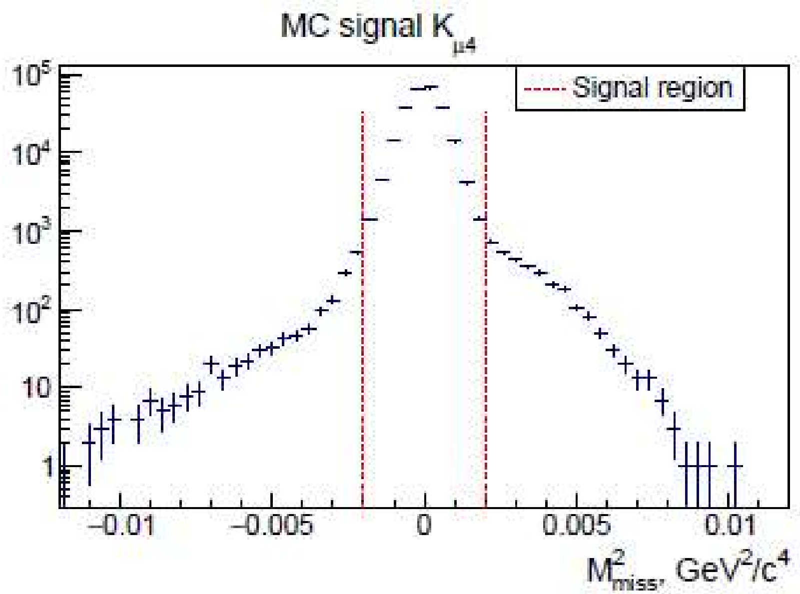


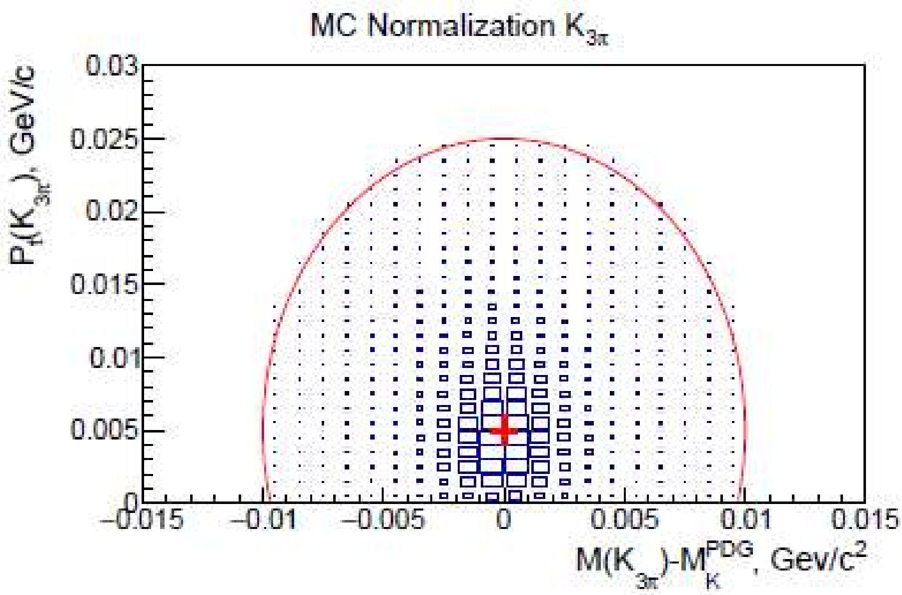


- Rejection of $\pi^\pm \rightarrow \mu^\pm\nu$ with a cut on $S_l = M(\mu^\pm\nu)^2$: S_l>0.03 GeV^2/c^4
- 3718 $K_{\mu4}$ candidates selected
- 2437 events in the M^2_{miss} signal region [-0.002,0.002] GeV^2/c^4

Acceptances

- $K^{00}_{\mu4}$ signal acceptance (full phase space)
  - $A_S = (0.651 \pm 0.001)\%$
- Restricted phase space ($S_l^{true} > 0.03$ GeV^2/c^4)
  - $A_S = (3.453 \pm 0.007)\%$
- Normalization acceptance
  - $A_N = (4.477 \pm 0.002)\%$





Residual background

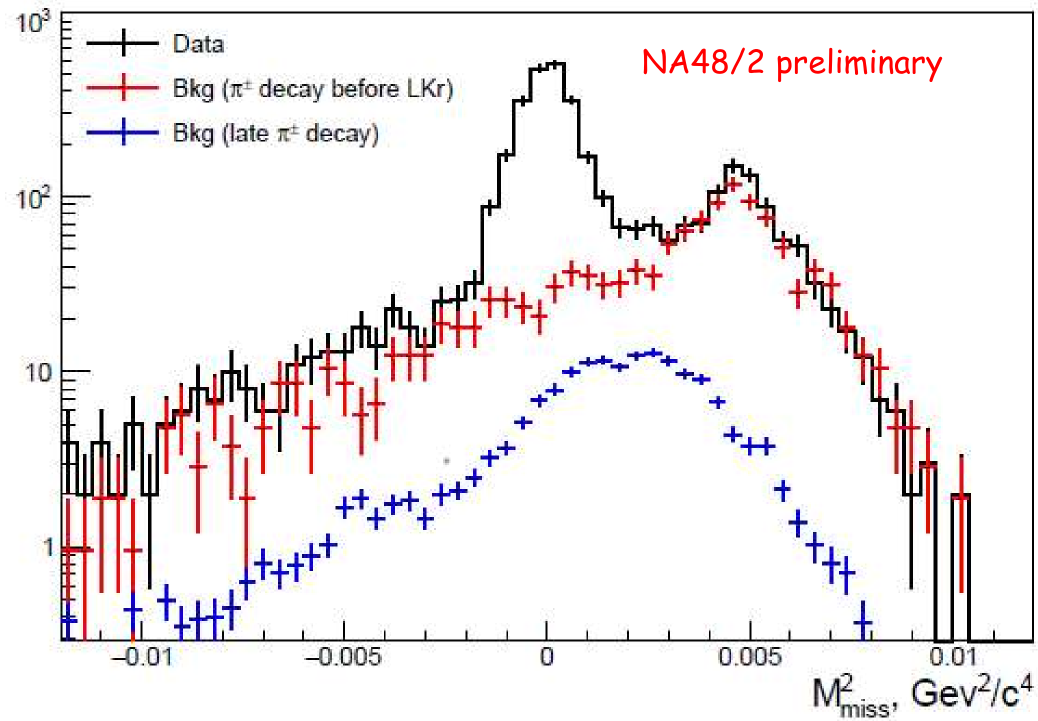
Coming from $K^{\pm} \rightarrow \pi^0\pi^0\pi^{\pm}$ with $\pi^{\pm} \rightarrow \mu^{\pm}\nu$ before the muon detector with a probability ~10% for $P(\pi^{\pm})$ ~ 10 GeV/c

Decay before the LKr calorimeter:

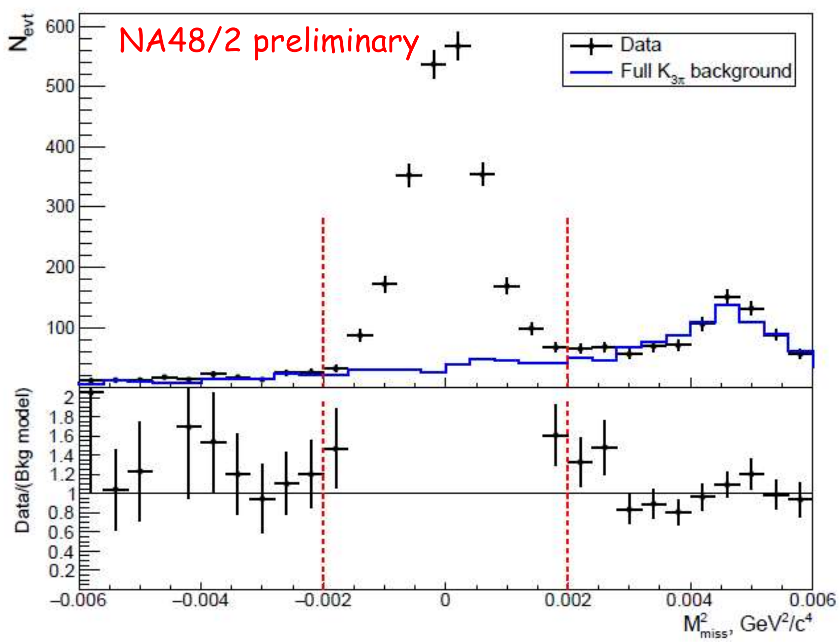
Estimation from MC

Late $\pi^{\pm}$ decay or muon emission in a late hadron shower:

Simulation not easy, use data with a background enhanced sample, selected with the ratio E_{LKr}/P_{DCH}



Signal extraction fit



2437 events in signal region

Background estimation with a fit for $-0.003 < M^2_{miss} < 0.006$, ignoring the signal region

Fit with a combination of background and signal tails

$354 \pm 33_{stat} \pm 62_{syst}$ background events

Systematics evaluated varying the way the background is estimated

Branching ratio evaluation

$$BR(K^{\pm} \to \pi^0 \pi^0 \mu^{\pm} \nu) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{trig} \cdot BR(K_{3\pi}^{00})$$

- N_S= candidates-background: 2437-(354±33$_{stat}$) = 2083±59$_{stat}$
- Normalization N_N= 72.99*10^6

- Normalization acceptance A_N=(4.477±0.002)%
- Acceptance for the restricted phase space A^r_S= (3.453±0.007)%
- Acceptance for the full phase space A_S= (0.651±0.001)%

- Trigger correction (from control triggers)
  - Ktrig=KCHT * KNUT = (0.998±0.002)*(1.0007±0.0007) = 0.999±0.002

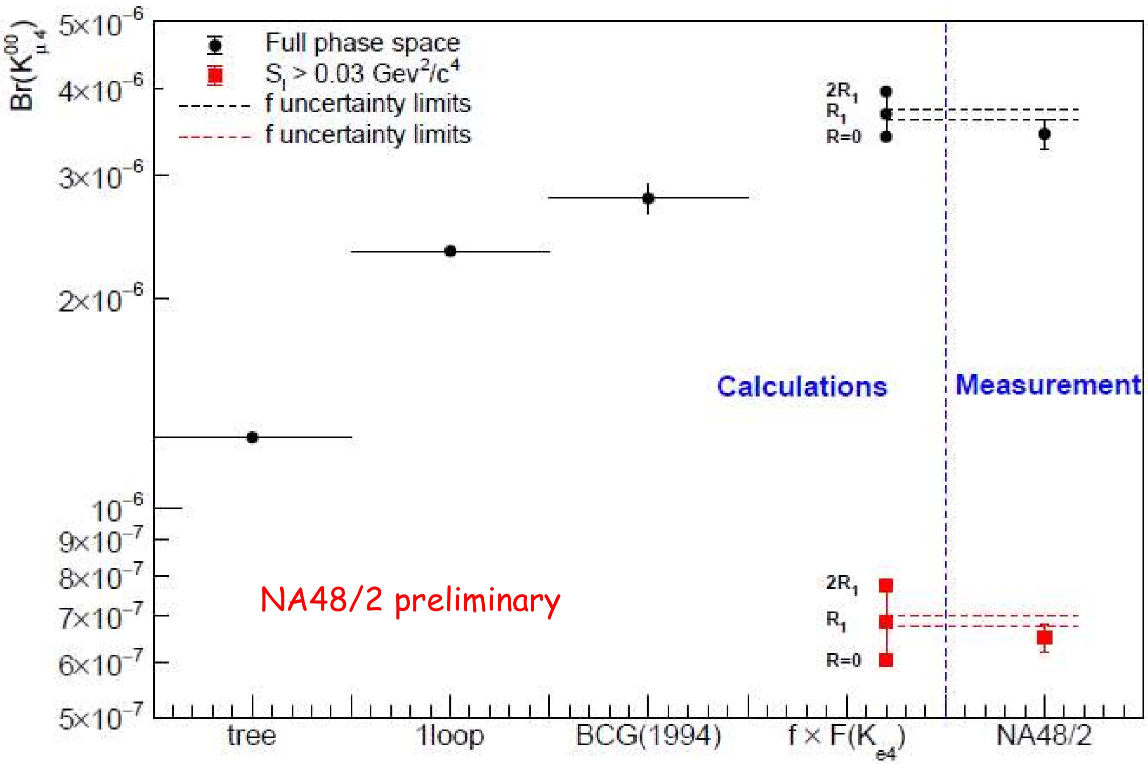
- PDG BR($\pi^0\pi^0\pi^+$) = (1.760±0.023)%

Branching ratios and error budget

	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%

- *Accidental obtained from side bands of time distribution*
- *MUV inefficiency uncertainty taken as full inefficiency effect*

Comparison with theory



Bijnens, Colangelo, Gasser
Nucl. Phys. B427 (1994) 427
Tree approximation
1-loop
Beyond 1-loop with measured
F from Rosselet et al.
Phys. Rev. D 15 (1977) 574

Updated by NA48/2 using:

$F(K_{e4})$ from NA48/2
R1 = R(1loop)
2020 PDG constants

Conclusions

- NA48/2 has observed for the first time the decay $K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu$
- 2437 signal candidates with a background of $354 \pm 33_{stat} \pm 62_{syst}$
- The preliminary result for the restricted phase space (S_l>0.03) is

$$BR(K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu, S_{\ell} > 0.03) = (0.65 \pm 0.019_{stat} \pm 0.024_{syst}) \times 10^{-6} = (0.65 \pm 0.03) \times 10^{-6}$$

- The preliminary result for the full space is

$$BR(K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu) = (3.4 \pm 0.10_{stat} \pm 0.13_{syst}) \times 10^{-6} = (3.4 \pm 0.2) \times 10^{-6}$$

- The results are consistent with a contribution of the R form factor, as from 1-loop ChPT computation
- A paper is in preparation