# *The NA62 experiment at CERN: status and perspectives*

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**CKM2010 – 6th International Workshop on CKM Unitarity Triangle**

**University of Warwick, UK, September the 9th, 2010**

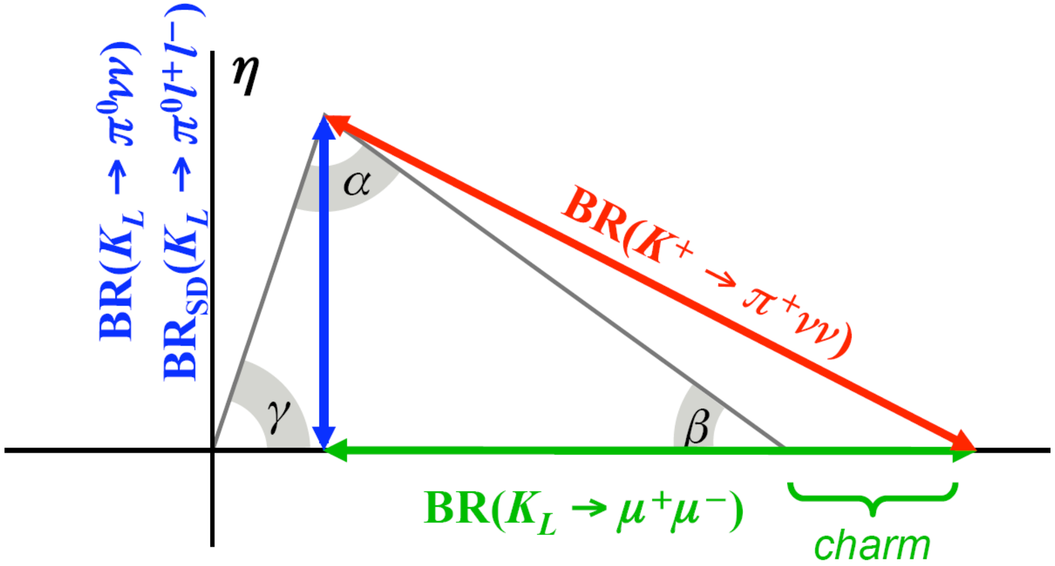
***member of the NA62 collaboration**

# *Golden K modes for new-physics search*

**FCNC processes dominated by Z penguin and box diagrams**

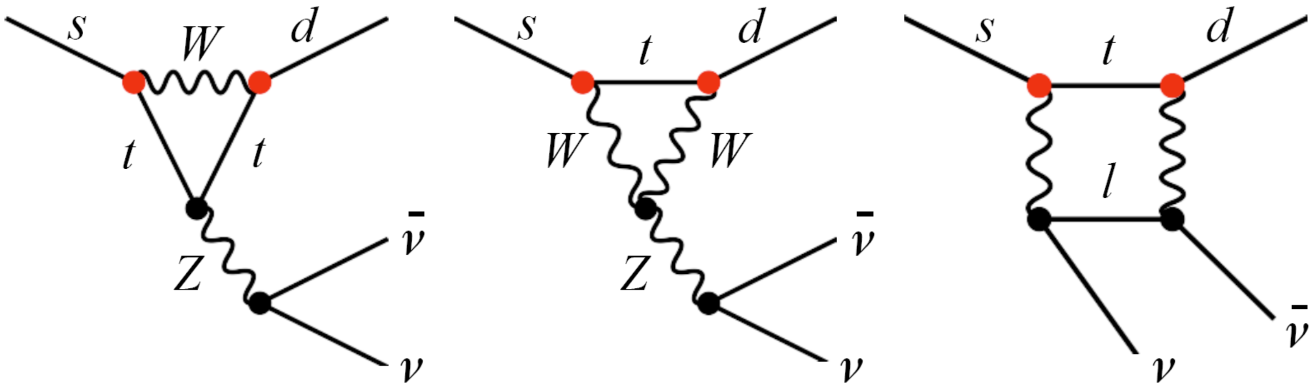
**Can give direct information on CKM matrix elements:**

- **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 CPV**




| | $\Gamma_{SD}/\Gamma$ | Irreducible theory err. (amp) | SM BR |
|---|---|---|---|
| $K_L \to \pi^0\nu\nu$ | >99% | 1% | $3 \times 10^{-11}$ |
| $K^+ \to \pi^+\nu\nu$ | 88% | 3% | $8 \times 10^{-11}$ |
| $K_L \to \pi^0 e^+ e^-$ | 38% | 15% | $3.5 \times 10^{-11}$ |
| $K_L \to \pi^0 \mu^+ \mu^-$ | 28% | 30% | $1.5 \times 10^{-11}$ |

# *SM prediction for $K \to \pi\nu\nu$*




**SM prediction [Buras et al., Mescia and Smith, Brod and Gorbahn]**

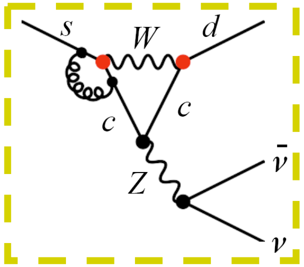
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[ \left( \frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right] = 8.5(7) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left( \frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = 2.6(4) \times 10^{-11}$$, **where** $x_q \equiv m_q^2/m_W^2$ **and** $\lambda = V_{us}$, $\lambda_c = V_{cs}^* V_{cd}$, $\lambda_t = V_{ts}^* V_{td}$

**Loops favor top contribution**

**Hadronic matrix elements from BR(Ke3) via isospin rotation:**

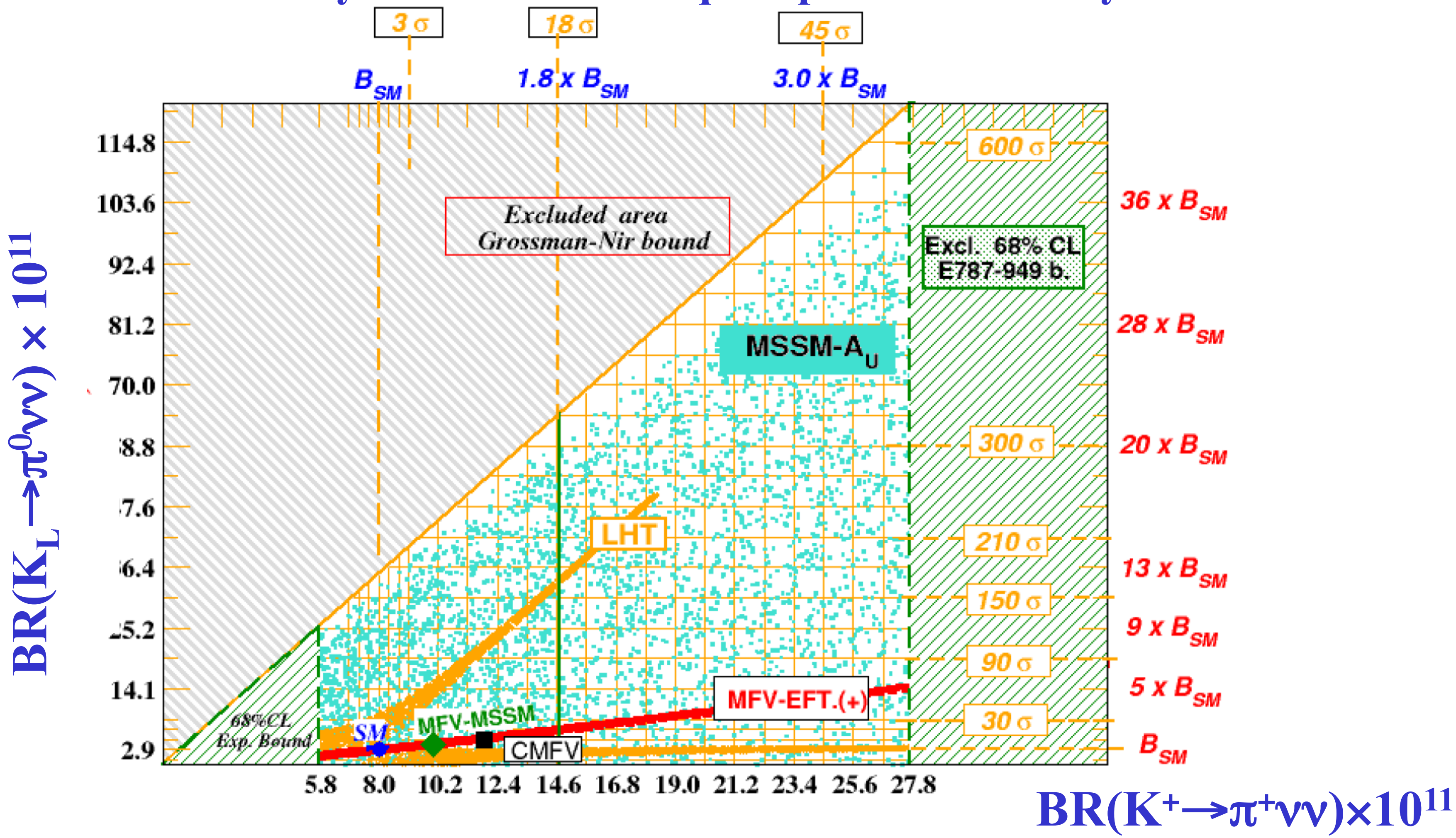
$$\kappa_+ = r_{K^+} \frac{3\alpha^2\,\mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$




**Charm contribute to theory error: non-parametric error ~7% for $K^+$, 3% for $K_L$**

# *SM prediction for $K \rightarrow \pi\nu\nu$*

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

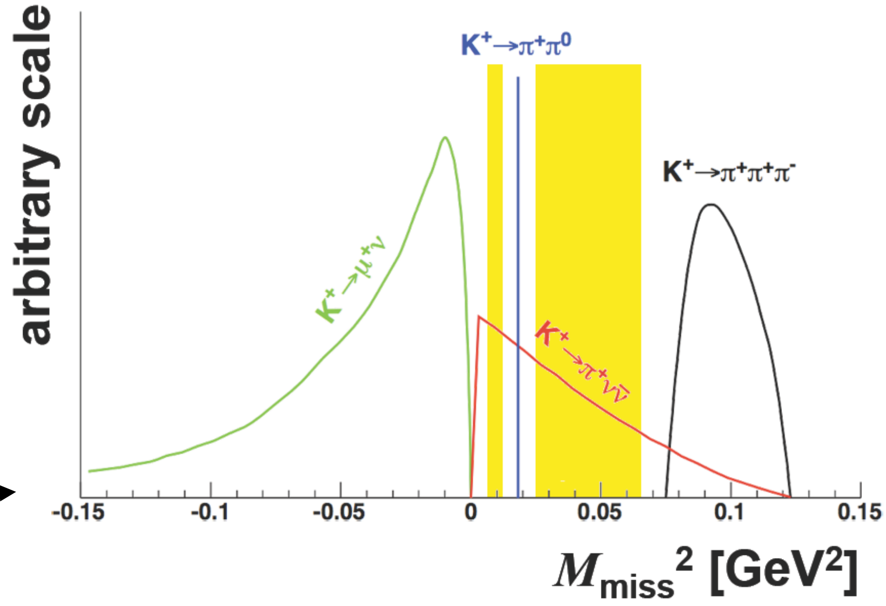


# *Experimental methods for $K^+ \to \pi\nu\nu$*

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

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

**Kinematic rejection for 2 body** →



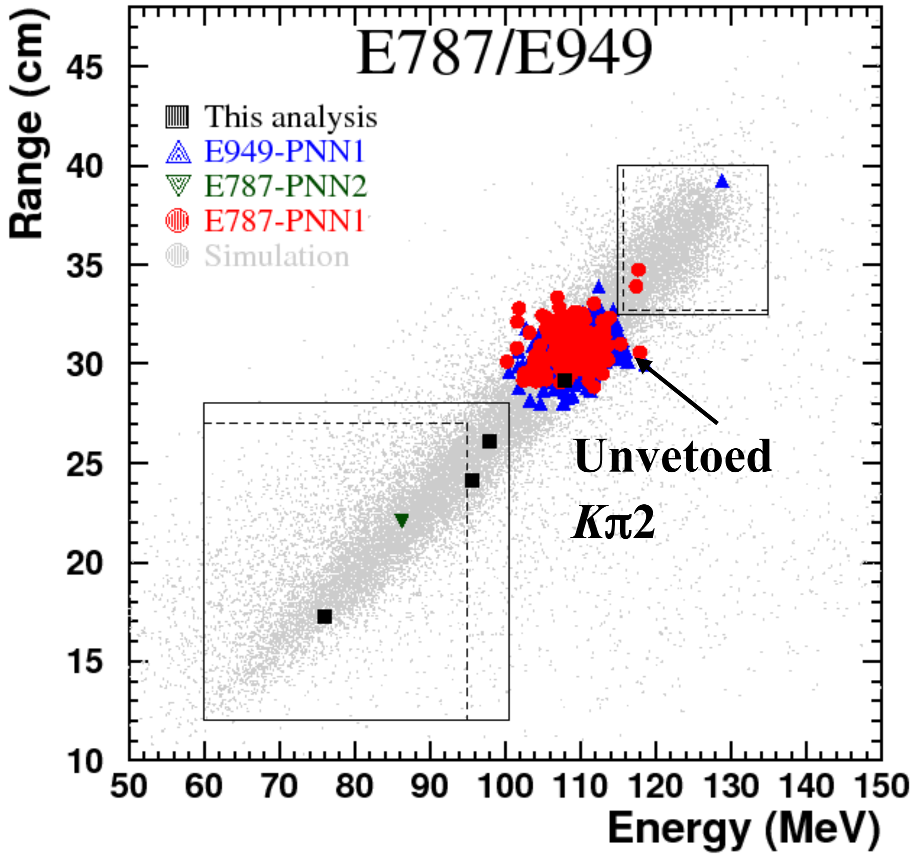

**To reach $10^{-12}$, PID & vetoes also reject unclosed bkg ($K_{l3}$, $K_{l4}$, …)**

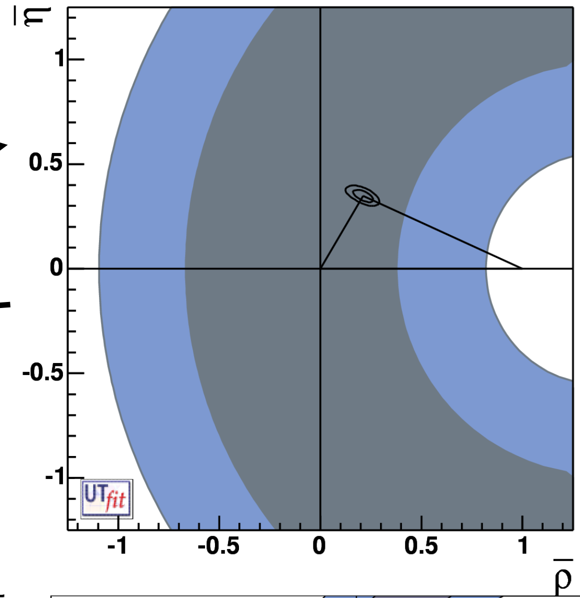
| | **Stopped $K^+$** | **Decay in flight** |
|---|---|---|
| **Kinematics** | $K^+$ at rest | Must track $K^+$ |
| **Photon vetoes** | Low-energy photons | High-energy photons |
| **PID** | Range<br>$\pi$-$\mu$-$e$ decay chain | Advanced Cerenkov counters<br>Muon detectors |

# *Final results from E787/E949 (2008)*

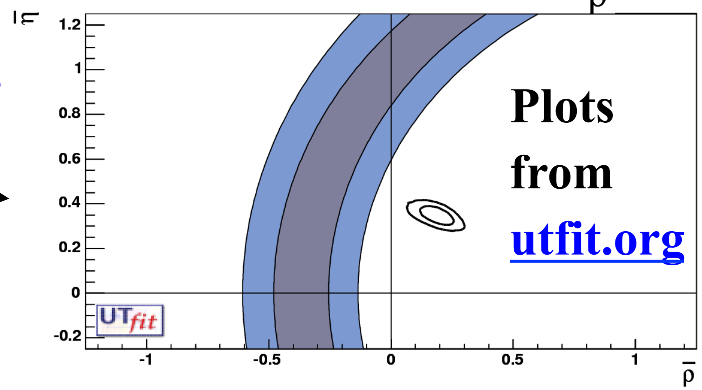
**Combined results, from E787 (1995-8 runs) & E949 (12-weeks run in 2001)**

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



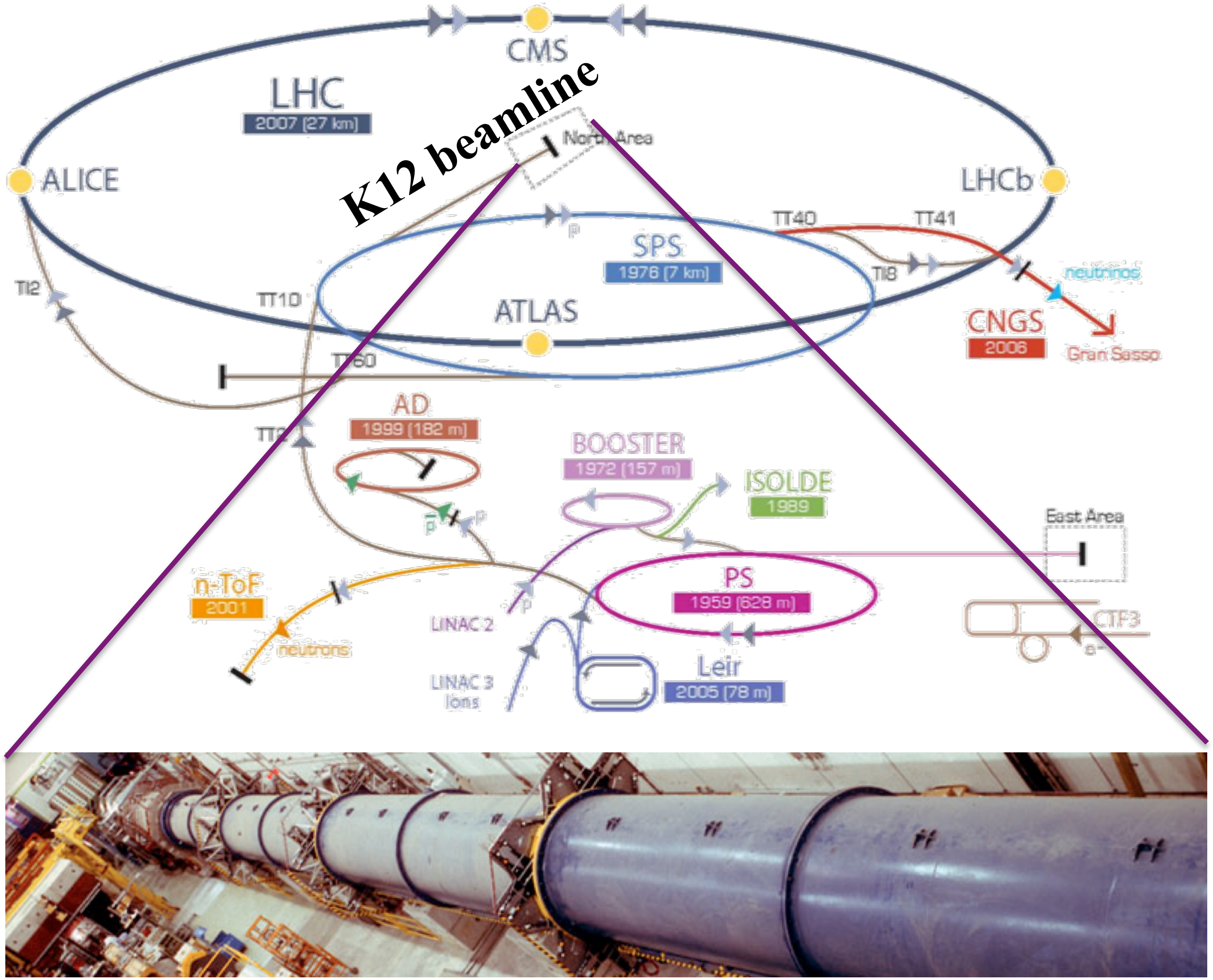

**Same central value, 100 evts**




**Plots from [utfit.org](http://utfit.org)**

**Prob. all 7 obs. evts are bkg is ~$10^{-3}$**

# *The in-flight approach: NA62 @ CERN*




**Improve intensity of existing NA48 beamline by ×50**

**400 GeV SPS primary proton beam, producing unseparated 75-GeV $K^+$ beam:**

- **~800 MHz beam**
- **6% are $K^+$, i.e., ~ 50 MHz**
- **~ 5 MHz decay in a 60-m fiducial volume**

# *NA62 guiding principles*

**Support a high-rate environment**

- **high-resolution timing**

**Kinematic rejection by cutting on missing mass at decay**

- **fast tracking to measure incoming K momentum**
- **high resolution tracking to measure daughter particle momenta**

**Rejection of $K_{\mu2,3,4}$, $K_{e2,3,4}$, … background, PID for all charged particles**

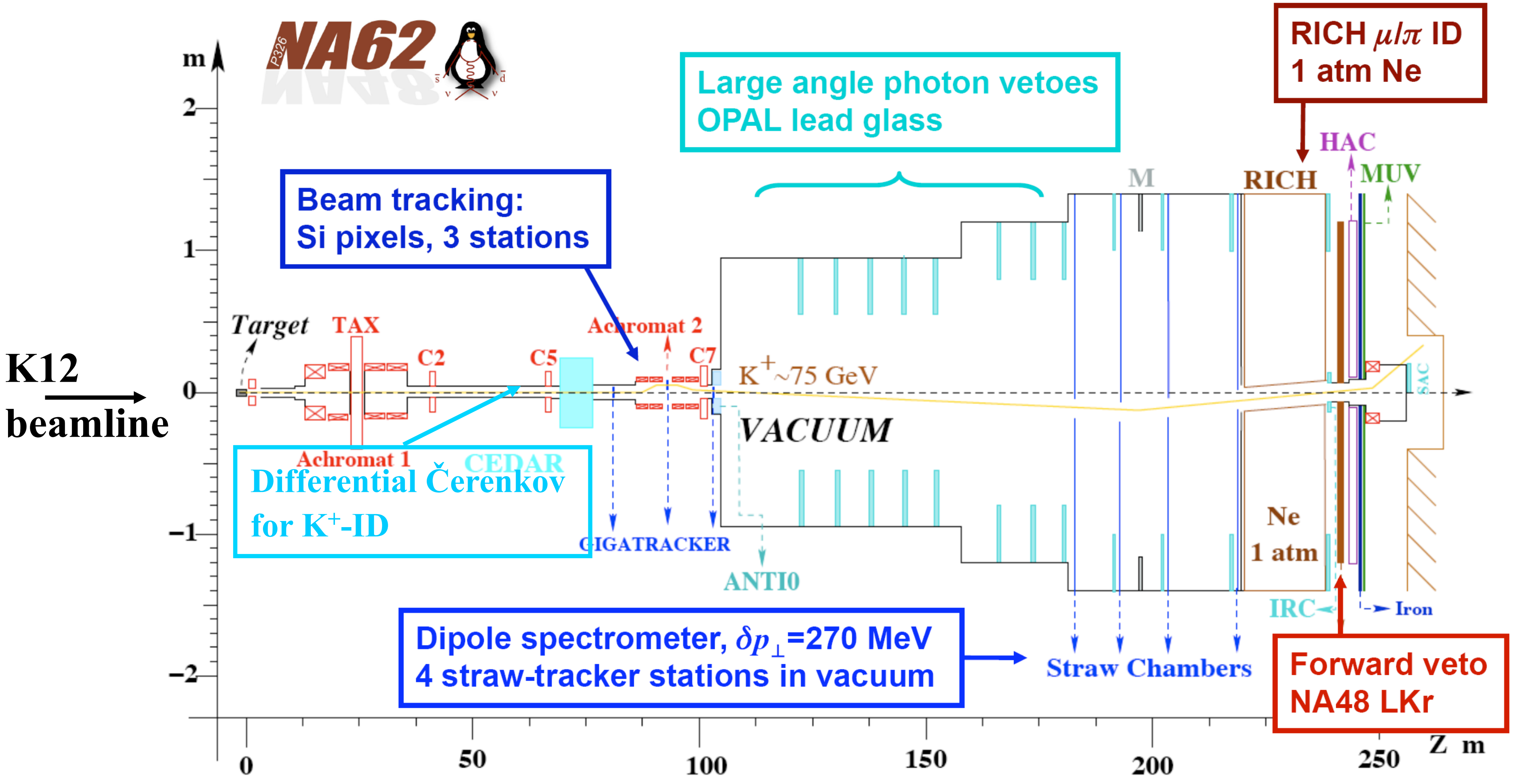
- **positive, non-destructive ID for incoming kaon**
- **ID for outgoing daughter pions, muons, electrons**
- **ID for outgoing muons**

**Rejection of modes with $\pi^0$'s and/or (possibly radiative) photons**

- **Hermetic, high-efficiency $\gamma$ vetoing from 0 out to 50 mrad angles**

**Redundancy of information**

# *The in-flight approach: NA62 @ CERN*

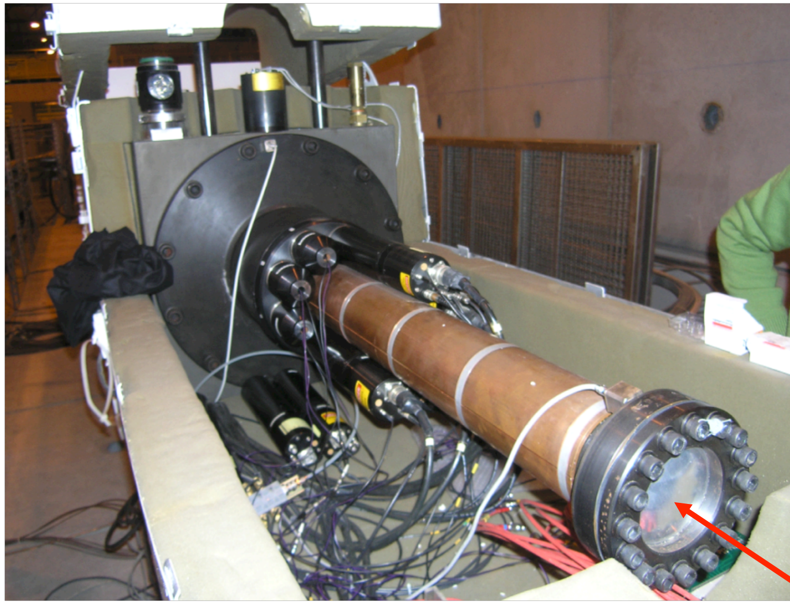


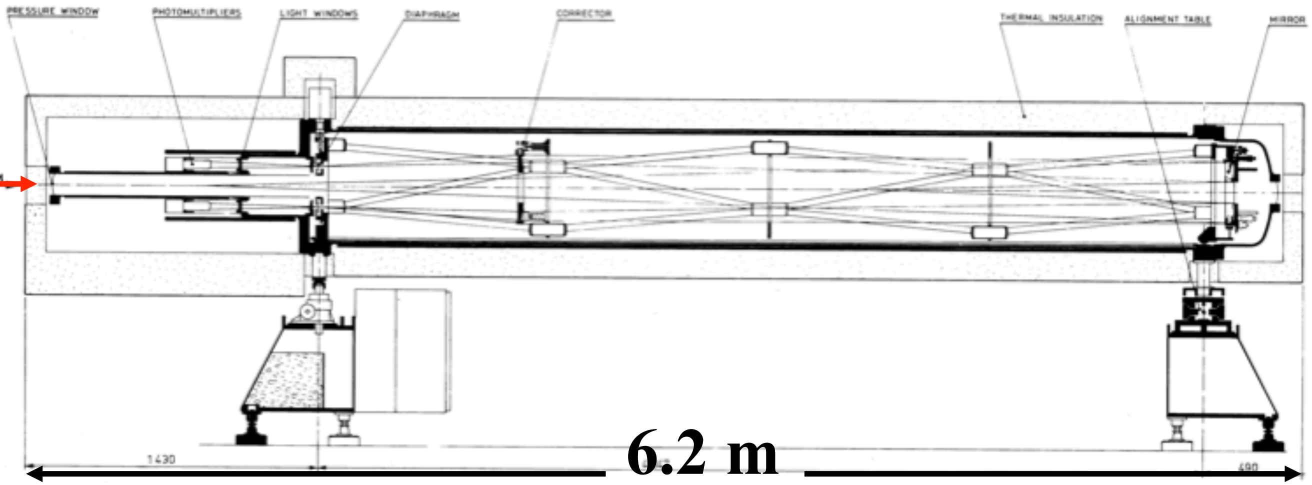
# *Iidentification of K's in the beam - CEDAR*

**Aim to identify 6% of K's in a 800-MHz momentum-selected p/π/K beam**

**Upgrade existing differential Cerenkov counter, to meet stringent requests:**

1. **excellent time resolution, O(100 ps)**
2. **sustain rates of O(MHz/mm²) in a single-γ counting operation**
3. **Sustain dose ~26 G/Y**



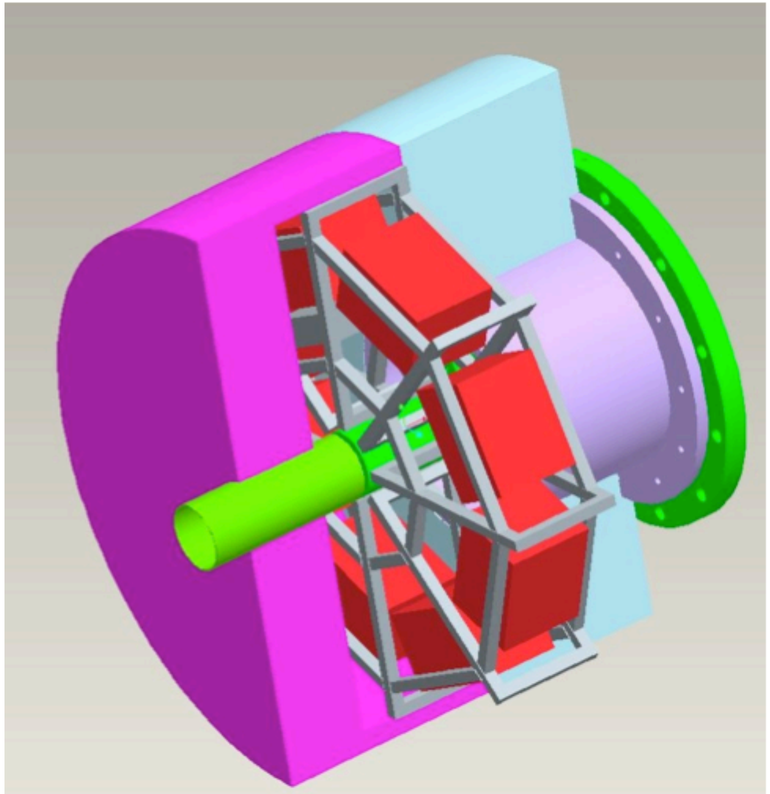



# *Positive identification of K's in the beam*

**Conceptual mechanical design, revision of optics**

**Built-in 2 halves for installation around beam pipe**

**Thermal insulation gas-tight structure**



**Hydrogen filled beam pipe**

**Support cylinder**

**Spider support structure for 8 sets of: mirror, Winston cone, PMT, removable electronic pods**

# *Positive identification of K's in the beam*

Revise gas and photo-detectors

- Use $H_2$ instead of Nitrogen

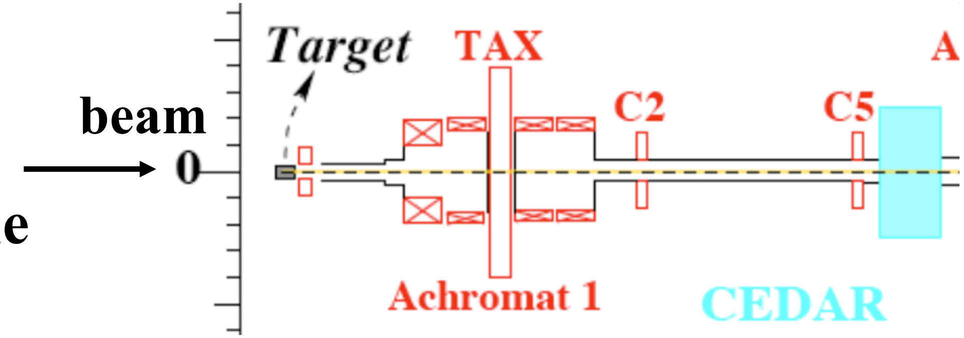
Hamamatsu R7400P PMT is one of the good options for purpose:

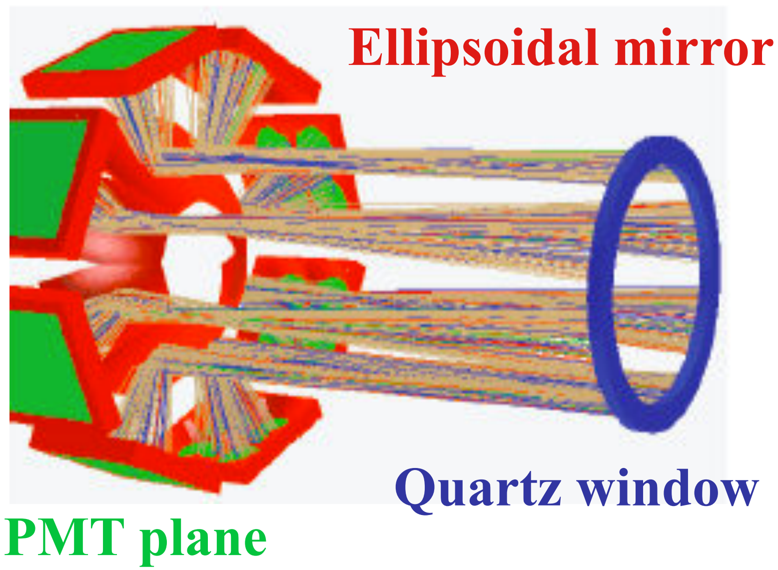
- Repetition rate up to 80 MHz
- Peak efficiency 18% for 405 nm γ's

FE design:

- NINO ASIC chip (discriminator + stretcher, output LVDS)
- HPTDC on board of Tell1 (used for LHCb, see later for details)

The wanted 50 MHz bandwidth is seen to be achieved in read out

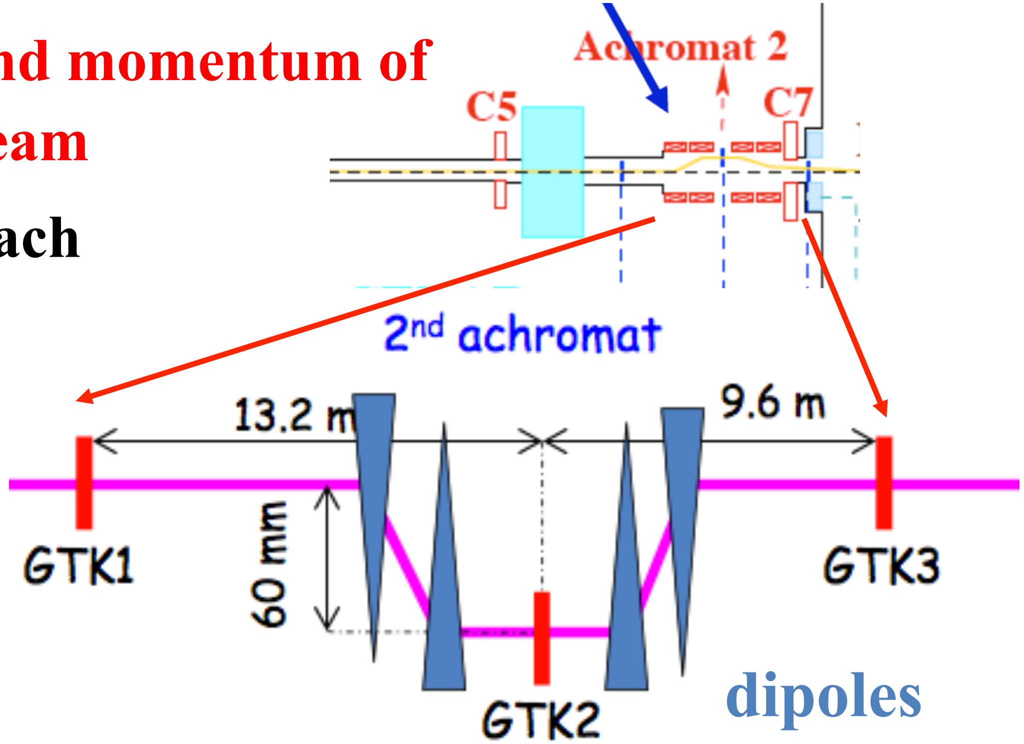


# *Fast tracking before decay volume – GTK*

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

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




**Other demanding constraints:**

- **100 μm space resolution**
- **$\delta p/p \sim 0.2\%$, i.e., $\delta p \sim 150$ MeV**
- **$\delta\alpha/\alpha \sim 12$ μrad**

**Structure:**

- **18000 300×300 $\mu m^2$ pixels, sensitive area of 60×27 $mm^2$**

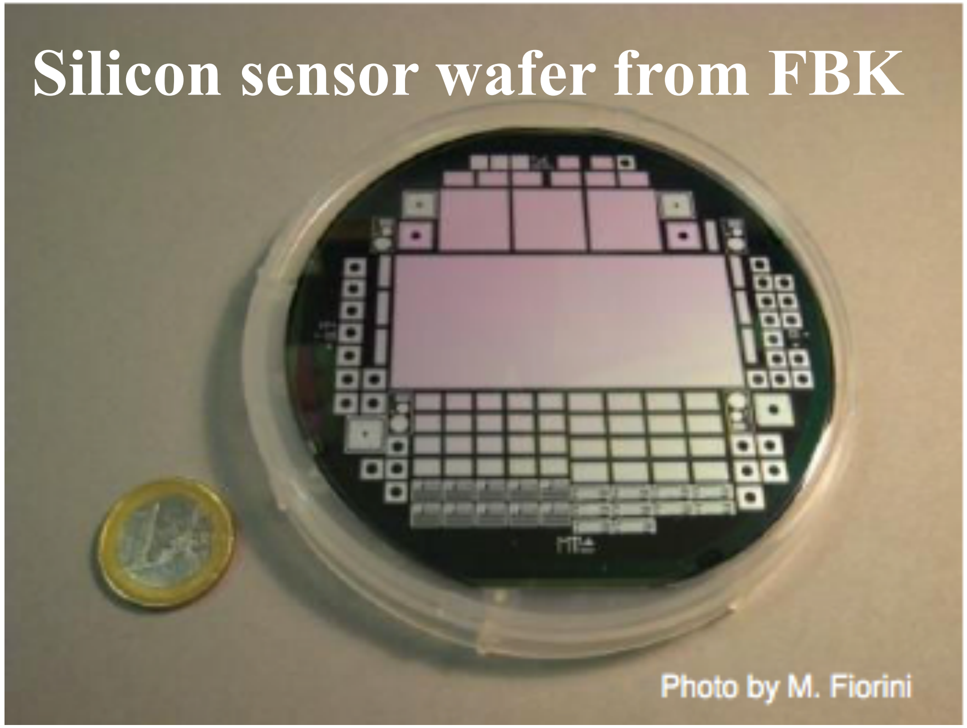
**Technological challenge:**

- **<1% hit mismatch @ 800 MHz → 200 ps time resolution**
- **read out able to sustain rates up to 150 KHz/pixel**

# *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 effects**
- **maintain noise < 200 e-**
- **operate with reasonable power consumption, < 2 W/cm$^2$**

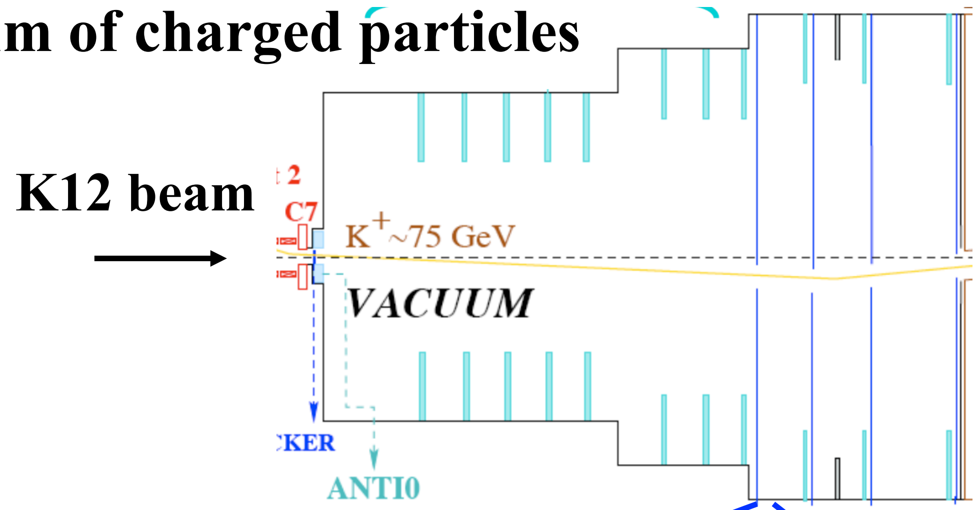



**R&D almost completed**

- **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**

# *Tracking of decay products – Straw tracker*




**Measure coordinates and momentum of charged particles originating from decay region**

**$\delta p/p < 0.5\%$**

- **Dipole $p_T$ kick ~ 270 MeV**
- **hit space resolution < 130 μm**

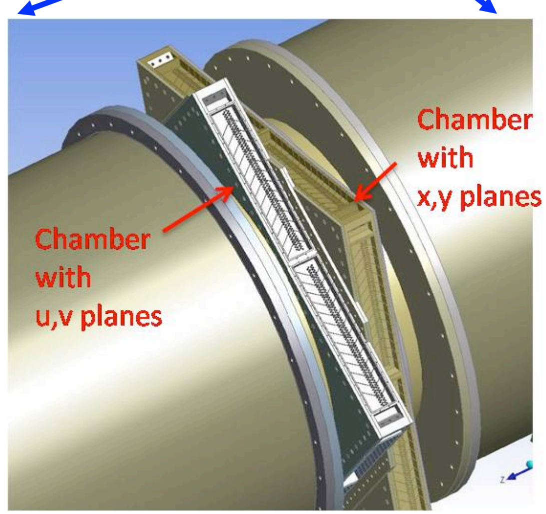
**Minimize multiple scattering**

- **no flanges**
- **no acceptance limitation from beam pipe**

**Operation in a $10^{-6}$ mbar vacuum**

**4 straw tube stations, 4 views/station, 4 layers/view**

- **2.1 m long, 9.8mm in diameter**
- **Particle rate up to 0.5 MHz**



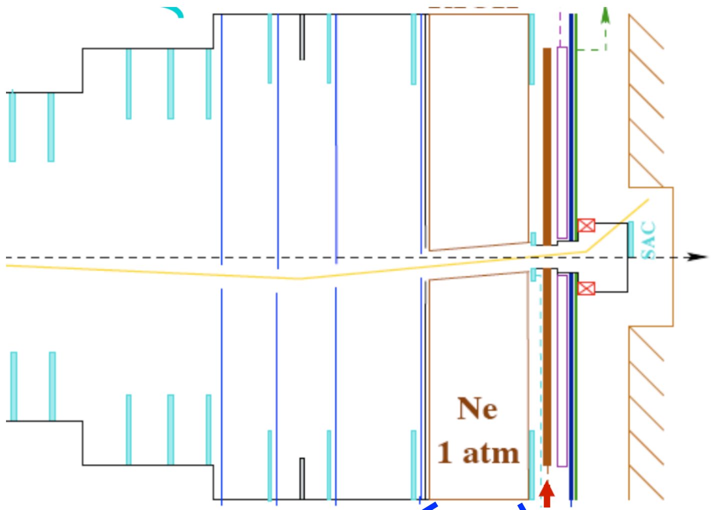
# *PID for decay products: RICH detector*

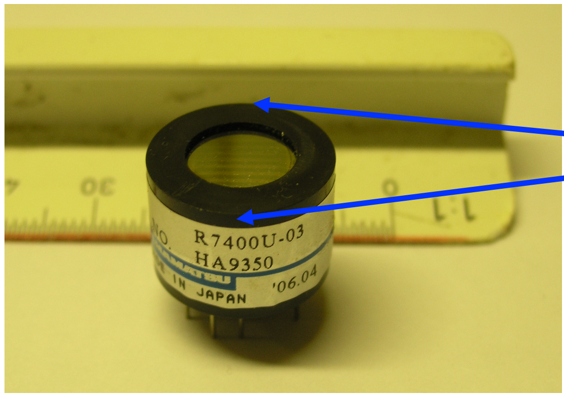
**μ rejection of 0.5% on top of MUV**

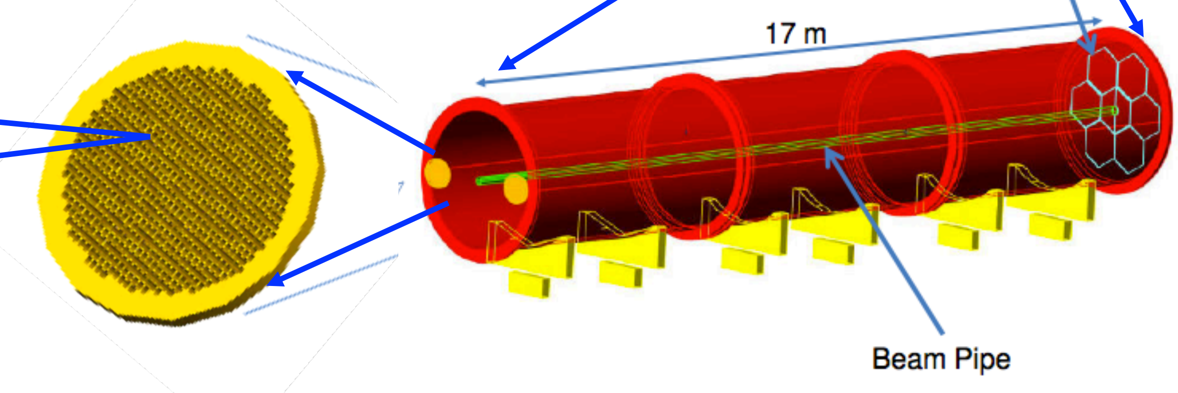
**Time measured @100 ps, to match w GTK**

**π/μ > 3 σ separation for p in 15—35 GeV**

- **Ring-imaging Cerenkov (RICH)**
- **volume 17 m long, 3 m diameter**
- **filled with 1 atm Ne**
- **18-mm pixels, for a total of 2000 PMT's**



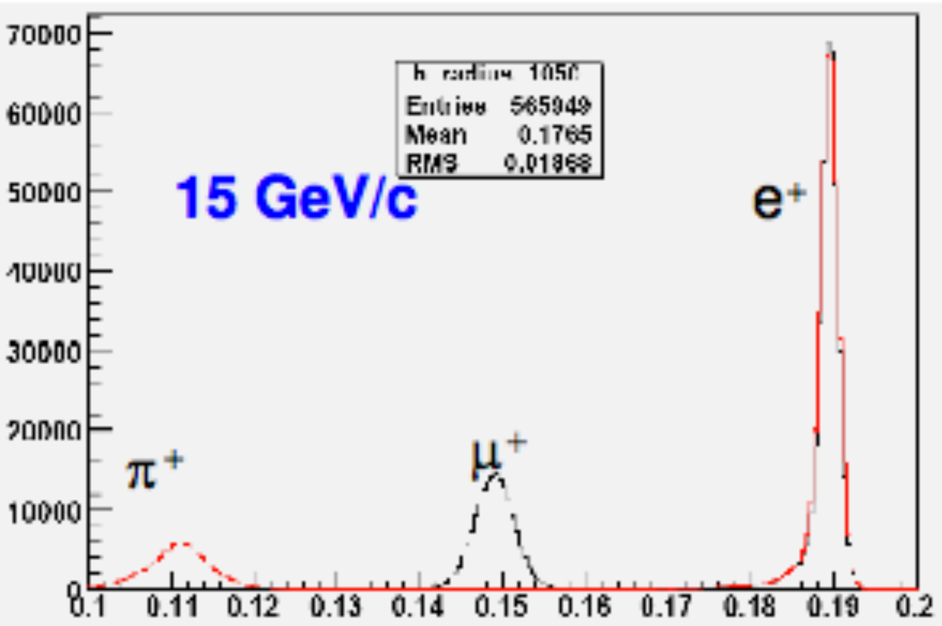



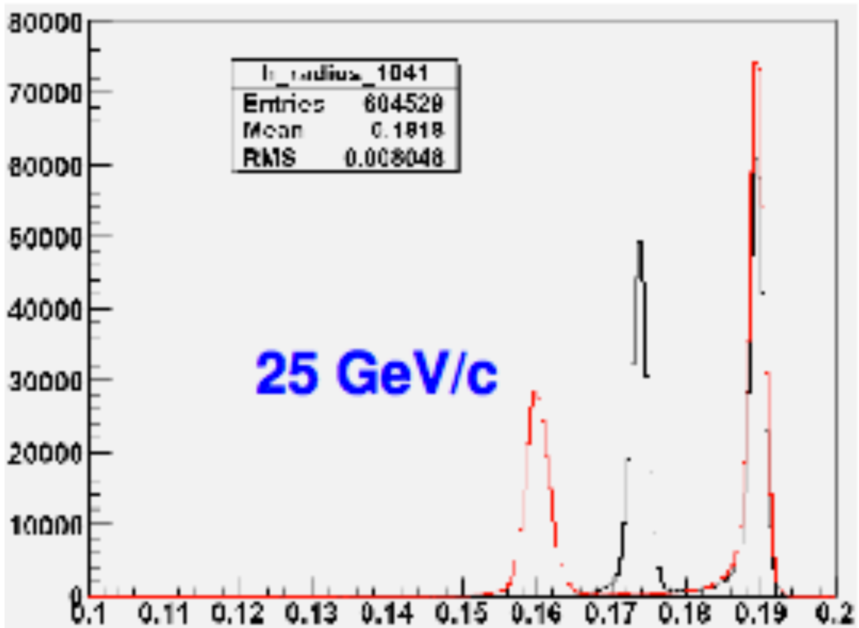
# *The RICH performance*

**Test prototype in 2009, ~400 PMT's instrumented**

**Full readout chain mounted:**

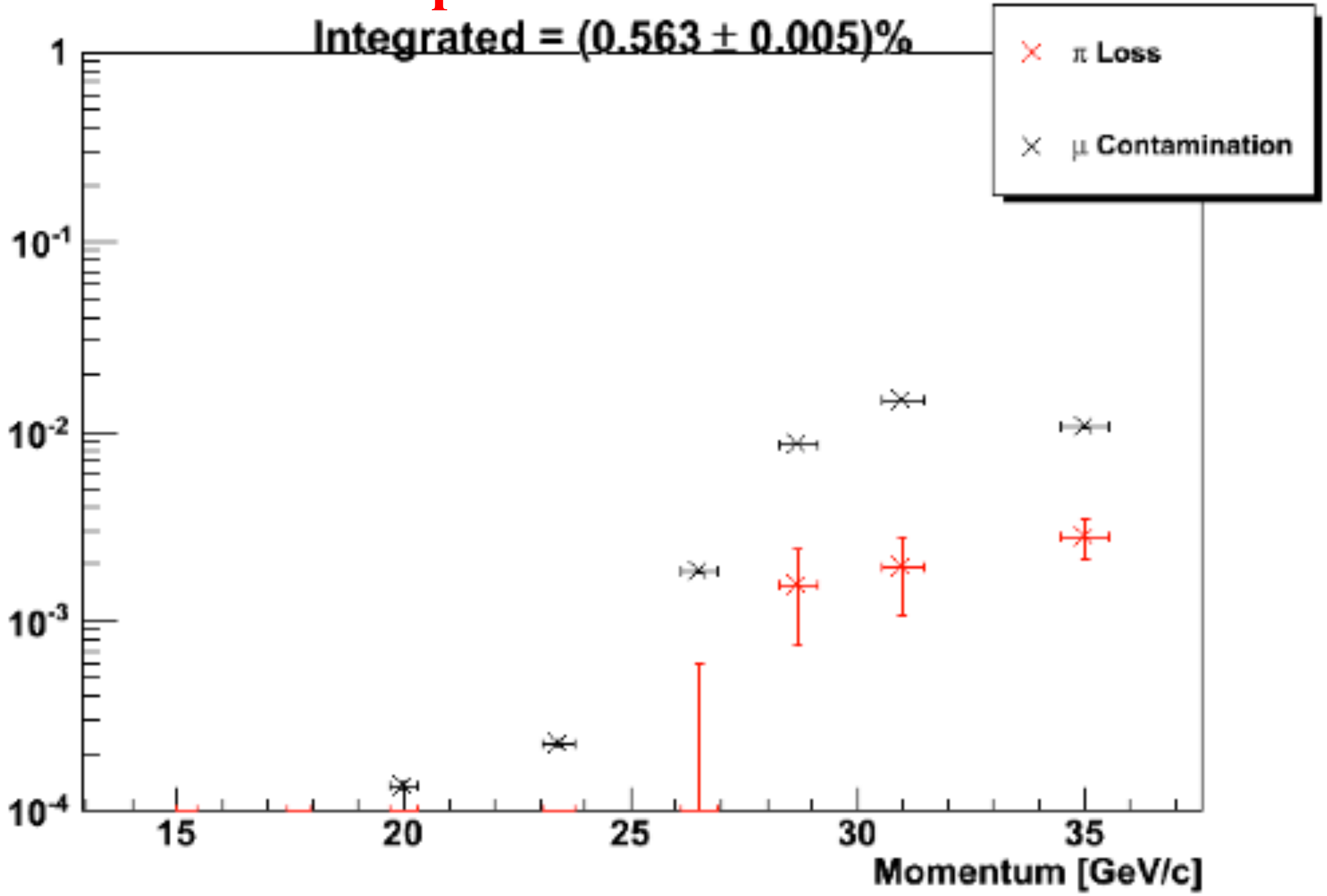
- **Hamamatsu R7400U-03**
- **FE, preamplifier + NINO card**
- **RO, Tell1 (like LHCb) equipped with 512 ch's HPTDC on board**



# *The RICH performance*

**Muon rejection better than 1% throughout the interesting p range, with an overall π loss of few per mils**




**Requirements satisfied, pion time resolution < 100 ps for 15 < p < 35 GeV**

# *Photon vetoing in NA62*

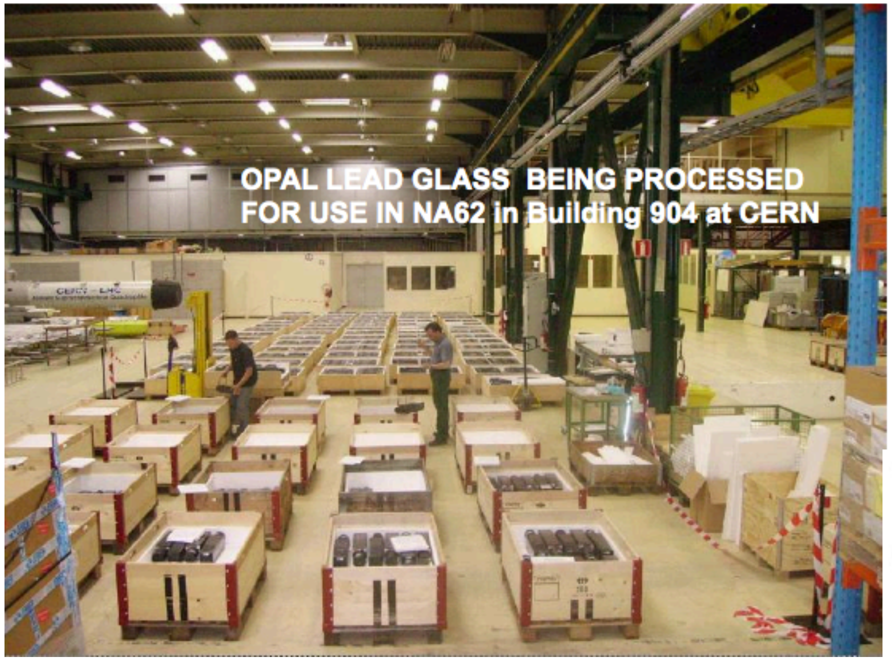
**Have to reject $K^+ \rightarrow \pi^+\pi^0$ @ the level of $10^{-12}$**

**Need $\pi^0$ rejection of $O(10^{-8})$ for γ's from K decay in fiducial volume (~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 calorimeter, $\sigma_E/E = 0.032/\sqrt{E[GeV]} + 0.09/E[GeV] + 0.0042$**
  - **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 MeV $< E_\gamma <$ 25 GeV**
  - **Able to operate in a vacuum of $10^{-6}$ mbar**

# *Large angle veto – the technology chosen*

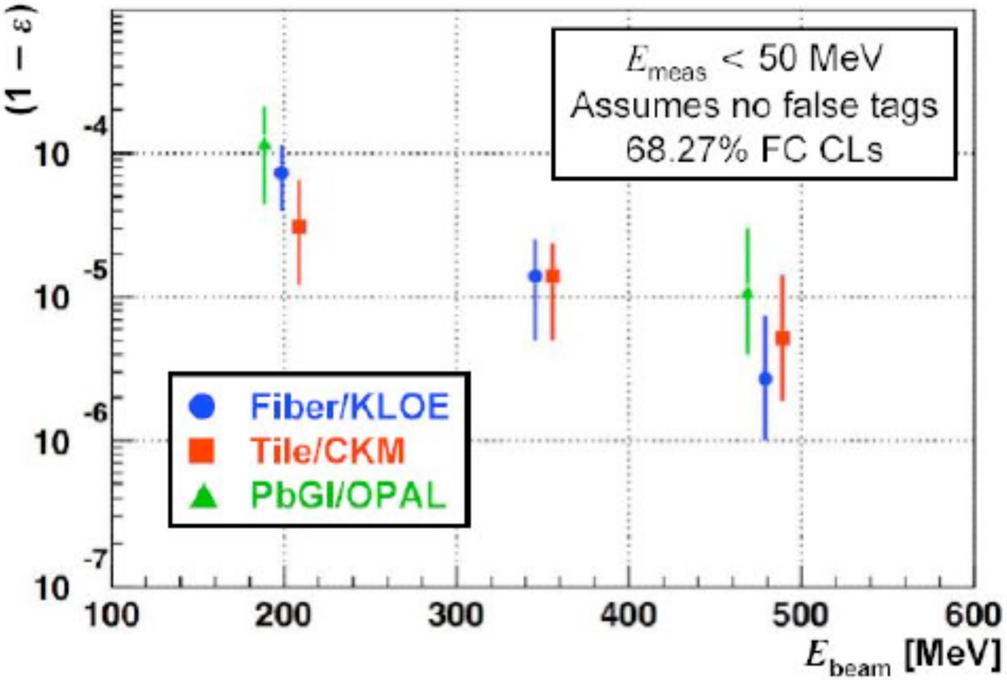



**10000 SF4 lead crystals available:**

- Used in the OPAL e.m. calorimeter
- We re-use part of the barrel
- 8 different crystal shapes
- Instrumented with R2238 Hamamatsu PMT's
- $\rho$=5.6 g/cm$^3$, $X_0$=1.5cm, $R_M$=2.6 cm

Lead glass detection efficiency measured in test beams and compared with scintillator-tile and fibers "spaghetti" calorimeters:

**Figure satisfies requests**

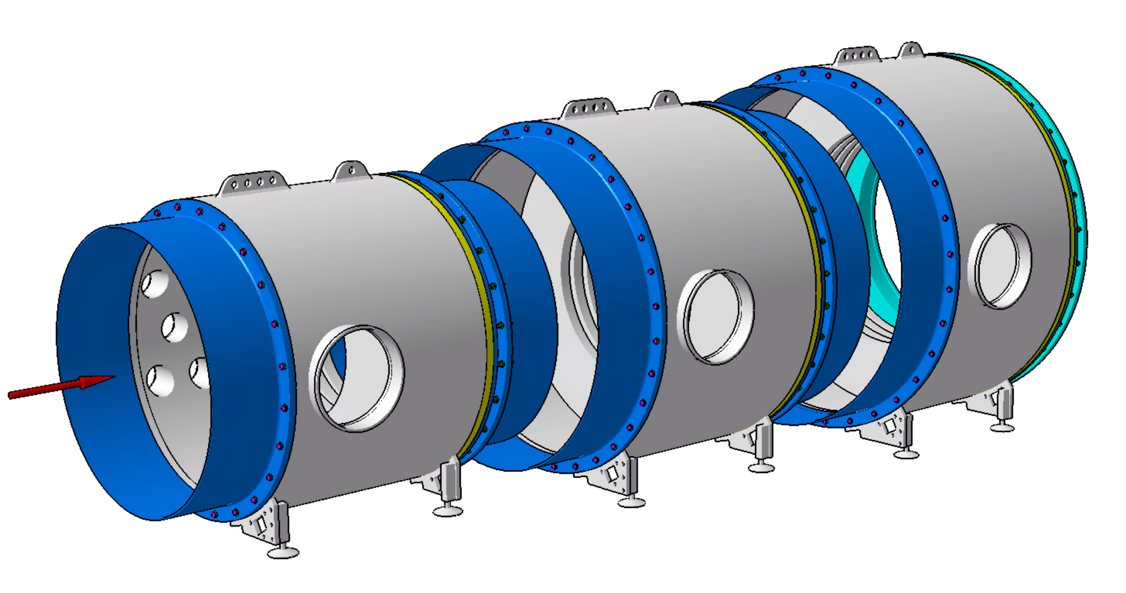


# *Large angle veto layout and geometry*

**Rearrange crystals in staggered layers (rings)**

**Install rings inside existing vacuum vessel (so called "blue tube")**

- **12 stations of increasing diameter to cover hermetically the range $\theta$ = 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**



# *LAV front-end electronics – requirements*

**Wide dynamic range: sensitivity to 20 MeV<$E_\gamma$< 20 GeV (1MIP ~ 80MeV):**

- Have to operate existing R2238 Hamamatsu PMT's at $10^6$ gain
- With ~ 0.3 pe/MeV, 1MIP ~ 4.5 pC, corresponding to a 20 mV / 50Ω peak
- A 20 GeV release corresponds to 10 V / 50Ω signal peak

**Veto detector basic requirements:**

- modest energy resolution, ≈ 10% at 1 GeV
- good time resolution, ~ 0.5 ns (intrinsic lead-glass + PMT ≈ 1 ns)
- able to sustain ≈ 1 MHz rate (real single lead glass rate > 100 kHz)
- able to safely handle signals with >10 V at peak

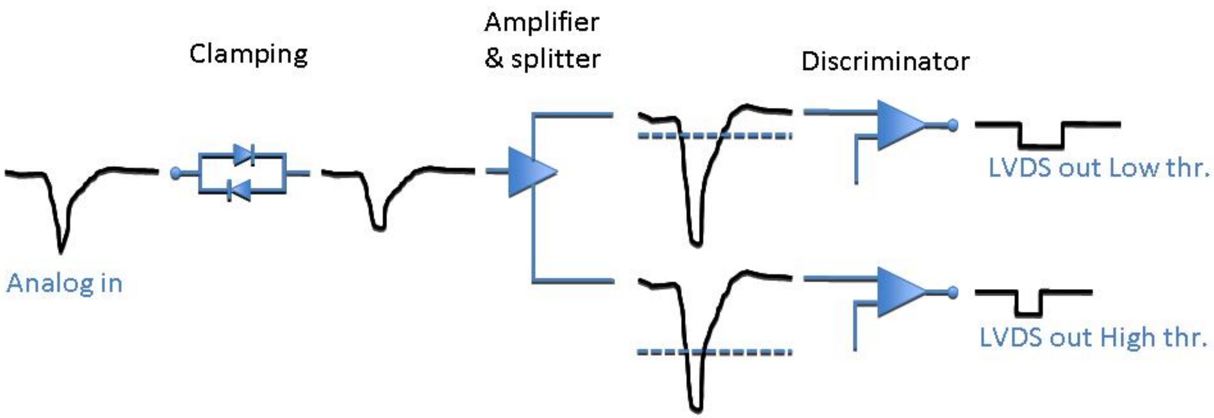
**Additional requirements:**

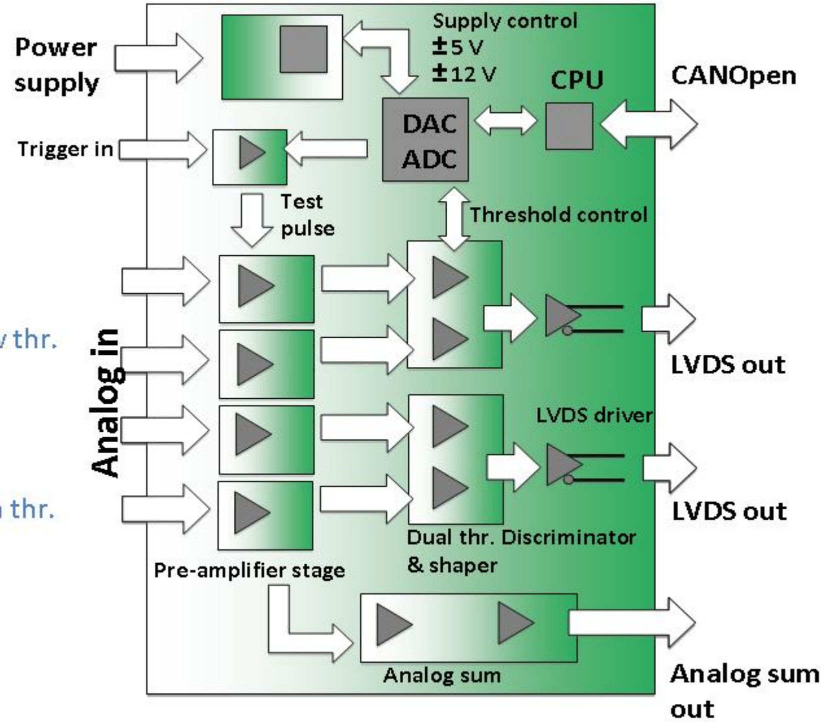
- simple & cost-effective electronics
- easy to scale & integrate with common TDAQ infrastructure

# *LAV front-end electronics – chosen design*

1. **Use time-over-threshold discriminator, multiple adjustable thresholds:**

   **Clamp, split into 2, amplificate, and discriminate (2 thresholds);**
   **Produce LVDS output, to TDC.**

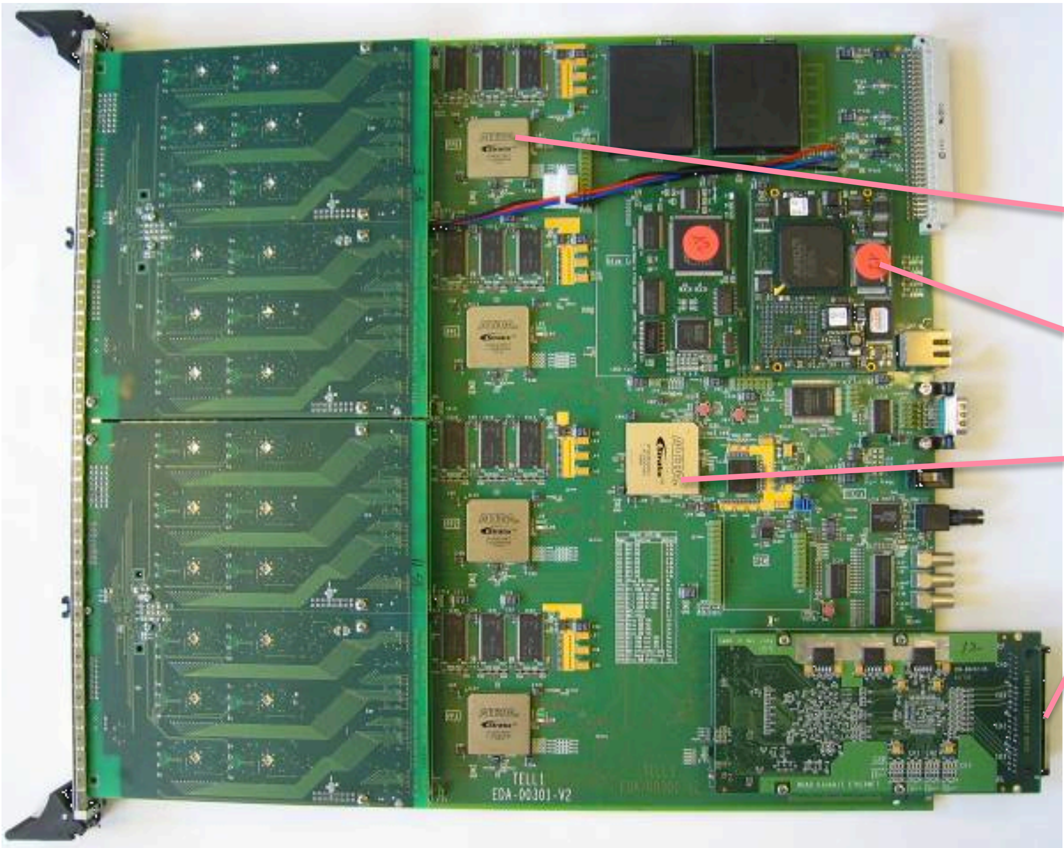



**Final prototype board, 8 channels, tested – passing now to construction phase**

# *LAV front-end electronics – chosen design*

1. **Use time-over-threshold discriminator, multiple adjustable thresholds:**
2. **Standard TDAQ infrastructure (based on TELL1 boards)**




**TELL1 DAQ interface board, designed for the LHCb experiment**

4 PreProcessor FPGA
(1 for each TDC)

1 AMD credit card PC

1 SyncLink FPGA

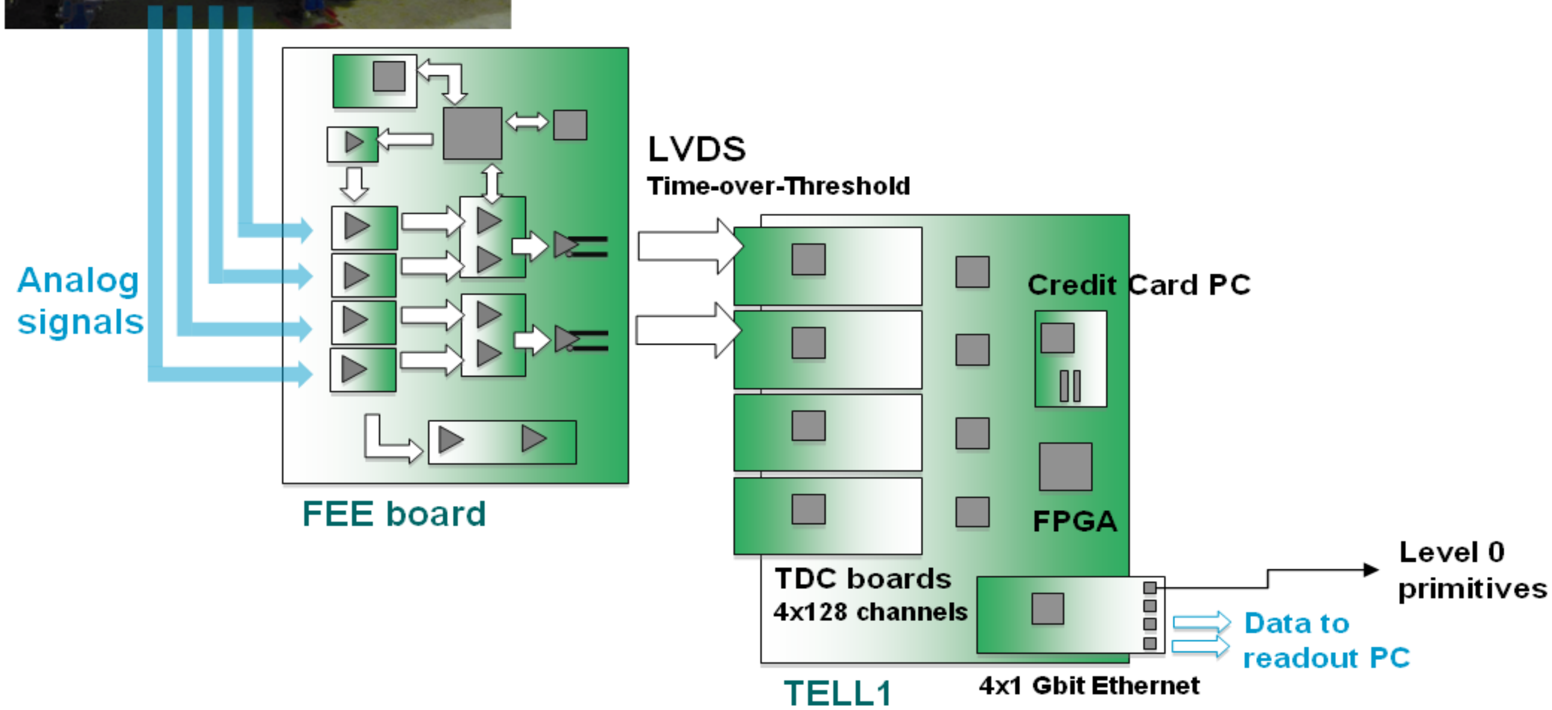
4 Gigabit Ethernet

Up to 4×128 channels of TDC
*or* 4×16 channels of FADC at 40MHz, 10bit
Data through-put up to 4 Gbit

# *LAV readout scheme*

**LAV information might be used for level 0 trigger decision**

**Primitives defined by FPGA programming**

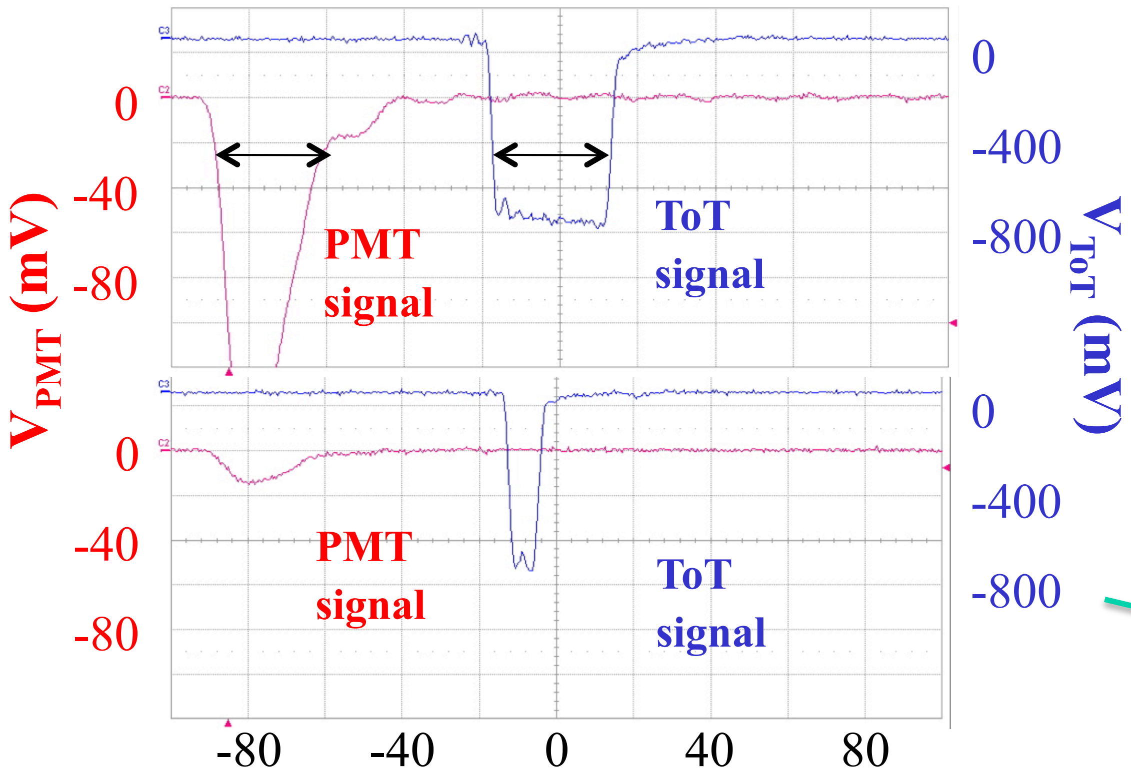



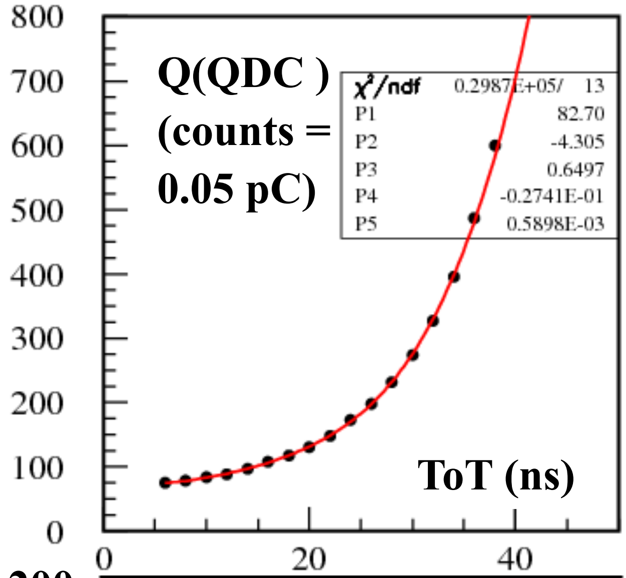
# *LAV front-end electronics – standalone tests*

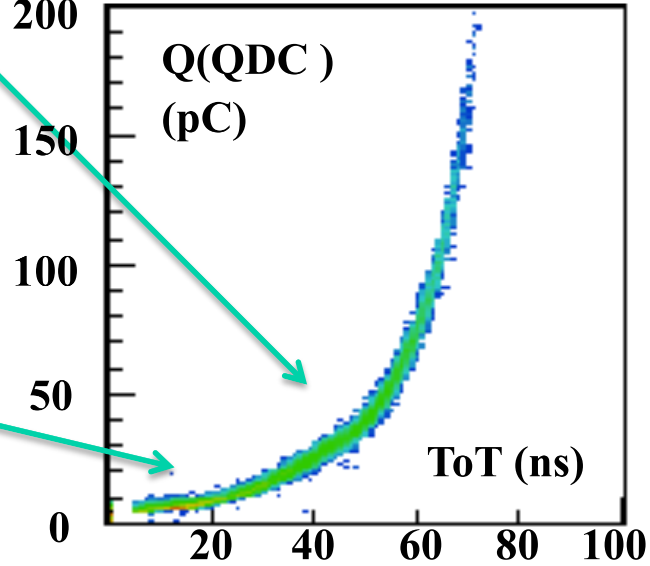
**Cosmic ray test: parametrize charge reconstructed by QDC's as a function of ToT**

**Few % resolution on Q with simple algorithms**

**(possibly implemented in FPGA for trigger)**

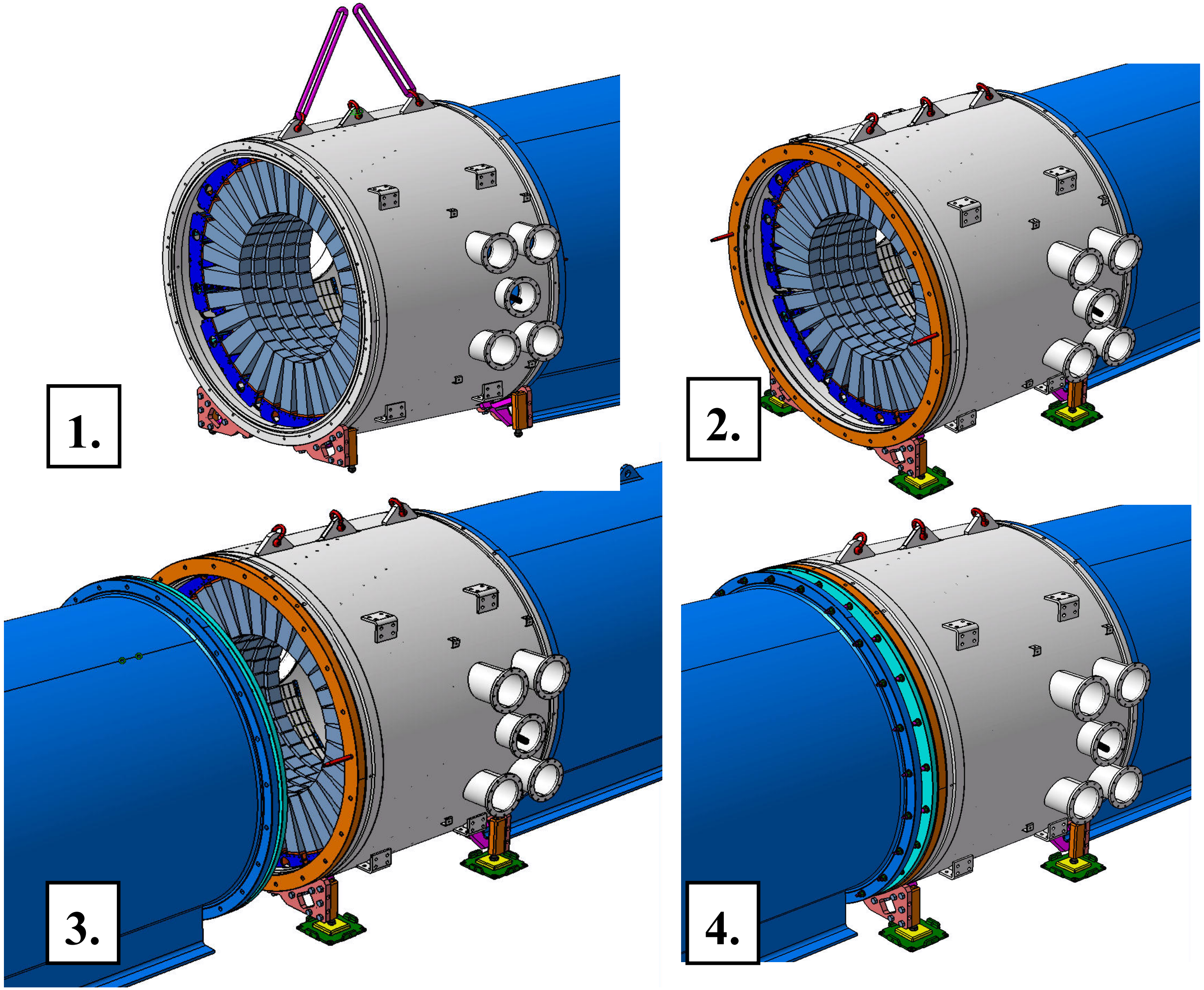


# *LAV installation into the vacuum tank*

1. **Each station is positioned by crane, exploiting conical rods**
2. **On free side, mount a sliding connection ring**
3. **Blue tube segment moved by crane**
4. **Final positioning by means of conical rods**



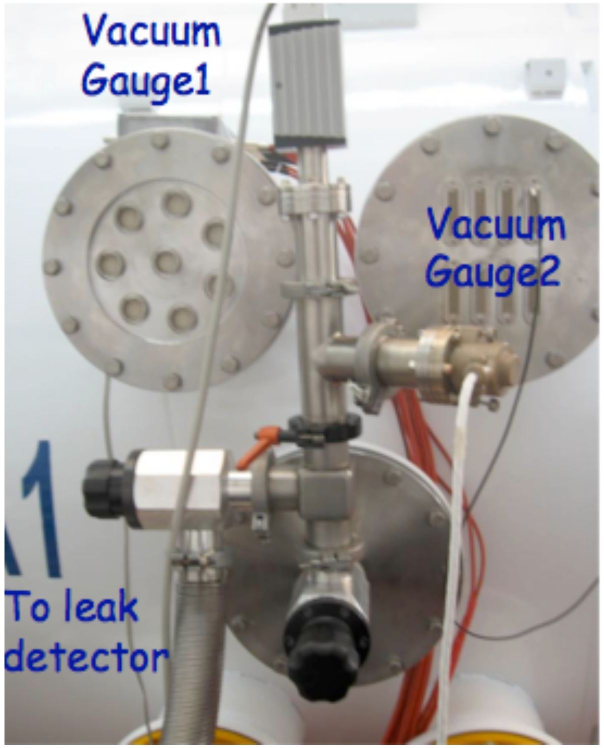
# *LAV installation and vacuum tests*

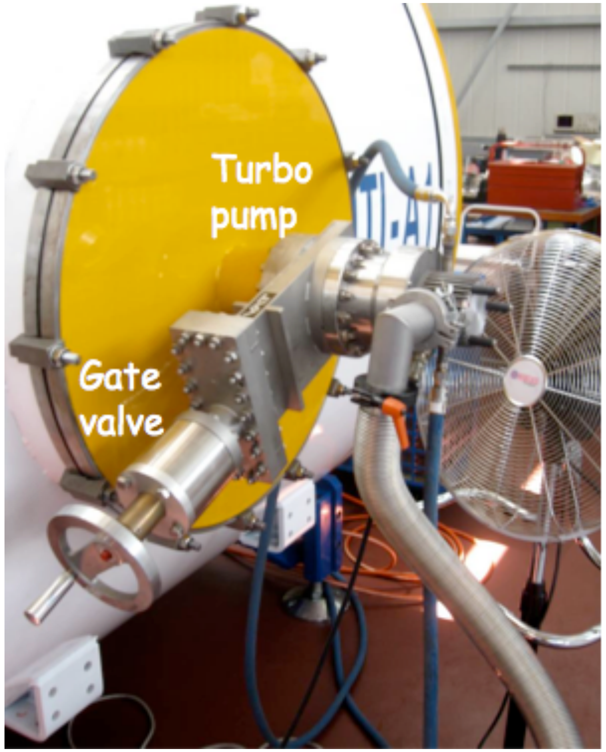
**First LAV station installed at CERN in 2009 allowed for many tests:**

1. **Long term vacuum & out-gassing tests**

**Leaks excluded above the $10^{-10}$ mbar l / s**

**Outgassing rate = (0.9±0.1) $10^{-3}$ mbar l/s, 14 days of pumping at 30°, within specs**



# *LAV performance*

**First LAV station installed at CERN in 2009 allowed for many tests:**

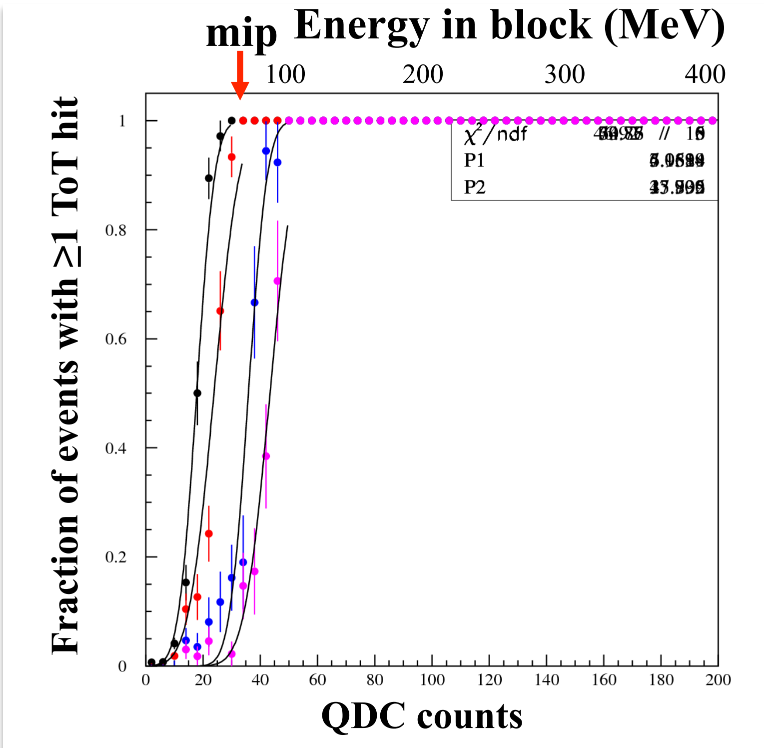
2. **Long term HV tests**
3. **Tests for the integration with decay tube**
4. **Tests with muon & electron beams with E = 2, 4, 6 GeV**

## Threshold optimization

**Energy scale deduced from gain measured during calibration**

**Compare: 7 mV, 10 mV, 15 mV, 25 mV thresholds**

- **Can safely put low threshold at ½ MIP**
- **Higher values used for the 2nd threshold, for slewing corrections**



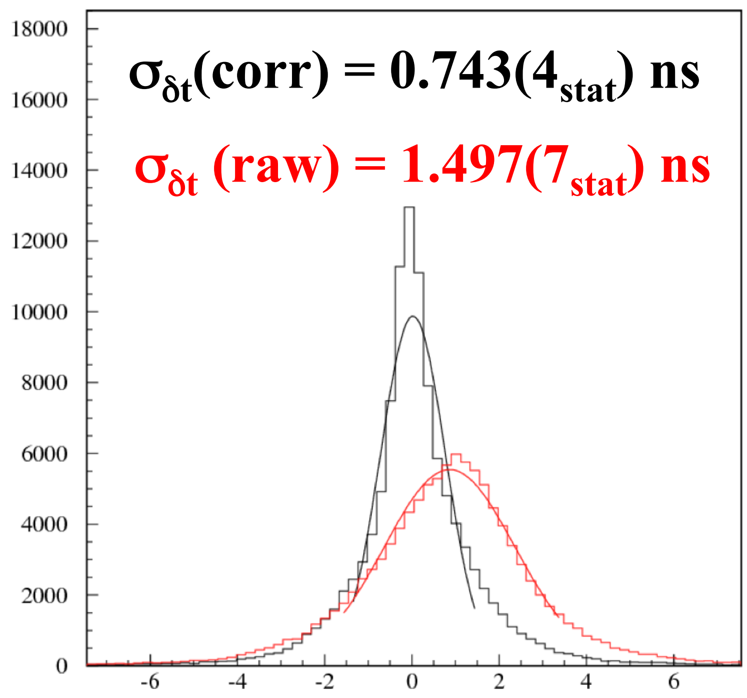
# *LAV performance*

**First LAV station installed at CERN in 2009 allowed for many tests:**

**4. Tests with muon & electron beams with E = 2, 4, 6 GeV**

## Time resolution

- **Analysis of 4-GeV electron data**
- **Time difference between 2 subsequent blocks**
- **Slewing correction 1/Q, using 2 thresholds**
- **Q evaluated from time over threshold, no use of QDC is made**
- **After slewing correction, $\sigma_t \approx 500$ ps / block**



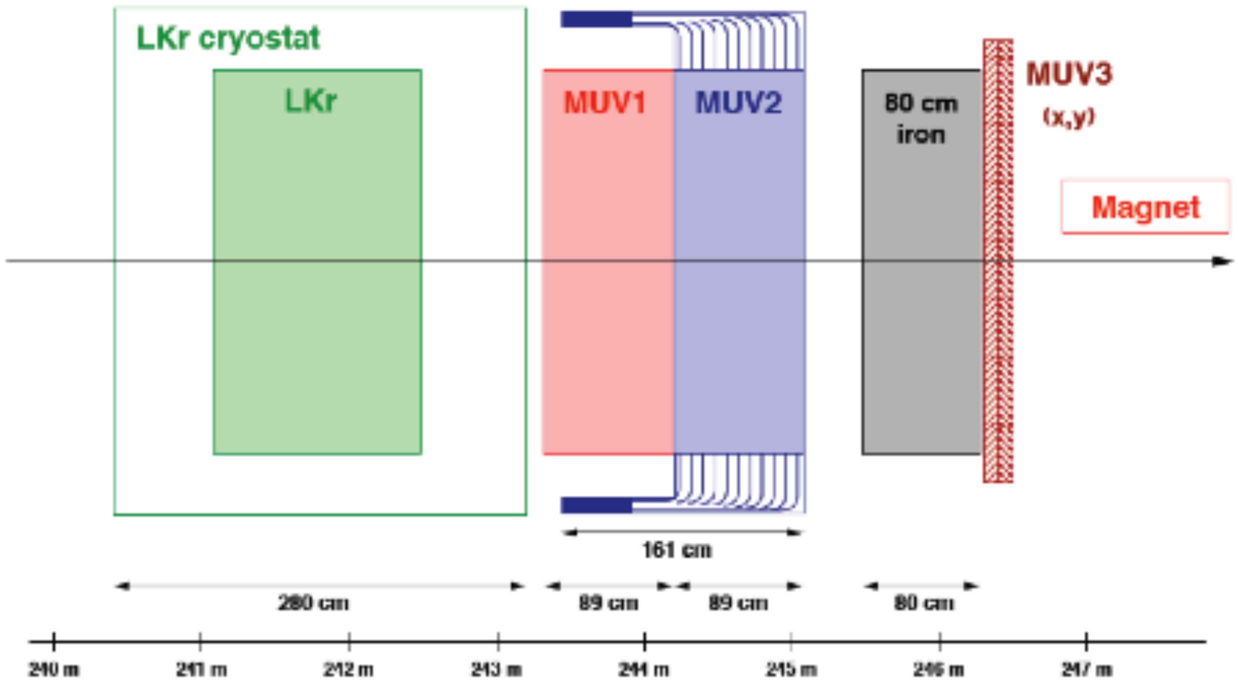

**Time difference, δt (ns)**

# *Muon vetoes (MUV)*

**Muon vetoes downstream LKr electromagnetic calorimeter**

**Redundant information with respect to RICH sub-detector**

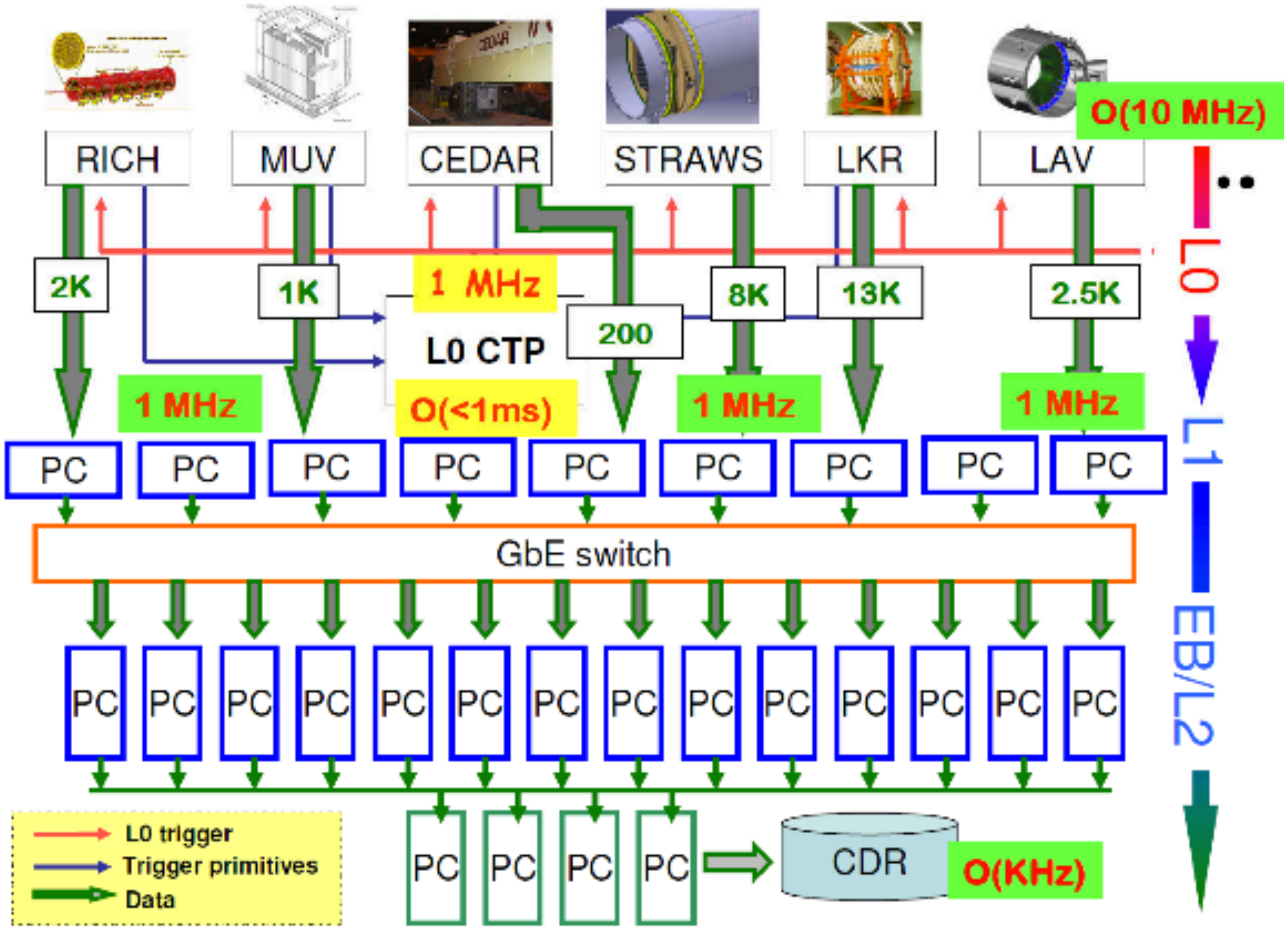
- **MUV1 build anew**
- **MUV2 by reuse of NA48 front module hadron calorimeter**
- **MUV3 after 80cm thick iron wall, fast response for trigger decision**



# *Trigger and data acquisition – an overview*

**Tell1-based TDC's common solution, possibly for all sub-detectors except LKr and GTK**

**All systems running on a coherent 40 MHz clock optically distributed through the TTC system**



# *NA62 expected sensitivity*

| Decay Mode | Events |
|---|---|
| Signal: $K^+ \rightarrow \pi^+\nu\nu$ *[ flux = $4.8\times10^{12}$ decay/year]* | *55 evt/year* |
| $K^+ \rightarrow \pi^+\pi^0$ *[$\eta_{\pi 0} = 2\times10^{-8}$ ($3.5\times10^{-8}$) ]* | 4.3% (7.5%) |
| $K^+ \rightarrow \mu^+\nu$ | 2.2% |
| $K^+ \rightarrow e^+\pi^+\pi^-\nu$ | ≤3% |
| Other 3 – track decays | ≤1.5% |
| $K^+ \rightarrow \pi^+\pi^0\gamma$ | ~2% |
| $K^+ \rightarrow \mu^+\nu\gamma$ | ~0.7% |
| $K^+ \rightarrow e^+(\mu^+)\ \pi^0\nu$, others | negligible |
| Expected background | ≤13.5% (≤17%) |

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

**year & running efficiency from NA48 story: ~100 days/year, 60% data taking efficiency**

# *NA62 past and future*

**In 2007-2008, NA62 “phase 1”:**

- **Runs with original NA48/2 detector, beam carefully tuned for the measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ at few per mil (see C. Lazzeroni talk, WGI)**
- **Data acquired useful for high-statistics studies of Kl3 form factor slopes, needed for Vus extraction (see M. Veltri Talk, WGI)**
- **In parallel, R&D studies for new sub-detectors started**
- **December 2008, approval by CERN research board**

**In 2009-2010, NA62 “phase 2”:**

- **Collaboration consolidated: at present 191 participants from 25 institutes**
- **Main beam tests for advanced prototypes (RICH, GTK) or parts of single sub-detectors (LAV)**

**In 2011-2012, construction and commissioning**

**In 2013, first physics run**

# *Conclusions – an exciting and near future…*

**Precision physics complementary to high-energy approach for NP search**

**The SM prediction for BR($K^+ \rightarrow \pi^+\nu\nu$) is theoretically robust at ~5% level**

**The present knowledge of BR leaves room for possible NP contributions:**

- **$K^+ \rightarrow \pi^+\nu\nu$ is a probe of unique sensitivity for NP BSM**

**NA62 @ CERN will measure BR($K^+ \rightarrow \pi^+\nu\nu$) @ 10% in 2 years (BR~$10^{-10}$)**

- **Ultra-rare decays: need fast tracking, very efficient vetoing, PID, redundancy**

**Intermediate goals of first physics run, thanks to ×50 increase in K flux:**

- **lepton universality test sensitive to NP: measure $R_K$ at the per mil level**
- **refine studies of strong interaction at low energies**
- **push semileptonic K decay studies to state-of-the-art**

# *… but (as usual) a lot of tough work on the way*