Status and prospects for the $Br(K^+ \to \pi^+ \nu \bar{\nu})$ measurement at NA62

Francesco Brizioli

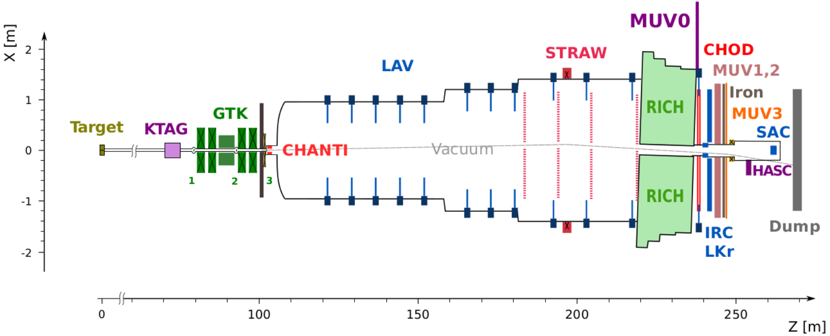
University of Perugia and INFN (Italy)

francesco.brizioli@pg.infn.it

on behalf of the NA62 Collaboration

September 15, 2020

NA62 beam and detector *[2017 JINST 12 P05025]*



- 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;

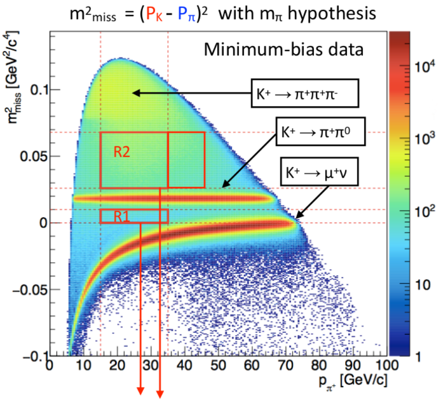
- CHOD: planes of scintillator pads and slabs;
- IRC: inner ring shashlik calorimeter;
- LKr: electromagnetic calorimeter filled with liquid krypton;
- MUV1,2: hadron calorimeter;
- MUV3: plane of scintillator pads for muon veto;
- HASC: near beam lead–scintillator calorimeter;
- SAC: small angle shashlik calorimeter.

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

Selection steps

- π^+ and K^+ tracks reconstruction
- $K^+ - \pi^+$ matching
- Decay vertex reconstruction
- π^+ identification (μ^+ rejection)
- photon rejection
- multi-track rejection
- kinematics (m^2_{miss} vs P_π)

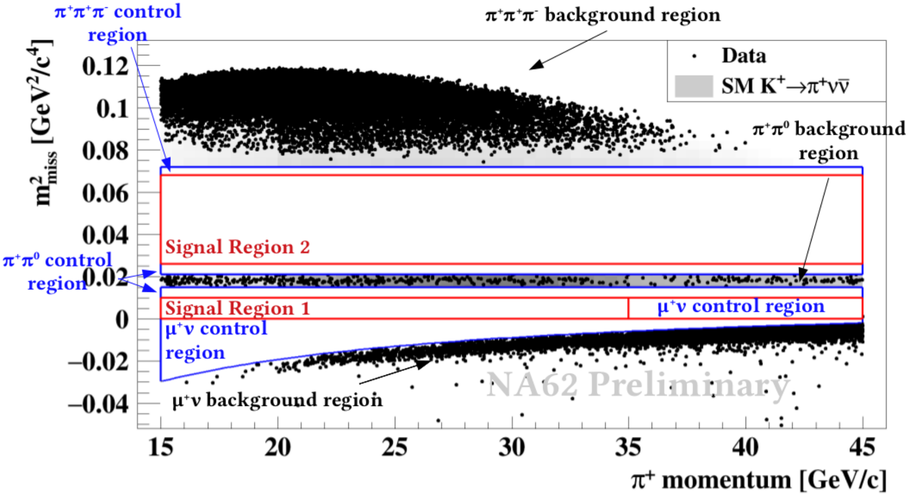
$$m^2_{miss} = (P_K - P_\pi)^2$$



Kinematic cuts to define signal regions R1 and R2

Events after $K^+ \to \pi^+ \nu \bar{\nu}$ selection (2018 data - Preliminary)

Control and signal regions **blinded**



Number of Kaon decays and Single Event Sensitivity

Normalization channel: $K^+ \to \pi^+\pi^0$

Same conditions of the signal selection, except for:

- minimum biased trigger
- photon and multiplicity rejection not applied
- different kinematic region

Number of kaon decays

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

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

N_K is an effective number of K^+ decays

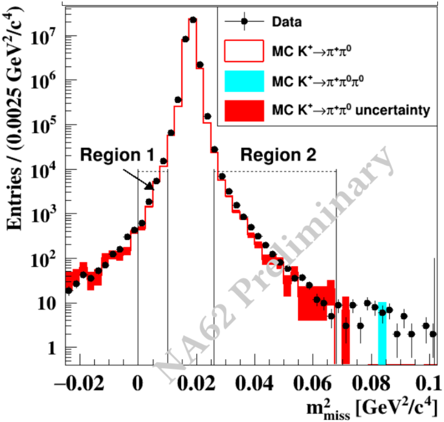
Single Event Sensitivity

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

- N_K : number of K^+ decays
- $A_{\pi\nu\nu}$: signal acceptance (from Monte Carlo)
- ϵ_{trig} : trigger efficiency
- ϵ_{RV} : random veto efficiency
- j : bins of momentum and instataneous beam intensity

Background from standard K^+ decays

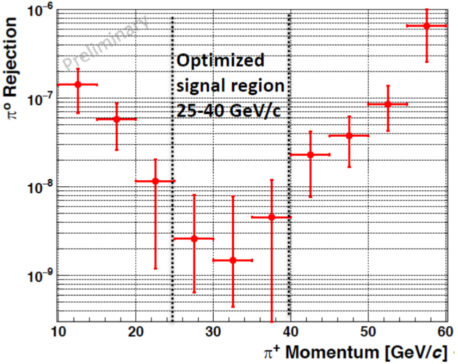
Control sample - $K^+ \to \pi^+\pi^0$ selection ortogonal to $K^+ \to \pi^+\nu\bar{\nu}$ selection



$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f^{kin}(region)$$

- $N^{exp}_{\pi\pi}(region)$: expected $\pi^+\pi^0$ events in $\pi\nu\nu$ region after $\pi\nu\nu$ selection
- $N(\pi^+\pi^0)$: events in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection
- $f^{kin}(region)$: fraction of $\pi^+\pi^0$ in signal region measured on control sample (ortogonal to the signal)
- **Data-driven estimation**
- Control regions for validation

Search for $\pi^0 \to$ *invisible* (in $K^+ \to \pi^+\pi^0$ decays)



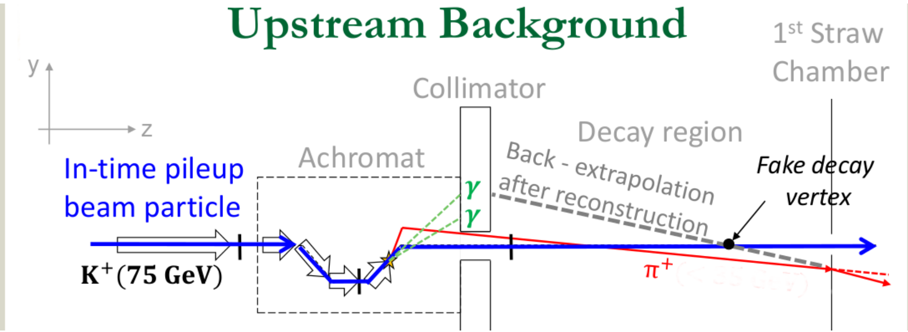
- Signal region: $K^+ \to \pi^+\pi^0$ kinematic region
- A-priori evaluation of π^0 suppression
- Same selection and trigger stream as $\pi\nu\nu$
- $Br(\pi^0 \to invisible)$ normalized to $\pi^0 \to \gamma\gamma$
- Expected background: 10^{+22}_{-8} events
- Observed events: 12

Preliminary result on 2017 data (paper in preparation)

$Br(\pi^0 \to invisible) < 4.4 \cdot 10^{-9}$ @ 90% CL

Factor of 60 improvement with respect to the state of the art.

Upstream background



Background source if:

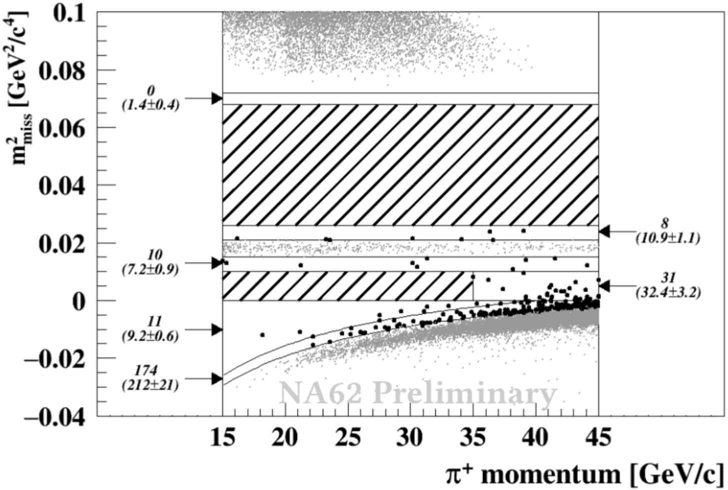
- a kaon decays upstream, and only a pion enters in the decay region
- there is an in-time pileup beam particle (in KTAG and GTK)
- the upstream generated pion enters in the decay region and is scattered in the first STRAW chamber.

Summary of expected signal and background (2018 data - Preliminary)

Process	Expected events in $\pi\nu\nu$ signal regions
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+\pi^- e^+\nu$	0.50 ± 0.11
$K^+ \to \pi^+\pi^+\pi^-$	0.24 ± 0.08
$K^+ \to \pi^+\gamma\gamma$	< 0.01
$K^+ \to l^+\pi^0\nu_l$	< 0.001
Upstream background	$3.30^{+0.98}_{-0.73}$
Total background	$5.28^{+0.99}_{-0.74}$

Opening control regions (2018 data - Preliminary)

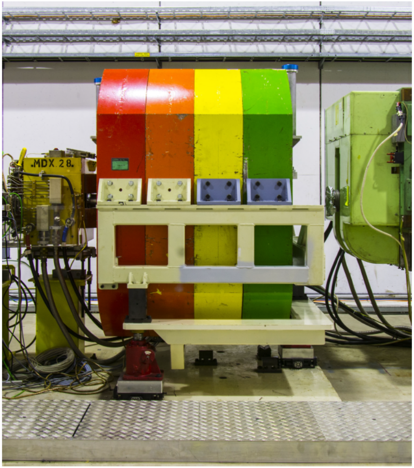
Signal regions **blinded**



Improvements with respect to the 2017 analysis

Replacement of the final collimator against Upstream bkg (June 2018)

before ——————————— after



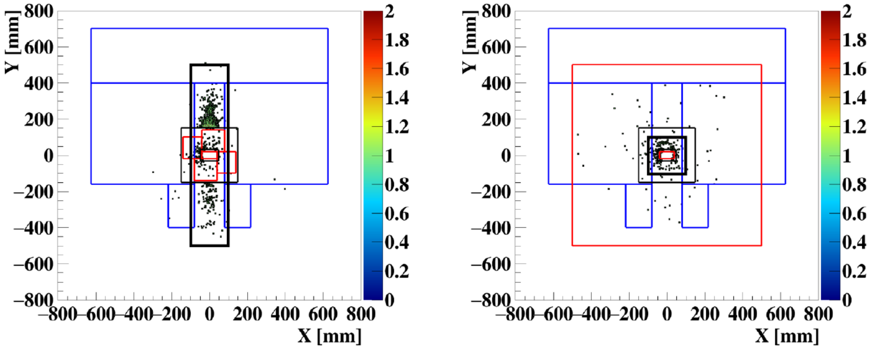
Improvements with respect to the 2017 analysis

Replacement of the final collimator against Upstream bkg

2018 data samples split into two sub-samples:

- 2018-S1: after the replacement of the collimator ($\sim$ 70% of the full 2018 in terms of N_K)
- 2018-S2: before the replacement of the collimator ($\sim$ 30% of the full 2018 in terms of N_K)

2017 data —— 2018-S1 data



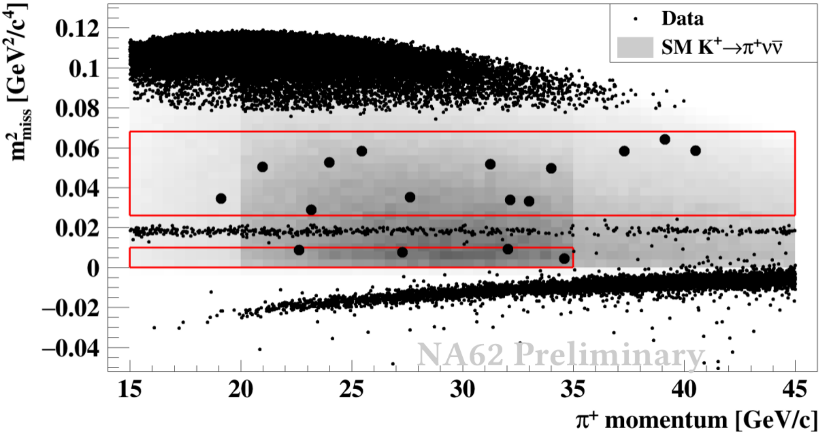
Improvements with respect to the 2017 analysis

	2017	2018-S2	2018-S1
N_K	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$Acc_{MC}(\pi\nu\nu)$	$(3.0 \pm 0.3)\%$	$(4.0 \pm 0.4)\%$	$(6.4 \pm 0.6)\%$
ϵ_{RV}	0.64 ± 0.01	0.66 ± 0.01	0.66 ± 0.01
ϵ_{trig}	0.87 ± 0.03	0.88 ± 0.04	0.88 ± 0.04
$N^{exp}_{\pi\nu\nu(SM)}$	2.16 ± 0.29	1.56 ± 0.21	6.02 ± 0.82
B/S	~ 0.7	~ 0.7	~ 0.7

Relevant improvements
(gain on signal efficiency between 2017 and 2018-S1 samples):

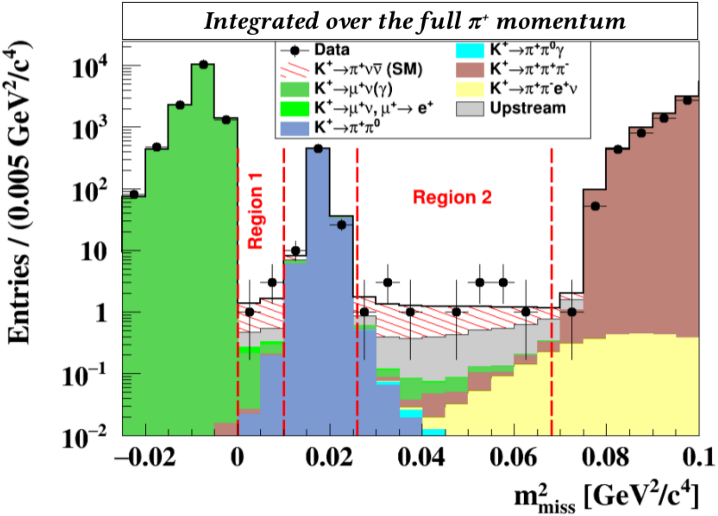
- selection optimized in bins of π^+ momentum (5 GeV/c size)
- cuts against upstream bkg, also with a multi-variate approach: $+50\%$
- definition of kinematic signal regions: $+30\%$
- π^+ identification (RICH and calorimeters): $+10\%$
- definition of decay Fiducial Volume: $+6\%$
- random veto (STRAW and LAV treatment): $+3\%$

Opening signal regions (2018 data - Preliminary)



Expected SM signal events: $7.58 \pm 0.40_{syst} \pm 0.75_{ext}$,
expected background events: $5.28^{+0.99}_{-0.74}$,
observed events: 17

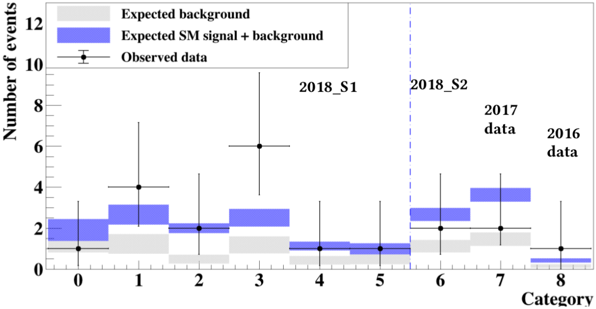
Opening signal regions (2018 data - Preliminary)



Expected SM signal events: $7.58 \pm 0.40_{syst} \pm 0.75_{ext}$, expected background events: $5.28^{+0.99}_{-0.74}$,
observed events: 17

Preliminary combined results 2016+2017+2018 data

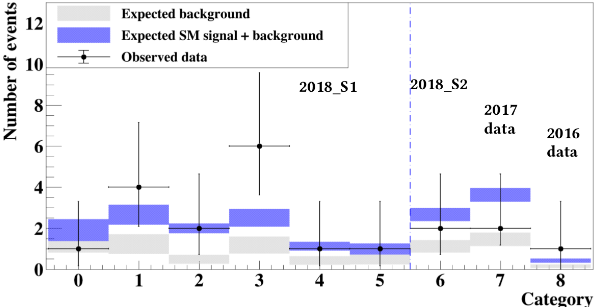
	2016 data	2017 data	2018 data
SES	$(3.15 \pm 0.24) \cdot 10^{-10}$	$(0.39 \pm 0.02) \cdot 10^{-10}$	$(0.111 \pm 0.007) \cdot 10^{-10}$
Expected SM signal	0.27 ± 0.04	2.16 ± 0.29	7.58 ± 0.85
Expected background	0.15 ± 0.09	1.50 ± 0.31	$5.28^{+0.99}_{-0.74}$
Observed events	1	2	17



- Maximum likelihood fit ($Br(\pi\nu\nu)$ as fit parameter) using signal and background expectation in each category
- 2018-S1 sample split in 6 categories, corresponding to the 5 GeV/c size π^+ momentum bins
- 2018-S2, 2017 and 2016 samples: one single category for each sample

Preliminary combined results 2016+2017+2018 data

	2016 data	2017 data	2018 data
SES	$(3.15 \pm 0.24) \cdot 10^{-10}$	$(0.39 \pm 0.02) \cdot 10^{-10}$	$(0.111 \pm 0.007) \cdot 10^{-10}$
Expected SM signal	0.27 ± 0.04	2.16 ± 0.29	7.58 ± 0.85
Expected background	0.15 ± 0.09	1.50 ± 0.31	$5.28^{+0.99}_{-0.74}$
Observed events	1	2	17

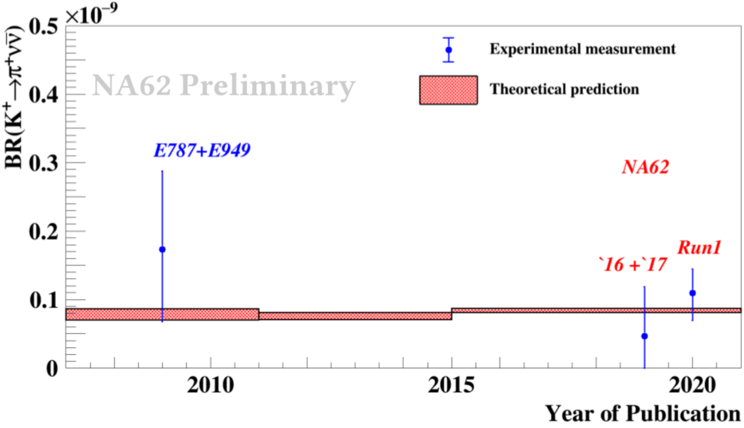


NA62 preliminary result (2016+2017+2018 data)

$$Br^{NA62}_{16+17+18}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.10^{+0.40}_{-0.35\,stat} \pm 0.03_{syst}) \cdot 10^{-10}$$

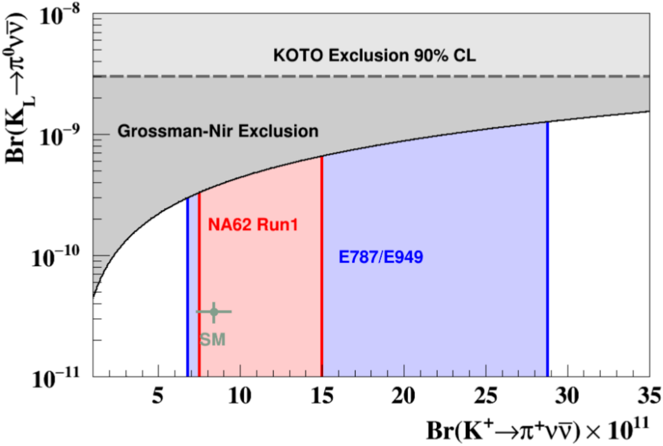
$$3.5\sigma \text{ significance, } P(only\ bkg) = 2 \cdot 10^{-4}$$

Status of $Br(K^+ \to \pi^+ \nu\bar{\nu})$ measurement - Preliminary



- $Br^{NA62}_{16+17+18}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.10^{+0.40}_{-0.35 stat} \pm 0.03_{syst}) \cdot 10^{-10}$ (Preliminary)
- $Br^{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$ *[Buras et al., JHEP11(2015)033]*

Status of $Br(K \to \pi\nu\bar{\nu})$ measurement - Preliminary



- $Br^{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$, $Br^{SM}(K_L \to \pi^0\nu\bar{\nu}) = (0.34 \pm 0.06) \cdot 10^{-10}$ *[Buras et al., JHEP11(2015)033]*
- Grossman-Nir limit: $Br(K_L \to \pi^0\nu\bar{\nu}) < 4.3 \cdot Br(K^+ \to \pi^+\nu\bar{\nu})$ *[Phys. Lett. B 398, 163 (1997)]*
- Speculation based on KOTO data: $Br(K_L \to \pi^0\nu\bar{\nu}) = 21^{+20}_{-11} \cdot 10^{-10}$ *[Phys. Rev. Lett. 124, 071801 (2020)]*

Prospects for $Br(K^+ \to \pi^+ \nu \bar{\nu})$ measurement

Data taking between CERN LS2 and LS3

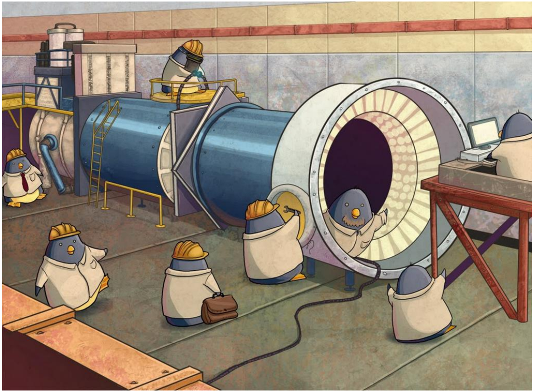
- Plans to strongly suppress the upstream background:
  - re-arranging beam line set-up to swipe away all π^+ from K^+ upstream decays (foreseen modifcations can be implemented using existing beam elements)
  - adding fourth Gigatracker station (GTK4) to reduce mistagging probability
  - installing a new veto-counter system before the final collimator around the beam pipe to detect particles produced in upstream kaon decays (small scintillator-lead-scintillator modules read out by fast photo-multipliers)
- installing a new calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background (in particular against $K^+ \to \pi^+ \pi^0$)
- **goal**: $Br(K^+ \to \pi^+ \nu \bar{\nu})$ measurement with about 20% statistical precision

Conclusions

- Relevant improvements in 2018 data analysis (hardware and software)
- $Br^{NA62}_{16+17+18}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.10^{+0.40}_{-0.35 stat} \pm 0.03_{syst}) \cdot 10^{-10}$
  3.5σ significance
- Most precise measurement ever performed for $K^+ \to \pi^+ \nu\bar{\nu}$ golden channel
- Large values with respect to SM expectation start to be excluded: high precision measurement needed

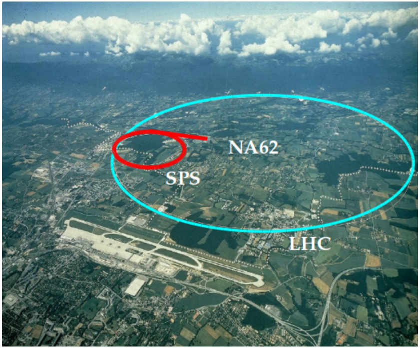
- Important hardware improvements forseen before restarting the data-taking: strong suppression of the main backgroung sources
- Plan to achieve $\sim 20\%$ precision running between CERN LS2 and LS3

SPARES



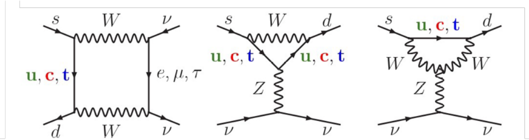
$K^+ \to \pi^+ \nu\bar{\nu}$ search @ NA62

- Full detector installation completed in 2016
- Physics runs in 2016, 2017 and 2018
- 2016 data result published
- 2017 data result submitted for publication
- 2018 data preliminary result presented at ICHEP 2020
- Data taking foreseen to restart after CERN LS2



NA62 is installed in the CERN *North Area*, exploiting a 400 GeV/c proton beam extracted from the SPS accelerator

The NA62 main goal: $Br(K^+ \to \pi^+ \nu \bar{\nu})$ measurement



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

Standard Model prediction

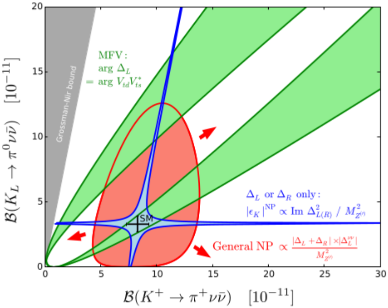
$$Br^{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$$ *[Buras et al., JHEP11(2015)033]*

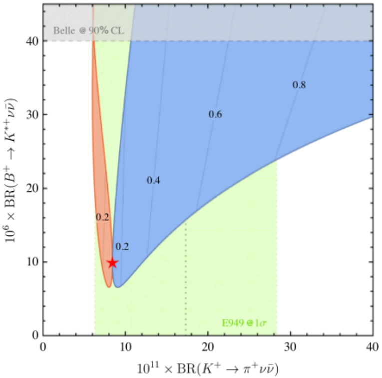
Experimental status

- BNL E787/E949, *Kaon rest frame* technique: $Br^{BNL}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$ *[Phys. Rev. D 77, 052003 (2008)] - [Phys. Rev. D 79, 092004 (2009)]*
- NA62 (2016+2017), decay in flight: $Br^{NA62}_{16+17}(K^+ \to \pi^+ \nu \bar{\nu}) < 1.78 \cdot 10^{-10}$ @ 90% *CL* *[arXiv:2007.08218] submitted to JHEP*

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

Sensitive to New Physics particles up to hundreds of TeV masses





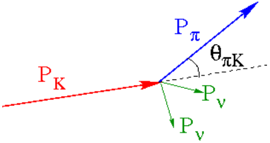
[Buras, Buttazzo, Knegjens, JHEP11 (2015) 166]
$K \to \pi\nu\bar{\nu}$ and ϵ'/ϵ in simplified new physics models

[Isidori et al., Eur. Phys. J. C (2017) 77: 618]
Probing lepton-flavour universality with $K \to \pi\nu\bar{\nu}$ decays

Experimental strategy

Keystones

- *in flight decay* technique ($P_K = 75\ GeV/c$)
- kinematic analysis (missing mass)
- charged particle identification
- muon and photon rejection
- Pion momentum range: $[15; 45]\ GeV/c$
- Signal and Control kinematic regions *blinded* during the analysis

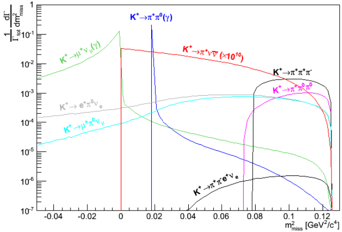


Required performance

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

Squared missing mass

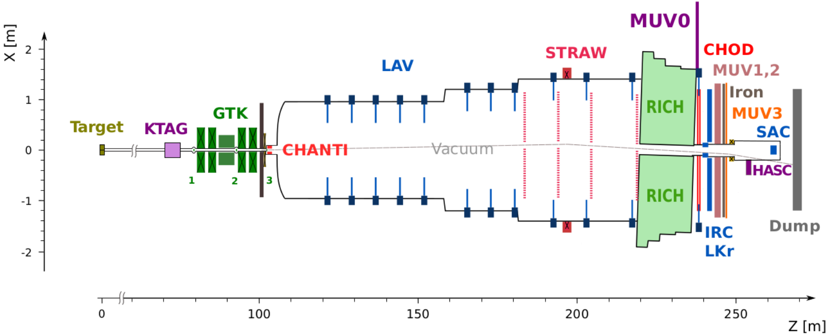
$$m^2_{miss} = (P_K - P_\pi)^2$$



K^+ main decays

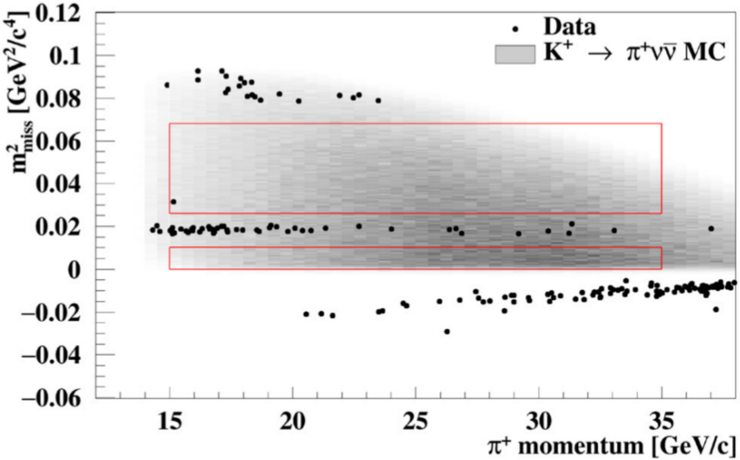
Decay channel	Branching Ratio
$K^+ \to \mu^+\nu$	$(63.56 \pm 0.11) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^- e^+\nu$	$(4.247 \pm 0.024) \cdot 10^{-5}$

NA62 beam and detector *[2017 JINST 12 P05025]*



- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadronic 75 GeV/c beam
- 70% pions, 24% protons, 6% kaons
- Nominal beam particle rate (at GTK3): 750 *MHz*
- 2017 data beam particle rate: 450 *MHz*
- Kaon decay rate in 60 m fiducial volume: 3 *MHz*.

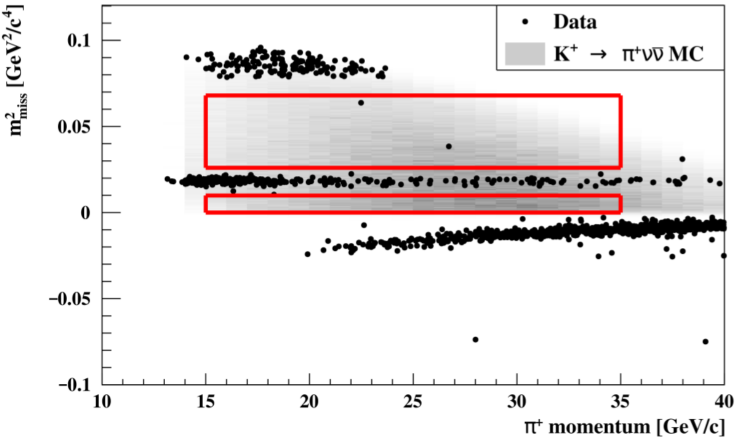
NA62 results on 2016 data



$$Br^{NA62}_{16}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 14 \cdot 10^{-10} \text{ @ } 95\% \; CL$$

[Physics Letters B 791 (2019) 156–166]

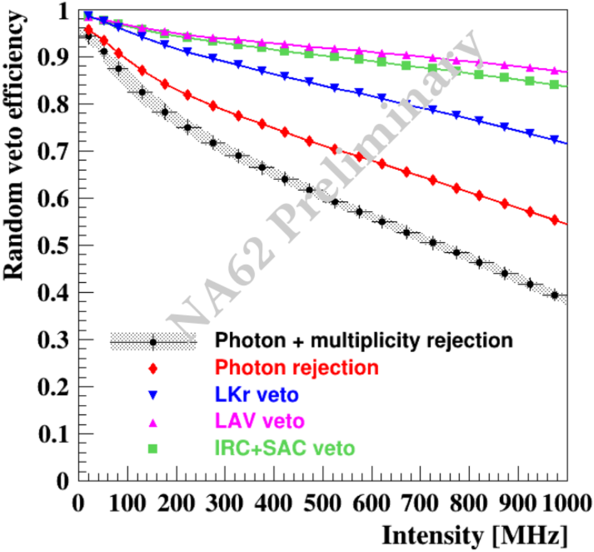
NA62 results on 2017 data



$$Br^{NA62}_{16+17}(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 1.78 \cdot 10^{-10} \text{ @ } 90\%\ CL$$

[arXiv:2007.08218] submitted to JHEP

Random veto VS Intensity (2018 data - Preliminary)



Single event sensitivity and number of expected events (2018 data - Preliminary)

Single event sensitivity

$$SES = (0.111 \pm 0.007_{syst}) \cdot 10^{-10}$$

SES error budget:

Source	**Relative uncertainty**
trigger	5%
MC acceptance	3.5%
random veto	2%
normalization background	0.7%
instantaneous intensity	0.7%
Total	6.5%

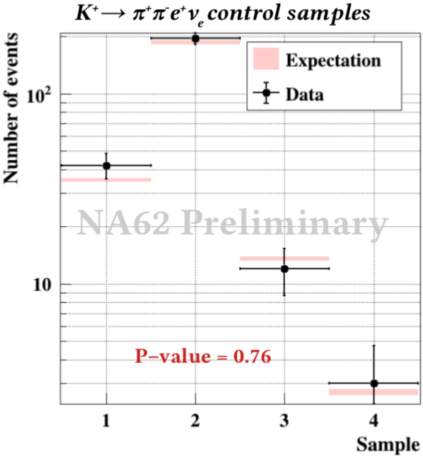
Number of expected SM events

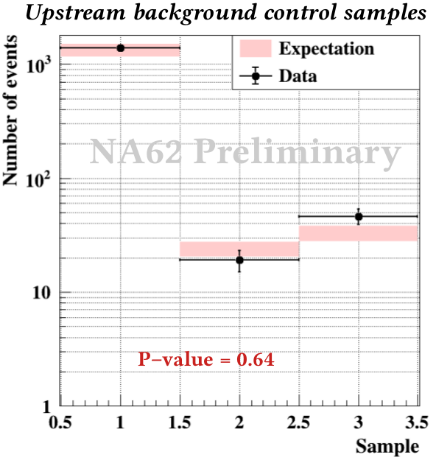
$$N^{exp}_{\pi\nu\nu}(SM) = \frac{Br_{\pi\nu\nu}(SM)}{SES} = 7.58 \pm 0.40_{syst} \pm 0.75_{ext}$$

External error: theoretical uncertainty on the SM prediction:

$Br_{\pi\nu\nu}(SM) = (0.84 \pm 0.10) \cdot 10^{-10}$ *[Buras et al., JHEP11(2015)033]*

K_{e4} and *upstream* background validation





Data samples defined by inverting signal selection criteria

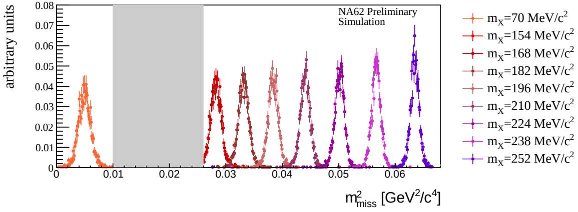
Break-down of the signal efficiency (2017 analysis)

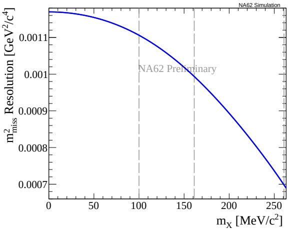
Kinematic selection and geometrical acceptance	0.16
Cut at final collimator against upstream background (box cut)	0.63
Z vertex cut to tighten the sensitive decay volume definition	0.90
Z vertex versus radius cut at Straw chamber against $K \to 3\pi$ background	0.90
Selection criteria against random veto (RV) in the veto detectors	0.64
Kaon-pion association efficiency	0.75
Particle Identification (PID) efficiency	0.65
Trigger efficiency	0.87
Detector efficiency	0.80
DAQ efficiency	0.75
Overall signal efficiency	0.013

https://na62.web.cern.ch/Documents/NA62Addendum1.pdf

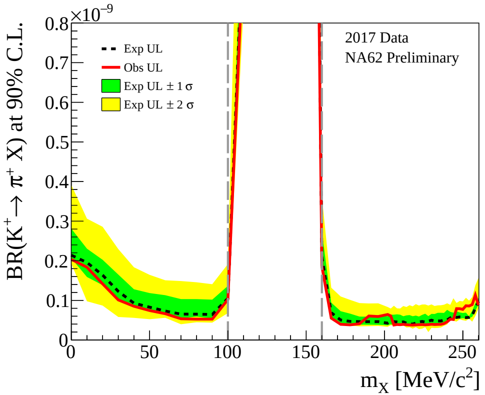
Search for $K^+ \to \pi^+ X$, X invisible: strategy

- Physical motivation: feebly interacting new particle foreseen in several models, e.g. Axion-Like Particle (ALP), QCD Axion, dark scalar, depending on m_X.
- Statistical reinterpretation of the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis: same selection (and same signal regions), normalization and background evaluation.
- Peak search in the observable $m^2_{miss} = (P_K - P_{\pi^+})^2$.
- Scan over different hypotheses for m_X.
- MC signal generation to compute acceptance and obtain the signal model: two body decay with 200 different mass hypotheses.





Search for $K^+ \to \pi^+ X$, X invisible: preliminary result



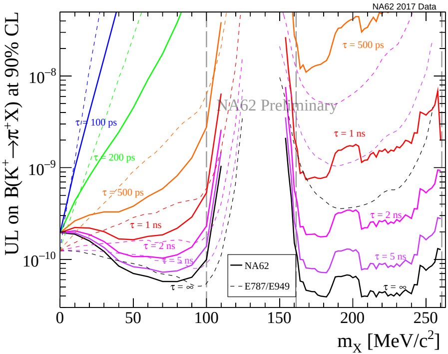
- Shape analysis in m^2_{miss}.
- Fully frequentist approach, profiled likelihood test statistic.
- Background from $\pi\nu\nu$ analysis parameterized with polynomial functions, including SM $K^+ \to \pi^+ \nu\bar{\nu}$.
- Signal shape: gaussian.

Preliminary result on 2017 data (paper in preparation)

$Br(K^+ \to \pi^+ X) < (0.5 - 2.0) \cdot 10^{-10}$ @ 90% CL for $m_X \in [0, 100]$ MeV/c^2

$Br(K^+ \to \pi^+ X) < (0.4 - 1.4) \cdot 10^{-10}$ @ 90% CL for $m_X \in [160, 260]$ MeV/c^2

Search for $K^+ \to \pi^+ X$, X decaying: preliminary result on 2017 data (paper in preparation)



- Assuming X decays to a visible SM particle, detected by the NA62 apparatus.
- $P = \exp\left(-\frac{\Delta L}{\beta\gamma c\tau}\right)$
- Simulation and corresponding upper limit for different τ_X values.
- Comparison with E949 Collaboration result.

Comparison with E949 Collaboration result [Phys. Rev. D 79, 092004 (2009)]

For X infinite life time:

- small improvement for $m_X \in [40, 80]\ MeV/c^2$;
- improvement of ~ 1 order of magnitude for $m_X \in [160, 260]\ MeV/c^2$.

New (preliminary) theoretical prediction for $Br(K \to \pi\nu\bar{\nu})$

By M. Gorbahn @ KAON 2019 Conference
https://indico.cern.ch/event/769729/contributions/3512037/

Uncertainty Analysis using UTfit values

$\mathcal{B}_+ \cdot 10^{11}$	Central:	8.510	$\mathcal{B}_L \cdot 10^{11}$	Central:	2.858
Error:	-0.543	0.555	Error:	-0.256	0.264
A	-0.34	0.352	A	-0.162	0.17
$\delta P_{c,u}$	-0.246	0.250	η	-0.162	0.167
X_t	-0.236	0.240	X_t	-0.113	0.115
ρ	-0.161	0.162	κ_l	-0.017	0.002
P_c	-0.185	0.187	λ	-0.001	0.00
κ_+	-0.041	0.041			
η	-0.037	0.039			
λ	-0.003	0.003			

- Precise theory prediction, suppression in standard model and current measurement at NA62 → classify new physics contributions

CKM input: $A = 0.826(12), \bar{\rho} = 0.148(13), \bar{\eta} = 0.348(10)$

10/27