“Result on rare decays from NA62”

FPCP 23/05/2013

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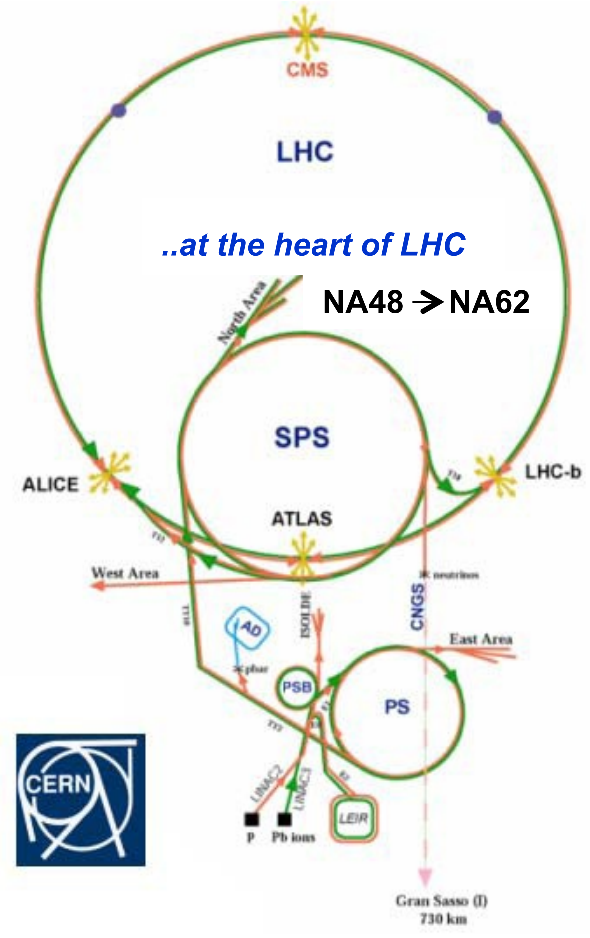
On behalf of the *NA62 collaboration*:
Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, Stanford, Sofia, Turin

Outline

- **NA62-2007/2008:** R_K with K_{l2} decays
  - principle of the measurement
  - analysis review
- **NA62**: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment
  - experimental methodology
  - main detectors description
- Conclusions



NA62

2007/2008

R_K with K_{l2} decays

Ke2: R_K and LFV

- The hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu 2}$ (no f_K)
- For this reason the SM prediction is very accurate $dR_K/R_K \sim 0.04\%$

$$R_K^{SM} = \frac{\Gamma(K \to e\nu_e)}{\Gamma(K \to \mu\nu_\mu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) =$$

$$= (2.477 \pm 0.001) \cdot 10^{-5}$$

[V.Cirigliano, I.Rosell JHEP 0710:005(2007)]

[Masiero et al. PRL 99 (2007) 231801]

- The only difference between electron and muon channel is due to the V-A coupling (helicity suppression)
- A small correction has to be included due to the IB part of the radiative decay

R_K *Beyond* Standard Model

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

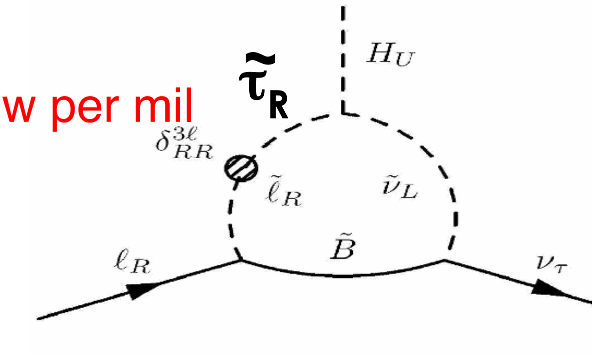
$$R_K^{LFV} \simeq R_K^{SM}\left[1+\left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\beta\right]$$

NP dominated by contribution of $e\nu_\tau$ final state, with effective coupling parametrized by $\Delta^{31}{}_R$ from a b-ino loop

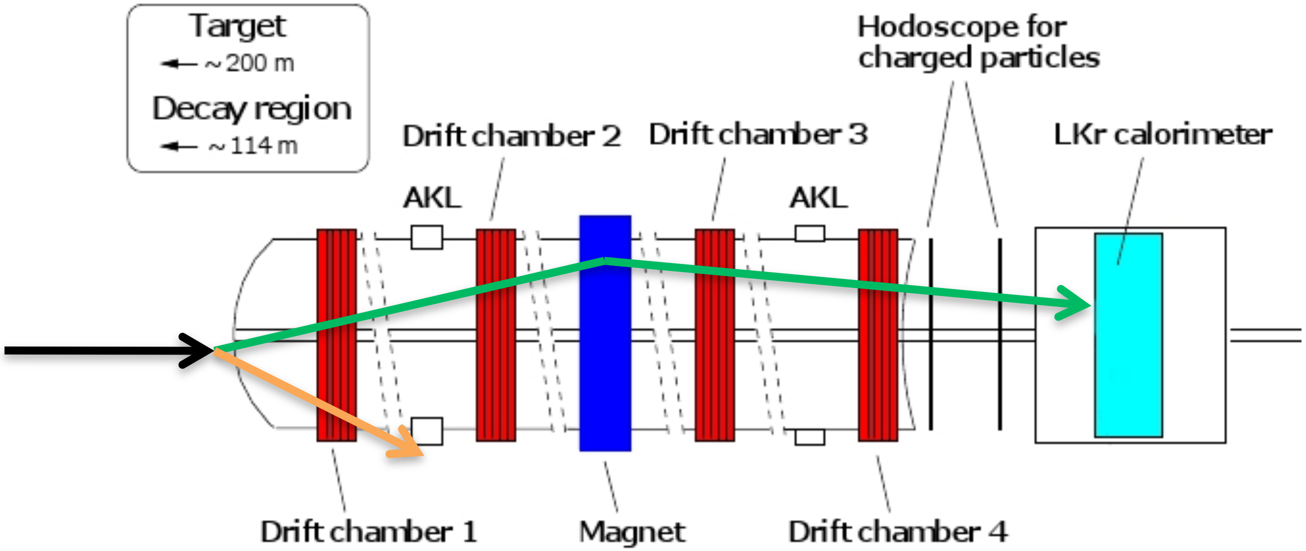
Possible NP due to heavy neutrinos

Experimental accuracy was δR_K ~1.3% (KLOE)

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



Ke2 @ NA62 2007/2008



- Goal: collect ~150000 signal events, better than 0.5% precision on RK
- Simultaneus K_{e2} and $K_{\mu 2}$ collection (both for K+ and K-)
- Because of higher rate of muons from beam halo in K- sample, we decided to run mostly with K+ with a ratio K+/K- ~5/1

NA62 2007/2008: Apparatus

Magnetic spectrometer

-> 4 view / DCH -> high efficiency

-> $\sigma_p/p = 0.48\% \oplus 0.009\% \cdot p$ [GeV/c]

Hodoscope

-> Fast trigger

-> $\sigma_t = 150$ps

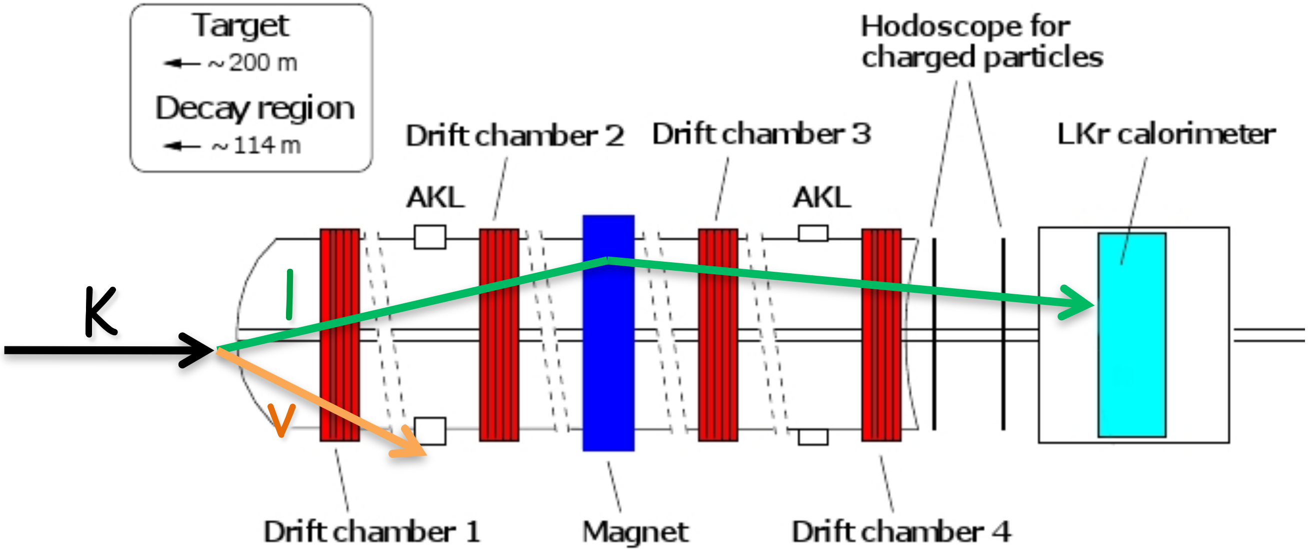
Electromagnetic calorimeter

-> ~7 m^3 liquid krypton (~27 X_0)

-> High granularity, quasi-homogeneous

-> $\sigma_E/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$ [GeV]

-> $\sigma_{x,y}$ ~1 mm (@ 20 GeV)



Measurement Strategy

K_{e2} and $K_{\mu 2}$ candidates collected simultaneously:

-> Many systematic effects reduced,

-> Measurement independent of the Kaon flux.

Particle identification with E/p (LKr and spectrometer)

MC simulations used to limited extent:

-> Acceptance correction (only for geometry),

-> Simulation of "catastrophic" bremsstrahlung by muons.

Analysis in 10 lepton momentum bins.

Signal events

Particle ID efficiency

Trigger Efficiency (>99.9%)

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

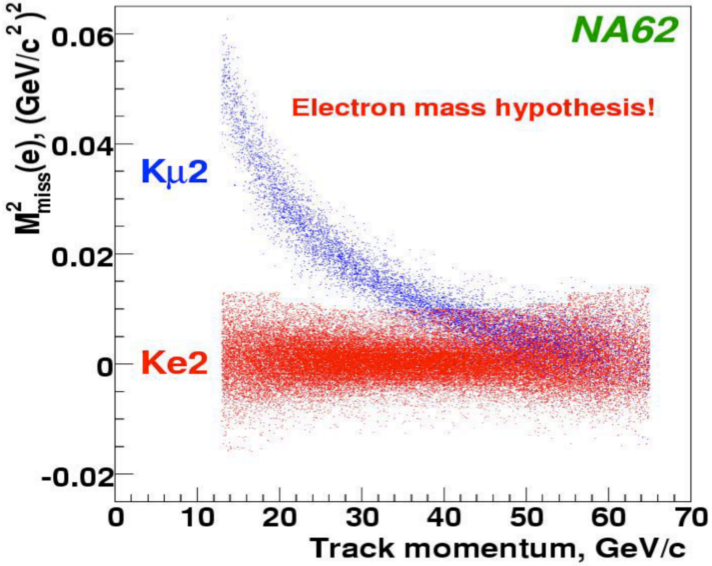
$K_{\mu 2}$ downscaling

Background Events (Main source of systematic errors)

Geometrical acceptance

Global LKr readout eff (0.998)

Signals Selection



Common reconstruction:

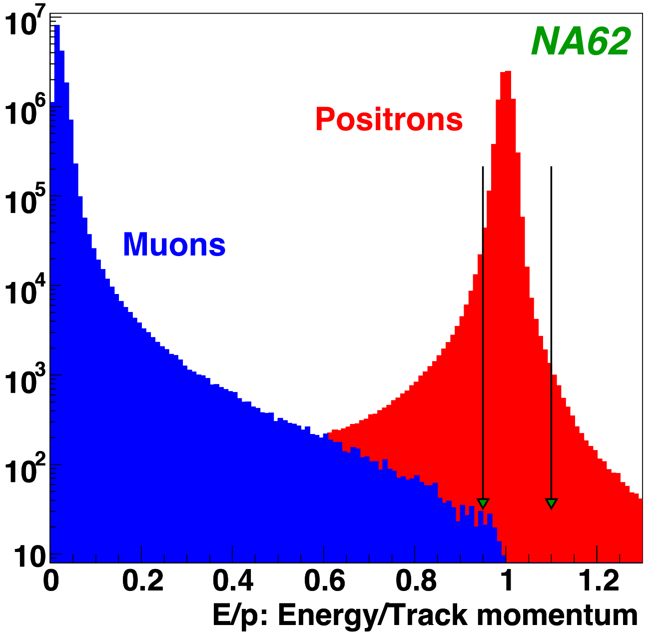
- -> 1 Reconstructed Track,
- ->Decay vertex defined as closest approach of track & nominal Kaon axis.
- -> Geometrical acceptance cuts,
- -> Limit on LKr extra energy deposition,
- -> Track momentum 13 GeV/c < p < 65 GeV/c

Kinematical separation => Excellent $K_{e2}/K_{\mu 2}$ separation at p<25 GeV/c:

- -> Missing mass $M^2 = (p_K - p_l)^2$
- -> P_K : Average measured with $K_{3\pi}$ decays

Particle Identification => Muon suppression ~10^6

- -> E/p = (LKr energy deposit/track momentum)
  - 0.90<E/p<1.10 for electrons with P≤25GeV,
  - 0.95<E/p<1.10 for electrons with P>25 GeV,
  - E/p<0.85 for muons.

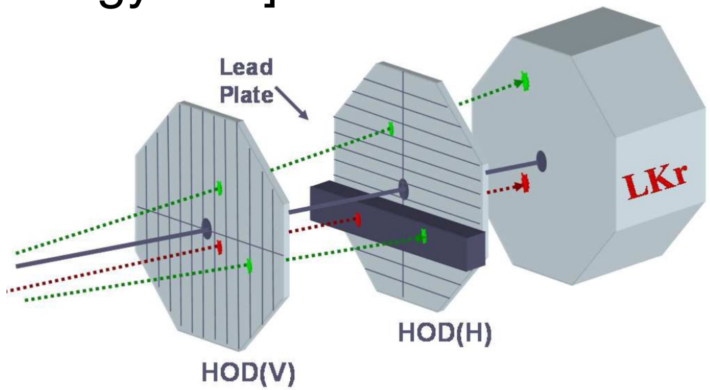


Analysis of Ke2/Kμ2 at NA62: μ background

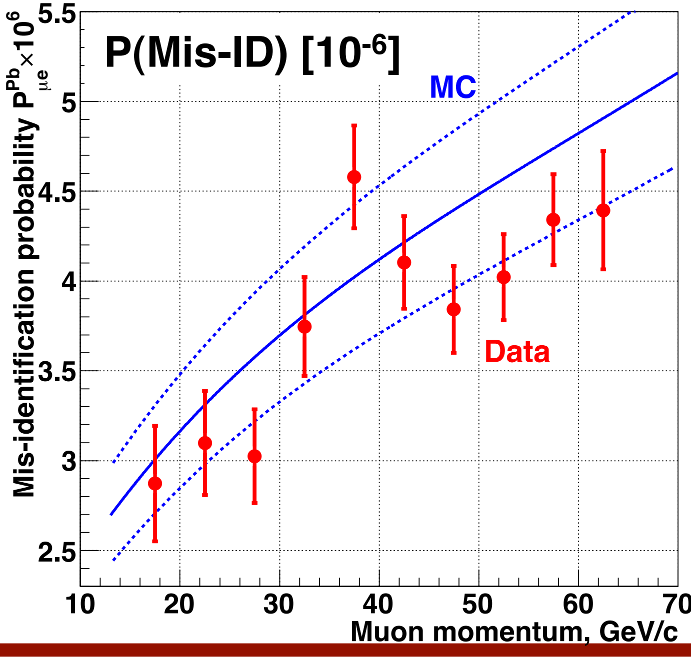
Electron ID efficiency: 99.28(5)%, measure probability the for μ's to fake *e*'s [**~4×10^{-6}** the so-called muon *"catastrophic"* energy loss]

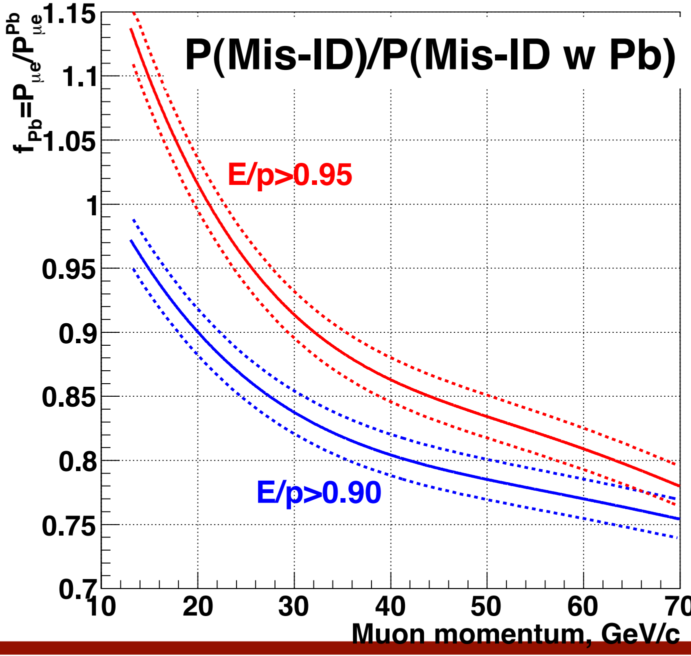
Subsample of data taken with a 9.2-X$_0$ Pb bar between HOD's, select μ's (pure @<10^{-8}) with MIP energy loss in Pb.

Correct method bias (ionization loss @ low P, brems. @ high P) with GEANT4



Evaluate 5.64(20)% Kμ2 bkg to Ke2

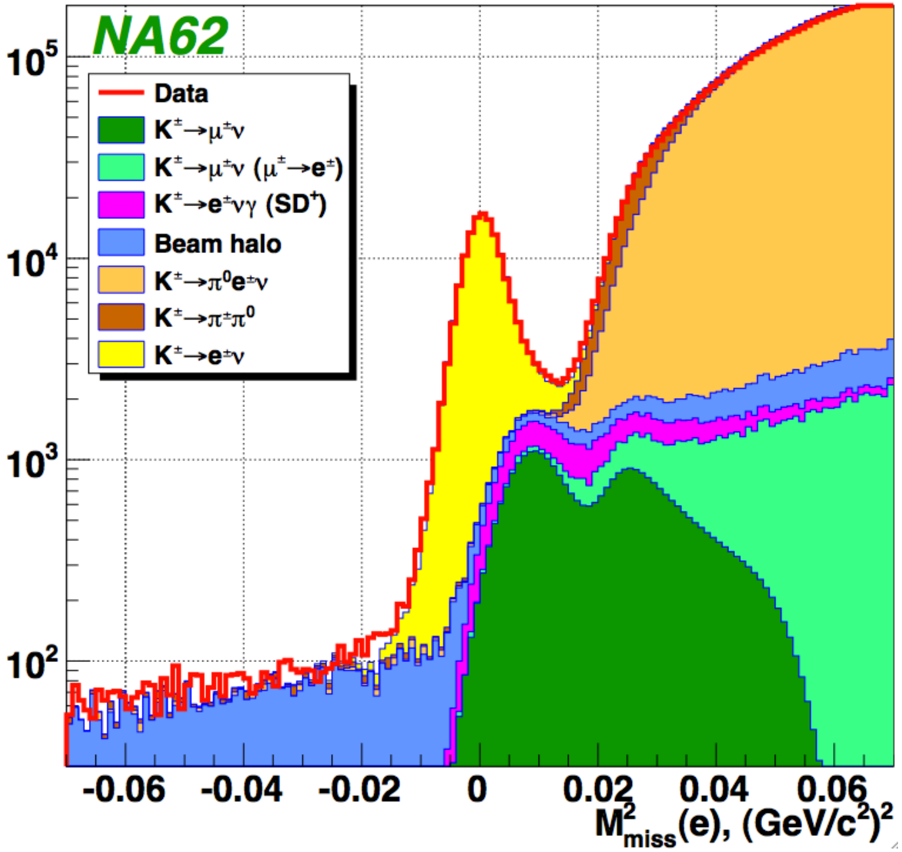

P(Mis-ID) [10^{-6}]

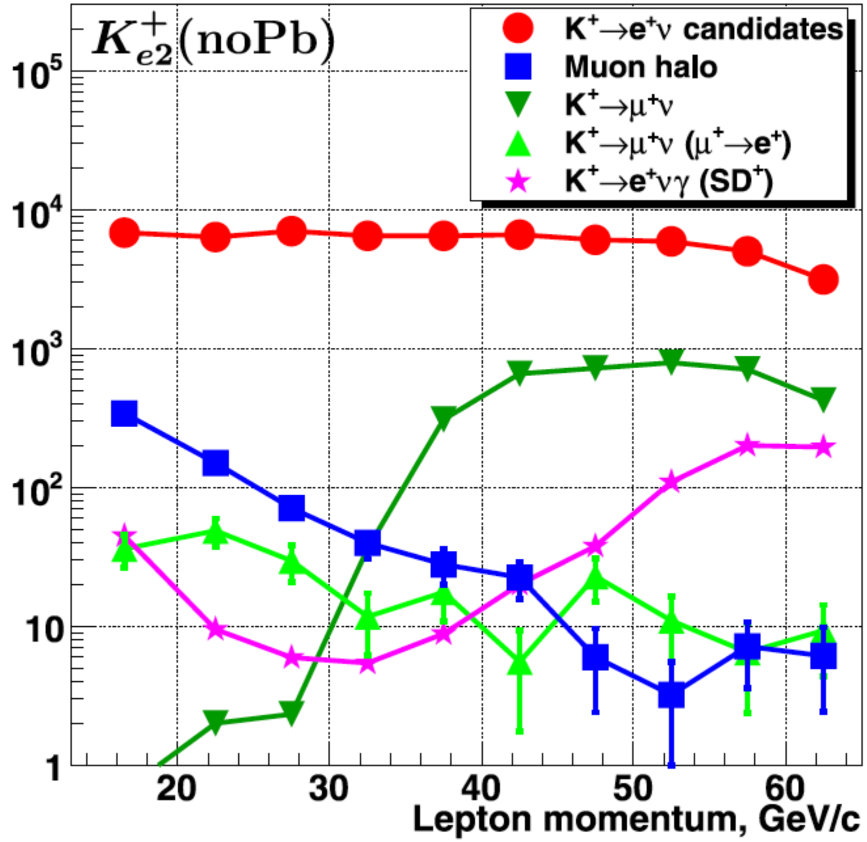

P(Mis-ID)/P(Mis-ID w Pb)

Analysis of $K_{e2}/K_{\mu2}$ at NA62: other backgrounds

World largest K_{e2} data set: **145958 K^{+}_{e2}** candidates, 10.95(27)% bkg

Source	$K\mu2$	$K\mu2(\mu \rightarrow e)$	$Ke2\gamma(SD^{+})$	$Ke3$	$K2\pi$	$K^{\mp}$	μ halo
Fraction %	5.64(20)	0.26(3)	2.60(11)	0.18(9)	0.12(6)	0.04(2)	2.11(9)



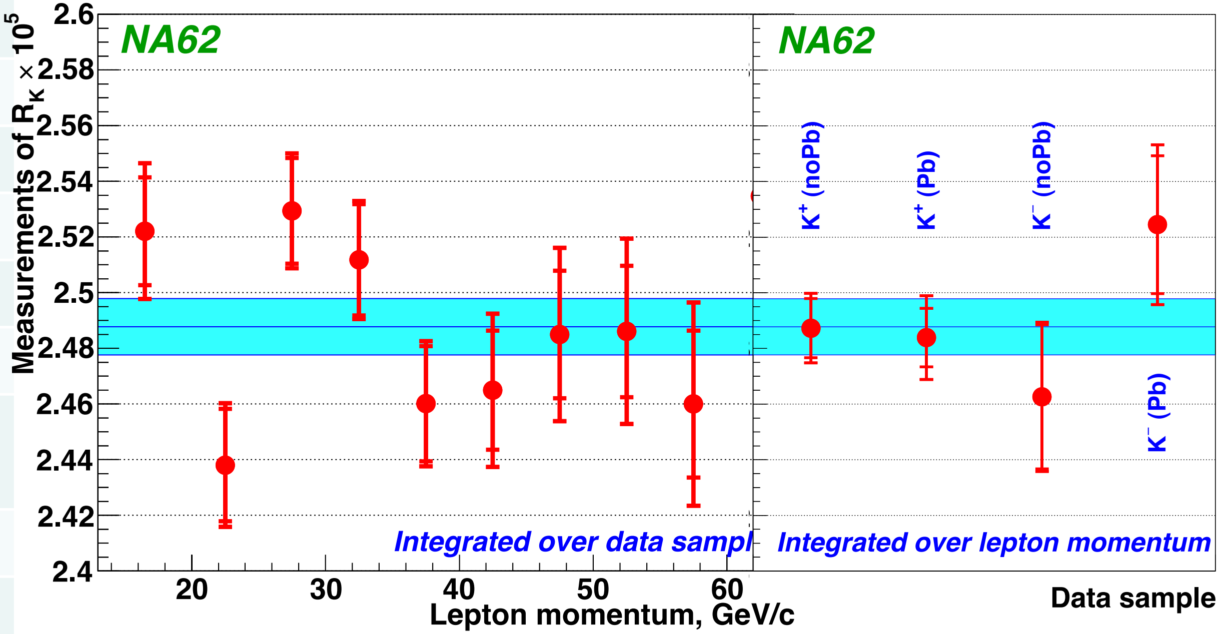


2012 R_K final result entire data set error budget

Analysis of R_K for the 4 configurations: K^+/K^- Lead bar/No lead bar
Analysis performed in lepton momentum bins, cuts optimized for resolution and background subtraction in each bin

Source	**δR_K (10^{-5})**
Statistics	0.007
Kμ2 bkg	0.004
Ke2γ SD+ bkg	0.002
Ke3, $\pi\pi^0$ bkg	0.003
Muon halo bkg	0.002
Material budget	0.002
Acceptance corr	0.002
DCH alignment	0.001
Electron ID	0.001
1 TRK trigger eff	0.001
LKr readout eff	0.001
Total	0.010

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



Fit over 40 independent measurements, 10 lepton momentum bins × 4 configurations:
χ^2 / Nd.o.f. = 47/39 (P = 18%)

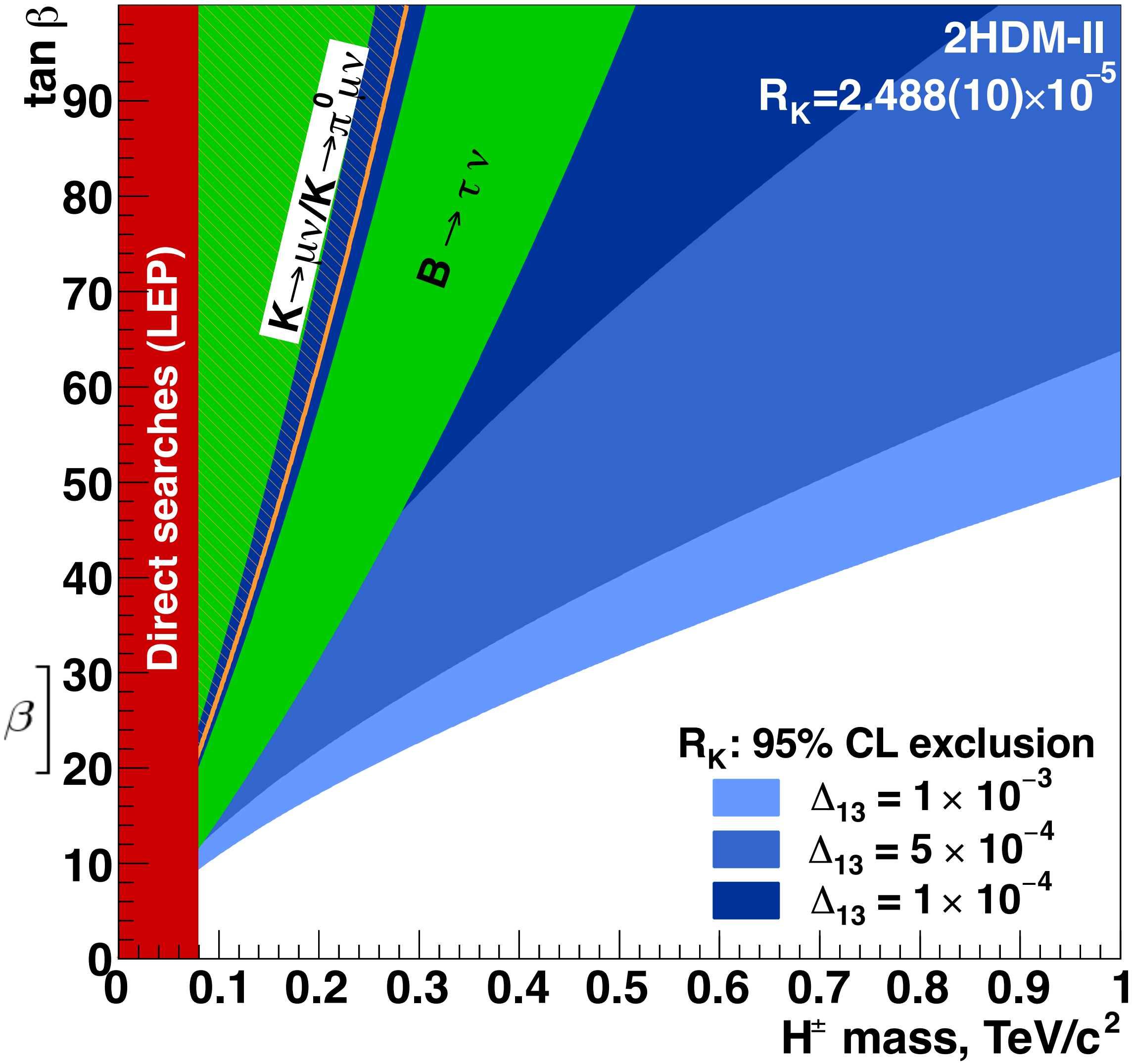
2012 R_K final result – impact for NP search

Compare NA62 result with

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

including possible NP from H^+:

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



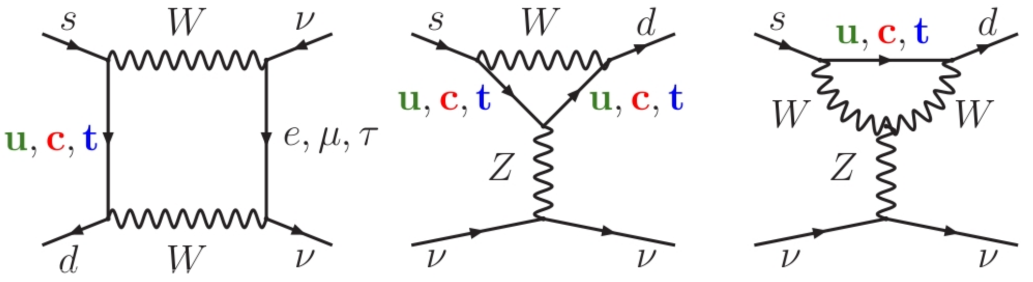
Error ~10 that of SM prediction, still room for future improvements

NA62

$K^+ \to \pi^+ \nu\bar{\nu}$ experiment

$K^+ \to \pi^+ \nu \bar{\nu}$: motivation

- FCNC process forbidden at tree level
- Only one loop contributions: Boxes and Penguins



SM prediction (10^{-11} units) [Brod, Gorbahn and Stamou Phys. Rev D 83, (2011) 034030]

$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = \kappa_+ (1 + \Delta_{\mathrm{EM}}) \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{\mathrm{Re}\lambda_t}{\lambda^5} X_t \right)^2 \right] = (7.81^{+0.80}_{-0.71} \pm 0.29)$$

$$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = (2.43^{+0.40}_{-0.37} \pm 0.06)$$

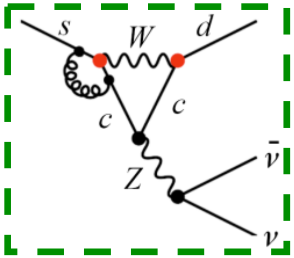
where $x_q \equiv m_q^2 / m_W^2$

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

Loops favor top contribution

Hadronic matrix elements from BR(Ke3) via isospin rotation

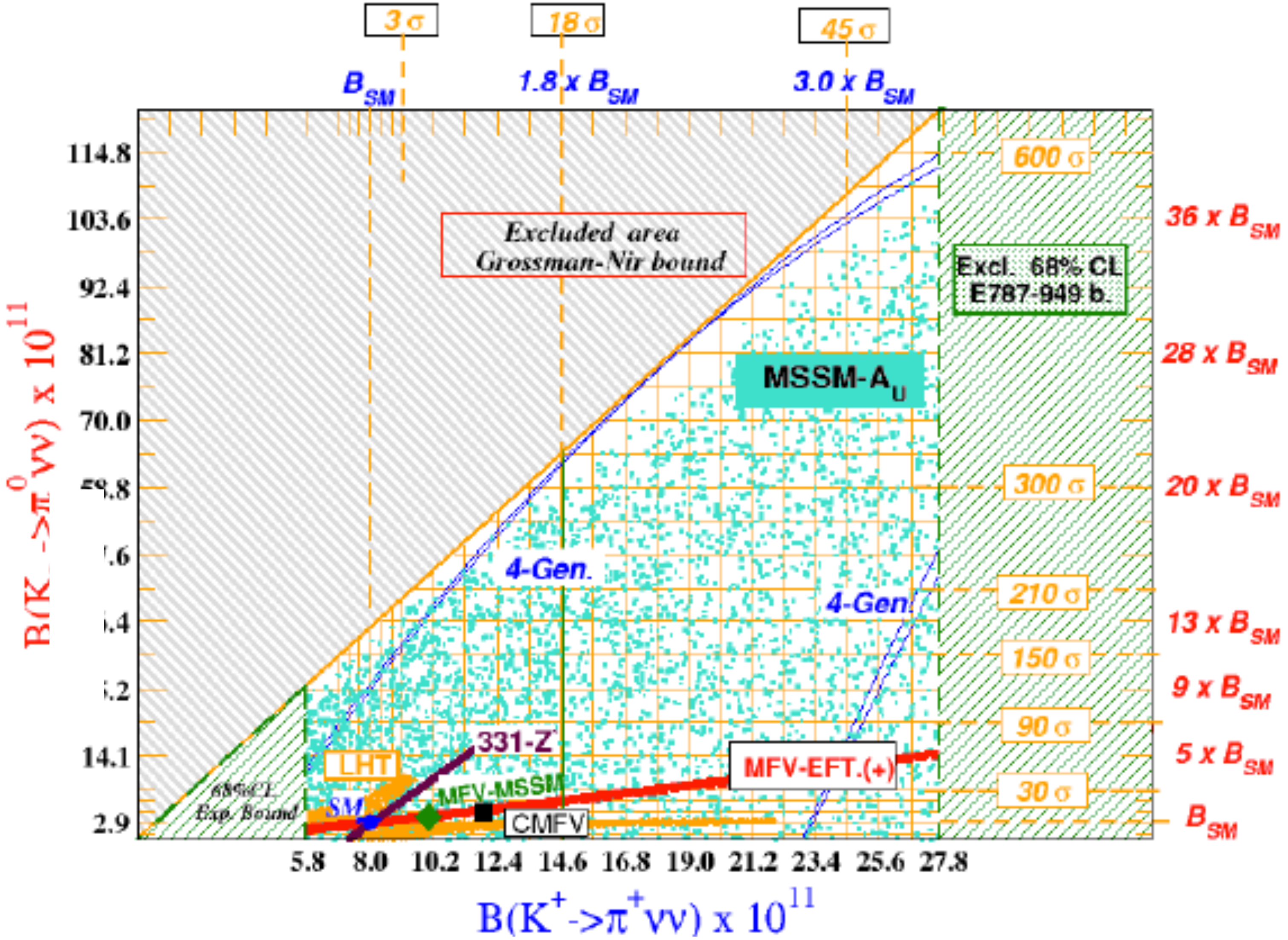
Charm contributes to theory error: 4% (2%) for K^+ (K_L)



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

Beyond-SM prediction for $K^+ \to \pi^+ \nu\bar{\nu}$: motivation

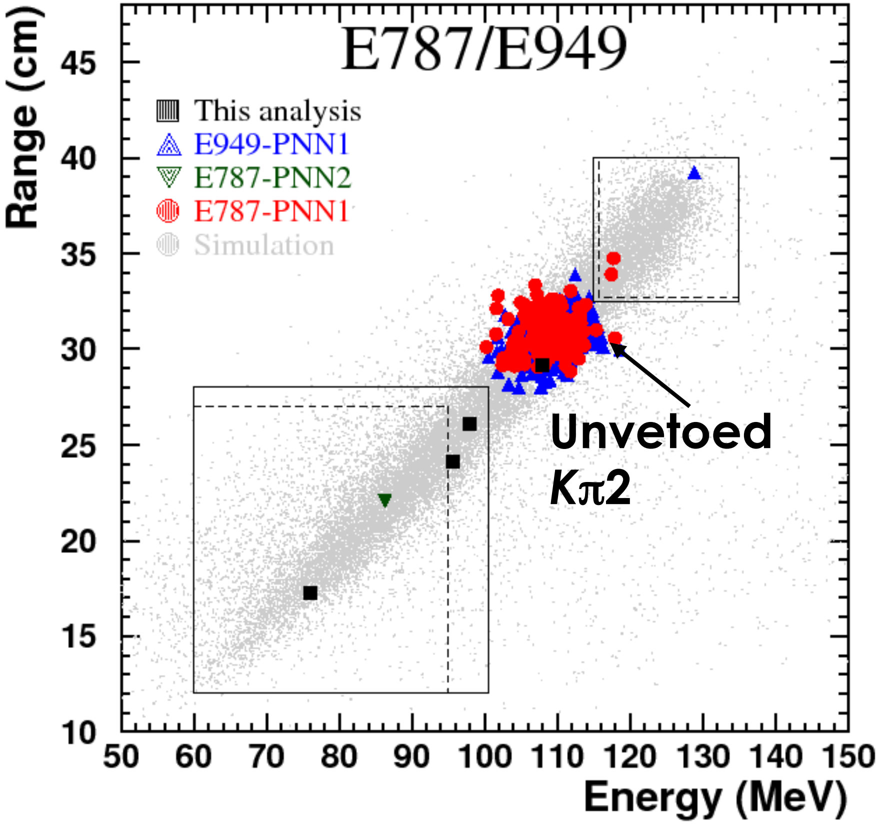
Deviations from SM by more than 10% quite possible in many NP models



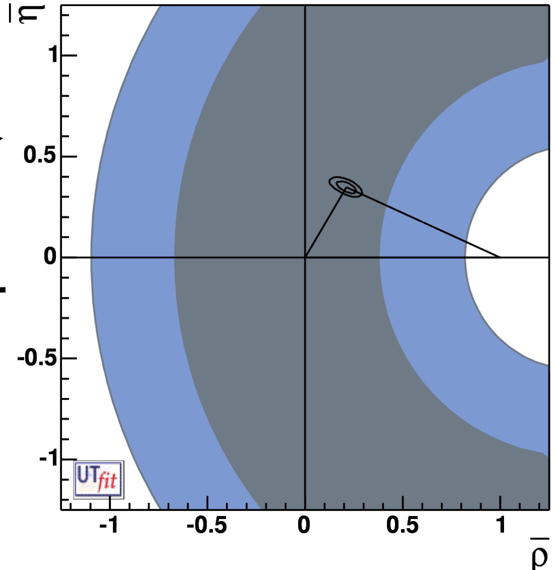
Experimental status for $K^+ \to \pi^+\nu\bar{\nu}$

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

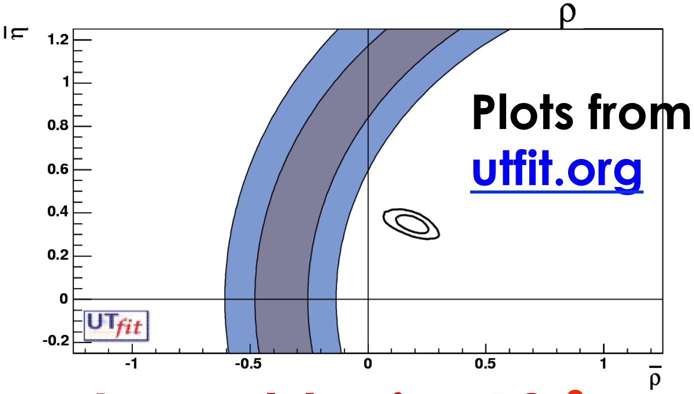
$$BR(K^+ \to \pi^+\bar{\nu}\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$



Unvetoed $K\pi2$



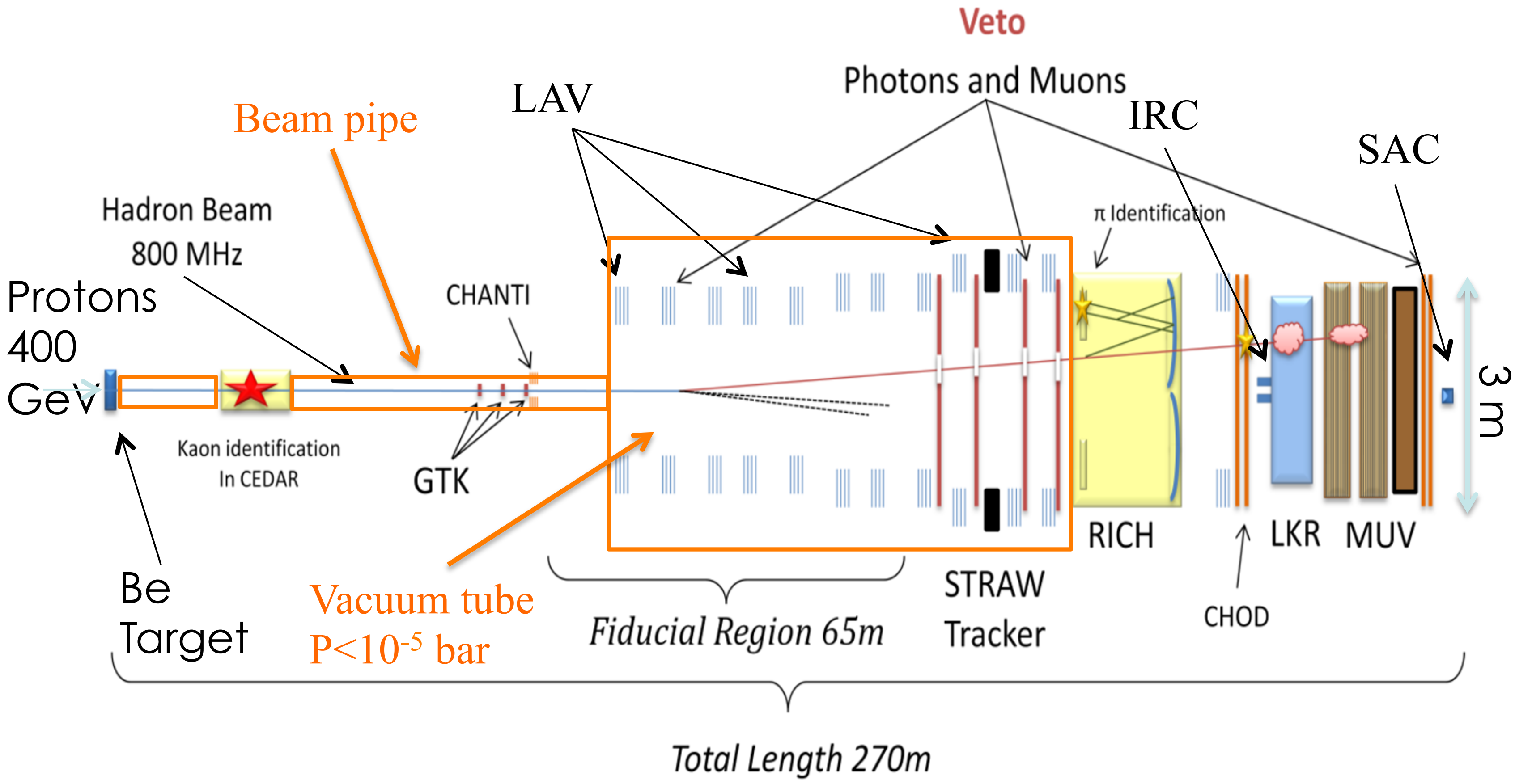
Same central value, 100 evts



Plots from utfit.org

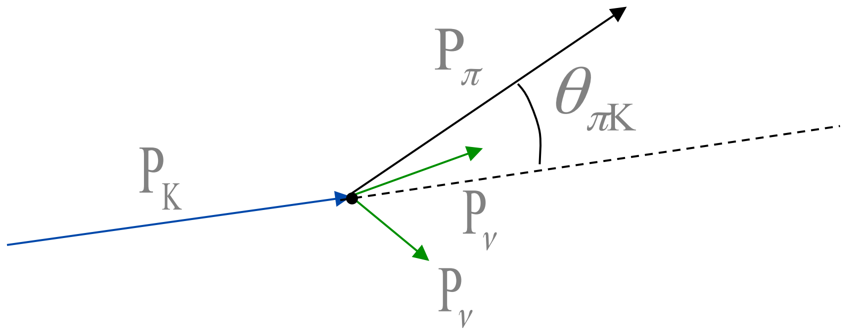
Expected bkg 2.6 events, prob. all 7 obs. evts are bkg is ~10^{-3}

$K^+ \to \pi^+ \nu \bar{\nu}$ @ NA62



- High energy unseparated kaon beam
- Decay in flight technique
- Goal: **O(100) events with S/B ~10**
- high-resolution timing, **charged hodoscope** (scintillator), σ_t **< 200 ps**

Kinematic reconstruction



$$m^2_{miss} \cong m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta^2_{\pi K}$$

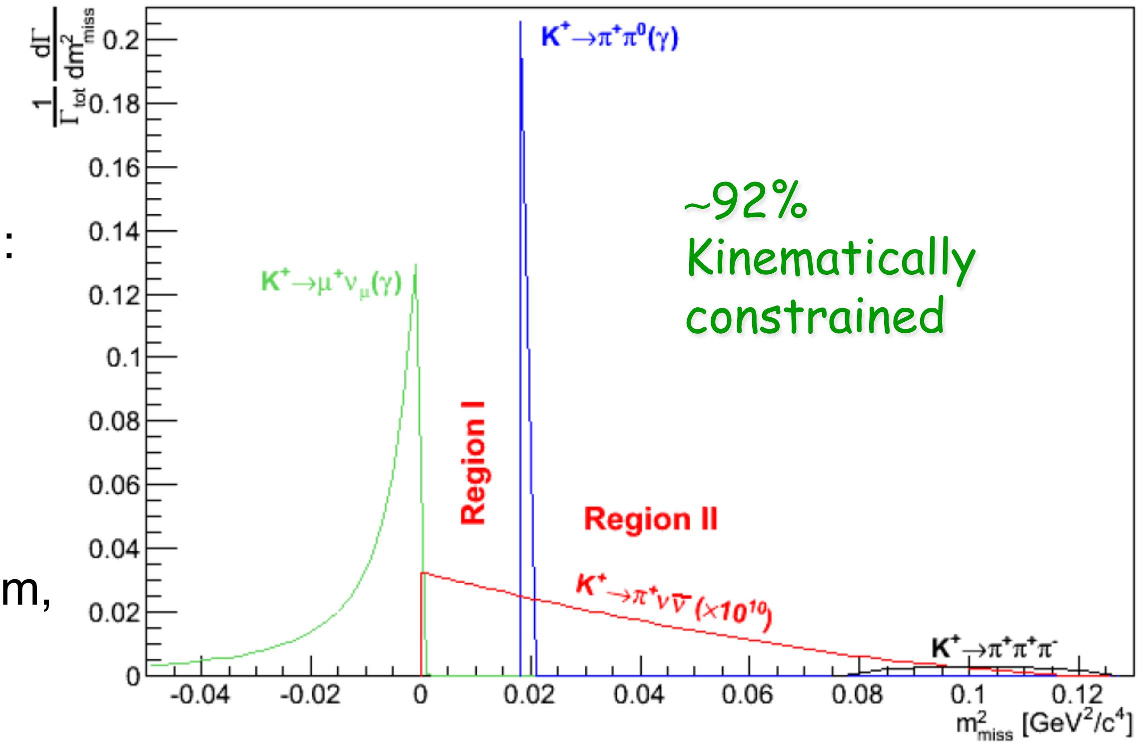
Requirements:

- low mult. scattering → low mass tracker operating in vacuum
- good space resolution

Solution

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

two background free regions



~92% Kinematically constrained

PID and Veto

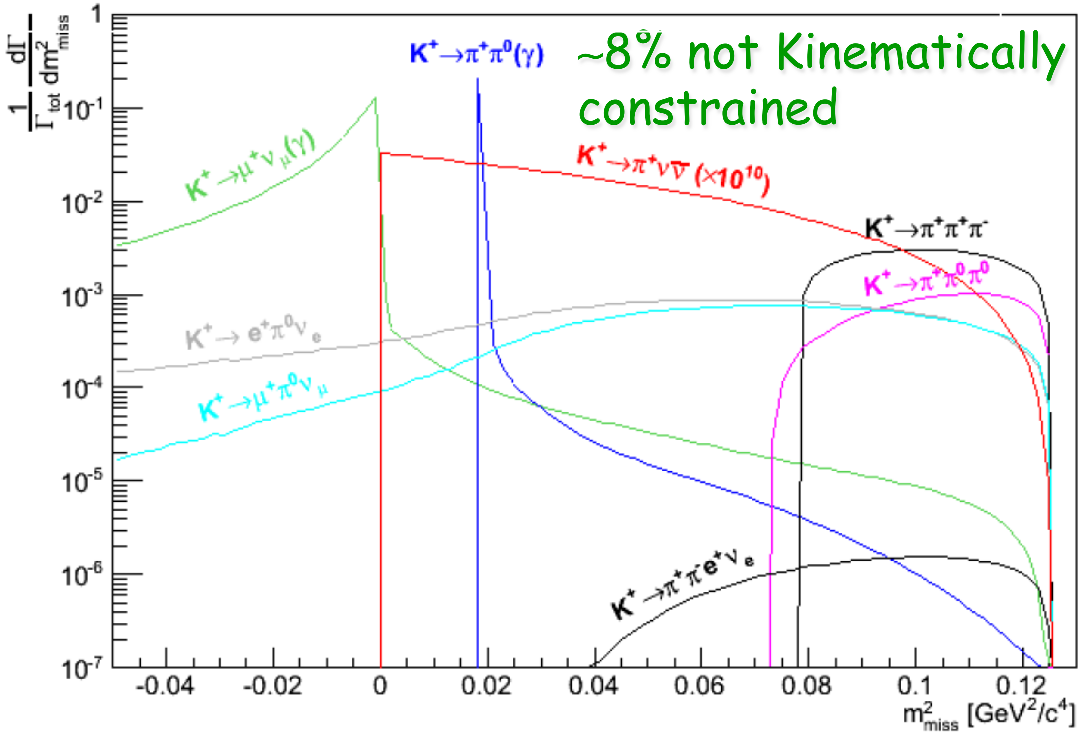
Rejection for K+ leptonic and semileptonic decay bkg, PID for all charged particles

- 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, $\sigma_t < 100$ ps
- ID for outgoing μ's: $1-\varepsilon < 10^{-5}$ for μ

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

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

Redundancy of information



~8% not Kinematically constrained

NA62 expected sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+\nu\nu$ *[flux = 4.8×10^{12} decay/year]*	55 *evt/year*
$K^+ \to \pi^+\pi^0$ $[\eta_{\pi 0} = 2\times10^{-8}]$	4.3%
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~0.7%
$K^+ \to e^+(\mu^+)\,\pi^0\nu$, others	negligible
Expected background	≤13.5%

Aim to obtain O(~10%) signal acceptance with <10% background

From NA48 past experience: run for ~100 days/year, efficiency of data taking ~60%

Conclusions

- In the flavour sector, new physics could appear both in MFV and in NON-MFV processes
- A precise R_K measurement in the Ke2 decay is a very powerful tool to constrain new physics parameters in case of presence of LFV mediators
- NA62-2007/2008 reached a sensitivity of 0.4%
- The measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ decay could be a good opportunity to find NP and to distinguish among NP models
- NA62 is a challenging experiments aiming at O(100) events with S/B=10

  Detector construction underway in 2013-2014. Data taking will start in 2014-2015

Spares

Kaon and Physics beyond the SM

New physics effects in Flavour Physics

[G.Isidori Capri, Flavianet 2008]

MFV: helicity suppressed observables are sensible to SUSY with large $\tan\beta$: ***$B \to ll$, $B \to l\nu$, $K \to l\nu$***

The B decays are suppressed (Vub<<Vus) while the ***$K \to e\nu$*** is $1.5 \cdot 10^{-5}$

Non-MFV: FCNC decays with high suppression in the standard model and clean theoretical prediction

The ***$K \to \pi\nu\nu$*** has a very clean SM prediction and has a λ^5 suppression

It's time for a precision measurement in ***K_{e2}*** and ***$K \to \pi\nu\nu$***!!!

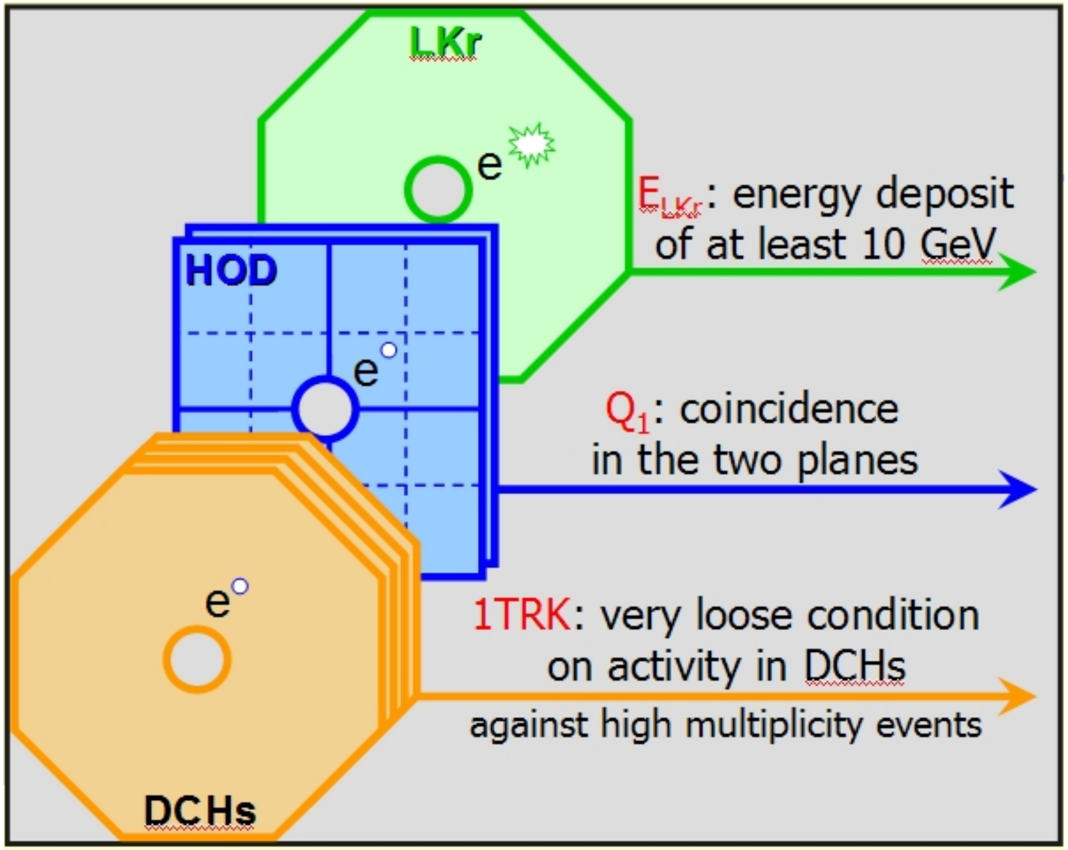
NA62-2007/08

Lepton universality in Kaon decays

NA62 (2015-16)

O(100) events measurement of ***BR ($K \to \pi\nu\nu$)***

NA62-2007/2008: Triggers



E_{LKr}: energy deposit of at least 10 GeV

Q_1: coincidence in the two planes

1TRK: very loose condition on activity in DCHs against high multiplicity events

Minimum Bias Hardware Trigger:

-> $K_{\mu 2}$ condition: 1TRK Q1

-> K_{e2} condition: 1TRK Q1 ELKr

Software Trigger:

-> P_{DCH} < 90 GeV/c

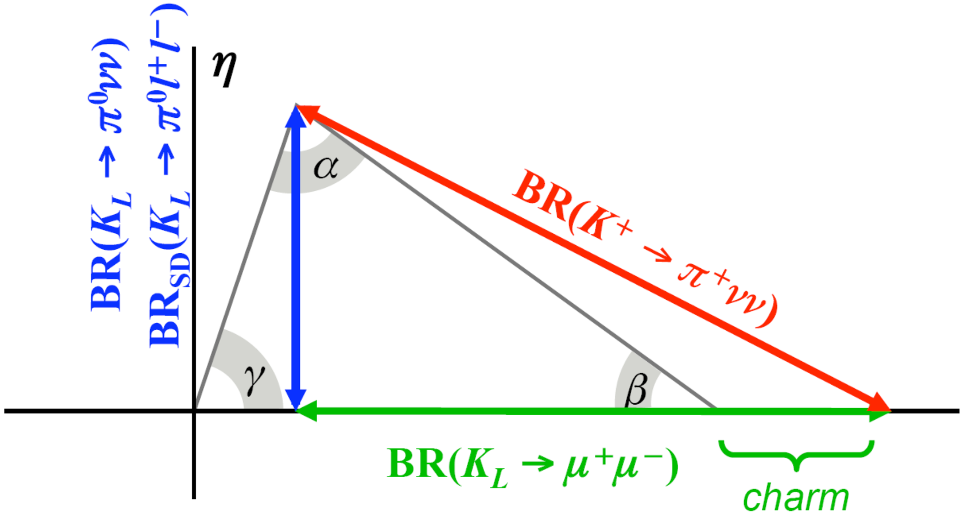
-> E_{LKr}/P_{DCH} > 0.6 (K_{e2} only)

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%**	8×10^{-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}

$K^+ \to \pi^+ \nu\bar{\nu}$: motivation

1) Short distance contributions (Wilson coefficients i.e. perturbative QCD) are dominant (hard GIM mechanism): Aq ~ $(mq)^2/(m_W)^2$ $\mathbf{V_{qs}V_{qd}}$

top quark is dominant, smaller contribution from charm negligible from up

2) The hadronic matrix element (LD) uncertainness benefits from the Isospin symmetry and well measured semileptonic $K^+ \to \pi^0 e^+ \nu_e$ decays:

$$\left|\frac{\langle \pi^+ \nu\bar{\nu}|H_w|K^+\rangle}{\langle \pi^0 e^+ \nu_e|H_w|K^+\rangle}\right|^2 = \left|\frac{\langle \pi^+|H_w|K^+\rangle}{\langle \pi^0|H_w|K^+\rangle}\right|^2 = 2r_+$$

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

$$BR(K^+ \to \pi^+ \bar{\nu}\nu) = 6 r_{K^+} BR(K^+ \to \pi^0 e^+ \nu) \frac{|G_l|^2}{G_F^2 |V_{us}|^2}$$

$$G_l = \frac{\alpha\, G_F}{2\pi \sin^2 \Theta_W} \left[V_{ts}^* V_{td} X(x_t) + V_{cs}^* V_{cd} X_{NL}^l\right]$$

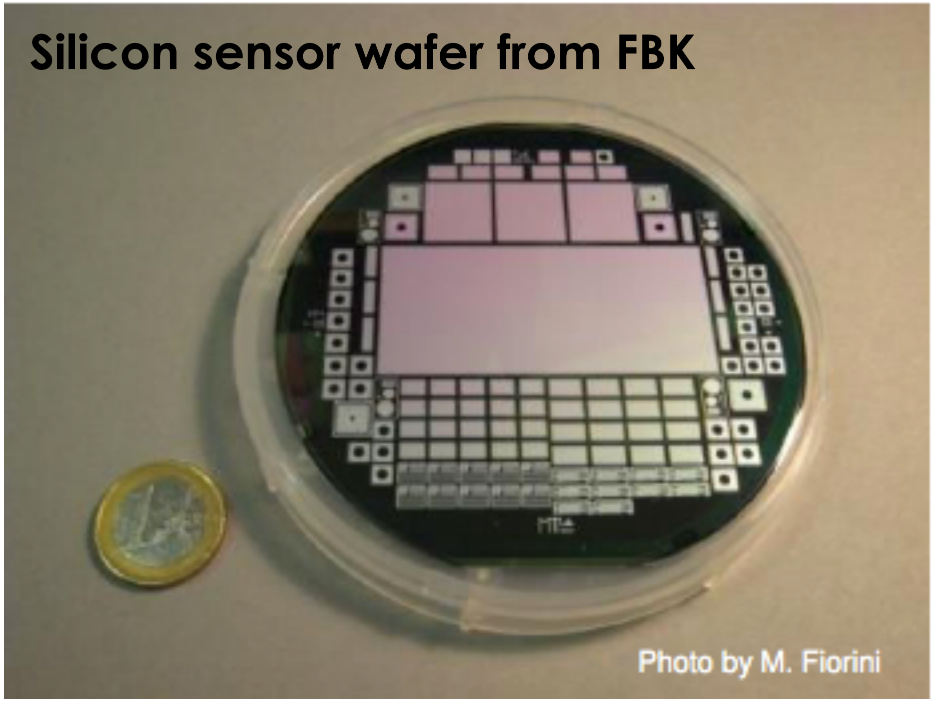
Effective coupling constant

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/cm^2

R&D completed



Silicon sensor wafer from FBK

Photo by M. Fiorini

2 read out prototypes developed & compared, both with FE circuits in 130-nm IBM CMOS technology

For details, see Report by J. Kaplon et al., IEEE NSS conference, Orlando, FA, USA

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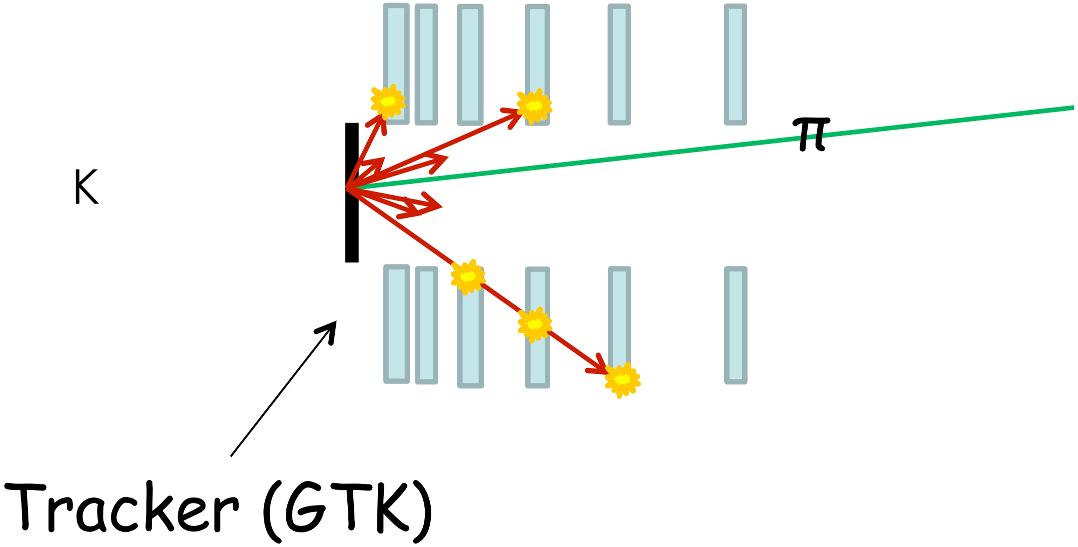
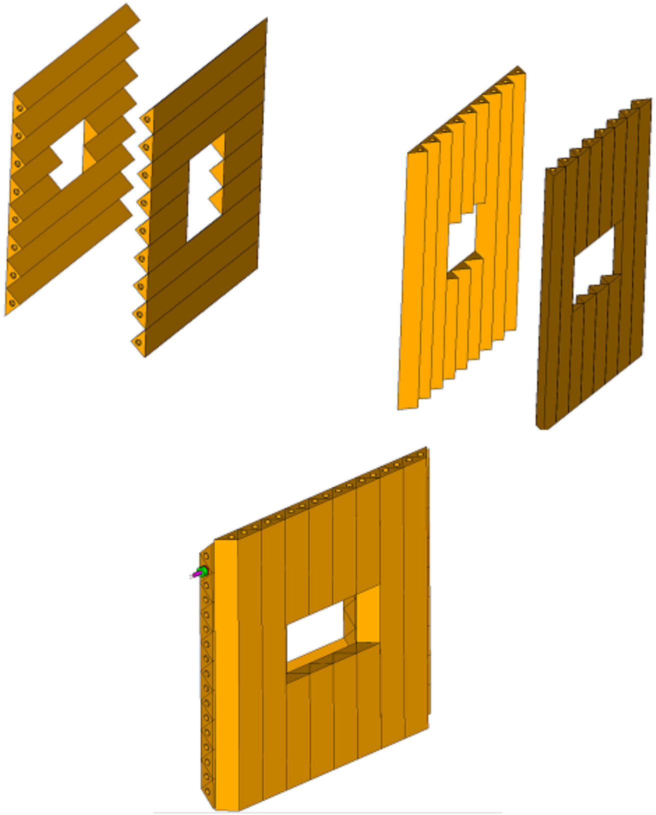




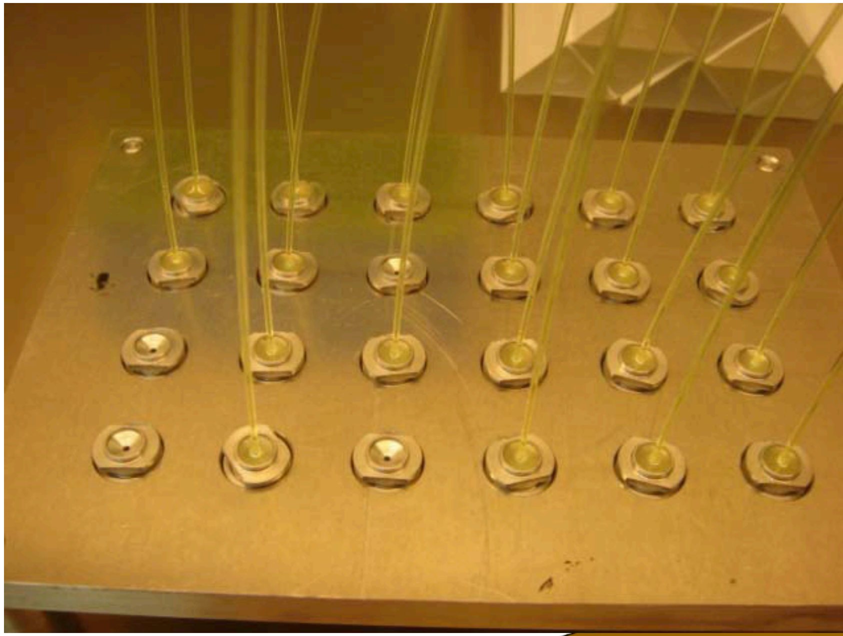
First station construction

Fibers – Connectors Gluing

A custom connector has been designed

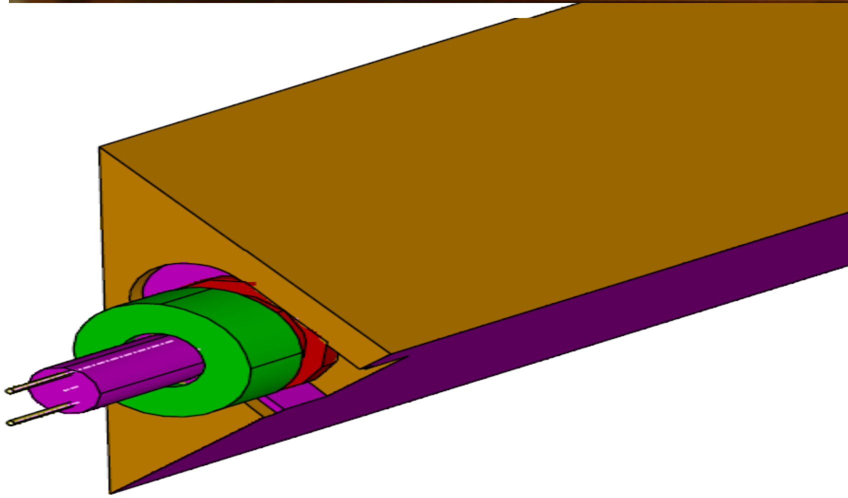
A Teflon cap define the reference plane for the fiber and protect the polished side of the fiber during transport and handling.

Fiber is glued using a small amount of ARALDITE 2011



Connectors – Bar Gluing

New solution using a sligthly modified bar design, with minimal need for glue, 3M «black» glue used



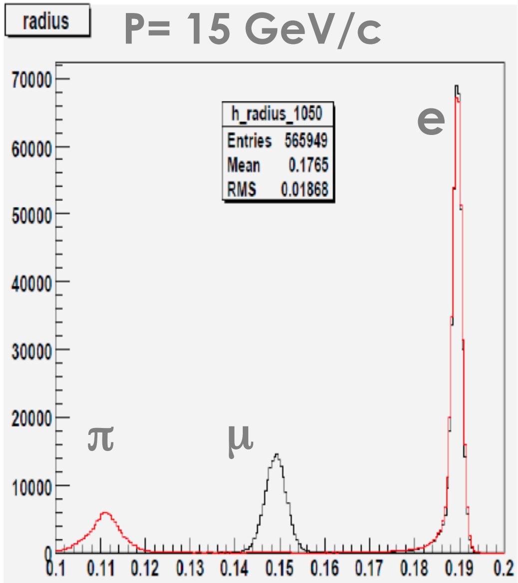
NA62: Rich

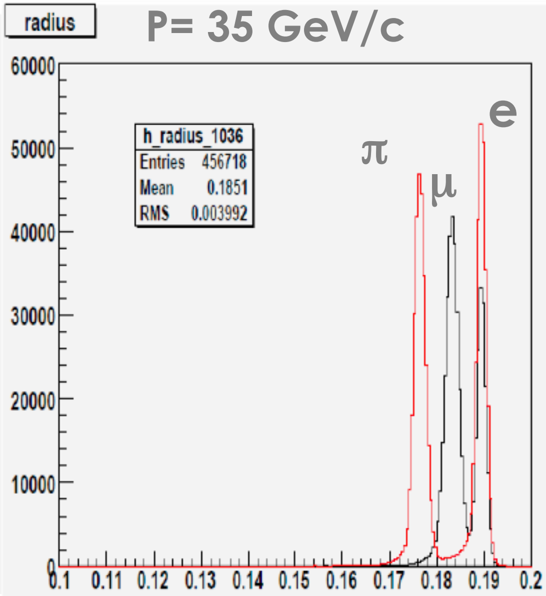
Requests:

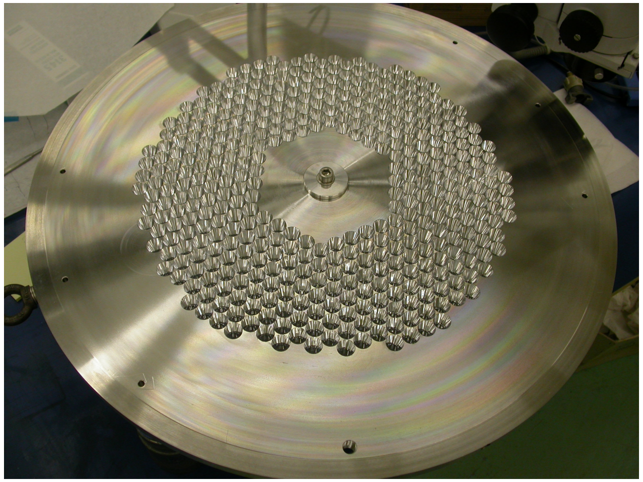
- Provide π/μ separation at 5×10^{-3} in the range $15<p<35$ GeV/c
- Measure track time with 100 ps res
- Provide the main trigger for charged particle

Solution:

- 18 m long tube filled with Neon
- Mirrors with f=17 m
- 2000 single anode PMTs, 1 cm in diameter
- 18mm “pixel” with Winston cones





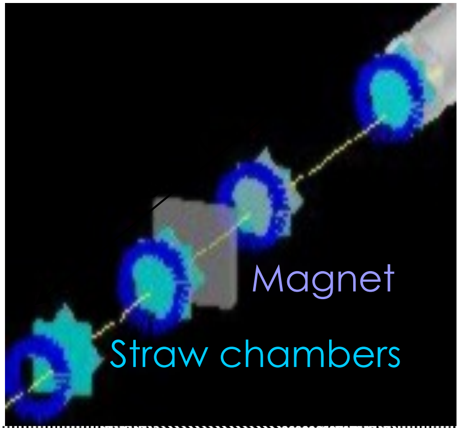


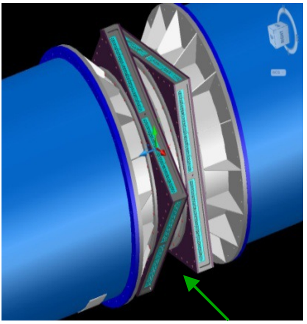
Straw chamber spectrometer

To measure momentum and direction of K^+ decay

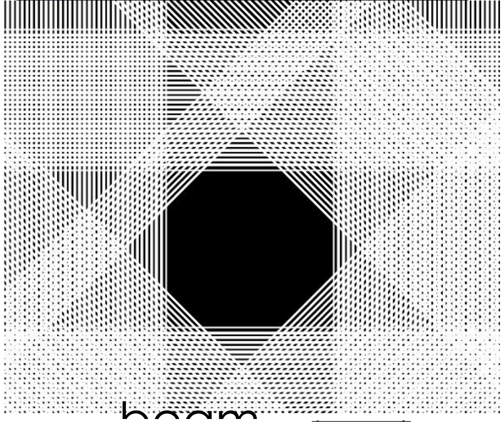
Requirements:
- low mass (multiple scattering),
- operating in vacuum
- good spatial and momentum resolution
- small inactive area around primary beam

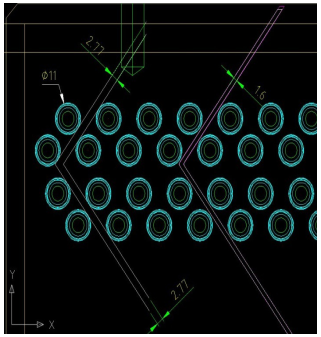
Solution:
four straw chambers and one magnet 256 MeV/c P_t
- 4 view/chamber XYUV
- 4 staggered layer/view (L/R ambiguity)
- 500 straws/view, 8000 grand total
- 9.6 mm radius mylar tube
- 2.1 m long
- X/X_0 ~0.1% per view

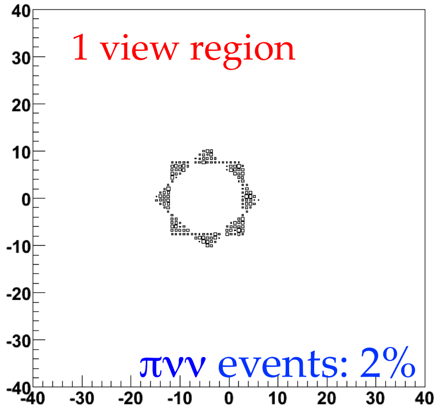


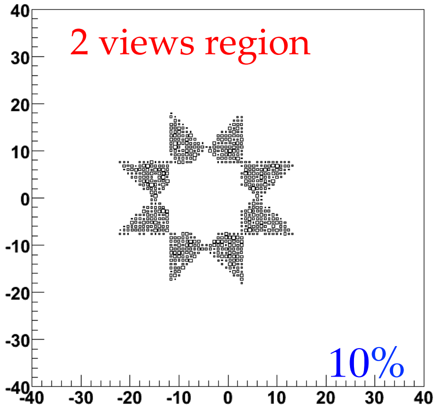


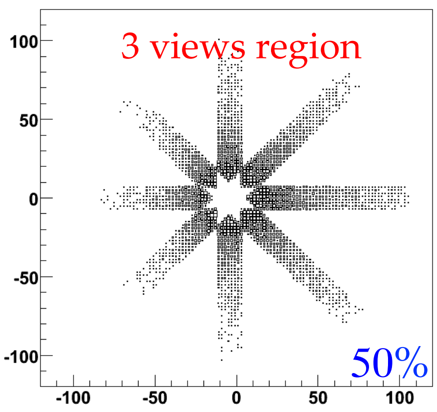
Two "cartesian" frames tilted of 45°

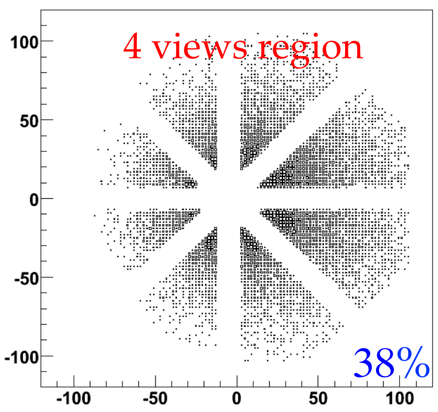












Photon vetoing in NA62

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 compact calorimeter
  - Inefficiency required $<10^{-6}$ for γ's above 6 GeV
- Small angle, 1 to ~8 mrad:
  - Re-use NA48 LKr calor. , $\sigma_E/E = 0.032/\sqrt{E[GeV]} + 0.09/E[GeV] + 0.0042$
  - 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 $100\ \text{MeV} < E_\gamma < 25\ \text{GeV}$
  - 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