Overview of NA62 Physics

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on behalf of the NA62 Collaboration

Triggering Discoveries in HEP II
Puebla, January 29-February 2, 2018

Outline

- The Kaon legacy
- NA48/n & NA62: brief history

- The measurement of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay

- Tests of SM and search for New Physics
  - Heavy Neutral Leptons
  - Lepton Flavour/Number Violation studies
  - Search for the Dark Photon

- Long term prospects
- Conclusions

The Kaon Legacy

The Kaon is the lightest kind of flavoured matter studied since the 60's to test fundamental properties of nature

The Standard Model was largely built from Kaons

- ➔ The theta-tau puzzle and the parity violation
- ➔ Strangeness and flavour conservation in Strong Interactions
- ➔ Universality of Weak Interaction
- ➔ Absence of Flavour Changing Neutral Currents and GIM mechanism
- ➔ Discovery of CP violation, indirect (ε) and direct (ε'/ε)

Kaons exhibit a very rich phenomenology, as «minimal flavour laboratory»

Why still Kaon physics?

Kaon decays are a powerful tool to

- ✓ study explicit Violations of SM, such as LFV/LNV
- ✓ probe the flavour sector by means of FCNC
- ✓ test of fundamental symmetries such as CP and CPT
- ✓ study of strong interaction at low energy: $\pi-\pi$ scattering, ChPT, hadron structure
- ✓ CKM unitarity tests and flavour mixing
- ✓ Search for long-lived low energy neutral particle

→ Ideal environment to search for New Physics

Flavour sector → probing extremely high energy scales:

precision frontier ***complementary*** to LHC energy frontier

Kaon Physics strikes back Buras@KAON 2016

Kaons at CERN

NA48
Main goal: Search for direct CPV
Measurement of ε'/ε
Beams: K_L / K_S

NA48/1
Main goal: Rare K_S decays and hyperon decays, CPV tests
Beams: K_S

NA48/2
Main goal: Search for direct CPV
Charge asymmetry measurement
Beams: K^+ / K^-

NA48

1997 → 2001
2002
2003
2004
2007
2008
2014 → 2018
2020
?

NA31 (1984-1990)
First evidence of direct CPV
Beams: K_L / K_S

NA62

NA62 - R_K
Main goal: Test of μ-e universality
R_K measurement
Beams: K^+ / K^-

NA62
Main goal: Rare kaon decays, measurement of $K^+ \to \pi^+\nu\bar{\nu}$
Beam: K^+

NA62 time scale

NA62 approuved to run until LS2

Current run **Run 3** **Run 4**

LS2 **LS3**

BR ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)
LFV and LNV decays
Hidden sector searches

Future plans

The main goal of the NA62 experiment is the measurement of the Branching Ratio of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay …..

….. but, many other physics opportunities

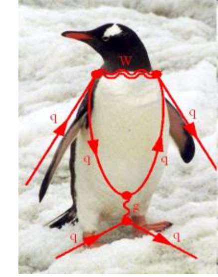
NA62 broad physics programme

The NA62 approach allows for a broad physics programme

- Standard physics
  - ➔ χPT studies: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$, $K^+ \to \pi\pi l^+\nu$
  - ➔ Lepton universality studies: $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$
- LFV/LNV in Kaon decays
  - ➔ $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^- l^+ l^+$,
- Heavy neutrino searches
  - ➔ $K^+ \to l^+\nu_H$
  - ➔ ν_H (from K, D decays) $\to \pi^\pm l^\mp$
- π^0 decays
  - ➔ $\pi^0 \to$ invisible, $\pi^0 \to 3\gamma$ (4γ), $\pi^0 \to \gamma U$
- Dark sector searches
  - ➔ Long living dark photon (from prompt mesons decays) $\to l^+l^-$
  - ➔ Long living axion-like (produced in beam-dump config.) $\to \gamma\gamma$

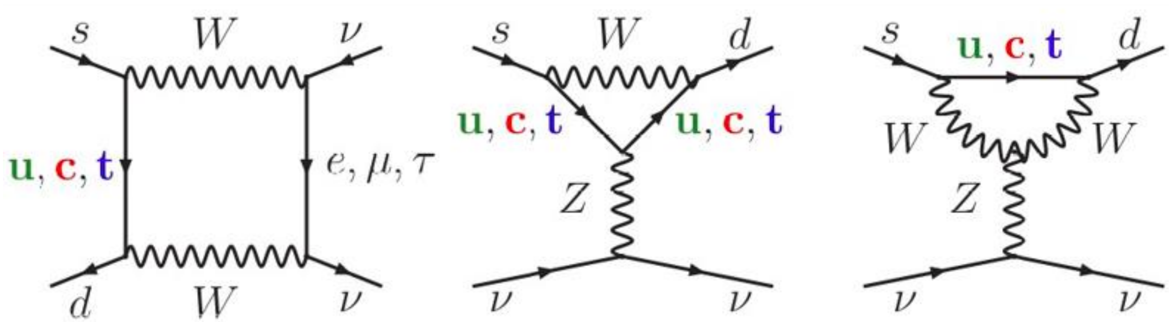
Measurement of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$

$K \to \pi\nu\nu$ in the SM ...



- FCNC process forbidden at tree level
- Short distance contribution dominated by Z penguin and W box diagrams
- “Super-clean” theoretically, hadronic ME extracted from measured quantities (K_{e3})
- Very small BR due to the CKM top coupling ⟹ $A \sim (m_t/m_W)^2|V_{ts}^* V_{td}| \approx \lambda^5$
- Measurement of $|V_{td}|$ complementary to those from B sector

- $\delta BR/BR = 10\%$ ⟹ $\delta|V_{td}|/|V_{td}| = 7\%$.



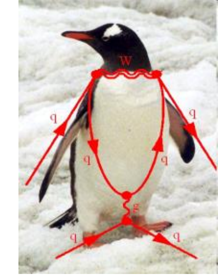
$$BR(K^+ \to p^+ n\bar{n} = (8.4 \pm 1.0) \times 10^{-11}$$

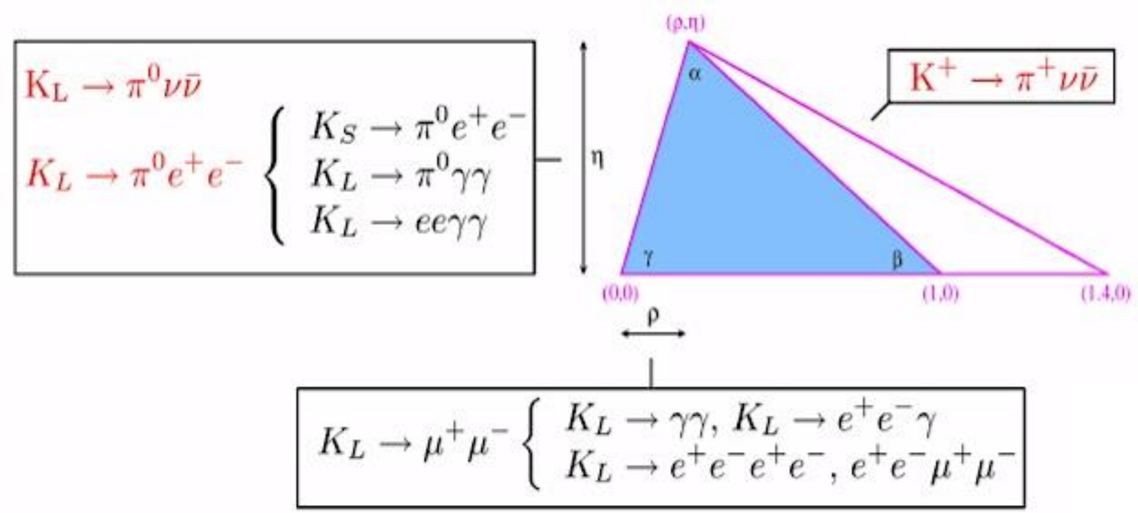
$$BR(K_L \to p^0 n\bar{n} = (3.4 \pm 0.6) \times 10^{-11}$$

[Buras et al., JHEP 1511 (2015) 033]

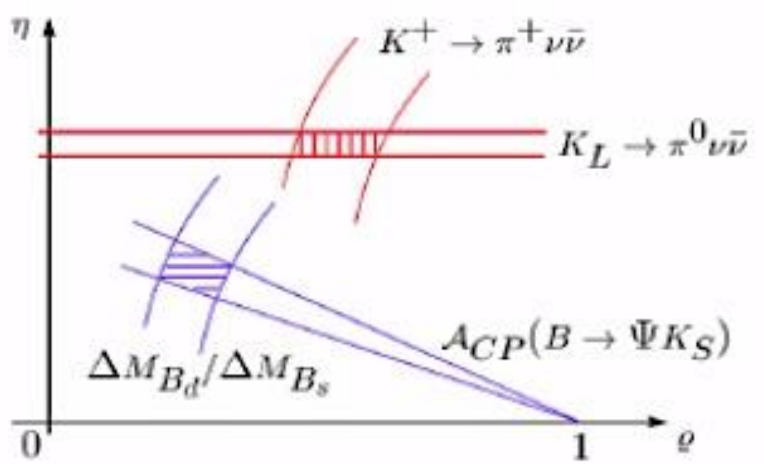
error dominated by CKM elements

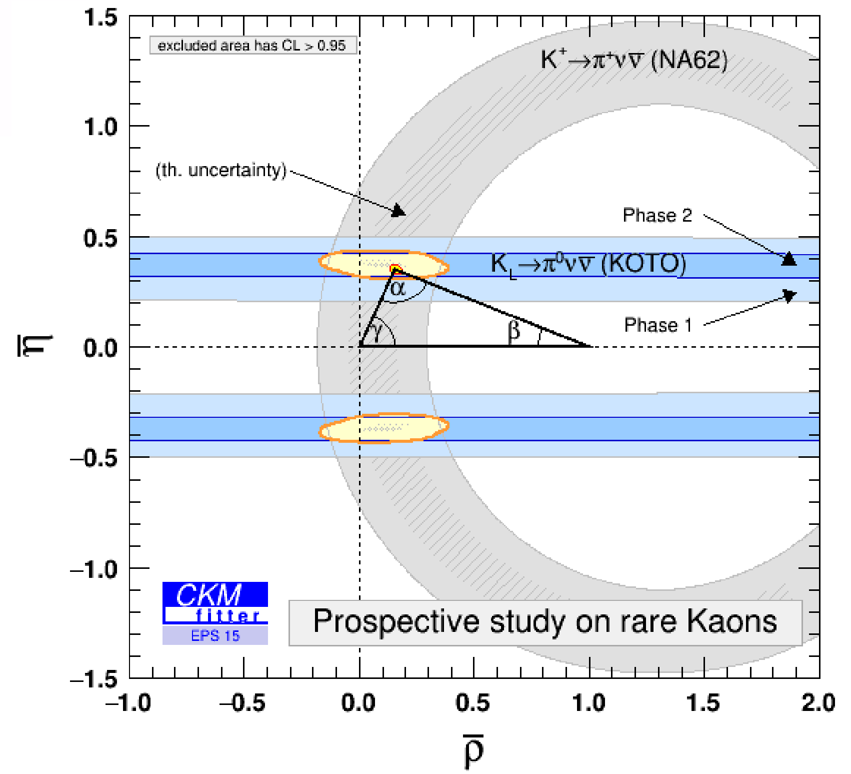
$K \rightarrow \pi\nu\nu$ in the SM ...





Kaons alone can fully constrain the CKM triangle



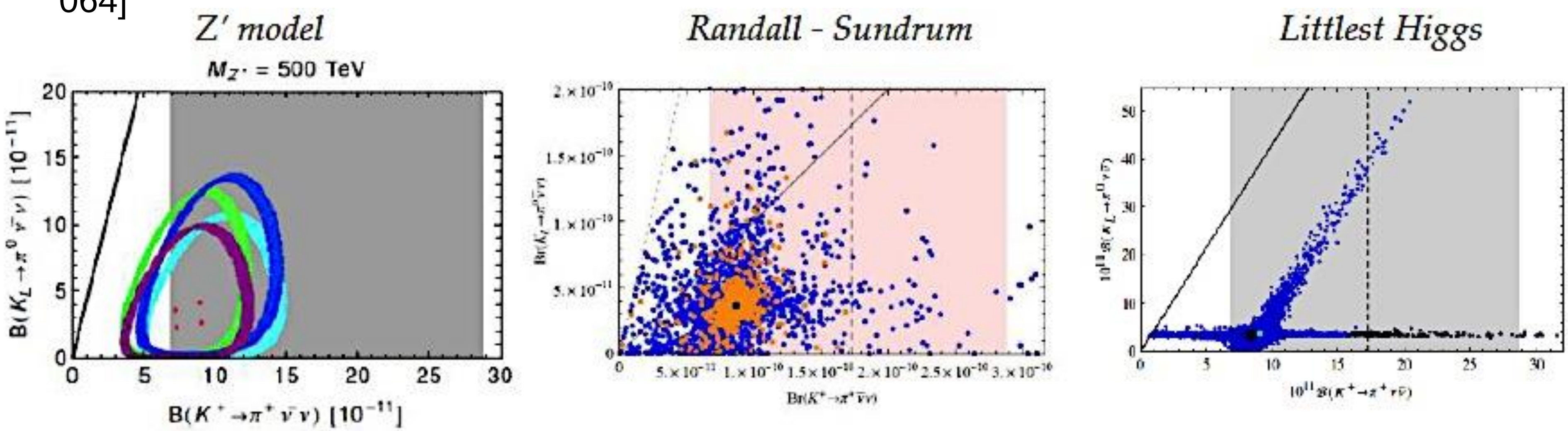


Comparison with B physics can provide hints on New Physics dynamics

. . . and beyond the SM

Several SM extensions predict sizable deviations for the BR

- Simplified Z, Z' models [Buras, Buttazzo, Knegjens, JHEP 1511 (2015) 166]
- Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- MSSM non-MFV [Tanimoto, Yamamoto arXiv:1603.0796, Isidori et al. JHEP 0608 (2006) 064]

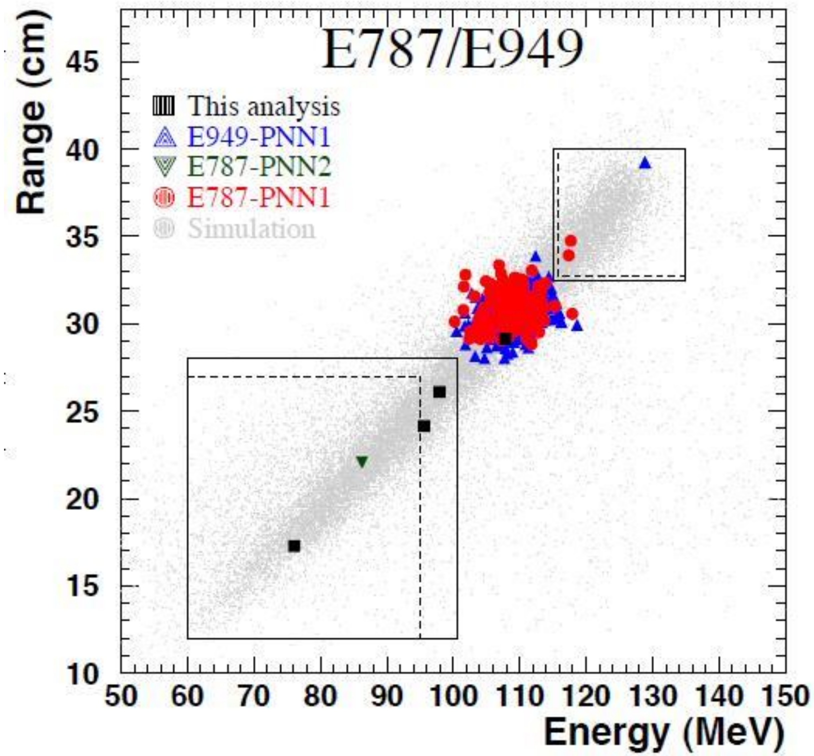


Measurement of the BR of the charged ($K^+ \to \pi^+ \nu\bar{\nu}$) and neutral ($K_L \to \pi^0 \nu\bar{\nu}$) modes can discriminate among different NP scenarios

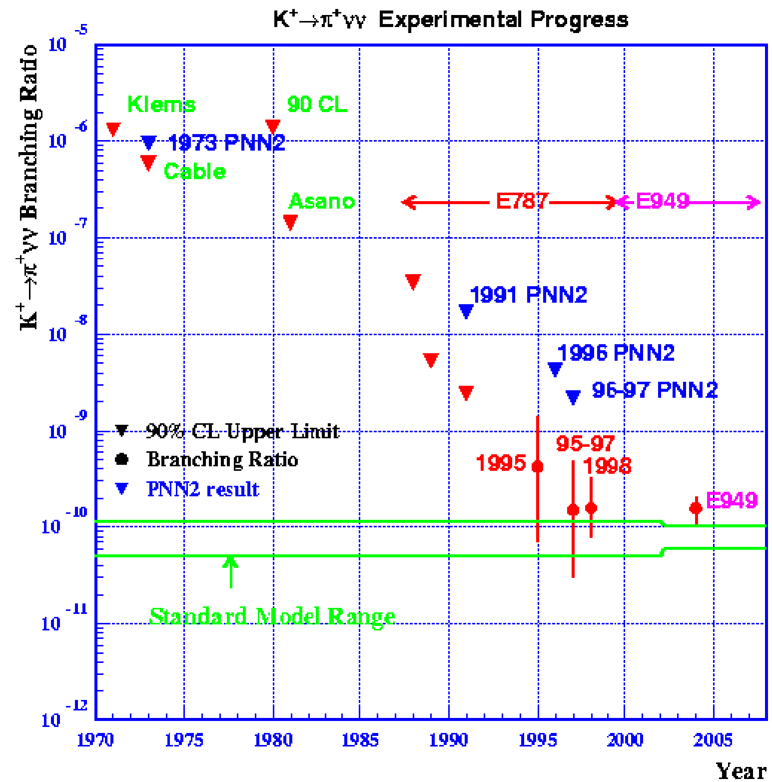
Experimental status

Final results from E787/E949 at BNL

$$BR\left(K^+ \to p^+ n\bar{n}\right) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$$



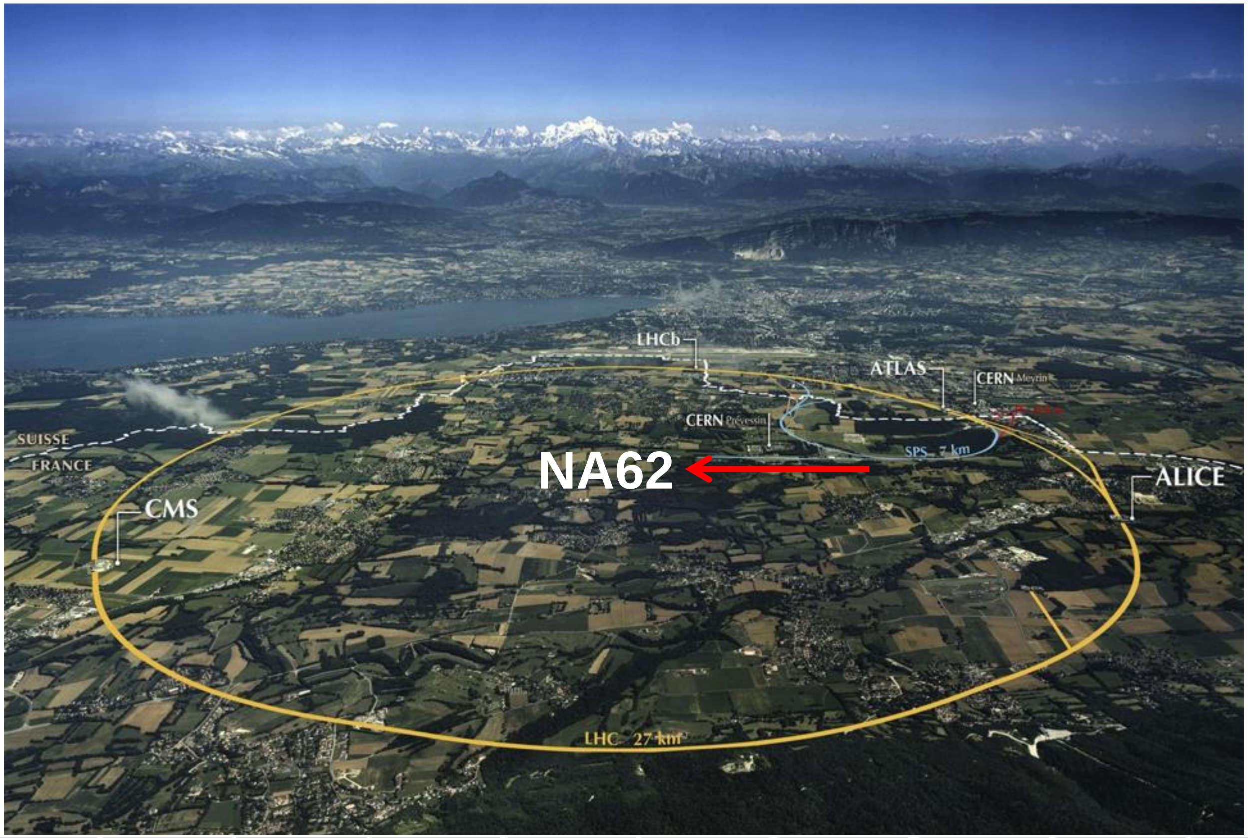
First search: 1969 (10^{-4}) Observation: 1997 (10^{-10})

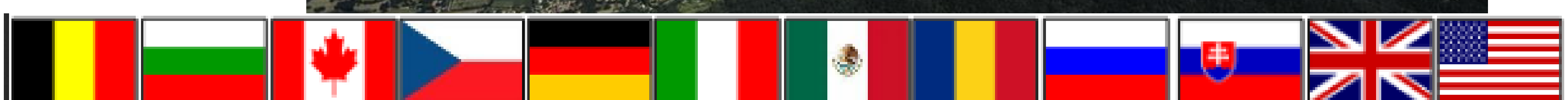


The probability that all 7 observed events are background is 10^{-3}

twice as large as, but still consistent with SM expectation

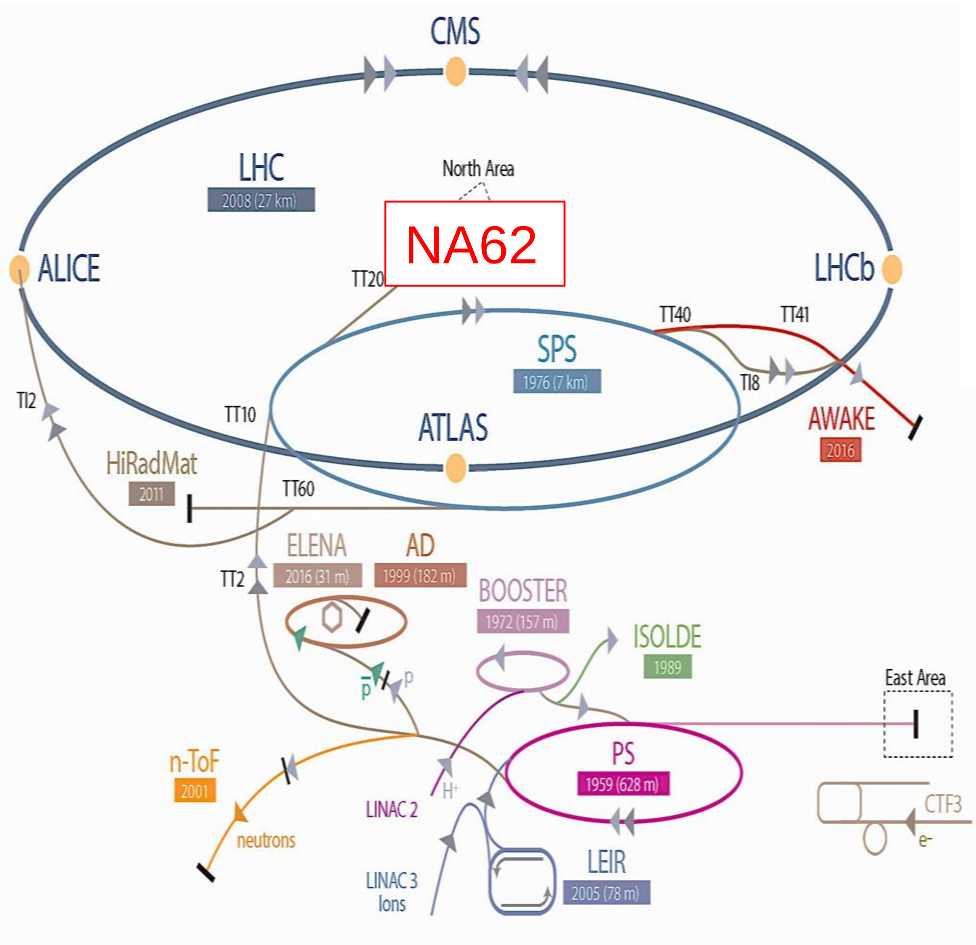
The NA62 experiment at CERN





Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moscow(INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver(UBC) → ~ 200 participants, ~ 30 institutions

The NA62 Kaon beam



- 400 GeV/c SPS primary protons
- 3×10^{12} protons/pulse
- 75 GeV/c un-separated hadron beam: π^+, K^+, p ($\Delta p/p$ ±1%)
- Kaon component → 6%
- 800 MHz → 50 MHz kaons → 6 MHz
- 4.8×10^{12} K^+ decays/y → SES ~ 10^{-12}

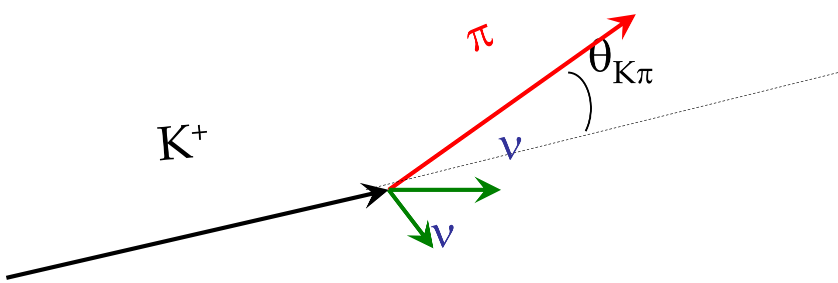
NA62 - Experimental principles

- Goal ➡ 10% precision Branching Ratio measurement
- *O*(100) $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events in ~ three years of data taking

➔ Statistics
- BR(SM) ~ 8.4 x 10^{-11}
- Acceptance: 10%
- K decays: 10^{13}

➔ Systematics
- $\geq 10^{12}$ background rejection
- $\leq$10% precision on background measurement

Very challenging experiment



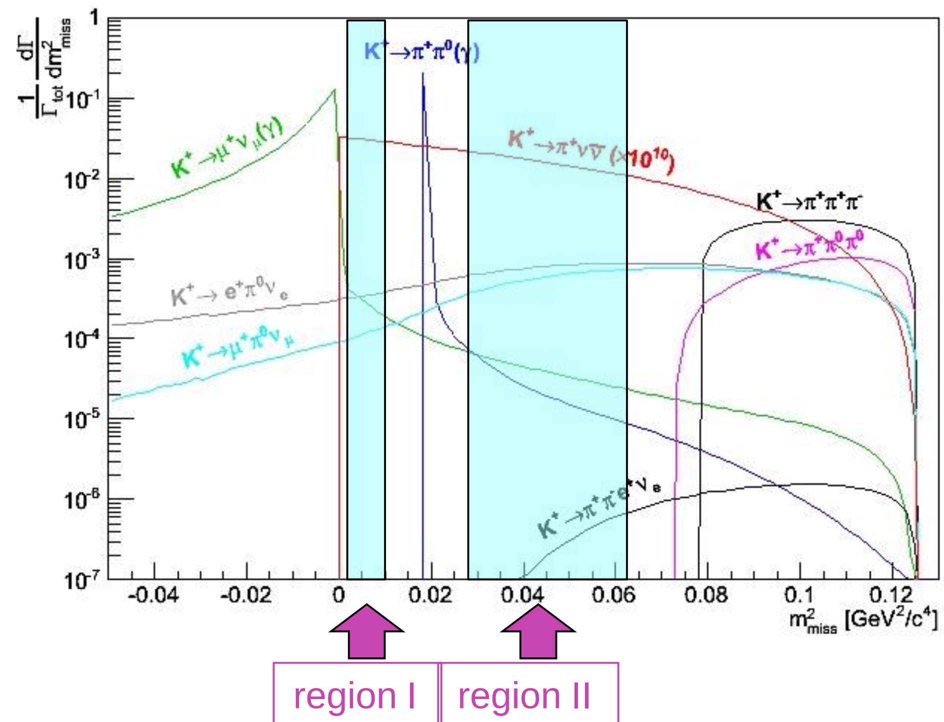
Weak signal signature

Huge background

Decay	BR
$\mu^+\nu$ $(K_{\mu 2})$	63.5%
$\pi^+\pi^0$ $(K_{\pi 2})$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$ (K_{e3})	5.1%
$\pi^0\mu^+\nu$ $(K_{\mu 3})$	3.3%

Background and kinematics

$m^2_{miss} = (P_K - P_\pi)^2$
defines two low background signal regions separated by $K^+ \to \pi^+\pi^0$



Keystones

- ✓ $\mathcal{O}$ (100 ps) timing between subdetectors
- ✓ $\mathcal{O}$ (10^4) background suppression from kinematics
- ✓ > 10^7 muon suppression
- ✓ > 10^7 π^0 (from $K^+ \to \pi^+\pi^0$) suppression

Detector layout

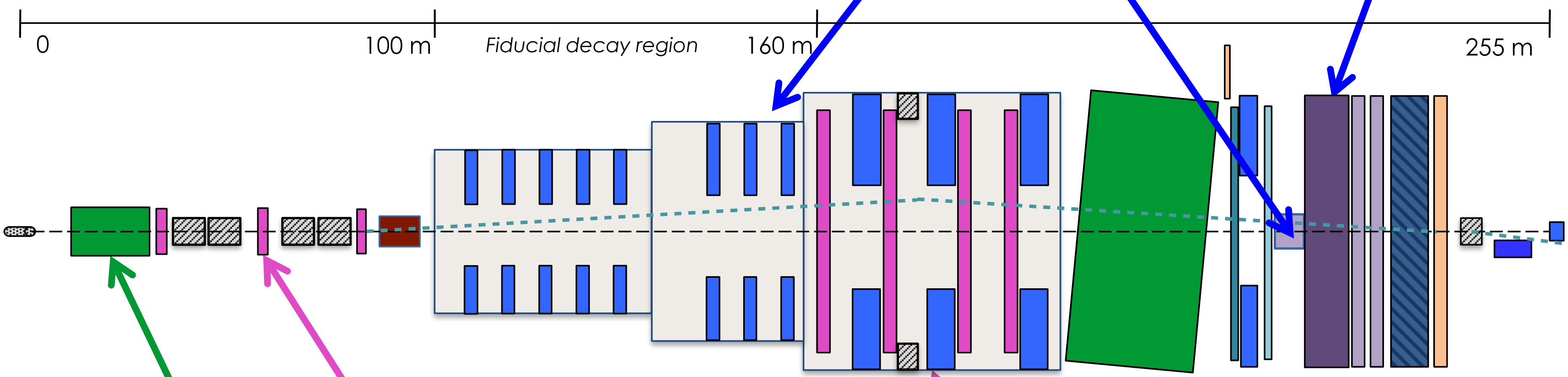
[NA62 Detector Paper, 2017 JINST 12 P05025]

Beam and secondary particle tracking

Hermetic photon vetoes

Particle Identification

LAV 8.5 - 50 mrad
LKr 1- 8.5 mrad
SAV < 1 mrad



KTAG - CEDAR
K^+ identification

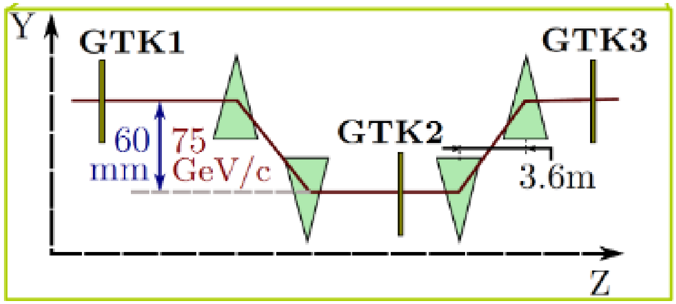
RICH
π/μ identification

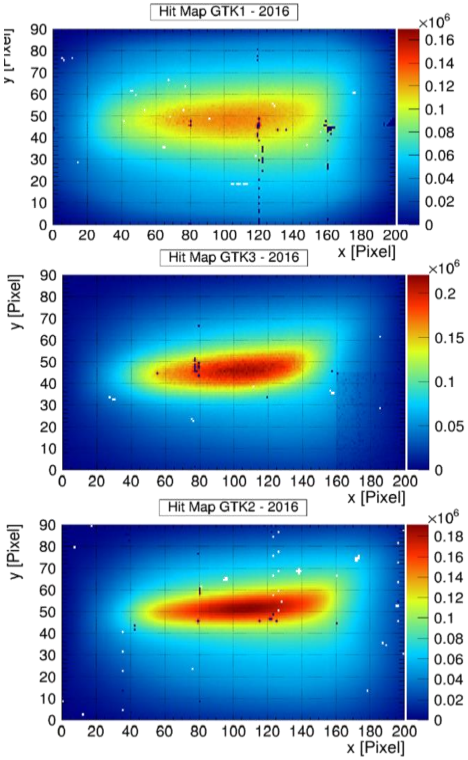
GIGATRACKER
3 Si-pixel stations, low mass

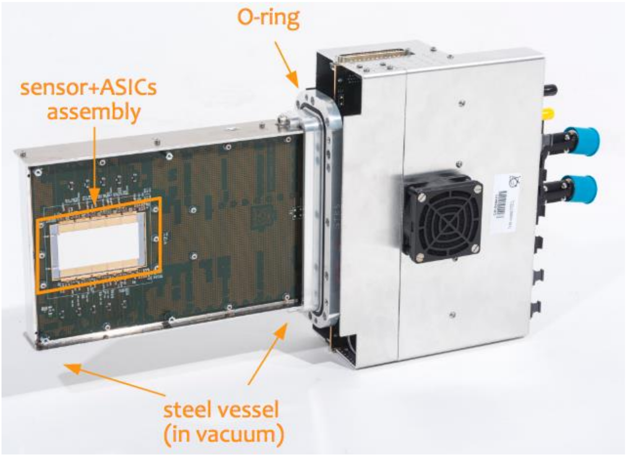
STRAW chambers in vacuum
4 stations + dipole magnet

Kaon identification and tracking

- Kaon Identification → **KTAG**
- CEDAR, a differential Cherenkov counter filled with Nitrogen
- excellent time resolution < 80 ps
- efficiency ~ 99%





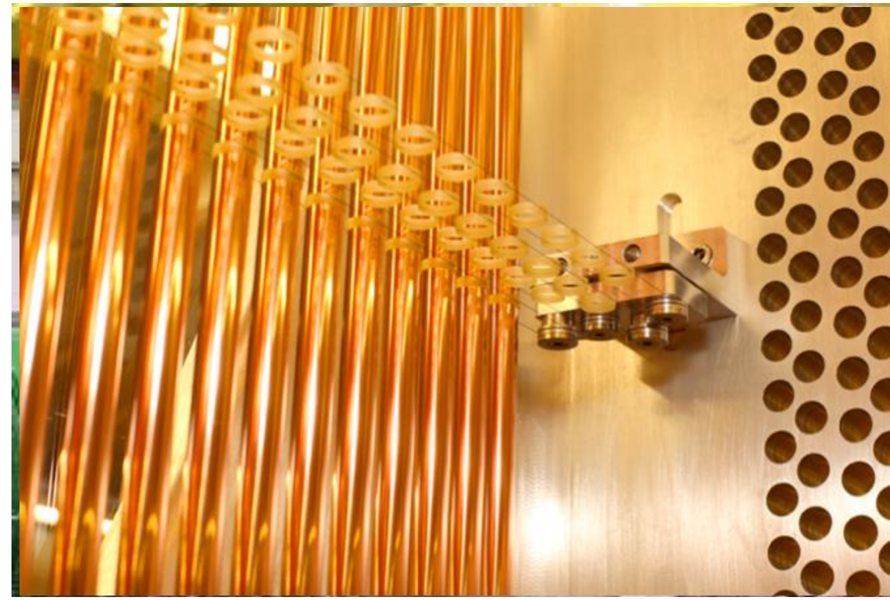


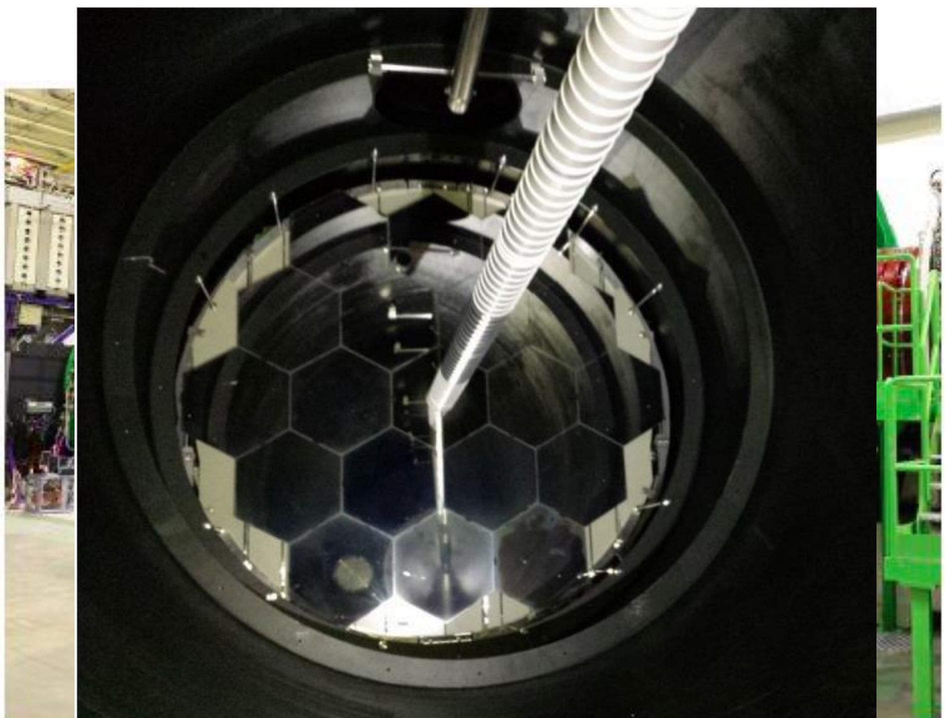
- Kaon tracking → **GTK**
- Beam spectrometer: 3 stations of Silicon pixel detectors + achromat
- time resolution ~ 130 ps per station
- momentum resolution $\Delta p/p < 0.4\%$

Secondaries identification and tracking

Tracking → **STRAW tubes**

- 4 chambers in vacuum + magnet
- $\sigma(p)/p \sim 0.32\%$□□ $0.008\% \times p$ (GeV/c)
- $\sigma(\theta) < 60\ \mu$rad
- $\sigma(x)$, $\sigma(y) \sim 130\ \mu$m

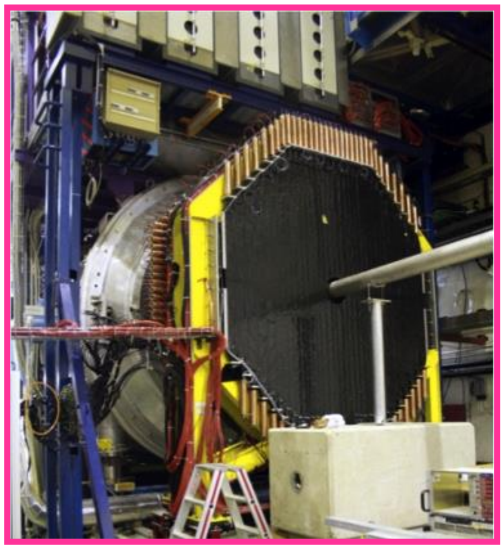




- PID → **RICH**
- Filled with neon at atm pressure
- 20 hexagonal mirrors
- Separate $\pi-\mu$ in $15 < p < 35$ GeV/c
- $\sim 90\%\ \pi$ ID efficiency, $\sim 1\%\ \mu$ mis-ID
- Measure pion crossing time with a resolution ~ 70 ps
- Provide a L0 trigger for ch. tracks

Charged vetos and muon detectors

Charged Hodoscope
- Inherited form NA48
- Level 0 trigger, rate 10 MHz
- time resolution ≈ 200 ps



Muon detector
- MUV 1+MUV 2 Fe/scintillator
  - hadronic/mip cluster ID
  - usable also in trigger (pion E)
- MUV 3 scintillator tiles & 2 PMs
- fast muon counter, inefficiency < %
- used in L0 trigger

CHANTI
- Veto inelastic interactions in GTK 3

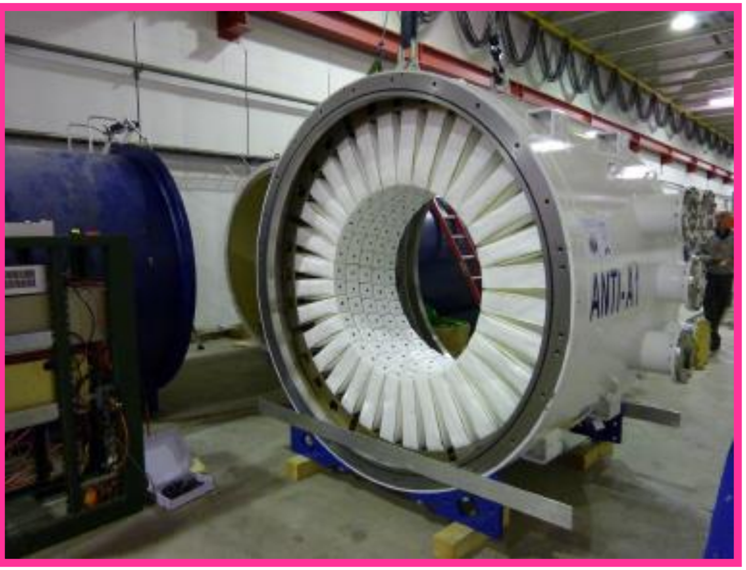
New CHOD
- scintillator tiles
- time resolution ~ 1.2 ns
- efficiency > 99%

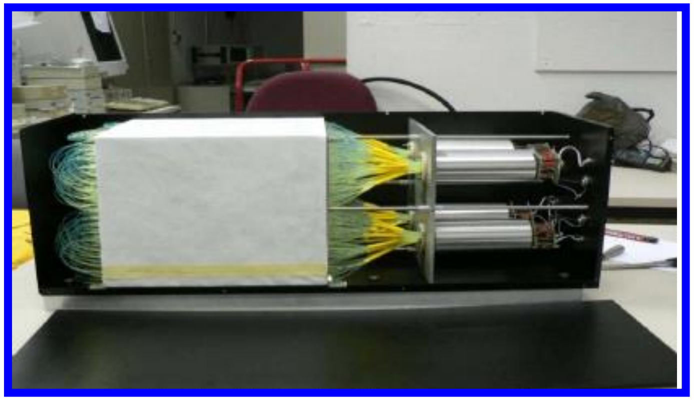
Veto systems

Large angle (8.5-50 mrad) (LAV)
- 12 stations (11 in vacuum)
- Lead glass blocks
- Inefficiency $<10^{-4}$ for E_γ > 200 MeV

Small angle < 1 mrad (IRC & SAC)
- "shashlyk" calorimeters
- Inefficiency $<10^{-4}$ for E_γ > 5 GeV

Intermediate angle(1-8 mrad) LKr
- Liquid Krypton Calorimeter
- Inefficiency $<10^{-5}$ for E_γ > 10 GeV





The NA62 experiment

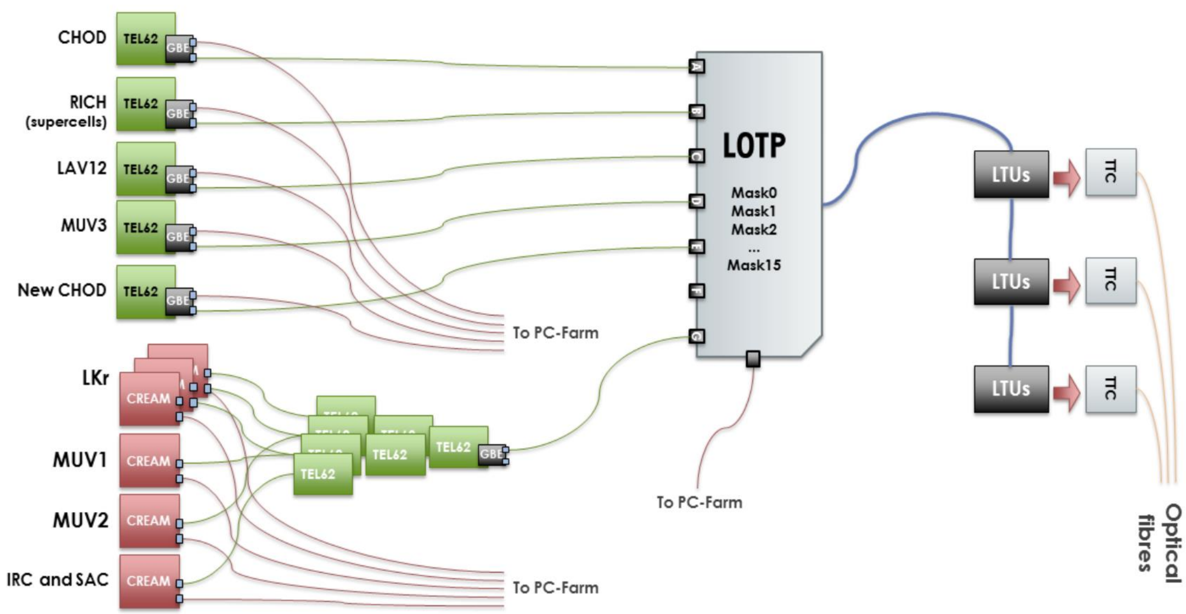
Trigger system

Detailed description in Dario's talk

L0 (Hardware level)
(RICH, LKr, LAV, MUV) ~10 → 1 MHz

L1 (Single Detector Software level) ~100 kHz

L2 (Multi-Detector Software level) ~10 kHz



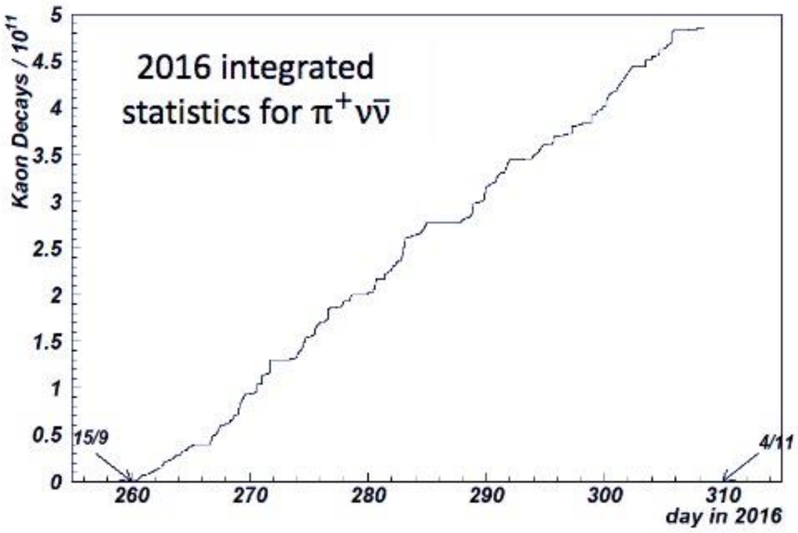
NA62 data taking

- ✓ 2014 - Pilot run
- ✓ 2015 - commissioning run
- ✓ 2016 - commissioning and physics run
- ✓ 2017 - physics run

Physics runs

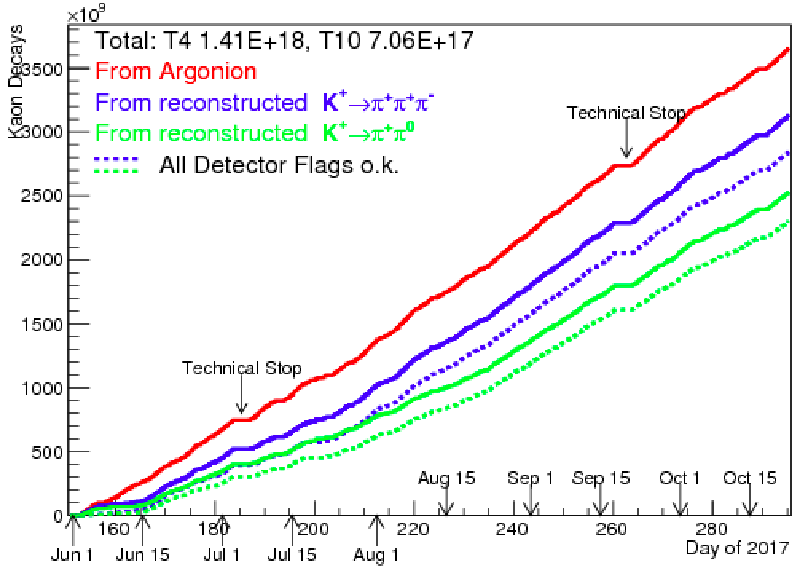
Physics run in 2016

- ✓ Stable data taking, intensity 13 x 10^{11} ppp on target (40% nominal)
- ✓ Limited by beam structure (including 50 Hz)
- ✓ ~ 4 x 10^{11} K^+ decays collected useful for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



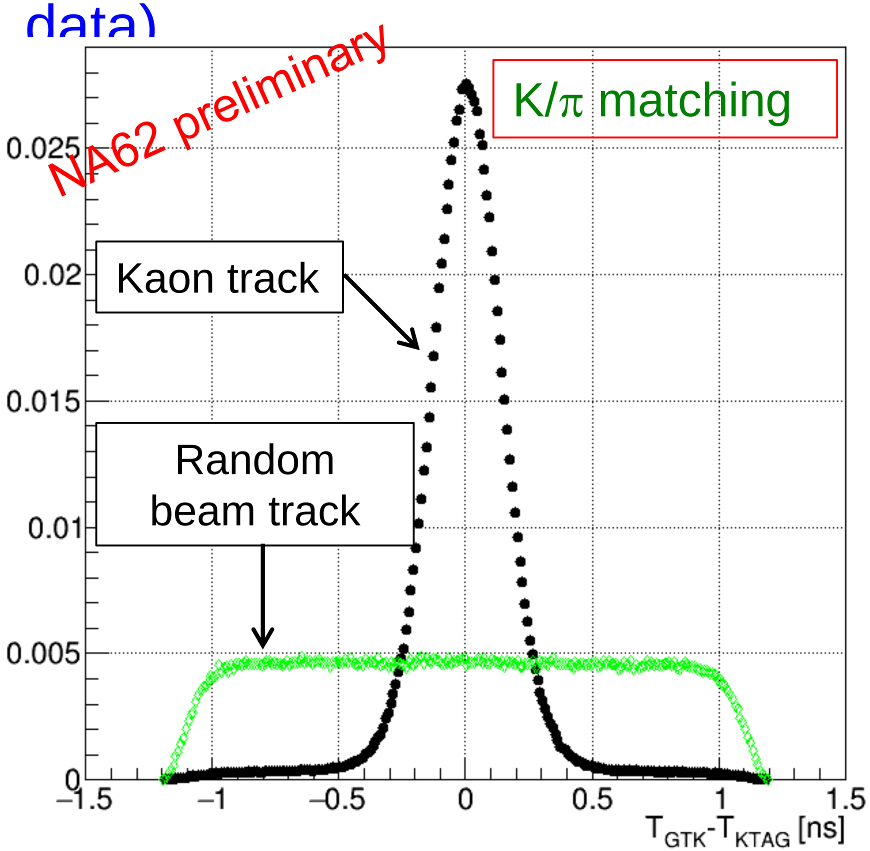
Physics run in 2017

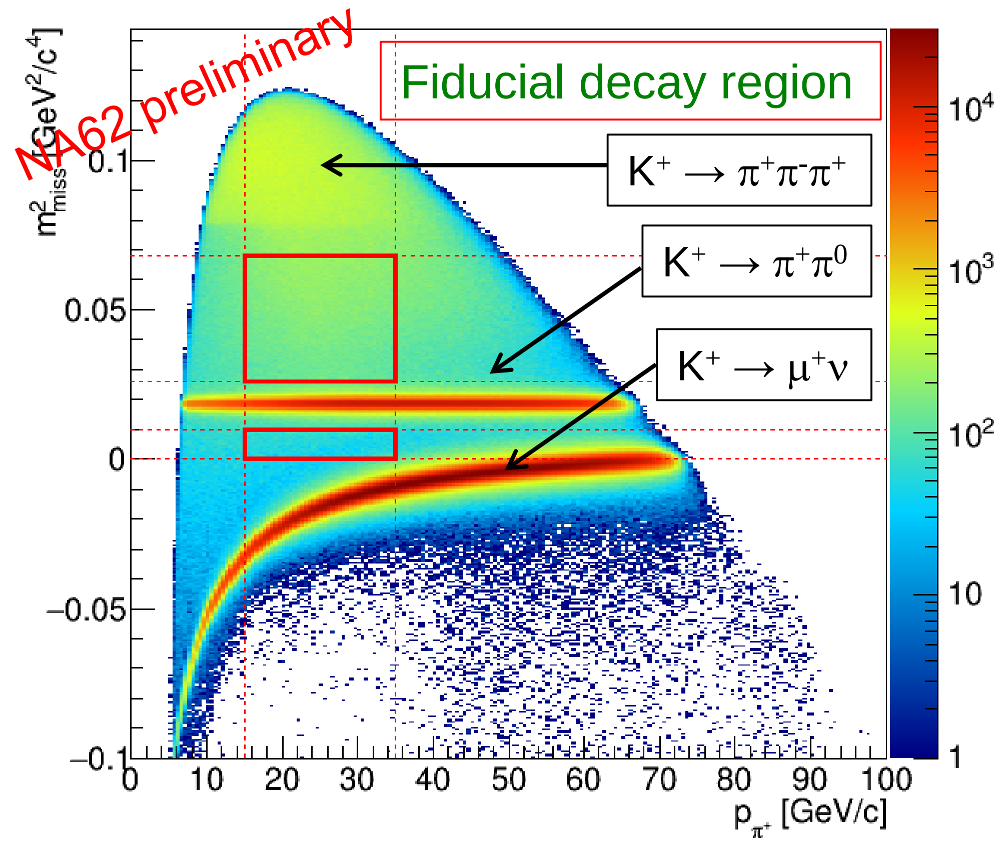
- ✓ Successful, ~ 3 x 10^{12} K^+ decays collected
- ✓ Expected similar conditions in 2018
- ✓ Number of decays should correspond to 10-15 signal events at the SM sensitivity depending on tighter/looser selection cuts
- ✓ Plan to run after LS2 to complete $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ measurement



NA62 signal regions

Analysis of 2.3 x 10^{10} K^+ decays (~ 5% of 2016 data)

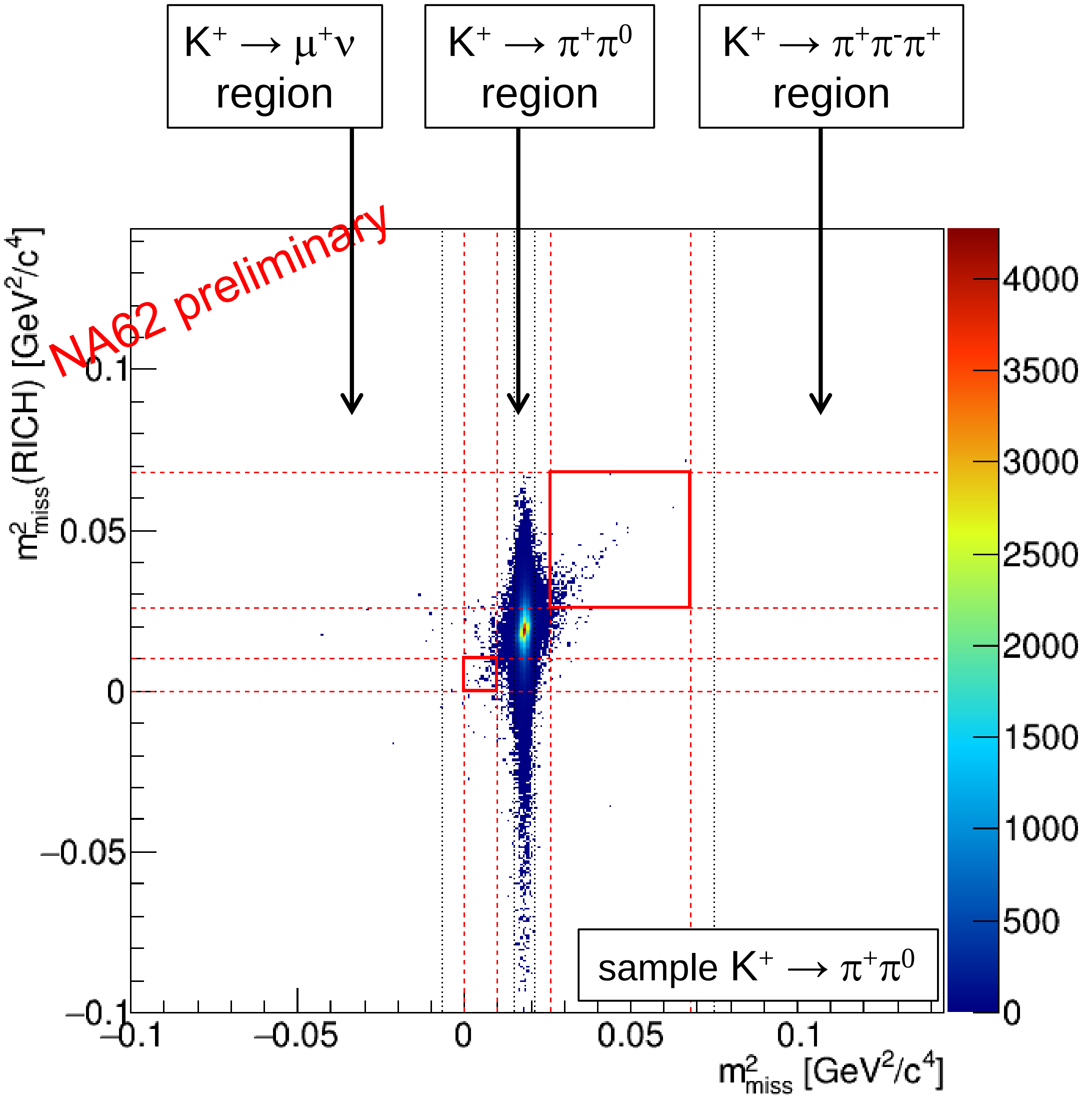




15 GeV/c < $p_{\pi+}$ < 35 GeV/c

- ✓ Timing π^+ $\sigma(t_{CHOD})$ ~ 250 ps, $\sigma(t_{RICH})$ ~ 150 ps
- ✓ Timing K^+ $\sigma(t_{KTAG})$ ~ 80 ps, $\sigma(t_{GTK})$~100 ps
- ✓ Spatial matching: intersection of GTK and Straw track σ(cda) ~ 1.5 mm
- ✓ Mis-tagging probability ~ 1.7 %

Kinematics and background



3 definitions of the missing mass

$$m^2_{miss} = \left(p^{GTK}_{K^+} - p^{STRAW}_{p^+}\right)^2$$

$$m^2_{miss}(RICH) = \left(p^{GTK}_{K^+} - p^{RICH}_{p^+}\right)^2$$

$$m^2_{miss}(beam) = \left(p^{beam}_{K^+} - p^{STRAW}_{p^+}\right)^2$$

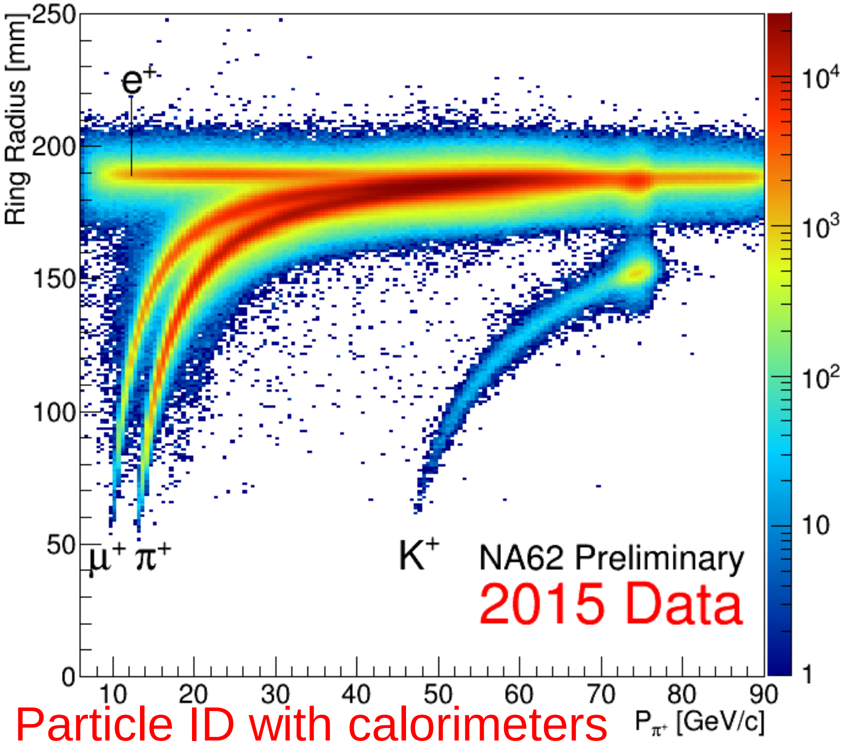
- ✓ Kinematical suppression measured on data
- ✓ Fraction of background events in the signal region

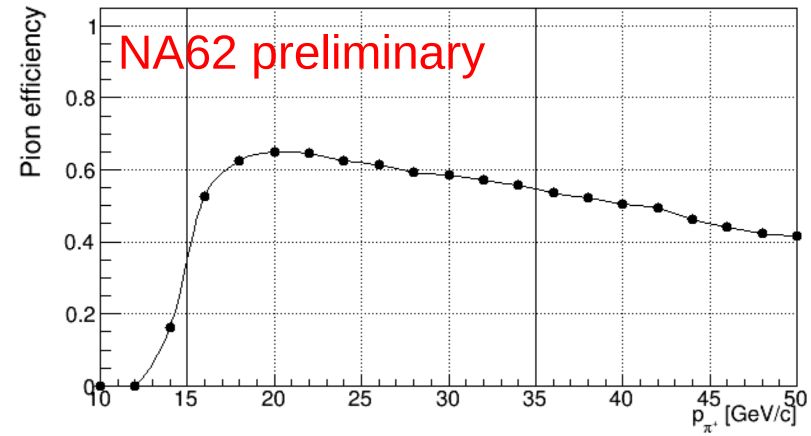
➔ $K^+ \rightarrow \pi^+\pi^0$ ~ 6 x 10^{-4}

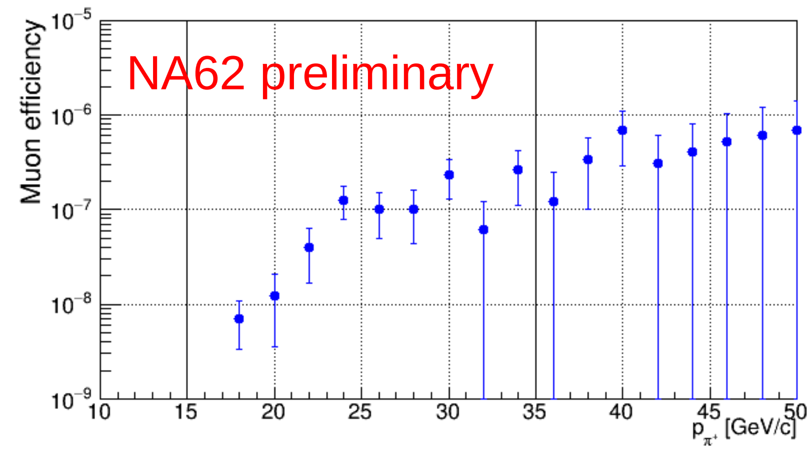
➔ $K^+ \rightarrow \mu^+\nu$ ~ 3 x 10^{-4}

Particle ID

RICH ring radius vs track momentum







Particle ID with calorimeters

- ✓ MVA on LKr and MUV 1/2
- ✓ $\varepsilon(\mu) \sim 10^{-5}$, $\varepsilon(\pi) \sim 80\%$

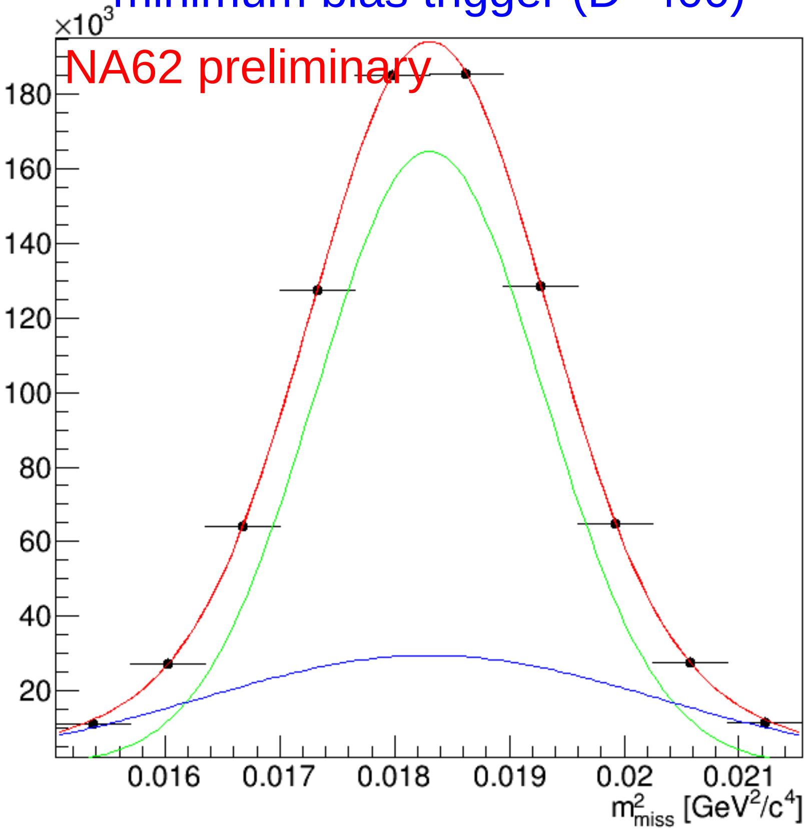
Particle ID with RICH

- ✓ $\varepsilon_{ring}(\pi) \sim 90\%$ (depends on $p_{\pi+}$)
- ✓ $\varepsilon(\mu) \sim 10^{-2}$, $\varepsilon(\pi) \sim 80\%$

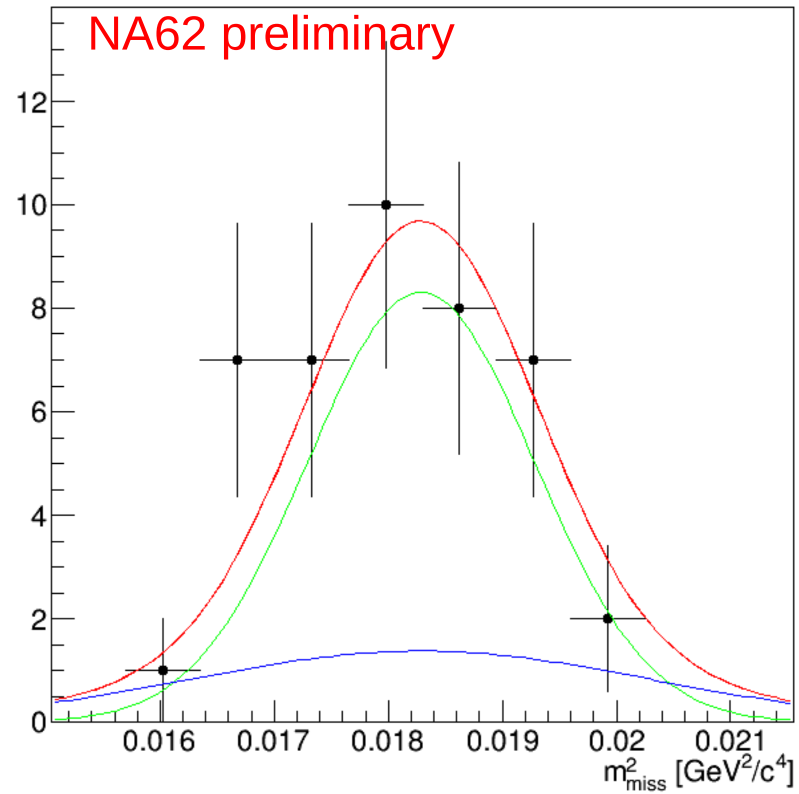
Combined PID performance using RICH and calorimeters: μ suppression $< 10^{-7}$

Photon rejection

before γ rejection
minimum bias trigger (D=400)



after γ rejection
($K^+ \rightarrow \pi^+\nu\bar{\nu}$ trigger)



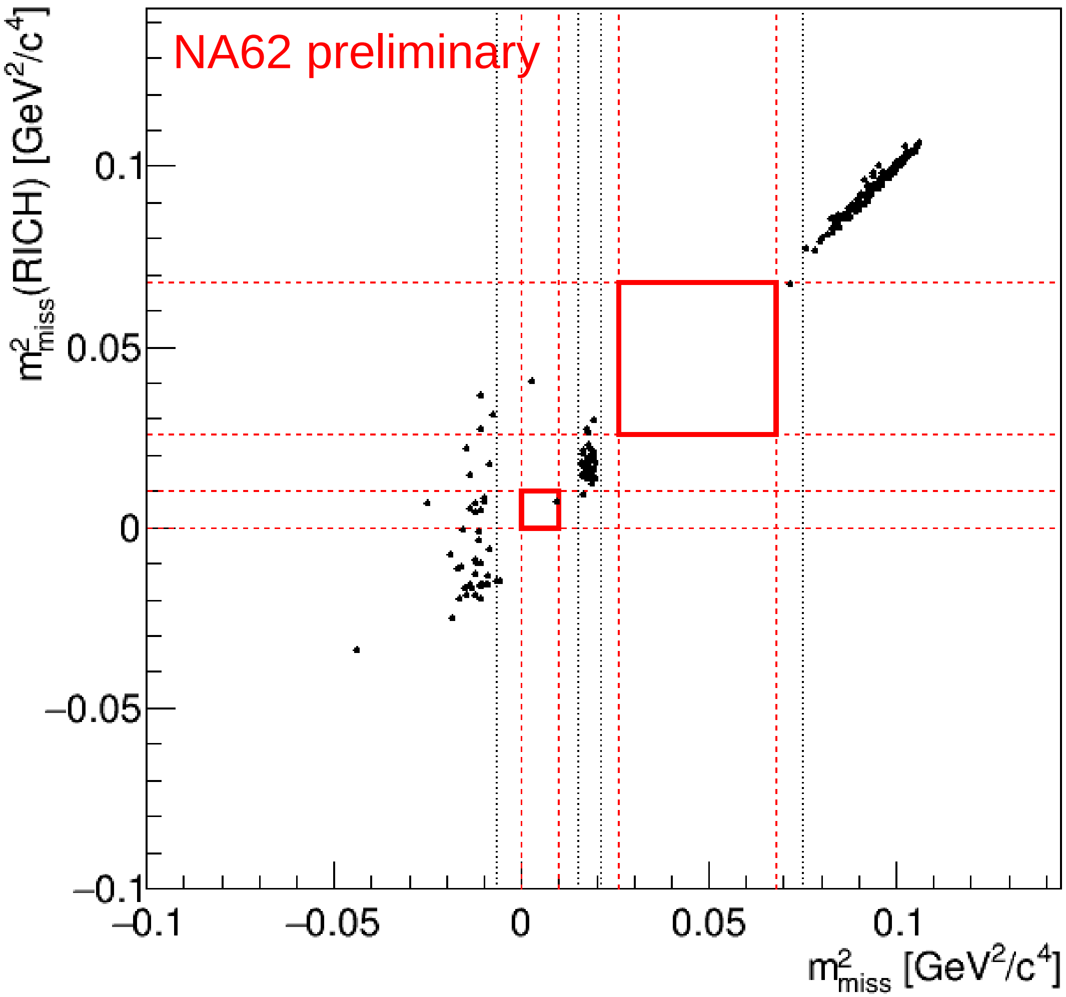
Photon Veto conditions: LKr, LAV, IRC, SAC

- $K^+ \rightarrow \pi^+\pi^0$ suppression (in the $K^+ \rightarrow \pi^+\pi^0$ region) $\varepsilon(\pi^0) = (1.2 \pm 0.2)\text{x}10^{-7}$
- 15-16 % $\pi\nu\nu$ accidental losses (measured on data)

Hermetic γ veto suppression of $\pi^0 \rightarrow \gamma\gamma < 10^{-7}$

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ - Preliminary Result

5% of 2016 data set, 2.3 x 10^{10} kaon decays



- ✓ Expected $\pi\nu\nu$ 0.064
- ✓ Expected backgrounds
  - $K^+ \rightarrow \pi^+\pi^0$ 0.024
  - $K^+ \rightarrow \mu^+\nu$ 0.011
  - $K^+ \rightarrow \pi^+\pi^-\pi^+$ 0.017
  - beam induced < 0.005
- ✓ Estimated with data driven methods
- ✓ Other backgrounds negligible

No events in signal region

Event in box has the missing mass outside the signal region (no GTK)

Analysis optimization in progress

$K^+ \to \pi^+ \nu\bar{\nu}$ - Outlook

- Analysis on the full 2016 data set is progressing
- Processing and preparation for the 2017 data set on-going, big sample (expected 10-15 $K^+ \to \pi^+\bar{\nu}\nu$ signal events)
- Data taking will resume in April 2018, until November 2018
- Then, Long Shut Down 2
- To reach ultimate sensitivity NA62 plans to continue data taking after LS2
- Along with the $K^+ \to \pi^+\nu\bar{\nu}$ measurement, a broad and rich programme of physics will be addressed.

Exotics @ NA62:
Heavy Neutrino, Dark Photon, LFV/LNV searches

Exotics @ NA62

The high-intensity setup, trigger system flexibility, and detector performance, as

- high - frequency tracking of beam particles
- redundant PID
- ultra-high-efficiency photon vetoes

make NA62 particularly suitable for searching for New Physics effect from different scenarios:

- Heavy Neutral Leptons (2015 data sample)
- Lepton Universality, LFV/LNV (2007-2008 data sample)
- Dark Photons (2016 data sample)
- ALPs – Axion Like Particles (2016 data sample)

Search for
Heavy Neutral Leptons (HNL)

HNL searches - motivations

- ✓ Observation of neutrino oscillations ➡ massive neutrinos need to be accommodated in the SM.
- ✓ Many SM extension proposed, involving massive "sterile" neutrinos (HNLs) which mix with the ordinary "active" neutrinos.
- ✓ For example, the νMSM [Asaka-Shaposhnikov, PLB 620 (2005) 17]

- 3 right-handed neutrinos, N_i, added in the SM
  - ➔ The lightest (N_1, mass $\mathcal{O}$ (10 keV)) is a Dark Matter candidate
  - ➔ $N_{2,3}$, mass $\mathcal{O}$ (1 GeV), introduce extra CPV phases to account for Baryon Asymmetry of the Universe (BAU) and produce SM neutrino masses
- The model explains simultaneously
  - ➔ neutrino oscillations and smallness of neutrino masses
  - ➔ cosmic Dark Matter (DM) candidate
  - ➔ Baryon Asymmetry of the Universe
- Active - sterile neutrino mixing described by a mixing matrix U

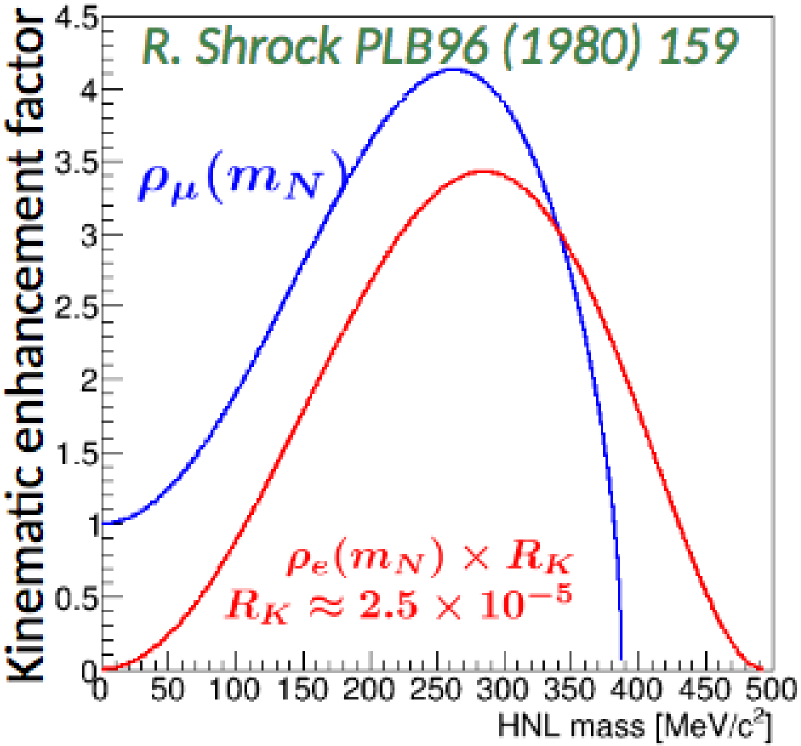
HNL searches with Kaons

In Kaon decays, if $m_N < (m_K - m_\ell)$ HNL are observable

PRODUCTION

- Search for peaks in $m_N^2 = m_{miss}^2 = (p_K - p_l)^2$

$$\Gamma(K^+ \to l^+ N) = \Gamma(K^+ \to l^+ n_l) \times r_l(m_N) \times |U_{l4}|^2$$



DECAY

- HNL decays only in SM particles

$$\Gamma(N \to SM\ particles) \propto |U_{l4}|^2 \times m_N^3$$

- if m_N < 500 MeV/c^2 main decays are:
- $N \to \pi^0 \nu$, $N \to \pi^\pm \mu^\mp$, $N \to \pi^\pm e^\mp$, $N \to \nu\nu\nu$

Searches in:

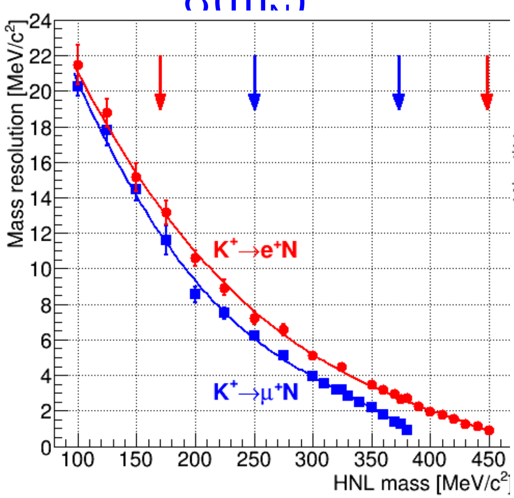
NA48/2 (2003 data), NA62-R_K (data 2007) and NA62 (data 2015)

→ Focus on NA62

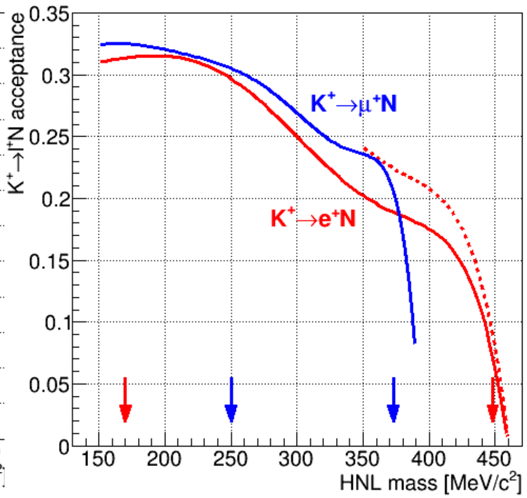
HNL searches at NA62 - 2015 data

Select decays $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$
Kaon decays in the fiducial volume: $N_K \sim 3.01 \times 10^8$

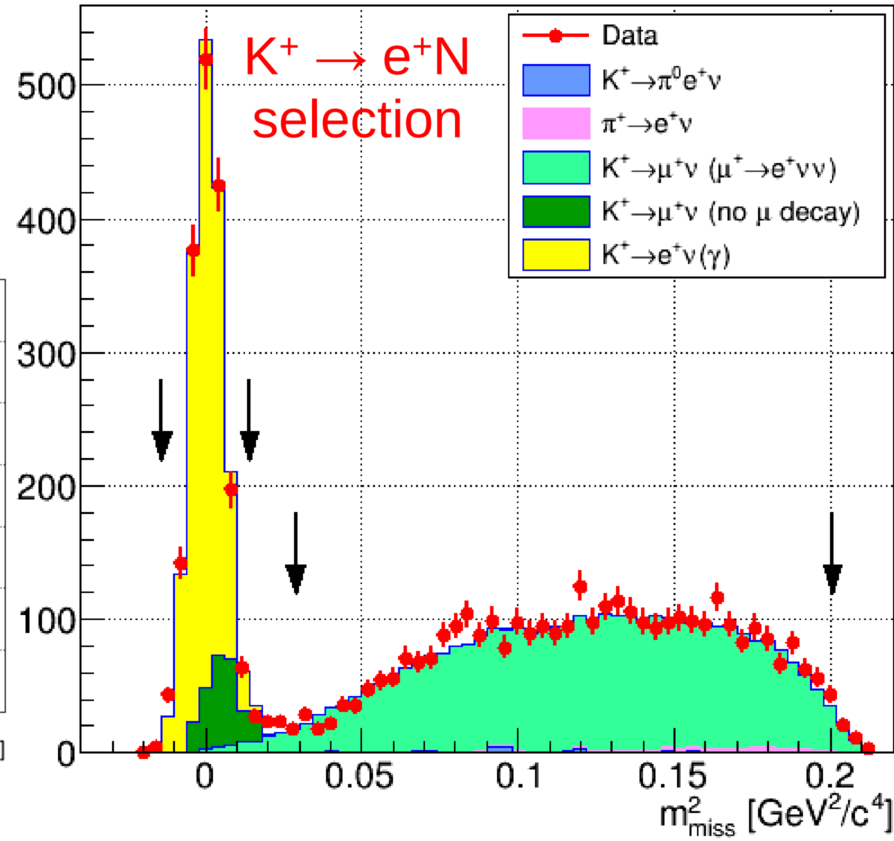
- ✓ Search for peaks in $m^2_{miss} = (p_K - p_l)^2$
- ✓ Signal region: $170 \leq m_{miss} \leq 448$ MeV/c^2
- ✓ HNL MC simulation:
  - Acceptance vs HNL mass $A(m_N)$
  - Missing mass res. vs HNL mass $\sigma(m_N)$



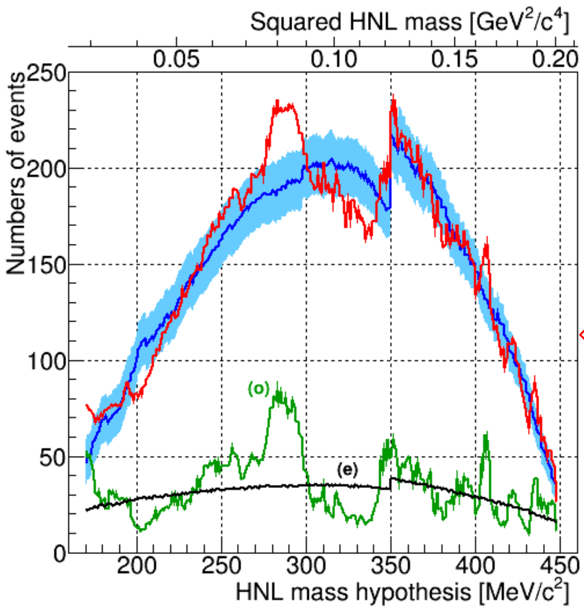
$A(m_N)$

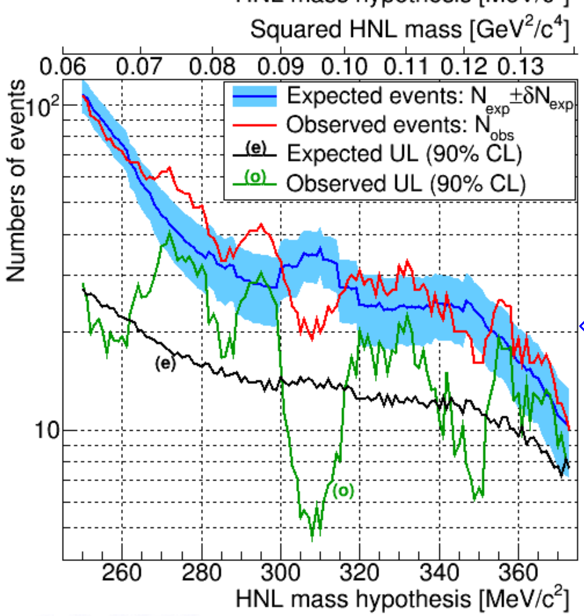


$\sigma(m_N)$



HNL searches at NA62 - results

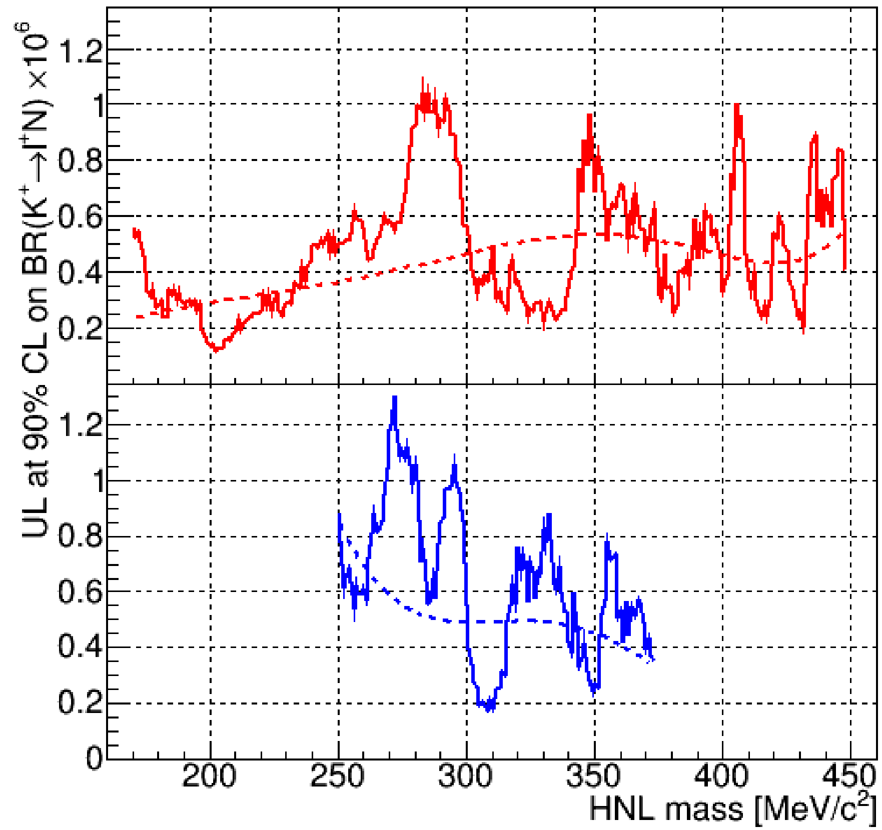




Number of expected and observed events and UL for each HNL mass hypothesis

$K^+ \rightarrow e^+N$

$K^+ \rightarrow \mu^+N$



Expected and observed upper limits on BR ($K^+ \rightarrow e^+N$) and BR ($K^+ \rightarrow \mu^+N$) for each HNL mass hypothesis

HNL searches at NA62 - global limits and prospects

Upper Limits on $|U_{l4}|^2$

$$|U_{l4}|^2 = \frac{BR(K^+ \to l^+ N)}{BR(K^+ \to l^+ \nu_l) \times r_l(m_N)}$$

NA62 2007 data analysis (1):

- Extends the mass range for Upper Limit on $|U_{\mu 4}|^2$
- Most stringent limit in $300 \leq m_{miss} \leq 375$ MeV/c^2

NA62 2015 data analysis (2):

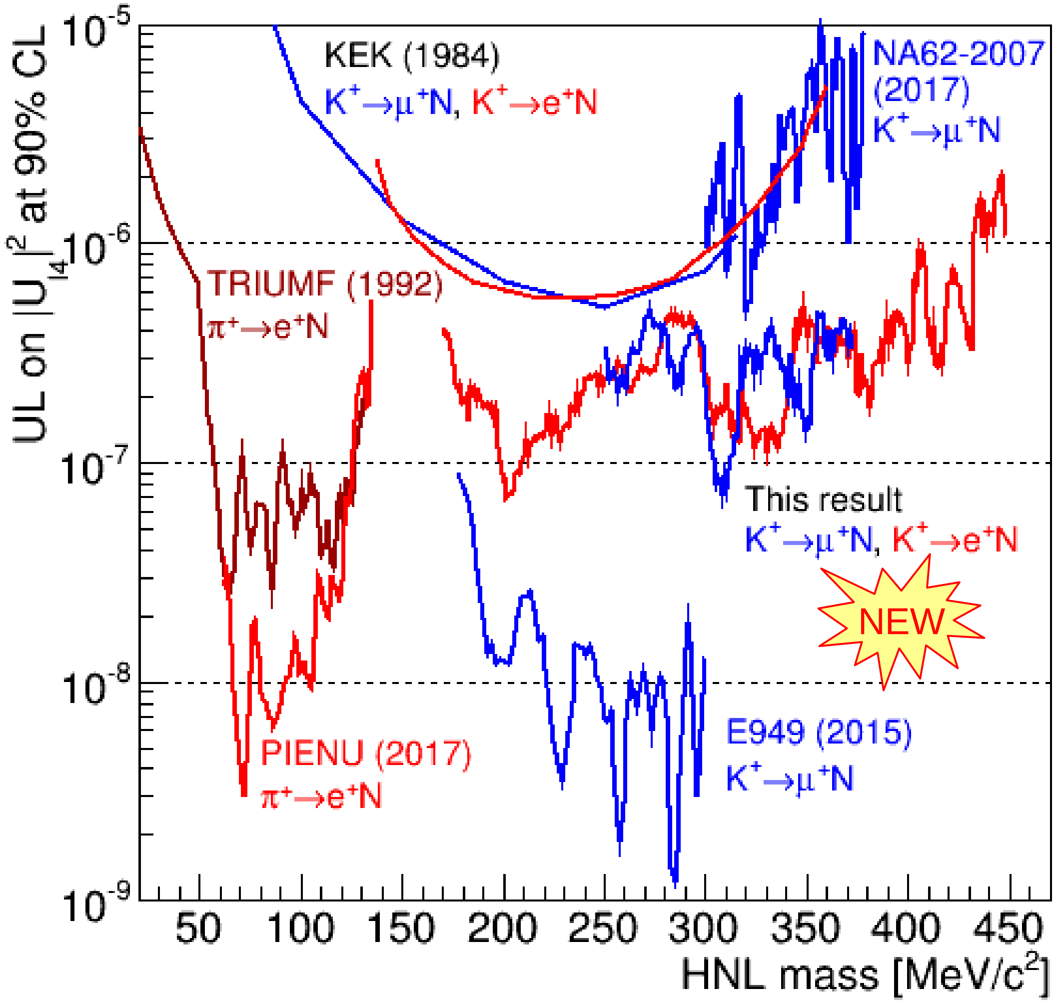
- Reaches 10^{-6}-10^{-7} limits on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$
- $170 \leq m_{miss} \leq 448$ MeV/c^2

NA62 prospects

- major improvements for beam and detector
- $|U_{e4}|^2$ limit expected to decrease, 1-2 orders of magnitude

(1) [Phys. Lett. B772 (2017) 712-718]

(2) [Phys. Lett. B778 (2018) 137-145]



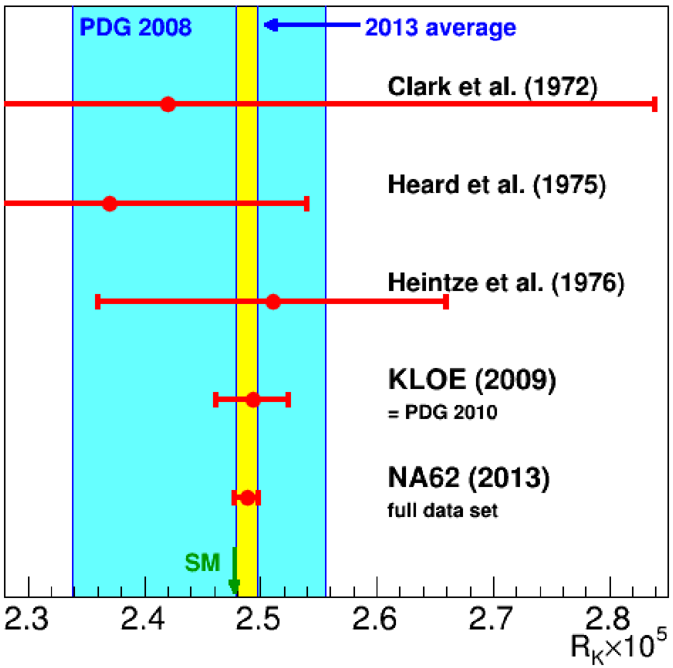
World comparison of Upper Limits from K^+ and π^+ decays

Lepton Universality and LFV/LNV

Lepton Universality - measurement of R_K

$$R_K = \frac{\Gamma\left(K^{\pm} \to e^{\pm}\nu_e\right)}{\Gamma\left(K^{\pm} \to \mu^{\pm}\nu_\mu\right)}$$

$$R_K = \frac{N(K_{e2}) - N_{BG}(K_{e2})}{N(K_{\mu 2}) - N_{BG}(K_{\mu 2})} \times \frac{A(K_{\mu 2}) \times f_\mu \times \varepsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \times \frac{1}{f_{LKr}}$$



$$R_K = \left(2.488 \pm 0.007_{stat} \pm 0.007_{syst}\right) \times 10^{-5}$$

- World Ke2 statistics increased by a factor of 10
- In agreement with SM expectation, within 1.2 σ
- Motivation for improved precision R_K measurements

World average	R_K x 10^5	precision
PDG 2008	2.447 ± 0.109	4.5%
2014	2.488 ± 0.009	0.4%

Phys Lett B 719 (2013) 326

Prospects:

NA62 ➡ 1 M events (downscaled trigger) expected (2 years data taking), statistical uncentainty ~ 0.1% ➡ Total uncertainty expected ~ 0.2%

LNV/LNC in $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ @ NA48/2

Same sign muon sample - LNV

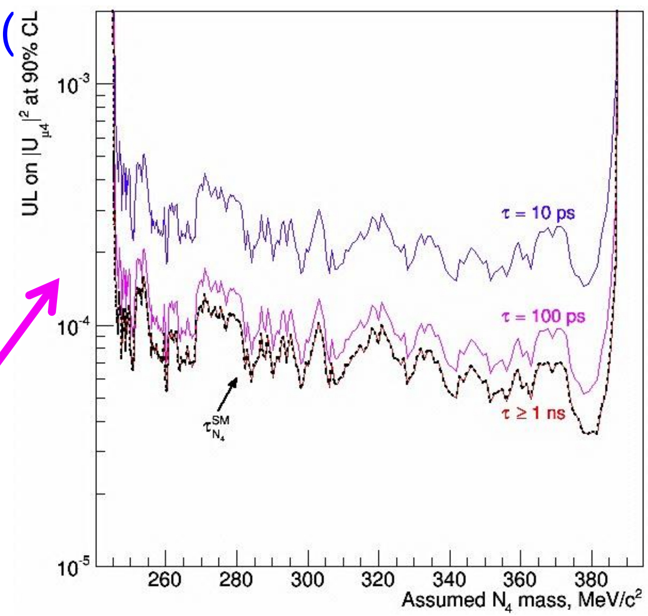
- Kaon decays in the fiducial region — $N_K = 2 \times 10^{11}$
- Observed events in the signal region — $N_{obs} = 1$
- Expected background (MC) — $N_{exp} = 1.160 \pm 0.865$
- Rolke-Lopez method for UL 90% CL — BR ($K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$) < 8.6 x 10-11 @

Opposite sign muon sample - LNC

- Kaon decays in the fiducial region — $N_K = 2 \times 10^{11}$
- Observed events in the signal region — $N_{obs} = 3489$
- Background — N_{exp} = (

LNV and LNC resonance search

- Search for 2-body resonances in $\pi\mu\mu$ candidates performed assuming different mass hypotheses, both for same sign and opposite sign muons
- Statistical significance never exceeds $+3\sigma$ - no signal observed
- From UL(BR), UL($|U_{\mu4}|^2$) can be extracted



[Phys. Lett. B769 (2017) 67-76]

Search for the Dark Photon in π^0 decays

Dark photon production in π^0 decays

- One of the simplest extension of the SM, aiming at explaining the abundance of Dark Matter in the Universe, predicts an extra U(1) gauge symmetry, with its corresponding gauge boson A', the Dark Photon (DP)
- The Dark Photon is characterized by two a priori unknown parameters, the mass $m_{A'}$ and the mixing parameter ε^2
- NA62 → also a π^0 factory, mainly from $K^+ \longrightarrow \pi^+\pi^0$
- Dark Photon production in $\pi^0 \to \gamma A'$ and subsequent A' decay

$$BR(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{M^2_{A'}}{M^2_{\pi^0}}\right)^3 BR(\pi^0 \to \gamma\gamma)$$

[B. Holdom, Phys. Lett. B166 (1986) 196] [Batell et al, PRD80 (2009) 095024]

→ NA48/2 searches of Dark Photon in Kaon and pion decays
  - → $\pi^0 \to \gamma A'$ and $A' \to e^+e^-$ [Phys. Lett. B 746 (2015) 178]
  - → $K^\pm \to \pi^0 X$, $X \to \mu^+\mu^-$ [Phys. Lett. B 769 (2017) 67]

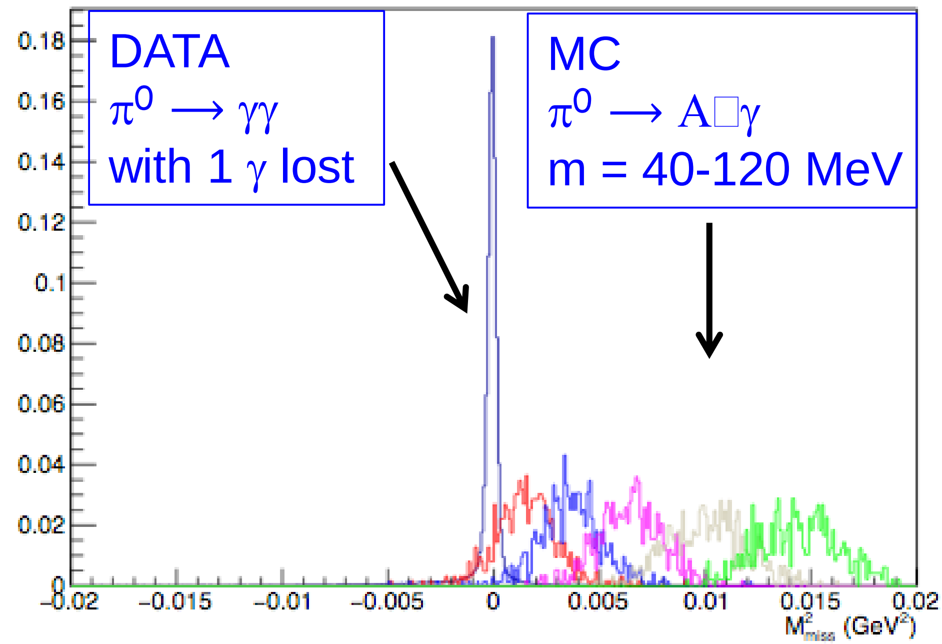
→ NA62 searches
  - → $\pi^0 \to \gamma A'$ and $A' \to \chi\chi$ (invisible)
  - → Long-lived $A' \to \mu^+\mu^-$ (in dump mode, work in progress)

Dark photon decay into invisible

- Data taking and analysis parasitic to $K^+ \longrightarrow \pi^+\nu\nu$, exploiting
  - extreme photon veto capability
  - high resolution tacking
  - in a high rate environment

$$M^2_{miss} = \left(P_{K^+} - P_{\pi^+} - P_{\gamma}\right)^2$$

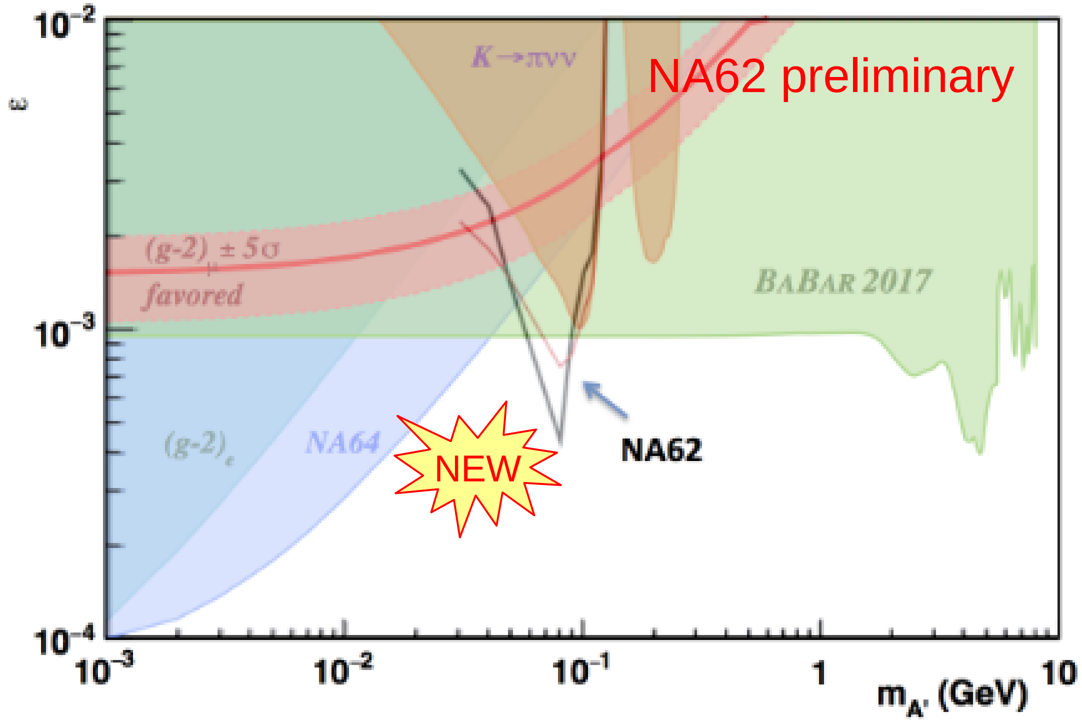
- ➔ Large sample of $K^+ \longrightarrow \pi^+\pi^0$
- ➔ The M^2_{miss} should peak around A' mass for $\pi^0 \longrightarrow A'\gamma$ decay and around zero for $\pi^0 \longrightarrow \gamma\gamma$ background
- ➔ data-driven background estimation
- ➔ The ratio of the number of signal events to the number of π^0's allows a determination of the ε coupling parameter



$$\frac{n_{sig}}{n_{\pi^0}} = \frac{BR\left(\pi^0 \rightarrow A'\gamma\right)}{BR\left(\pi^0 \rightarrow \gamma\gamma\right)} \varepsilon_{sel}\varepsilon_{trig}\varepsilon_{mass}$$

Dark Photon - Result

- ➔ Data sample: ~ 1.5 x 10^{10} K^+ decays
- ➔ DP mass range: ~ 50 MeV/c^2 < $m_{A'}$ < ~ 90 MeV/c^2
- ➔ No statistically significant excess observed
- ➔ New Upper Limit at 90% CL in the coupling (ε) vs mass plane

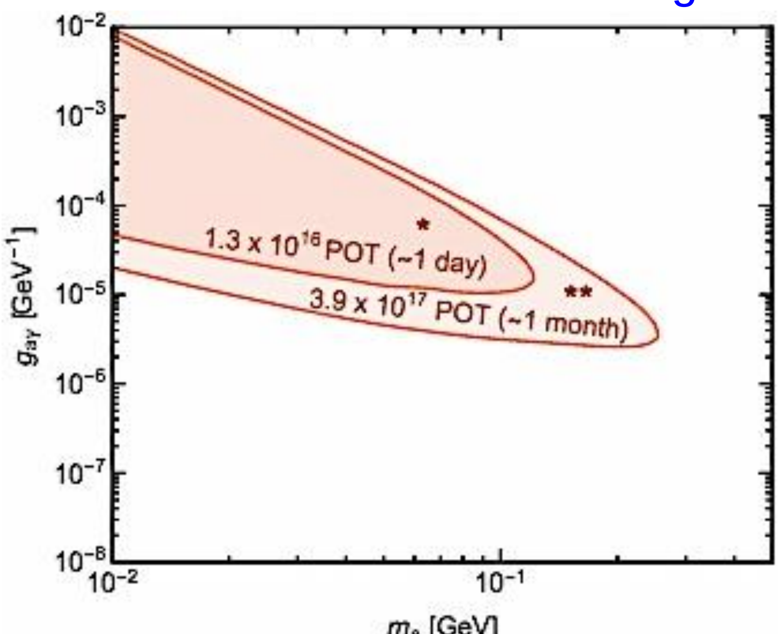


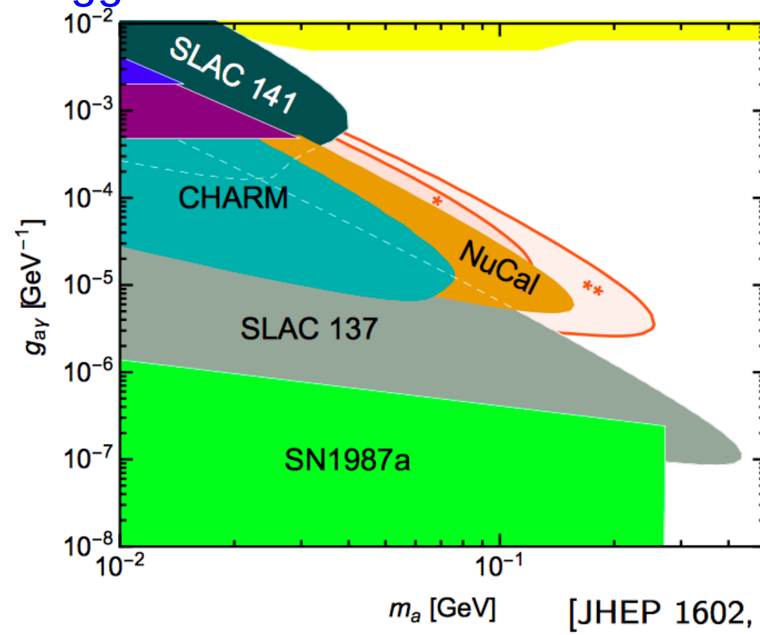
Results indicate that the statistical capability of NA62 allows an improvement on previous recent results.

Axion-Like Particles (ALPs)

NA62 offers a very good discovery potential for Axion-Like Particles (ALPs) in the MeV to GeV range weak coupling

- ✓ Pseudo-scalar ALP created by photon fusion (Primakov effect);
- ✓ Long-lived, weakly-interacting particles produced along with nominal beam
- ✓ NA62 has the possibility to dump the beam by closing TAX and removing target
- ✓ Collected ~ 1 x 10^{16} POT using dedicated triggers in 2017





[JHEP 1602, 018]

Projected NA62 sensitivity in the parameter plane, for 1 day and 1 month of data taking

Parameter regions overlaid with previous experiments and astrophysical constraints

Analysis on-going

Future prospects

Current run **Run 3** **Run 4**

LS2 **LS3**

A rich program can be carried out in Run 3 with minimal/no upgrades to the present set-up

Future plans

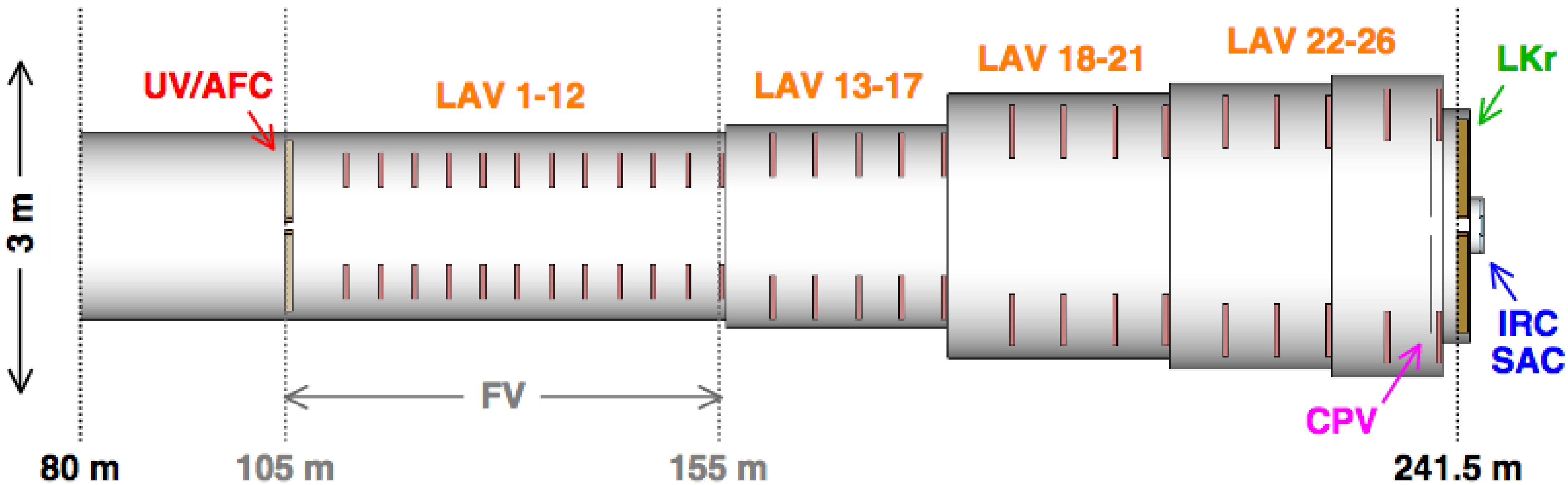
- ✓ Refine $K^+ \longrightarrow \pi^+\nu\bar{\nu}$ measurement, if needed
- ✓ With the present K^+ set-up, in dedicated runs, can reach unprecedented LFV/LNV sensitivity in K^+ and π^0 decays
- ✓ Runs in “beam-dump” mode, possibility to search for NP in the hidden sector: Heavy Neutral Leptons, Dark Photons, Axion/Axion-Like-Particles

What next?

- The $K \to \pi\nu\nu$ full picture needs the measurement of
  charged and neutral mode
  - $K^+ \to \pi^+\nu\bar{\nu}$ ⇒ NA62, current Run and Run 3
  - $K_L \to \pi^0\nu\bar{\nu}$ ⇒ KOTO at JPARC
- New measurements??

- Idea to make the measurement of $K_L \to \pi^0\nu\nu$ at CERN SPS
  - high energy experiment (p_K = 70 GeV), complementary to KOTO
  - photons from K_L decays boosted forward, makes photon veto easier
  - possibility to reuse NA62 detector (partially)
  - require 2 x 10^{13} ppp, i.e. 6 x NA62, currently not available
  - aim to collect ~ 60 SM events in 5 years from 2026 with S/B ~ 1
- Project discussed at CERN as part of Physics Beyond Colliders

K_LEVER - an experiment to measure $K_L \rightarrow \pi^0 \nu\nu$



Target sensitivity:
5 years starting Run 4

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

δBR/BR($\pi^0 \nu\nu$) ~ 20%

Main detector/veto systems:

UV/AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 liquid-krypton calorimeter
IRC/SAC	Small-angle vetoes
CPV	Charged-particle veto

C. Lazzeroni @ PBC - nov 2017

Conclusions

Kaon physics has played a substantial role in establishing the basis of the SM

After more than 70 years, Kaons still provide stringent tests of the SM and ways to look beyond it, searching for NP (LFV/LNV, LU, exotics……. CPV….)

NA62 experiment

- ✓ running and collecting data for $K^+ \rightarrow \pi^+ \nu\nu$ measurement
  - ✓ 5% of 2016 statistics analysed, no signal observed, expected 0.064
  - ✓ analysis of 2016 and 2017 data sets in progress, expect 10-15 SM events
  - ✓ data taking will resume in 2018 and, possibly, after LS2
- ✓ Improved limits on the search of HNL, DP, other exotics….

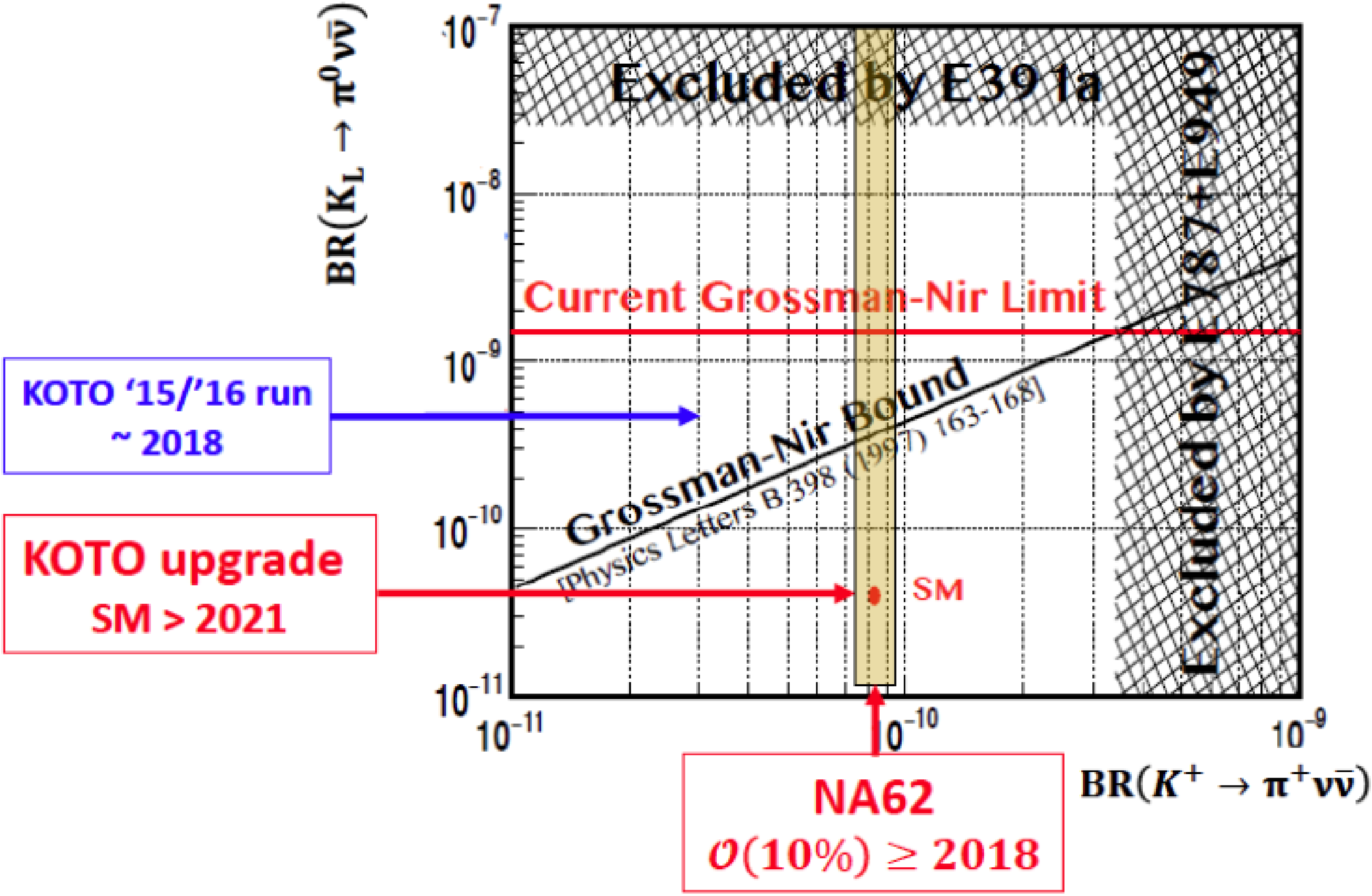
Kaon measurements at the frontier of precision physics
A lot of exciting physics ahead!


Thank you!

NA62 Penguins at work

Additional information

$K \to \pi\nu\nu$ prospects



K_LEVER - timeline

Status and timeline

Project timeline - target dates:

2017-2018	**Project consolidation** • Beam test of crystal pair enhancement • Consolidate the design
2019-2021	**Detector R&D**
2021-2025	**Detector construction** • Possible K12 beam test if compatible with NA62
2024-2026	**Installation during LS3**
2026-	**Data taking beginning Run 4**

Expression of Interest to SPSC

- **Actively seeking new collaborators**
- **Institutes interested so far: Birmingham, Bristol, Charles U., Comenius U., Dubna, Ferrara, Florence, Frascati, George Mason U., Glasgow, La Sapienza, Louvain, Mainz, Moscow INR, Naples, Perugia, Pisa, Protvino, Sofia, Tor Vergata, Turin.**