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

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on behalf of the NA62 Collaboration

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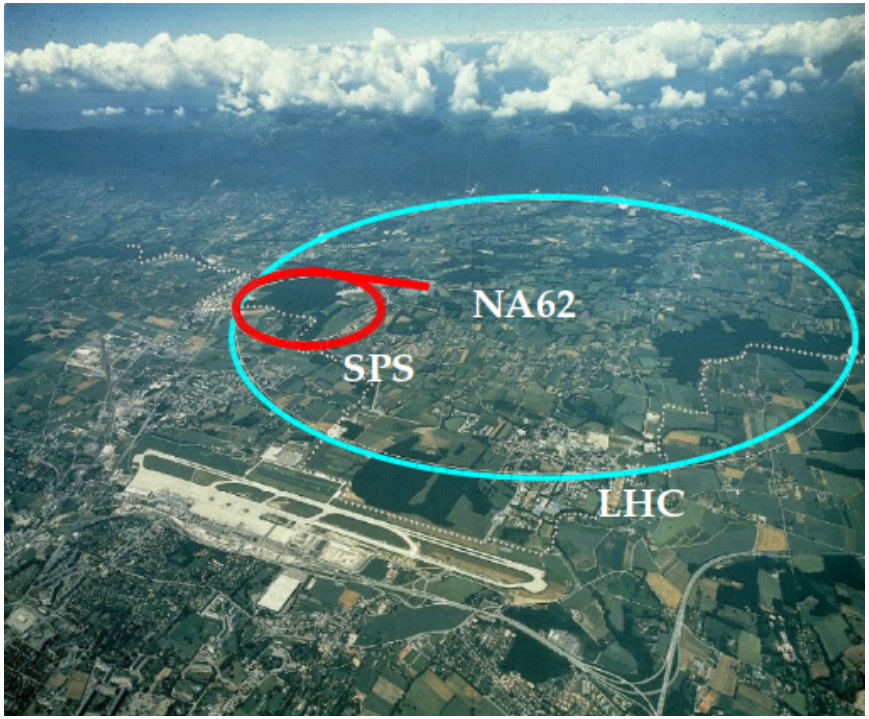
Outline

- $Br(K^+ \to \pi^+ \nu\bar{\nu})$ measurement:
  - physics case
  - experimental strategy
  - Single Event Sensitivity
  - background estimation and validation
  - preliminary results on 2016+2017 data
  - prospects for 2018 data and next data taking

- Exotic searches related to $K^+ \to \pi^+ \nu\bar{\nu}$ analysis:
  - $\pi^0 \to$ *invisible*
  - $K^+ \to \pi^+ X$ **(new preliminary result!)**

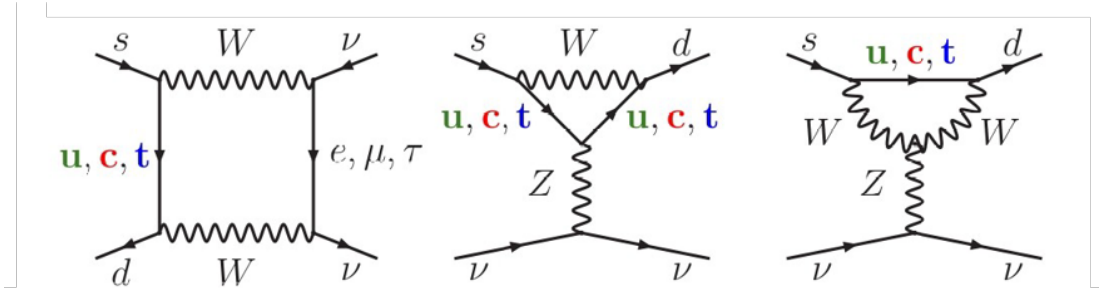
$K^+ \to \pi^+ \nu\bar{\nu}$ search @ NA62

- Full detector installation completed in 2016
- Physics runs in 2016, 2017 and 2018
- $K^+ \to \pi^+ \nu\bar{\nu}$ results on 2016 data published
- $K^+ \to \pi^+ \nu\bar{\nu}$ preliminary results on 2017 data in this talk
- 2018 data analysis on going
- Data taking foreseen to restart after CERN LS2 to measure $Br(K^+ \to \pi^+ \nu\bar{\nu})$



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]*

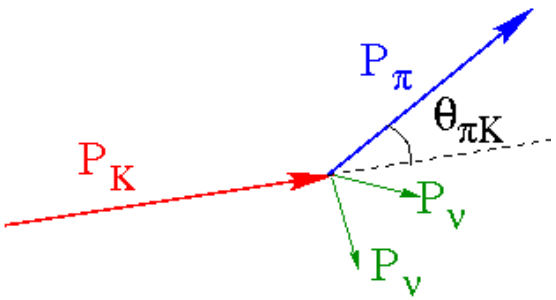
Experimental status

- 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), decay in flight: $Br^{NA62}(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \cdot 10^{-10}$ @ 95% *CL* *[Physics Letters B 791 (2019) 156–166]*

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: $[15; 35]\ GeV/c$
- Signal and Control kinematic regions *blinded* during the analysis

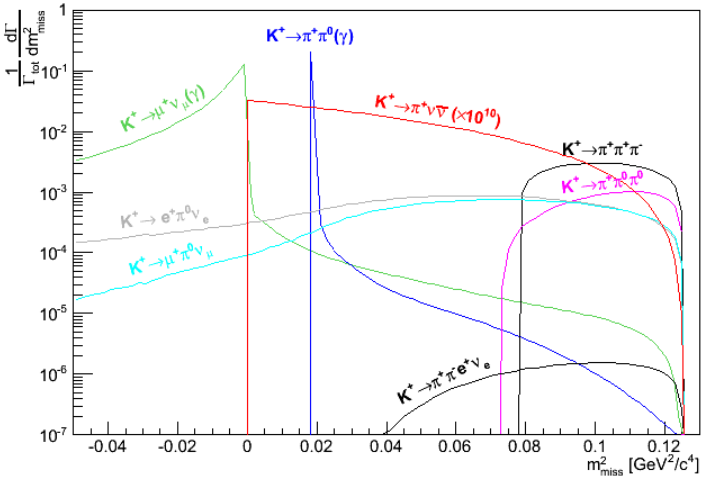


Required performance

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

Squared missing mass

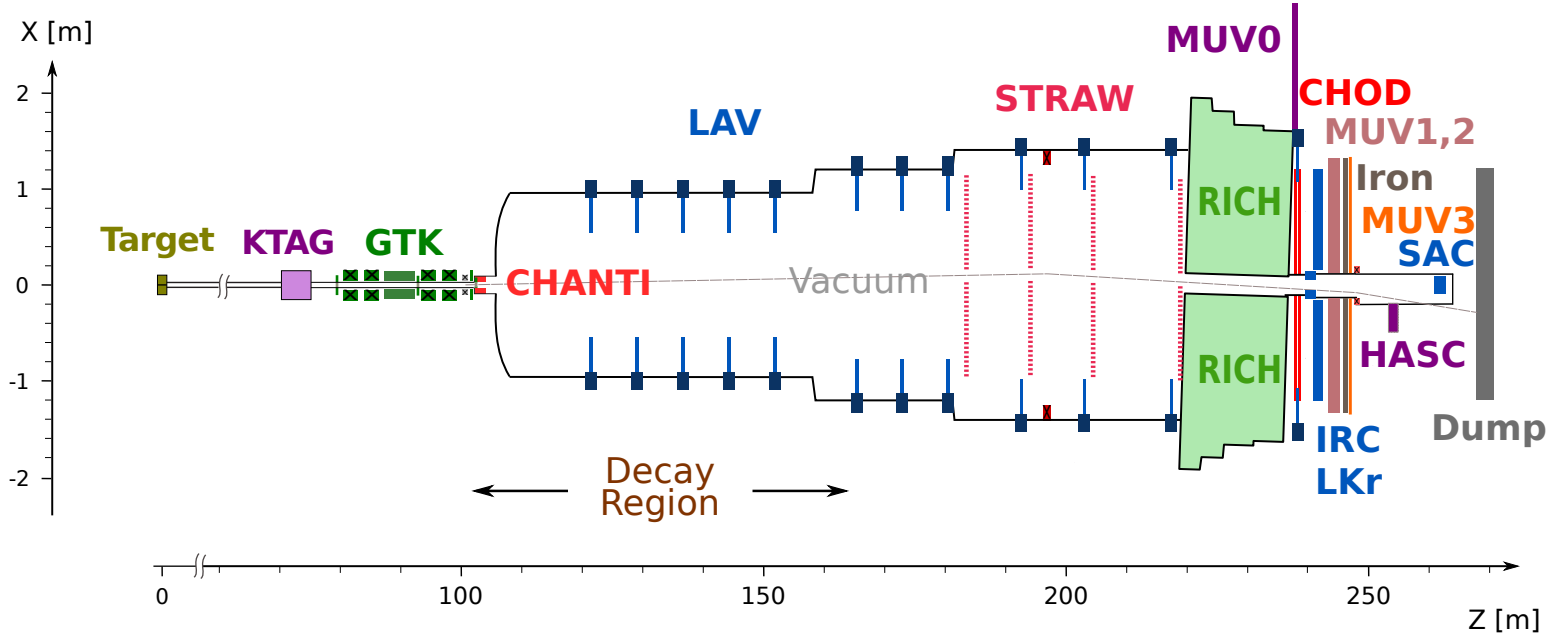
$$m^2_{miss} = (P_K - P_\pi)^2$$



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*.

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

Selection

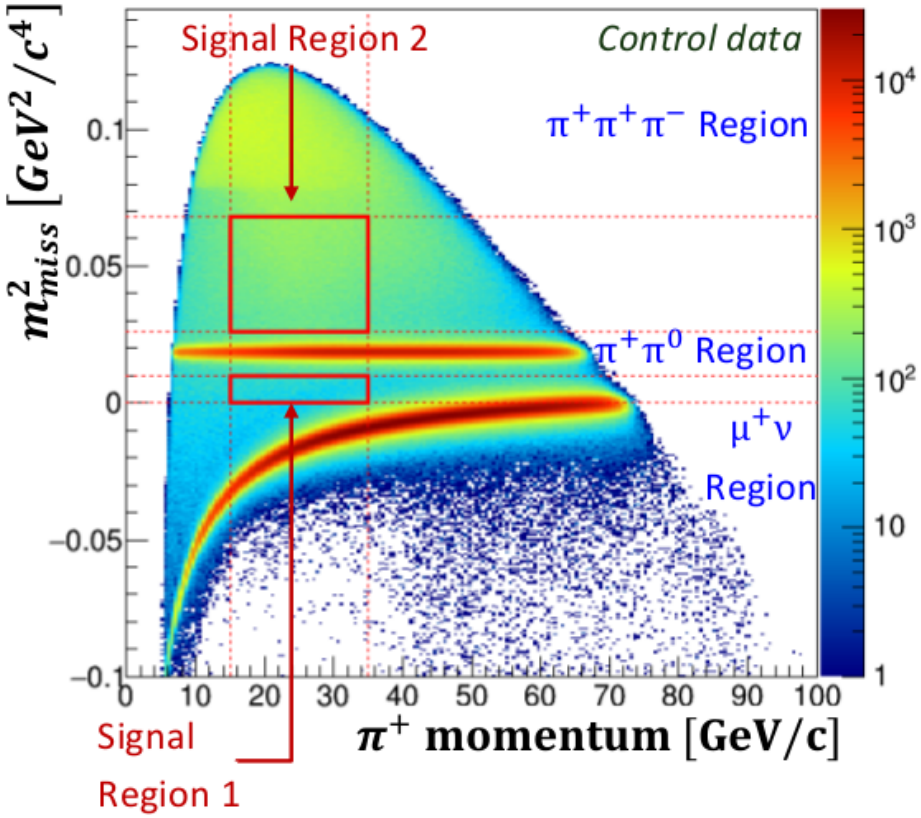
- $K^+ - \pi^+$ matching
- K^+ decay in fiducial volume
- π^+ identification (PID)
- photon rejection
- multi-track rejection
- kinematics (m^2_{miss} *vs* P_π)

Measured performances

- KTAG-GTK-RICH timing: $O(100\ ps)$
- π^+ ID (RICH+CALO): $\epsilon(\mu) \simeq 10^{-8}$ @ $\epsilon(\pi) \simeq 64\%$
- π^0 efficiency: $\simeq 1.4 \cdot 10^{-8}$
- $\sigma(m^2_{miss}) \simeq 10^{-3}\ GeV^2/c^4$

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

K^+ decays selection without PID and photon/multi-track rejection



Single Event Sensitivity (2017 data - Preliminary)

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

Same conditions of the signal selection, except for:

- minimum bias 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 trigger
- $A_{\pi\pi}$: normalization decay acceptance $\simeq 8.5\%$ (from Monte Carlo)
- $Br_{\pi\pi}$: normalization decay Branching Ratio

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

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 $\simeq 3\%$ (from Monte Carlo)
- ϵ_{trig} : trigger efficiency
- ϵ_{RV} : random veto efficiency
- j : bins of momentum and instataneous beam intensity

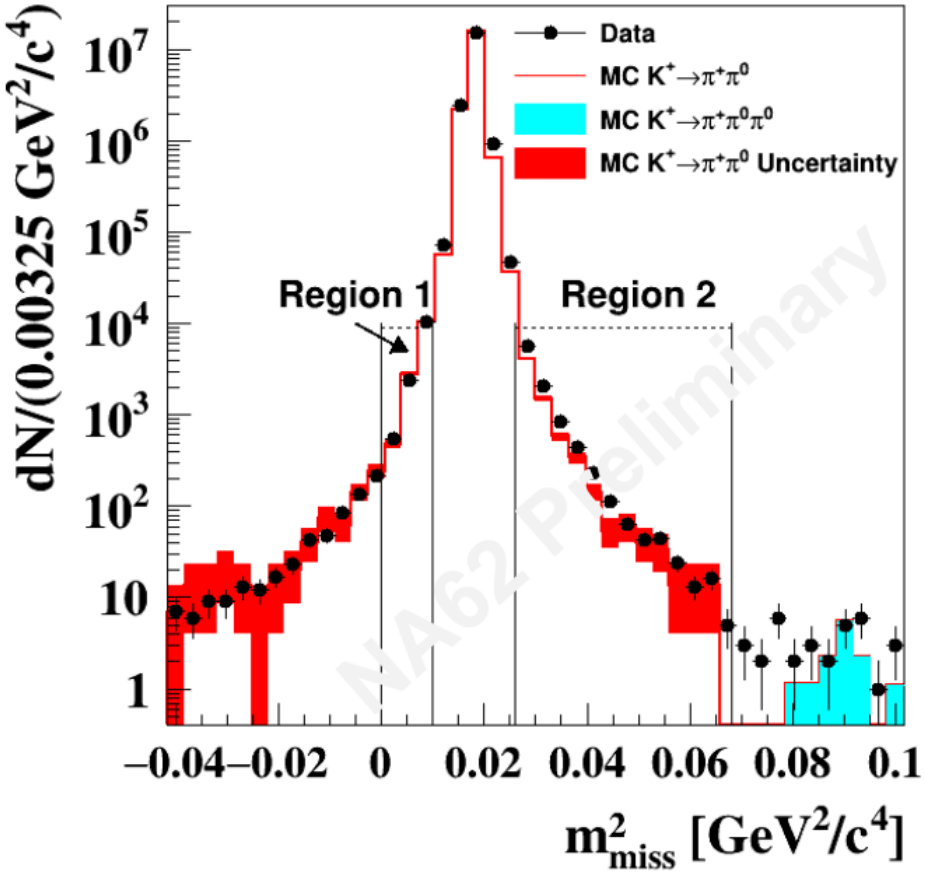
$$SES = (0.39 \pm 0.02_{syst}) \cdot 10^{-10}$$

Summary of expected signal and background (2017 data - Preliminary)

Process	**Expected events in $\pi\nu\nu$ signal regions**
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$2.16 \pm 0.12_{syst} \pm 0.26_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$	$0.11 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu,\ \mu \to e\nu\nu$	$0.04 \pm 0.02_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

Estimation of background from standard K^+ decays

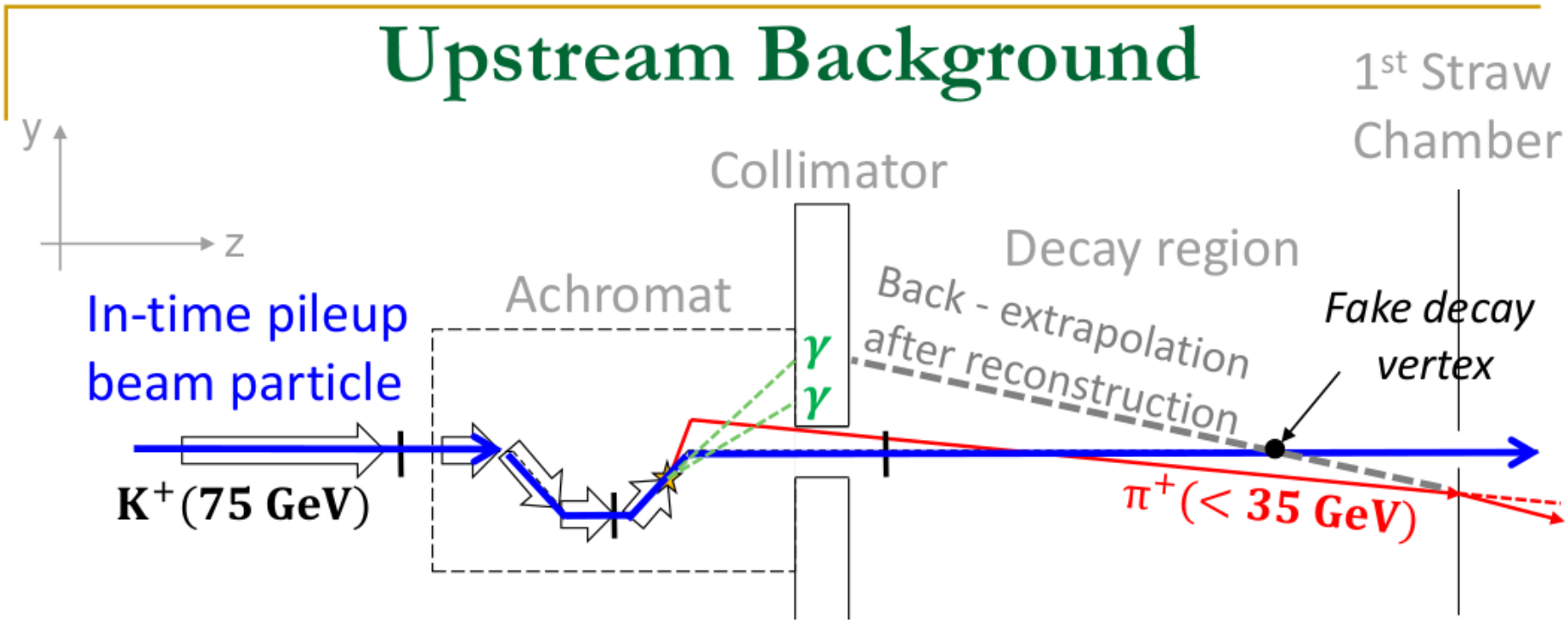
Control sample - $K^+ \to \pi^+\pi^0$ selection



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

- $N^{exp}_{\pi\pi}(region)$: 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 data
- **Data-driven estimation**
- Control regions for validation

Upstream background

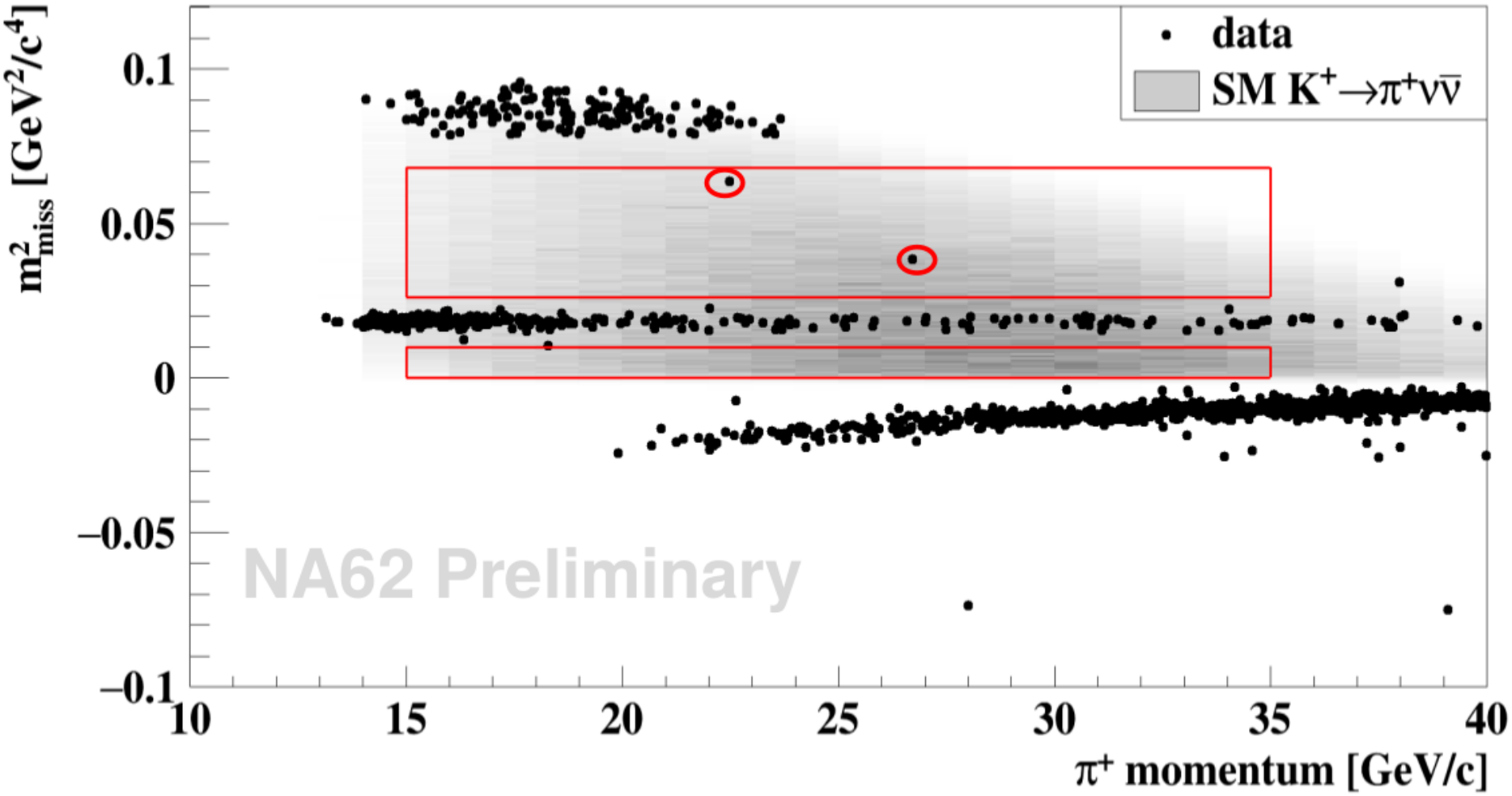


Background source if:

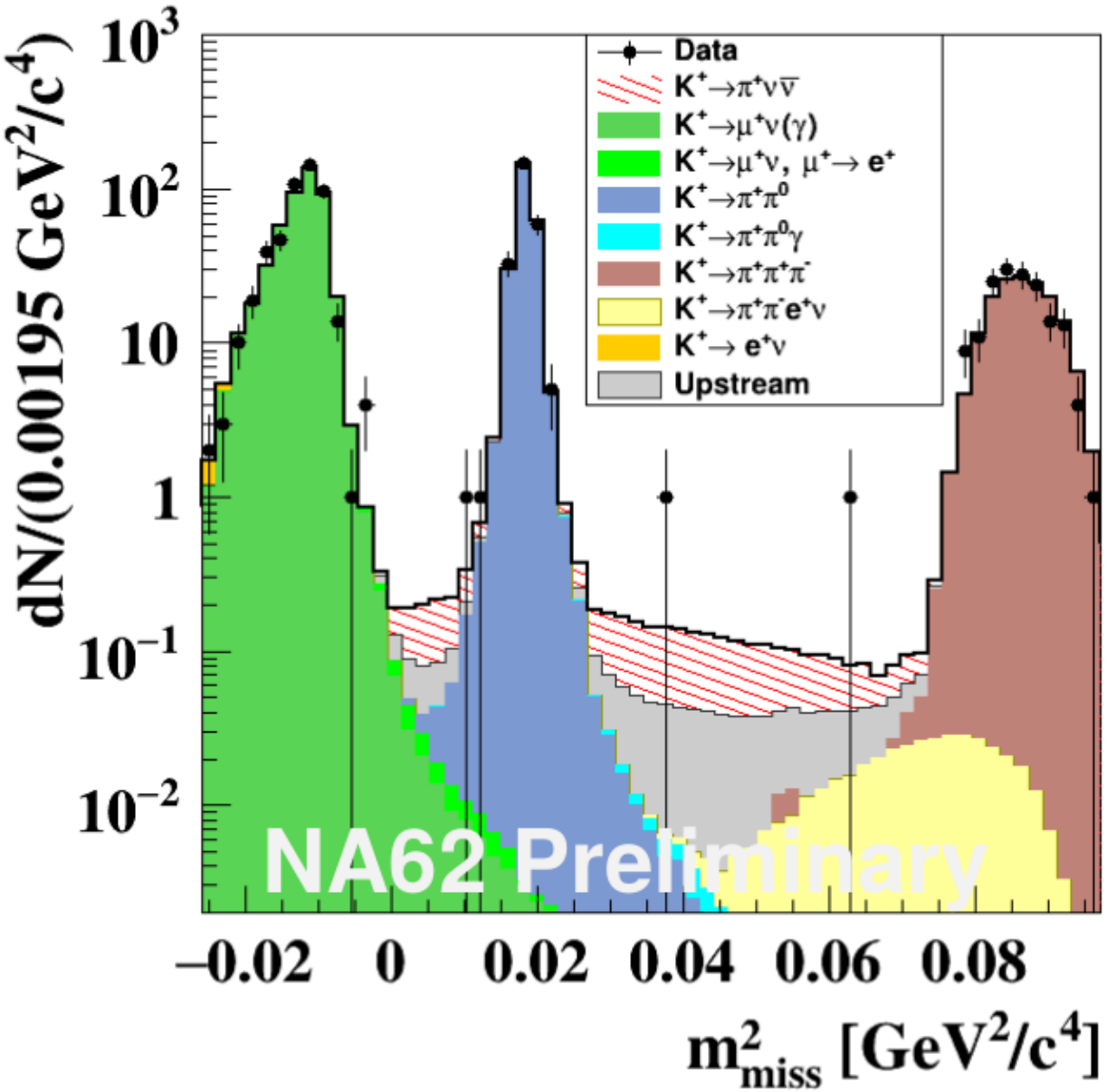
- a kaon decays upstream, and only a pion enters in the decay region
- there is an in-time pileup beam particle (in KTAG and GTK)
- the upstream generated pion enters in the decay region and is scattered in the first STRAW chamber.

Results - opened signal regions (2017 data - Preliminary)

Opened signal regions: 2 events observed



m^2_{miss} signal and backgrounds (2017 data - Preliminary)



Preliminary combined results 2016 + 2017 data (paper in preparation)

	2016 data	2017 data
SES	$(3.15 \pm 0.24) \cdot 10^{-10}$	$(0.39 \pm 0.02) \cdot 10^{-10}$
Expected signal	0.27 ± 0.04	2.16 ± 0.29
Expected background	0.15 ± 0.09	1.50 ± 0.31
Observed events	1	2

Preliminary *Br* measurement on 2016+2017 data

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 2.44 \cdot 10^{-10} \text{ @ } 95\% \ CL$$
$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \cdot 10^{-10} \text{ @ } 90\% \ CL$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \cdot 10^{-10} \text{ (two-sided 68\% band)}$$

CLs method: [A.L. Read, J. Phys. G 28 (2002) 2693.]

Expected (background only)

$$Br^{expected}(K^+ \to \pi^+ \nu\bar{\nu}) < 1.32\,(1.62) \cdot 10^{-10} \text{ @ } 90\,(95)\ \%\ CL$$

SM prediction

$$Br^{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$$

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

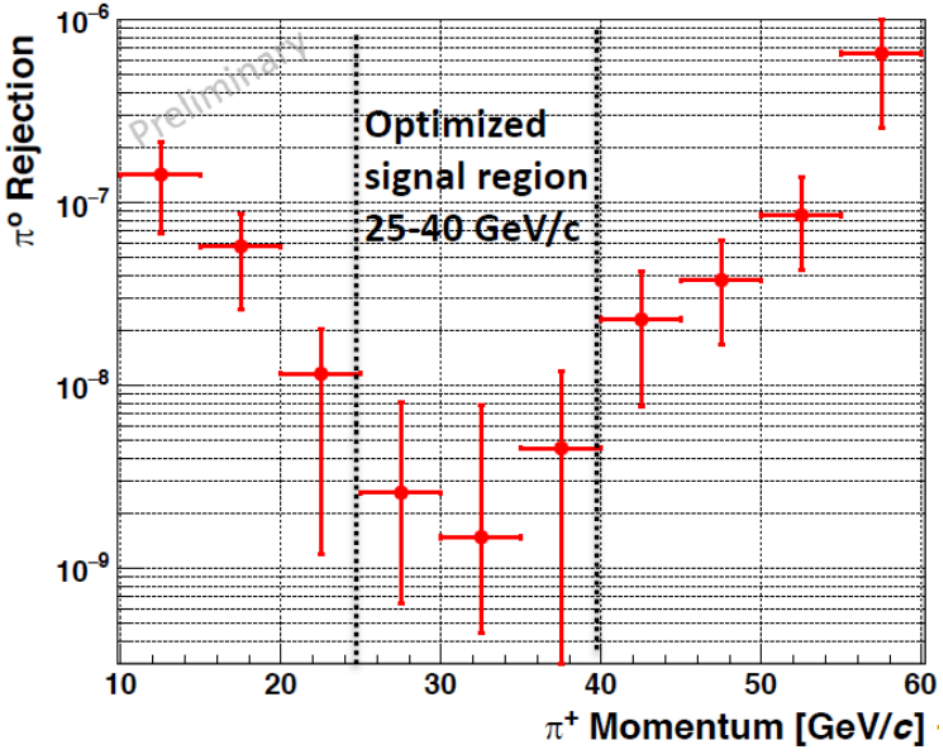
2018 data prospects

- analysis on going, with a factor 2 more than 2017 statistics
- on going studies to optimize the selection, increase signal efficiency, reduce the random veto

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
  - 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 charged pions and photons from upstream kaon decays
- **goal**: $Br(K^+ \to \pi^+ \nu\bar{\nu})$ measurement with about 20% statistical precision

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

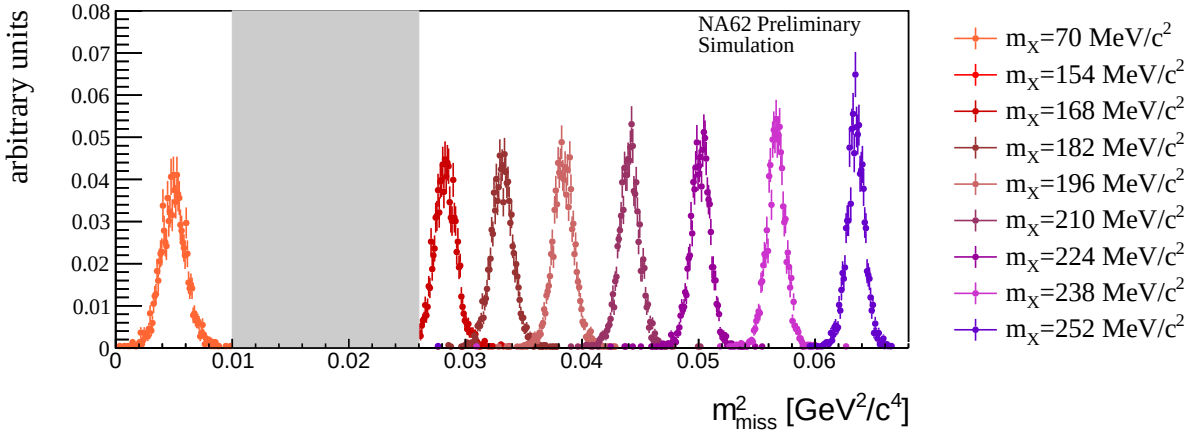
Preliminary result (paper in preparation)

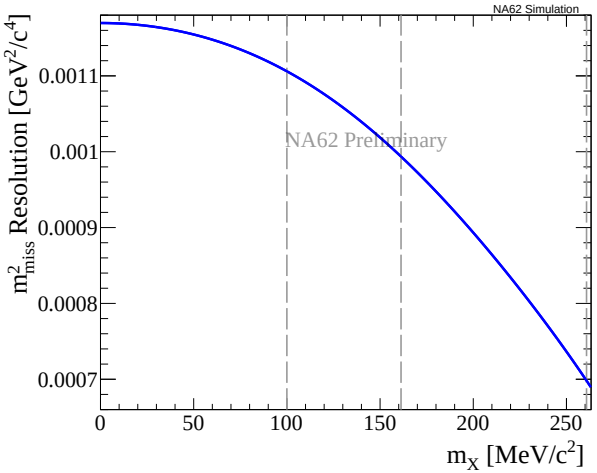
$Br(\pi^0 \to invisible) < 4.4 \cdot 10^{-9}$ @ 90% CL

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

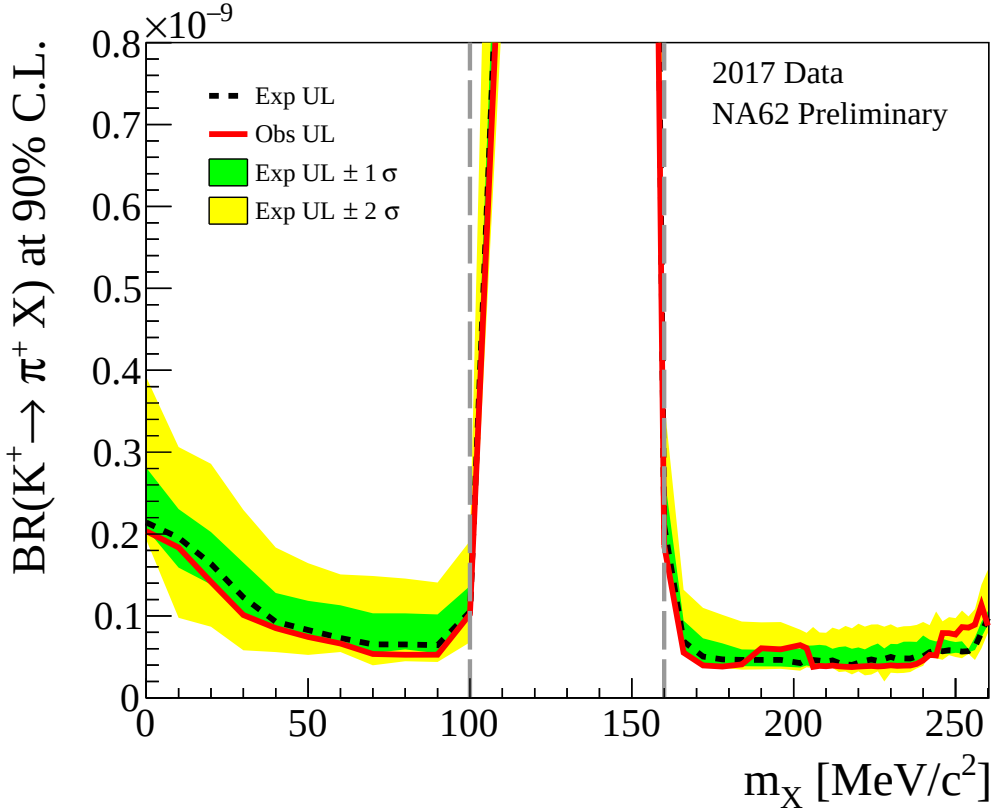
Search for $K^+ \to \pi^+ X$, X invisible: strategy

- 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

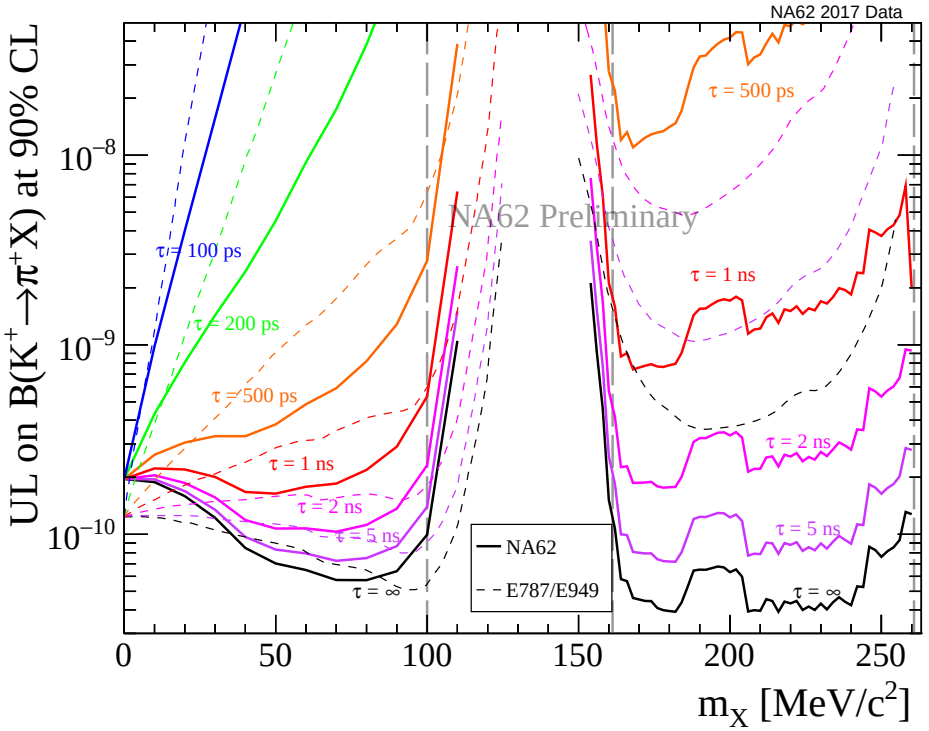


- Shape analysis in m^2_{miss}.
- Fully frequentist approach, profiled likelihood test statistic.
- Background from $\pi\nu\nu$ analysis parameterized with polynomial functions, including SM $K^+ \to \pi^+\nu\bar{\nu}$.
- Signal shape: gaussian.

Preliminary result (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 (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 $m_X \in [160, 260]\ MeV/c^2$.

Conclusions

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

Combined 2016+2017 preliminary NA62 results (paper in preparation):

- 1+2 signal candidates observed
- $Br(K^+ \to \pi^+\nu\bar{\nu}) < 1.85\ (2.44) \cdot 10^{-10}$ @ 90 (95)% CL
- $Br(K^+ \to \pi^+\nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \cdot 10^{-10}$ (two-sided 68% band)
- Starting to constrain the largest enhancements allowed by NP models

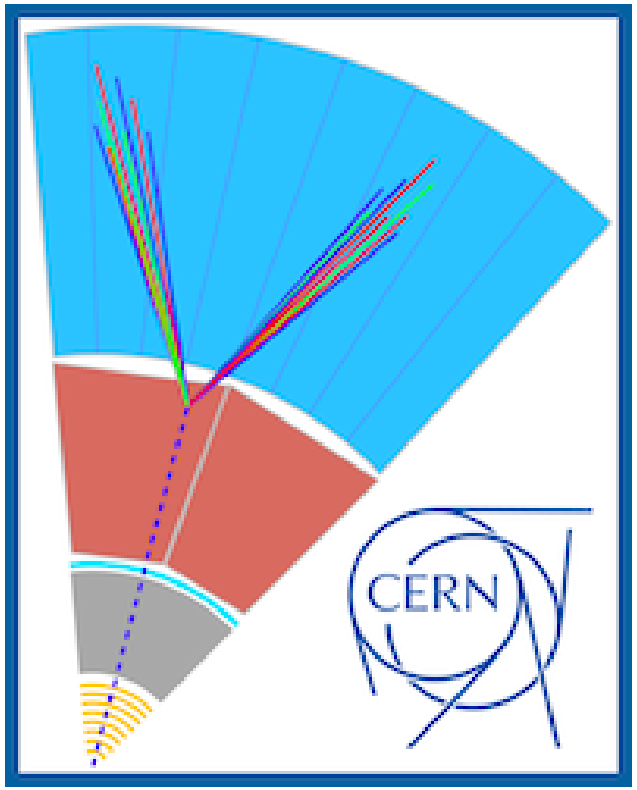
Prospects:

- $\simeq$ 10 SM events expected in the full 2016-2018 data sample
- With data taking between CERN LS2 and LS3:
  $Br(K^+ \to \pi^+\nu\bar{\nu})$ measurement with about 20% statistical precision

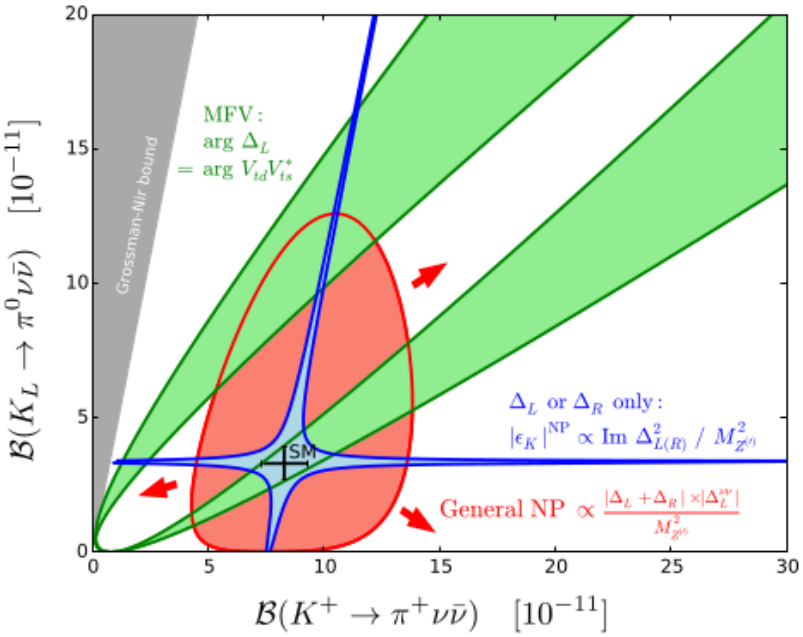
Exotic searches related to $K^+ \to \pi^+\nu\bar{\nu}$ search (papers in preparation)

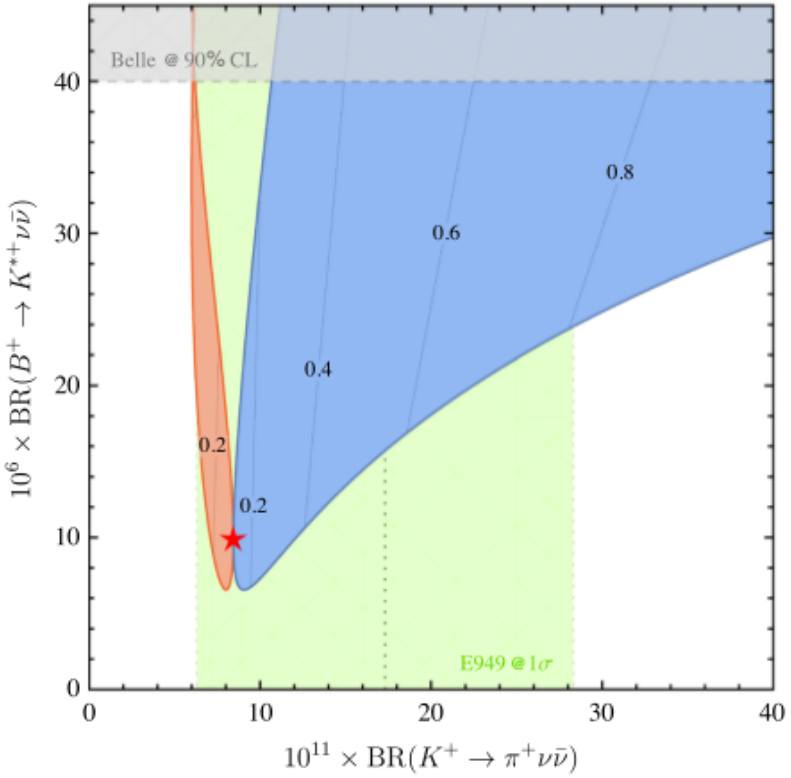
- $Br(\pi^0 \to invisible) < 4.4 \cdot 10^{-9}$ @ 90% CL (improvement by a factor of 60)
- $Br(K^+ \to \pi^+ X) < (0.5 - 2.0) \cdot 10^{-10}$ @ 90% CL for $m_X \in [0, 100]\ MeV/c^2$
- $Br(K^+ \to \pi^+ X) < (0.4 - 1.4) \cdot 10^{-10}$ @ 90% CL for $m_X \in [160, 260]\ MeV/c^2$
  (improvement of $\sim$ 1 order of magnitude)

SPARES



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

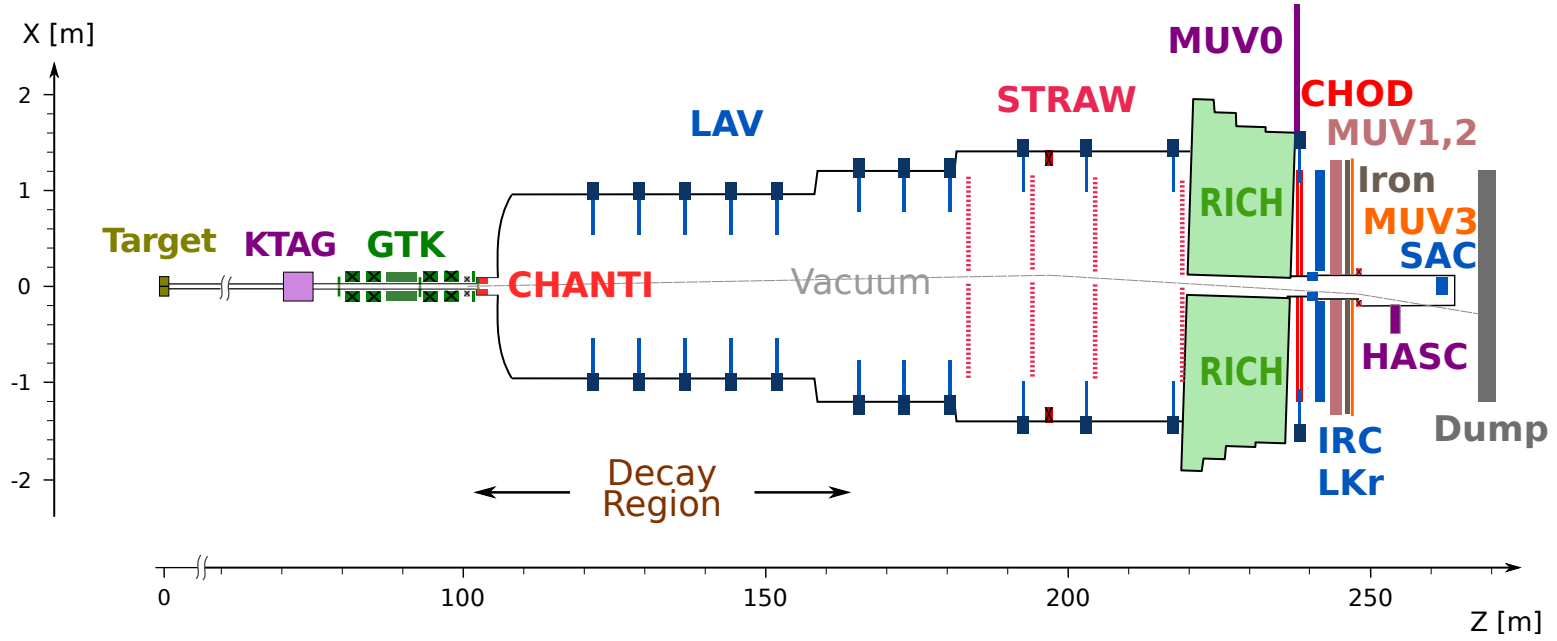




[Buras, Buttazzo, Knegjens, JHEP11 (2015) 166]
$K \to \pi\nu\bar{\nu}$ and ϵ'/ϵ in simplified new physics models

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

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

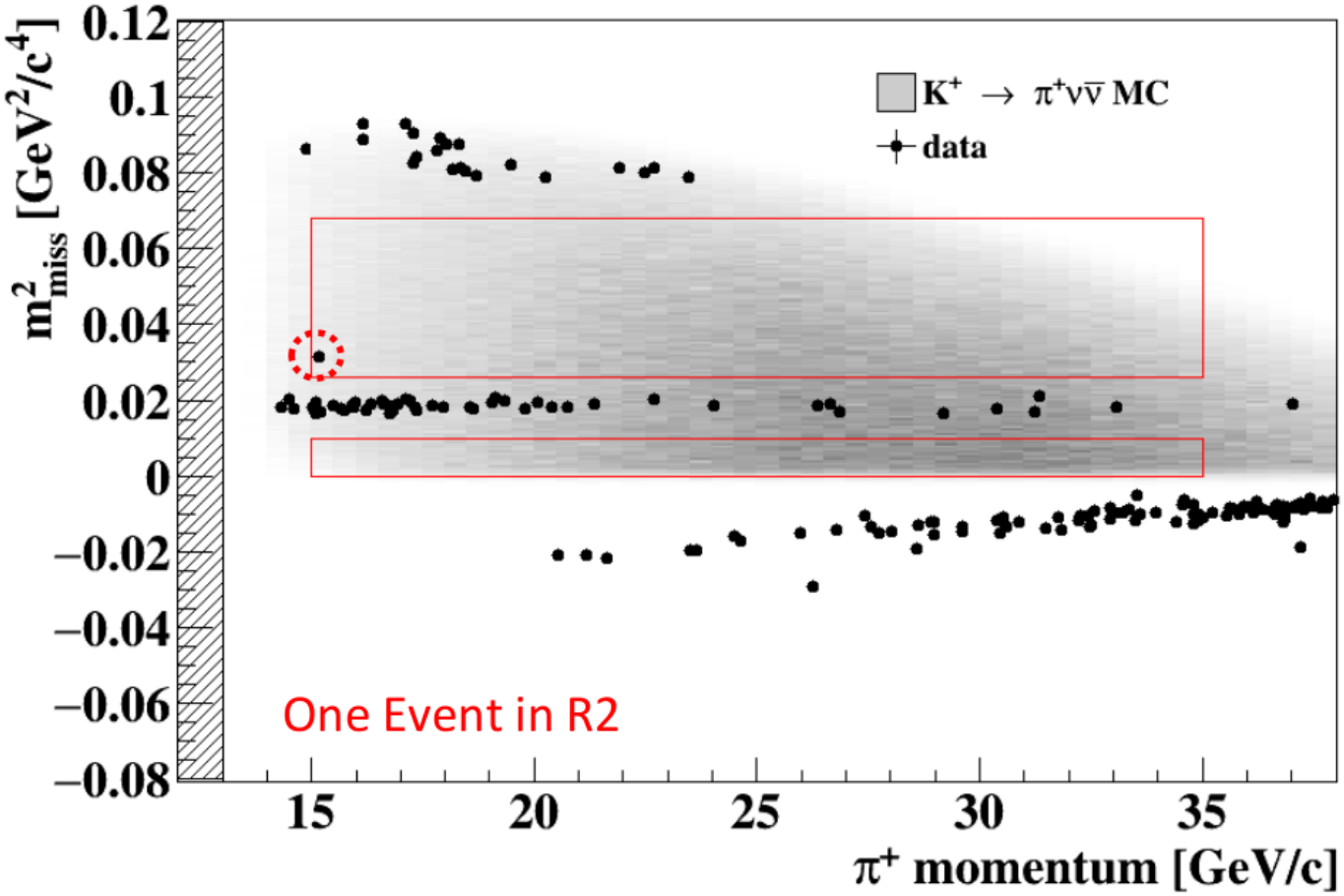


- KTAG: Cherenkov threshold counter;
- GTK: Si pixel beam tracker;
- CHANTI: ring stations of scintillator slabs;
- LAV: lead glass ring calorimeters;
- STRAW: straw magnetic spectrometer;
- RICH: Ring Imaging Cherenkov counter;
- MUV0: off-acceptance plane of scintillator pads;

- 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.

NA62 results on 2016 data

$K^+ \to \pi^+ \nu\bar{\nu}$ selection on 2016 data



$Br^{NA62}(K^+ \to \pi^+\nu\bar{\nu}) < 14 \cdot 10^{-10}$ @ 95% *CL*

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

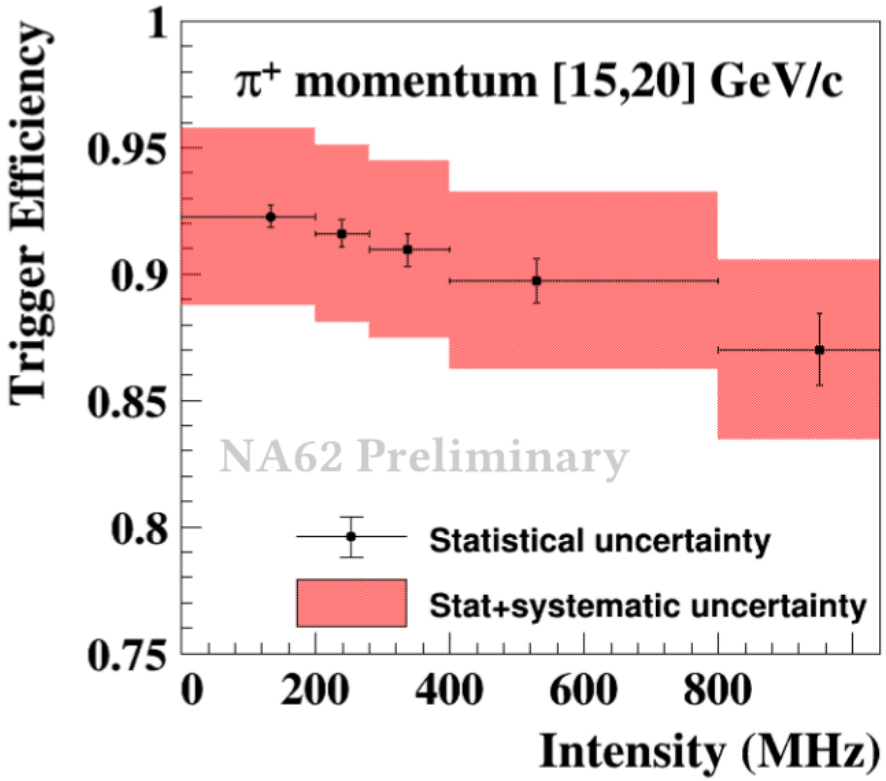
Trigger and random veto eff. (2017 data - Preliminary)

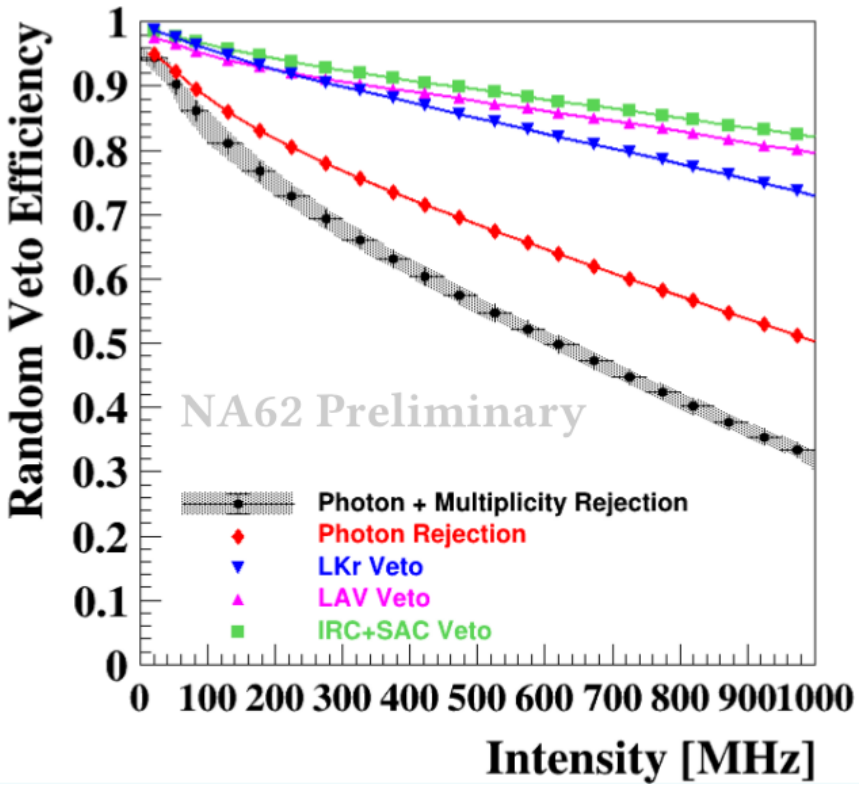
Trigger efficiency

Measured on data using
$K^+ \to \pi^+\pi^0$ events
$\epsilon_{trig} = (87 \pm 3)\%$

Random veto efficiency

Measured on data using
$K^+ \to \mu^+\nu$ events
$\epsilon_{RV} = (63.8 \pm 1.4)\%$





Single event sensitivity and number of expected events (2017 data - Preliminary)

Single event sensitivity

$$SES = (0.389 \pm 0.021_{syst}) \cdot 10^{-10}$$

SES error budget:

Source	**Uncertainty** $\times 10^{10}$
L0 trigger	± 0.015
Acceptance	± 0.012
Random veto	± 0.008
L1 trigger	± 0.003
Normalization background	negligible

Number of expected events

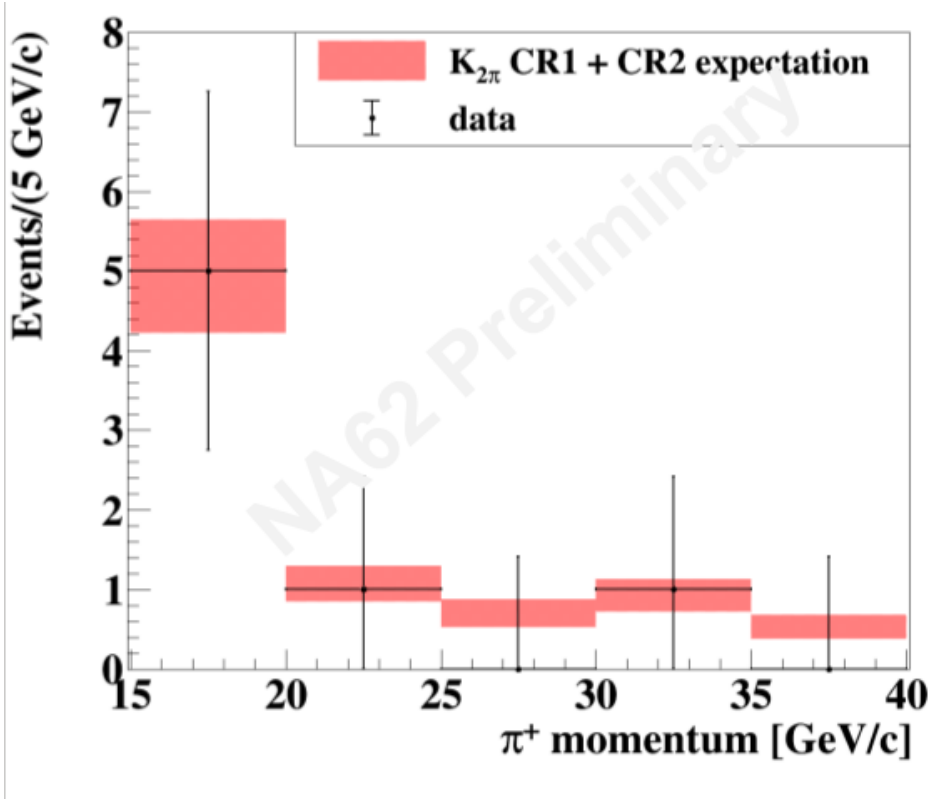
$$N^{exp}_{\pi\nu\nu}(SM) = \frac{Br_{\pi\nu\nu}(SM)}{SES} = (2.16 \pm 0.12_{syst} \pm 0.26_{ext})$$

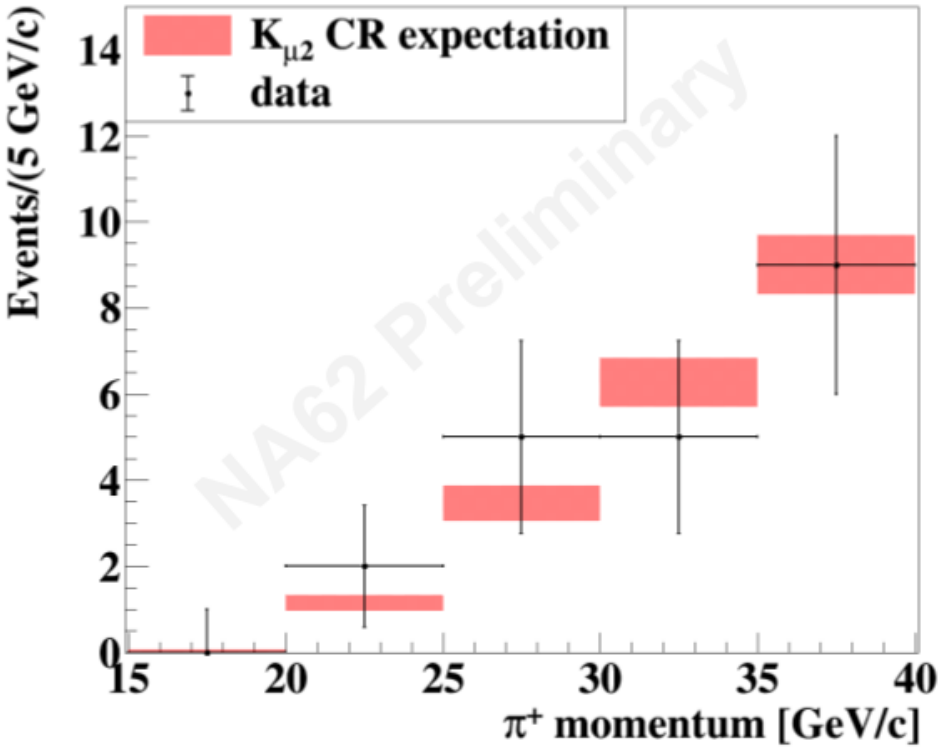
External error: theoretical uncertainty on the SM prediction:

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

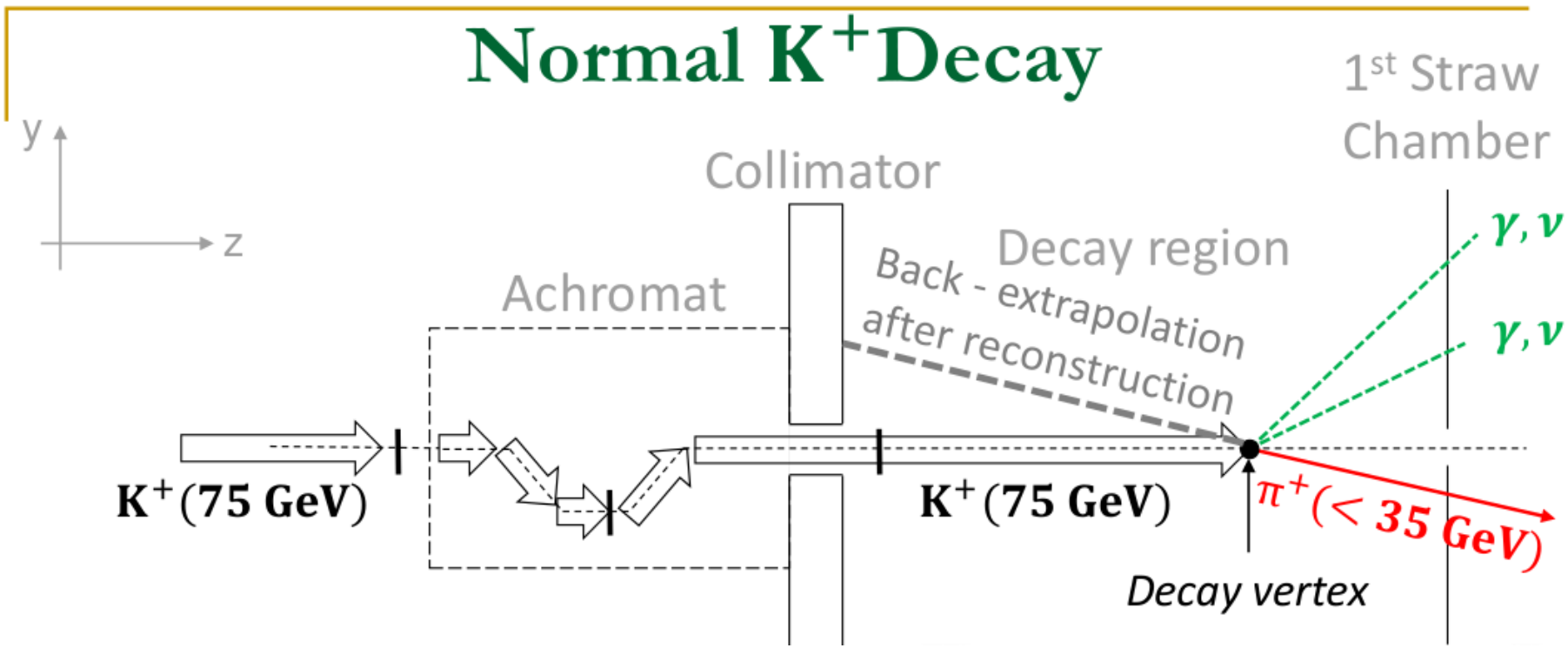
Background validation: $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$

Expected and observed $\pi^+\pi^0$ and $\mu^+\nu$ events in control regions





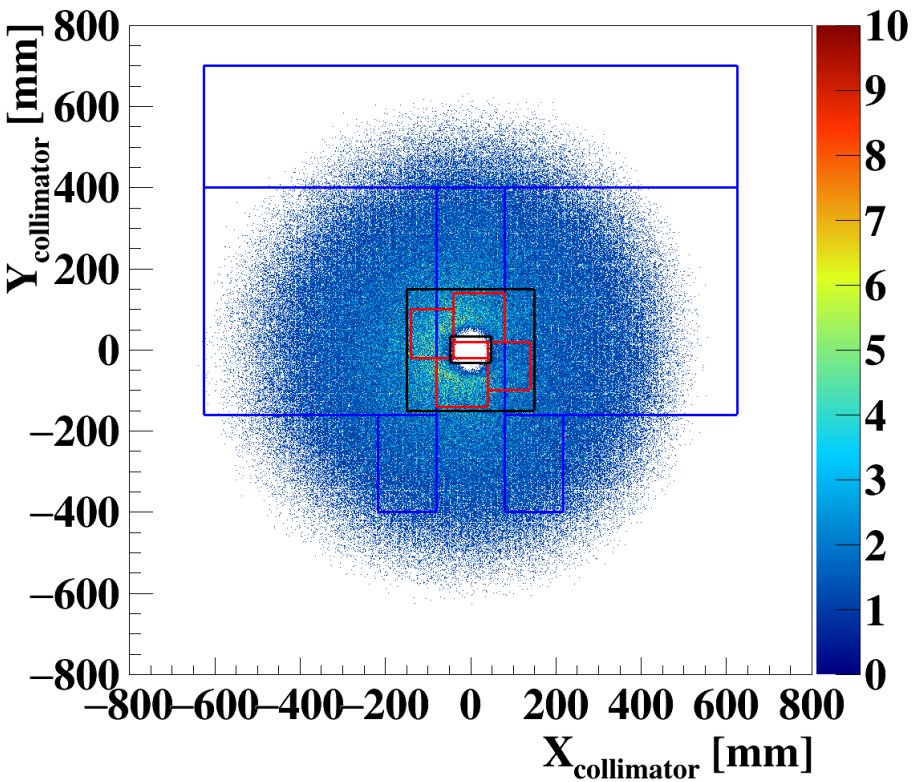
Upstream background

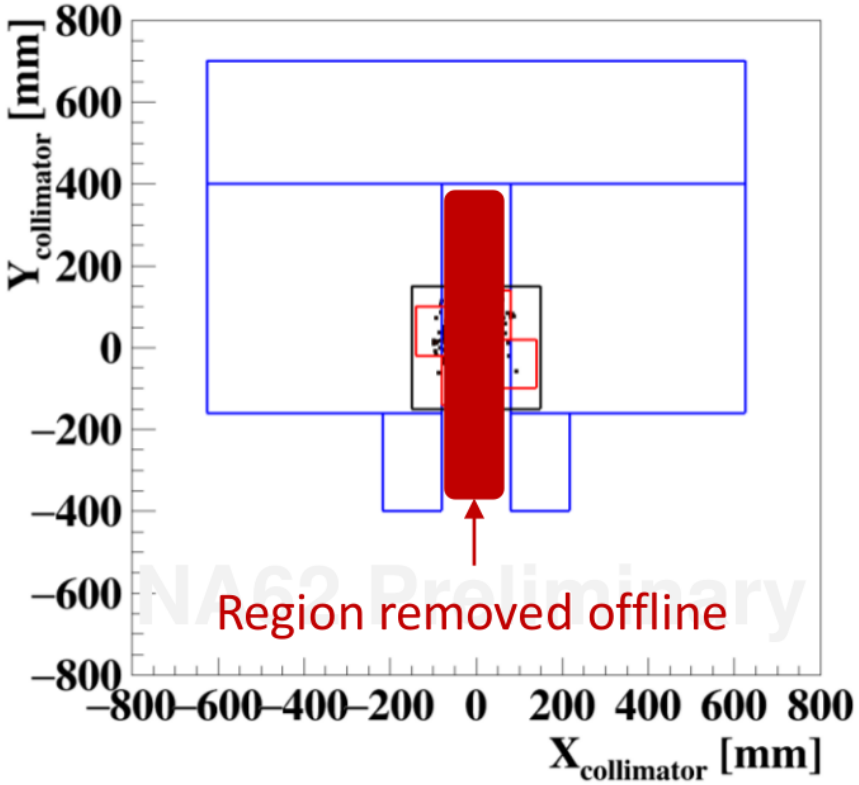


The back-extrapolation of the downstream track at the Collimator is *far* from the beam direction. Downstream tracks back-extrapolated near beam-pipe hole rejected.

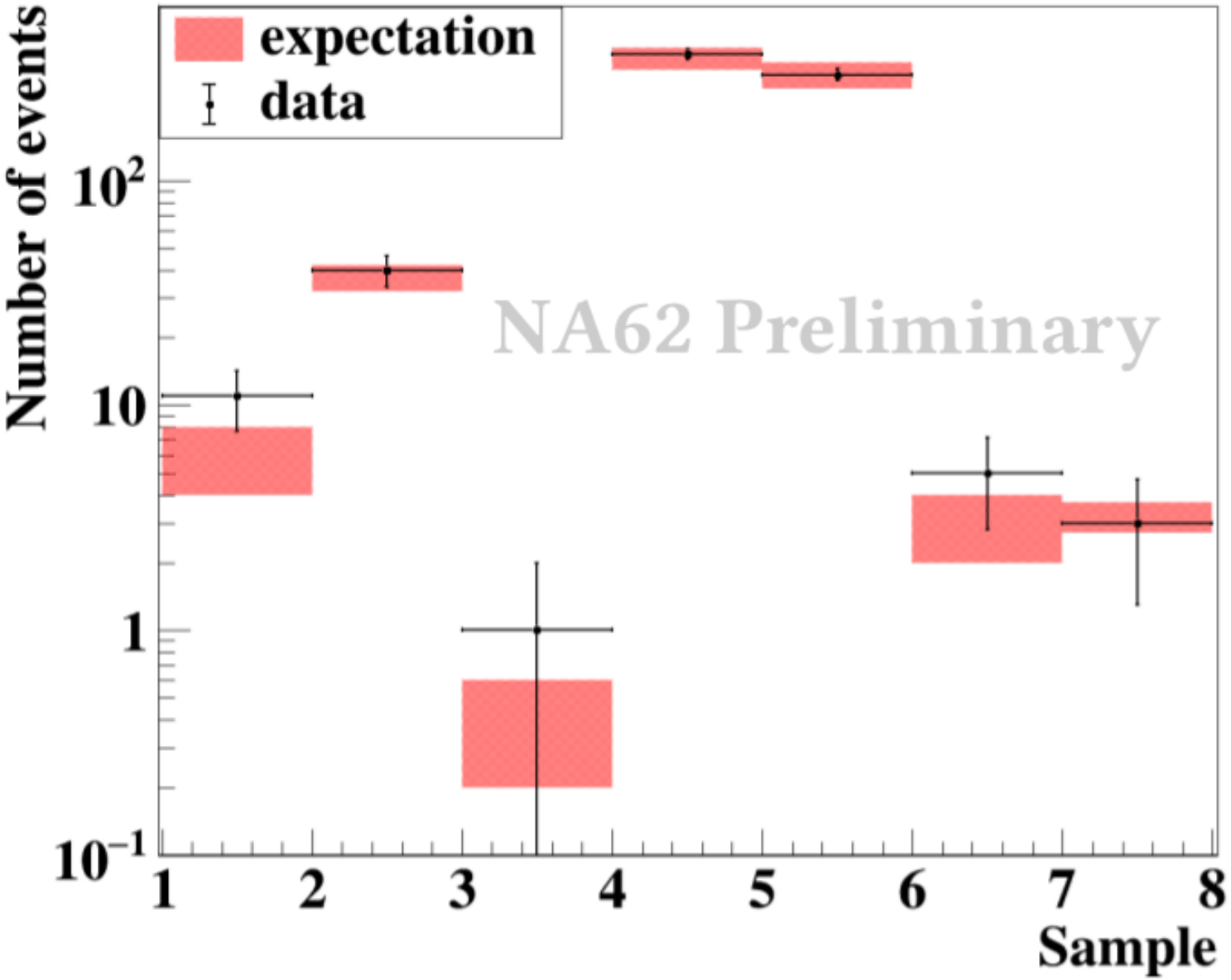
Upstream background cut

Back-extrapolated track position (at the final collimator)





Upstream background validation



Preliminary results from the 2017 data

SES (single event sensitivity)	$(0.39 \pm 0.02) \cdot 10^{-10}$
Expected signal	2.16 ± 0.29
Expected background	1.50 ± 0.31
Observed $K^+ \to \pi^+ \nu\bar{\nu}$ candidates	2

Preliminary Br measurement on 2017 data

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 2.11 \cdot 10^{-10} \text{ @ } 95\% \ CL$$
$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.76 \cdot 10^{-10} \text{ @ } 90\% \ CL$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.20^{+0.69}_{-0.20}) \cdot 10^{-10} \text{ (two-sided 68\% band)}$$

CLs method: [A.L. Read, J. Phys. G 28 (2002) 2693.]

Expected (background only)

$$Br^{expected}(K^+ \to \pi^+ \nu\bar{\nu}) <$$
$$1.41\,(1.76) \cdot 10^{-10} \text{ @ } 90\,(95)\,\% \ CL$$

SM prediction

$$Br^{SM}(K^+ \to \pi^+ \nu\bar{\nu}) =$$
$$(0.84 \pm 0.10) \cdot 10^{-10}$$

Results from the 2016 data

Observed $K^+ \to \pi^+ \nu\bar{\nu}$ candidates	1
SES (single event sensitivity)	$(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$
Expected background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

Branching Ratio measurement - upper limits

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 11 \cdot 10^{-10} \text{ @ } 90\% \ CL$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \cdot 10^{-10} \text{ @ } 95\% \ CL$$

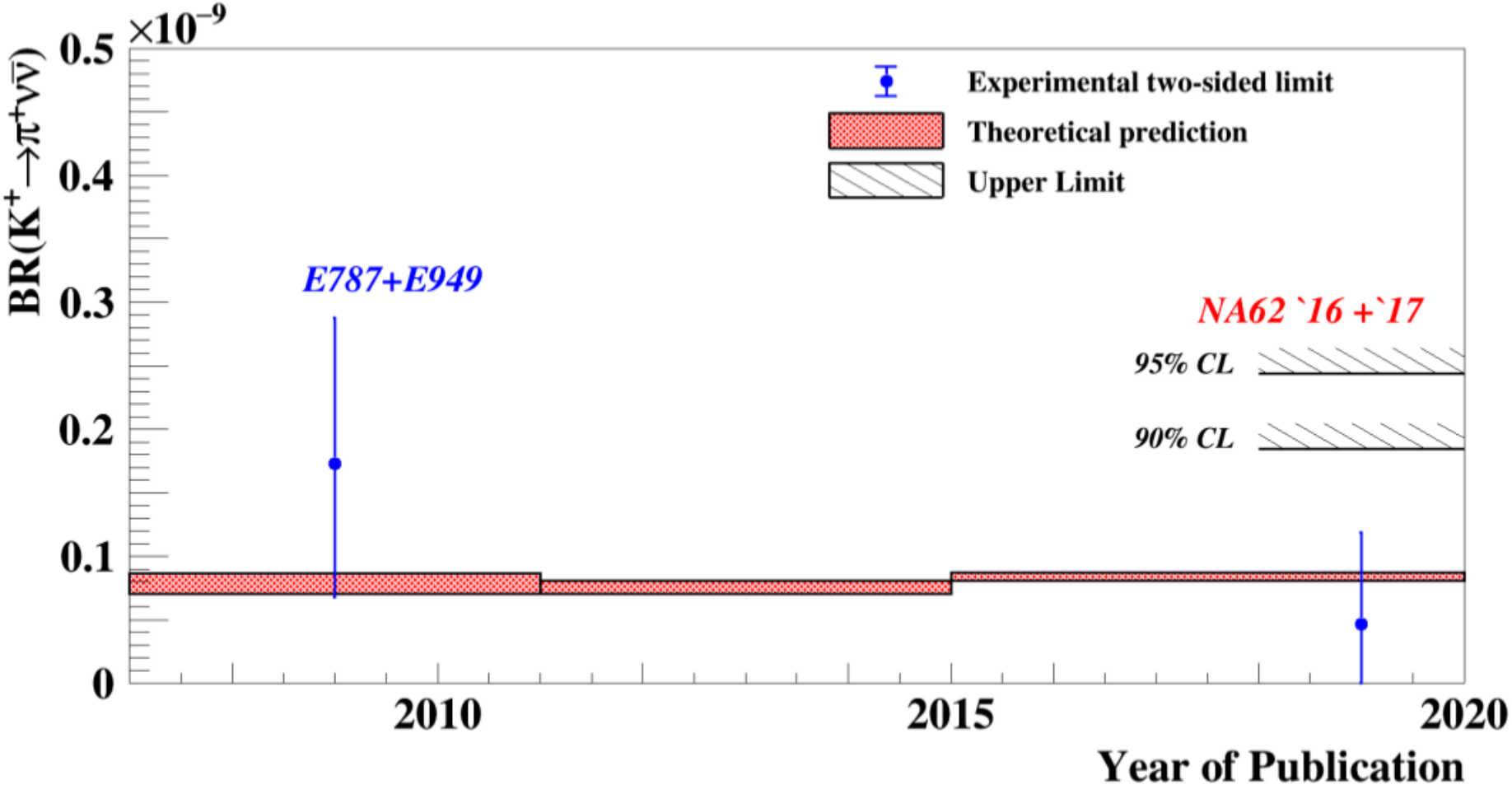
Expected upper limit

$$Br^{expected}(K^+ \to \pi^+ \nu\bar{\nu}) < 10 \cdot 10^{-10} \text{ @ } 95\% \ CL$$

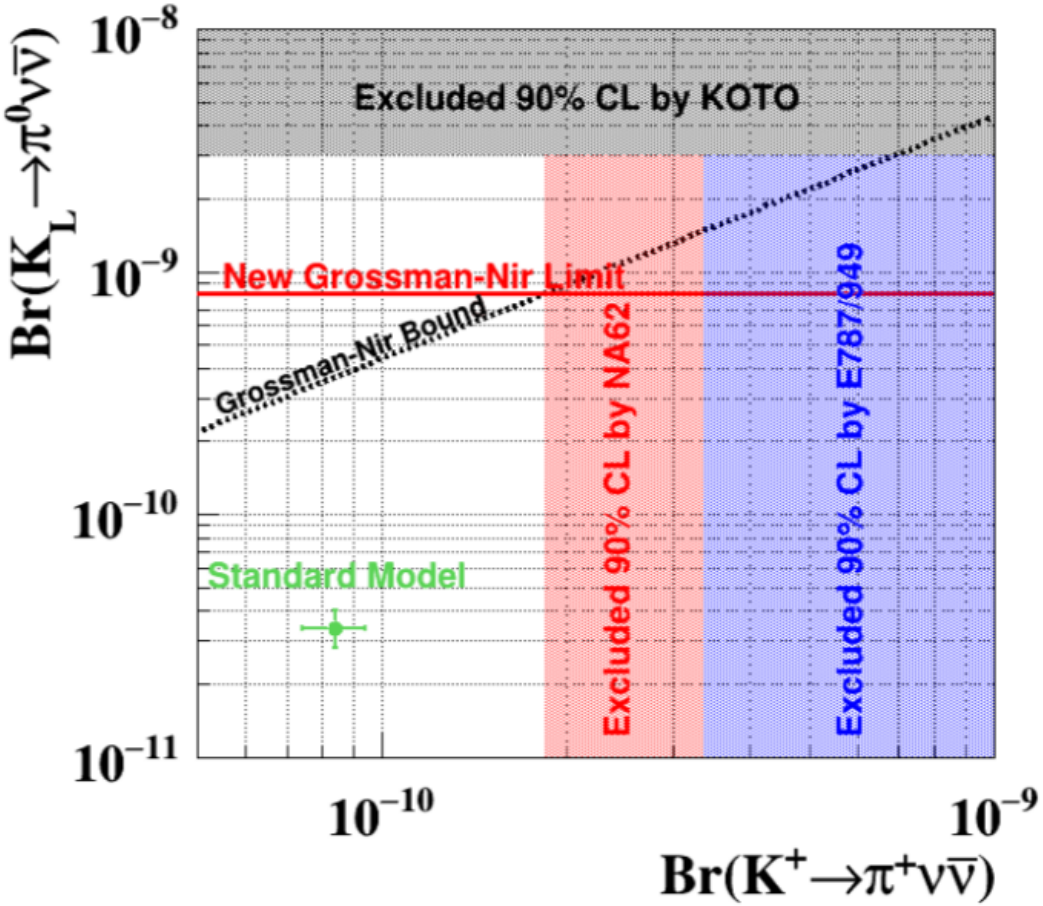
SM prediction

$$Br^{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ update (preliminary)



$K \to \pi\nu\bar{\nu}$ excluded regions (preliminary)



Constraints on the largest enhancements allowed by NP models.

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

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