A taste of flavor physics from the NA62 experiment 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 achievements

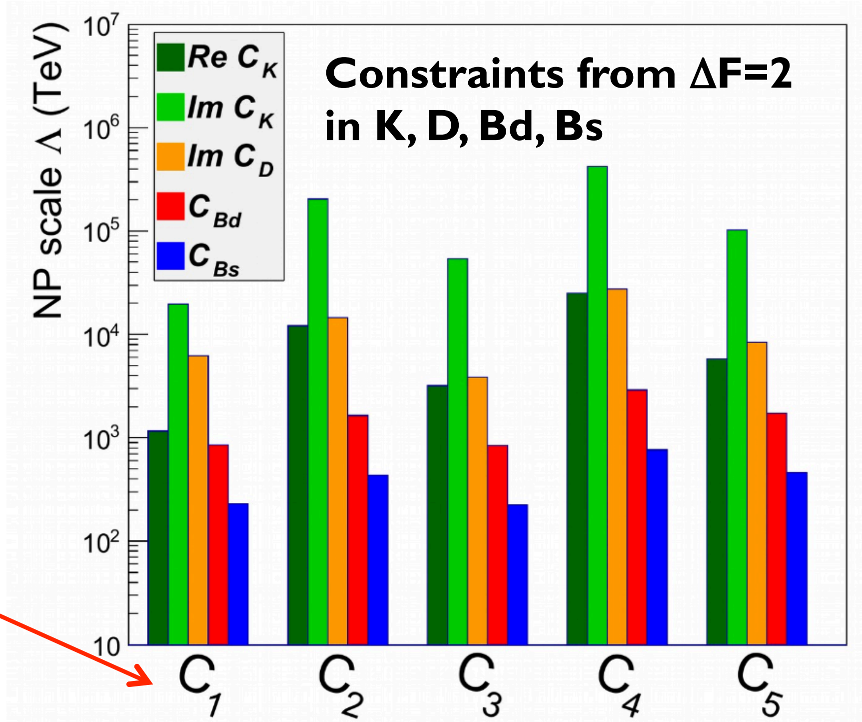
Precise study of low-energy L_{QCD}, including L_{QED} and L_{IB}:

- **Strong ππ phase shifts from non-leptonic K decays, e.g., Ke4**
- **Radiative decays, testing contributions from NLO and NNLO ChPt**

30 years of precision study of L_{ew}:

- **$|\varepsilon_K| = (2.221 \pm 0.006)10^{-3}$ provides:**
- **the stringest constraint on NP in ΔF=2 if NP coupling $LF_{NP} \sim 1$ and no flavor suppression assumed:**

$$A_{SM}+A_{NP}=K_{SM}\frac{\alpha_W}{4\pi}\frac{F_{CKM}}{M_W^2}+K_{NP}L\frac{F_{NP}}{\Lambda^2}$$



Will be a significant constraint for NP beyond CKM, if charm error under control

K physics – CP violation still of interest

30 years of precision study of L_{ew}:

$R(\varepsilon'/\varepsilon) = (16.4 \pm 1.9)10^{-4}$ might become a NP test soon:

lattice progress to beat uncertainty from cancellations btw e.m. and strong penguins: $\Delta I=3/2$ @ 10%, exploring $\Delta I=1/2$, $Re(A_0)$ @ 35%

Will reach 10% in 5 years from now, possibly complementing $K_L \rightarrow \pi^0\nu\nu$!

In excess with respect to the SM expectation by > ~x2 (lattice, large Nc, ...)

Deviation from the SM in $R(\varepsilon'/\varepsilon)$ and $K_L \rightarrow \pi^0\nu\nu$ were said to be anticorrelated...

.. but can be correlated in certain models [Buras, et al., arXiv:1507.08672]

K physics – A test of gauge universality

30 years of precision study of L_{ew}:

A precise gauge universality test: in SM,

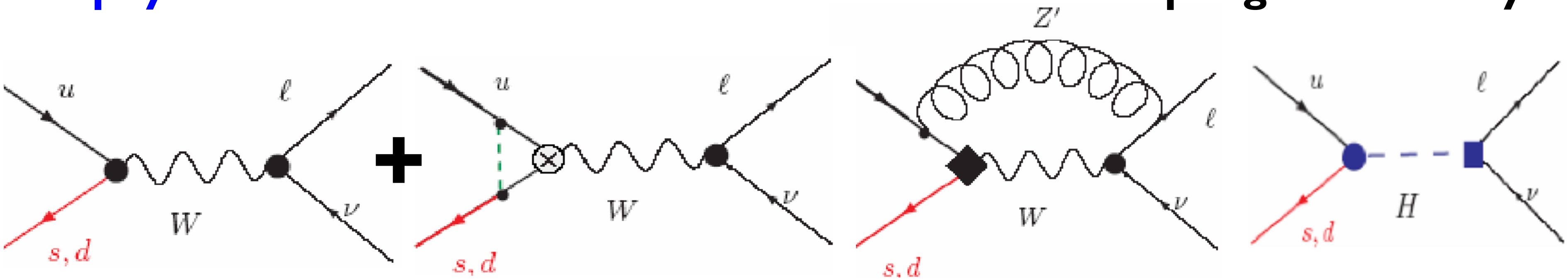
$$G_F^2 (|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime}) = (g_w/M_w)^2 \; [V_{ub} \text{ negligible}]$$

One can test for possible breaking of one of the two conditions:

CKM unitarity: is $(|V_{ud}|^2 + |V_{us}|^2) = 1$?

coupling universality: is $G_F^2 (|V_{ud}|^2 + |V_{us}|^2) = G^2(\text{from } \mu \text{ lifetime})$?

New physics extensions of the SM can indeed break coupling universality:



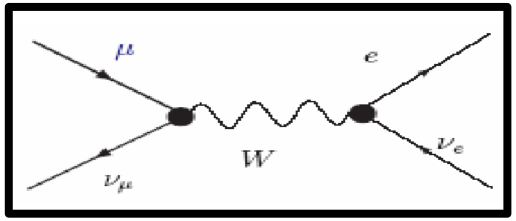
SM + NP $\propto G_F^2 |V_{uq}|^2 (1 + a\, M_W^2/M_{NP}^2)^2$, naively $a_{tree} \sim 1$, $a_{loop} \sim g^2_W/16\pi^2$

K physics – A test of gauge universality

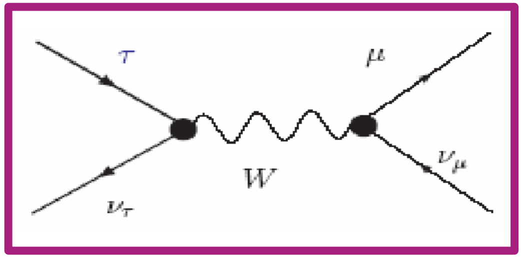
A measurement of $G_{CKM} = G_F\,(|V_{ud}|^2 + |V_{us}|^2)$ with error @ 5 10^{-3}

- **is sensitive to tree masses $M_{NP} \sim 10$ TeV and to loop masses $M_{NP} \sim 1$ TeV**
- **is competitive with ew precision tests:**

$G_F = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$ ←
[MuLan arXiv:1301.0504]

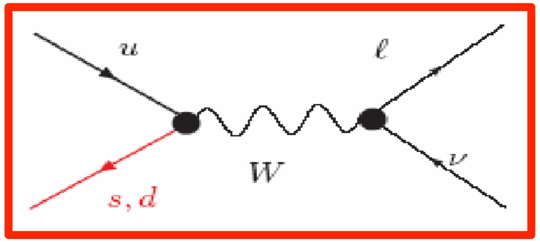


$G_\tau = 1.1678(26) \times 10^{-5}\ \mathrm{GeV}^{-2}$ ←



$G_{ew} = 1.1655(12) \times 10^{-5}\ \mathrm{GeV}^{-2}$ ← **$\alpha_{em} + M_W + s_W$ [ew precision tests]**

$G_{CKM} = 1.1638(04) \times 10^{-5}\ \mathrm{GeV}^{-2}$ ←



K physics – past, recent past, near future

30 years of precision study of L_{ew}:

After the legacy, $|\varepsilon_K|$, $R(\varepsilon'/\varepsilon)$, Gauge universality test:

Lepton number violation test from $K^\pm \rightarrow \pi\, \mu^\pm\mu^\pm$ at NA48/2

Dark photon search from $\pi^0 \rightarrow e^+e^-\gamma$ decays at NA48/2

LFV search from R_K = Ke2/Kμ2 at NA62 and FF of π^0_D (phase zero)

The future towards high sensitivity frontier from full-intensity NA62:

- **The golden mode: $K^+ \rightarrow \pi^+\nu\nu$**
- **$K^+ \rightarrow \pi\mu e$ and other LFV modes**
- **π^0 rare decays**
- **Not only K: short/long-lived DM: Dark γ's, heavy neutral leptons, ALP's, ...**

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)

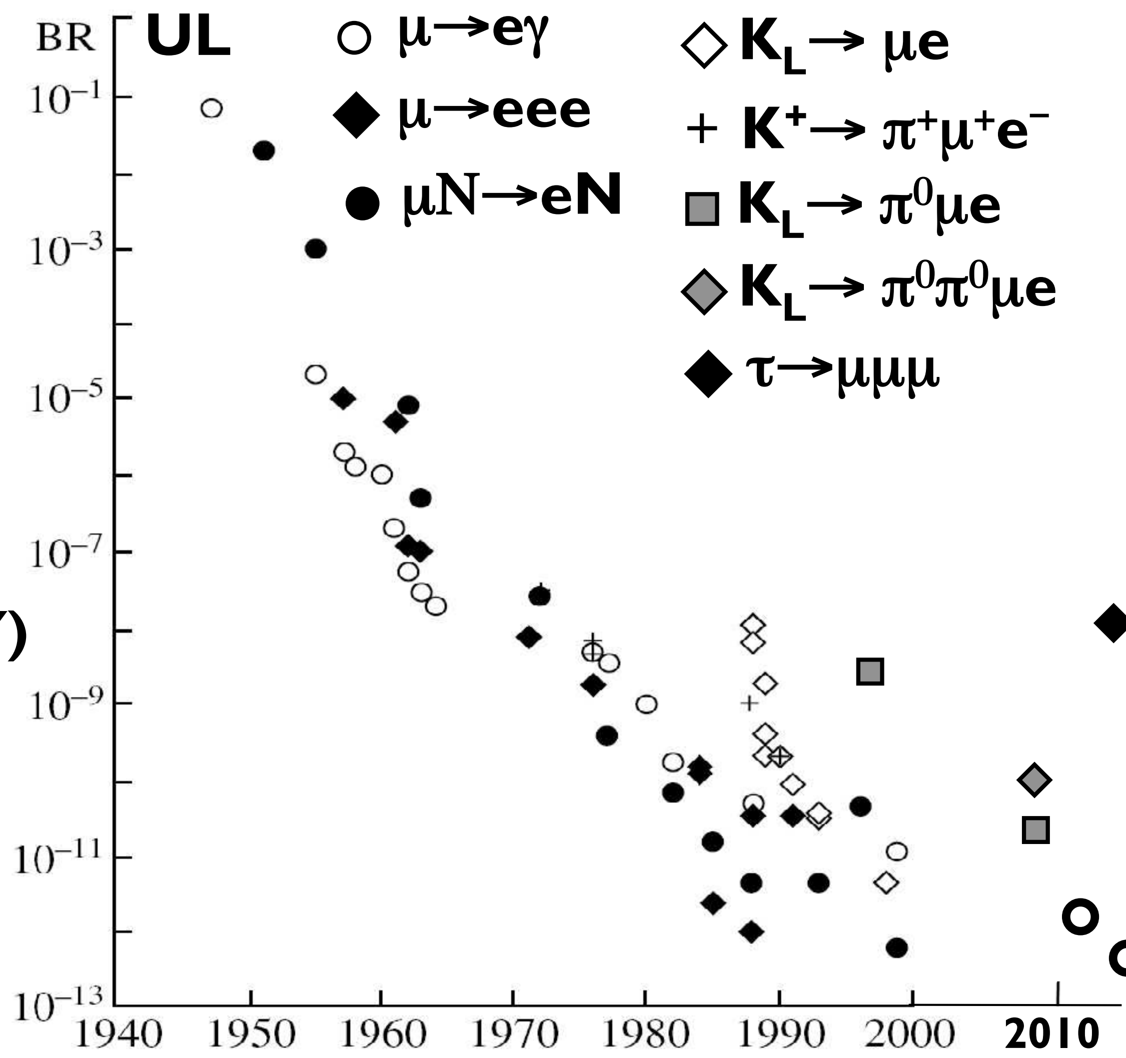
Compare with:

$\mu \to e\gamma$ @ MEG

$\mu N \to eN$ @ Mu2e

$\tau \to e/\mu\ \gamma$, lh, 3lept @ LHCb, B fact.

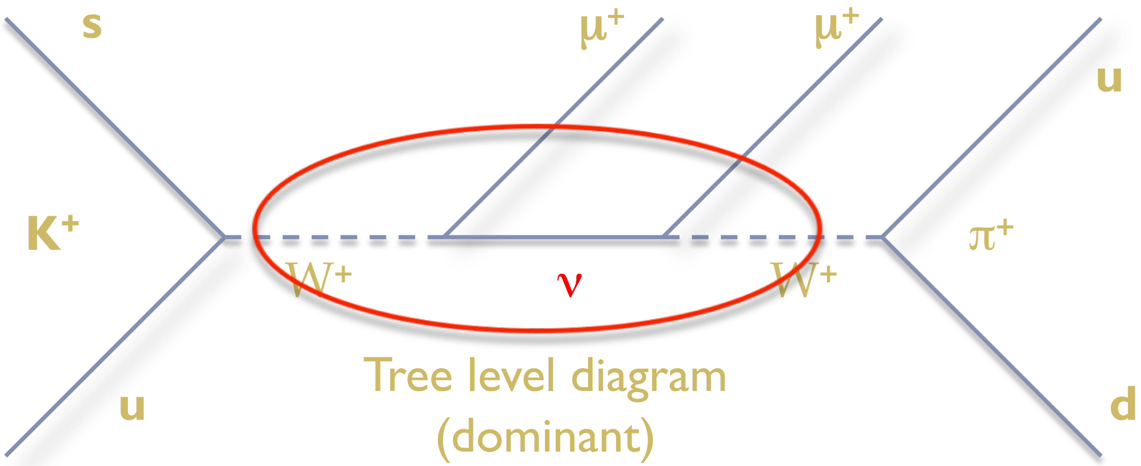
$\mu \to eee$ @ Mu3e future exp. at PSI



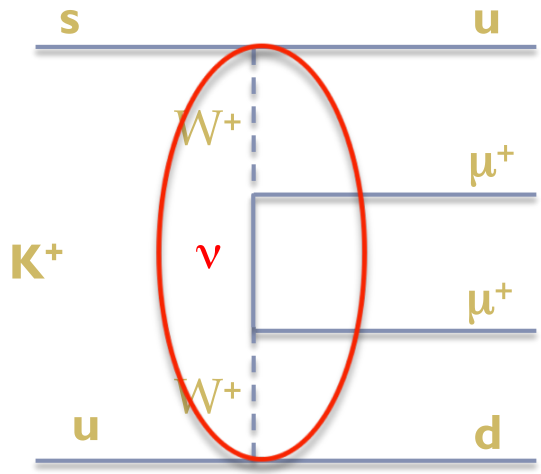
[Landsberg arXiv:hep-ph/0410261 + my updates]

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

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



Tree level diagram
(dominant)

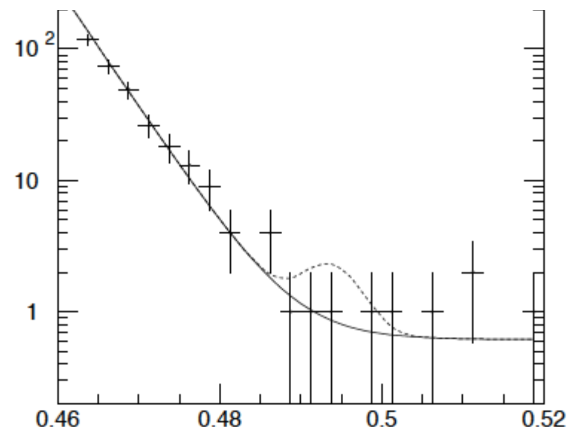


Expected BR depends on effective ν mass

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]

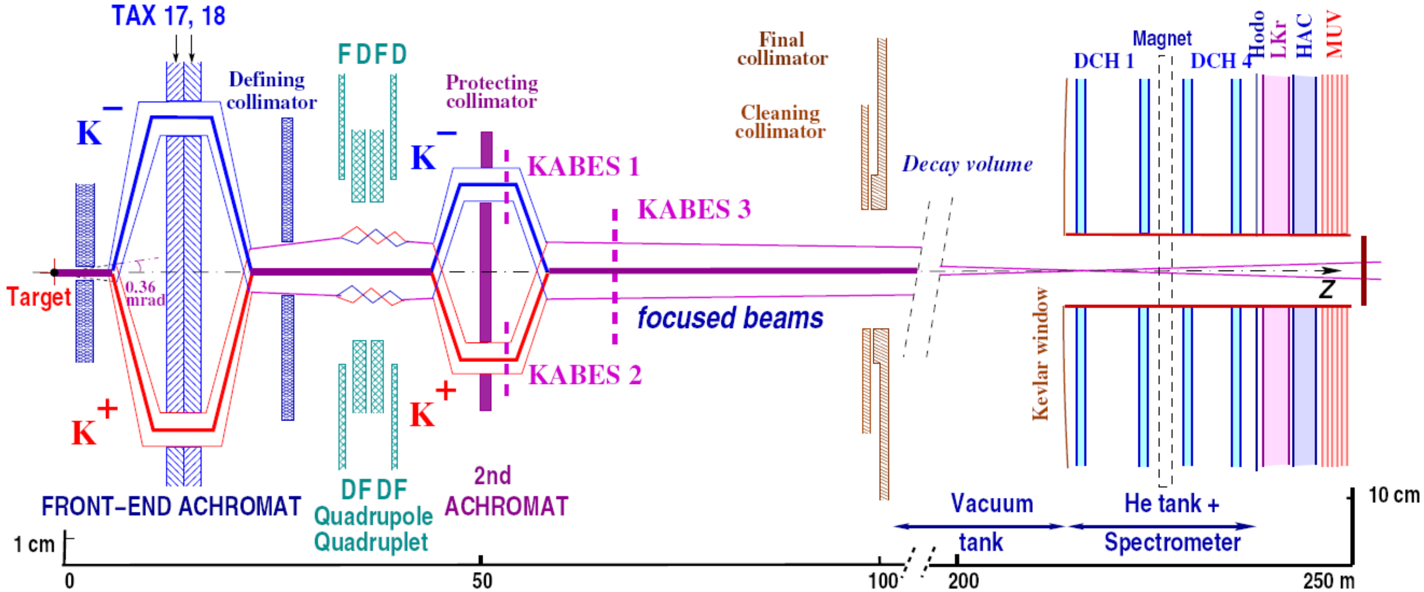


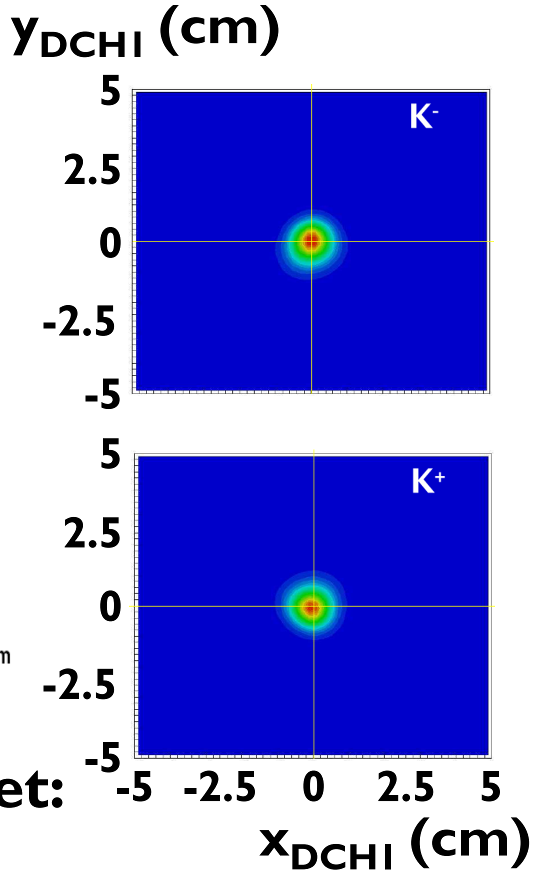
$M_{\pi\mu\mu}$ **(GeV)**

Setup of the NA48/2 experiment

NA48/2: unseparated, simultaneous $K^{\pm}$ highly collimated beams, designed to precisely measure $K^{\pm} \rightarrow \pi^{+,0}\pi^{-,0}\pi^{\pm}$ 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 (σ~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

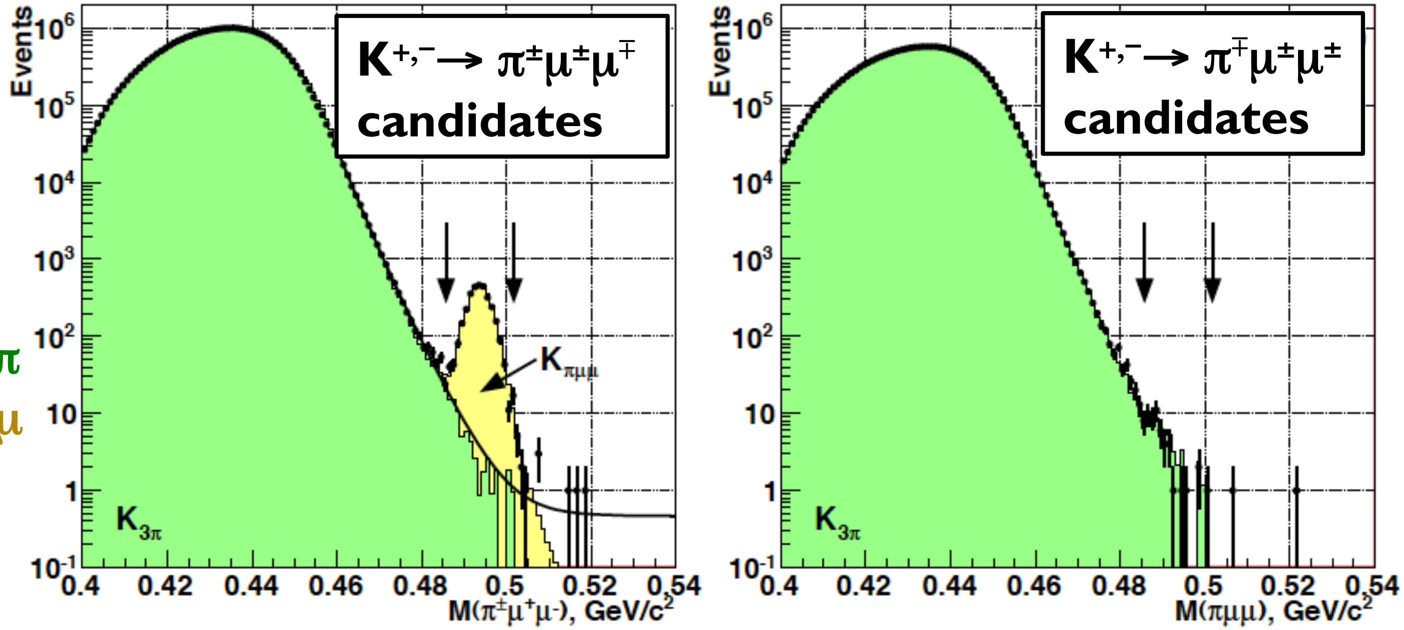
Normalization sample equivalent to 1.4×10^{11} K decays in FV

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 $52.6 \pm 19.8_{syst}$ expected from MC:

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

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

NP from a precise measurement of RK

SM prediction @ 0.04%, benefits of cancellation of hadronic uncertainties (no f_K): $R_K = \Gamma(Ke2)/\Gamma(K\mu 2) = 2.477(1) \times 10^{-5}$ [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]**:**

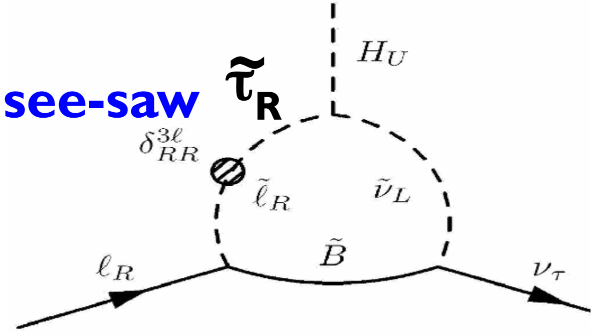
$$R_K^{LFV} \simeq R_K^{SM}\left[1+\left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2\tan^6\beta\right]$$

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)

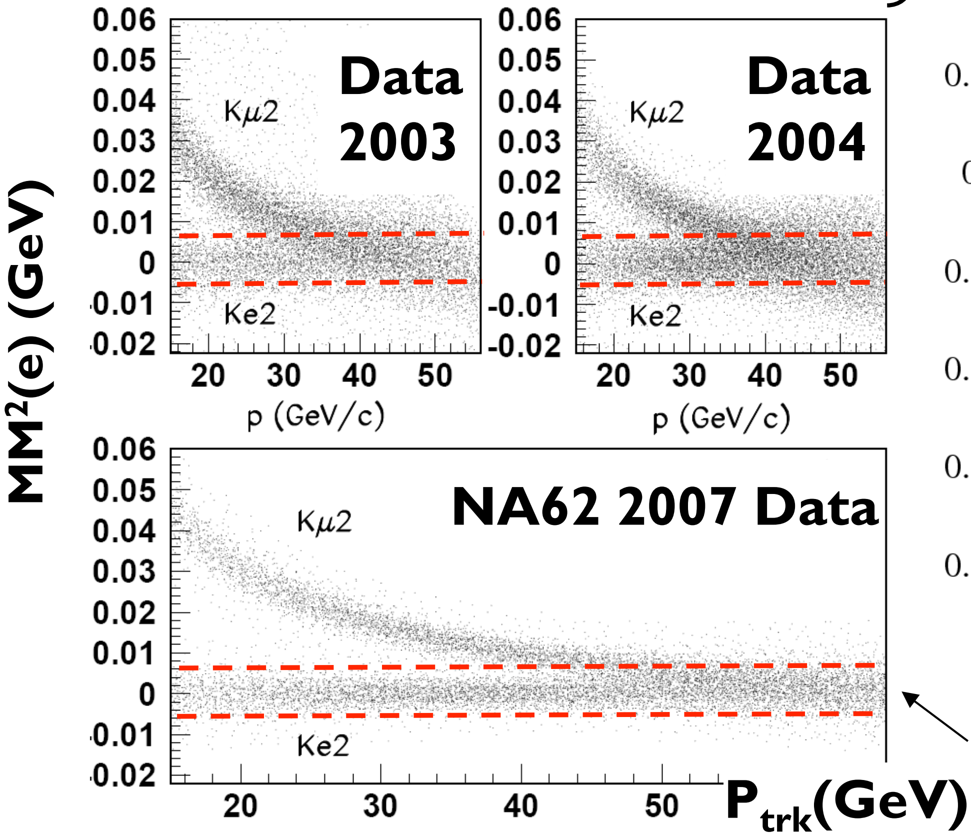
New measurement of R_K interesting, if error is pushed @ few per mil

Analysis of Ke2/Kμ2 at NA62 – 2007 data

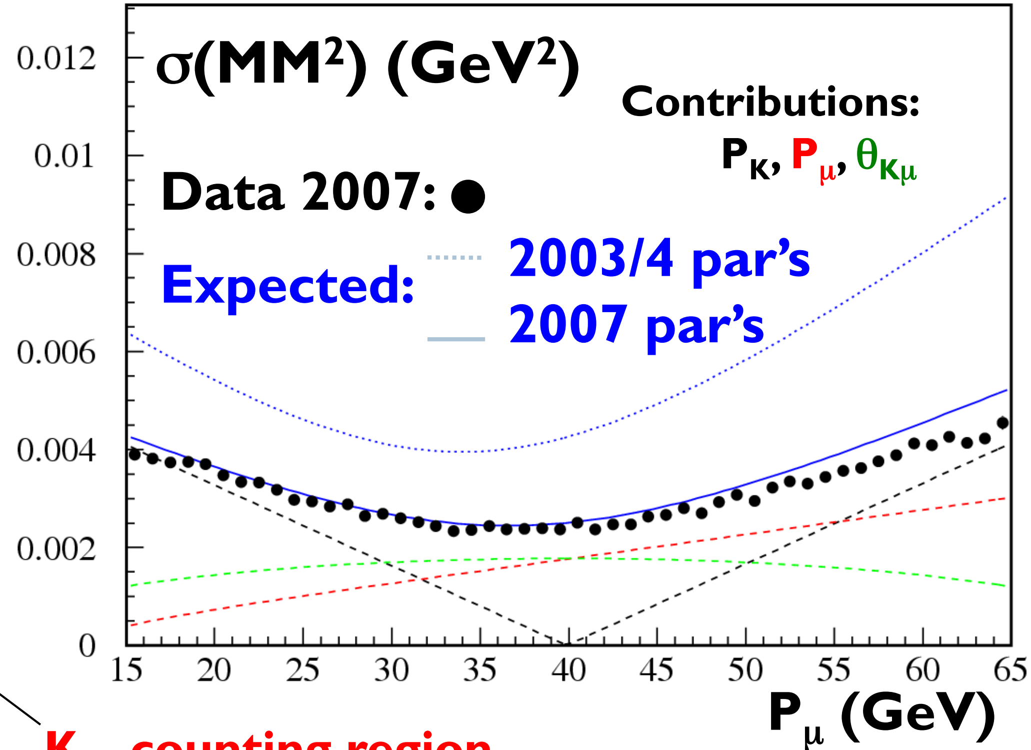
After experience with NA48/2, design of NA62 run optimized for R_K:

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

→ $\sigma_p/p = 0.48\% + 0.009\%\, p(\text{GeV})$
MM^2 resolution improved
Better separation for Ke2 and Kμ2



K_{e2} counting region



Analysis of Ke2/Kμ2 at NA62: μ background

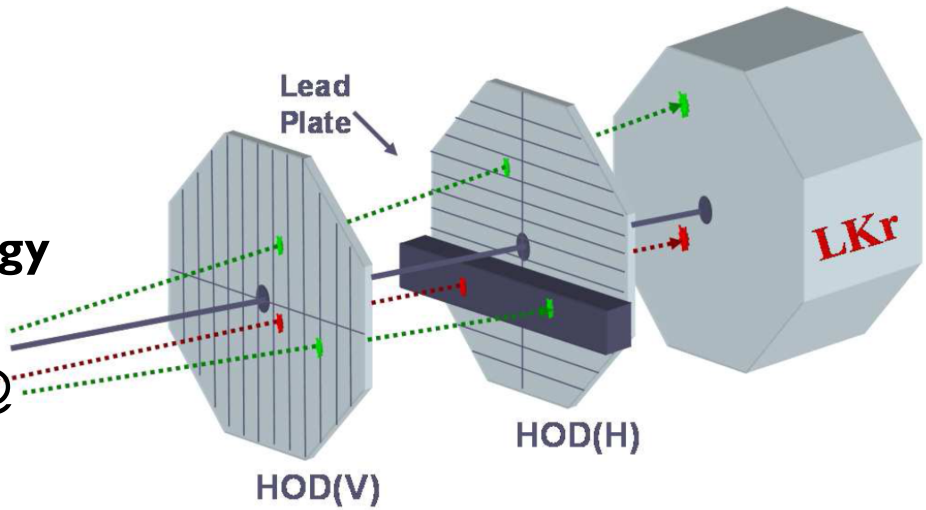
Analysis starting samples:

- **K_{e2} trigger:** 1 trk (hodoscope) & 1-trk activity in DCH's & E_{LKr}>10 GeV
- **$K_{\mu2}$ 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:

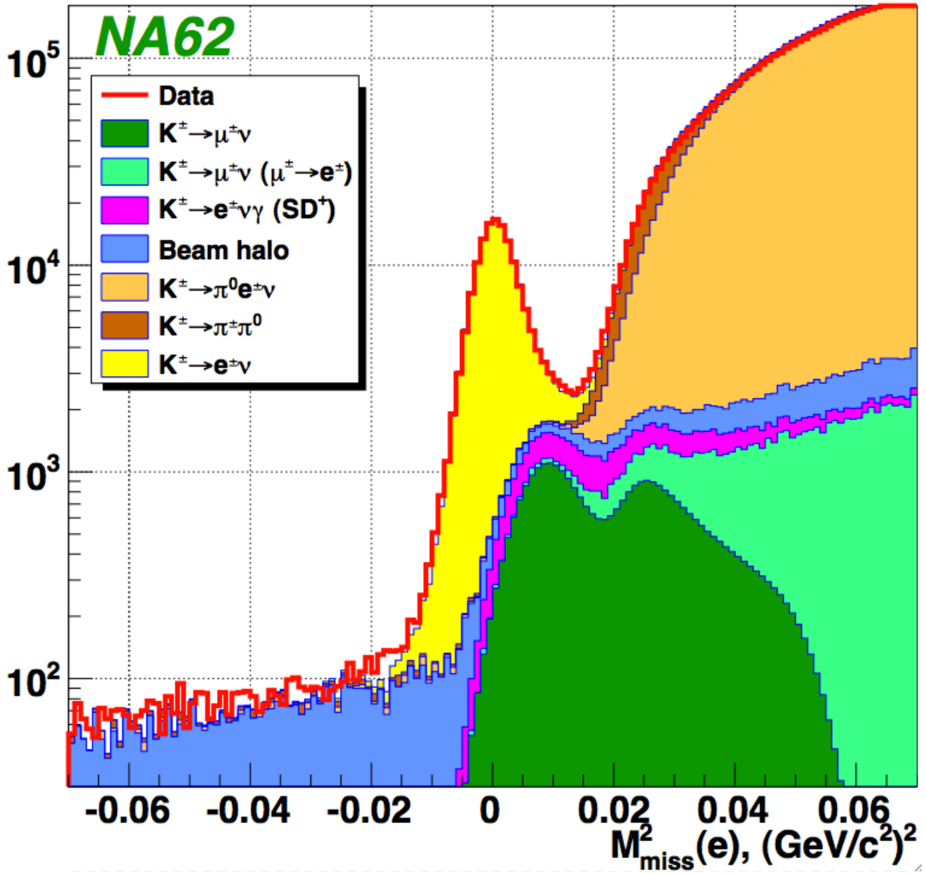
- Subsample of data taken with a 9.2-X_0 Pb bar between HOD's
- Select μ's (pure @<10^{-8}) with MIP energy loss in Pb
- Correct method bias (ionization loss @ low P, brems. @ high P) w GEANT4

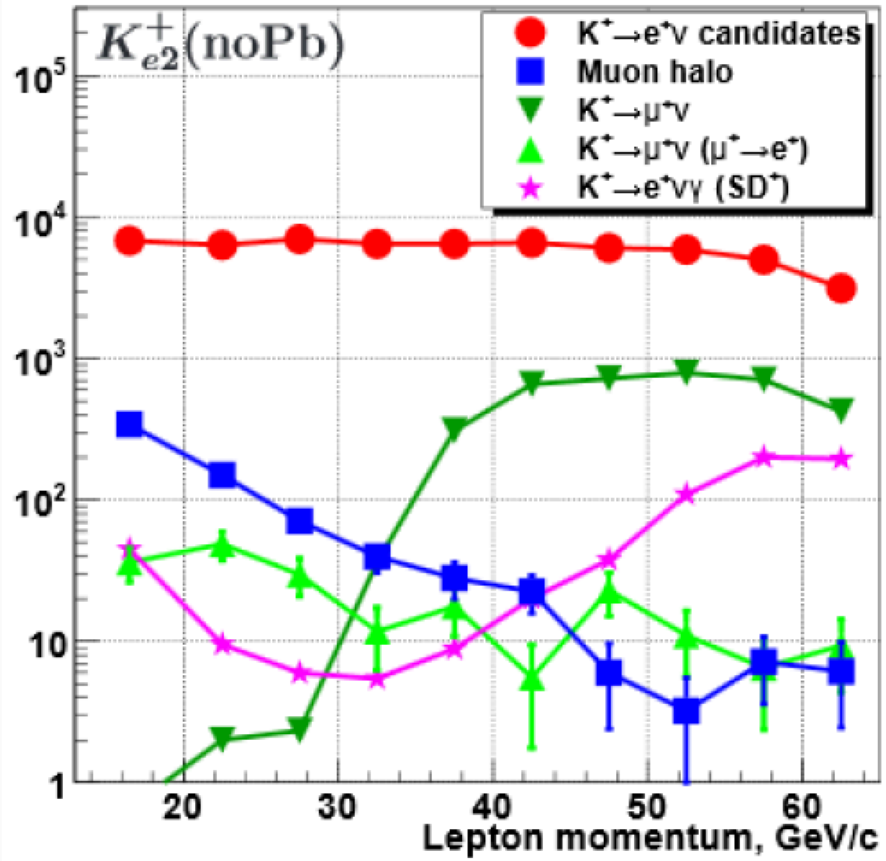


Analysis of Ke2/Kμ2 at NA62: other backgrounds

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)

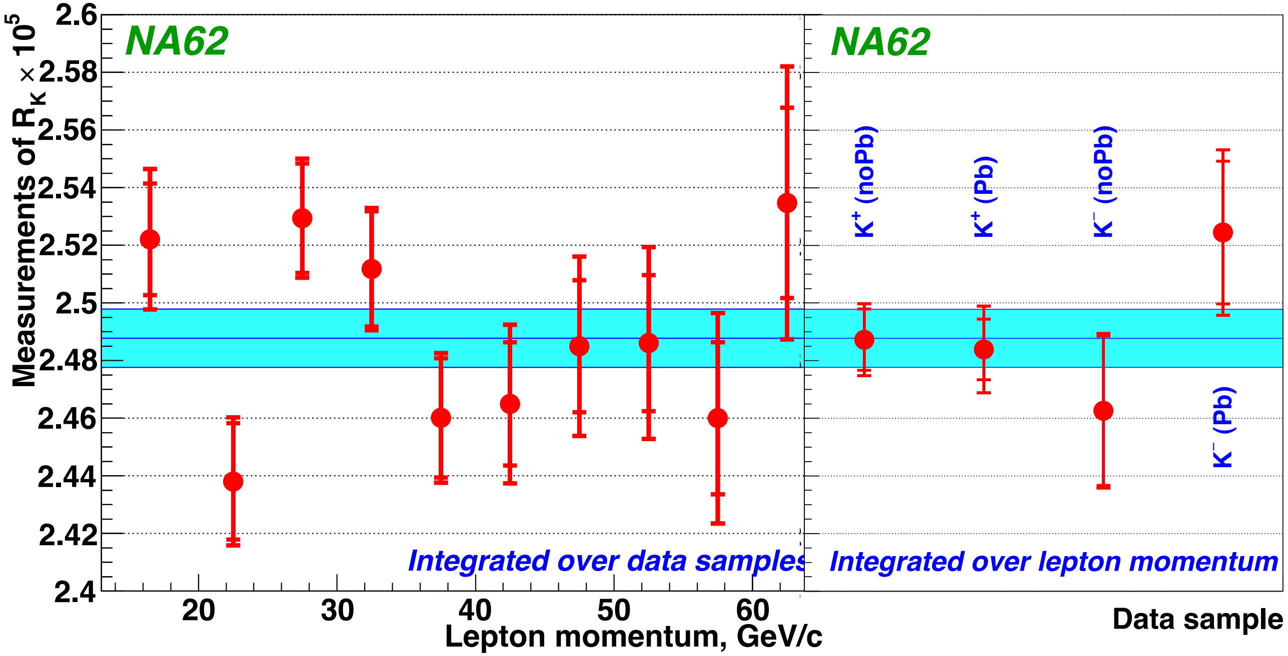




2013 NA62 RK result and error budget

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
Kμ2 bkg	0.004
Ke2γ SD+ bkg	0.002
Ke3, ππ⁰ 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

Result,

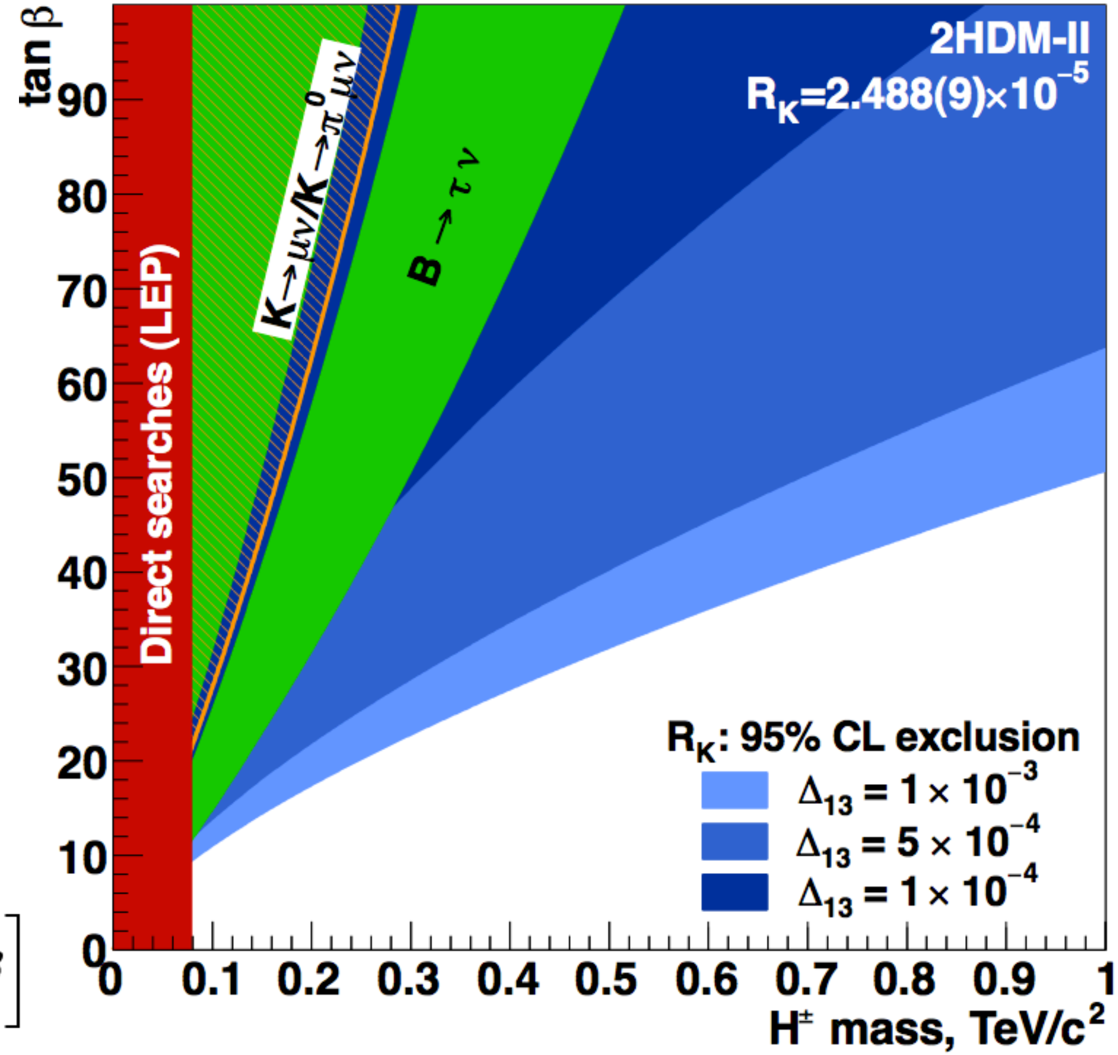
$R_K = 2.488(7)_{stat}(7)_{syst} 10^{-5}$ [PLB 719 (2013) 326],

dominates world average
To be compared 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

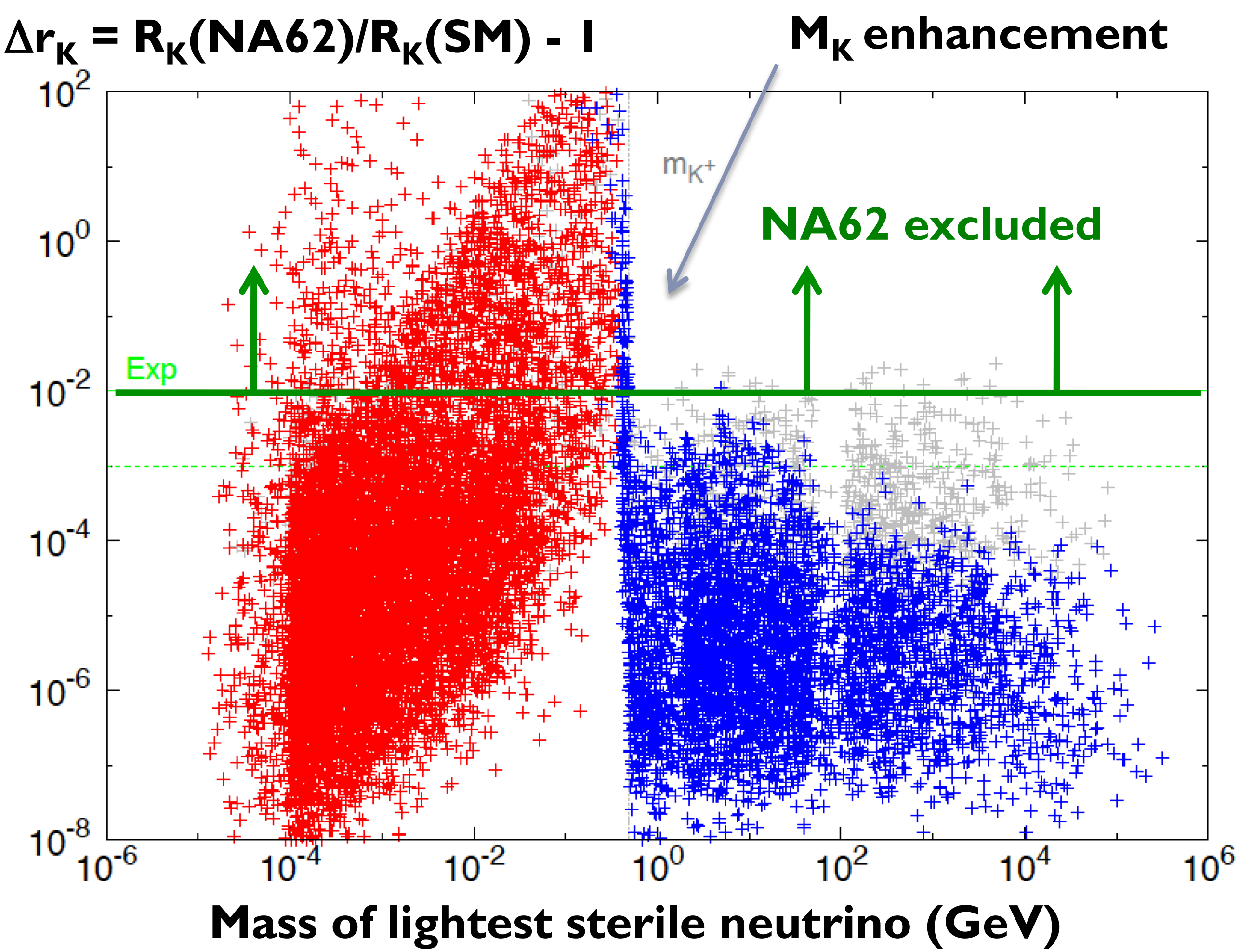
Probe NP from sterile ν's w inverse see-saw [Abada et al. JHEP 1402 (2014) 091]

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

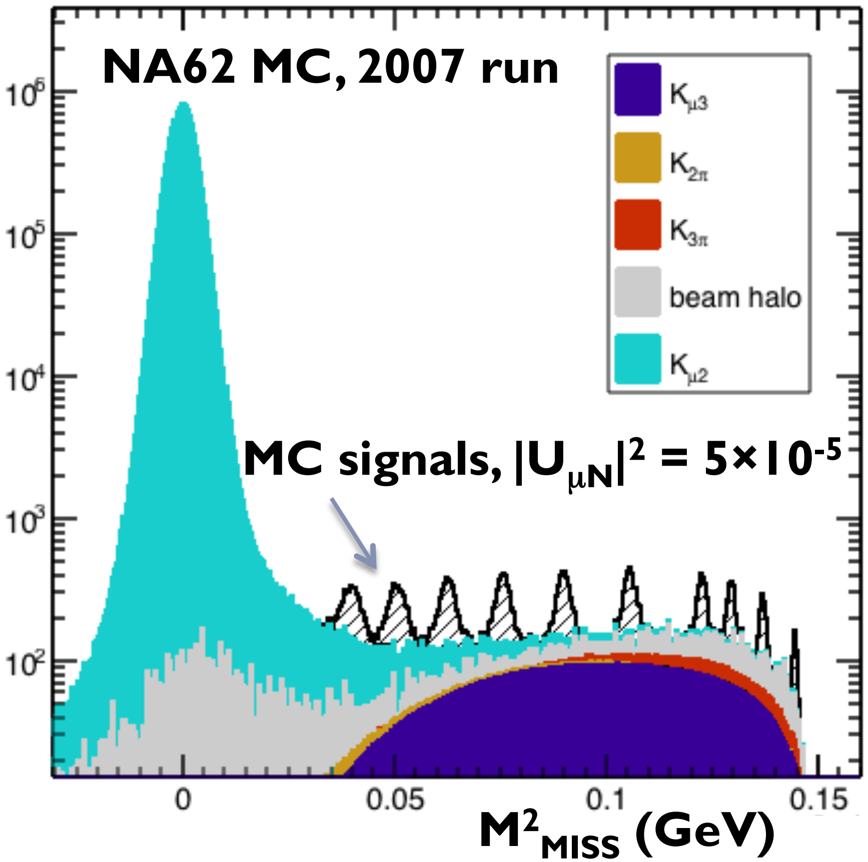
Models excluded by present μ→eγ MEG result

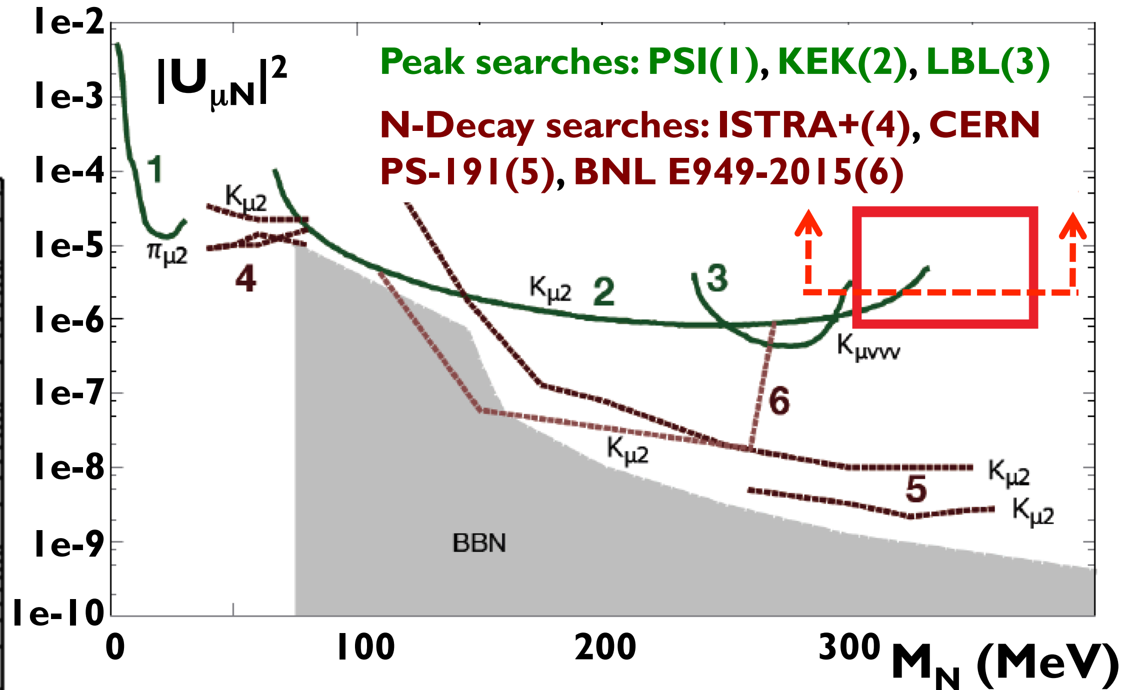


Searching for direct production of sterile ν's

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

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





NA62 (2007 data) competitive w past peak-based searches for M_N > ~250 MeV

Decay searches complementary to peak

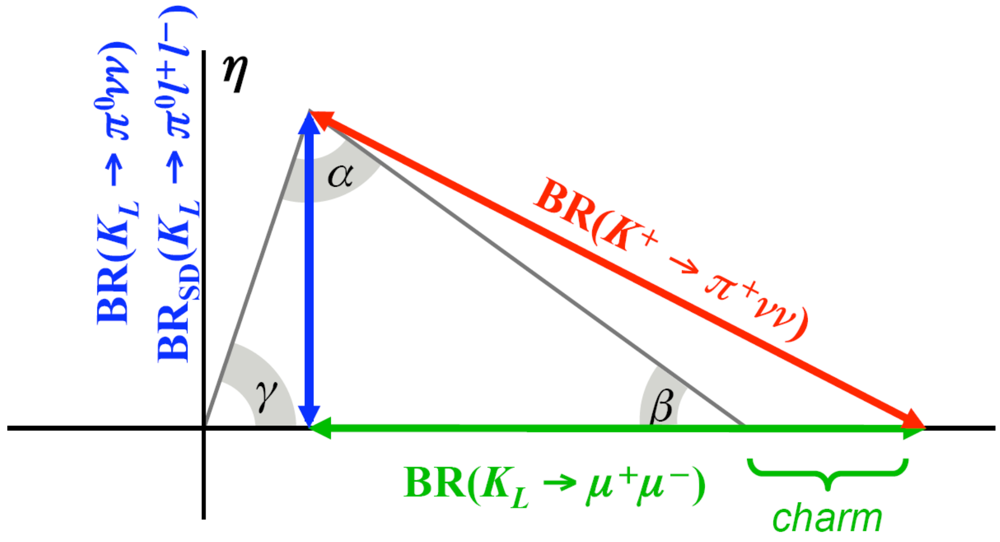
NA62 analysis (2007 data) almost completed

K physics – the future: golden modes for NP

FCNC processes dominated by Z-penguin and box diagrams

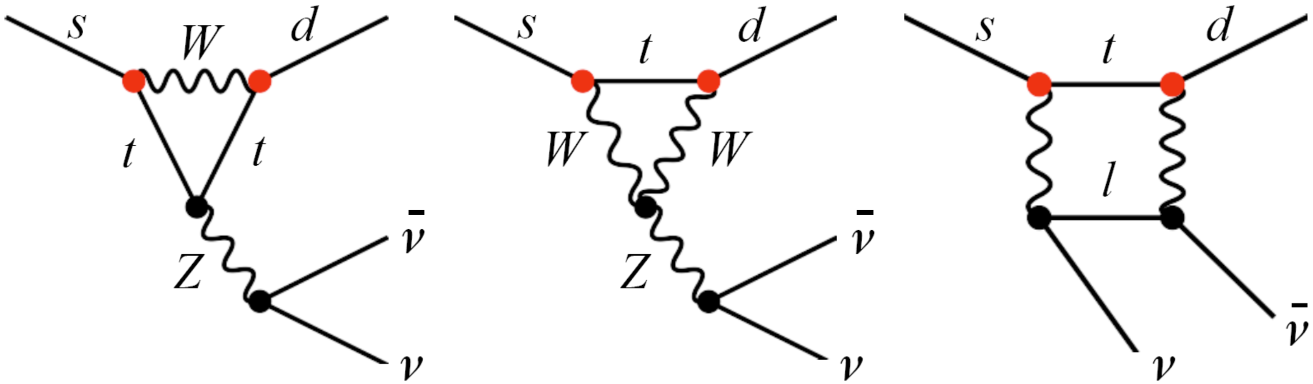
Can give direct information on CKM matrix elements:

- **No long distance contributions from processes with intermediate γ's**
- **Hadronic matrix elements can be obtained from BR's of leading K decays**
- **$K_L \to \pi^0 \nu\nu$ is nearly pure due to direct CPV (1% contribution from mixing CPV)**



	Γ_{SD}/Γ	Irreducible theory err. (amp)	SM BR
$K_L \to \pi^0 \nu\nu$	>99%	2%	3×10^{-11}
$K^+ \to \pi^+ \nu\nu$	88%	4%	9×10^{-11}
$K_L \to \pi^0 e^+ e^-$	38%	15%	3.5×10^{-11}
$K_L \to \pi^0 \mu^+ \mu^-$	28%	30%	1.5×10^{-11}

SM prediction for K→πνν



SM prediction [Brod, et al. 2011, CMK input update Buras et al. 2015]

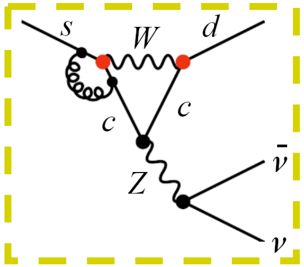
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1+\Delta_{\mathrm{EM}}) \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{\mathrm{Re}\lambda_t}{\lambda^5} X_t \right)^2 \right] = (9.11 \pm 0.72) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = (3.00 \pm 0.31) \times 10^{-11}$$ **where** $x_q \equiv m_q^2/m_W^2$,

$$\lambda = V_{us}, \quad \lambda_c = V_{cs}^* V_{cd}, \quad \lambda_t = V_{ts}^* V_{td}$$

Loops favor top contribution

Hadronic matrix elements from BR(Ke3) via isospin rotation



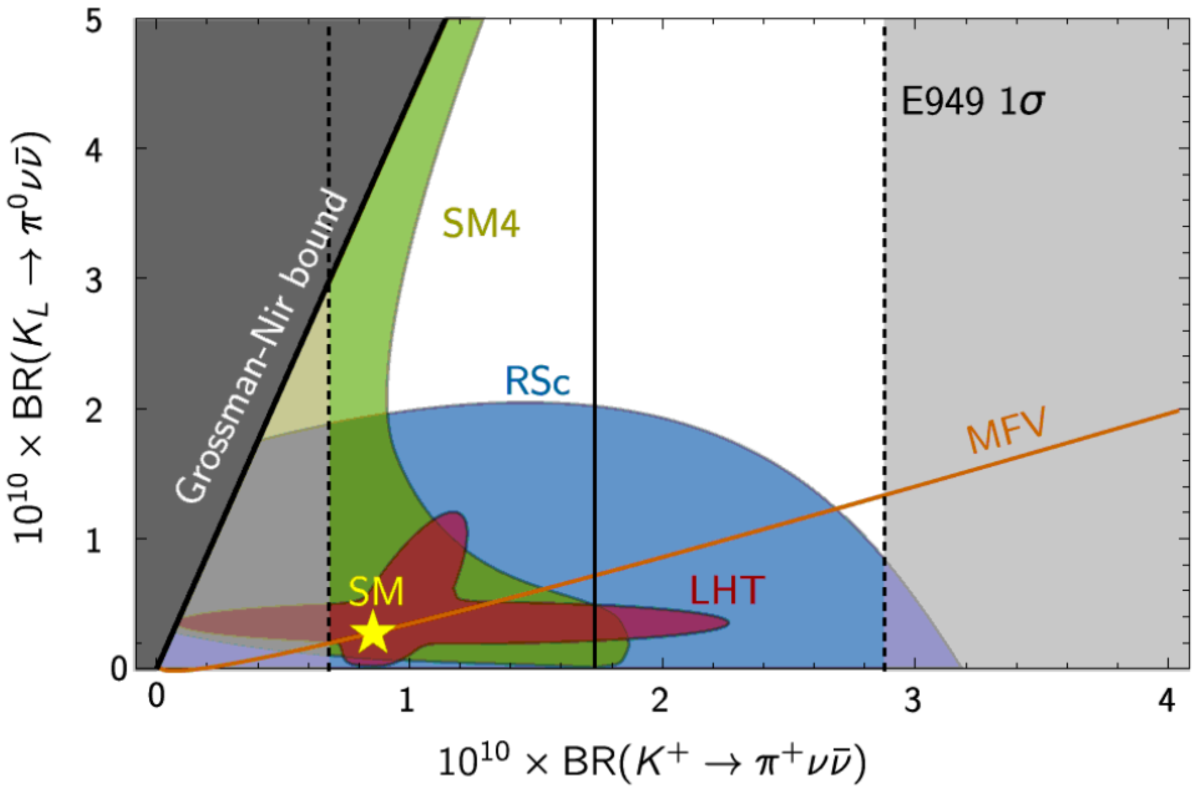
Charm contributes to theory error: 4% (2%) for K^+ (K_L)

Error on input parameters (V_{cb}, ρ, η, ...) dominant wrt other theory errors

Beyond-SM sensitivity for K→πνν

Deviations from SM by more than 10% quite possible in many NP models:

- Littlest Higgs Model with T-parity
- Minimal Flavor Violation
- Randall-Sundrum with custodial protection
- 4th generation

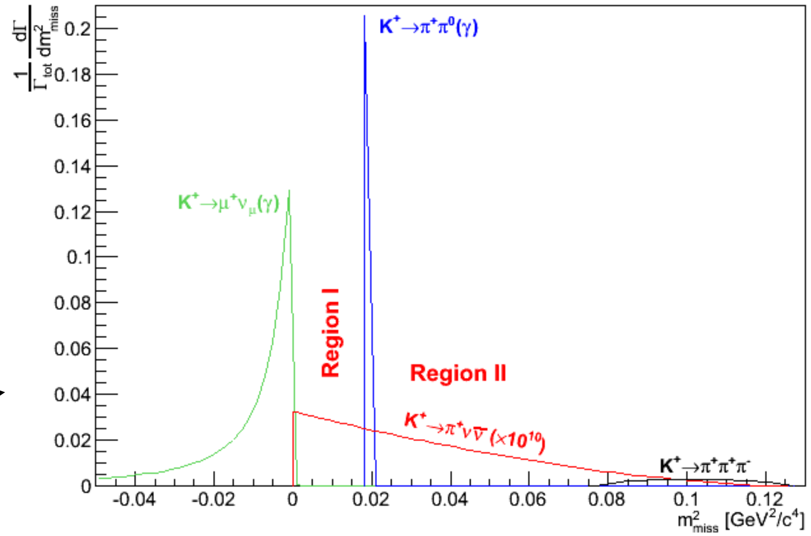


Experimental methods for $K^+ \rightarrow \pi^+\nu\nu$

Main backgrounds to $K^+ \rightarrow \pi^+\nu\nu$:

- **$K^+ \rightarrow \mu\nu$ with π ID for μ**
  - **need excellent PID, especially μ/π**
- **$K^+ \rightarrow \pi\pi^0(\gamma)$ with γ's lost**
  - **need excellent γ vetoes**

Kinematic rejection for 2 body →



To reach 10^{-12}, PID & vetoes also reject unclosed bkg (K_{l3}, K_{l4}, …)

	Stopped K^+	Decay in flight
Kinematics	K^+ at rest	Must track K^+
Photon vetoes	Low-energy photons	High-energy photons
PID	Range π-μ-e decay chain	Advanced Cerenkov counters Muon detectors

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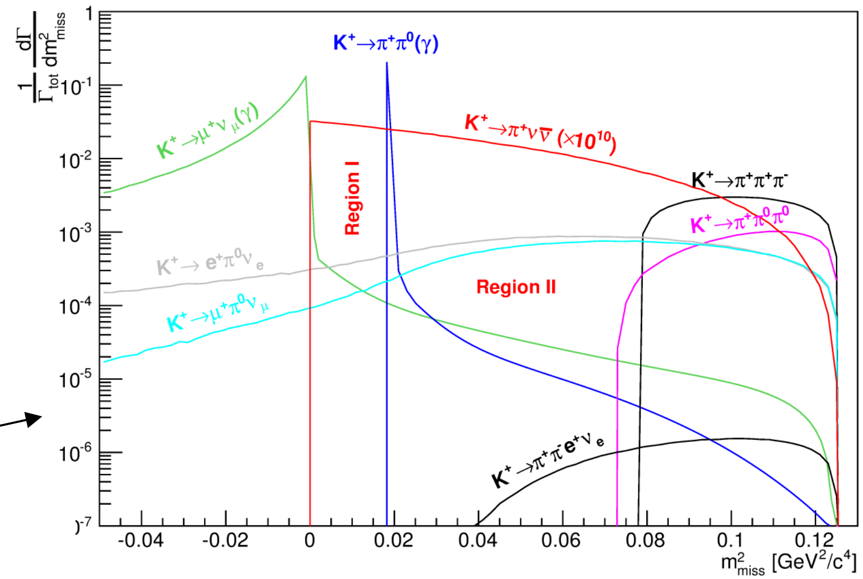
Kinematic rejection for multibody →



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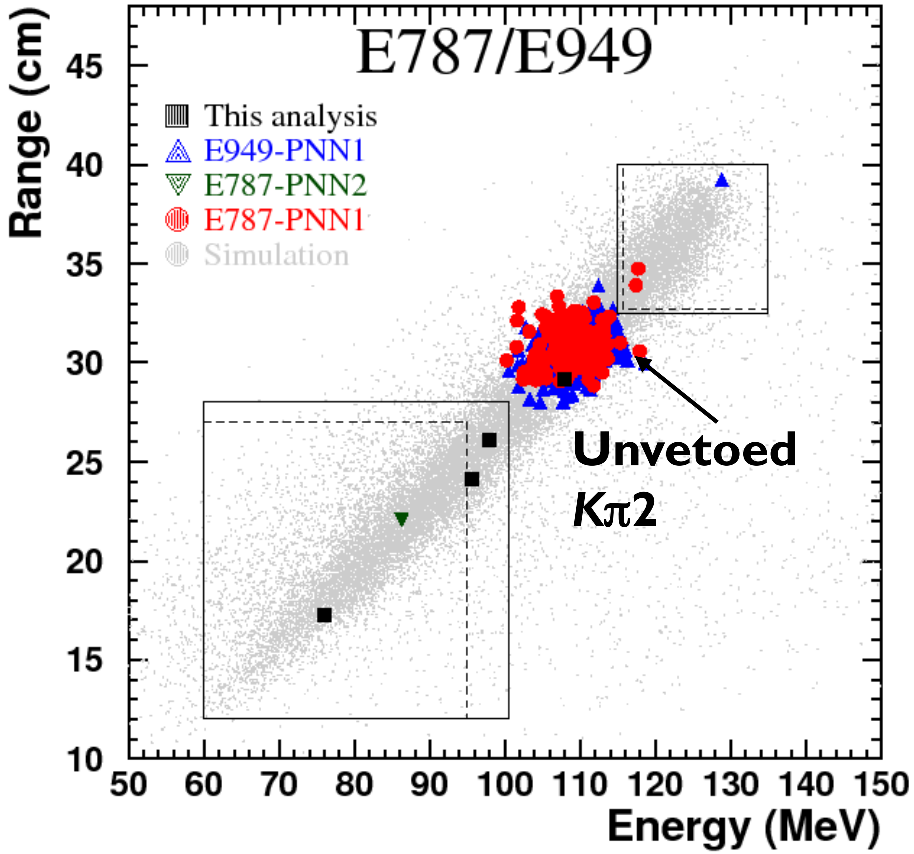
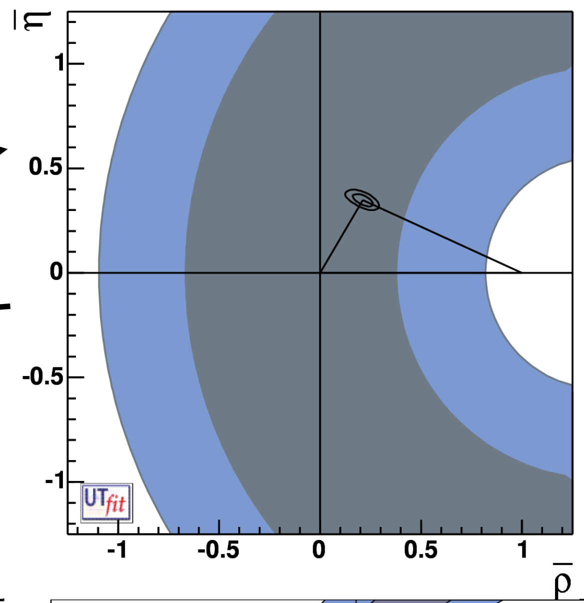
Experimental status for $K^+ \rightarrow \pi^+\nu\nu$

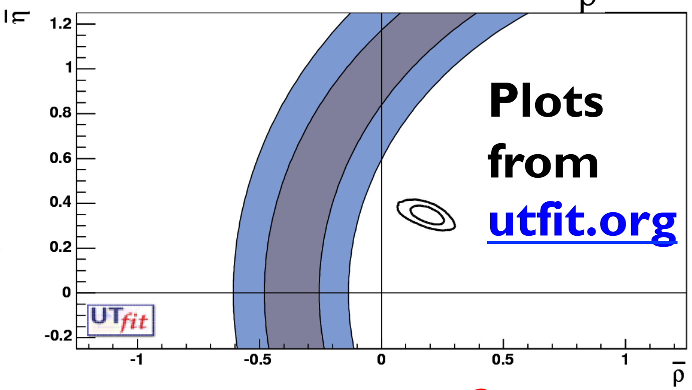
In 2008, combine E787 (1995-8 runs) & E949 (12-weeks run in 2001) results

$BR(K^+ \rightarrow \pi^+\nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$





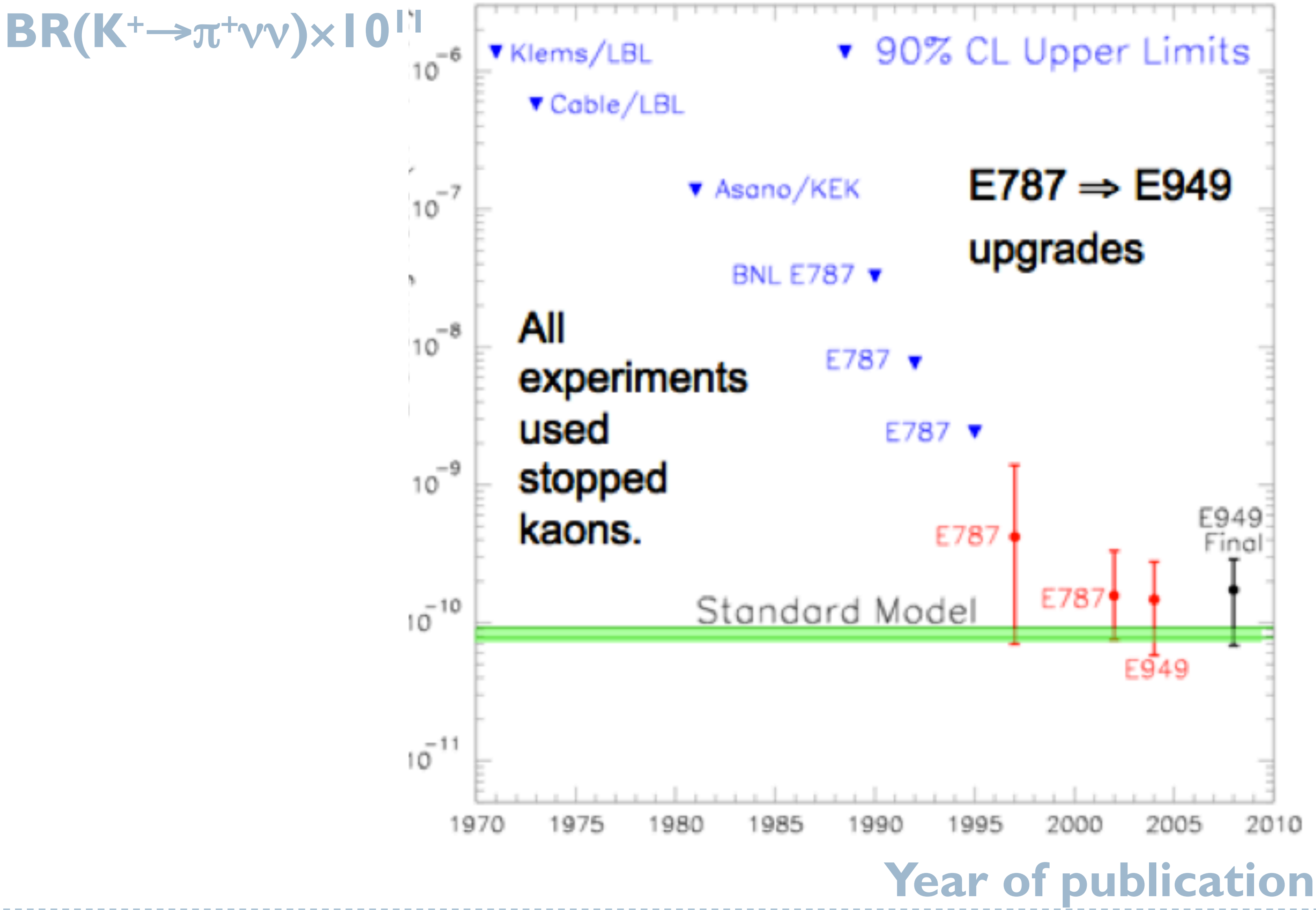
Same central value, 100 evts



Plots from utfit.org

Expected bkg 2.6 events, prob. all 7 obs. evts are bkg is $\sim 10^{-3}$

Hopefully not the end of a long story...



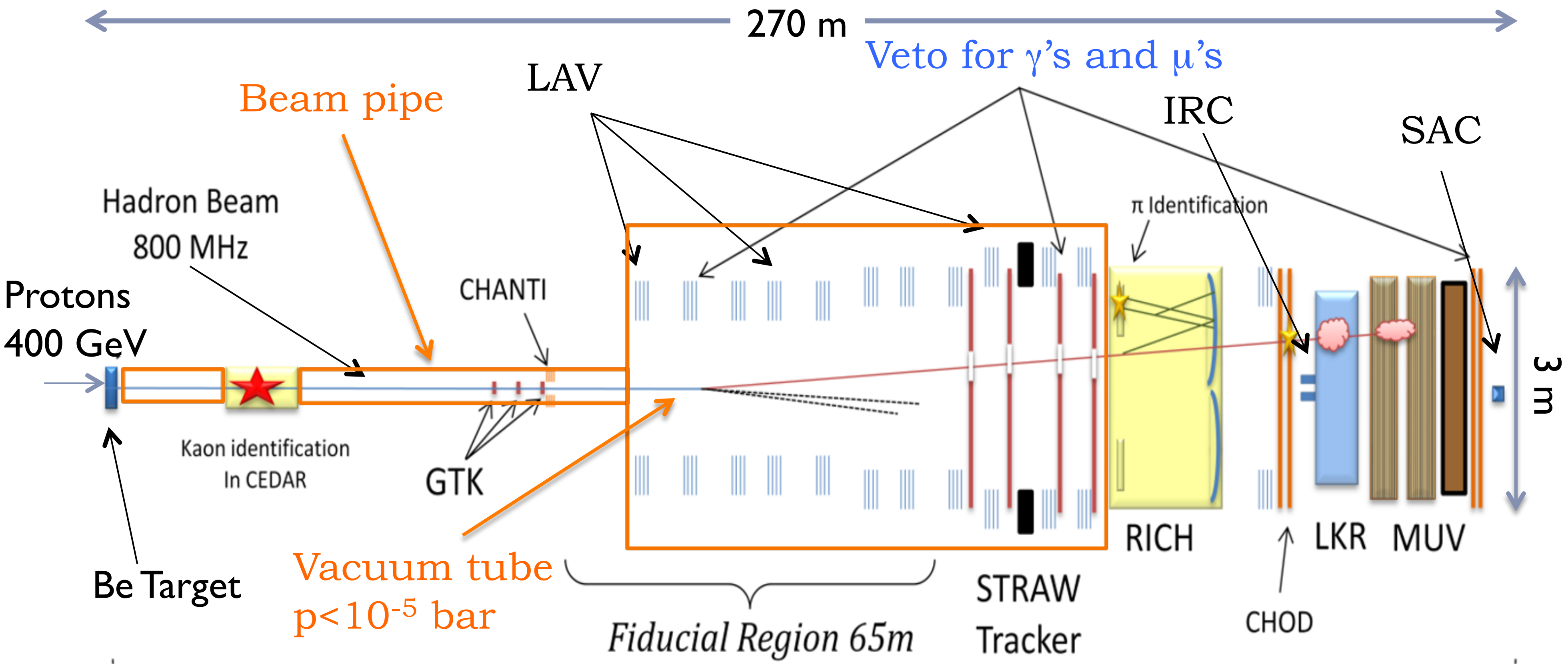
…major improvements with present NA62

Major beam and detector upgrades for $K^+ \rightarrow \pi^+ \nu\nu$

	NA48/2	NA62-RK	NA62
Data taking	2003-4	2007-8	**2014-17**
Primary intensity (ppp)	7×10^{11}	7×10^{11}	**3×10^{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}	**1.2×10^{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 (6% K+) , ~10 MHz downstream

Three-level trigger scheme:
- **L0 HW,** (FPGA) from ~10 to 1 MHz, <1-ms latency
- **L1 SW,** event info (no LKr), 100 KHz out
- **L2 SW,** full info, output few KHz

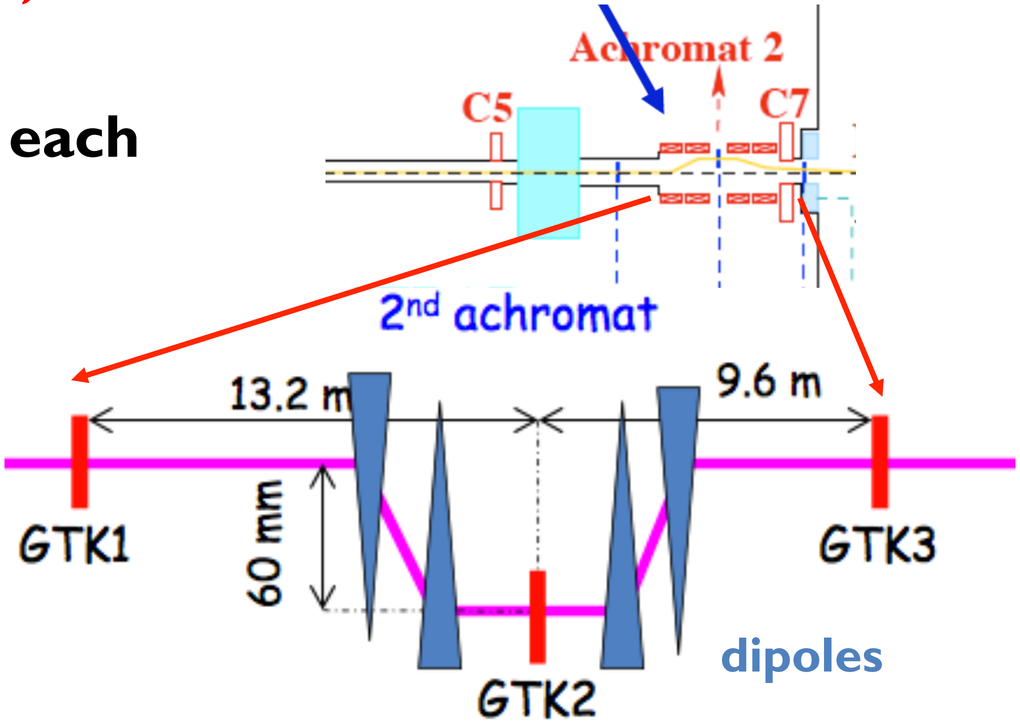
Fast tracking before decay volume – GTK

Aim to measure time, coordinates, and momentum of individual particles in a 800 MHz beam

3 silicon μ-pixel stations, <0.5% X_0 each

Other demanding constraints:

- **100 μm space resolution**
- **δp/p ~ 0.2%, i.e., δp ~ 150 MeV**
- **δα/α ~ 12 μrad**



Structure:

- **18000 300×300 μm² pixels, sensitive area of 60×27 mm²**

Technological challenge:

- **<1% hit mismatch @ 800 MHz → 200 ps time resolution**
- **sustain rate up to 150 KHz/pixel → μ-channel cooling (1st time in HEP)**

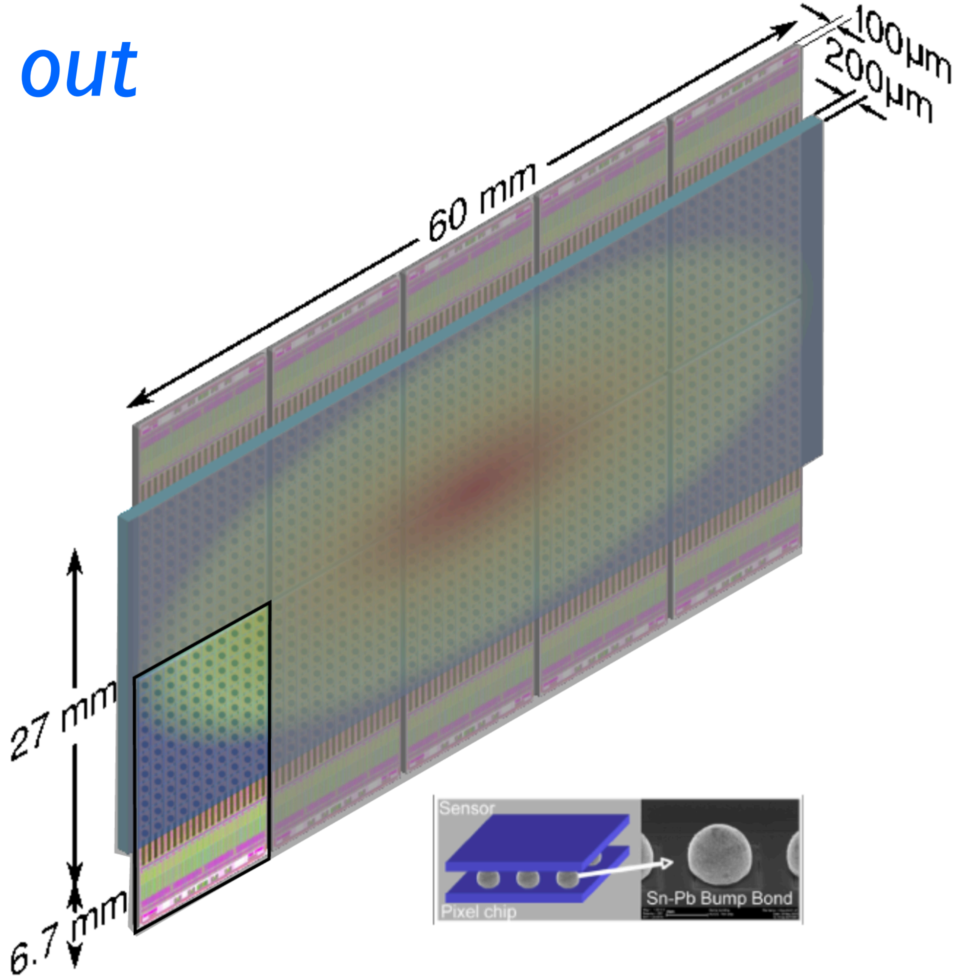
GTK technology and read out

Have to read out with dead time <100 ns, with a charge/pixel varying between 0.8 fC (5000 e-) to 10 fC (60000 e-)

- **have to correct for slewing**
- **maintain noise < 200 e-**
- **operate with reasonable power consumption, < 2 W/cm²**

Sensor [FBK,CIS] : p-in-n/n-in-p, 300-600 V bias, 200 μm thick

10 TDCPix chips/station: 130 nm CMOS(IBM), thinned at 100 μm



3 stations during 2015 run: measured 215 ps time resolution@300 V

For details, see Talk by M. Perrin-Terrin, 14th VCI, Wien, AT

Photon vetoing in NA62

Have to reject $K^+ \rightarrow \pi^+\pi^0$ @ the level of 10^{-12}

Need π^0 rejection of $O(10^{-8})$ for γ's from K decay in FV (~60 m)

A composite system:

- **Very small angle, below 2 mrad**
  - **A new system of compact calorimeters**
  - **Inefficiency required $<10^{-6}$ for γ's above 6 GeV**
- **Small angle, 1 to ~8 mrad:**
  - **Re-use NA48 LKr calorimeter, $\sigma_E/E = 3.2\%/\sqrt{E[GeV]} + 9\%/E[GeV] + 0.42\%$**
  - **Inefficiency measured $<10^{-5}$, for γ's above 6 GeV**
- **Large angle, ~8 to 50 mrad:**
  - **A new veto system (LAV system)**
  - **Inefficiency required $< \sim 10^{-4}$ for 100 MeV $< E_\gamma <$ 25 GeV**
  - **Able to operate in a vacuum of 10^{-6} mbar**

Large angle veto layout and geometry

Rearrange SF4 lead crystals from OPAL in staggered layers (rings)
Install rings inside existing vacuum vessel (so called "blue tube")

12 stations of increasing diameter cover hermetically the range θ = 7–50 mrad

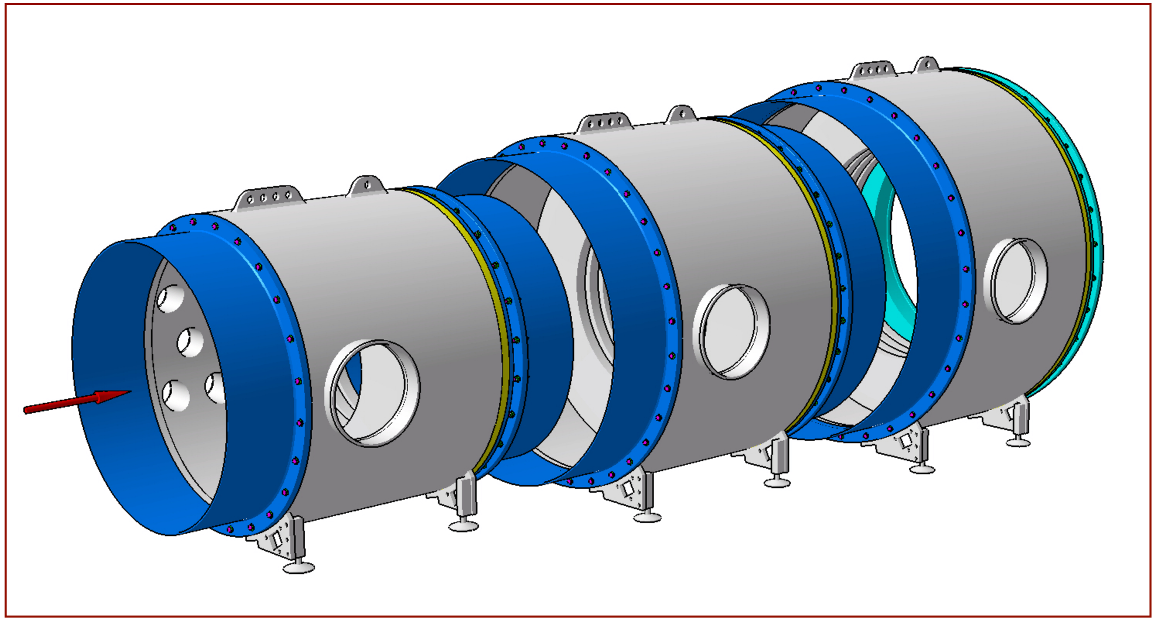
3 different sizes of vacuum vessels (last downstream station operated in air)

4 to 5 layers/station for a total depth of 29 to 37 X_0, particles traverse > 20 X_0

32 to 48 crystals/layer

A total of ~ 2500 blocks

Fully operated in 2015



A new redundant PID @ NA62: the RICH

Require: 10^2 μ-vs-π rejection for $15 < p < 35$ GeV, time resolution ~ 100 ps

A ring-imaging Cherenkov counter (RICH) with a 17m long vessel

200 m^3 of Neon as radiator, refractive index $n-1 = 62.8 \times 10^{-6}$ at $\lambda = 300$ nm

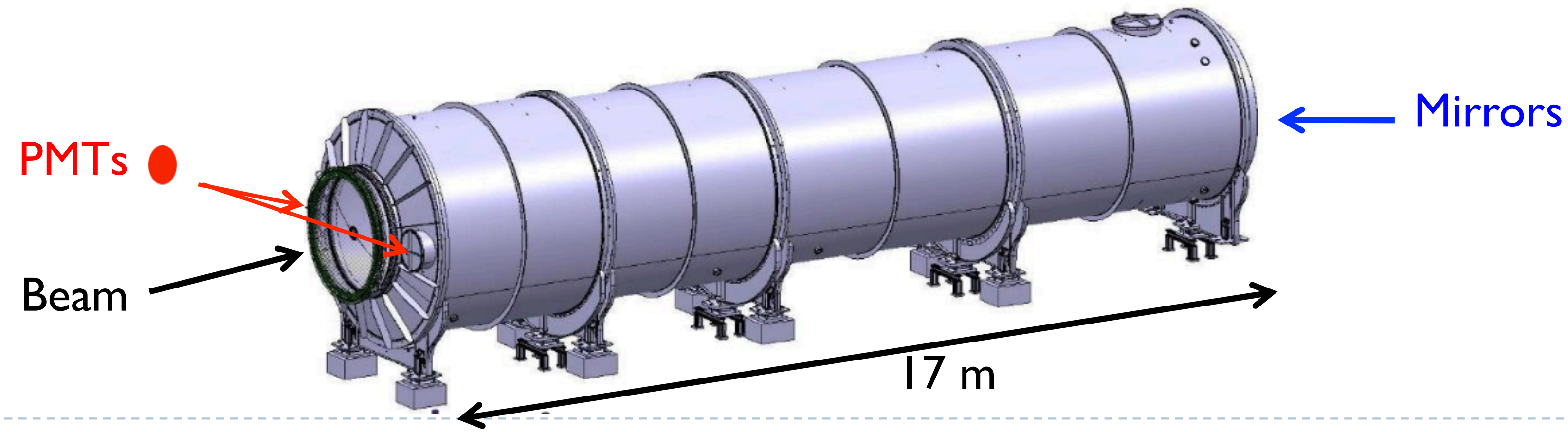
- Pion momentum threshold of 12 GeV/c

20 hexagonal mirrors (35 cm side) and 2 semi-hexagonal mirrors (around beam pipe)

- Average reflectivity better than 90%
- Pointed towards left & right detection disks

RO based on 1952 Hamamatsu R7400U-03 PMTs in 2 Al disks placed in upstream endcap

FE: custom current amplifier, differential output, NINO chips



Performance of the NA62 RICH

Analysis of 2015 physics runs at 10% and 40% beam intensity wrt nominal

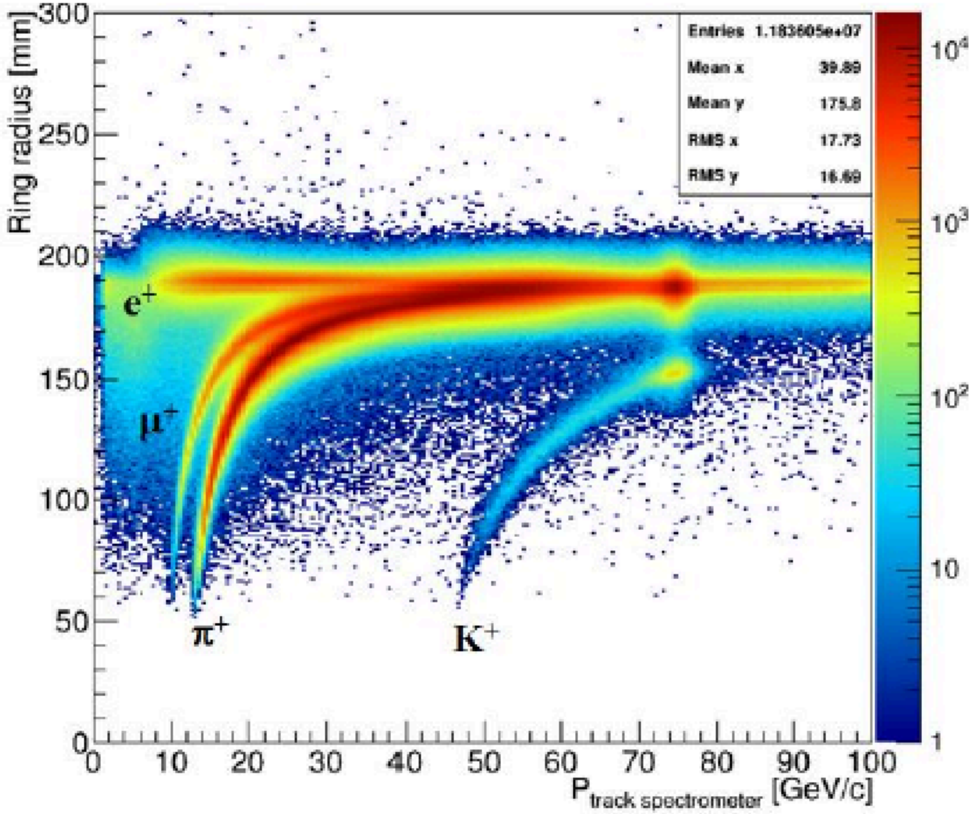
Perform matching using direction from spectrometer track

Correlate radius of reconstructed Cherenkov ring to momentum measured by spectrometer

Preliminary results:

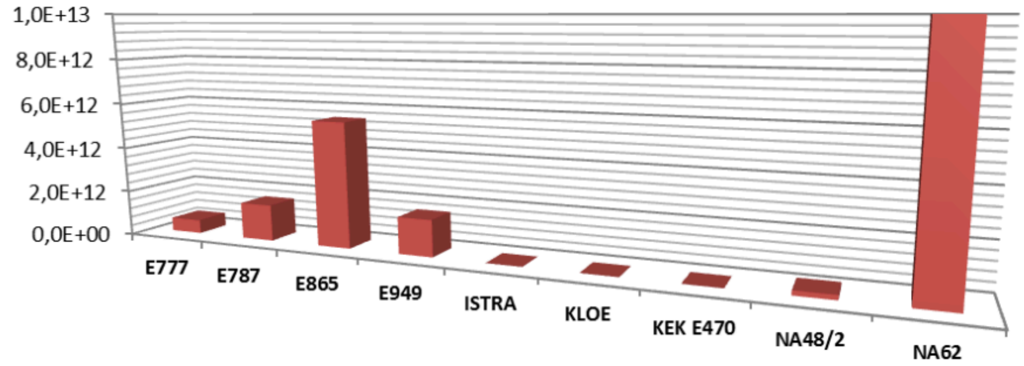
π-vs-μ rejection factor: 50

average efficiency of
ring reconstruction for pions: 83%



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)

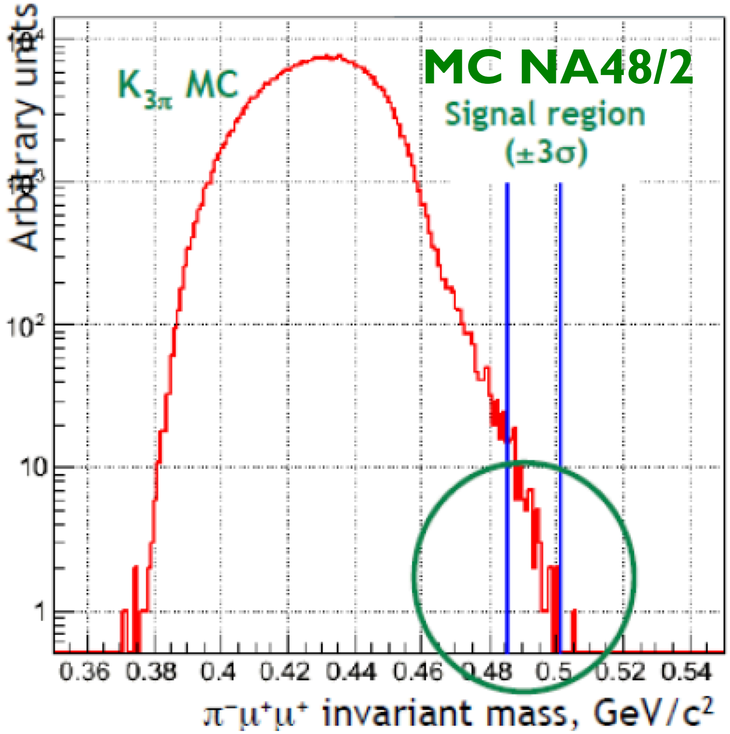
With acceptances of few to ten % efficiency, prospects to reach SES of 10^{-12}

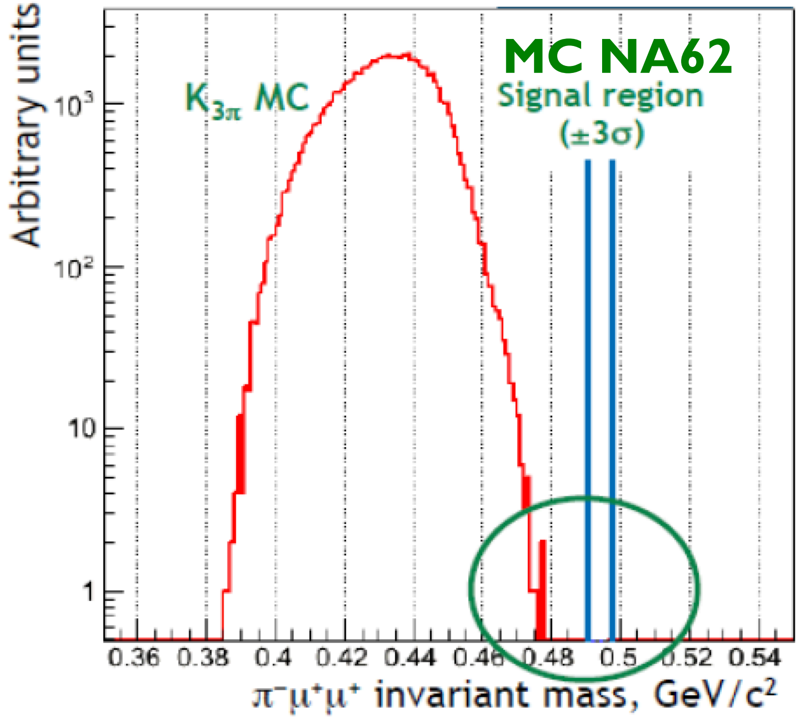
… and a broad physics program…

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9\times10^{-11}\ m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h\to\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

… 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 the study of rare 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

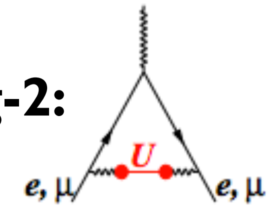
Feasibility studies started on several decays

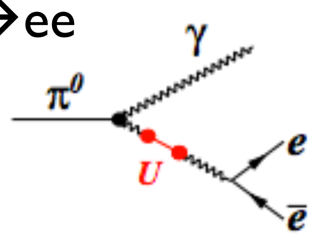
Mode	Observable	NP Motivation	SM	Present	Experiment
$\pi^0 \rightarrow 3\gamma$	BR	C-violation	Forbidden	$< 3.1 \times 10^{-8}$	Crystal Box, 1988
$\pi^0 \rightarrow 4\gamma$	BR, kinematics	Light exotic scalars	10^{-11}	$< 2 \times 10^{-8}$	Crystal Box, 1988
$\pi^0 \rightarrow$ inv	BR	RH neutrinos, LFV	$< 10^{-13}$ (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 $\pi^0 \rightarrow U\gamma$, $U \rightarrow ee$

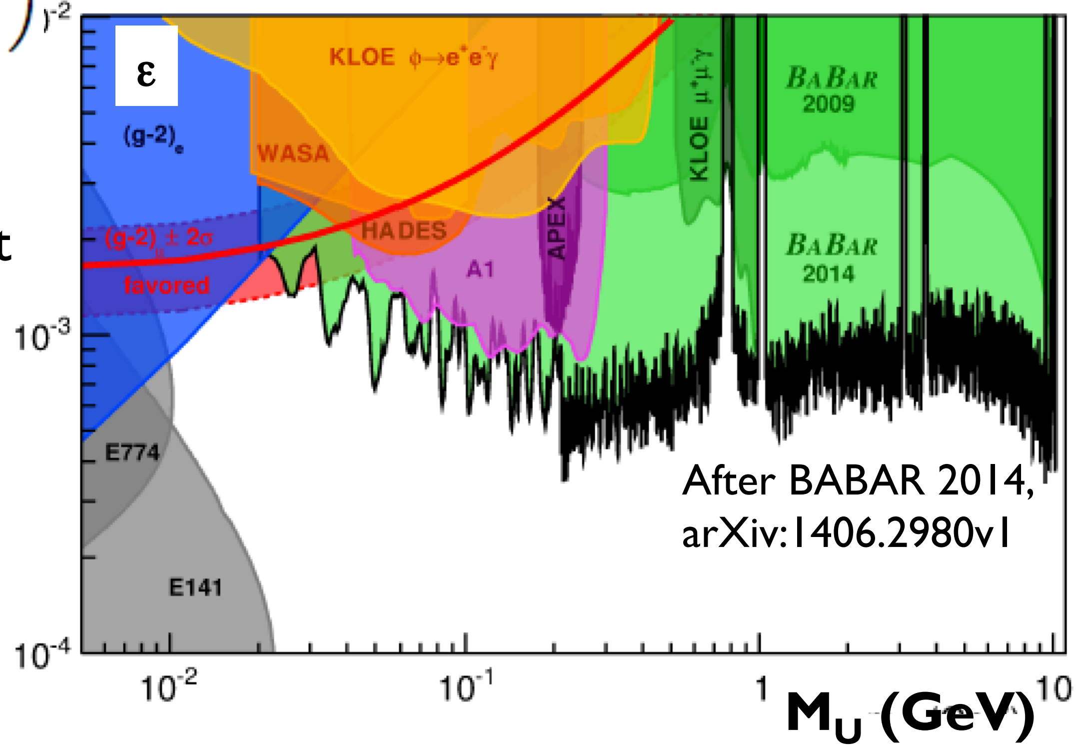
U boson enters as NP contribution to muon g-2:





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

For M_U < 2 Mμ, and effective coupling ε~10^{-3} width is ~ eV: U decay is prompt

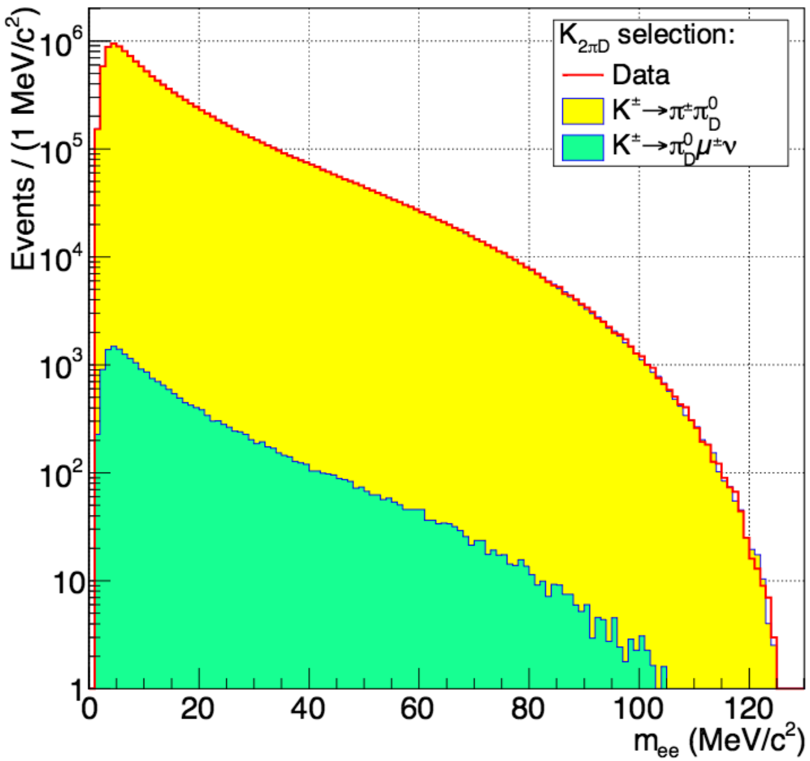


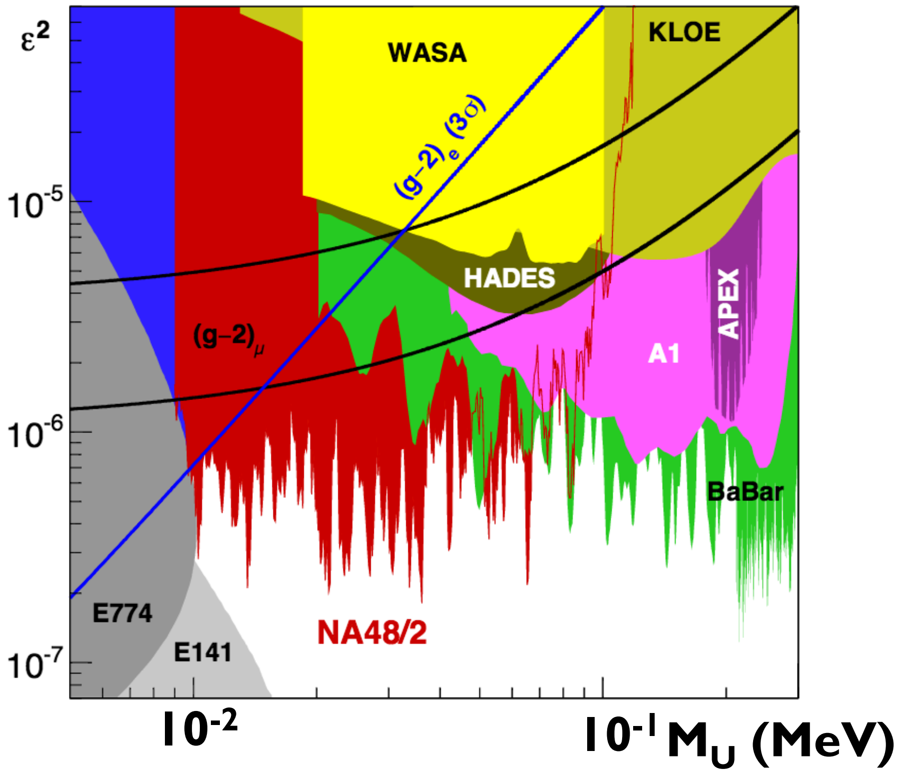
Recent results from NA48/2 and NA62

NA48/2: select ~1.7 10^7 $\pi^0 \rightarrow \gamma ee$ decays, from $K \rightarrow \pi\pi^0$, $\mu\nu\pi^0$

No peak observed in the ee invariant mass, on top of irreducible background, π^0_D

Exclude @ 90% CL in a g-2-favored region, improve for $9 < M_U < 70$ MeV
[arXiv:1510.02632] Moreover, FF slope for $\pi 0_D$ measured at NA62 [M. Koval @ LaThuile'16]



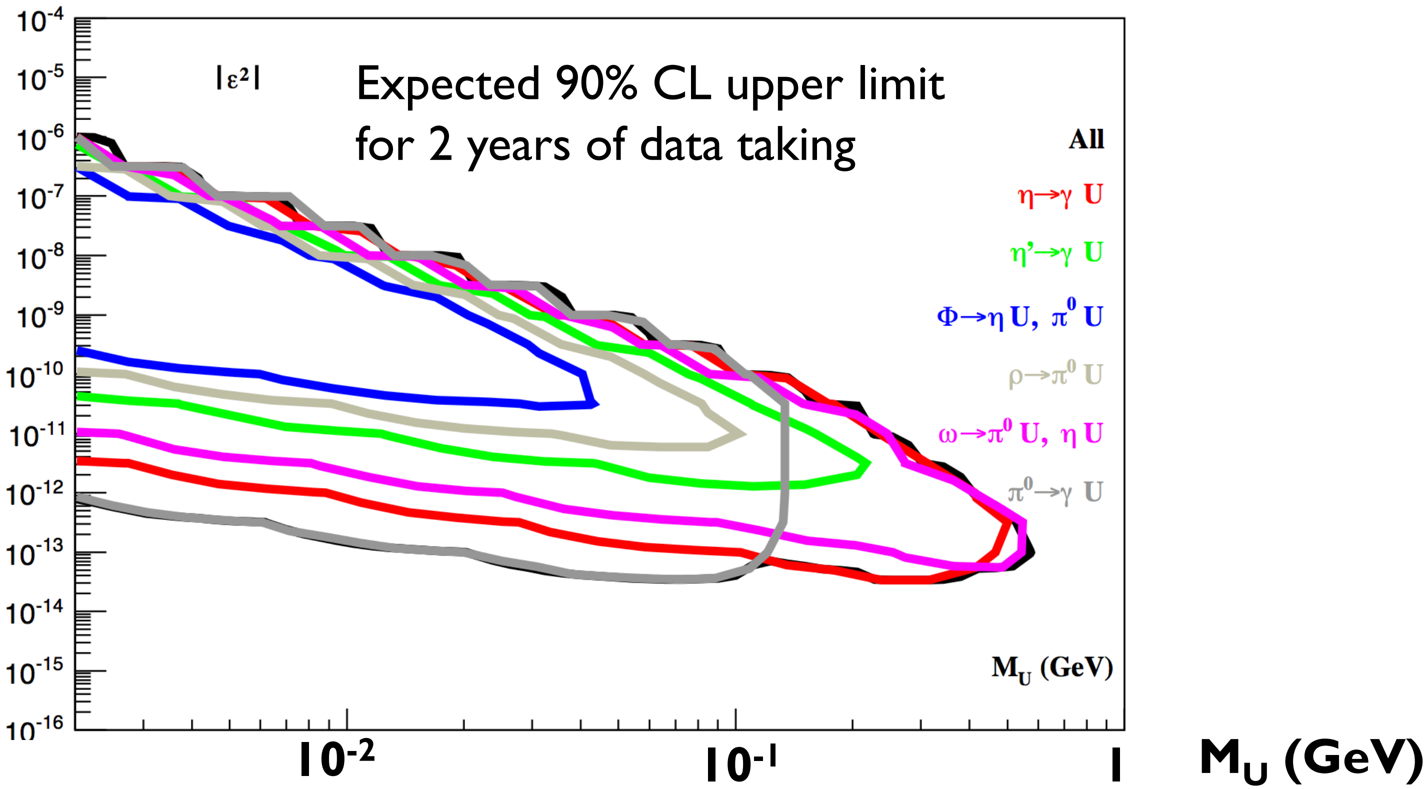


Not only K: search for U bosons at NA62

At NA62: 3-track trigger + PID: rate sustainable, expect 10^8 $\pi 0_D$/year, e^+e^- invariant mass resolution improves by x2 over NA48/2: expect > x10 sensitivity improvement

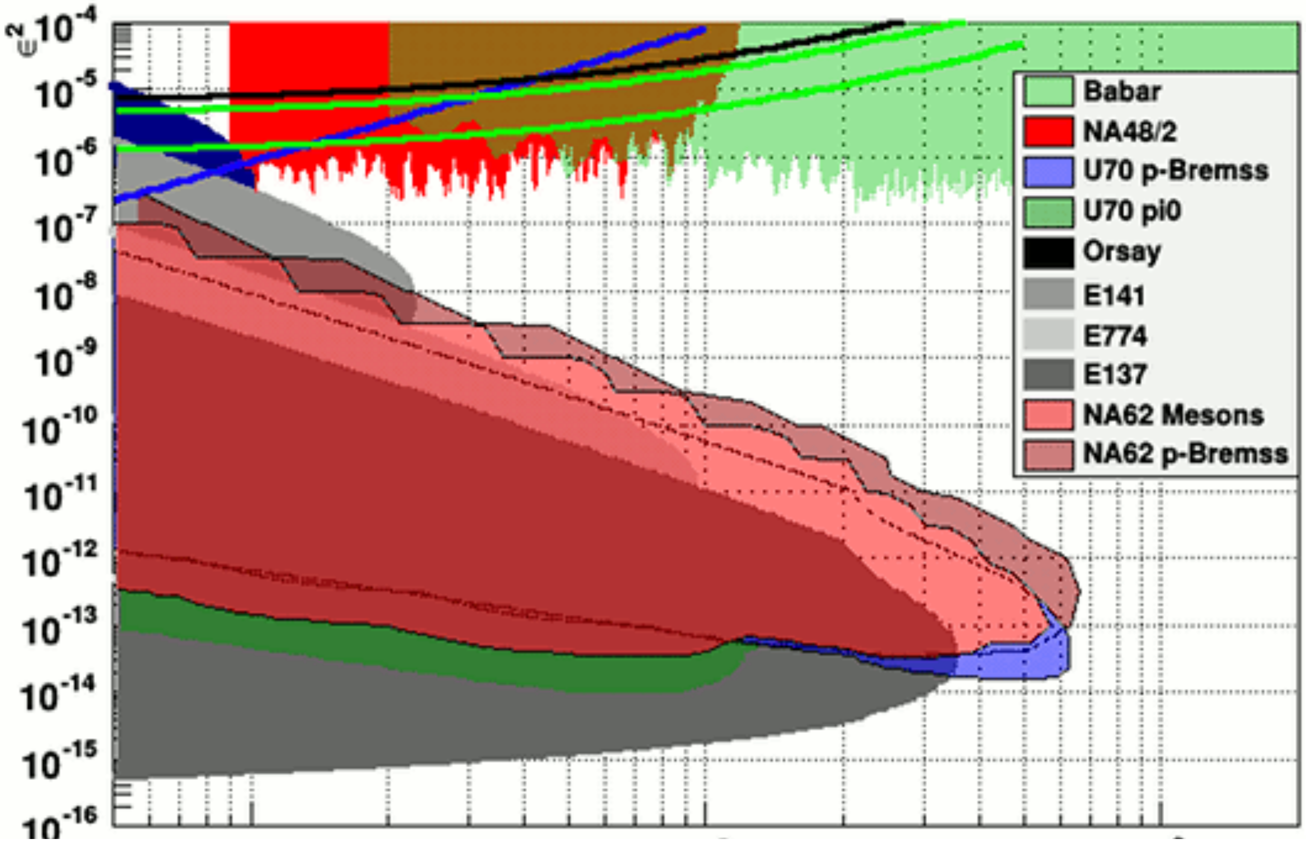
NA62 can exploit **meson (π^0, η, η', ω, Φ, ρ) decays** at production to long-lived U's

Will search for e^+e^- and $\mu^+\mu^-$ pairs in the NA62 fiducial volume



Search for U bosons at NA62

Expected (zero-background) sensitivity should improve on present limits



Expected 90% CL UL for $U \to l^+l^-$ after 2 years of data taking:

U from meson decays vs U from p-Bremsstrahlung

Acceptance and trigger efficiency included

Riv. Nuovo Cim. 38 (2015) 10, 449 + my evaluations for NA62

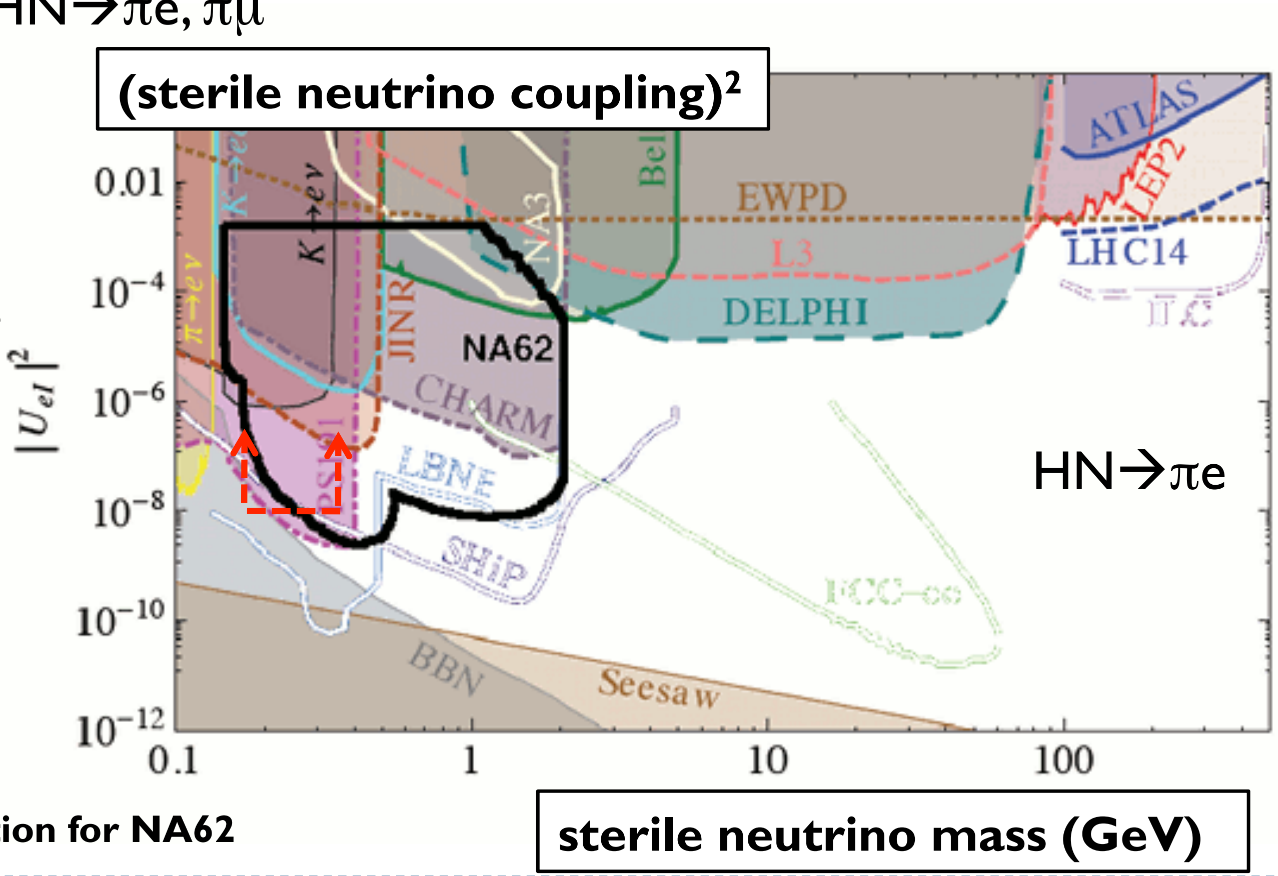
Heavy neutral leptons from meson decays

Mesons ($D_{(s)}$, K's) produced at target might decay to long-lived exotic particles reaching the NA62 decay volume

The simplest signatures for heavy neutral leptons correspond to two-body (semi)leptonic decays: HN→πe, πμ

Production + decay: yield ~ (coupling)^4

Complementary to the invisible search from Ke2 decays using 2015 data from NA62 (expectation, which should exceed limit from 0νββ decays)



arXiv:1504.04855 + **my evaluation for NA62**

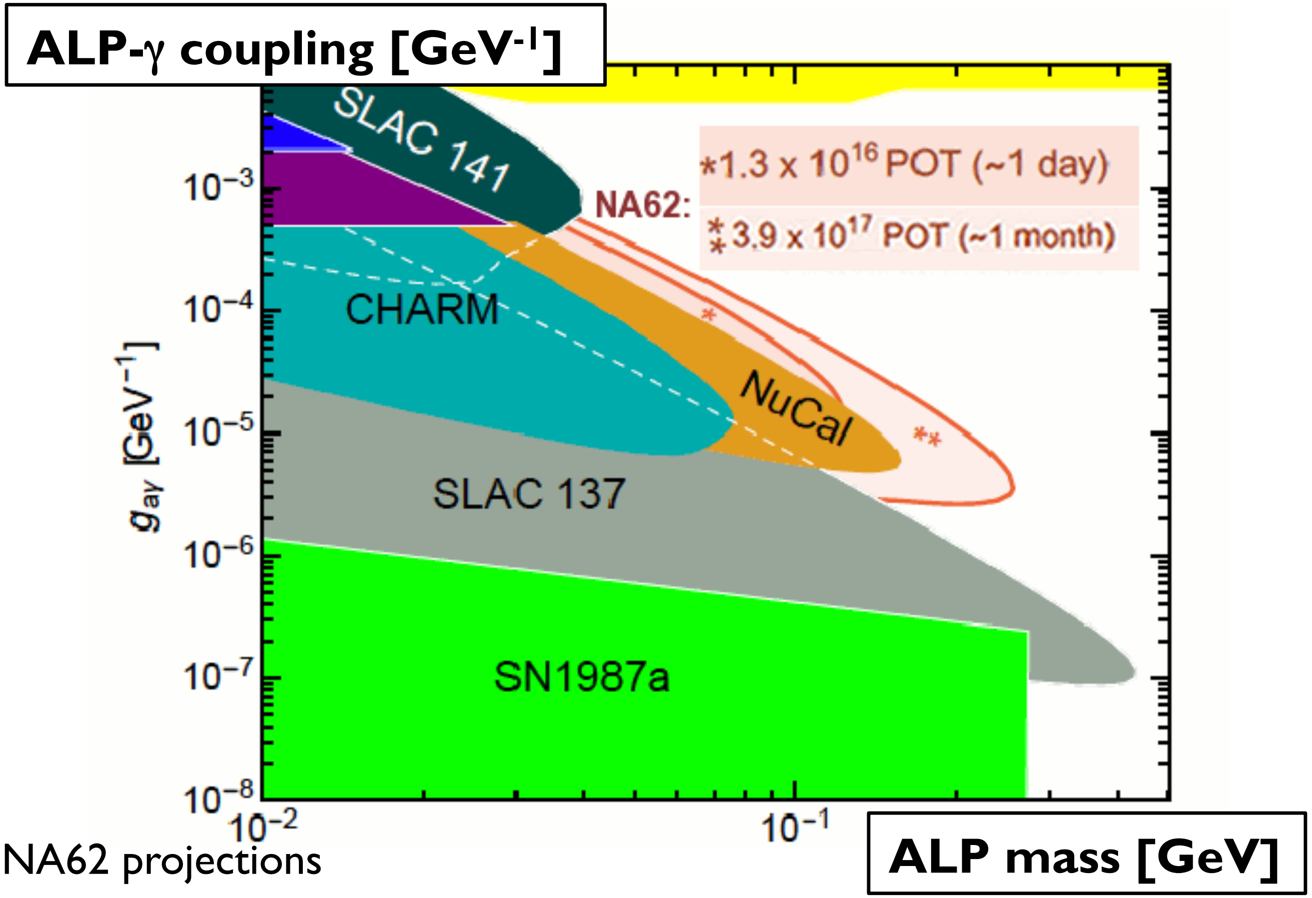
Expected NA62 sensitivity on ALP's

Search for light (pseudo-)scalar particles coupled to two gauge bosons (here, SM photons) produced at target and decaying to $\gamma^{(*)}\gamma^{(*)}$ in the NA62 fiducial volume

Difficult search to be performed during the standard data taking: here **stick on beam-dump mode**

Production mechanism studied: Primakoff production

Expected zero-background sensitivity for 1 day (*) and 1 month (**) runs in beam dump mode improves on present results



JHEP 1602 (2016) 018 + includes NA62 projections

Conclusions: NA62 past, present, and future...

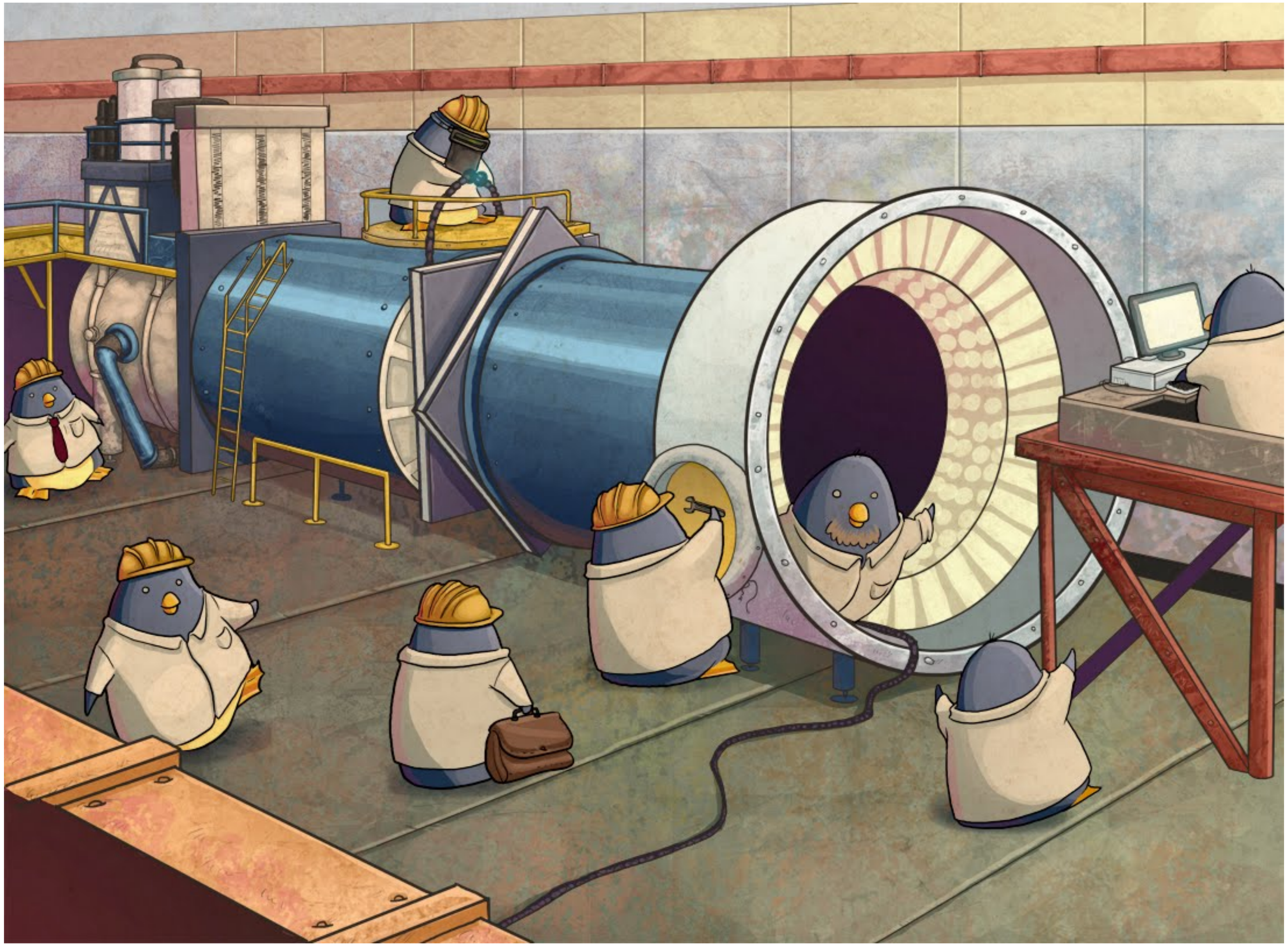
In 2007-2008, NA62 "RK phase":

- **Runs with original NA48/2 detector, beam carefully tuned for the measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$, 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}, and short-lived dark photon and HNL search**
- **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**
- **October 2014, pilot run after long shutdown**
- **2015, first physics with full detector: 2 x 10^{10} triggers on tape**
- **2016-17, towards a 10% measurement of $K \rightarrow \pi\nu\nu$ in 2 years of data taking**
    - **+ a broad physics program: LFV, dark sector, π^0/K rare decays, etc.**

…obviously, after a fair amount of work!



NA62 guiding principles

Support a high-rate environment

high-resolution timing, charged hodoscope (scintillator), σ_t < 200 ps

Kinematic rejection of ~10^4 by cutting on missing mass at decay

- **fast tracking of incoming particles: 3 Si-pixel stations, δx~200 μ, hit ε > 99%, provide $\delta P/P$~0.2%, sustain 800 MHz beam flux, σ_t < 200 ps/station**
- **tracking of daughter particles: 4 stations of straw tubes in vacuum, hit ε > 99%, provide $\delta P/P$<1%, sustain 500 kHz in hottest area**

Rejection of ~10^3 for $K_{\mu2,3,4},_{e2,3,4}$, … bkg, PID for all charged particles

- **positive, non-destructive ID for incoming K: Thr. Č, σ_t~100 ps, >99% K purity, 50 MHz operation**
- **ID for daughter pions, muons, electrons: RICH, reduces μ bkg < 1% up to 35 GeV, σ_t < 100 ps**
- **ID for outgoing μ's: iron/scintillator calorimeters, $1-\varepsilon < 10^{-5}$ for μ's**

Rejection of ~10^8 for modes with π^0's and ~10^4 for single photon

- **Hermetic, high-efficiency γ veto, 0--50 mrad: 5×10^{-8} rejection for $K\rightarrow\pi\pi^0$**

Redundancy of information

K→πe⁺e⁺: sensitivity on coupling and mass

If the Majorana neutrino is kinematically accessible, sensitivity enhanced due to resonant production

Atre, et al., http://arxiv.org/pdf/0901.3589v2.pdf

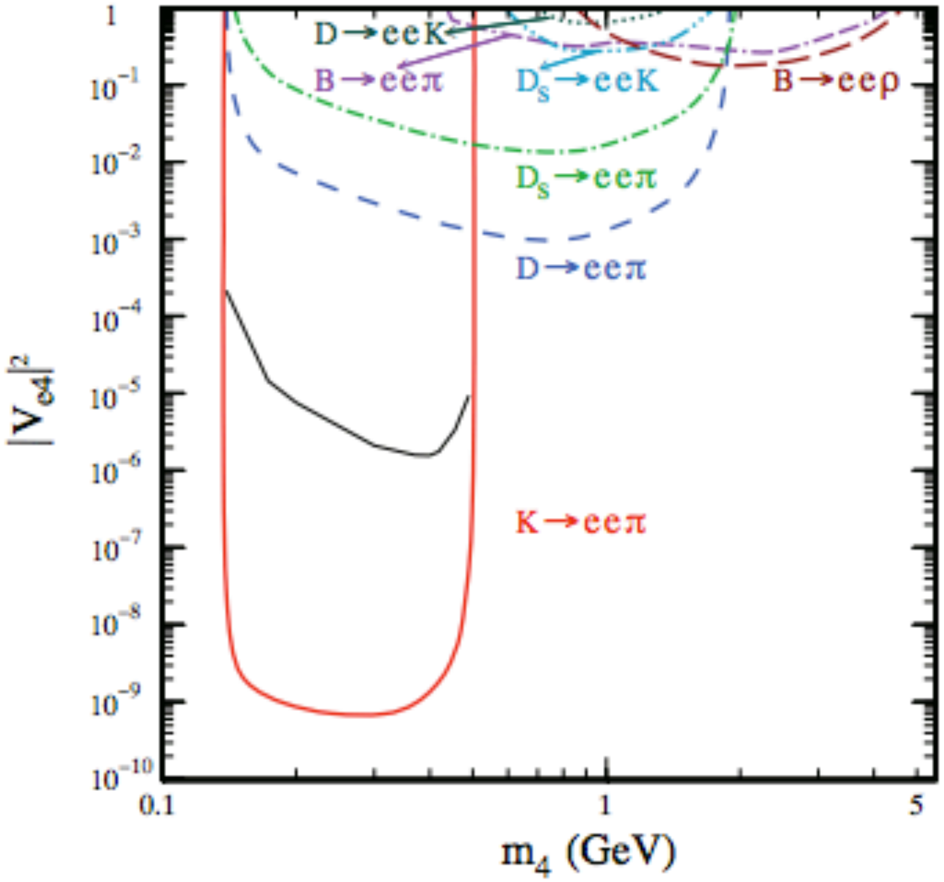


Figure 9: Excluded regions above the curves for $|V_{e4}|^2$ versus m_4 from $M_1^+ \to e^+e^+M_2^-$ searches. The thin black line corresponds to an estimate of the bound from $K^+ \to e^+e^+\pi^-$ once the probability of decay of N_4 in the detector is taken into account.

Motivations for a search of $\pi^0 \rightarrow$ Invisible

$\pi^0 \rightarrow \nu\nu$ forbidden by angular momentum if ν is a mass-less left-handed particle

$$BR(\pi^0 \to \nu\nu) = \sim 3 \cdot 10^{-8} k \left(\frac{m_\nu}{m_\pi}\right)^2 \sqrt{1 - 4\left(\frac{m_\nu}{m_\pi}\right)^2}$$

for each Dirac (k=1) or Majorana (k=2)-neutrino with mass $m_\nu < m_{\pi 0} / 2$

Experimental limit (ALEPH) on $m_{\nu\tau}$ implies $BR(\pi^0 \to \nu\nu) < 5\times10^{-10}$

Cosmological limit more stringent on $m_{\nu\tau}$, $BR(\pi^0 \to \nu\nu) < 10^{-13}$

Present direct experimental limit $BR(\pi^0 \to \nu\nu) < 2.7\text{x}10^{-7}$ (E949, 2005)

NA62 can reach BR sensitivity $\sim 10^{-10}$ as a by-product of the $K^+ \rightarrow \pi^+\nu\nu$ analysis