

# Measurement of the very rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay from NA62

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on behalf of the NA62 Collaboration

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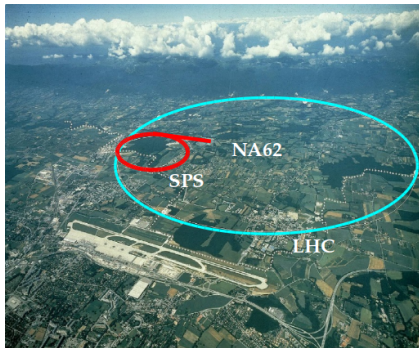


## $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ measurement at NA62

- Physics case
- Beam and detector
- Experimental strategy
- Signal selection
- Single Event Sensitivity
- Background estimation and validation
- Result from 2016+2017+2018 data
- Reinterpretation for  $K^+ \rightarrow \pi^+ X$  search
- Prospects

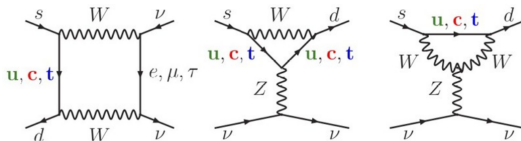
# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ search @ NA62

- Full detector installation completed in 2016
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  physics runs in 2016, 2017 and 2018
- Result from 2016+2017 data is published [JHEP 11 (2020) 042]
- Result from 2016+2017+2018 data (Run 1) accepted for publication by JHEP [arXiv 2103.15389] → **this seminar!**
- Data taking will resume in July after CERN LS2



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

# The physics case: $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$



- $\bar{s} \rightarrow \bar{d} \nu \bar{\nu}$  transition: **flavour changing neutral current** process (GIM mechanism) with high CKM suppression
- **Clean theoretical prediction:** short distance contributions
- Hadronic matrix elements: obtained from  $K^+ \rightarrow \pi^0 l^+ \nu$  ( $K_{l3}$ ) measurements and SU(2) isospin symmetry

Standard Model prediction [*Buras et al., JHEP11(2015)033*]

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

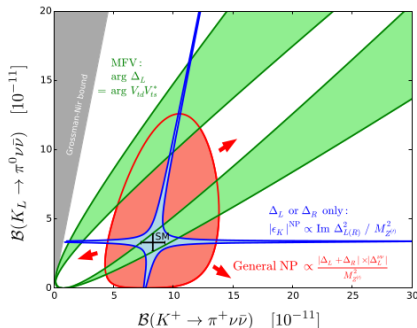
main uncertainty due to CKM elements knowledge:

$$Br^{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.839 \pm 0.030) \cdot 10^{-10} \cdot \left( \frac{|V_{cb}|}{40.7 \cdot 10^{-3}} \right)^{2.8} \cdot \left( \frac{\gamma}{73.2^\circ} \right)^{0.74}$$

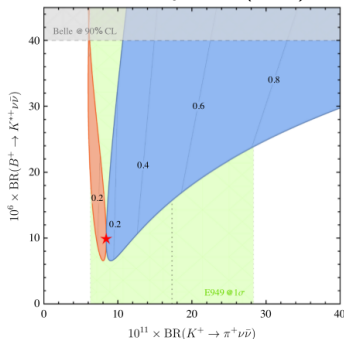
# The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay beyond the Standard Model

New Physics search,  $Br$  sensitive to the highest mass scales

[Buras et al., JHEP11 (2015) 166]



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



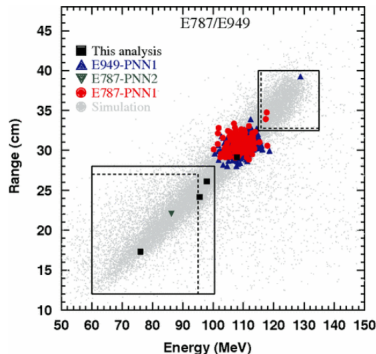
New Physics models for  $K \rightarrow \pi \nu \bar{\nu}$

MFV; Simplified Z, Z'; LFU violation; Custodial Randall-Sundrum; MSSM; Littlest Higgs with T-parity; Leptoquarks.

# Experimental status before NA62

## BNL E787/E949 experiments

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



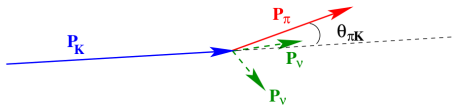
- Kaon *decay-at-rest* technique
- sensitivity for  $\sim 1$  SM signal event
- 7 events observed in signal regions
- statistical reweighing procedure to take into account the background

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

# NA62: the experimental strategy

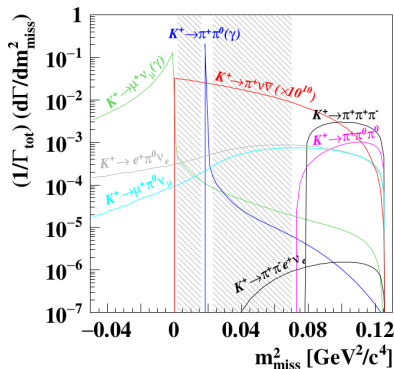
## Keystones

- decay-in-flight technique ( $P_K = 75 \text{ GeV}/c$ )
- main kinematic variable:  $m_{\text{miss}}^2 = (P_K - P_\pi)^2$
- pion momentum range:  $[15; 45] \text{ GeV}/c$
- charged particle identification
- muon and photon rejection
- signal and control kinematic regions *blinded* during the analysis



## Required performance

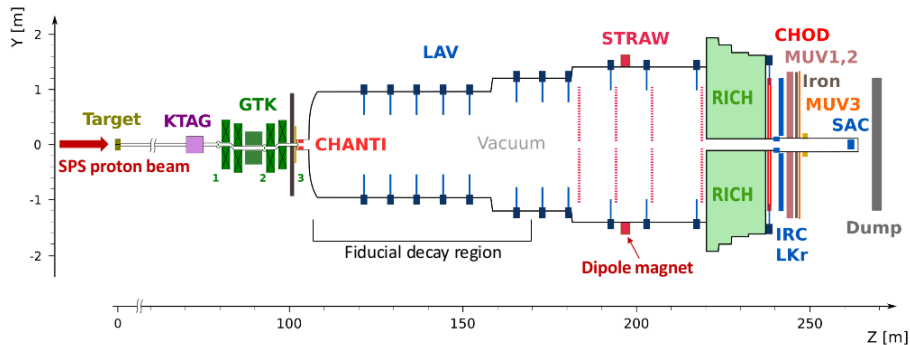
- time coincidence:  $O(100 \text{ ps})$
- kinematic rejection:  $O(10^4)$
- muon rejection:  $> 10^7$
- $\pi^0$  rejection:  $> 10^7$



## $K^+$ main (background) decays

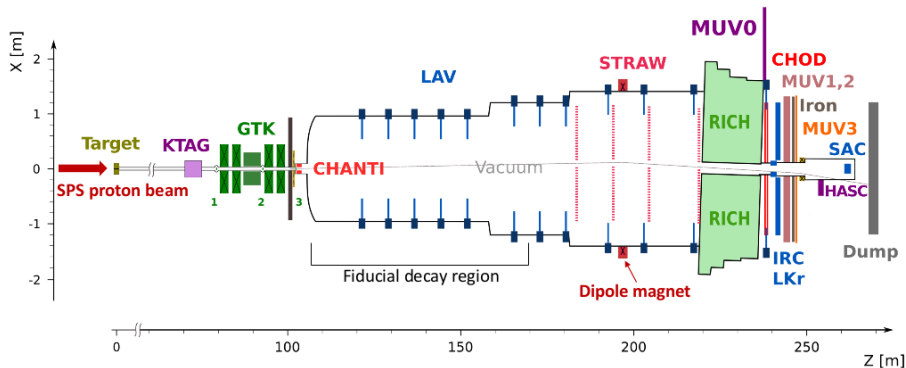
Decay channel	Branching Ratio
$K^+ \rightarrow \mu^+ \nu (K_{\mu 2})$	$(63.56 \pm 0.11) \cdot 10^{-2}$
$K^+ \rightarrow \pi^+ \pi^0 (K_{2\pi})$	$(20.67 \pm 0.08) \cdot 10^{-2}$
$K^+ \rightarrow \pi^+ \pi^+ \pi^- (K_{3\pi})$	$(5.583 \pm 0.024) \cdot 10^{-2}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu (K_{e4})$	$(4.247 \pm 0.024) \cdot 10^{-5}$

# NA62 beam [2017 JINST 12 P05025]



- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadron 75 GeV/c beam
- 70% pions, 24% protons, 6% kaons
- Nominal beam particle rate (at GTK3): 750 MHz
- Average beam particle rate during 2018 data-taking: 450 – 500 MHz

# NA62 detector [2017 JINST 12 P05025]

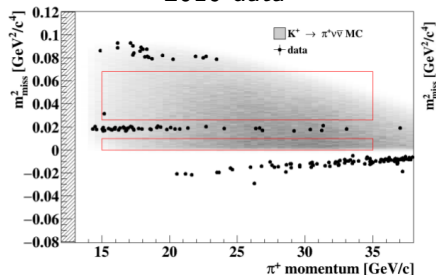


- KTAG: Cherenkov threshold counter;
- GTK: Si pixel beam tracker;
- CHANTI: stations of plastic scintillator bars;
- LAV: lead glass ring calorimeters;
- STRAW: straw magnetic spectrometer;
- RICH: Ring Imaging Cherenkov counter;
- MUV0: off-acceptance plane of scintillator pads;

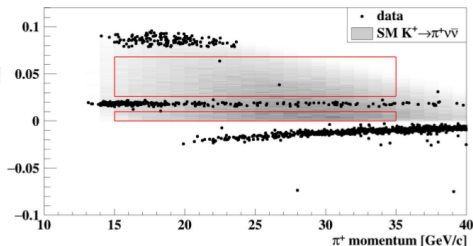
- CHOD: planes of scintillator pads and slabs;
- IRC: inner ring shashlik calorimeter;
- LKr: electromagnetic calorimeter filled with liquid krypton;
- MUV1,2: hadron calorimeter;
- MUV3: plane of scintillator pads for muon veto;
- HASC: near beam lead-scintillator calorimeter;
- SAC: small angle shashlik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

# NA62 results of the 2016 and 2017 data analyses

2016 data



2017 data



## 2016 result

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

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

## 2016+2017 result

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

[JHEP 11 (2020) 042]

# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection

## Selection steps

- $\pi^+$  and  $K^+$  tracks reconstruction
- $K^+ - \pi^+$  matching
- decay vertex reconstruction
- $\pi^+$  identification ( $\mu^+$  rejection)
- photon rejection
- multi-track rejection
- kinematics ( $m_{miss}^2$  vs  $p_\pi$ )

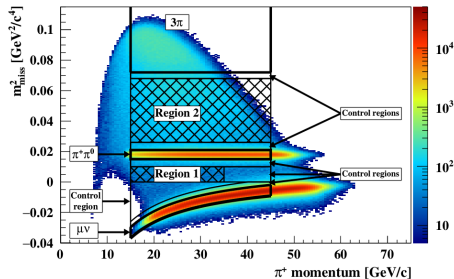
## $\pi \nu \nu$ trigger stream

- L0 (hardware): presence of charged particle + muon and photon veto
- L1 (software):  $K^+$  ID, photon veto, track reconstruction

## Minimum bias trigger stream

- Presence of charged particle (L0 only)

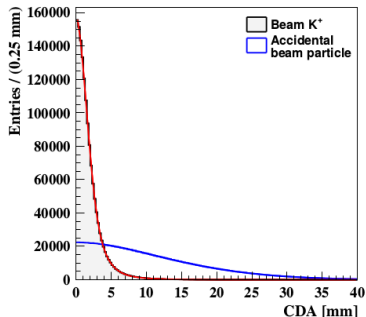
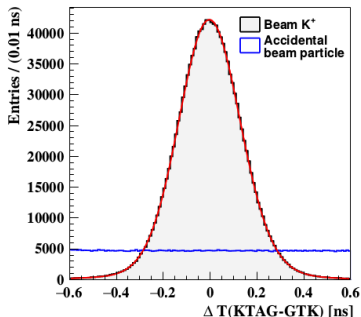
$$m_{miss}^2 = (P_K - P_\pi)^2$$



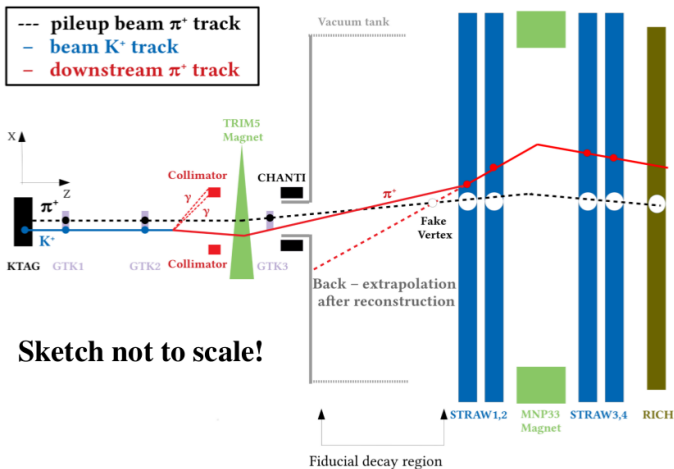
# $K^+ - \pi^+$ matching

- Time and space matching discriminant based on  $\Delta T(\text{RICH}, \text{KTAG}, \text{GTK})$  and CDA (*closest distance of approach*)
- $|\Delta T| < 0.5$  ns,  $\text{CDA} < 4$  mm
- Reconstructed decay vertex inside the fiducial volume:  $Z \in [105; 170]$  m

data -  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  control sample



# Upstream event

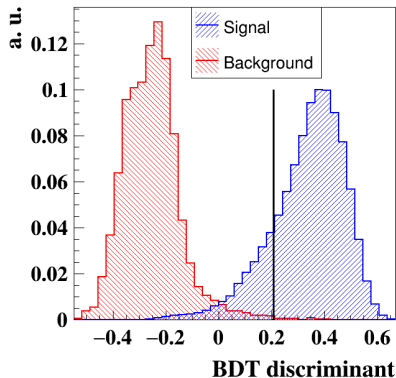


- a kaon decays upstream the fiducial decay region
- only a  $\pi^+$  enters the fiducial decay region
- there is an in-time pileup beam particle (in GTK)
- the upstream  $\pi^+$  is scattered in the first STRAW chamber.

# Upstream events rejection

- $K^+ - \pi^+$  matching conditions + *geometrical variables*:  
 $(X, Y)_{\text{Collimator}}$ ,  $(X, Y, Z)_{\text{vtx}}$ , *track slope*
- BDT or cut-based approach applied on geometrical variables
- **BDT approach possible only after the installation of a new final collimator in June 2018**
- BDT signal training sample: MC simulation
- BDT background training sample: out of time data ( $|\Delta T| > 0.5$  ns)

BDT discriminant  
for Signal and Background



Both samples normalized to 1  
 $\epsilon(\text{sig}) \sim 83\% @ \epsilon(\text{bkg}) \sim 0.5\%$

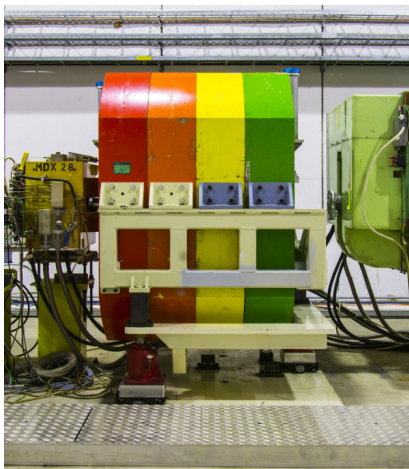
# The new collimator

Replacement of the final collimator against upstream events  
(June 2018)

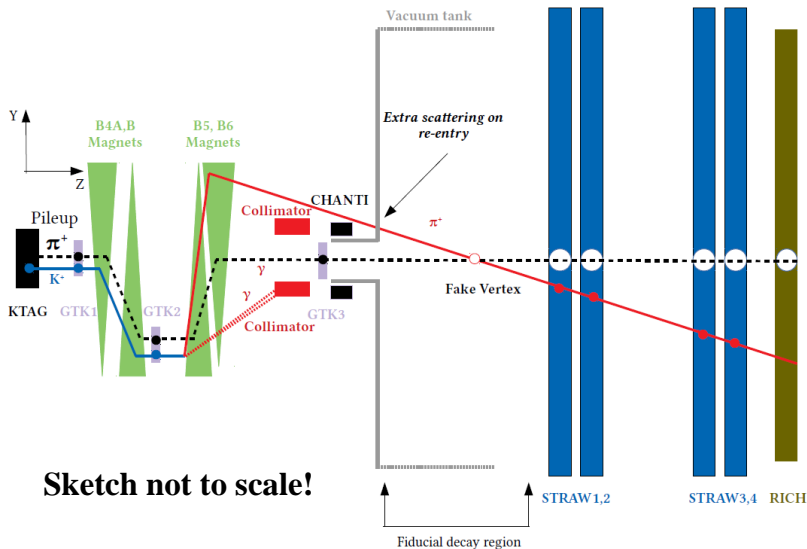
OLD COL



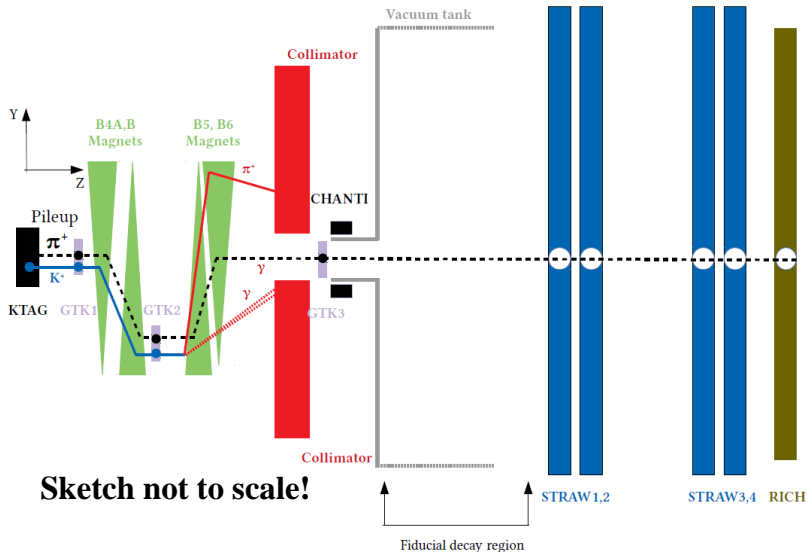
NEW COL



# A particular upstream event in the OLD COL configuration



# The same upstream event in the NEW COL configuration

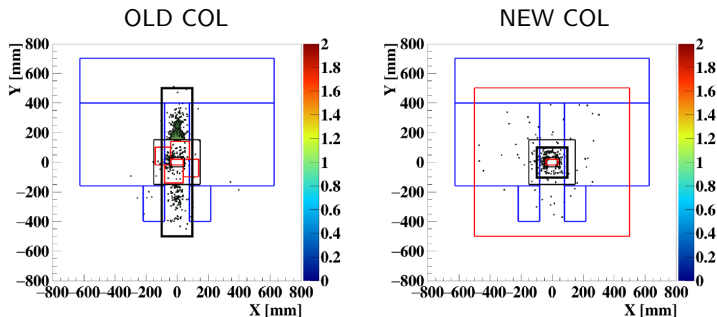


# Effect of the new collimator

2018 data samples split into two sub-samples:

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

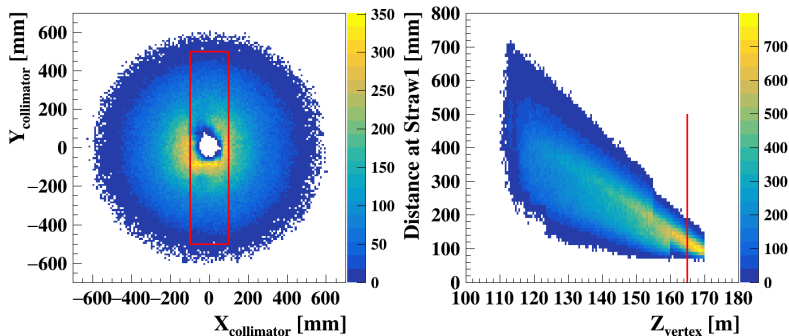
Track extrapolation at collimator in enriched sample of upstream events (data).  
Red boxes: collimator coverage.



**Two different selections for the two sub-samples!**

# BDT against upstream events: improvement in signal efficiency

MC  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  after cut on BDT discriminant



Main BDT variables:  $(X, Y)_{\text{collimator}}$ ,  $Z_{\text{vertex}}$ , Distance at Straw1

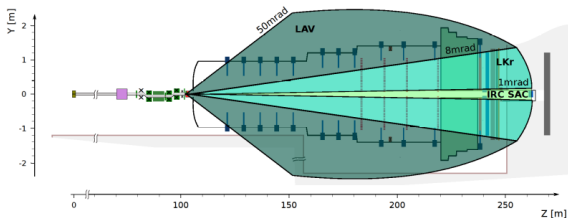
Red lines: cut-based selection (2018-OLDCOL sample)

Fiducial decay region extended from  $Z \in [105 - 165]$  m to  $Z \in [105 - 170]$  m

# PID and photon rejection

PID conditions optimized in bins of  $\pi^+$  momentum:

- RICH:  $\epsilon(\mu) \sim 3 \cdot 10^{-3}$  at  $\epsilon(\pi) \sim 0.85$
- Calorimeters (with BDT approach) and MUV3:  $\epsilon(\mu) \sim 10^{-5}$  at  $\epsilon(\pi) \sim 0.82$



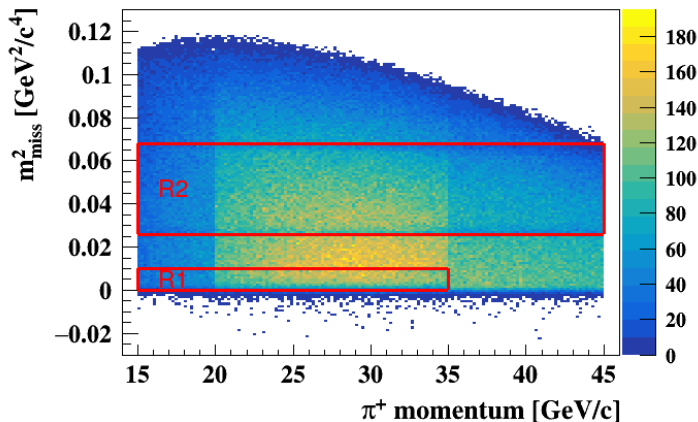
Photon rejection optimized taking into account correlations with  $Z_{\nu\tau X}$  and  $\pi^+$  momentum:

- $\pi^0$  rejection inefficiency (average):  $\sim 2 \cdot 10^{-8}$

# Kinematic selection

MC  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  after the full selection.

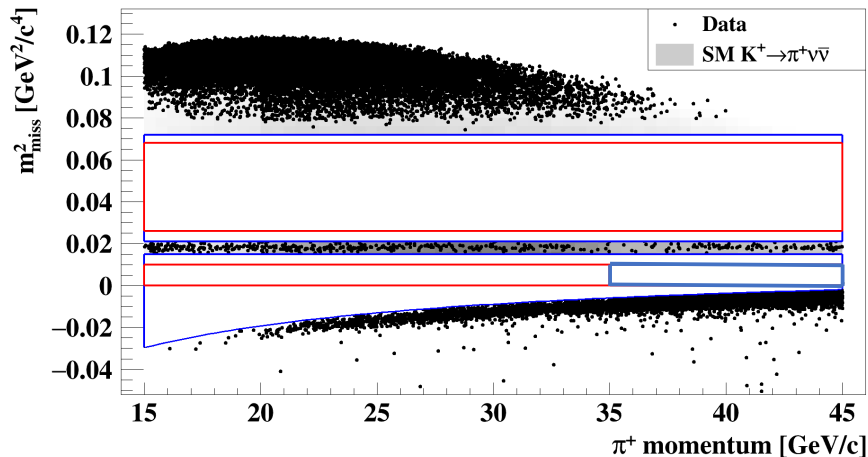
Red boxes represent the final kinematic cuts (signal regions).



Region at higher  $m_{miss}^2$  (R2) extended up to 45 GeV/c momentum.  
Discontinuities due to selection optimization in bins of momentum.

# Events after $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection

Control (blue) and signal (red) regions **blinded**



# Number of Kaon decays and Single Event Sensitivity

Normalization channel:  $K^+ \rightarrow \pi^+ \pi^0$  ( $\pi^0 \rightarrow \gamma\gamma$ )

Same criteria 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  $K^+ \rightarrow \pi^+ \pi^0$  observed events
- $D$  : Down-scaling factor applied to the minimum bias trigger
- $A_{\pi\pi}$  : normalization selection acceptance (from MC)
- $Br_{\pi\pi}$  : normalization decay Branching Ratio

$N_K$  is an effective number of  $K^+$  decays

## $N_K$ in 2018 data

$$N_K(2018) \simeq (0.8_{OLD\text{COL}} + 1.9_{NEW\text{COL}}) \cdot 10^{12} \simeq 2.7 \cdot 10^{12}$$

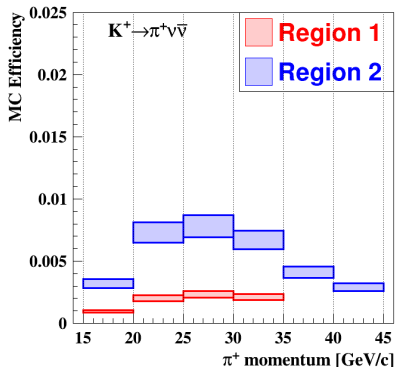
## Single Event Sensitivity

$$SES = \frac{1}{N_K \cdot \sum_j (A_{\pi\nu\nu}^j \cdot \epsilon_{trig}^j \cdot \epsilon_{RV}^j)}$$

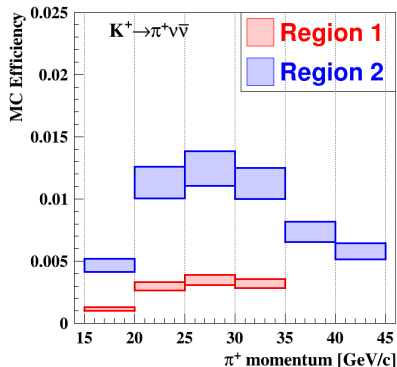
- $N_K$  : number of  $K^+$  decays
- $A_{\pi\nu\nu}$  : signal selection acceptance (from MC)
- $\epsilon_{trig}$  : trigger efficiency
- $\epsilon_{RV}$  : random veto efficiency
- $j$  : bins of  $\pi^+$  momentum

# Signal selection acceptance in MC

OLD COL



NEW COL

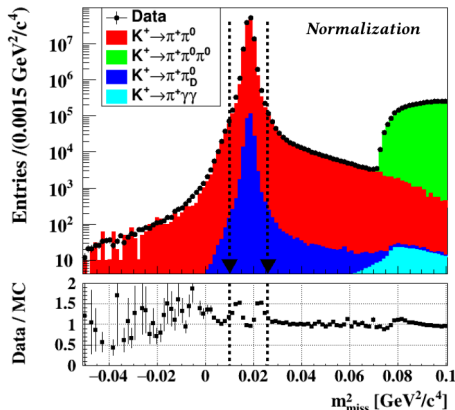


$$A_{\pi\nu\nu}(OLD COL) \simeq 4.0\% , A_{\pi\nu\nu}(NEW COL) \simeq 6.4\%$$

- Sizeable improvement in the NEWCOL sample
- Region 20-35 GeV/c the most sensitive in both samples

# Uncertainty of MC acceptance

Systematic uncertainty of 3.5% assigned to the SES  
due to Data/MC discrepancy

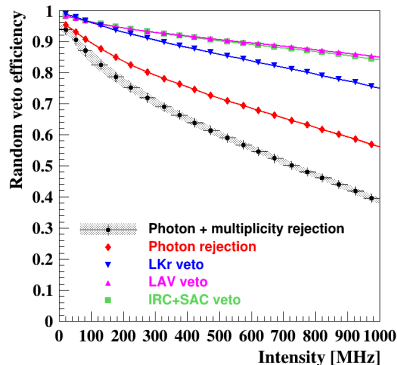


Cancellation of systematic effects  
in the *normalization process*:

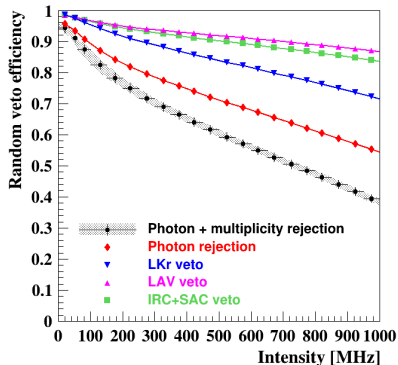
- $\pi^+$  ID and reconstruction
- detectors efficiencies
- $K^+$  ID and reconstruction
- beam-related acceptance loss

# Random veto efficiency

OLD COL



NEW COL



$\epsilon_{RV} = (66 \pm 1)\%$  (average) in both sub-samples.

- Measured in  $K^+ \rightarrow \mu^+ \nu$  control sample (minimum bias data)
- Systematic uncertainty due to radiative correction, computed with MC
- Slightly improved treatment of STRAW and LAV with respect to 2017

# Trigger efficiency

- Measured in minimum bias data, exploiting  $K^+ \rightarrow \mu^+ \nu$  and  $K^+ \rightarrow \pi^+ \pi^0$  control samples.
- $\epsilon_{trig} = (89 \pm 5)\%$  (average) in both the sub-samples.

## Systematic uncertainty of $\epsilon_{trig}$

- Counting number of events in  $K^+ \rightarrow \mu^+ \nu$  region:
  - after signal-like selection
  - in the  $\pi \nu \nu$  trigger data sample
- Comparing with expected events:
  - after the same selection
  - in the minimum bias trigger data sample
- Disagreement assigned as systematic uncertainty

# Single Event Sensitivity and number of expected events

## Single Event Sensitivity

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

**SES error budget:**

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

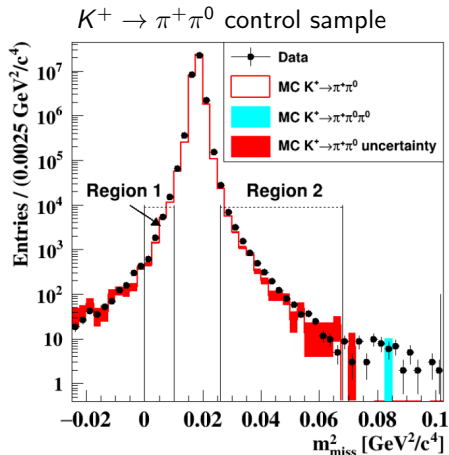
## Number of expected SM events

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

External error: theoretical uncertainty of the SM prediction:

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

# Background from standard $K^+$ decays: $K^+ \rightarrow \pi^+\pi^0$

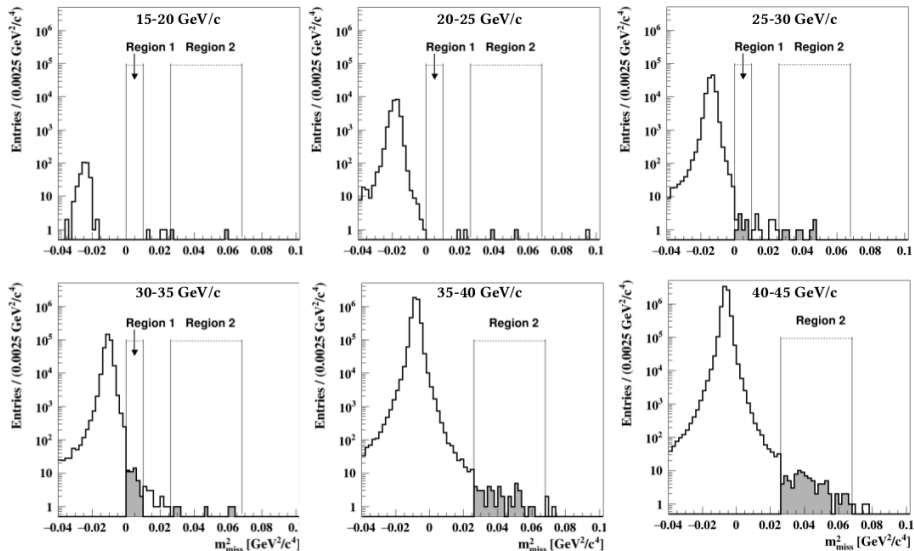


$$N_{\pi\pi}^{\text{exp}}(\text{region}) = N(\pi^+\pi^0) \cdot f^{\text{kin}}(\text{region})$$

- **Data-driven estimation**
- $N_{\pi\pi}^{\text{exp}}(\text{region})$ : 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
- $f^{\text{kin}}(\text{region})$ : fraction of  $\pi^+\pi^0$  in signal region measured in minimum bias sample (orthogonal to the signal)
- Control regions for validation

# Background from standard $K^+$ decays: $K^+ \rightarrow \mu^+ \nu$

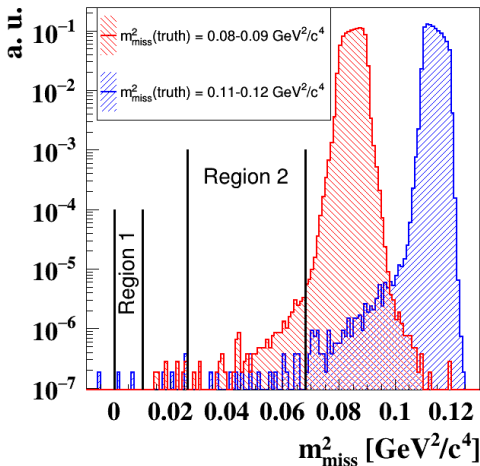
Data-driven estimation;  $\pi^+$  momentum range (15-45 GeV/c) split in bins



# Background from standard $K^+$ decays: $K^+ \rightarrow \pi^+\pi^+\pi^-$

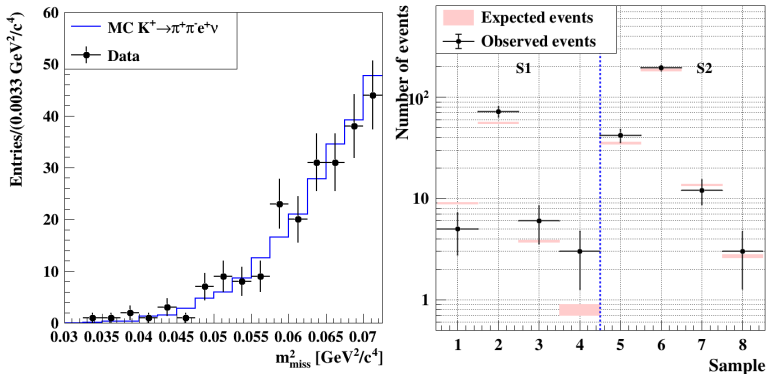
$K^+ \rightarrow \pi^+\pi^+\pi^-$  MC sample  
after  $K^+ - \pi^+$  matching

- Resolution of  $m_{miss}^2$  depends on  $m_{miss}^2$
- $m_{miss}^2$  resolution measured in MC  $K^+ \rightarrow \pi^+\pi^+\pi^-$ , after  $K^+ - \pi^+$  matching applied only
- MC resolution model applied to data in  $K^+ \rightarrow \pi^+\pi^+\pi^-$  region after full  $K^+ \rightarrow \pi^+\nu\bar{\nu}$  selection



# Background from standard $K^+$ decays: $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$

$K_{e4}$  validation samples, Data vs MC

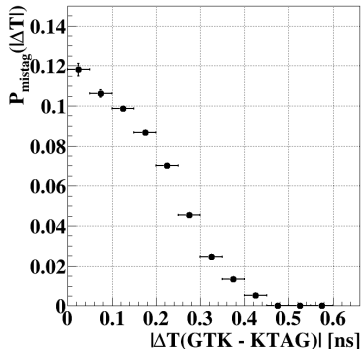


- Impossible to define background and control regions
- Number of expected events estimated as for the signal (MC)
- $K_{e4}$  validation samples obtained inverting at least one of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  criteria (e.g. multiplicity rejection)

# Upstream background estimation

- Data-driven estimation
- $N_{\text{evts}}^{\text{upstream}}$  measured in an enriched upstream events sample:  
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  selection with inverted CDA condition

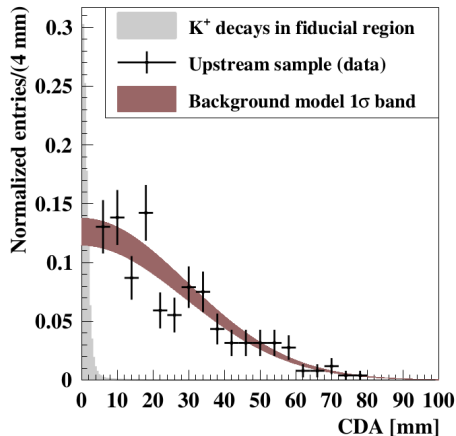
Mistagging probability  $P_{\text{mistag}}$



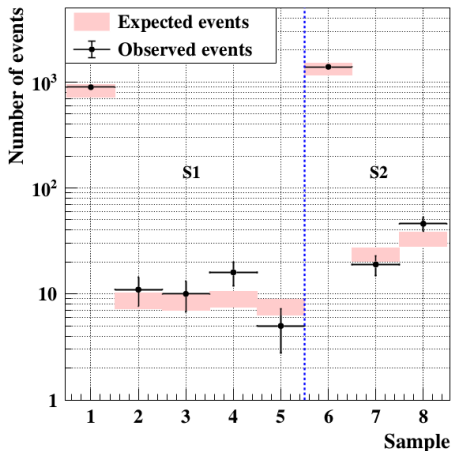
- $N_{\text{bkg}}^{\text{upstream}} = N_{\text{evts}}^{\text{upstream}} \cdot P_{\text{mistag}}$
- $P_{\text{mistag}}$  given by the  $K^+ - \pi^+$  matching algorithm ( $\Delta T$  and CDA)
- $P_{\text{mistag}}$  measured in data as a function of  $|\Delta T(\text{GTK} - \text{KTAG})|$

# Upstream background estimation and validation

CDA model for upstream events



Upstream validation samples



Validation samples defined by inverting signal selection criteria

# Summary of expected signal and background

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

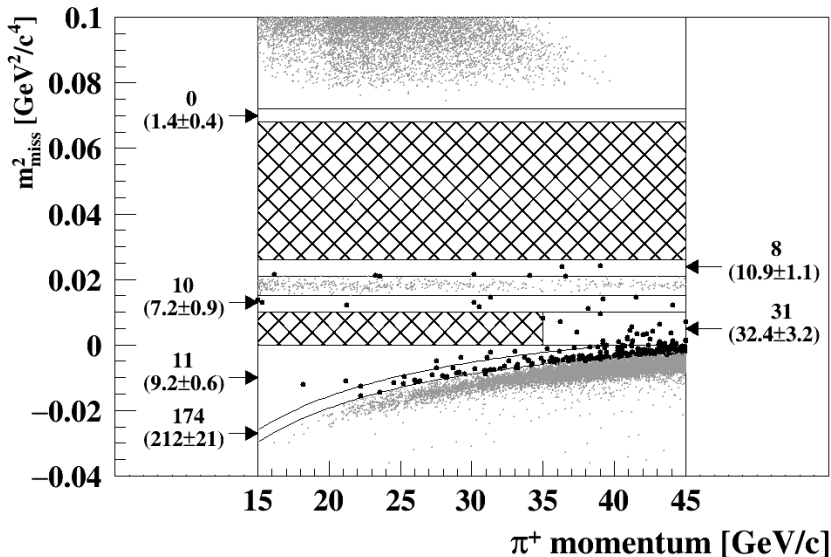
# Improvements of signal efficiency

	2017	2018-OLDCOL	2018-NEWCOL
$N_K$	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$A_{\pi\nu\nu}$	$(3.0 \pm 0.3)\%$	$(3.95 \pm 0.40)\%$	$(6.37 \pm 0.64)\%$
$\epsilon_{RV}$	$0.64 \pm 0.01$	$0.66 \pm 0.01$	$0.66 \pm 0.01$
$\epsilon_{trig}$	$0.87 \pm 0.03$	$0.89 \pm 0.05$	$0.89 \pm 0.05$
$N_{\pi\nu\nu(SM)}^{exp}$	$2.16 \pm 0.29$	$1.56 \pm 0.21$	$6.02 \pm 0.82$
$B/S$	$\sim 0.7$	$\sim 0.7$	$\sim 0.7$

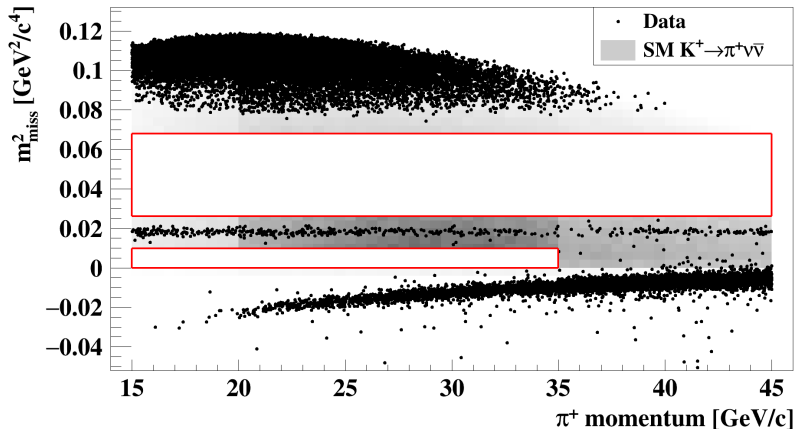
Sizeable improvements in 2018 data analysis (hardware and software):  
increase of signal efficiency with the same B/S ratio!

# Opening control regions

Observed (expected) events in control regions. Signal regions **blinded**



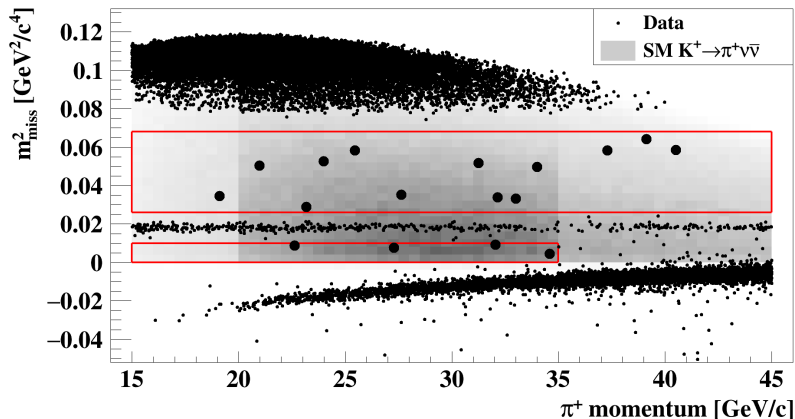
# Ready to open the signal regions



Expected SM signal events:  $7.58 \pm 0.40_{\text{sys}} \pm 0.75_{\text{ext}}$

Expected background events:  $5.28^{+0.99}_{-0.74}$

# Opening signal regions

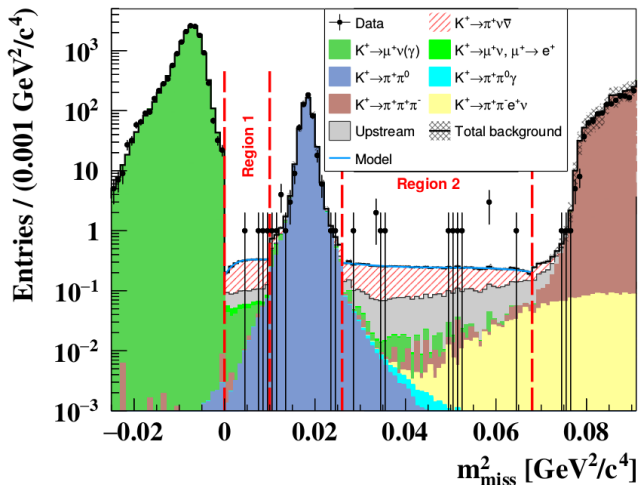


Expected SM signal events:  $7.58 \pm 0.40_{\text{syst}} \pm 0.75_{\text{ext}}$

Expected background events:  $5.28^{+0.99}_{-0.74}$

**Observed events: 17**

# Opening signal regions



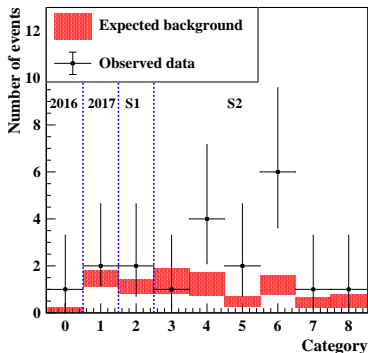
Expected SM signal events:  $7.58 \pm 0.40_{\text{syst}} \pm 0.75_{\text{ext}}$

Expected background events:  $5.28^{+0.99}_{-0.74}$

**Observed events: 17**

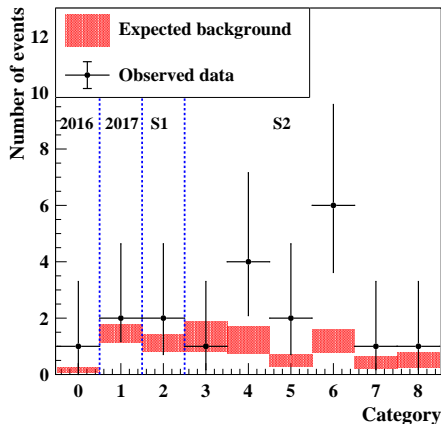
# Combined result 2016+2017+2018 data

	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	$0.27 \pm 0.04$	$2.16 \pm 0.29$	$7.58 \pm 0.85$
Expected background	$0.15 \pm 0.09$	$1.50 \pm 0.31$	$5.28^{+0.99}_{-0.74}$
Observed events	1	2	17



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

# Result from NA62 Run 1 (2016+2017+2018 data)

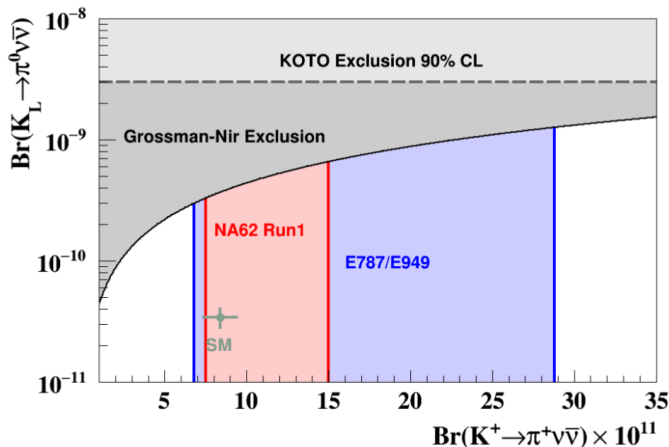


[arXiv 2103.15389] accepted for publication by JHEP

$$Br_{16+17+18}^{NA62}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.06^{+0.40}_{-0.34_{stat}} \pm 0.09_{syst}) \cdot 10^{-10}$$

3.4 $\sigma$  significance,  $P(\text{only bkg}) = 3.4 \cdot 10^{-4}$

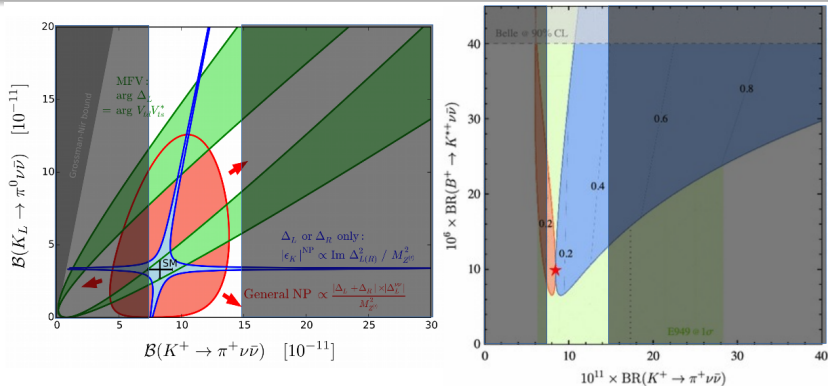
# Status of $Br(K \rightarrow \pi \nu \bar{\nu})$ measurement



- $Br^{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$  ,  $Br^{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (0.34 \pm 0.06) \cdot 10^{-10}$   
[Buras et al., JHEP11(2015)033]
- Grossman-Nir limit:  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 4.4 \cdot Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  [Phys. Lett. B 398, 163 (1997)]

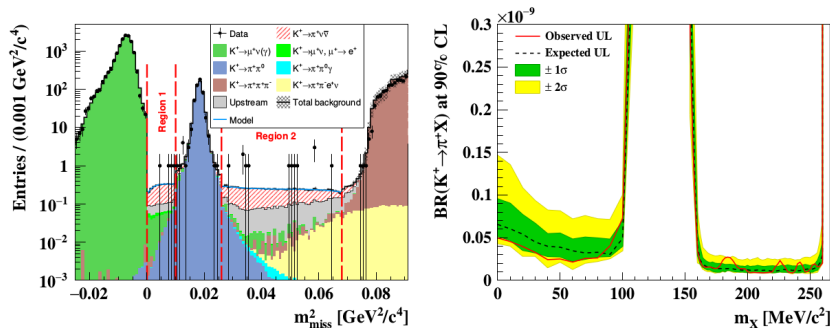
# New $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ measurement from NA62 and BSM scenarios

$$Br_{16+17+18}^{NA62}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.06_{-0.34}^{+0.40}{}_{stat} \pm 0.09_{syst}) \cdot 10^{-10}$$



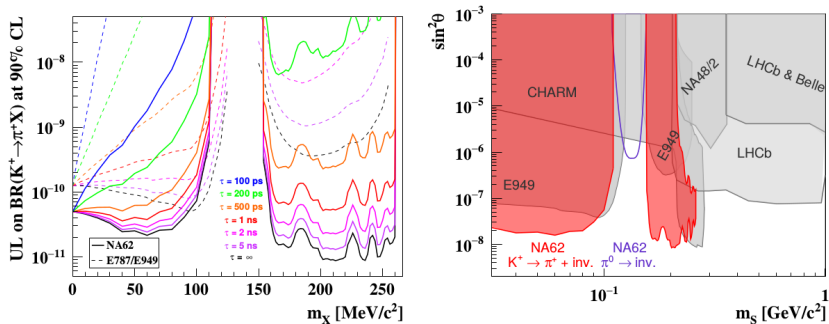
Large  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  values with respect to SM expectation start to be improbable:  
high precision measurement needed!

# Search for $K^+ \rightarrow \pi^+ X$ , where $X$ is a new feebly interacting scalar or pseudo-scalar particle



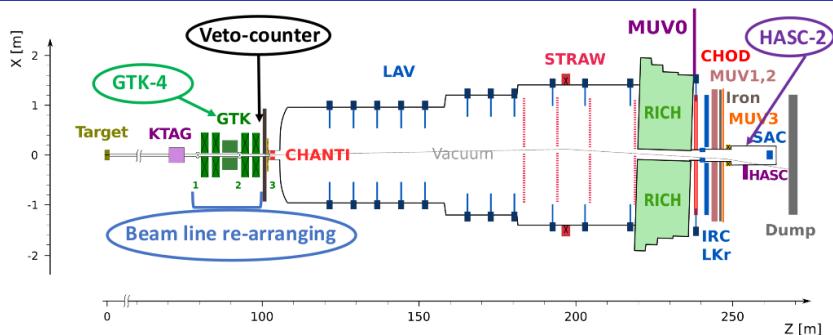
- Search for a peak in the reconstructed  $m_{\text{miss}}^2$  distribution, centred at the squared value of the  $X$  mass,  $m_X^2$
- Resolution of  $m_{\text{miss}}^2$ : from 0.0012 GeV<sup>2</sup>/c<sup>4</sup> at  $m_X = 0$  to 0.0007 GeV<sup>2</sup>/c<sup>4</sup> at  $m_X = 260$  MeV/c<sup>2</sup>
- $A_{\pi\nu\nu}$  replaced with  $A_{\pi X}$  from MC simulation
- SM  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  is the main background

# Results of search for $K^+ \rightarrow \pi^+ X$ in NA62 Run 1 [arXiv 2103.15389] accepted for publication by JHEP



- Limits set simulating different  $X$  lifetimes, assuming  $X$  decaying into SM particles that are always detected if in acceptance
- Limits interpreted also within BC4 model [J. Phys. G 47, 010501 (2020)] where  $X$  is a dark scalar, in terms of the parameter of mixing with the Higgs boson ( $\theta$ ). Constraints also from NA62 search for  $\pi^0 \rightarrow \text{invisible}$  decays [JHEP 02, 201 (2021)]

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



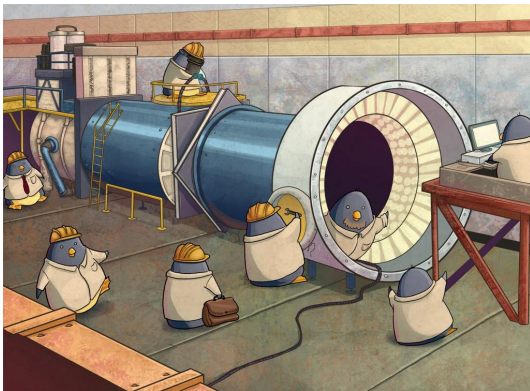
## Data taking between CERN LS2 and LS3 (will resume in July!)

- Upstream background suppression: beam line re-arranging to swipec away upstream  $\pi^+$ , adding a fourth Gigatracker station (GTK-4), new veto-counter system to detect upstream decays products
- additional off-axis calorimeter (HASC-2) to further suppress  $K^+ \rightarrow \pi^+ \pi^0$  background
- goal:  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  measurement with  $O(10\%)$  statistical precision

# Conclusions

- New result from NA62 Run 1:  
 $Br_{16+17+18}^{NA62}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.06_{-0.34}^{+0.40}{}_{stat} \pm 0.09_{syst}) \cdot 10^{-10}$
  - Most precise measurement ever performed for the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  golden channel
  - First statistically significant observation of this ultra-rare process ( $3.4\sigma$  significance)
  - Sizable improvement on upper limit of  $Br(K^+ \rightarrow \pi^+ X$
  - Large  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  values with respect to SM expectation start to be improbable: high precision measurement needed
- 
- Important hardware improvements ongoing for the next data-taking: strong suppression of the main background sources
  - Plan to achieve  $O(10\%)$  precision with data collected between CERN LS2 and LS3

# SPARES



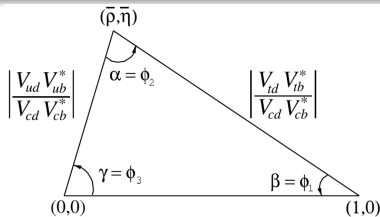
# $K^+$ meson in the flavor physics context

CKM matrix:

- quark mixing in weak interactions
- unitarity (triangle): univesality of weak interactions
- 3 real parameters + 1 complex phase: CP violation
- Important test for the Standard Model

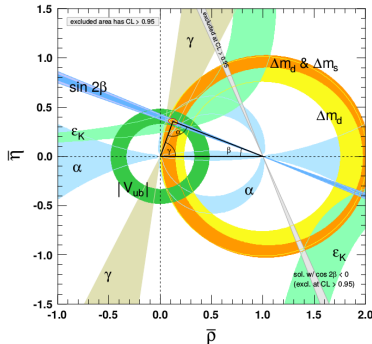
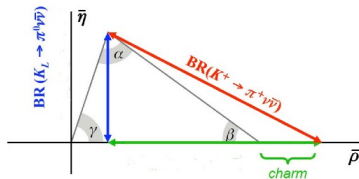
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{weak} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \times \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{flavor}$$

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



$|K^+\rangle = |u, \bar{s}\rangle$ , lightest meson after  $\pi$ , decays via weak interaction.  
Good experimental laboratory for the flavor physics sector.

# $K \rightarrow \pi \nu \bar{\nu}$ and unitarity triangle



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

$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ (1 + \Delta_{EM}) \cdot \left[ \left( \frac{\Im(\lambda_t)}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\Re(\lambda_c)}{\lambda} P_c(X) + \frac{\Re(\lambda_t)}{\lambda^5} X(x_t) \right)^2 \right]$$

$$Br(K_L \rightarrow \pi^0 \nu \bar{\nu}) = \kappa_L \cdot \left( \frac{\Im(\lambda_t)}{\lambda^5} X(x_t) \right)^2$$

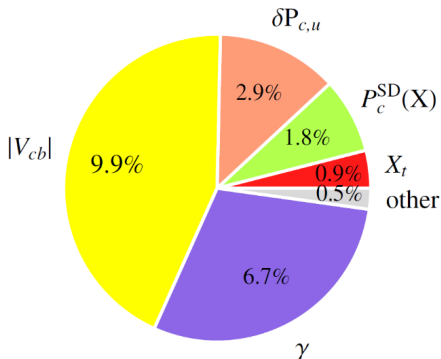
# $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ in the SM

Standard Model prediction [*Buras et al., JHEP11(2015)033*]

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

main uncertainty due to CKM elements knowledge:

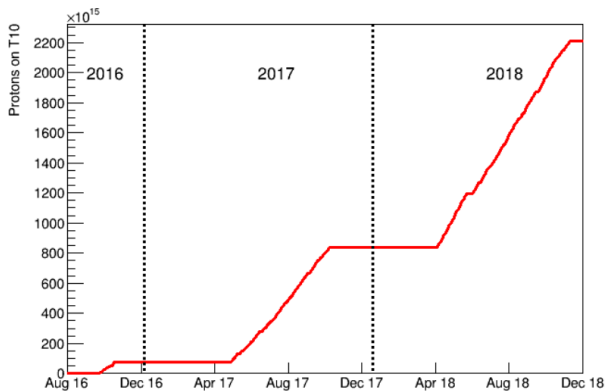
$$Br^{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.839 \pm 0.030) \cdot 10^{-10} \cdot \left( \frac{|V_{cb}|}{40.7 \cdot 10^{-3}} \right)^{2.8} \cdot \left( \frac{\gamma}{73.2^\circ} \right)^{0.74}$$



# New Physics models for $K \rightarrow \pi \nu \bar{\nu}$

- MFV and Simplified Z, Z' models:  
[Buras, Buttazzo, Kneijens, JHEP11(2015)166]
- LFU violation models:  
[Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Custodial Randall-Sundrum:  
[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- 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 models:  
[S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]

# NA62 luminosity during Run 1 (2016-2018)



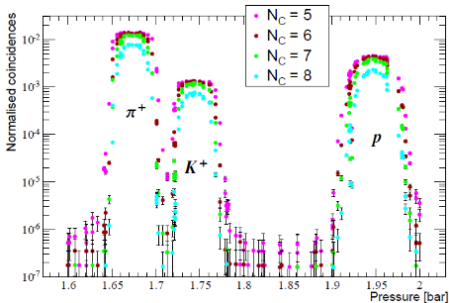
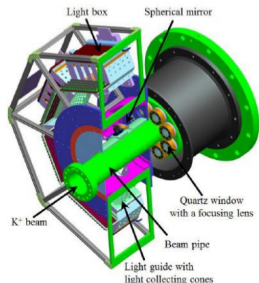
## Protons on Target

- $N^{POT}(2016) \simeq 0.1 \cdot 10^{18}$
- $N^{POT}(2017) \simeq 0.8 \cdot 10^{18}$
- $N^{POT}(2018) \simeq 1.3 \cdot 10^{18} \simeq (0.4_{OLD\,COL} + 0.9_{NEW\,COL}) \cdot 10^{18}$
- $N^{POT}(Run\,I) \simeq 2.2 \cdot 10^{18}$

# Beam particle tagging: KTAG

KTAG: a Cherenkov threshold counter.

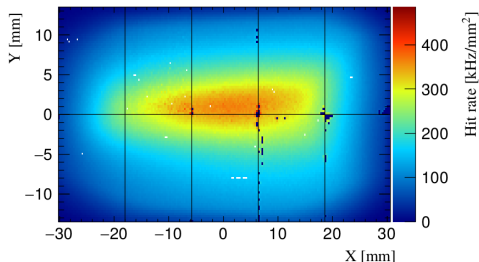
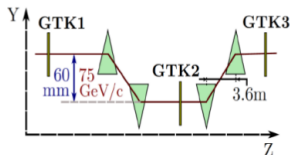
- Filled with nitrogen ( $N_2$ ) at 1.75 bar at room temperature.
- Geometrically aligned with the beam.
- Time resolution:  $\simeq 70$  ps
- Kaon tagging efficiency:  $> 95\%$



# Beam particle tracking: GTK

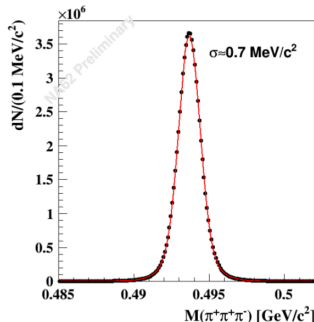
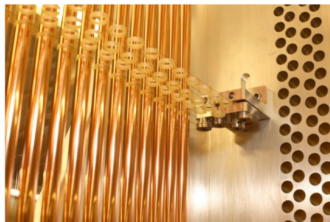
GTK: a silicon pixels tracker.

- 3 stations
- In each station: 18.000 pixels of  $300 \times 300 \mu\text{m}^2$  ( $< 0.5 X_0$ )
- Read out by application-specific integrated circuits (ASIC) arranged in two rows of five chips
- Time resolution:  $< 150 \text{ ps}$  per station
- RICH and KTAG used as time reference



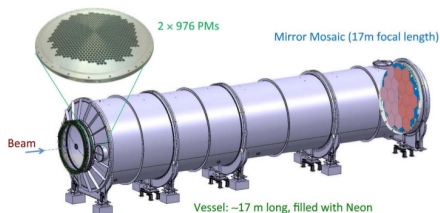
# Pion tracking: STRAW Spectrometer

- 4 straw chambers and a large aperture dipole magnet ( $\simeq 1.8 X_0$ )
- Each straw chamber is composed of two modules providing 4 different views.
- Gas inside the straws: 70% Ar and 30%  $CO_2$
- Each chamber contains 1792 straws of 9.82 mm diameter and 2160 mm length, made by 36  $\mu m$  thick polyethylene terephthalate (PET)
- $> 95\%$  reconstruction efficiency

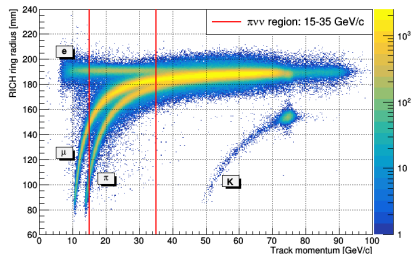


# Charged Particle Identification: RICH

- Ring Imaging CHerenkov counter, filled with neon gas
- Muon suppression factor  $> 100$
- Time resolution  $\simeq 80\text{ps}$



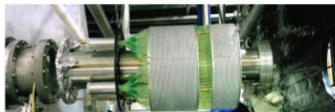
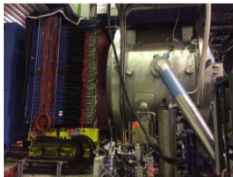
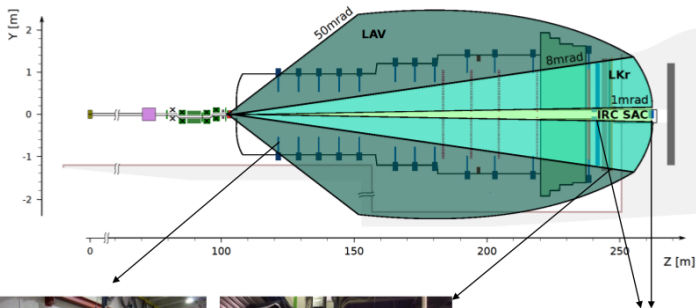
2017-A - One track events



$$\cos \theta_C = \frac{1}{n \cdot \beta} \rightarrow m^2 = m^2(p, R) = p^2 \cdot \left( \frac{F^2 \cdot n^2}{F^2 + R^2} - 1 \right)$$

# Photon rejection: LKr, LAV, IRC, SAC

Hermeticity against photons emitted in standard kaon decays up to 50 mrad



# Improvements of signal efficiency

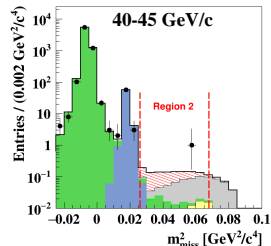
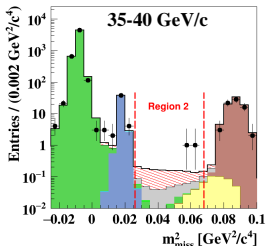
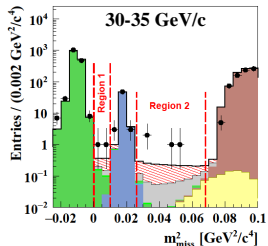
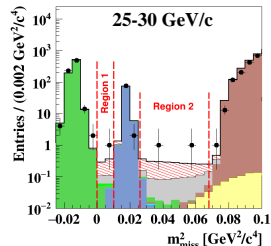
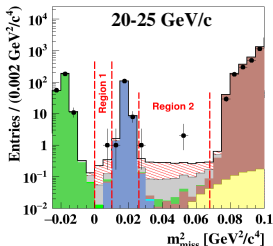
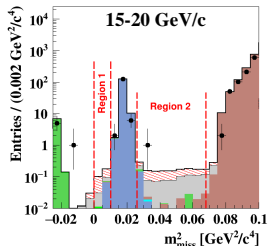
	2017	2018-OLDCOL	2018-NEWCOL
$N_K$	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$A_{\pi\nu\nu}$	$(3.0 \pm 0.3)\%$	$(3.95 \pm 0.40)\%$	$(6.37 \pm 0.64)\%$
$\epsilon_{RV}$	$0.64 \pm 0.01$	$0.66 \pm 0.01$	$0.66 \pm 0.01$
$\epsilon_{trig}$	$0.87 \pm 0.03$	$0.89 \pm 0.05$	$0.89 \pm 0.05$
$N_{\pi\nu\nu(SM)}^{exp}$	$2.16 \pm 0.29$	$1.56 \pm 0.21$	$6.02 \pm 0.82$
$B/S$	$\sim 0.7$	$\sim 0.7$	$\sim 0.7$

Single improvements of signal efficiency between 2017 and 2018-NEWCOL samples:

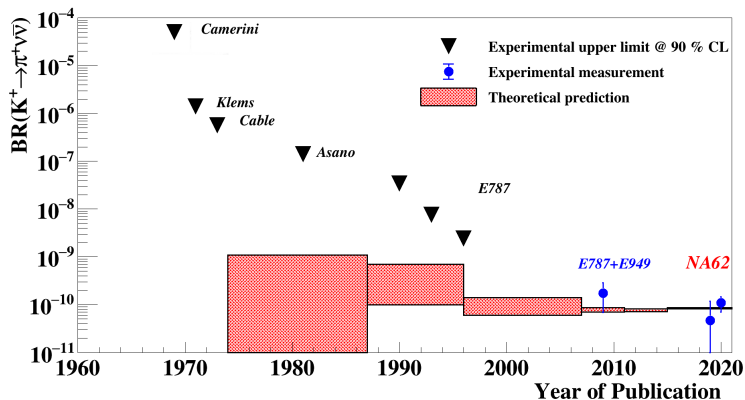
- selection optimized in bins of  $\pi^+$  momentum (5 GeV/c size)
- cuts against upstream bkg, also with a multi-variate approach: +50% in  $A_{\pi\nu\nu}$
- definition of kinematic signal regions: +30% in  $A_{\pi\nu\nu}$
- $\pi^+$  identification (RICH and calorimeters): +10% in  $A_{\pi\nu\nu}$
-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

# Opening signal regions

$\pi^+$  momentum range (15-45 GeV/c) split in six bins (5 GeV/c size)



# Status of $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ measurement

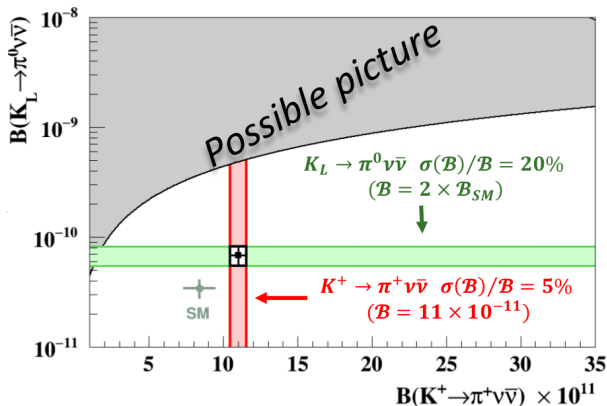


- $Br_{16+17+18}^{NA62}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.06_{-0.34}^{+0.40} \pm 0.09_{syst}) \cdot 10^{-10}$
- $Br^{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$  [Buras et al., JHEP11(2015)033]

# A possible picture for the future (after CERN LS3)

By G. Ruggiero @ ICHEP 2020

<https://indico.cern.ch/event/868940/contributions/3905707/>

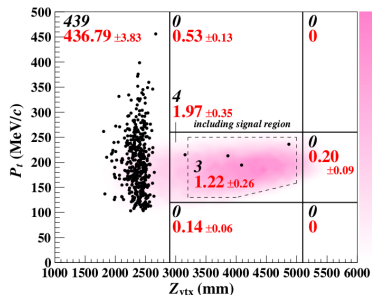


Large values with respect to SM expectation start to be excluded:  
high precision measurement needed!

# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC KOTO experiment

2016-2018 data result  
[PRL 126, 121801 (2021)]

- expected SM signal events:  
 $\simeq 0.05$
- expected background events:  
 $1.22 \pm 0.26$
- observed events:  $N_{obs} = 3$
- $Br(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 49 \cdot 10^{-10}$  @ 90% CL



Speculation based on 2016-2018 KOTO data:  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 21_{-11}^{+20} \cdot 10^{-10}$   
[PRL 124, 071801 (2020)]

Previous limit by KOTO (2015 data):  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 30 \cdot 10^{-10}$  @ 90% CL  
[PRL 122, 021802 (2019)]

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

By M. Gorbahn @ KAON 2019 Conference

<https://indico.cern.ch/event/769729/contributions/3512037/>

## Uncertainty Analysis using UFit 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	$\eta$	-0.162	0.167
$X_t$	-0.236	0.240	$X_t$	-0.113	0.115
$\rho$	-0.161	0.162	$\kappa_I$	-0.017	0.002
$P_c$	-0.185	0.187	$\lambda$	-0.001	0.00
$\kappa_+$	-0.041	0.041			
$\eta$	-0.037	0.039			
$\lambda$	-0.003	0.003			

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

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

10/27