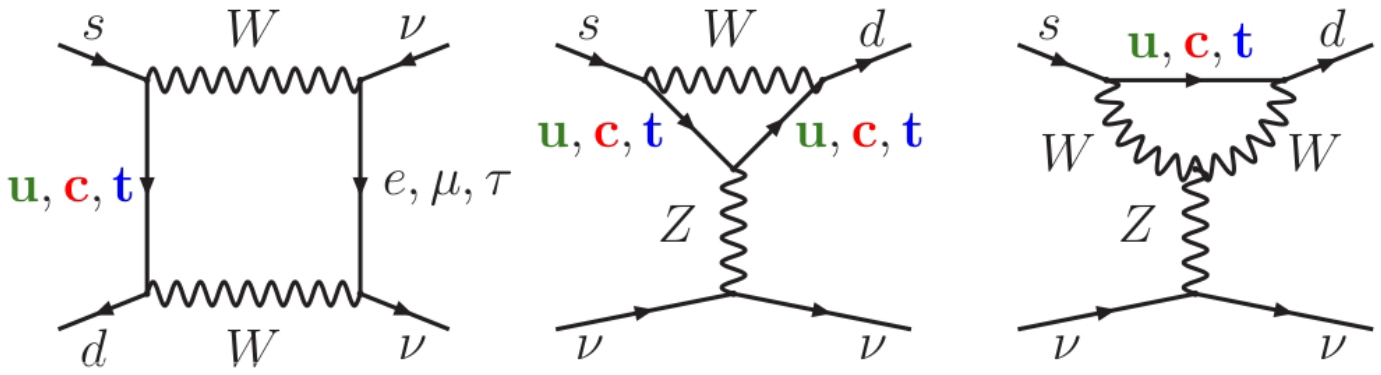
Attività e prospettive dell'esperimento NA62

F. Ambrosino, M. D'Errico, G. De Nardo, C. Di Donato, R. Fiorenza, R. Giordano, P. Massarotti, M. Merola, M. Mirra, M. Napolitano, G. Saracino

Riunione Gruppo 1, Napoli 21/12/2021

$K^+ \to \pi^+ \nu\bar{\nu}$ decay

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



- **Very clean theoretically:**
  - **SD contribution dominate $A_q \sim \frac{M_q^2}{M_W^2} V_{qs}^* V_{qd}$**
  - **Hadronic matrix element related to the precisely measured BR ($K^+ \to \pi^0 e^+ \nu_e$)**

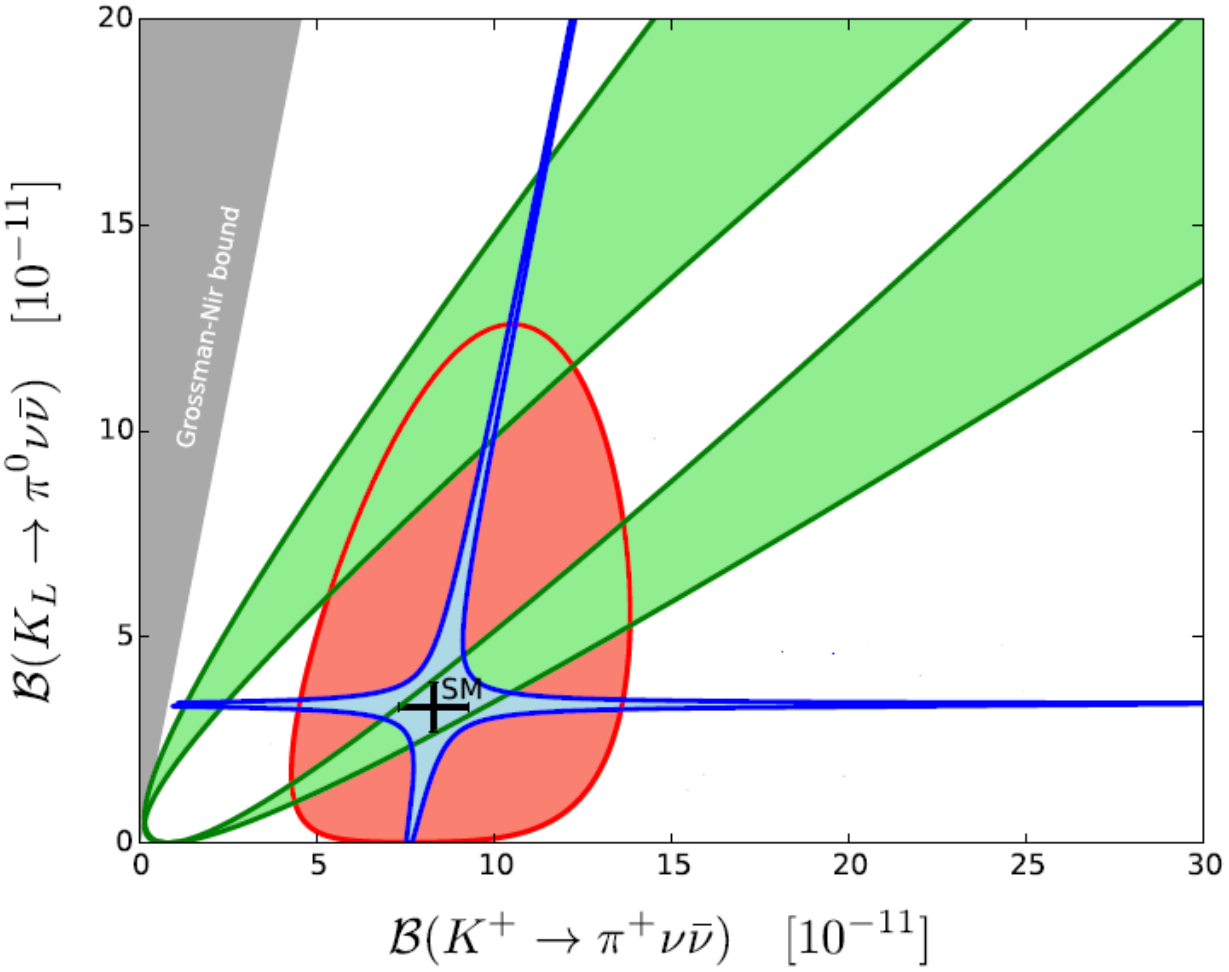
- **BR proportional to $|V_{ts}^* V_{td}|^2$**

- **SM prediction [Buras. et. al., JHEP11(2015)033]**

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

$K^+ \to \pi^+ \nu\bar{\nu}$ beyond SM

Possibility to distinguish among different models

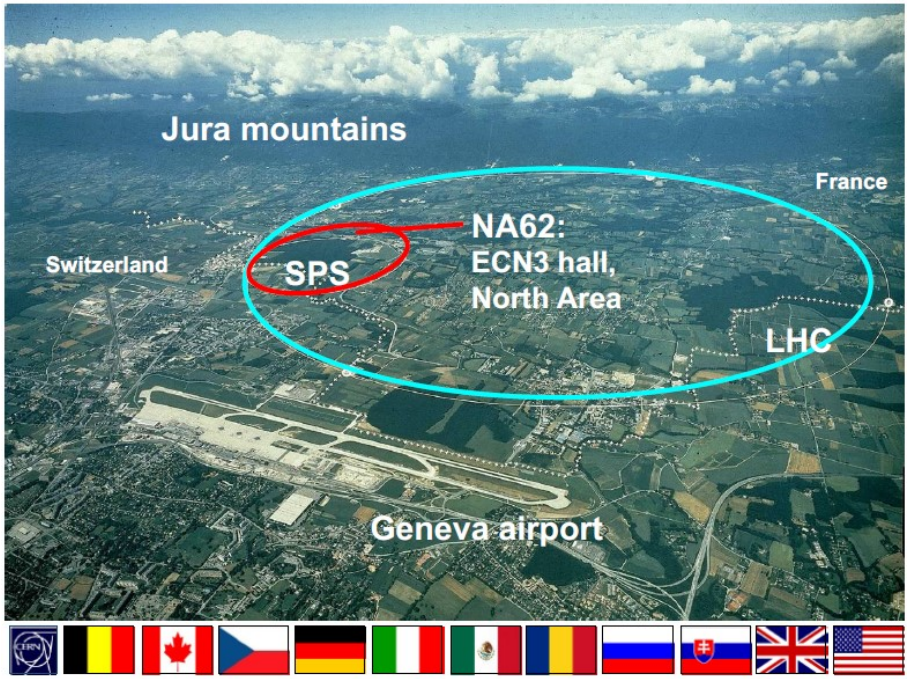


- **Models with a CKM-like structure of flavour interactions (e.g. MFV)**
- **Models with new flavour and CP-violating interactions in which either left or right handed currents fully dominate (e.g. Z or Z' FCNC scenarios)**
- **Models like Randall-Sundrum**

NA62 experiment @ CERN

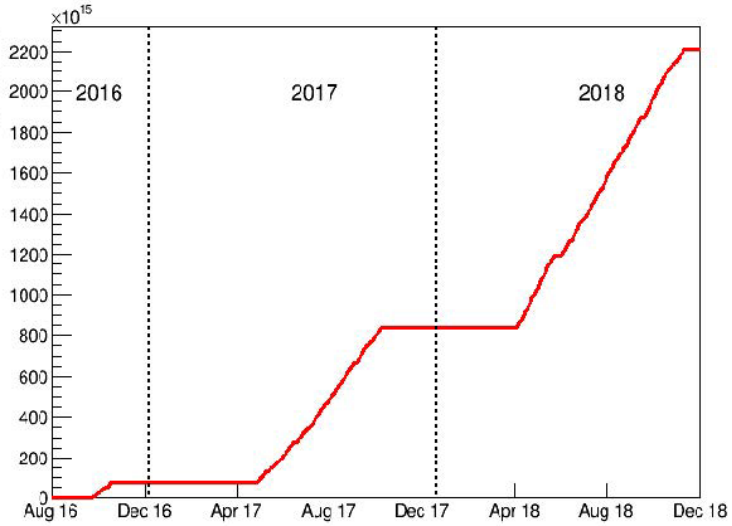
Fixed target experiment at CERN SPS.
Main NA62 goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement to 10% precision with a novel decay-in-flight technique.
Officially approved to run up to LS3.

Currently ~300 participants from 31 institutions.



NA62 timeline and dataset

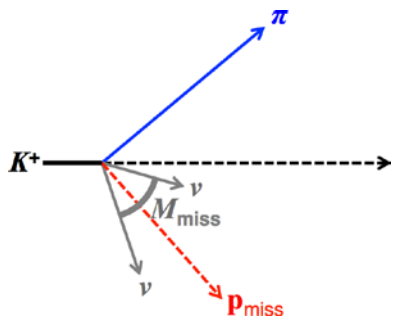
Run 1 (2016-2018) integrated luminosity: 2.2×10^{18} POT collected



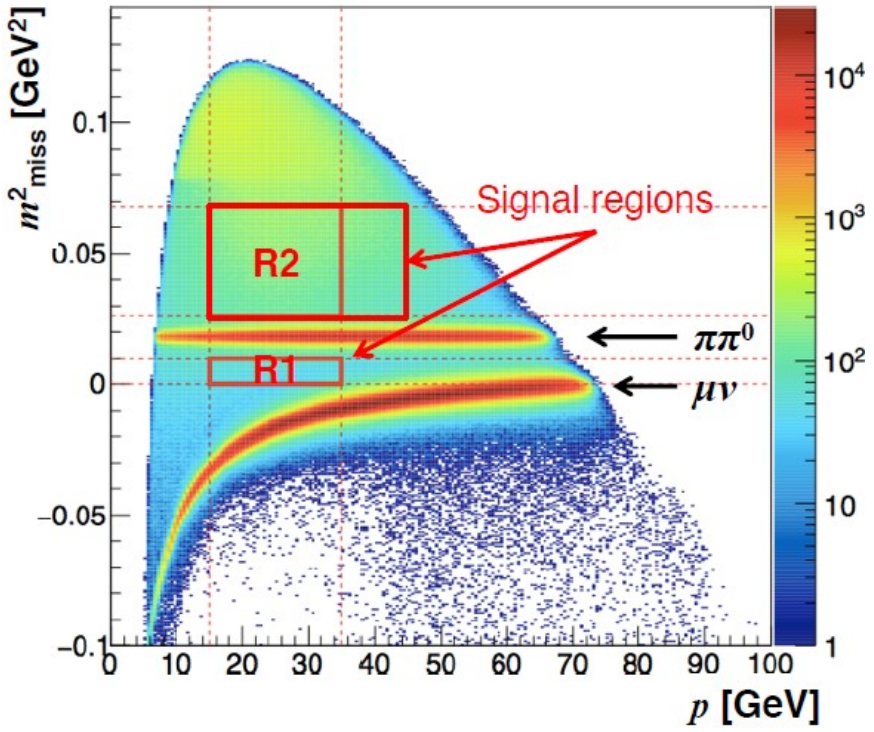
- **Commissioning run 2015: minimum bias data (~3×10^{10} protons/pulse).**
- **Physics run 2016 (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.**
- **Physics run 2017 (160 days, ~1.9×10^{12} ppp): 2×10^{12} useful K^+ decays.**
- **Physics run 2018 (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.**
- **Run 2 in progress: June 2021 till LS3 (~3×10^{12} ppp).**

$K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62

Signal: BR = (8.4 ± 1.0) × 10^{-11}



K track in
π track out
No other particles in final state
$m^2_{miss} = (P_K - P_\pi)^2$



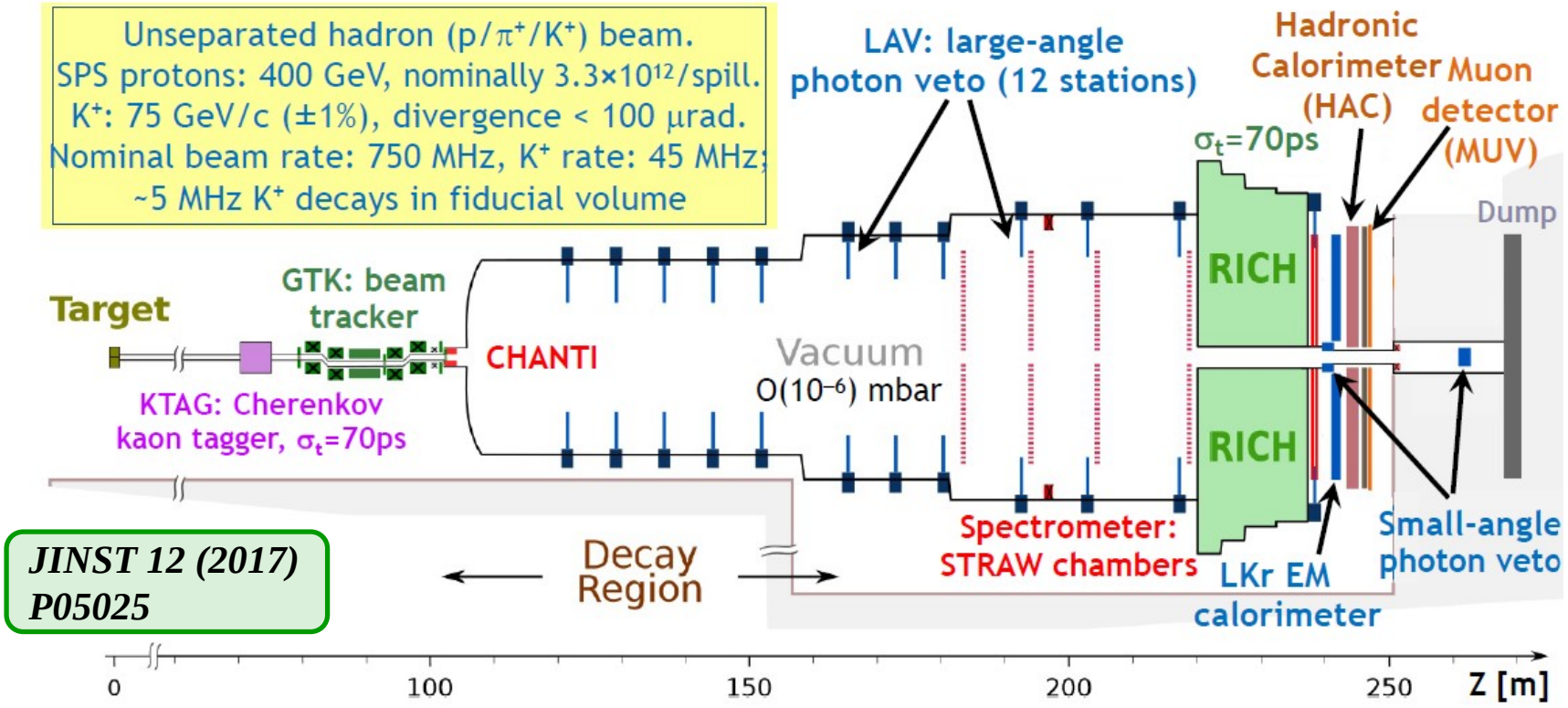
Main backgrounds

$K^+ \to \mu^+ \nu(\gamma)$ BR = 63.5%
$K^+ \to \pi^+ \pi^0(\gamma)$ BR = 20.7%
$K^+ \to \pi^+ \pi^+ \pi^-$ BR = 5.58%
Upstream beam background

Selection criteria

K^+ beam identification
Single track in final state
π^+ identification (μ^+/e^+ event rejection)
γ rejection

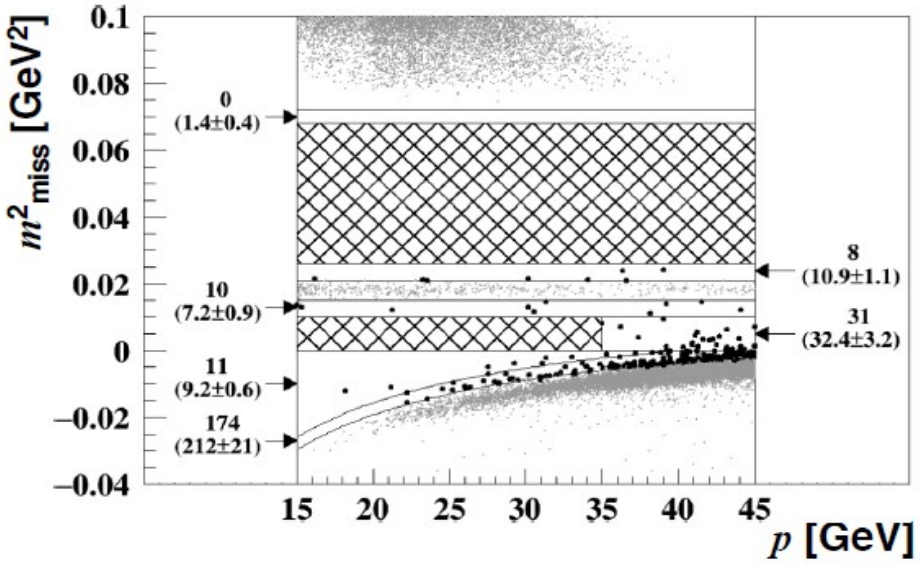
Beamline and detector



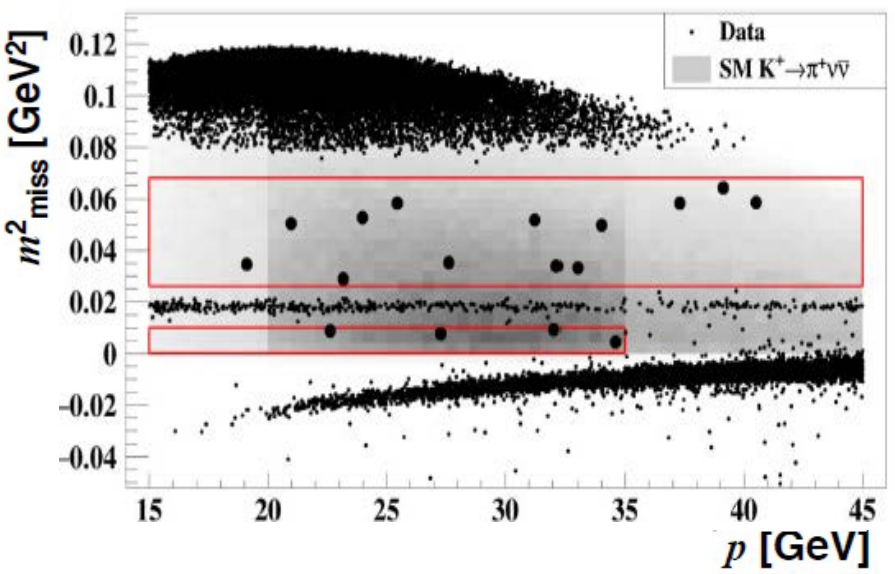
- ✓ **Excellent time resolution:** $\mathcal{O}$**(100 ps) to match beam and daughter particle information**
- ✓ **Kinematics: rejection of main** K **modes** 10^{-4} **via kinematics reconstruction**
- ✓ **PID capability (RICH+LKr+MUV):** $\mathcal{O}(10^{-6})$ **muon suppression**
- ✓ **High-efficiency photon veto:** 10^{-8} **rejection of** π^0 **for** $E(\pi^0) > 40$ **GeV**

NA62 Run 1 final result

Background estimates for 2018



17 signal candidates in 2018 data



NA62 2016-2018 data : *JHEP 06 (2021) 093*

Expected SM sig: $10.01 \pm 0.42_{sys} \pm 1.19_{ext}$

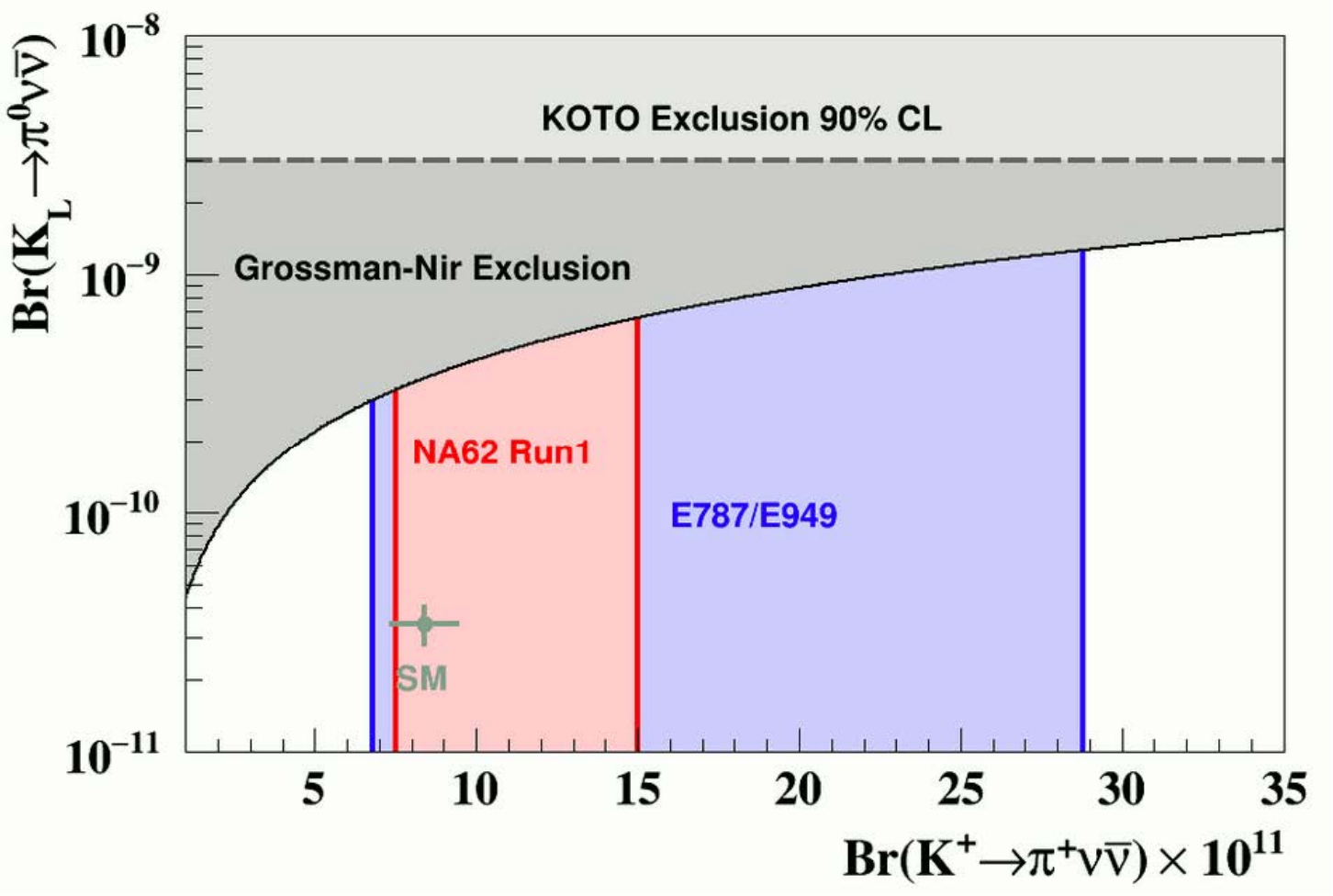
Expected bkg: $7.03^{+1.05}_{-0.82}$ evts

20 events observed

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\,|_{stat} \pm 0.9_{sys}\right) \times 10^{-11}$ **(3.4σ significance)**

NA62 Run 1 final result

Most precise determination of the decay rate to date. Part of parameter space already ruled out



NA62 Run 2

NA62 has resumed data taking in July 2021

Key modifications to reduce background from upstream decays and interactions:

- **Rearrangement of beamline elements**
- **Add 4th station to GTK beam tracker**
- **New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe**
- **New downstream veto for photon conversion in the beampipe**
- **Run at higher beam intensity (70% → 100%)**

Expect to measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) to better than 20%

A general purpose experiment in kaon sector

Flavour Physics with kaons

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Main goal:
BR($K^+ \to \pi^+ \nu\nu$)

Search for lepton flavour and number violation, rare and forbidden decays:

$K^+ \to \pi^- e^+ e^+ (\gamma)$
$K^+ \to \pi^- \mu^+ \mu^+ (\gamma)$
$K^+ \to \gamma l^+ \nu$
$K^+ \to \pi^+ \mu^\pm e^\mp (\gamma)$
$K^+ \to \pi^- \mu^+ e^+ (\gamma)$
$\pi^0 \to e^+ e^-$,
$\pi^0 \to e^+ e^- e^+ e^-$
$\pi^0 \to \gamma\gamma\gamma$, $\pi^0 \to \gamma\gamma\gamma\gamma$

Hidden sector Physics

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

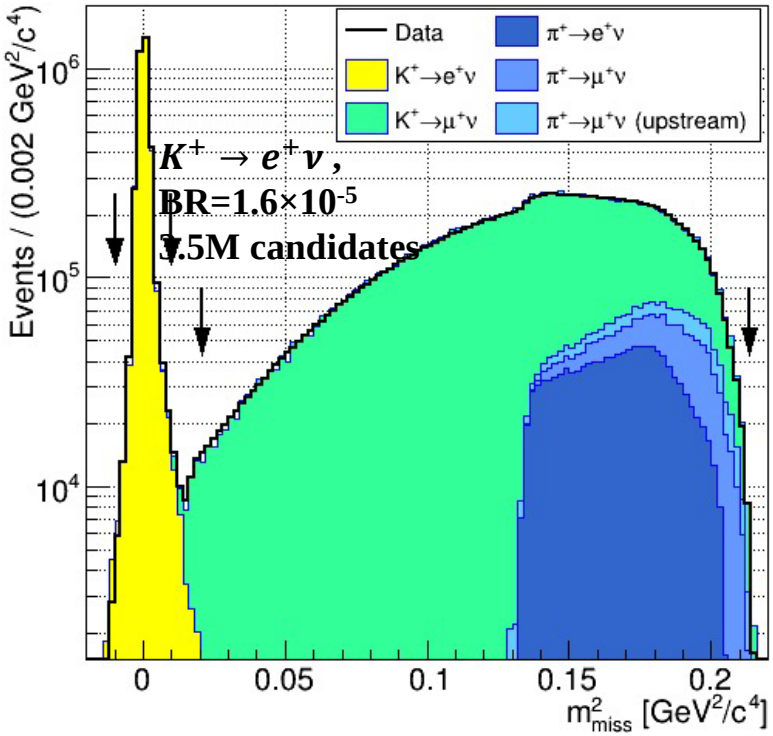
Heavy neutral Lepton(H)
Dark Photon(A'), Axion Like Particle (ALPs), Dark Scalar (S) in K decays:
$K^+ \to \mu^+$ H, $K^+ \to e^+$ H
$K^+ \to \pi^+ \pi^0$ with $\pi^0 \to A'\gamma$

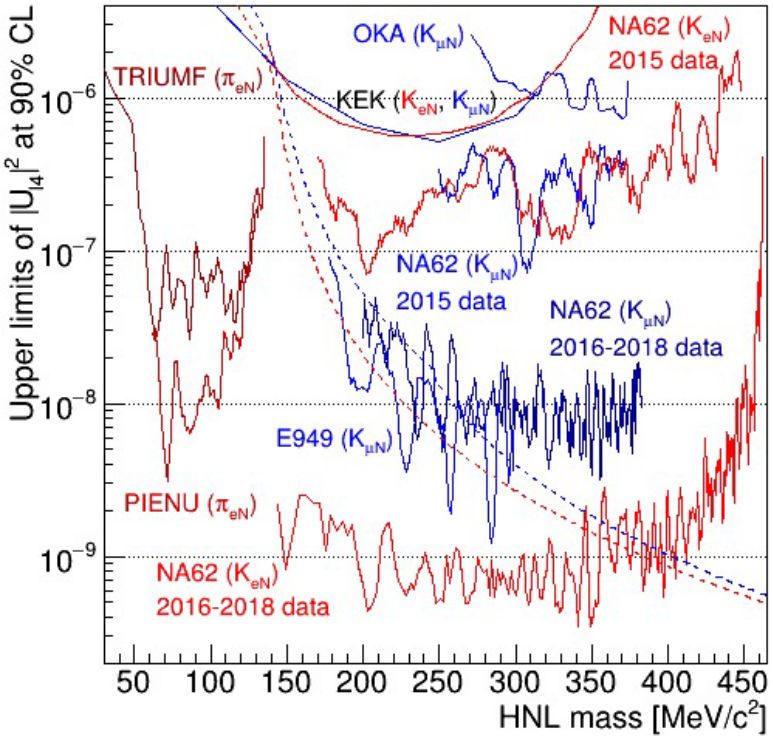
A general purpose experiment in kaon sector

Recent results on hidden-sector mediator production and other BSM physics in kaon decays:

- **searches for heavy neutral leptons from $K^+ \to l^+\nu$ decays**

Events with a K^+ in the initial state and a lepton (e^+ or μ^+) in the final state; squared missing mass $m^2_{miss} = (P_k - P_l)^2$ using STRAW and GTK trackers; HNL production signal: a spike above continuous missing mass spectrum.





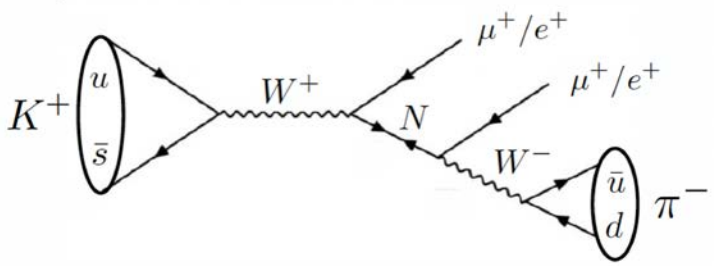
PLB 807 (2020) 135599, PLB 816 (2021) 136259

A general purpose experiment in kaon sector

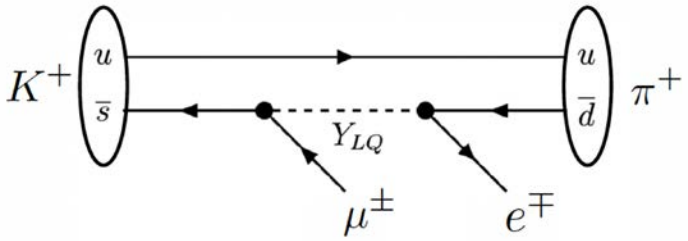
Recent results on hidden-sector mediator production and other BSM physics in kaon decays:

- **searches for LNV/LFV in K^+ and π^0 decays**

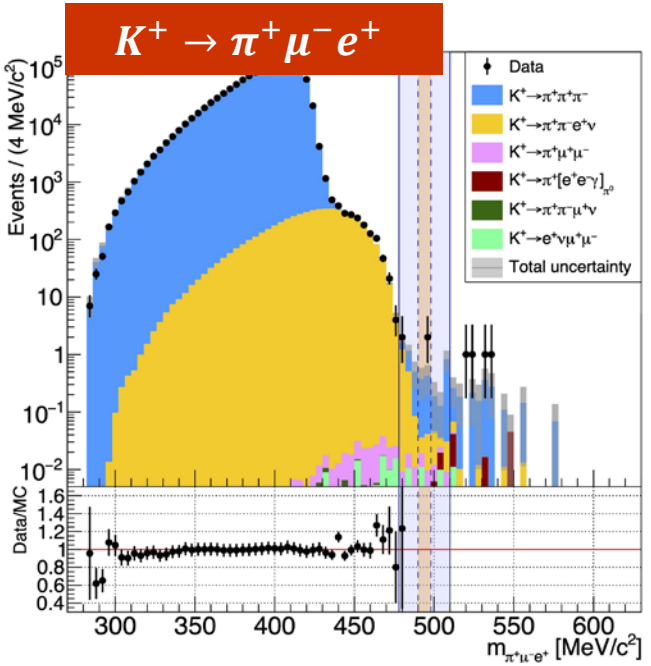
- **Lepton number violation:**



- **Lepton flavour violation:**



- **Experimental signature: 3 charged tracks with $\pi^\pm\mu^\mp e^+$**
- **Consistent with closed kinematics K^+ decay**
- **The invariant mass $M_{\pi\nu e}$ used to distinguish between signal and background**
- **Main bkg π mis-ID and decay in flight measured with data**
- **Normalized with $K^+ \to \pi^+\pi^+\pi^-$**



A general purpose experiment in kaon sector

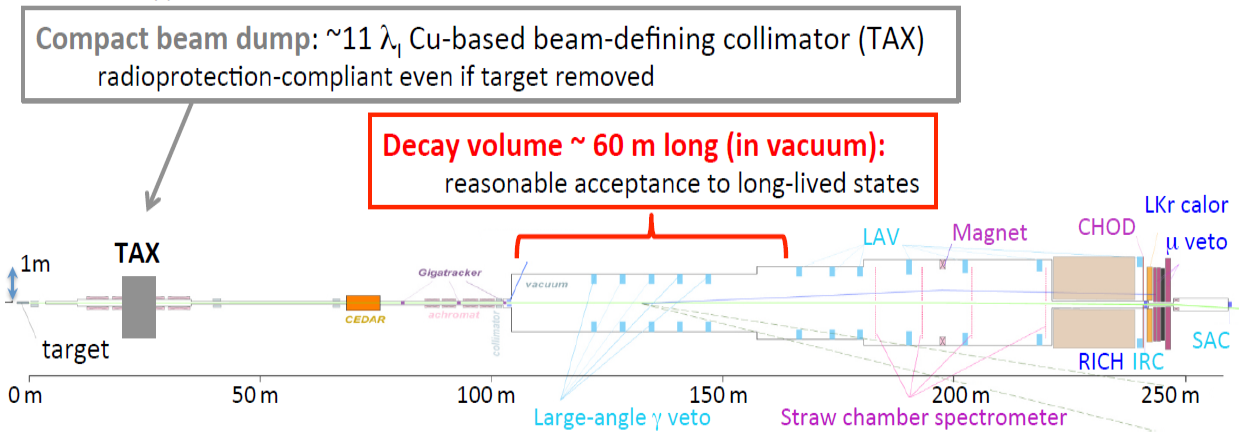
Recent results on hidden-sector mediator production and other BSM physics in kaon decays:

- **searches for LNV/LFV in K^+ and π^0 decays**

	Previous UL @ 90% C.L	NA62 UL @ 90% C.L		
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data → improved by factor 2	Phys. Lett. B 797 (2019) 134794
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	2.2×10^{-10}	2017 data → improved by factor 3	
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data → improved by factor 12	arXiv:2105.06759 (submitted to PRL)
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data → improved by factor 8	
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data → improved by factor 13	
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	-	sensitivity similar to the previous search	
$\pi^0 \to \mu^+e^-$	3.8×10^{-10}	-	sensitivity similar to the previous search	
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8}	-	Ongoing analysis: 2017 data $S.E.S \sim 1 \times 10^{-10}$	
$K^+ \to e^-\nu\mu^+\mu^+$	no limit	-	Ongoing analysis: 2017 data $S.E.S \sim 5 \times 10^{-11}$	

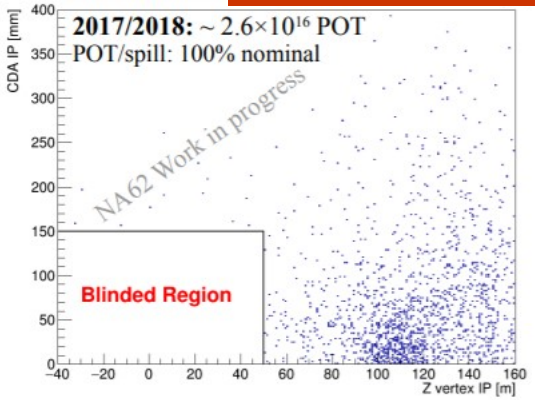
NA62 in dump mode

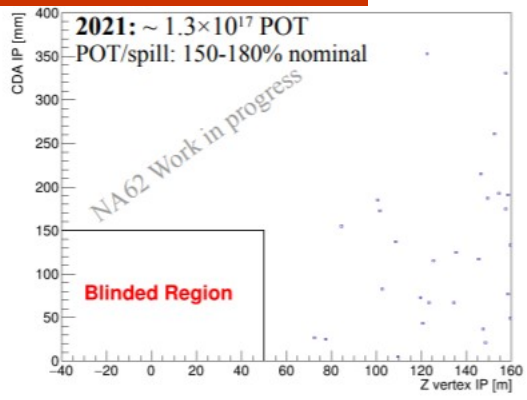
Dark sector particles can be produced also upstream of the experiment in the collisions of protons with the main upstream collimators moved into the closed position and removing the beryllium target for K+ production. Visible final states of dark sector particles produced upstream and probed by the NA62 experimental apparatus



In 2021 O(200) background reduction, despite higher intensity!

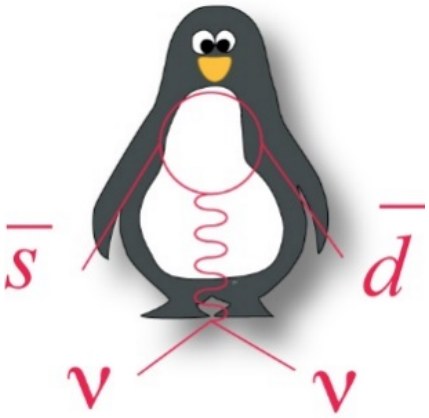
Preliminary $\mu^+\mu^-$ pair analysis





Naples working group

F. Ambrosino (PO)
M. D'Errico (Postdoc)
G. De Nardo (PO)
C. Di Donato (PA)
R. Fiorenza (PhD)
R. Giordano (PA)



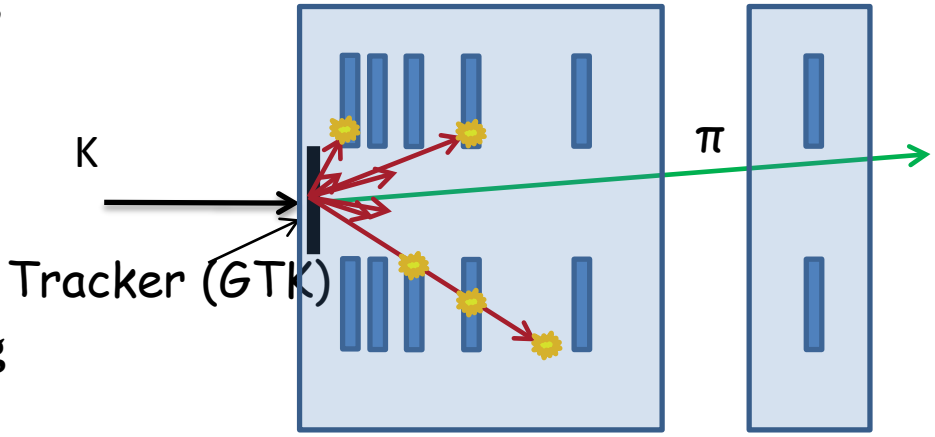
P. Massarotti (PA)
M. Merola (RTDB)
M. Mirra (Ric. INFN) - resp. loc.
M. Napolitano (senior)
G. Saracino (PA)

Activities in NA62

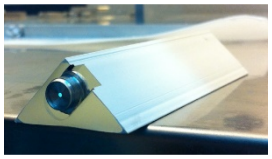
- Full responsabily of the CHANTI detector: hw/sw maintanece, data quality analysis
- Involved in the main channel analysis ($K^+ \to \pi^+ \nu\bar{\nu}$), in lepton flavor universality measurements and dark sector
- Ongoing studies for GTK read-out firmware improvements

CHANTI postcard

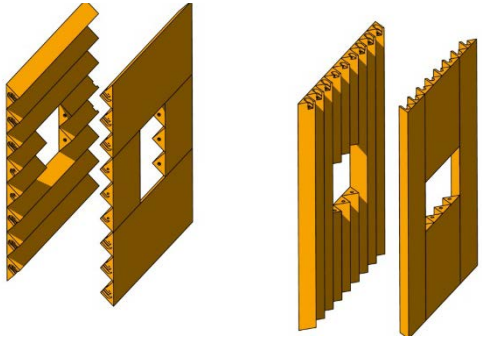
Detector proposed and built entirely in Naples, thanks to the INFN mechanical design and workhop service.
Six guard rings to veto kaon inelastic interaction on GTK3 and beam background.
Staggered scintillator bars with triangular section read via WLS fibers and SiPM forming 6 xy sensitive planes



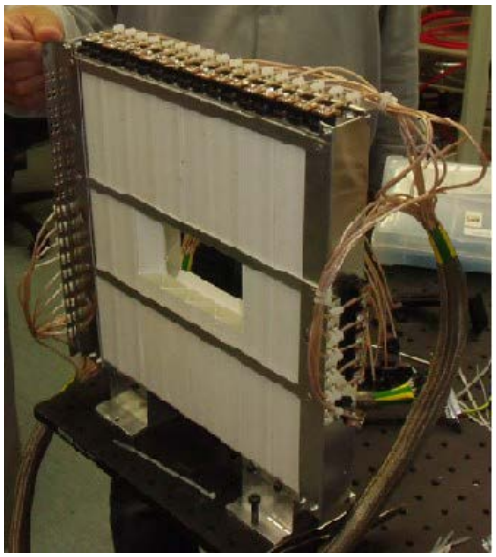
Scintillator bar



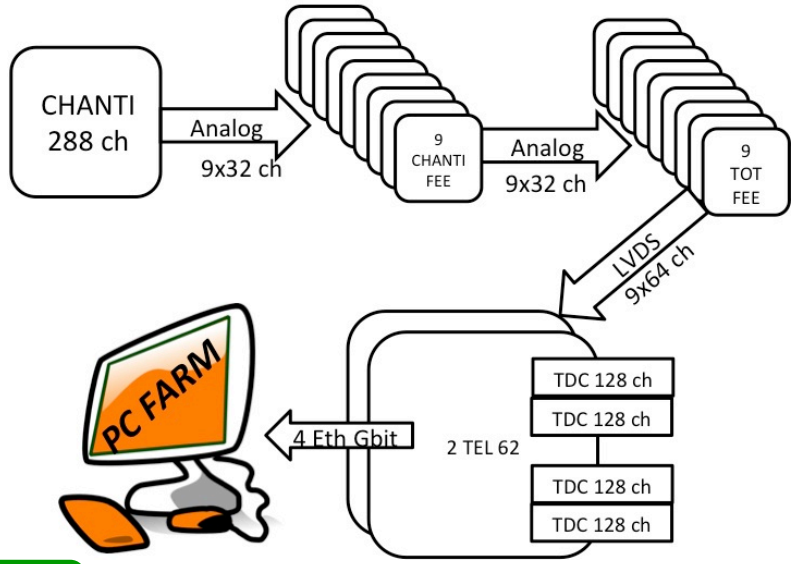
Layout of the X/Y layers



Fully cabled station



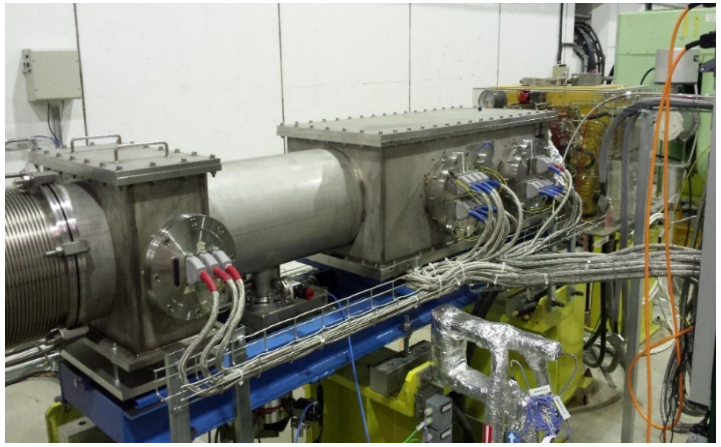
Front end electronics

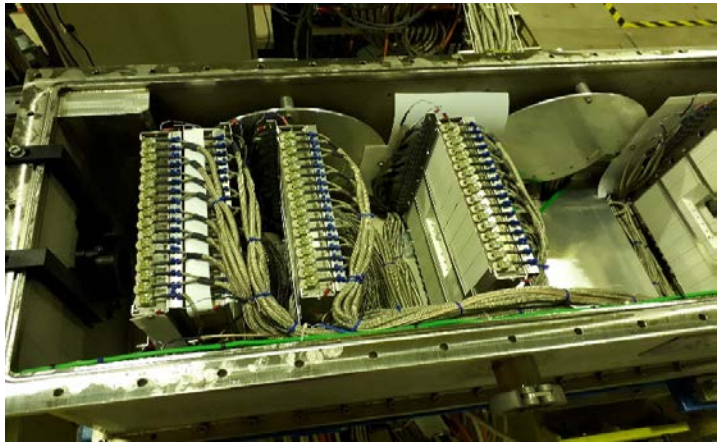


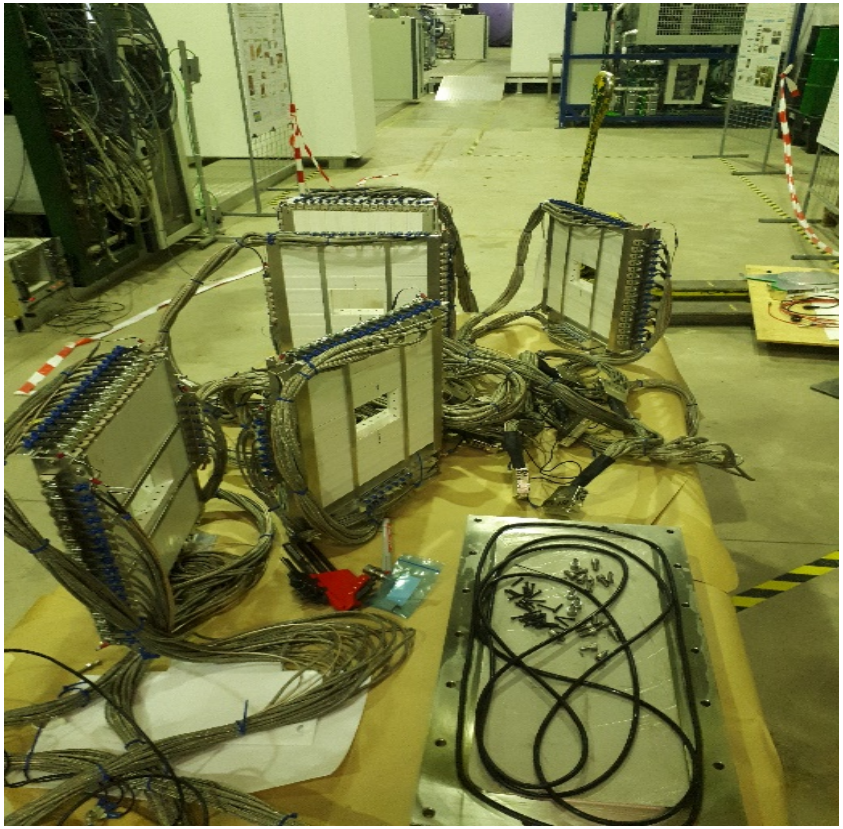
JINST 11 (2016) P03029

CHANTI in 2021 run

- **New FE boards installed to cope with the higher intensity reached in 2021 run**
- **During LS2 all SiPMs for the CHANTI , originally installed in 2014, were replaced by new ones to prevent aging effect due to radiation damages of the silicon crystal structure. This intervention required a big effort from L. Roscilli and F. Cassese**



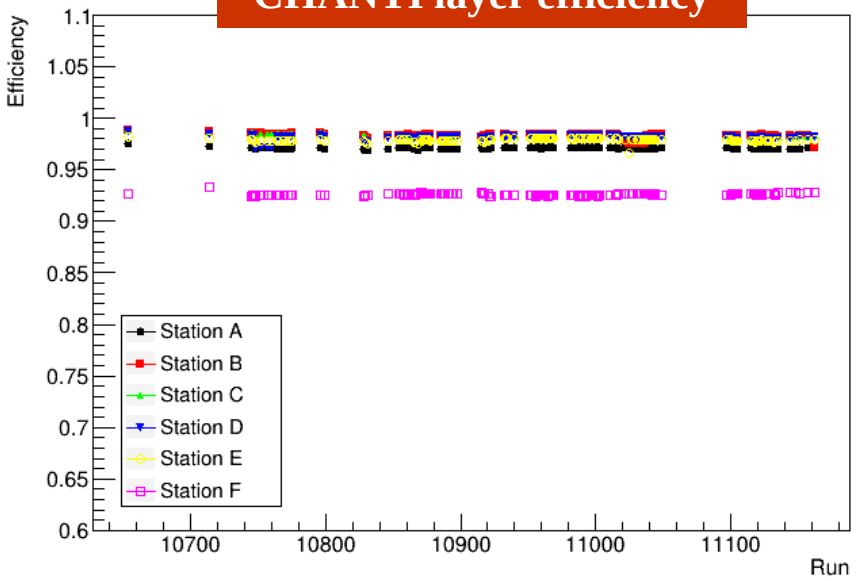




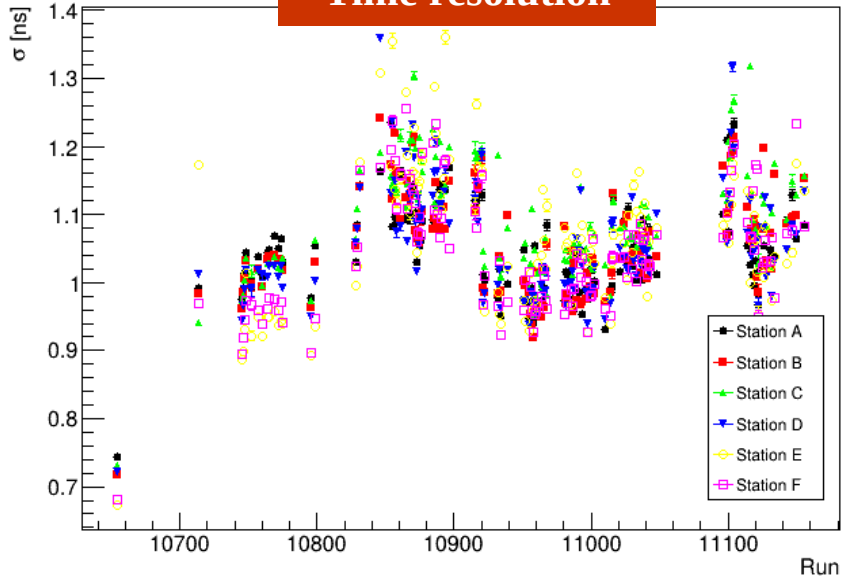
CHANTI in 2021 run

The new hw configuration, with the general improvements in TDAQ (e.g. choke) allowed a succesful and smooth data taking from the detector point of view

CHANTI layer efficiency



Time resolution

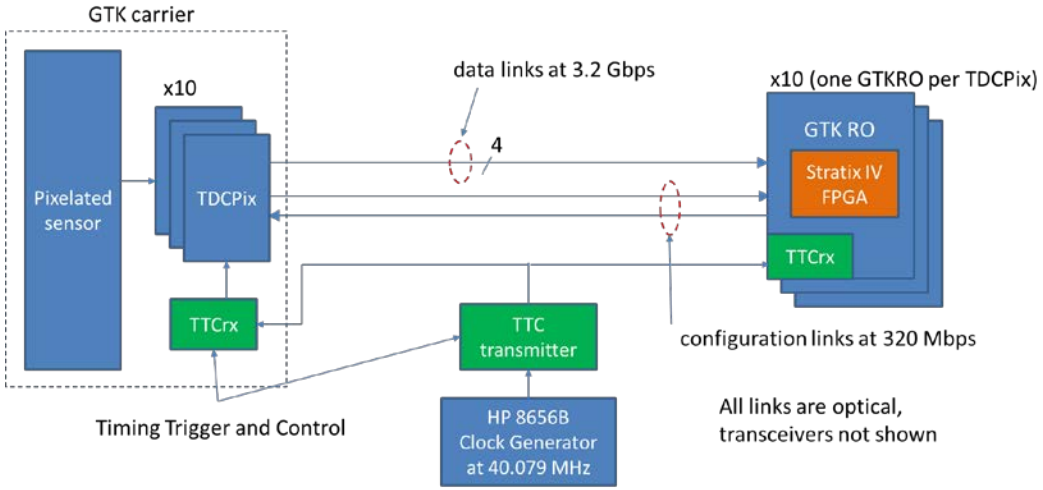


SiPM show rapid increase in dark current and an unexpected evidence for radiation damage. Investagation ongoing to understand the cause; a new SiPM replacement is foreseen for the 2022 data taking

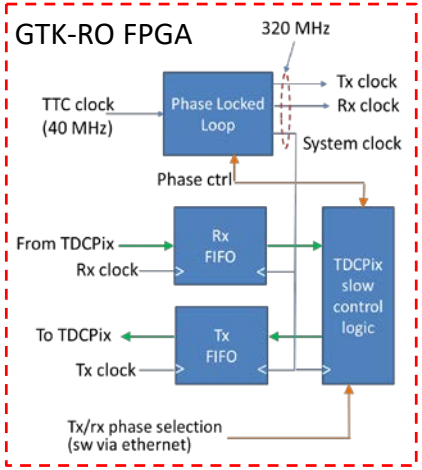
GTK read-out firmware

GTK read-out was one of the main issue during the 2021 run preventing the data taking stability. Since November, R. Giordano works on the GTK-RO firmware design in collaboration with INFN FE

- Loss of lock on configuration links to/from TDCPix chips
- Loss of entire bursts => inefficiency, hot topic to be addressed
  - Possibly related to relative phase issues between Tx and Rx clocks (320 MHz)
  - Previous solution: shifting GTK-RO system clock phase (4 equally-spaced phases, 781ps step) for Tx and selecting rising/falling edge for Rx



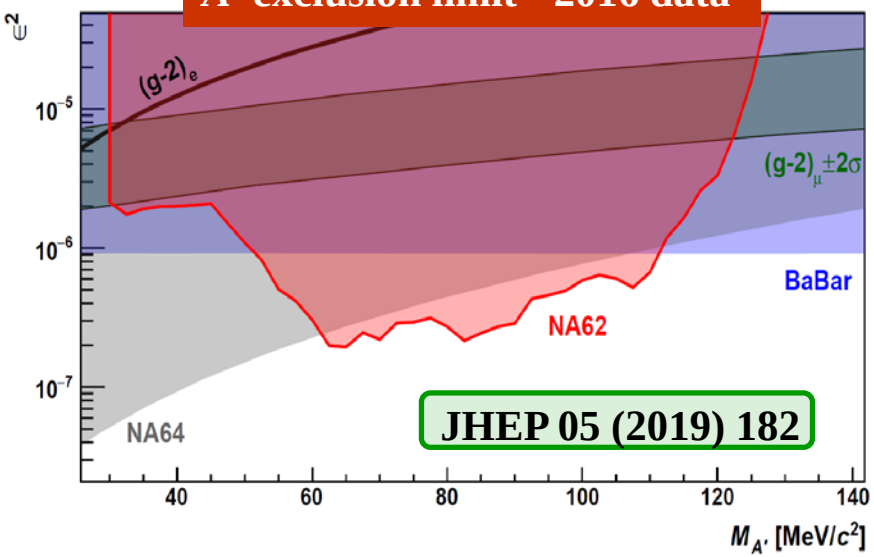
- New approach fully decouples Tx and Rx clocks
  - finer-grade phasing, 24 + 24 independent phases (130ps step) for Tx and Rx + dedicated FIFOs
  - Implemented in GTK fw, tested over the last weeks



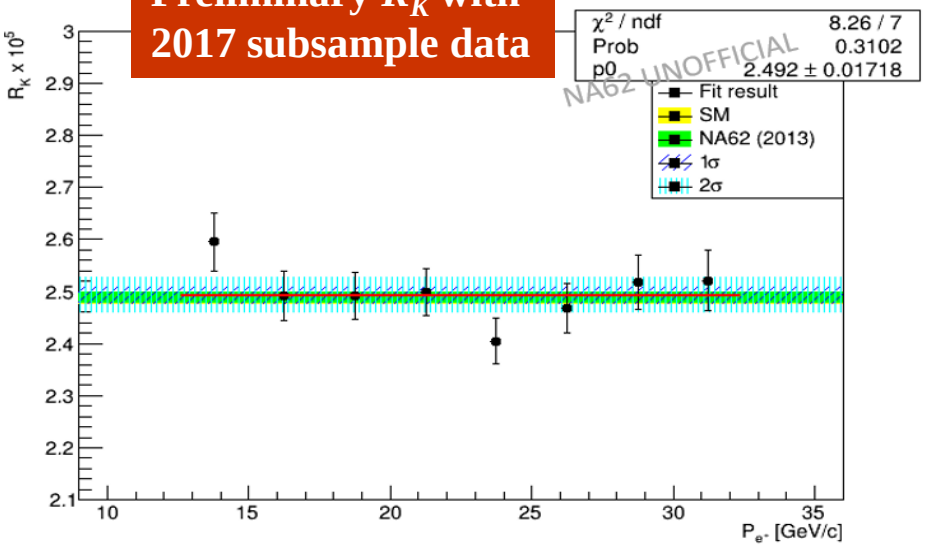
Analysis activities

- **Backgounds and random veto studies for the main analysis $K^+ \to \pi^+ \nu\bar{\nu}$ (see R.Fiorenza's talk)**
- **Measurement of the lepton flavor universality with $R_K = \Gamma(K^+ \to e^+ \nu_e)/\Gamma(K^+ \to \mu^+ \nu_\mu)$**
- **Search for an invisible dark photon in π^0 decays: $K^+ \to \pi^+ \pi^0$, $\pi^0 \to A'\gamma$, $A' \to inv$**

A' exclusion limit - 2016 data

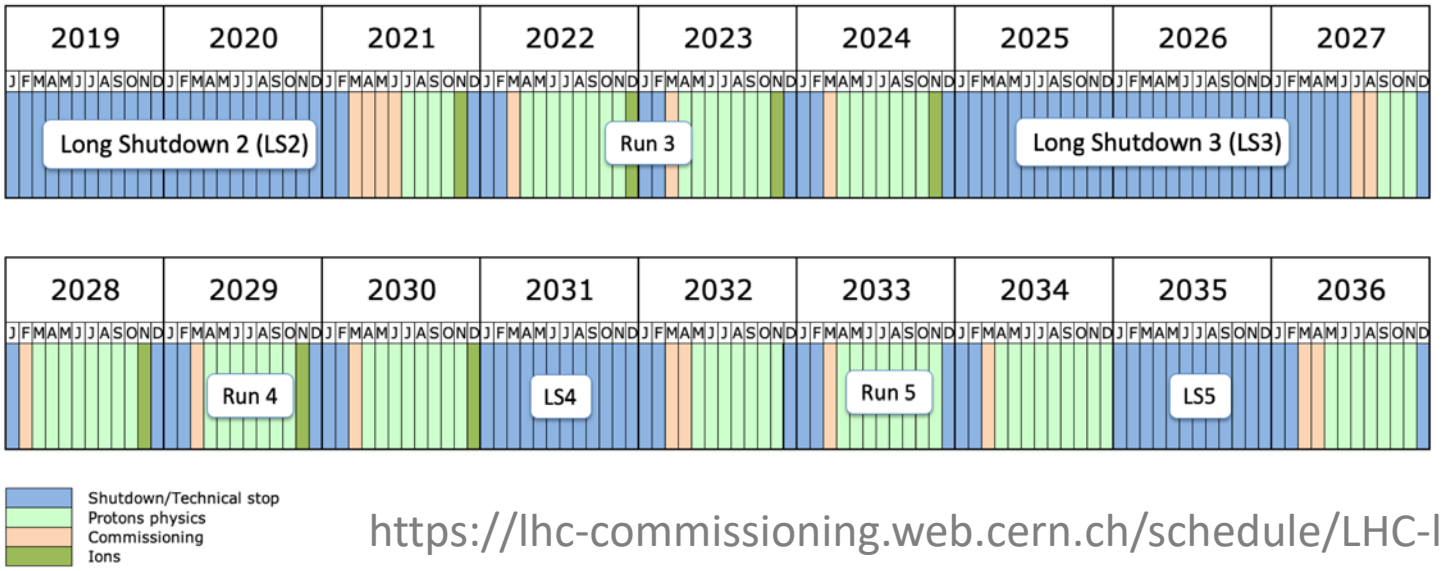


Preliminary R_K with 2017 subsample data



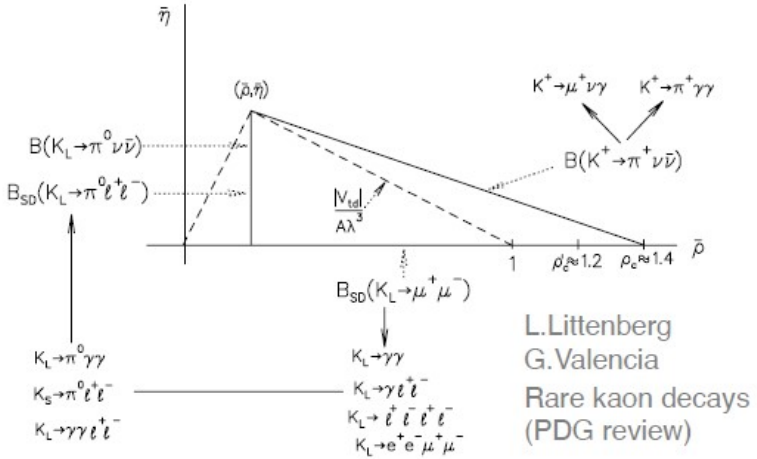
Kaon physics perspectives

Fixed target runs planned to accompany LHC running through 2036



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

There is an opportunity at the SPS for an integrated program to pin down new physics in kaon decays.
Measurement of all rare kaon decay modes - charged and neutral - to give clear insight into the flavor structure of new physics

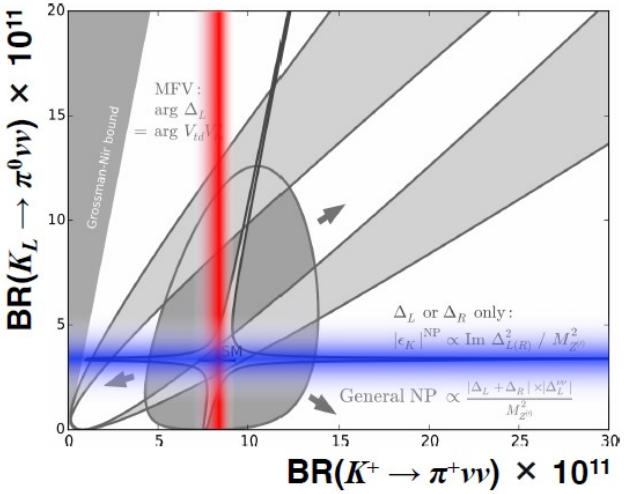


High-statistics $K^+ \to \pi^+ \nu\bar{\nu}$ @ CERN

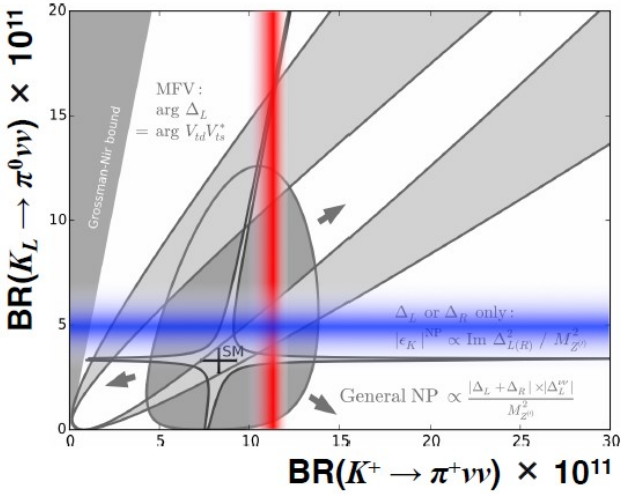
The NA62 decay-in-flight technique is now well established! Background estimates validated by in-depth study with data and MC

Possible next step: an experiment at the SPS to measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) to within ~5%!

Requires 4x increase in intensity



- BR($K^+ \to \pi^+\nu\nu$) = **BR_{SM}** with δBR = **5%**
- BR($K_L \to \pi^0\nu\nu$) = **BR_{SM}** with δBR = **20%**



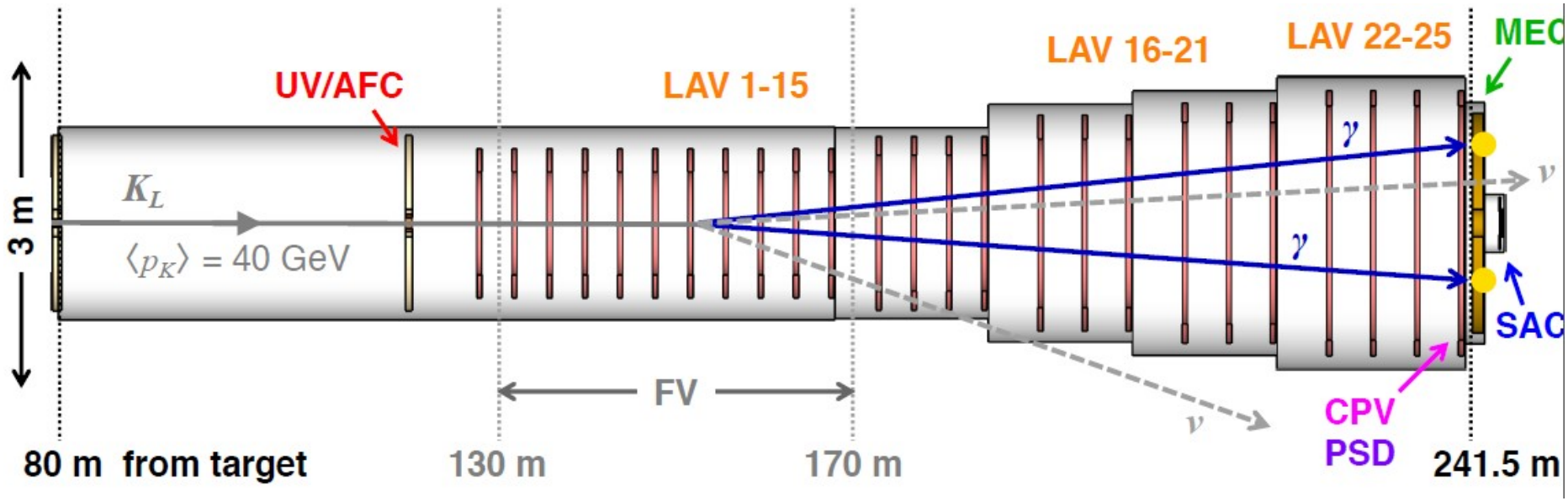
- BR($K^+ \to \pi^+\nu\nu$) = **1.33 BR_{SM}** with δBR = **5%**
- BR($K_L \to \pi^0\nu\nu$) = **1.50 BR_{SM}** with δBR = **20%**

Key challenges:

- **Require much improved time resolution to keep random veto rate under control**
- **Must maintain other key performance specifications at high-rate: low material budget, single photon efficiencies, control of non-gaussian tails, etc.**
- **For example: σt ~20 ps time resolution for Cerenkov detectors for beam tagging and secondary PID**

$K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS

400-GeV SPS proton beam on Be target at z = 0 m



KLEVER target sensitivity:
5 years starting Run 4

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

δBR/BR($\pi^0 \nu\nu$) ~ 20%

- **High-energy experiment: complementary to KOTO**
- **Photons from K_L decays boosted forward**
- **Makes photon vetoing easier - veto coverage only out to 100 mrad**
- **Roughly same vacuum tank layout and fiducial volume as NA62**

Conclusions

- **Kaon Physics is a portal to explore physics beyond the SM.**
- **$K^+ \to \pi^+ \nu\bar{\nu}$ analysis on Run1 data is completed with a world-leading measurement.**
- **NA62 Run 2 started in July 2021. Naples working group involved both on detector side (full responsibility of CHANTI, working ongoing on GTK readout firmware) and on physics analysis for the main channel $K^+ \to \pi^+ \nu\bar{\nu}$, lepton universality and dark sector**
- **NA62 will take data until LS3, to approach theory precision for the BR($K^+ \to \pi^+ \nu\bar{\nu}$) and set new limits in the kaon sector**
- **Plans for longer term high-intensity kaon beam experiments beyond LS3**
  - **Charged beam ($K^+ \to \pi^+ \nu\bar{\nu}$)** — **~$7\times10^{18}$ POT/year [4x wrt NA62]**
  - **Neutral beam ($K_L \to \pi^0 \nu\bar{\nu}$, $K_L \to \pi^0 l^+ l^-$)** — **~10^{19} POT/year [6x wrt NA62]**
  - **Beam dump (ALPs, HNLs, dark scalars, etc)** — **~10^{19} POT by LS4**; **~10^{19} POT/year [6x wrt NA62]**