Kaon Experiments at CERN

Evgueni Goudzovski

(University of Birmingham)

eg@hep.ph.bham.ac.uk

Outline:

1) CERN kaon programme and the NA62 experiment
2) The golden decay mode: $K^+ \to \pi^+ \nu \bar{\nu}$
3) Lepton flavour/number violation in K decays
4) The dark photon and rare π^0 decays
5) Selected recent results and prospects
6) Possible long-term developments

Particle physics seminar

IFIC Valencia • 10 June 2014

Energy & precision frontiers

Discovery of a **Higgs boson**: success of the **Standard Model** (SM)

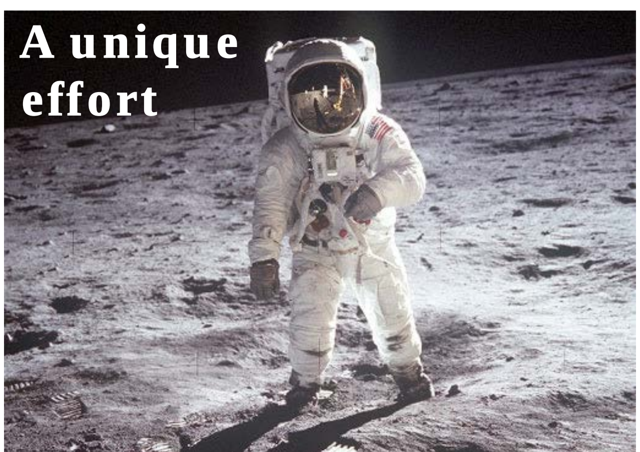
Limitations of the SM:
SM matter ≈ **5%** of total mass-energy

⇨ **"New physics"** extensions:
undiscovered particles

Searches for New physics: two complementary approaches

Energy frontier (LHC)

Direct production of new particles
in high-energy collisions.

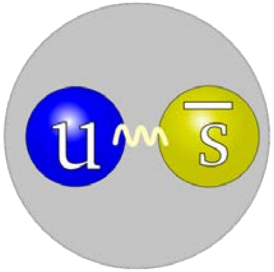


Precision (intensity) frontier

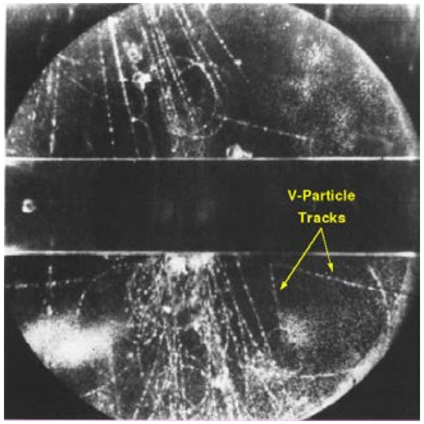
Low-energy observables:
tests of precise SM predictions
for rare or forbidden processes.

Precision frontier: kaon physics

The kaon:



- One of the lightest unstable particles;
  the "**minimal flavour laboratory**".
- Discovered in **1947**.
- High production rates: high statistical precision.
- Essential in establishing the
  foundations of particle physics
  (quark mixing, matter-antimatter asymmetry).
- Current focus: searches for **new physics**
  with rare and forbidden decays.



Kaon physics facilities

BNL
E865, E777, E787, E949

CERN
NA48, **NA62**, **LHCb**

IHEP Protvino
ISTRA+, OKA, KLOD

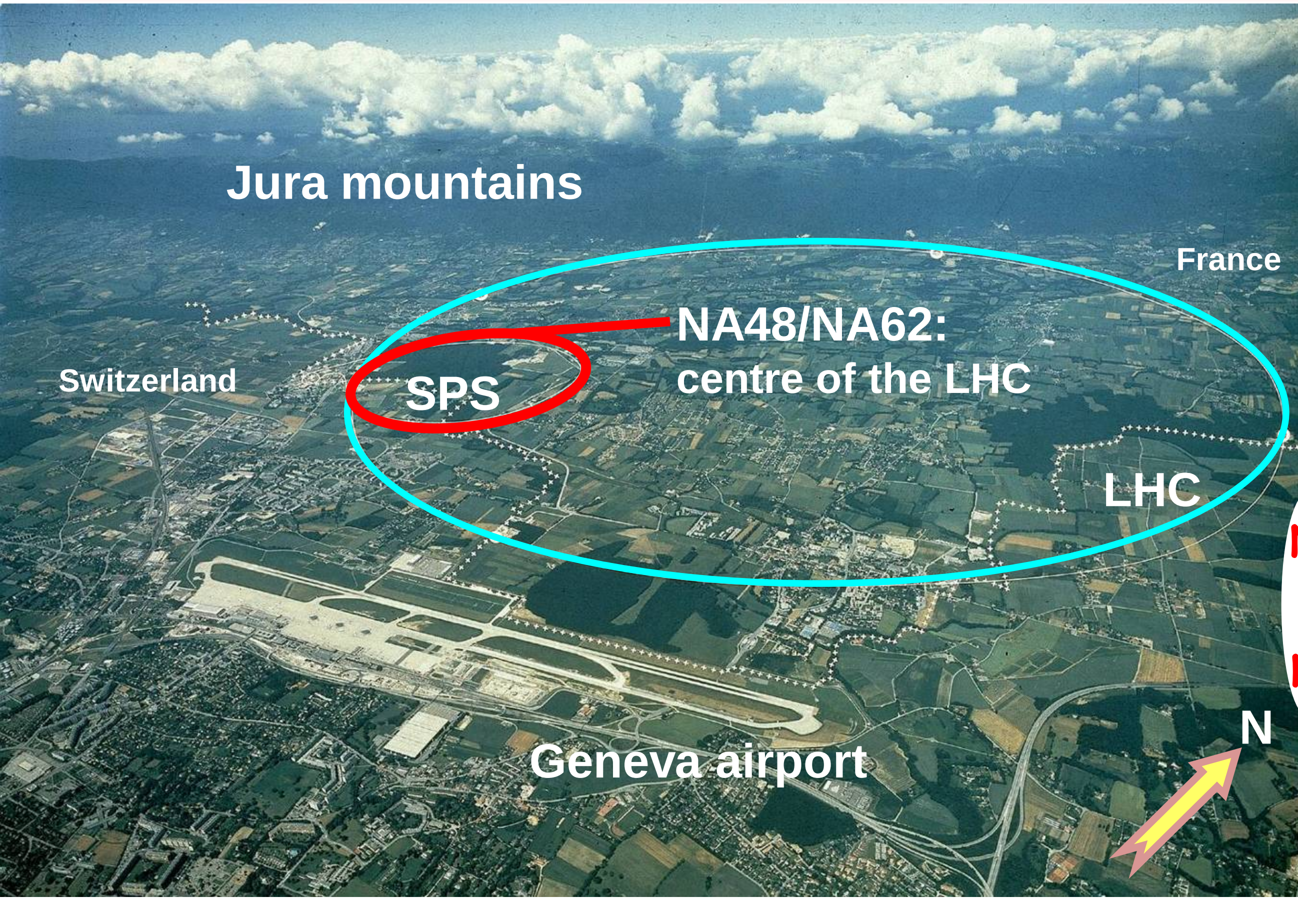
FNAL
KTeV, ORKA

LNF
KLOE, KLOE-2

KEK/J-PARC
E391a, **KOTO**, TREK

A variety of experimental techniques:
K decay-in-flight (e.g. CERN), stopped **K^+**, ϕ factory

CERN NA48/NA62 experiments



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

NA62
- 2012: technical run
- *2014:* 1st $K^+\to\pi^+\nu\bar{\nu}$ run

Kaon decay in flight experiments.
NA62: currently **~200** participants, **29** institutions

Recent $K^{\pm}$ experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	*NA62* (*K^+; planned*)
Data taking period	2003–2004	2007–2008	*2014–2017*
Beam momentum, GeV/c	60	74	75
RMS momentum bite, GeV/c	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV/c	120	265	270
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	1.7	1.2	0.8
K decays in fiducial volume	2×10^{11}	2×10^{10}	1.2×10^{13}
Main trigger	multi-track; $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	$e^{\pm}$	$K_{\pi\nu\nu}$ + ...

Same detector (NA48)

The new NA62 detector:

- beam spectrometer and kaon tagger;
- improved mass reconstruction and particle identification;
- hermetic photon veto.

NA48/2 and NA62-R_K detector

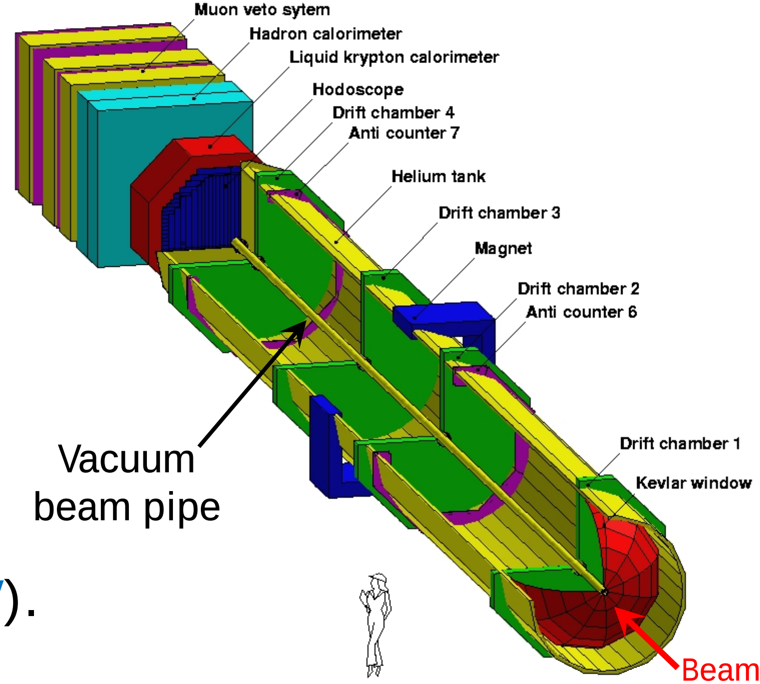
2003–2008: charged kaon beams,
the "old" NA48 detector

Narrow momentum band $K^{\pm}$ beams:
P_K= 60 (74) GeV/c, $\delta P_K/P_K$ ~ 1% (rms).

- Maximum $K^{\pm}$ decay rate ~100 kHz;
- **NA48/2:** six months in 2003–04;
- **NA62-R_K:** four months in 2007.

Principal subdetectors:

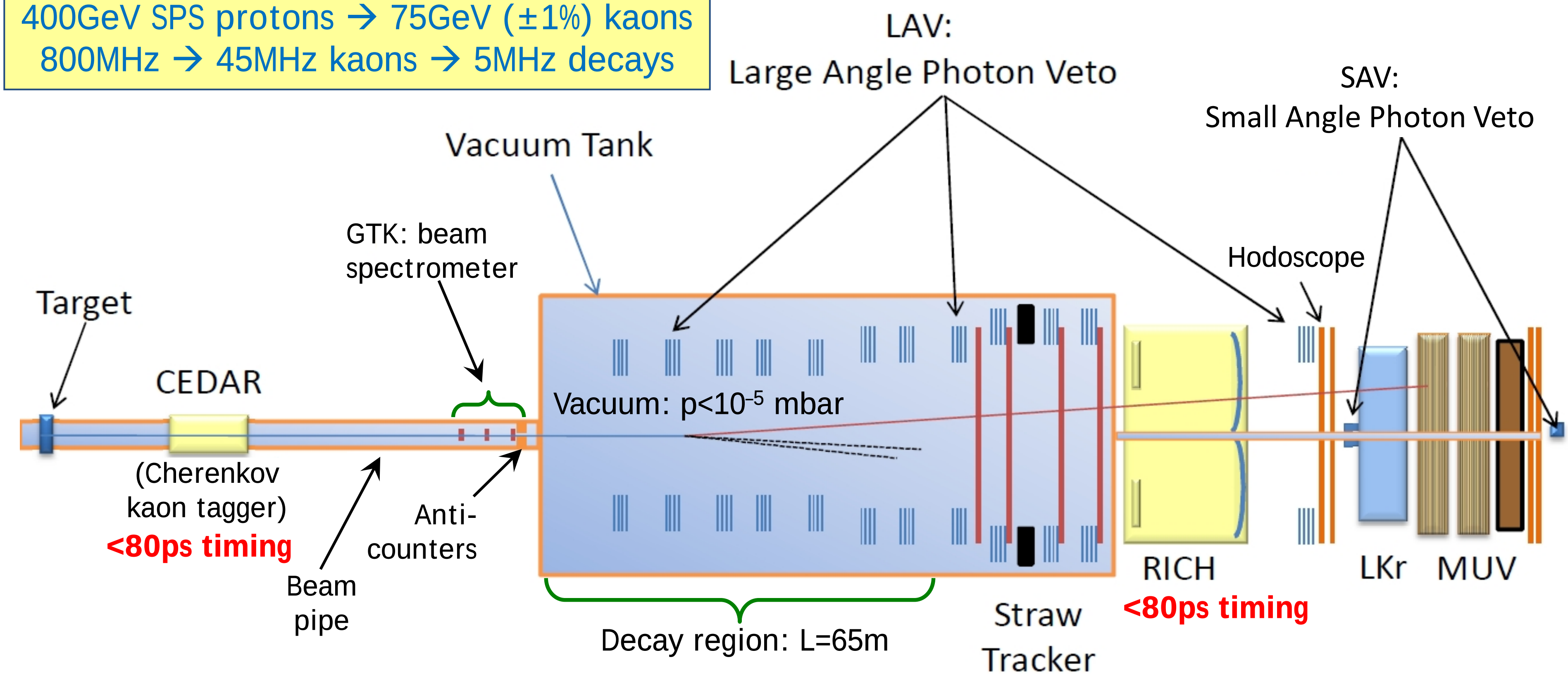
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy ⇒ efficiency;
  $\delta p/p = 0.48\% \oplus 0.009\%p$ [GeV/c] (in 2007)
- Scintillator hodoscope
  Fast trigger, time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} \oplus 0.6\text{mm}$ (1.5mm@10GeV).



NA62 detector

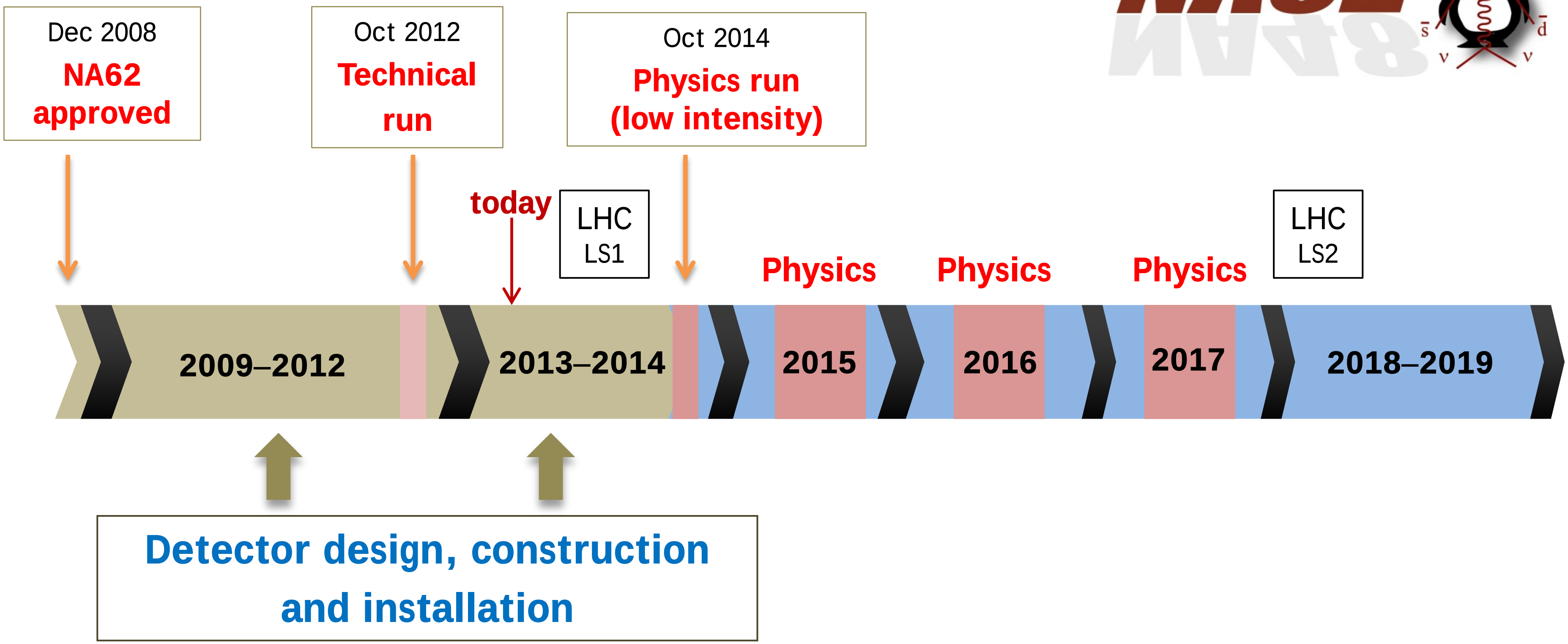
Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
800MHz → 45MHz kaons → 5MHz decays

Total length: ~270m



- Kinematic rejection factors (limited by beam pileup and tails of MCS): **5×10^3** for **$K^+\to\pi^+\pi^0$**, **1.5×10^4** for **$K\to\mu^+\nu$**.
- Hermetic photon veto: **$\sim10^8$** suppression of $\pi^0\to\gamma\gamma$.
- Particle ID (RICH+LKr+MUV): **$\sim10^7$** muon suppression.

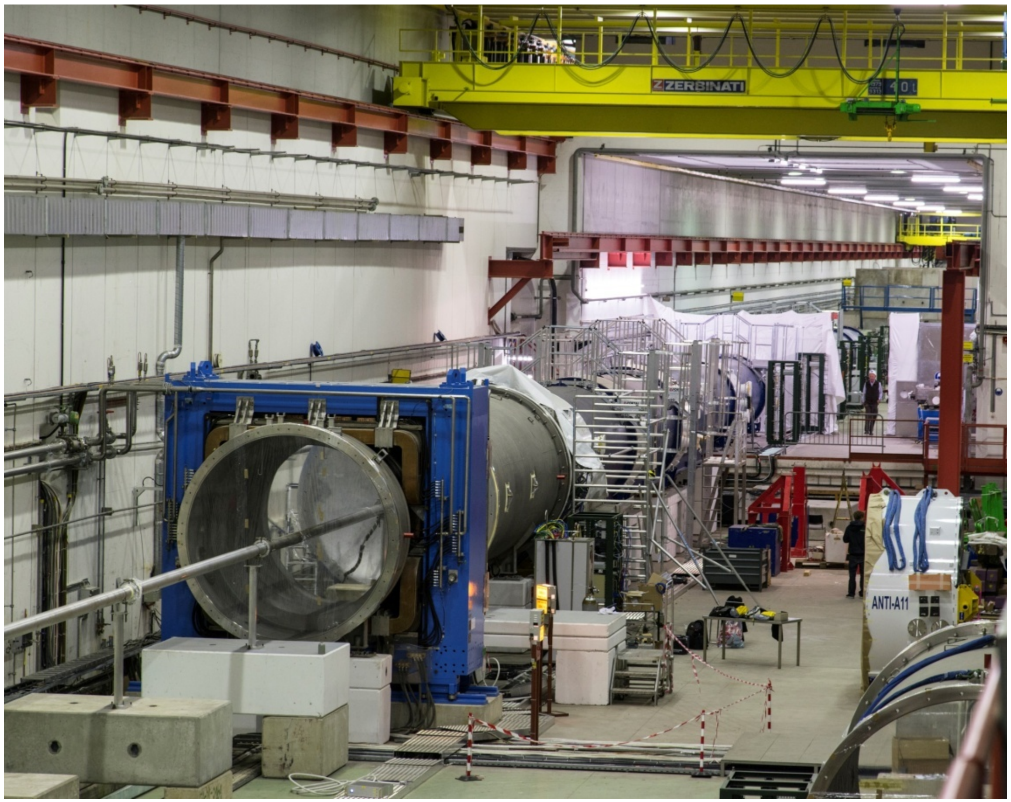
NA62 timeline



- Five years of construction interleaved with a technical run in **October 2012**
- First run with full detector: **October–December 2014**
- Physics data taking between the two LHC Long Shutdowns (LS1 to LS2)

NA62 construction & tests

General view, October 2012



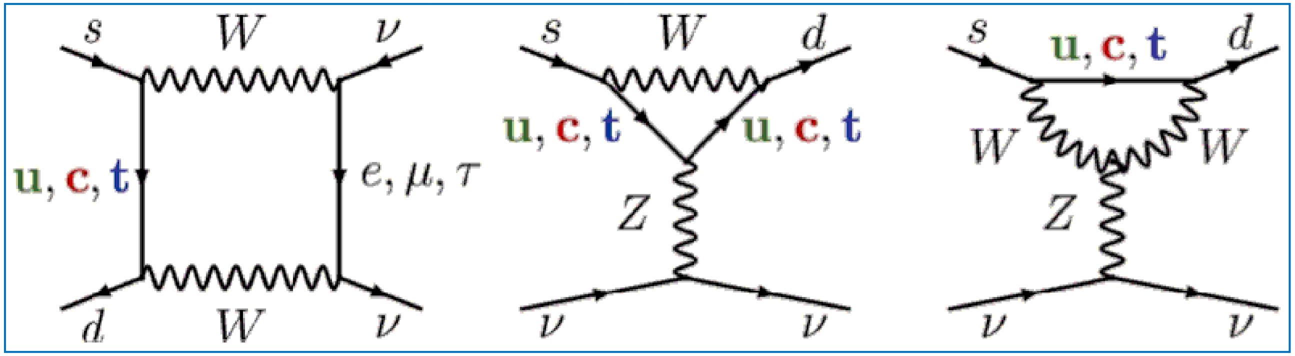
Photon veto (LAV) installation

Cherenkov kaon tagger (CEDAR+KTAG)

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

The challenge: $K\to\pi\nu\bar{\nu}$

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

SM branching ratios

Brod et al., PRD 83 (2011) 034030

Mode	$BR_{SM}\times10^{11}$
$K^+\to\pi^+\nu\bar{\nu}(\gamma)$	7.81±0.75±0.29
$K_L\to\pi^0\nu\bar{\nu}$	2.43±0.39±0.06

CKM parametric

Intrinsic

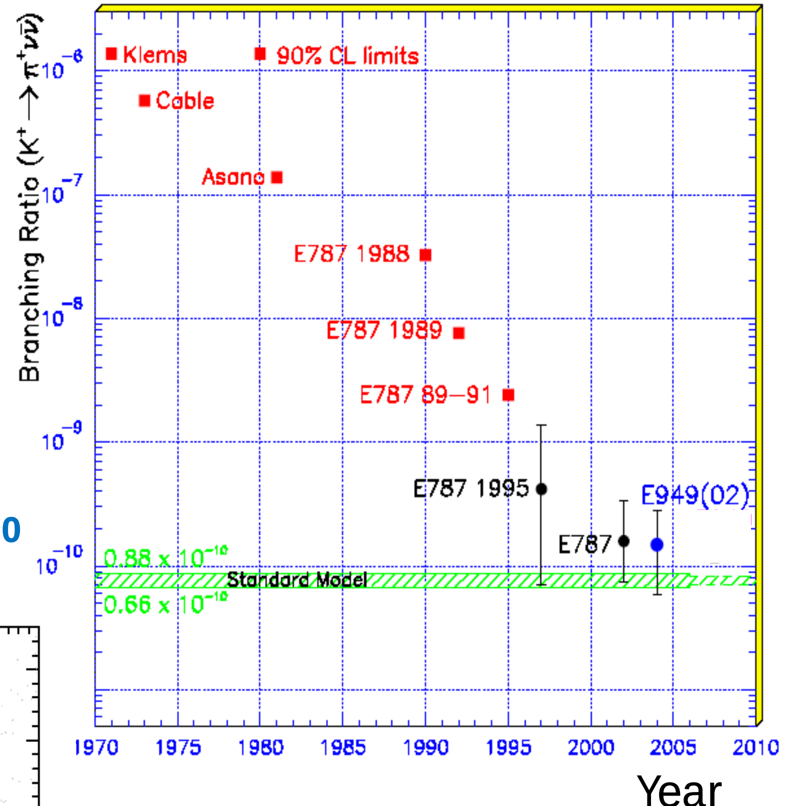
Theoretically clean,
almost unexplored,
sensitive to new physics.

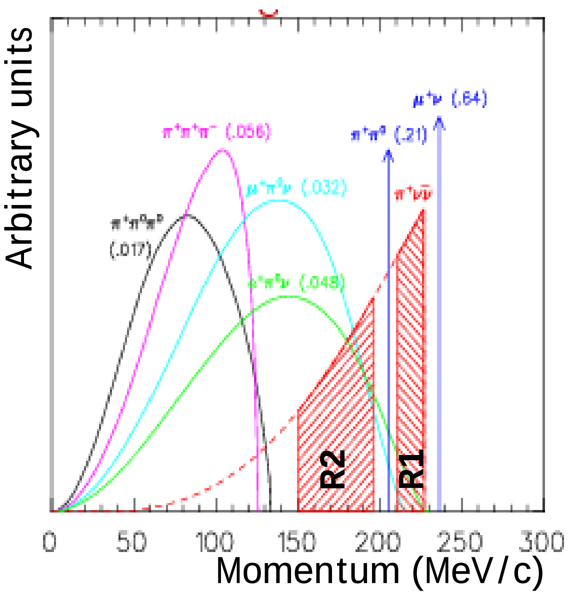
$K^+ \to \pi^+ \nu \bar{\nu}$ at BNL E747/E949

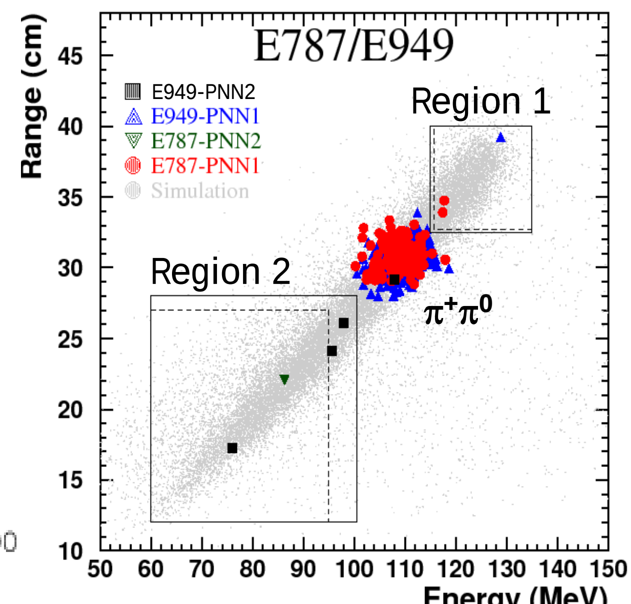
Technique: K^+ decay at rest

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

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





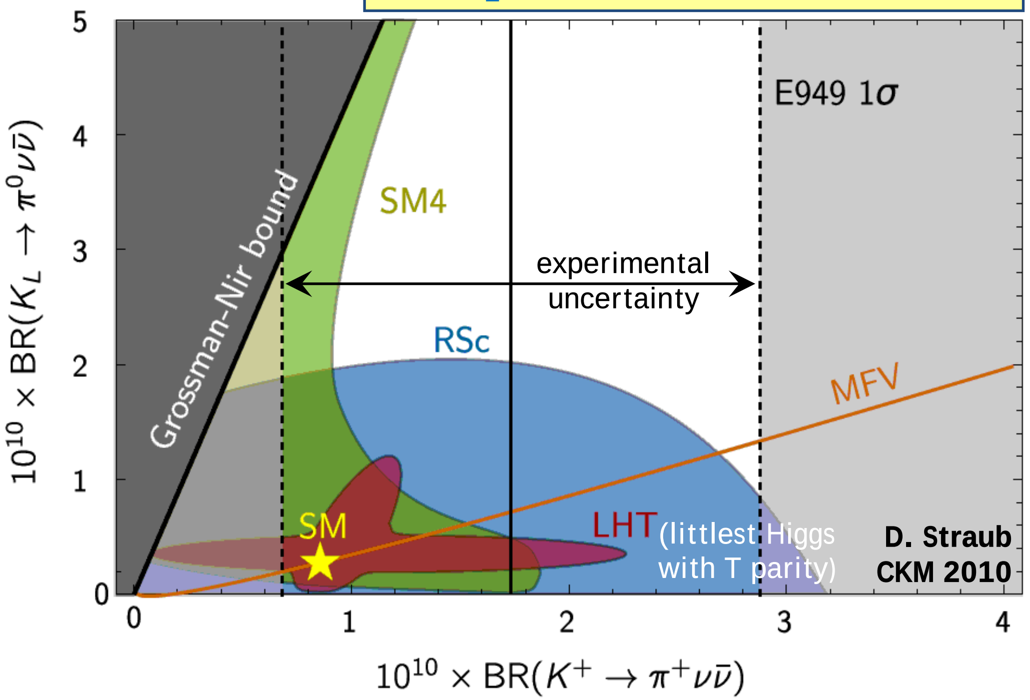


Background mainly in Region 2, due to $K_{2\pi}$ decay with π^+ scattering in the target.

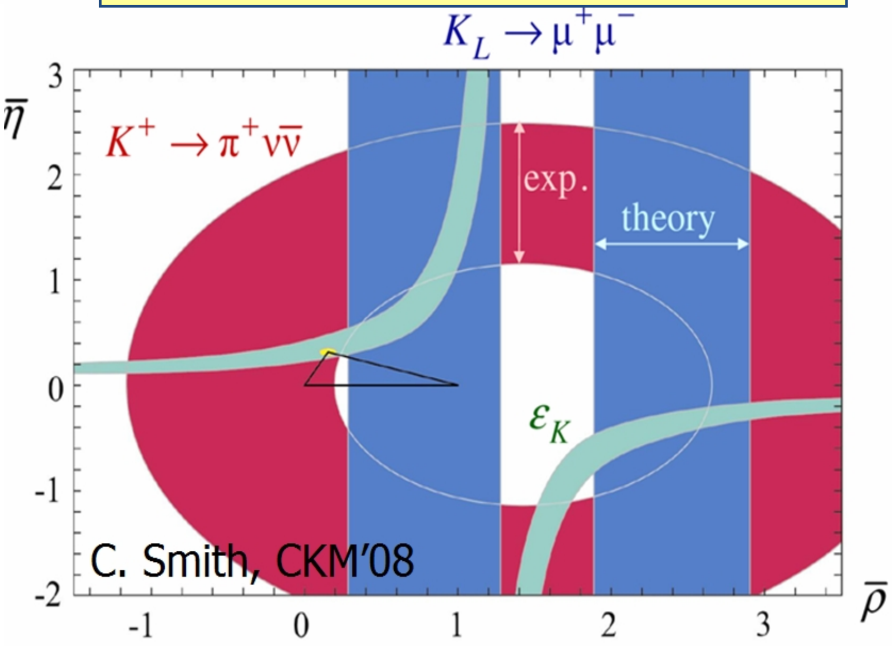
PRL 101 (2008) 191802; PRD 79 (2009) 092004

Experiment vs theory

BR($K_L \to \pi^0\nu\bar{\nu}$) vs BR($K^+ \to \pi^+\nu\bar{\nu}$)



CKM unitarity triangle with kaons



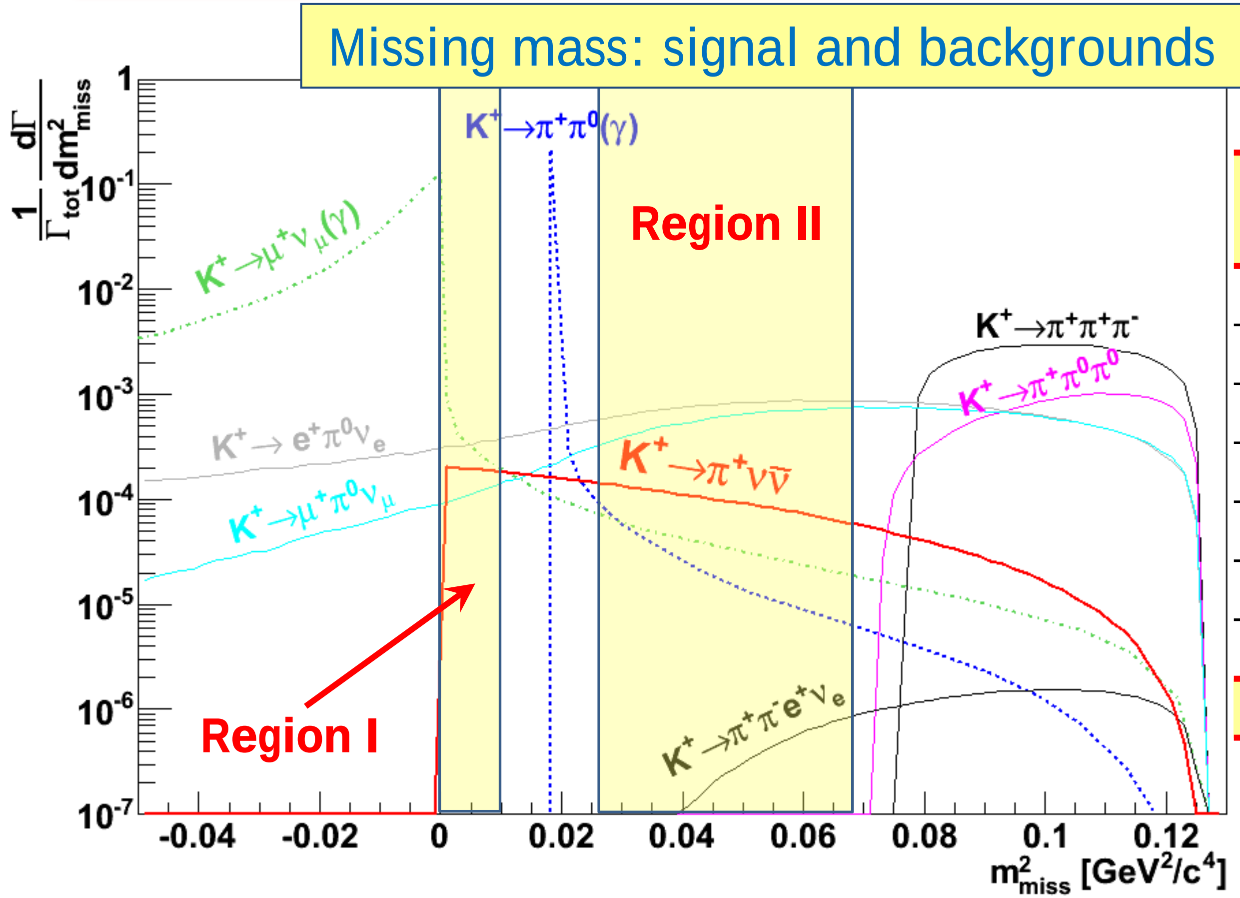
NA62 aim: collect O(100) SM $K^+ \to \pi^+\nu\bar{\nu}$ decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

Signature: high momentum **K^+** (**75GeV/c**) → low momentum π^+ (**15–35 GeV/c**).

Advantages: max detected K^+ decays/proton (**$p_K/p_0 \approx 0.2$**); efficient photon veto (**>40 GeV** missing energy); good π^+ vs μ^+ identification with RICH.

Un-separated beam (**6%** kaons) → higher rates, additional backgrounds.

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



Signal & backgrounds (events/year)	
Signal	45
$K^+\to\pi^+\pi^0$	5
$K^+\to\mu^+\nu$	1
$K^+\to\pi^+\pi^+\pi^-$	<1
Other 3-track decays	<1
$K^+\to\pi^+\pi^0\gamma$ (IB)	1.5
$K^+\to\mu^+\nu\gamma$ (IB)	0.5
Total background	**<10**

92% of total **BR(K^+)**:

- ❖ Outside the signal kinematic region.
- ❖ Signal region is split into **Region I** and **Region II** by the **$K^+\to\pi^+\pi^0$** peak.

8% of total **BR(K^+)** including multi-body:

- ❖ Span across the signal region (not rejected by kinematic criteria).
- ❖ Rejection relies on **vetoes**, **PID**.

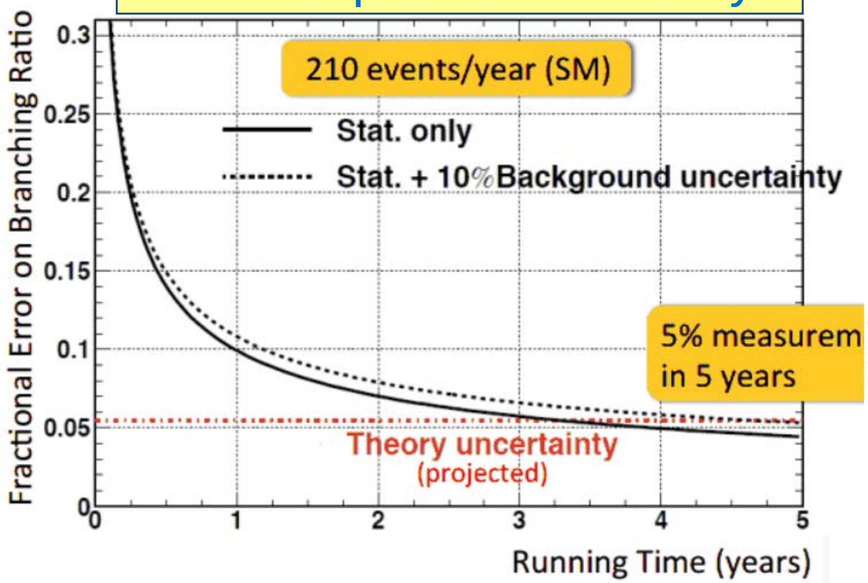
Other $K_{\pi\nu\nu}$ experiments

ORKA proposal @ FNAL (K^+)

- Builds on BNL stopped-kaon technique.
- Goal: **O(10^3)** SM **$K^+ \to \pi^+ \nu\nu$** events.
- Higher sensitivity than NA62 due to more time scheduled for data taking.

22 May 2014: DOE P5 "cannot recommend moving ahead with ORKA at this time"

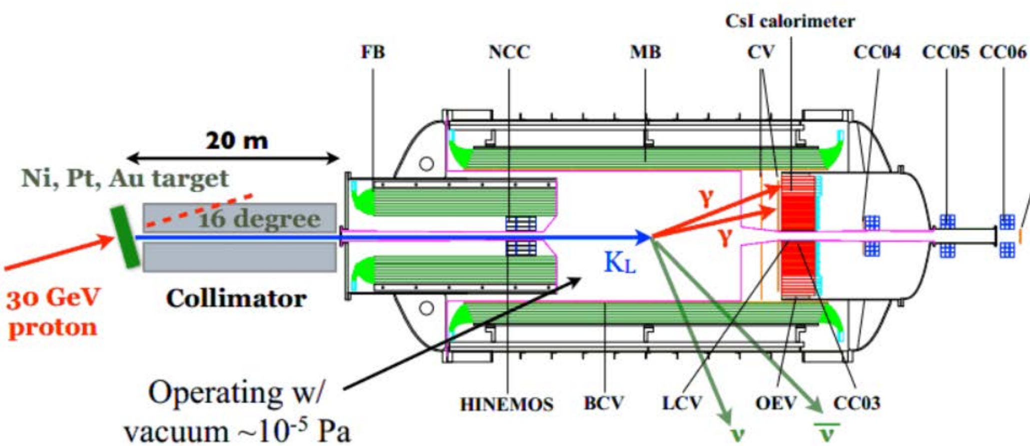
ORKA expected sensitivity



KOTO @ J-PARC (K_L):

- Builds on KEK E391a technique.
- E391a: **BR<6.8×10^{-8}** @ 90%CL.
- Expect **~10^3** times higher sensitivity.
- Goal: **~3** SM **$K_L \to \pi^0 \nu\nu$** events.
- Data taking: **2013–2017**.
- Possibly to be followed by KOTO-2: **~100** SM events.

"Two photons + nothing"



Lepton Flavour and Lepton Number Violation

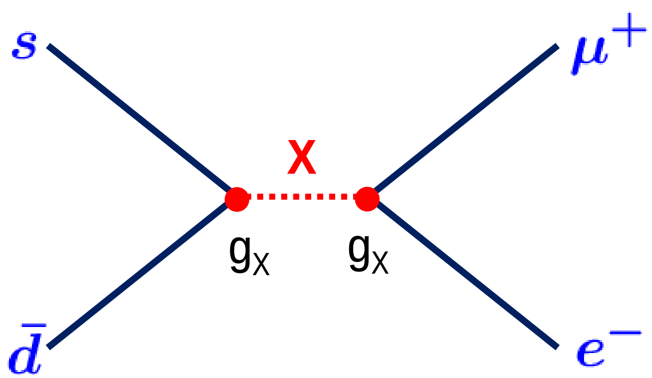
LFV in kaon decays

Kaons: historically competitive in searches for LFV phenomena

- Copious production: high statistics.
- Simple decay topologies: clean experimental signatures.
- Source of tagged π^0 via $K^+ \to \pi^+\pi^0$, $K_L \to 3\pi^0$, … :
  best limits for LFV π^0 decays.

Tree-level contributions: high NP mass scales accessible

Example: $K_L \to \mu^+ e^-$



Dimensional argument:

$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W} \cdot \frac{M_W}{M_X} \right)^4$$

For $g_X \approx g_W$ and $\mathcal{B} \sim 10^{-12}$,

$$M_X \sim 100\ \mathrm{TeV}$$

LFV in $K^{\pm}$ and π^0 decays

Mode	UL at 90% CL	Experiment	Reference
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL E777/E865	PRD 72 (2005) 012005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	1.1×10^{-9}	CERN NA48/2	PLB 697 (2011) 107
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	PL 62B (1976) 485
$K^+ \to e^-\nu\mu^+\mu^+$	no data		
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	FNAL KTeV	PRL 100 (2008) 131803
$\pi^0 \to \mu^-e^+$	3.6×10^{-10}		

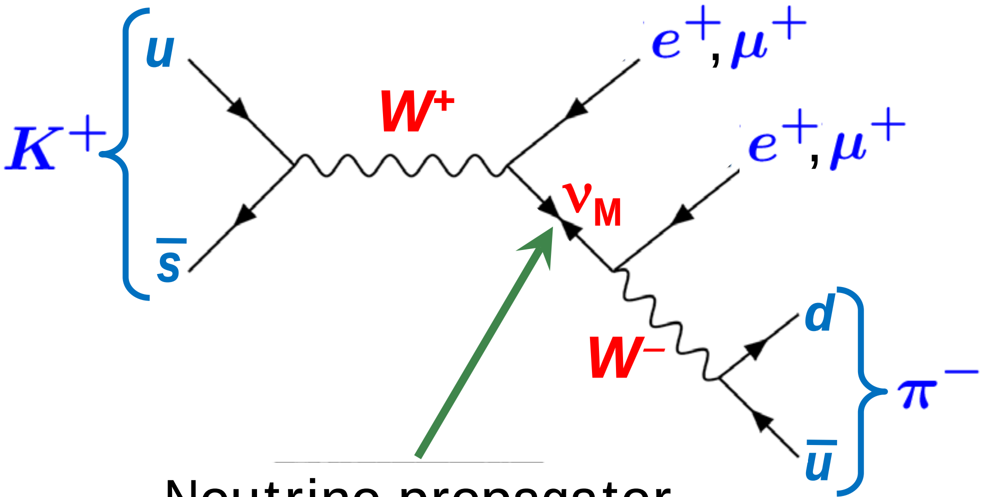
* CERN NA48/2 sensitivities for these 3 modes are similar to those of BNL E865

Expected NA62 single event sensitivities:
~10^{-12} for $K^{\pm}$ decays, **~10^{-11}** for π^0 decays.

- NA62 is capable of improving on all these decay modes.
- Possibly worse sensitivity to decays to **ee** pairs (trigger downscaling).
- The 2014 data alone might be competitive (e.g. $K^+ \to \pi^-\mu^+\mu^+$).

Sensitivity to Majorana neutrino

$$K^+ \to \pi^- \ell_1^+ \ell_2^+, \quad \ell = e, \mu$$



Neutrino propagator

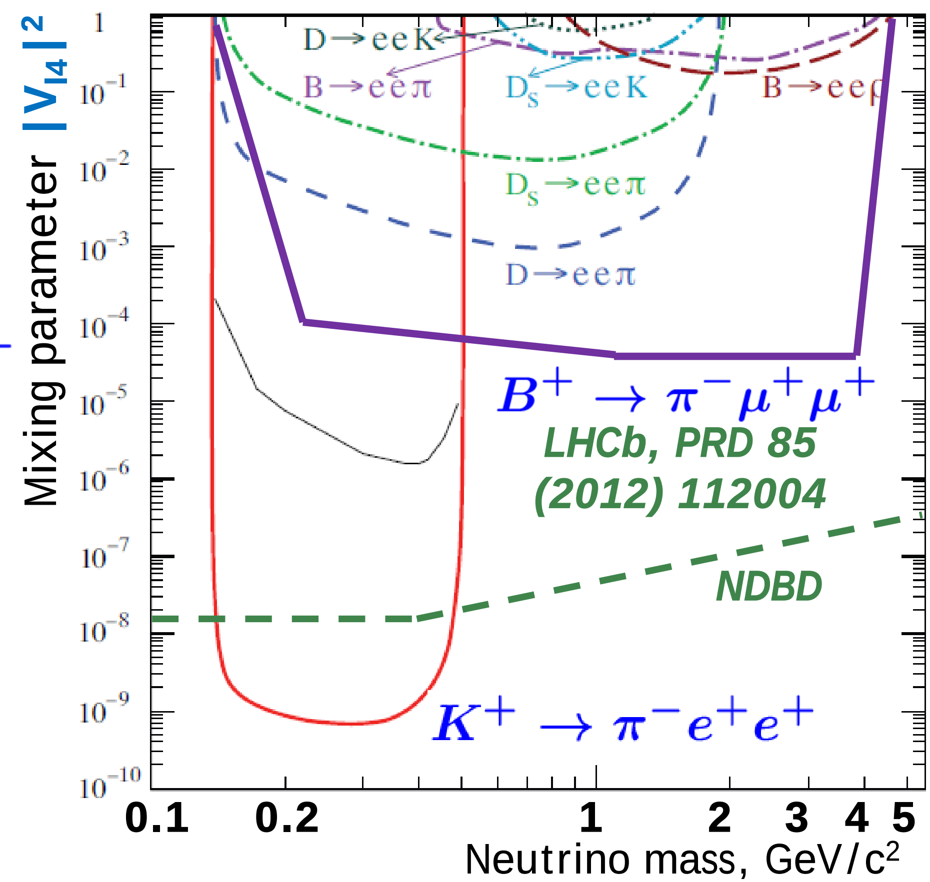
$$\frac{1}{q^2 - m_\nu^2}$$

→ resonant enhancement for

$$m_\pi \lesssim m_\nu \lesssim m_K$$

Littenberg and Shrock, PLB491 (2000) 285

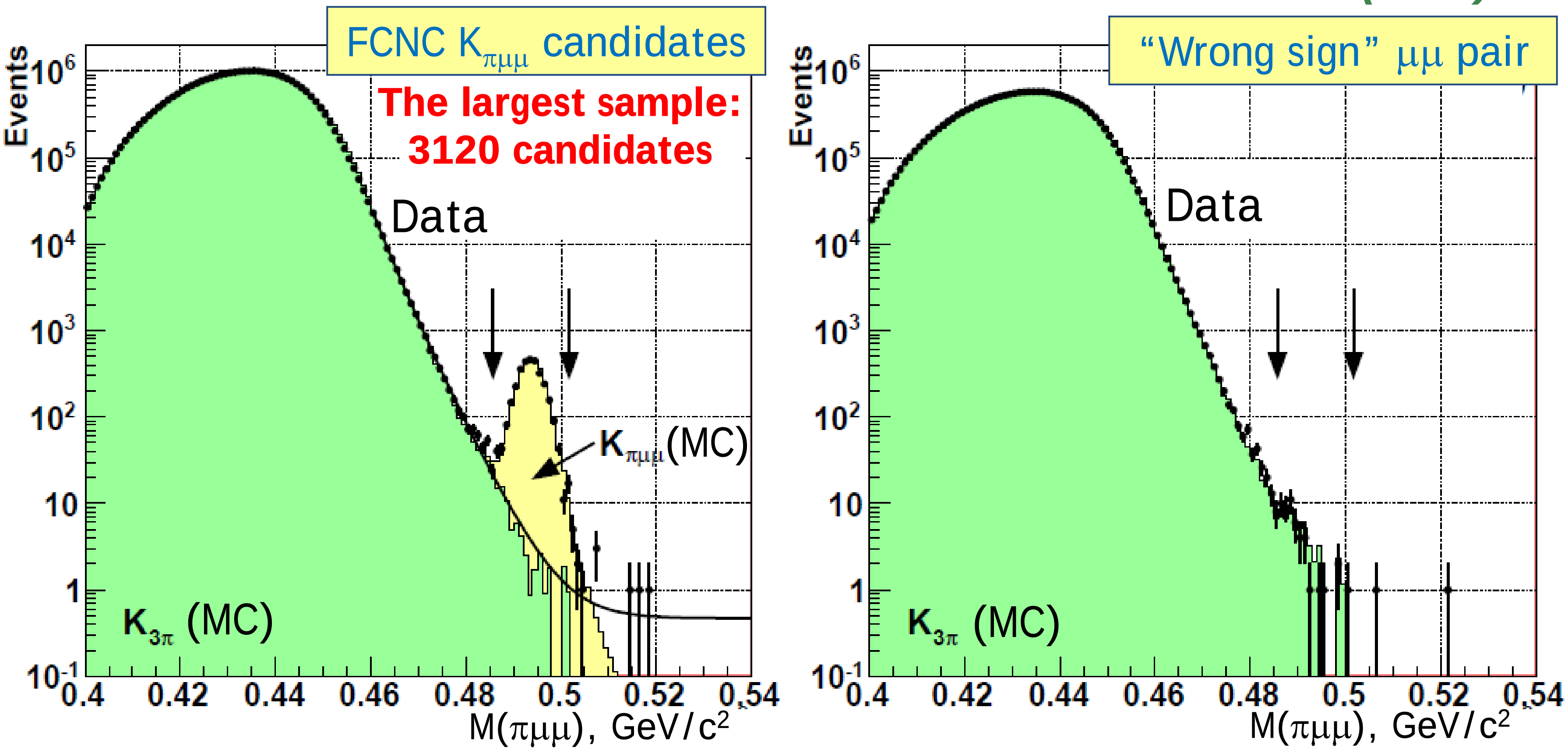
Majorana neutrino exclusion regions from existing data



Plot from Atre et al., JHEP 0905 (2009) 030

NA48/2 $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$ upper limit

PLB 697 (2011) 107



N_{data} = 52
N_{bkg} = 52.6±19.8$_{syst.}$

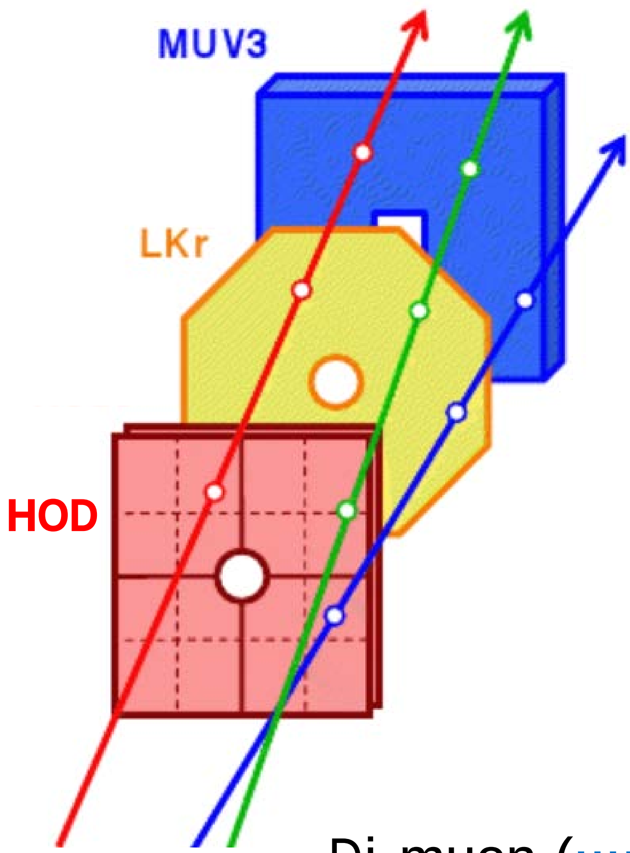
$$\mathcal{B}(K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1\times10^{-9}$$ @90% CL

- ❖ Precision limited by background from $\pi^{\pm}\to\mu^{\pm}\nu$, despite SES ≈ 3×10^{-11}.
- ❖ Flat phase space assumed (rather than Majorana neutrino exchange).
- ❖ A dedicated re-analysis has a potential sensitivity of ~10^{-10}.

NA62: di-lepton trigger

NA62 three-track decay rate upstream HOD: **F_{3track} = 640 kHz**

→ **Too high** to collect all three-track decays (the NA48/2 approach)



Available L0 trigger primitives:

- **Q_N**: at least **N** hodoscope quadrants;
- **LKR(x)**: total LKr energy deposit of at least **x** GeV;
- **MUV_N**: hits in at least **N** MUV3 pads.

L0 trigger conditions for di-lepton collection:

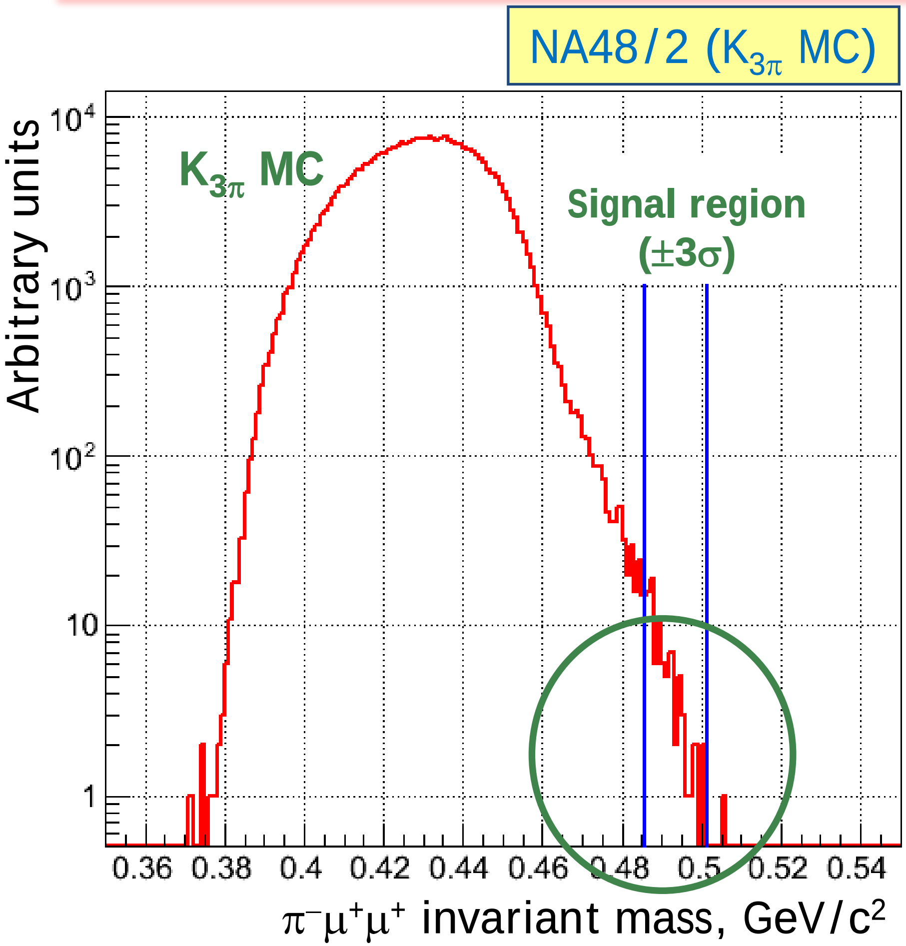
ee pair:	$Q_2 \times$ LKR(10)
μe pair:	$Q_2 \times$ LKR(10) $\times$ MUV_1
$\mu\mu$ pair:	$Q_2 \times$ MUV_2

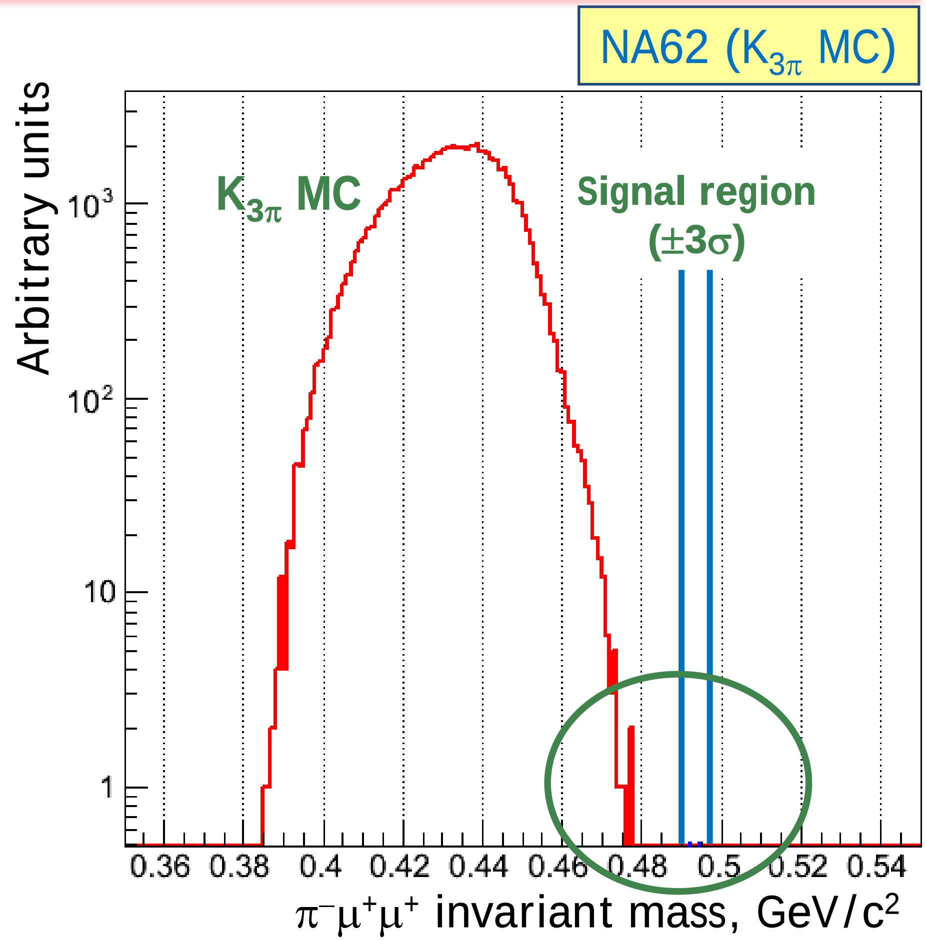
Di-muon ($\mu\mu$) rate dominated by accidentals;

ee and **μe** rates dominated by $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+\pi^0$.

Total rate **F ~ 100 kHz**: charge blind di-lepton collection is feasible.

$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ at NA62





NA48/2: $K_{3\pi}$ background to $K_{\pi\mu\mu}$ due to $\pi^{\pm}\to\mu^{\pm}\nu$ decays in the spectrometer

NA62: no $K_{3\pi}$ background expected due to high spectrometer P_T (**270** vs **120 MeV/c**) and improved $\pi\mu\mu$ mass resolution (**1.1** vs **2.6 MeV/c²**)

Search for the dark photon and rare π^0 decays

Dark photon: experimental status

Pospelov, PRD80 (2009) 095002

Secluded U(1) sector with weak admixture to photons: a natural SM extension.

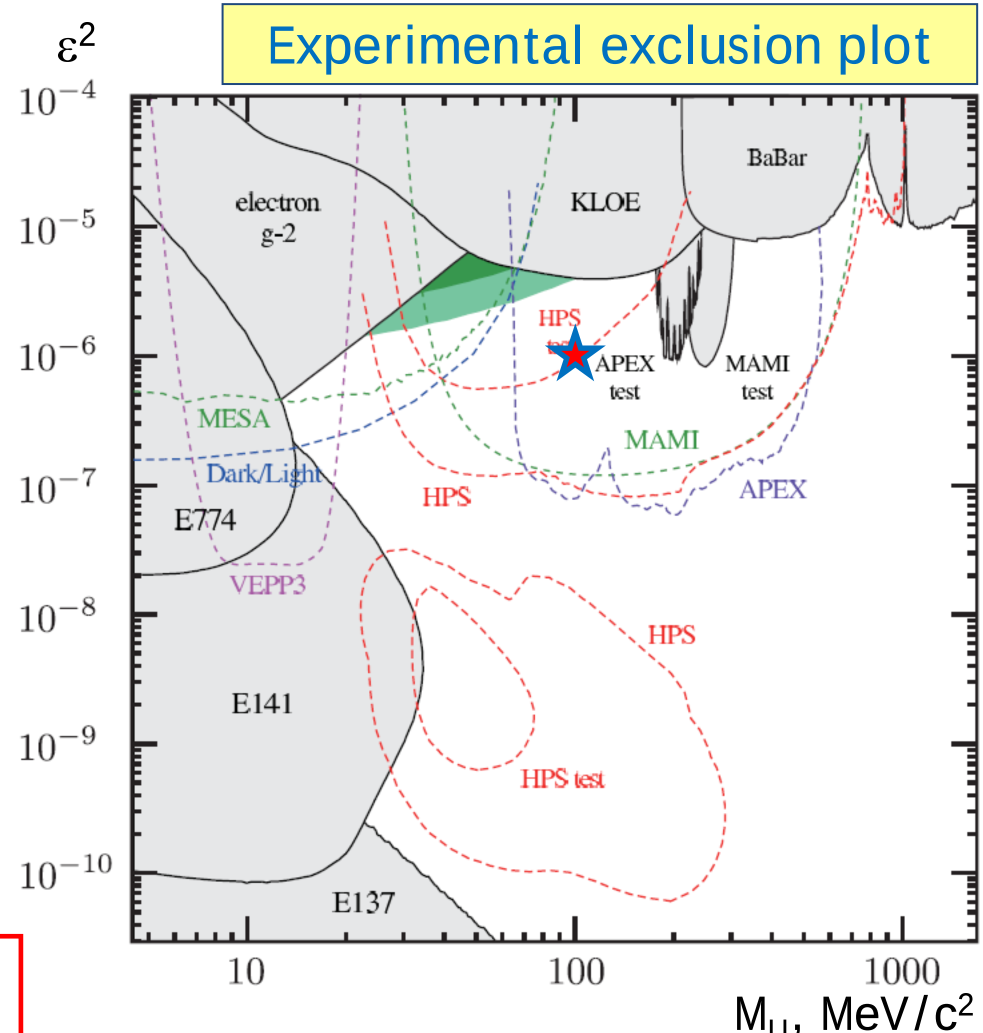
A new light vector boson: the **dark photon**.

Possible parameters:
mixing parameter: $\varepsilon^2 \sim (\alpha/\pi)^2 \sim 10^{-6}$,
DP mass: $M_U \sim \varepsilon M_Z \sim 100$ MeV/c^2.

Explains astrophysical observations and the **3.6σ** muon **g–2** anomaly.
Davoudiasl et al., PRD89 (2014) 095006

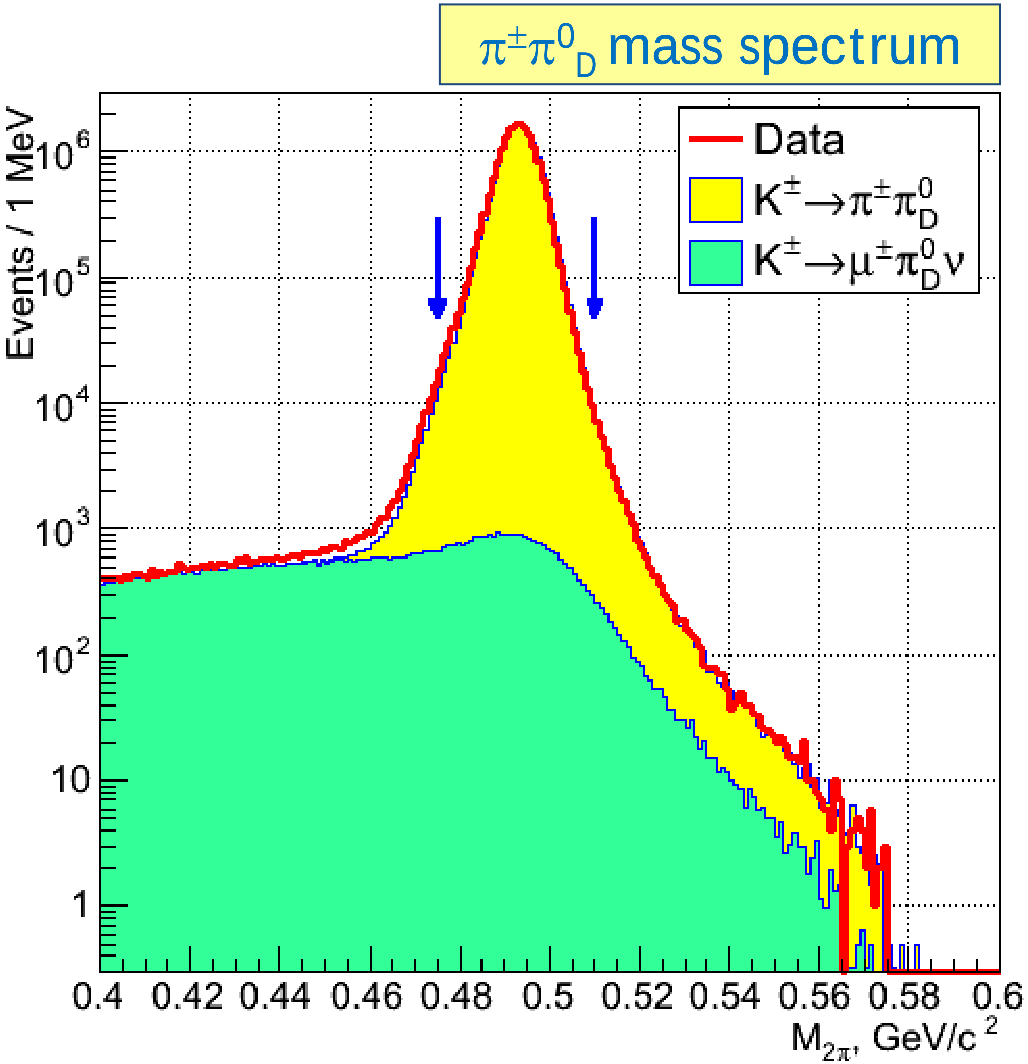
NA48/NA62 are well suited to explore the favoured region ($\varepsilon^2 \approx 10^{-6}$, $M_U \approx 100$ MeV/c^2)

Experimental exclusion plot



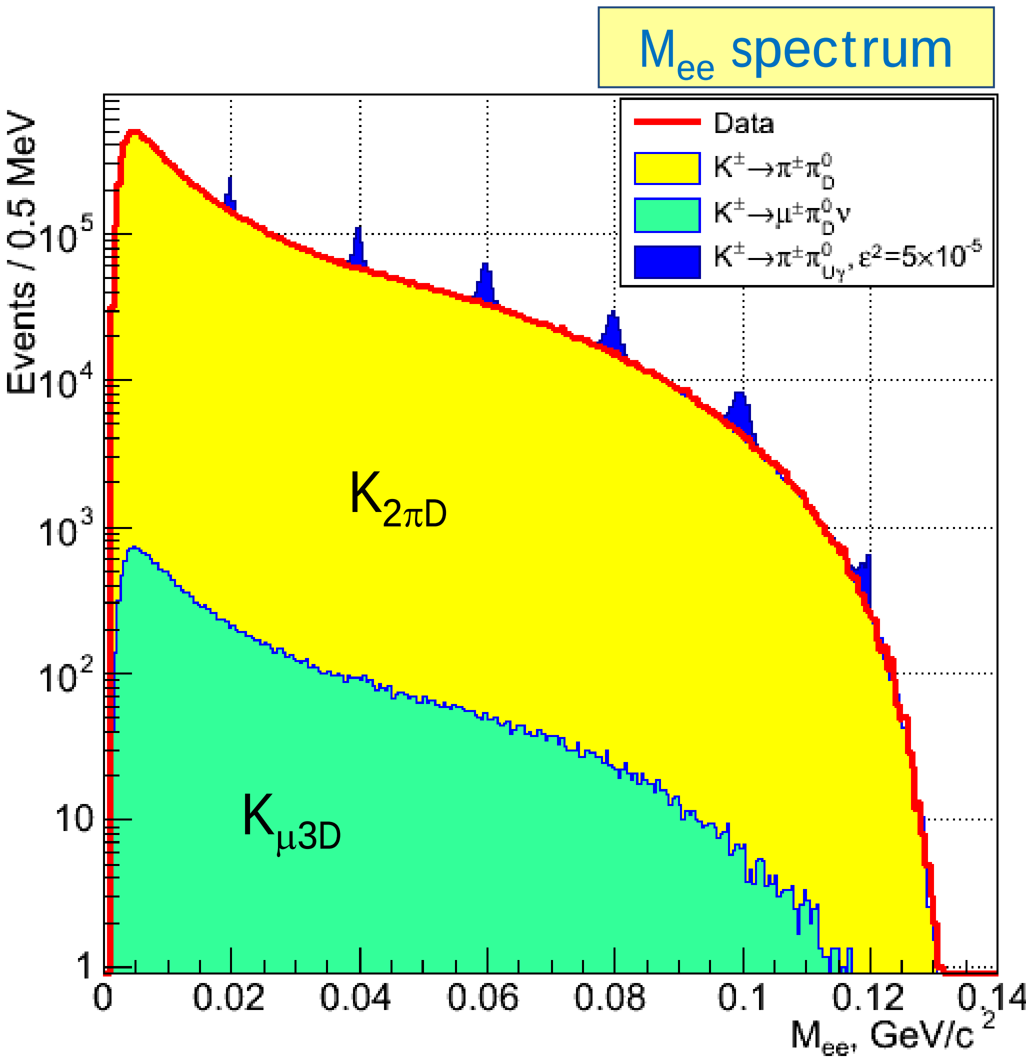
Plot from Endo et al., PRD86 (2012) 095029

NA48/2: $\pi^0_D \to e^+e^-\gamma$ sample



- Search for $\pi^0 \to U\gamma$, $U \to e^+e^-$. Assume $BR(U \to e^+e^-)=1$, reasonable for $M_U<2M_\mu$.
- An **existing data sample** collected in 2003–2004 with a 3-track trigger. Trigger efficiency: **~99%**.
- Large sample of tagged fully reconstructed π^0_D decays: 2×10^7 $K^\pm \to \pi^\pm\pi^0_D$.

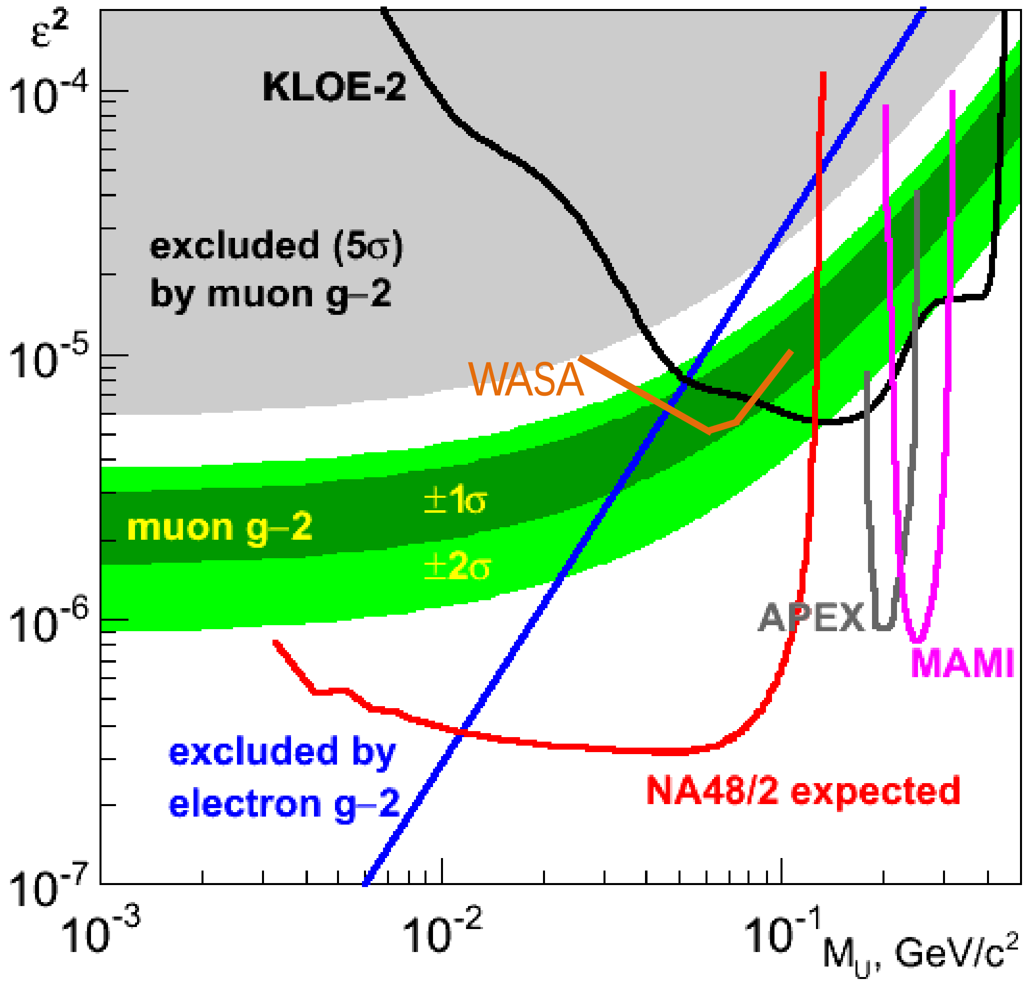
NA48/2: M_{ee} spectrum of π^0_D



- Mean DP free path **~1mm**: identical **$\pi^0 \to U\gamma$** and **π^0_D** topologies.
- Sensitivity to DP is limited by **$K_{2\pi D}$** background fluctuation.
- **Upper limit** ~ **(Kaon Flux)$^{-1/2}$** × **(Acceptance)$^{-1/2}$** × **(M_{ee} resolution)$^{+1/2}$**
- Flux **~2×10^{11}** , acceptance **~5%**.
- Spectrometer resolution: **$\delta M_{ee} \approx 0.012 M_{ee}$** (**<1.4 MeV/c**).

Form-factor and DP analyses in progress.
Future π^0_D samples unlikely to bring large improvements.

NA48/2 vs other limits at low M_U



<u>Experimental constraints</u>

Electron and muon g–2:
Endo et al., PRD86 (2012) 095029

KLOE-2 [$\phi \to \eta e^+ e^-$]:
Babusci et al., PLB720 (2013) 111

A1 @ MAMI (Mainz Microtron)
Merkel et al.,
PRL106 (2011) 251802

APEX @ J-LAB
Abrahamyan et al.,
PRL107 (2011) 191804

WASA @ COSY [$\pi^0 \to \gamma e^+ e^-$]:
Adlarson et al., PLB726 (2013) 187

NB: the NA48/2 curve is the expected sensitivity, not a result yet

Rare π^0 decays at NA62

Single-event sensitivities for π^0 decays: **$\sim 10^{-11}$**

Decay mode	Experimental status	Reference	Physics interest
$\pi^0 \to e^+e^-\gamma$	$BR(\pi^0 \to U\gamma)<10^{-5}$ 30 MeV$<M_U<$100 MeV	WASA @ COSY PLB726 (2013) 187	Dark forces
$\pi^0 \to e^+e^-e^+e^-$	$BR = 3.34(16)\times 10^{-5}$	KTeV @ FNAL PRL100 (2008) 182001	Off-shell vectors
$\pi^0 \to e^\pm\mu^\mp$	$BR<3.6\times 10^{-10}$	KTeV @ FNAL PRL100 (2008) 131803	LFV
$\pi^0 \to 3\gamma$	$BR<3.1\times 10^{-8}$	Crystal Box @ LANL PRD38 (1988) 2121	C violation: $BR_{SM}\sim 10^{-31}$
$\pi^0 \to 4\gamma$	$BR<2\times 10^{-8}$		$BR_{SM}=2.6\times 10^{-11}$ NP: light scalars $\pi^0 \to SS$, $S \to \gamma\gamma$
$\pi^0 \to \nu\bar{\nu}$ (also $K^+ \to \pi^+ X$)	$BR<2.7\times 10^{-7}$	E949 @ BNL PRD72 (2005) 091102	RH neutrinos, dark matter

Selected recent results and prospects

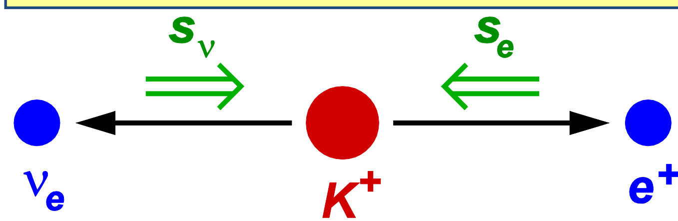
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ in the SM

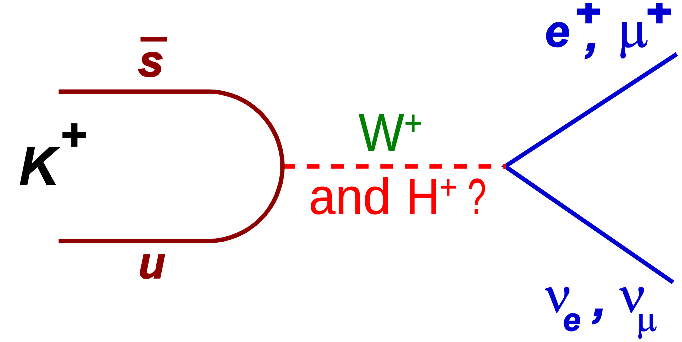
Lepton Universality test:

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{Helicity suppression: } f\sim 10^{-5}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1 + \delta R_K^{\text{rad.corr.}})}_{\text{Radiative correction (well known, few \%)}}$$

Radiative correction
(well known, few %)

Helicity suppression: f~10^{-5}



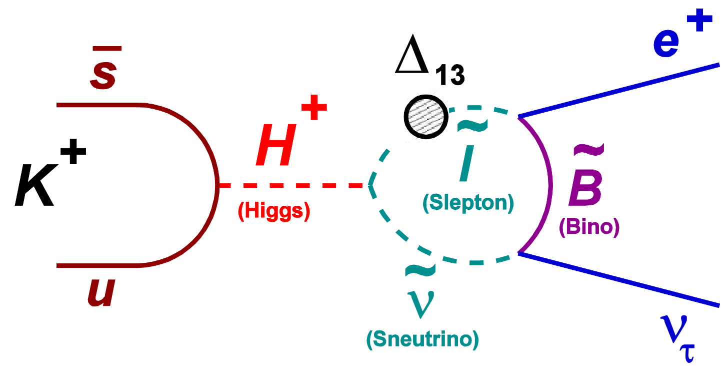


- **SM**: excellent sub-permille accuracy, not obstructed by hadronic uncertainties.
- Measurements of R_K and R_π have long been considered as LU tests.
- **Suppression of the SM contribution**: potentially accessible NP contributions.

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano and Rosell, PRL99 (2007) 231801

$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ beyond the SM



2HDM - tree level

$K^\pm \to l^\pm \nu$ can proceed via charged Higgs $H^\pm$ (in addition to $W^\pm$) exchange

→ Does not affect the ratio R_K

2HDM - one-loop level

Dominant contribution to R_K: $H^\pm$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement can be experimentally accessible

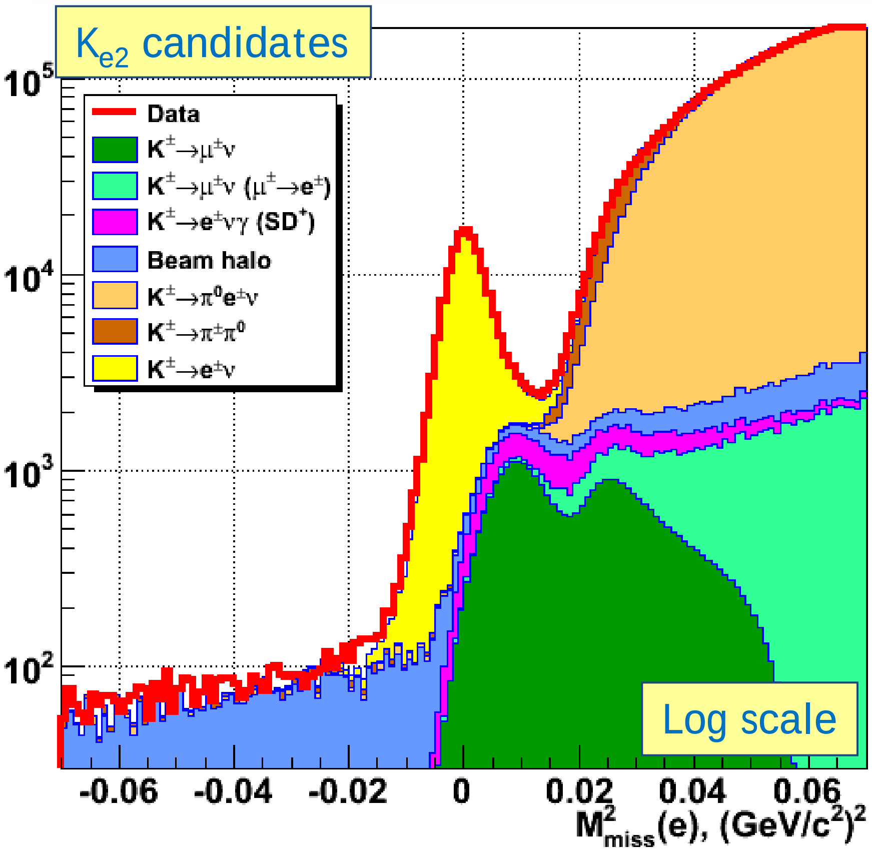
Masiero, Paradisi and Petronzio, PRD 74 (2006) 011701, JHEP 0811 (2008) 042

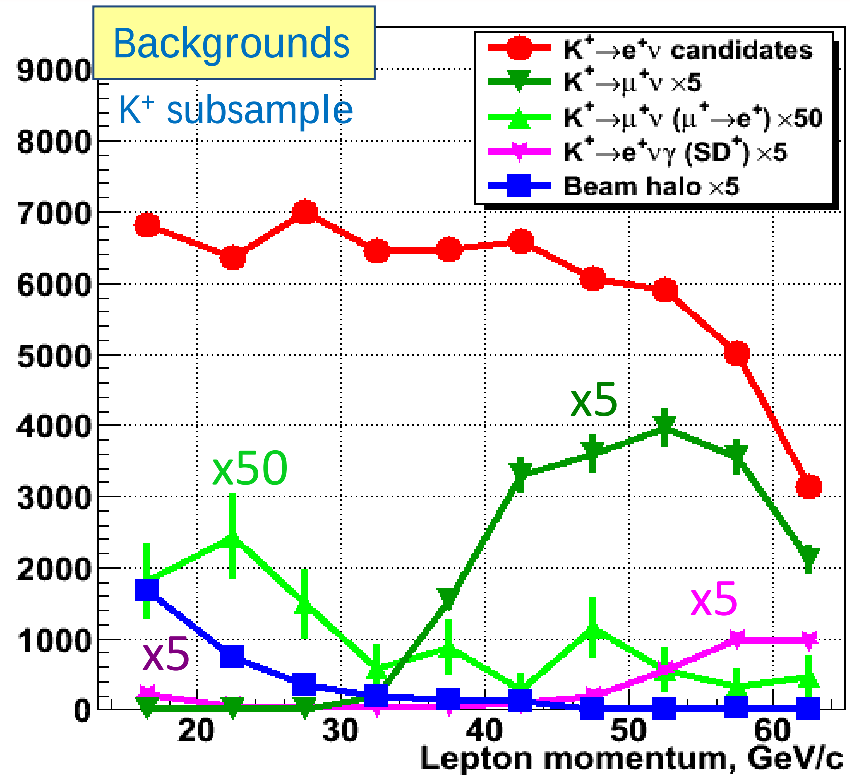
$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$

⇒ sensitive to slepton mixing

- MSSM: **~1%** effect possible
  Girrbach and Nierste, arXiv:1202.4906
- However limited by $B_{(S)} \to \mu^+\mu^-$ measurements
  Fonseca, Romão and Teixeira, EPJC 72 (2012) 2228
- Sensitive to SM extensions with 4th generation, sterile neutrinos
  Lacker and Menzel, JHEP 1007 (2010) 006; Abada et al., JHEP 1302 (2013) 048

NA62-R_K data: K_{e2} sample





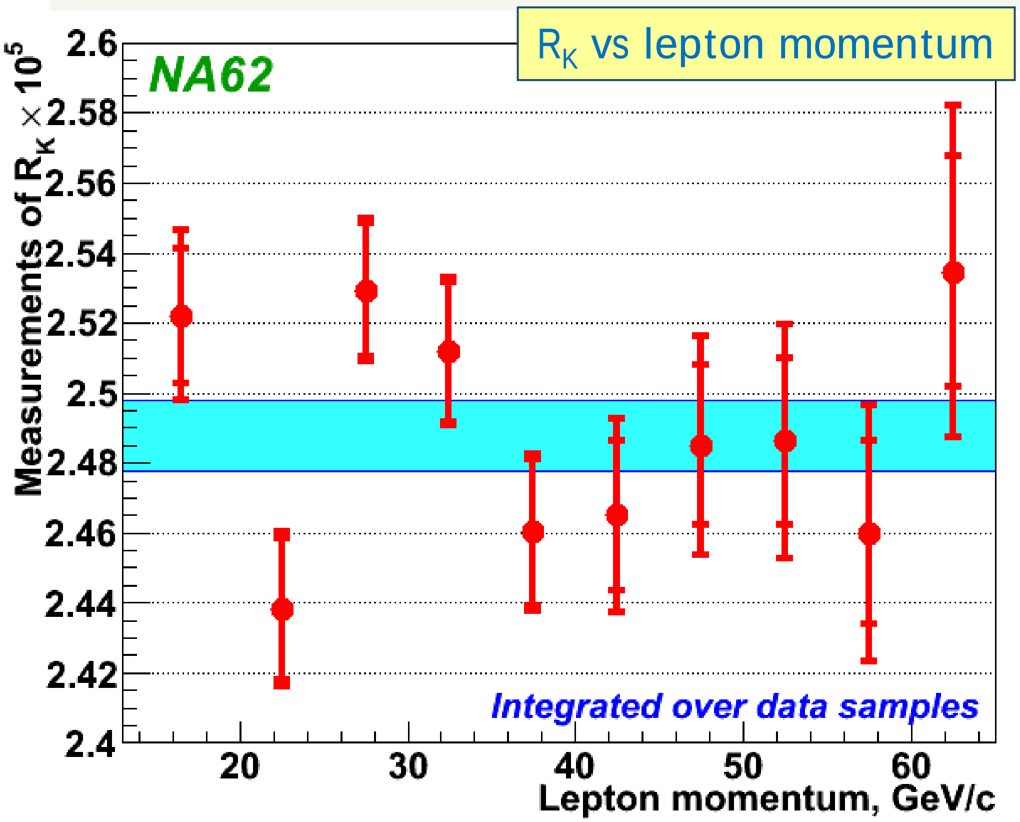
145,958 $K^\pm\to e^\pm\nu$ candidates.
Background: $B/(S+B)=(10.95\pm0.27)\%$.
Electron ID efficiency: $(99.28\pm0.05)\%$.

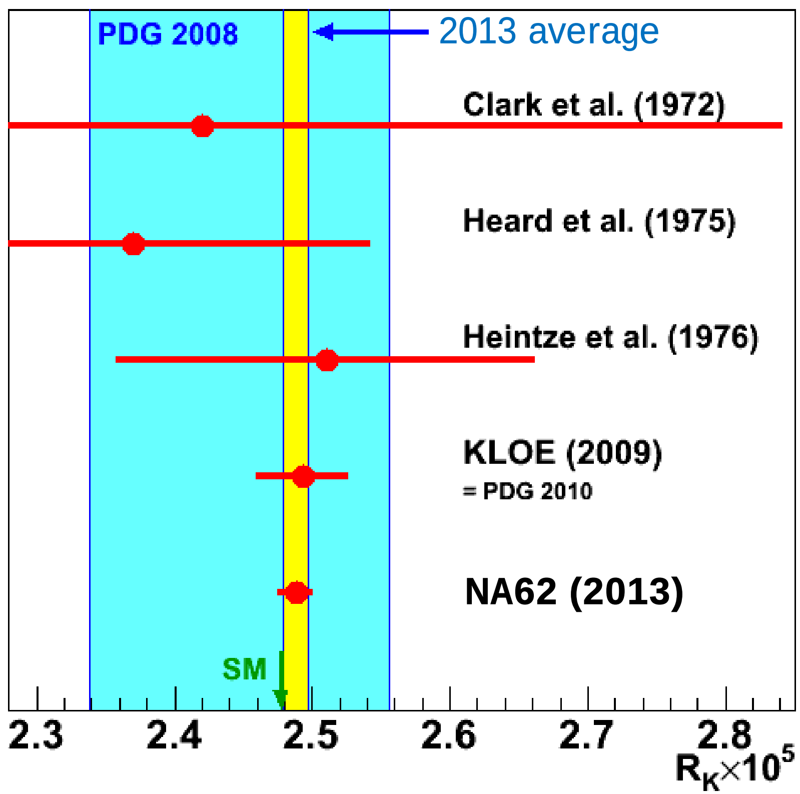
Source	B/(S+B)
$K_{\mu2}$	$(5.64\pm0.20)\%$
$K_{\mu2}$ ($\mu\to e$)	$(0.26\pm0.03)\%$
$K_{e2\gamma}$ (SD)	$(2.60\pm0.11)\%$
$K_{e3(D)}$	$(0.18\pm0.09)\%$
$K_{2\pi(D)}$	$(0.12\pm0.06)\%$
Opposite sign K	$(0.04\pm0.02)\%$
Beam halo	$(2.11\pm0.09)\%$
Total	$(10.95\pm0.27)\%$

NA62-R_K final result

$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$
$= (2.488 \pm 0.010) \times 10^{-5}$

PLB719 (2013) 326





World average	$R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
2013	2.488±0.009	0.4%

NA62 prospects:
improve precision by a factor ~2.
Competitor: TREK@J-PARC.

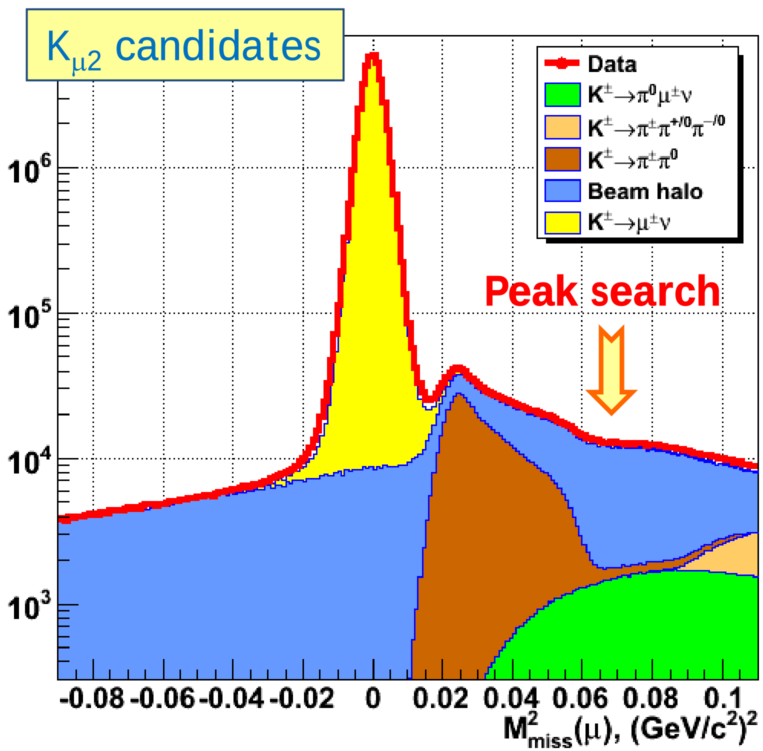
$K_{\mu 2}$: heavy neutral leptons (HNL)

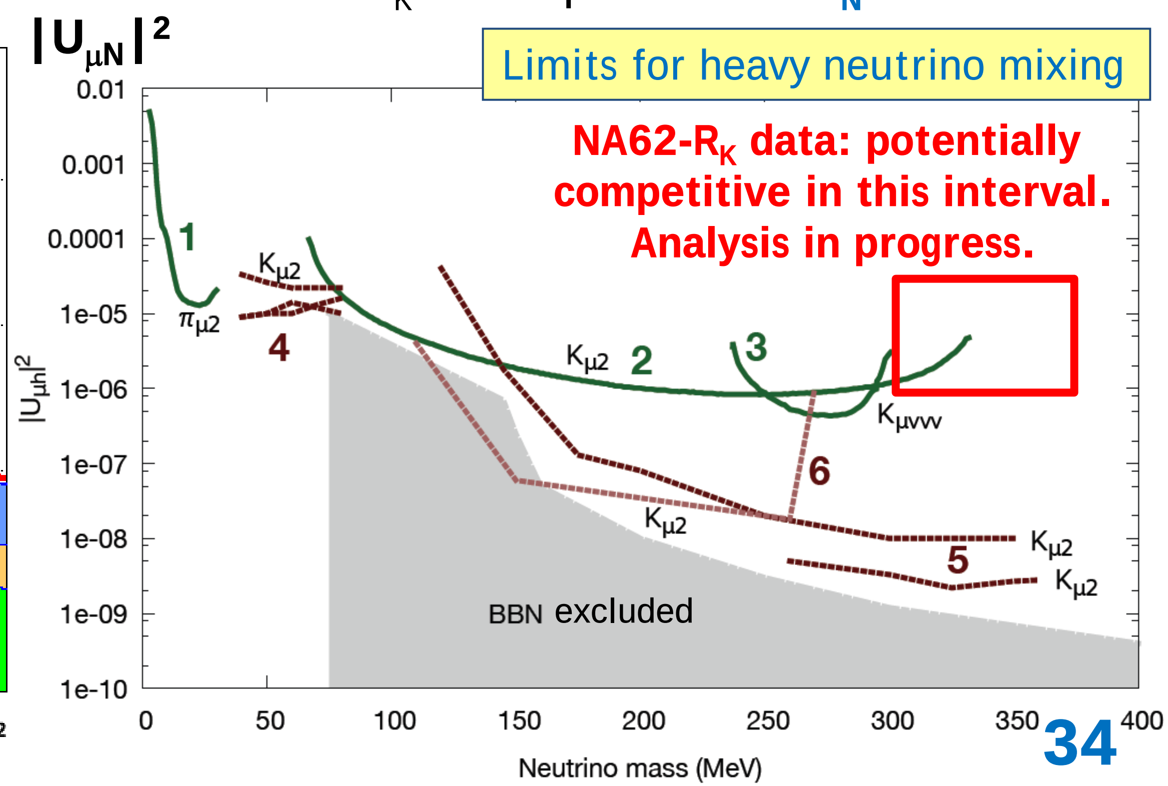
Neutrino minimal SM (**νMSM**):
3 heavy sterile RH Majorana νs (**$N_{1,2,3}$**).
m_1~10 keV/c^2: dark matter candidate.
m_2~m_3~1 GeV/c^2:
observable in **$K^{\pm}$**, **$D^{\pm} \to l^{\pm} N$** decays.

Asaka et al., PLB 631 (2005) 151

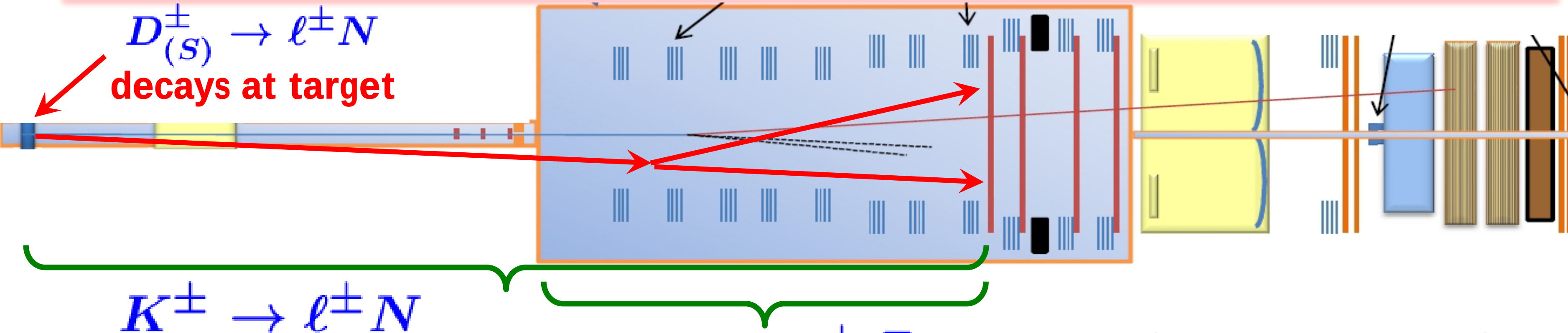
NA62-R_K subsample: 18M **$K^+ \to \mu^+ \nu_\mu$**.
"Peak search" for HNL: **$K^+ \to \mu^+ N$**.

- NA62-R_K UL if no backgrounds: **$|U_{\mu N}|^2 < 10^{-7}$, 0.1 GeV/c^2 < M_N < 0.38 GeV/c^2**.
- Sensitivity is limited by background fluctuation (mainly beam halo).
- NA62-R_K is competitive at **$M_N \approx 0.3$ GeV/c^2**.

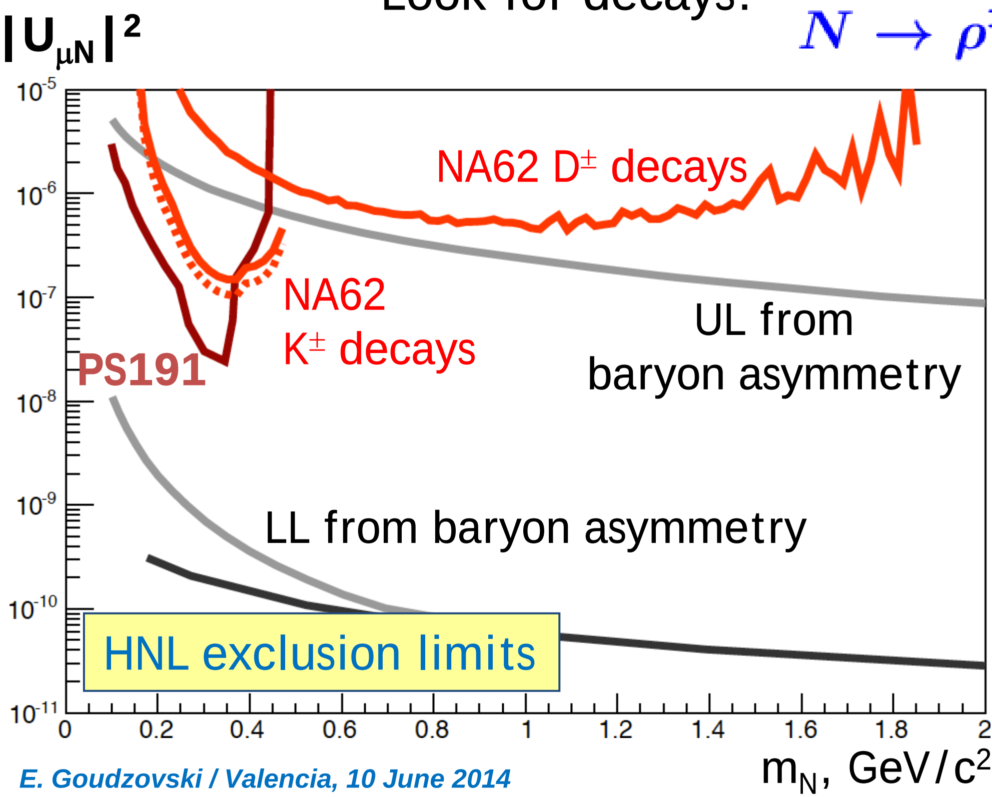




NA62 as a beam-dump experiment



Look for decays: $N \to \pi^{\pm}\ell^{\mp}$ **(0.14 GeV/c² < m_N < 1.9 GeV/c²)**
$N \to \rho^{\pm}\ell^{\mp}$ **(0.8 GeV/c² < m_N < 1.9 GeV/c²)**



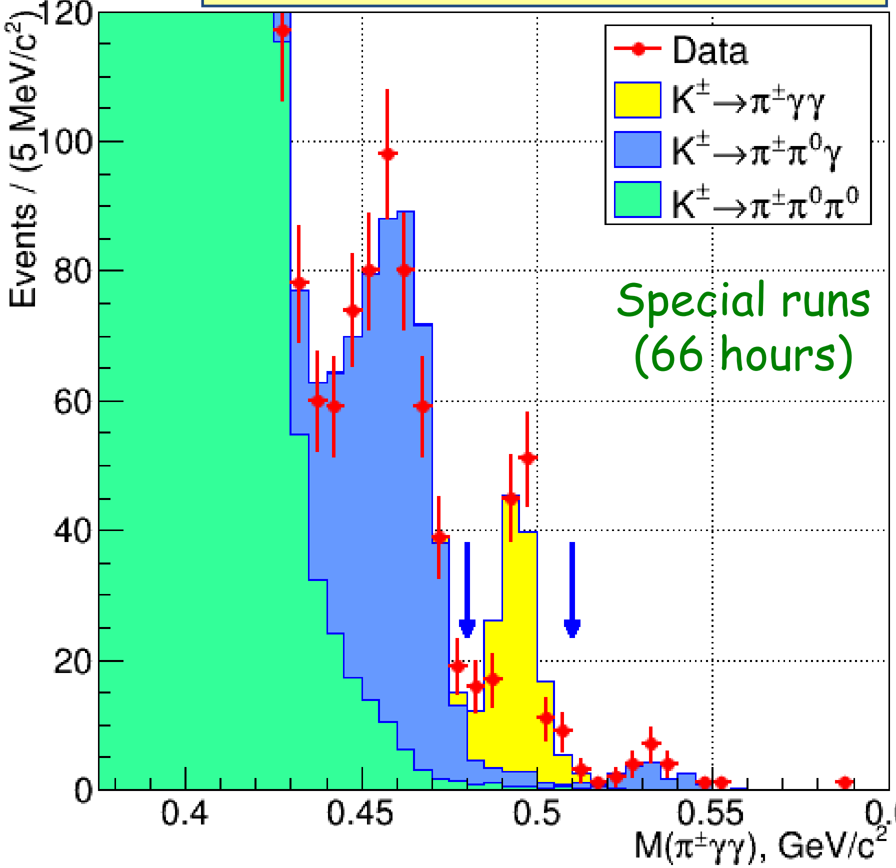
Hardware/trigger improvements are required to record $\pi^{\pm}\ell^{\mp}$ pairs (trigger for $\rho^{\pm}\ell^{\mp}$ pairs already exists).

Decay searches for HNL at mass scale expected in the **νMSM** (**~1 GeV/c²**).

Compatible with the **$K_{\pi\nu\nu}$** programme; first step in testing **νMSM** as an explanation for **BAU**.

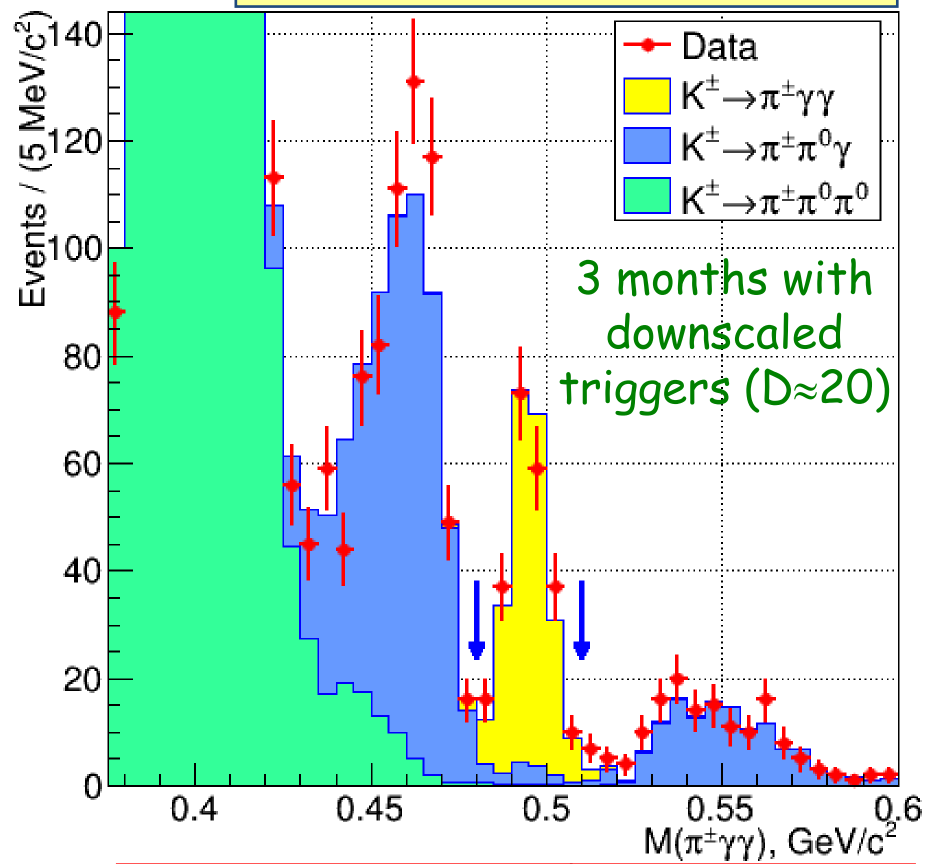
Minimum bias data: $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$

NA48/2: PLB730 (2014) 141

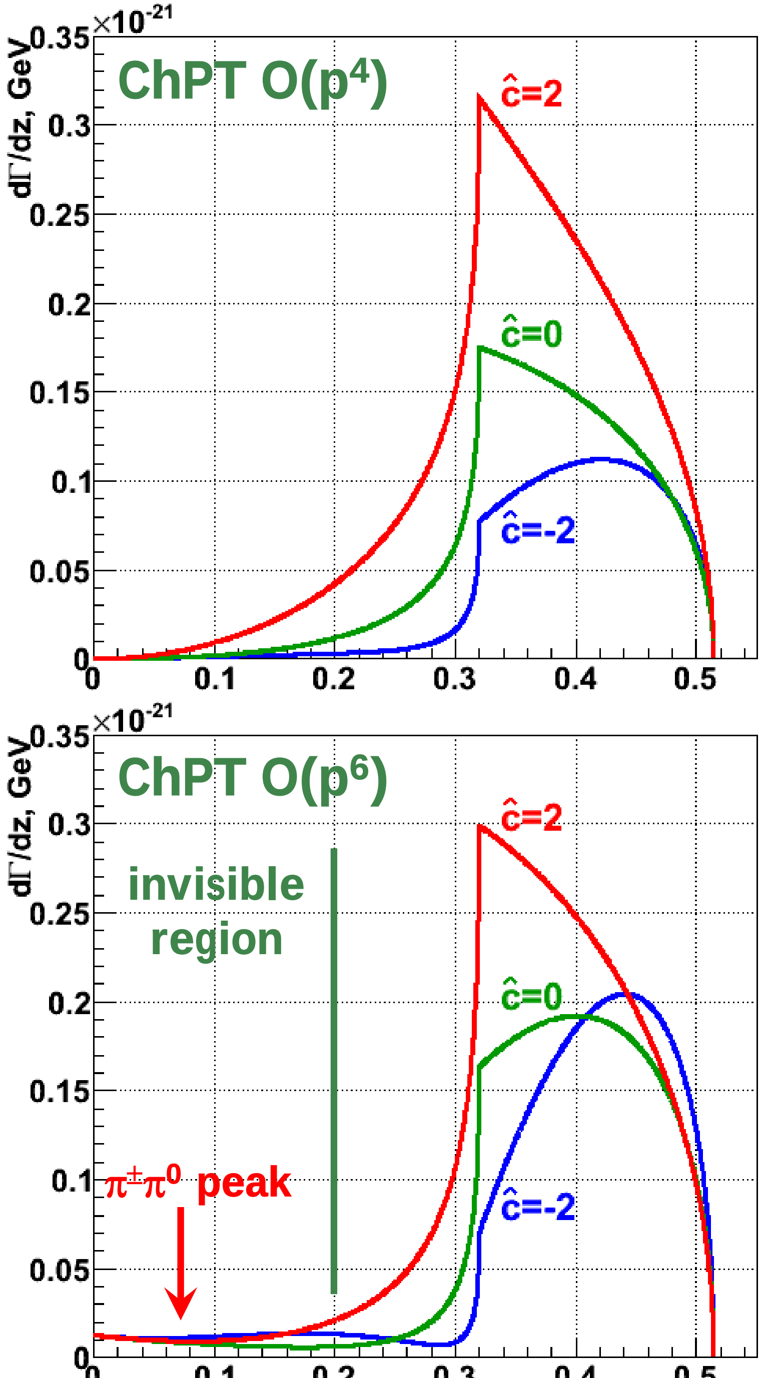


$K_{\pi\gamma\gamma}$ candidates	149
$K_{2\pi(\gamma)}$ background	11.4±0.6
$K_{3\pi}$ background	4.1±0.4
$K_{\pi\gamma\gamma}$ signal	134±12

NA62-R$_K$: PLB732 (2014) 65



$K_{\pi\gamma\gamma}$ candidates	232
$K_{2\pi(\gamma)}$ background	15.3±1.1
$K_{3\pi}$ background	2.1±0.3
$K_{\pi\gamma\gamma}$ signal	215±15



ChPT description

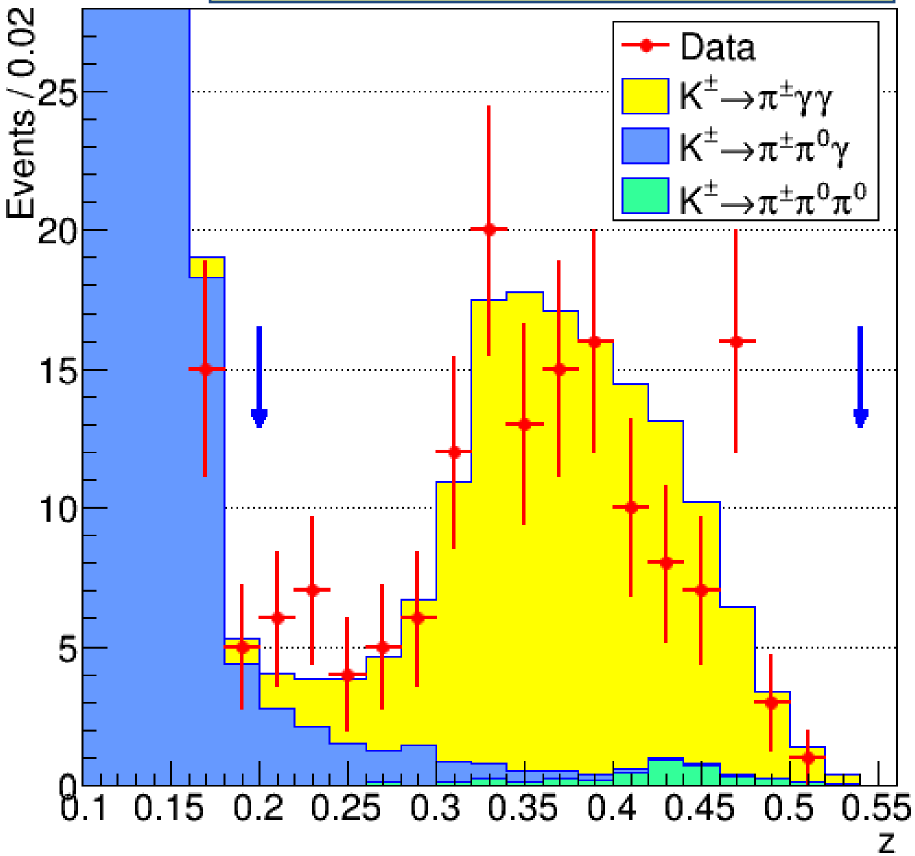
D'Ambrosio, Portoles, PLB386 (1996) 403

$$z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \quad y = \frac{p(q_1-q_2)}{m_K^2}$$

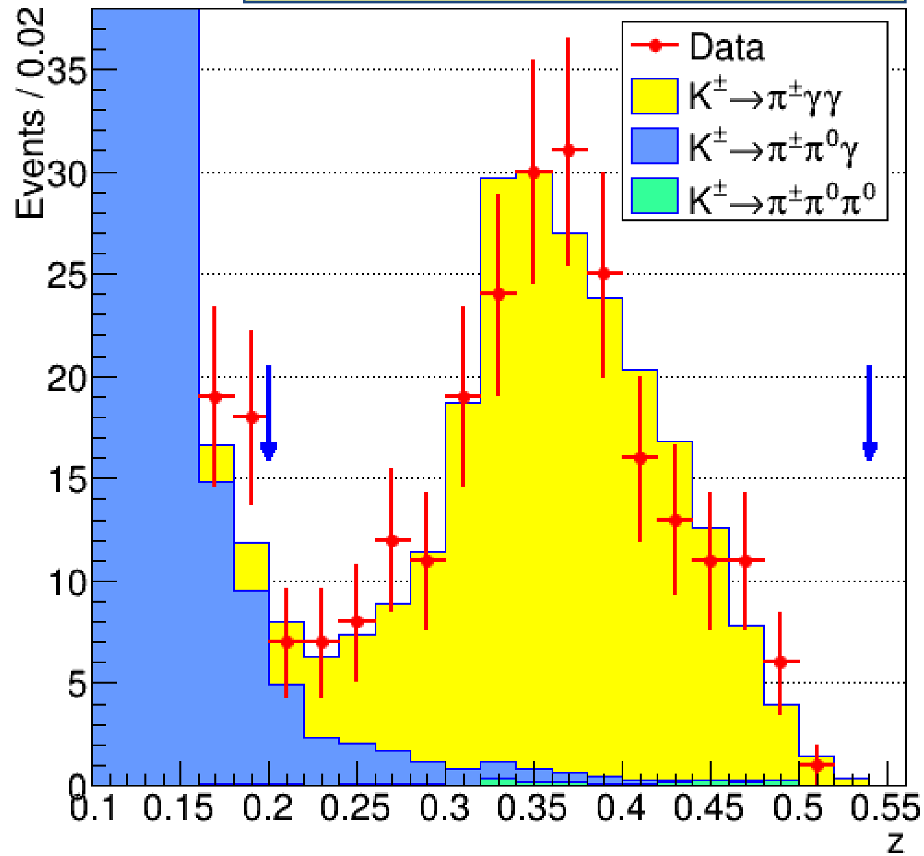
- Leading ChPT contribution at **O(p⁴)**.
- Rate and spectrum determined by a single "unknown" parameter: **ĉ**.
- A number of fixed external inputs: $\mathbf{G_8}$, $\mathbf{K_{3\pi}}$ amplitude parameters, "polynomial contributions" (η_i).
- Dominated by pion loop amplitude: cusp at di-pion threshold $\mathbf{z=(2m_\pi/m_K)^2=0.32}$.
- ChPT **O(p⁶)**: non-zero **dΓ/dz** at **z=0** and a (weak) **y**-dependence of **dΓ/dz**.

Fits to ChPT description

NA48/2: PLB730 (2014) 141



NA62-R$_K$: PLB732 (2014) 65



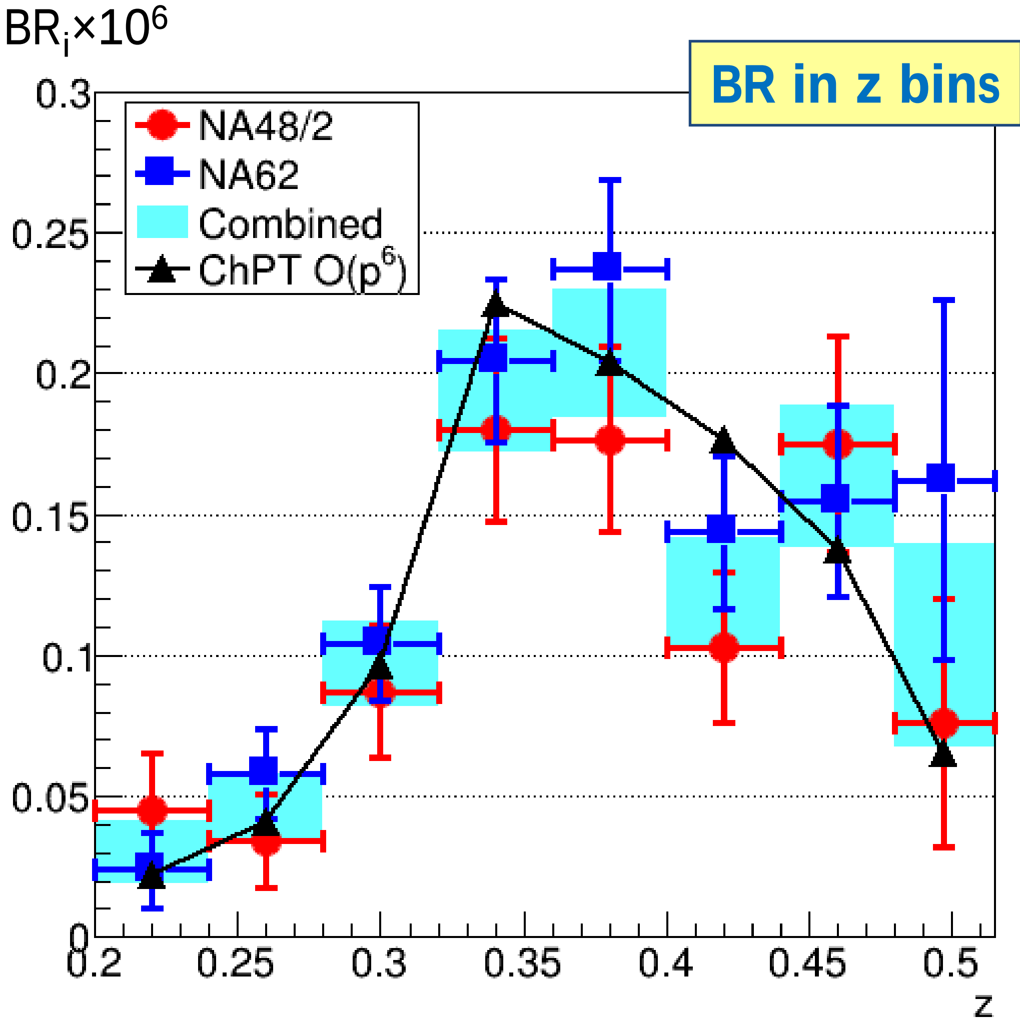
→ *First published evidence for the cusp at di-pion threshold predicted by ChPT*

NA48/2 & NA62-R$_K$ combined measurements:

$\hat{c}_4 = 1.72 \pm 0.20_{stat} \pm 0.06_{syst}$; $\hat{c}_6 = 1.86 \pm 0.23_{stat} \pm 0.11_{syst}$

(NB: they depend on the external parameters)

Model-independent BR($K^{\pm}\to\pi^{\pm}\gamma\gamma$)



Model-independent BR measurement in narrow **z** bins is possible:

✓ acceptance in bins is almost independent of the assumed **dΓ/dz**;

✓ weak **y**-dependence of the differential rate and acceptance.

Final result with **349** events:

$$\mathbf{BR_{MI}(z>0.2) = (0.965 \pm 0.061_{stat} \pm 0.014_{syst}) \times 10^{-6}}$$

Published: PLB732 (2014) 65

*NA62 can collect **~10^5 $K^+\to\pi^+\gamma\gamma$** events with a minimum bias trigger*

Long-term possibilities: personal view

❖ **Run 2014–2017**: dedicated to $K^+\to\pi^+\nu\nu$ (**~100** SM events) and other rare **K** and π decays. **Suggestions for the physics programme?**

SPS LS2: 2018–2019

❖ **Run 2020–2023** possibilities:

a) Upgrades to improve precision on $K^+\to\pi^+\nu\nu$ (**~1000** SM events).

b) Switch to neutral beam to pursue $K_L\to\pi^0 l^+ l^-$ and prototype studies for $K_L\to\pi^0\nu\nu$. Need **~10** times higher SPS proton intensity (**~10^{13} ppp**). Have to cope with GHz photon and neutron fluxes.

c) Focus on heavy neutral lepton searches (in particular, add shielding upstream of the decay volume).

SPS LS3: 2024

❖ **Run 2025–2028** possibility:

Next generation $K_L\to\pi^0\nu\nu$ experiment? Significant detector R&D required.

Summary

- **NA48/2** (2003–2004): a multi-purpose $K^{\pm}$ experiment.
  - ✓ $K^{\pm}$ physics at a new precision level (16 peer-reviewed papers so far);
  - ✓ Several rare $K^{\pm}$ and π^0 decay analyses in progress.

- **NA62-R$_K$** (2007–2008): minimum bias electron trigger.
  - ✓ Lepton Universality test at record **0.4%** precision:
    $BR(K^{\pm}\to e^{\pm}\nu)/BR(K^{\pm}\to\mu^{\pm}\nu) = (2.488\pm0.010)\times10^{-5}$;
  - ✓ rare decays, heavy neutral leptons: analyses in progress.

- **NA62** (2014–2017): high-intensity K^+ experiment, ready to start.
  - ✓ expected single event sensitivities for K^+ decays: $\sim10^{-12}$;
  - ✓ preparing for a (low intensity) physics run in 2014;
  - ✓ a diverse physics programme is taking shape;
  - ✓ proof-of-concept for the longer term programme.