Probing new physics with rare kaon decays at CERN SPS

Venelin Kozhuharov

Laboratori Nazionali di Frascati - INFN

University of Sofia

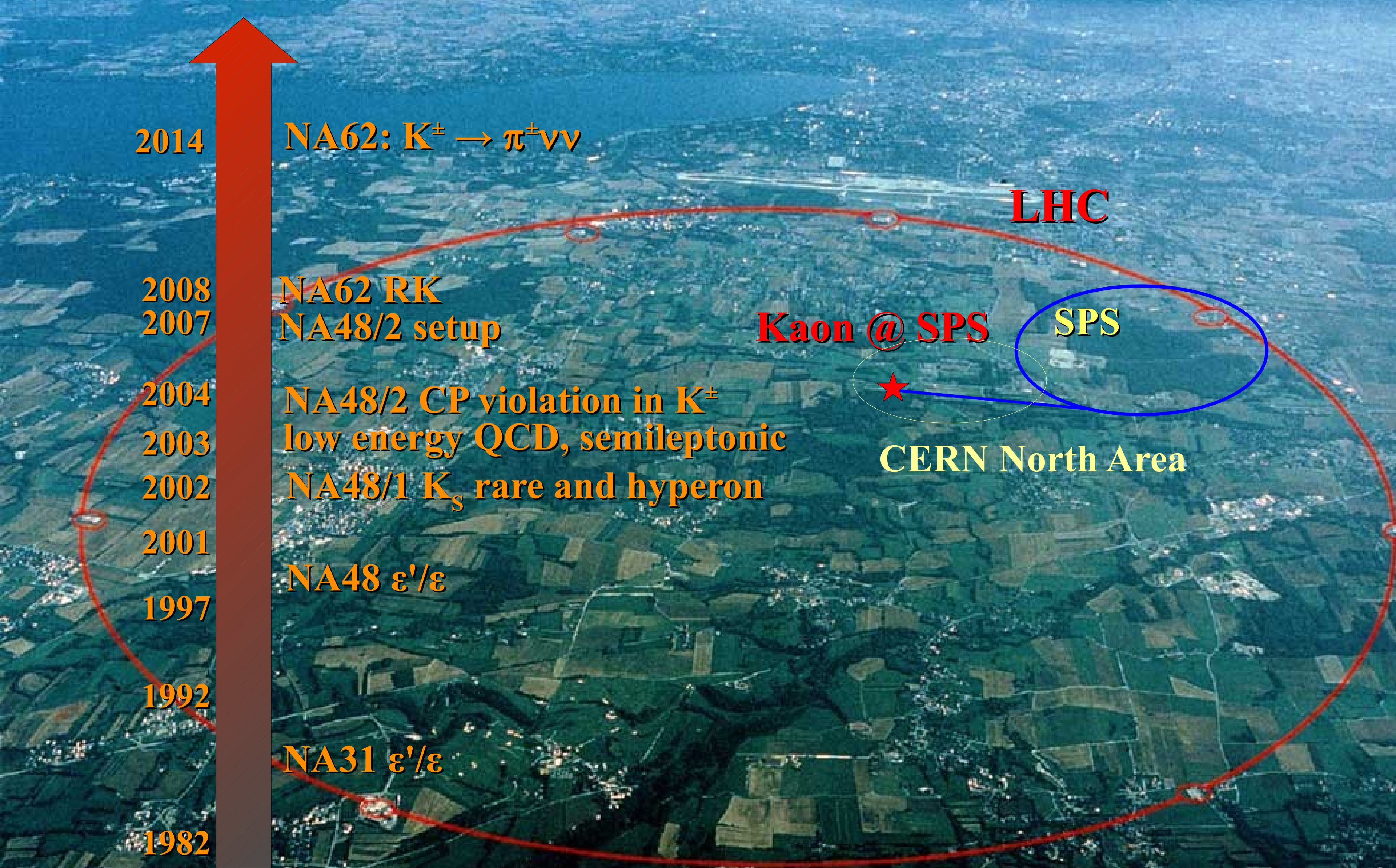
Rencontres de Blois

1 June 2016

on behalf of the NA48/2 and NA62 collaborations*

**Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin, Vancouver*

The CERN kaon factory



Overview

- Probing new physics with $K^{\pm} \rightarrow \pi^{\pm/\mp}\mu^{\pm}\mu^{\mp/\pm}$
  - LNV
  - Search for resonances in $M_{\mu\mu}$, $M_{\pi\mu}$ distributions
- Towards measuring $K^{+} \rightarrow \pi^{+}\nu\nu$
  - Motivation
  - Experimental setup
  - Current status
- Conclusions

$K^{\pm} \to \mu^{\pm}\pi\mu$ new physics case

- Lepton number violation – $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$
- Majorana neutrinos

  Asaka and Shaposhnikov, PLB 620 (2005) 17

  – Dark Matter + Baryon Asymmetry of the Universe (BAU) + low mass of SM ν

  – can be explained by adding three sterile Majorana neutrinos N_i to the SM

    - lightest O(keV) → Dark Matter candidate
    - Others: O(100 MeV – GeV), seesaw for ν_s

- Inflatons

  Shaposhnikov and Tkachev, PLB 639 (2006) 414

  – νMSM + a real scalar field (inflaton χ) with scale-invariant couplings

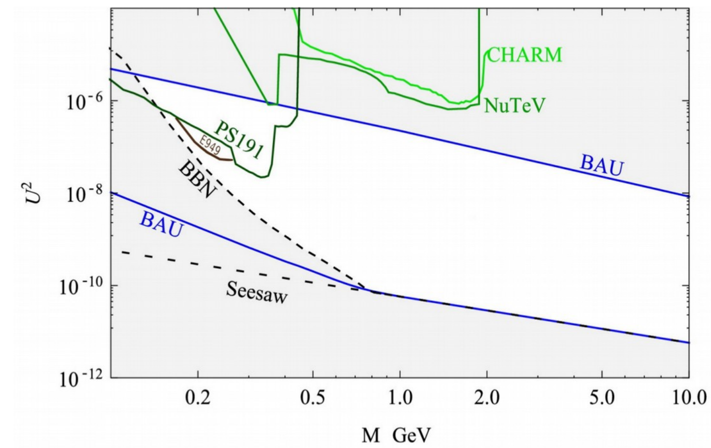
  – Explains Universe homogeneity and isotropy on large scales + structures on smaller scales

  – χ-Higgs mixing with mixing angle θ

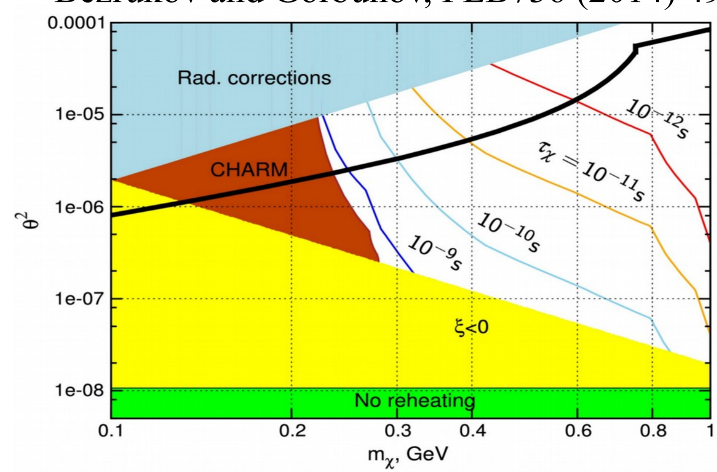
  – χ-Higgs coupling → Universe reheating

  – $\tau(\chi) \sim (10^{-8} - 10^{-12})$ s

Gorbunov and Timiryasov, PLB 745 (2015) 29



Bezrukov and Gorbunov, PLB736 (2014) 494



NA48/2 detector setup

Magnetic spectrometer (DCH)

4 drift chambers

$p_{\perp}^{kick}$ = 121 MeV/c

$\Delta p/p = 1\% \oplus 0.044 * p$ [GeV/c]

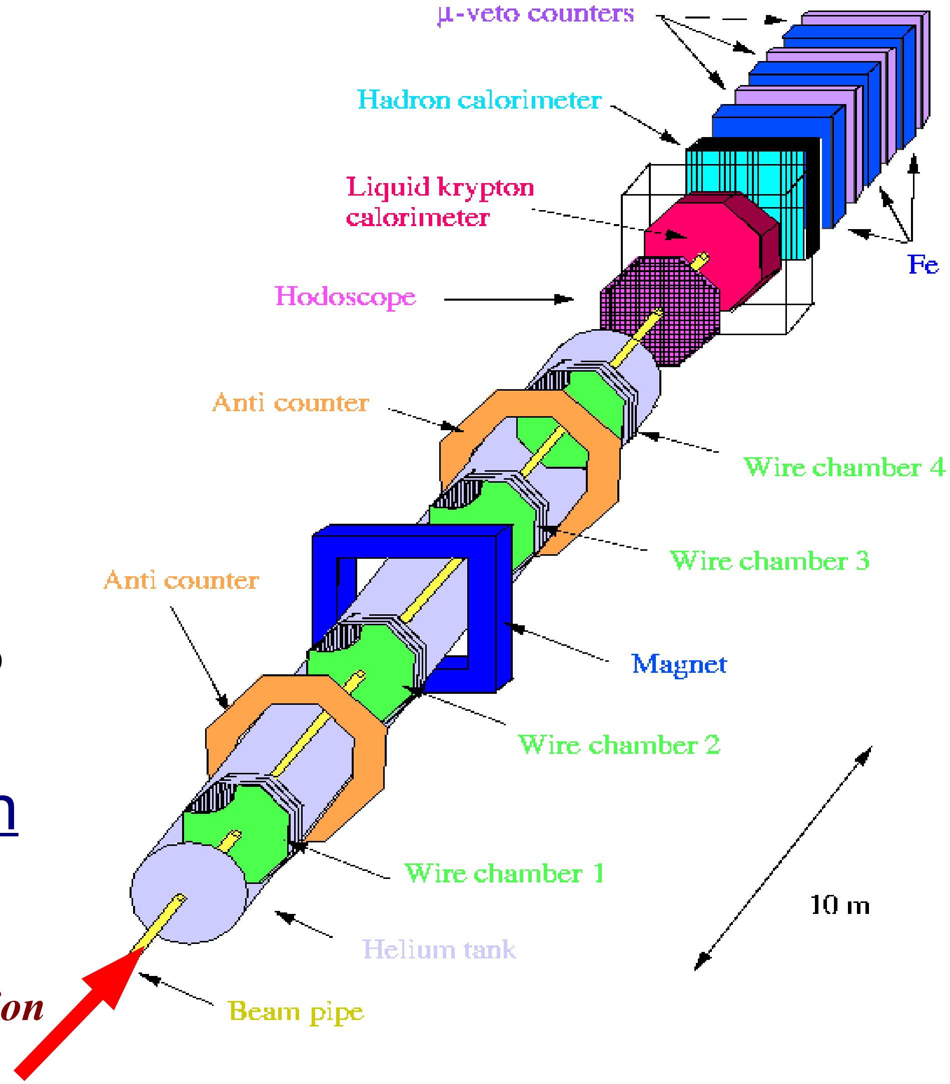
Hodoscope

$\sigma(t)$ = 150 ps

Liquid Krypton Calorimeter

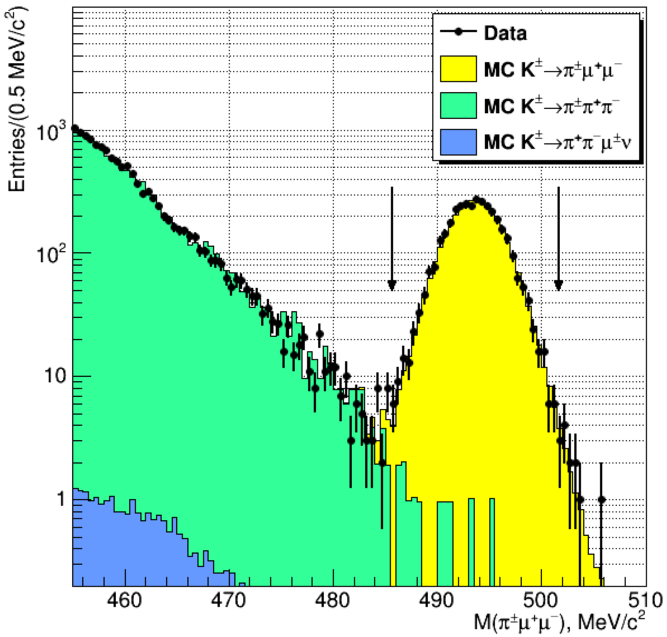
$\Delta E/E \cong 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$

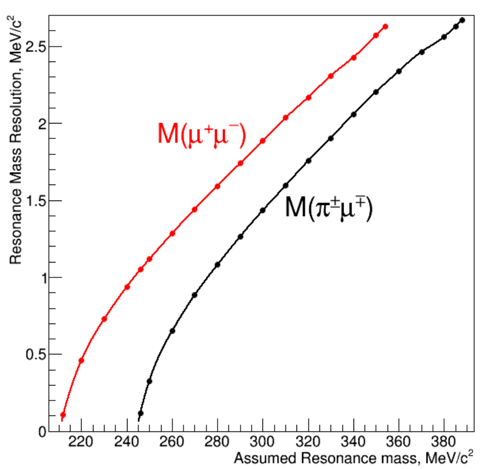
Hadron Calorimeter, Muon counters, Anticounters, Kaon Beam Spectrometer



~ 2×10^{11} $K^{\pm}$ decays in the fiducial volume

$K^{\pm}\rightarrow\pi^{\pm}\mu^{\pm}\mu^{\mp}$

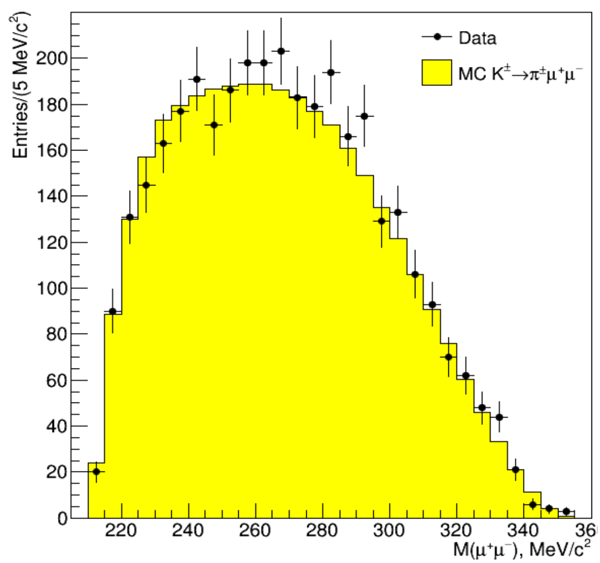


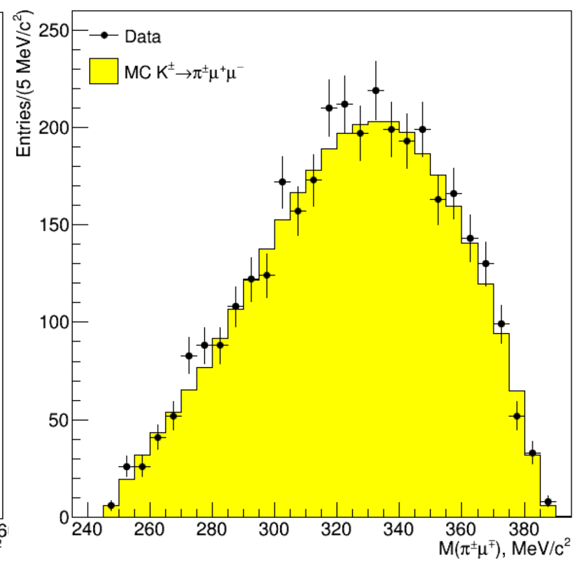


- Event selection
  - One 3-track vertex
  - PID: $\mu^+\mu^-$, 1 π
  - Total P_T consistent with zero
- Signal Region: $|M(\pi^{\pm}\mu^{+}\mu^{-}) - M(K)| < 8$ MeV/c²

3489 $K^{\pm}\rightarrow\pi^{\pm}\mu^{+}\mu^{-}$ candidates

Background: (0.36 ± 0.10)%, $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$

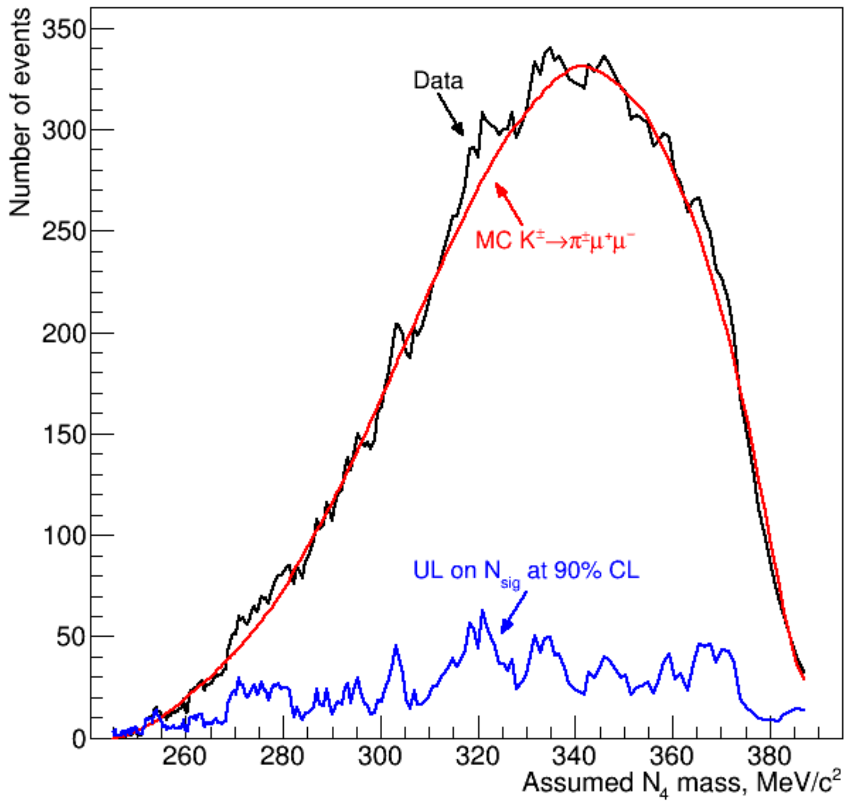


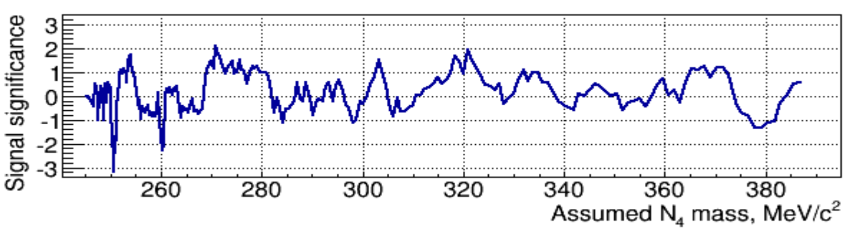


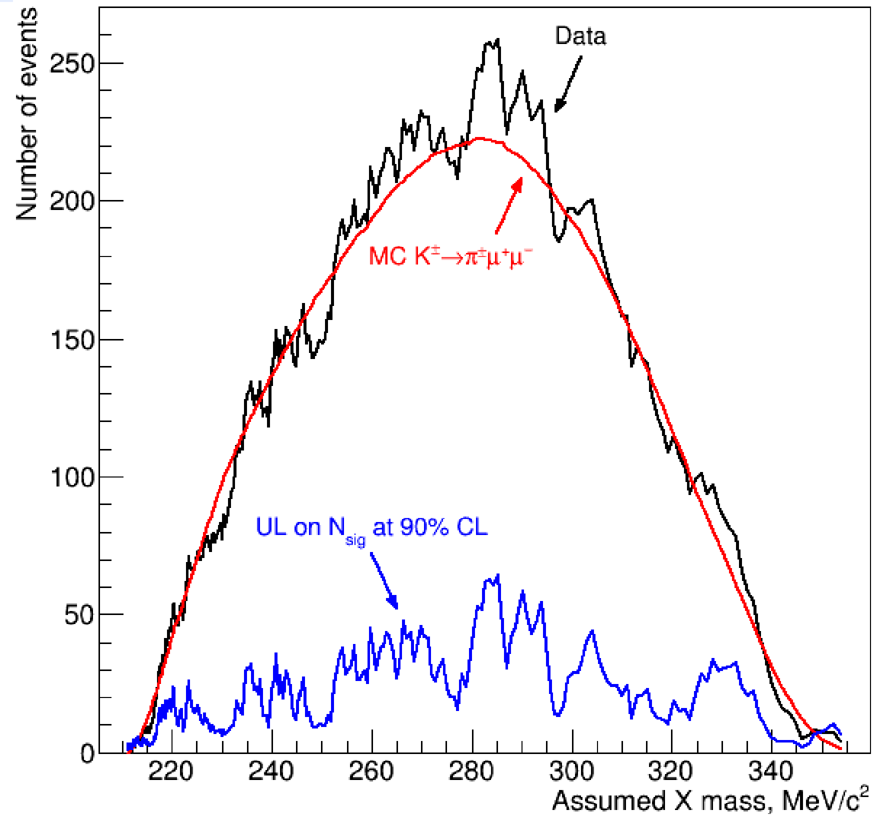
- Looking for excess of events in a region around M_Y

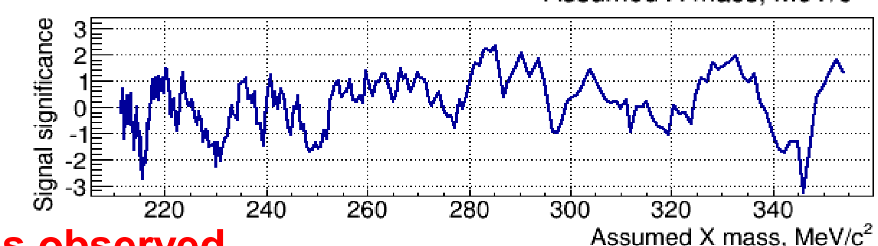
$|M(\pi\mu) - M(Y)| < 2\,\sigma_{M(\pi\mu)}$ or $|M(\mu\mu) - M(Y)| < 2\,\sigma_{M(\mu\mu)}$

$K^{\pm}\rightarrow\pi^{\pm}\mu^{\pm}\mu^{\mp}$ mass scan







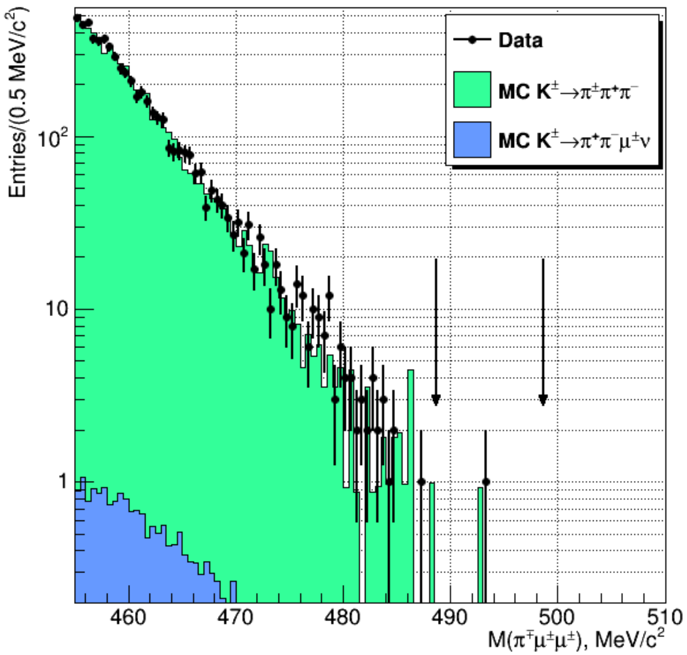


No excess observed

Statistical significance: $z=\frac{N_{obs}-N_{\exp}}{\sigma(N_{obs})\oplus\sigma(N_{\exp})}$

- Rolke-Lopez statistical treatment for UL on N_{sig} (M_Y)

$K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$



- Blind analysis – selection definition
  - $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$ MC simulation
  - $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ MC simulation
  - Control region $M(\pi\mu\mu) < 480$ MeV
- Background: additional $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ MC sample
- Event selection – similar with $K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}$
  - 2 same sign muons, 1 pion
  - Signal region: $|M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) - M(K)| < 8$ MeV/c²

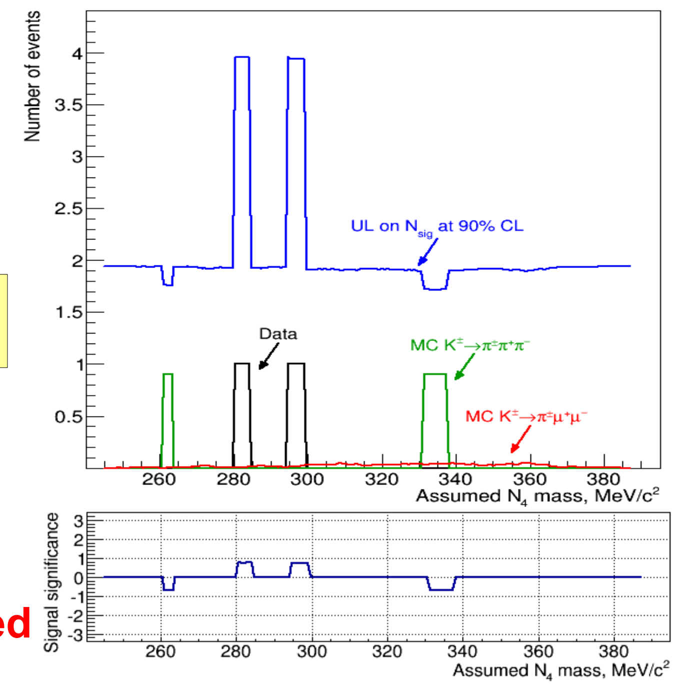
$N_{obs} = 1$

$N_{exp} = 1.163 \pm 0.875$ (MC)

- Rolke-Lopez statistical treatment for UL on N_{sig}

$BR(K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ @ 90 % CL

- Rolke-Lopez statistical treatment for UL on N_{sig} for each test mass
  - 2 possibilities to construct $M(\pi\mu)$, select the closest to the tested mass



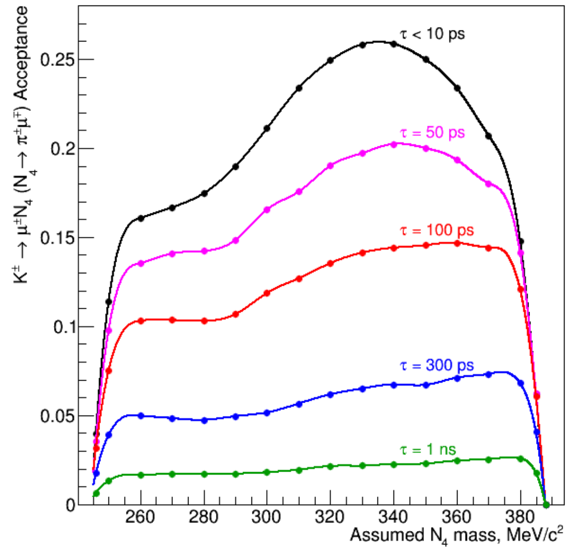
No excess observed

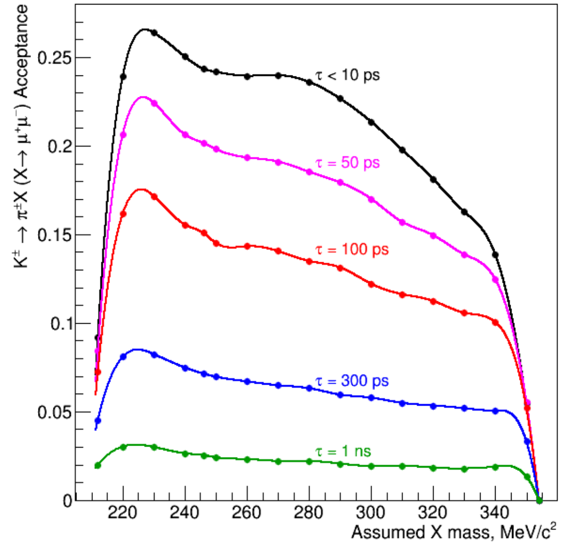
Results interpretations

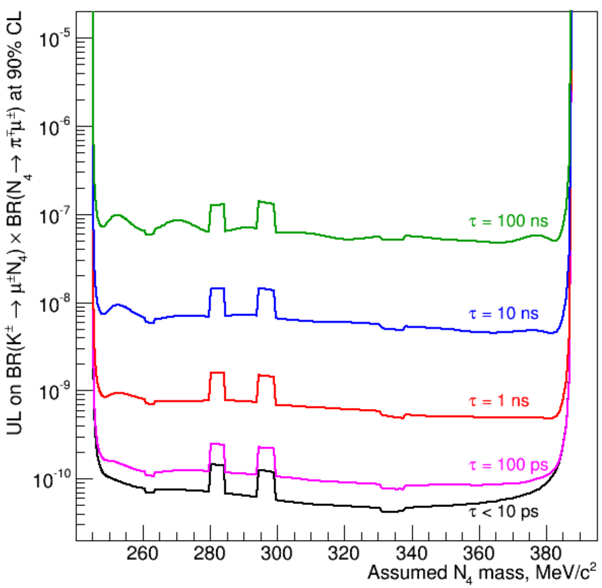
- Translate into upper limits for particular models

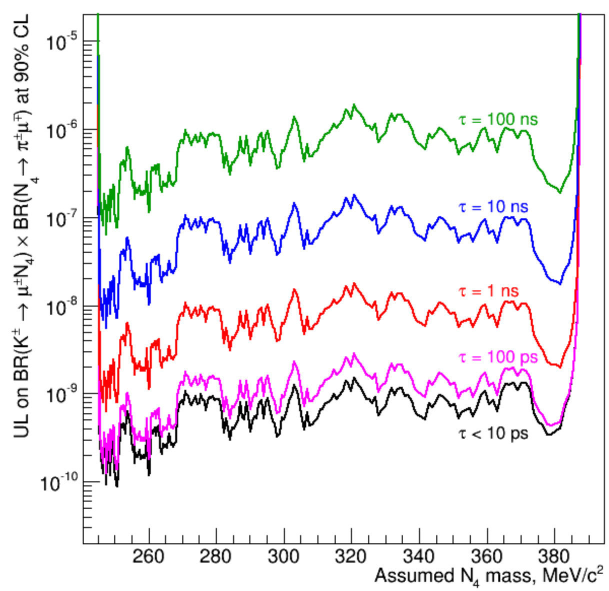
$$UL\left(BR\left(K \rightarrow \mu/\pi + Y\right) x\, BR\left(Y \rightarrow \mu + \pi/\mu\right)\right) = \frac{UL\left(N_{sig}\right)}{N_K * Acceptance}$$

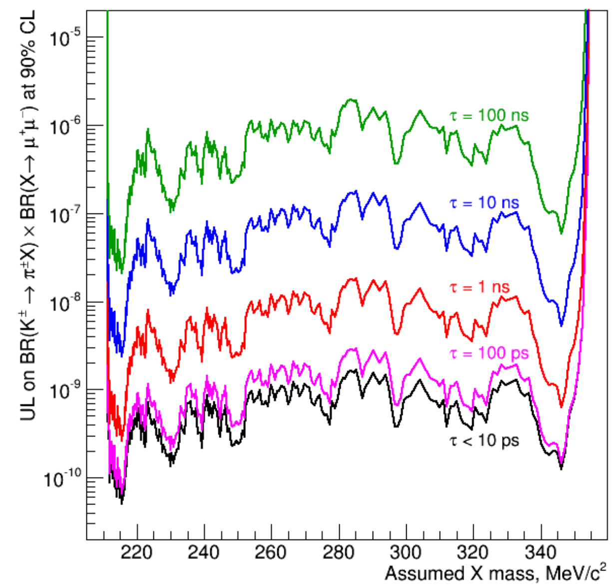
$$Y = \begin{cases} N_4,\ N_4 \rightarrow \pi\mu \\ X,\ X \rightarrow \mu\mu \end{cases}$$



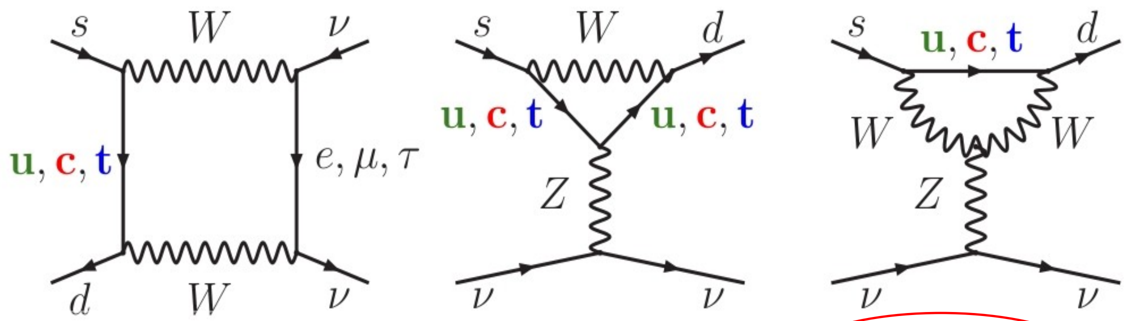








FCNC decays: K→πνν



$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)\right) = \kappa_+ (1+\Delta_{\mathrm{EM}}) \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} \left(P_c + \delta P_{c,u}\right) + \frac{\mathrm{Re}\lambda_t}{\lambda^5} X_t \right)^2 \right]$$

$\lambda = V_{us}$

$\lambda_c = V^*_{cs} V_{cd}$

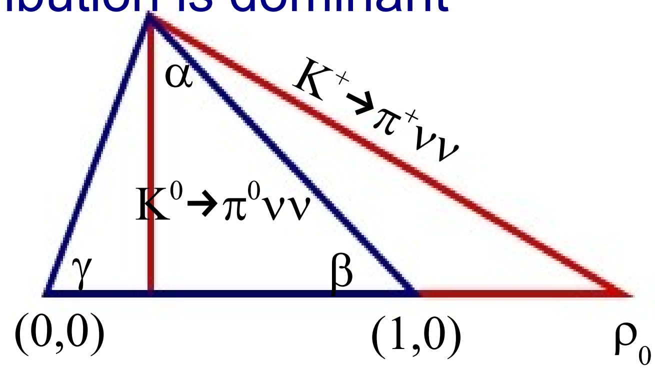
$\lambda_t = V^*_{ts} V_{td}$

k_+ - hadronic matrix element
measured from semileptonic decays

charm quark contribution

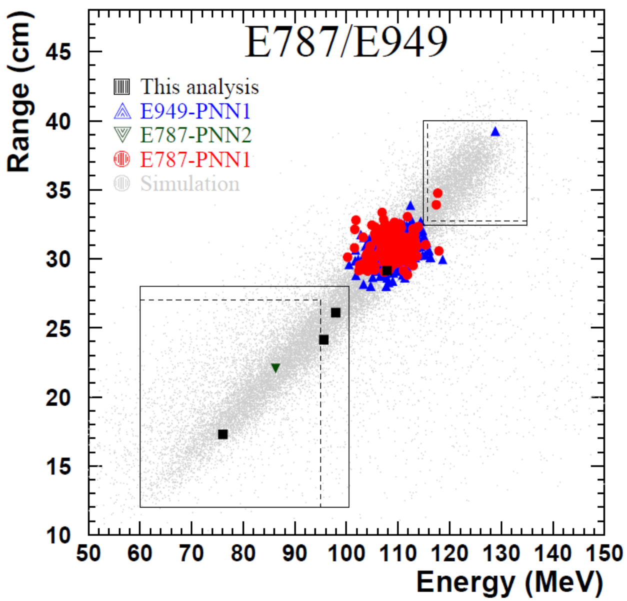
- Very clean theoretically – short distance contribution is dominant
- Charm loop under control

- Standard Model prediction:
  Br ($K^+ \to \pi^+ \nu\nu$) = $(8.4 \pm 1.0) \cdot 10^{-11}$
  Brod et al, Phys. Rev. D, 034030 (2011)
  Buras et al., JHEP 1511 (2015) 166



$K^{\pm}\rightarrow\pi^{\pm}\nu\nu$ status

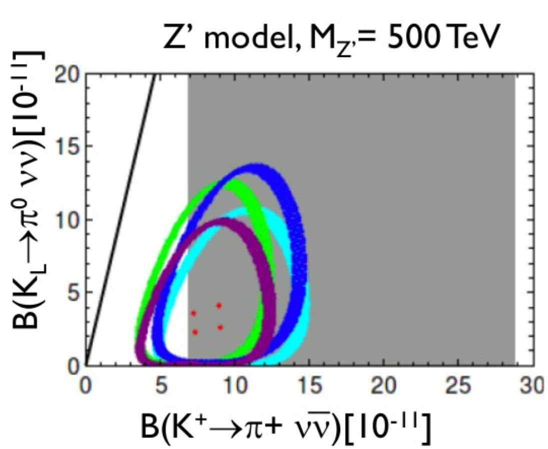
Phys. Rev. D, 79 (2009), p. 092004

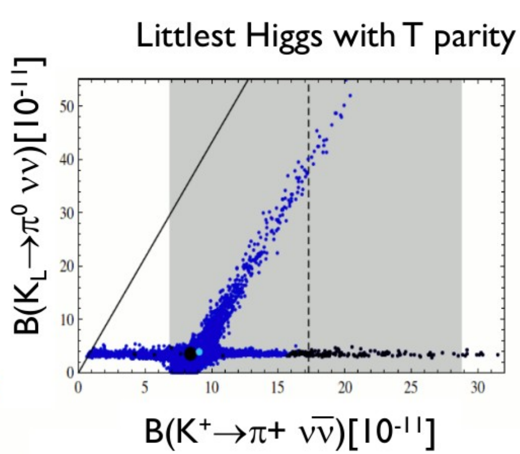


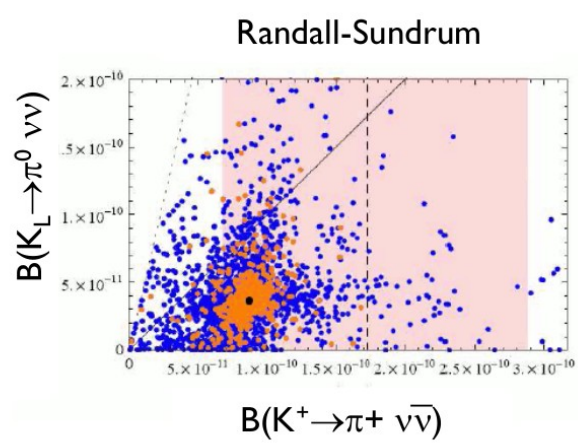
- E949 result based on 7 events:

  $Br\ (K^{+}\rightarrow\pi^{+}\nu\nu) = (1.73^{+1.15}_{-1.05})*10^{-10}$

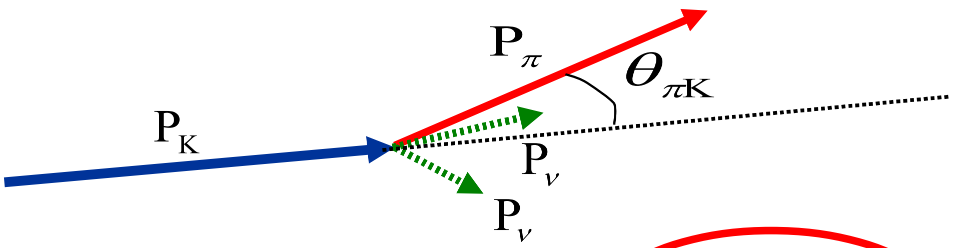
- $K^{+}\rightarrow\pi^{+}\nu\nu$ sensitive to NP contribution
  - Simplified Z, Z' models
    Buras et al., JHEP 1511 (2015) 166
  - Littlest Higgs with T-parity
    Blanke et al., EPJ C76 (2016) no.4, 182
  - Custodial Randall-Sundrum
    Blanke et al, JHEP 0903 (2009) 108
  - MSSM non-MFV
    Tanimoto, Yamamoto, PTEP 2015 no.5, 053B07
    Isidori et al., JHEP 0608 (2006) 064





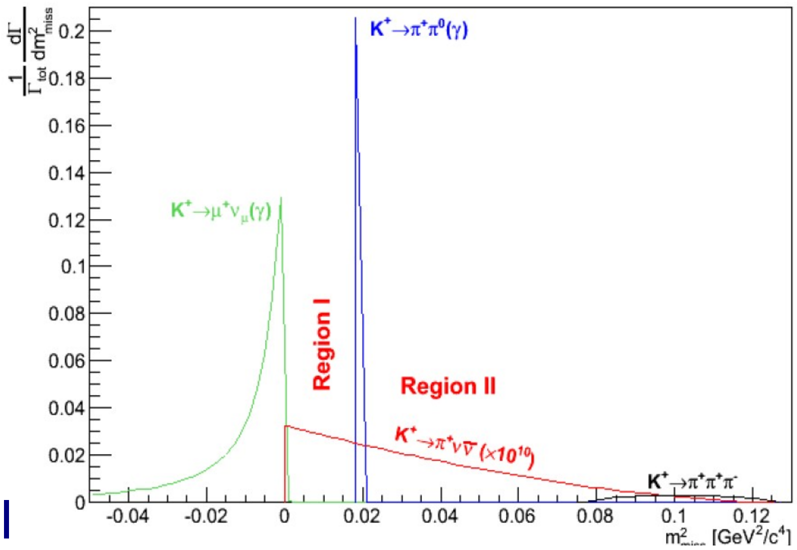


Experimental technique

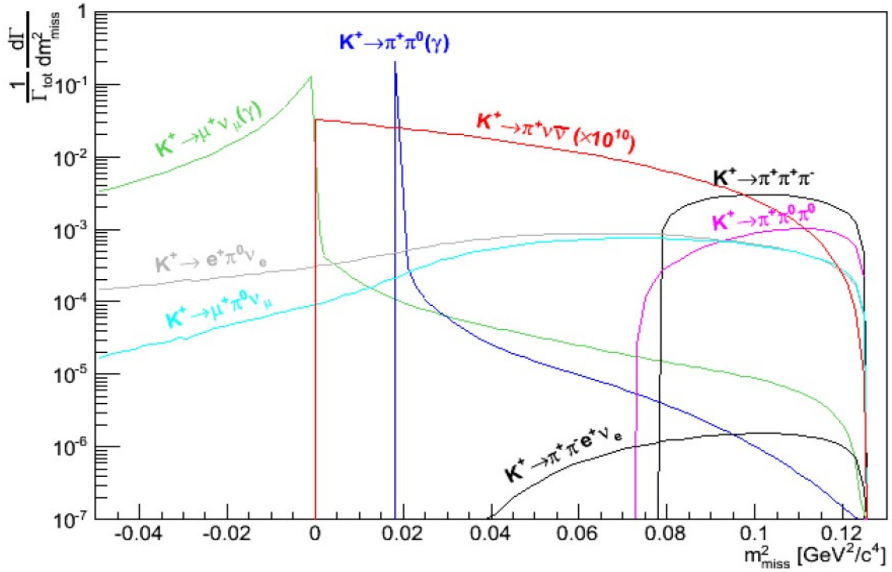


$$m^2_{miss} = m^2_K + m^2_\pi - 2(E_K E_\pi - p_K p_\pi \cos\theta_{K\pi})$$

measured quantities



- Single observable decay product in the final state
- 92% of the background has closed kinematics: **define 2 signal regions**



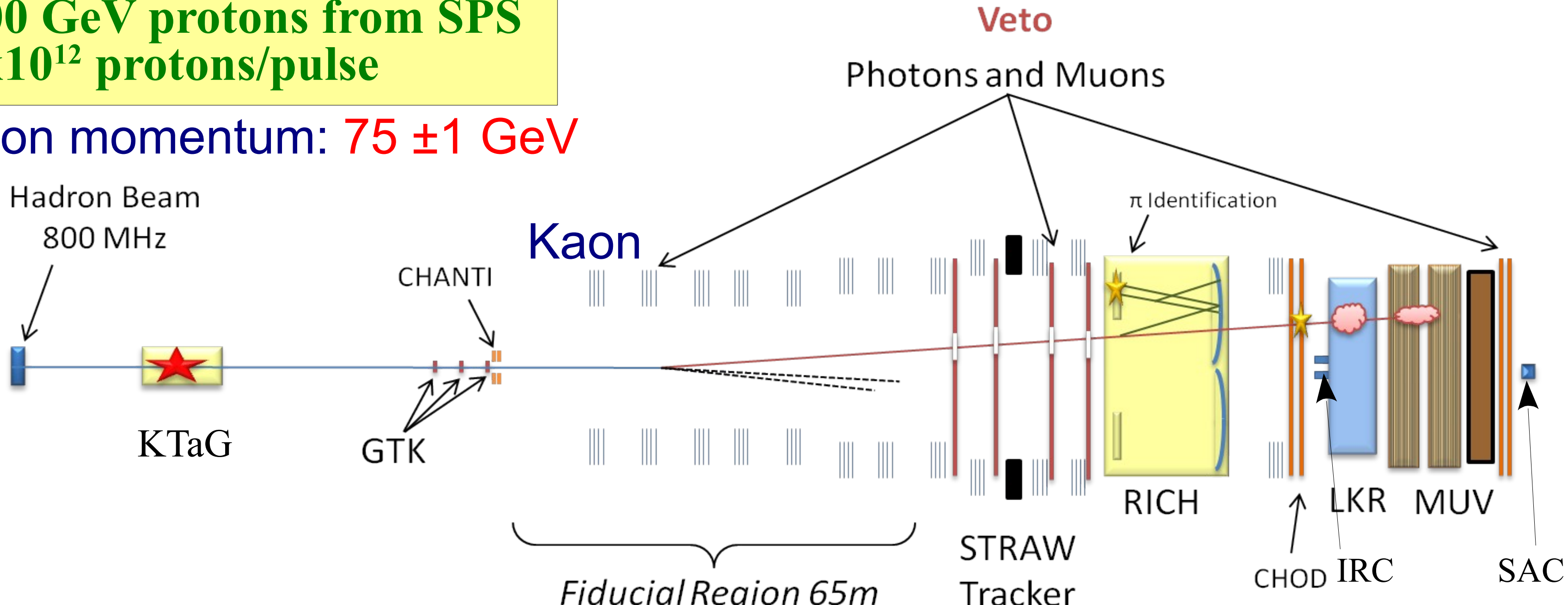
Event selection

Particle identification
Kinematics reconstruction
Particle vetoing

Experimental setup

400 GeV protons from SPS
$3x10^{12}$ protons/pulse

Kaon momentum: 75 ±1 GeV



Unseparated hadron beam: kaon component 6%

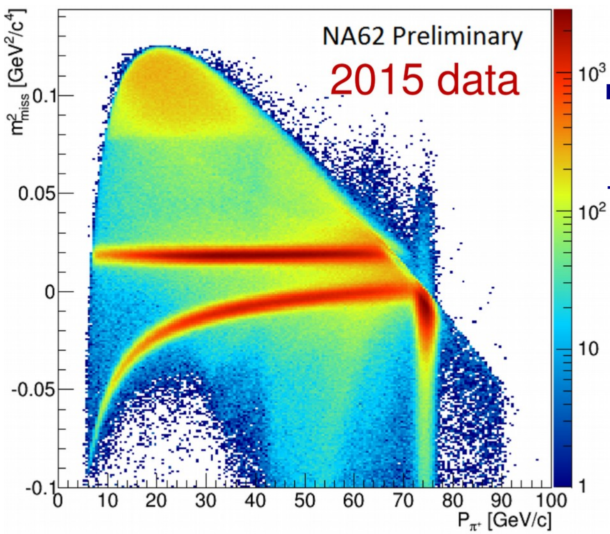
Expected $4.5*10^{12}$ kaon decays per year

- Data taking in 2014 and 2015
  - Beam commissioned up to nominal intensity
  - Performance studies (minimum bias data)
  - Nominal intensity data with CALO trigger

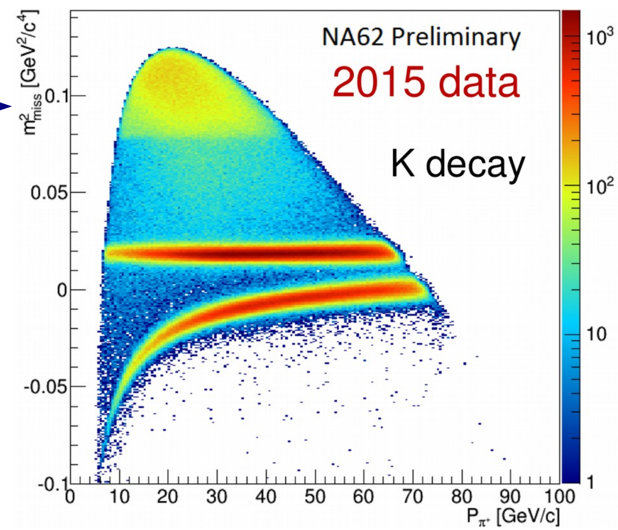
Almost all systems commissioned

GTK and L1(L2) partially

Particle ID



Kaon ID



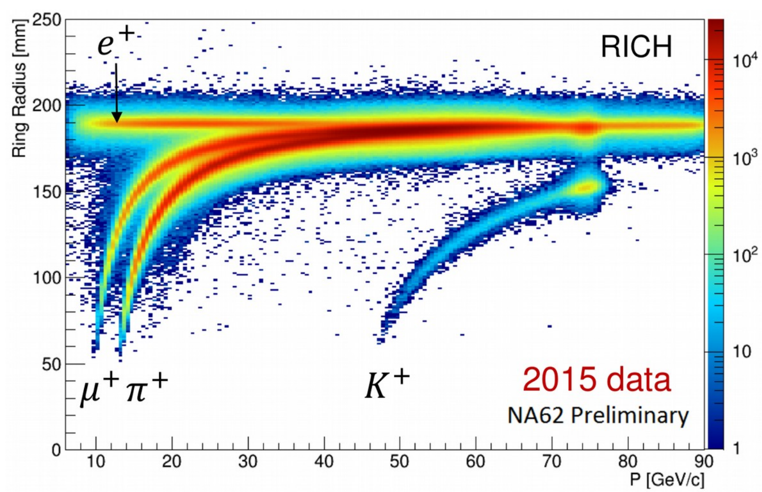
Selection

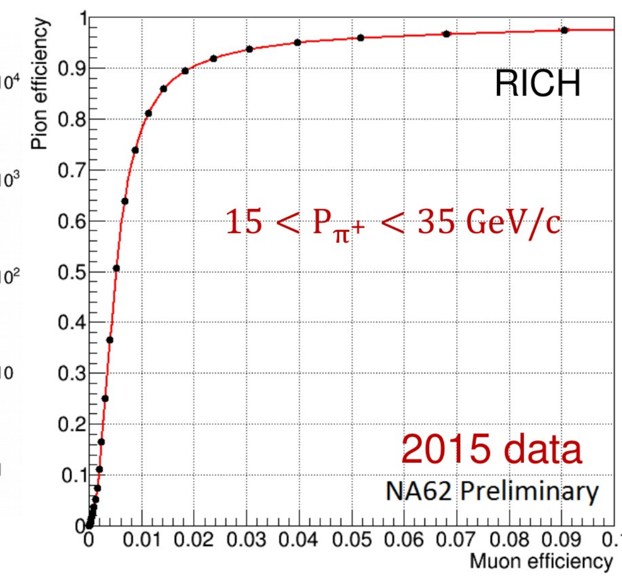
- Single downstream track (DS)
- Beam track matching the downstream track
- Kaon ID
- Downstream track matching energy in calorimeters

- Pion PID: **RICH**

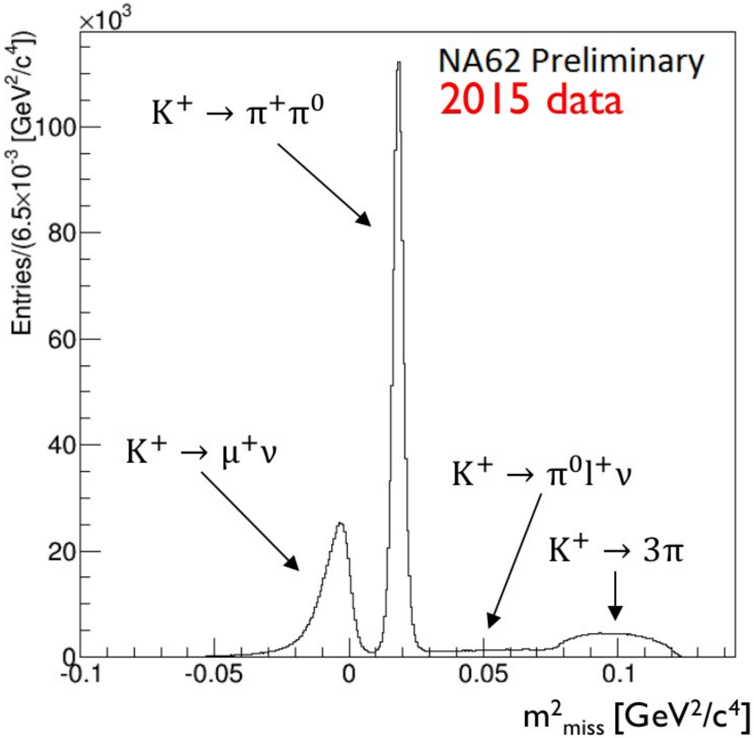
15 GeV/c < $P_{\pi+}$ < 35 GeV/c

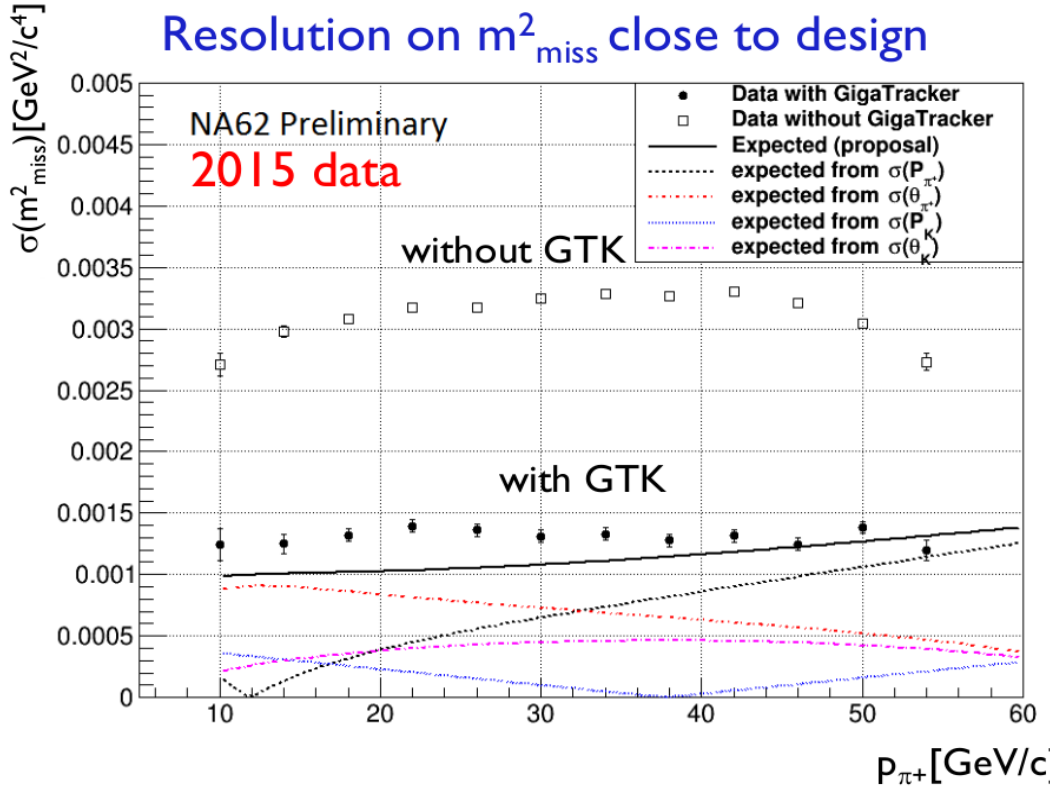
- O(10^2) π/μ separation
- 80 % efficiency for π^+ in 2015





Kinematics

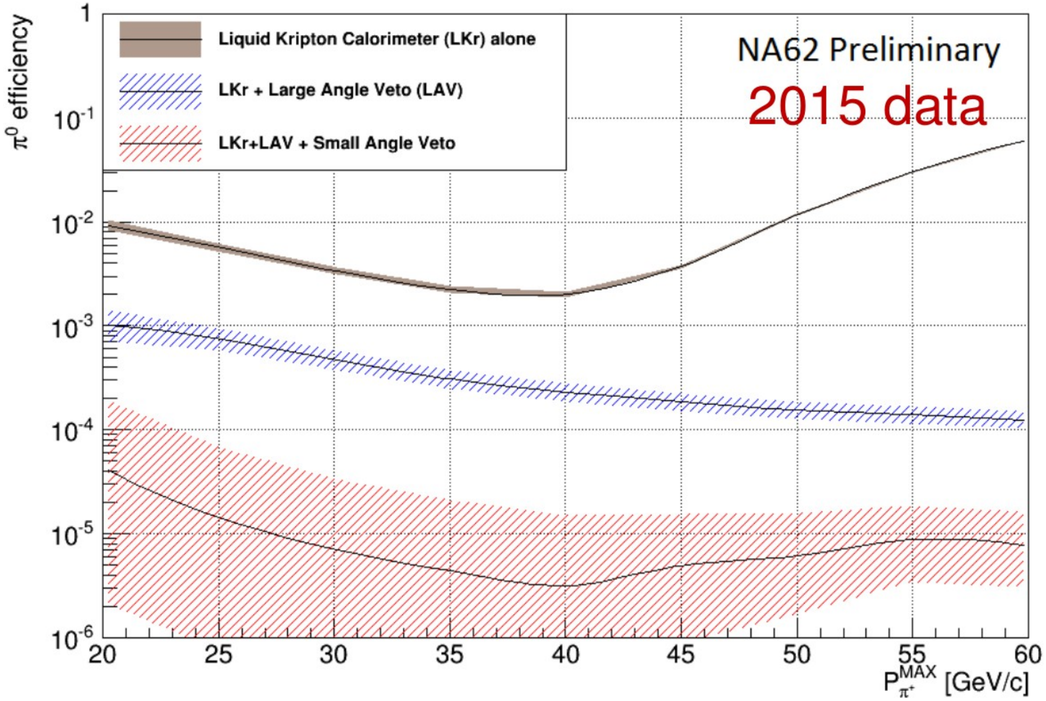




- $|M_{miss}|^2$ reconstruction
  - Si-pixel beam tracker
  - Straw tube tracker in vacuum
- Studied with $K^+ \to \pi^+\pi^0$ events, LKr calorimeter selection
- $O(10^3)$ suppression factor in 2015 achieved (10^5 expected)

Vetoing

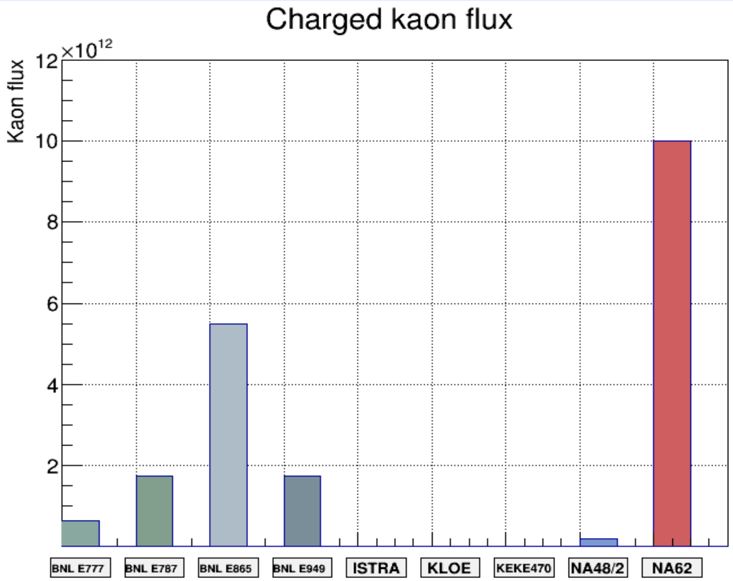
- Photon veto
  - LKr , LAV, SAC, IRC
  - 10^8 π^0 rejection factor expected
  - $E(\pi^0) > 40$ GeV for $K^+ \rightarrow \pi^+\pi^0$
  - Selected $K^+ \rightarrow \pi^+\pi^0$ sample based on kinematics
  - 2015 efficiency measurement statistically limited



- Muon rejection
  - In 2015: calorimetry, cut based
  - $10^4 - 10^6$ μ^+ suppression
  - 90% – 40% π^+ efficiency

- Time resolutions
  - Kaon ID: < 100 ps
  - Beam track: < 200 ps
  - Downstream track: < 200 ps
  - Calorimeters 1-2 ns

NA62: kaon factory



- Excellent particle veto efficiency
- Excellent momentum resolution
- Particle ID efficiency
- High kaon flux

Mode	Present	Expected
R_K	0.4%	**0.2%**
$K^+ \to \pi^+ \gamma\gamma$	<500 events	**10^5 events**
$K^+ \to \pi^0 \pi^0 e^+ \nu$	66000	**$O(10^6)$**
$K^+ \to \pi^0 \pi^0 \mu^+ \nu$	-	**$O(10^5)$**

Mode	BSM Physics	90% CL present limit	NA62
$K^+ \to \pi^+ \mu^+ e^-$	LFV	**$1.3 * 10^{-11}$**	**$10^{-12}/10^{-13}$**
$K^+ \to \pi^+ \mu^- e^+$	LFV	**$5.2 * 10^{-10}$**	**$10^{-12}/10^{-13}$**
$K^+ \to \pi^- \mu^+ e^+$	LNV	**$5 * 10^{-10}$**	**$10^{-12}/10^{-13}$**
$K^+ \to \pi^- e^+ e^+$	LNV	**$6.4 * 10^{-10}$**	**10^{-12}**
$K^+ \to \pi^- \mu^+ \mu^+$	LNV	**$1.1 * 10^{-9}$**	**$10^{-12}/10^{-13}$**
$K^+ \to \mu^- \nu e^+ e^+$	LFV/LNV	**$2 * 10^{-8}$**	**10^{-12}**
$K^+ \to e^- \nu \mu^+ \mu^+$	LFV/LNV	**No data**	**10^{-12}**
$K^+ \to \pi^+ X^0$	New particle	**$5.9 * 10^{-11}, m_{X_0} = 0$**	**10^{-12}**
$K^+ \to \pi^+ \chi\chi$	New particle	**-**	**10^{-12}**
$K^+ \to \pi^+ \pi^+ l^- \nu$	$\Delta S \neq \Delta Q$	**$1.2 * 10^{-8}$**	**10^{-11}**
$K^+ \to \pi^+ \gamma$	Angular momentum	**$2.3 * 10^{-9}$**	**10^{-12}**
$K/D \to l \nu_h$, $\nu_h \to \pi l$	Heavy neutrino		
$\pi^0 \to$ invisible, $\pi^0 \to 3/4\gamma$, $\pi^0 \to U \gamma$			
Dark sector: long living dark photon, long living ALPs			

Conclusion

- Rare kaon decays provide a very challenging opportunity to search for physics beyond the Standard Model
- Different LNV and heavy neutrino models probed through $K^{\pm} \rightarrow \pi^{\pm/\mp}\mu^{\pm}\mu^{\mp/\pm}$ decays
- NA62 experiment is commissioned and tested up to nominal intensity
- NA62 currently takes data – 200 days run in 2016

10% measurement of Br($K^{+} \rightarrow \pi^{+}\nu\nu$) waits behind the corner