$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ AT NA62

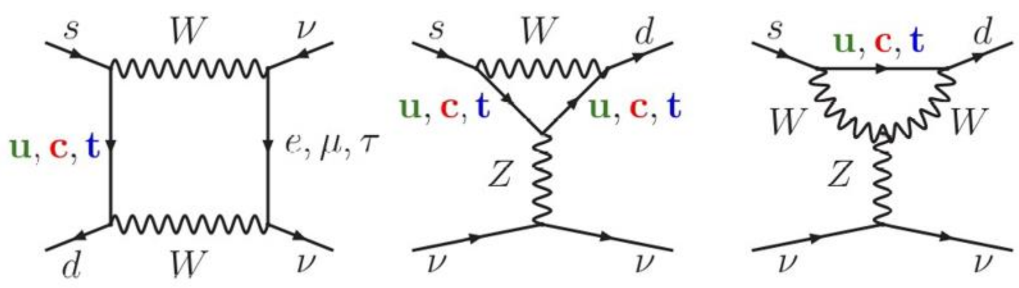
- $K^+ \rightarrow \pi^+ X$ at NA62
- $K_L \rightarrow \pi^0 \nu\bar{\nu}$ at KOTO

RENATO FIORENZA (on behalf of NA62 collaboration)
renato.fiorenza@cern.ch

WORKSHOP PHI
09/11/2022

Scuola Superiore Meridionale
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
INFN NAPOLI

THE $K^+ \to \pi^+ \nu\bar{\nu}$ DECAY: STATE OF THE ART



- FCNC s → d, high CKM suppression
- Theoretically clean: short distance contribution
- Hadronic form factor measured with $K_{\ell 3}$
- Uncertainty largely from CKM parameters

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$$

JHEP 11 (2015) 033

- Previous experimental measurement at E787/E949
- Decay-at-rest technique

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{BNL} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

Phys. Rev. D 79 (2009) 092004

NA62 2016 data: 1 event observed

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16} < 14 \times 10^{-10} \text{ @ 95\% CL}$$

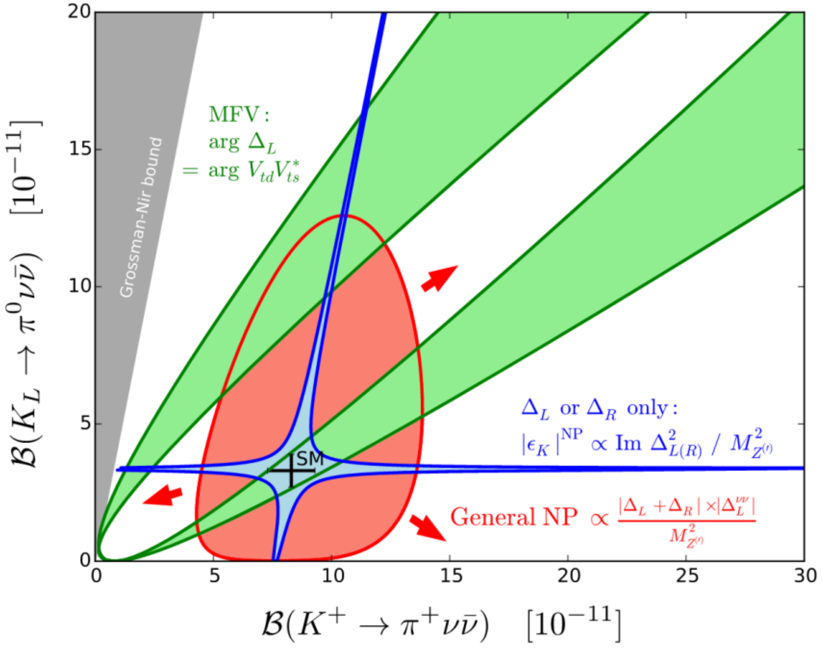
Phys. Lett. B 791 (2019) 156

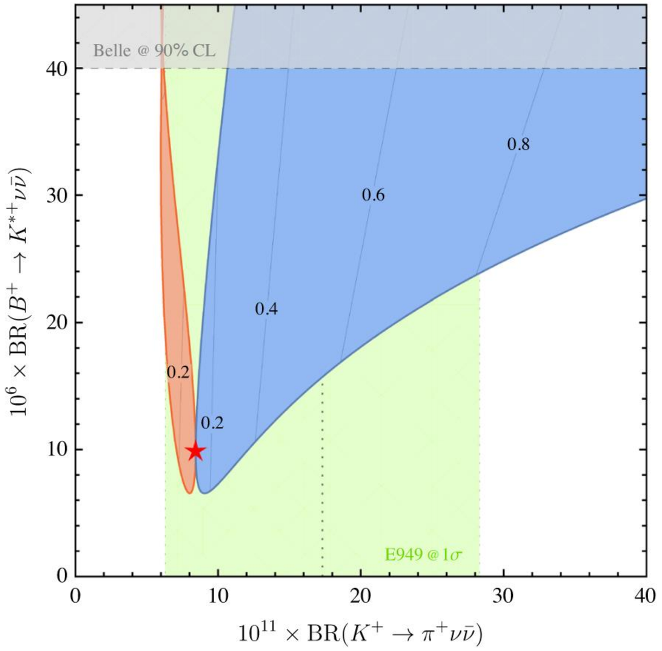
NA62 2017 data: 2 events observed

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16+17} = (0.48^{+0.72}_{-0.48}) \times 10^{-10}$$

JHEP 11 (2020) 042

THE $K^+ \to \pi^+ \nu\bar{\nu}$ DECAY: NEW PHYSICS SENSITIVITY



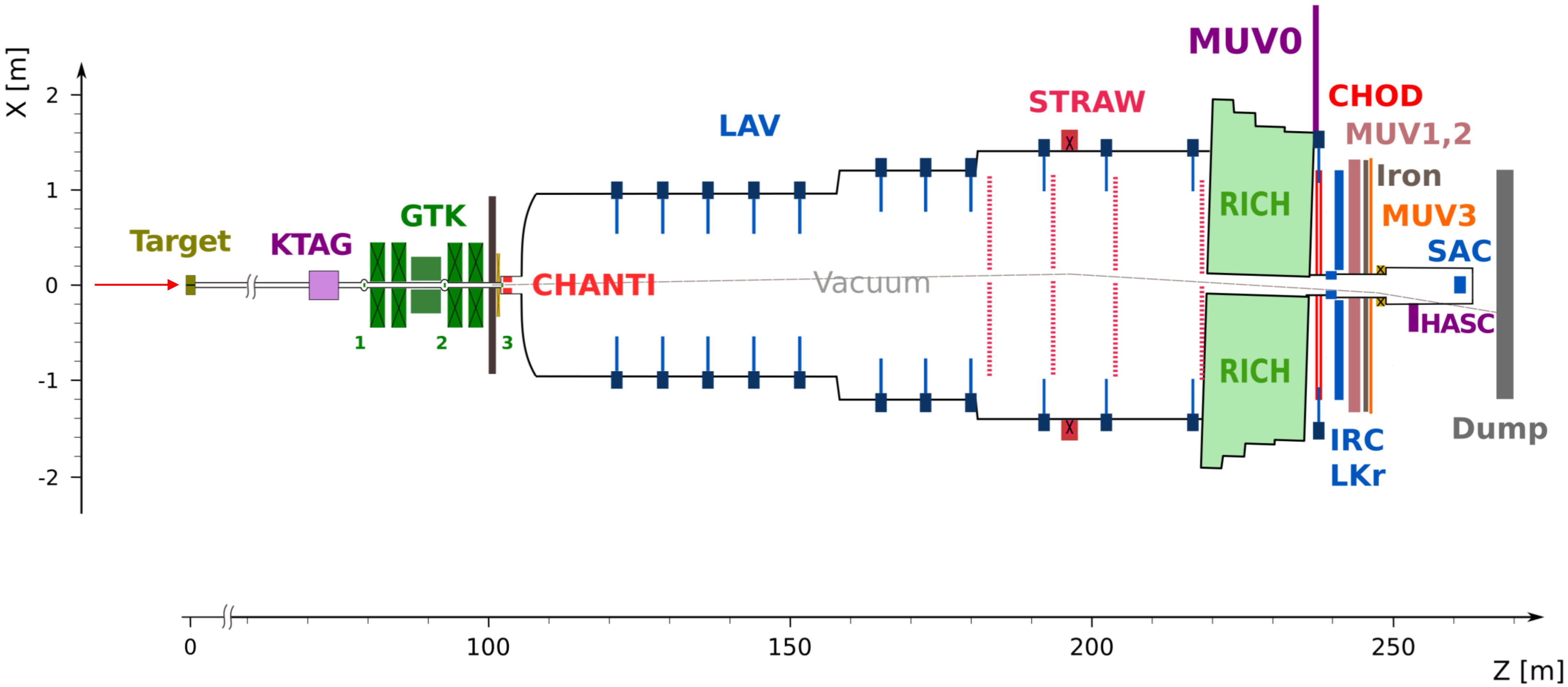


- Custodial Randall-Sundrum
  JHEP 0903 (2009) 108
- MSSM analyses
  JHEP 0608 (2006) 064
- Simplified Z, Z' models
  JHEP 11 (2015) 166
- Littlest Higgs with T-parity
  Eur.Phys.J. C76 (2016) 182
- LFU violation models
  Eur. Phys. J. C (2017) 77: 618
- Leptoquarks
  arXiv:1802.00786v1 (2018)
- Constraints from existing measurements (correlations model dependent)

THE NA62 EXPERIMENT

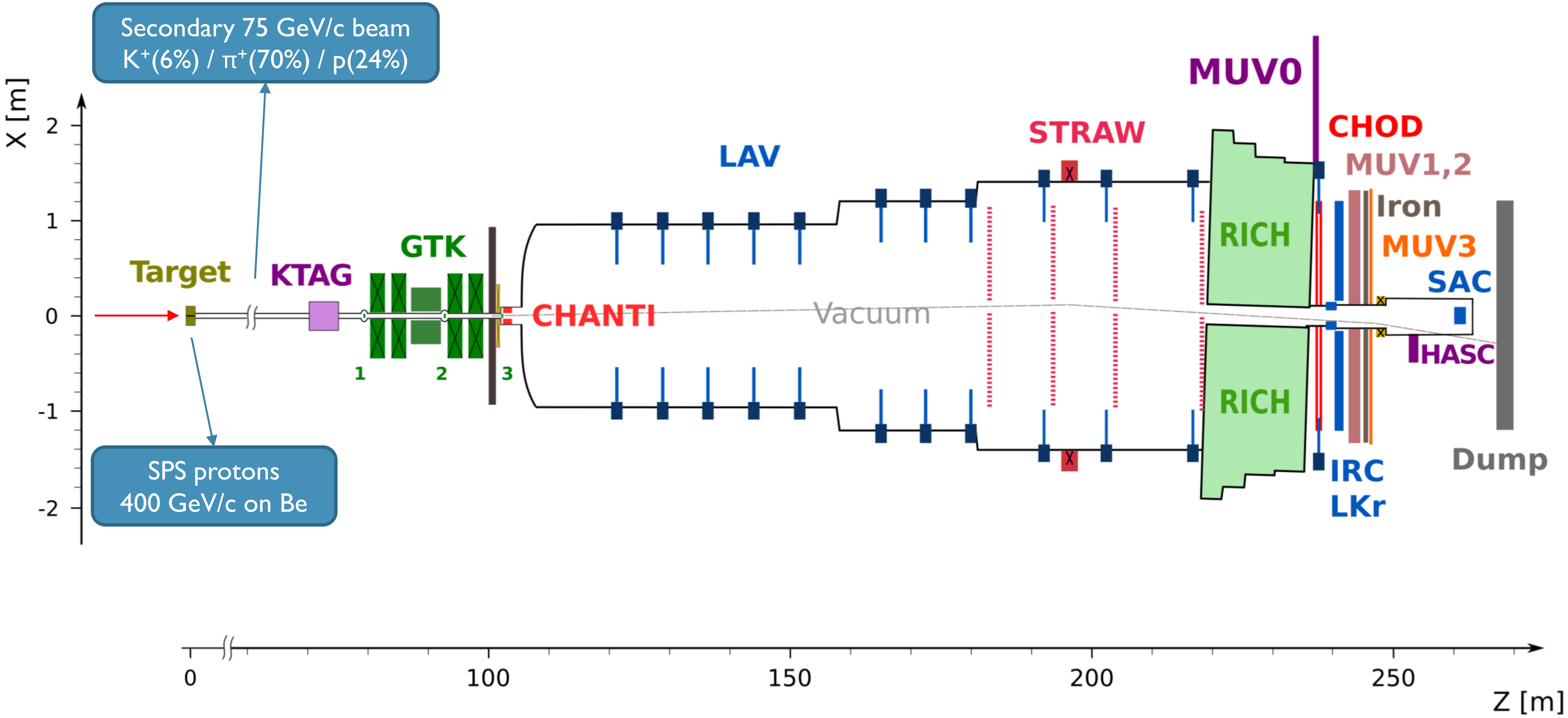
- High-precision kaon experiment
- Technique:
  - Fixed target
  - Decay-in-flight
- Broad physics program:
  - Measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) → this talk
  - Precision measurements → M. D'Errico, 10/11
  - Tests of LFV / LNV → E. Minucci, today; M. Corvino, 11/11
  - Exotic searches (DP, DS, ALP, HNL) → A. Kleimenova, 11/11
  - CKM matrix studies → F. Brizioli, 11/11
- Timeline:
  - 2016 – 2018: First data taking run (2.2×10^{18} protons on target)
  - 2021 – ongoing: Second data taking run with improved detector
  - Future: upgrade (HIKE) → M. Moulson, 11/11

THE NA62 DETECTOR



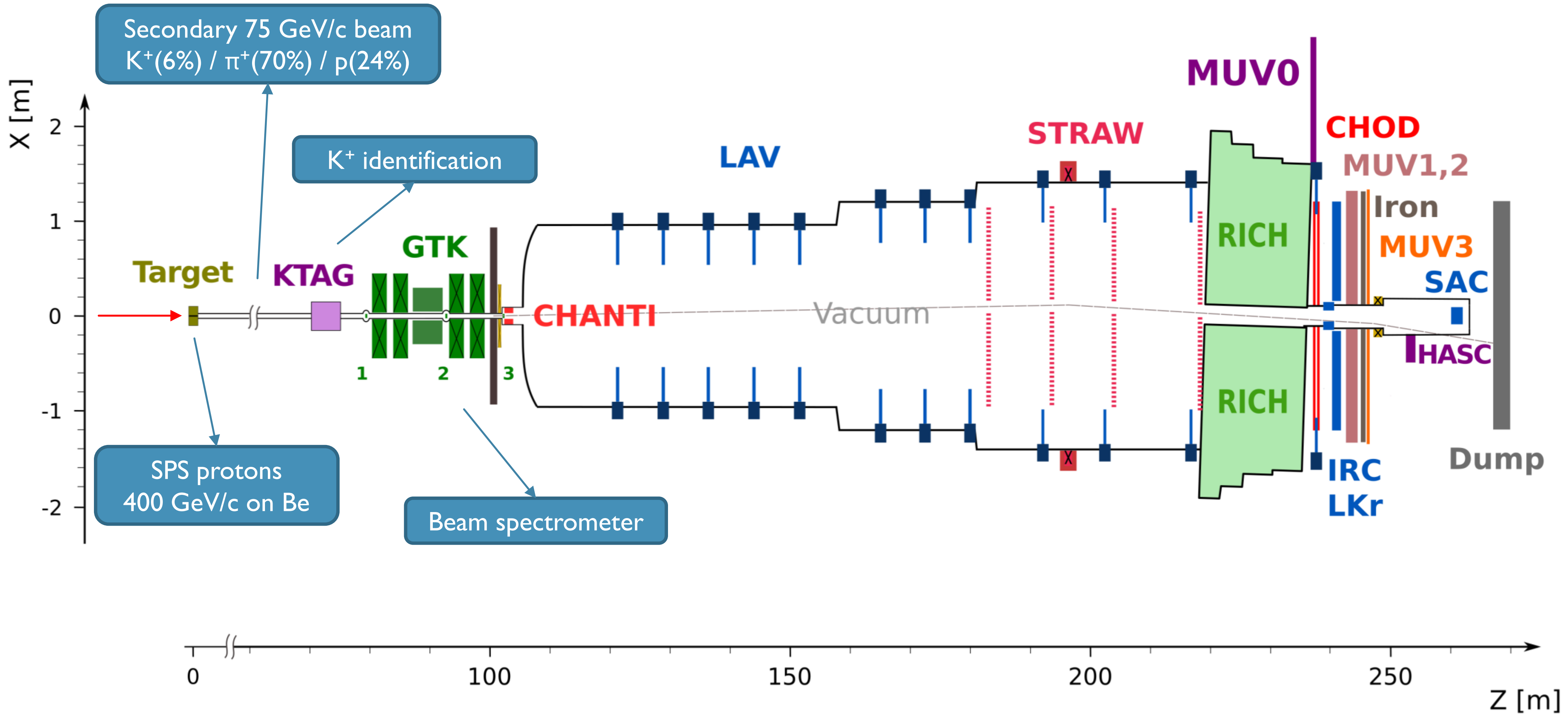
JINST 12 (2017) P05025

THE NA62 DETECTOR



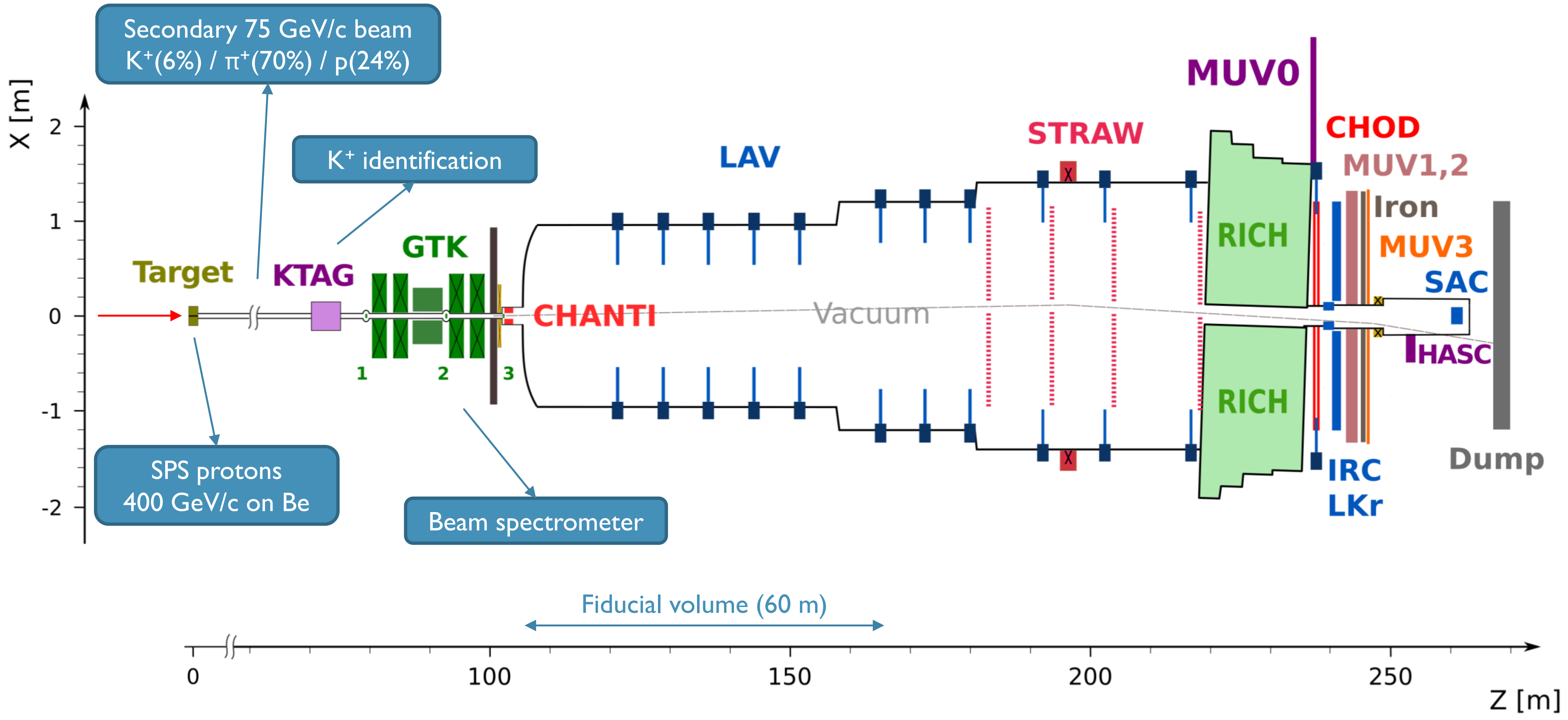
JINST 12 (2017) P05025

THE NA62 DETECTOR



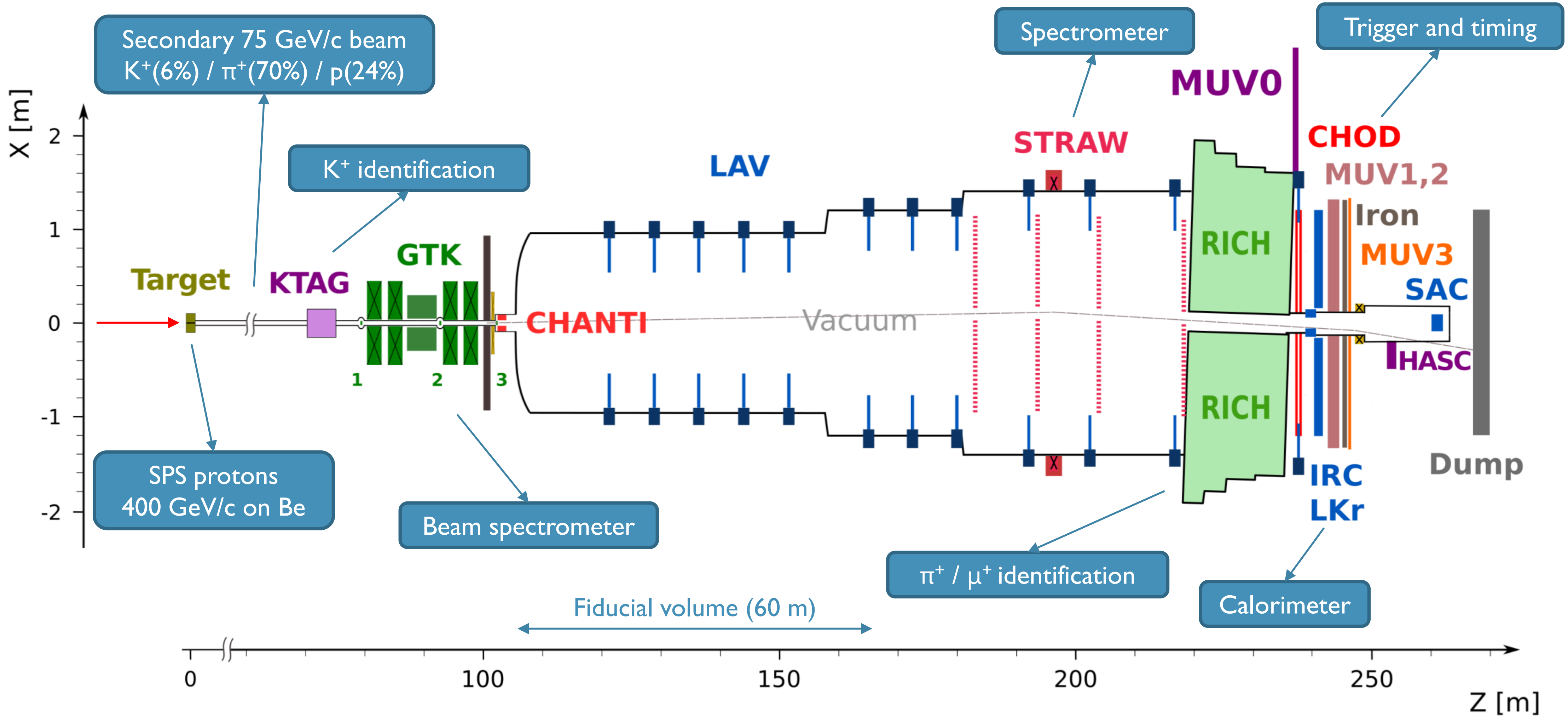
JINST 12 (2017) P05025

THE NA62 DETECTOR



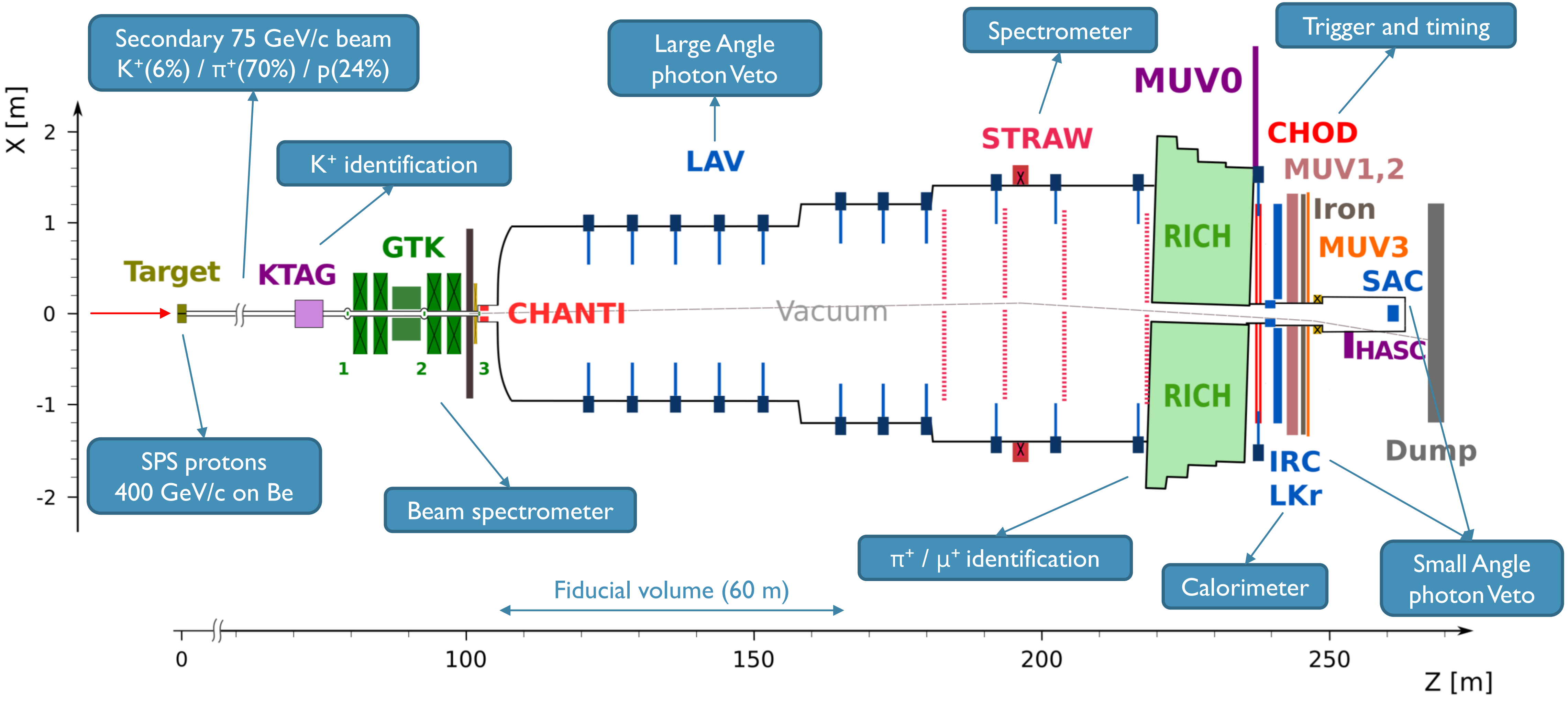
JINST 12 (2017) P05025

THE NA62 DETECTOR



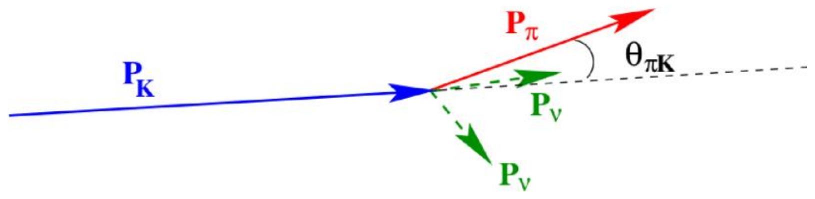
JINST 12 (2017) P05025

THE NA62 DETECTOR

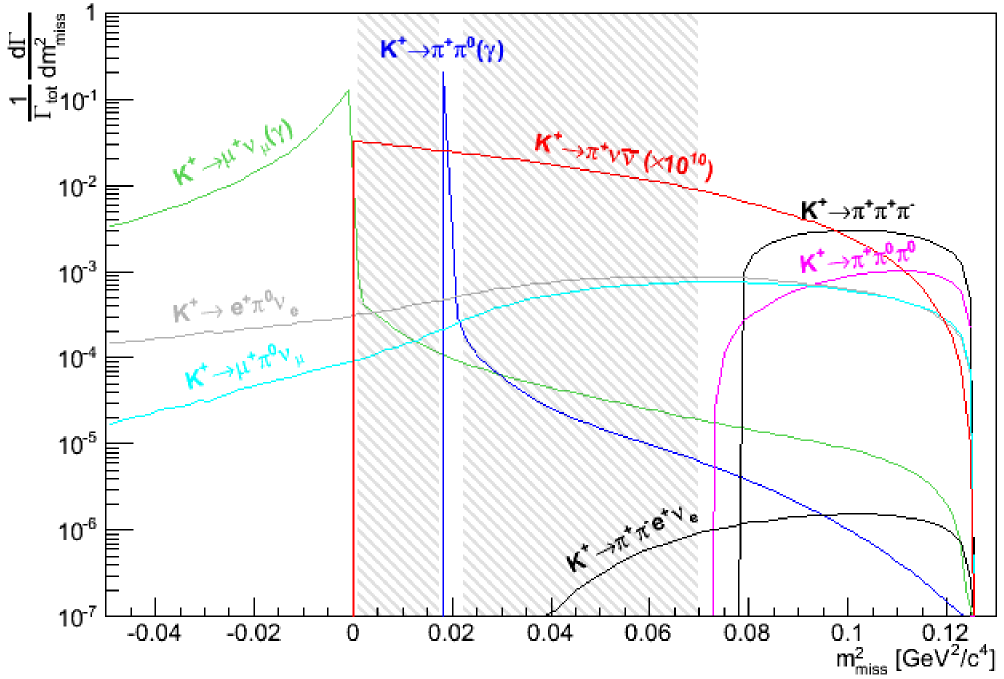


JINST 12 (2017) P05025

ANALYSIS STRATEGY



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



Main K^+ (bkg) decay modes	BR
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	64×10^{-2}
$K^+ \to \pi^+\pi^0$ ($K_{2\pi}$)	21×10^{-2}
$K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)	5.6×10^{-2}
$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4})	4.3×10^{-5}

Keystones

- Momentum range: $15 < P_\pi < 45$ GeV/c
- Blind analysis
- 7 categories depending on hardware and momentum
- MVA used for particle ID and upstream bkg rejection
- Kinematic suppression $O(10^4)$
- Muon rejection $O(10^7)$
- π^0 rejection $O(10^7)$
- Excellent time resolution O(100 ps)

SINGLE EVENT SENSITIVITY

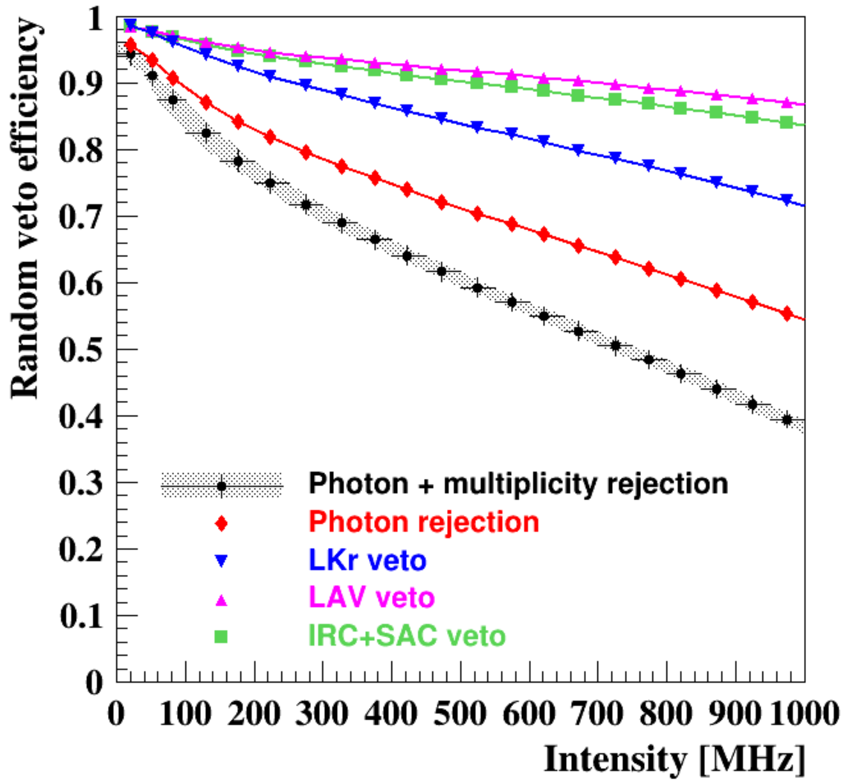
$$N^{exp}_{\pi\nu\nu} = N_{\pi\pi}\, \varepsilon^{PNN}_{trig}\, \varepsilon_{RV} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

$$SES = \frac{BR(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

	Subset S1 *	Subset S2 *
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
ϵ^{PNN}_{trig}	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N^{exp}_{\pi\nu\bar{\nu}}$	$1.56 \pm 0.10 \pm 0.19_{ext}$	$6.02 \pm 0.39 \pm 0.72_{ext}$

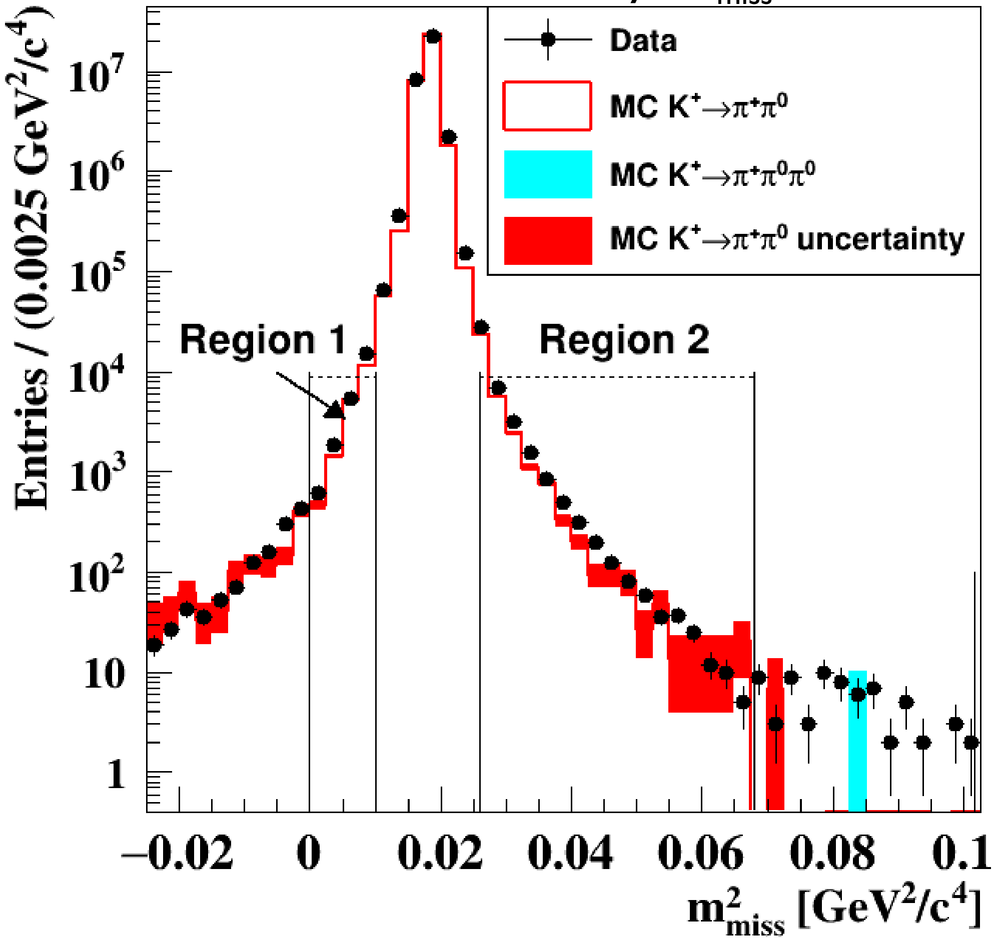
* different hardware configurations

- $K^+ \to \pi^+ \pi^0$ normalization channel
- Cancellation of systematic effects
- Random Veto: efficiency loss due to extra activity



BACKGROUND FROM K^+ DECAYS

Control $\pi^+ \pi^0$ data to study m^2_{miss} distribution



Number of events in $\pi^+ \pi^0$ region after $\pi\nu\nu$ selection

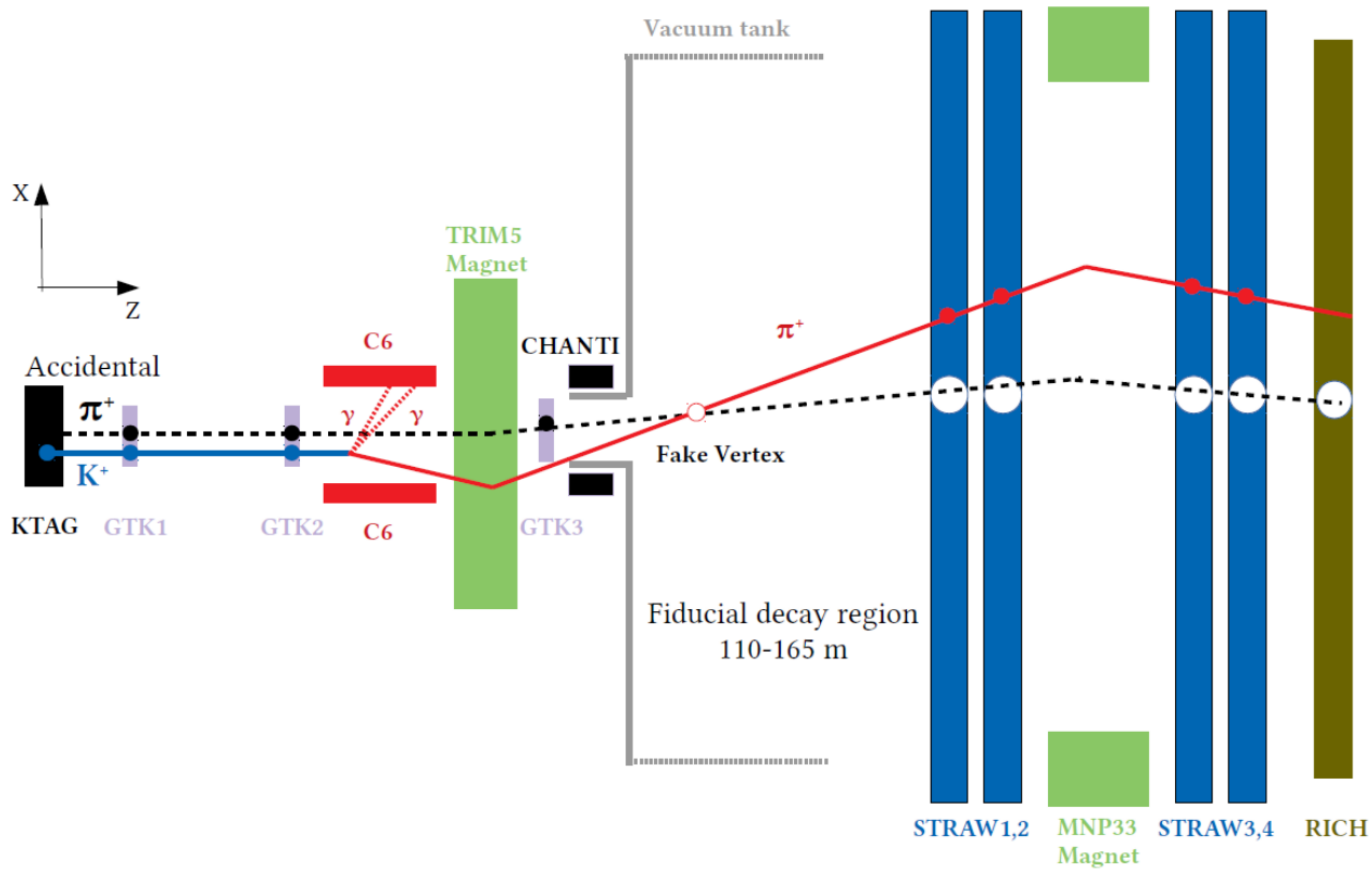
$$N^{exp}_{\pi\pi}(SR) = N(\pi^+\pi^0)\ f_{kin}(SR)$$

Expected $K^+ \to \pi^+ \pi^0$ events in signal region

Fraction of $\pi^+ \pi^0$ in signal region, measured on control data

- $K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \pi^+ \pi^+ \pi^-$ backgrounds: similar procedure
- $K^+ \to \pi^+ \pi^- e^+ \nu_e$ evaluated with MC simulations
- Validation with control regions

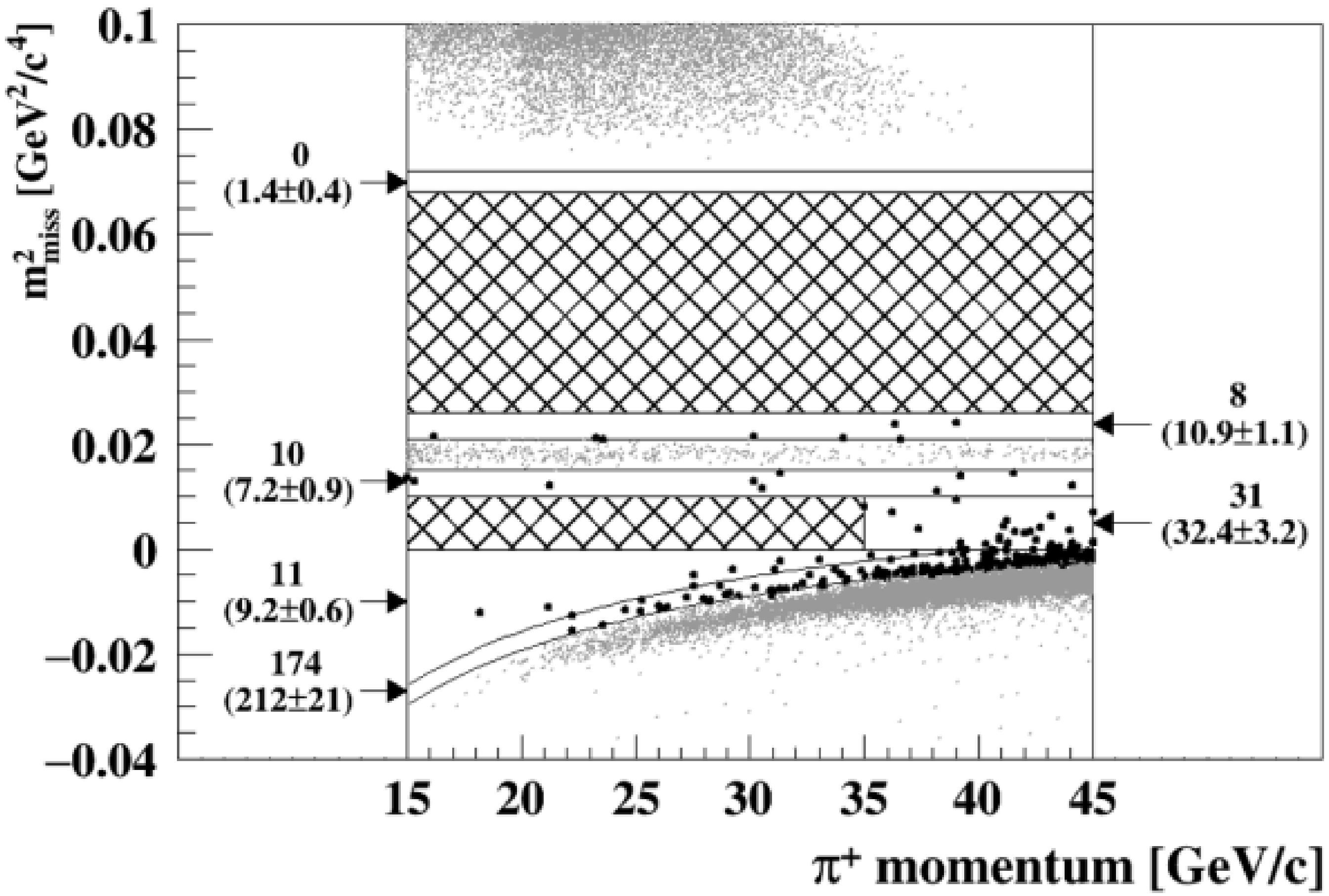
UPSTREAM BACKGROUND



- Pions produced upstream of the fiducial volume
  - Early kaon decays
  - Interaction of beam particles with beam spectrometer material
- Fake association of detected pions to accidental particles

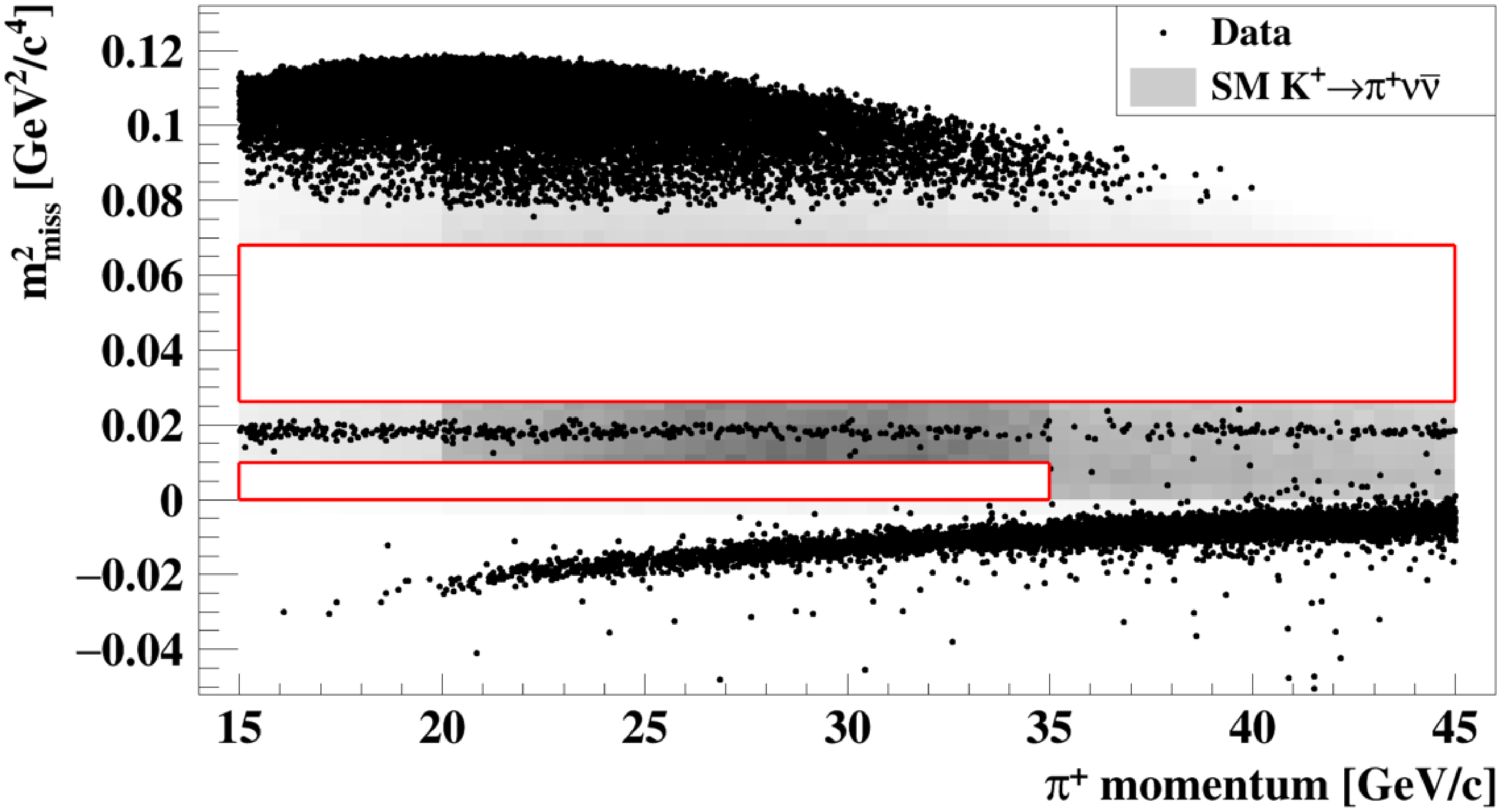
- New collimator installed in June 2018
- Geometrical cuts & BDT cut on backtracked pion position
- Kaon-pion association effective
- Data-driven background estimation

EXPECTED BACKGROUND SUMMARY

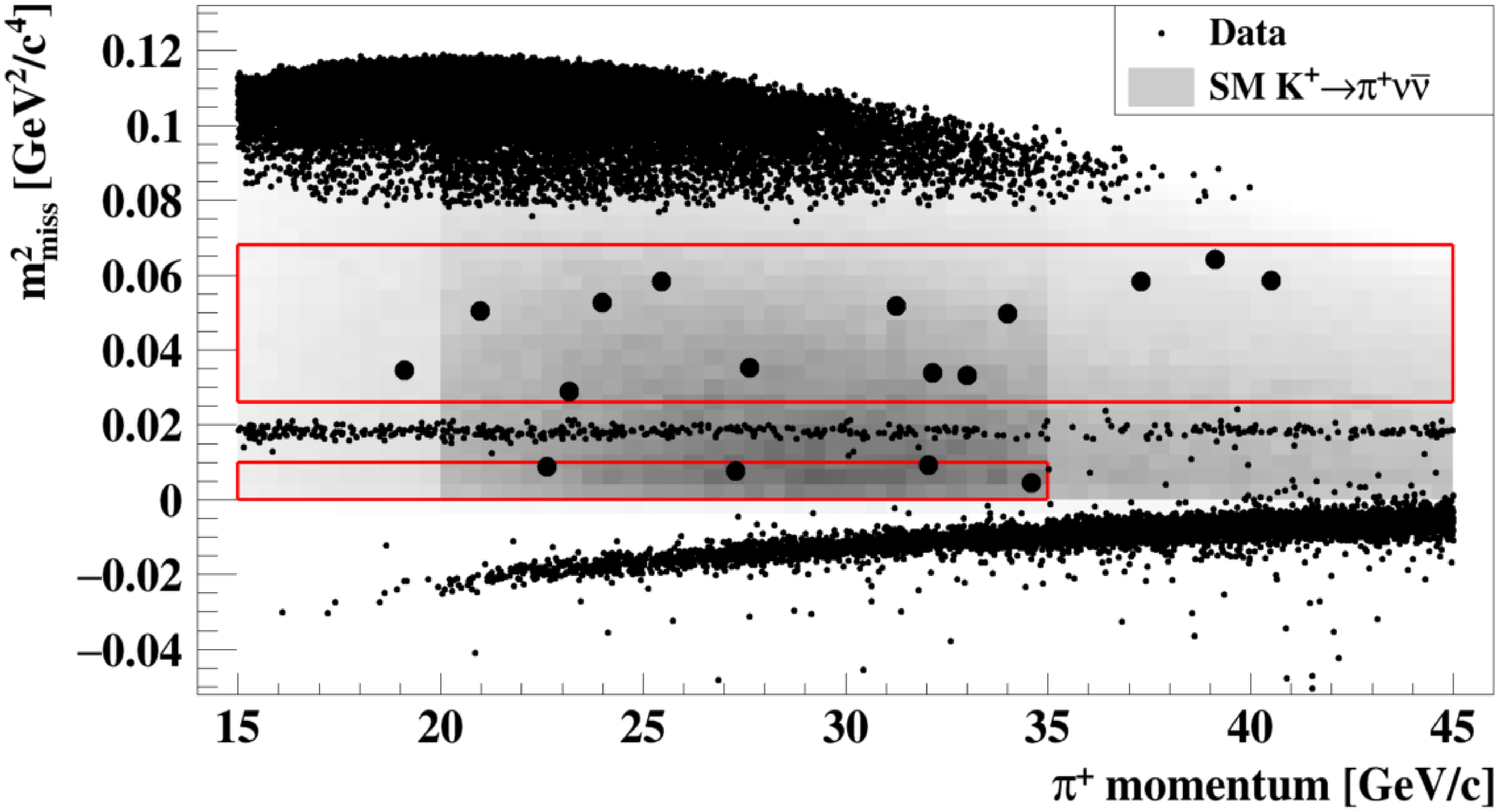


Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^- e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

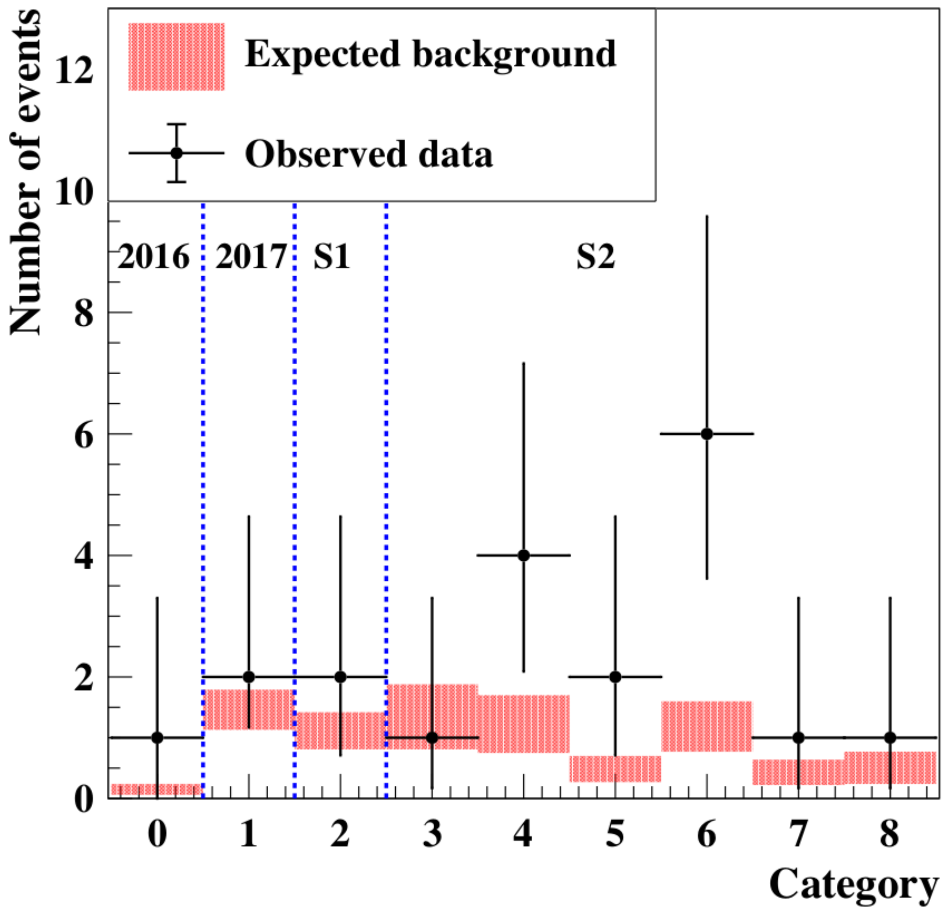
2018 DATA: BEFORE UNBLINDING



2018 DATA: AFTER UNBLINDING



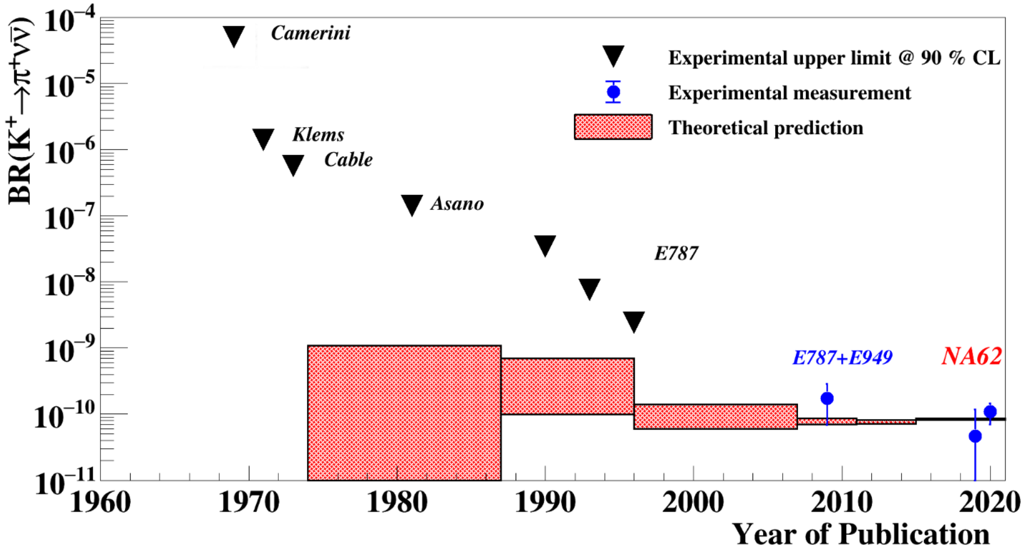
2016+2017+2018 RESULT SUMMARY



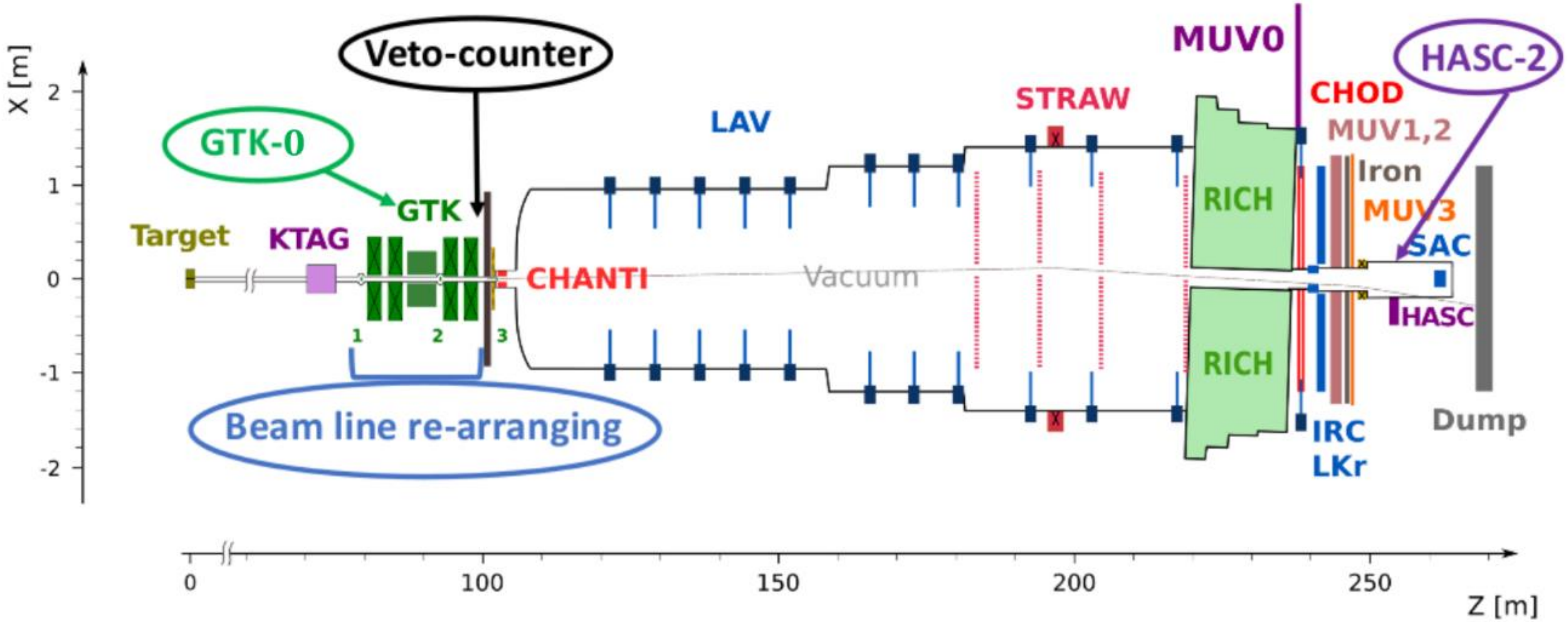
- Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$
- Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})^{NA62}_{16+17+18} = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

JHEP 06 (2021) 093



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ BETWEEN 2021 AND LS3



- Improvements in LKr reconstruction
- Optimizations in the analysis: random veto stable, background rejection, acceptance increased

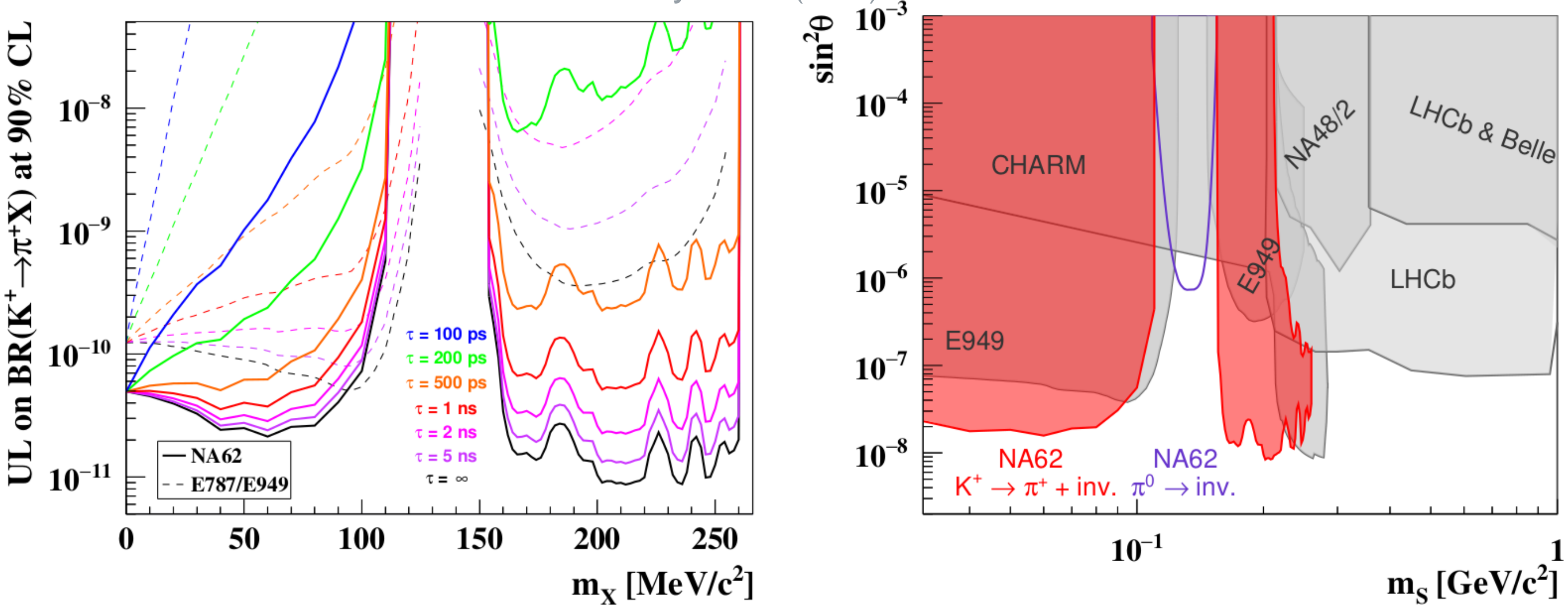
- Additional GTK station
- Beam line re-arranging to swipe away upstream π^+
- New VetoCounter to detect upstream decays
- HASC-2 to further suppress $K^+ \rightarrow \pi^+ \pi^0$ decays
- Intensity increased from 60% to 100% of nominal

Goal: reach O(10%) precision by LS3

SEARCH FOR $K^+ \to \pi^+ X$

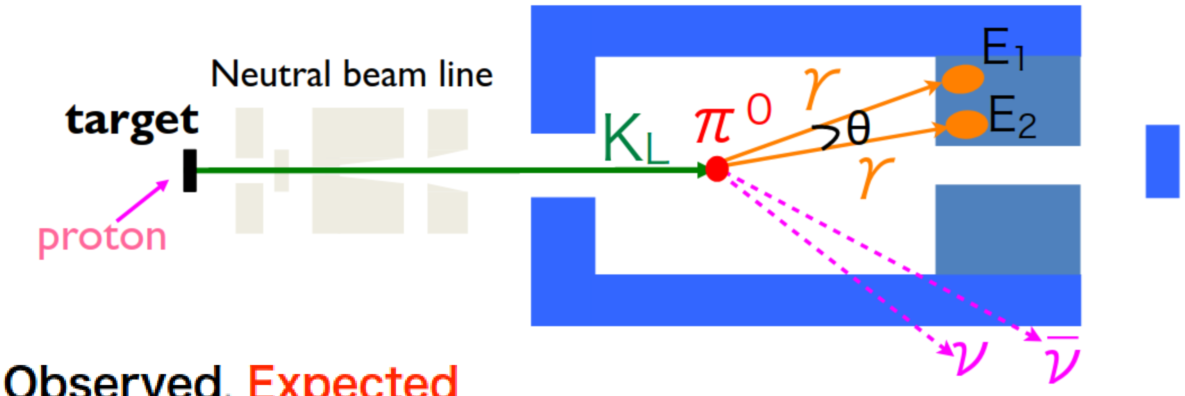
- Peak search in m^2_{miss} distribution
- Width from resolution
- Main background: SM $K^+ \to \pi^+ \nu\bar{\nu}$
- Acceptance from MC simulation

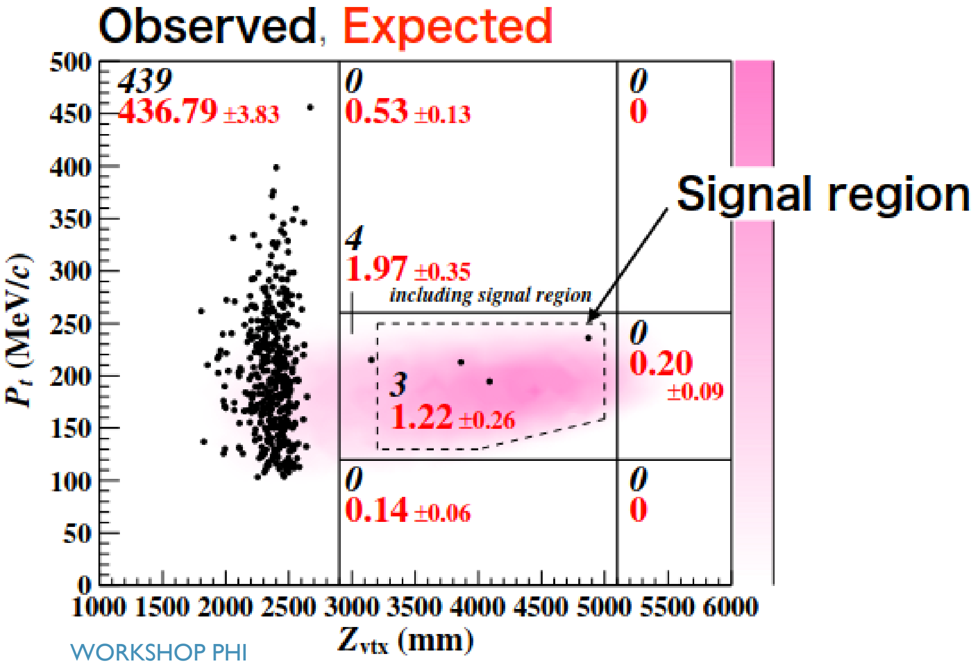
JHEP 06 (2021) 093



- Limits with finite lifetime: assume decay to visible particles in geometric acceptance
- Interpretation in dark scalar model with mixing with Higgs ($\sin^2\theta$)

$K_L \to \pi^0\nu\bar{\nu}$: THE KOTO EXPERIMENT AT J-PARC





2015 dataset Phys.Rev.Lett. 122, 021802

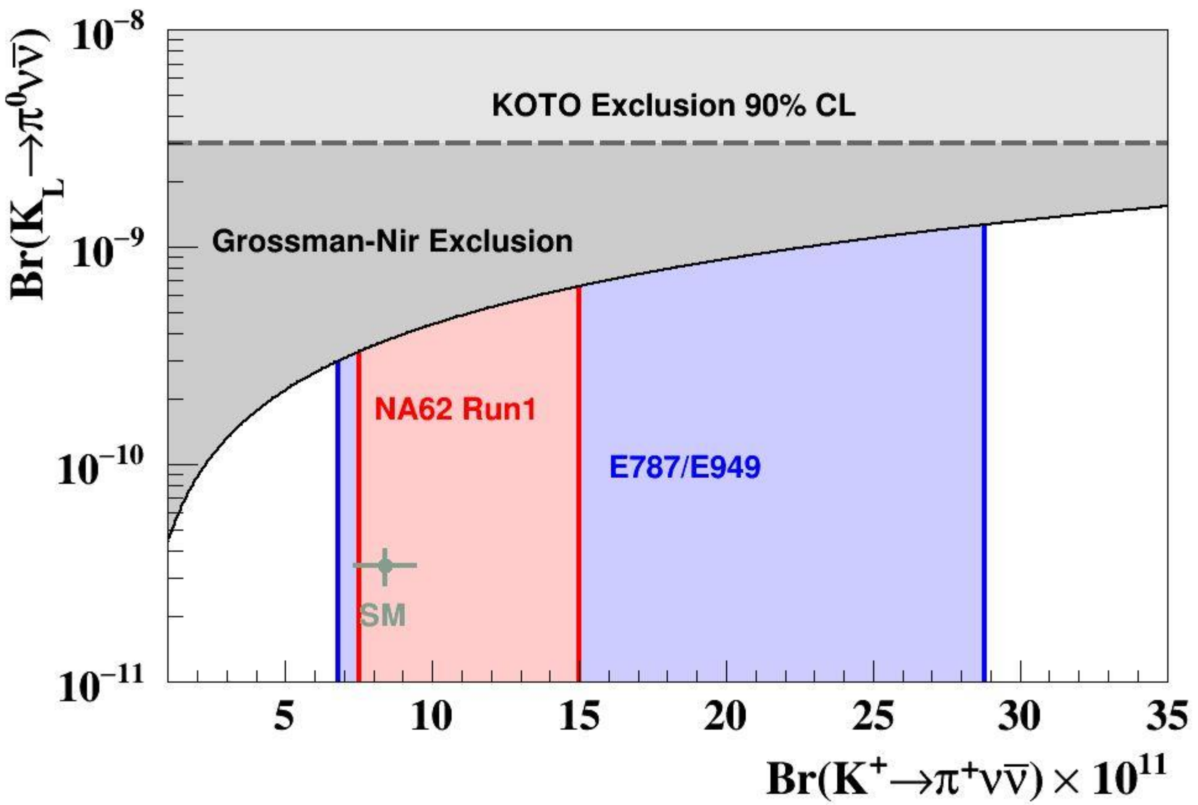
- SES = $(1.30 \pm 0.01_{stat} \pm 0.14_{syst}) \times 10^{-9}$
- 0 observed events
- BR($K_L \to \pi^0\nu\bar{\nu}$) < 3.0×10^{-9} @ 90% C.L.

2016 – 2018 dataset Phys.Rev.Lett. 126, 121801

- SES = $(7.20 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$
- 3 observed events
- 1.22 ± 0.26 expected background events
- BR($K_L \to \pi^0\nu\bar{\nu}$) < 4.9×10^{-9} @ 90% C.L.

SUMMARY & OUTLOOK

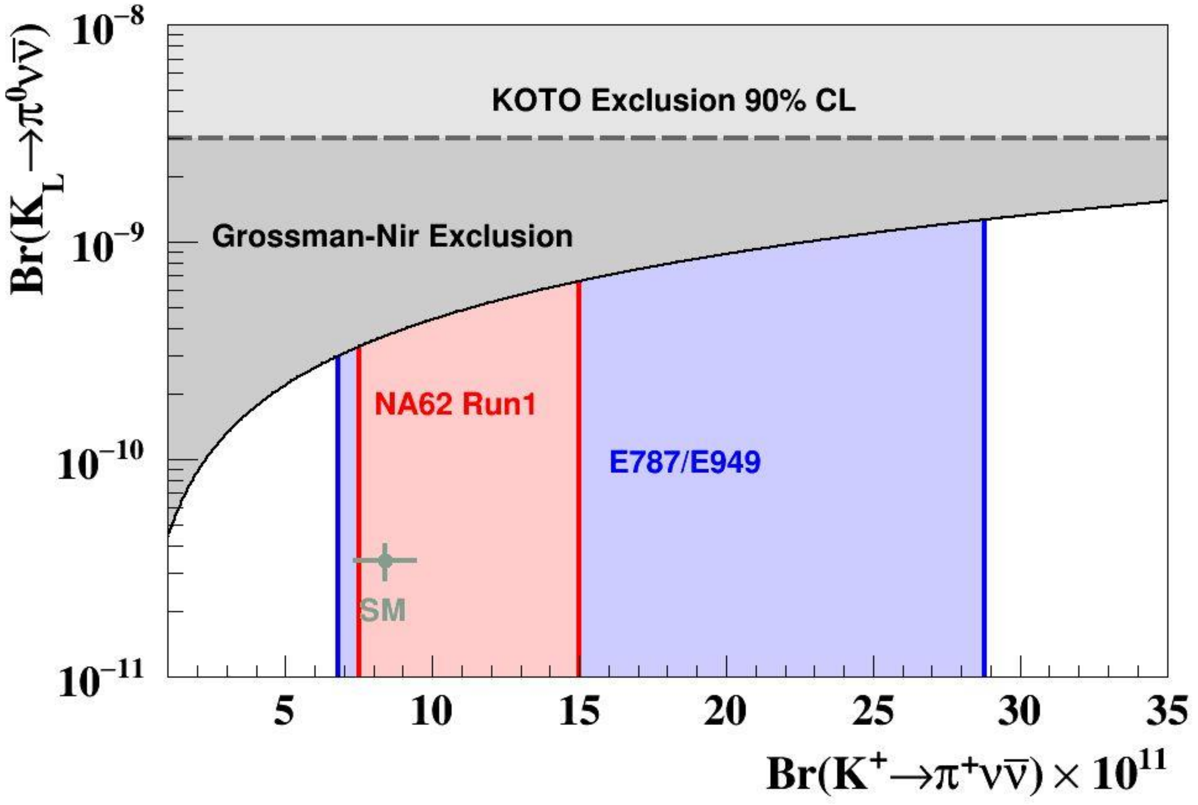
- NA62 Run 1 result:
  $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$
- Most precise measurement ever of $BR(K^+ \to \pi^+ \nu\bar{\nu})$
- First observation of this ultra-rare decay (3.4σ significance)



- Run 2: improved detector, increased intensity
- More precision is needed!

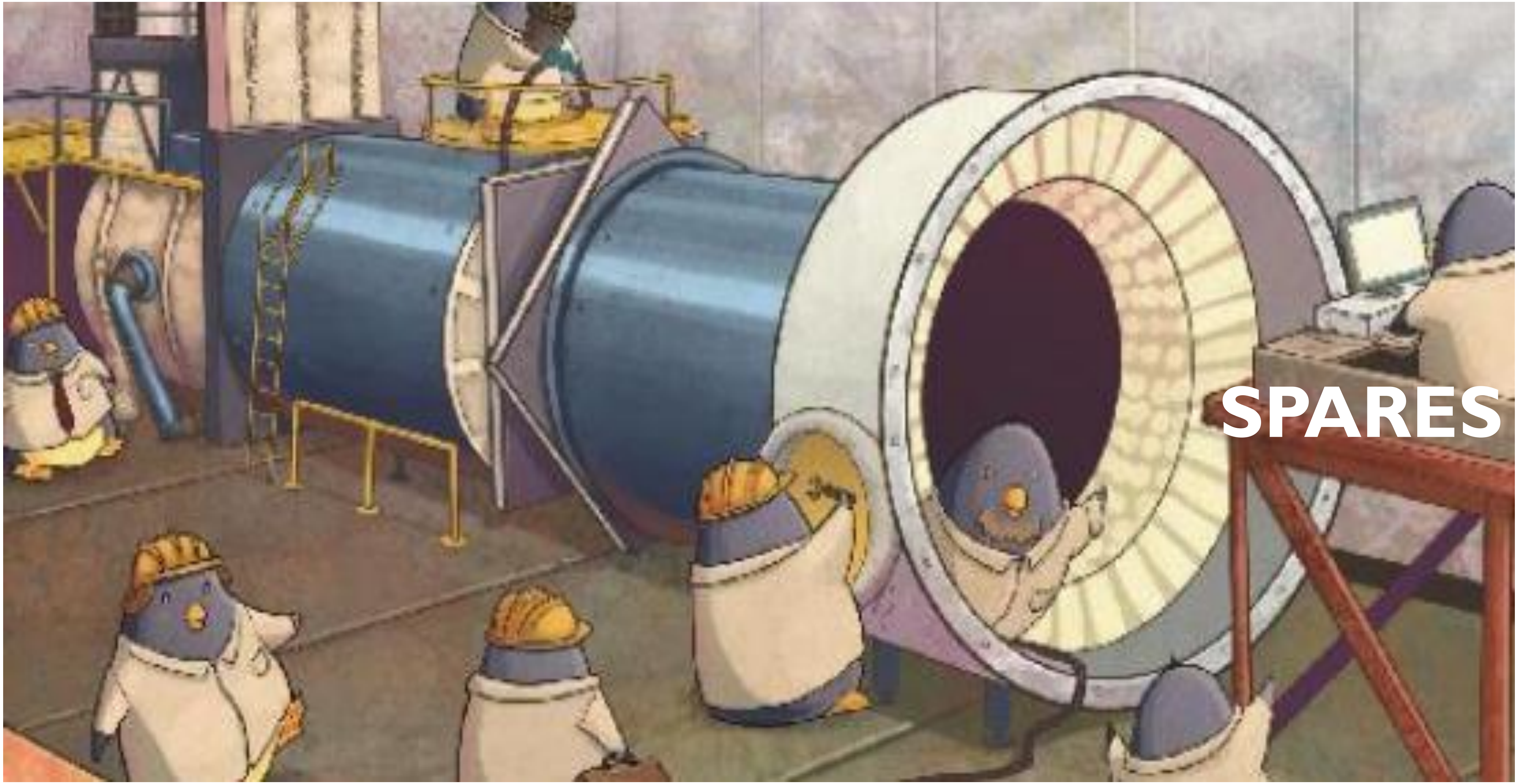
SUMMARY & OUTLOOK

- NA62 Run 1 result:
  $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$
- Most precise measurement ever of $BR(K^+ \to \pi^+ \nu\bar{\nu})$
- First observation of this ultra-rare decay (3.4σ significance)



- Run 2: improved detector, increased intensity
- More precision is needed!

THANK YOU!



SPARES

RECENT THEORETICAL PROGRESS

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$$

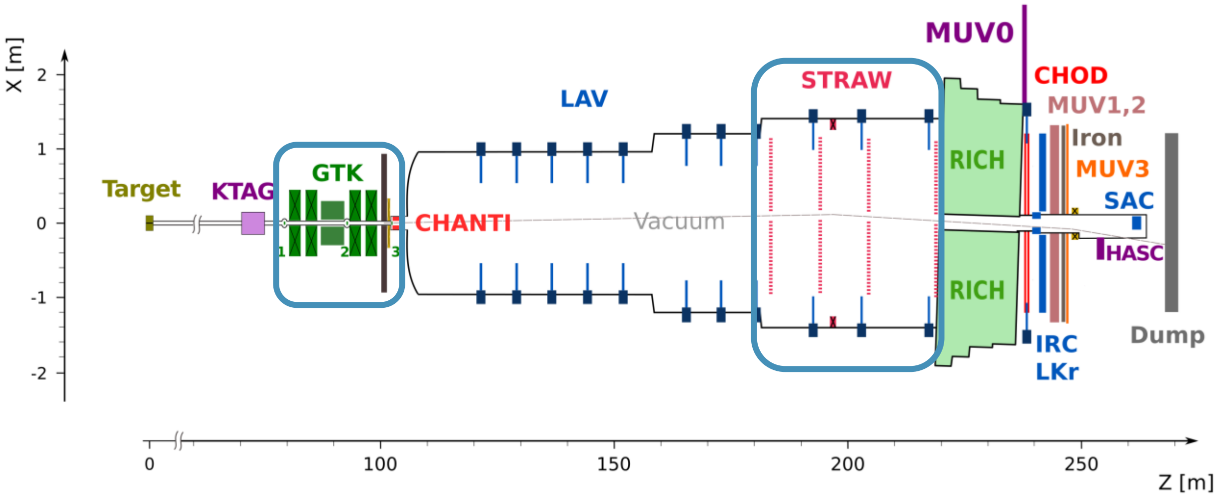
Acta Phys. Polon. B 53.6 (2021) A1

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (7.73 \pm 0.61) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.59 \pm 0.29) \times 10^{-11}$$

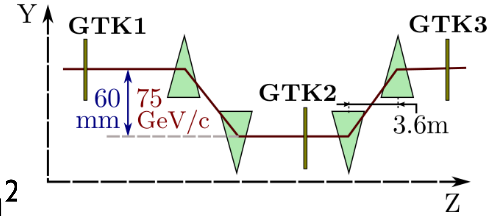
PoS BEAUTY2020 (2021) 056

NA62 DETECTOR



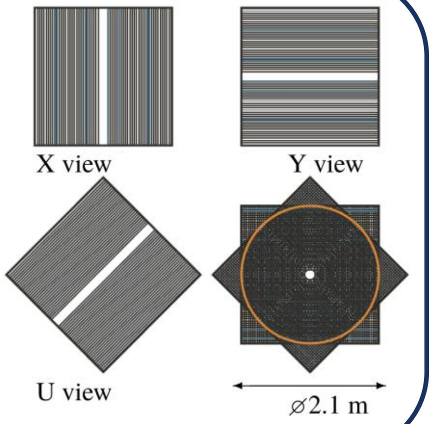
GigaTracKer

- 3 stations
- Si pixel size 300 × 300 μm^2
- σ_p / p = 0.2%, σ_θ = 16μrad, σ_t = 100 ps

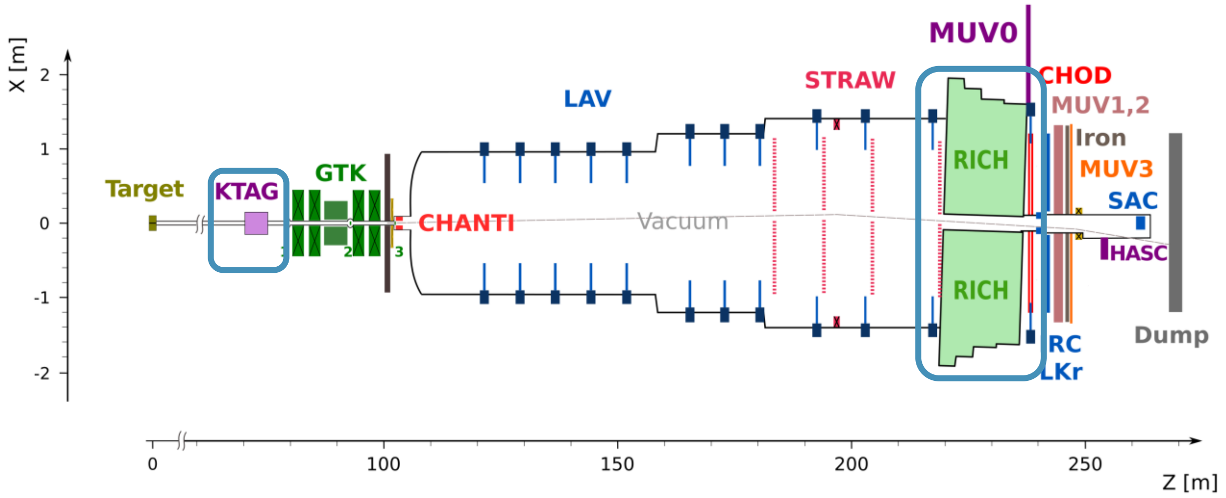


STRAW

- 4 straw tube chambers
- 4 views each
- $\sigma_p/p = 3\times10^{-3} \oplus 5\times10^{-5}\text{GeV}^{-1}\, p$
- $\sigma_\theta/\mu\text{rad} = 10 + 500\ \text{GeV}/p$



NA62 DETECTOR



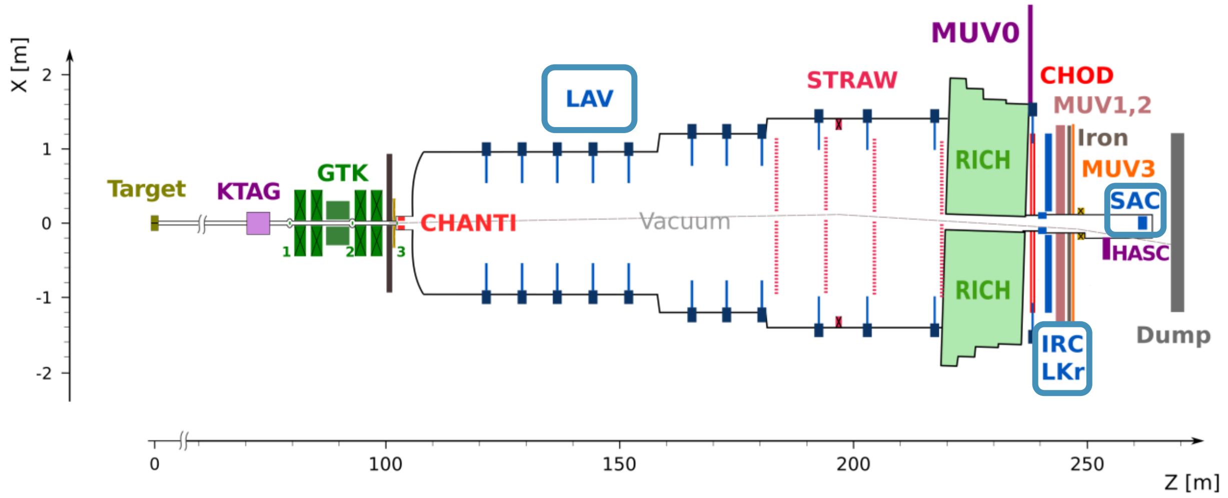
Kaon TAGger

- Differential Cherenkov counter
- 5 m long vessel
- N_2 at 1.75 bar
- σ_t = 70 ps

Ring Imaging CHerenkov counter

- Differential Cherenkov counter
- Ne at atmospheric pressure
- σ_t = 100 ps

NA62 DETECTOR



Large-Angle Veto

- 12 stations
- EM calorimeters (PbO 75%)
- Hermetic for photons between 10 and 50 mrad

LKr

- Photons emitted between 1 and 10 mrad + particle ID
- σ_E / E = 1.4% for E ~ 25 GeV
- $\sigma_{X,Y}$ ~ 1mm
- σ_t ~ 0.5 to 1 ns

Small-Angle Veto

- IRC + SAC
- Ensure hermeticity for photons down to 0°