The NA62 Kaon Factory

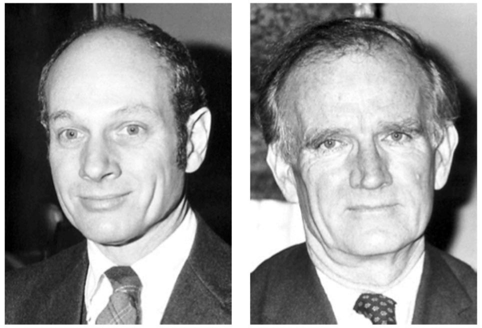
DANIELSSON HANS , OCTOBER 9 2023

Content

- Kaon history
- Motivation and Requirements
- Choice of detector layout
- The beam
- Detector performance and a few examples
- Present results
- Future

Kaons have been very important in high-energy physics

CP violation

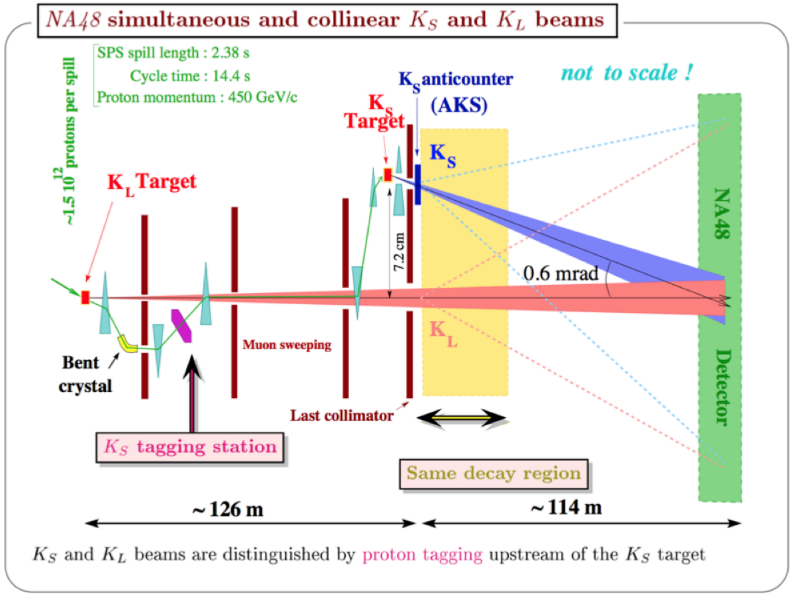


James Cronin (left)
and
Val Fitch (right)

- Nobel price in 1980 for the discovery of violations of fundamental symmetry principles in the decays of neutral K-mesons

Measuring ε'/ε: NA48@CERN

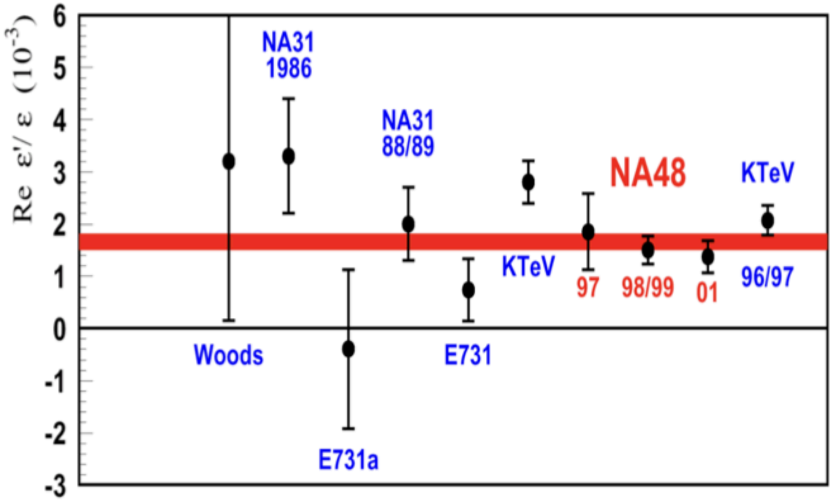
CP violation in neutral kaon decays



Rare Kaon Decays:

$K^+ \longrightarrow \pi^+ \overline{\nu} \nu$: NA62 at CERN

ε′/ε Timeline & Recognitions



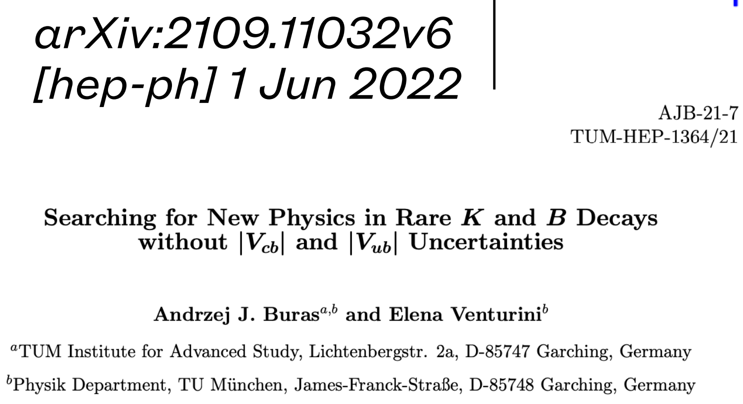
Italo Mannelli and Heinrich Wahl

EPS Young Physicist Prize 2003: G. Unal
EPS High Energy and Particle Physics Prize 2005: Heinrich Wahl and the NA31 Collaboration
APS Panofsky prize 2007: I. Mannelli, H. Wahl and B. Winstein

Physics Motivation & Strategy

- While the **energy frontier** is limited by the reach of the **Large Hadron Collider (LHC)** in terms of centre-of-mass energy, no such limitation exists in principle for **rare decays**, making them a highly valued complementary approach in the search for new phenomena.
- The choice of the **decay-in-flight technique** is motivated by the possibility of obtaining an integrated flux of $\mathcal{O}(10^{13})$ kaon decays over a few years of data-taking. **CERN SPS** is a unique tool for this task

The K → π $\nu\nu$ decays: a theoretical clean environment



arXiv:2109.11032v6 [hep-ph] 1 Jun 2022

AJB-21-7
TUM-HEP-1364/21

Searching for New Physics in Rare K and B Decays without $|V_{cb}|$ and $|V_{ub}|$ Uncertainties

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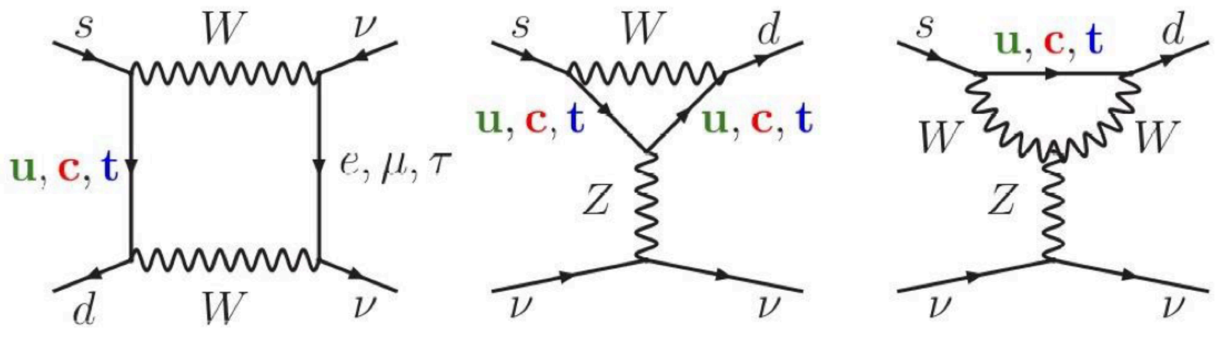
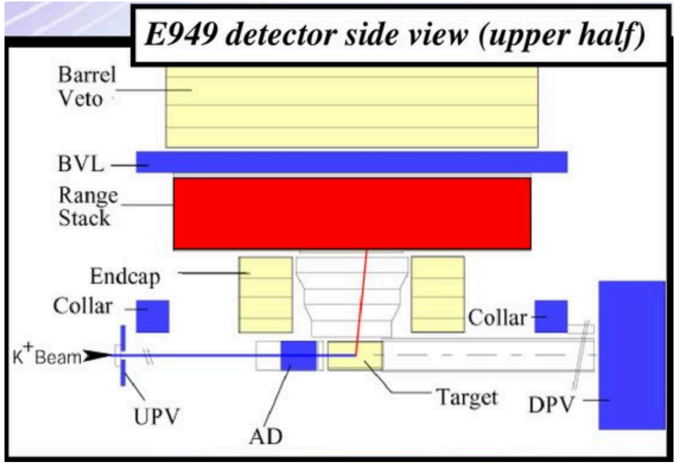
FCNC loop processes: s→d coupling and highest CKM suppression

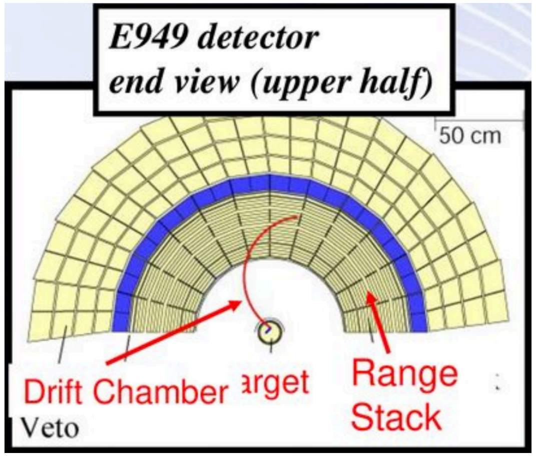


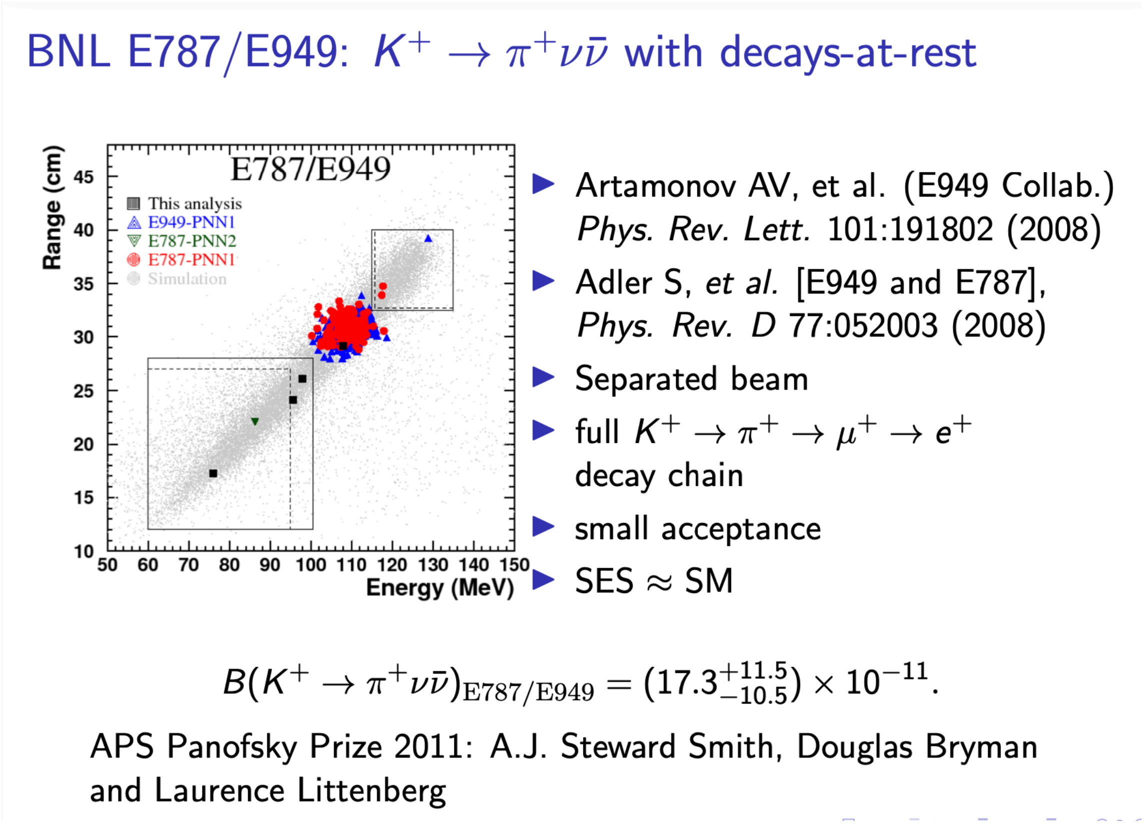
Very clean theoretically: Short distance contribution. No hadronic uncertainties

- Recent most accurate estimate of the branching ratio:
- $B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$

$K \to \pi \nu\nu$ Prior to NA62 decays at rest E787/E949







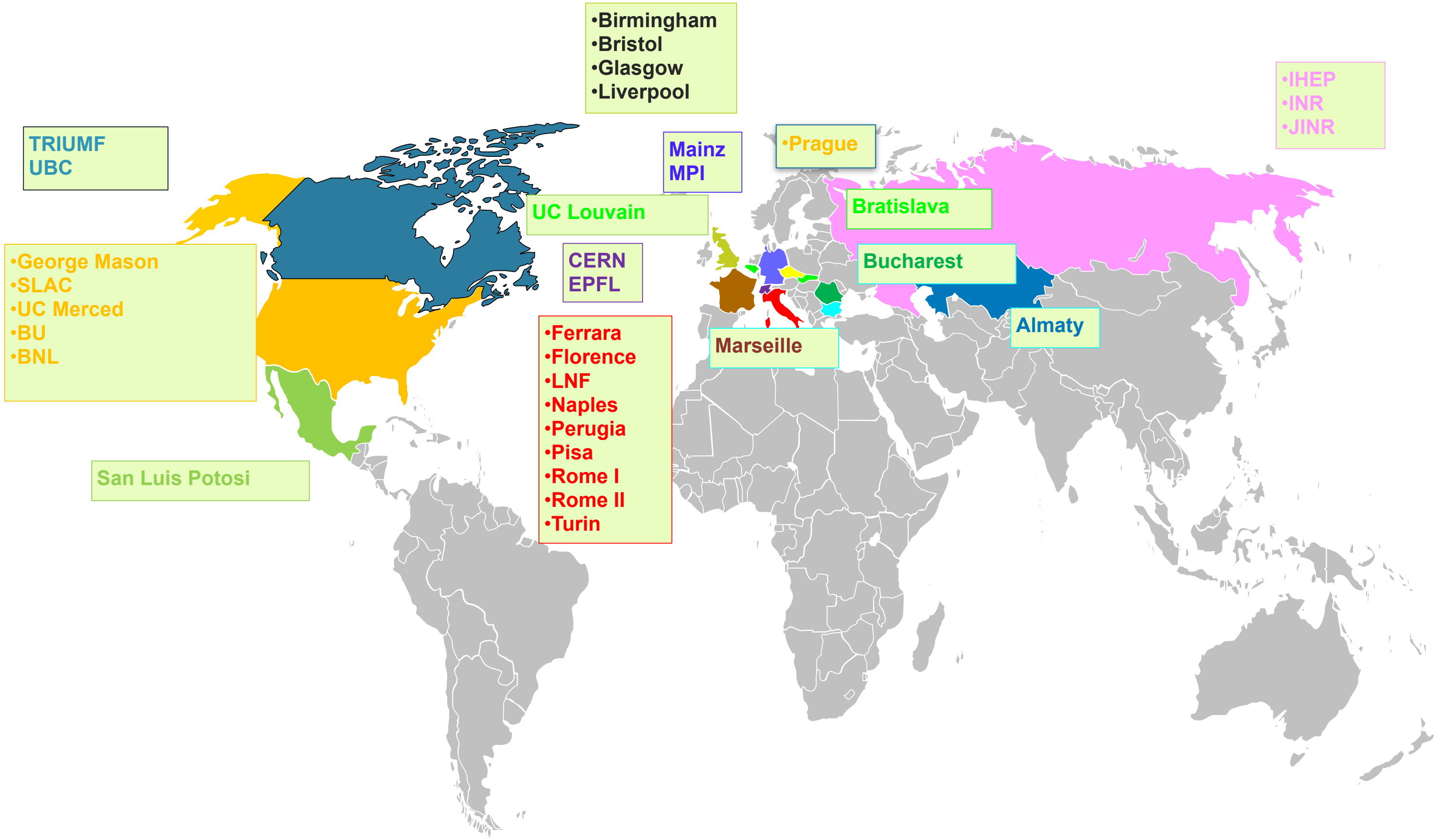
BNL E787/E949: $K^+ \to \pi^+\nu\bar\nu$ with decays-at-rest

- Artamonov AV, et al. (E949 Collab.) *Phys. Rev. Lett.* 101:191802 (2008)
- Adler S, *et al.* [E949 and E787], *Phys. Rev. D* 77:052003 (2008)
- Separated beam
- full $K^+ \to \pi^+ \to \mu^+ \to e^+$ decay chain
- small acceptance
- SES ≈ SM

$$B(K^+ \to \pi^+\nu\bar\nu)_{\mathrm{E787/E949}} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}.$$

APS Panofsky Prize 2011: A.J. Steward Smith, Douglas Bryman and Laurence Littenberg

The NA62 Collaboration



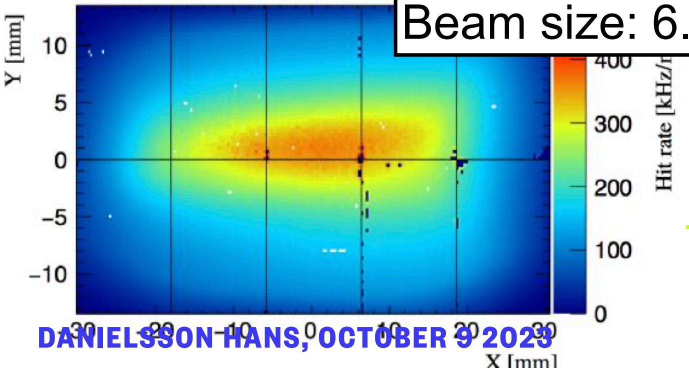
2005	Proposal
2009	Approved
2010	Technical design
2012	Technical run (partial layout)
2014	Pilot Run
2015-18	Physics Runs
2021-2025	Physics Runs

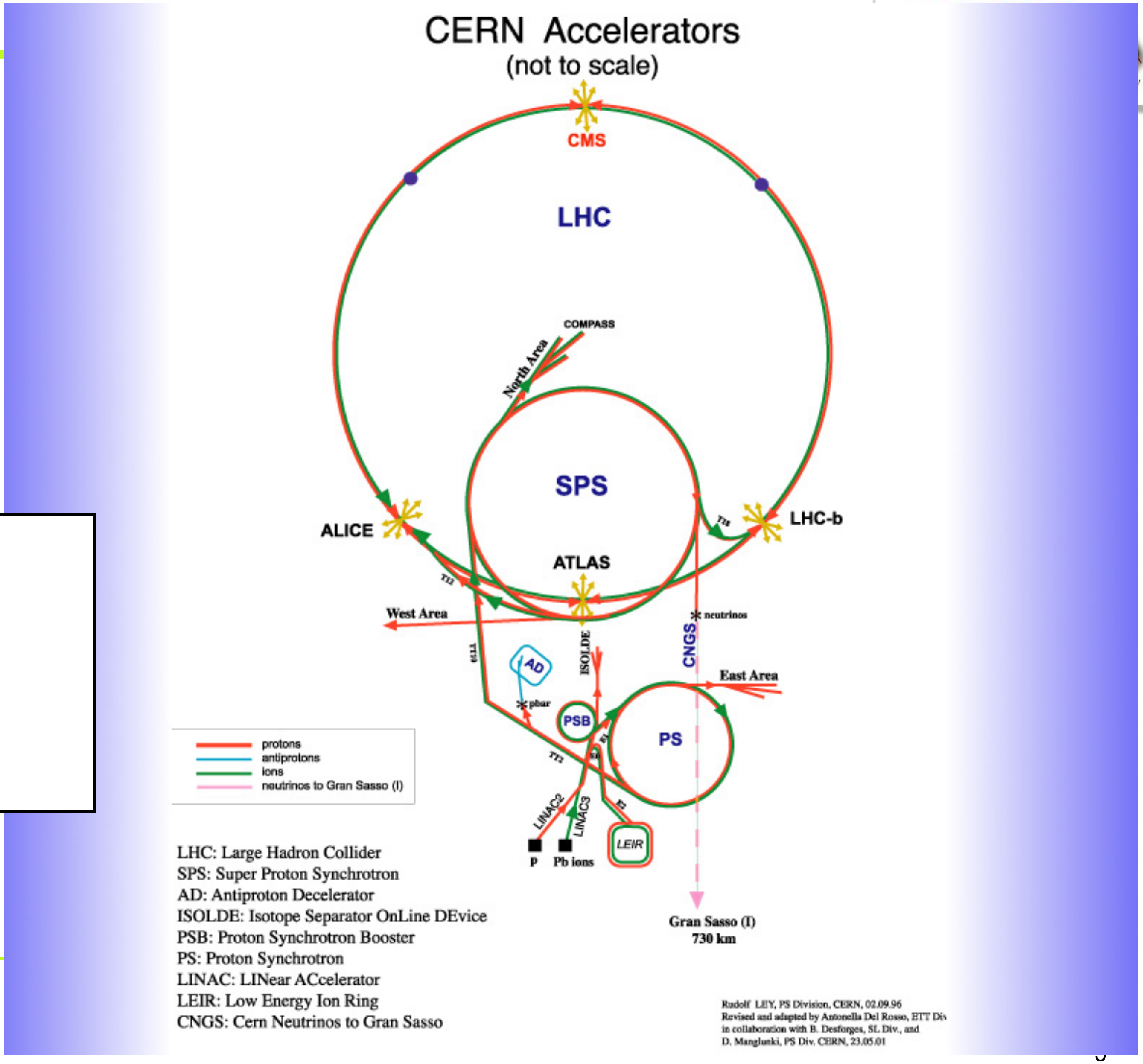
The Beam

- Given: proton beam from SPS with the energy 400 GeV 2×10^{12} p/s
- By optimisation K^+ ratio, momentum separation and acceptance we get:

Beryllium Target

Secondary beam
p=75 GeV/c
$\Delta p/p$~1%
K(6%),π(70%) p(23%)
Total: ~800 MHz
Beam size: 6.0x3cm

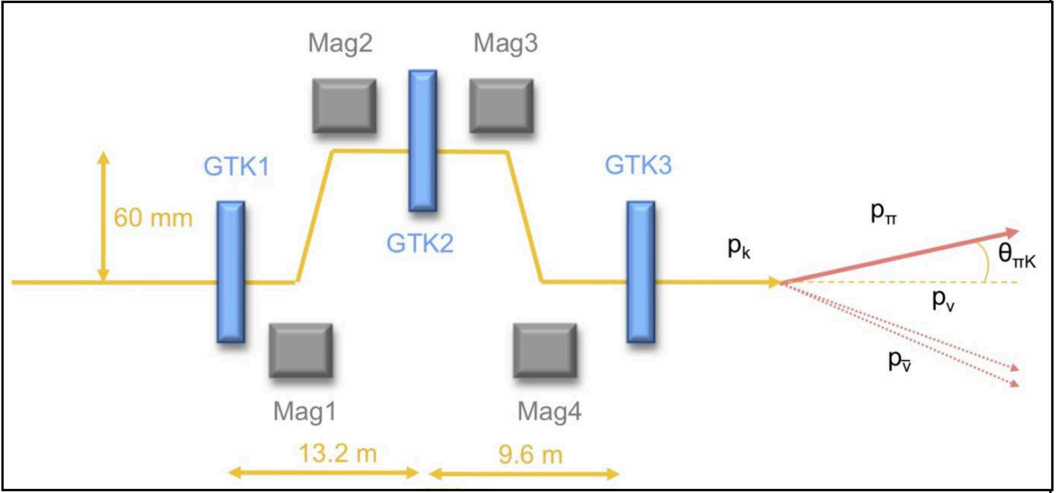


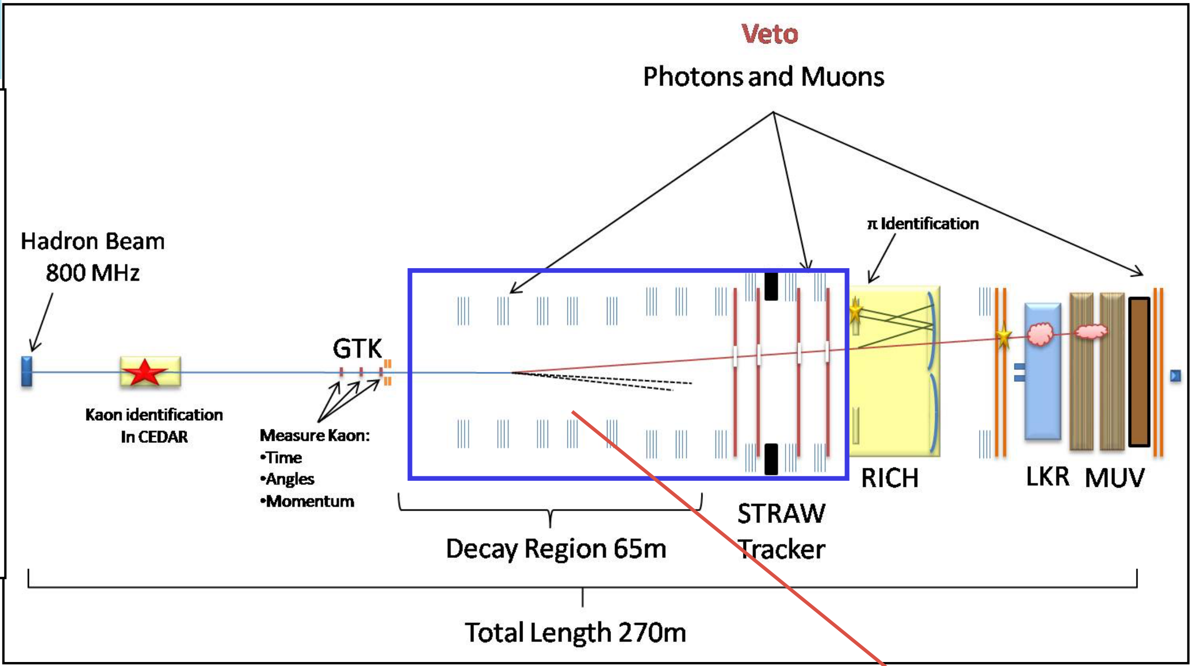


The Experimental Layout

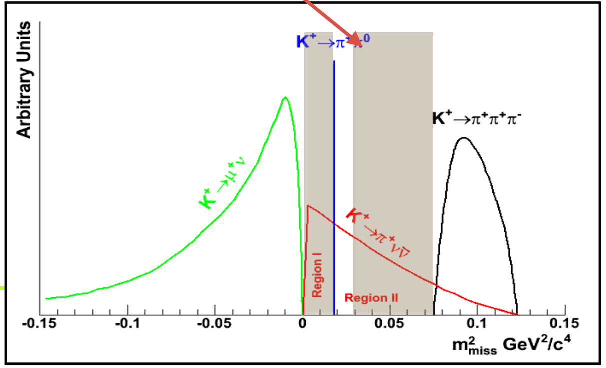
$K \to \pi \nu\nu$

GTK



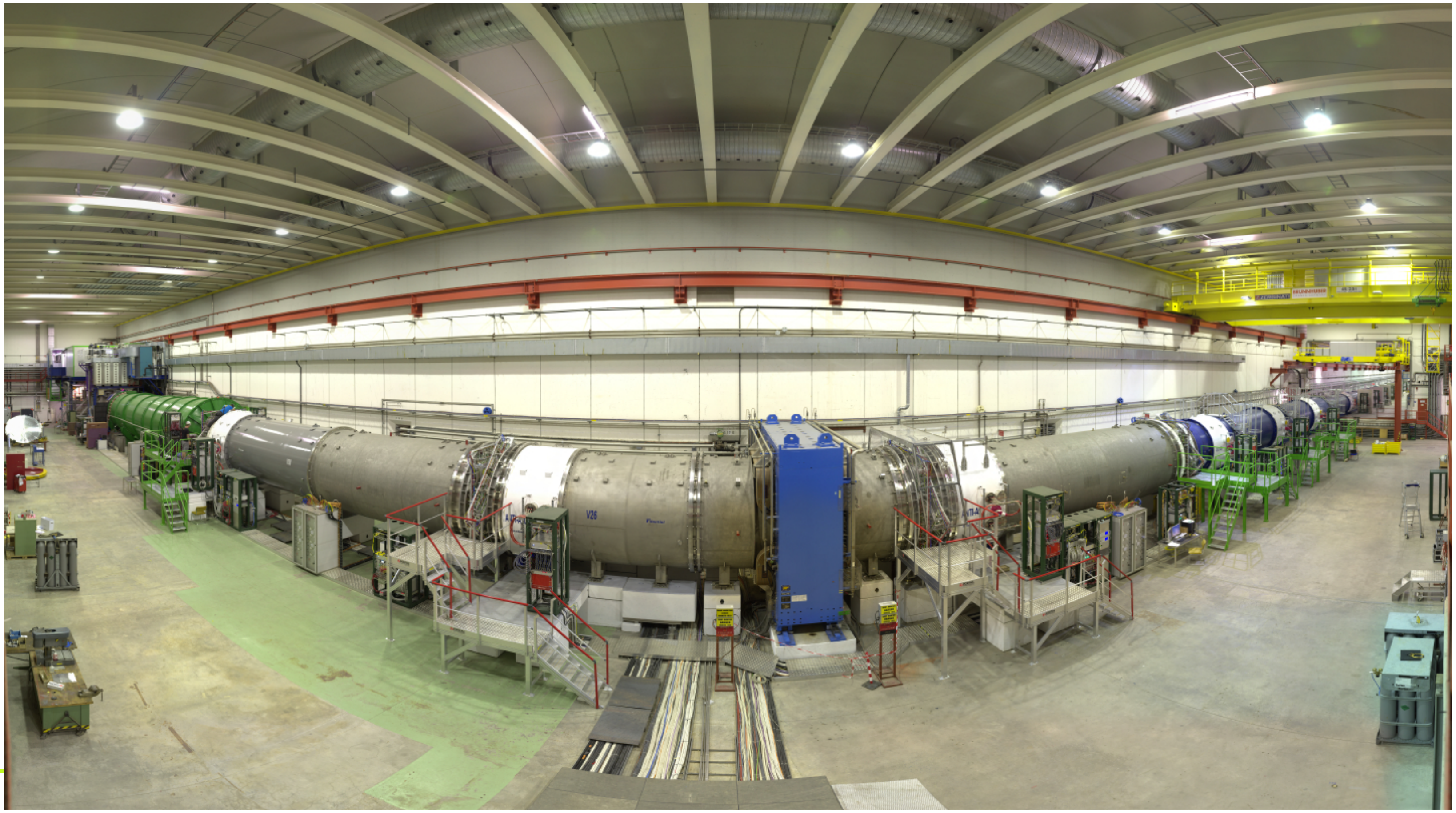


- Vertex
- Matching
- Signal in LKr and MUV
- Missing mass plot and signal region



The Experiment in the ECN3 Hall

- Different types of detectors in NA62:
  - Tracking and PID:
    - **KTAG, GTK, Straw Spectrometer,** CHOD, **RICH**
  - Veto detectors:
    - MUV, **LKR, LAV**, SAC, IRC



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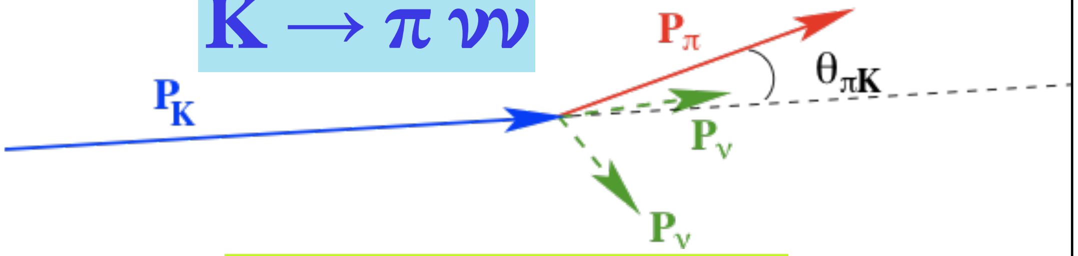
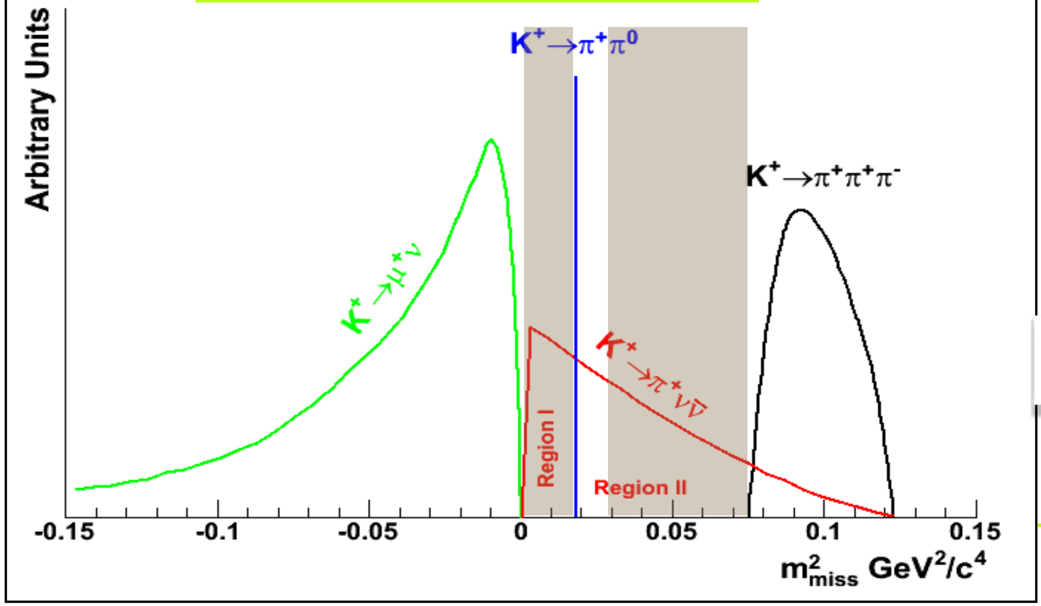
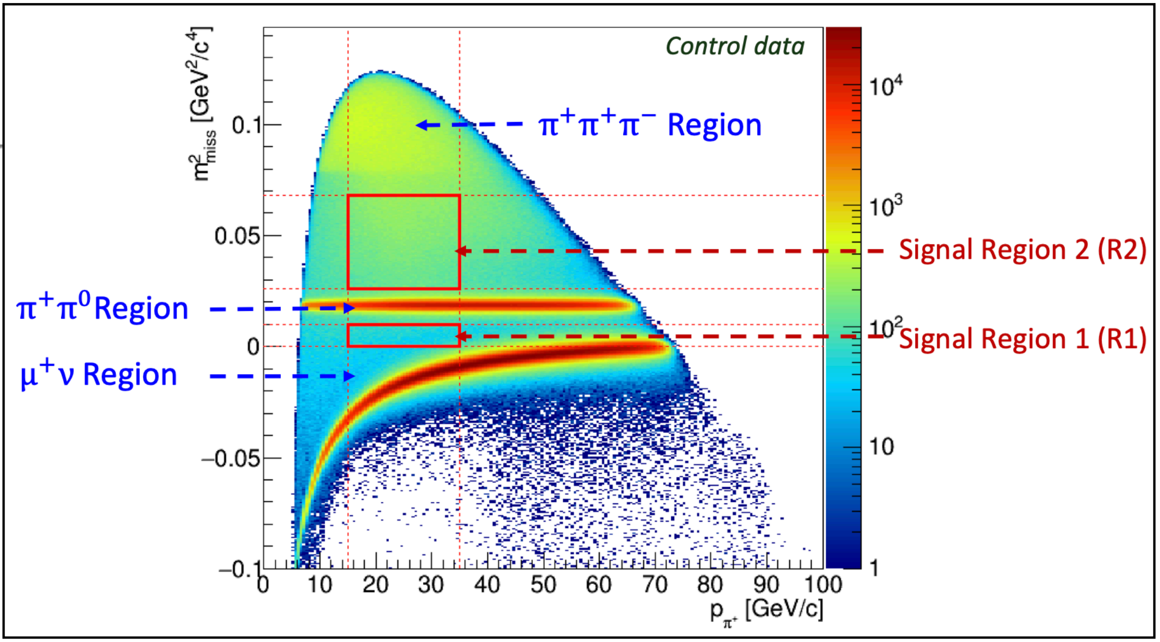
NA62 and the “in-fligt” Technique

$K \rightarrow \pi \nu\nu$



TWO SIGNAL REGIONS





$$m^2_{miss} \equiv m^2_{miss}(\text{Straw}, \text{GTK}) = (P_{\pi^+} - P_{K^+})^2, \ \ m_{\pi^+} \text{ hypothesis}$$

K^+ - π^+ matching

CRUCIAL FOR EFFICIENT DATA TAKING AND MINIMISE BACKGROUND

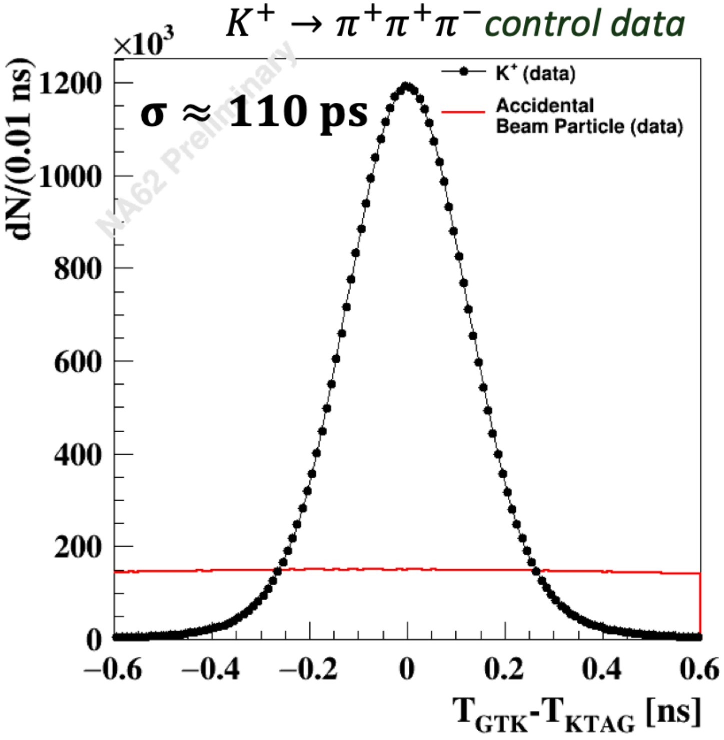
CDA="CLOSEST DISTANCE OF APPROACH"

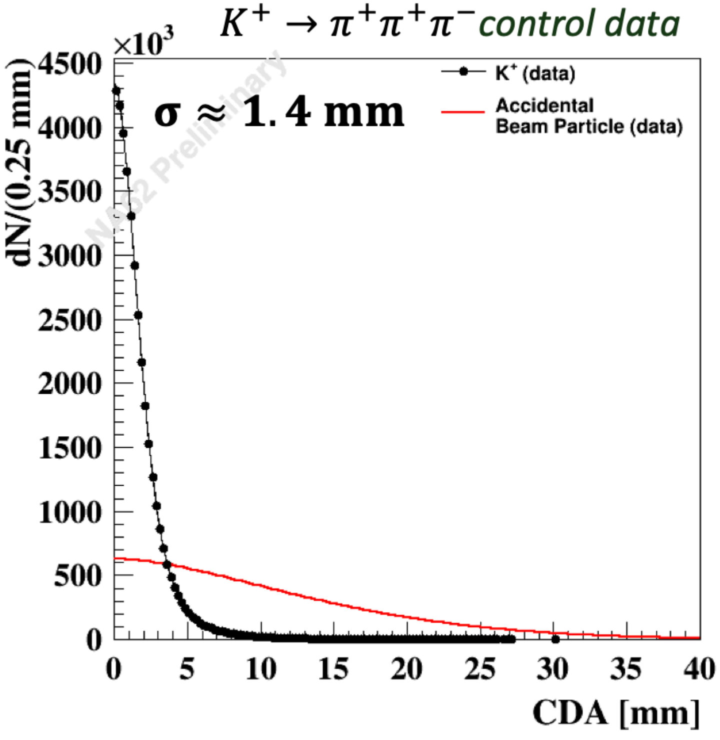
KTAG – GigaTracker – RICH time matching → Kaon decay time ($\mathbf{t_{decay}}$)

GigaTracker – Straw Spectrometer spatial matching (CDA)

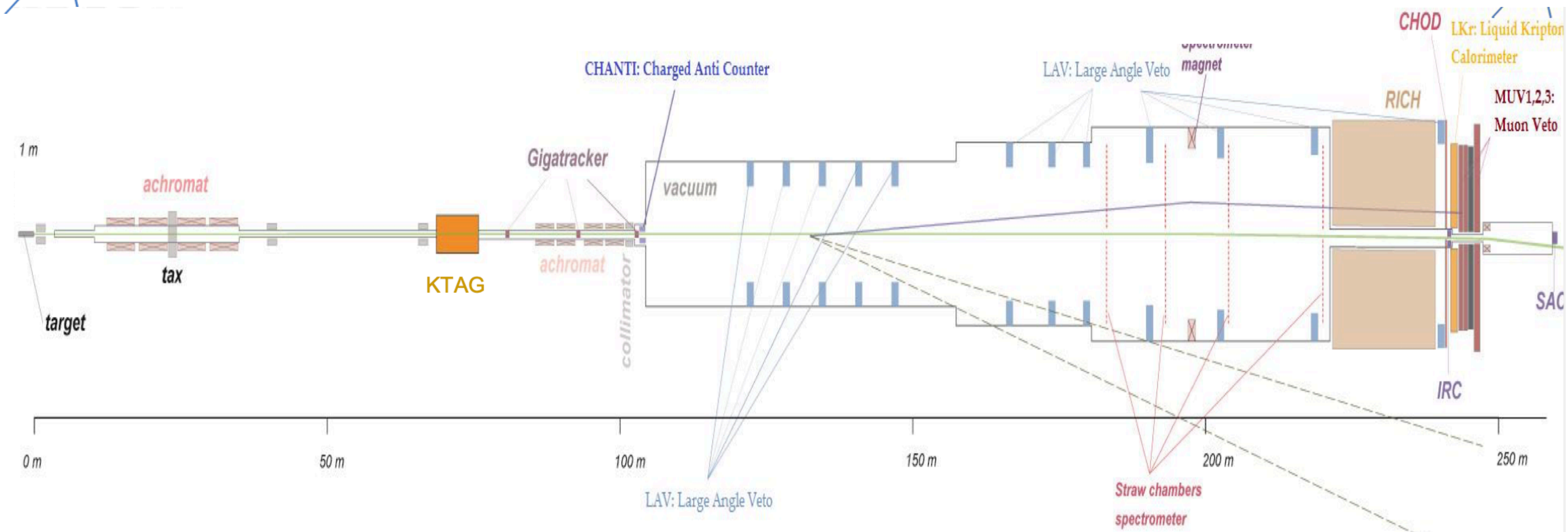
3.5% (<1%) K^+ mis-tag if K^+ track (not) present, dependent on beam intensity

75% K^+ reconstruction and ID efficiency





Scheme for π νν selection



- One reconstructed track in the Straw (π^+ track)
- Signal in RICH compatible with only 1 π^+ hypothesis
- Signal in Calorimeters (CHOD, LKr, MUV1,2,3) compatible with only 1 π^+ hypothesis
- No clusters in LKr compatible with γ hypothesis
- No signals in LAVs, IRC, SAC compatible with γ hypotesis

- At least one track in Gigatracker matched in space and time with the π^+ track (K^+ track) and compatible with the beam parameters (75 GeV/c)
- No extra activity in CHANTI compatible with a MIP signal
- Signal in KTAG compatible with a K hypothesis
- Z vertex in the first 60 m of the decay volume

Process	Branching ratio
$K^+\to\pi^+\pi^0$	0.2066
$K^+\to\mu^+\nu_\mu$	0.6356
$K^+\to\pi^+\pi^+\pi^-$	0.0558
$K^+\to\pi^+\pi^- e\ \nu_e$	4.3×10^{-5}
$K^+\to\pi^+\nu\bar{\nu}$ (SM)	**8.4×10^{-11}**

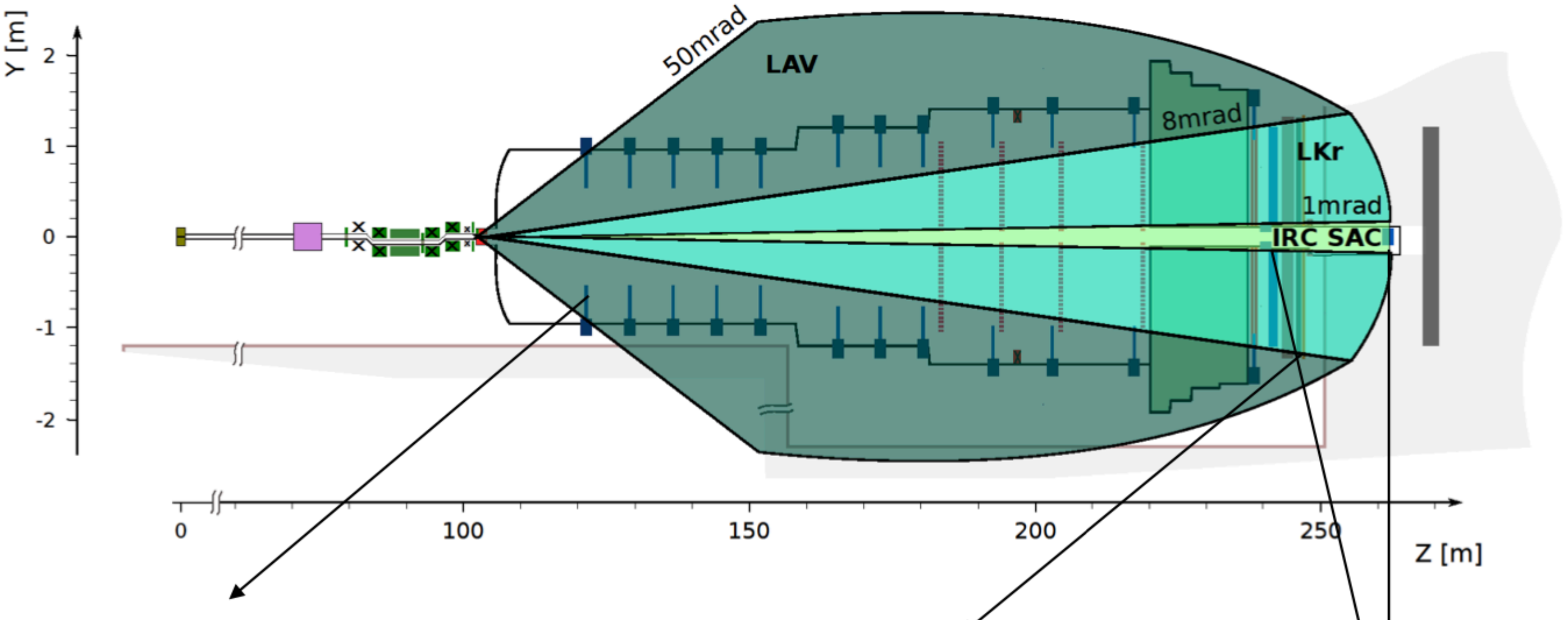
$15 < P_{\pi+} < 35$ GeV/c

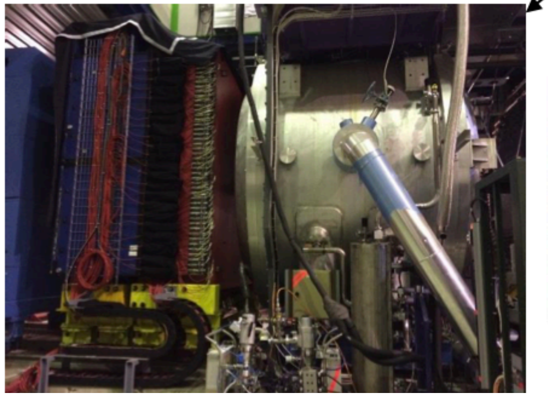
Background suppression

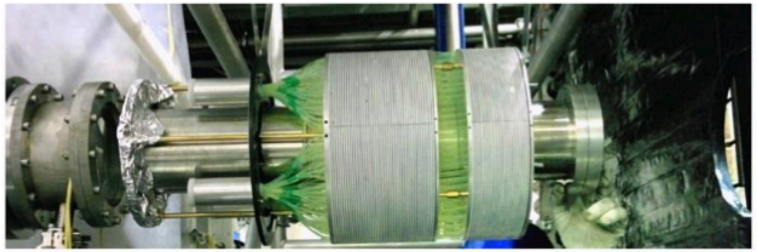
- $\mathcal{O}$ 100ps Timing between sub-detectors
- $\mathcal{O}$ 10^4 Background suppression from kinematics
- $> 10^7$ Muon suppression
- $> 10^7$ π^0 (from $K+ \rightarrow \pi^+\pi^0$) suppression

Photon (π^0) Rejection

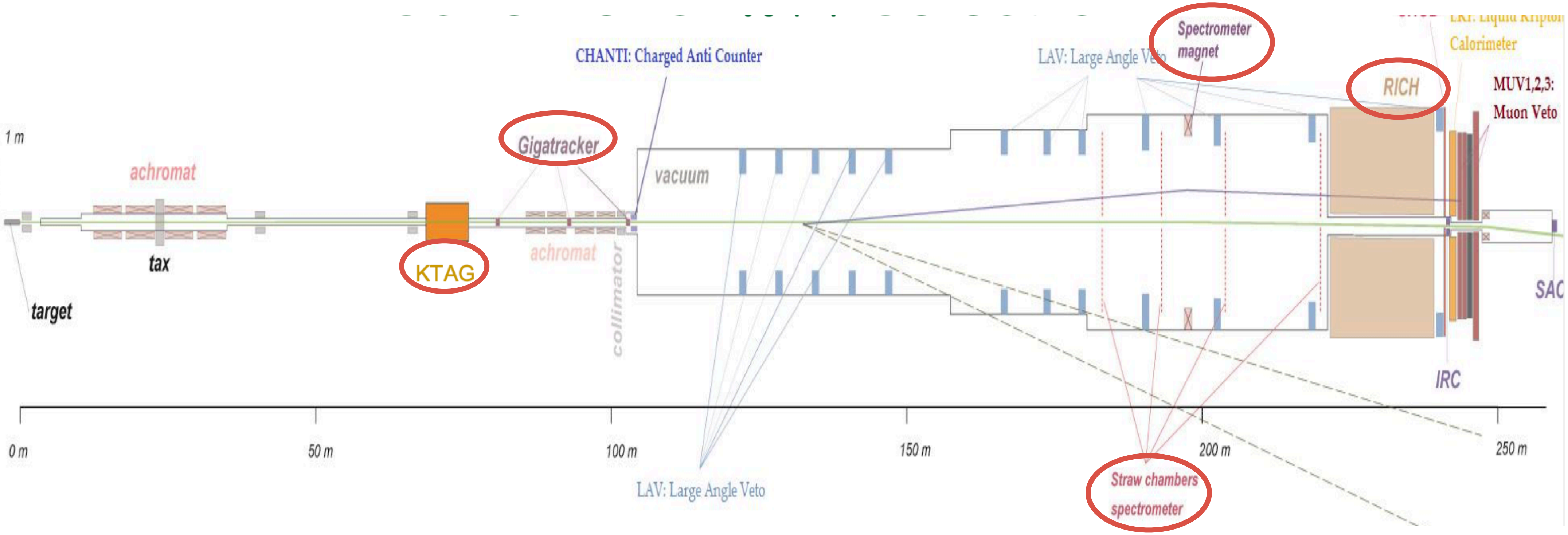
HERMETICITY AGAINST PHOTONS EMITTED IN STANDARD KAON DECAYS UP TO 50 MRAD







The Detectors

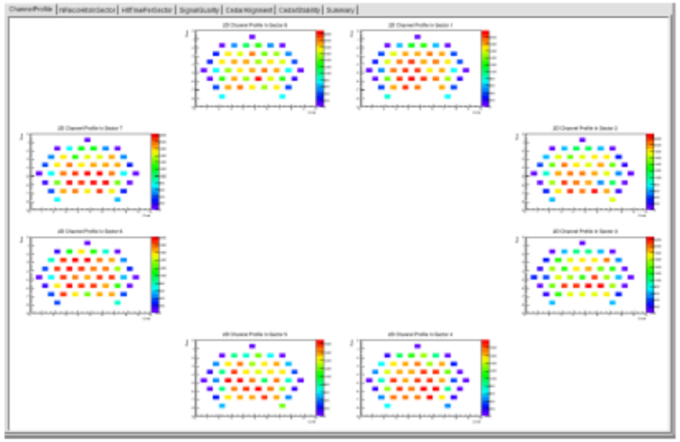


Kaon ID and timing: KTAG

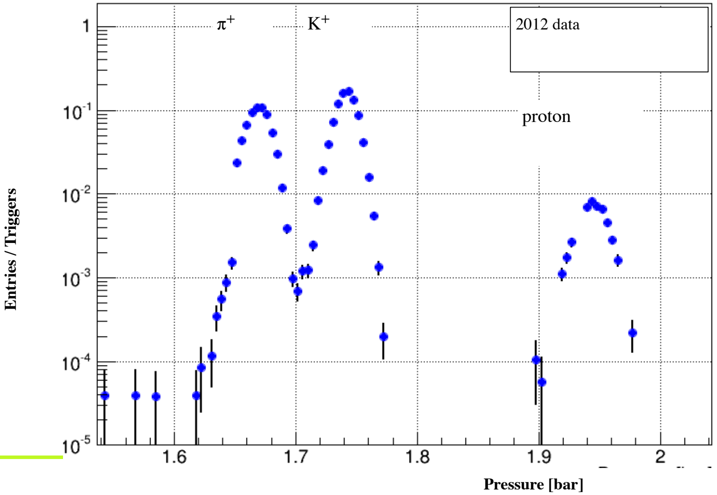
- CEDAR optics (radiator N_2)
- Cerenkov light split in 8 spots
- TDC readout (48 x 8 PMs)
- < 100 ps time resolution
- > 95% K ID efficiency (> 99.9% purity)
- Rate at full intensity 50 MHz
- Commissioned in 2014

NITROGEN RADIATOR UNTIL 2022

PM occupancy screenshot from 2014 data



KTAG K/π/p separation

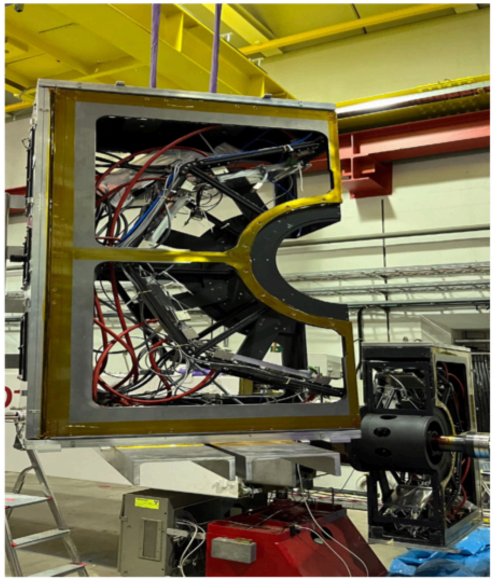


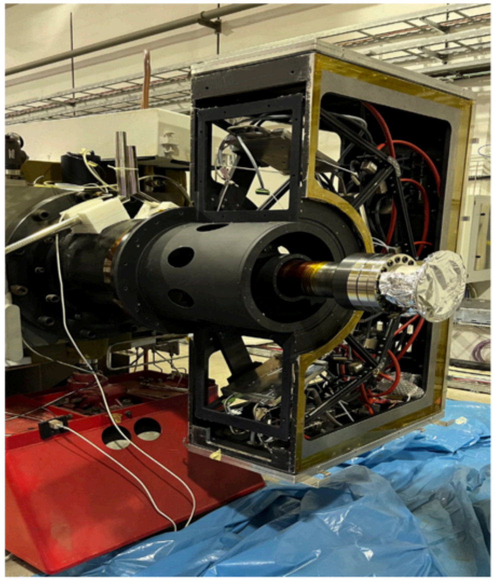
New CEDAR-H in 2023

Installation into NA62 beamline

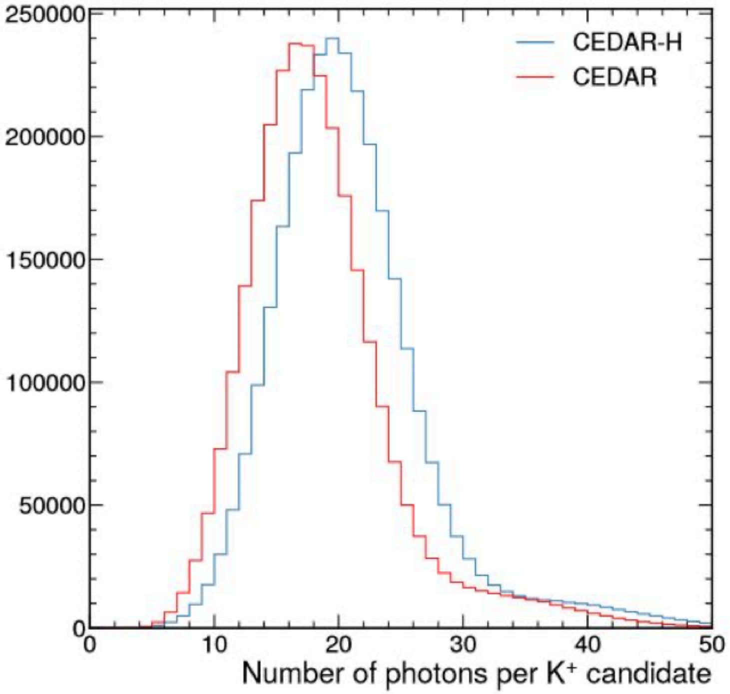
The installation was conducted between the end of 2022 run and start of 2023 run

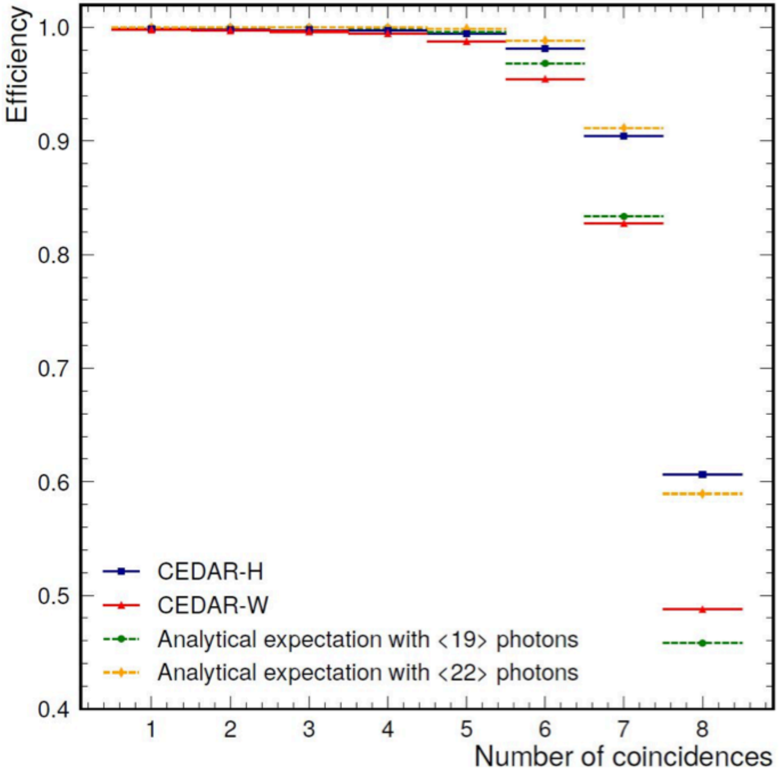
CEDAR-H was transported to ECN3 and installed, replacing the original CEDAR in NA62 beam line.





CEDAR-H Performance





$$\sigma_t^K = \frac{\sigma_t^{PMT}}{\sqrt{N_{PMT}}} \approx 65ps$$

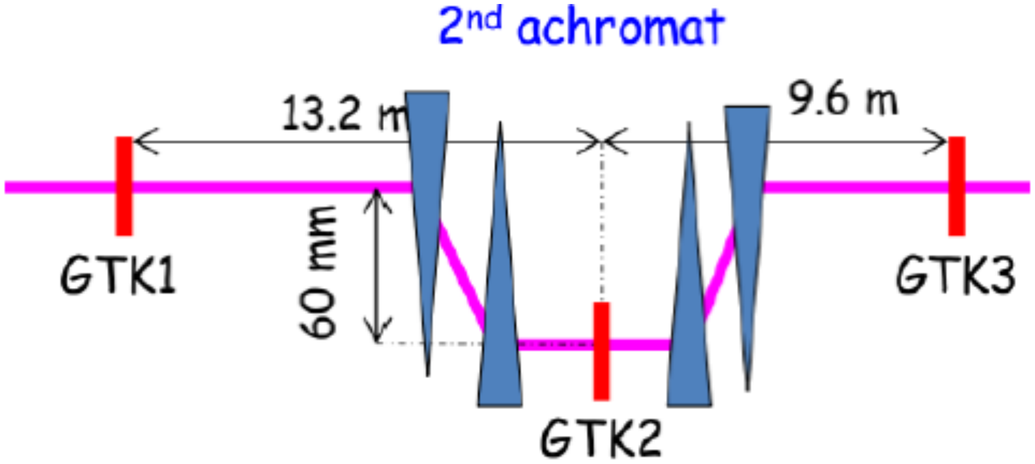
The photon yield with CEDAR-H is 10-15% larger wrt to the yield achieved using previous CEDAR with nitrogen

The K^+ ID efficiency based on 5 coincidences is greater than 99.5%

GTK Beam Tracker

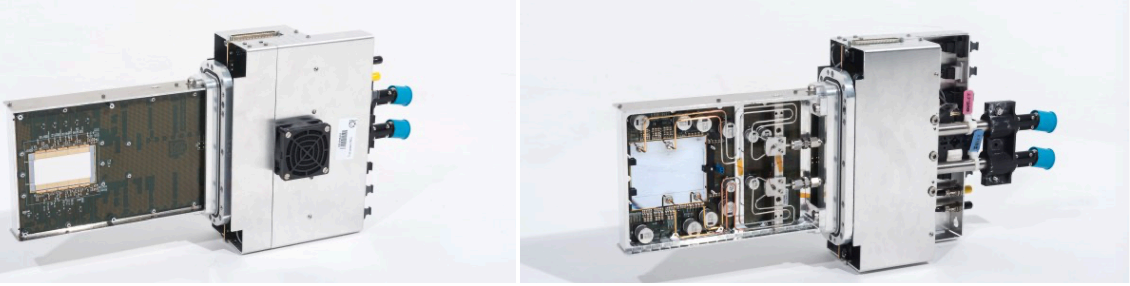
AIM: **MEASURE TIME, DIRECTION, AND MOMENTUM OF ALL THE BEAM TRACKS AT A GHZ RATE**

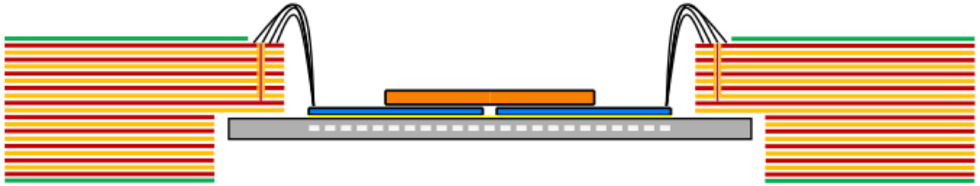
- Gigatracker: 3 Si pixel stations on the beam
- Provide precise momentum, time and angular measurements on all beam tracks
- Cooled down using a microchannel technique
- On sensor TDC readout chip
- $X/X_0 < 0.5\%$ / station,
- Rate at full intensity 750 MHz

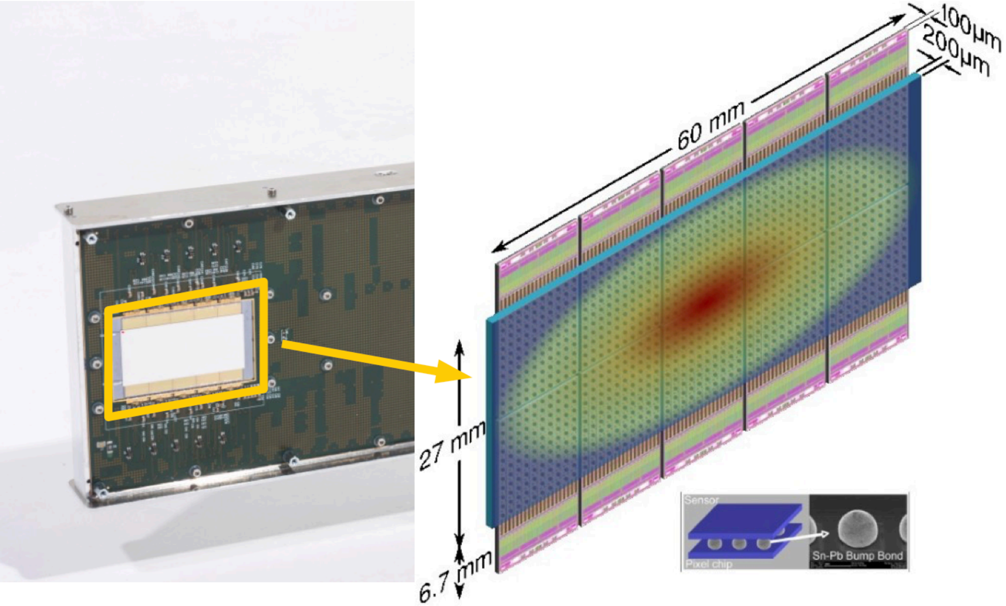


GTK: State-of-the-art 4D Tracking

- **Sensor:**
  - n-in-p and p-in-n
    27×60 mm2
    200 μm thick (0.2% X0)
  - Bump bonded to 10 chips Bump-Bonding:
    - Sn-Ag bumps
  - Benzocyclobutane deposited to avoid discharges.
  - **TDCPix:**
    IBM 130nm CMOS technology
  - 100 μm thick (0.1% X0)
    -1800 pixels of 300 × 300 μm2
  - Peaking time: 5ns

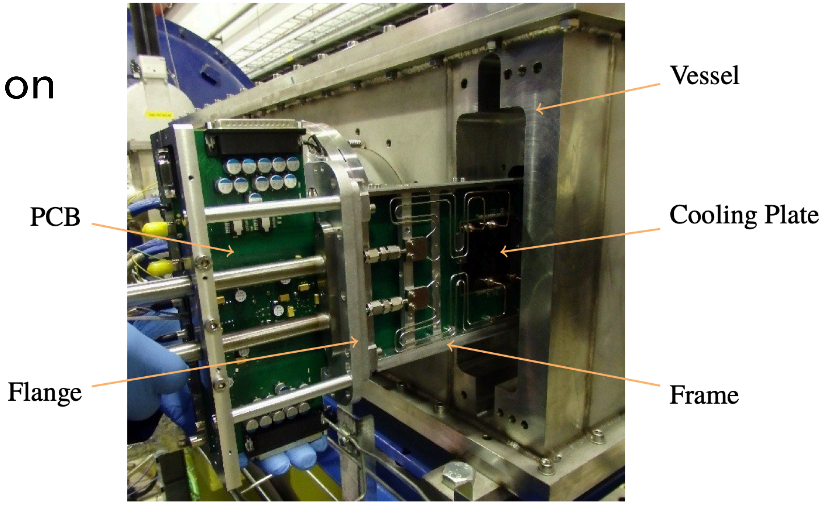


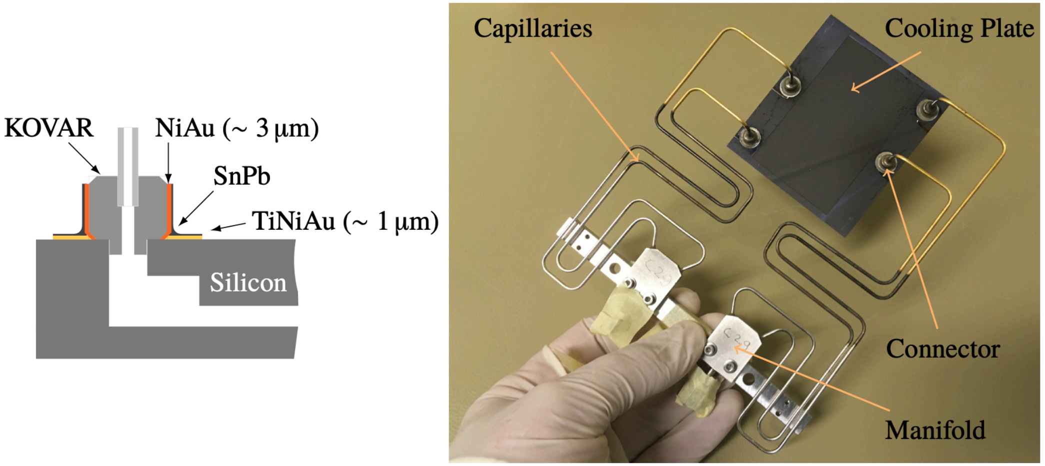




State of the art: Micro-channel cooling

- GTK 3 installation

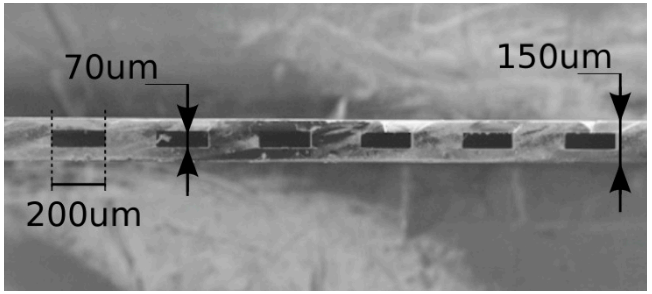




(a)

(b)

- Cross-section of the ooling plate



(a) Cross view of the connectors between the plate and the capillaries. (b) The two cooling plate circuits are connected to capillaries each by one set of inlet and outlet. The capillaries are then brazed on manifolds that are connected to the cooling distribution circuit.

Time Resolution (bias 100V)

Conditions

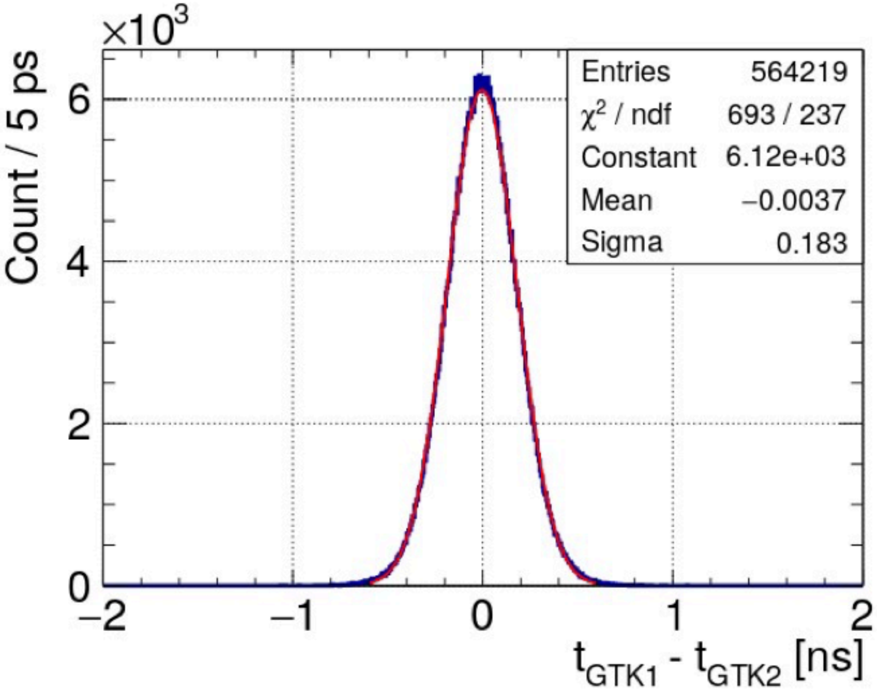
- At detector installation in 2016
- Sensor Type: n-in-p
- Operation bias: 100 V

Two Measurement Methods

- Time difference between GTKs KTAG RICH ($\sigma_t < 100$ ps)
- Time difference between the 3 GTK stations

Results

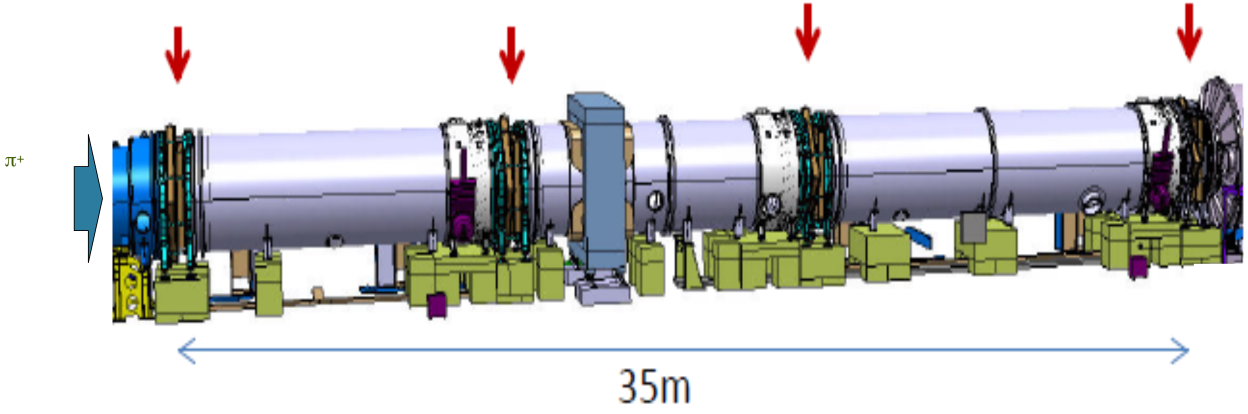
- Hit time resolution: 130 ps
- Track time resolution: 75 ps
- Design resolution matched

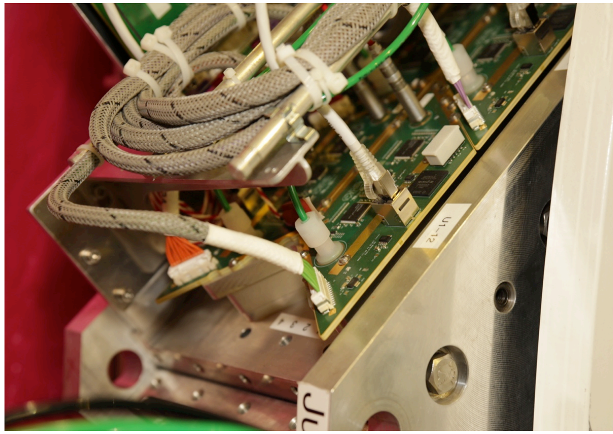


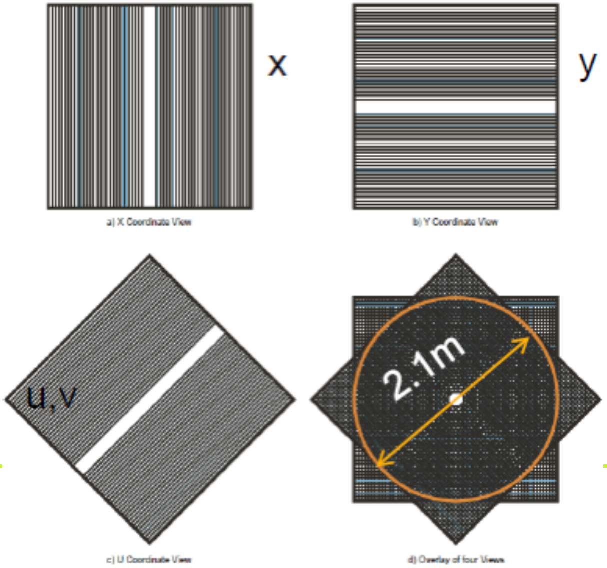
GTK1	132.0 ps
GTK2	127.1 ps
GTK3	129.2 ps

The Straw Spectrometer

- In vacuum 1x10^{-6} mbar
- 4 Chambers; 1 cm ∅ straws
- $X/X_0 < 0.5\%$ / chamber
- 0.5 Tm magnet (2x2 aperture)
- TDC readout (~7200 straws)
- Rate at full intensity: 10 MHz

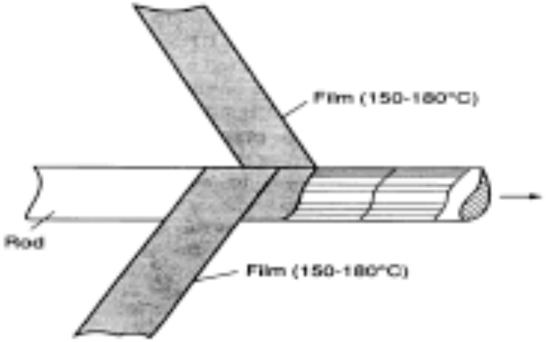




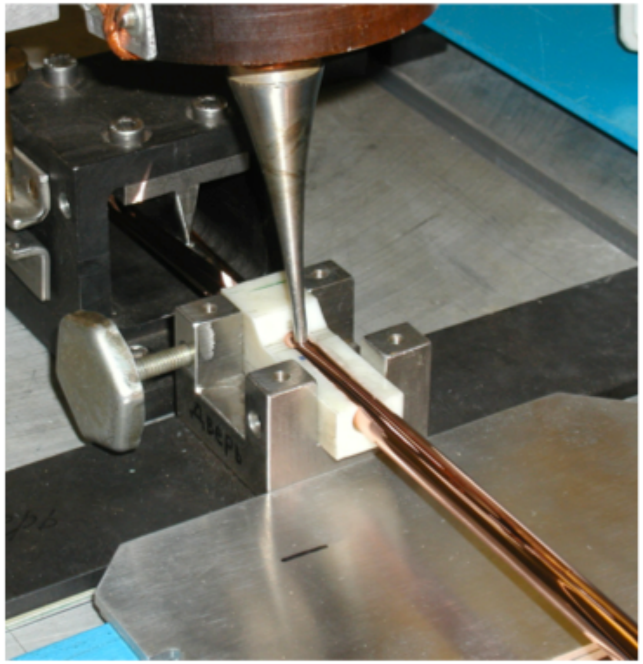


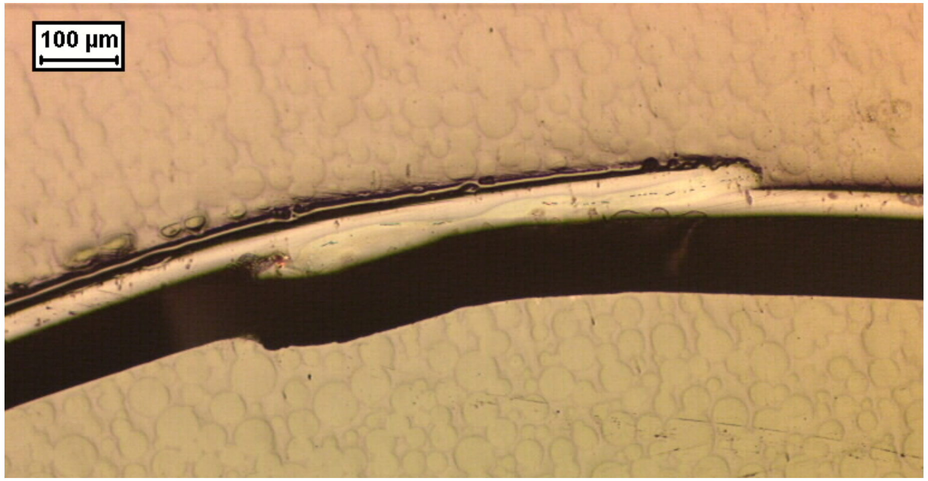
Straws by Ultrasonic Welding

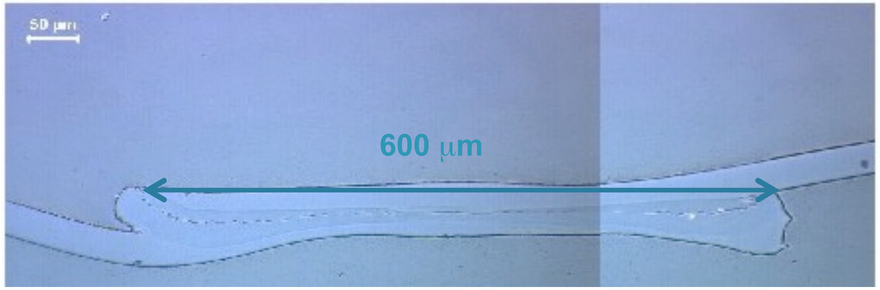
“Classical straw winding”



Ultrasonic welding







Straw Quality Control:

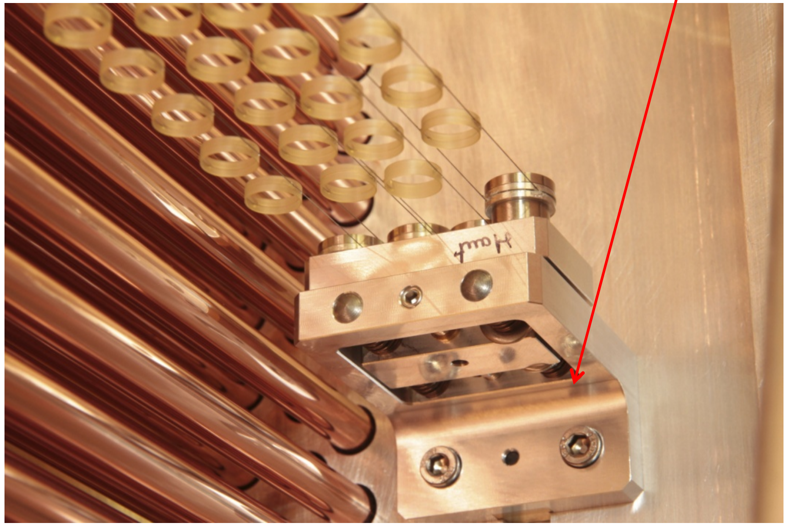
- All straws are leak tested after a short (15 min) pressure test at 3 bar
- The strength of the weld is verified at both straw ends (traction test)
- The electrical conductivity between the two straw ends is measured

Straw spacer : 2 per plane

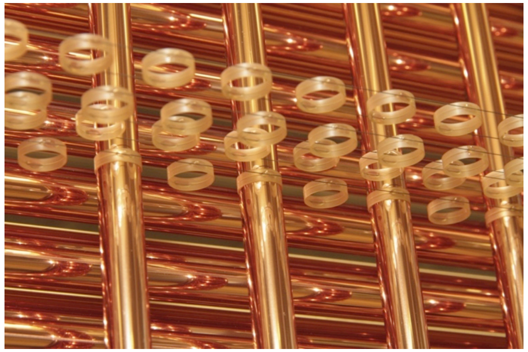
CRUCIAL IN ORDER TO KEEP THE STRAWS STRAIGHT!

The spacer is adjustable:
lateral position and in tension

Detail of the spacer support



Detail of the spacer

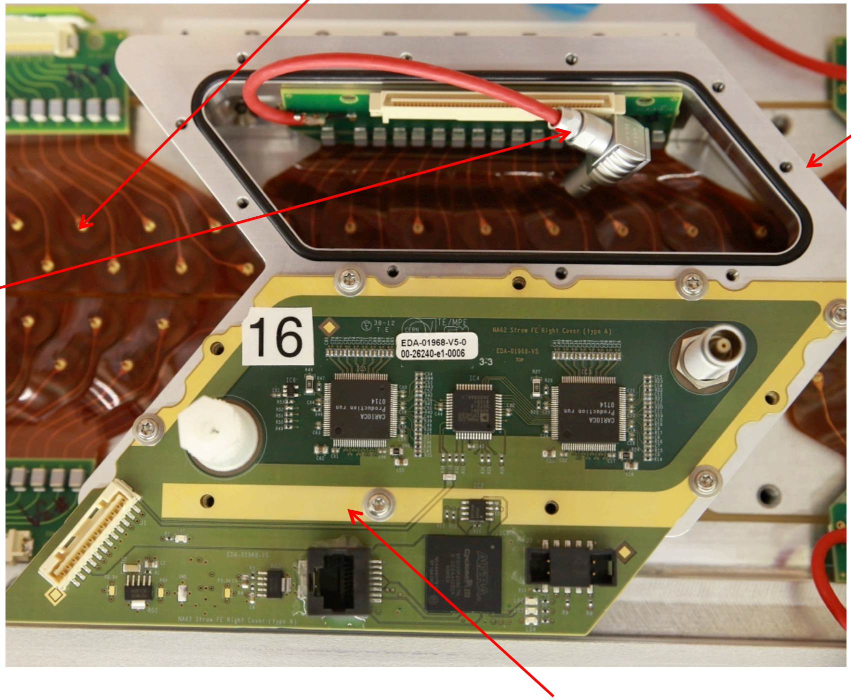


Straw spectrometer Front-End

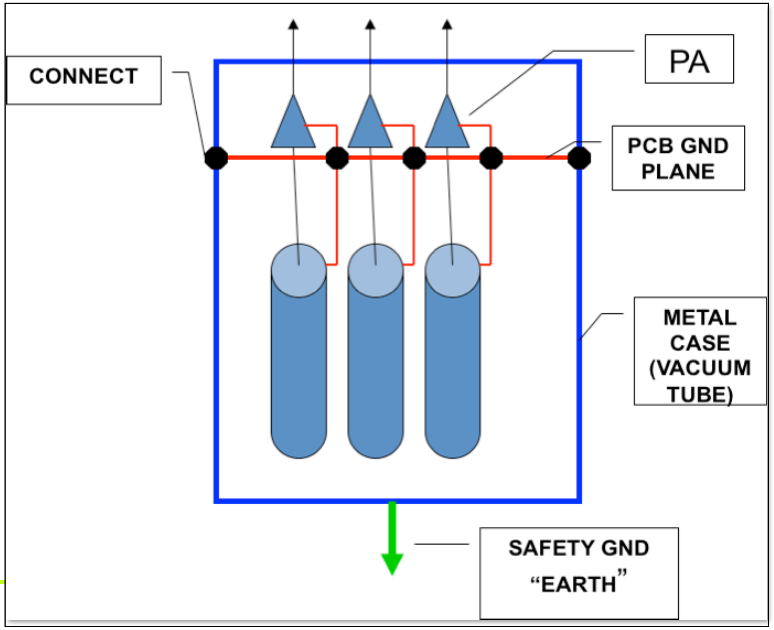
Custom made gold-plated crimp-tubes to connect the wires gold-plated Tungsten 30 μm in diameter

The Dismountable manifolds supports the cover and provides the modularity for the gas distribution (16 straws)

For the high-voltage and signal connection a flex-rigid circuit board (web) is used. The web contains HV capacitors, signal connector and HV connectors

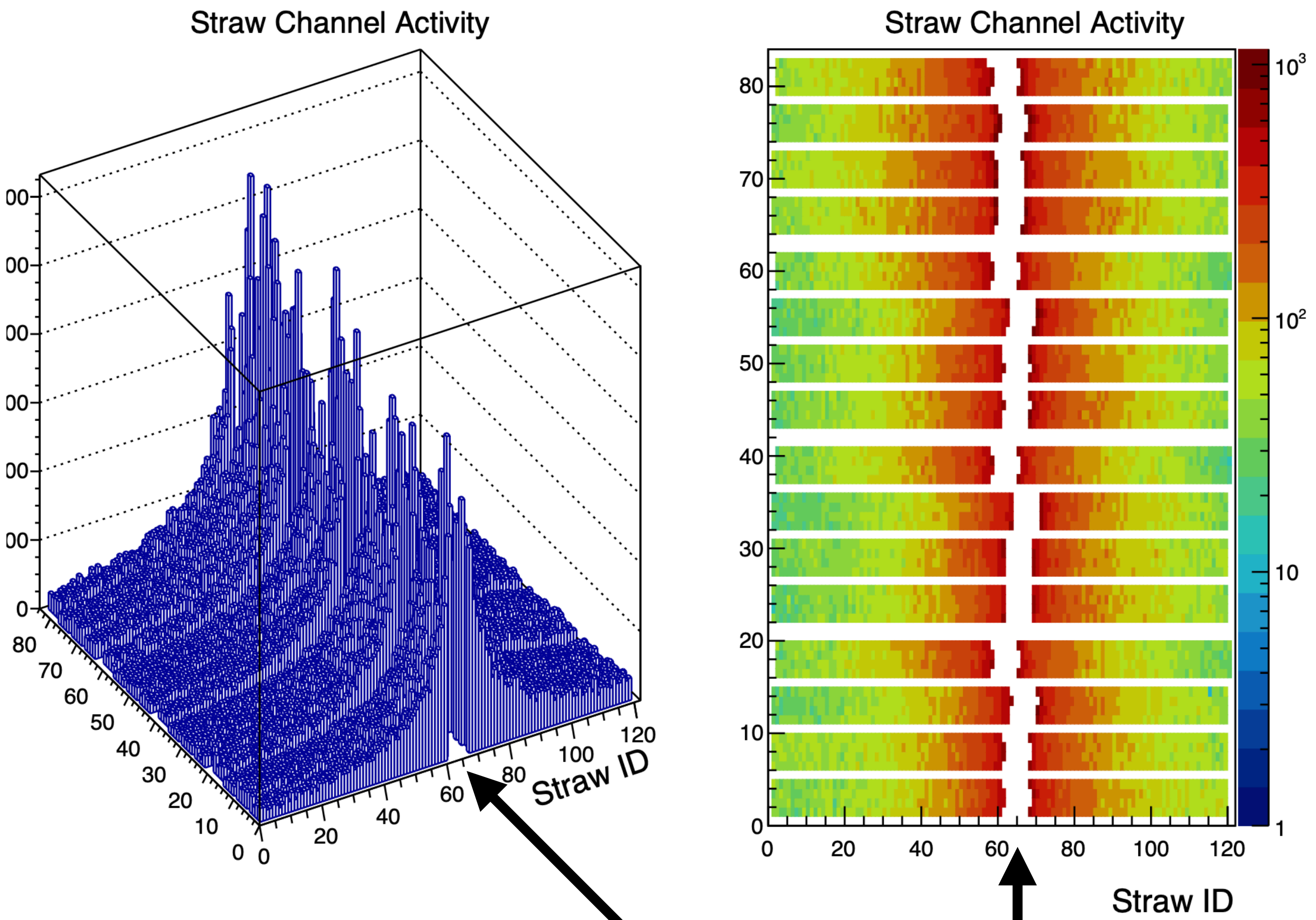


The PCB host the front-end electronics and closes the gas manifolds. The modularity is 16 straws and the PCB can withstand the ambient pressure in case of a broken straws



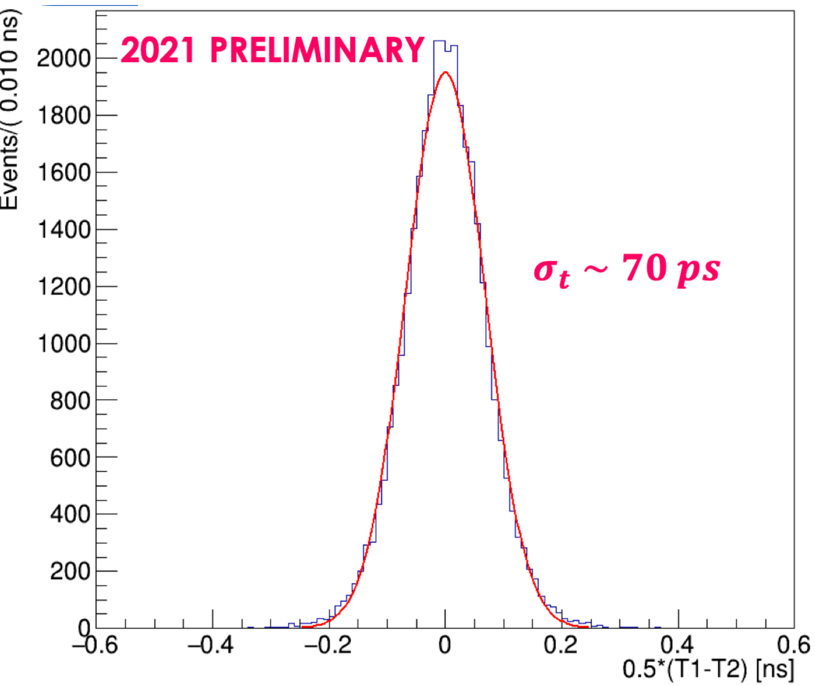
Oline Monitor Plot September 2023

- 7168 Straws
- 3 not working in 2023

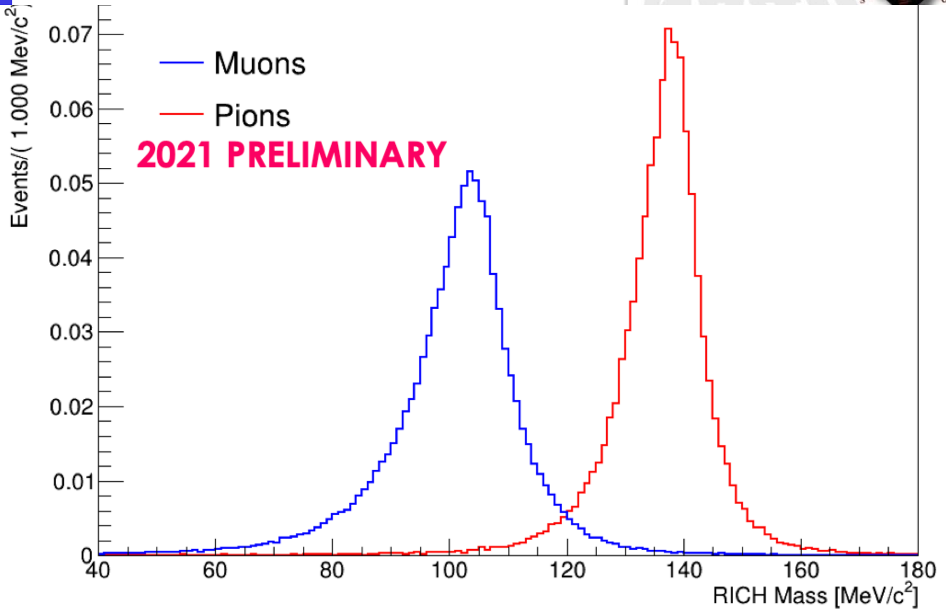


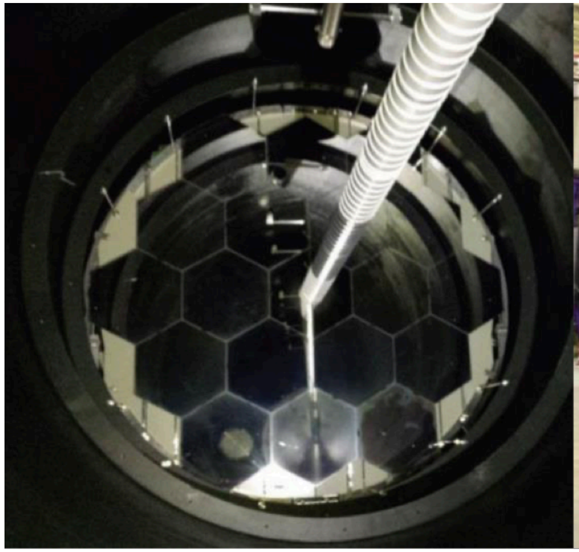
Beam direction

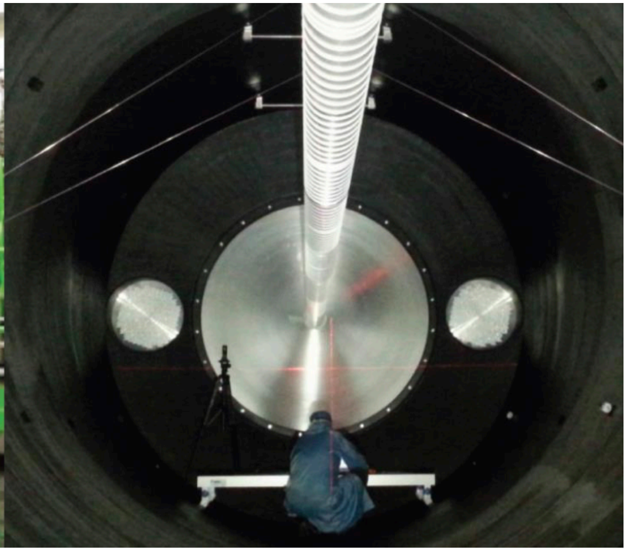
The RICH



- RICH Requirements
- μ+ mis-ID < 1% in momentum range $15 < p\pi < 35$GeV/c
- Time resolution of O $100\ ps$
- Provide a L0 trigger for charged tracks

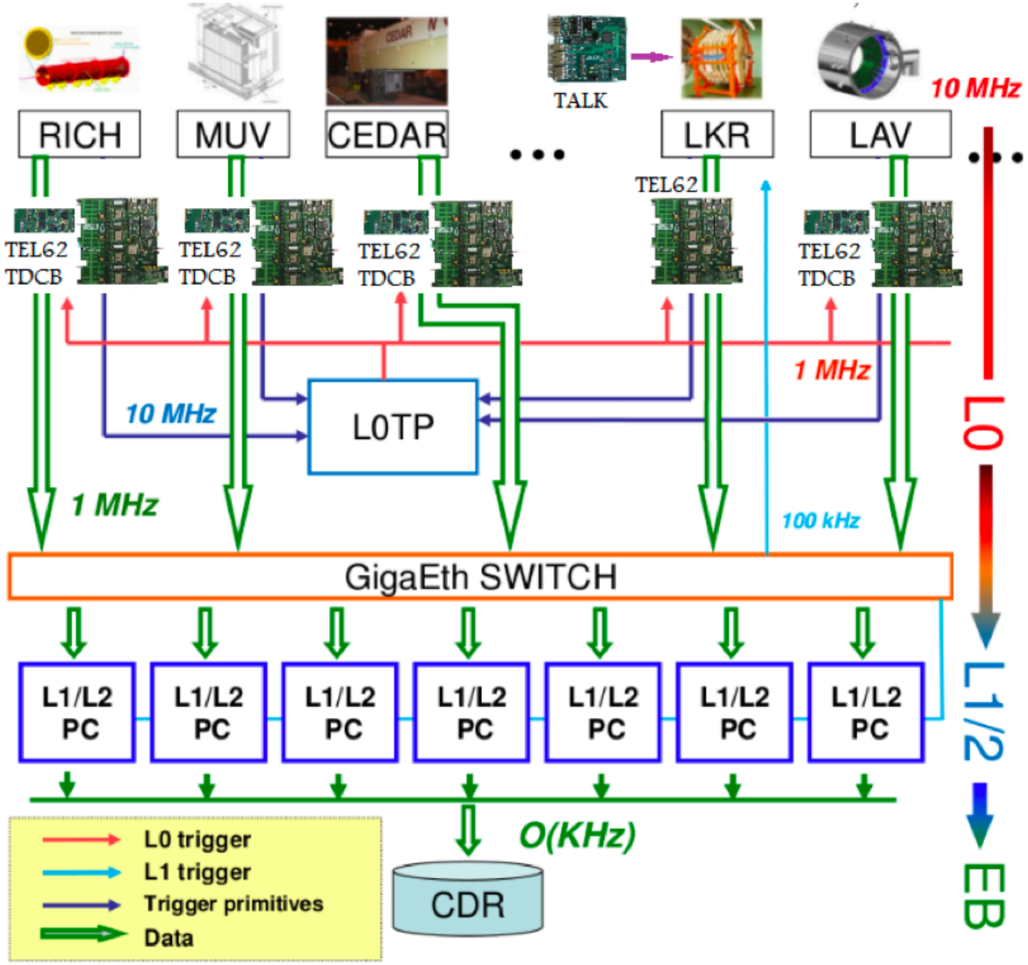






Trigger and DAQ

The schematic represents an overview of the NA62 trigger system. The information, stored in primitives, is generated in a subset of detectors and transmitted to L0TP, where is processed in order to reduce the rate from 10 MHz to 1 MHz. Data satisfying the L0 selection are moved from all the detectors to the PC-Farm, where high level triggers (L1 and L2) are applied, reducing the rate from 1 MHz to about 20 kHz. Only the events passing the three selections, L0, L1, and L2, are written on disk by the Central Data Recording (CDR) service.

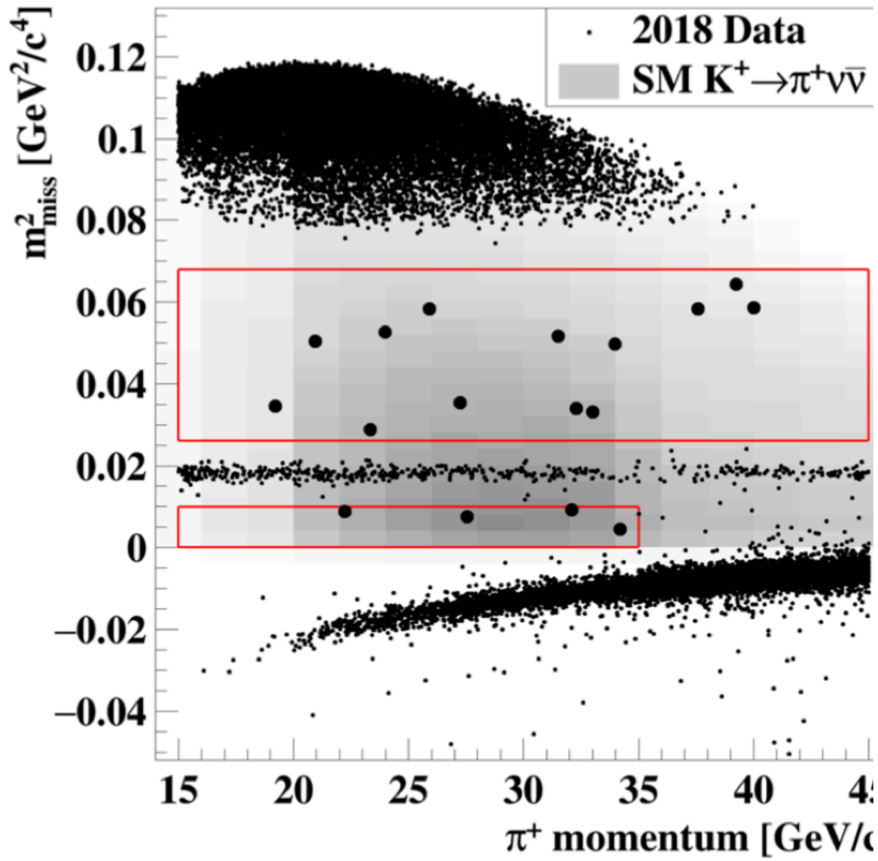


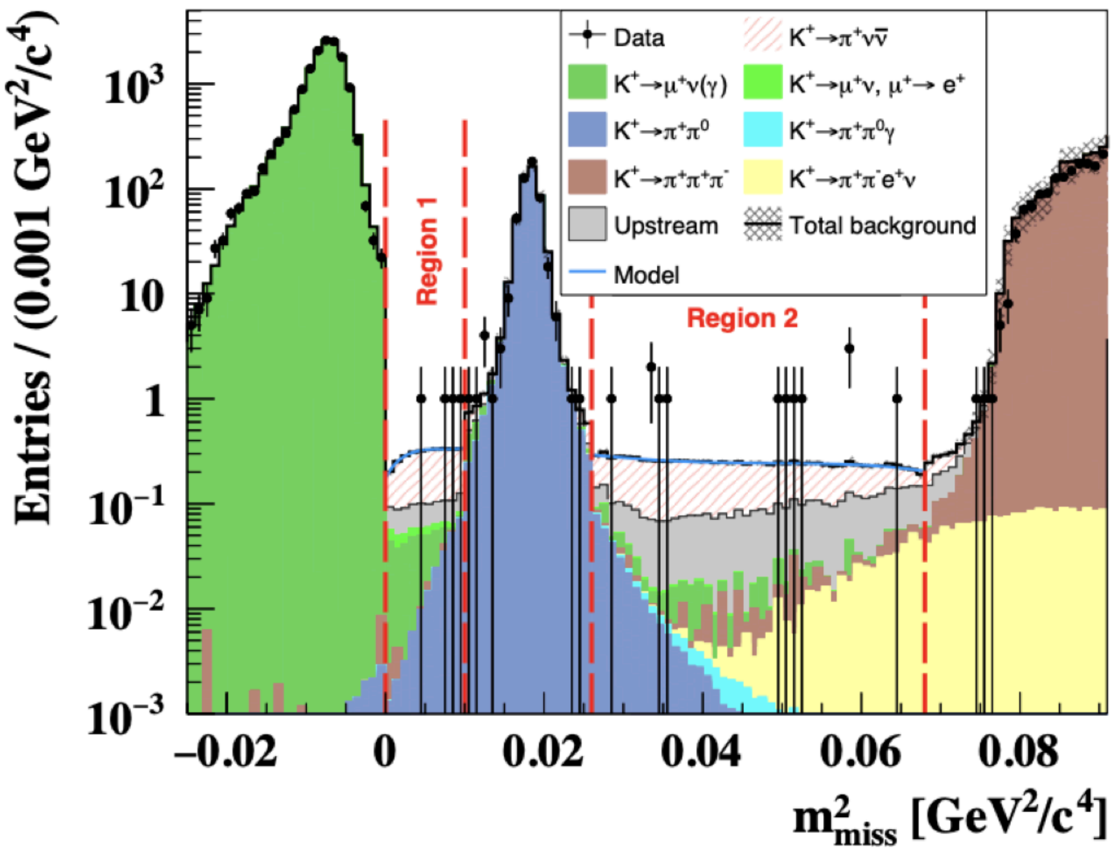
🟥	L0 trigger
🟦	L1 trigger
🟪	Trigger primitives
🟩	Data

RESULT: 1 MHZ REDUCED TO ABOUT 20 KH

Results

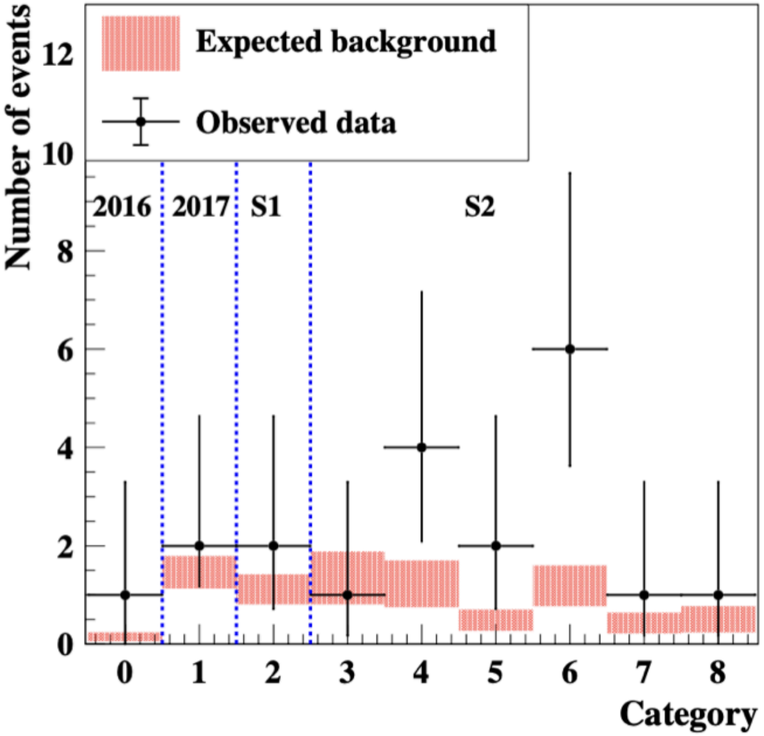
NA62 2018 Data JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]





NA62 Combined Results (2016,2017 and 2018)

JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]



$$SES = (0.839 \pm 0.053_{\text{syst}}) \times 10^{-11},$$

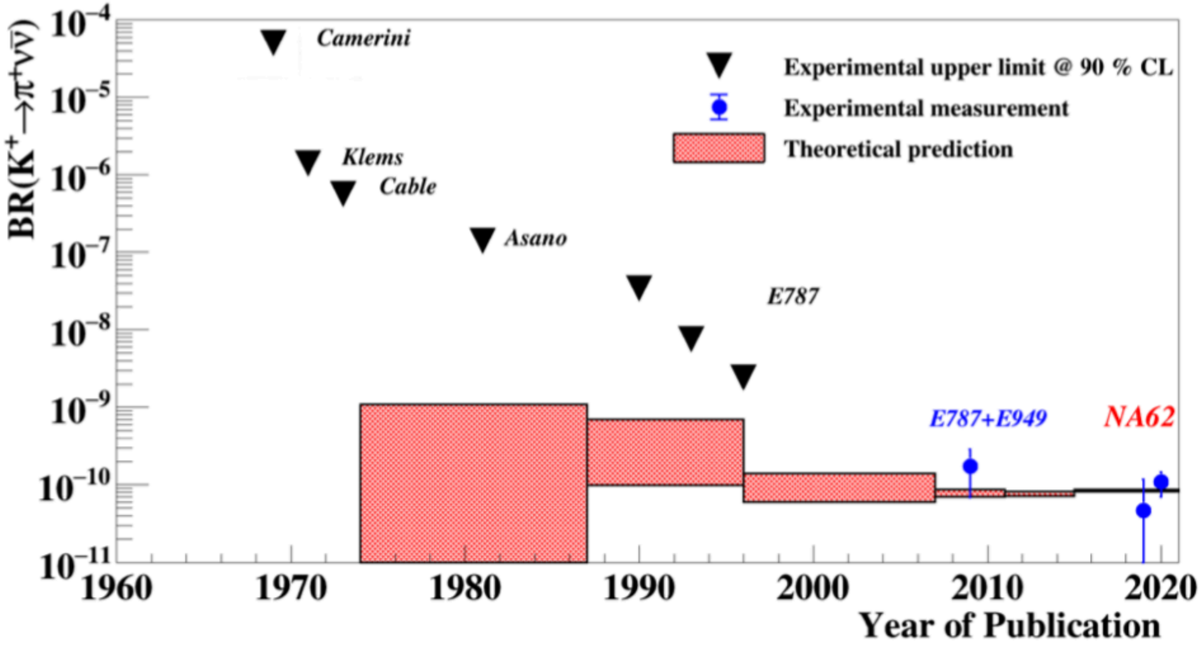
$$N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}},$$

$$N^{\text{exp}}_{\text{background}} = 7.03^{+1.05}_{-0.82}.$$

$$B(K^{+} \to \pi^{+}\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\ (stat) \pm 0.9\ (syst)) \times 10^{-11}$$

20 Candidates 3.4 σ significance, $P(back.only)\ 3.4 \cdot 10^{-4}$

Historical



- NA62 2016 data
  E. Cortina Gil *et al.* [NA62], Phys. Lett. B **791**, 156-166 (2019) doi:10.1016/j.physletb.2019.01.067 [arXiv:1811.08508 [hep-ex]
- NA62 2017 data
  E. Cortina Gil *et al.* [NA62], JHEP 11:042 (2020) [arXiv:2007.08218 [hep-ex]
- NA62 2018 data
  E. Cortina Gil *et al.* [NA62], JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]

With restricted data taking periods (end 2025) and hardware limitations at higher intensity, NA62 can aim for a 15 % BR_{SM} measurement

Long Shutdown 3 start in 2026

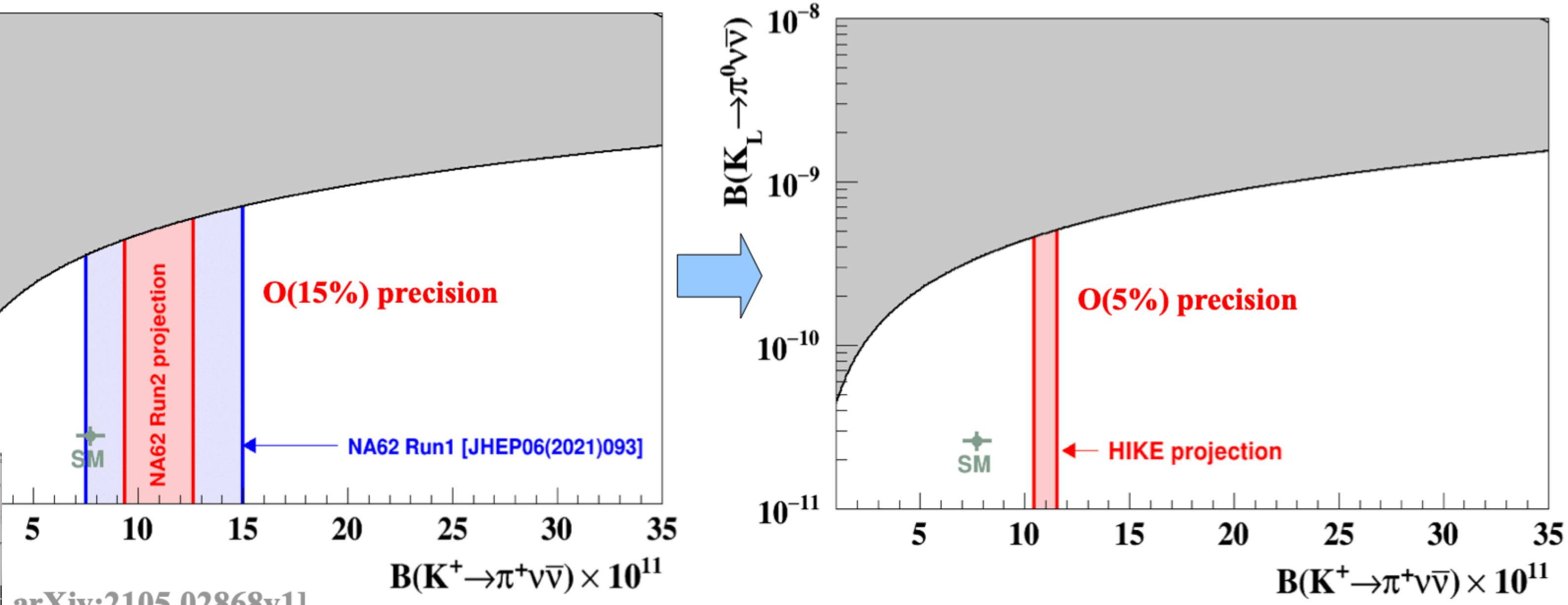
2030 and Beyond

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ @ HIKE: physics reach

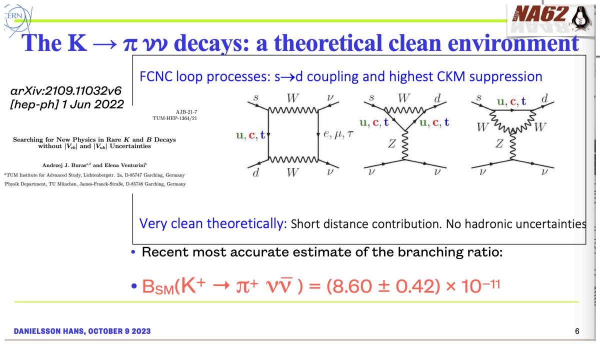
Measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$): precision test of the Standard Model

Model-independent standard candle constraining many BSM scenarios,
present or future

From NA62 to HIKE



arXiv:2105.02868v1]



The $K \rightarrow \pi \nu\nu$ decays: a theoretical clean environment

arXiv:2109.11032v6 [hep-ph] 1 Jun 2022

AJB-21-7
TUM-HEP-1364/21

Searching for New Physics in Rare K and B Decays without $|V_{cb}|$ and $|V_{ub}|$ Uncertainties

Andrzej J. Buras[a,b] and Elena Venturini[b]

[a]TUM Institute for Advanced Study, Lichtenbergstr. 2a, D-85747 Garching, Germany
[b]Physik Department, TU München, James-Franck-Straße, D-85748 Garching, Germany

FCNC loop processes: s→d coupling and highest CKM suppression

Very clean theoretically: Short distance contribution. No hadronic uncertainties

- Recent most accurate estimate of the branching ratio:
- $B_{SM}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$

DANIELSSON HANS, OCTOBER 9 2023 6

From NA62 to HIKE: precision on BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) improved by 3x!

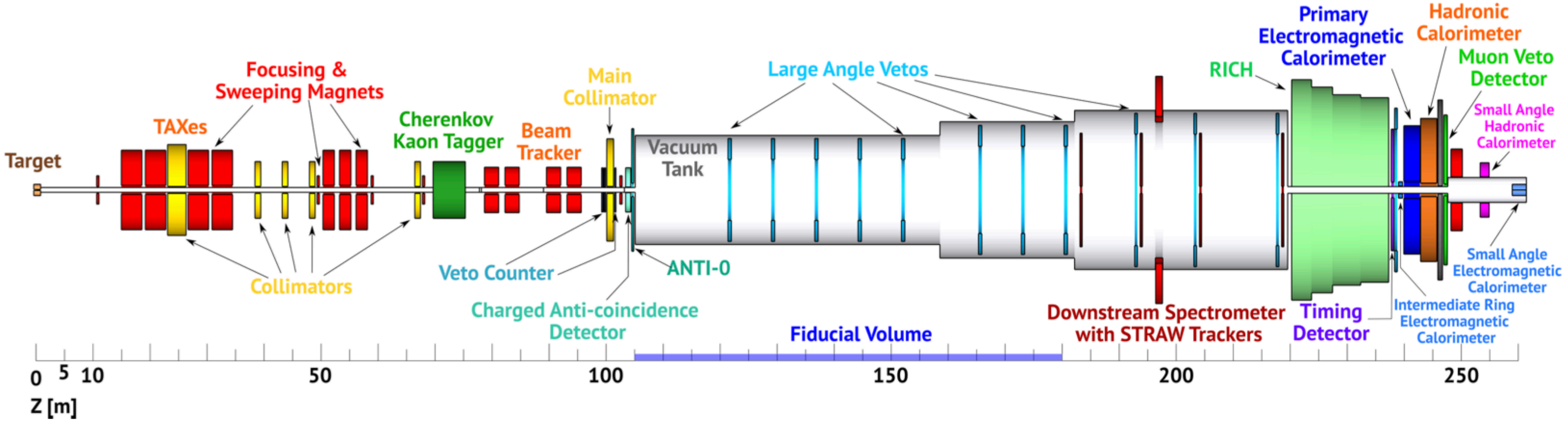
$K^+ \to \pi^+ \nu\bar{\nu}$ at CERN: HIKE-Phase1

→ Max possible intensity in HIKE-Phase1 (after major beamline upgrades):

1.2 ×10^{13} POT / spill = 4x NA62 max beam intensity

Statistical power: 2×10^{13} Kaon decays in decay volume per year (7×10^{18} POT / year)

NA62-like design of experiment will work at high intensity



<u>HIKE-Phase1 improvements wrt NA62:</u>

– **Improved timing is the crucial element** to be able to stand the intensity increase

– **Equal or better key performances** at high-rate to keep background under control [e.g. kinematic rejection, photon rejection, PID]

– Up to x2 **increase in signal acceptance** thanks to new, more granular/performant detectors [higher efficiency in K-π association, PID, kinematic rejection] & fully-software trigger

– Further **suppress dominant background** from upstream K^+ decays

Further reading and publications

- *Search for K^+ decays into the $\pi^+e^+e^-e^+e^-$ final state*, arXiv: 2307.04579 [hep-ex] (2023), submitted to Phys. Lett. B.
- *A study of the $K^+ \to \pi^0 e^+ \nu \gamma$ decay*, arXiv: 2304.12271 [hep-ex] (2023), submitted to JHEP.
- *Search for dark photon decays to $\mu^+\mu^-$ at NA62*, arXiv: 2303.08666 [hep-ex] (2023), submitted to JHEP.
- *A search for the $K^+ \to \mu^- \nu e^+ e^+$ decay*, Phys. Lett. B 838 (2023) 137679.
- *A measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay*, JHEP 11 (2022) 011.
- *Searches for lepton number violating $K^+ \to \pi^-(\pi^0)\, e^+e^+$ decays*, Phys. Lett. B 830 (2022) 137172.
- *Search for Lepton Number and Flavor Violation in K^+ and π^0 Decays*, Phys. Rev. Lett. 127 (2021) 131802.
- *Measurement of the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay*, JHEP 06 (2021) 093.
- *Search for K^+ decays to a muon and invisible particles*, Phys. Lett. B 816 (2021) 136259.
- *Search for a feebly interacting particle X in the decay $K^+ \to \pi^+ X$*, JHEP 03, (2021) 058.
- *Search for π^0 decays to invisible particles*, JHEP 02, (2021) 201.
- *An investigation of the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay*, JHEP 11 (2020) 042.
- *Search for heavy neutral lepton production in K^+ decays to positrons*, Phys. Lett. B 807 (2020) 135599.
- *Searches for lepton number violating K^+ decays*, Phys. Lett. B 797 (2019) 134794.
- *Search for production of an invisible dark photon in π^0 decays*, JHEP 1905 (2019) 182.
- *First search of $K^+ \to \pi^+\nu\bar{\nu}$ using the decay-in-flight technique*, Phys. Lett. B 791 (2019) 156.

- *Search for heavy neutral lepton production in K^+ decays*, Phys. Lett. B 778 (2018) 137.

References

1. CERN-80-07, “Precise measurements of particle production by 400 GeV/c protons on beryllium targets”, Atherton, Henry W ; Bovet, Claude ; Doble, Niels T ; Piemontese, L ; Placci, Alfredo ; Placidi, Massimo ; Plane, David E ; Reinharz, Max ; Rossa, Edouard ; Von Holtey, G
2. “NA62 Technical Design” https://na62.web.cern.ch/Documents/TD_Full_doc_v10.pdf
3. "The beam and detector of the NA62 experiment at CERN”, https://iopscience.iop.org/article/10.1088/1748-0221/12/05/P05025/pdf

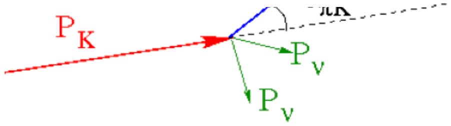
Spares

Choice of detector layout

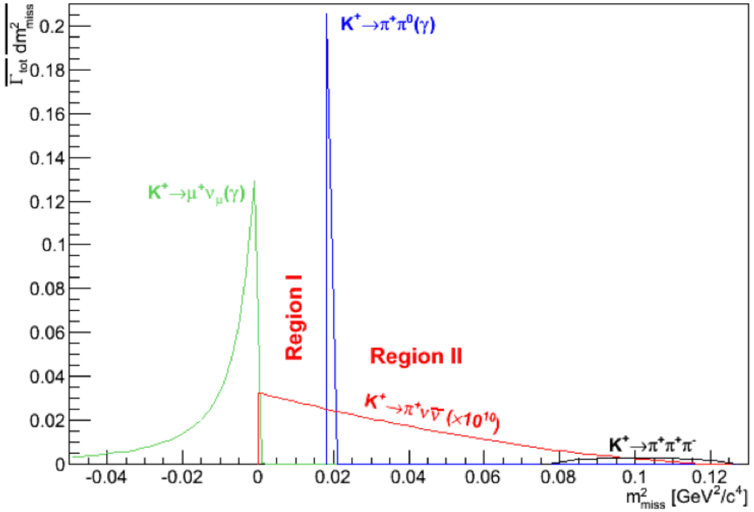
- The **400 GeV/c** proton beam from the **CERN SPS** accelerator enables the production of a **75 GeV/c secondary kaon beam**
- The advantage of using a high-energy proton beam $\mathcal{O}(10^{13})$ kaon decays over a few years) is the reduction of non-kaon-related accidental background due to the higher kaon production cross section
- **Kaon identification** is provided by a **CEDAR** differential Cherenkov counter equipped with a photon detection system **KTAG**
- Downstream of the decay region, the **STRAW tracker** measures the trajectories and momenta of the charged products of K^+ decays. To minimize multiple scattering, the straw chambers, which are constructed of ultra-light material, are installed inside the vacuum. The tracker consists of four chambers and a large-aperture dipole magnet (MNP33) providing a momentum kick to charged particles of 270 MeV/c in the horizontal plan

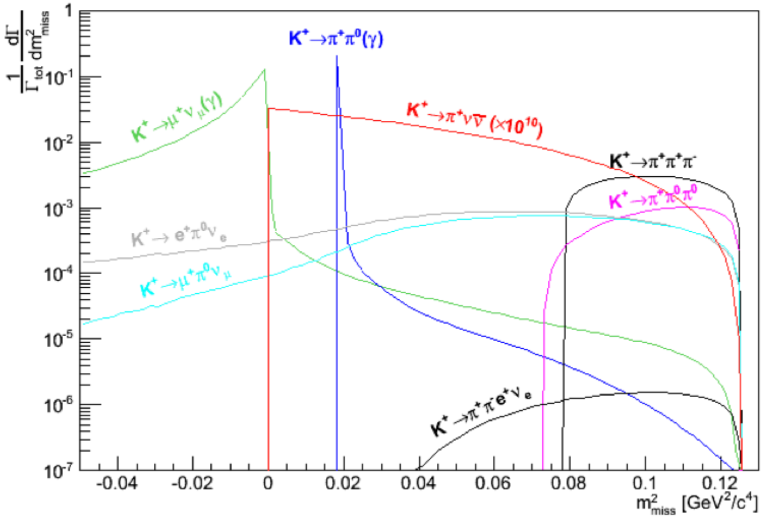
Signal and background

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



- Background
  - 1) K⁺ decay modes 2) Accidental single track matched with a K-like track
- Kaon Decays





- Accidental single tracks
  - Beam interactions in the beam tracker
  - Beam interactions with the residual gas in the vacuum region.