Status of the NA62 experiment

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Outline

- Motivations for PNN (and more)
- The CERN Kaon factory
- Recent results (a personal selection)
- Prospects

NP: hunting high and low

- Some well known open questions in SM :
  - Hierarchy
  - Neutrino masses and mixings
  - Origin of Dark Matter
  - Matter/antimatter asymmetry
  - Strong CP problem
- New physics at TeV scale not found (so far)

Explore **higher mass scale** via virtual production (ultrarare processes)….
…or search for **light (but feebly coupled) particles** in production and/or decay

K→πνν and SM

- FCNC processes : no tree-level SM contribution
- $\sin^5\theta_C$ suppression (top loop dominance)
- Hadronic part from K_{e3} : accurate prediction in SM
- Theoretical uncertainty dominated by CKM elements.

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

Buras et al., JHEP 1511

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

Precision of prediction limited by CKM parameters

Knowledge of γ, V_{cb} and V_{ub} will be improved by LHCb and Belle II

See also most recent results: J. Buras, E. Venturini Eur. Phys. J. C 82 (2022) 7, 615
G. D'Ambrosio, A.M. Iyer, F. Mahmoudi, S. Neshatpour arxiv:2206.14748v1

K→πνν and NP at high mass

Simplified Z and Z' models

Buras, Buttazzo, Knegjens, JHEP 1511

May test scales up to 2000 TeV (!) in generic NP scenarios.
Or «just» 50-100 TeV for pure L/R NP

LFU violation models

Bordone, Buttazzo, Isidori, Monnard
Eur.Phys.J. C77 (2017) no.9, 618

ν_τ contributes to the decay

K→πνν and NP at high mass

Non-MFV MSSM @10 TeV

M.Tanimoto and K. Yamamoto
PTEP 2016 (2016) no.12, 123B02

Randal-Sundrum models with custodial symmetry

Blanke, Buras, Duling, Gemmler, Gori
JHEP 0903 (2009) 108

See also: Blazek, Matak Int.J.Mod.Phys. A29 (2014)
Isidori et al., JHEP 0608 (2006) 064

K→πX and NP at low mass

- Limits on $K \to \pi X$ translate in strong limits on ALPs or scalars in the usual mass/coupling plane

PBC workshop report, *Eur.Phys.J.C* 81 (2021) 11, 1015

M. Bauer, M. Neubert, S. Renner, M.Schnubel and A. Thamm JHEP 09 (2022) 056

The needle in the haystack

- Unconstrained kinematics, backgrounds 10^{10} times higher than signal....
- Need for a dedicated kaon factory !

The CERN kaon factory

- 400 GeV protons extracted from SPS
- Up to 3.3 x10^{12} **p**rotons **o**n **t**arget /spill
- T10 target : 1 λ_{int} Be target→ 75 GeV/c secondary hadron beam

Up to ≈5·10^{12} kaon decays/year in 60 m decay volume

- Possibility to dump the beam onto 22 λ_{int} Cu «target»

Up to 10^{18} pot/year to search for exotic particles with very low background

The CERN kaon factory

RUN 2 : 2021-2025. Nominal intensity + upgraded detector.
We are taking data of excellent quality right **now** !

NA62 @ CERN SPS

RUN 2 upgrades

- Achromat design optimized against upstream bkg
- Added fourth GTK station
- Upstream veto before/after last collimator
- Added 2nd HASC module to improve π^0 rejection

NA62 @ CERN SPS

- Time resolution: O(100) ps
- Beam and decay tracking: sq. missing mass resolution **10^{-3} GeV^2**
- Particle id: O(**10^7**) μ vs π rejection for 15 GeV< p < 35 GeV
- Photon detection: O(**10^7**) π^0 rejection
- Primary goal: precision measurement of BR($K^+ \to \pi^+ \nu\nu$)

JINST 12 P05025 (2017)

Some recent results

- $K^+ \to \pi^+ \bar{\nu}\nu \; and \; K^+ \to \pi^+ X$ (full RUN 1)
- Precision measurement of $K^+ \to \pi^+ \mu^+ \mu^-$
- LFV/LNV searches
- Beam dump search for dark photon $A' \to \mu^+ \mu^-$

Not covered in this talk: HNL searches, Ke3γ and T invariance test, $K^+ \to \pi^+ \gamma\gamma$ ...

RUN 1 result on πνν

- 2016+2017+2018 data [JHEP 06 (2021) 093]
- $N_S^{ex} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- $N_B^{ex} = 7.03^{+1.05}_{-0.82}$
- 1+2+17 events observed →Bkg only $p = 3.4 \times 10^{-4}$
- Significance 3.4σ

$$\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11} @ 68\,\%\ \text{CL}$$

RUN 1 result on πνν

RUN 1 result on πνν

68% CL interval

RUN 1 result on $K^+ \to \pi^+ X$

[JHEP 06 (2021) 093]

High resolution peak search in missing mass:
$0.7 < \sigma_{m^2_{miss}} < 1.2 \quad (10^{-3} GeV^2/c^4$ units)

$K^+ \to \pi^+ \nu\bar{\nu}$ is the main background !

RUN 1 result on $K^+ \to \pi^+ X$

- Limits on $K \to \pi X$ translate in strong limits on ALPs or scalars in the usual mass/coupling plane

PBC workshop report, *Eur.Phys.J.C* 81 (2021) 11, 1015

M. Bauer, M. Neubert, S. Renner, M.Schnubel and A. Thamm JHEP 09 (2022) 056

Precision measurement of $K^+ \to \pi^+\mu^+\mu^-$

- Almost bkg free selection of a process with BR $\simeq 10^{-7}$
- Fit to extract form factor in the spectrum of the dynamical variable $z = m^2_{\mu\mu}/m^2_K$

- Normalization ($K \to 3\pi$)
- Effective number of kaon decays $\simeq 3.5 \times 10^{12}$

Precision measurement of $K^+ \to \pi^+\mu^+\mu^-$

- Almost bkg free selection of a process with BR $\simeq 10^{-7}$
- Fit to extract form factor in the spectrum of the dynamical variable $z = m^2_{\mu\mu}/m^2_K$

- Signal ($K \to \pi\mu\mu$)
- $N_S = 27679$ evts with 8 bkg evt expected

Precision measurement of $K^+ \to \pi^+\mu^+\mu^-$

$$\mathcal{B}_{\pi\mu\mu} = (9.15 \pm 0.06_{\text{stat}}) \times 10^{-8}$$

- Almost bkg free selection of a process with BR $\simeq 10^{-7}$
- Fit to extract form factor in the spectrum of the dynamical variable $z = m_{\mu\mu}^2/m_K^2$

- Fit to $d\Gamma(K^+ \to \pi^+\mu^+\mu^-(\gamma))/dz$
- Precise treatment of rad. corrections (NLO)

Precision measurement of $K^+ \to \pi^+\mu^+\mu^-$

Form factor parameters compatible with $K \to \pi ee$ (LFU test)

- Almost bkg free selection of a process with BR $\simeq 10^{-7}$
- Fit to extract form factor in the spectrum of the dynamical variable $z = m_{\mu\mu}^2/m_K^2$

- Fit to $d\Gamma(K^+ \to \pi^+\mu^+\mu^-(\gamma))/dz$
- Precise treatment of rad. corrections (NLO)

G. D'Ambrosio, A.M. Iyer, F. Mahmoudi, S. Neshatpour arxiv:2206.14748v1

G. D'Ambrosio, M. Knecht, S. Neshatpour arXiv:2209.02143

LFV/LNV searches

- LNV (same sign leptons) mediated by Majorana neutrinos. Similar to $0\nu\beta\beta$.

- Signatures: $K^+ \to \pi^- \ell^+ \ell^+$ with $\ell = e, \mu$ or $K^+ \to \mu^- \bar{\nu}_\mu \, \ell^+ \ell^+$ with $\ell = e, \mu$

LFV/LNV searches

- LFV (opposite sign different family) mediated by Leptoquarks

- Signature: $K^+ \to \pi^+ \ell_1^+ \ell_2^-$ with $\ell_1 = e, \mu$ and $\ell_2 = \mu, e$

LFV/LNV searches

LFV/LNV searches

Decay channel	Previous $\mathcal{B}$ UL (PDG)	NA62 $\mathcal{B}$ UL	statistics	improvement
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}, ref [6]	25% of Run 1	$\sim$ factor 2
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}, ref [7]	full Run 1	$\sim$ factor 12
$K^+ \to \pi^- \pi^0 e^+ e^+$	–	8.5×10^{-11}, ref [7]	full Run 1	–
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}, ref [8]	2017-18	$\sim$ factor 12
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}, ref [8]	2017-18	$\sim$ factor 8
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}, ref [8]	2017-18	$\sim$ factor 10
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	8.1×10^{-11}, ref [9]	full Run 1	$\sim$ factor 250

[6] Searches for lepton number violating K^+ decays. NA62 Collaboration. *Phys. Lett. B* **797** (2019) 134794, [1905.07770]
[7] Searches for LNV $K^+ \to \pi^- (\pi^0) e^+ e^+$ decays. NA62 Collaboration. *Phys. Lett. B* **830** (2022) 137172, [2202.00331]
[8] Search for lepton number and flavour violation in K^+ and π^0 decays. NA62 Collaboration. *Phys. Rev. Lett.* **127** (2021) 13, 131802, [2105.06759]
[9] Paper in preparation

Dark photon @ NA62

- Extra U(1) massive gauge singlet
- Mixing with SM hypercharge
- ε and $\mathbf{m_{A'}}$ are free parameters

- Searches at NA62 :
  - o Invisible modes ($K^+ \to \pi^+ A'$ or $K^+ \to \pi^+ \pi^0$ and $\pi^0 \to \gamma A'$)
  - o Production at target/dump and decays:

    $A' \to ee$ or $A' \to \mu\mu$

NA62 in beam dump mode

- TAXes closed and target removed
- Improved sweeping; intensity 1.5 times nominal
- 1 track and 2 track triggers
- Search for $A' \to \mu^+\mu^-$

NA62 in beam dump mode

2021 RUN

$(1.40 \pm 0.28) \times 10^{17}$ POT collected in ~ 10 days of data taking

$A' \rightarrow \mu^+\mu^-$

- Control samples: same sign leptons (combinatorial background)

	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p\ (N \geq N_{obs})$	$p\ (L \leq L_{obs})$
Outside CR	62.5 ± 9.4	53	0.79	0.46
CR	0.46 ± 0.07	0	1.0	1.0
SR	0.040 ± 0.006	0	1.0	1.0

	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p\ (N \geq N_{obs})$	$p\ (L \leq L_{obs})$
Outside CR	9.1 ± 1.4	8	0.67	0.88
CR	0.050 ± 0.007	0	1.0	1.0
SR	0.005 ± 0.001	0	1.0	1.0

$A' \rightarrow \mu^+\mu^-$

	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p\ (N \geq N_{obs})$	$p\ (L \leq L_{obs})$
Outside CR	26.3 ± 3.4	28	0.41	0.74
CR1	0.29 ± 0.04	1	0.25	0.25
CR2	0.58 ± 0.07	1	0.44	0.44
CR3	1.70 ± 0.22	2	0.50	0.68
CR1+2+3	2.57 ± 0.33	4	0.26	0.24
CR	0.17 ± 0.02	0	1.0	1.0
SR	0.016 ± 0.002	–	–	–

- 1 event observed in SR
- Probability of non-zero counts in SR given the bkg only hyp. is 1.59%
- Global 2.4 σ significance

Signal shape not taken into account for the significance

$A' \to \mu^+\mu^-$

90% CL UL
NA62 $A' \to \mu\mu$, obs.
$A' \to \mu\mu$, exp. $\pm 1\sigma$
$A' \to \mu\mu$, exp. $\pm 2\sigma$
Past experiments
NA62 Preliminary
ε
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{3}
$M_{A'}$ [MeV]

Prospects

- NA62 experiment will take data up to the LS3 (2025)
- It will collect data both in «kaon mode» and in «dump mode» (10^{18}pot by 2025)
- Detectors & analysis upgrades improved reconstruction efficiency, background rejection and random veto levels.
- Starting 2022 we are running at 100% nominal intensity with good spill quality.
- O(10%) precision on $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ will be reached by LS3 with optimization of the analysis.

Prospects

- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ @ 10%

The (near) future: HIKE

- A comprehensive, multi-staged project for kaon physics at CERN after LS3 : the High Intensity Kaon Experiment (HIKE) project.
- Measurement of all of rare kaon decays, charged and neutral
- Need to increase intensity at level 4x (charged beam) or 6x (neutral beam). Beamline design studies already started.

HIKE program

Step 1: High-intensity K^+ experiment to measure BR($K^+ \to \pi^+\nu\nu$) to ~5%

- Also study lepton universality/number/flavor violation:
  $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$, $K^+ \to \pi^+\ell\ell$, $K^+ \to \pi^-\ell^+\ell^+$, $K^+ \to \pi^+\mu e$
- Radiative and Dalitz decays, chiral parameters, precision measurements

Step 2: Experiment for rare K_L decays with charged particles

- K_L beamline, as in KLEVER
- Tracking and PID for secondary particles, as in NA62
- $K_L \to \pi^0\ell^+\ell^-$
  Excellent π^0 mass resolution – look for signal peak over Greenlee background
- Lepton universality/number/flavor violation in K_L decays
- Radiative K_L decays and precision measurements
- Measurement of K_L, n, and Λ fluxes and halo to prepare for K_L phase

During steps 1&2: Periodic runs with dumped beam, accumulate 10^{19} pot

Step 3: Measurement of BR($K_L \to \pi^0\nu\nu$) to ~20%: KLEVER

HIKE physics program

Observable	Target	Motivation
K^+ phase		
$K^+ \to \pi^+ \nu\nu$	BR to ~5%	New physics in FCNC decays
$K^+ \to \pi^+ \ell\ell$	Form factors at ~1% level	LFUV
$K^+ \to \pi\mu e$, $\pi^- \ell^+ \ell^+$	$O(10^{-12})$ sensitivity	LFV, LNV
$R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$	R_K to ~0.1%	LFUV
$K^+ \to \pi^+\gamma\gamma$, $\pi^+\pi^0\gamma$, $\pi^+\pi^0 ee$	As best as possible	Chiral parameters (LECs)
Hybrid phase		
$K_L \to \pi^0 \ell\ell$	Observation	New physics in FCNC decays
$K_L \to \mu\mu$	BR to < 1%	New physics in FCNC decays
$K_L \to \mu e$, $\pi^0 \mu e$	$O(10^{-12})$ sensitivity	LFV
$K_L \to \gamma\gamma$, $\pi^0\gamma\gamma$	As best at possible	Ancillary to $K_L \to \mu\mu$, LECs
K_L phase (K_LEVER)		
$K_L \to \pi^0 \nu\nu$	BR to ~20%	New physics in FCNC decays

Plus periodic runs with dumped beam to accumulate 10^{19} pot to search for exotic, long-lived particles

Conclusions

- The CERN Kaon factory has a vast and unique physics program for the search of NP , complementary to what can be done at LHC and B-factories
- High quality physics results are being published by the collaboration.
- The current run (2021-2025) will allow to fully exploit the physics reach with the current NA62 setup
- In a longer time-scale the HIKE project will measure all rare decay modes of charged and neutral kaons: stay tuned !

Additional material

RUN 2 upgrades

RUN 2 upgrades

GTK reco inefficiency

Background reduction: VetoCounter

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HIKE phase 1

- The in-flight technique is firmly established and a 5% measurement of the charged PNN mode is attainable with appropriate modifications to the current design of NA62 to cope with high intensity.
- Improve time resolution to reduce random veto
- Keep detector/daq performances with higher rates
- Tests of possible configuration have started.
- See also M. Moulson talk @ KAON 2022 for details

High intensity beams

Beam and target simulations

Thermal load on dump collimator

CNGS rod target

Thermal simulations of target and TAX dump collimator

- Identified upgrades needed for high-intensity beam
- Target: CNGS-like design: carbon-carbon supports, pressurized air cooling
- TAX: Cooling elements nearer to center of collimator, like for SPS beam dump

Dose rate simulation in ECN3, K_L beam

Neutral beam and prompt surface dose

- **Neutrons:** Shielding adequate to reduce surface dose; need access shaft airlock
- **Muons:** Additional shielding at target and/or at downstream end of ECN3

High-intensity kaon experiments at the CERN SPS – M. Moulson (Frascati) – KAON 2022 – Osaka, Japan 16 September 2022 11

Experimental challenges: STRAW

For 4x intensity:

- **Increase rate capability**
  - Reduce straw diameter
  - Use fast shaping
- **Further improve momentum resolution**
  - Reduce material budget
  - Improve position resolution

Design studies in progress at CERN and Dubna

- **Straw diameter 9.8 → 5 mm**
- **Trailing-time resolution: 30 → 6 ns**
- **Maximum drift time: 150 → 80 ns**
- **Rate capability increased 6-8x**
- Layout: 4 chambers, ~21000 straws
- Decreased straw wall thickness: 36 → 20 μm
- Material budget: 1.7 → 1.4% X_0

Experimental challenges: GTK

At 4x intensity GTK will track 3 GHz!

- **Time resolution < 50 ps per plane, no non-gaussian tails!**
- Smaller pixels to reduce occupancy: $< 300 \times 300\ \mu m^2$
- Efficiency: > 99% (incl. fill factor)
- Reduced material budget: 0.3-0.5% X_0
- Beam intensity: 3 GHz over ~ 3x6 cm^2
- Maximum local intensity: 8 MHz/mm^2
- Radiation resistance: 2.3×10^{15} n eq/cm^2/yr

NA62 Gigatracker station

Continue to improve planar sensors while monitoring progress on new technologies

Possible synergies with ongoing development efforts:

LGAD: Low Gain Avalanche Detectors

TimeSPOT: time-stamping 3D sensors

High-intensity kaon experiments at the CERN SPS – M. Moulson (Frascati) – KAON 2022 – Osaka, Japan 16 September 2022 15

Experimental challenges: KTAG

KTAG for 4x intensity:

- **Tag 200 MHz of K^+ in 3 GHz beam**
- **Need 4x better time resolution: ~20 ps!**
- Max detected photon rate: ~8 MHz/cm^2
- Single-photon capability with σ_t = 50-70 ps
- Good radiation resistance
- **Same vessel, new photodetectors**

Microchannel plate (MCP) PMTs

- Excellent time resolution (~20 ps)
- Low dark noise
- Single-photon sensitivity
- High gain, good QE
- Good filling factor
- Input rate capability ~MHz/cm^2

- **Susceptible to aging: QE drops due to to ion feedback to photocathode Effect of aging must be investigated and/or mitigated**

High-intensity kaon experiments at the CERN SPS – M. Moulson (Frascati) – KAON 2022 – Osaka, Japan 16 September 2022 16

KLEVER

- Most of the upgrades foreseen for high intensity charged beam will be used also for the neutral beam data taking.
- Simulations show that a 20% measurement of $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ in 5 years is challenging but possible with the KLEVER design.
- A rich physics program will be exploited with high intensity kaon beams !
- See also M. Moulson talk @ KAON 2022 for details

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

KLEVER

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 ~ 1

δBR/BR($\pi^0 \nu\nu$) ~ 20%

Studied in context of Physics Beyond Colliders

- 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

Exotic, long-lived particles in HIKE

Searches for visible decays in beam-dump mode

- Low rate in detector allows for potentially much higher beam intensity
- 10x statistics of 2021-2025 data (at least 10^{19} pot)
- Sensitive to forward processes, complimentary to off-axis experiments
  E.g., SHADOWS, an off-axis experiment proposed to run concurrently in ECN3

Searches for invisible decays during kaon running: $K \to \pi X$

- Projected sensitivities to scalars and ALPs for HIKE K^+ and K_L programs

Precision Measurement: $K^+ \to \pi^0 e^+ \nu_e \gamma$

Normalisation $K^+ \to \pi^0 e^+ \nu_e$ selection: m^2_{miss}

Signal $K^+ \to \pi^0 e^+ \nu_e \gamma$ selection: m^2_{miss}

T-odd observable ξ

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E^j_\gamma, \theta^j_{e,\gamma})}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

- 3 phase-space definitions (j=1,2,3).
- **<1% Precision measurement of R**: improved by factor between 2.0 and 3.6
- 6-7% relative discrepancy with ChPT $\mathcal{O}(p^6)$

	E_γ cut (*)	$\theta_{e,\gamma}$ cut (*)	$O(p^0)$ ChPT [EPJ C 50, 557]	ISTRA+	OKA	**NA62 preliminary**
R_1 ($\times 10^2$)	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10^\circ$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
R_2 ($\times 10^2$)	$E_\gamma > 30$ MeV	$\theta_{e,\gamma} > 20^\circ$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
R_3 ($\times 10^2$)	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

T-odd observable ξ (in the kaon rest frame):

$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3} \; ; \; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

Non-zero A_ξ values due to NLO (one-loop) electromagnetic corrections

	R1	R2	R3
A_ξ ($\times 10^2$)	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$

Joel Swallow
QNP2022

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Exotics: HNL Production Searches

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches

- For $|U_{e4}|^2$: complimentary to search for $\pi^+ \to e^+ N$ at PIENU
- For $|U_{\mu 4}|^2$: complimentary to search for $\pi^+ \to \mu^+ N$ at BNL-E949
- Both cases: complimentary to HNL decay searches at T2K.
- An upper limit at 90% CL $\mathscr{B}(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$ and similar limits on $\mathscr{B}(K^+ \to \mu^+ X)$, where X = invisible.

[PLB 807 (2020) 135599][PLB 816 (2021) 136259]

$K^+ \to e^+ N$

- Trigger = PNN (no downscale)
- $N_K^{eff}(K_{eN}) = (3.52 \pm 0.02) \times 10^{12}$

$K^+ \to \mu^+ N$

- Trigger = Control , Downscale = 400
- $N_K^{eff}(K_{\mu N}) = (4.29 \pm 0.02) \times 10^{9}$

Fit results

$\hat{c}_6 = 1.713 \pm 0.075_{stat.}$

$$\mathcal{B}(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat.}) \times 10^{-7}$$

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Radiative Corrections in $K^+ \to \pi^+\mu^+\mu^-$

- Radiative corrections based on [Eur. Phys. J. C70 (2010) 219], extended beyond the soft-photon approximation, see talk by Tomas Husek
- One-photon-inclusive $K_{\pi\mu\mu}$ differential decay width:

$$\frac{d\Gamma(z)}{dz} = \frac{d\Gamma_{3\text{-body}}(z)}{dz} + \frac{d\Gamma_{4\text{-body}}(z)}{dz} = g(z) \cdot |W(z)|^2 + \frac{d\Gamma_{4\text{-body}}(z)}{dz}$$

  → $|W(z)|^2$: form factor
  → $g(z)$: function describing kinematics + NLO electromagnetic effects
  → 3-body: $K^+ \to \pi^+\mu^+\mu^-$ final state
  → 4-body: $K^+ \to \pi^+\mu^+\mu^-\gamma$ final state
- NA62: first to use NLO EM corrections, including hard-photon emission simulation
  → Hard-photon definition: $(P_\pi + P_\gamma)^2 - m_\pi^2 > 100\ \text{MeV}^2$, P_π, P_γ: 4-momenta
  → Ratio of integrated decay widths (4-body / 3-body): $\approx 1.6\%$

$$\left(\frac{d\Gamma(z)}{dz}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$$

- ChPT form factor parameter measurement
  → Fit of data points, using
  $W(z) = G_F m_K^2 (a_+ + b_+ z) + W^{\pi\pi}(z)$
  → Pion-loop term parameter values from [arXiv:2209.02143]:
  $\alpha_+ = (-20.40 \pm 0.18) \times 10^{-8}$
  $\beta_+ = (-2.05 \pm 0.06) \times 10^{-8}$