NA62: Kaon physics at CERN

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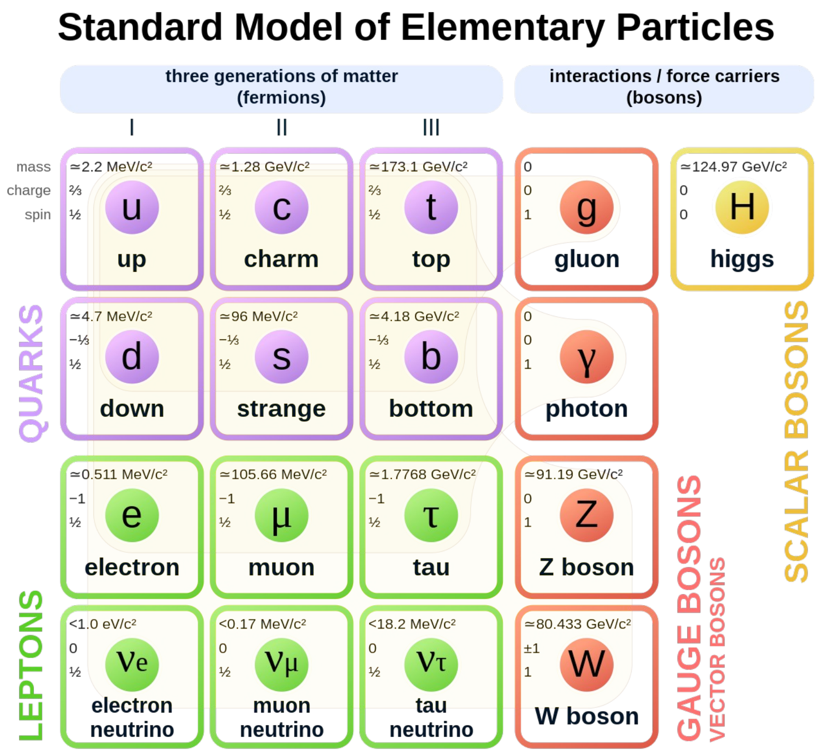
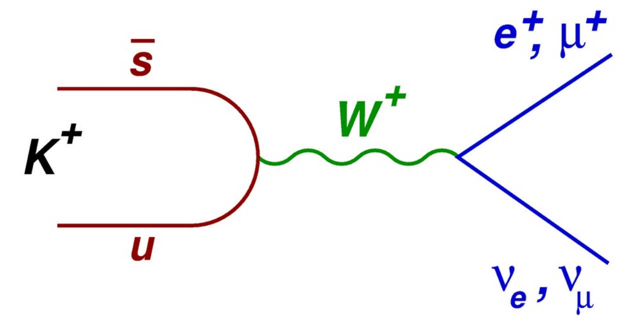
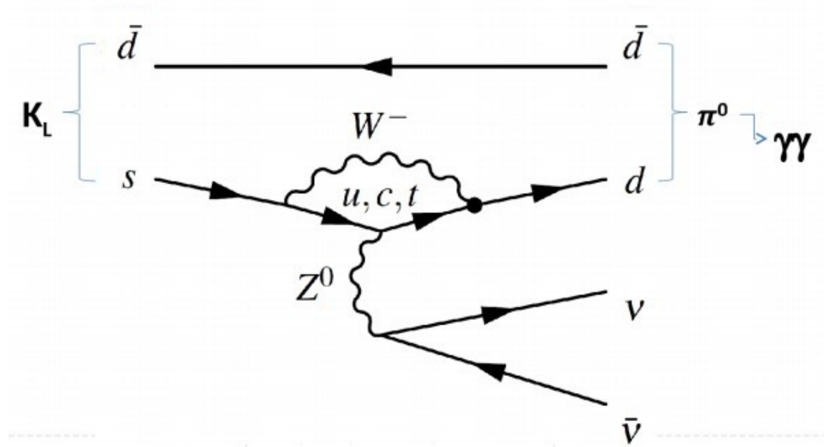
John Dainton Fest – Daresbury Laboratory, UK – 07/07/2023

Standard Model: a very successful theory!

Standard Model (SM): a mathematical description of the microscopic world (elementary particles and their interactions/decays)







Continuously confirmed by experiments since '70s!
[Latest confirmation: **Higgs boson discovery** (2012)]

Standard Model: the end of the story?

But..

We know SM is incomplete:

– Cannot explain neutrino masses (small, but not 0!)
– Cannot explain observation in the macroscopic world (matter-antimatter asymmetry in the Universe, dark matter, ...)

→ **Some yet-undiscovered particles ("new physics") are waiting for us!**

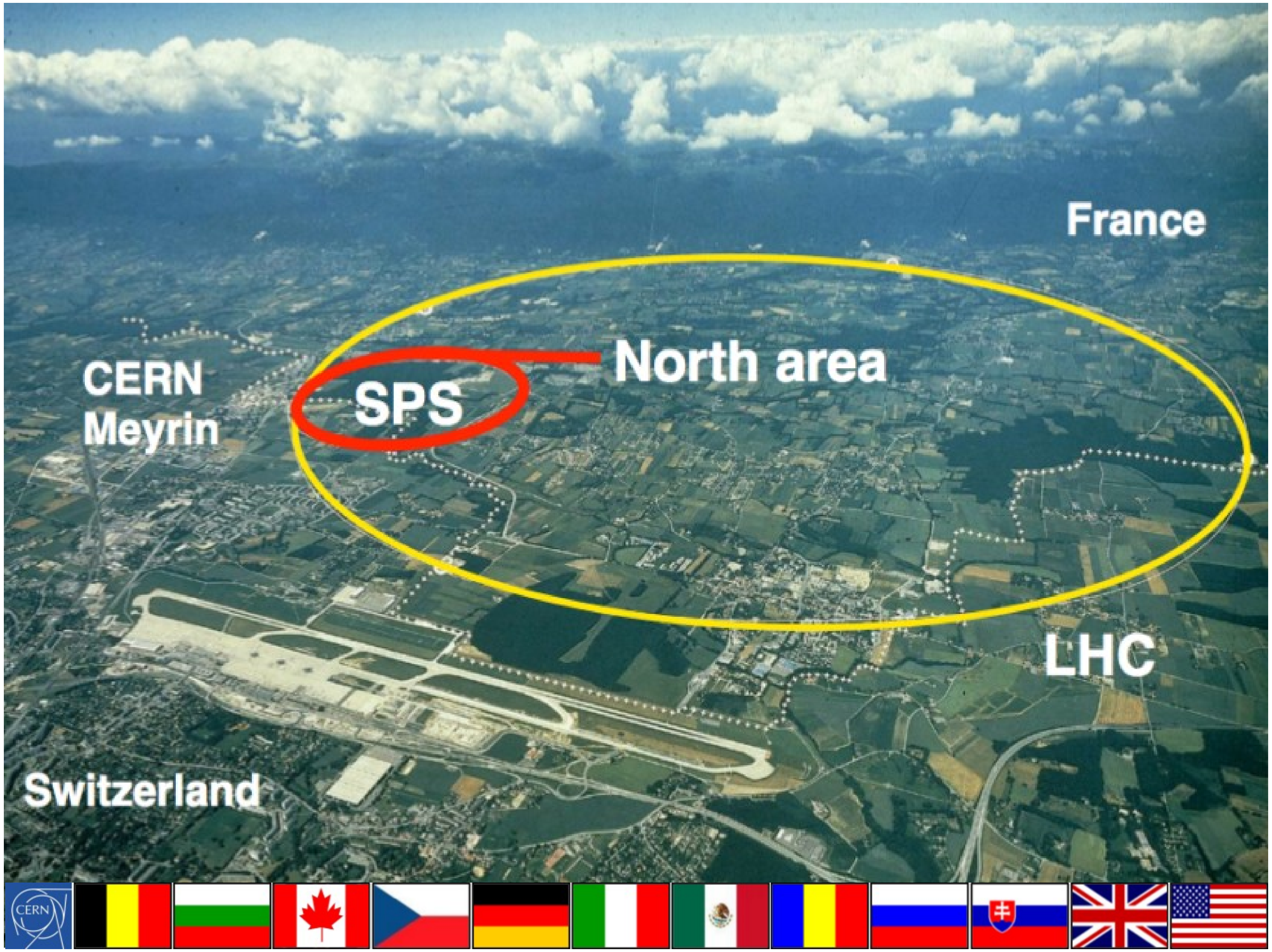
– Two approaches:

energy frontier (LHC) vs precision frontier (rare decays)

Kaon decay experiments
the quintessential precision frontier experiments:
– few decay modes
– simple final states
– large statistics
→ **Long history of successes!**

The NA62 experiment @ CERN

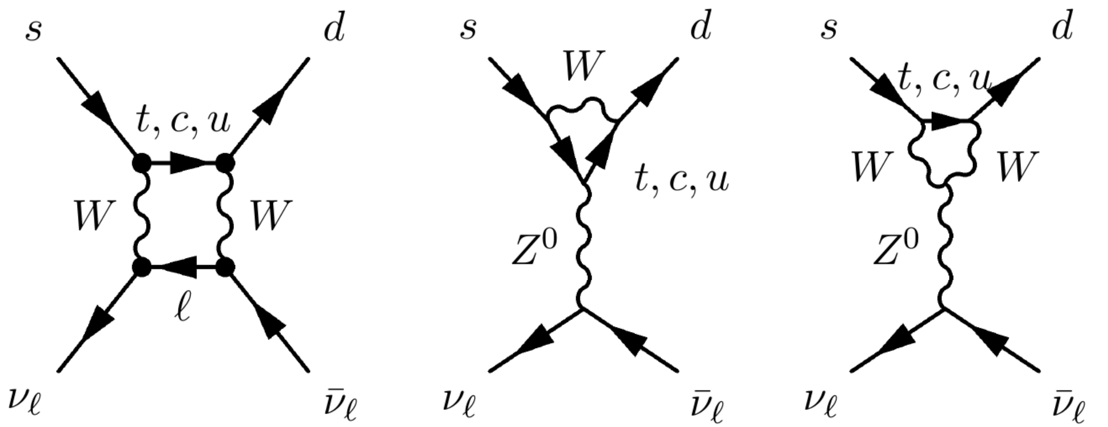
NA62 is the last from a long tradition of fixed-target Kaon experiments in the CERN North Area

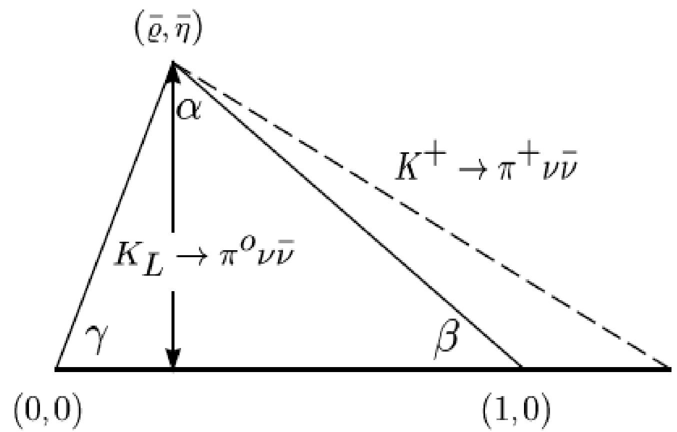


History of NA48/NA62 experiments		
1997 ↓ 2001	NA48 (K_S/K_L)	Re ε'/ε **Discovery of direct CPV**
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV, Rare K^+/K^- decays
2007 ↓ 2008	NA62-R_K (K^+/K^-)	$R_K = \Gamma(K^\pm \to e^\pm\nu) / \Gamma(K^\pm \to \mu^\pm\nu)$, Rare K^+/K^- decays
2016 ↓ 2025	**NA62 (K^+)**	**$K^+ \to \pi^+ \nu\bar{\nu}$, Rare K^+ and π^0 decays**

NA62: currently ~ 200 participants, 29 institutions from 12 countries

$K^+ \to \pi^+ \nu\bar{\nu}$: motivation & theory





- FCNC forbidden at tree level: 1-loop contributions as leading order
- Highly CKM suppressed: $BR(K^+ \to \pi^+ \nu\bar{\nu}) \sim |V_{ts}^* V_{td}|^2 \sim \lambda^{10}$

} high sensitivity to new physics

- Dominated by short-distance contribution (top quark)
- *t* quark contribution @ NLO QCD and 2-loop EW corrections, *c* quark @ NNLO QCD and 1-loop EW corrections
- Hadronic matrix element from $BR(K^\pm \to e^\pm \pi^0 \nu)$

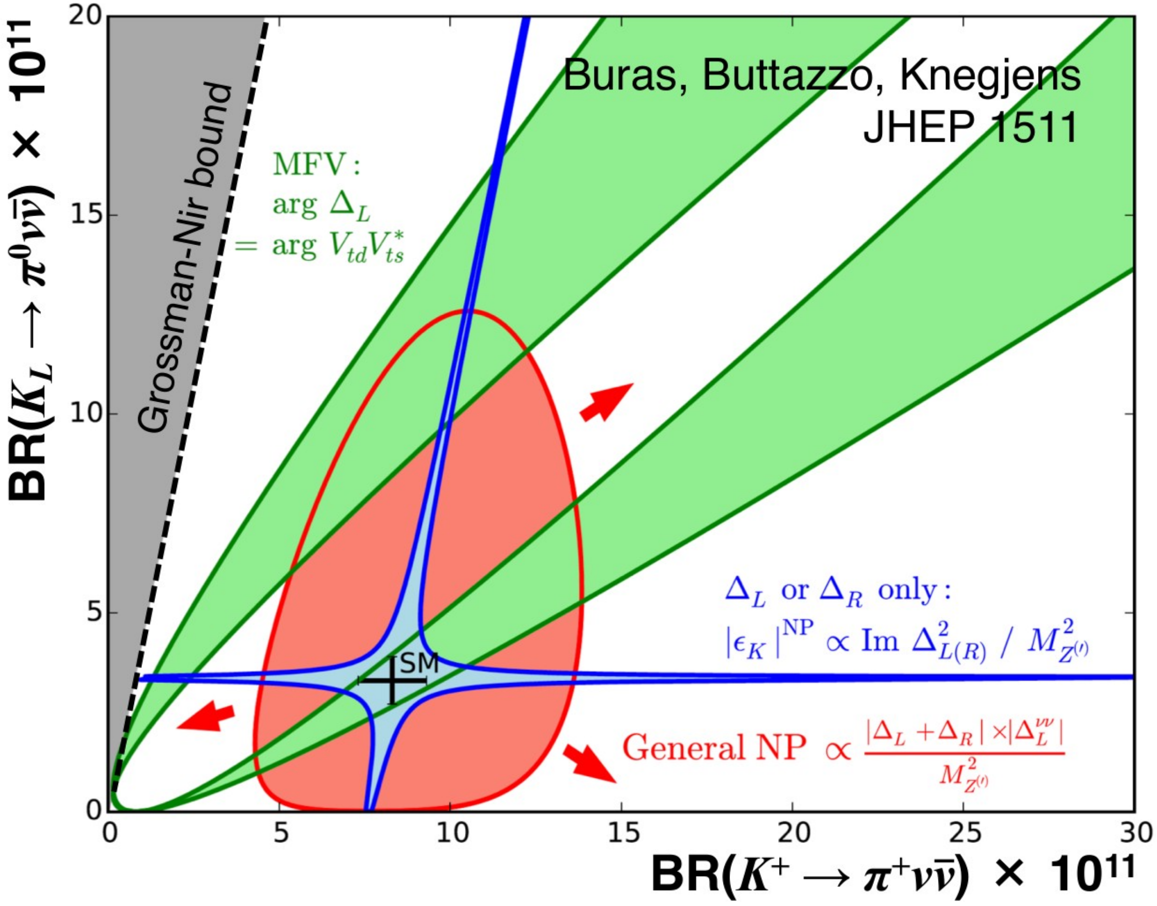
} high-precision theoretical prediction

- Measurement of $|V_{td}|$ complementary to those from $B-\bar{B}$ mixing or $B^0 \to \rho\gamma$
- Constraints on CKM unitary triangle

SM prediction:
$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$
Buras *et al.*, JHEP 1511 (2015) 033.

$K^+ \to \pi^+ \nu\bar{\nu}$: new physics scenarios

New physics affects K^+ and K_L BRs differently
Measurements of both can discriminate among NP scenarios



Models with:

- CKM-like flavor structure
  - MFV
- New flavor-violating interactions with dominant LH or RH couplings
  - Z/Z′ with pure LH/RH couplings
  - Littlest Higgs with T parity
- None of the above constraints
  - Randall-Sundrum

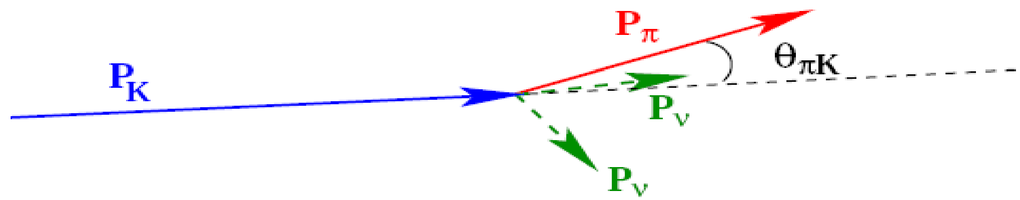
Grossman-Nir bound

Model-independent relation

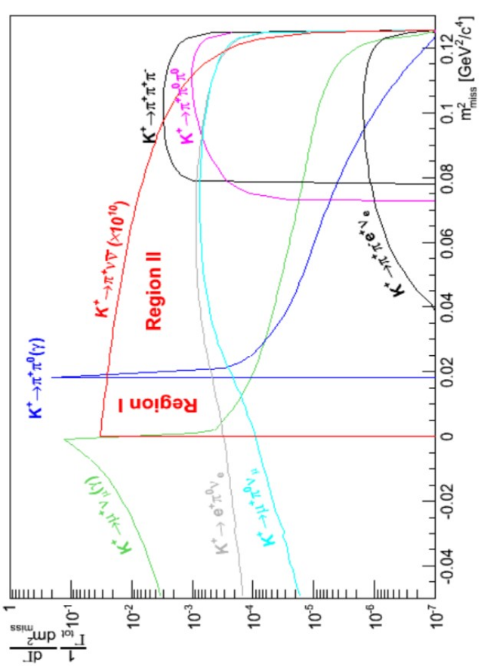
$$\frac{\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

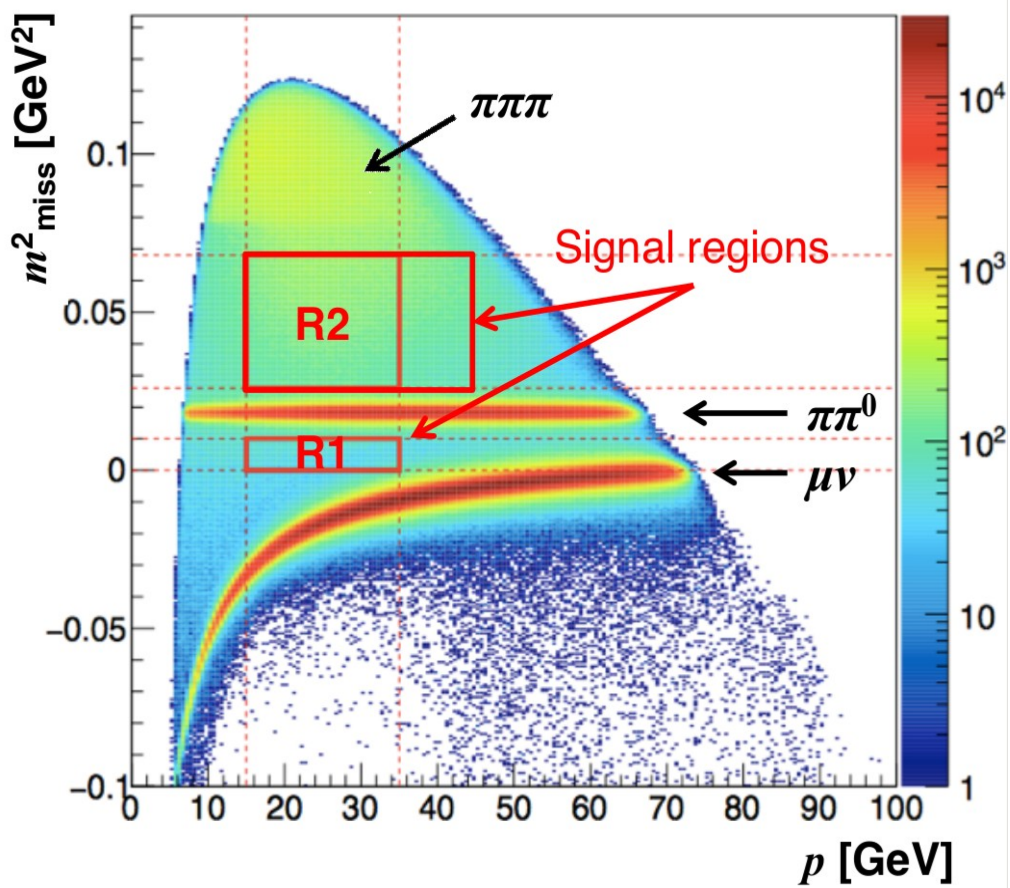
$K^+ \to \pi^+\nu\bar{\nu}$ at NA62: strategy

$K^+ \to \pi^+\nu\bar{\nu}$ signature:
Kaon track +
Pion track +
NOTHING ELSE



$$m^2_{miss} \approx m^2_K\left(1-\frac{|p_\pi|}{|p_K|}\right)+m^2_\pi\left(1-\frac{|p_K|}{|p_\pi|}\right)-|p_K||p_\pi|\theta^2_{\pi K}$$



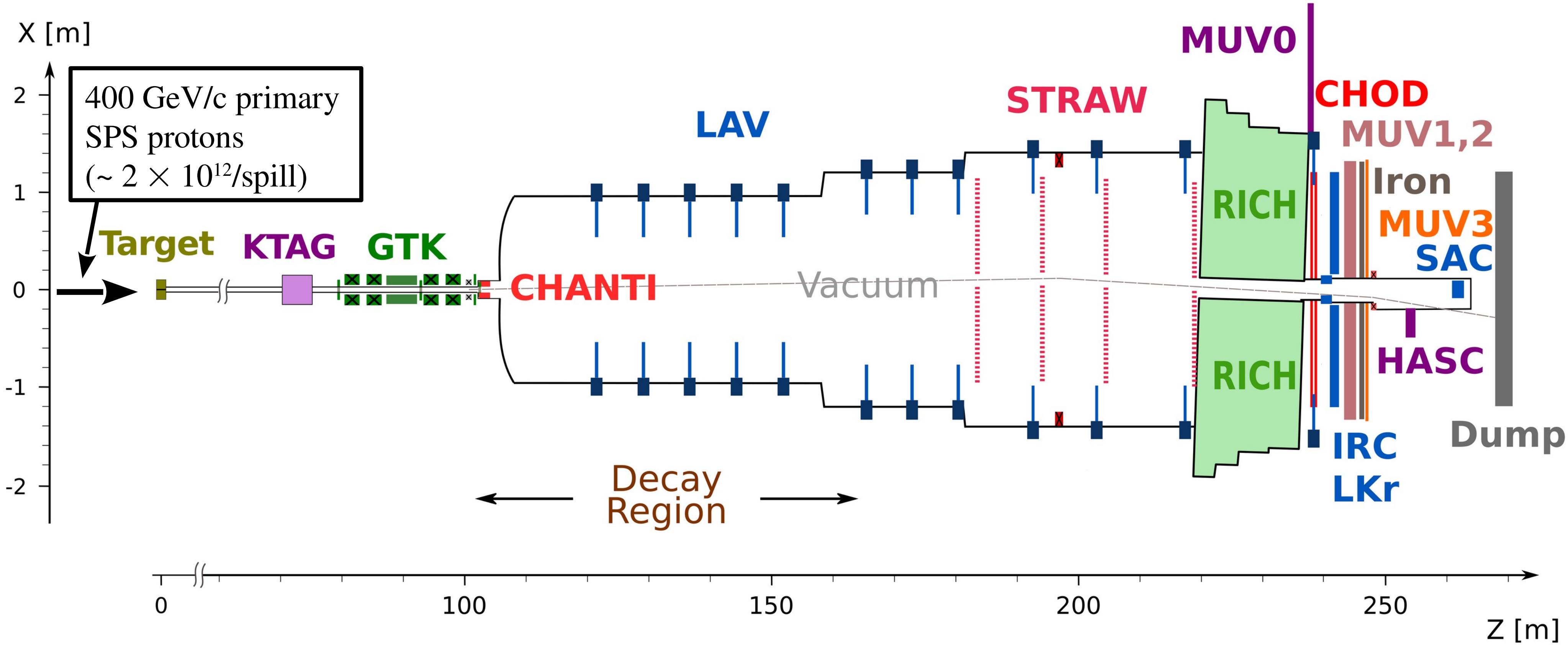


Main backgrounds:
$BR(K^+ \to \mu^+\nu) = 63.5\%$
$BR(K^+ \to \pi^+\pi^0) = 20.7\%$

NA62 Keystones:
- Precise tracking
- PID (in particular π/μ)
- Photon rejection
- Precise timing: O(100 ps)

Background rejection at ~ 10^{11} level

The NA62 beam and detector



Secondary hadron beam:

- Composition: K^+ (6%) / π^+ (70%) / p (24%)
- p = 75 GeV/c, $\Delta p/p \sim 1\%$
- 100 mrad divergence (RMS)
- 60 × 30 mm^2 transverse size
- Intensity: 750 MHz (45 MHz K^+)

Decay region:

- 60 m long fiducial volume
- Vacuum ~ $O(10^{-6}$ mbar)
- ~ 5 MHz K^+ decay rate

The NA62 beam and detector

...and this is how it really looks!

The NA62 beam and detector (2012)

...but let's have a look back at how it started!

The NA62 proposal (2005)

John Dainton was the chair of the SPSC when the committee **recommended the approval** of project P326, today known as NA62!

CERN-SPSC-2005-013
SPSC-P-326
11.6.2005

Proposal to Measure
the Rare Decay $K^+ \to \pi^+ \nu\bar{\nu}$ at the CERN SPS

CERN, Dubna, Ferrara, Florence, Frascati, Mainz, Merced, Moscow, Naples, Perugia, Protvino, Pisa, Rome, Saclay, Sofia, Turin

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Minutes of the 74th Meeting of the SPSC
Held on Tuesday and Wednesday, 15th-16th November 2005

5. FOLLOW UP FROM PREVIOUS MEETINGS

5.1 NA48-3 / P326

It is now becoming apparent that CERN, which has a well established record of excellence in this field, is the most appropriate platform for a future Kaon physics program, so that the proposed experiment is not only important, but most likely also unique.

The detailed list of concerns raised at the last SPSC has been discussed with the P326 proponents, with a formal meeting being held on November 14.

The SPSC referees were impressed with the answers received, the quality of the ongoing work, and progress over the three months since the last meeting.

An R&D program is defined, and a detailed planning and list of milestones have been provided. Requests for beam team in 2006 to study a number of outstanding experimental issues have been submitted.

The SPSC reaffirms its recommendation to support this R&D program.

The SPSC supports the requests for test-beam time and **recommends them for approval**, since these tests, and that of the LKr calorimeter photon detection efficiency in particular, are crucial to establishing the feasibility of the proposed experiment

Formally, the new collaboration does not yet have a recognised status. **The SPSC recommends** that the P326 proponents be assigned a recognised status, in order to effectively pursue the program of R&D and beam tests, further strengthen the collaboration, and make progress towards full approval.

Minutes of the 75th Meeting of the SPSC
Held on Tuesday and Wednesday, 24th-25th January 2006

- The Chairman reported on the 174th meeting of the Research Board (RB) in December 2005:
  - the RB was asked, and agreed, to confirm support for the R&D program for 2006 by the P326 proposal "Proposal to Measure $K^+ \to \pi^+ \nu\nu$ at the SPS" (SPSC-2005-013/P-326); the RB took note of the on-going R&D programme to make the necessary improvements in detectors for these measurements;

The birth of NA62-UK (2007-2010)

In 2007, **Birmingham** (Cristina Lazzeroni) **joined the NA62 collaboration**
<u>Expression of interest in major upgrade of a Cherenkov differential detector (CEDAR)</u>
But needed **funding + necessary infrastructure to allow the construction**

In 2008, Cristina Lazzeroni visited several groups from UK universities,
who expressed interest to join NA62, to seek for new collaborators.
It was then, when she met **John Dainton** & John Fry in Liverpool.
Impressed by the group and the facilities, on the way home,
she called Augusto Ceccucci saying "**this is it, we can build it!**"

At that point, it became clear that the best opportunity to procure funding
was to **apply for an ERC Advanced Grant with John Dainton as the PI**
John Dainton's clear vision of the global physics picture was instrumental in writing
the first successful experimental HEP case in an ERC Advanced Grant

ERC Advanced Grant 2010 **All domains** **List of selected Principal Investigators (by country of host institution)**

DAINTON	John	University of Liverpool	UK	UniversaLepto	Test of Lepton Flavour Universality with Kaon Decays	PE2

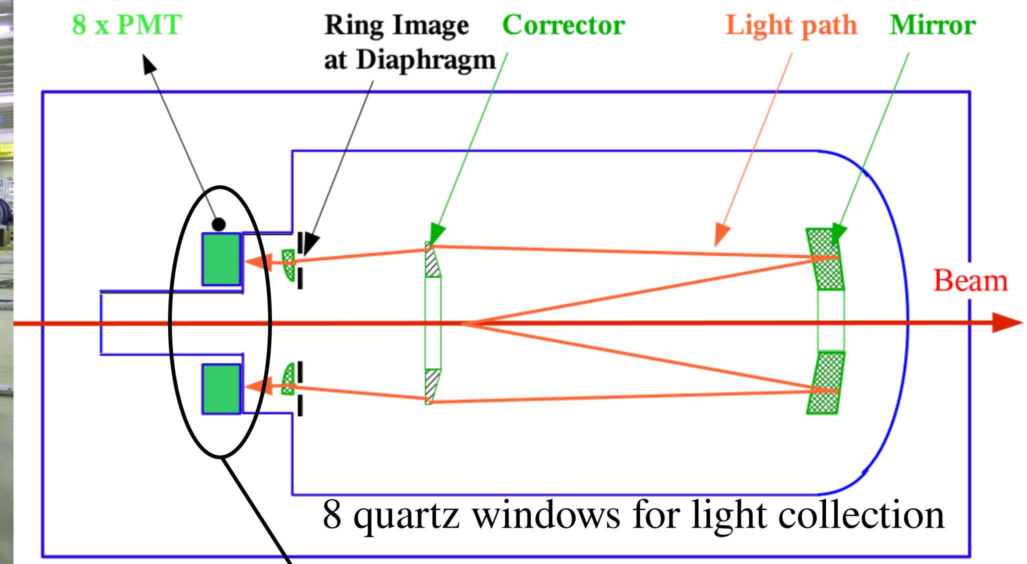
This allowed the **construction of the Cedar/KTAG detector**
and a **considerable expansion of the NA62-UK group**
(funding several PhD students & post-docs)

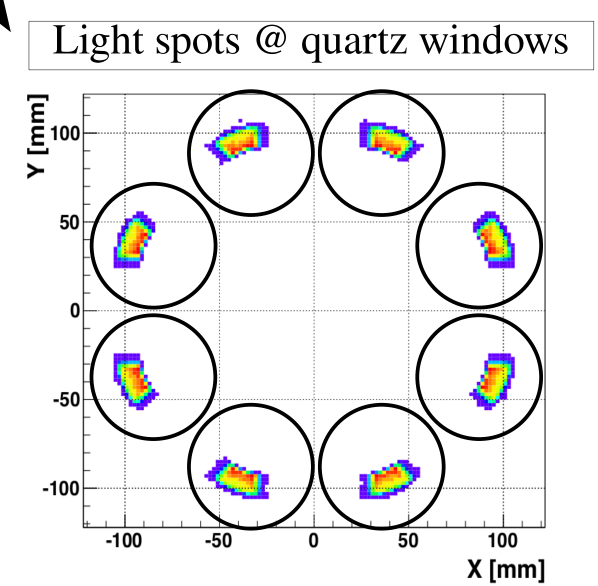
The CEDAR detector

CEDAR: ChErenkov Differential counter with Achromatic Ring focus

CEDAR characteristics:

- 1.1 m³ of Nitrogen @ 1.7 bar as radiator
- Adjustable diaphragm aperture (0→20 mm)



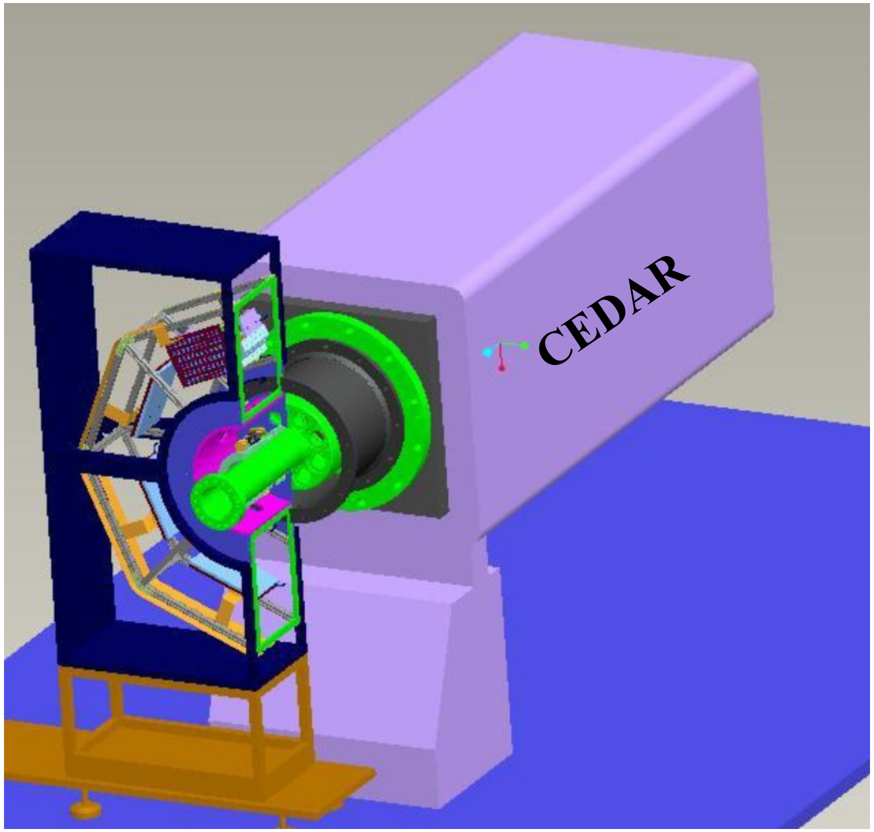


Kaon ID system requirements vs CEDAR:

- Kaon ID efficiency of at least 95% ✓
- Pion Mis-ID probability < 10^{-4} ✓
- Kaon Time resolution < 100 ps ✗
- Sustain a ~ 45 MHz kaon rate ✗

The KTAG upgrade (2010-2014)

Kaon TAGger (KTAG): Major upgrade of old differential Cherenkov detector (CEDAR)



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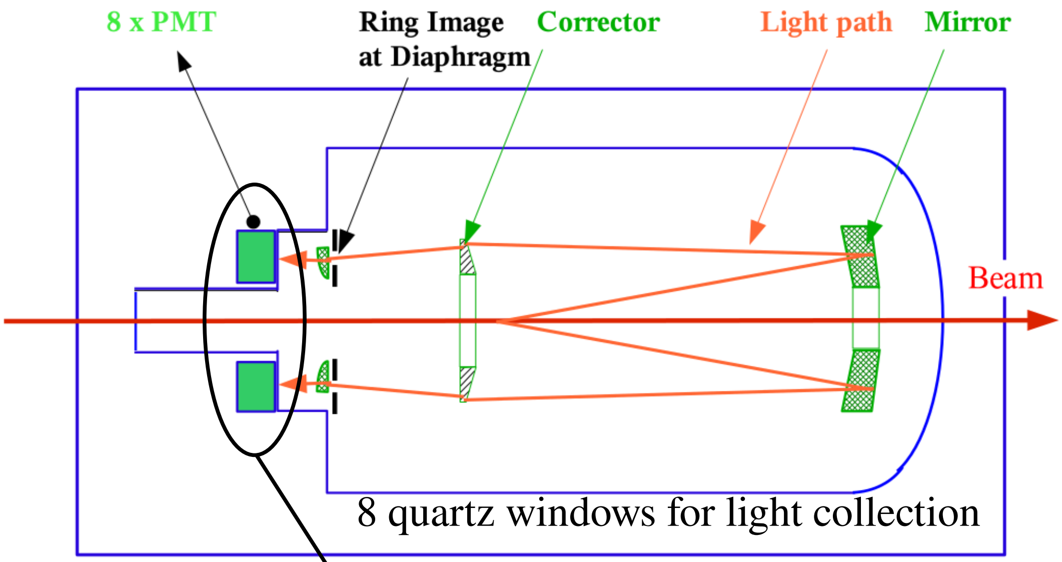

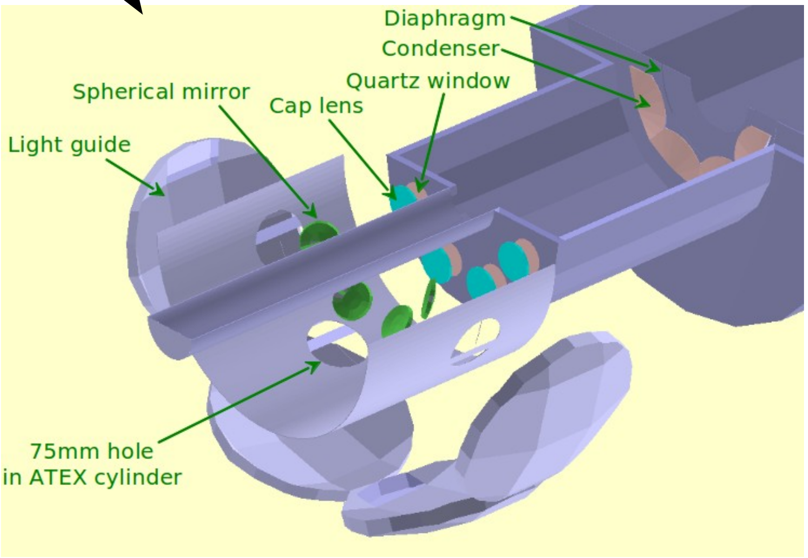

Kaon ID system requirements vs CEDAR/KTAG:

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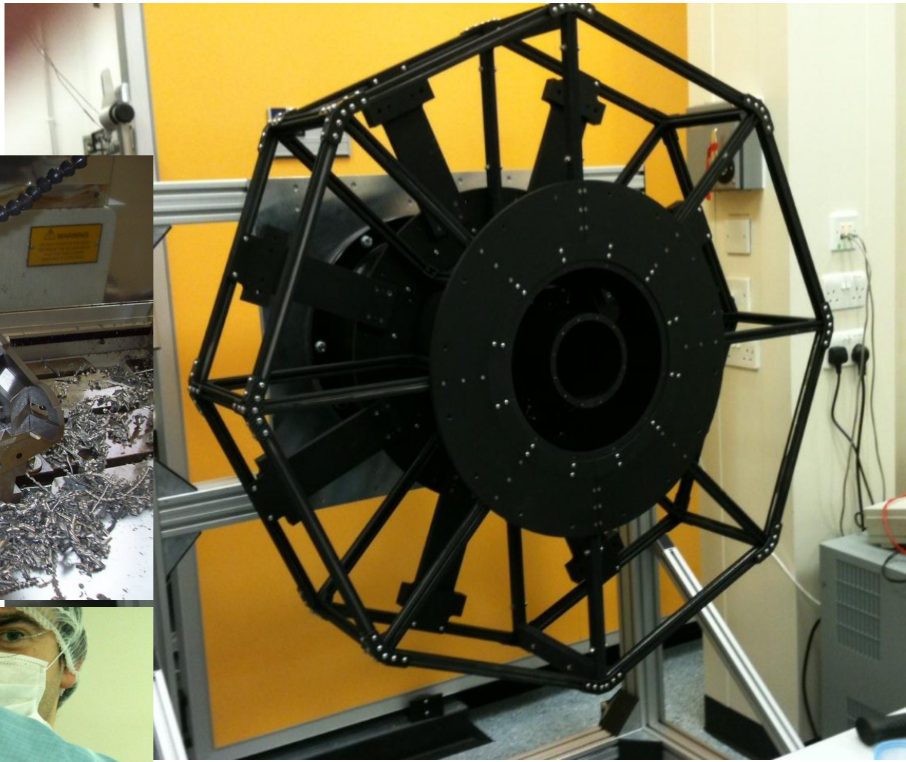
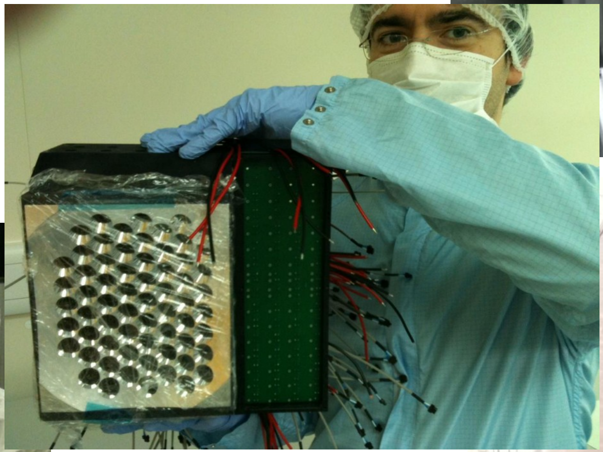
The KTAG upgrade (2010-2014)

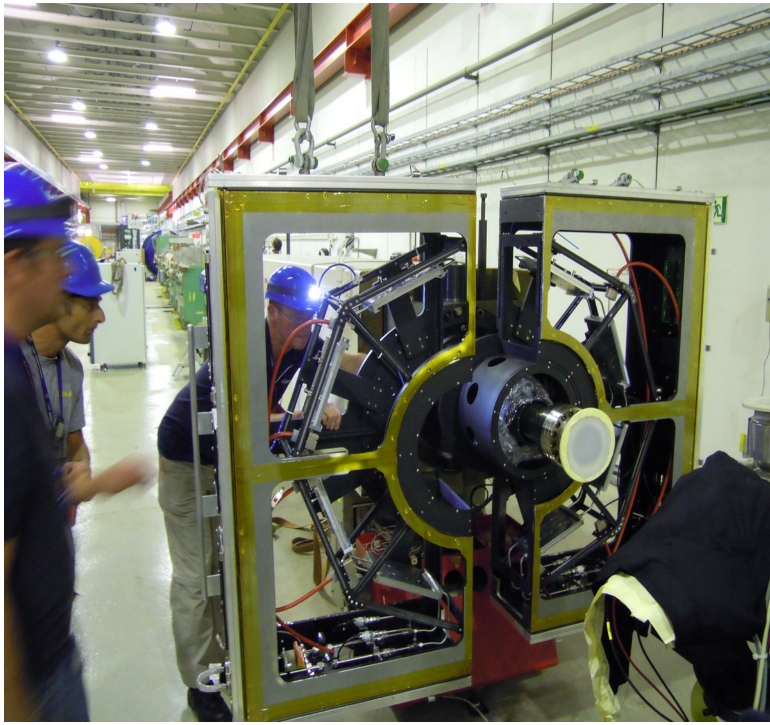
KTAG mechanics + photodetectors
(January – August 2012)





The KTAG upgrade (2010-2014)

KTAG delivery
+ installation at CERN
(September 2012)



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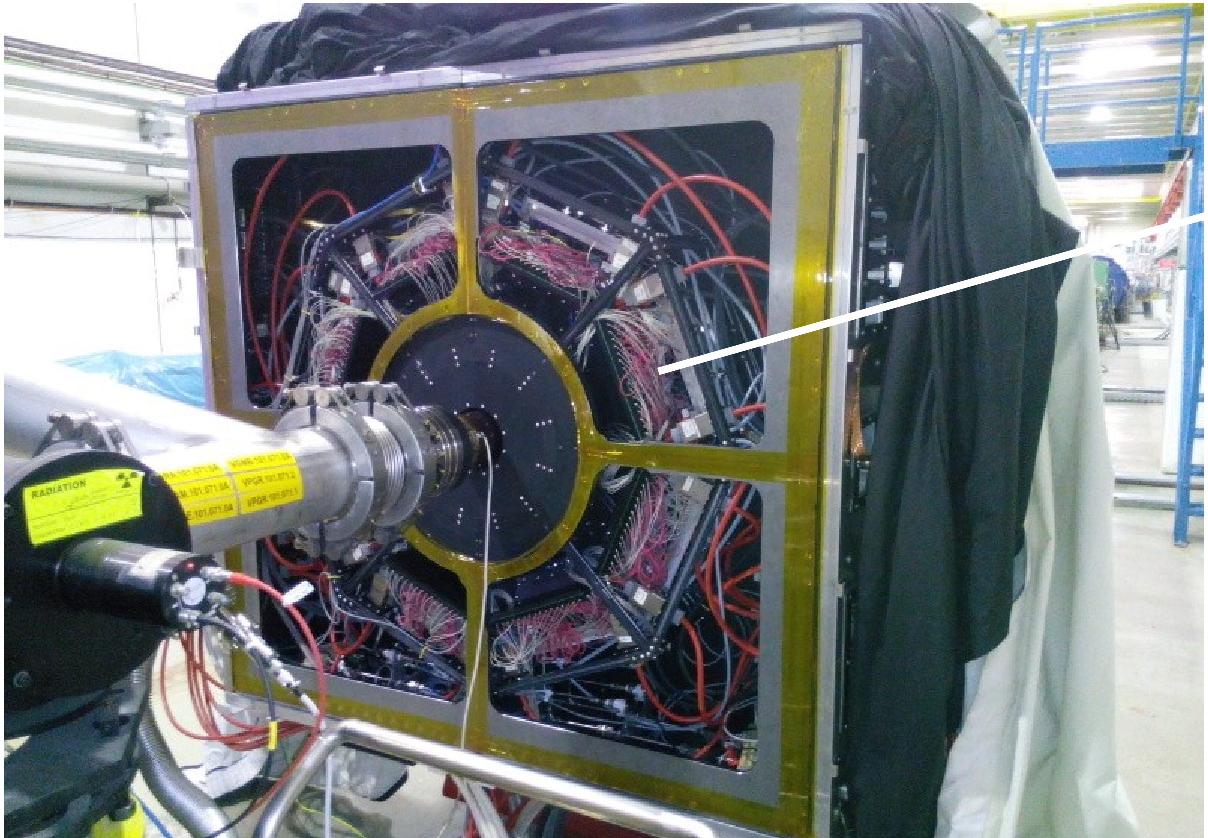
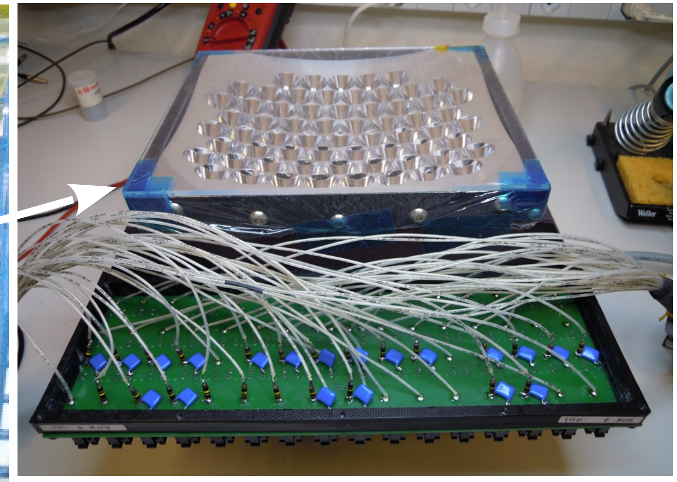


E. Goudzovski *et al.*, NIM A (2015) 86



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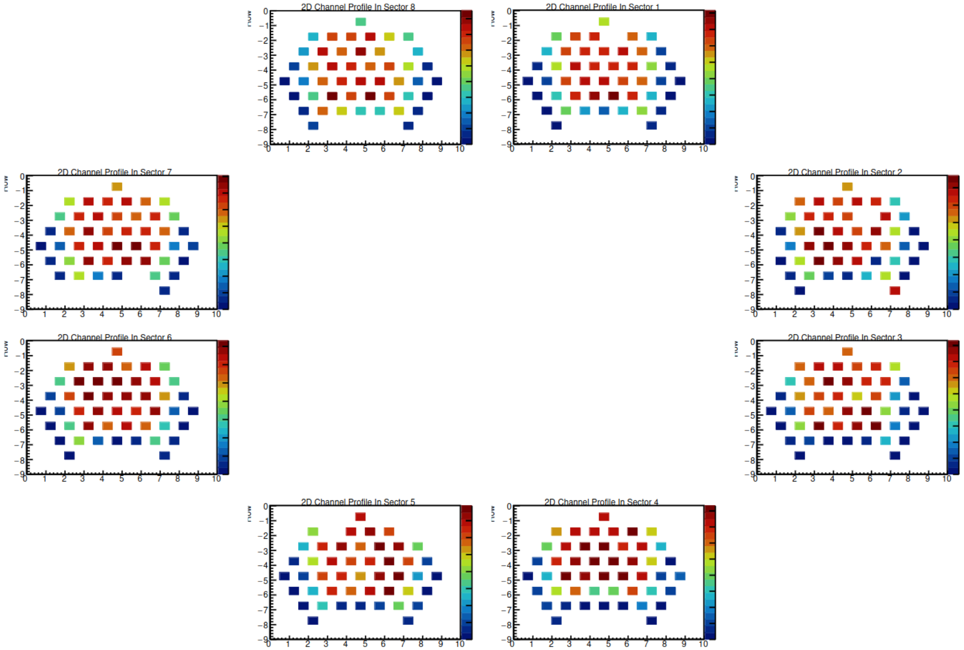
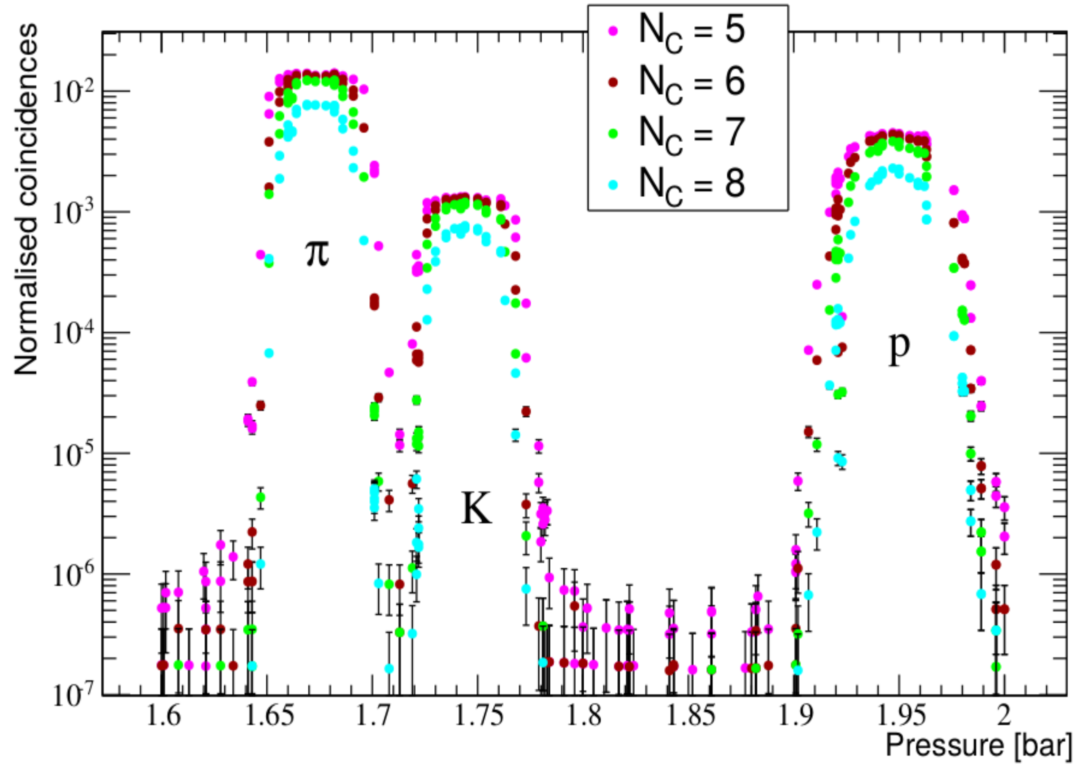
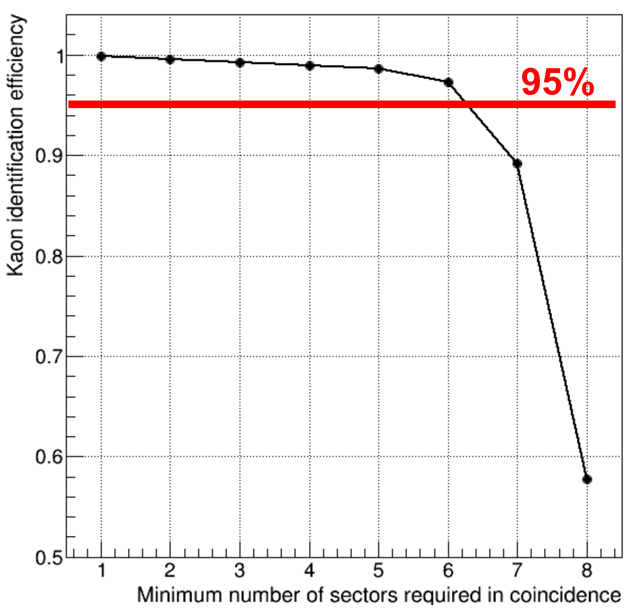
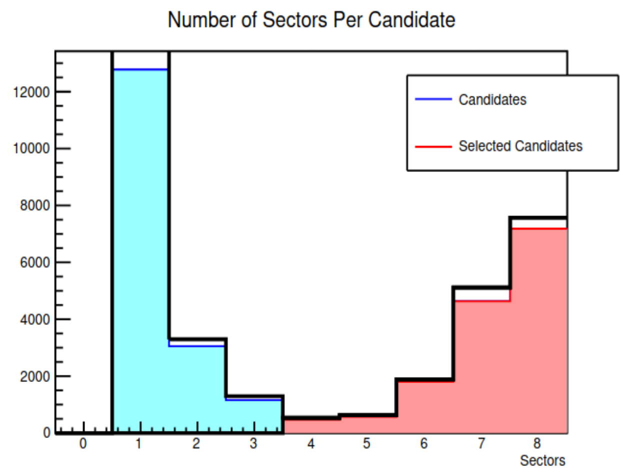
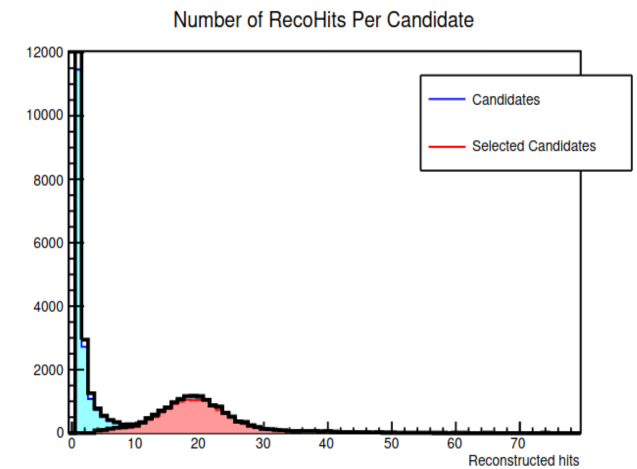
The KTAG performances



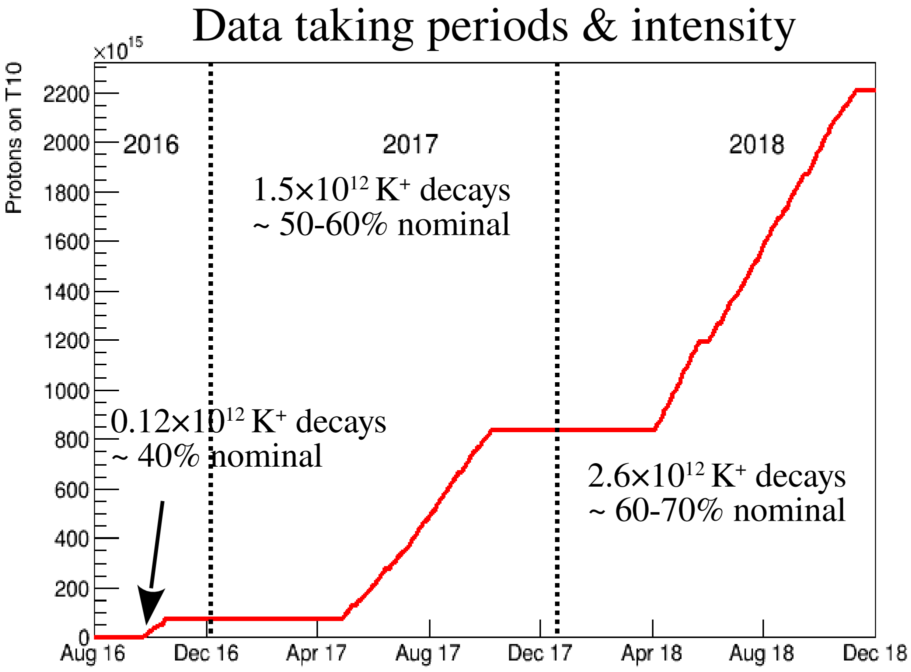








The NA62 Run1 (2016-2018)



2.2×10^{18} protons on target,
5×10^{12} K^+ decays collected

The $K^+ \to \pi^+ \nu\bar{\nu}$ result: 2016-2018 data

2018 data:

JHEP 06 (2021) 093

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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Combined NA62 2016-2018 data

SES = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$

Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

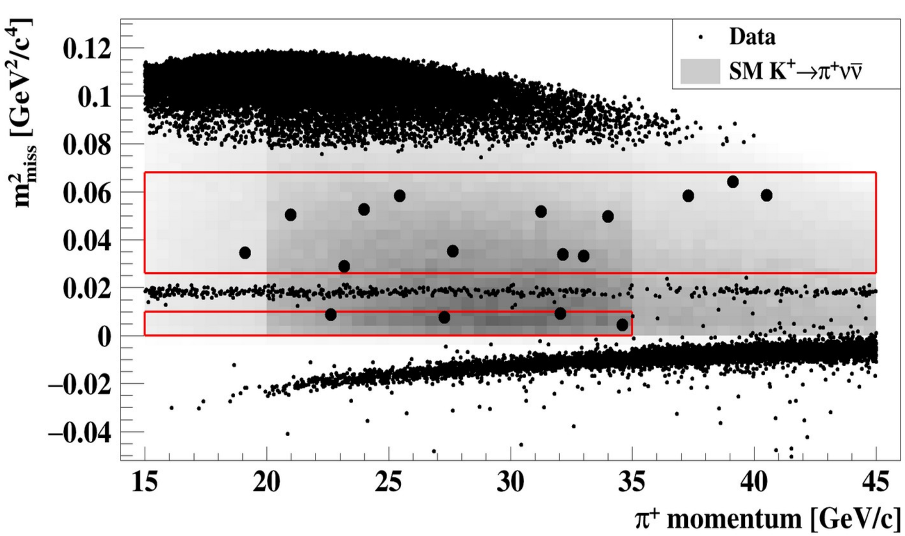
Expected bkg: $7.03^{+1.05}_{-0.82}$

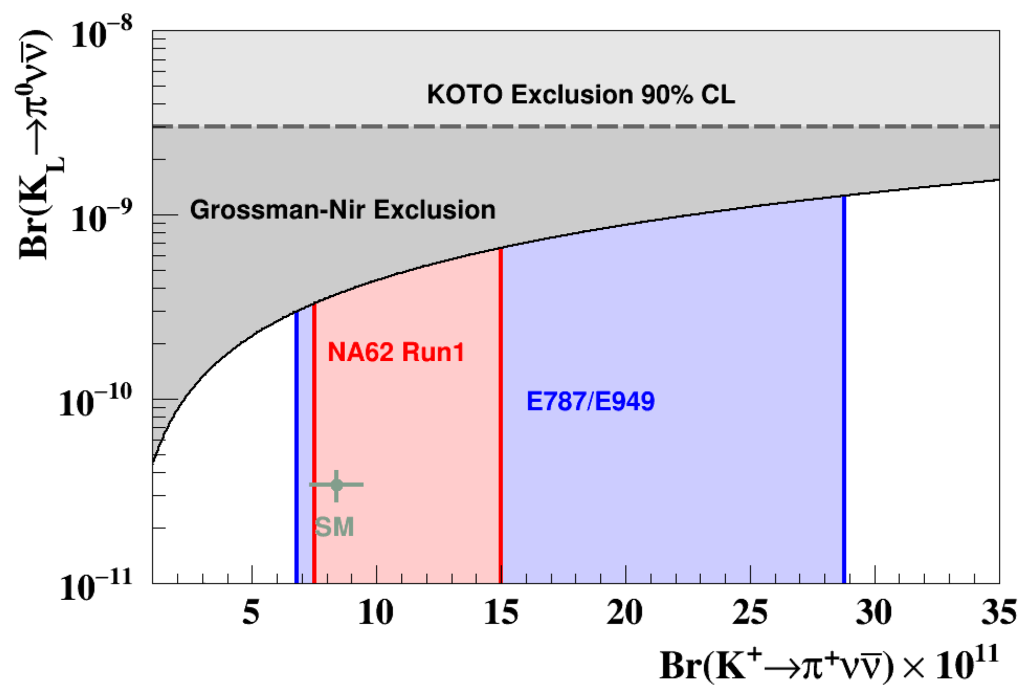
Observed: 20 (1+2+17) events

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

3.4σ significance, most precise measurement to date!

Expected: 7.6 signal + 5.4 background events
Observed: 17 $K^+ \to \pi^+ \nu\bar{\nu}$ candidates!





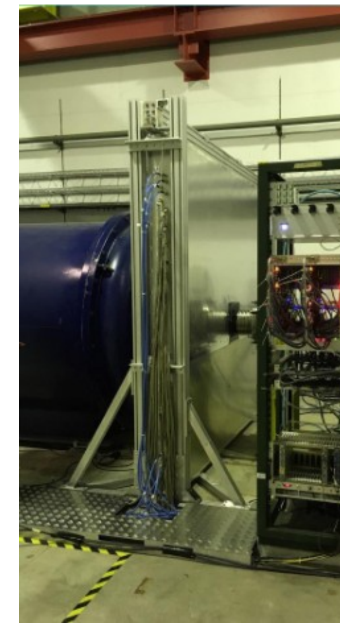
The NA62 Run2 (2021-2025)

NA62 recommended by SPSC and approved by Research Board until LS3

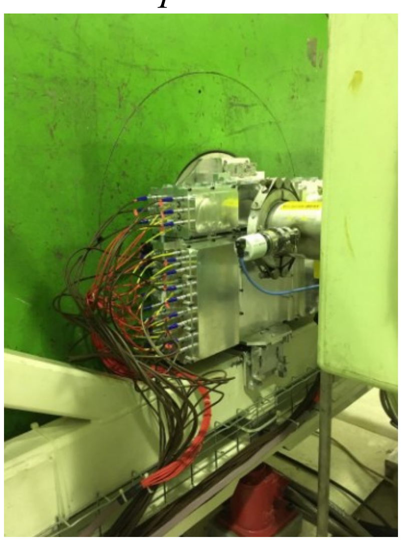
Improvements in NA62 Run2:

- DAQ stability improved: run at higher beam intensity (70% → 100%)
- Rearrangement of beamline elements around GTK achromat
- Added 4th station to GTK beam tracker
- Additional veto counters around beam pipe (both upstream/downstream the FV)
- New veto hodoscope upstream of decay volume (ANTI0)
- New hydrogen-filled Kaon identification detector (CEDAR-H) to reduce material along the beam line (since 2023)

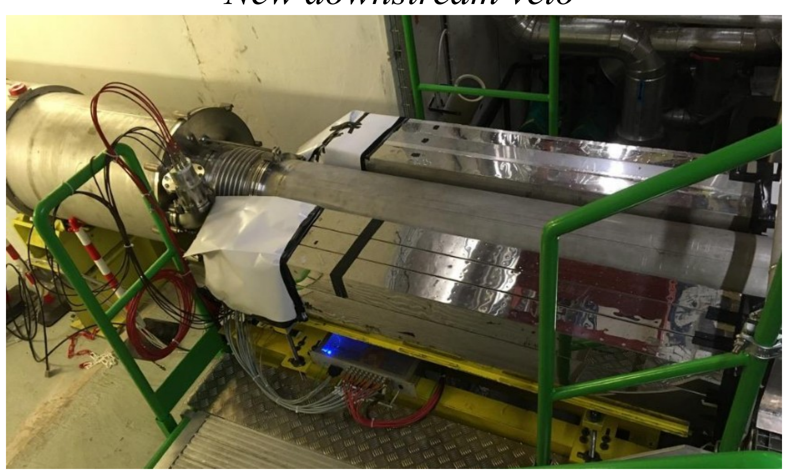
New ANTI0



New upstream veto



New downstream veto



New CEDAR-H

HIKE: a bright future for K physics

2020 Update of the European Strategy for Particle Physics (CERN-ESU-014):
Rare kaon decays at CERN mentioned in "Other **essential activities** for particle physics" (Sec. 4)

High-Intensity Kaon Experiments (HIKE):

Long-term Kaon physics programme @ CERN SPS, covering ~ 20 years

Two experimental phases with different beam and detector layout:

- **Phase 1**: $K^+ \to \pi^+ \nu\bar{\nu}$ @ 5% precision + many other rare K^+ decays
- **Phase 2**: $K_L \to \pi^0 \ell^+ \ell^-$ (ℓ = e, μ) @ 20% precision + many other rare K_L decays


SPSC-I-257

HIKE, High Intensity Kaon Experiments at the CERN SPS

Letter of Intent

The HIKE Collaboration

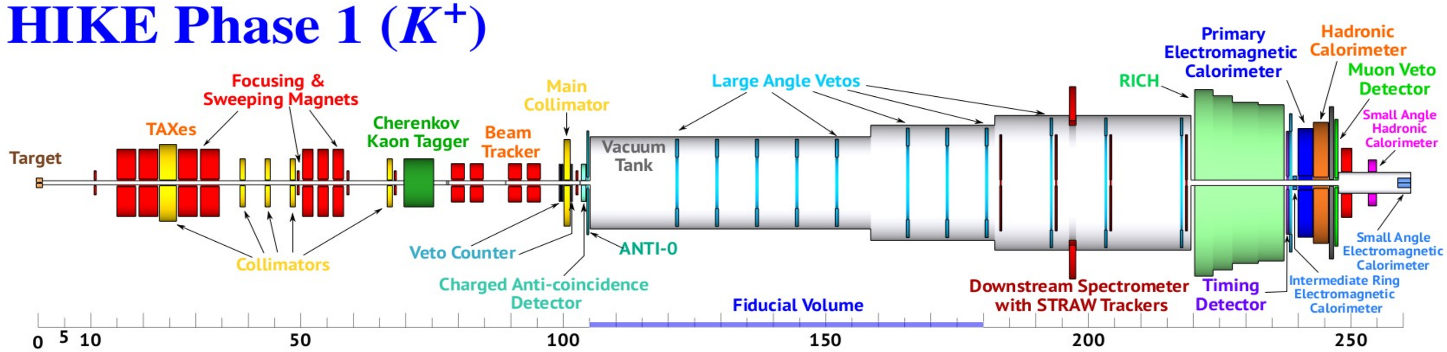
CERN-SPSC-2022-031 / SPSC-I-257
07/11/2022

Abstract

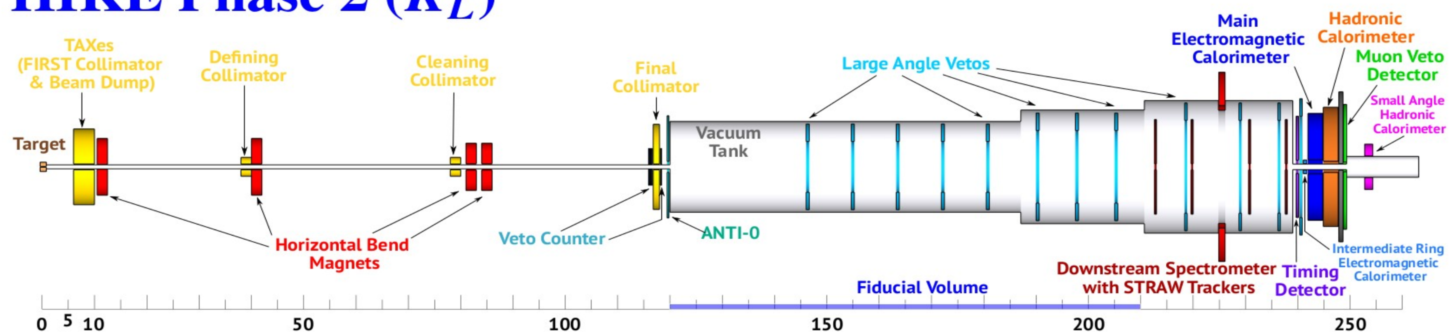
A timely and long-term programme of kaon decay measurements at a new level of precision is presented, leveraging the capabilities of the CERN Super Proton Synchrotron (SPS). The proposed programme is firmly anchored on the experience built up studying kaon decays at the SPS over the past four decades, and includes rare processes, CP violation, dark sectors, symmetry tests and other tests of the Standard Model. The experimental programme is based on a staged approach involving experiments with charged and neutral kaon beams, as well as operation in beam-dump mode. The various phases will rely on a common infrastructure and set of detectors.

175 collaborators from 37 institutions

HIKE Phase 1 (K^+)



HIKE Phase 2 (K_L)



Future and ambitious programme to continue what John Dainton helped to ignite!

Thank you John!

John's clear vision of the role of kaon physics in the global physics picture was instrumental in **recommending the approval of NA62**

John was absolutely pivotal in securing the **ERC Advanced Grant application**

John has not only a **fine knowledge of physics**,
but also insights of "how things work" and the intricacy of the human nature.
He often supported me when I was the NA62 Spokesperson

John has always had at heart the **future of the young generation**.
I'm one of the many he has supported during the years