Precision test of the Standard Model with Kaon decays at CERN

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Kaon physics – The landscape

Kaon is the lightest strange particle, studied since 60's to test fundamental properties of nature

The SM @ E ~ M_K appears remarkably simple:

$$L_{SM} = L_{QCD}(m_u = m_d, m_s) + L_{QED} + L_{IB}(m_u - m_d) + L_{ew}$$

- only 2 parameters in L_{QCD}: m_s and $m_d \sim m_u \sim (m_d+m_u)/2$
- L_{QED} and L_{IB} isospin-breaking: often neglected, but add 3rd parameter
- L_{ew} is the link to physics at electroweak scale
  - breaks many symmetries: P, CP, flavor

Kaons reach the highest sensitivity to CPT violation, QM tests

Competitive with B decays to test NP in LFV or CPV transitions

K physics – past, present, future

Precise study of low-energy L_{QCD}, including L_{QED} and L_{IB}:

Strong $\pi\pi$ phase shifts from non-leptonic K decays, e.g., Ke4 see P. Cenci's talk

Radiative decays, testing contributions from NLO ChPt, see F. Costantini's talk

30 years of precision study of L_{ew}:

$|\varepsilon_K| = (2.221 \pm 0.006)10^{-3}$, significant CKM constraint (progress on B_K, now @ 1.3%!)

$R(\varepsilon'/\varepsilon) = (16.8 \pm 1.4)10^{-4}$, will be a NP test soon, w lattice progress to beat uncertainty from cancellations btw e.m. and strong penguins

Gauge universality test: CKM unitarity satisfied @ $< 10^{-3}$ level from main K decays

LFV search (test H^+ exchange) from RK = Ke2/Kμ2 at NA62, this talk

Lepton number violation test from $K^{\pm} \to \pi \mu^{\pm}\mu^{\pm}$ at NA48/2, this talk

The future towards high-intensity/sensitivity frontier, this and G. Ruggiero talks

LFV – Search for NP signals from K decays

Decades searching for LFV transitions, forbidden/ultra rare in SM

Sensitivity ~ up by × 10^2 per decade, limits due to statistics more than background

NP with < ~100 TeV mediator masses ruled out (some model dependence: Technicolor, SUSY)

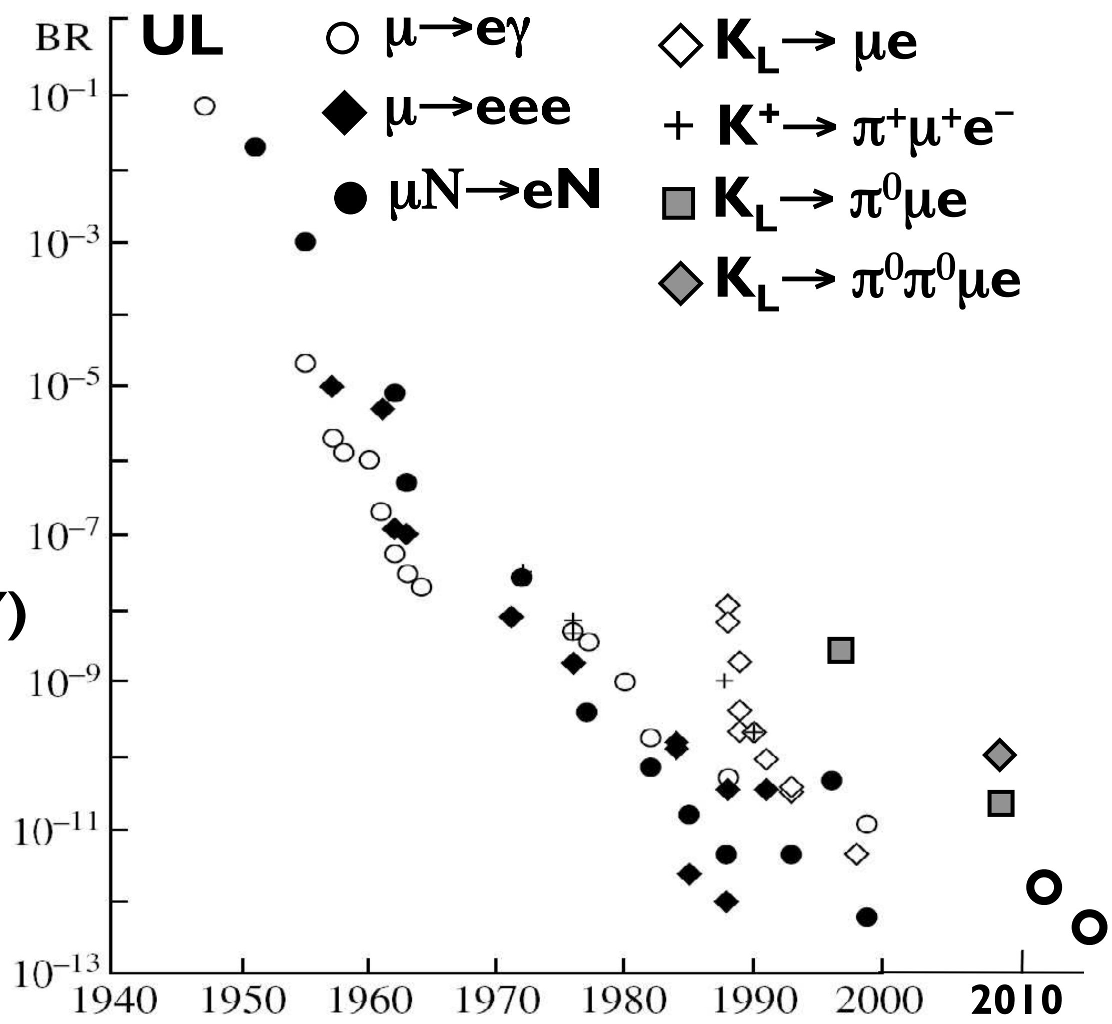
Compare with:

$\mu \to e\gamma$ @ MEG → F. Renga

$\mu N \to eN$ @ Mu2e → G. Tassielli

$\tau \to e/\mu\,\gamma$, lh, ll^+l^- @ LHCb, Babar

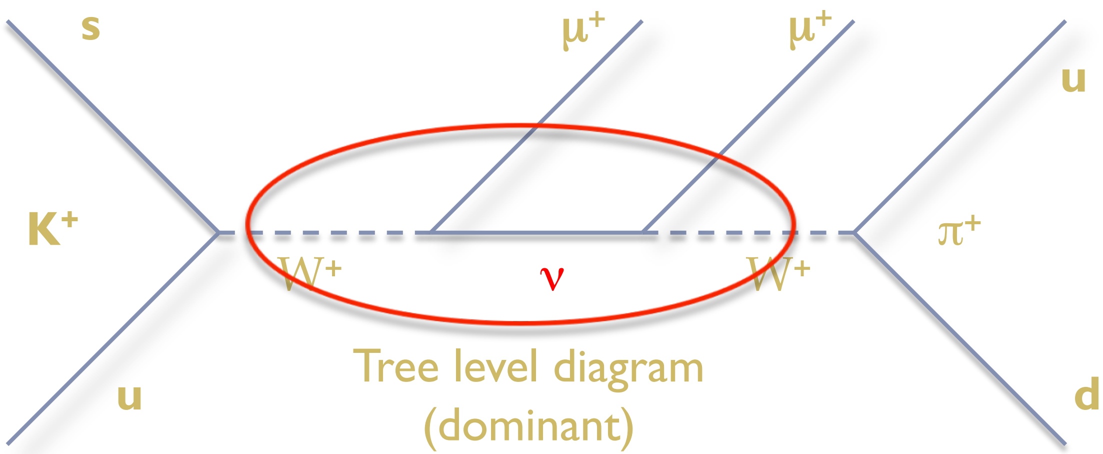
$\mu \to eee$ @ Mu3e future exp. at PSI

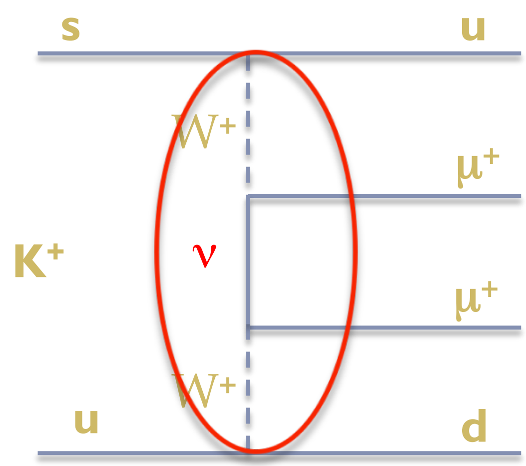


[Landsberg arXiv:hep-ph/0410261 + my updates]

Lepton number violation in $K^+ \rightarrow \pi^- \mu^+ \mu^+$

Transition possible in NP, if mediated by a Majorana neutrino, ν



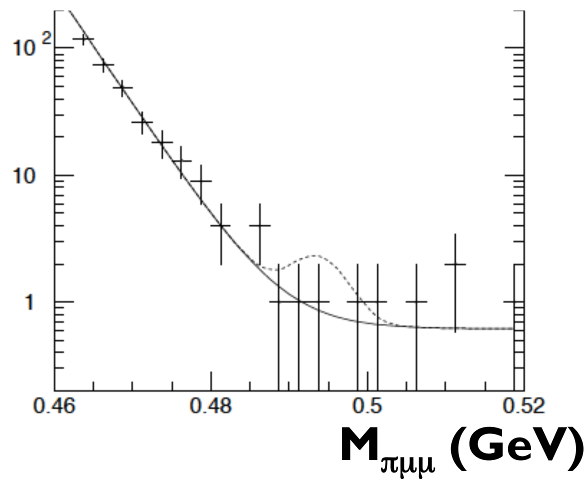


Expected BR depends on effective ν mass

If 100 < Mν < 300 MeV, ν is kinematically accessible → limits on coupling from K decays are most stringent than from any other source

From bkg evaluation to 400 $\pi^+\mu^+\mu^-$ events:

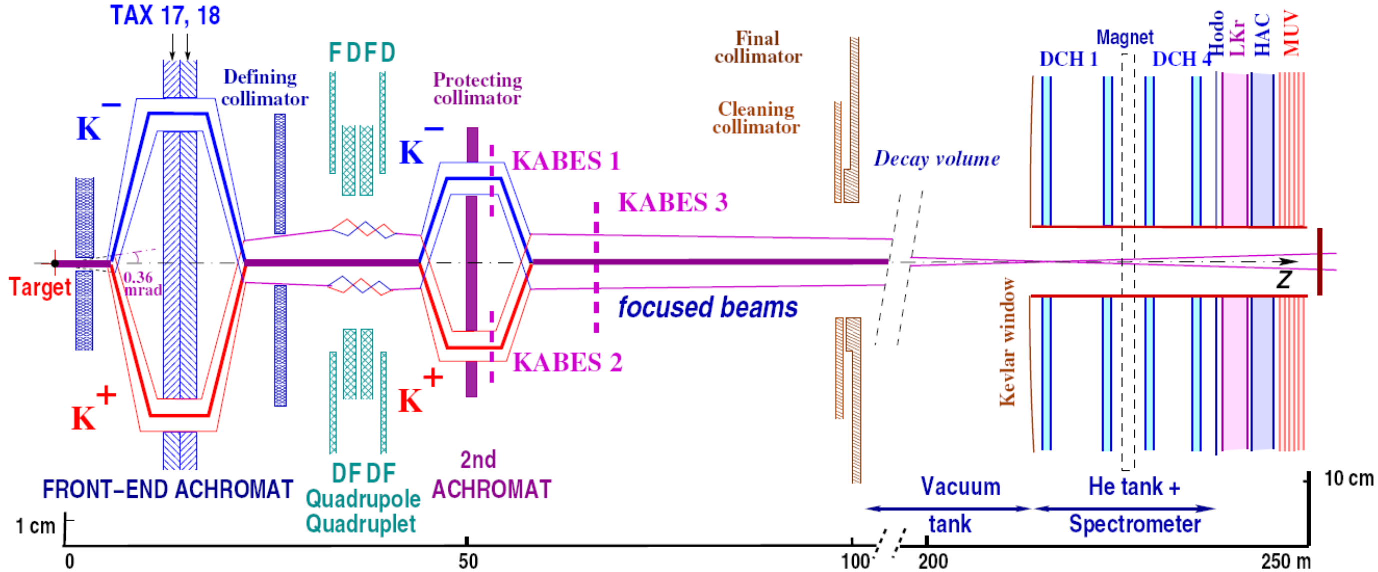
BR < 3×10^{-9} [E865 collaboration PRL85(2000)2877]

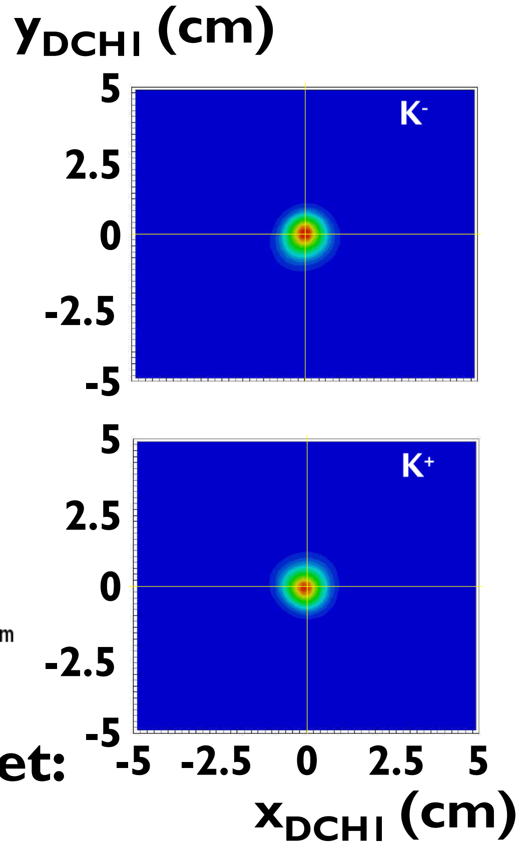


Setup of the NA48/2 experiment

NA48/2: unseparated, simultaneous $K^{\pm}$ highly collimated beams, designed to precisely measure $K^{\pm} \to \pi^{+,0}\pi^{-,0}\pi^{\pm}$ dalitz-plot density

- **$p_K \sim 60$ GeV, $\sigma_p \sim 3$ GeV (3.8% p-bite)**
- **spot of 10 mm FWHM @ DCH1 entrance**





Track decay products with 4 DCH's + dipole magnet:

- **$P_{\perp}$ kick of 120 MeV after DCH2**
- **$\sigma_p/p \sim 1.02\% \oplus 0.044\%$ p [GeV/c]**

Analysis of $K \rightarrow \pi\mu\mu$ at NA48/2

Scintillator hodoscope:

- **establish event time ($\sigma \sim 150$ ps), fundamental for L1 trigger**

DCH online reconstruction and vertex at L2 trigger

LKr calorimeter: efficient vetoing, excellent e.m. energy resolution

- **$\sigma_E/E = 3.2\%/\sqrt{E[GeV]} \oplus 9\%/E[GeV] \oplus 0.42\%$**
- **$\sigma_{x,y} = 4.2mm/\sqrt{E[GeV]} \oplus 0.6$ mm, granularity of 13,248 2×2 cm^2 cells**

Hadron calorimeter, Muon veto system (MUV)

Analysis samples acquired in 2003-4:

$K_{\pi\mu\mu}$: 3-track trigger (hodoscope), 1 vertex from 3 DCH tracks, 2 of them with MUV hits

$K_{\pi\pi\pi}$: trigger, acceptance cuts common with $K_{\pi\mu\mu}$, used as normalization

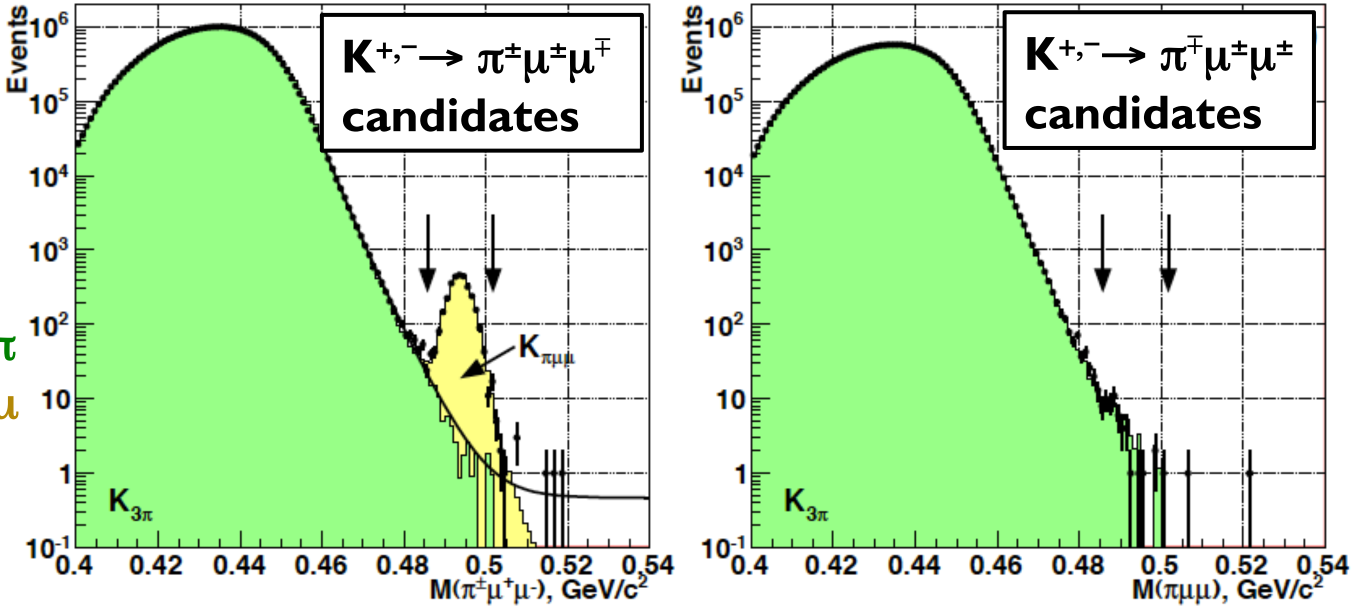
Normalization sample equivalent to 1.4×10^{11} K decays in FV

Analysis of K→πμμ at NA48/2

Total invariant mass for correct- vs wrong-sign events

MC K→πππ

MC K→πμμ



52 candidates $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$, vs $52.6\pm19.8_{syst}$ expected from MC:

- **BR($K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$) < 1.1×10^{-9} @ 90% CL [PLB 697(2011)107]**
- **Improves on previous results by x3**

Settle the road for future major improvements at NA62, see later

Motivations for a precise measurement of RK

SM prediction @ 0.04%, benefits of cancellation of hadronic uncertainties (no f_K): $R_K = \Gamma(Ke2)/\Gamma(K\mu2) = 2.477(1) \times 10^{-5}$ [Cirigliano Rosell arXiv:0707:4464]

Helicity suppression as NP boost [Masiero PRD74(2006)011701, JHEP0811(2008)042]

In R-parity MSSM, LFV can induce O(1%) effect [Girrbach, Nierste, arXiv:1202.4906]**:**

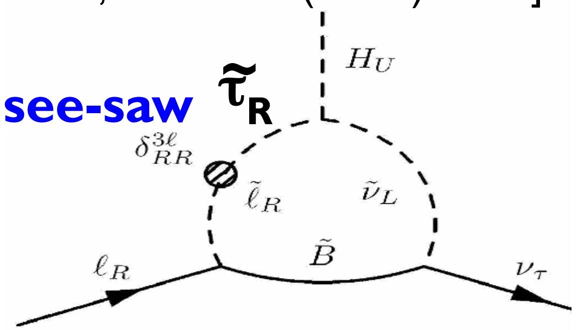
$$R_K^{LFV} \simeq R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\beta\right]$$

NP contribution from $e\nu_\tau$ state, eff. coupling $\Delta^{31}{}_R$ from b-ino/s-tau loop

In MSSM, NP << 0.1% after Higgs, B → τν, μμ [Fonseca et.al, EPJ C72 (2012) 2228]

… but NP @ >1% in SM + sterile fermions in Inverse see-saw

[Abada, et al.: JHEP 1302 (2013) 48, JHEP 1402 (2014) 091]



Experimental accuracy was δR_K ~1.3% (KLOE)

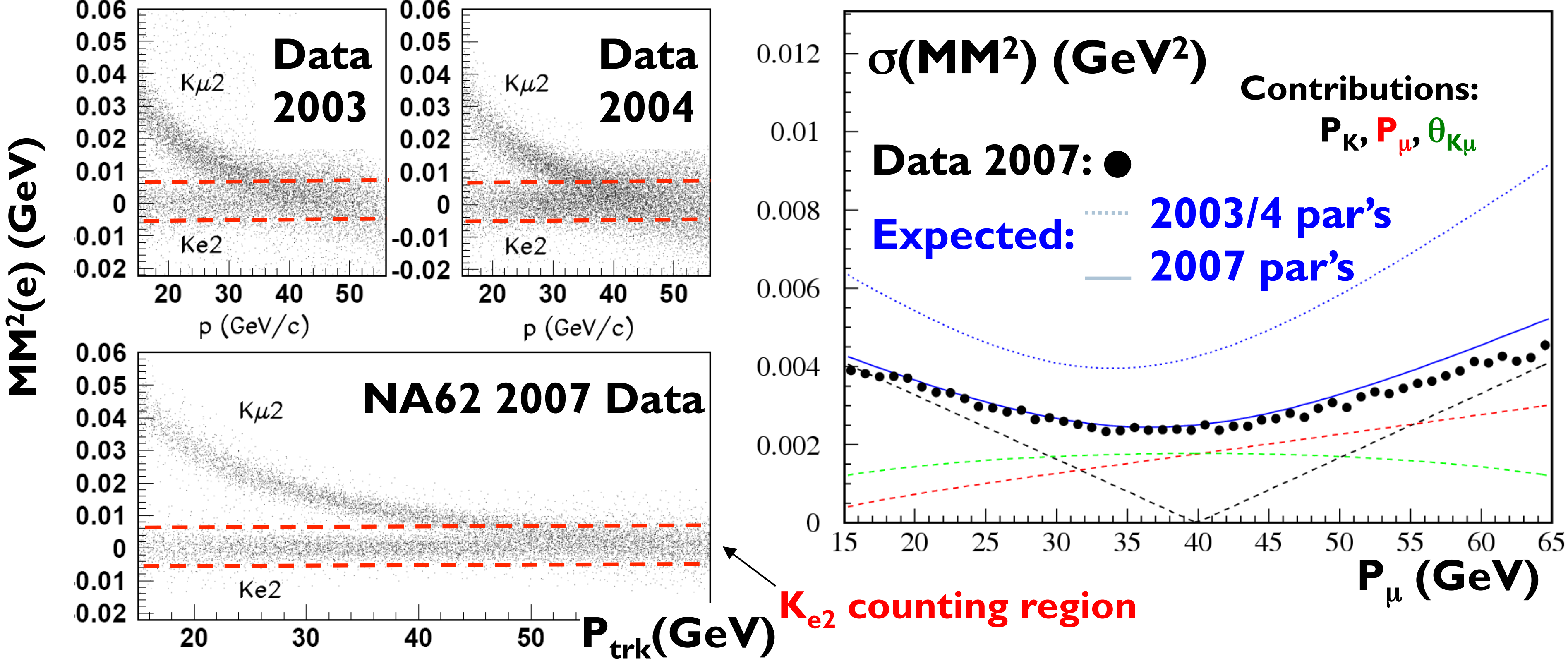
New measurement of R_K interesting, if error is pushed @ few per mil

Analysis of Ke2/Kμ2 at NA62 – 2007 data

After experience with NA48/2, design of NA62 run optimized for R_K:

- **P_K: ~60 GeV → ~74 GeV**
- **Momentum bite: 3.8% → 2.5%**
- **$P_\perp$ kick: 120 MeV → 265 MeV**

σ_p/p = 0.48% + 0.009% p(GeV)
MM^2 resolution improved
Better separation for Ke2 and Kμ2



Analysis of Ke2/Kμ2 at NA62: μ background

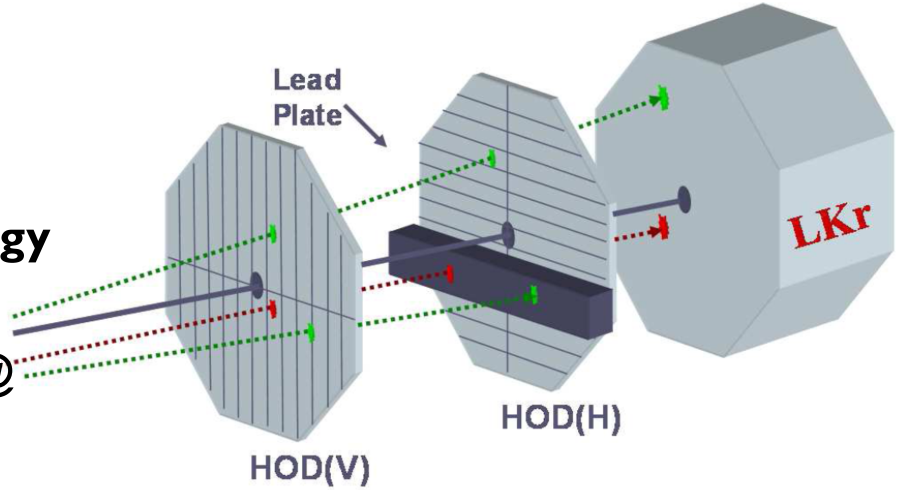
Analysis starting samples:

- **K_{e2} trigger:** 1 trk (hodoscope) & 1-trk activity in DCH's & E_{LKr}>10 GeV
- **$K_{\mu 2}$ trigger:** 1 trk (hodoscope) & 1-trk activity in DCH's, downscaled

Electron ID by LKr: (0.90 to 0.95)<E_{cl}/P_{trk}<1.10, μ rejection by ~10^6!

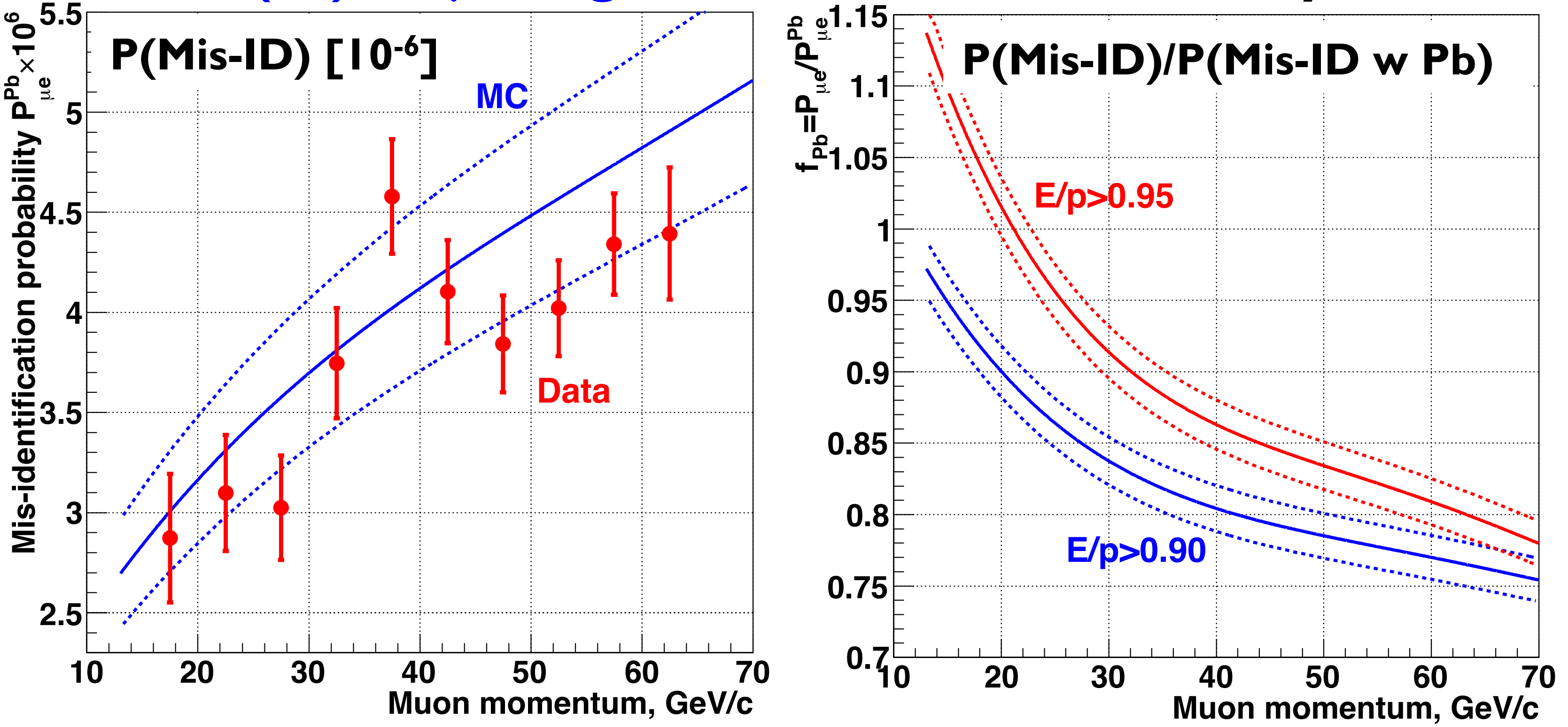
Electron ID efficiency: 99.28(5)%, check probability for μ's to fake e's [~4×10^{-6}, due to the so-called muon "catastrophic" energy loss] by direct measurement:

- **Subsample of data taken with a 9.2-X_0 Pb bar between HOD's**
- **Select μ's (pure @<10^{-8}) with MIP energy loss in Pb**
- **Correct method bias (ionization loss @ low P, brems. @ high P) w GEANT4**



Analysis of Ke2/Kμ2 at NA62: μ background

Evaluate 5.64(20)% Kμ2 bkg to Ke2, error dominated by statistics



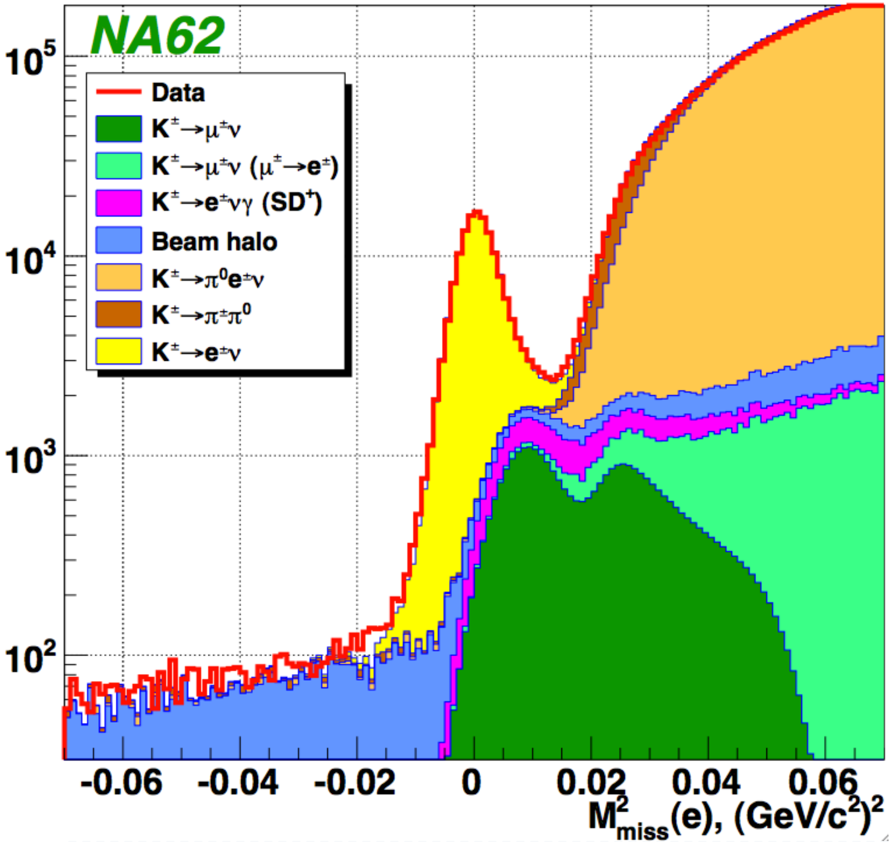
Analysis of R_K for the 4 configurations: K^+/K^- Lead bar/No lead bar

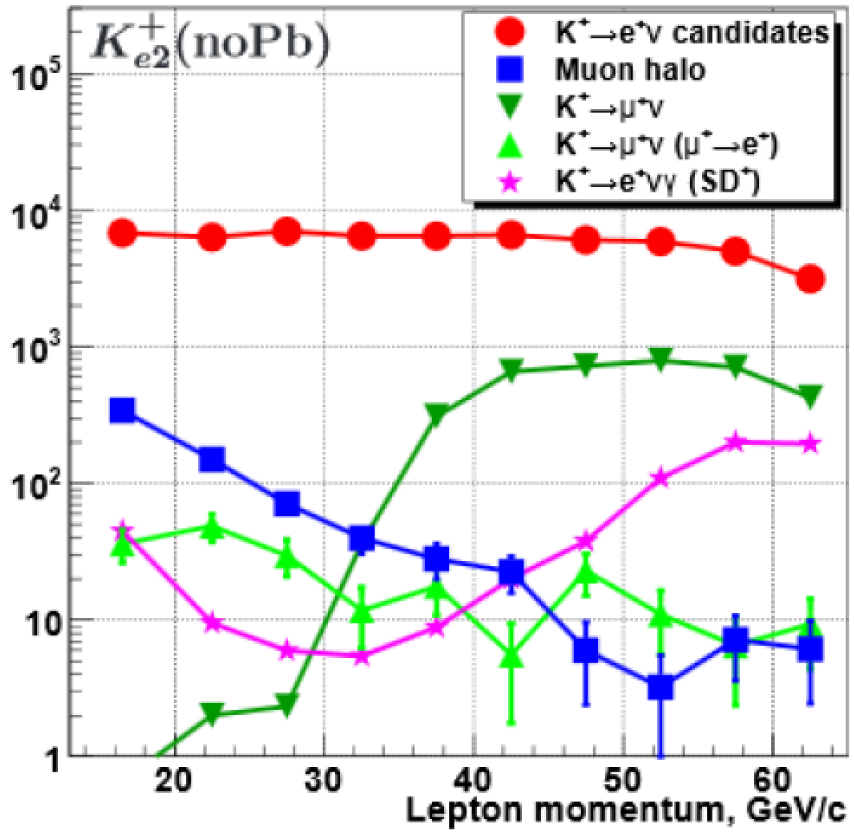
Analysis tuned in lepton momentum bins, allowing reliability check of μ mis-ID evaluation, bkg subtraction, and acceptance correction

Analysis of Ke2/Kμ2 at NA62: other backgrounds

World largest Ke2 data set, 145958 K^+e2 candidates, 10.95(27)% bkg

Source	Kμ2	Kμ2(μ→e)	Ke2γ(SD⁺)	Ke3	K2π	K∓	μ halo
Fraction, %	5.64(20)	0.26(3)	2.60(11)	0.18(9)	0.12(6)	0.04(2)	2.11(9)

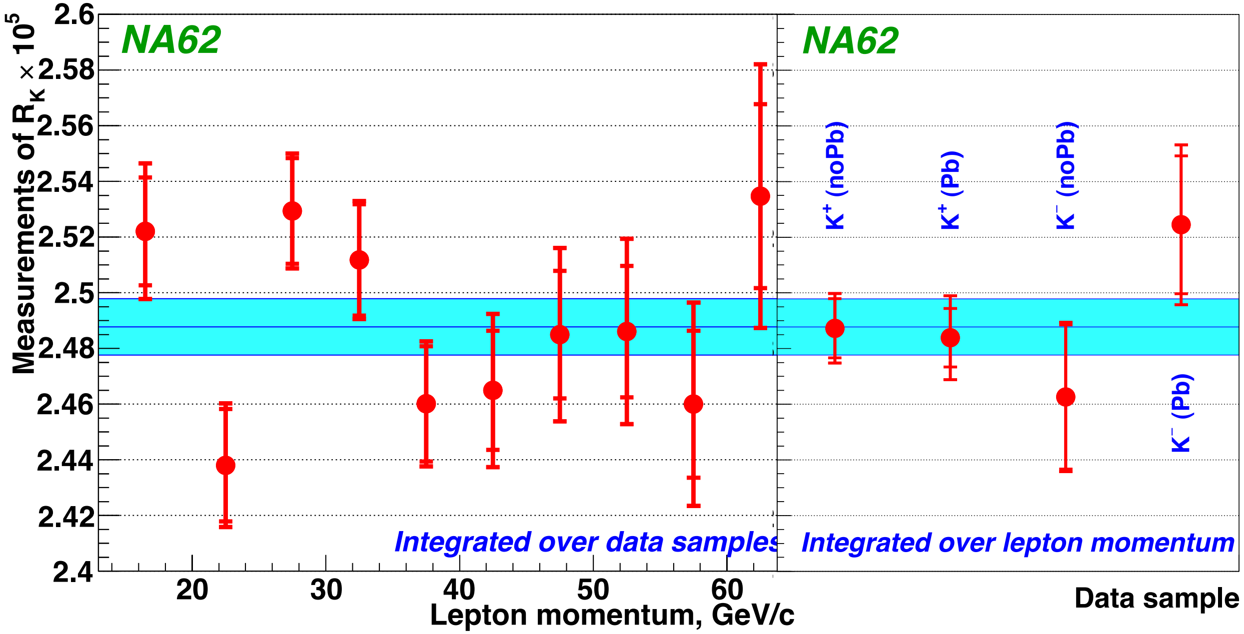




2013 NA62 RK result and error budget

Entire data set: $R_K = 2.488(7)_{stat}(7)_{syst} 10^{-5}$ [PLB 719 (2013) 326]

Source	δR_K (10^{-5})
Statistics	0.007
$K\mu2$ bkg	0.004
$Ke2\gamma$ SD+ bkg	0.002
Ke3, $\pi\pi^0$ bkg	0.003
Muon halo bkg	0.002
Material budget	0.002
Acceptance corr	0.002
DCH alignment	0.001
Electron ID	0.001
1 TRK trigger eff	0.001
LKr readout eff	0.001
Total	0.010



Fit over 40 independent measurements, 10 lepton momentum bins × 4 configurations:

χ^2 / Nd.o.f. = 47/39 (P = 18%)

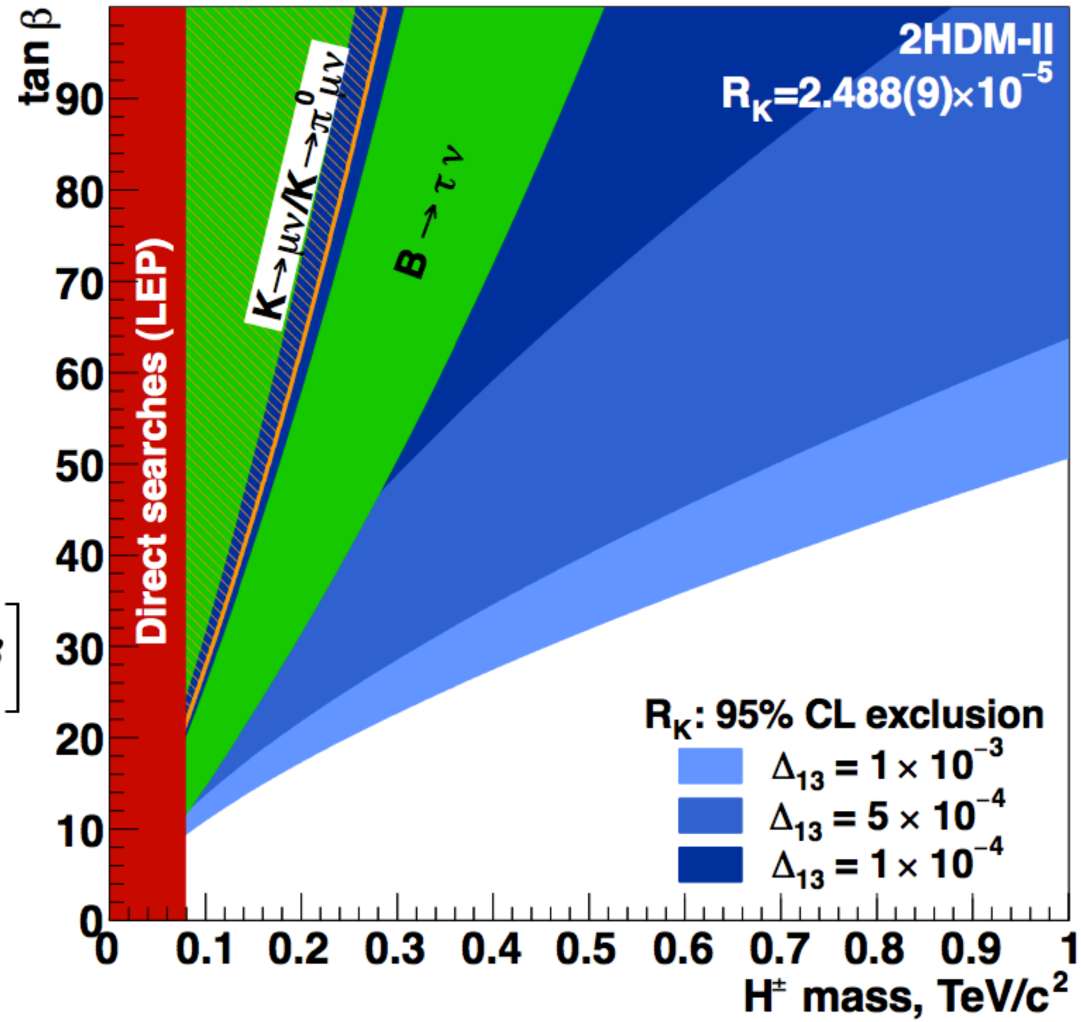
RK final result, impact for NP search: MSSM

Compare present world average with

$R_K(SM) = 2.477(1)10^{-5}$

including possible NP from H^+:

$$R_K^{LFV} \simeq R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\beta\right]$$



Error ~10 that of SM prediction, room for future improvements with NA62

RK NA62 result, impact for sterile neutrinos

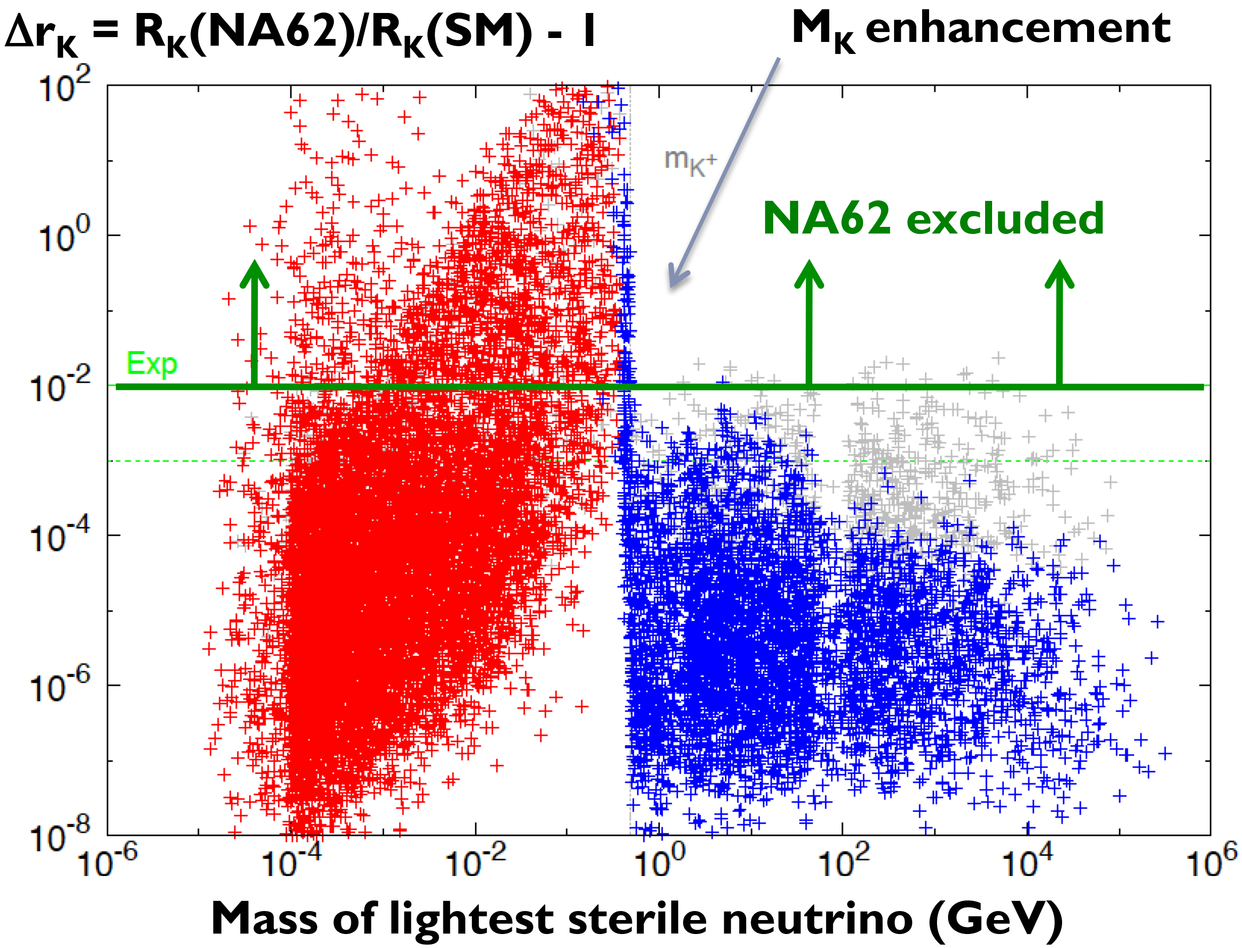
Probe NP from sterile ν's w inverse see-saw [Abada et al. JHEP 1402 (2014) 091]

Color code:

All high-energy experimental bounds, B and τ decays, Γ(Z→νν), etc. + cosmological bounds satisfied

Cosmological bounds (Large scale structure, Lyman-α data, X-ray searches, etc.) relaxed

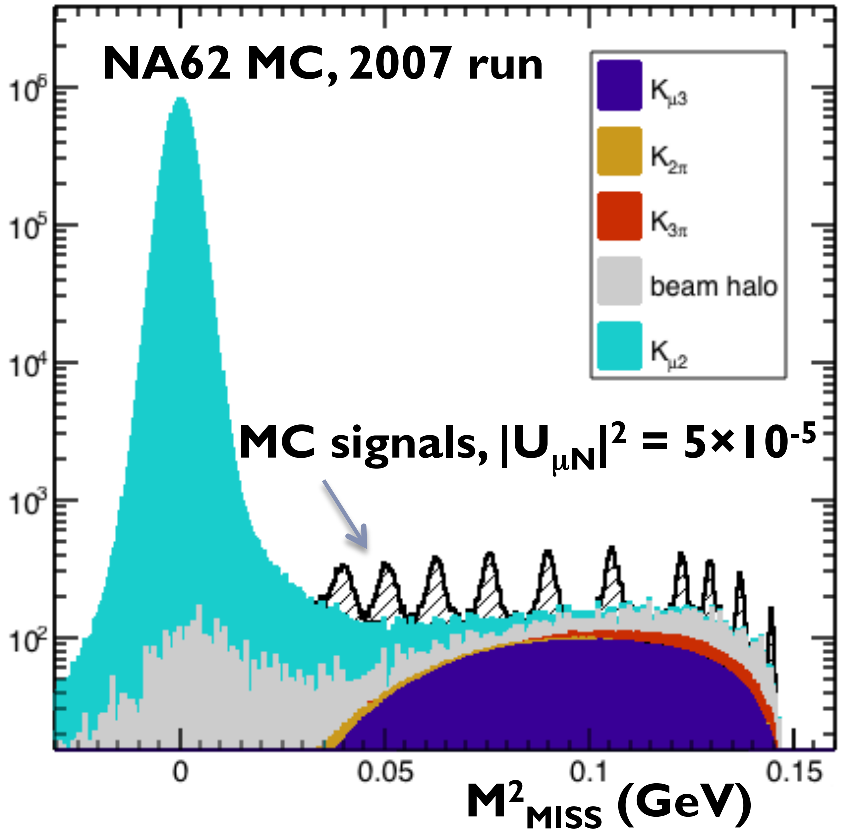
Models excluded by present μ→eγ MEG result

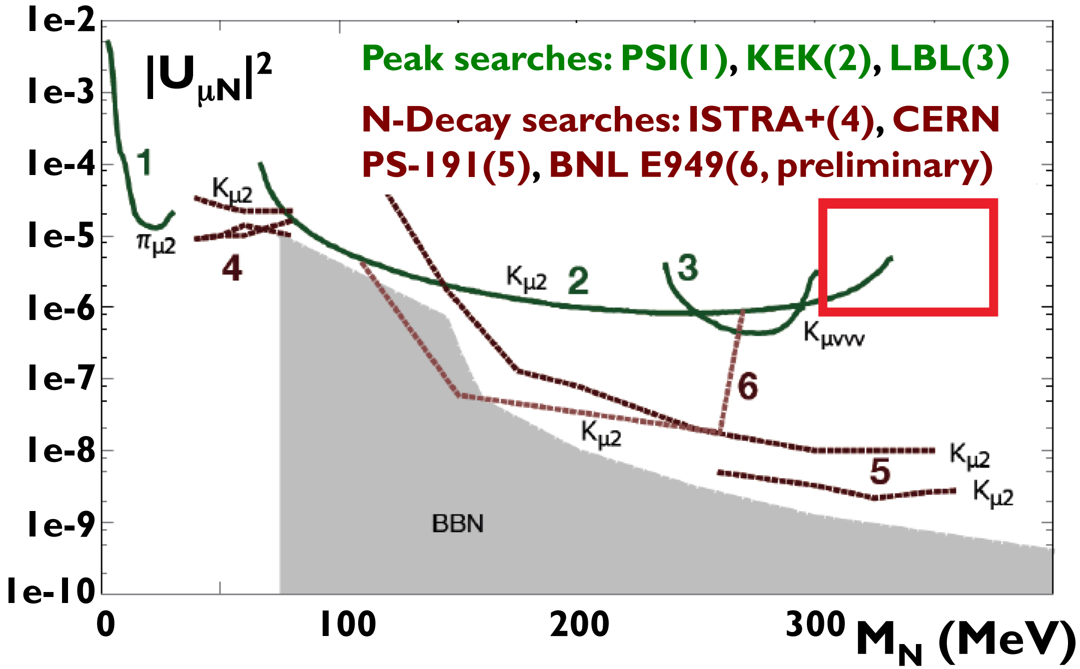


Searching for direct production of sterile ν's

Search using Kμ2 selected data (normalization channel for R_K), ~ 18 M Evts

Search for peaks due to $K^+ \to \mu^+ N$, signal strength due to $U_{\mu N}$ mixing





NA62 competitive w past peak-based searches, if M_N > ~250 MeV

Decay searches are model-dependent but tend to be more sensitive than peak

NA62 analysis is in progress

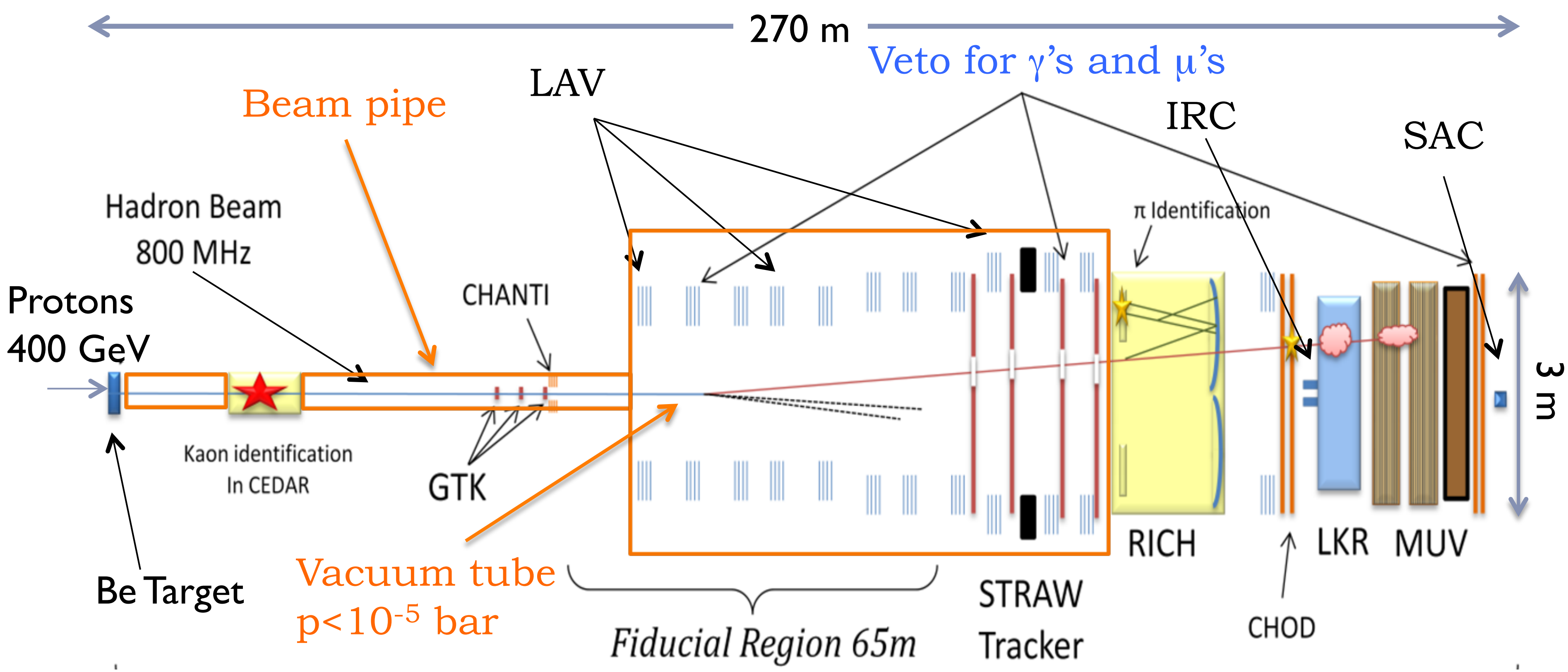
Expect sizable improvements with new NA62

Major beam and detector upgrades for $K^+ \rightarrow \pi^+\nu\nu$, see talk by G. Ruggiero

	NA48/2	NA62-RK	NA62
Data taking	2003-4	2007-8	**2014-17**
Primary intensity (ppp)	7×10^{11}	7×10^{11}	$\mathbf{3 \times 10^{12}}$
Solid angle (μsterad)	~0.4	~0.4	**~12.7**
Beam momentum (GeV)	60	74	75
RMS momentum bite (GeV)	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV	120	265	270
$M(K \rightarrow \pi^+\pi^+\pi^-)$ resolution, MeV	1.7	1.2	0.8
K decays in fiducial region	2×10^{11}	2×10^{10}	$\mathbf{1.2 \times 10^{13}}$
Main trigger	Multi-track, $K \to \pi^+\pi^0\pi^0$	$1e^{+-}$	$K \to \pi\nu\nu$ + ...

New: beam spectrometer, efficient γ vetoes at large angle, redundant PID

The new NA62 experiment @ CERN

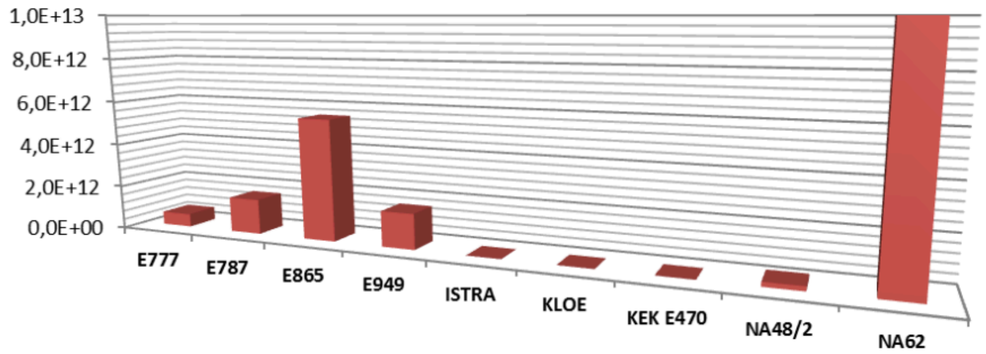


750 MHz on beam spectrometer, 10 MHz on downstream detectors

Fully flexible, FPGA-based trigger:
- **L0 HW, from 10 to 1 MHz, <1-ms latency**
- **L1 SW single-detector based, 100 KHz out**
- **L2 SW full info, output few KHz**

Intensity allowing LFV searches from K decays…

NA62 will collect the world-largest K^+ decay sample, ~ 1×10^{13} in 2 years of data taking



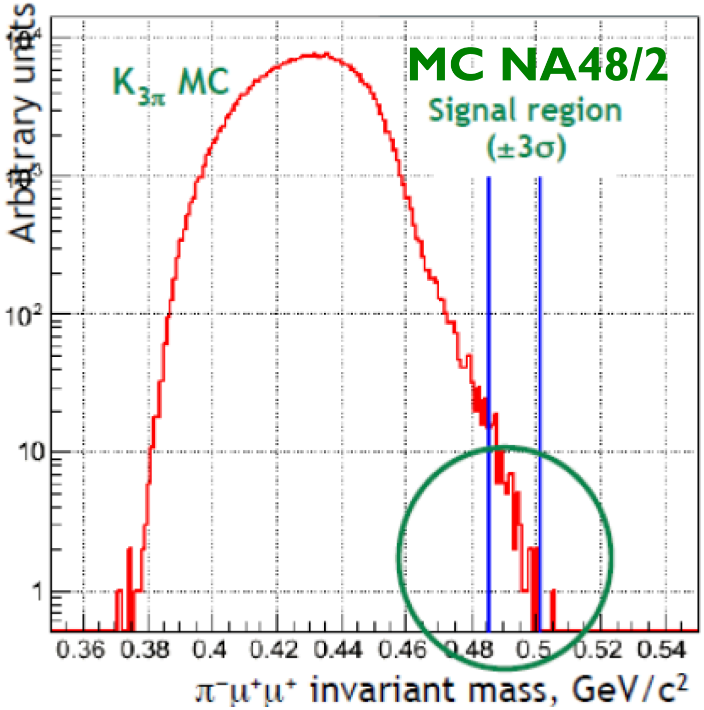
Mode	UL at 90% CL	Experiment	Reference
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	E777/E865	PRD 72 (2005) 012005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	E865	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	E865	PRL 85 (2000) 2877
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	E865	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	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		

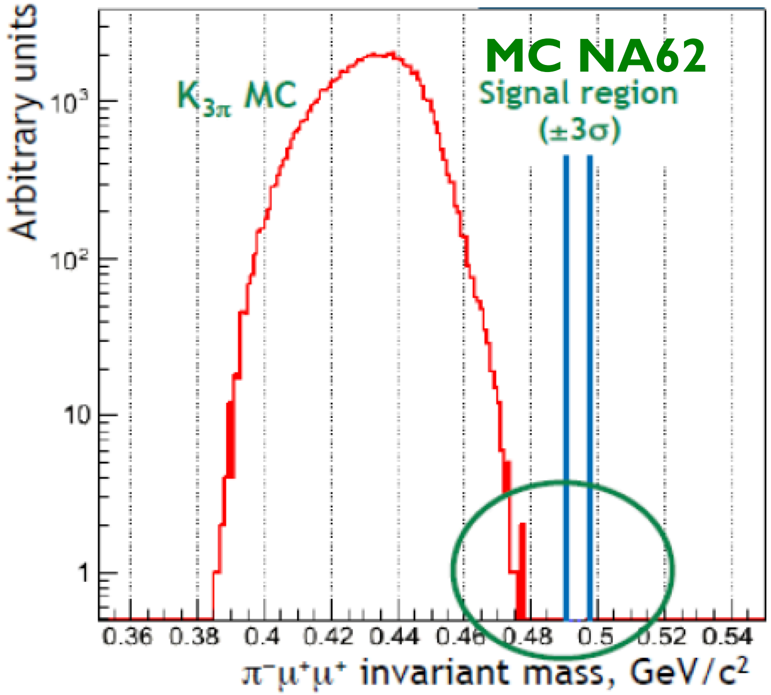
3-track decay parasitic to main trigger w L0 bandwidth of O(10 kHz)

With acceptances of few to ten % efficiency, prospects to reach SES of 10^{-12}

… for example, $K^+ \rightarrow \pi^- \mu^+ \mu^+$…

Major improvements expected at NA62





NA48/2: bkg to $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ from $K^\pm \rightarrow \pi^\mp \pi^\pm \pi^\pm$ + $\pi^\pm \rightarrow \mu^\pm \nu$ in the spectrometer

NA62: negligible background thanks to redundant PID capabilities

Resolution on invariant mass $\sigma_M(\pi^\mp \mu^\pm \mu^\pm)$ ~ 2.6 (1.1) MeV @ NA48/2 (NA62)

Expect a factor of 100 to 1000 improvement at NA62

…and from π^0 decays…

One year of data taking yields 1.3×10^{11} π^0's from $K\rightarrow \pi\pi^0$

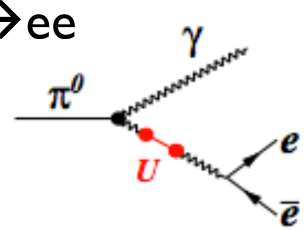
Intense π^0 "tagged beam" allowing many promising studies

Feasibility studies started on several decays

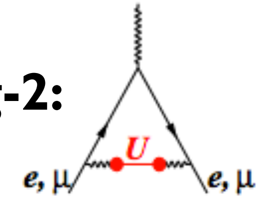
Mode	Observable	NP Motivation	SM	Present	Experiment
$\pi^0 \rightarrow 3\gamma$	BR	C-violation	Forbidden	$< 3.1 \times 10^{-8}$	Crystal Box, 1988
$\pi^0 \rightarrow 4\gamma$	BR, kinematics	Light exotic scalars	10^{-11}	$< 2 \times 10^{-8}$	Crystal Box, 1988
$\pi^0 \rightarrow$ inv	BR	RH neutrinos, LFV	$< 10^{-13}$ (Cosm. limit)	$< 3 \times 10^{-7}$	E949, 2005
$\pi^0 \rightarrow e\mu$	BR	LFV	Forbidden	$< 4 \times 10^{-10}$	KTeV, 2008
$\pi^0 \rightarrow eeee$	Kinematics	SI, em T-Viol, off-shell vectors	$3.26(18) \times 10^{-5}$	$3.34(16) \times 10^{-5}$	KTeV, 2008
$\pi^0 \rightarrow ee\gamma$	Kinematics	Dark vector bosons	No boson	Several exclusions	Several

… for example a study of π^0->eeγ…

Search for a U boson, dark-force mediator, from the chain $\pi^0 \to U\gamma$, $U \to ee$



U boson enters as NP contribution to muon g-2:



$$\Gamma_{U\to e^+e^-} = \frac{1}{3}\alpha\epsilon^2 M_U \sqrt{1-\frac{4m_e^2}{M_U^2}}\left(1+\frac{2m_e^2}{M_U^2}\right)$$

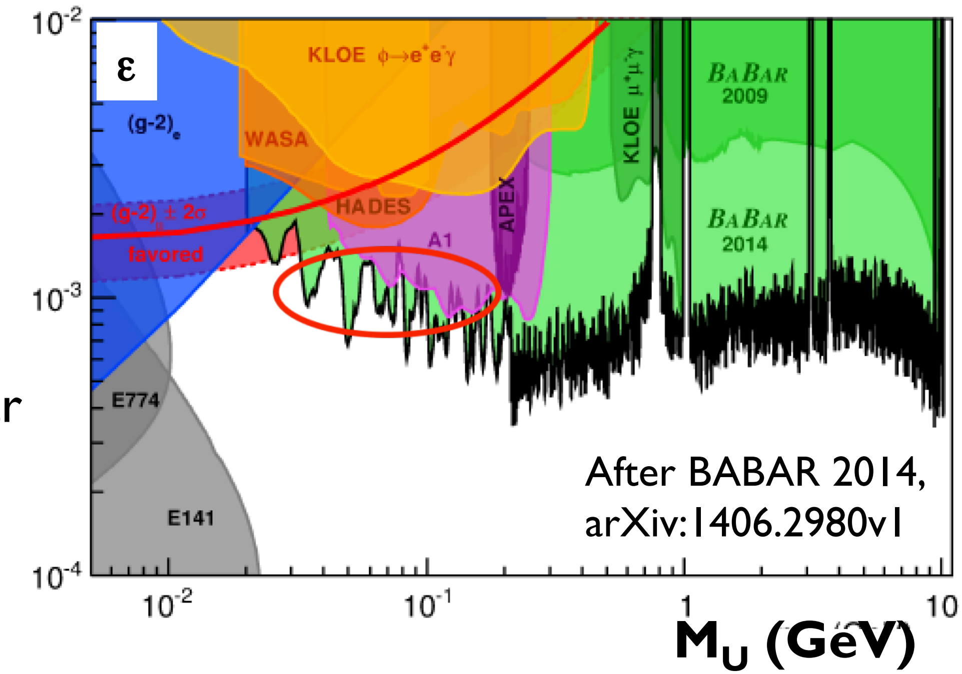
For $M_U < 2\,M\mu$, and effective coupling $\varepsilon \sim 10^{-3}$ width is ~ eV: U decay is prompt

Analysis in progress at NA48/2

At NA62: acquire w 3-track trigger + PID: rate sustainable, expect 10^8 candidates/year

e^+e^- invariant mass resolution ~ 1 MeV

Expect ~10^2 sensitivity improvement for $30<M_U<100$ MeV, up to $\varepsilon^2 \sim 10^{-6}$



After BABAR 2014, arXiv:1406.2980v1

...and from other mesons

Mesons produced at target might decay to long-lived exotic particles reaching the NA62 decay volume

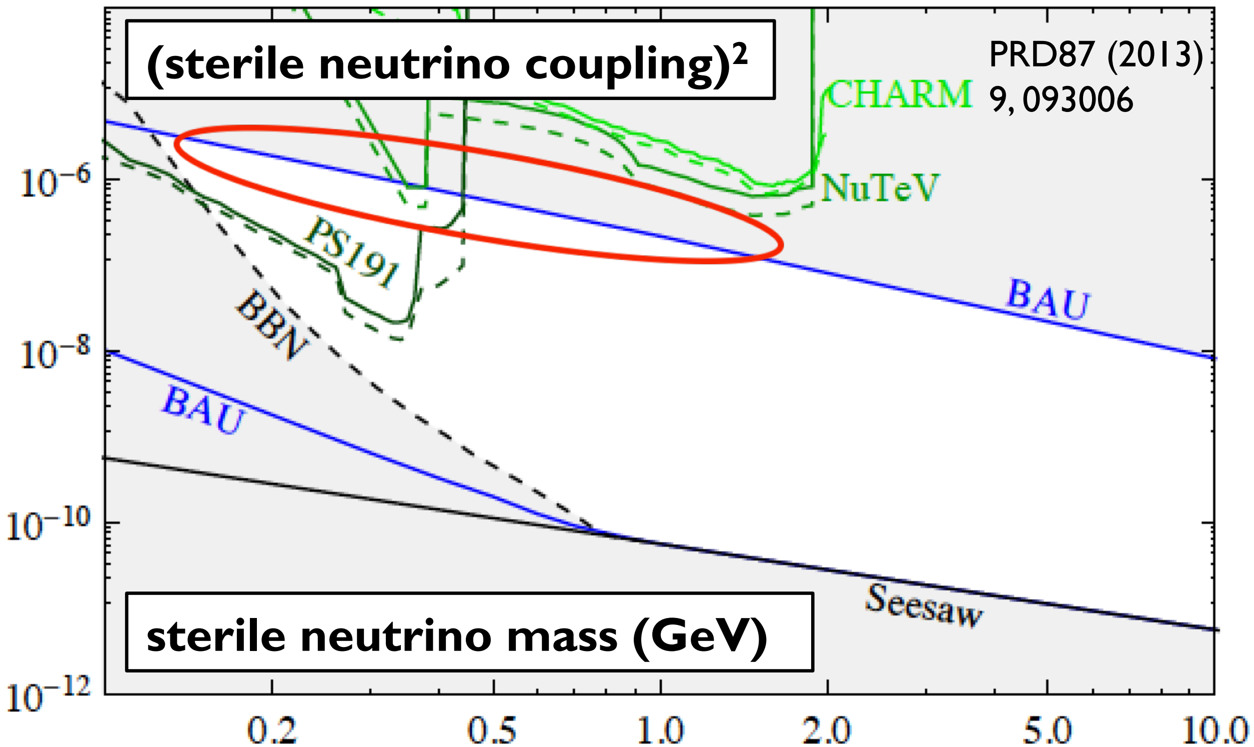
The simplest signatures correspond to two-body (semi)leptonic decays: πe, $\pi\mu$ (sterile neutrinos) or ee, $\mu\mu$ (Dark vectors, see later)

Production + decay: yield ~ (coupling)^4

With the K yield and **O(10^{15}) D^{+-}, D_S^{+-} produced per year**

NA62 might play a role..

Feasibility studies ongoing



Conclusions: NA62 past, present, and future

In 2007-2008, NA62 "RK phase":

- **Runs with original NA48/2 detector, beam carefully tuned for the measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$, now at 0.4%**
- **Data acquired with NA48/2 still useful for Lepton Number violation studies: $K^{\pm} \rightarrow \pi \mu^{\pm}\mu^{\pm}$ at 10^{-9}**
- **Parallel R&D studies for new sub-detectors, new NA62 approved by CERN research board at December 2008**

From 2009, developing the new NA62 experiment:

- **In 2011-2014, construction & commissioning: dry & technical runs**
- **At October 2014, first physics run after long shutdown, towards a 10% measurement of $K \rightarrow \pi\nu\nu$ in 2 years of data taking**
- **Prospects for improvements on many LFV and NP studies: Possible SES of ~10^{-12} on K^+ 3-track decays, ~10^{-10} on π^0 decays, sensitivity to sterile neutrino and NP vector searches: compete w KOTO, Trek @ J-Parc...**

…obviously, after a fair amount of work!