Status of the NA62 Experiment

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on behalf of the NA62 Collaboration

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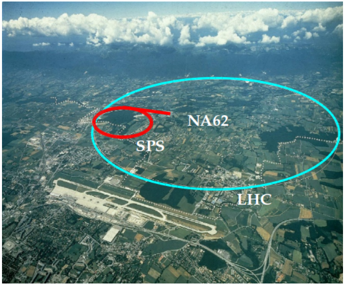
Workshop on "Flavour changing and conserving processes" 2019 (FCCP2019)

The NA62 experiment

Main goal: measurement of BR($K^+ \to \pi^+ \nu \bar{\nu}$) with *O(100)* events

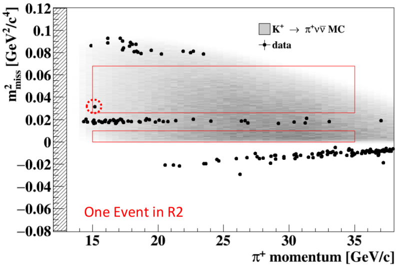


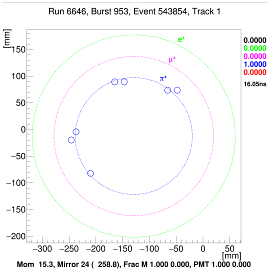
NA62 Collaboration consists of ∼200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Merced, Moskow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, Turin, TRIUMF, Vancouver UBC

Status of the experiment

- Full detector installation completed in 2016.
- Three years of data taking for physics completed: 2016-2018.
- First results with 2016 data presented last year (see below).
- 2017 data analysis ongoing (this talk), analysis of 2018 data will follow.
- Request for beam after the LS2 at CERN (2021-2024) will be submitted soon.

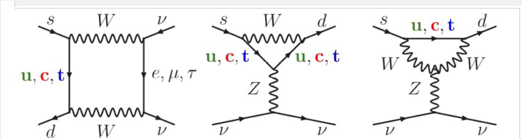
From 2016 analysis:
0.27 ± 0.04 SM event expected, $0.15^{+0.09}_{-0.04}$ estimated background, 1 event observed:





$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \cdot 10^{-10}$ @ 95% CL *[Phys. Let. B 791 (2019) 156]*

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay in the Standard Model framework



- $\bar{s} \to \bar{d}\nu\bar{\nu}$ **transition**: flavour changing neutral current process, strongly suppressed by CKM and GIM mechanisms.
- **Very precise theoretical prediction**: dominated by short distance contributions, small uncertainties due hadronic matrix element, measured with K_{l3} decays.

Standard Model prediction:

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

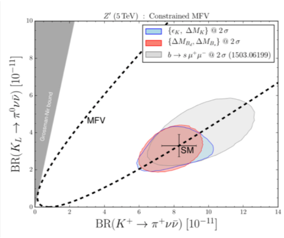
[Buras. et. al., JHEP11(2015)033]

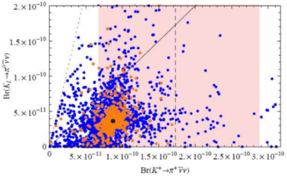
Branching Ratio: status of the art (BNL E787/E949)

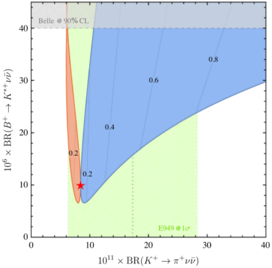
$$BR^{BNL}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$$

[Phys. Rev. D 77, 052003 (2008)] - [Phys. Rev. D 79, 092004 (2009)] Kaon rest frame technique.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay beyond the Standard Model







Simplified new physics models with Z'
Buras, Buttazzo, Knegjens
[JHEP11 (2015) 166]

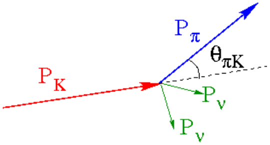
Custodial Randall-Sundrum
Blanke, Buras, Duling, Gemmler, Gori
[JHEP 0903 (2009) 108]

LFU violating models
Isidori et al.
[Eur. Phys. J. C (2017) 77: 618]

- MSSM analyses, [Blazek, Matak, Int. J. Mod. Phys. A29 (2014) no.27], [Isidori et al. JHEP 0608 (2006) 064]
- Littlest Higgs with T-parity, [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- Leptoquarks, [S. Fajfer, N.Košnik, L. Vale Silva, Eur.Phys.J. C78 (2018)]

Experimental strategy

- *in flight decay* technique ($P_K = 75 GeV/c$)
- kinematic analysis (missing mass)
- charged particles identification
- muons and photons rejections
- Pion momentum range: $[15; 35]$ GeV/c
- Analysis performed in 4 momentum bins, each 5 GeV/c wide
- Signal and Control kinematic regions *blinded* during the analysis

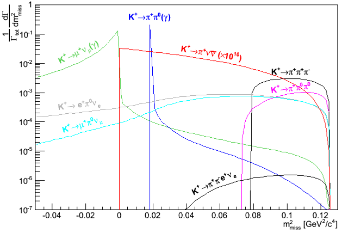


Performance required:

- time coincidence: $O(100\ ps)$
- kinematic rejection: $O(10^4)$
- muon rejection: $> 10^7$
- π^0 rejection: $> 10^7$

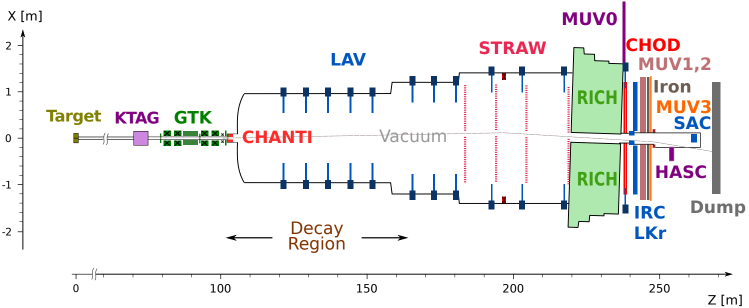
Missing mass

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



Decay channel	Branching Ratio
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08) \cdot 10^{-2}$
$K^+ \to \mu^+\nu$	$(63.56 \pm 0.11) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^- e^+\nu$	$(4.247 \pm 0.024) \cdot 10^{-5}$

NA62 beam



SPS proton beam

- 400 GeV/c protons impinging on the beryllium target
- $2 \cdot 10^{12}$ proton/spill
- $\sim$3. s effective spill length
- $\sim 10^{18}$ POT/year

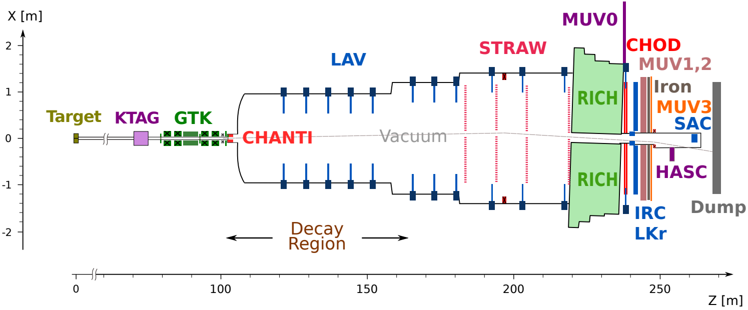
Secondary beam

- 75 GeV/c momentum, 1% bite
- 100 mrad divergence (RMS)
- 60×30 mm^2 transverse size
- 70% pions, 24% protons, 6% kaons
- Beam particles rate: 750 MHz at GTK3

Decay region

- 75 m long fiducial region
- Kaon decays rate: $\sim$ 5 MHz.
- Vacuum $\sim$ $O(10^{-6})$ mbar

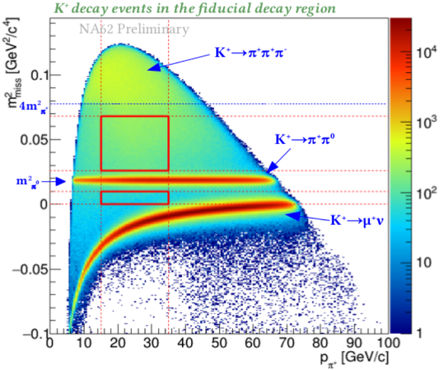
NA62 sub-detectors



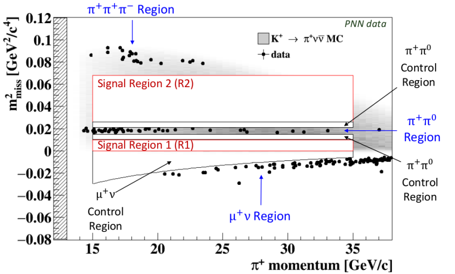
- KTAG: Cherenkov threshold counter;
- GTK: Si pixel beam tracker;
- CHANTI: ring stations of scintillator slabs;
- LAV: lead glass ring calorimeters;
- STRAW: straw magnetic spectrometer;
- RICH: Ring Imaging Cherenkov counter;
- MUV0: off-acceptance plane of scintillator pads;
- CHOD: planes of scintillator pads and slabs;
- IRC: inner ring shashlik calorimeter;
- LKr: electromagnetic calorimeter filled with liquid krypton;
- MUV1,2: hadron calorimeter;
- MUV3: plane of scintillator pads for muon veto;
- HASC: near beam lead–scintillator calorimeter;
- SAC: small angle shashlik calorimeter.

Kinematic: signal and control regions

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



From 2016 analysis:



Kinematic regions

- 2 (blinded) signal regions
- expected background in the signal regions estimated from the tails of the distributions
- (blinded) control regions to validate the expected background predictions

Status of the analysis of 2017 data

Selection and performances

Selection similar to that applied to 2016 data:

- Single track decay topology
- Improved π^+ identification
- Photon rejection
- Multi-track rejection

Performances in line with expectation, with some improvements:

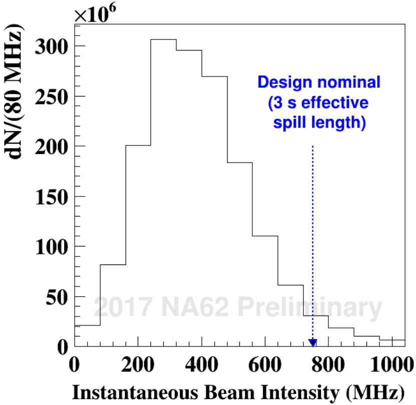
- Improved LKr reconstruction
- Improved π^0 rejection
- Improved pileup treatment

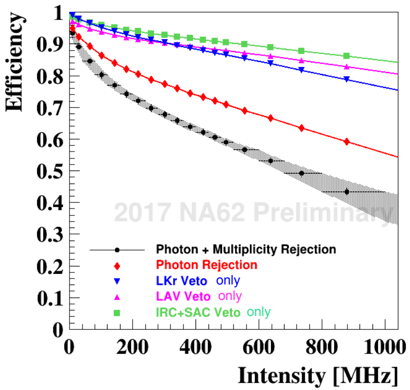
Main 2017 performances:

- $\epsilon_{\mu^+} = 10^{-8}$ (64% π^+ efficiency)
- $\epsilon_{\pi^0} = (1.4 \pm 0.1) \cdot 10^{-8}$
- $\sigma(\mathrm{m}^2_{\mathrm{miss}}) = 10^{-3}\ \mathrm{GeV}^2/c^4$
- $\sigma_t \sim O(100\ \mathrm{ps})$

Beam intensity effects

- Investigation with $K^+ \to \mu^+\nu$ collected with control triggers
- GTK out-of-time activity: wide range of intensity, extending well above design specs

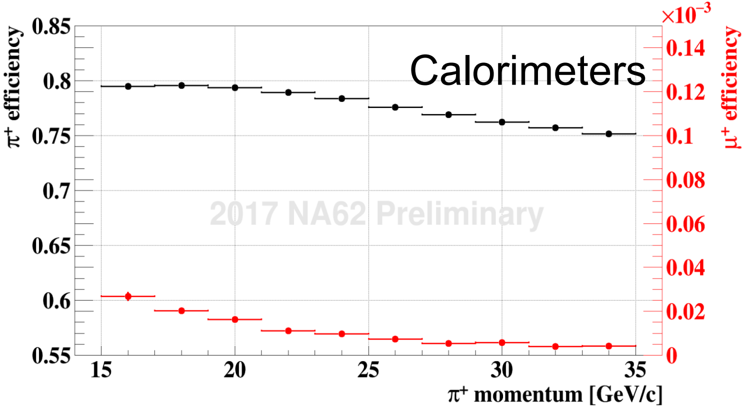




Accidental signal loss scales linearly from 2016: 37% on average

Charged Particle Identification: Calorimeters

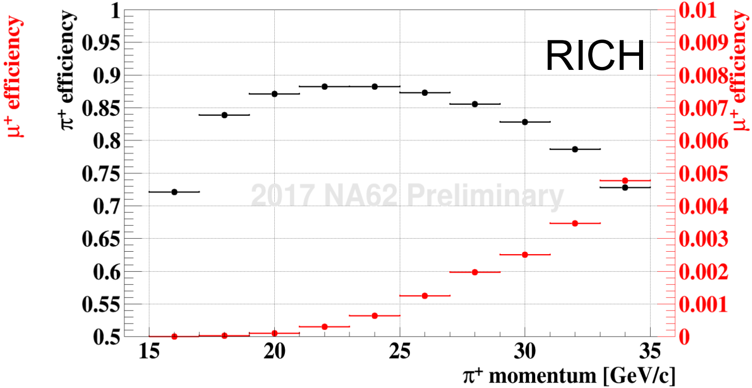
- BDT classifier trained on 2016 data including: energy, energy sharing, clusters shape in the LKr, MUV1 and MUV2
- Completed by MUV3 anti-coincidence request



$\Rightarrow$ no effect from higher beam intensity

Particle Identification: $\pi - \mu$ separation with RICH

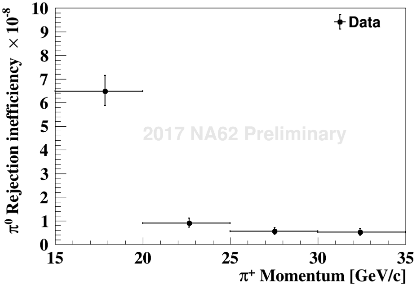
- Track driven Likelihood particle ID discriminant
- Particle mass extracted using track momentum

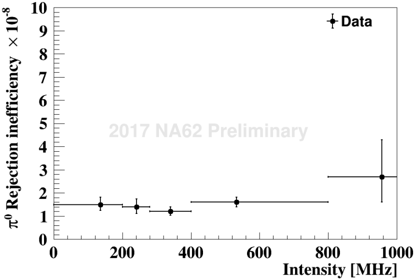


Slightly improved usage of RICH variables with respect to 2016 analysis

Photon rejection: LAV, LKr, IRC and SAC

Rejection efficiency for π^0 from $K^+ \to \pi^+\pi^0$ measured on data





- Better treatment of pileup in IRC and SAC, improved LKr reconstruction
- Average rejection efficiency for π^0: $(1.4 \pm 0.1) \cdot 10^{-8}$ (40% better wrt 2016)
- π^0 rejection efficiency does not depend on beam intensity within uncertainty

Kaon flux and Single Event Sensitivity

$K^+ \to \pi^+\pi^0$ selected as **normalization channel** in control trigger

Normalization channel selection

Same conditions of the signal selection, except for:

- photon and multiplicity rejection not applied
- different cuts on the missing mass

Kaon flux

$$N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}}$$

- N_K : number of K^+ decays
- $N_{\pi\pi}$: number of $K^+ \to \pi^+\pi^0$ observed events
- D : Down-scaling factor applied to the trigger
- $A_{\pi\pi}$: normalization decay acceptance (Monte Carlo)
- $BR_{\pi\pi}$: normalization decay Branching Ratio

Single Event Sensitivity

$$SES = \frac{1}{N_K \cdot \sum_j (A^j_{\pi\nu\nu} \cdot \epsilon^j_{trig} \cdot \epsilon^j_{RV})}$$

- SES : single event sensitivity
- N_K : number of K^+ decays
- $A_{\pi\nu\nu}$: signal acceptance (Monte Carlo)
- ϵ_{trig} : trigger efficiency
- ϵ_{RV} : random veto efficiency
- j : momentum bin index

Single event sensitivity for 2017 data

Kaon flux:

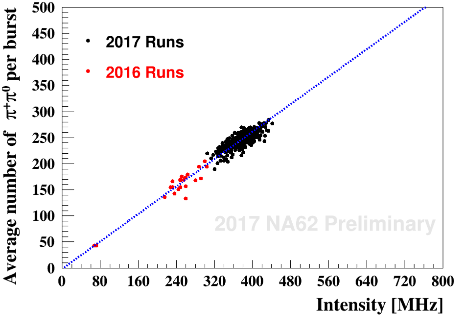
$$N_K = (1.3 \pm 0.1) \cdot 10^{12}$$

Single Event Sensitivity:

$$SES = (0.34 \pm 0.04) \cdot 10^{-10}$$

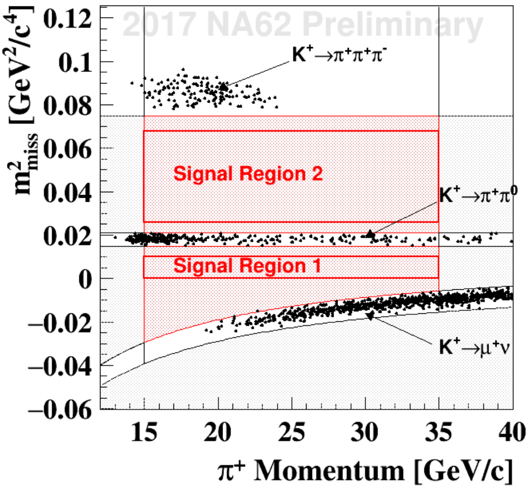
Expected $K^+ \to \pi^+ \nu \bar{\nu}$ events:

$$N(K^+ \to \pi^+ \nu \bar{\nu})_{SM} = 2.5 \pm 0.4$$



SES scales linearly with intensity, i.e. no additional losses within uncertainty, other than those expected from accidental losses

2017 data after $K^+ \to \pi^+ \nu \bar{\nu}$ selection



Signal and control regions kept masked, as well as region below $K^+ \to \mu^+ \nu$ region, used to validate upstream background

Background studies

Backgrounds from $K^+ \to \pi^+\pi^0(\gamma)$, $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^-$ due to m^2_{miss} mis-reconstruction:

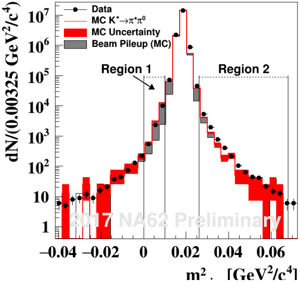
- similar procedure with respect to 2016 analysis (data driven), but also including studies of possible intensity effects
- Assumed that cuts defining signal regions are independent of π^0 rejection, particle identification and multiplicity rejection
- Control samples selected on data allow modeling of m^2_{miss} mis-reconstruction

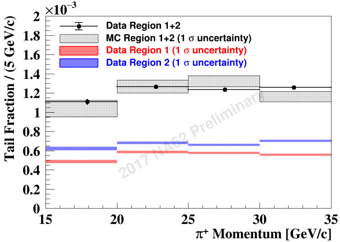
Background from $K^+ \to \pi^+\pi^-e^+\nu$ estimated from simulation

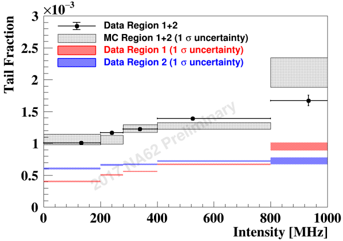
Process	Expected events in signal regions
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$
Upstream Background	Analysis on–going

Background from $K^+ \to \pi^+\pi^0(\gamma)$

- Sample selected on control data tagging the π^0 with 2 clusters in the LKr
- Radiative background estimated separately
- 60% (20%) of $\pi^+\pi^0$ entering R1 (R2) come from mis-reconstruction due to K-π matching (pileup in the GTK)
  $\Rightarrow$ small intensity dependence



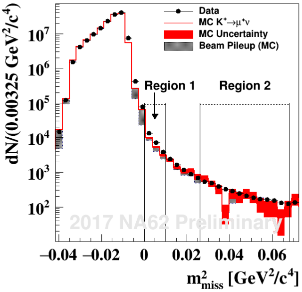


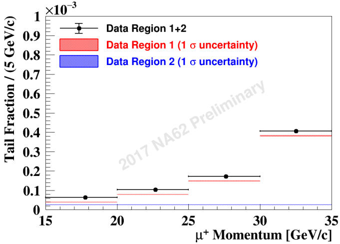


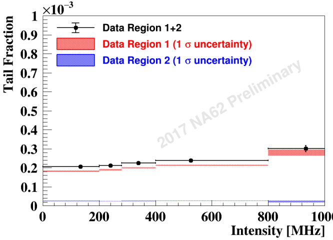
Excellent Data/MC agreement once pileup effect is included

Background from $K^+ \to \mu^+\nu$

- Sample selected on control data tagging the μ^+ with MUV3 signals
- Strongly depends on momentum for kinematic reasons
- No significant dependence on intensity

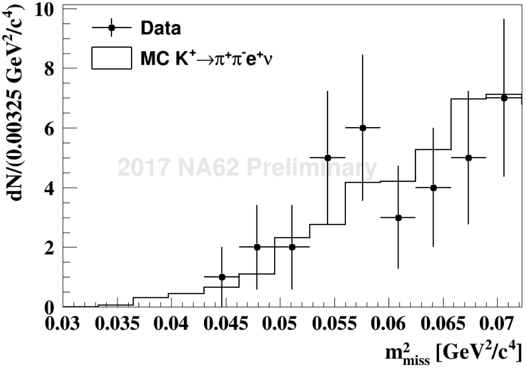






Background from $K^+ \to \pi^+\pi^-e^+\nu$

- Suppression relies on multiplicity rejection
- Kinematics and topology are strongly correlated
  $\Rightarrow$ contribution estimated by MC
- MC sample of $1.5 \cdot 10^9$ events
- Sample enriched inverting multiplicity criteria used to validate simulation



Upstream background

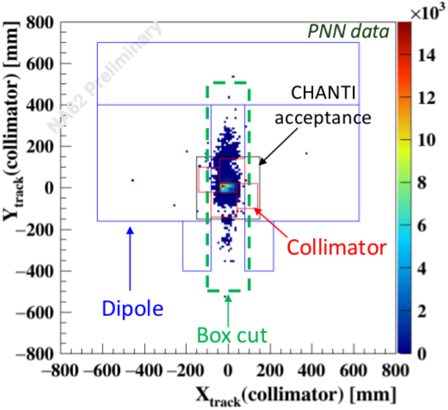
Possible sources:

- decays along the beam line
- particles interactions with the beam tube or the GTK material
- accidental matching between the K^+ and the π^+ tracks

2016 strategy:

- Identified and studied inverting K-π matching requests
- Data-driven estimation of the contribution
- Box cut reduced the signal acceptance by $\sim 35\%$

From 2016 analysis:

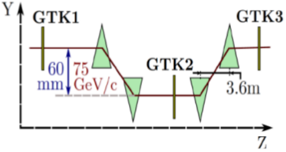


Upstream background: $0.050^{+0.090}_{-0.030}|_{stat}$

Total background: $0.152^{+0.092}_{-0.033}|_{stat} \pm 0.013_{syst}$

Interventions to reduce the *Upstream* background

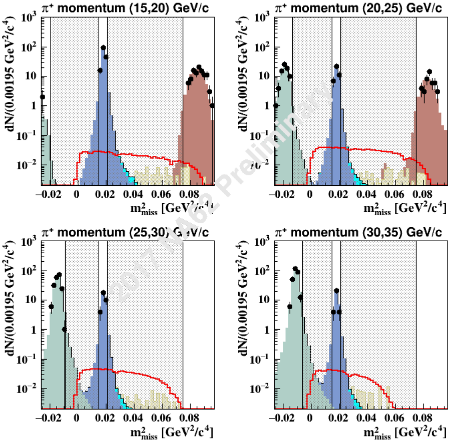
September 2017



June 2018

Background summary (no upstream)

- 2017 data allows detailed validation of background models
- Background distributions from control data are normalised separately to the number of events remaining in the background regions after the $K^+ \to \pi^+ \nu \bar{\nu}$ selection
- Signal (in red) normalised to 2017 expected number of SM events
- Shape differs between signal regions, and changes with pion momentum



Remarkable agreement between modeled m^2_{miss} and remaining events in background regions confirms validity of background evaluation from kaon decays in fiducial region

Other NA62 analyses

Search for lepton number violating K^+ decays
[Physics Letters B 797 (2019) 134794]

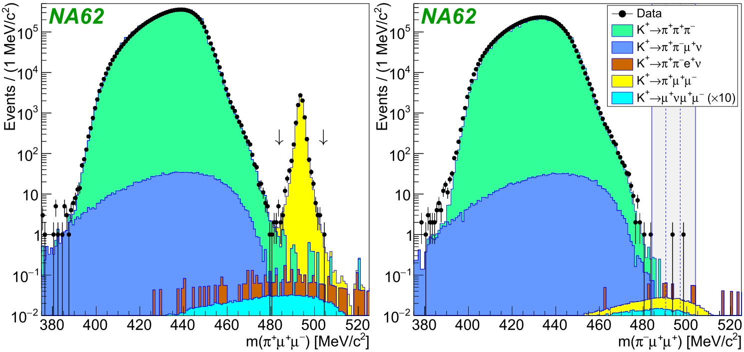
Search for production of an invisible dark photon in π^0 decays
[JHEP 1905 (2019) 182]

Lepton Number Violation in $K^+ \to \pi^- l^+ l^+$ decays

Lepton Number Violation predicted in BSM models, e.g. via Majorana heavy neutrinos

[A. Atre et al., JHEP 0905 (2009) 030], [L. Littemberg et al., Phys.Lett.B491 (2000) 285]

$K^+ \to \pi^+ \mu^+ \mu^-$ **(SM)** $\qquad$ $K^+ \to \pi^- \mu^+ \mu^+$ **(LNV)**



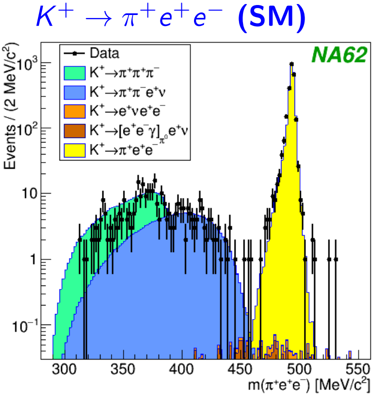
Expected background in signal region: 0.91 ± 0.41
Candidates observed in the blinded signal region: 1

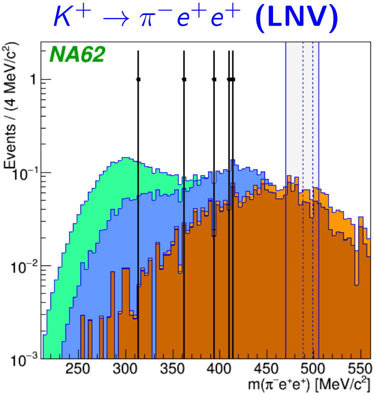
Upper limit: BR($K^+ \pi^- \mu^+ \mu^+$) $< 4.2 \cdot 10^{-11}$ @ 90% CL (two times better than previous limit)

Lepton Number Violation in $K^+ \to \pi^- l^+ l^+$ decays

Lepton Number Violation predicted in BSM models, e.g. via Majorana heavy neutrinos

[A. Atre et al., JHEP 0905 (2009) 030], [L. Littemberg et al., Phys.Lett.B491 (2000) 285]





Expected background in signal region: 0.16 ± 0.03
Candidates observed in the blinded signal region: 0

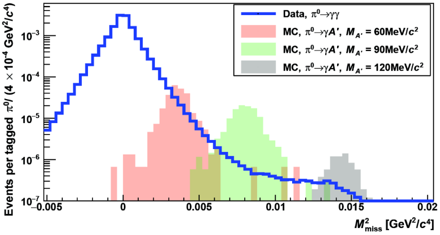
Upper limit: $BR(K^+\pi^- e^+ e^+) < 2.2 \cdot 10^{-10}$ @ 90% CL (three times better than previous limit)

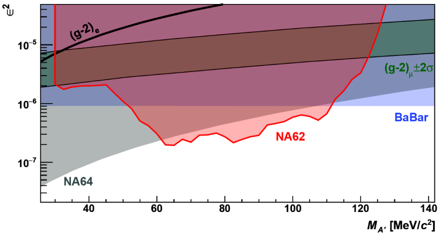
Search of dark photon in π^0 decays

Simplest hidden sector model introduces one extra U(1) gauge symmetry with a corresponding gauge boson: the dark photon.
The coupling constant and the charges can be generated through kinematic mixing between QED and the new U(1) gauge boson.

[B. Holdom, Phys. Lett. B166 (1986) 196] [Batell et al., PRD 80 (2009) 095024]

Search in the chain $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$





1% of data collected in 2016, no statistically significant excess

Conclusions and outlook

- Analysis of 2017 data (2016-like style) almost completed, stay tuned! (Estimate of upstream background on-going)
- 2017 single event sensitivity is 10 times better than for 2016
- Signal-over-background ratio due to kaon decays in fiducial decay region does not deteriorate with increasing beam intensity
- Precise evaluation of statistics collected in 2018 is on-going
- Strong effort to improve the accidental losses, and further decrease the background
- Looking also to increase signal acceptance with a global re-optimization of analysis strategy
- Further data taking is necessary to reach the proposed precision
- Many other analyses ongoing in the data collected in the 2016-2018 period