Kaon physics experiments

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Outline:

1) $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ measurements at NA62 and KOTO.
2) Rare and forbidden kaon decays at NA62.
3) Kaon and hyperon physics at LHCb.
4) The KLEVER initiative at CERN: $K_L \to \pi^0 \nu\nu$ measurement.

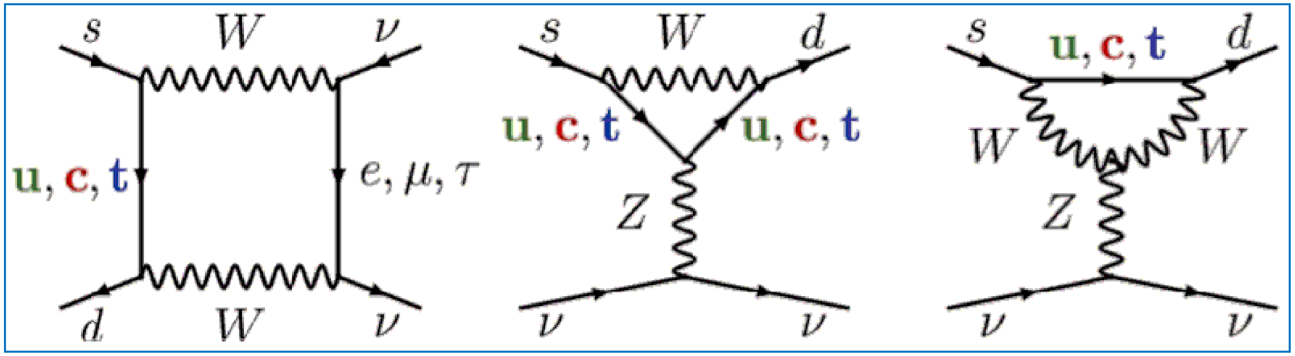
European Research Council
Established by the European Commission

UK input to EPPSU meeting
IPPP Durham • 17 April 2018

EXCELLENCE IN SCIENCE

Rare kaon decays: $K\to\pi\nu\bar{\nu}$

SM: box and penguin diagrams



Ultra-rare decays with
the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V^*_{ts}V_{td}| \sim \lambda^5$$

- Hadronic matrix element is related to a measured quantity ($K^+\to\pi^0 e^+\nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from $B-\bar{B}$ mixing or $B^0\to\rho\gamma$.

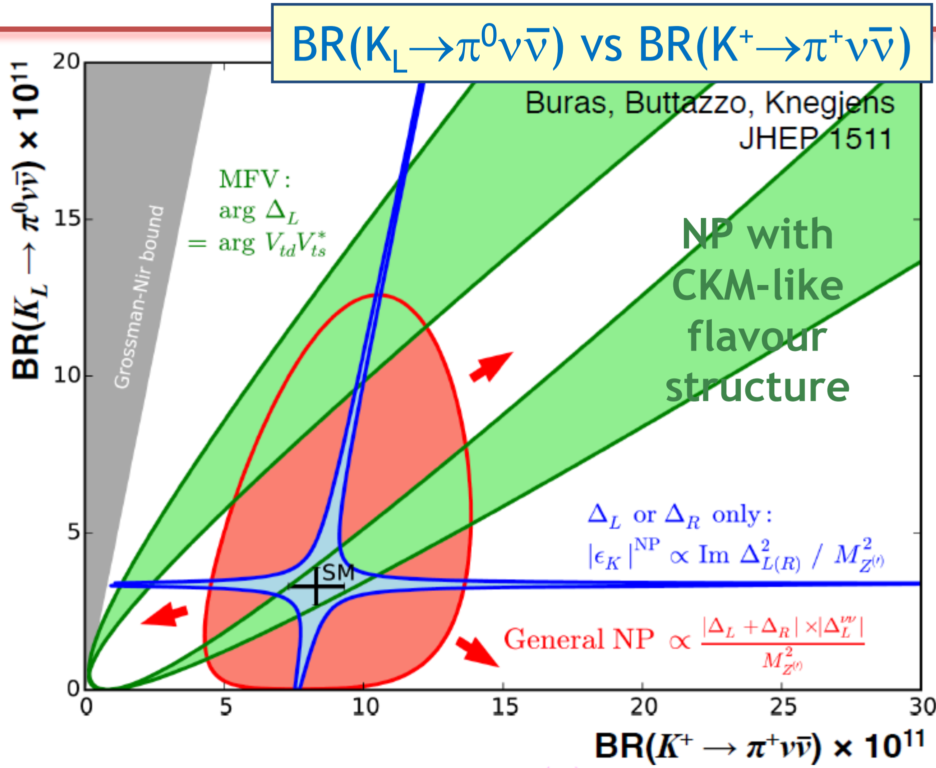
SM branching ratios
Buras et al., JHEP 1511 (2015) 033

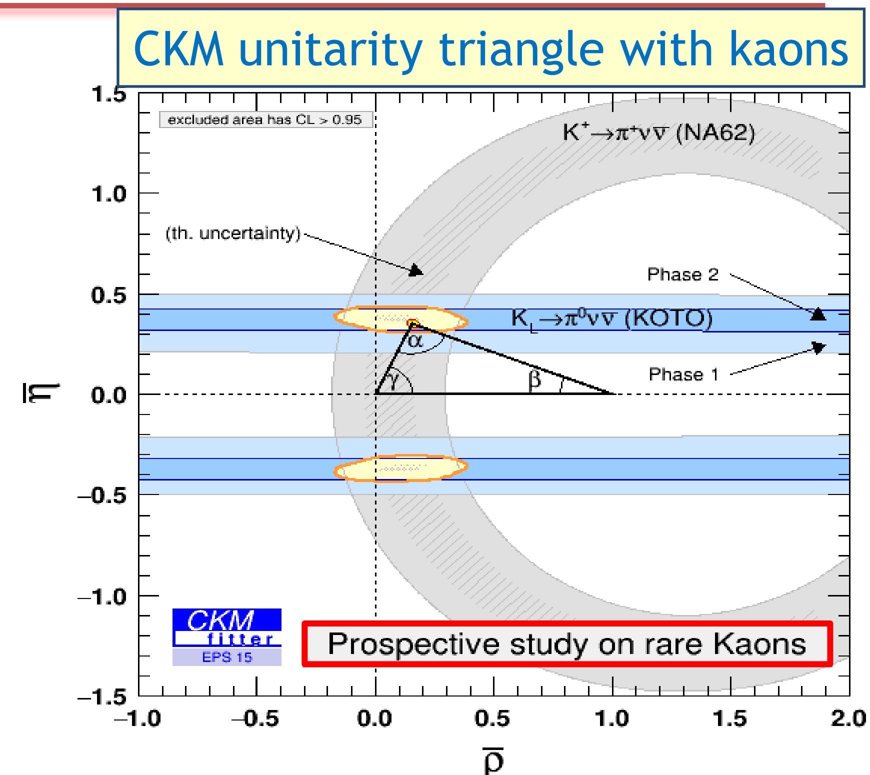
Mode	$BR_{SM}\times 10^{11}$
$K^+\to\pi^+\nu\bar{\nu}(\gamma)$	8.4 ± 1.0
$K_L\to\pi^0\nu\bar{\nu}$	3.4 ± 0.6

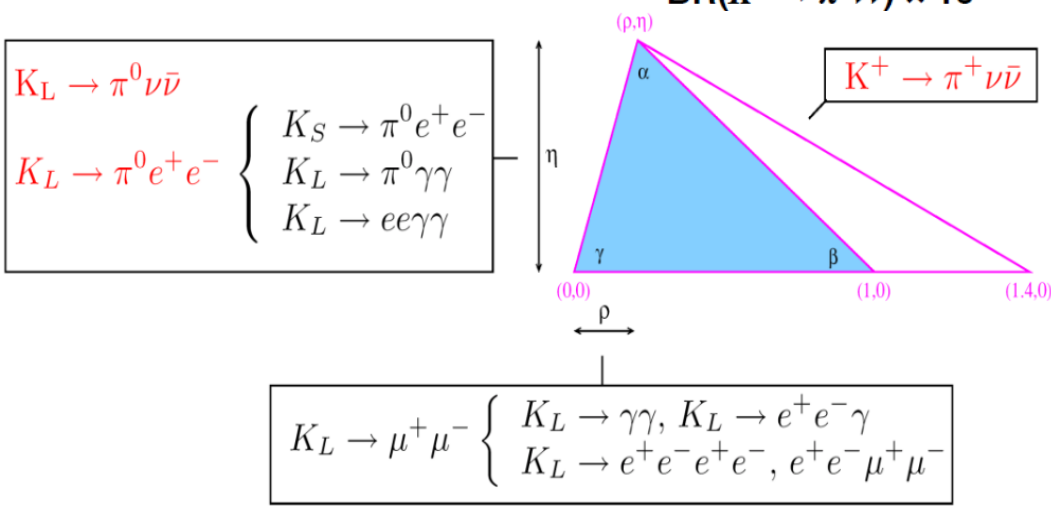
The uncertainties are largely parametric (CKM)

Theoretically clean,
almost unexplored,
sensitive to new physics.

$K\to\pi\nu\bar{\nu}$: connection to flavour physics







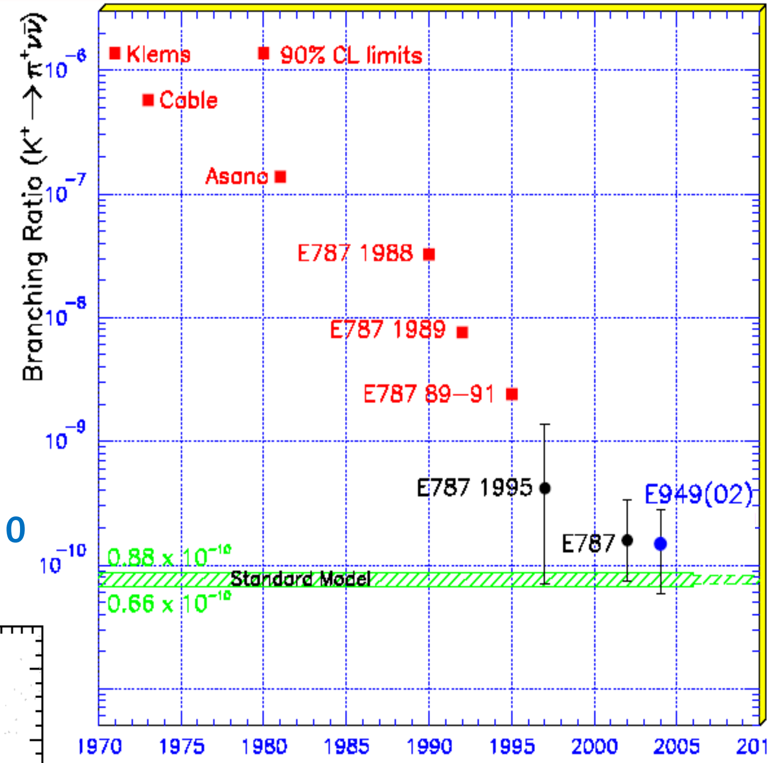
- It is essential to measure both $K^+\to\pi^+\nu\nu$ and $K_L\to\pi^0\nu\nu$ decays.
- Kaon physics alone can fully constrain the unitarity triangle.
- Comparison with B physics can provide description of NP flavour dynamics.

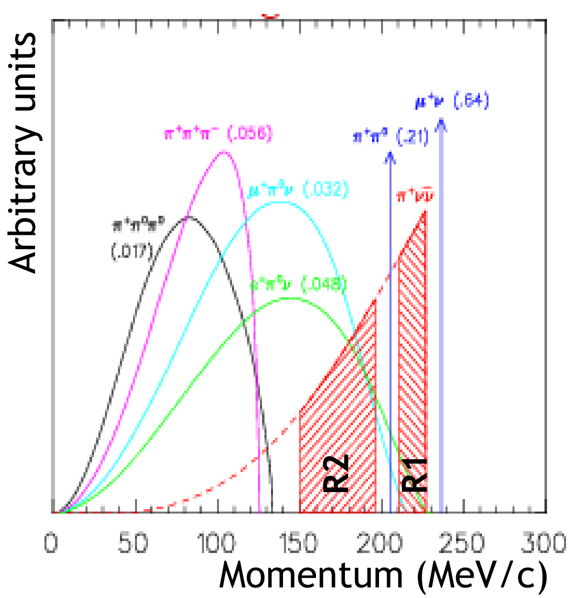
$K^+ \to \pi^+ \nu\bar{\nu}$: experimental status

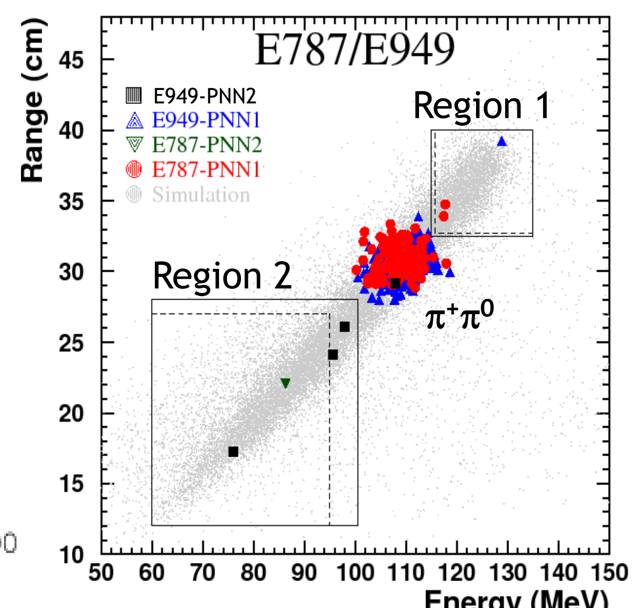
Technique: K^+ decay at rest

Data taking: E787 (1995–98), E949 (2002).
Separated K^+ beam (710 MeV/c, 1.6 MHz).
PID: range (entire $\pi^+ \to \mu^+ \to e^+$ decay chain).
Hermetic photon veto system.

Observed candidates: **7**
Expected background: **2.6**
Final result: **$BR = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$**



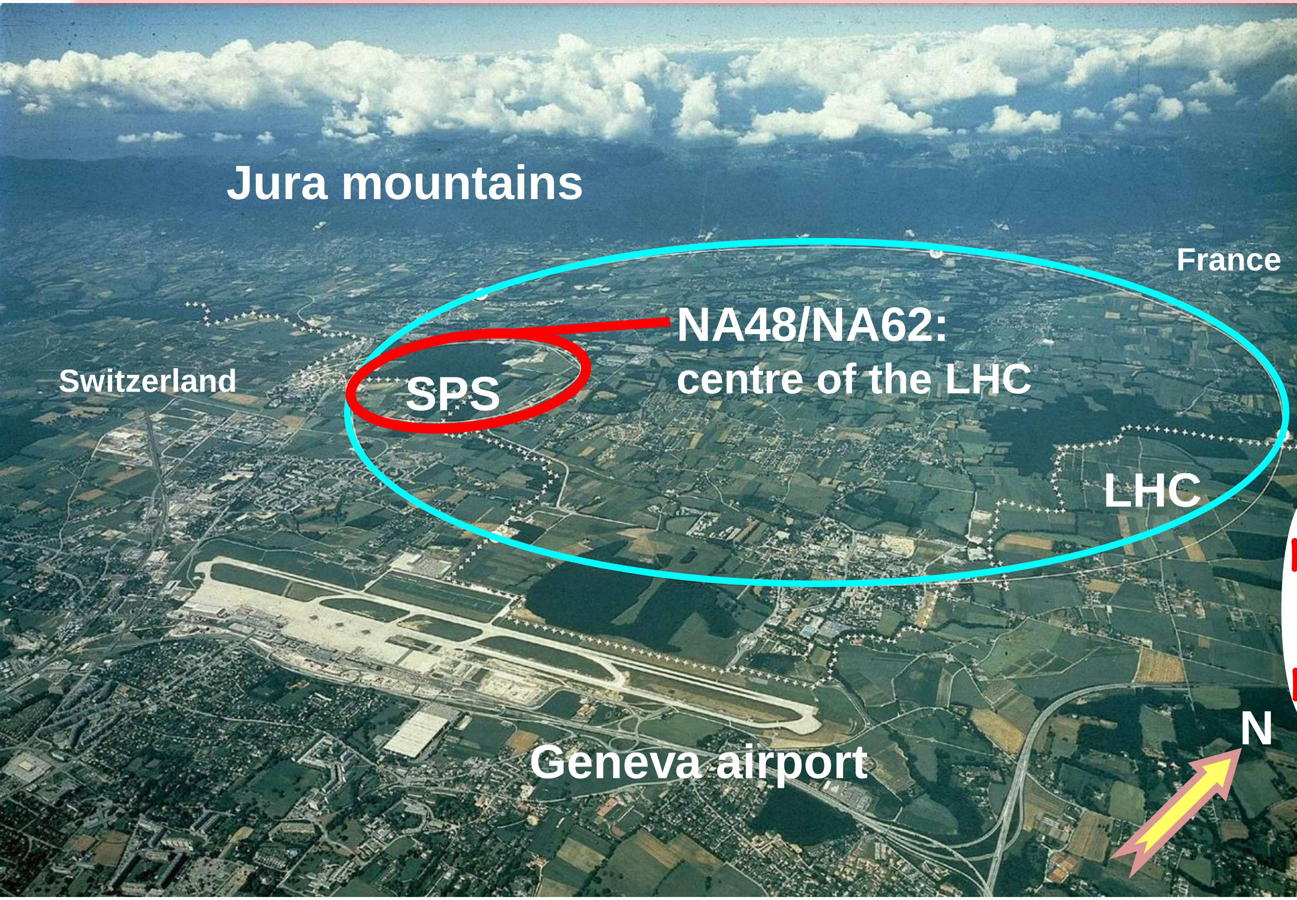




Background is mainly in Region 2, due to $K_{2\pi}$ decay with π^+ scattering in the target.

PRL 101 (2008) 191802;
PRD 79 (2009) 092004

NA62 at CERN: $K^+ \to \pi^+ \nu\nu$



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

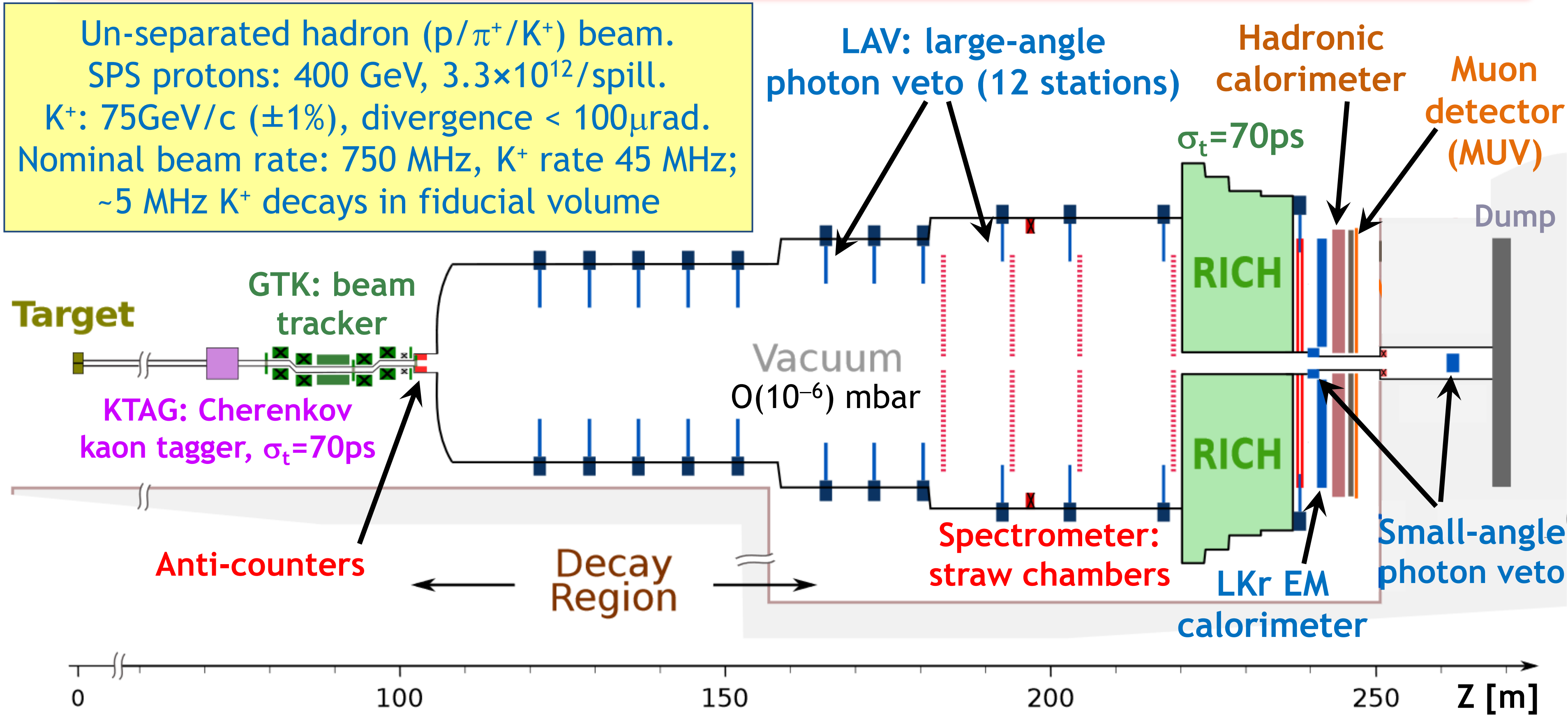
NA62
- 2015: commissioning
- 2016–18: physics run

Main goal: an improved $K^+ \to \pi^+ \nu\nu$ measurement with a novel decay-in-flight technique.

Major UK contribution: 11% of the collaboration.

The NA62 detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3.3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
Nominal beam rate: 750 MHz, K^+ rate 45 MHz;
~5 MHz K^+ decays in fiducial volume



- Pion momentum 15 GeV/c<p<35 GeV/c: missing energy of at least 40 GeV.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression = 3×10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): muon suppression = 1×10^{-8}.
- Kinematic rejection factors (limited by beam pileup & MCS tails): 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.

NA62 physics programme

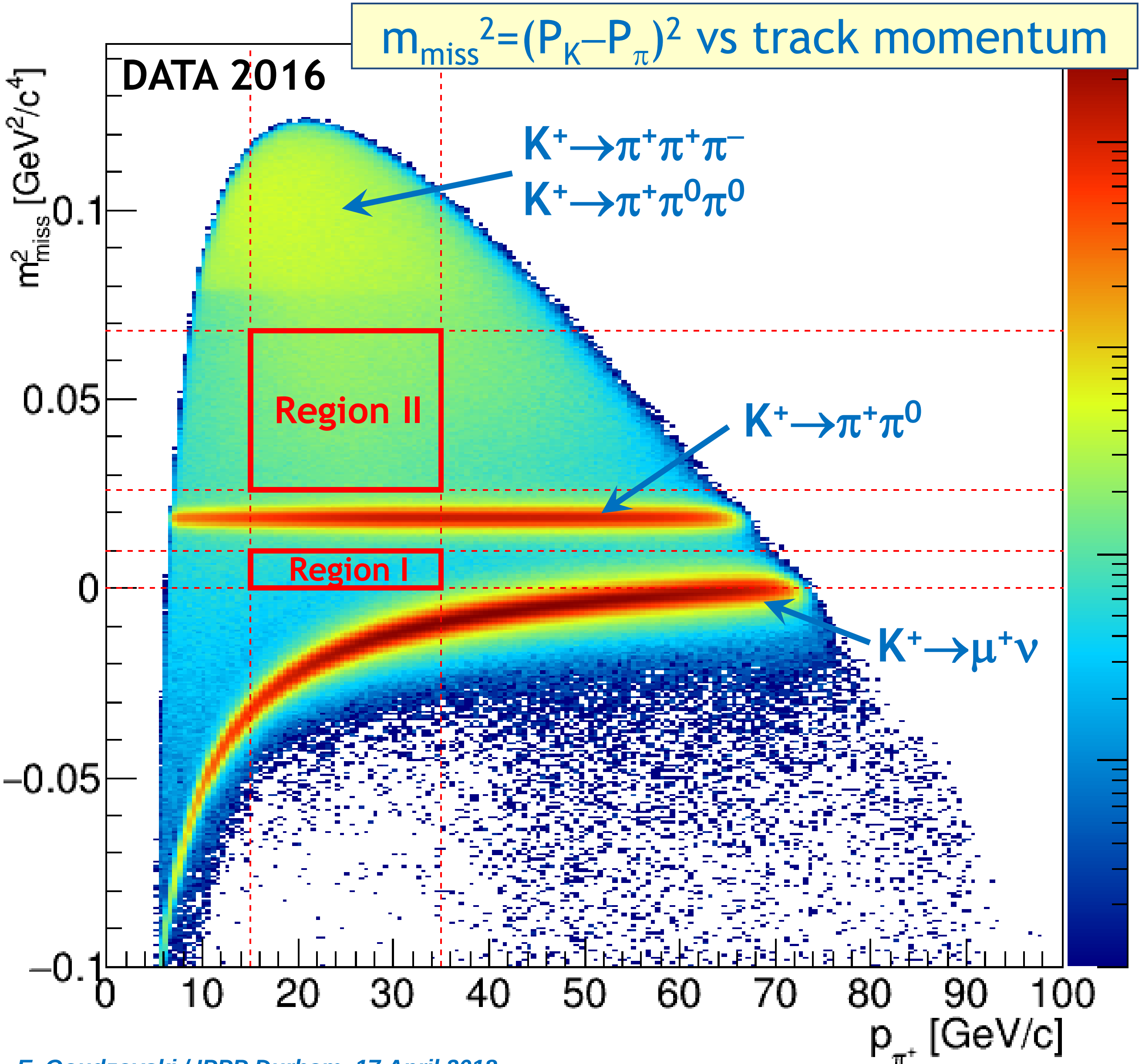
- **NA62 Run in 2016–2018**: data collection in progress.
  - ✓ Optimized for $K^+ \to \pi^+ \nu\nu$; not a multi-purpose K^+ decay experiment.
  - ✓ Several searches at nominal SES~10^{-12}: $K^+ \to \pi^+ A'$, $\pi^0 \to \nu\nu$.
  - ✓ A limited number of rare decays to be measured: world's largest samples of $K^+ \to \pi^+ \mu^+ \mu^-$, $K^+ \to \ell^+ \nu\gamma$, $K^+ \to \pi^+ \gamma\gamma$.
  - ✓ Lepton universality test: $R_K = BR(K^+ \to e^+ \nu)/BR(K^+ \to \mu^+ \nu)$.
  - ✓ LNV/LFV searches at ~10^{-11} level: $K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi^+ \mu e$, $\pi^0 \to \mu e$, …
  - ✓ Searches for heavy neutral lepton production: $K^+ \to \ell^+ N$.
  - ✓ Searches for long-lived (O(1ns)) light particles, e.g. $K^+ \to \pi^+ S$, $S \to \mu^+ \mu^-$.

- **NA62 Run in 2021–2023**: part of Physics Beyond Colliders study at CERN
  - ✓ Existing apparatus: no capital investment.
  - ✓ Further $K^+ \to \pi^+ \nu\nu$ data collection to reach 100 SM events.
  - ✓ Beam dump operation with 10^{18} pot (=3 months of data taking): competitive searches for hidden sector (long-lived HNL, DP, ALP).
  - ✓ Trigger improvements foreseen for forbidden decays.

NA62 data collection

- Commissioning run 2015: minimum bias (~1% of nominal beam intensity). Most systems commissioned and meet the design requirements.
- Physics run 2016 (40% intensity, limited by beam quality): 1.2×10^{11} K^+ useful decays (1 month) for $K^+\to\pi^+\nu\nu$ analysis; analysis completed
- Physics run 2017 (65% intensity): ~3×10^{12} useful K^+ decays.
- Physics run 2018 started last week: 218 days scheduled.

NA62: $K_{\pi\nu\nu}$ signal region definition



Main K^+ decay modes (>90% of BR) rejected kinematically.

Design kinematical resolution on m_{miss}^2 has been achieved ($\sigma=1.0\times10^{-3}$ GeV^4/c^2).

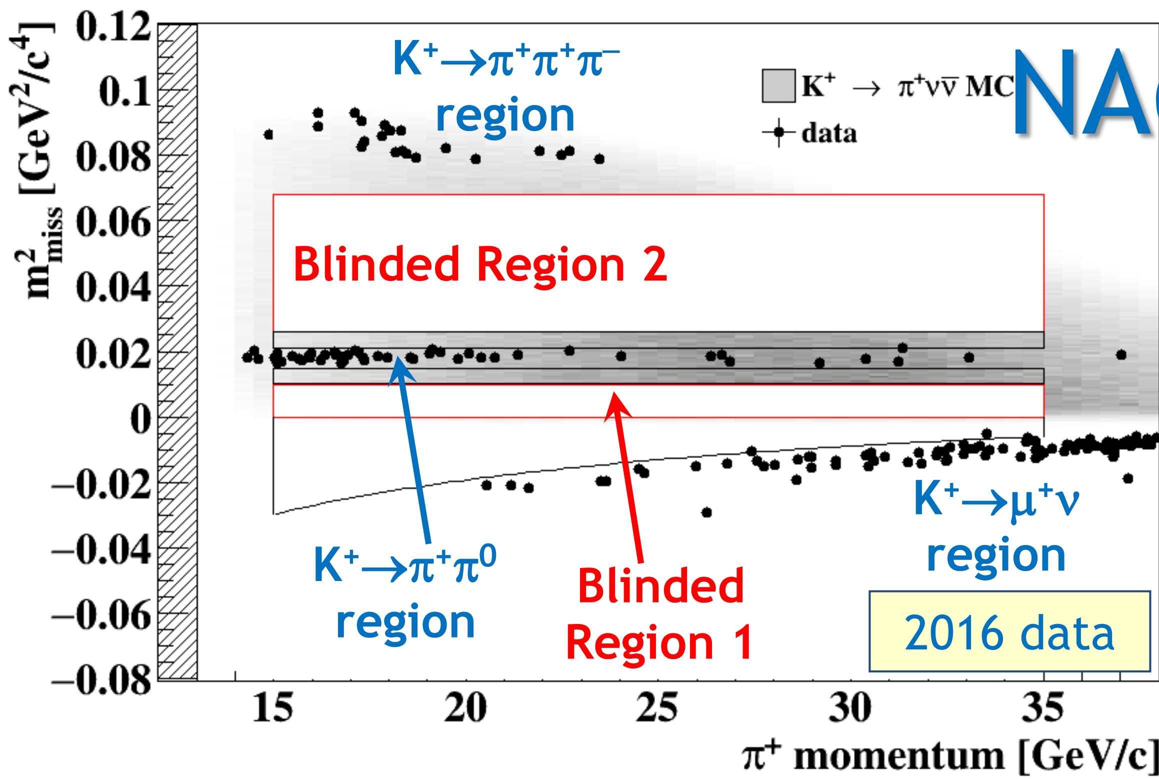
Measured kinematical background suppression:

- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & Cherenkov detectors): μ suppression 10^{-8}.
- ✓ Hermetic photon veto: suppression of $\pi^0\to\gamma\gamma$ decays 3×10^{-8}.

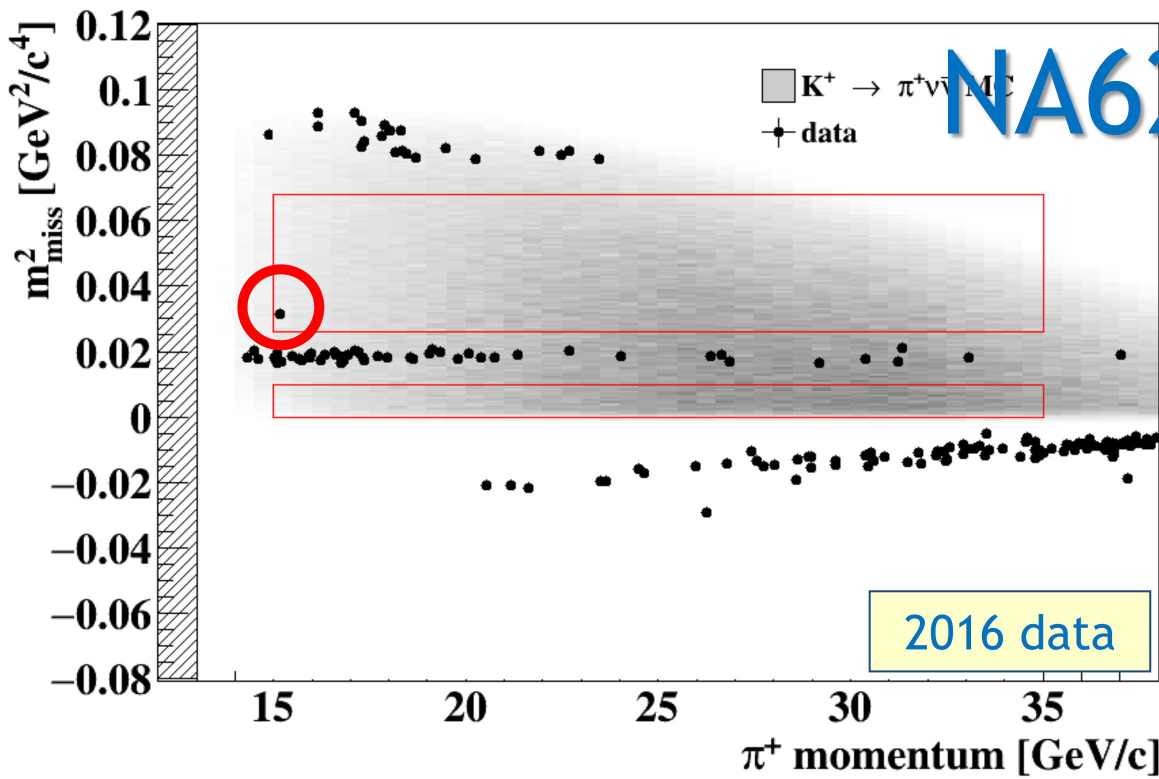
NA62: 2016 data

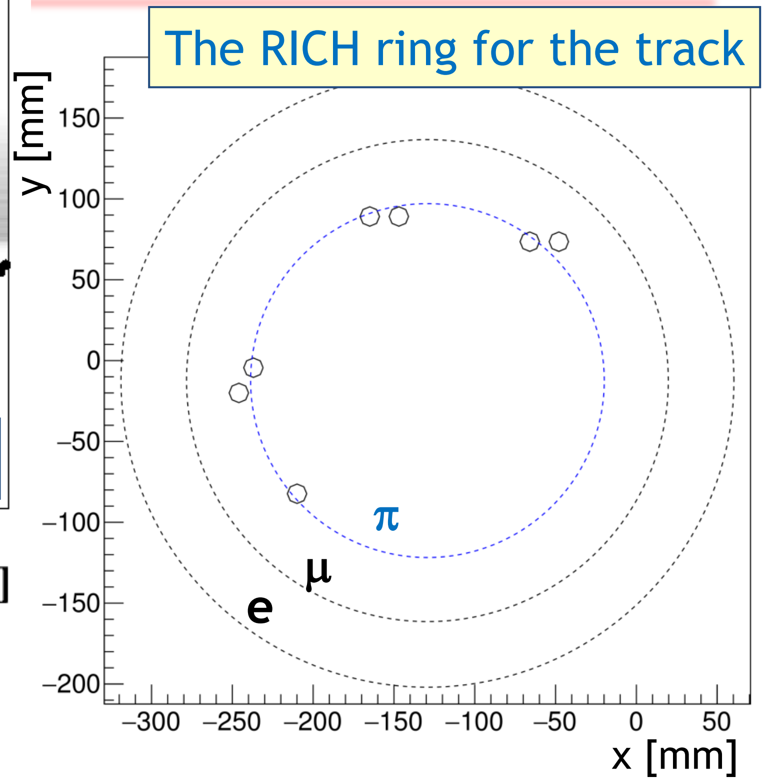


Process	Expected events in R1 + R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.029_{syst} \pm 0.032_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.018^{+0.024}_{-0.017}\|_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}$
Total background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

- Data sample: one month at **40%** of nominal intensity.
- Number of kaon decays: **$N_K=(1.21\pm0.02_{syst})\times10^{11}$**.
- The analysis procedure is fully established.
- Background estimates are mostly data-driven.
- Signal acceptance: **$A_{\pi\nu\nu}=(4.0\pm0.1)\%$**.
- Single-event sensitivity: **SES = $(3.15\pm0.24)\times10^{-10}$**.

NA62: 2016 result





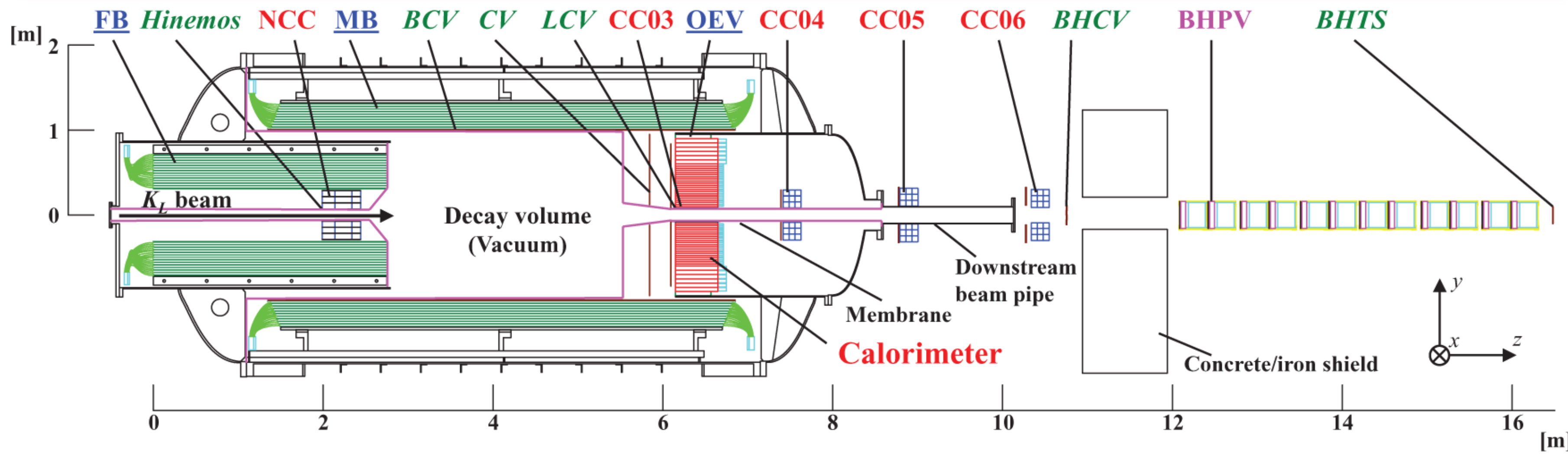
One $K^+\rightarrow\pi^+\nu\nu$ candidate observed:
$BR(K^+\rightarrow\pi^+\nu\nu) < 11\times10^{-10}$ at **90%** CL.

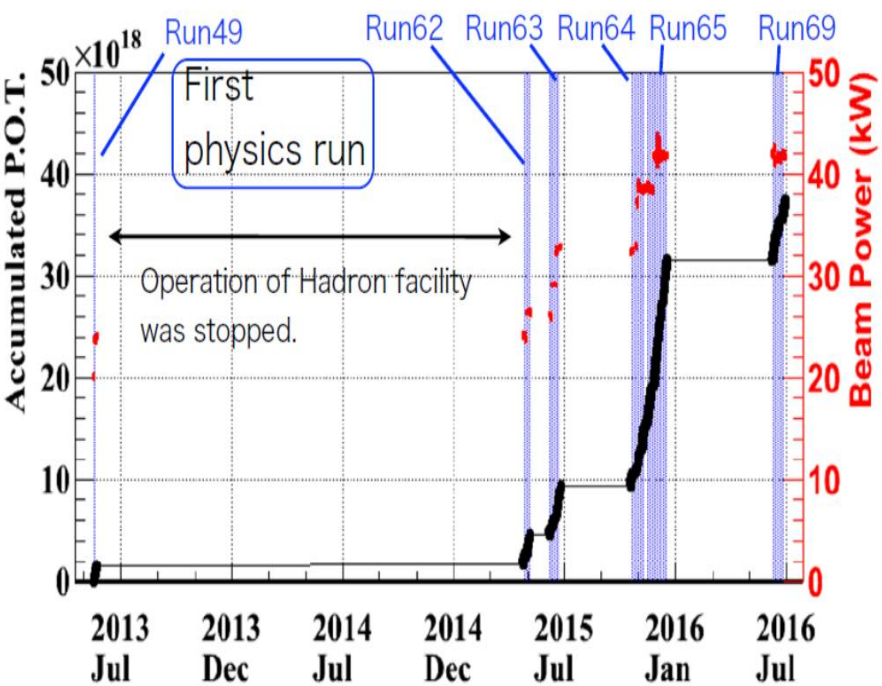
BNL 949 (K^+ decay at rest): **$BR(K^+\rightarrow\pi^+\nu\nu) = (1.73^{+1.15}_{-1.05})\times10^{-10}$**

SM prediction: **$BR(K^+\rightarrow\pi^+\nu\nu) = (0.84\pm0.10)\times10^{-10}$**

- The NA62 decay-in-flight technique works.
- Non-trivial result with ~1% of the total statistics foreseen.
- Improved beamline shielding in 2017: improved acceptance/background.

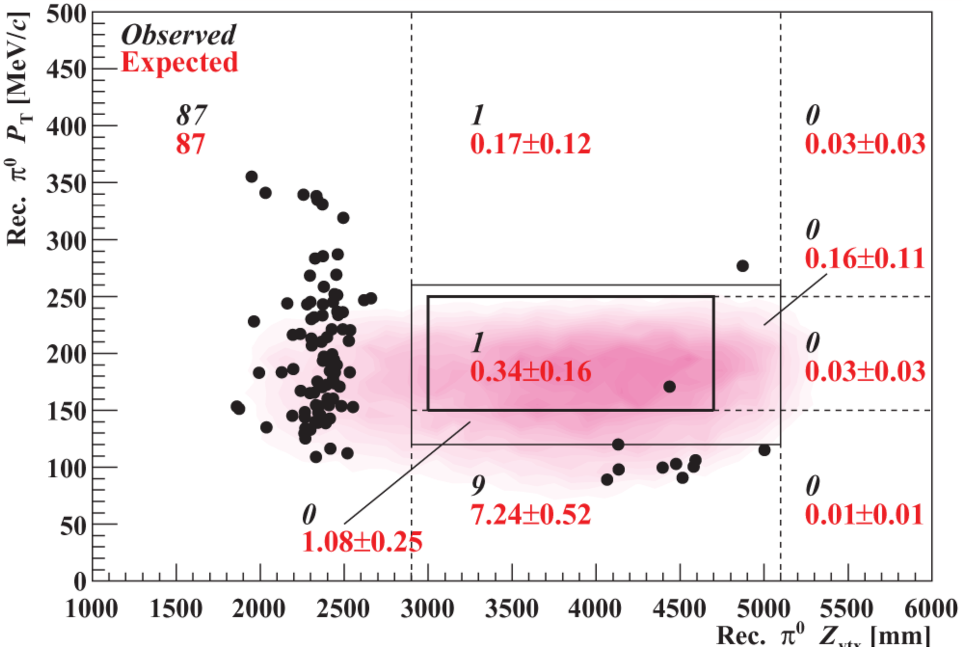
KOTO at J-PARC: $K_L \to \pi^0 \nu\nu$





- Protons of **30 GeV/c**, **16°** production angle: K_L spectrum peaks at **1.4 GeV/c**.
- Beam composition: K_L, neutrons, photons.
- Fiducial decay region length: **3 m**.
- CsI calorimeter + hermetic veto.
- In 2013, 3×10^{13} pot per **2 s** pulse (**25 kW**).
- Higher intensity in 2015/16: **30/42 kW**.
- Analysis of **2013** data **is complete**; **2015/16** sample is **~20** times larger.

KOTO: result with 2013 data

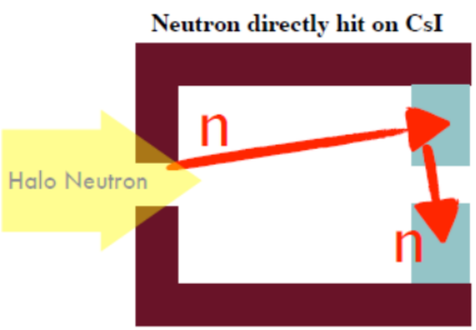


[PTEP 2017, 021C01]

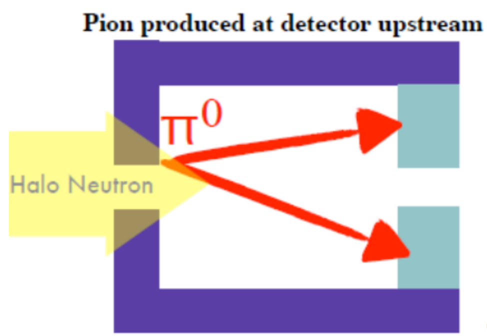
Result with 2013 data:

- About 100h of data; SES = 1.3×10^{-8}.
- Background dominated by halo neutrons.
- Signal acceptance = 1.02%.
- One event observed, with an expected background of 0.34±0.16.
- $BR(K_L\to\pi^0\nu\nu)<5.1\times10^{-8}$ at 90% CL.
- The strongest limit is still 2.6×10^{-8} *[KEK E391a, PRD81 (2010) 072004]*

Principal backgrounds:



(0.18±0.15)



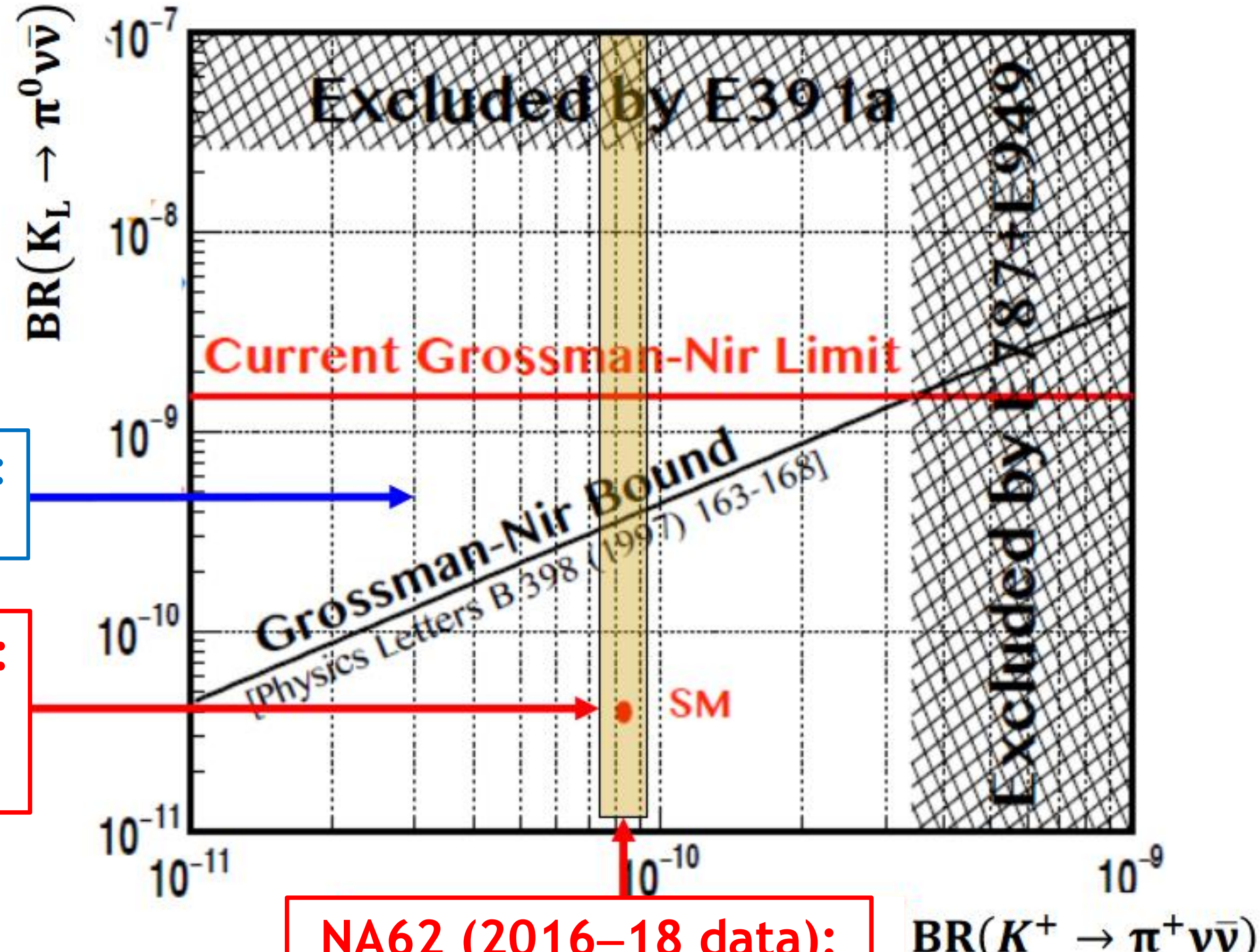
(0.056±0.056)

Also, $K_L\to\pi^0\pi^0$ and $K_L\to\gamma\gamma$ backgrounds

Improvements in 2015/16:

- Better photon-neutron ID in calorimeter (cluster+pulse shape).
- Thinner vacuum window: reduction of π^0 production by neutrons.
- SES with the 2015/16 sample $<10^{-9}$.
- Further upgrades are in progress.
- SM sensitivity ($\sim10^{-11}$) by 2021.

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



KOTO 2015/16 result: in 2018?

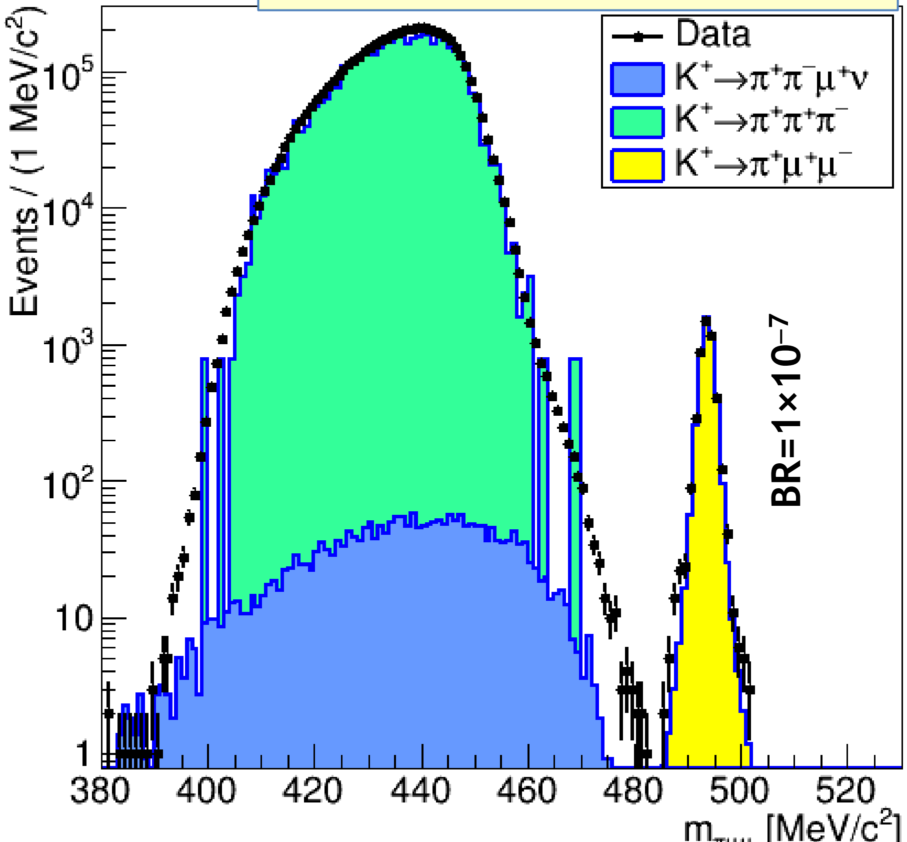
KOTO upgrade: SM sensitivity after 2021

NA62 (2016–18 data): ~20 SM events by 2020

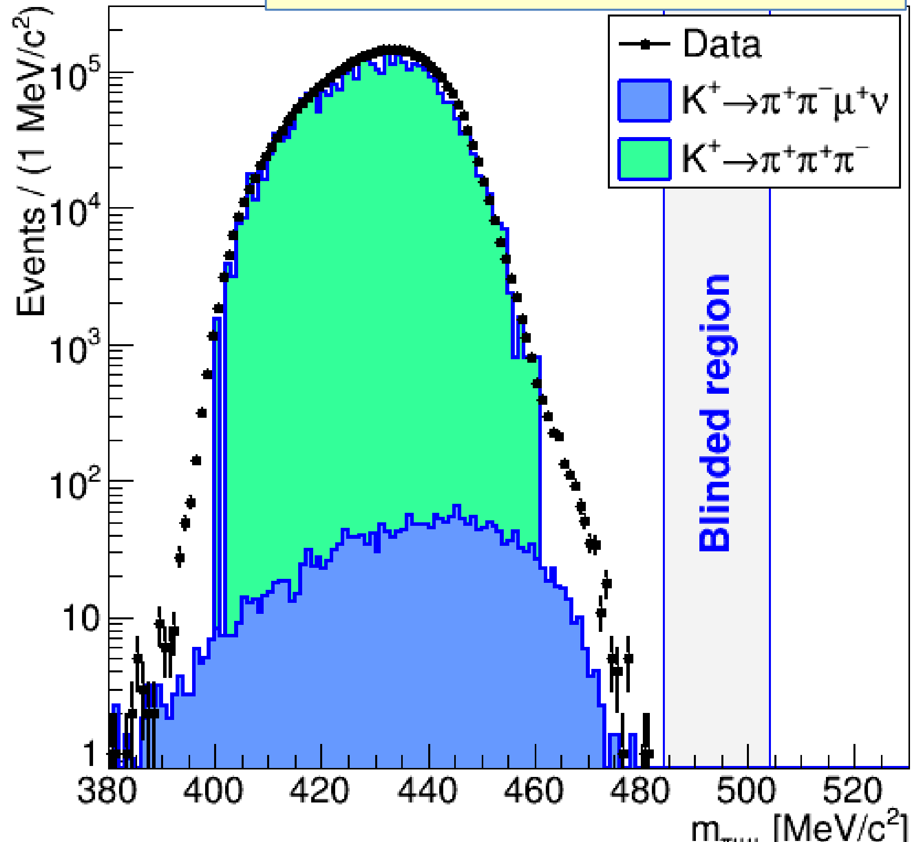
~100 SM events by 2025?

NA62 $K^+ \to \pi\mu\mu$ analyses

$K^+ \to \pi^+\mu^+\mu^-$ mass spectrum

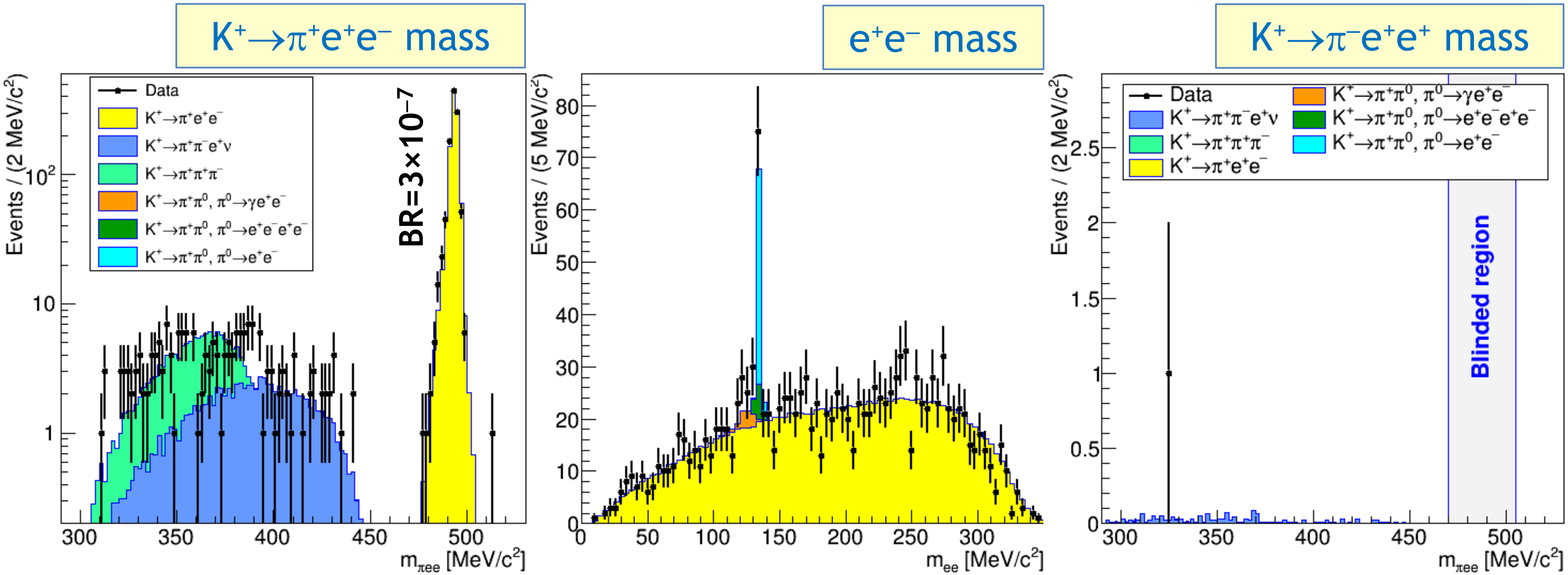


$K^+ \to \pi^-\mu^+\mu^+$ mass spectrum



- ❖ About **30%** of the 2016+2017 data set: **6.3×10^{11} K^+** decays.
- ❖ World's largest **$K^+ \to \pi^+\mu^+\mu^-$** sample: **4.6k** events.
- ❖ Expect a competitive **$K^+ \to \pi^+\mu^+\mu^-$** measurement with **~10k** events: **LU test**.
- ❖ Search for **$K^+ \to \pi^-\mu^+\mu^+$** is not limited by background; **SES=2×10^{-11}**.
- ❖ Search for **$K^+ \to \pi^+ X$, $X \to \mu^+\mu^-$**: **SES~10^{-10}** for lifetimes up to **O(1 ns)**.

NA62 $K^+ \to \pi ee$ analyses



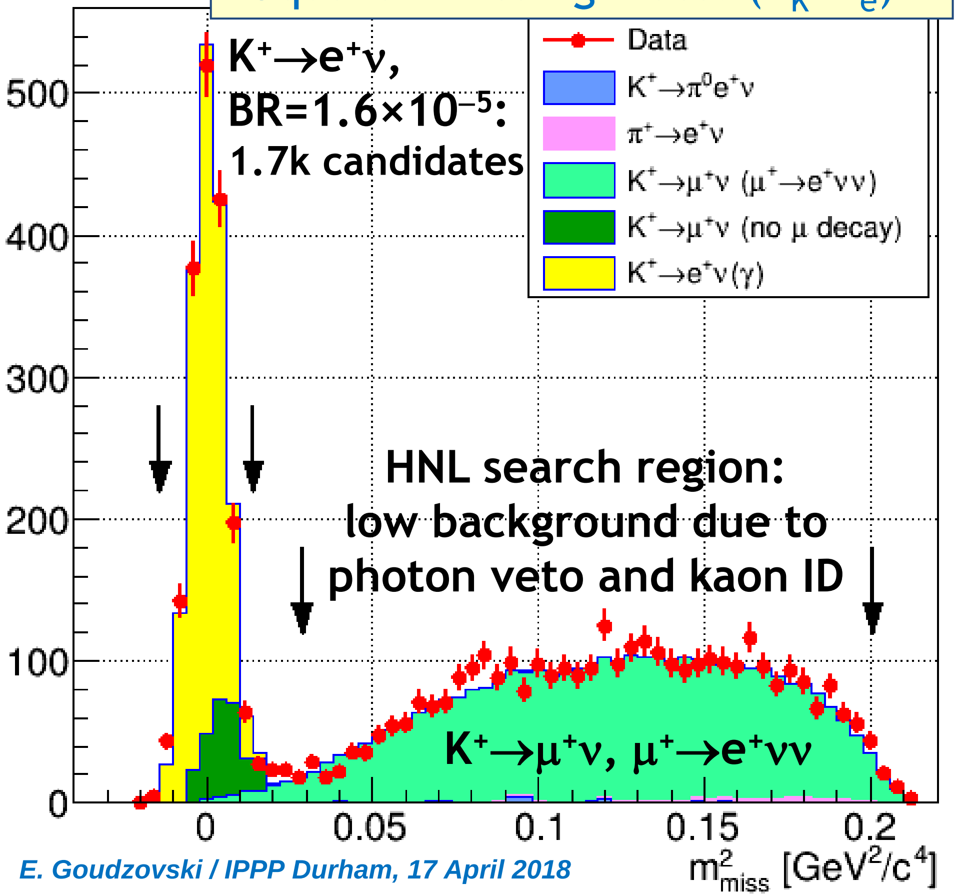
- Dedicated (downscaled) 3-track trigger lines are in operation.
- About **30%** of the 2016+2017 data set: **1.3×10^{11} K^+** decays.
- For **m_{ee}>140 MeV/c^2**, background-free **$K^+ \to \pi^+ e^+ e^-$** sample, **1.1k** events.
- First observation of **$K^+ \to \pi^+ e^+ e^-$** in the region **m_{ee}<140 MeV/c^2**.
- Search for **$K^+ \to \pi^- e^+ e^+$** is not limited by background; **SES=2×10^{-10}**.
- Search for **$K^+ \to \pi^+ X$, $X \to e^+ e^-$, 10<m_X<100 MeV/c^2**: **SES~10^{-9}** for lifetime **≪1 ns**.

NA62: $K^+ \to \ell^+ N$ (2015 data)

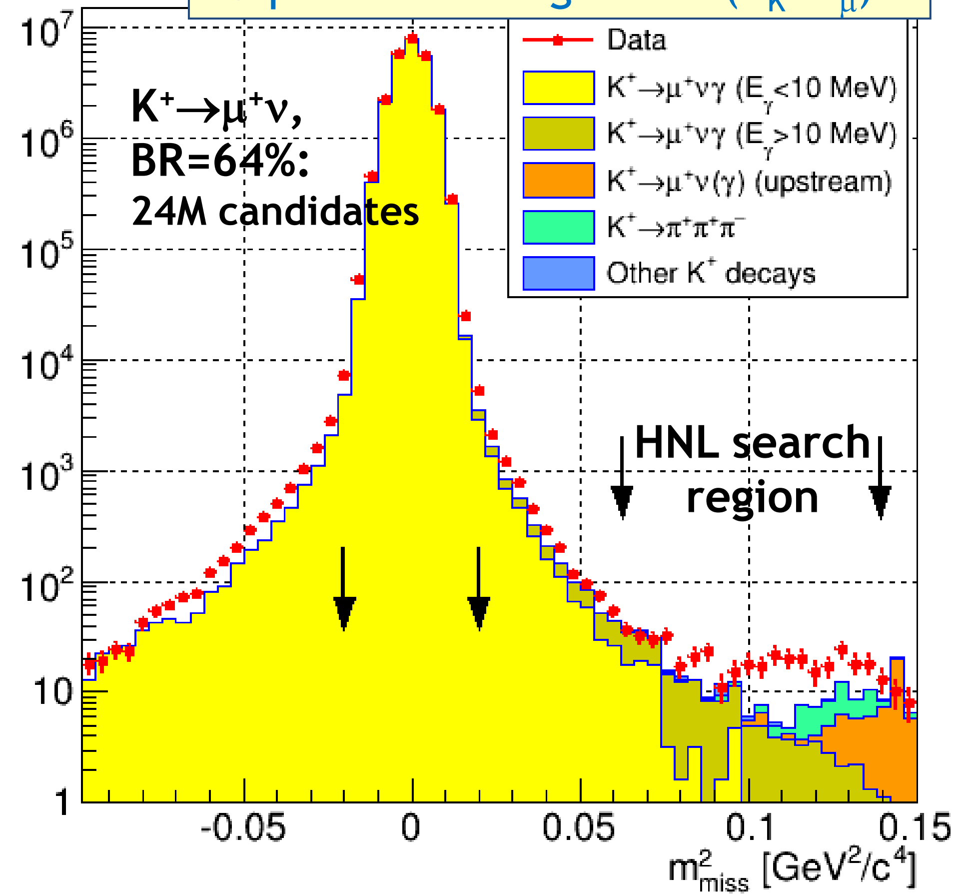
Phys. Lett. B778 (2018) 137

- Minimum bias data (1% intensity); 12k spills (5 days).
- Numbers of K^+ decays in fiducial volume:
  $N_K = (3.01 \pm 0.11) \times 10^8$ in positron case; $N_K = (1.06 \pm 0.12) \times 10^8$ in muon case.
- Beam tracker not available: kaon momentum is estimated as the beam average.
- HNL production signal: **a spike above continuous missing mass spectrum**.

Squared missing mass: $(P_K - P_e)^2$



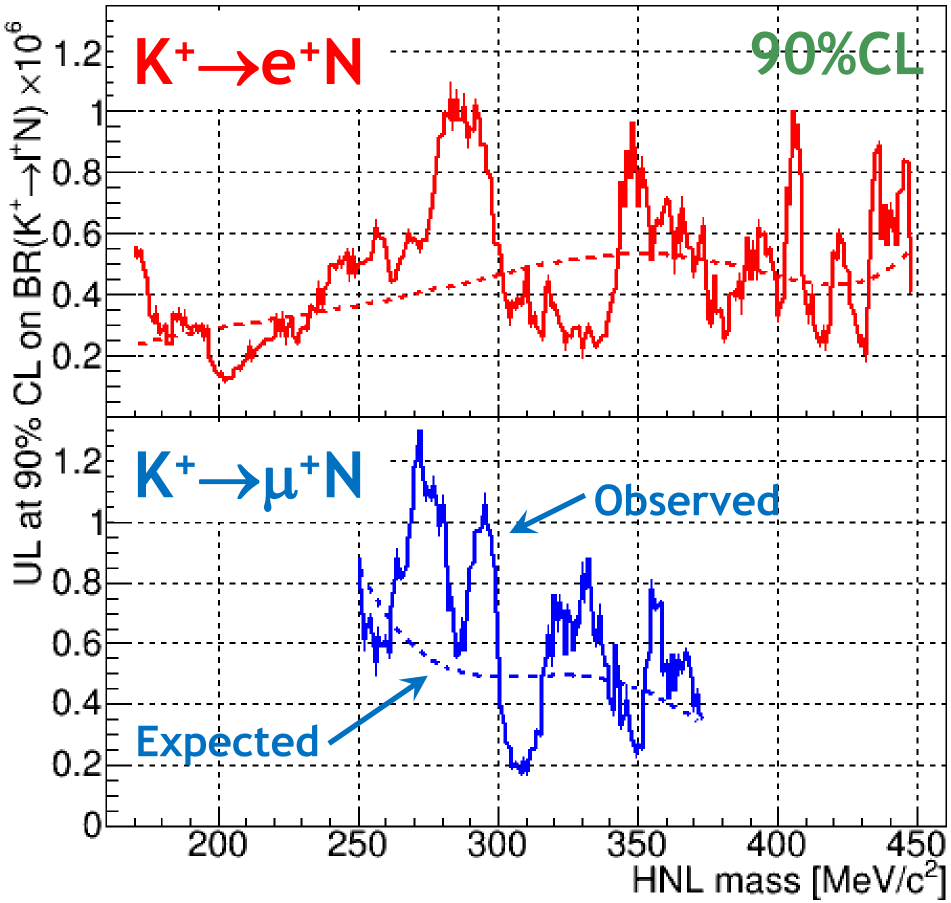
Squared missing mass: $(P_K - P_\mu)^2$



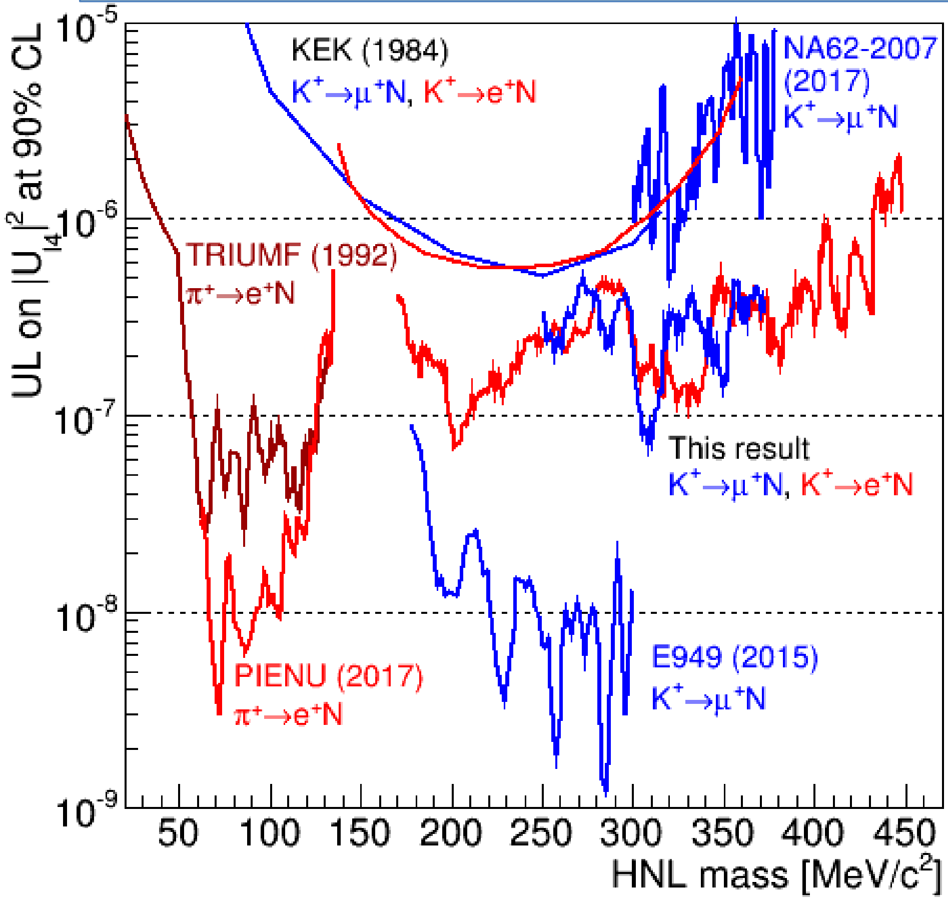
NA62 limits on HNL production

Phys. Lett. B778 (2018) 137

Upper limits on BR($K^+ \to \ell^+ N$)



$|U_{\ell 4}|^2$ limits from production searches



- Reached 10^{-6}–10^{-7} limits for $|U_{\ell 4}|^2$ in the 170–448 MeV/c^2 mass range; improvement on the world data in 5 days and without the beam tracker.
- Estimated sensitivity with the full sample: ~10^{-9} for $|U_{e4}|^2$, ~10^{-8} for $|U_{\mu 4}|^2$.

K_S physics at LHCb

❖ A new upper limit on $K_S \to \mu^+\mu^-$ with 3 fb^{-1}: *[EPJC 77 (2017) 678]*

$$\boxed{\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) < 0.8(1.0) \times 10^{-9} \text{ at } 90(95)\% \text{ of CL}}$$

Ultimate LHCb sensitivity: down to 10^{-11}.

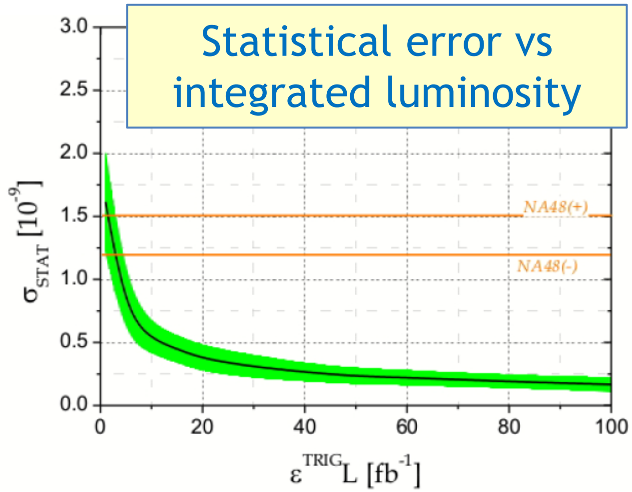
SM prediction: $\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$

❖ A sensitivity study performed for $K_S \to \pi^0\mu^+\mu^-$.

Prospects to improve over NA48/1 measurement:

$$\mathcal{B}\left(K^0_S \to \pi^0\mu^+\mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$$

[PLB599 (2004) 197]



❖ A sensitivity study performed for $K_S \to \pi^+\pi^-e^+e^-$.

Potentially competitive with NA48 measurements (23k events)

$\mathcal{B}(K^0_S \to \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$ *[EPJ C30 (2003) 33; PLB694 (2011) 301]*

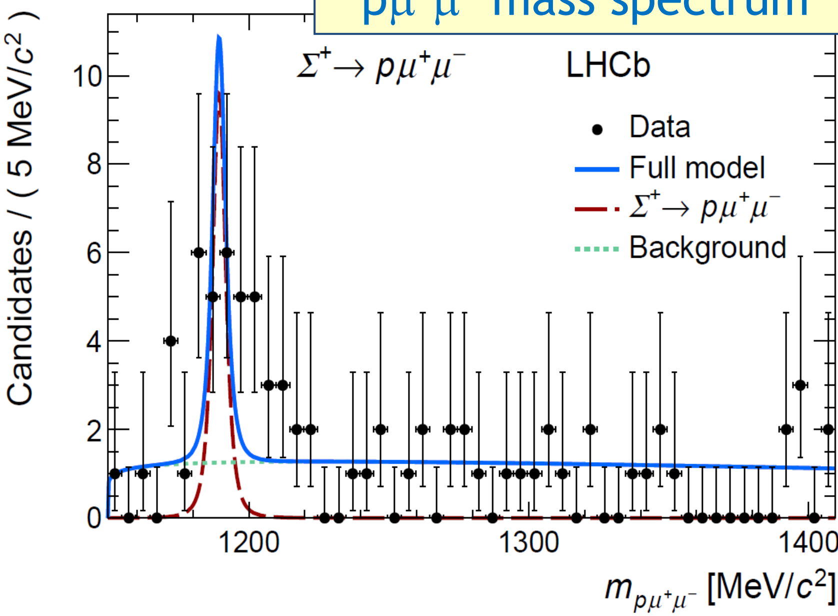
❖ Possibly first searches for $K_S \to \ell^+\ell^-\ell^+\ell^-$ (SM BRs below 10^{-10})?

(More details: talks by F. Dettori and M. Ramos Pernas at RKF workshop, Feb 2018)

LHCb: evidence for $\Sigma^+ \to p\mu^+\mu^-$

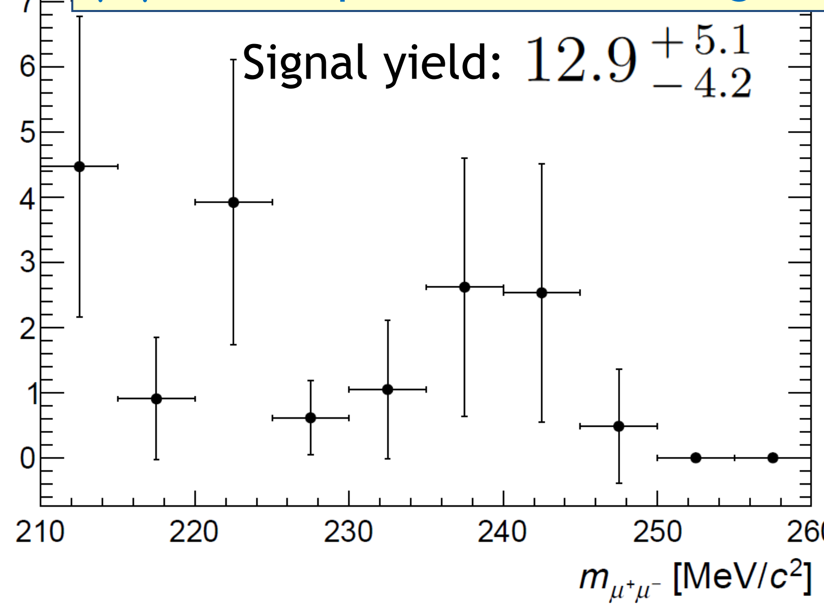
- A rare FCNF decay: $1.6\times10^{-8} < BR_{SM} < 9.0\times10^{-8}$. *arXiv:1712.08606*
- HyperCP anomaly: 3 candidates, all with $m(\mu^+\mu^-) \approx 214$ MeV/c^2. *[PRL94 (2005) 021801]*
- LHCb analysis: full 2011+12 sample, 3 fb^{-1}.

$p\mu^+\mu^-$ mass spectrum



$\mu^+\mu^-$ mass spectrum for the signal

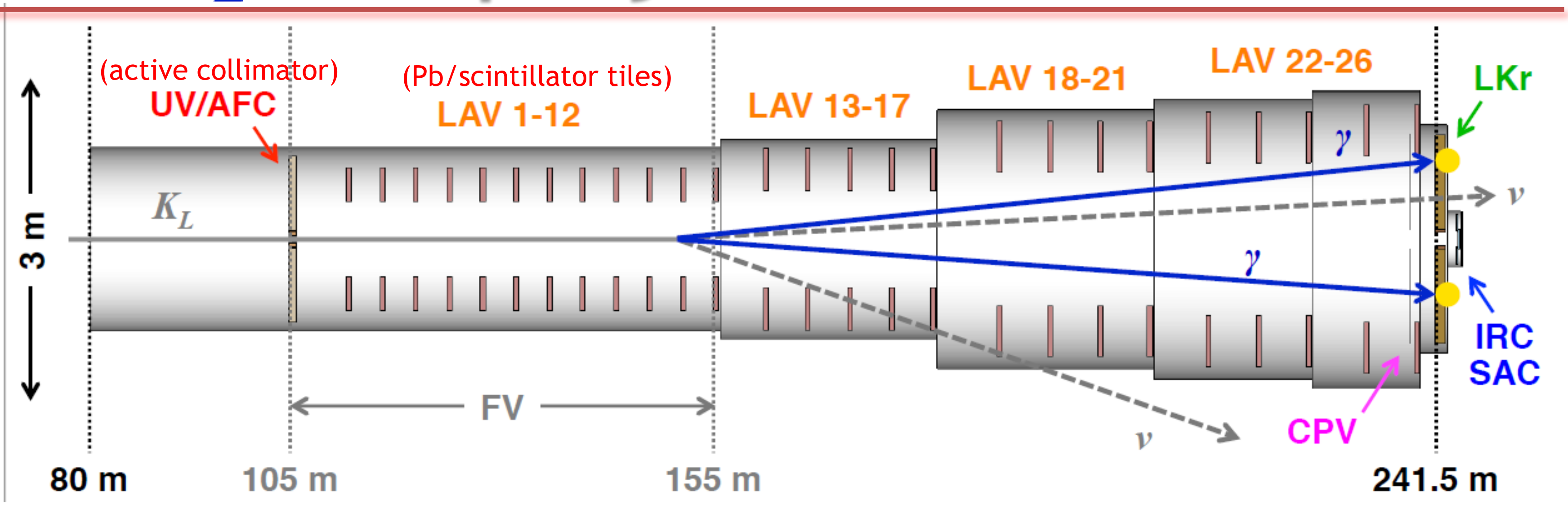
Signal yield: $12.9\,^{+5.1}_{-4.2}$



Decay rate measurement: $\boxed{\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.1\,^{+1.6}_{-1.2}) \times 10^{-8}}$

- Consistent with SM prediction; no evidence for the HyperCP resonance.
- A precision measurement is foreseen with Run II data.
- Proposals to measure baryon dipole moments *(arXiv:1612.06769, 1708.08483)* and to study semileptonic baryon decays.

KLEVER project at CERN: 2026+



- A new $K_L \rightarrow \pi^0 \nu\nu$ experiment at CERN with SES~0.5×10^{-12} (i.e. 60 SM events) and S/B~1 with 5 years of data taking is under consideration for 2026+.
- Mean K_L momentum of 97 GeV/c: easier photon veto wrt KOTO.
- Longer K_L lifetime, tight collimation: need 5×10^{19} pot/year (6x NA62 intensity).
- Target area and transfer line upgrade is under study.
- Re-use NA62 infrastructure and possibly parts of detector (LKr, HAC).
- Possibly add a tracking system? Then $K_L \rightarrow \pi^0 \ell^+ \ell^-$ (BR_{SM}~10^{-11}) are accessible.

Project represented at CERN Physics Beyond Collider study; expression of interest to CERN SPSC in preparation.

Summary

- Active kaon experiments; NA62@CERN, KOTO@J-PARC, LHCb@CERN. UK makes major contributions to the CERN kaon experiments.
- **By 2020,** expect major improvement of the experimental information on $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$. Also, the ultimate sensitivity of the NA62 method will be understood.
- **By 2025,** expect a $K^+ \to \pi^+ \nu\nu$ measurement to **10%** precision (NA62) and the first evidence for $K_L \to \pi^0 \nu\nu$ (KOTO).
- On the same time scale, expect many new NA62/LHCb results on rare/forbidden kaon decays, lepton universality, LF/LN conservation tests, HNL production, etc.
- **After 2025:** a dedicated $K_L \to \pi^0 \nu\nu$ experiment at CERN to collect **60** SM events with **S/B~1** in **5** years?