Results and Perspectives from the NA62 Experiment at CERN

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on behalf of the NA62 Collaboration

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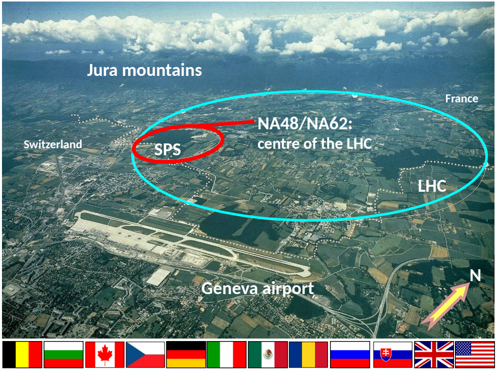
Kaon Decay in Flight Experiments at CERN



NA62: ≈200 participants, 30 institutes

NA31 (1980s): K_L/K_S
$\to$ First evidence of Direct CP violation in neutral Kaon Decays

NA48 (1997 – 2001): K_L/K_S
$\to$ Direct CP violation discovery

NA48/1 (2002): K_s, hyperons
$\to$ Rare decay studies

NA48/2 (2003 – 2004): K^+/K^-
$\to$ $K^\pm$ precision measurements

NA62 (2007): K^+/K^-
$\to$ Lepton universality: $K_{e2}/K_{\mu 2}$

NA62 (2015 –): K^+
$\to$ Main goal: BR($K^+ \to \pi^+ \nu \bar{\nu}$)
$\to$ Rare decay studies
$\to$ LFV, LNV decays
$\to$ Search for heavy ν, axions, . . .

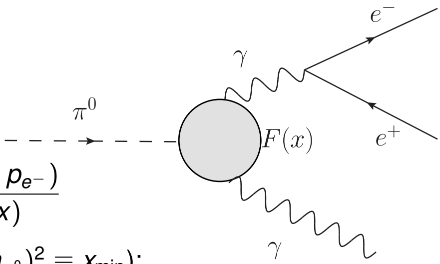
Outline

1. NA62 preliminary result:

NEW π^0 transition form factor slope measurement (2007 data analysis)

2. $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio measurement at NA62: status and prospects

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



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

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

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

Transition Form Factor (TFF)

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

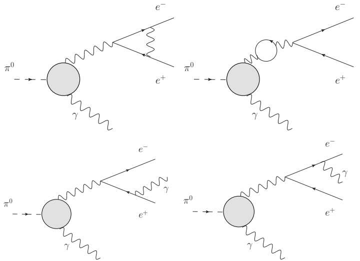
$$F(x) \approx 1 + a\, x, \qquad a: \textit{TFF slope parameter}$$

- 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

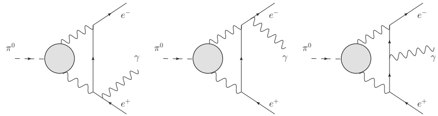
π^0_D: Radiative Corrections

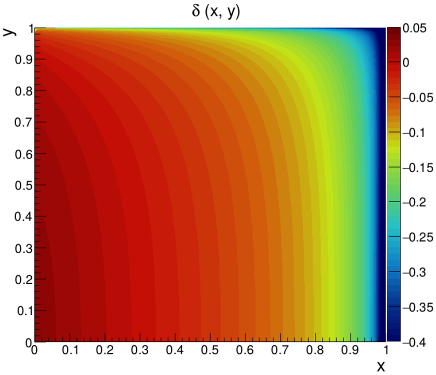
Mikaelian and Smith
Phys.Rev. D5 (1972) 1763



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

Husek, Kampf and Novotny
Phys.Rev. D92 (2015) 5, 054027

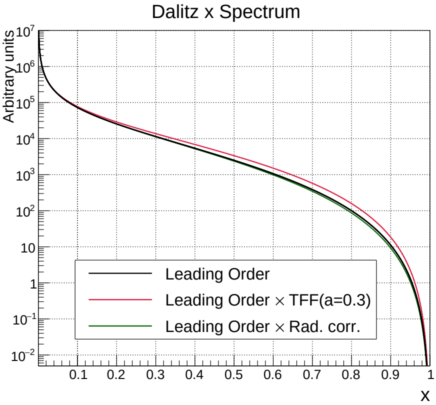




→ Corrections included in the simulation
→ Radiative photon emission simulated

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

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



- 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]

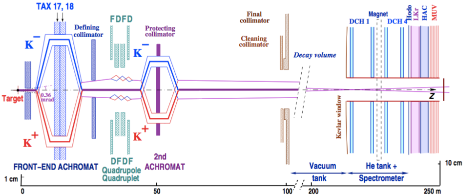
  $\rightarrow$ Comparison of TFF slope prediction with model independent measurement: important test of the theory models

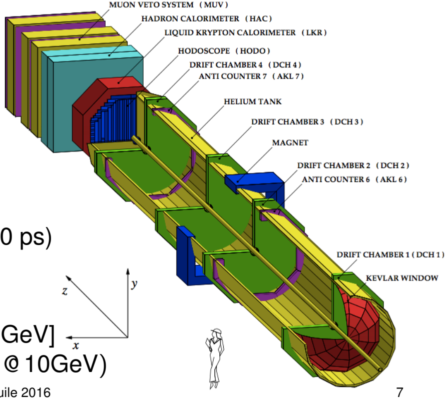
NA62 Experiment and Detector in 2007

- Main goal:
  $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ measurement:
  Phys. Lett. B 719 (2013) 326
- $K^\pm$ beam momentum: (74 ± 2) GeV/c
- Main trigger: electron from K_{e2}
  $\to$ Efficient for π^0_D decays

Principal subdetectors:

- Magnetic spectrometer (4 DCHs)
  $\to$ 4 views/DCH $\to$ high efficiency
  $\to$ $\sigma_p/p = 0.48\% \oplus 0.009\% \cdot p$ [GeV/c]
- Scintillator hodoscope (HOD)
  $\to$ Low-level trigger, time measurement (150 ps)
- Liquid Krypton EM calorimeter (LKr)
  $\to$ High granularity, quasi-homogeneous
  $\to$ $\sigma_E/E = (3.2/\sqrt{E} \oplus 9/E + 0.42)\%$ [E in GeV]
  $\to$ $\sigma_x = \sigma_y = (4.2/\sqrt{E} \oplus 0.6)$ mm (1.5 mm @ 10GeV)





$K^\pm \to \pi^\pm \pi^0; \pi^0 \to \gamma e^+ e^-$ Selection

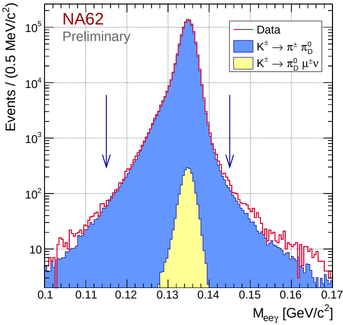
NA62 Data Sample:

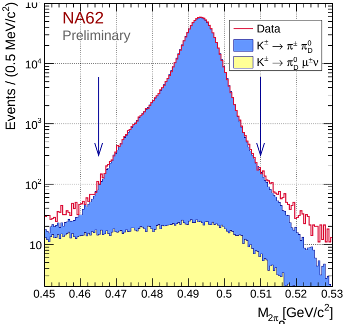
- $\sim 2 \times 10^{10}$ kaon decays in the decay region
- $\sim 5 \times 10^9$ boosted π^0 mesons from $K_{2\pi}$
  Mean free path of π^0: few μm (negligible)
- $\sim 6 \times 10^7$ π^0_D decays produced

Most important selection criteria:

- Three-track vertex topology
- One photon candidate in LKr calorimeter
- Reconstructed invariant mass of $e^+e^-\gamma$:
  115 MeV/c^2 $< M_{ee\gamma} <$ 145 MeV/c^2
- Reconstructed invariant mass of $\pi^\pm\pi^0$:
  465 MeV/c^2 $< M_{2\pi} <$ 510 MeV/c^2
- Reconstructed Dalitz x variable: $0.01 < x < 1$
- Missing momentum consistent with the beam size

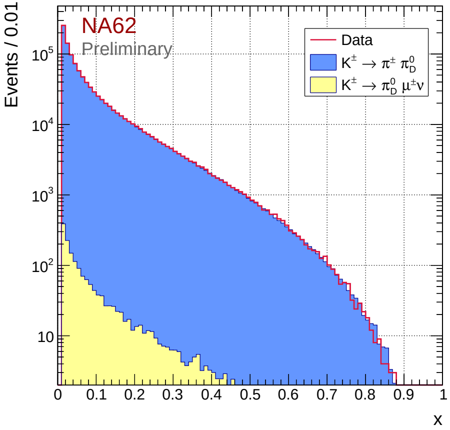
$\to$ 1.05×10^6 fully reconstructed π^0_D events



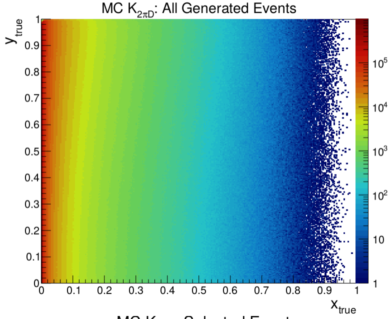


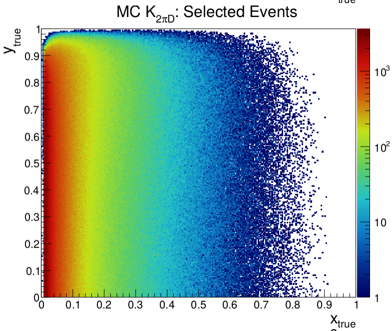
π^0_D Decay Sample

1.05×10^6 fully reconstructed π^0_D events with $x > 0.01$:



Monte Carlo simulation:





π^0 TFF Slope: NA62 Preliminary Result

Fit procedure:

- Split reconstructed Dalitz x data into equal population bins
- Compare data with simulation (constant TFF slope: $a_{\text{sim}} = 0.032$)
  $\rightarrow$ To obtain simulated x distribution, corresponding to different a slope: re-weight simulated events with weight $w(a) = (1 + a\, x_{\text{true}})^2 / (1 + a_{\text{sim}}\, x_{\text{true}})^2$
- Minimise $\chi^2(a)$ Data/Simulation comparison wrt a

Fit result:

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

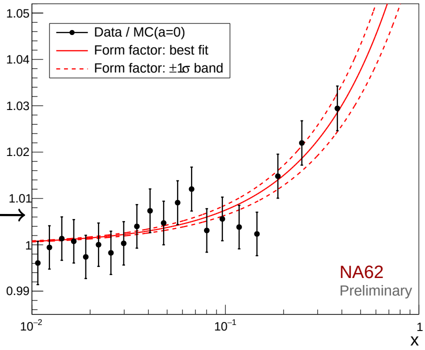
$(\chi^2/\text{n.d.f} = 52.5/49$, p-value: $0.34)$

Fit result illustration $\longrightarrow$

$\rightarrow$ Data / Simulation(a=0) ratio

$\rightarrow$ 20 equal population bins

$\rightarrow$ Points are in bin barycenters



π^0_D: Systematic Uncertainties

Source	$\delta a (\times 10^2)$
Statistical – Data	0.49
Statistical – MC	0.20
Beam momentum spectrum simulation	0.30
Spectrometer momentum scale	0.15
Spectrometer resolution	0.05
LKr non-linearity and energy scale	0.04
Particle mis-ID	0.08
Accidental background	0.08
Neglected π^0_D sources in MC	0.01

NA62 preliminary result on π^0 TFF slope parameter:

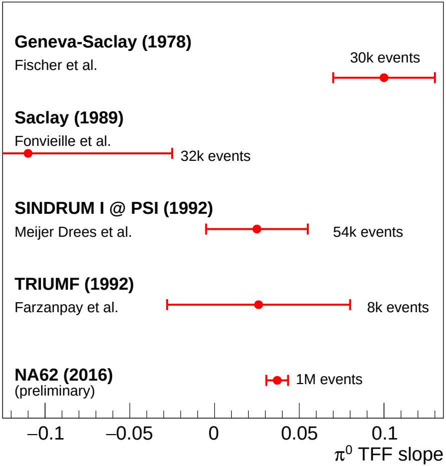
$$a = (3.70 \pm 0.53_{\mathrm{stat}} \pm 0.36_{\mathrm{syst}}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2}$$

NEW

Presented for the first time today.

π^0 TFF Slope: World Data

π^0 TFF Slope Measurements from π^0_D



TFF slope theory expectations:

K. Kampf et al., EPJ C46 (2006), 191.
Chiral perturbation theory:
$a = (2.90 \pm 0.50) \times 10^{-2}$

M. Hoferichter et al., EPJ C74 (2014), 3180.
Dispersion theory:
$a = (3.07 \pm 0.06) \times 10^{-2}$

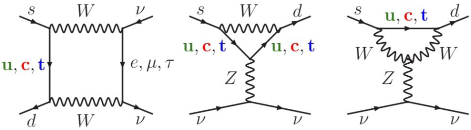
T. Husek et al., EPJ C75 (2015) 12, 586.
Two-hadron saturation (THS) model:
$a = (2.92 \pm 0.04) \times 10^{-2}$

CELLO measurement:

H. J. Behrend et al., Z. Phys. C49 (1991), 401.
Extrapolation of space-like momentum region data fit to VMD model:
$a = (3.26 \pm 0.26_{\text{stat}}) \times 10^{-2}$

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

- FCNC loop process, highly CKM suppressed, theoretically clean



- Dominated by short-distance contribution (BR $\sim |V_{ts}^* V_{td}|^2$)
- Sensitive to new physics, complementary to LHC searches
- SM prediction:

$$\mathrm{BR_{SM}}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$

[A.J. Buras et al., JHEP 1511 (2015) 033]

- Previous measurement (7 observed events):

$$\mathrm{BR_{exp}}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$$

[BNL E787/E949: PRL101 (2008) 191802]

NA62 Experiment

Goal

- Branching ratio measurement of $K^+ \to \pi^+\nu\bar{\nu}$
- 10 % measurement precision, Signal / Background $\sim$ 10
- Collection of $O(50)$ events per year of data taking

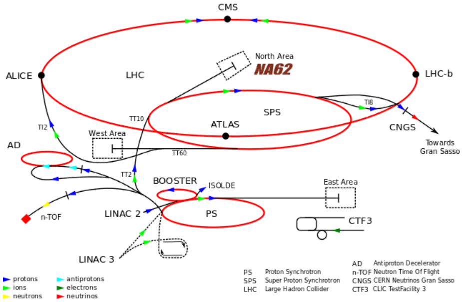
Requirements

- Large statistics, 4.5×10^{12} K^+ decays per year
  - High intensity kaon beam
  - Signal acceptance $\sim$ 10%
- Background rejection factor $> 10^{12}$
- Remaining background known to at least 10% precision

Technique

- High momentum K^+ beam (75 GeV/c) with kaon decay in flight
- Low momentum π^+ selection ($p_\pi < 35$ GeV/c) $\to$ large missing E

NA62 Beamline

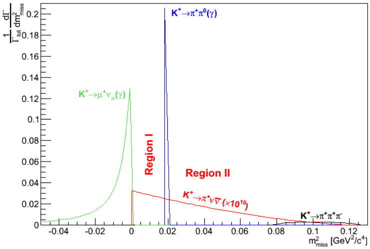


- Primary SPS protons (400 GeV/c)
- Protons on Be target: 3×10^{12} / pulse
- Secondary hadronic beam, p = 75 GeV/c $\sim 6\%\ K^+$ (others: π^+, protons)
- Total rate at beam tracker: 750 MHz
- Rate downstream: 10 MHz
- Simultaneous operation with LHC

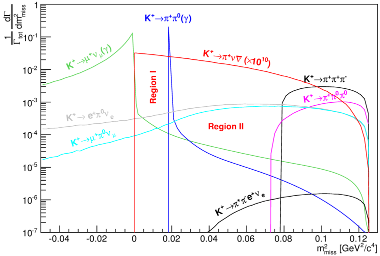
Signal and Main Backgrounds

- Signal signature: one K^+ track, one π^+ track, **nothing else**
- Backgrounds:
  1. K^+ decay modes
  2. Accidental single track matched with a kaon like track
- Kinematic variable: $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$
  - Two m^2_{miss} regions for event candidates are defined

92% background rejection by kinematic cuts



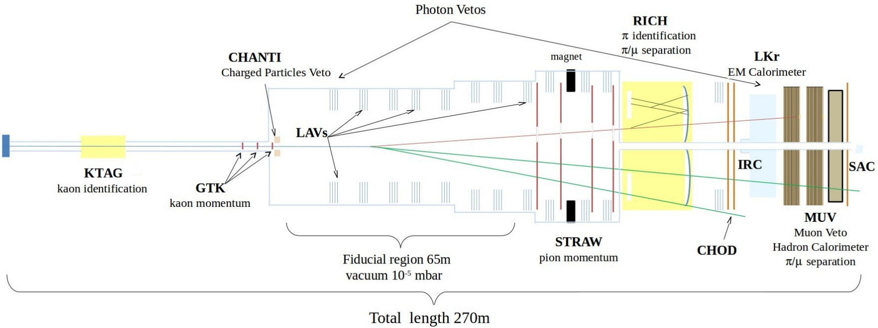
8% of background not separated by kinematics



$\Rightarrow$ Need for efficient photon vetoes and particle ID

Guiding Principles for the NA62 Detectors

1. High intensity and precise timing (< 1 ns)
2. Good tracking detectors → K^+ (GTK) and π^+ (Straw) momentum vectors
3. Hermetic veto detectors → photons (LAV, LKr, SAC, IRC), muons (MUV)
4. Particle identification → kaons in the beam (KTAG), π/μ separation (RICH)

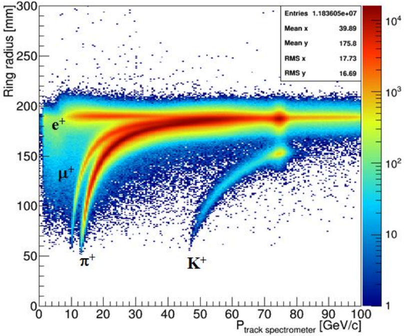


NA62 Status

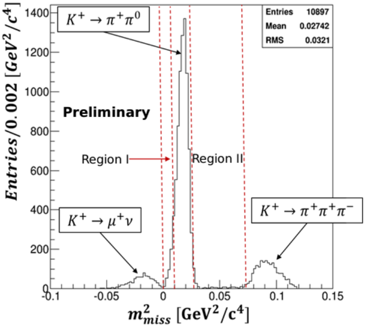
- 2014: NA62 pilot physics run
- 2015: First physics run: $\to 2 \times 10^{10}$ triggers recorded on tape
- 2016: Resume data taking

NA62 Status

Ring radius in RICH vs. Momentum



$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



- Only small part of data sample presented
- Reconstructed m^2_{miss} plot:
  - Preliminary calibrations and track reconstruction used
  - No photon and muon rejection
  - No pion/muon separation
- Analysis ongoing, stay tuned!

Summary

1. NA62 π^0 transition form factor slope measurement:

NEW

$$a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2}$$

   - Preliminary result based on NA62 2007 data analysis
   - Neutral pions from $K^\pm \to \pi^\pm \pi^0$ decays
   - $\sim$1 million fully reconstructed π^0_D decays
   - Improves TFF precision in the time-like momentum region

2. $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio measurement status
   - NA62 Beam line fully commissioned
   - NA62 Detector installation completed
   - Physics data taking started in 2015

NA62 Sensitivity

Decay	events / year
$K^+ \to \pi^+\nu\bar{\nu}$ [SM]	45
$K^+ \to \pi^+\pi^0$	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
$K^+ \to \mu^+(e^+)\pi^0\nu$, others	negligible
Total background	< 10

Nominal intensity: 4.5×10^{12} K^+ decays in the fiducial region / year

Cut and count analysis without any optimization

Further NA62 Physics Program

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	5.9×10^{-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	$(2.488 \pm 0.010) \times 10^{-5}$	>×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	-	$O(10^5)$