Neutral pion form factor measurement and Search for $K^+ \to \pi^+ \nu \bar{\nu}$ at NA62

Michal Zamkovsky

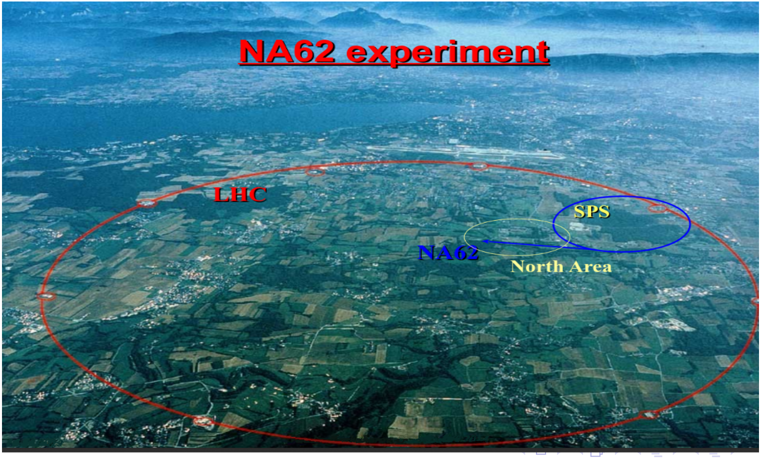
Charles University in Prague

July 13, 2016

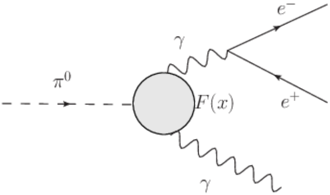
Outline

- Measurement of the π^0 transition form factor on 2007 data
- Status and prospects for $\mathrm{K}^+ \rightarrow \pi^+ \nu \bar{\nu}$
    - Theoretical motivation
    - NA62 setup
    - Event selection and analysis strategy
    - Analysis status/prospects

- SPS experiment NA62 - North Area experiment, Prèvessin
- Extracting 74 GeV/c K^+ from 400 GeV/c proton beam
- First phase (2007) using NA48 detector setup - π^0 TFF measurement



Dalitz Decay: $\pi^0 \to e^+e^-\gamma$



- π^0_D decay - kinematic variables x, y :

$$x = \frac{(p_{e^+} + p_{e^-})}{m^2_{\pi^0}}, \quad y = \frac{2p_{\pi^0} \cdot (p_{e^+} - p_{e^-})}{m^2_{\pi^0}(1-x)}$$

- Differential decay width ($r^2 = (2m_e/m_{\pi^0})^2 \equiv m_{min}$):

$$\frac{1}{\Gamma(\pi^0_{2\gamma})} \frac{d^2\Gamma(\pi^0_D)}{dxdy} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} (1 + y^2 + \frac{r^2}{x})(1 + \delta(x,y))|F(x)|^2$$

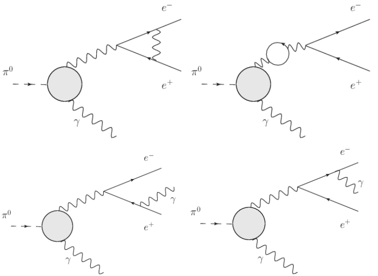
F(x) $\approx 1 + ax$ $\qquad$ a : *TFF slope parameter*

- π^0 TFF slope measurement at NA62 (Kaon decay experiment)
  - $K^\pm \to \pi^\pm\pi^0$ decay: source of tagged π^0 decays (BR($K_{2\pi}$) $\approx$ 21%)
  - NA62 in 2007: data taking conditions optimized for $e^\pm$ from $K^\pm \to e^\pm\nu_e$
    $\to$ large and clean sample of $K^\pm \to \pi^\pm\pi^0$; $\pi^0 \to \gamma e^+e^-$ decays

π^0_D : *Radiative Corrections*

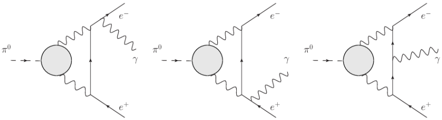
Mikaelian and Smith

Phys. Rev. D5(1972) 1763

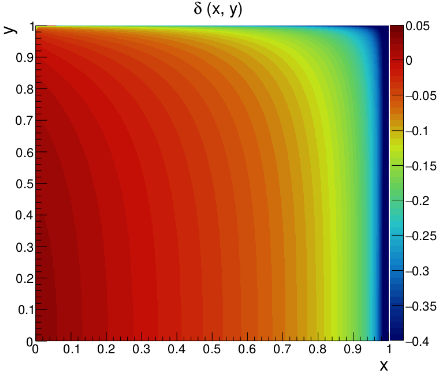


Husek, Kampf and Novotny

Phys. Rev. D92(2015) 5, 054027



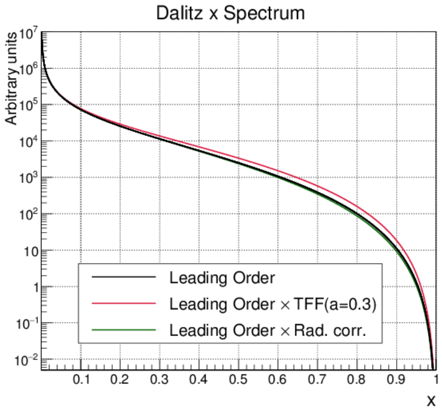
$$\frac{d^2\Gamma}{dxdy} = \left(\frac{d^2\Gamma}{dxdy}\right)_0 (1 + \delta(x,y))$$



- Corrections included in the simulation
- Radiative photon emission simulated

π^0_D : $d\Gamma/dx$ *and Transition Form Factors*

$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d\Gamma(\pi^0_D)}{dx} = \frac{2\alpha}{3\pi}\frac{(1-x)^3}{x}(1+\frac{r^2}{x})\sqrt{1-\frac{r^2}{x}}(1+\delta(x,y))(1+ax)^2$$



- π^0 TFF slope expectation from Vector Meson Dominance model: $a \approx 0.03$
- π^0 TFF theoretical models enter hadronic light-by-light scattering (HLbL) contribution to $(g-2)_\mu$
- See recent overview and references in: A. Nyffeler, arXiv:1602.03398 [hep-ph]
  $\rightarrow$ Comparison of TFF slope prediction with model independent measurement: important test of the theory models

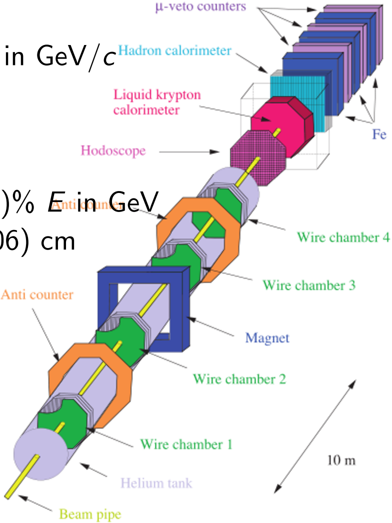
Experimental setup in 2007 NA62

- Detector performances and resolutions:

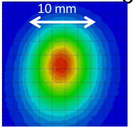
DCH
$$\sigma_x = \sigma_y = 90\mu\text{m}$$
$$\sigma_p/p = (1.02 \oplus 0.044 \cdot p)\%\ p \text{ in GeV}/c$$

HOD
$$\sigma_t \sim 150 \text{ ps}$$

LKr
$$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%\ E \text{ in GeV}$$
$$\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06) \text{ cm}$$

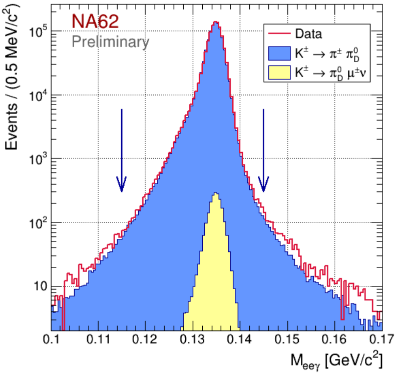


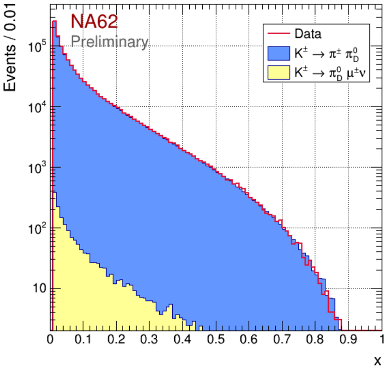
- Beam: simultaneous K^+ and K^- with a central momentum 60 GeV/$c \pm 3.8\%$ (rms)
  - Focused at DCH1 with $\sim$ 10 mm transverse size
  - Superimposed beam axes within 1 mm



π^0_D : *TFF Selection*

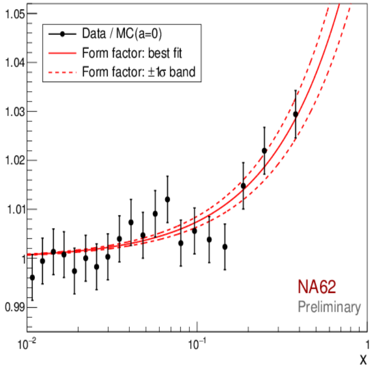
- Selection: 3-track topology, photon in LKr, full kinematic closure, x > 0.01
- 1.05×10^6 fully reconstructed $\pi^0 \to \gamma e^+ e^-$
- TFF obtained by adjusting the simulation to the data x spectrum

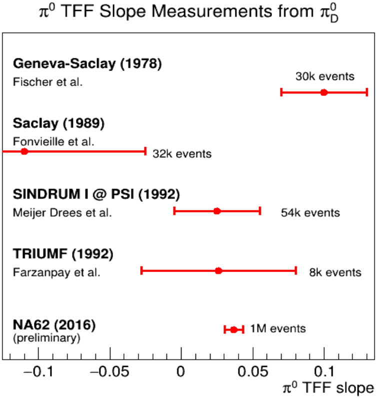




$\pi^0 \to \gamma e^- e^+$ *TFF: Preliminary results*

$$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$$



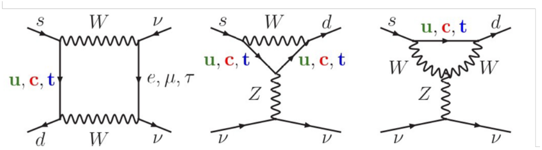


TFF Theory expectations:

- $a = 2.90 \pm 0.50 \times 10^{-2}$, χPT, [K. Kampf et al. EPJ C46 (2006), 191]
- $a = 3.07 \pm 0.06 \times 10^{-2}$, dispersion theory, [M. Hoferichter et al. EPJ C74 (2014), 3180]
- $a = 2.92 \pm 0.04 \times 10^{-2}$, two-hadron saturation, [T. Husek et al. EPJ C75 (2015) 12, 586]

$K^+ \to \pi^+ \nu\bar{\nu}$: Theoreticalmotivation

- FCNC loop process: s→d coupling and highest CKM suppression



- Very clean theoretically: Short distance contribution and no hadronic uncertainties - Hadronic matrix element extracted from well-known decay $K^+ \to e^+ \nu \pi^0$
- SM predictions: [Buras et al. arXiv:1503.02693], [Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 (2011)]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2}\right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

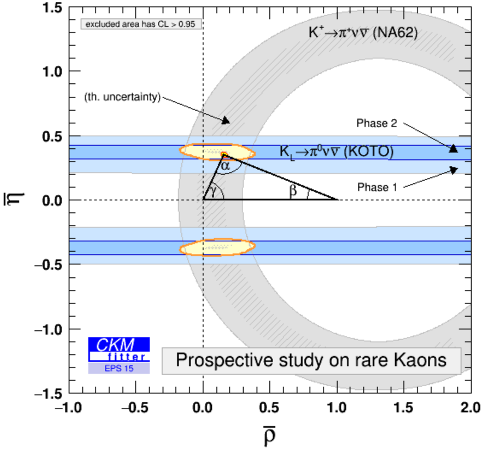
$$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6) \cdot 10^{-11}$$

- Experiments:

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys.Rev.D77, 052003(2008), Phys.Rev.D79, 092004(2009)

$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ Phys.Rev.D81, 072004(2010)

- BR($K^+ \to \pi^+\nu\bar{\nu}$) with 10% uncertainties allows to determine $|V_{td}|$ at 9% [Buras 0405132]
- With BR($K^+ \to \pi^+\nu\bar{\nu}$), BR($K^0_L \to \pi^0\nu\bar{\nu}$) the CKM unitarity triangle can be built independently from B observables:

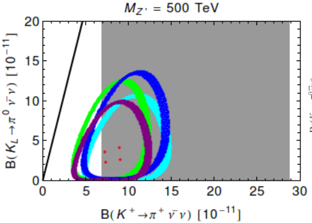


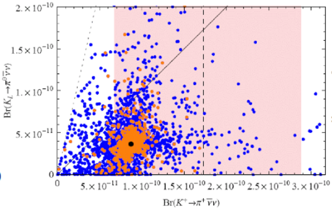
Going Beyond the Standard Model

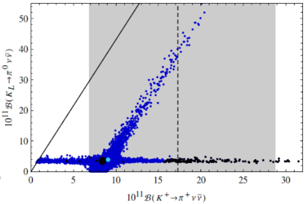
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, arXiv:1507.08672 (2015)]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, arXiv:1507.06316 (2015)]
- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV [Blazek, Matak Int.J.Mod.Phys.A29 (2014) 1450162;
  Tanimoto, Yamamoto PTEP (2015) 053B07; Isidori et al. JHEP 0608 (2006) 064]

- Constraints from existing measurements (correlations model dependent):
  Kaon mixing and CPV, CKM fit, K,B rare meson decays,
  NP limits from direct searches

Z′ model | *Randall − Sundrum* | *LittlestHiggs*



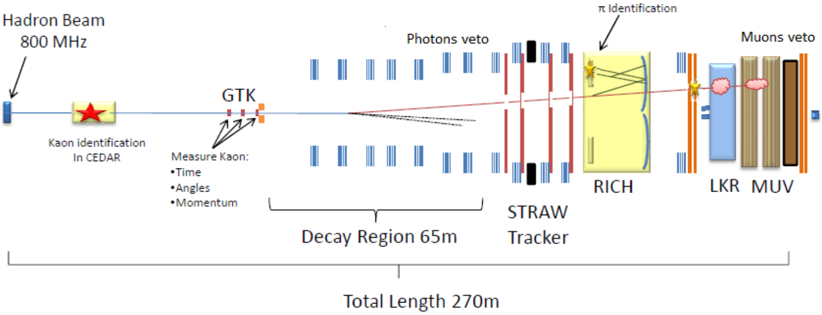




- Main goal:
  - Collect O(100) signal events in 2 years ⇒ 10^{13} Kaon decays
  - Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% precision
  - Signal acceptance $\sim$ 10%
  - Systematics: <10% precision background measurement
  - $> 10^{12}$ background rejection ($<$ 20% background)
- Further goals:
  - Measure $|V_{td}|$ with $\sim$10% accuracy
  - Probe several NP scenarios in $K^+ \to \pi^+ \nu\bar{\nu}$
  - Probe NP in similar processes (e.g. $K^+ \to \pi^+ X$)
- Beyond the baseline:
  - LFV/LNV decays with 3 tracks in the final state
  - Heavy neutrino searches
  - π^0 decays
  - Dark photon searches

Detector layout

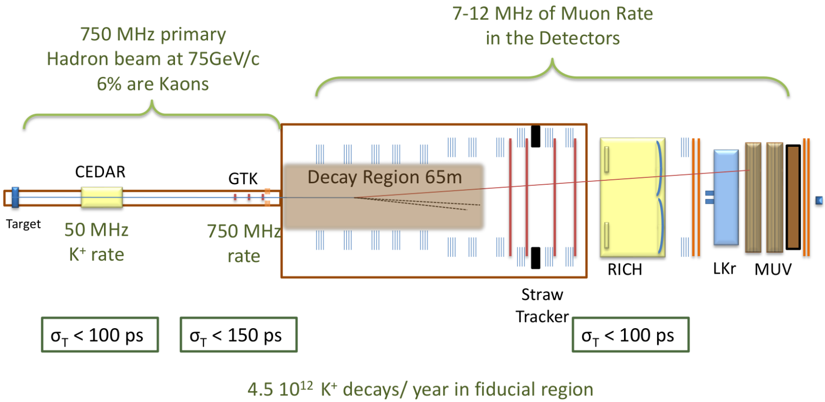
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

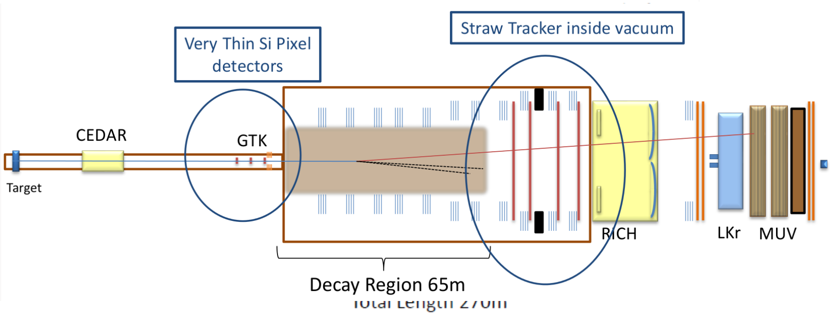
Detector layout

- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

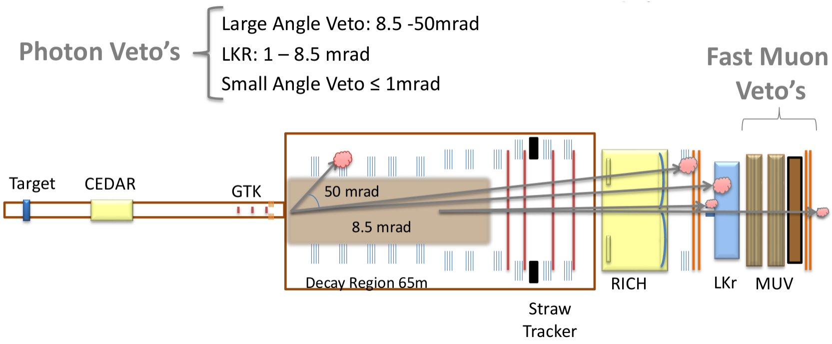
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

Detector layout

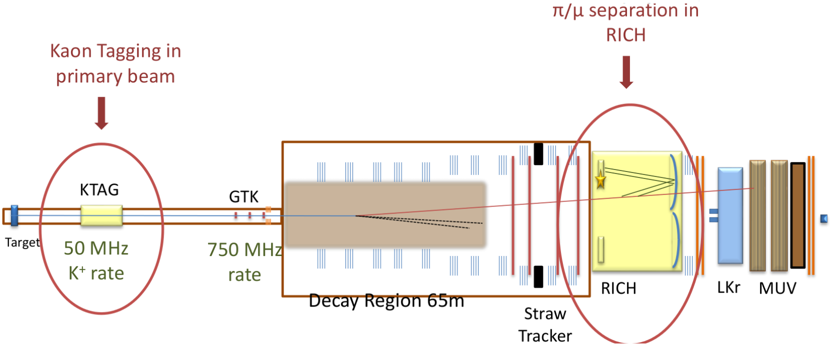
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

Detector layout

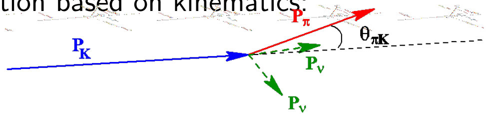
- $\sim$ 11MHz of K^+ decays



- High Intensity and fast Timing
- Low Mass Tracking
- Hermetic Vetoing for Photons and Muons
- Particle ID

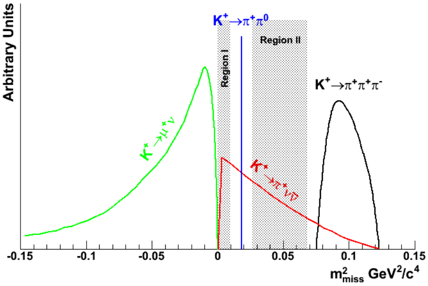
Scheme for $K^+ \to \pi^+ \nu\bar{\nu}$

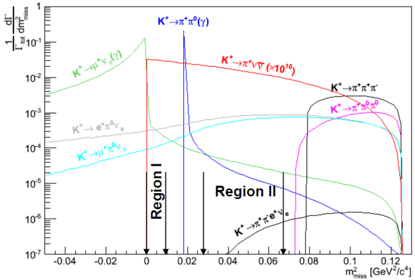
- Reconstruction based on kinematics:



$$m^2_{miss} = (P_K - P_\pi)^2 \approx m^2_k \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\vartheta^2_{\pi K}$$

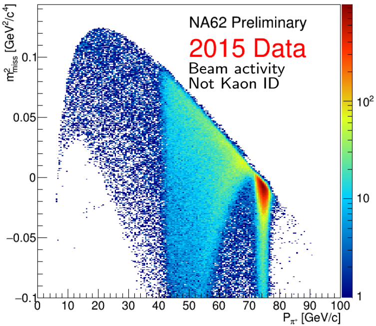
- 92% of Kaon decays are kinematically constrained
- Expected 45 SM signal events/year with $\leq$ 10 background

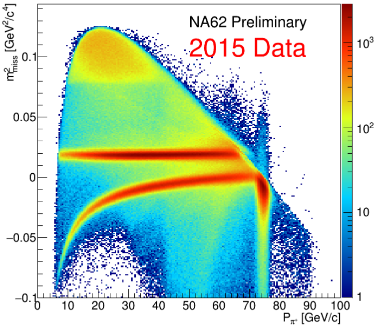




One-track selection

- Single downstream track topology
- Beam track matching the downstream track
- Beam track matching a K signal in Kaon ID
- Downstream track matching energy

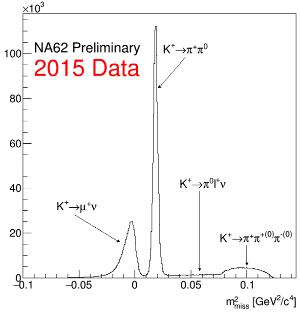


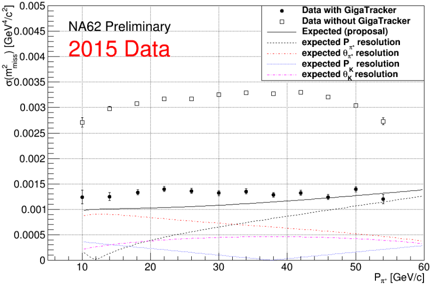


Time resolutions:

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

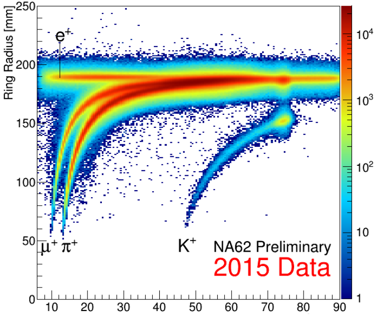
Kinematics

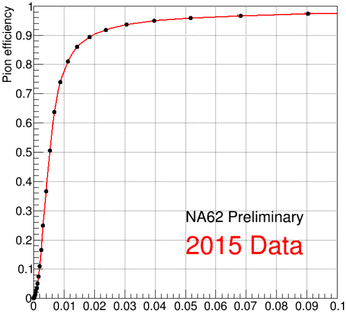




- Technique: Si-pixel tracker; Straw tube tracker in vacuum
- Goal: $O(10^4 \div 10^5)$ suppression factor of the main kaon decay modes
- $P_{\pi^+} < 35$ GeV$/c$: best $K^+ \to \mu^+\nu$ suppression
- Kinematics studied on $K^+ \to \pi^+\pi^0$ selected using LKr calorimeter. Resolutions close to the design. $O(10^3)$ kinematic suppression factor in 2015.

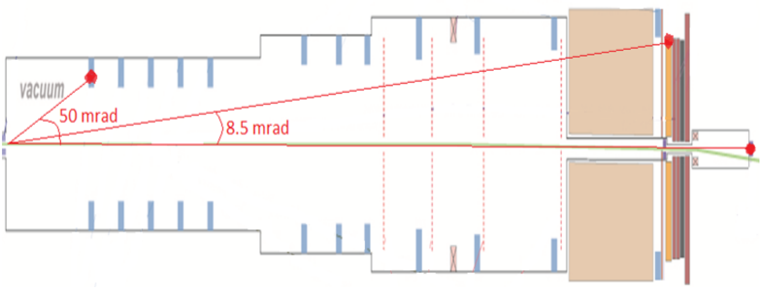
Particle ID



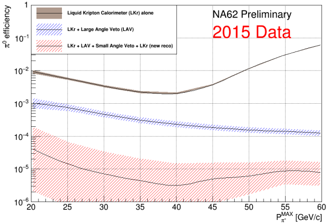


- Technique: RICH and calorimeters
- Goal: O(10^7) μ/π separation to suppress mainly $K^+ \to \mu^+\nu$
  $15 < P_{\pi^+} < 35$ GeV/c: best μ/π separation in RICH
- Pure samples of pions and muons selected using kinematics
- RICH: O(10^2) μ/π separation, 80% π^+ efficiency in 2015
- Calorimeters: $10^4 \div 10^6$ μ^+ suppression, 90% $\div$ 40% π^+ efficiency in 2015 using a cut analysis. Room for improvements.

Photon rejection



- Technique: EM calorimeters exploiting correlations between γs' from π^0
- Goal: O(10^8) rejection π^0 from $K^+ \rightarrow \pi^+\pi^0$
- $P_{\pi^+} < 35$ GeV$/c \Rightarrow E_{\pi^0} > 40$GeV
- Measured on data using $K^+ \rightarrow \pi^+\pi^0$ selected kinematically
- 2015 measurement statistically limited



Conlusions

- Preliminary world best measurement of the π^0 transition form factor slope (NA62 2007 data):

$$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$$

- $\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}$ branching ratio measurement
  - The decay provides unique opportunities for NP searches complementary to LHC
  - The NA62 is aimed at measuring BR($\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}$) with $\sim$10% precision by collecting O(100) events in two years of data taking
  - Most detectors were successfully commissioned during the 2014-2015 runs; detector performance within expectations
  - NA62 is taking data in 2016-2018

Analysis strategy and background sources

- Key analysis requirements:
  - 2 signal regions in m^2_{miss}
  - $15 < P_{\pi^+} < 35$ GeV/c
  - 65 m long decay region
- Expected 45 SM signal events/year with ≤ 10 background
- Main background sources:

Decay mode	event/year
$K^+ \to \pi^+\nu\bar{\nu}$ SM	45
Total Background	10
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^+\pi^-$	< 1
$K^+ \to \pi^+\pi^- e^+\nu$ + other 3 track decays	< 1
$K^+ \to \pi^+\pi^0\gamma^{IB}$	1.5
$K^+ \to \mu^+\nu\gamma^{IB}$	0.5
$K^+ \to \pi^0 e^+(\mu^+)\nu$ + others	negligible

- Other possible background:
  - Accidental tracks in time with kaon tracks
  - Beam-gas and upstream interactions

Further NA62 physics programme

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9\times10^{-11}\ m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h\to\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$