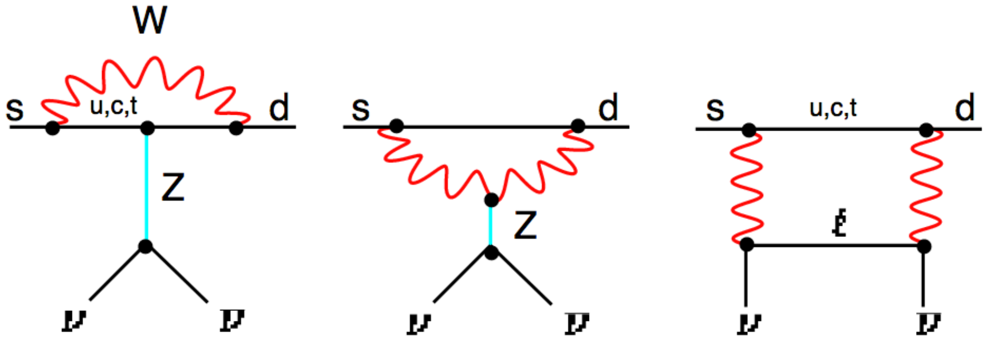
Recent results from NA62 on $K^+ \rightarrow \pi^+\nu\bar{\nu}$

T. Spadaro (LNF – INFN)

The K→$\pi\nu\nu$ transition in the SM



An ultra-rare FCNC process, theoretically very clean:

- Hard GIM, A ~ $m_q^2/m_W^2\, V_{qs}^*\, V_{qd}$ with $q = u, c, t$
- Dominantly short distance: no contribution from *u*-quark line, no amplitudes with intermediate photons

$$\mathcal{H}_{\rm eff} = \sum_{l=e,\mu,\tau} \frac{G_l}{\sqrt{2}} (\bar{s}d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A}$$

SM prediction for K→πνν

$$\mathcal{H}_{\text{eff}} = \sum_{l=e,\mu,\tau} \frac{G_l}{\sqrt{2}} (\bar{s}d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A}$$

Hadronic matrix element related by isospin to that for Ke3 decays,

$$BR(K^+ \to \pi^+ \bar{\nu}\nu) = 6 r_{K^+} BR(K^+ \to \pi^0 e^+ \nu) \frac{|G_l|^2}{G_F^2 |V_{us}|^2}$$

$$BR(K^0 \to \pi^0 \bar{\nu}\nu) = 6 \frac{\tau_{K_L}}{\tau_{K^+}} r_{K_L} BR(K^+ \to \pi^0 e^+ \nu) \frac{(\mathrm{Im}\, G_l)^2}{G_F^2 |V_{us}|^2}$$

- Phase space + isospin-breaking effects: $r_{K+} \sim 0.9$, $r_{KL} \sim 0.94$
- G_l dominated by top ($V_{ts}^* V_{td}$) with small charm contribution for K$^+$ ($V_{cs}^* V_{cd}$)

K→πνν as a precision flavor test

SM uncertainty dominated by CKM elements [Buras et al., JHEP 1511]:

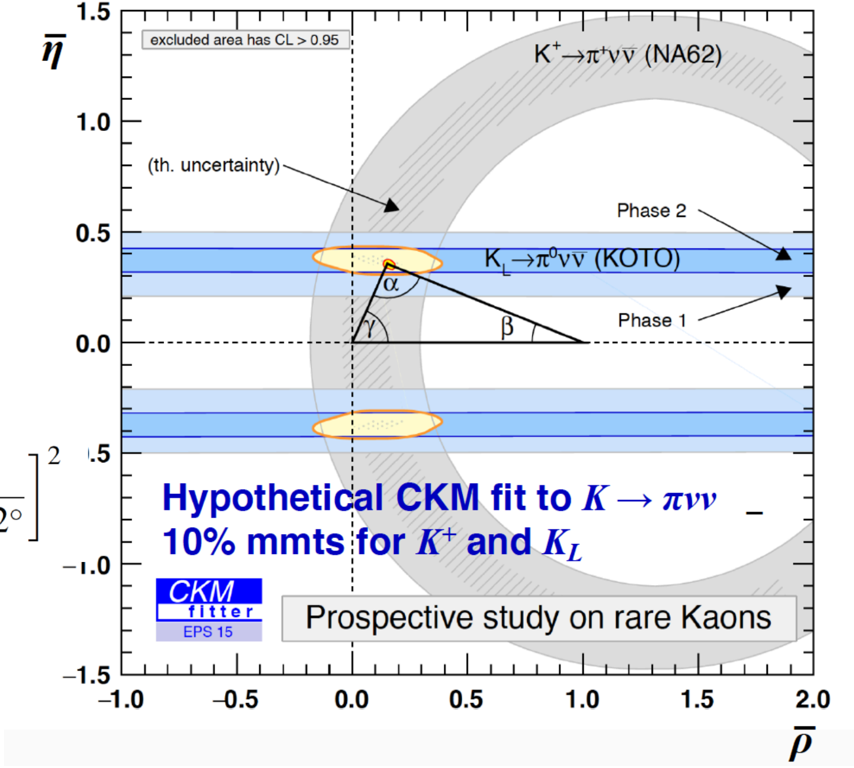
- BR($K^+\rightarrow\pi\nu\nu$) = (8.4 ± 1.0) × 10^{-11}

$$= (8.39\pm0.30)\times10^{-11}\cdot\left[\frac{|V_{cb}|}{0.0407}\right]^{2.8}\cdot\left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

- BR($K_L\rightarrow\pi\nu\nu$) = (3.4 ± 0.6) × 10^{-11}

$$= (3.36\pm0.05)\times10^{-11}\cdot\left[\frac{|V_{ub}|}{3.88\times10^{-3}}\right]^{2}\cdot\left[\frac{|V_{cb}|}{0.0407}\right]^{2}\cdot\left[\frac{\sin\gamma}{\sin73.2^\circ}\right]^{2}$$

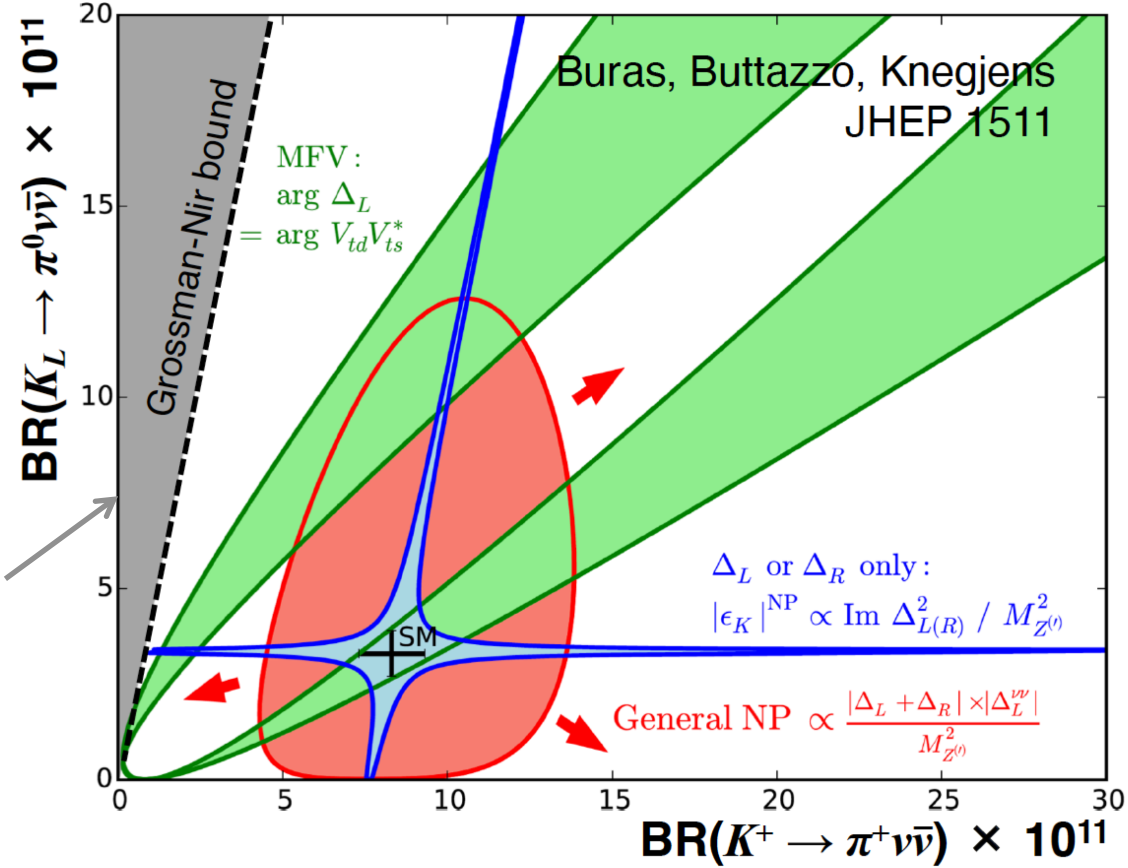
- Intrinsic theory uncertainty 1.5—3.5%



K→πνν sensitivity to NP effects

$$\frac{\Gamma(K_L \rightarrow \pi\nu\nu)}{\Gamma(K^+ \rightarrow \pi\nu\nu)} < 1$$

[PLB 398, 163 (1997)]



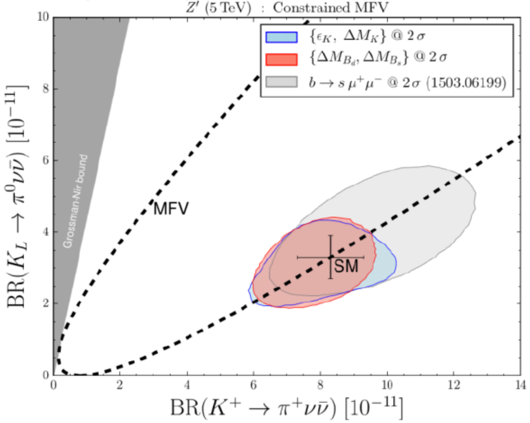
Models with CKM-like flavor structure

Models with new LH/RH dominating flavor structure

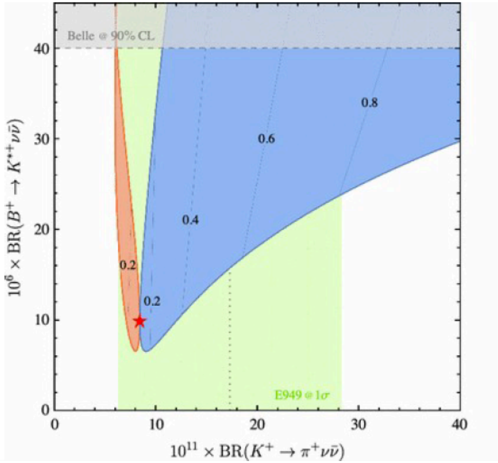
K→πνν reduced list of NP models

- Custodial Randall-Sundrum [Buras et al., JHEP 0903 (2009) 108]
- MSSM analyses [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Leptoquarks [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]

Z'(5 TeV) in Constrained MFV



LFU violation



The effort to reach the needed sensitivity

2005 EoI of P-326: goal to identify ~ 35 SM $K^+ \rightarrow \pi\nu\nu$ decays / year with S/B ~ 10
Need a new experimental apparatus and a new K^+ beam line
2007 CERN-SPSC-2007-035: technology decisions (LAV, RICH, SAC, STRAW)

2009 Project approved by INFN CCS (under N. Cabibbo), temporary budget secured

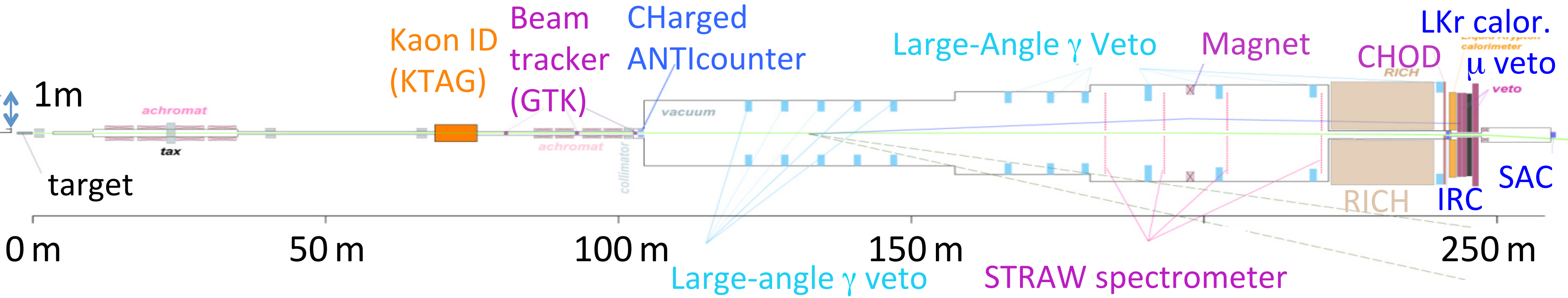
2011 MoU ratified by funding agencies

2014 Most subdetectors built. GTK, LKr trigger, and TDAQ under completion
2015 Detector built and operational, first test run
2016--2018 First physics run

NA62: a high-intensity setup

High-intensity secondary charged hadron beam produced from SPS proton beam:

- **$1.1\ 10^{12}$ 400-GeV protons/s from ~3 s SPS spills onto a Be target**
- Secondary 75-GeV beam selected: 1% momentum bite, X,Y divergence < 100 μrad



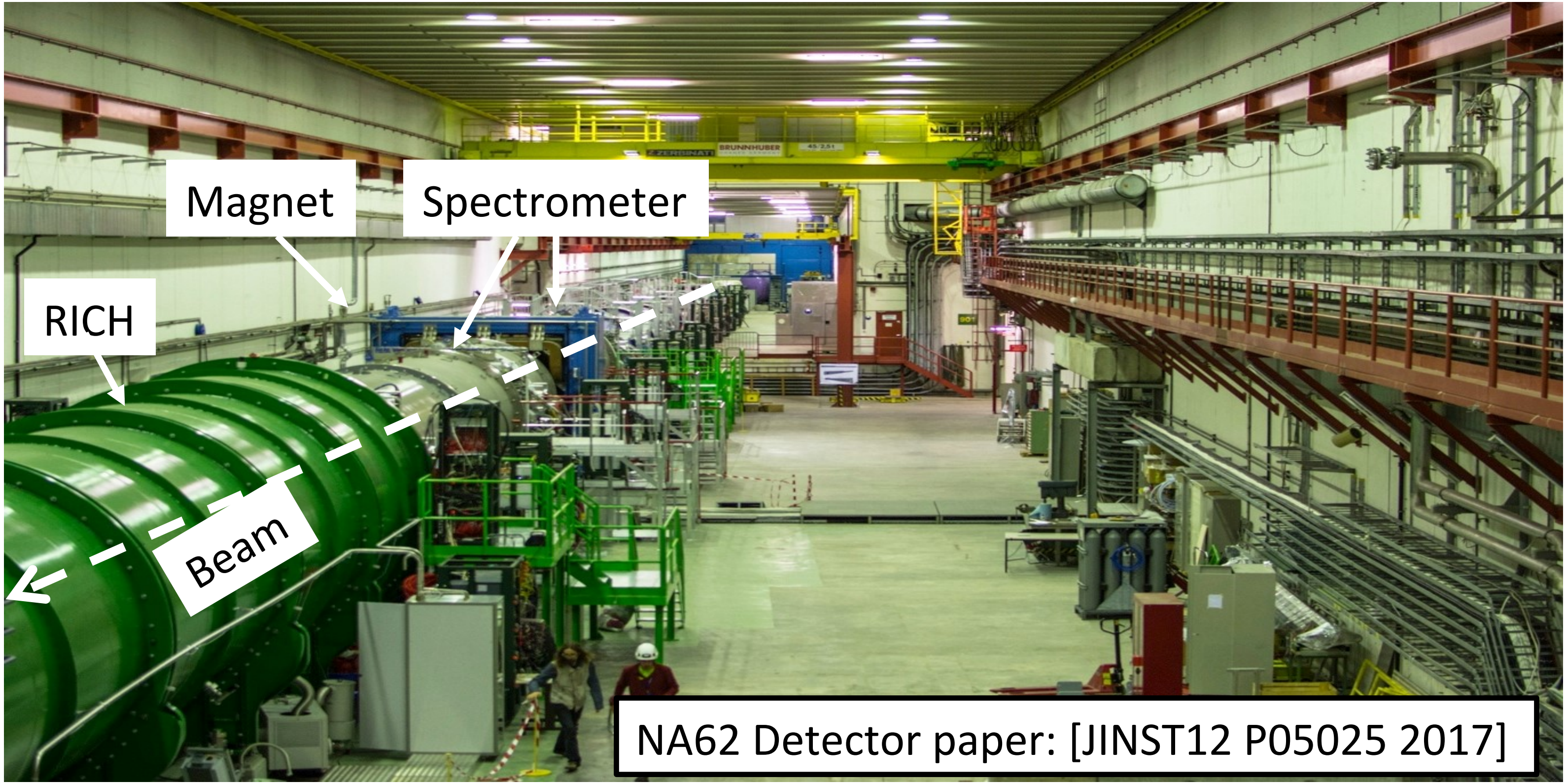
Can **track 750 MHz beam** (6% K^+) and sustain ~5 MHz K^+ decay in a **60-m long FV in vacuum**

Kinematics, rejection of main K modes 10^4—10^5 via kinematic reconstruction

PID capability, μ vs π rejection of $O(10^8)$ for $15 < p(\pi^+) < 35$ GeV

High-efficiency veto of additional photons, $O(10^8)$ rejection of π^0's for $E(\pi^0) > 40$ GeV

NA62: a high-intensity setup



NA62 Detector paper: [JINST12 P05025 2017]

NA62 pillars: beam particle-ID

N2-based differential Cerenkov detector, 1.75 bar, $\sigma_t = 70$ ps, $\varepsilon_K > 95\%$ ($N_C \geq 5$), $\varepsilon_\pi < 10^{-4}$

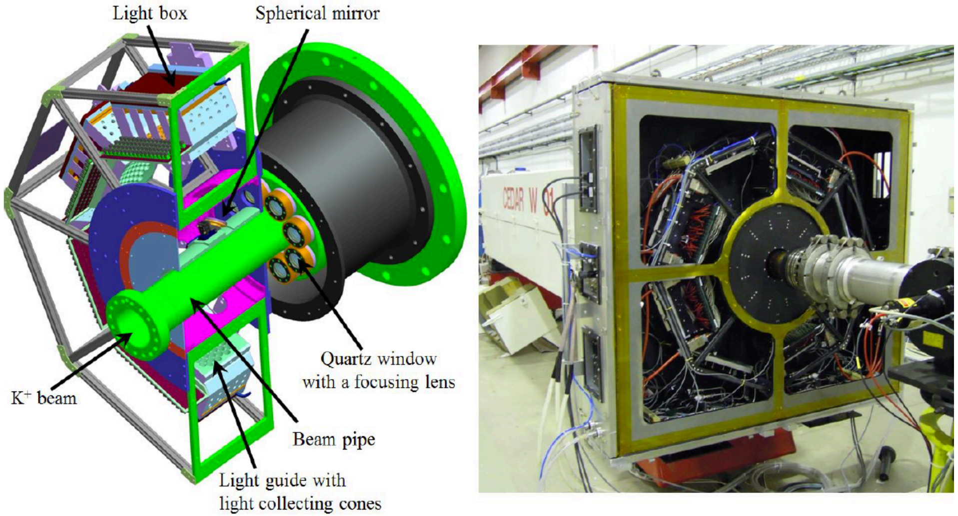
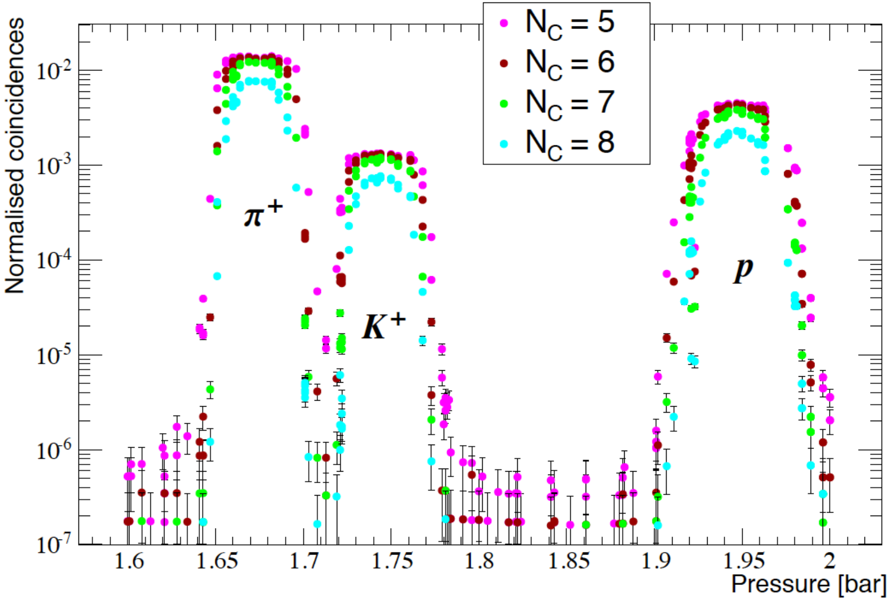
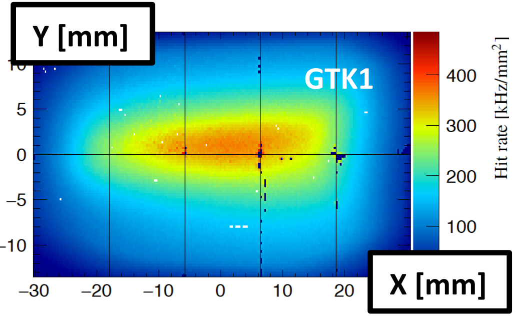


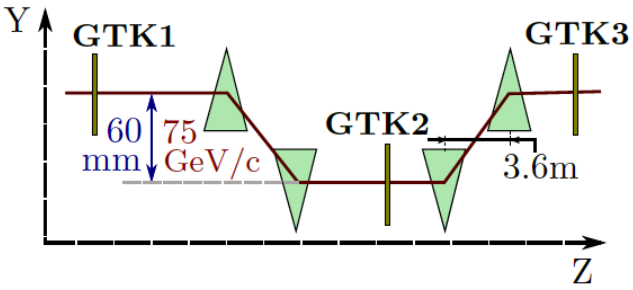
Figure 8. Left: drawing of the upstream part of the CEDAR and the KTAG. Right: KTAG and CEDAR the NA62 beam line during a test run in 2012, with four of the eight sectors equipped.

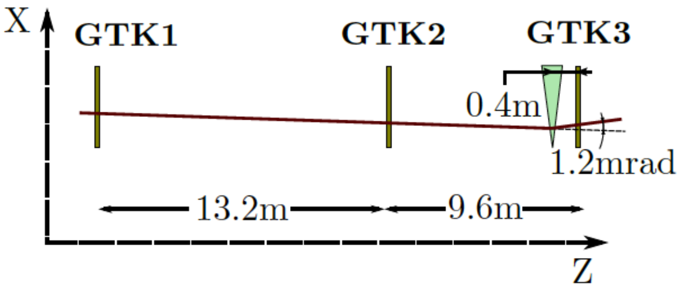


NA62 pillars: beam tracking

3 stations of Si detectors in a magnetic achromat: σ_t = 100 ps, σ_p = 0.15 GeV/*c*, σ_θ = 16 μrad

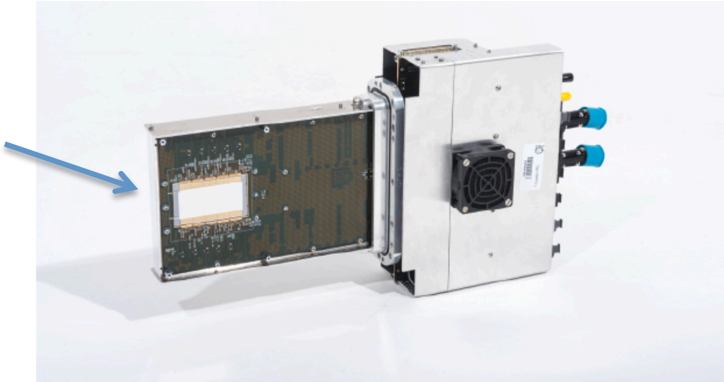






σ_Y @ GTK2 ~ 600 μm / (Δp/p [%])

62×27 mm^2 sensor area:
200×90 pixels, each
300×300 μm^2 in size



Thickness in active area 510 μm:

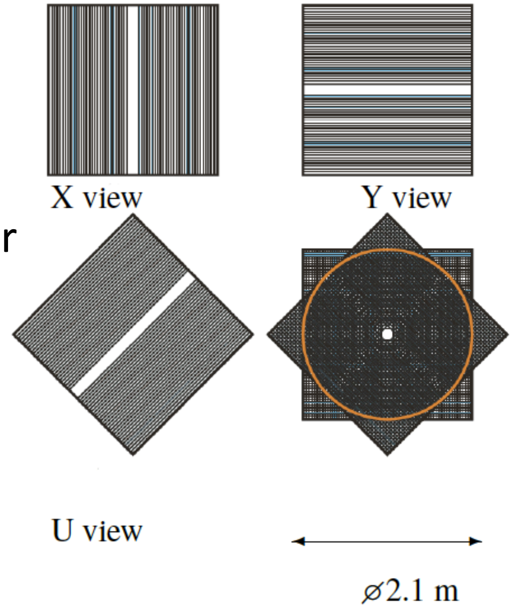
- sensor: 200 μm
- RO chip: 100 μm
- Cooling plate: 210 μm

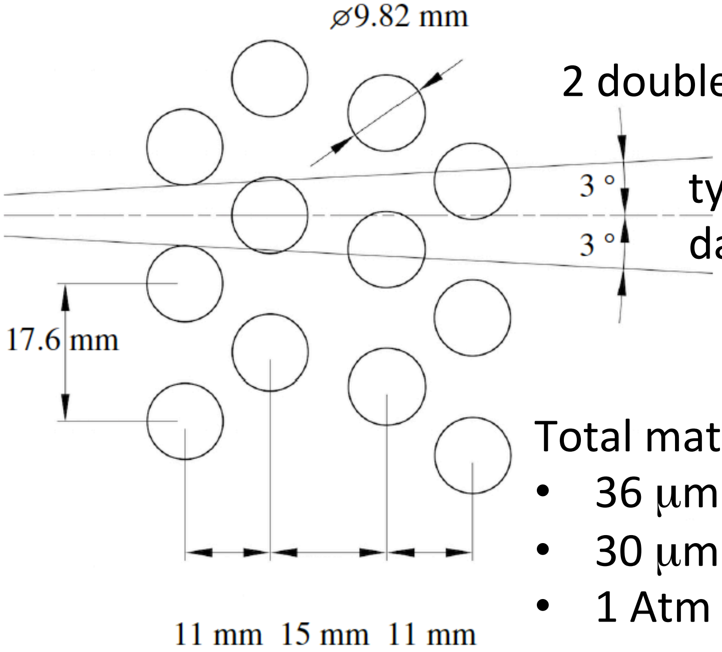
NA62 pillars: downstream tracking

Tracking in vacuum: 2+2 straw-tube stations, dipole magnet Δp_t = 270 MeV magnet:

σ_p/p = 0.3—0.4%, σ_t ~ 5 ns

4 views / chamber





2 double layers / view

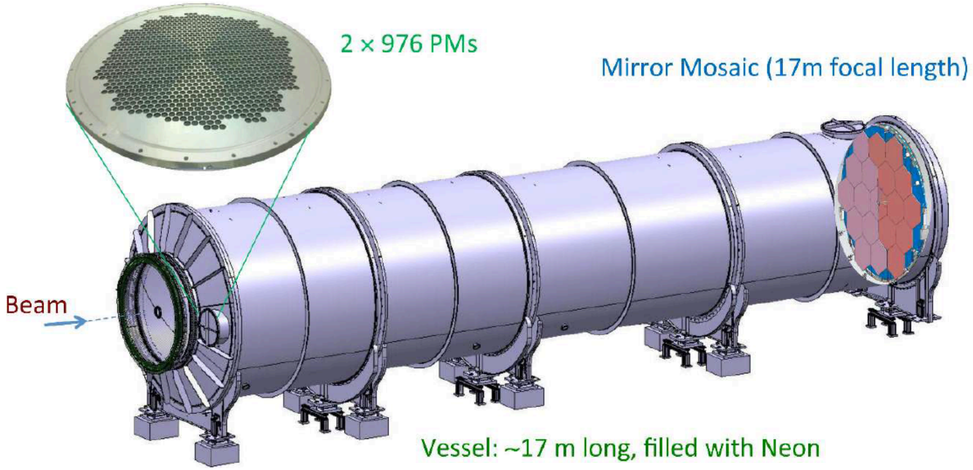
typical K^+ daughter tracks

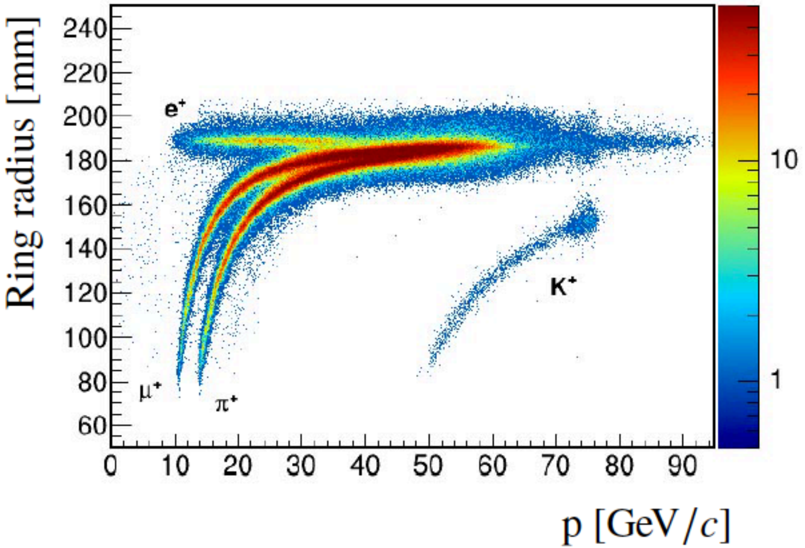
Total material ~1.8% X_0:

- 36 μm PET
- 30 μm W anode wire
- 1 Atm Ar:CO_2 70:30

NA62 pillars: downstream PID

Downstream particle identification: 17 m long RICH, 1 bar Ne, n-1 ~ 6.7 × 10^{-5}, $\sigma_t < 100$ ps



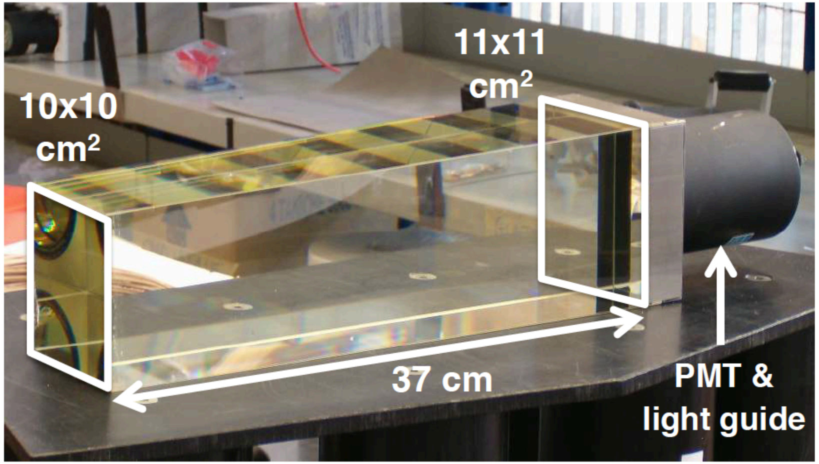


Identify π^+ mesons with ~75% efficiency, rejection power for μ^+ ~ 10^{-5} for $15 < p_\pi < 35$ GeV/*c*

NA62 pillars: hermetic particle veto

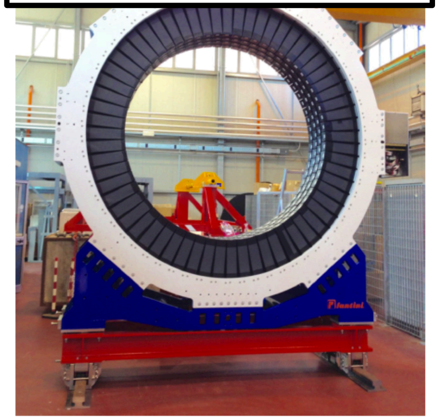
Hermetic veto system to achieve O(10^8) rejection of π^0 mesons:

- 12 rings of LAV stations, $\sigma_t \sim 1$ ns, inefficiency ~ 10^{-4} for γ's E > 200 MeV, $8.5 < \theta < 50$ mrad
  - 2496 refurbished OPAL lead-glass blocks
  - LAV 1—11 operating in vacuum, LAV 12 in air



LAV 1, 1.8 m diam

LAV 12, 2.8 m diam



NA62 pillars: hermetic particle veto

Hermetic veto system to achieve O(10^8) rejection of π^0 mesons:

- LKr calorimeter, σ_t ~ 0.5--1 ns, inefficiency < 10^{-5} for γ's E > 10 GeV, 1 < θ < 8.5 mrad
  - Reused from NA48, read-out in zero-suppression mode via FADC
  - New readout + custom FPGA processing to allow L0 trigger operation

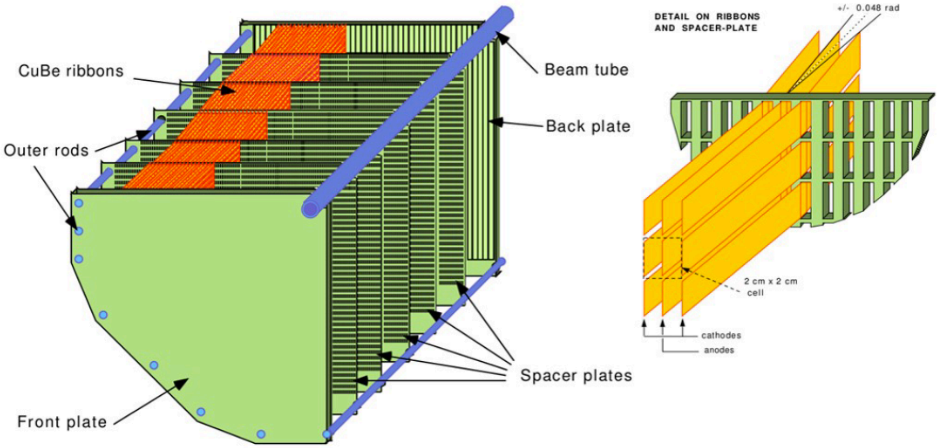


Figure 34. Left: schematic of the calorimeter structure (one quadrant). Right: detail of the calorimeter cells.

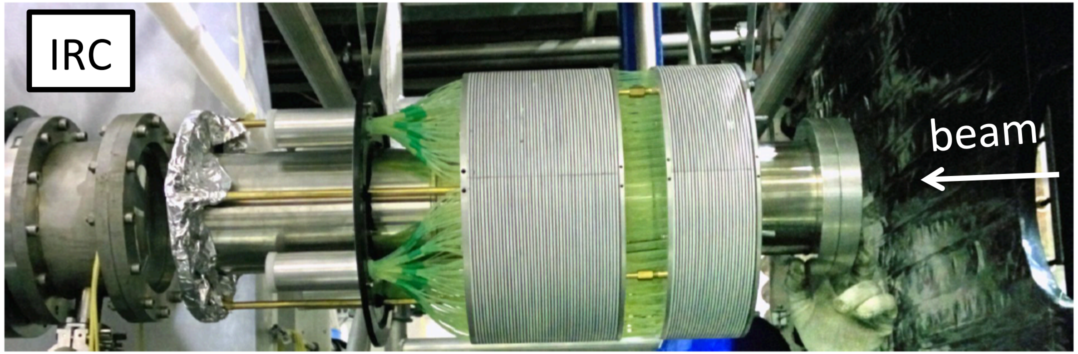
NA62 pillars: hermetic particle veto

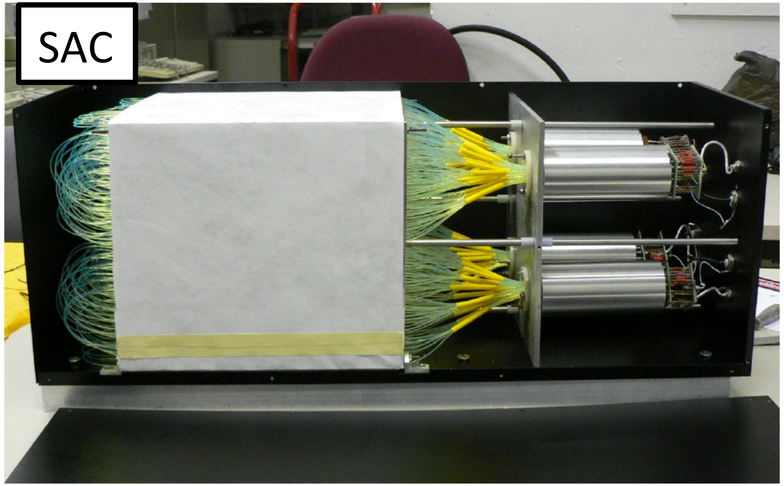
Hermetic veto system to achieve O(10^8) rejection of π^0 mesons:

2 scintillator-Pb shashlik cal., IRC-SAC, inefficiency < 10^{-3--4} for γ's with $0 < \theta < 2$ mrad

IRC: 2 annular rings, O ~120 -- 290 mm

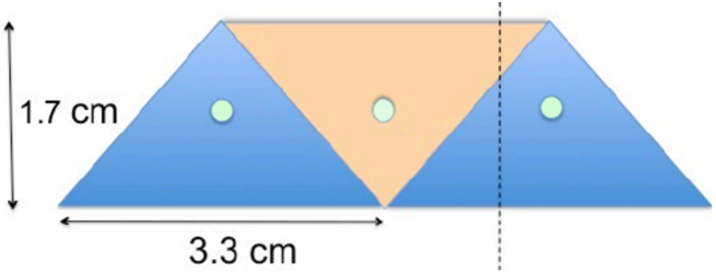
SAC: 205×205 mm^2 just upstream of the beam dump

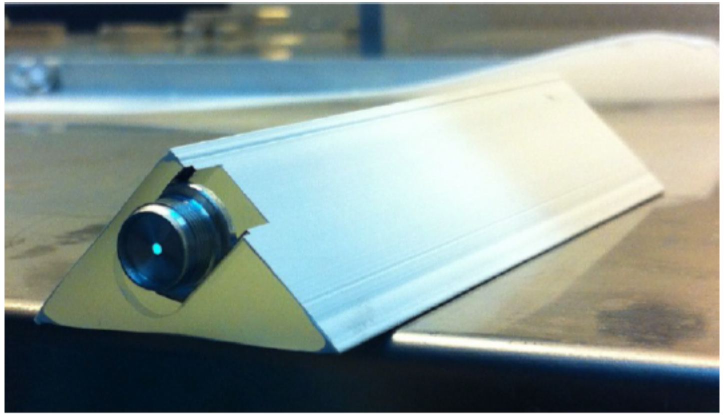


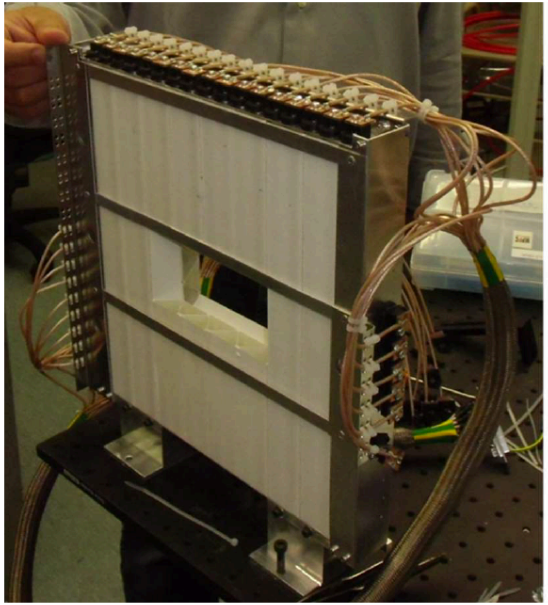


NA62 pillars: additional veto capability

6 stations of scintillator bars, SiPM RO, 99% efficiency, $\sigma_t \sim 1$ ns against interactions in GTK3
2 additional counters MUV0, HASC against multi-track final states

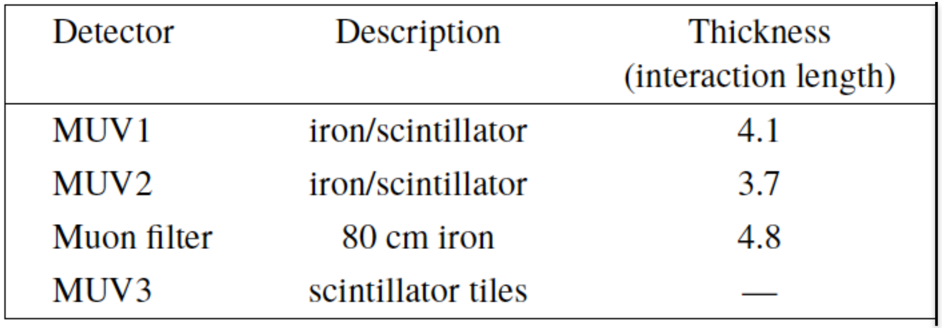




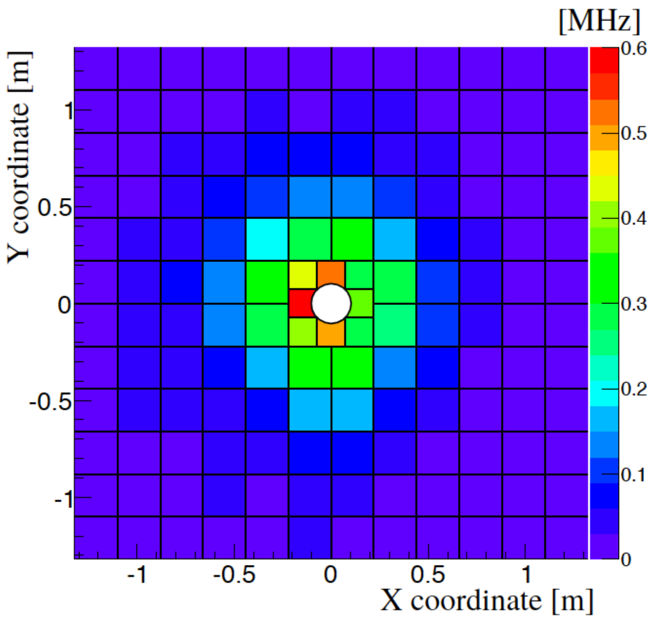


NA62 pillars: additional PID capability

Additional particle identification: 2 hadronic calorimeters, 80 cm Fe, MUV3 hodo. $\sigma_t = 400$ ps



Detector	Description	Thickness (interaction length)
MUV1	iron/scintillator	4.1
MUV2	iron/scintillator	3.7
Muon filter	80 cm iron	4.8
MUV3	scintillator tiles	—



LKr + MUV1,2 as a compensated hadronic calorimeter:

$$\sigma E / E = 0.115 + 0.38 / \sqrt{E[\mathrm{GeV}]} + 1.37 / E[\mathrm{GeV}]$$

MUV3 rate up to 600 KHz / tile, participating at L0 trigger

After MUV3 veto, π^+ vs μ^+ ID with ε >75% vs few 10^{-3} with calorimeters, for $15 < p < 35$ GeV

NA62 pillars: downstream timing

Downstream time measured by two scintillator hodoscope just upstream of LKr, σ_t ~ 200 ps
scintillator tiles, SiPM RO (CHOD) + re-used NA48-CHOD

At nominal intensity, rates up to **1 MHz** / tile

Detectors used to initiate the L0 trigger

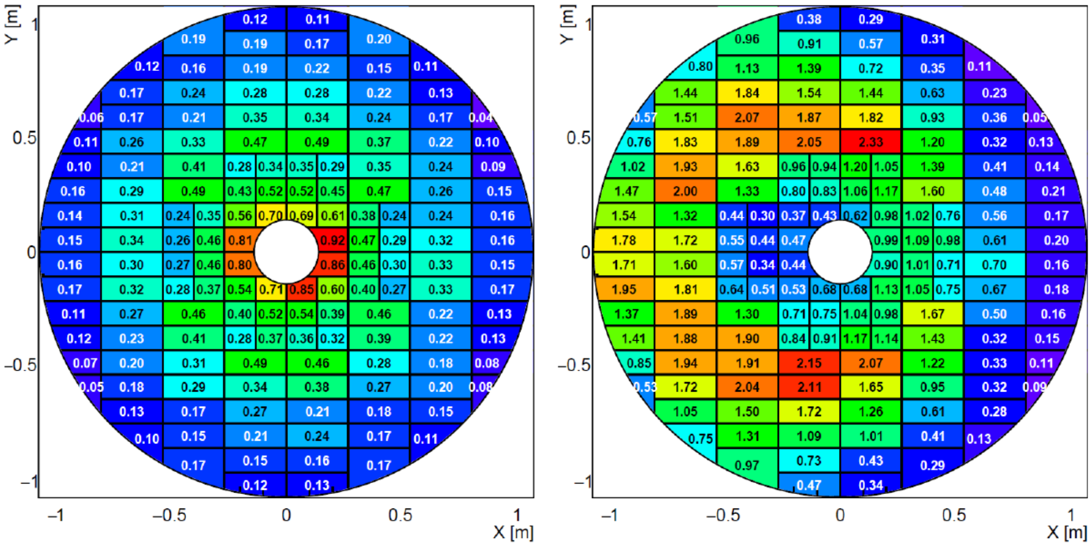


Figure 49. Left: expected rates in CHOD tiles at nominal beam intensity (in MHz). Right: probability of detecting a signal in each CHOD tile for $K^+ \to \pi^+ \nu\bar{\nu}$ decays satisfying the signal selection conditions 105 m < Z_{vertex} < 165 m and 15 GeV/c < p_π < 35 GeV/c in each tile (in percent). Both are calculated with MC simulations.

NA62 TDAQ

Common RO TDC-based (100 ps LSB) for LAV, MUV3, CHOD's, RICH, CHANTI, KTAG, SAC, IRC

DAQ TELL62 boards: major re-design of the TELL1 LHCb boards + HPTDC-based mezzanines

Exceptions:

STRAW: custom signal processing + CARIOCA RO chips (developed for LHCb muon system)

GTK (custom board) LKr (FADC) with logic based on ALTERA Stratix IV GX 110 FPGA

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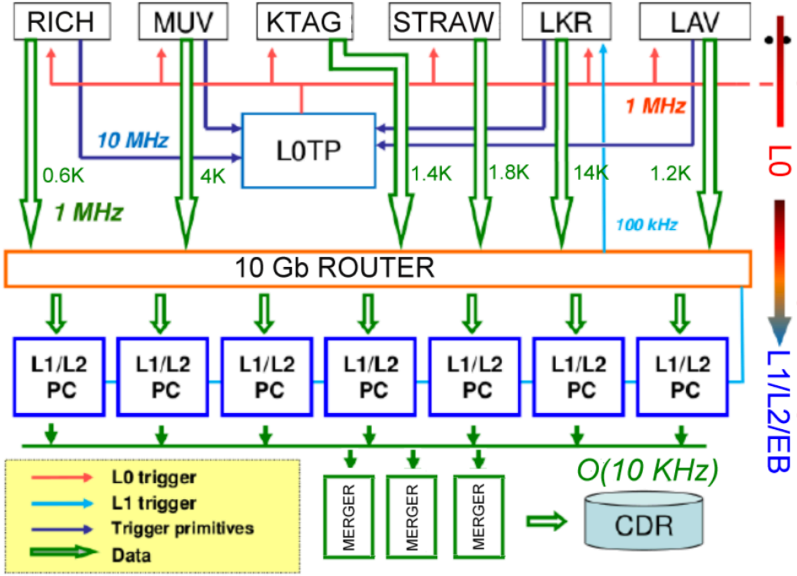
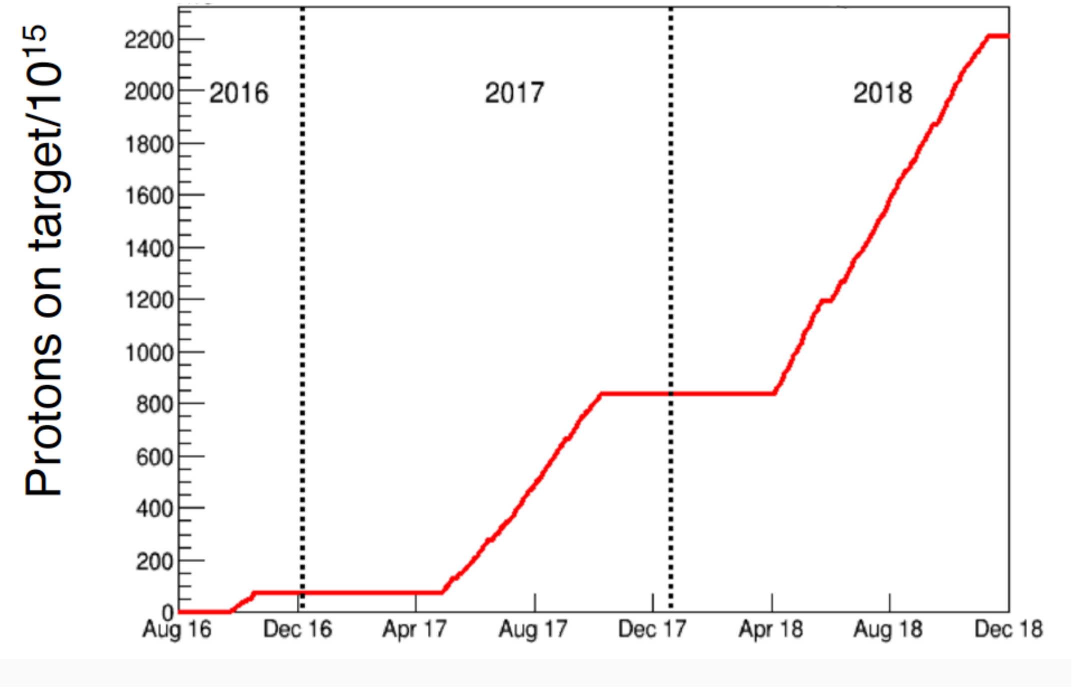


First version of clock distribution system based on NA62 modification of ALICE LTU's

Time Trigger Control (TTC) clock distribution system adopted from CERN

The NA62 data taking

Overall ~2.2 × 10^{18} protons on target in Run 1, three rounds of K→πνν analysis



2016 40% of nominal intensity
0.12 × 10^{12} K^+ decays in FV
PLB 791 (2019) 156-166

2017 60% of nominal intensity
1.5 × 10^{12} K^+ decays in FV
ArXiv:2007.08218 [hep-ex] (submitted to JHEP)

2018 60-70% of nominal intensity
2.6 × 10^{12} K^+ decays in FV
Preliminary @ ICHEP 2020

Instantaneous beam intensity in single spills can vary by up to 2 times the average

$K^+ \rightarrow \pi^+\nu\nu$ analysis scheme

Search for $\pi\nu\nu$ decays with a dedicated trigger: “1 Track” + Emiss

L0
RICH signal & 1—4 CHOD tiles in time not in opposite quadrants
E(LKr) < 30 GeV and ≤ 1 LKr clusters in time, no signal from MUV3 tiles in time

L1
A K^+ KTAG signal in time & ≤2 LAV hits in time & 1 STRAW Track < 50 GeV, q = +1

Offline selection:

1. **Reconstruct vertex by matching in time and space beam and daughter tracks**
2. **Kinematics**
3. **PID (RICH & LKr-MUVs)**
4. **Veto any in-time activity (LAV, LKr, IRC-SAC, multiplicity conditions, etc.)**

Normalize to minimum-bias trigger $K^+ \rightarrow \pi^+\pi^0(\gamma)$ selected after steps 1—3 applied

$K^+ \rightarrow \pi^+\nu\nu$ analysis scheme

Single-event sensitivity: $SES = \frac{1}{N_{K+} \cdot \epsilon_{\pi\nu\nu} \cdot \epsilon_{trig}^{PNN}} = \frac{\mathrm{BR}(K^+ \to \pi^+\pi^0)}{D \cdot N_{\pi\pi}} \frac{\epsilon_{\pi\pi} \cdot \epsilon_{trig}^{MB}}{\epsilon_{\pi\nu\nu} \cdot \epsilon_{trig}^{PNN}}$

D = downscaling factor of minimum-bias trigger, 400

$\varepsilon_{trig}^{MB} \sim 1$

$\varepsilon_{\pi\pi} / \varepsilon_{\pi\nu\nu}$ allows cancellation of part of systematic uncertainties (e.g., Detector, TDAQ inefficiencies)

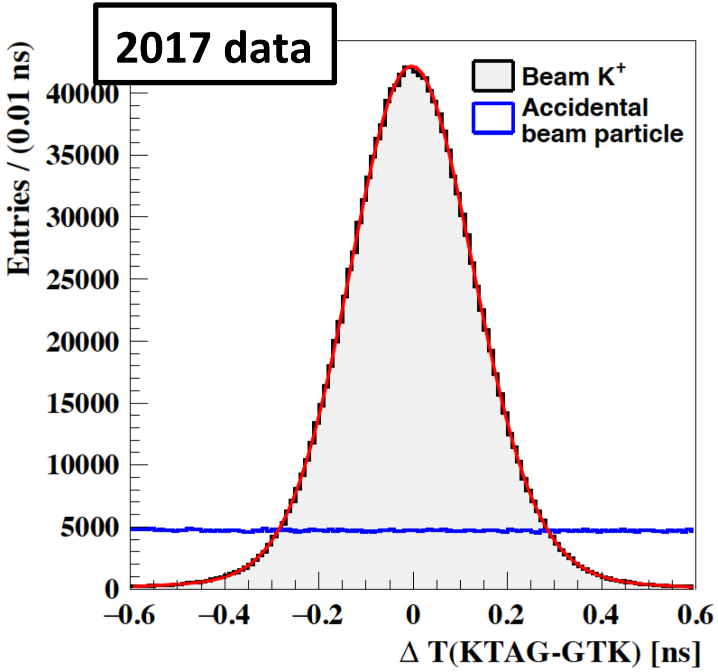
SES evaluated in bins of π^+ momentum and instantaneous intensity

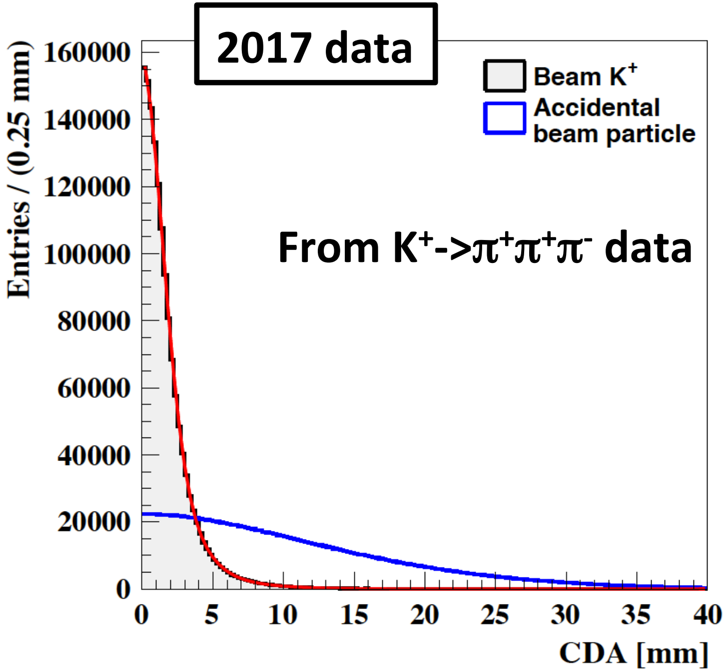
Counting analysis, data-driven background expectation

Blind analysis, validated in data control regions

$K^+ \rightarrow \pi^+ \nu\nu$ selection scheme: vertex

Evaluate GTK-KTAG time diff. and closest distance of approach (CDA) of K^+, π^+ tracks



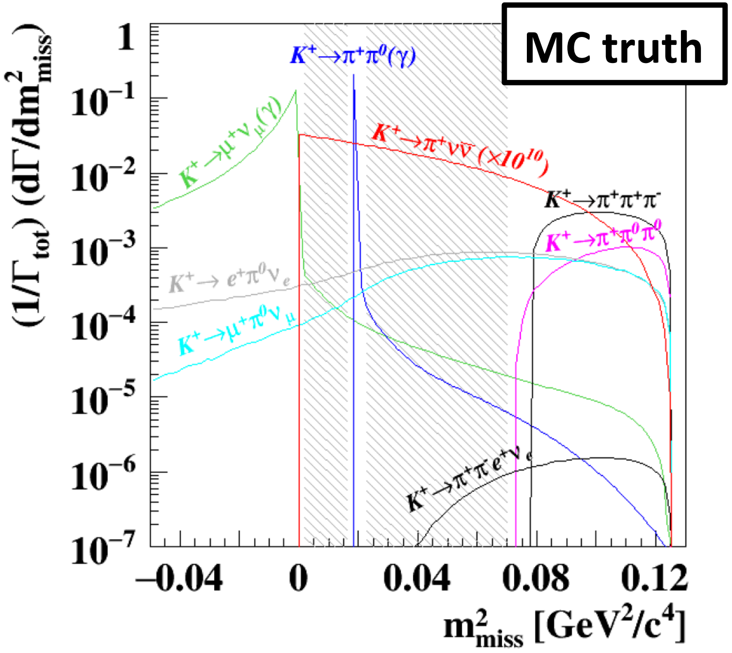


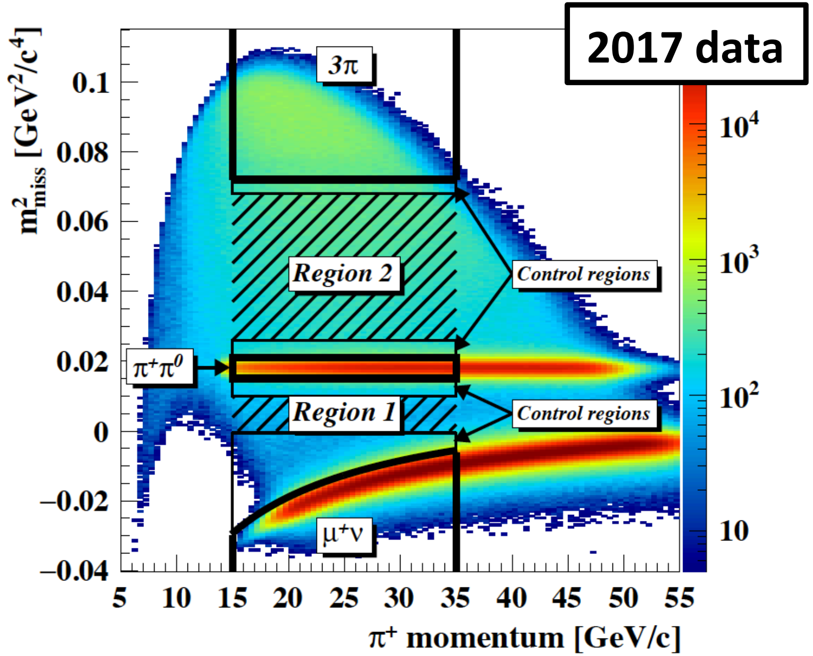
From $K^+ \rightarrow \pi^+\pi^+\pi^-$ data

High-intensity setup: dedicated conditions to prevent accidental pairing

$K^+ \rightarrow \pi^+\nu\nu$ selection scheme: kinematics

Evaluate $M_{miss}^2 = (p_K - p_\pi)^2$ for vertices in the region $105 < Z_{vertex} < 165$ m

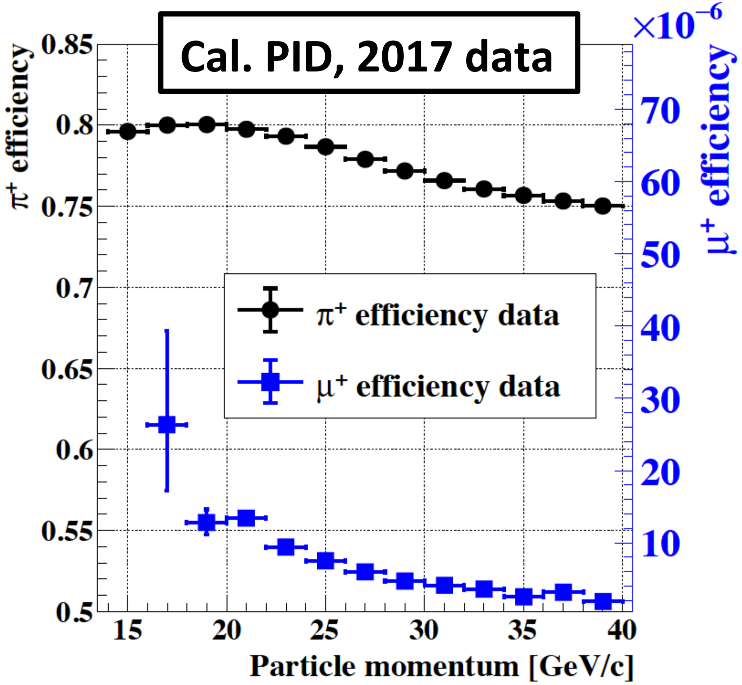


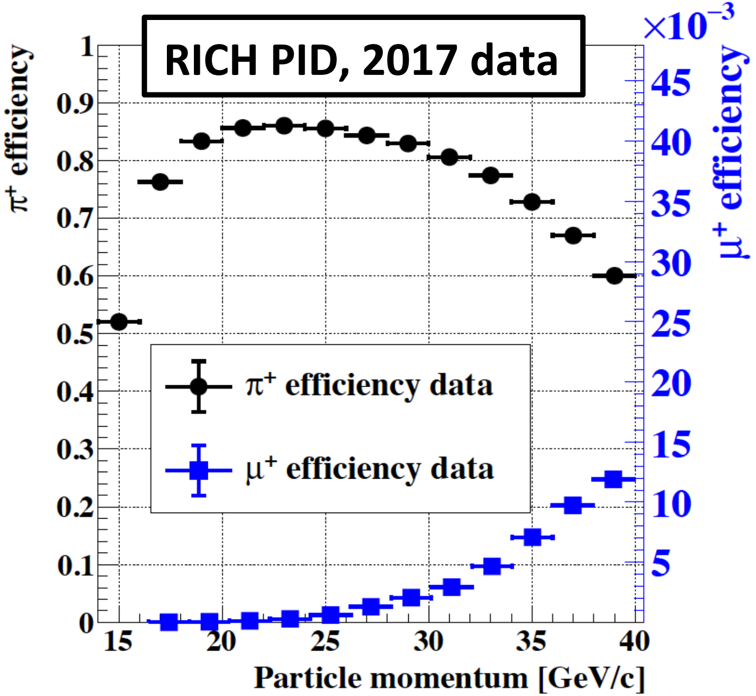


Retaining R1—R2 achieves a rejection factor of ~ 10^4 for K^+ decay backgrounds

$K^+ \rightarrow \pi^+\nu\nu$ selection scheme: PID

Calorimeters and RICH in combination for π^+ vs μ^+ identification



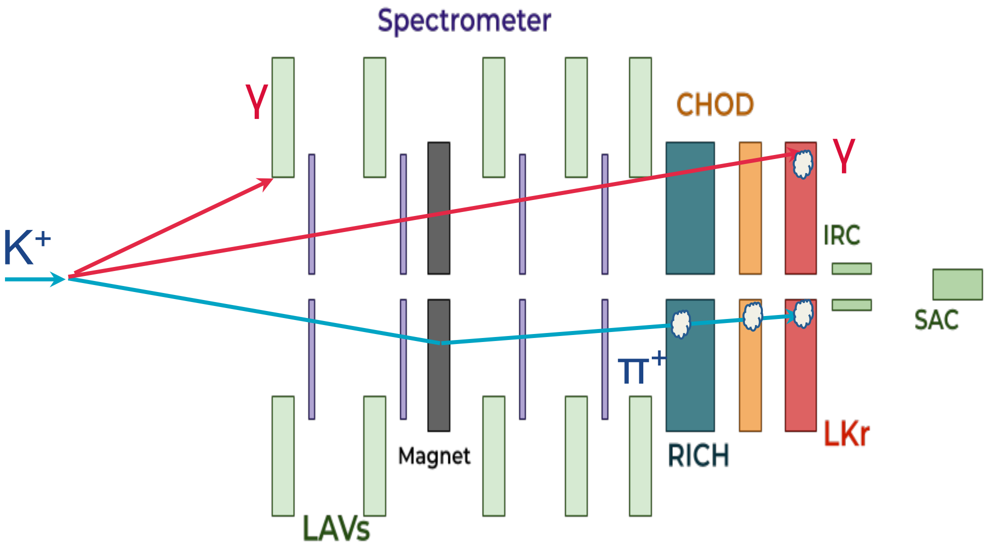


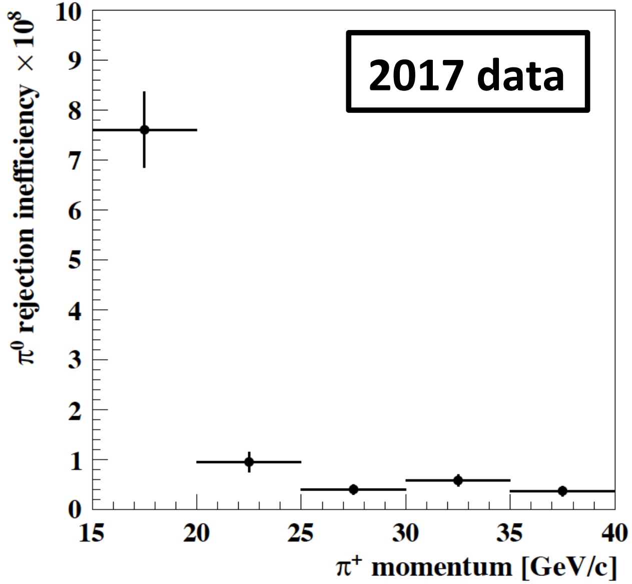
π^+ PID achieved with ~70% efficiency and 10^{-6} contamination of non-π^+ backgrounds

Veto any additional in-time activity

Veto on additional in-time photons using LAVs, LKr, IRC-SAC

To reject early photon conversions RICH and CHOD multiplicities are used, too





Expected performance of veto system confirmed by data

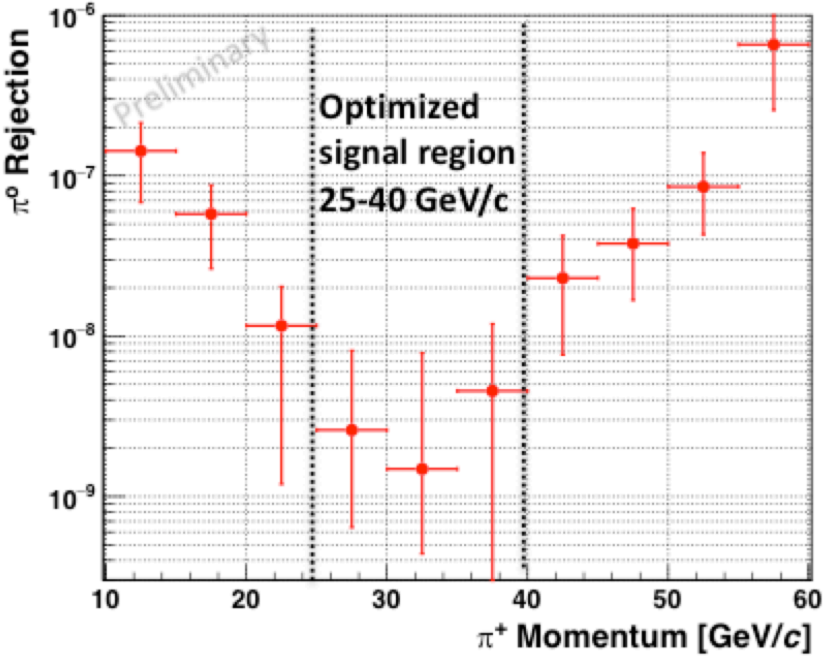
π^0 rejection as a search for π^0-> invisible

$0.015 < M_{miss}^2 < 0.021$ GeV^2 selects a $K^+ \rightarrow \pi^+\pi^0(\gamma)$ sample with $< 10^{-5}$ contamination

γ detection efficiency by tag&probe analysis, π^0 rejection by MC convolution

Validate in data side-bands with π^0 rejection $O(10^{-7})$: $\pi^0 \rightarrow$inv. excluded by BNL E949

[PR D72 (2005) 091102]



$$\boxed{BR(\pi^o \rightarrow invisible) = BR(\pi^o \rightarrow \gamma\gamma) \times \frac{N_{signal}}{N_{\pi^o}} \times \frac{1}{\epsilon_{\pi^o Detection}\epsilon_{trigger}}}$$

π^0 rejection expected = ($2.8^{+5.9}_{-2.1}$) x 10^{-9}

Expect 10^{+22}_{-8} background events from 4.4 x 10^9 $K^+ \rightarrow \pi^+\pi^0$ decays

Observe 12 events

BR(π^0 ->invisible) < 4.4 x 10^{-9} @ 90% CL

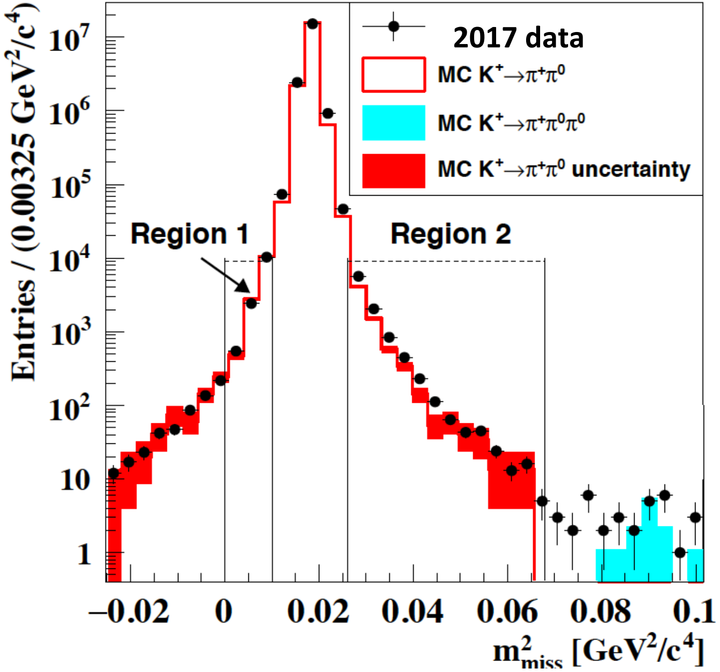
Improve by x 60 on past measurement

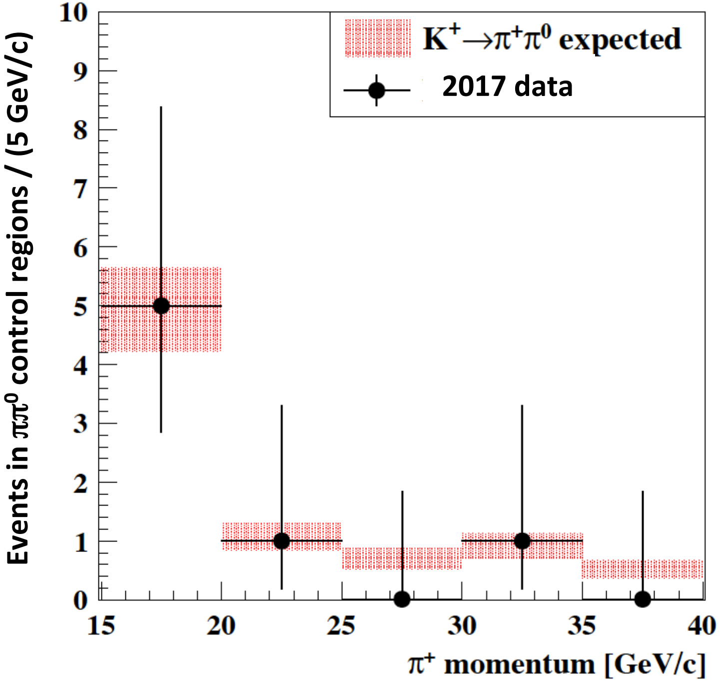
Background from K^+ decays: $\pi^+\pi^0$

Factorization between kinematic and photon-veto rejections

Kinematic rejection from min.-bias control sample with π^0 reconstructed in the LKr

Kinematic tails from K—π mismatch and π MS





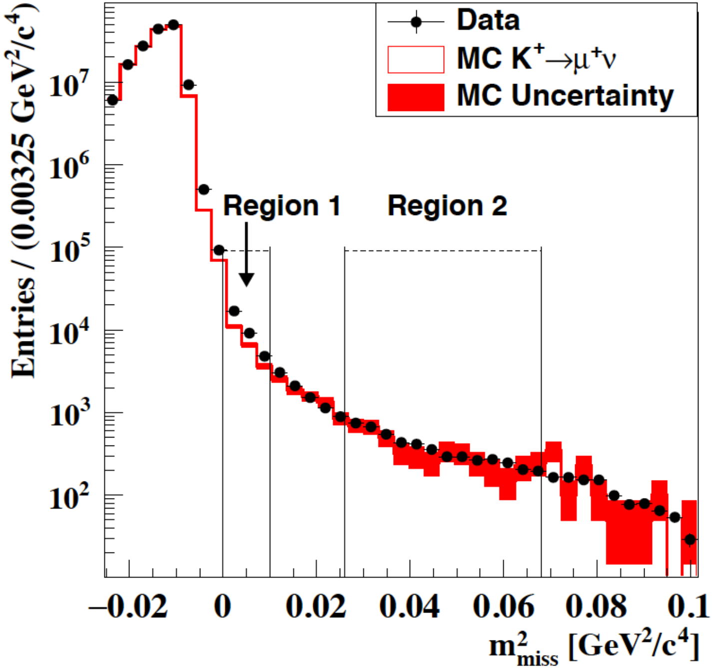
Background estimate validated in side-bands of the $\pi\pi^0$ region

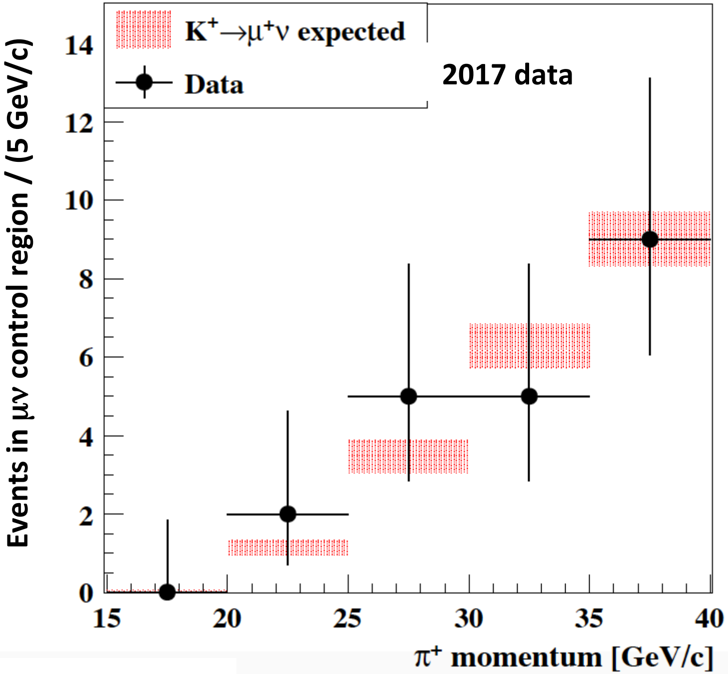
Background from K^+ decays: $\mu^+\nu$

Factorization between kinematic and PID rejections

Kinematic rejection from min.-bias control sample with μ^+ PID and no use of M_{miss}^2

Kinematic tails from μ MS



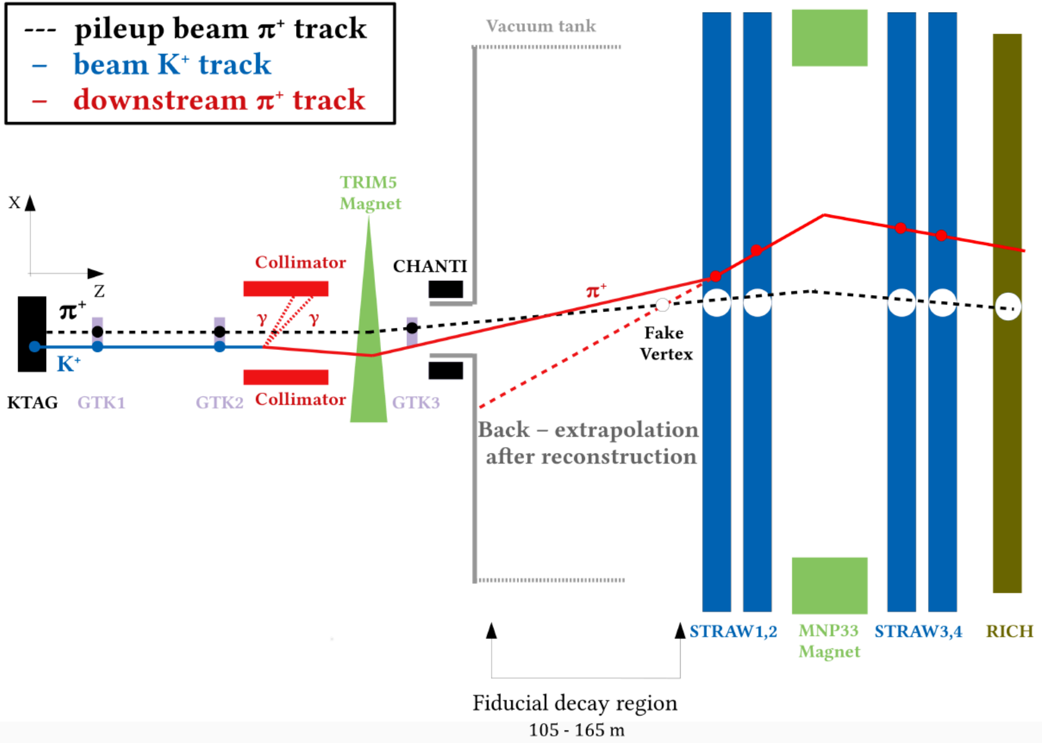


Background estimate validated in lower side-band of R1

Background from upstream activity

Accidental K—π matching or π^+ produced by nuclear interactions upstream of GTK3

An example with decay upstream GTK1 and large MS of π in STRAW station 1 occurs

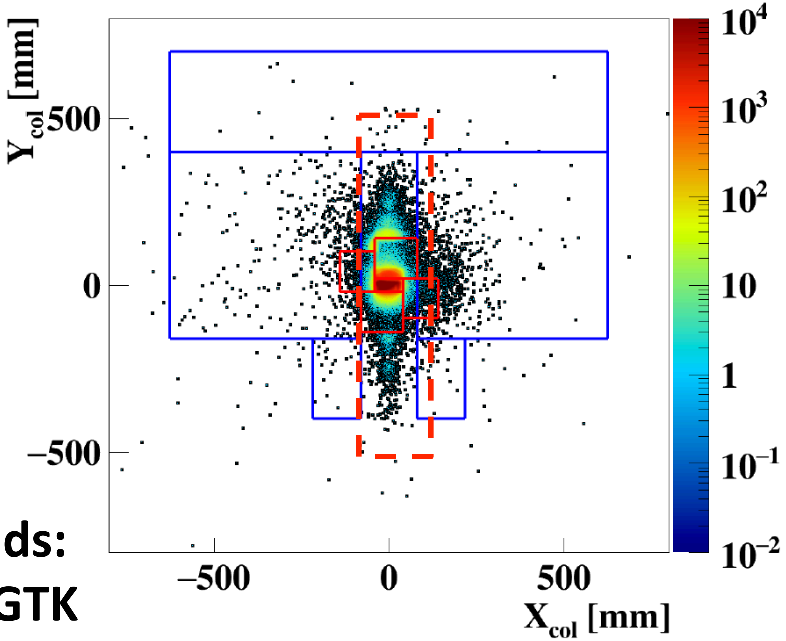


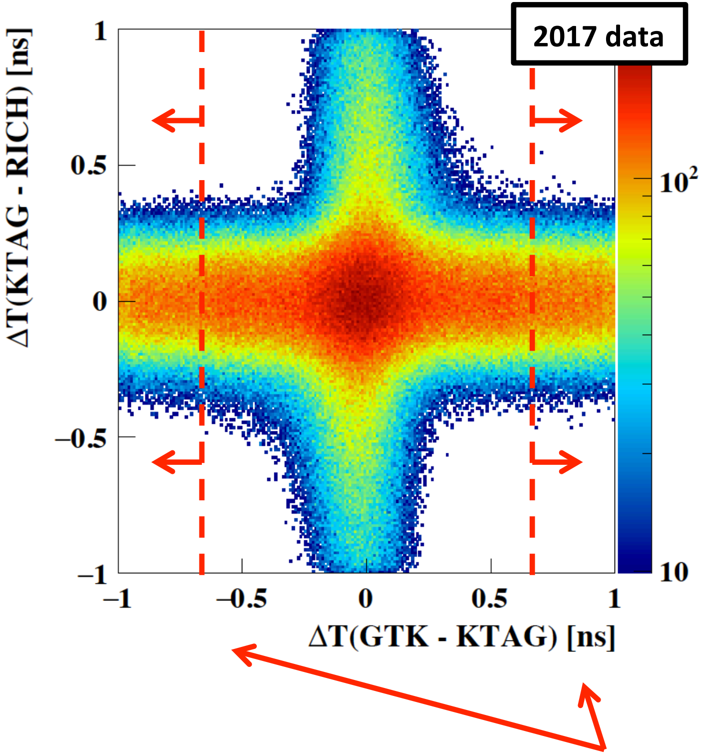
Background from upstream activity

Distributions from control sample with inverted K—π CDA condition

Events dominated by K→$\pi\pi^0$, 3π decays downstream of GTK1

Dedicated cuts applied to reject these backgrounds: BOX + CHANTI&GTK veto, cut on Z_{vtx}



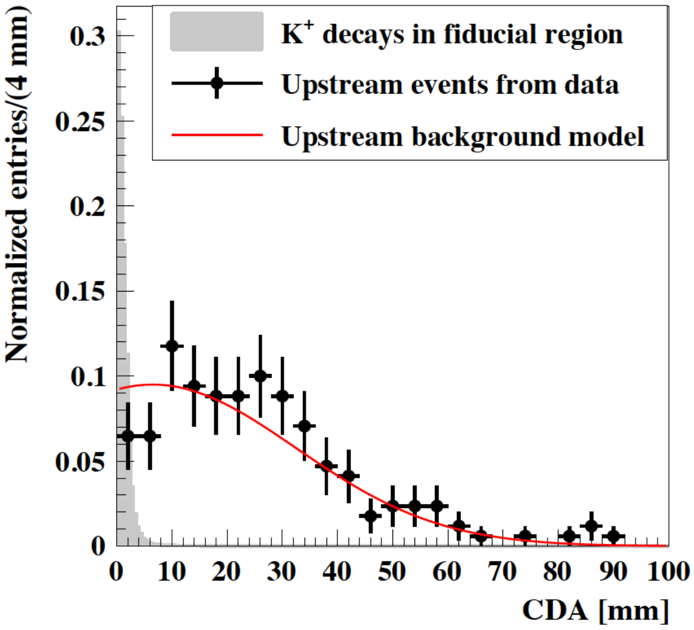


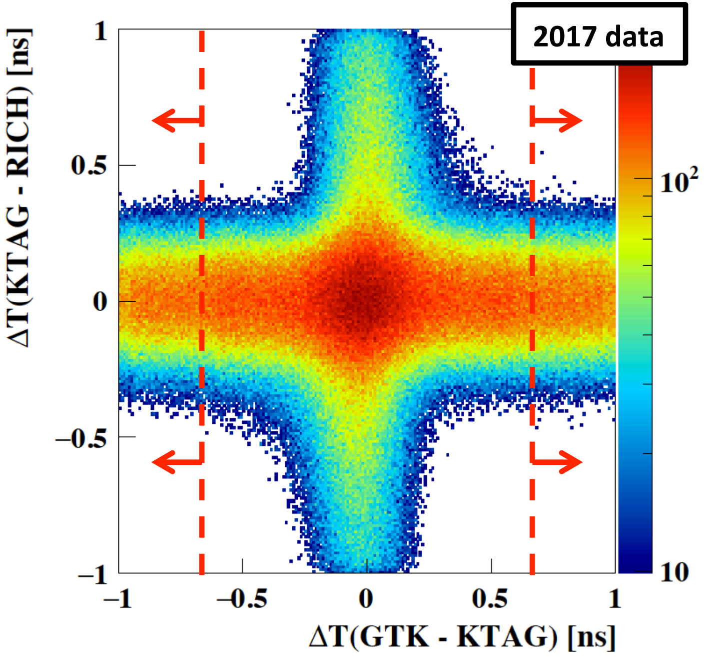
Background estimate from specific model, validated vs data control samples, e.g.

Background from upstream activity

Background model from control sample with inverted K—π CDA condition + MC

Validated vs data control samples: ΔT(GTK–KTAG) side bands



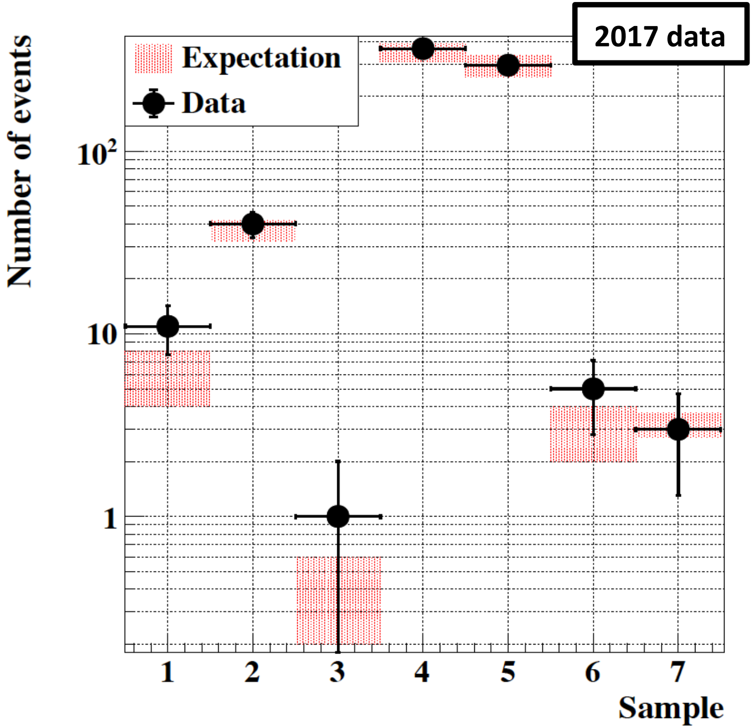


Background from upstream activity

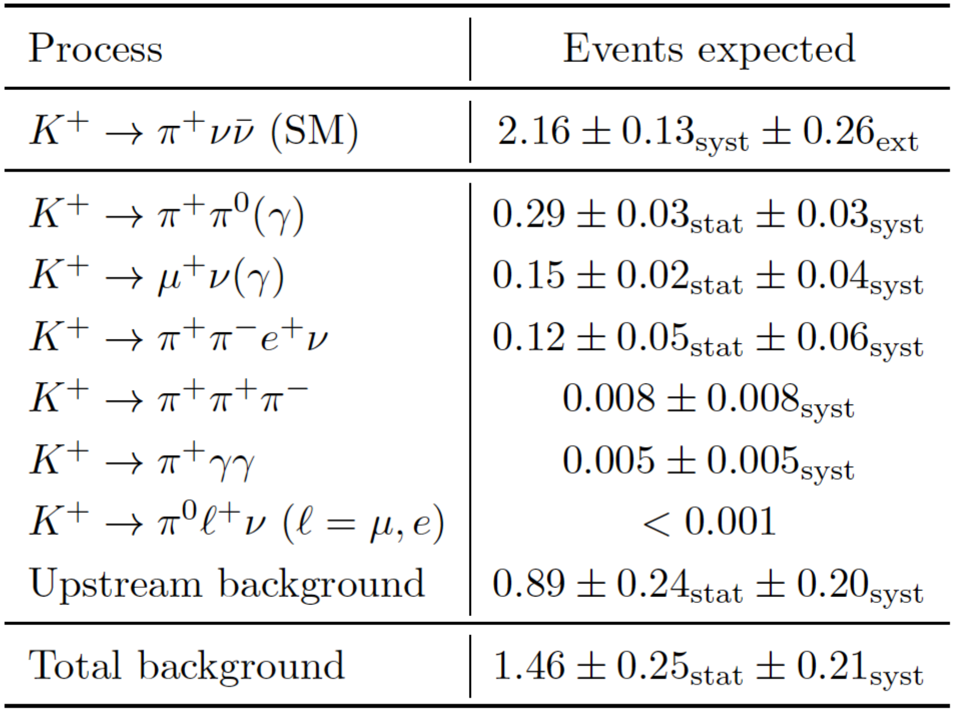
Background model from control sample with inverted K—π CDA condition + MC

Validated vs data control samples:

1. |Xcoll| < 100 mm, |Ycoll| < 140 mm
2. |Xcoll| < 100 mm, |Ycoll| > 140 mm
3. $M_{miss}^2 < -0.05\ GeV^2$
4. As 1, with no GTK-CHANTI veto conditions
5. As 2, with no GTK-CHANTI veto conditions
6. As 3, with no GTK-CHANTI veto conditions
7. Inverted GTK-CHANTI veto conditions



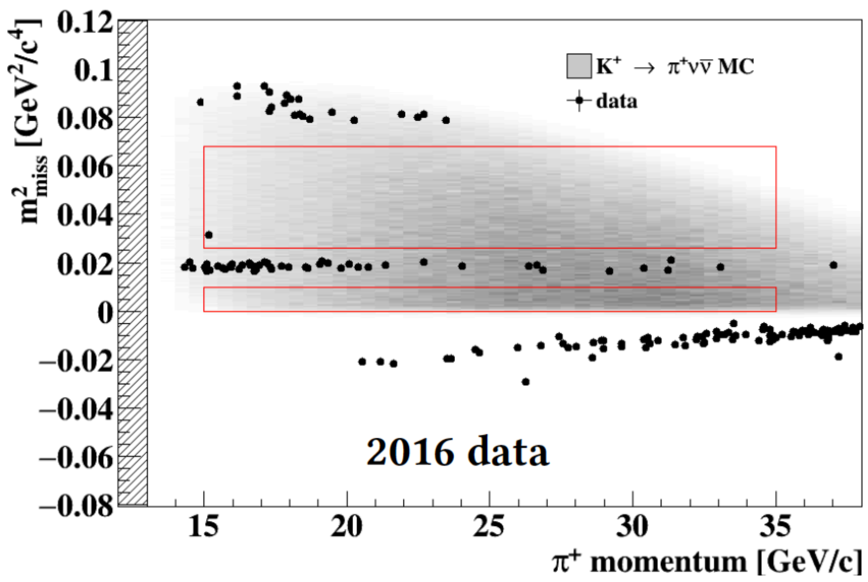
Background estimates in 2017

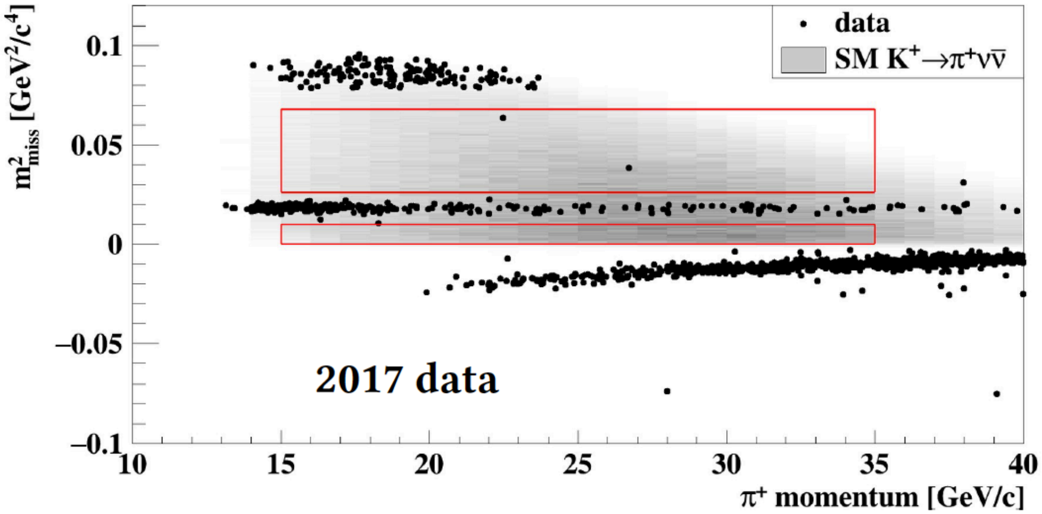


Process	Events expected
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$2.16 \pm 0.13_{\text{syst}} \pm 0.26_{\text{ext}}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	$0.29 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}}$
$K^+ \to \mu^+ \nu (\gamma)$	$0.15 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.12 \pm 0.05_{\text{stat}} \pm 0.06_{\text{syst}}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.008 \pm 0.008_{\text{syst}}$
$K^+ \to \pi^+ \gamma\gamma$	$0.005 \pm 0.005_{\text{syst}}$
$K^+ \to \pi^0 \ell^+ \nu$ $(\ell = \mu, e)$	< 0.001
Upstream background	$0.89 \pm 0.24_{\text{stat}} \pm 0.20_{\text{syst}}$
Total background	$1.46 \pm 0.25_{\text{stat}} \pm 0.21_{\text{syst}}$

Analyses results: 2016 and 2017 data

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

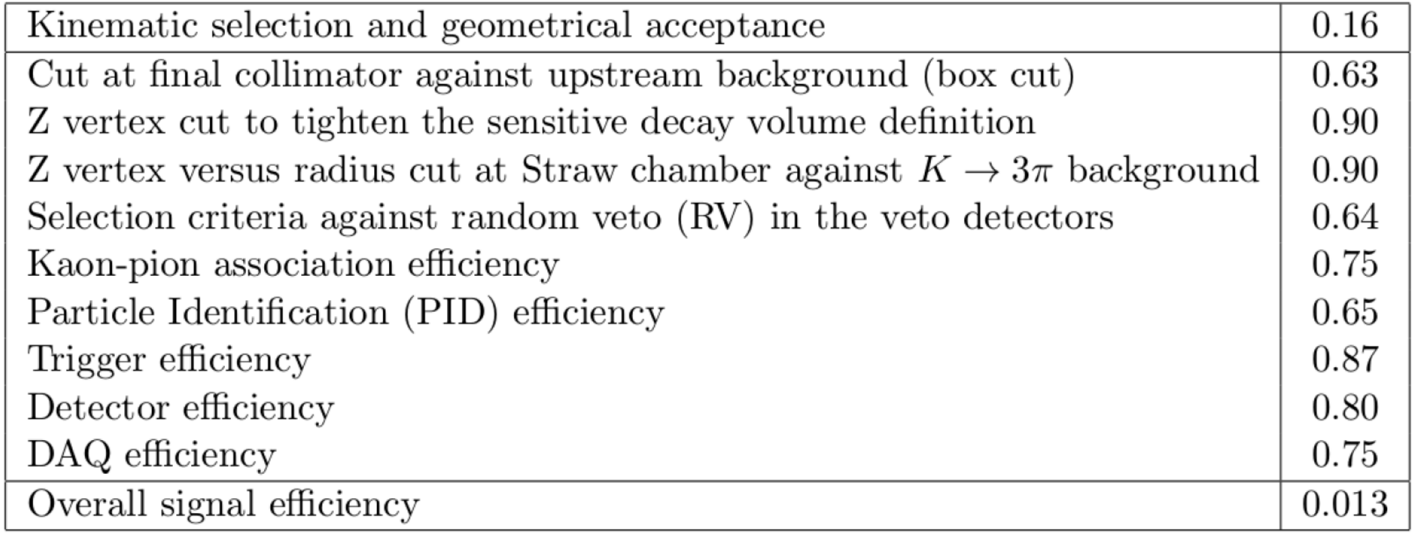




2016: BR($K \rightarrow \pi\nu\nu$) $< 14 \times 10^{-10}$ @ 90% CL **2016-17: BR($K \rightarrow \pi\nu\nu$) $< 1.78 \times 10^{-10}$ @ 90% CL**

Lessons learned from 2017

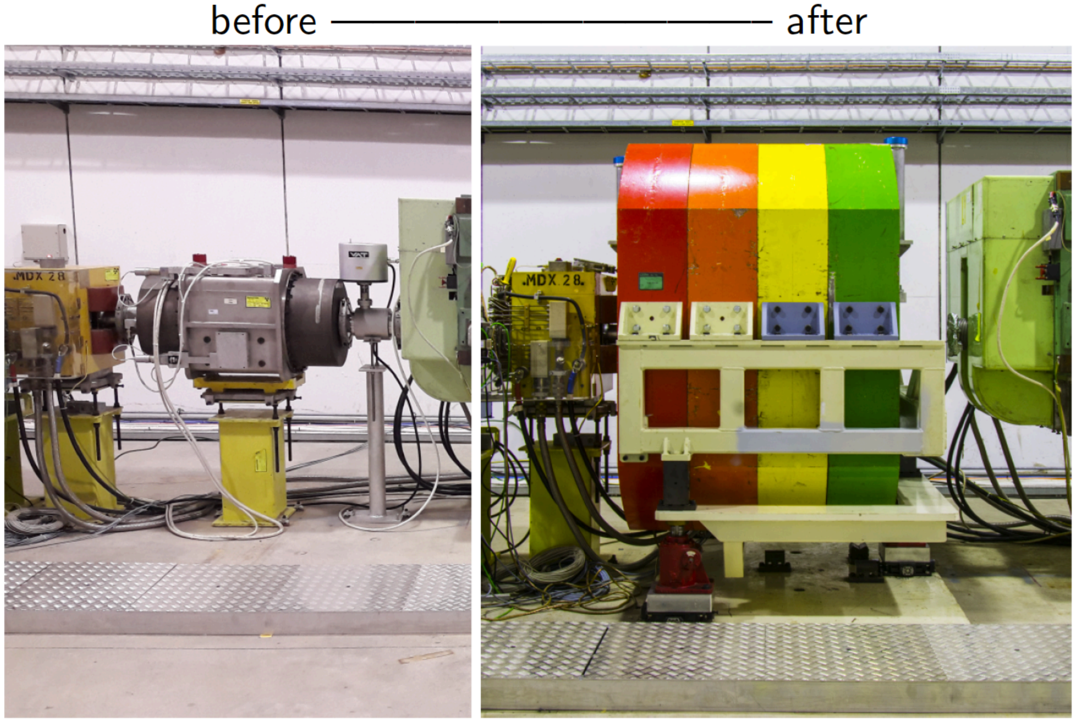
1. Significant background due to upstream activity and related inefficiency to be reduced
2. Certain analysis conditions inducing non-negligible efficiency loss can be fine tuned
3. Kinematic regions can be significantly extended partly improving the corresponding efficiency



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

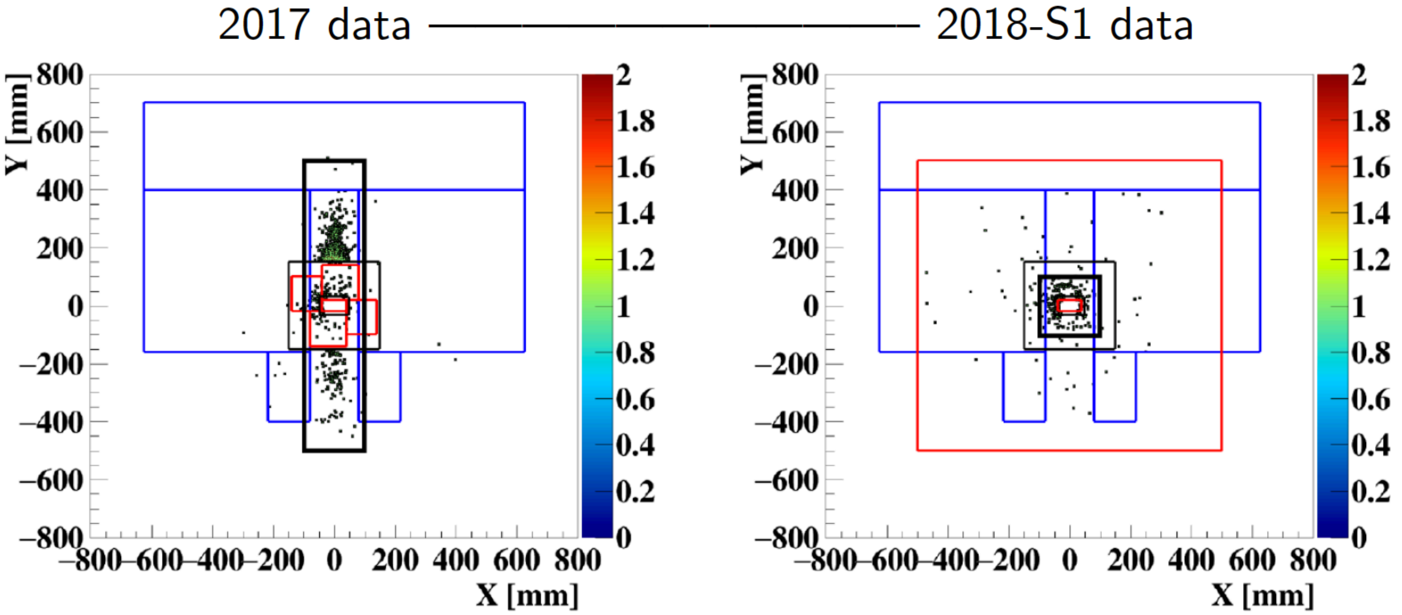
Actions taken

1. Improved absorption with new collimator in June 2018: increased transverse coverage



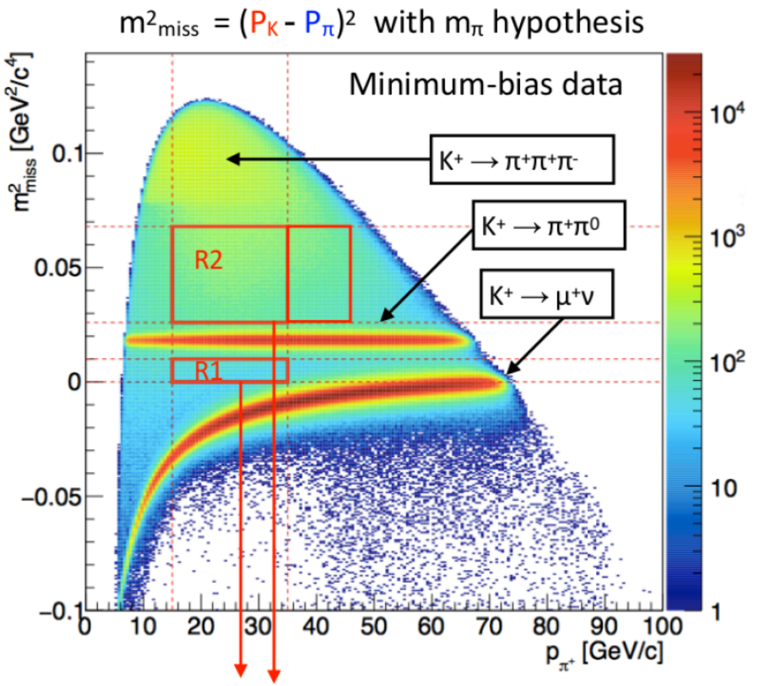
Actions taken: hardware intervention

1. Improved absorption with new collimator in June 2018: 80% of 2018 in new conditions (“S1”)



Actions taken: analysis refinements

2. Analysis re-optimized in bins of π^+ momentum (5 GeV width):
3. cuts against upstream bkg, using a multi-variate approach: gain +50%
4. re-definition of kinematic signal regions: gain +30% (R2 extended)
5. optimisation of PID (RICH and calorimeters): gain +10%
6. improved definition of decay fiducial volume: gain +6%
7. improved veto conditions to reduce random veto (STRAW and LAV treatment): gain +3%



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

Kinematic cuts to define signal regions R1 and R2

Analysis of 2018 data vs 2017

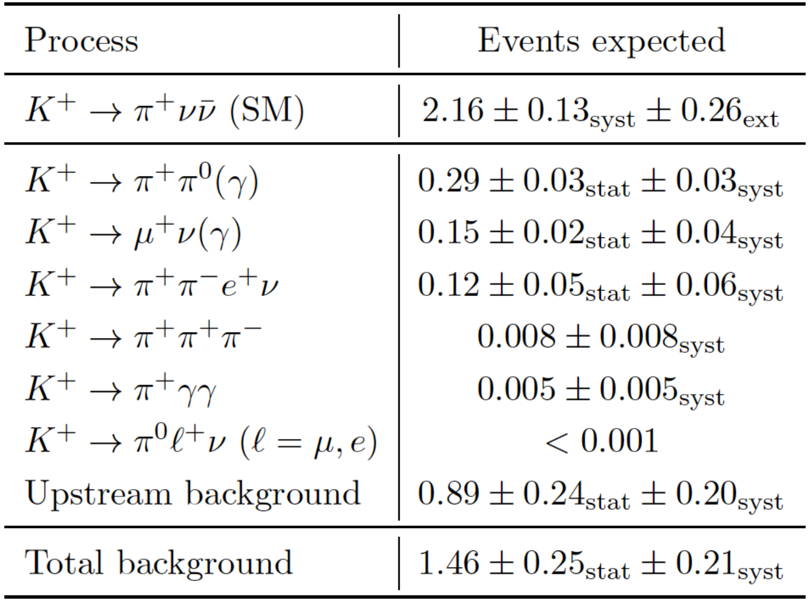
Expected B/S maintained after optimization

	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

*** Do not include efficiency loss common to πνν and ππ: TDAQ, Detector, etc.**

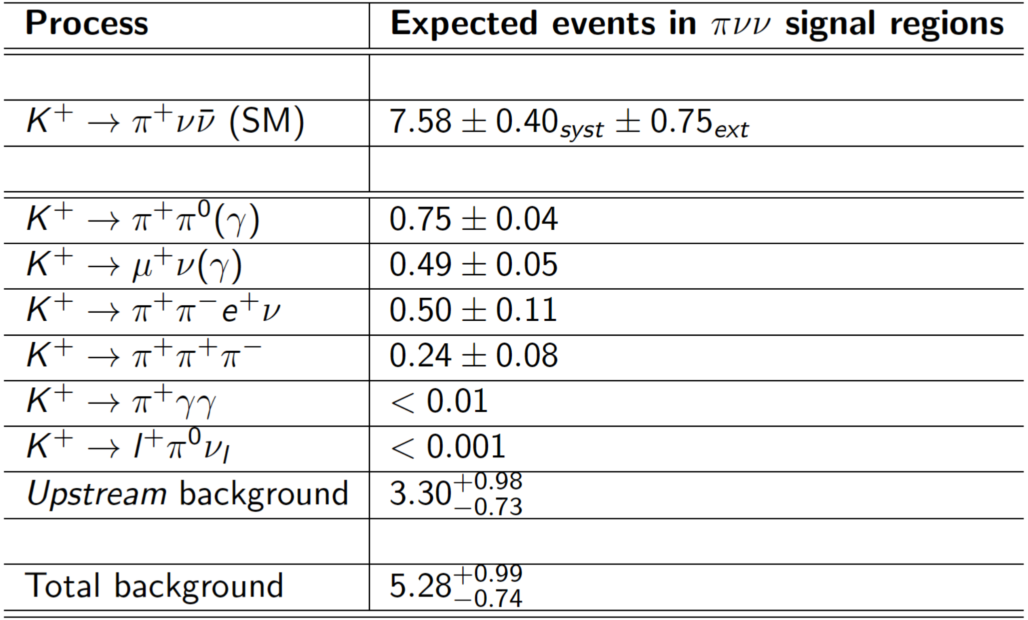
Expected signal and background

Published analysis, 2017 data



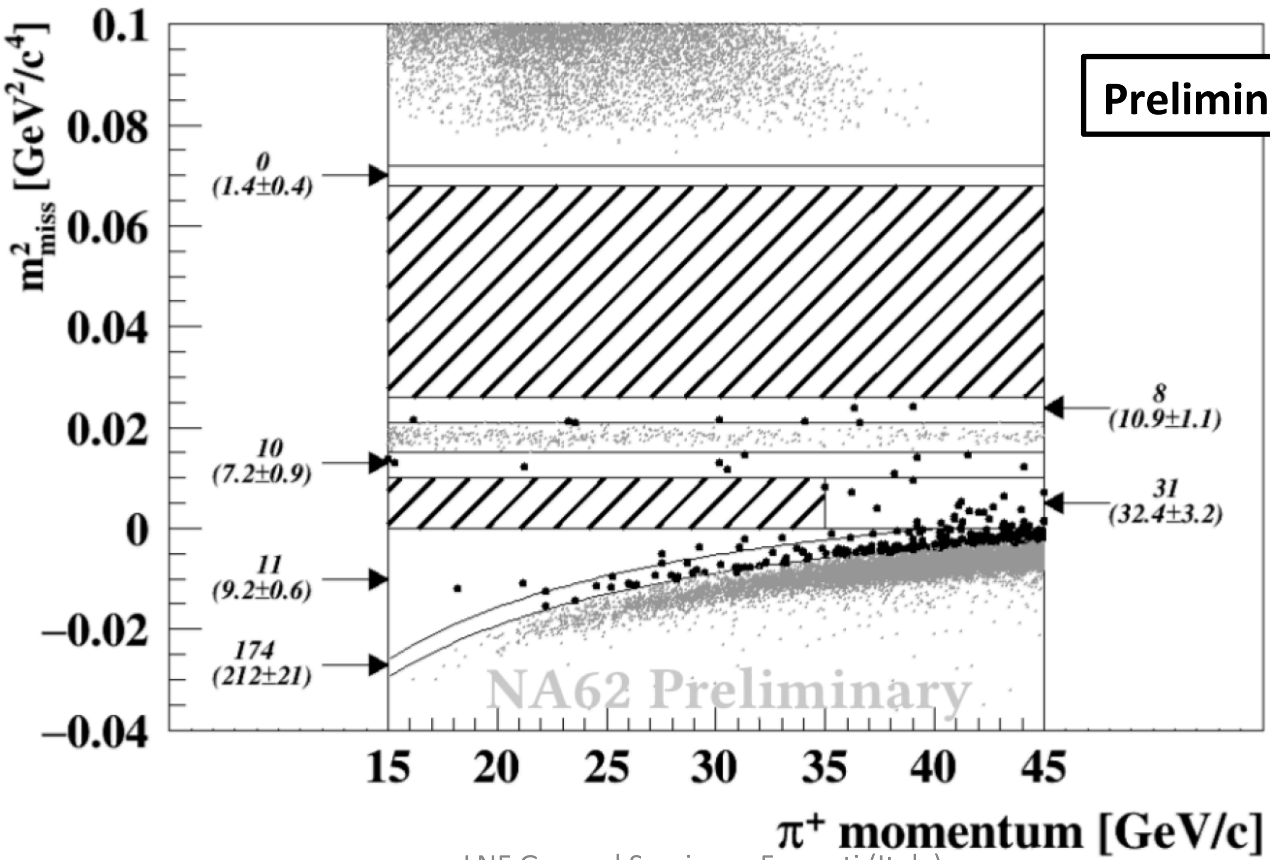
Process	Events expected
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$2.16 \pm 0.13_{\mathrm{syst}} \pm 0.26_{\mathrm{ext}}$
$K^+ \to \pi^+\pi^0(\gamma)$	$0.29 \pm 0.03_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}}$
$K^+ \to \mu^+\nu(\gamma)$	$0.15 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.12 \pm 0.05_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.008 \pm 0.008_{\mathrm{syst}}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{\mathrm{syst}}$
$K^+ \to \pi^0\ell^+\nu$ ($\ell = \mu, e$)	< 0.001
Upstream background	$0.89 \pm 0.24_{\mathrm{stat}} \pm 0.20_{\mathrm{syst}}$
Total background	$1.46 \pm 0.25_{\mathrm{stat}} \pm 0.21_{\mathrm{syst}}$

Preliminary analysis, 2018 Data



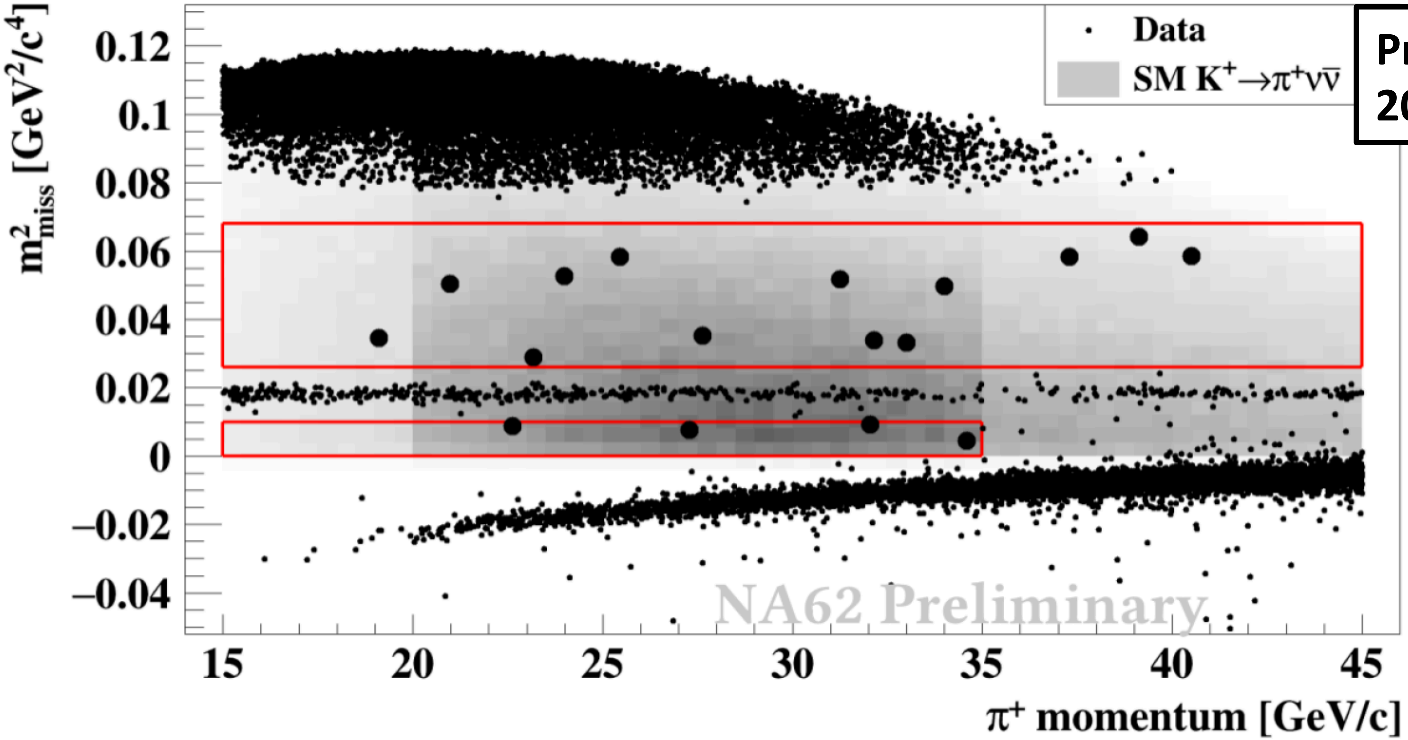
Process	**Expected events in $\pi\nu\nu$ signal regions**
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+\pi^- e^+\nu$	0.50 ± 0.11
$K^+ \to \pi^+\pi^+\pi^-$	0.24 ± 0.08
$K^+ \to \pi^+\gamma\gamma$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

Background validation in control regions



Preliminary, 2018 Data

Signal region opened, 2018 data

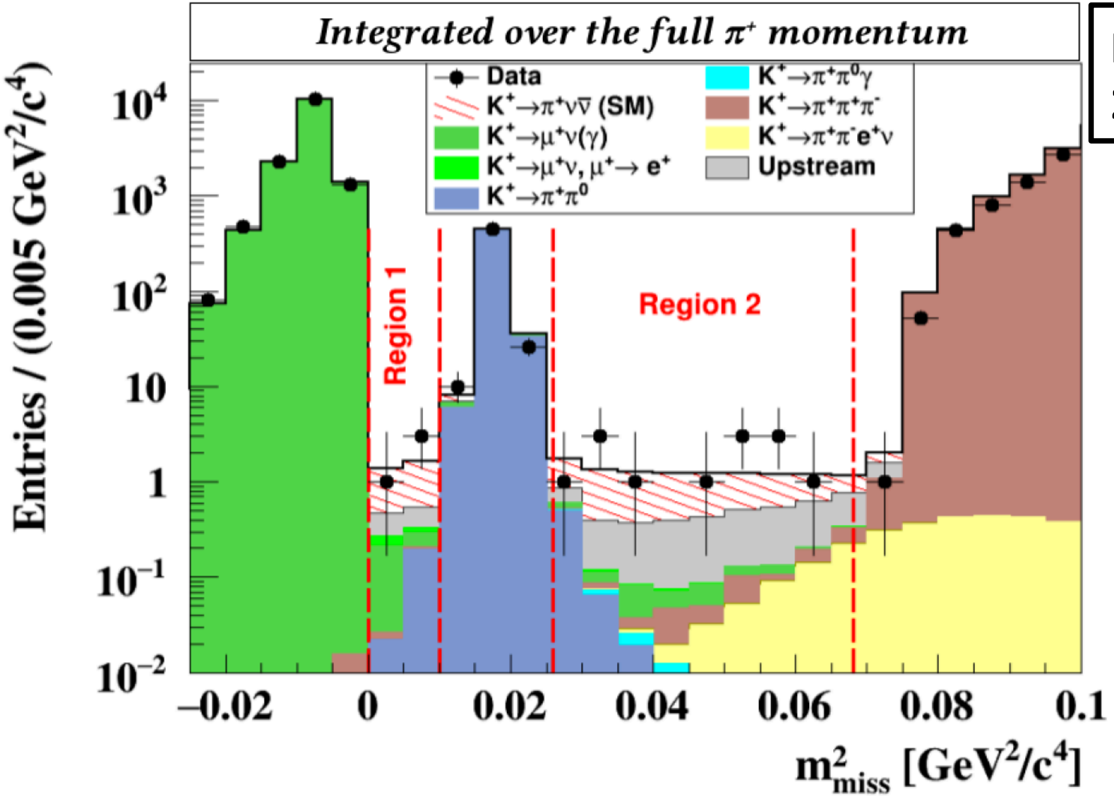


Preliminary, 2018 Data

17 events observed

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

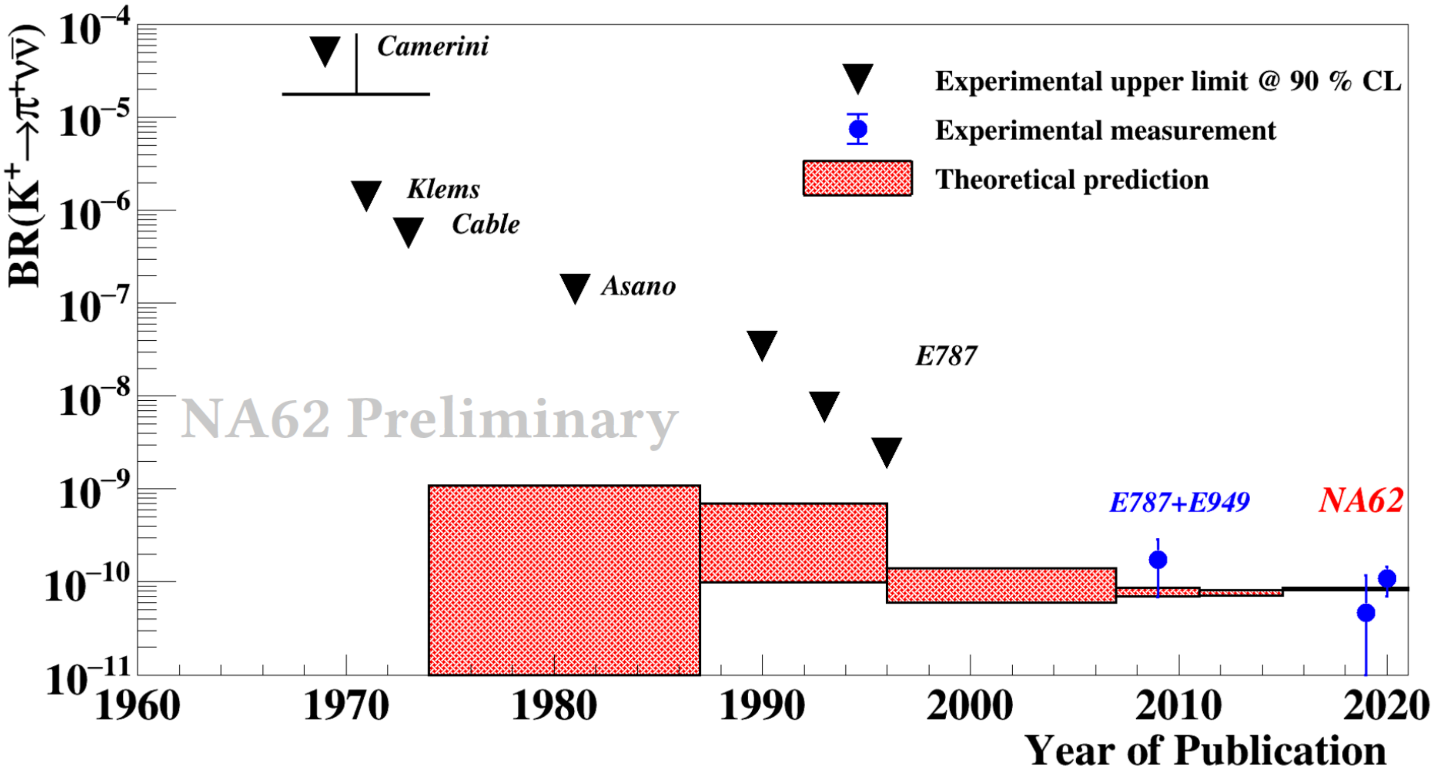
Expected and observed M_{miss}^2 distribution



Preliminary analysis, 2018 Data

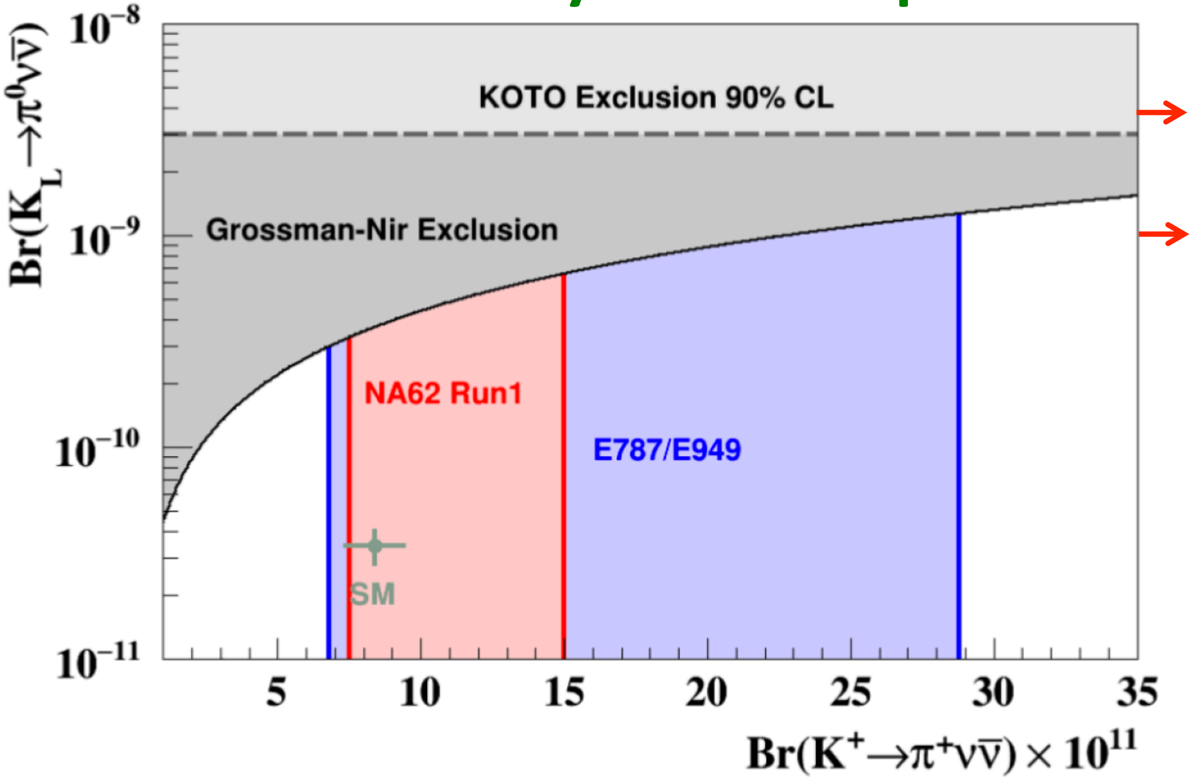
Bumps due to $K^+ \rightarrow \pi^+ X$, $X \rightarrow$ invisible would appear with $\sigma \sim 1.1\ (0.8)\times10^{-3}\ \mathrm{GeV}^2$ in R1 (R2)

A new measurement in a long journey



Combined 2016—2018 result: BR = (11.0 $^{+4.0}_{-3.5}$$_{stat}$ ± 0.3$_{syst}$) × 10^{-11}, 3.5-σ significance

Physics implications



→ **Speculation based on KOTO data [PRL 124 (2020) 071801]:**

→ **$\mathrm{BR}(K_L \to \pi \nu \nu) = (21\,^{+20}_{-11}) \times 10^{-10}$**

Combined 2016—2018 result: $\mathrm{BR} = (\,11.0\,^{+4.0}_{-3.5\,\mathrm{stat}} \pm 0.3_{\mathrm{syst}}\,) \times 10^{-11}$, 3.5-$\sigma$ significance

Conclusions and prospects

With the decay-in-flight technique NA62 obtained the most precise measurement of K→πνν

The probability of a background-only observation is ~ 2 × 10^{-4}

New-physics effects generating large excess are beginning to be ruled out

A new data taking will allow a total uncertainty of O(10%) on BR(K→πνν) to be reached

Continuation requested from LS2 to LS3 [CERN_SPSC_2019_039]: July 2021—2024

Goal to run at 100% of the nominal intensity

Setup improvements under way, to drastically reduce background from upstream activity:

1. **Re-design of the beamline region in the 2nd achromat**
2. **Add a fourth GTK station to provide redundancy and reduce K—π mis-tagging**
3. **Add a new large-angle beam-activity veto counter upstream of the final collimator**

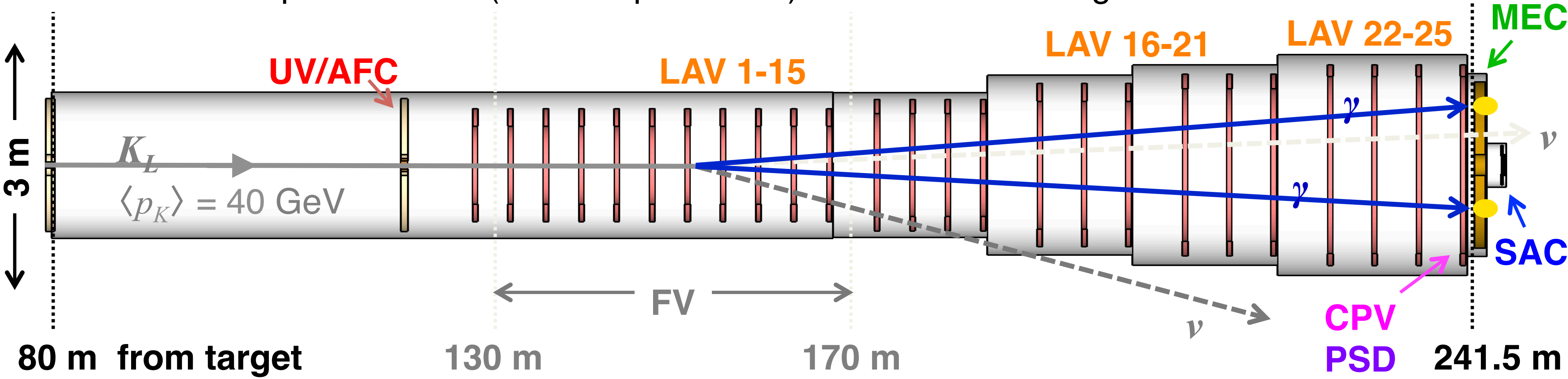
To further suppress K^+ decay background (e.g., $\pi\pi^0$), a new HASC added upstream of dump

Proposals for physics program after Q2 2027 put forward, including K^+, K_L →πνν and K_L →πll

Spare slides

KLEVER, a $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment at the SPS

400-GeV SPS proton beam (2×10^{13} pot/16.8 s) incident on Be target at **z = 0 m**



KLEVER target sensitivity:

5 years starting Run 4

60 SM $K_L \rightarrow \pi^0 \nu\nu$
S/B ~ 1

δBR/BR($\pi^0 \nu\nu$) ~ 20%

Main detector/veto systems:

UV/AFC	**Upstream veto/Active final collimator**
LAV1-25	**Large-angle vetoes (25 stations)**
MEC	**Main electromagnetic calorimeter**
SAC	**Small-angle vetoes**
CPV	**Charged particle veto**
PSD	**Pre-shower detector**

Future plans

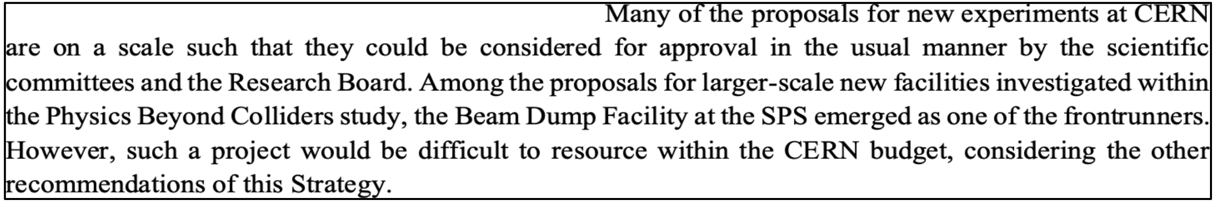
NA62 high-intensity K+ discussion, Jan 19:

- **Goal: Measure BR($K^+ \to \pi^+ \nu\nu$) to 5%**
- **4x primary intensity ("NA62x4"),** based on feasibility studies for KLEVER beam
- Technological challenges, esp. beam and spectrometer tracking
  - Adopt calorimetry and veto designs from KLEVER
- Significant interest from NA62 collaboration and community

Outcome of European Strategy Update:

- Support for intensity frontier physics reaffirmed
  - Rare kaon decays explicitly mentioned in supporting document
- Physics Beyond Collider programs generally supported
- SPS beam dump facility judged to be to expensive

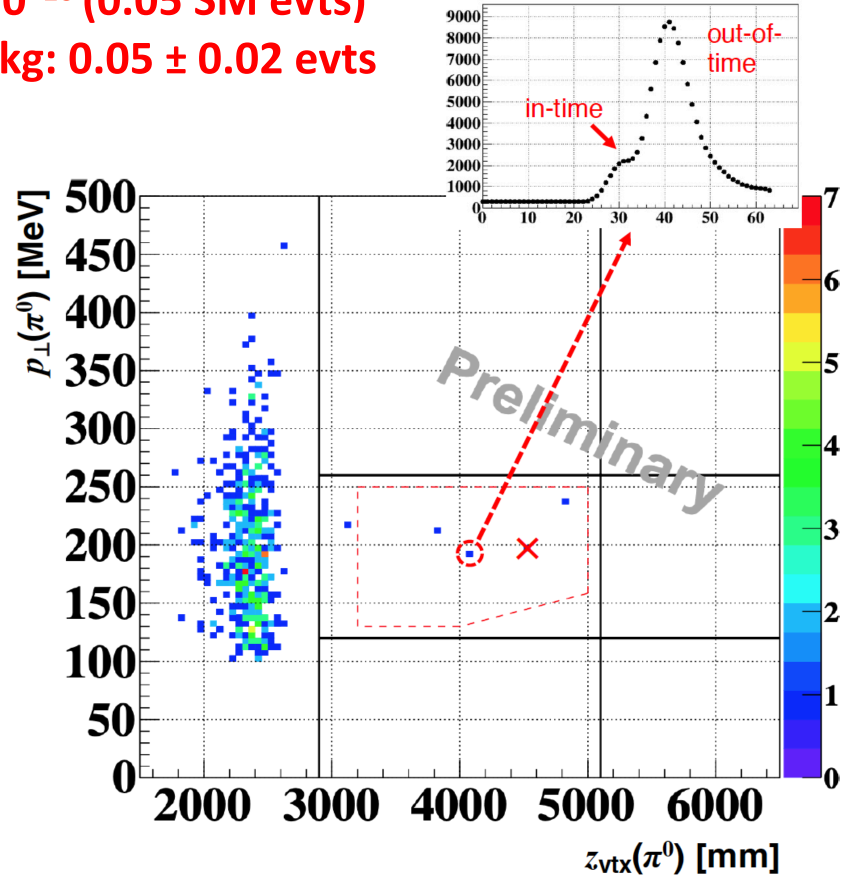
CERN-ESU-014 June 2020



Many of the proposals for new experiments at CERN are on a scale such that they could be considered for approval in the usual manner by the scientific committees and the Research Board. Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

KOTO Status

KOTO preliminary (KAON, Sep 2019)
SES: 6.9×10^{-10} (0.05 SM evts)
Expected bkg: 0.05 ± 0.02 evts

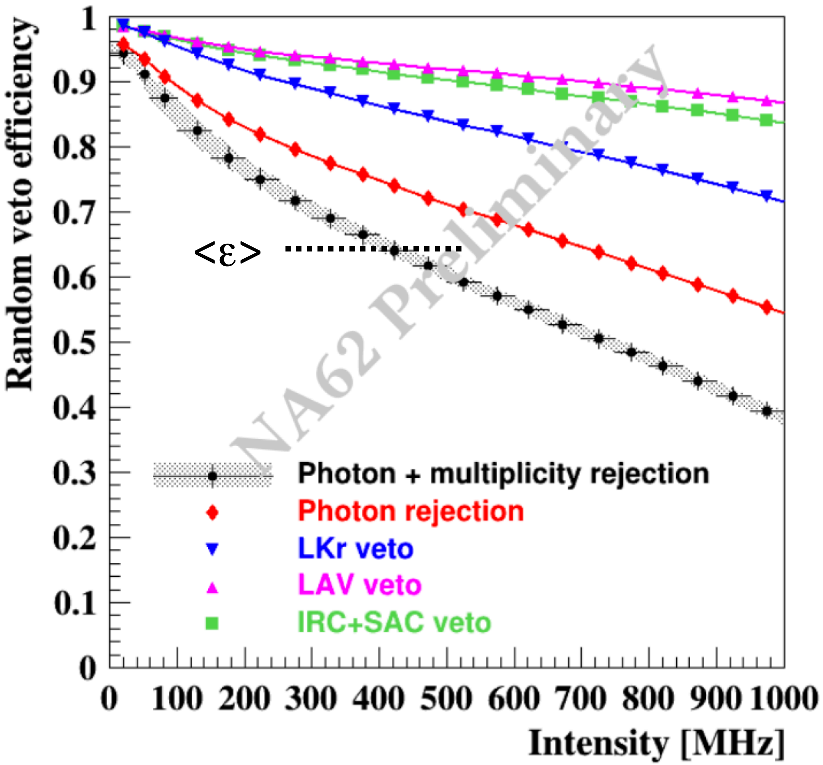


New background estimates
Preliminary (ICHEP 2020)

Source	**Expected (68%CL)**
$K_L \to \pi^0\pi^0$	< 0.05
$K_L \to \pi e \nu$ overlap pulse	< 0.05
$K_L \to ee\gamma$	< 0.05
$K_L \to \gamma\gamma$ core	< 0.06
$K_L \to \gamma\gamma$ halo	< 0.10
$K^+ \to \pi^0 e^+ \nu$	0.90 ± 0.27
$K^+ \to \pi^+ \pi^0$	0.09 ± 0.09
$K^+ \to \pi^0 \mu^+ \nu$	< 0.12
π^0 from n in CV	< 0.05
Total	**1.05 ± 0.28**

Analysis being finalized
Publication expected soon

Random-veto efficiency vs intensity



Result stability