Kaon Experiments at CERN

Evgueni Goudzovski

(University of Birmingham, eg@hep.ph.bham.ac.uk)

on behalf of NA48/2 and NA62 collaborations

Outline:

1) Introduction to CERN kaon programme
2) The golden decay mode: $K^+\to\pi^+\nu\bar{\nu}$
3) Lepton flavour/number violation in K decays
4) Rare π^0 decays
5) Selected recent results, ongoing analyses
6) Summary

"Triggering Discoveries in High Energy Physics"
University of Jammu, India • 9 September 2013

Kaon physics facilities

BNL
E865, E777, E787, E949

CERN
NA48, NA62

IHEP Protvino
ISTRA+, OKA, *KLOD*

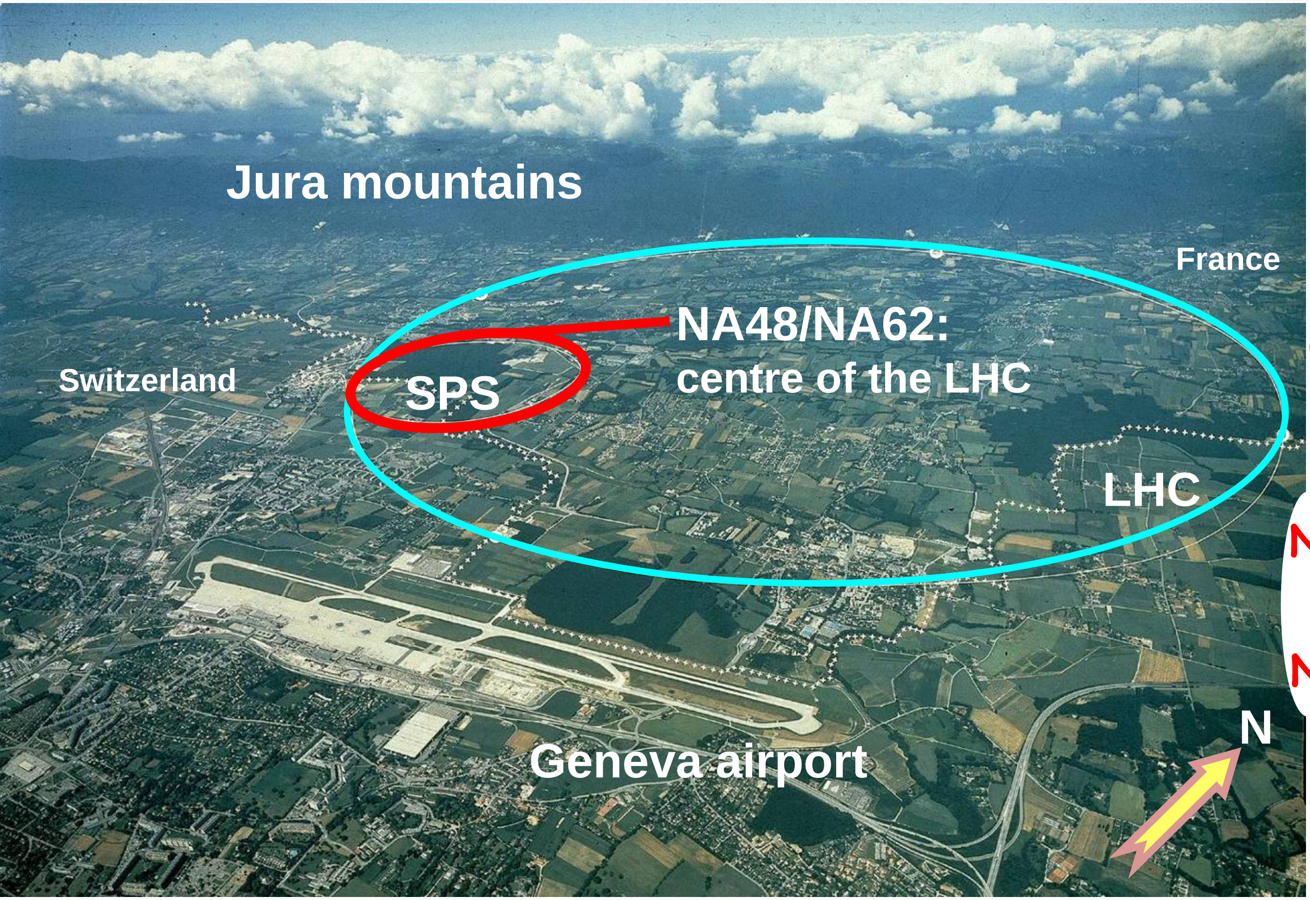
FNAL
KTeV, *ORKA*

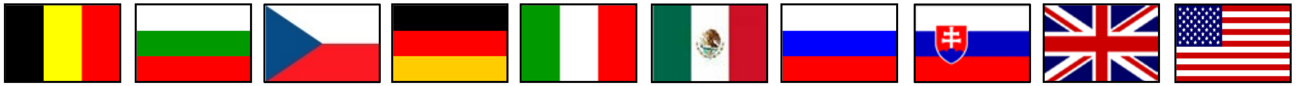
LNF
KLOE, KLOE-2

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: $K^\pm_{e2}/K^\pm_{\mu2}$**	**tests**
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	**tests**
NA62	**2012: technical run**	
	***2014:* 1st $K^+\to\pi^+\nu\bar{\nu}$ run**	

Kaon decay in flight experiments.
NA62: currently **~200** participants, **27** 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**
$M(K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-})$ 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; **$K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$**	**$e^{\pm}$**	**$K_{\pi\nu\nu}$ + ...**

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

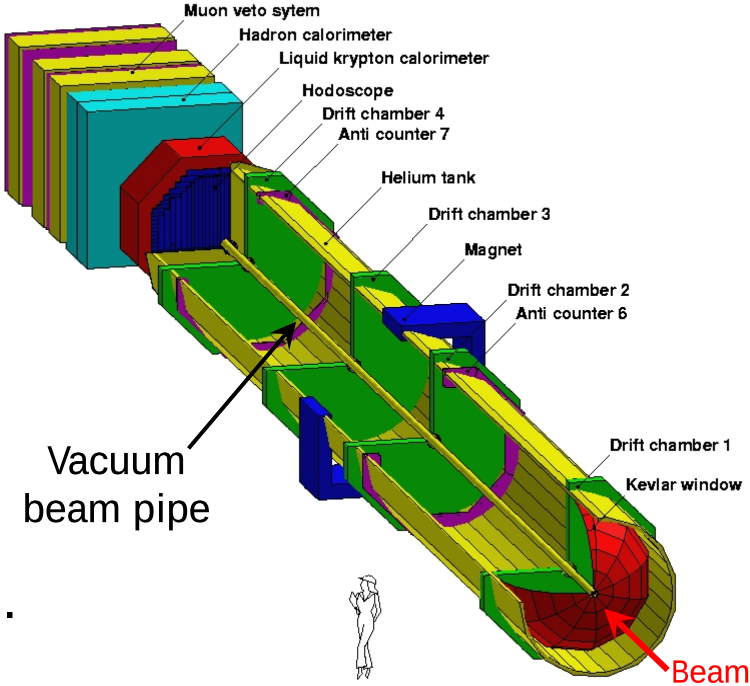
2003–2008: charged kaon beams,
the NA48 detector

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:

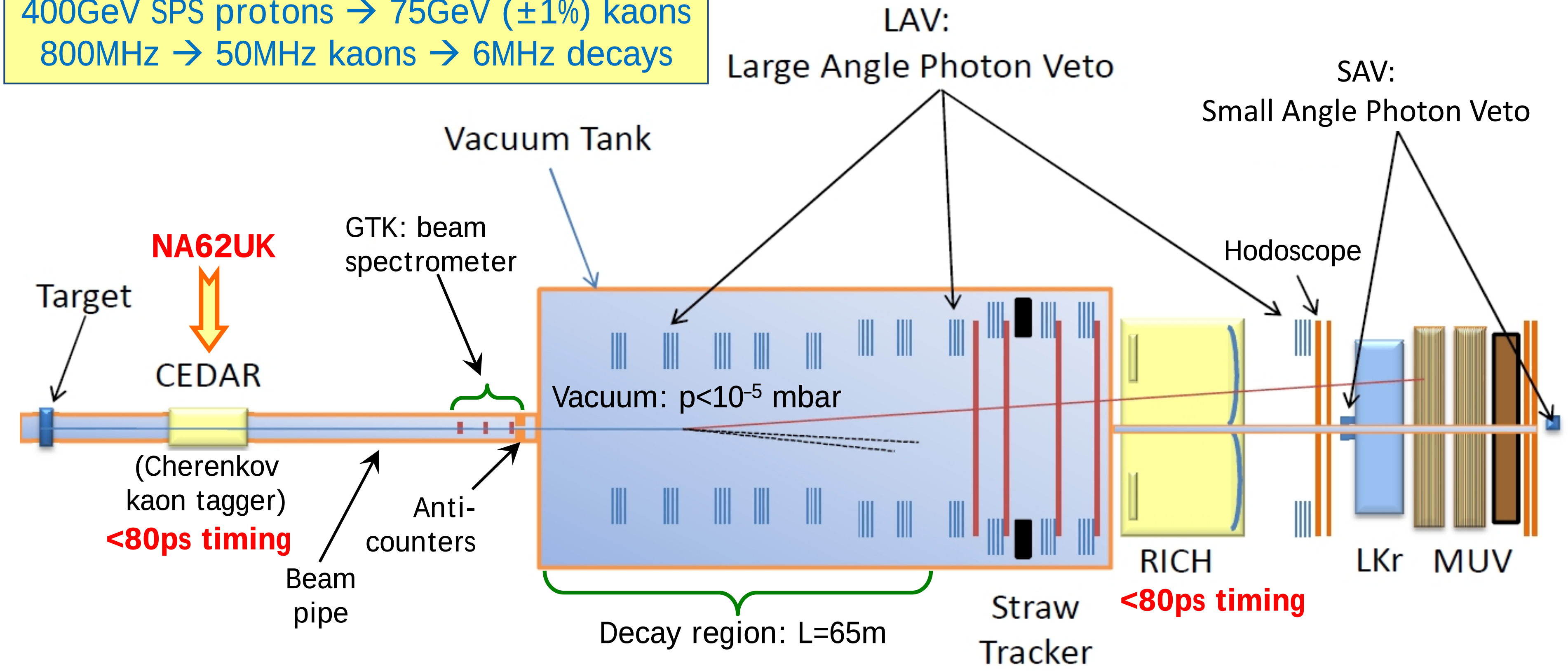
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy ⇒ efficiency;
  $\delta p/p = 0.48\% \oplus 0.009\%p$ [GeV/c] (in 2007)
- Scintillator hodoscope
  Fast trigger, time measurement (**150ps**).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$ [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 → 50MHz kaons → 6MHz decays

Total length: ~270m



LAV:
Large Angle Photon Veto

SAV:
Small Angle Photon Veto

Vacuum Tank

GTK: beam spectrometer

Hodoscope

NA62UK

Target

CEDAR

(Cherenkov kaon tagger)

<80ps timing

Vacuum: $p<10^{-5}$ mbar

Beam pipe

Anti-counters

Decay region: L=65m

Straw Tracker

RICH

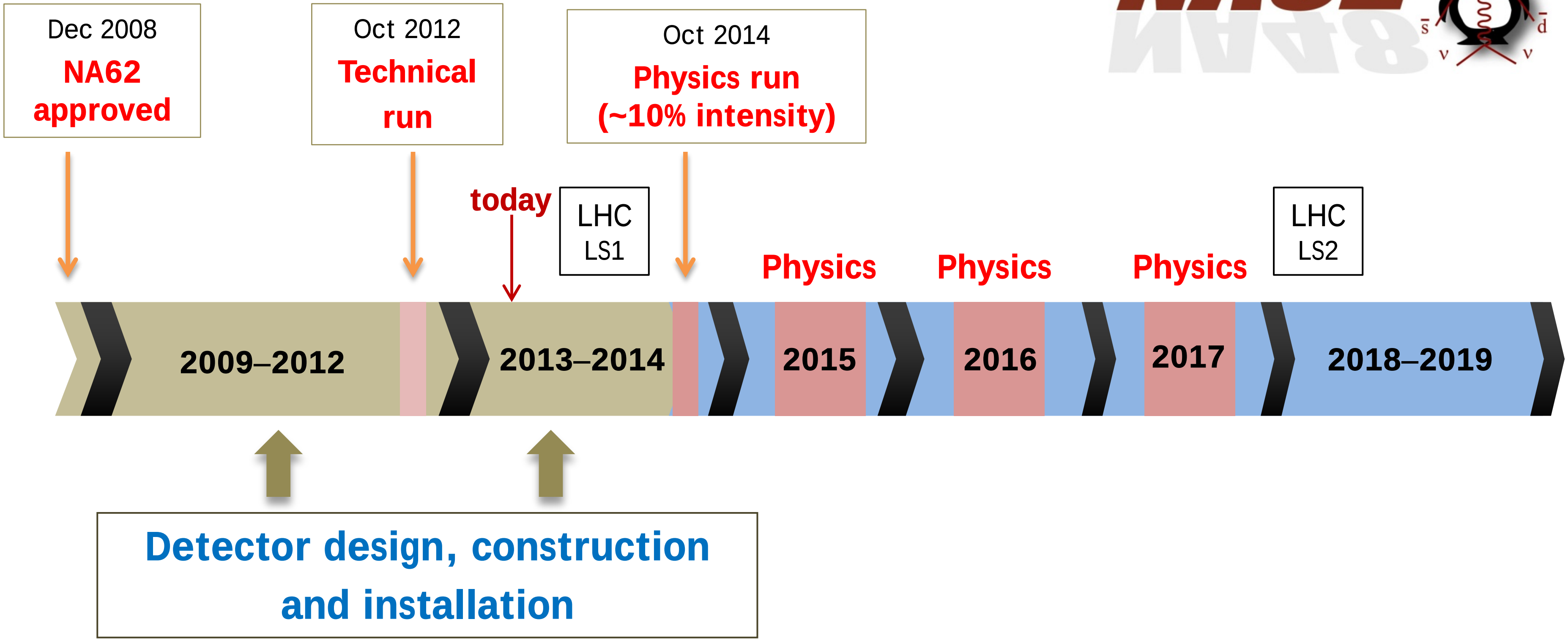
<80ps timing

LKr

MUV

- 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.

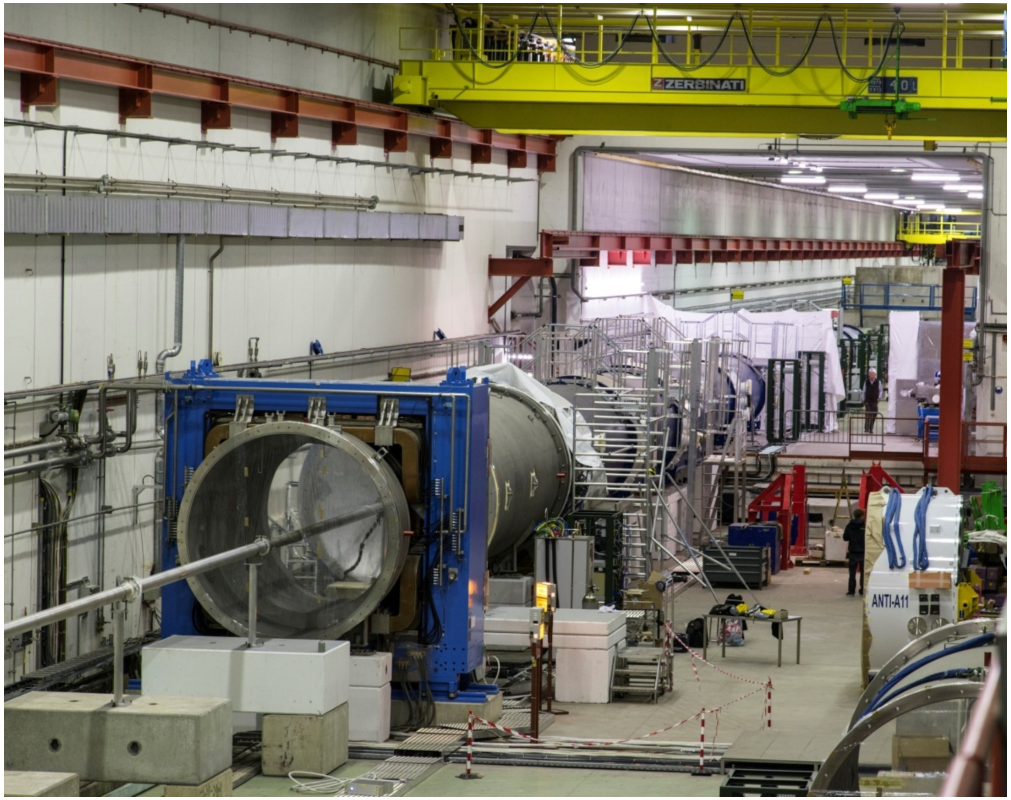
NA62 timeline



- 5 years of construction interleaved with a technical run in **October 2012**
- First run with full detector: **October–December 2014**
- Physics data taking runs before LHC Long Shutdown 2 (LS2)

NA62 construction & tests

Vacuum tank view in 2012



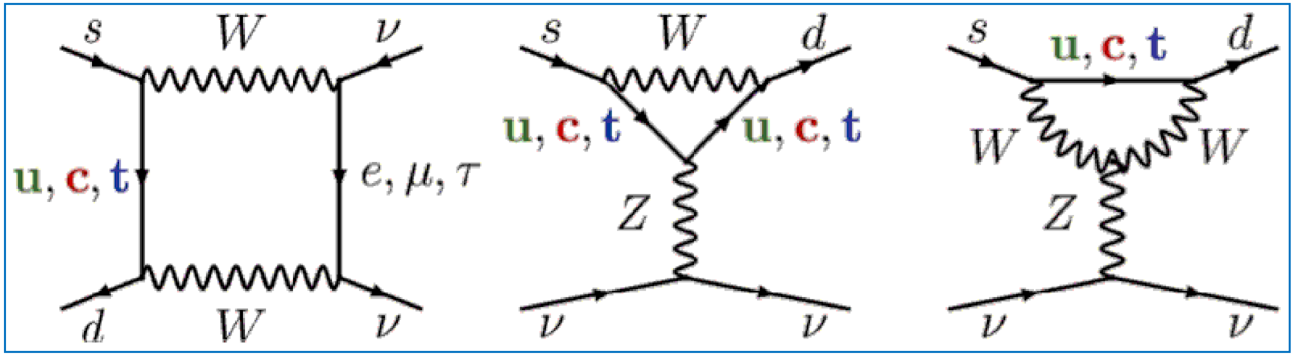
Photon veto (LAV) installation

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 (**$K^+\to\pi^0 e^+\nu$**).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of **$|V_{td}|$** complementary to those from B–B mixing or **$B^0\to\rho\gamma$**.
- Optimal probe for non-MFV *(Gino Isidori, ESPP open symposium 2012)*

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

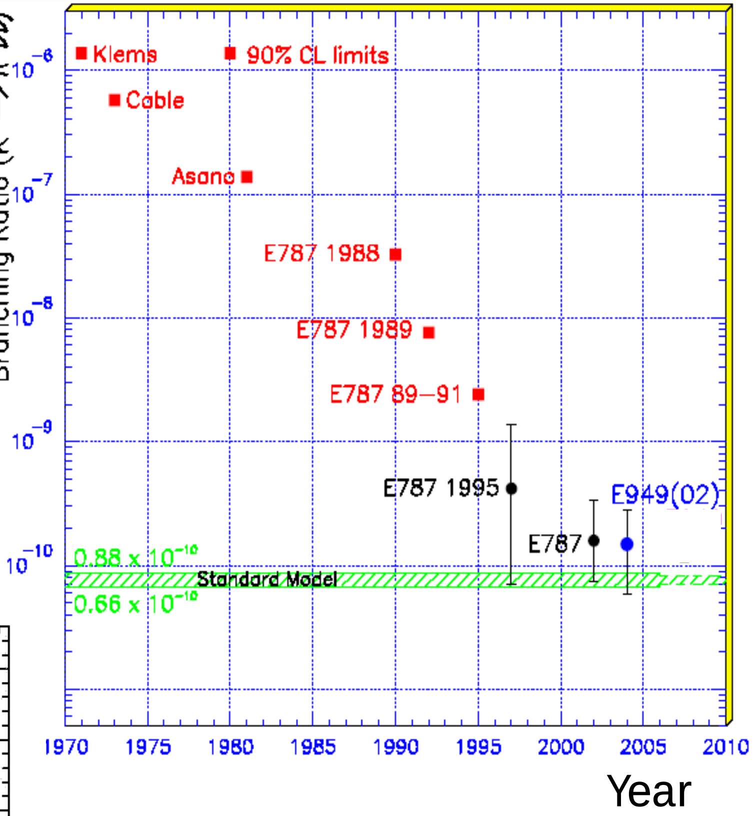
Theoretically clean,
sensitive to new physics,
almost unexplored

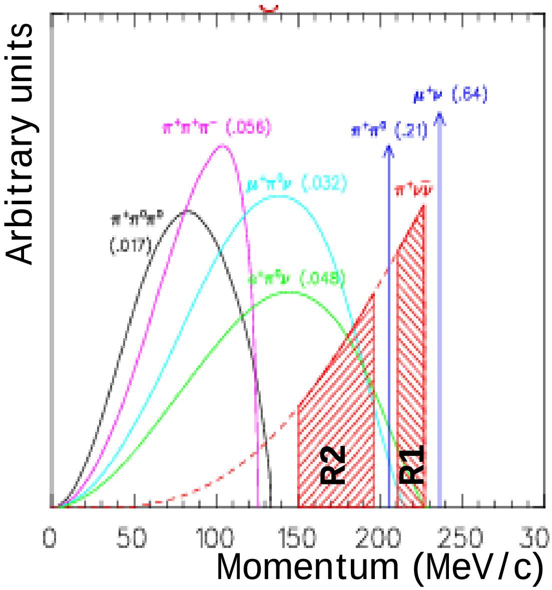
$K^+\to\pi^+\nu\bar{\nu}$ at BNL E747/E949

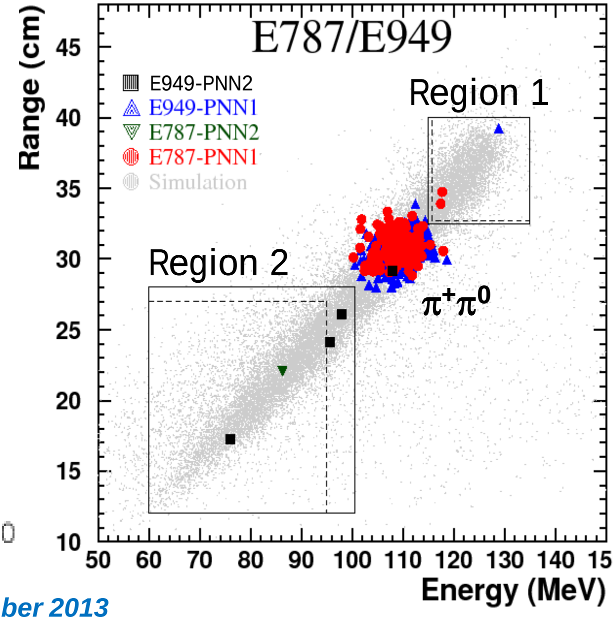
Technique: K^+ decay at rest

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 = $(1.73^{+1.15}_{-1.05})\times10^{-10}$**





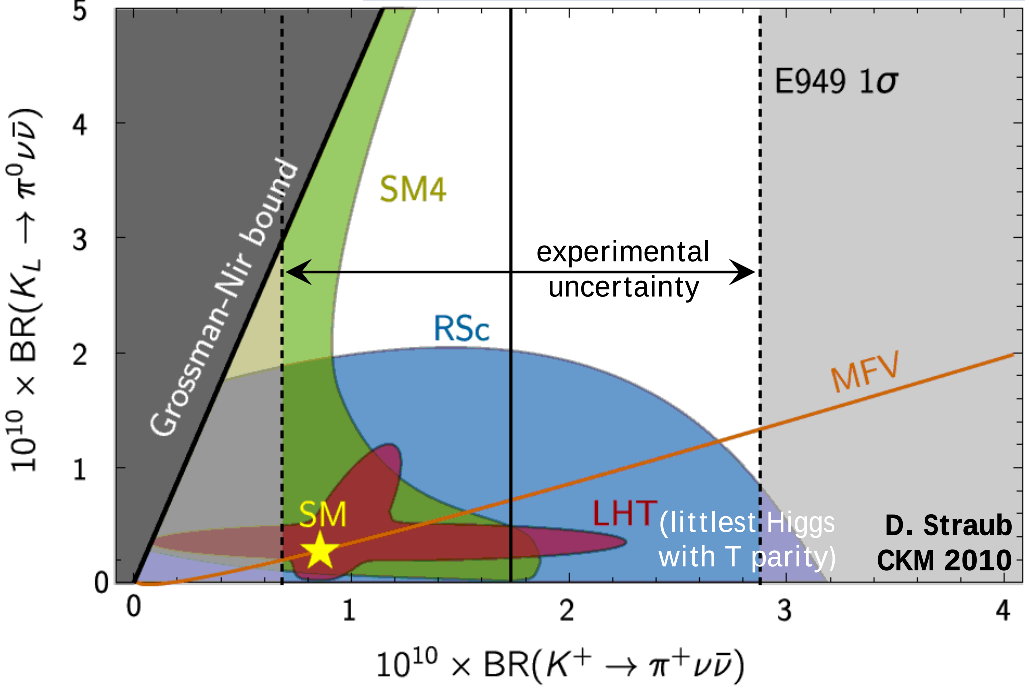


Significant background
in Region 2 from the $K_{2\pi}$
decay with π^+ scattering
in the target.

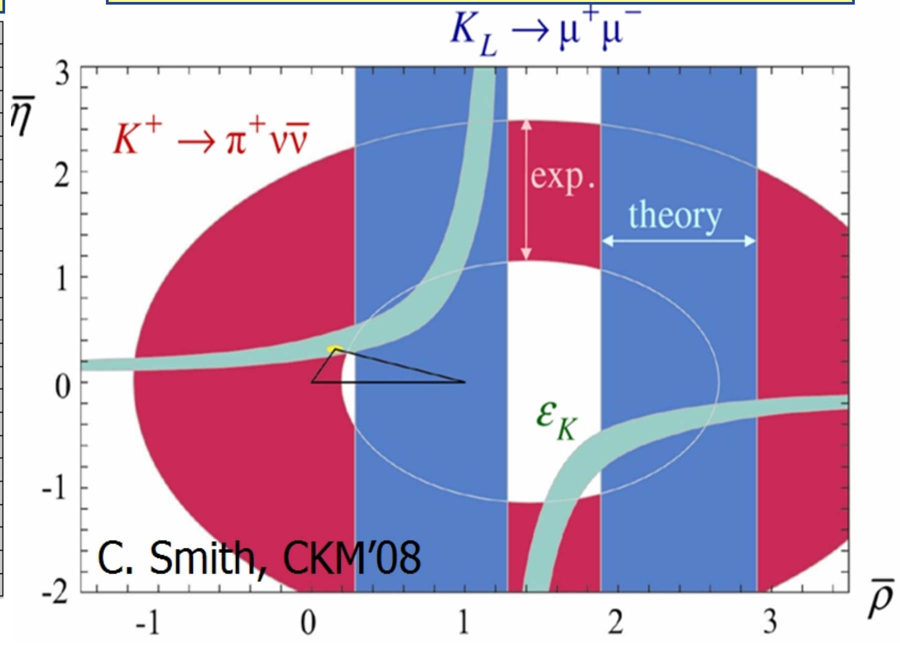
PRL 101 (2008) 191802;
PRD 79 (2009) 092004

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 2 years of data taking using a novel decay-in-flight technique.

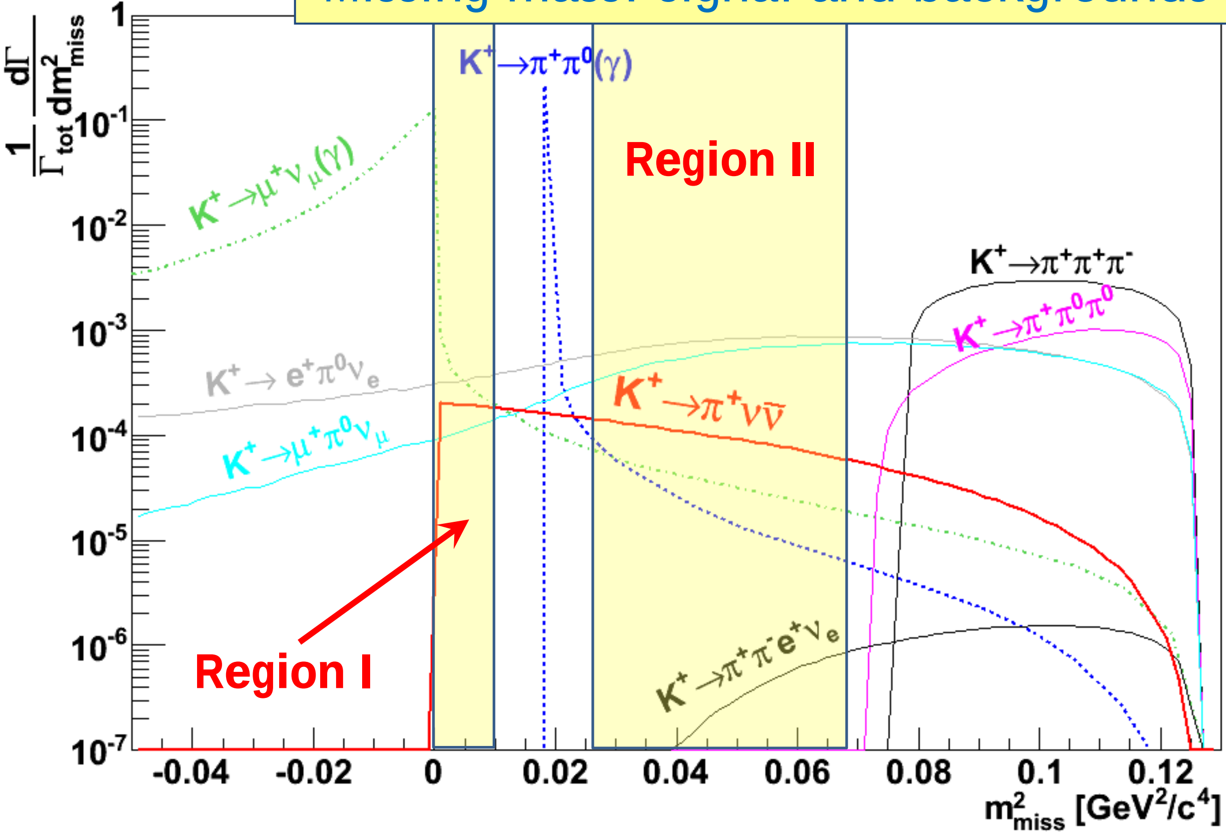
Decay signature: high momentum K^+ (75GeV/c) → low momentum π^+ (15–35 GeV/c).

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

Missing mass: signal and backgrounds



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**.

$K_{\pi\nu\nu}$ measurements worldwide

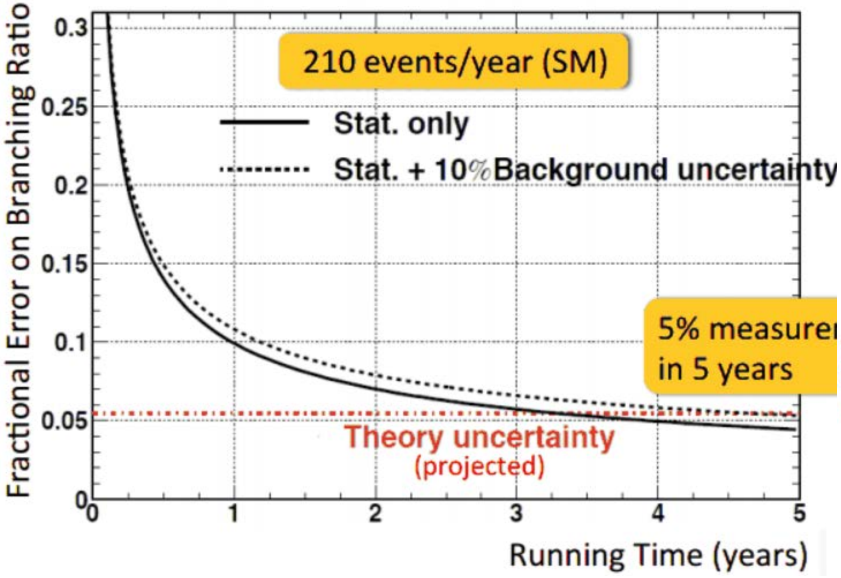
ORKA @ FNAL Main Injector (K^+):

- Builds on BNL stopped-kaon technique.
- Expect **~100** times higher sensitivity.
- Goal: **O(1000)** SM **$K^+\to\pi^+\nu\nu$** events.
- Fits inside the CDF solenoid.
- Re-use CDF infrastructure.

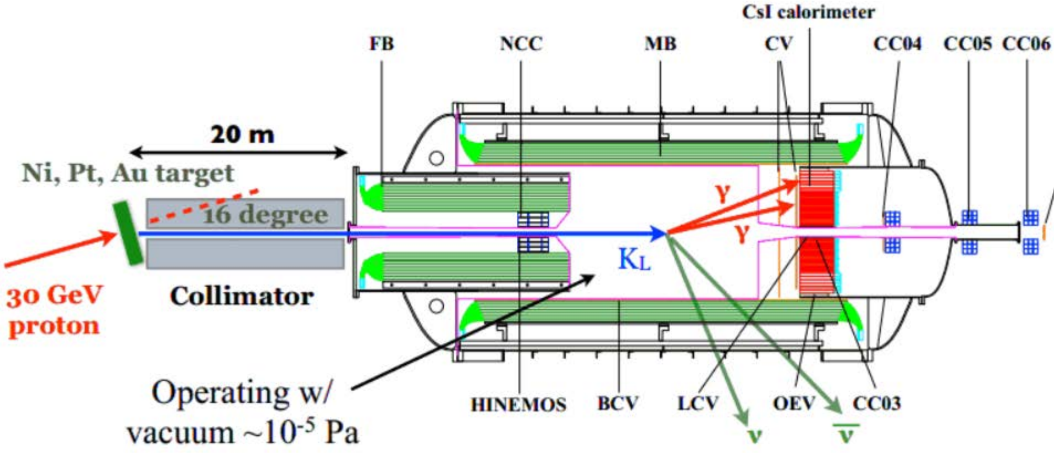
KOTO @ J-PARC (K_L):

- Builds on KEK E391a technique.
- E391a: **$BR<6.8\times10^{-8}$** @ 90%CL.
- Expect **$\sim10^3$** times higher sensitivity.
- Goal: **~3** SM **$K_L\to\pi^0\nu\nu$** events.
- Data taking: **2013–2017**.
- Possible step 2: **~100** SM events.

ORKA expected sensitivity



"Two photons + nothing"



Lepton Flavour and Lepton Number Violation

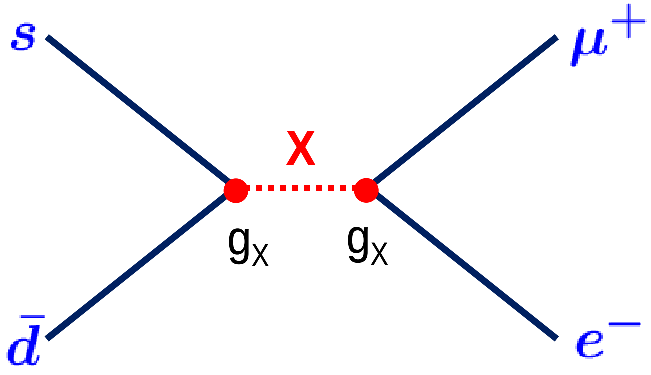
LFV in K decays

Kaons: historically competitive in searches for LFV phenomena

- Copious production: high statistics.
- Simple decay topologies: clean experimental signatures.
- Source of tagged π^0 via $K^+\to\pi^+\pi^0$, $K_L\to3\pi^0$, … :
  best limits for LFV π^0 decays.

High NP mass scales accessible for tree-level contributions

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



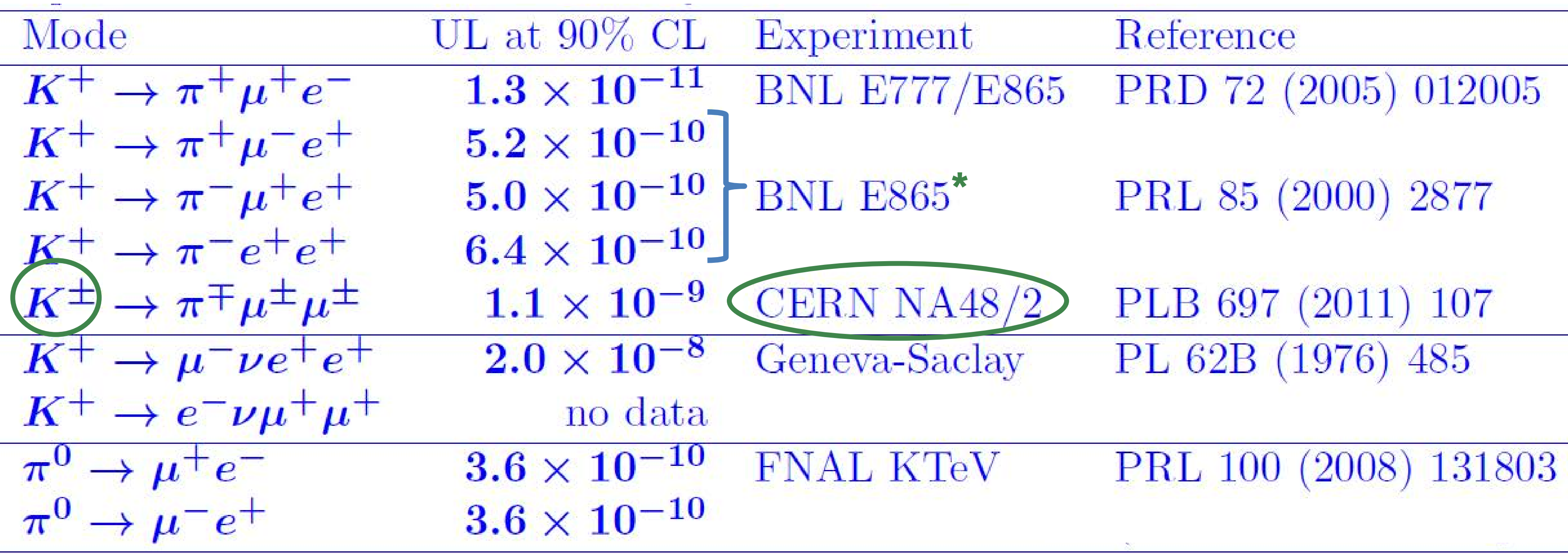
Dimensional argument:

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

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

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

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}		
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}		
$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	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}		

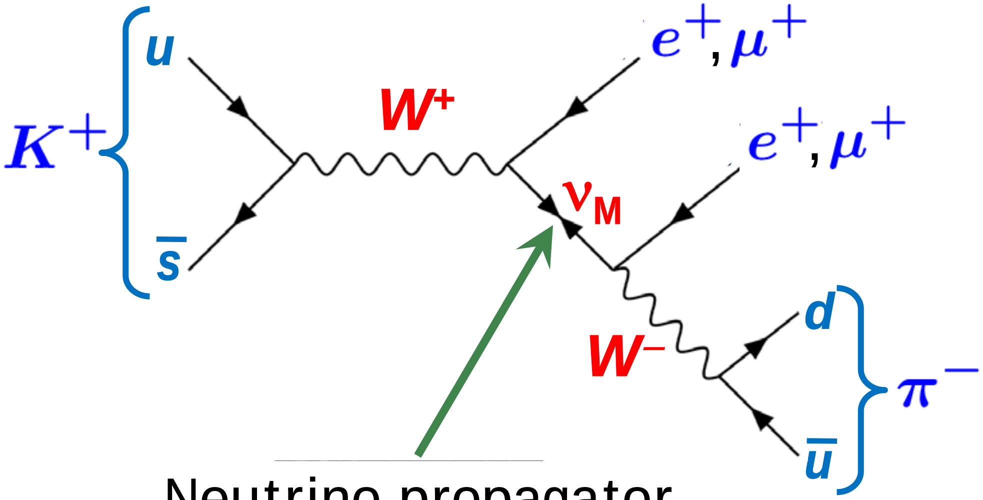
* CERN NA48/2 sensitivities for these 3 modes are similar to those of BNL E865

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;
- ❖ 2014 run alone: competitive for some modes (e.g. $K^+\to\pi^-\mu^+\mu^+$).

Sensitivity to Majorana neutrino

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



Neutrino propagator

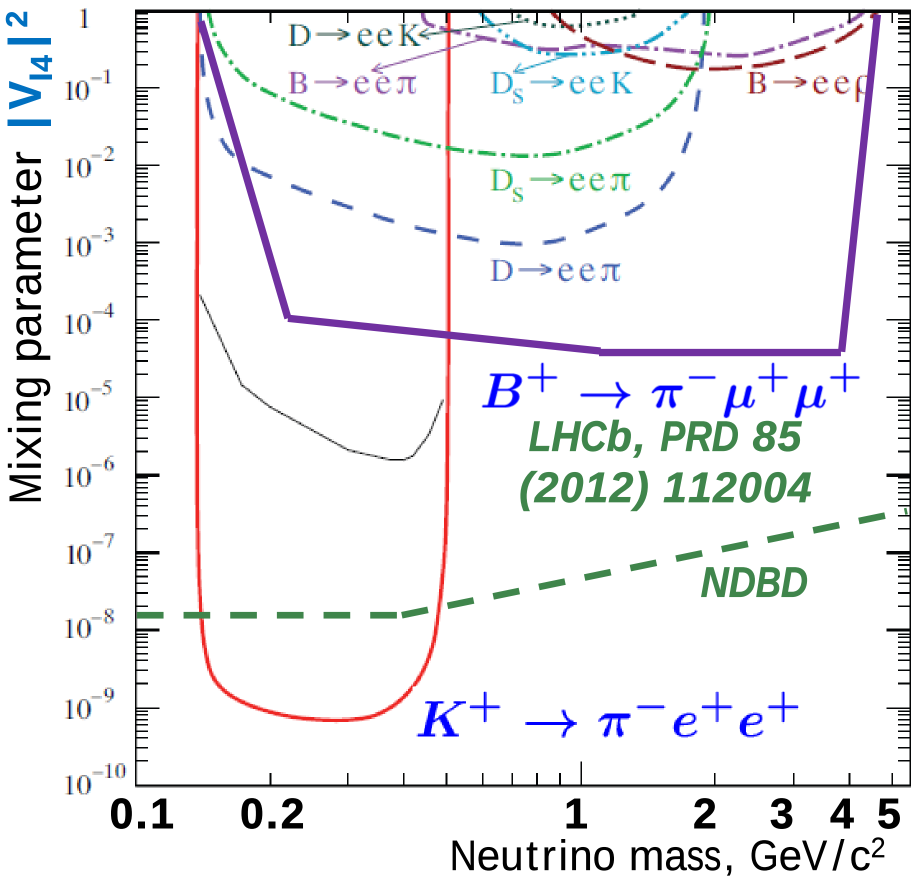
$$\frac{1}{q^2 - m_\nu^2}$$

→ resonant enhancement for

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

Littenberg and Shrock, PLB491 (2000) 285

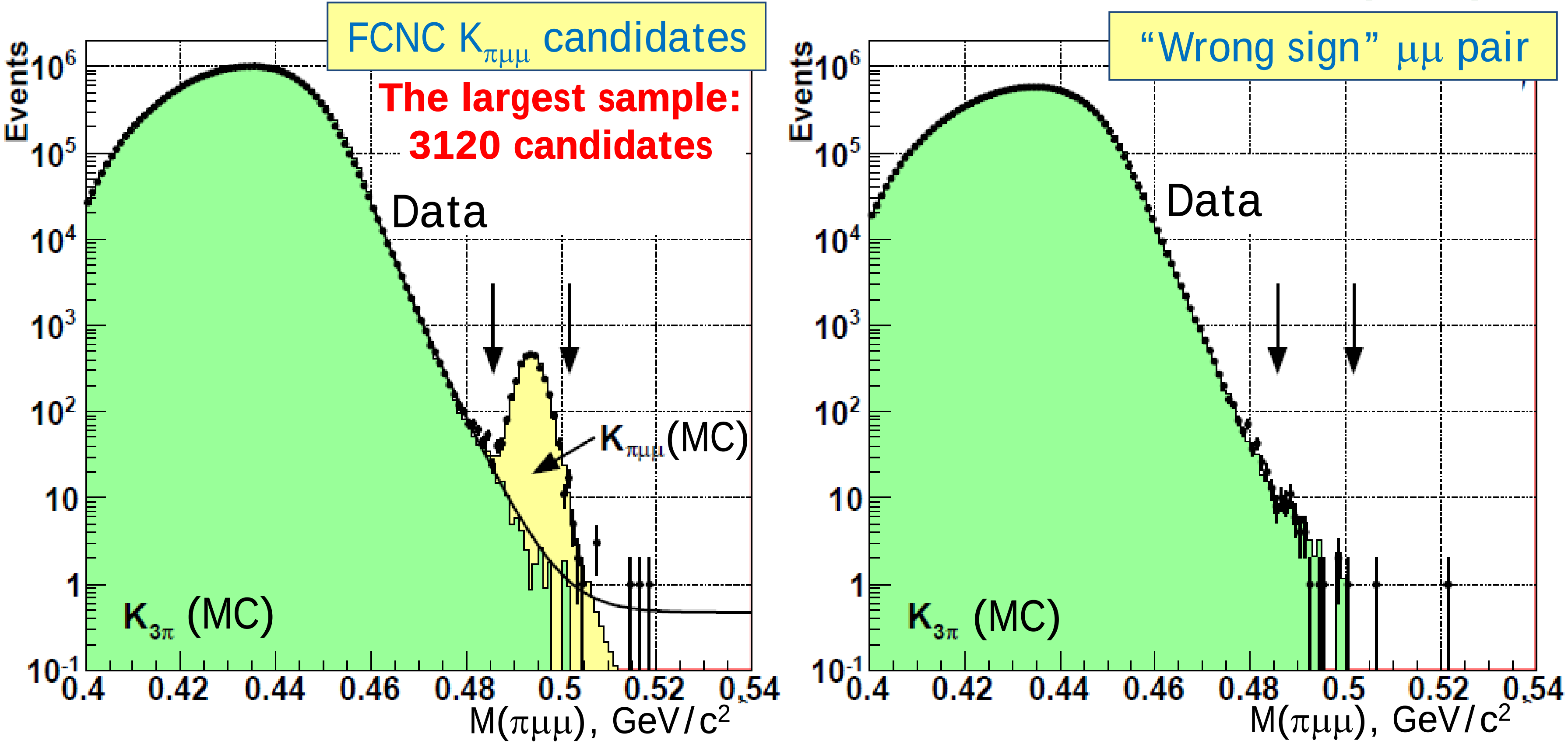
Majorana neutrino exclusion regions from existing data



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



FCNC $K_{\pi\mu\mu}$ candidates

The largest sample: 3120 candidates

"Wrong sign" $\mu\mu$ pair

N_{data} = 52

$N_{bkg} = 52.6 \pm 19.8_{syst.}$

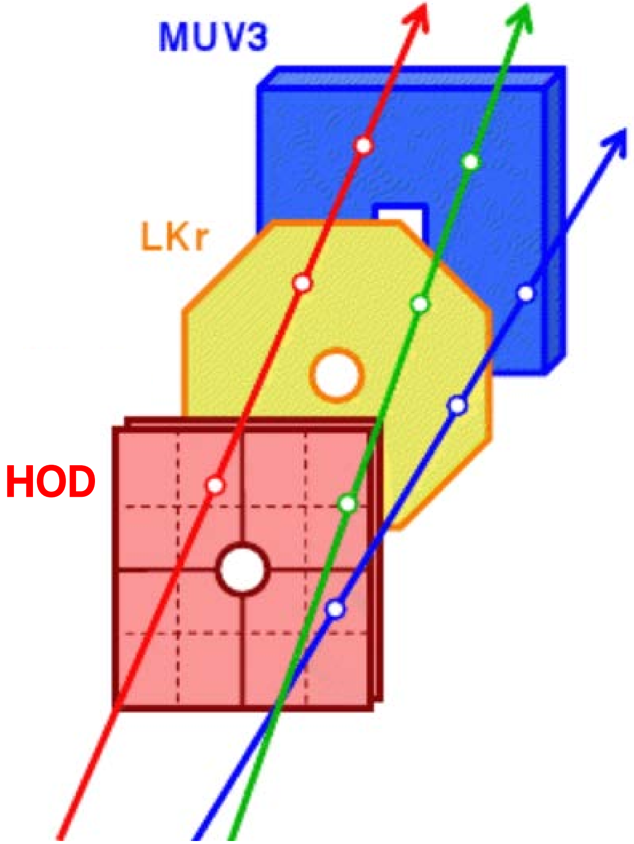
⇒ $\mathcal{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \times 10^{-9}$ **@90% CL**

- 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 **$\sim10^{-10}$**.

NA62: di-lepton trigger

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

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



Available L0 trigger primitives:

- **Q_N**: at least N hodoscope quadrants;
- **$LKR_N(x)$**: at least N LKr clusters with energy E>x GeV;
- **MUV_N**: hits in at least N MUV3 pads;
- **RICH** hit multiplicity.

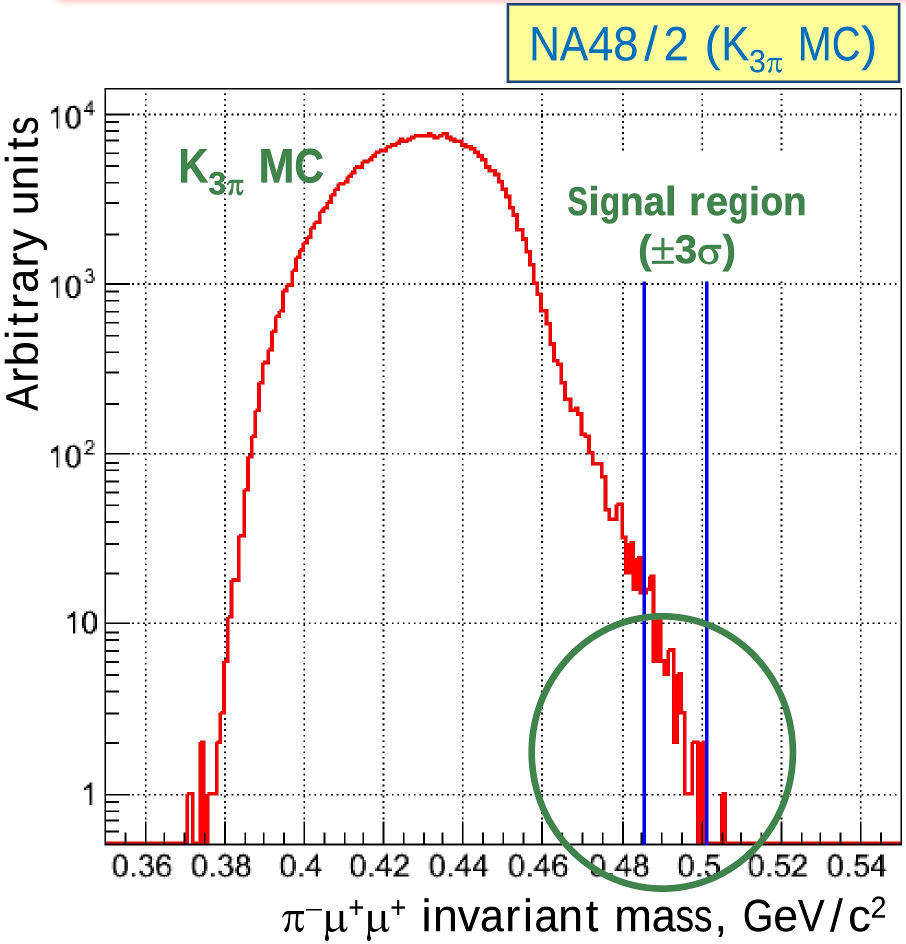
Possible L0 triggers for LFV searches:

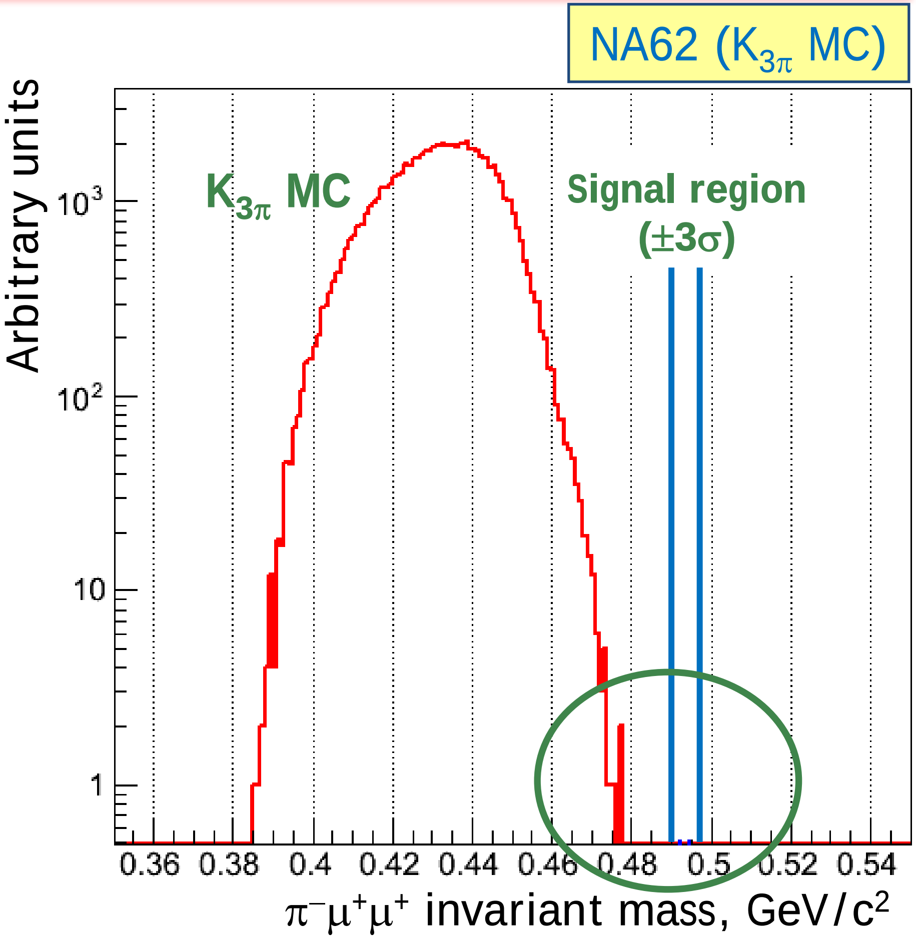
ee pair: **Q_2** × **$LKR_2(15)$**
μe pair: **Q_2** × **$LKR_1(15)$** × **MUV_1**
μμ pair: **Q_2** × **MUV_2**

Total lepton pair L0 rate (dominated by **$K^+ \to \pi^+\pi^+\pi^-$**): **F = few × 10 kHz**

→ *Charge-blind lepton pair collection is feasible*

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





NA48/2: $K_{3\pi}$ background to $K_{\pi\mu\mu}$ due to $\pi^{\pm}\rightarrow\mu^{\pm}\nu$ 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/c^2**)

Rare π^0 decays

Dark photon: experimental status

M.Pospelov, PRD80 (2009) 095002

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

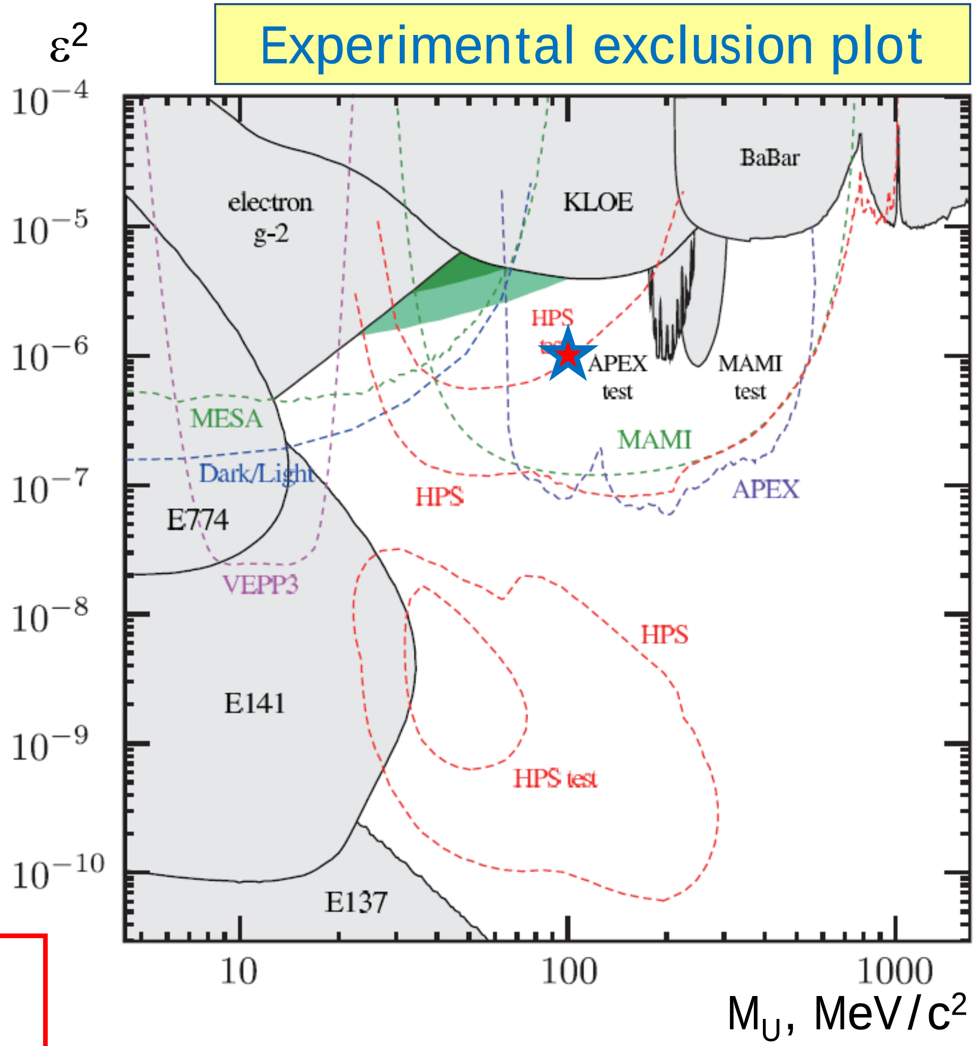
A new light vector boson: the **dark photon**.

Possible parameters:
mixing parameter: **$\varepsilon \sim \alpha/\pi \sim 10^{-3}$**,
DP mass: **$M_U \sim \varepsilon M_Z \sim 100$ MeV/c^2**.

Can explain some astrophysical observations as well as the muon **g–2** anomaly.

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

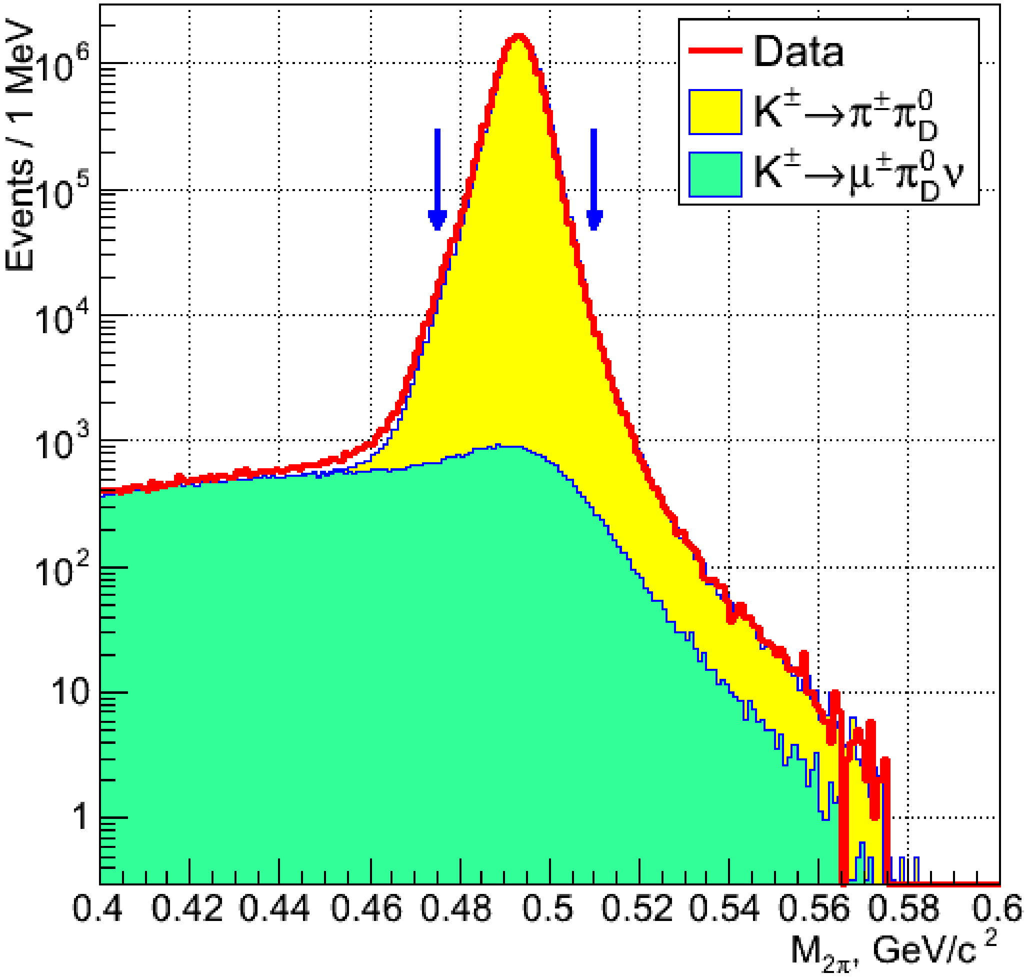
Experimental exclusion plot



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

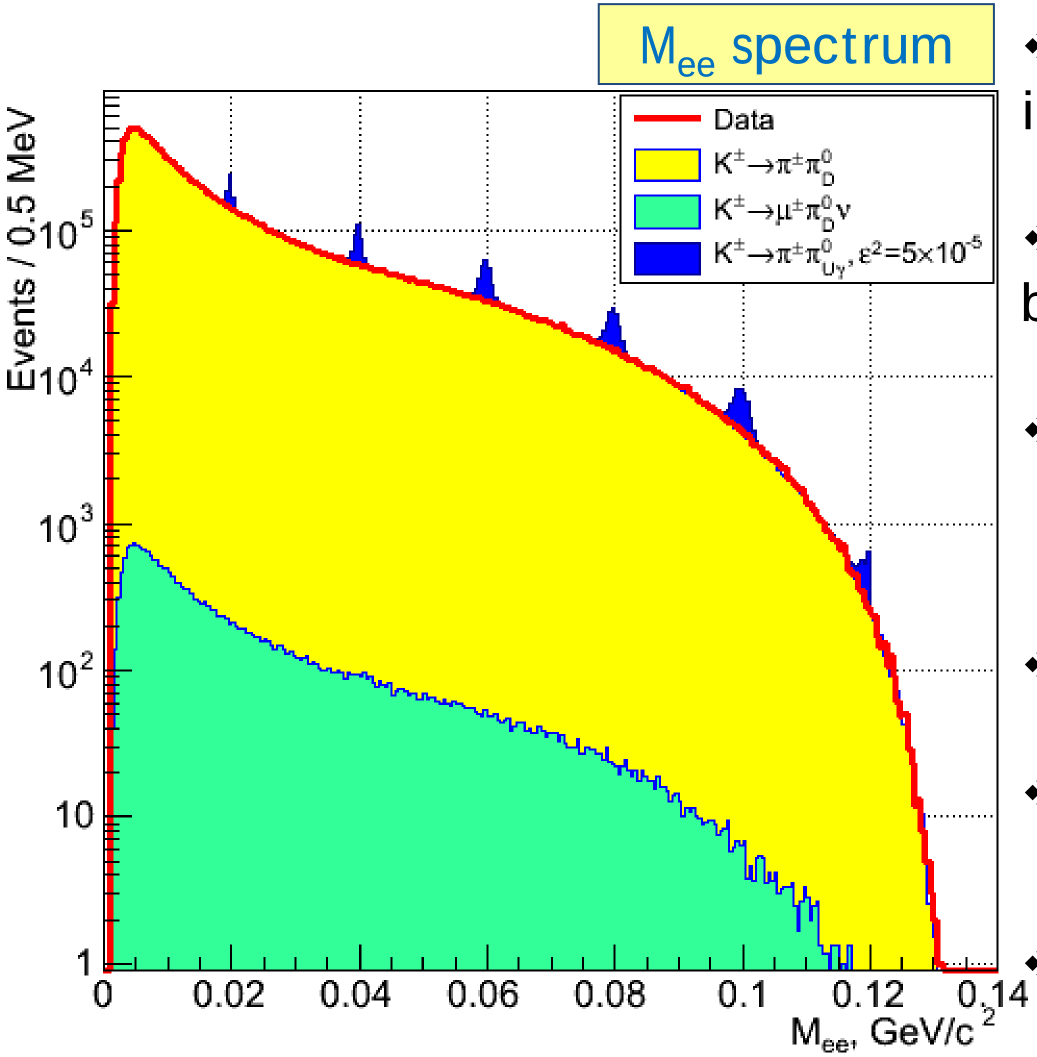
NA48/2: $\pi^0_D \to e^+e^-\gamma$ sample

$\pi^\pm\pi^0_D$ mass spectrum



- ❖ An **existing data sample** collected in 2003–2004 with a 3-track trigger. Trigger efficiency: **~98%**.
- ❖ Large sample of tagged π^0_D decays: **~2×10⁷** $K^\pm \to \pi^\pm\pi^0_D$.
- ❖ Further π^0_D samples available from $K^\pm \to \pi^0_D l^\pm \nu$ decays.
- ❖ Search for $\pi^0 \to U\gamma$, $U \to e^+e^-$. $BR(U \to e^+e^-)=1$ for $M_U<2M_\mu$.

NA48/2: π^0_D M_{ee} spectrum



M_{ee} spectrum

π^0 form-factor measurement on-going

❖ Mean dark photo free path **~1mm**: identical signatures $\pi^0 \to U\gamma$ and π^0_D.

❖ Sensitivity to dark photon limited by $K_{2\pi D}$ background fluctuation.

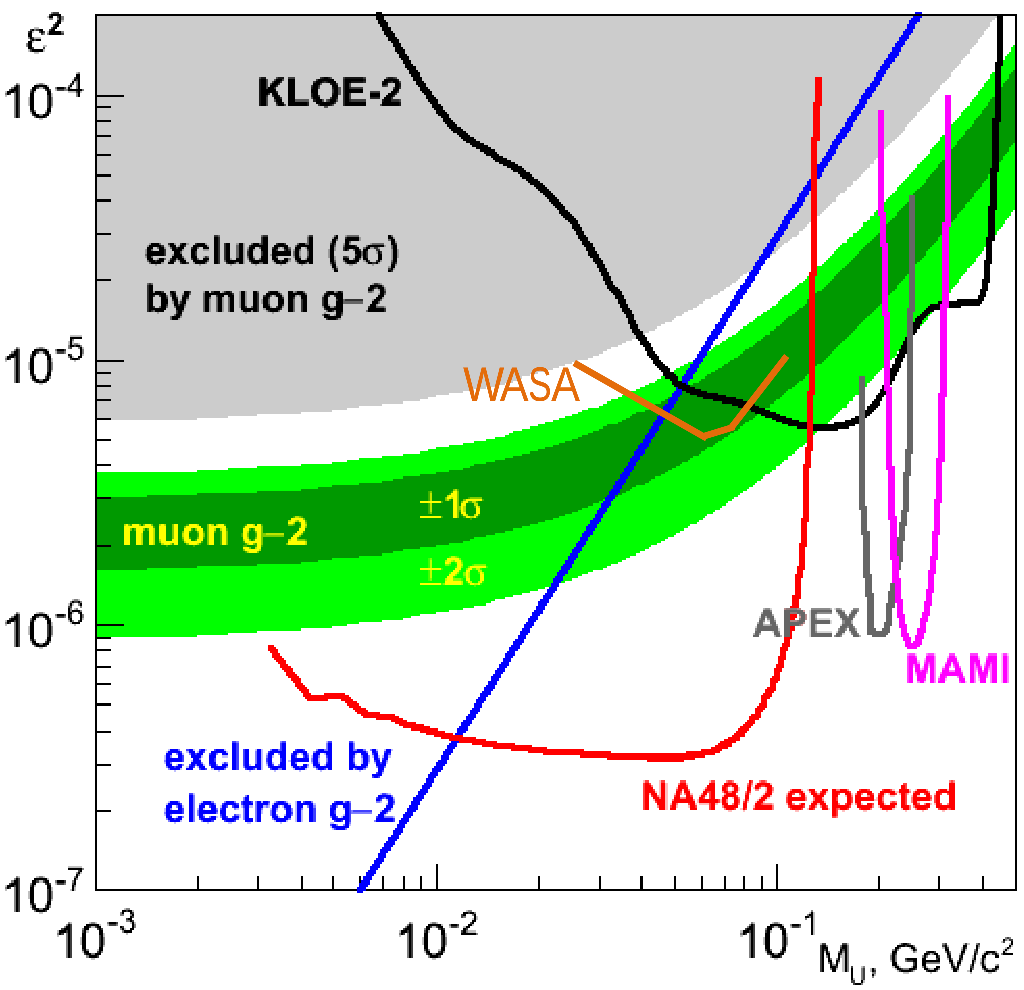
❖ **Upper limit** ~ **(Kaon Flux)$^{-1/2}$** × **(Acceptance)$^{-1/2}$** × **(M_{ee} resolution)$^{-1/2}$**

❖ Flux **~2×10^{11}**, acceptance **~5%**.

❖ Spectrometer resolution: **$\delta M_{ee} \approx 0.012 M_{ee}$** (**<1.4 MeV/c**).

❖ **M_{ee}** resolution can be improved using the **$(P_K - P_\pi)^2$** constraint.

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 [$\phi \rightarrow \eta e^+e^-$]:
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 preliminary [$\pi^0 \rightarrow \gamma e^+e^-$]:
Adlarson et al., arXiv:1304.0671

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

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 arXiv:1304.0671	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 $\pi^0 \to SS$, $S \to \gamma\gamma$
$\pi^0 \to \nu\bar{\nu}$	$BR < 2.7 \times 10^{-7}$	E949 @ BNL PRD72 (2005) 091102	RH neutrinos, LFV

NA62: “neutral” π^0 decays

$\pi^0 \to 3\gamma$

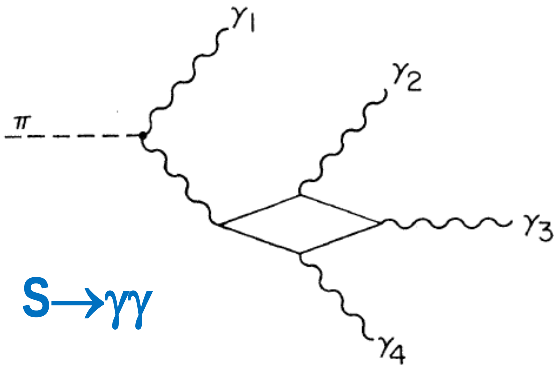
C-violating decay: **$BR_{SM} \sim 10^{-31\pm6}$** *[Dicus, PRD12 (1975) 2133]*

NP not beyond the corner, e.g. non-commutative QED: **$BR_{NP} \sim 10^{-21}$**
[Grosse, Liao, PLB520 (2001) 63]

Experiment: **$BR_{exp} < 3.1\times10^{-8}$** ($\pi^-$ stopped at proton target)
[PRD38 (1988) 2121]

$\pi^0 \to 4\gamma$

SM: dominated by QED electron-loop,
$BR_{SM} = (2.6\pm0.1)\times10^{-11}$
[Bratkovskaya et al., PLB359 (1995) 217]



Deviation: e.g. NP involving light scalars, **$\pi^0 \to SS$**, **$S \to \gamma\gamma$**
$BR_{exp} < 2\times10^{-8}$ *[PRD38 (1988) 2121]*

NA62 may improve these limits to **$BR \sim 10^{-10}$**,
however a dedicated trigger has to be implemented

NA62: the invisible π^0 decay

For a given flavour of massive neutrino (**$m_\nu < m_\pi/2$**),

$$\mathcal{B}(\pi^0 \to \nu\bar{\nu}) \approx 3 \times 10^{-8} k (m_\nu/m_\pi)^2 \sqrt{1 - 4(m_\nu/m_\pi)^2}$$

$$k = \begin{cases} 1, \text{ Dirac type} \\ 2, \text{ Majorana type} \end{cases}$$

From ν_τ mass: **$m_{\nu\tau} < 18.2$ MeV/c²**, $\mathcal{B}(\pi^0 \to \nu\bar{\nu}) < 5 \times 10^{-10}$

[ALEPH, EPJ C2 (1998) 395]

From primordial nucleosynthesis: $\mathcal{B}(\pi^0 \to \nu\bar{\nu}) < 3 \times 10^{-13}$

[Lam, Ng, PRD44 (1991) 3345; see also Natale, PLB258 (1991) 227]

Possible BR enhancement due to NP with RH neutrino states

Direct experimental limit: **$BR < 2.7 \times 10^{-7}$**,
by-product of the BNL $K^+ \to \pi^+ \nu\bar{\nu}$ analysis *[PRD72 (2005) 091102]*

NA62 experimental signature is similar to $K^+ \to \pi^+ \nu\bar{\nu}$.
The limit can be improved to **$BR \sim 10^{-10}$**.

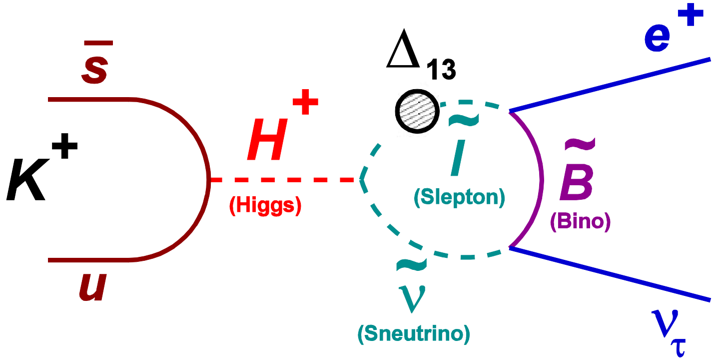
Selected recent results, ongoing analyses

$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ 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

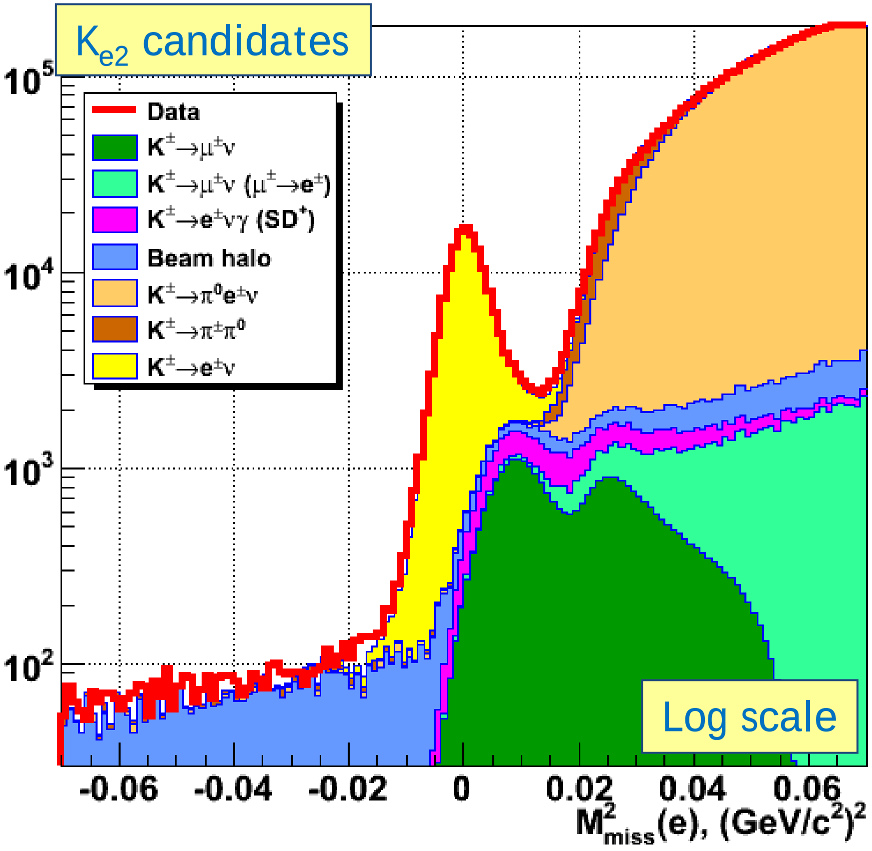
Masiero, Paradisi and Petronzio, PRD 74 (2006) 011701, JHEP 0811 (2008) 042

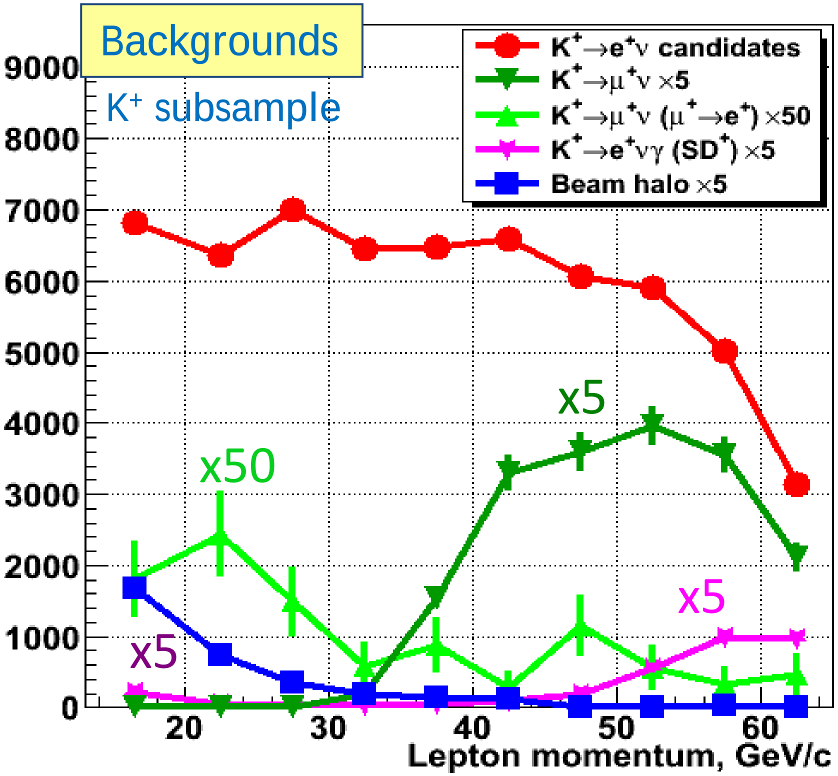
$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right] \Longrightarrow$$

sensitive to slepton mixing

- MSSM: **~1%** effect possible
  Girrbach and Nierste, arXiv:1202.4906
- However limited by the recent $B_{(S)} \to \mu^+\mu^-$ 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





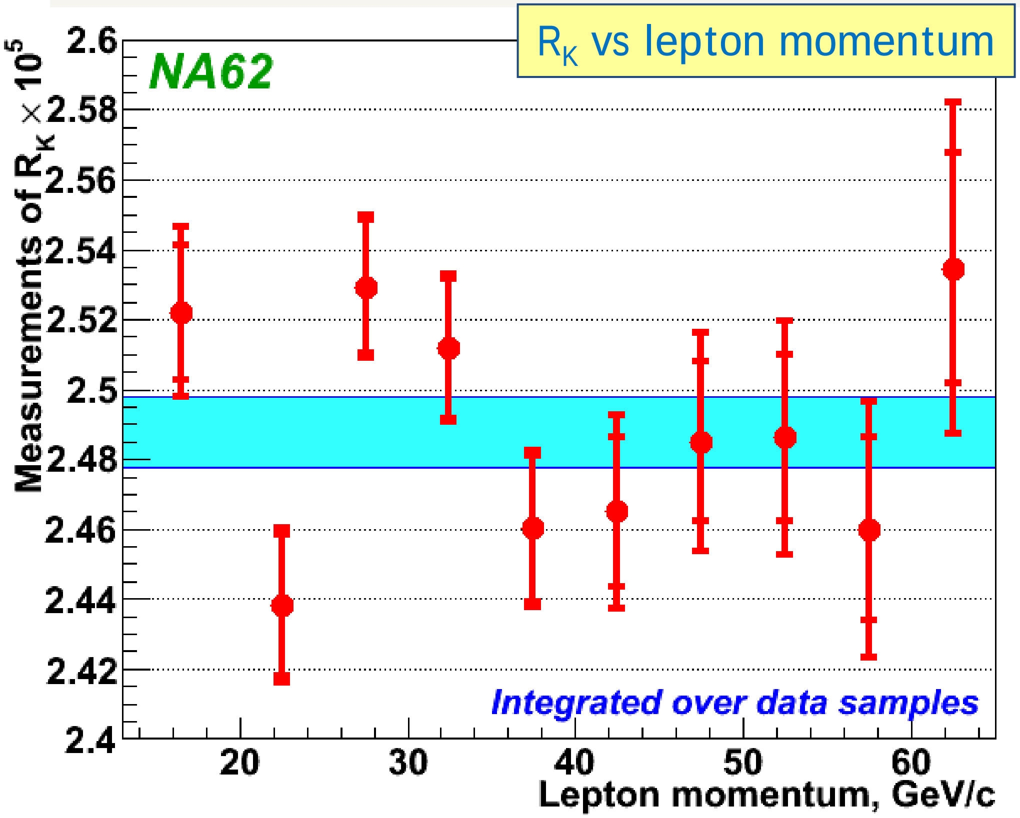
145,958 $K^\pm \to e^\pm \nu$ candidates.
Background: $B/(S+B) = (10.95 \pm 0.27)\%$.
Electron ID efficiency: $(99.28 \pm 0.05)\%$.

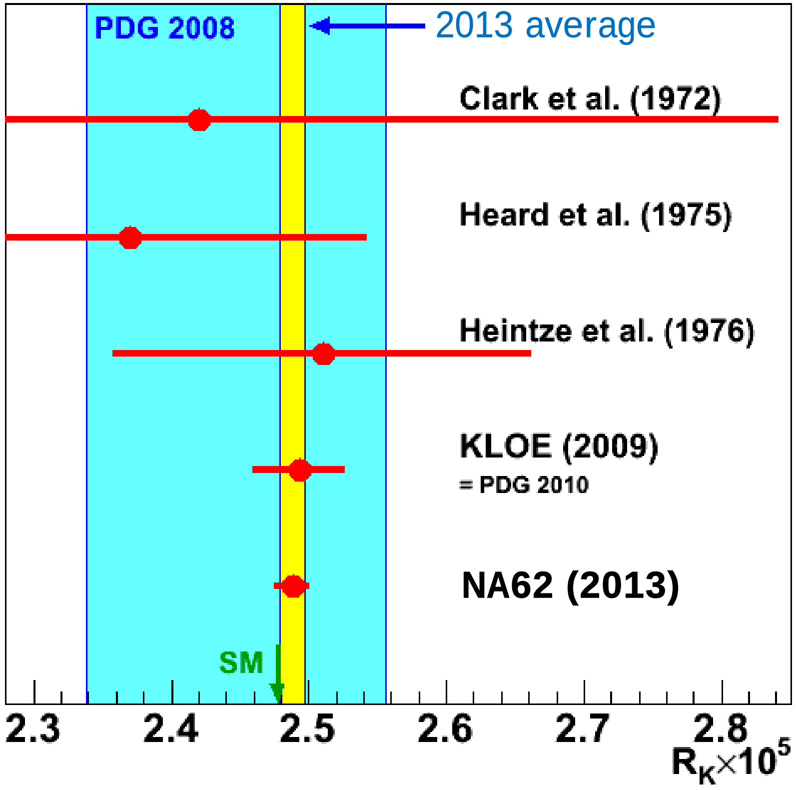
Source	B/(S+B)
$K_{\mu 2}$	$(5.64 \pm 0.20)\%$
$K_{\mu 2}$ ($\mu \to e$)	$(0.26 \pm 0.03)\%$
$K_{e2\gamma}$ (SD)	$(2.60 \pm 0.11)\%$
$K_{e3(D)}$	$(0.18 \pm 0.09)\%$
$K_{2\pi(D)}$	$(0.12 \pm 0.06)\%$
Opposite sign K	$(0.04 \pm 0.02)\%$
Beam halo	$(2.11 \pm 0.09)\%$
Total	$(10.95 \pm 0.27)\%$

NA62-R_K final result

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

PLB 719 (2013) 326



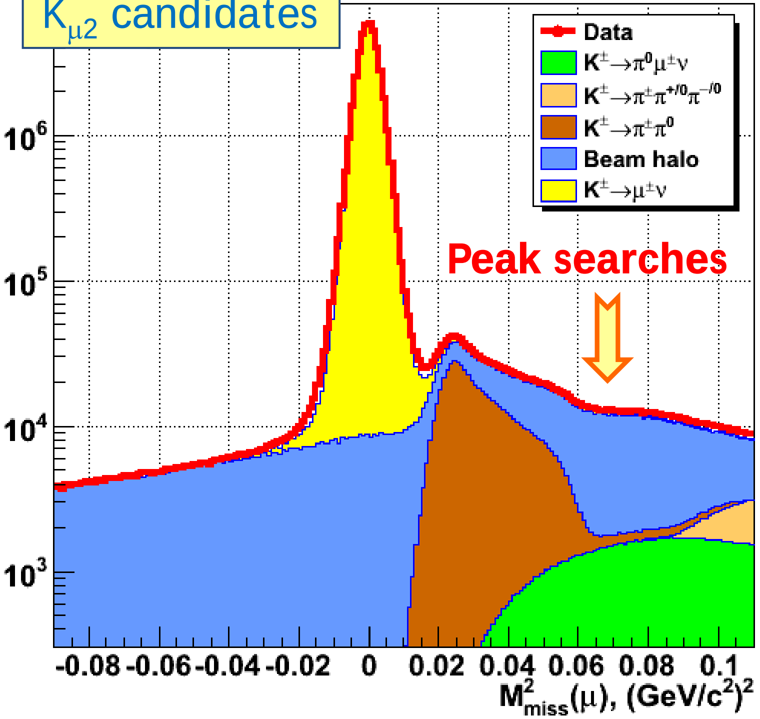


World average	$R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
2013	2.488±0.009	0.4%

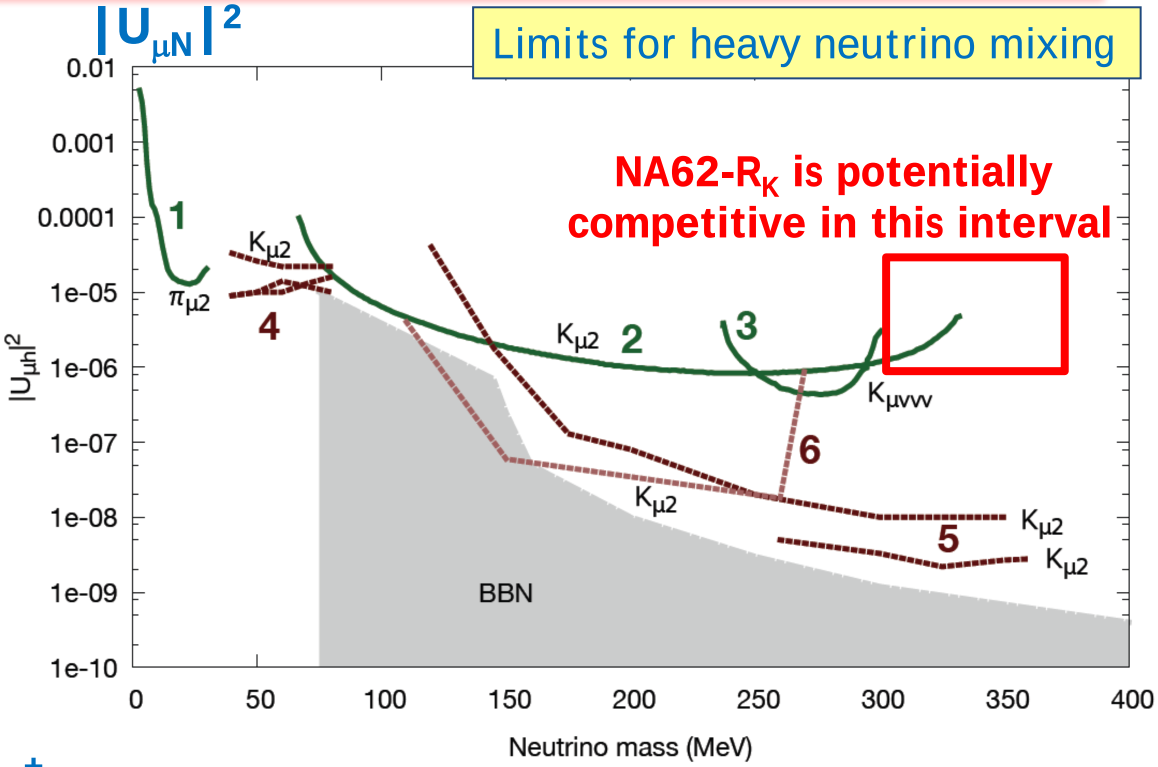
NA62 prospects:
improve the uncertainty
by a factor ~2

$K_{\mu 2}$: heavy sterile neutrinos

$K_{\mu 2}$ candidates



Limits for heavy neutrino mixing



NA62-R_K subsample: 18.0M $K^+ \to \mu^+ \nu_\mu$.

→ Search for heavy sterile neutrino: $K^+ \to \mu^+ N$.

- NA62-R_K UL if no backgrounds:
  $|U_{\mu N}|^2 < 10^{-7}$, 100 MeV/c^2 < M_N < 380 MeV/c^2.
- Sensitivity is limited by background fluctuation (mainly beam halo).
- NA62-R_K is competitive at high M_N.

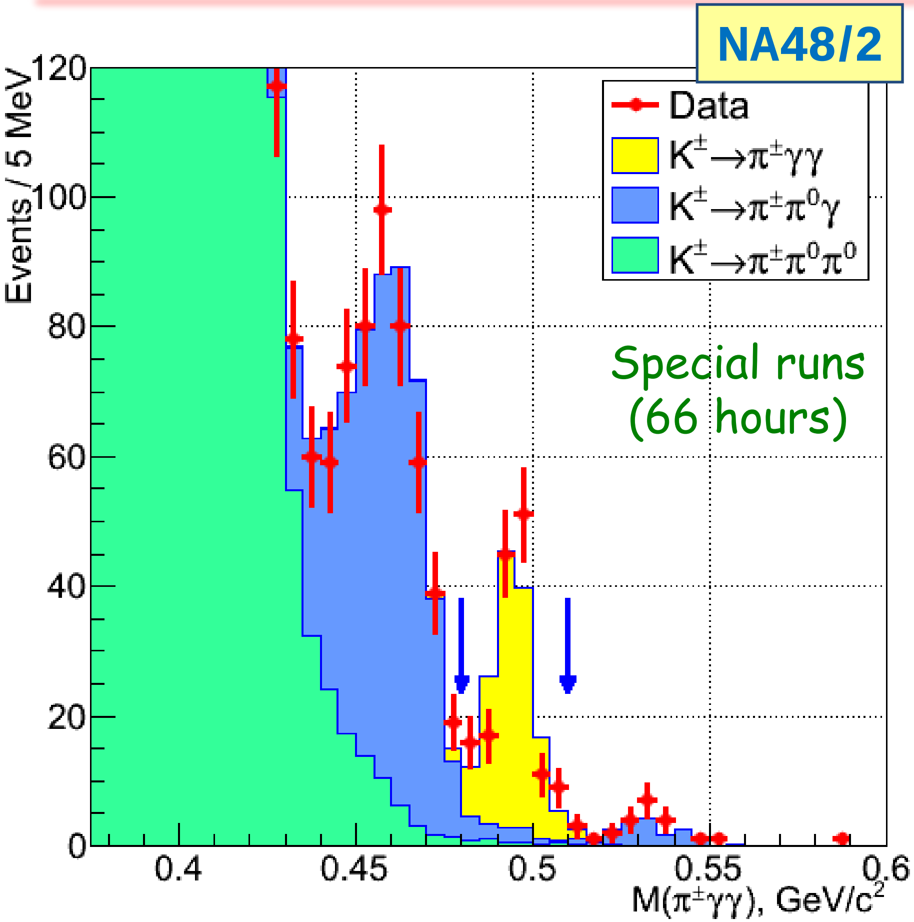
Peak searches (long-lived ν_h)

1. PSI, PLB 105 (1981) 263.
2. KEK, PRL 49 (1982) 1305.
3. LBL, PRD 8 (1973) 1989.

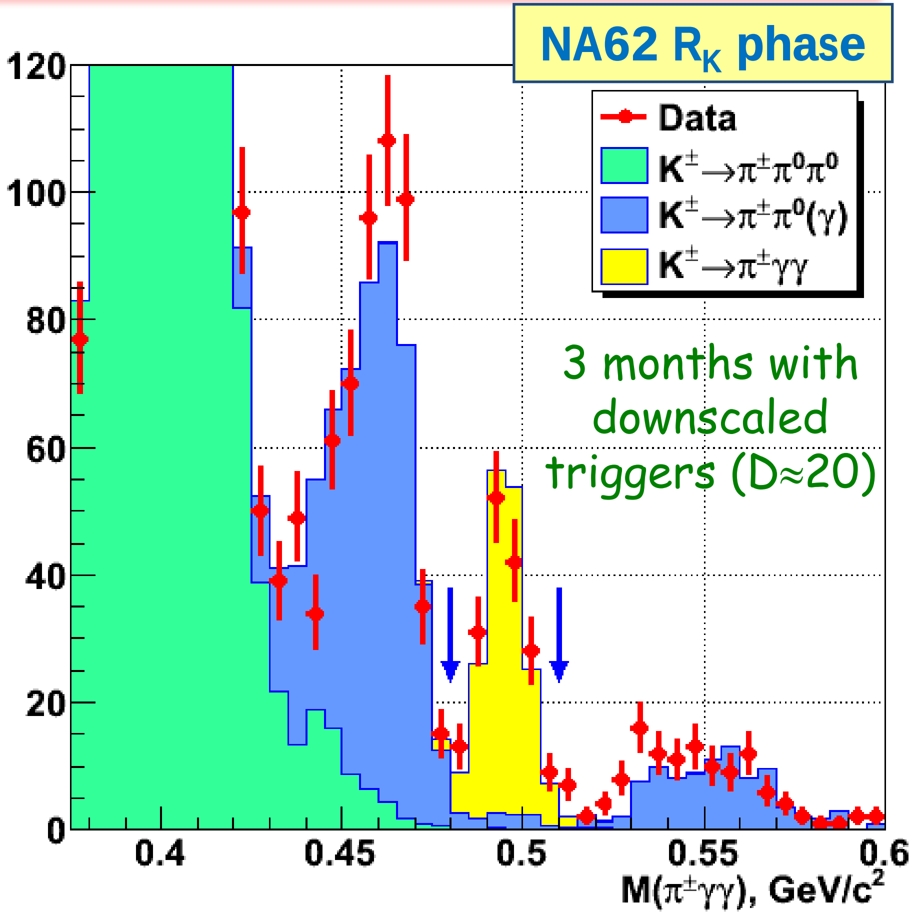
Decay searches (short-lived ν_h)

4. ISTRA+, PLB 710 (2012) 307.
5. CERN-PS191, PLB 203 (1988) 332
6. BNL-E949, preliminary

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


NA48/2

Special runs (66 hours)

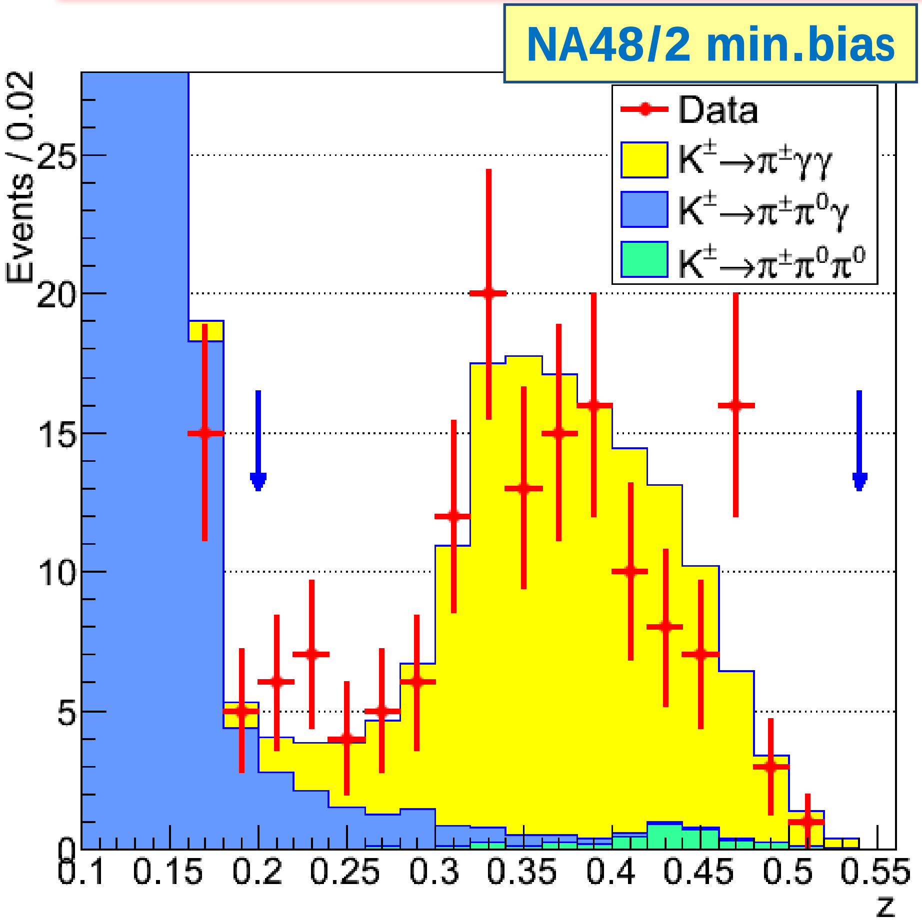

NA62 R_K phase

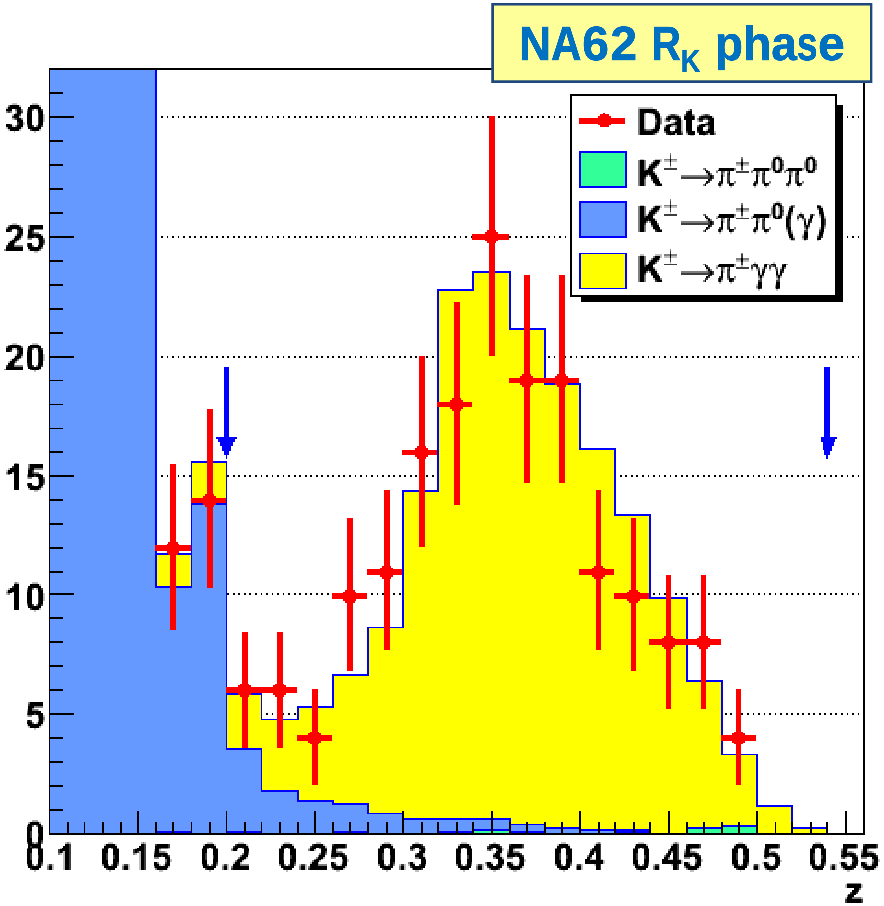
3 months with downscaled triggers (D≈20)

$K_{\pi\gamma\gamma}$ 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

$K_{\pi\gamma\gamma}$ candidates	175
$K_{2\pi(\gamma)}$ background	11.1±1.0
$K_{3\pi}$ background	1.3±0.3
$K_{\pi\gamma\gamma}$ signal	163±13

Fits to ChPT description





→ Data support the ChPT prediction: cusp at di-pion threshold

NA48/2 final result: **$BR_{MI}(z>0.2) = (0.877 \pm 0.087_{stat} \pm 0.017_{syst}) \times 10^{-6}$**

Measurement of the ChPT parameters: publications in preparation

Summary

- ❖ **NA48/2** (2003–2004): a multi-purpose $K^{\pm}$ experiment.
  - ✓ $K^{\pm}$ physics at a new precision level (15 PL, EPJ papers so far);
  - ✓ $K^{\pm}$ and π^0 rare decay analyses are on-going.

- ❖ **NA62-R_K** (2007–2008): minimum bias electron trigger.
  - ✓ Lepton Universality test at a 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 neutrinos: analyses on-going.

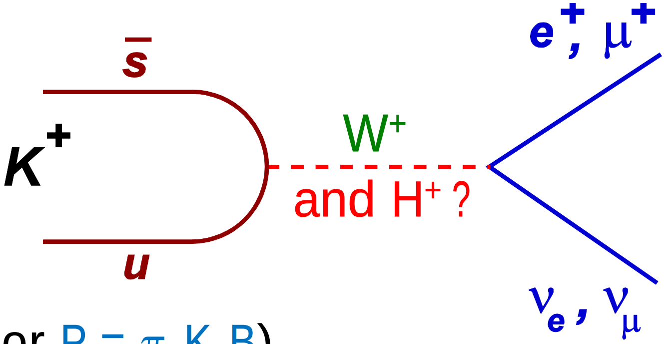
- ❖ **NA62** (construction/commissioning).
  - ✓ expected single event sensitivity for K^+ decays: $\sim10^{-12}$;
  - ✓ preparing for the physics run in 2014 (low intensity);
  - ✓ a diverse physics programme is taking shape;
  - ✓ friends and competitors worldwide (including J-PARC, FNAL).

Spare slides

Leptonic meson decays

Light leptons: SM contribution suppressed by angular momentum conservation

$$\Gamma(P^+ \to l^+\nu) = \frac{G_F^2 M_P M_l^2}{8\pi}\left(1-\frac{M_l^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2$$



Models with 2 Higgs doublets (2HDM-II including SUSY): sizeable charged Higgs (**H±**) exchange contributions.

$$\frac{\Gamma(P^\pm\to\ell^\pm\nu)}{\Gamma^{SM}(P^\pm\to\ell^\pm\nu)} = \left[1-\left(\frac{M_P}{M_H}\right)^2 \frac{\tan^2\beta}{1+\varepsilon_0\tan\beta}\right]^2$$

(for P = π,K,B)

Hou, PRD 48 (1993) 2342;
Isidori, Paradisi, PLB 639 (2006) 499

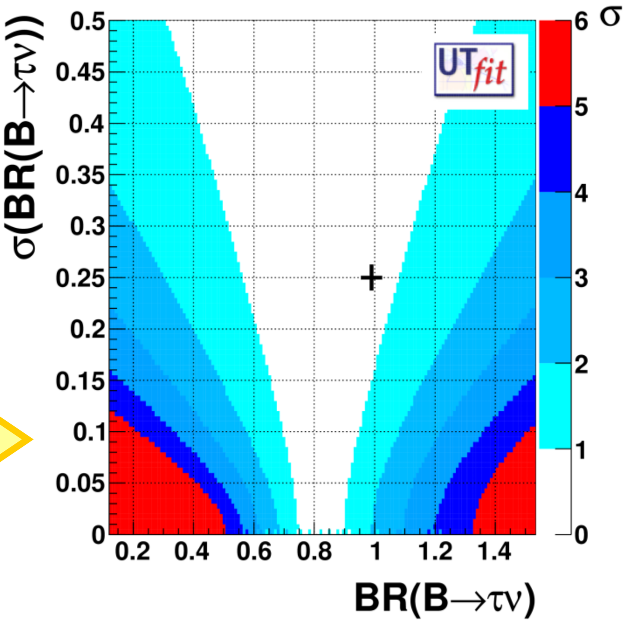
$\pi^+\to l^+\nu$: $|\Delta\Gamma/\Gamma_{SM}| \sim 2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \sim 10^{-4}$
$K^+\to l^+\nu$: $|\Delta\Gamma/\Gamma_{SM}| \sim 2(m_K/m_H)^2 \tan^2\beta \sim 10^{-3}$

… smaller than SM prediction uncertainties (f_P, V_{CKM})

Potentially larger effect in $B^+\to\tau^+\nu$:

Experiment: $BR_{exp}(B^+\to\tau^+\nu) = (0.99\pm0.25)\times10^{-4}$

SM: $BR_{SM}(B^+\to\tau^+\nu) = (0.83\pm0.08)\times10^{-4}$



(UTfit, winter 2013)

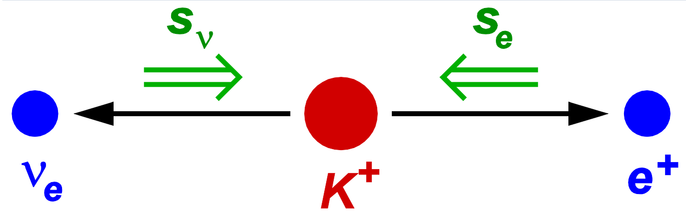
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ in the SM

Lepton Universality test:

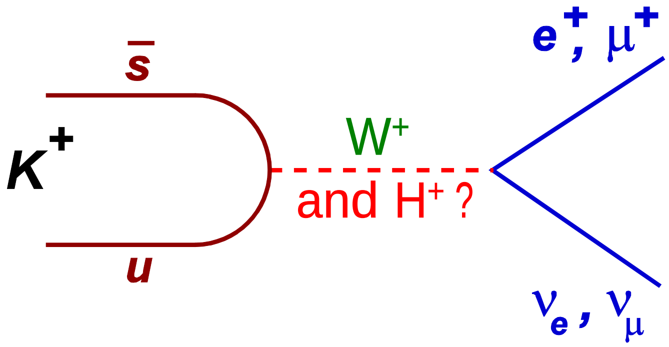
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{\left(1 + \delta R_K^{\mathrm{rad.corr.}}\right)}$$

Helicity suppression: f~10^{-5}

Radiative correction
(well known, few %)



- **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.

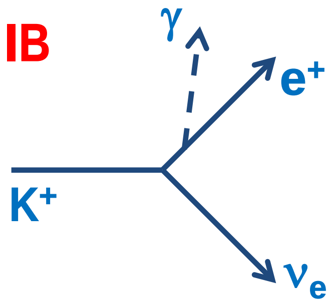


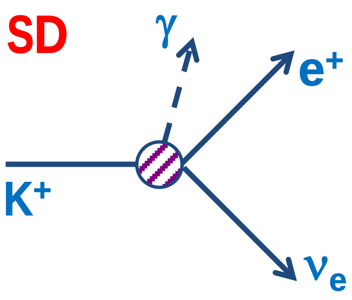
$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano and Rosell, PRL99 (2007) 231801

The radiative $K^\pm\to e^\pm\nu\gamma$ decay

R_K is inclusive of IB radiation by definition.
SD: background.





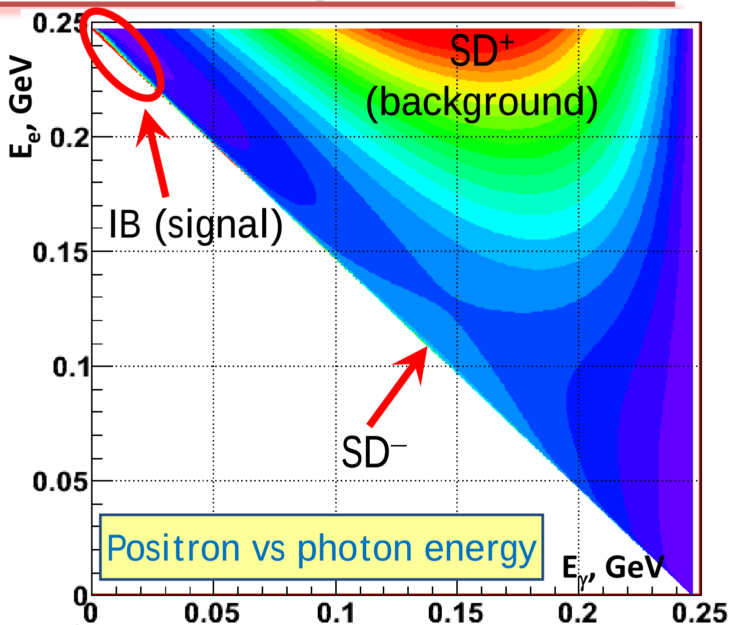
SD component is not helicity suppressed:

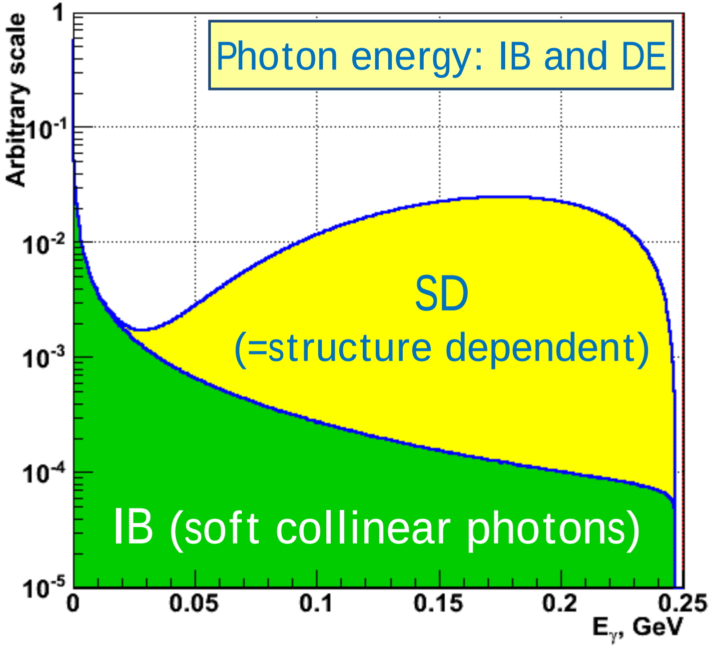
$BR(K^+\to e^+\nu\gamma\ SD) \sim BR(K^+\to e^+\nu)$

Background subtraction uses external input:
KLOE measurement of the form factor leads to
$BR(SD^+) = (1.37\pm0.06)\times10^{-5}$.

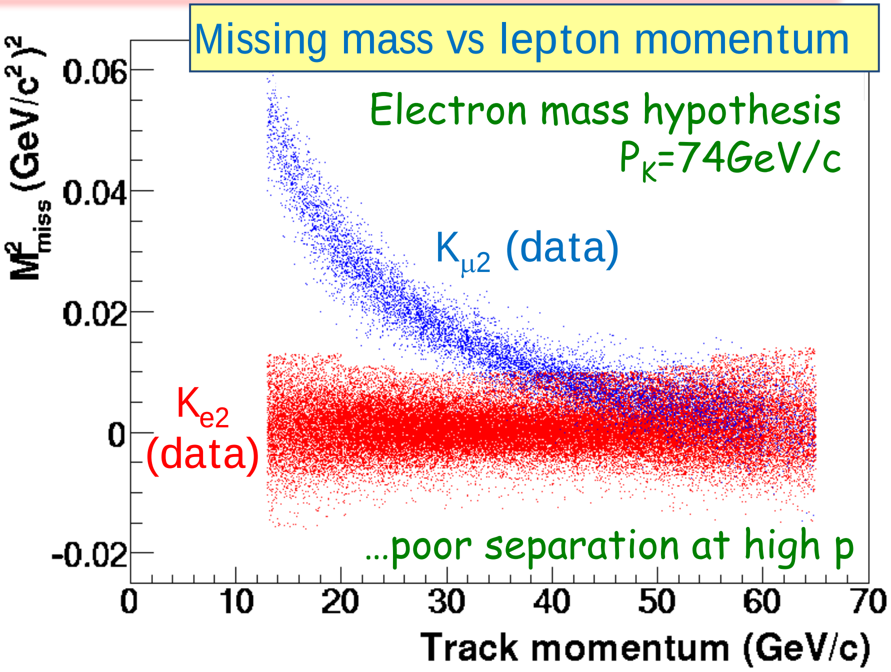
EPJC 64 (2009) 627

Background: **$B/(S+B) = (2.60\pm0.11)\%$**





K_{e2} vs $K_{\mu 2}$ selection



Large common part (topological similarity)

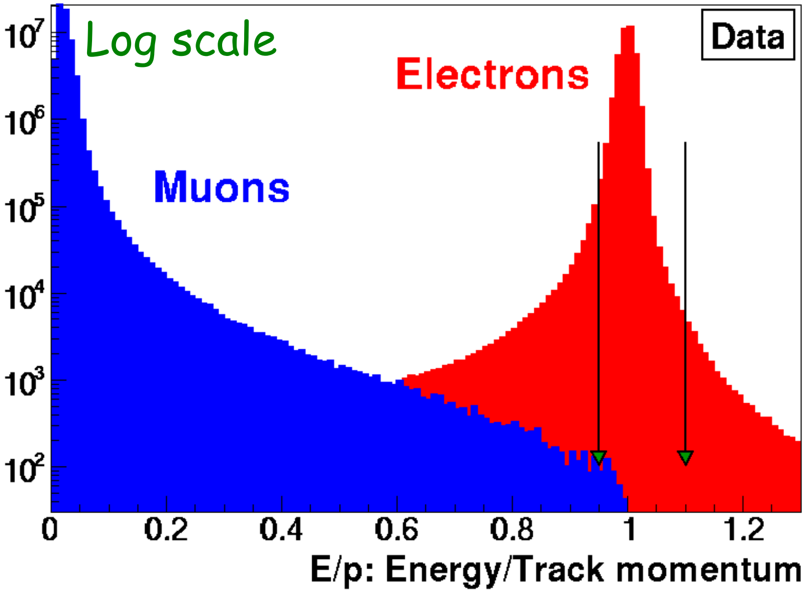
- one reconstructed track (lepton candidate);
- geometrical acceptance cuts;
- K decay vertex: closest approach of lepton track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c<p<65GeV/c.

Kinematic identification

missing mass $\boxed{M^2_{miss} = (P_K - P_l)^2}$

P_K : average monitored with $K_{3\pi}$ decays

→ sufficient $K_{e2}/K_{\mu 2}$ separation at p_{lepton}<30GeV/c



Lepton identification

E/p = (LKr energy deposit/track momentum).

(0.90 to 0.95)<E/p<1.10 for electrons,

E/p<0.85 for muons.

→ powerful $\mu^\pm$ suppression in $e^\pm$ sample (~10^6)