Search for rare Kaon decays at NA62

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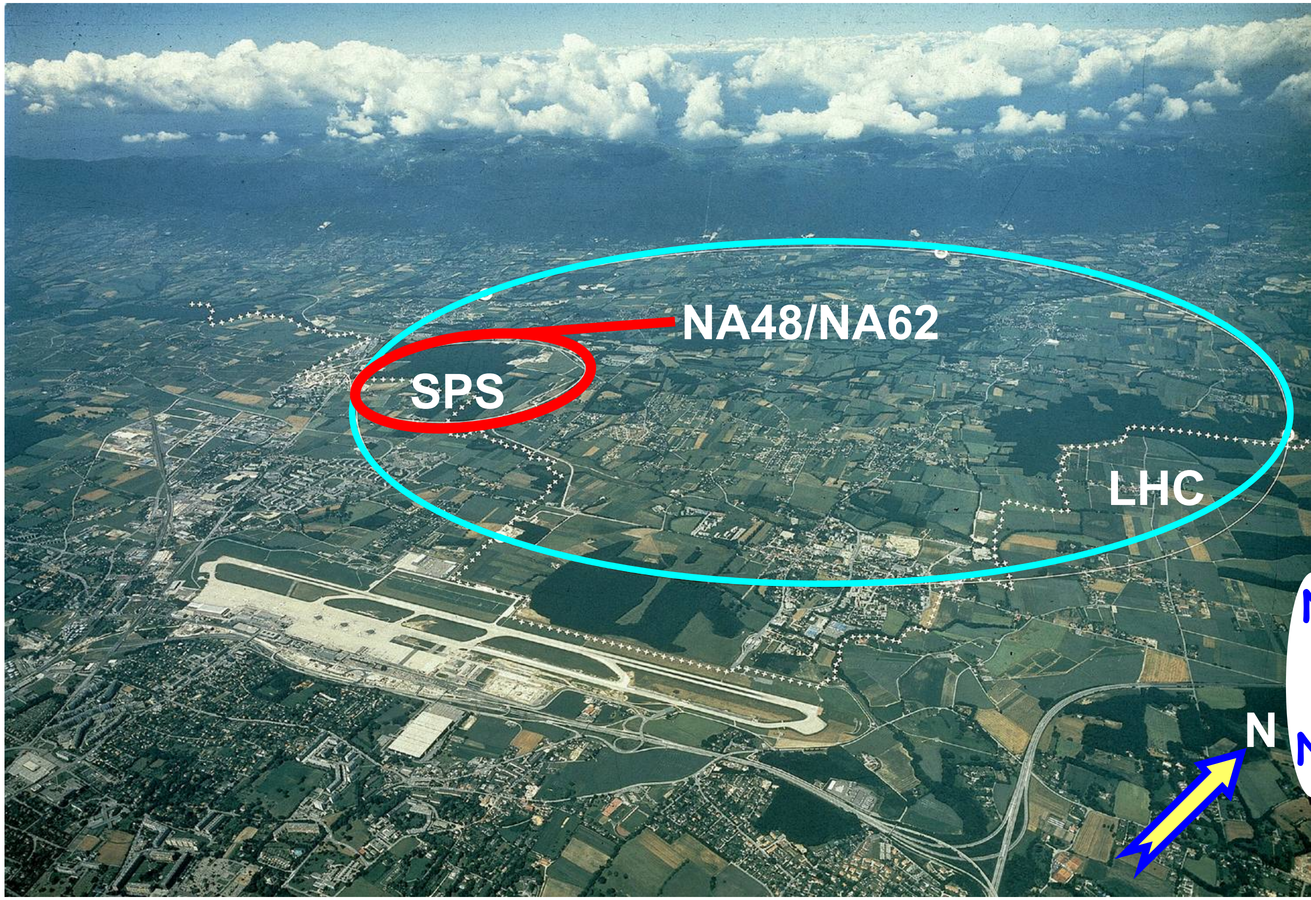
Outline:

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) Selected recent results, ongoing analyses
5) Summary

NA48+NA62



Primary SPS protons (400 GeV/c): 1.8×10^{12}/SPS spill
Un-separated secondary positive beam

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)
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$

NA62
- 2007–2013: design & construction
- 2012: test run
- 2014-17: data taking

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

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	*NA62* (*K^{+}*)
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.

Sensitivities to other rare decays

Composition: $K^+(\pi^+)$ = 5%(63%).
K^+ decaying in vacuum tank: 18%.

K^+ flux used	Modes	
~10^{13} (NA62)	In the fiducial region	
~10^{12}	LFV (μ^+e^-) $K^+\to\pi^+\nu\nu$	dedicated triggers
~10^{11} (NA48/2)	K_{e4}^{+-} K_{e4}^{00} (in progress) $K^+\to\pi^+e^+e^-$ $K^+\to\pi^+\mu^+\mu^-$ $K^+\to\pi^+\pi^0\gamma$ $K^+\to\pi^+\gamma e^+e^-$ $K^+\to\pi^+\pi^0e^+e^-$ (in progress) LFV (ee, μ^+e^+, μ^-e^+)	dedicated triggers
~10^{10} (NA62-R_K)	$K^+\to e^+\nu$ LFV ($\mu^+\mu^+$)	downscaled triggers
~10^{9}	$K^+\to\pi^+\gamma\gamma$	downscaled triggers
Below 10^{9}	$K_{\mu4}$	

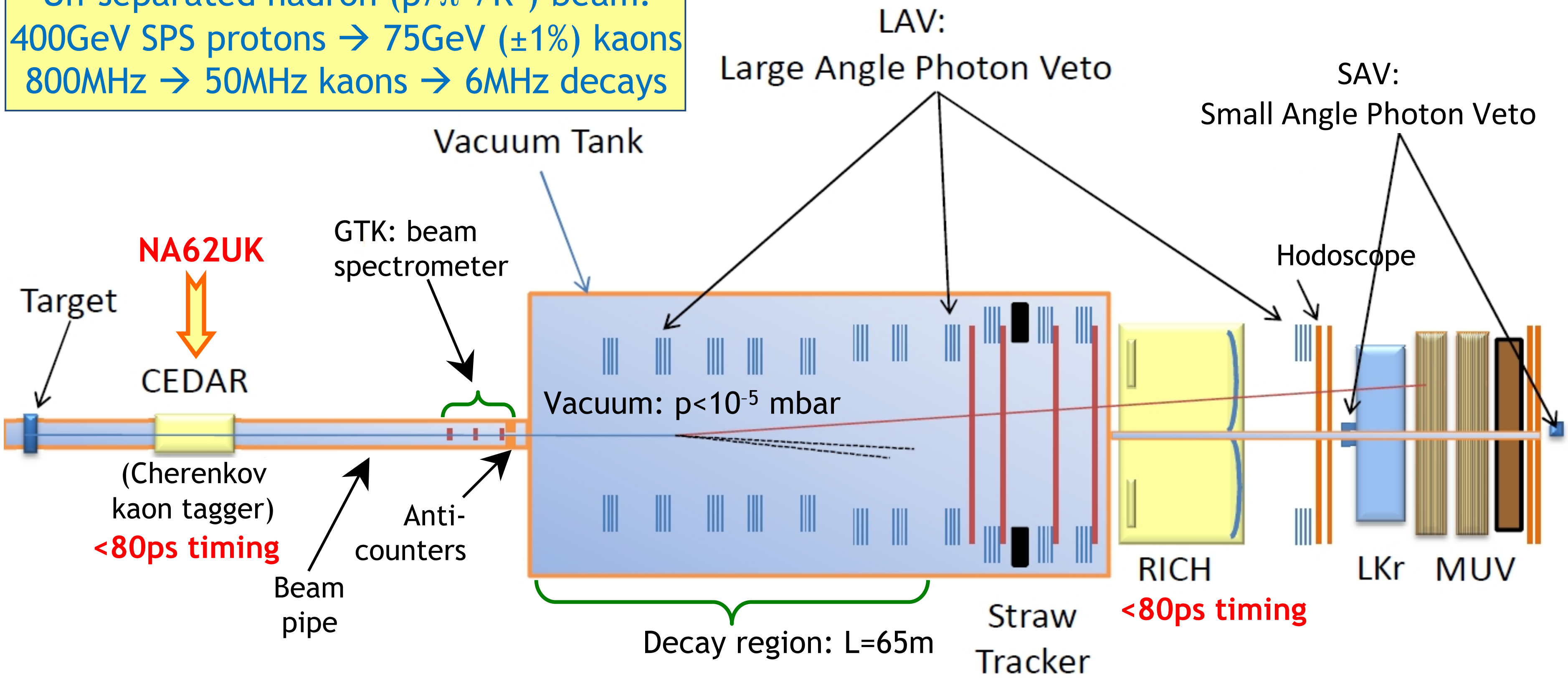
Typical acceptance ~ 10 - 15%

NA62 detector

Kaon decay in flight experiment
Currently ~**200** participants, **27** institutions

Total length: ~270m

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
800MHz → 50MHz kaons → 6MHz decays

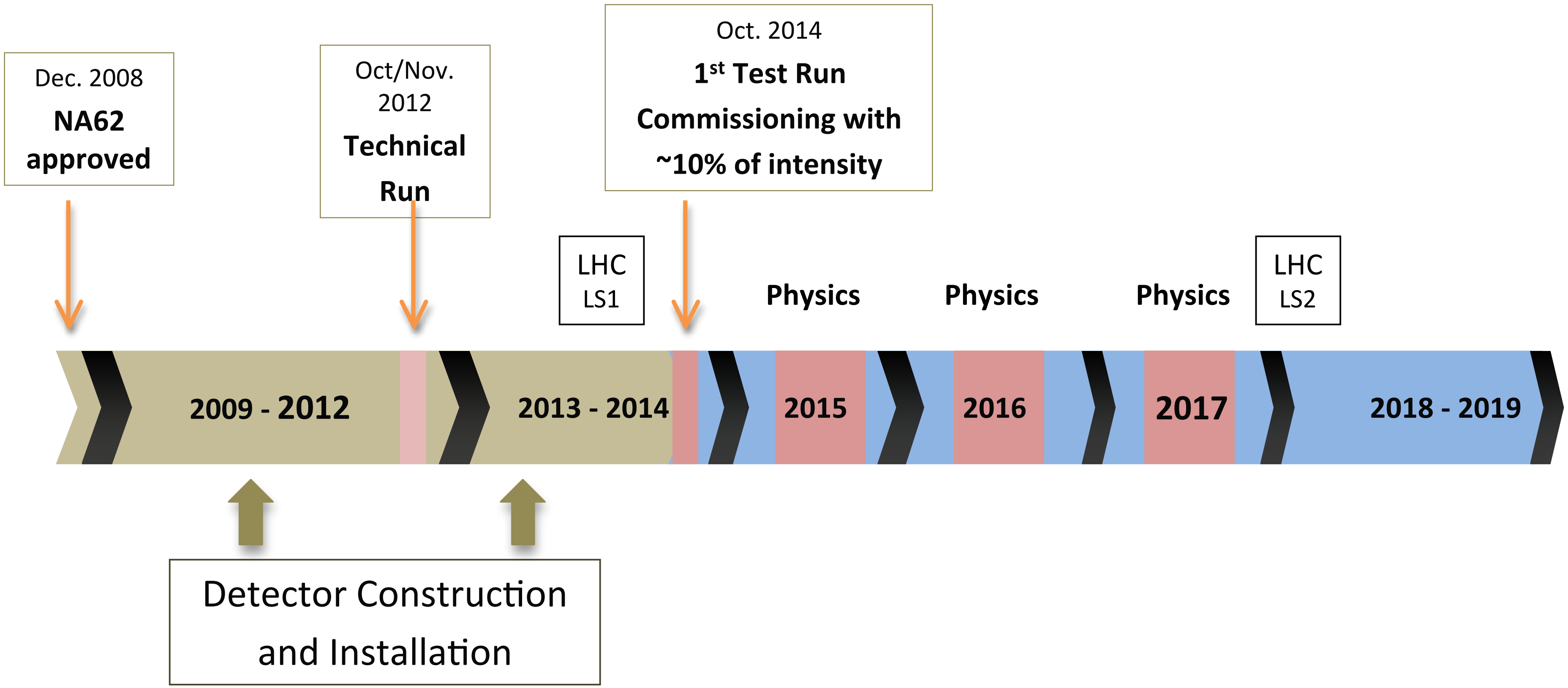


Kinematic rejection factors (limited by beam pileup and tails of MCS):
5×10^3 for $K^+\to\pi^+\pi^0$, 1.5×10^4 for $K\to\mu^+\nu$.

Hermetic photon veto: ~10^8 suppression of $\pi^0\to\gamma\gamma$.

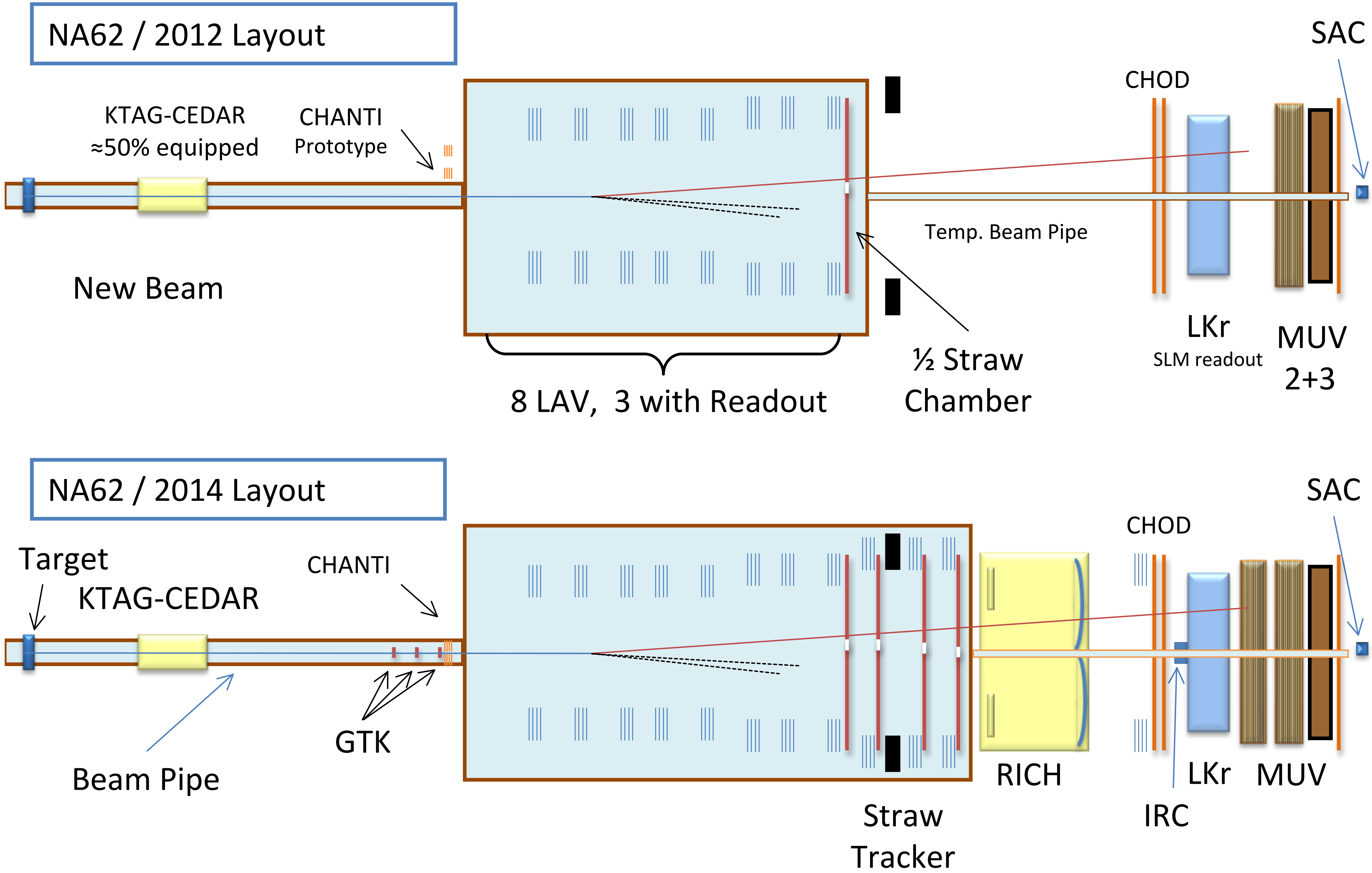
Particle ID (RICH+LKr+MUV): ~10^7 muon suppression.

NA62 Timeline



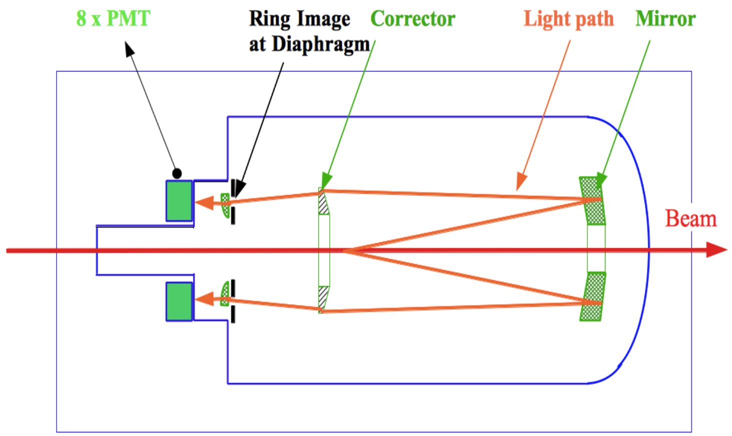
- 5 years of construction interleaved with a Technical Run in fall 2012
- In 2014 a first Run with “full” detector (GTK and MUV1 to be installed during the Run)
- 3 years of Physics data taking before LHC Long Shutdown 2 (LS2)

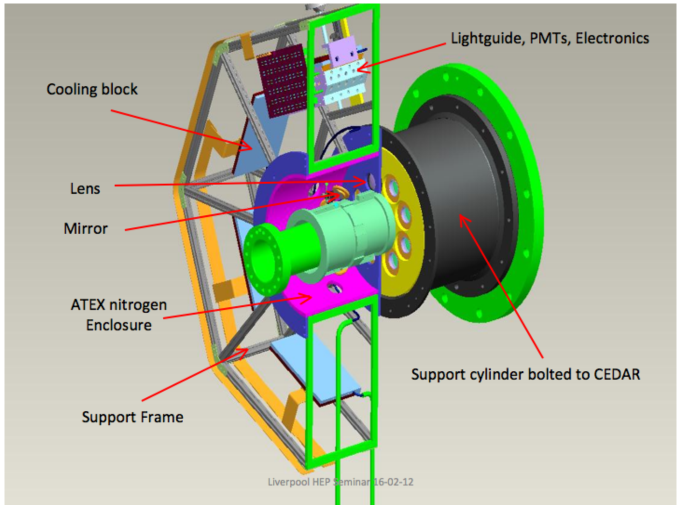
NA62 Detector 2012 and 2014



KTAG (CEDAR)

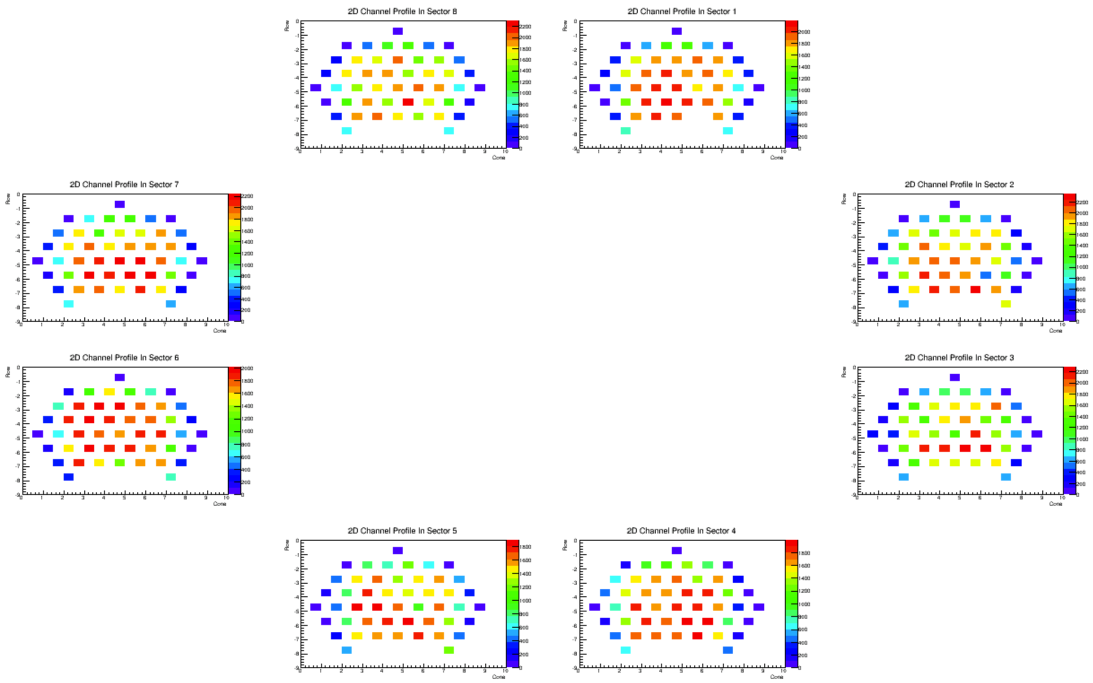
UK: responsibility of all aspects of detector



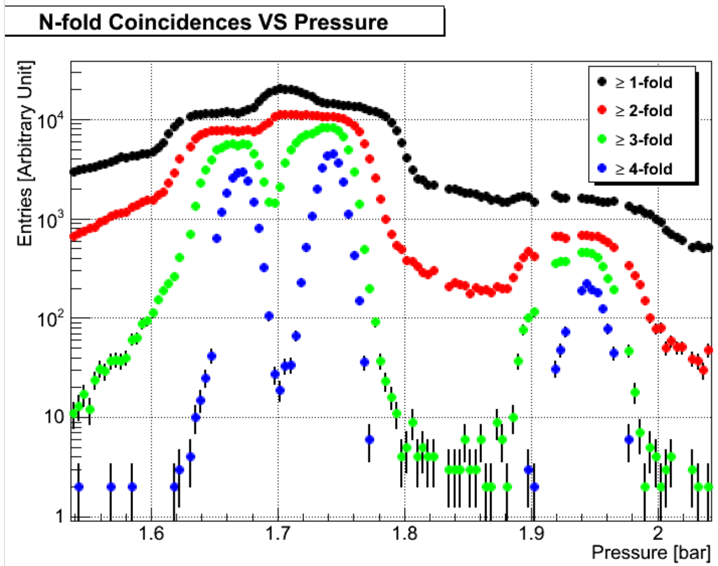


UK in very strong position in NA62:

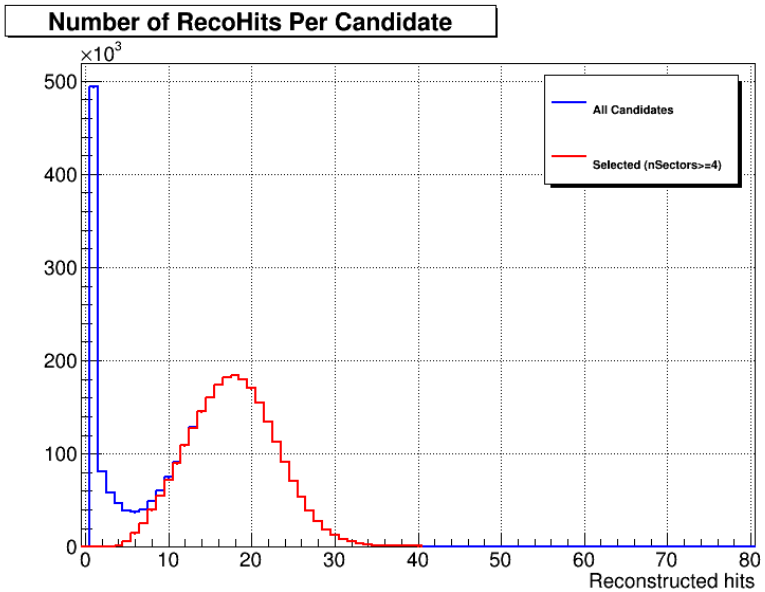
KTAG, Trigger+Clock distribution, Software coordination, Analysis Co-coordination and leadership



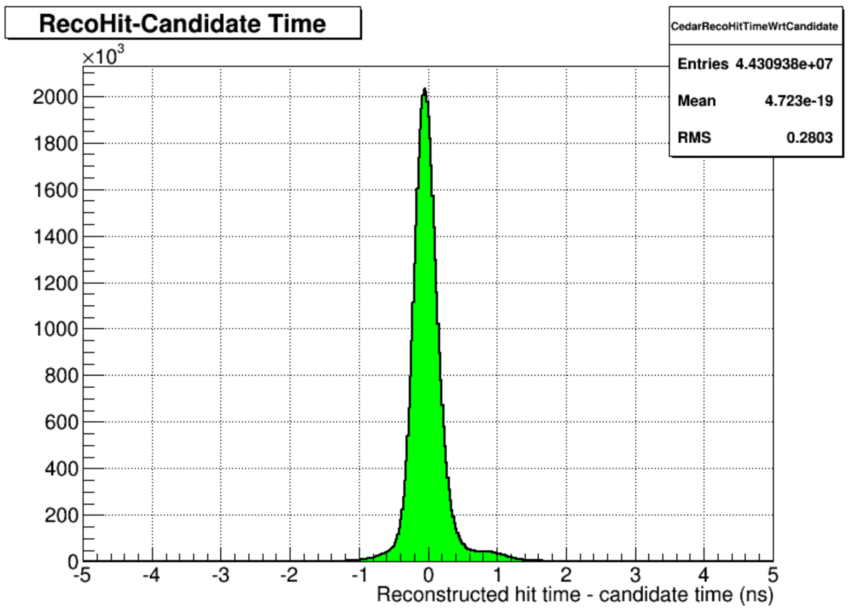
2D Channel Profile In Sector 8
2D Channel Profile In Sector 1
2D Channel Profile In Sector 7
2D Channel Profile In Sector 2
2D Channel Profile In Sector 6
2D Channel Profile In Sector 3
2D Channel Profile In Sector 5
2D Channel Profile In Sector 4



N-fold Coincidences VS Pressure
Entries [Arbitrary Unit]
Pressure [bar]
≥ 1-fold
≥ 2-fold
≥ 3-fold
≥ 4-fold



Number of RecoHits Per Candidate
All Candidates
Selected (nSectors>=4)
Reconstructed hits



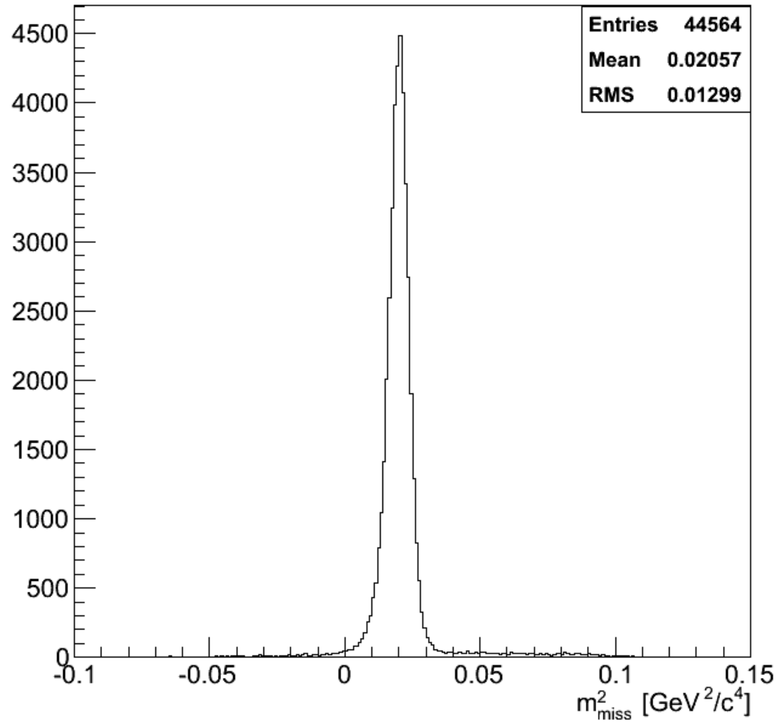
RecoHit-Candidate Time
CedarRecoHitTimeWrtCandidate
Entries 4.430938e+07
Mean 4.723e-19
RMS 0.2803
Reconstructed hit time - candidate time (ns)

Commissioning with $K^+ \rightarrow \pi^+\pi^0$

- 2012 set – up:
  - KTAG (50% PMs), 1 straw plane, CHOD, LKr (30% readout), MUV2, MUV3

Selection based on LKR signal and time coincidences

- $\langle m^2_{miss} \rangle = (0.0199 \pm 0.0005)\ GeV^2/c^4$
- $\sigma(m^2_{miss}) = 3.8 \times 10^{-3} GeV^2/c^4$
- $m^2(\pi^+) = 0.0195\ GeV^2/c^4$
- Time resolution: KTAG 150 ps, LKr 350 ps, CHOD 400 ps, MUV3 450 ps.
- KTAG efficiency about 87% (corresponding to 95% for a fully instrumented detector).
- 6% of events with a muon in-time (upper limit to the punch-through)

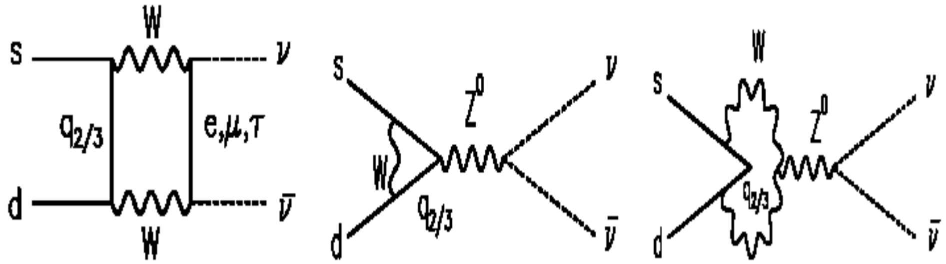


2014 Commissioning in progress !

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

$K\to\pi\nu\nu$: Theory in the Standard Model

- **FCNC loop processes**
- **SM precision surpasses any other FCNC process involving quarks**
- **Short distance dynamics dominated**



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

$$x(q) \equiv \frac{m_q^2}{m_W^2}$$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \cdot \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

Charm contribution

Top contribution

$$\kappa_+ = r_{K^+} \cdot \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \cdot \lambda^8$$

The Hadronic Matrix Element is <u>measured</u> and isospin rotated

Brod et al., PRD 83 (2011) 034030

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

Theoretically clean,
sensitive to new physics,
almost unexplored

BNL E787/949: $K^+ \to \pi^+ \nu\nu$

Technique: K^+ decay at rest

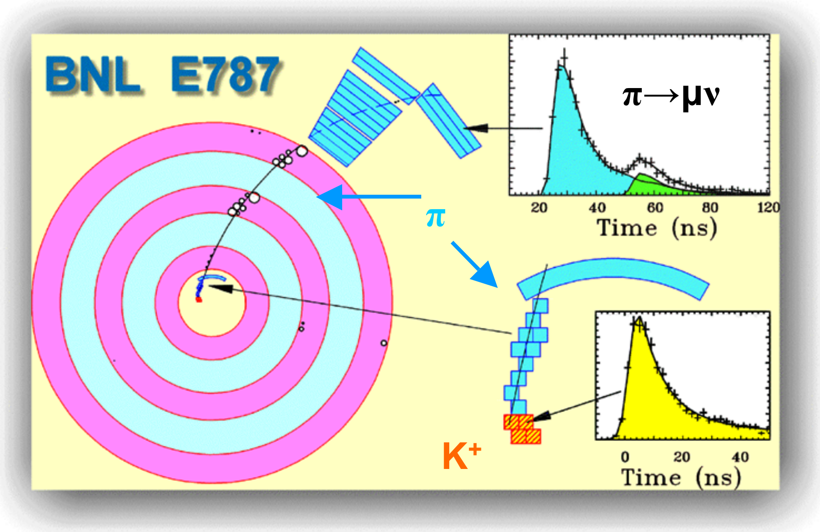
Data taking: E787 (1995–98), E949 (2002)

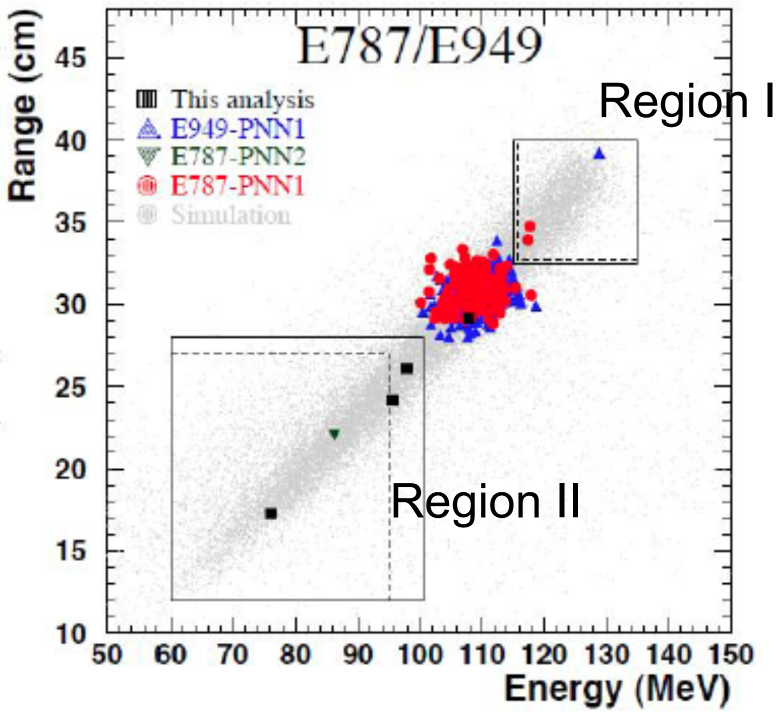
Separated K^+ beam (710 MeV/c, 1.6MHz)

PID: range (entire $\pi^+ \to \mu^+ \to e^+$ decay chain)

Hermetic photon veto system

1.8 x 10^{12} stopped K^+, ~0.1% signal acceptance





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

E787/E949: $BR(K^+ \to \pi^+ \nu\nu) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$

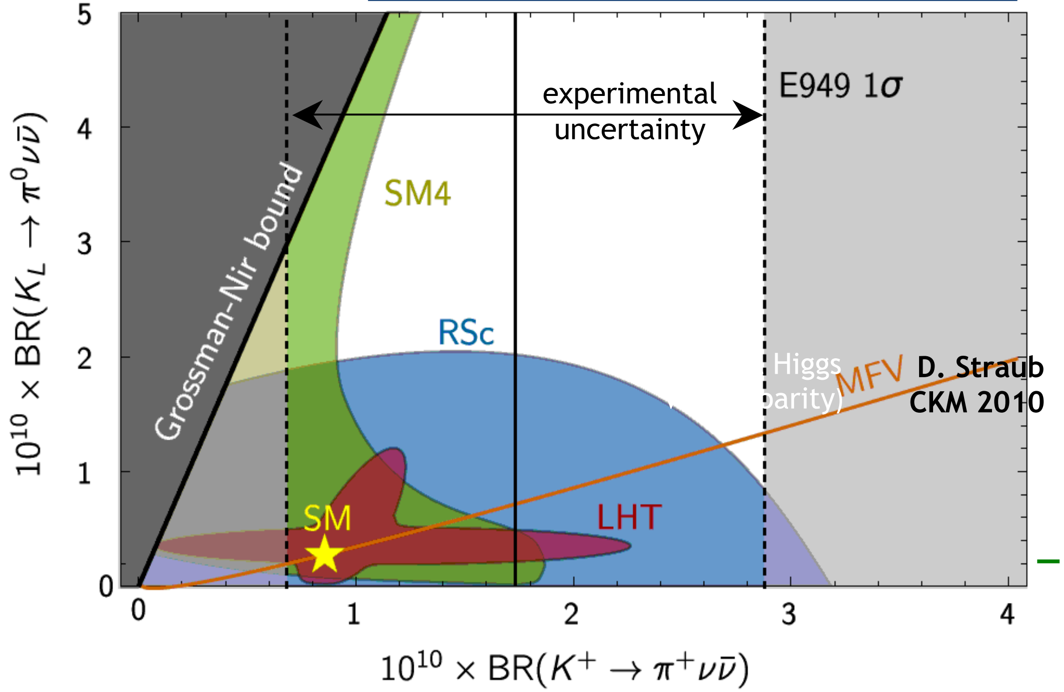
PRL 101 (2008) 191802; PRD 79 (2009) 092004

- **7 observed candidates, 2.6 expected background**
- **Probability that 7 observed events are all background is 10^{-3}**
- **Still compatible with SM within errors**

Experiment vs theory

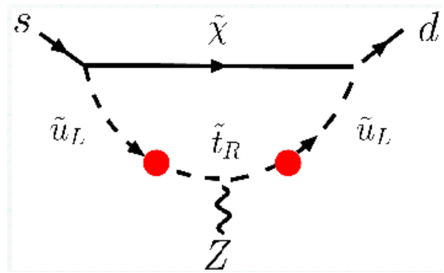
(hep-ph/0906.5454, hep-ph/0812.3803,hep-ph/1002.2126, hep-ph/0604074)

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



$BR(K^+ \to \pi^+ \nu\nu) \times 10^{10}$: selected models	
SM	0.82±0.08
MFV (hep-ph/0310208)	1.91
EEWP (NPB697 (2004) 133, hep-ph/0402112)	0.75±0.21
EDSQ (PRD70 (2004) 093003, hep-ph/0407021)	up to 1.5
MSSM (NPB713 (2005) 103, hep-ph/0408142)	up to 4.0

- Eexperiments:
  - NA62 @ CERN
  - KOTO @ JPARC



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

NA62 aim: collect O(100) SM $K^+ \to \pi^+ \nu\nu$ decays with <20% background in 2 years of data taking using a novel decay-in-flight technique

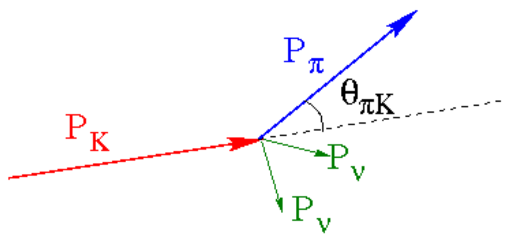
Decay signature: high momentum K^+ (75GeV/c) → low momentum π^+ (15–35 GeV/c)

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

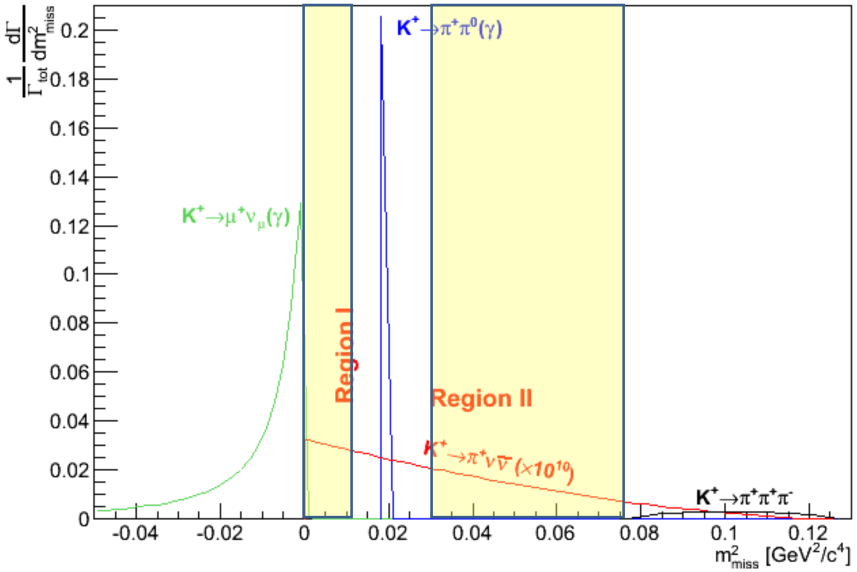
Kinematic variable:

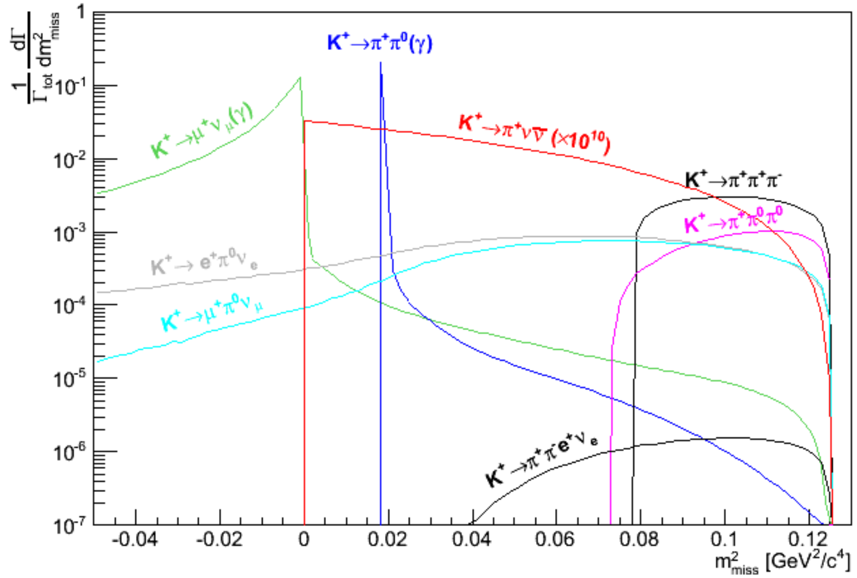
$$m^2_{miss} = (P_K - P_{\pi^+})^2$$



Backgrounds

K decays





Background

1) K^+ decay modes

2) Accidental single track matched with a K-like track

Accidental single tracks:

Beam interactions in the beam tracker

Beam interactions with the residual gas in the vacuum 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

Lepton Flavour and Lepton Number Violation Search for Heavy neutrinos

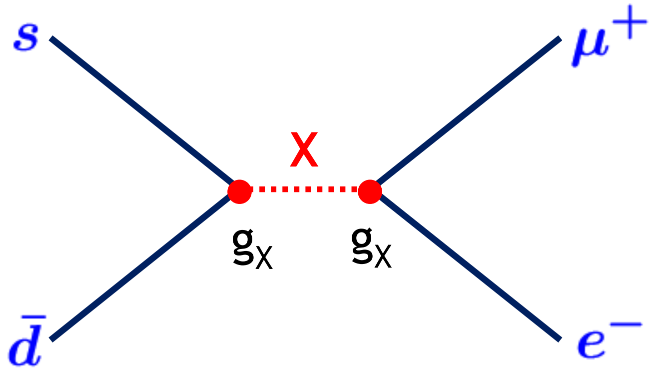
UK-lead initiative and leadership

LFV in kaon decays

Copious production: high statistics
Simple decay topologies: clean experimental signatures

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 $K^{\pm}$ 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		

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

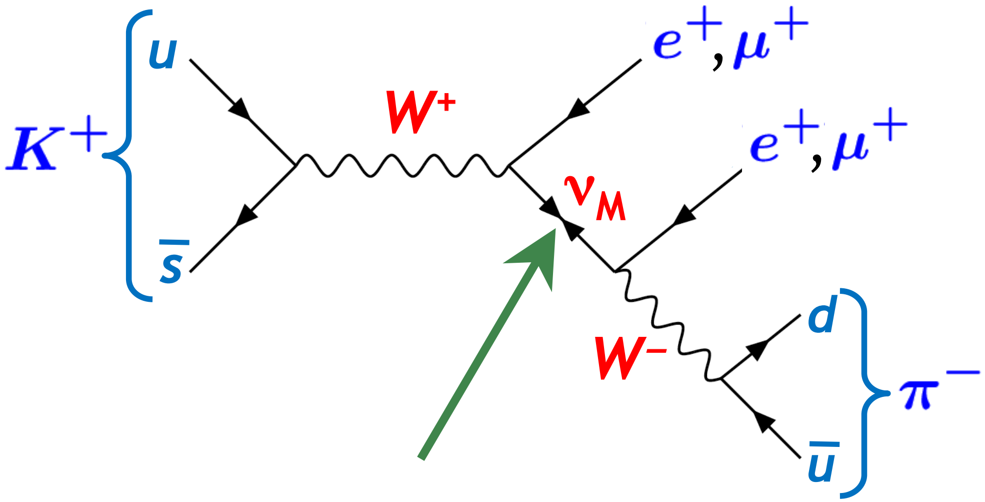
Expected NA62 single event sensitivities: **~10^{-12}** for $K^{\pm}$ decays

NA62 is already capable of improving on all these decay modes
e.g. 2003-4 data $K^+ \to \pi^-\mu^+\mu^+$:

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

Sensitivity to Majorana neutrino

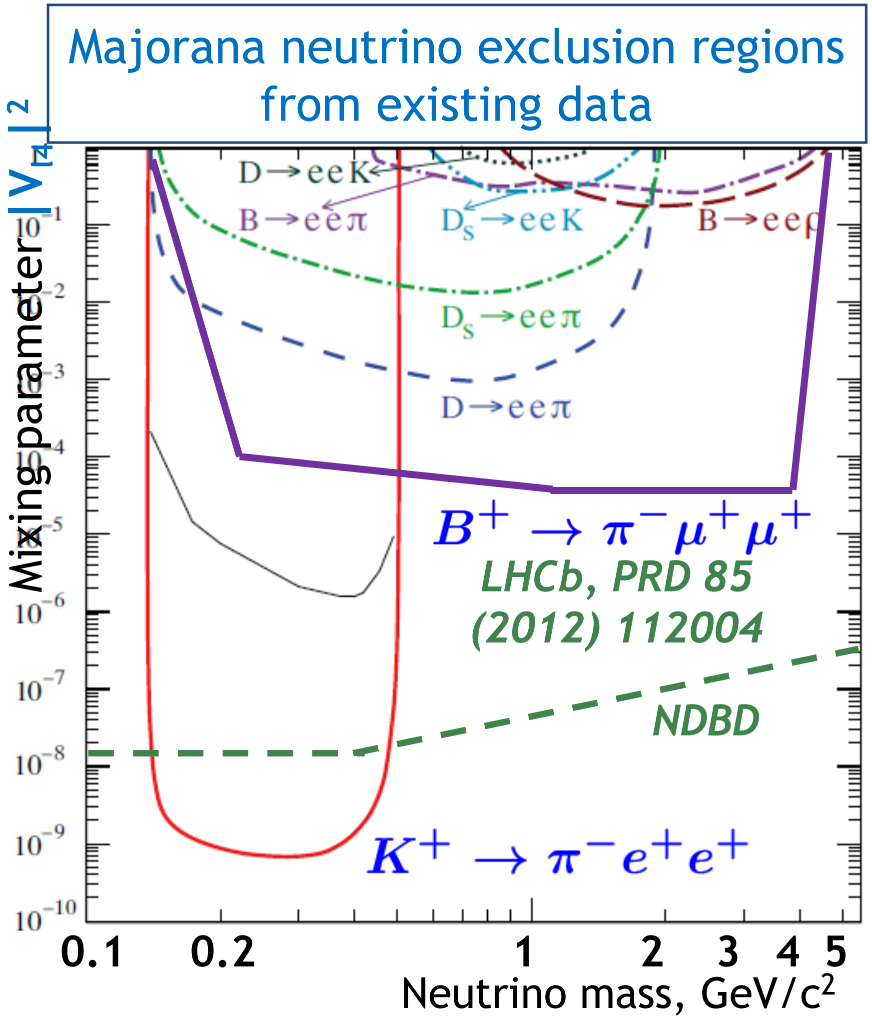
$$K^+ \to \pi^- \ell_1^+ \ell_2^+, \quad \ell = e, \mu$$



resonant enhancement for

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

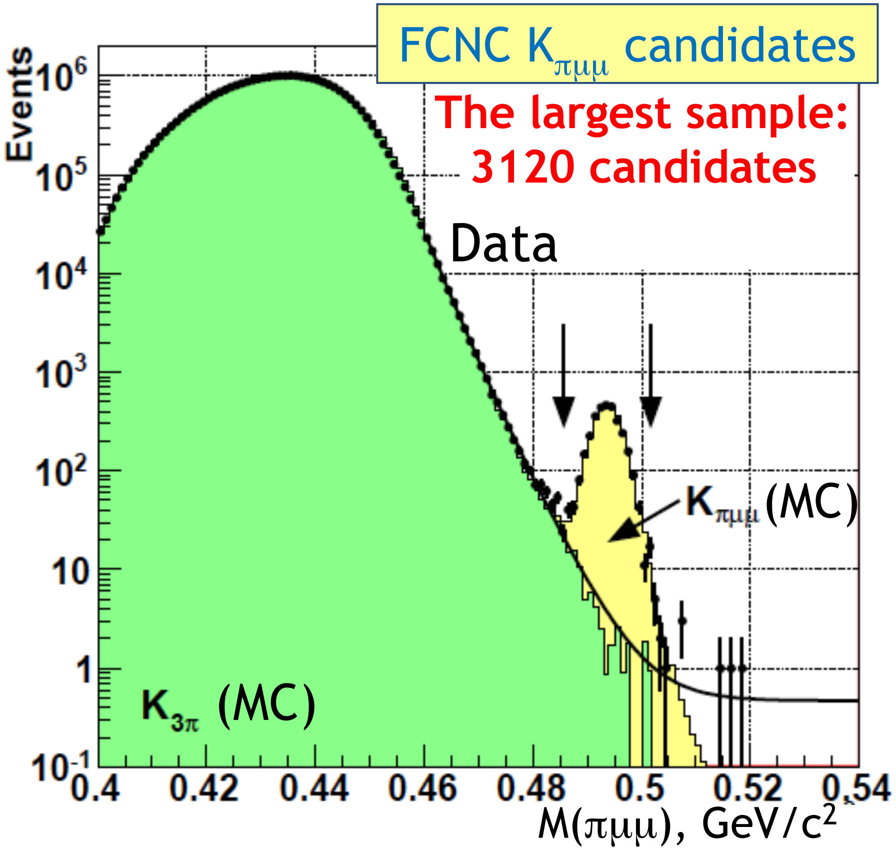
Littenberg and Shrock,
PLB491 (2000) 285

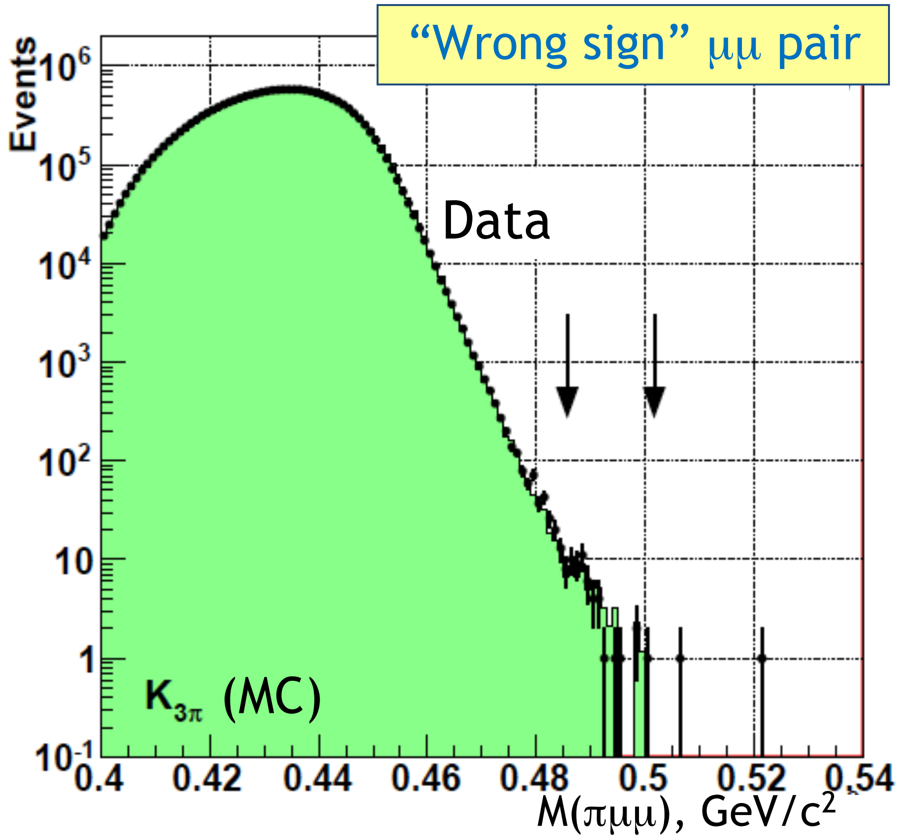


Plot from Atre et al.,
JHEP 0905 (2009) 030

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

PLB 697 (2011) 107





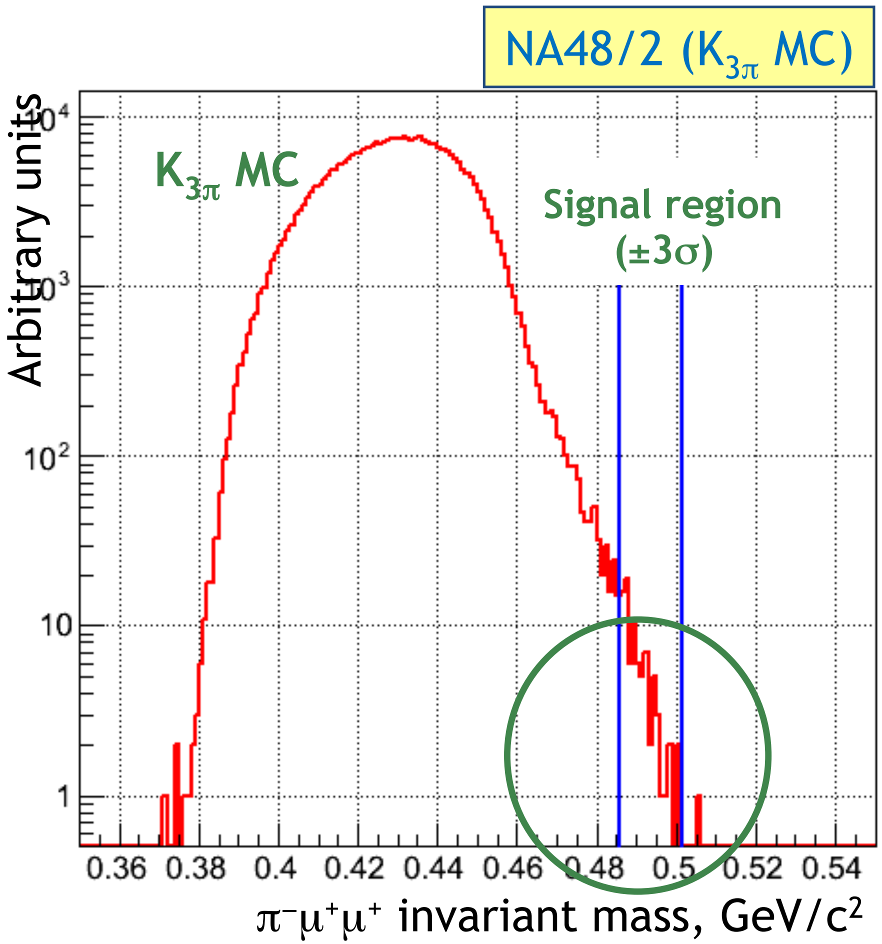
$N_{data} = 52$

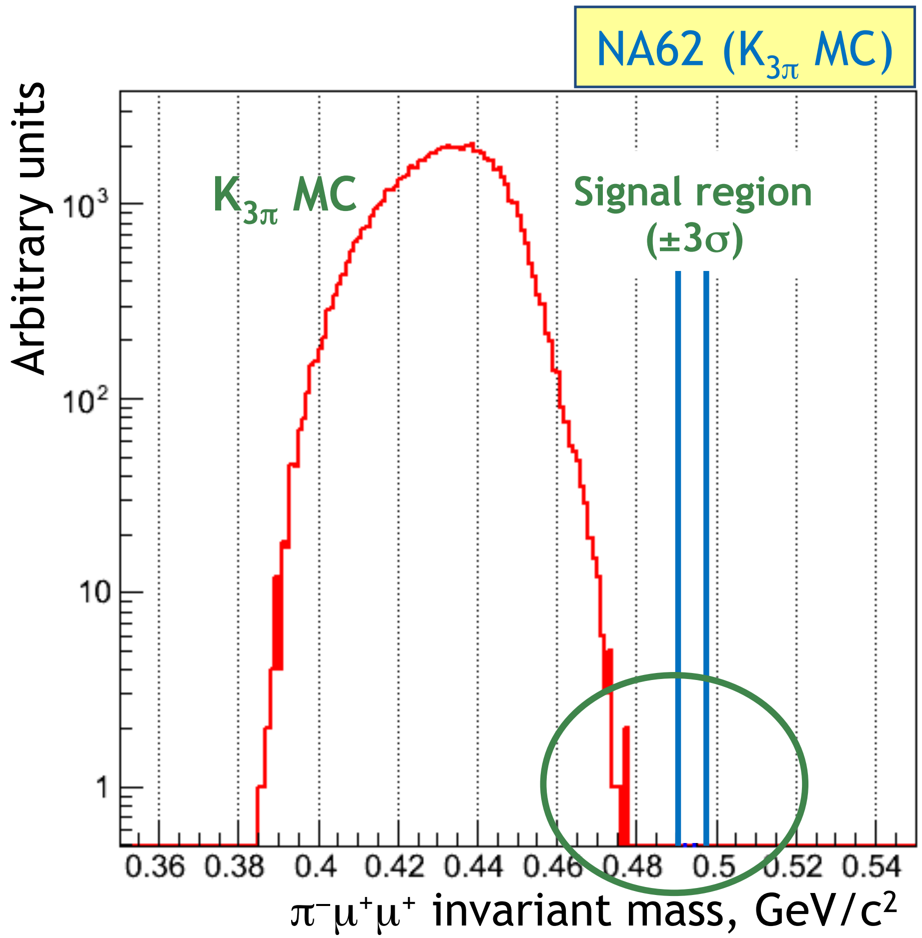
$N_{bkg} = 52.6 \pm 19.8_{syst.}$ ⟹ $\mathcal{B}(K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \times 10^{-9}$ @90% CL

Precision limited by background from $\pi^{\pm} \rightarrow \mu^{\pm}\nu$, despite SES ≈ 3×10^{-11}.

A dedicated on-going analysis for Majorana ν has a potential sensitivity of ~10^{-10}

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



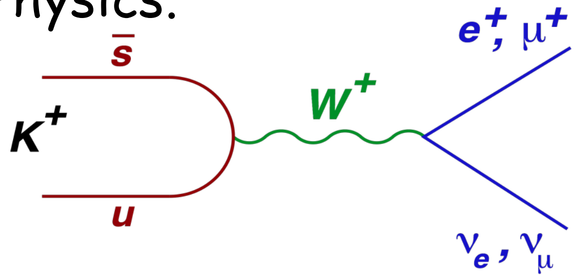


NA48/2: $K_{3\pi}$ background to $K_{\pi\mu\mu}$ due to $\pi^{\pm}\rightarrow\mu^{\pm}\nu$ decays in the spectrometer

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)

R_K in the SM

A precise measurement of the ratio of $K \to l\nu_l$ leptonic decays provides an ideal test of SM and indirect search for New Physics.



Hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu2}$
SM prediction: excellent sub-permille accuracy

R_K is sensitive to lepton flavour violation and its SM expectation:

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

Helicity suppression: f~10^{-5}

Radiative correction (few %) due to $K^+ \to e^+ \nu \gamma$ (IB) process, by definition included into R_K
[V.Cirigliano, I.Rosell JHEP 0710:005 (2007)]

helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

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

Phys. Rev. Lett. 99 (2007) 231801

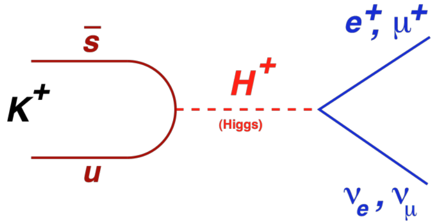
R_K beyond the SM

In the MSSM large tanβ scenario, the presence of LFV terms (charged Higgs coupling) introduces extra contributions to the SM amplitude ~1% effect
Girrbach and Nierste, arXiv:1202.4906

2HDM - tree level

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

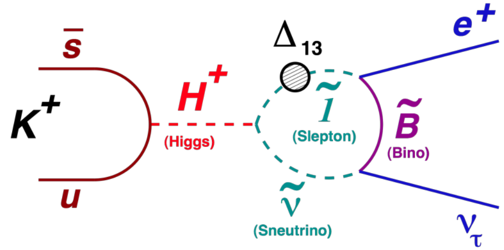
→ Does not affect the ratio R_K



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



PRD 74 (2006) 011701, JHEP 0811 (2008) 042

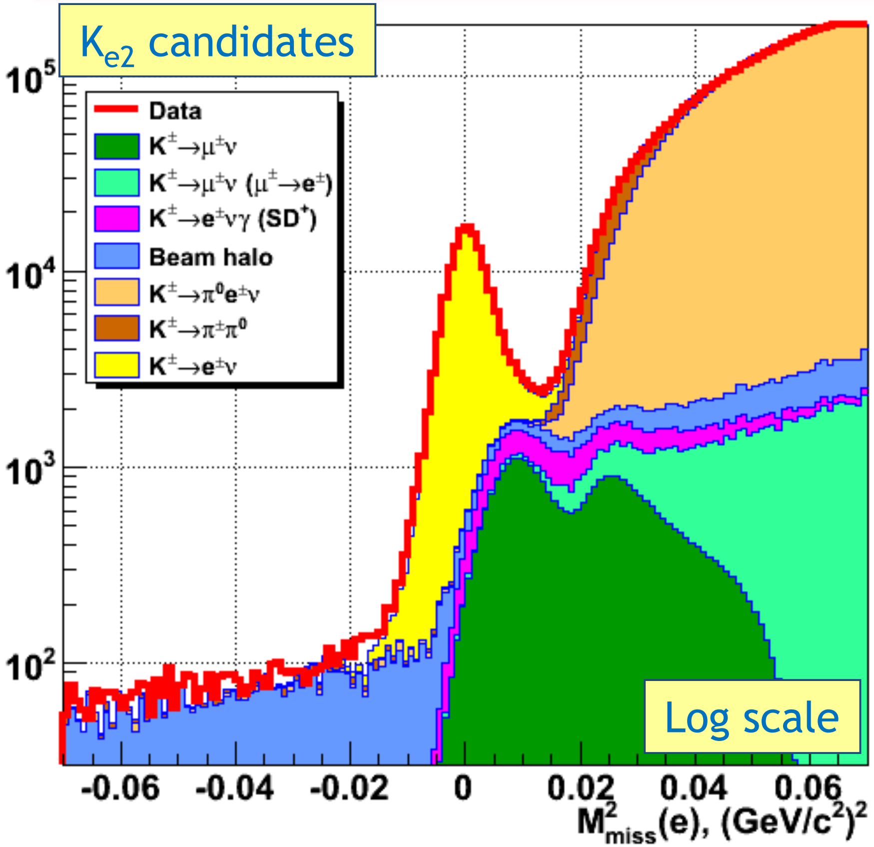
$$R_K^{LFV} = \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma_{LFV}(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

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

Limited by the recent B and τ measurements
Fonseca, Romão and Teixeira, EPJC 72 (2012) 2228

Sensitive to SM extensions with 4th generation, sterile neutrinos, unconstrained MSSM
Lacker and Menzel, JHEP 1007 (2010) 006;
Abada et al., JHEP 1302 (2013) 048

NA62-R_K data: K_{e2} sample



Source	B/(S+B)
$K_{\mu2}$	(5.64±0.20)%
$K_{\mu2}$ ($\mu\to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD)	(2.60±0.11)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Opposite sign K	(0.04±0.02)%
Beam halo	(2.11±0.09)%
Total	(10.95±0.27)%

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

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

[Phys. Lett. B 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%

R_K: Future prospects

Future NA62 (data taking in 2014–2015):

Hermetic veto (large-angle and small-angle veto counters) will strongly decrease the background.
Beam spectrometer (beam tracker plus beam Cherenkov) will allow time correlation between incoming kaons and decay products (improved PID).

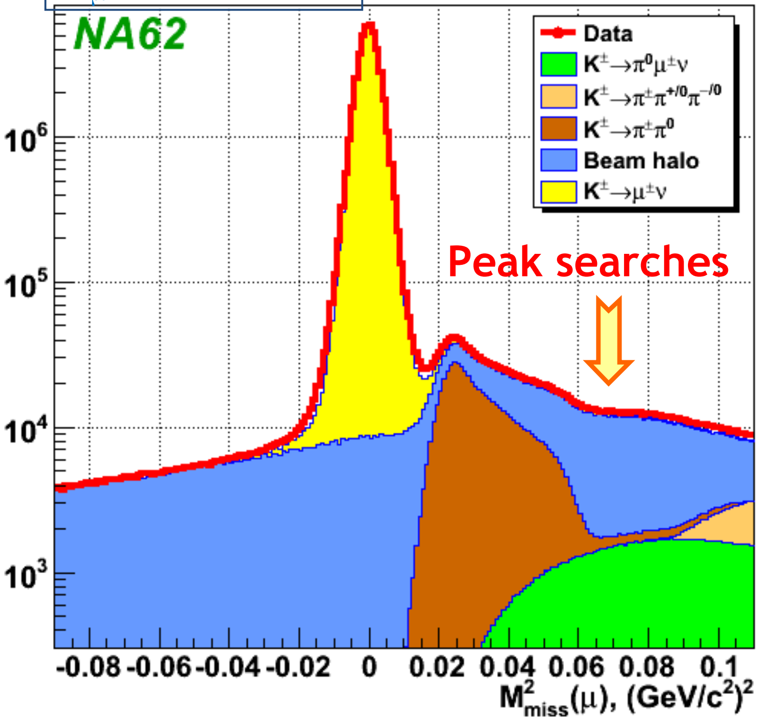
Only the $K_{\mu 2}$ ($\mu \rightarrow e$) background will remain: well known ~0.1% contamination.

Assuming an analysis at low lepton momentum and not using electron ID, measurement of R_K with much improved relative precision is feasible.

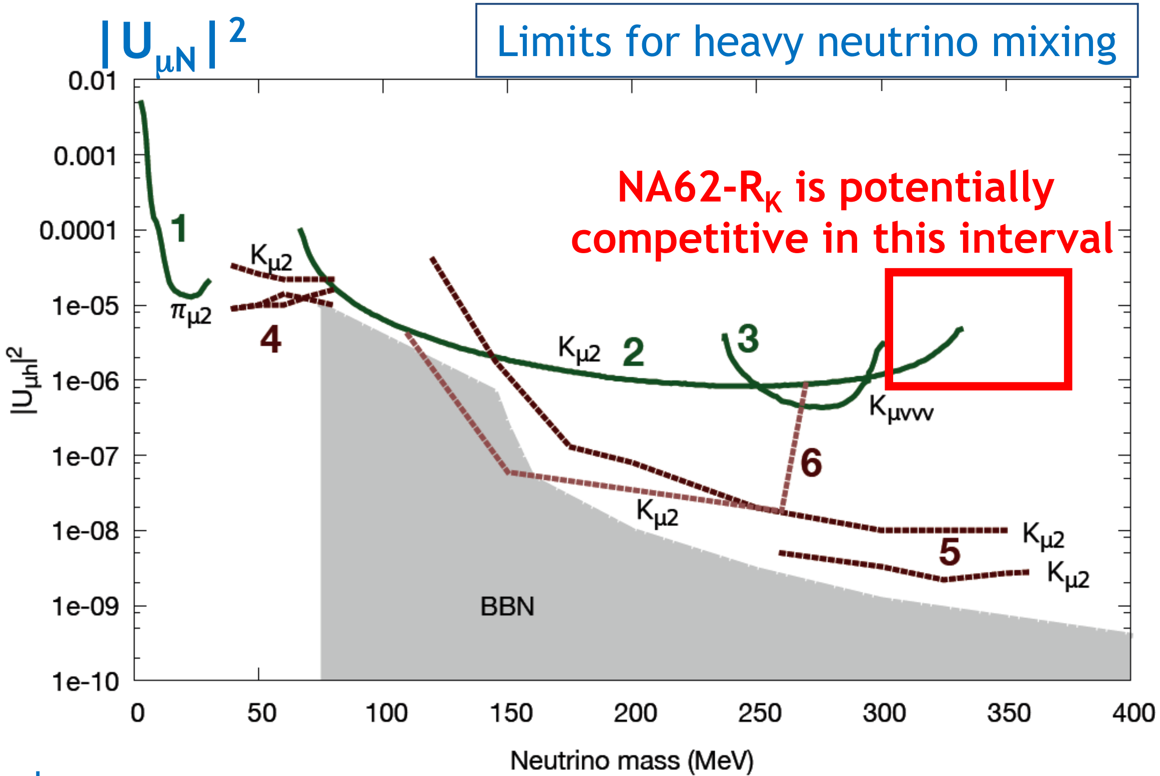
Required statistical uncertainty is ~0.05% → few million K_{e2} candidates.
Required kaon decay flux: $N_K \sim 10^{12}$
Expected NA62 flux: $N_K \sim 10^{13}$

$K_{\mu 2}$: 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 Upper Limit 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

Analysis in progress

Other selected recent results, ongoing analyses

All done in UK

The $K^{\pm} \to \pi^{\pm} \gamma \gamma$ process according to ChPT

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_{K^\pm}}{(8\pi)^3} \cdot \left[z^2 \cdot \left(|A + B|^2 + |C|^2 \right) + \left(y^2 - \frac{1}{4}\lambda(1, z, r_\pi^2) \right)^2 \cdot \left(|B|^2 + |D|^2 \right) \right]$$

$$y = \frac{p \cdot (q_1 - q_2)}{m_{K^\pm}^2} \qquad z = \frac{m_{\gamma\gamma}^2}{m_{K^\pm}^2}$$

$\lambda(a,b,c)=a^2+b^2+c^2-2(ab+ac+bc)$

$r_\pi = m\pi/n$

- @ $O(p^4)$: $A(z, \hat{c})$ (loop ampl.) ≈ 90%
  $C(z, y)$ (pole ampl.) ≈10%

  B, D = 0

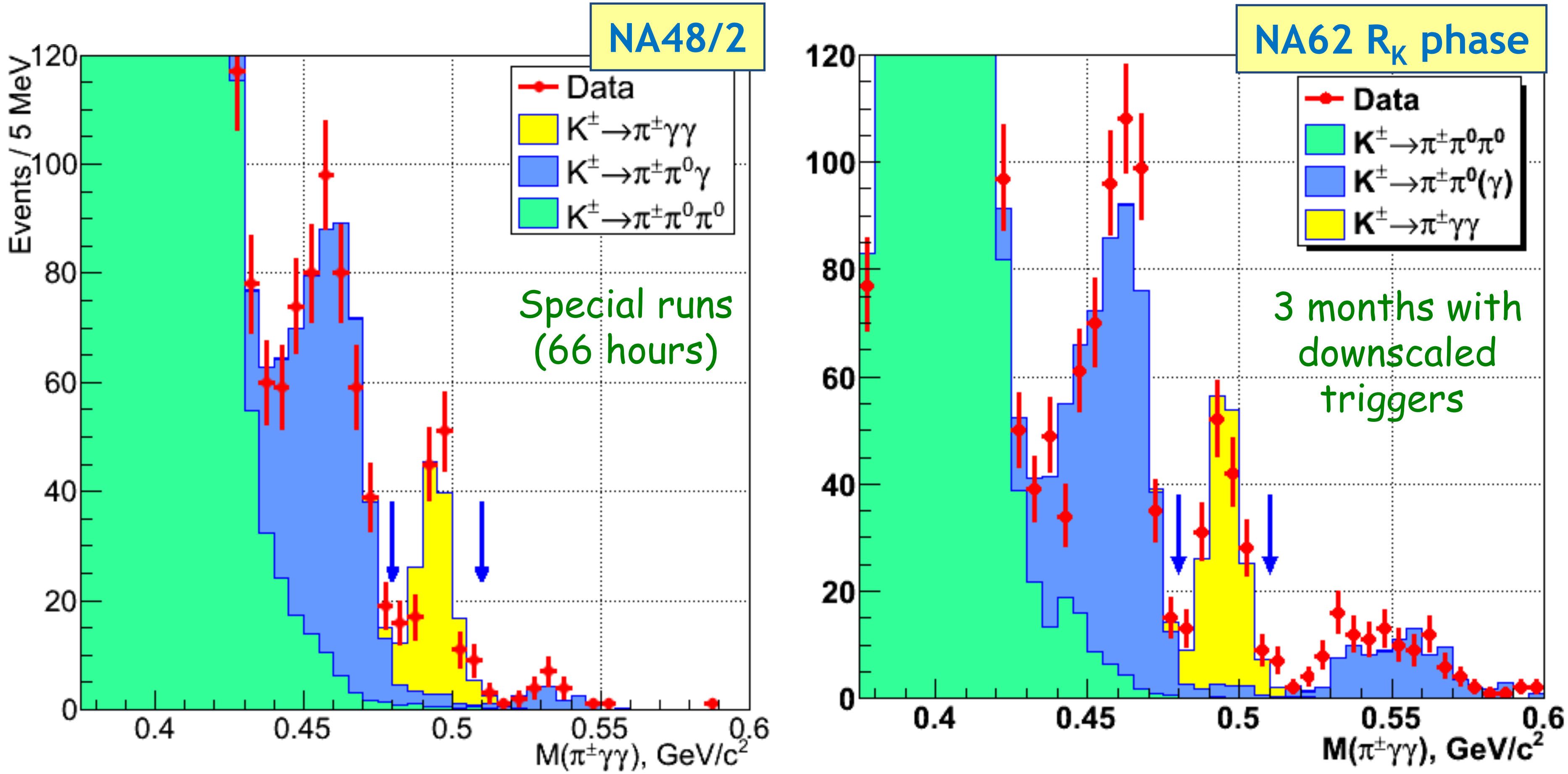
- @ LO $O(p^4)$ the A contribution gives a cusp from $M(\gamma\gamma)=m(\pi^+)+m(\pi^-)$
- @ NLO $O(p^6)$ the B contribution appears and becomes dominant at low z
- Rate & spectrum depend on the O(1) unknown parameter $\hat{c}$

$\hat{c} = 128\, \pi 2/3\, [\, 3\, (L_9 + L_{10}) + (N_{14} - N_{15} - 2\, N_{18})]$

Strong couplings

weak couplings

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

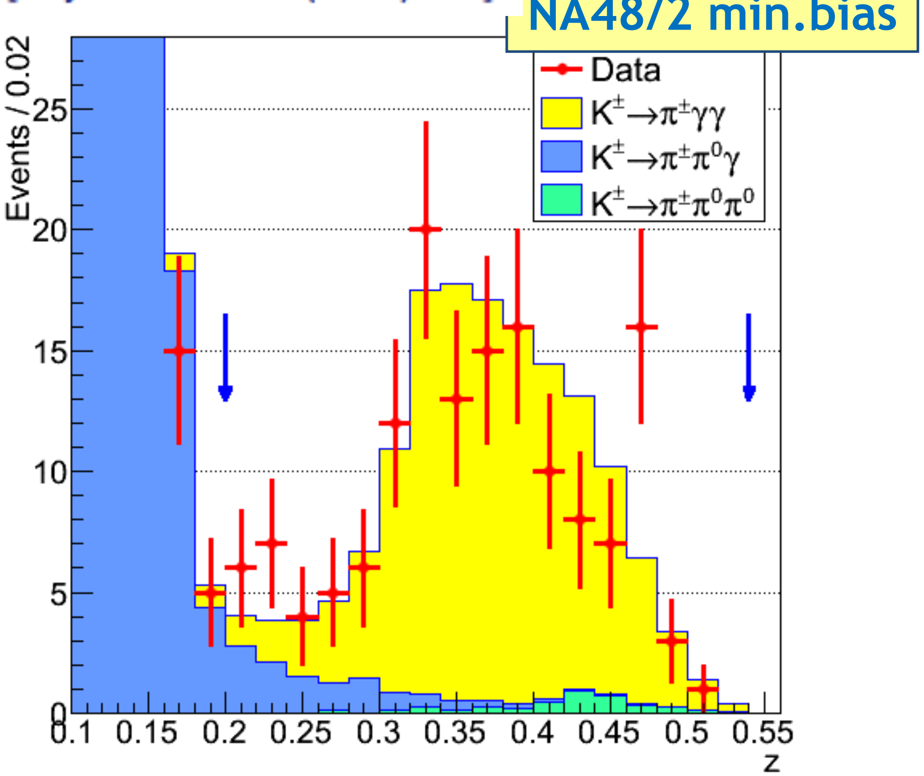


$K_{\pi\gamma\gamma}$ candidates	149
$K_{2\pi(\gamma)}$ background	11.4±0.6
$K_{3\pi}$ background	4.1±0.4
$K_{\pi\gamma\gamma}$ signal	133

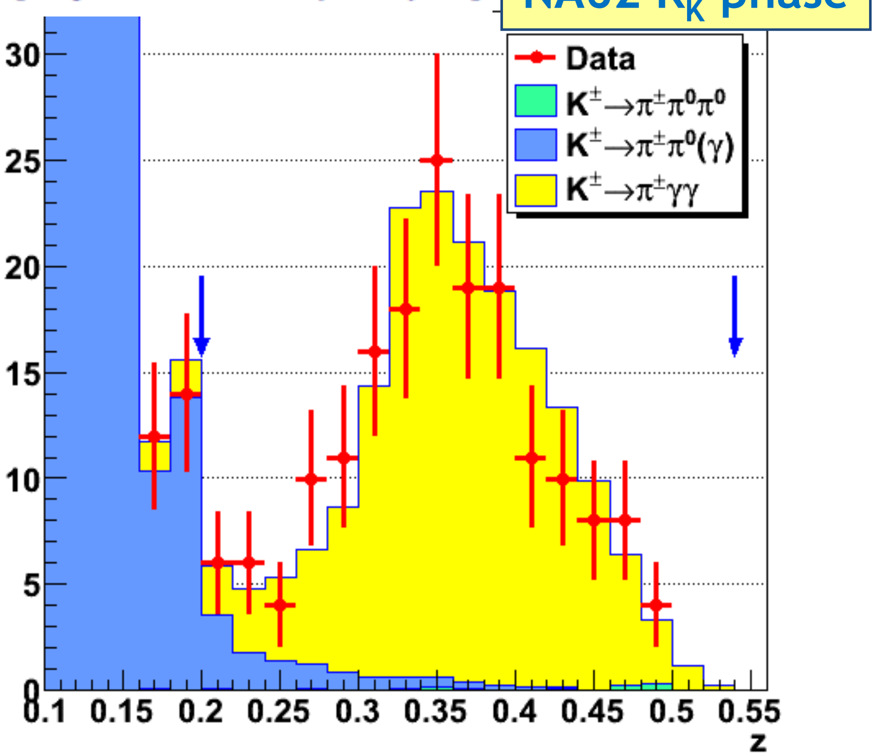
$K_{\pi\gamma\gamma}$ candidates	232
$K_{2\pi(\gamma)}$ background	15.3±1.1
$K_{3\pi}$ background	2.1±0.3
$K_{\pi\gamma\gamma}$ signal	215

Fits to ChPT description

NA48/2 (2003, 2004)
[Phys. Lett. **B730** (2014) 141]



***NA62 R_K-phase* (2007)**
[Phys. Lett. **B732** (2014) 65]



Data support the ChPT prediction of a cusp at di-pion threshold

NA48/2 & NA62-RK combined measurement:

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

Improved precision wrt BNL E787 (31 $K^+ \to \pi^+ \gamma\gamma$ candidates, *PRL 79 (1997) 4079*) and NA48/2 (120 $\mathbf{K^\pm \to \pi^\pm \gamma e^+ e^-}$ candidates, *PLB659 (2009) 493*)

Dark photon: experimental status

M.Pospelov, PRD80 (2009) 095002

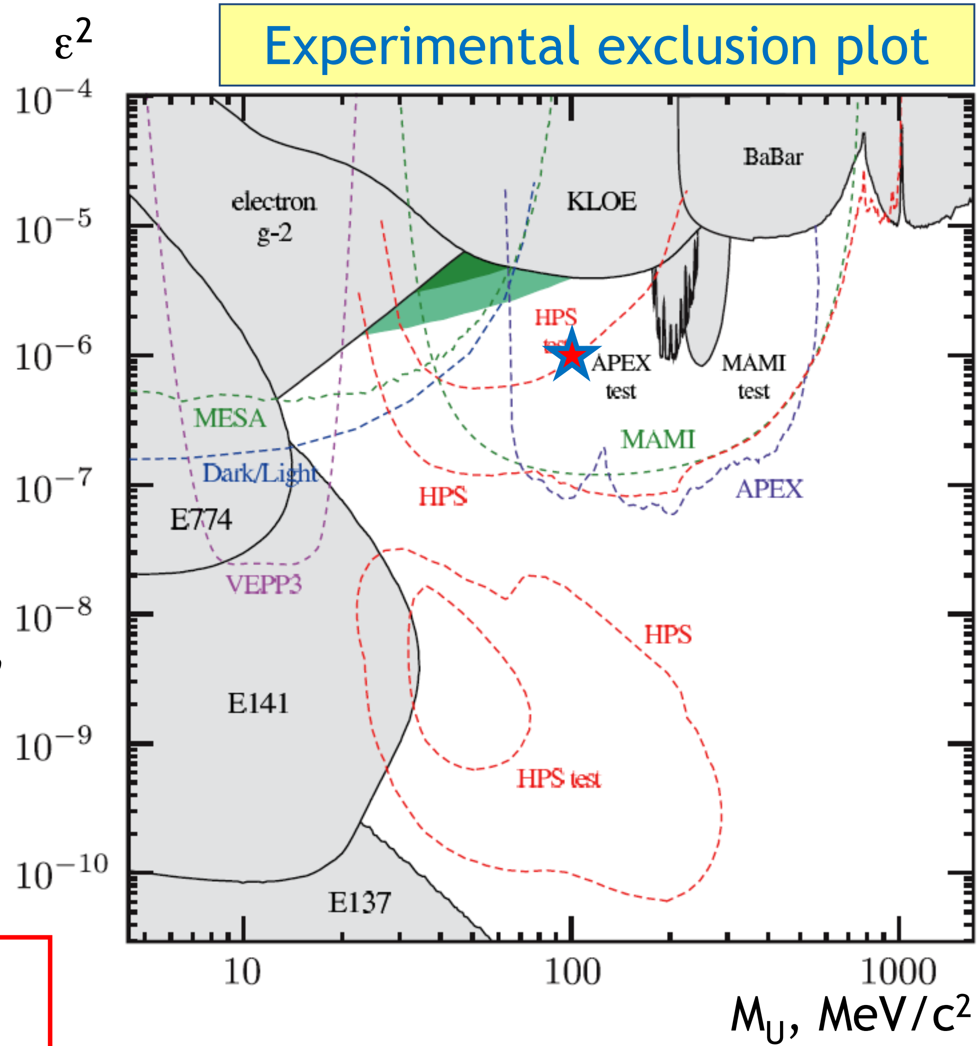
Secluded U(1) sector with weak admixture to photons: a natural SM extension.

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

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

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



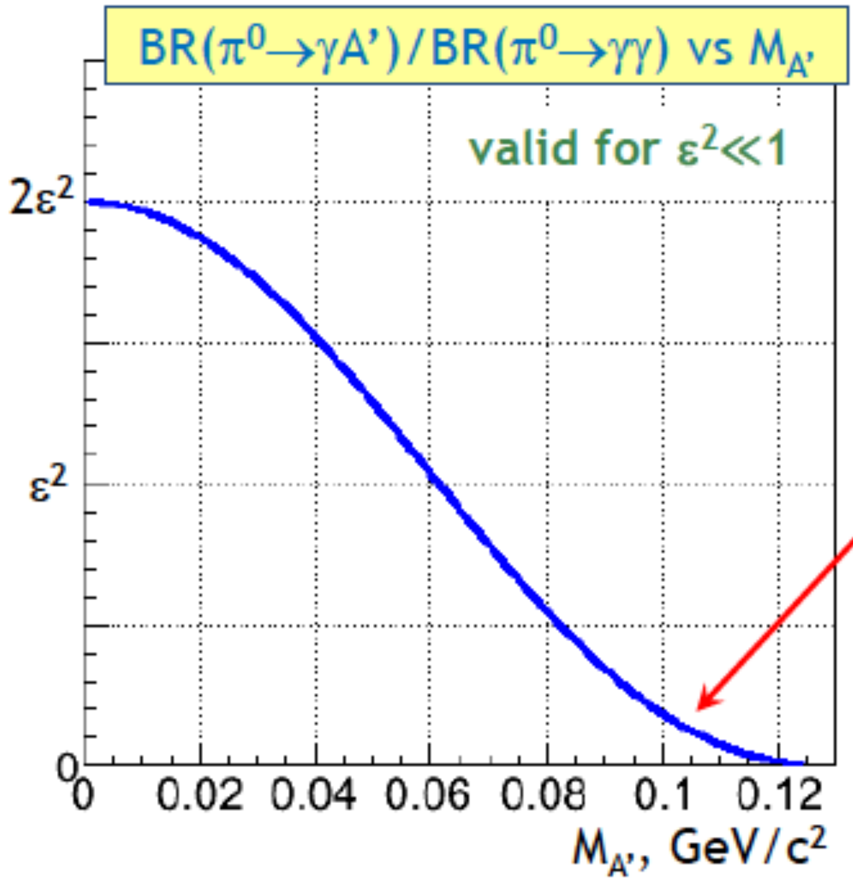
Plot from M.Endo et al., PRD86 (2012) 095029

DP production in $\pi^0 \to \gamma A'$ decay

Batell, Pospelov and Ritz, PRD80 (2009) 095024

$$\frac{\mathcal{B}(\pi^0 \to \gamma U)}{\mathcal{B}(\pi^0 \to \gamma\gamma)} \approx 2\epsilon^2 |F(M_U^2)|^2 \left(1 - \frac{M_U^2}{M_\pi^2}\right)^3$$

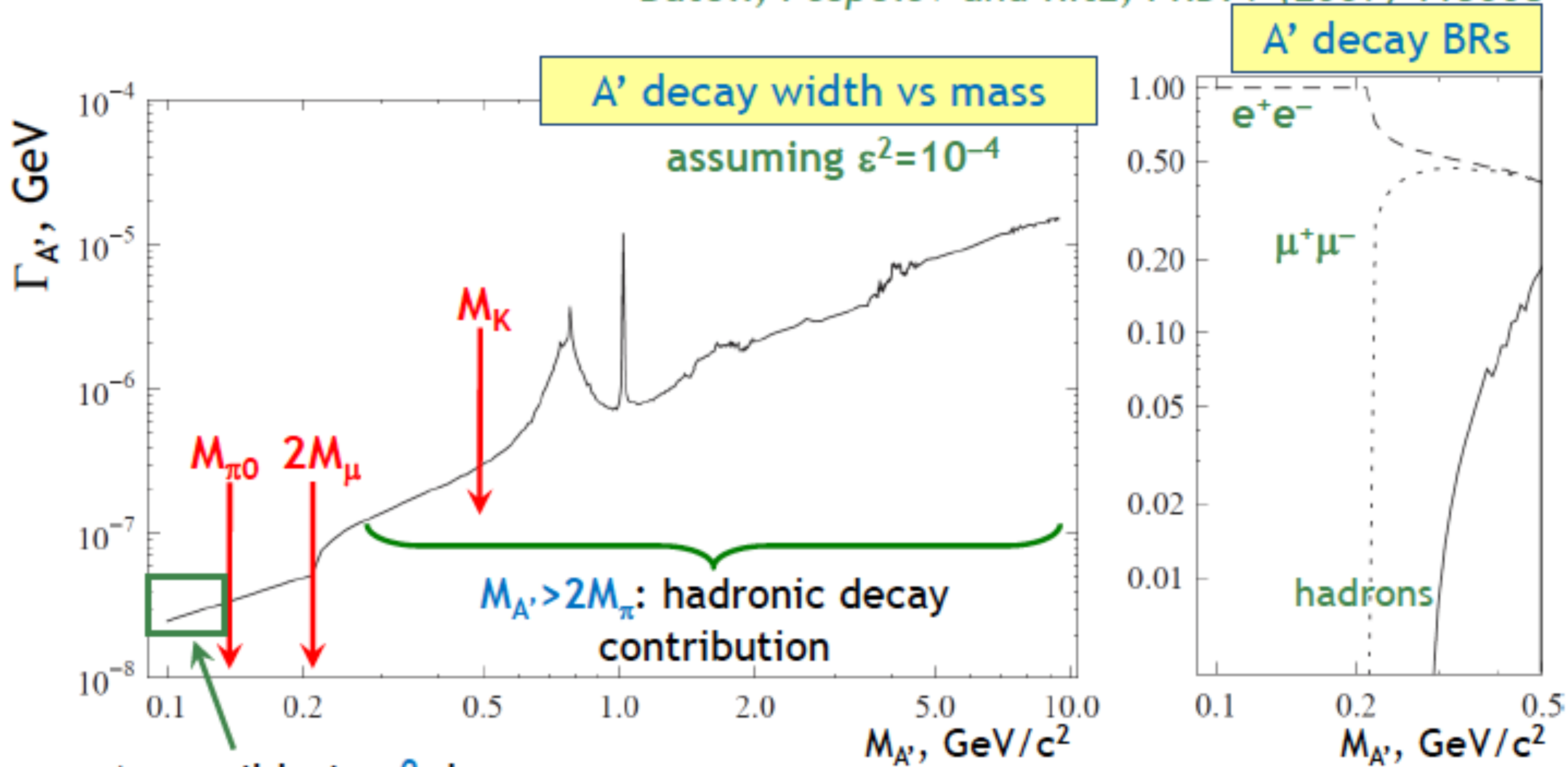
π^0 transition form factor: little effect



Kinematical suppression of $\pi^0 \to \gamma A'$ decay for large $M_{A'}$

DP decays into SM fermions

Batell, Pospelov and Ritz, PRD79 (2009) 115008



Accessible in π^0 decays:

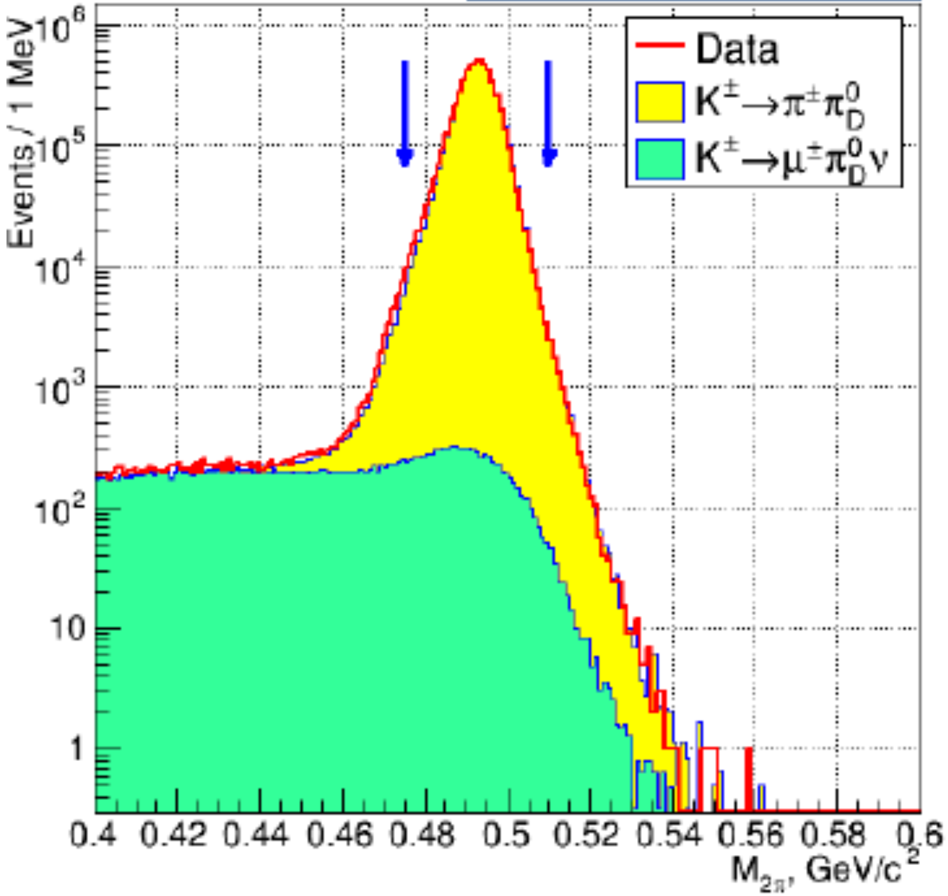
$$\Gamma(A' \to e^+e^-) = \frac{\alpha}{3}\epsilon^2 M_{A'}\sqrt{1-\frac{4m_e^2}{M_{A'}^2}}\left(1+\frac{2m_e^2}{M_{A'}^2}\right) \approx \alpha\varepsilon^2 M_{A'}/3$$

Assuming decays only into SM fermions, BR($A'\to e^+e^-$) = 1.

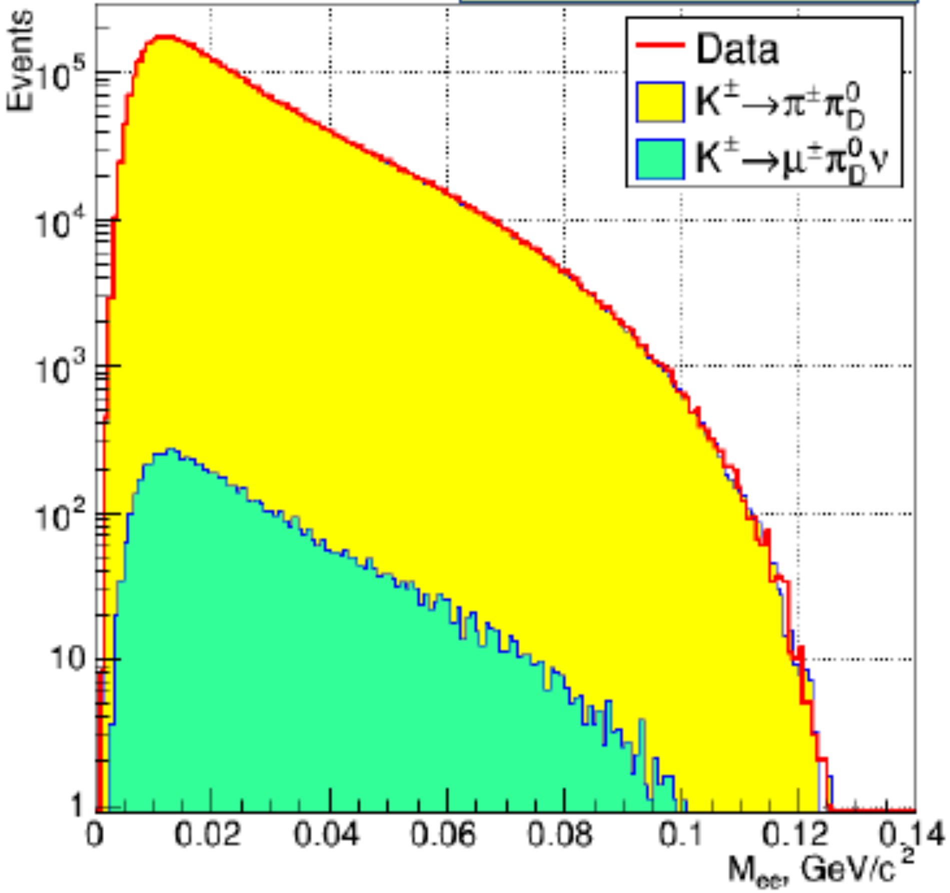
$K_{2\pi D}$ data sample

Large sample of tagged π^0_D decays: $\sim 2\times10^7$ $K^\pm\to\pi^\pm\pi^0_D$.

$M_{2\pi}$: data and MC



M_{ee}: data and MC



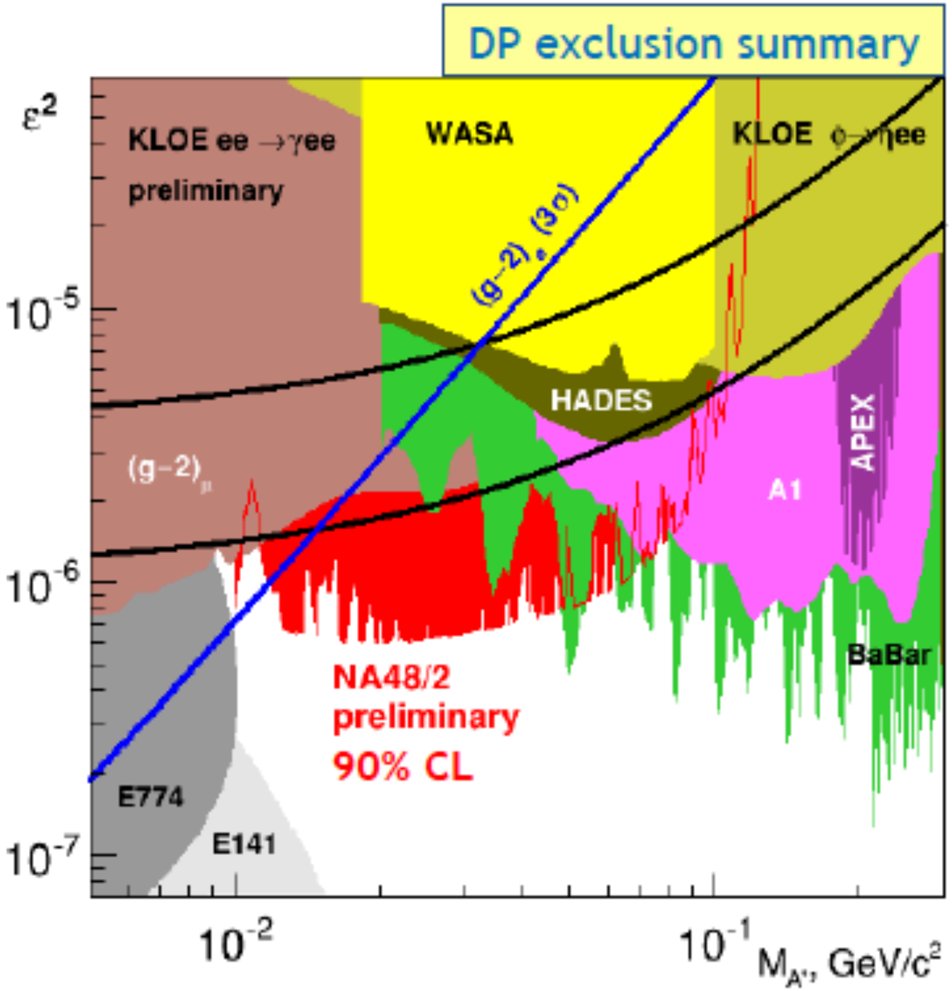
Selection optimized for $K_{2\pi D}$ (total P_T consistent to zero).

Candidates: $N(K_{2\pi D}, M_{ee}>10\text{MeV}/c^2)=4.687\times10^6$, $K_{\mu 3D}$ contribution: 0.15%.

Semileptonic $K^\pm$ decays ($K^\pm\to\pi^0_D l^\pm\nu$, large P_T) can be included.

NA48/2 preliminary limit

[NEW: September 2014]



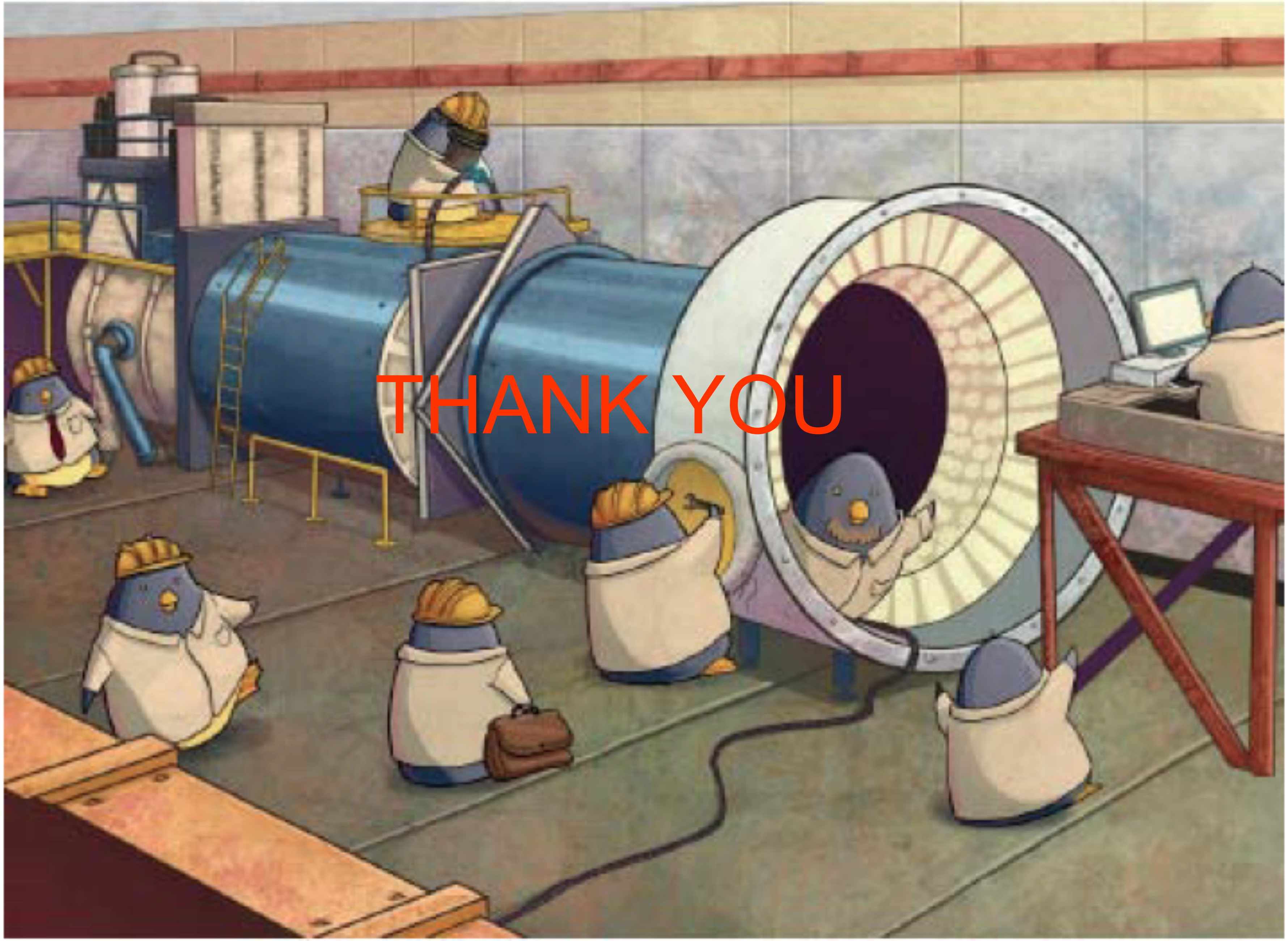
- We conservatively assume $N_{observed}=N_{expected}$ in cases when $N_{observed}<N_{expected}$. Therefore there are no downward spikes.
- Improvement of the existing limits in the range 10–60 MeV/c^2.
- If DP couples to SM fermions and photons and decays only to electrons, it is ruled out as the explanation for anomalous $(g-2)_\mu$.

Summary

- ❖ **NA62-R_K** (2007–2008) and NA48: minimum bias electron trigger.
  - ✓ Lepton Universality test at record 0.4% precision: $BR(K^\pm \to e^\pm \nu)/BR(K^\pm \to \mu^\pm \nu) = (2.488 \pm 0.010) \times 10^{-5}$;
  - ✓ Dark photon limit (new)
  - ✓ ChiPT tests
  - ✓ rare decays, heavy neutrinos: analyses on-going.

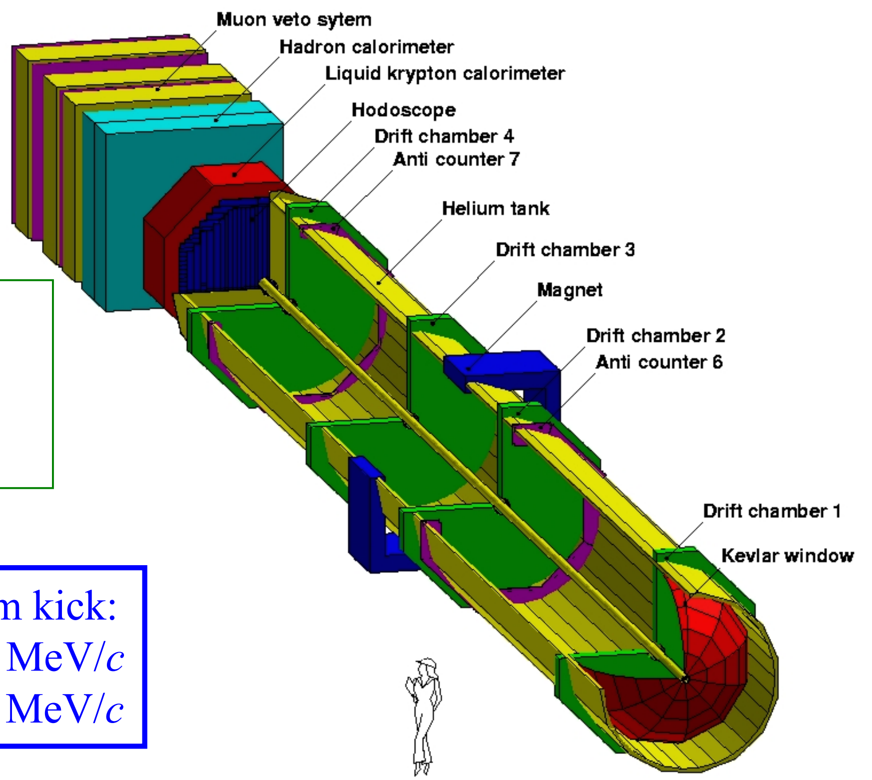
- ❖ **NA62** (now commissioning; physics data from 2015)
  - ✓ expected single event sensitivity for K^+ decays: $\sim \mathbf{10^{-12}}$;
  - ✓ preparing for the physics run in 2014 (low intensity);
  - ✓ a diverse physics programme is taking shape;

UK has a big role in NA62
Opportunity of collaboration with KOTO
and with B experiments for LFV/LNV and rare decays


THANK YOU

Spares

Detector



Magnetic spectrometer:

$\sigma_p/p = (1.0 \oplus 0.044\ p)\%$ [GeV/c] 2004

$\sigma_p/p = (0.48 \oplus 0.009\ p)\%$ [GeV/c] 2007

Trigger Hodoscope:

σ_t=150ps

Momentum kick:
2004: 120 MeV/*c*
2007: 265 MeV/*c*

LKr electromagnetic calorimeter:

$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$

(E in GeV)

$\sigma_x = \sigma_y \sim 1.5$mm for E=10 GeV

$\sigma(M_{\pi\pi^0\pi^0}) = 1.4$ MeV/c^2

E/p ratio used for e/π discrimination

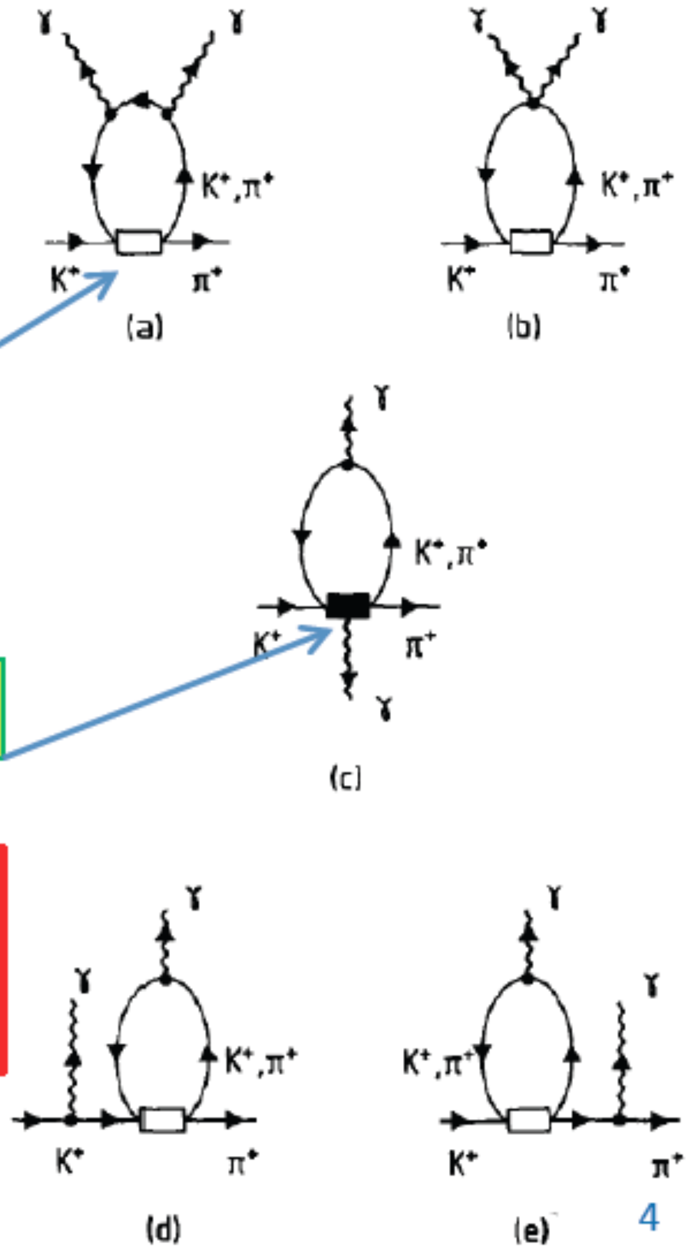
- ~100 m long decay region in vacuum
- Similar acceptance between K^+ and K^- beams checked reversing magnetics fields
- Pion decay products, from the hadronic beam, remain into the beam pipe

One-loop diagrams

$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$

Weak vertex

Weak + e.m. vertex

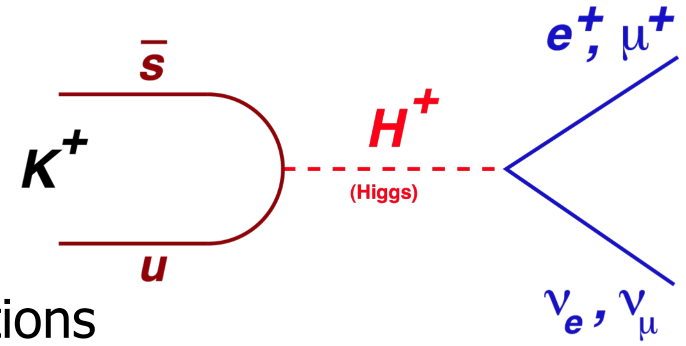


"Radiative K decays and CPV in ChPT"
G. Ecker, A. Pich, E. De Raphael
Nucl.Phys. B 303 (1988)

Leptonic meson decays: $P^+ \to l^+ \nu$

SM contribution is helicity suppressed:

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



Sizeable tree level charged Higgs ($H^\pm$) contributions
in models with two Higgs doublets (2HDM including SUSY)

PRD48 (1993) 2342; Prog.Theor.Phys. 111 (2004) 295

(numerical examples for M_H=500GeV/c², tanβ = 40)

$\pi^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \approx 2\times10^{-4}$

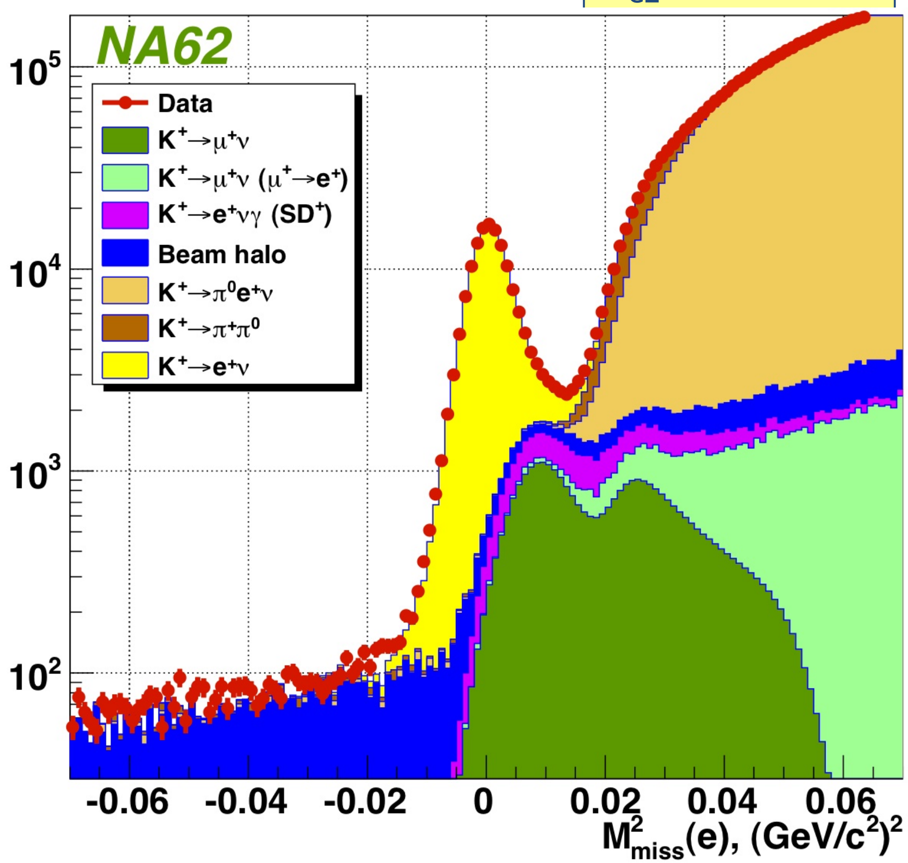
$K^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_K/m_H)^2 \tan^2\beta \approx 0.3\%$

$D^+_s \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_D/m_H)^2\, (m_s/m_c) \tan^2\beta \approx 0.4\%$

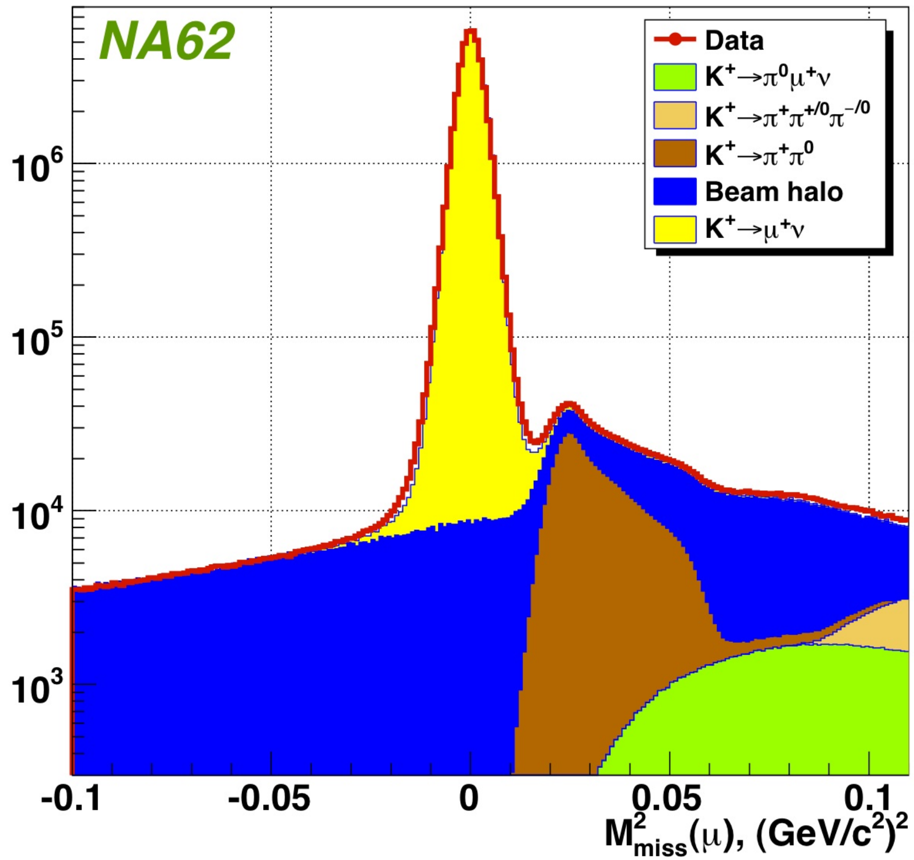
$B^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_B/m_H)^2 \tan^2\beta \approx 30\%$

NA62 data set for R_K

K_{e2} candidates



$K_{\mu 2}$ candidates



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

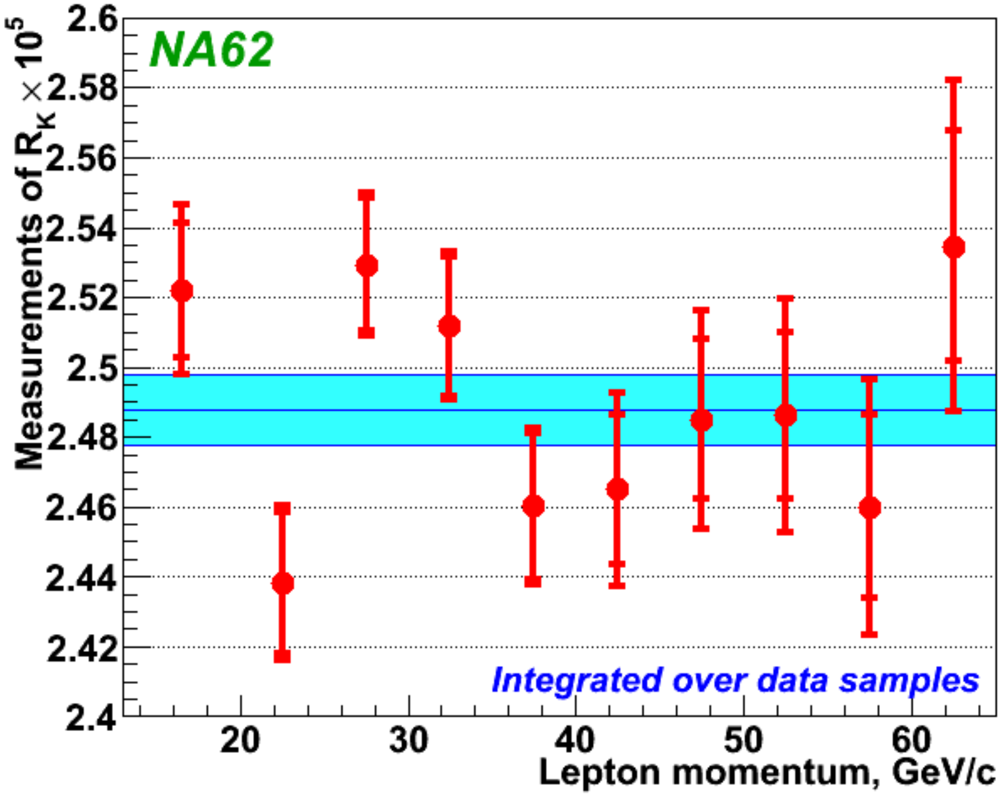
42.817M candidates
with low background
B/(S+B) = (0.50±0.01)%

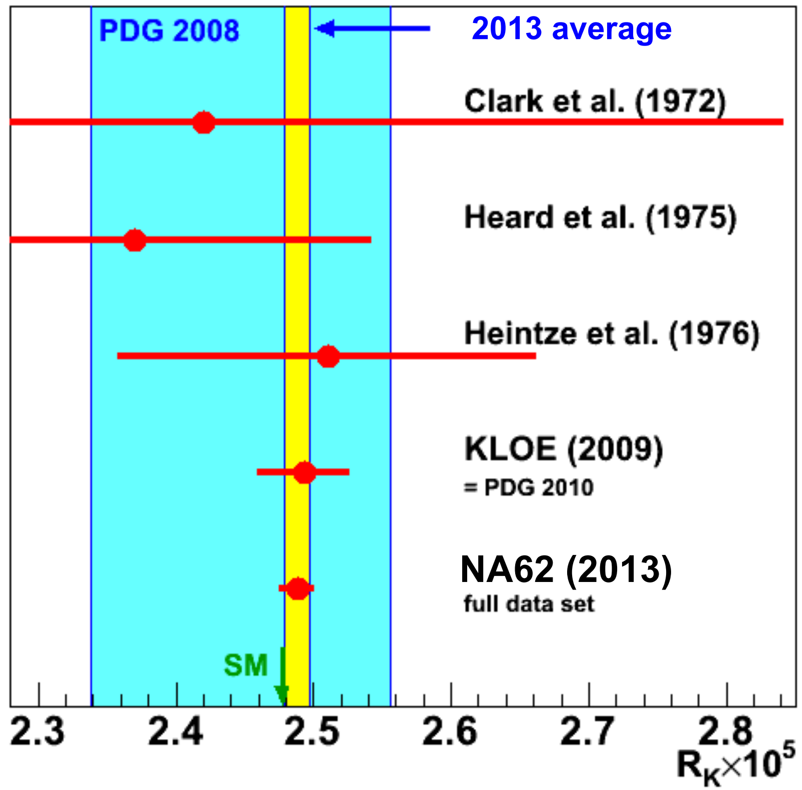
NA62 final result

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

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

[Phys. Lett. B 719 (2013) 326]





Independent measurements in lepton momentum bins

(systematic errors included, partially correlated)

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

Br($K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$): full kinematic range

Measured $\hat{c}$ translates into model-dependend $BR(K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma)$ in the full kinematic range

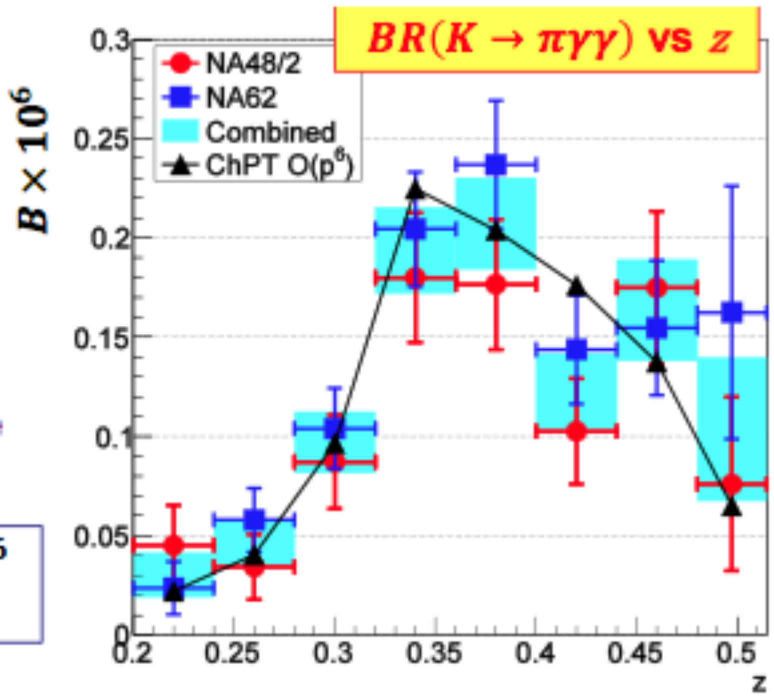
Obtained by integration of the ChPT O(p^6) differential decay rate:
NA48/2 (2003,2004): $B_{ChPT} = (0.910 \pm 0.072\ stat \pm 0.022\ syst) \times 10^{-6}$
NA62 *R_K-phase* (2007): $B_{ChPT} = (1.058 \pm 0.066\ stat \pm 0.044\ syst) \times 10^{-6}$
Under the assumed O(p^6) parametrisation!

- **Combination of the *NA48/2* (2003,2004) and *NA62 R_K-phase* (2007) results**
- **Same set of external parameters used in the measurement of $\hat{c}$ parameter by *NA48/2* and *NA62 R_K-phase***

Combined:
[Phys. Lett. **B732** (2014) 65]
$\hat{c}_4 = 1.72 \pm 0.20\ stat \pm 0.06\ syst$
$\hat{c}_6 = 1.86 \pm 0.23\ stat \pm 0.11\ syst$

Integrating the O(p^6) differential decay rate for the combined value of $\hat{c}_6$:

$B_{ChPT} = (1.003 \pm 0.051\ stat \pm 0.024\ syst) \times 10^{-6}$
[Phys. Lett. **B732** (2014) 65]



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

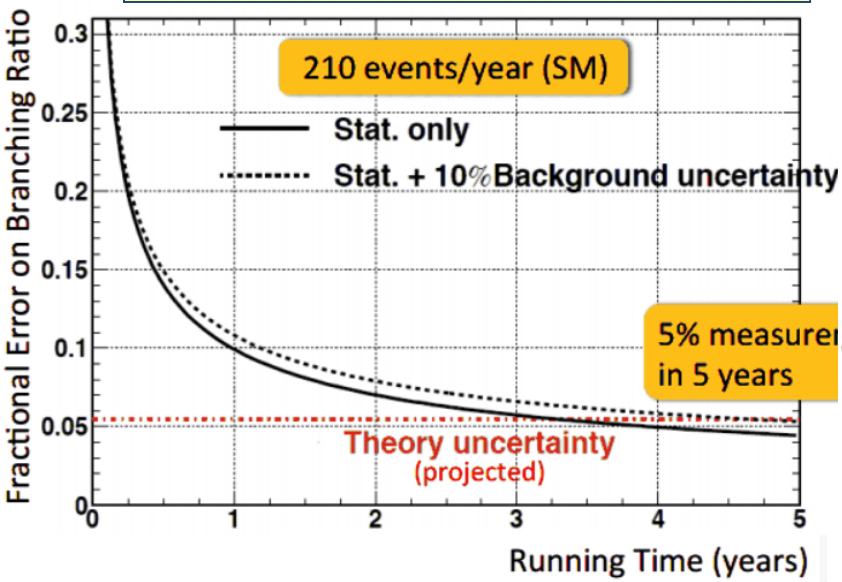
ORKA @ FNAL Main Injector (K^+):

- Builds on BNL stopped-kaon technique.
- Expect ~100 times higher sensitivity.
- Goal: $O(10^3)$ SM $K^+ \to \pi^+ \nu\nu$ events.
- Fits inside the CDF solenoid.
- Re-use CDF infrastructure.

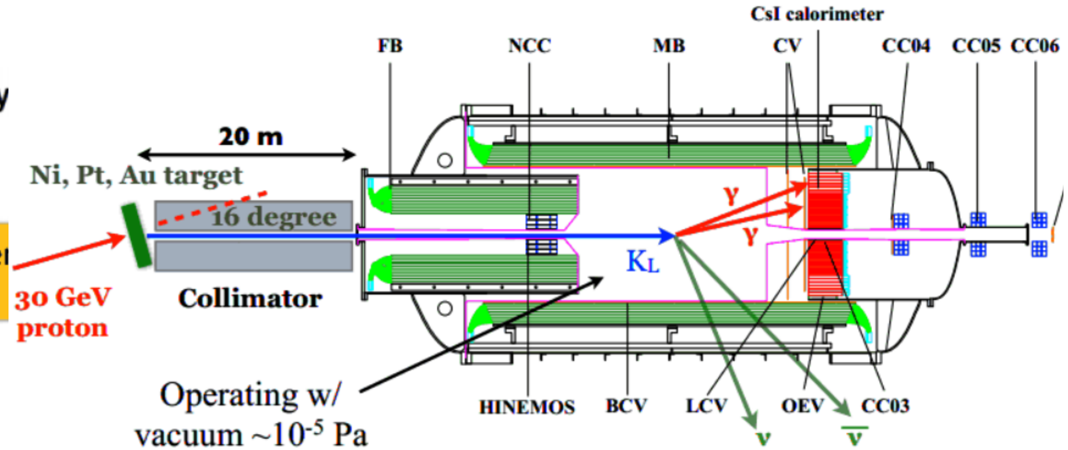
KOTO @ J-PARC (K_L):

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

ORKA expected sensitivity



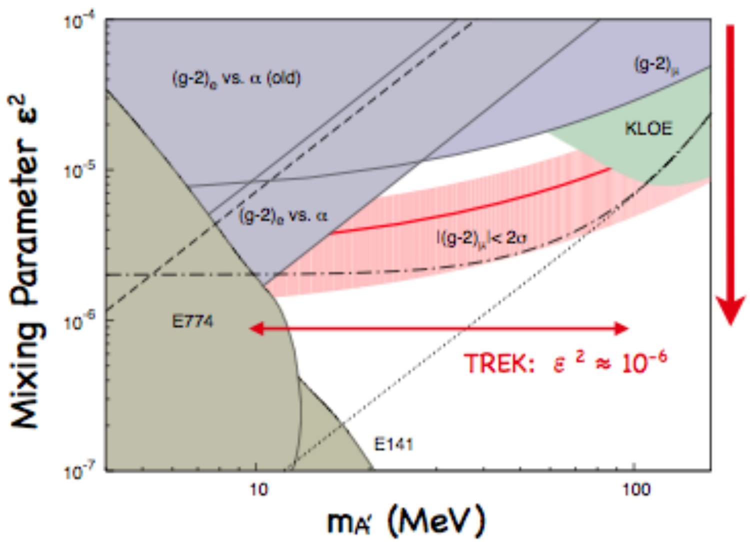
"Two photons + nothing"



Overview of TREK

TREK detector: Upgrade of E246 detector for the study of various Kaon decay channels at **J-PARC**.

installing/running FY2014/2015



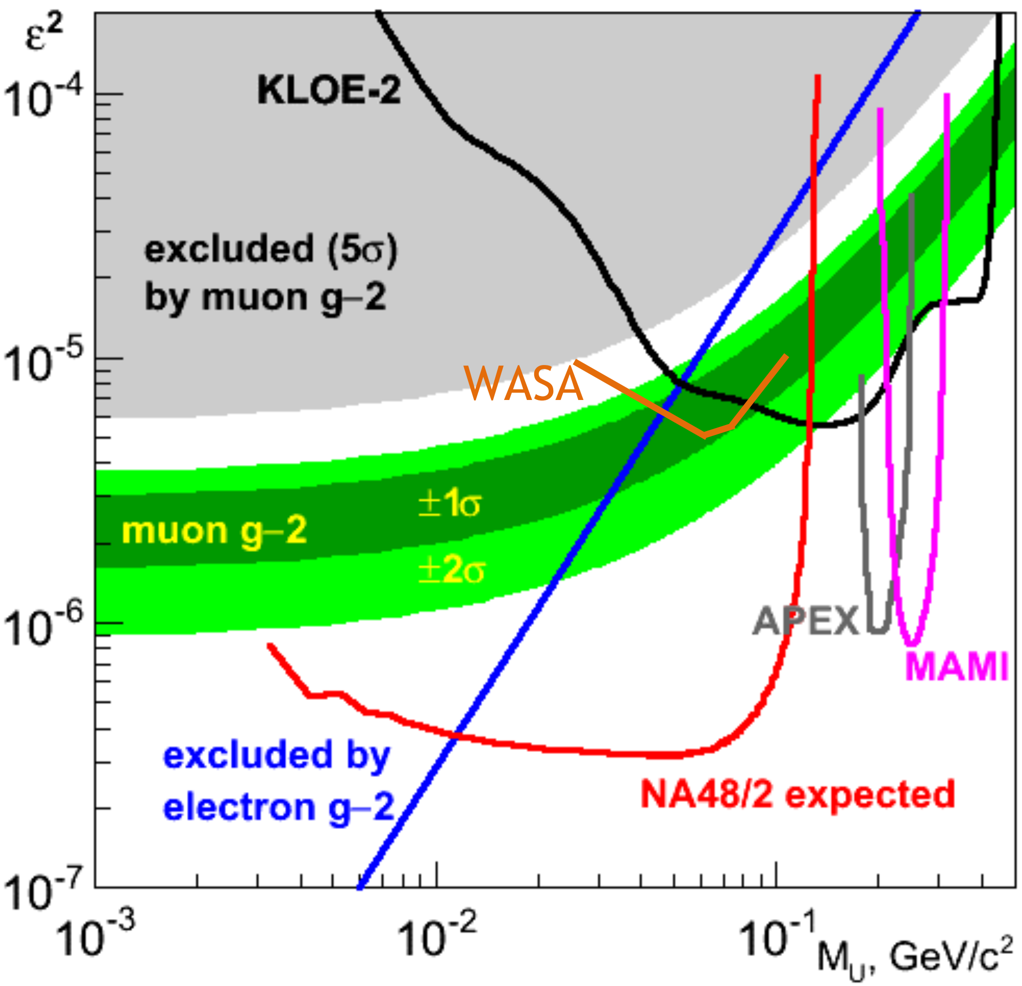
T. Beranek and M. Vanderhaeghen, Phys. Rev. D **87**, 015024 (2013)

Search for lepton universality violation in a measurement of the ratio of the K_{e2} and $K_{\mu 2}$ decay widths	$K^+ \rightarrow e^+\nu$ $K^+ \rightarrow \mu^+\nu$ 0.25% precision
Search for a heavy sterile neutrino	$K^+ \rightarrow \mu^+ N$ $\lvert U\rvert<2\ 10^{-8}$ for M<200 MeV
Search for dark light	$K^+ \rightarrow \pi^+ A' \rightarrow \pi^+ e^+ e^-$ $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$

SM extensions with massive gauge boson A'
Sensitivity: mixing parameter ~10^{-6} for 10<M(A')<100 MeV

M. Abe et al., Phys. Rev. D **73**, 072005 (2006)

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

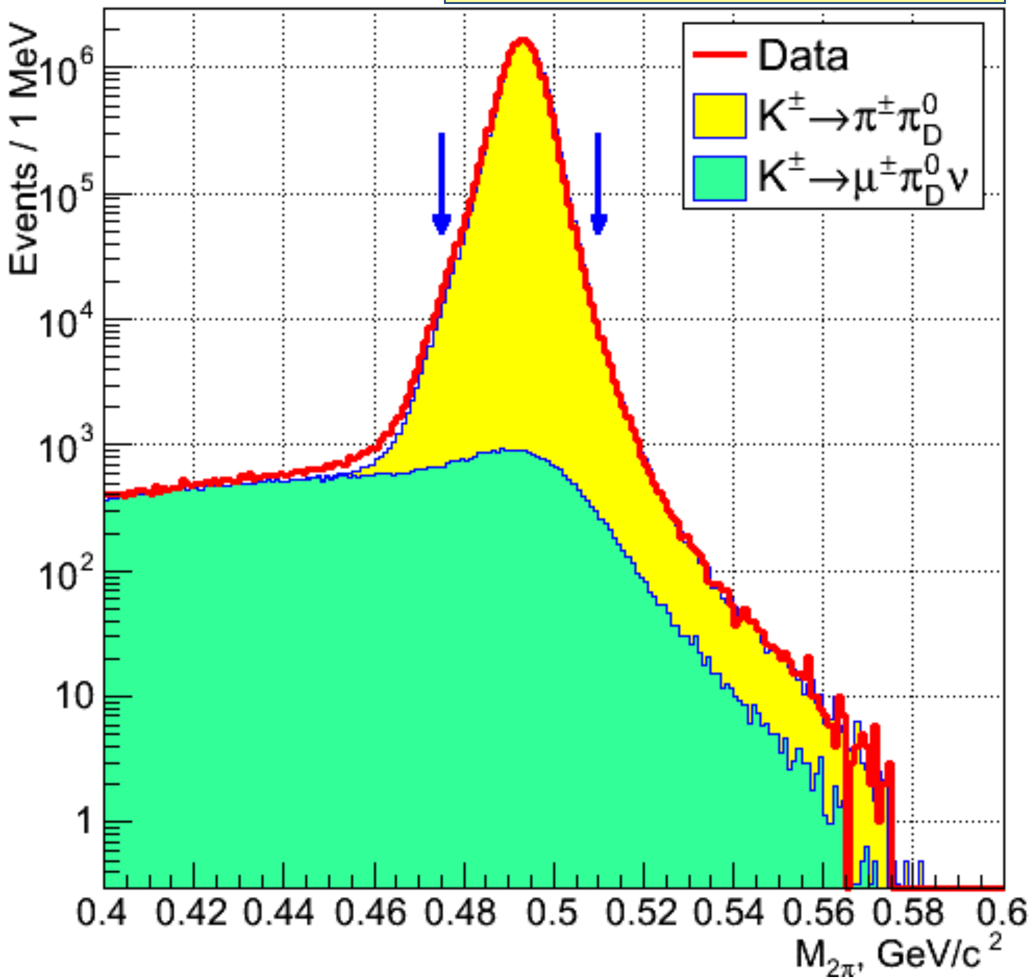
APEX @ J-LAB
Abrahamyan et al.,
PRL107 (2011) 191804

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

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

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%**.

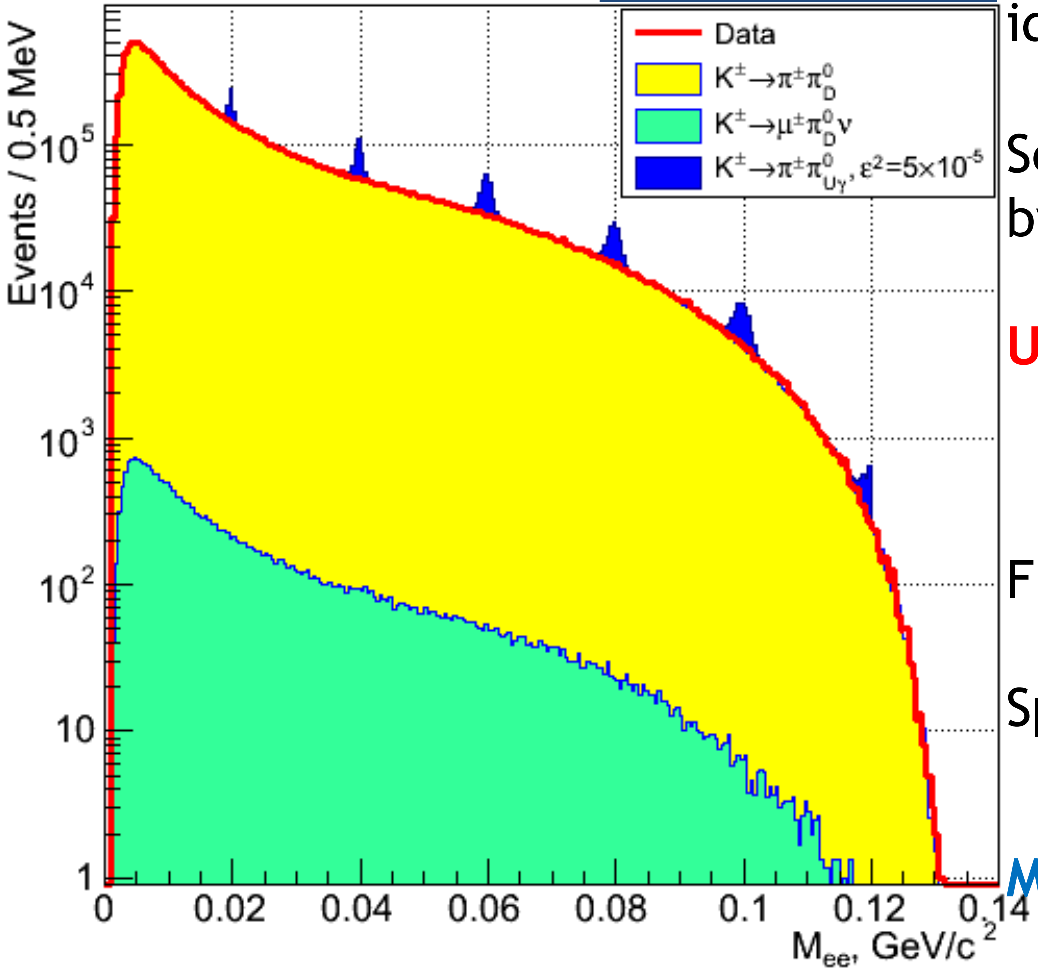
Large sample of tagged π^0_D decays: **~2×10^7 $K^\pm\to\pi^\pm\pi^0_D$**.

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: M_{ee} spectrum of π^0_D

M_{ee} spectrum



π^0 form-factor measurement on-going

Mean dark photon 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.

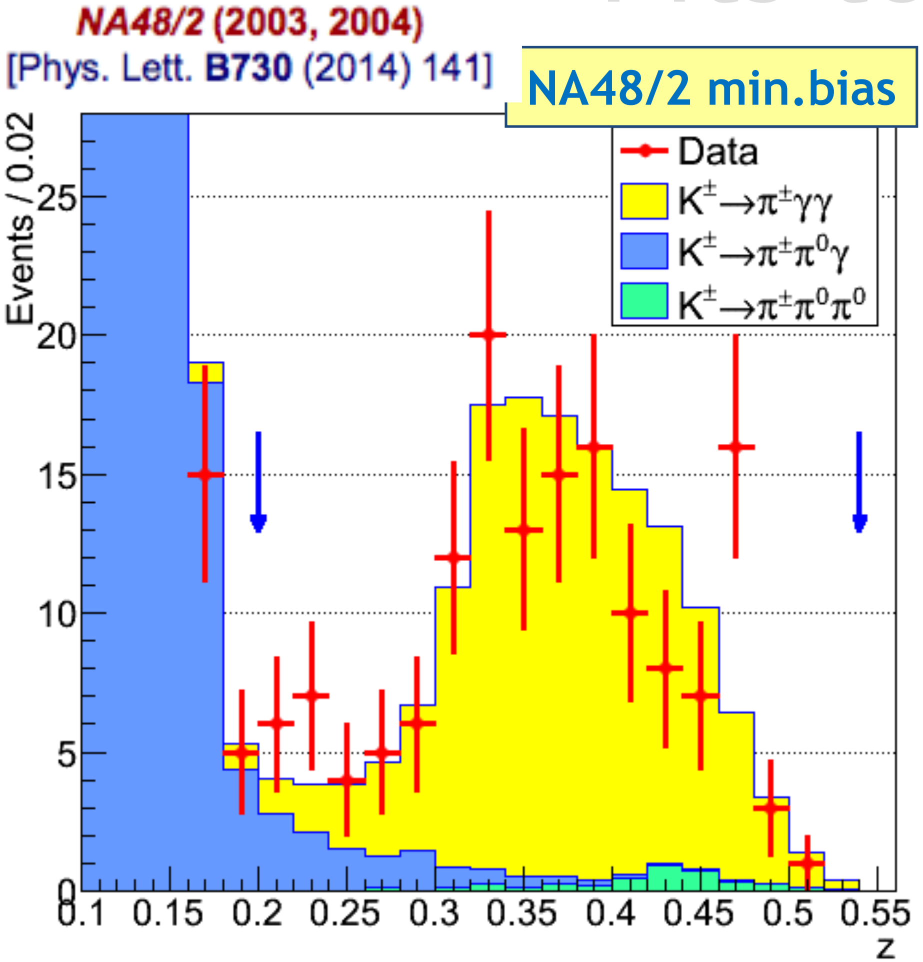
Upper limit ~ **(Kaon Flux)$^{-1/2}$** × **(Acceptance)$^{-1/2}$** × **(M_{ee} resolution)$^{-1/2}$**

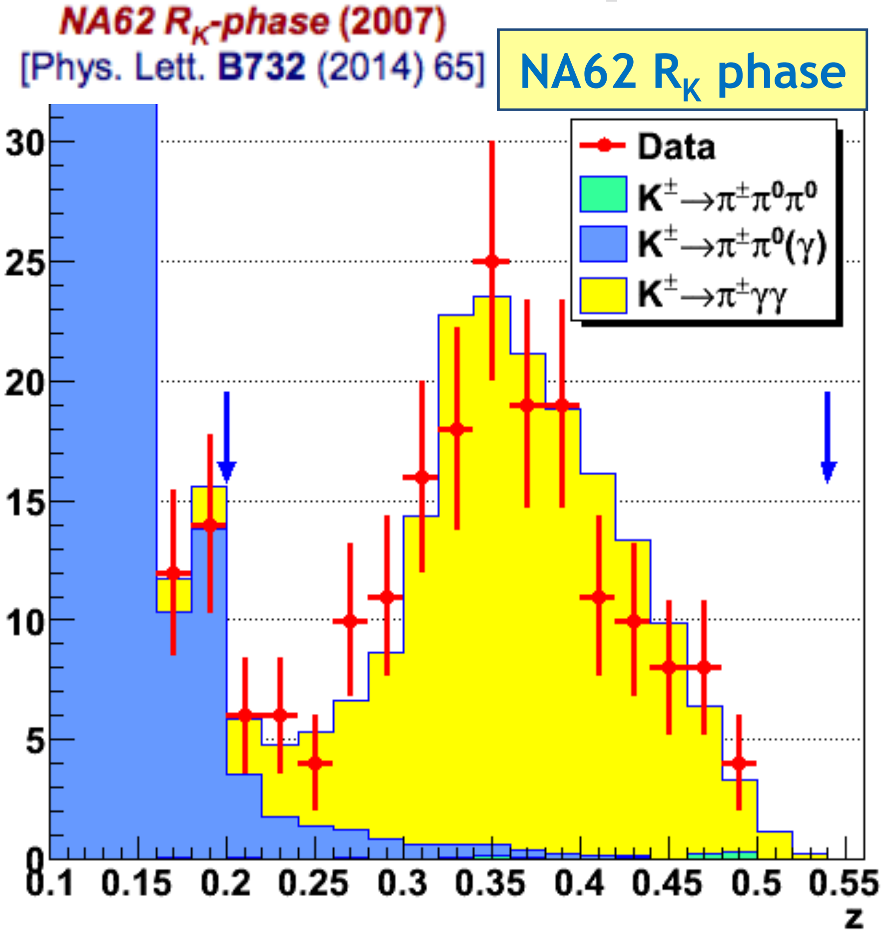
Flux **~2×10^{11}** , acceptance **~5%**.

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.

Fits to ChPT description





Cusp-like behaviour at $z = (2m_\pi/m_K)^2$
Consider only region $z > 0.2$

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

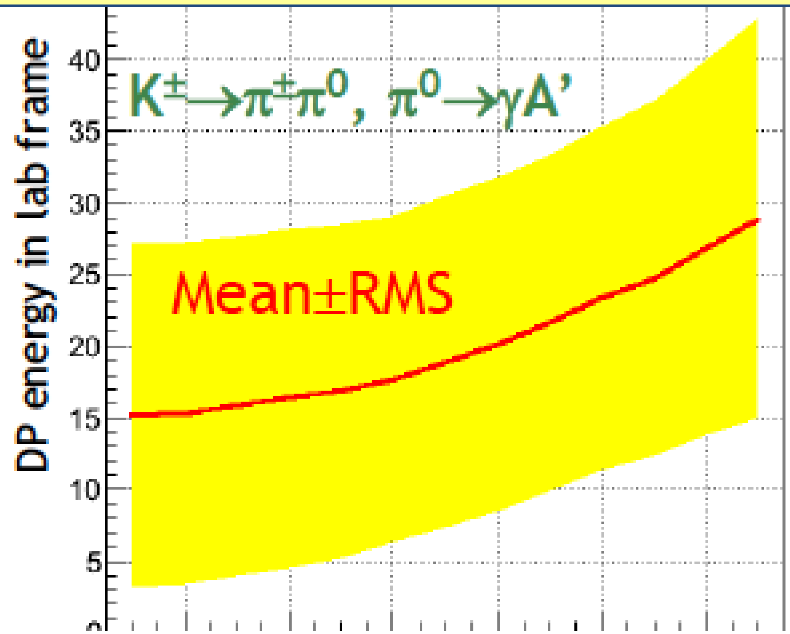
DP lifetime and mean p

Assuming decays to SM fermions only,
decay width for $M_e \ll M_{A'} < 2M_\mu$: $\Gamma_{A'} \approx \alpha\varepsilon^2 M_{A'}/3$, $BR(A' \to e^+e^-)$

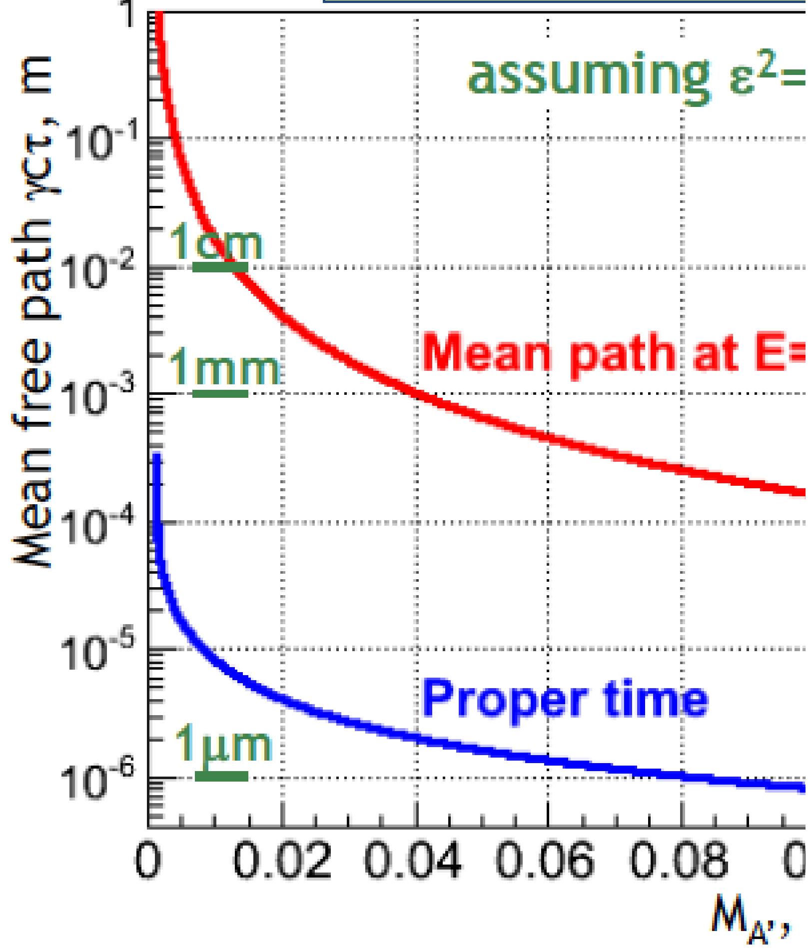
Proper lifetime:

$$c\tau = \frac{\hbar c}{\Gamma_U} \approx 80\ \mathrm{nm} \times \frac{10^{-6}}{\epsilon^2} \times \left(\frac{M_U}{\mathrm{GeV}}\right)^{-1}$$

DP energy in lab frame vs mass



DP mean path vs



NA48/2 data sam

- Method: exclusive search for the decay chain $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$, $\pi^{0}\rightarrow\gamma A'$, $A'\rightarrow$e
  Fully reconstructed final state, 3-track vertex topology.

- Identical to $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}_{D}$, $\pi^{0}_{D}\rightarrow\gamma e^{+}e^{-}$; $BR(K_{2\pi D})=0.24\%$:
  sensitivity is limited by the irreducible $K_{2\pi D}$ background.

- Sensitivity: $UL(\varepsilon^{2}) \sim (\text{Kaon Flux})^{-1/2} \times (\text{Acceptance})^{-1/2} \times (M_{ee}$ resolu

- Number of kaon decays: $N_{K} \approx 2\times10^{11}$.
  - ✓ That is $\approx 4\times10^{10}$ π^{0} tagged decays in vacuum from $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$ decays
  - ✓ Efficient trigger chain for 3-track vertices throughout the data tal
    based on HOD multiplicity (L1) and DCH track reconstruction (L2

- Signal acceptance: depending on $M_{A'}$, up to 2.5%.

- Spectrometer mass resolution: $\sigma_{Mee} \approx 0.012\times M_{ee}$.

π^0_D background simulat

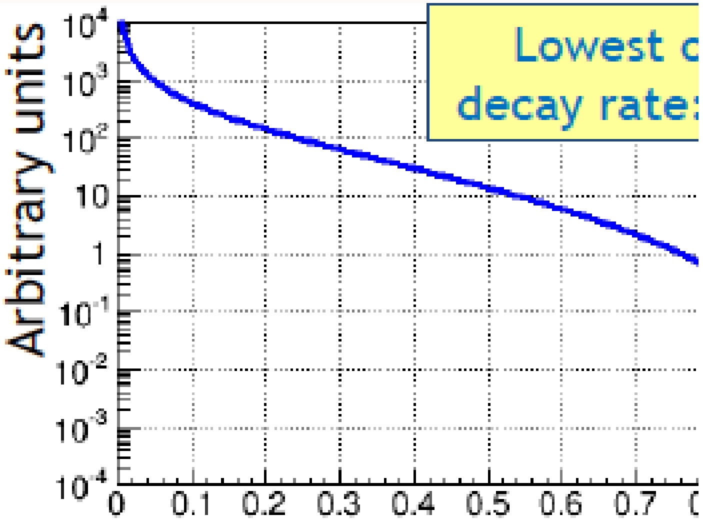
Kinematic variables:

$x = (q_1+q_2)^2/m_\pi^2 = (m_{ee}/m_\pi)^2$, $y = 2p(q_1-q_2)/[m_\pi^2\,(1-x)]$.

(1) Differential decay rate (lowest order):

$$\frac{1}{\Gamma_0}\frac{d^2\Gamma(\pi^0\to\gamma e^+e^-)}{dxdy} = \frac{\alpha}{\pi}|F(x)|^2\frac{(1-x)^3}{4x}\left(1+y^2+\frac{r^2}{x}\right)$$

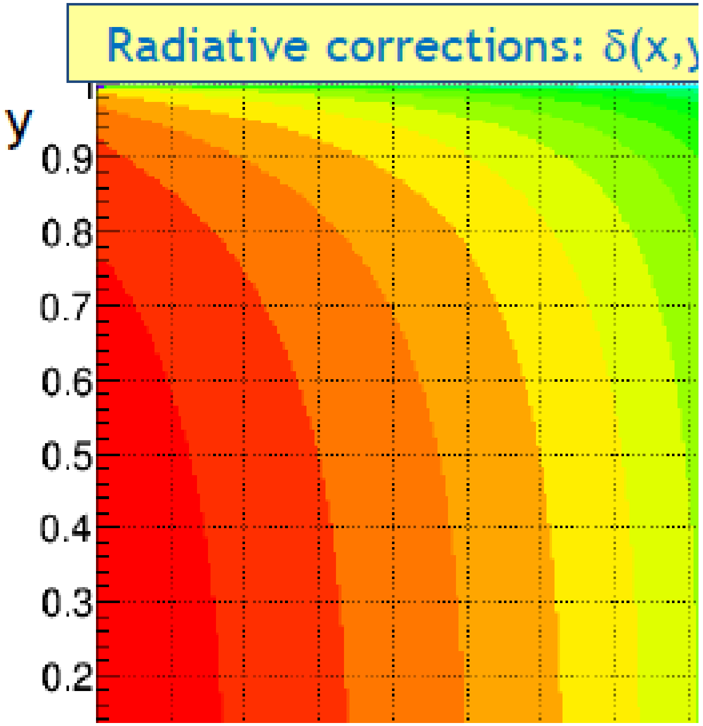
$(r=2m_e/m_\pi)$



(2) Radiative corrections:

$$\frac{d\Gamma}{dxdy} = \delta(x,y)\frac{d\Gamma^0}{dxdy}$$

Mikaelian and Smith, PRD5 (1972) 1763
Improved numerical precision:
Husek, Kampf and Novotný, to be published



(3) π^0 transition form-factor: $F(x)=1+ax$.

- ✓ TFF slope (PDG, dominated by $e^+e^-\to e^+e^-\pi^0$ measurement): $a=0.032\pm0.004$.
- ✓ Modified TFF slope value is used for

DP signal: peak in M_{ee} spectrum

- Scanned DP mass range: 10 MeV/c^2<M_{DP}<125 MeV/c^2.
- Below 10 MeV/c^2, acceptance is low and difficult to simulate.
- Variable DP mass step: $\approx 0.5\sigma_{Mee}$.
- DP mass hypotheses tested: 398.
- Confidence intervals for $N_{A'}$ are computed from $N_{expected}$, $N_{observed}$ and $\delta N_{observed}$ in the signal mass window using the Rolke-Lopez method.
- Signal mass window optimized for maximum sensitivity: $\pm 1.5\sigma_{Mee}$ (acceptance vs π^0_D background).
- $\delta N_{observed}$ is a statistical uncertainty: limited MC statistics and the limited control sample for trigger efficiency measurement.