

The kaon programme at CERN

Evgueni Goudzovski

(University of Birmingham)

eg@hep.ph.bham.ac.uk

Outline:

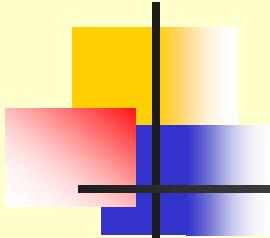
- 1) Introduction to the CERN kaon experiments;
- 2) Present: Leptonic K decays and lepton universality tests;
- 3) Future: the ultra-rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay.



UNIVERSITY OF
BIRMINGHAM

Particle Physics Seminar • LAPP Annecy
30 March 2010





Flavour physics in the LHC era

Searches for physics beyond the Standard Model:
two complementary approaches in the laboratory

Energy frontier (Tevatron, LHC)

Determine the energy scale of NP
by direct production of NP particles.
Limited by LHC beam energy.



Intensity frontier

Determine the flavour structure of NP via
virtual effects in precision observables:
deviations from precise SM predictions in
rare or forbidden processes.

CP violation in
B and K systems

Universality tests
in B and K

Rare B and K
decays

A collective effort



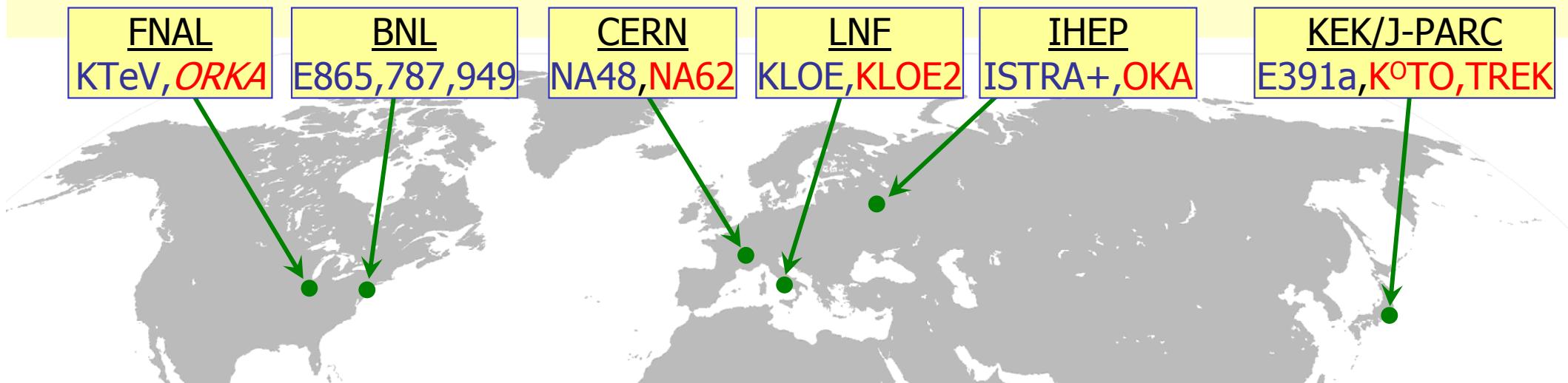
- LFV in μ and τ decays
- Neutron EDM
- $(g-2)_\mu$
- Improved CKM fits

Searches at intensity frontier historically tremendously successful:
GIM before discovery of charm, CPV before discovery of top & bottom

K physics in the new millennium

A new generation of high statistics kaon experiments have been in operation during the last decade.

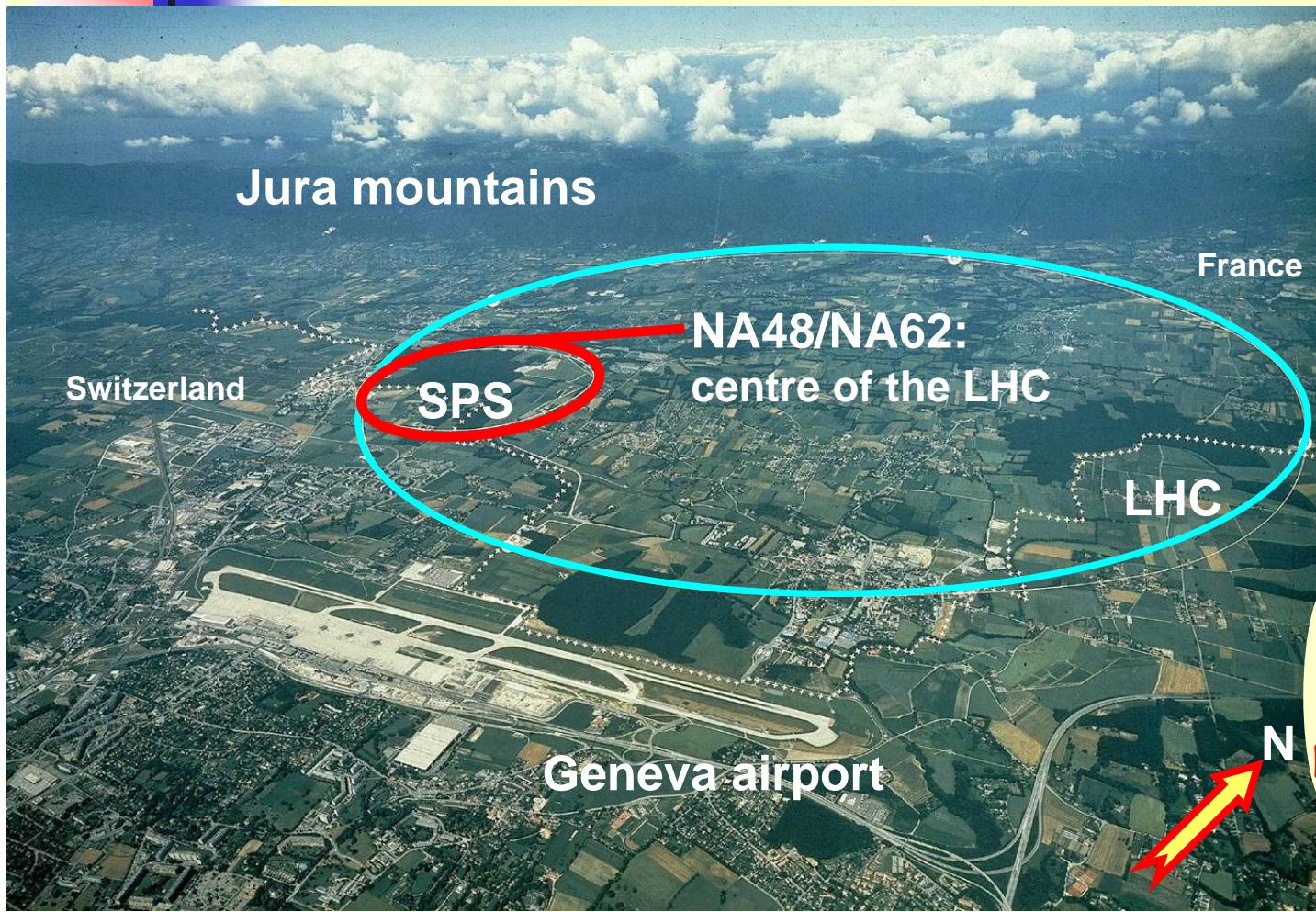
Variety of experimental techniques: decay-in-flight, ϕ factory, stopped K.



Significant progress in many fields in the last years:

- Direct CP violation (ε'/ε);
 - Precision determination of $|V_{us}|$;
 - Precision tests of the Chiral Perturbation Theory;
 - Searches for Lepton Flavor Universality Violation;
 - Searches for New Physics in ultra-rare decays.
- } This talk

CERN NA48/NA62 experiments



NA62: Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

Earlier: NA31

1997: $\varepsilon'/\varepsilon: K_L + K_S$

1998: $K_L + K_S$

NA48
discovery
of direct
CPV

1999: $K_L + K_S$ | K_S HI

2000: K_L only | K_S HI

2001: $K_L + K_S$ | K_S HI

NA48/1

2002: K_S /hyperons

NA48/2

2003: K^+ / K^-

2004: K^+ / K^-

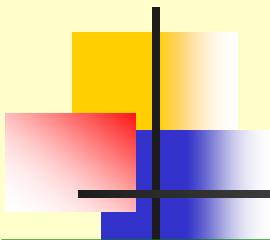
NA62
(R_K phase)

2007: $K^\pm_{e2} / K^\pm_{\mu 2}$ tests

2008: $K^\pm_{e2} / K^\pm_{\mu 2}$ tests

NA62

2007–2013:
design & construction
2012: first data taking



The decay-in-flight technique

2003-: experiments with charged kaons at CERN

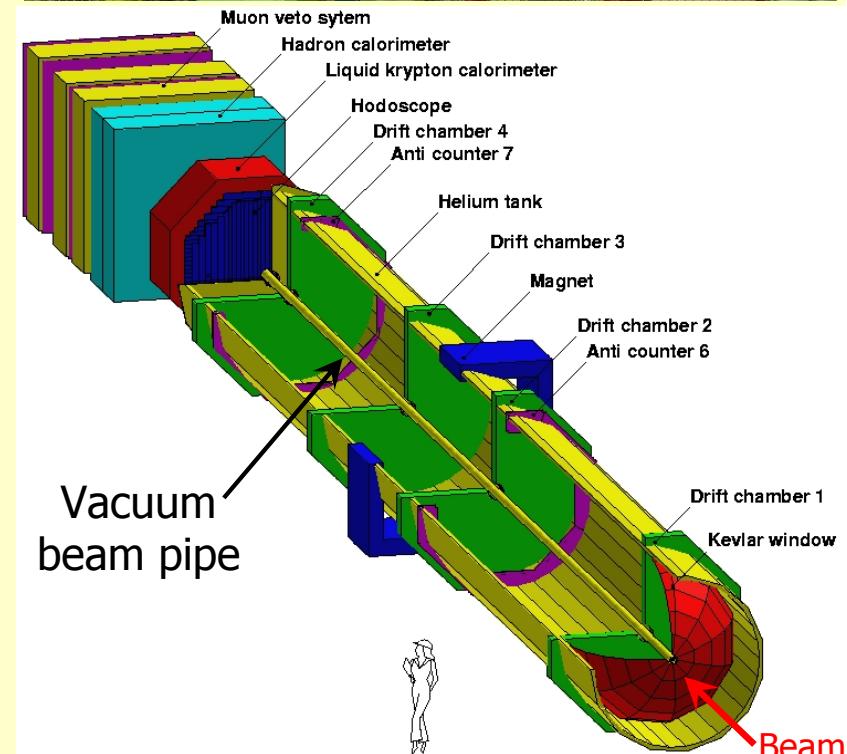
Narrow momentum band K^\pm beams:

$P_K = 60 \text{ (74) GeV/c}$, $\delta P_K / P_K (\text{RMS}) \sim 1\%$.

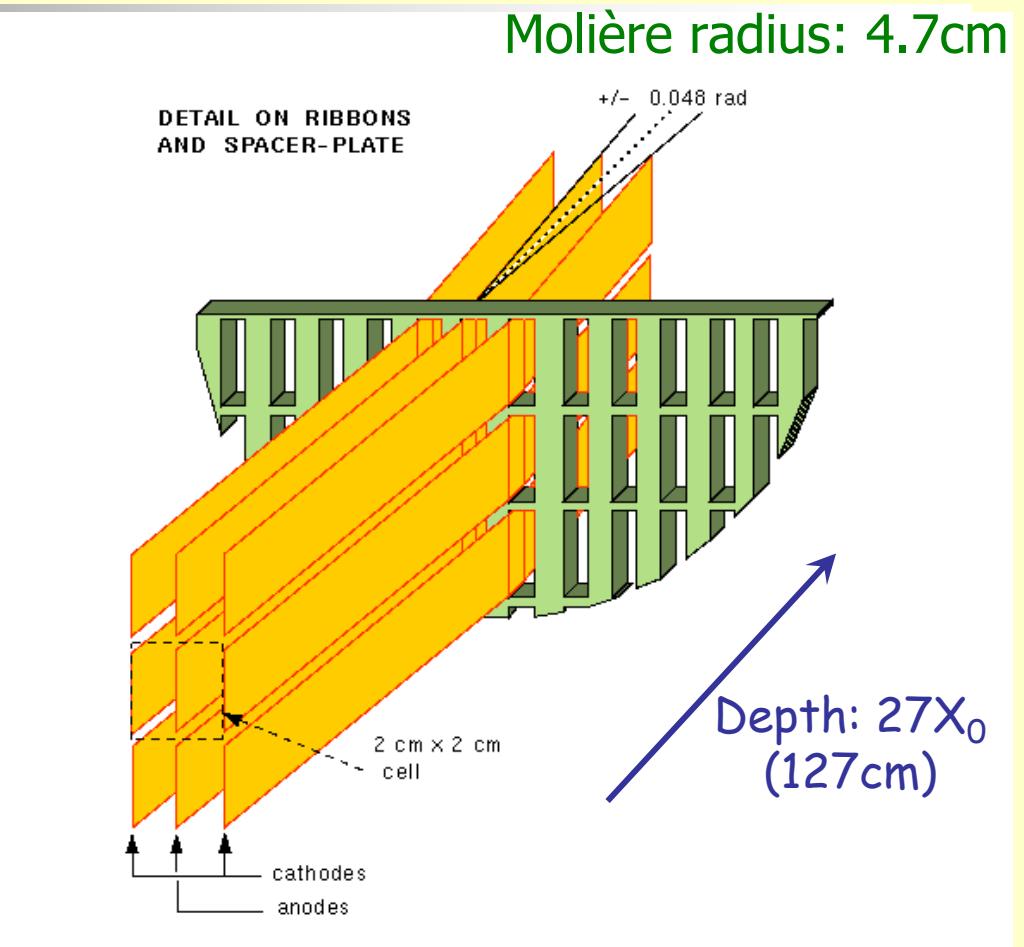
- NA48/2: six months in 2003-04;
- NA62 (R_K phase): four months in 2007.

Principal subdetectors until 2008:

- Magnetic spectrometer (4 DCHs):
4 views/DCH: redundancy \Rightarrow efficiency;
 $\Delta p/p = 0.47\% + 0.020\% * p$ [GeV/c] (in 2007)
- Hodoscope
fast trigger, precise time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
High granularity, quasi-homogeneous;
 $\sigma_E/E = 3.2\% / E^{1/2} + 9\% / E + 0.42\%$ [GeV];
 $\sigma_x = \sigma_y = 4.2\text{mm} / E^{1/2} + 0.6\text{mm}$ (1.5mm@10GeV).

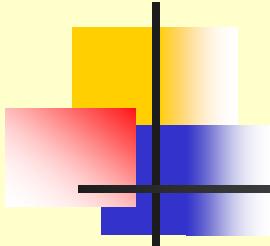


Electromagnetic LKr calorimeter



Transversal segmentation: 13,248 cells ($2 \times 2\text{cm}^2$),
no longitudinal segmentation.

- Photon detection (or photon veto);
- Two-photon resolution: $\sim 2\text{cm}$.
- Electron vs muon identification.



Leptonic kaon decays

$$(K^+ \rightarrow l^+ \nu)$$

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

Angular momentum conservation \rightarrow SM contribution is suppressed

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

Models with 2 Higgs doublets (2HDM-II including SUSY):
sizeable charged Higgs (H^\pm) exchange contributions.

$$\frac{\Gamma(P^\pm \rightarrow \ell^\pm \nu)}{\Gamma_{\text{SM}}(P^\pm \rightarrow \ell^\pm \nu)} = \left[1 - \left(\frac{M_P}{M_H} \right)^2 \frac{\tan^2 \beta}{1 + \varepsilon_0 \tan \beta} \right]^2 \quad (\text{for } P=\pi, K, B)$$

Hou, PRD48 (1993) 2342;
Isidori, Paradisi, PLB639 (2006) 499

numerical examples for $M_H=500\text{GeV}/c^2$, $\tan\beta = 40$

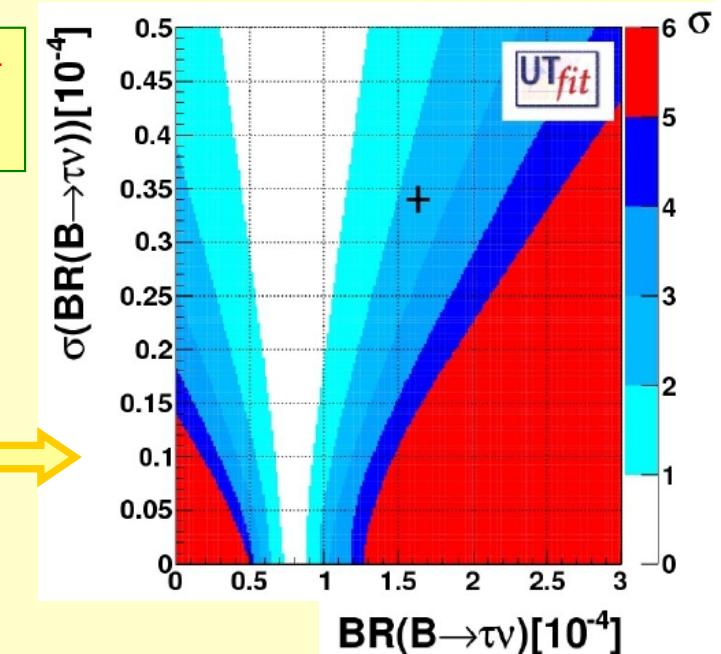
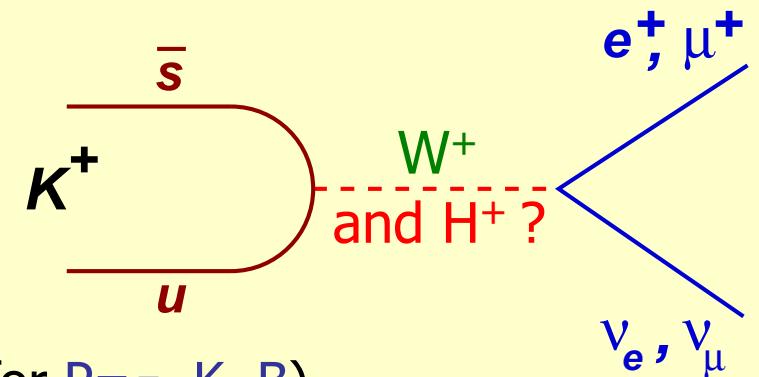
$$\begin{aligned} \pi^+ \rightarrow l\nu: \quad \Delta\Gamma/\Gamma_{\text{SM}} &\approx -2(m_\pi/m_H)^2 m_d/(m_u+m_d) \tan^2\beta \approx -2 \times 10^{-4} \\ K^+ \rightarrow l\nu: \quad \Delta\Gamma/\Gamma_{\text{SM}} &\approx -2(m_K/m_H)^2 \tan^2\beta \approx -0.3\% \end{aligned}$$

... obstructed by hadronic (f_P) and CKM uncertainties

H^\pm exchange in $B^\pm \rightarrow \tau^\pm \nu$:

BaBar+Belle: $\text{Br}_{\text{exp}}(B \rightarrow \tau \nu) = (1.65 \pm 0.34) \times 10^{-4}$
(PDG 2011 partial update)

Standard Model: $\text{Br}_{\text{SM}}(B \rightarrow \tau \nu) = (0.79 \pm 0.08) \times 10^{-4}$
(UTfit, M.Bona, EPS 2011)



$K_{\mu 2}$: sensitivity to new physics

Flavianet Kaon WG, EPJC69 (2010) 399

Comparison of $|V_{us}|$ determined from helicity-suppressed $K_{\mu 2}$ decays vs "helicity-allowed" K_{l3} decays

To reduce uncertainties of hadronic and EM corrections to $K_{\mu 2}$:

average from nuclear β decays,
PRC79 (2009) 055502

$$R_{\mu 23} = \left(\frac{f_K/f_\pi}{f_+(0)} \right)^{-1} \left(\left| \frac{V_{us}}{V_{ud}} \right| \frac{f_K}{f_\pi} \right)_{\mu 2} \overbrace{\frac{|V_{ud}|_{0+ \rightarrow 0+}}{[|V_{us}| f_+(0)]_{\ell 3}}}^{\text{Measured with } K_{\mu 2}/\pi_{\mu 2}}$$

Lattice QCD input

Measured with $K_{\mu 2}/\pi_{\mu 2}$

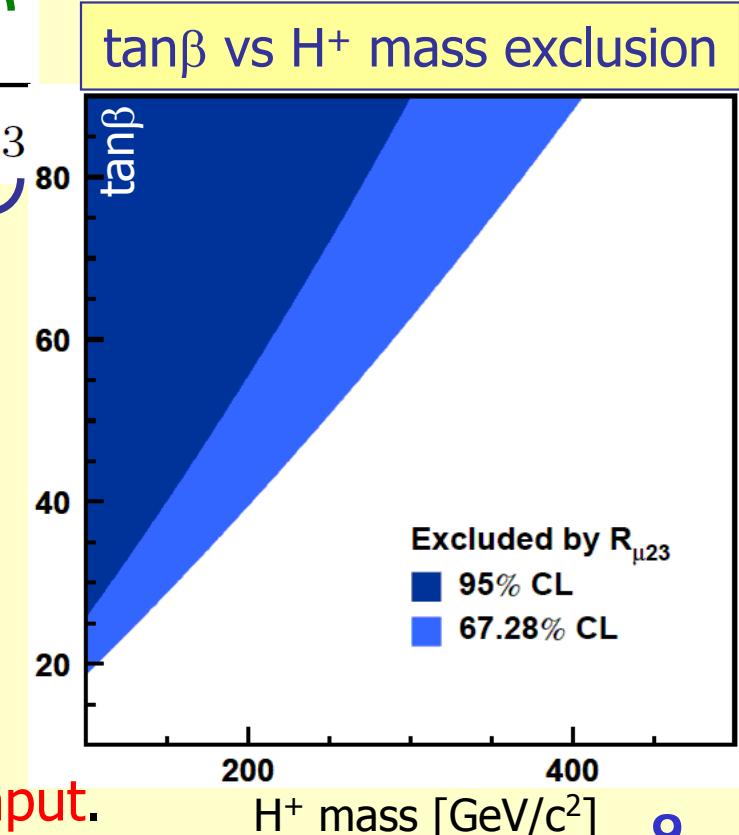
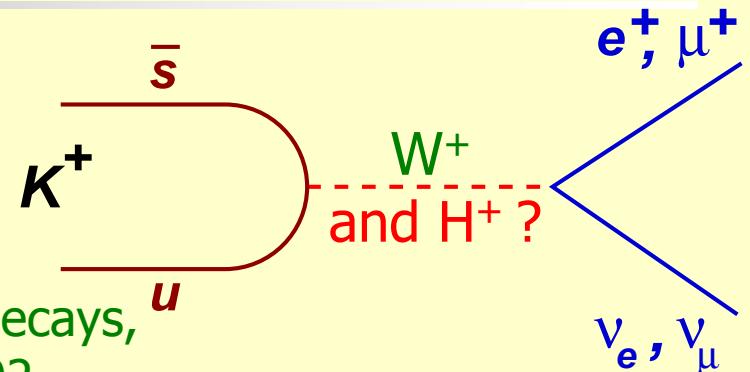
Measured with $K \rightarrow \pi \mu \nu$

SM expectation: $R_{\mu 23} = 1$.

Charged Higgs mediated currents lead to

$$R_{\mu 23} \approx \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$$

Experiment: $R_{\mu 23} = 0.999(7)$, limited by lattice QCD input.



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

Lepton Flavour Universality (LFU): not a fundamental law (violated in ν sector).
 New physics models (e.g. SUSY): significant LFU violation.

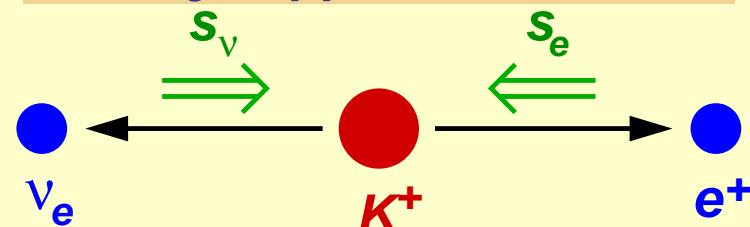
Observable sensitive to LFU violation:

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

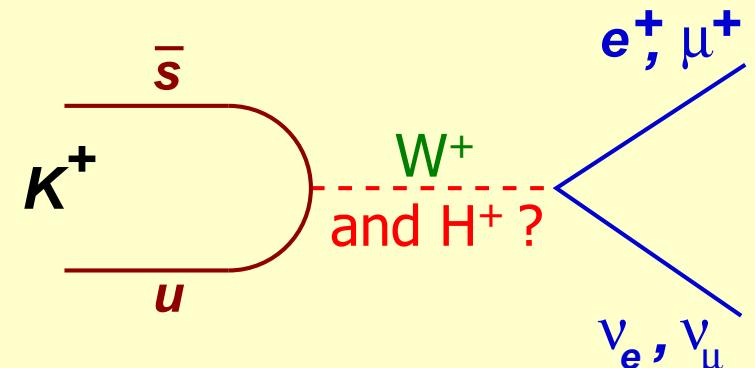
SM

Radiative correction
(well known, few %)

Helicity suppression: $f \sim 10^{-5}$



- SM prediction: excellent sub-permille accuracy:
free of hadronic uncertainties.
- Measurements of R_K (and R_π) have long been considered as tests of LFU.
- NP contributions accessible experimentally due to the suppression of the SM value.



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

Cirigliano, Rosell, PRL99 (2007) 231801

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

2HDM – tree level

(including SUSY)

K_{l2} can proceed via exchange of charged Higgs H^\pm instead of W^\pm
 → 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

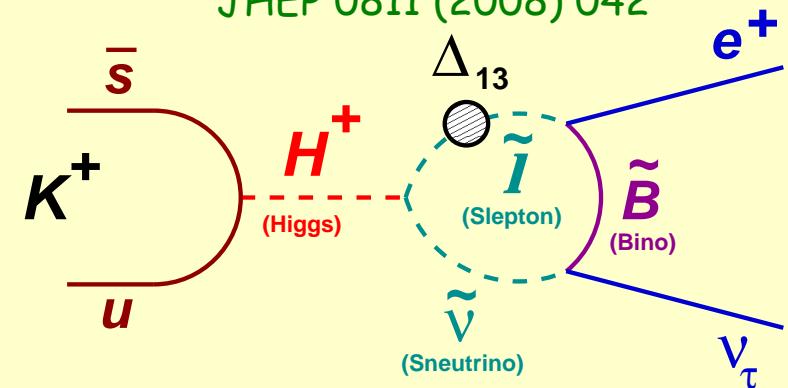
$$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

↓
uniquely sensitive
to slepton mixing

Girrbach, Nierste, arXiv:1202.4906:

$\mathcal{O}(1\%)$ enhancement possible without contradicting any experimental constraints.

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



- $\sim \tan^6 \beta$, cf. $B_s \rightarrow \mu^+ \mu^-$;
- Possibly the first evidence for the charged Higgs boson?

Large effects in B decays due to $(M_B/M_K)^4 \sim 10^4$:

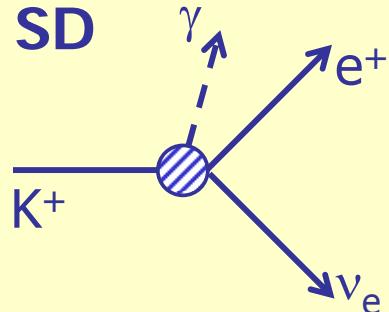
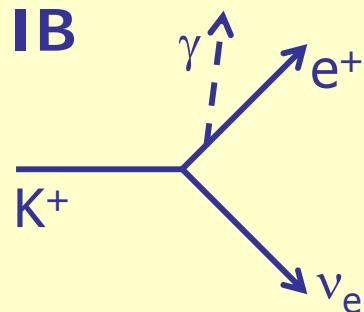
$B_{\mu\nu}/B_{\tau\nu} \rightarrow \sim 50\%$ enhancement;

$B_{e\nu}/B_{\tau\nu} \rightarrow$ enhanced by \sim one order of magnitude.

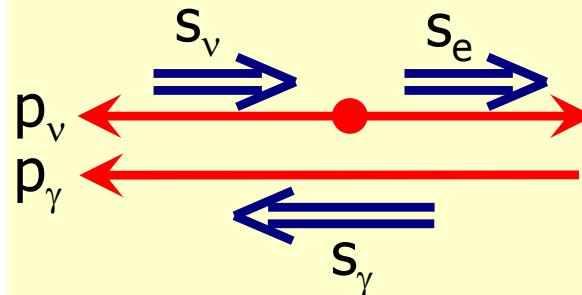
Out of reach: $\text{Br}^{\text{SM}}(B_{e\nu}) \approx 10^{-11}$

Radiative $K^\pm \rightarrow e^\pm \nu_e \gamma$ process

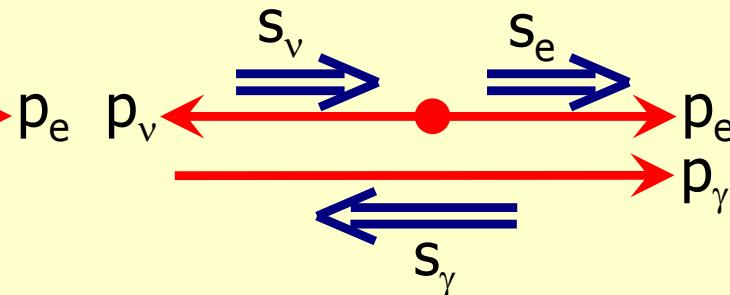
R_K is inclusive of IB radiation by definition.
SD: significant background. INT: negligible.



SD⁺: positive γ helicity



SD⁻: negative γ helicity

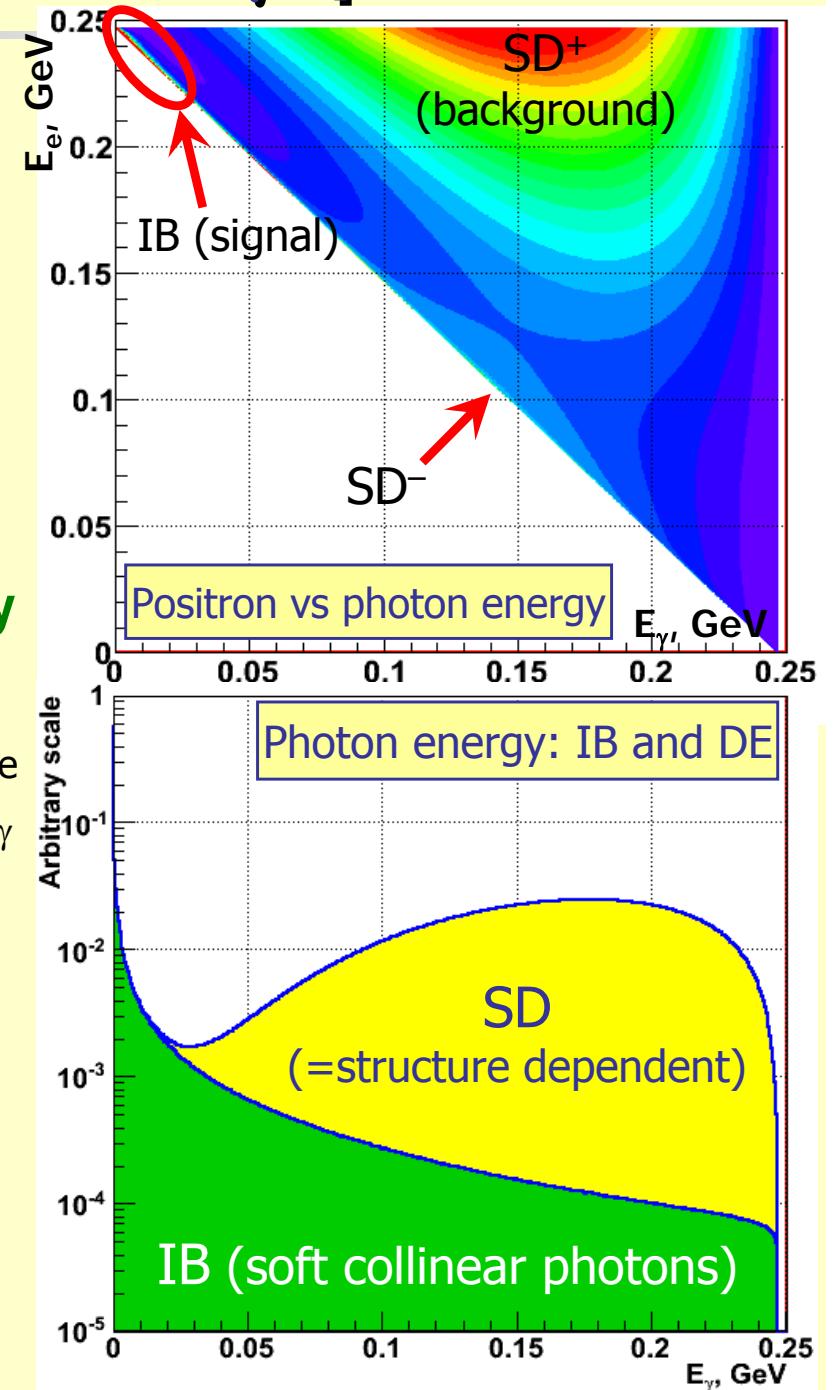


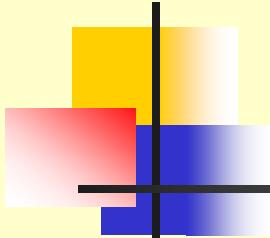
SD radiation is not helicity suppressed.

KLOE measurement of the form factor leads to
 $BR(SD^+, \text{full phase space}) = (1.37 \pm 0.06) \times 10^{-5}$.

(EPJC64 (2009) 627)

Background: $B/(S+B) = (2.60 \pm 0.11)\%$





Measurement strategy

with the NA62 (R_K phase) 2007 data set

(1) $K_{e2}/K_{\mu 2}$ candidates are collected concurrently:

→ no kaon flux measurement; several systematic effects cancel at first order
(e.g. reconstruction/trigger efficiencies, time-dependent effects).

(2) Counting experiment, independently in 10 lepton momentum bins
(owing to strong momentum dependence of backgrounds and event topology)

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_{\mu} \times \varepsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

↓ ↓ ↓ ↓ ↓ ↓
 prescaling of numbers of particle ID eff LKr readout efficiency
 $K_{\mu 2}$ trigger background events (measured) (measured)
 ↓ ↓ ↓ ↓ ↓
 numbers of selected geometric trigger eff MC simulations used
 K_{l2} candidates acceptance (measured) to a limited extent
 ↓ ↓ ↓
 correction (measured)

(3) Data-driven muon halo background subtraction:

- Alternating K^+/K^- beams (K^+ : 65%, K^- : 8%, **simultaneous**: 27%);
- K^+ only samples used to measure background in K^- samples & vice versa.

K_{e2} vs K_{μ2} selection

Large common part (topological similarity)

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

Kinematic identification

missing mass

$$M_{miss}^2 = (P_K - P_l)^2$$

P_K : average measured with K_{3π} decays

→ Sufficient K_{e2}/K_{μ2} separation at p_{track} < 30GeV/c

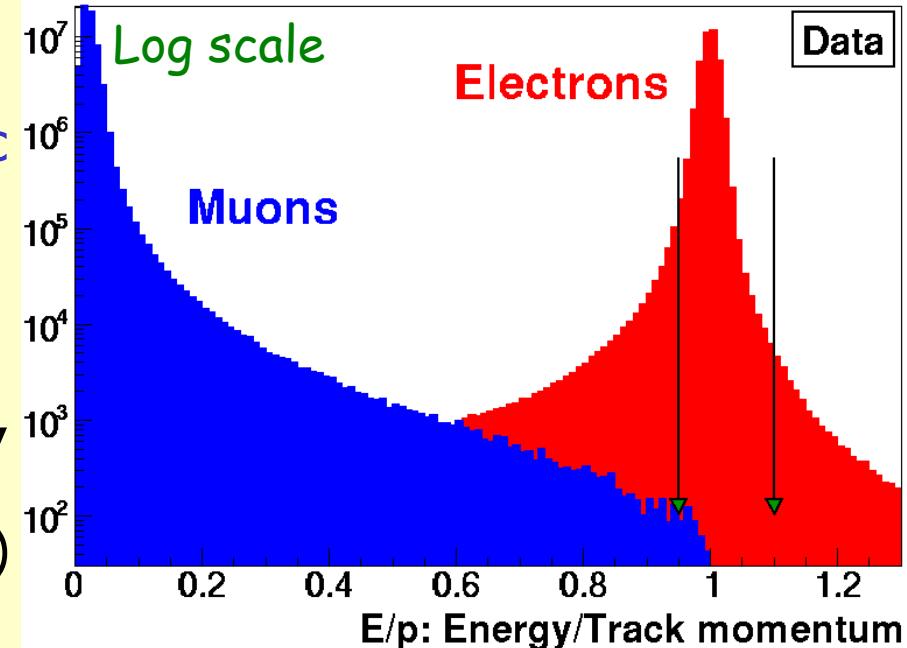
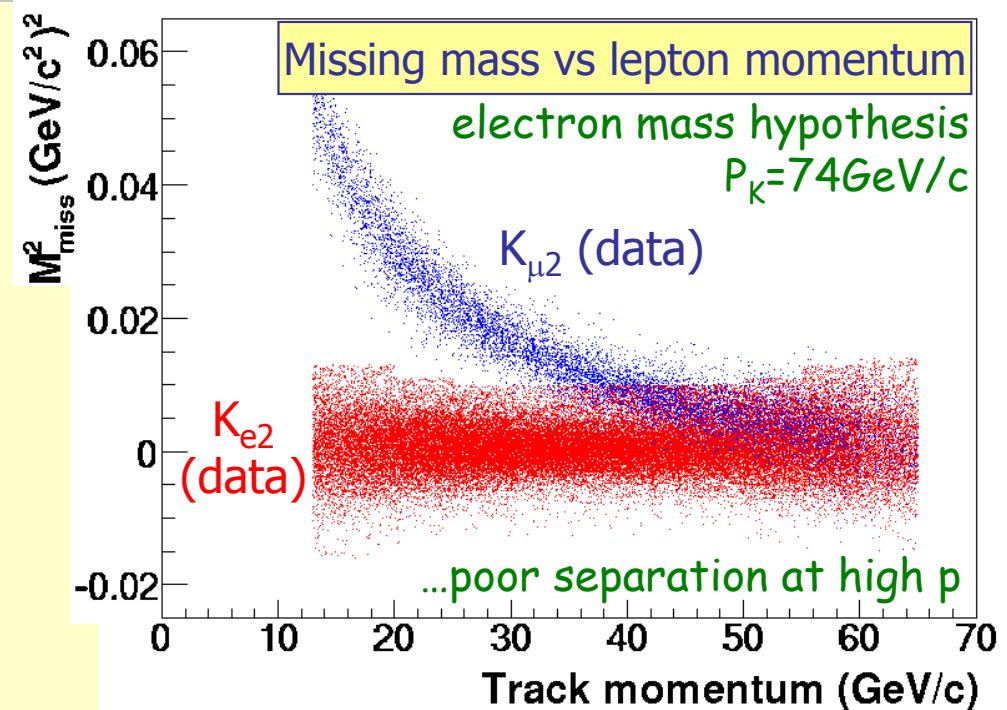
Lepton identification

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

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

E/p < 0.85 for muons.

→ Powerful μ[±] suppression in e[±] sample (~10⁶)



$K_{\mu 2}$ background in K_{e2} sample

Background source

Muon 'catastrophic' energy loss in LKr by emission of energetic bremsstrahlung photons.
 $P_{\mu e} \sim 3 \times 10^{-6}$ (and momentum-dependent).

$P_{\mu e} / R_K \sim 10\%$:
 $K_{\mu 2}$ decays represent a major background

Direct measurement of $P_{\mu e}$

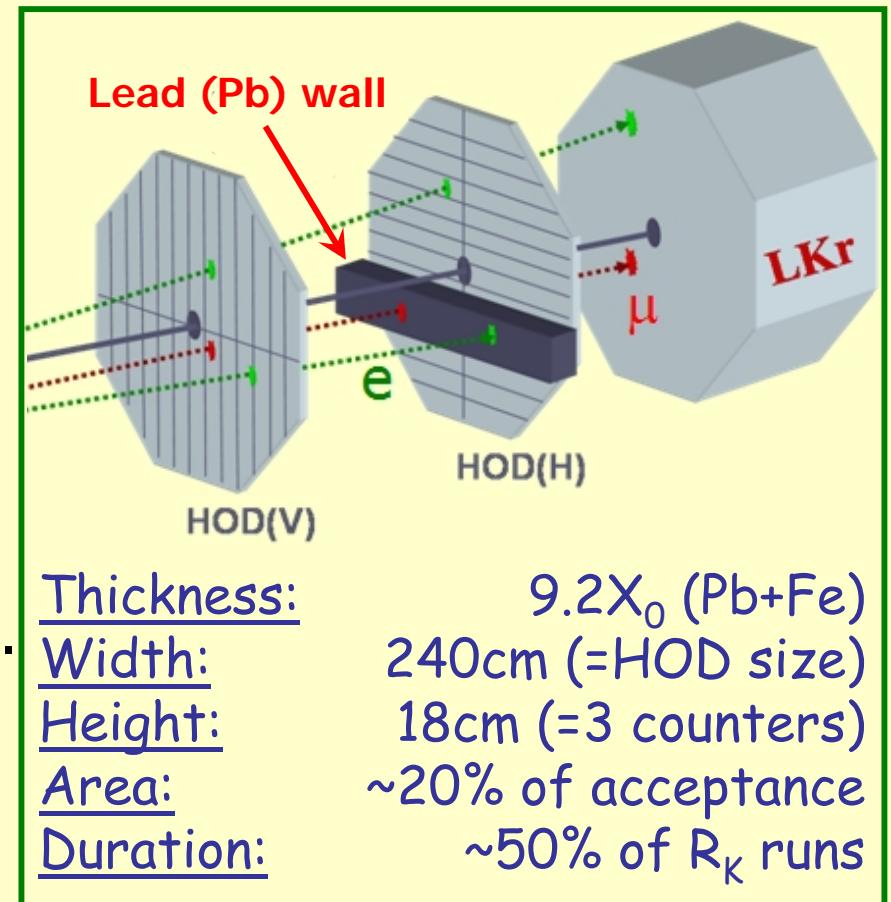
Pb wall ($9.2X_0$) in front of LKr: suppression of $\sim 10^{-4}$ electron contamination due to $\mu \rightarrow e$ decays.

$K_{\mu 2}$ candidates, track traversing Pb, $p > 30\text{GeV}/c$, $E/p > 0.95$: electron contamination $< 10^{-8}$.

$P_{\mu e}$ is modified by the Pb wall:

- ionization losses in Pb (low p);
- bremsstrahlung in Pb (high p).

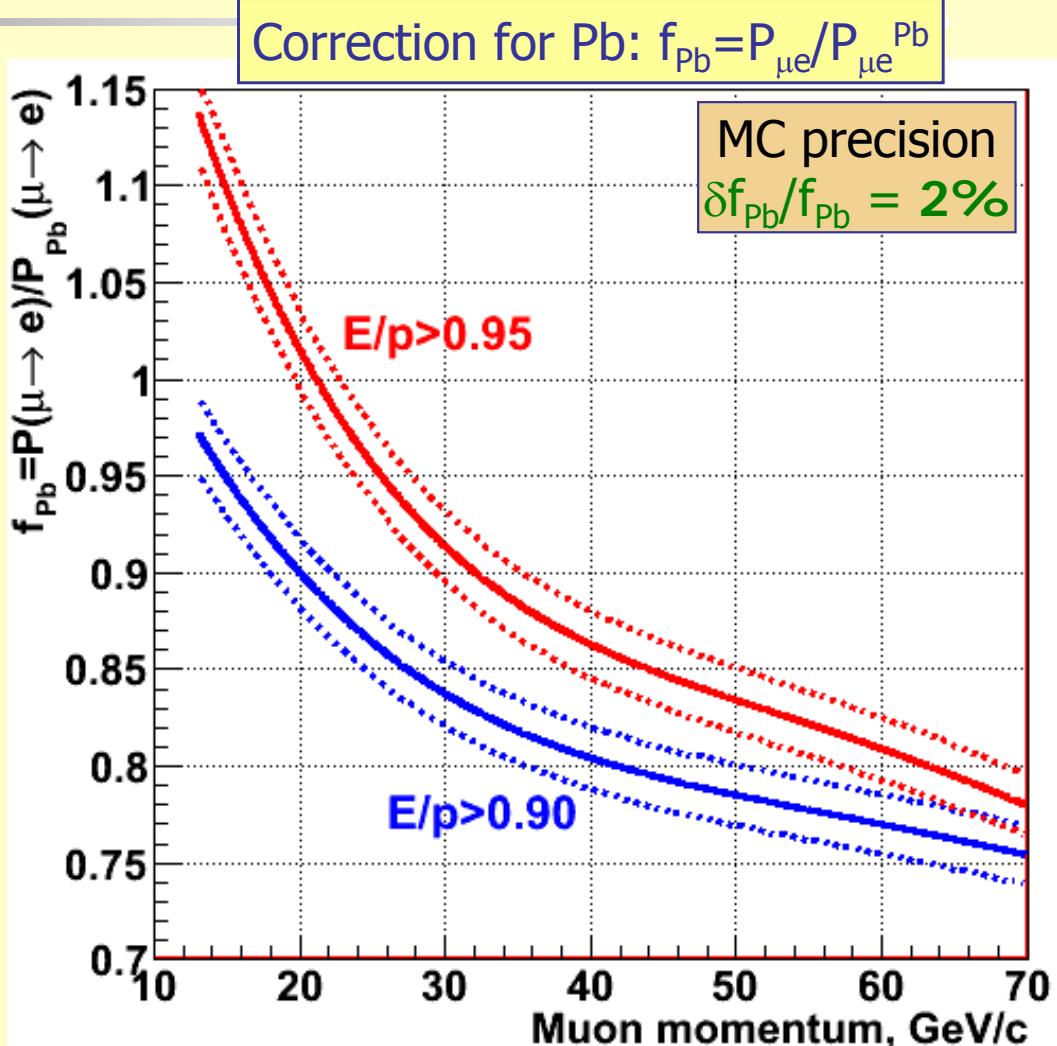
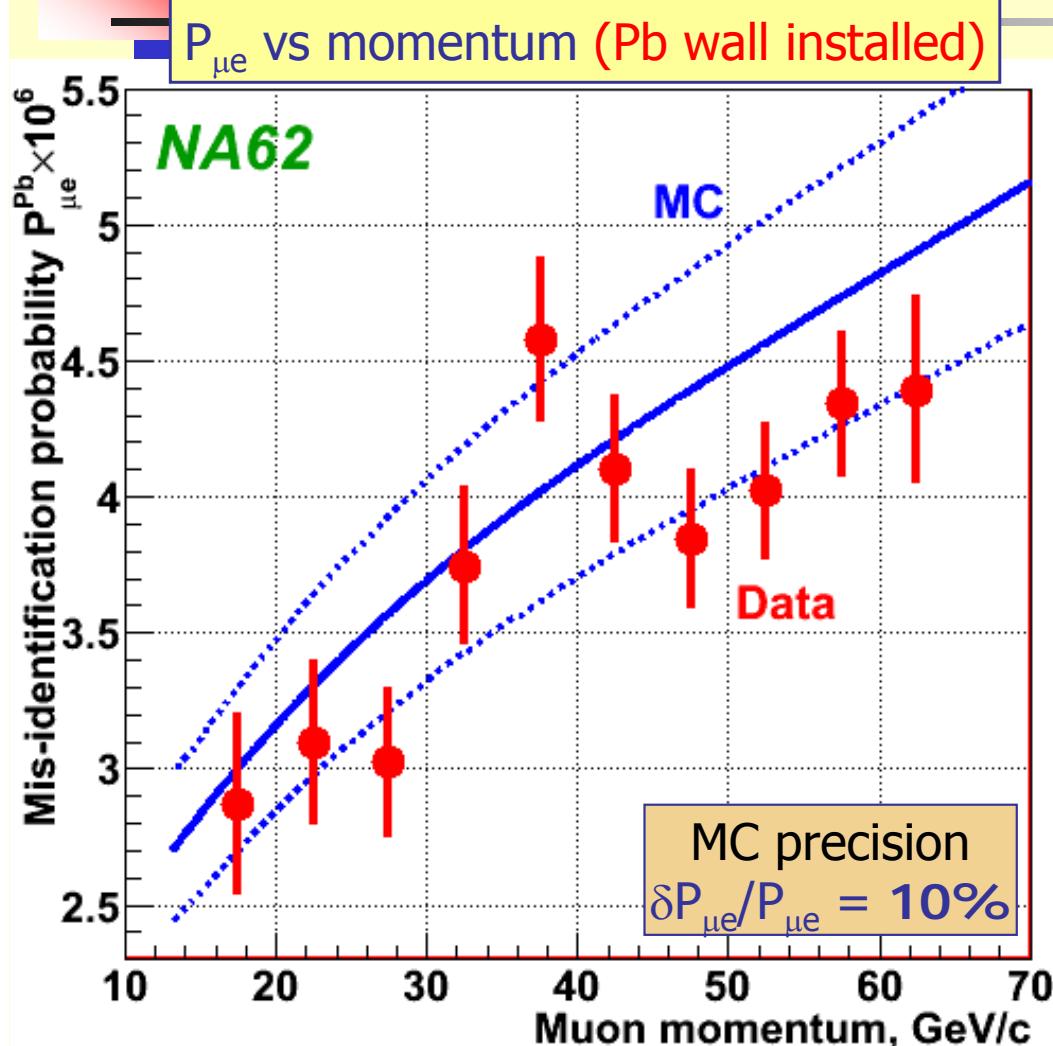
The correction $f_{\text{Pb}} = P_{\mu e} / P_{\mu e}^{\text{Pb}}$ is evaluated with a dedicated Geant4-based simulation



4 data samples with different background conditions:

$K^+(\text{Pb}), K^+(\text{noPb}),$
 $K^-(\text{Pb}), K^-(\text{noPb}).$

Muon mis-identification



Result: $B/(S+B) = (5.64 \pm 0.20)\%$

Uncertainty is ~ 3 times smaller than the one obtained solely from simulation

Uncertainties:

limited control data sample (0.16%),

MC correction δf_{Pb} (0.12%),

M_{miss}^2 vs P_{track} correlation (0.08%).

Stability checks:

vs lower E/p cut, upper HOD energy deposit.

$K_{\mu 2}$ with $\mu \rightarrow e$ decay in flight

For NA62 conditions
 (74 GeV/c beam, ~ 100 m decay volume),

$$N(K_{\mu 2}, \mu \rightarrow e \text{ decay})/N(K_{e 2}) \sim 10$$

$K_{\mu 2} (\mu \rightarrow e)$ naively seems a huge background

Muons from $K_{\mu 2}$ decay are fully polarized:
 Michel electron distribution

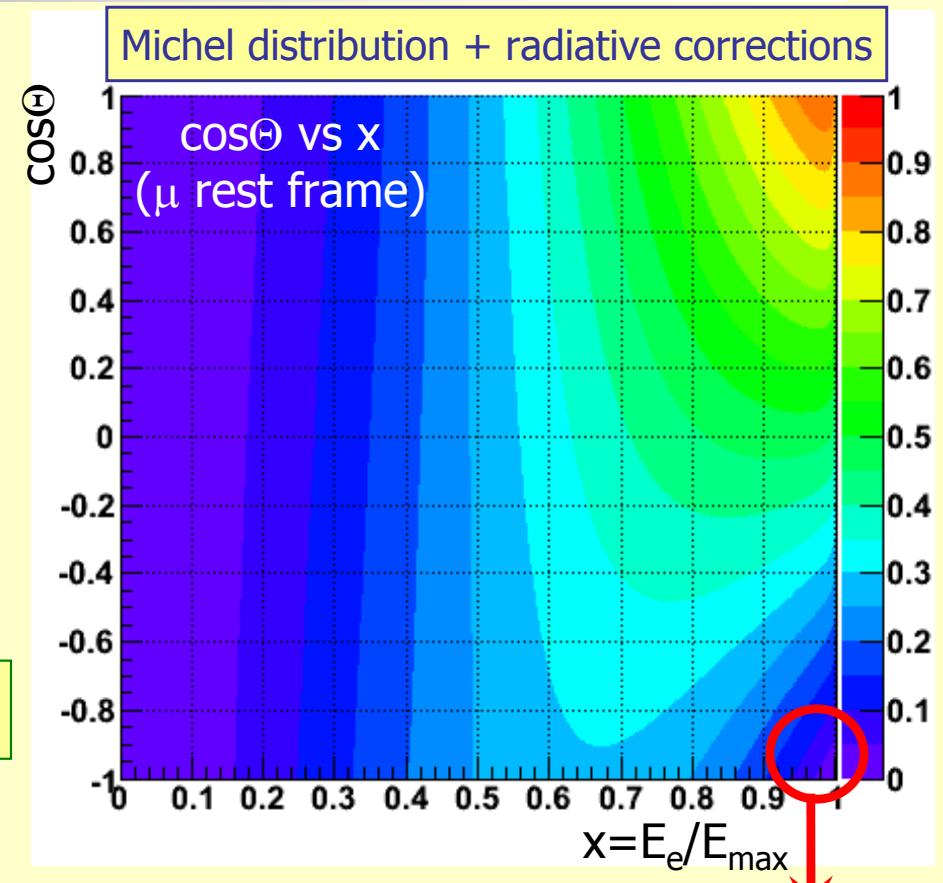
$$d^2\Gamma/dx d(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

$$x = E_e/E_{\max} \approx 2E_e/M_\mu,$$

Θ is the angle between p_e and the muon spin
 (all quantities are defined in muon rest frame).

$$\text{Result: } B/(S+B) = (0.26 \pm 0.03)\%$$

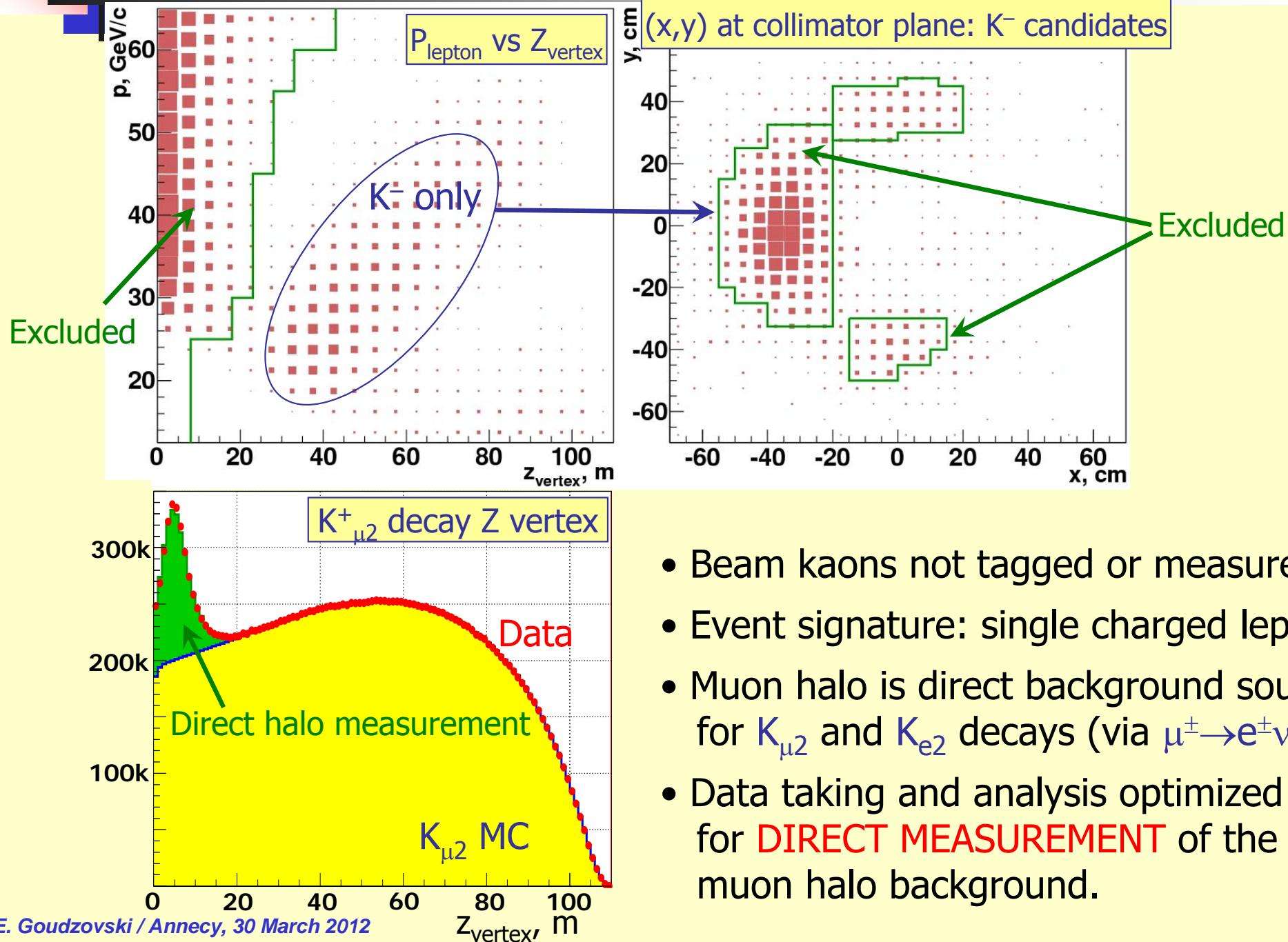
Important but not dominant background



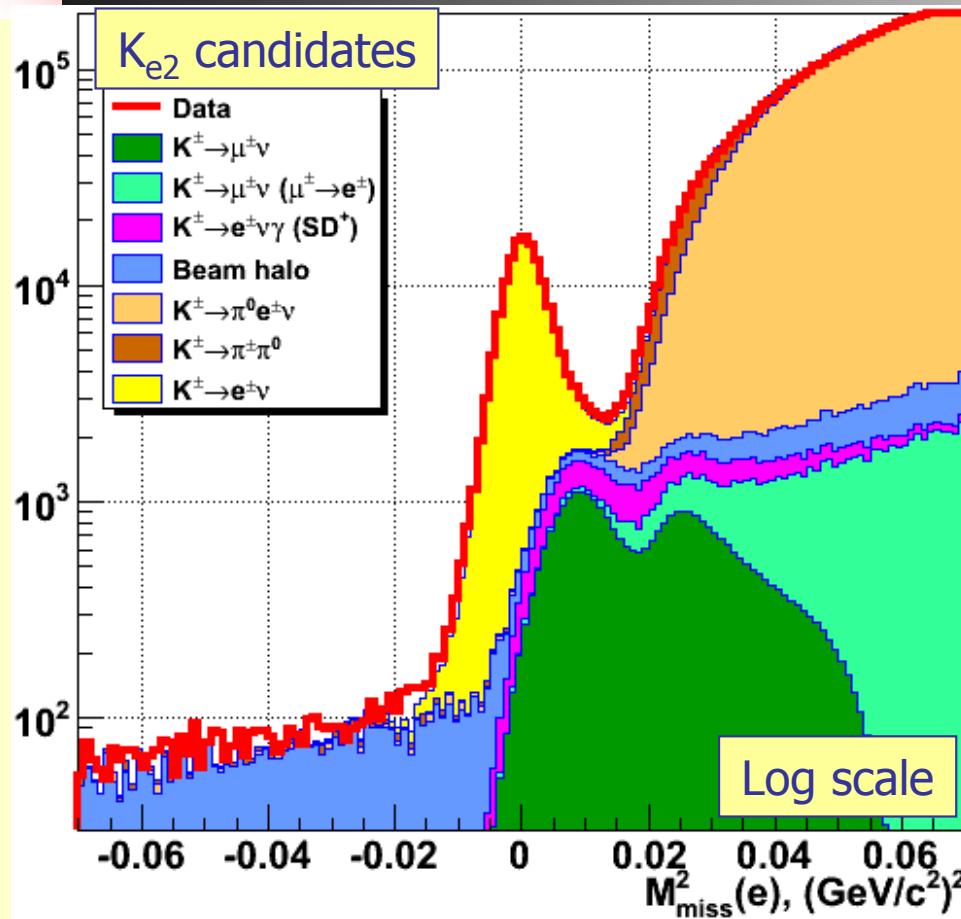
Only energetic forward electrons
 (passing M_{miss} , E/p , vertex CDA cuts)
 are selected as $K_{e 2}$ candidates:
 (high x , low $\cos\Theta$).

They are naturally suppressed
 by the muon polarisation

Muon halo background

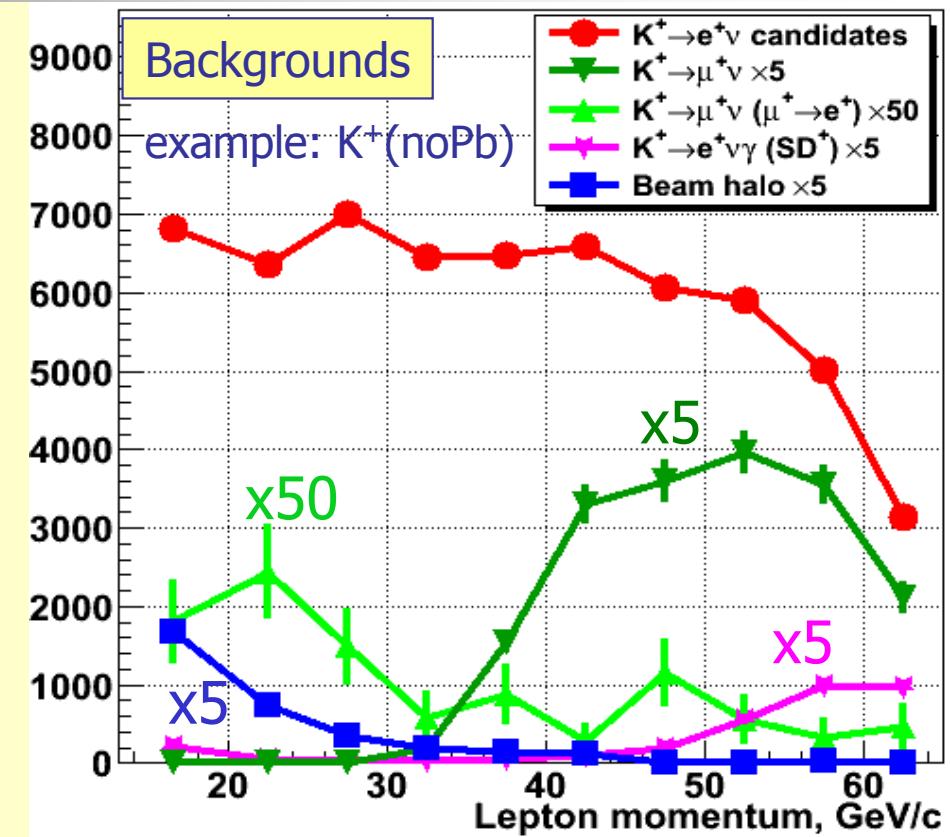


K_{e2} sample



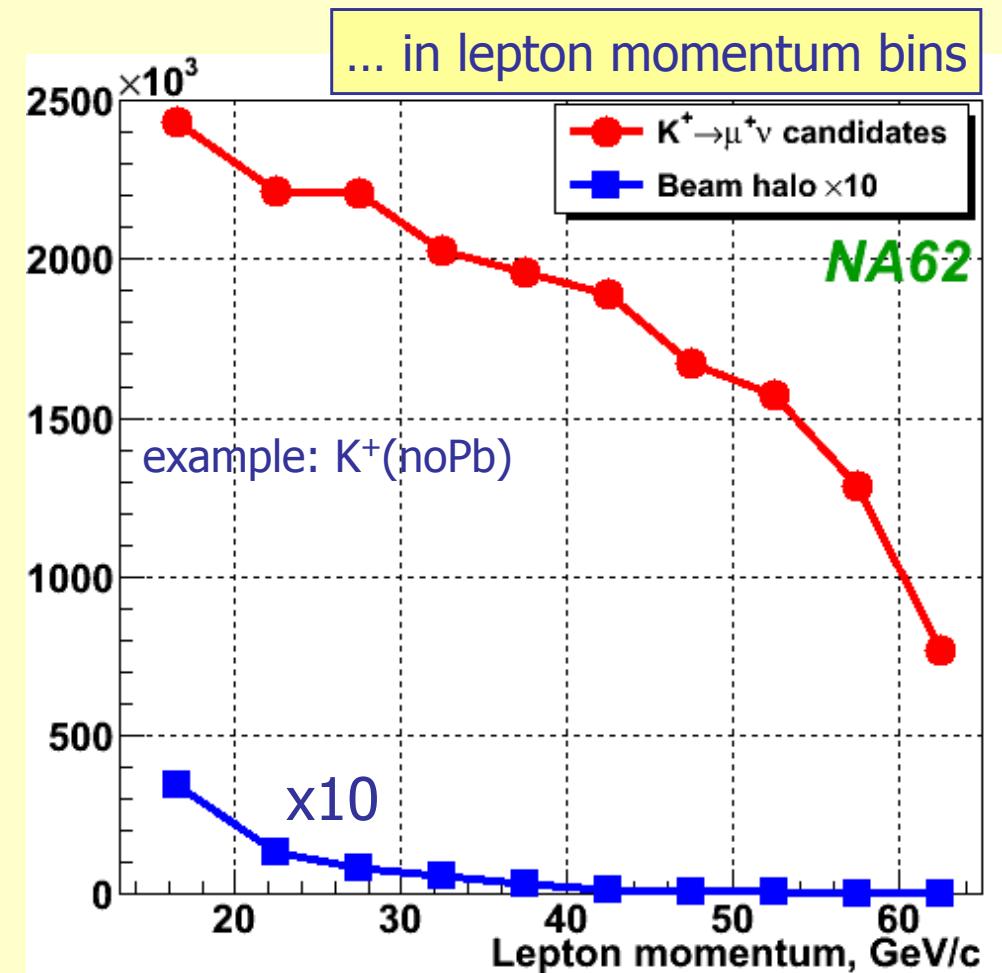
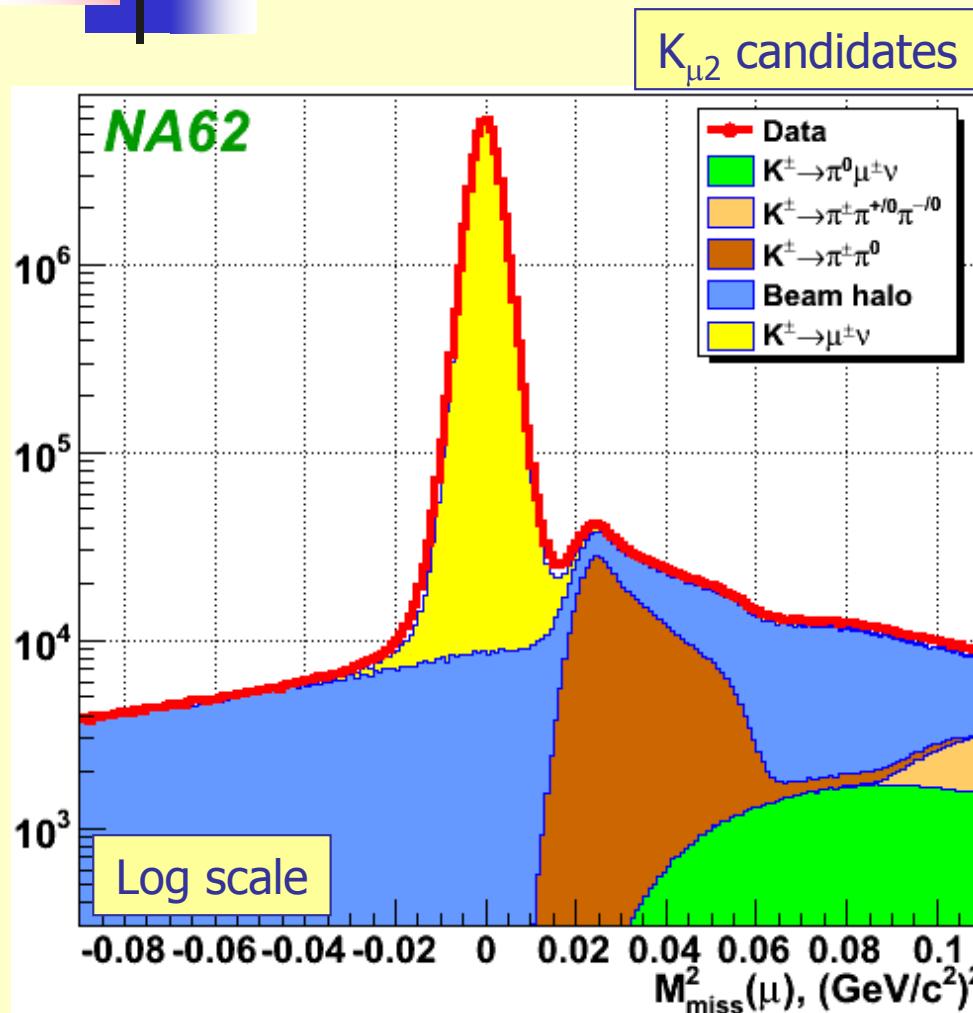
145,958 K $\pm \rightarrow e^\pm \nu$ candidates.
 Background: B/(S+B)=(10.95±0.27)%.
 Electron ID efficiency: (99.28±0.05)%.

cf. KLOE: 13.8K candidates,
 ~90% electron ID efficiency, 16% background

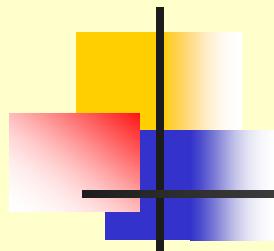


Source	B/(S+B)
K $_{\mu 2}$	(5.64±0.20)%
K $_{\mu 2}$ ($\mu \rightarrow e$)	(0.26±0.03)%
K $_{e2\gamma}$ (SD $^+$)	(2.60±0.11)%
K $_{e3(D)}$	(0.18±0.09)%
K $_{2\pi(D)}$	(0.12±0.06)%
Wrong sign K	(0.04±0.02)%
Muon halo	(2.11±0.09)%
Total	(10.95±0.27)%

$K_{\mu 2}$ sample



42.817M candidates (pre-scaled trigger).
 $B/(S+B) = (0.50 \pm 0.01)\%$,
background dominated by beam halo.



Electron ID efficiency (f_e)

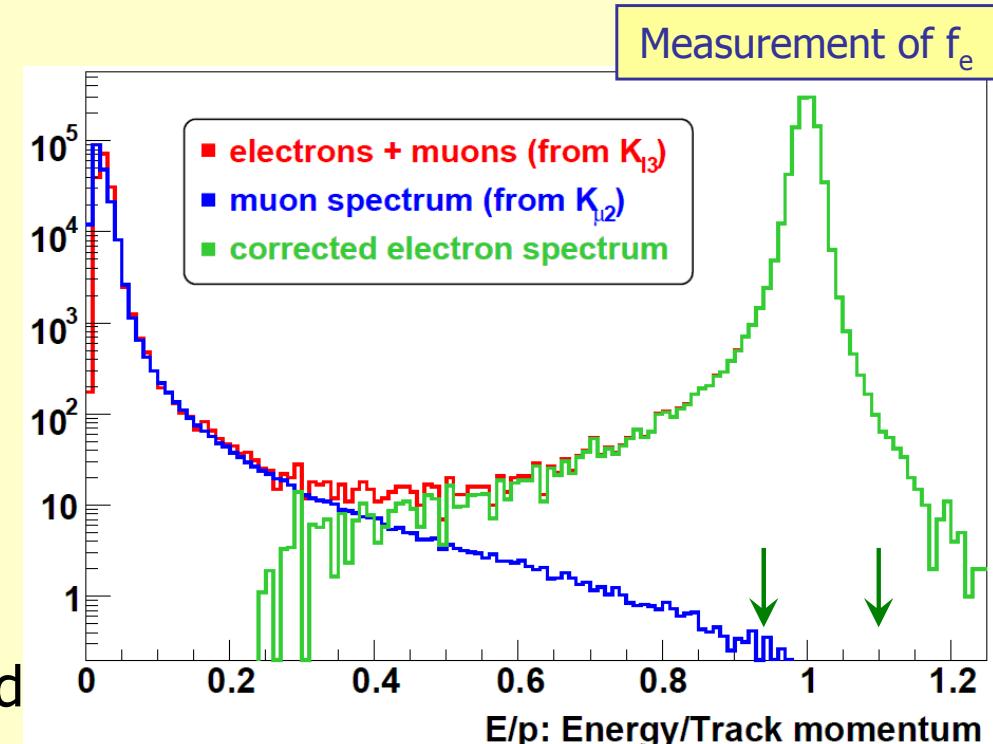
Measured directly with samples of pure electrons:

- $K^\pm \rightarrow \pi^0 e^\pm \nu$ from main K^\pm data taking
(limited momentum range: $p < 50\text{GeV}/c$);
- $K_L \rightarrow \pi^\pm e^\pm \nu$ from a **special** 15h K_L run
(wider electron momentum range,
due to broad K_L momentum spectrum).

Measurement with $K^\pm \rightarrow \pi^0 e^\pm \nu$ decays:

- Selected event sample consists of $K^\pm \rightarrow \pi^0 e^\pm \nu$ and some $K^\pm \rightarrow \pi^0 \mu^\pm \nu$ events;
- To subtract the muon component,
normalised muon E/p spectrum measured
using the $K_{\mu 2}$ sample is used.

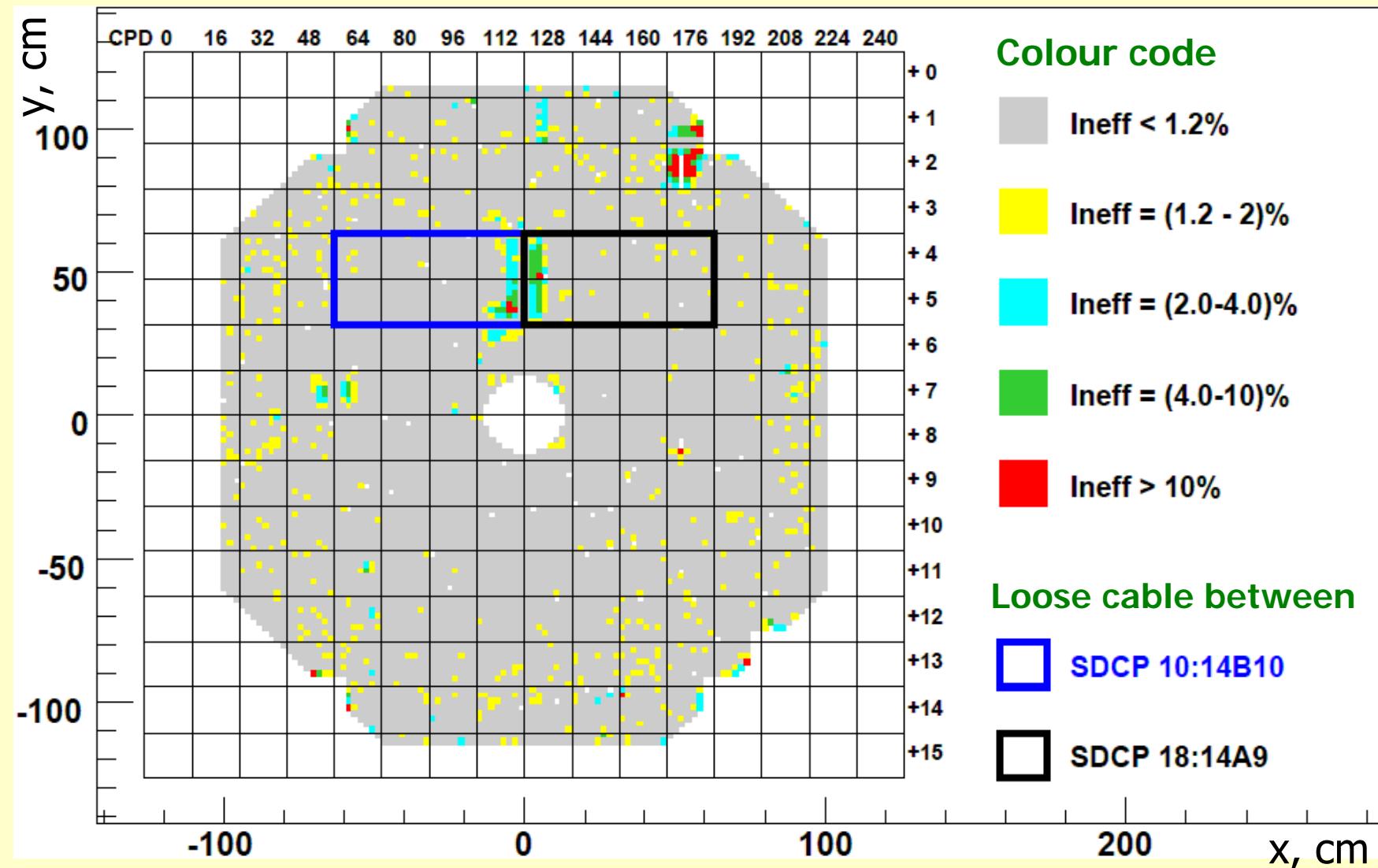
Measurement with $K_L \rightarrow \pi^\pm e^\pm \nu$ is more complicated:
the pion component also contributes to the spectrum.



Excellent agreement between K^\pm and K_L methods.
Average ID efficiency: $(99.28 \pm 0.05)\%$, weak momentum dependence.

LKr inefficiency map

Electron ID efficiency is monitored vs time for every $2 \times 2 \text{cm}^2$ cell.
An example of (poor) inefficiency map is presented below.

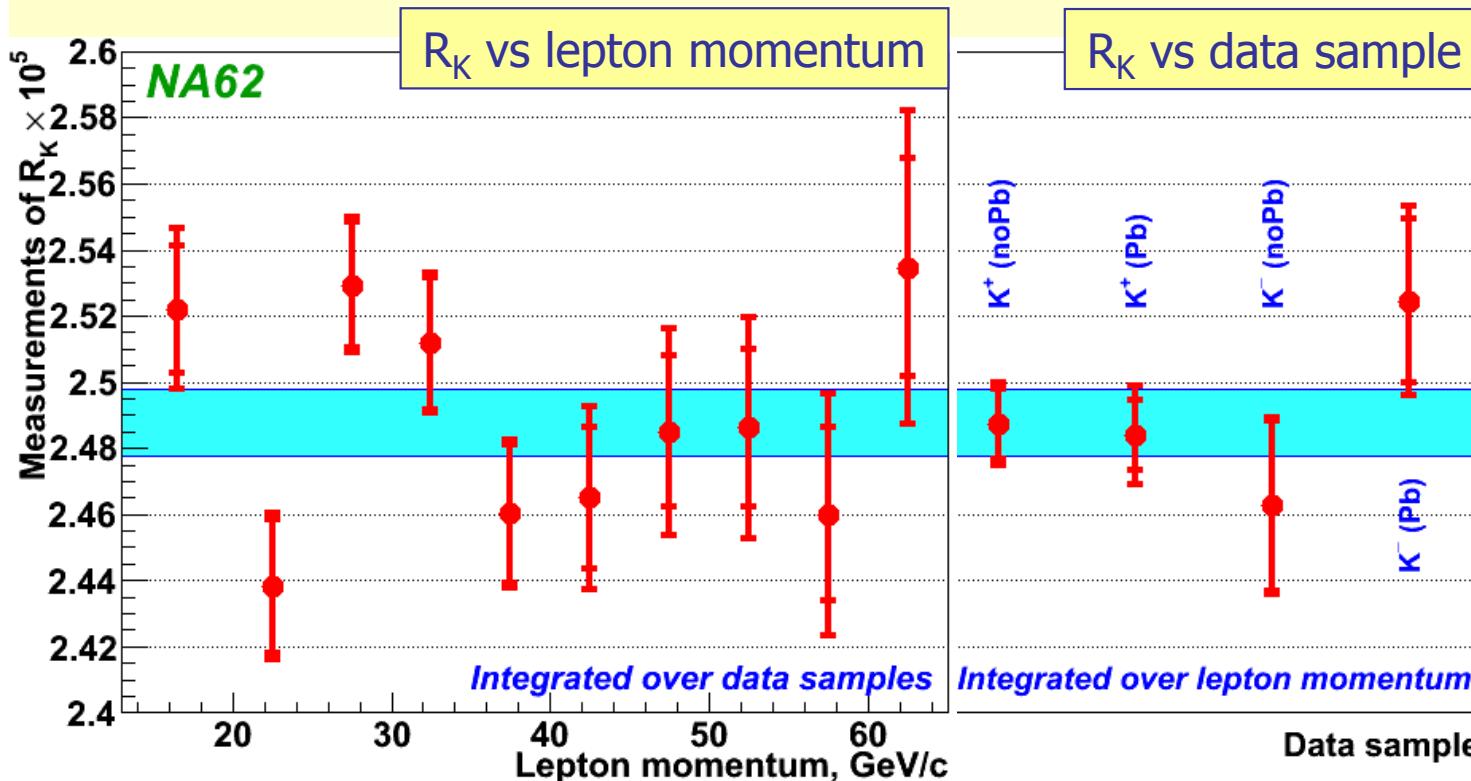


The result (full NA62 data set)

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

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

Fit over 40 measurements (4 data samples \times 10 momentum bins)
including correlations: $\chi^2/\text{ndf}=47/39$.

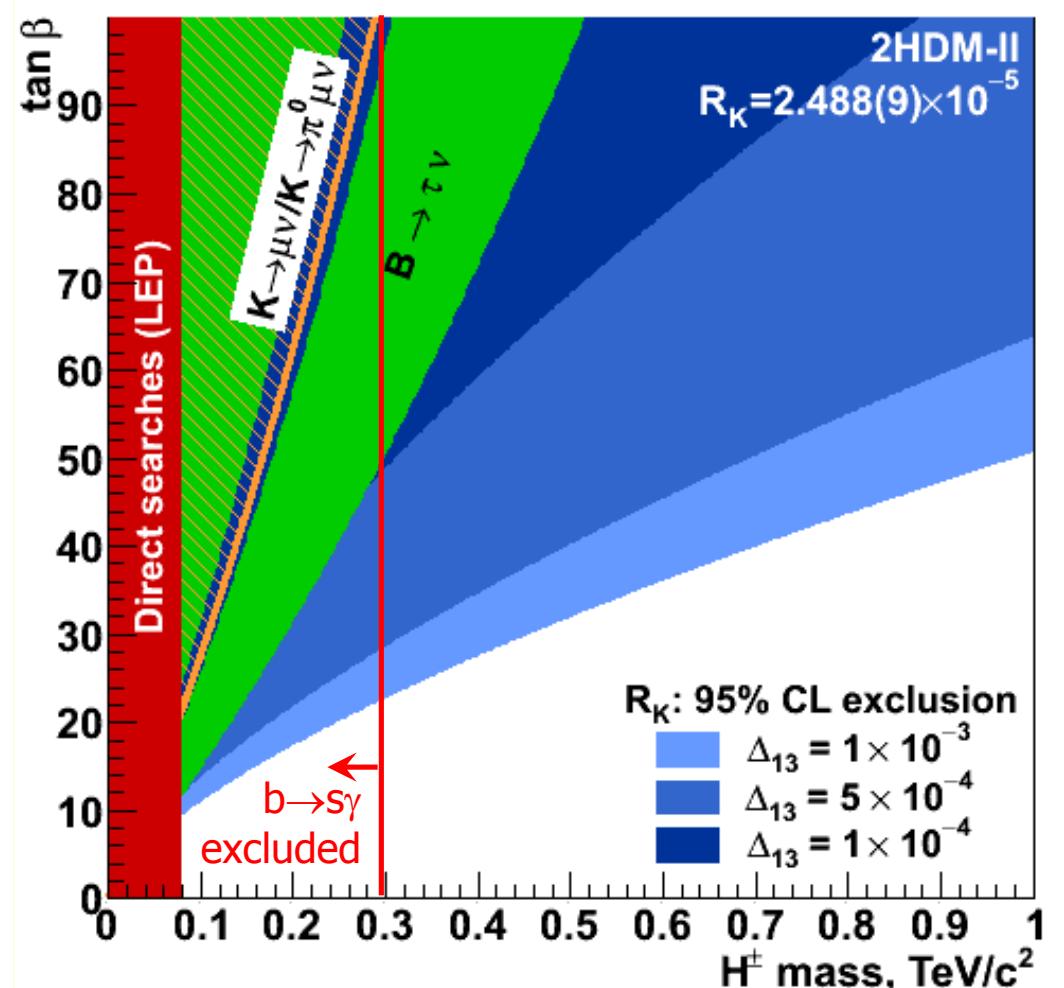
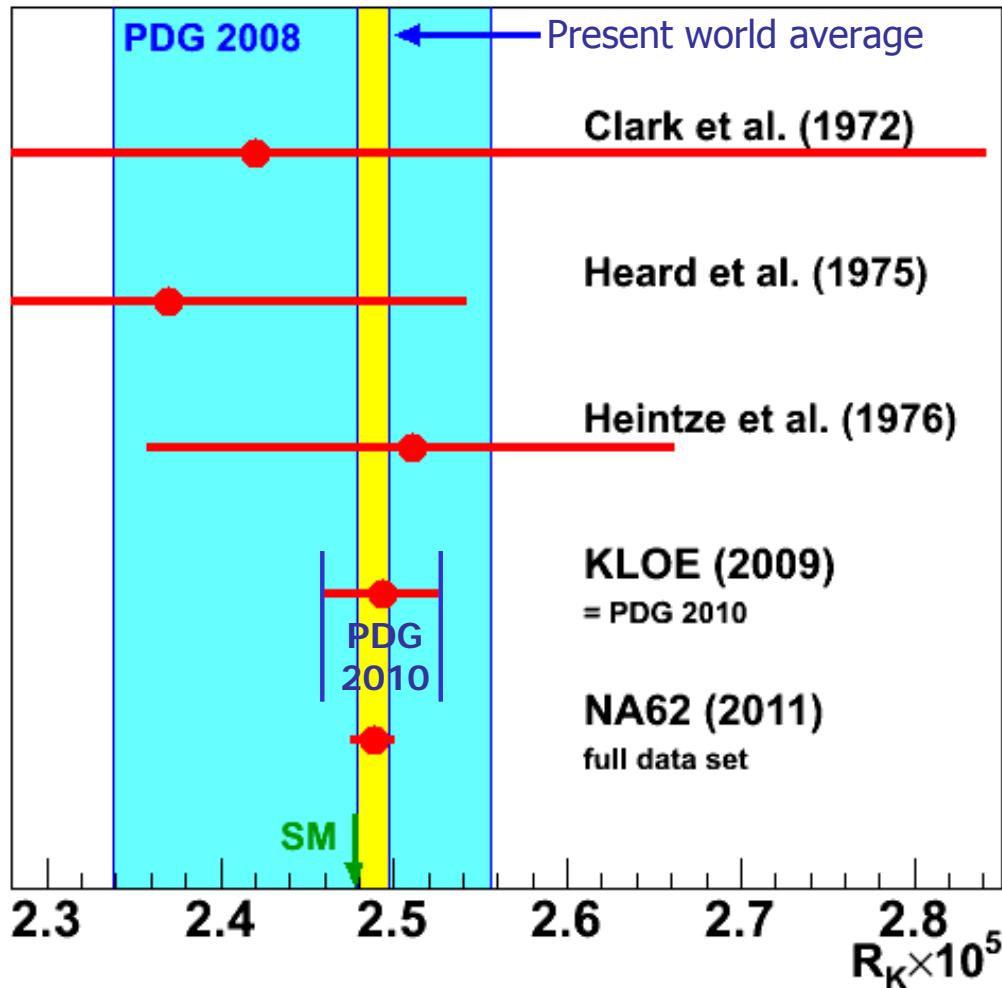


Uncertainty source	$\delta R_K \times 10^5$
Statistical	0.007
K _{μ2} background	0.004
K [±] → e [±] νγ (SD ⁺)	0.002
K [±] → π ⁰ e [±] ν, K [±] → π [±] π ⁰	0.003
Beam halo background	0.002
Matter composition	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron identification	0.001
1TRK trigger efficiency	0.001
LKr readout efficiency	0.001
Total uncertainty	0.010

Partial (40%) data set: PLB 698 (2011) 105.

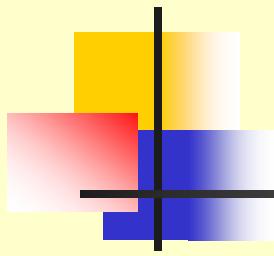
Full data set: paper to be submitted in April/May 2012.

R_K world average



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

Other limits on 2HDM-II:
 PRD 82 (2010) 073012.
 SM with 4 generations:
 JHEP 1007 (2010) 006.



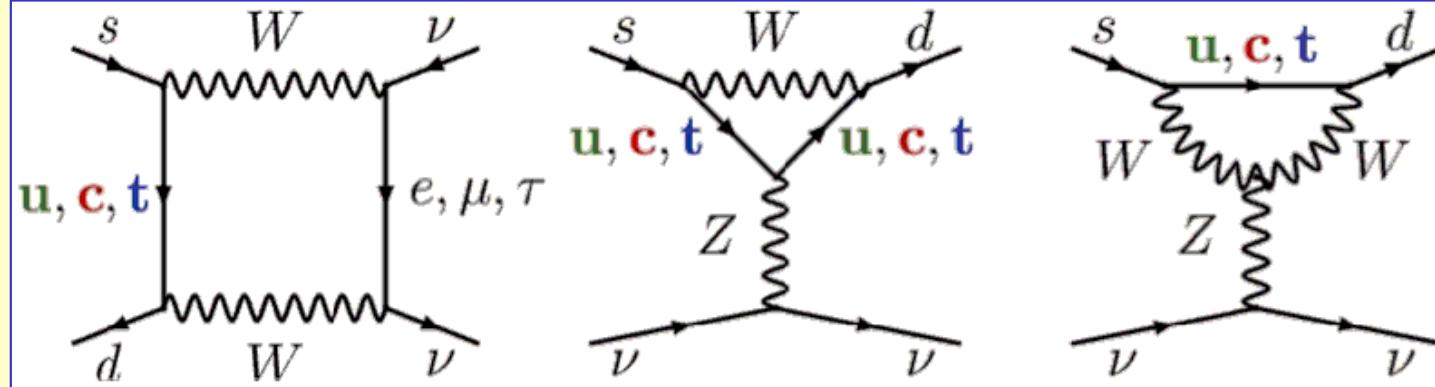
The “golden mode”: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

K $\rightarrow\pi\nu\bar{\nu}$: introduction

Theoretically clean, sensitive to new physics, almost unexplored

Ultra-rare decays with
the highest CKM suppression:
 $A \sim (m_t/m_w)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

SM: box and penguin diagrams



SM branching ratios

(Brod et al., PRD83 (2011) 034030)

Mode	$BR_{SM} \times 10^{11}$
$K^+ \rightarrow \pi^+ \nu \bar{\nu} (\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

CKM parametric Intrinsic

- Hadronic matrix element can be related to measured quantities ($K \rightarrow \pi e \nu$ form factors).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from $B \bar{B}$ mixing and $B^0 \rightarrow \rho \gamma$.
- $\delta BR/BR = 10\%$ would lead to $\delta |V_{td}| / |V_{td}| = 7\%$.

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: BNL E787/E949

Technique: K^+ decay at rest.

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

1.6MHz of K^+ (710 MeV/c) stopped in target.

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

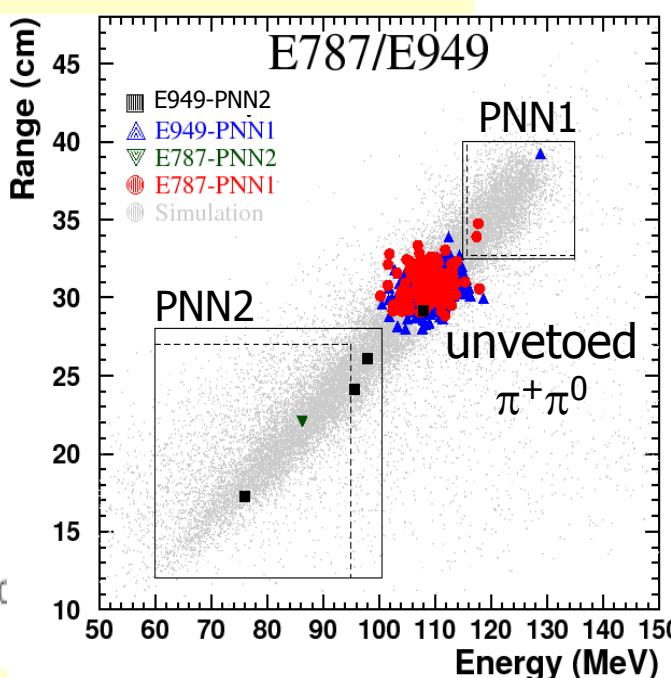
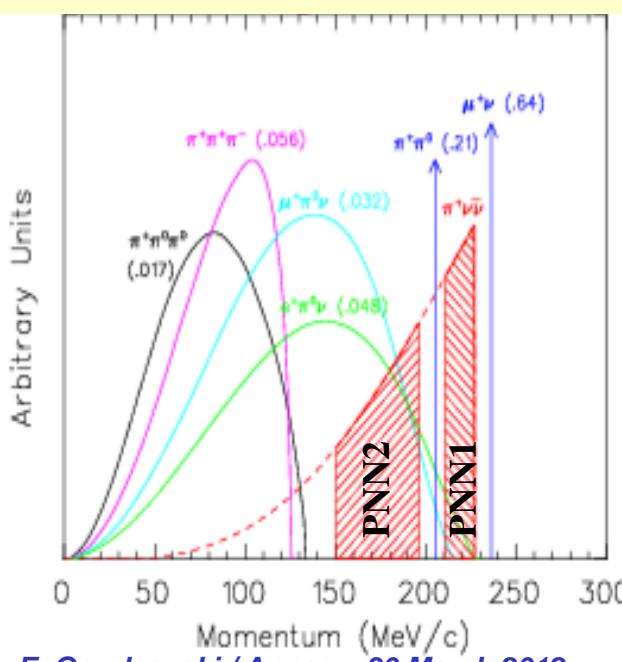
Hermetic photon veto system.

Observed candidates: 7

Expected background: 2.6

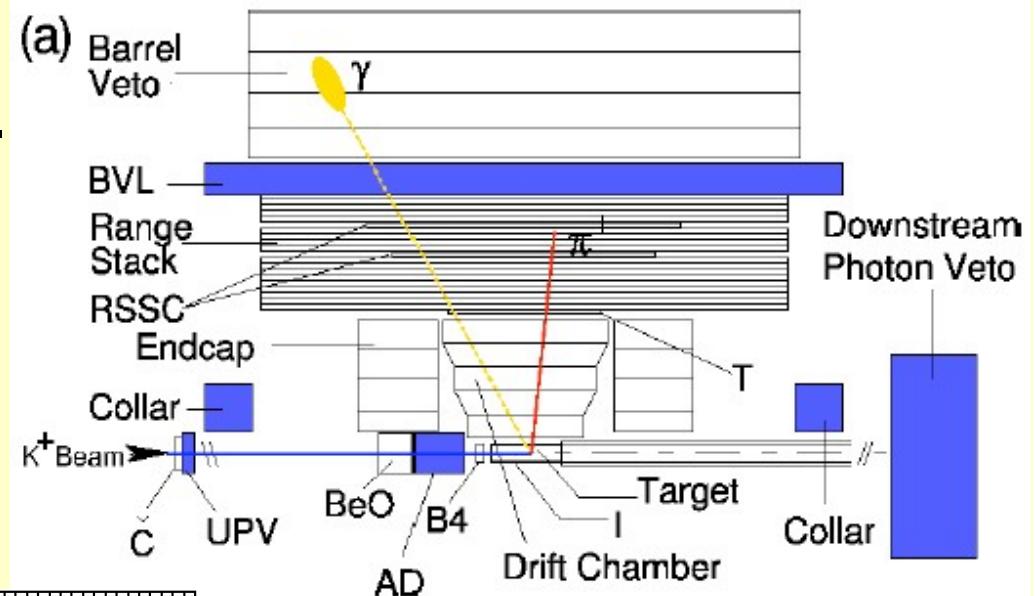
Final result: $BR = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

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



E. Goudzovski / Annecy, 30 March 2012

Barrel detector: 1T solenoid field

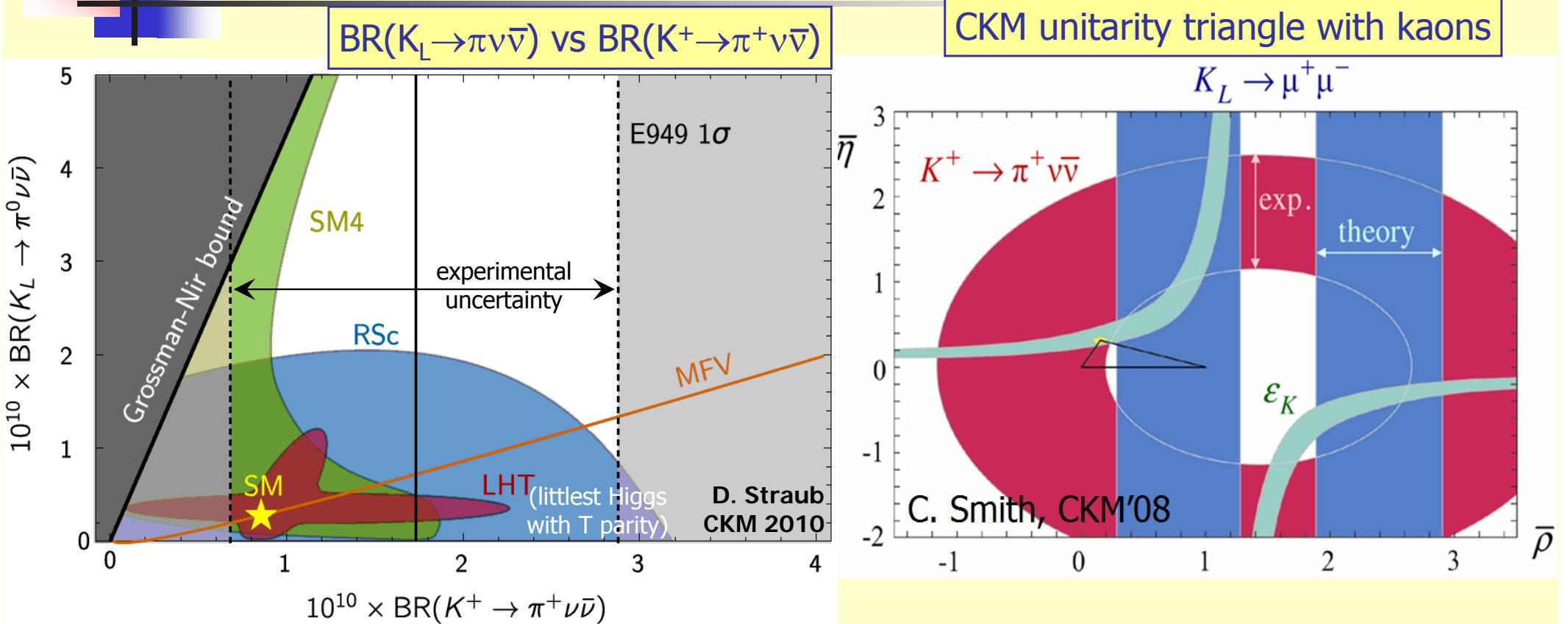


Discovery of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay!
 $K_L \rightarrow \pi^0 \nu \bar{\nu}$ never observed.

Limitations of E787/E949:

- low acceptance ($\sim 1\%$);
- significant background ($\sim 30\%$) due to π scattering in the target.

Situation after the BNL experiment



NA62@CERN aims to collect $O(100)$ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays with $\sim 10\%$ background in 2 years of data taking using a novel decay-in-flight technique.

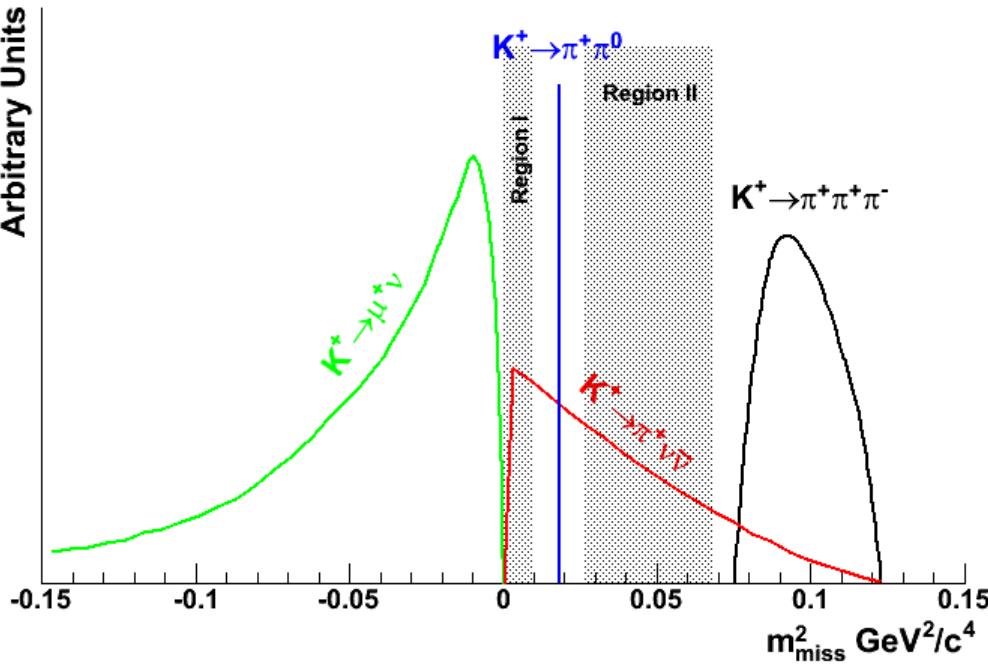
Decay signature: high momentum K^+ ($75\text{GeV}/c$) \rightarrow low momentum π^+ ($15\text{-}35\text{ GeV}/c$).

Advantages: high K^+ production rate ($\sim p_K^{-2}$); high acceptance ($\sim 10\%$); efficient photon veto ($>40\text{ GeV}$ missing energy) + good π^+/μ^+ separation by RICH.

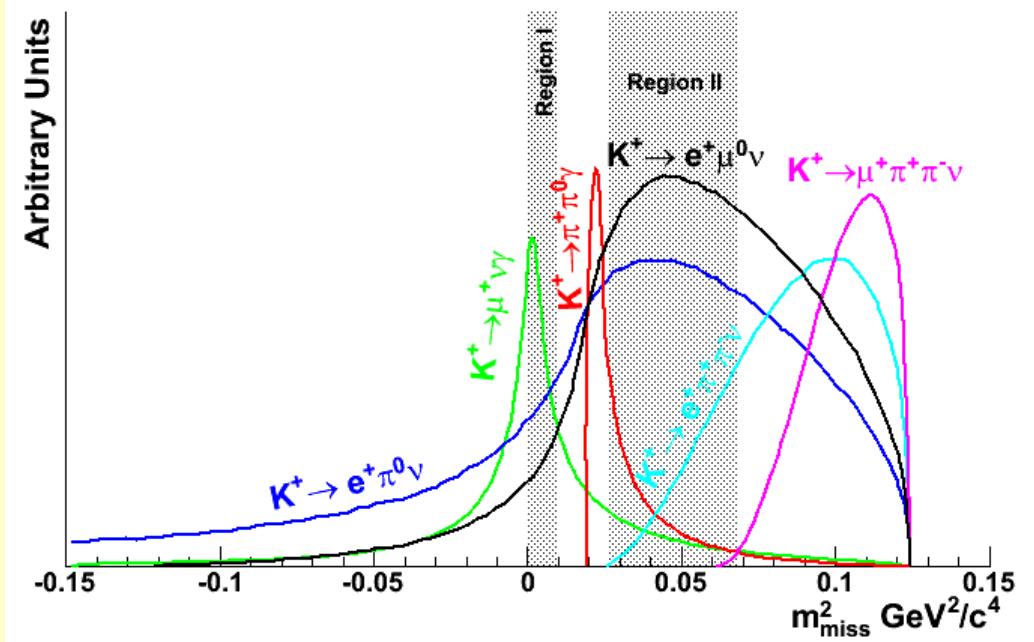
However, un-separated beam (6% kaons) \rightarrow higher rates in some detectors.

NA62: signal region

Kinematically constrained



NOT kinematically constrained



92% of total background BR

- ▶ Definition of the signal region
- ▶ $K^+ \rightarrow \pi^+\pi^0$ forces us to split it into two parts (**Region I and Region II**)

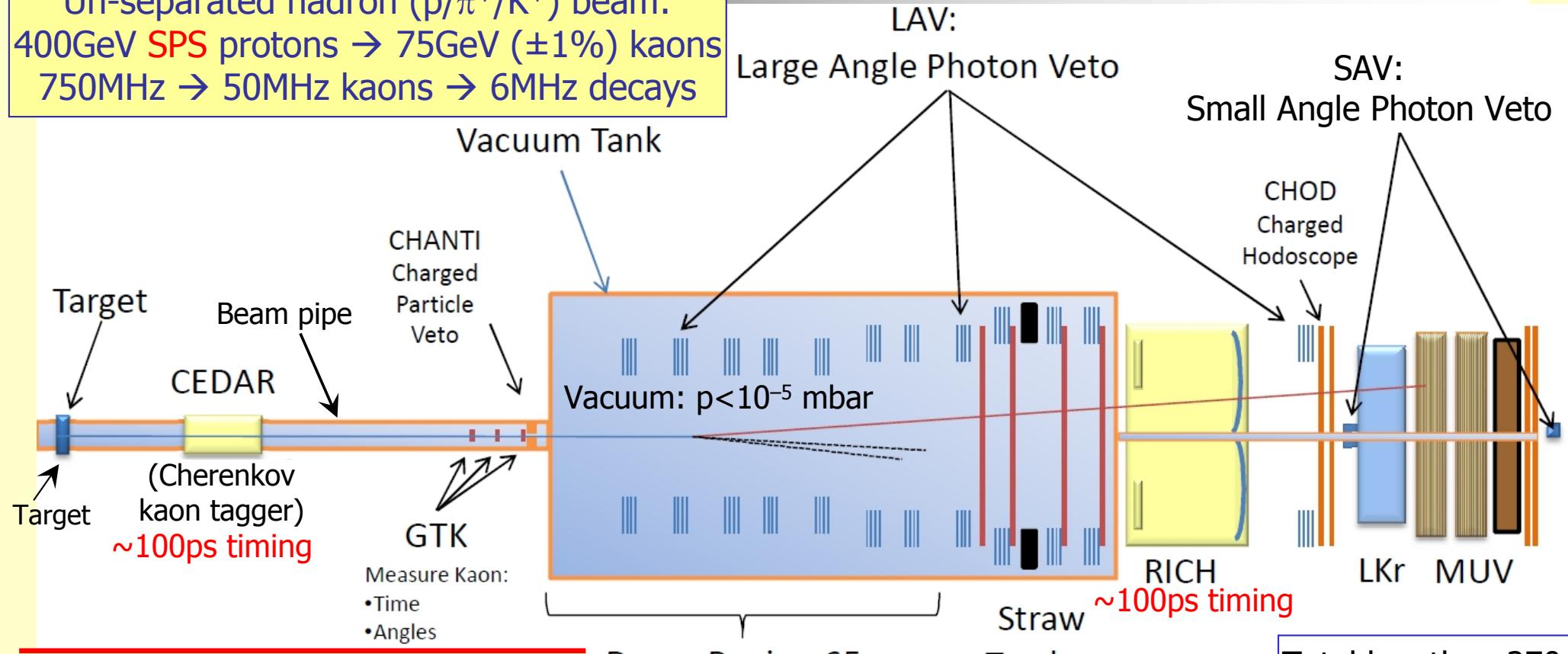
8% of total background BR

- ▶ Span across the signal region
- ▶ Rejection relies on vetoes/PID

Kinematic rejection power: $\sim 10^4$ ($K^+ \rightarrow \pi^+\pi^0$), $\sim 10^5$ ($K^+ \rightarrow \mu^+\nu$).
 → Two signal regions almost free of background.

NA62: sensitivity

Un-separated hadron ($p/\pi^+/K^+$) beam:
 400GeV SPS protons \rightarrow 75GeV ($\pm 1\%$) kaons
 $750\text{MHz} \rightarrow 50\text{MHz}$ kaons $\rightarrow 6\text{MHz}$ decays



Expected signal & backgrounds

Signal	45 evt/year
$K^+ \rightarrow \pi^+ \pi^0$	4.3%
$K^+ \rightarrow \mu^+ \nu$	2.2%
$K^+ \rightarrow 3 \text{ charged tracks}$	<4.5%
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	$\sim 2\%$
$K^+ \rightarrow \mu^+ \nu \gamma$	$\sim 0.7\%$
Total background	<13.5%

- 5×10^{12} K^+ decays/year \rightarrow record SES of $\sim 10^{-12}$;
- Hermetic veto: $\sim 5 \times 10^{-8}$ suppression of $\pi^0 \rightarrow \gamma\gamma$;
- Kinematics: $\sim 10^{-4}$ suppression of $K \rightarrow \pi^+ \pi^0$.
- Construction in progress; first technical run in 2012;
- Physics data taken driven by CERN accelerator schedule.

The wider NA62 programme

- Lepton Flavour Universality test

$$R_K = \text{BR}(K^+ \rightarrow e^+ \nu) / \text{BR}(K^+ \rightarrow \mu^+ \nu).$$

Well established decay-in-flight technique.

Expected NA62 precision: $\delta R_K / R_K < 0.2\%$.

Competitor: TREK@J-PARC (stopped K^+).

- Searches for lepton flavour/number violation

$$K^+ \rightarrow \pi^+ \mu^+ e^- , K^+ \rightarrow \pi^+ \mu^- e^+ , K^+ \rightarrow \pi^- \mu^+ e^+ ,$$

$$K^+ \rightarrow \pi^- \mu^+ \mu^+ , K^+ \rightarrow \pi^- e^+ e^+ .$$

Current upper limits: $\sim 10^{-10} \dots 10^{-11}$.

Expected NA62 limits

(subject to trigger configuration): $\sim 10^{-12}$.

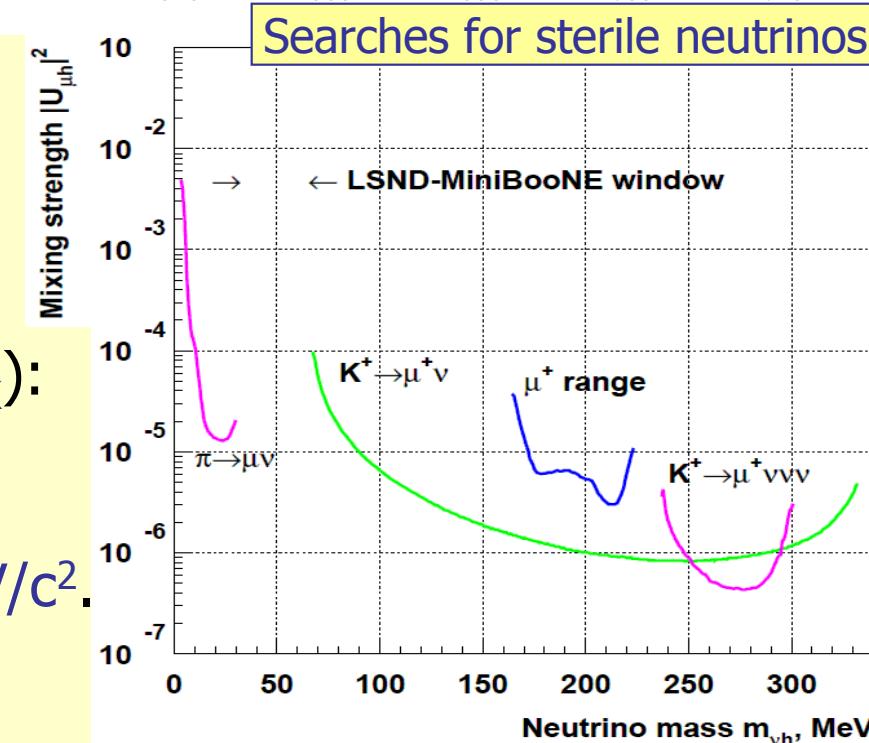
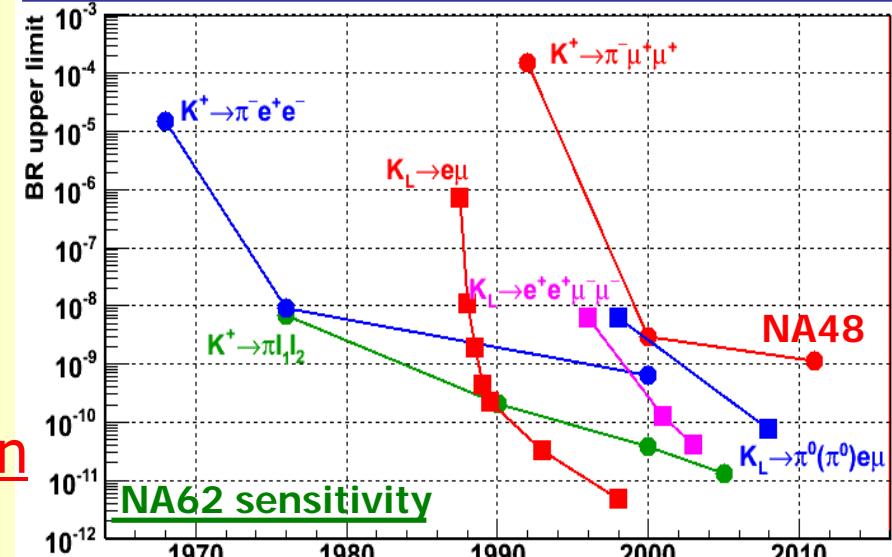
- Searches for heavy sterile neutrinos ($m_\nu < m_K$):

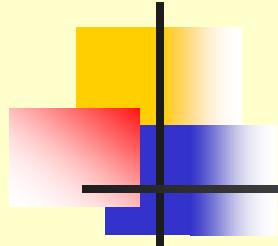
$$K^+ \rightarrow \mu^+ \nu_H \text{ via missing mass or } \nu_H \rightarrow \nu \gamma \text{ decay.}$$

Possible interpretation of LSND/MiniBooNE results: existence of neutrino with $m \sim 60 \text{ MeV}/c^2$.

S.N.Gninenko, PRD83 (2011) 015015

Searches for LFV/LNF: BR upper limit vs year

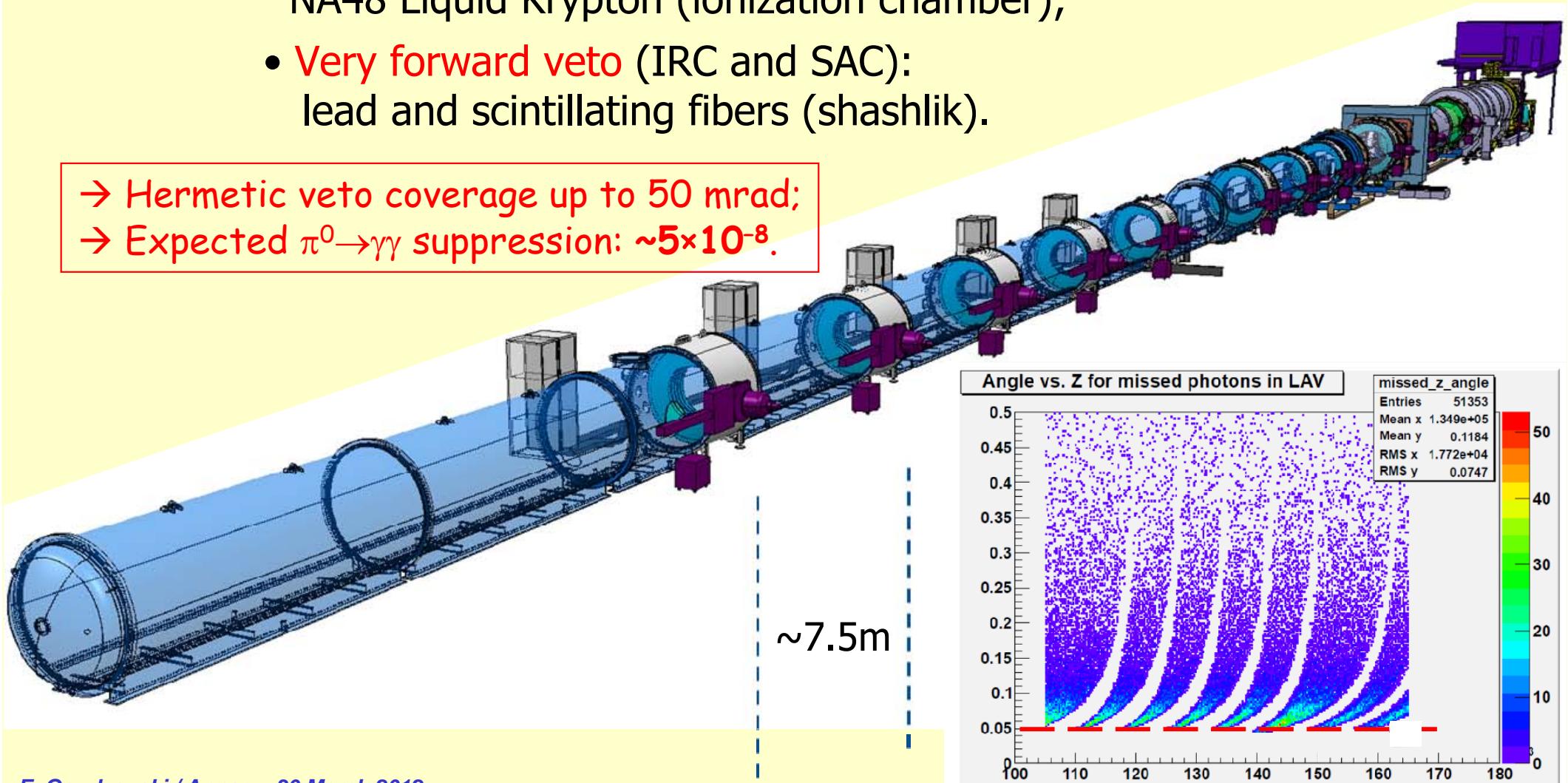


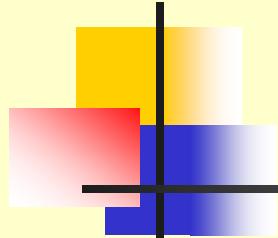


NA62 photon vetoes

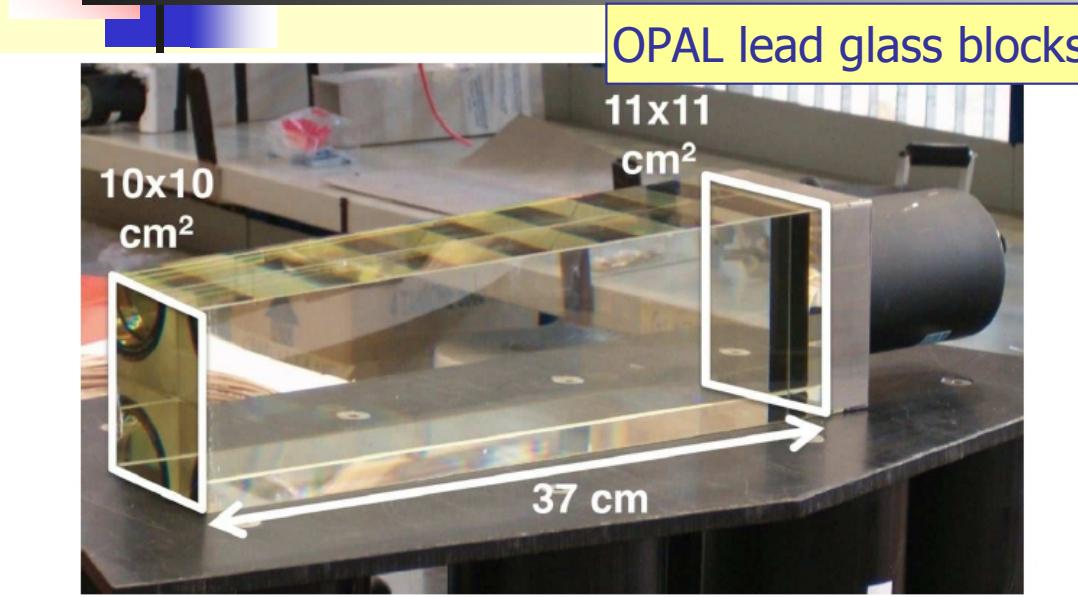
- Large-angle vetoes (LAV): lead-glass Cherenkov counters (former OPAL barrel);
- Forward veto: NA48 Liquid Krypton (ionization chamber);
- Very forward veto (IRC and SAC): lead and scintillating fibers (shashlik).

→ Hermetic veto coverage up to 50 mrad;
→ Expected $\pi^0 \rightarrow \gamma\gamma$ suppression: $\sim 5 \times 10^{-8}$.





Construction of LAV detectors

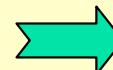
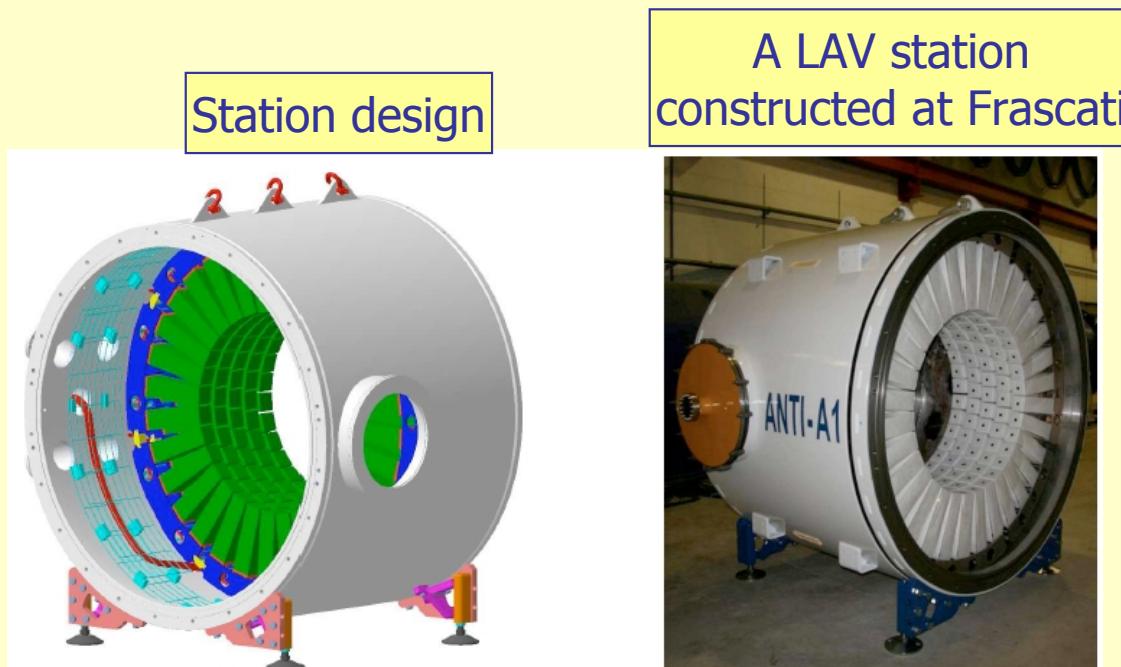


Detector:

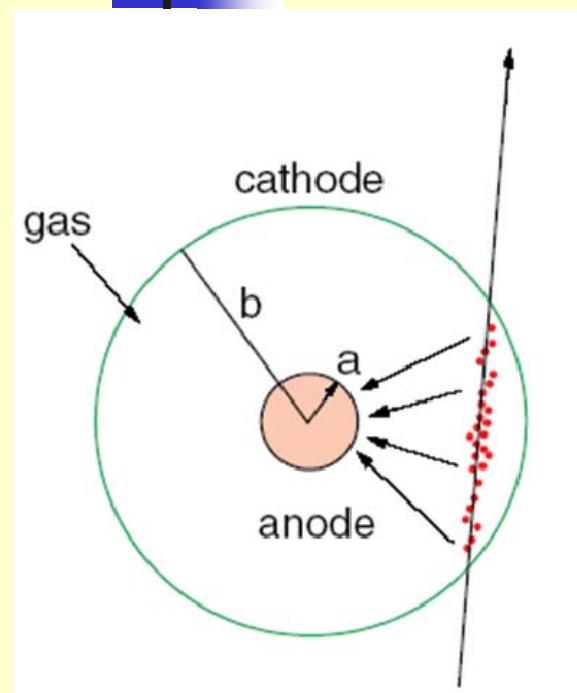
- 12 stations;
- 4 block types:
inner radii vary from 537 to 1072mm;

Each station:

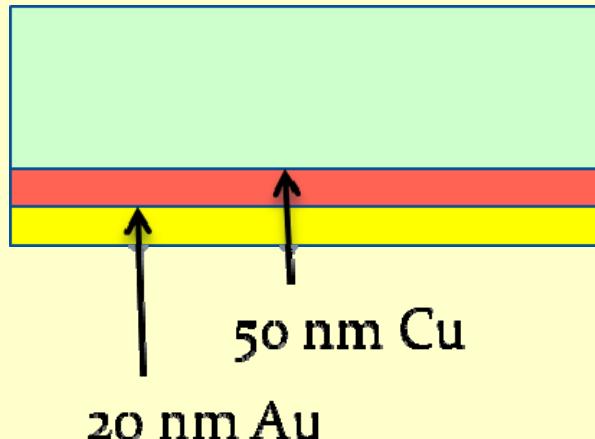
- 4 or 5 staggered layers;
- 160 to 256 Pb glass blocks.



Construction of the straw tracker to operate in vacuum

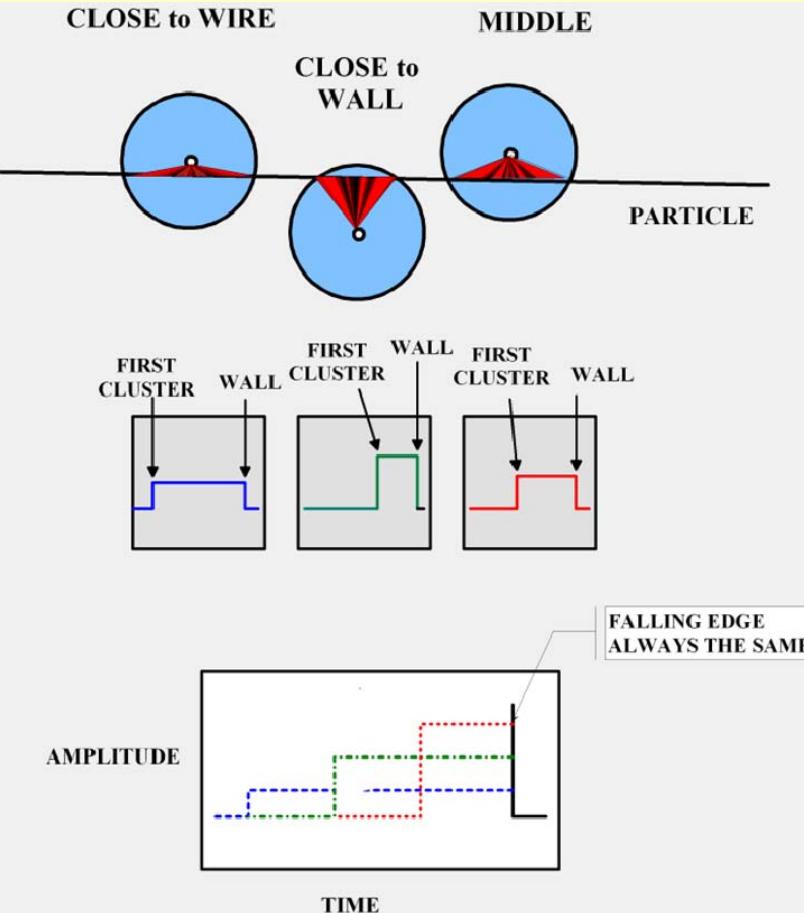


36 µm Mylar

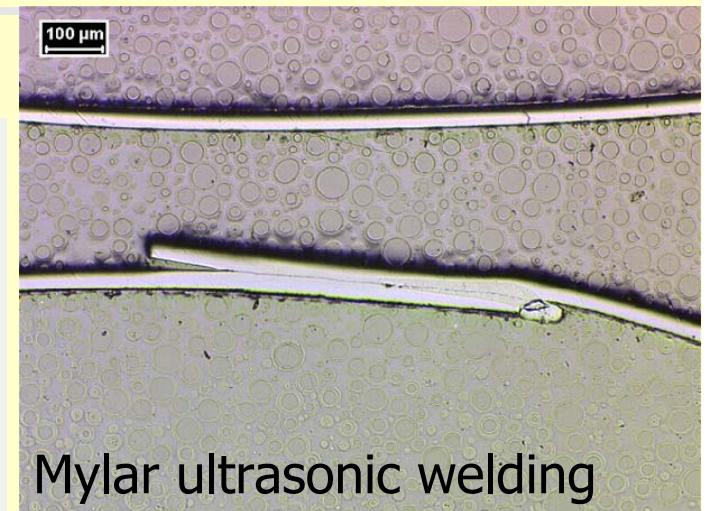


E. Goudzovski / Annecy, 30 March 2012

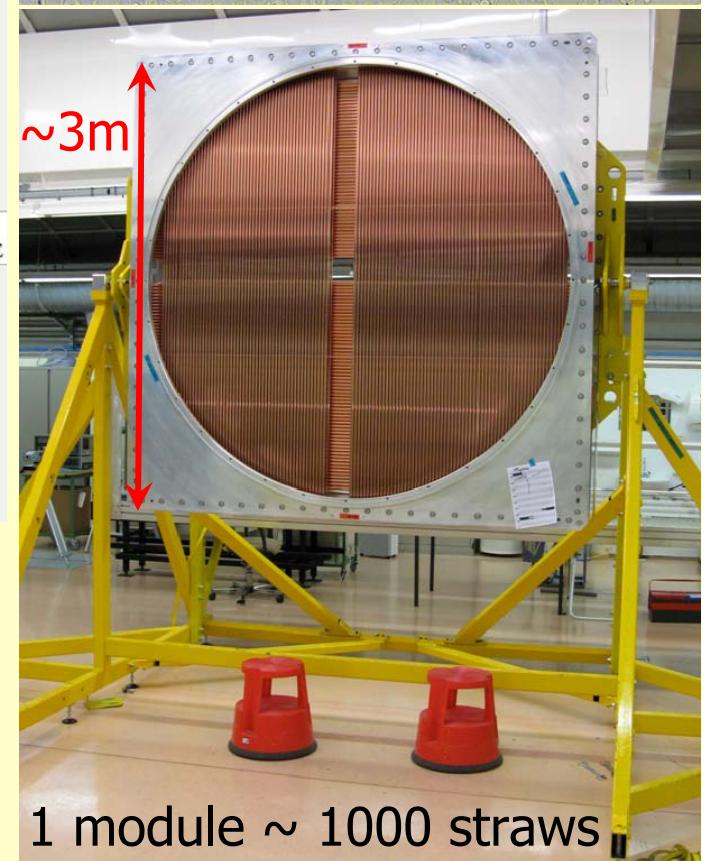
The straw principle:



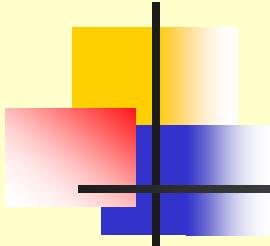
- Falling edge has the same time for all straws on track;
- Rising edge and amplitude give the distance to wire.



Mylar ultrasonic welding

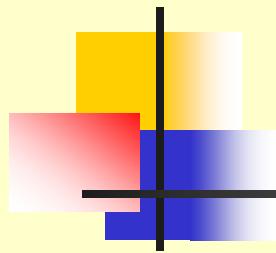


1 module ~ 1000 straws



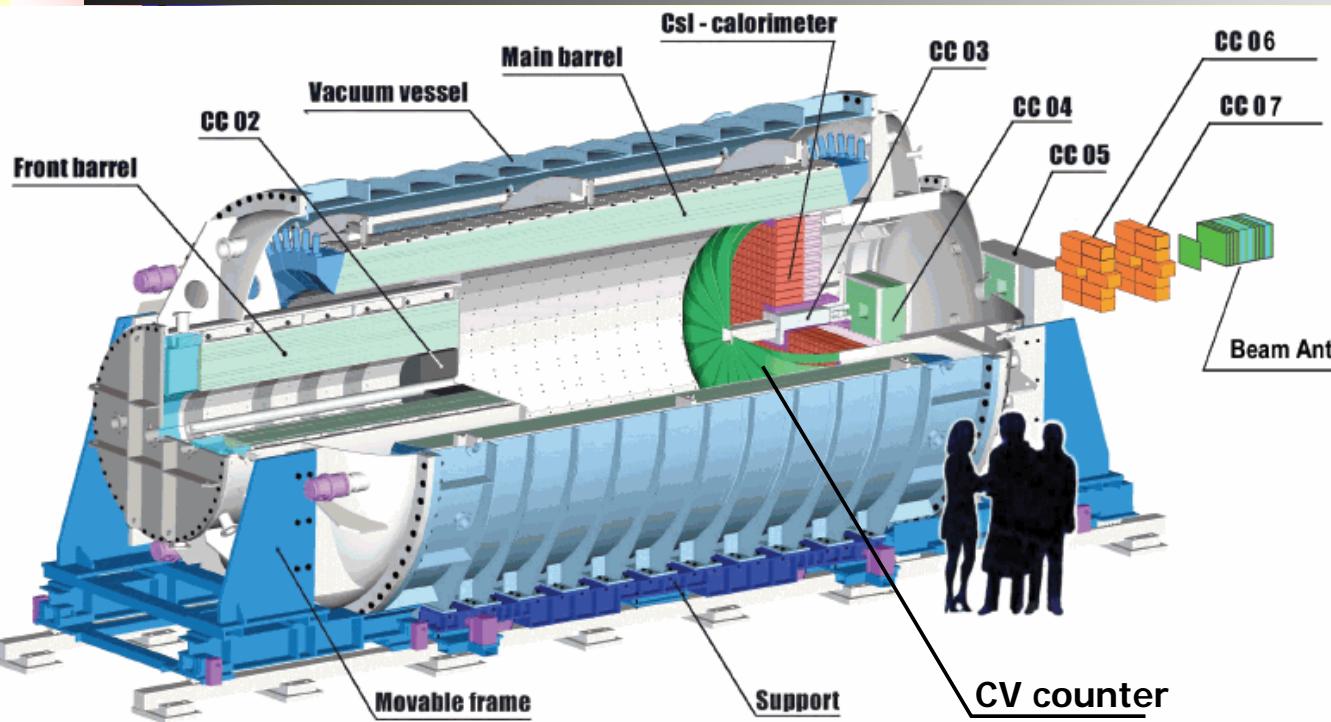
Conclusions

- New precise measurement of the helicity-suppressed ratio $R_K = \Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$ successfully completed:
→ record precision; in agreement with the SM;
non-trivial bounds on the 2HDM parameters.
- The $K \rightarrow \pi\nu\bar{\nu}$ decays are extremely suppressed and precisely predicted within the SM.
→ unique sensitivity to new physics;
→ a way of pushing the energy frontier above 14 TeV pp interactions.
- NA62: first experiment aiming to measure $\text{BR}(K \rightarrow \pi\nu\bar{\nu})$ to $\sim 10\%$ precision.
→ a timely measurement complementary to the LHC flavour programme.
- The NA62 programme spans well beyond the flagship decay mode.
→ Lepton flavour and number violation,
sterile neutrinos, radiative decays, ...



Spare slides

KEK E391a: $K_L \rightarrow \pi^0 \nu \bar{\nu}$



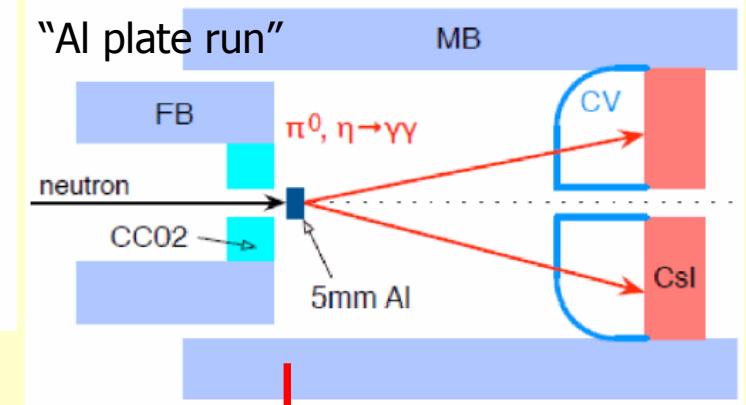
Good physics runs (Runs 2,3):
Feb-Dec 2005

Pencil K_L beam, 2.5×10^{18} PoT.

Calorimeter:

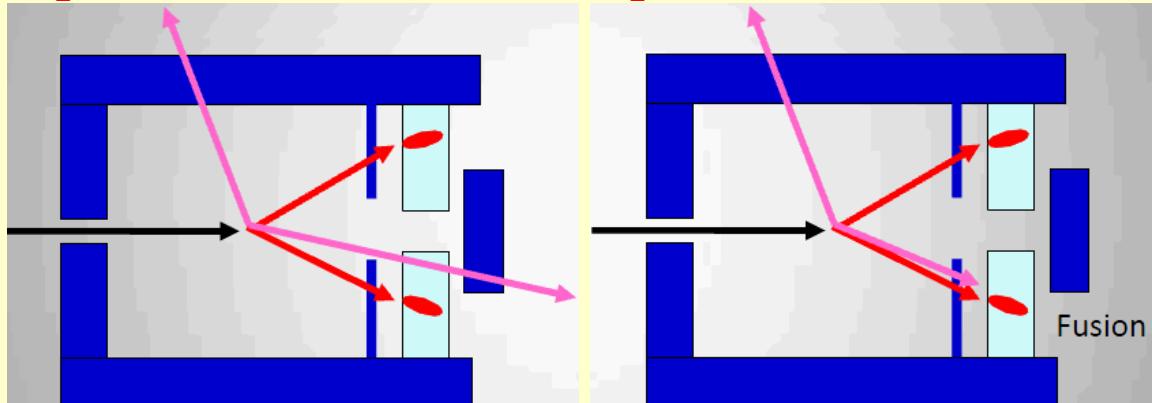
$496 (7 \times 7 \times 30) \text{ cm}^3$ CsI crystals

Veto: Pb+scintillator+WLS fibers



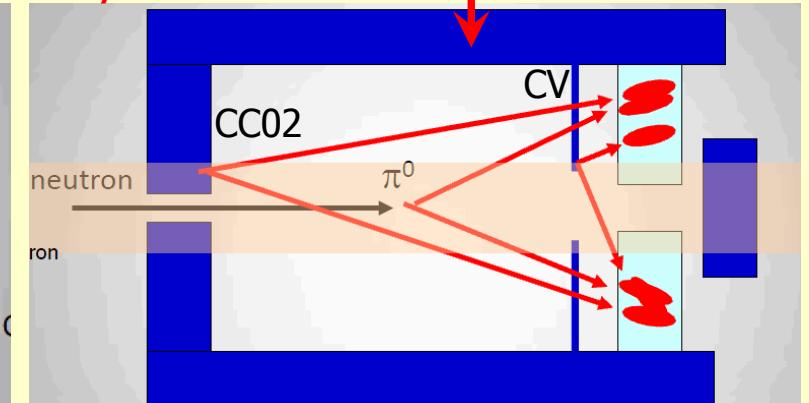
Principal backgrounds:

$K_L \rightarrow \pi^0 \pi^0$ (2 lost photons) $K_L \rightarrow \pi^0 \pi^0$ (merged clusters)



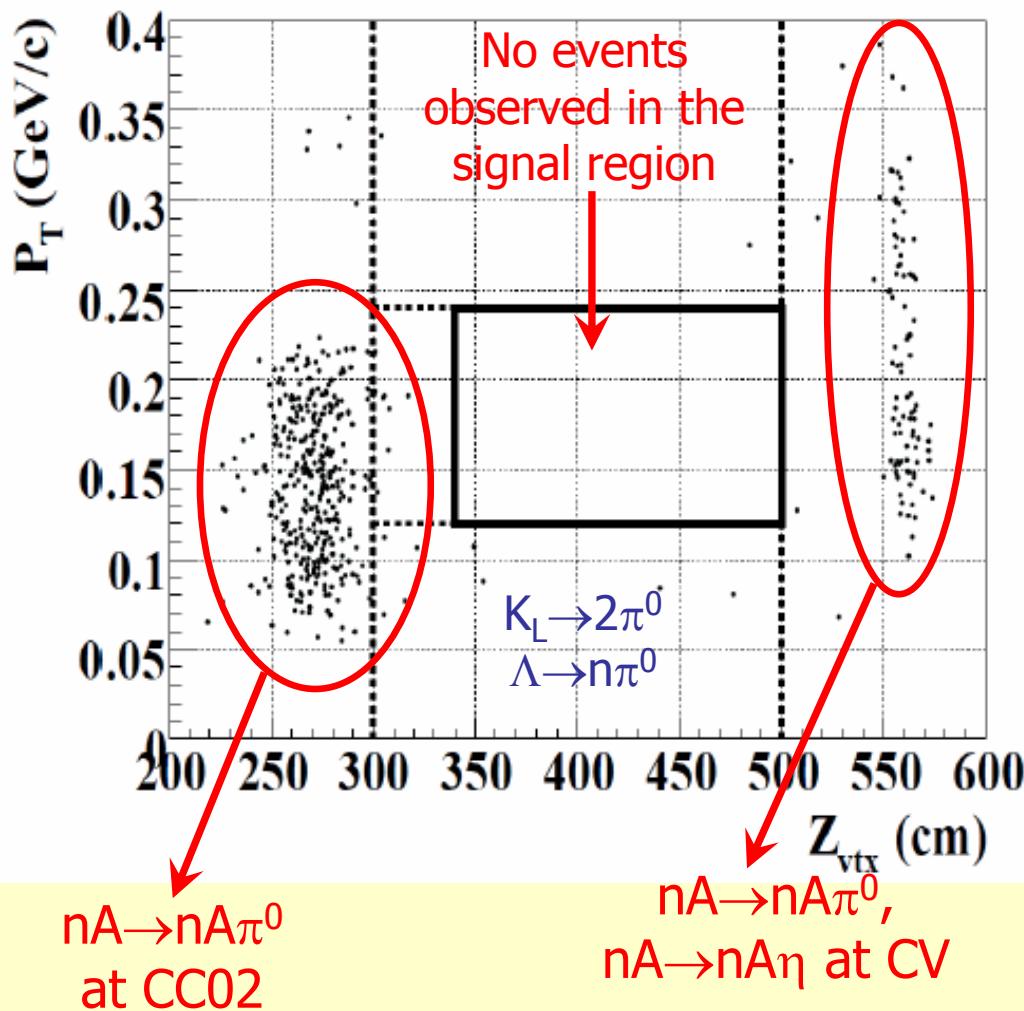
π^0/η production
by halo neutrons

FLUKA simulation
validated with data



KEK E391a: final result

Signature: a high- $p_T \pi^0$ + nothing
Blind analysis technique employed.



Background source	Estimated number of BG
halo neutron BG	0.66 ± 0.39
CC02- π^0	< 0.36
CV- π^0	0.19 ± 0.13
K_L^0 decay BG	$(2.4 \pm 1.8) \times 10^{-2}$
$K_L^0 \rightarrow \pi^0 \pi^0$	negligible
$K_L^0 \rightarrow \gamma\gamma$	negligible ($\mathcal{O}(10^{-4})$)
charged modes	negligible ($\mathcal{O}(10^{-4})$)
other BG	< 0.05
backward π^0	negligible ($\mathcal{O}(10^{-4})$)
residual gas	
total	0.87 ± 0.41

Background is dominated by beam interactions

Number of K_L decays:

$$N = (8.70 \pm 0.17_{\text{stat}} \pm 0.59_{\text{syst}}) \times 10^9$$

Signal acceptance: $\sim 1\%$

$$\text{SES: } (1.11 \pm 0.02_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-8}$$

Final result:

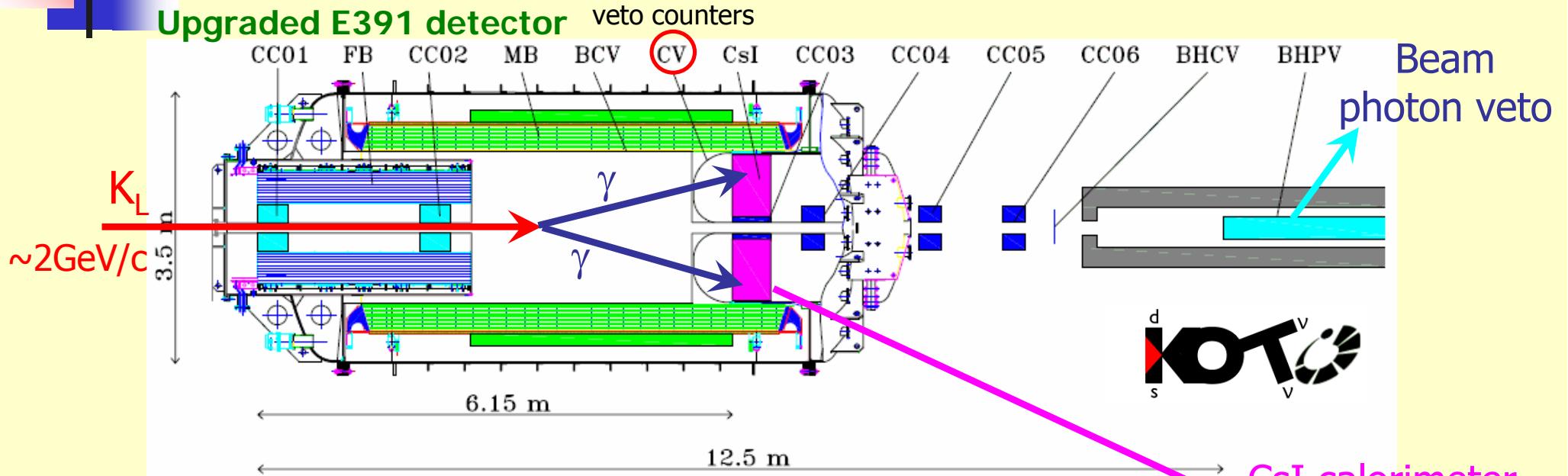
$$\text{BR}(K_L \rightarrow \pi^0 \bar{v} v) < 2.6 \times 10^{-8} \text{ @90% CL}$$

PRD81 (2010) 072004

Order of magnitude above the GN limit;
seen as preparation for JPARC E14 ³⁸

$K_L \rightarrow \pi^0 \nu \bar{\nu}$: E14(KOTO)@J-PARC

physics runs: 2012–

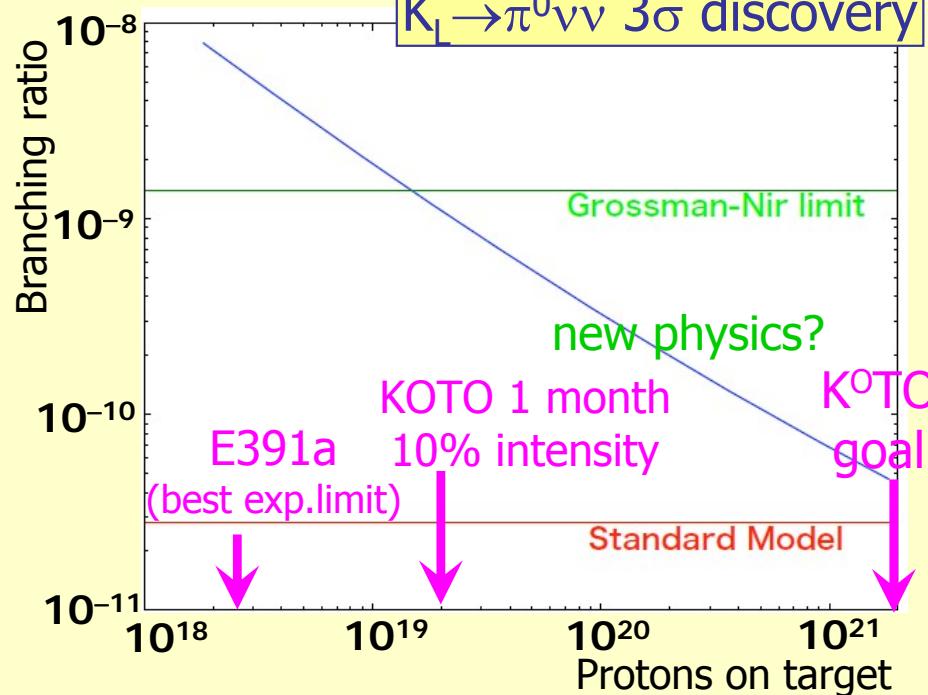


$K_L \rightarrow \pi^0 \nu \bar{\nu}$ 3 σ discovery

CsI calorimeter
(KTeV crystals)

Signal & background (3 years)
PoS(KAON09)047

Signal	2.7
$K_L \rightarrow \pi^0 \pi^0$	1.7
Halo neutron: CC02	0.01
Halo neutron: CV- π^0	0.08
Halo neutron: CV- η	0.3
Total background	2.1

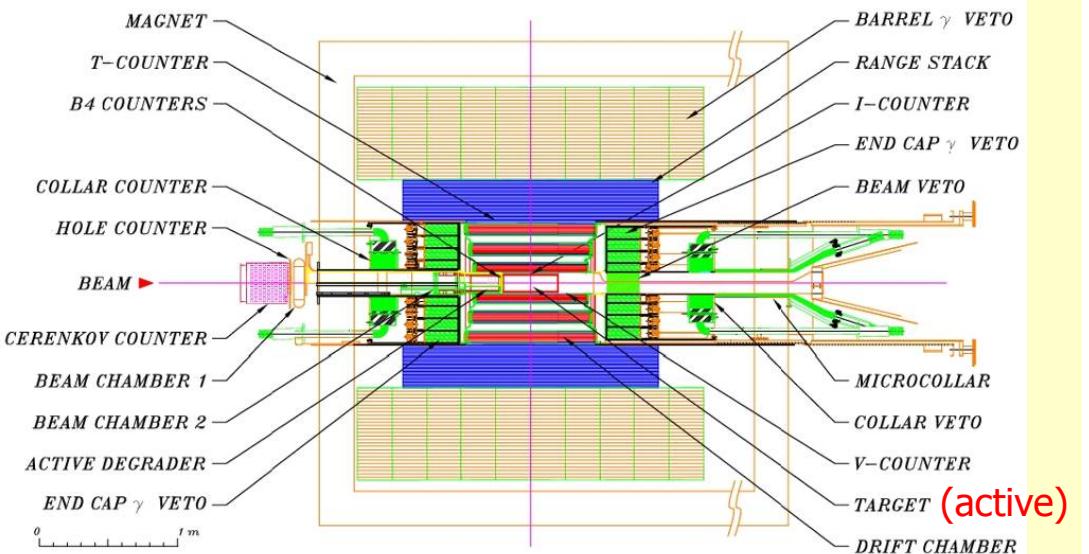
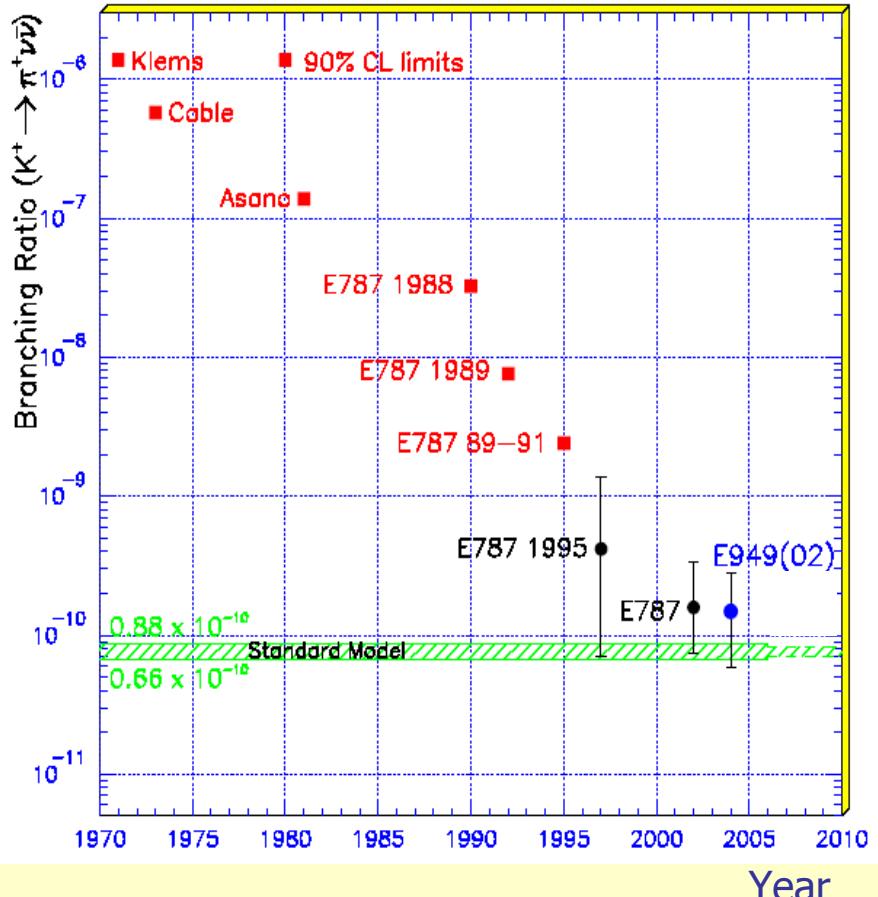


Follow-up proposal in the US

ORKA (Fermilab proposal 1021):
improved version of the E949 detector;
210 SM events/year expected

(November 2011)

History of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ measurements



P1021 Relative uncertainty on $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

